Massive widowed stars:

Runaways and walkaways from binary disruptions

Mathieu Renzo

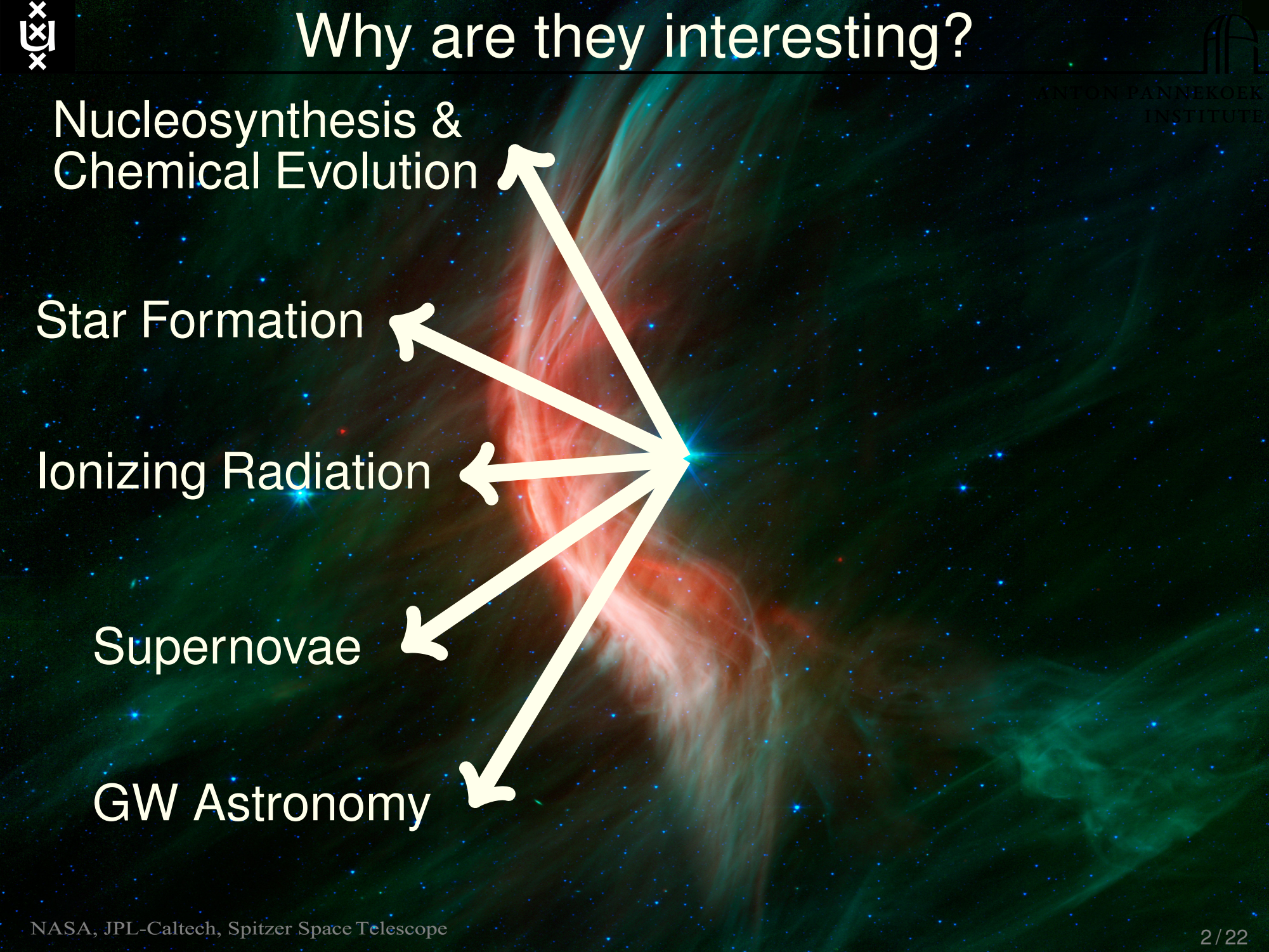
PhD in Amsterdam

Collaborators: S. E. de Mink, E. Zapartas, Y. Götberg, S. Justham, F. R. N. Schneider, R. G. Izzard, H. Sana

NASA, JPL-Caltech, Spitzer Space Telescope

Bin Cosmos

Why are they interesting?



NASA, JPL-Caltech, Spitzer Space Telescope

Why are they interesting?

Nucleosynthesis & Chemical Evolution

Star Formation

Ionizing Radiation

Supernovae

GW Astronomy

$\sim$10% of O type stars are runaways

($v \gtrsim 30\,\mathrm{km\ s^{-1}}$)

(e.g., Blaauw '61, Gies '87, Stone '91)

$\sim$70% of O type stars are in close binaries

(e.g., Mason *et al.* '09, Sana & Evans '11, Sana *et al.* '12, Kiminki & Kobulnicky '12, Kobulnicky *et al.* '14, Almeida *et al.* '16)

NASA, JPL-Caltech, Spitzer Space Telescope

Why are they interesting?

Nucleosynthesis & Chemical Evolution

Star Formation

Ionizing Radiation

Supernovae

GW Astronomy

$\sim$10% of O type stars are runaways
($v \gtrsim 30\,\mathrm{km\ s^{-1}}$)

(e.g., Blaauw '61, Gies '87, Stone '91)

$\sim$70% of O type stars are in close binaries

(e.g., Mason *et al.* '09, Sana & Evans '11, Sana *et al.* '12, Kiminki & Kobulnicky '12, Kobulnicky *et al.* '14, Almeida *et al.* '16)

Preliminary:

$\sim$20 walkaways *formed* for each O-type runaway

(e.g., Renzo *et al.*, in prep, de Mink *et al.* '14)

NASA, JPL-Caltech, Spitzer Space Telescope

Astrophysical implications...

...of disrupting binaries

ANTON PANNEKOEK INSTITUTE

- Feedback
- “Binarity” hidden in single stars
- Massive Star Formation

Astrophysical implications...

...of disrupting binaries

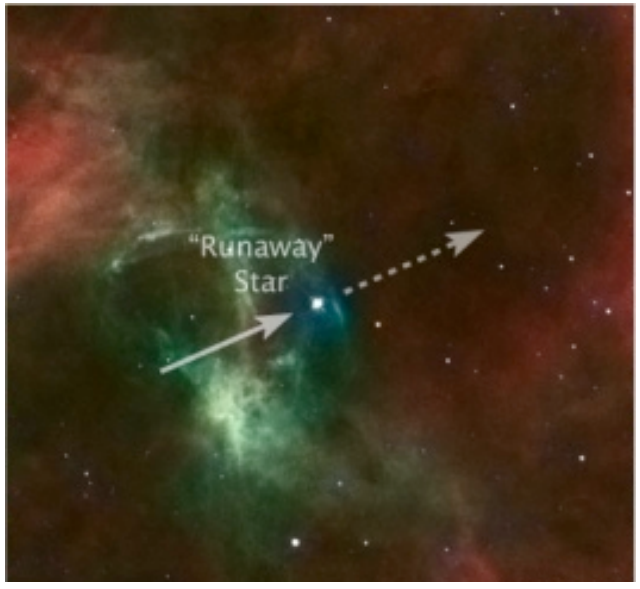
ANTON PANNEKOEK INSTITUTE

- Feedback
- "Binarity" hidden in single stars
- Massive Star Formation

- Enhancement of massive stars feedback
  - Larger volume
  - Spatial spread of CCSN

    (e.g., Conroy & Kratter '12)
  - increase in ionizing radiation $f_{\rm esc}$

    (e.g., Kimm & Cen '14)



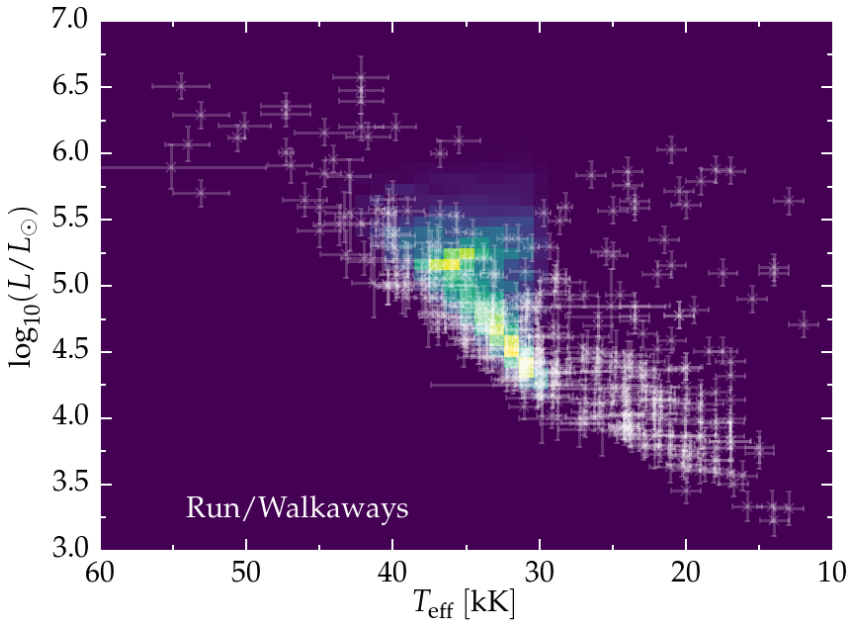
Astrophysical implications...

...of disrupting binaries

ANTON PANNEKOEK INSTITUTE

- Feedback
- “Binarity” hidden in single stars
- Massive Star Formation

- Contamination of field with binary products
  - Are “single” stars really single?
  - Have they always been?



Astrophysical implications...

...of disrupting binaries

ANTON PANNEKOEK INSTITUTE

- Feedback
- “Binarity” hidden in single stars
- Massive Star Formation

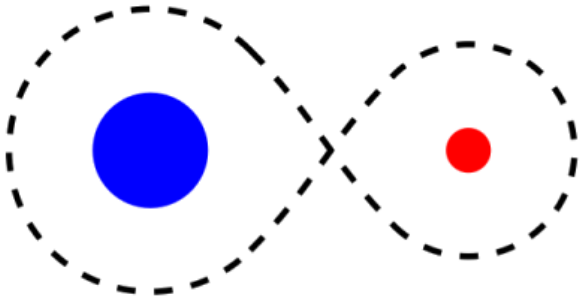
- **Massive star formation**
  - are isolated massive stars formed “in situ”?

(e.g., Bestenlehner *et al.* ’11, Gavramadze *et al.* ’12)

VFTS 682

Outline

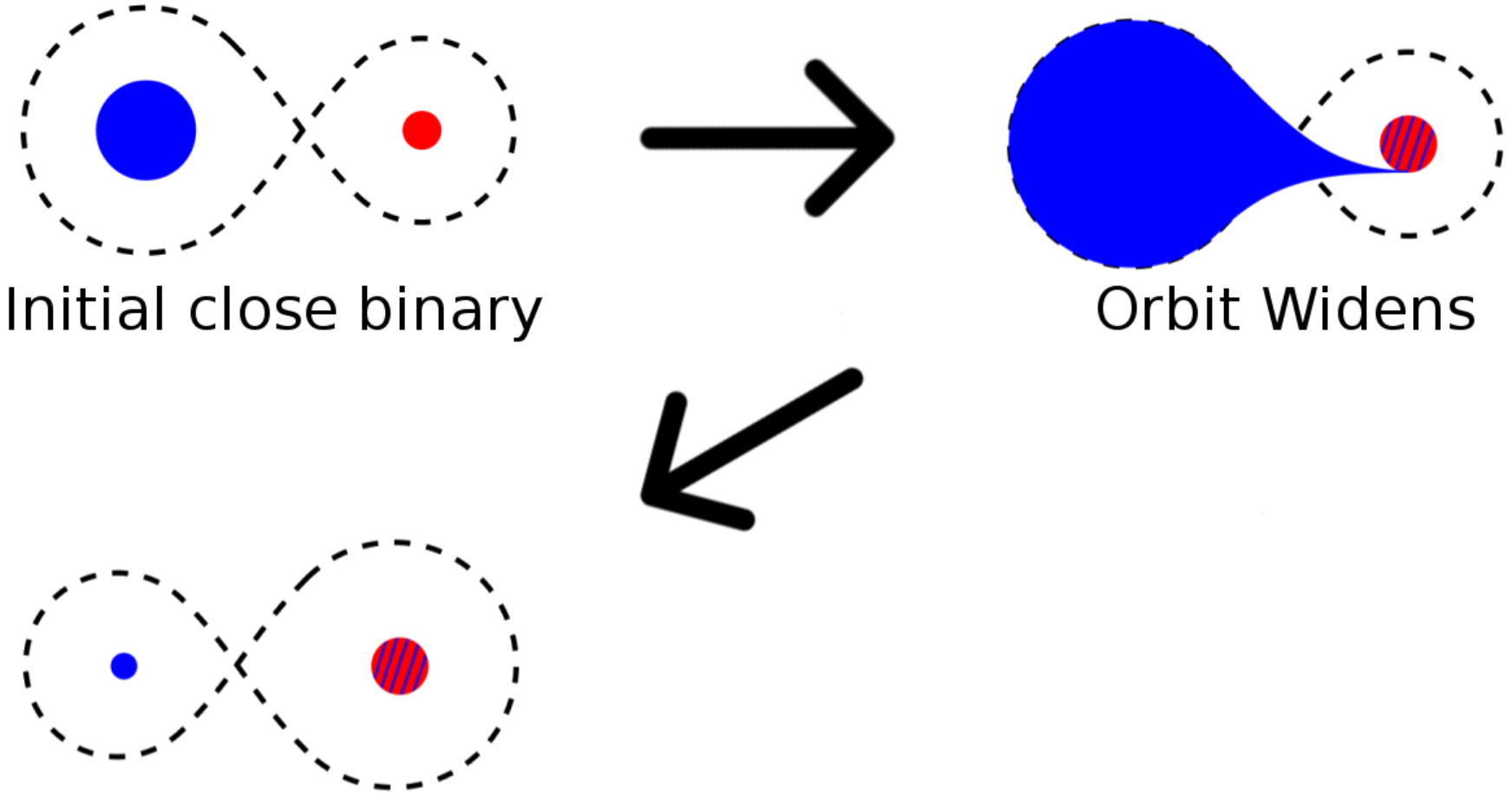
Binary disruption



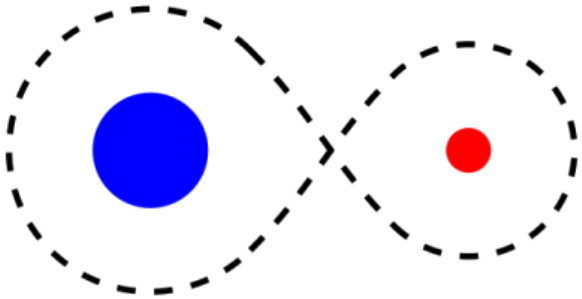
Initial close binary

Binary disruption

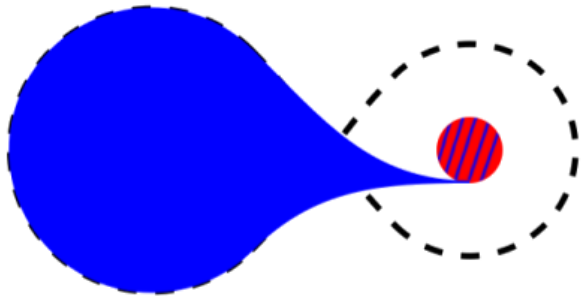
Binary disruption



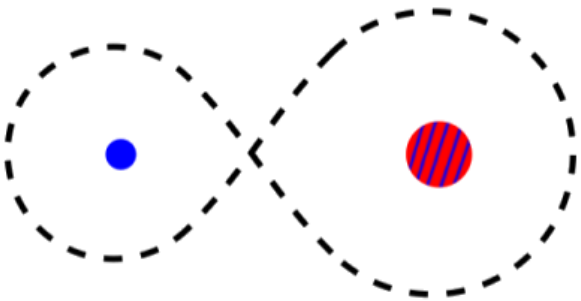
Binary disruption



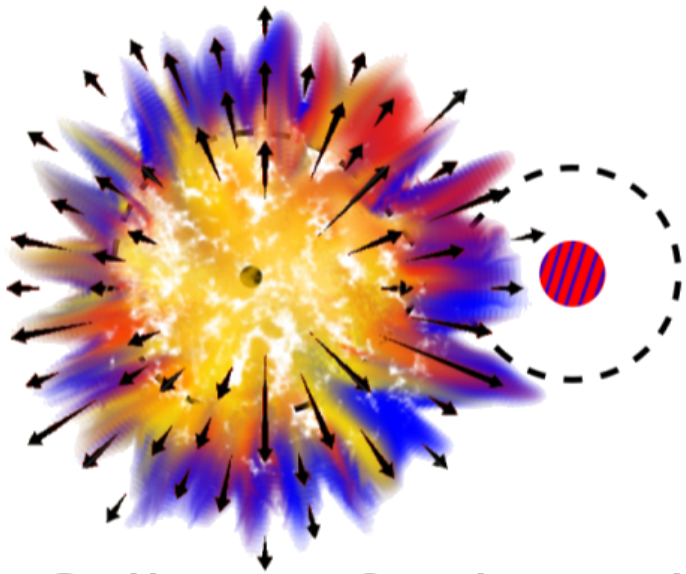
Initial close binary



Orbit Widens

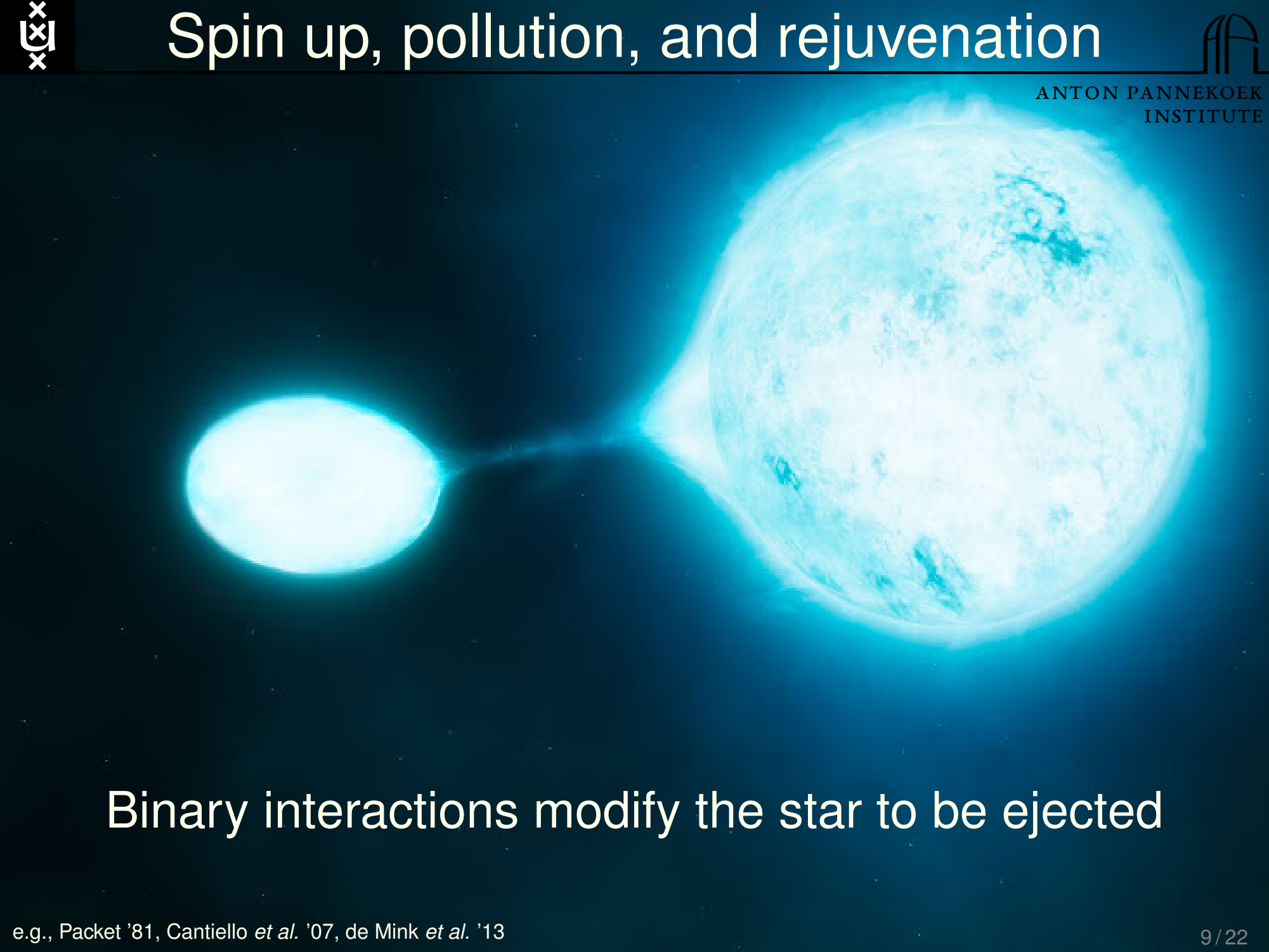


Stripped star + Accretor



Core Collapse & Disruption

Spin up, pollution, and rejuvenation

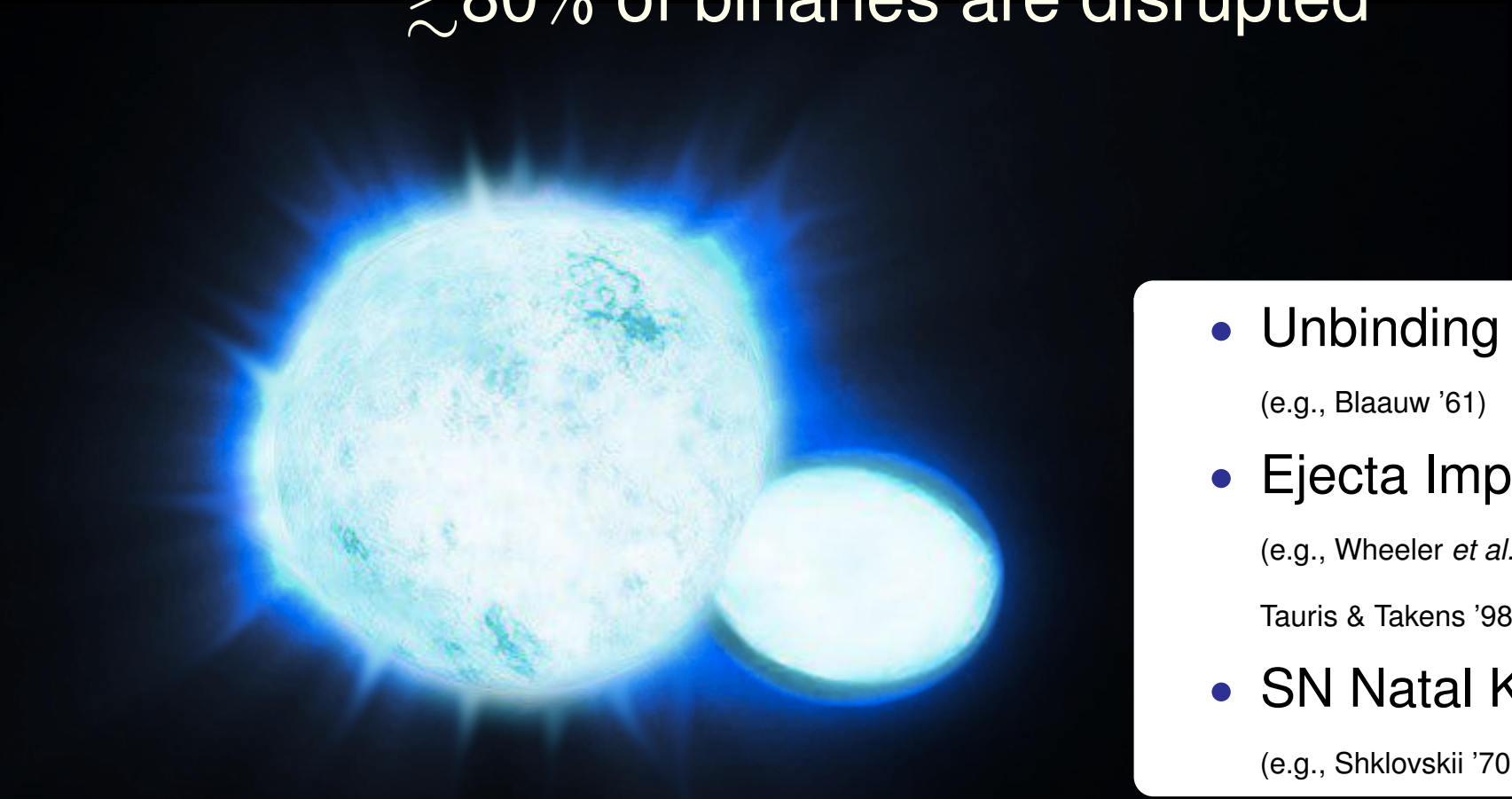


Binary interactions modify the star to be ejected

e.g., Packet '81, Cantiello *et al.* '07, de Mink *et al.* '13

What exactly disrupts the binary?

$\gtrsim$80% of binaries are disrupted



- Unbinding Matter

  (e.g., Blaauw '61)

- Ejecta Impact

  (e.g., Wheeler *et al.* '75,

  Tauris & Takens '98, Liu *et al.* '15)

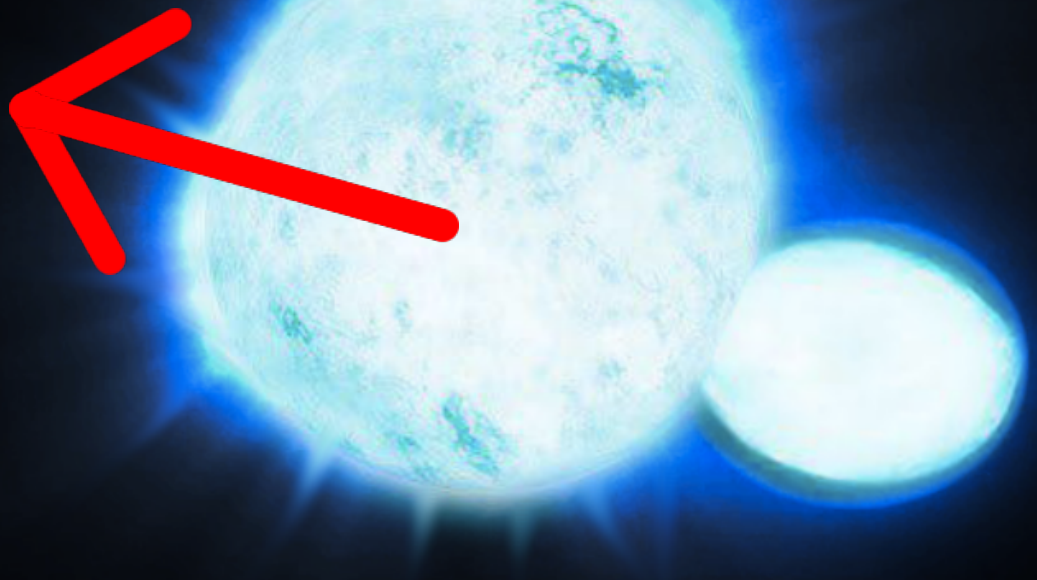
- SN Natal Kick

  (e.g., Shklovskii '70, Janka '16)

$$v_2^{\mathrm{post-SN}} \simeq v_{2,\mathrm{orb}}^{\mathrm{pre-SN}}$$

What exactly disrupts the binary?

$\gtrsim$80% of binaries are disrupted



- Unbinding Matter

  (e.g., Blaauw '61)

- Ejecta Impact

  (e.g., Wheeler *et al.* '75,

  Tauris & Takens '98, Liu *et al.* '15)

- SN Natal Kick

  (e.g., Shklovskii '70, Janka '16)

$$v_2^{\mathrm{post-SN}} \simeq v_{2,\mathrm{orb}}^{\mathrm{pre-SN}}$$

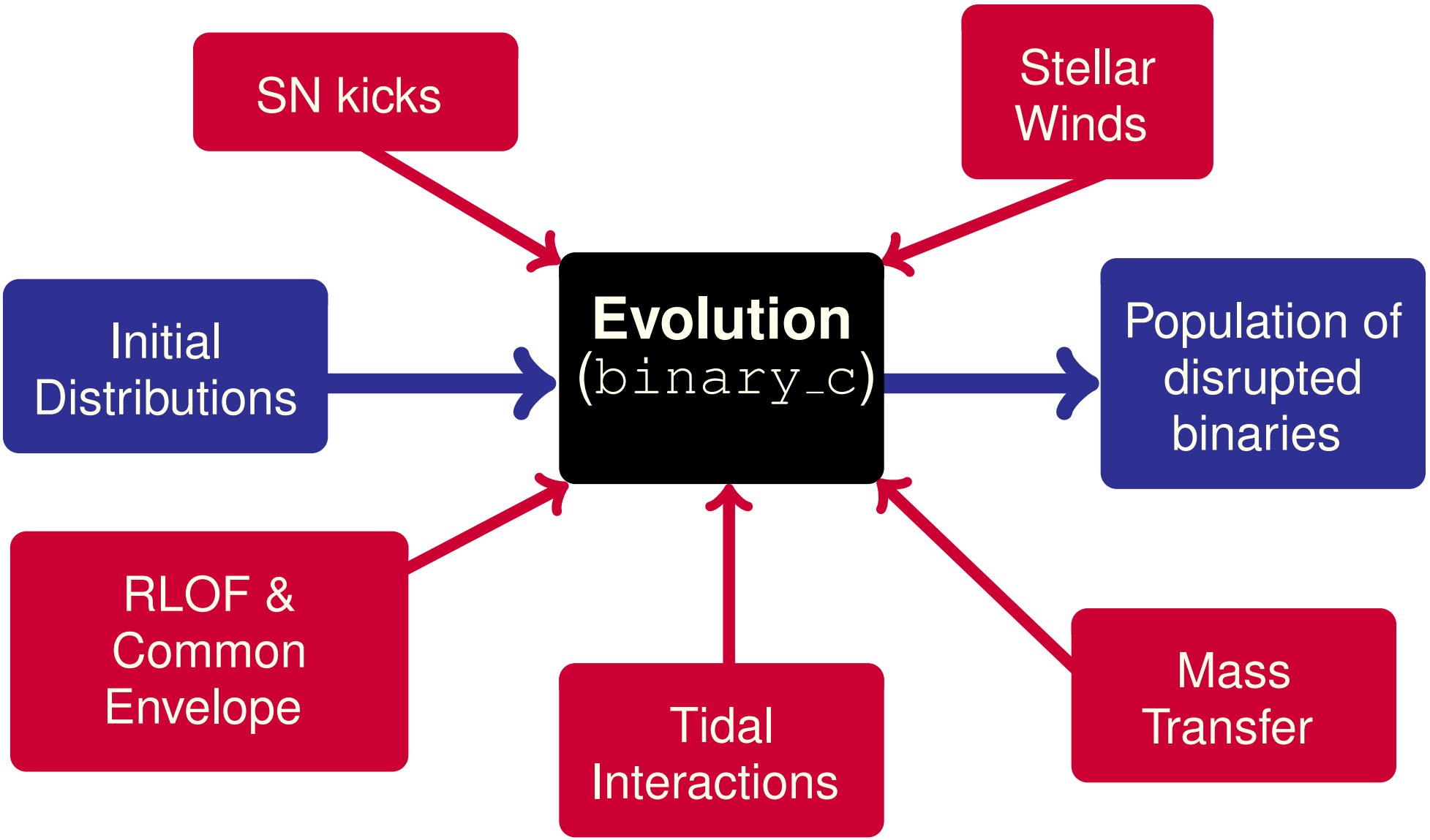
Outline

ANTON PANNEKOEK INSTITUTE

What I do: Population Synthesis

ANTON PANNEKOEK INSTITUTE

Fast $\Rightarrow$ Allows statistical tests of the inputs & assumptions



Izzard *et al.* '04, '06, '09; de Mink *et al.* '13

Outline

Introduction

Astrophysical implications

How to make fast stars?

- Dynamical ejection from cluster
- Disruption of binaries

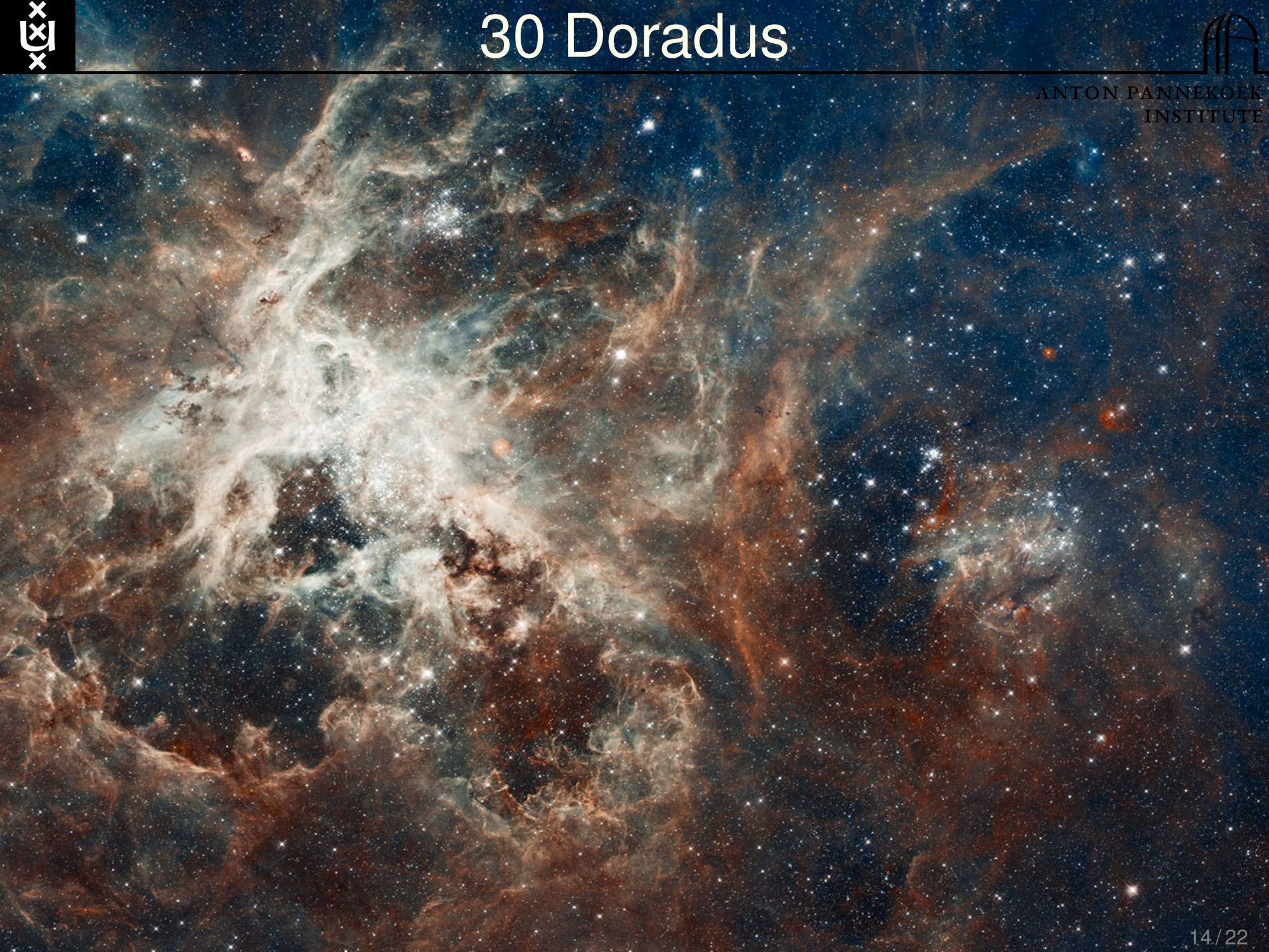
Methods: population synthesis

Preliminary results

- O-type runaways in 30 Doradus
- Walkaways in the Milky Way

Conclusions

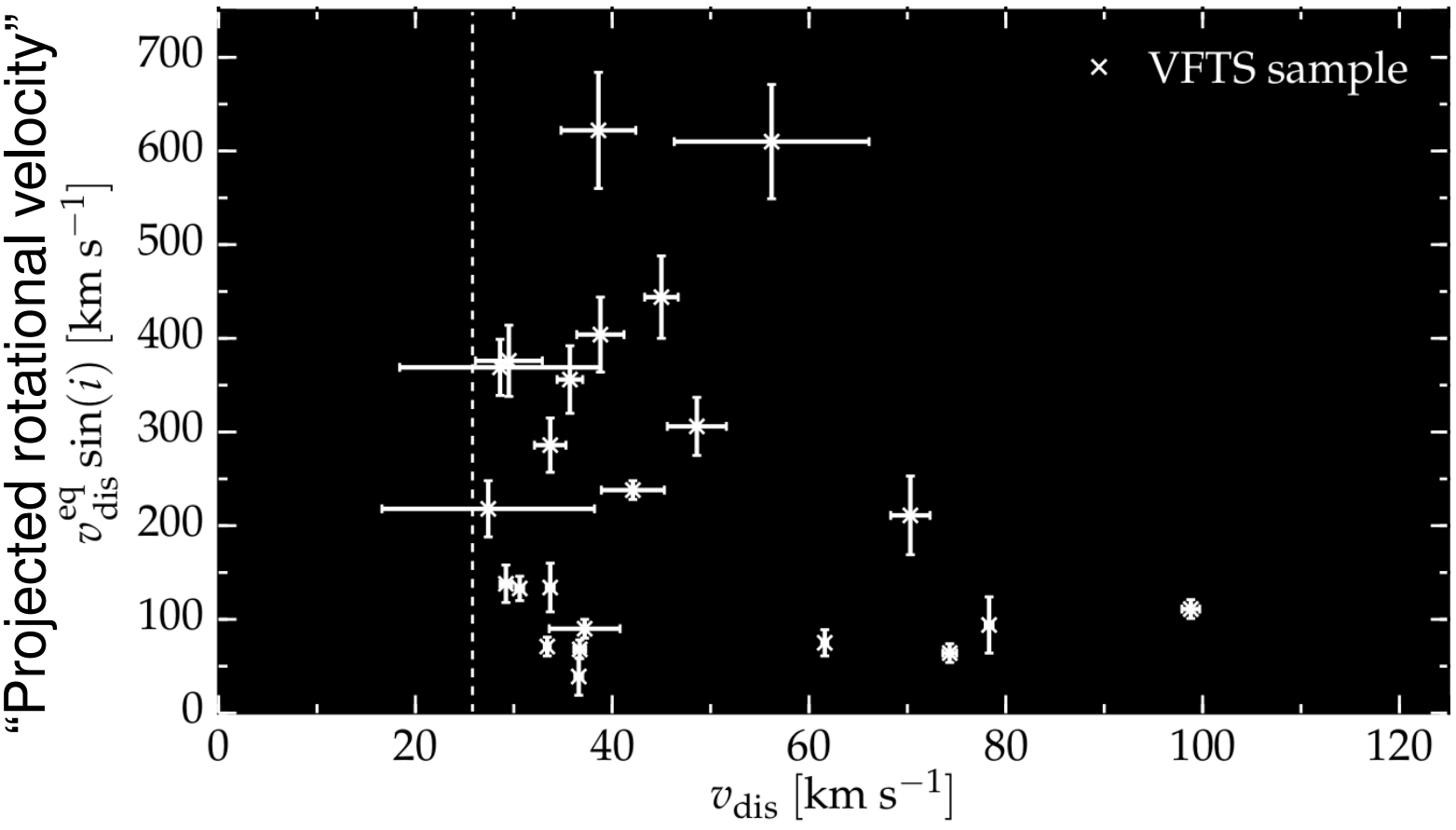
30 Doradus



O-type runaways

ANTON PANNEKOEK INSTITUTE

Largest homogeneous sample available to date



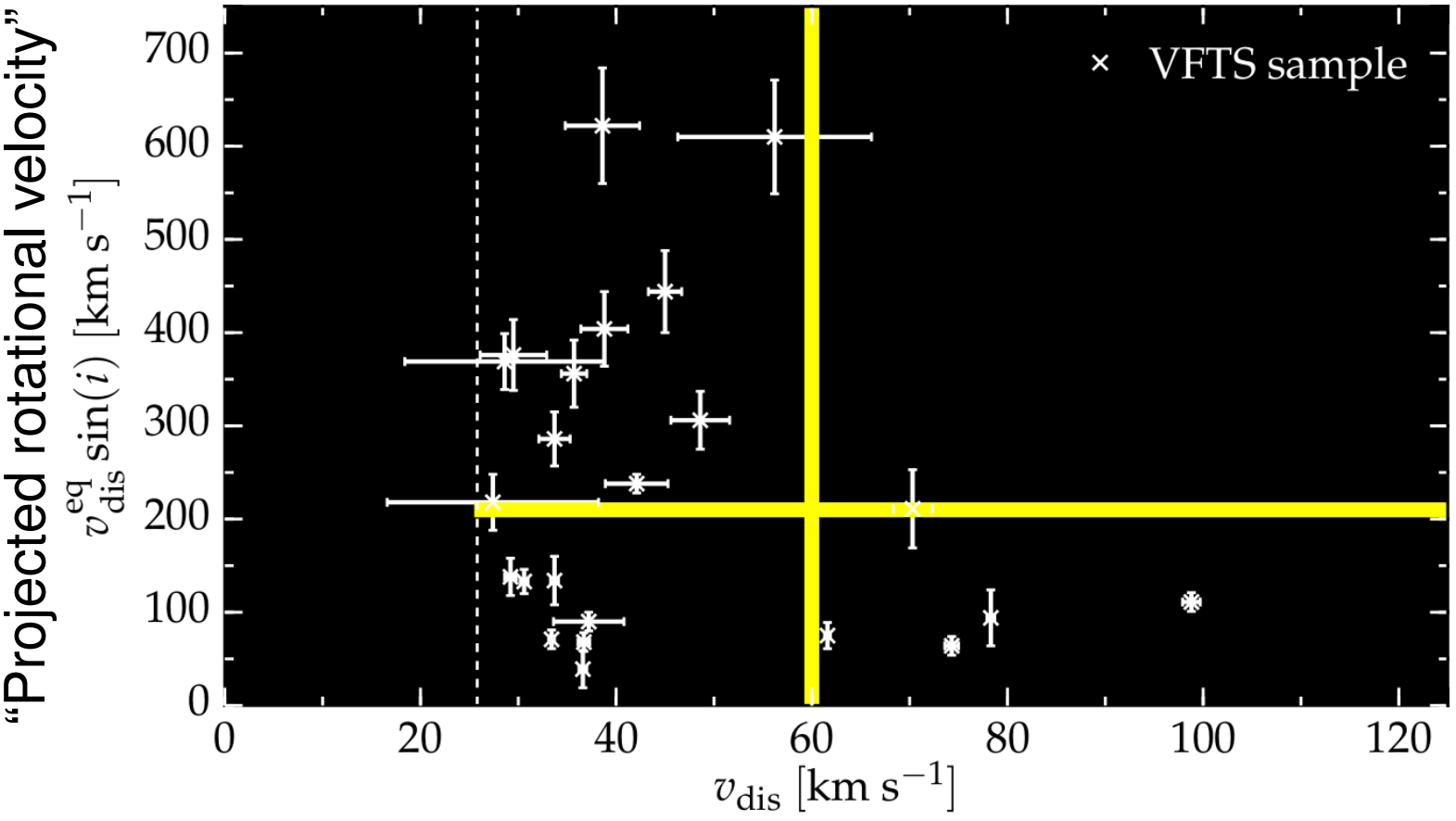
"Line of sight velocity"

Sana *et al.*, VFTS collaboration, in prep.

O-type runaways

ANTON PANNEKOEK INSTITUTE

Largest homogeneous sample available to date



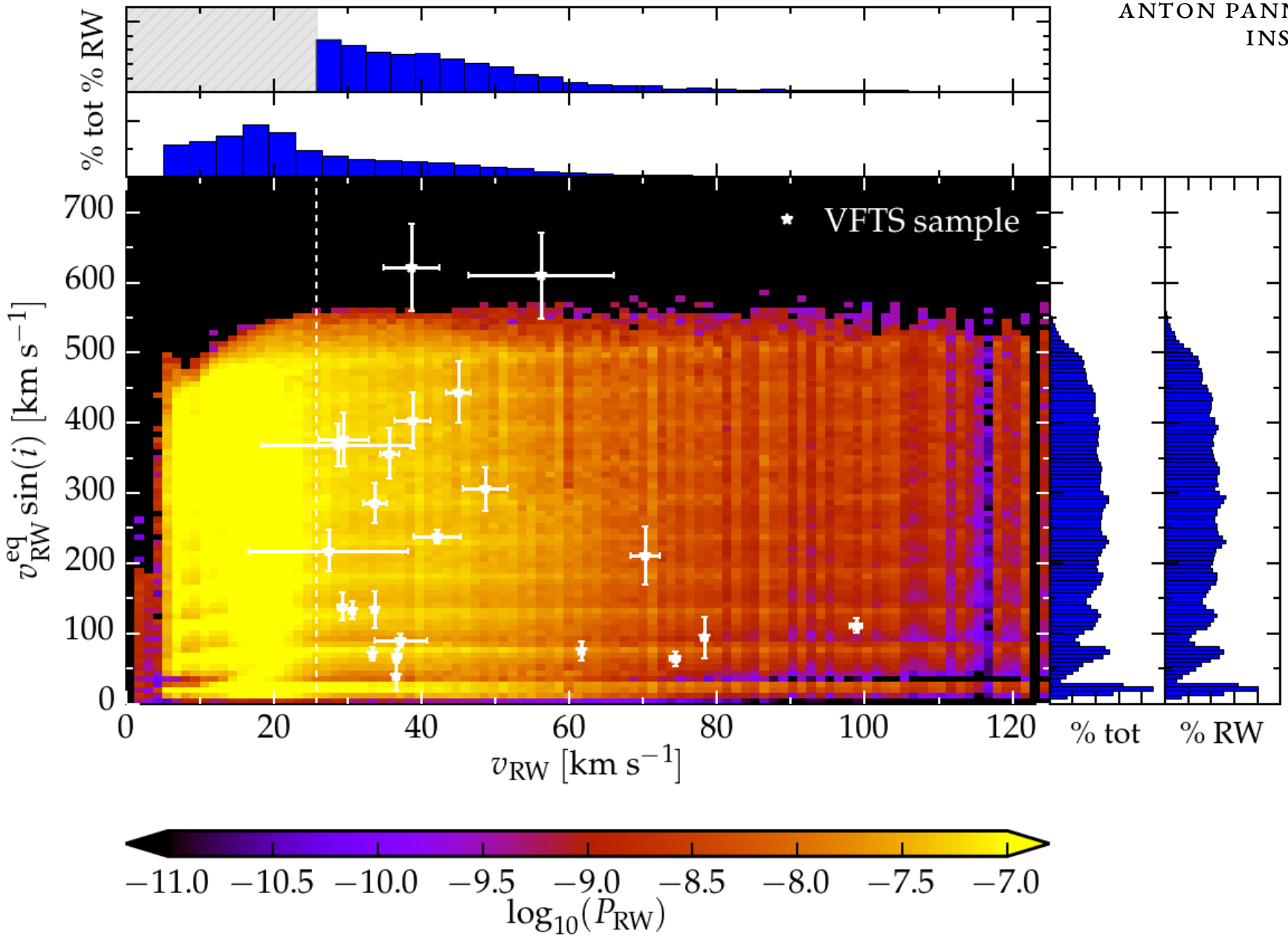
"Projected rotational velocity"

"Line of sight velocity"

Sana *et al.*, VFTS collaboration, in prep.

O-type runaways

ANTON PANNEKOEK
INSTITUTE



"Projected rotational velocity"

"$\log_{10}$(Number density)"

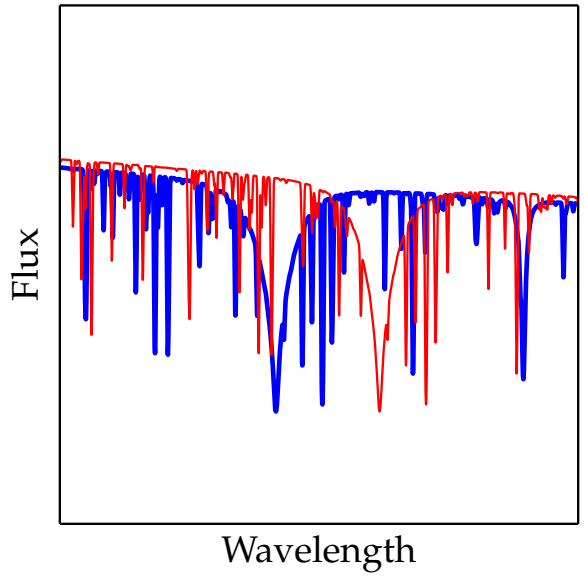
Outline

ANTON PANNEKOEK INSTITUTE

How to measure stellar velocities?

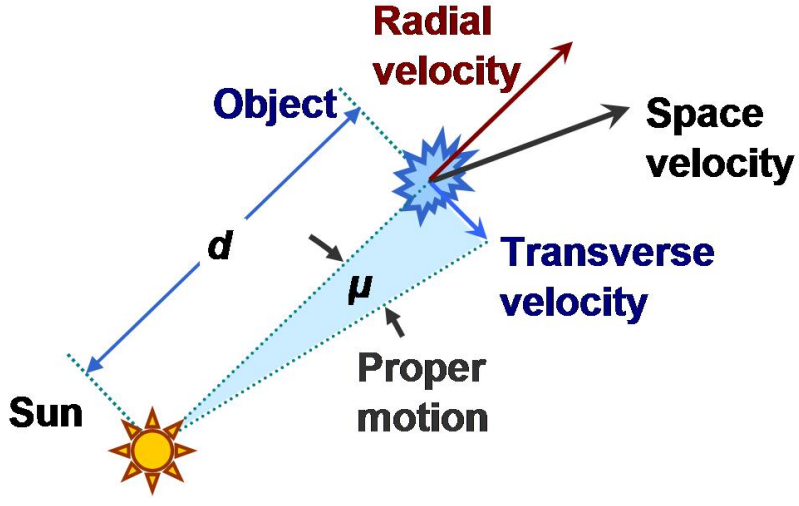
ANTON PANNEKOEK INSTITUTE

Line of sight velocity:
Doppler shifts $\Rightarrow$



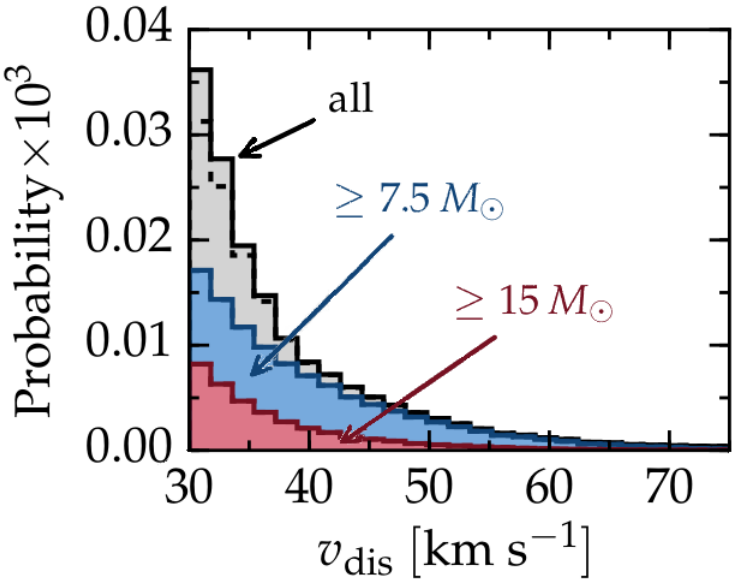
Transverse velocity:
Proper motions

(if distance known) $\Rightarrow$



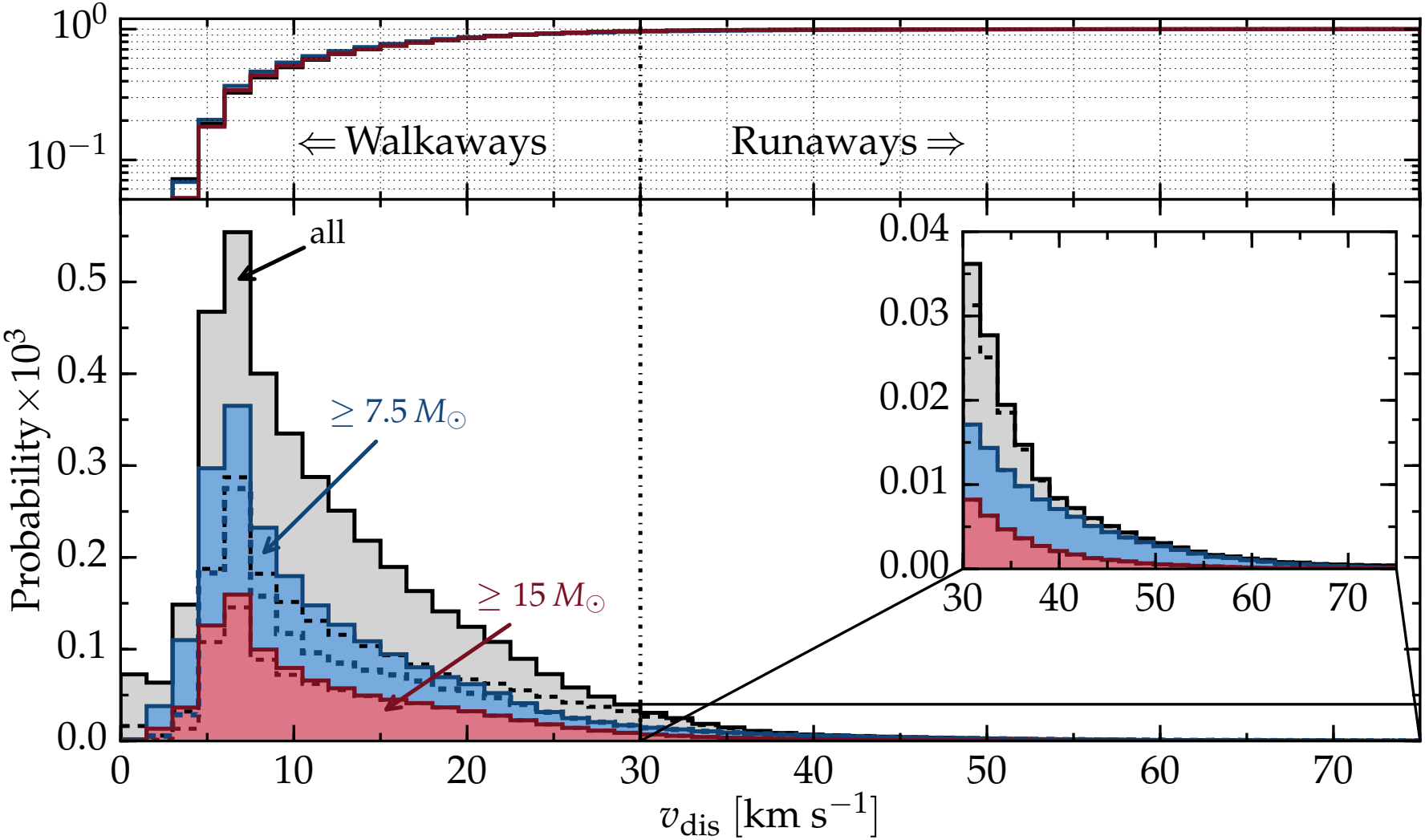
Gaia will give proper motions & distances

Velocity distribution: Runaways



Velocity distribution: Walkaways

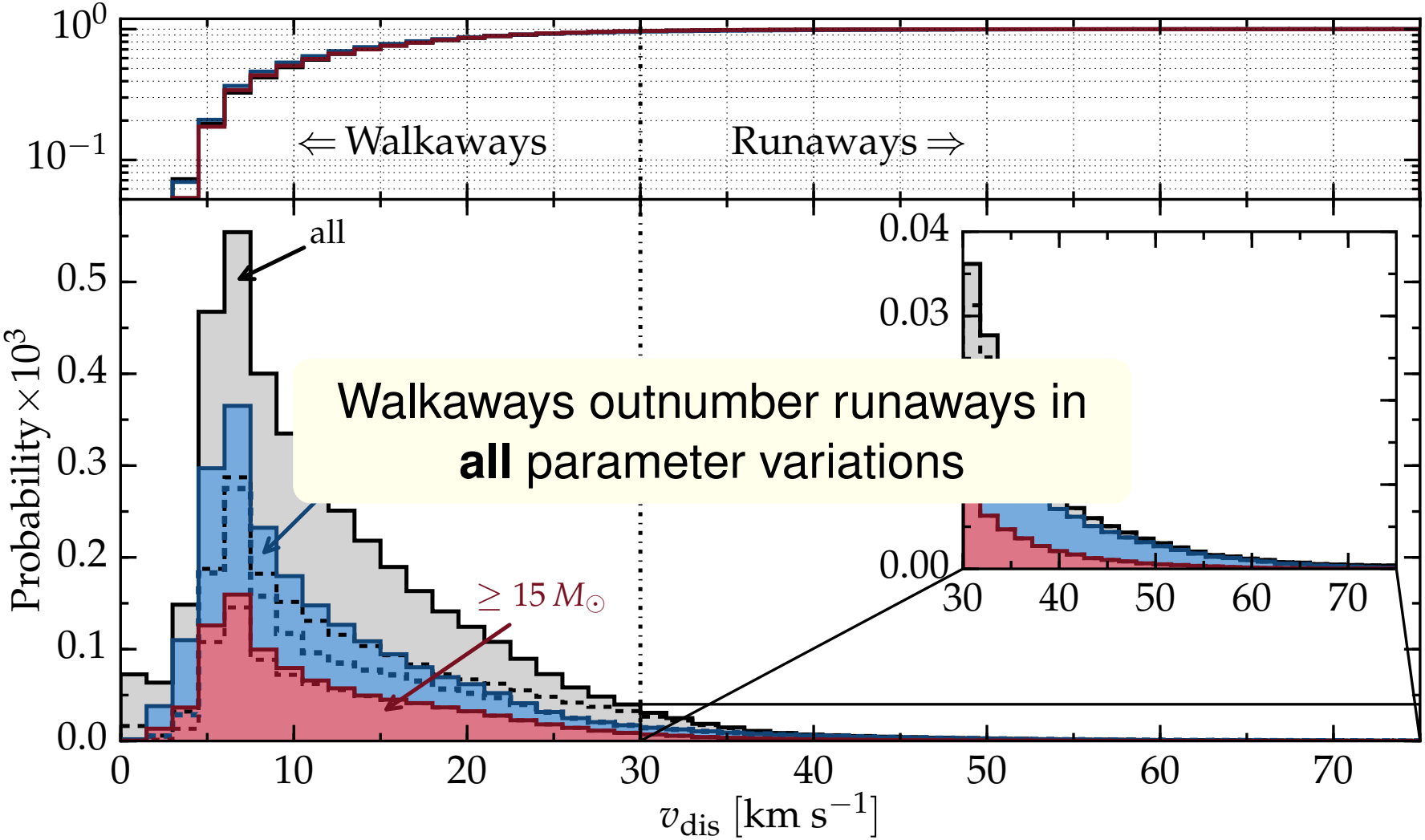
ANTON PANNEKOEK INSTITUTE



- For each runaway there are $\sim$ 20 walkaways in the galaxy
- All runaways have accreted mass from a companion

Velocity distribution: Walkaways

ANTON PANNEKOEK INSTITUTE



- For each runaway there are $\sim$ 20 walkaways in the galaxy
- All runaways have accreted mass from a companion

Outline

ANTON PANNEKOEK INSTITUTE

Introduction

Astrophysical implications

How to make fast stars?

- Dynamical ejection from cluster
- Disruption of binaries

Methods: population synthesis

Preliminary results

- O-type runaways in 30 Doradus
- Walkaways in the Milky Way

Conclusions

Conclusions

ANTON PANNEKOEK INSTITUTE

$\sim$ 80% **of binaries disrupted by first SN**

Massive walk/runaways stars...

(regardless of their final velocity)

- ...“pollute” the field with binary products
- ...carry info on previous binary evolution
- ...can be used to learn about companion explosion
- ...enhance the massive stars feedback

Conclusions

ANTON PANNEKOEK INSTITUTE

$\sim$ 80% **of binaries disrupted by first SN**

Massive walk/runaways stars...

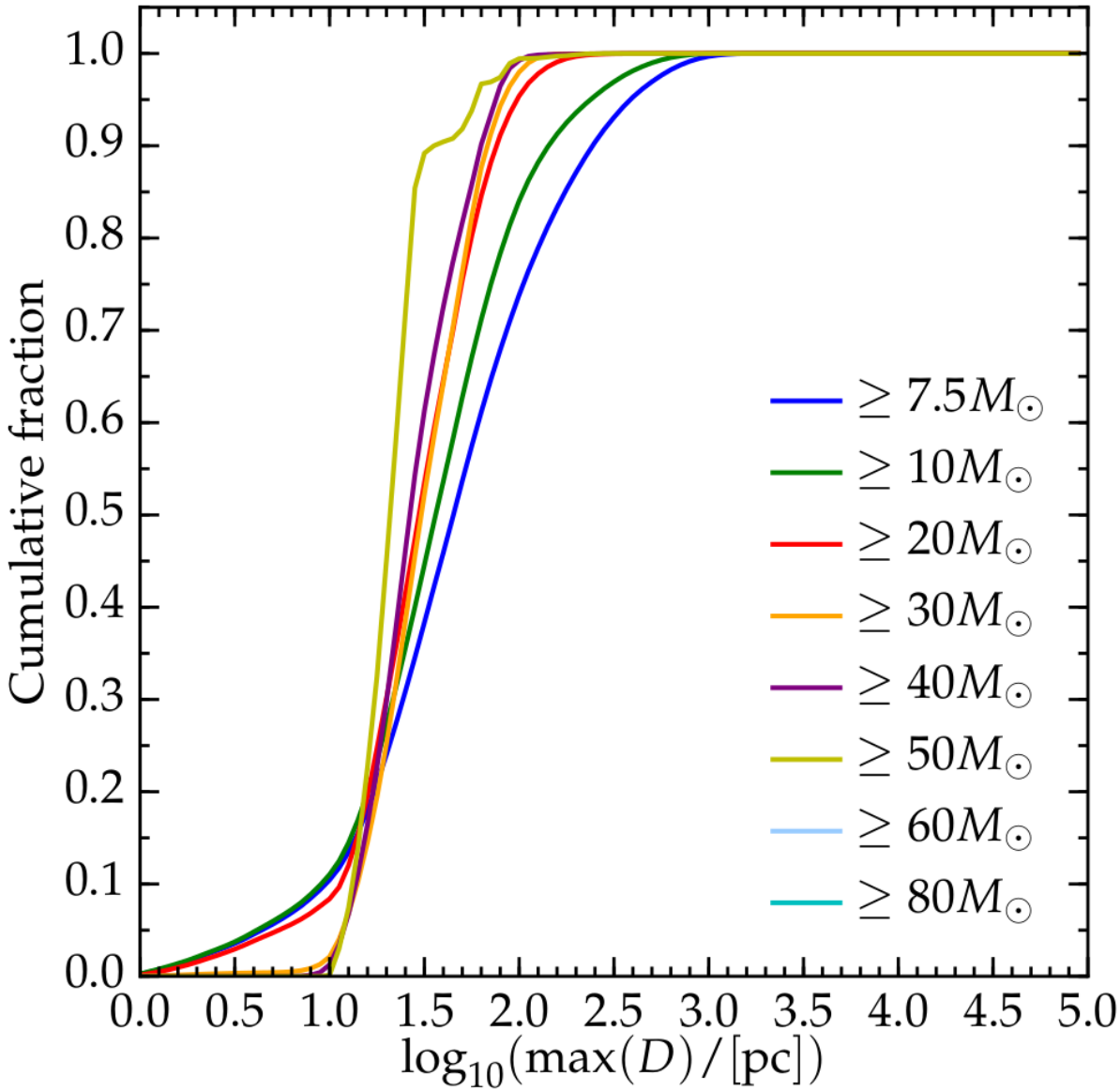
(regardless of their final velocity)

- ..."pollute" the field with binary products
- ...carry info on previous binary evolution
- ...can be used to learn about companion explosion
- ...enhance the massive stars feedback

Thank you!

Backup slides

Where do they die?

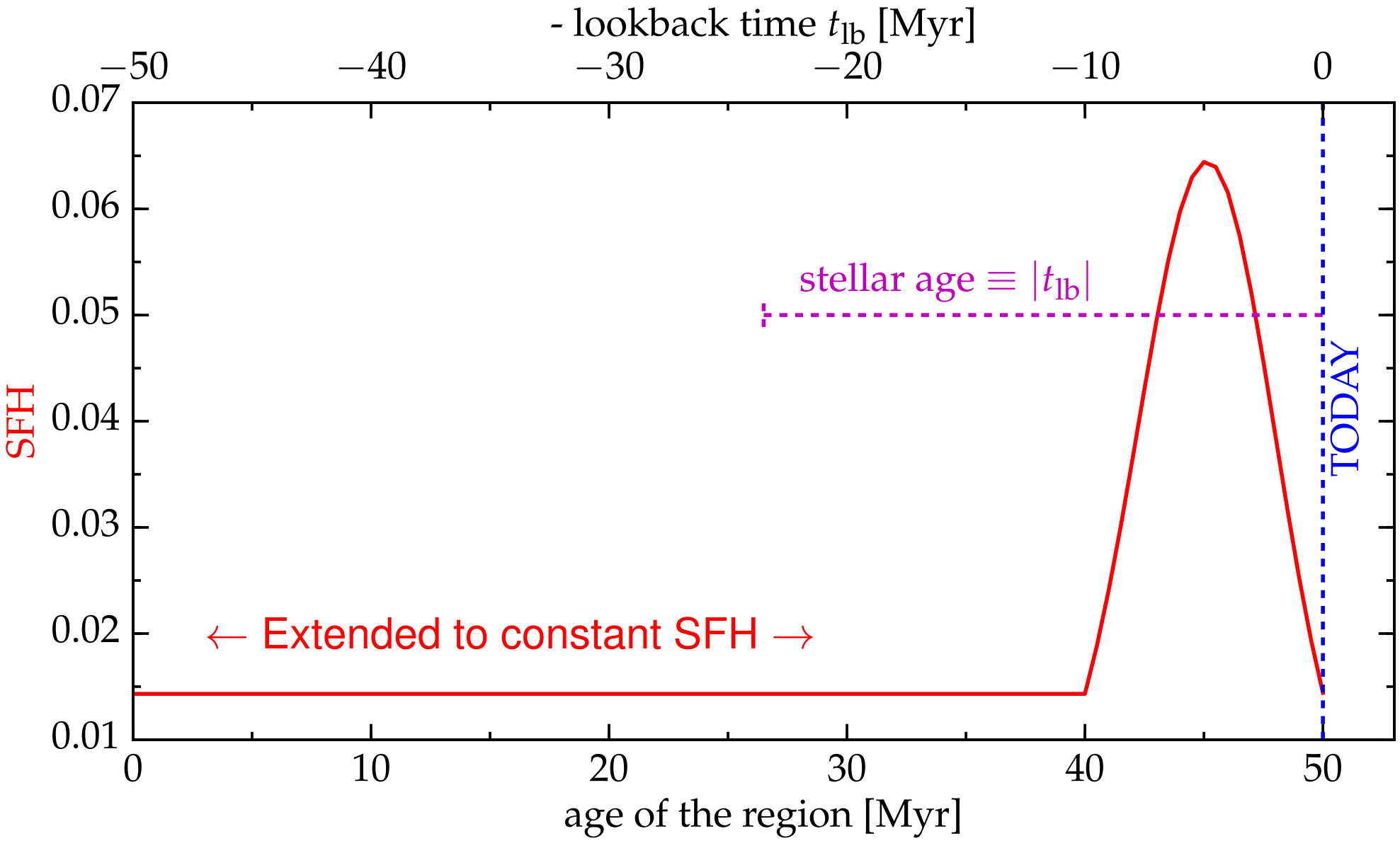


"Distance traveled"

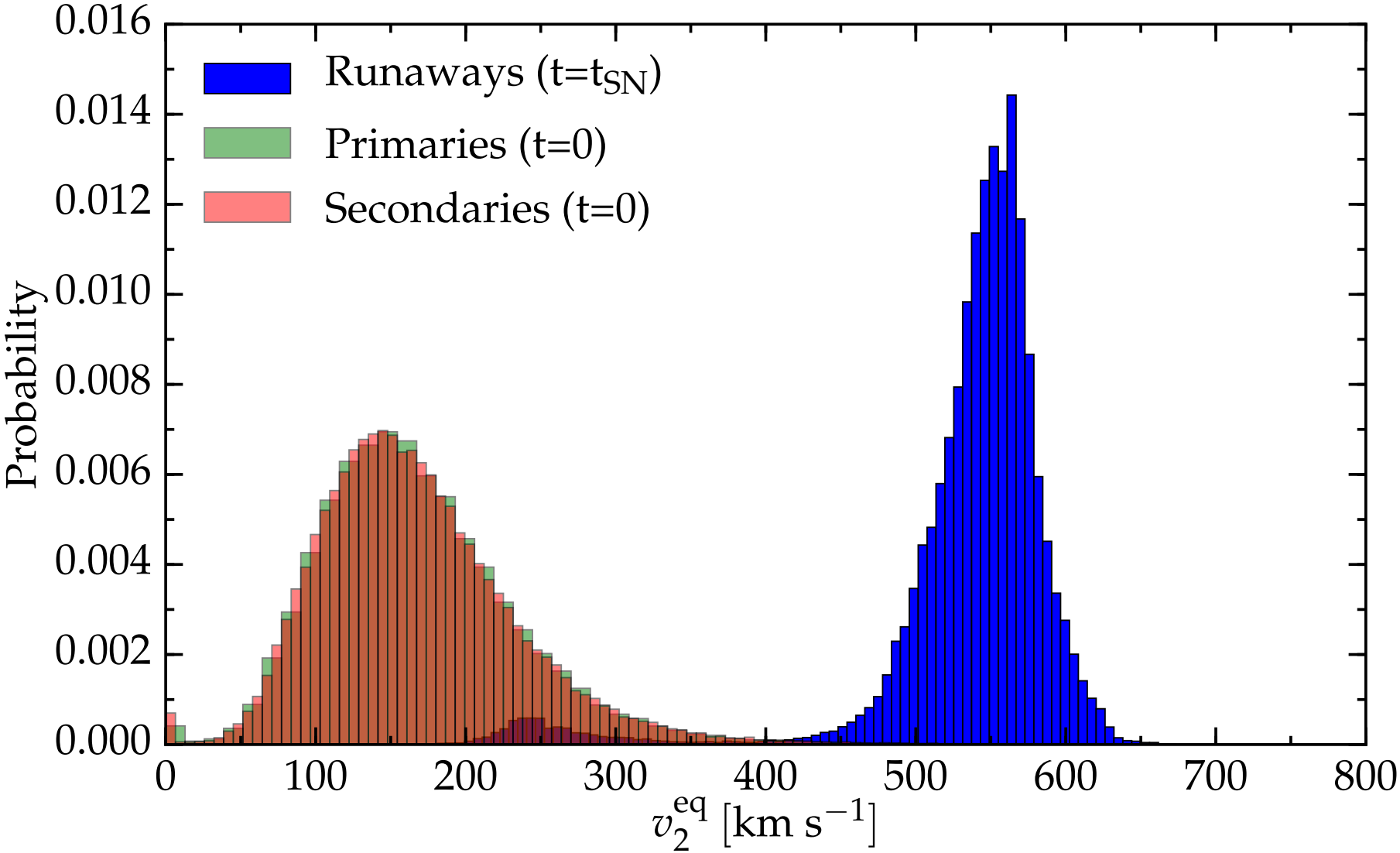
No potential well, $\sigma_{\mathrm{kick}} = 265\,\mathrm{km\ s^{-1}}$

30 Doradus Star Formation History

ANTON PANNEKOEK
INSTITUTE

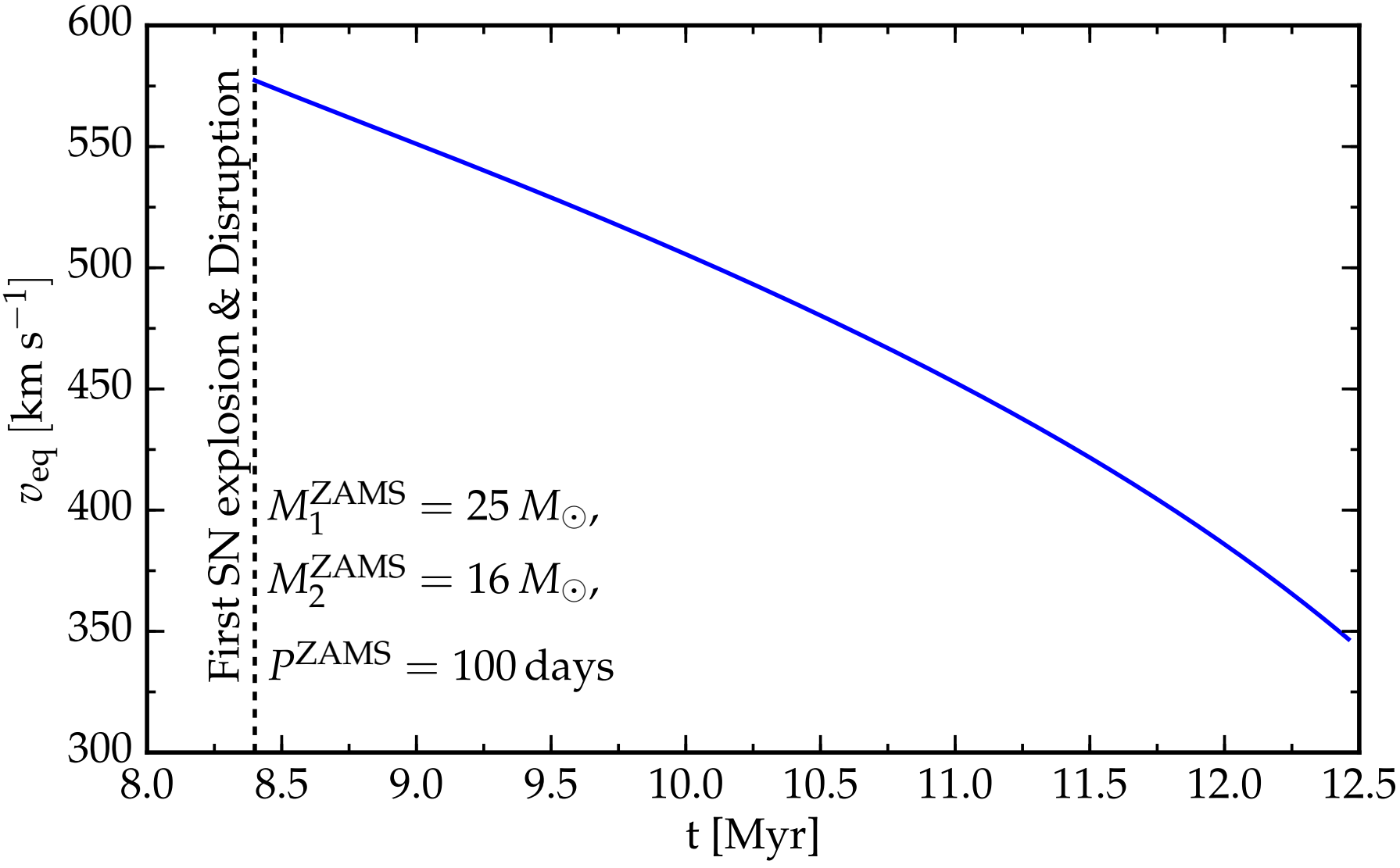


Initial Rotational Velocities



Rotation @ t=0 from O. Ramirez-Agudelo *et al.* '15

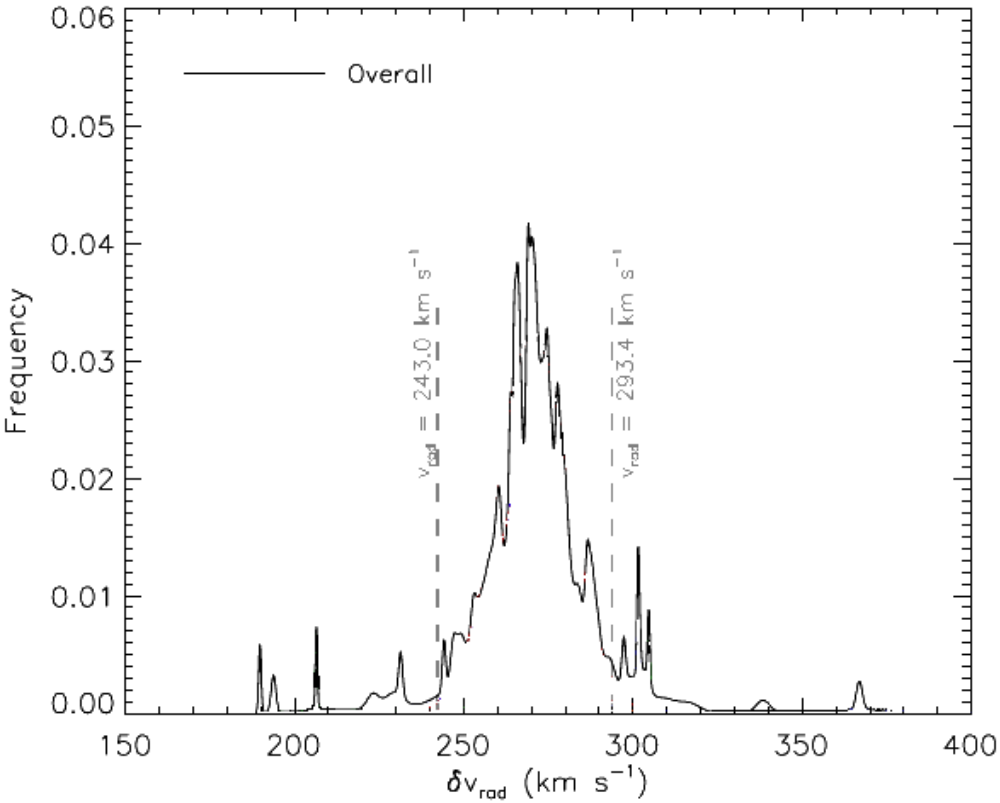
Spin Down: Winds



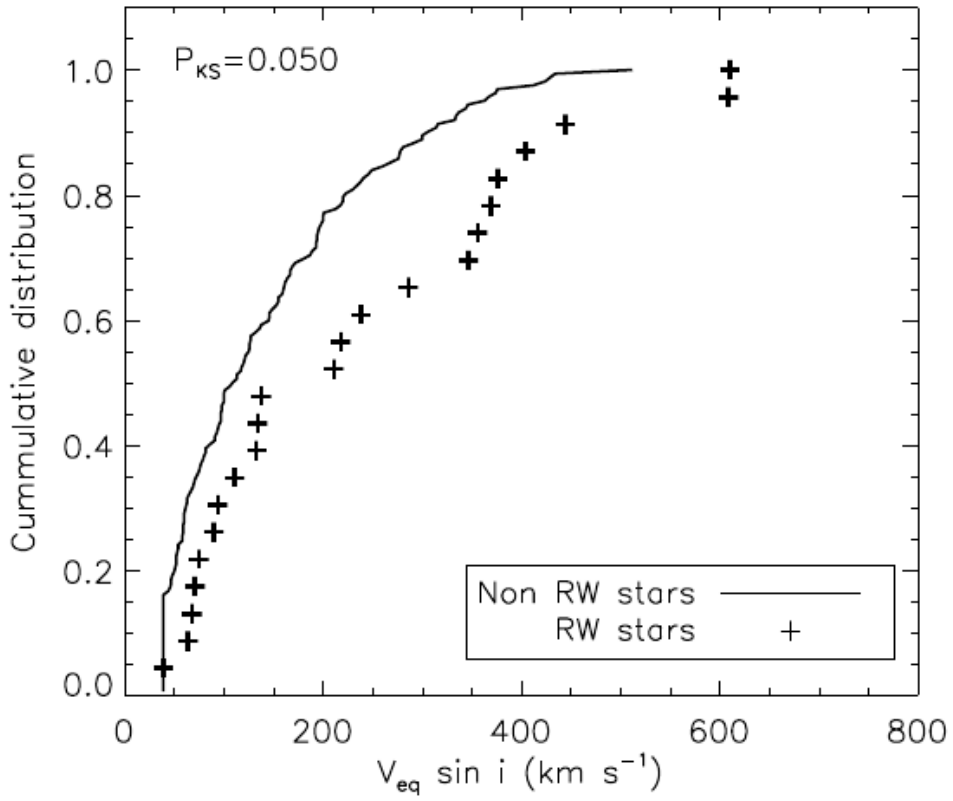
Properties of the RWs in 30 Dor

ANTON PANNEKOEK INSTITUTE

Line of Sight Velocities



Rotational Velocities



Credits: H. Sana *et al.* (in prep.)

Soon proper motions!

(Lennon *et al.* in prep.)

SN natal kicks

ANTON PANNEKOEK INSTITUTE

Orbit from Tauris & Takens '98

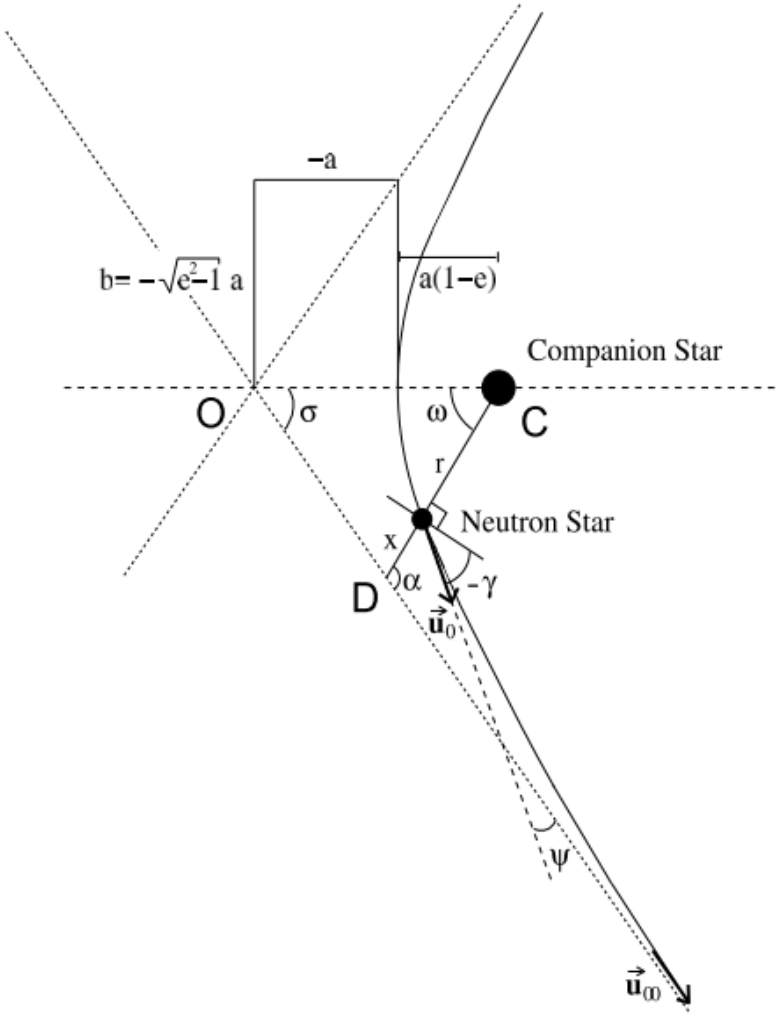


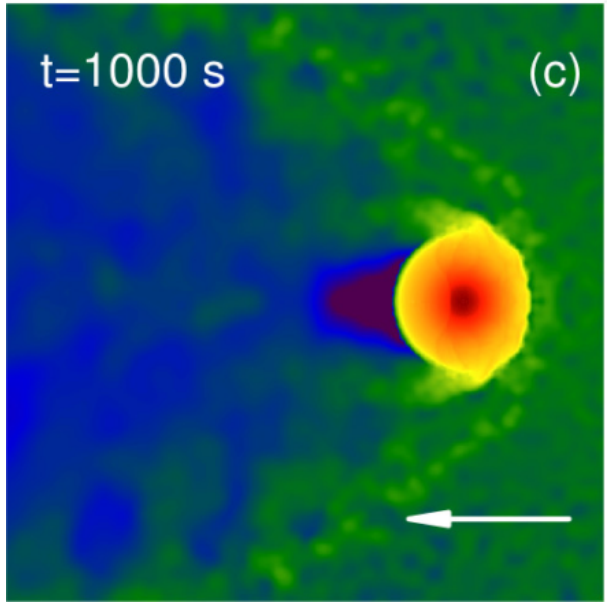
Fig. 2. Geometry of the orbital plane of a disrupted system ($e > 1$, $a < 0$) after an asymmetric supernova explosion. The reference frame is fixed on the companion star (C).

Fallback from Fryer *et al.* '12

(Rapid SN mechanism)

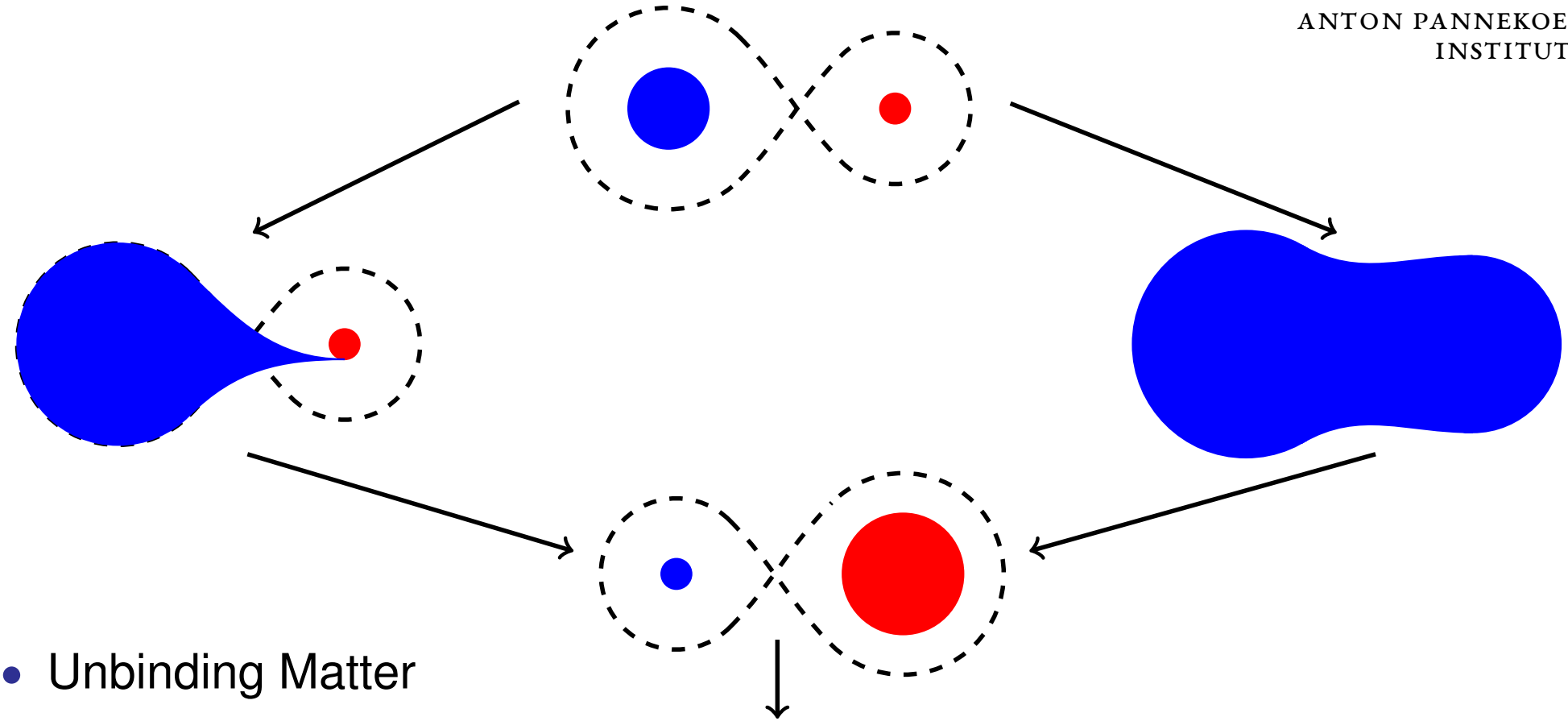
$$\begin{cases} M_{\rm fb} = 0.2\,M_\odot & M_{\rm CO} < 2.5\,M_\odot \\ M_{\rm fb} = 0.286 M_{\rm CO} - 0.514\,M_\odot & 2.5\,M_\odot \leqslant M_{\rm CO} < 6.0\,M_\odot \\ f_{\rm fb} = 1.0 & 6.0\,M_\odot \leqslant M_{\rm CO} < 7.0\,M_\odot \\ f_{\rm fb} = a_1 M_{\rm CO} + b_1 & 7.0\,M_\odot \leqslant M_{\rm CO} < 11.0\,M_\odot \\ f_{\rm fb} = 1.0 & M_{\rm CO} \geqslant 11.0\,M_\odot \end{cases}$$

Ejecta impact from Liu *et al.* '15



Binary Disruption

ANTON PANNEKOEK
INSTITUTE



- Unbinding Matter

  (e.g., Blaauw ’61)

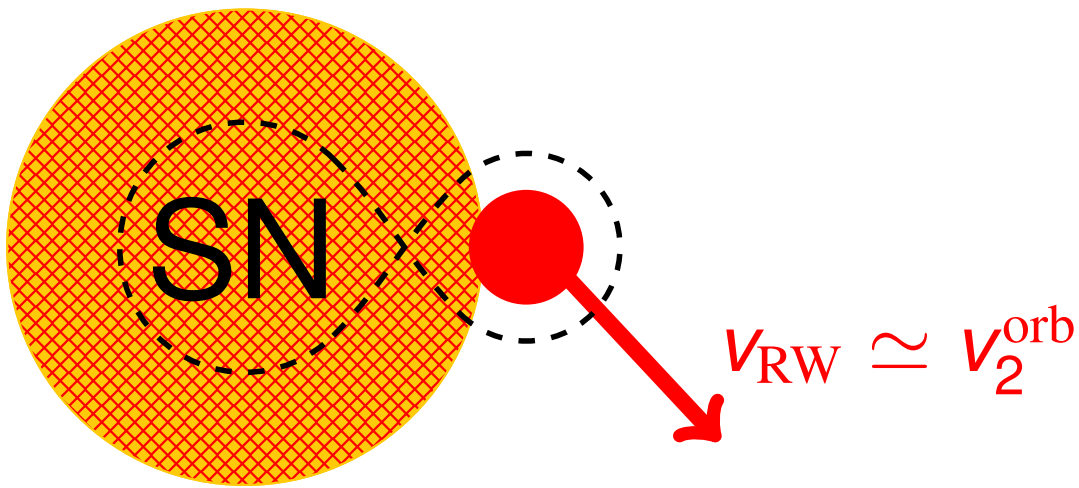
- SN Natal Kick

  (e.g., Shklovskii ’70, Janka ’16)

- Ejecta Impact

  (e.g., Wheeler *et al.* ’75,

  Tauris & Takens ’98, Liu *et al.* ’15)



(potential) Physics lessons...

...from disrupted binaries

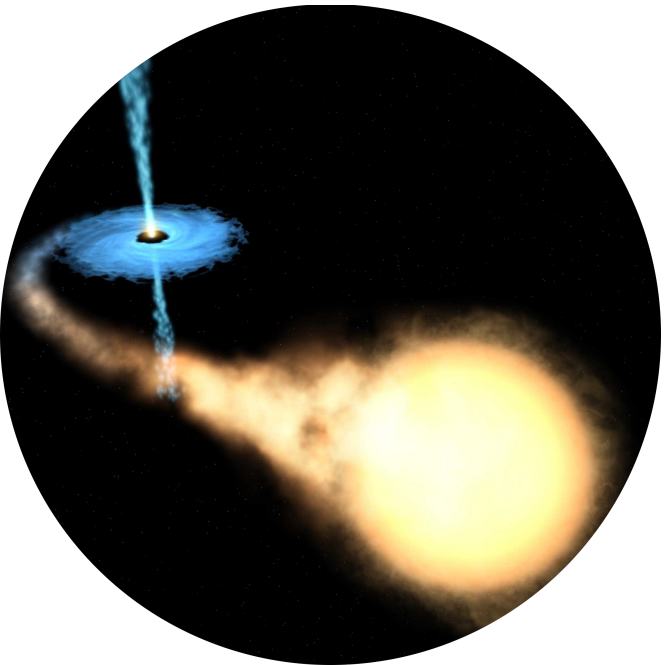
ANTON PANNEKOEK INSTITUTE

- BH kicks
- Binary evolution

Do BH receive natal kicks?

Spatial distribution of X-ray binaries

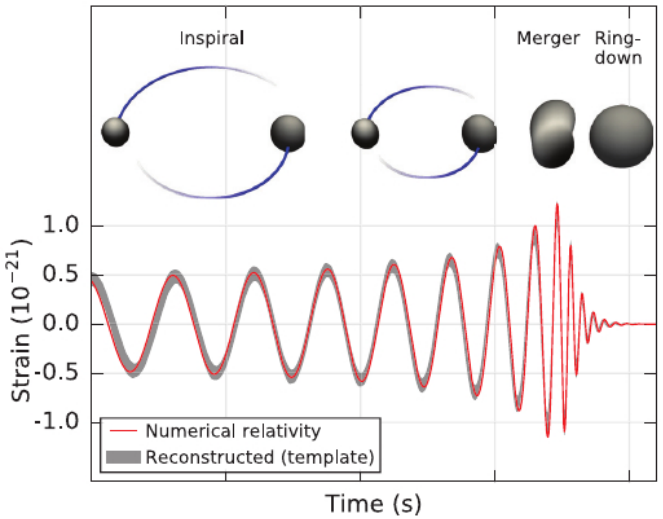
(e.g., Repetto *et al.* '12,'15,'16, Mandel '16)



Massive (and WR) runaways

(Dray *et al.* '05)

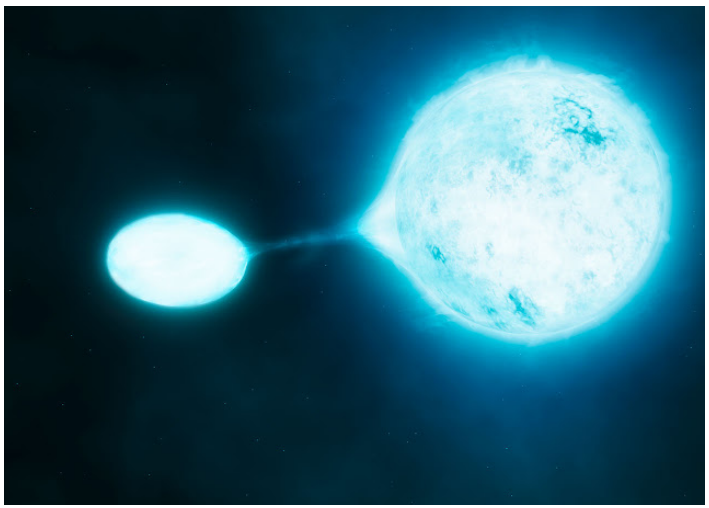
Disrupted binaries are "failed" GW sources!



- BH kicks
- Binary evolution

Constraints on binary physics

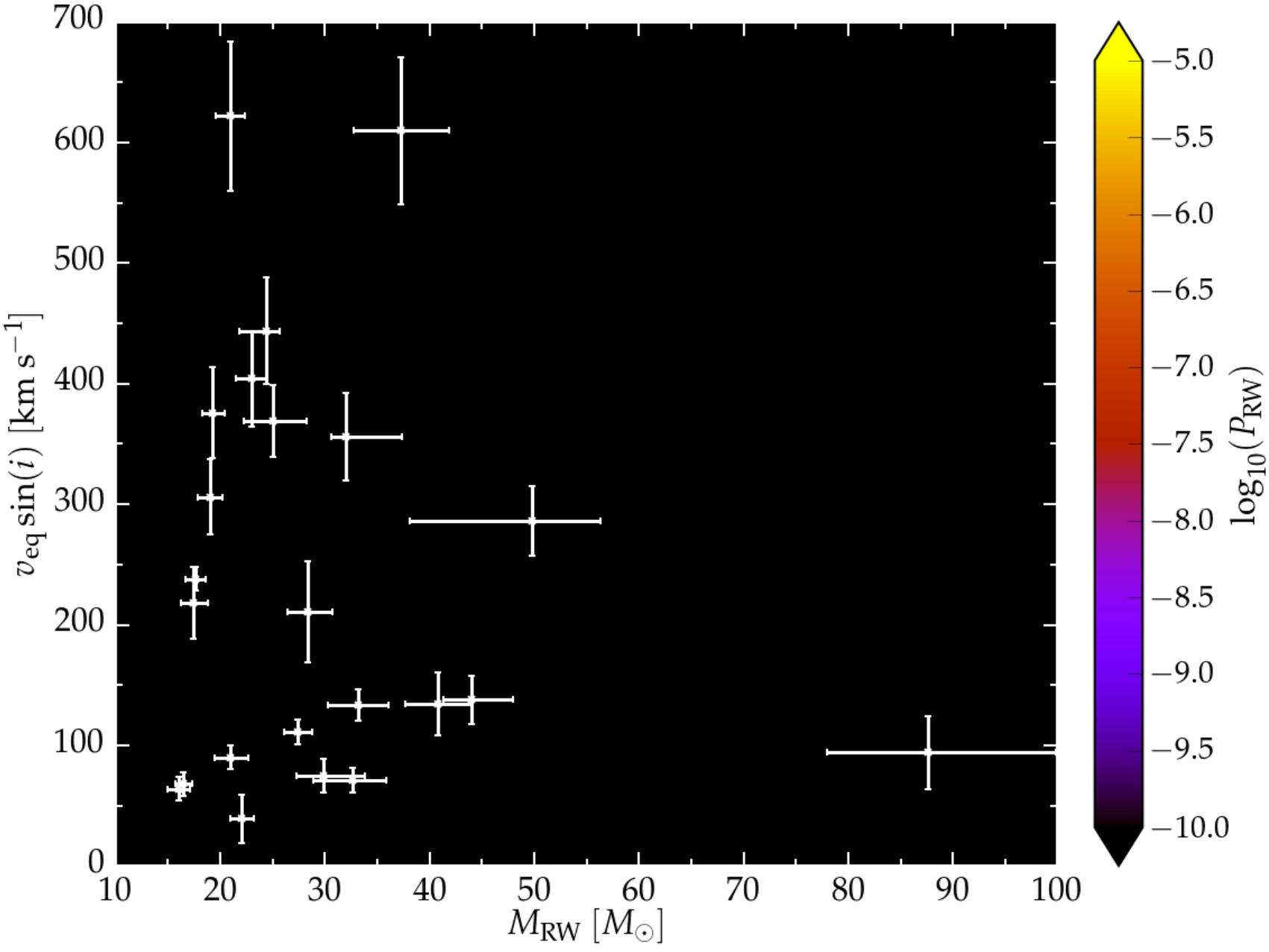
- Orbital evolution $\Leftrightarrow$ pre-SN period
- Mass transfer efficiency $\Leftrightarrow$ pre-SN M_2
- Angular momentum loss $\Rightarrow$ isotropic re-emission, circumbinary disk, etc.



Mass-rotation correlation

ANTON PANNEKOEK INSTITUTE

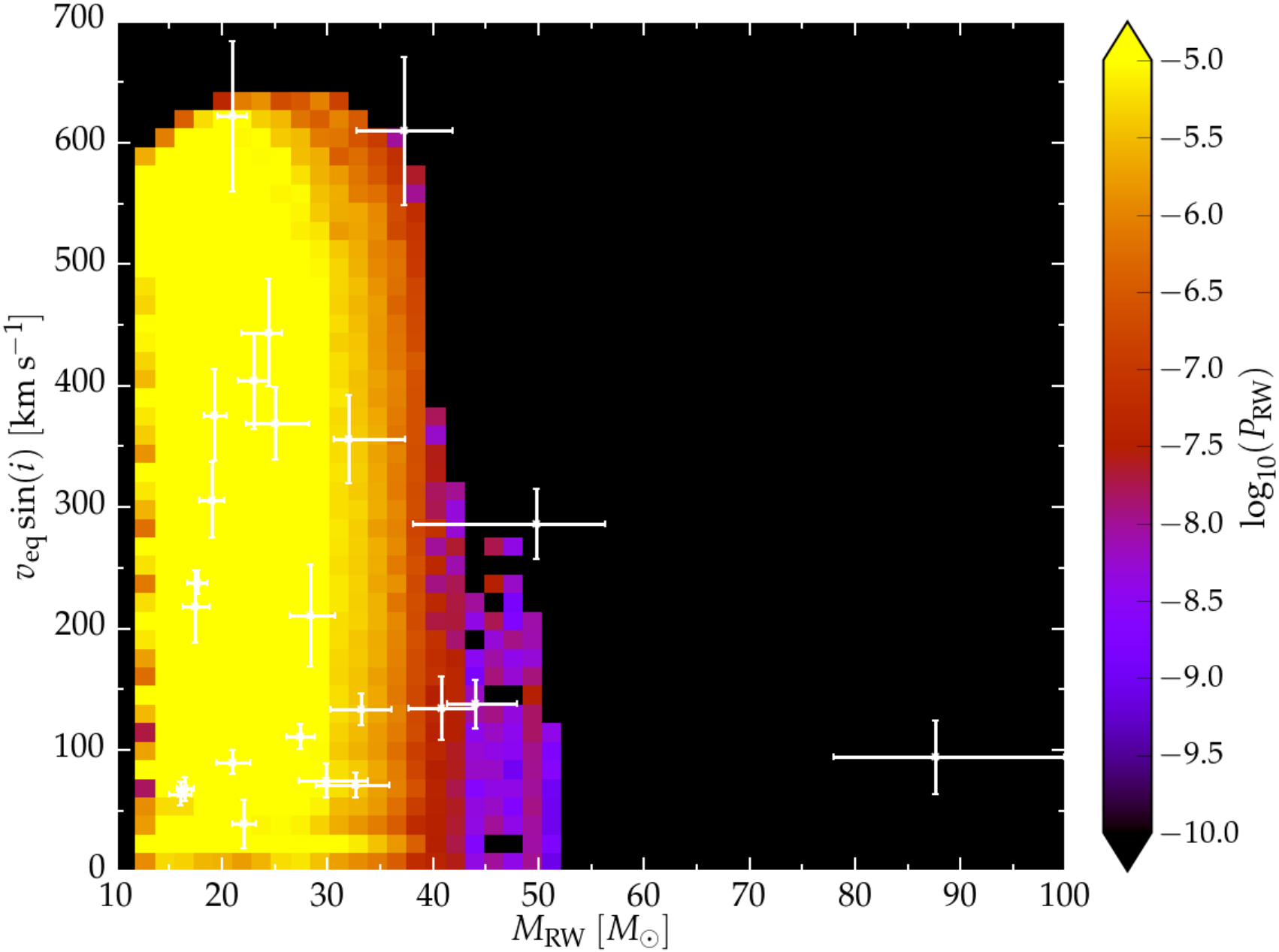
Runaways only



Mass-rotation correlation

ANTON PANNEKOEK INSTITUTE

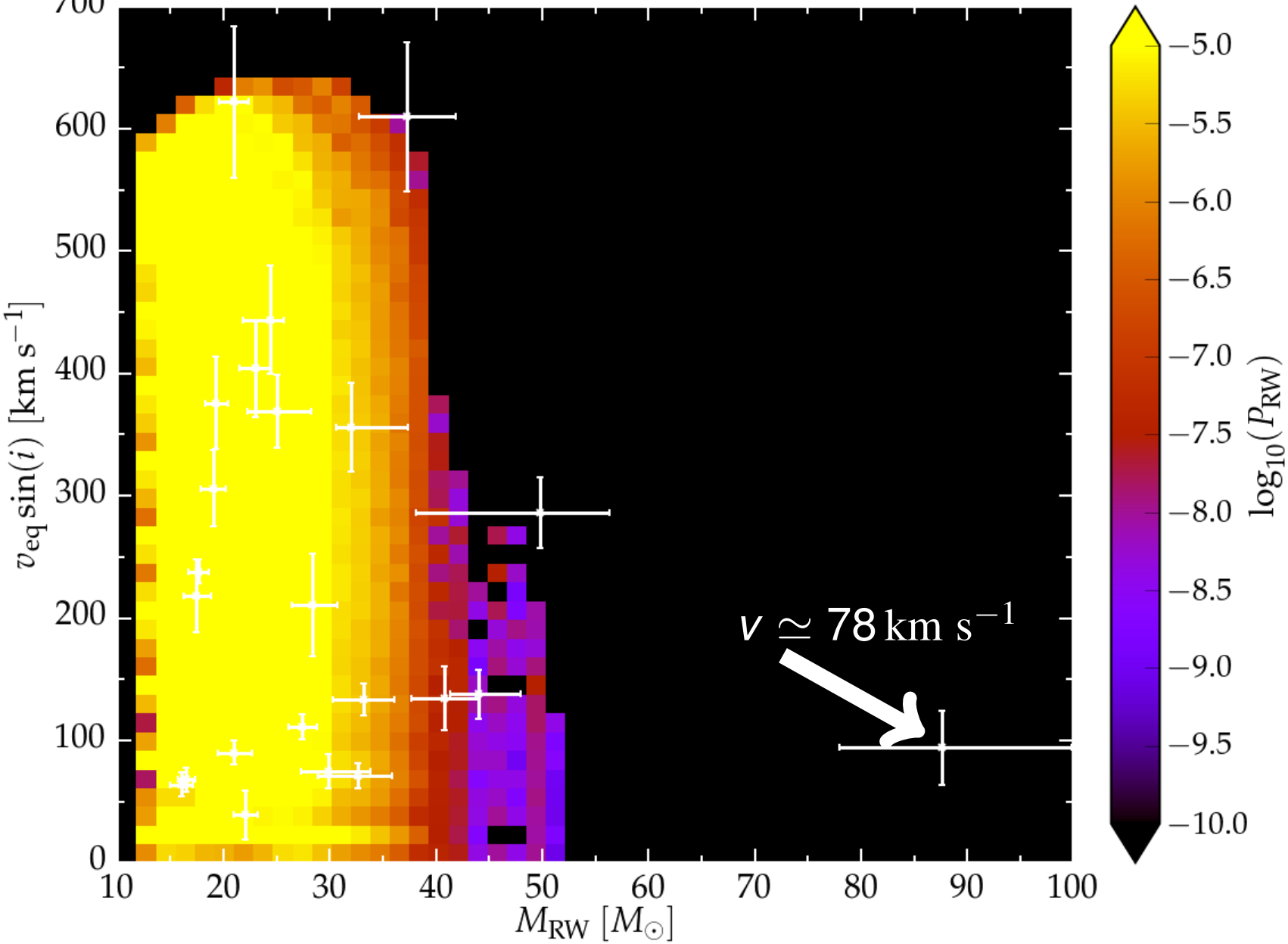
Runaways only



Mass-rotation correlation

ANTON PANNEKOEK INSTITUTE

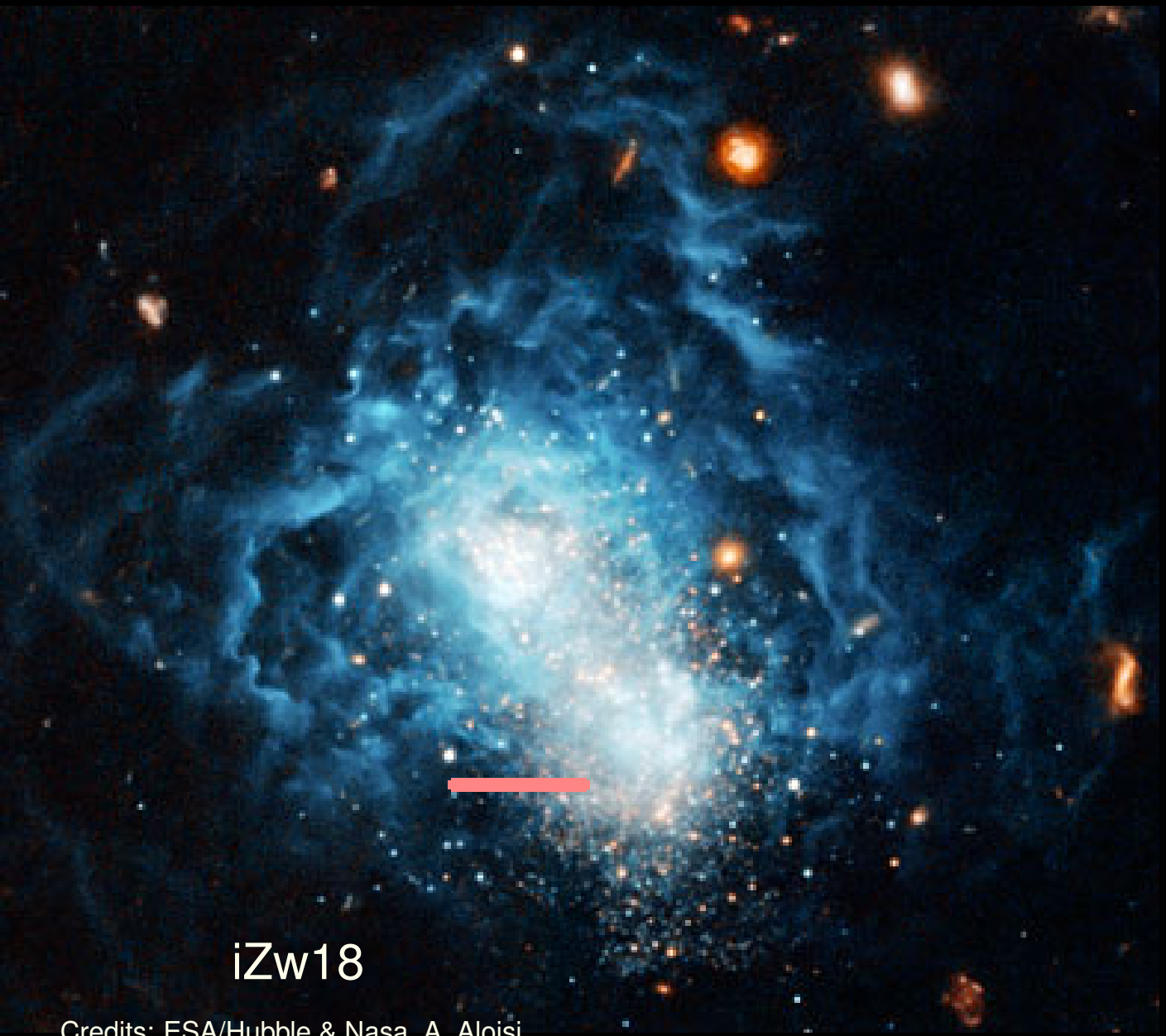
Runaways only



Where do they die?

Credits: ESA/Hubble & Nasa, A. Aloisi

Where do they die?

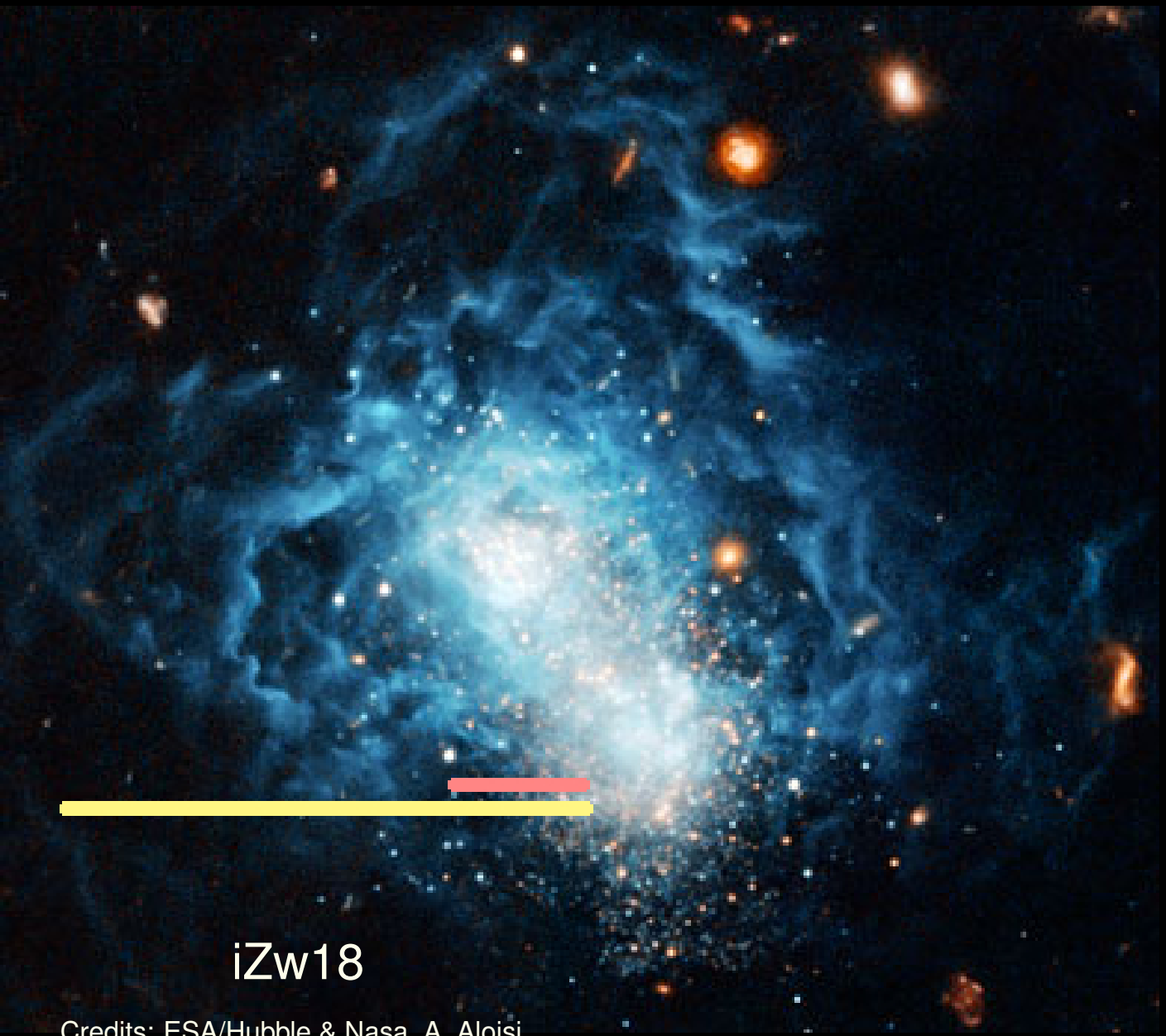


Credits: ESA/Hubble & Nasa, A. Aloisi

for $M \geq 7.5\,M_{\odot}$:

$\langle D \rangle = 128\,\mathrm{pc}$

Where do they die?



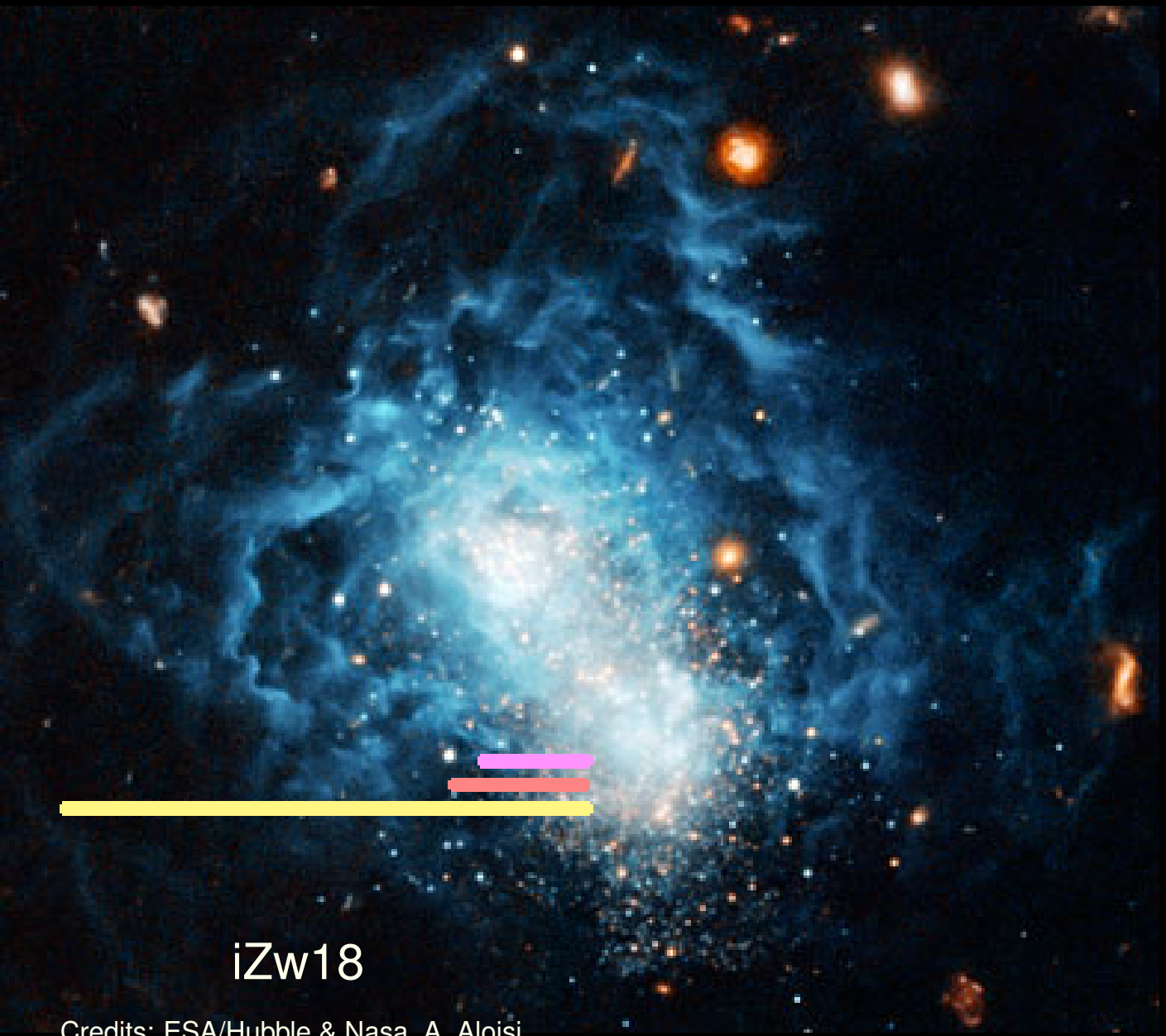
Credits: ESA/Hubble & Nasa, A. Aloisi

for $M \geq 7.5\,M_{\odot}$:

$\langle D \rangle = 128\,\mathrm{pc}$

$\langle D_{\mathrm{run}} \rangle = 525\,\mathrm{pc}$

Where do they die?



Credits: ESA/Hubble & Nasa, A. Aloisi

for $M \geq 7.5\,M_{\odot}$:

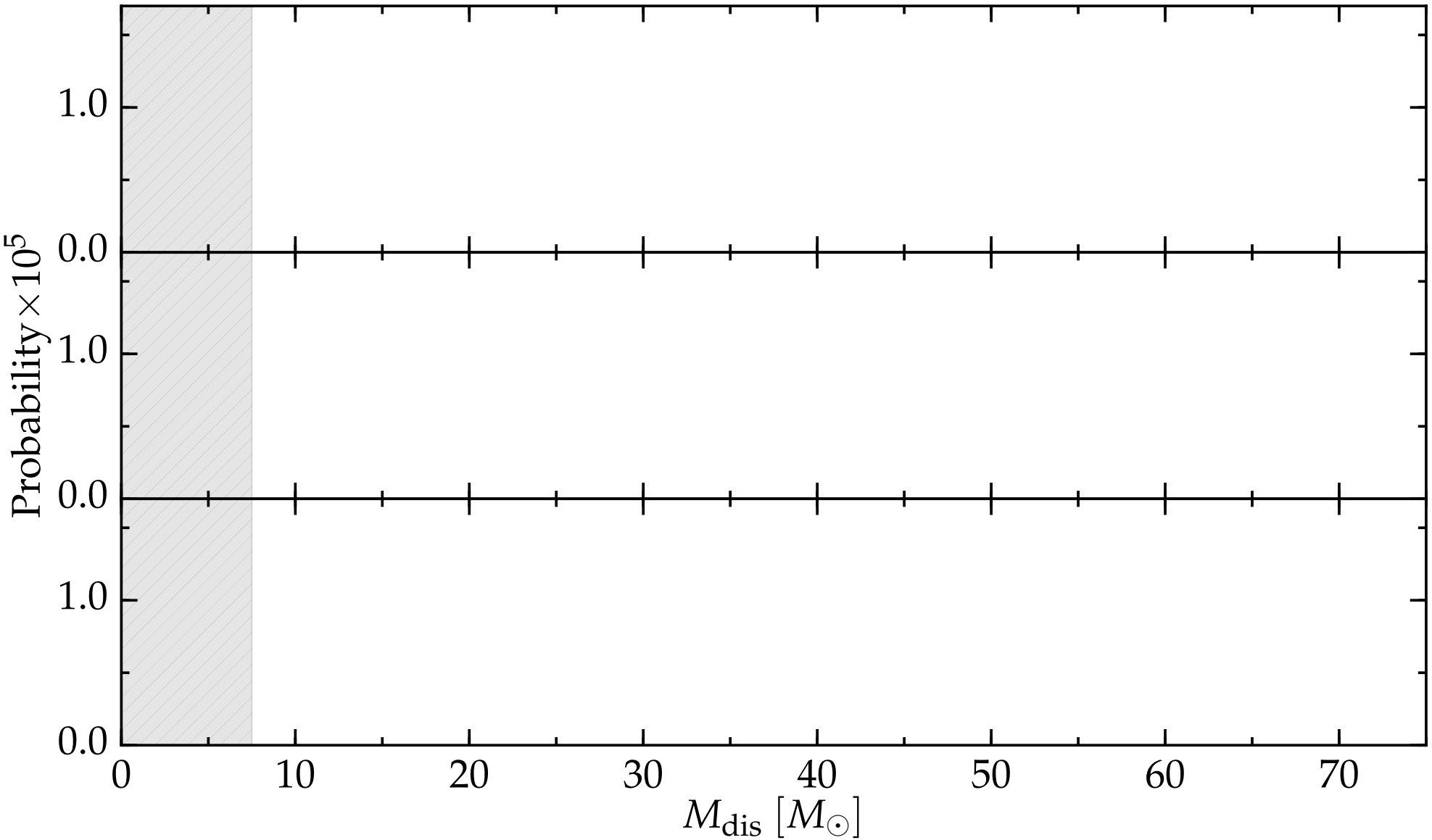
$\langle D \rangle = 128\,\mathrm{pc}$

$\langle D_{\mathrm{run}} \rangle = 525\,\mathrm{pc}$

$\langle D_{\mathrm{walk}} \rangle = 103\,\mathrm{pc}$

How to test BH kick physics?

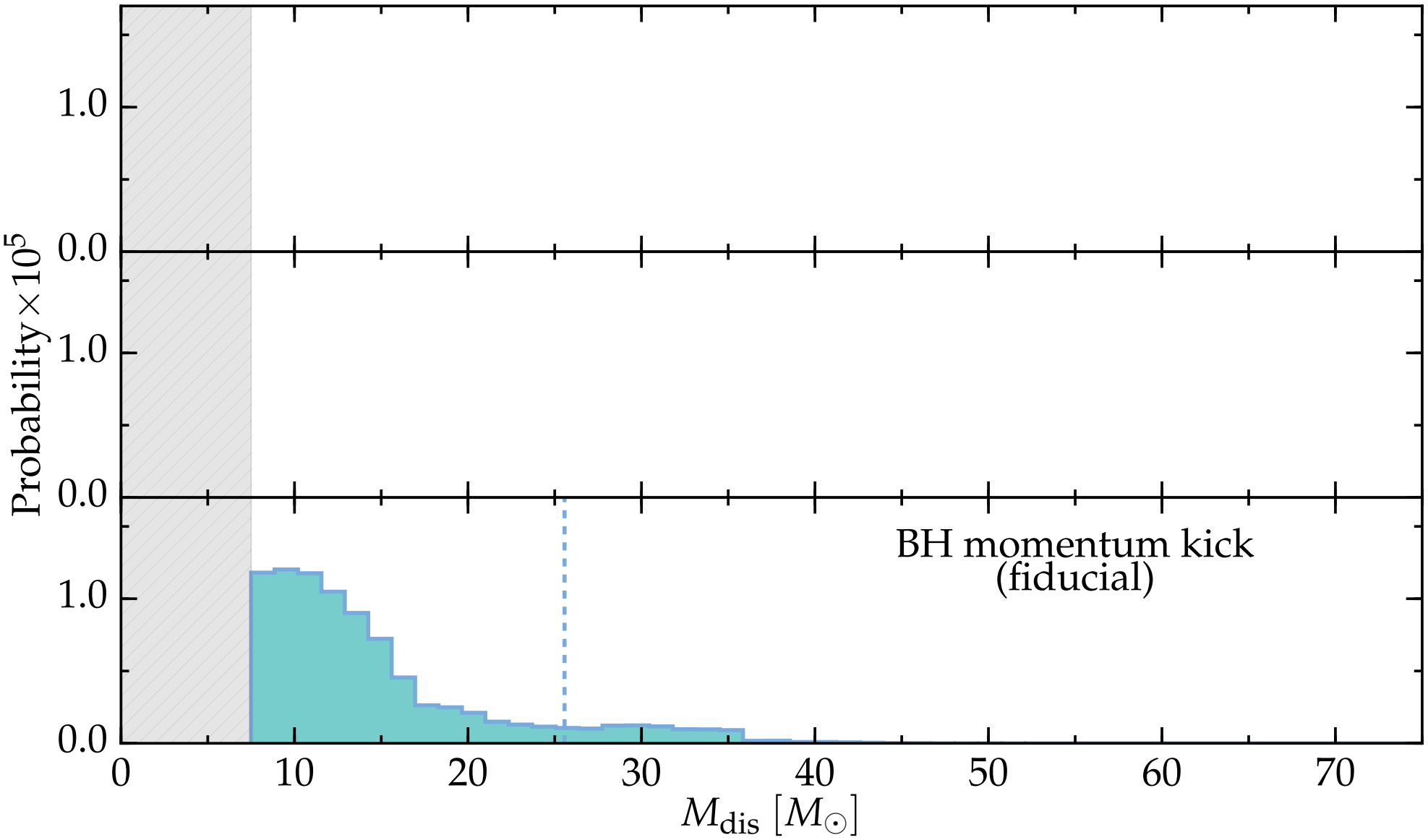
ANTON PANNEKOEK
INSTITUTE



BH $\Leftrightarrow$ $M_{\rm BH} \geq 2.5\,M_\odot$, Only $v \geq 30\,{\rm km\ s^{-1}}$ and $M_{\rm dis} \geq 7.5\,M_\odot$

(Massive) runaway mass function

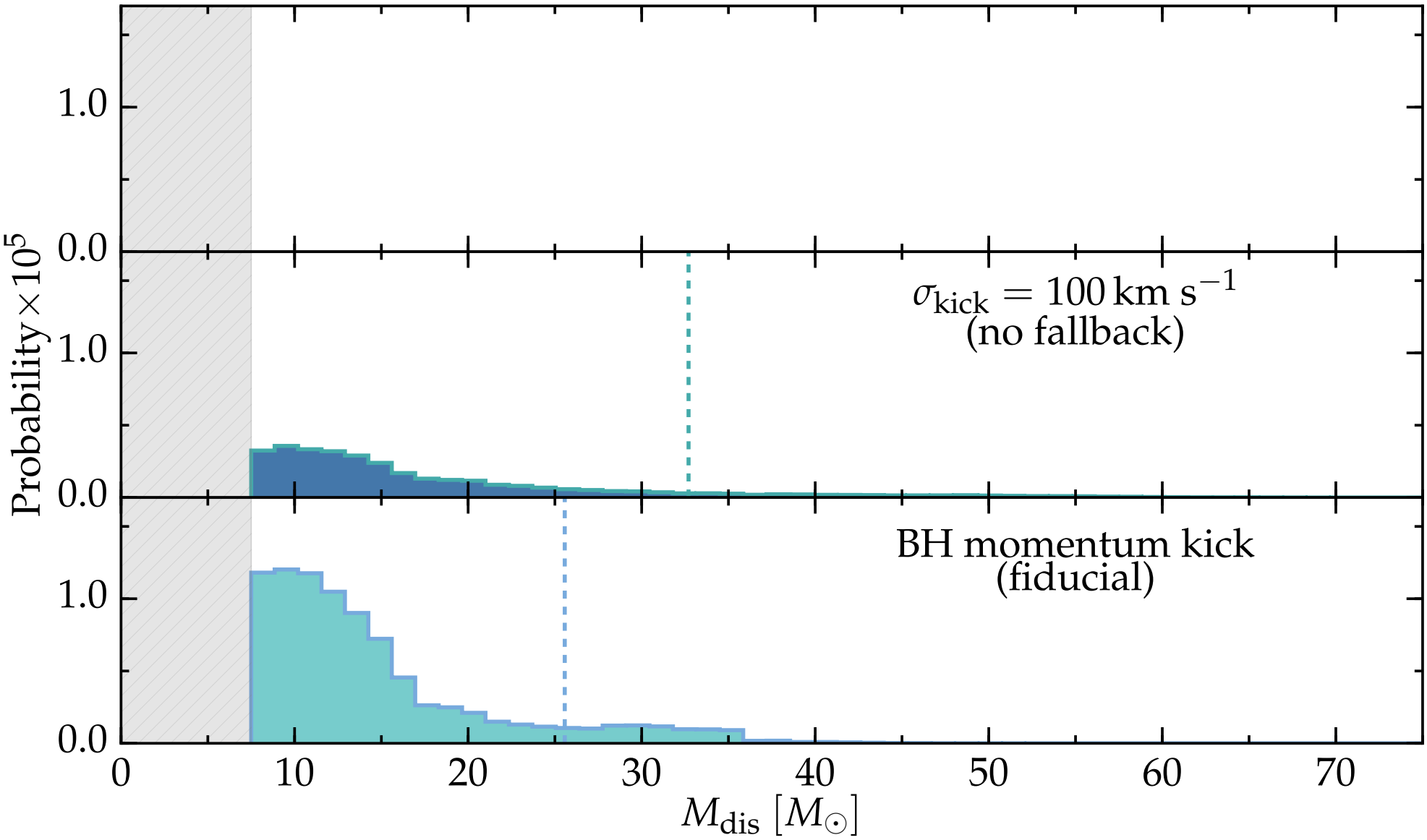
ANTON PANNEKOEK
INSTITUTE



BH $\Leftrightarrow$ $M_{\rm BH} \geq 2.5\,M_\odot$, Only $v \geq 30\,{\rm km\ s^{-1}}$ and $M_{\rm dis} \geq 7.5\,M_\odot$

(Massive) runaway mass function

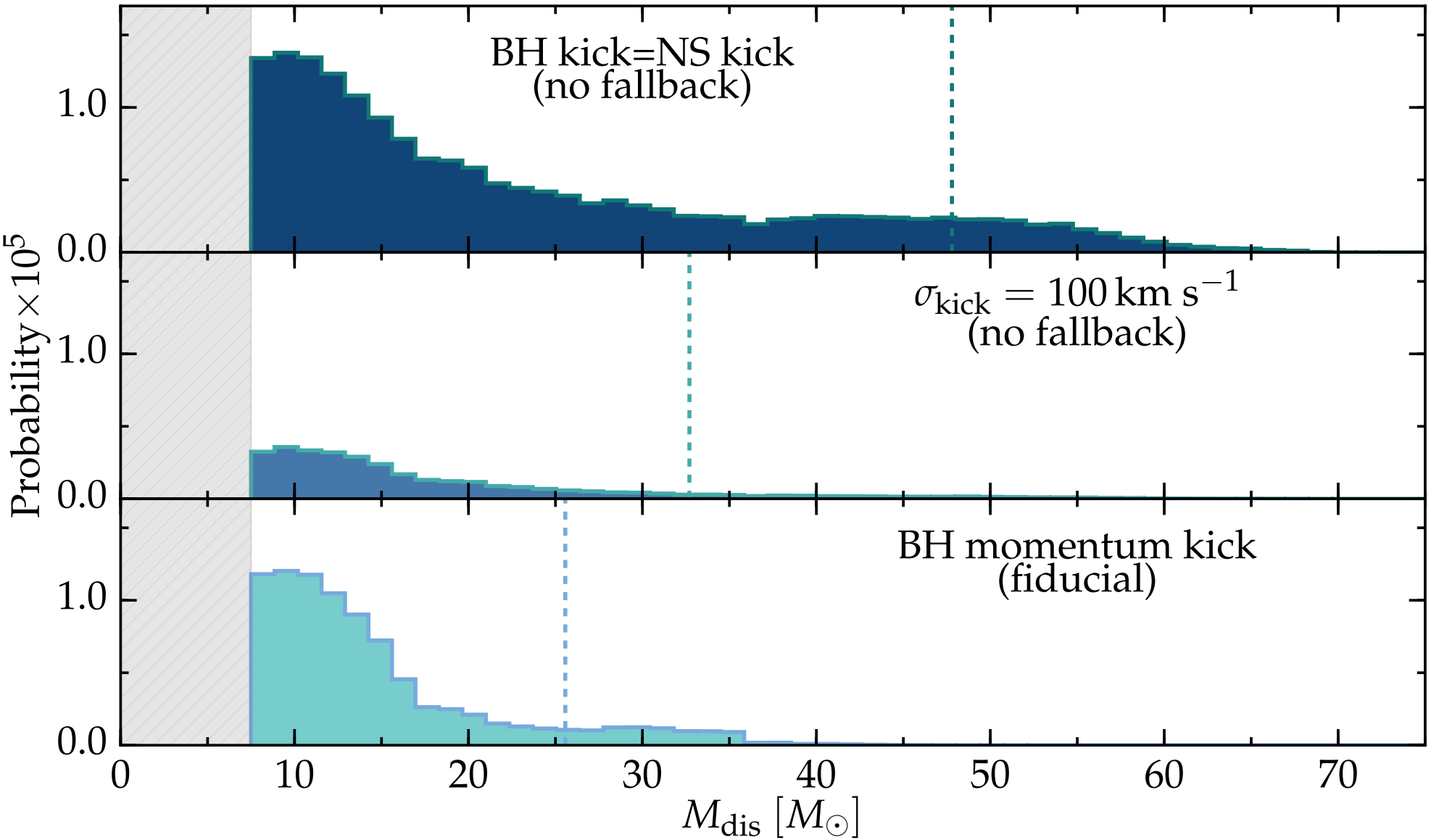
ANTON PANNEKOEK
INSTITUTE



BH $\Leftrightarrow$ $M_{\rm BH} \geq 2.5\,M_\odot$, Only $v \geq 30\,{\rm km\ s^{-1}}$ and $M_{\rm dis} \geq 7.5\,M_\odot$

(Massive) runaway mass function

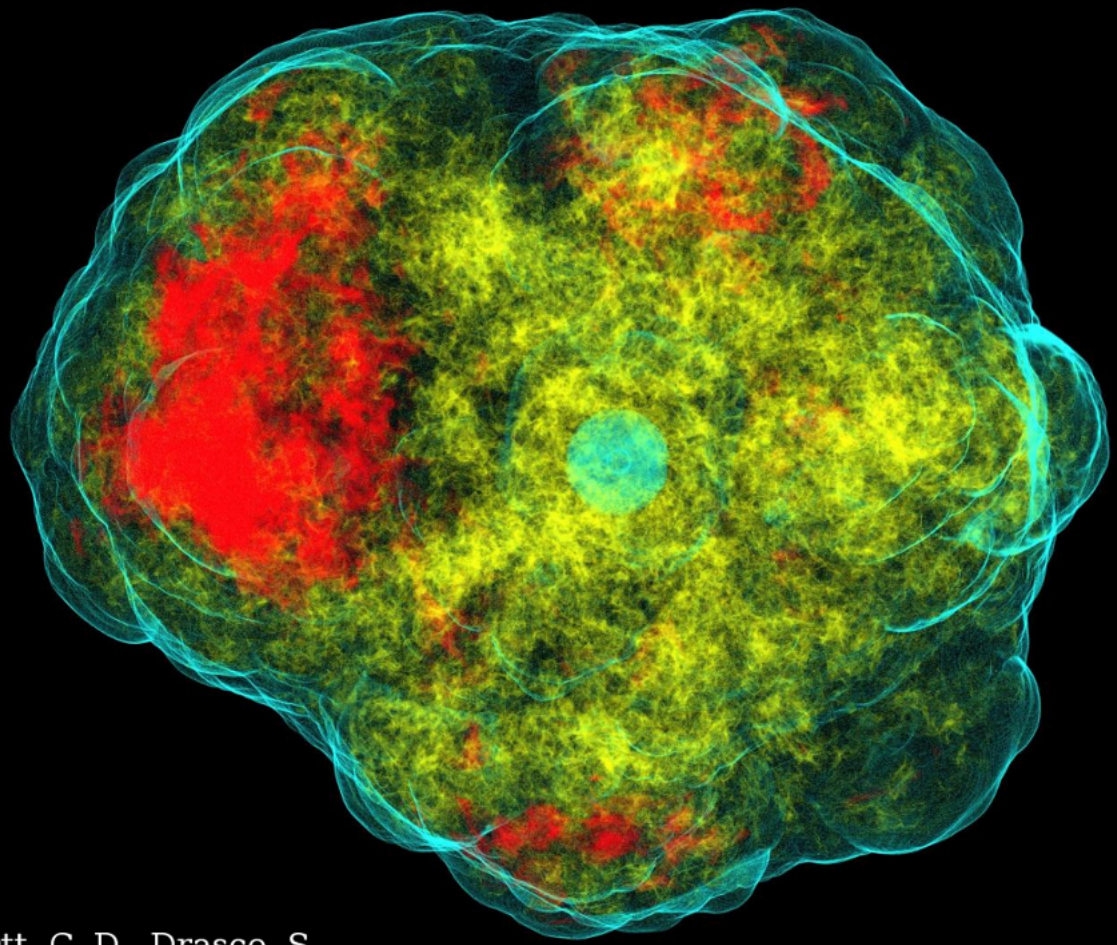
ANTON PANNEKOEK INSTITUTE



BH $\Leftrightarrow$ $M_{\rm BH} \geq 2.5\,M_\odot$, Only $v \geq 30\,{\rm km\ s^{-1}}$ and $M_{\rm dis} \geq 7.5\,M_\odot$

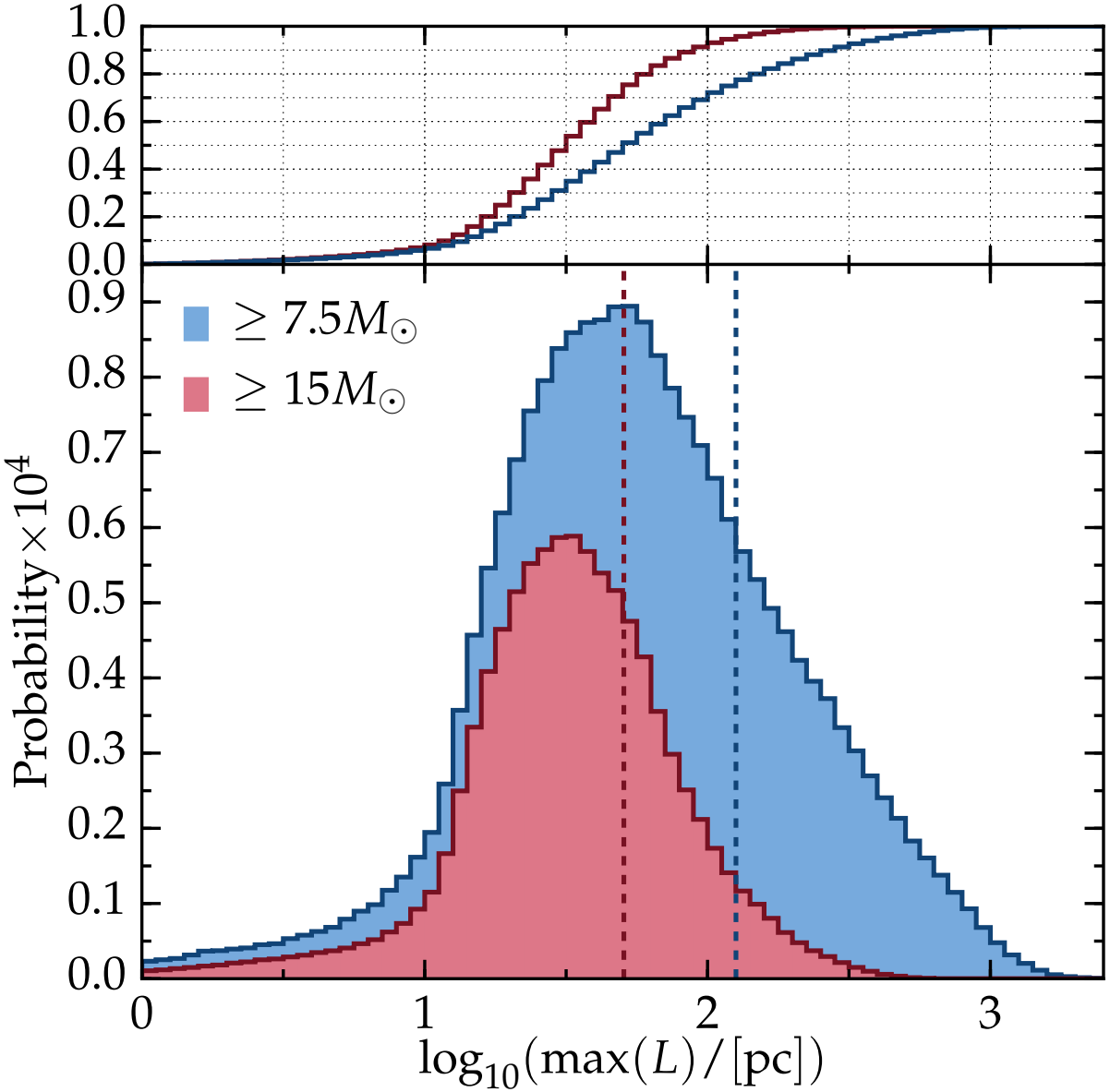
SN natal kick

ν emission and/or ejecta anisotropies



Credits: Ott, C. D., Drasco, S.

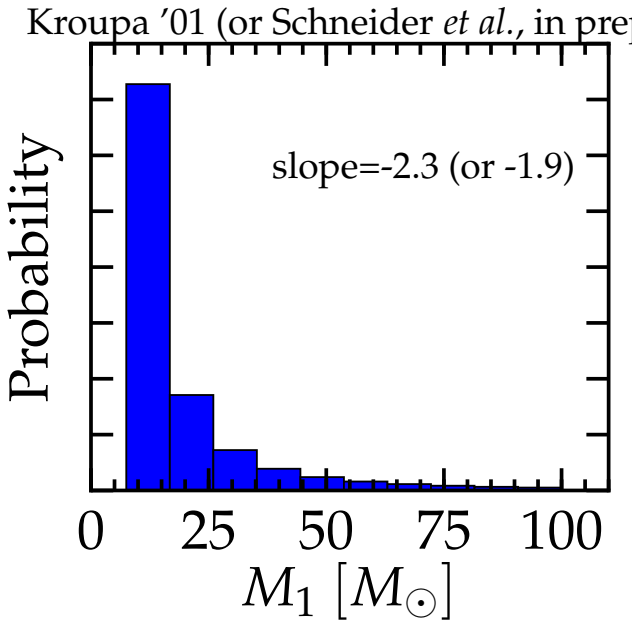
Where do they die?

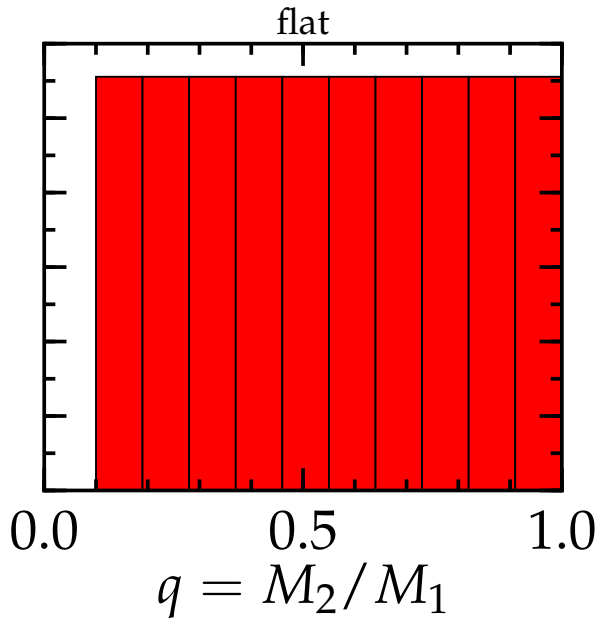


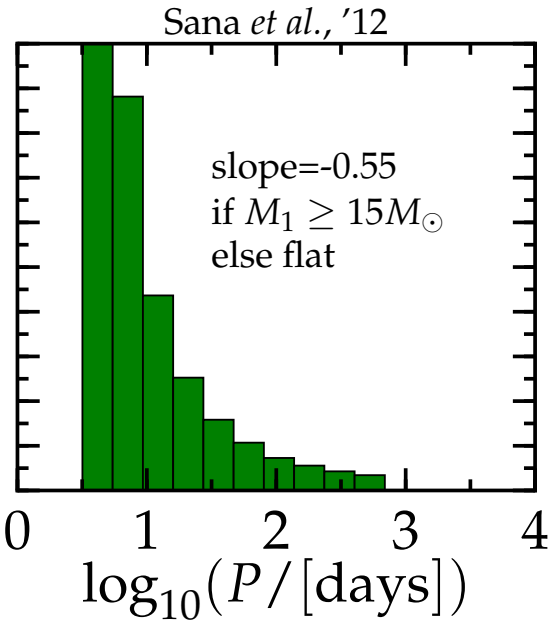
"Distance traveled"

No potential well, $\sigma_{\mathrm{kick}} = 265\,\mathrm{km\ s^{-1}}$

Initial Distributions

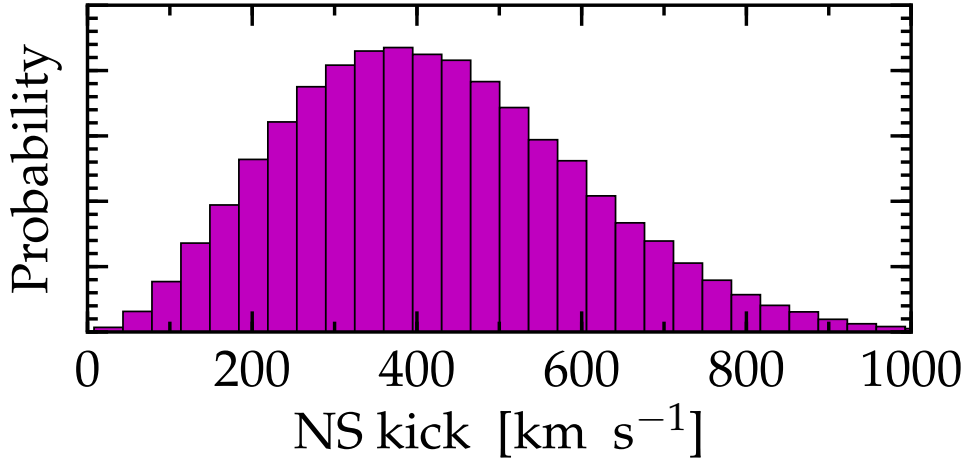






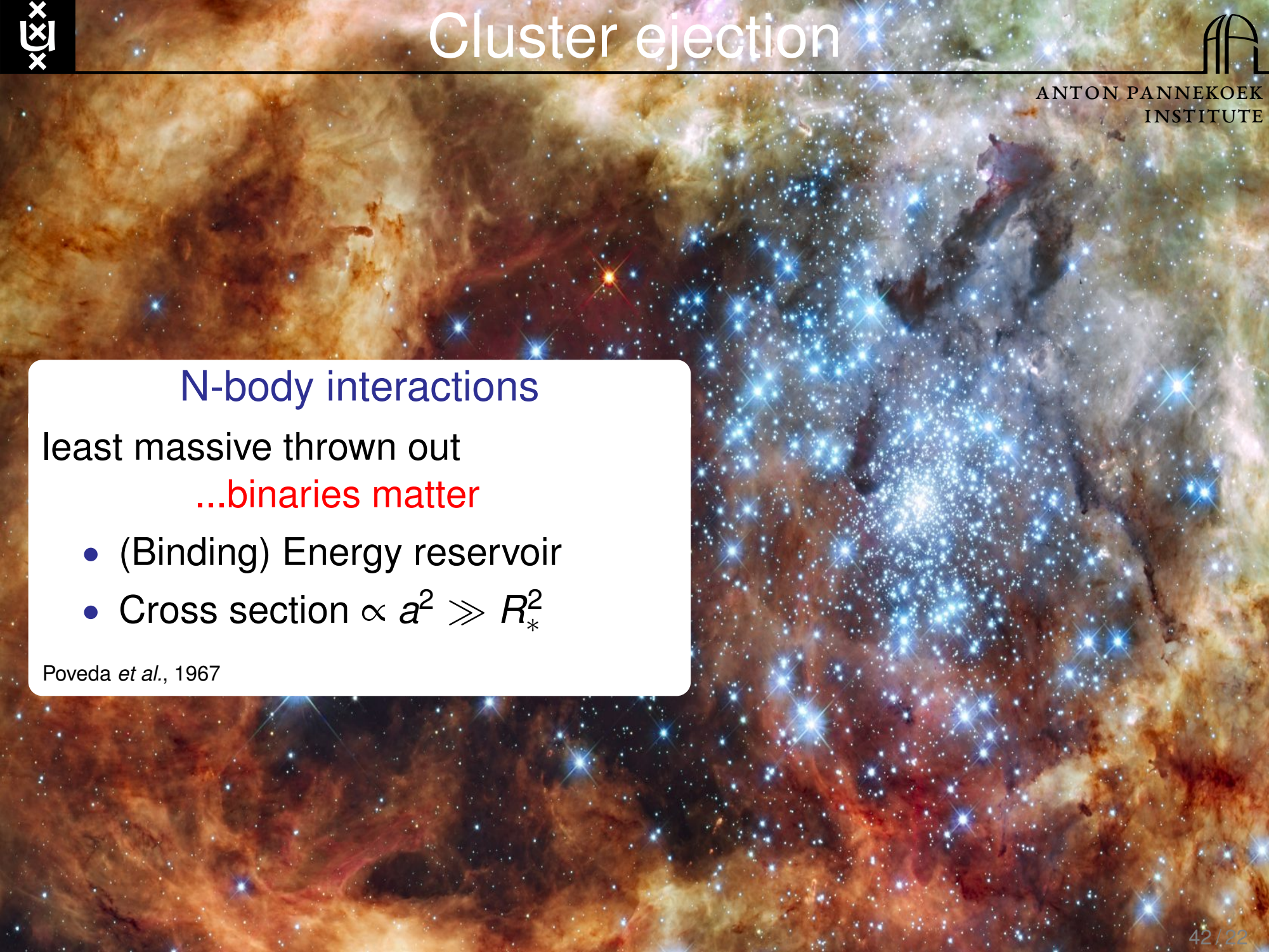
Maxwellian $\sigma_{v_{\text{kick}}} = 265\,\text{km s}^{-1}$ + Fallback rescaling

(from Fryer *et al.* '12)



Hobbs *et al.* '05

Cluster ejection



N-body interactions

least massive thrown out

...binaries matter

- (Binding) Energy reservoir
- Cross section $\propto a^2 \gg R_*^2$

Poveda *et al.*, 1967