Massive stars and binaries: why & how?

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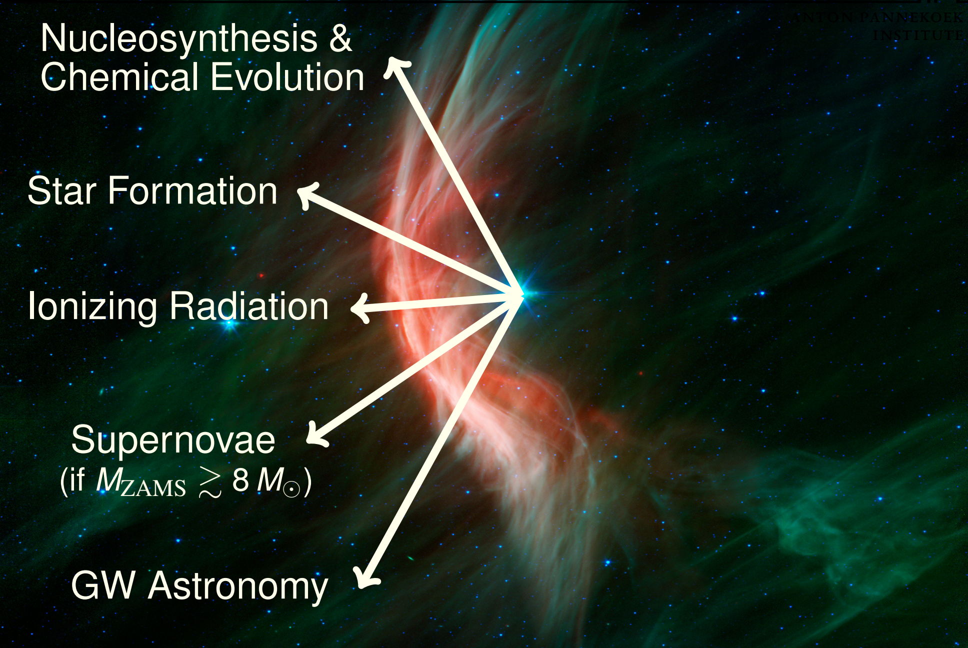
PhD in Amsterdam

NASA, JPL-Caltech, Spitzer Space Telescope

Why are Massive Stars Important?



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Why are Massive Stars Important?

Nucleosynthesis & Chemical Evolution

Star Formation

Ionizing Radiation

Supernovae (if $M_{\mathrm{ZAMS}} \gtrsim 8\,M_{\odot}$)

GW Astronomy

$\sim$ 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)

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

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

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30 Doradus

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$$Z = Z_{\mathrm{LMC}}$$

Massive stars have companions

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Average number of companions $f_O \simeq 2.8$

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Physical processes

- Irradiation
- Mass Transfer
- Tidal effects

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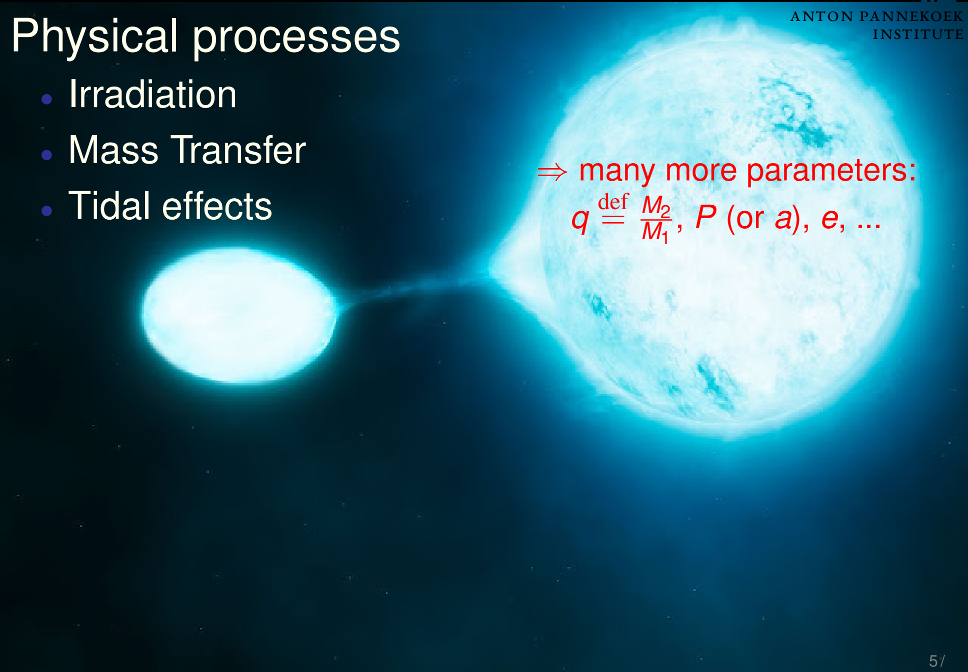

$\Rightarrow$ many more parameters:

$q \overset{\text{def}}{=} \frac{M_2}{M_1}$, P (or a), e, ...

Binary Zoo

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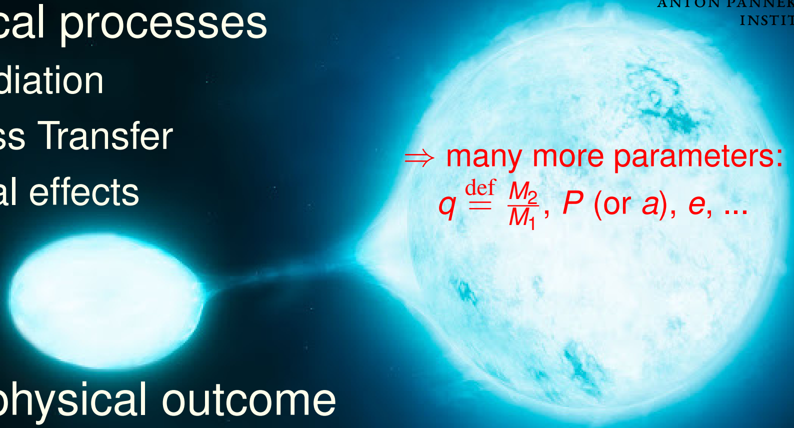
Physical processes

- Irradiation
- Mass Transfer
- Tidal effects



$\Rightarrow$ many more parameters:

$q \stackrel{\text{def}}{=} \frac{M_2}{M_1}$, P (or a), e, ...

Astrophysical outcome

- Stripped stars
- Contact binaries
- Runaways & “walkaway” stars
- Mergers

Outline

Introduction: Massive Stars

Computational astrophysics

- Stellar evolution & structure
- Binary Population Synthesis

(If you care) preliminary results

- Can stellar wind change the final fate of a massive star?
- What physics can we learn from breaking apart binaries?

What should **not** happen

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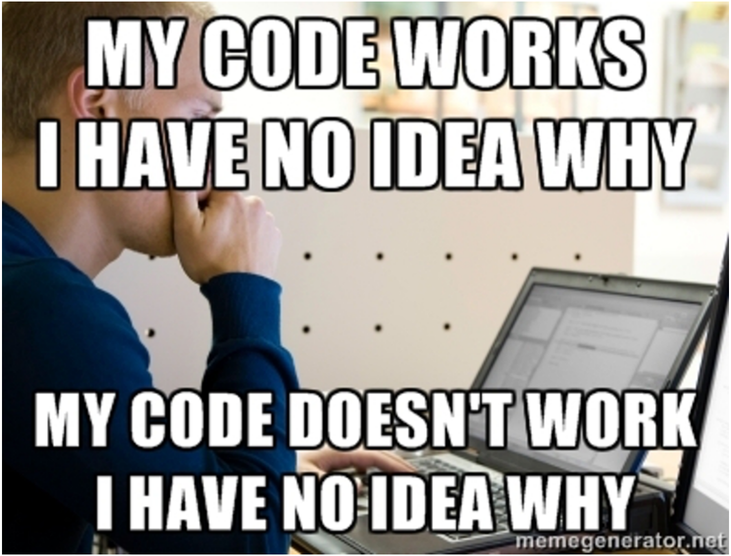

How can we “look” inside a star?

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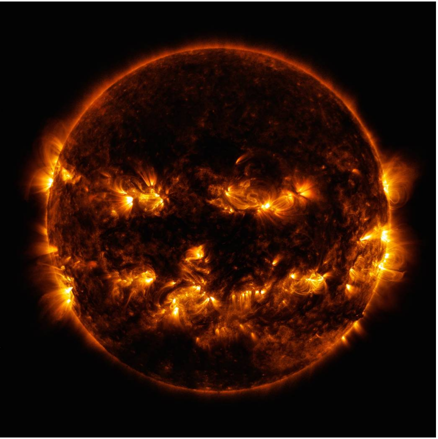
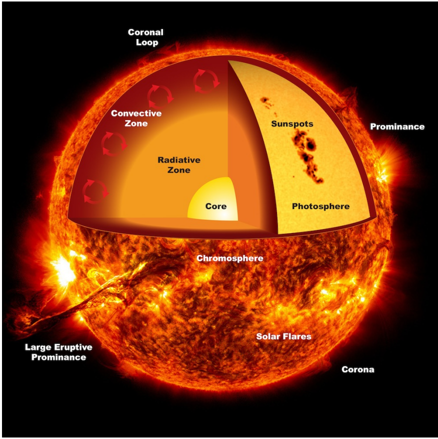
Figures Credits: NASA



$\overset{?}{\Longrightarrow}$



How can we "look" inside a star?

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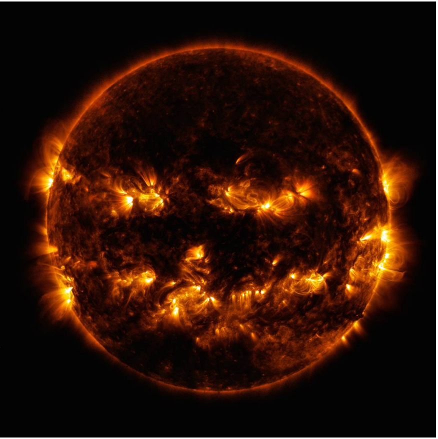
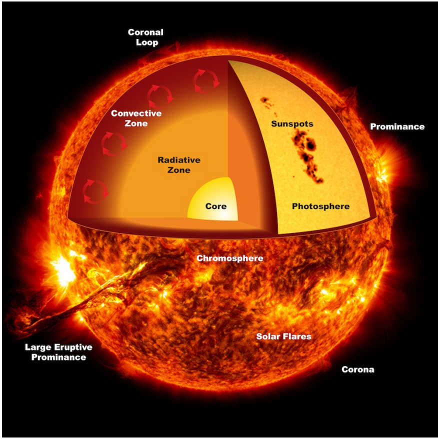
Figures Credits: NASA



? ⇒



We simply can't!!

Other Q: How can we observe how *one* star evolves?

So what to do?

1. Build a theory from first principles;
2. Plug it in a computer;
3. Get out a ***model***;
4. Find a smart way to compare it to what we *can* observe.

Advantages

- Full control over the parameters $\Rightarrow$ Numerical Experiments;
- Allow to focus on interesting things (e.g. no reddening!);
- Allow to deal with long-lasting, rare, inaccessible phenomena;

Drawbacks

- Numerical errors;
- Limited computational resources;
- Nature $\gg$ Theory $\gg$ Model.

"All models are wrong, but some are useful" – G. Box

The Stellar Evolution Code:

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MESA

is a *tool*, not a theory!

What does it stand for?

Modules for
Experiments in
Stellar
Astrophysics

References:

Paxton *et al.* 2011, ApJs192,3

Paxton *et al.* 2013, ApJs208,4

Paxton *et al.* 2015, ApJs220,15

`mesa.sourceforge.net`

`mesastar.org`

Open Source ⇔ Open Know How

"An algorithm must be seen to be believed" – D. Knuth

Prohibitive computational cost of 3D
$\Rightarrow$ 1D, but stars are *not* spherical-symmetric!

Need of parametric approximations for:

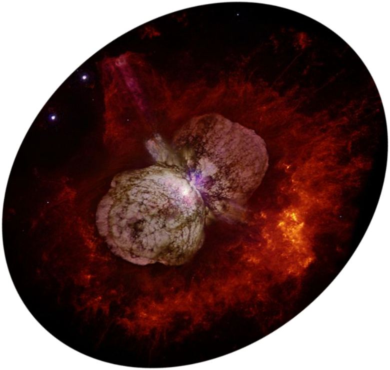
- Rotation $\Rightarrow$ “Shellular Approximation”;
- Magnetic Fields;
- Convection $\Rightarrow$ Mixing Length Theory (MLT);
- (Some) mixing processes;
- ...

Beware of systematic errors!

Hydrostatic approximation

$$\frac{dP}{dr} = -\frac{Gm(r)\rho}{r^2}$$

... but stars are not necessarily static!



Other examples:

- He flash,
- Outburst and Eruptions,
- Impulsive mass loss,
- RLOF,
- ...

Figure: η Car, APOD.

Dynamical correction to **static** equilibrium

$$\frac{dP}{dr} = -\frac{Gm(r)\rho}{r^2} - a(r)\rho$$

$$a(r) \stackrel{\text{def}}{=} \frac{dv}{dt} = \frac{d^2r}{dt^2} \ll \frac{Gm(r)}{r^2}$$

"Calculated Passively"

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"Calculated Passively"

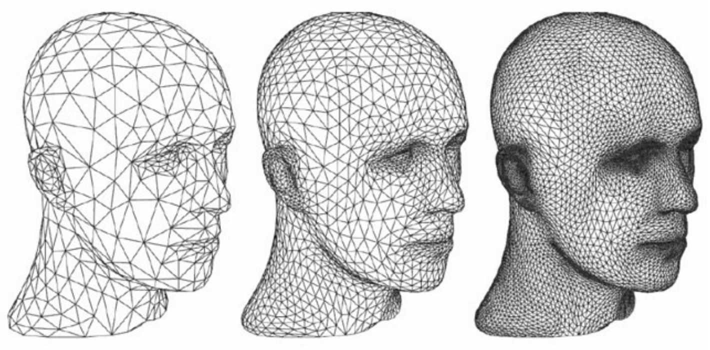
Explicitly time-dependent reformulation

$$\frac{\partial v}{\partial t} = -\frac{Gm(r)}{r^2} - \frac{4\pi r^2}{3}\frac{dP}{dm} + g_{\mathrm{visc}}$$

(Euler eq. + reformulation of all stellar structure equations)

Discretization

$$\frac{df}{dx} \rightarrow \frac{f(x_{k+1}) - f(x_k)}{x_{k+1} - x_k}$$



Spatial Discretization (Meshing)

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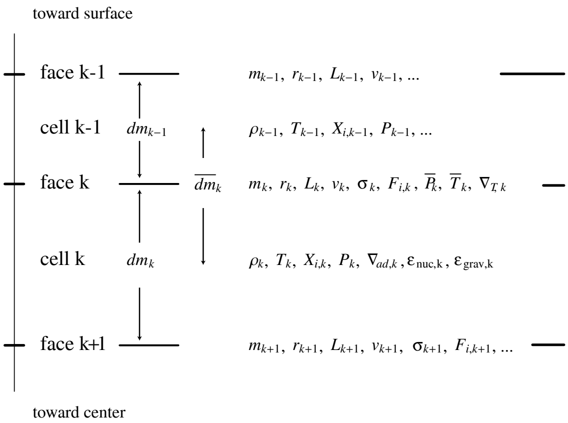

- Intensive quantities (e.g. T,ρ) averaged by mass within each cell;
- Extensive quantities (e.g. m,L) calculated at outer cell boundary.

Check that physical results do *not* depend on discretization but $\sim t_{KH}, t_M$, etc.

Timestep

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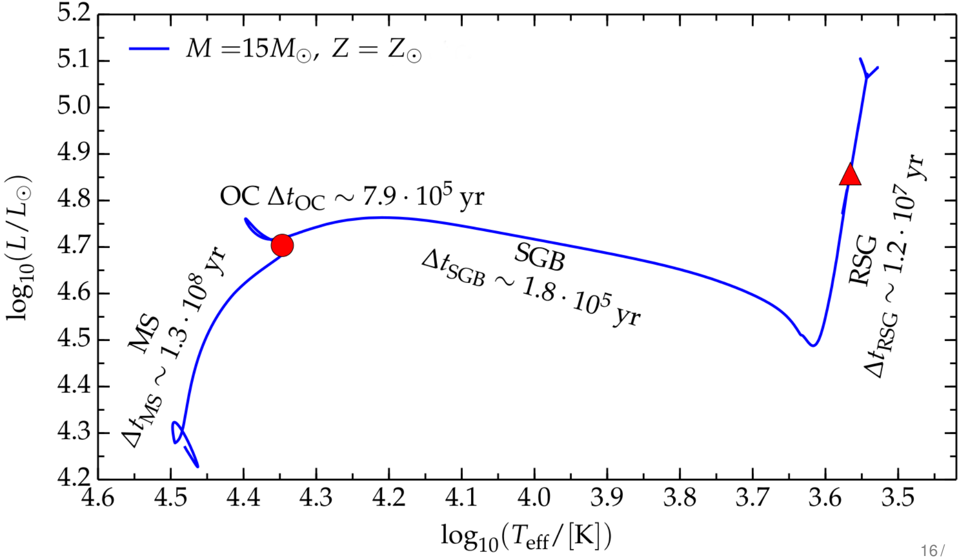
allow for computation, but resolve physical processes



Reformulation of the (1D-) Equations

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Physical Theory: Numerical Implementation:

$$\frac{dP}{dr} = -\frac{Gm(r)\rho}{r^2} \quad (+a\rho) \qquad \Leftrightarrow$$

$$\frac{dm}{dr} = 4\pi r^2 \rho \qquad \Leftrightarrow$$

$$\frac{dT}{dr} = -\frac{3}{16\pi ac}\frac{\kappa\rho L}{r^2 T^3} \qquad \Leftrightarrow$$

$$\frac{dL}{dr} = 4\pi r^2 \rho \varepsilon \qquad \Leftrightarrow$$

$$P \equiv P(\rho, \mu, T) \qquad \Leftrightarrow$$

$$\left.\frac{dX_i}{dt}\right|_r = \left[\sum_j \mathcal{P}_{j,i}(T,\rho) - \sum_k \mathcal{D}_{i,k}(T,\rho)\right] + \left[\sigma_i \nabla^2 X_i\right]$$

$$\Updownarrow$$

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Physical Theory: | **Numerical Implementation:**

$$\frac{dP}{dr} = -\frac{Gm(r)\rho}{r^2} \quad (+a\rho) \quad \Leftrightarrow \quad \frac{P_{k-1}-P_k}{0.5(dm_{k-1}-dm_k)} = -\frac{Gm_k}{4\pi r_k^4} - \frac{a_k}{4\pi r_k^2}$$

$$\frac{dm}{dr} = 4\pi r^2 \rho \quad \Leftrightarrow \quad \ln(r_k) = \frac{1}{3}\ln\left[r_{k+1}^3 + \frac{3}{4\pi}\frac{dm_k}{\rho_k}\right]$$

$$\frac{dT}{dr} = -\frac{3}{16\pi ac}\frac{\kappa\rho L}{r^2 T^3} \quad \Leftrightarrow \quad \frac{T_{k-1}-T_k}{(dm_{k-1}-dm_k)/2} = -\nabla_{T,k}\left(\left.\frac{dP}{dm}\right|_k\right)\frac{\tilde{T}_k}{\tilde{P}_k}$$

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Interlude: coordinates

Lagrangian

$$v \equiv v(m, t)$$

Eulerian

$$v \equiv v(\mathbf{r}, t)$$

Reformulation of the (1D-) Equations

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The Matrix to Solve

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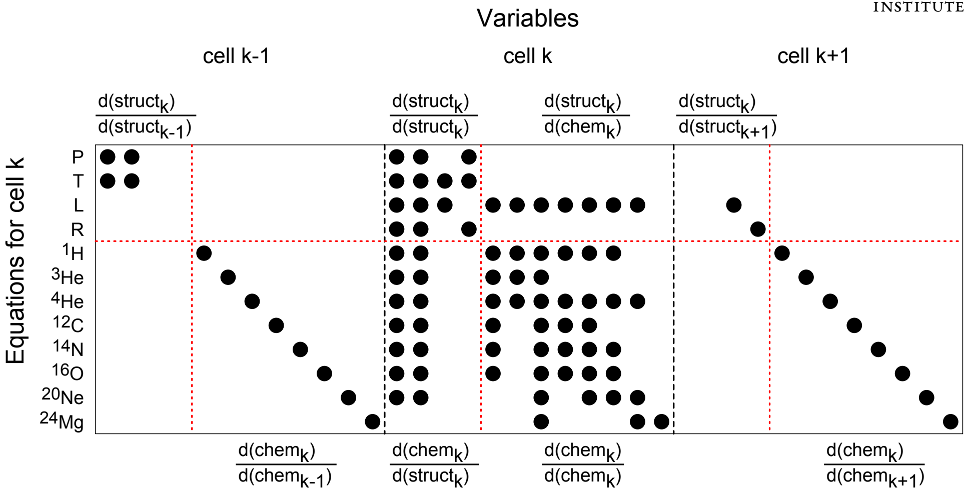

Figure: From Paxton *et al.* 2013, ApJs, 208, 4. Black dots are non-zero entries.

Algorithm

- Henyey code: varies all the quantities in each zone until an acceptable solution is found ($\neq$ Shooting Method);
- Generalized Newton-Raphson solver ($\Rightarrow$ FIRST ORDER):

$$0 = \mathbb{F}(y) \simeq \mathbb{F}(y_i + \delta y_i) = \mathbb{F}(y_i) + \left[\frac{d\mathbb{F}(y)}{dy}\right]_i \delta y_i + O((\delta y_i)^2) \quad ;$$

$$\delta y_i \simeq -\frac{\mathbb{F}(y_i)}{\left[\frac{d\mathbb{F}(y)}{dy}\right]_i}$$

$$\Downarrow$$

$$y_{i+1} = y_i + \delta y_i$$

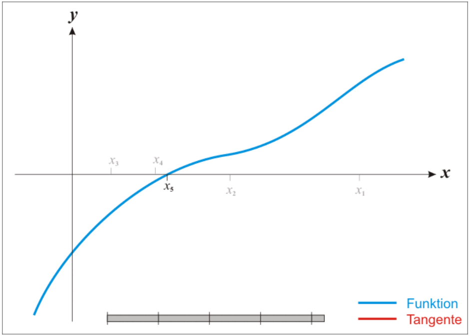

Figure: From Wikipedia

NR-Solver Iterations

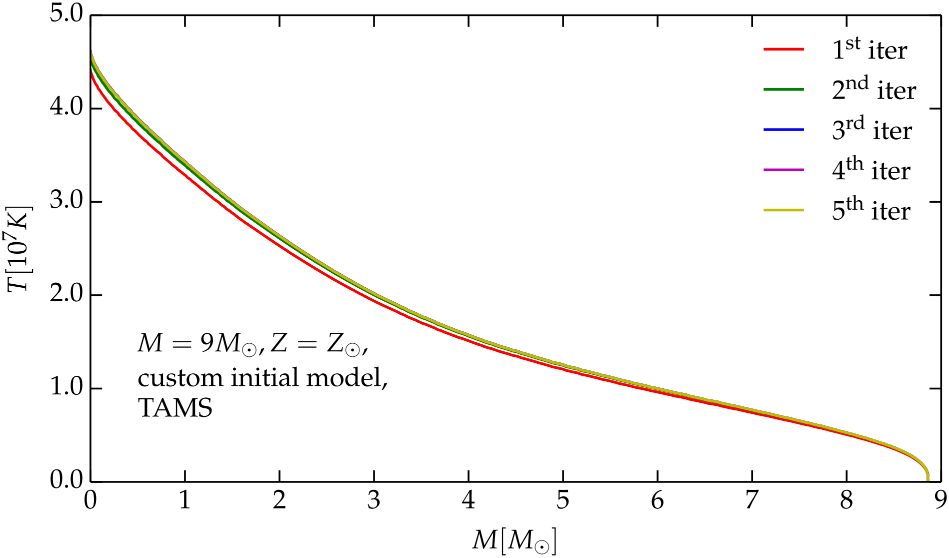

Figure: Two models after the end of core hydrogen burning

Outline

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Introduction: Massive Stars

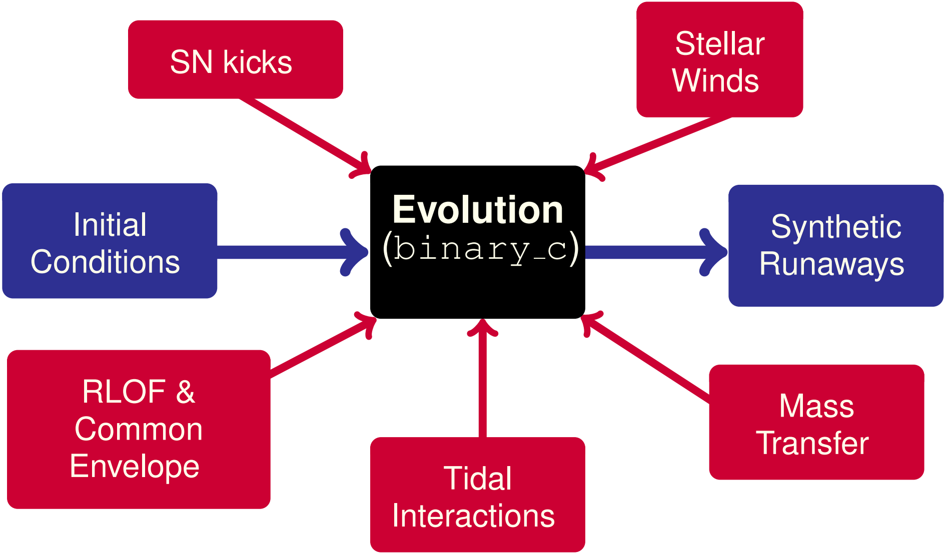
Computational astrophysics

- Stellar evolution & structure
- Binary Population Synthesis

(If you care) preliminary results

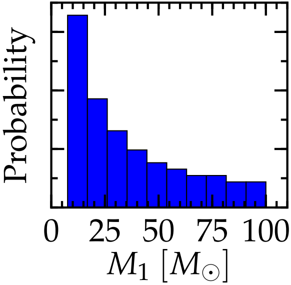
- Can stellar wind change the final fate of a massive star?
- What physics can we learn from breaking apart binaries?

Fast ⇒ Allows statistical tests of the inputs & assumptions

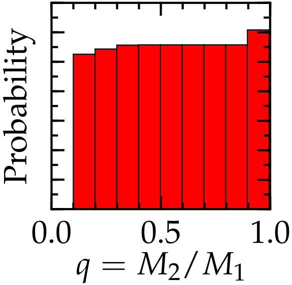


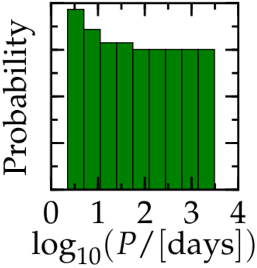
binary_c: R. G. Izzard *et al.* ’04, ’06, ’09; S. E. de Mink *et al.* ’13

Initial Distributions



Kroupa '01

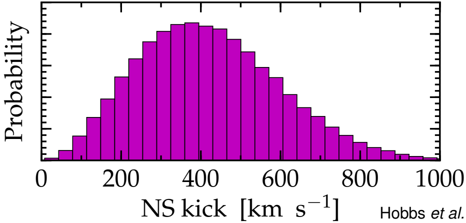




Sana *et al.* '12

Total Population: 2×10^6 stars

Maxwellian $\sigma_{v_{\mathrm{kick}}} = 265[\mathrm{km\ s^{-1}}]$



Hobbs *et al.* '05

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Star Formation

Ionizing Radiation

Supernovae (if $M_{\mathrm{ZAMS}} \gtrsim 8\,M_\odot$)

GW Astronomy

Mass loss for the environment:

- Pollution of ISM
- Tailoring of CSM
- Trigger for Star Formation

Mass loss for the star

- Evolutionary Timescales
- Appearance & Classification (e.g. WR)
- Light Curve and Explosion Spectrum
- Final Fate: BH, NS or WD?

NASA, JPL-Caltech, Spitzer Space Telescope

Possible Mass Loss Mechanisms

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Radiative Driving

$\Downarrow$

Stellar Winds

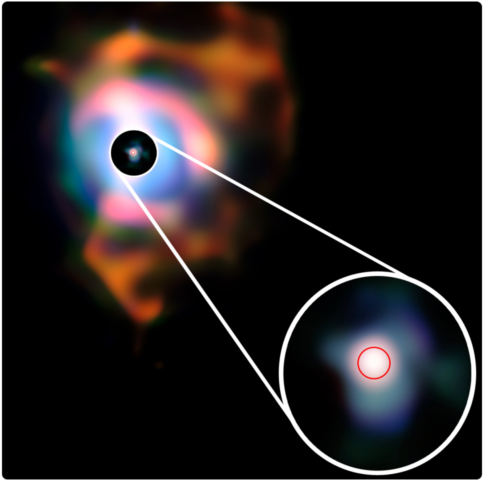

Figure: Betelgeuse

Possible Mass Loss Mechanisms

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Dynamical Instabilities

$\Downarrow$

LBVs, Impulsive Mass Loss,

Pulsations,

Super-Eddington Winds

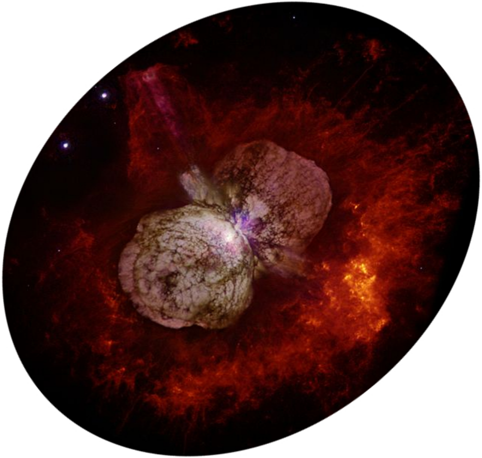


Figure: η Carinae.

Possible Mass Loss Mechanisms

Binary interactions

$\Downarrow$

Roche Lobe Overflow, Common Envelope, Fast rotation

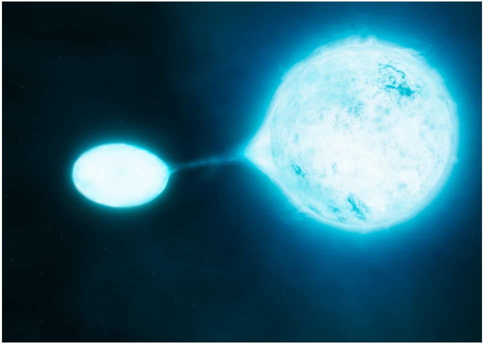
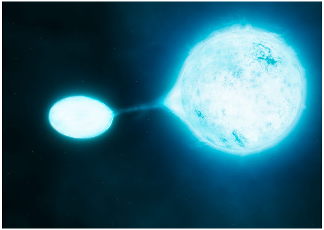
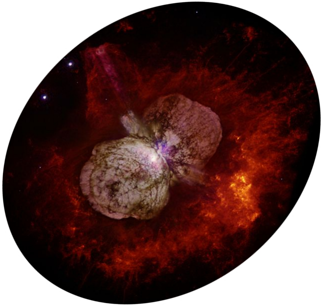


Figure: Artist Impression

Mass loss is dynamical...



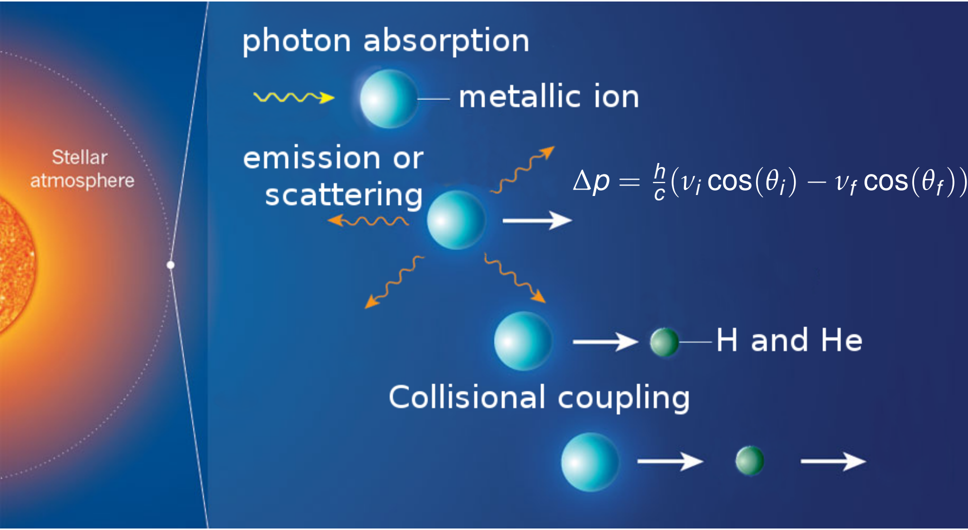


... but stellar evolution codes assume hydrostatic equilibrium:

$$\frac{dP}{dr} = -\frac{Gm(r)\rho}{r^2}$$

Open question: **Which dominates in term of total mass lost?**

Radiatively Driven Winds in One Slide



Problems: High Non-Linearity and Clumpiness

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Inhomogeneities:

$$f_{\rm cl} \stackrel{\rm def}{=} \frac{\langle\rho^2\rangle}{\langle\rho\rangle^2} \neq 1 \Rightarrow \dot{M} \neq 4\pi r^2 \rho v(r)$$

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Risk:

Possible overestimation of the wind mass loss rate

Mass loss in MESA

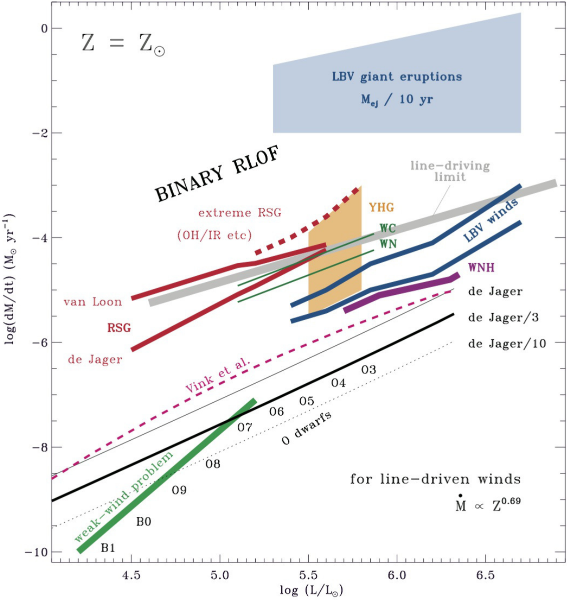

Figure: From Smith 2014, ARA&A, 52, 487S

(Semi–)Empirical parametric models.

Efficiency factor:

$$\dot{M}(L, T_{\rm eff}, Z, R, M, ...)$$

$$\Downarrow$$

$$\eta \dot{M}(L, T_{\rm eff}, Z, R, M, ...)$$

η is a **free** parameter:

$$\eta \in [0, +\infty)$$

Combination of algorithms

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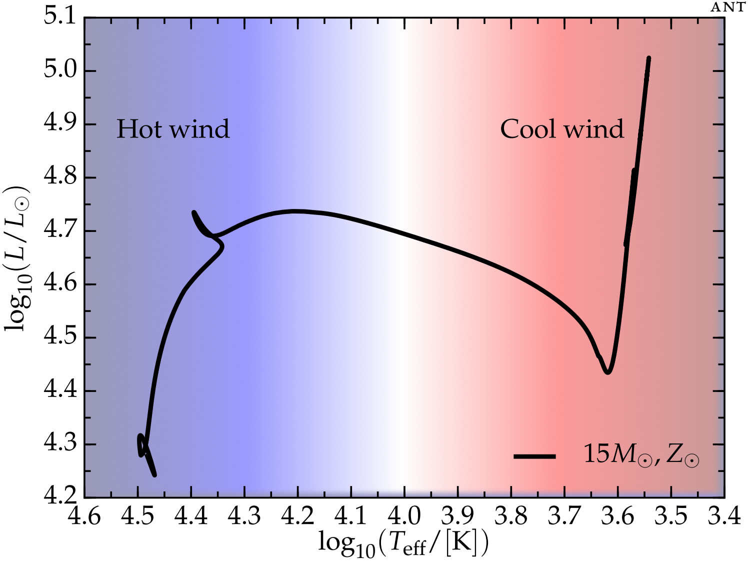

WR wind $\Leftrightarrow X_s < 0.4$

MESA grid varying dM/dt

Grid of $Z_\odot \simeq 0.019$, non-rotating stellar models:

- Initial mass:

$$M_{\rm ZAMS} = \{15,\ 20,\ 25,\ 30,\ 35\}\ M_\odot;$$

- Efficiency:

$$\eta = \left\{1,\ \frac{1}{3},\ \frac{1}{10}\right\};$$

- Combinations of wind mass loss rates for "hot" ($T_{\rm eff} \geq 15\ [\rm kK]$), "cool" ($T_{\rm eff} < 15\ [\rm kK]$) and WR:

Kudritzki *et al.* '89; Vink *et al.* '00, '01;
Van Loon *et al.* '05; Nieuwenhuijzen *et al.* '90;
De Jager *et al.* '88;
Nugis & Lamers '00; Hamann *et al.* '98.

Wind mass loss history

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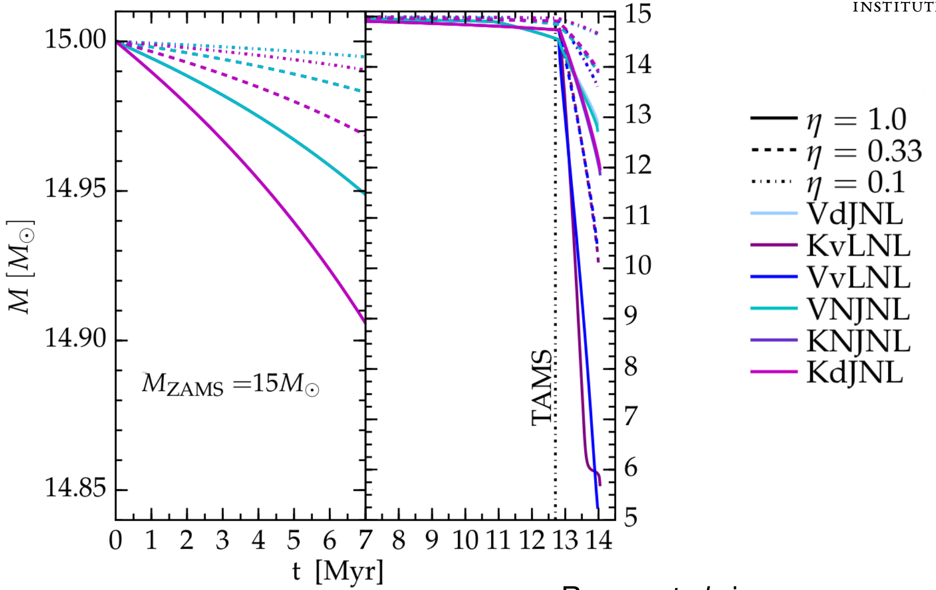

Renzo *et al.*, in prep.

Impact on the final mass

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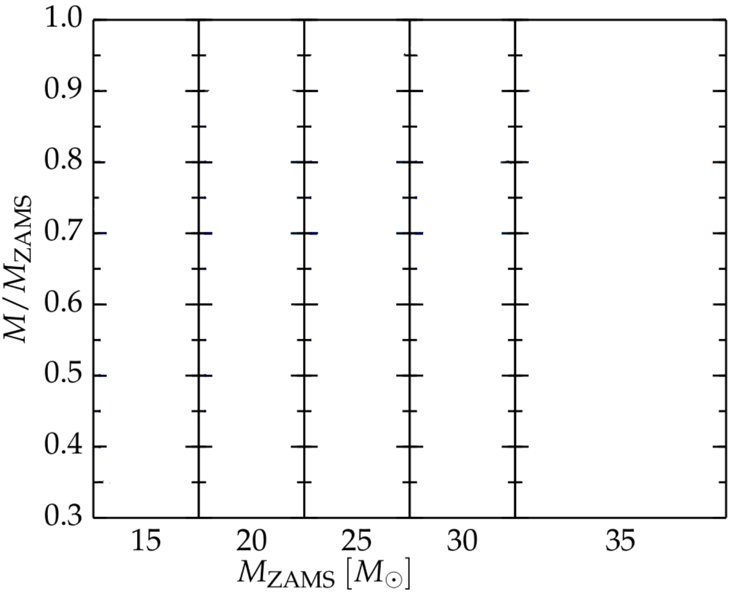


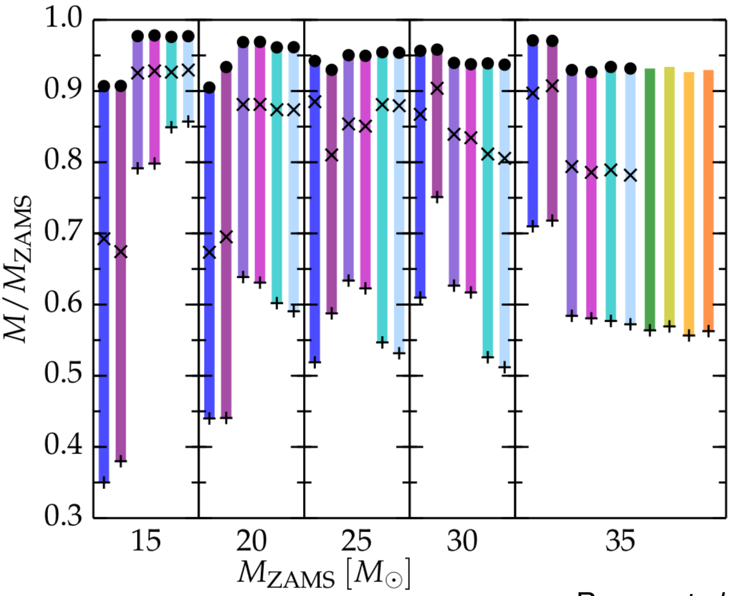
MESA

Legend:

- • $\eta = 0.1$
- x $\eta = 0.33$
- + $\eta = 1.0$

Renzo *et al.*, in prep.

Impact on the final mass



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MESA

Legend:

- • $\eta = 0.1$
- x $\eta = 0.33$
- + $\eta = 1.0$

$\eta \rightarrow$ largest uncertainty

Renzo *et al.*, in prep.

Impact on the final mass

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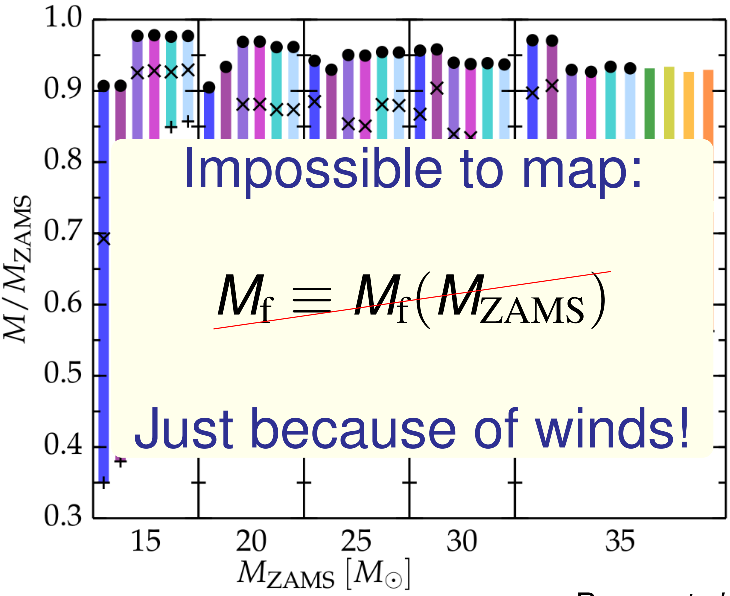

Impossible to map:

$$M_f \equiv M_f(M_{ZAMS})$$

Just because of winds!

MESA

Legend:

- • $\eta = 0.1$
- x $\eta = 0.33$
- + $\eta = 1.0$

$\eta \rightarrow$ largest uncertainty

Renzo *et al.*, in prep.

"Explodability" & Compactness

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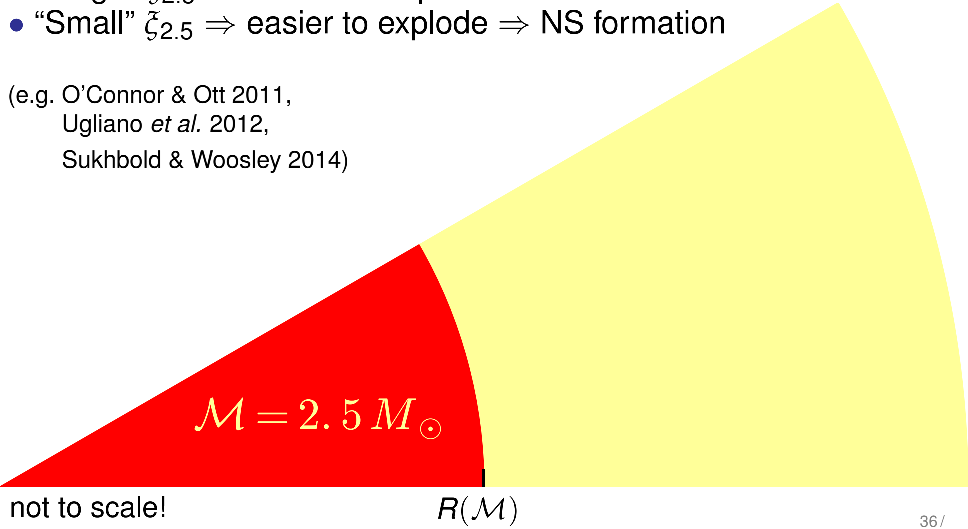
$$\xi_{\mathcal{M}}(t) \stackrel{\text{def}}{=} \frac{\mathcal{M}/M_\odot}{R(\mathcal{M})/1000\ \text{km}}$$

- "Large" $\xi_{2.5}$ ⇒ harder to explode ⇒ BH formation
- "Small" $\xi_{2.5}$ ⇒ easier to explode ⇒ NS formation

(e.g. O'Connor & Ott 2011,
Ugliano *et al.* 2012,
Sukhbold & Woosley 2014)



not to scale!

Core @ O depletion

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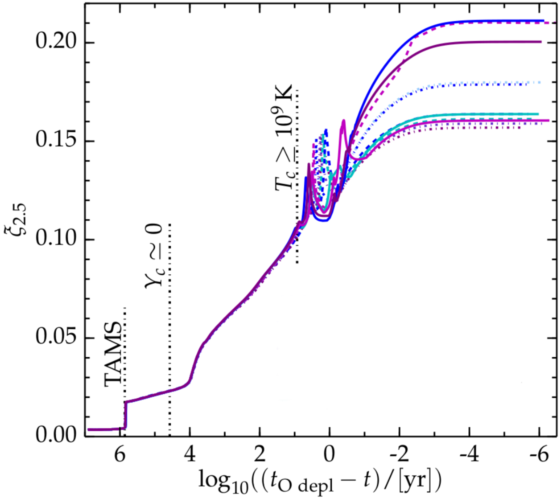
$M_{\rm ZAMS} = 25\,M_{\odot}$ MESA models



Renzo *et al.*, in prep.

Critical point: Ne core burning/C shell burning

$\xi_{2.5}$ @ O depletion

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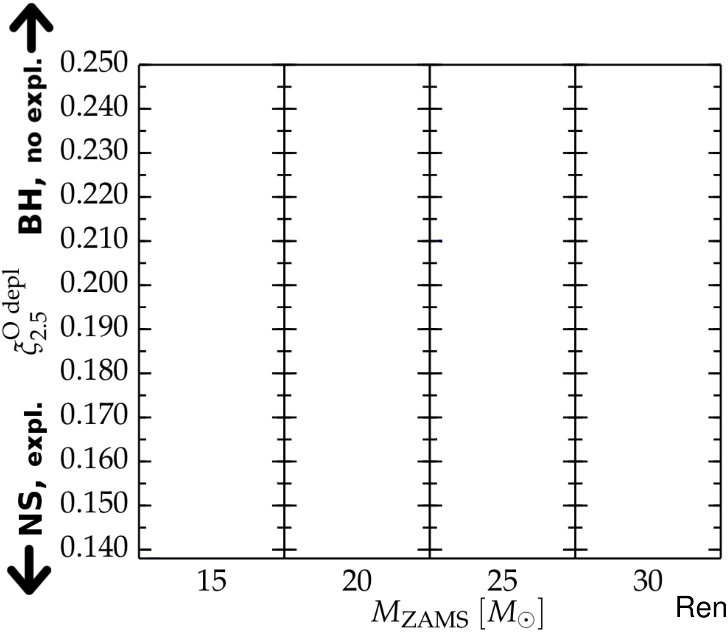

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$\xi_{2.5}$ @ Oxygen Depletion

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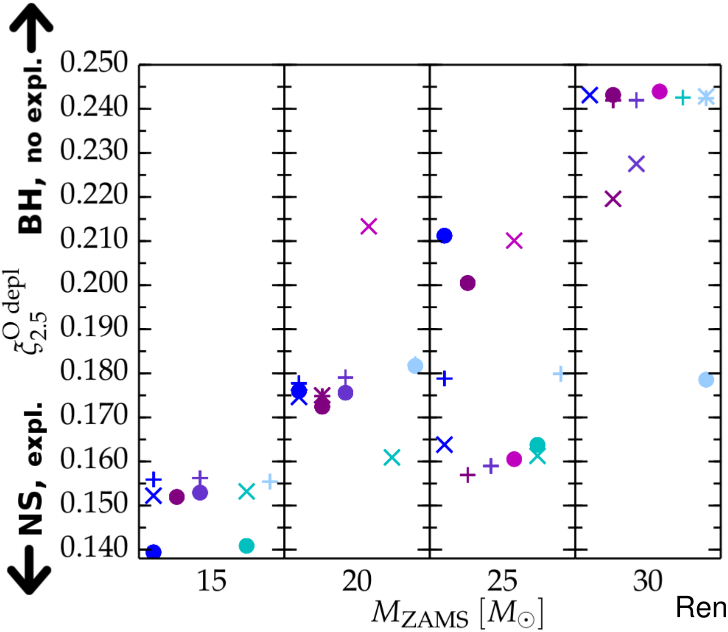


Legend:

- • $\eta = 0.1$
- **x** $\eta = 0.33$
- **+** $\eta = 1.0$

Post O burning evolution

⇓

Core contraction

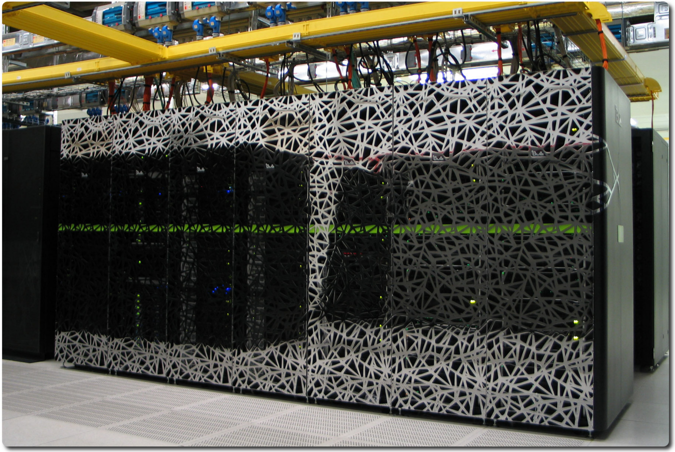
⇓

Amplification of the differences.

Renzo *et al.*, in prep.

Computing Advanced Burning Stages

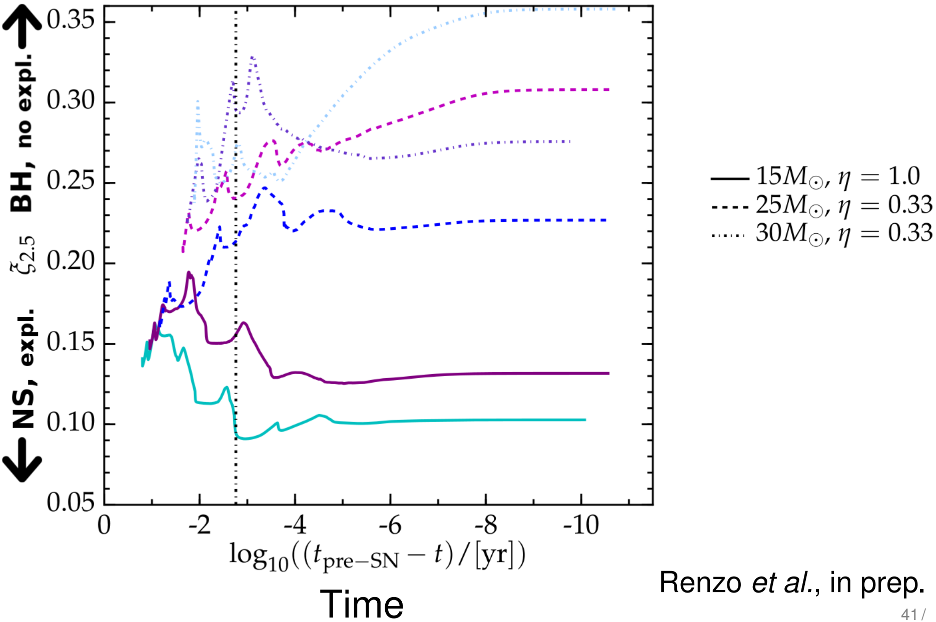
- Initially small effect $\Rightarrow N_{\mathrm{zones}} \gtrsim 20\,000$;
- Complex nuclear burning $\Rightarrow N_{\mathrm{iso}} \gtrsim 200$;



SurfSara's Cartesius Computer.

Post O burning evolution

Si shell burning →



Renzo *et al.*, in prep.

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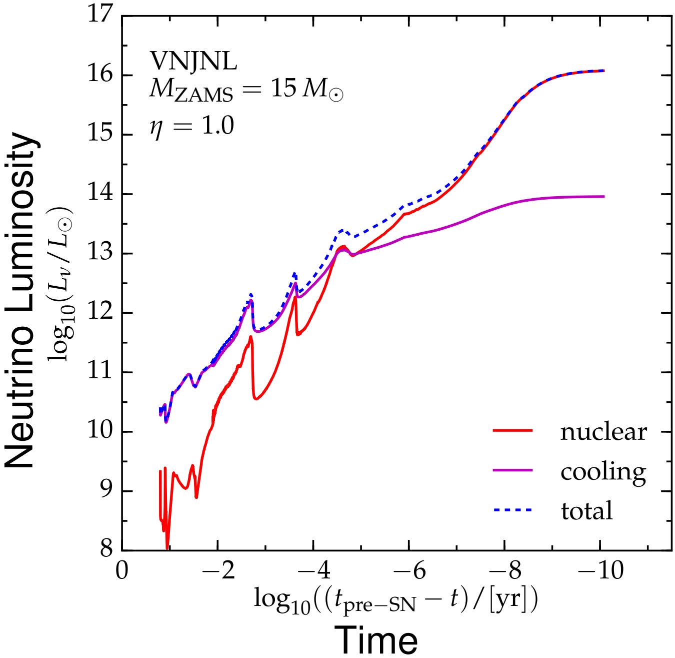

Fuel ignition in (partially) degenerate environment

⇓

Flash

Renzo *et al.*, in prep.

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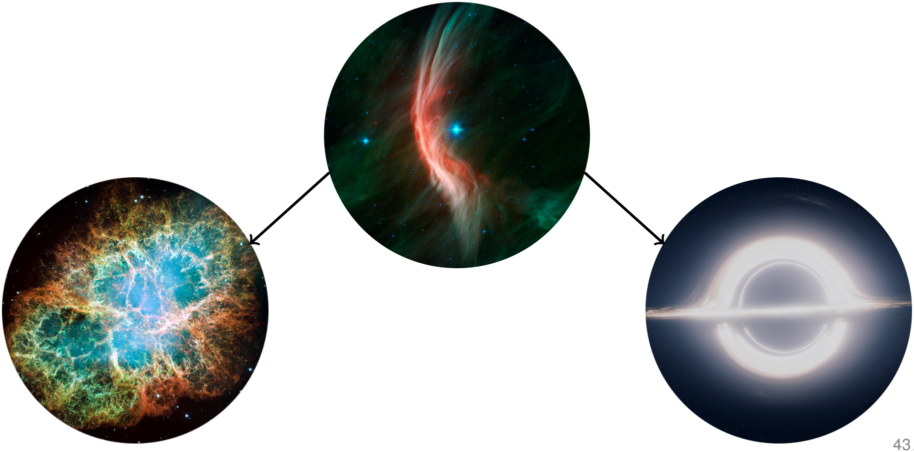
Uncertainties in stellar winds:

- pre-SN mass $\Rightarrow$ no $M_f \equiv M_f(M_{\mathrm{ZAMS}})$ map;
- core structure $\Rightarrow$ “explodability” & remnant.



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Introduction: Massive Stars

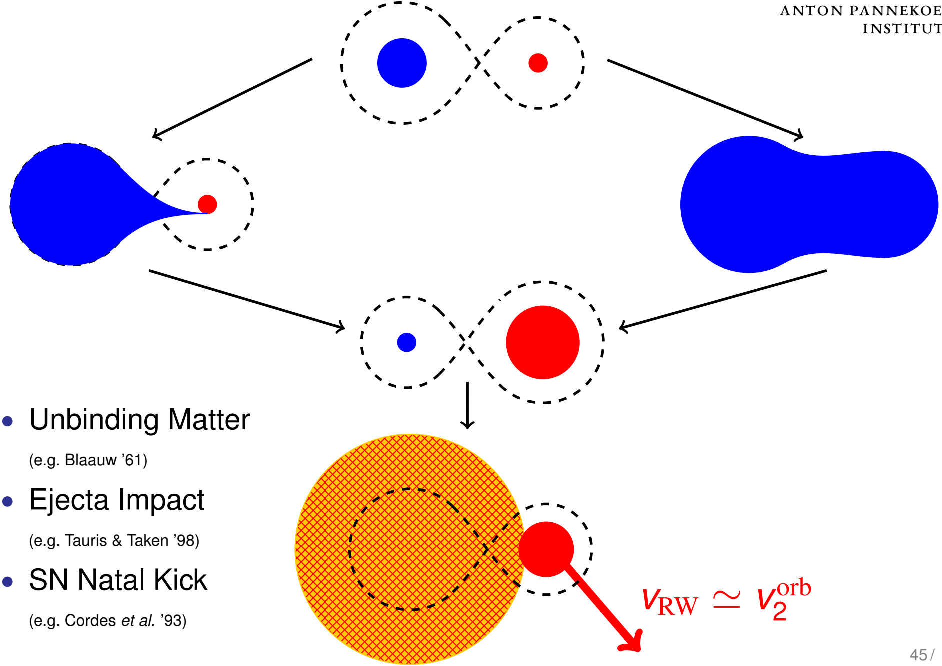
Computational astrophysics

- Stellar evolution & structure
- Binary Population Synthesis

(If you care) preliminary results

- Can stellar wind change the final fate of a massive star?
- What physics can we learn from breaking apart binaries?

From Binary to Runaway



- Unbinding Matter

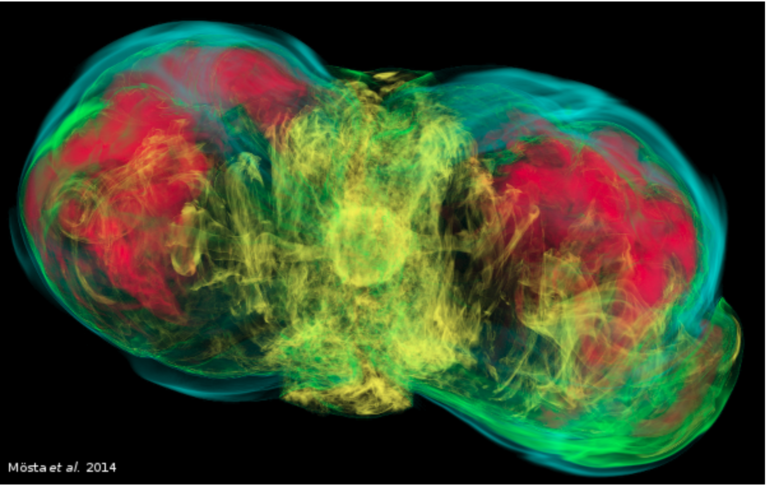
  (e.g. Blaauw '61)

- Ejecta Impact

  (e.g. Tauris & Taken '98)

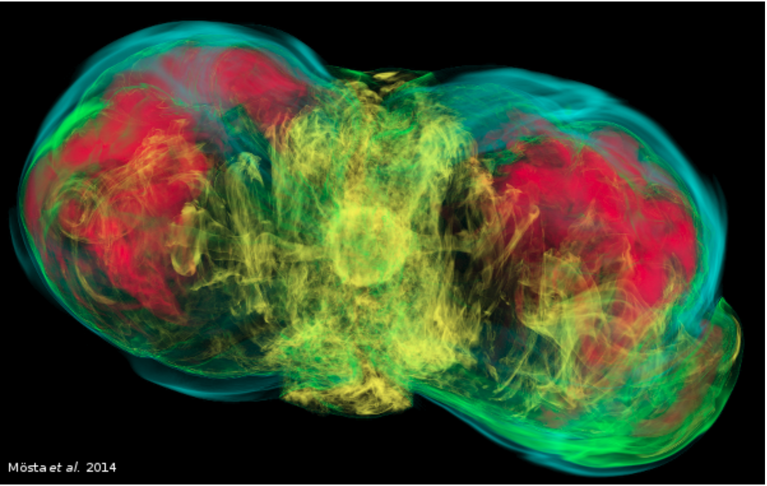
- SN Natal Kick

  (e.g. Cordes *et al.* '93)

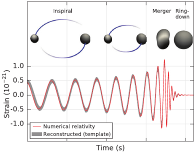


ν emission and/or ejecta anisotropies

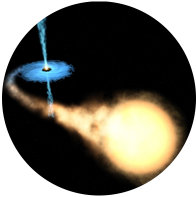
SN natal kick



Runaways



Gravitational Waves



XRBs

ν emission and/or ejecta anisotropies

30 Doradus

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$$Z = Z_{\rm LMC}$$

Preliminary: Velocity Distribution

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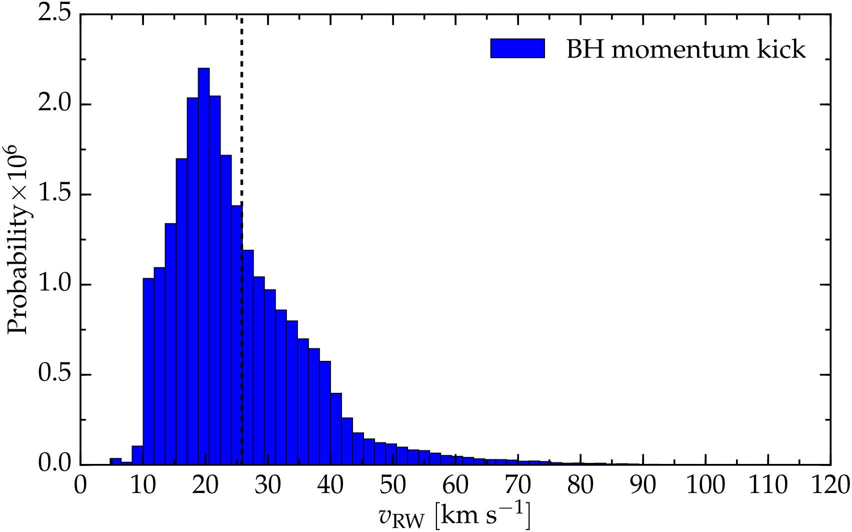
O-type from disrupted binaries only



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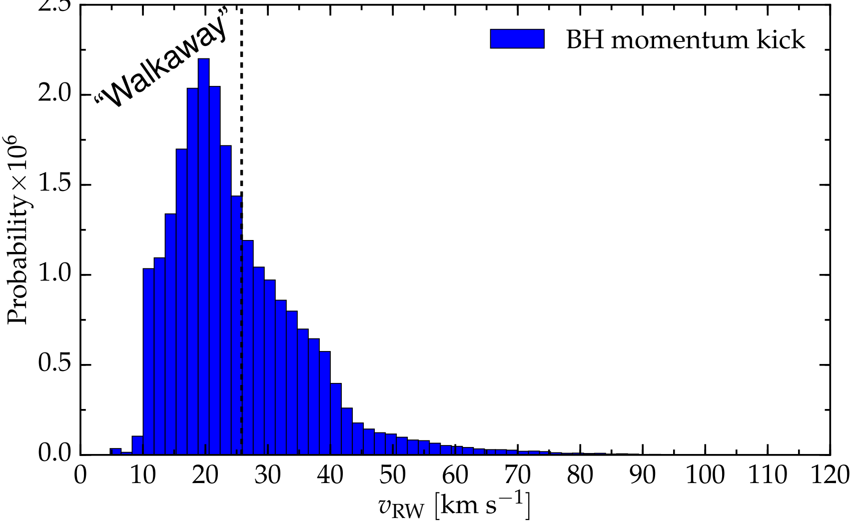
O-type from disrupted binaries only



Preliminary: Velocity Distribution

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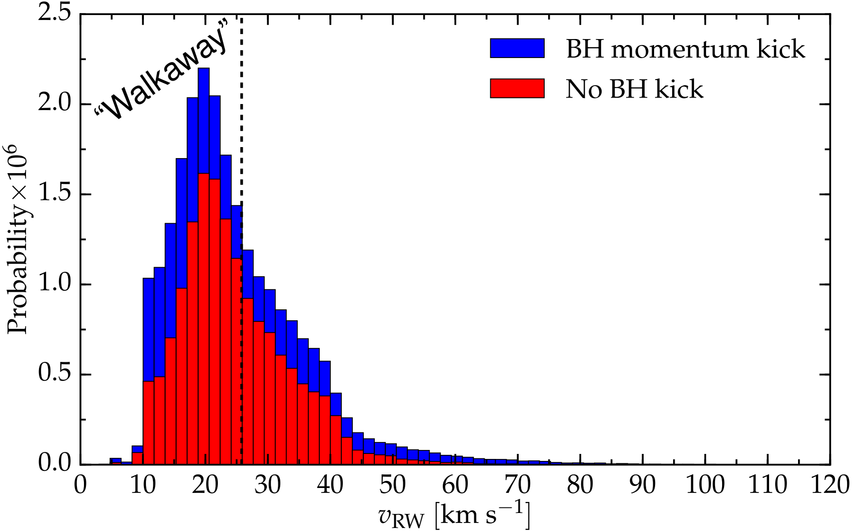
O-type from disrupted binaries only



Rotational Velocity & LOS velocity

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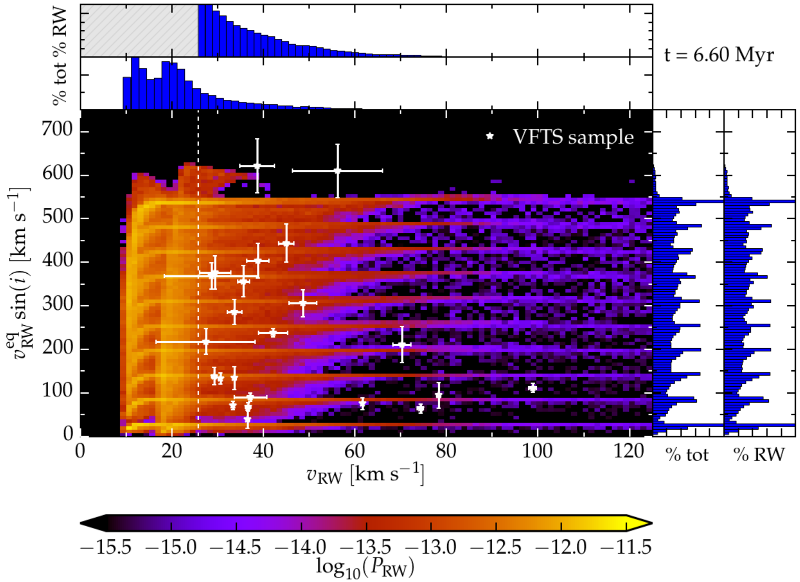
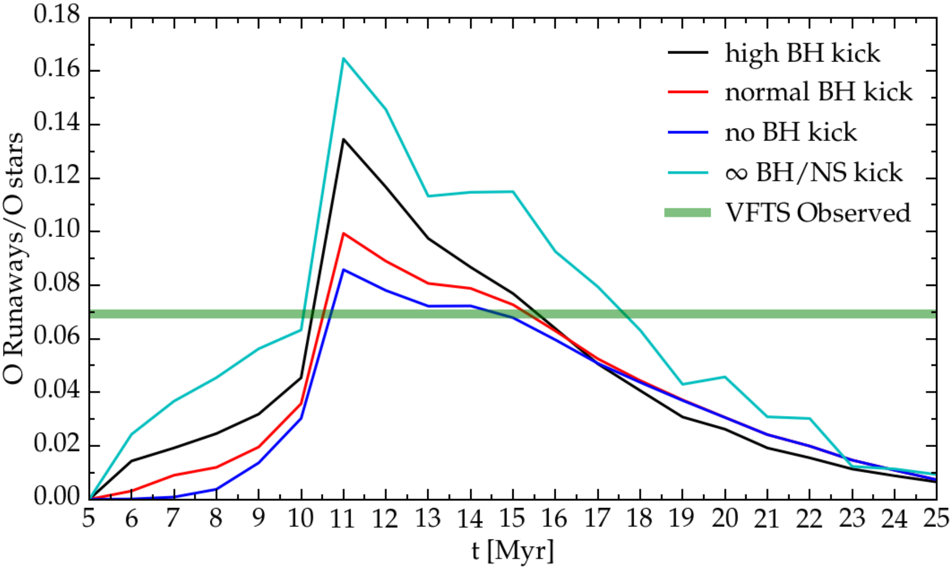
~ Rotational velocity



~ Line of sight velocity

Disrupted ratio



Mass function of disrupted binaries