Statistics and Error Analysis

Science is based on measurements
& measurements come with some level of uncertainty

measurements test and/or motivate
theoretical understanding

therefore, understanding uncertainties
is KEY in science - science is never about "facts"

Uncertainties originate in two fundamentally different ways:

- measurement errors/uncertainty

  example : number of galaxies in an image

- sample vs. parent distribution

  example : use that number to estimate the density of galaxies on the sky

Uncertainties come in two fundamentally different flavors:

- random errors (limits on precision)

example : how bright is a star

12.1, 12.13, 12.128, or 12.12758909 mag ?

- systematic errors (limits on accuracy)

example : how did dirt in my telescope affect the measurement?

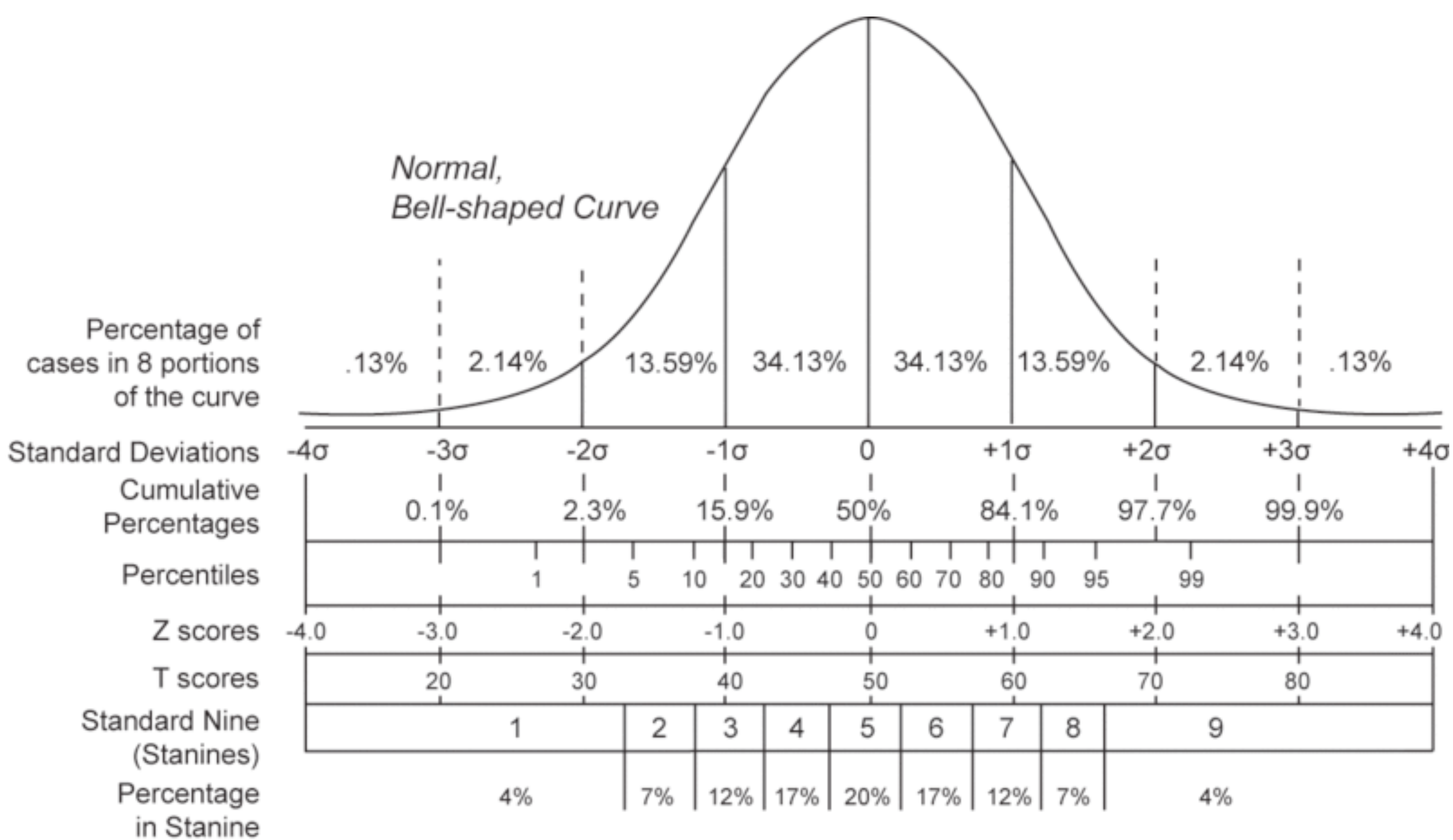
Random errors come with a well developed formalism and techniques for minimizing their effect

- combining results from multiple INDEPENDENT measurements reduces the random error

- the scatter in measurements is typically normally distributed (i.e. Gaussian)

(the sum of these measurements, from which the average is computed, does have Gaussian properties thanks to the central limit theorem)

$$\frac{1}{\sigma\sqrt{2\pi}}\ \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$



Since measurements will bounce around, we need to parameterize the distribution...

• Mean (average): $$\mu = \frac{1}{N}\sum_i x_i$$

• Median: Half of the values are larger, and half of the values are smaller.
– Robust to outliers
– If you have an even number of points, take the average of the middle two

• Mode The most probable value (one that occurs most often).

Example: An observation is made in which a single star is observed 7 times. the number of counts detected from that star in each observation is:

80, 120, 103, 90, 94, 103,17

Mean: (80+120+103+90+94+103+17)/7 = 86.7
Median: 94
Mode: 103

- Variance: $\sigma^2 = \langle (x-\mu)^2 \rangle$
- Standard Deviation: $\sigma = \sqrt{\langle x^2 \rangle - \langle x \rangle}$ **or** $\sigma = \sqrt{\frac{1}{N}\sum_i (x_i - \bar{x})^2}$

Standard deviation is important for determining uncertainties. For a Gaussian distribution,
$\longrightarrow$ 68.3% probability that the true values is within 1 σ of the mean
$\longrightarrow$ 95.4% probability that the true values is within 2 σ of the mean
$\longrightarrow$ 99.7% probability that the true values is within 3 σ of the mean

uncertainties are then usually quoted via +-

example: $X = 3.5 \pm 0.3 \qquad (1\sigma)$

be careful with significant figures...

$$X = 3.5123 \pm 0.3234$$

shows you don't understand errors!

“Robust” Statistics

- Iterative ***“Sigma Clipping”*** is a common technique in astronomy for dealing with outliers

  example: cosmic rays

- Basic method (iterative):

1. Compute the mean (median) and standard deviation.
2. Reject all points >Nσ away from the mean (median) as outliers.
   A typical value for N might be 5 or 10. How do you choose this?
3. Recompute the mean (median) and standard deviation, and again reject outliers.
4. Repeat until you are no longer rejecting any points.

MANY OTHER APPROACHES AS WELL

Mathematical Descriptions of Distributions

Binomial Distribution (good for binary outcome problems)

$$P_B(x, n, p) = \left(\begin{array}{c} n \\ x \end{array} \right) p^x q^{n-x}$$

$q \equiv 1 - p$

p: probability of "true" outcome

n: total number of trials

x: number of "true" outcomes

$$\left(\begin{array}{c} n \\ x \end{array} \right) \equiv \frac{n!}{x!(n-x)!}$$

Poisson Distribution (good for counting problems)

special case of binomial for which p<<1

$$P_B(x, n, p) = \frac{1}{x!}\frac{n!}{(n-x)!}p^x(1-p)^n(1-p)^{-x}$$

$$\frac{n!}{(n-x)!} = n(n-1)(n-2)...(n-x+2)(n-x+1)$$

x terms that are all approx. n

$$= n^x$$

$$n^x p^x \rightarrow (np)^x \approx \mu^x \qquad (1-p)^{-x} \rightarrow 1 \text{ as } p \rightarrow 0$$

$$\lim_{p\to 0}(1-p)^n = \lim_{p\to 0}[(1-p)^{1/p}]^\mu$$

$$= (\frac{1}{e})^\mu = e^{-\mu}$$

$$\lim_{p\to 0} P_B(x,n,p) = P_P(x,\mu) \equiv \frac{\mu^x}{x!}e^{-\mu}$$

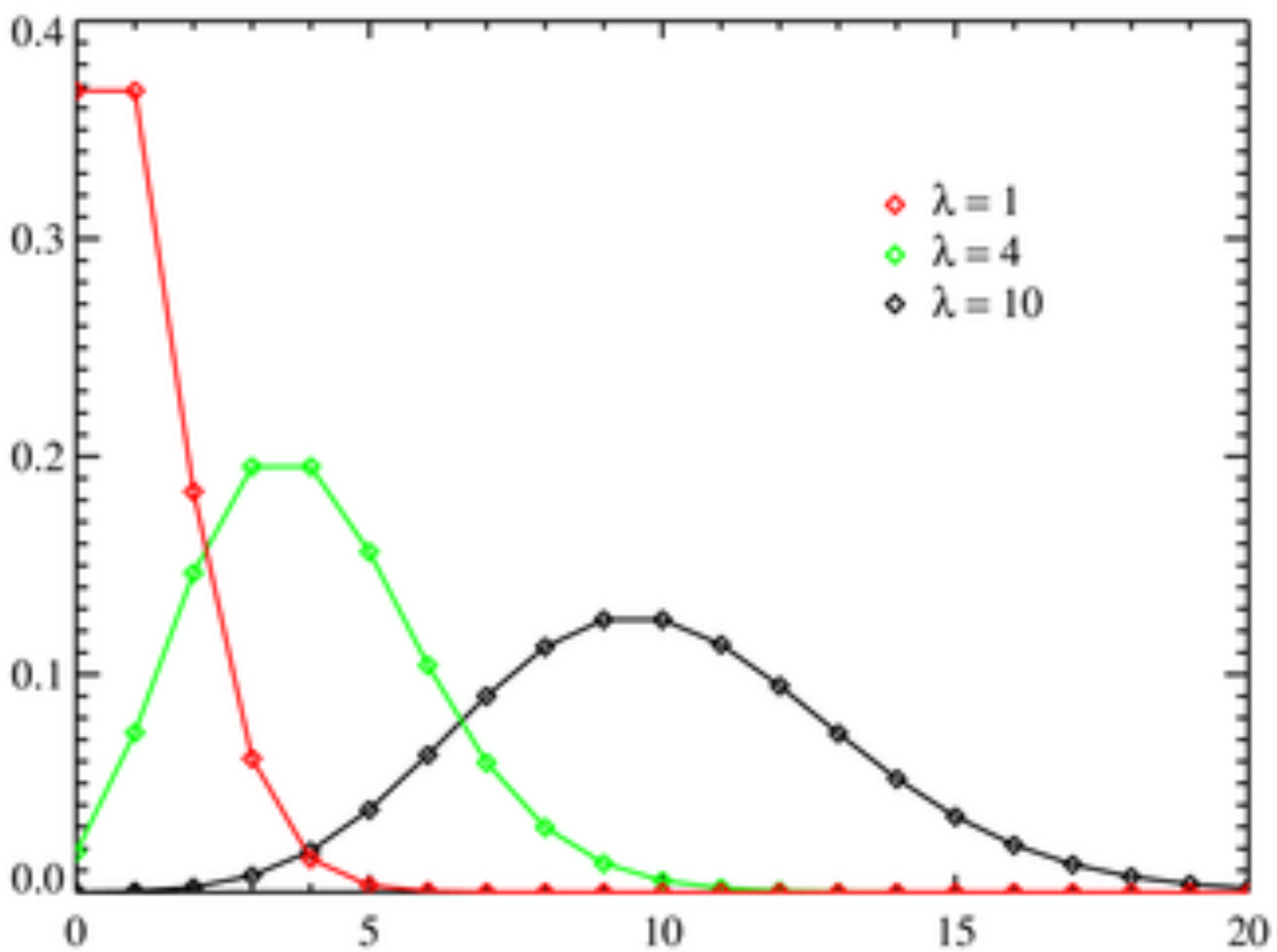
$P_P \neq 0$ as $x \to 0$

mean $= \mu$

standard deviation $= \sqrt{\mu}$

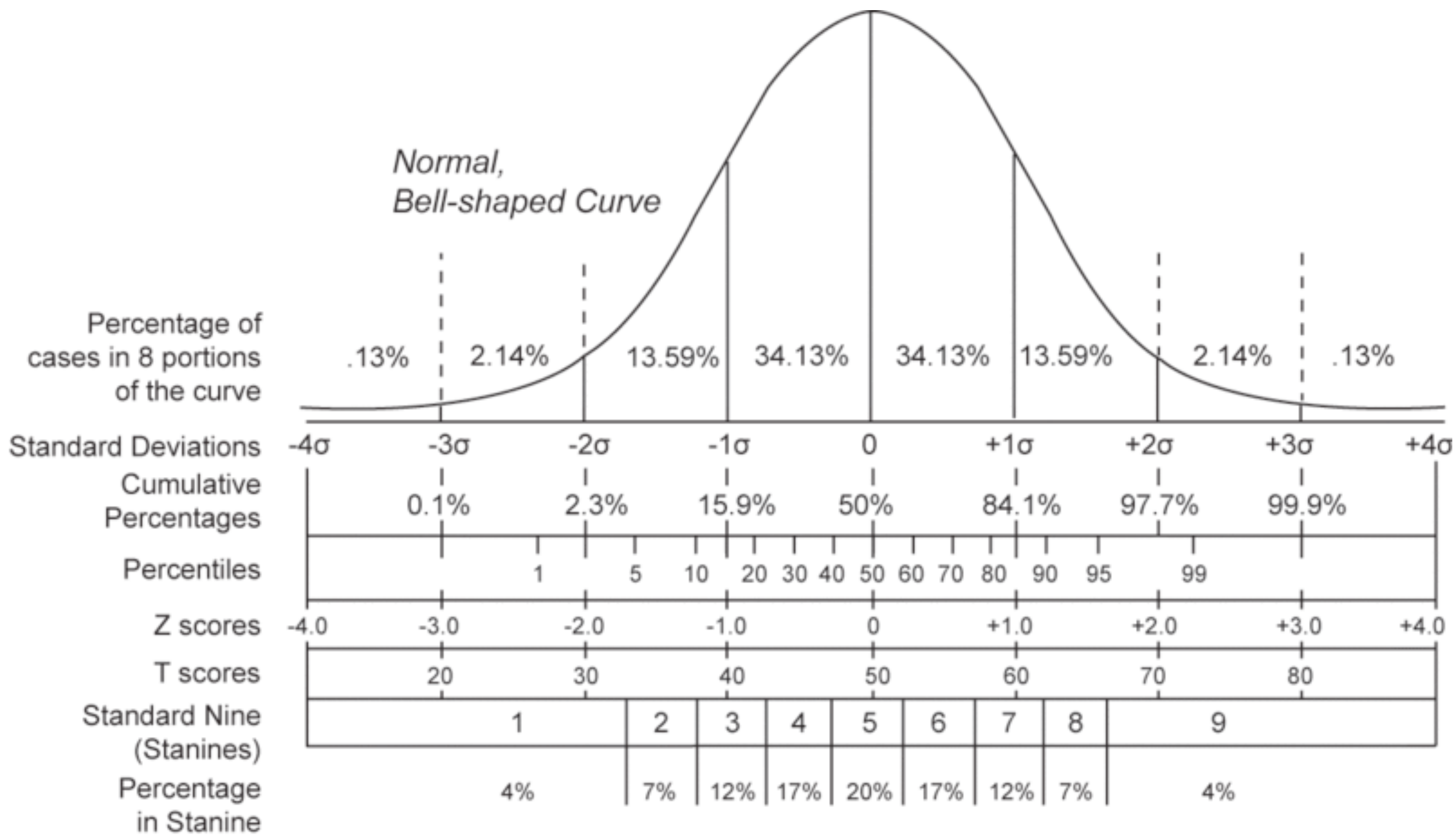
Example, if four photons arrive on average every second you would use as model a Poisson distribution with lambda $\lambda = 4$

From the plot below (green lambda=4 curve) we see that there is a ~20% chance of collecting exactly 4 photons in 1 second (even though this is the average value). The probability of collecting 8 photons is ~ 4%.



Gaussian (Poisson as mean gets large)

$$P_G(x,\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$



Propagation of Errors

measurements are often combined in calculations - how do the errors in individual measurements propagate to the final quantity?

example: $V = L \cdot W \cdot H$ L,W, H each has an error

$$\Delta V \approx \Delta L \frac{\partial V}{\partial L} + ...$$

more general case ...

$$x = f(u, v, ...)$$

$$x_i - \bar{x} \approx (u_i - \bar{u})\frac{\partial x}{\partial u} + (v_i - \bar{v})\frac{\partial x}{\partial v} + ...$$

$$\lim_{N\to\infty} \frac{1}{N}(x_i - \bar{x})^2 \equiv \sigma_x^2 = \lim_{N\to\infty} \frac{1}{N} \sum [...]^2$$

$$\sigma_x^2 \approx \sigma_u^2 (\frac{\partial x}{\partial u})^2 + \sigma_v^2 (\frac{\partial x}{\partial v})^2 + ...$$

(sets all cross-terms to zero - equivalent to assuming all variables are 100% independent)

Examples:

- addition:

$$x = 3.5 \pm 0.2, y = 8.2 \pm 1.2$$

$$z = x + y, \sigma_z = ?$$

$$\sigma_z^2 = (1)^2(0.2)^2 + (1)^2(1.2)^2$$

$$\sigma_z^2 = 0.04 + 1.44 = 1.48$$

$$\sigma_z = 1.22$$

$$z = 11.7 \pm 1.2$$

not much point in working hard to reduce uncertainty in x

- subtraction

$$x = 123.20 \pm 0.87, y = 123.12 \pm 0.73$$

$$z = x - y, \sigma_z = ?$$

$$\sigma_z^2 = (1)^2(0.87)^2 + (1)^2(0.73)^2$$

$$\sigma_z^2 = 0.7569 + 0.5329 = 1.2898$$

$$\sigma_z = 1.14$$

$$z = 0.08 \pm 1.14$$

difficult to look for difference between two large numbers - this is why we don’t observe in daytime!

multiplication and exponents:

$$x = 3.2 \pm 0.3, y = 6.5 \pm 1.2$$

$$z = xy^3, \sigma_z = ?$$

$$\sigma_z^2 = (y^3)^2(\sigma_x)^2 + (3xy^2)^2(\sigma_y)^2$$

$$\sigma_z^2 = (6.5^3)^2(0.3)^2 + (3 \cdot 3.2 \cdot 6.5^2)^2(1.2)^2$$

Fitting a model

many times you need to compare to a model
(an equation)

$$\chi^2 = \sum_{j=1}^{n} \frac{(y_j - model(x_j))^2}{\sigma_j^2}$$

$$\text{perfect agreement } \rightarrow \chi^2 = 0$$

$$\text{expected agreement } \rightarrow \chi^2 = \sum \frac{\sigma^2}{\sigma^2} = N$$

can use the distribution of chi^2 to rule out models
(never to “prove” the validity of a model)

unusually large chi^2 must show model is poor

- chi^2 can also be large because N is large
(so need to normalize by N)

- chi^2 can be artificially low because you have a lot of free parameters in the model (so need to normalize by free parameters) reduced $\rightarrow \chi^2 = \chi^2/\nu$, where $\nu = N -$ No. of free parameters

df	0.995	0.99	0.975	0.95	0.90	0.10	0.05	0.025	0.01	0.005
1	---	---	0.001	0.004	0.016	2.706	3.841	5.024	6.635	7.879
2	0.010	0.020	0.051	0.103	0.211	4.605	5.991	7.378	9.210	10.597
3	0.072	0.115	0.216	0.352	0.584	6.251	7.815	9.348	11.345	12.838
4	0.207	0.297	0.484	0.711	1.064	7.779	9.488	11.143	13.277	14.860
5	0.412	0.554	0.831	1.145	1.610	9.236	11.070	12.833	15.086	16.750
6	0.676	0.872	1.237	1.635	2.204	10.645	12.592	14.449	16.812	18.548
7	0.989	1.239	1.690	2.167	2.833	12.017	14.067	16.013	18.475	20.278
8	1.344	1.646	2.180	2.733	3.490	13.362	15.507	17.535	20.090	21.955

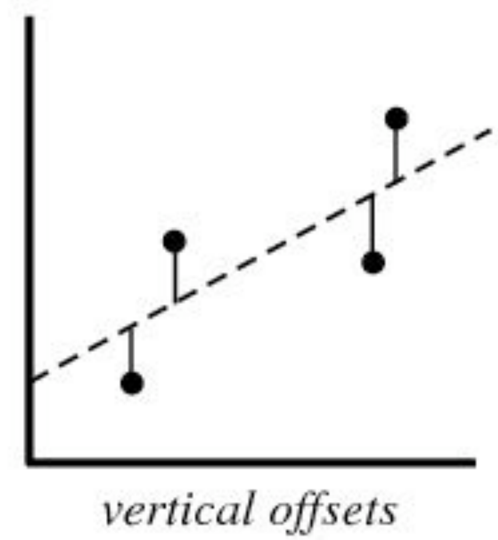
these are for chi^2 where df is nu

fitting a model

least-squares fitting of a line (minimize the vertical offsets, inversely weighted by sigmas)

in general,

$$R^2 \equiv \sum [y_i - f(x_i, a_1, a_2, ..., a_n)]^2$$



for a line

$$f = a_1 + a_2 x$$

to minimize R solve $\dfrac{\partial(R^2)}{\partial a_i} = 0$

see http://mathworld.wolfram.com/LeastSquaresFitting.html

solving for the linear coefficients and their uncertainties (y = a + bx)

$$a = \frac{1}{\Delta}\left(\sum \frac{x_i^2}{\sigma_i^2}\sum \frac{y_i}{\sigma_i^2} - \sum \frac{x_i}{\sigma_i^2}\sum \frac{x_i y_i}{\sigma_i^2}\right)$$

$$b = \frac{1}{\Delta}\left(\sum \frac{1}{\sigma_i^2}\sum \frac{x_i y_i}{\sigma_i^2} - \sum \frac{x_i}{\sigma_i^2}\sum \frac{y_i}{\sigma_i^2}\right)$$

$$\Delta = \sum \frac{1}{\sigma_i^2}\sum \frac{x_i^2}{\sigma_i^2} - \left(\sum \frac{x_i}{\sigma_i^2}\right)^2$$

$$\sigma_a^2 \approx \frac{1}{\Delta}\sum \frac{x_i^2}{\sigma_i^2}$$

$$\sigma_b^2 \approx \frac{1}{\Delta}\sum \frac{1}{\sigma_i^2}$$

Many other tests available to answer
a range of questions:

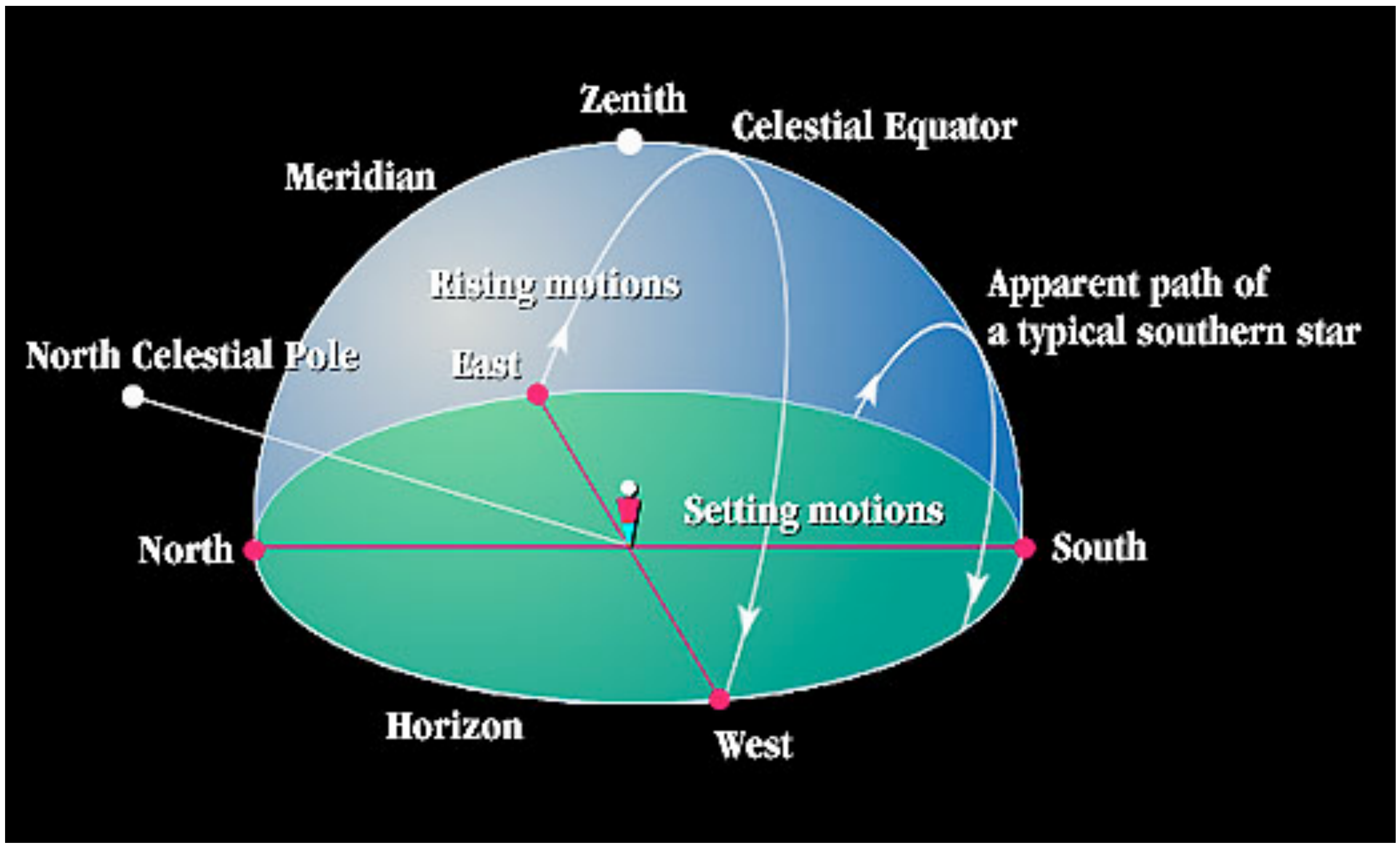
- does X relate to Y? Correlation analysis

- is the distribution of X inconsistent with that of Y? KS test

- are there subpopulations in X? clustering analysis

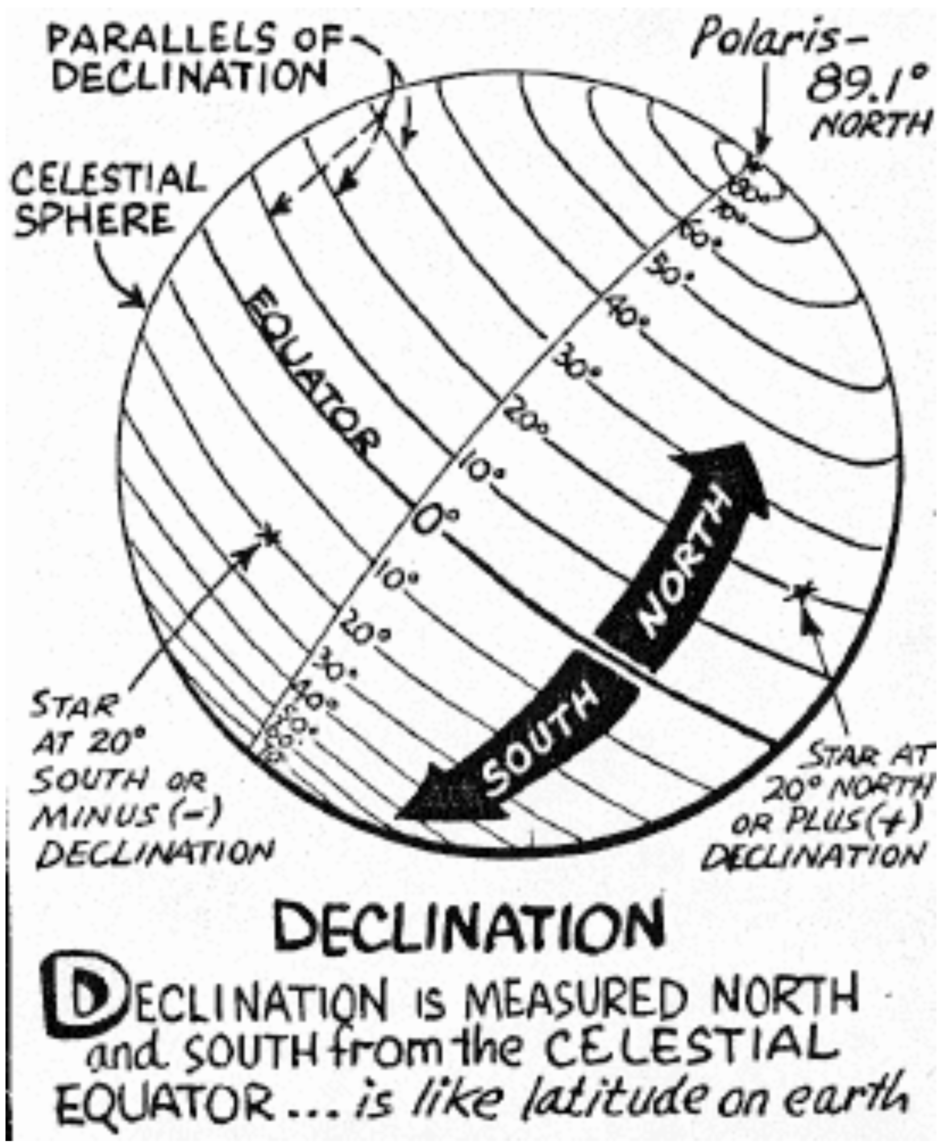
- is there an underlying driving quantity? principle component analysis

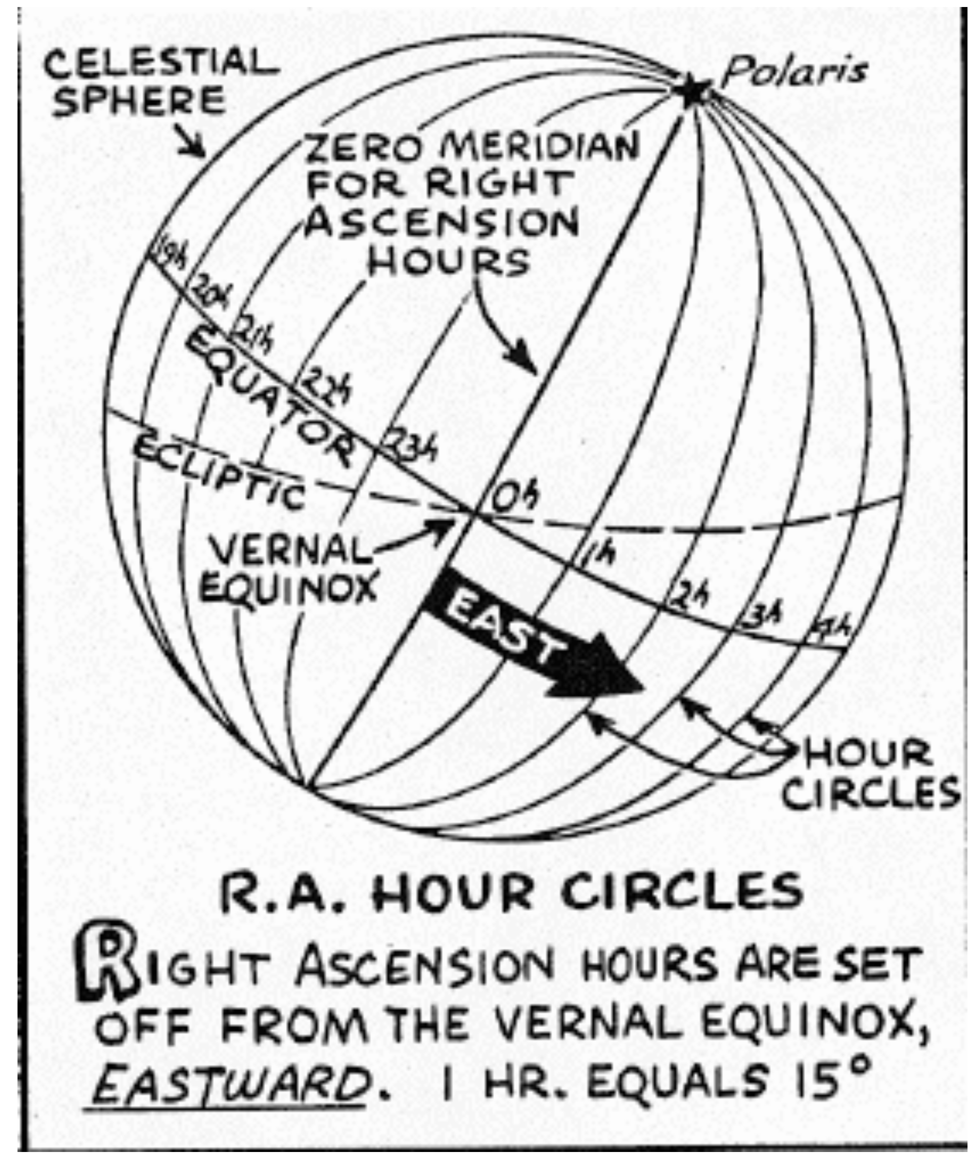
Coordinates, Catalogs, and Surveys



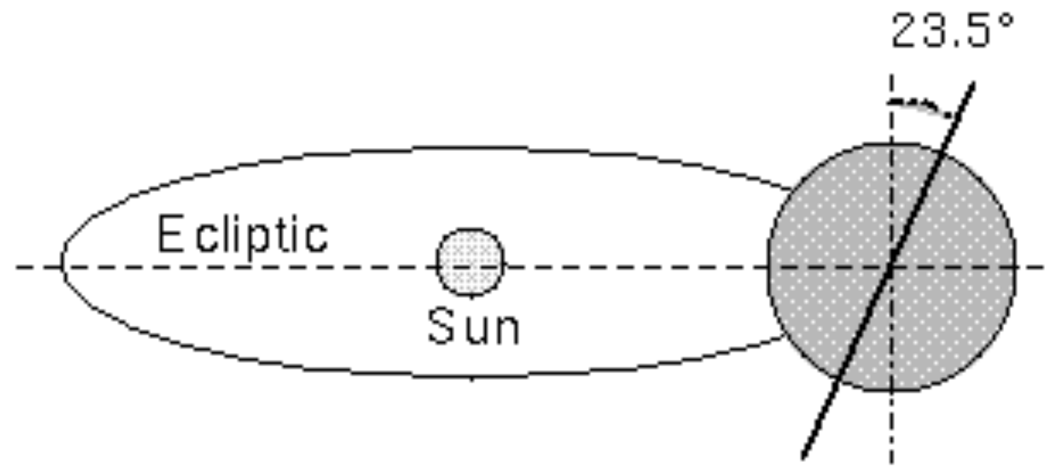
observer in northern hemisphere

Right ascension & Declination (α, δ)

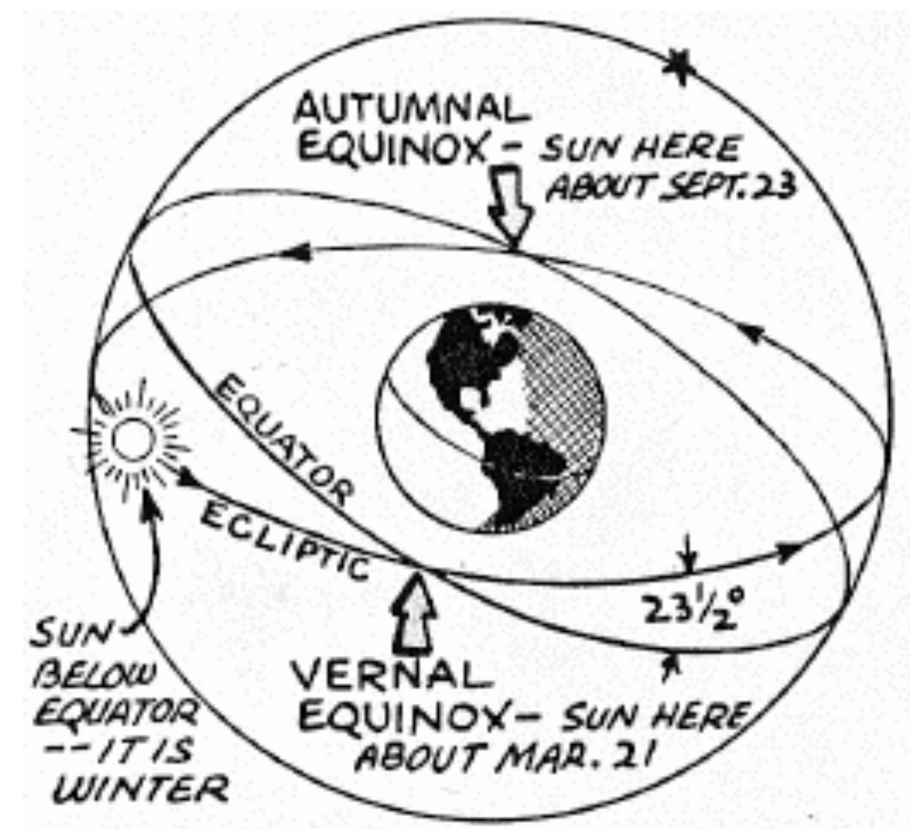




some material from http://www.astro.virginia.edu/class/oconnell/astr130/motions-coords-f08.html



Earth's rotation axis is tilted by 23.5° with respect to the ecliptic (its orbital plane).



THE EQUINOXES

THE EQUINOXES ARE THE TWO POINTS WHERE THE ECLIPTIC CROSSES THE CELESTIAL EQUATOR

ecliptic coordinates are not aligned with ra,dec

Declination is measured (in degrees) north or south of the celestial equator. The North and South celestial poles have DECs of +90 and -90 degrees, respectively. The equator has DEC 0.

RA is measured in time units of hours, minutes, and seconds up to one sidereal day. Therefore, RA values run from 0 hours to $23^h59^m59^s$.

Zero RA definition is arbitrary

At equator, one hour of RA corresponds to 15 degrees of arc. At other declinations one hour of RA corresponds to fewer than 15 degrees of arc. Beware confusion between "minutes" and "seconds" of time and those of arc!

$$\Delta\alpha('') = \Delta\alpha(time) \cdot 15 cos\delta$$

things to remember:

sidereal time is the H.A. of the vernal equinox
(sidereal day 4 min shorter than solar day)

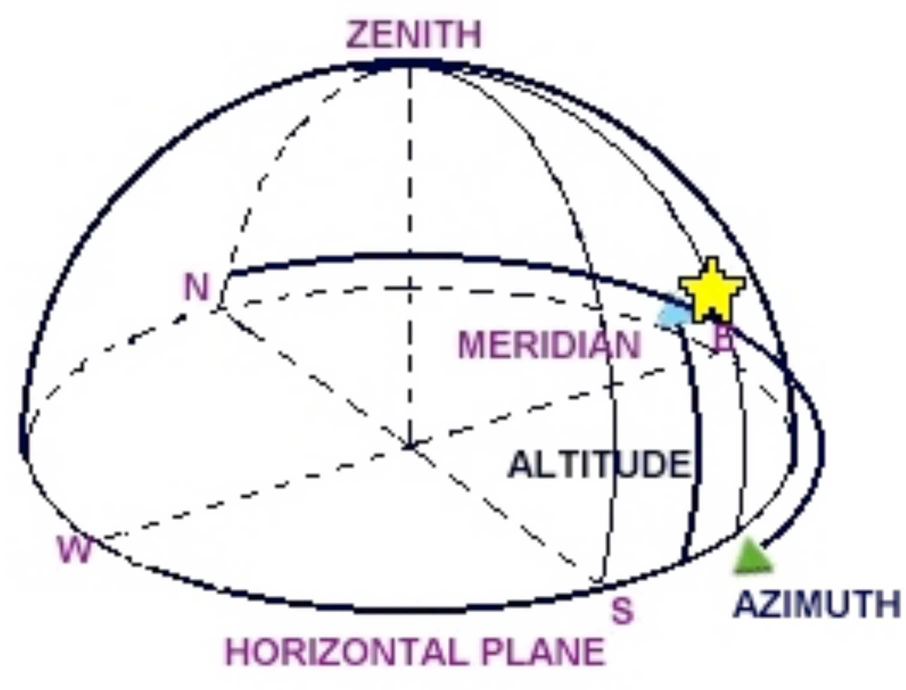
ra = 0 overhead at midnight on Sept. 21

ra = 12 overhead at midnight on March 21

each month corresponds to ~ 2 sidereal hours

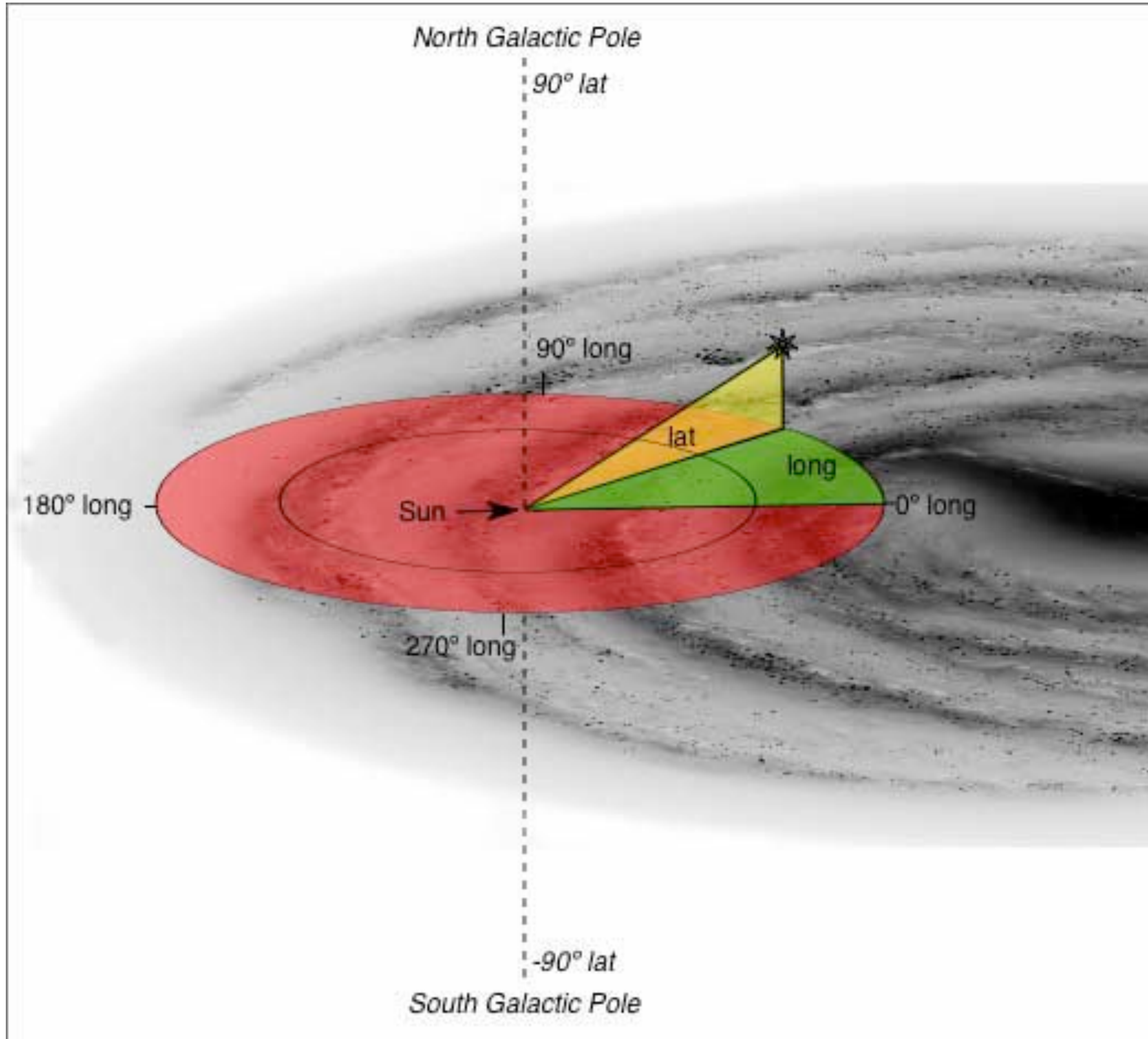
UT (universal time) is the local solar time
at Greenwich, England

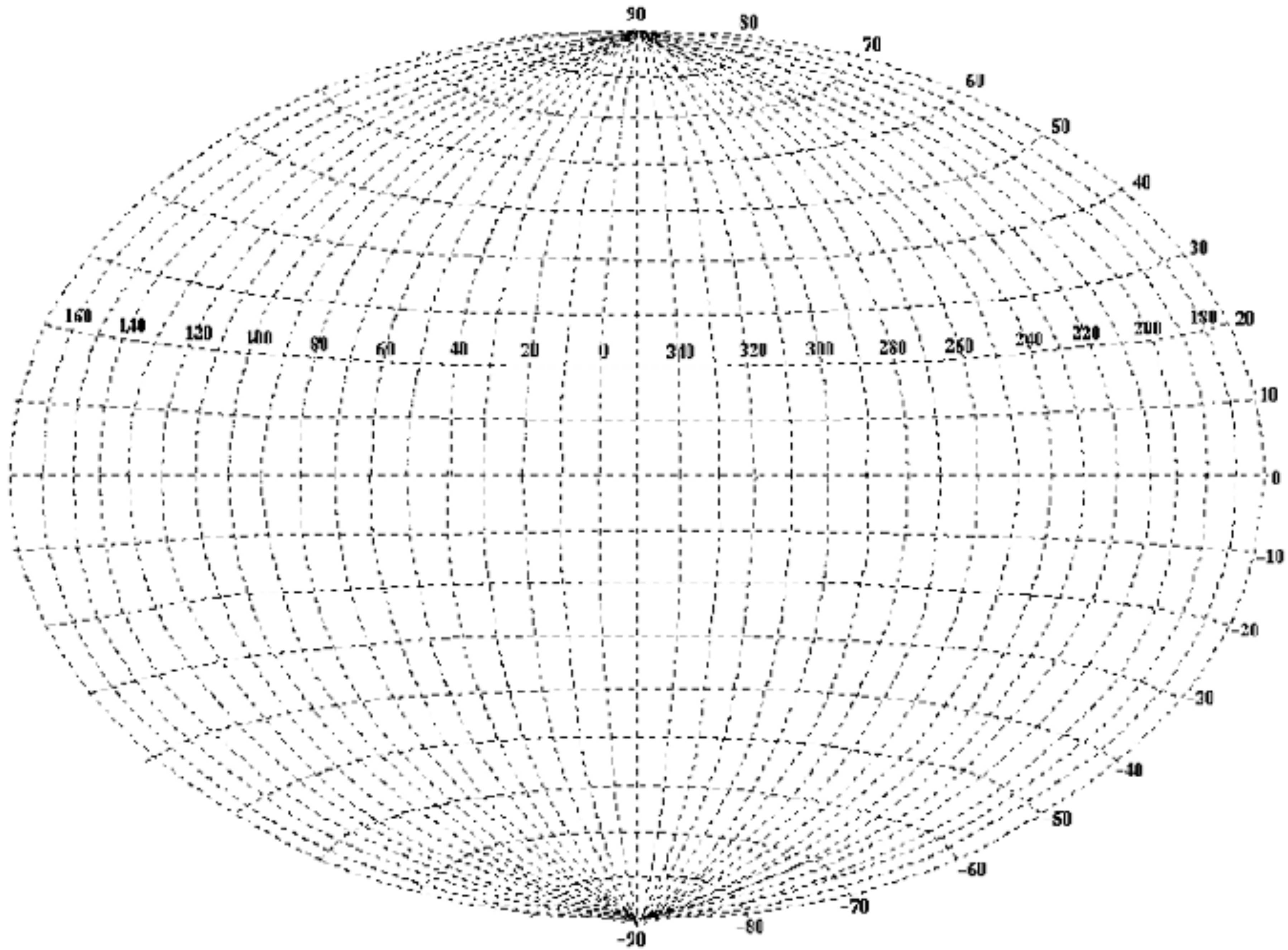
Alt-Az Coordinates



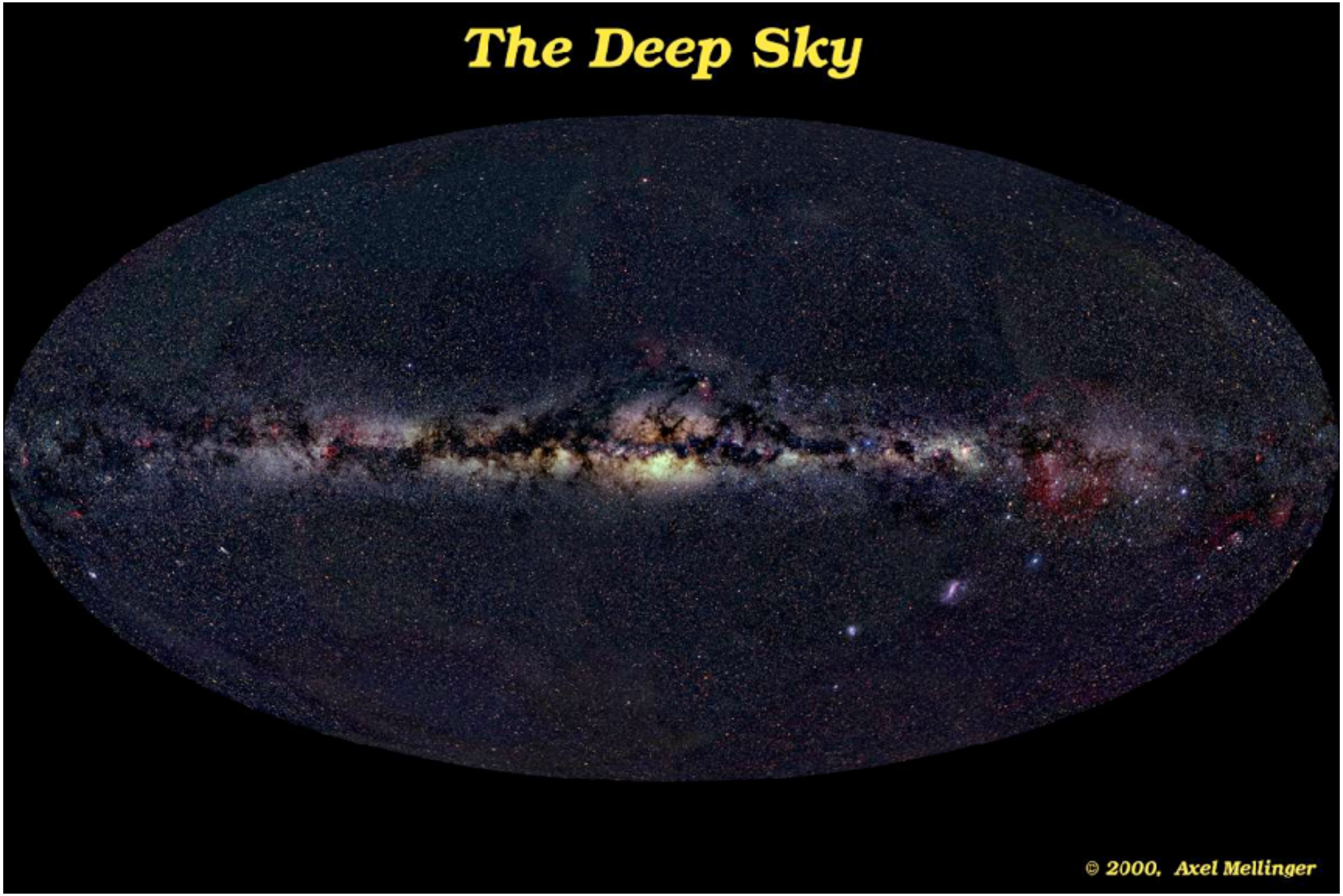
more telescope are now alt-az (although user coordinates are still ra,dec)

Galactic Coordinates





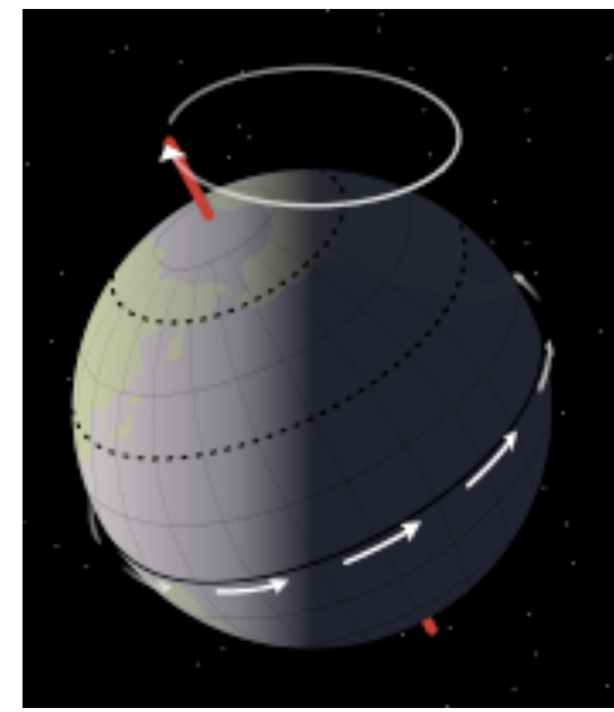
plotting galactic coordinates


The Deep Sky
© 2000, Axel Mellinger

Do coordinates change?

- precession and nutation (Earth's wobble)

precession loop takes ~ 25,500 yrs



Vega will be near the
north celestial pole in
12000 yrs

50"/yr

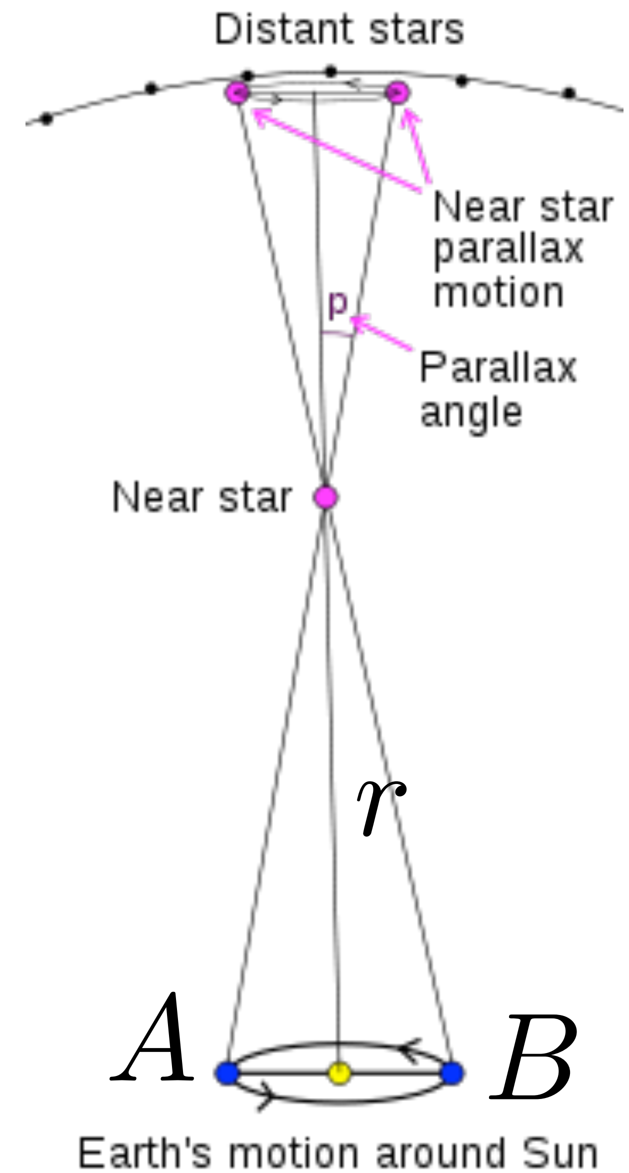
need to specify "epoch" of coordinate system

- parallax

$$\frac{AB}{2\pi r} = \frac{P''}{360^\circ \cdot 3600''/^\circ}$$

$$r = 206265\frac{AB}{P''}$$

$$P'' = 1/r(pc)$$

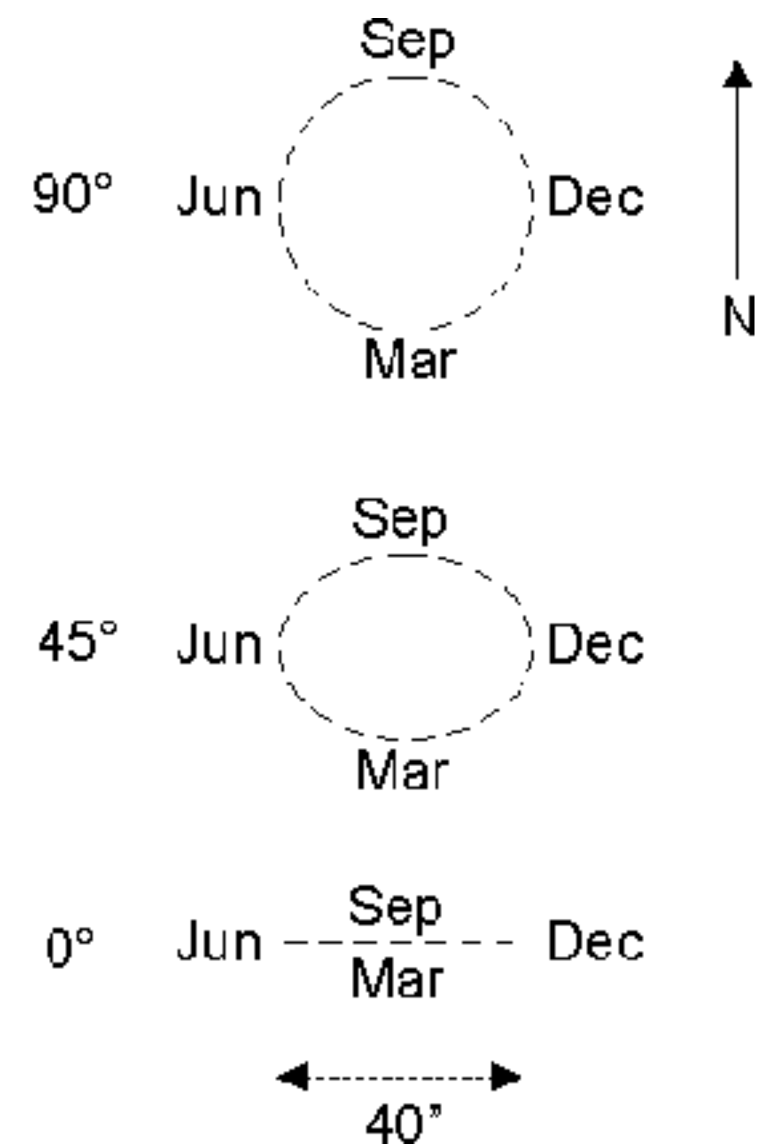


- proper motion

Barnard's star 10.3 arcsec/yr

- aberration of starlight

due to finite velocity of light and Earth's velocity



at ecliptic longitude 270 and various ecliptic latitudes

- atmospheric refraction

bending of light path by atmosphere (pushes apparent object toward zenith)

1 arcmin at 45 deg altitude

5 arcmin at 10 deg altitude

34 arcmin at 0 deg altitude

color dependent

Catalogs

- Messier catalog (the reason for M 31, M51, etc.)

- Bonner Durchmusterung (BD), Cordoba Durchmesterung, Cape Photographic Durchmusterung
  (year ~ 1900, estimated magnitude)

- Henry Draper Catalog (HS) - Harvard, 1918 (Annie Jump Cannon and Edward Pickering), spectral classification of 250,000 stars

- Bright Star catalog ~ 9100 stars

- New General Catalog (NGC) - Dreyer 1988, revised, updated by Sulentic & Tifft (1973)

- SAO (all sky, V < 10, 259,000 stars)

- IRAS point source catalog (IR measurements all sky)

- Hubble atlas (galaxies)

- Revised Shapley-Ames Catalog (Sandage & Tammann 1981)

- Third Reference Catalog of Bright Galaxies (RC3) (de Vaucouleurs et al)

- Atlas of Pecular Galaxies (Arp 1966)

- Catalog of Rich Clusters of Galaxies (Abell et al. 1989)

- Digitized Sky Survey (DSS), Palomar all sky

- Burstein & Heiles (more recently Schlegel, Davis, and Finkbeiner) for galactic extinction
  http://astron.berkeley.edu/davis/dust/

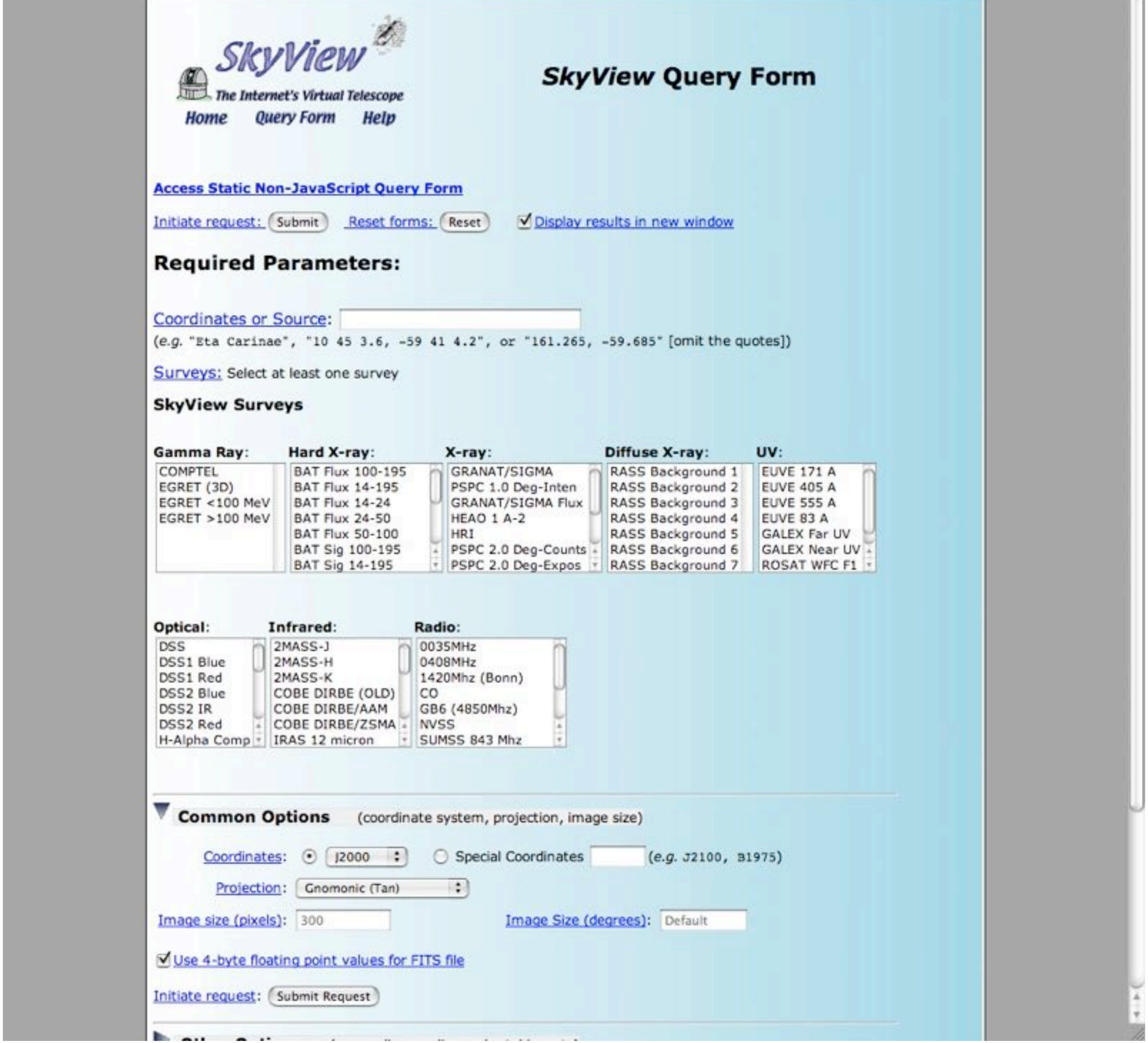
- 2 Micron All-Sky survey (2MASS)

- Hipparcos

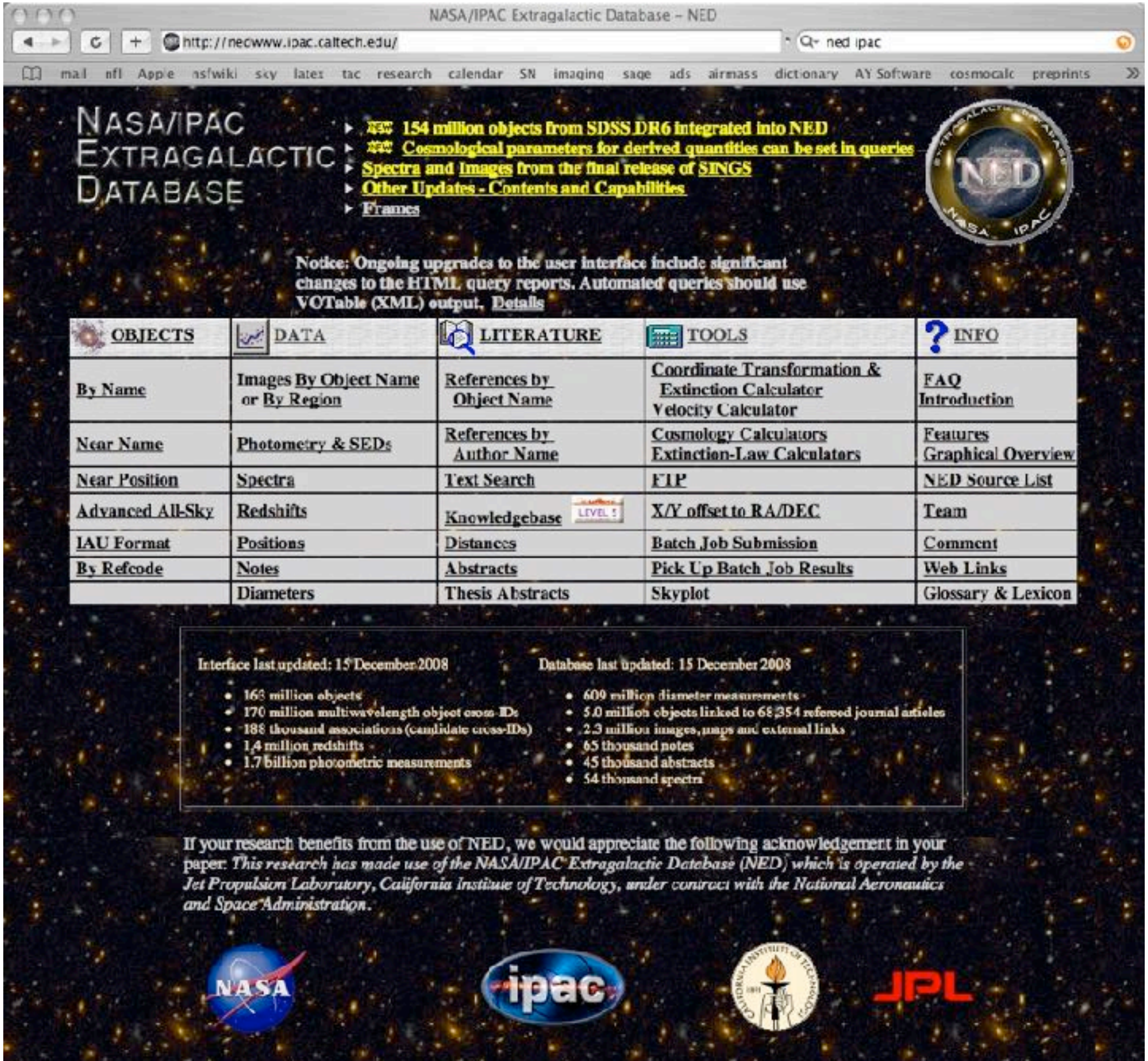
- Sloan Digital Sky Survey (SDSS)

Web Resources

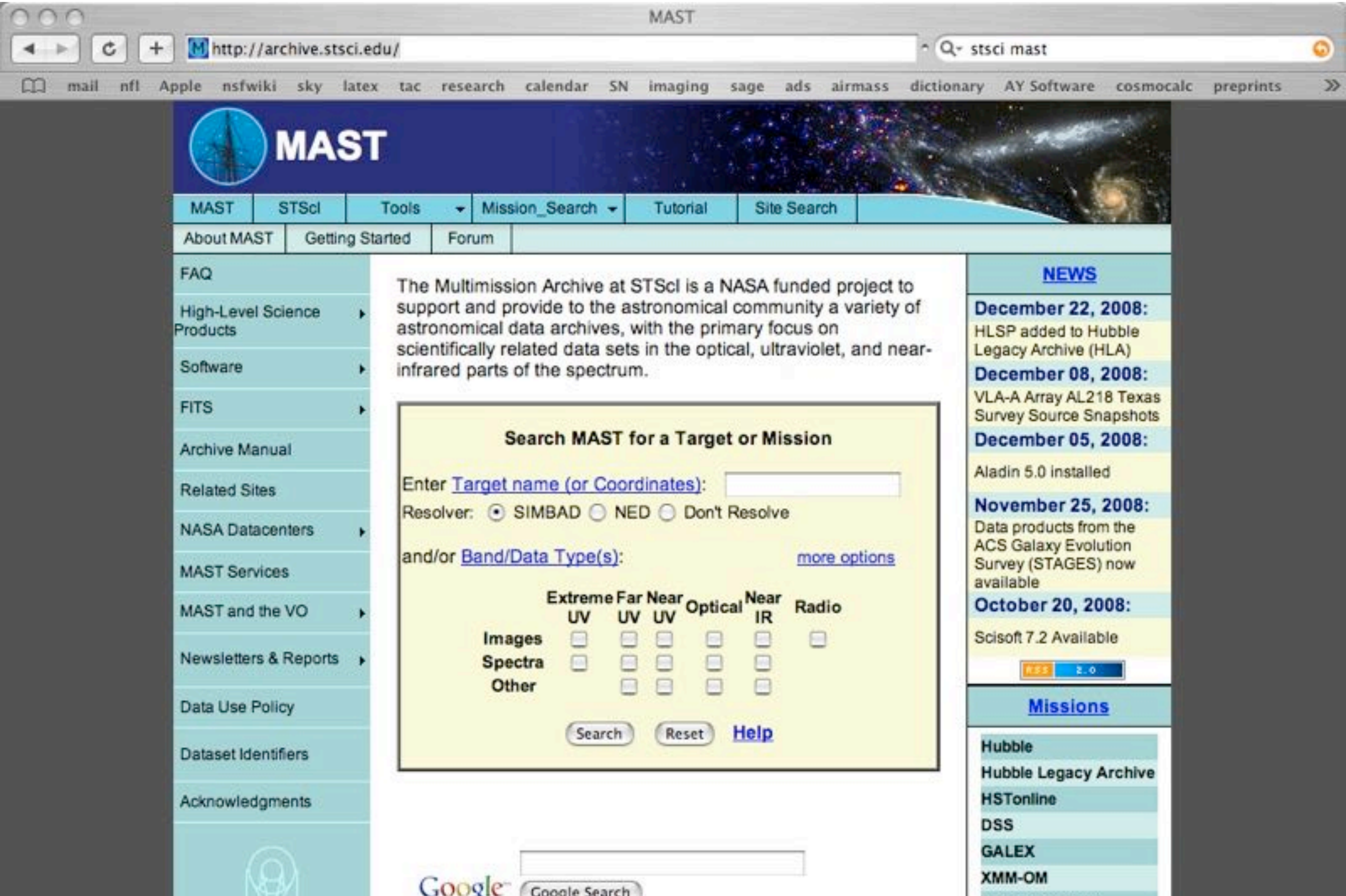
- skyview (http://skyview.gsfc.nasa.gov/)


SkyView
The Internet's Virtual Telescope
Home
Query Form
Help
SkyView Query Form
Access Static Non-JavaScript Query Form
Initiate request: Submit
Reset forms: Reset
Display results in new window
Required Parameters:
Coordinates or Source:
(e.g. "Eta Carinae", "10 45 3.6, -59 41 4.2", or "161.265, -59.685" [omit the quotes])
Surveys: Select at least one survey
SkyView Surveys
Gamma Ray:
COMPTEL
EGRET (3D)
EGRET <100 MeV
EGRET >100 MeV
Hard X-ray:
BAT Flux 100-195
BAT Flux 14-195
BAT Flux 14-24
BAT Flux 24-50
BAT Flux 50-100
BAT Sig 100-195
BAT Sig 14-195
X-ray:
GRANAT/SIGMA
PSPC 1.0 Deg-Inten
GRANAT/SIGMA Flux
HEAO 1 A-2
HRI
PSPC 2.0 Deg-Counts
PSPC 2.0 Deg-Expos
Diffuse X-ray:
RASS Background 1
RASS Background 2
RASS Background 3
RASS Background 4
RASS Background 5
RASS Background 6
RASS Background 7
UV:
EUVE 171 A
EUVE 405 A
EUVE 555 A
EUVE 83 A
GALEX Far UV
GALEX Near UV
ROSAT WFC F1
Optical:
DSS
DSS1 Blue
DSS1 Red
DSS2 Blue
DSS2 IR
DSS2 Red
H-Alpha Comp
Infrared:
2MASS-J
2MASS-H
2MASS-K
COBE DIRBE (OLD)
COBE DIRBE/AAM
COBE DIRBE/ZSMA
IRAS 12 micron
Radio:
0035MHz
0408MHz
1420Mhz (Bonn)
CO
GB6 (4850Mhz)
NVSS
SUMSS 843 Mhz
Common Options (coordinate system, projection, image size)
Coordinates: J2000
Special Coordinates (e.g. J2100, B1975)
Projection: Gnomonic (Tan)
Image size (pixels): 300
Image Size (degrees): Default
Use 4-byte floating point values for FITS file
Initiate request: Submit Request

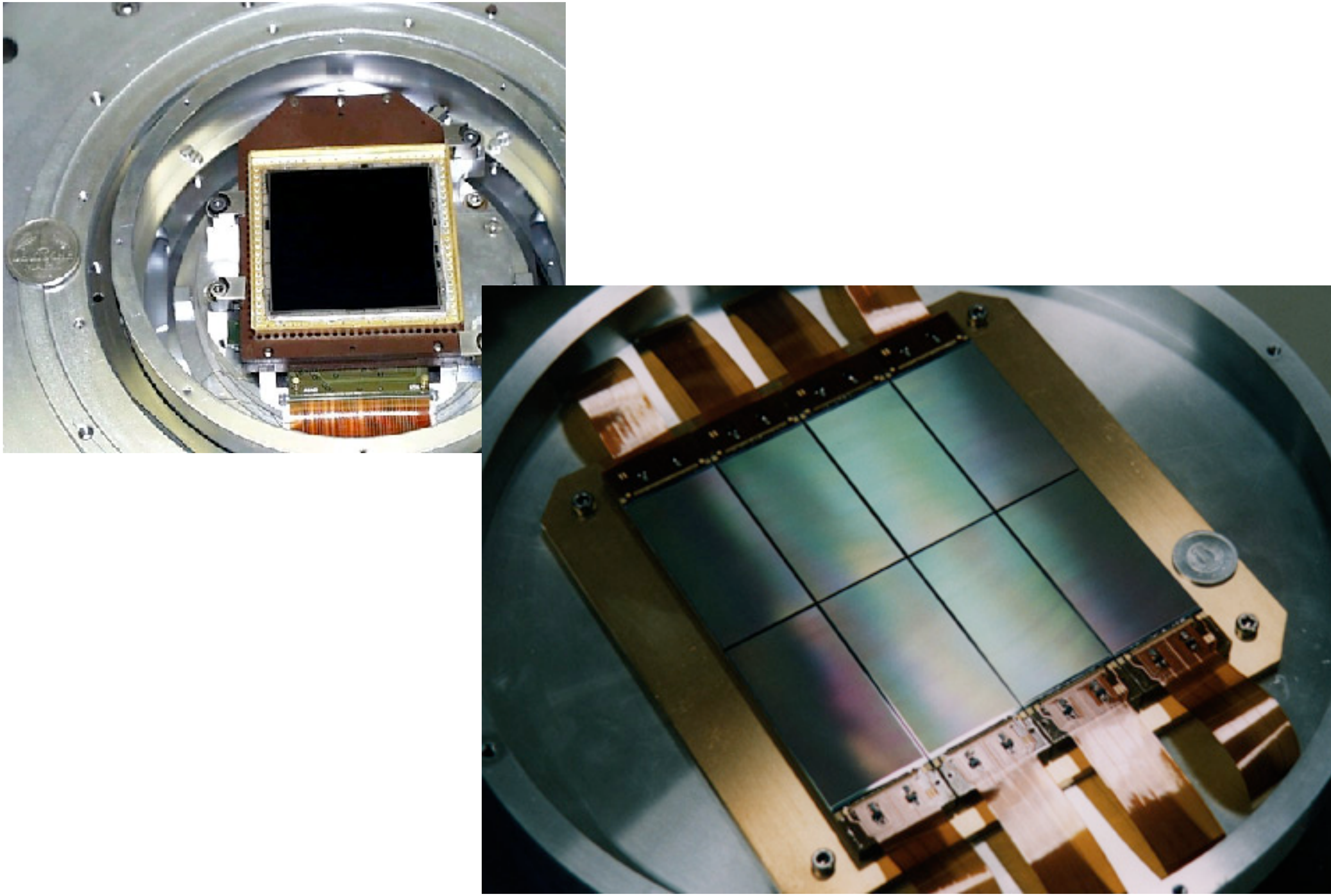
NED (http://nedwww.ipac.caltech.edu/)



MAST (http://archive.stsci.edu/)



Detectors



Properties of an "Ideal" Detector

- every photon detected
- measures time, wavelength, position
- large field-of-view (i.e. large detector)
- spatial resolution matches best possible
- uniform response to differing photons (and photon fluxes)

Properties of an “Ideal” Detector (cont.)

- can record large number of photons
- no “dead” time
- non-destructive reads
- no noise added

3 basic types of detectors

- photon detectors

photon is absorbed and creates a charge carrier

1) lead to a chemical change (photography)

2) modulate a current

3) move to an output amplifier

These are used in X-ray, UV, visible and IR

- thermal detectors

absorb photons and thermalize the energy

example: bolometers (used in long-wavelength IR, submm)

- coherent detectors

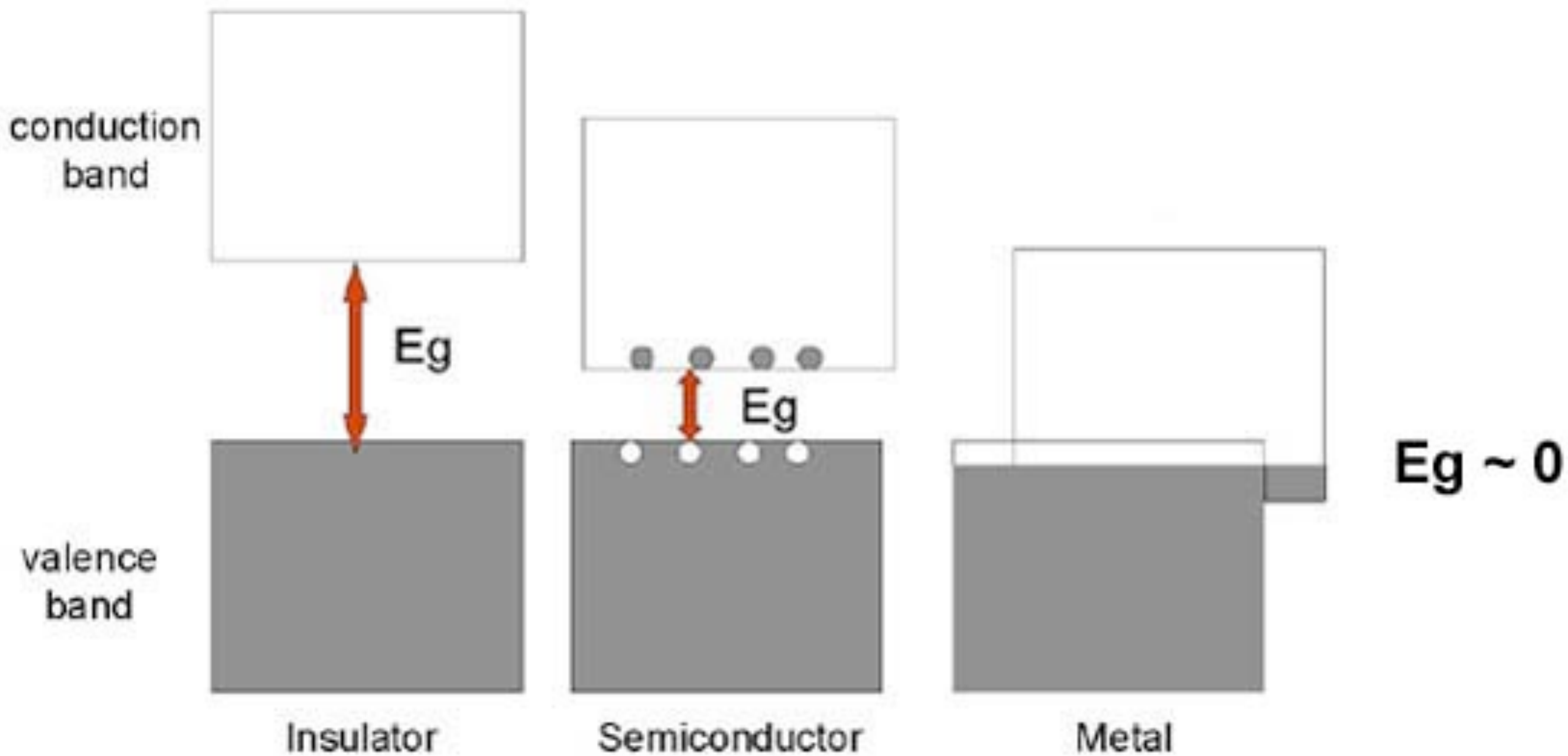
respond to electric field of incoming signal

used at radio and submm wavelengths

Photoelectric Effect

incoming light can liberate electron
if it has enough energy

whether electrons are liberated depends
on the wavelength (energy) of the light
rather than total flux (fundamental result
for quantum nature of light)



longest wavelength photon a material can detect

$$E_g = hc/\lambda_{cut-off}$$

$$\lambda_{cut-off} = 1.24\mu m/E_g(eV)$$

Material	Minimum	$E_{g,300}$ [eV]	Reported $E_{g,300}$ [eV]
Si	X	1.124	1.12-1.1242
Ge	L	0.663	0.66-0.67
GaAs	G	1.424	1.42-1.43
AlAs	X	2.163	2.14-2.168
InAs	G	0.360	0.354-0.37
InP	G	1.350	1.34-1.351
GaP	X	2.261	2.26-2.272

for Si $\lambda_{cut-off} = 1.24/1.124\mu m \sim 1\mu m$

IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
							2 He 4.003
		5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
		13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80
47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)

The Need to Cool Detectors

thermal excitation can also pump electrons

classically --> $$n_{cond}/n_{valence} = e^{-E_g/kT}$$

corrected for QM (Fermi-Dirac statistics)

$$n_{cond} = 2(\frac{2\pi m^* kT}{h^2})^{3/2} e^{-E_g/2kT}$$

m^* effective electron mass (~ 1.1 electron masses for Si) for Si ($E_g = 1.1$ eV)

at 300 K $n_{cond} \sim 1.4 \times 10^{10}\mathrm{cm}^{-3}$

at 77 K $n_{cond} \sim 1.8 \times 10^{-18}\mathrm{cm}^{-3}$

so cold Si is a good material for a detector,
but how do you get it to work as a detector?

Charge-Coupled Devices (CCD)

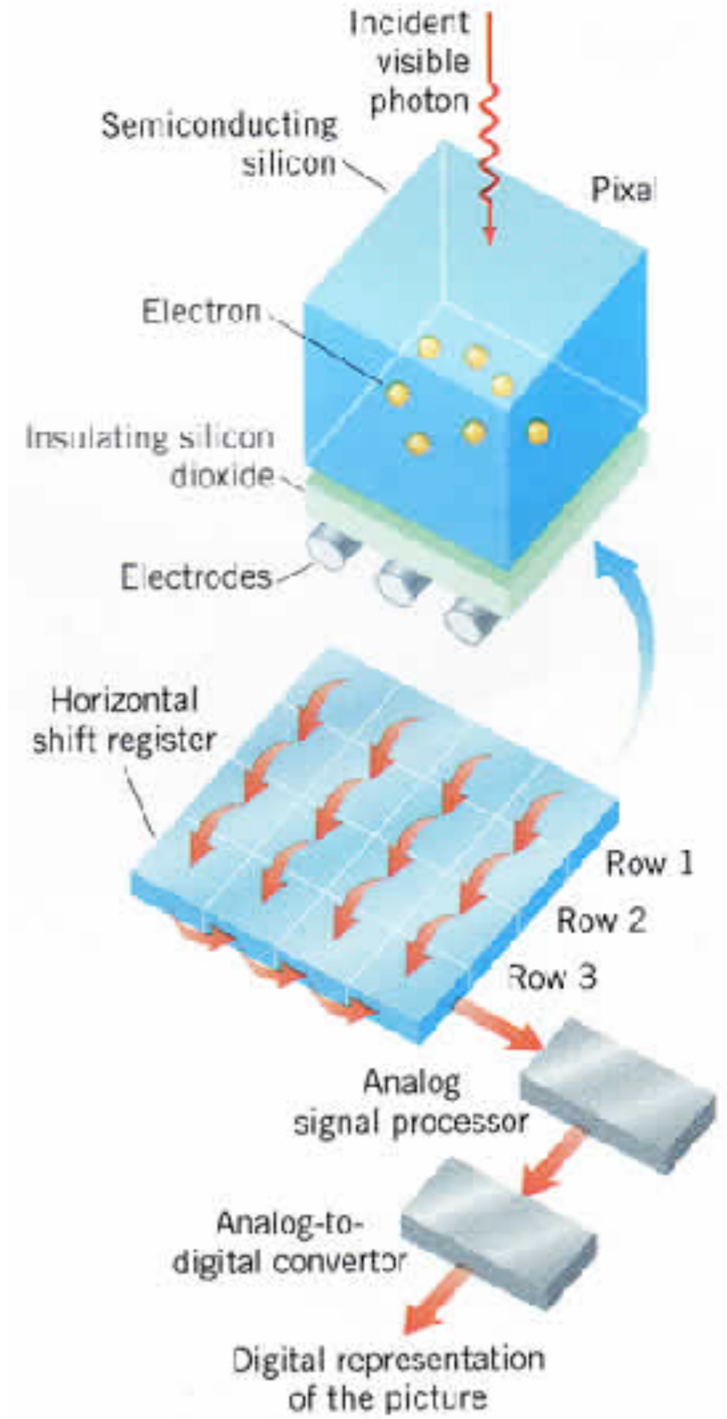
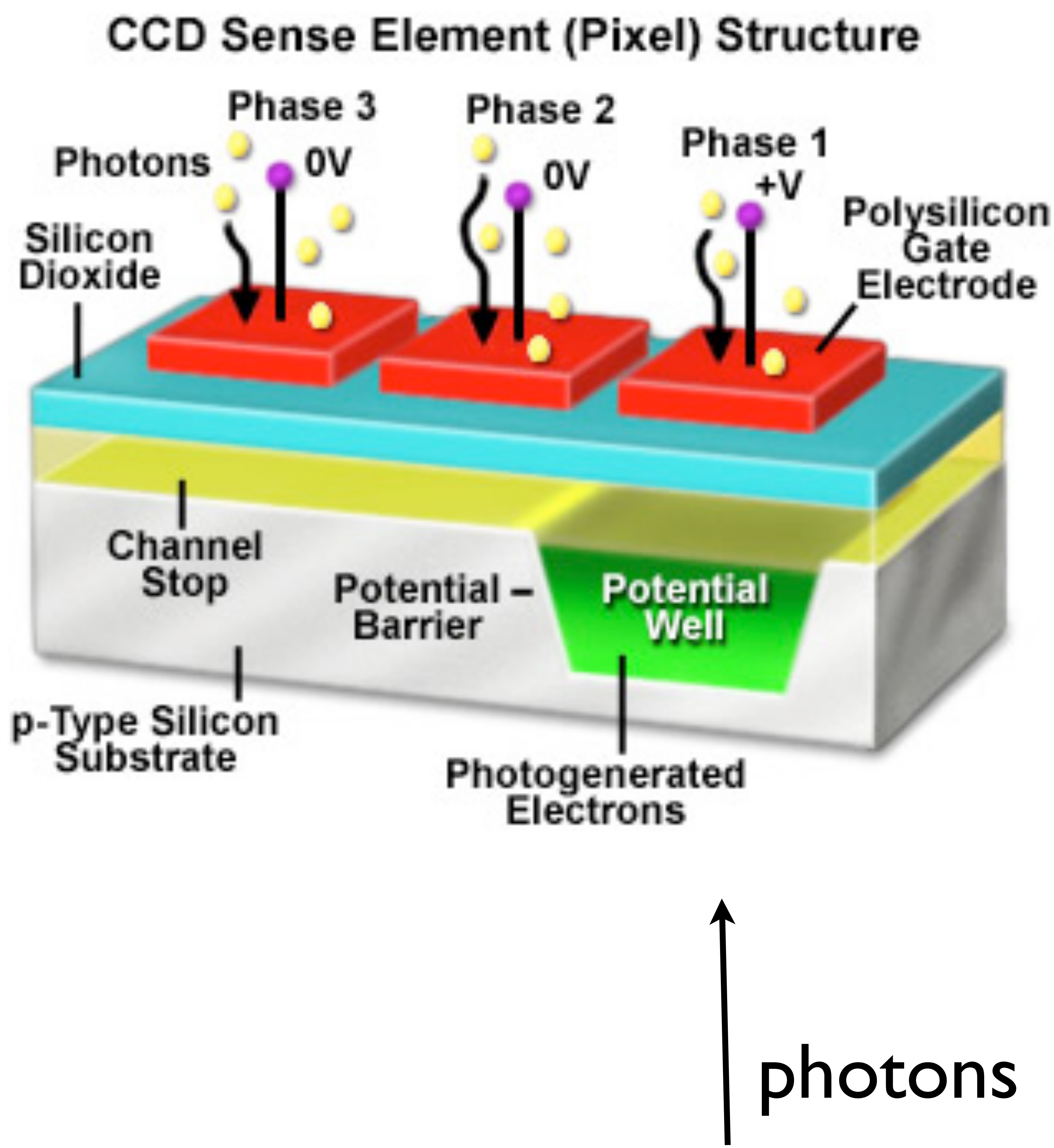


Figure 29.7 A CCD array can be used to capture photographic images using the photoelectric effect.

from here http://tonydude.net/NaturalScience100/Topics/3Mind/timages_mind/ccd_s.jpg



in astronomy, typically backside illuminated

Readout pattern

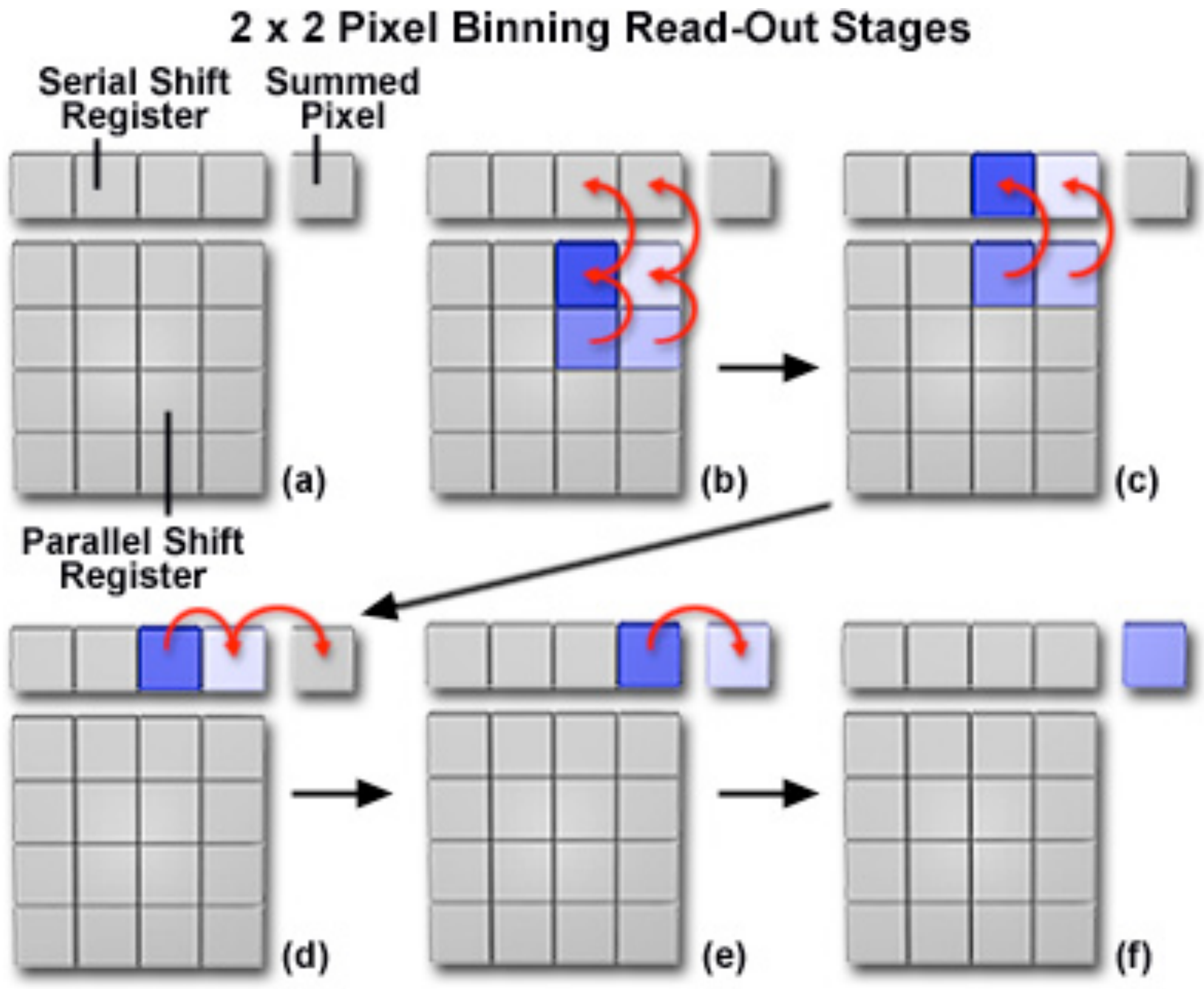
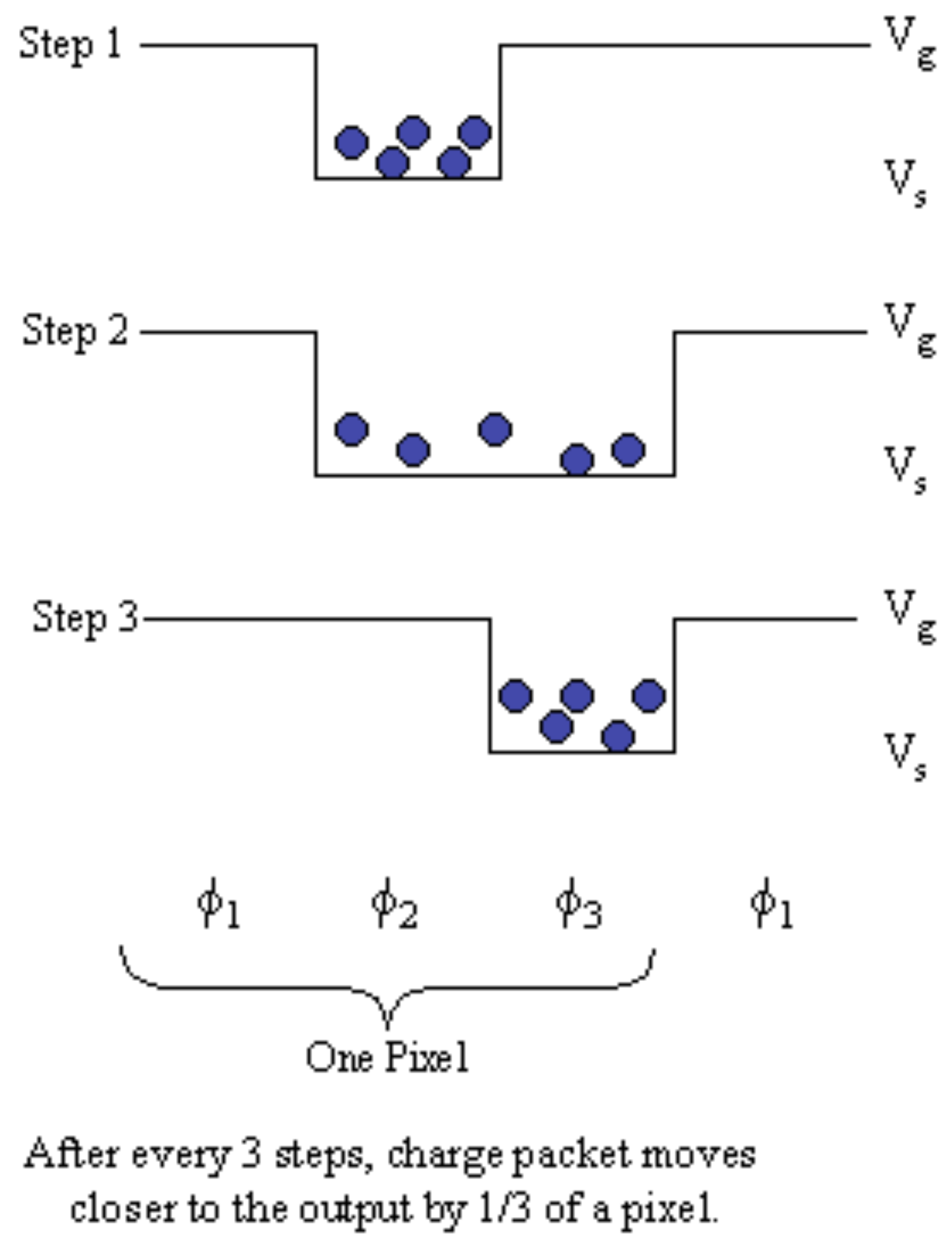


Figure 1

http://digitalimagingu.com/articles/images/pixelbinningfigure1.jpg

“clocking”



http://www.jyi.org/volumes/volume3/issue1/images/peterson_threephase.gif electrical circuit is then used to

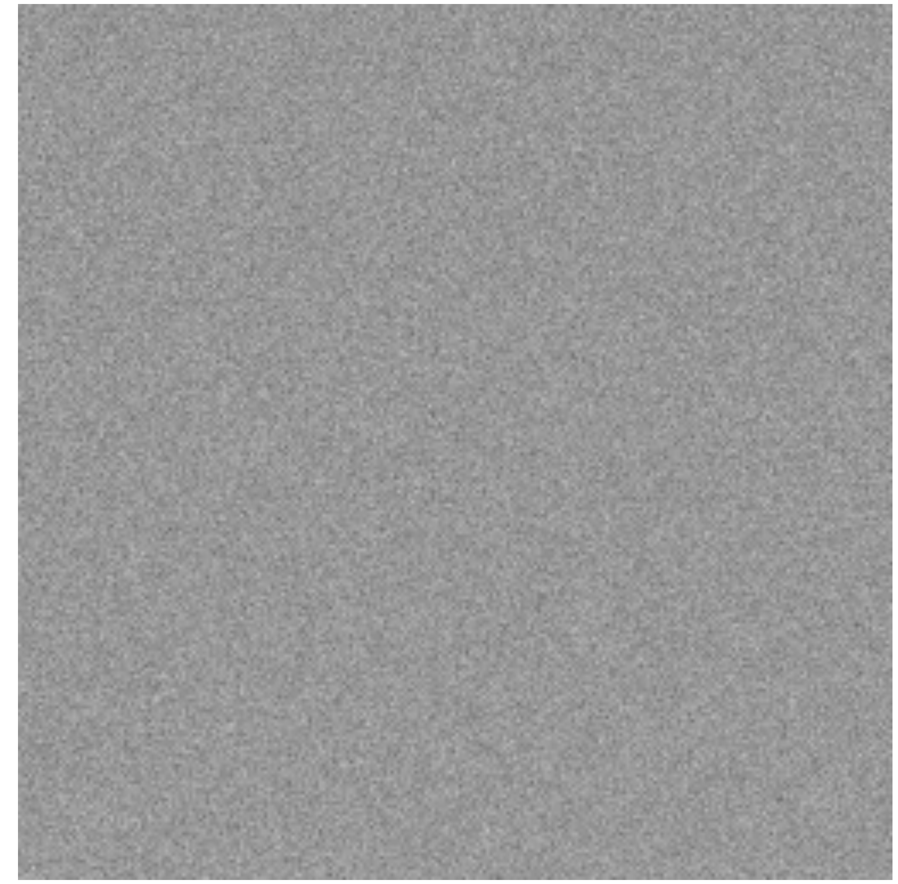
1) amplify the signal

2) convert the analog signal to digital

the amplification adds noise, the analog-to-digital conversion can also add noise, but also limits "resolution" and dynamic range

Noise sources

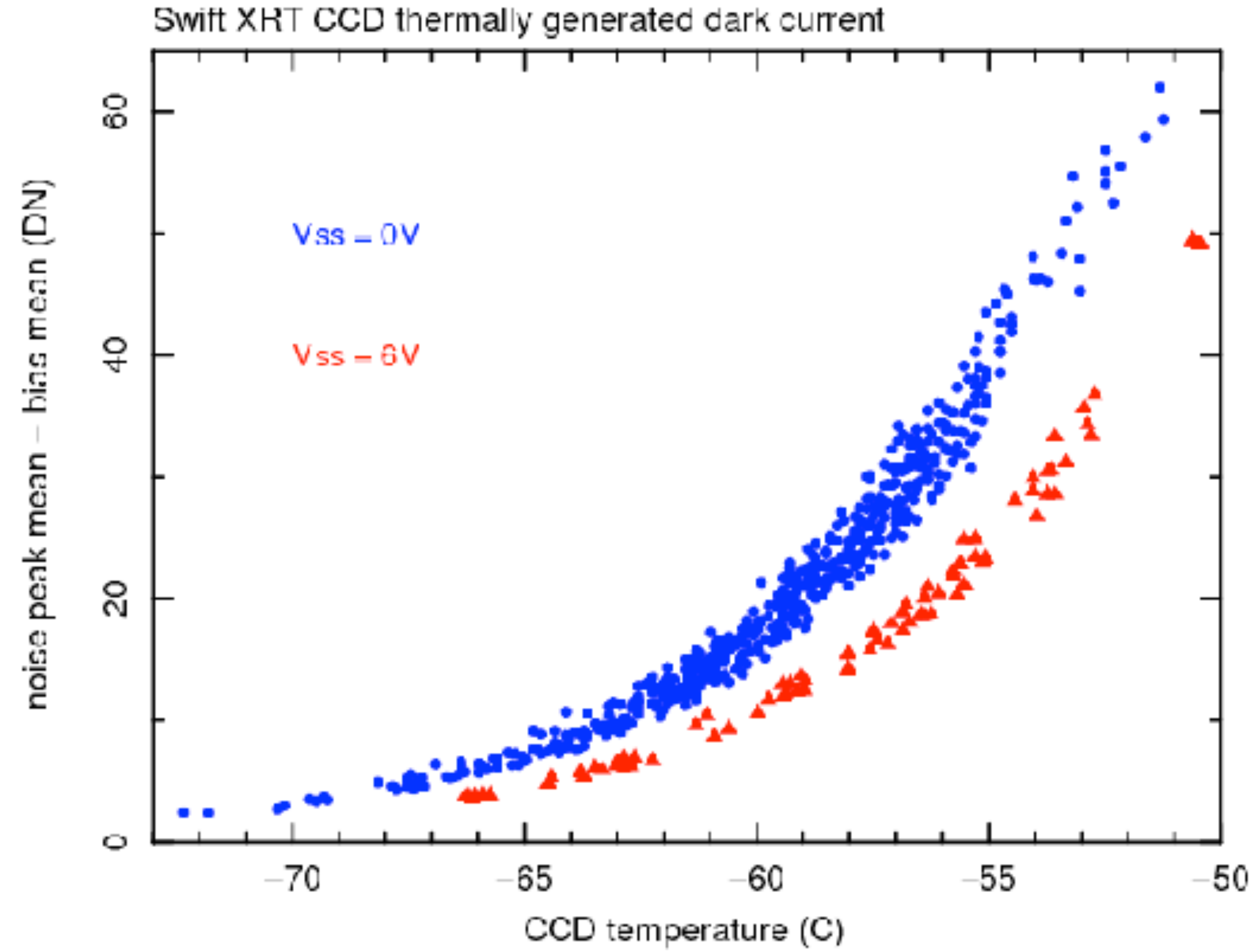
1) read noise



typically expressed
in terms of rms electrons

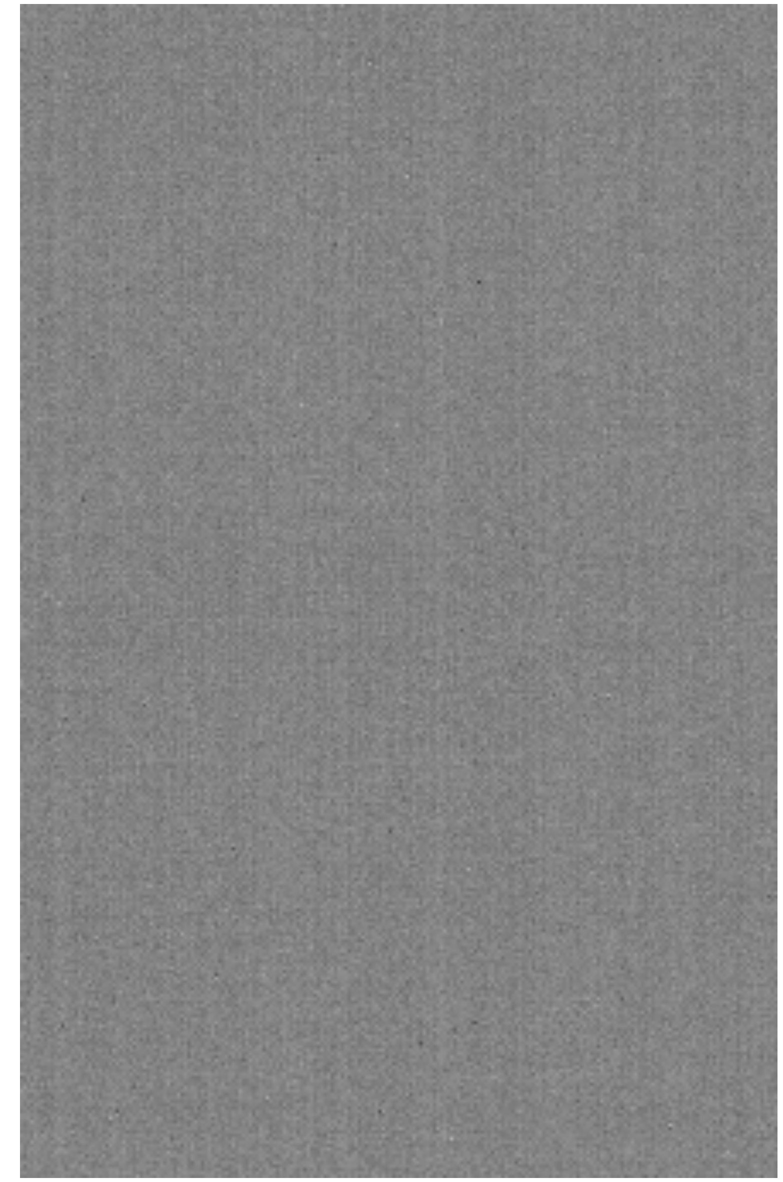
typical values are in the few e- rms
best cases get down to 1 or 2 e- rms

- dark current (dark noise) due to thermal generation of e-’s (or other non-source)



typically this is negligible (< few e-’s per hour)

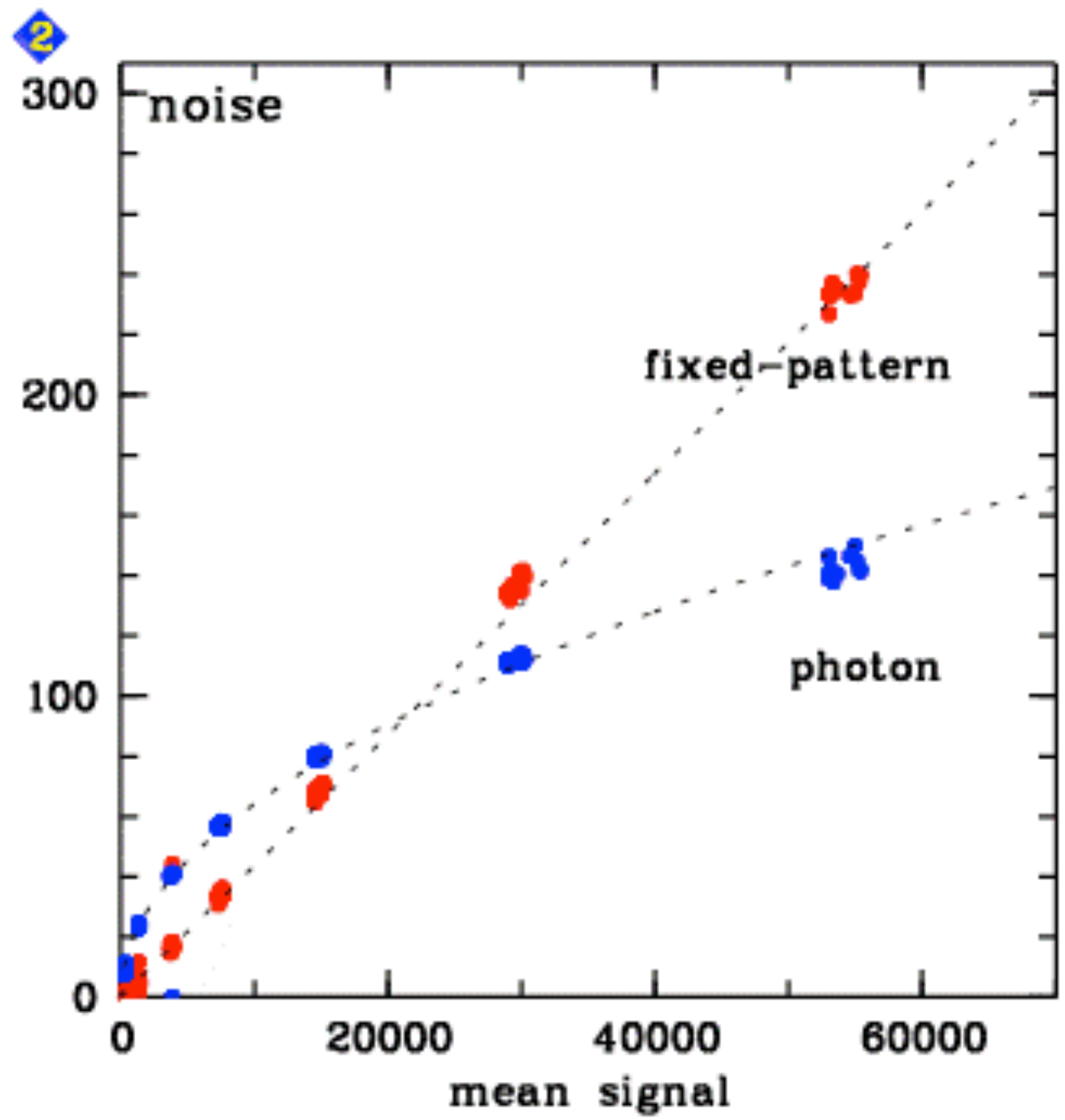
- Fixed Pattern “noise”



usually seen in average
of many “blank” exposures

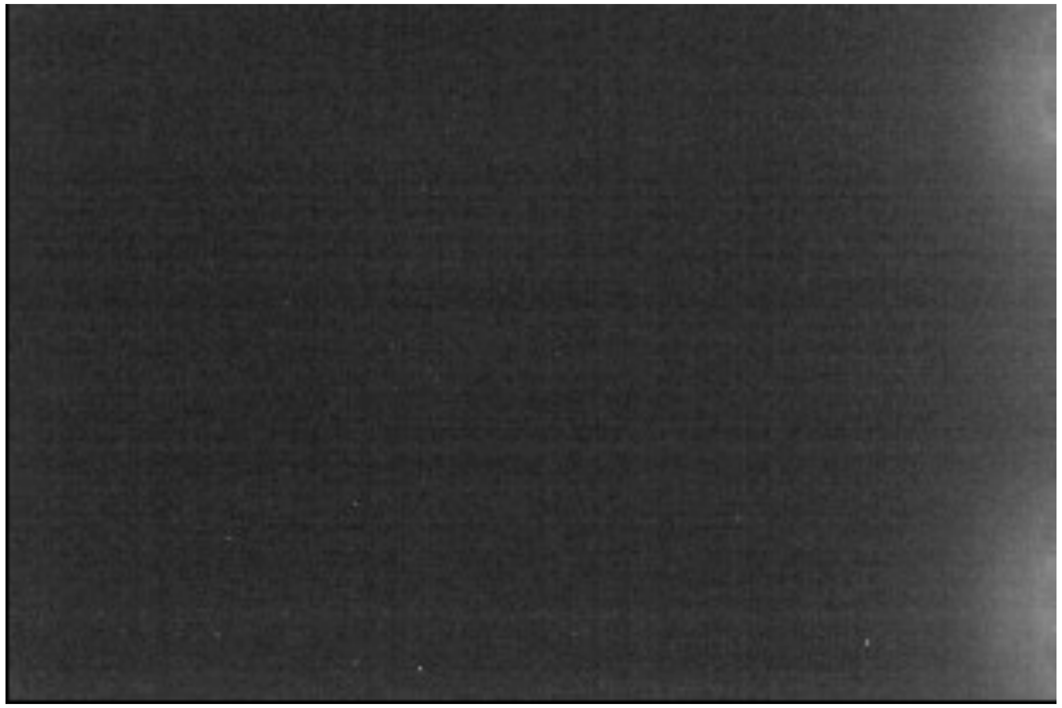
due either to
systematic differences in readout
or pixel-pixel sensitivity
variations

- Fixed Pattern “noise”

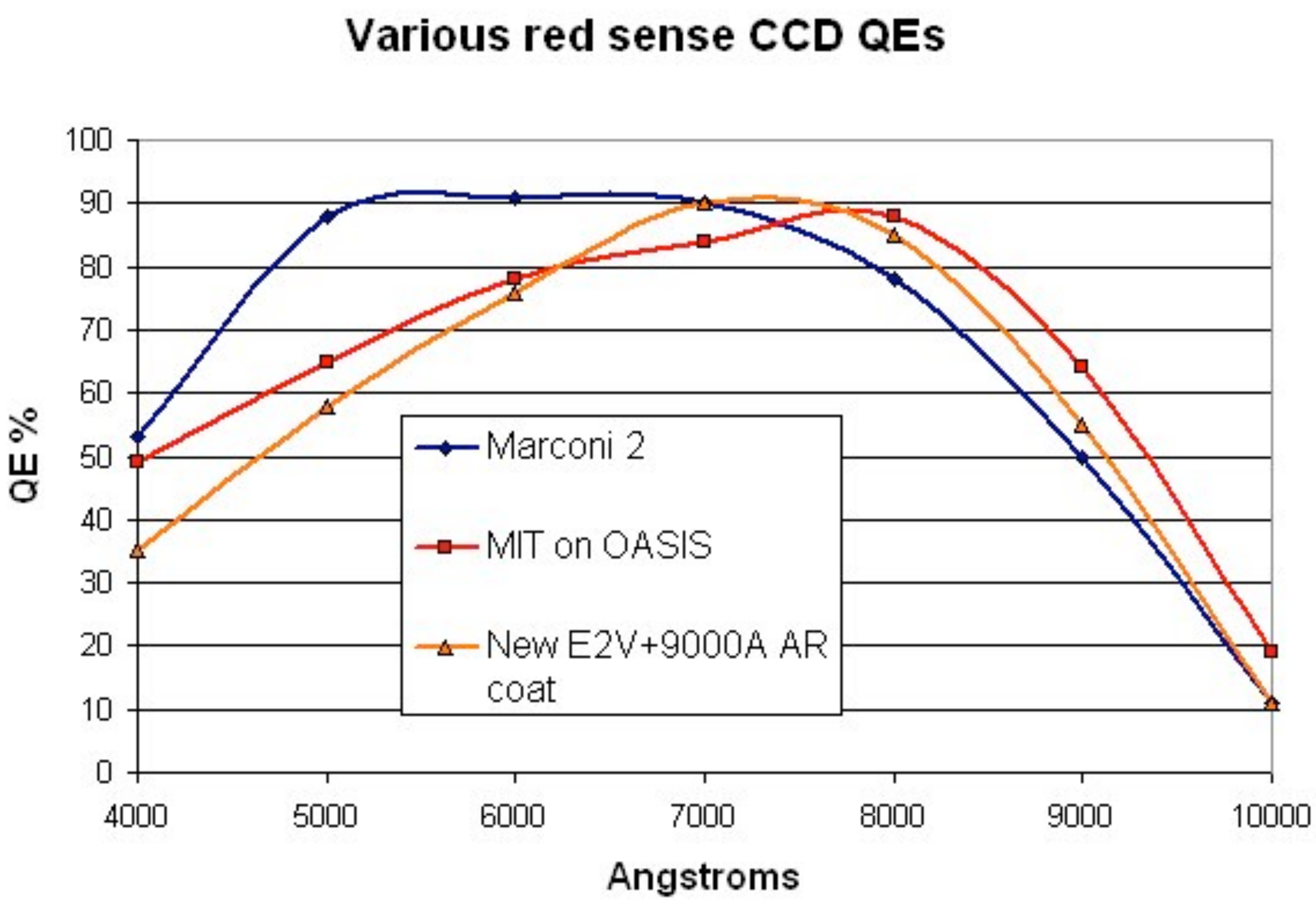


Other issues....

example: amplifier glow



Quantum Efficiency



depends on CCD thickness & coatings

- front illuminated not favored (blue photons absorbed by gates, gates create complex QE variations)

- backside devices must be thin (< tens of mu) for photons to reach wells

- QE limited by reflection at back surface (coatings important)

- red sensitivity typically drops due to CCDs being too thin

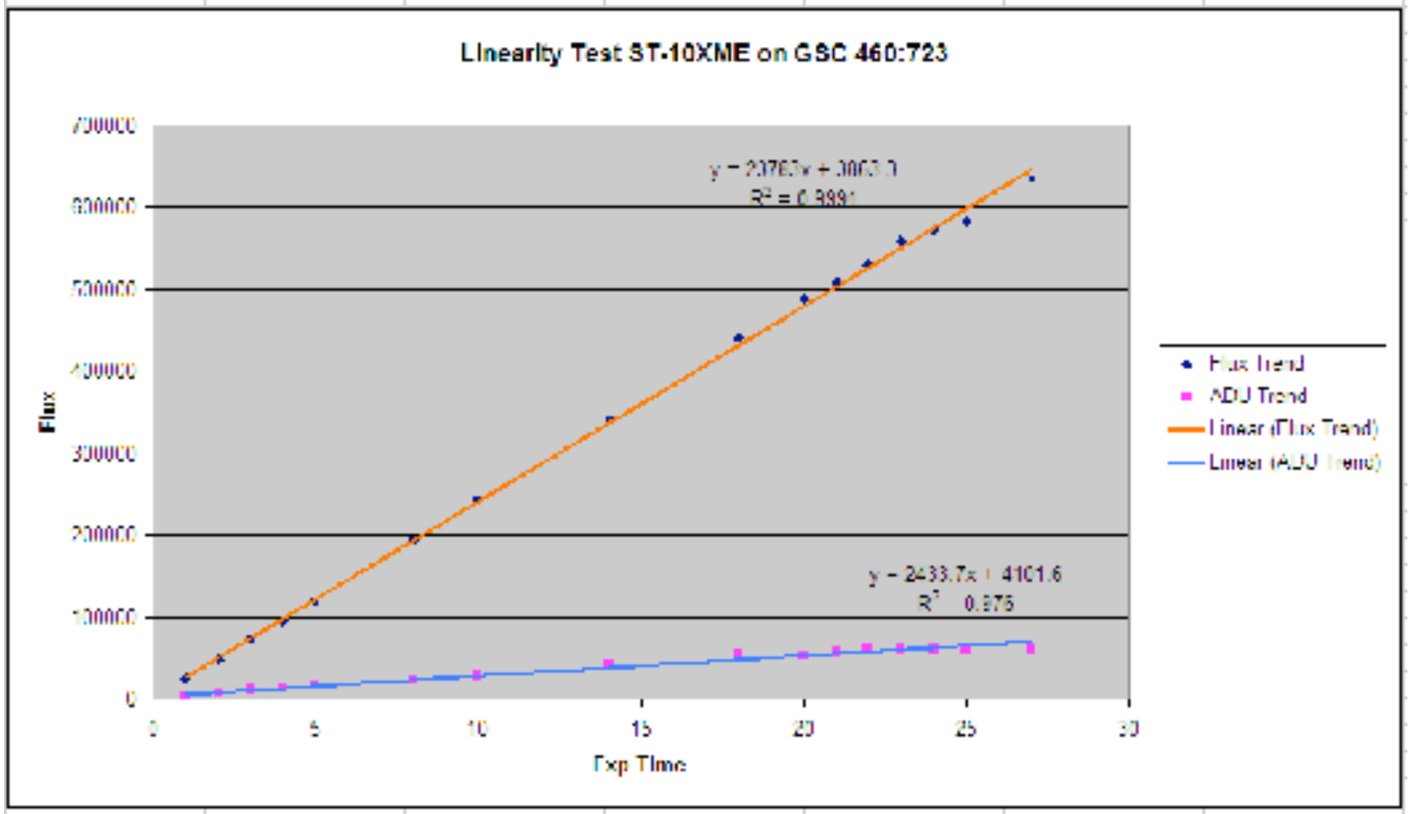
Characterizing CCDs

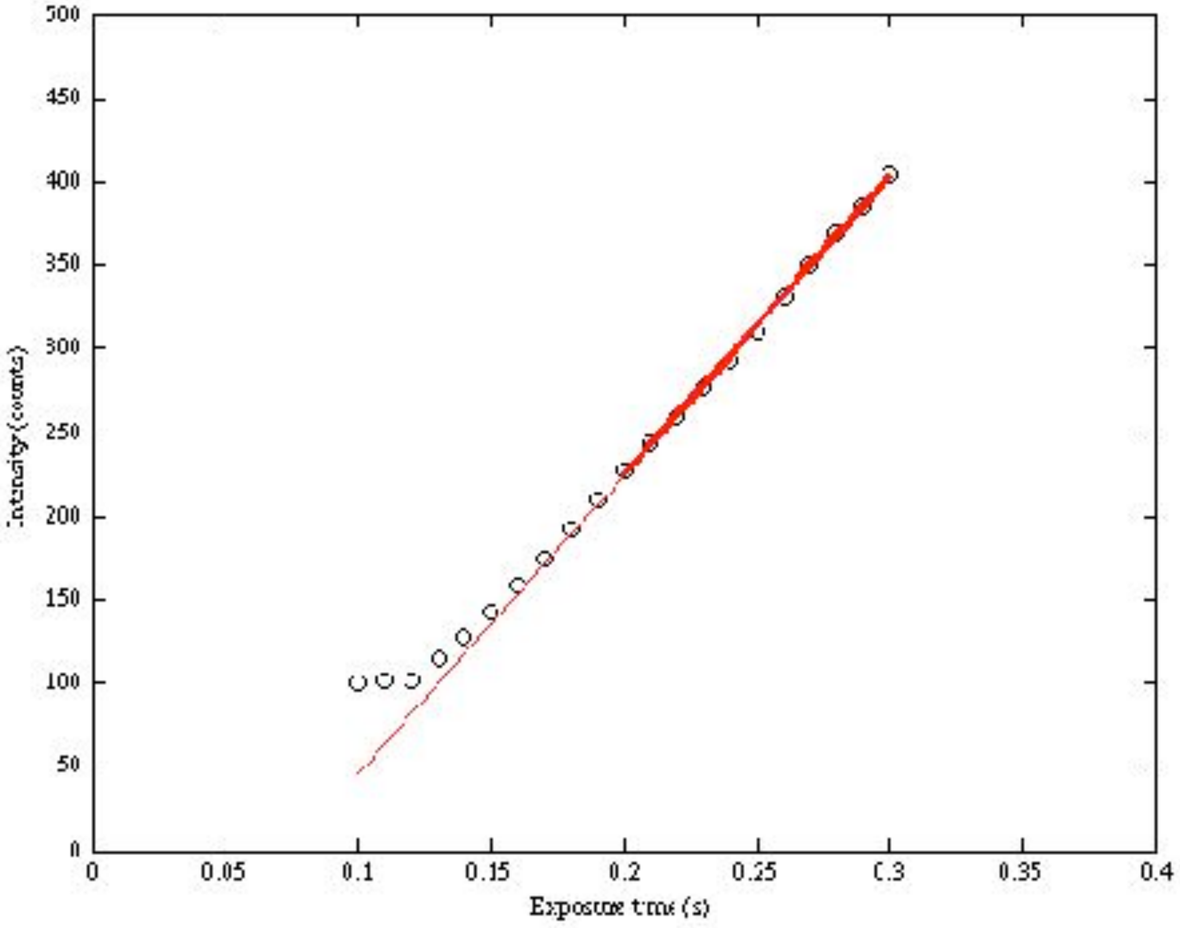
- QE
- read noise
- gain

conversion between "counts" or DN and electrons

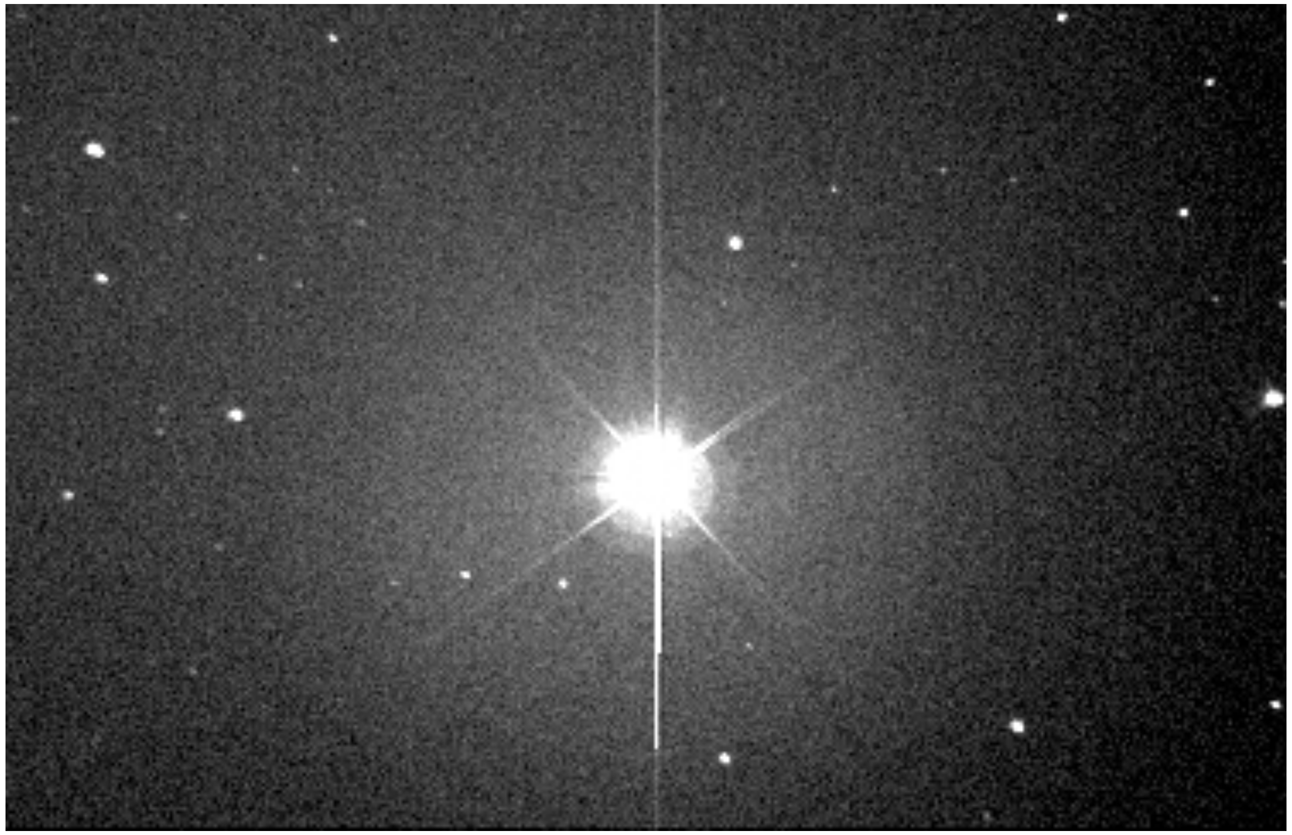
- linearity

examples

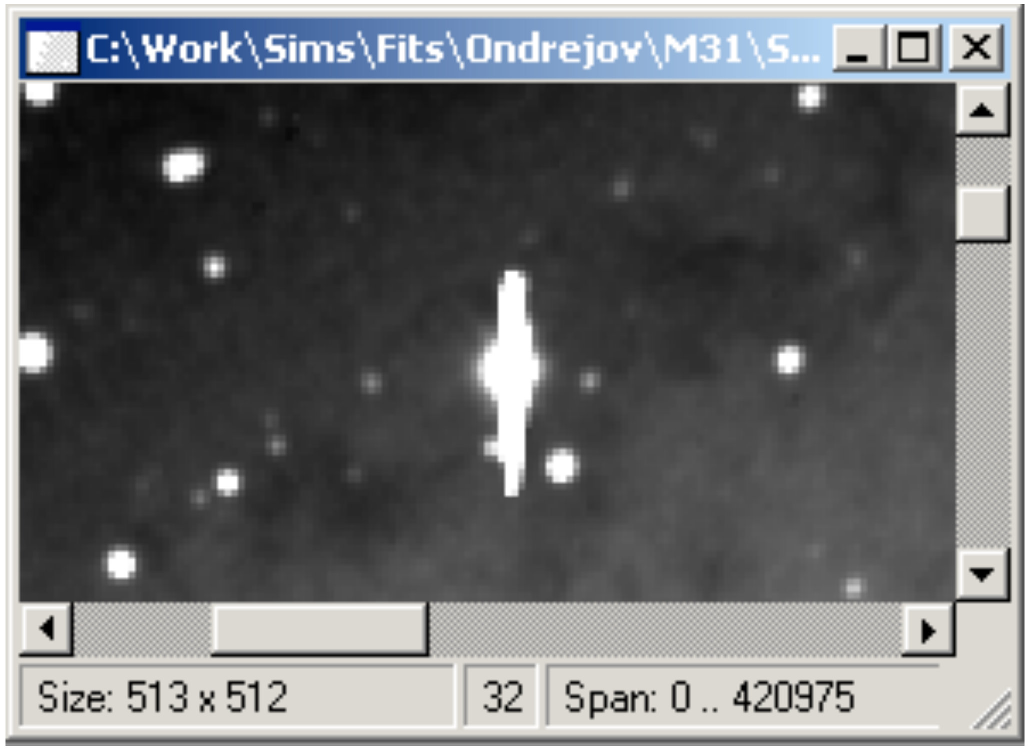




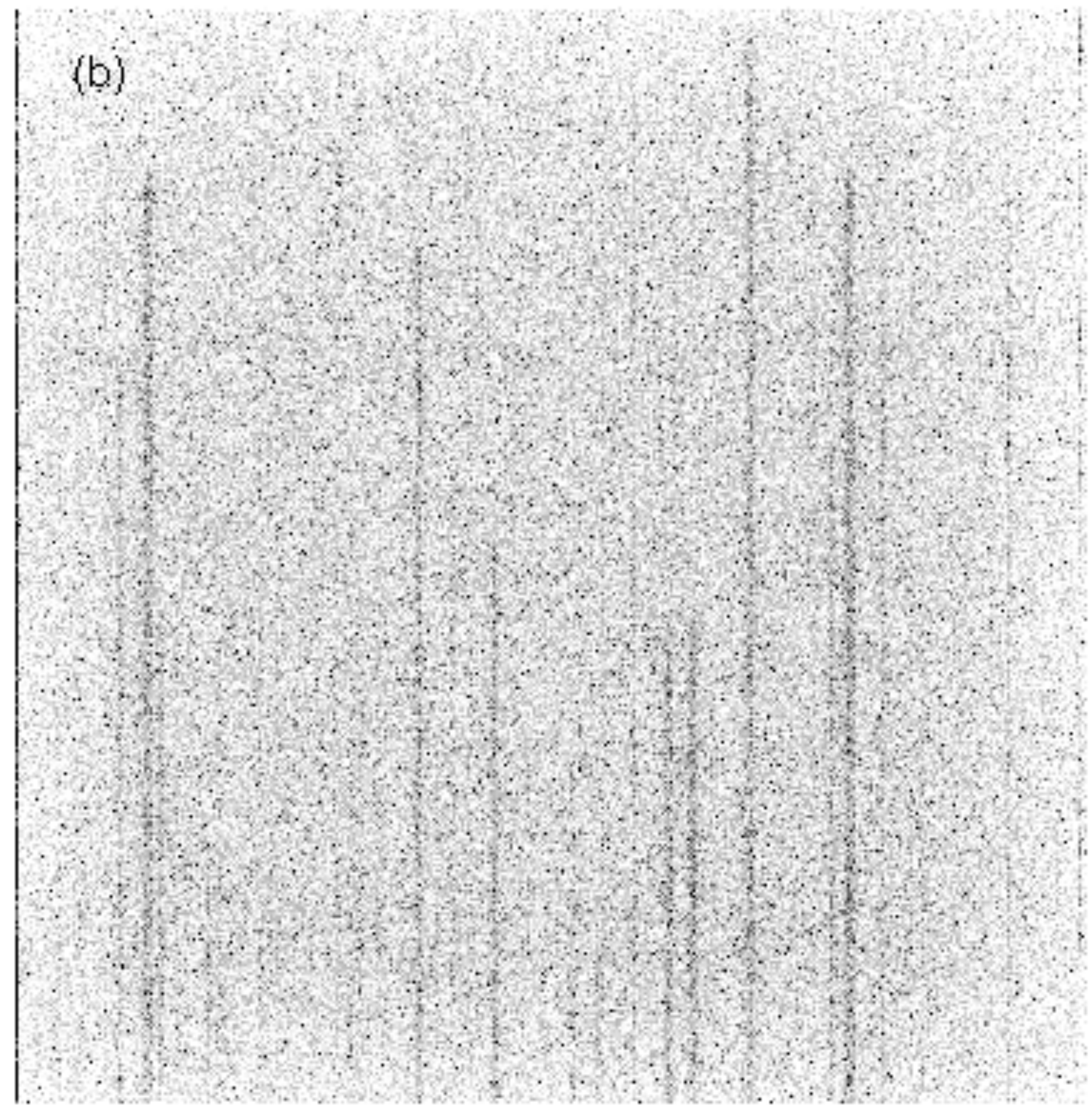
- full well depth



blooming



- CTE (charge transfer efficiency)



http://www.stsci.edu/instruments/wfpc2/Wfpc2_hand/HTML/ch4_ccd_AFrame_21.gif

- bias level & structure

bias is an added level to the counts (in the amplifier) to move the counts away from 0 (for statistical purposes)

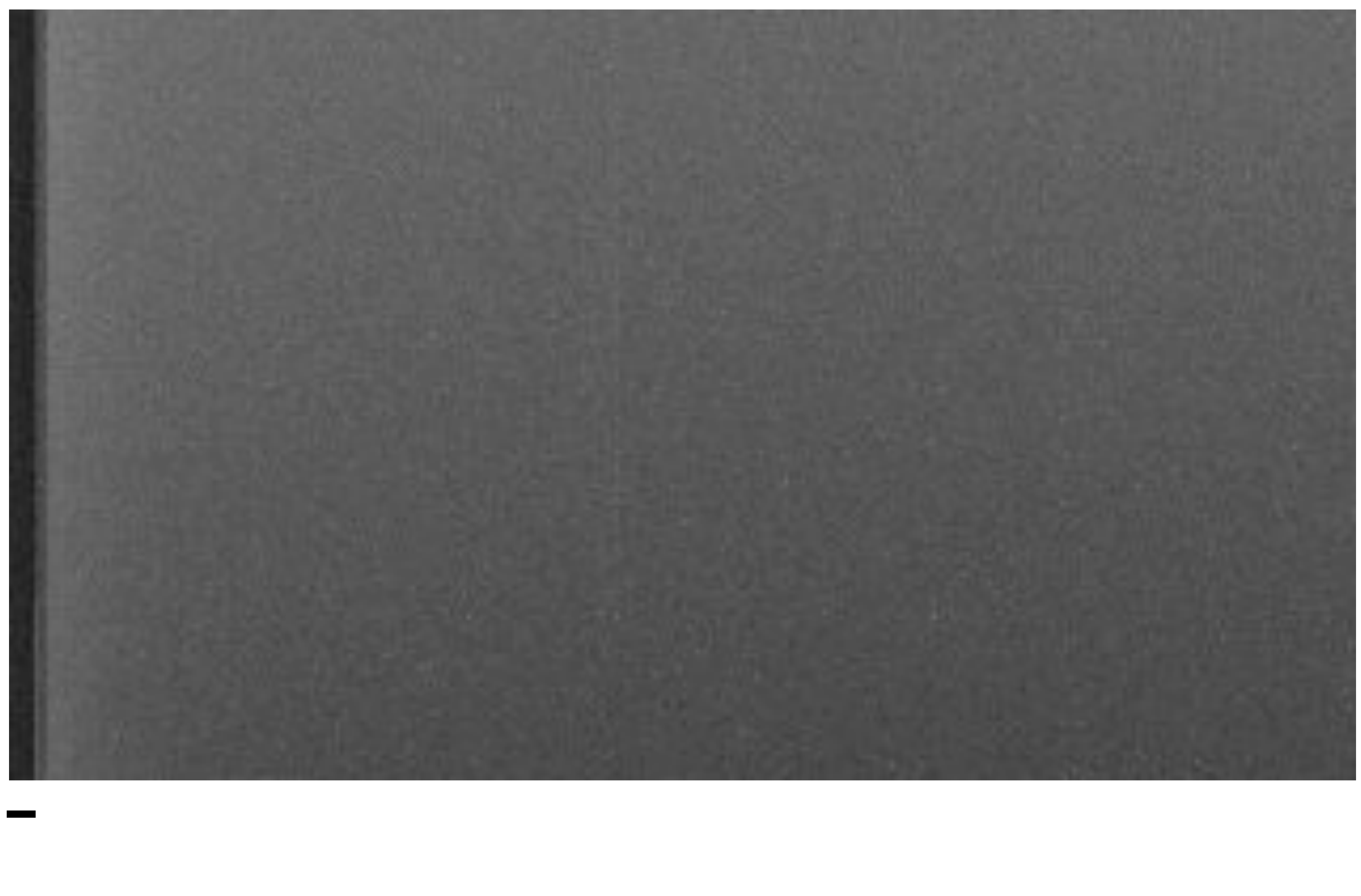
- fat zero

counts added at the pixel level (by flashing a light, for example) to fill charge traps (typically not needed any more)

Correcting your CCD frames

1) removing the bias level

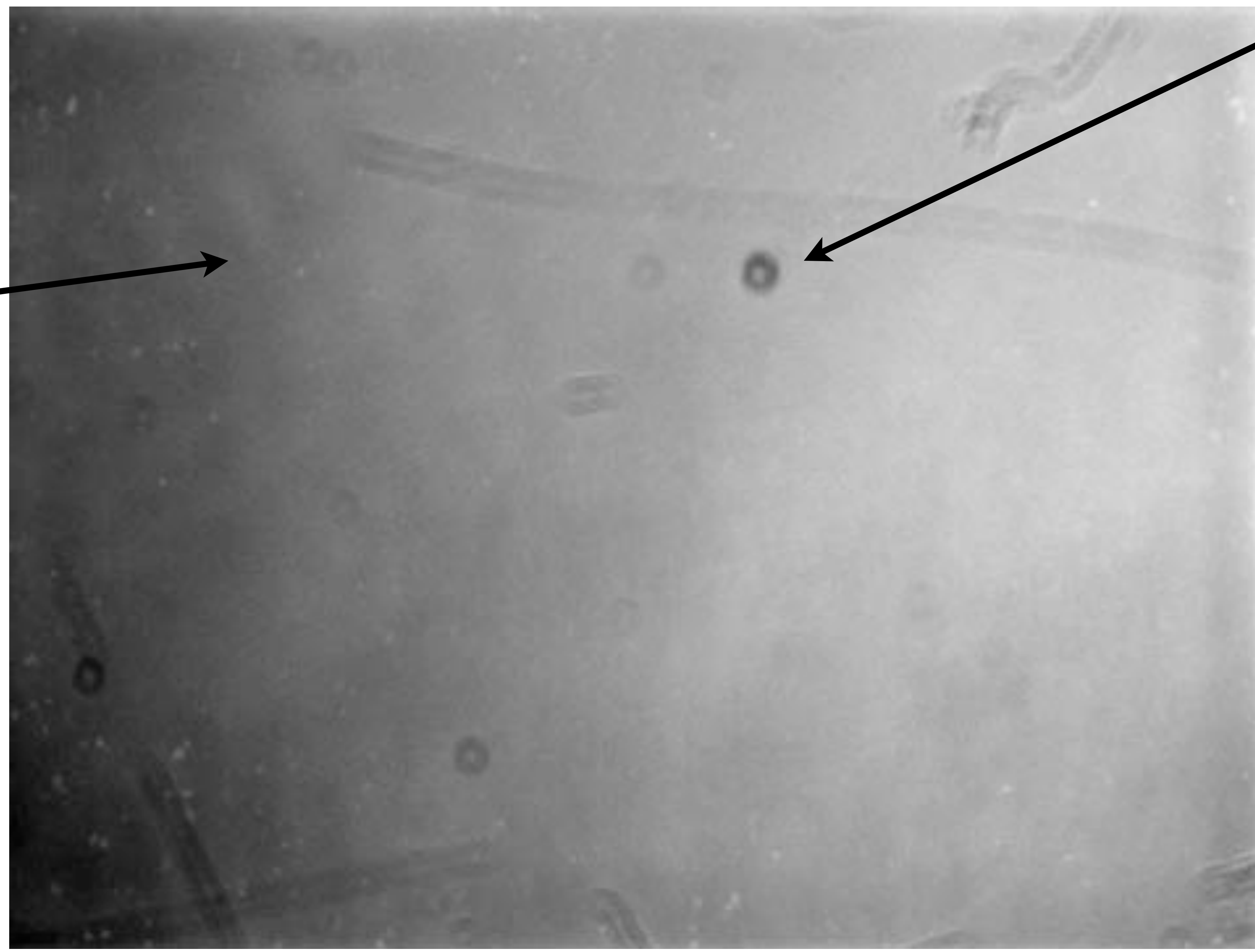
bias frame (0 sec exposure)



overscan (not real pixels, just more sampling of the amplifier signal)

2) “flat fielding”

removes pixel-to-pixel variations by comparing to an image of a “flat field”



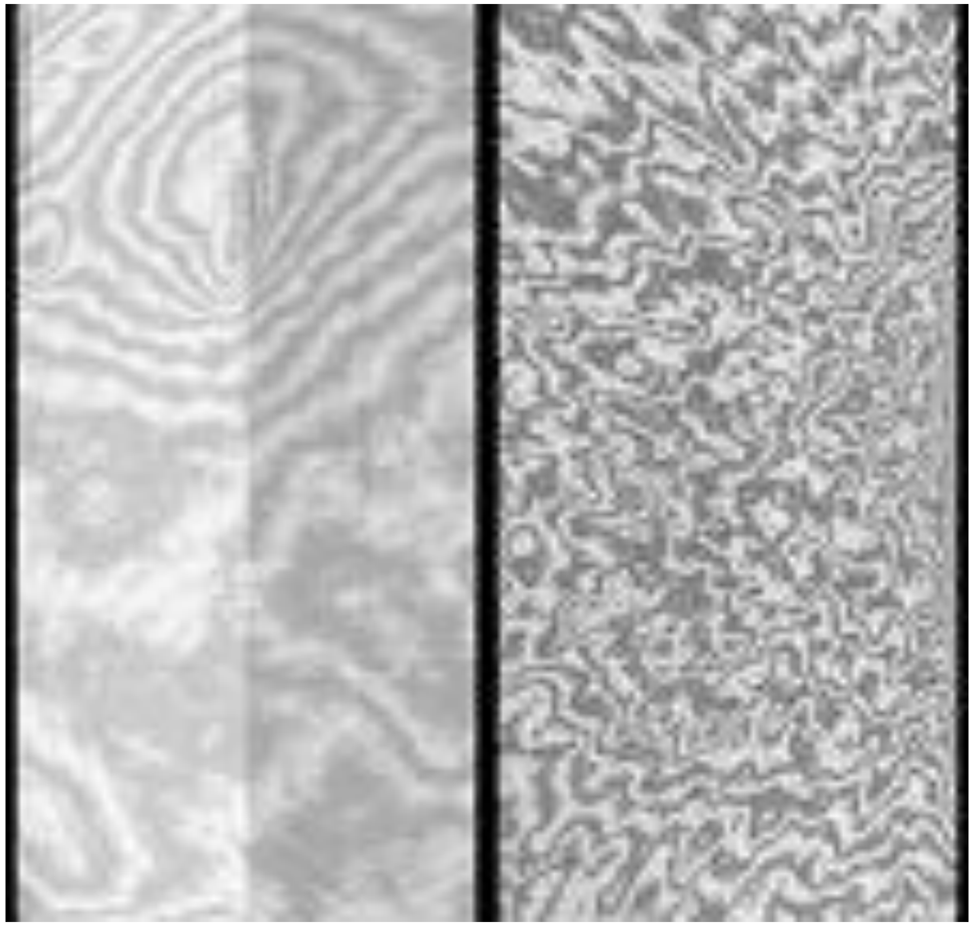
fringing?

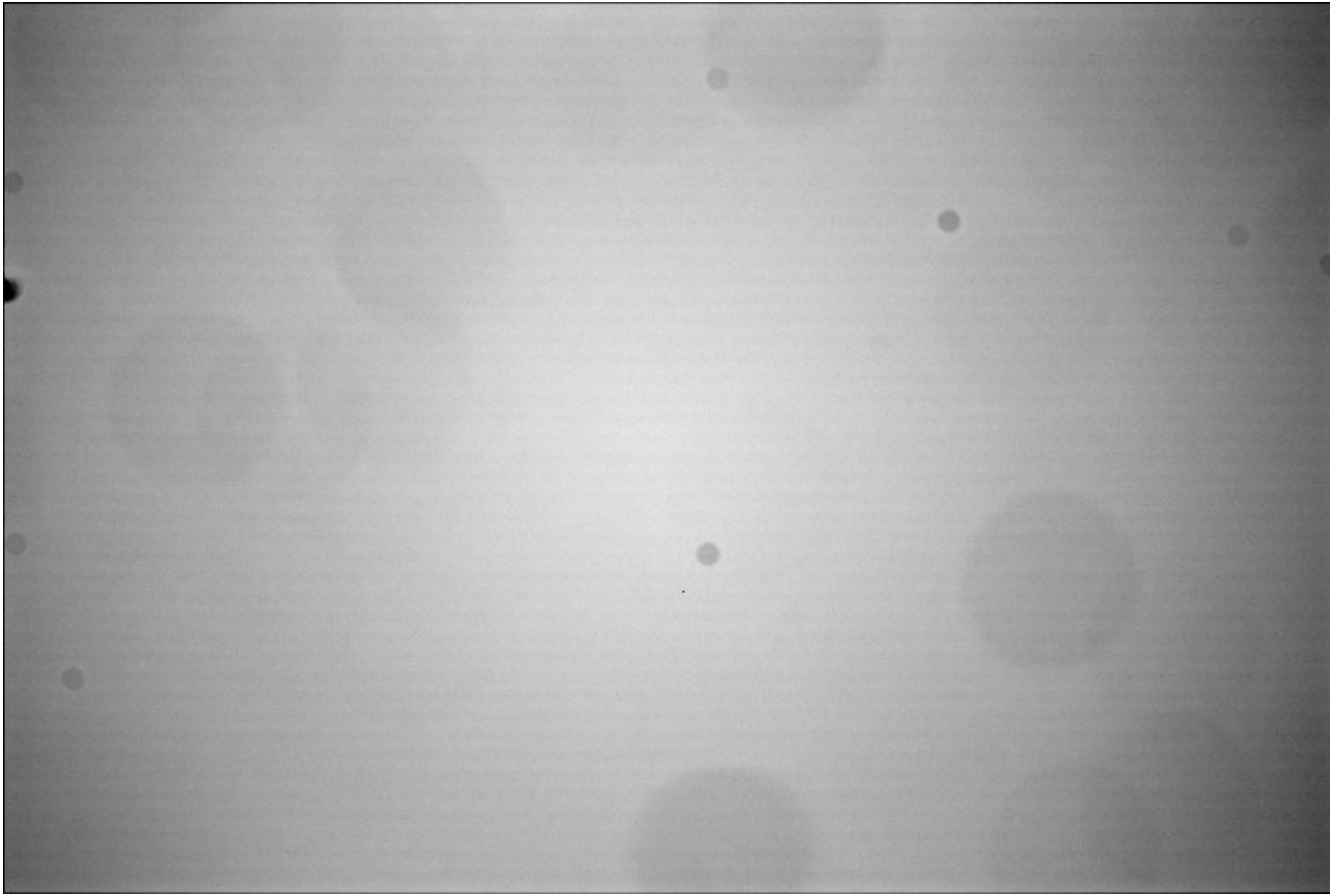
dust?

hair?

window scratch?

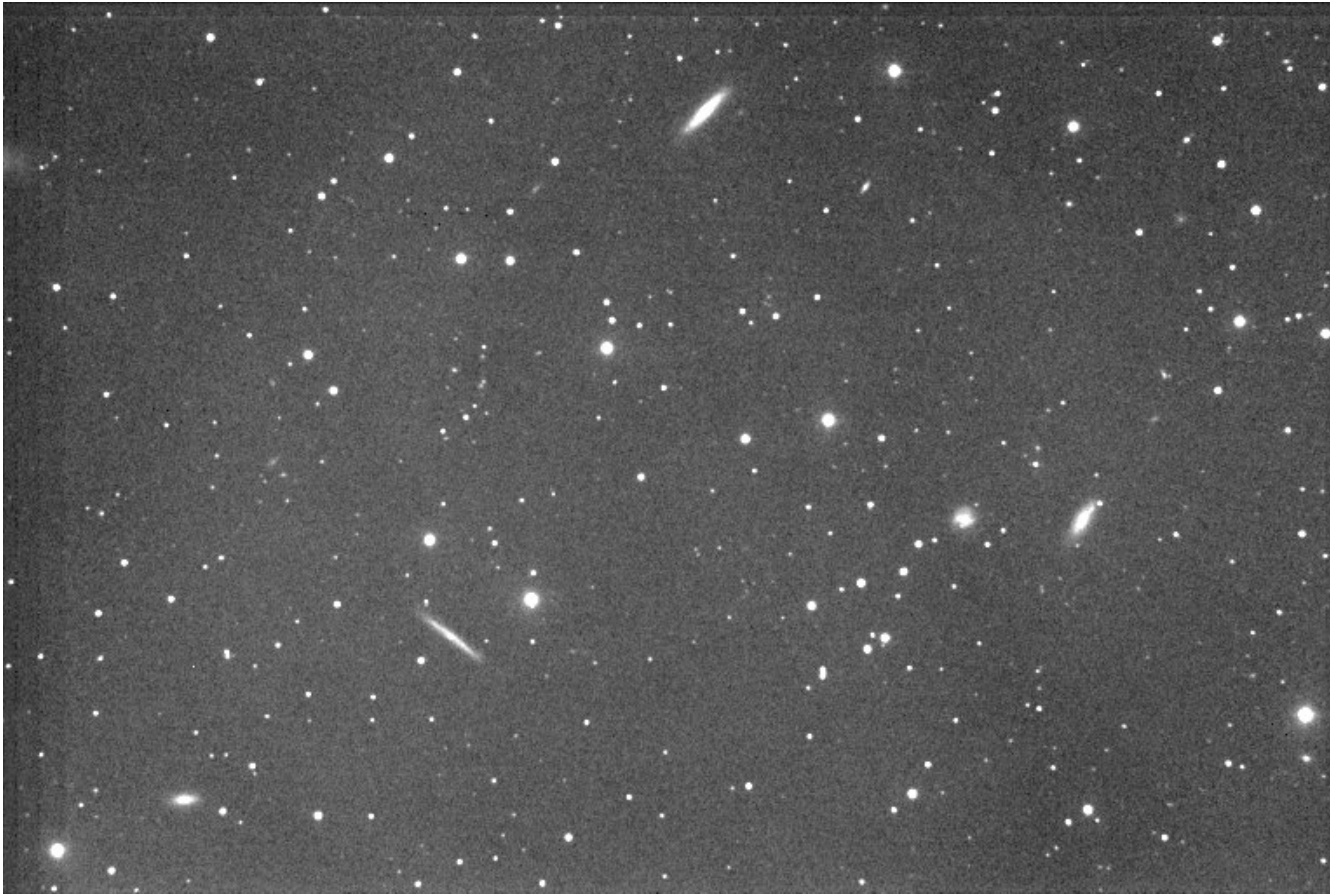
example of fringing





http://www.astrosurf.com/~buil/iris/tutorial2/doc8_us.htm

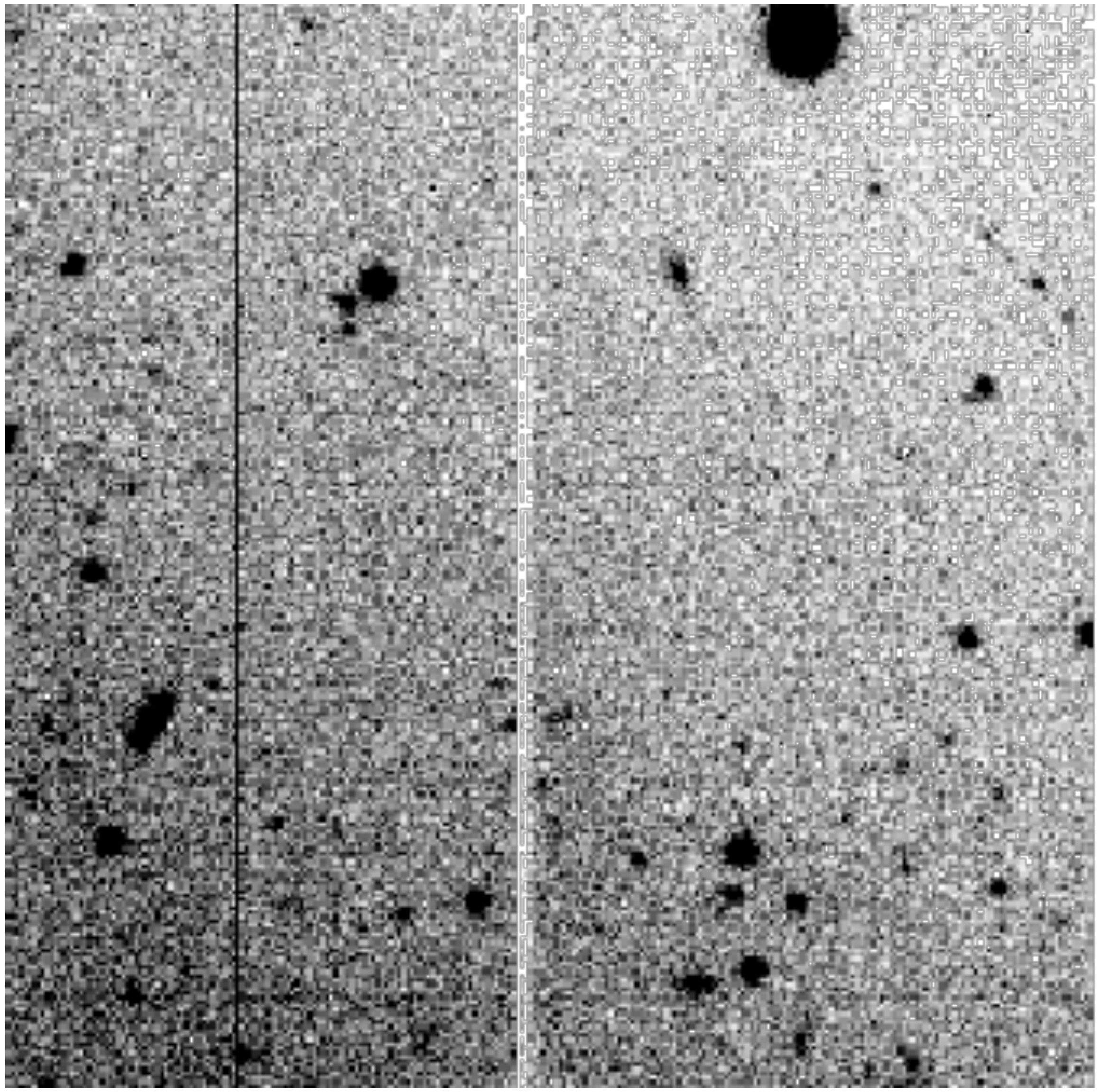
http://www.astrosurf.com/~buil/iris/tutorial2/doc8_us.htm



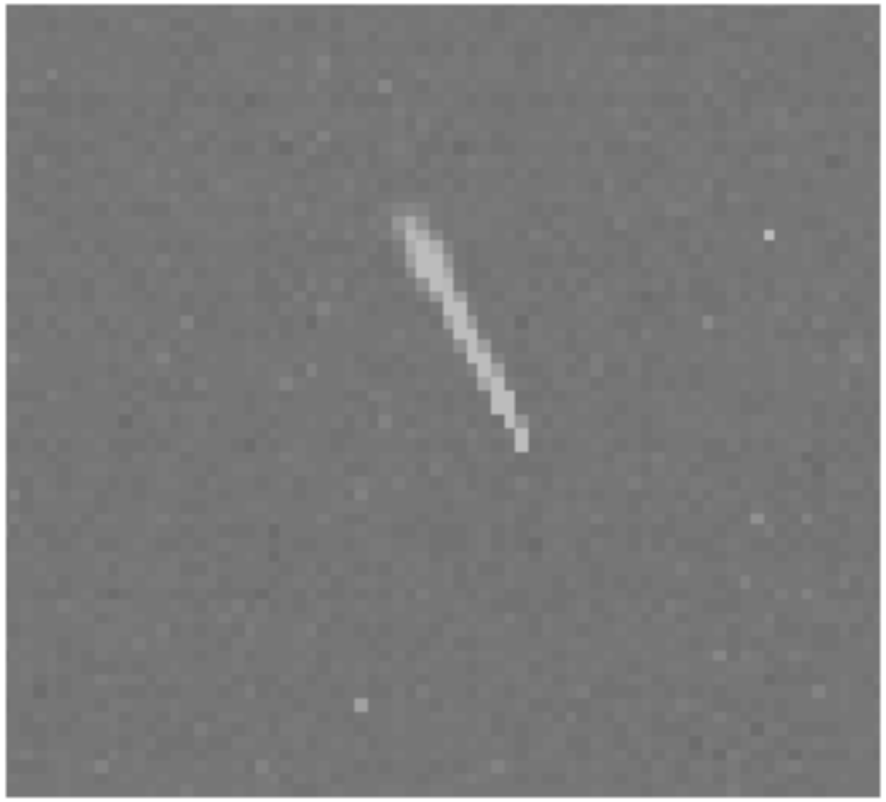
Other problems...

bad columns (or pixels)

interpolate over,
or combine dithered
images



cosmic rays



detect and interpolate over
or
combine multiple images

Image Reduction and Analysis Facility (IRAF)

http://iraf.noao.edu/

structure:

packages (set of related tasks) - need to be called to have access to those tasks

tasks - these do the work

mkiraf (sets up your account) only needs to be executed once

cl (starts IRAF) needs to be done each time you want to run iraf tasks

run from an xgterm to get access to graphics windows

use ds9 (or saoimage) to view images

after typing cl

```
xgterm
    NOAO PC-IRAF Revision 2.12.2-EXPORT Sun Jan 25 16:09:03 MST 2004
    This is the EXPORT version of PC-IRAF V2.12 supporting most PC systems.

    Welcome to IRAF.  To list the available commands, type ? or ??.  To get
    detailed information about a command, type `help command'.   To  run  a
    command  or  load  a  package,  type  its name.   Type  `bye' to exit a
    package, or `logout' to get out of the CL.   Type `news'  to  find  out
    what is new in the version of the system you are using.   The following
    commands or packages are currently defined:

      dataio.     language.   noao.       proto.      stsdas.     utilities.
      dbms.       lists.      obsolete.   rvsao.      system.
      images.     mscred.     plot.       softools.   tables.
cl> 
```

there are multiple tasks that do the same thing (and often there are tasks and supertasks that call a set of tasks)

here we will focus on :

colbias (for bias subtraction)

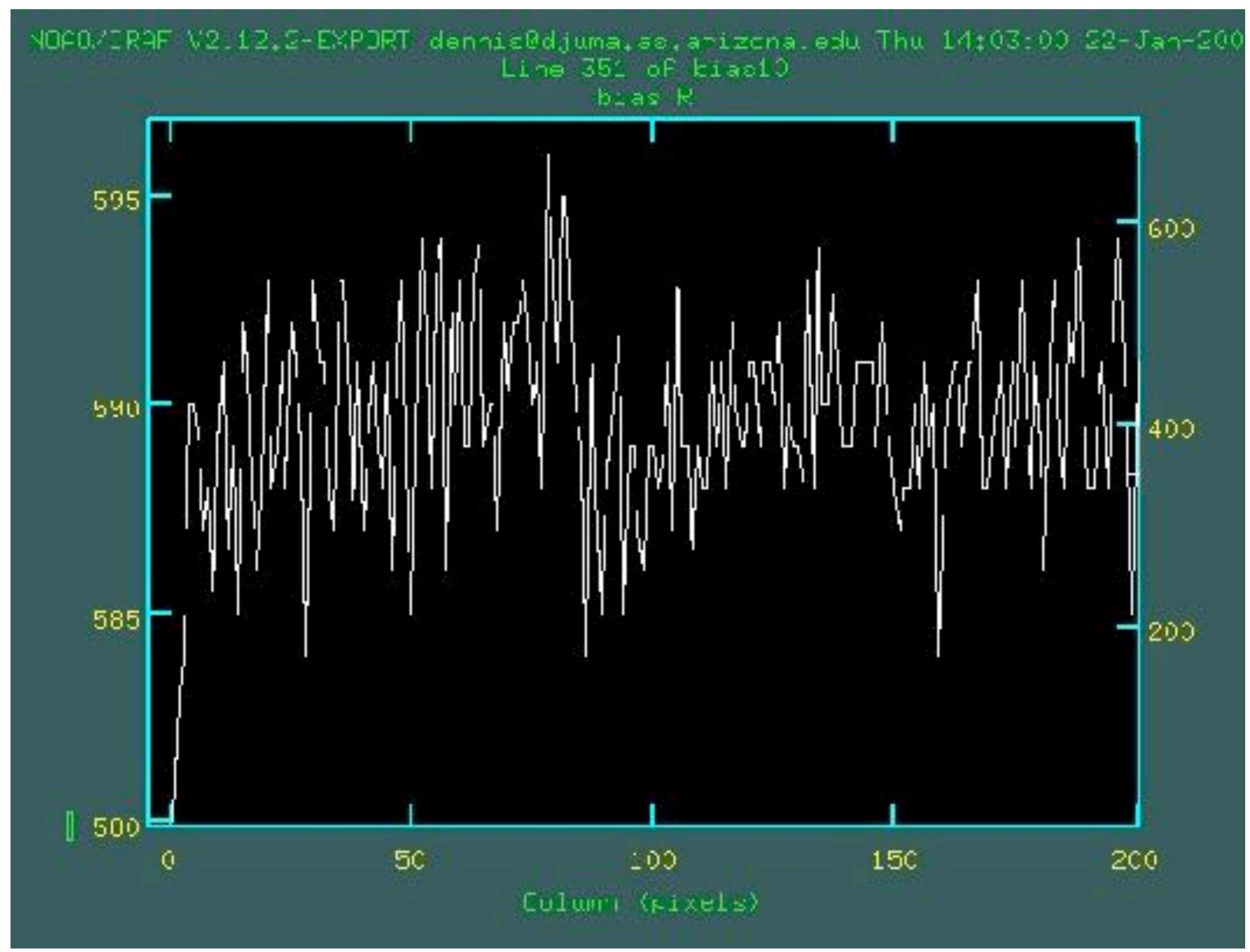
imarith (for image math)

imcombine (for combining images)

doing bias subtraction

1) identify overscan region (use either the image or take a cut across the image using implot task)

what columns (or rows) define the overscan?



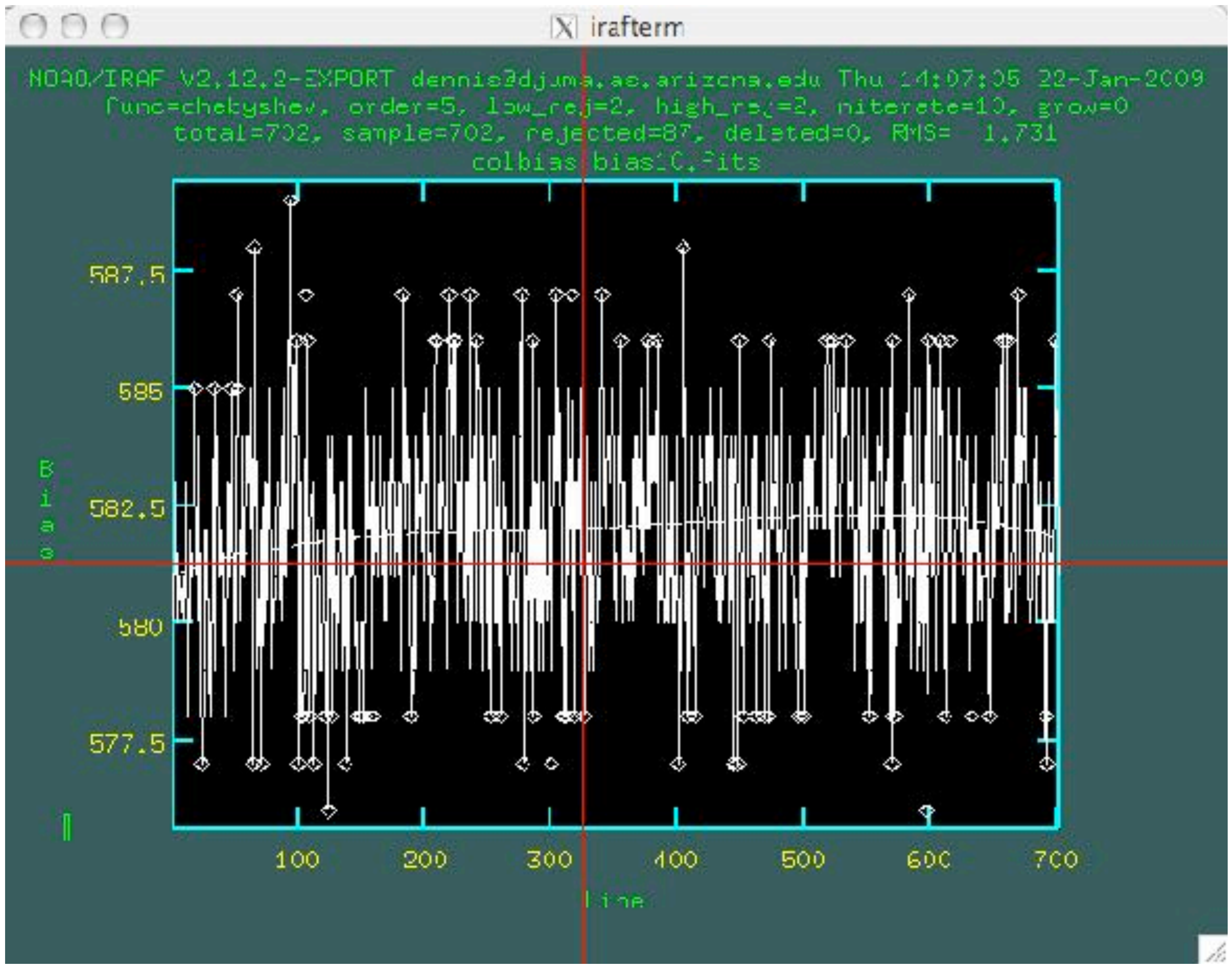
epa (edit parameter) colbias

```
xgterm
                                   I R A F
                    Image Reduction and Analysis Facility
PACKAGE = bias
   TASK = colbias

input   =                         Input images
output  =                         Output images
(bias   =        [1205:1217,*]) Bias section
(trim   =           [5:1190,*]) Trim section
(median =                   no) Use median instead of average in column bias?
(interac=                   no) Interactive?
(functio=            chebyshev) Fitting function
(order  =                    5) Order of fitting function
(low_rej=                   2.) Low sigma rejection factor
(high_re=                   2.) High sigma rejection factor
(niterat=                   10) Number of rejection iterations
(logfile=                     ) Log files
(graphic=             stdgraph) Graphics output device
(cursor =                     ) Graphics cursor input
(mode   =                   ql)

                                                        ESC-? for HELP
```

no parenthesis - it will ask you

parenthesis - it will take the values in the parameter file (or ask if empty)

do interactive until you're sure things are working



order of fit looks good, outlier rejection is ok (probably too aggressive)

- then subtract overscan from ALL images

- then combine bias frames and determine whether there is any residual 2-D structure to subtract

- then normalize all flat field frames (use imstat to determine mean and divide by mean using imarith)

- then combine frames to make superflat

- divide object frames by superflat

- examine to determine if more adjustments are necessary

- shift images using imshift and imalign so that the objects are aligned

- combine (using imcombine) frames to remove/correct for bad pixels/columns and cosmic rays

Photometry

measuring flux from astronomical objects

- separate object flux from backgrounds
- measure ALL flux from object

"sky" is underneath all objects &
no objects have sharp edges

Magnitude system

$$m_1 - m_2 = 2.5log(f_2/f_1)$$

magnitudes are always relative, always a ratio (a logarithmic ratio)

5 magnitude difference corresponds to a factor of 100 in flux

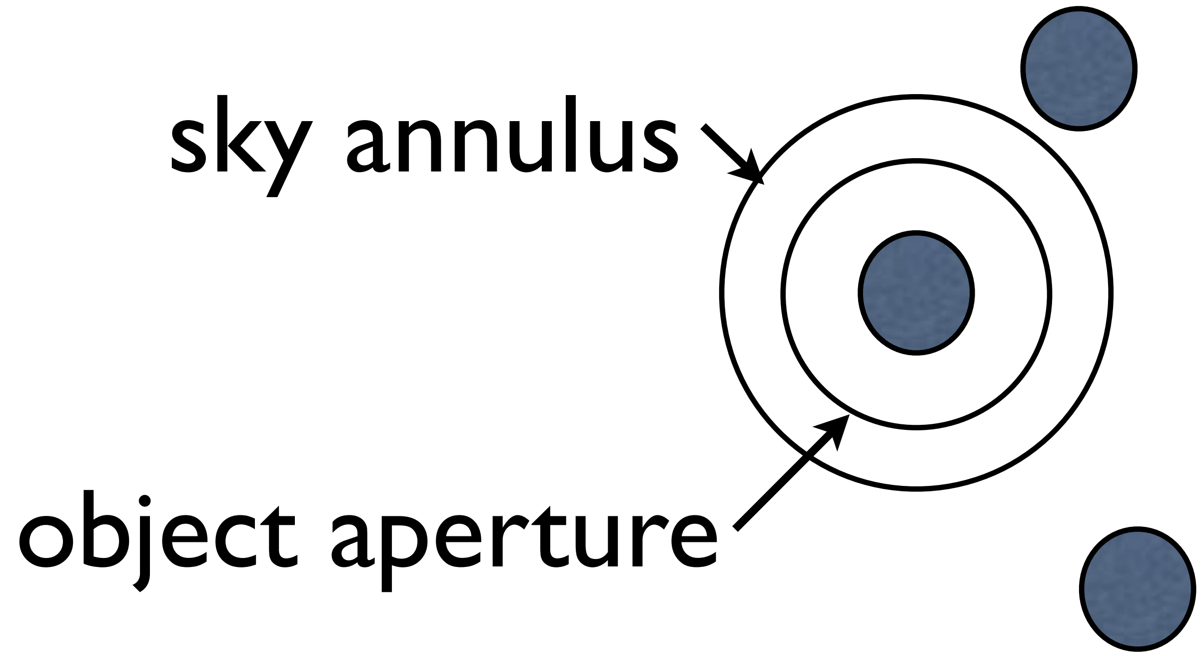
different systems (most common, Vega system in which Vega mag = 0)

smaller magnitudes are brighter!

measure the flux from a known object
compare it to your target object

known objects are standard stars

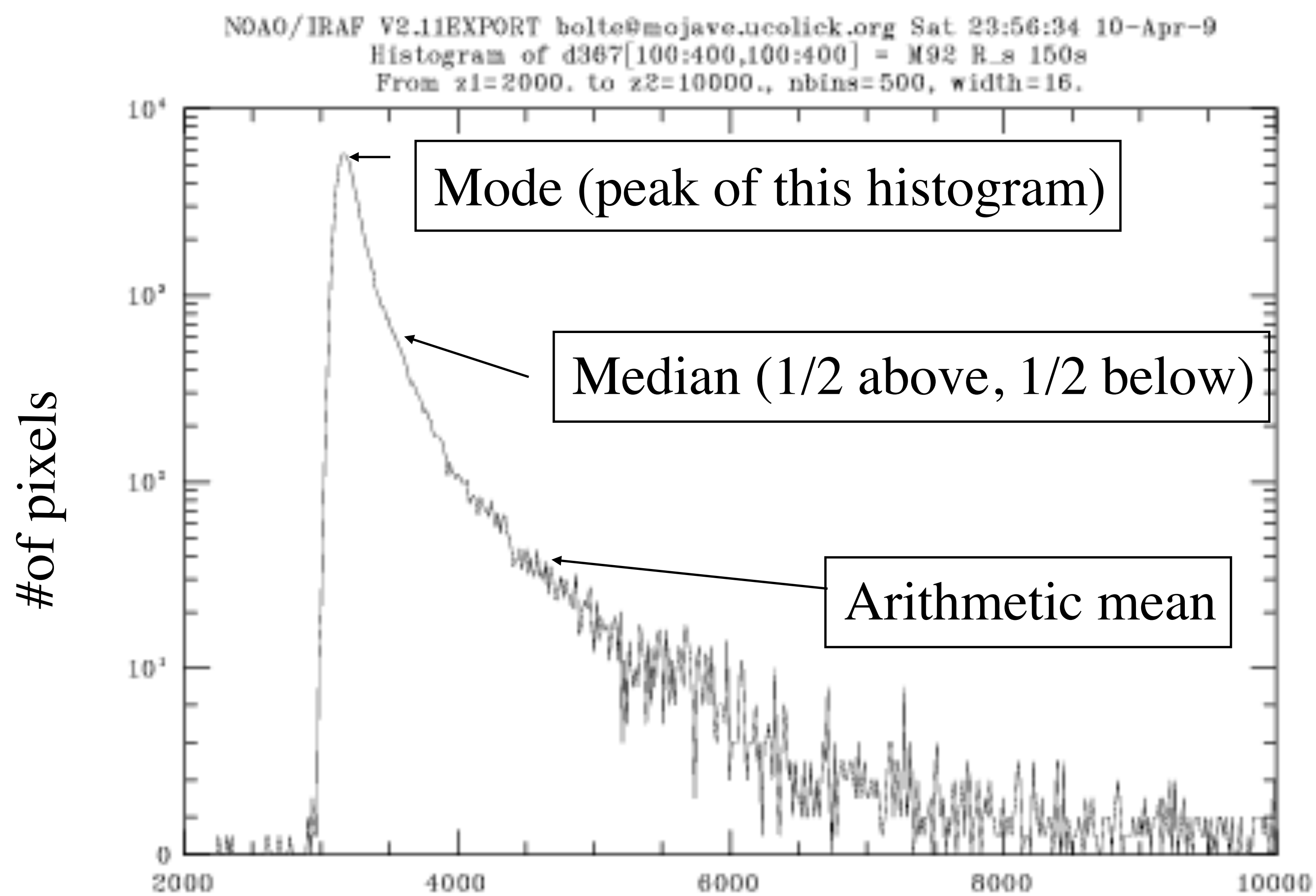
need to account for wavelength differences
and atmospheric extinction



1) maximize object aperture, while still leaving room for sky annulus (consider noise sources) will still need aperture correction

2) sky annulus should start far away enough from object to avoid contamination and extend as far out as possible while yet avoiding contamination

Issues when determining background sky value

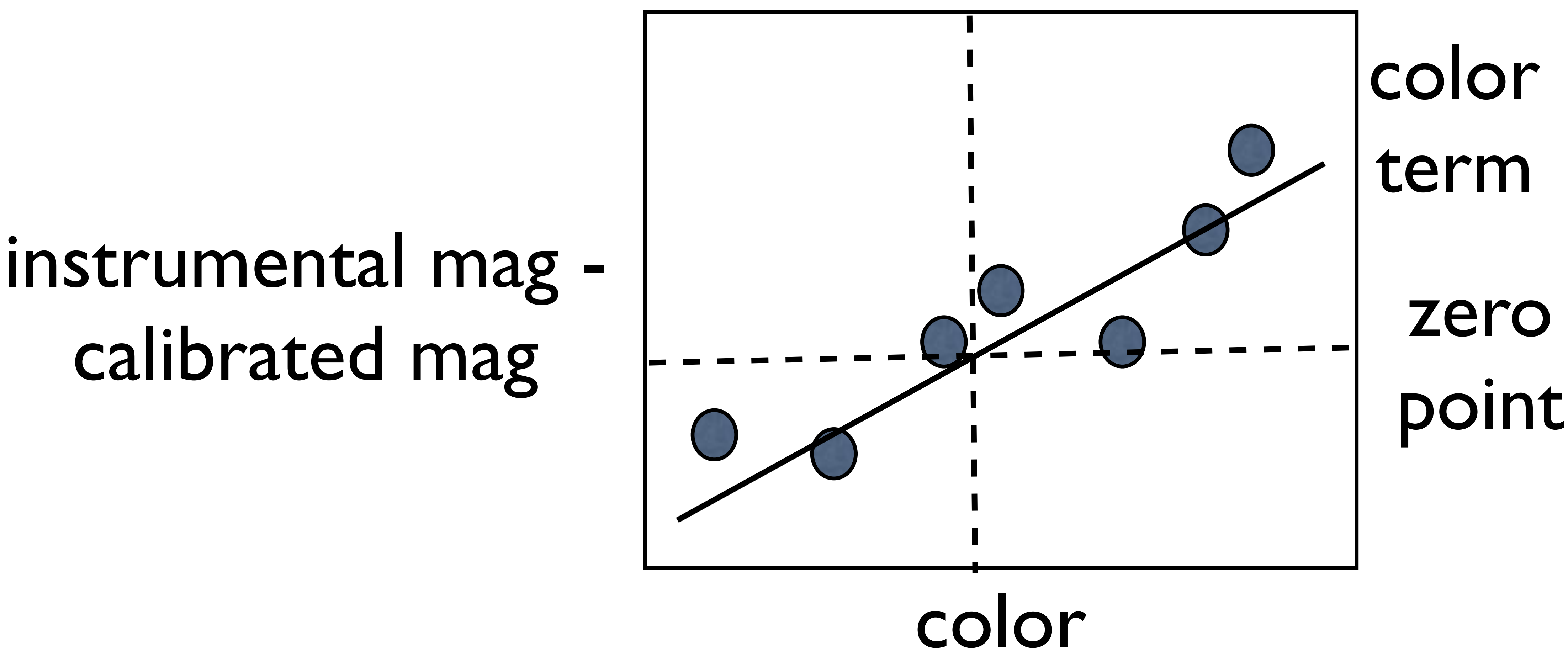


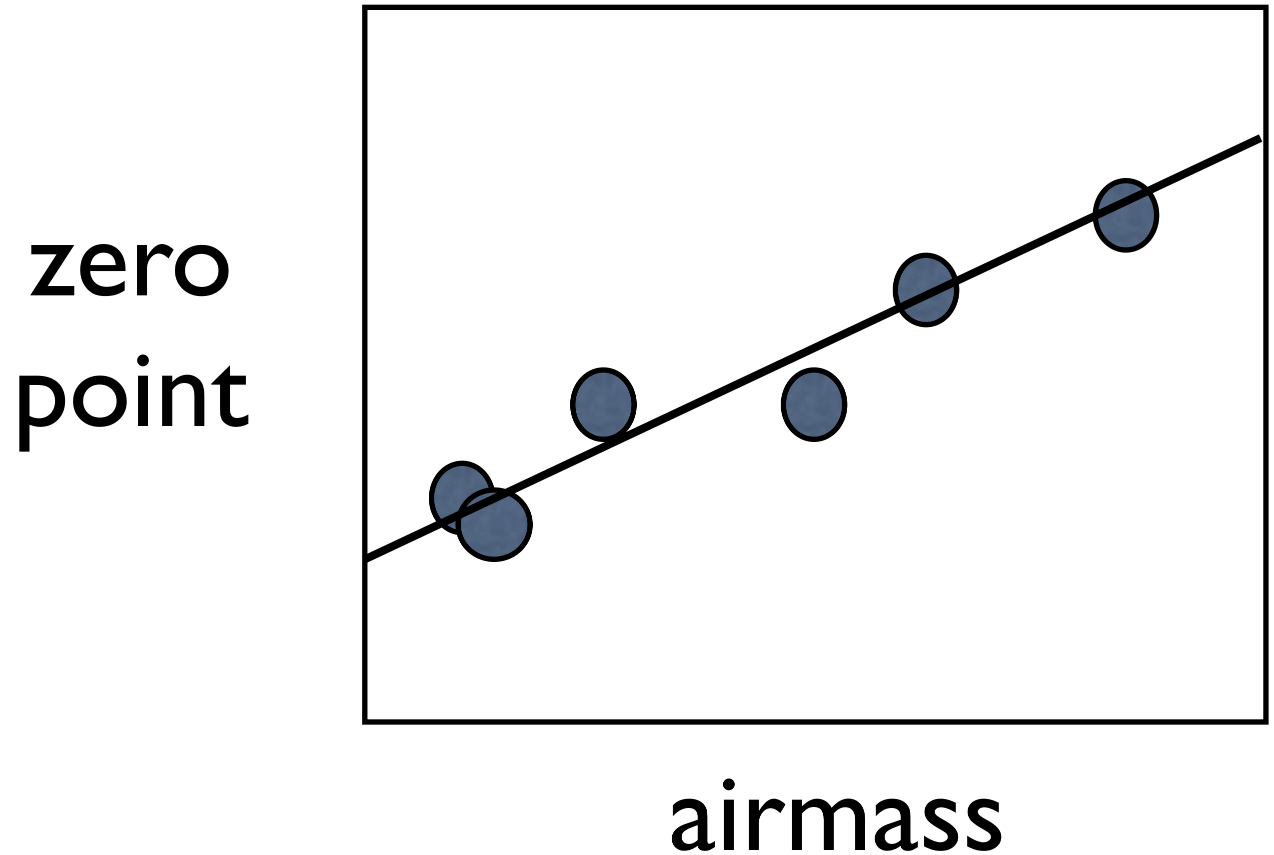
Which do you think is the best approximation of the sky value?

Calibration

- measure a good number of stars to minimize random errors and have a range of intrinsic colors

instrumental magnitudes --> log(counts/sec)



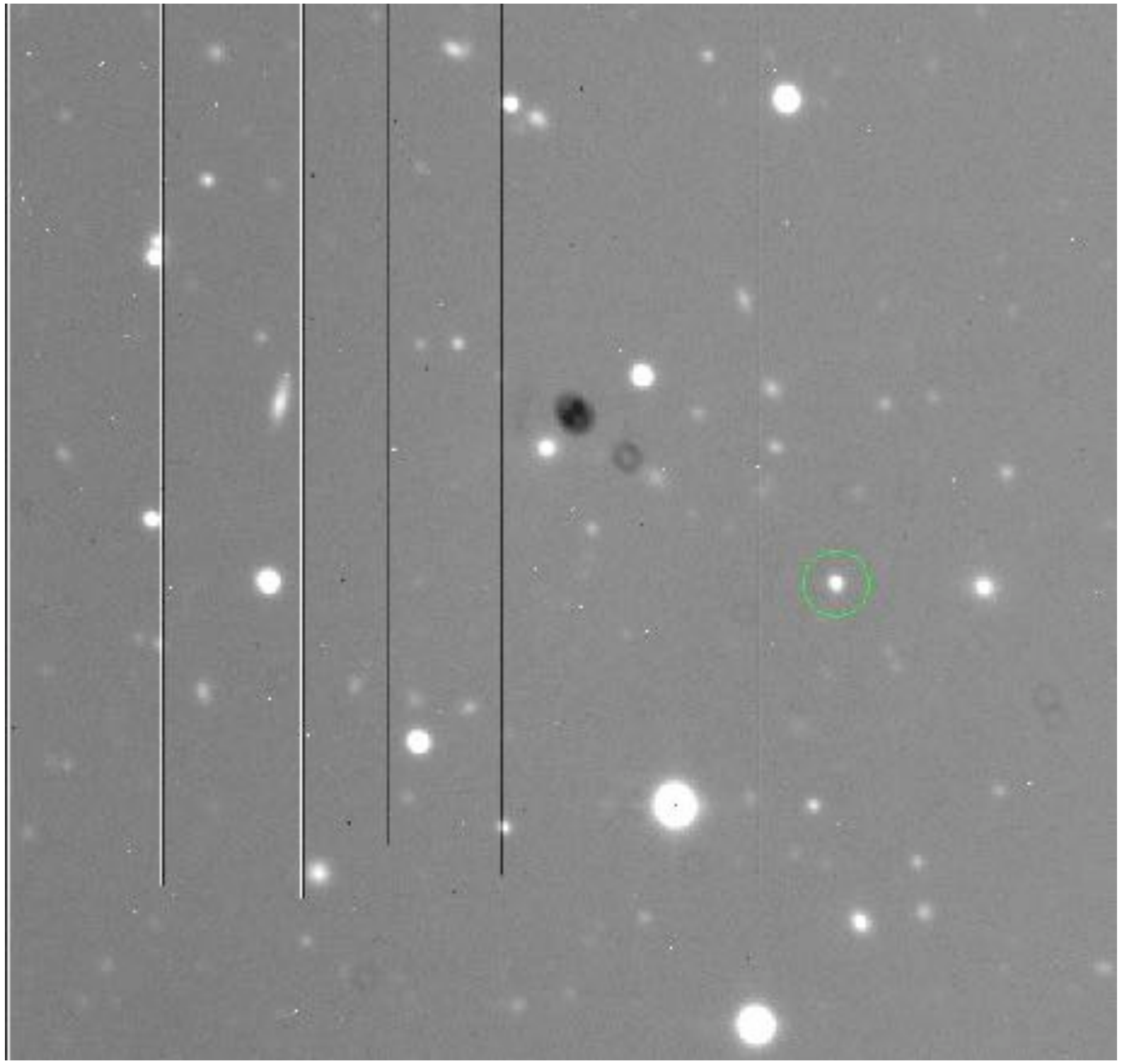


magnitude = instrumental mag + zero point + color term + airmass term + aperture correction

Photometry in IRAF

load tasks digiphot & apphot

edit parameters of
task phot



you’ll need to epa
photpars,
fitskypars,datapars

```
xgterm
                                    I R A F
                      Image Reduction and Analysis Facility
PACKAGE = apphot
   TASK = phot

image   =              object1  The input image(s)
skyfile = []                    The input sky file(s)
(coords =                     ) The input coordinate files(s) (default: image.coo.?
(output =              default) The output photometry file(s) (default: image.mag.?
(plotfil=                     ) The output plots metacode file
(datapar=                     ) Data dependent parameters
(centerp=                     ) Centering parameters
(fitskyp=                     ) Sky fitting parameters
(photpar=                     ) Photometry parameters
(interac=                  yes) Interactive mode ?
(radplot=                  yes) Plot the radial profiles in interactive mode ?
(icomman=                     ) Image cursor: [x y wcs] key [cmd]
(gcomman=                     ) Graphics cursor: [x y wcs] key [cmd]
(wcsin  =             )_.wcsin) The input coordinate system (logical,tv,physical,wo
(wcsout =            )_.wcsout) The output coordinate system (logical,tv,physical)
(cache  =             )_.cache) Cache the input image pixels in memory ?
(verify =            )_.verify) Verify critical parameters in non-interactive mode
(update =            )_.update) Update critical parameters in non-interactive mode
(verbose=           )_.verbose) Print messages in non-interactive mode ?
(graphic=          )_.graphics) Graphics device
(display=           )_.display) Display device
(mode   =                  ql)
```

interactive, radplot => yes

```
xgterm
                              I R A F
                  Image Reduction and Analysis Facility
PACKAGE = apphot
   TASK = photpars

(weighti=              constant) Photometric weighting scheme for wphot
(apertur=   5,7,10,12,14,16,18) List of aperture radii in scale units
(zmag   =                   25.) Zero point of magnitude scale
(mkapert=                   yes) Draw apertures on the display
(mode   =                    ql)
```

← select aperture set

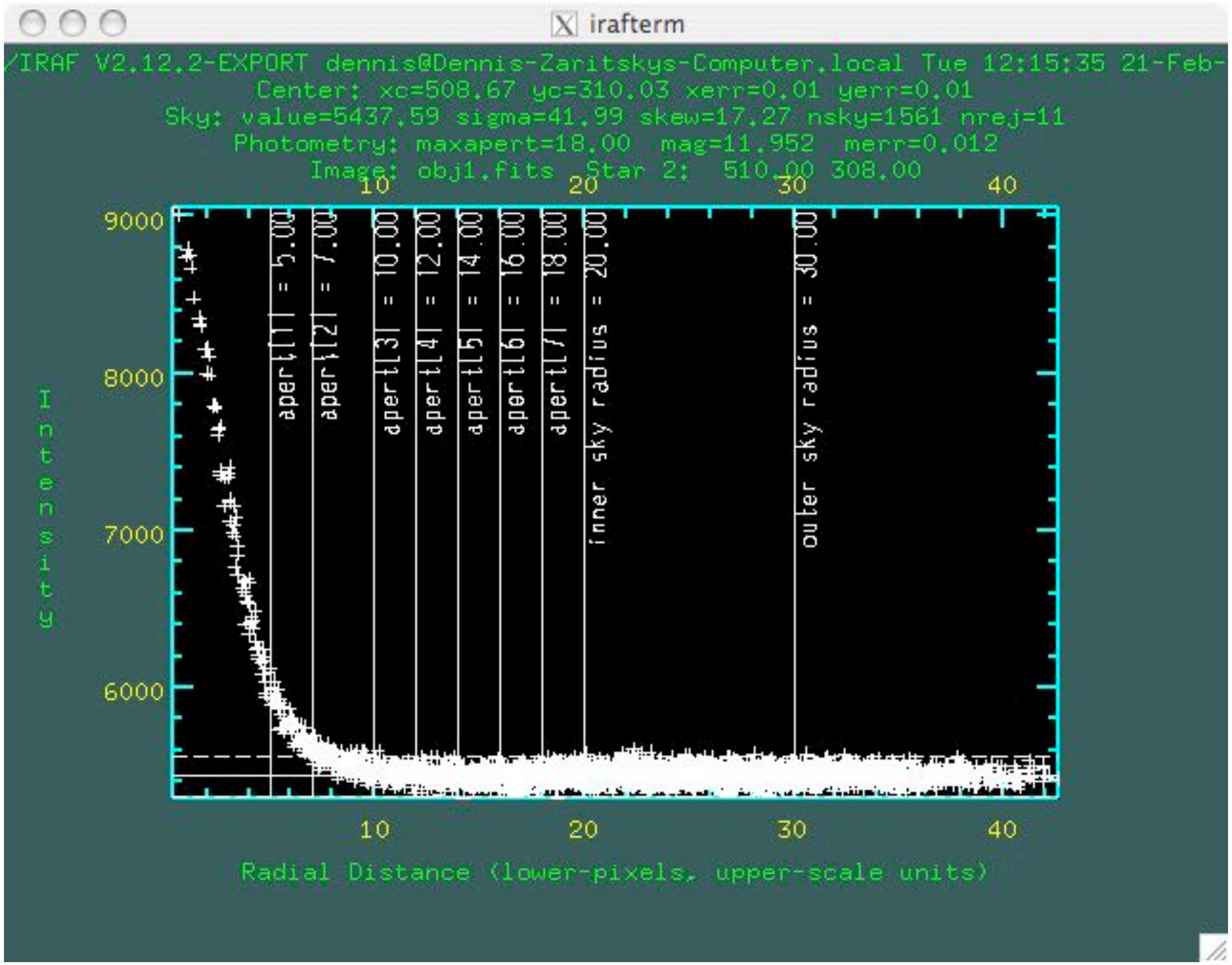
set sky annulus →

```
xgterm
                              I R A F
                  Image Reduction and Analysis Facility
PACKAGE = apphot
   TASK = fitskypars

(salgori=              centroid) Sky fitting algorithm
(annulus=                   20.) Inner radius of sky annulus in scale units
(dannulu=                   10.) Width of sky annulus in scale units
(skyvalu=                    0.) User sky value
(smaxite=                    10) Maximum number of sky fitting iterations
(sloclip=                    0.) Lower clipping factor in percent
(shiclip=                    0.) Upper clipping factor in percent
(snrejec=                    50) Maximum number of sky fitting rejection iterations
(sloreje=                    3.) Lower K-sigma rejection limit in sky sigma
(shireje=                    3.) Upper K-sigma rejection limit in sky sigma
(khist  =                    3.) Half width of histogram in sky sigma
(binsize=                   0.1) Binsize of histogram in sky sigma
(smooth =                    no) Boxcar smooth the histogram
(rgrow  =                    0.) Region growing radius in scale units
(mksky  =                   yes) Mark sky annuli on the display
(mode   =                    ql)




                                                           ESC-? for HELP
```

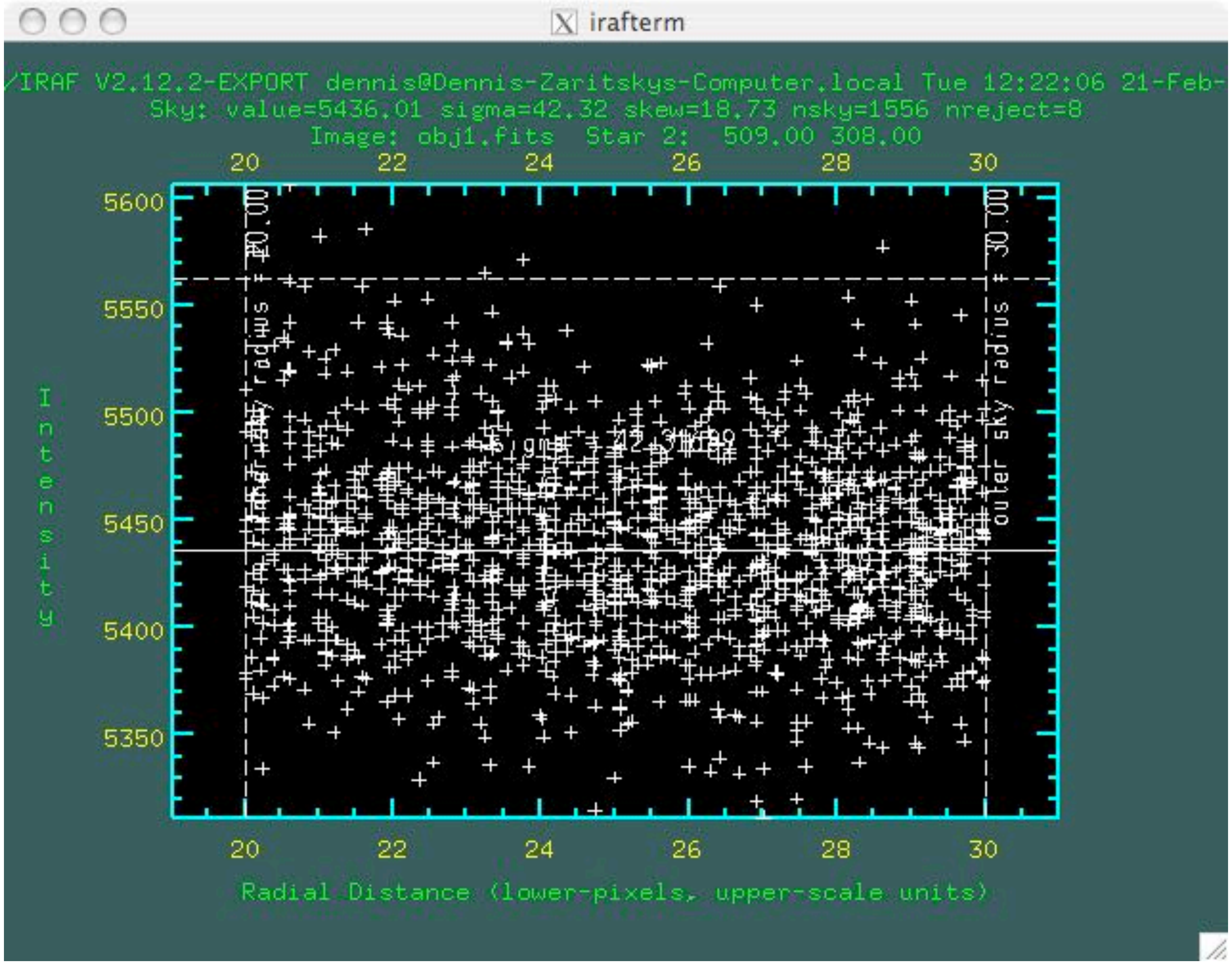
set datapars to get good uncertainty estimates

xgterm

```
                                 I R A F
                    Image Reduction and Analysis Facility
PACKAGE = apphot
   TASK = datapars

(scale  = []             1.) Image scale in units per pixel
(fwhmpsf=                2.5) FWHM of the PSF in scale units
(emissio=                yes) Features are positive ?
(sigma  =              INDEF) Standard deviation of background in counts
(datamin=              INDEF) Minimum good data value
(datamax=              INDEF) Maximum good data value
(noise  =            poisson) Noise model
(ccdread=                   ) CCD readout noise image header keyword
(gain   =                   ) CCD gain image header keyword
(readnoi=                 0.) CCD readout noise in electrons
(epadu  =                 1.) Gain in electrons per count
(exposur=                   ) Exposure time image header keyword
(airmass=                   ) Airmass image header keyword
(filter =                   ) Filter image header keyword
(obstime=                   ) Time of observation image header keyword
(itime  =                 1.) Exposure time
(xairmas=              INDEF) Airmass
(ifilter=              INDEF) Filter
(otime  =              INDEF) Time of observation
(mode   =                 ql)
($nargs =                  0)

                                                        ESC-? for HELP
```

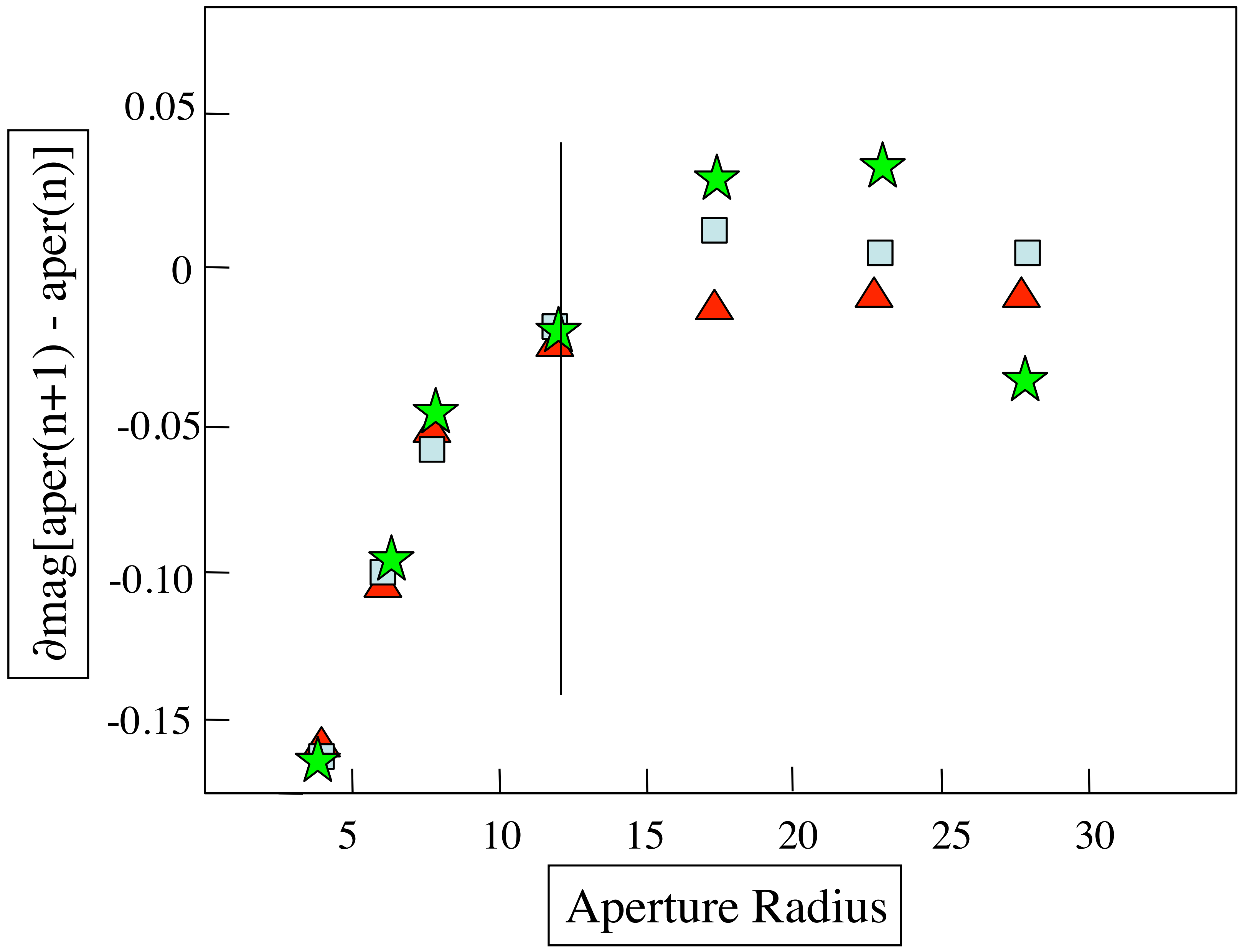


phot - space bar

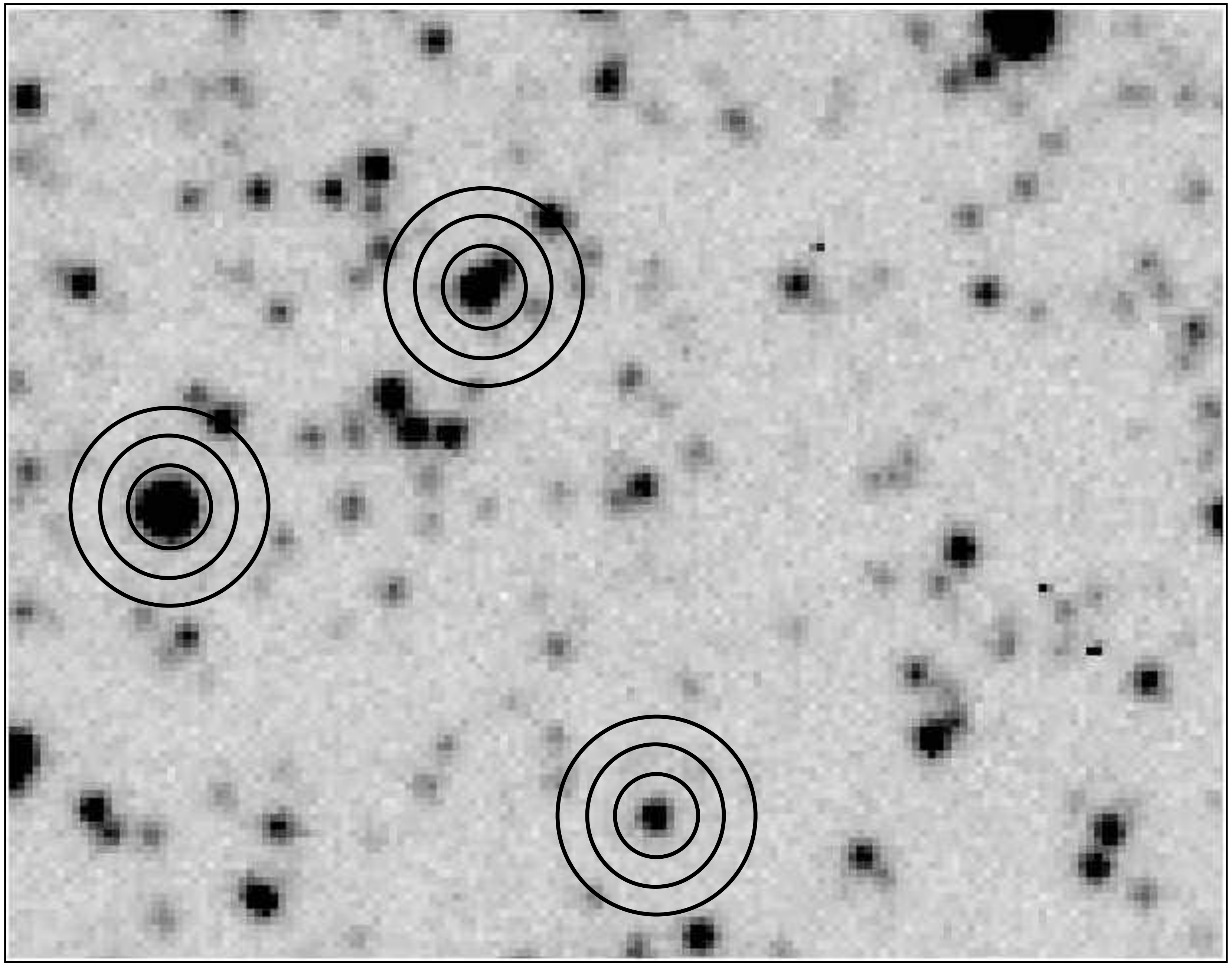

irafterm
/IRAF V2.12.2-EXPORT dennis@Dennis-Zaritskys-Computer.local Tue 12:22:06 21-Feb-
Sky: value=5436.01 sigma=42.32 skew=18.73 nsky=1556 nreject=8
Image: obj1.fits Star 2: 509.00 308.00
20 22 24 26 28 30
5600 5550 5500 5450 5400 5350
Intensity
outer sky radius = 30.00
Radial Distance (lower-pixels, upper-scale units)

phot - t

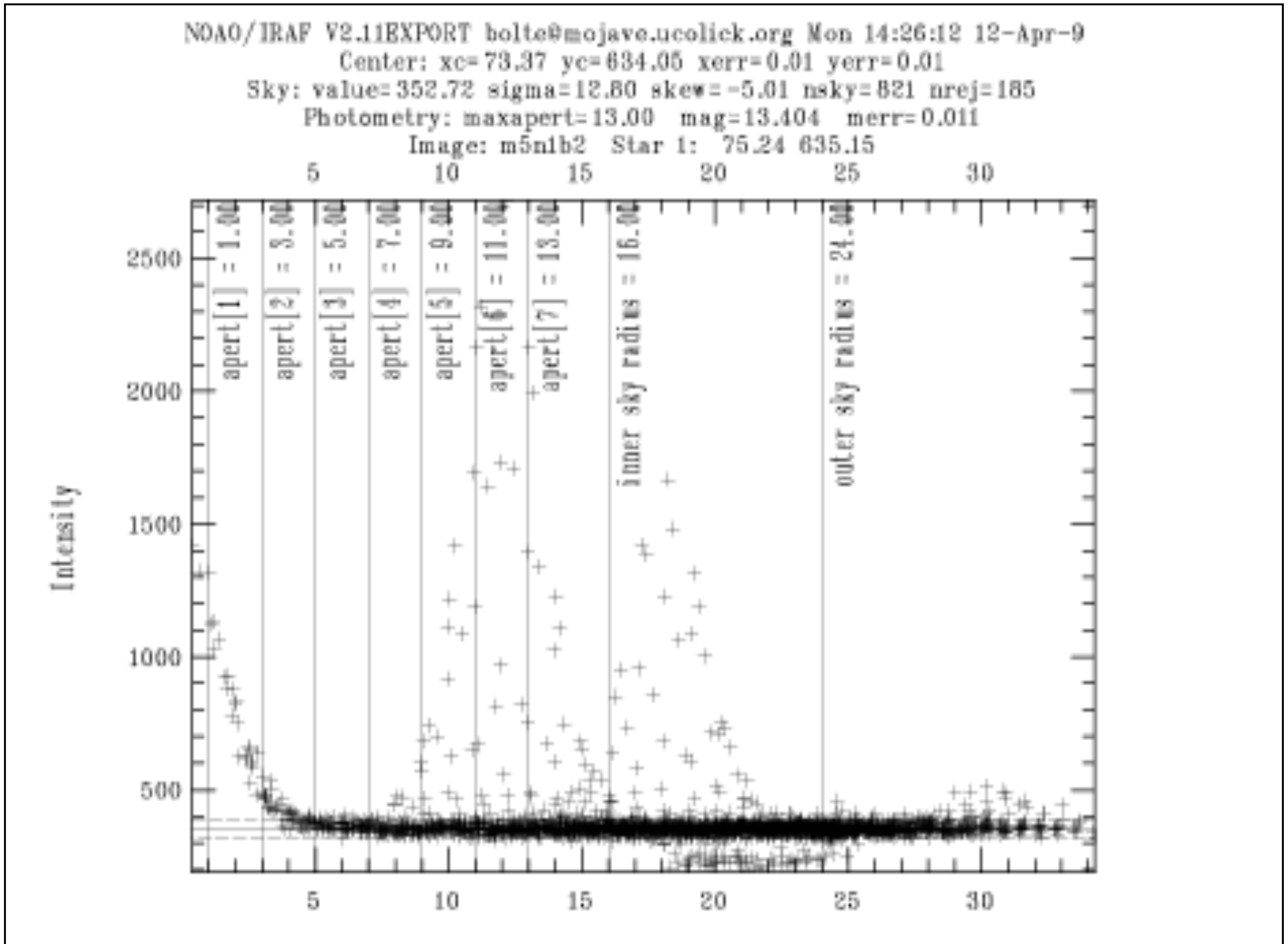
Photometry growth curve



Nested apertures and sky annulus

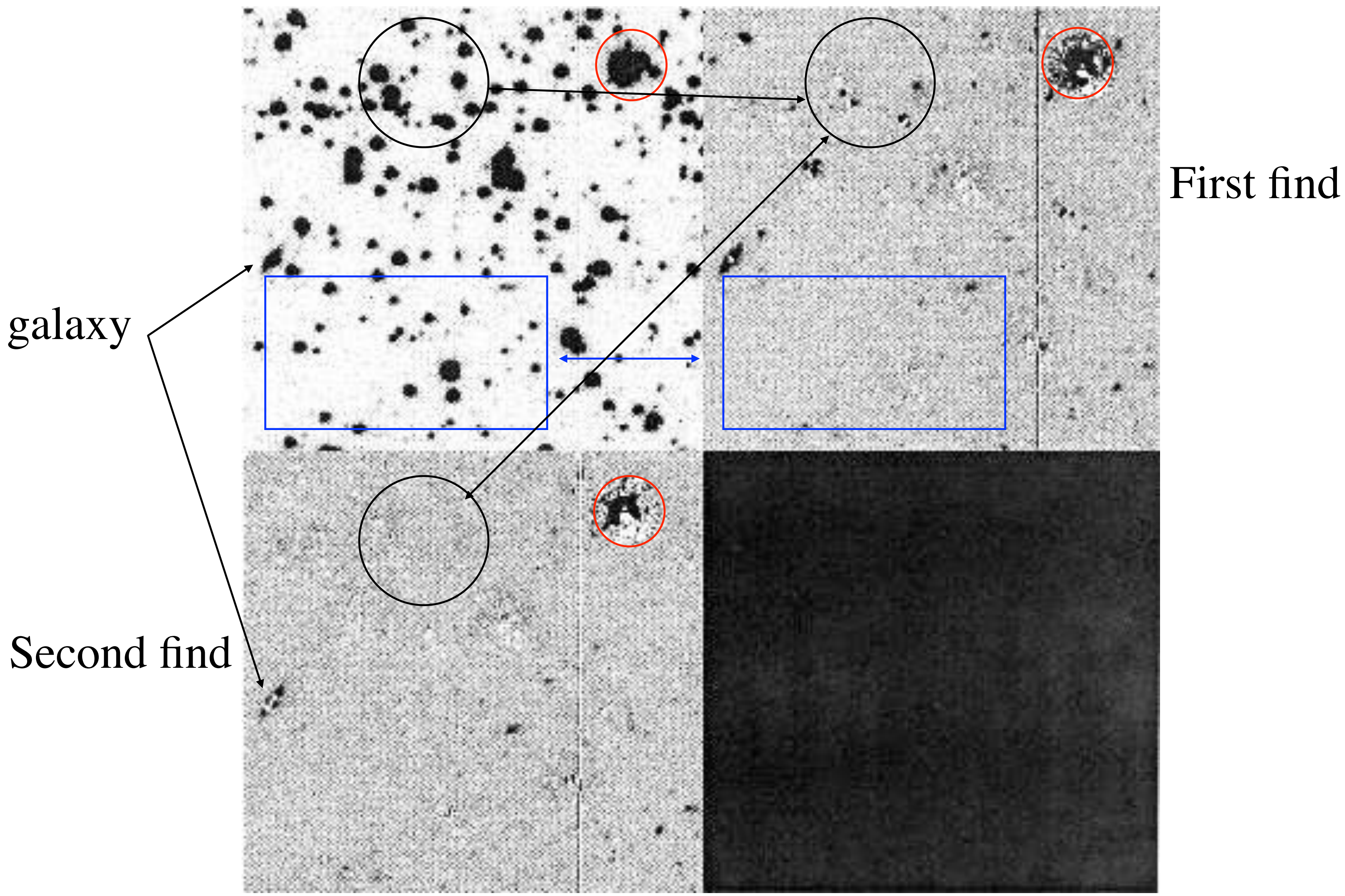


crowded-field photometry



neighbors are more of a problem in apertures than in sky annulus - why?

DAOPHOT - example of crowded field photometry



Filter Systems

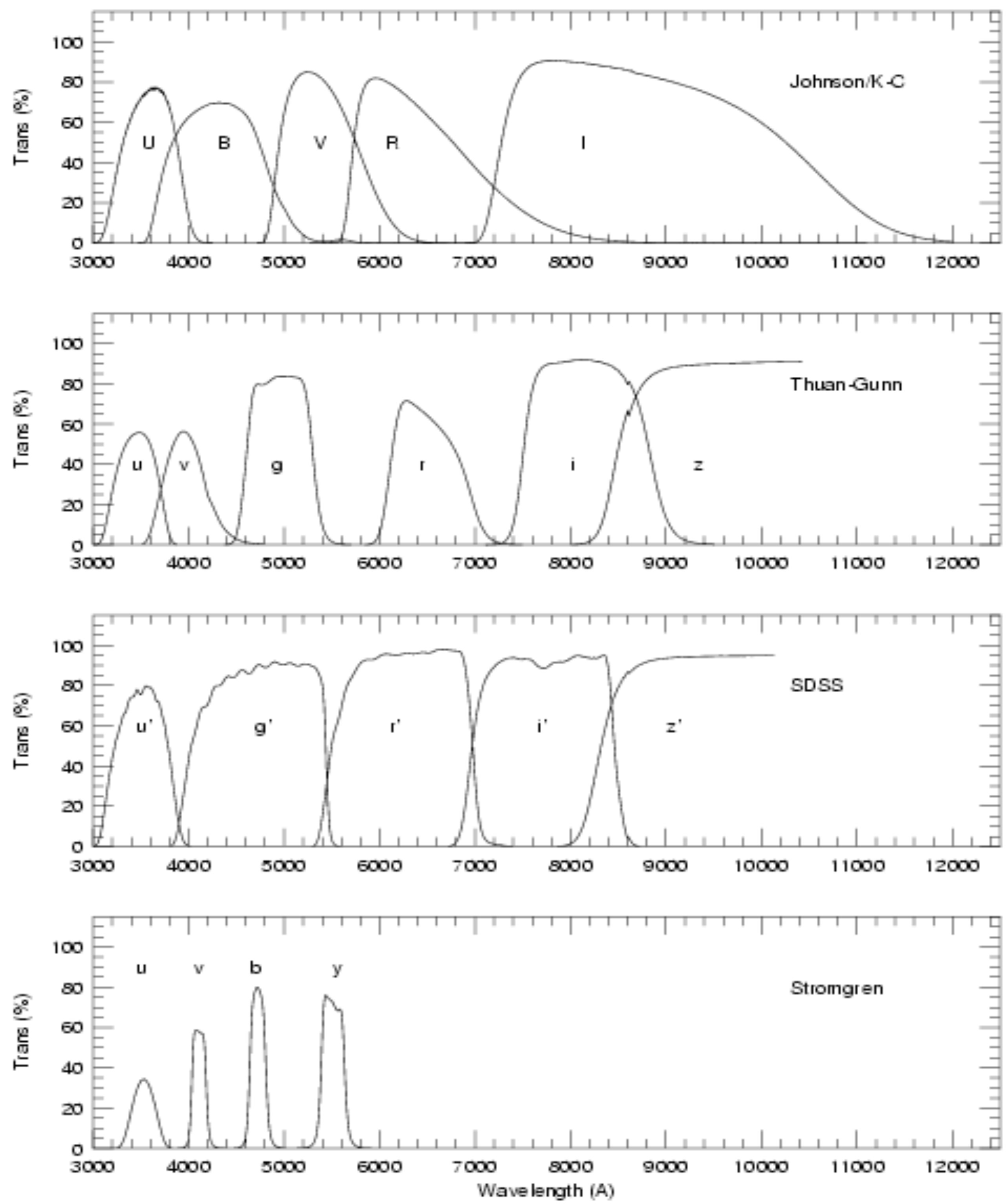
Filters come in a wide range of widths and cental wavelengths to accommodate the science goal.

Broad band ~ 1000Å wide

Narrow band ~ 10 - 100Å wide

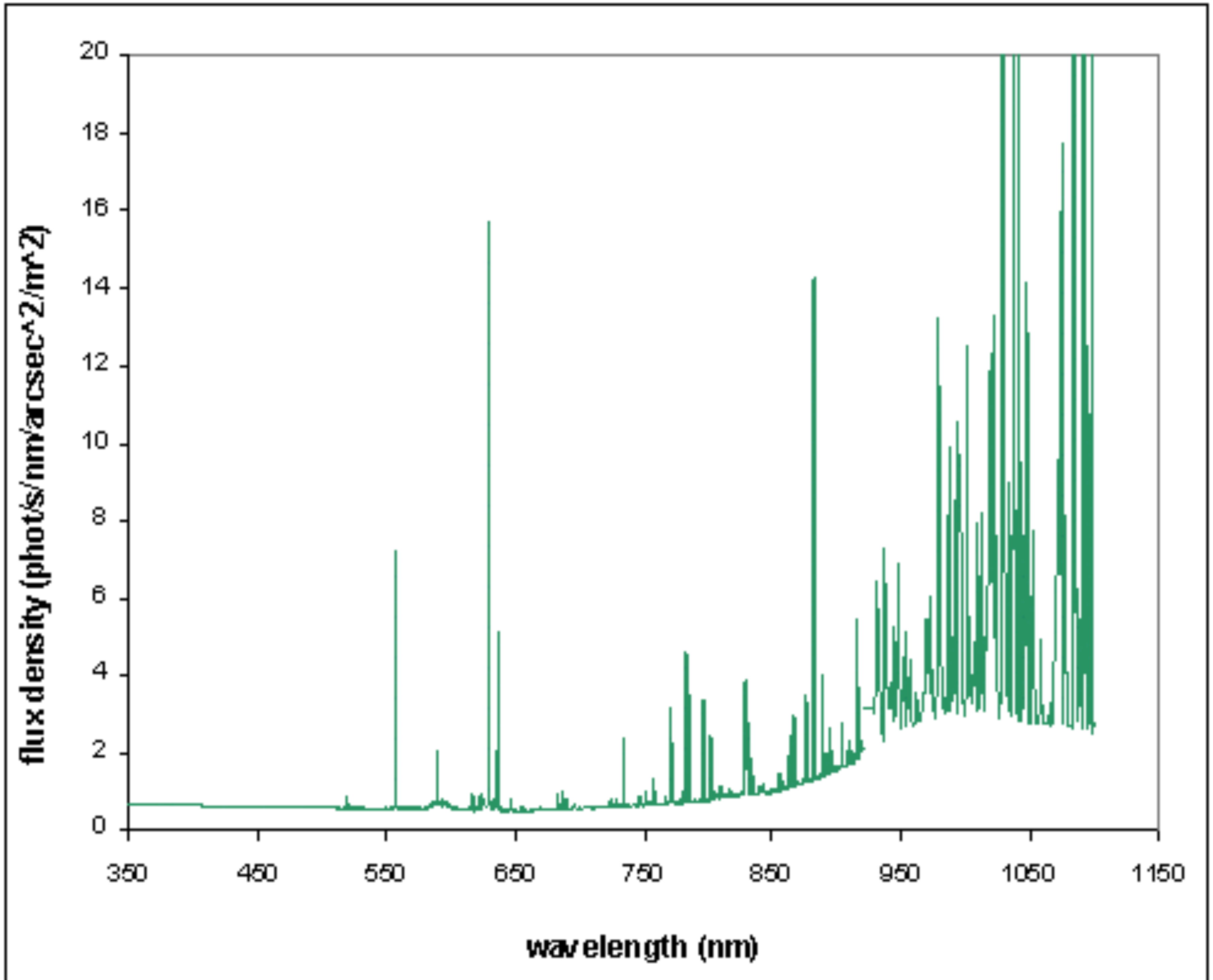
Measuring colors is ``poor-man's spectroscopy"

3100Å is the UV atmospheric cutoff



1.1μ silicon bandgap

Optical sky spectrum



Why are colors expressed as m1-m2?

Why are zero point corrections additive?

Why are airmass corrections additive?

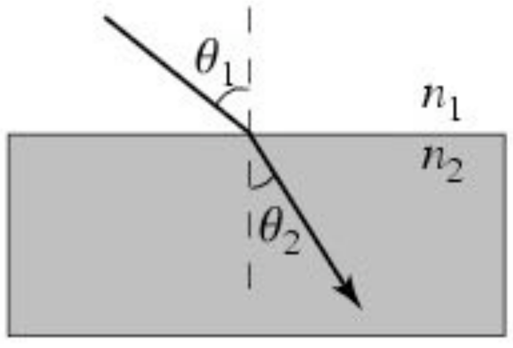
Is there a magnitude system that makes physical sense?

Is there anything like a "TOTAL flux" measurement?

Telescope Basics

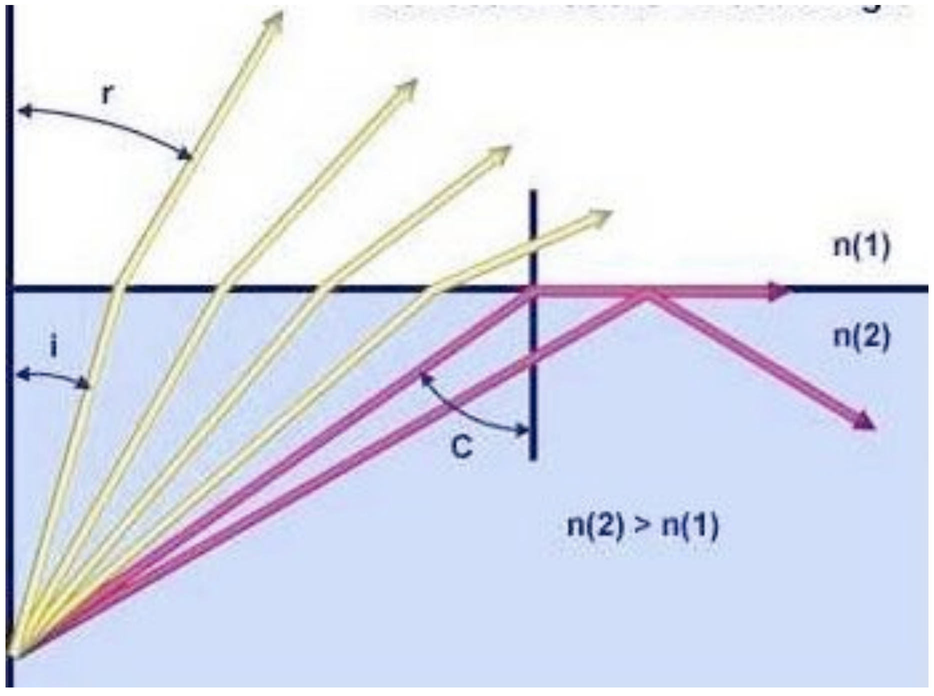
Optics

refraction: snell's law



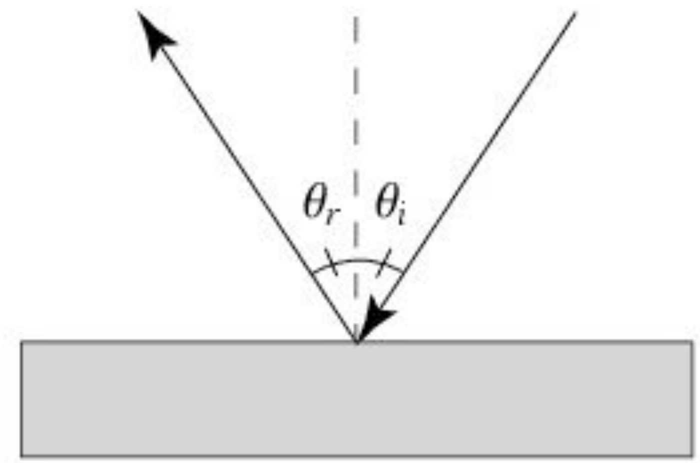
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

arises due to differences in propagation velocity

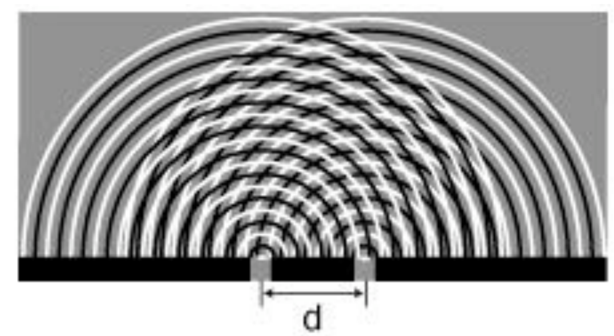


http://galileo.phys.virginia.edu/classes/usem/SciImg/home_files/introduction.htm http://scienceworld.wolfram.com/physics/Reflection.html

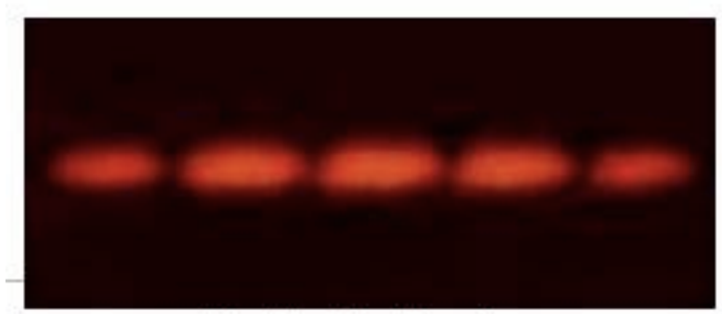
Reflection



Diffraction



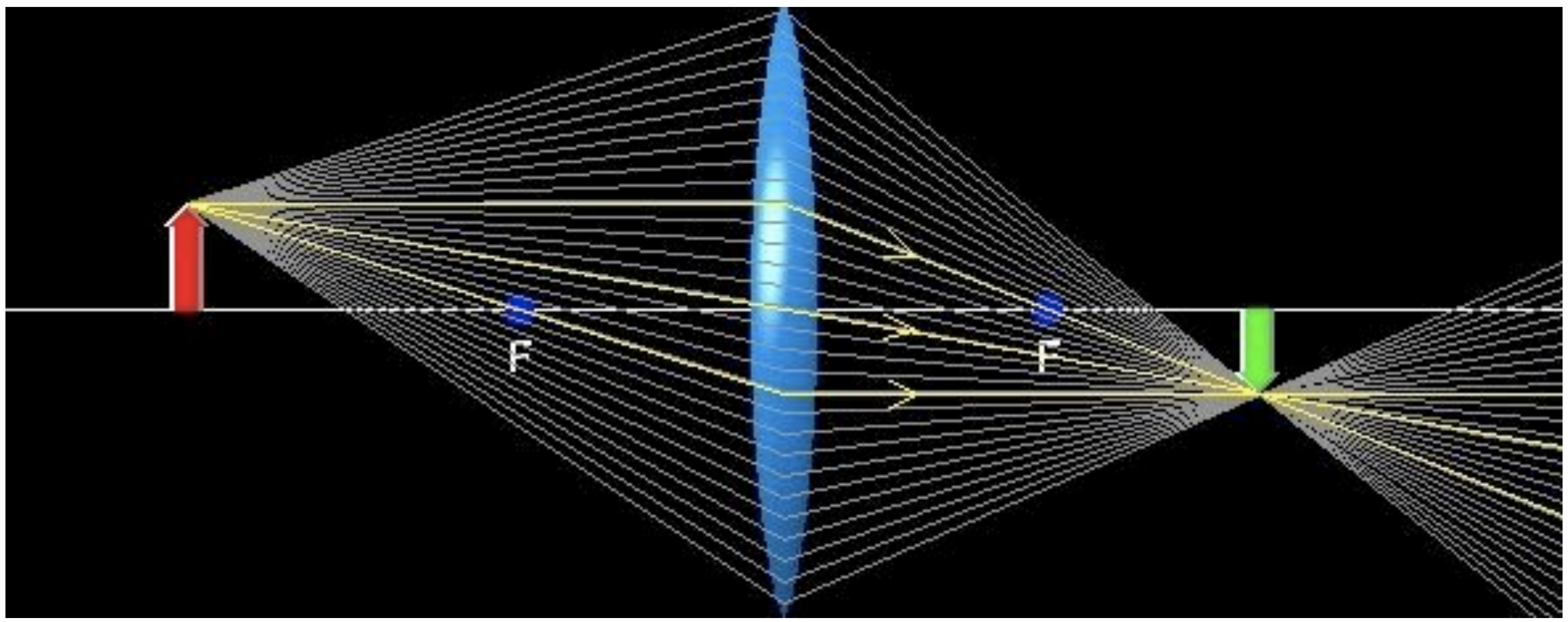
Double-slit diffraction



Double-slit diffraction

http://en.wikipedia.org/wiki/Diffraction

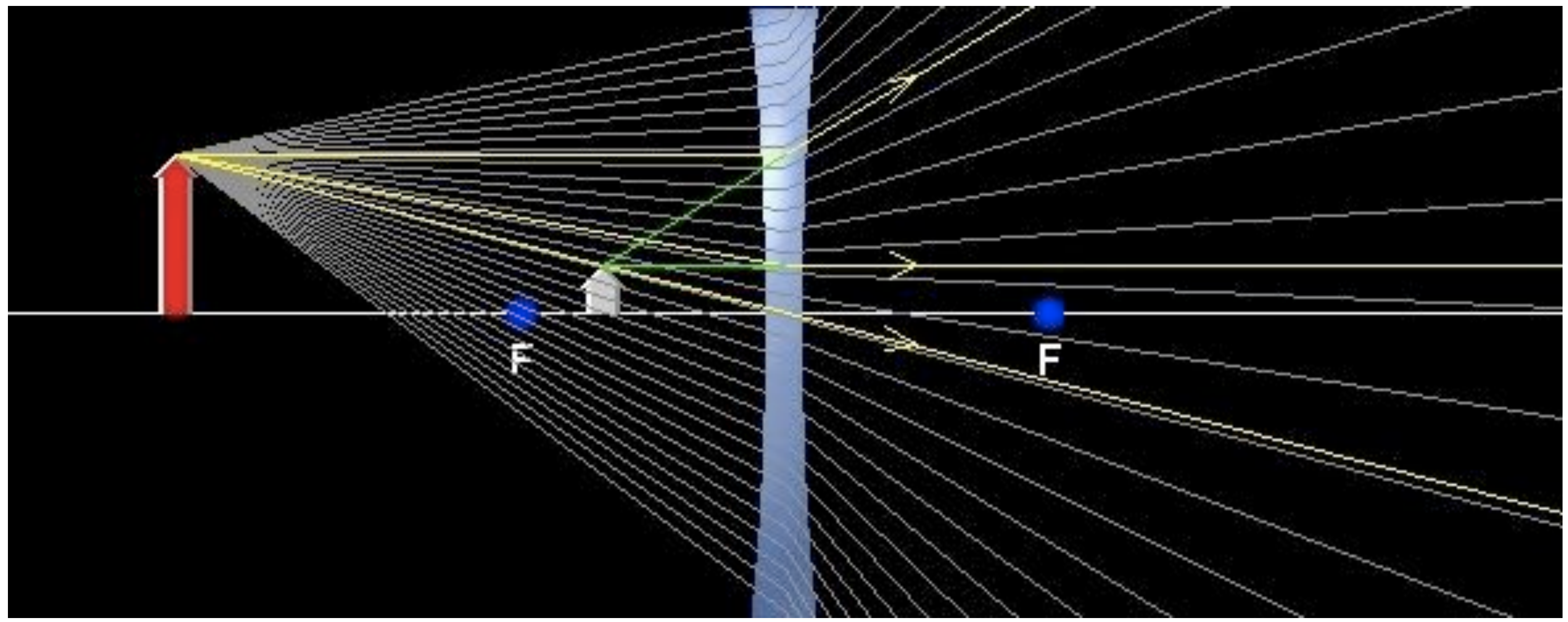
Converging (convex) lens



$$1/d_{image} + 1/d_{object} = 1/f$$

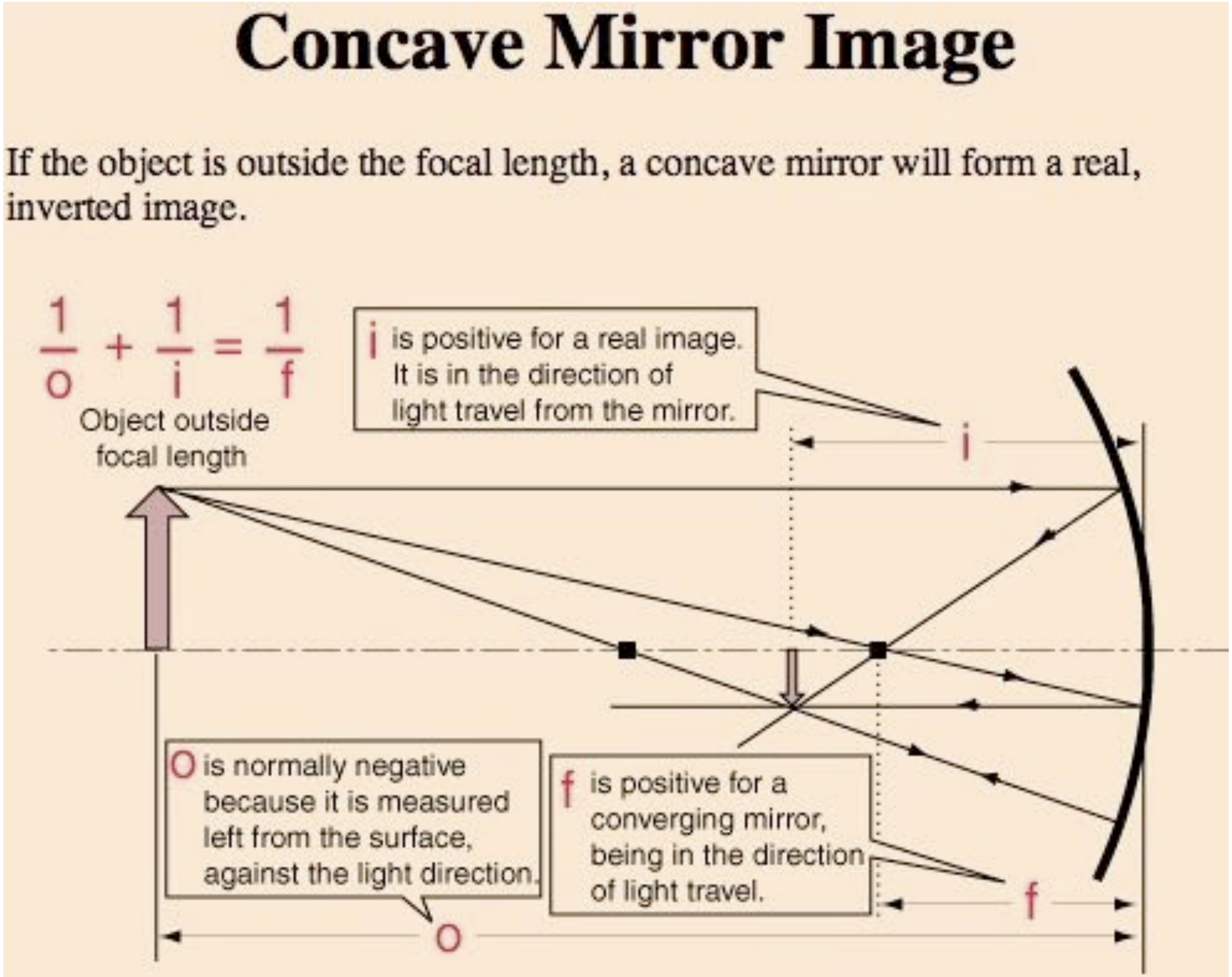
focal length is the distance to image for an object at infinity

diverging (concave) lens



In combination, converging and diverging lenses can provide the optical parameters you need

Mirrors


Concave Mirror Image
If the object is outside the focal length, a concave mirror will form a real, inverted image.
1/o + 1/i = 1/f
Object outside focal length
i is positive for a real image. It is in the direction of light travel from the mirror.
i
O is normally negative because it is measured left from the surface, against the light direction.
f is positive for a converging mirror, being in the direction of light travel.
f
o

Telescope parameters

1) Focal ratio : ratio of focal length to aperture
fast vs. slow (affects FOV, plate scale, S/N)

2) plate scale : $s(\text{mm/arcsec}) = f(\text{m})/206.25$

where f is focal length (in meters)

3) field of view (FOV): depends on aperture stops, aberrations (and less directly on detector size)

4) aperture size: affects light gathering capability and best-possible image quality

“fast” telescopes have...

wider FOVs

(all for fixed detector parameters)

more light/pixel

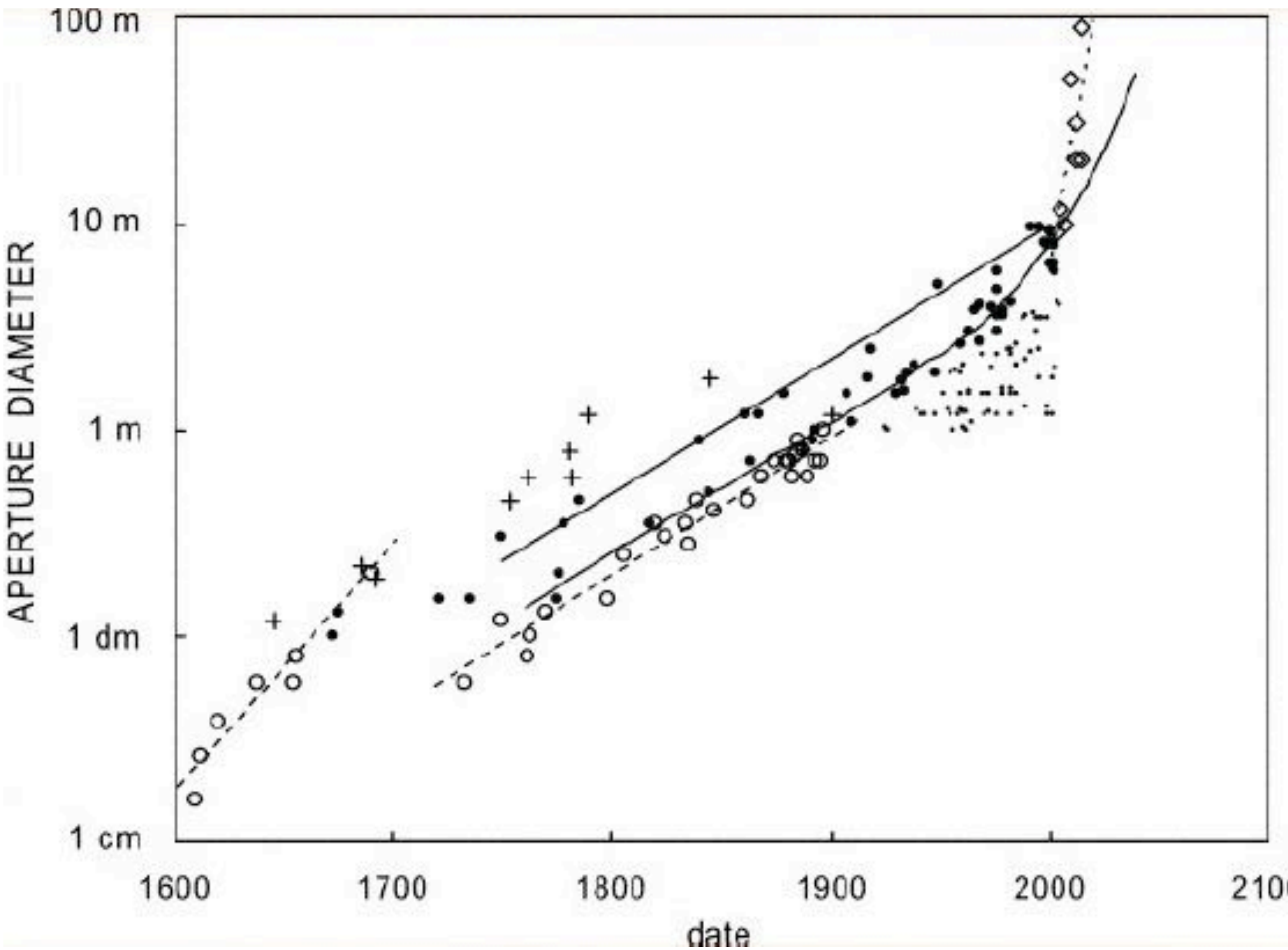
lower spatial resolution

a smaller telescope structure

more technical challenges to construct

a more curved focal plane

a larger secondary



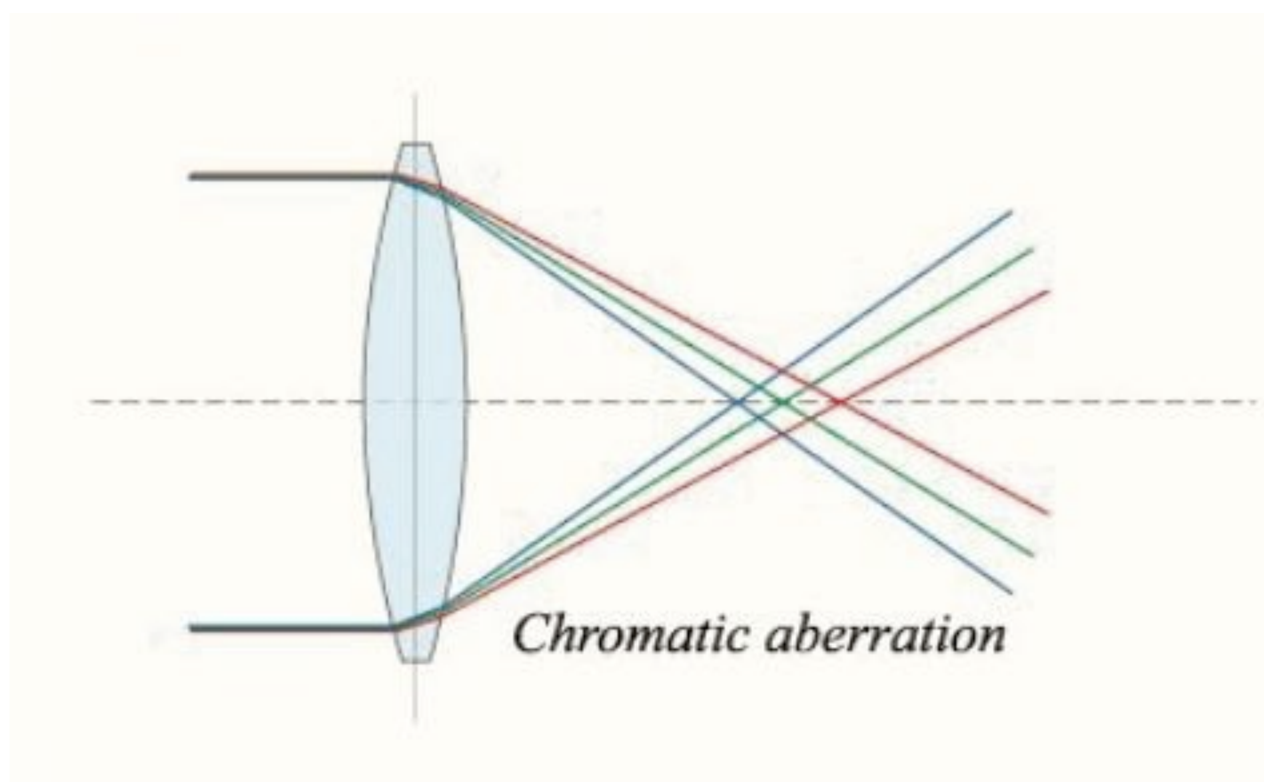
Racine 2004, PASP

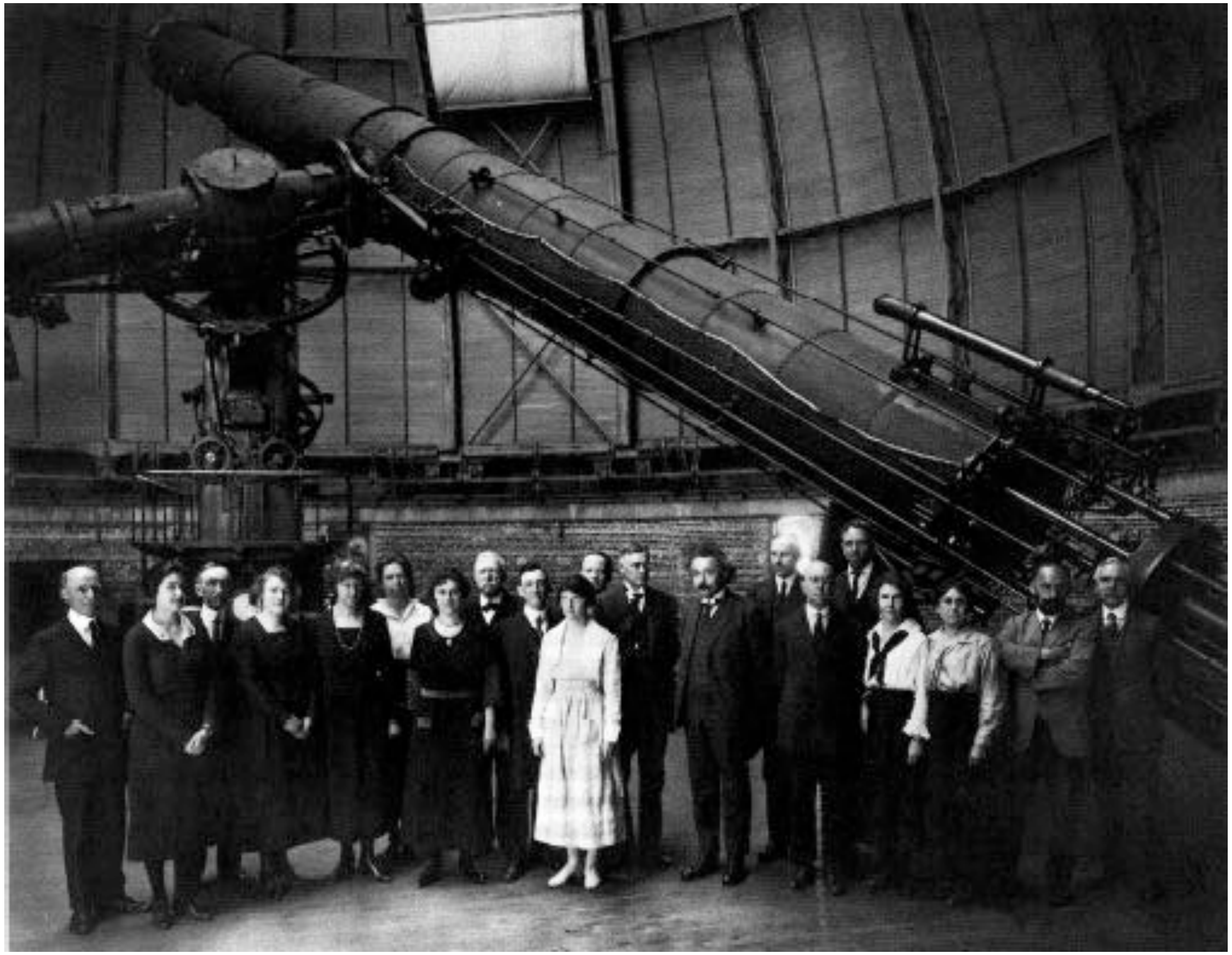
Refractors vs. Reflectors (lenses vs. mirrors)

refractors first...

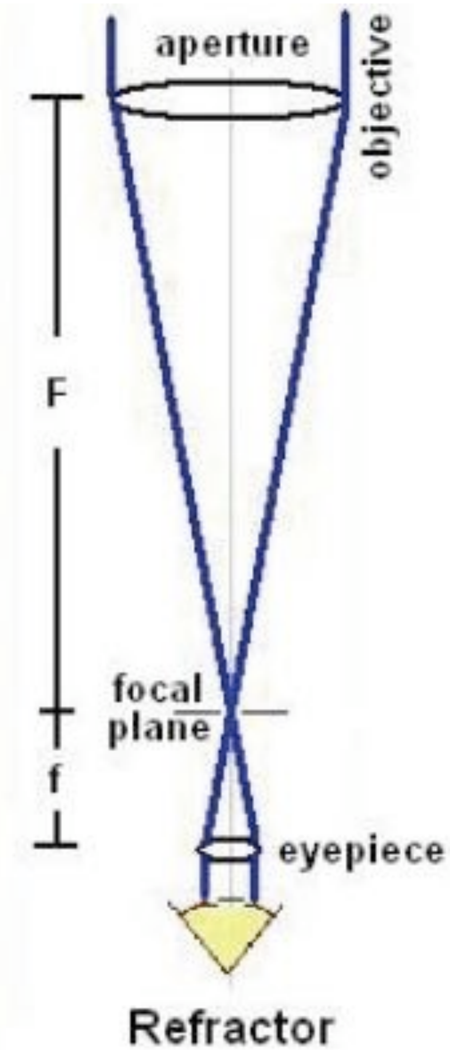
primary element determines aperture size
and sets aperture stop

limitations: aperture size, length, chromatic aberrations





Yerkes 40-inch refractor

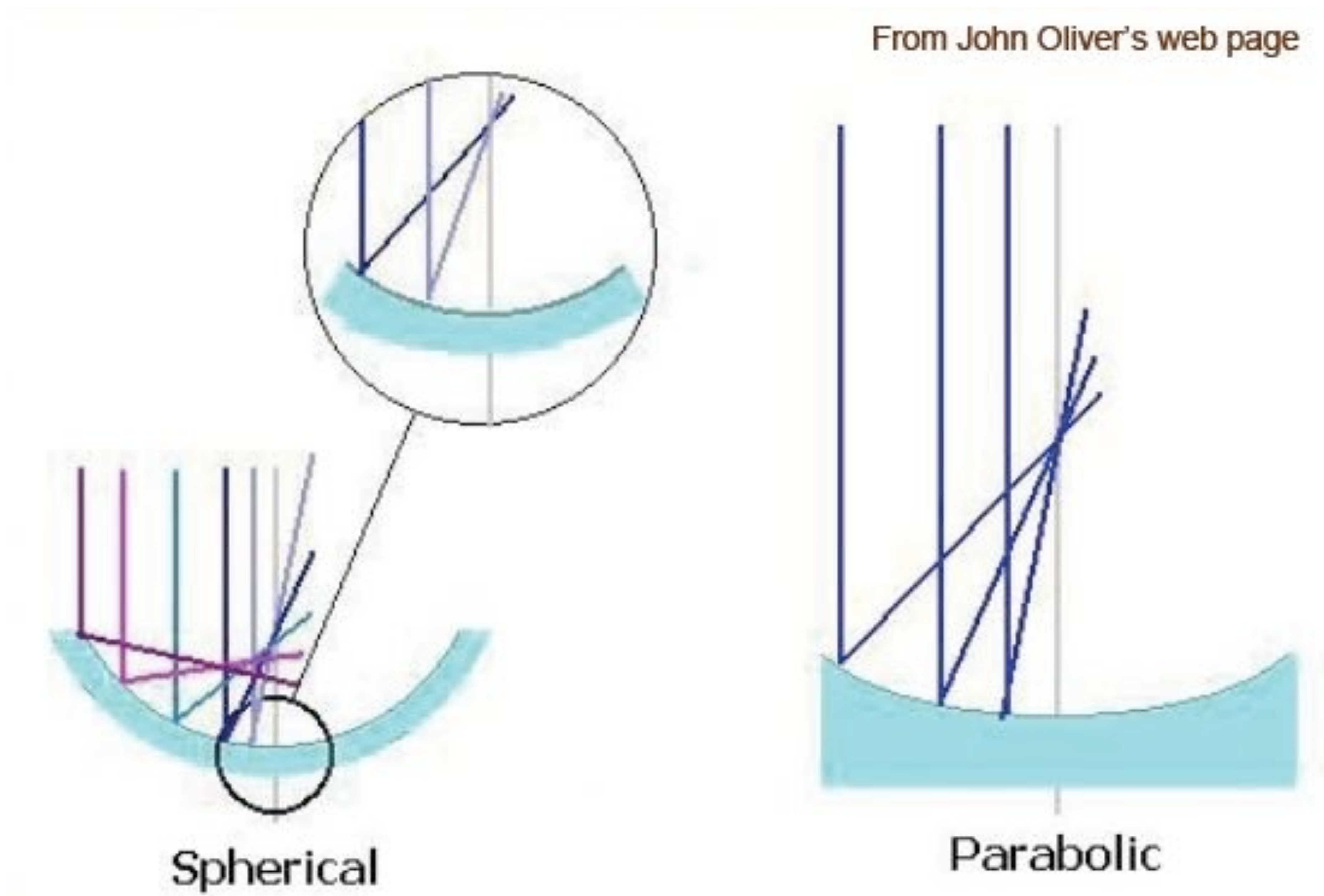


eyepiece for
human use only

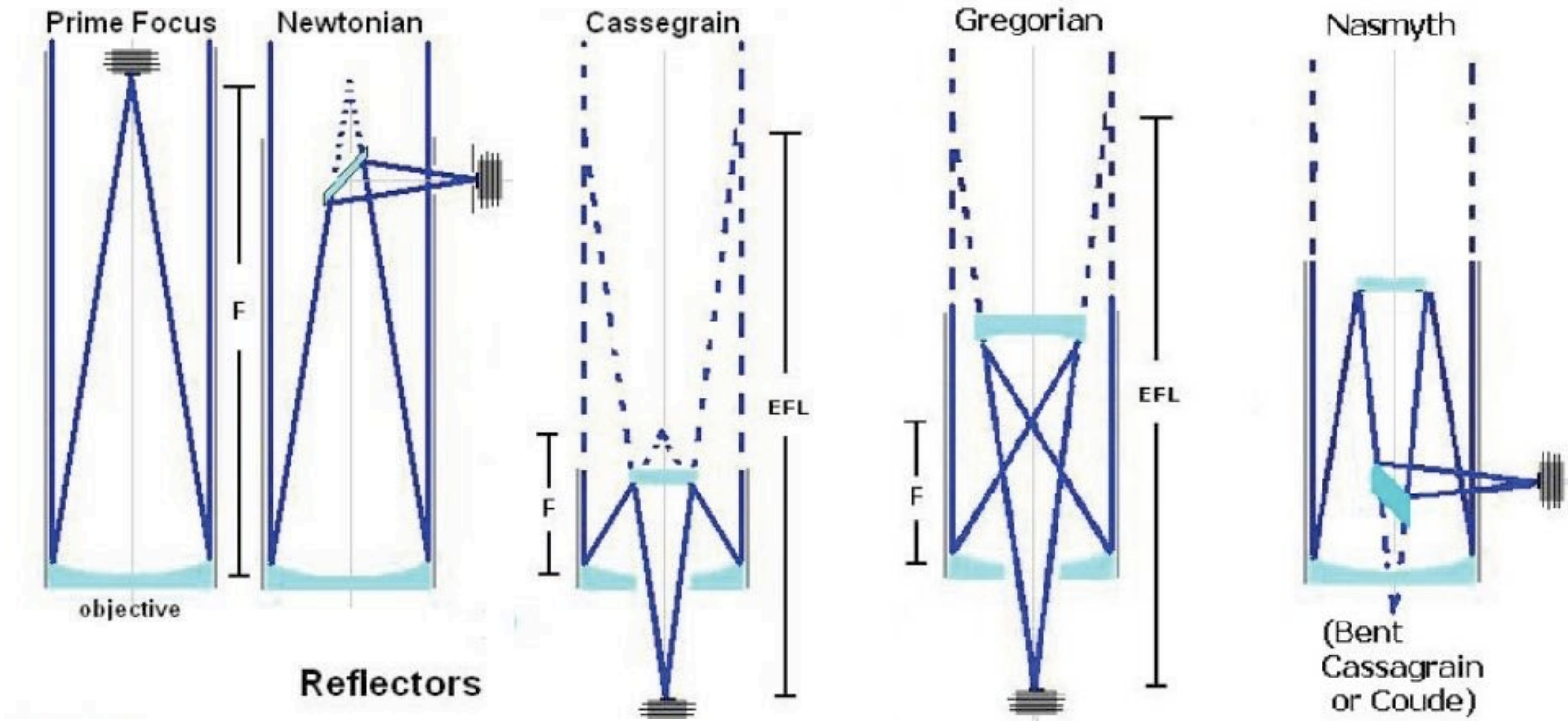
http://cosmos.phy.tufts.edu/~zirbel/laboratories/Telescope.pdf

Mirrors

Curvature of primary mirrors



differing foci



Prime Focus

minimizes optics

typically much “faster” than other foci

Newtonian

mostly for amateur telescope due to placement of focal plane

Cassegrain

parabolic primary, hyperbolic secondary

compact telescope (for the effective focal length)

central obscuration and diffraction spikes

convenient focal plane location (although subject to flexure)

Ritchey-Chretien (hyperbolic primary & secondary) has advantages in aberrations

Nasmyth and bent-cass

allow instrument placement either on
stable platforms on at least allow multiple ports

Telescope Mounts : Alt-Az vs. equatorial

Altitude-Azimuth motion

one axis doesn't fight gravity

tracks in both axes

dead-zone at zenith

field rotation

Equatorial mount

aligned with polar rotation axis

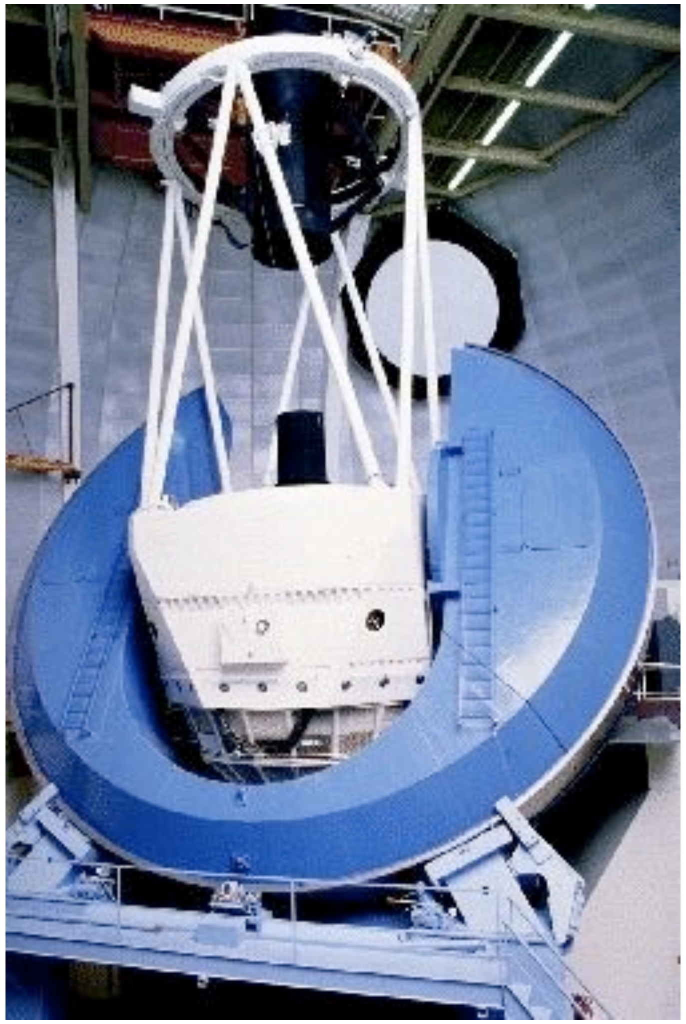
track using motion in one axis

gravity asymmetry

no field rotation

Many types of equatorial mounts...

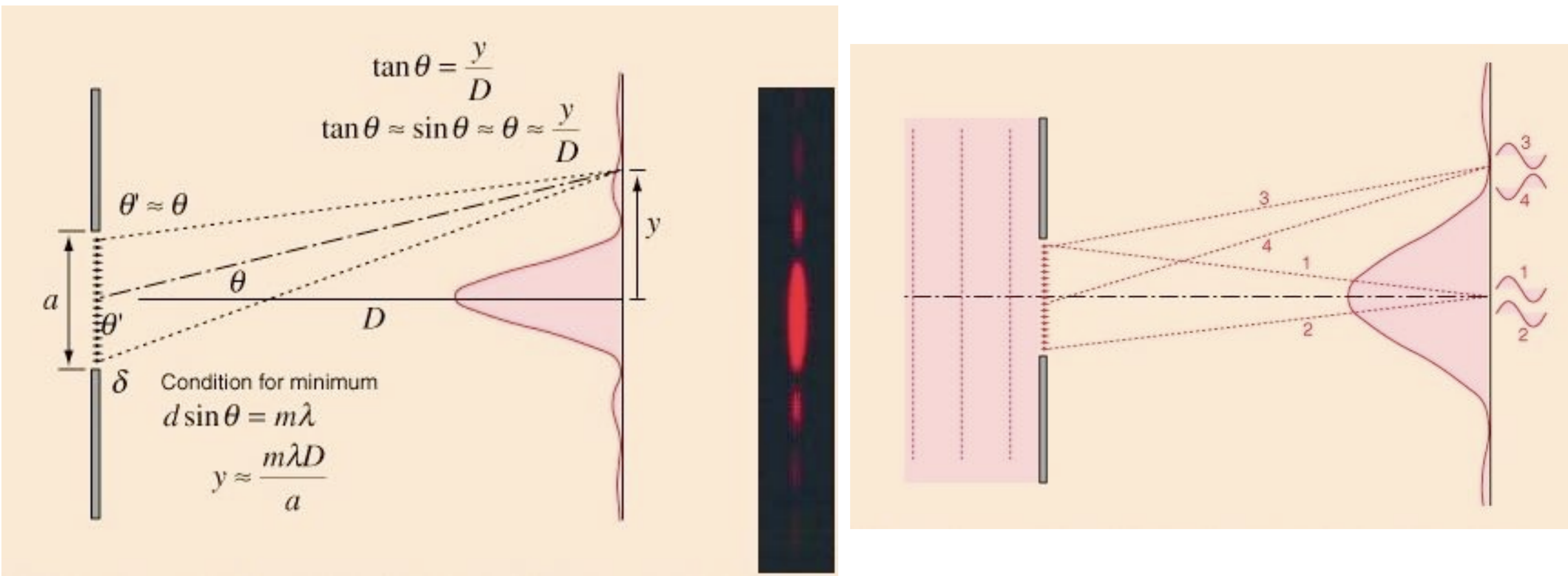
Many different types of equatorial mounts...



Telescope Basics (continued)

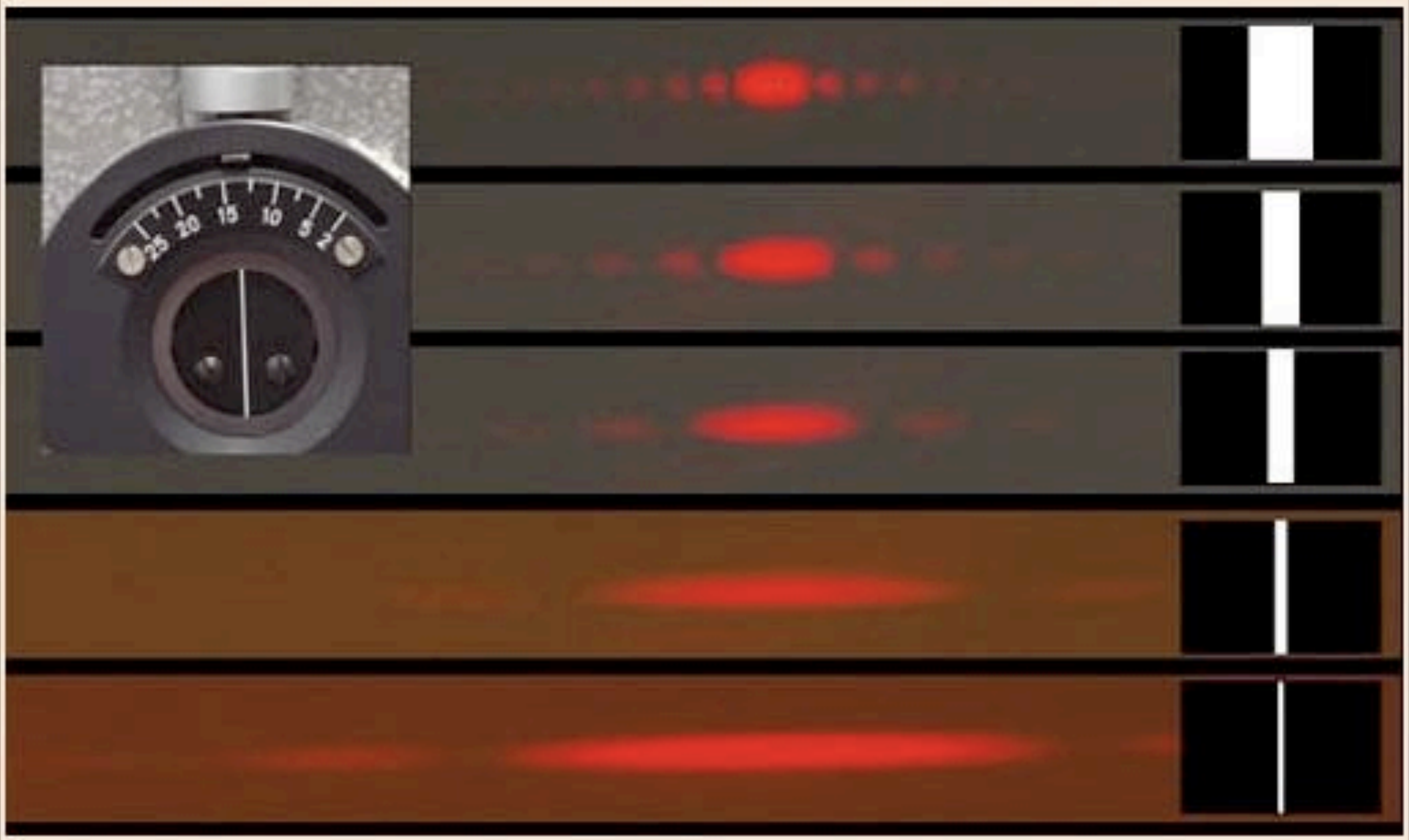
Image quality

Single-slit diffraction



http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/sinslit.html

Single Slit Diffraction for Different Slit Widths



Airy Disk

diffraction limit,   angular resolution ~ 1.22 lambda/D

Example: HST

D = 2.4m

lambda = 5000 Angstroms

= 5 x 10^-7 m

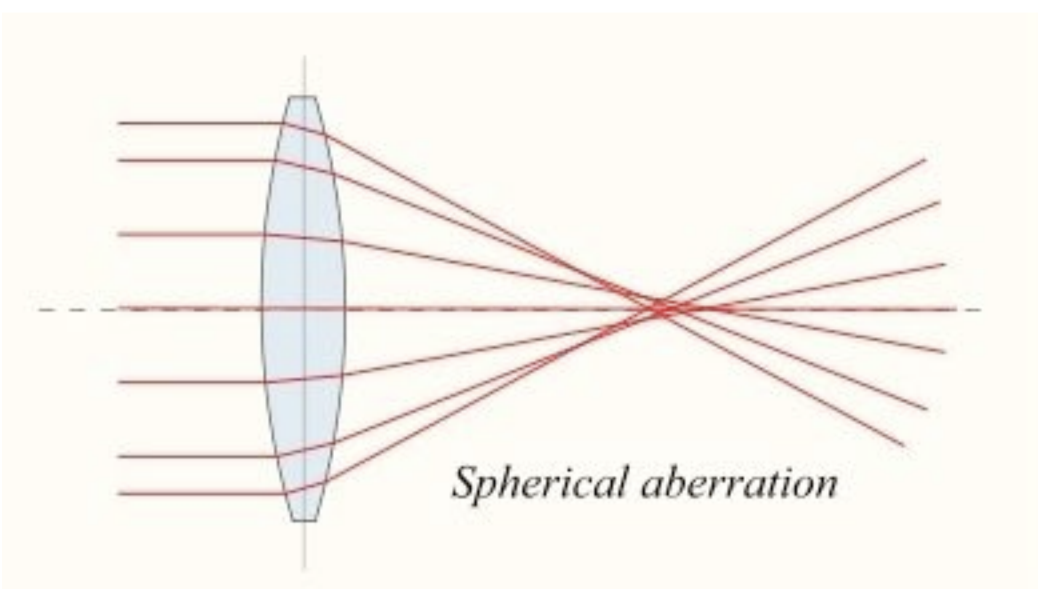
theta = (1.22 x 5 x 10^-7/2.4) radians

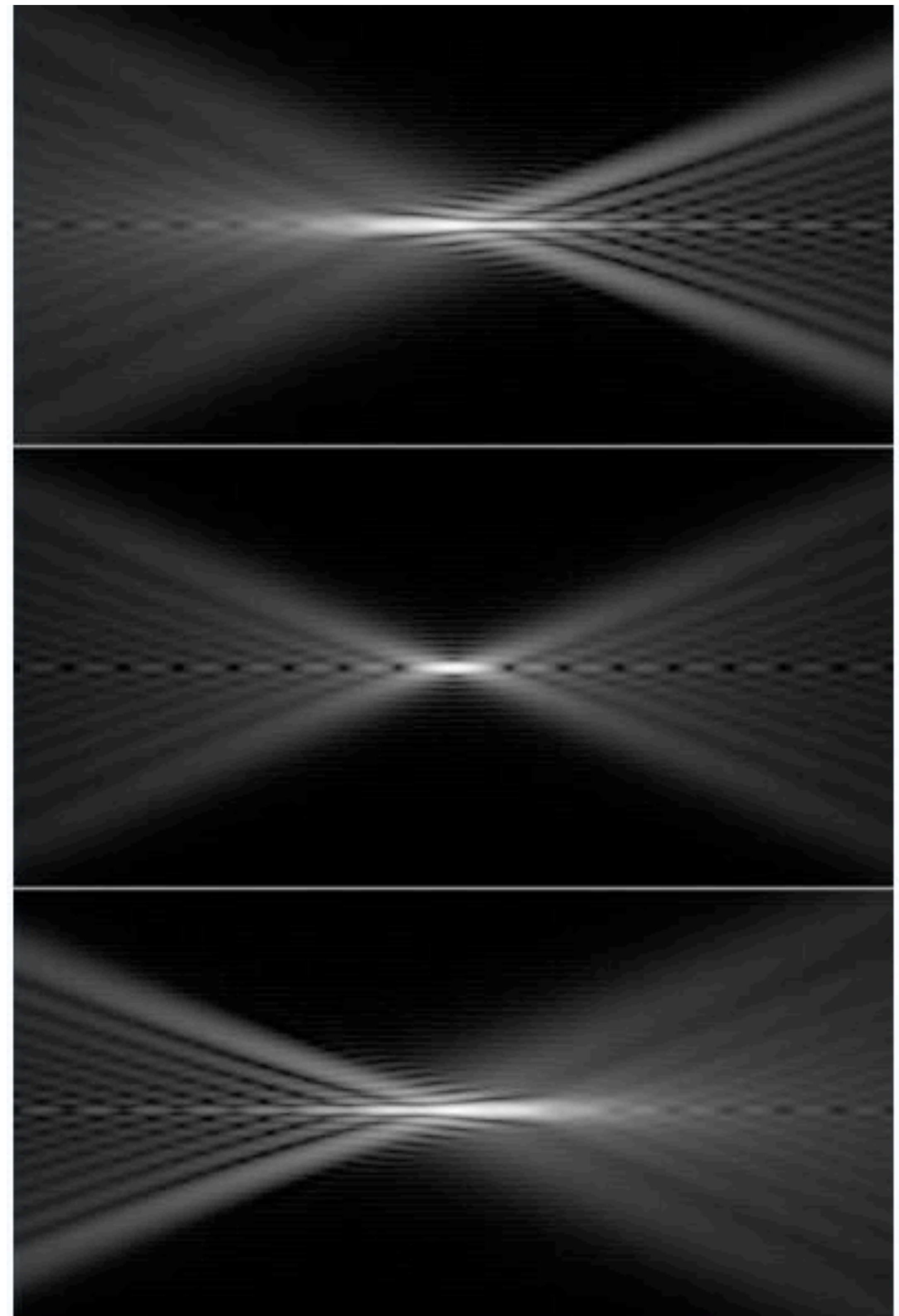
= 0.05 arcsec

(1 radian = 206265 arcsec)

Aberrations

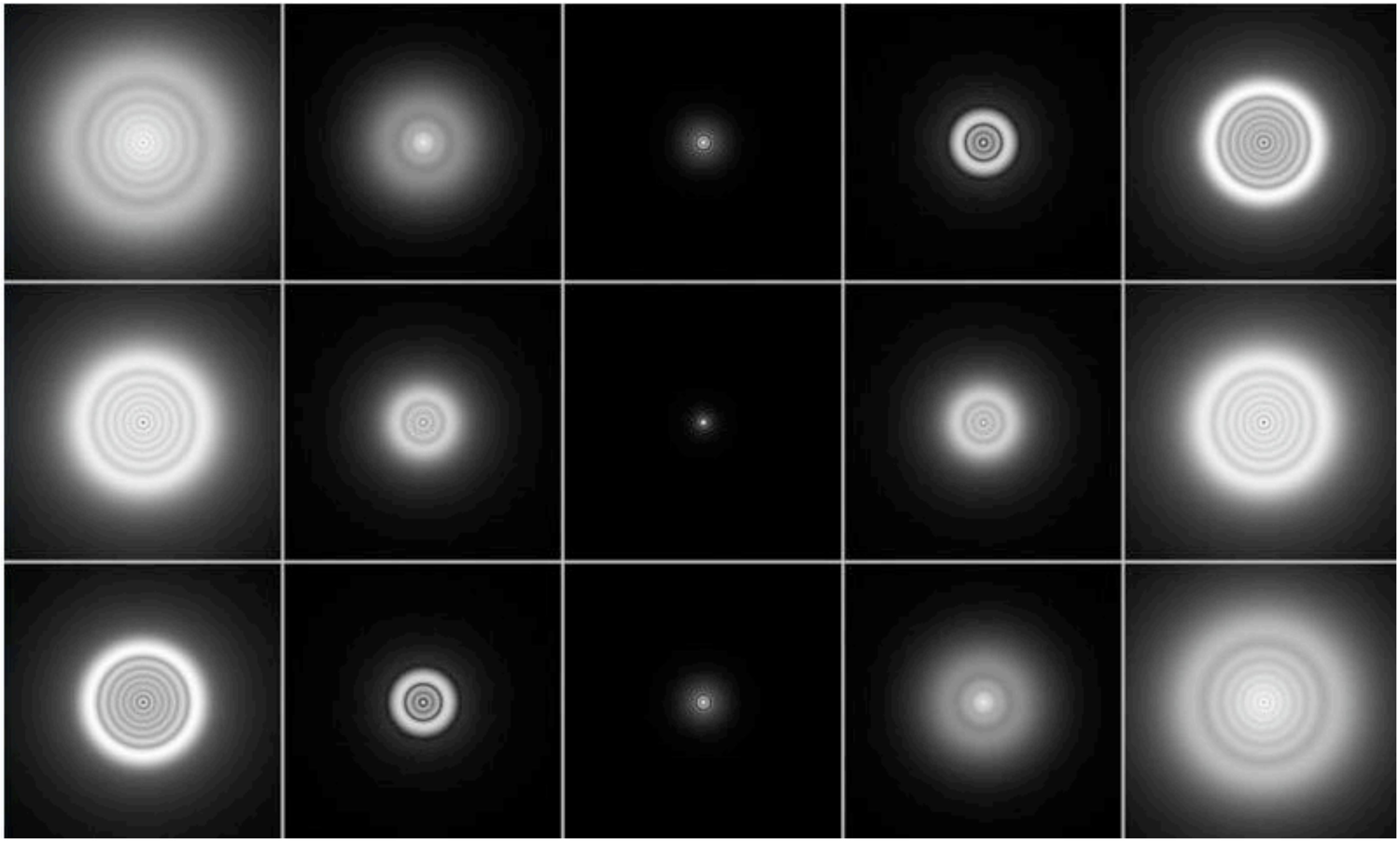
Spherical Aberration





Spherical Aberration

Under & Over corrected

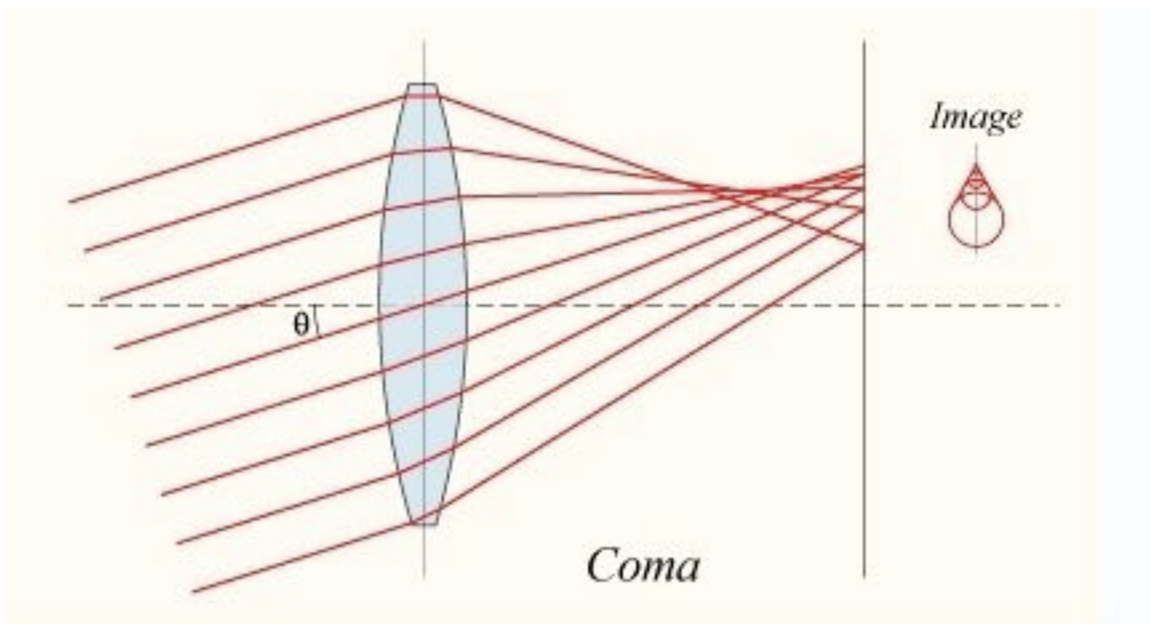


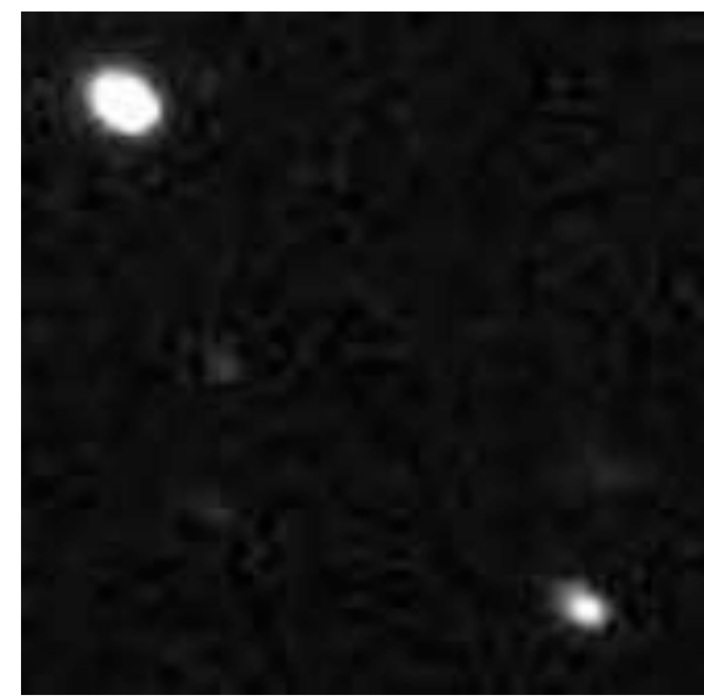
Focus

http://en.wikipedia.org/wiki/Spherical_aberration

Coma

in theory





in practice

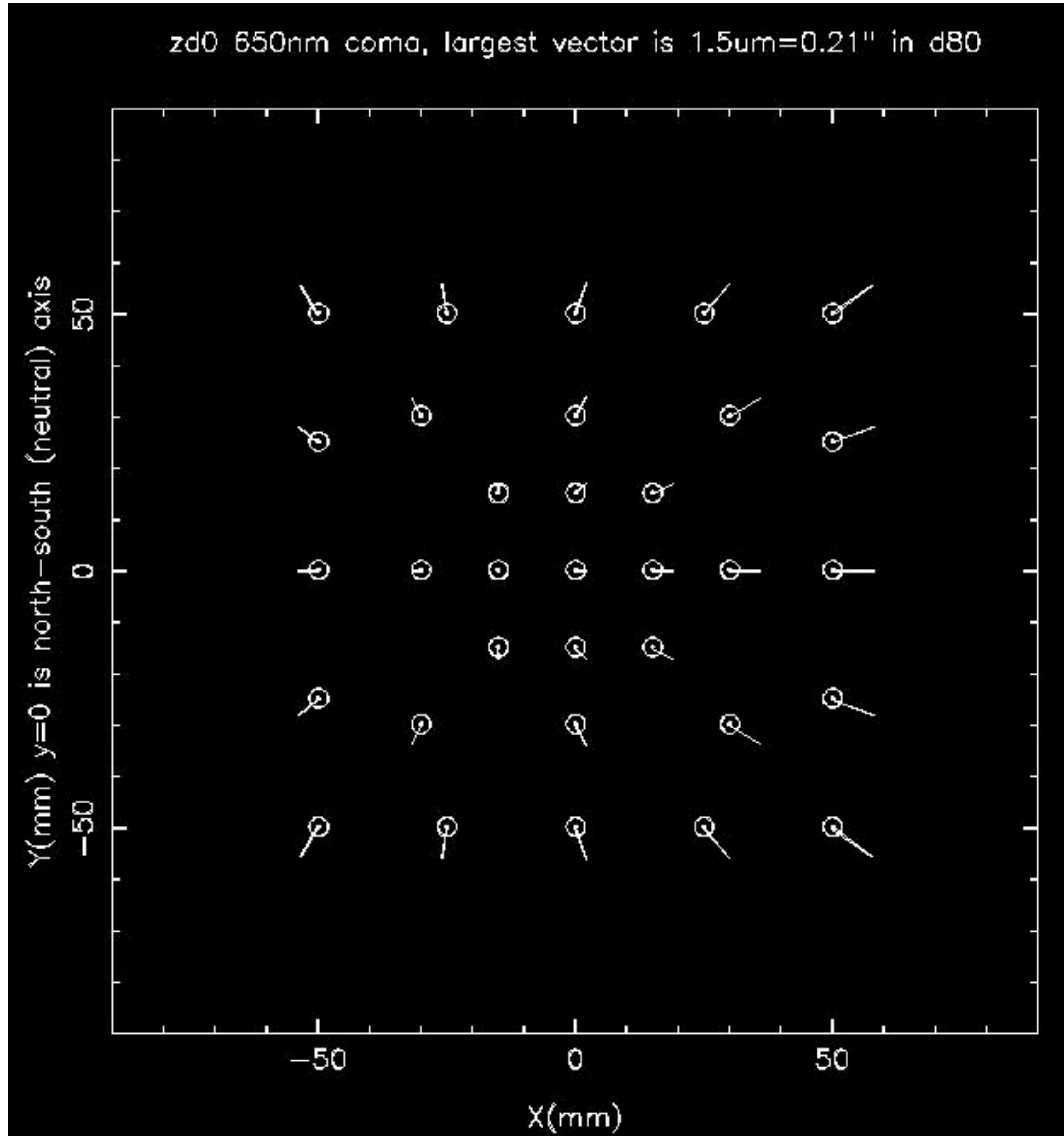
http://upload.wikimedia.org/wikipedia/en/7/75/Lens-coma.png

http://images.google.com/imgres?imgurl=http://www.rcopticalsystems.com/images/coma.jpg

http://www.sidus.org/tecnicaDintorni/opticalAberration/comaSfero/fuoco.jpg

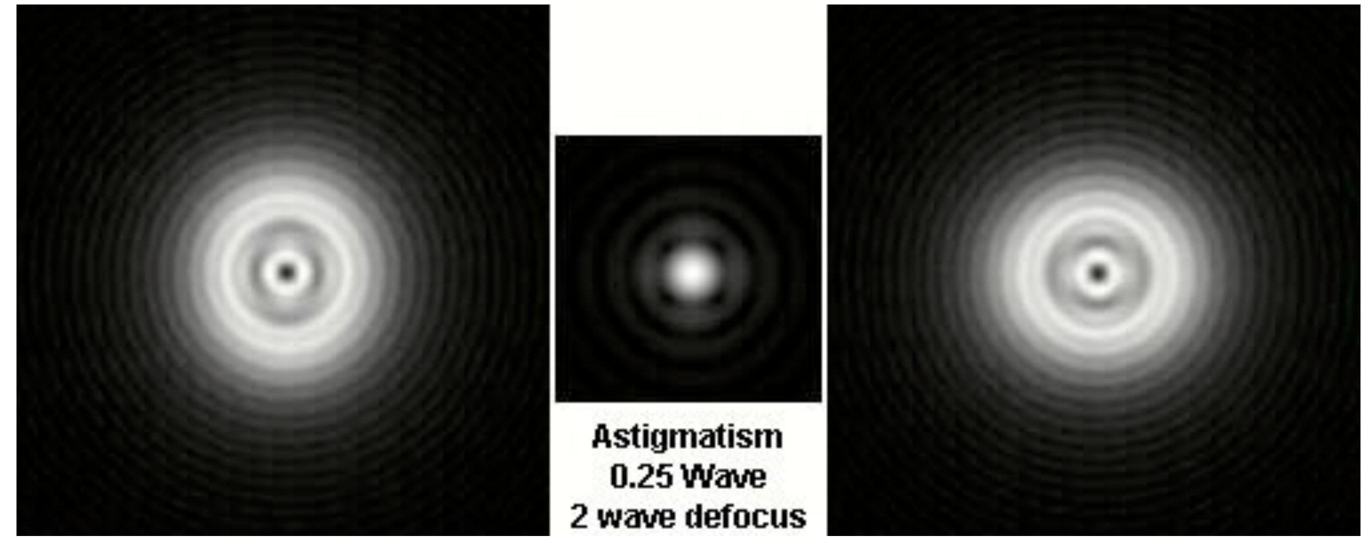
Coma

gets worse toward field edges



Astigmatism

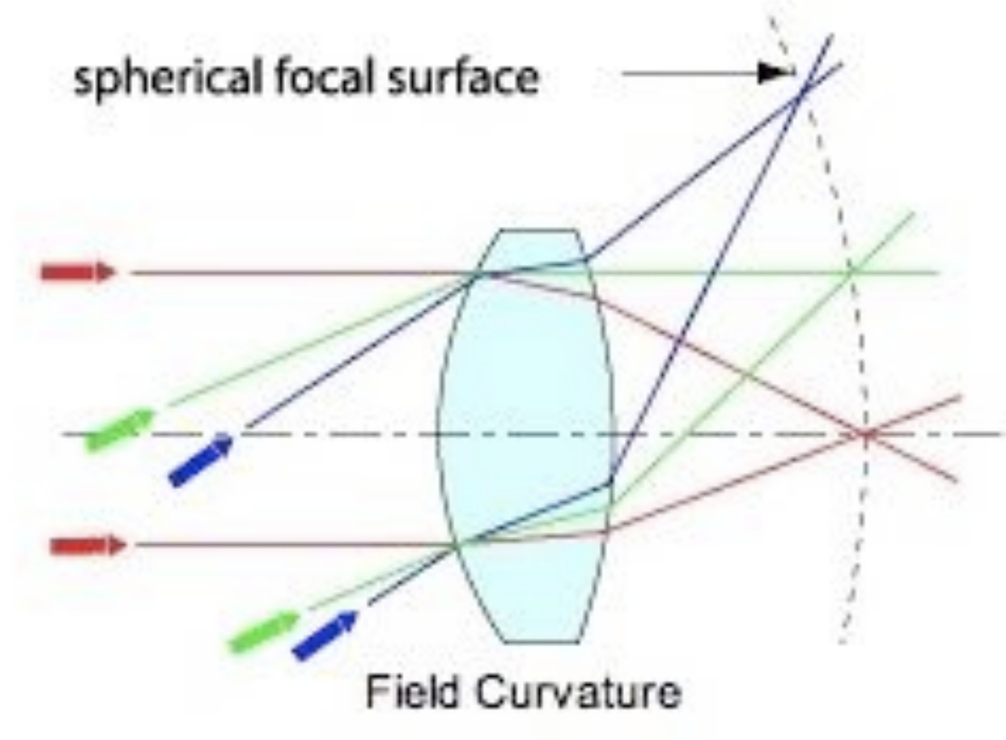
asymmetry in mirror/lens



in practice, see elongation change orientation on either side of focus

http://aberrator.astronomy.net/assets/auto_generated_images/img_475a63a0.jpg

Field Curvature

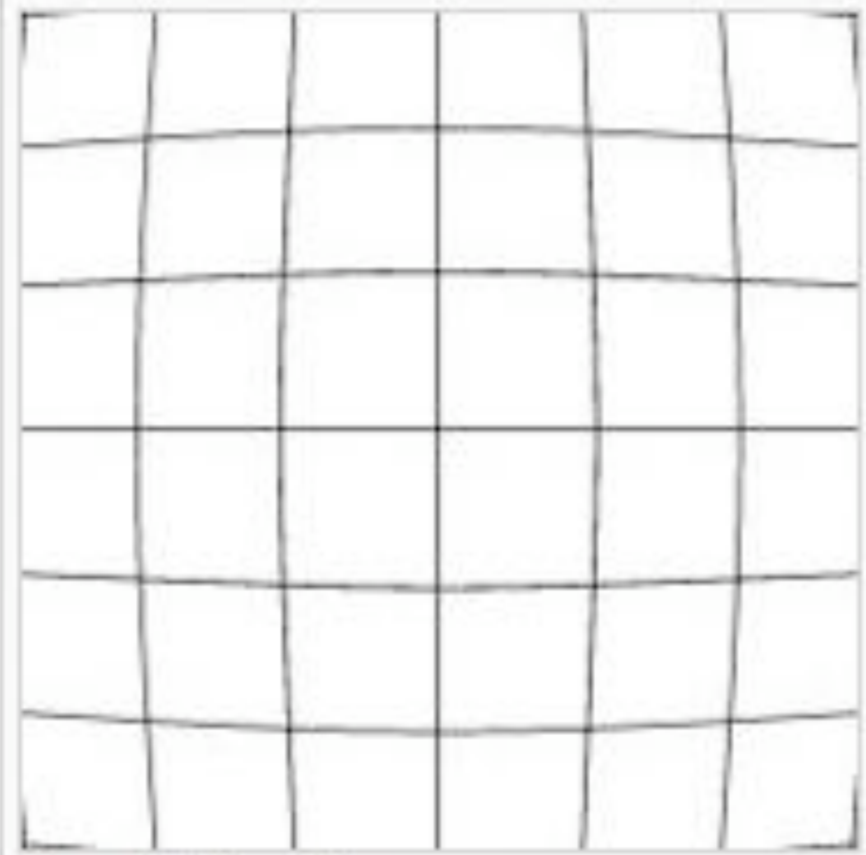


focus using stars across your field to get an average value

http://www.mellesgriot.com/products/optics/fo_3_2_4.htm

Field Distortions

Barrel Distortion

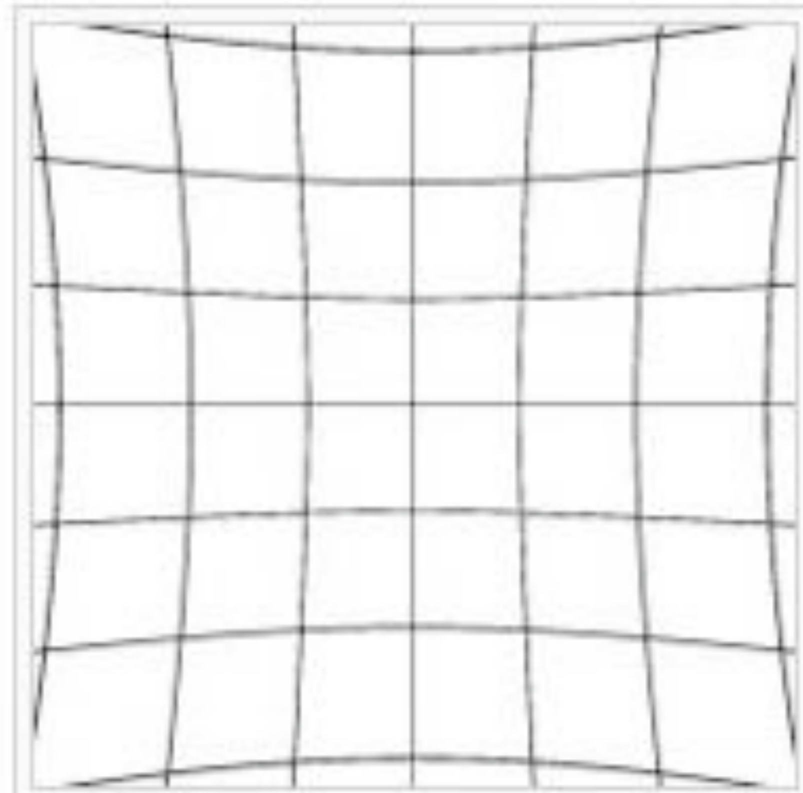


Barrel Simulation

important if you care about astrometry and/or image shapes

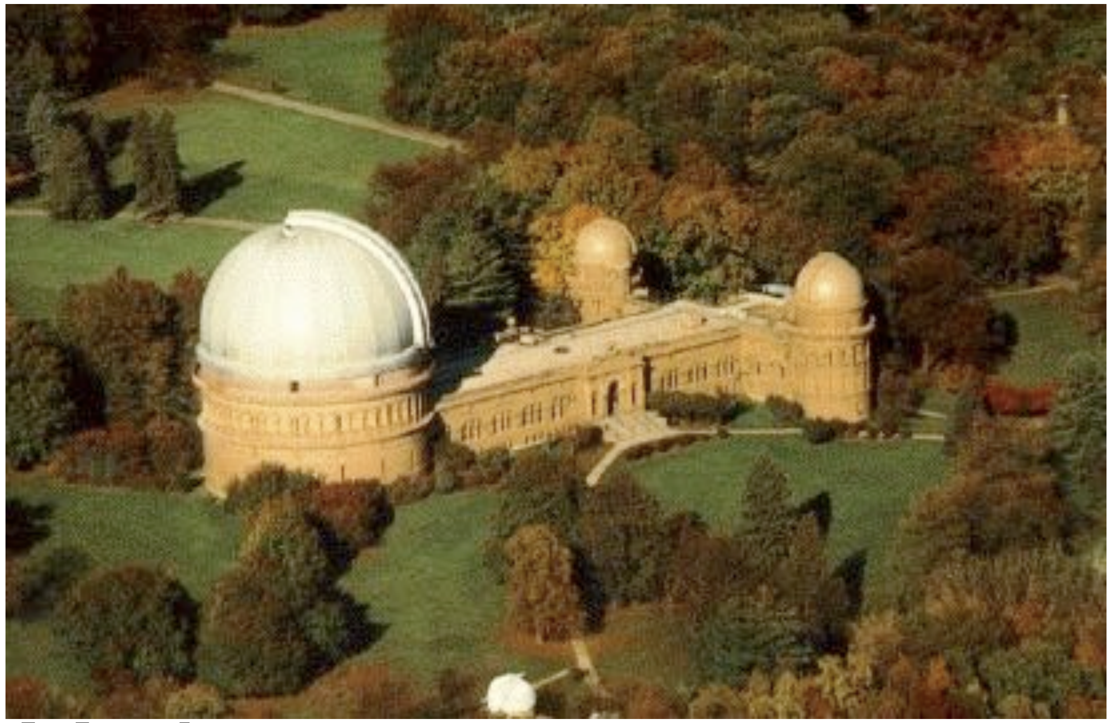
Pincushion Distortion

as with barrel distortion, due to its typical mangitude it is important only in certain cases



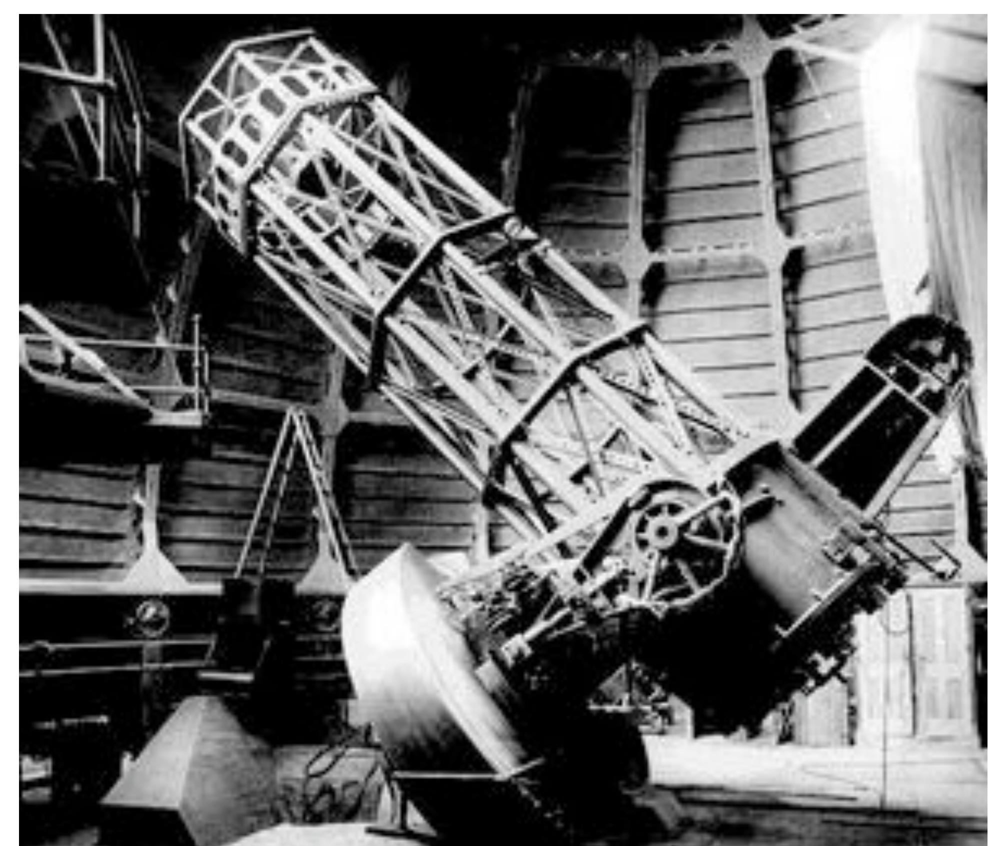
Pincushion Simulation

Telescopes you should know about....



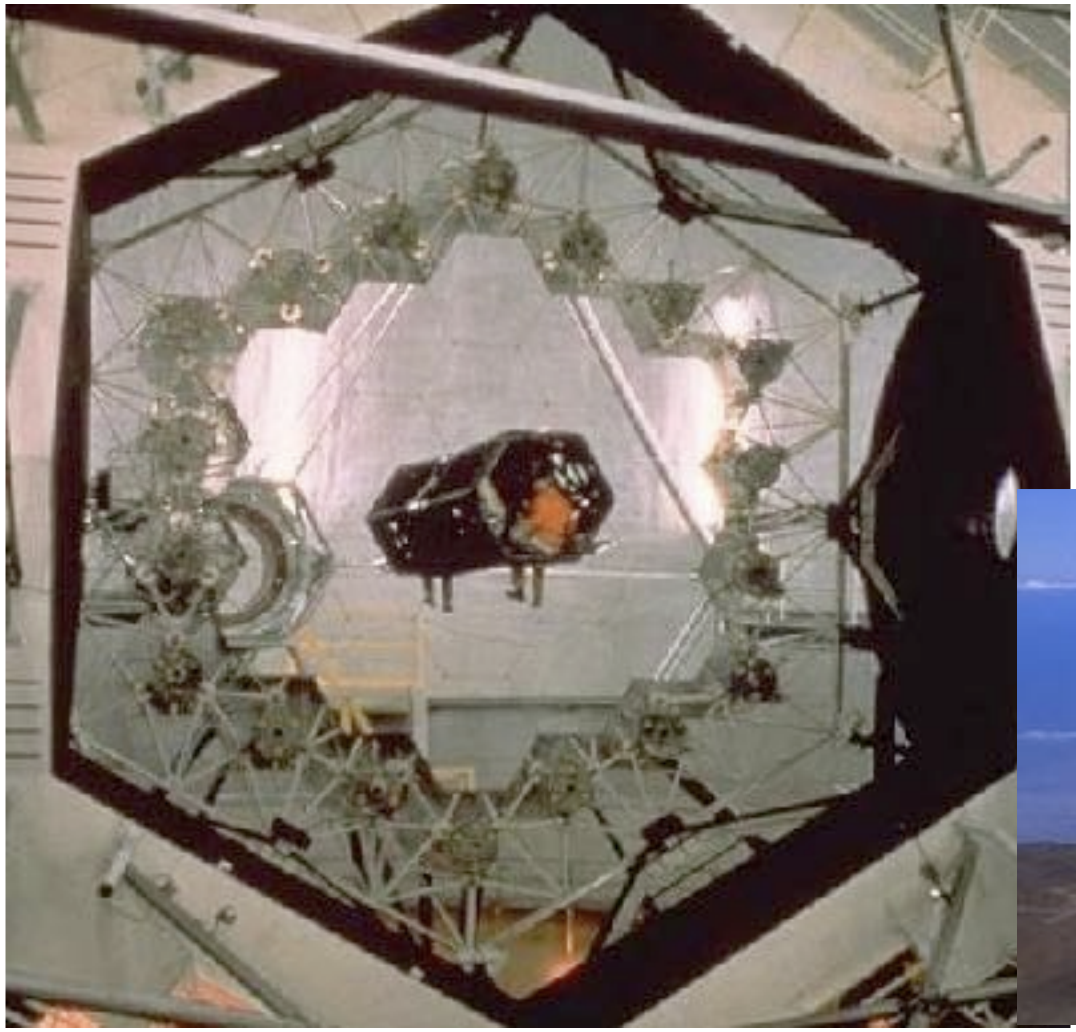
Yerkes

Mt. Wilson



Palomar 5m

MMT

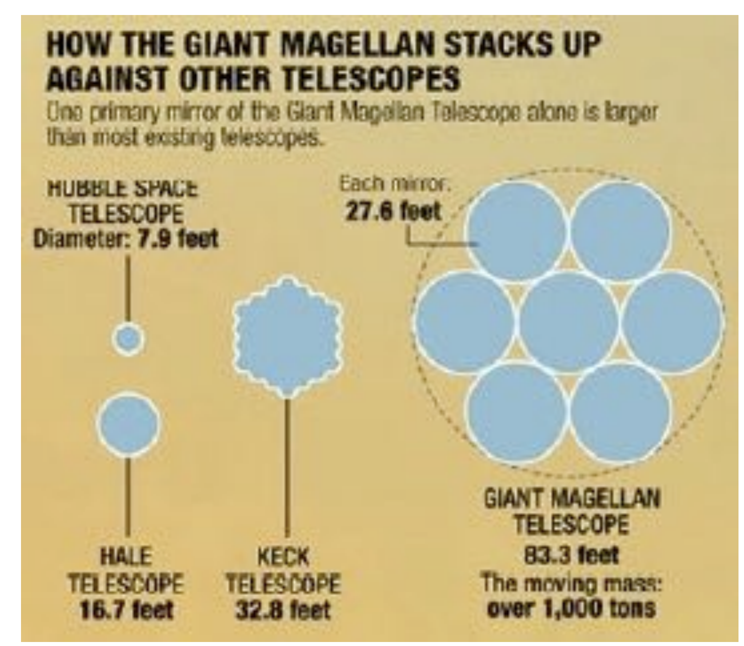


Keck & Mauna Kea summit

VLT (European)

Large
Binocular
Telescope

Giant Magellan Telescope



The Atmosphere and Astronomical Observations

Diminishes incoming radiation: scattering, absorption

Affects images: refraction, turbulence

Adds background light

most of this material comes from http://www.astro.ufl.edu/~anthony/course1.html and links therein

Scattering & Absorption

One key factor is size of particles (d) vs. wavelength

Rayleigh scattering for $d \ll \lambda, \mathrm{effect} \propto \lambda^{-4}$

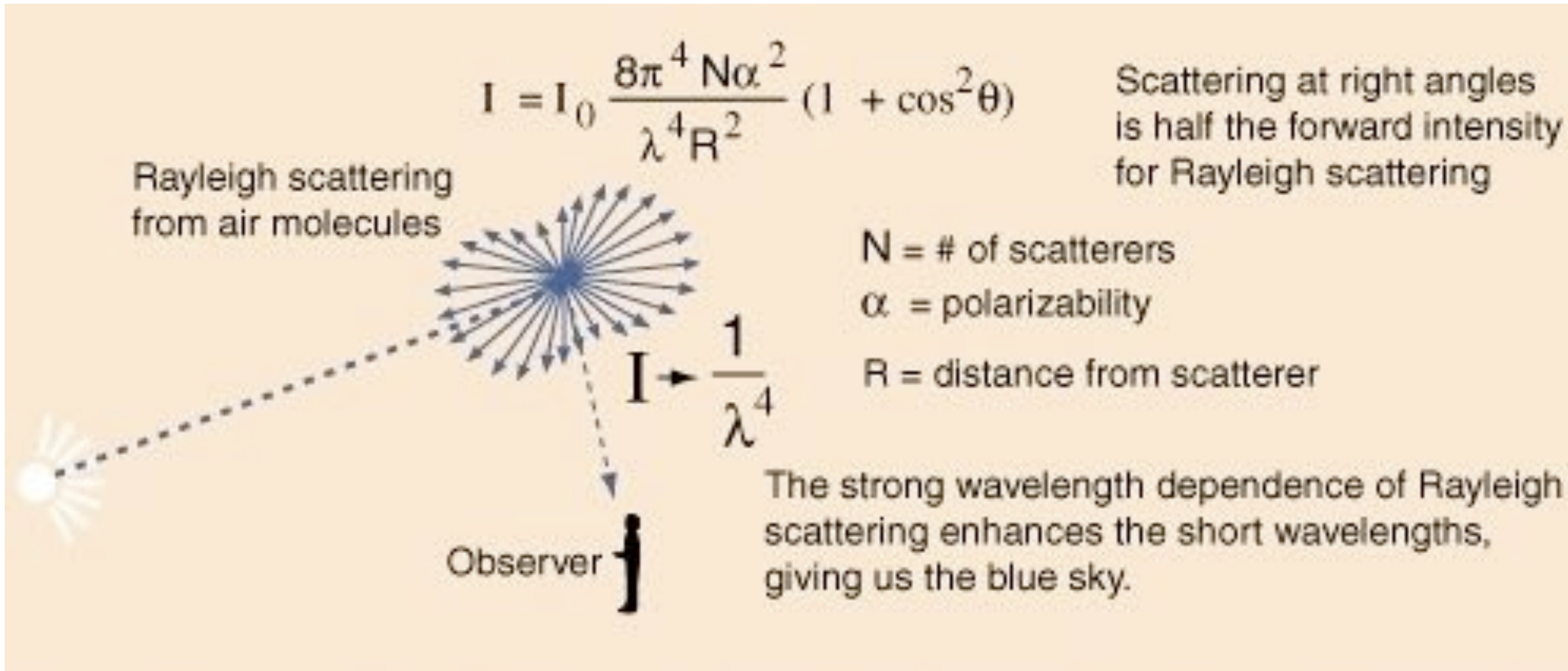
Mie scattering for $d \geq \lambda, \mathrm{weak}\ \lambda\ \mathrm{dependence}$

Non-selective scattering for

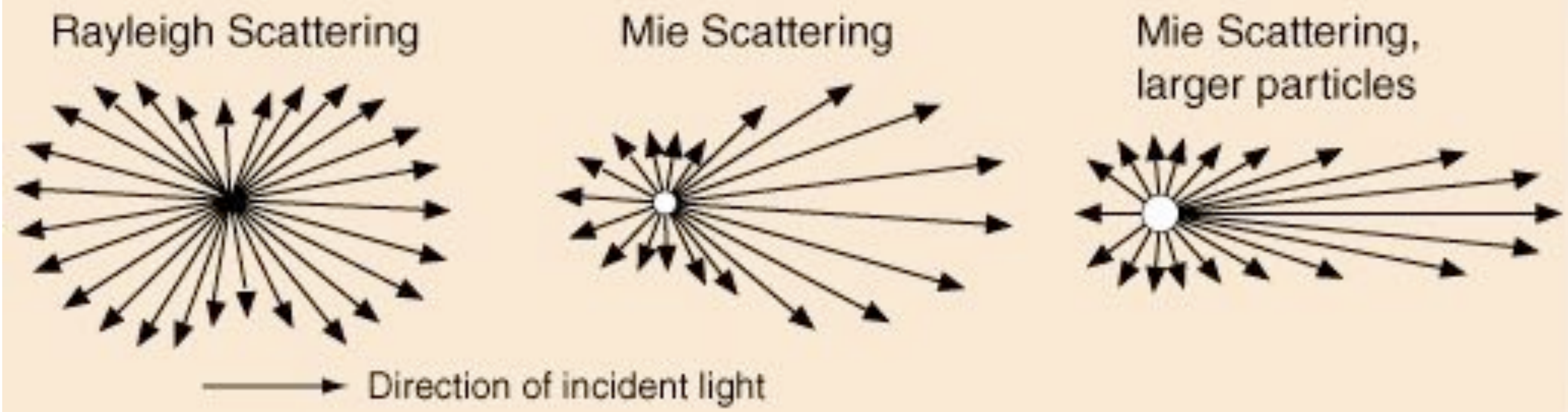
$$d \gg \lambda, \mathrm{no}\ \lambda\ \mathrm{dependence}$$

Rayleigh scattering

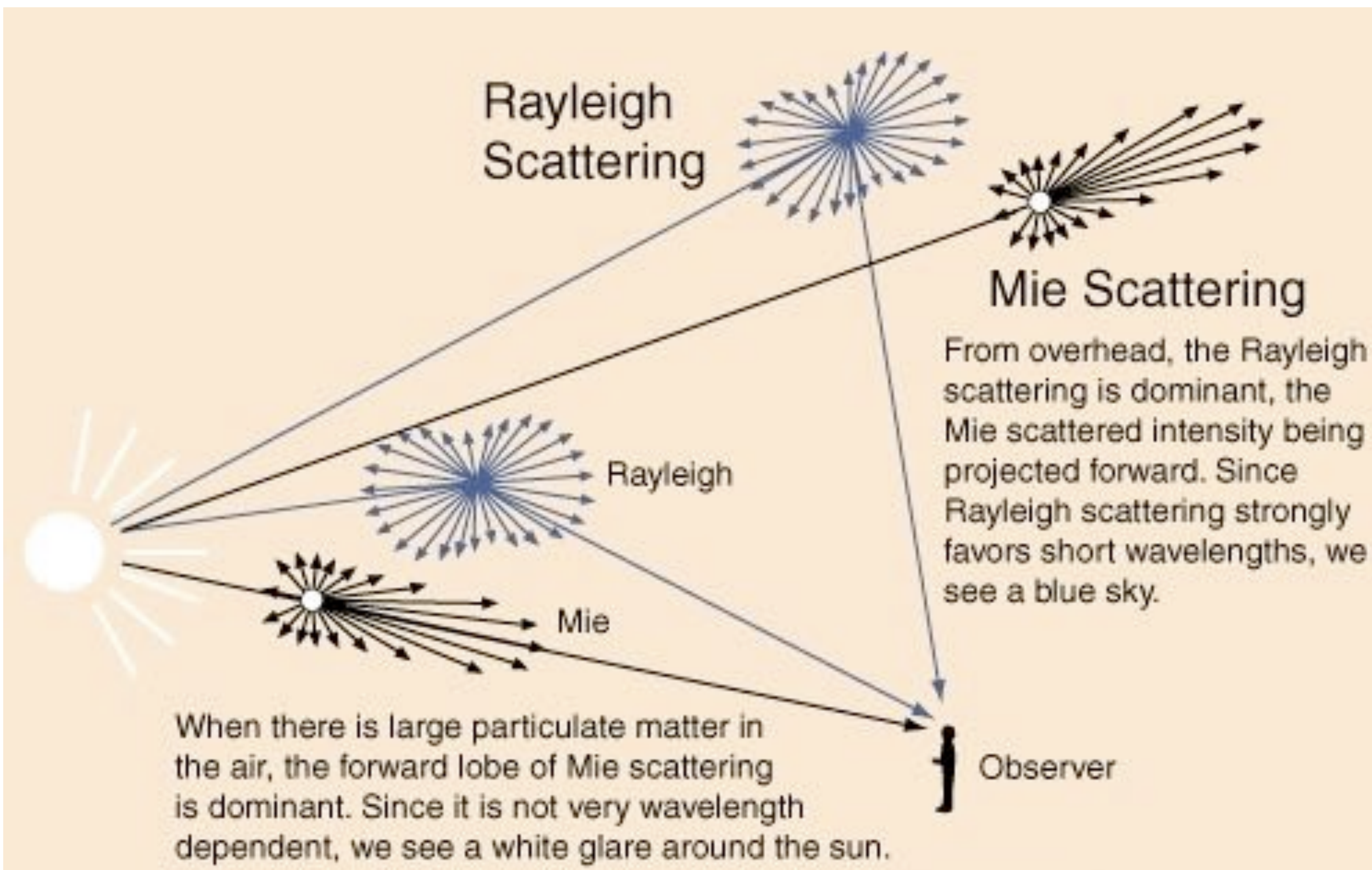
http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/blusky.html



Mie scattering

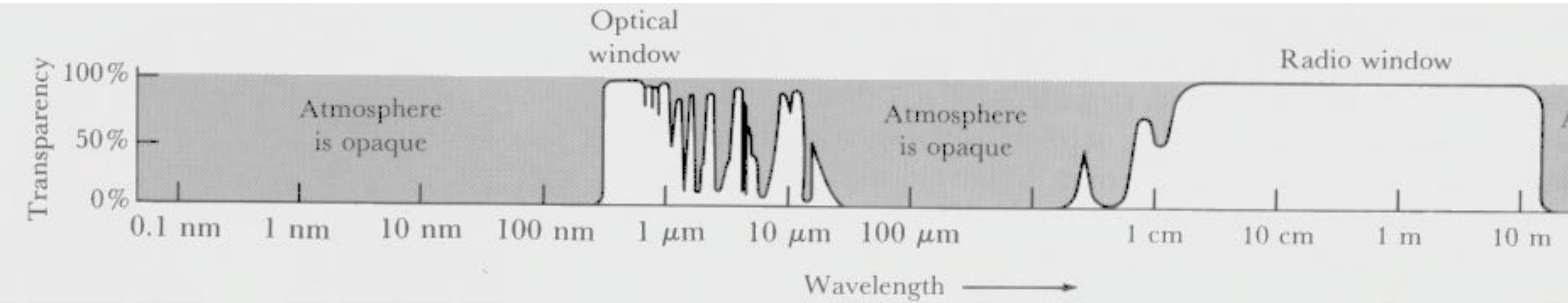


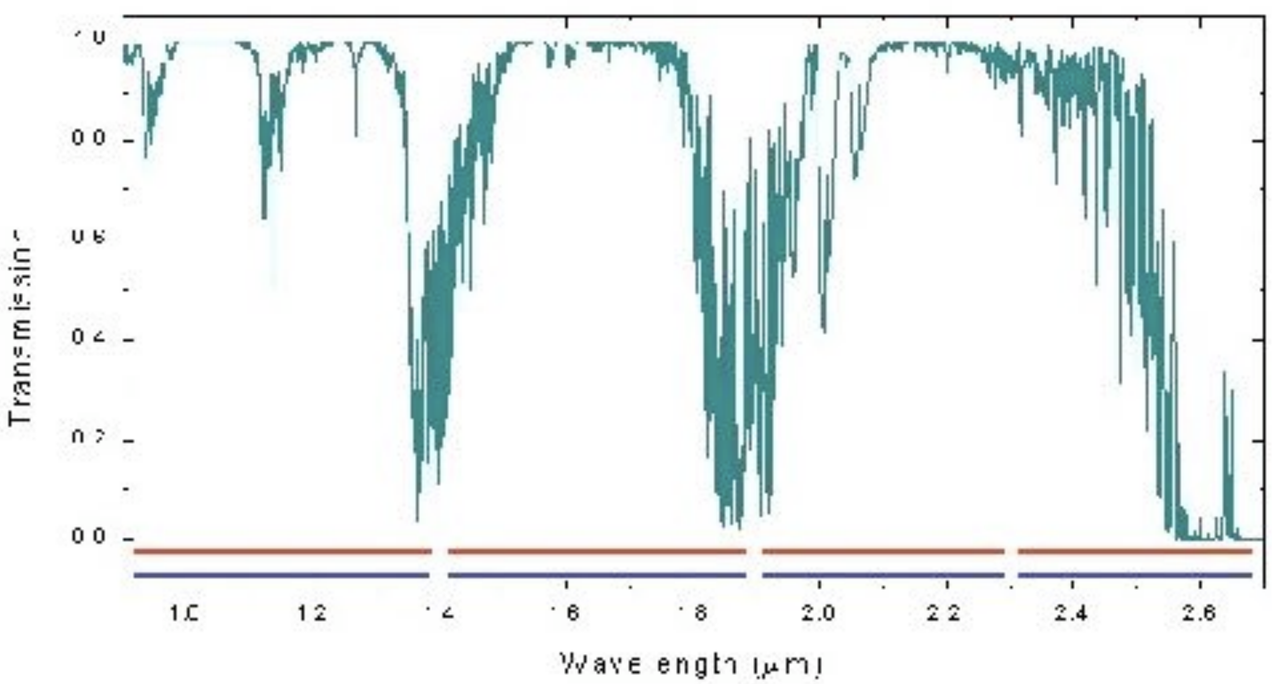
Mie scattering is not strongly wavelength dependent and produces the almost white glare around the sun when a lot of particulate material is present in the air. It also gives us the the white light from mist and fog.

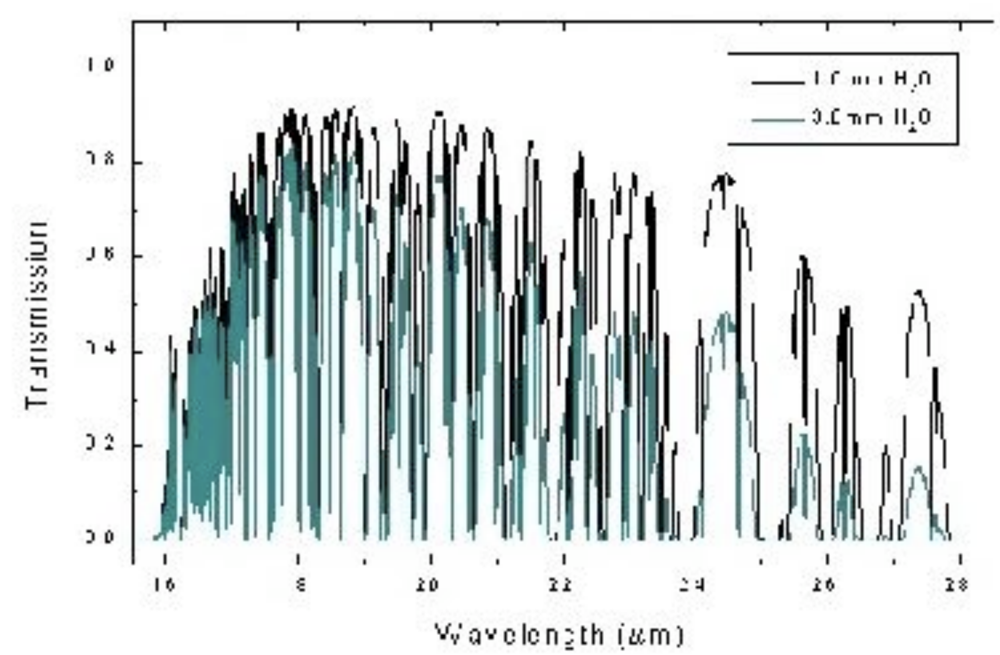


http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/blusky.html

Absorption

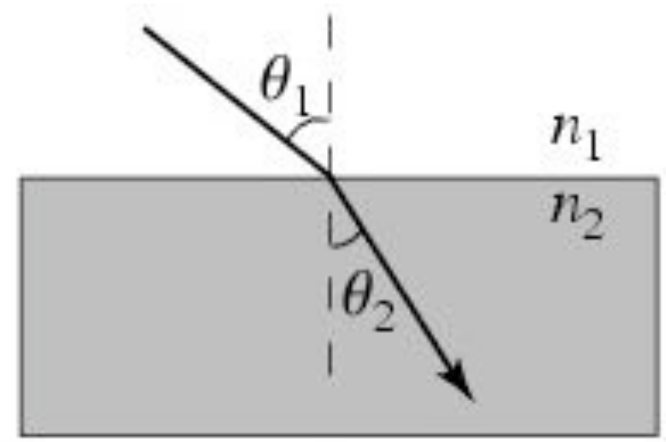






http://www.gemini.edu/sciops/ObsProcess/obsConstraints/ocTransSpectra.html

Refraction



$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

for vacuum $n_1 = 1.0$ while for air $n_2 = 1.0002926$

http://scienceworld.wolfram.com/physics/SnellsLaw.html

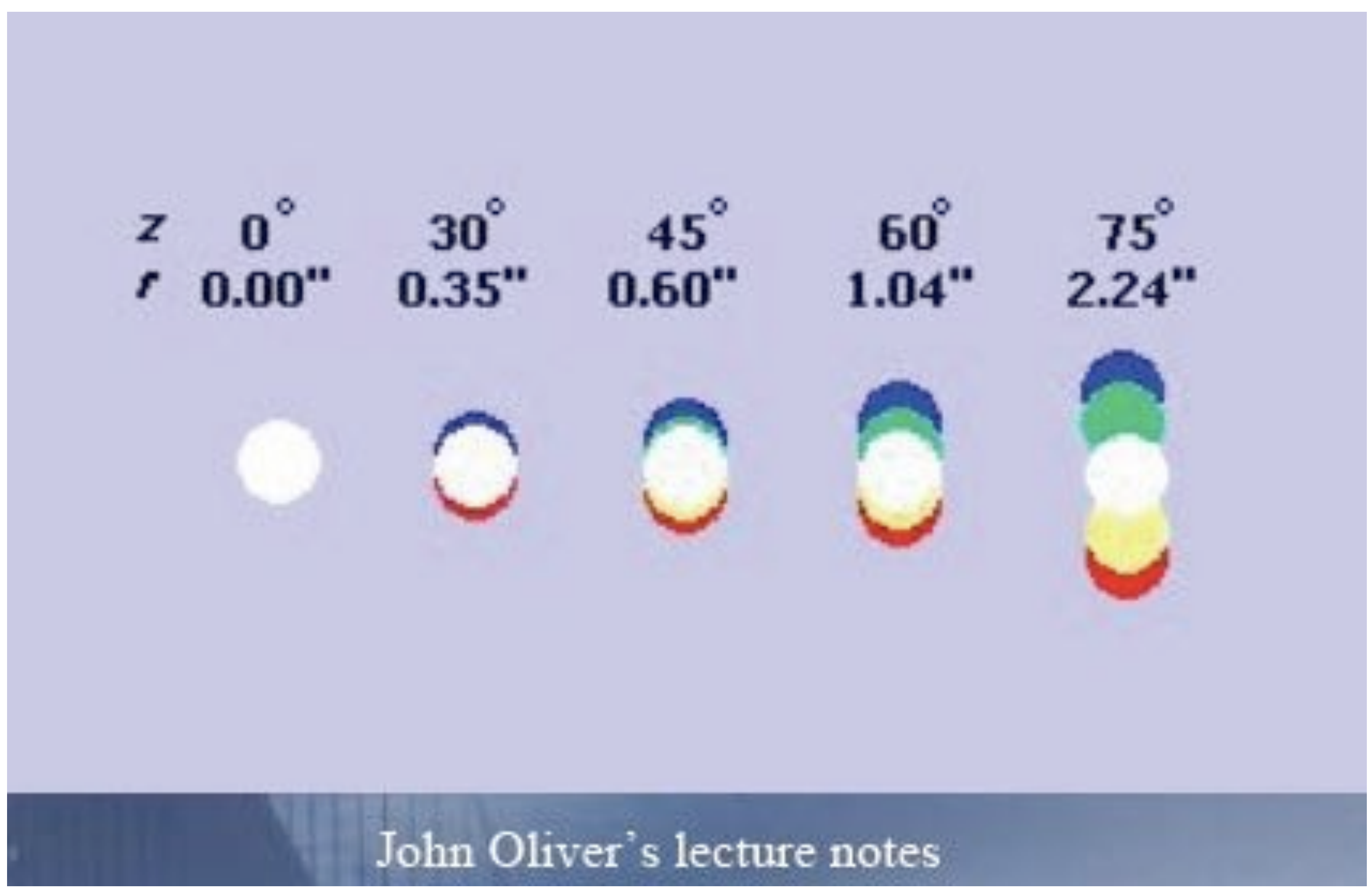
The temperature (and pressure) gradient in the atmosphere causes bending of light rays. This is called atmospheric refraction. Light rays from the low sun or moon will refract more closer to the horizon. This is why the setting or rising sun (and moon) appears flattened: the light rays from the lower part of the sun's disk refract more than the rays emerging from the top, and the vertical angle over which you see the sun is decreased - it is flattened.

Text and image from www.weatherphotography.com

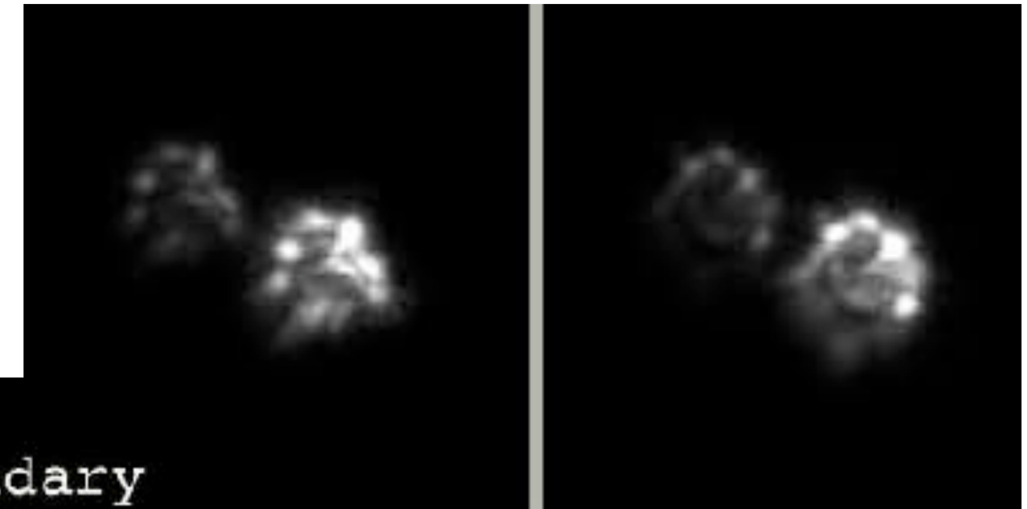
refraction's impact on observing

absolute positioning : depends on zenith angle

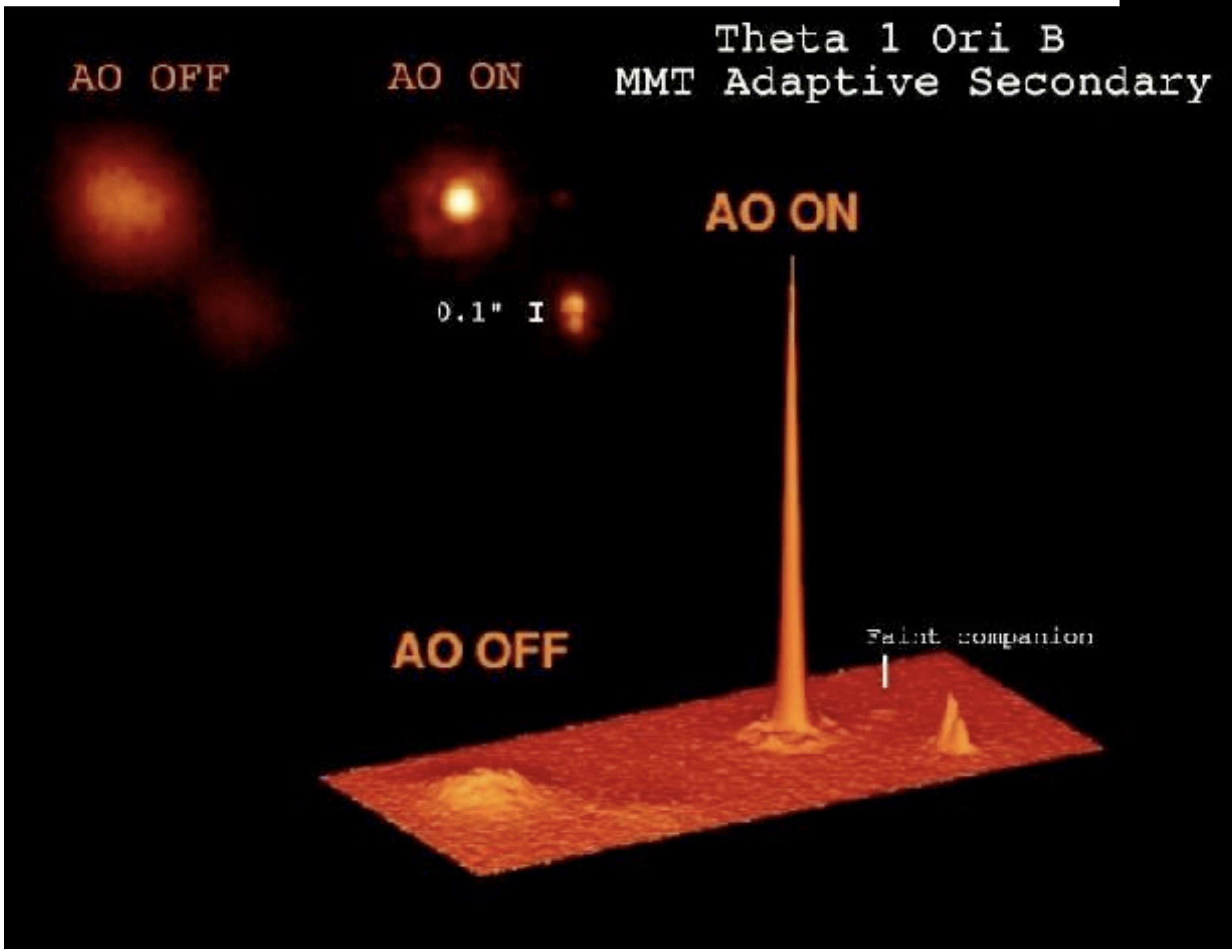
differential positioning depending on wavelength



http://www.gmd.de/People/Udo.Zlender/astro/miz02a.jpg



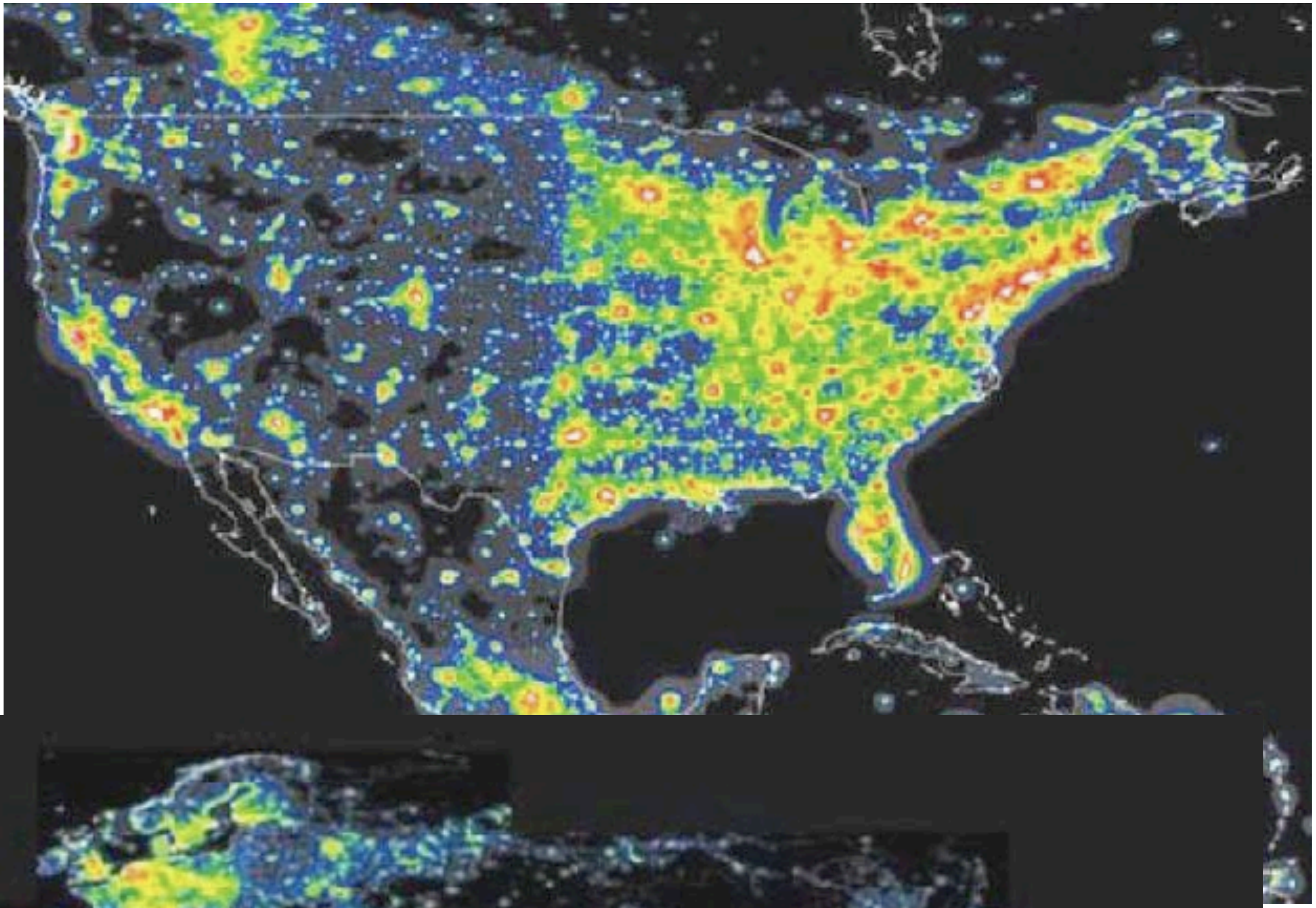
scintillation and seeing

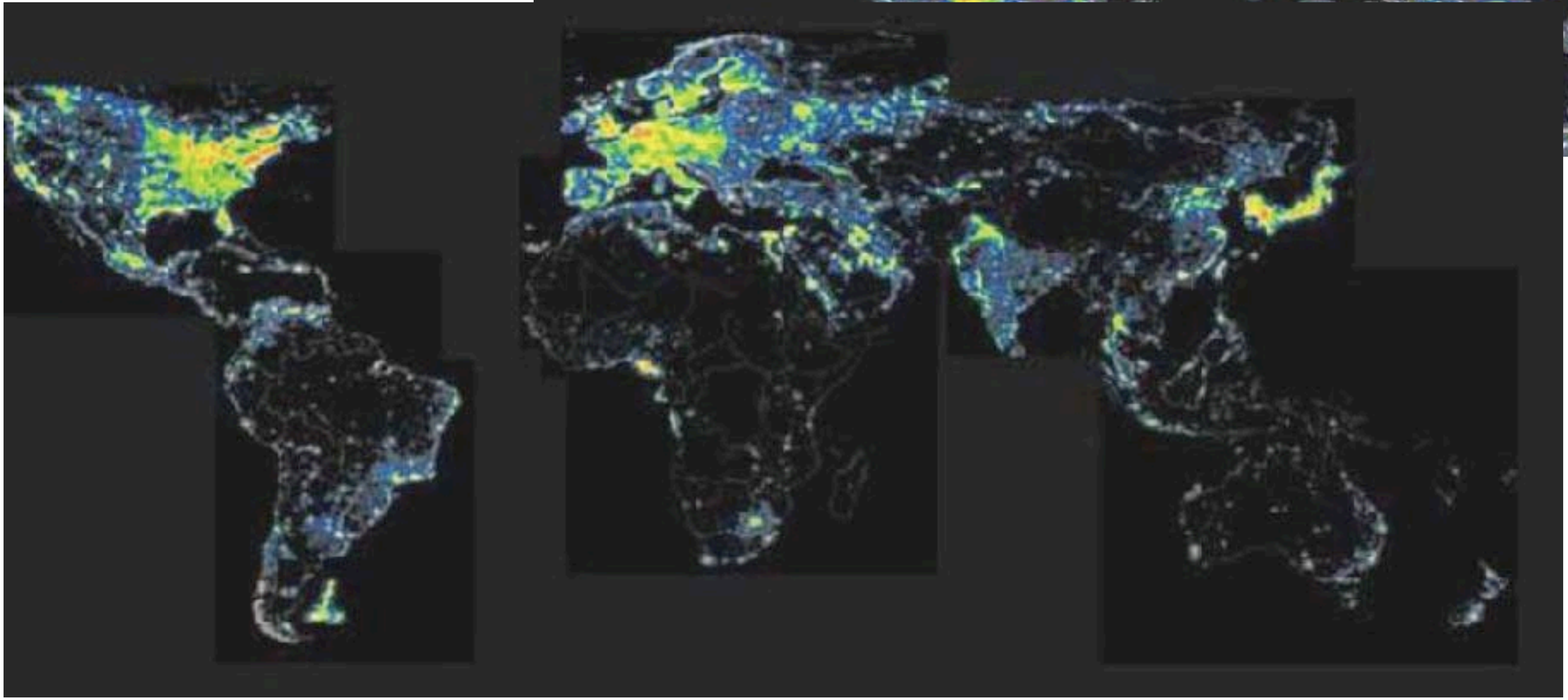


http://exoplanet.as.arizona.edu/~lclose/talks/ins/ESO_MMTAO_3

Backgrounds

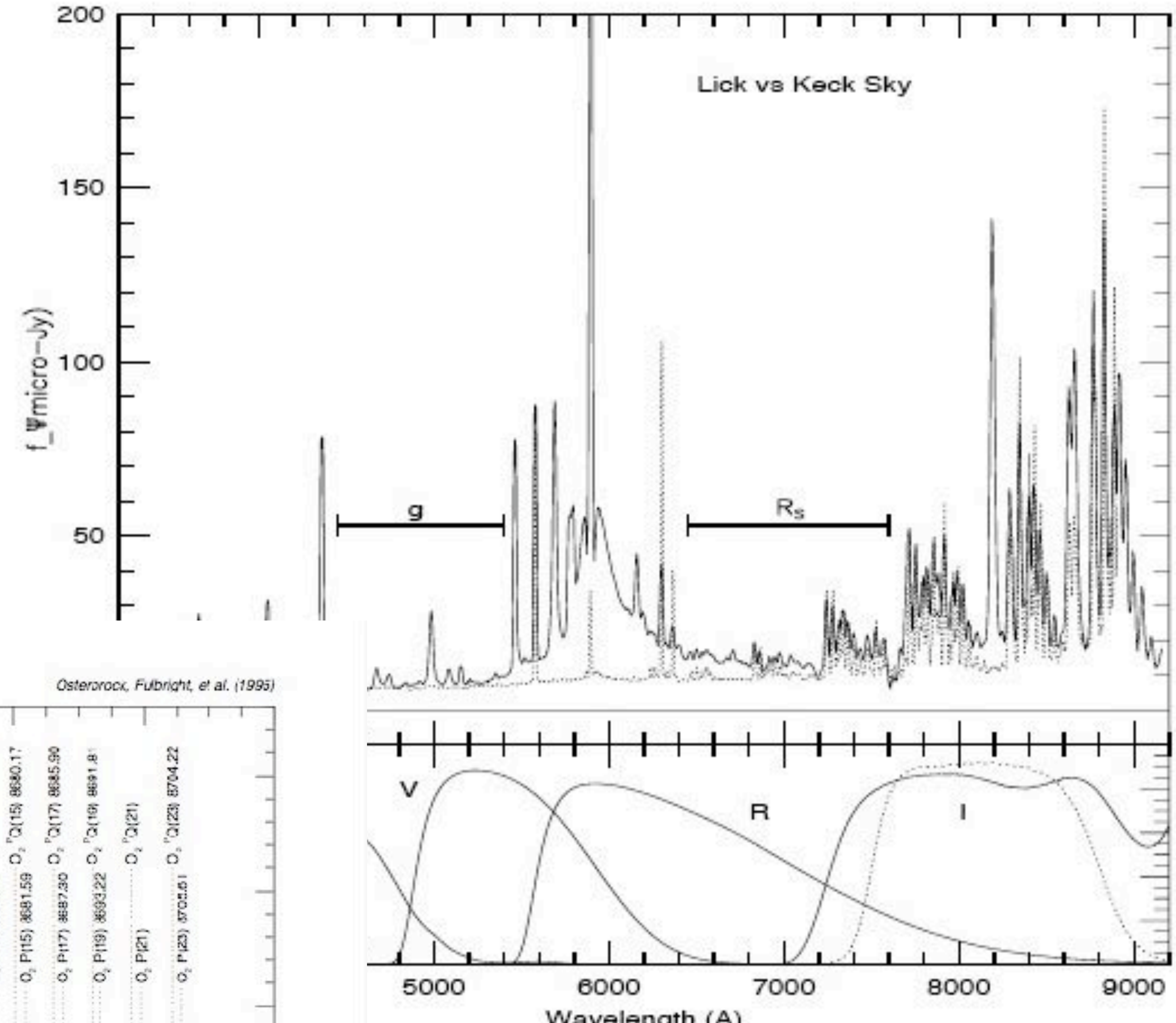
man-made

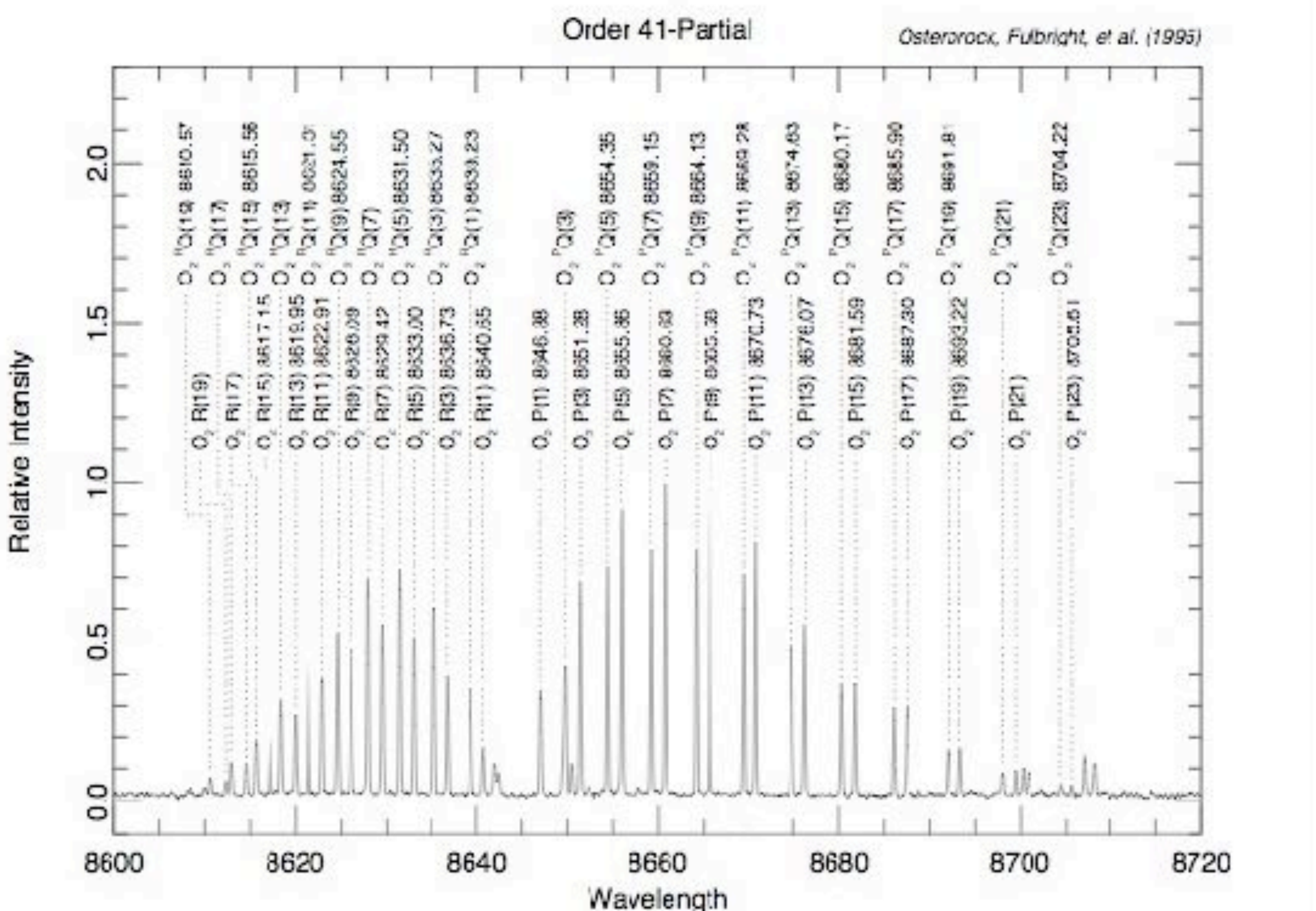




Backgrounds

natural
- the atmosphere

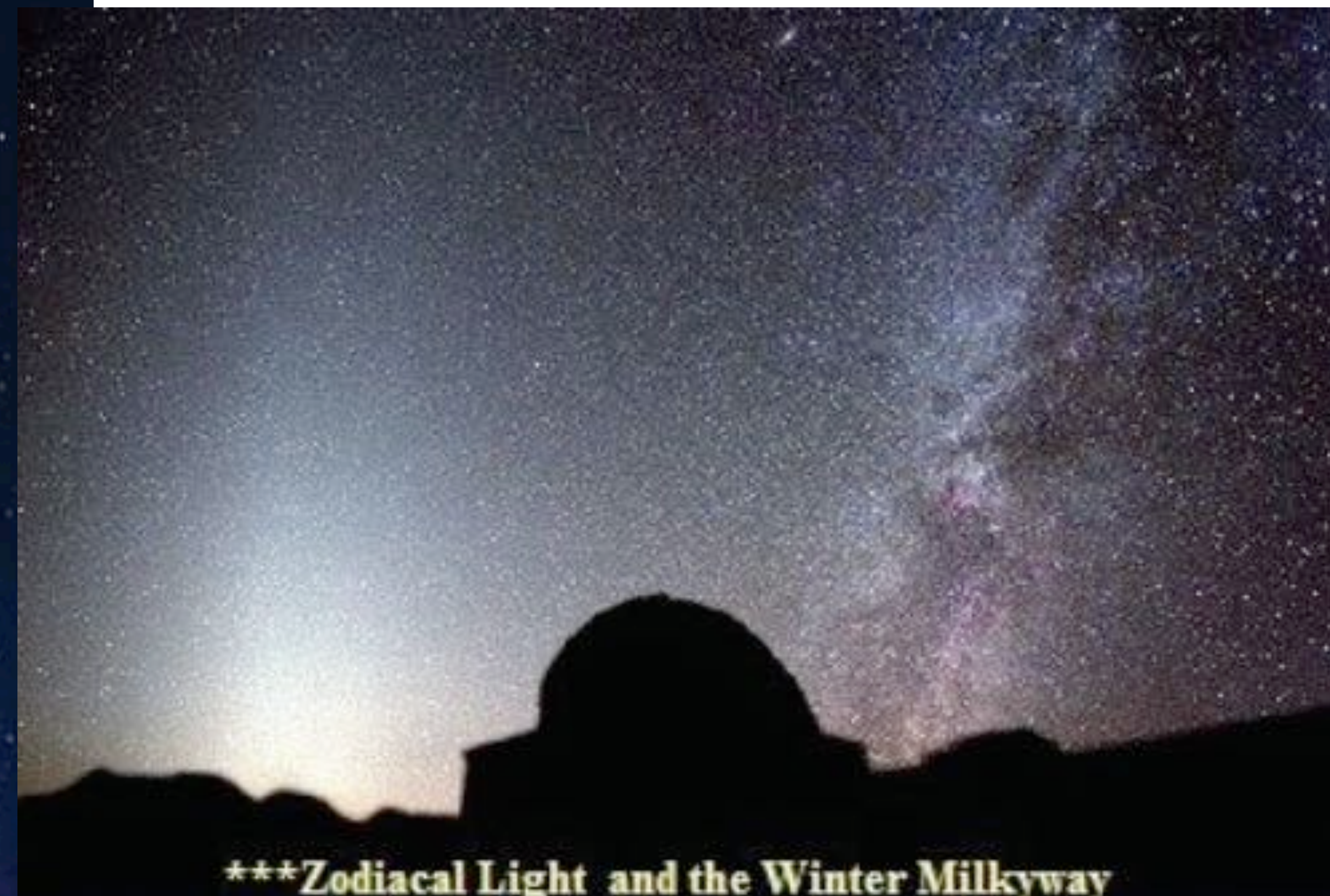




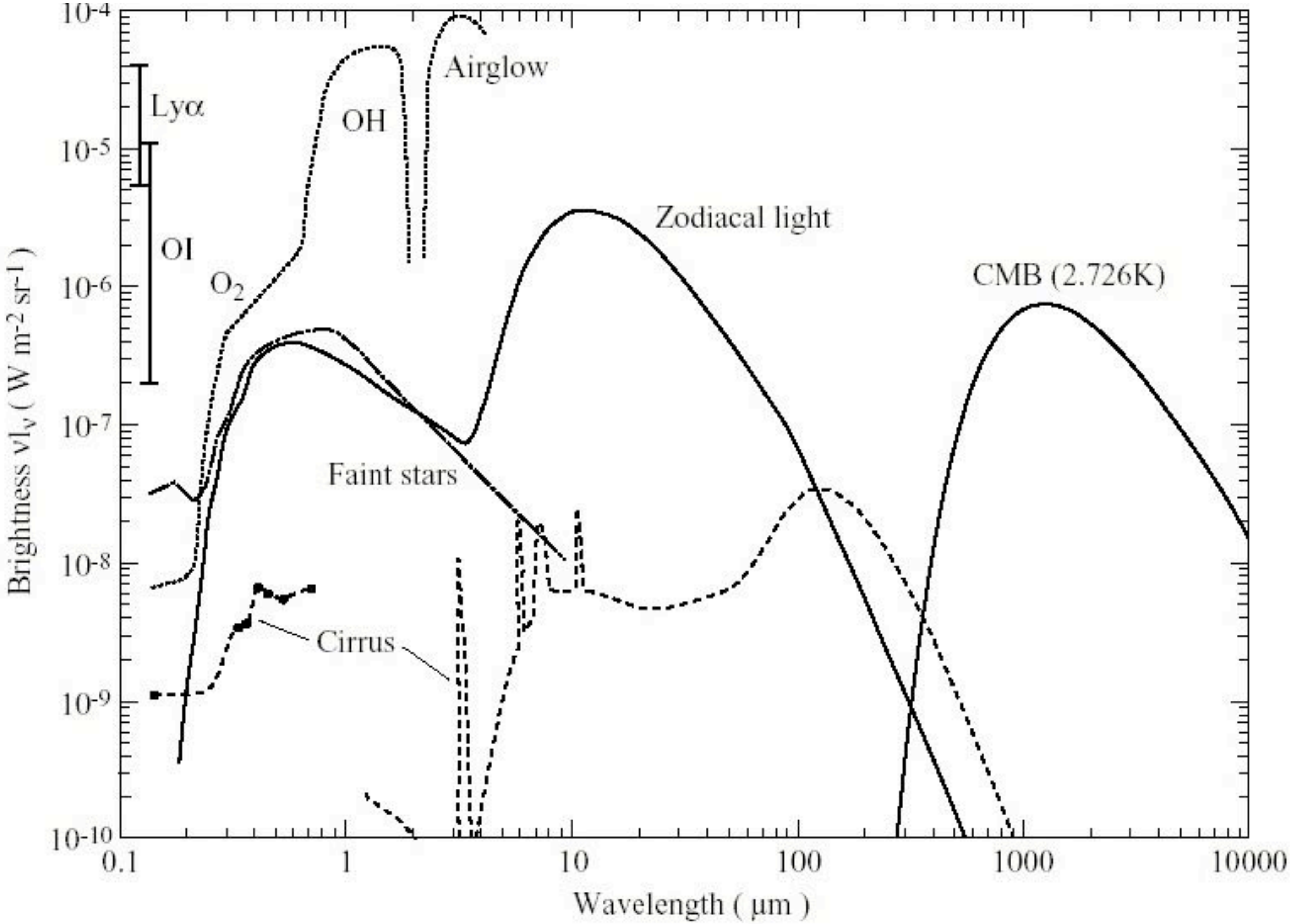
http://www.ucolick.org/~bolte/AY257/s_n.pdf

http://www.ucolick.org/%7Ejfulb/OH.html

natural - beyond Earth

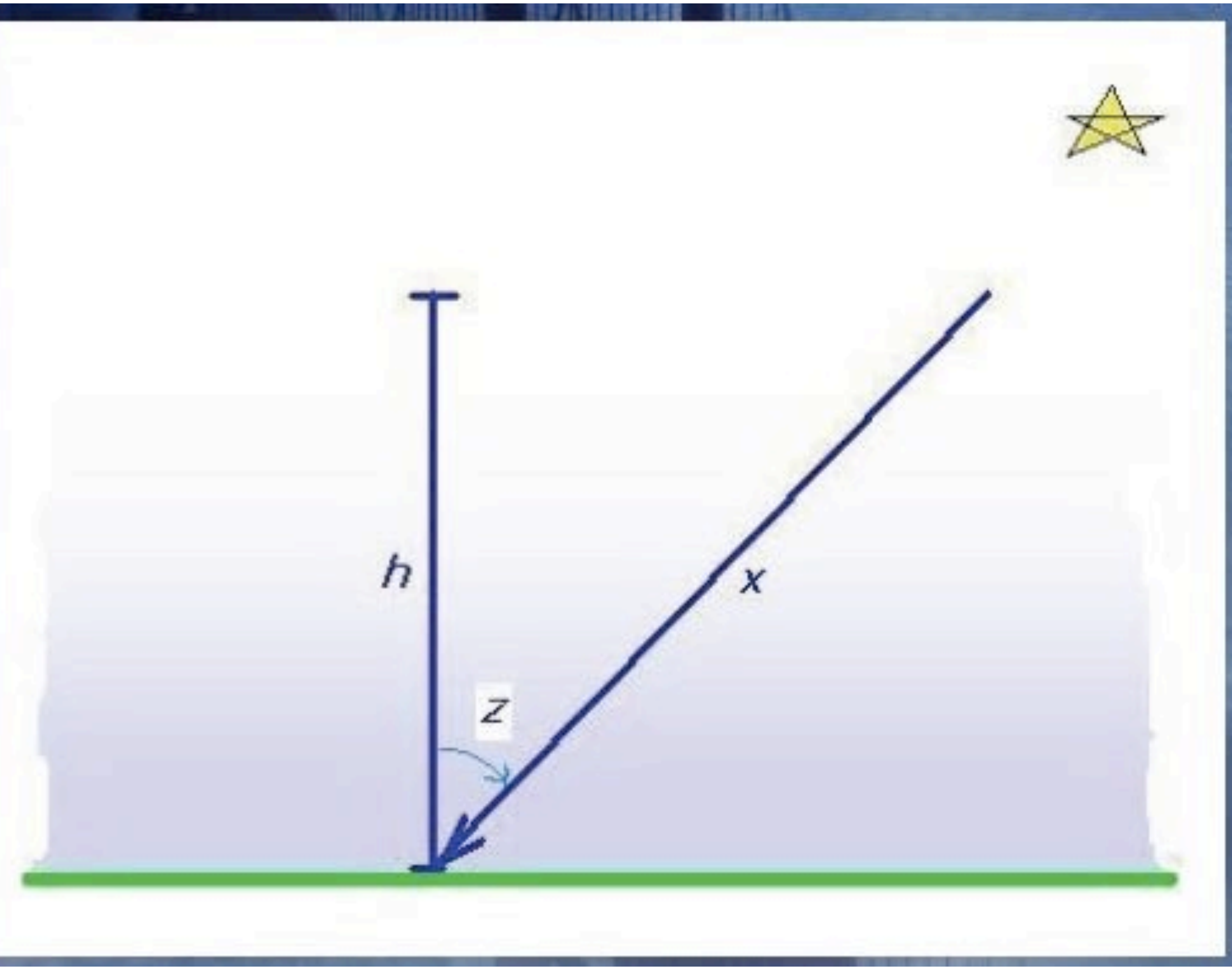


Left: Zodiacal light at Mauna Kea, http://www.jplnet.com/1htm/photoe.html
Right: Photo by Jack Newton, www.arizonaskyvillage.com



http://ssc.spitzer.caltech.edu/documents/compendium/resolution/leinert.gif

Airmass



Define:
h= height of atmosphere
x= path length through atmosphere to star
z=zenith angle = 90º - altitude

For planar atmosphere, $x=h \sec(z)$
Defining h=1, airmass=x=sec (z)
The plane parallel approx. is decent for $z<60^{\circ}$.

A more accurate approximation is

$$x=\sec(z)-0.0018167\,(\sec(z)-1)-0.002875*(\sec(z)-1)^2-0.008083\,(\sec(z)-1)^3$$

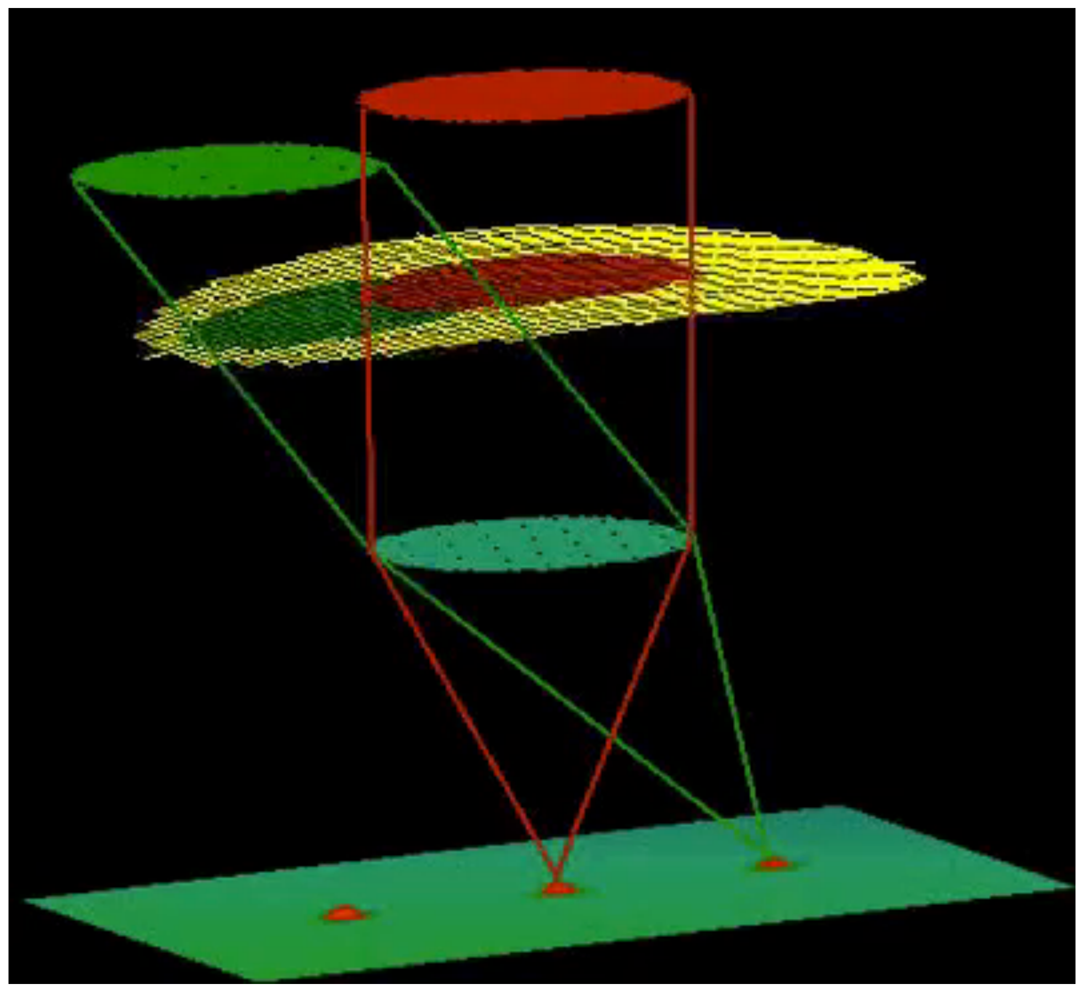
Adaptive Optics

- when seeing dominates image quality, big telescopes only do slightly better than small ones (because more care has been taken on improving seeing)

- one solution is to go above the atmosphere

- another solution is to remove the atmospheric blurring

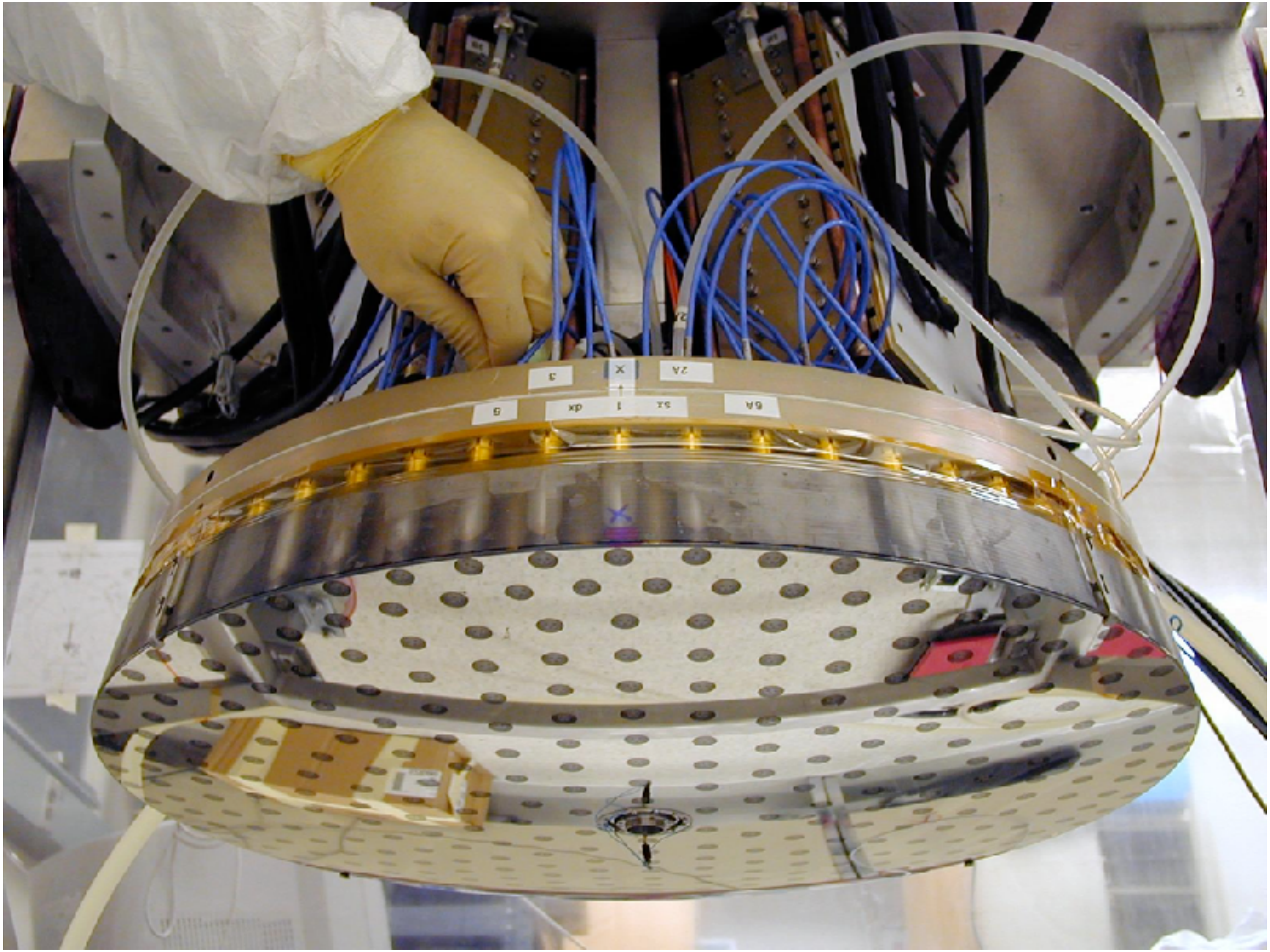
variations in density & temperature in the atmosphere affect the light travel paths



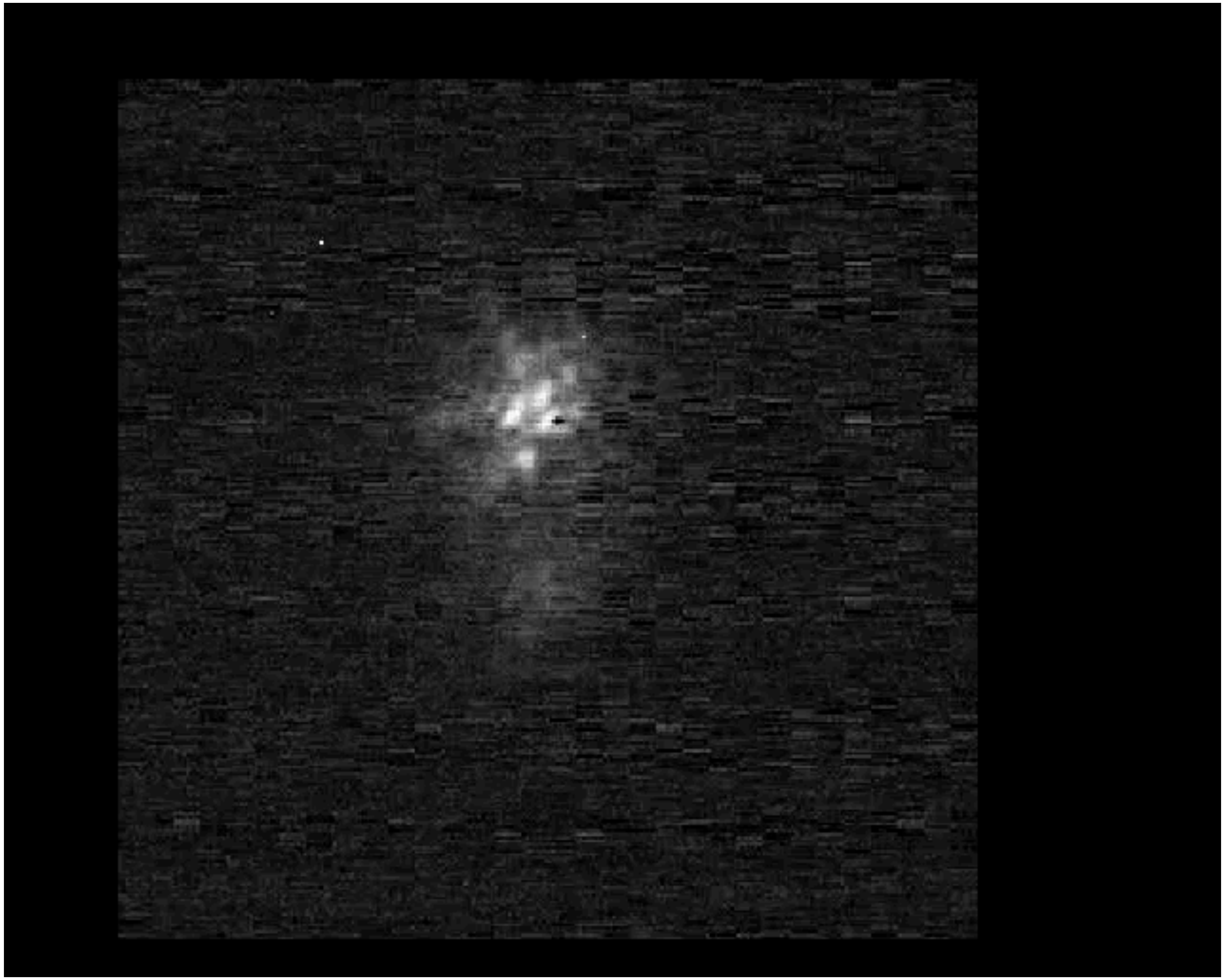
AO in a “nutshell”

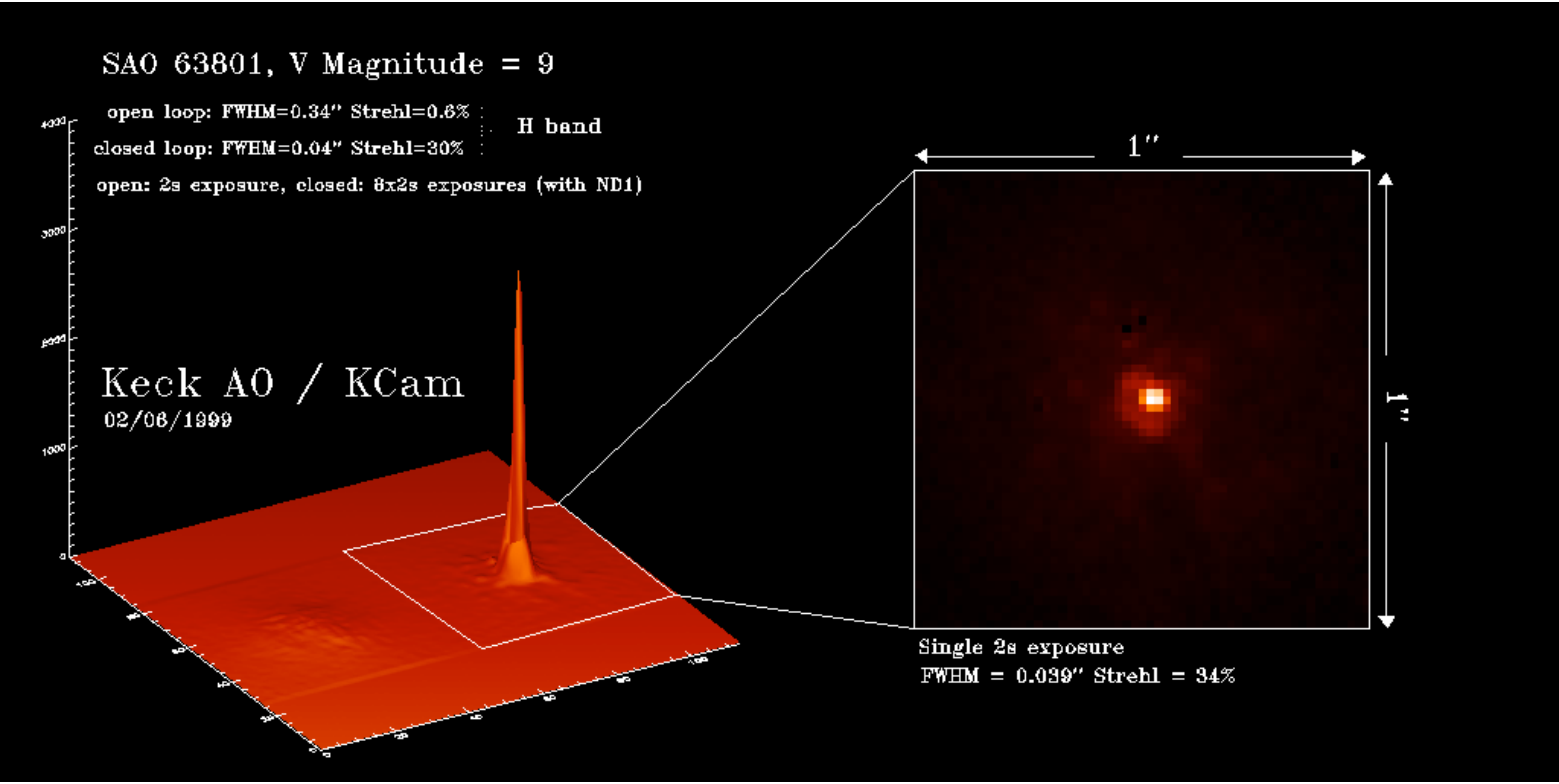
1) sense (very quickly) how the image is being warped by the atmosphere (~1000/sec)

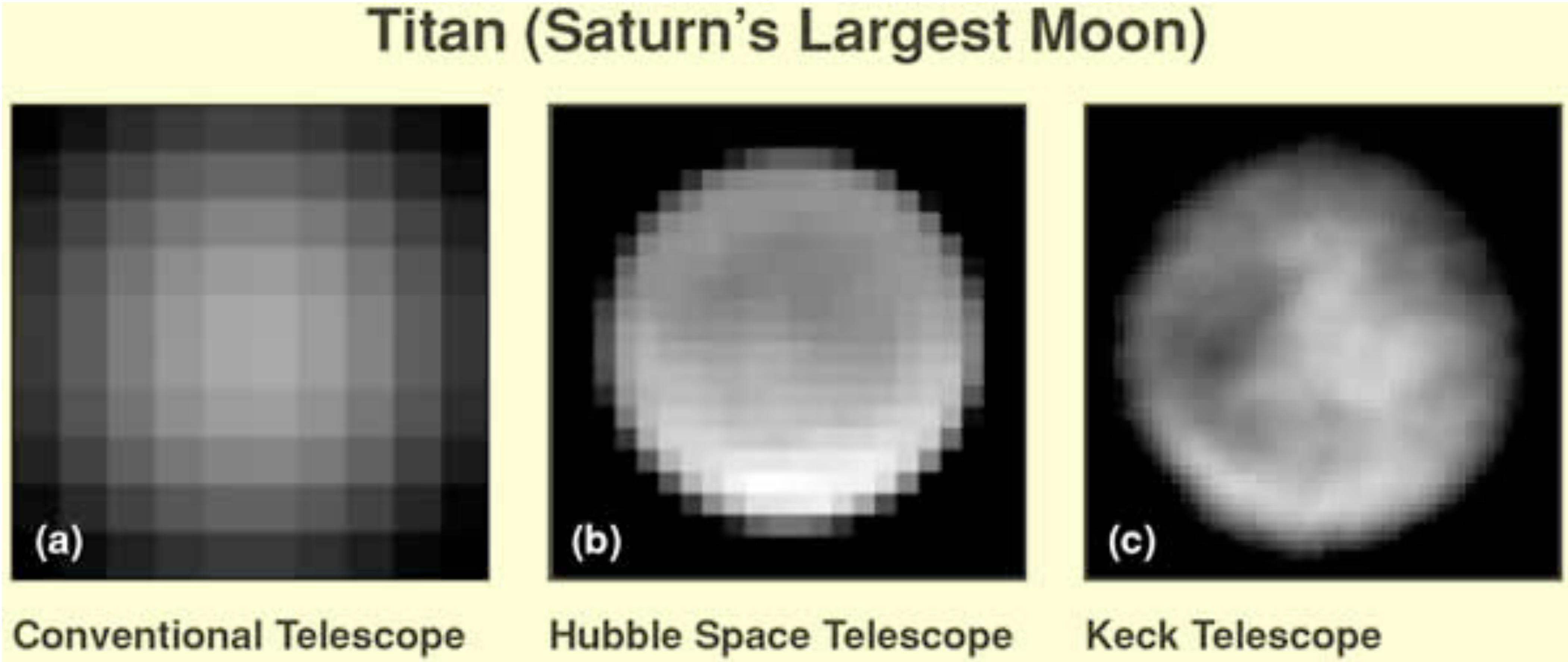
2) interpret those distortions, calculate how to bend a “rubber”mirror to undo those distortion

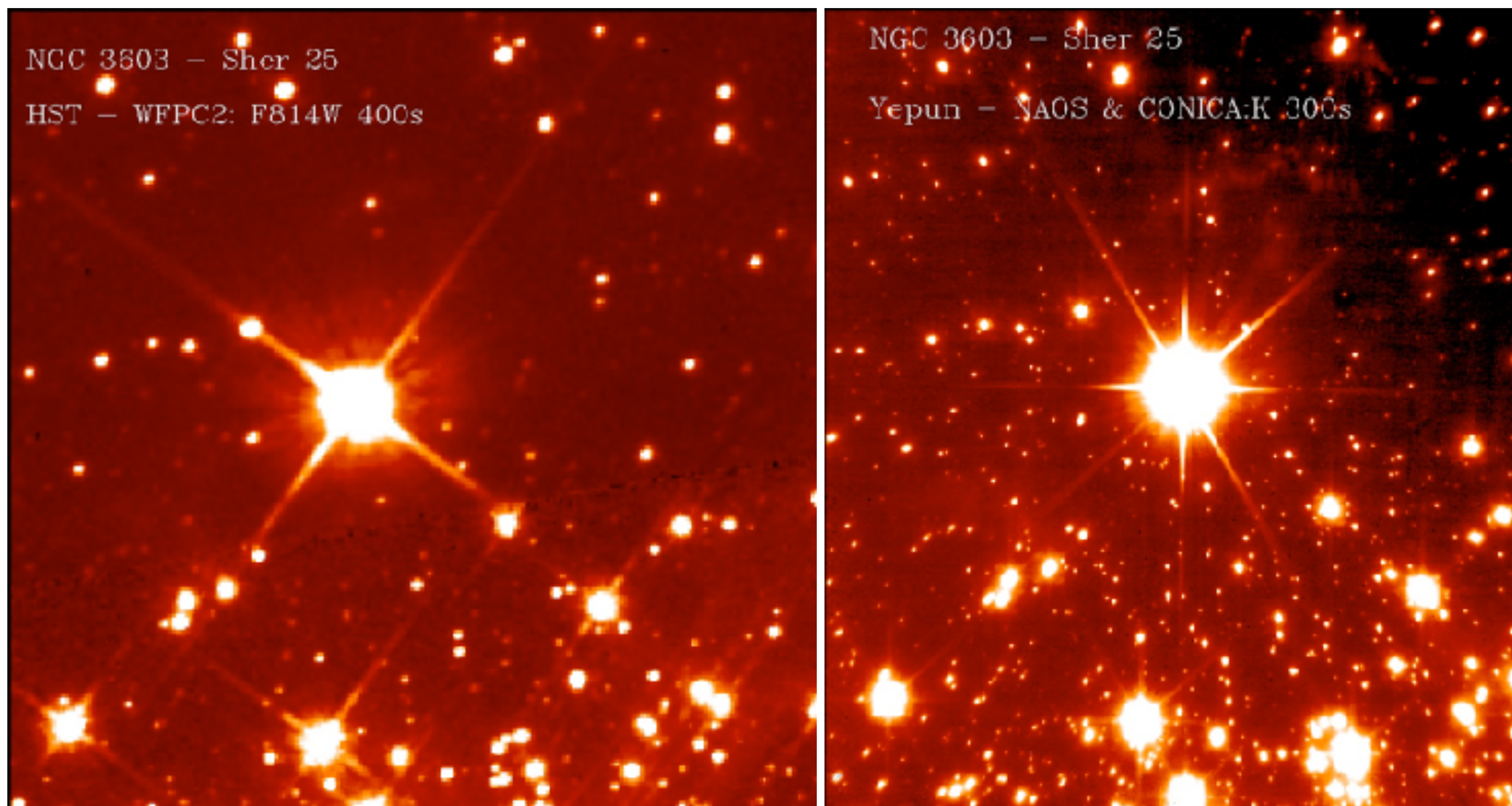


MMT secondary (AO mirrors often small & in the instrument)




SAO 63801, V Magnitude = 9
open loop: FWHM=0.34" Strehl=0.6%
closed loop: FWHM=0.04" Strehl=30%
H band
open: 2s exposure, closed: 8x2s exposures (with ND1)
Keck AO / KCam
02/06/1999
1"
1"
Single 2s exposure
FWHM = 0.039" Strehl = 34%


Titan (Saturn's Largest Moon)
(a)
(b)
(c)
Conventional Telescope
Hubble Space Telescope
Keck Telescope


NGC 3603 – Sher 25
HST – WFPC2: F814W 400s
NGC 3603 – Sher 25
Yepun – NAOS & CONICA:K 300s

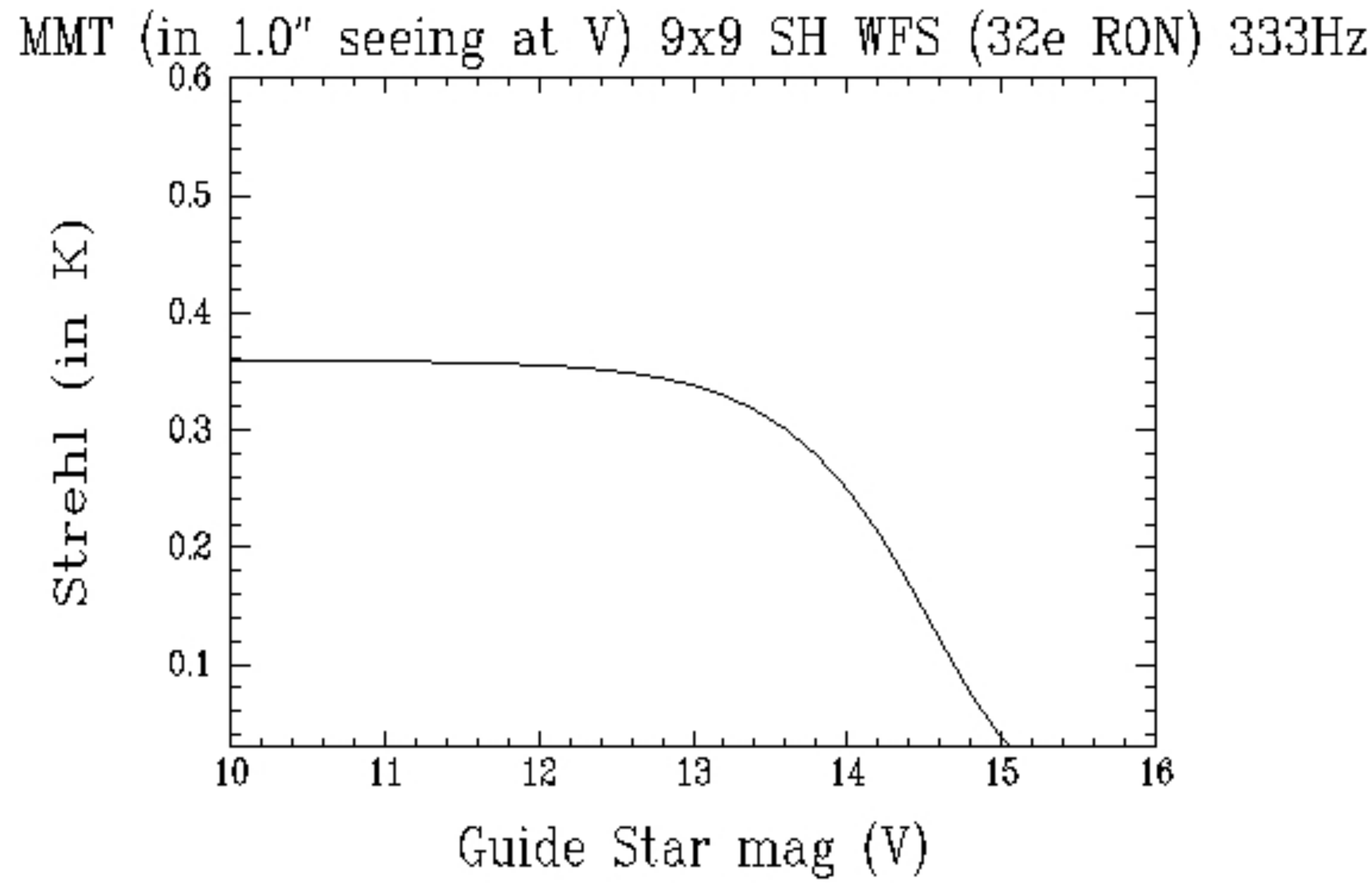
Limitations

- $r_0 \propto \lambda^{5/6}$ (isoplanatic patch size)

implies that it gets harder and harder
to correct at bluer wavelengths
(current systems work only to the near IR)

- requires a bright source (so that you get
enough signal 1000/sec!)

soln' is lasers (which are working
now at several observatories)



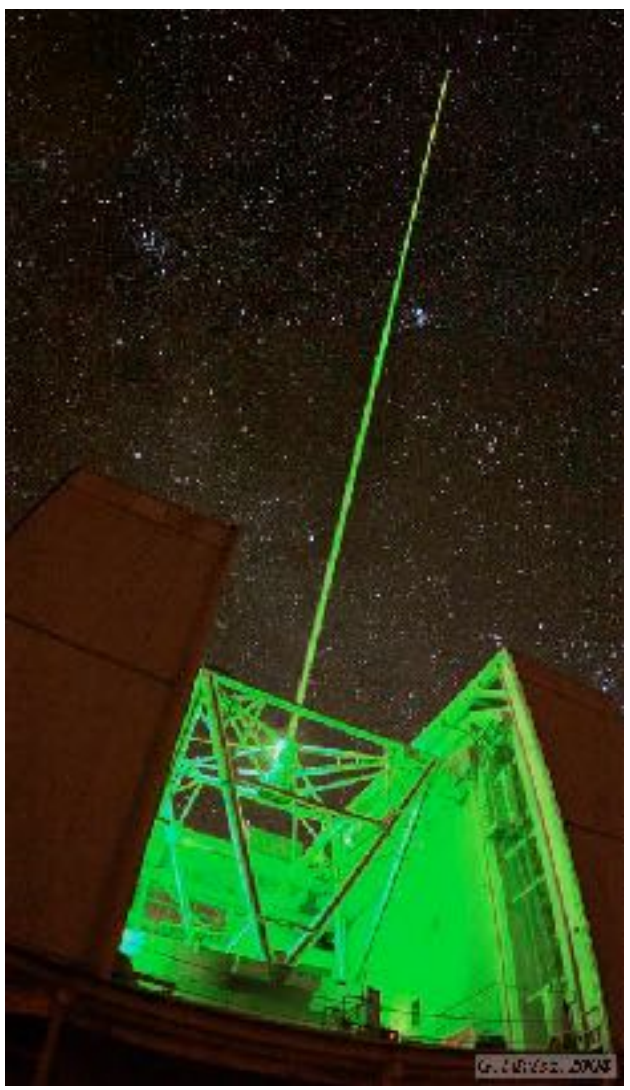
Strehl measures the ratio of the flux in the central peak vs. diffraction limit

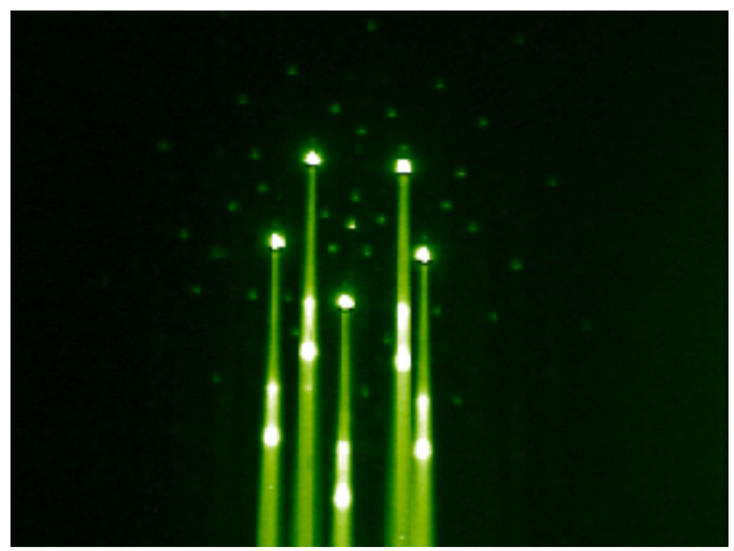
VLT

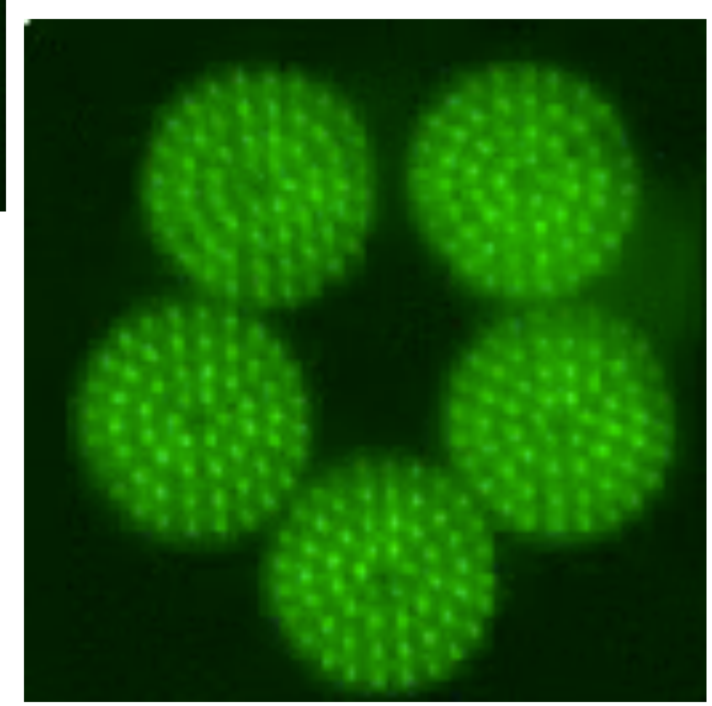
MMT

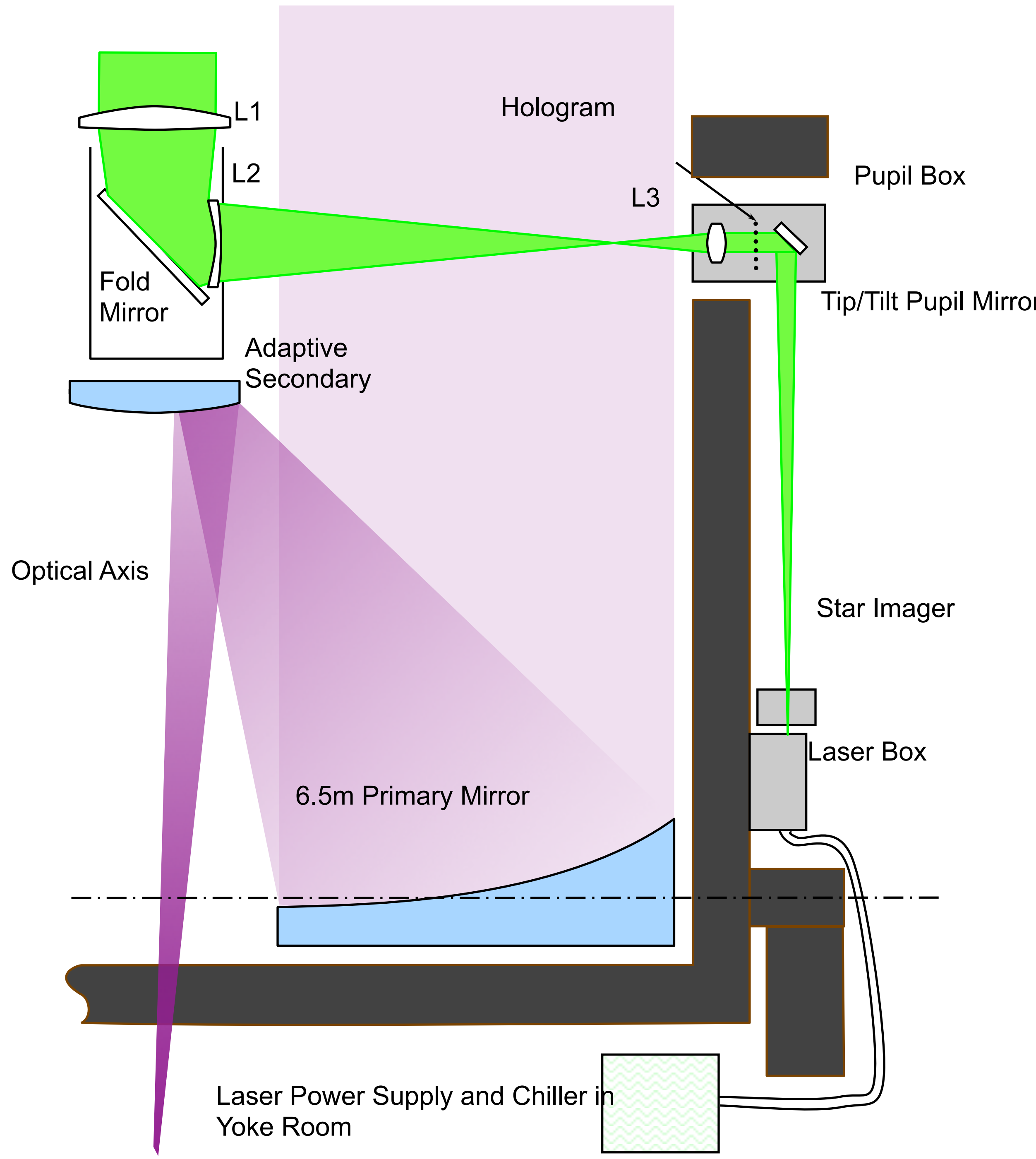
- correction worsens quickly as you move away from the reference object

solution: Multi-Conjugate Adaptive Optics (MCAO)

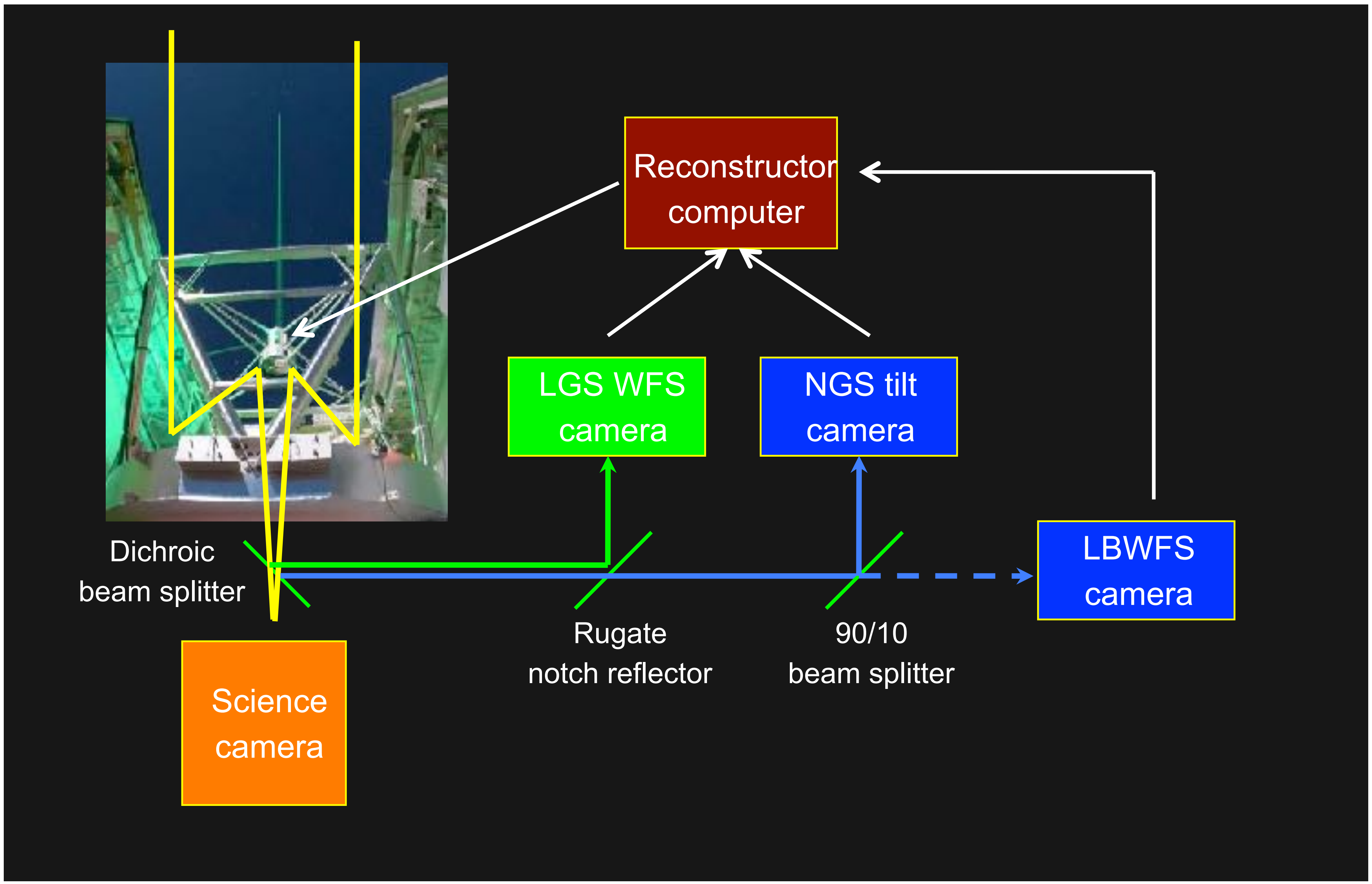






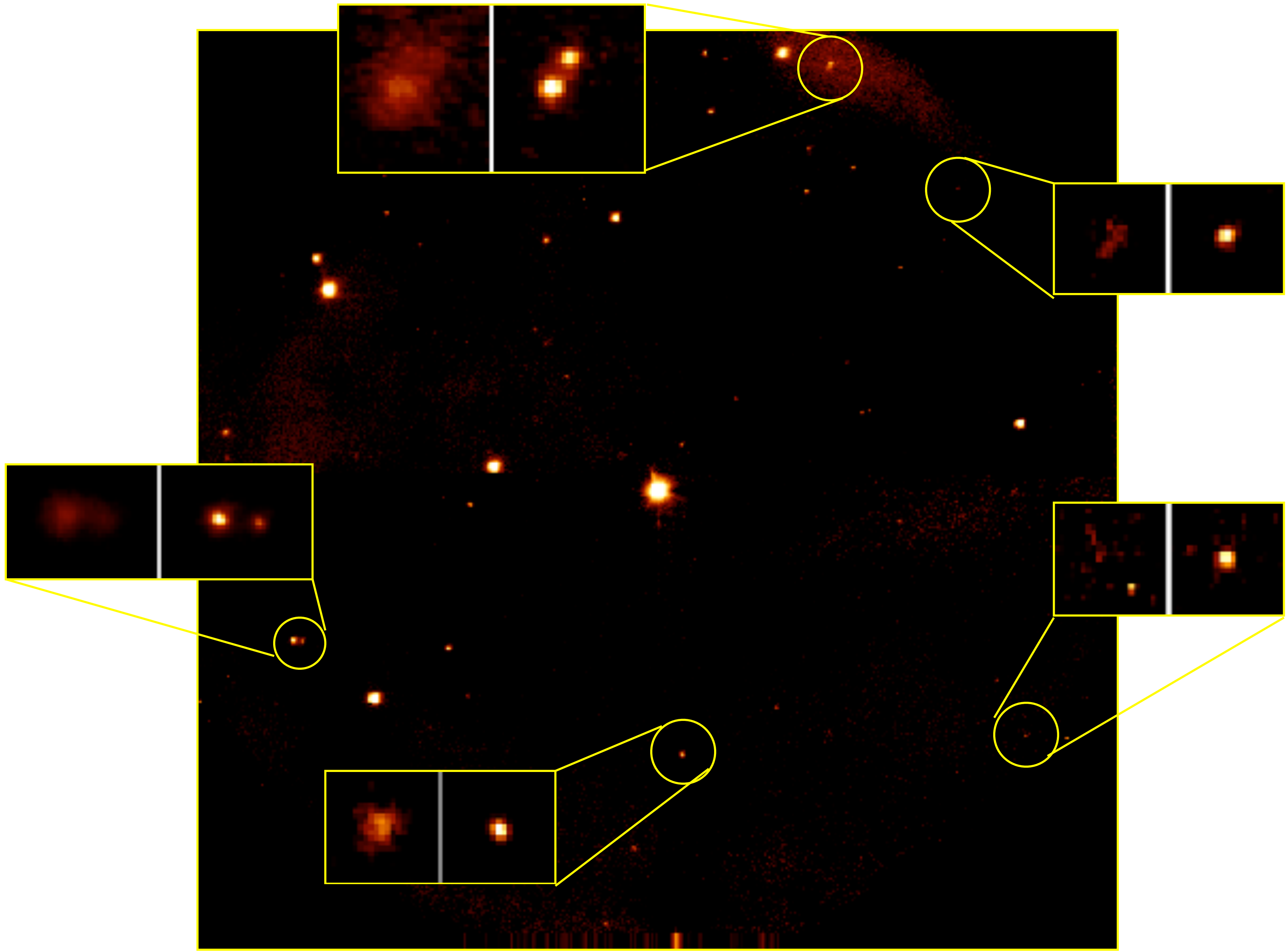

L1
L2
Hologram
Pupil Box
L3
Fold
Mirror
Tip/Tilt Pupil Mirror
Adaptive
Secondary
Optical Axis
Star Imager
Laser Box
6.5m Primary Mirror
Laser Power Supply and Chiller in
Yoke Room

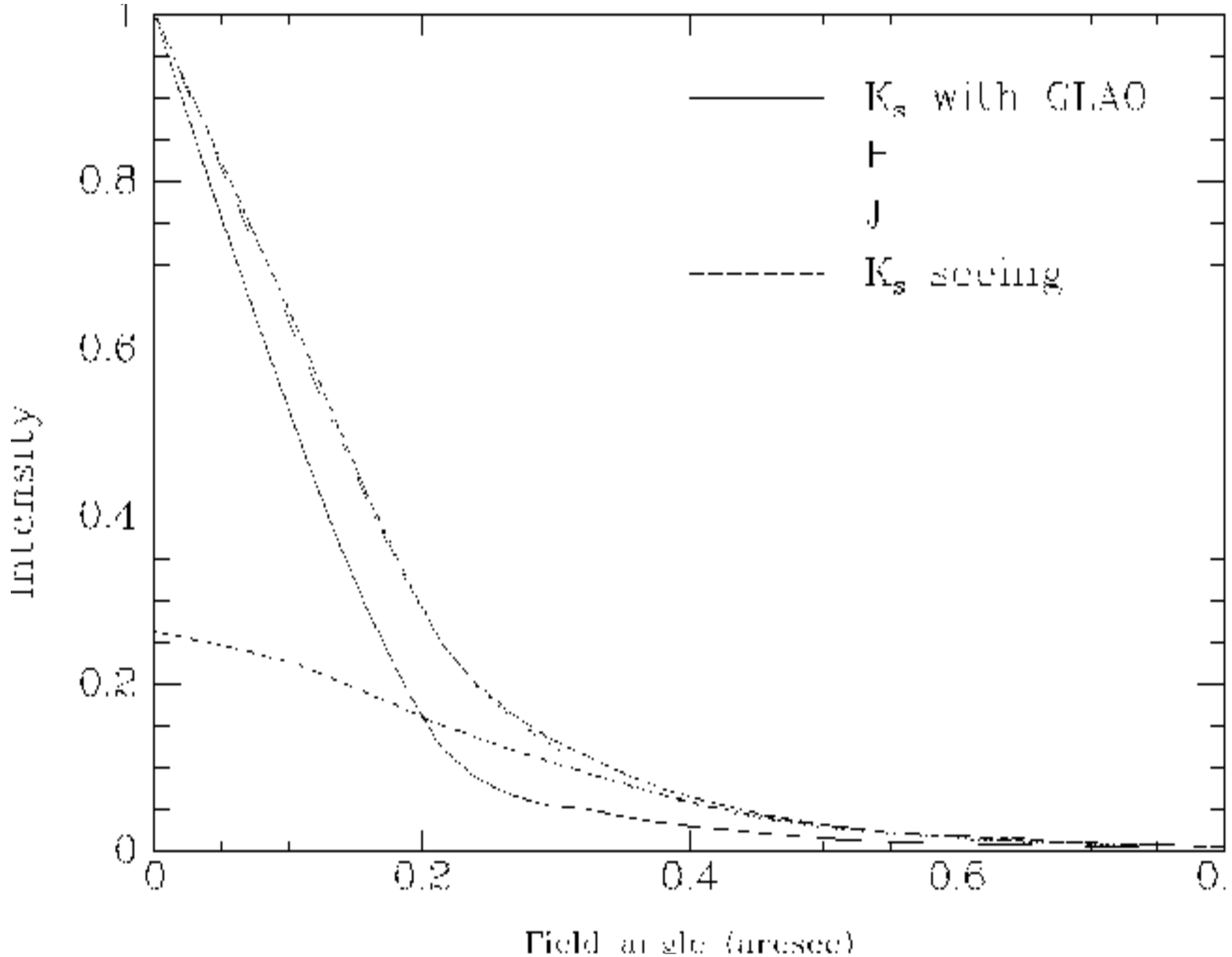
Functional block diagram



corrects at 400 Hz

M36





Ks with GLAO
H
J
Ks seeing
Intensity
Field angle (arcsec)
0
0.2
0.4
0.6
0.8
1

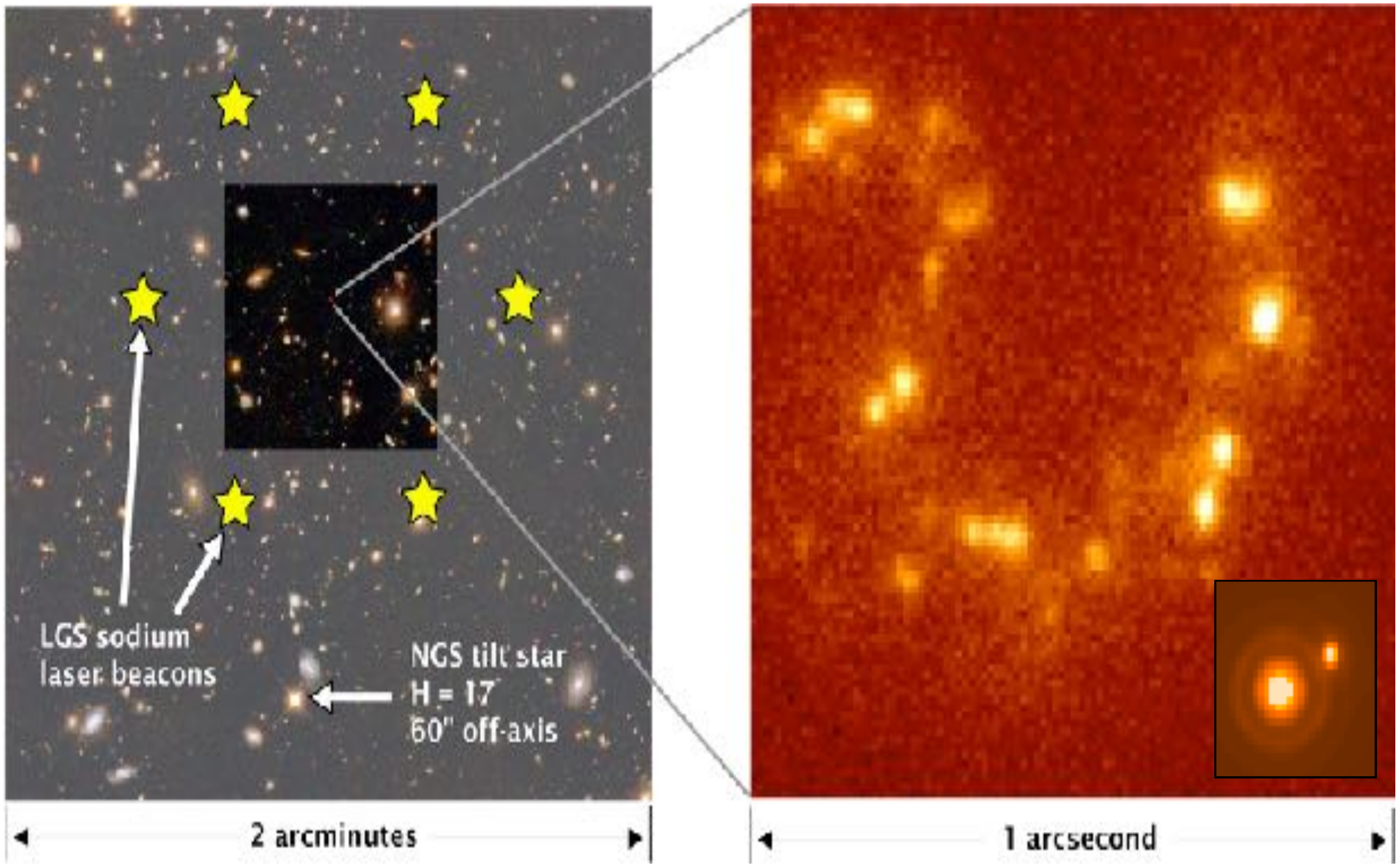
currently AO has become a commonplace technique at many telescopes.

almost all large D>4m telescopes have facility AO systems either running or close to operational.

diffraction-limited scopes gain as D^4 power on point sources ==> advantage to AO on large telescopes.

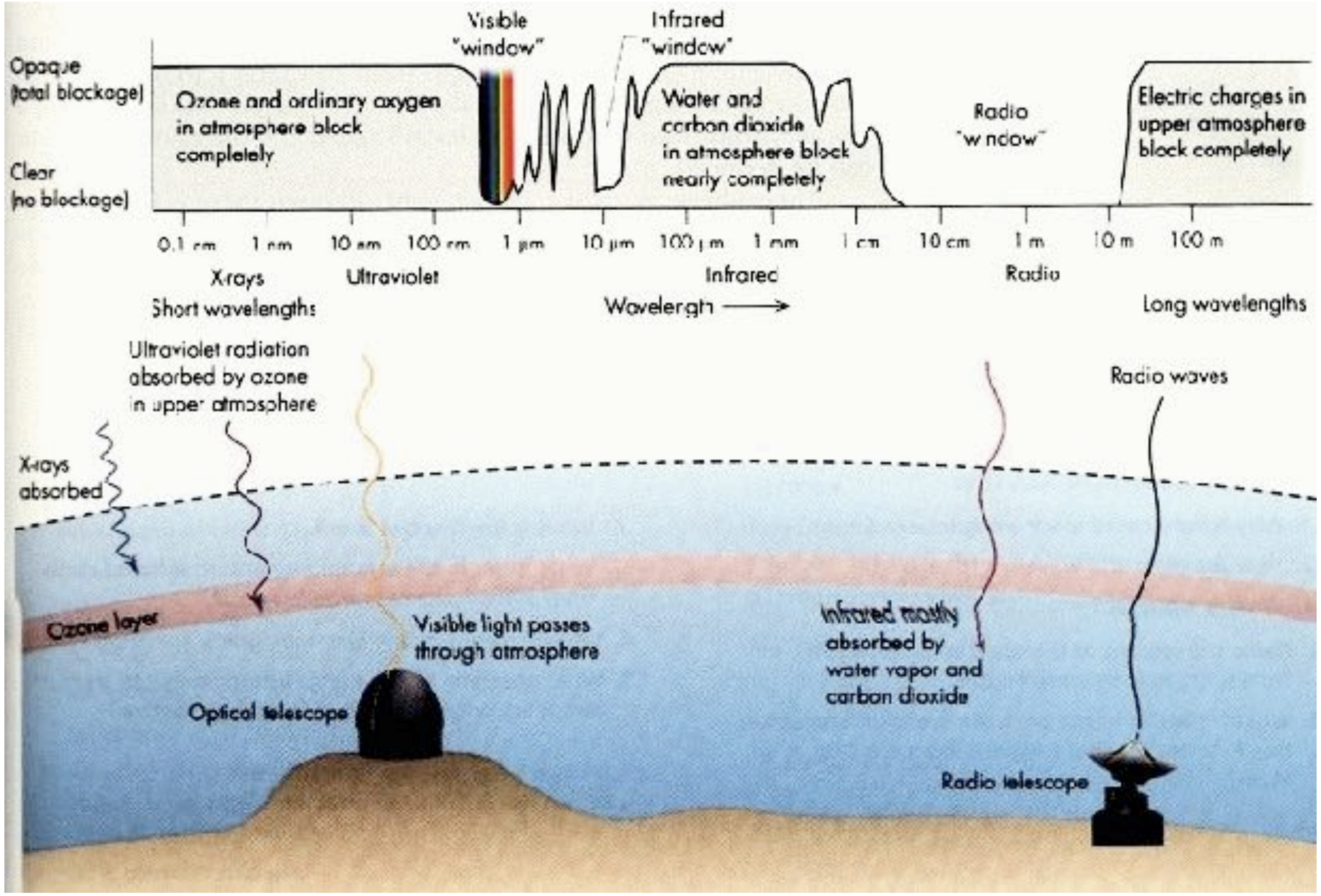
AO is now common technique practiced by experts and general IR astronomers.

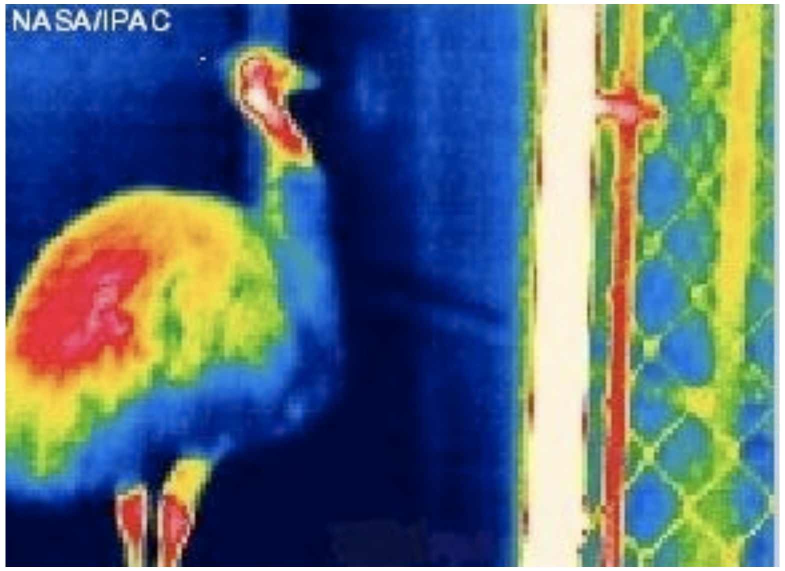
Simulated AO imaging

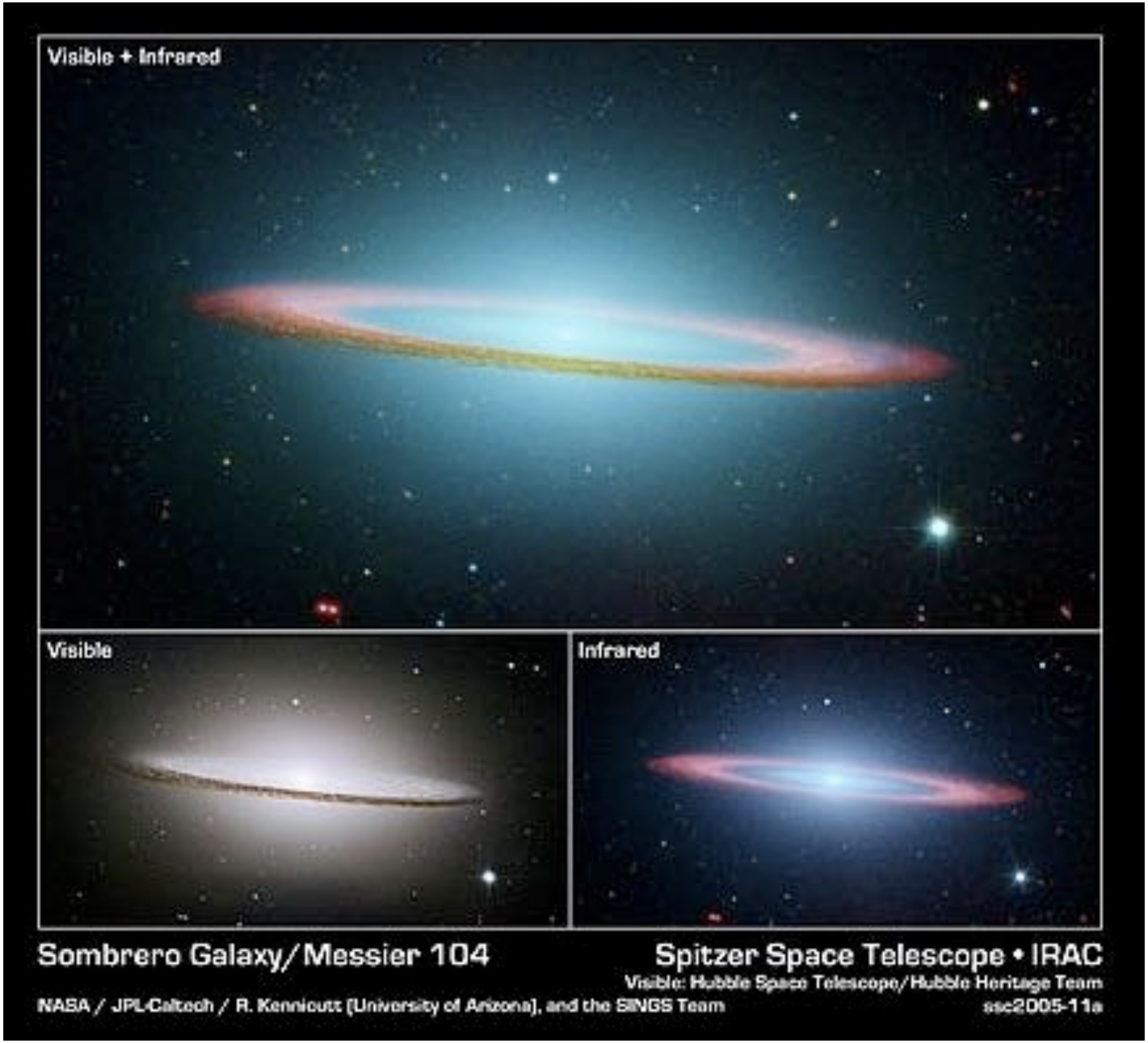


- Simulated K-band image at the diffraction limit of the 25 m aperture

Infrared Observing






Visible + Infrared
Visible
Infrared
Sombrero Galaxy/Messier 104
Spitzer Space Telescope • IRAC
Visible: Hubble Space Telescope/Hubble Heritage Team
NASA / JPL-Caltech / R. Kennicutt (University of Arizona), and the SINGS Team
ssc2005-11a

Wavelength range (micrometres)	Astronomical bands
0.65 to 1.0	R and I bands
1.25	J band
1.65	H band
2.2	K band
3.45	L band
4.7	M band
10	N band
20	Q band
450	submillimeter

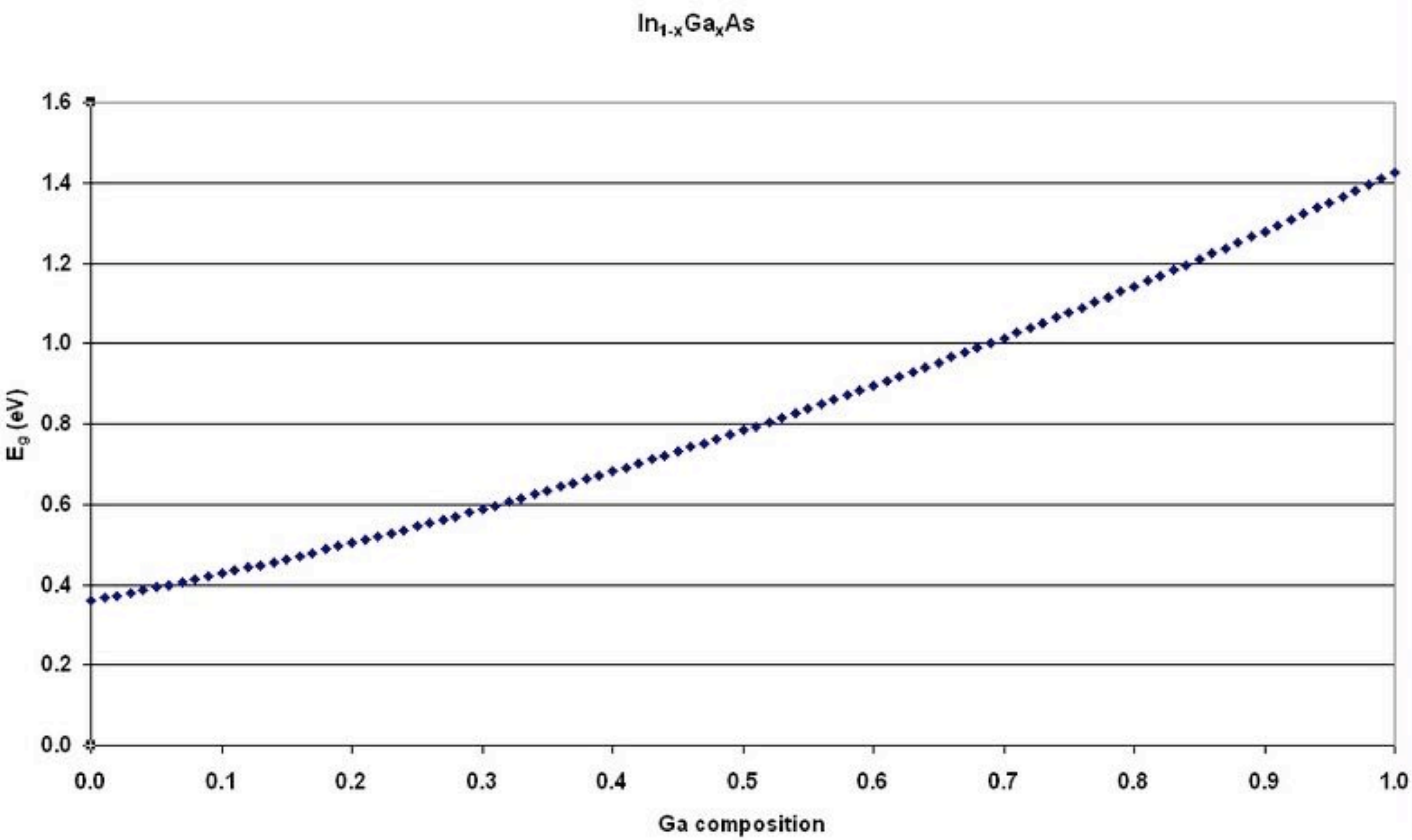
from wikipedia

Some detector materials...

Type	Spectral range (µm)
Indium gallium arsenide (InGaAs) photodiodes	0.7-2.6
Germanium photodiodes	0.8-1.7
Lead sulfide (PbS) photoconductive detectors	1-3.2
Lead selenide (PbSe) photoconductive detectors	1.5-5.2
Indium arsenide (InAs) photovoltaic detectors	1-3.8
Platinum silicide (PtSi) photovoltaic detectors	1-5
Indium antimonide (InSb) photoconductive detectors	1-6.7
Indium antimonide (InSb) photodiode detectors	1-5.5
Mercury cadmium telluride (MCT, HgCdTe) photoconductive detectors	2-25
Mercury zinc telluride (MZT, HgZnTe) photoconductive detectors	?

from wikipedia

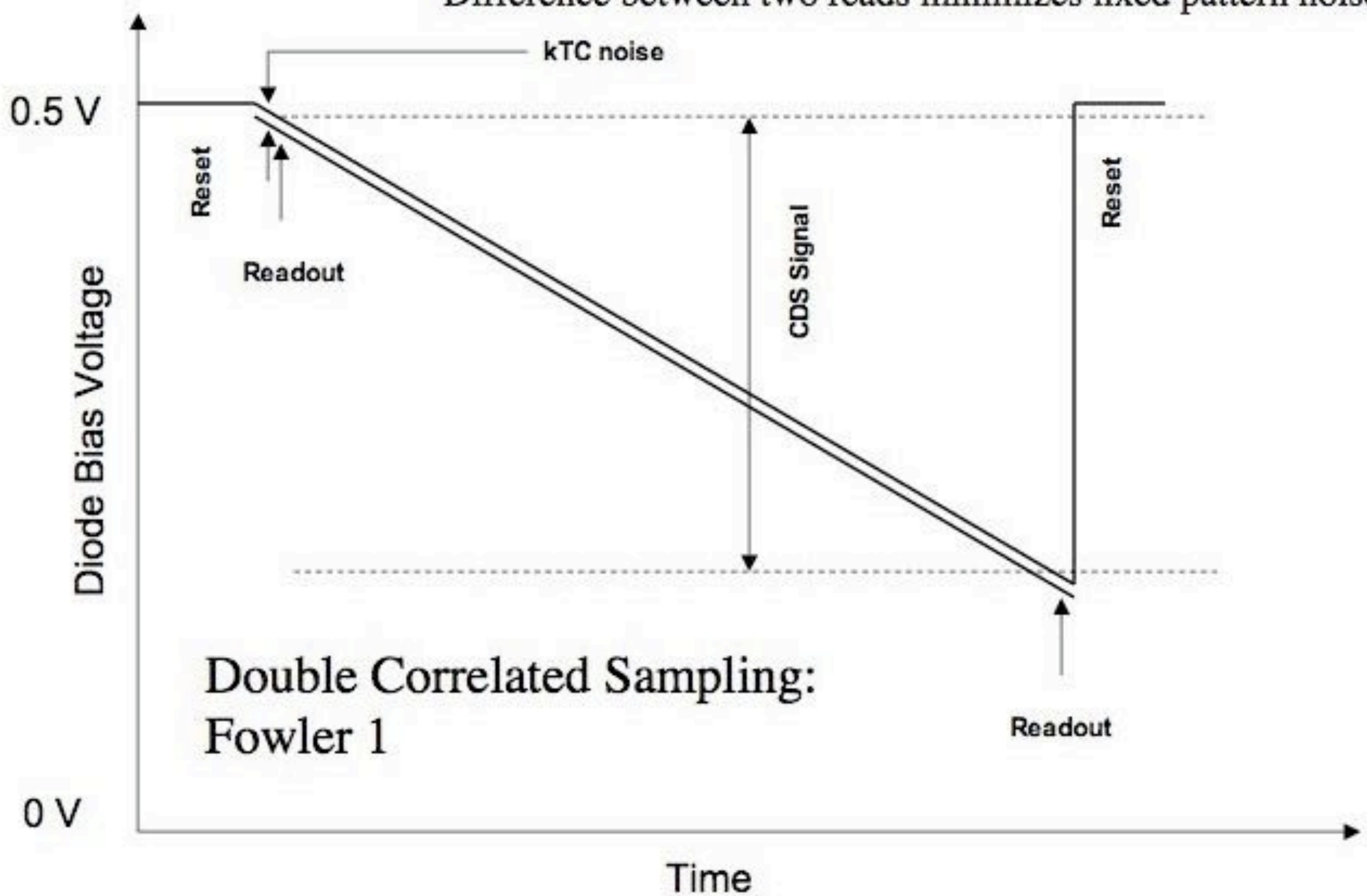
don’t forget bolometers...



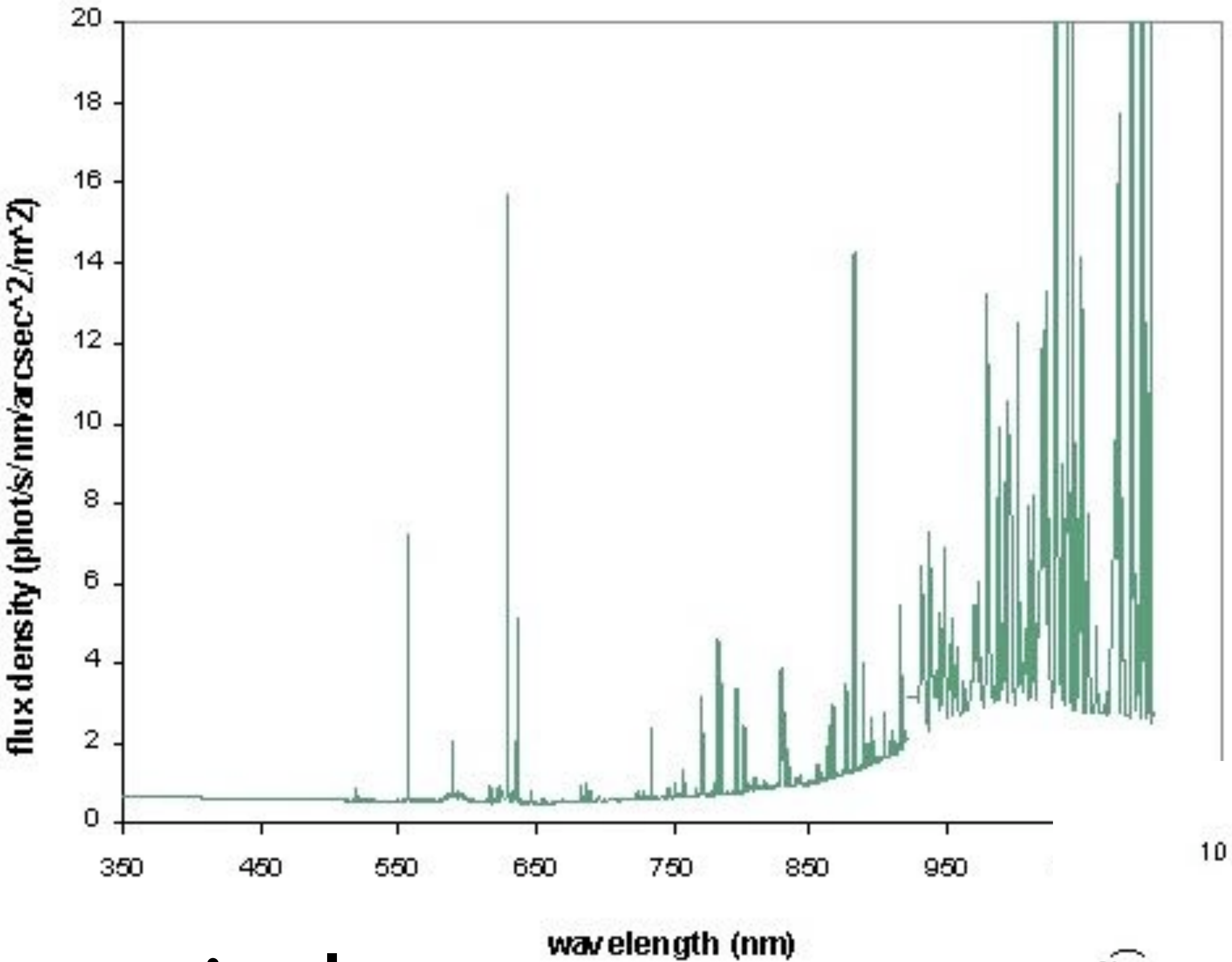
$In_{1-x}Ga_xAs$
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
E_g (eV)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Ga composition

Pixel Readout

- •Non-destructive Readout
- •Photo-electrons accumulate until reset
- •Difference between two reads minimizes fixed pattern noise

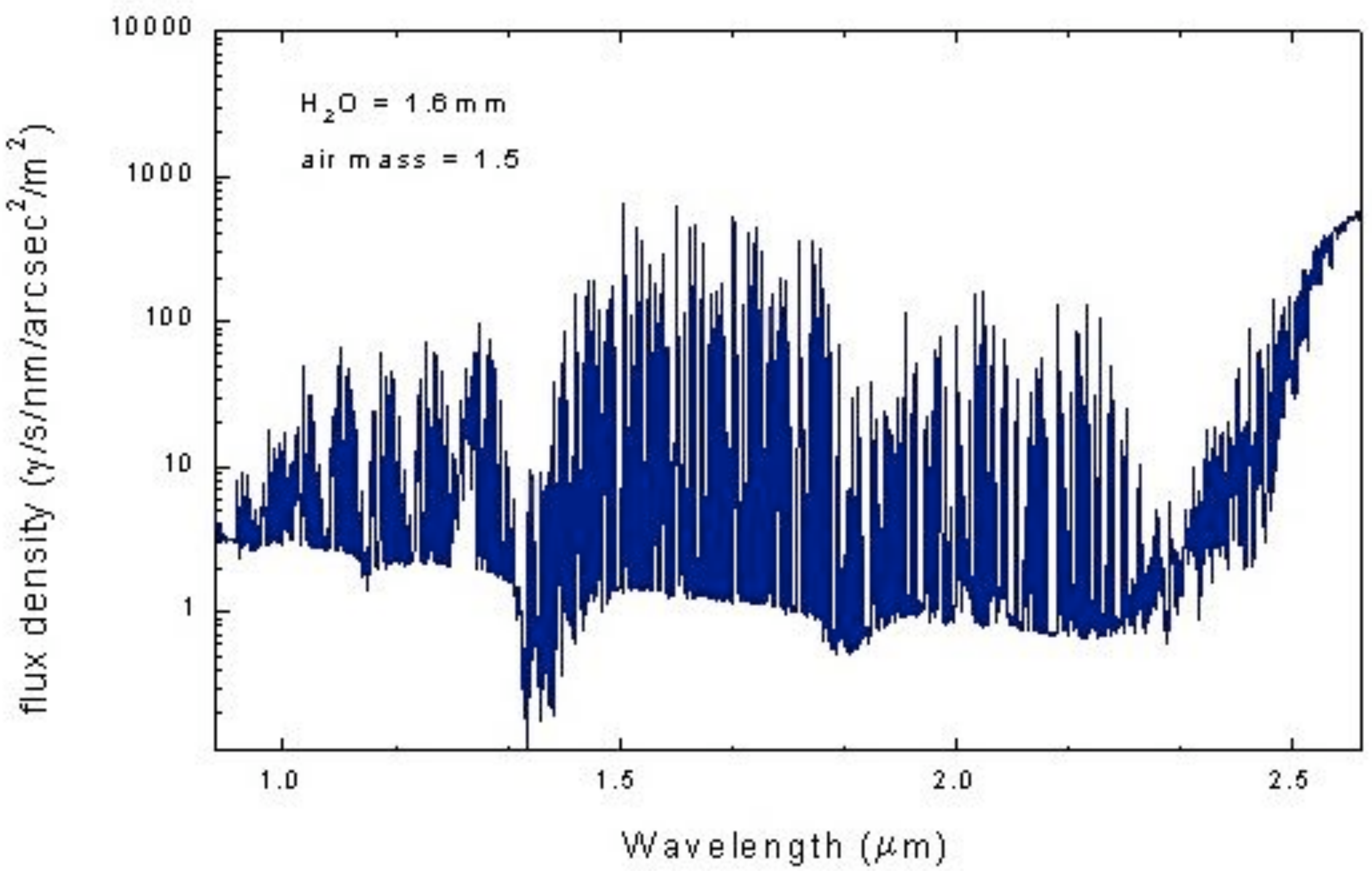


Background

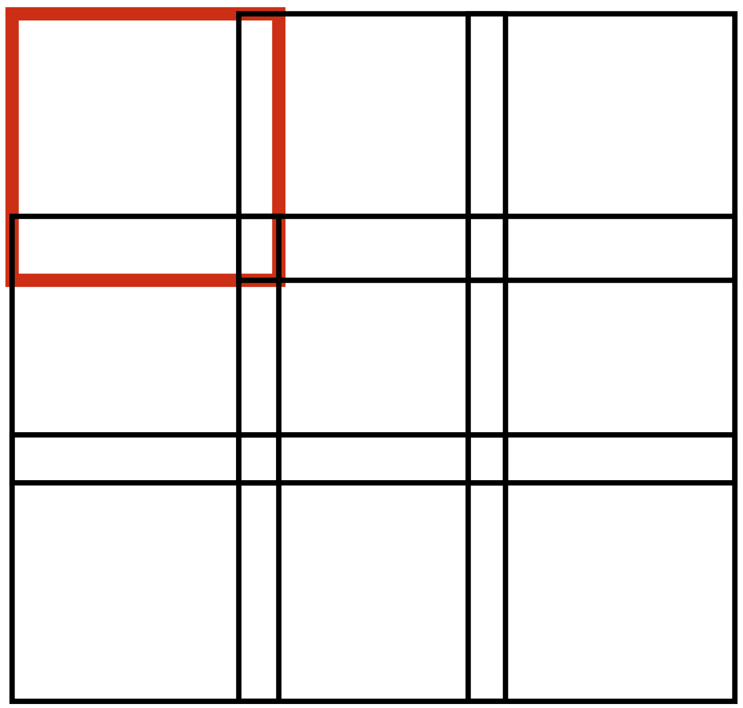


optical

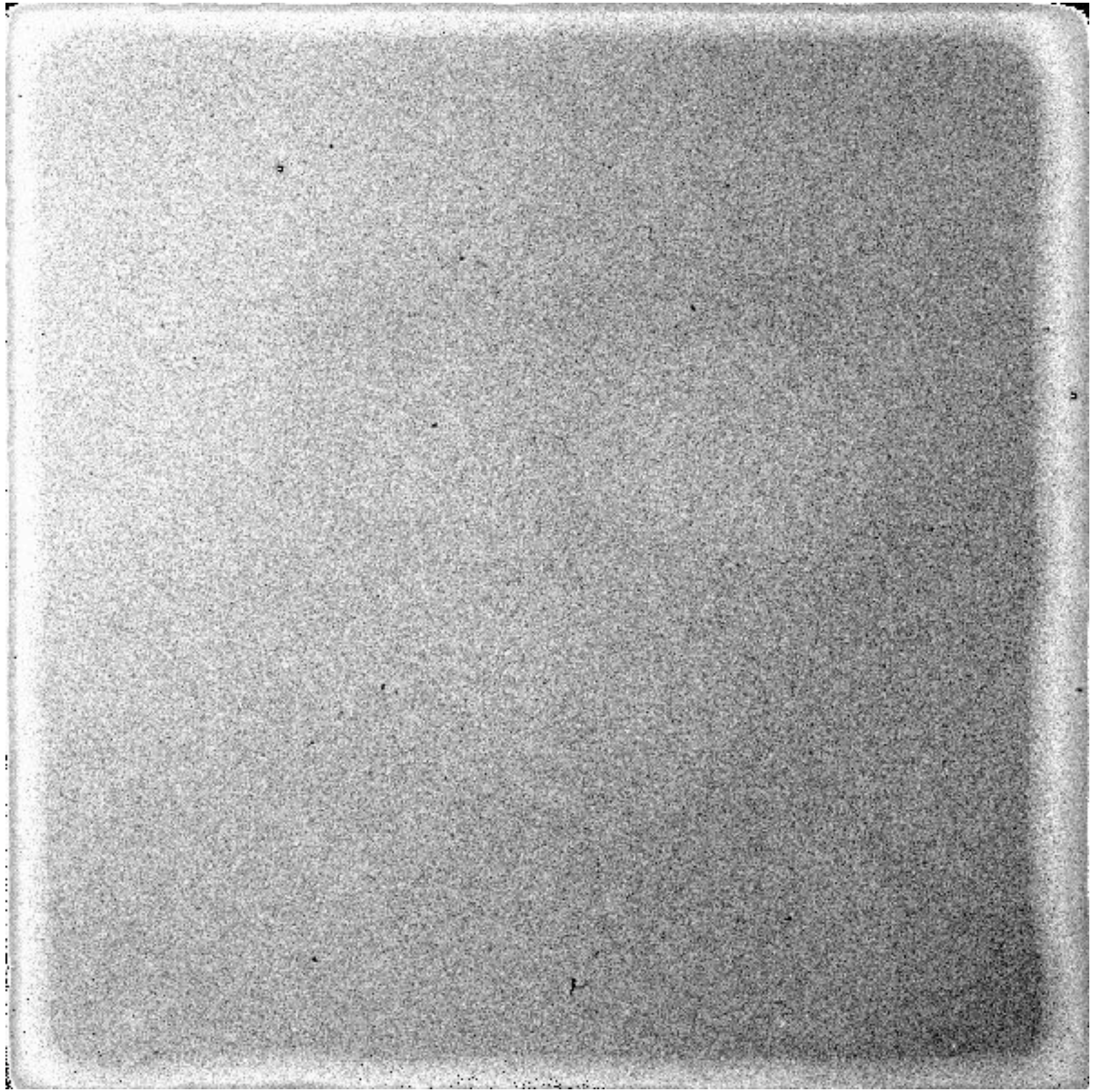
IR

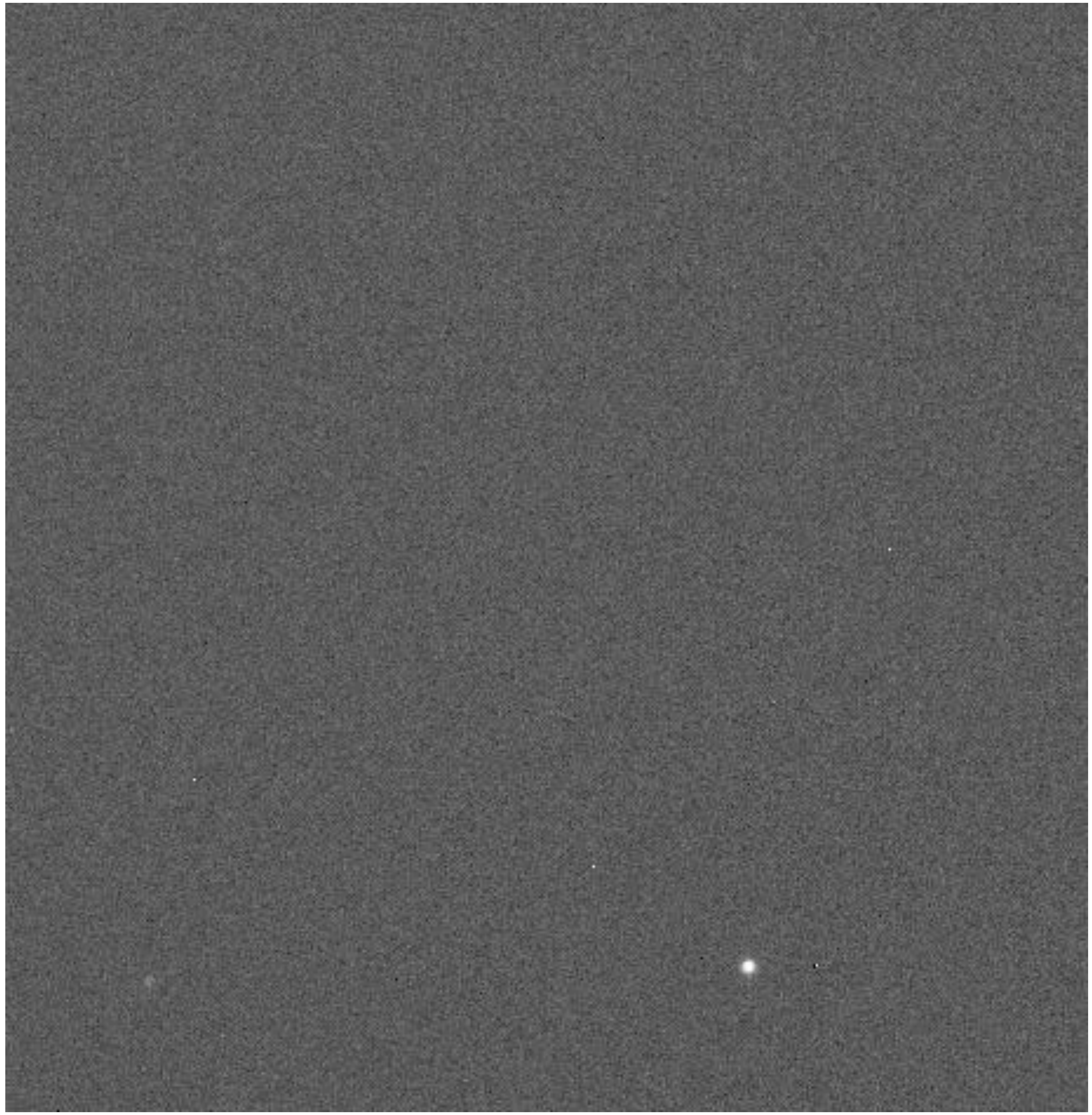


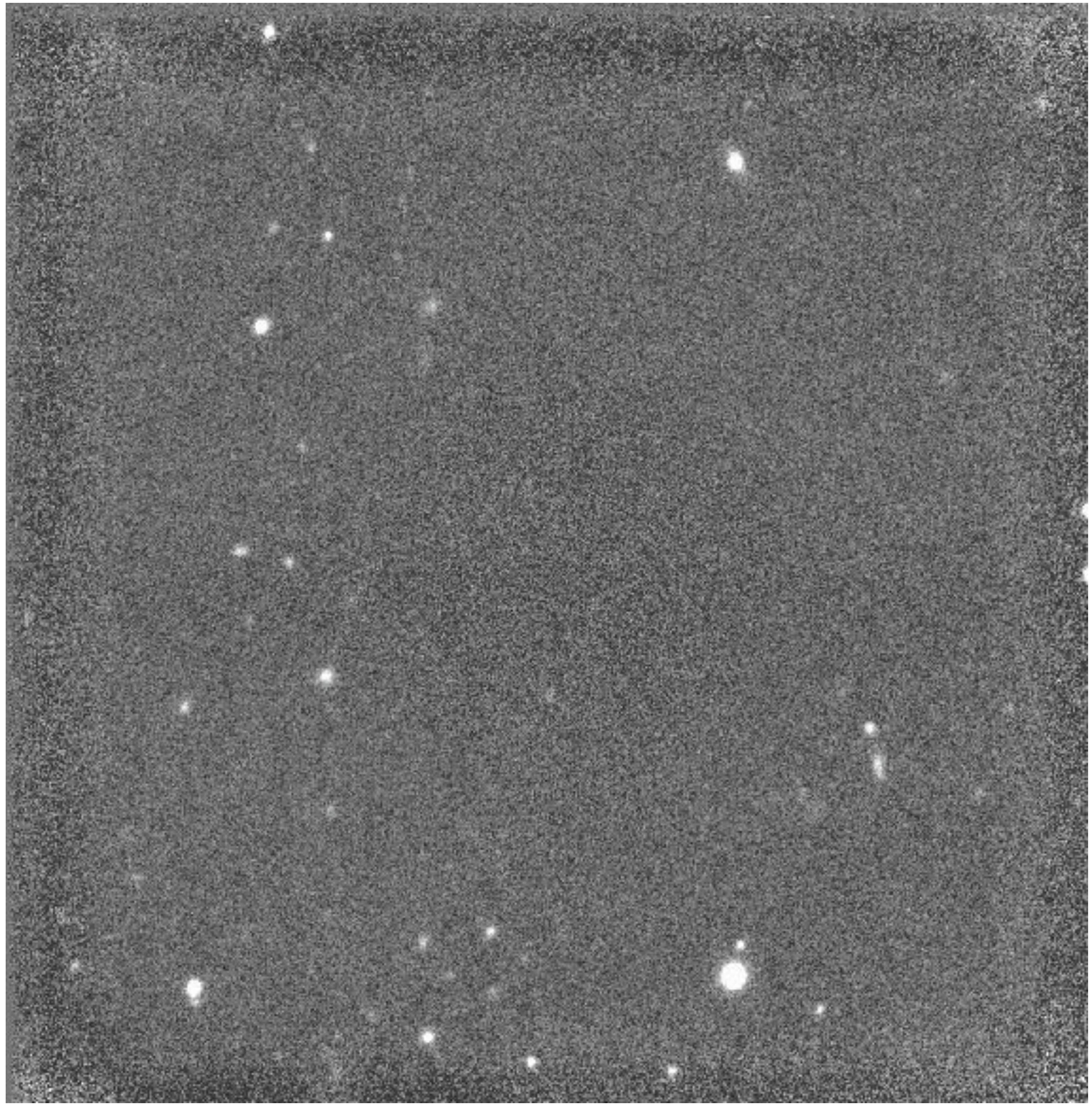
dither pattern



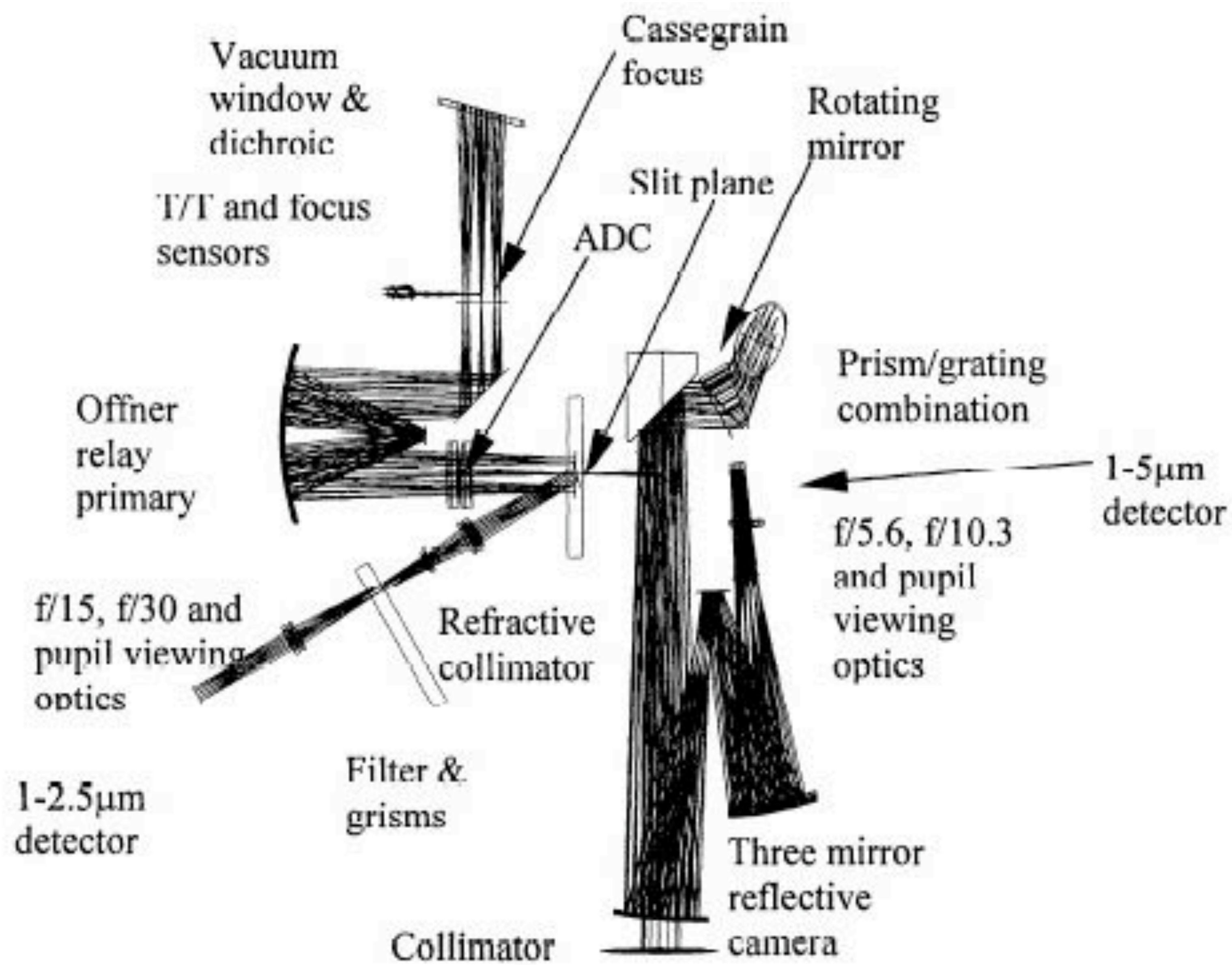
overlapping set of frames can serve as flats, sky, and map a larger area







instrument design considerations...

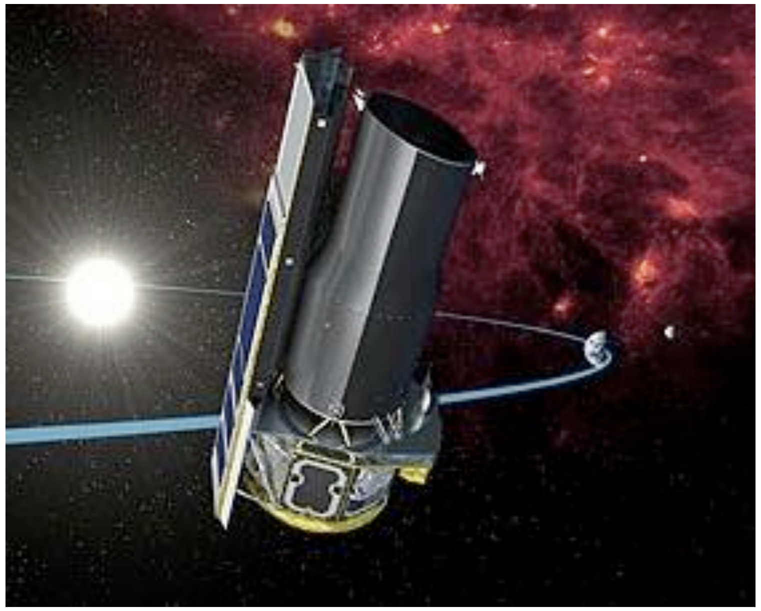


Aries: PI Don McCarthy

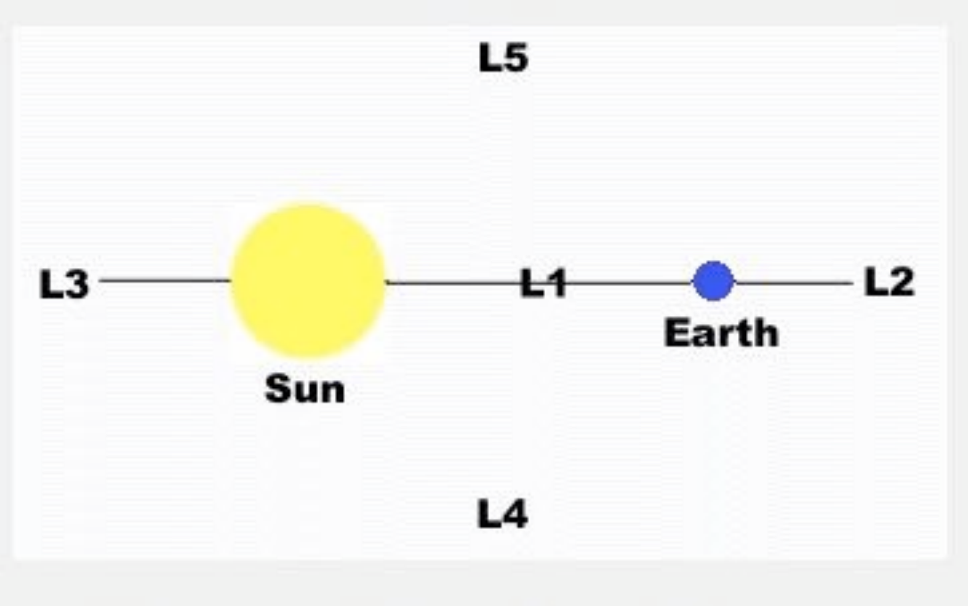
Spitzer Space Telescope

0.85m telescope

3 cryo-cooled instruments
(cover 3-180 microns)



James Webb Space Telescope

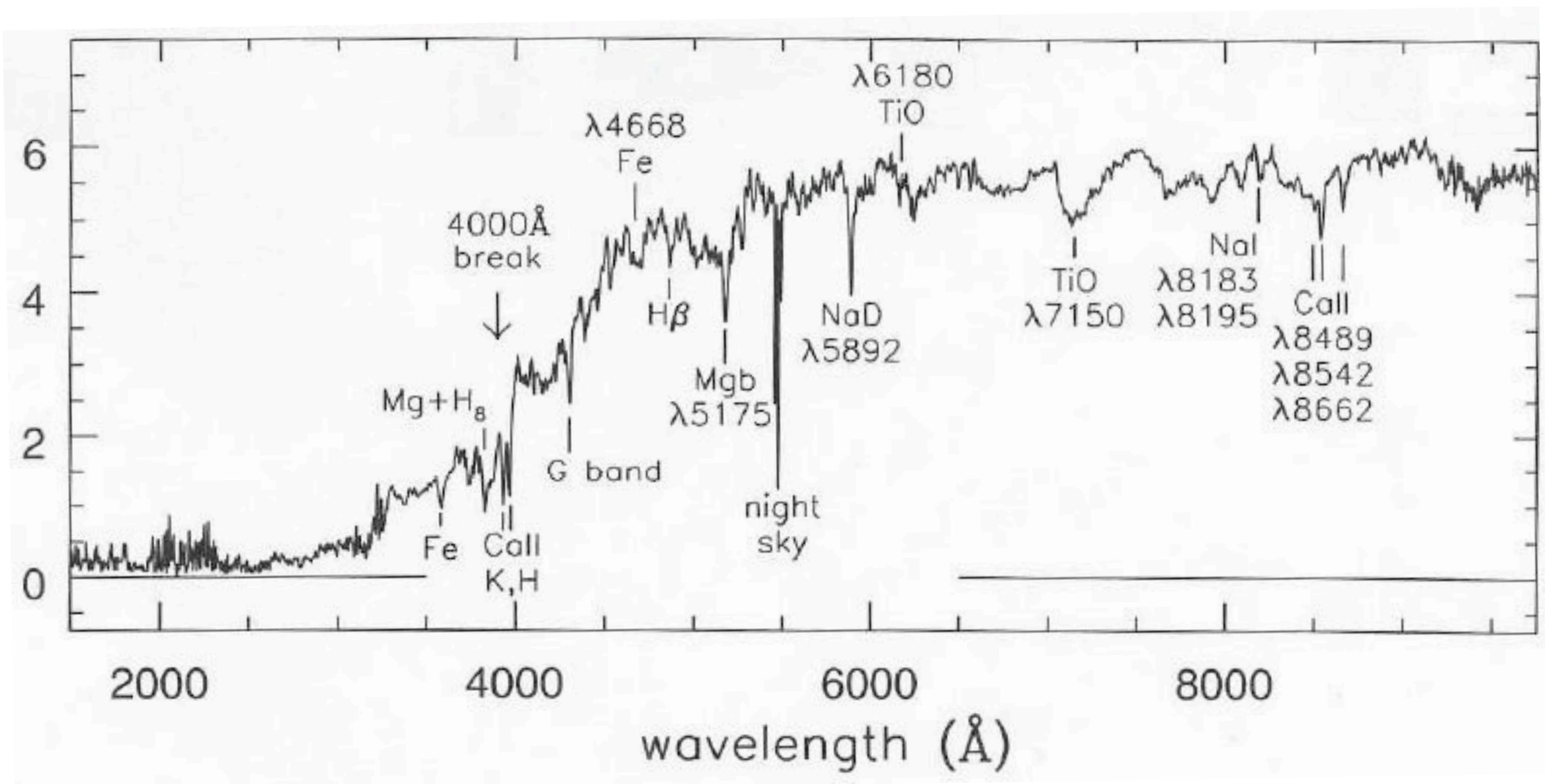


The five Lagrangian points of the Earth-Sun system.

launch 2018

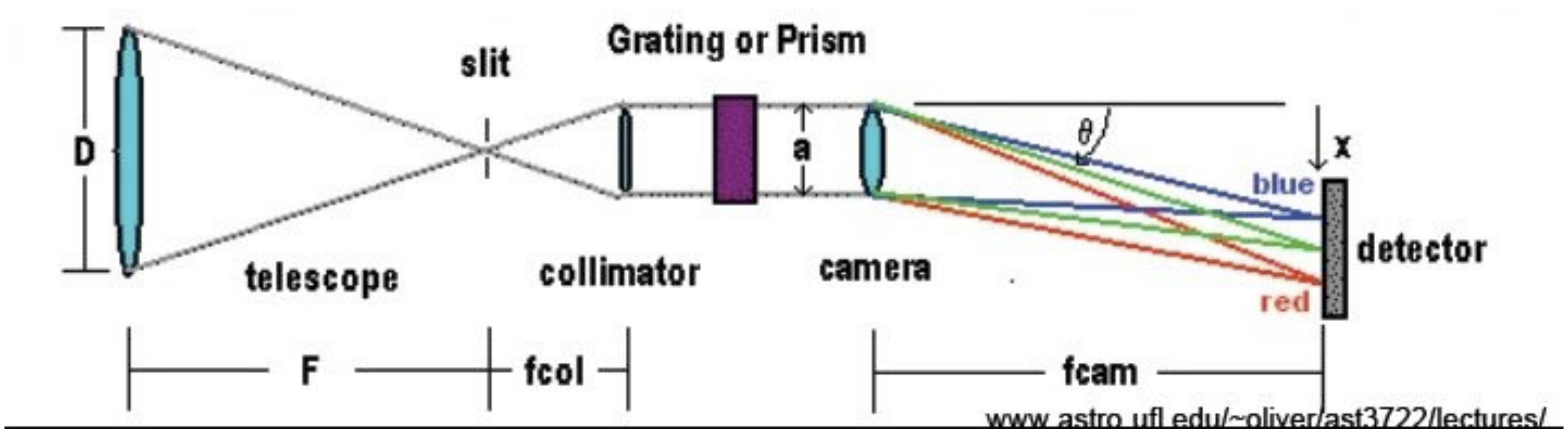
Spectroscopy

What is a (power) spectrum?   What can we learn?



from A. Gonzalez's lectures & http://burro/astr.cwru.edu

Basic spectrograph layout



slit: defines spectrograph image profile, limits sky

collimator: converts diverging beam to parallel

grating/prism: dispersive element

camera: refocuses light to make image of the slit

Characterizing a spectrograph:

dispersion: by how much are different wavelength spread out (determined by dispersive element)

angstroms/mm, angstroms/pixel

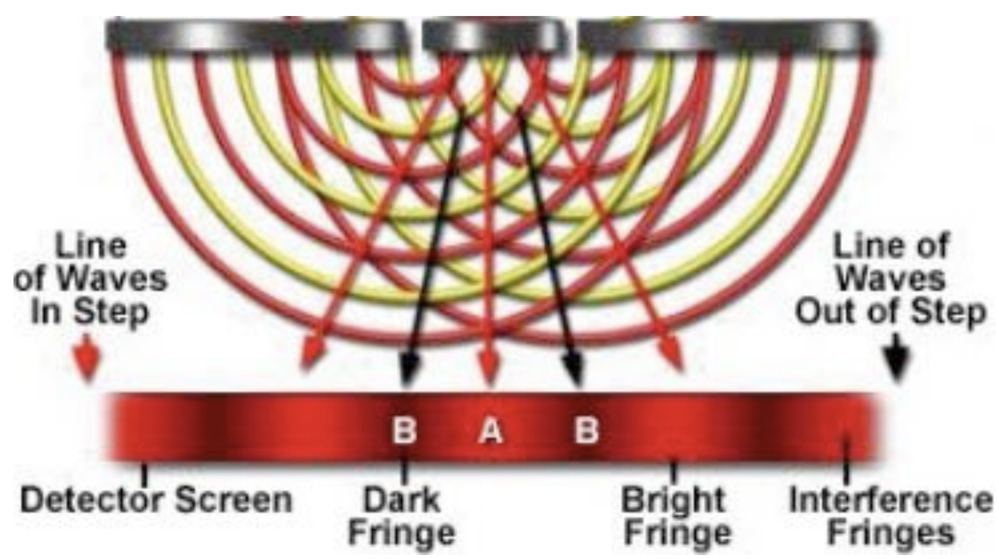
resolution: how well can you measure wavelength differences? Determined by slit, camera, detector, and dispersive element

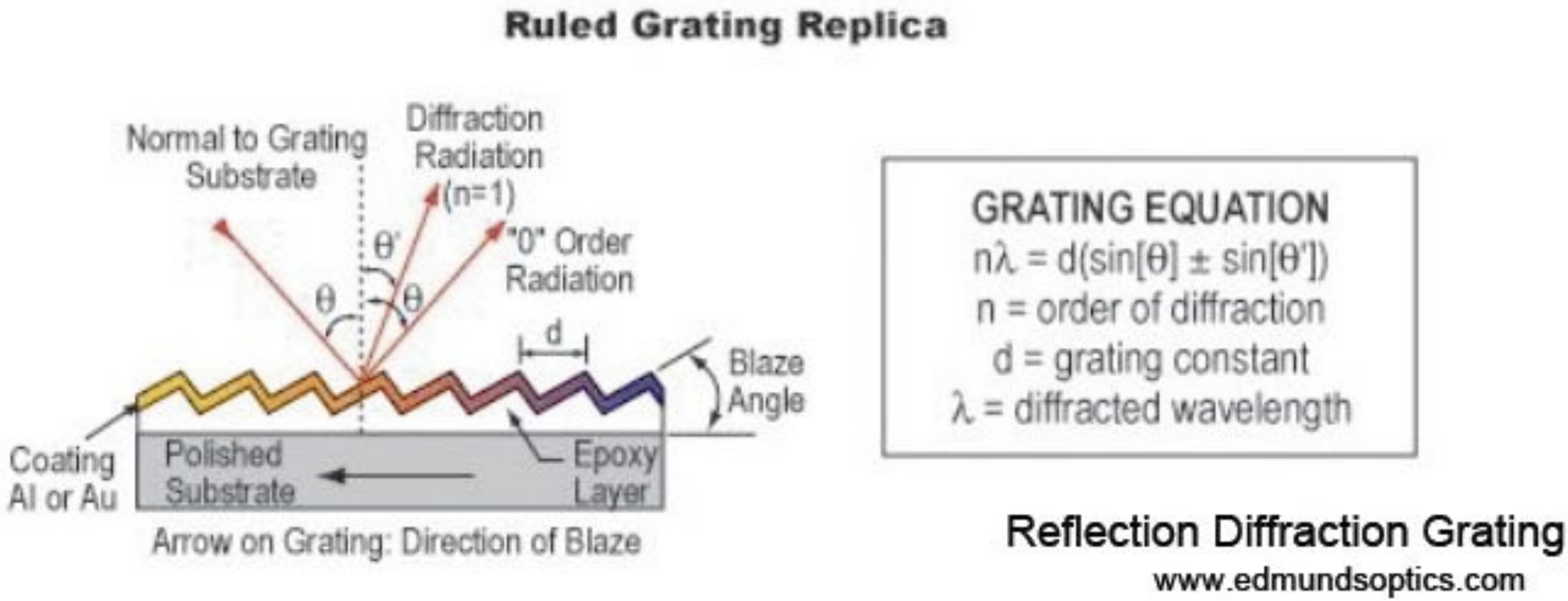
angstroms, relative to wavelength (R values)

Dispersive elements

prisms: limited by range of index of refraction

diffraction gratings : much more flexibility





L = grating effective focal length

$$\frac{d\lambda}{dx} = \frac{Ld\cos\theta}{n}$$

how can you affect resolution?

typical numbers:

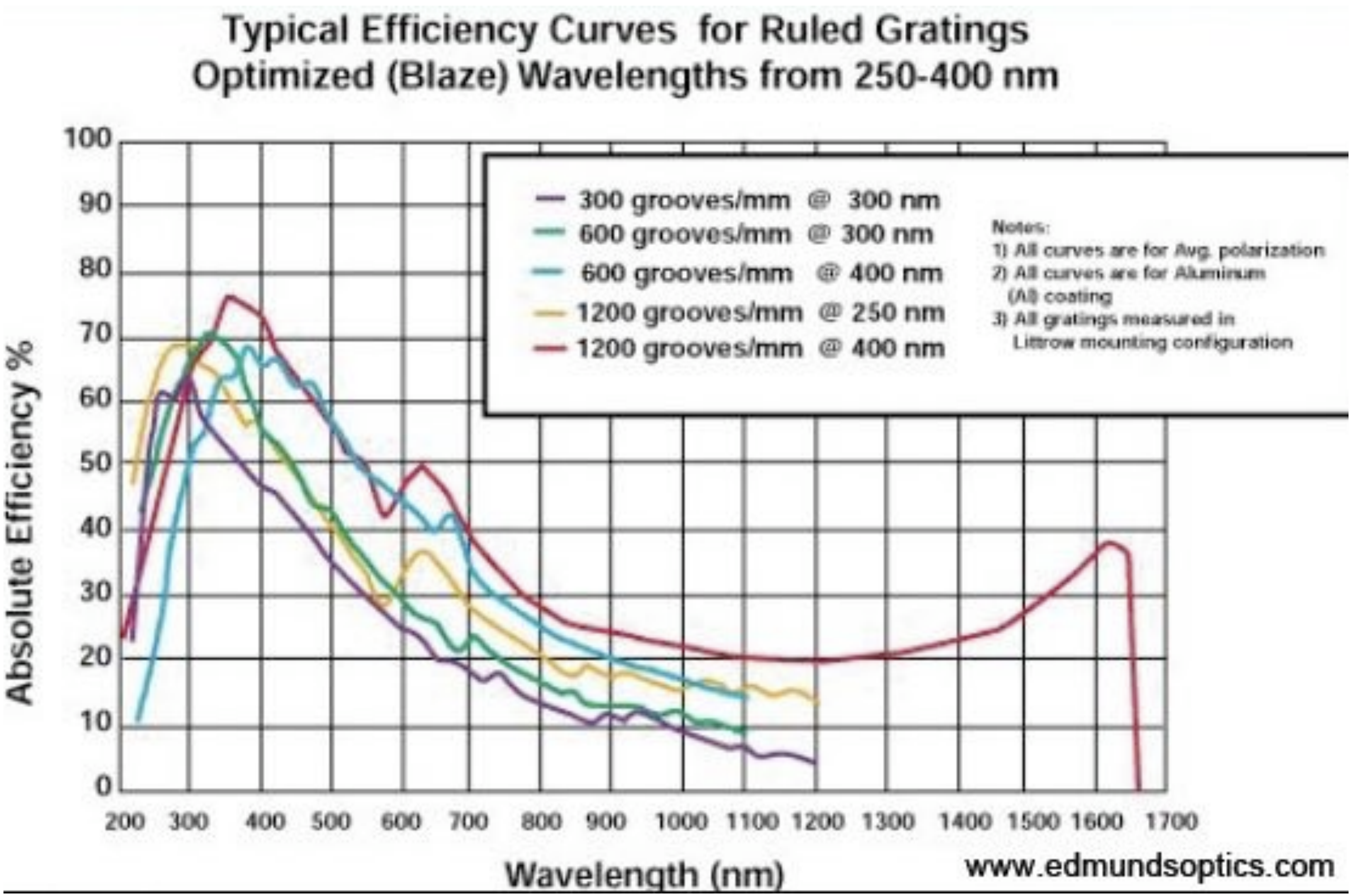
gratings range from few hundred to 1200 lines/mm

typically observing in first order
(other orders blocked or off CCD)

blaze angles are usually low

resolutions are usually few to tens of Angstroms

useful range of an order ~ $\lambda(\mathrm{blaze})/n$



Typical Efficiency Curves for Ruled Gratings
Optimized (Blaze) Wavelengths from 250-400 nm
300 grooves/mm @ 300 nm
600 grooves/mm @ 300 nm
600 grooves/mm @ 400 nm
1200 grooves/mm @ 250 nm
1200 grooves/mm @ 400 nm
Notes:
1) All curves are for Avg. polarization
2) All curves are for Aluminum (Al) coating
3) All gratings measured in Littrow mounting configuration
Absolute Efficiency %
0
10
20
30
40
50
60
70
80
90
100
200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700
Wavelength (nm)
www.edmundsoptics.com

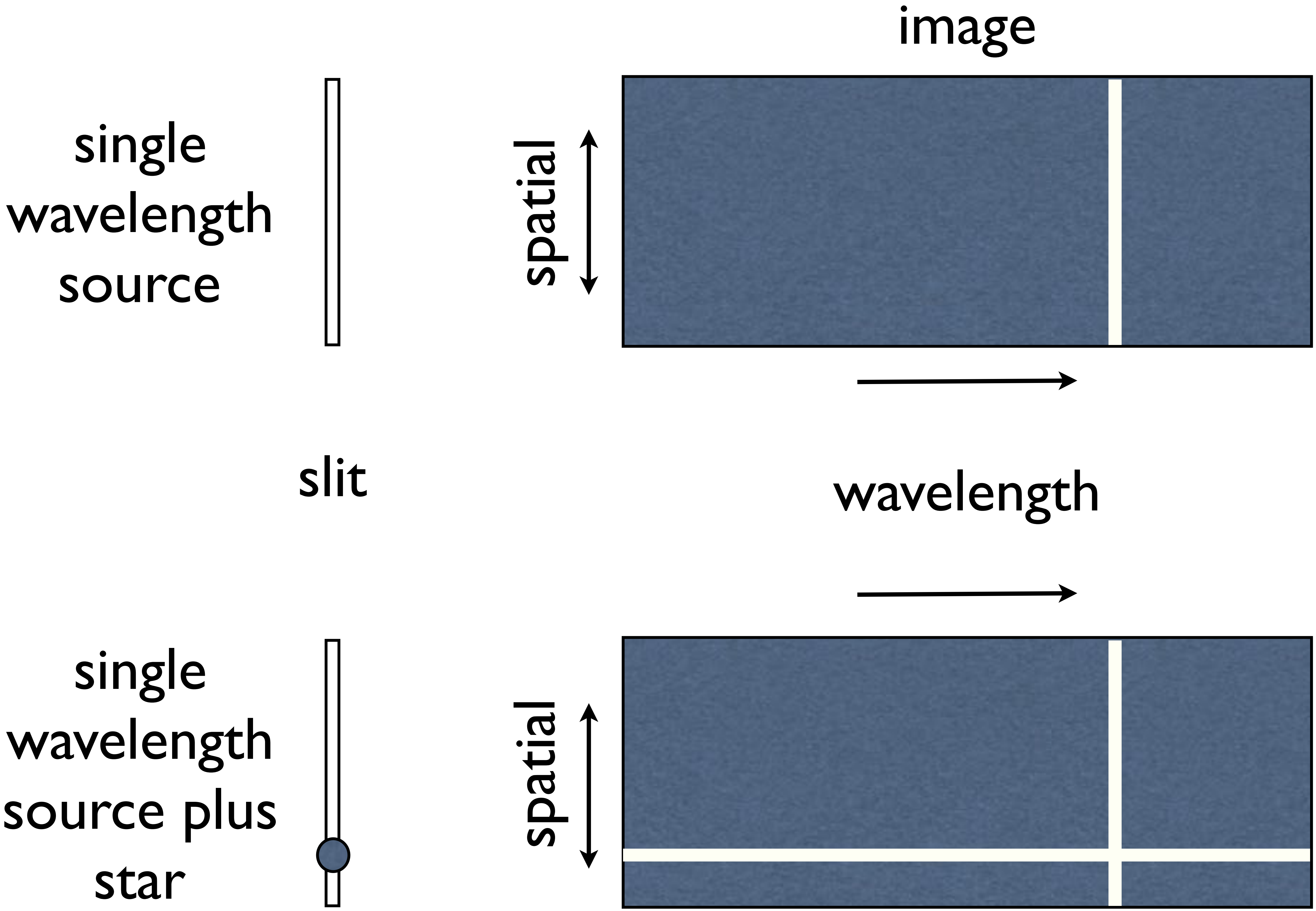


image
single wavelength source
spatial
slit
wavelength
single wavelength source plus star
spatial

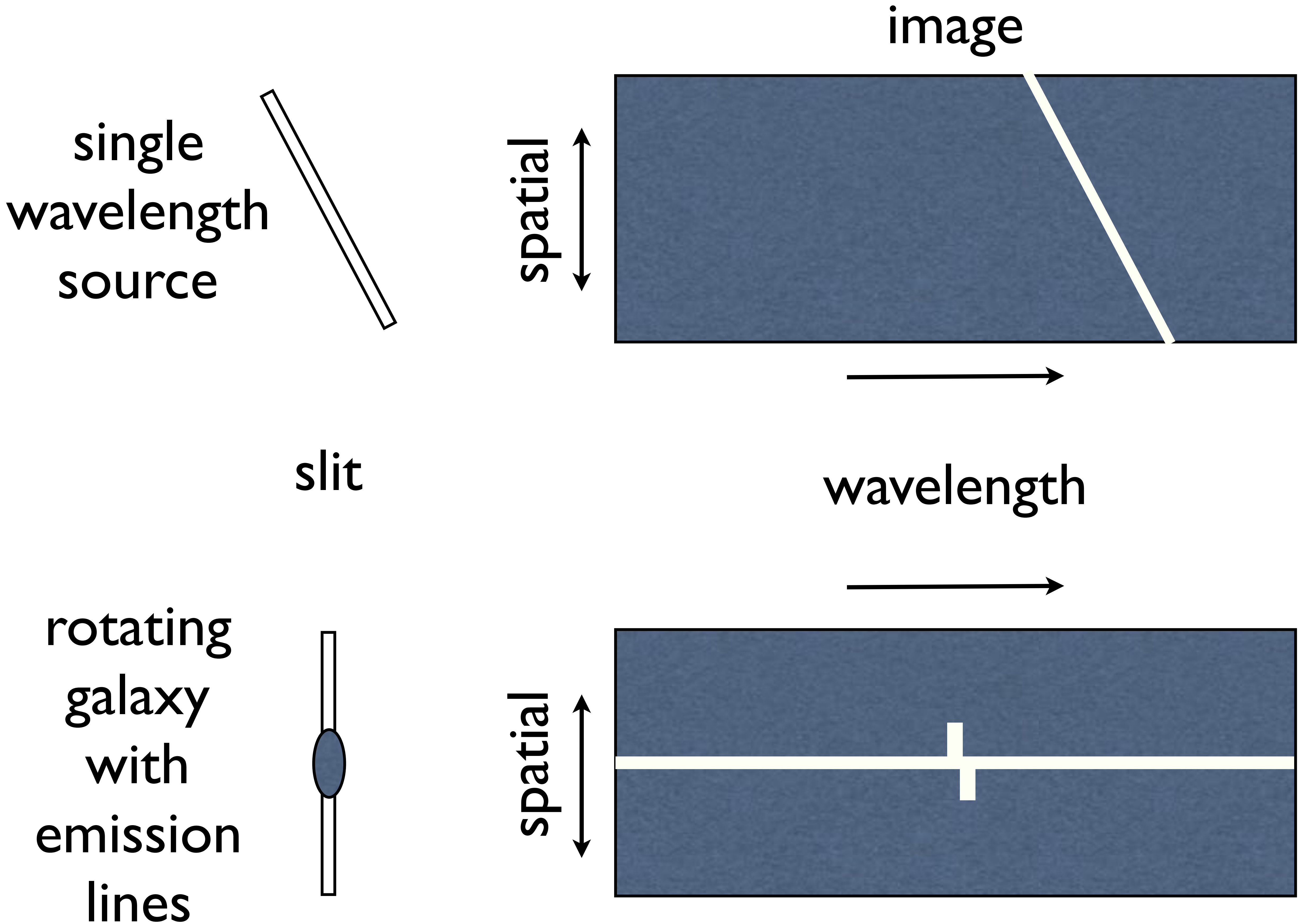


image
single
wavelength
source
spatial
slit
wavelength
rotating
galaxy
with
emission
lines
spatial

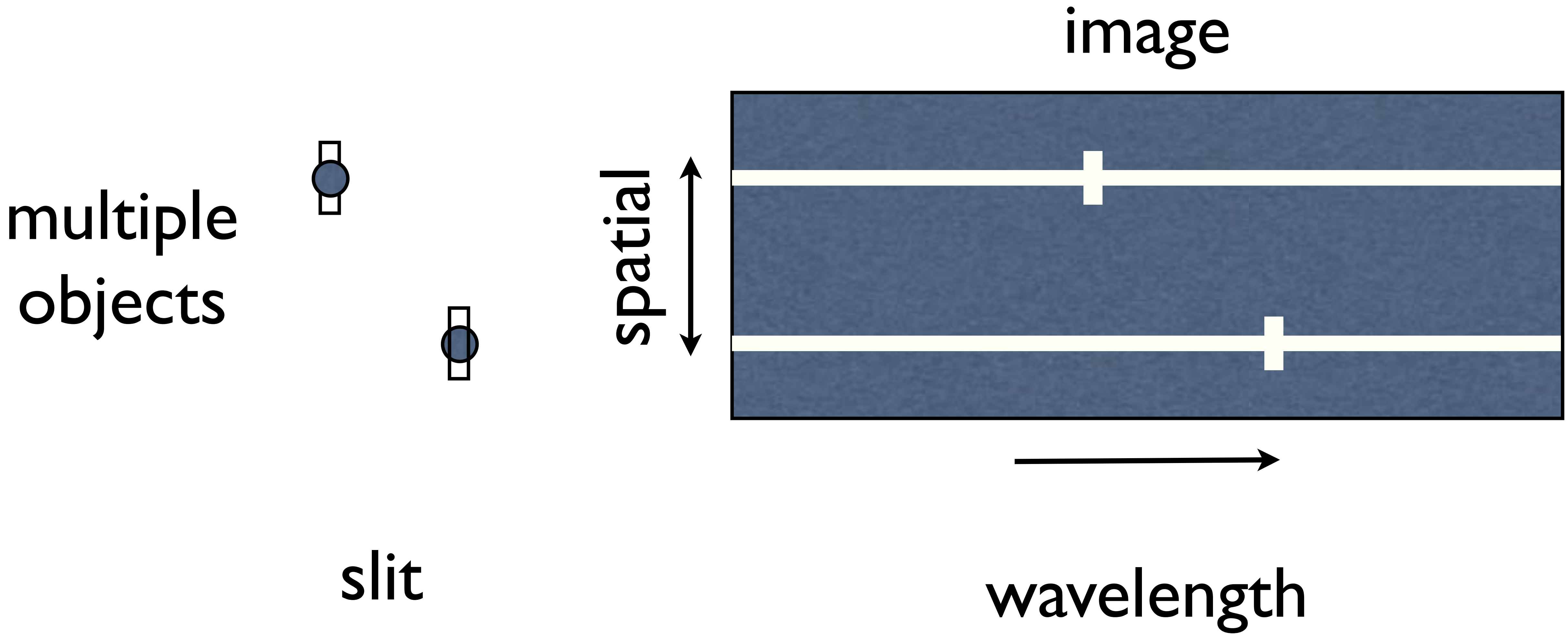
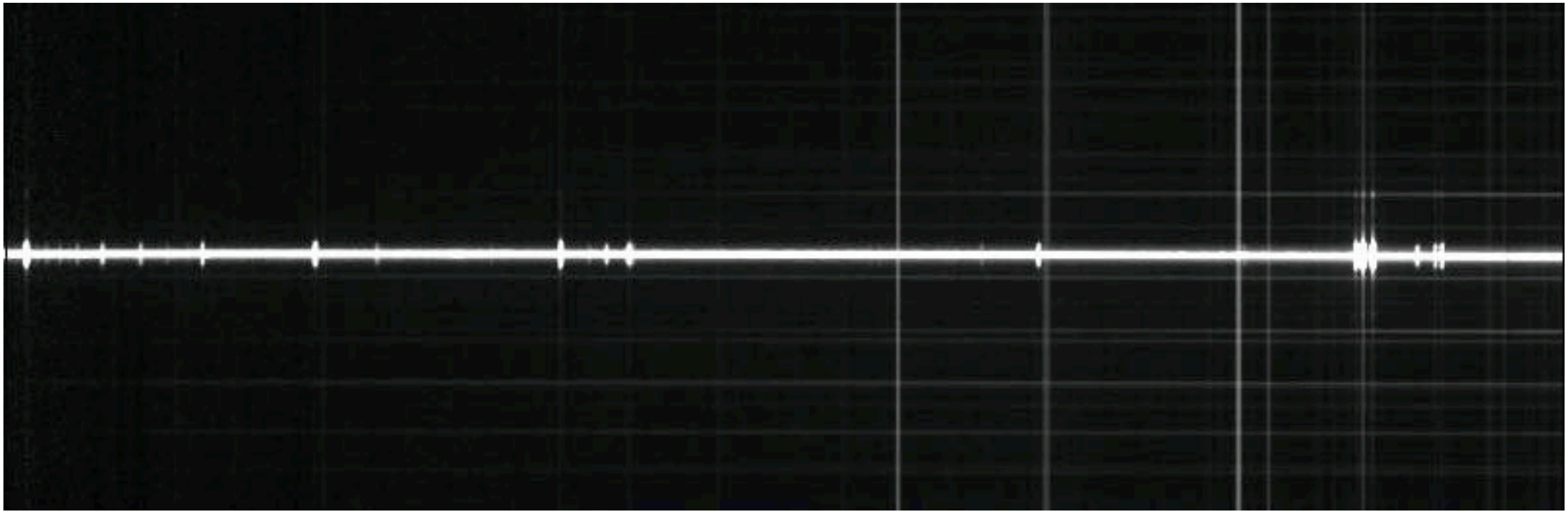


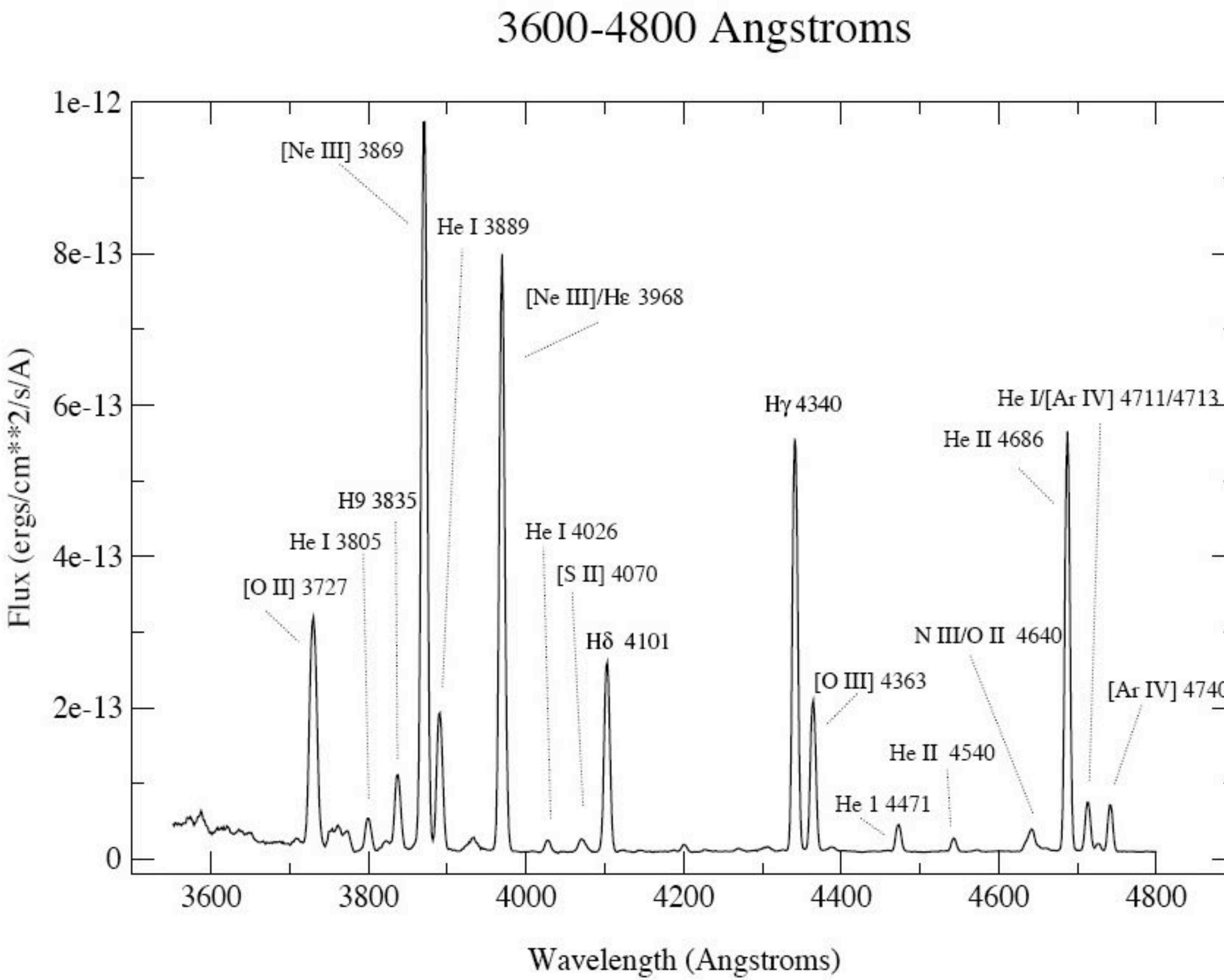
image
multiple objects
spatial
slit
wavelength



planetary nebula spectrum

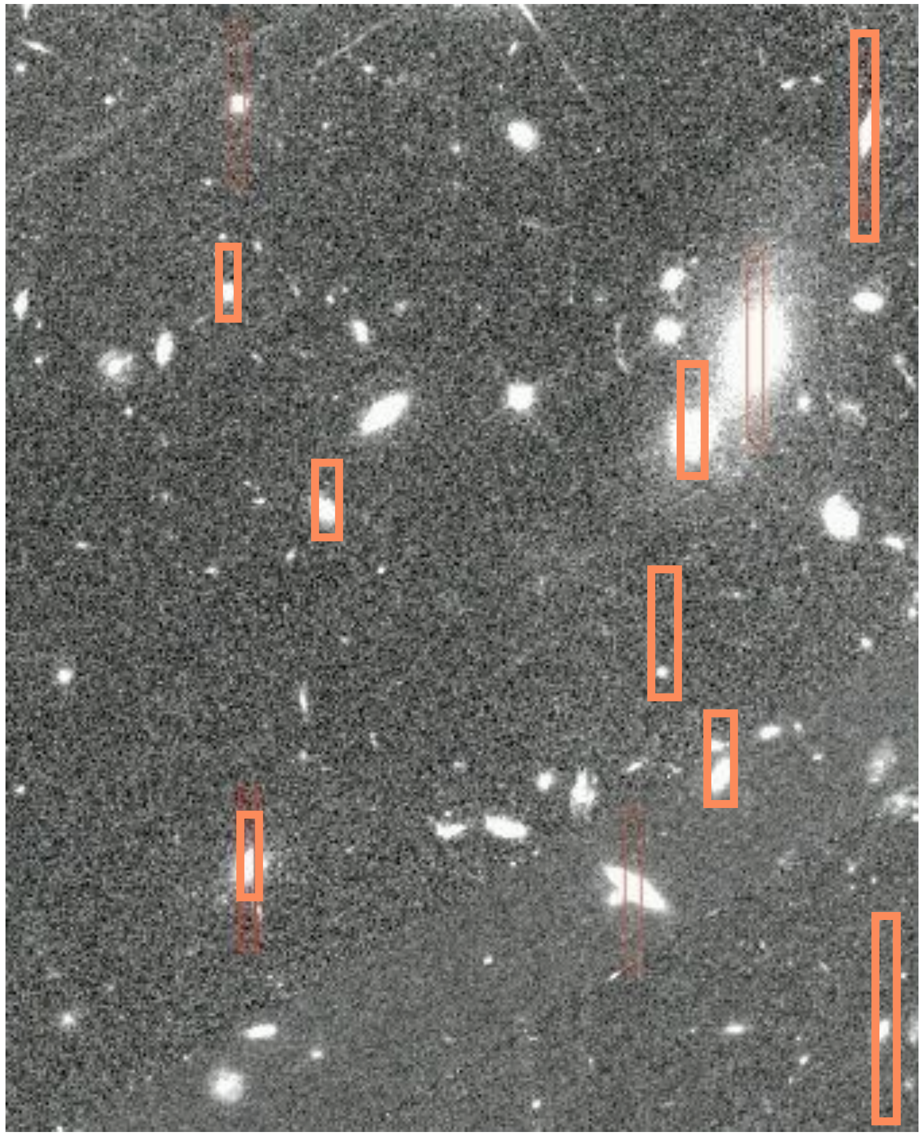
http://www.chara.gsu.edu/~cantrell/m146.htm

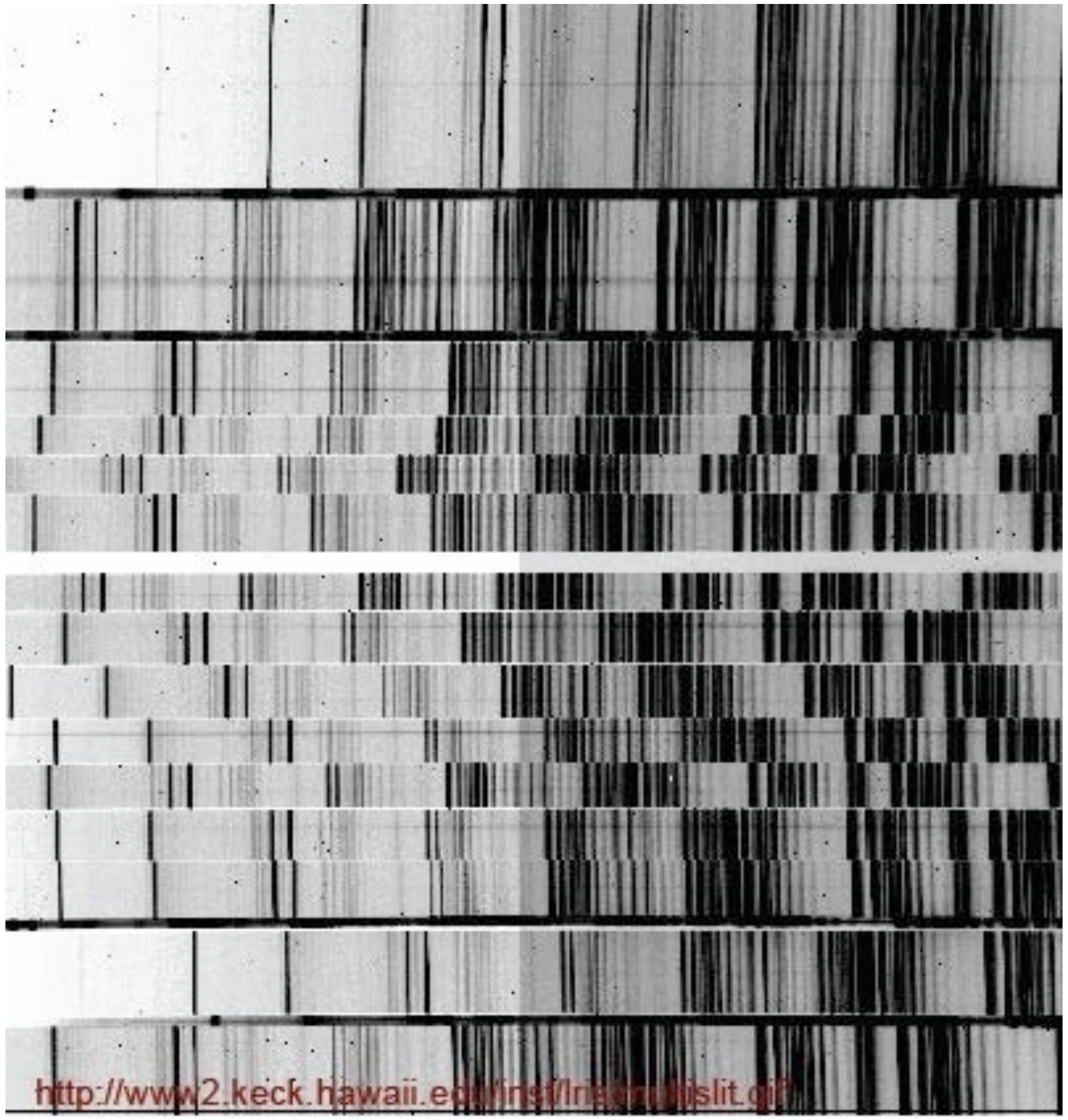
(not the same spectrum as previous slide)



http://oit.williams.edu/nebulae/PDF/template1.pdf

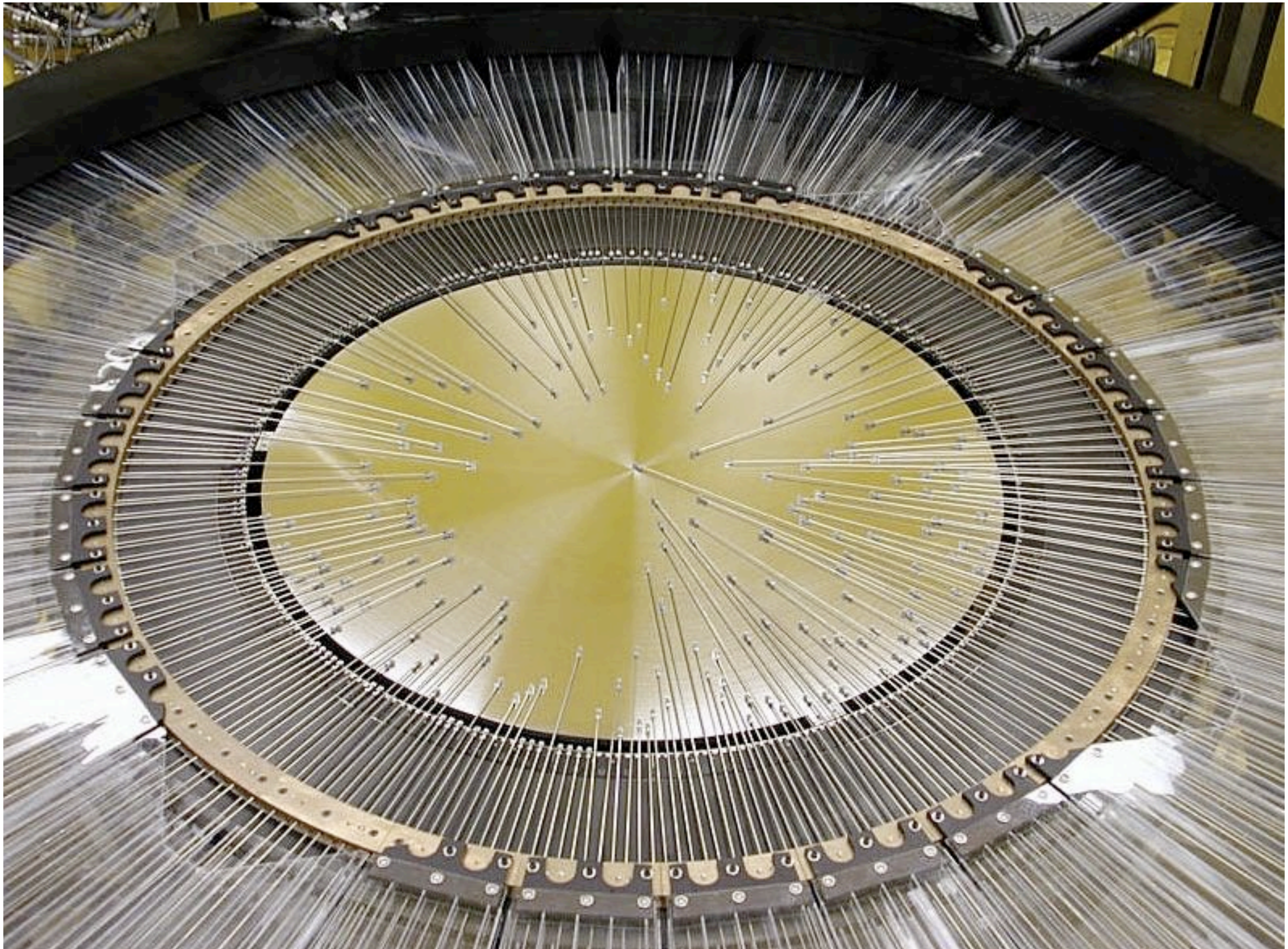
Multiobject Spectrographs

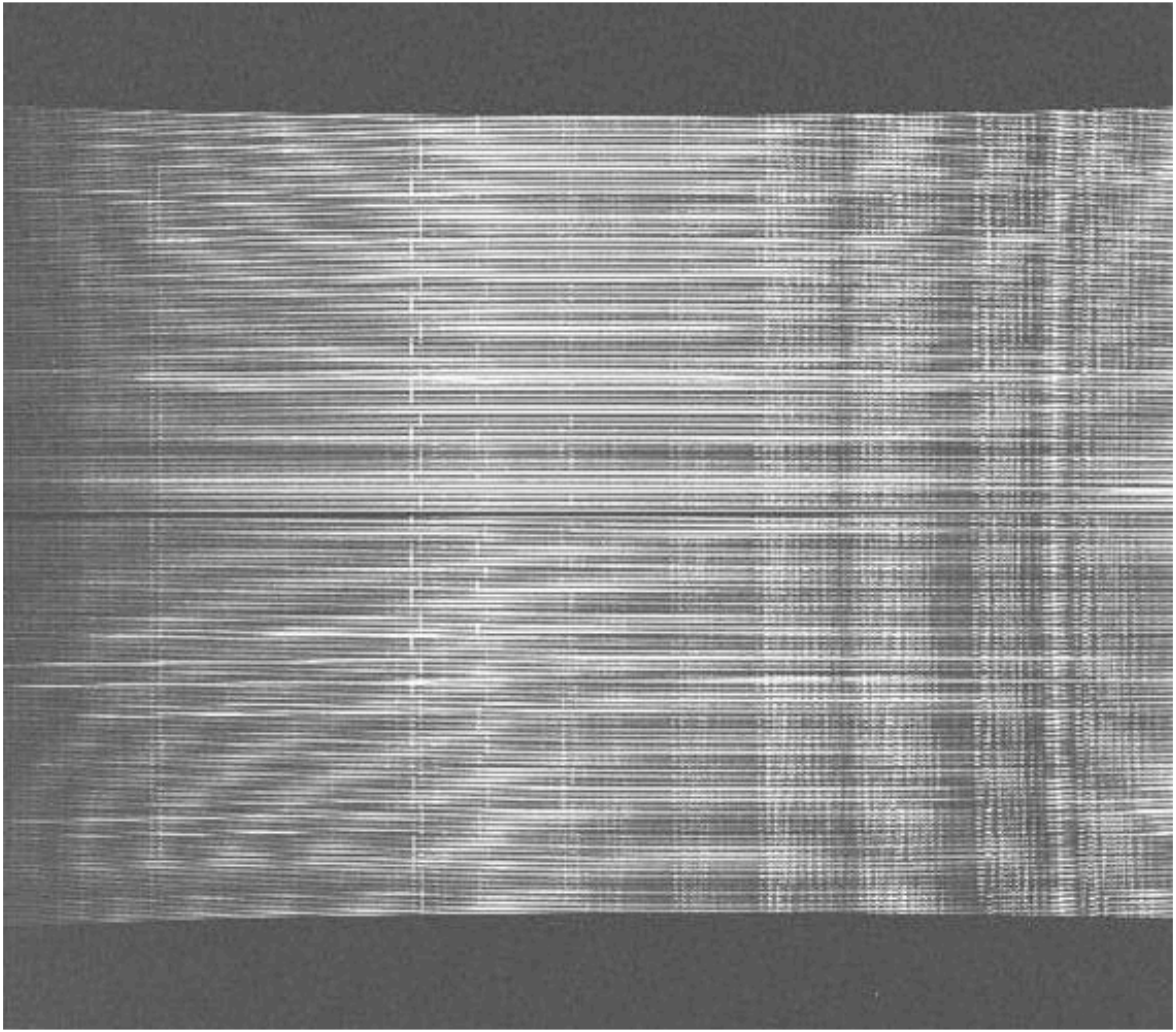




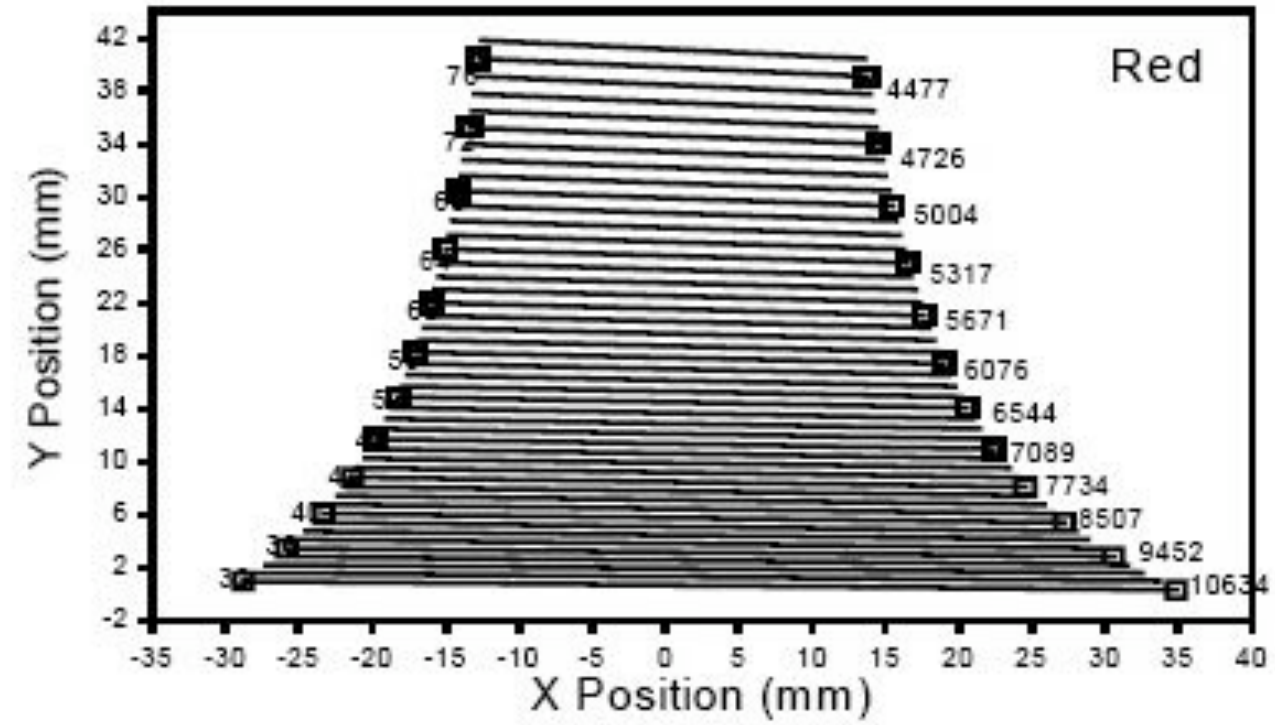
(these don't correspond, just done for example)

hectospec (at MMT)





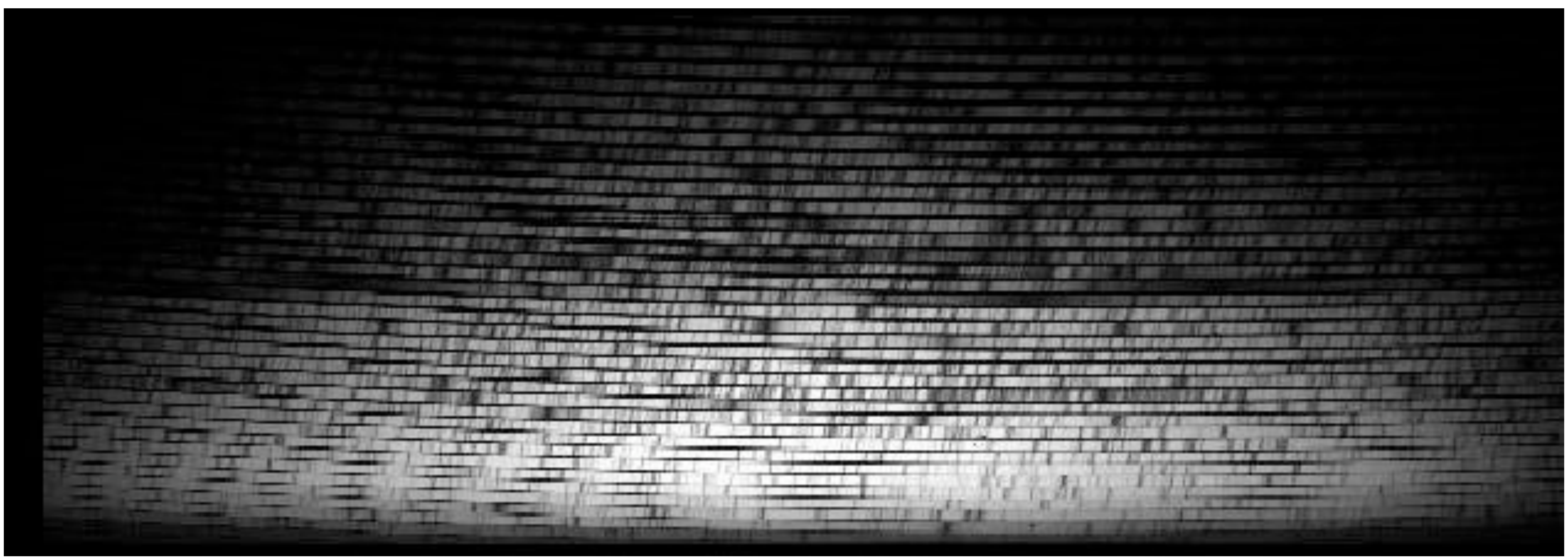
High-resolution Spectroscopy



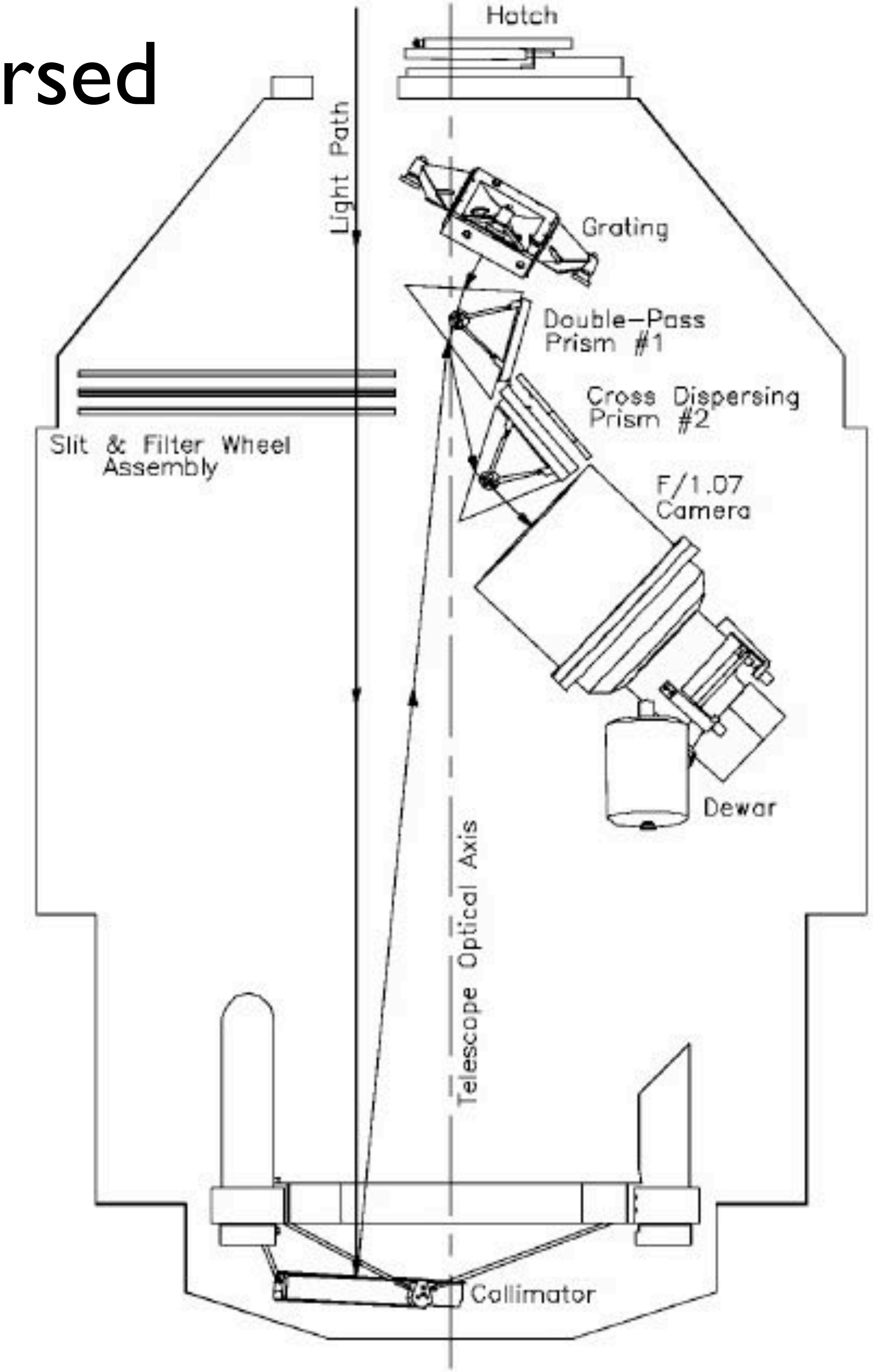
special Echelle gratings

high blaze angles, observe in very high order

typically cross disperse to get more coverage



an example of a cross-dispersed spectrograph

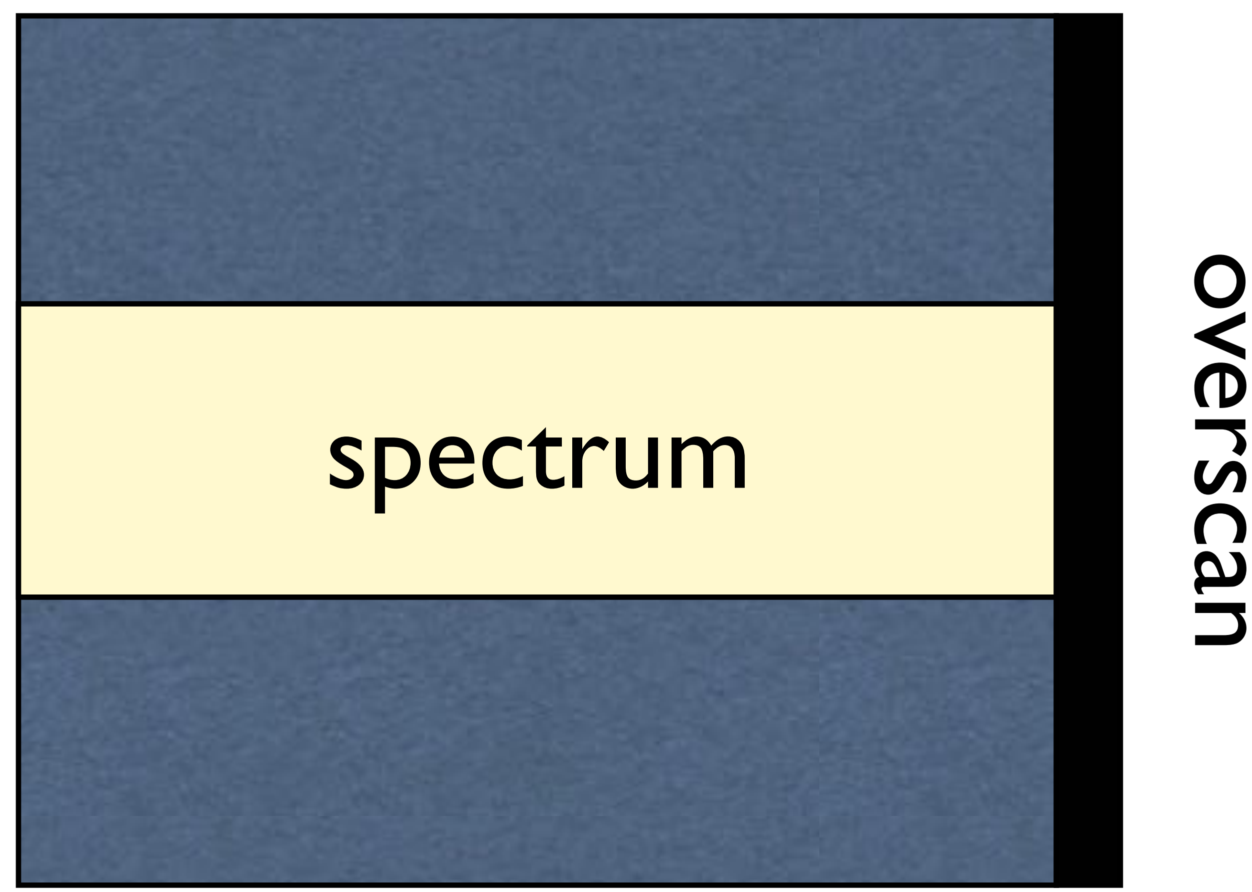


ESI at Keck

Spectroscopic Data Reduction

spectra usually not full CCD

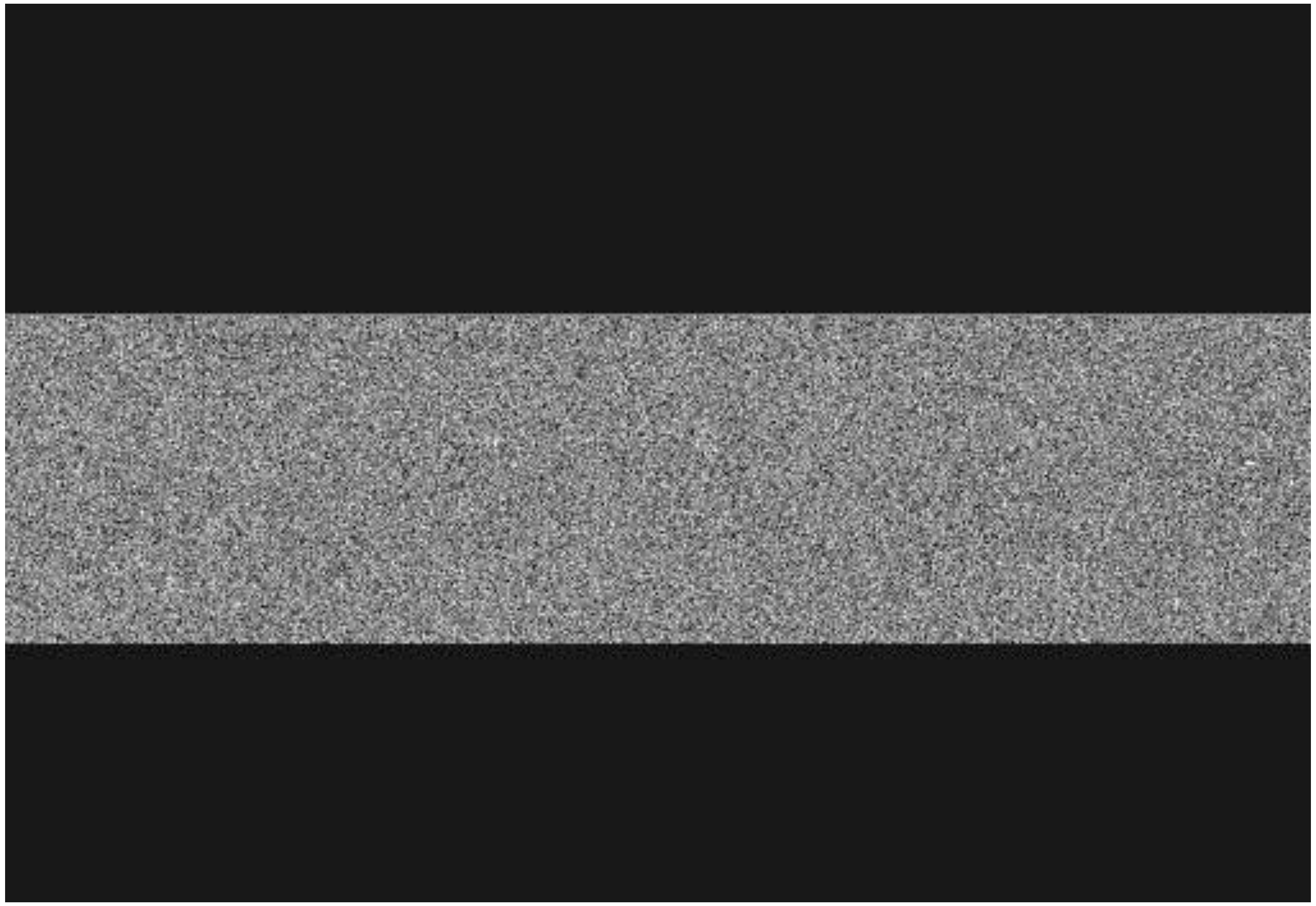
sometimes trimmed & binned at telescope



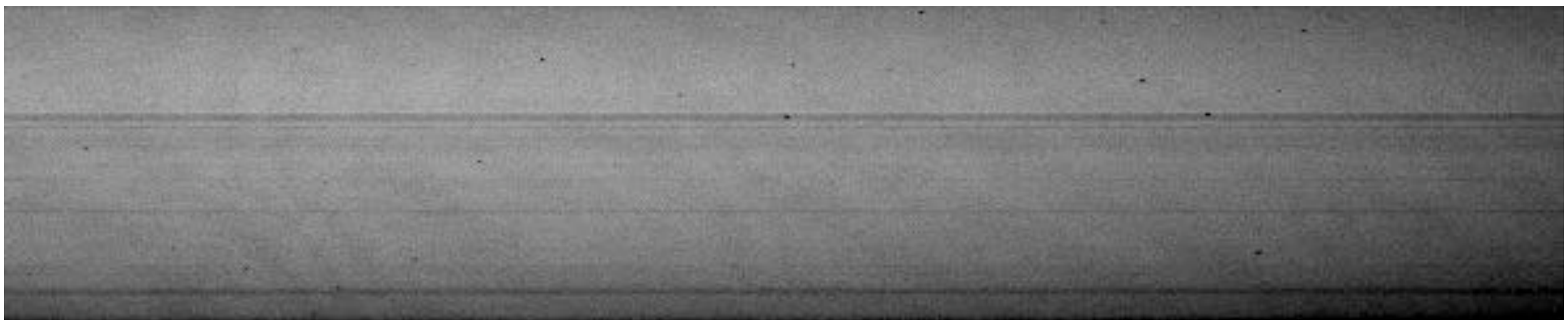
1) debias and trim

use same tasks as with images (colbias,linebias)

2-D bias subtraction, if necessary



2) flat field

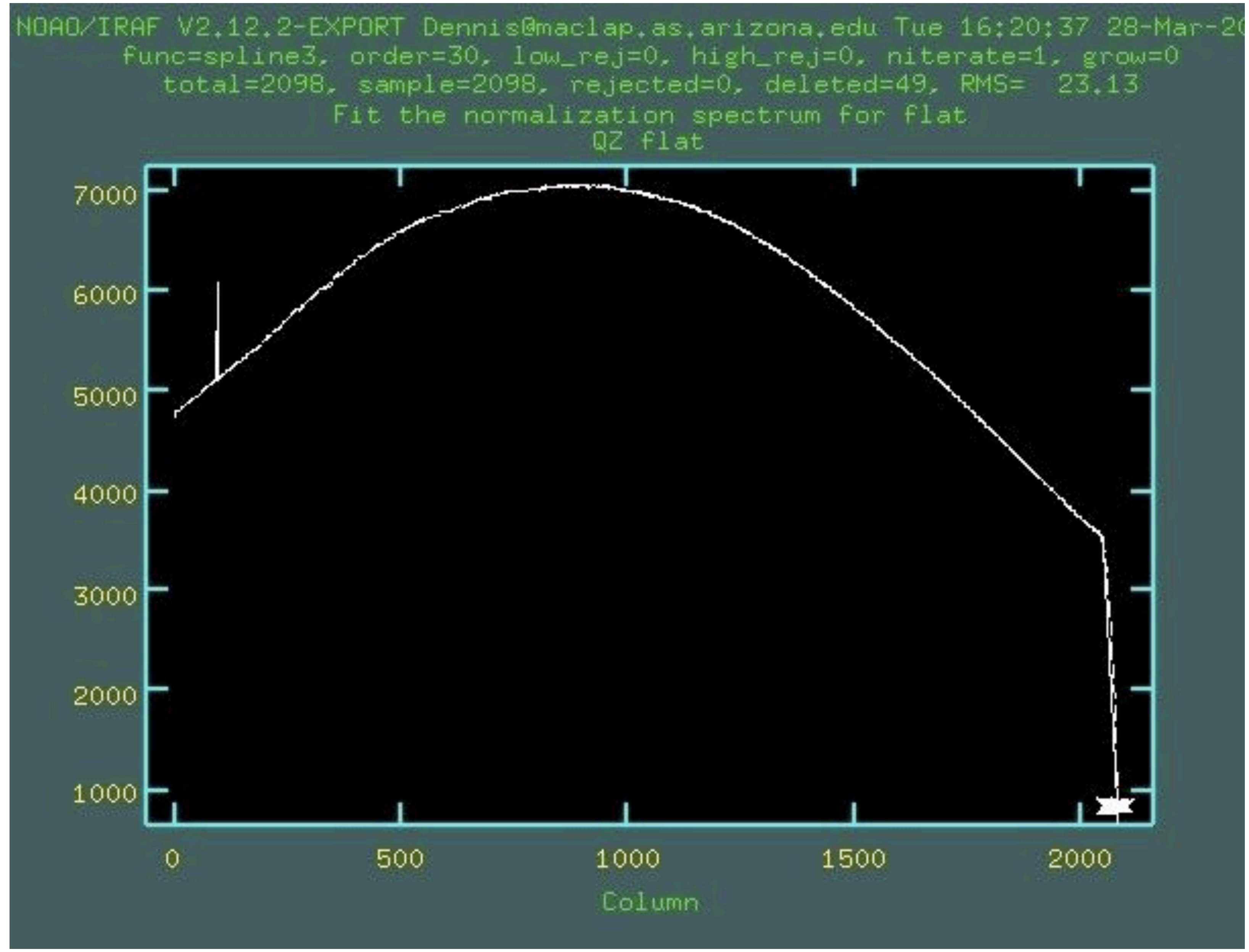


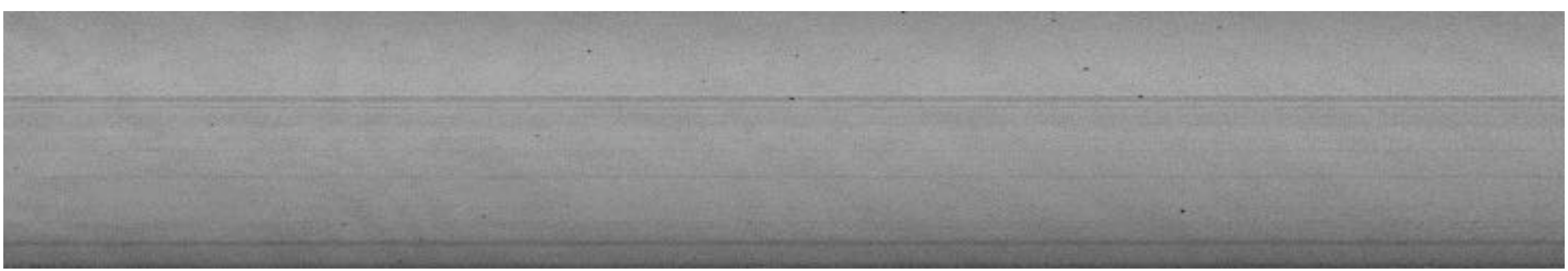
usually internal or in the dome

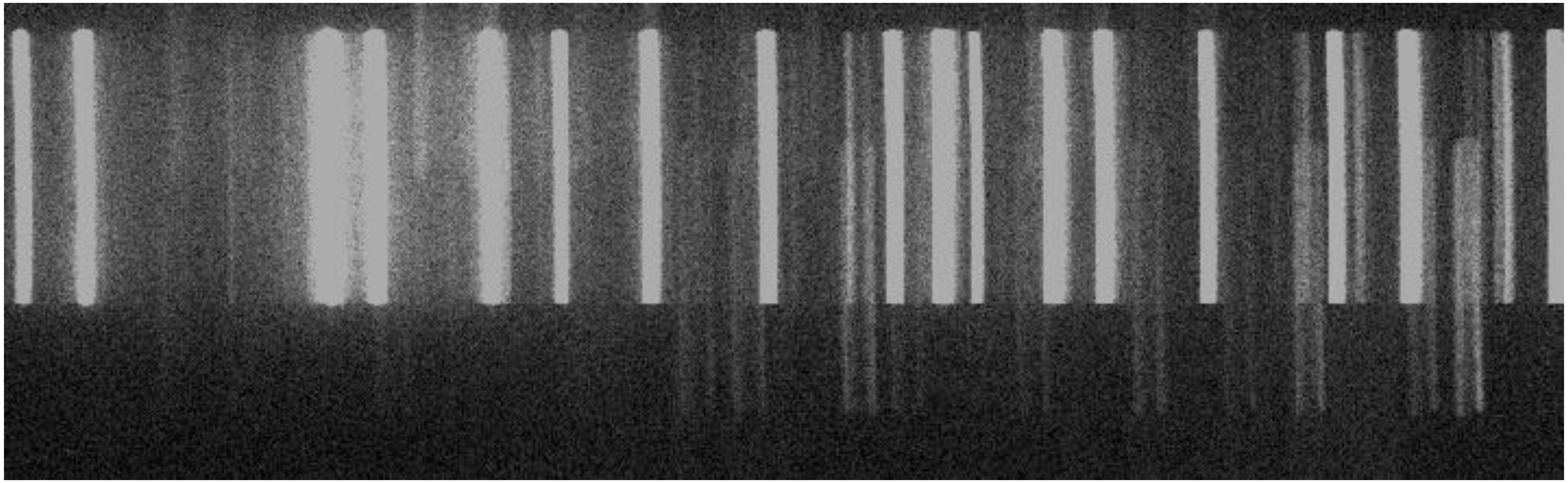
need to remove lamp spectral shape

also see horizontal banding due to slit imperfections

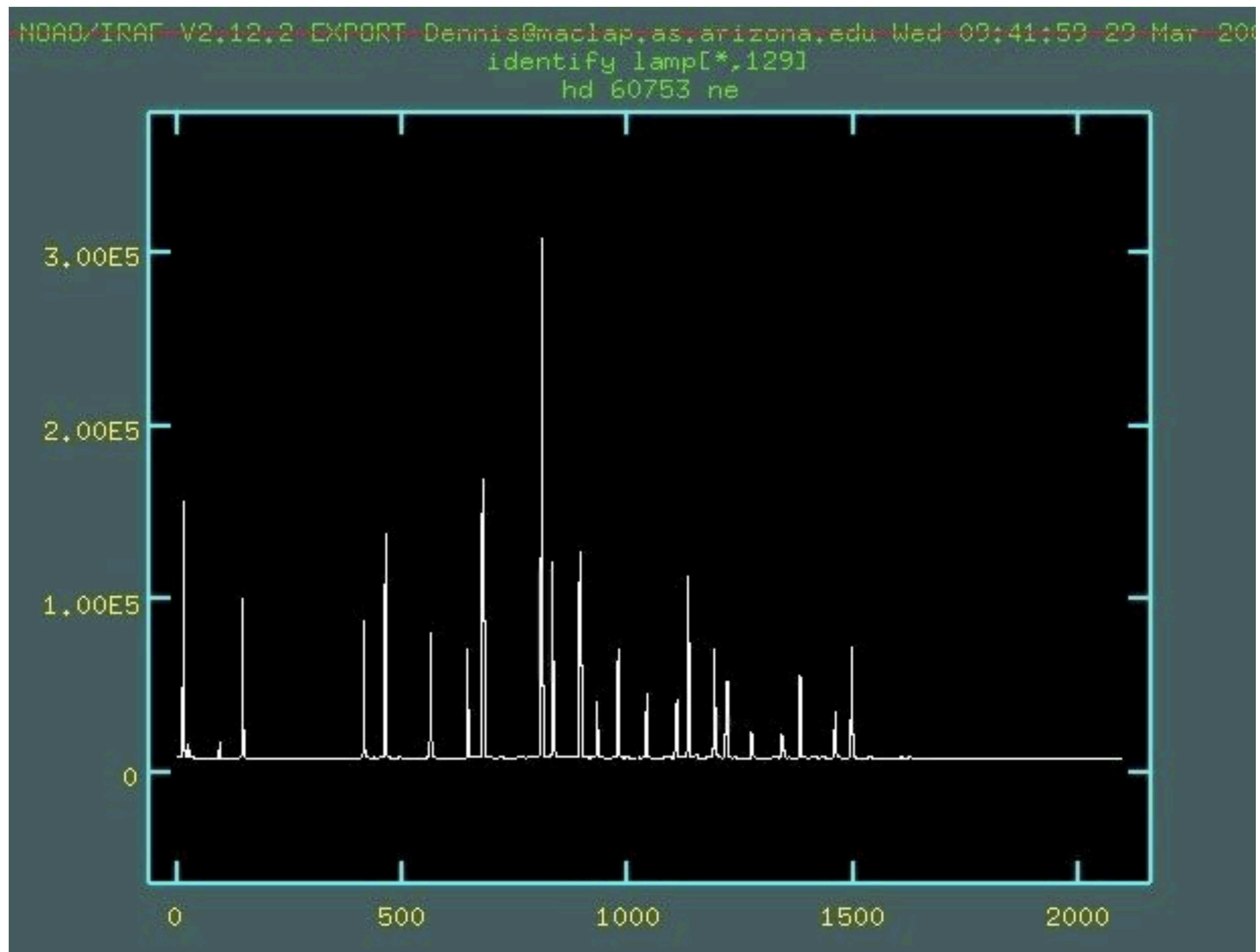
twod.long.response



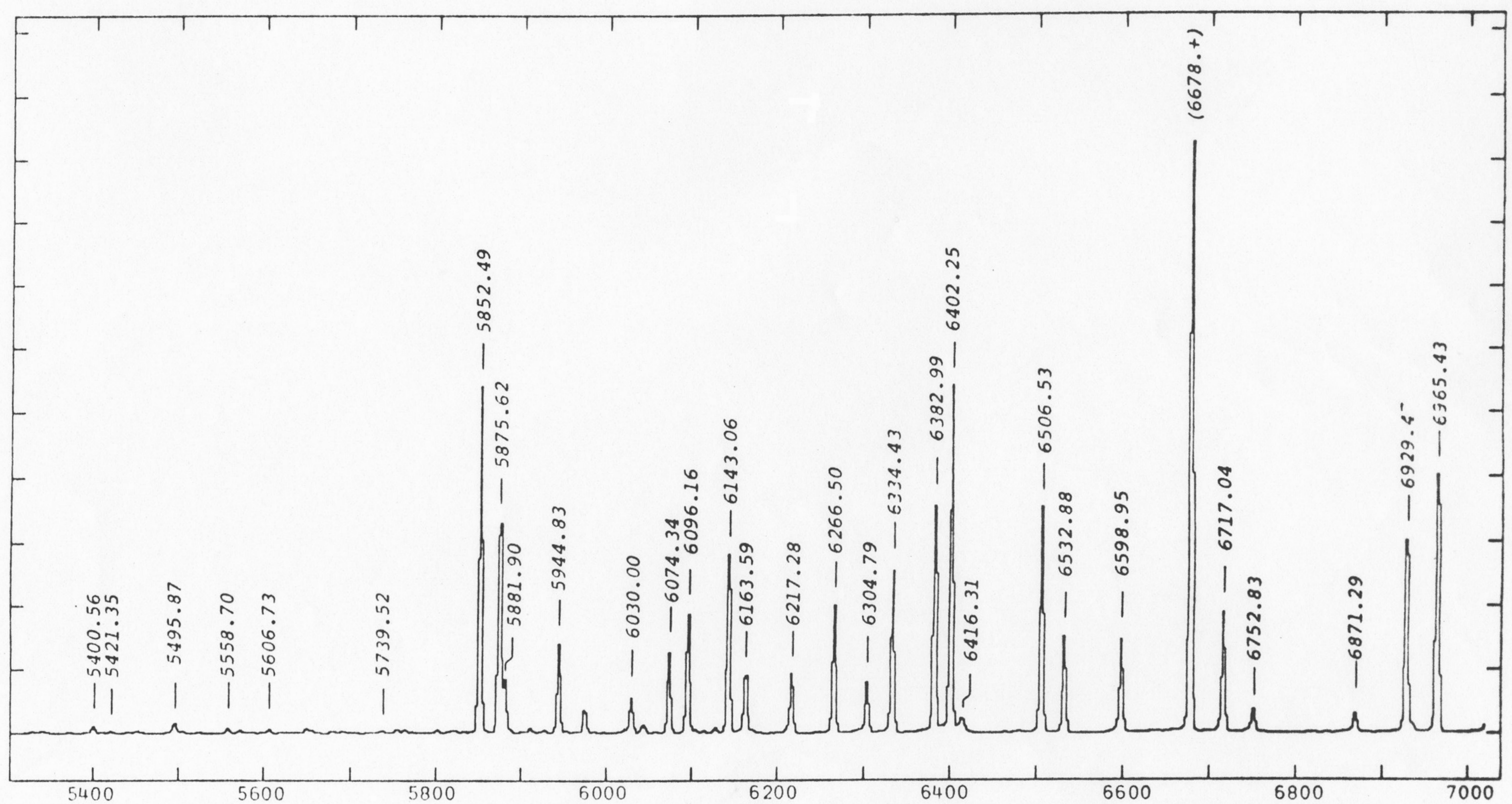




3) wavelength calibration

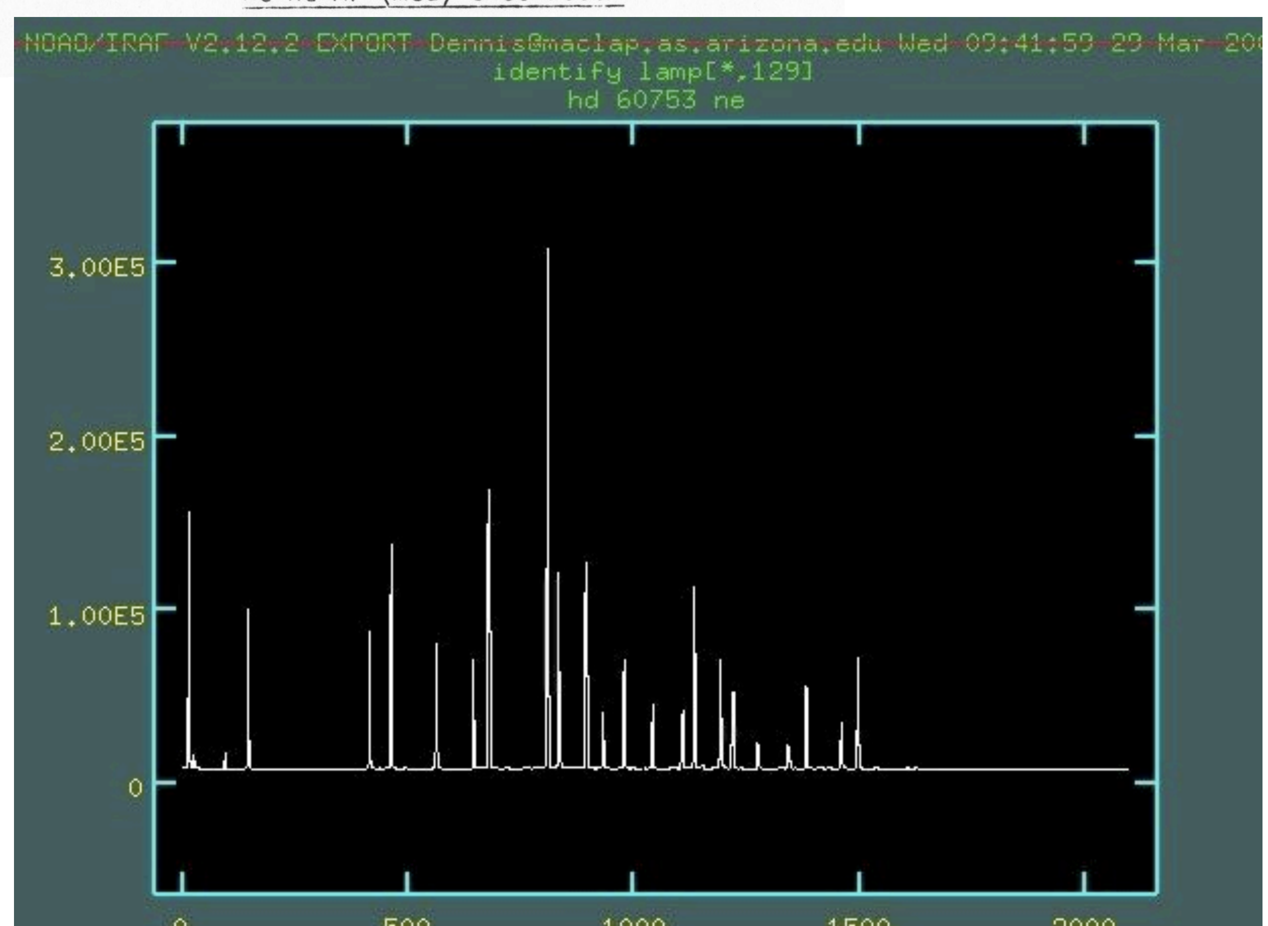


identify & reidentify

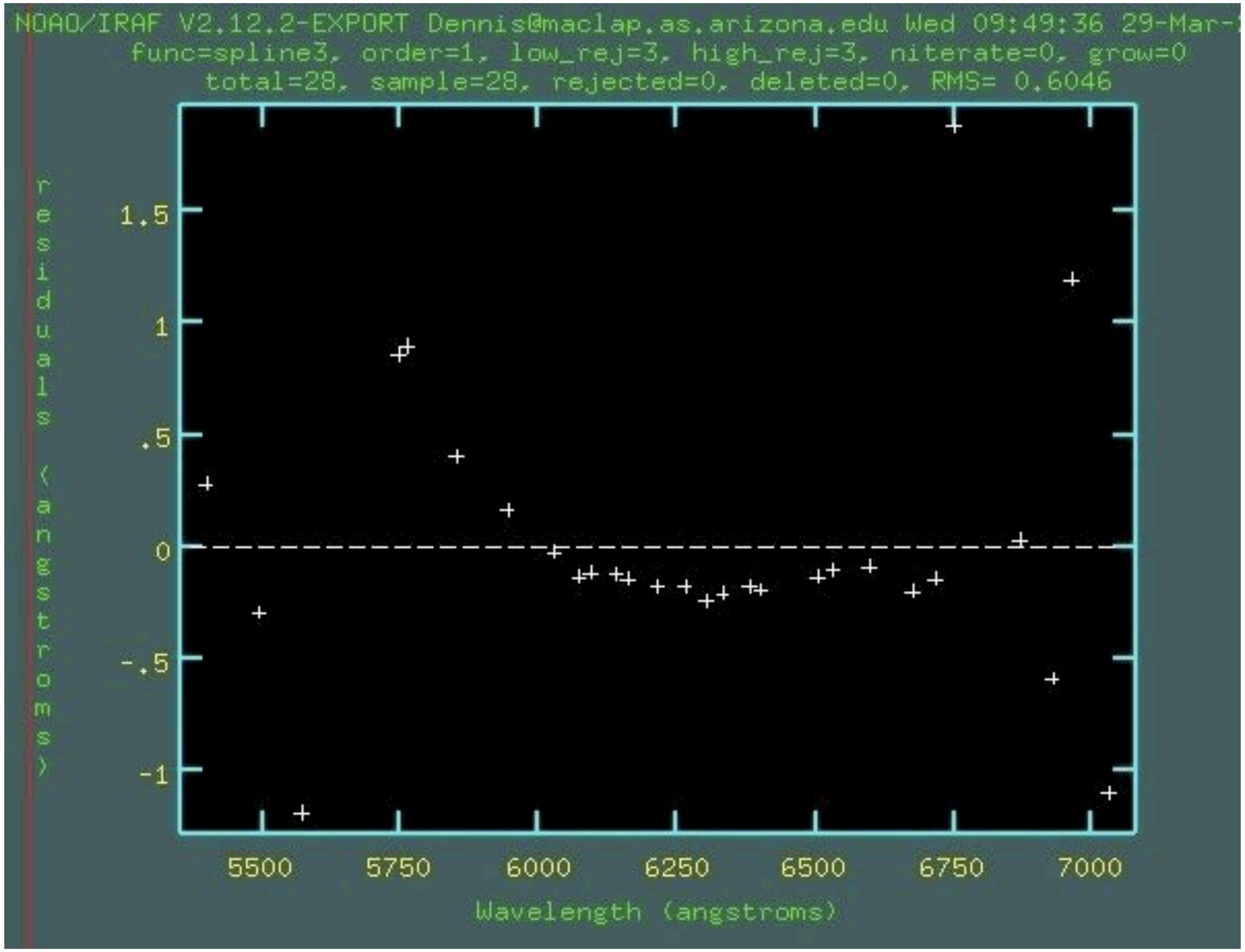


He-Ne-Ar (med) 5400-7000A

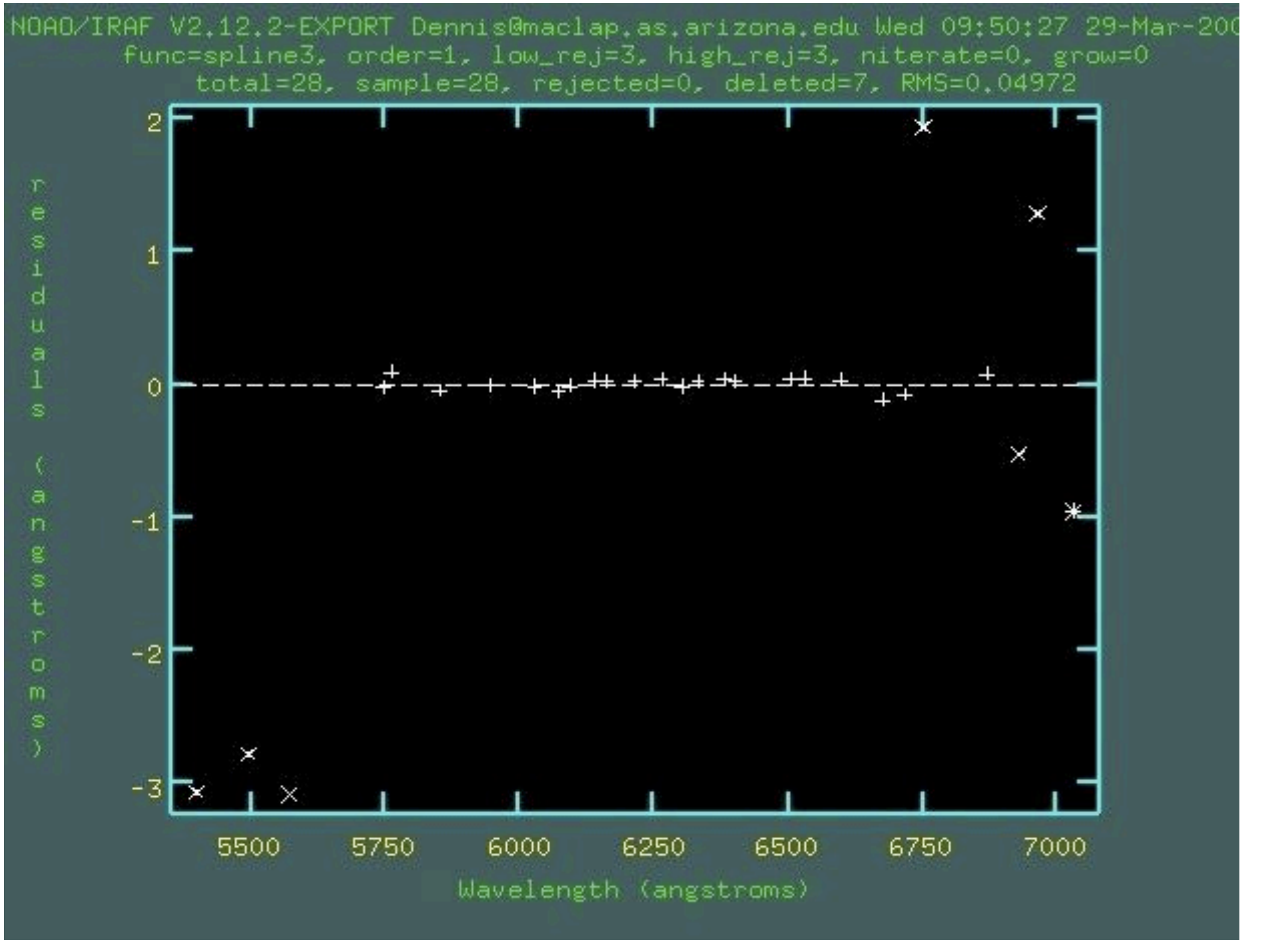
match calibration spectrum to yours



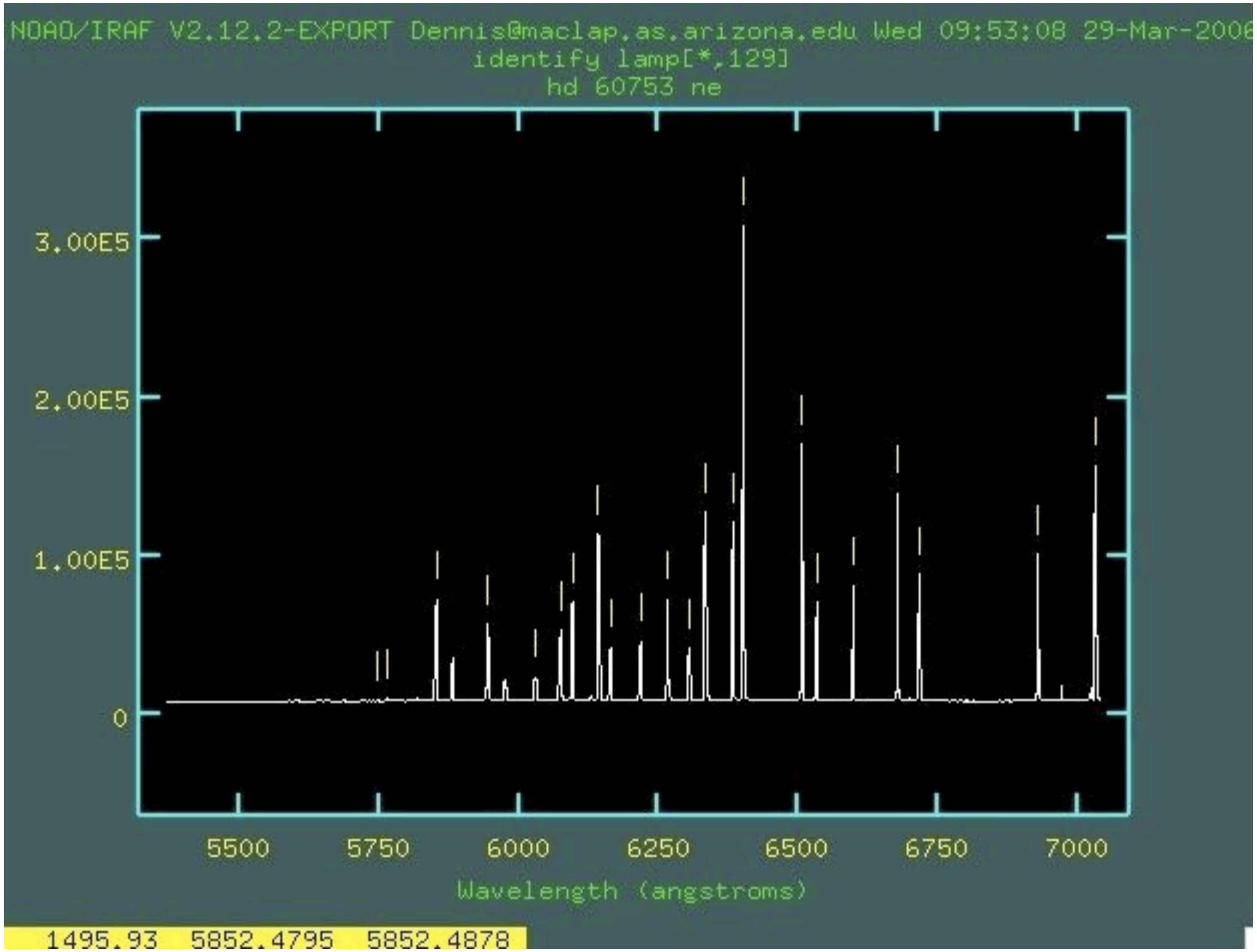
first attempt: mark a few lines and then use ‘l’ command to find other lines



remove outliers and refit



also try changing function & order, then iterate



now run reidentify to apply this solution to various rows across your 2-D lamp spectrum

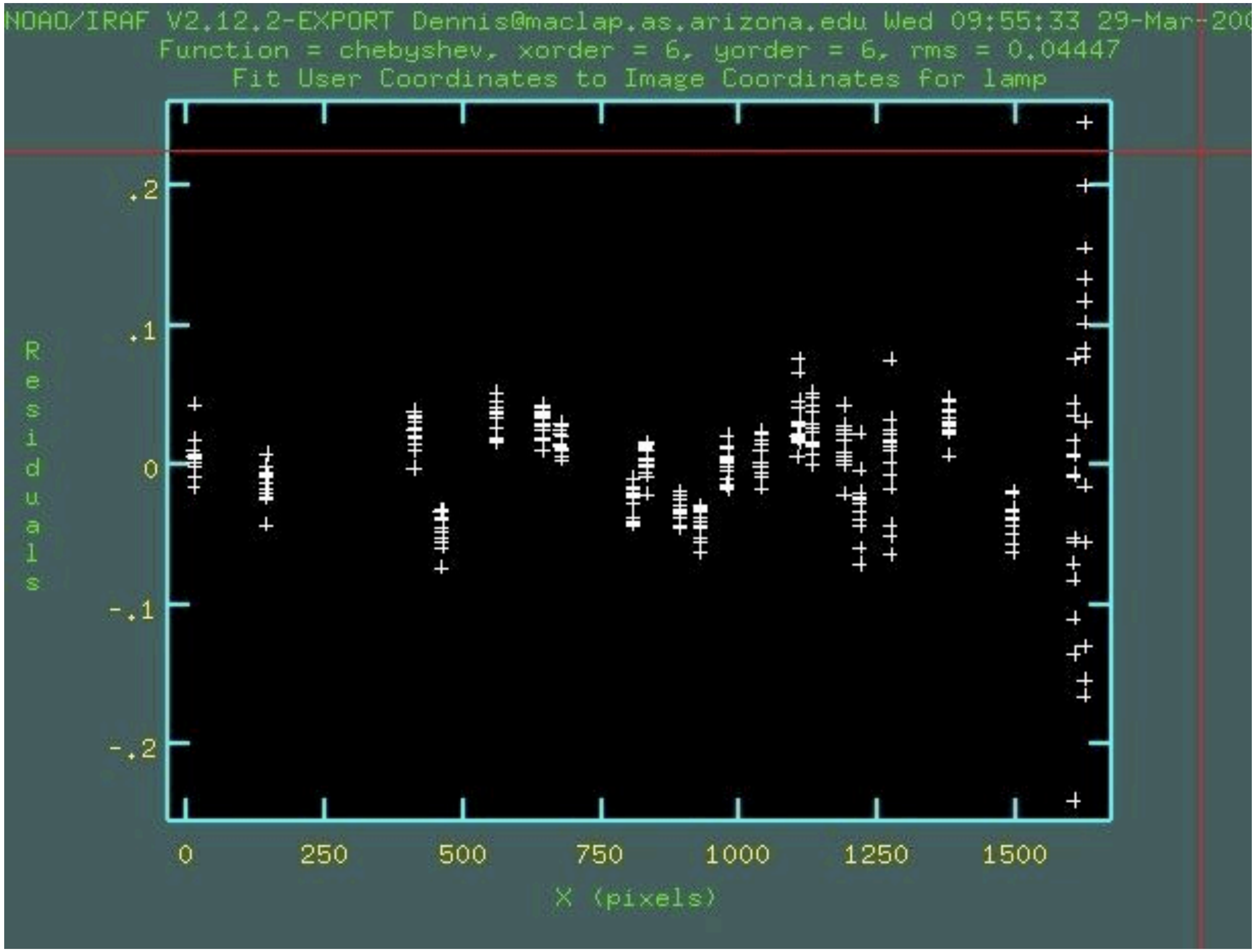
4) rectification (fitcoords & transform)

fitcoords

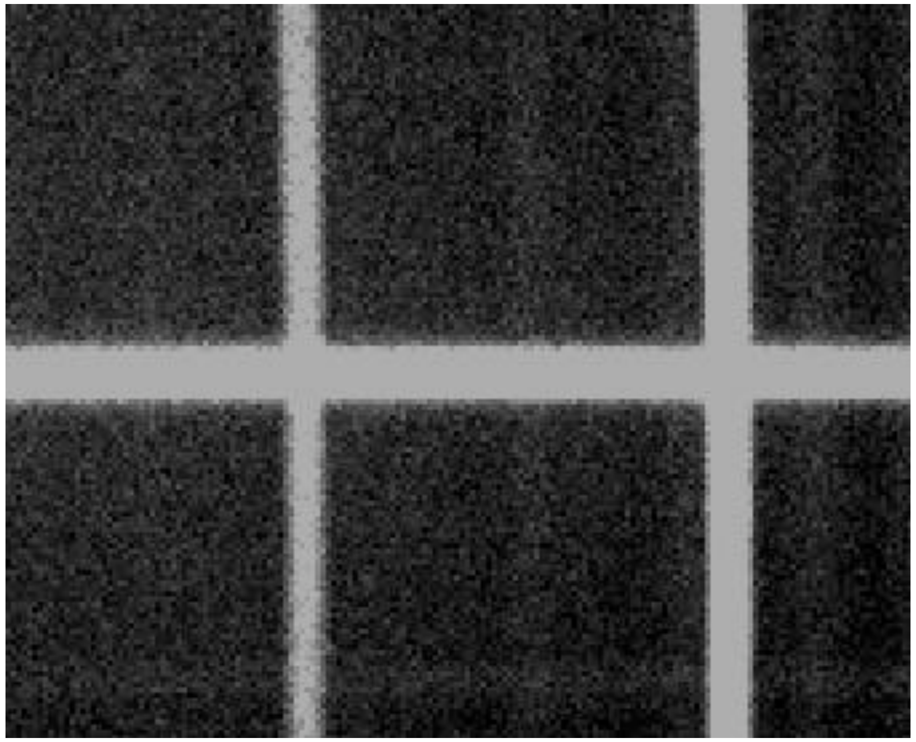
view different axes

remove outliers

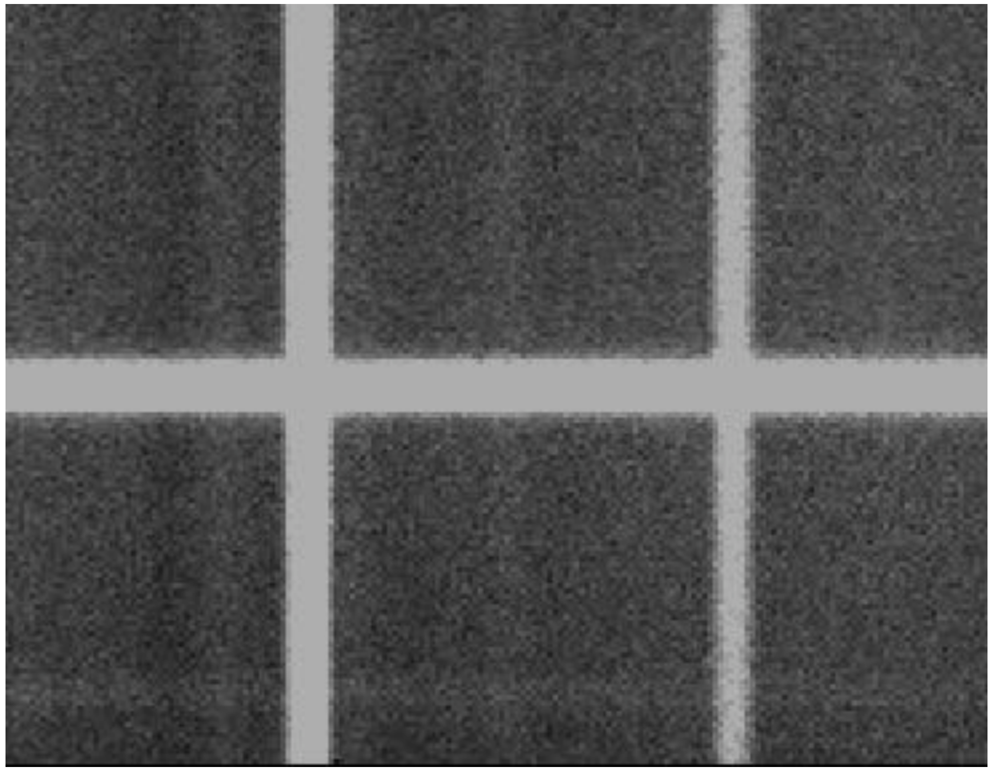
iterate



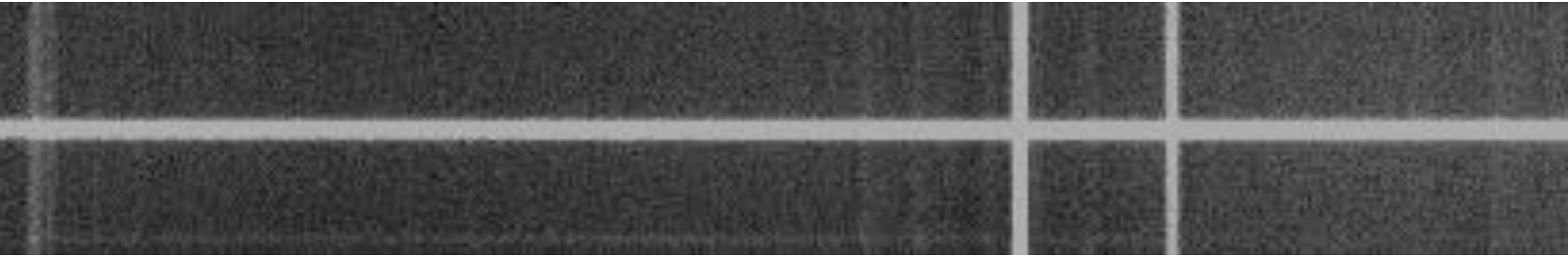
before transform



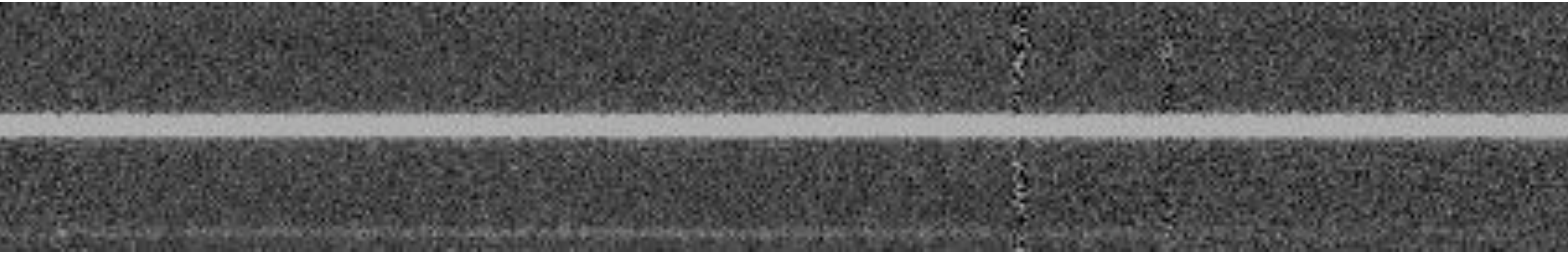
after transform

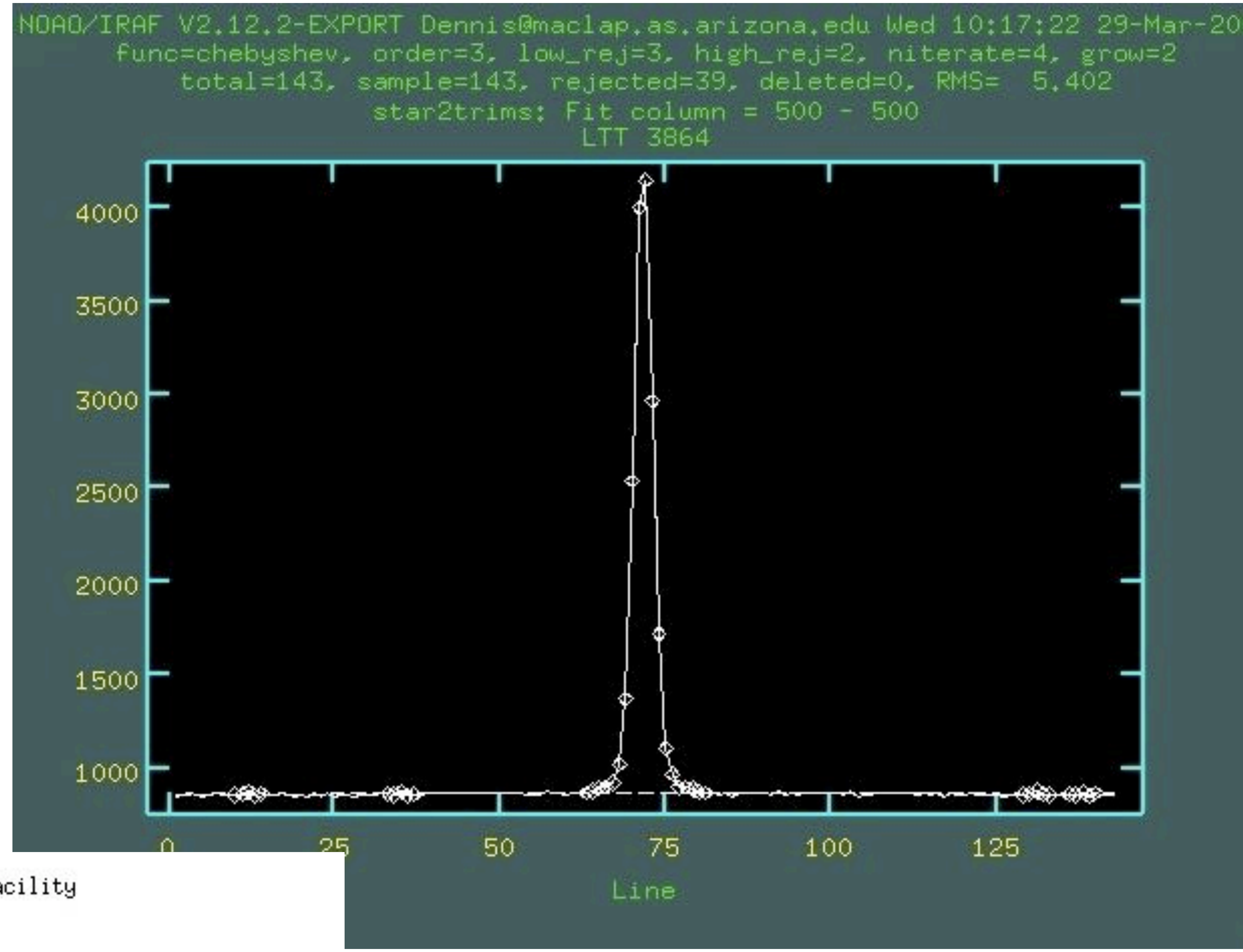


5) sky subtraction (background)



after sky subtraction

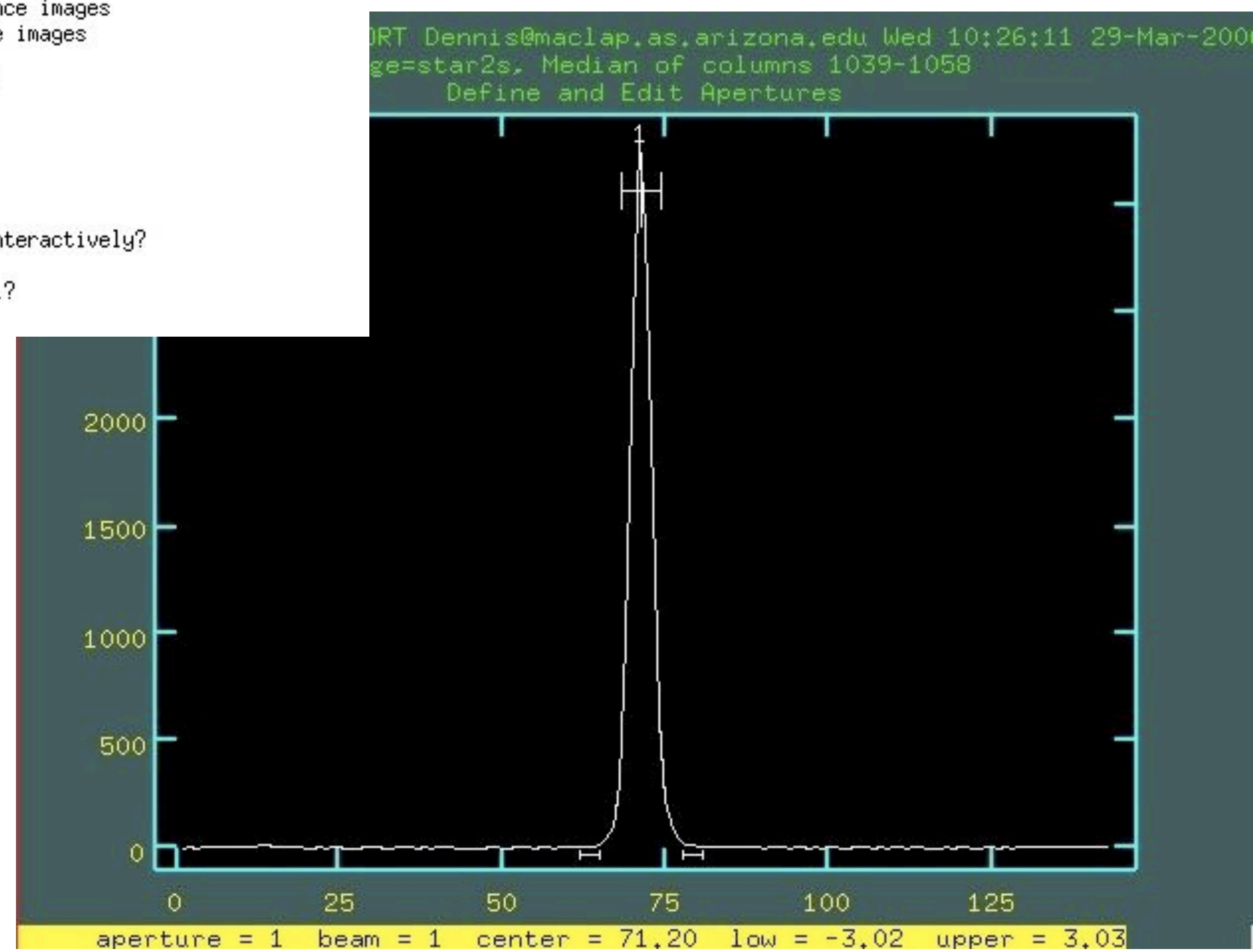





```
                                    I R A F
                      Image Reduction and Analysis Facility
PACKAGE = longslit
   TASK = background

input   =                        Input images to be background subtracted
output  =                        Output background subtracted images
(axis   =                      2) Axis along which background is fit and subtract
(interac=                    yes) Set fitting parameters interactively?
(sample =                      *) Sample of points to use in fit
(naverag=                      1) Number of points in sample averaging
(functio=              chebyshev) Fitting function
(order  =                      3) Order of fitting function
(low_rej=                     4.) Low rejection in sigma of fit
(high_re=                     4.) High rejection in sigma of fit
(niterat=                      3) Number of rejection iterations
(grow   =                     2.) Rejection growing radius
(graphic=               stdgraph) Graphics output device
(cursor =                       ) Graphics cursor input
(mode   =                     ql)

                                          ESC-? for HELP
```

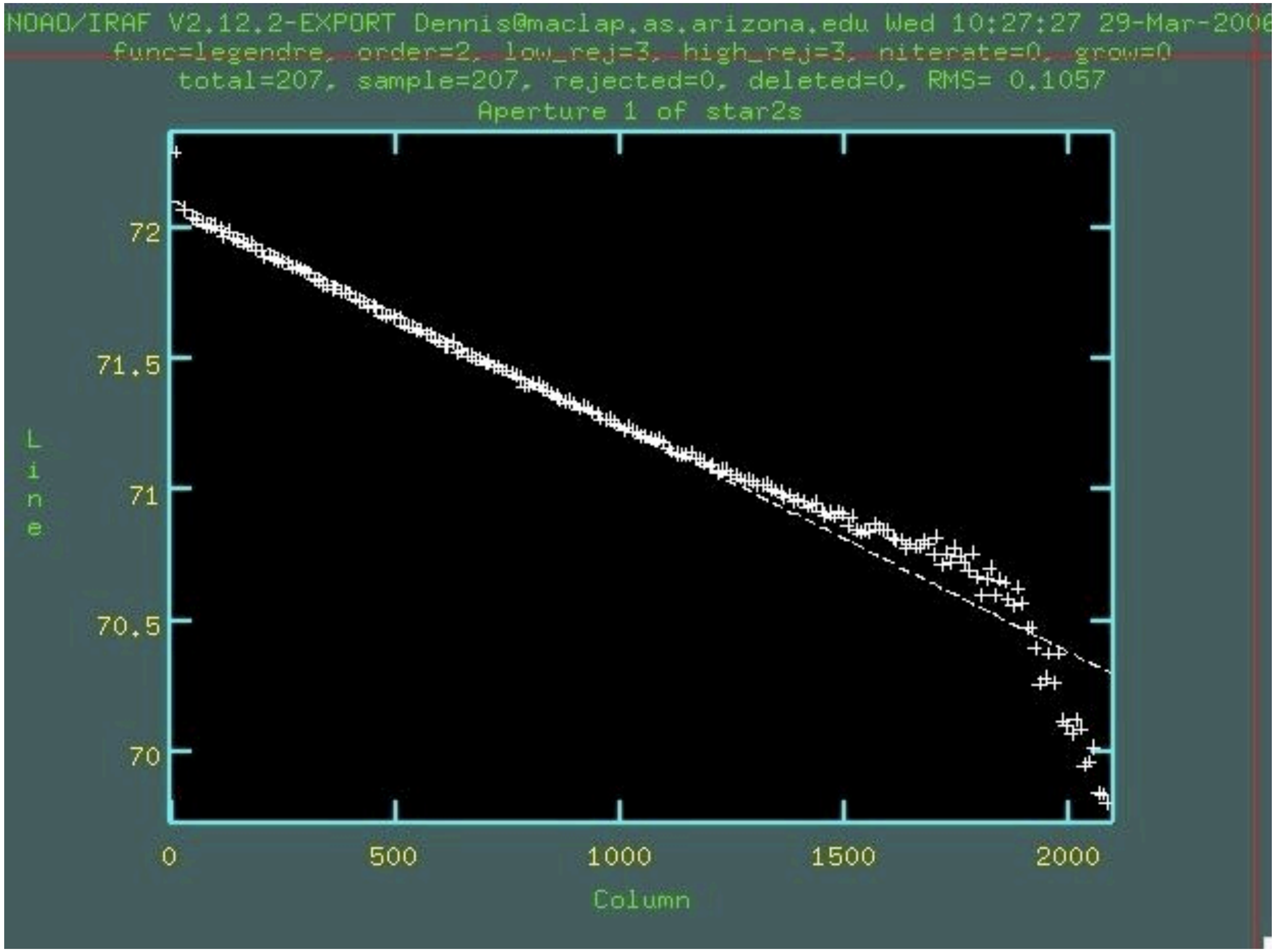
6) extraction (apextract.apall)

```
                               I R A F
                  Image Reduction and Analysis Facility
PACKAGE = apextract
   TASK = apall

input   =                     List of input images
(output =                   ) List of output spectra
(apertur=                   ) Apertures
(format =           onedspec) Extracted spectra format
(referen=                   ) List of aperture reference images
(profile=                   ) List of aperture profile images

(interac=                yes) Run task interactively?
(find   =                yes) Find apertures?
(recente=                yes) Recenter apertures?
(resize =                yes) Resize apertures?
(edit   =                yes) Edit apertures?
(trace  =                yes) Trace apertures?
(fittrac=                yes) Fit the traced points interactively?
(extract=                yes) Extract spectra?
(extras =                 no) Extract sky, sigma, etc.?
(review =                 no) Review extractions?
```

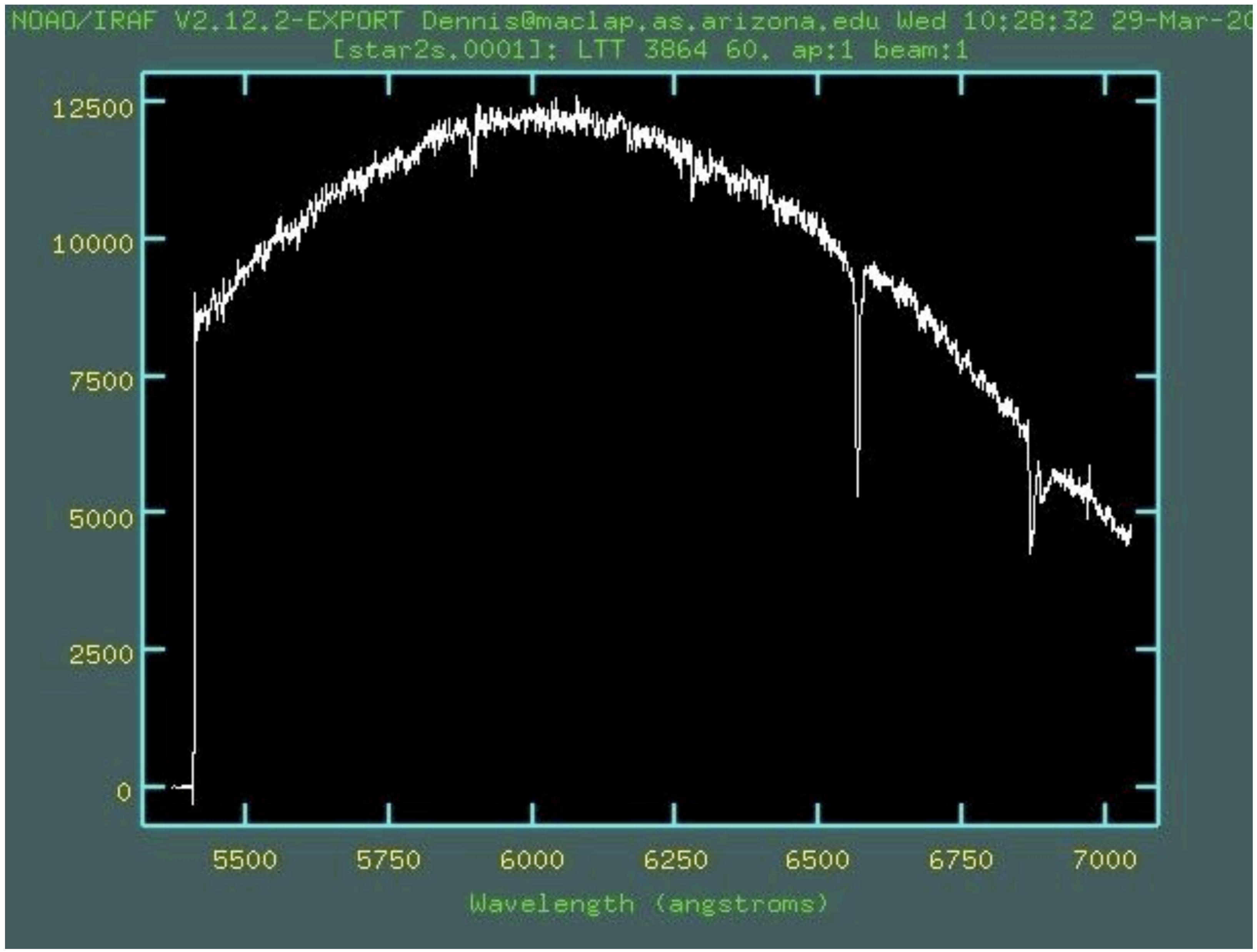


find spectra

trace the spectrum

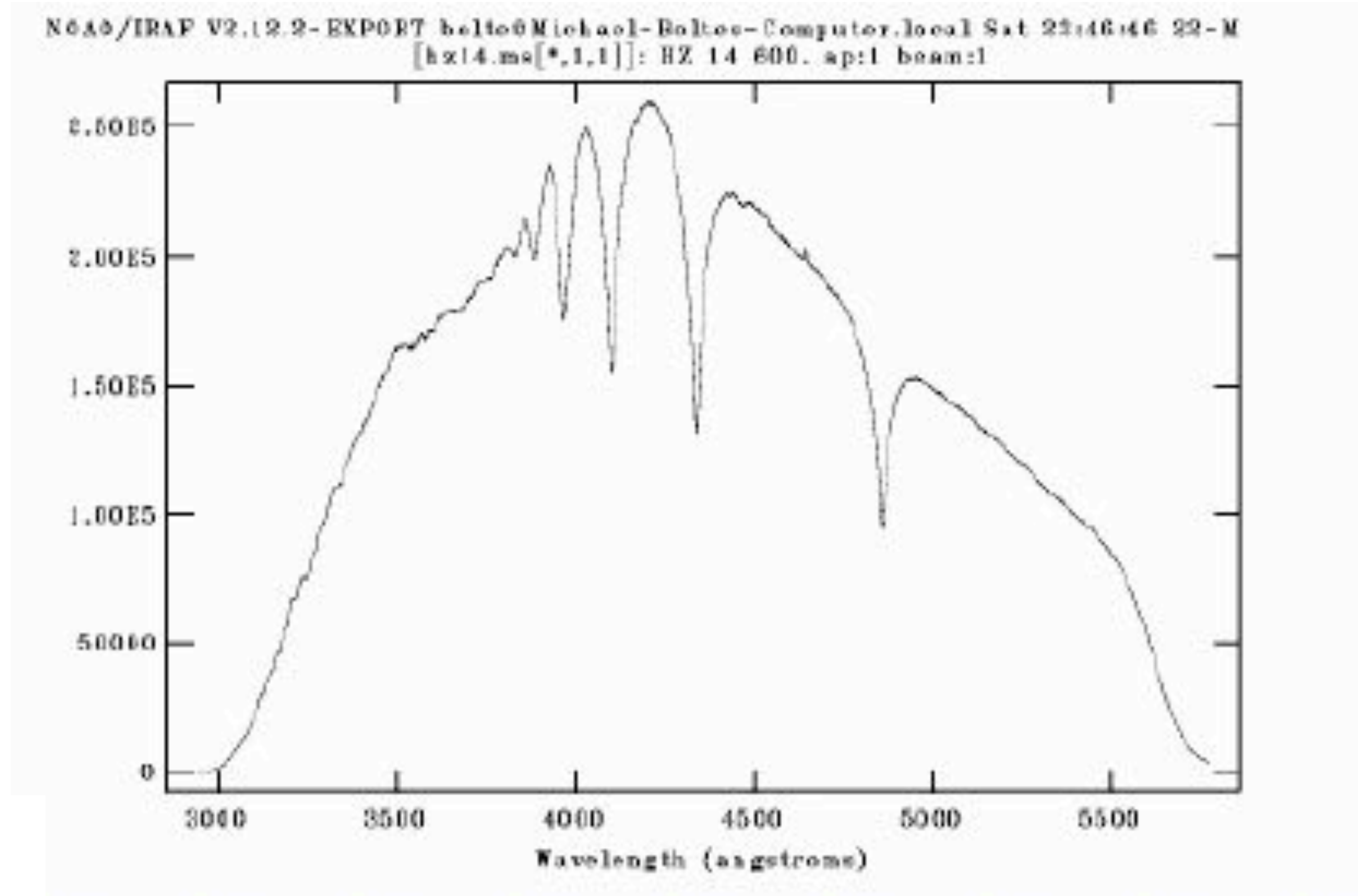


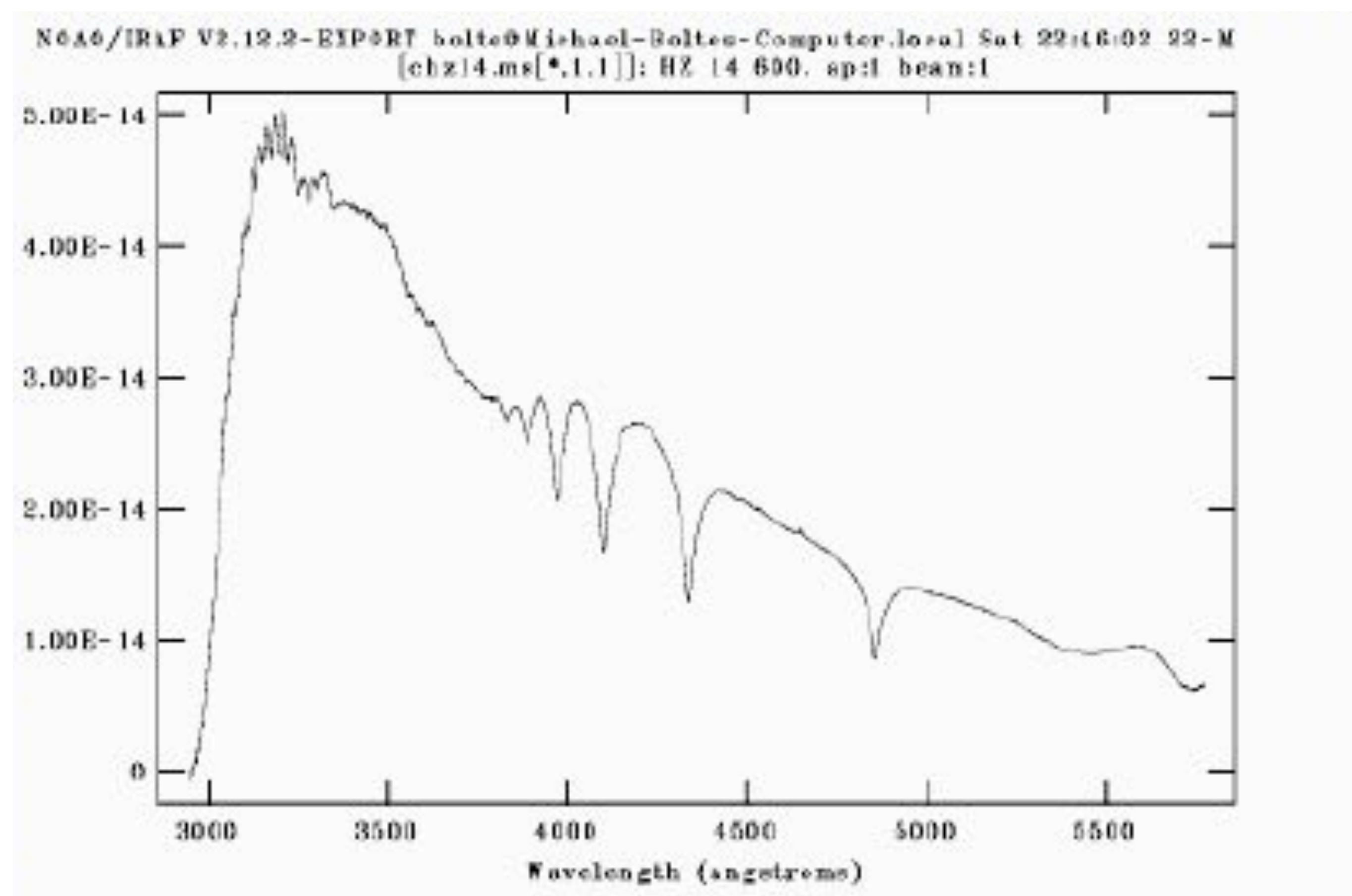
extract and display (oned.splot) spectrum



7) flux calibrate

use spectrum of known star to convert from counts to erg/s/cm^2/A

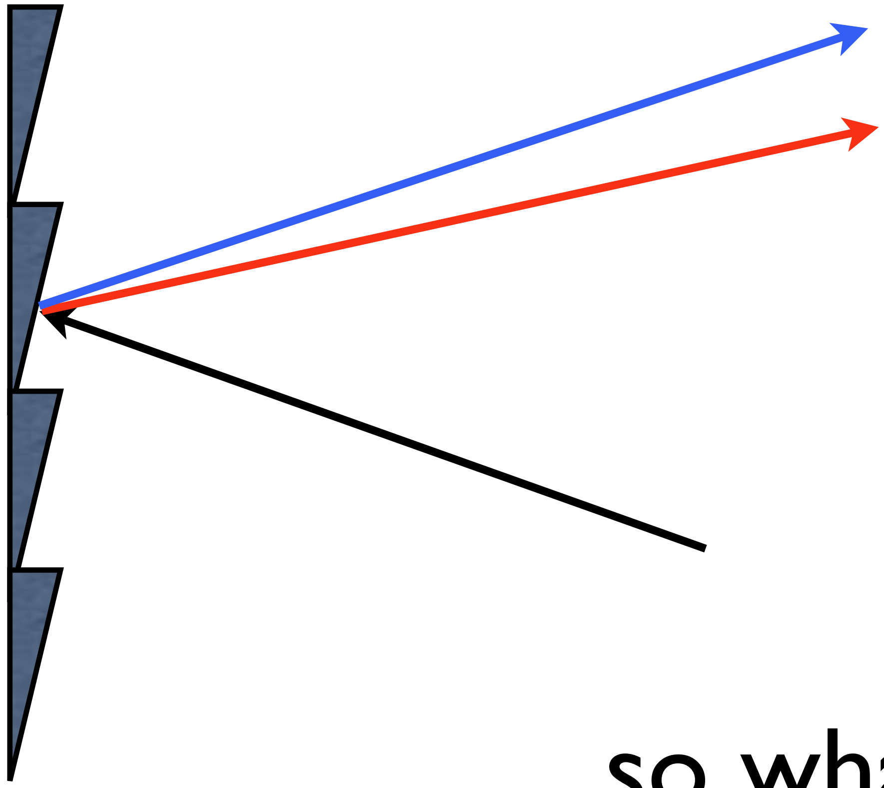




from M. Bolte's notes

Topics in Spectroscopy

Order blocking

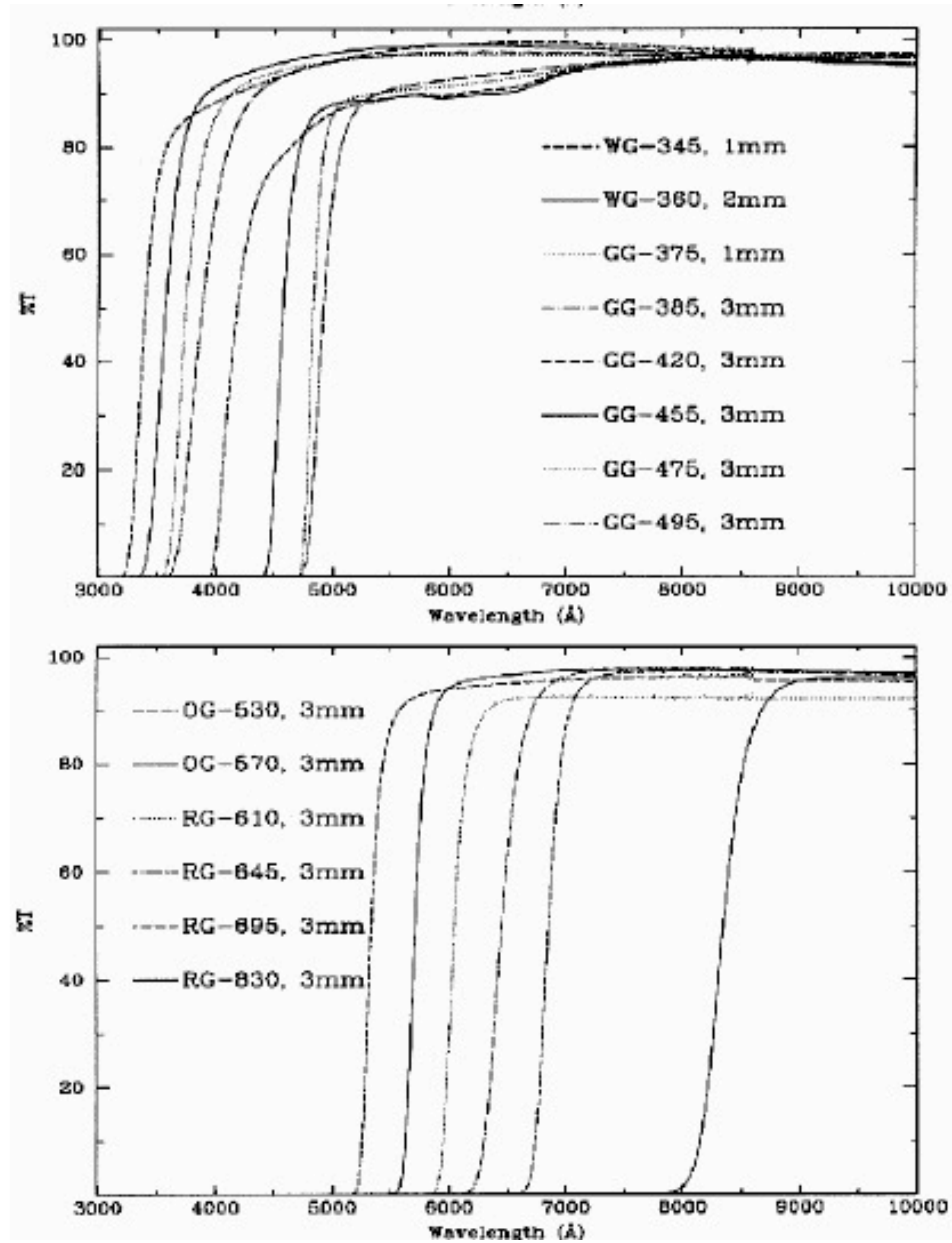


n=1	n=2	n=3
4000 A	2000	1333
8000 A	4000	2666

so what filter would block n = 1?

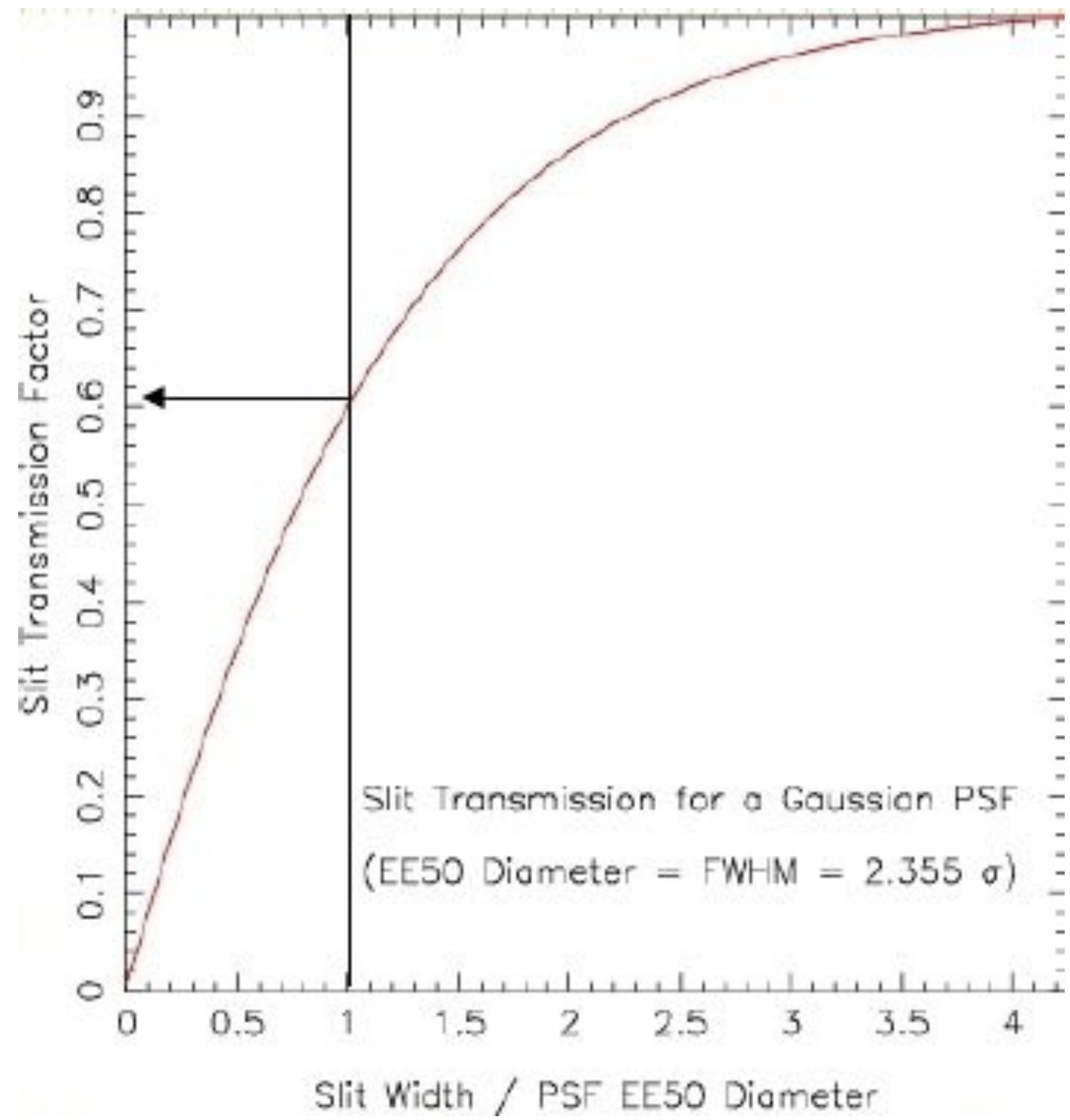
from M. Bolte's course notes

order blocking filter curves



Slit width considerations

balance sky contamination, flux included, and resolution



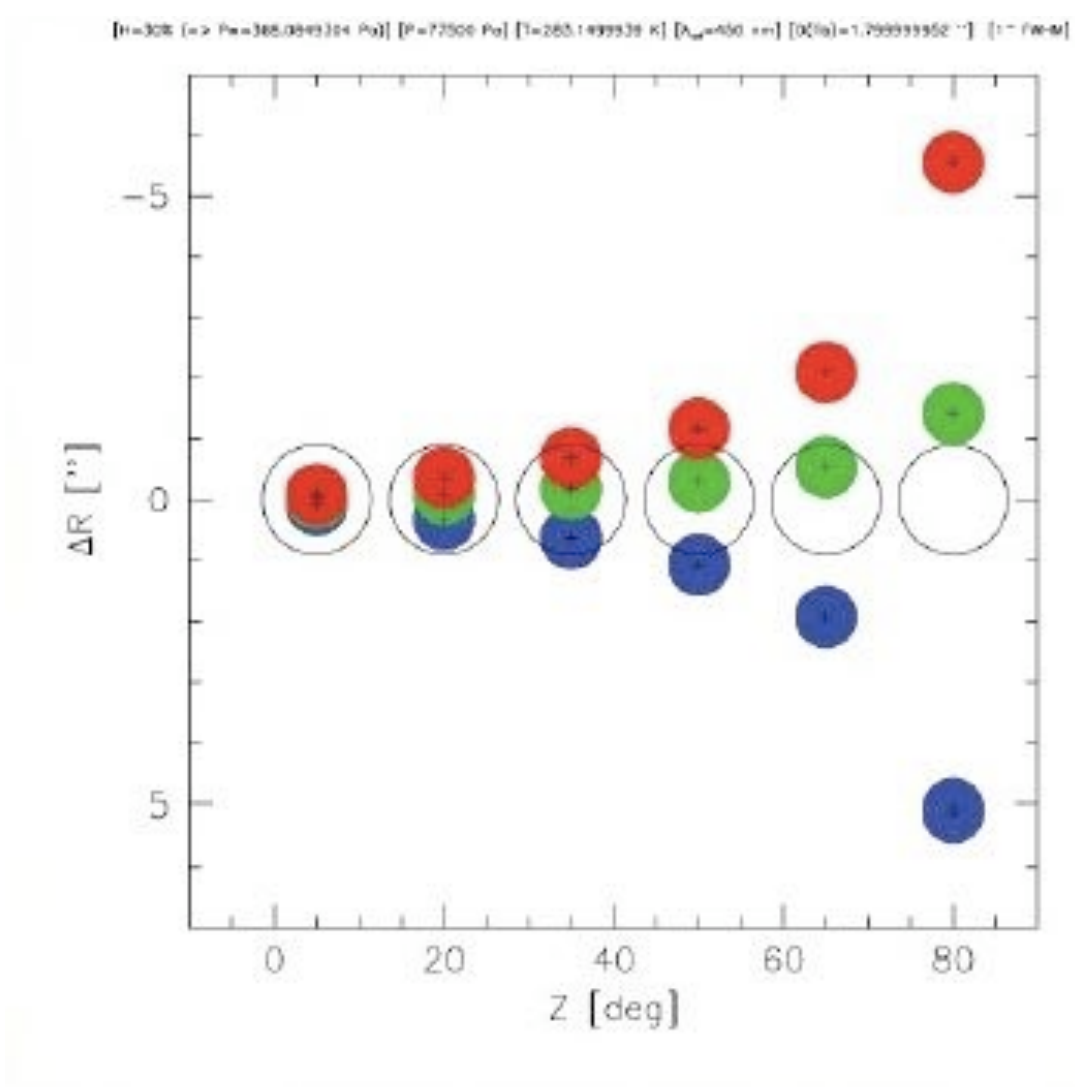
How should you take your photometric standards?

Do you need to worry about your calibrations?

Differential Atmospheric Refraction

index of refraction

$$\Delta\theta = 206265[(n_{\lambda 1} - 1) - (n_{\lambda 2} - 1)] \tan z$$

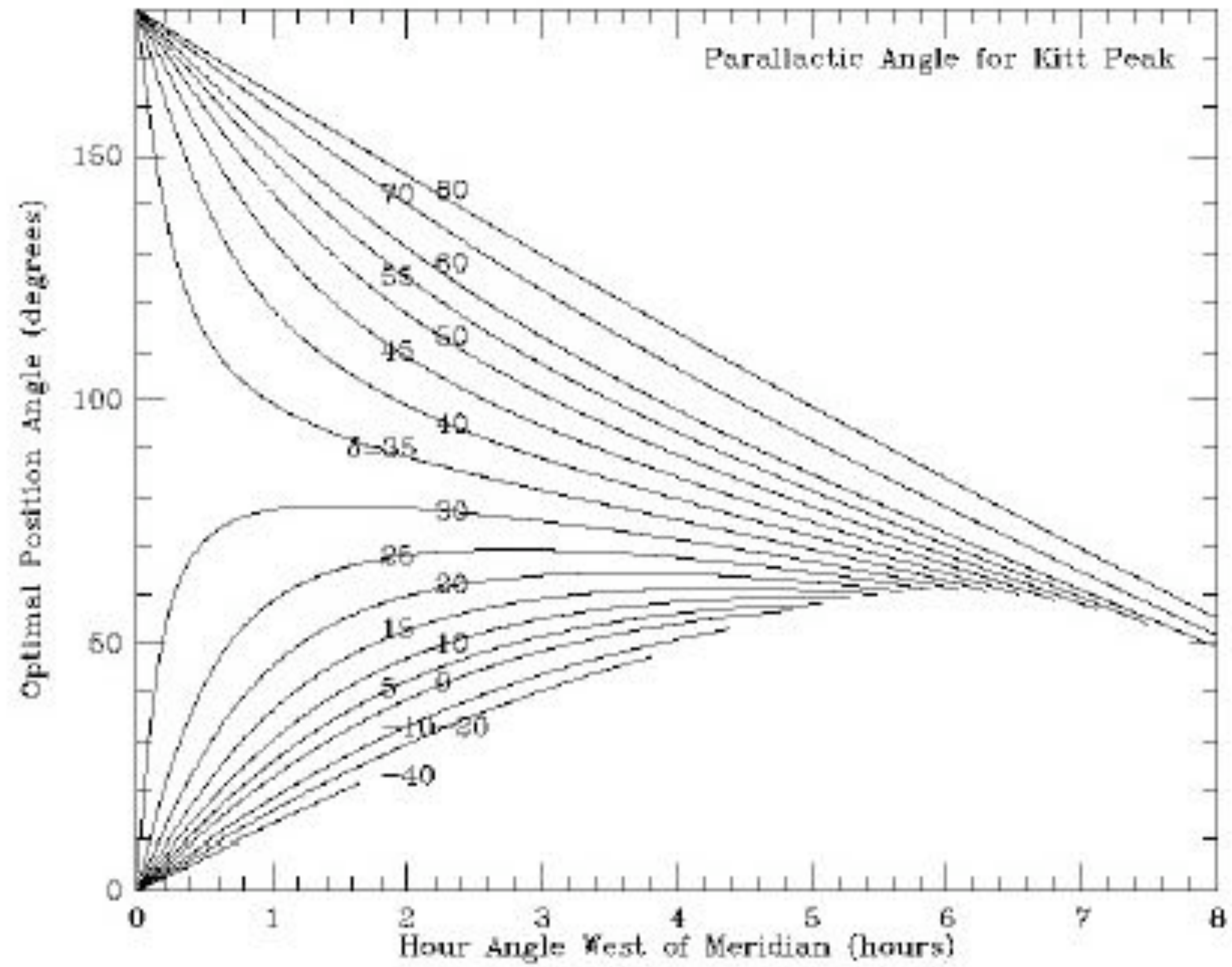


light loss

acquisition/guiding problems

Solutions

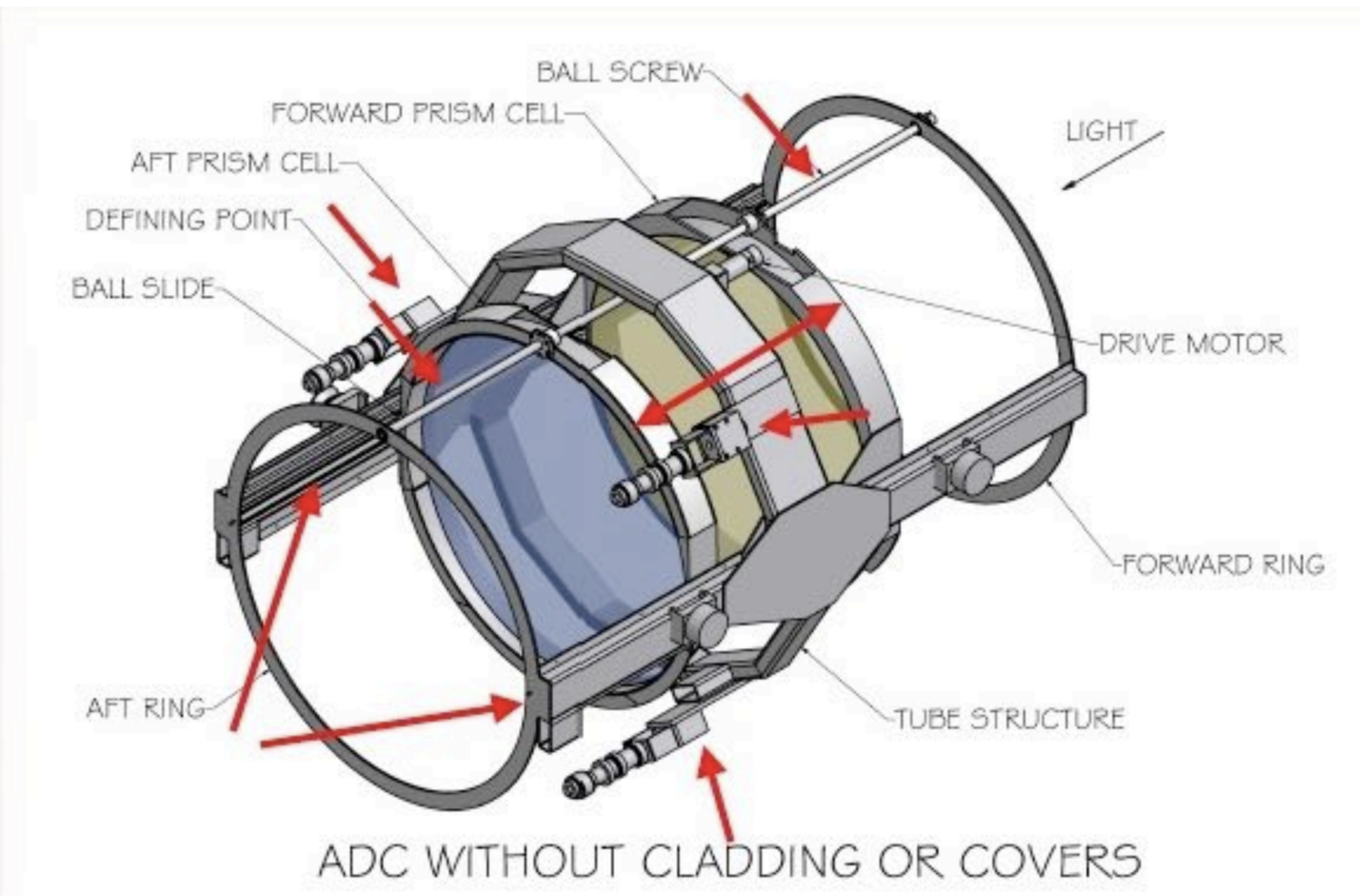
Align slit with parallactic angle

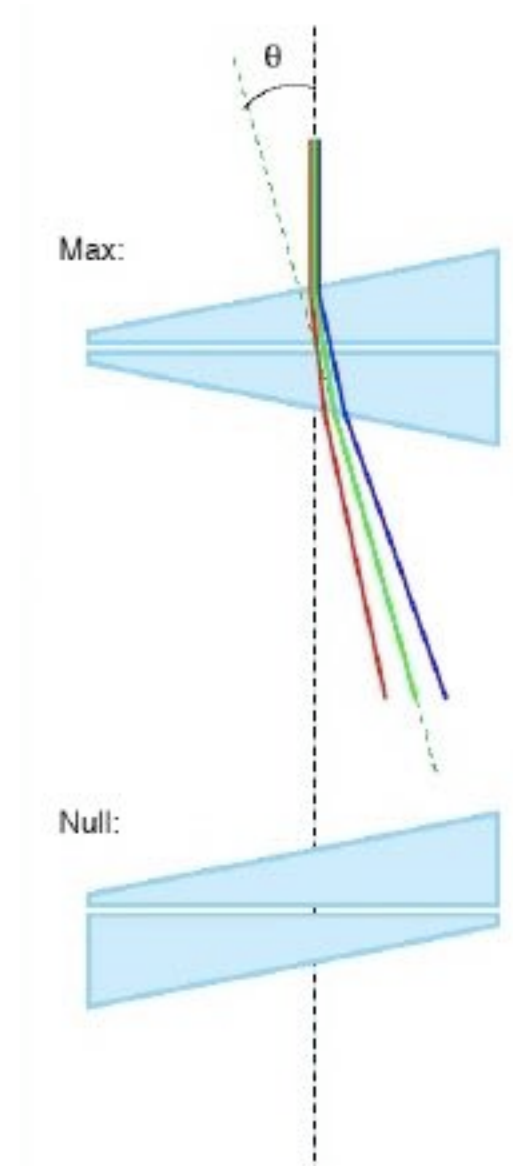


differential refraction happens along slit, no light loss

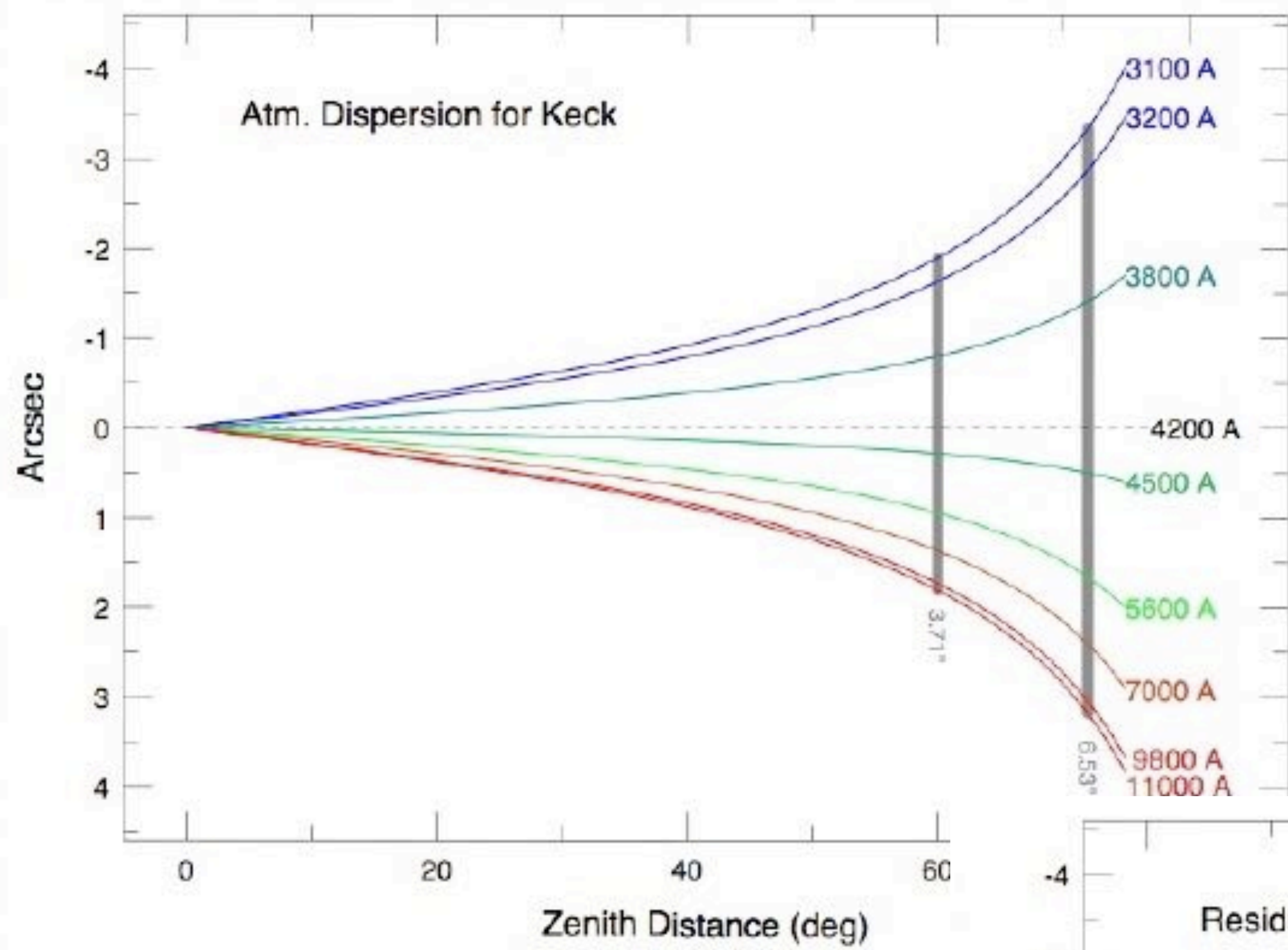
Solutions (continued)

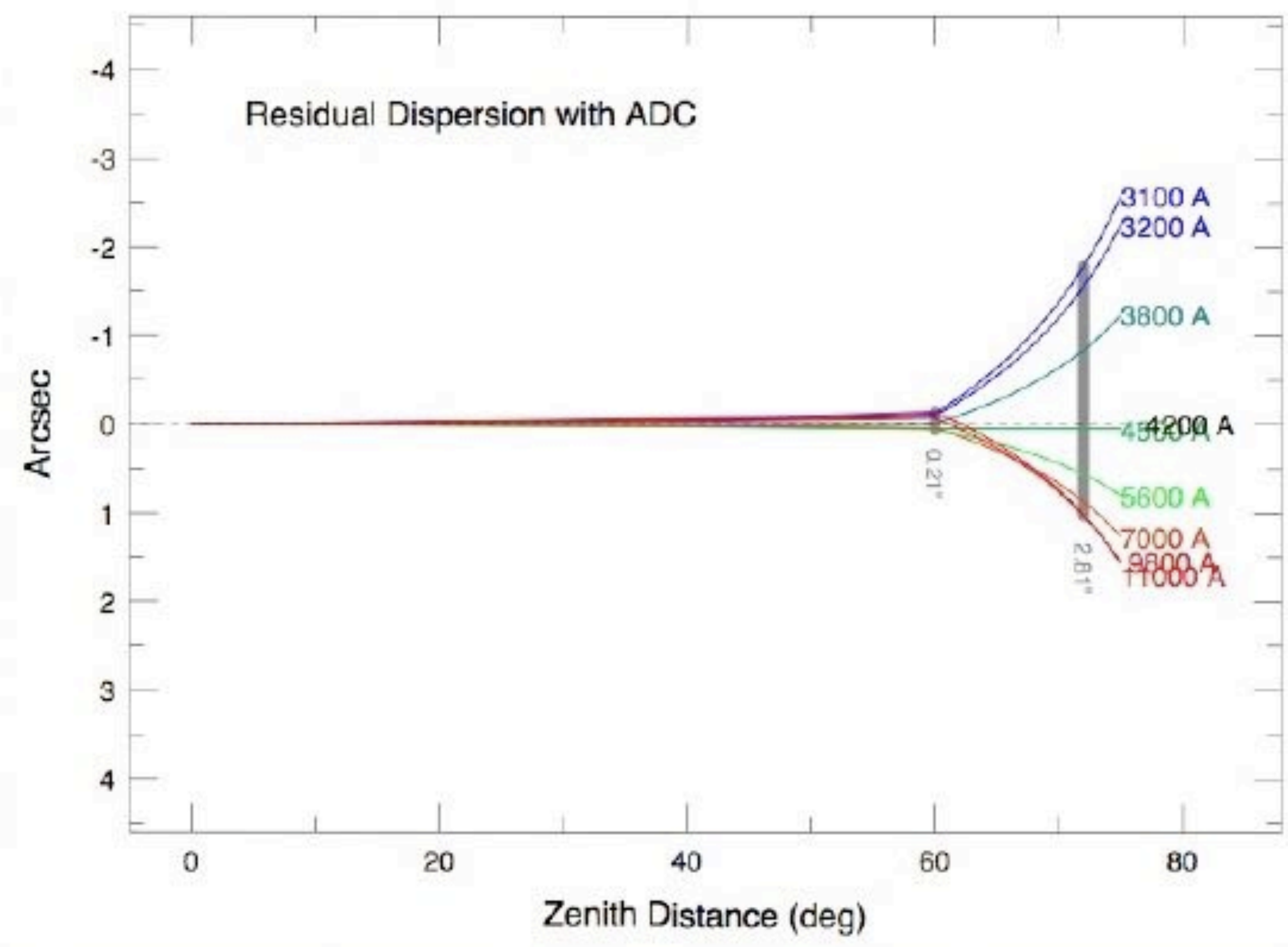
Atmospheric Dispersion Corrector





No ADC





with ADC

Setting up to observe

- focus

  telescope focus (image must focus on slit)

  spectrograph focus (light rays must be parallel at grating)

  camera focus (usually stable and not available to user) for telescope focus

can check spatial extent of objects if spectrograph is focused

can check images on guide camera if guide camera is focuses

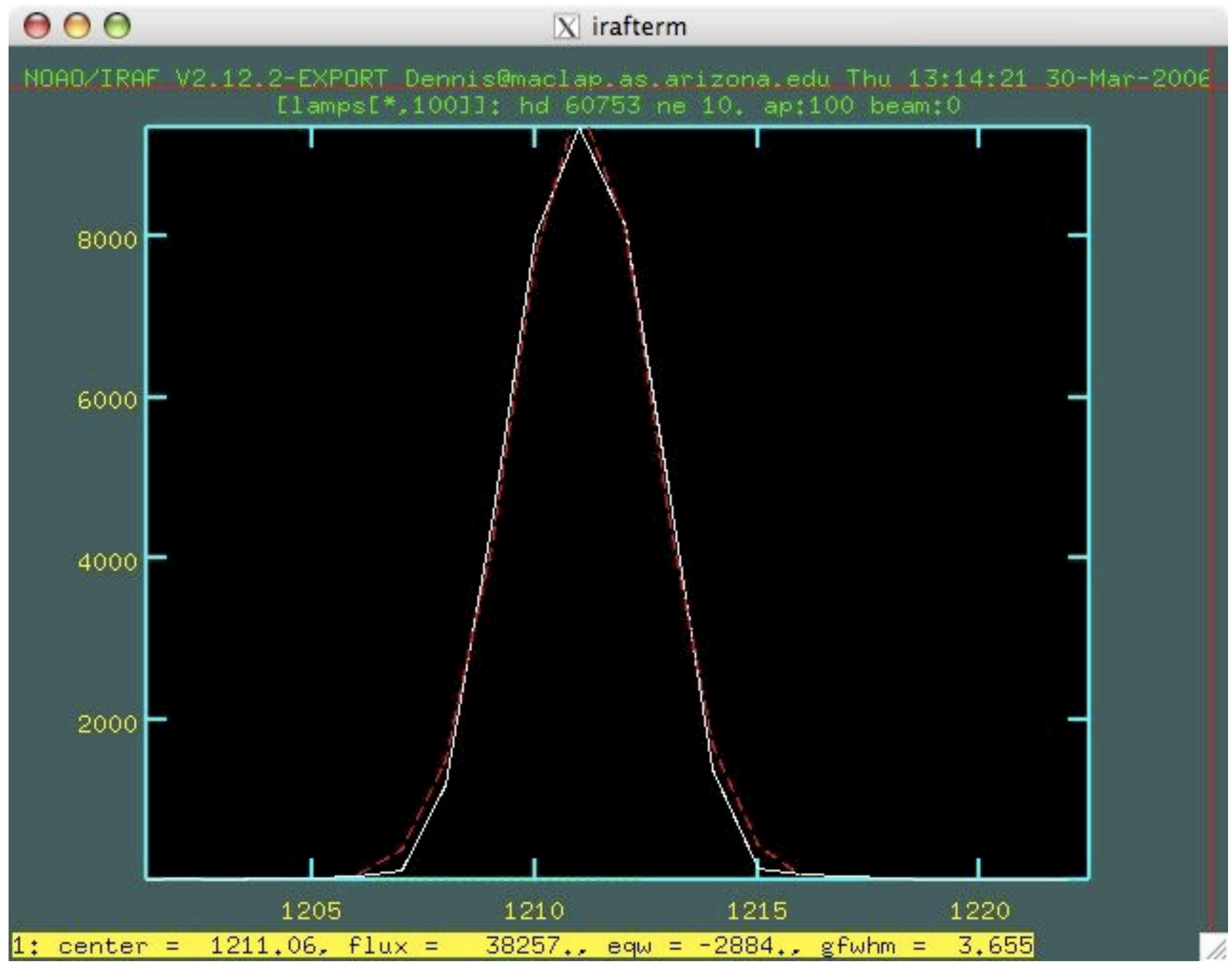
other “fancier” ways are available on more modern telescopes for spectrograph focus

change collimator setting to minimize width of calibration lamp lines

(can vary with temperature and orientation)

or pinhole test

'a' to expand, 'k' to fit model



- select binning and trim region

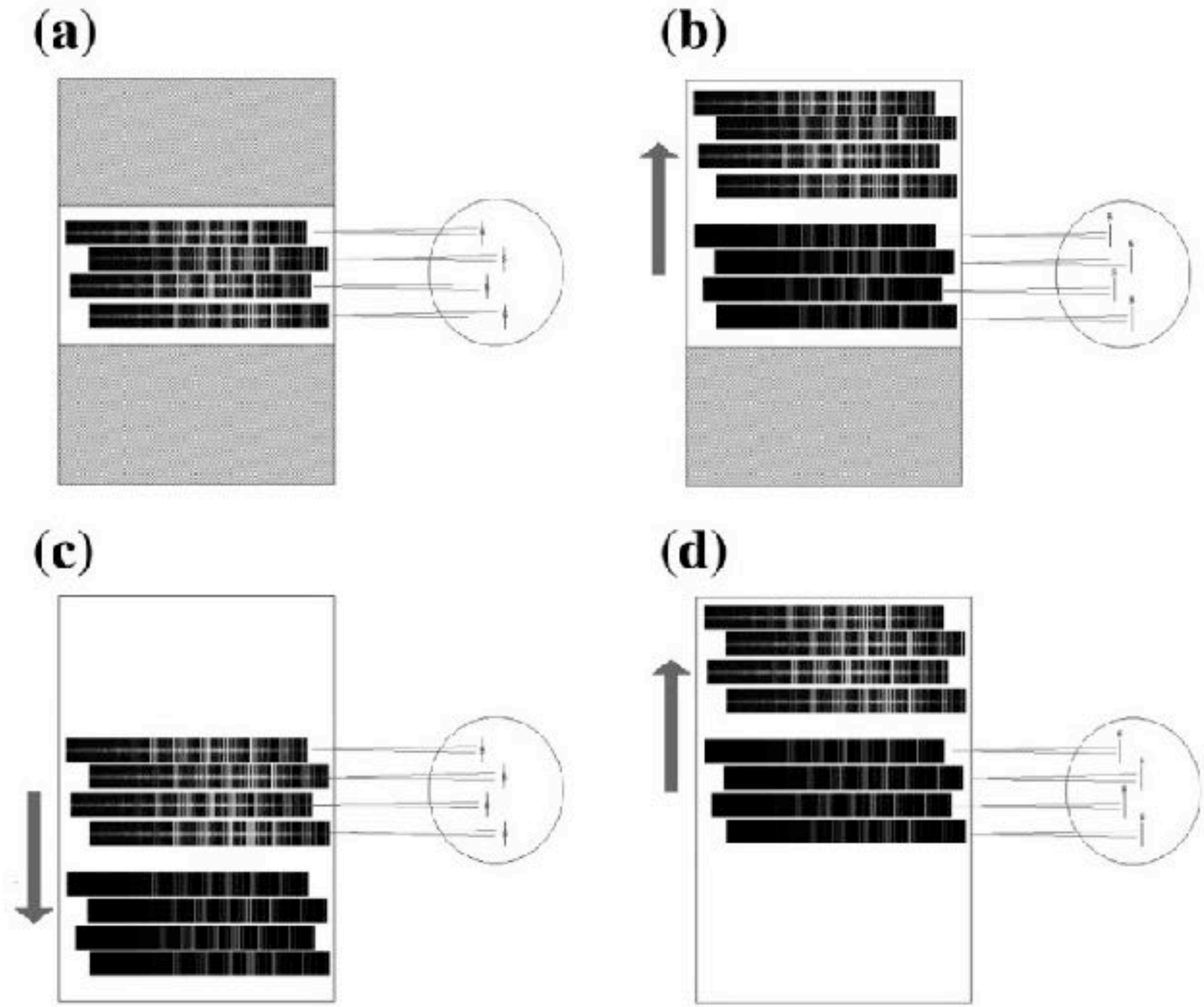
- take biases, flats, and wavelength calibration lamps (verify wavelength coverage)

- repeat flats and calibration lamps for every slit size to be used

- observing prep. (slit orientation, offset positions?, set of calibrators (spectrophotometric, velocity, atmospheric absorption))

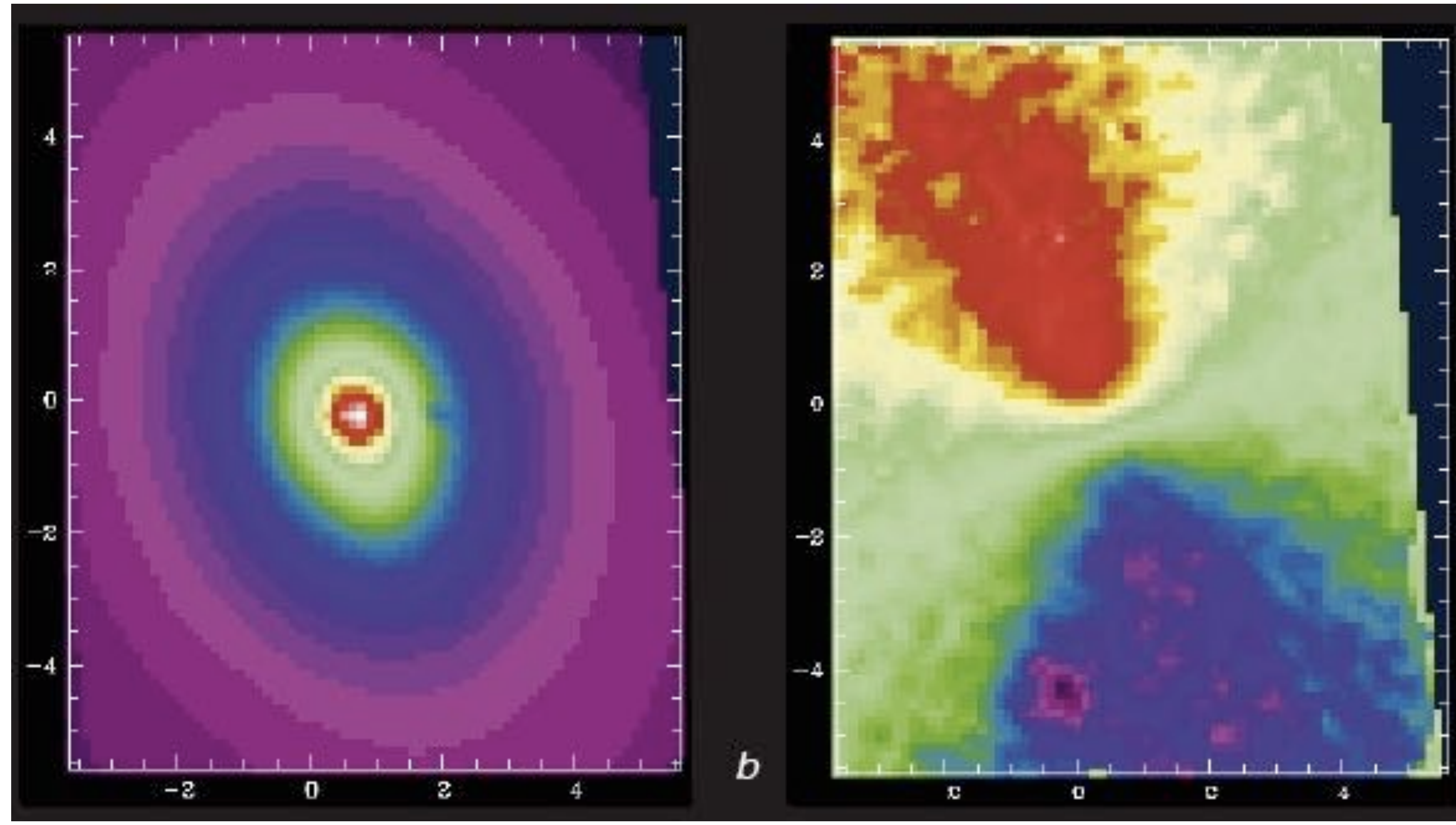
New Techniques/Applications

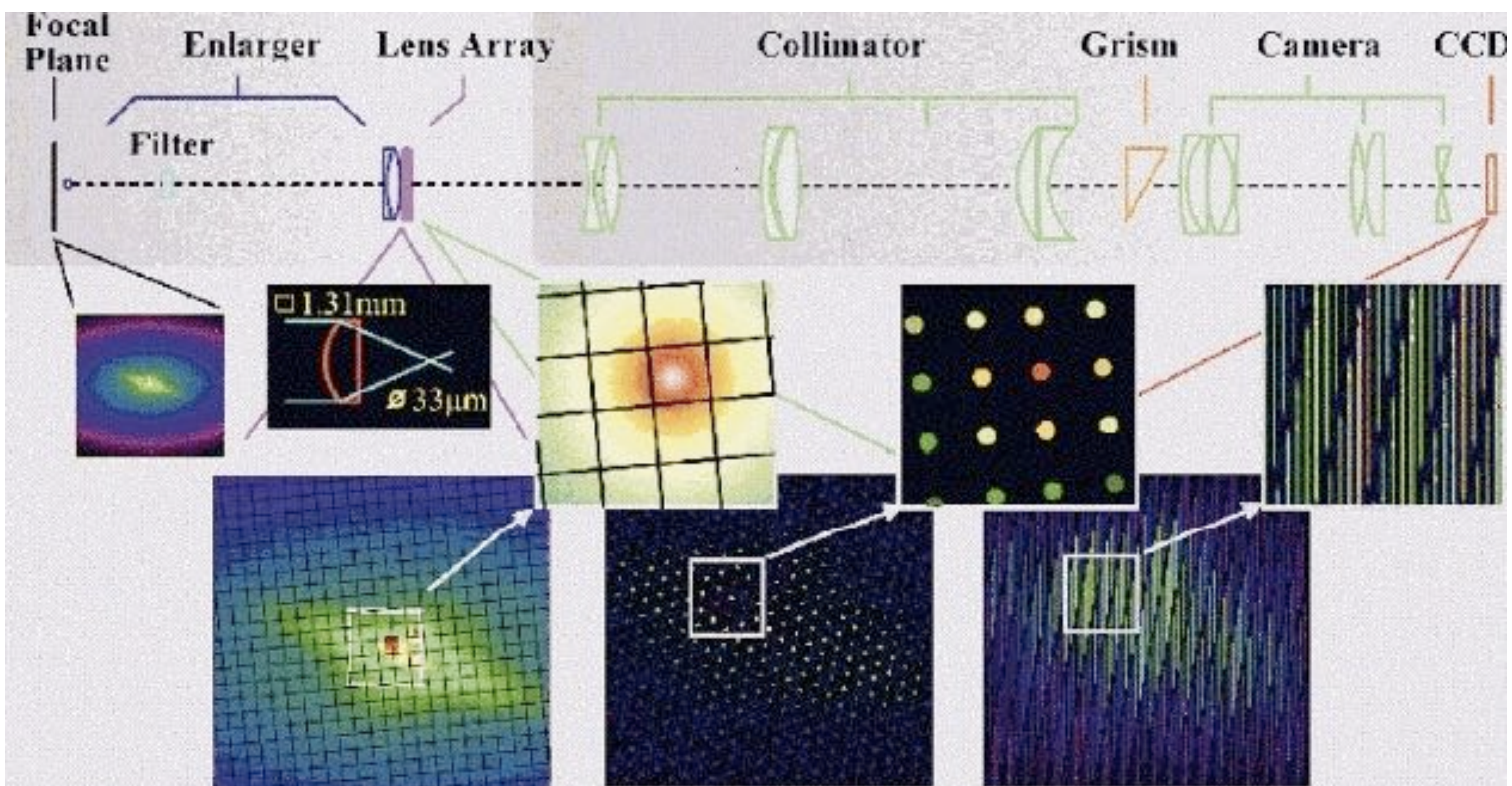
nod-&-shuffle



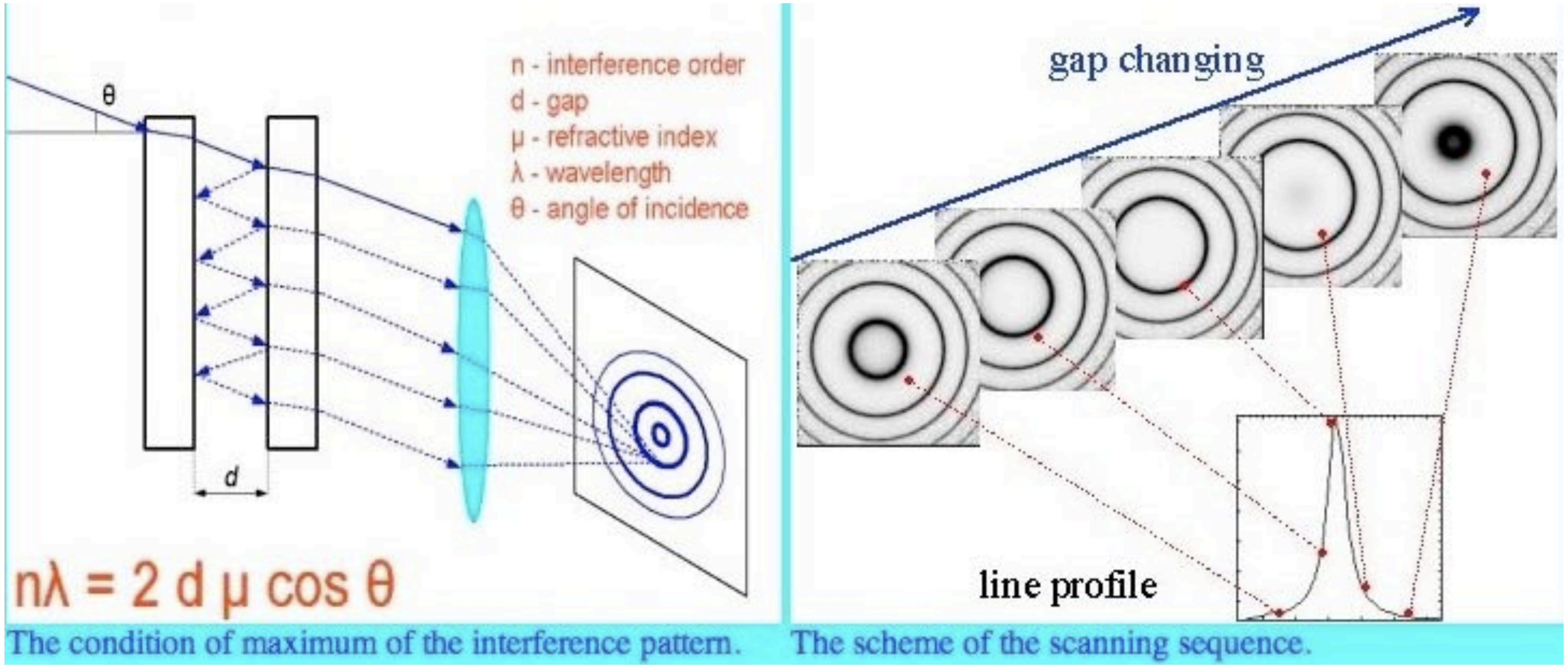
Glazebrook & Bland-Hawthorn

Integral Field Spectroscopy

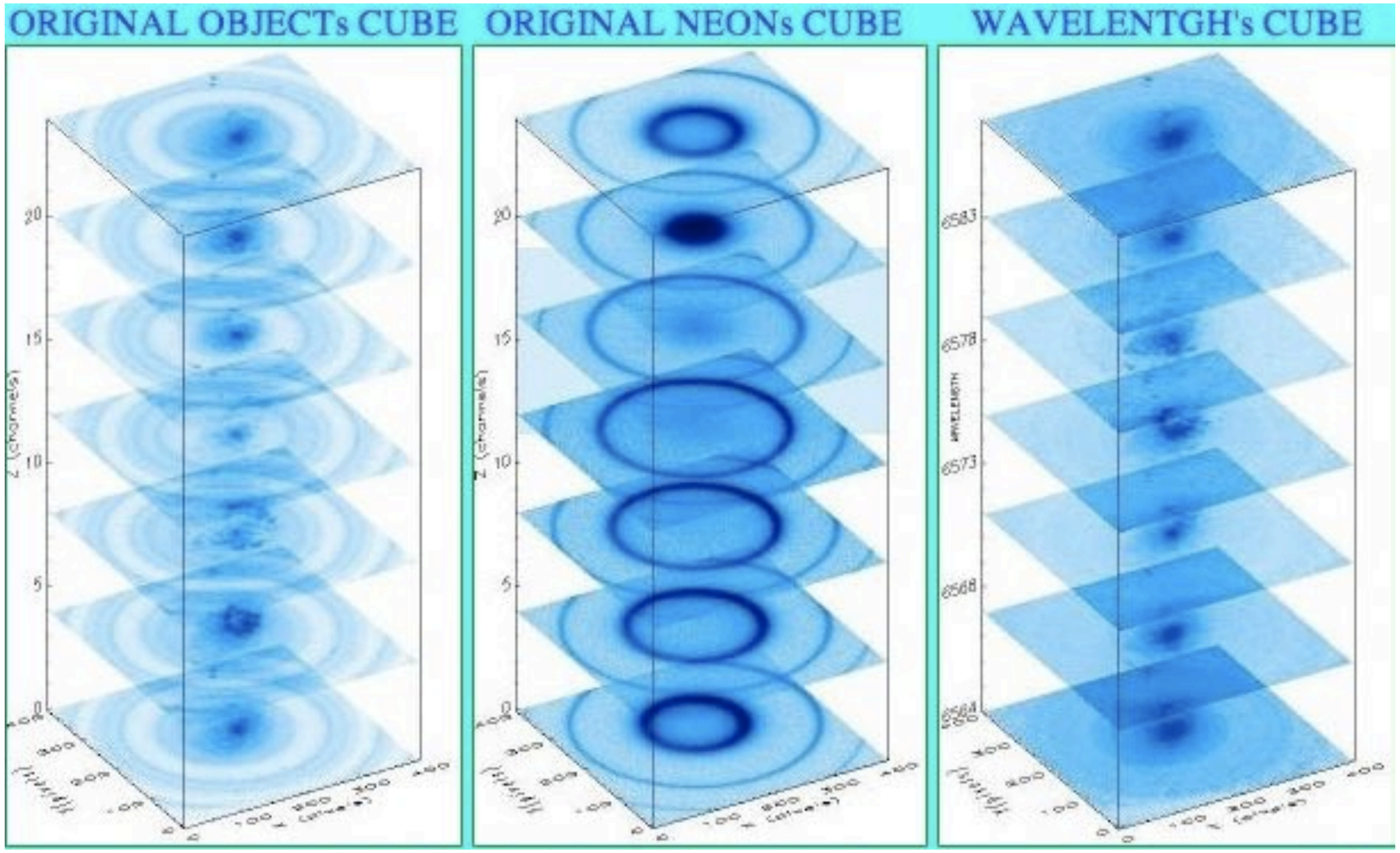




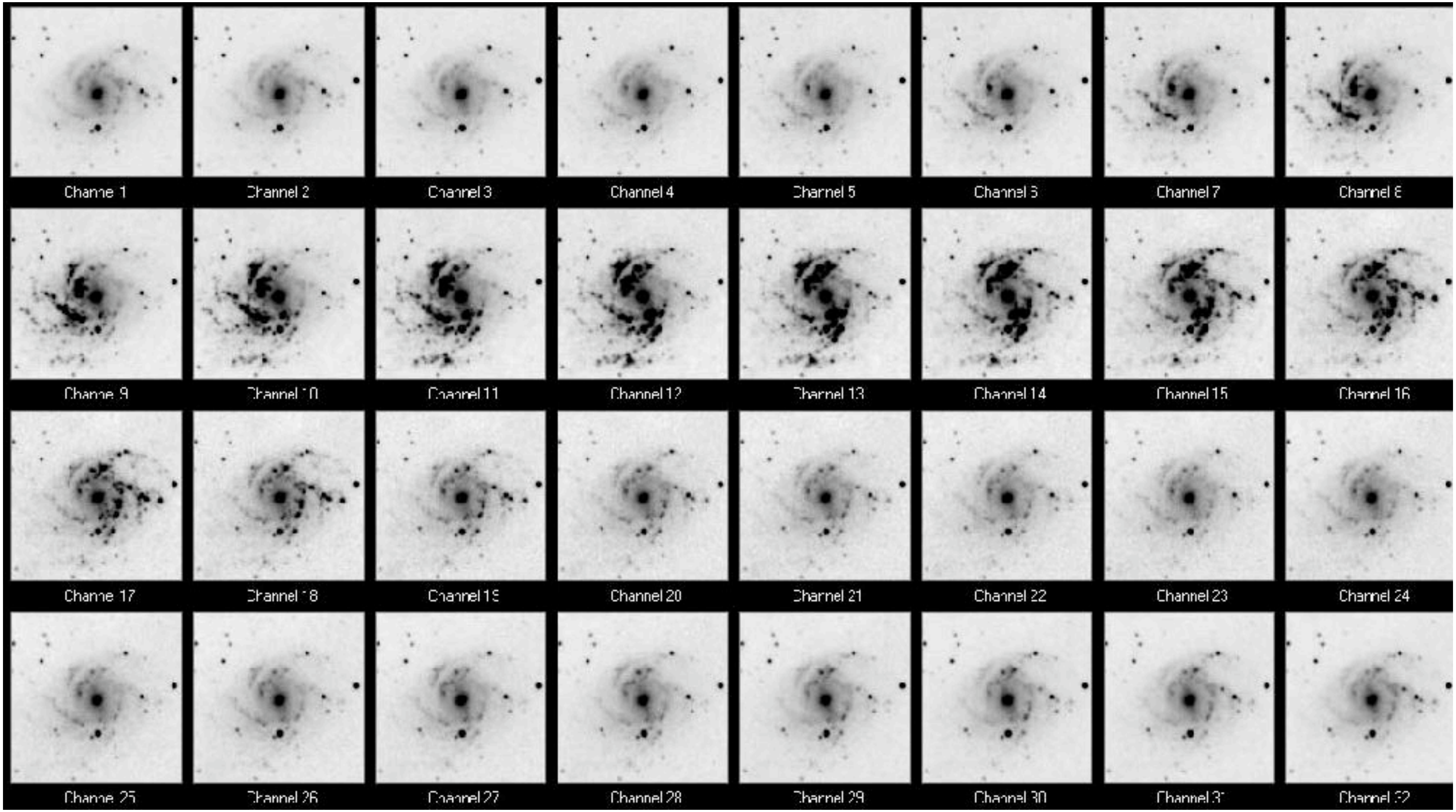
Fabry-Perot



n - interference order
d - gap
μ - refractive index
λ - wavelength
θ - angle of incidence
θ
d
nλ = 2 d μ cos θ
gap changing
line profile
The condition of maximum of the interference pattern.
The scheme of the scanning sequence.



ORIGINAL OBJECTs CUBE
ORIGINAL NEONs CUBE
WAVELENTGH's CUBE

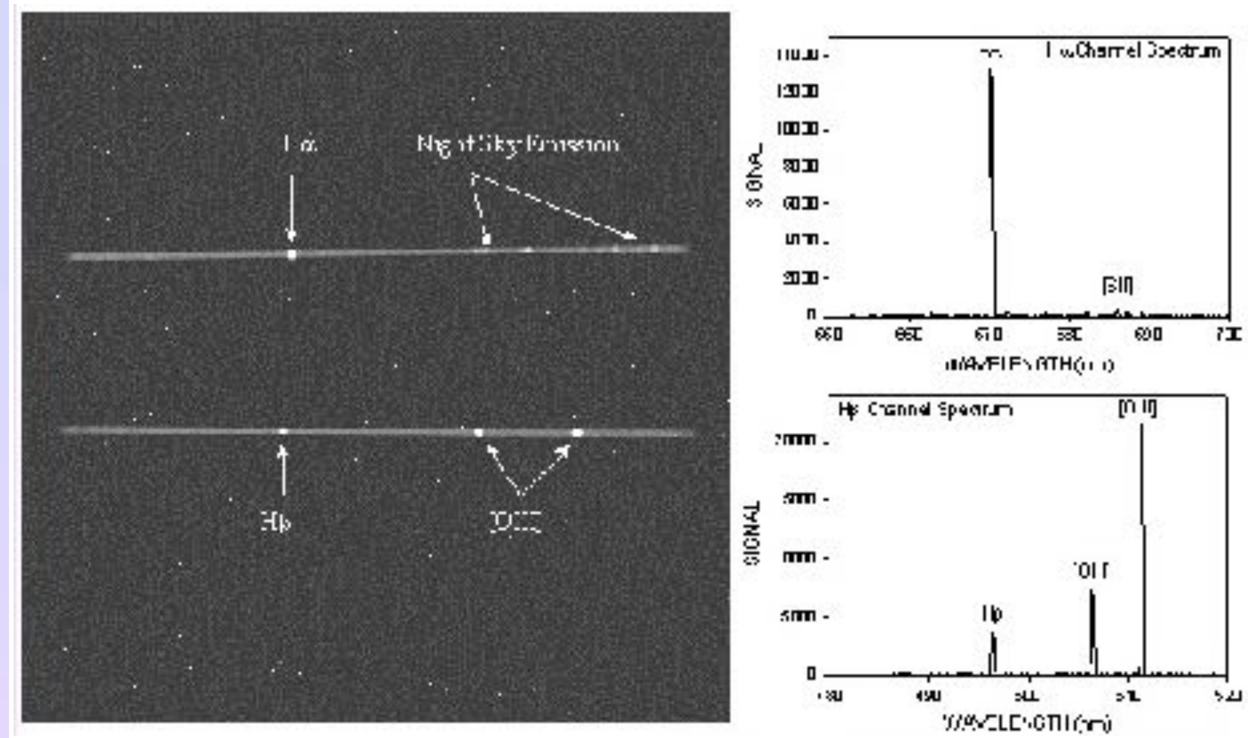

Channel 1
Channel 2
Channel 3
Channel 4
Channel 5
Channel 6
Channel 7
Channel 8
Channel 9
Channel 10
Channel 11
Channel 12
Channel 13
Channel 14
Channel 15
Channel 16
Channel 17
Channel 18
Channel 19
Channel 20
Channel 21
Channel 22
Channel 23
Channel 24
Channel 25
Channel 26
Channel 27
Channel 28
Channel 29
Channel 30
Channel 31
Channel 32

Volume-Phase Holographic Gratings

change index of refraction within element

Typical VP Grating Parameters

- Line density: 300 to 6000 l/mm
- Index modulation (Δn): 0.02 to 0.10
- Ave. index (n): 1.5
- Grating depth (d): 4 to 30 μm
- Wavelength range: 0.4 to 1.5 μm
  - may be viable from 0.3 to 2.8 μm.
- Grating size: 75 by 100 mm
  - limited by holographic exposure system
  - expandable to 500 by 700 mm



OH suppression

fibers

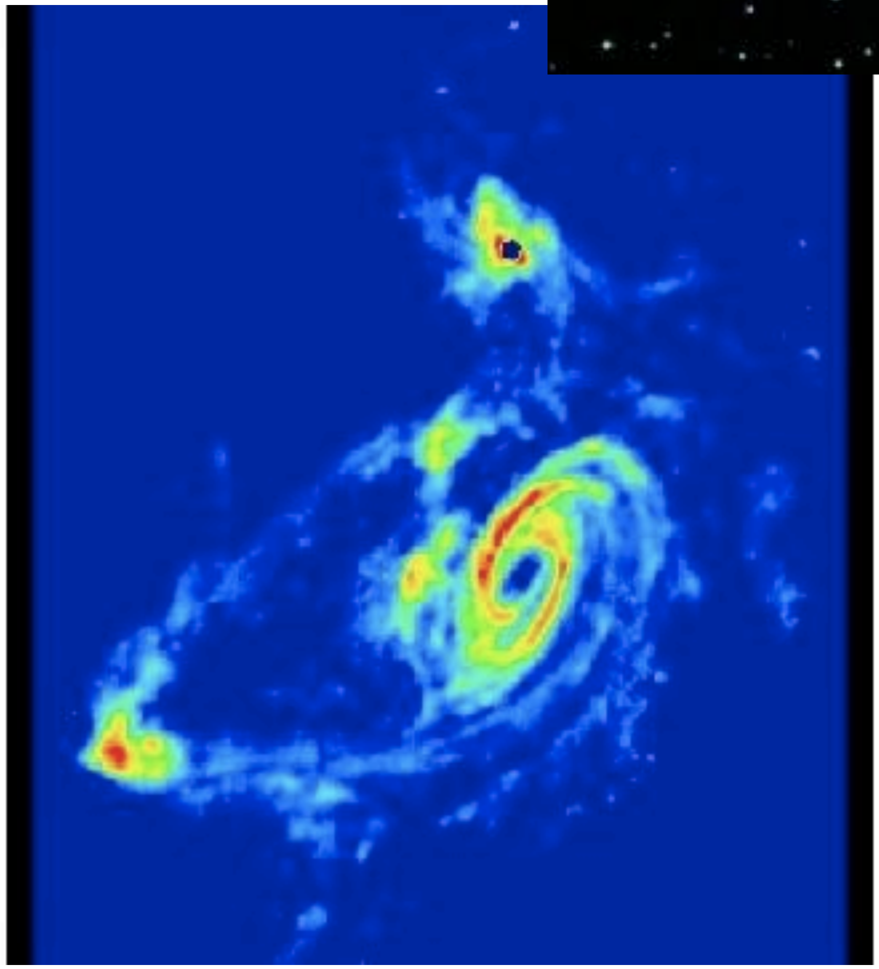
image reconstruction

Radio Astronomy

History

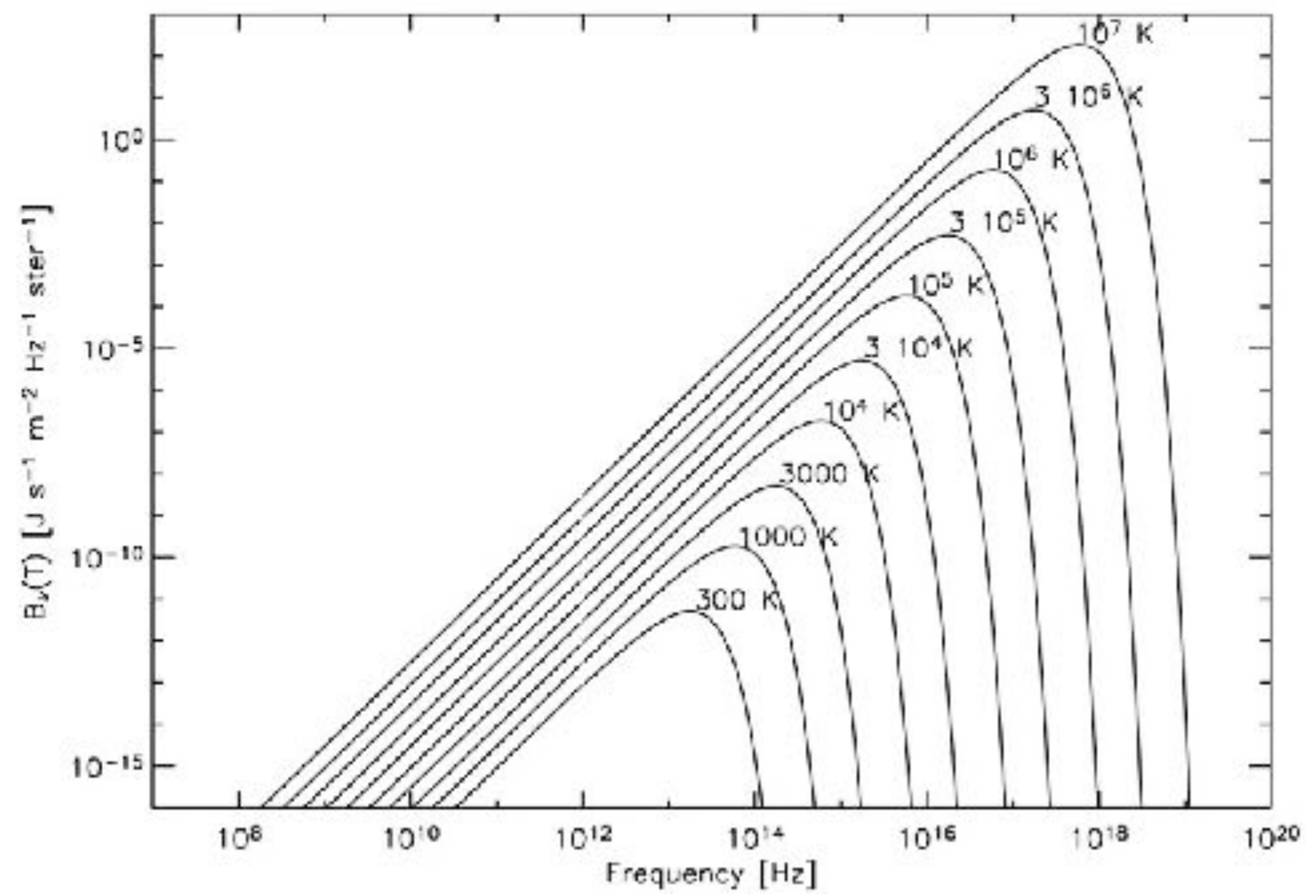
1932: Jansky detects "cosmic scatter"
1937: Reber builds 9.5m background telescope
1940: Reber puiblishes 1st ApJ paper
1944: van der Hulst predicts H I line frequency
1951: Ewen and Purcell detect HI line
1964: Penzias & Wilson 3K CMB
1968: Bell & Hewitt discover pulsars

- gamma rays (> ~1 MeV)
- hard X-rays (10-1000 keV)
- soft X-rays (1-10 A)
- EUV (~100 A)
- UV (~1000 A)
- visible (4000-7000 A -- 400-700 nm)
- near IR (~1 micron)
- IR (10 microns)
- THz (~100 microns--3000 GHz)
- submillimeter (300 GHz - 700 GHz)
- millimeter (30 GHz - 300 GHz)
- microwave (3 GHz - 30 GHz)
- decimeter (300 MHz - 3 GHz) ("cable" TV/UHF band)
- meterwave (30 MHz - 300 MHz) (TV/FM/HF band)
- dekameter (3 MHz - 30 MHz) (Shortwave
- AM band (0.5 MHz - 1.7 MHz)



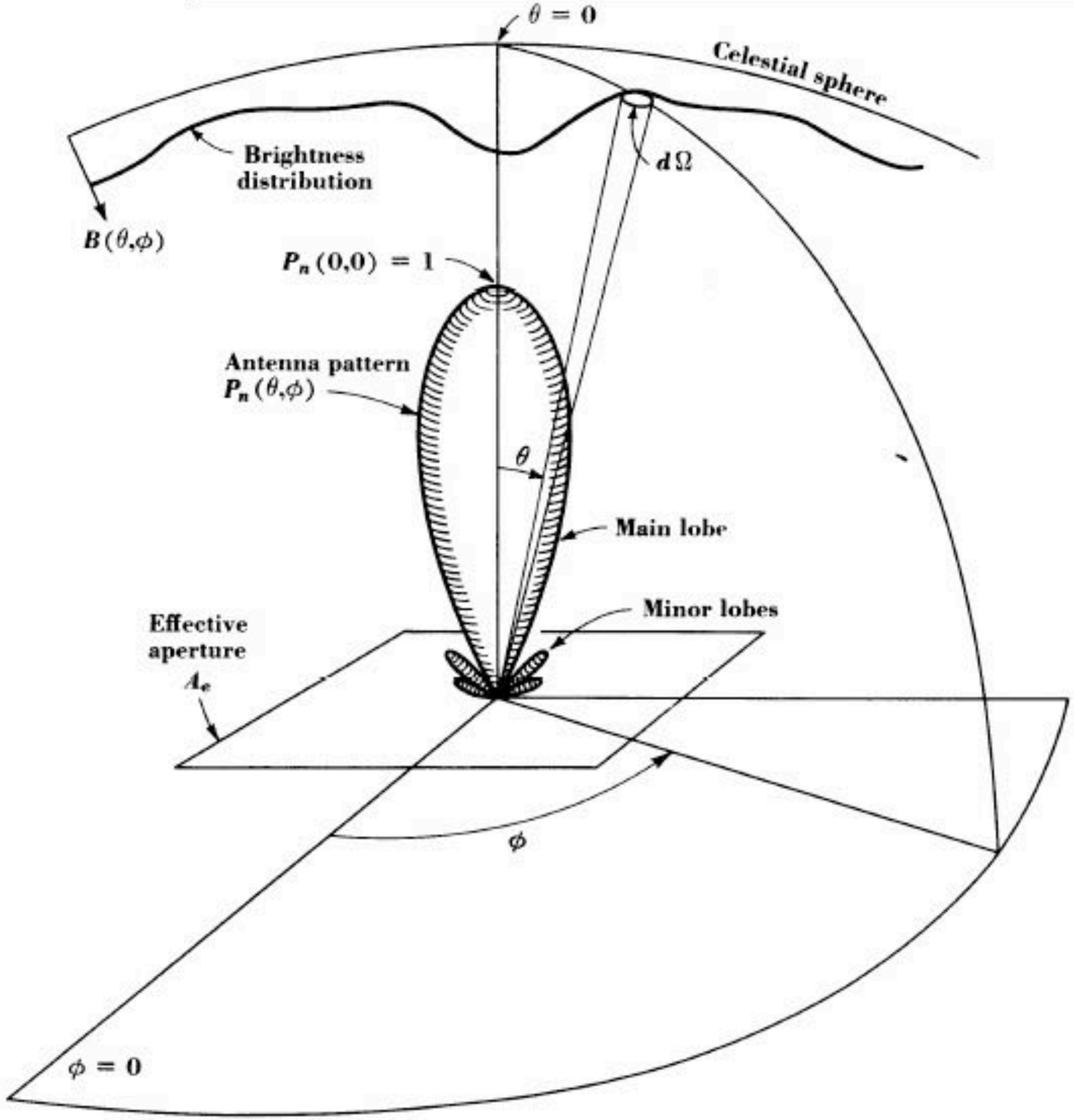
these notes come from http://web.njit.edu/~dgary/728 by Prof. Dale Gary

Brightness Temp.



if unresolved then integral over object

if resolved then integral over beam



Normalized antenna pattern $P_n(\theta,\phi)$ (max = 1)

Radio astronomers like to relate everything to temperature!

$$\text{Received power} \quad W = \frac{1}{2} A_e \iint_{\Omega} B(\theta,\phi) P_n(\theta,\phi)\, d\Omega$$

Extended source: Size >> beam of brightness temperature T_B

$$\text{Extended source: Size} \gg \text{beam of brightness temperature } T_B$$

$$W \approx \frac{1}{2} B\, A_e \Omega_A = \frac{kT_B}{\lambda^2} A_e \Omega_A$$

EXACT result. Can see this is roughly the same as $\theta = \lambda/D$ (diffraction limit)

$$\text{Antenna theorem:} \quad A_e \Omega_A = \lambda^2$$

$\therefore W = kT_B$ Turn this round and ***define*** antenna temp. $T_A = W/k$

$$\text{Compact source: write } S_A = \iint_{\Omega} B(\theta,\phi) P_n(\theta,\phi)\, d\Omega = \frac{2kT_B}{\lambda^2} \Omega_S$$

Definition of T_B & Ω_S

$$W = kT_A = \frac{1}{2} A_e S_A = \frac{kT_B}{\lambda^2} A_e \Omega_S$$

$$\Rightarrow \boxed{S_A = \frac{2kT_A}{A_e}}$$

Antenna Temperature, brightness temperate and measured power

$$T_A = T_B \frac{\Omega_S}{\Omega_A} \quad \text{(compact source)}$$

$$T_A = T_B \quad \text{(extended source)}$$

Photon/wave crossover

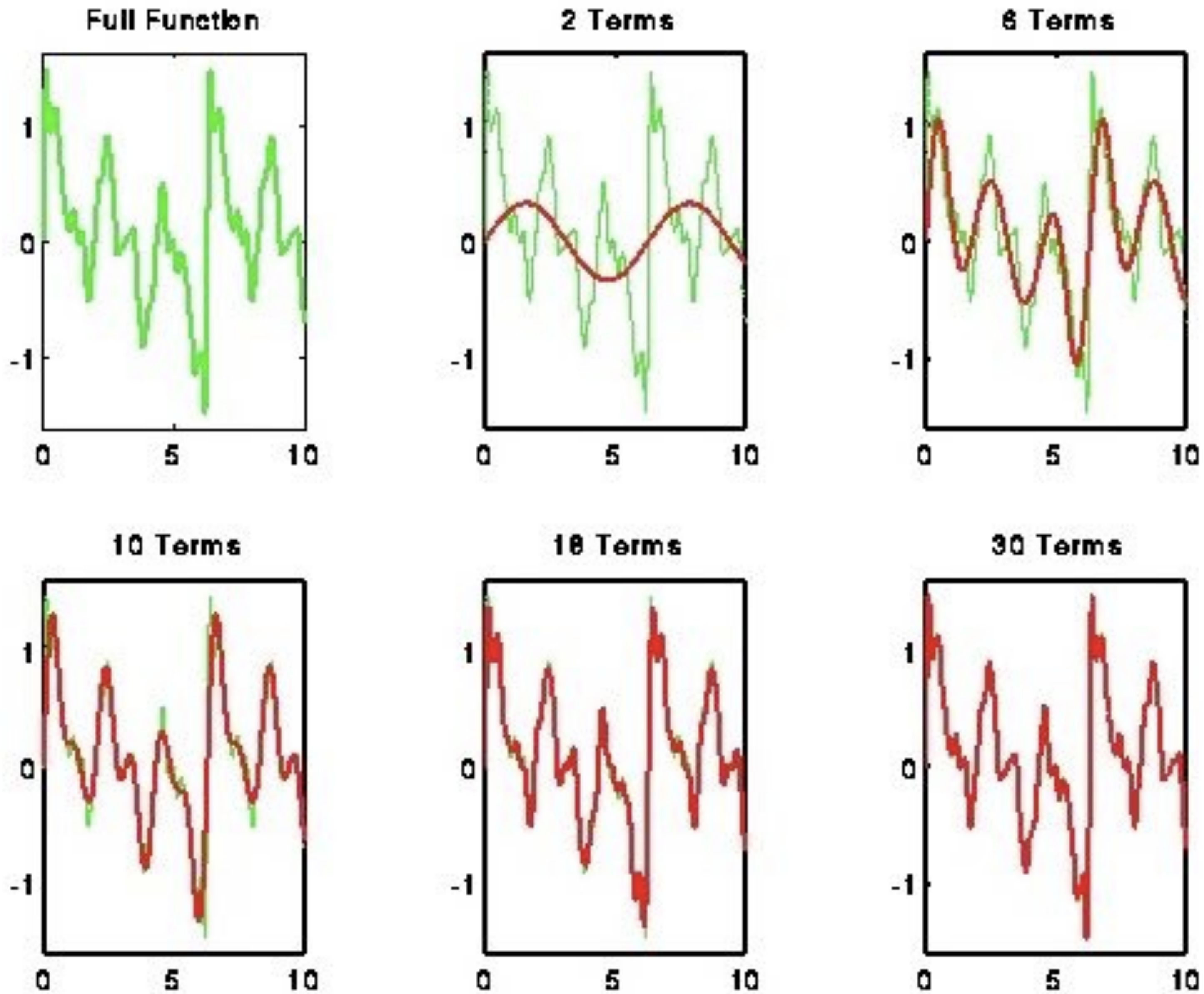
$h\upsilon = kT$

T=100K

υ = 2000 Ghz λ=144 μm

T=10K

υ = 200 Ghz λ=1.4 mm



$$h(t) \quad \Leftrightarrow \quad H(f)$$

$$h(t) = \int_{-\infty}^{\infty} H(f) e^{-2\pi i f t} df$$
$$H(f) = \int_{-\infty}^{\infty} h(t) e^{2\pi i f t} dt$$

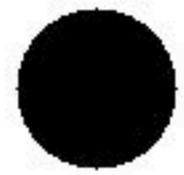
convolution and Fourier transforms

$$g * h \iff G \cdot H$$

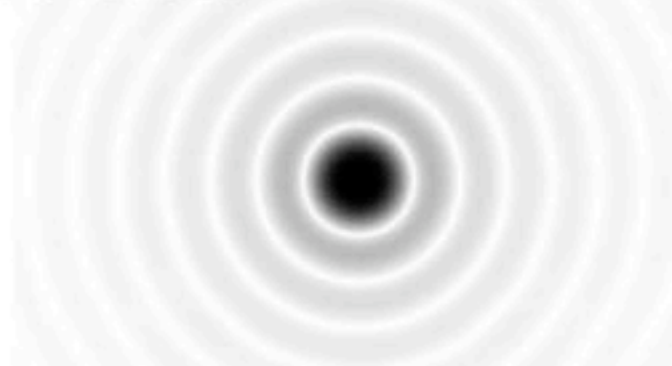
many good demonstration exercises at

http://www.jhu.edu/signals/

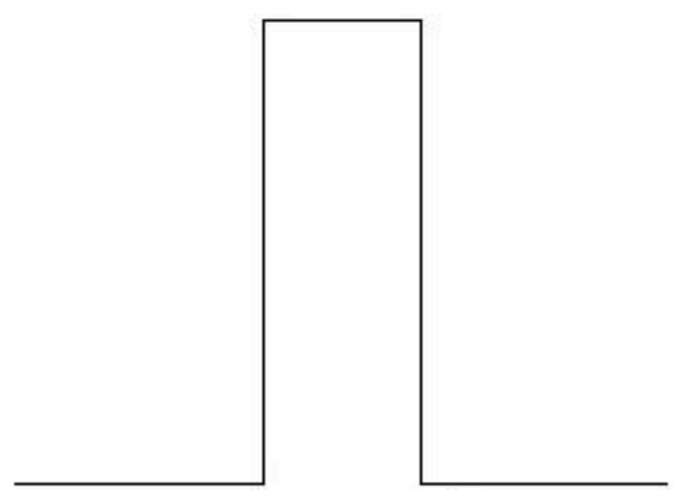
Fourier Transform relationship of aperture and beam



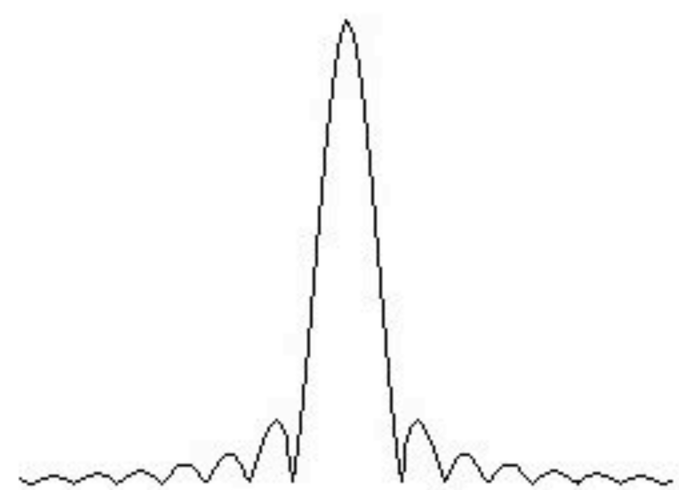
circular aperture



"diffraction" pattern



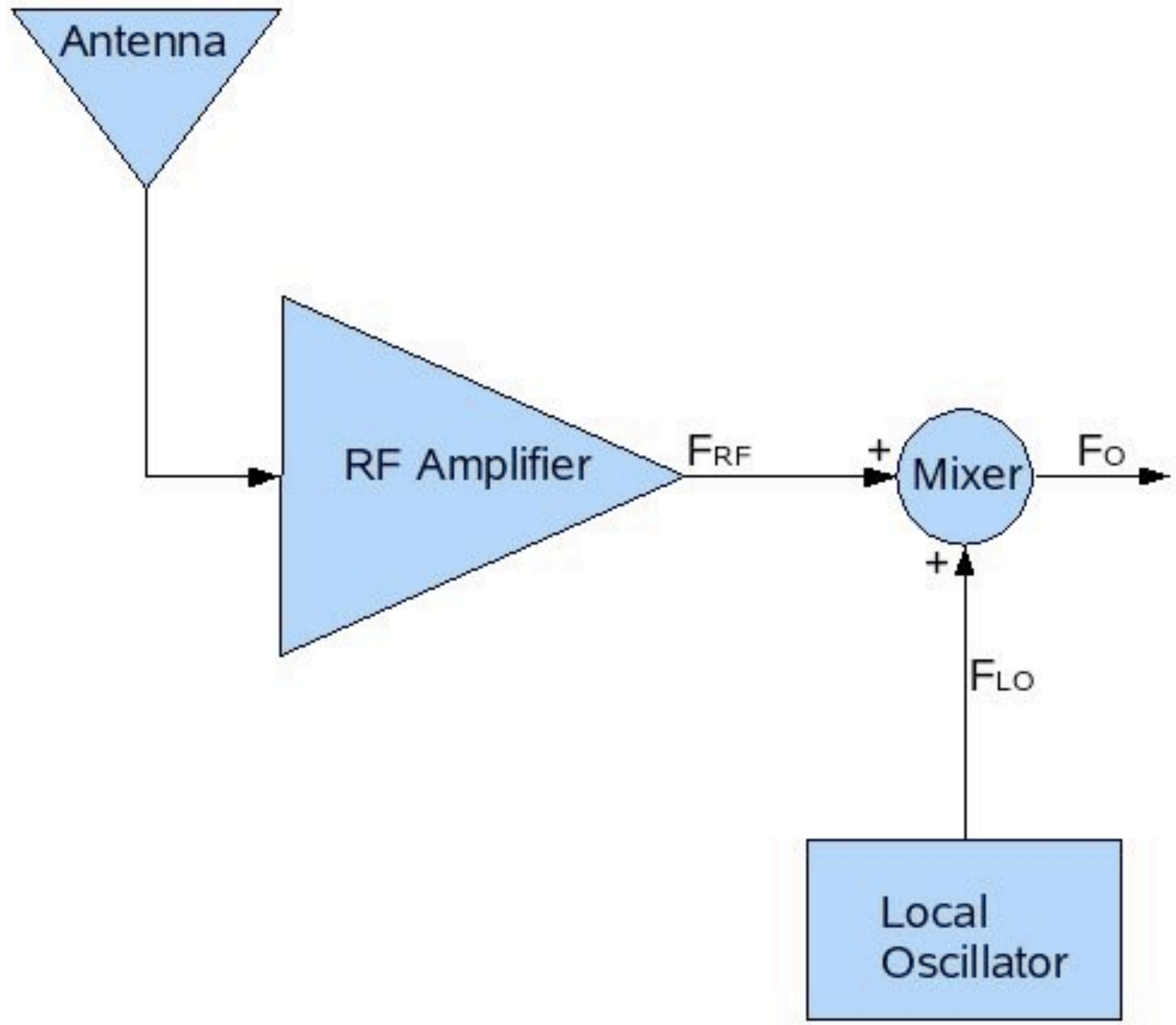
cross-section of aperture



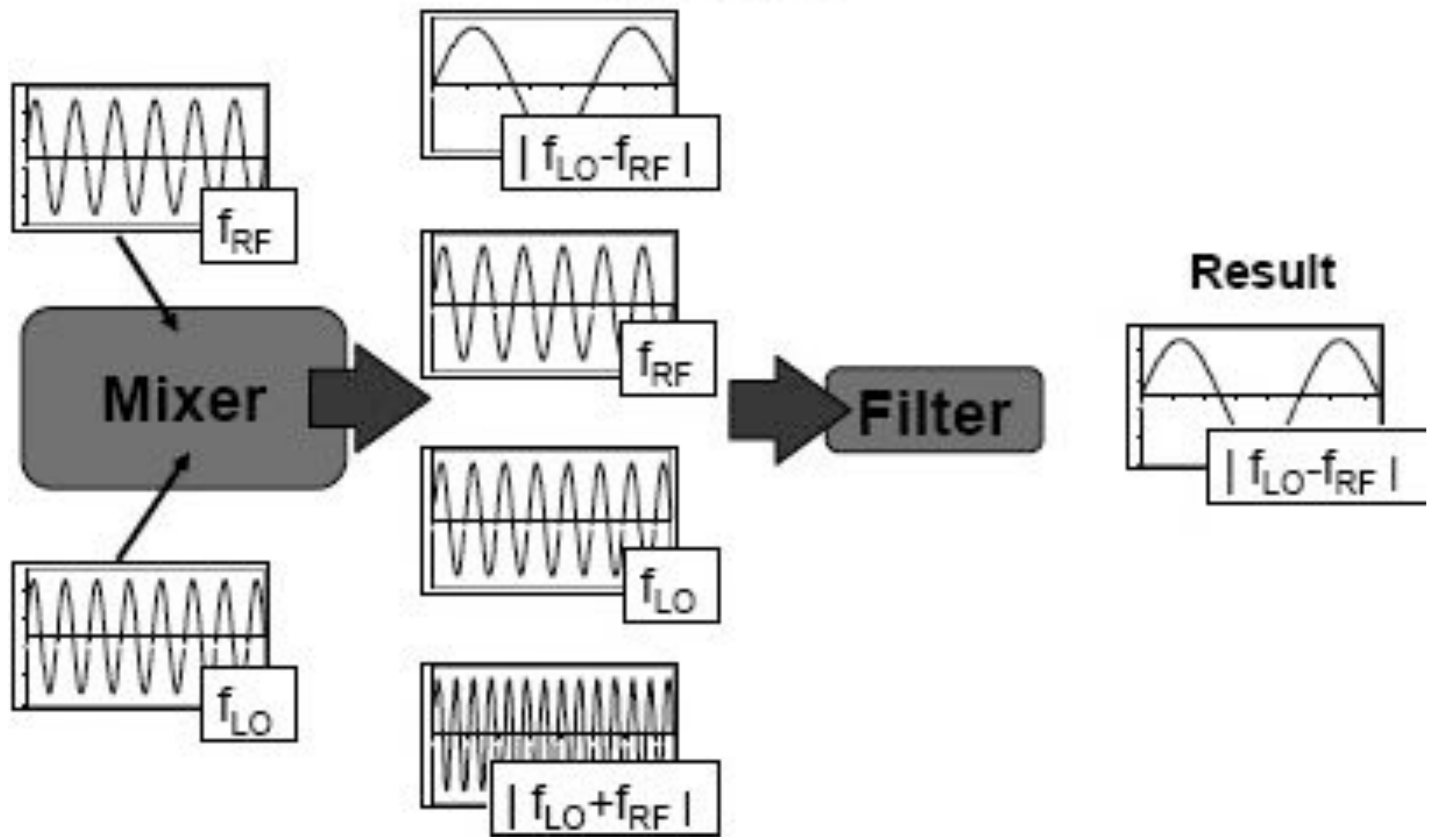
cross-section of diffraction pattern

$$f(u,v) = \int\int_{\text{all sky}} F(l,m)\, e^{-2\mathrm{p}i(ul + vm)}\, dl\, dm$$

$$F(l,m) = \int\int_{\text{aperture}} f(u,v)\, e^{2\mathrm{p}i(ul + vm)}\, du\, dv$$

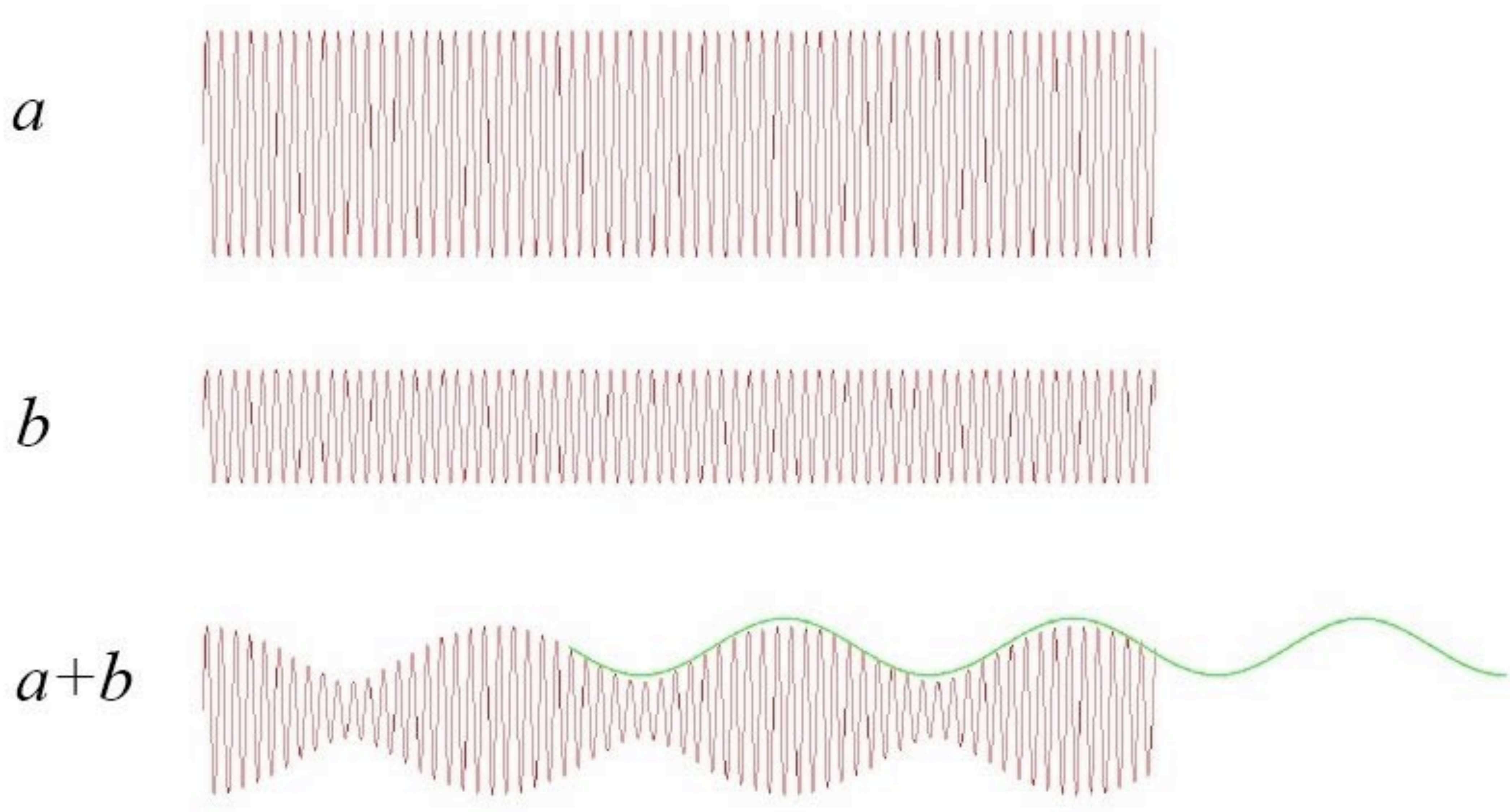

Antenna
RF Amplifier
FRF
+
Mixer
FO
+
FLO
Local
Oscillator

How does Super-heterodyning Work?



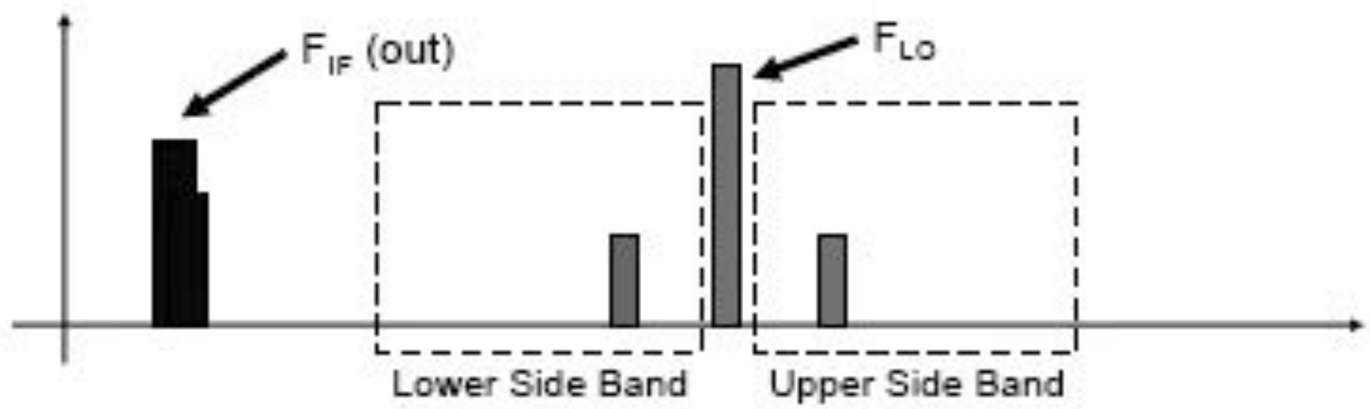
http://phobos.physics.uiowa.edu/~clang/radio/receiver_9feb06.pdf

$$ae^{iw_1 t} + be^{iw_2 t} = ae^{iw_1 t}(1 + (a - b)e^{i(w_1 - w_2)t}) + be^{iw_2 t}$$

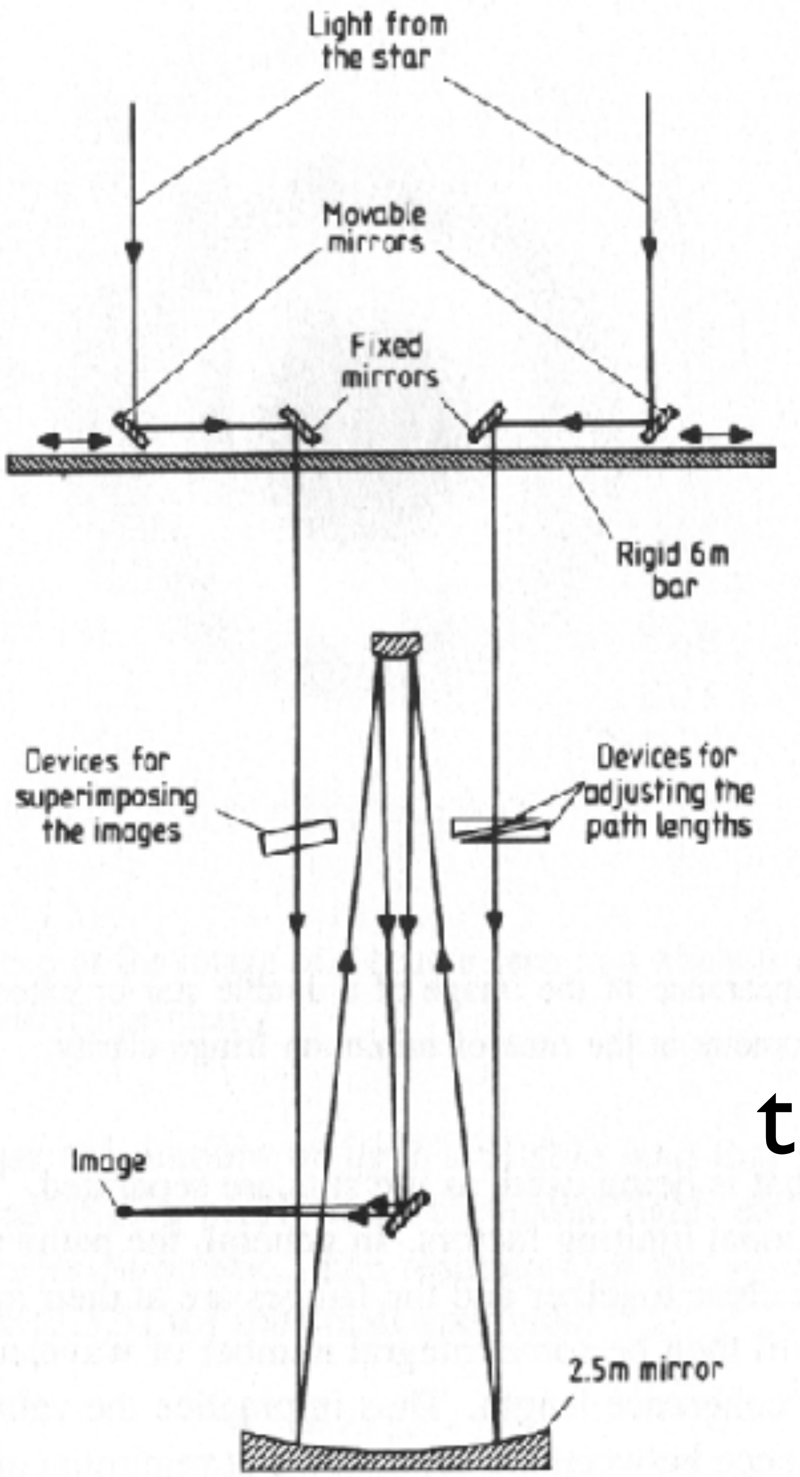


http://cartman.pha.jhu.edu/~kgb/Classes/ObsAst/class23-25.pdf

Single Side Mixers



- Super-heterodyning reduces the input signal by mixing with the LO signal, regardless of which side of the LO the input is located.



Michelson stellar interferometer

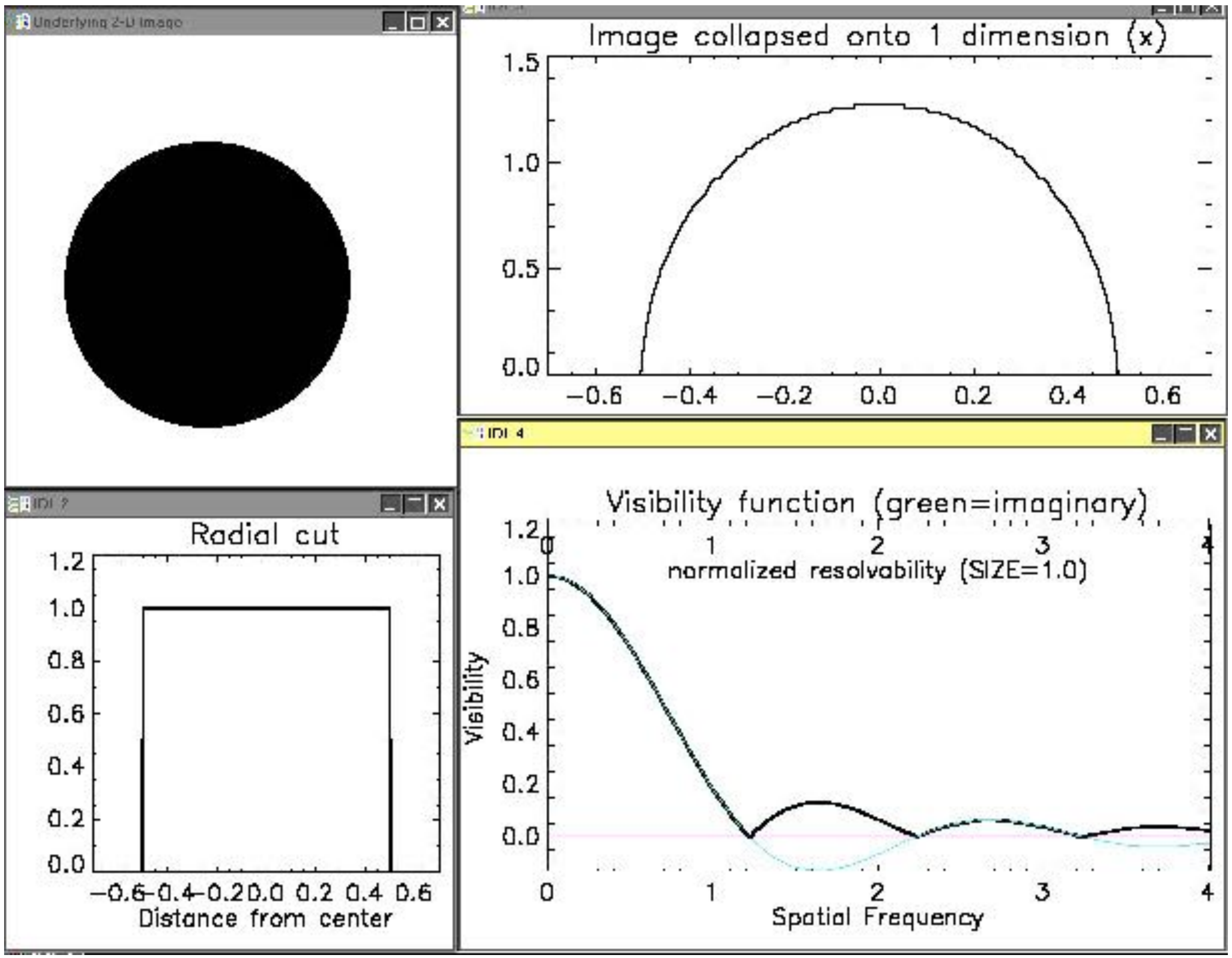
signals multiplied (correlated)

the amplitude of the correlated signal
as a function of separation
is the visibility function

some material from Prof. D. Carter's notes

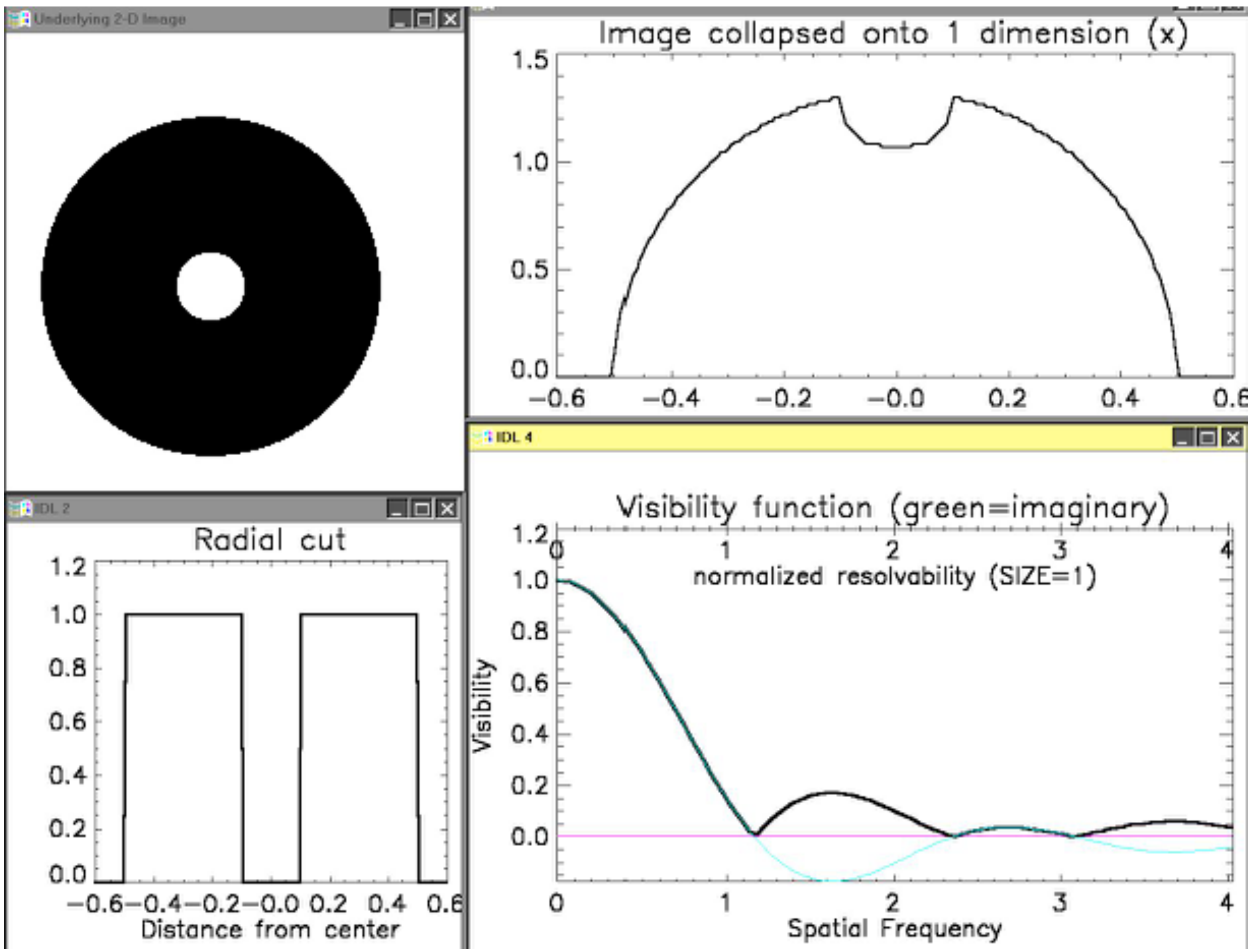
Examples of visibility functions

Uniform disk, D=1



Examples of visibility functions

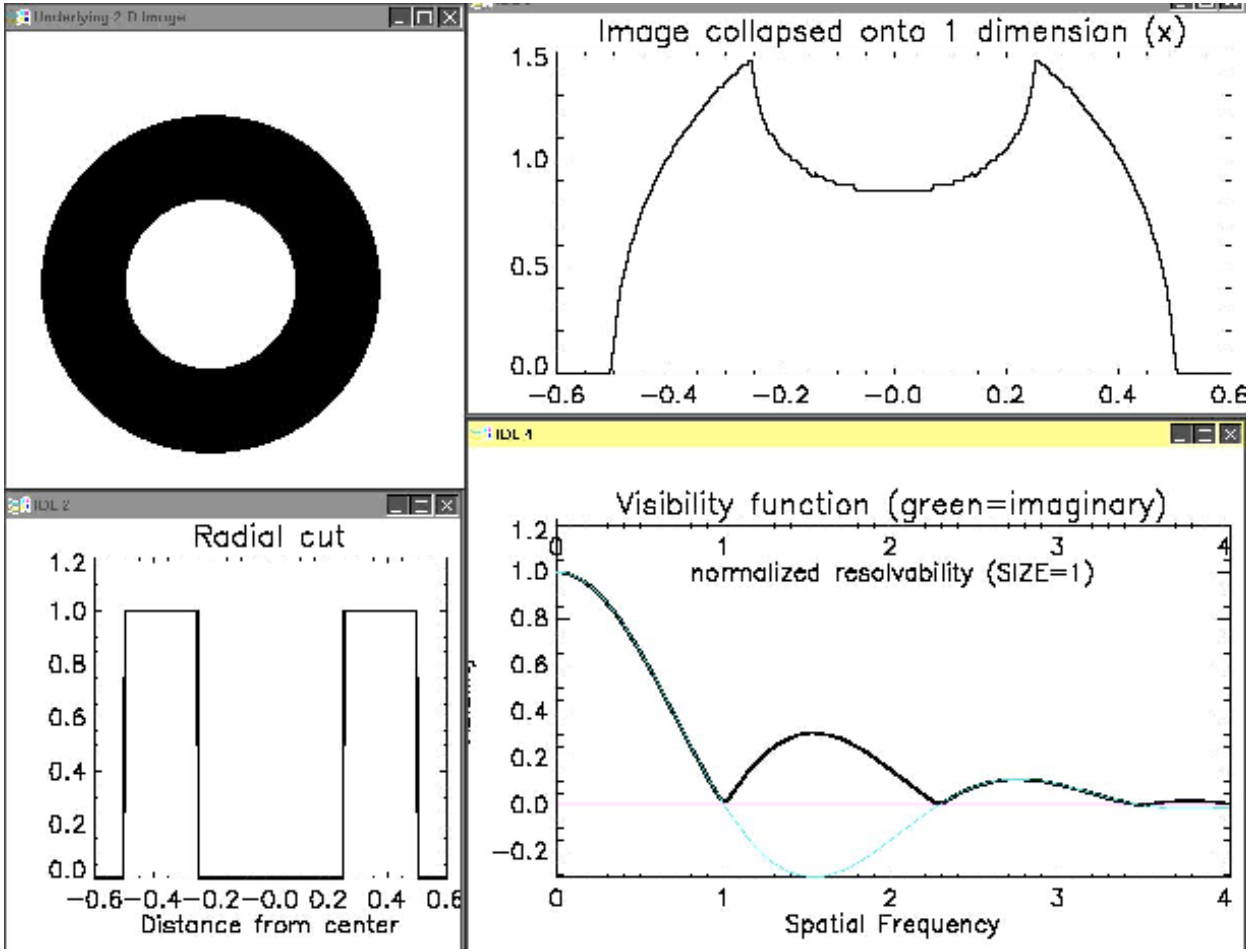
Uniform disk D=1, minus hole D=.2



http://www.strw.leidenuniv.nl/~meisner/

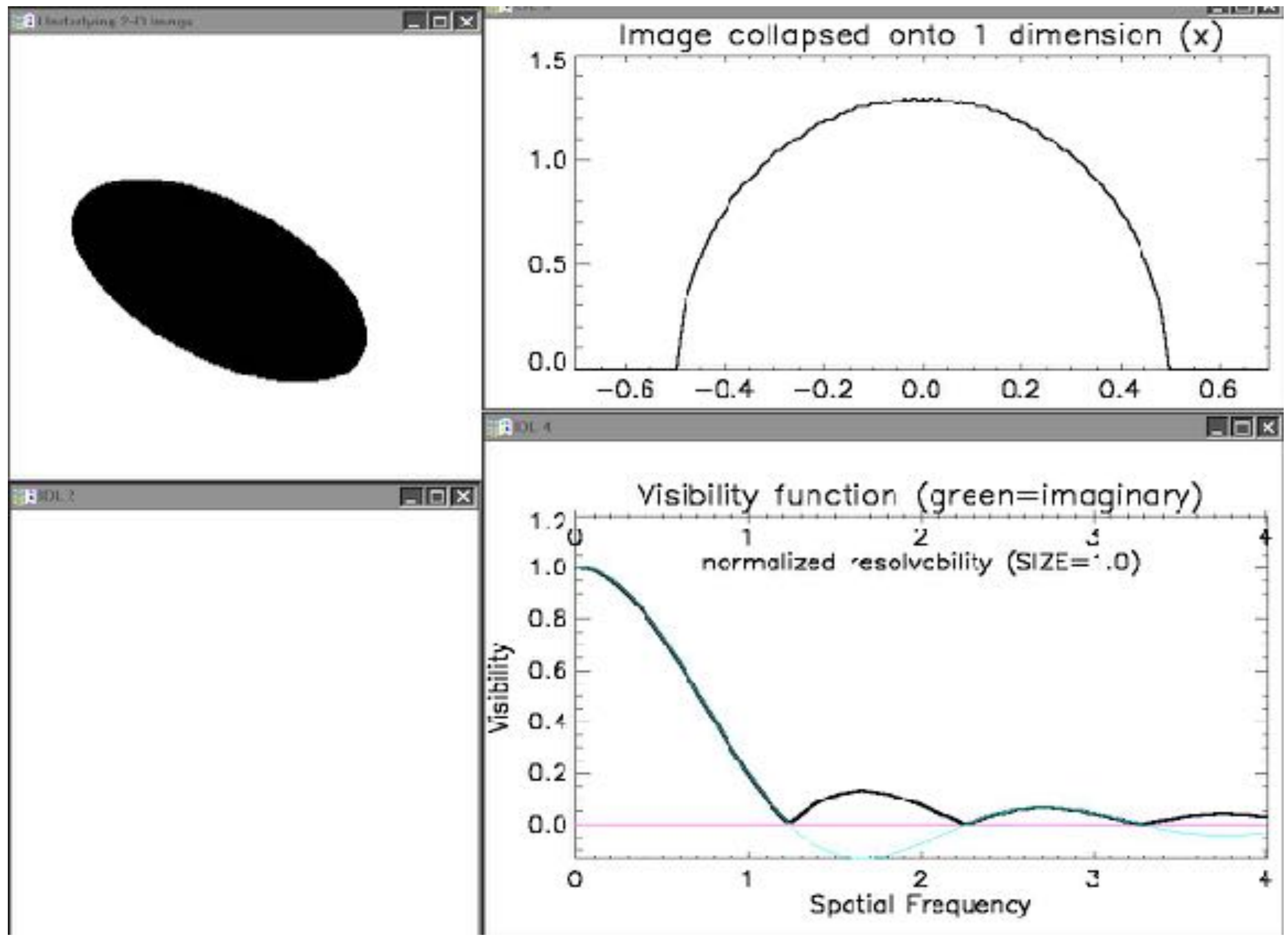
Examples of visibility functions

Uniform disk D=1, minus hole D=.5



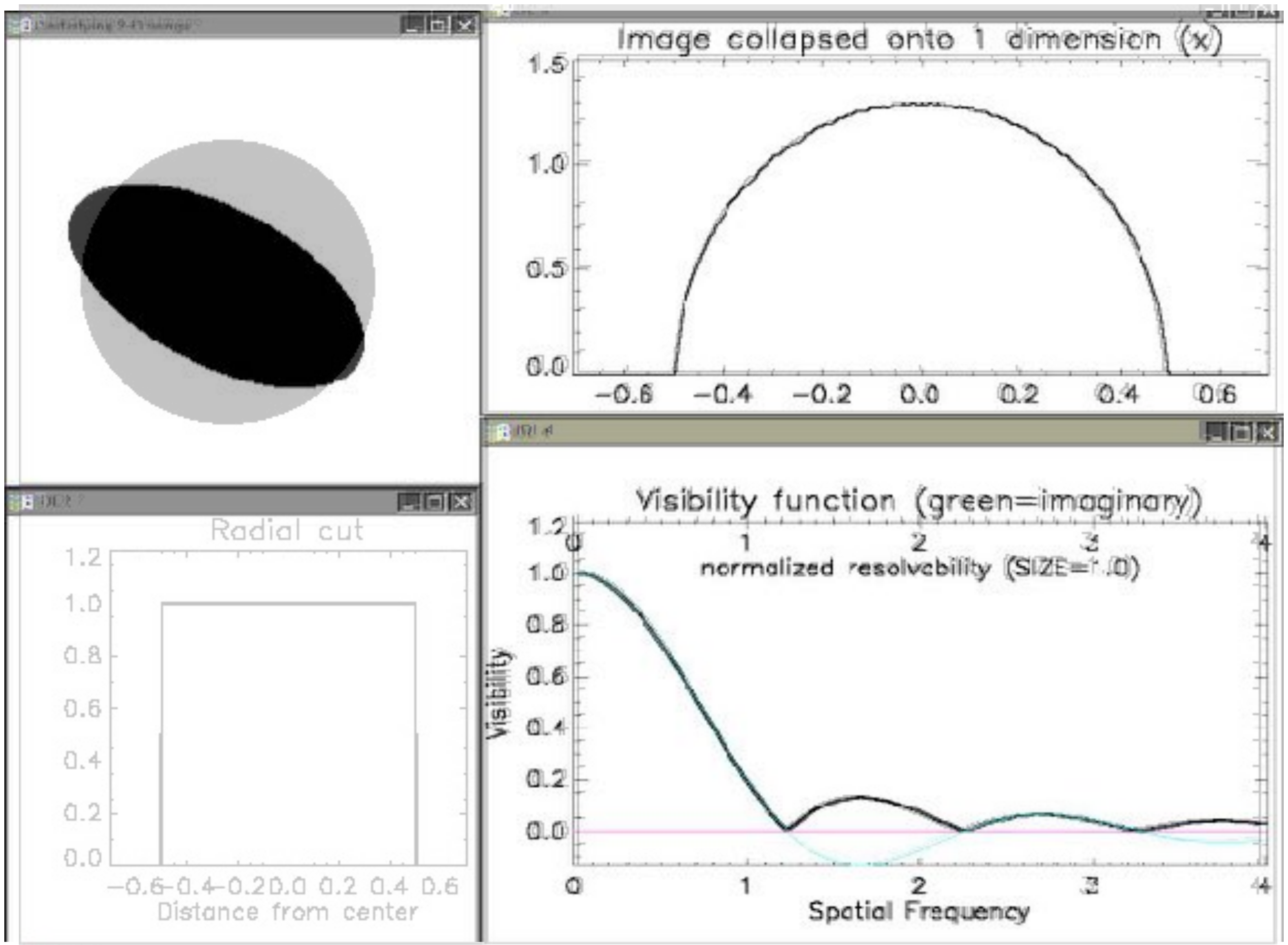
Examples of visibility functions

Solving for an ELLIPSE:



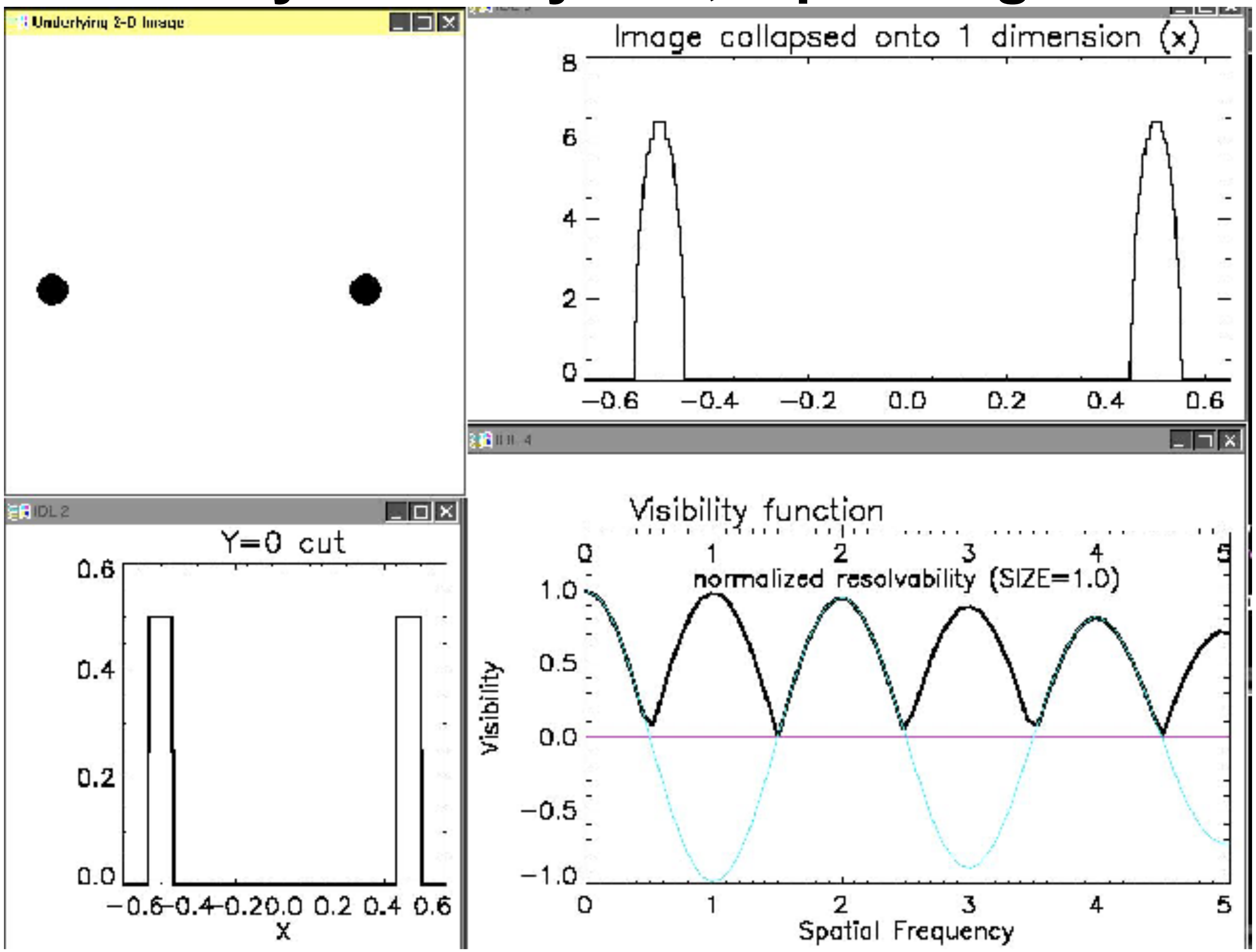
Visibility curve identical to UD.

To solve for parameters of ellipse, need to measure visibilities at 3 (or more) distinct position angles…

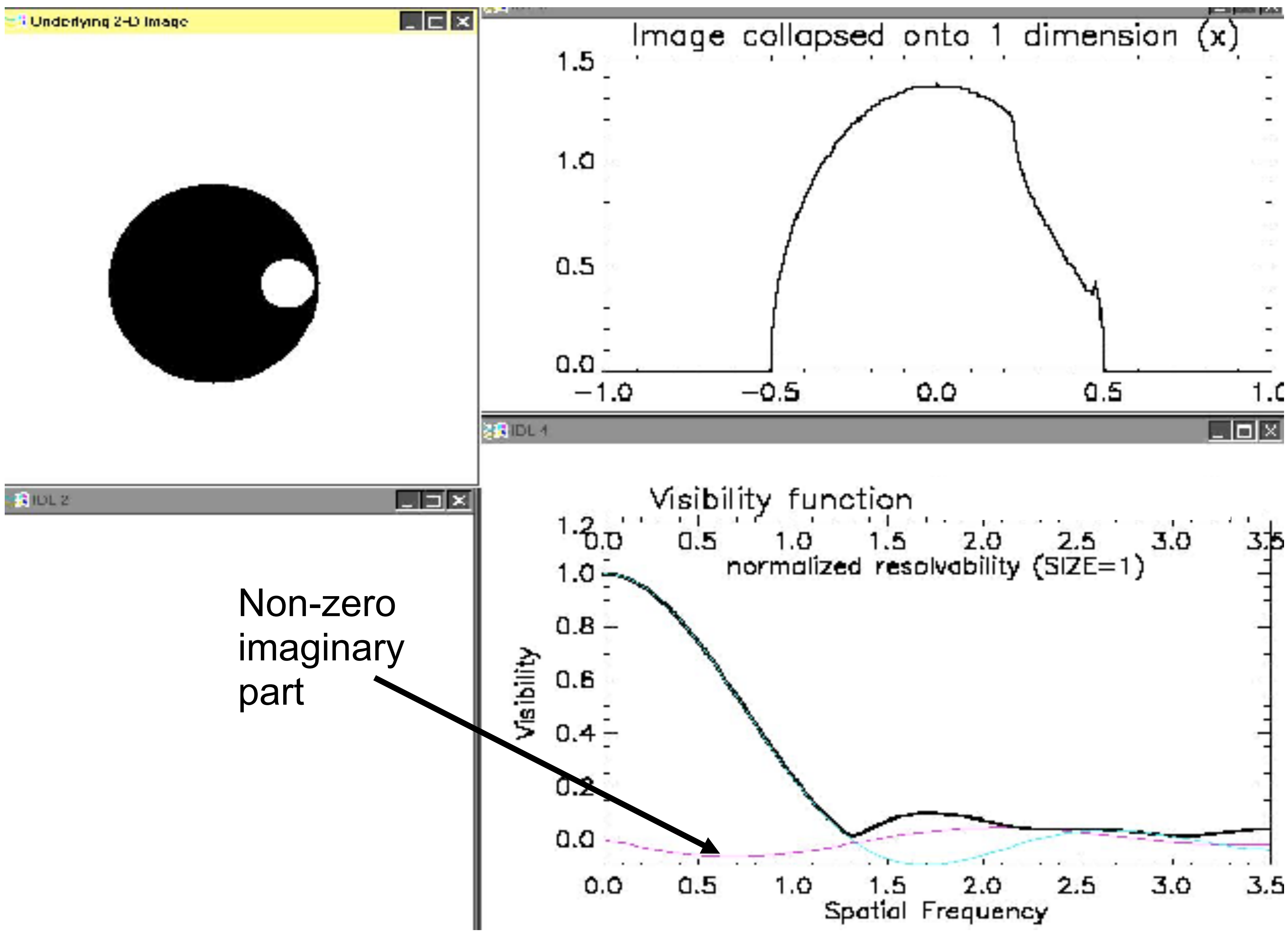


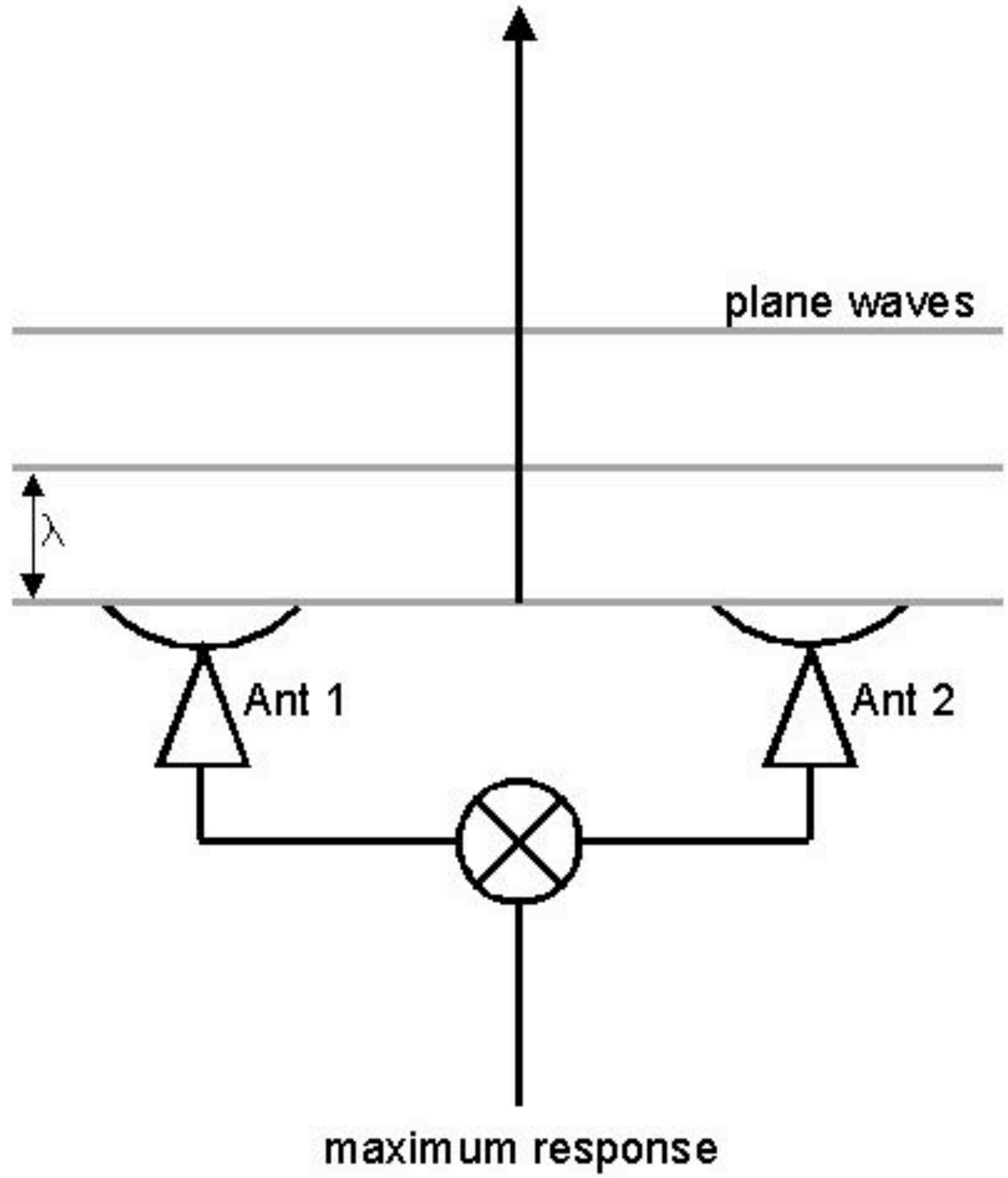
circle and ellipse visibility curves overlaid

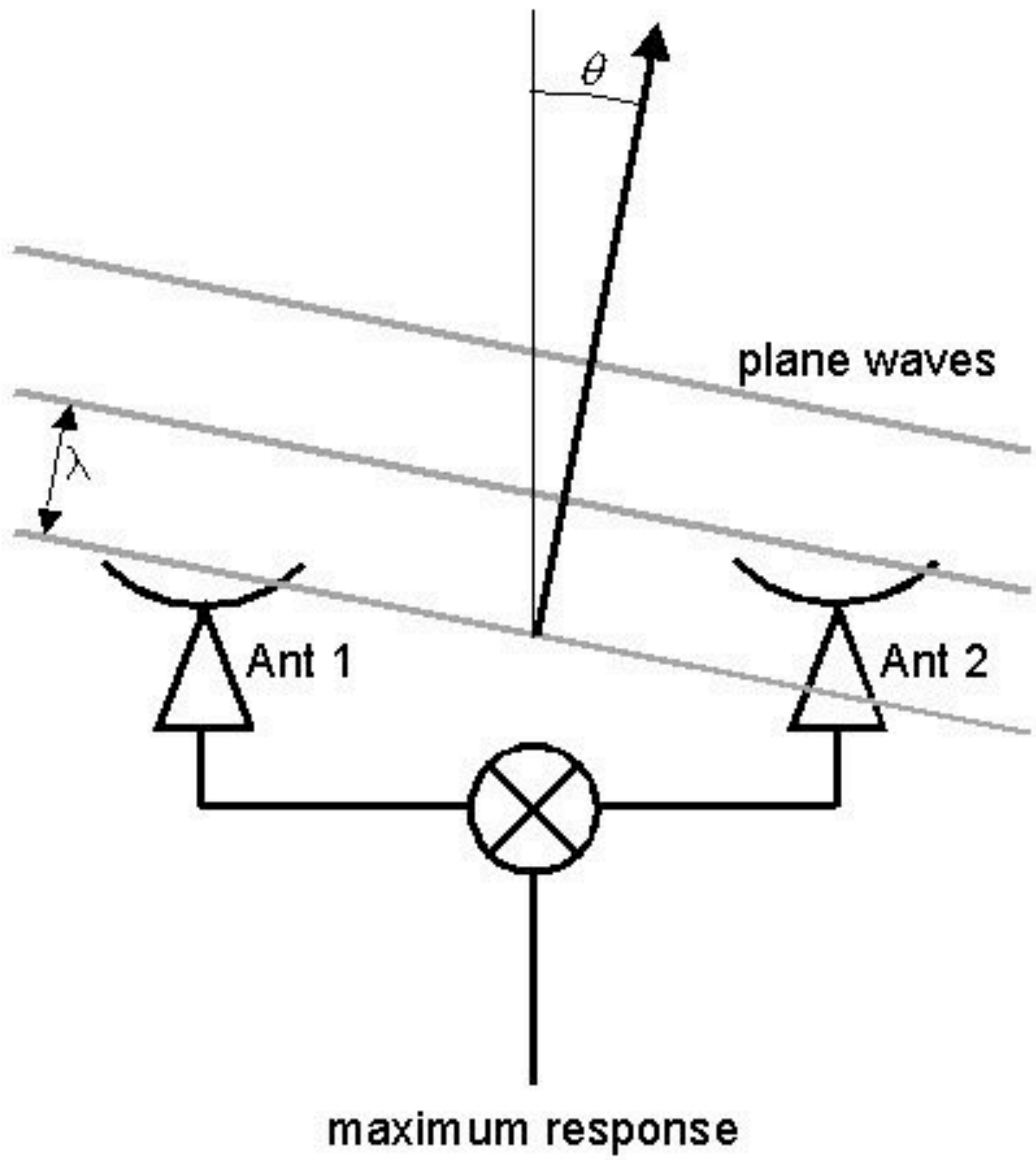
Visibility of binary star, equal brightness

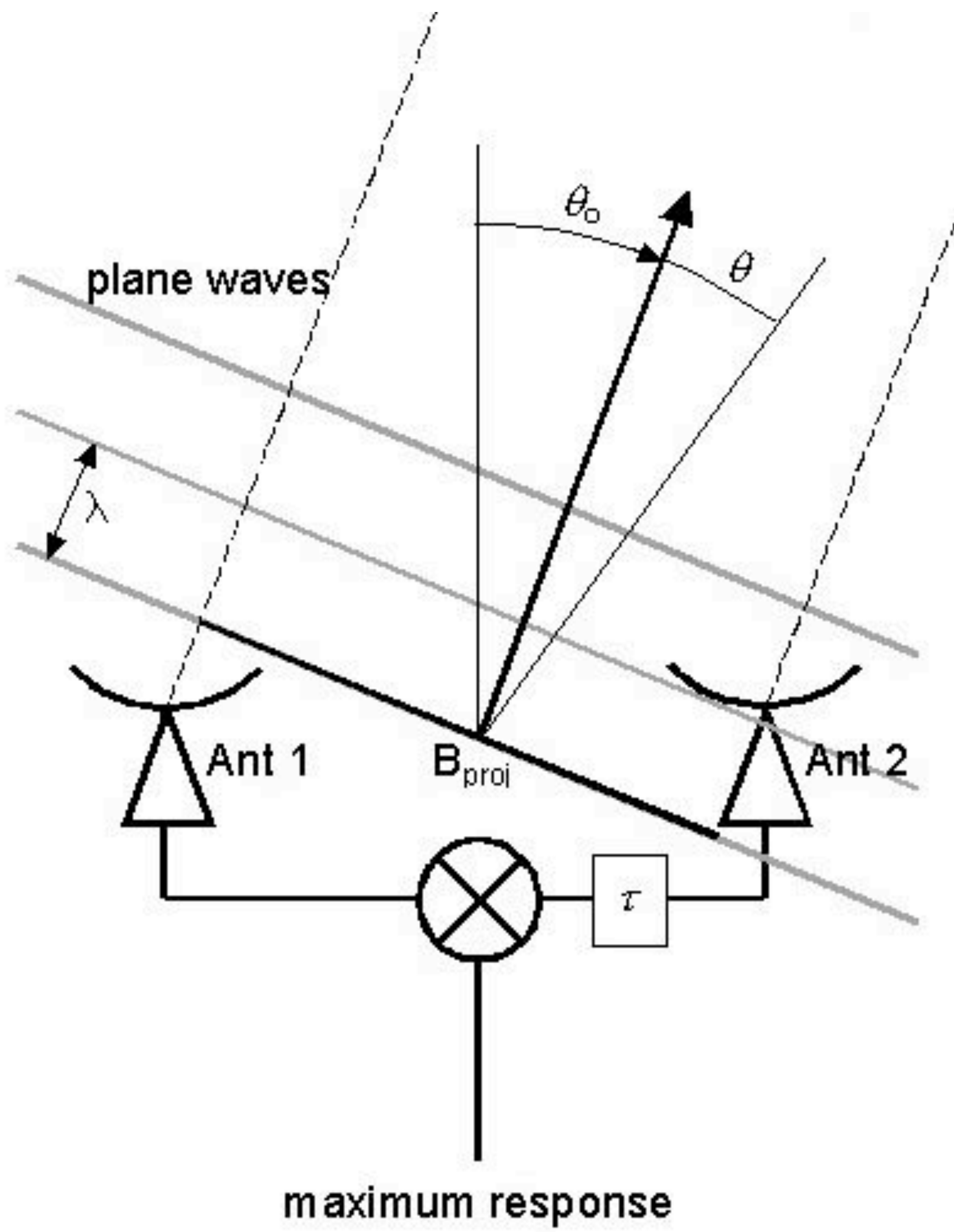


Another example where PHASE is the most sensitive quantity: planet transiting a star

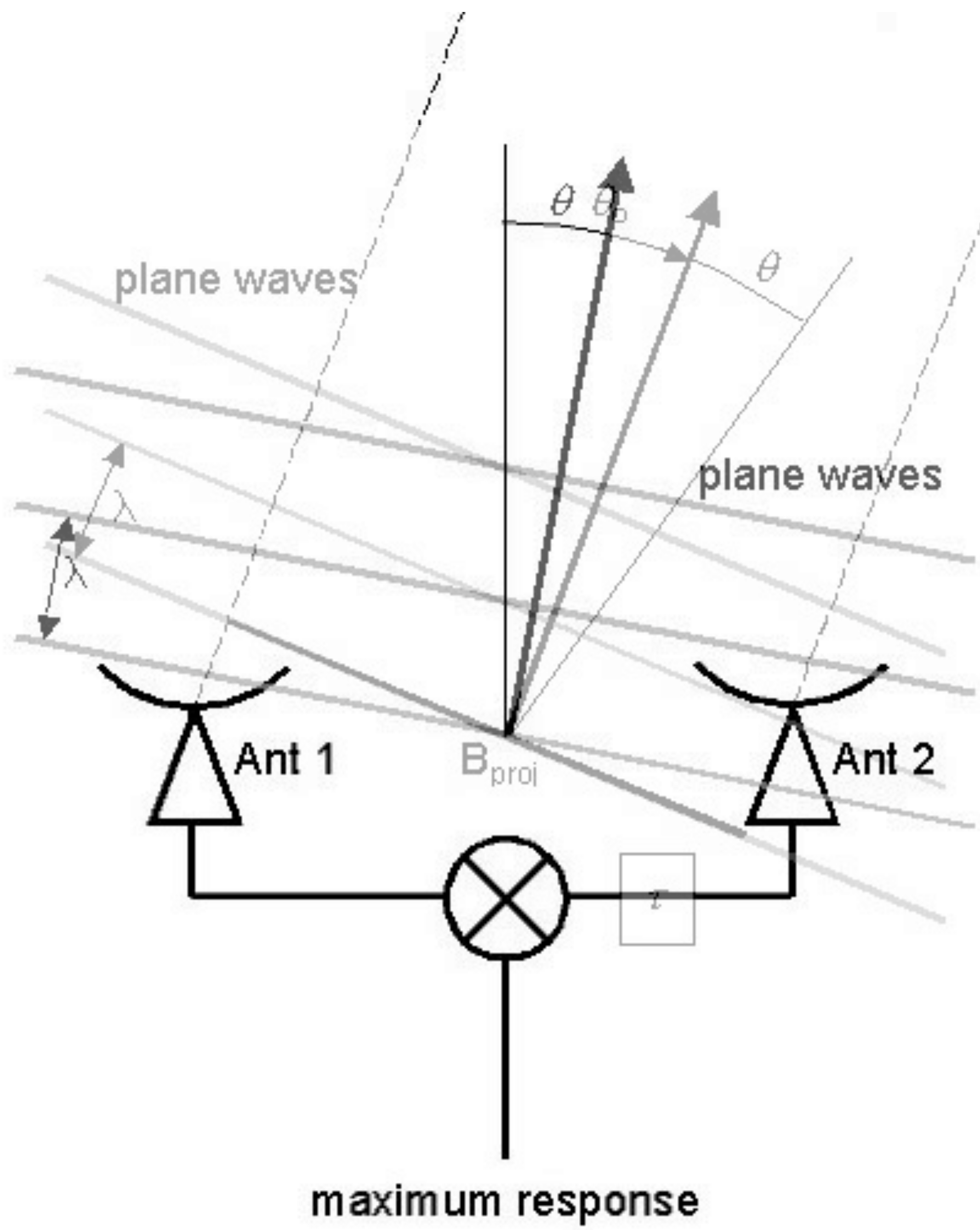



plane waves
λ
Ant 1
Ant 2
maximum response

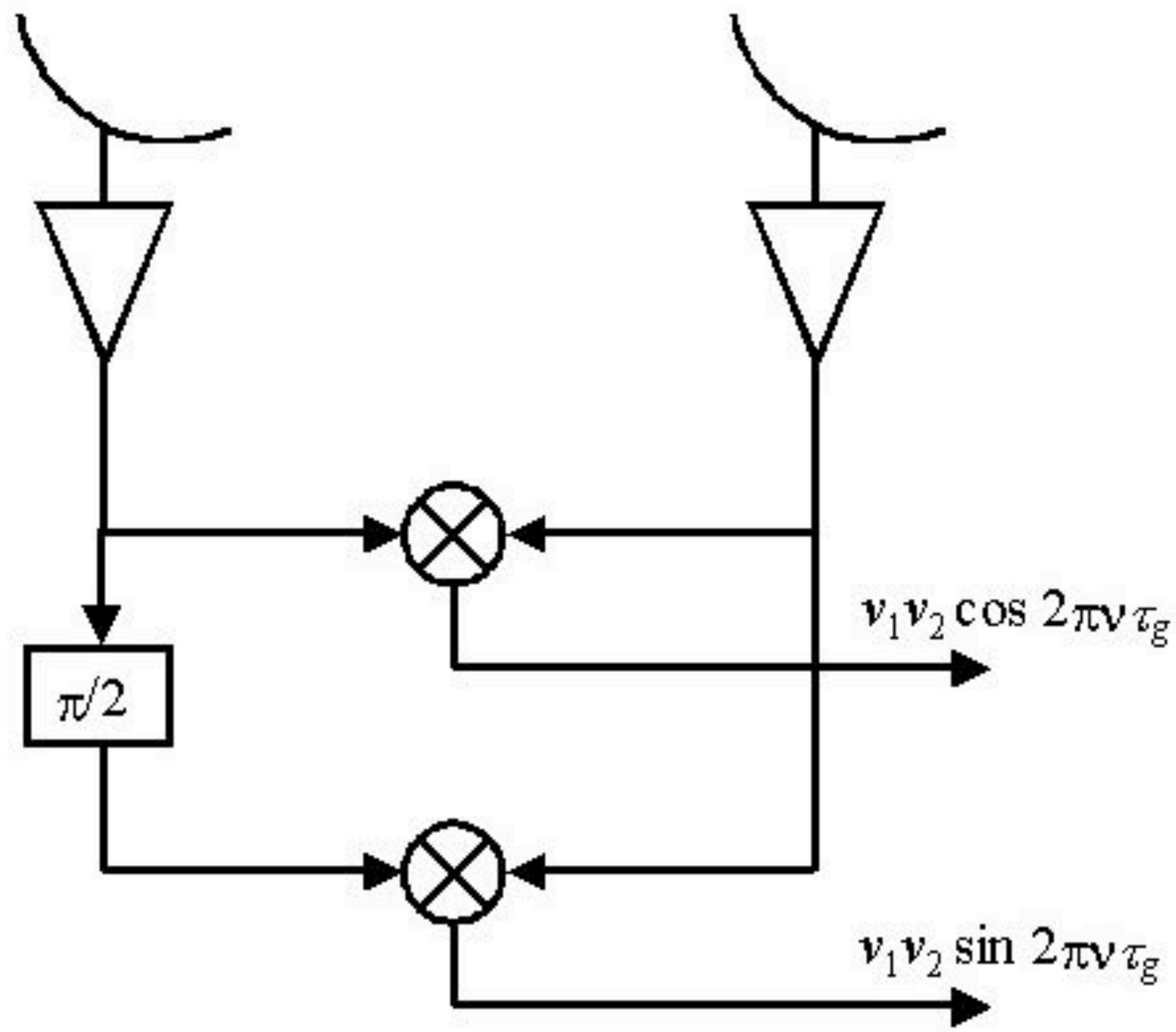

θ
plane waves
λ
Ant 1
Ant 2
maximum response



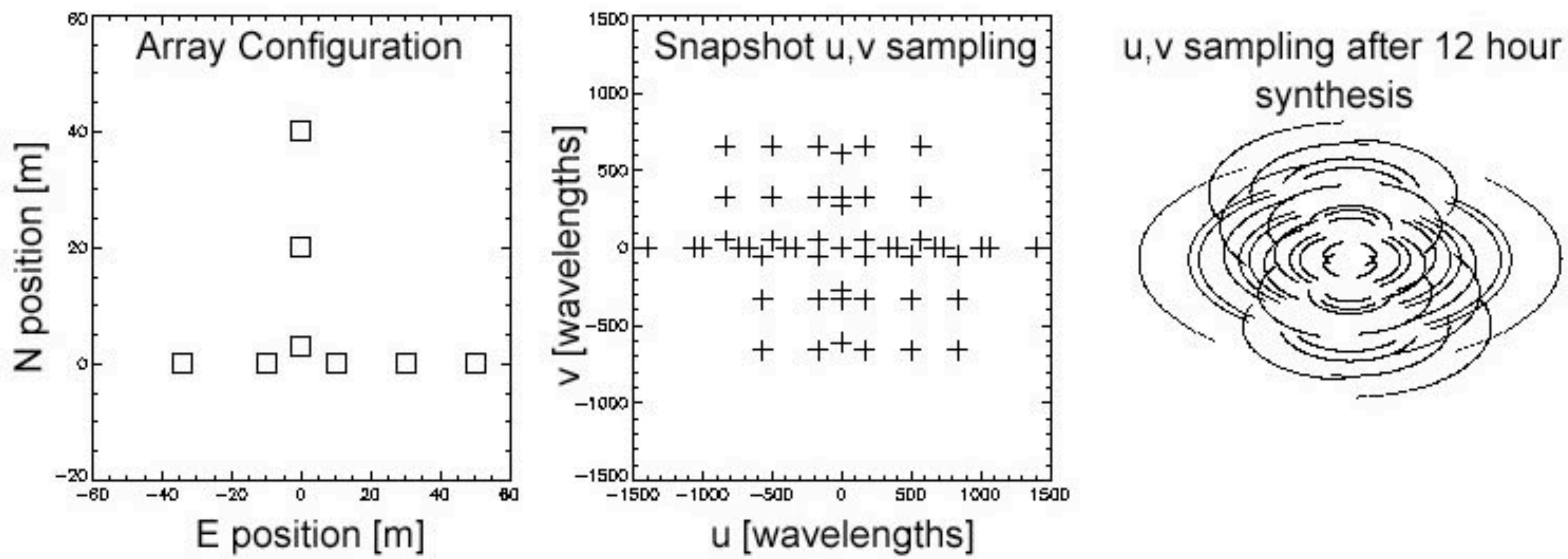
plane waves
θ_o
θ
λ
Ant 1
B_{proj}
Ant 2
τ
maximum response

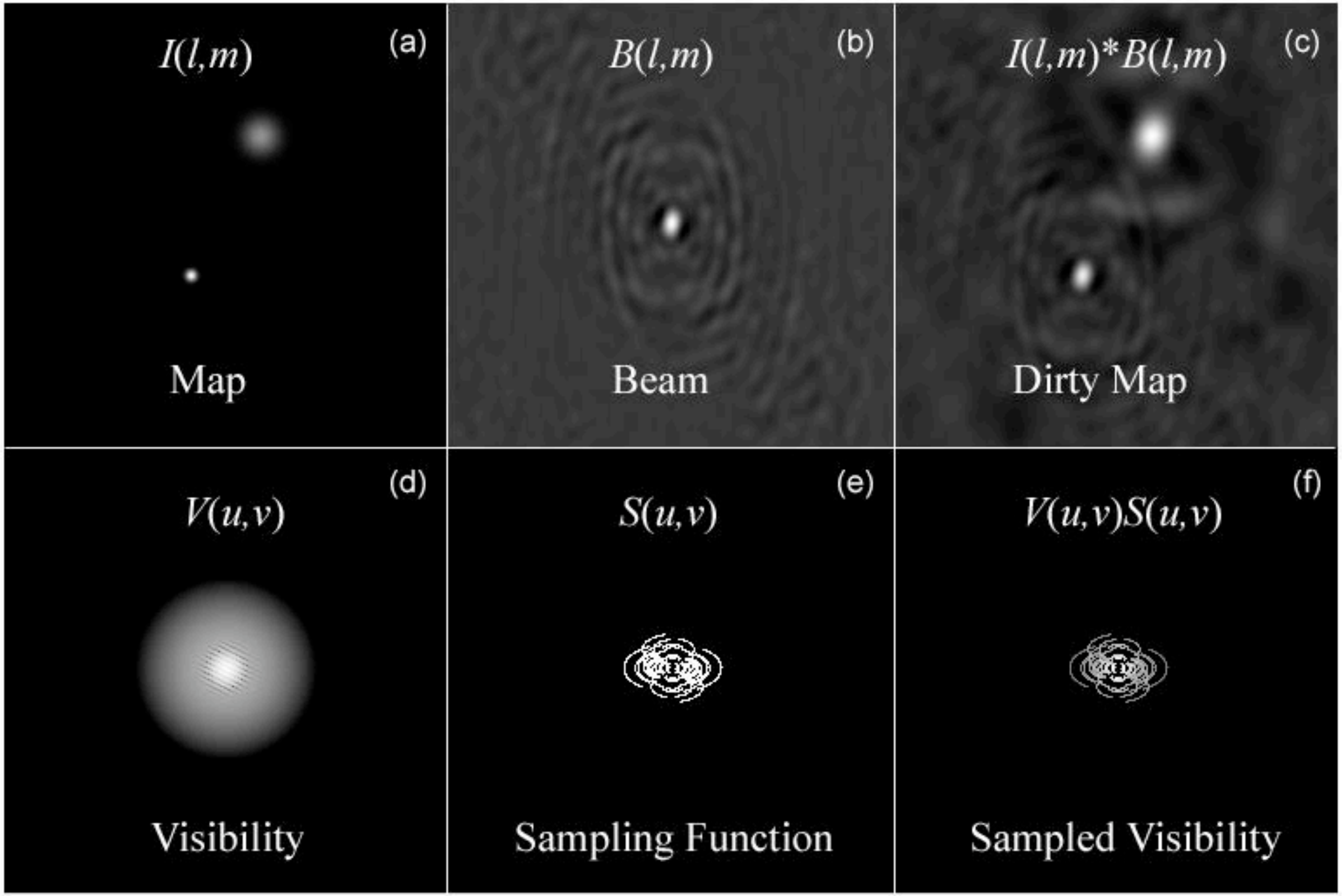


plane waves
plane waves
θ θ_0
θ
λ
λ
Ant 1
B_{proj}
Ant 2
τ
maximum response



π/2
$v_1 v_2 \cos 2\pi\nu\tau_g$
$v_1 v_2 \sin 2\pi\nu\tau_g$


Array Configuration
N position [m]
E position [m]
Snapshot u,v sampling
v [wavelengths]
u [wavelengths]
u,v sampling after 12 hour synthesis

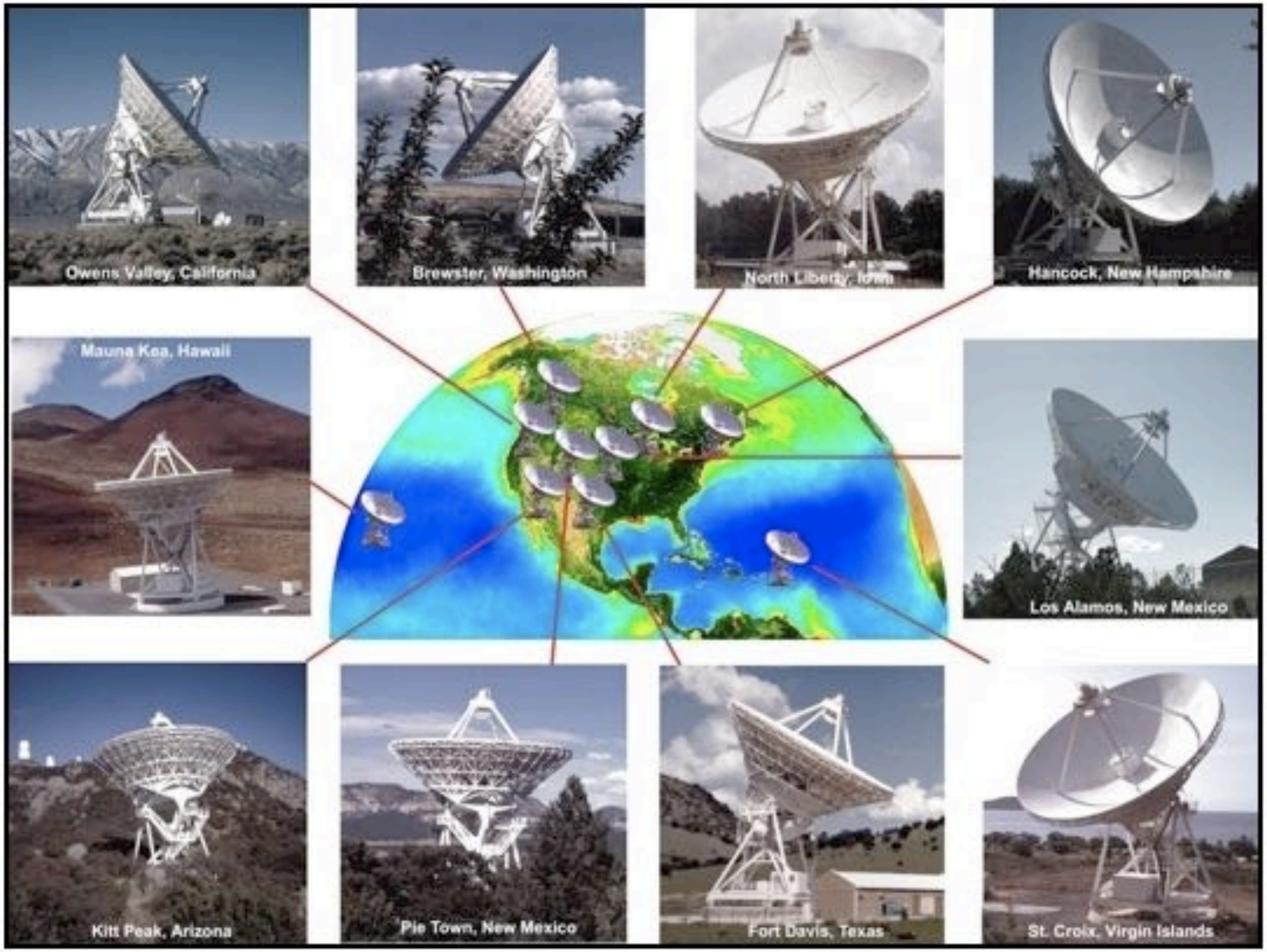


subtract delta function * dirty beam

iterate

stop when you've reached noise

VLA


Owens Valley, California
Brewster, Washington
North Liberty, Iowa
Hancock, New Hampshire
Mauna Kea, Hawaii
Los Alamos, New Mexico
Kitt Peak, Arizona
Pie Town, New Mexico
Fort Davis, Texas
St. Croix, Virgin Islands

VLBA

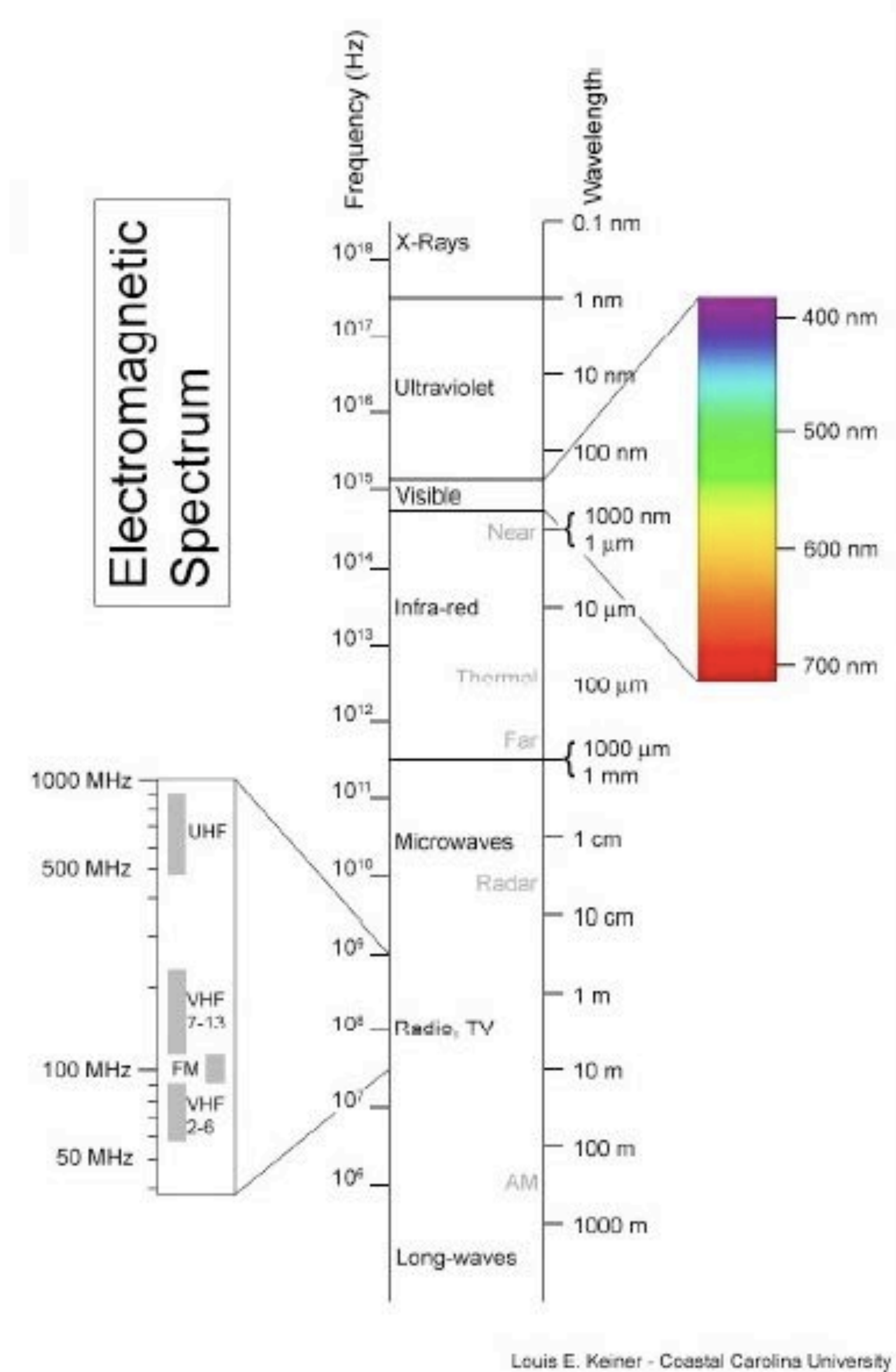
UV Astronomy

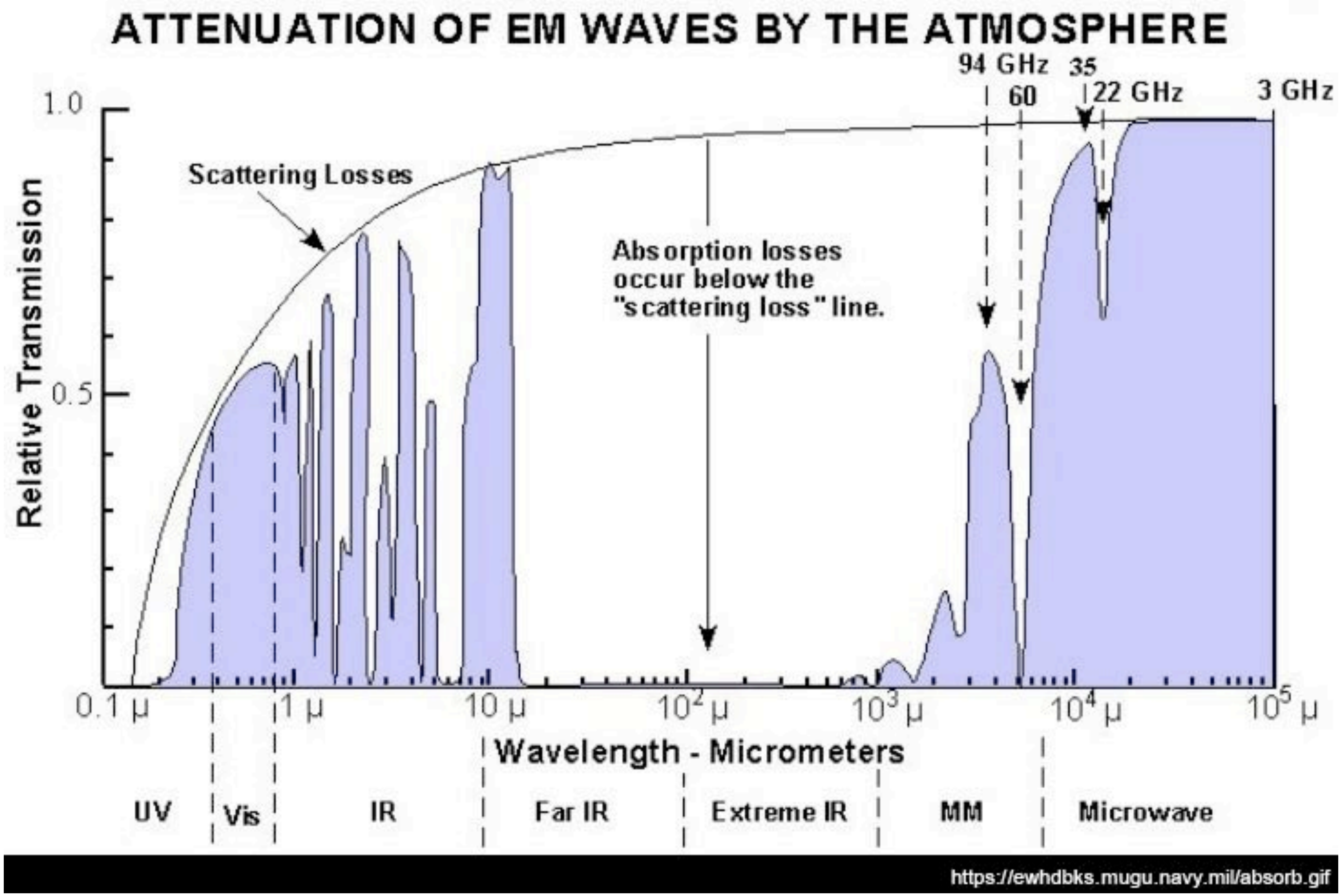
near UV, ~3200 - 4000A

mid UV, ~ 2000 - 3200A

far UV, ~ 912 - 2000A

extreme UV, ~ 10- 912A




ATTENUATION OF EM WAVES BY THE ATMOSPHERE
94 GHz
35
60
22 GHz
3 GHz
1.0
0.5
Relative Transmission
Scattering Losses
Absorption losses
occur below the
"scattering loss" line.
0.1 μ
1 μ
10 μ
10² μ
10³ μ
10⁴ μ
10⁵ μ
Wavelength - Micrometers
UV
Vis
IR
Far IR
Extreme IR
MM
Microwave
https://ewhdbks.mugu.navy.mil/absorb.gif

Andromeda Galaxy
GALEX

Andromeda Galaxy
Visible light image (John Gleason)

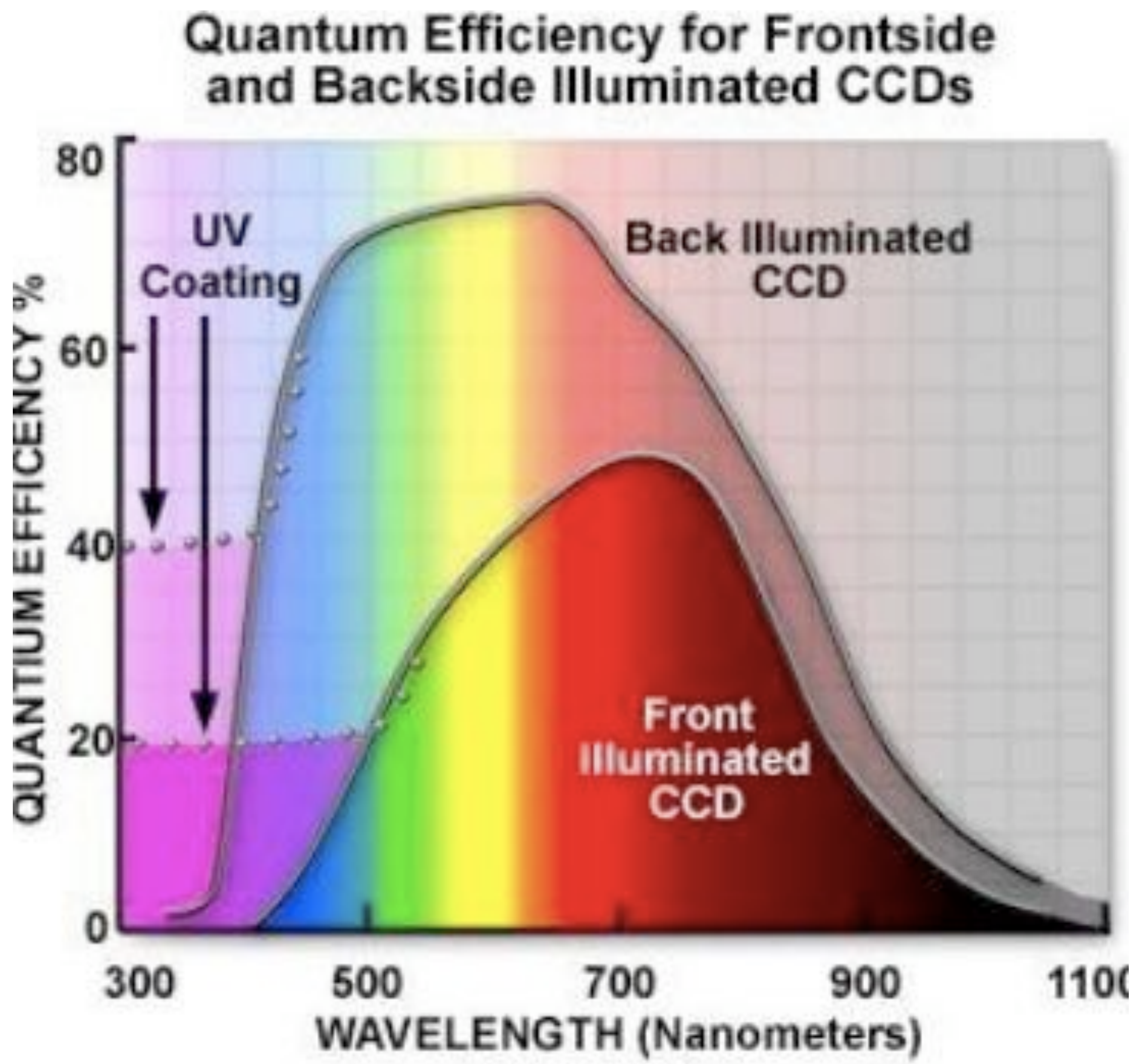
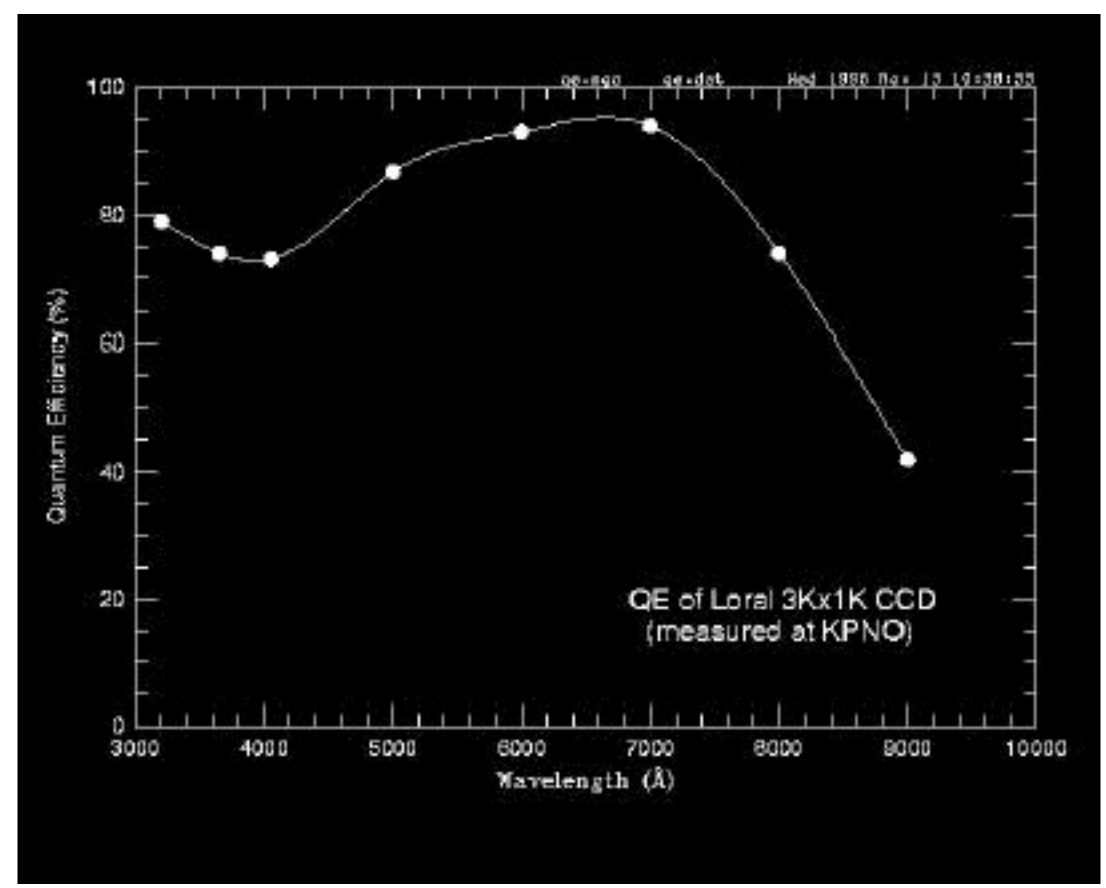
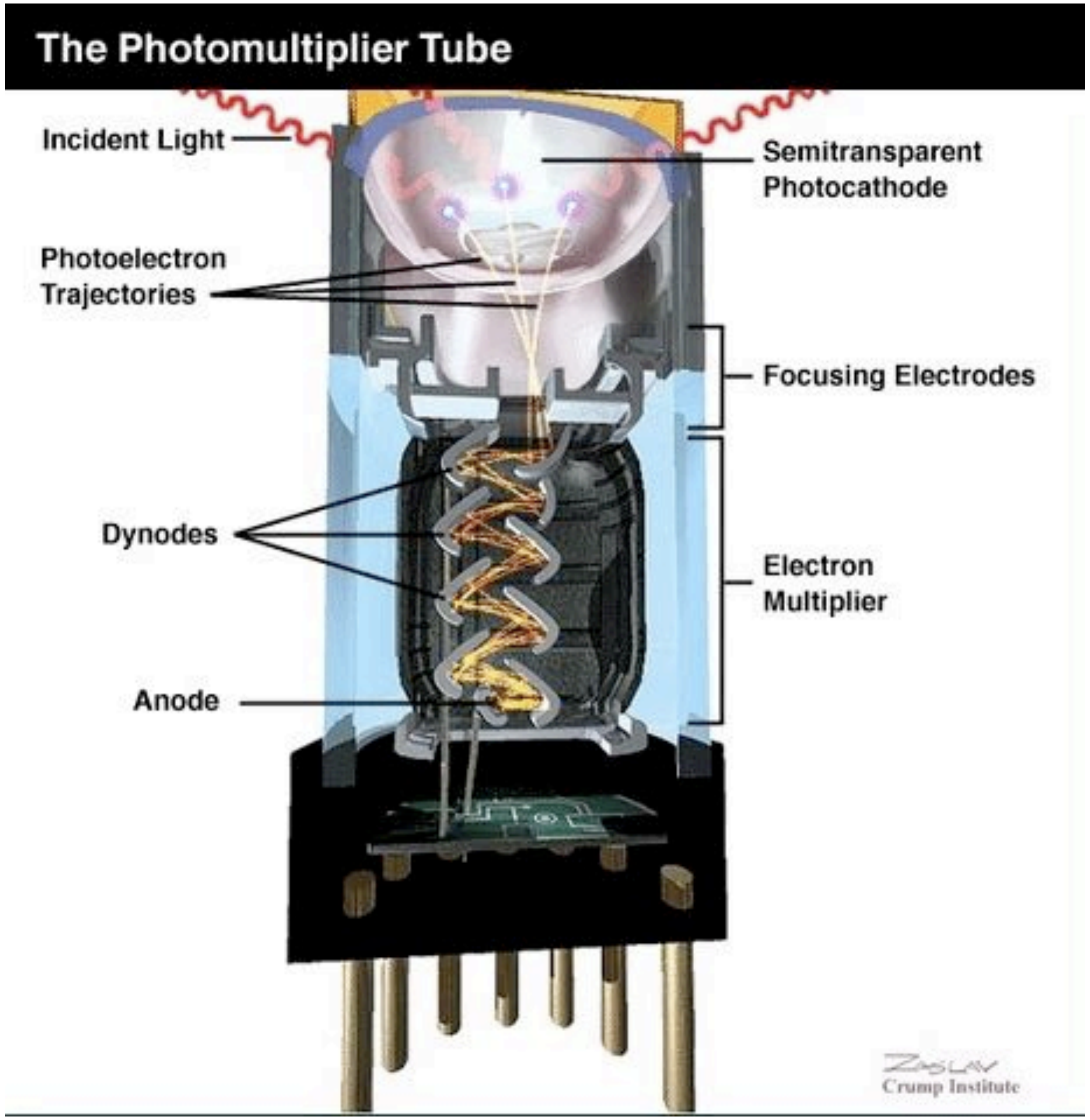
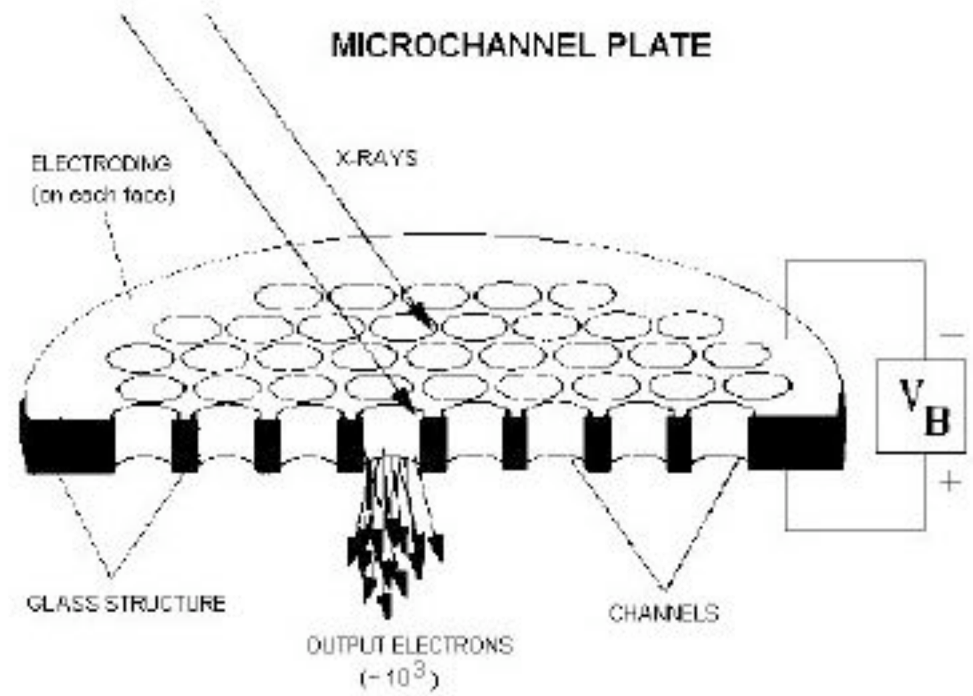

Quantum Efficiency for Frontside
and Backside Illuminated CCDs
QUANTUM EFFICENCY %
80
60
40
20
0
UV
Coating
Back Illuminated
CCD
Front
Illuminated
CCD
300
500
700
900
1100
WAVELENGTH (Nanometers)

Figure 3

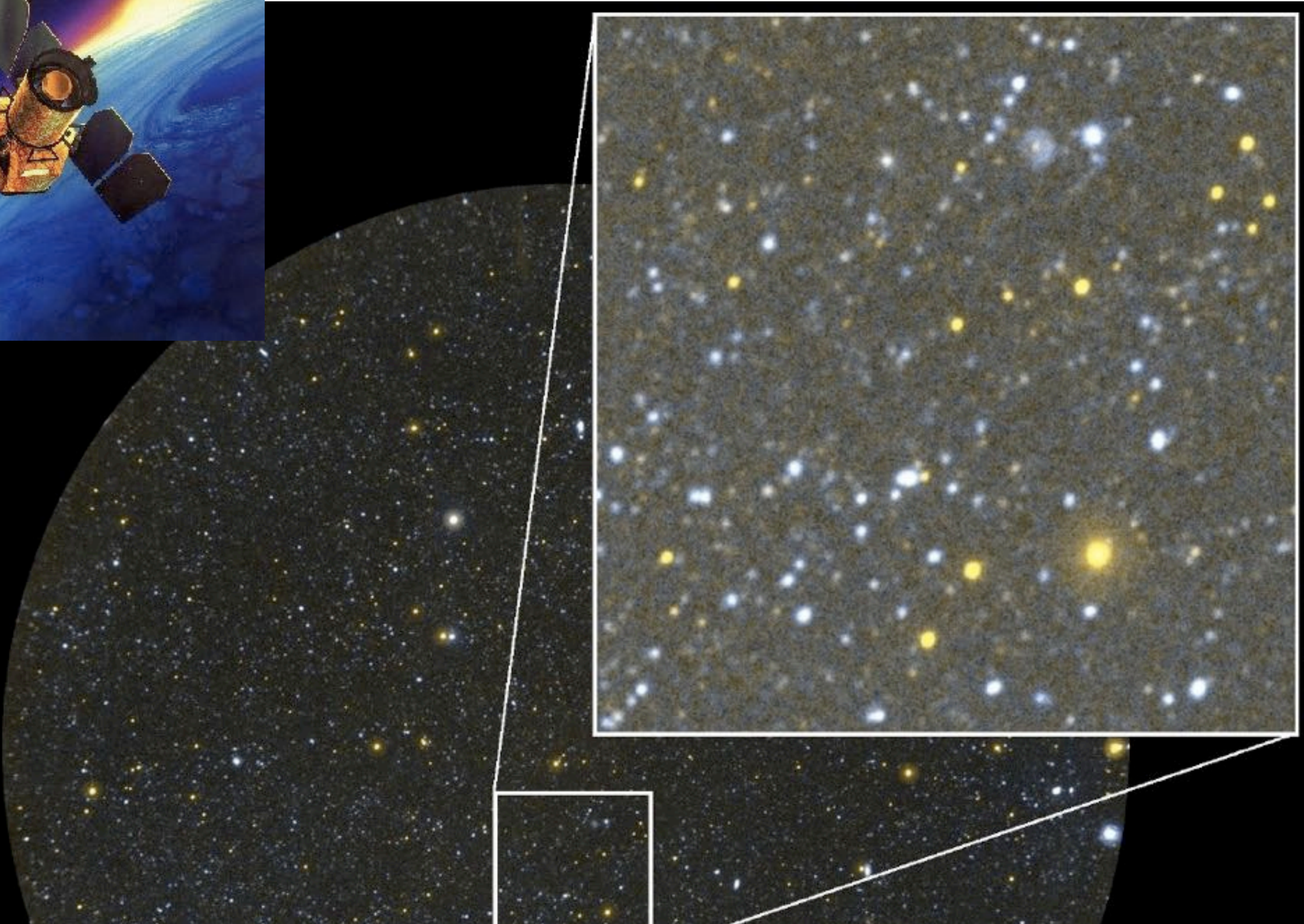

Quantum Efficiency (%)
100
80
60
40
20
0
3000
4000
5000
6000
7000
8000
9000
10000
Wavelength (Å)
QE of Loral 3Kx1K CCD
(measured at KPNO)



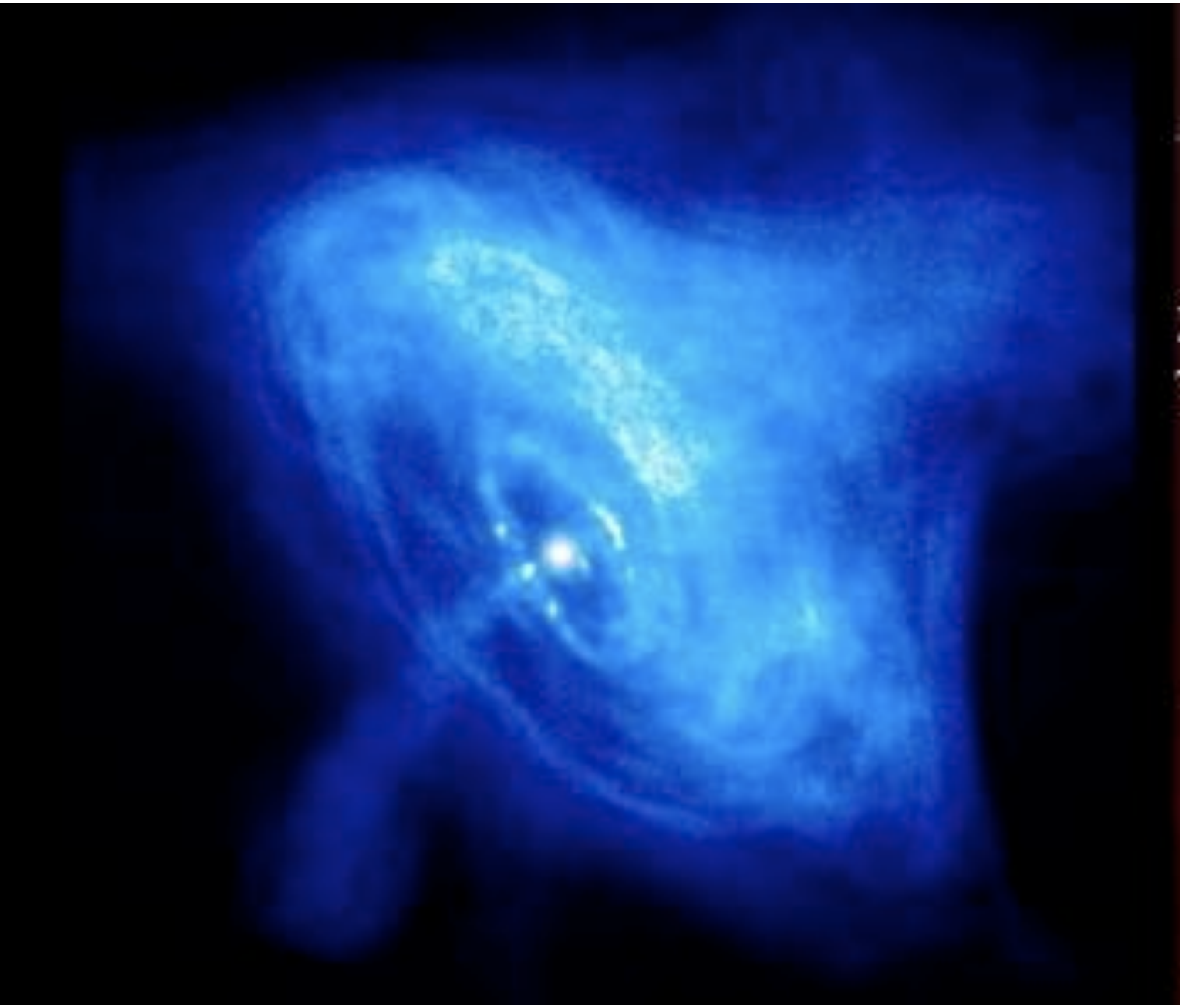


see also image intensifiers

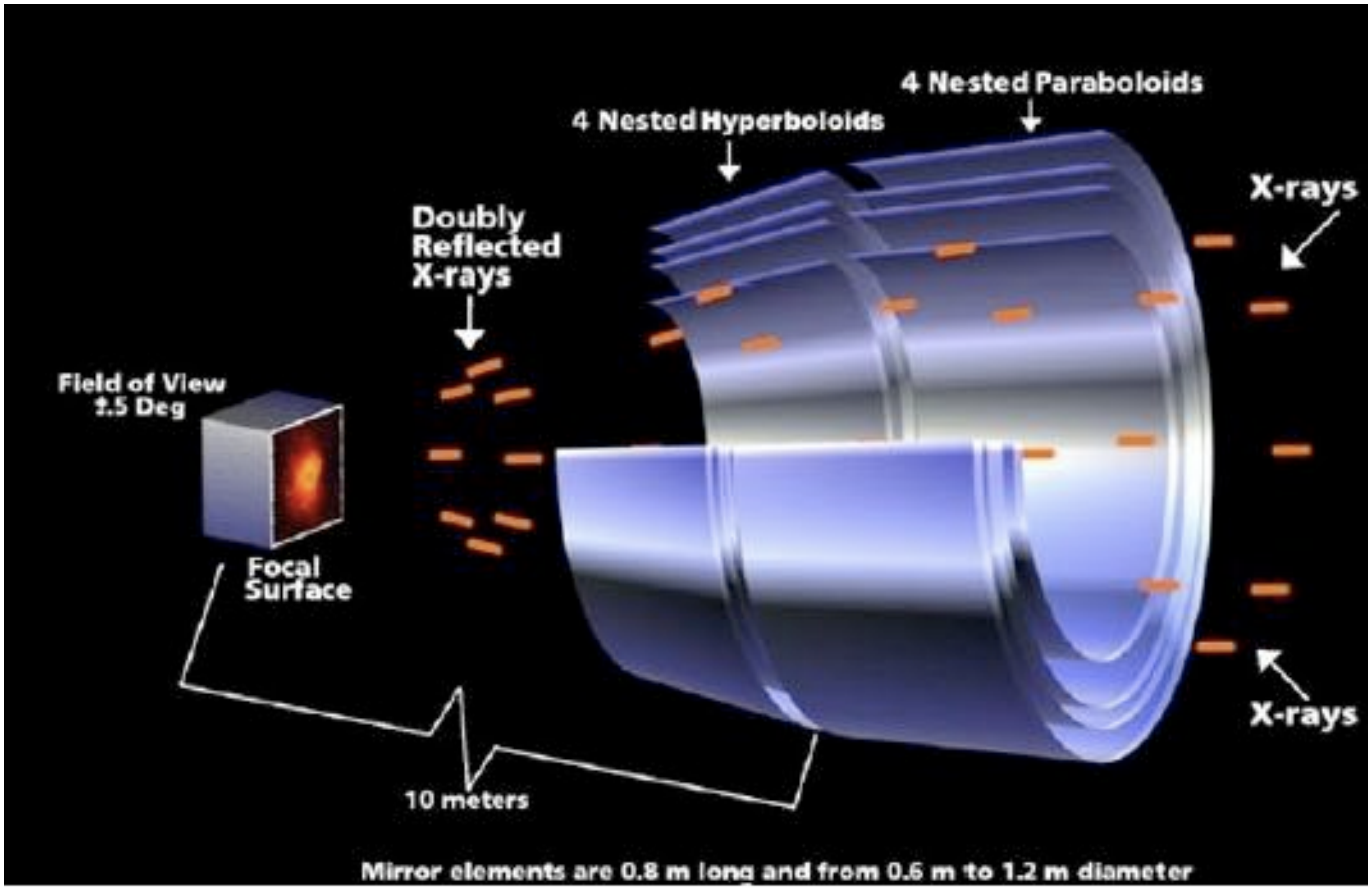
GALEX



X-Ray Astronomy

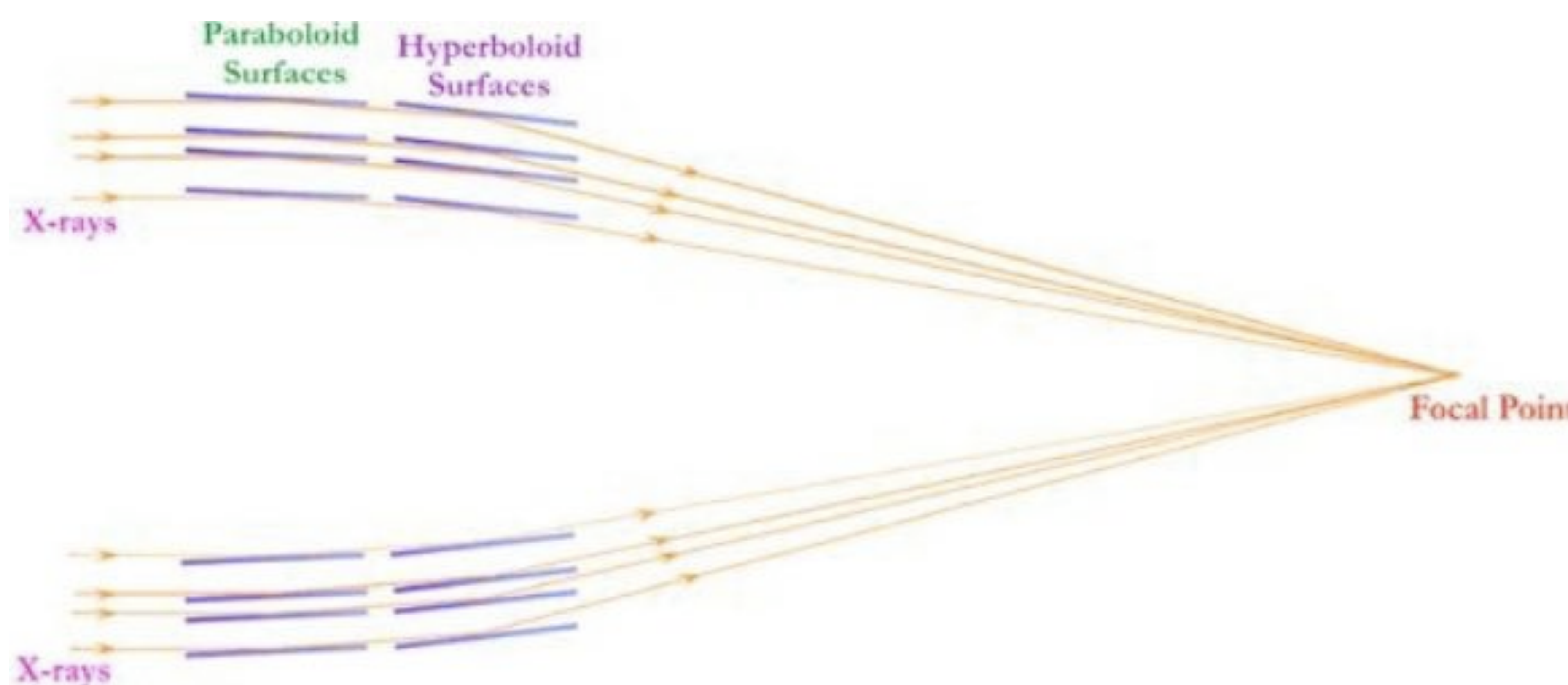
currently: Chandra (high resolution), XMM-Newton (more sensitivity, larger FOV)

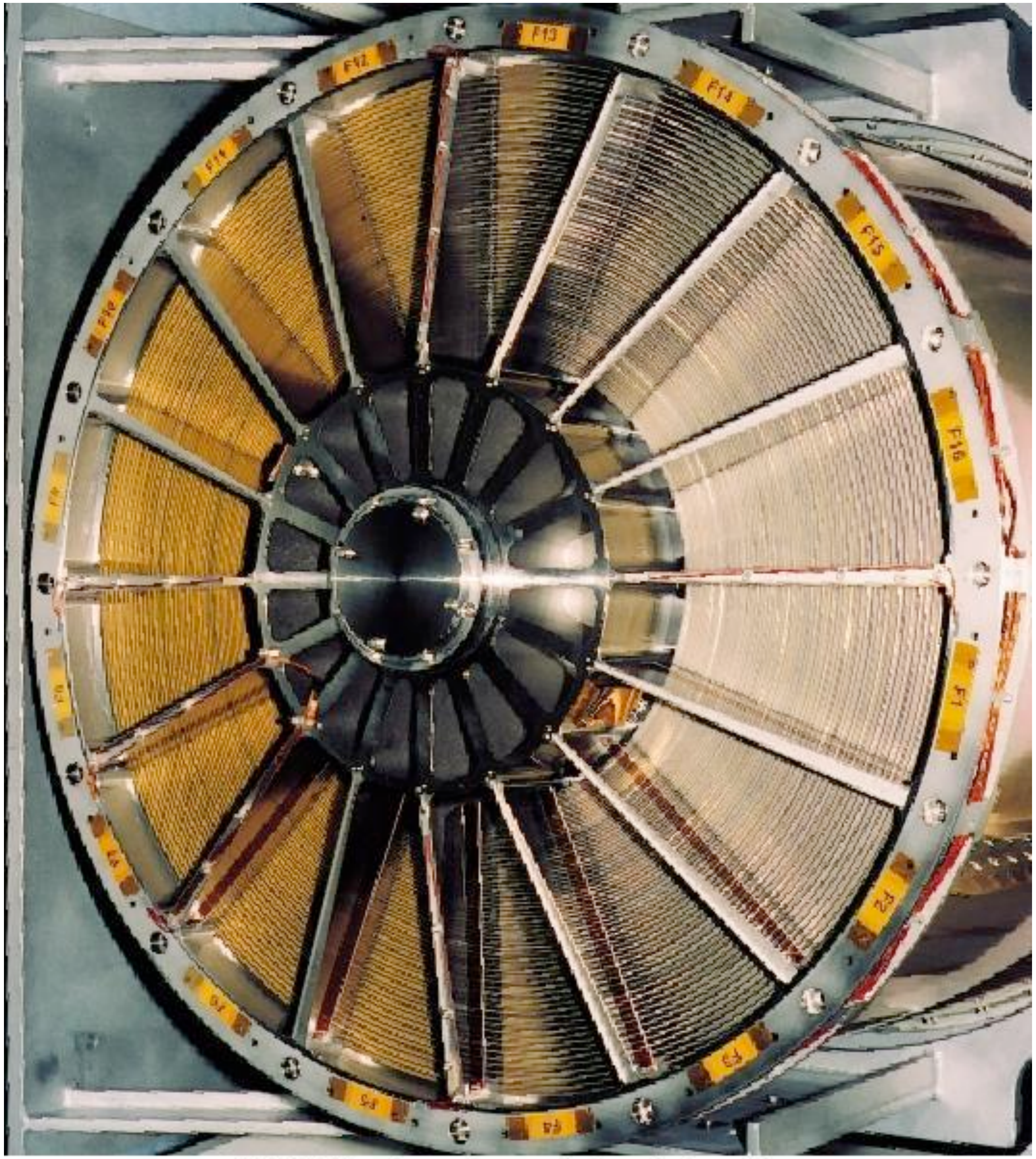

4 Nested Paraboloids
4 Nested Hyperboloids
X-rays
Doubly Reflected X-rays
Field of View ±.5 Deg
Focal Surface
10 meters
X-rays
Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter

critical angle for external reflection $\theta = 69.4\sqrt{\rho}/E$

angle (arcmin) density (cgs) energy (keV)

for gold (density = 19.3 g/cm^3, angle is 5.1 degrees at 1 keV)

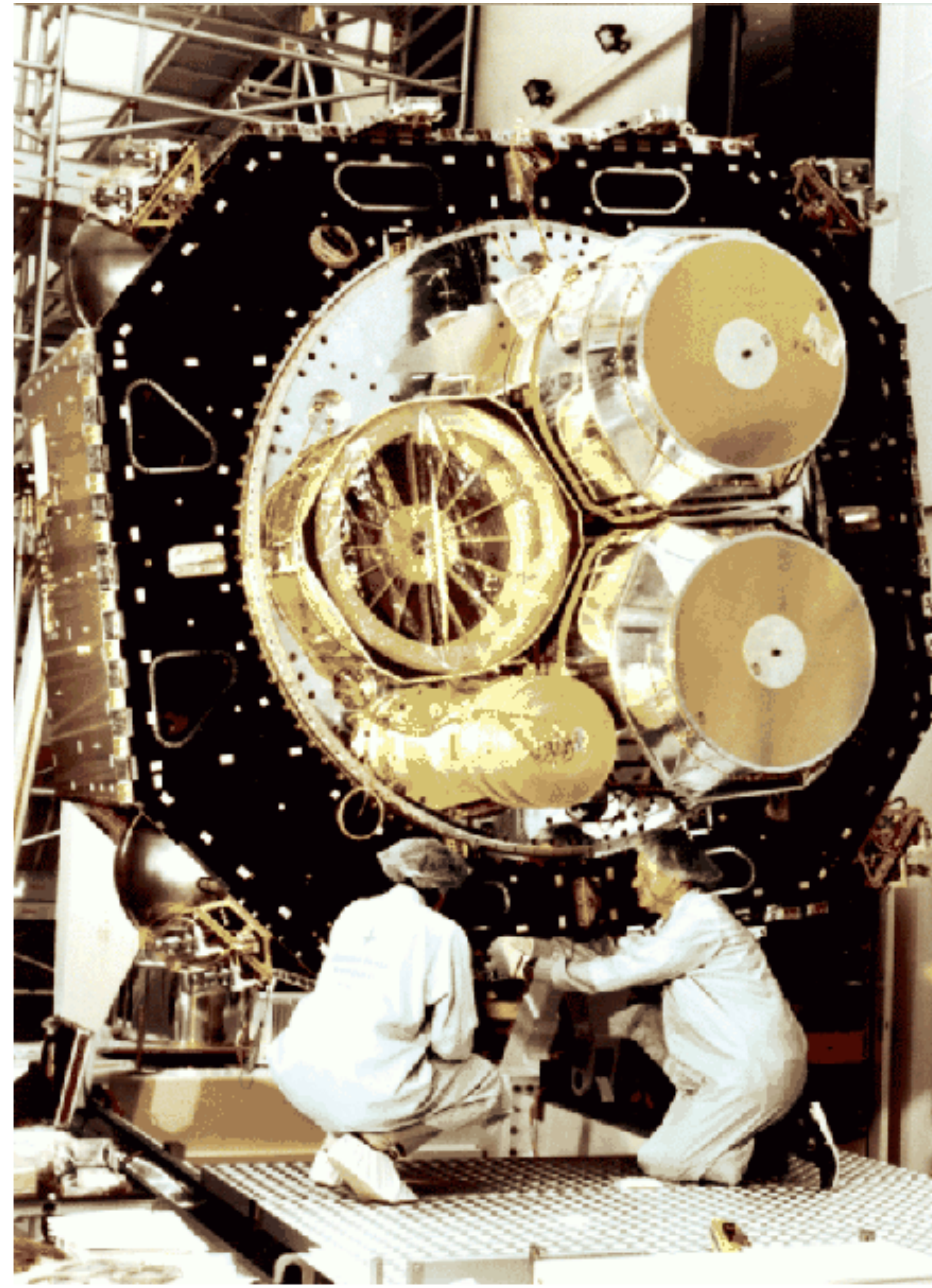




XMM-Newton mirrors during integration

Image courtesy of Dornier Satellitensysteme GmbH

European Space Agency

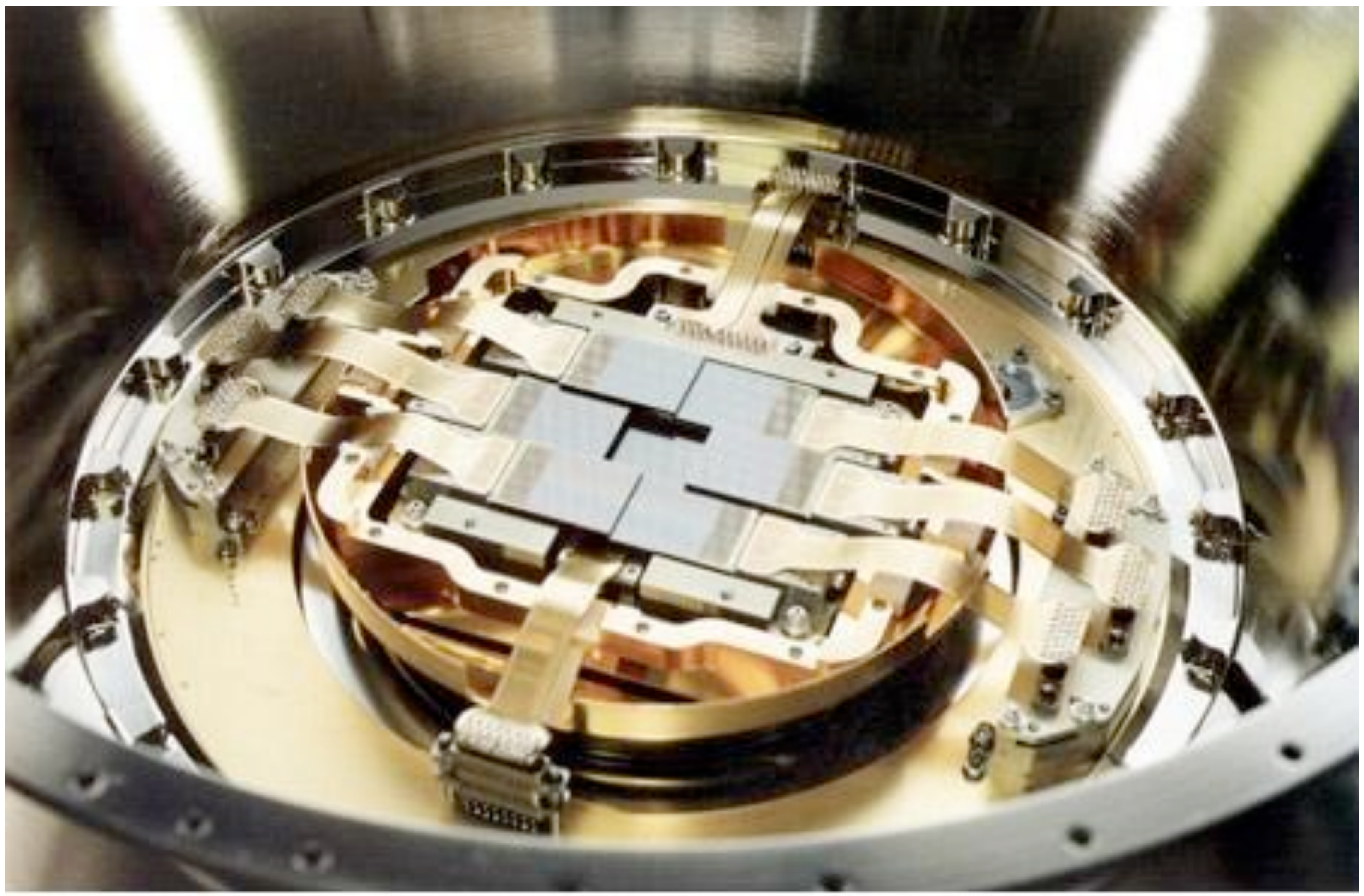


XMM-Newton mirrors during integration

Image courtesy of Dornier Satellitensysteme GmbH

European Space Agency

CCDs can be X-ray detectors (but the behavior is very different than in optical)



EPIC-MOS CCDs

Image courtesy of Leicester University, University of Birmingham, CEA Service d'Astrophysique Saclay

European Space Agency

X-ray CCDs

high spatial resolution

good energy resolution

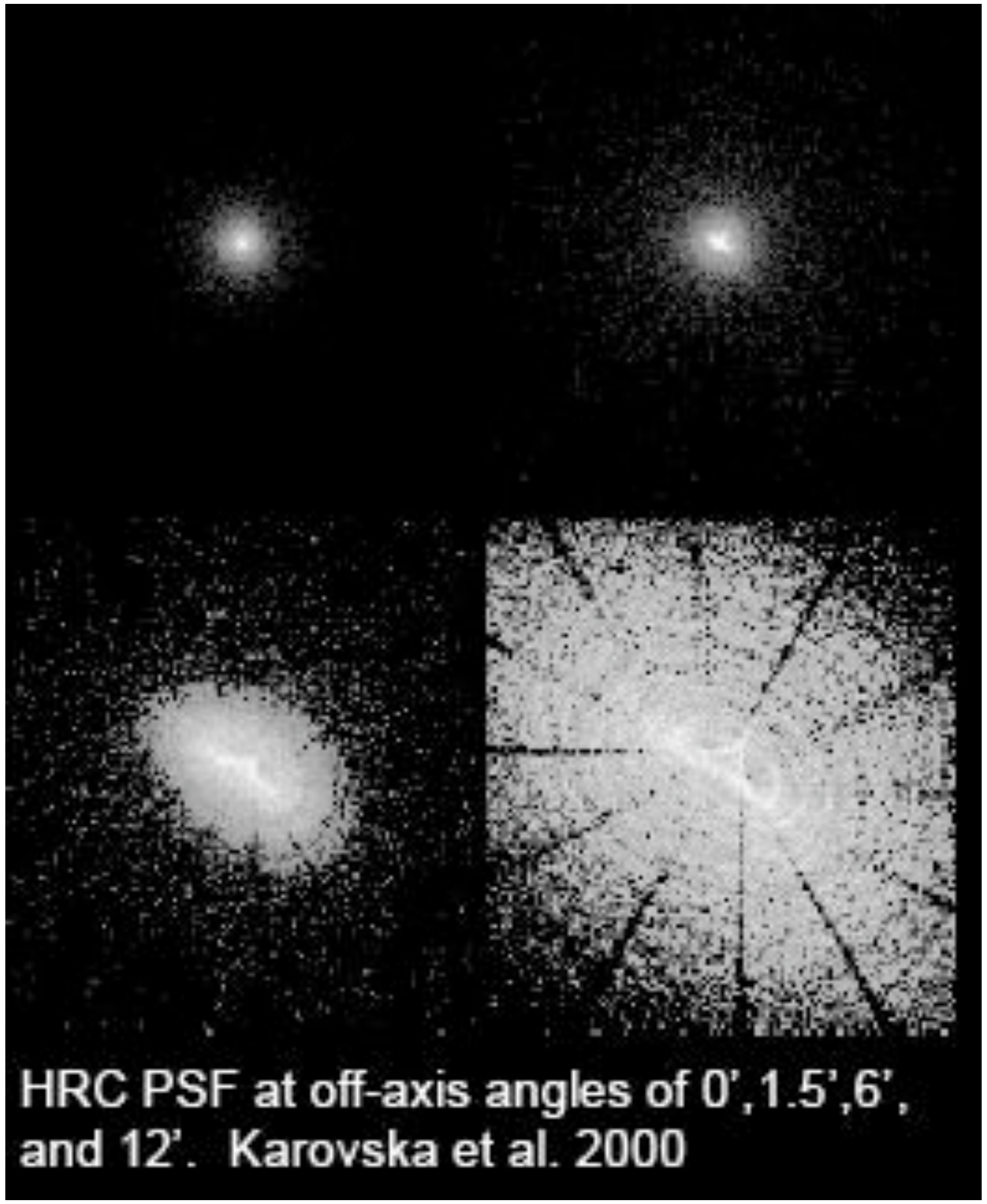
$$\Delta E = 2.35(\sigma^2_{READOUT} + \sigma^2_{PHOTON})^{1/2}$$

$$\Delta E = 2.35(w^2 n^2 + fEw)^{1/2}$$

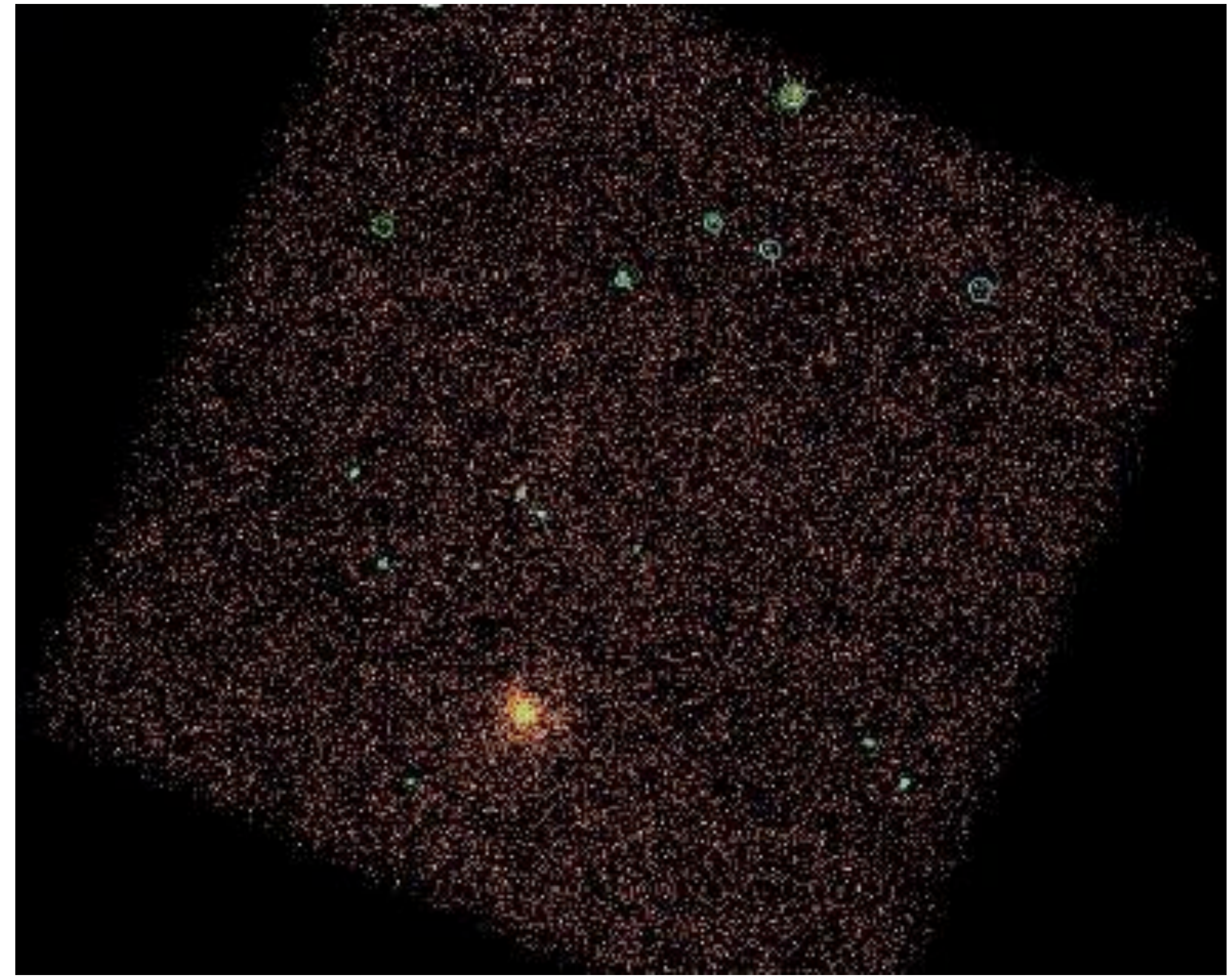
$$w = 3.65 \text{ ev/pair}$$

$$f = 0.12$$

$$n = 9 \text{ e}^-$$



PSF highly spatially variable



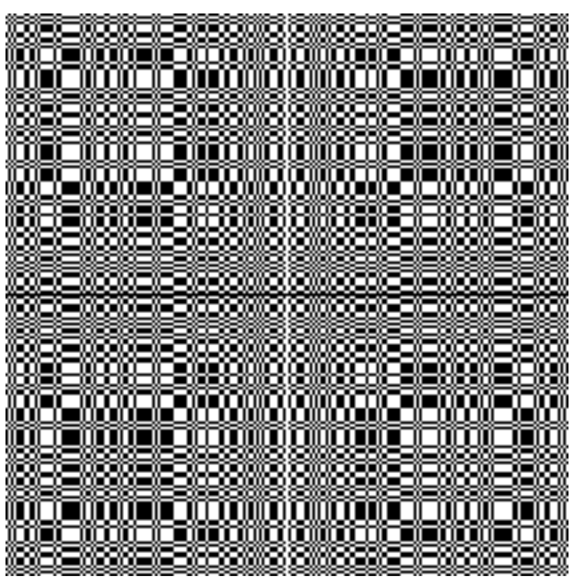
noise dominated by counting statistics/background

type	E	resolution	where
grazing incidence mirror	< 10 keV	to 0.5”	satellite
coded aperture	to 1MeV	to 5’	balloon/ satellite
compton telescope	1-20 MeV	1 - 3 deg	balloon/ satellite
spark chamber	30-1000 Mev	1- 3 deg	balloon/ satellite
air shower	10^5 - 10^7 MeV	~ 1 deg	atmosphere

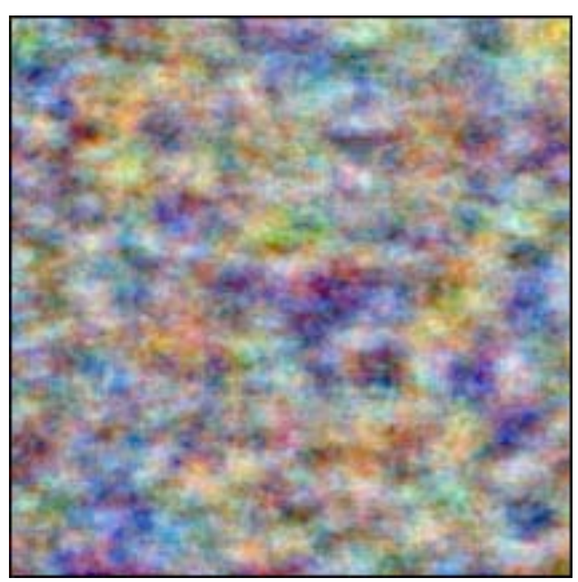
coded apertures

pinhole camera: low throughput

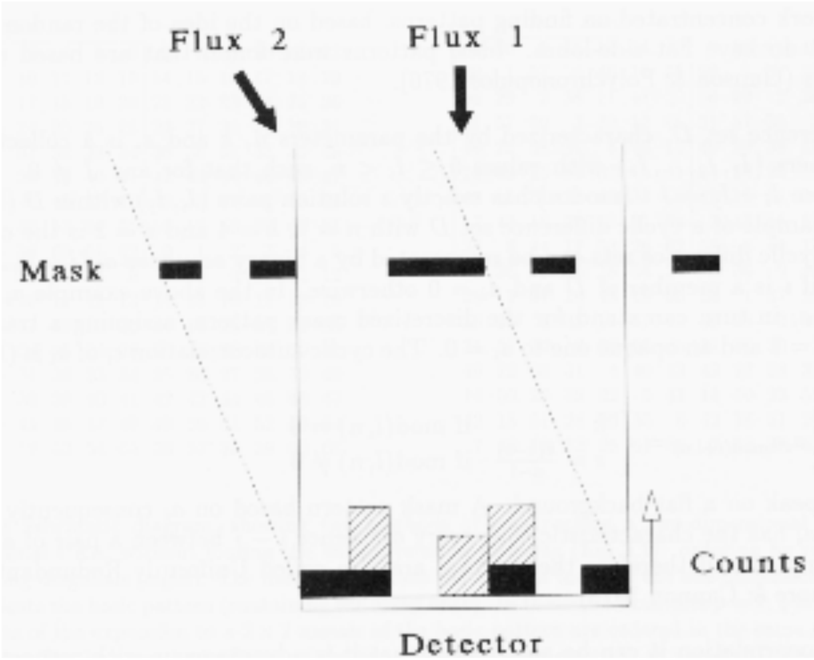
multiple pinholes: confusing overlap

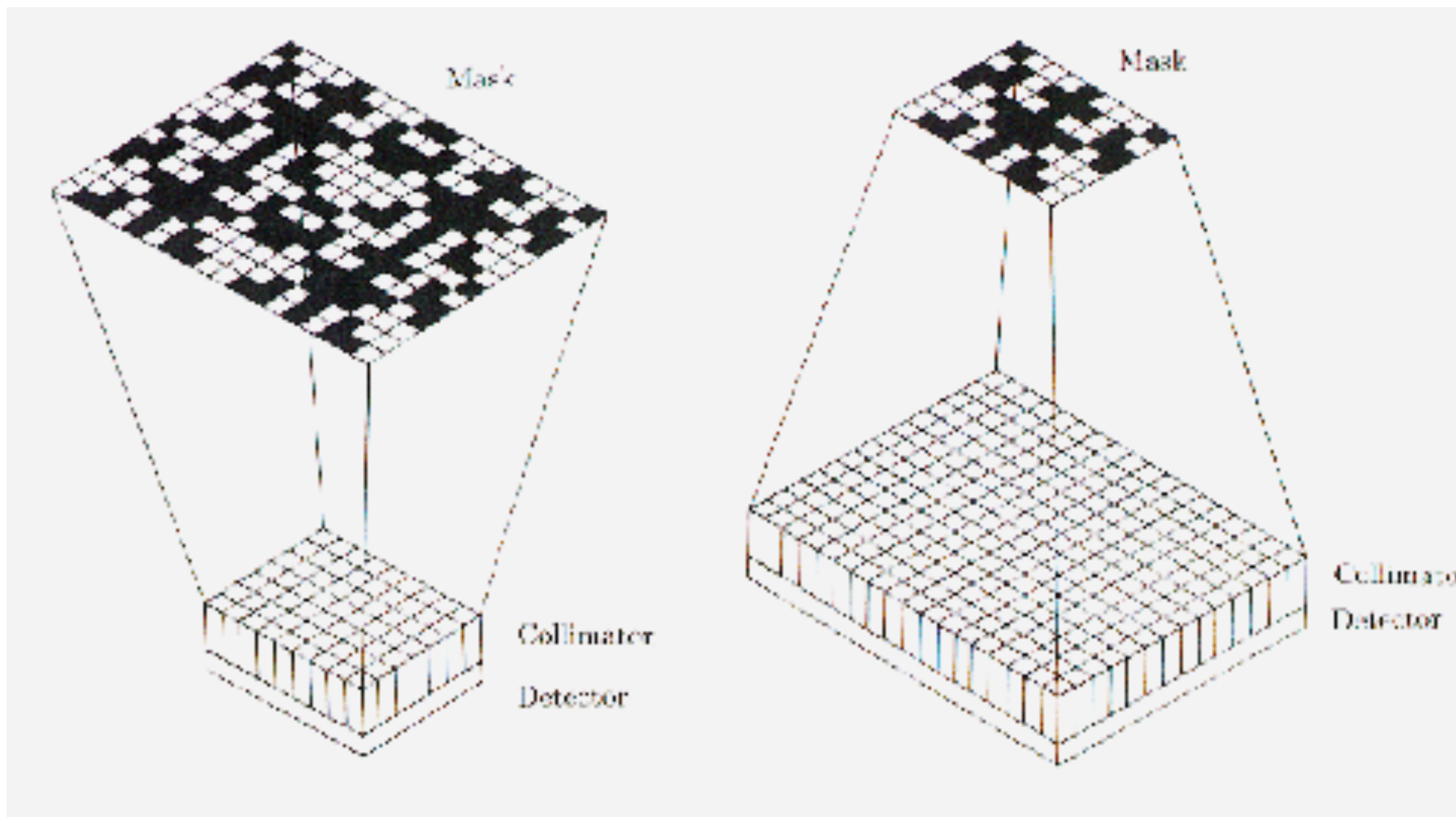


complex pattern to maximize uniqueness

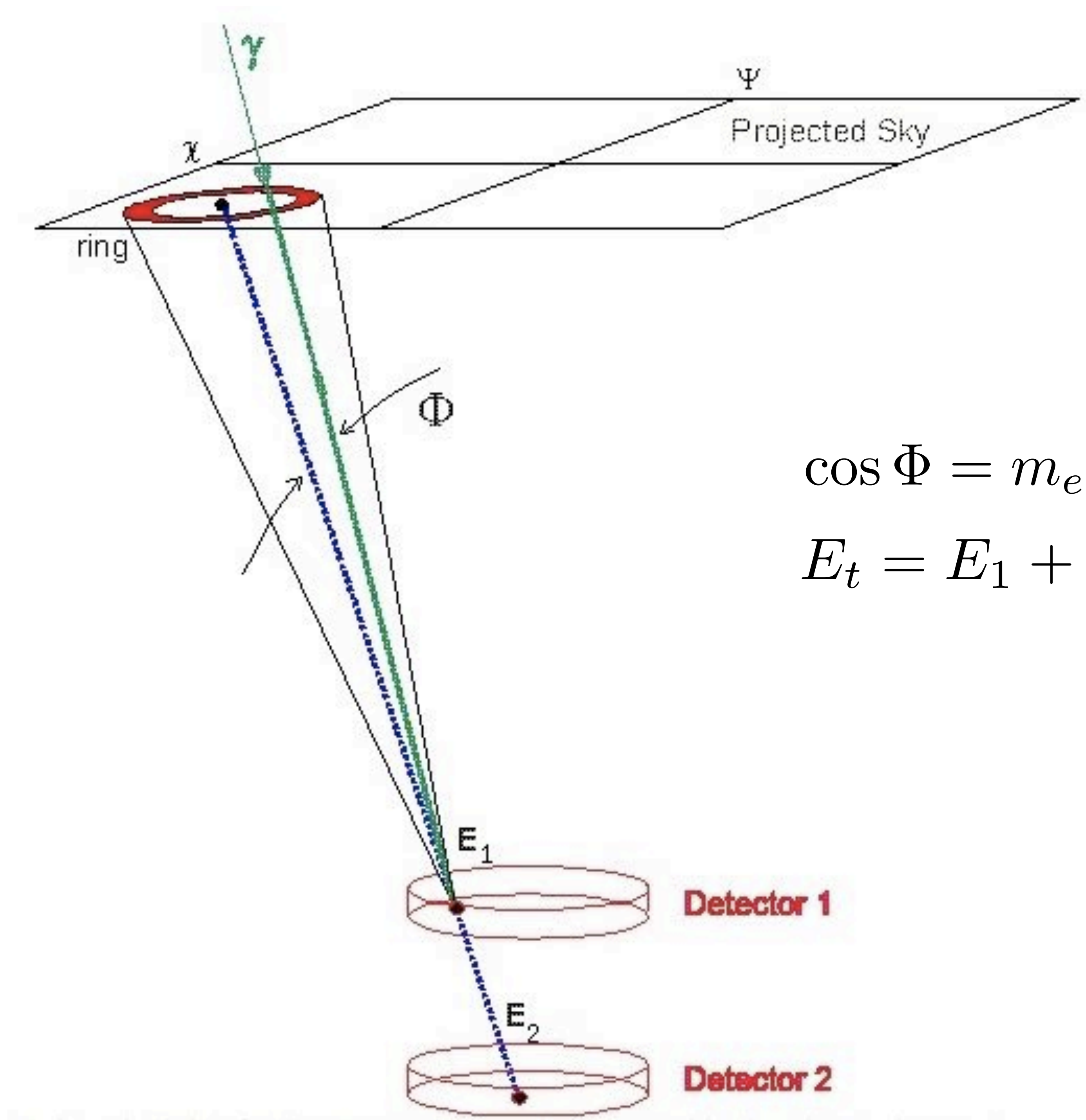


Coded Apertures





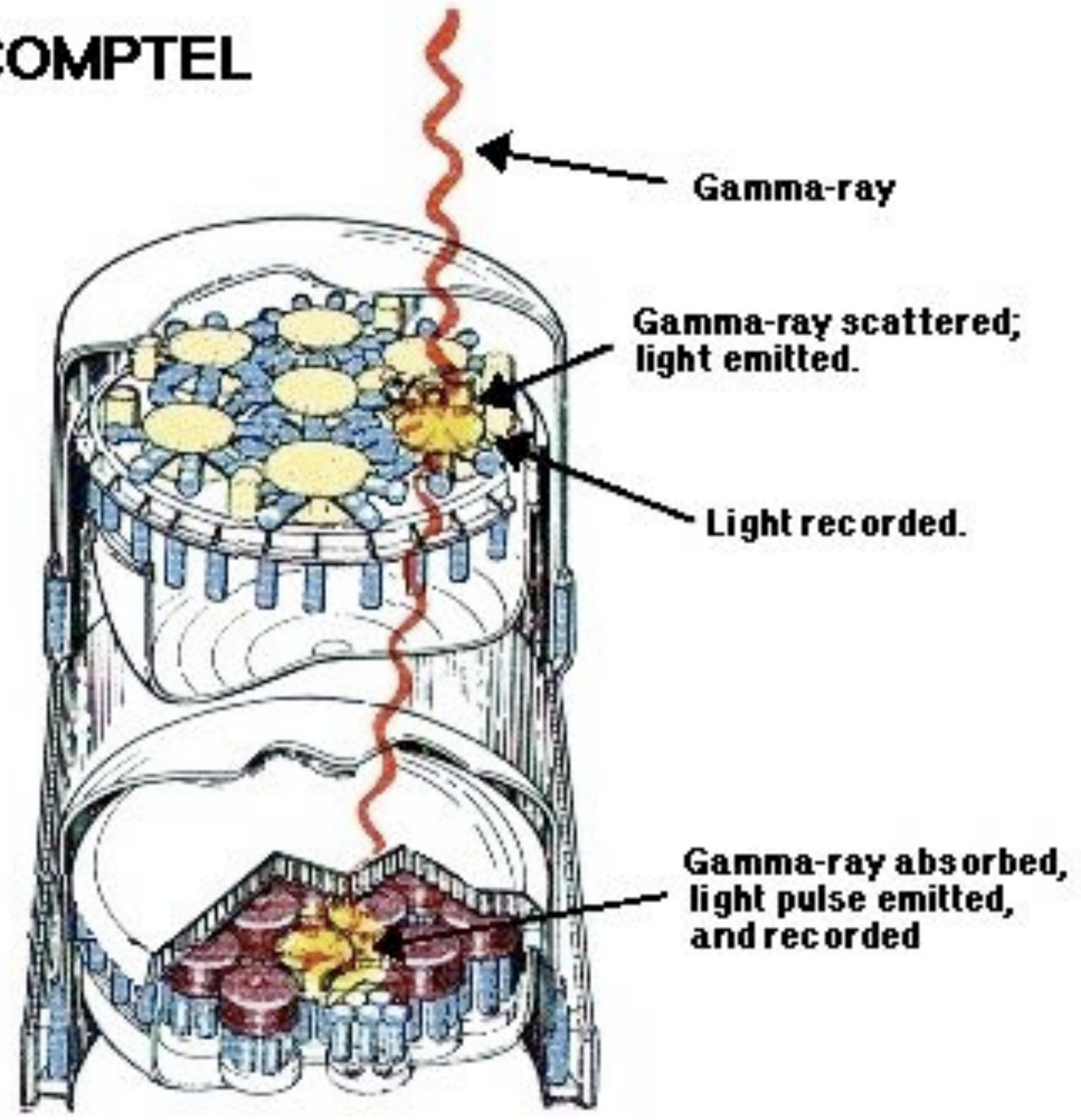
Compton Telescope



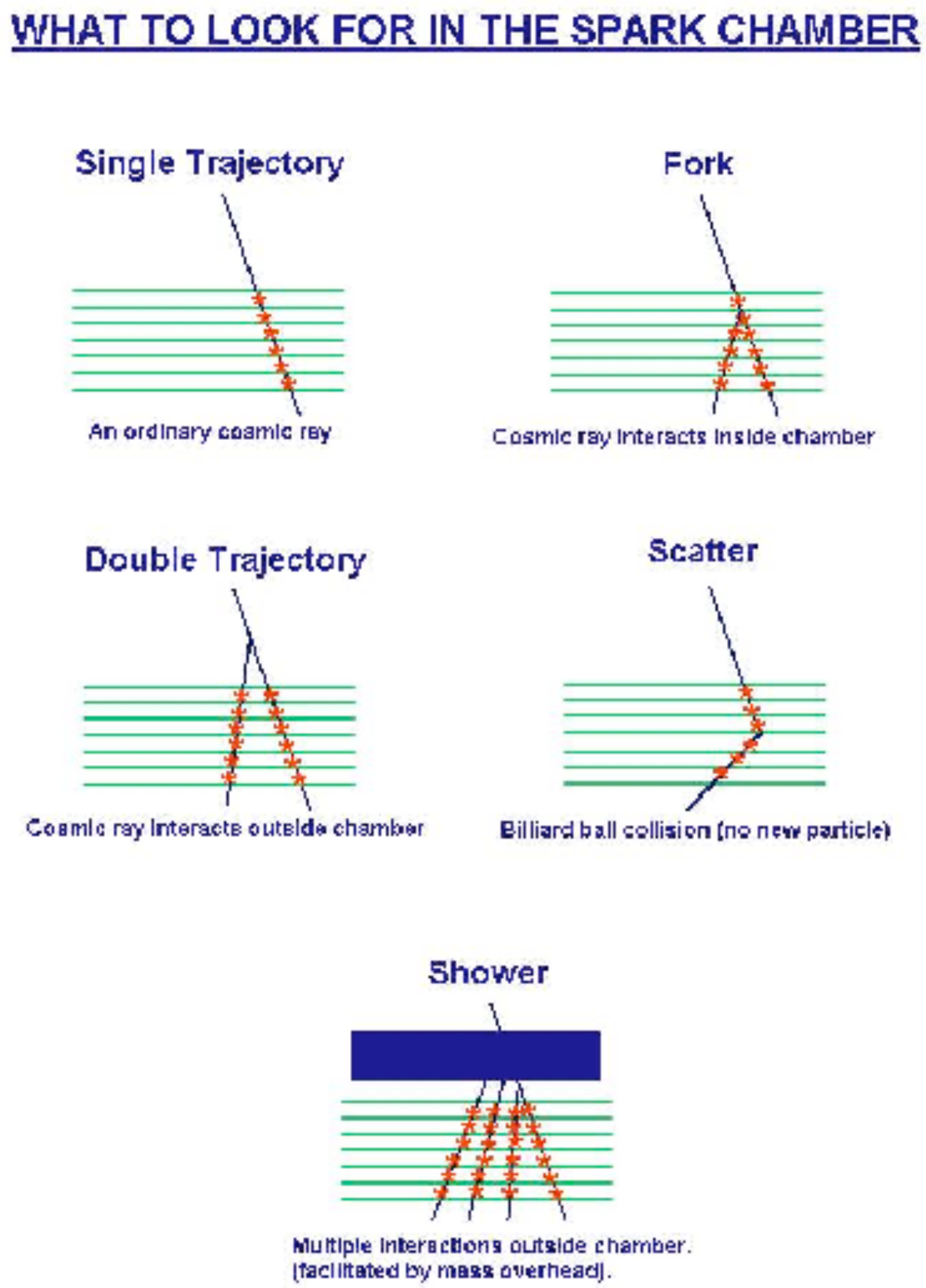
$$\cos\Phi = m_e c^2 (1/(E_t - E_1) - 1/E_1)$$

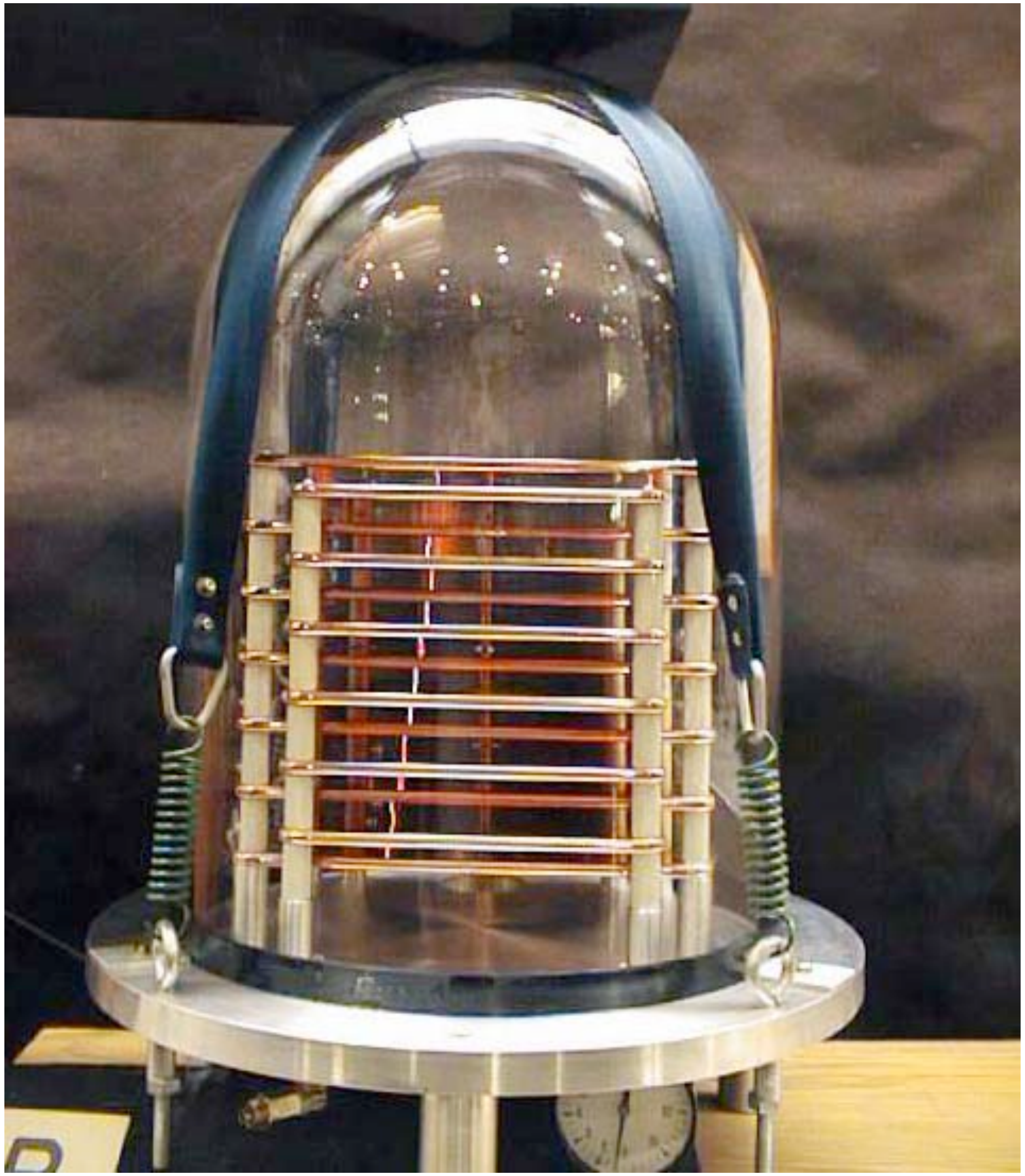
$$E_t = E_1 + E_2$$

COMPTEL

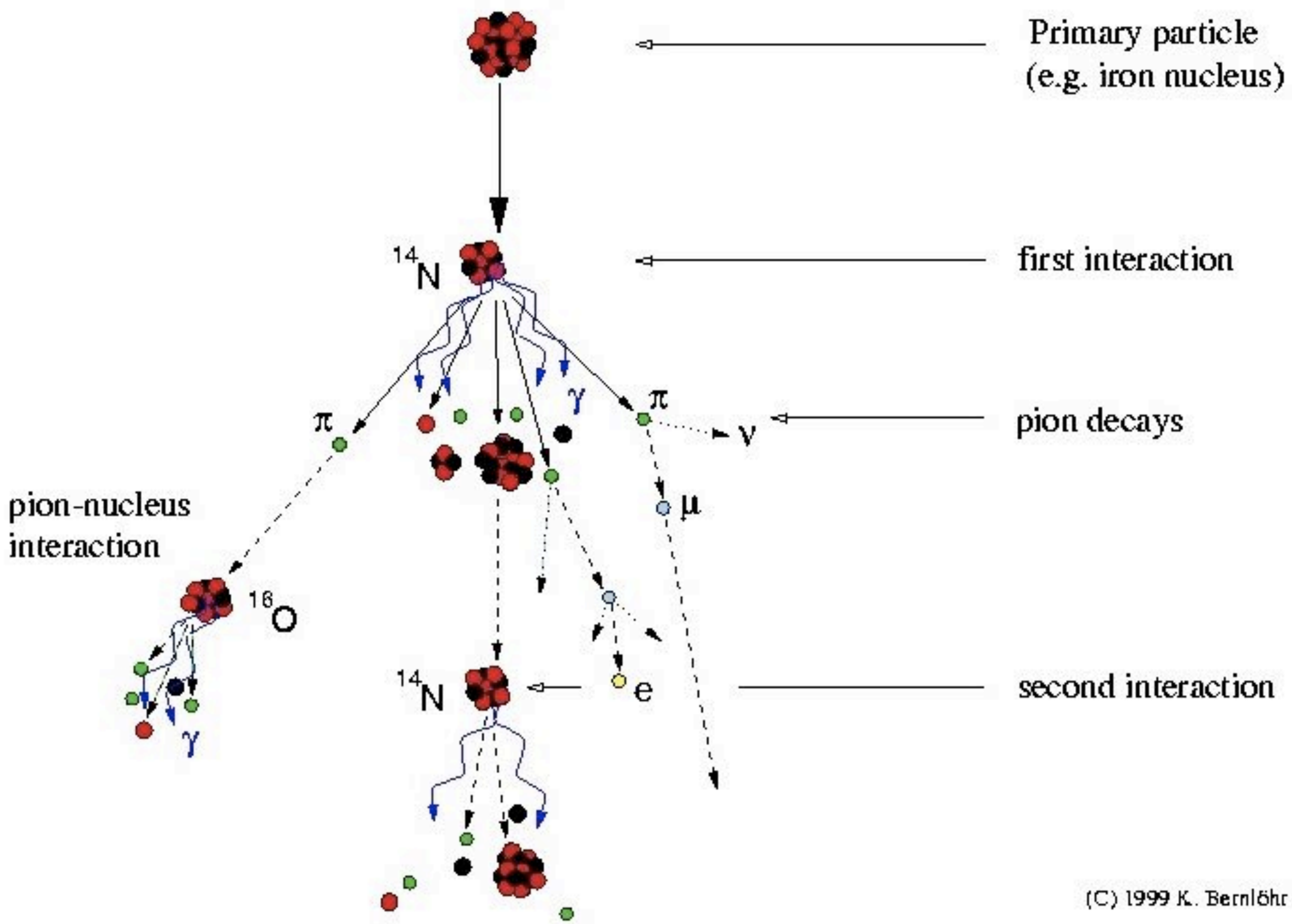

Gamma-ray
Gamma-ray scattered; light emitted.
Light recorded.
Gamma-ray absorbed, light pulse emitted, and recorded

Spark Chambers

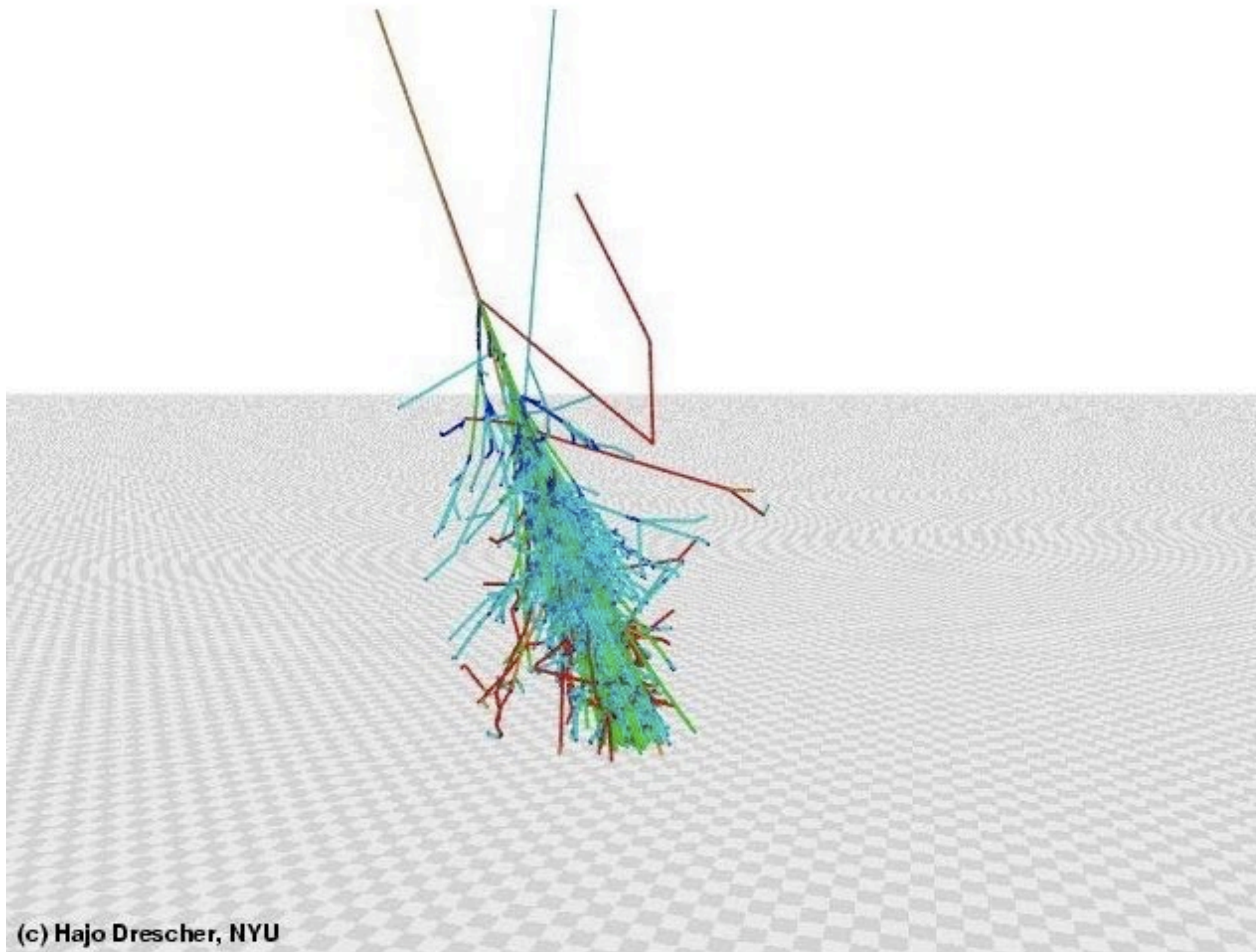




Development of cosmic-ray air showers



Air Showers



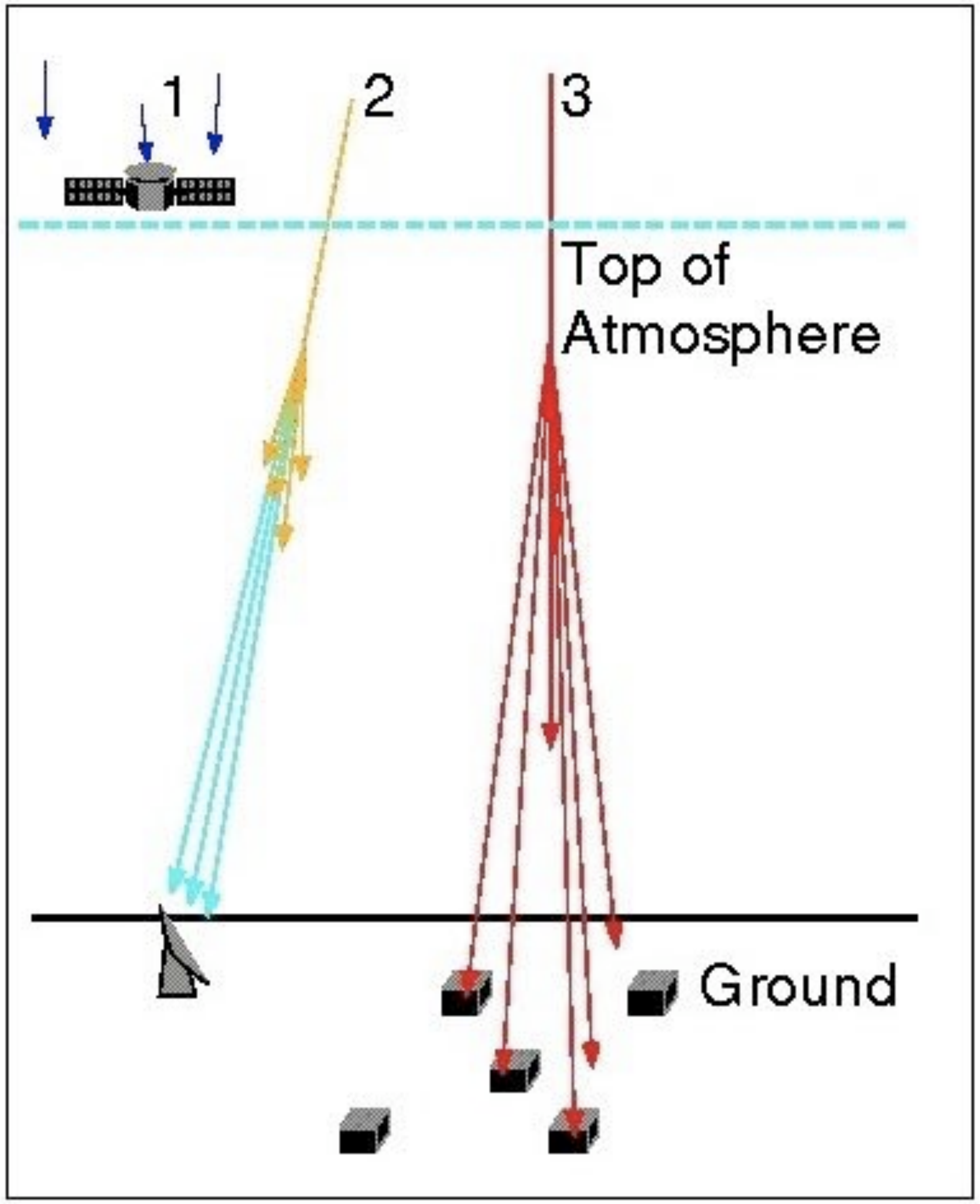
each square on the ground is 1km square

http://www.th.physik.uni-frankfurt.de/~drescher/CASSIM/

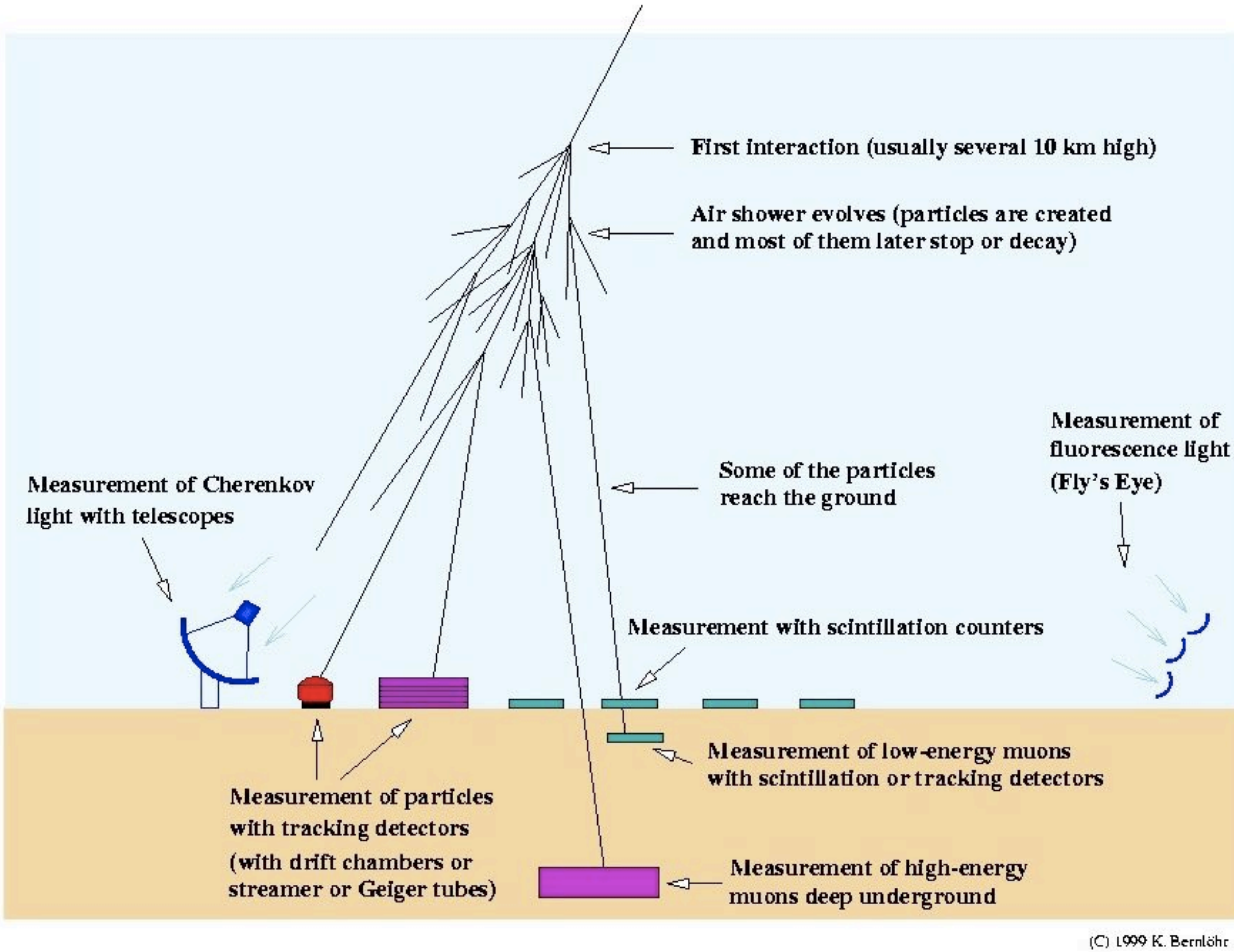
1. low E cosmic rays detected by satellites

2. intermediate E cosmic rays detected via Cerenkov radiation

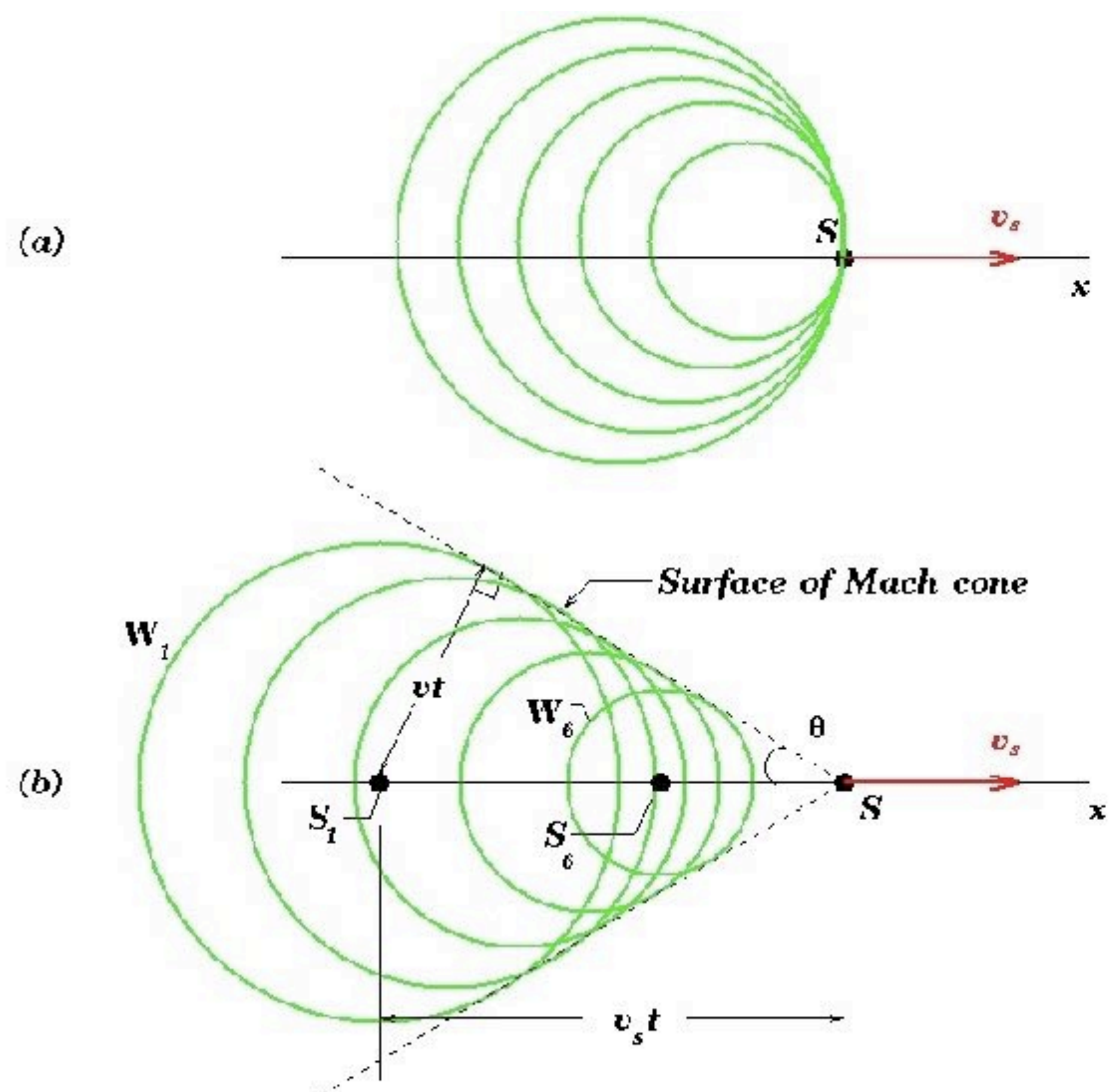
3. high E cosmic rays detected with ground particle detectors



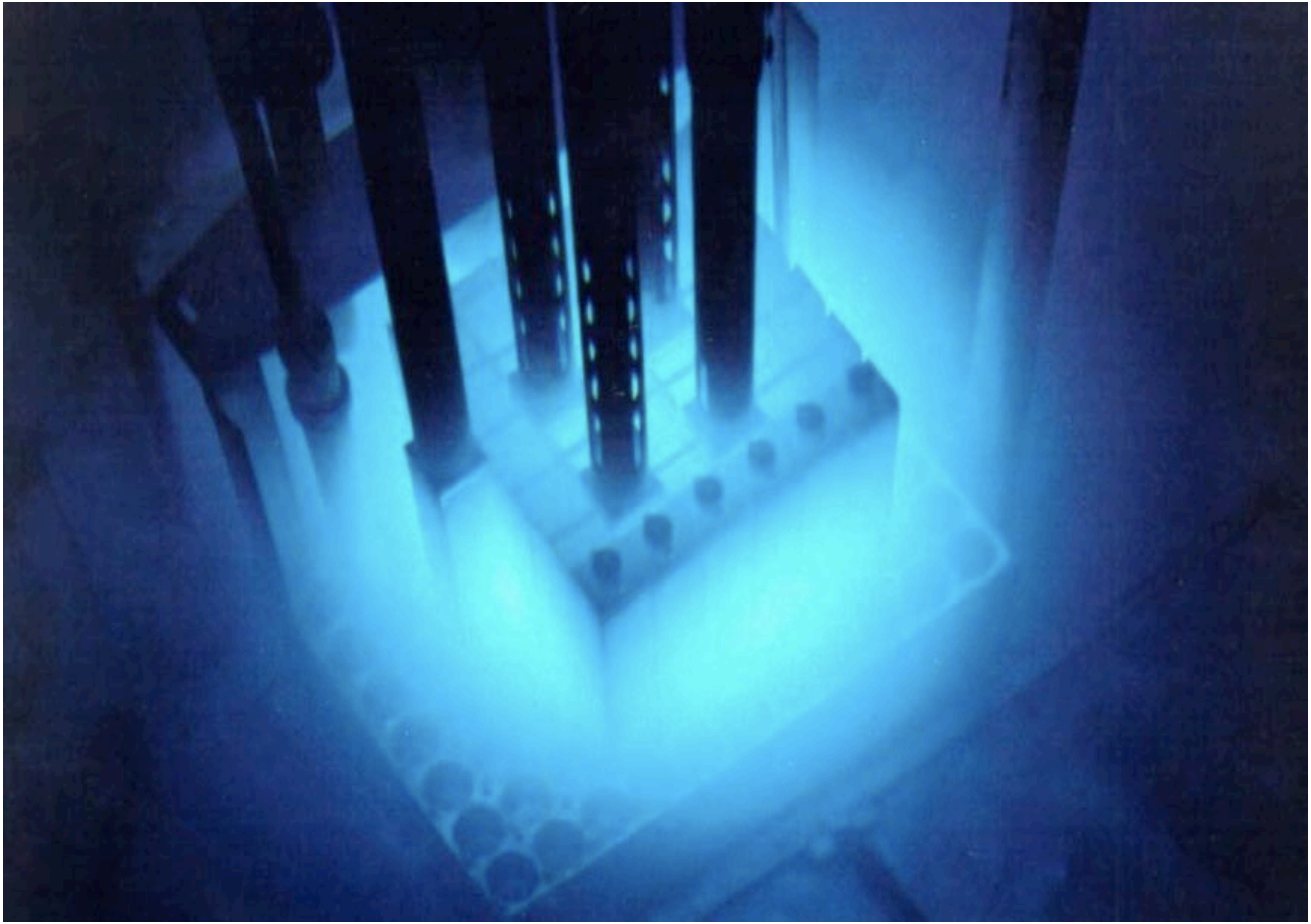
Measuring cosmic-ray and gamma-ray air showers



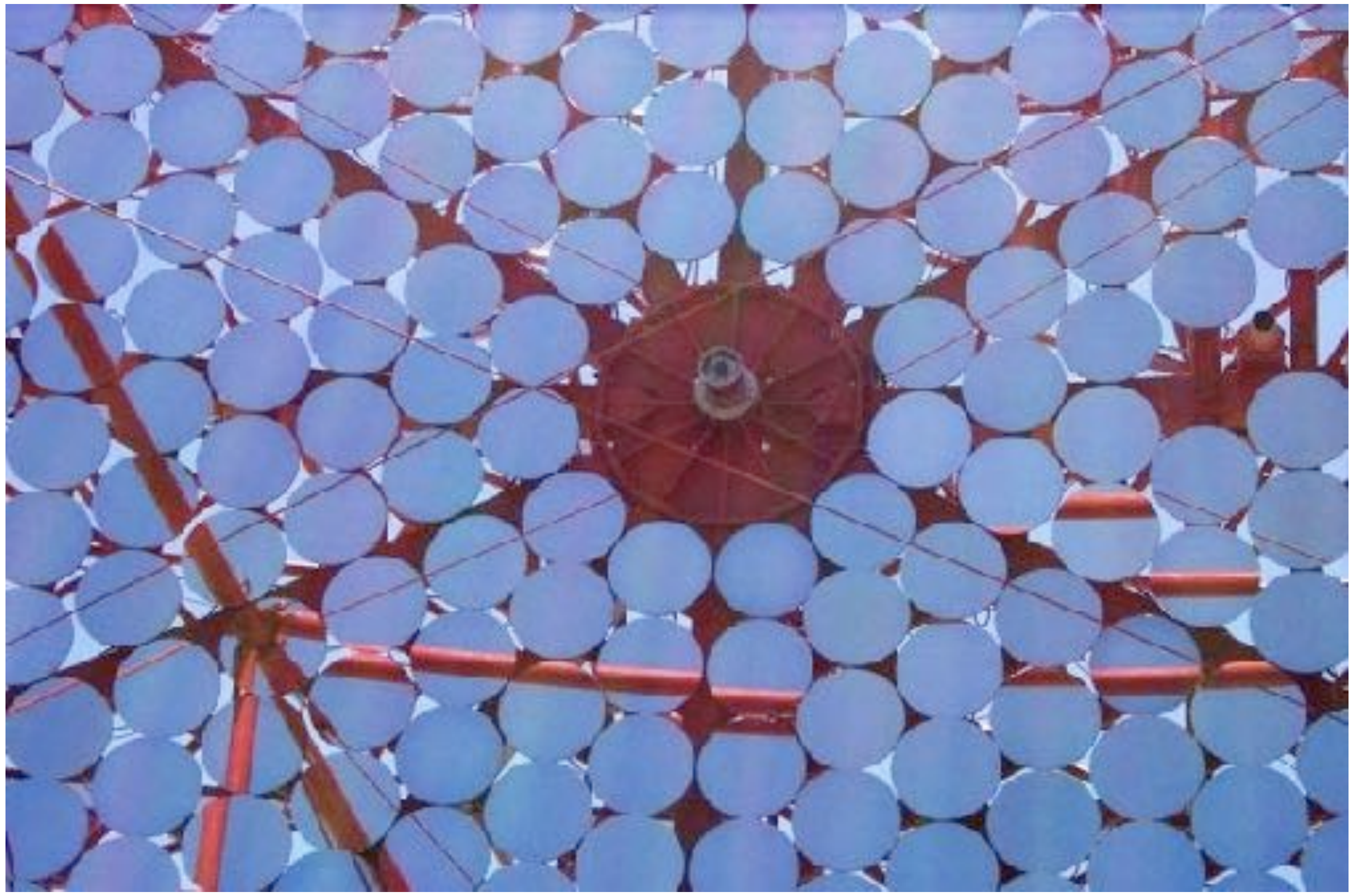
Cerenkov Radiation



dept.physics.upenn.edu/.../ gif/mach_fronts.gif

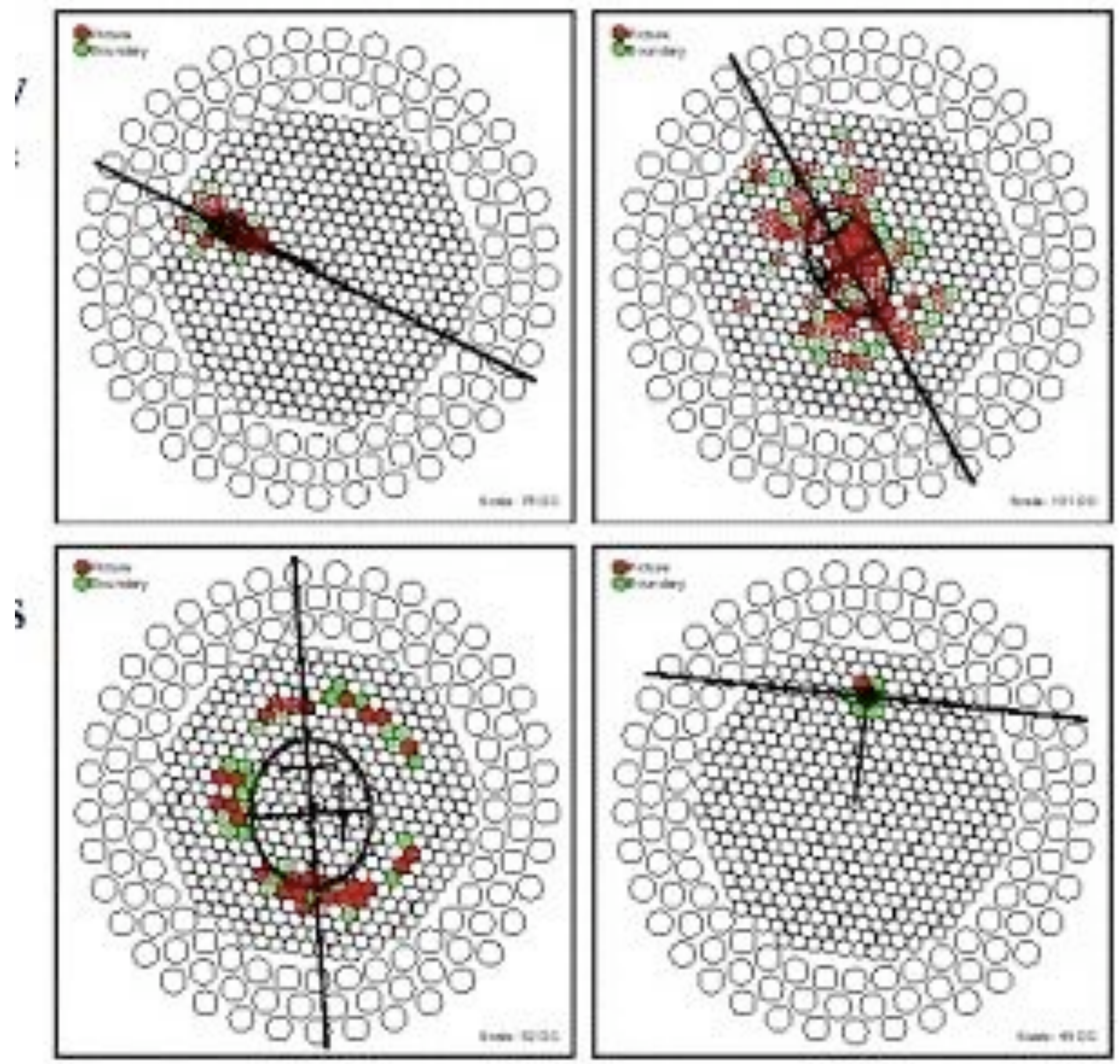


H.E.S.S. telescope(s)



gamma ray shower

charged cosmic ray

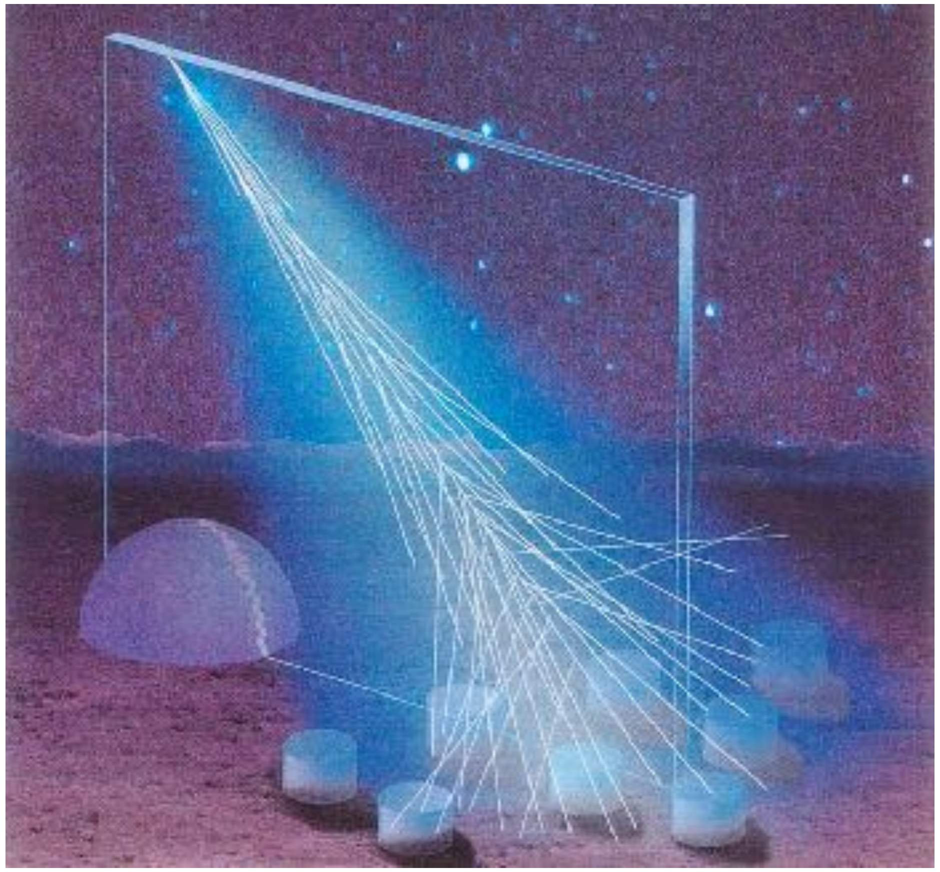


single muon

noise?

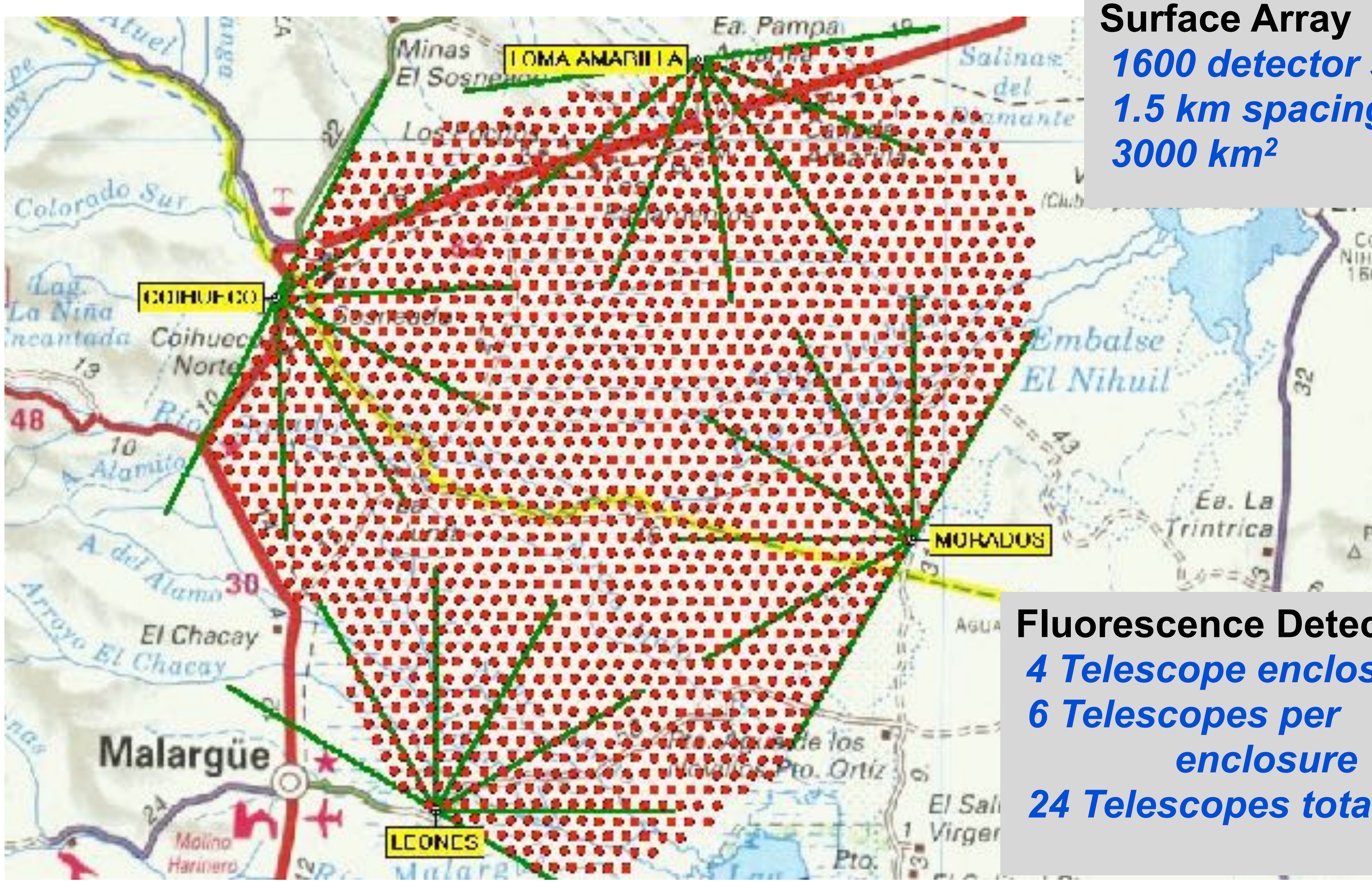
http://people.umass.edu/hepex/Veritas.html

One example: Pierre Auger Observatory



http://www.auger.org/index.html

The Observatory Plan



Surface Array
- *1600 detector stations*
- *1.5 km spacing*
- *3000 km^2*

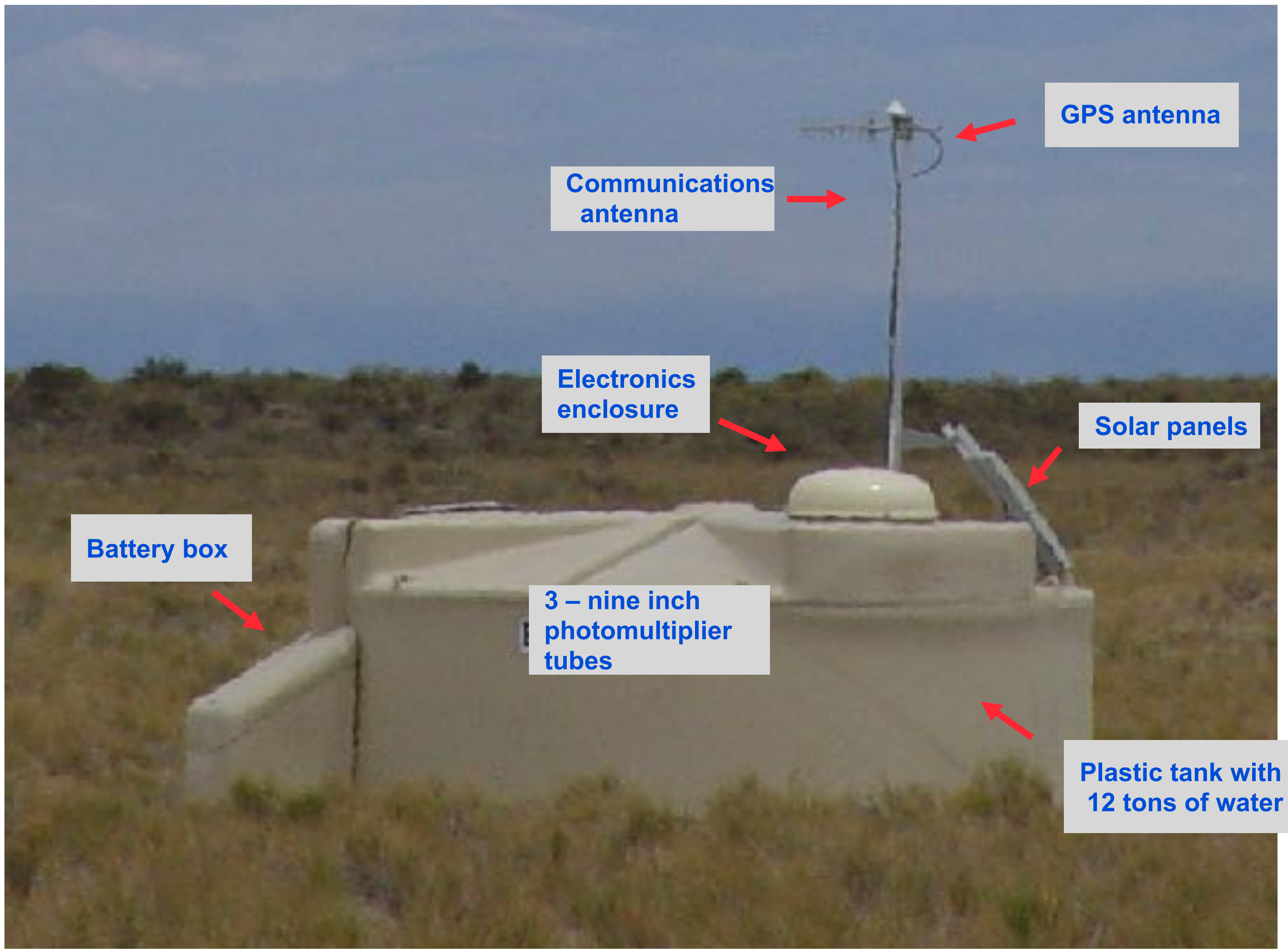
Fluorescence Detectors
- *4 Telescope enclosures*
- *6 Telescopes per enclosure*
- *24 Telescopes total*

10^19 ev cosmic rays arrive 1 particle/yr/sq. km

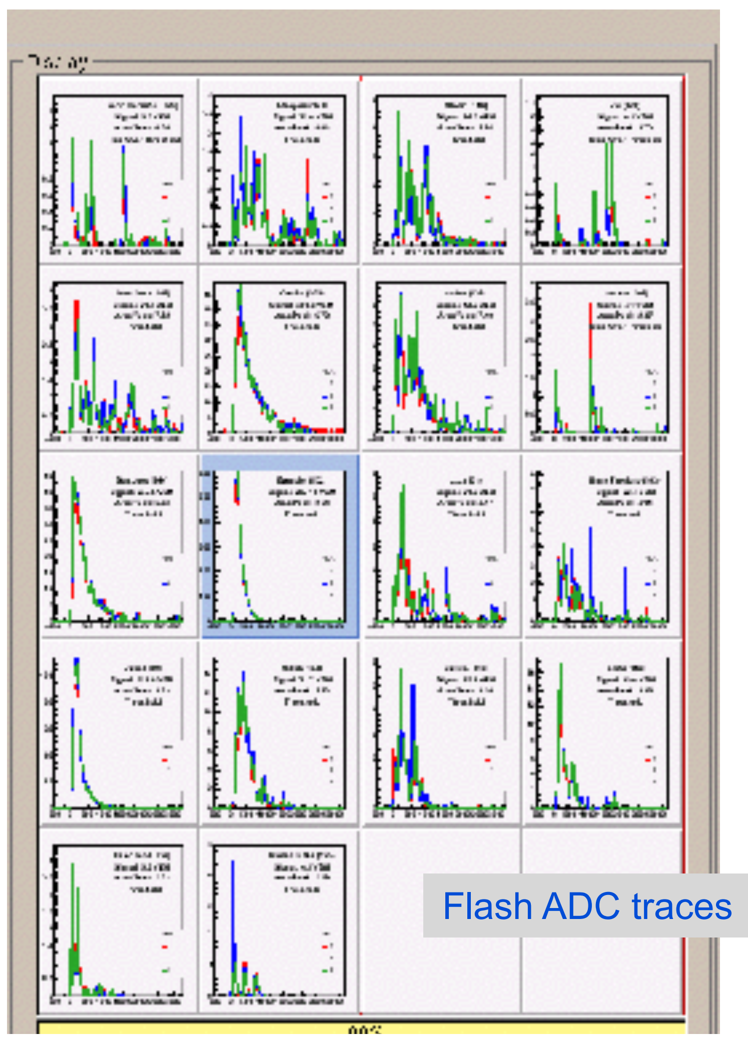
10^20 ev, 1particle/century/sq. km

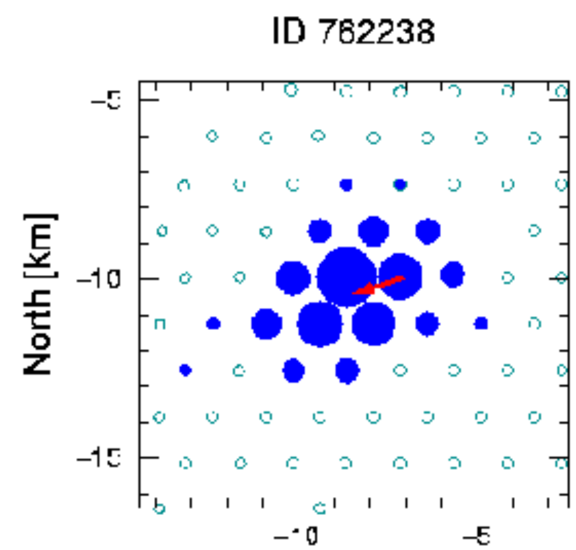
the observatory = size of Rhode Island

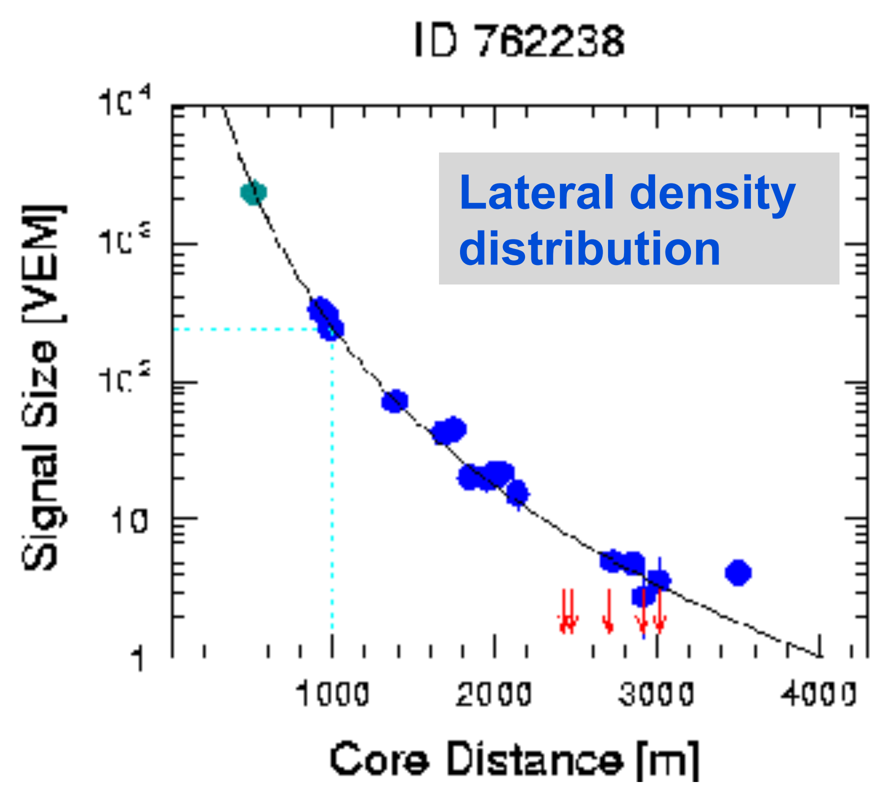
The Surface Array Detector Station



Example Surface Array Event
Θ~ 48°, ~ 70 EeV

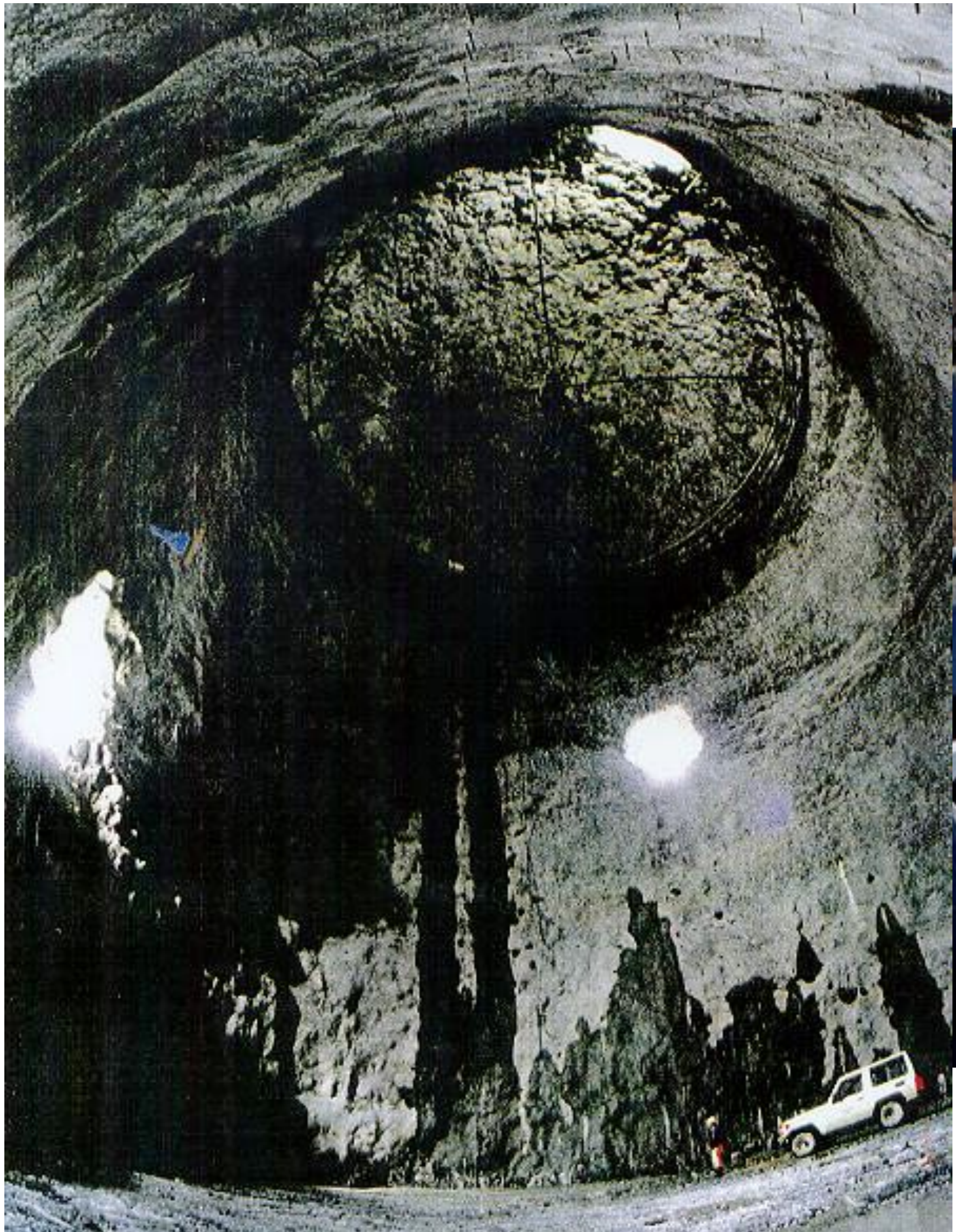


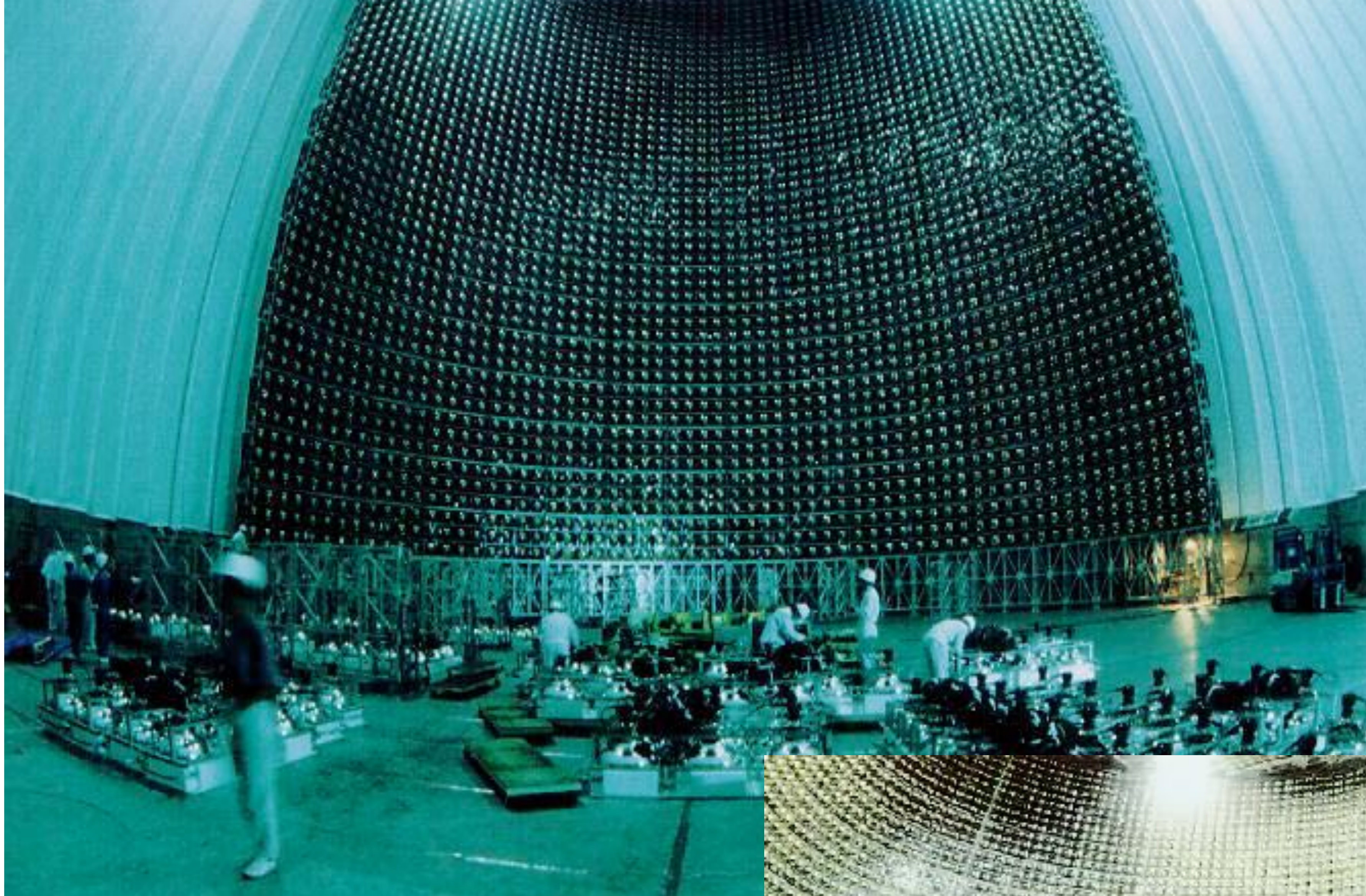
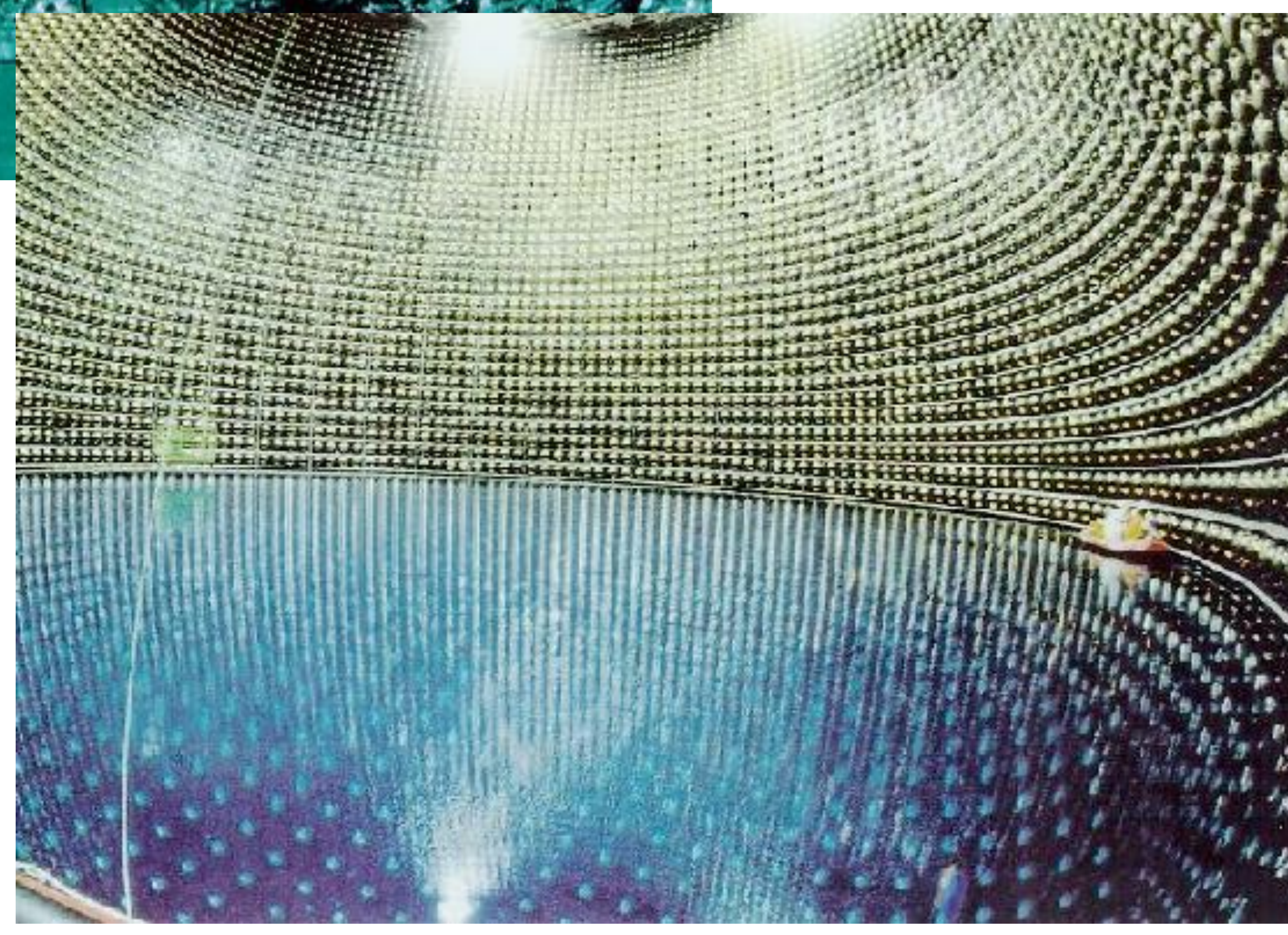


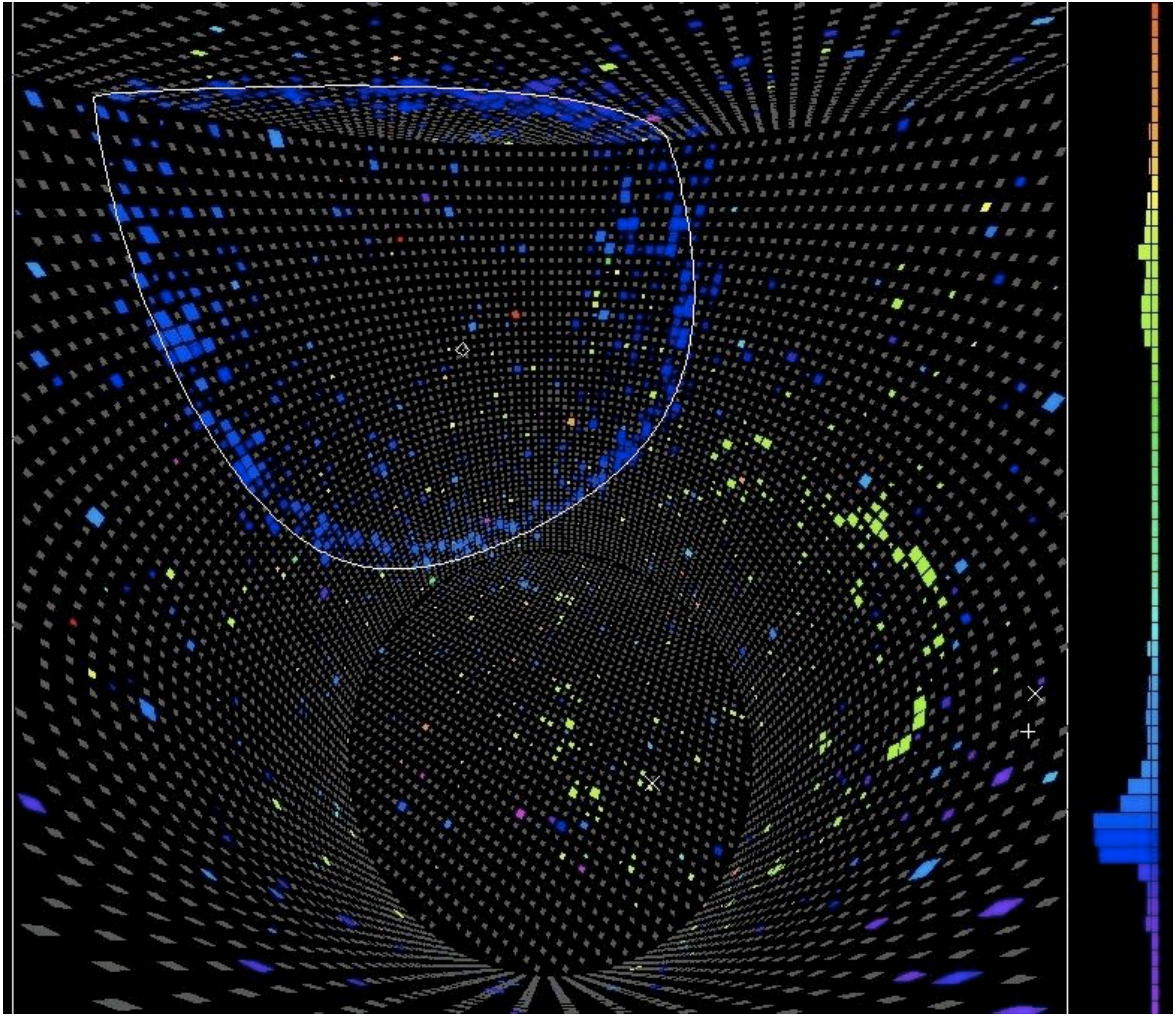


Super-Kamiokande

to detect solar (and other) neutrinos, proton decay



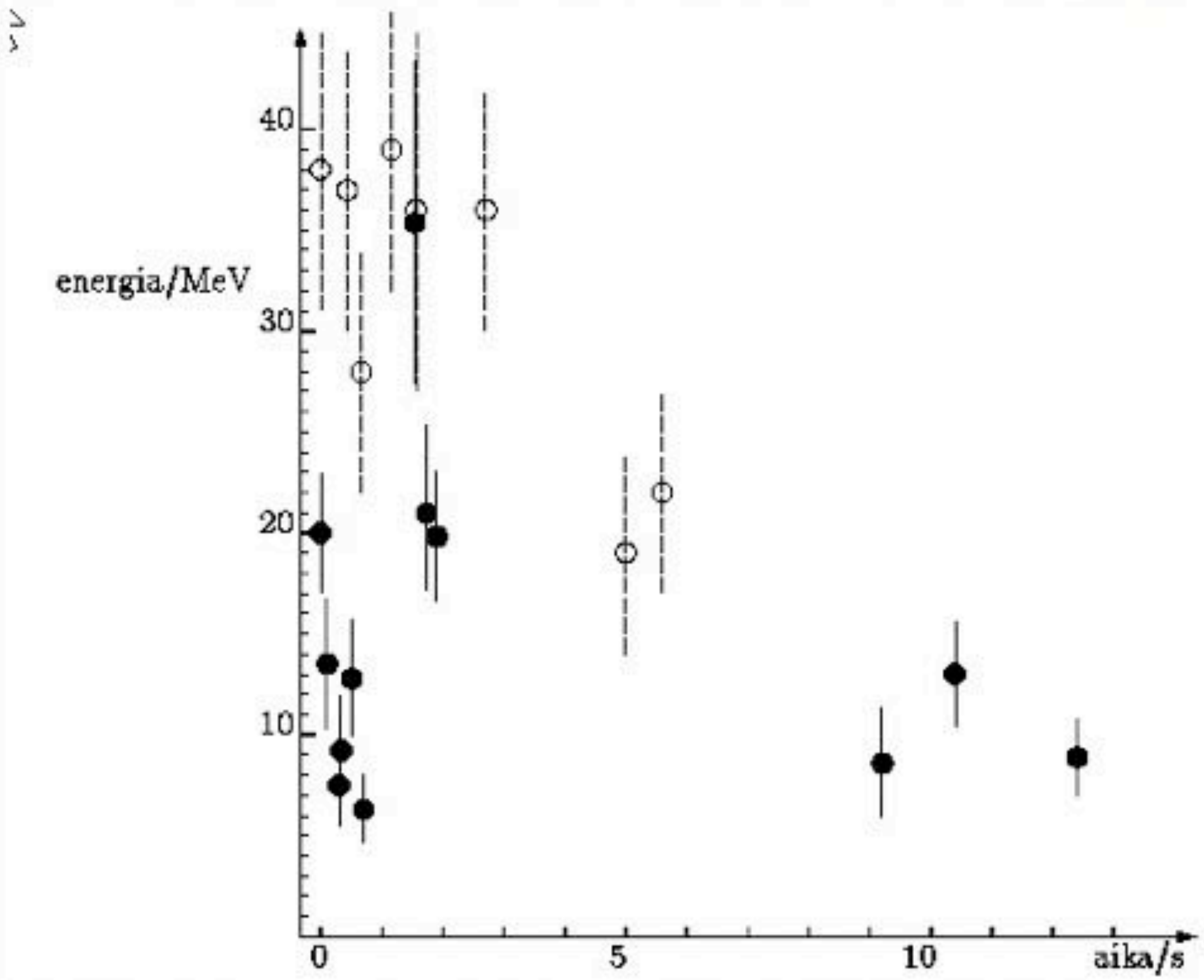



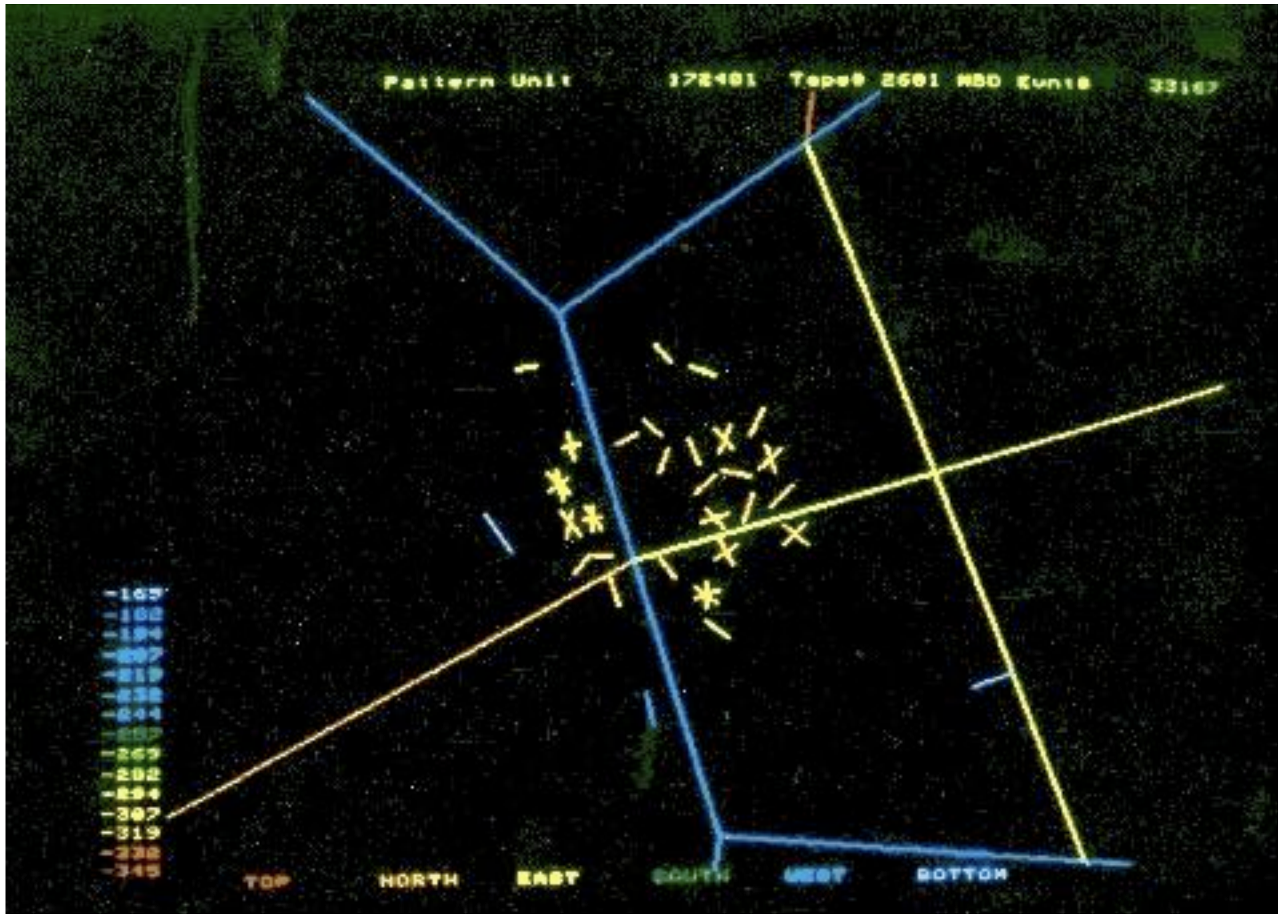


The observations of SN1987A

Progenitor: Sandulaek -89^0 202 at Large Magellanic Cloud. Mass 15-18 solar masses.

Optical observation 24 February 1987. Neutrino observations at February 23 7:35 UTC:





from IMB

DM Direct Detection Experiments

Completed

- CDMS
- CRESST I
- EDELWEISS
- MAC-HE3
- SIMPLE
- XENON10
- ZEPLIN
- ZEPLIN II

Ongoing

- ArDM
- CDMS II
- CLEAN/DEAP
- COUP
- CRESST II
- DAMA/LIBRA
- EDELWEISS II
- LUX
- TEXONO
- WARP
- XENON100
- ZEPLIN III

Future

- EURECA
- LUX-20T
- Super CDMS

Indirect Detection Experiments

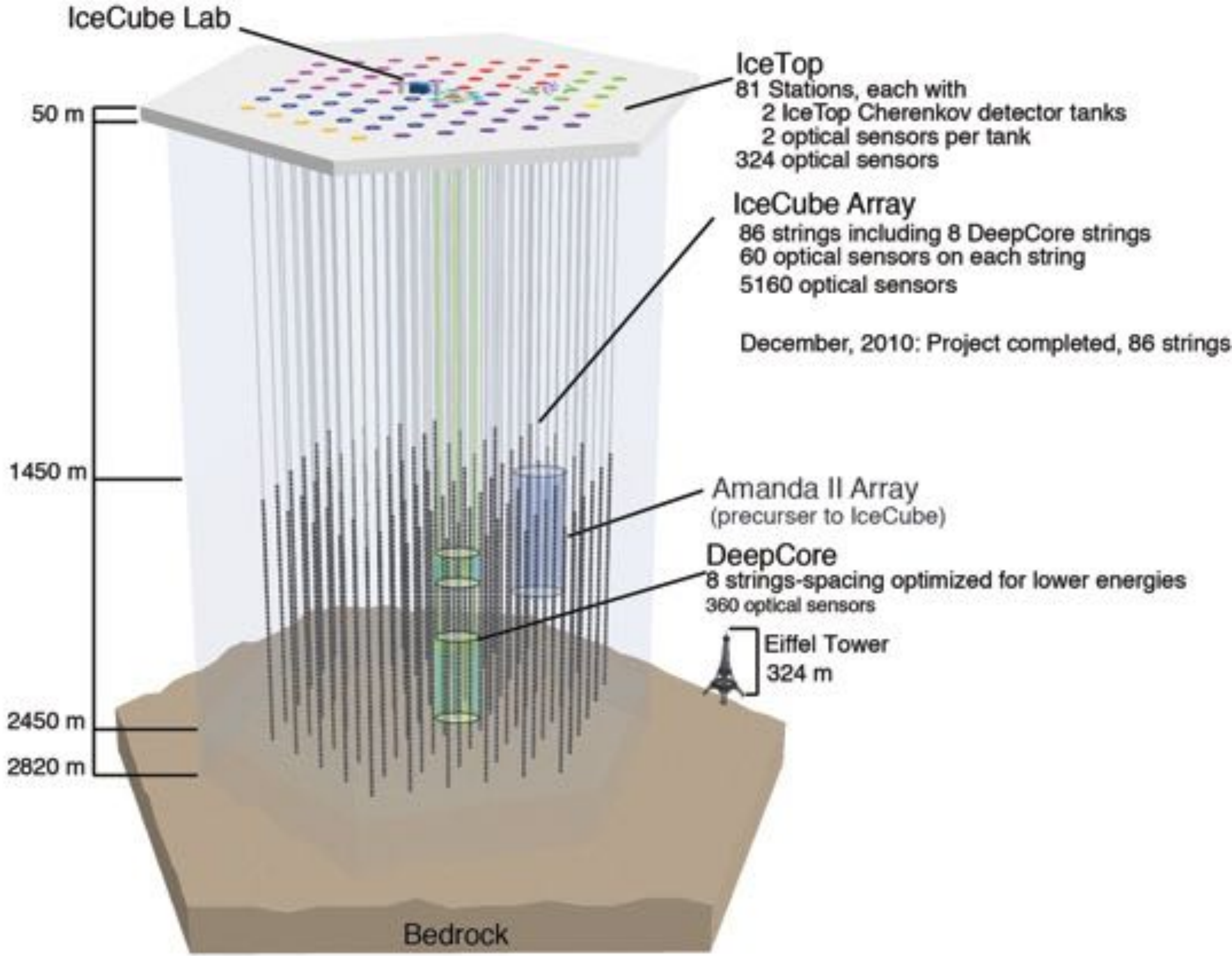
- AMANDA
- ANTARES
- AUGER
- GLAST
- HESS
- ICECUBE
- SUPER-KAMIOKANDE

5160 detectors

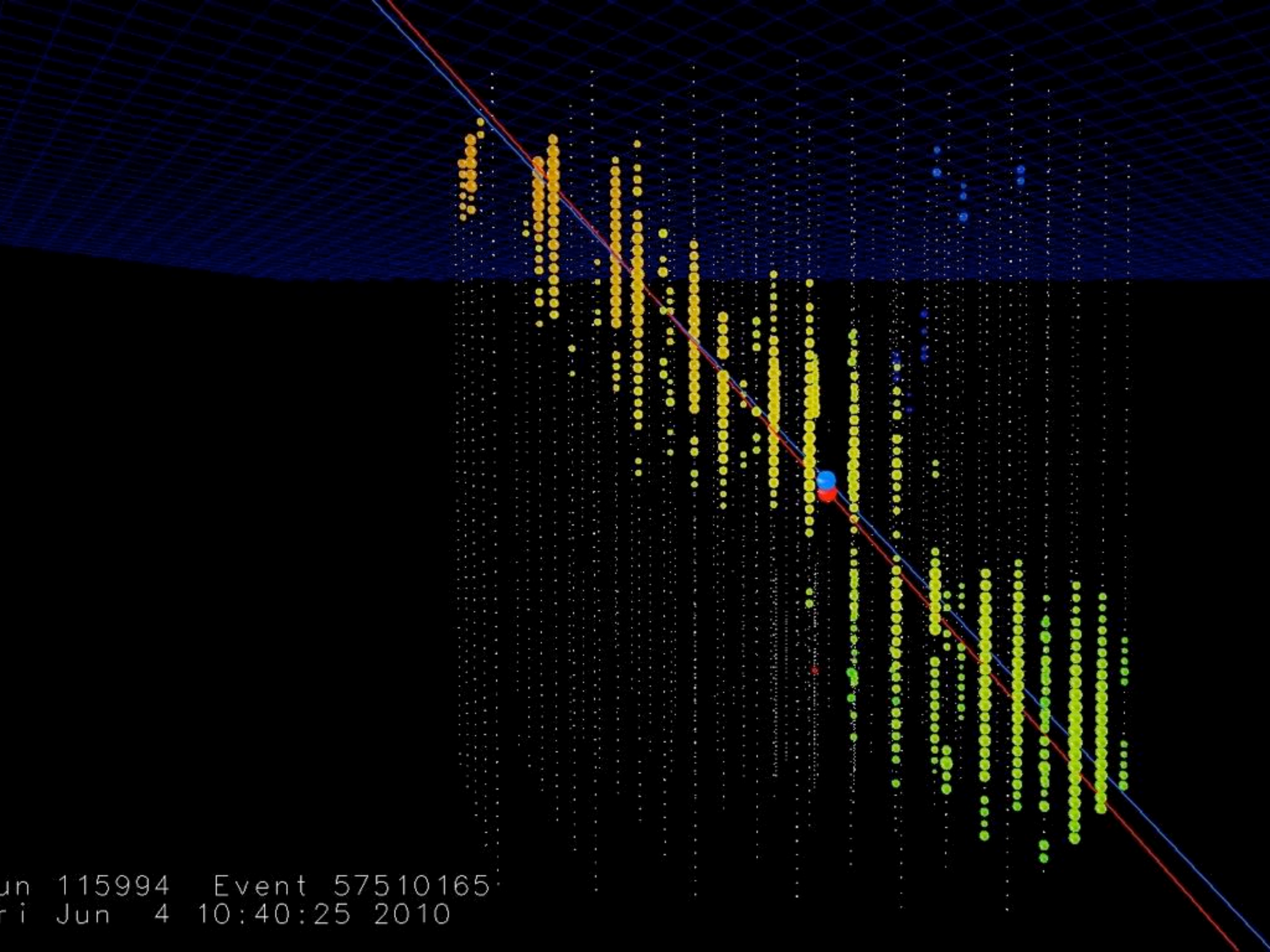
up to 1.5 miles deep

for every 1 cosmic muon, 10^6 CR-related muons

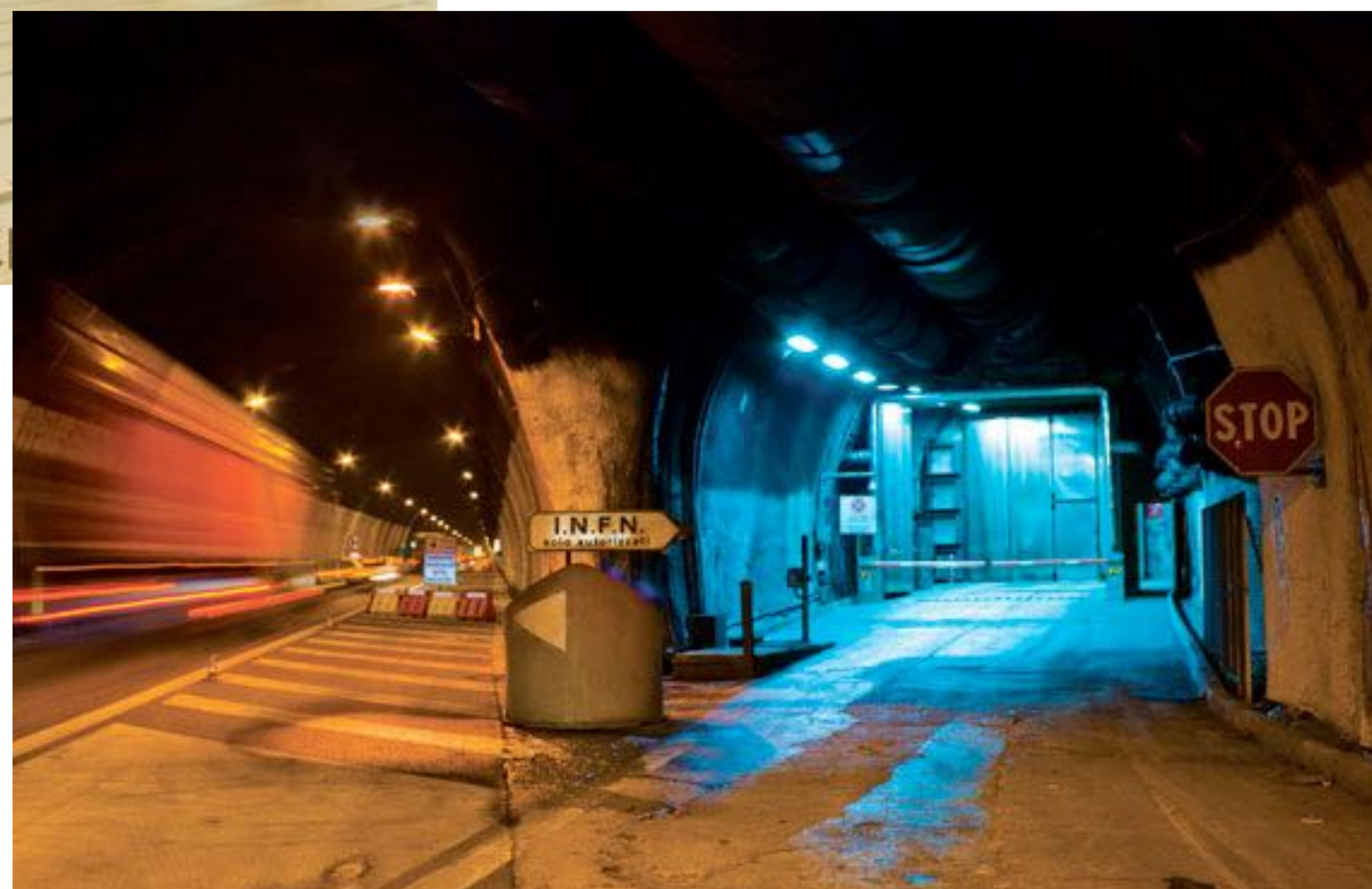
“looks” north

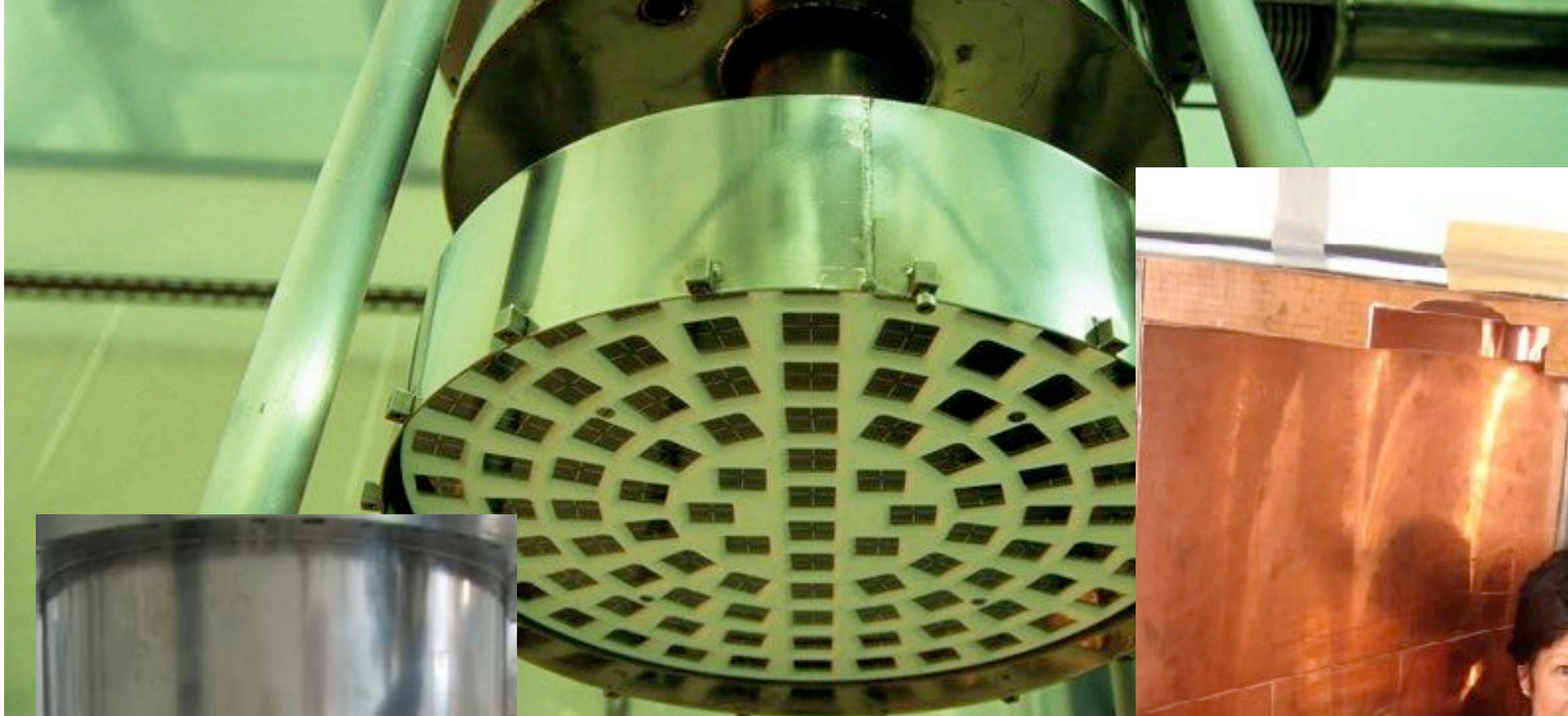


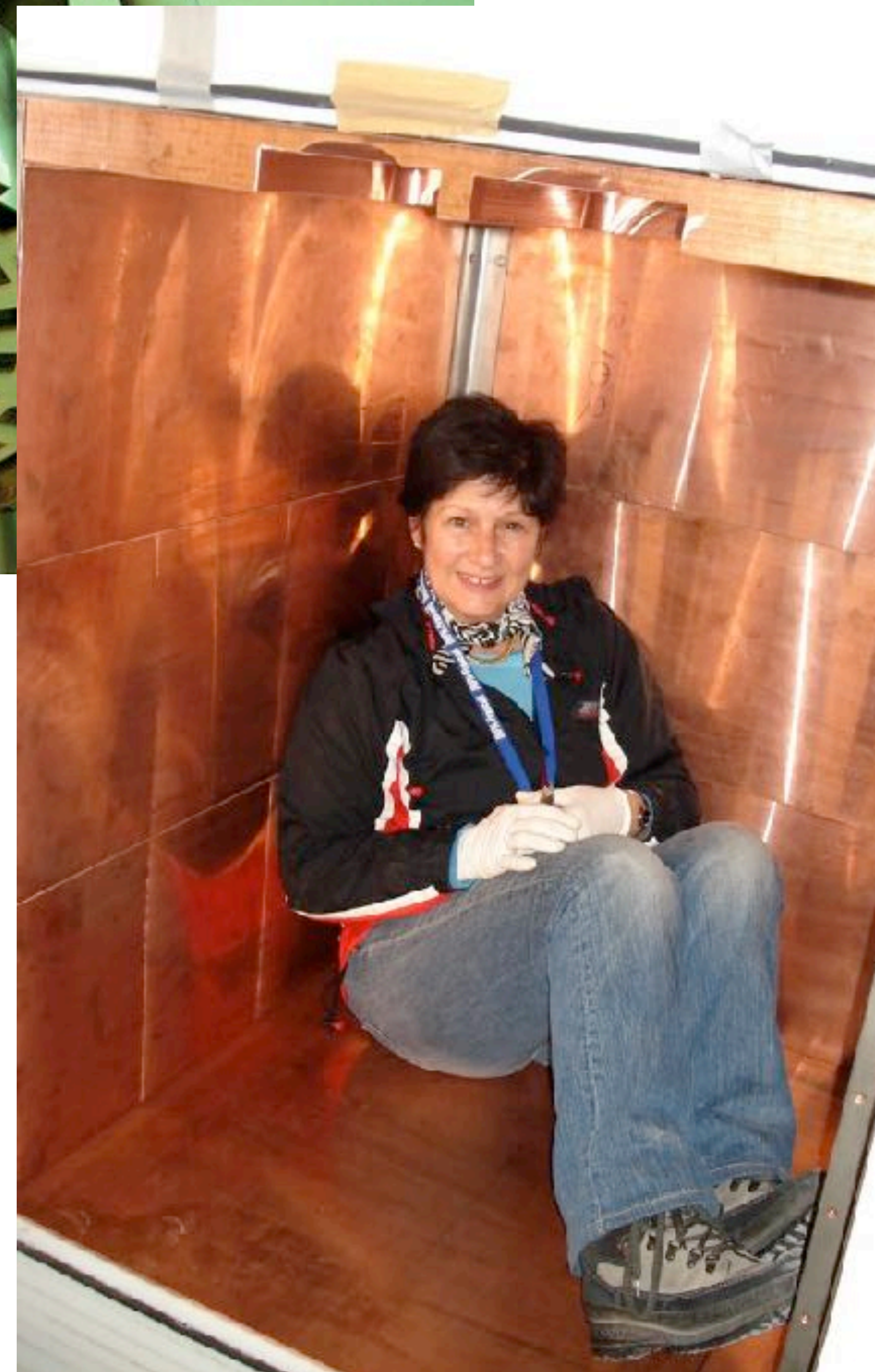
IceCube Lab
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
Amanda II Array
(precurser to IceCube)
DeepCore
8 strings-spacing optimized for lower energies
360 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock

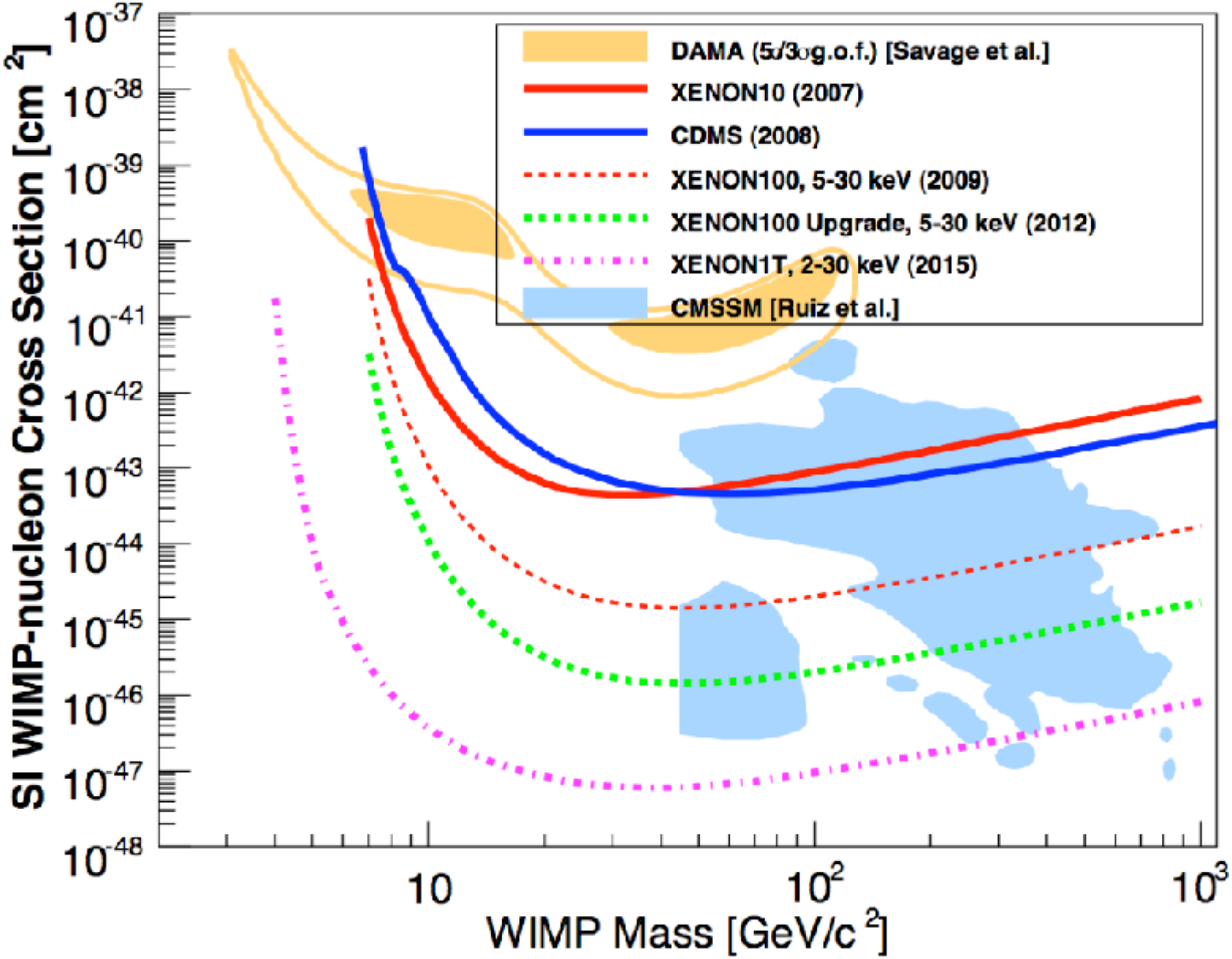

un 115994 Event 57510165
ri Jun 4 10:40:25 2010

XENON100 to detect WIMPS

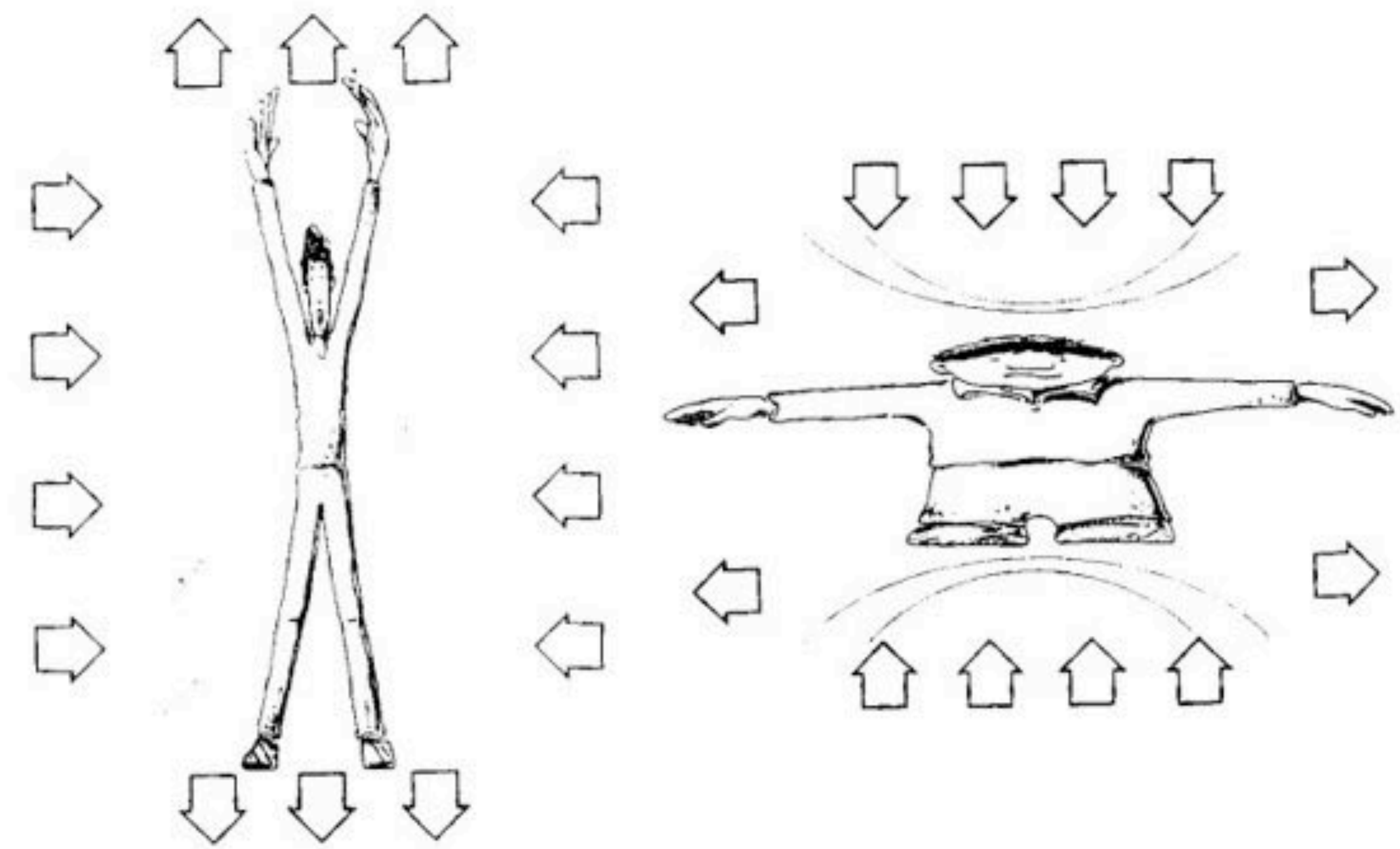

I.N.F.N.
STOP

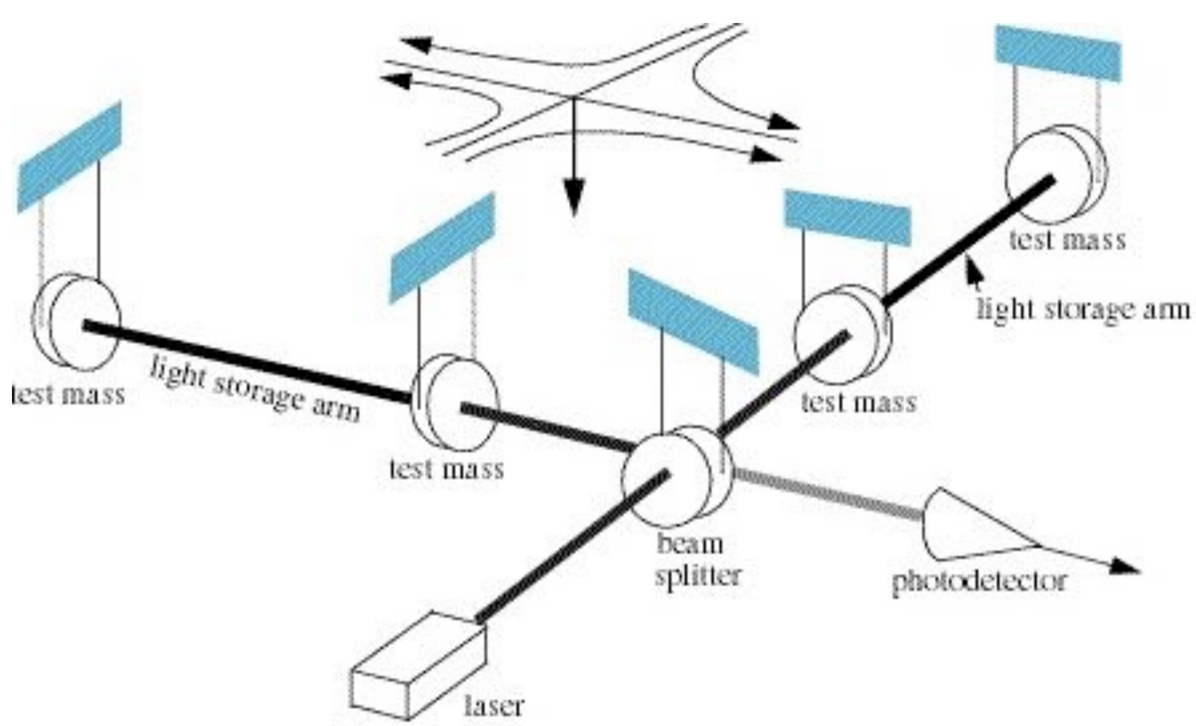




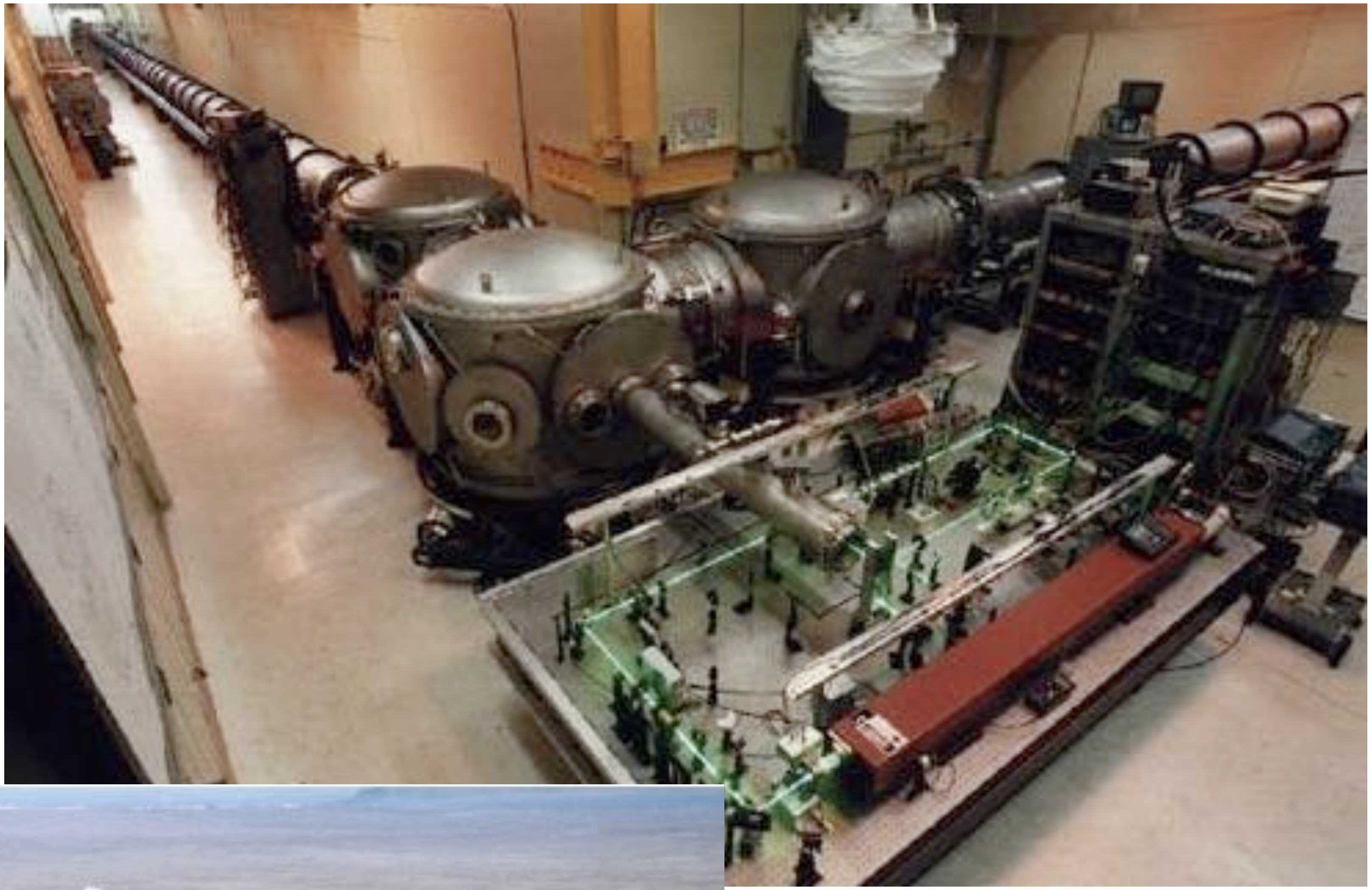

DAMA (5σ/3σ g.o.f.) [Savage et al.]
XENON10 (2007)
CDMS (2008)
XENON100, 5-30 keV (2009)
XENON100 Upgrade, 5-30 keV (2012)
XENON1T, 2-30 keV (2015)
CMSSM [Ruiz et al.]
SI WIMP-nucleon Cross Section [cm 2]
WIMP Mass [GeV/c 2]
10
10^2
10^3
10^-37
10^-38
10^-39
10^-40
10^-41
10^-42
10^-43
10^-44
10^-45
10^-46
10^-47
10^-48

Gravitational Waves

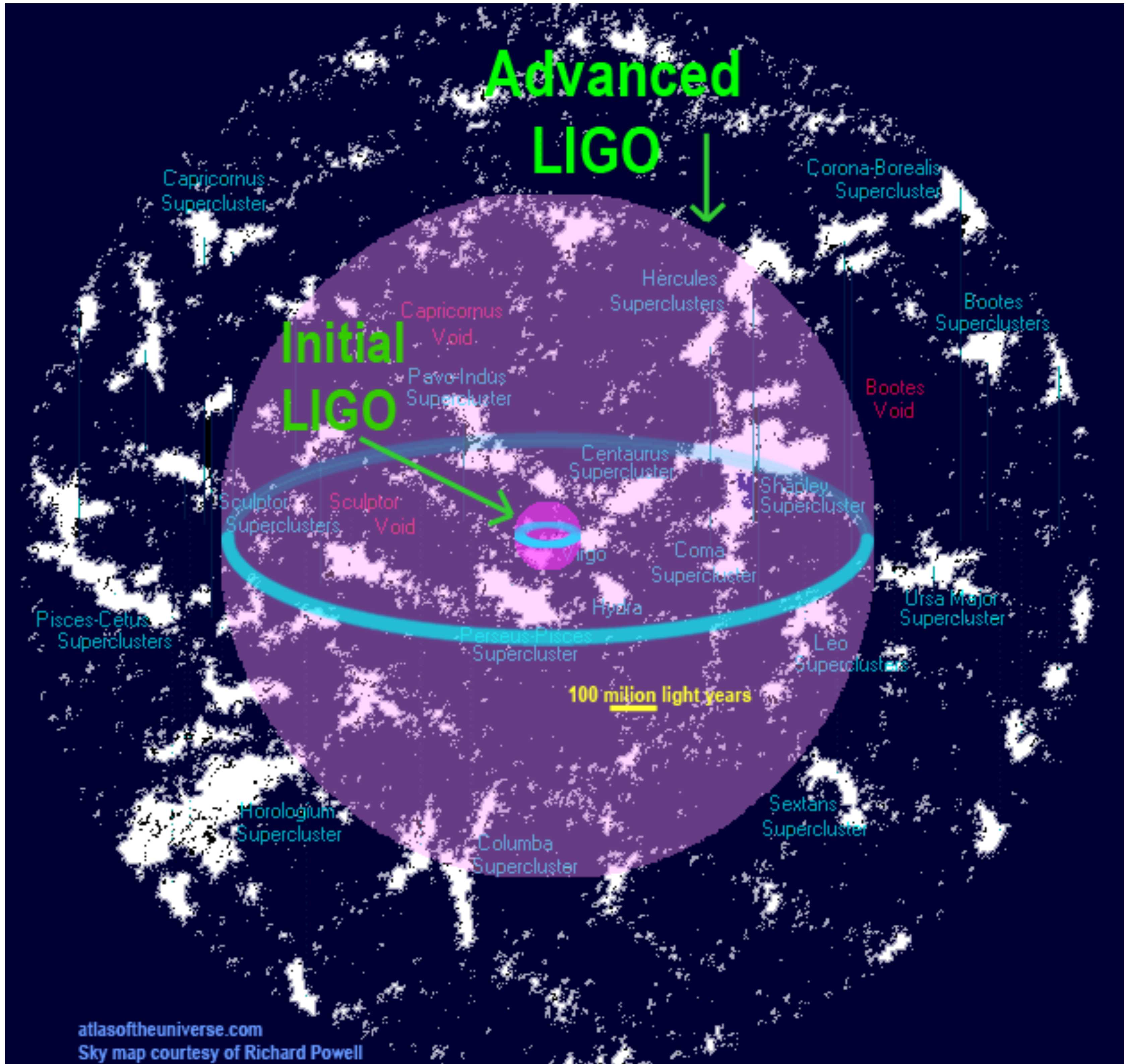


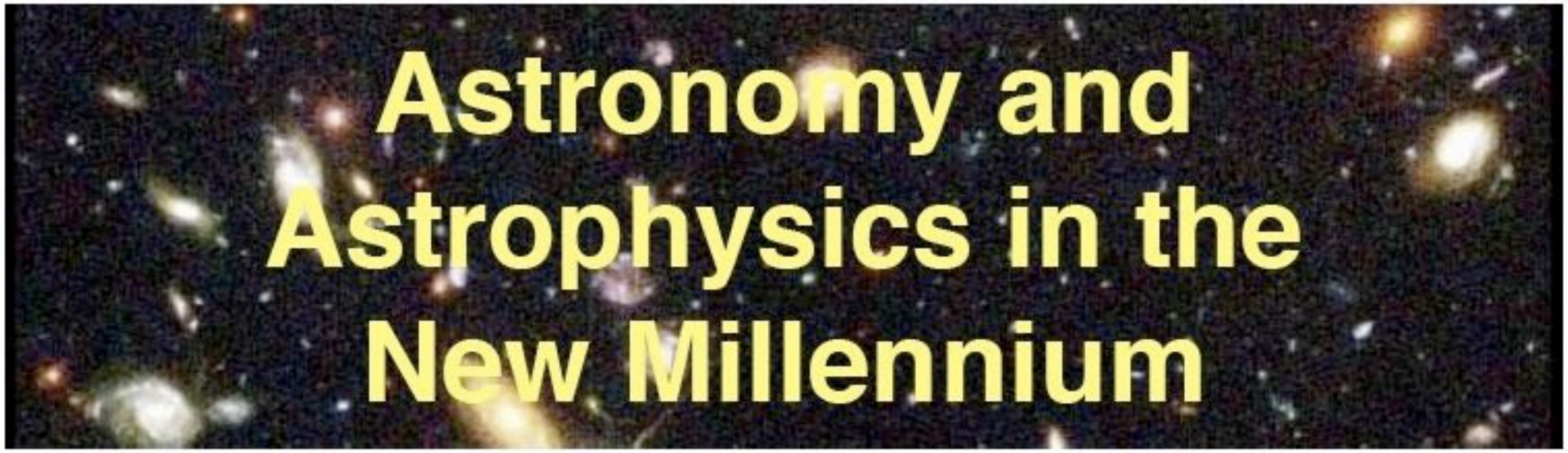


LIGO



Advanced LIGO



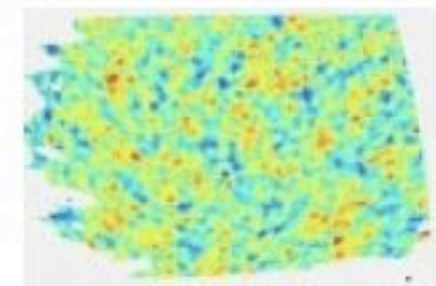
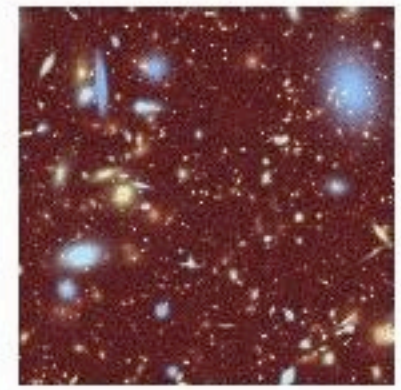
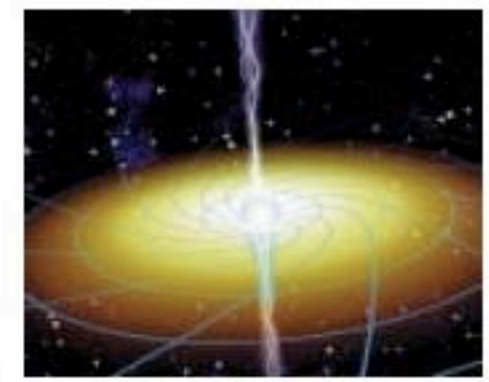


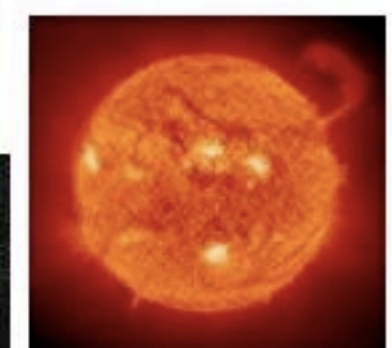
Astronomy and Astrophysics Survey Committee

Co-Chairs
Christopher F. McKee
and Joseph H. Taylor, Jr.

Key Scientific Problems for the Coming Decade

- Determining the large scale properties of the universe
- Studying the dawn of the modern universe
- Understanding the formation and evolution of black holes of all sizes
- Studying the formation of stars and their planetary systems, and the birth and evolution of giant and terrestrial planets.
- Understanding how the astronomical environment affects Earth

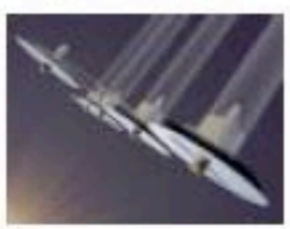















Prioritized Equipment Initiatives and Estimated Federal Costs ($M FY00)

MAJOR INITIATIVES

Next Generation Space Telescope (NGST)	1000
Giant Segmented-Mirror Telescope (GSMT)	350
Constellation-X Observatory	800
Expanded Very Large Array (EVLA)	140
Large-aperture Synoptic Survey Telescope (LSST)	170
Terrestrial Planet Finder (TPF)	200*
Single-Aperture Far InfraRed (SAFIR) Observatory	100*
Subtotal for major programs	2,760

Prioritized Equipment Initiatives and Estimated Federal Costs ($M FY00)

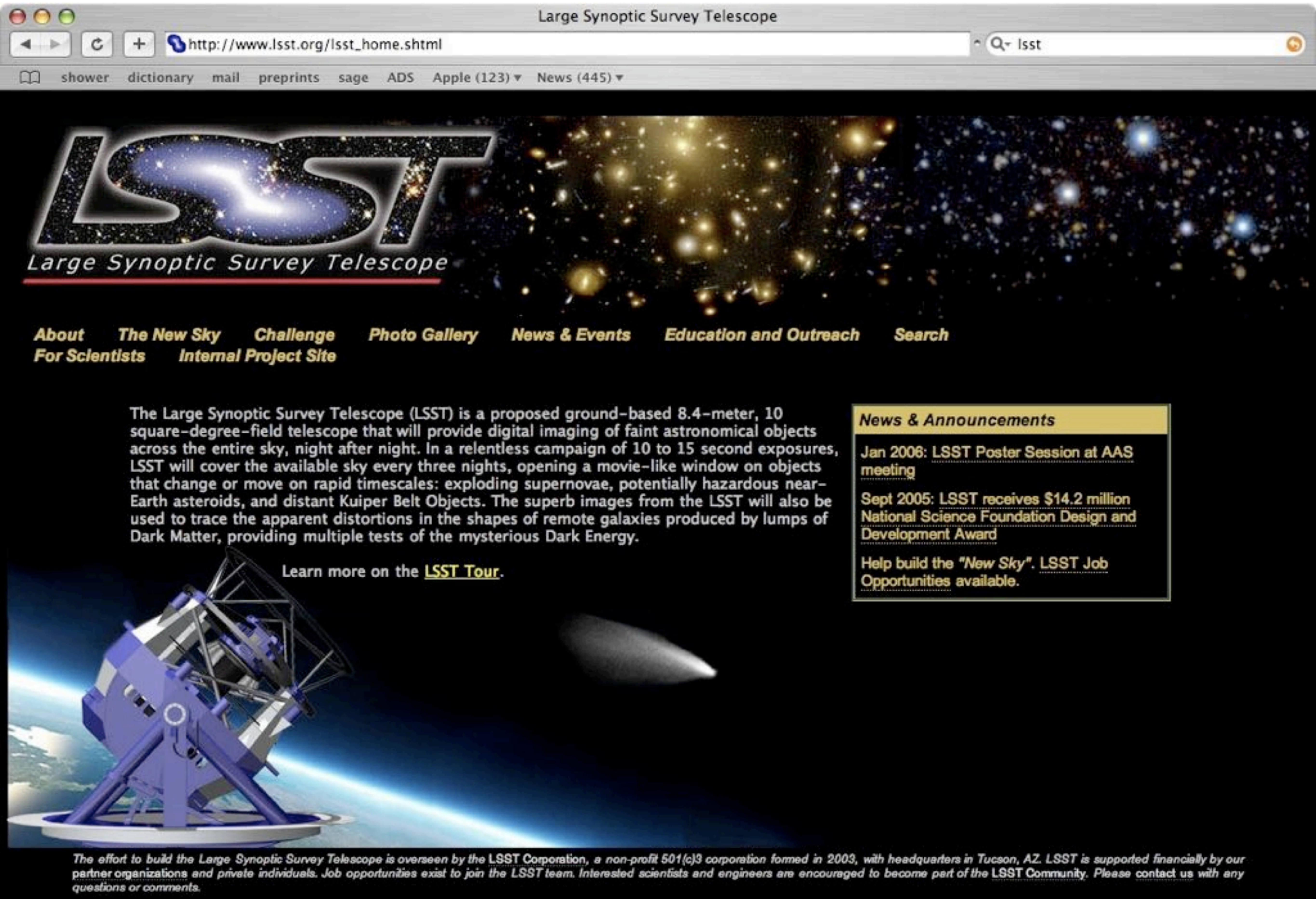
MODERATE INITIATIVES

Telescope System Instrumentation Program (TSIP)	50
Gamma-ray Large Area Space Telescope (GLAST)	300
Laser Interferometer Space Antenna (LISA)	250
Advanced Solar Telescope (AST)	60
Square Kilometer Array (SKA) Technology Development	22
Solar Dynamics Observer (SDO)	300
Combined Array for Research in Millimeter-wave Astronomy (CARMA)	11
Energetic X-ray Imaging Survey Telescope (EXIST)	150
Very Energetic Radiation Imaging Telescope Array System (VERITAS)	35
Advanced Radio Interferometry between Space and Earth (ARISE)	350
Frequency Agile Solar Radiotelescope (FASR)	26
South Pole Submillimeter Telescope (SPST)	50
Subtotal for moderate initiatives	1,604

Prioritized Equipment Initiatives and Estimated Federal Costs ($M FY00)

SMALL INITIATIVES

National Virtual Observatory (NVO)	60
Other small initiatives	246
Subtotal for small initiatives	306


Large Synoptic Survey Telescope
http://www.lsst.org/lsst_home.shtml
lsst
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LSST
Large Synoptic Survey Telescope
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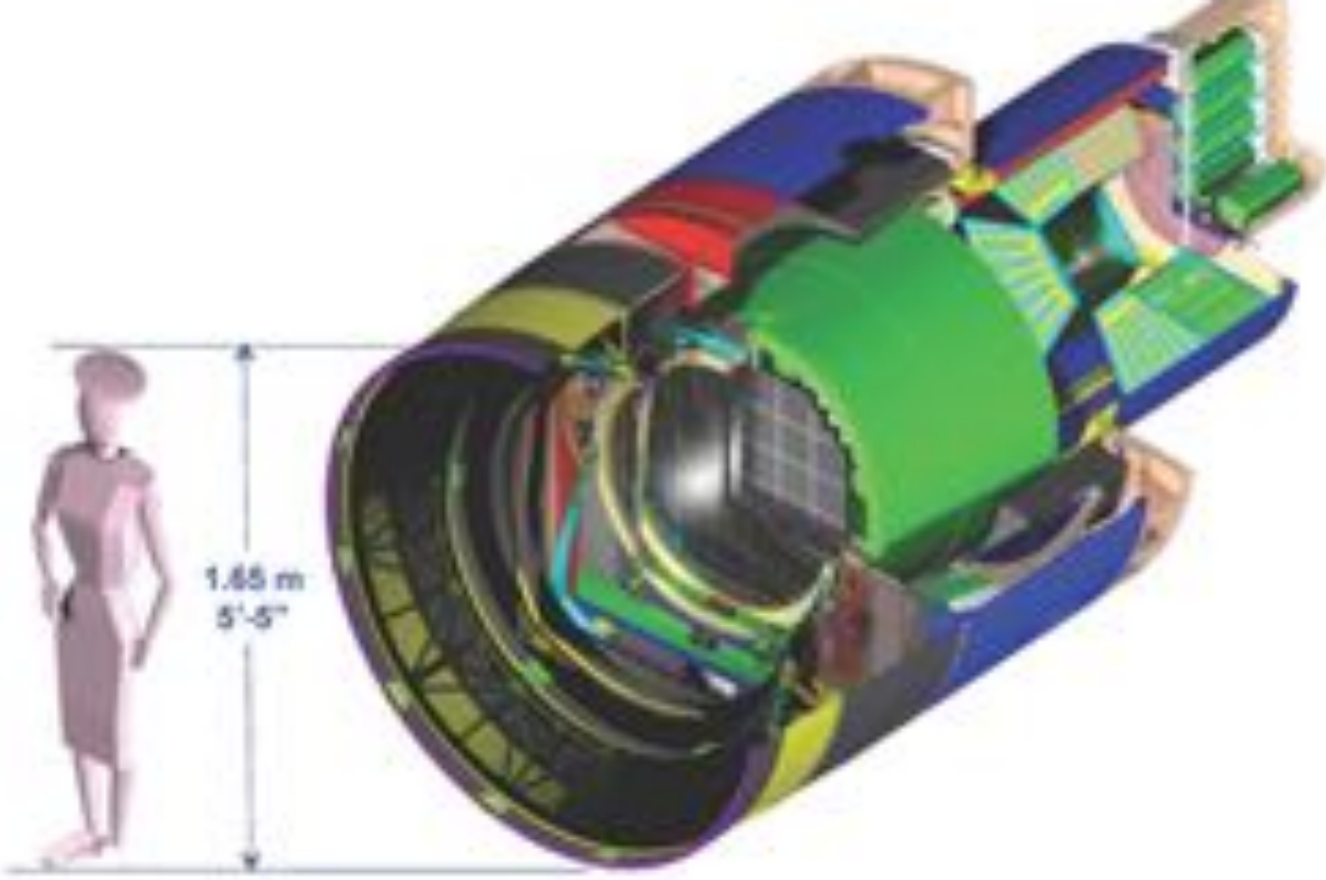
For Scientists Internal Project Site
The Large Synoptic Survey Telescope (LSST) is a proposed ground-based 8.4-meter, 10 square-degree-field telescope that will provide digital imaging of faint astronomical objects across the entire sky, night after night. In a relentless campaign of 10 to 15 second exposures, LSST will cover the available sky every three nights, opening a movie-like window on objects that change or move on rapid timescales: exploding supernovae, potentially hazardous near-Earth asteroids, and distant Kuiper Belt Objects. The superb images from the LSST will also be used to trace the apparent distortions in the shapes of remote galaxies produced by lumps of Dark Matter, providing multiple tests of the mysterious Dark Energy.
Learn more on the LSST Tour.
News & Announcements
Jan 2006: LSST Poster Session at AAS meeting
Sept 2005: LSST receives $14.2 million National Science Foundation Design and Development Award
Help build the "New Sky". LSST Job Opportunities available.
The effort to build the Large Synoptic Survey Telescope is overseen by the LSST Corporation, a non-profit 501(c)3 corporation formed in 2003, with headquarters in Tucson, AZ. LSST is supported financially by our partner organizations and private individuals. Job opportunities exist to join the LSST team. Interested scientists and engineers are encouraged to become part of the LSST Community. Please contact us with any questions or comments.

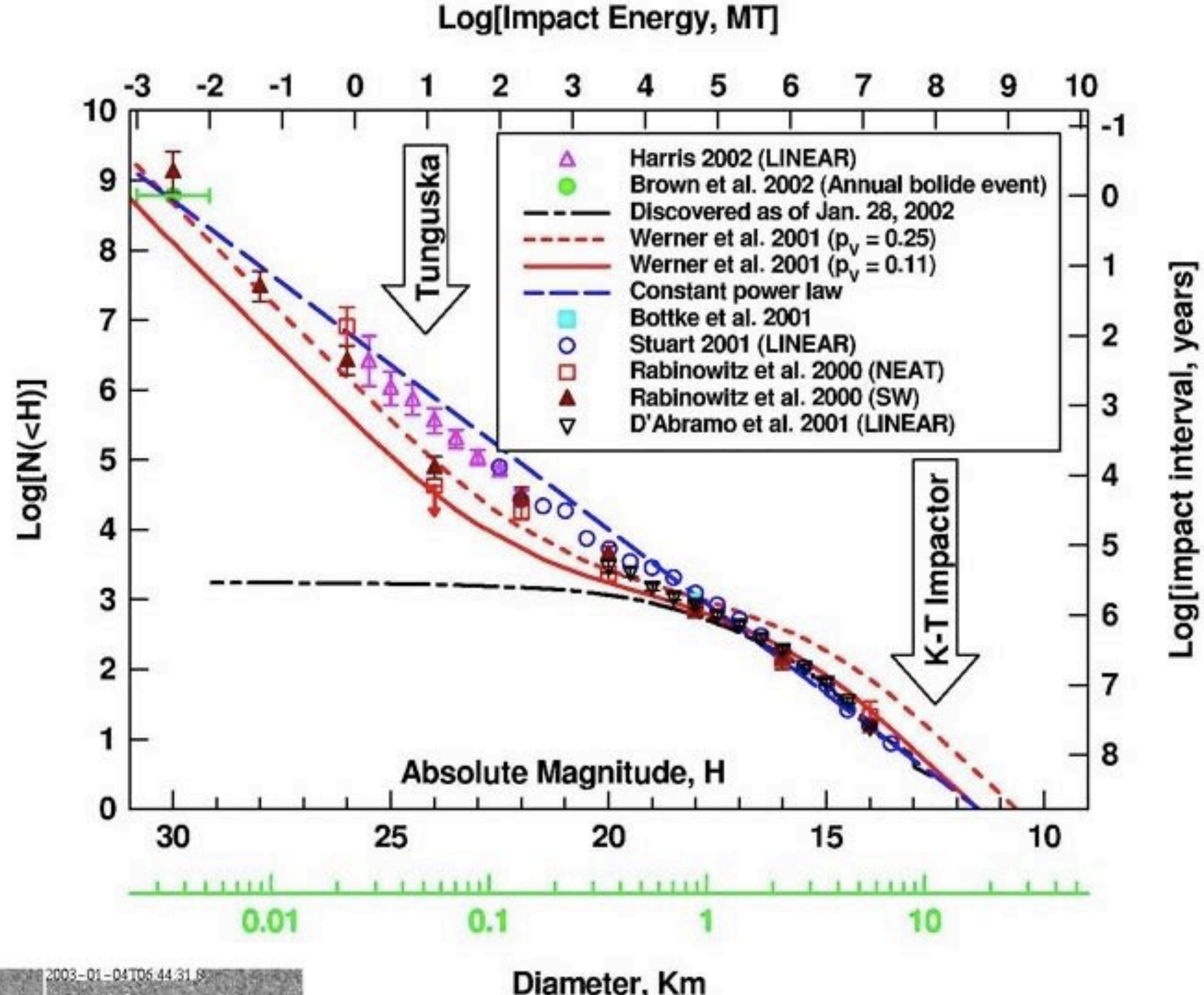

M2

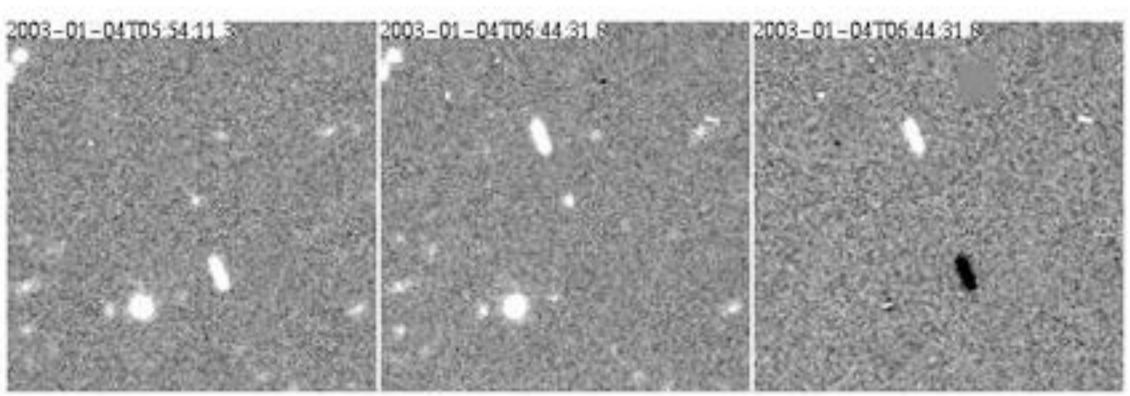
M1&M3


1.65 m
5'-5"

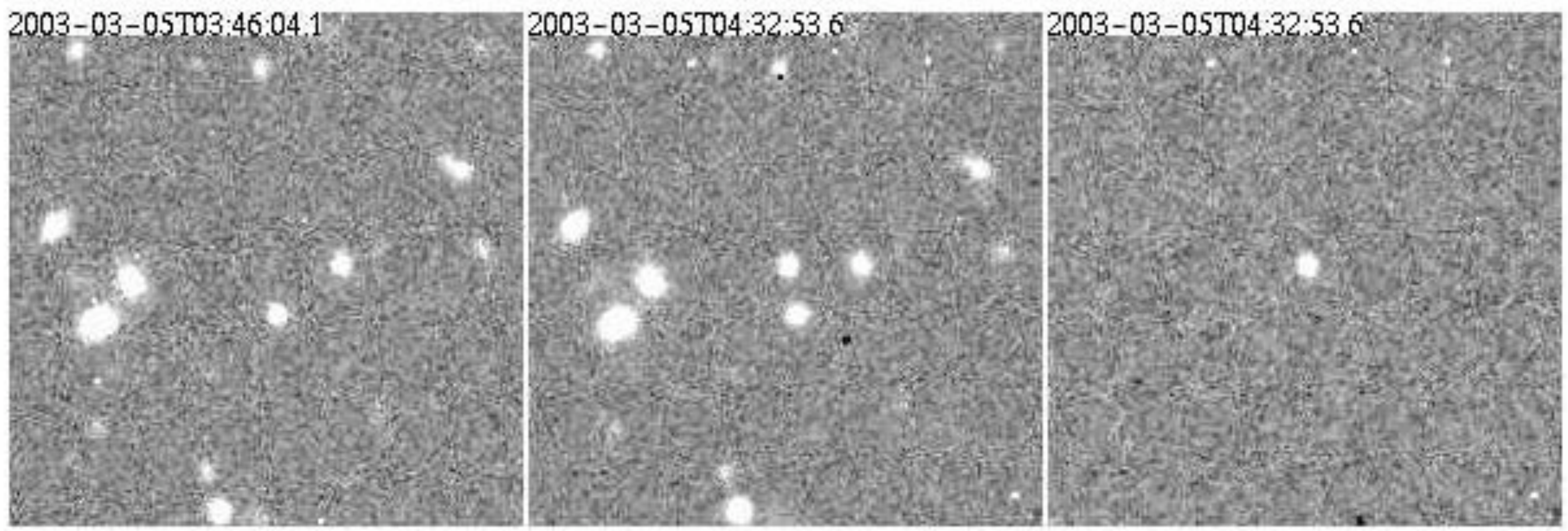
Site preparation has begun!

Transients :known





Transients: unknown

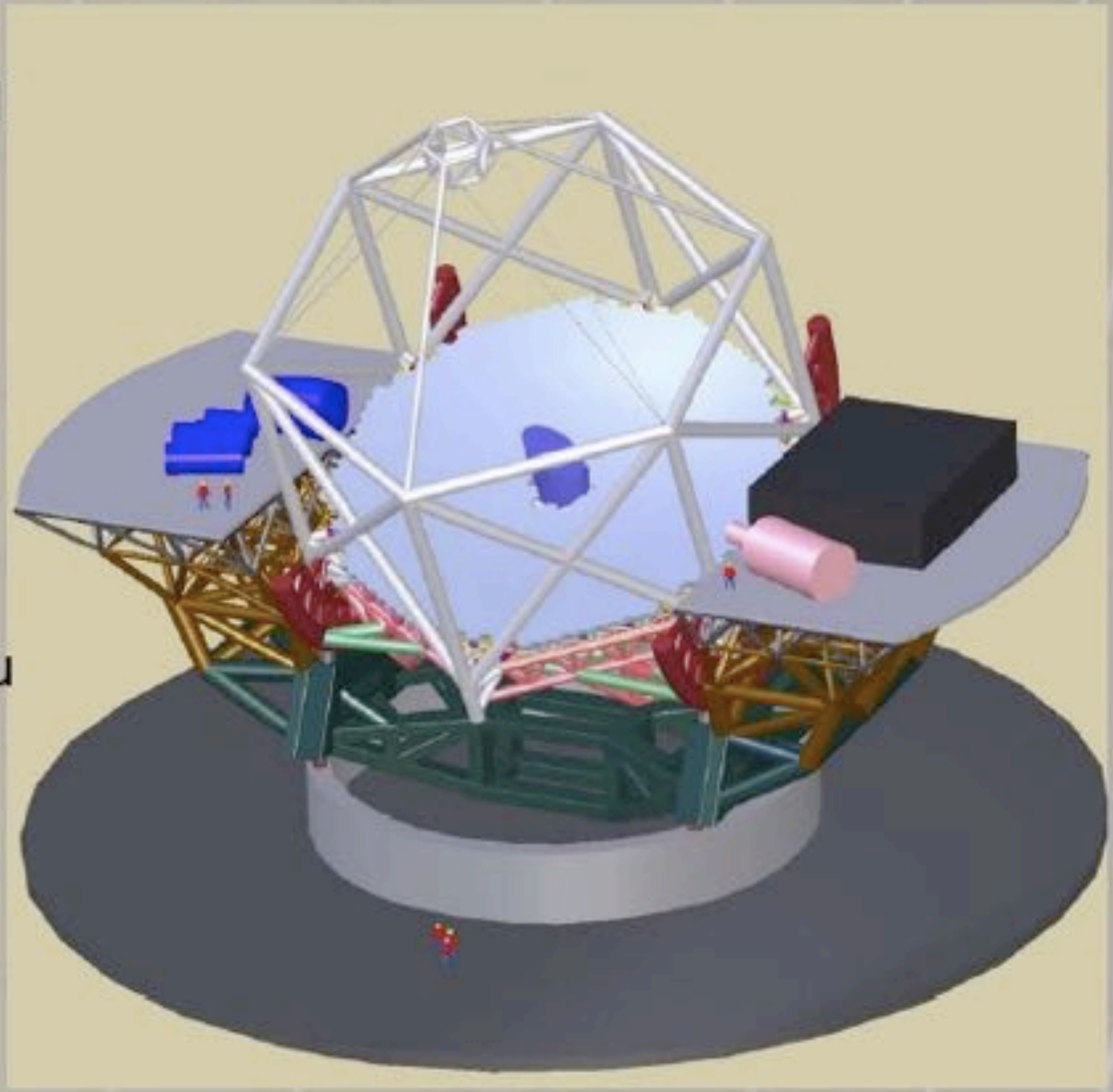


Optical burst detected by difference imaging (right hand frame) in the Deep Lens Survey.

30 TB/night

Single TMT Reference Design

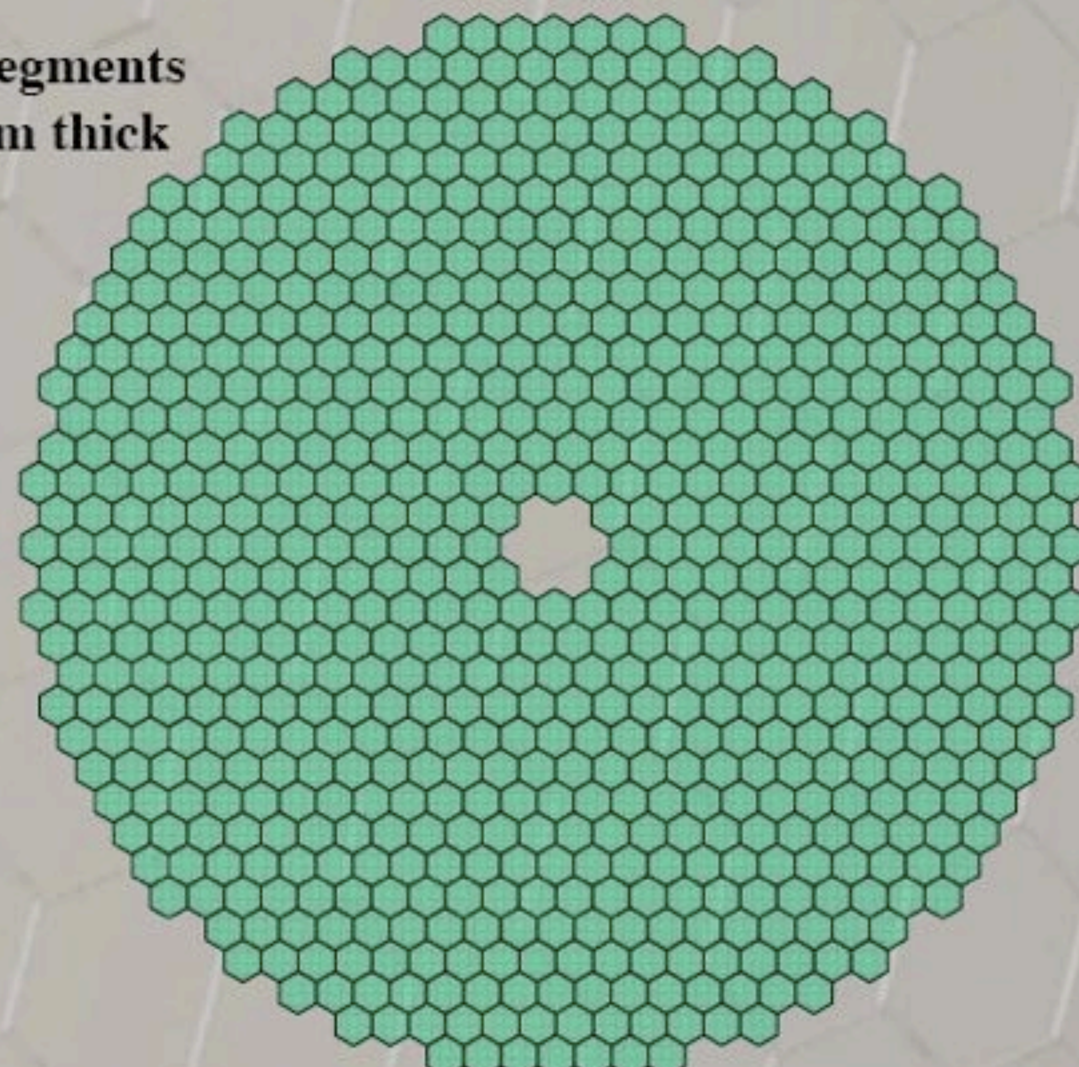
- 30m filled aperture, highly segmented
- Aplanatic Gregorian (AG) two mirror telescope
- f/1 primary
- f/15 final focus
- Field of view 20 arcmin
- Elevation axis in front of the primary
- Wavelength coverage 0.31 – 28 μm
- Operational zenith angle range 1° thru 65°
- Both seeing-limited and adaptive optics observing modes
- AO system requirements and architecture defined
- First generation instrument requirements defined



UC, Caltech, Canada,China, Japan,India

30m Primary Mirror Concept

738 × 1.2m segments each 0.060m thick



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- Home
- Overview
- Image Gallery
- News
- Science Case
- Calendar
- Reports
- Links
- Login

UA,
Carnegie,
Harvard,
Smithsonian,
UT,
Texas A&M,
U. Chicago,
Australia,
S. Korea, Sao
Paulo

The Giant Magellan Telescope (GMT)—the product of more than a century of astronomical research and telescope-building by some of the world's leading research institutions—will open **a new window on the universe for the 21st century.** Scheduled for completion around 2016, the GMT will have the resolving power of a 24.5-meter (80 foot) primary mirror—**far larger than any other telescope ever built**. It will answer many of the questions at the forefront of astrophysics today and will pose new and unanticipated riddles for future generations of astronomers.

The GMT will produce images up to 10 times sharper than the Hubble Space Telescope.

GMT Partner Institutions: The GMT Consortium Welcomes Australian National University as a new GMT Partner more...

[redacted]

GMT – Mirror Casting Success

http://www.gmto.org/newsitems/mirrorblank

gmt

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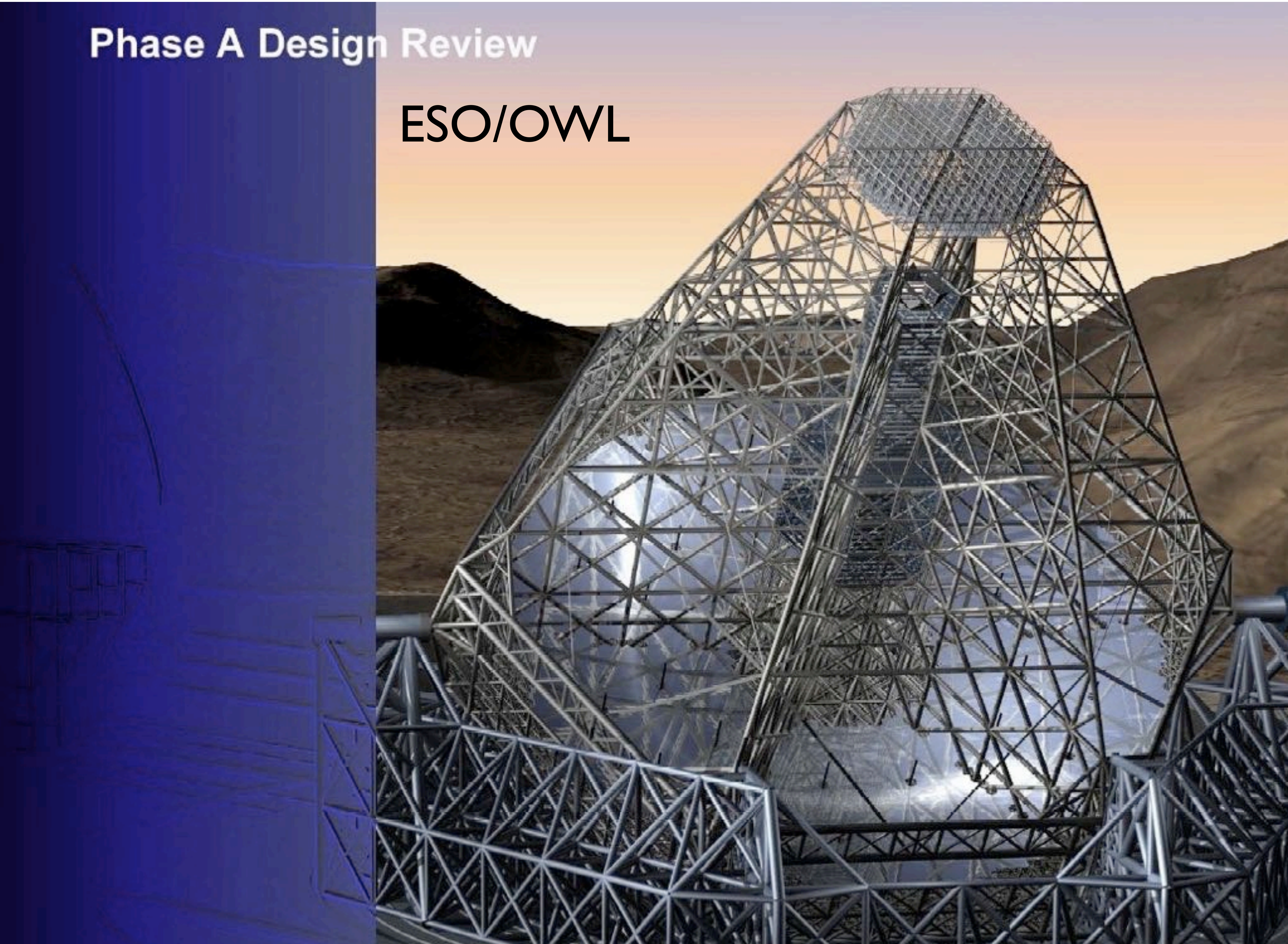
- Home
- Overview
- Image Gallery
- News
- Science Case
- Calendar
- Reports
- Links
- Login

Mirror Casting Success

The casting of the first of seven primary mirror segments for the Giant Magellan Telescopes is complete.

Casting completed on the first 8.4 meter (27.5-foot) primary mirror segment. The Giant Magellan Telescope's primary mirror will be comprised of a total of seven segments, providing the resolving power of a 24.5-

ESO/OWL



[redacted]

$$S/N = \frac{N_* t_{exp}}{\sqrt{(N_s + N_*)t_{exp} + N_{DET}}}$$

telescope size increases N*

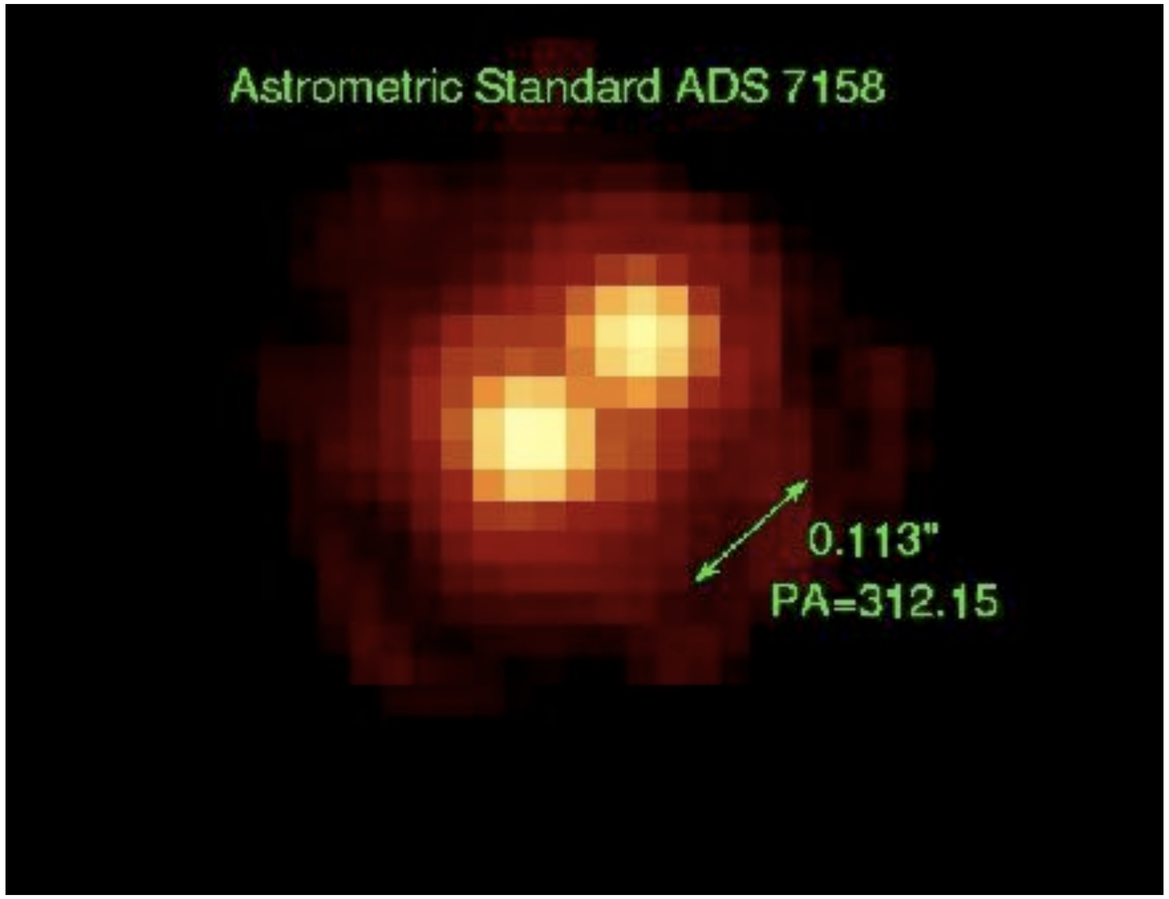
image quality decreases Ns

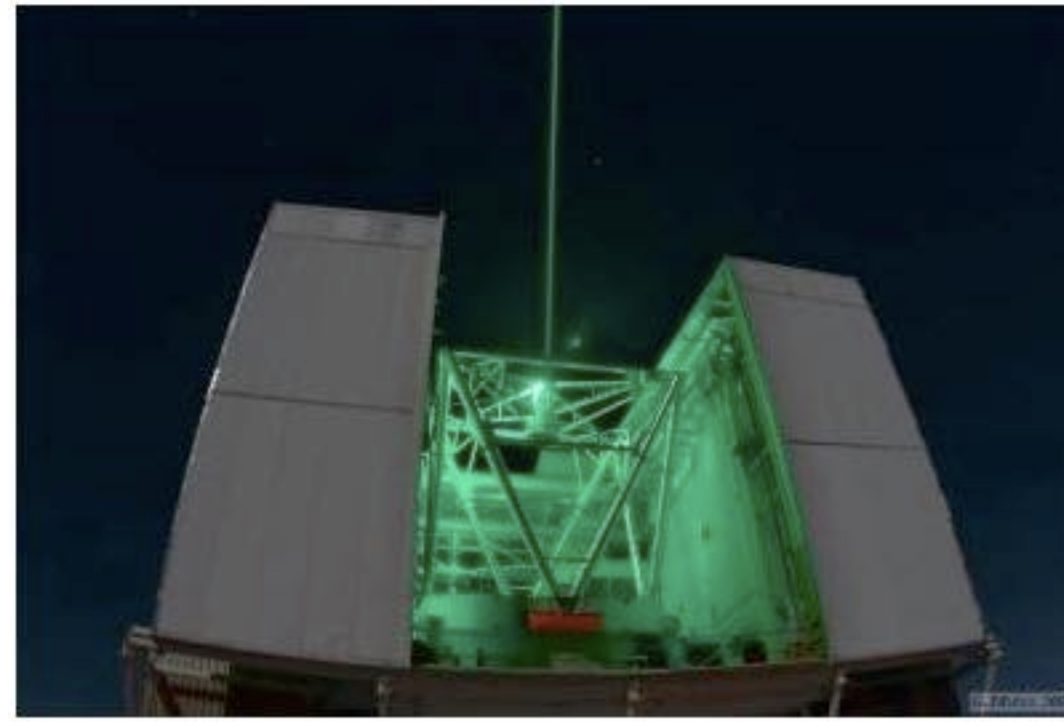
going from 4m to 8m increased N* by 16 (and S/N by 4)

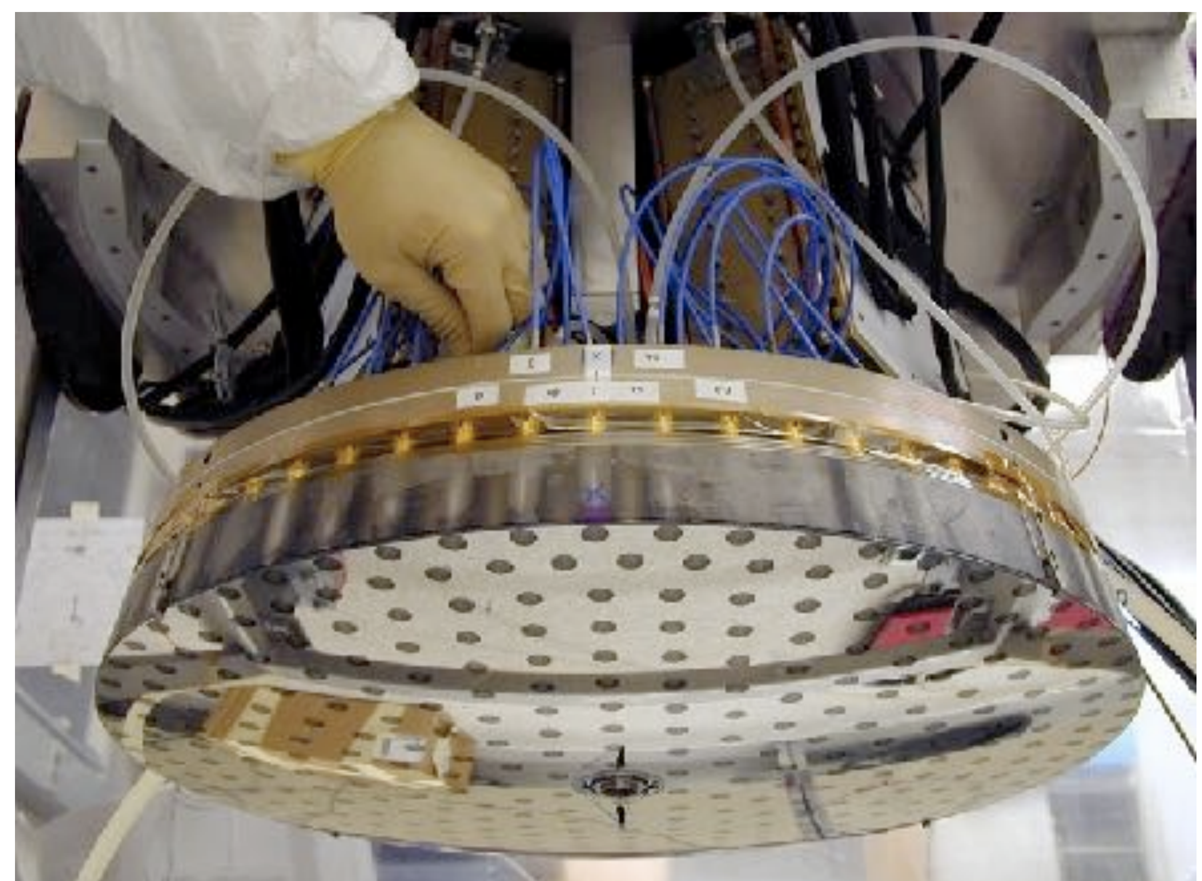
decreasing seeing from 1 to 0.5 arcsec cut sky by 4 (and increased S/N by 2)

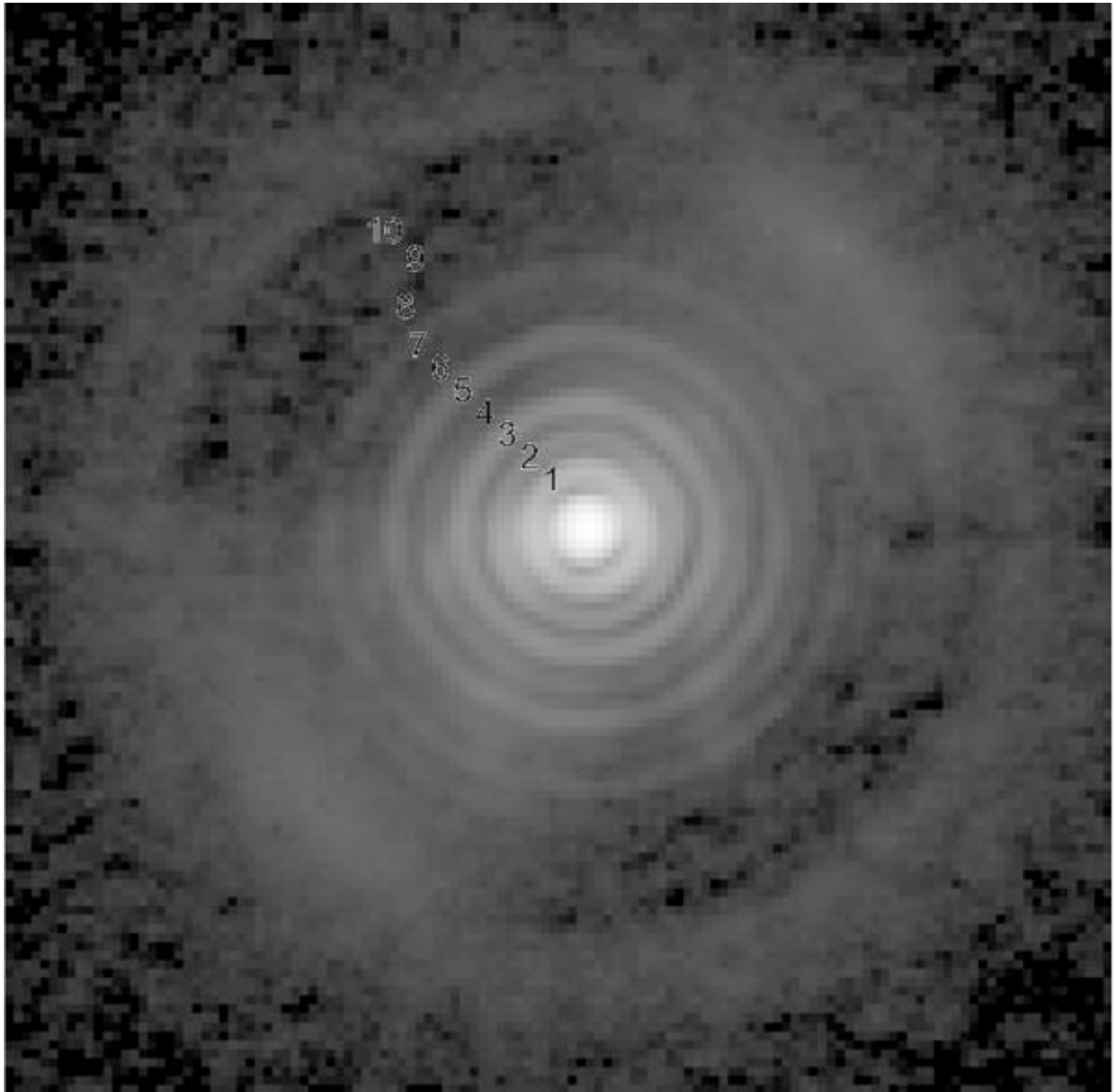
getting to diffraction limit would improve by 1000 (and S/N by ~30)

Adaptive Optics








10
9
8
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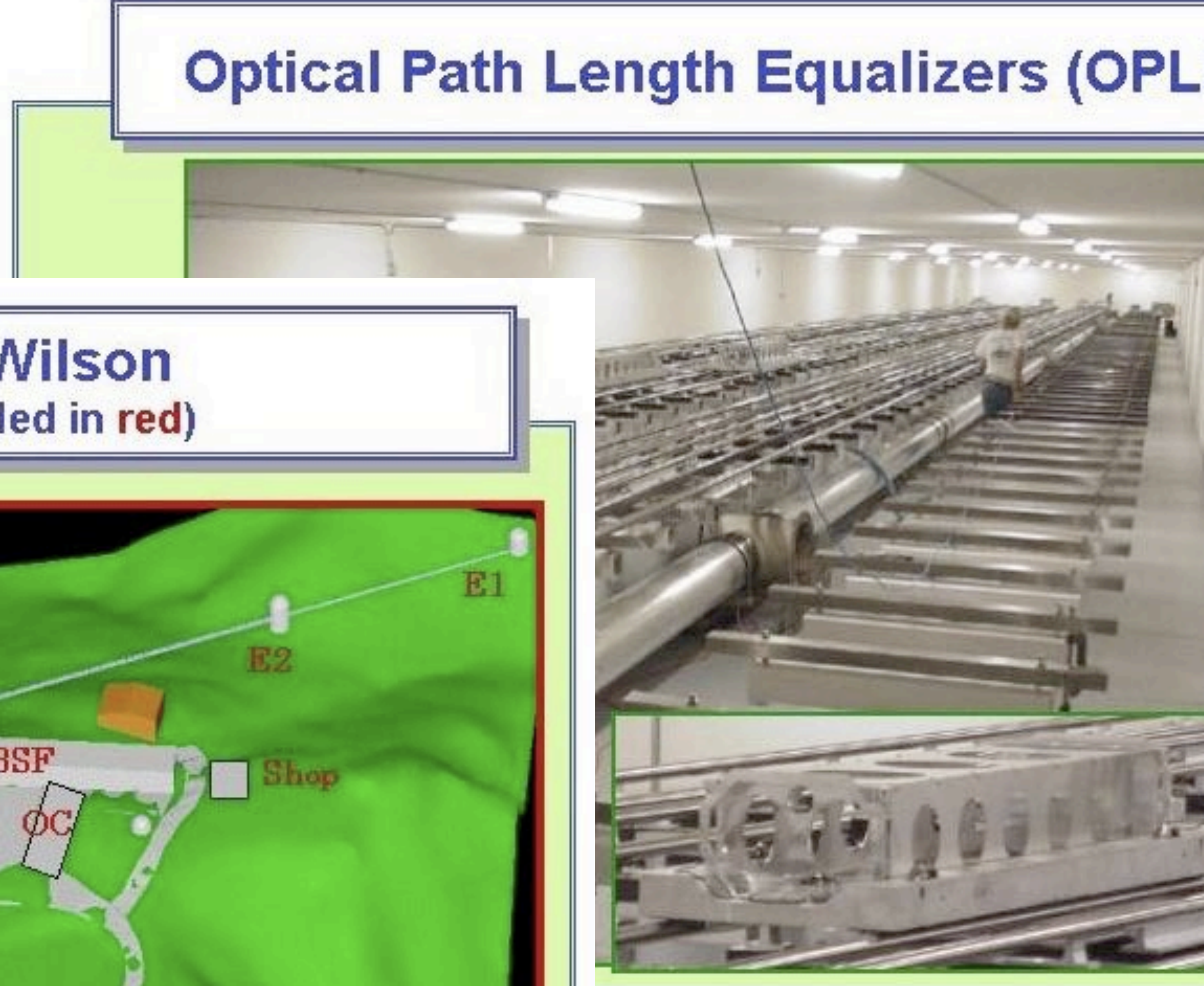
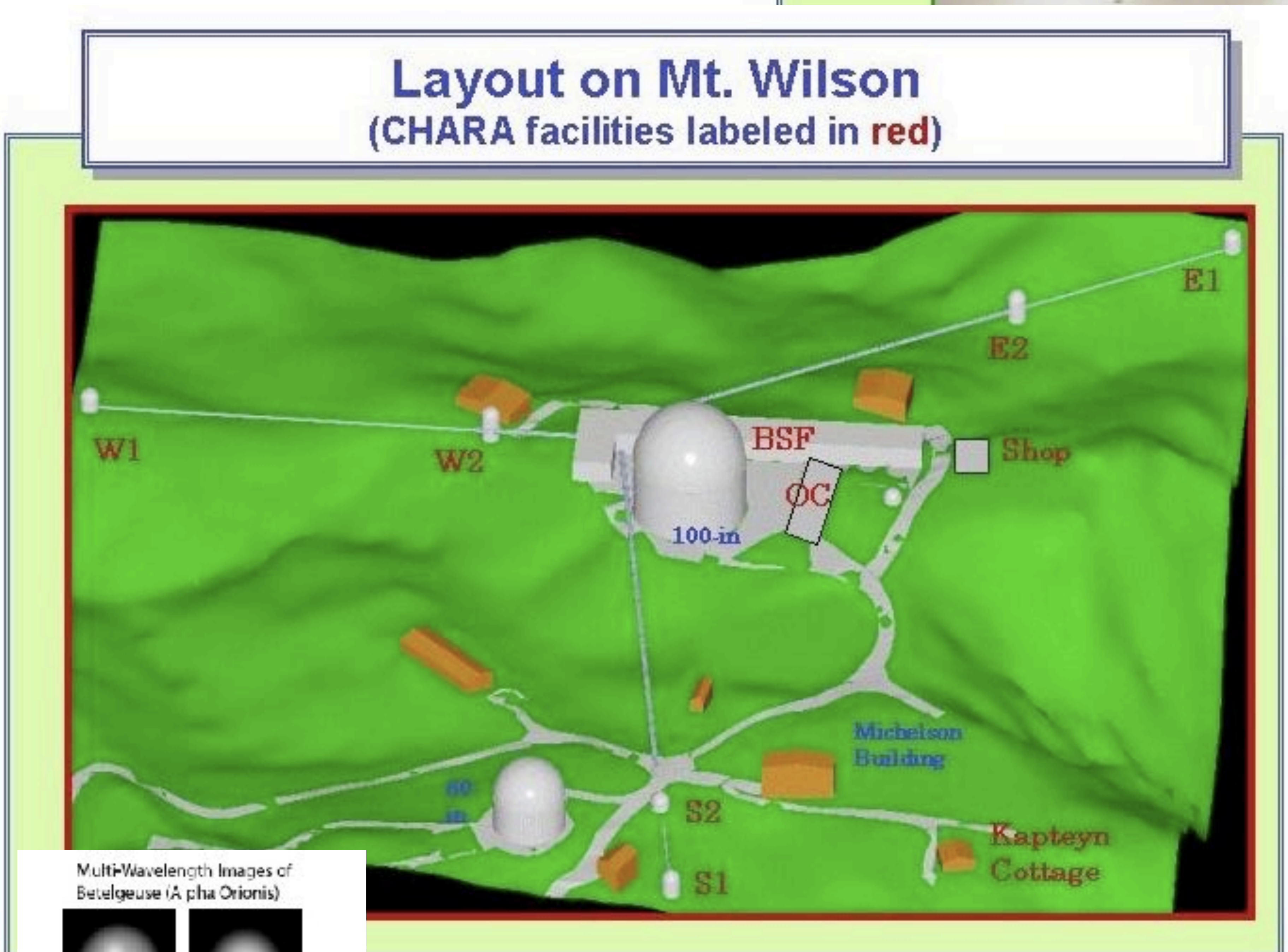
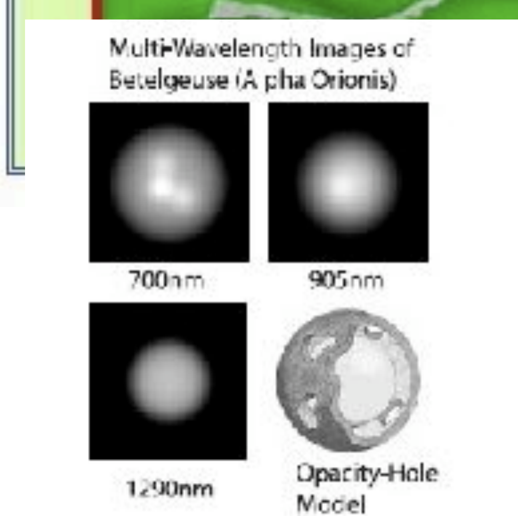
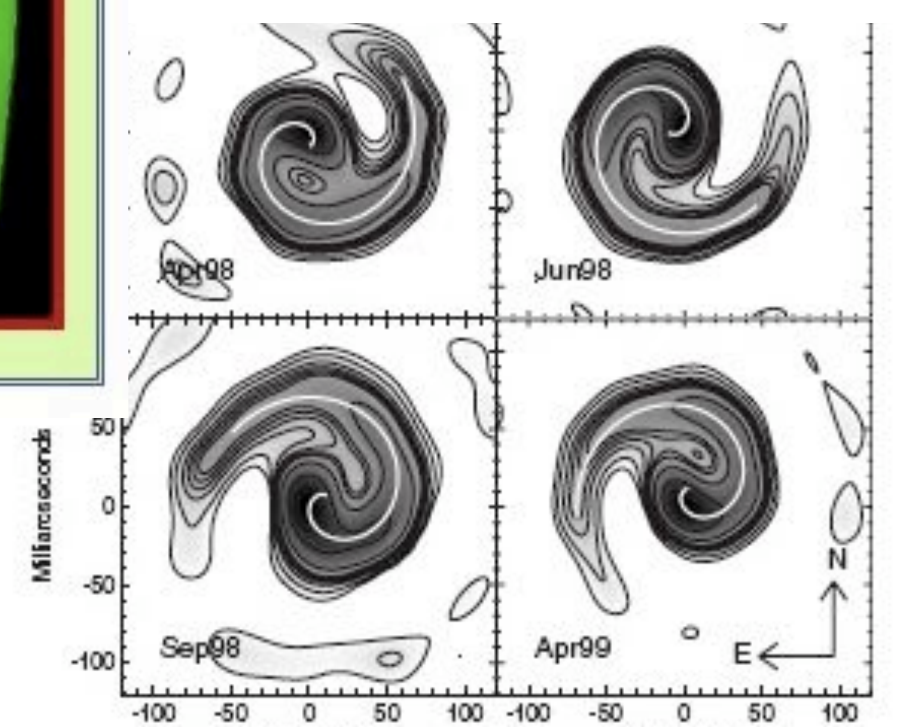
2
1

Optical interferometry










US National Virtual Observatory
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(examples: 3C273 12 29 06, +02 03 08.6 187.27, 2.05)
Full DataScope Interface
View Catalog Coverage Maps and Source Inventories for the position or object name you are interested in.
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Full Coverage Maps Interface
Query Databases and Cross-Match Object Lists from some of the largest on-line catalogs in astronomy (Open SkyQuery).
Perform Source Extraction and Object Identification by detecting objects in your own images and matching them with objects in the major survey catalogs (WESIX).
Explore the Multiwavelength Sky in the Vicinity of Transient Events that have recently been observed (VOEventNet).
Repair Image Coordinates in images with inaccurate or misaligned coordinate systems. NOAO WCS fixer | Pittsburgh WCS fixer
Make mosaics from 2MASS, DPOSS, or SDSS images (Montage).
Summer School
Announcing the 2006 NVO SUMMER SCHOOL 6-14 September 2006 Aspen Meadows Resort, Aspen, Colorado
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NVO Research Initiatives Awarded $25k Stipends
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www.virtualobservatory.org offers access to NVO tools that will bring gigabytes of high-quality science data into your classroom.

The James Webb Space Telescope