Explosions in massive binaries:

"widowed" stars and consequences for GW astronomy

Mathieu Renzo
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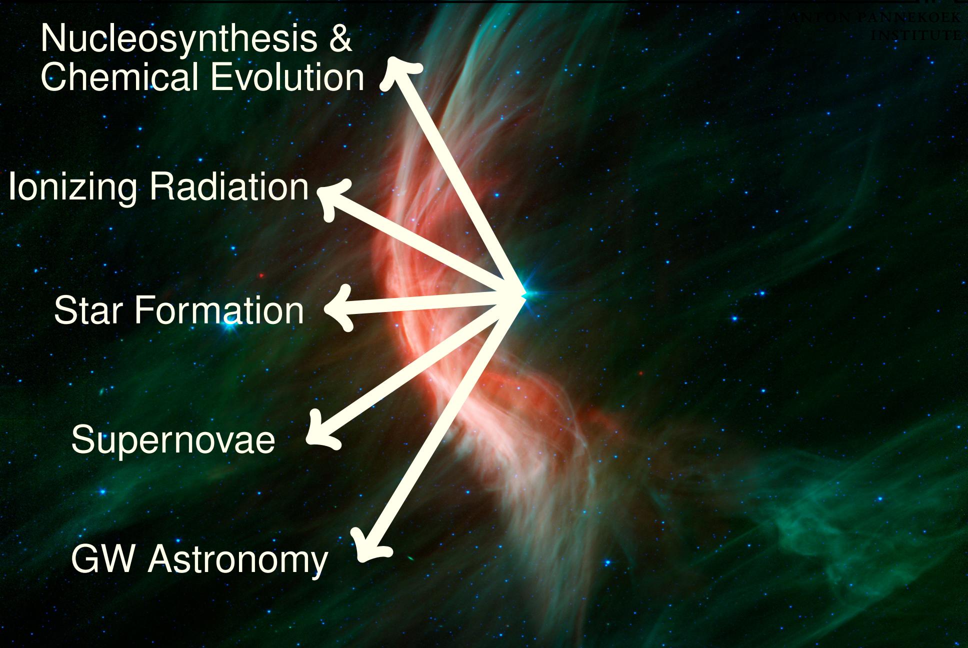
Collaborators: S. E. de Mink, E. Zapartas, Y. Götberg, E. Laplace, R. J. Farmer, S. Toonen, S. Justham, R. G. Izzard, P. Marchant, D. J. Lennon, H. Sana, S. N. Shore, ...

NASA, JPL-Caltech, Spitzer Space Telescope

Why are massive stars important?



NASA, JPL-Caltech, Spitzer Space Telescope

Why are massive stars important?

Nucleosynthesis &
Chemical Evolution

Ionizing Radiation

Star Formation

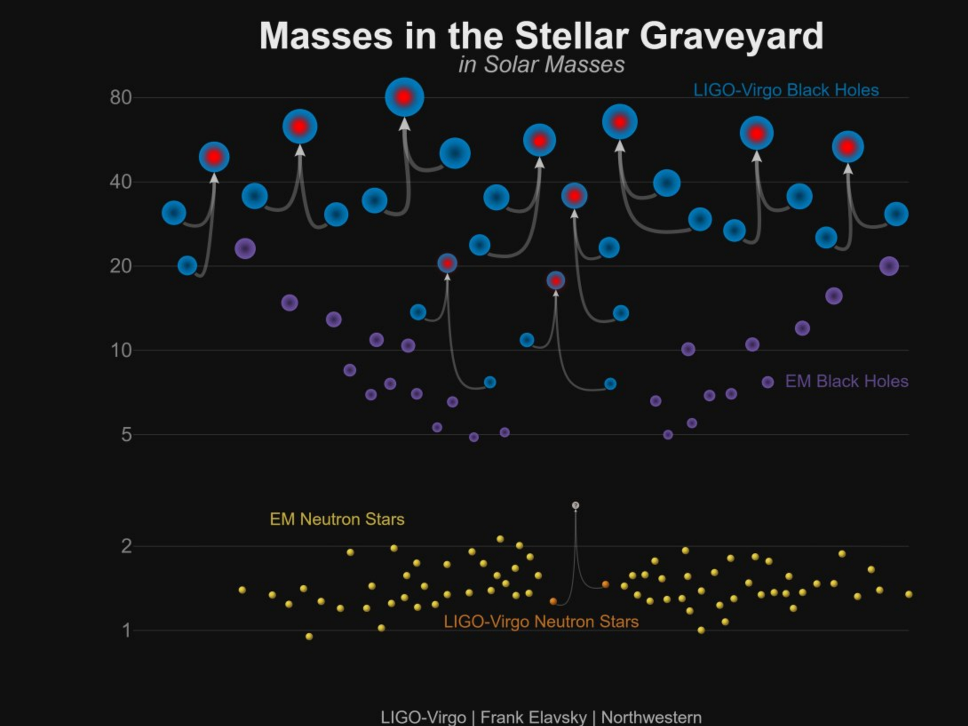
Supernovae

GW Astronomy

$\sim$70% of O type stars will interact with a companion

(e.g., Mason *et al.* ’09, Sana & Evans ’11, Sana *et al.* ’12, Kiminki & Kobulnicky ’12, Kobulnicky *et al.* ’14, Almeida *et al.* ’17)

NASA, JPL-Caltech, Spitzer Space Telescope


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

Outline

BH or NS?

- Single stars winds impact on the core structure

Keep the stars together

- The most common evolution for massive binaries
- Constraints on BH kicks using runaway “widow”

The most massive (stellar) BHs

- (Pulsational) pair instability
- The BH mass distribution
- Induced eccentricity

Conclusions

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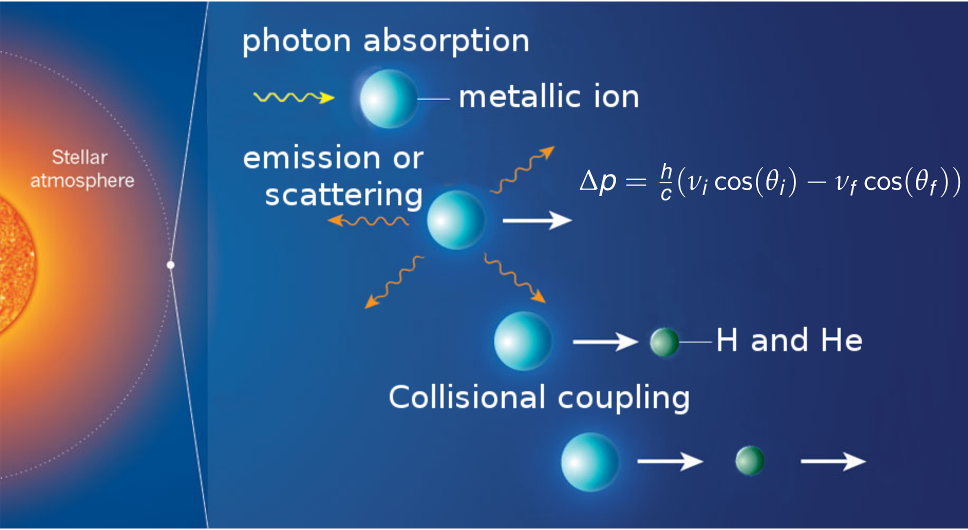
Radiatively Driven Winds in One Slide



Problems: High Non-Linearity and Clumpiness

Clumpiness

Inhomogeneities:

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

Risk:

Possible overestimation of the wind mass loss rate

Inhomogeneities:

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

Grid of $Z_\odot$ non-rotating models:

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

$$\eta = 1,\ \frac{1}{3},\ \frac{1}{10}$$

Combinations of wind mass loss rates for "hot" ($T_{\mathrm{eff}} \geq 15\ [\mathrm{kK}]$), "cool" ($T_{\mathrm{eff}} < 15\ [\mathrm{kK}]$) 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.

Impact on the final mass

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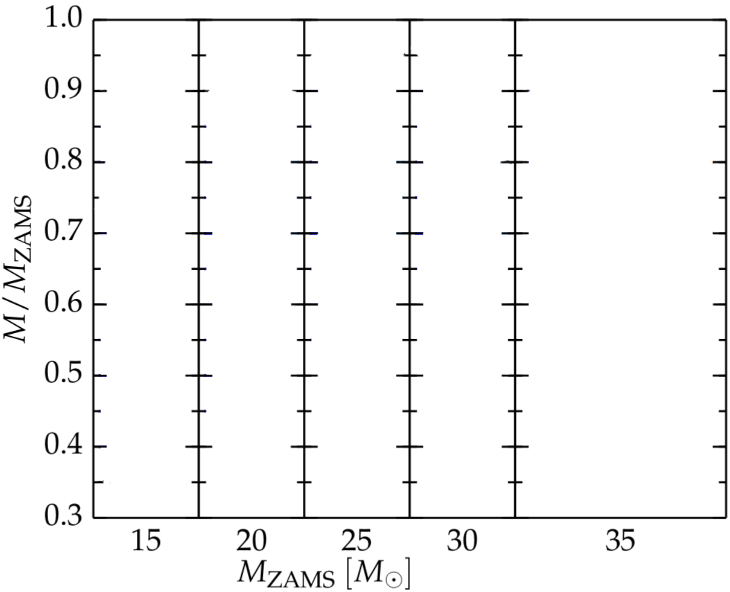


MESA

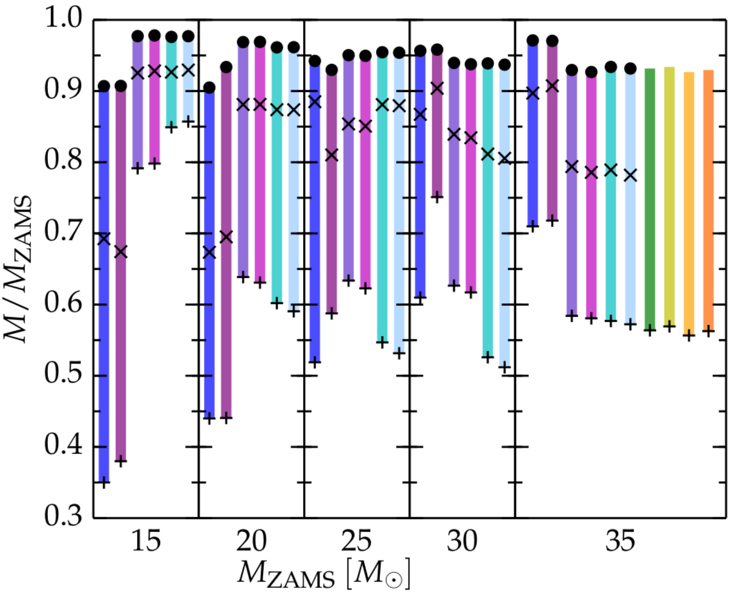
Legend:

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

$\eta \rightarrow$ largest uncertainty

Renzo *et al.* '17

Impact on the final mass



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Pre-explosion appearance

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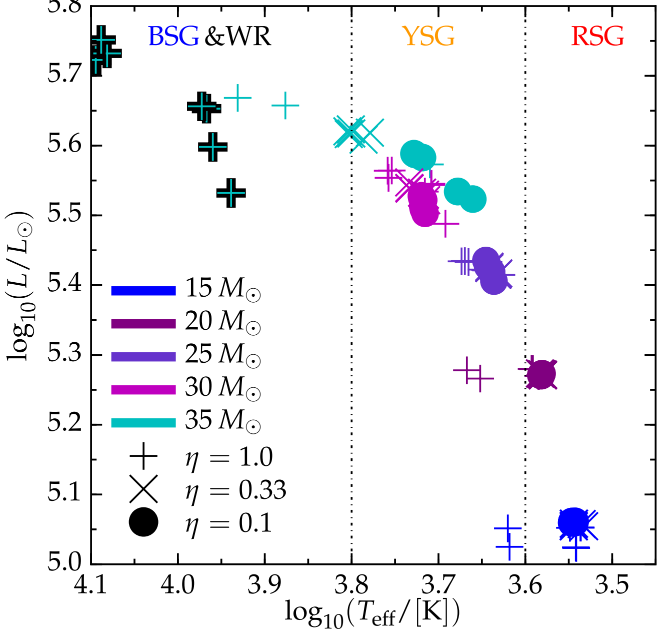
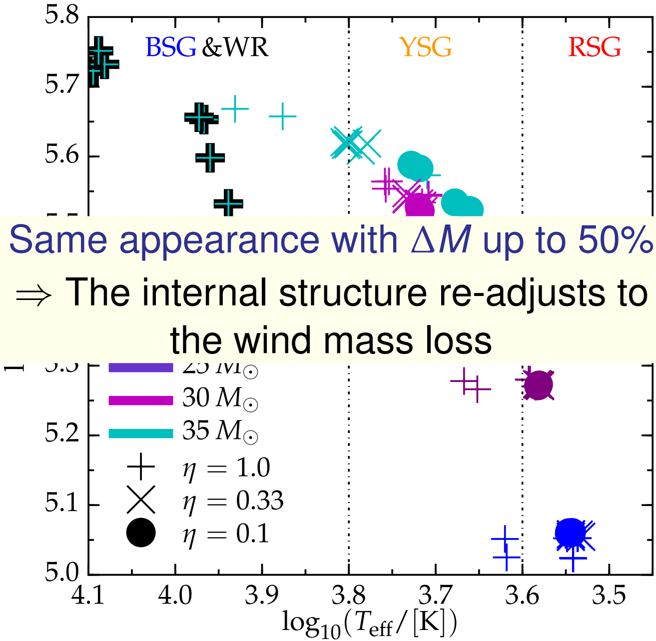


Renzo *et al.* '17

Pre-explosion appearance



Same appearance with ΔM up to 50%

$\Rightarrow$ The internal structure re-adjusts to the wind mass loss

“Explodability” & Compactness

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

Single parameter to describe the core structure

e.g., O’Connor & Ott ’11,

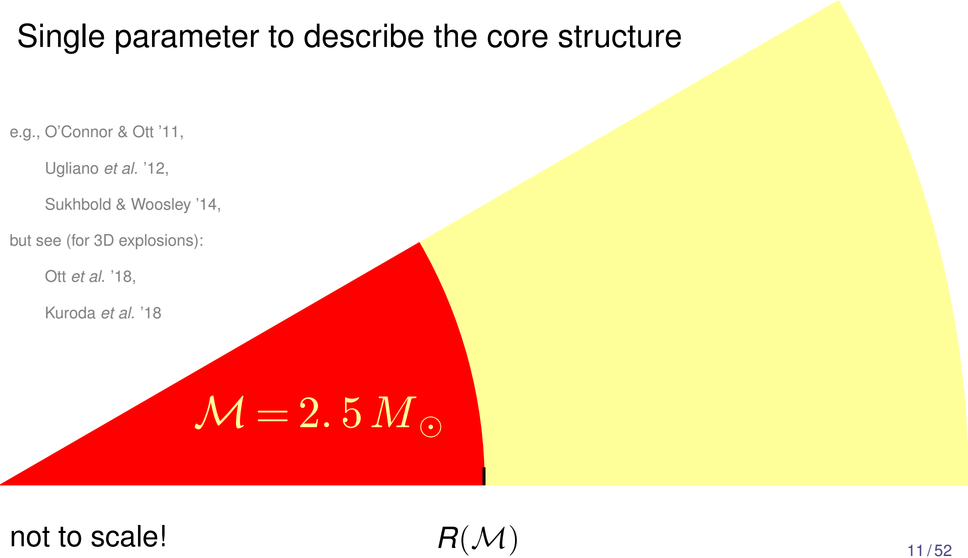
Ugliano *et al.* ’12,

Sukhbold & Woosley ’14,

but see (for 3D explosions):

Ott *et al.* ’18,

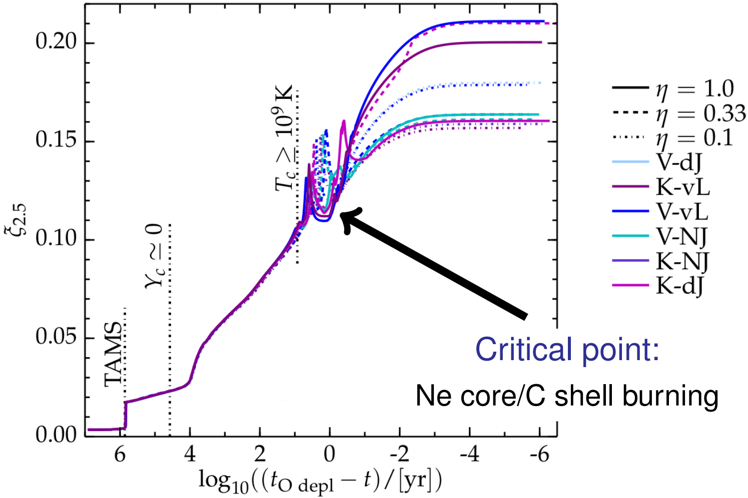
Kuroda *et al.* ’18



not to scale!

Core structure at O depletion

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



Critical point:

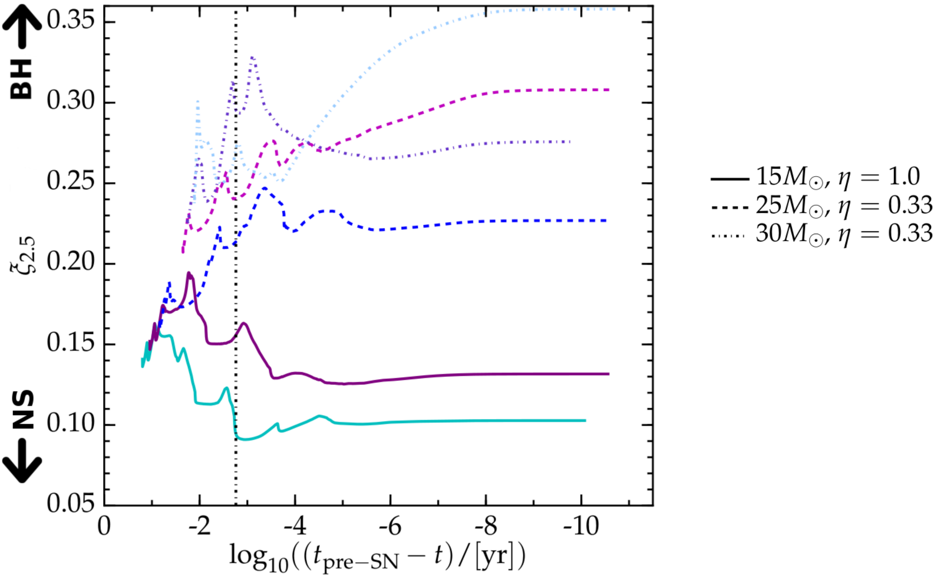
Ne core/C shell burning

Log time to O depletion

Renzo *et al.* ’17

Post O burning evolution

Si shell burning →



Log time to core-collapse

Renzo *et al.* ’17

Post O burning evolution

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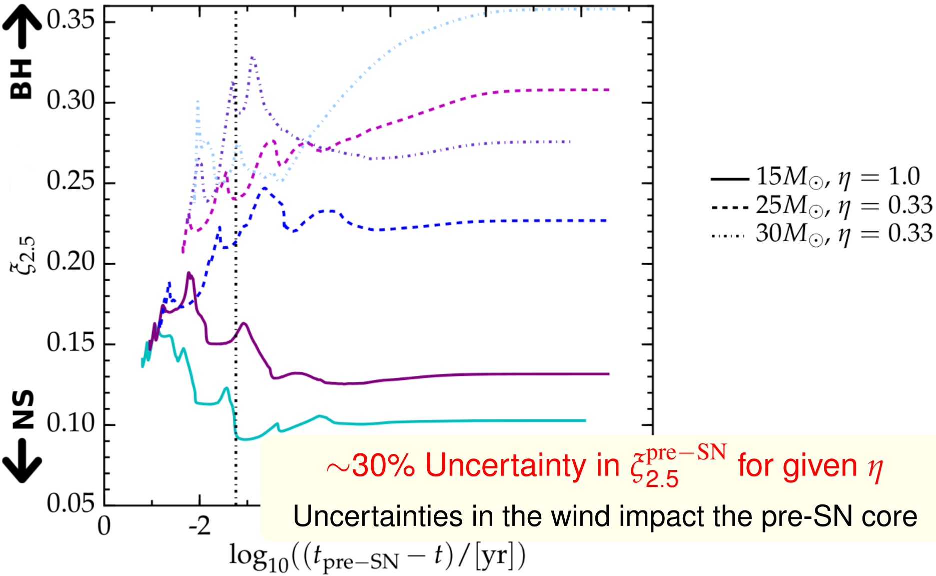

$\sim$30% Uncertainty in $\xi_{2.5}^{\mathrm{pre-SN}}$ for given η

Uncertainties in the wind impact the pre-SN core

Log time to core-collapse

Renzo *et al.* '17

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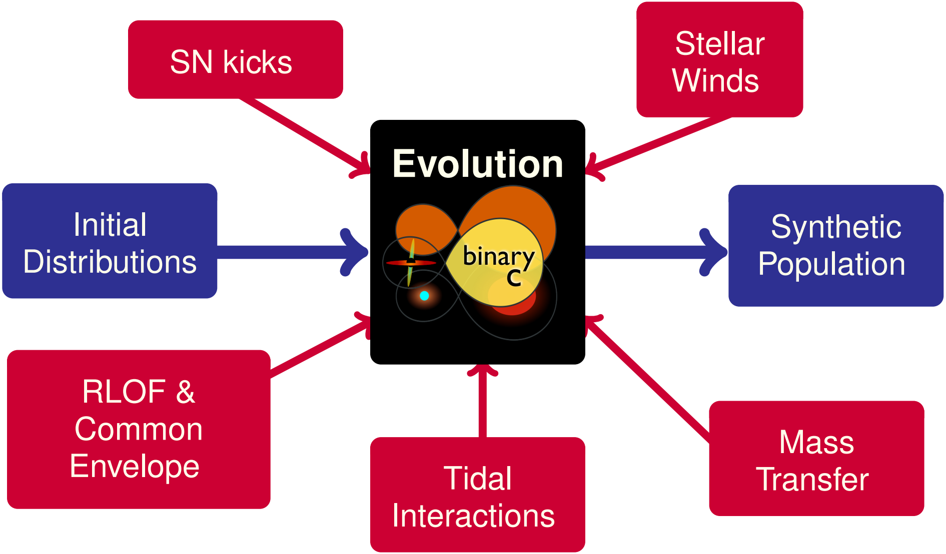
Methods: Population Synthesis

Fast ⇒ Allows statistical tests of the inputs & assumptions



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

Binary disruption

Credits: ESO, L. Calçada, M. Kornmesser, S.E. de Mink

Spin up, pollution, and rejuvenation

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The binary disruption shoots out the accretor

Spin up: Packet '81, Cantiello *et al.* '07, de Mink *et al.* '13
Pollution: Blaauw '93
Rejuvenation: Hellings '83, Schneider *et al.* '15

What exactly disrupts the binary?

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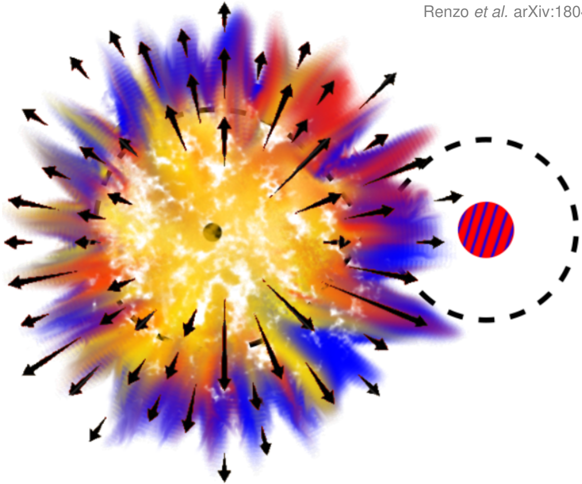
86^{+11}_{-9}% of massive binaries are disrupted

Renzo *et al.* arXiv:1804.09164, Eldridge *et al.* 11, De Donder *et al.* 97



- 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)

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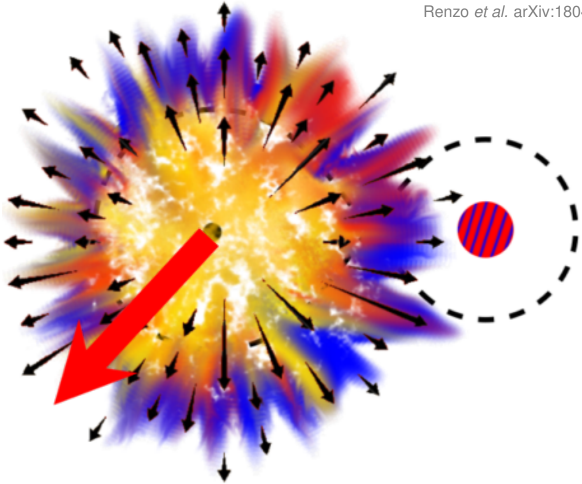

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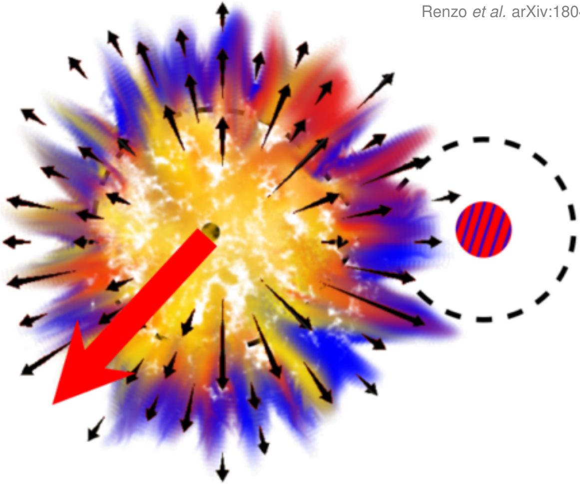

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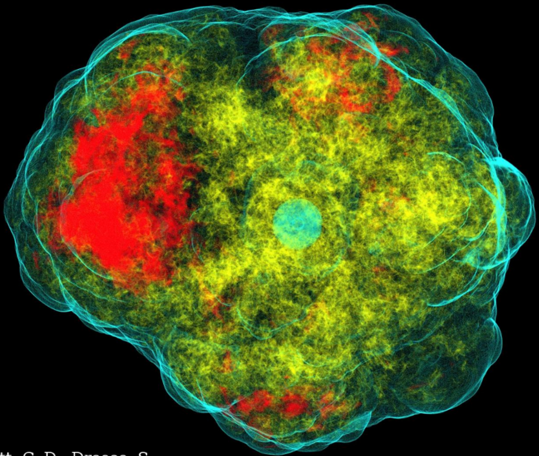
$$v_{\mathrm{dis}} \simeq v_{2,\mathrm{orb}}^{\mathrm{pre-SN}} = \frac{M_1}{M_1+M2}\sqrt{\frac{G(M_1+M2)}{a}}$$

Most binaries produce a slow "walkaway" star

SN natal kick

Observationally: $v_{\mathrm{pulsar}} \gg v_{\mathrm{OB-stars}}$

Physically: ν emission and/or ejecta anisotropies



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

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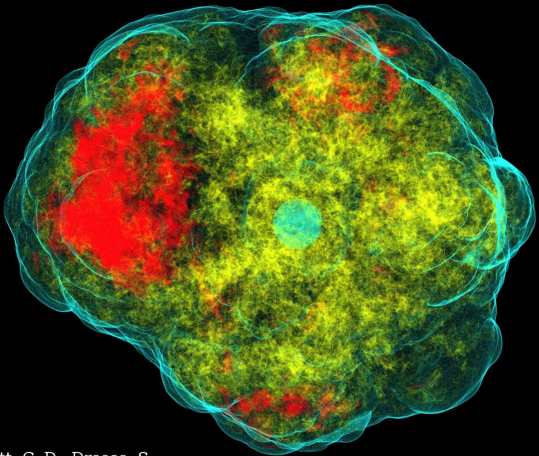

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BH kicks?

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A way to constrain BH kicks with *Gaia*

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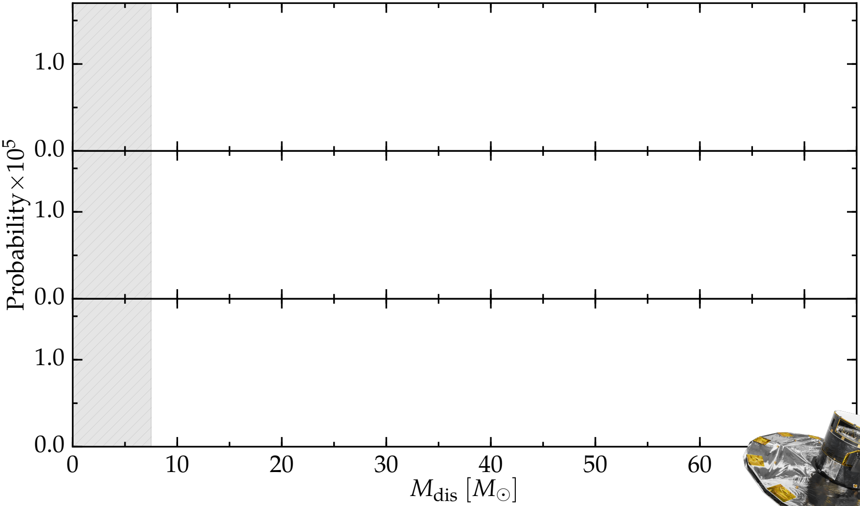
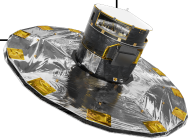
Massive runaways mass function ($v \geq 30\,\mathrm{km\ s^{-1}}$, $M \geq 7.5\,M_{\odot}$)





gaia

Renzo *et al.*, submitted, arXiv:1804.09164

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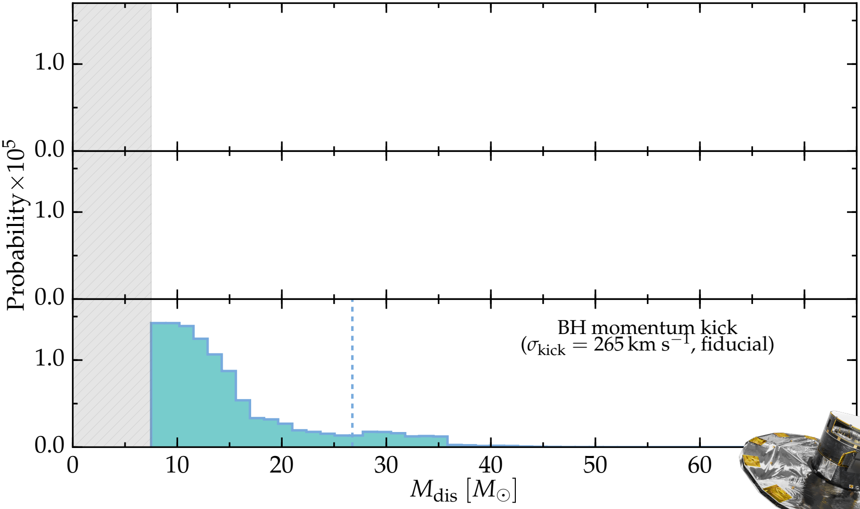

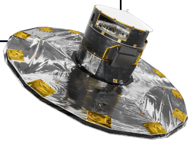

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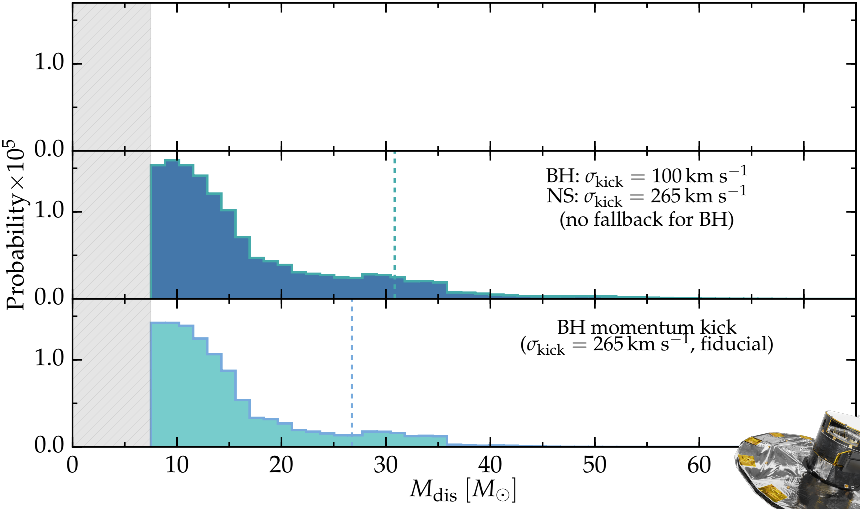

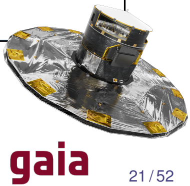

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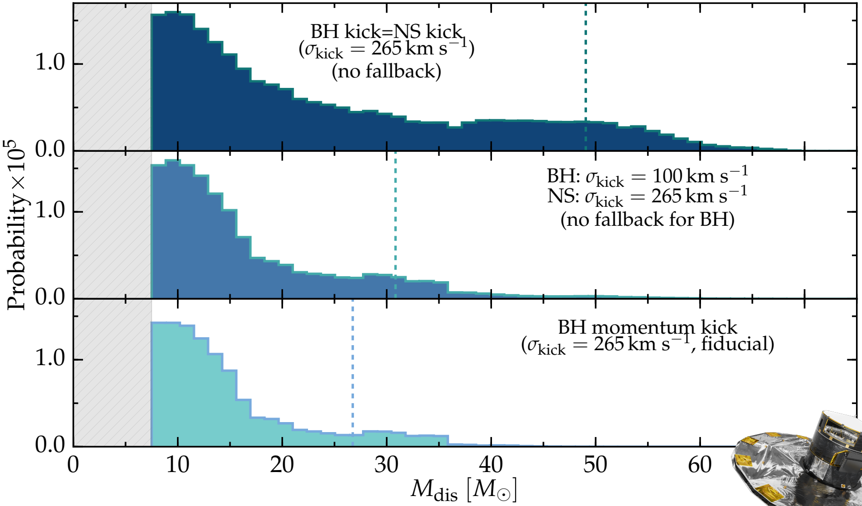

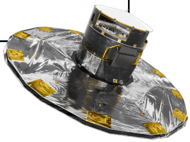

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Radiation dominated:

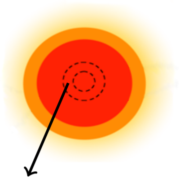
$$P_{\rm tot} \simeq P_{\rm rad}$$

$$M_{\rm He} \gtrsim 32\,M_\odot$$

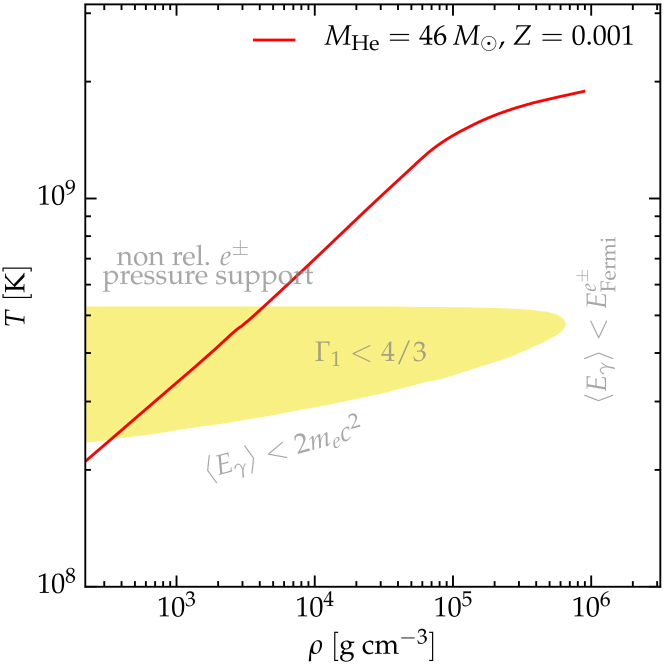
Woosley 2017,

Marchant, Renzo *et al.* arXiv:1810.13412,

Renzo, Farmer *et al.*, to be submitted

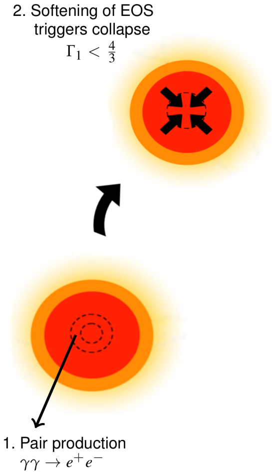


$$\Gamma_1 \stackrel{\mathrm{def}}{=} \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$$



He core computed with MESA

Renzo, Farmer, *et al.*, to be submitted

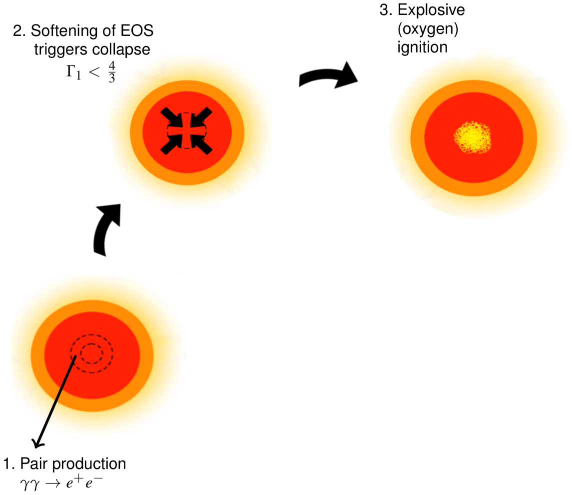


Thermal timescale

$$\tau \propto \frac{GM_{\mathrm{He}}^2}{RL_\nu} \quad , \quad L_\nu \gg L$$

(Fraley 68)

Renzo, Farmer, *et al.*, to be submitted



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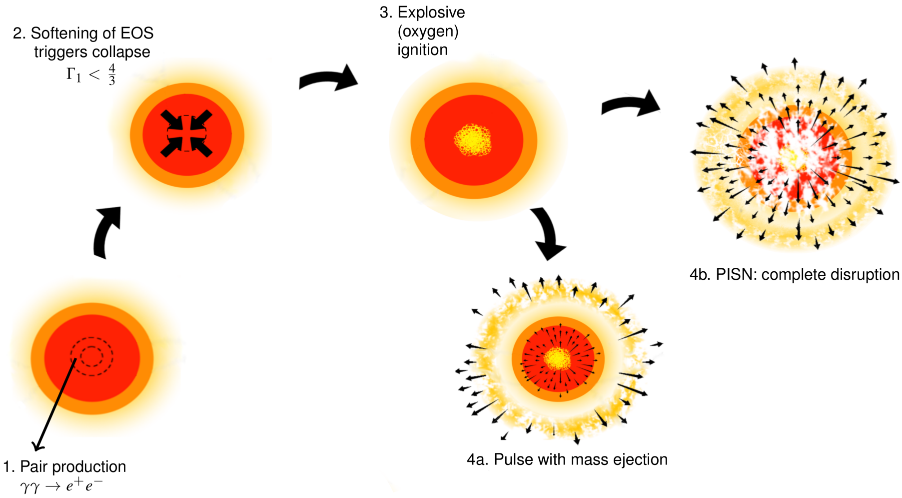

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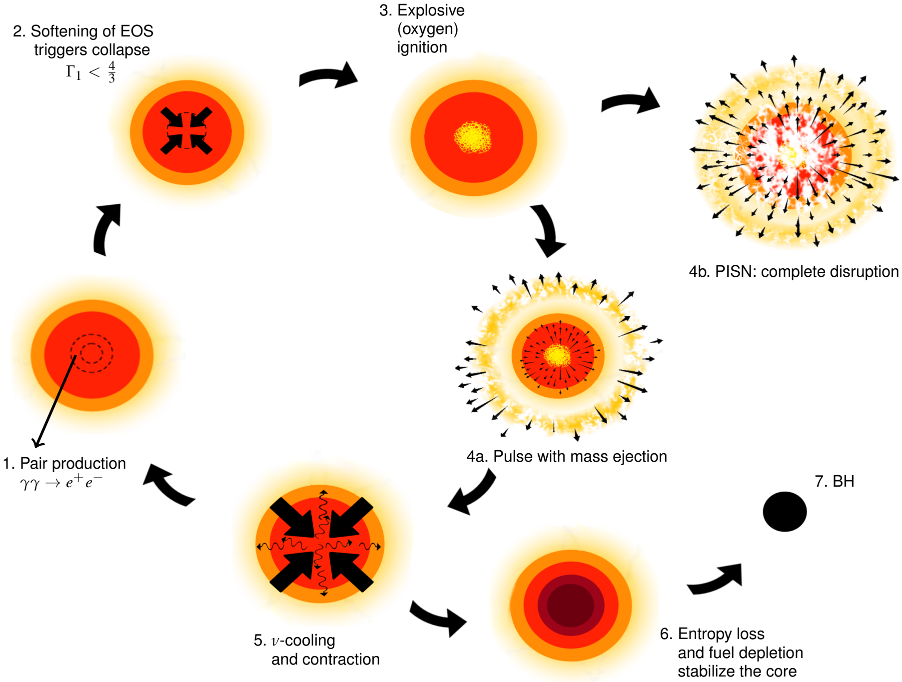

Renzo, Farmer, *et al.*, to be submitted

Example: 40 $M_\odot$ He core

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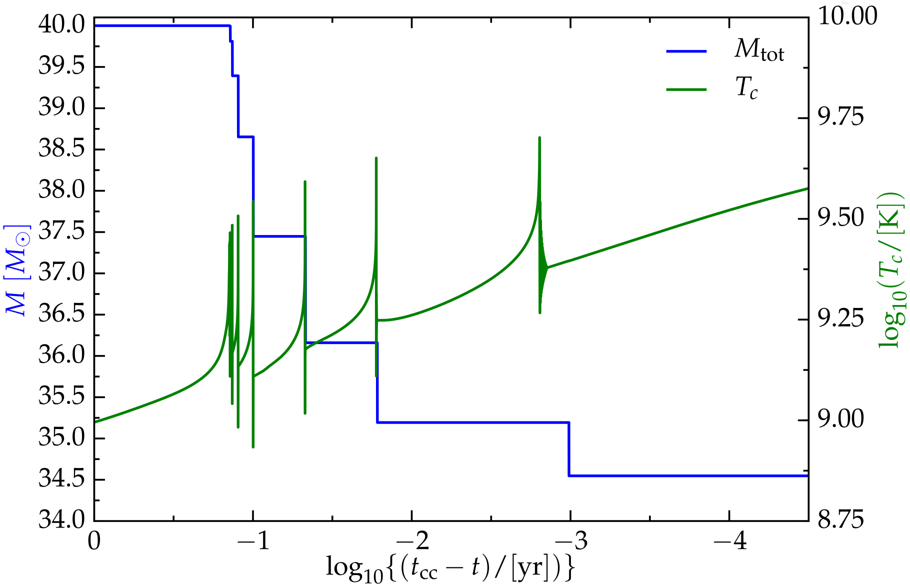

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The origin of very massive BHs

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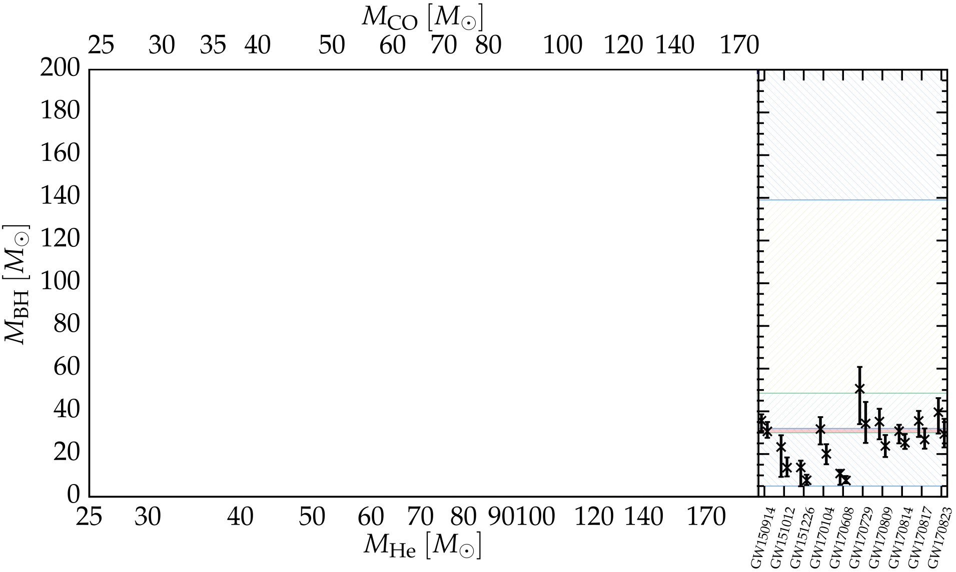
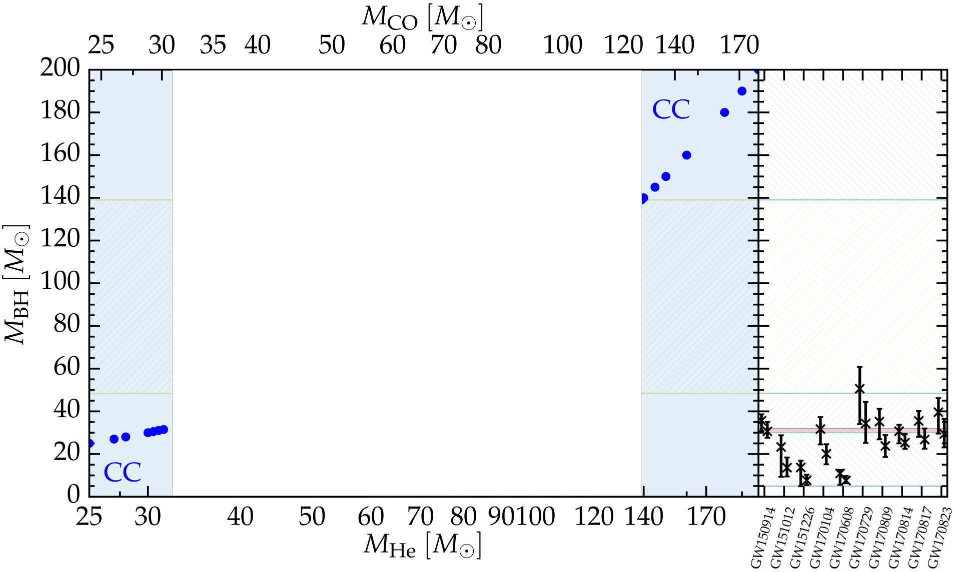


He core mass

Renzo, Farmer *et al.*, (in prep.)



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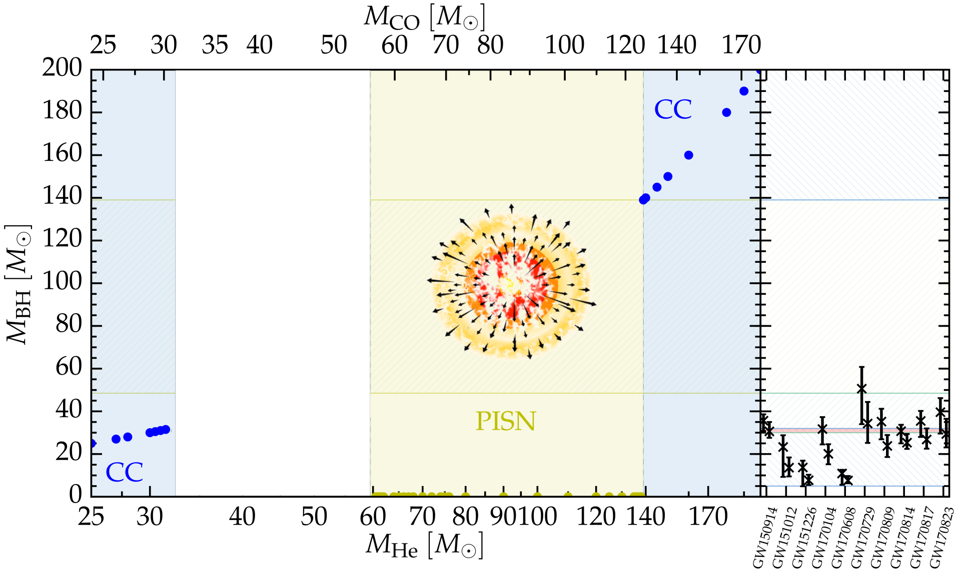

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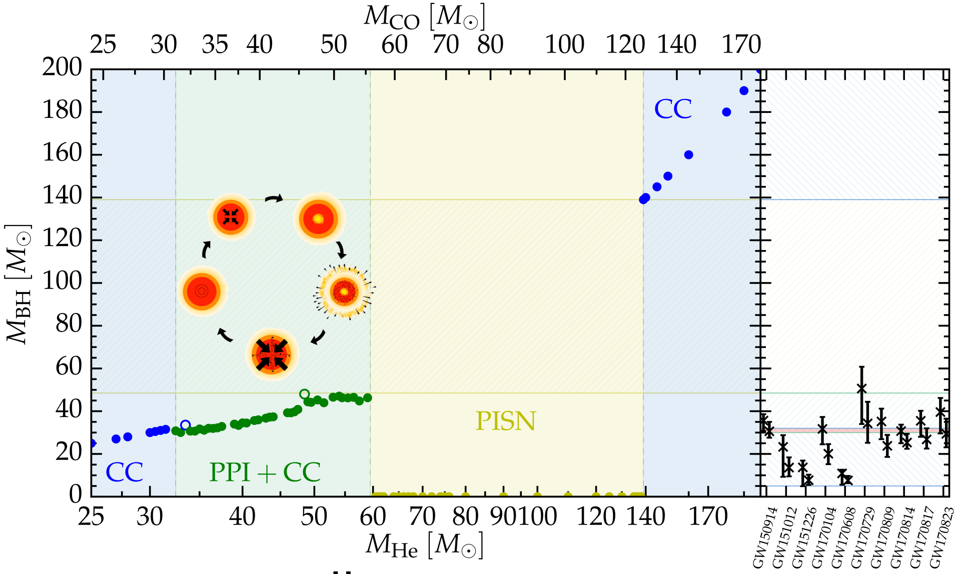

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Metallicity variations?

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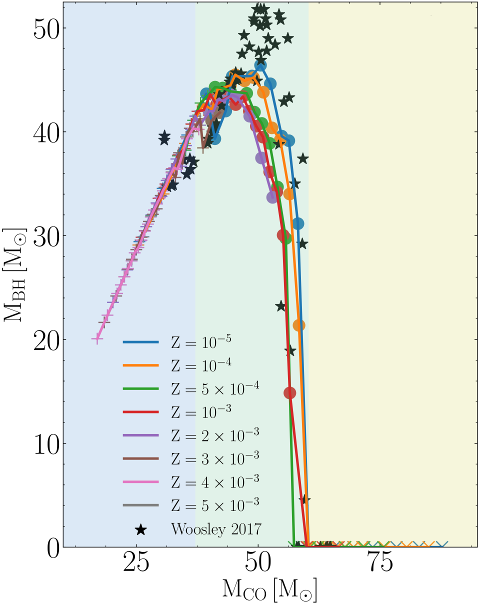


CO core mass

Other robustness tests:

- Spatial & temporal resolution
- Wind mass loss rate
- $^{12}C(\alpha, \gamma)^{16}O$ rate

Farmer, Renzo, *et al.* (in prep.)

Takahashi 18

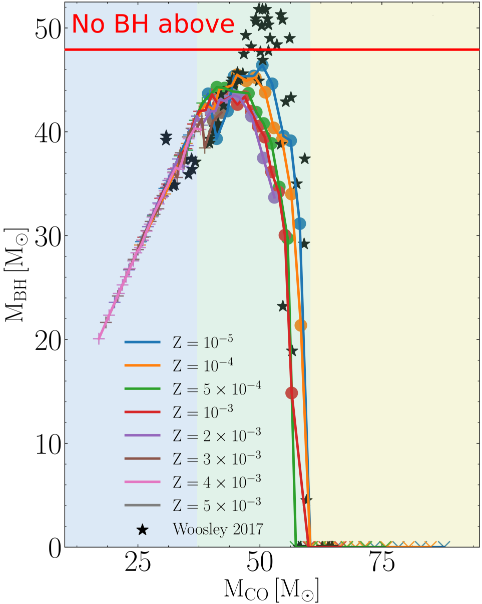
Woosley 17, 19

$\Downarrow$

max{BH mass} robust as function of M_{CO}

(rate will vary with Z)

Metallicity variations?



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Chirp Mass Distribution

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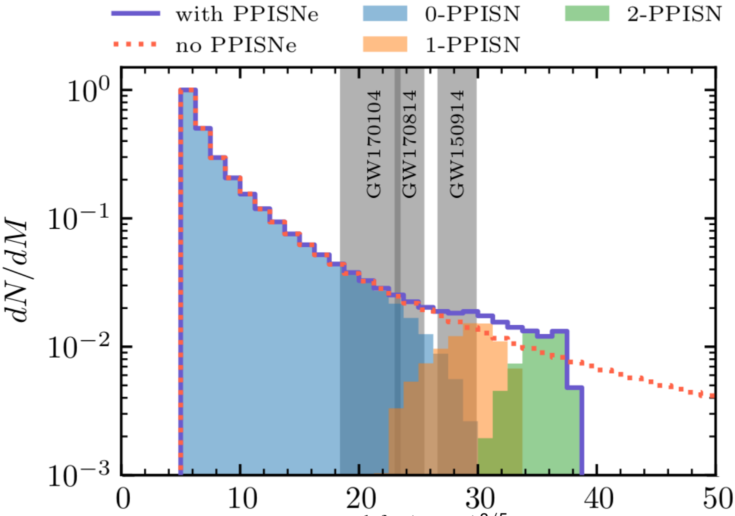


$$M_{\rm chirp} \stackrel{\rm def}{=} \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}}\ [M_\odot]$$

Chirp Mass

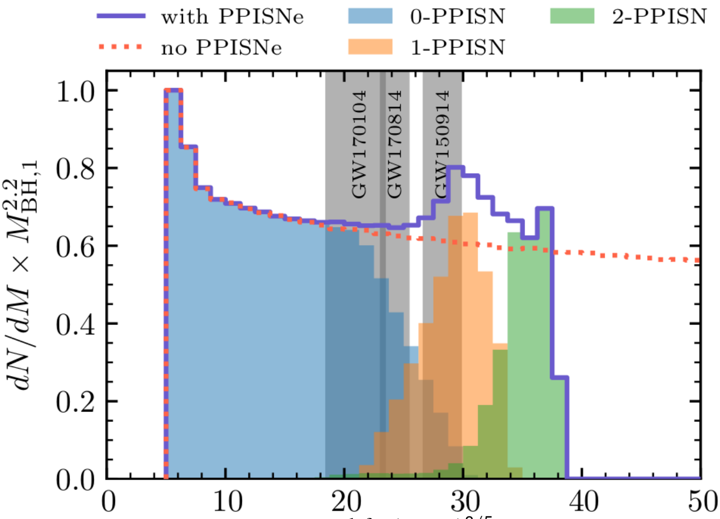
$$\frac{dN}{dM_{\rm He}} \propto M_{\rm He}^{-2.35}$$

$$q \stackrel{\rm def}{=} \frac{M_2}{M_1} \geq 0.5$$

(motivated by LVC 2016)

Chirp Mass Distribution

(Fishbach & Holtz 2017)



$$M_{\mathrm{chirp}} \stackrel{\mathrm{def}}{=} \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}}\ [M_\odot]$$

Chirp Mass

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Marchant, Renzo, *et al.*, submitted, arXiv:1810.13412

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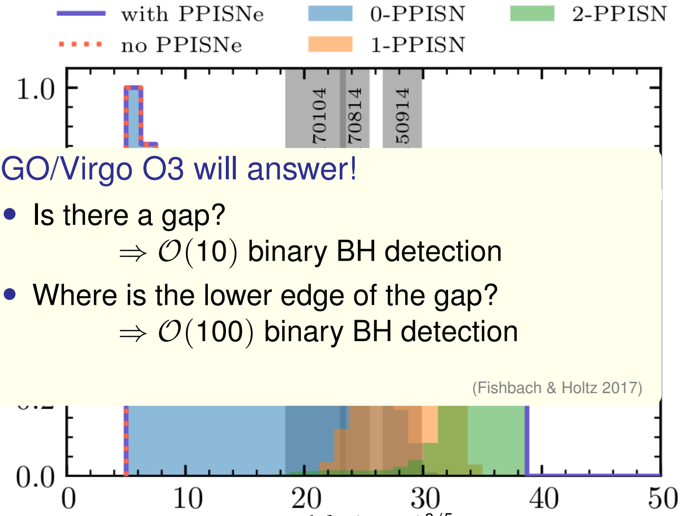

(Fishbach & Holtz 2017)

LIGO/Virgo O3 will answer!

- Is there a gap?
  $\Rightarrow \mathcal{O}(10)$ binary BH detection
- Where is the lower edge of the gap?
  $\Rightarrow \mathcal{O}(100)$ binary BH detection

(Fishbach & Holtz 2017)

$$\frac{dN}{dM_{\mathrm{He}}} \propto M_{\mathrm{He}}^{-2.35}$$

$$q \stackrel{\mathrm{def}}{=} \frac{M_2}{M_1} \geq 0.5$$

(motivated by LVC 2016)

$$M_{\mathrm{chirp}} \stackrel{\mathrm{def}}{=} \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}} \; [M_\odot]$$

Chirp Mass

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BH or NS?

- Single stars winds impact on the core structure

Keep the stars together

- The most common evolution for massive binaries
- Constraints on BH kicks using runaway “widow”

The most massive (stellar) BHs

- (Pulsational) pair instability
- The BH mass distribution
- Induced eccentricity

Conclusions

Post common envelope PPI

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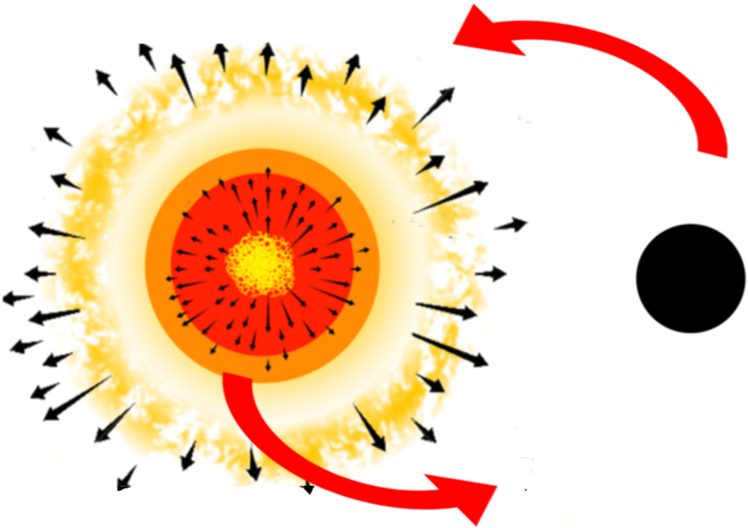
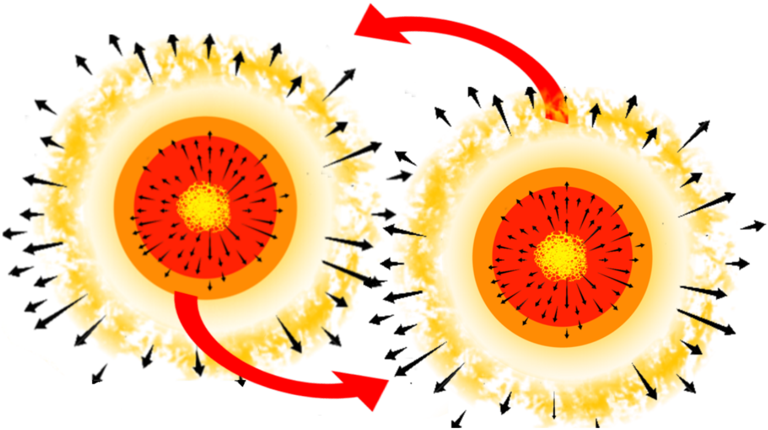


$$\Delta e = \frac{\Delta M}{M_1 + M_2 - \Delta M}$$



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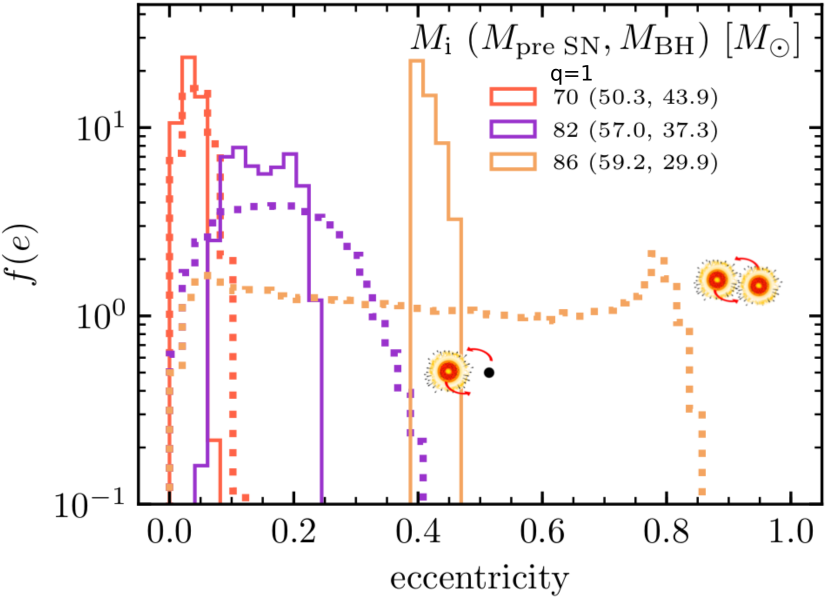
Eccentricity distribution



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Conclusions

Take home points

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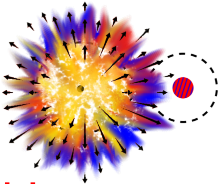
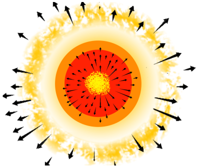
- **Uncertain wind mass loss rates influence the pre-SN core**
  $\Rightarrow$ systematic bias in SN initial conditions and outcome?



- **The vast majority of binaries are disrupted**
  $\Rightarrow$ X-ray binaries and GW sources are exceptions
- **Binarity leaves imprint on the ejected star**
- **“Widow” companions ejected constrain BH kicks**

Simulations of Pulsational Pair Instability possible with MESA
including self-consistently dynamical evolution



- **can modify binary orbit and remnant spin**
  $\Rightarrow$ Signature on gravitational wave signals?
- **determines BH masses below PISN gap**

Take home points

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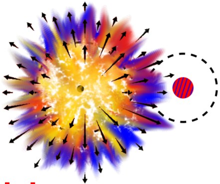
- **Uncertain wind mass loss rates influence the pre-SN core**

  ⇒ systematic bias in SN initial conditions and outcome?



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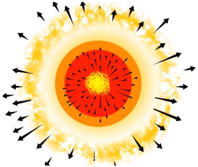

- **can modify binary orbit and remnant spin**

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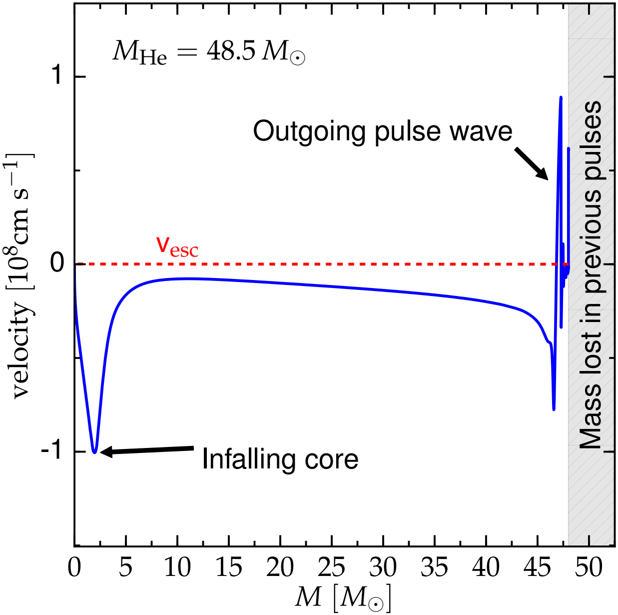
Thank you!

Backup slides

Upper-limits in BH mass



How many pulses?

- as a function of He core mass

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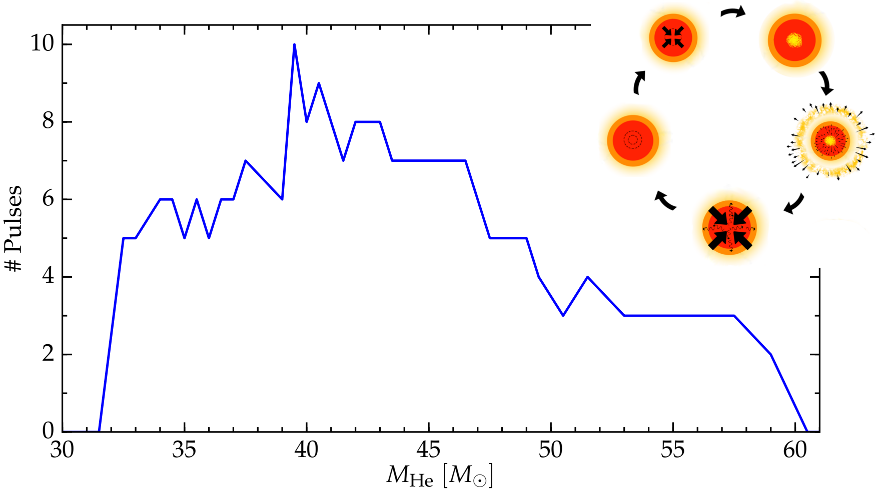

One pulse = One mass ejection

When do the pulsate?

- as a function of He core mass

Pulses timing

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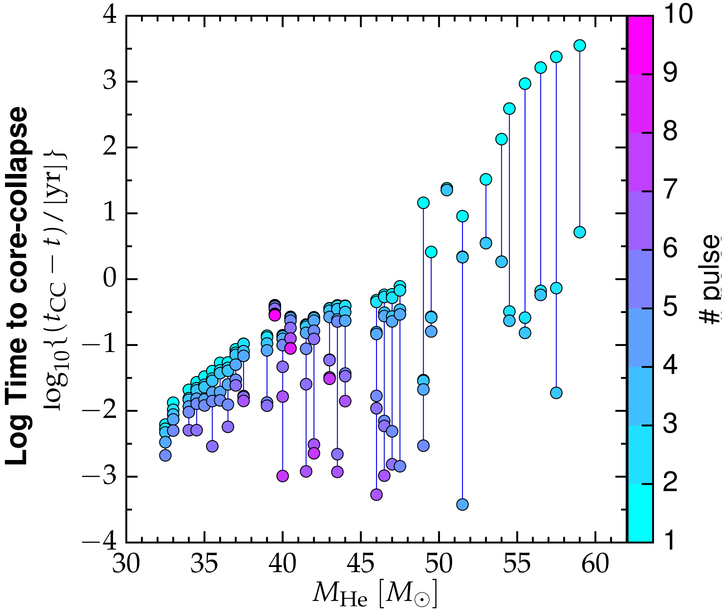
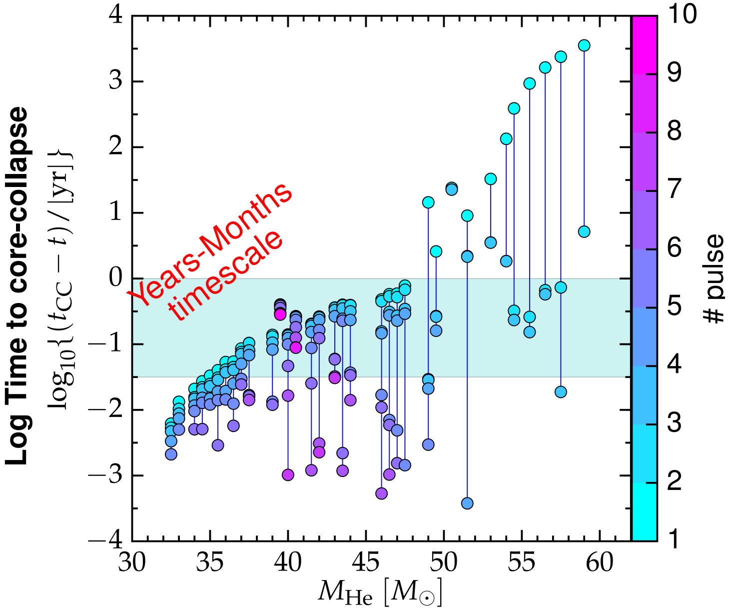


Renzo, Farmer *et al.*, to be submitted

Pulses timing



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How much mass is ejected per pulse?
How much mass is ejected in total?

- as a function of He core mass

Mass lost per pulse

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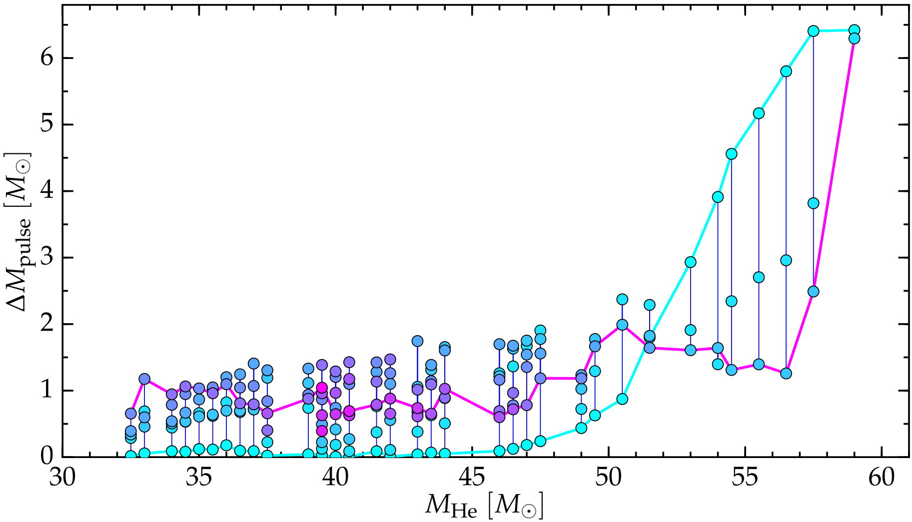
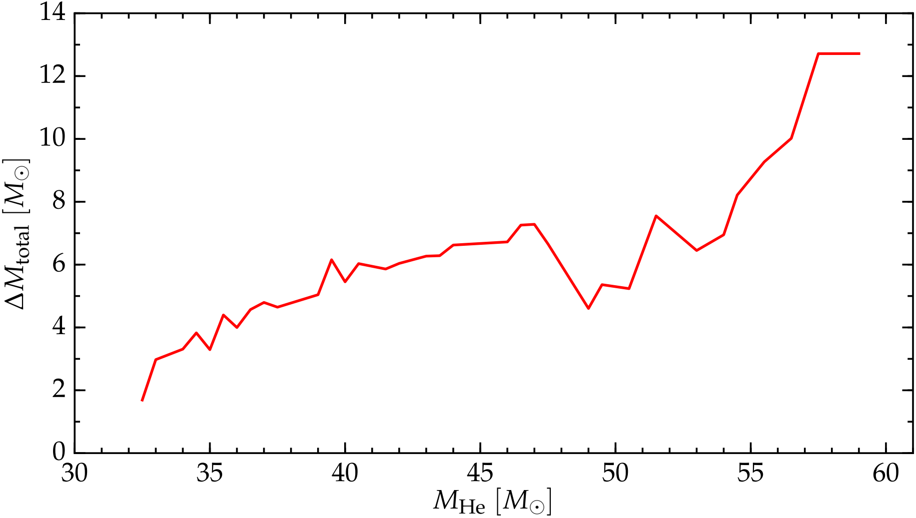


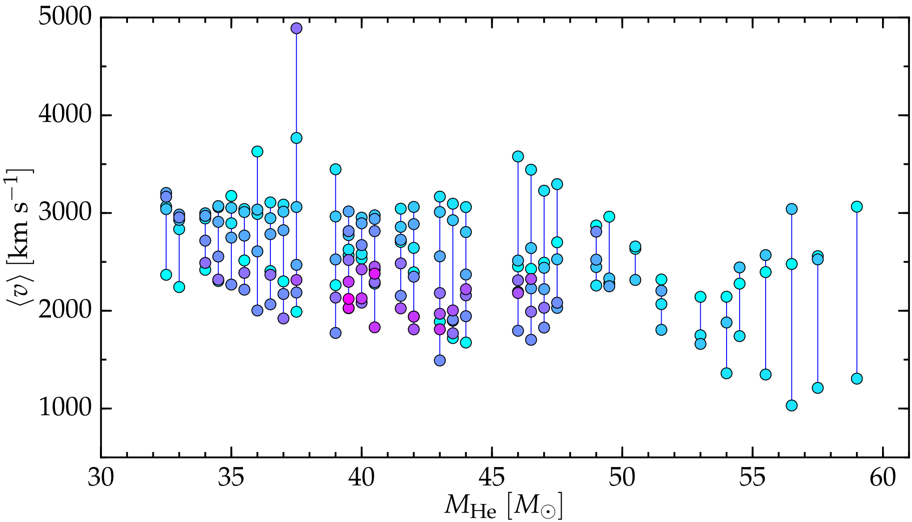
Total mass lost



How fast are the ejected shells?

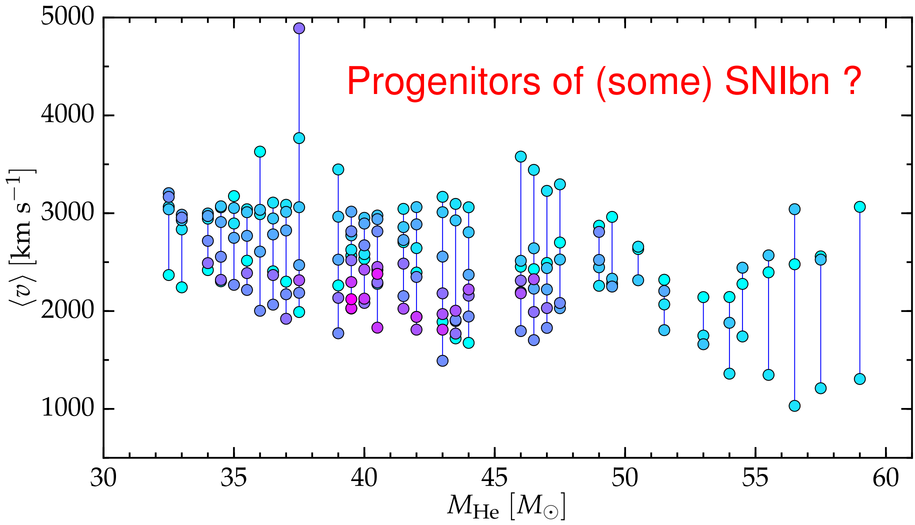
- as a function of He core mass

Center of mass velocity



Renzo, Farmer *et al.*, to be submitted

Center of mass velocity



Can the mass shell collide?

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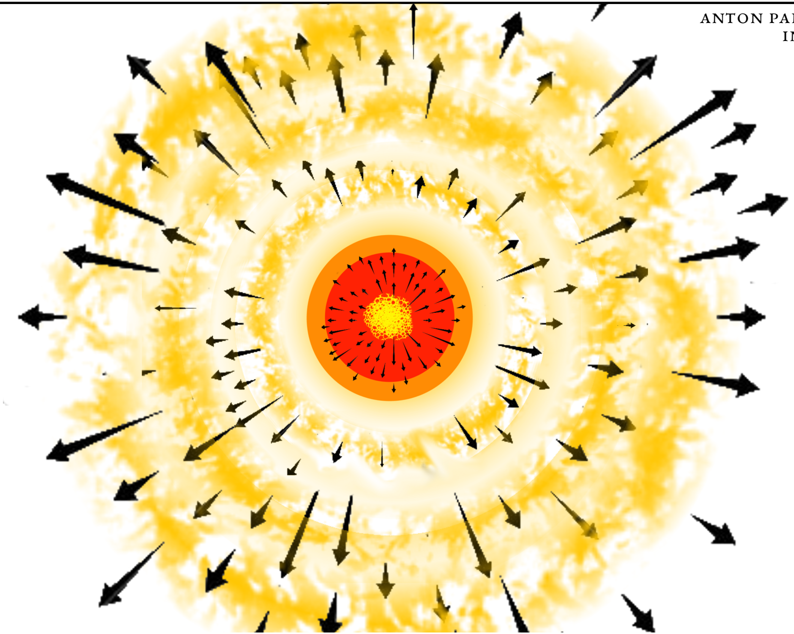
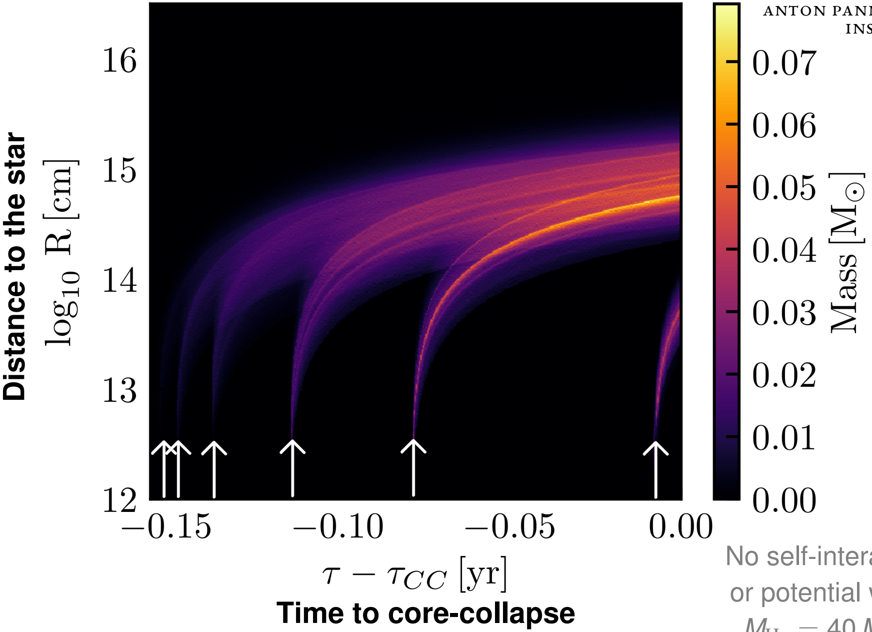


Woosley *et al* 07, Chen *et al.* 14, Woosley 17, Renzo, Farmer *et al.*, to be submitted

Can the mass shells collide?



No self-interaction or potential well

$M_{\rm He} = 40\,M_\odot$

Renzo, Farmer *et al.*, to be submitted

Example: 40 $M_\odot$ He core

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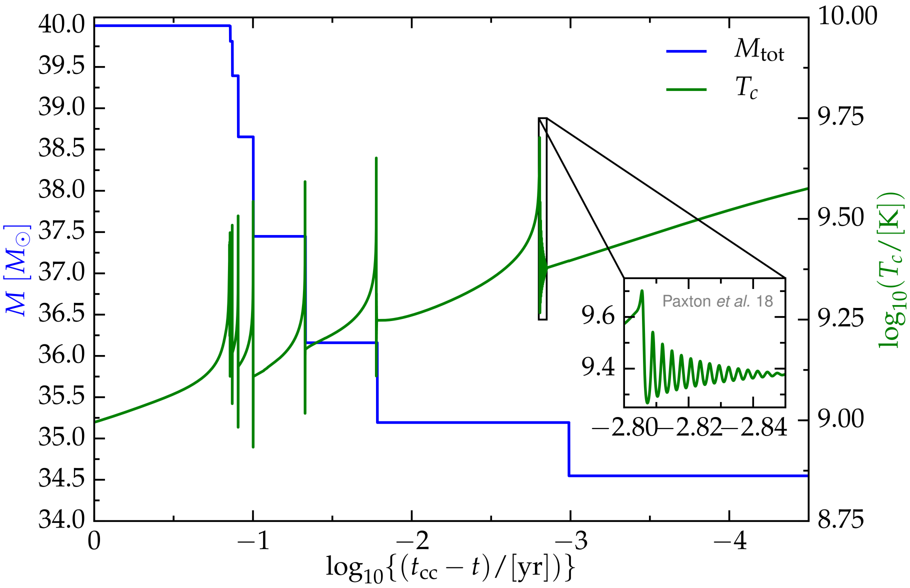

Log Time to core-collapse

Renzo, Farmer *et al.*, to be submitted

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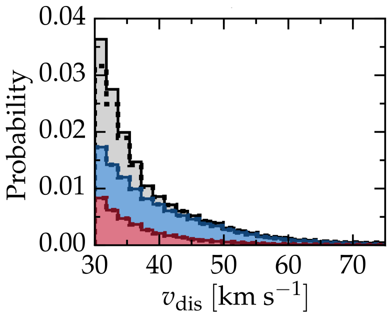

Velocity distribution: Walkaways

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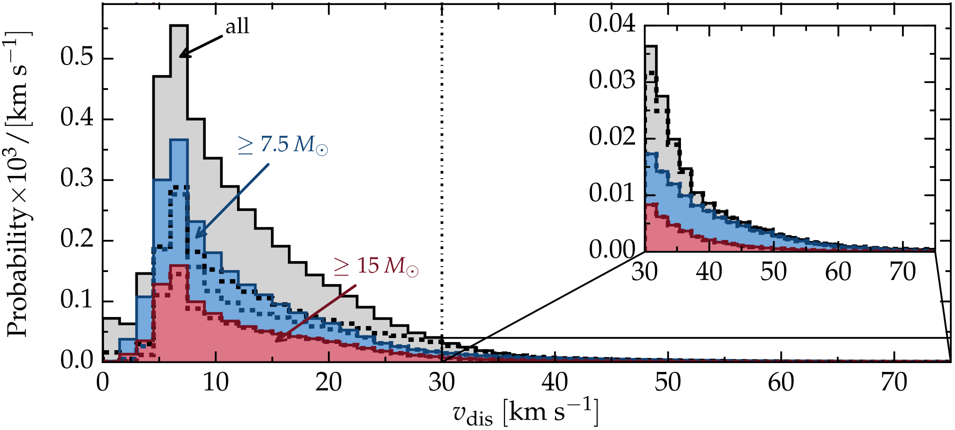
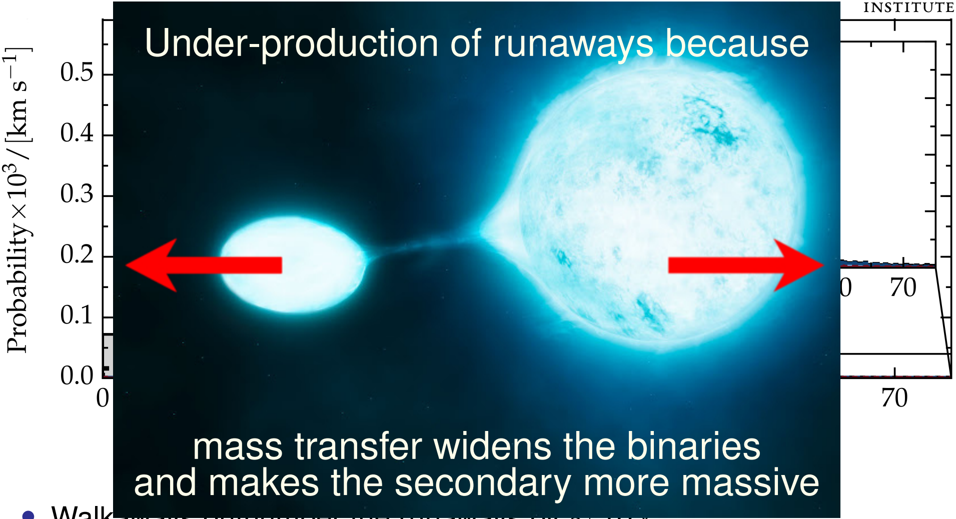


Take home points:

- Walkaways outnumber the runaways by $\sim 10\times$
- Binaries barely produce $v_{dis} \gtrsim 60\,\mathrm{km\ s^{-1}}$
- All runaways from binaries are post-interaction objects

Velocity distribution: Walkaways



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Renzo *et al.*, submitted, arXiv:1804.09164

Example: 40 $M_\odot$ He core with MESA

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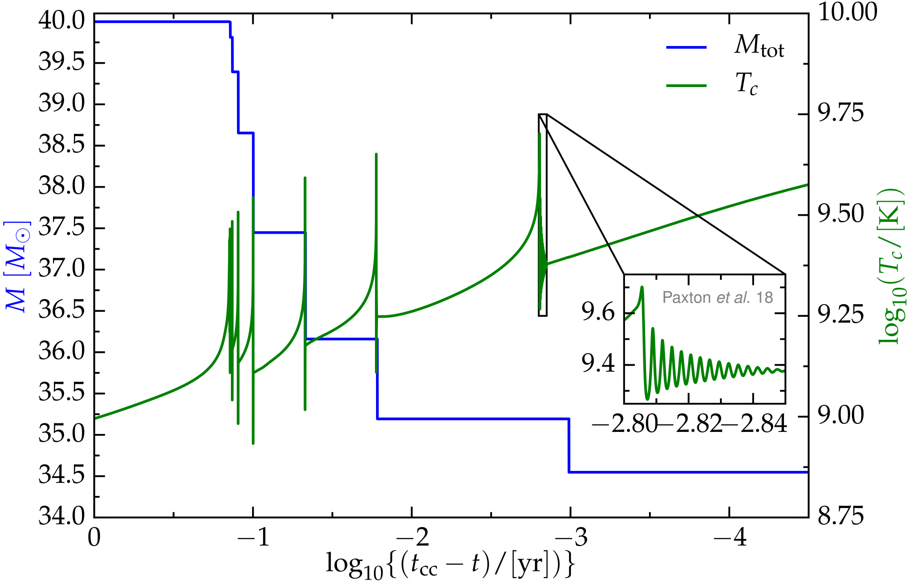
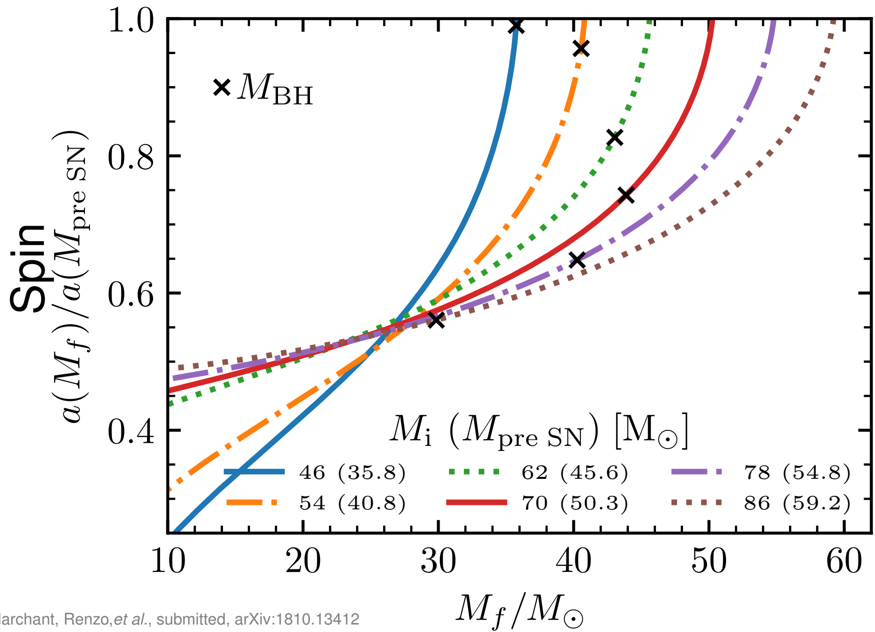


Log Time to core-collapse

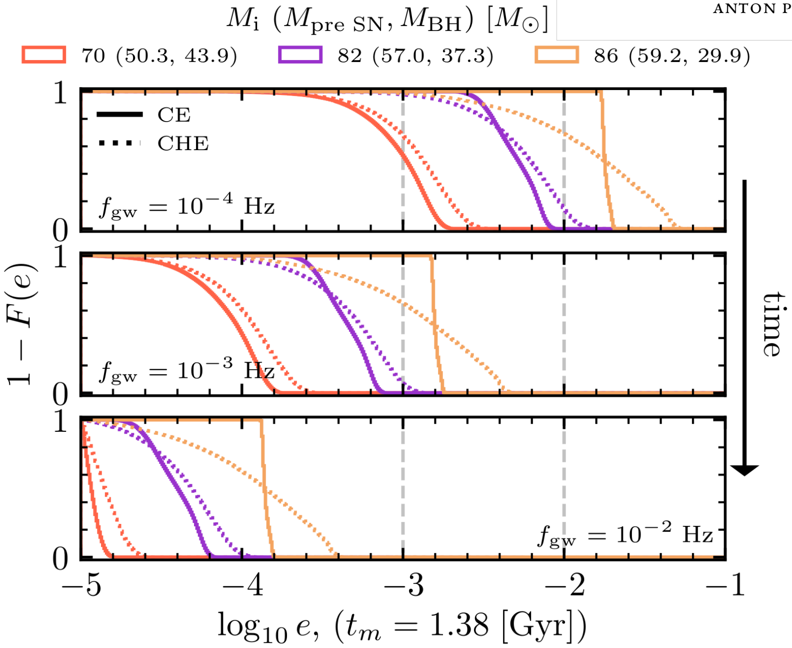
Renzo, Farmer *et al.* (in prep.)

Spin down due to PPI ejecta



Marchant, Renzo, *et al.*, submitted, arXiv:1810.13412

GW circularization



Marchant, Renzo, Farmer *et al.*, arXiv:1810.13412

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