Explosions in massive binaries:

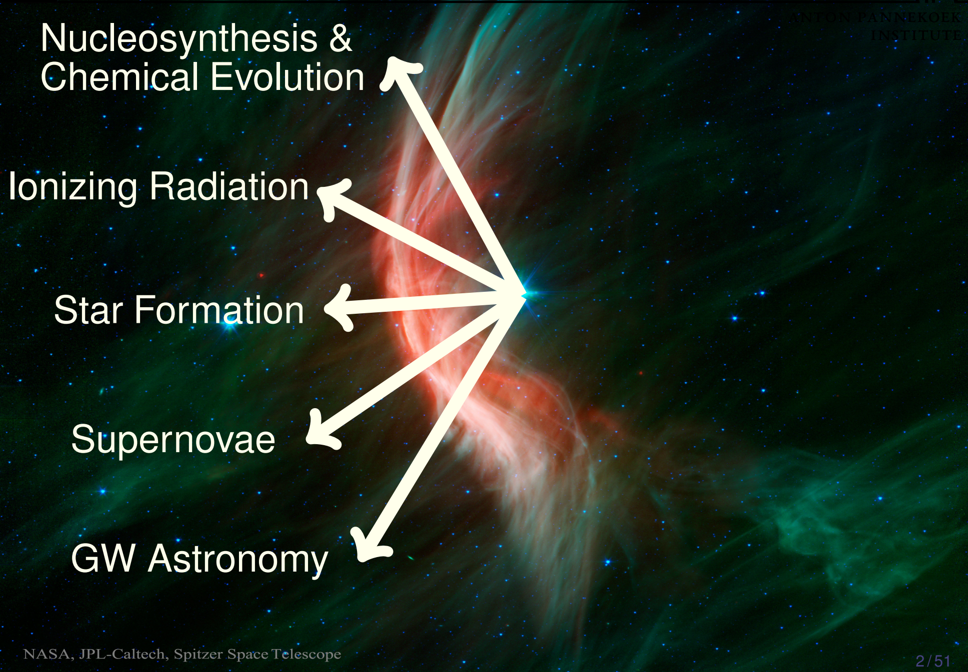
"widowed" stars and consequences for GW astronomy

NASA, JPL-Caltech, Spitzer Space Telescope

Mathieu Renzo
PhD in Amsterdam

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, ...

Why are massive stars important?



Nucleosynthesis & Chemical Evolution

Ionizing Radiation

Star Formation

Supernovae

GW Astronomy

NASA, JPL-Caltech, Spitzer Space Telescope

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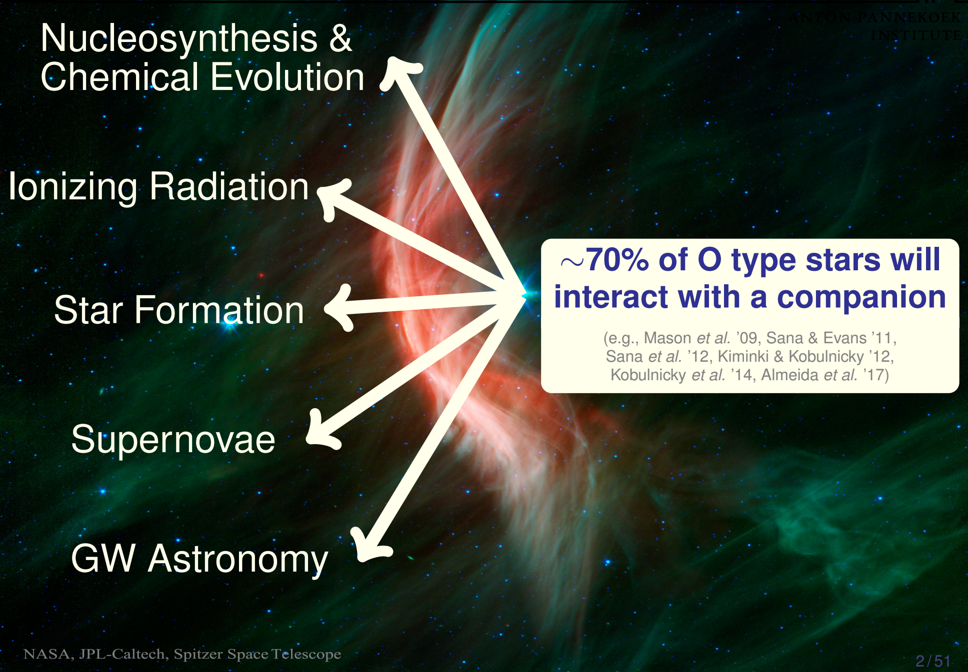

Nucleosynthesis & Chemical Evolution

Ionizing Radiation

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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)

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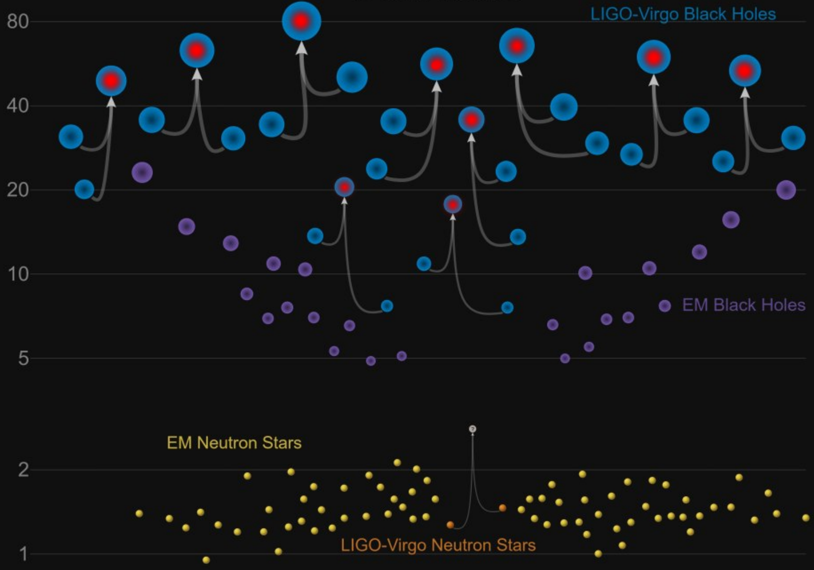
Masses in the Stellar Graveyard

in Solar Masses



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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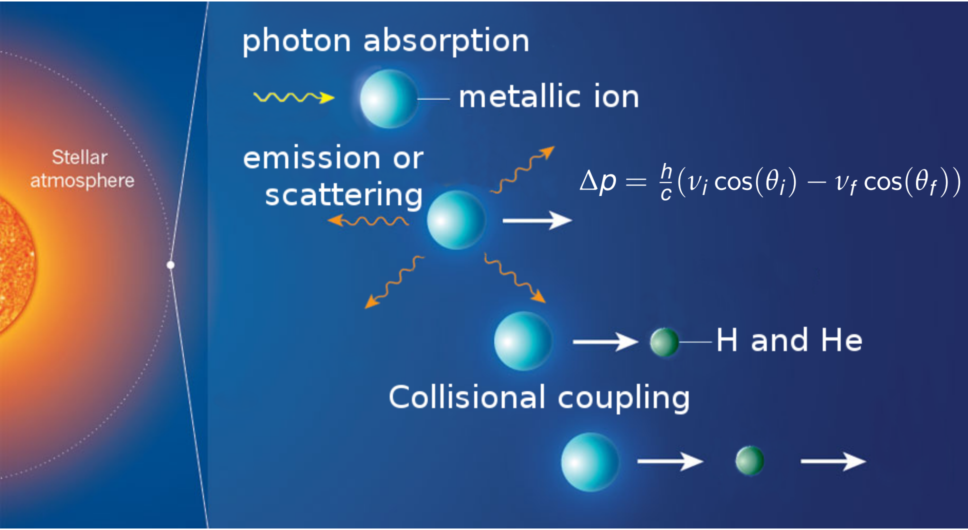
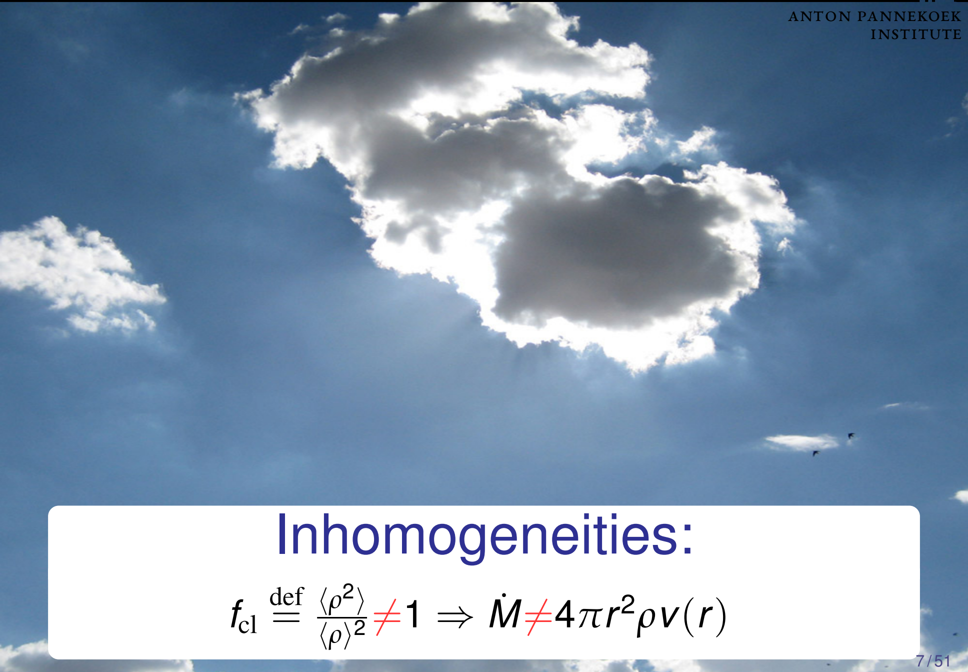
Radiatively Driven Winds in One Slide



$$\Delta p = \frac{h}{c}(\nu_i \cos(\theta_i) - \nu_f \cos(\theta_f))$$

Problems: High Non-Linearity and Clumpiness

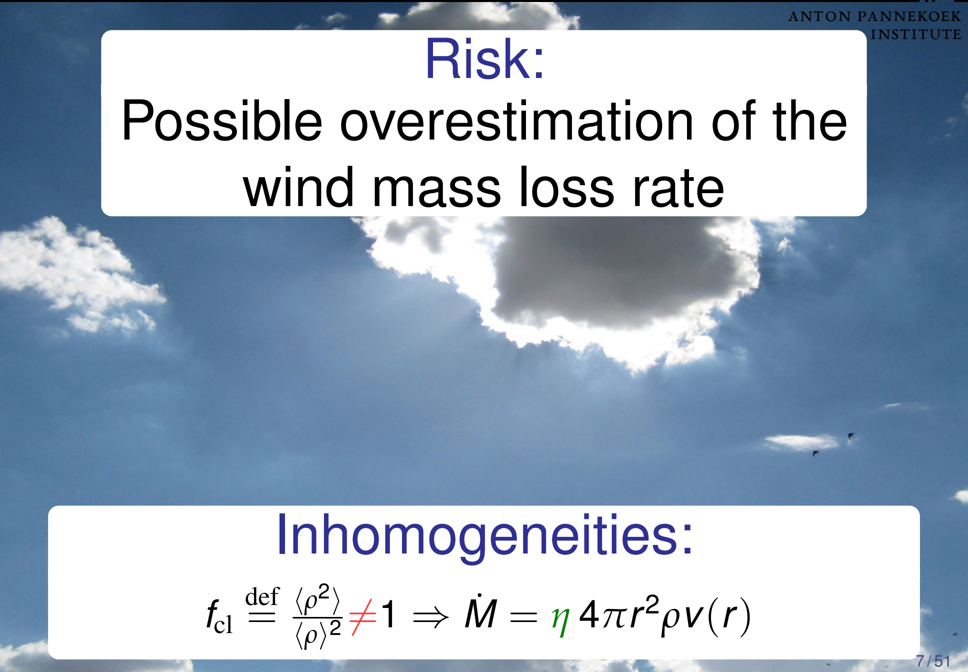
Clumpiness



Inhomogeneities:

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

Clumpiness



Risk:

Possible overestimation of the wind mass loss rate

Inhomogeneities:

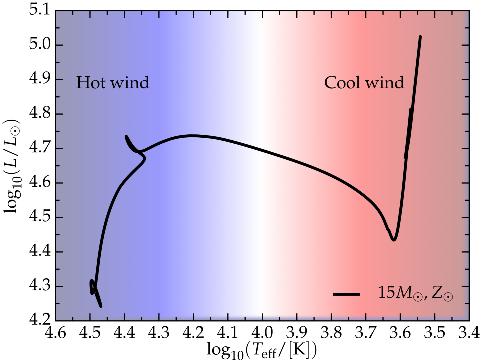
$$f_{\mathrm{cl}} \overset{\mathrm{def}}{=} \frac{\langle\rho^2\rangle}{\langle\rho\rangle^2} \neq 1 \Rightarrow \dot{M} = \eta\, 4\pi r^2 \rho v(r)$$

MESA grid varying dM/dt

Aim: quantify systematic uncertainty

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

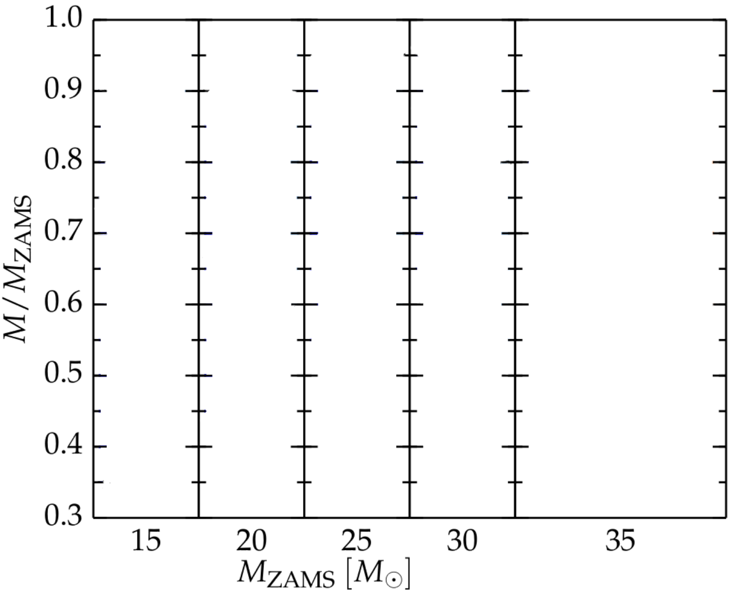
$$M_{\mathrm{ZAMS}} = 15,\ 20,\ 25,\ 30,\ 35\ M_\odot$$
$$\eta \equiv \sqrt{f_{\mathrm{cl}}} = 1,\ \tfrac{1}{3},\ \tfrac{1}{10}$$



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

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



MESA

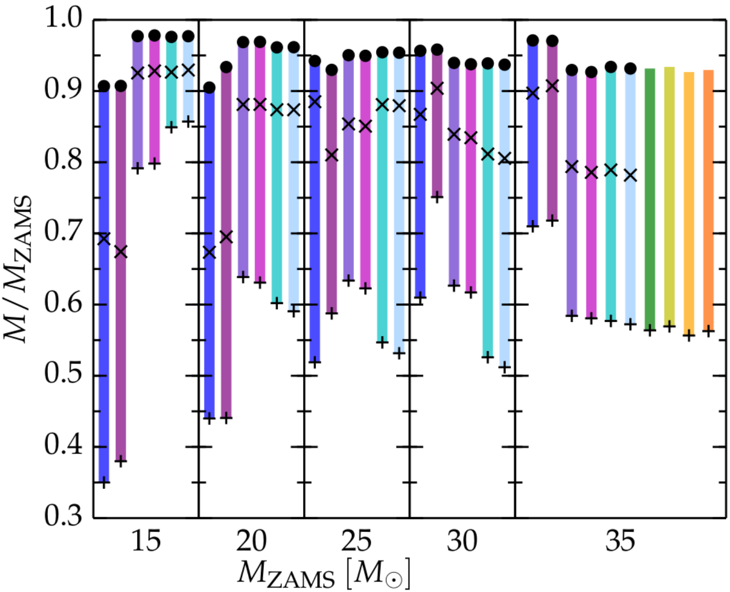
Legend:

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

$\eta \rightarrow$ largest uncertainty

Renzo *et al.* ’17

Impact on the final mass



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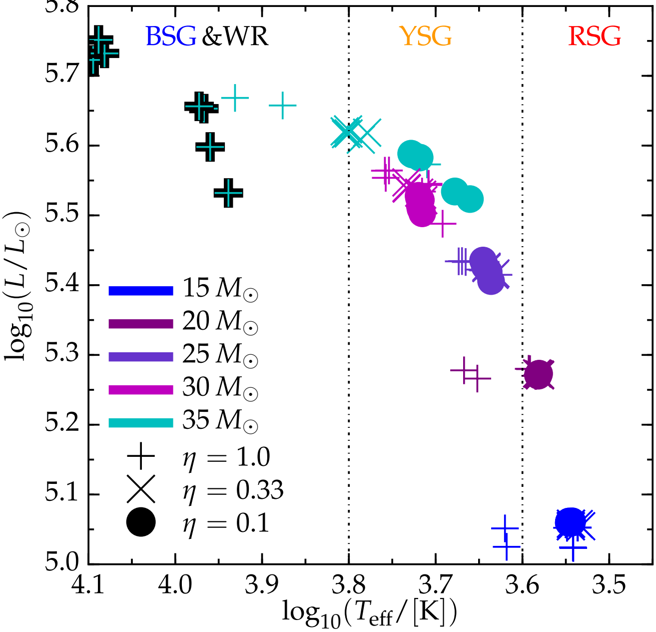
Pre-explosion appearance



Renzo *et al.* '17

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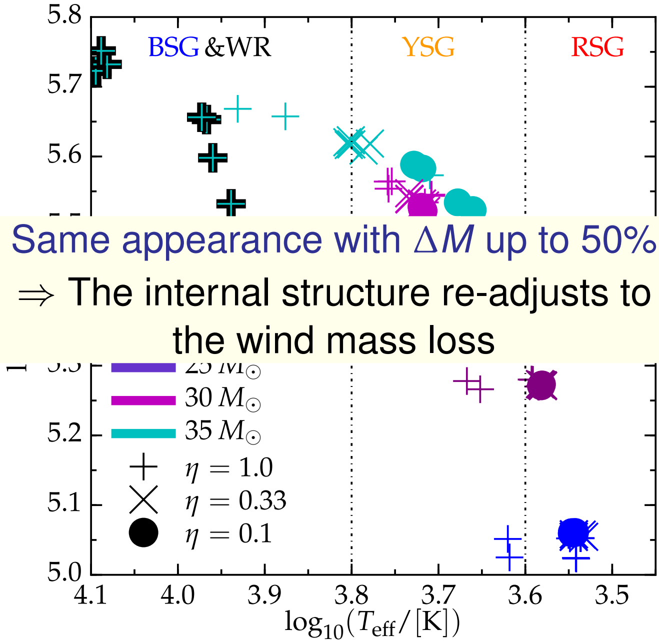


Same appearance with ΔM up to 50%

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

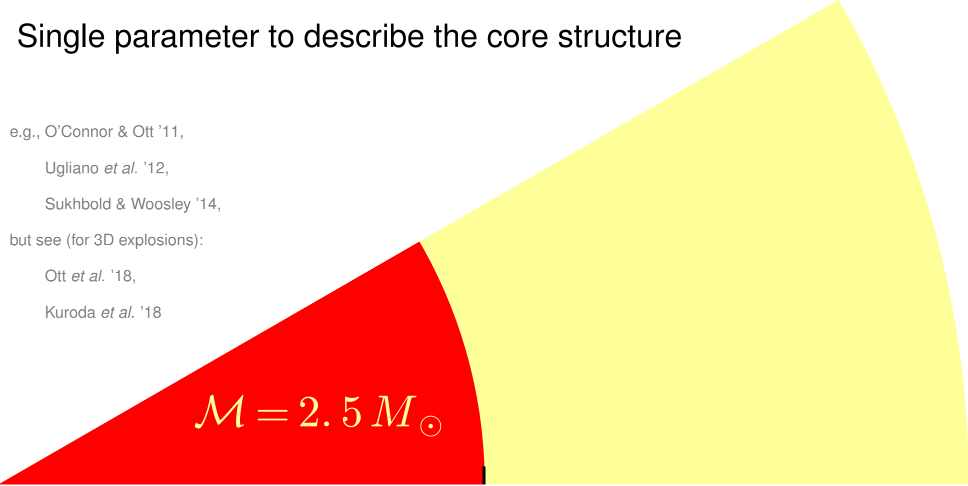
Renzo *et al.* '17

“Explodability” & Compactness

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

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

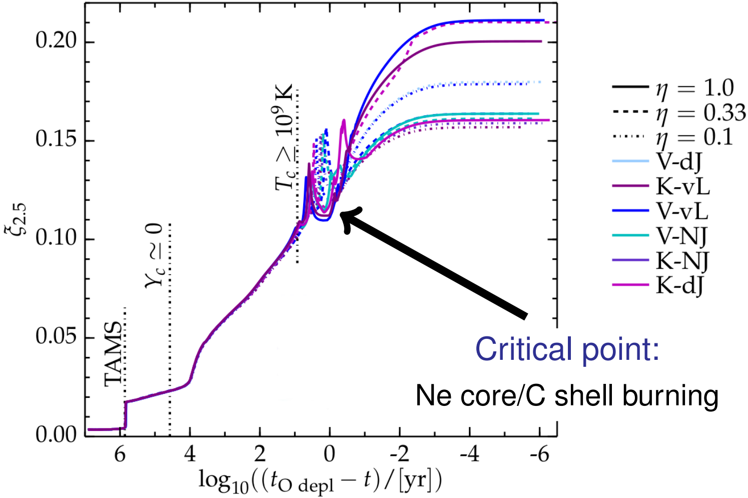


not to scale!

$R(\mathcal{M})$

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

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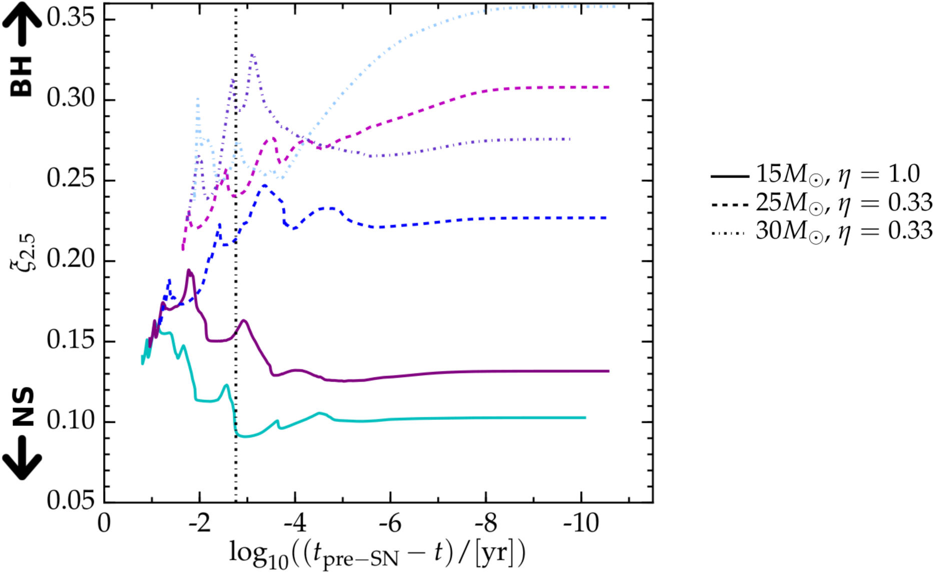
Si shell burning →



Log time to core-collapse

Renzo *et al.* '17

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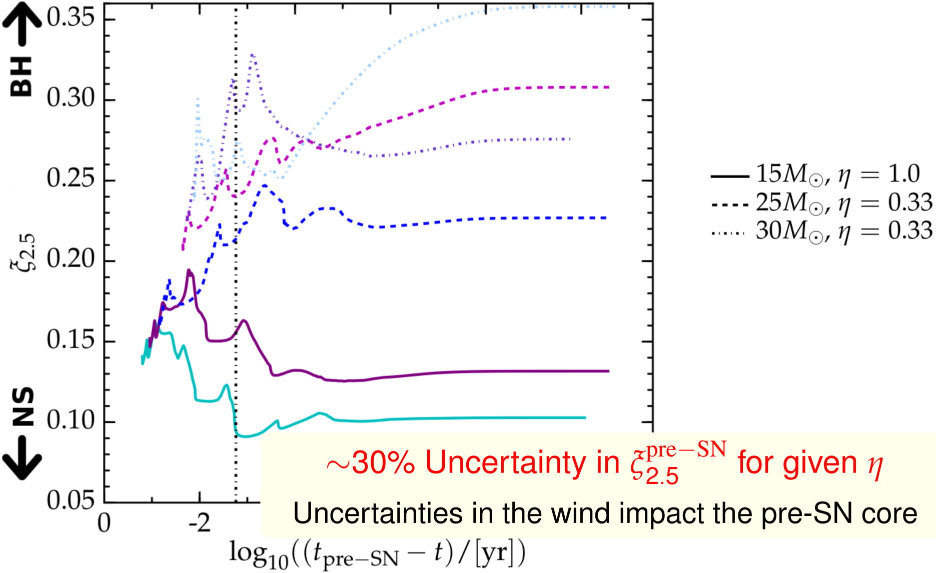

~30% Uncertainty in $\xi_{2.5}^{\mathrm{pre-SN}}$ for given η

Uncertainties in the wind impact the pre-SN core

Log time to core-collapse

Renzo *et al.* '17

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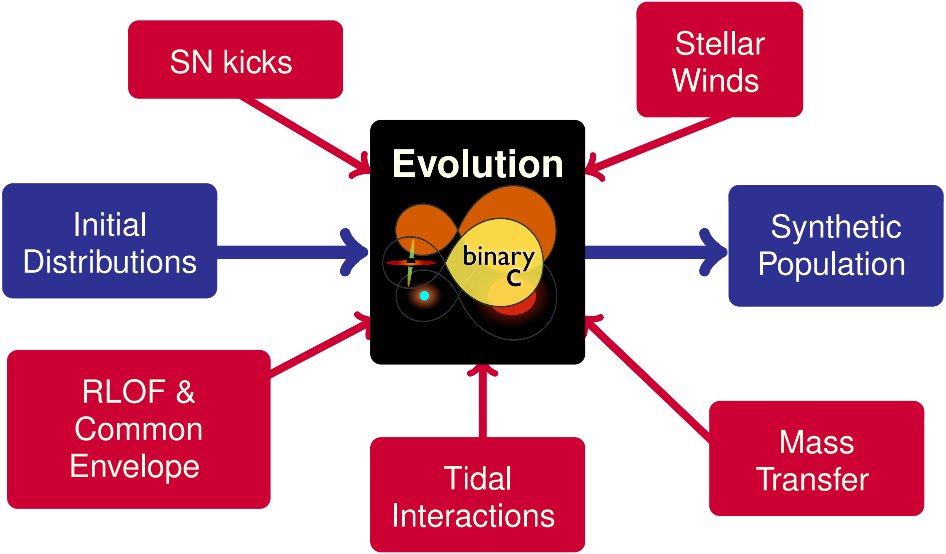
Methods: Population Synthesis

Fast ⇒ Allows statistical tests of the inputs & assumptions



SN kicks

Stellar Winds

Initial Distributions

Evolution

Synthetic Population

RLOF & Common Envelope

Tidal Interactions

Mass Transfer

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

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.* ’16

What exactly disrupts the binary?

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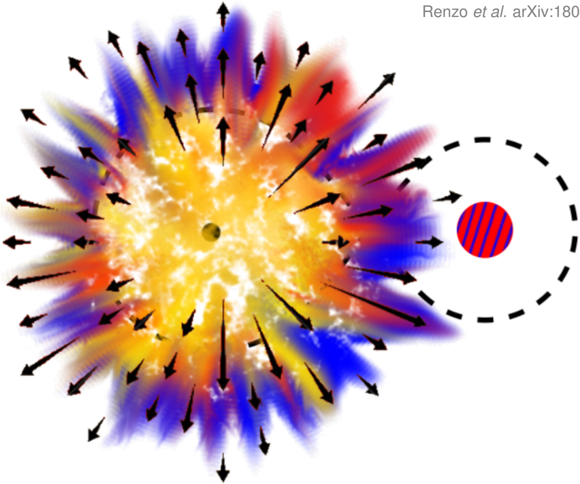
$86^{+11}_{-9}\%$ of massive binaries are disrupted

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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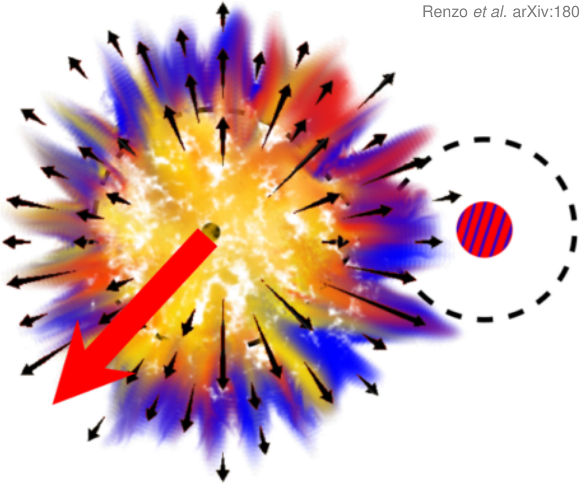

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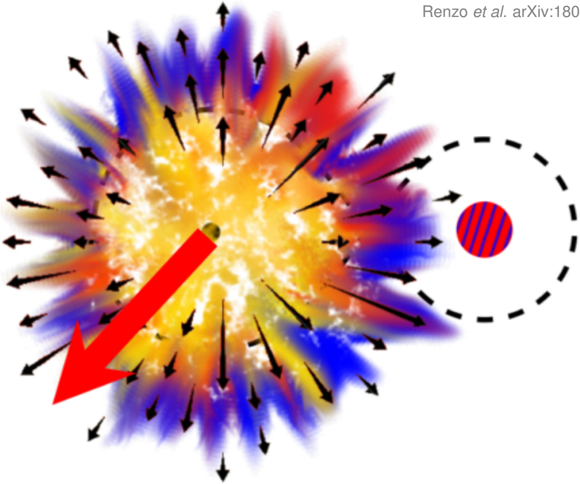

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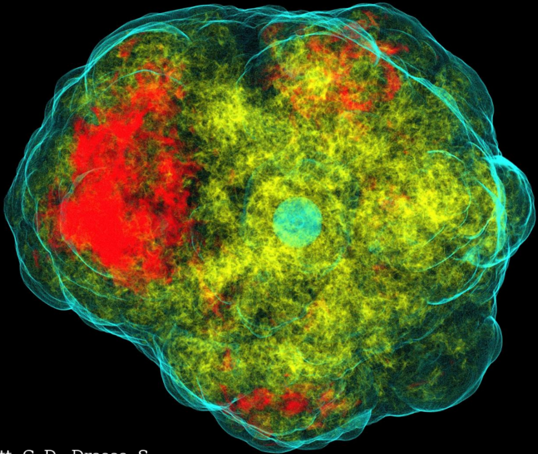
$$v_{\mathrm{dis}} \simeq v_{2,\mathrm{orb}}^{\mathrm{pre-SN}} = \frac{M_1}{M_1+M2}\sqrt{\frac{G(M_1+M2)}{a}}$$

Most binaries produce a slow "walkaway" star

SN natal kick

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

Physically: ν emission and/or ejecta anisotropies



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

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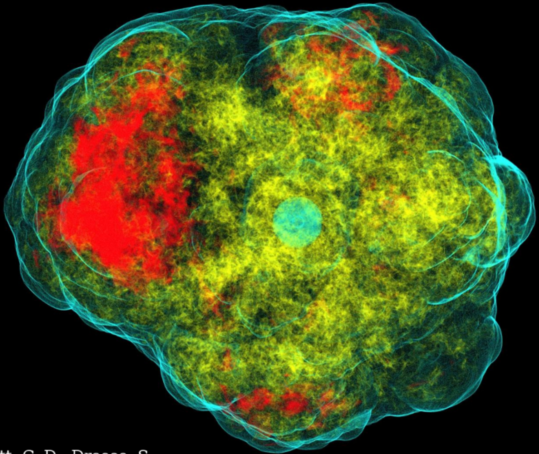

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BH kicks?

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A way to constrain BH kicks with *Gaia*

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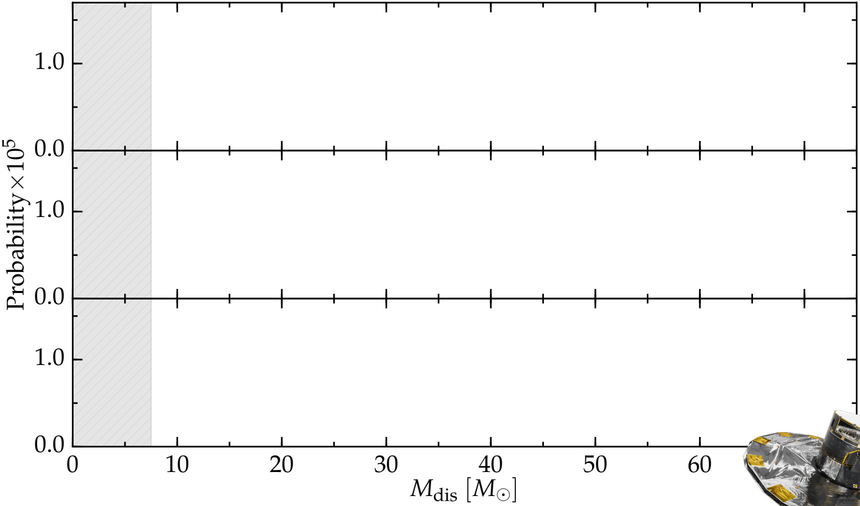
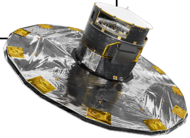
Massive runaways mass function ($v \geq 30\,\mathrm{km\ s^{-1}}$, $M \geq 7.5\,M_{\odot}$)





gaia

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

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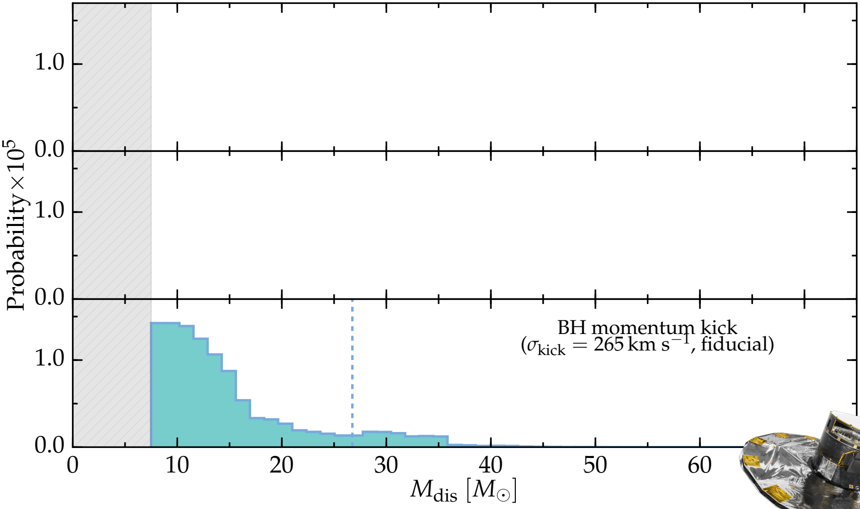

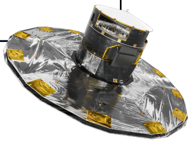

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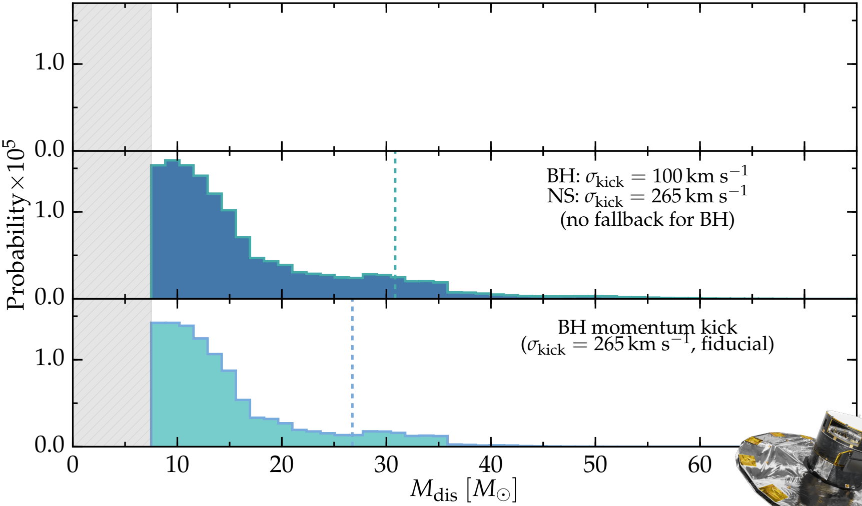

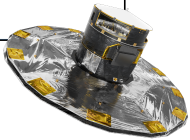

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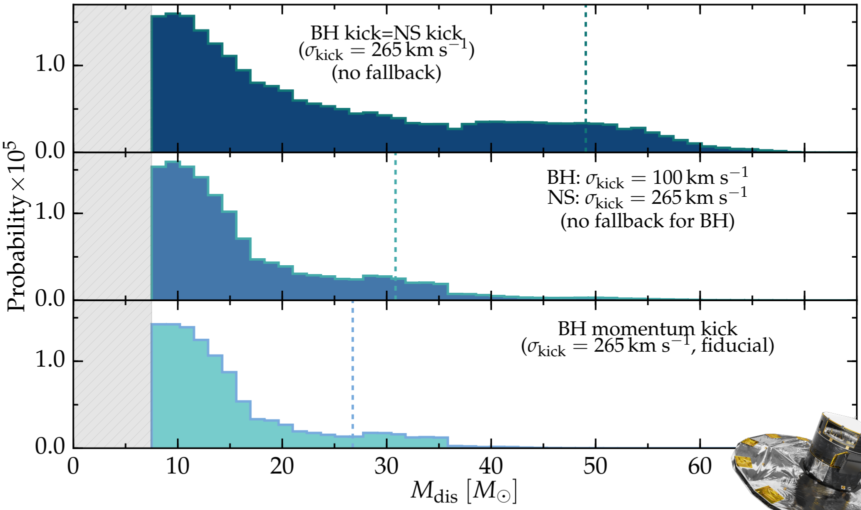

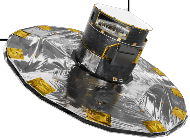

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Radiation dominated:

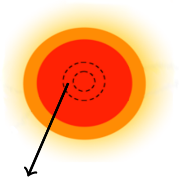
$P_{\mathrm{tot}} \simeq P_{\mathrm{rad}}$

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

Woosley 2017,

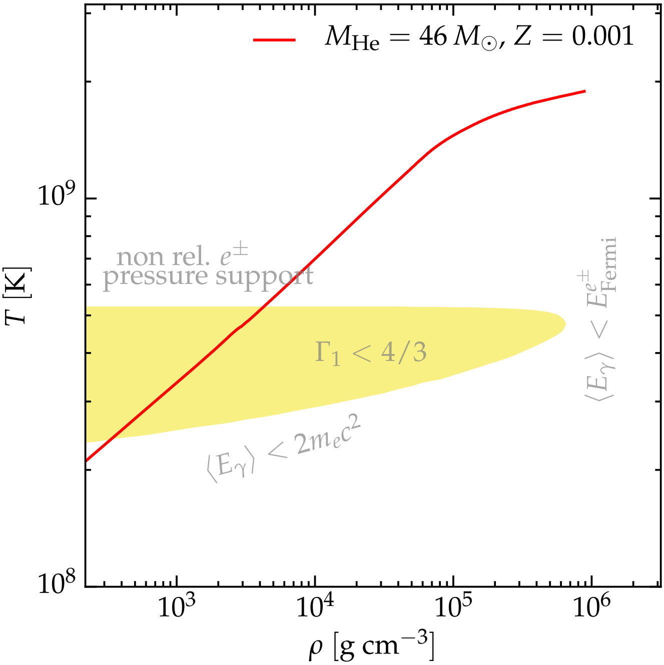
Marchant, Renzo *et al.* arXiv:1810.13412,

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



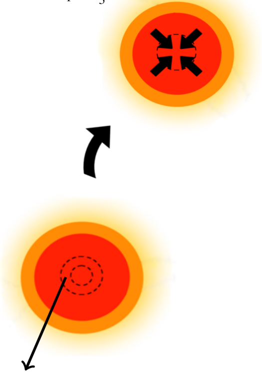
1. Pair production
$\gamma\gamma \rightarrow e^+e^-$

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



He core computed with MESA

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



2. Softening of EOS triggers collapse $\Gamma_1 < \frac{4}{3}$

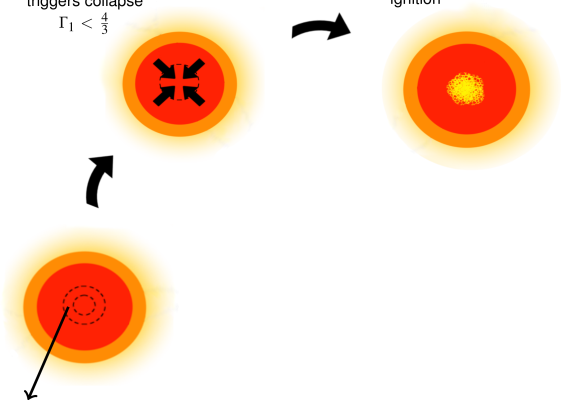
1. Pair production $\gamma\gamma \rightarrow e^+e^-$

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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3. Explosive
(oxygen)
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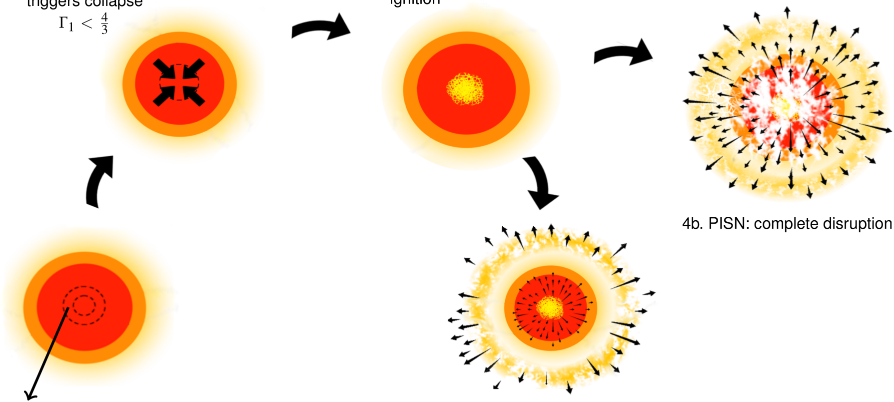
Renzo, Farmer, *et al.*, to be submitted



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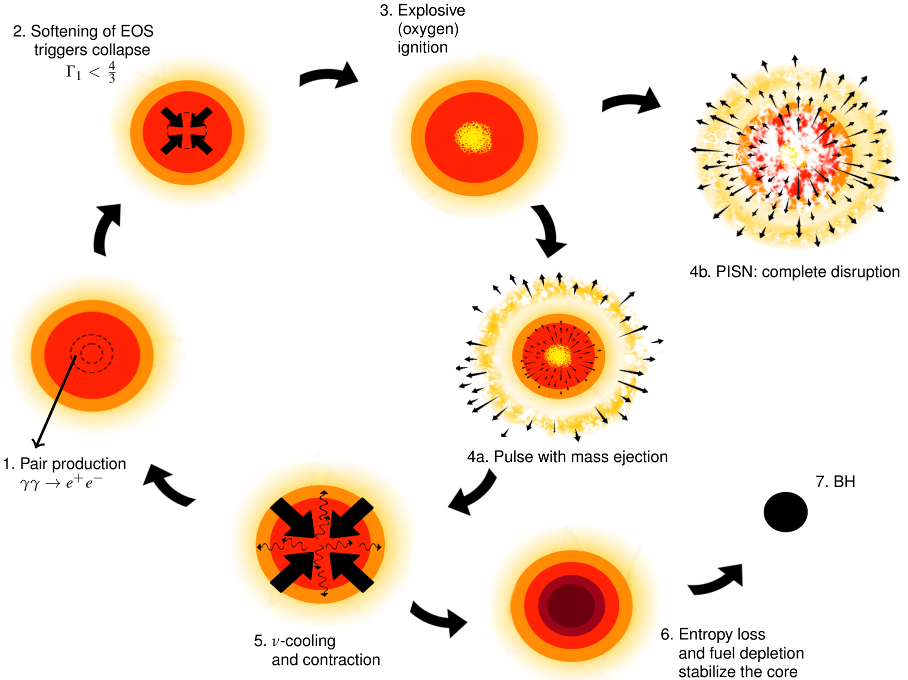
3. Explosive (oxygen) ignition

4a. Pulse with mass ejection

4b. PISN: complete disruption

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



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4b. PISN: complete disruption

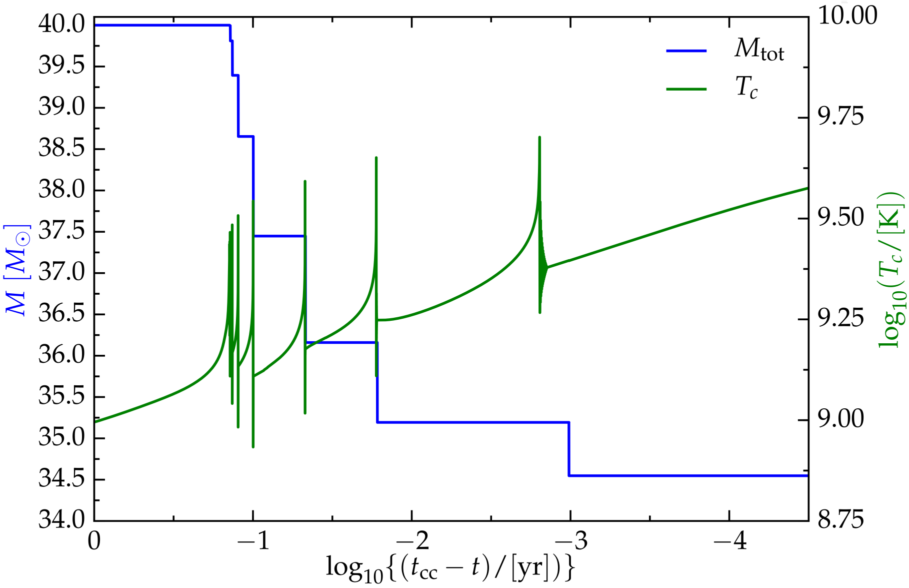
5. ν-cooling
and contraction

6. Entropy loss
and fuel depletion
stabilize the core

7. BH

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

Example: 40 $M_\odot$ He core



Log Time to core-collapse

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

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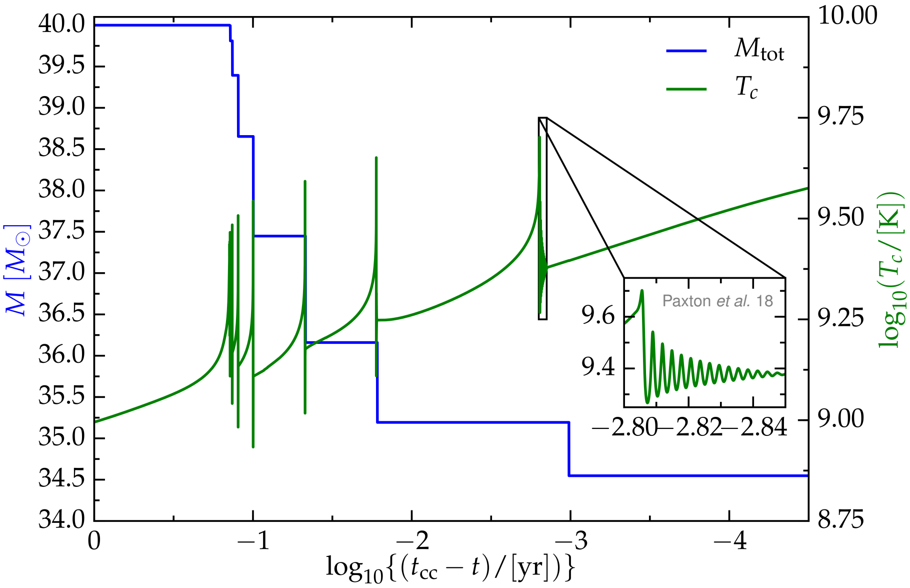

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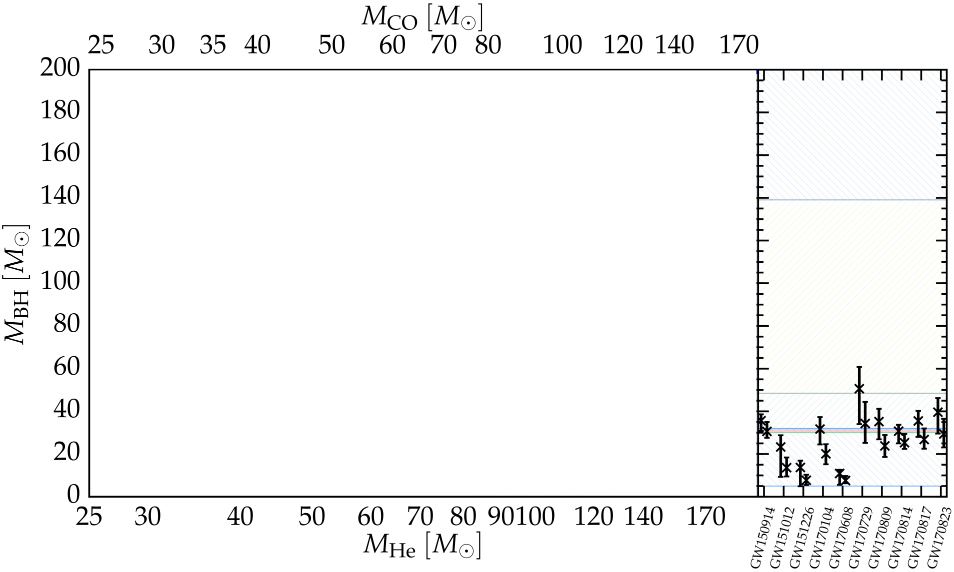
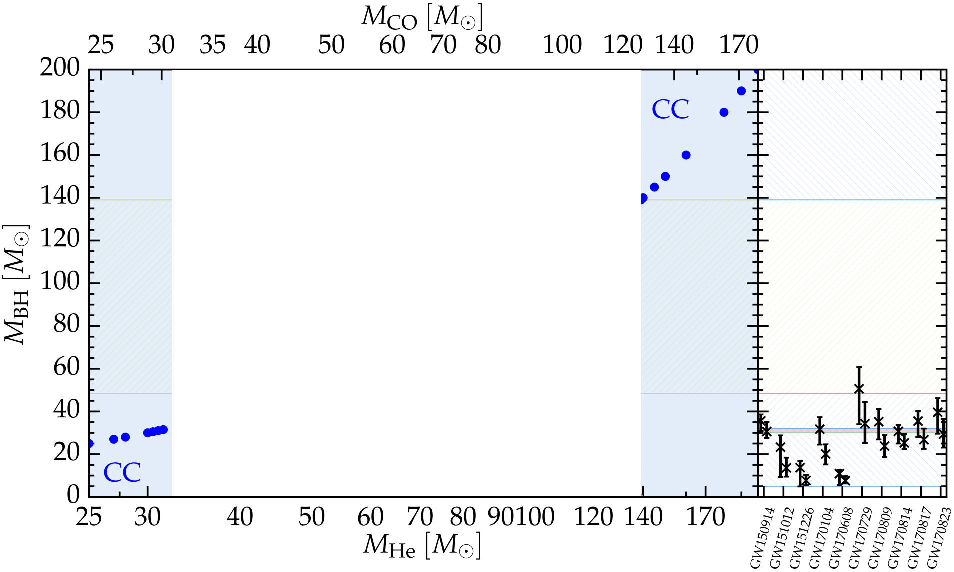
The origin of very massive BHs



He core mass

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

The origin of very massive BHs



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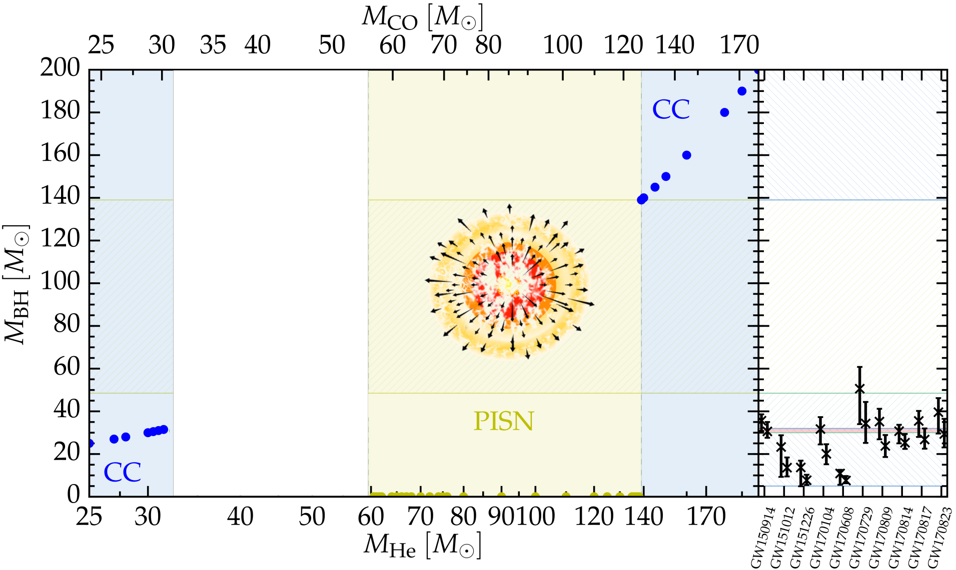

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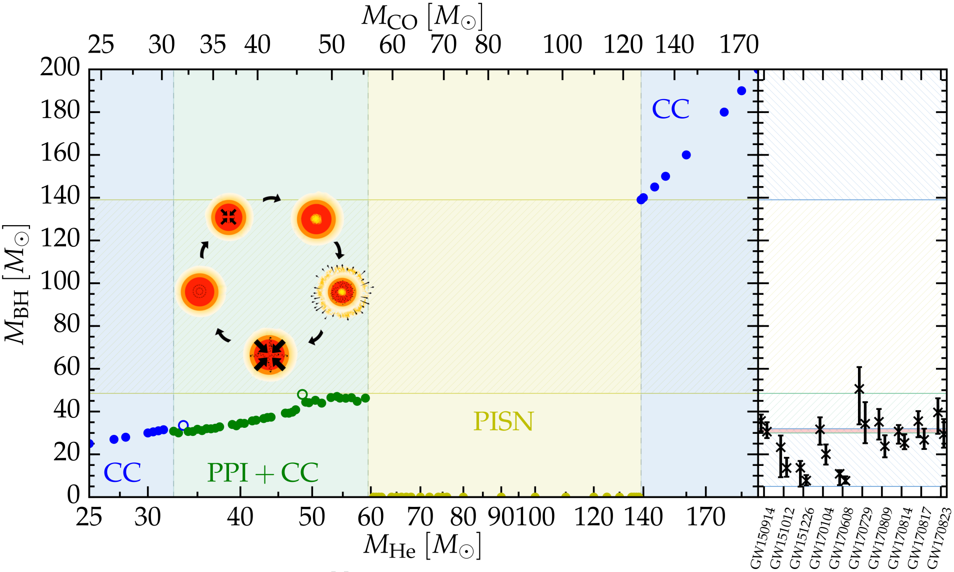

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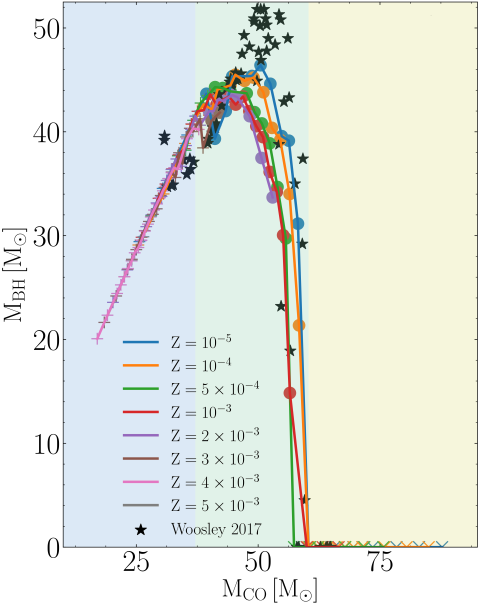
Metallicity variations?



CO core mass

Other robustness tests:

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

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

Takahashi 18

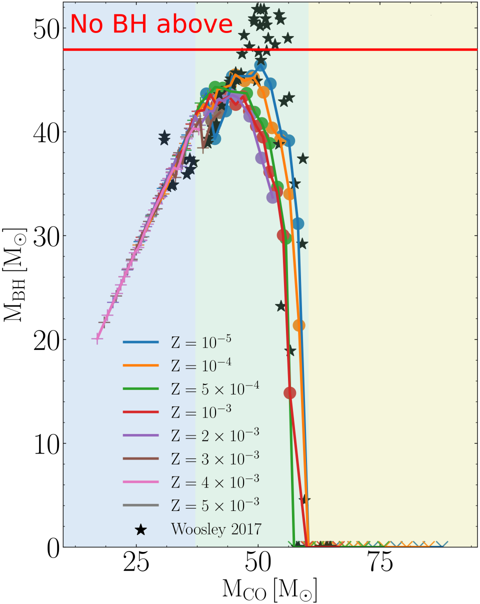
Woosley 17, 19

$\Downarrow$

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

(rate will vary with *Z*)

Metallicity variations?



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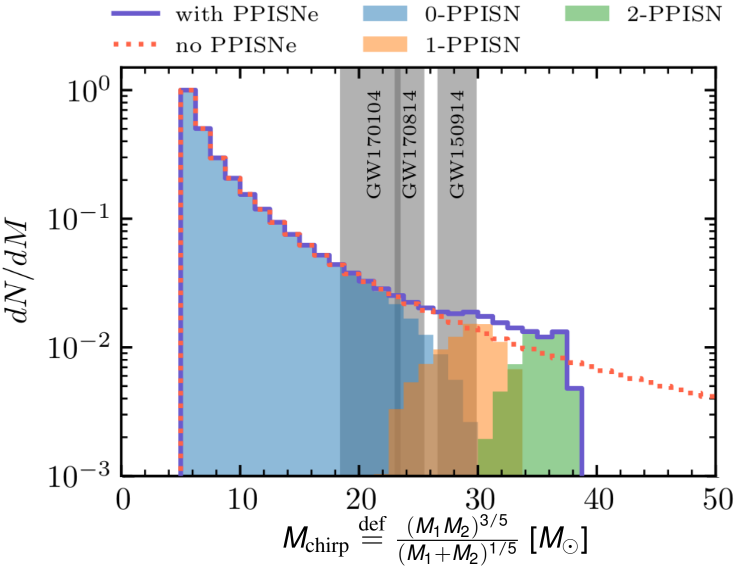
Chirp Mass Distribution



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

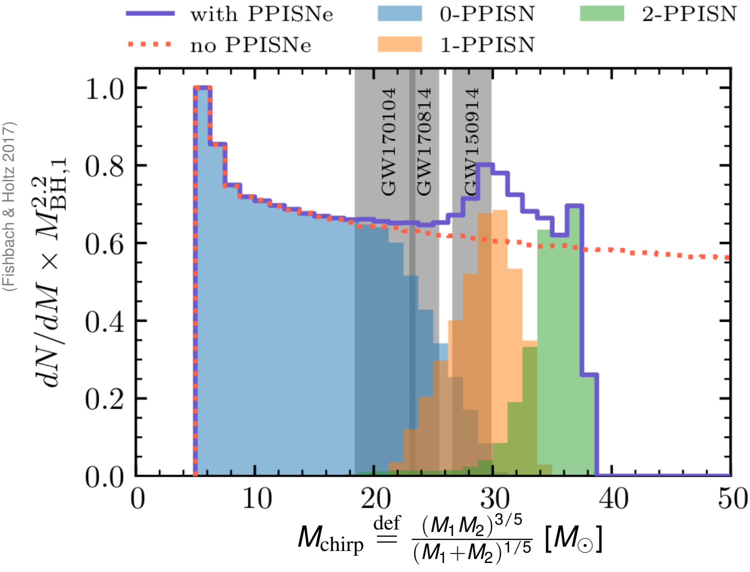
$$q \overset{\text{def}}{=} \frac{M_2}{M_1} \geq 0.5$$

(motivated by LVC 2016)

Chirp Mass

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

Chirp Mass Distribution



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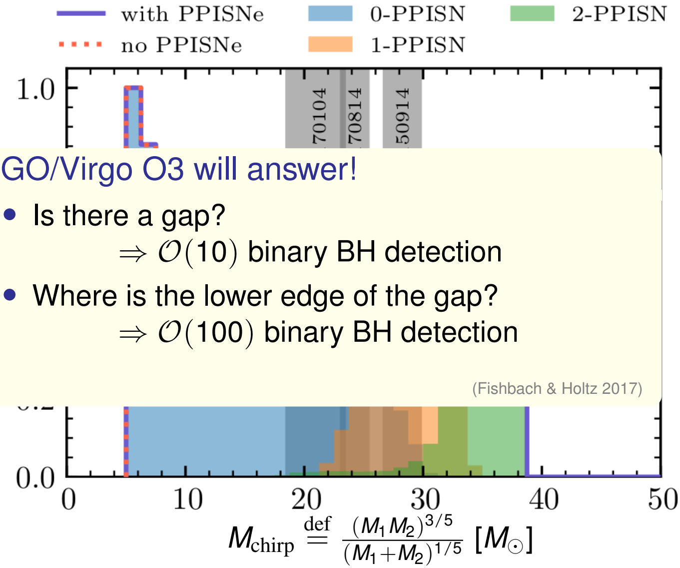
Chirp Mass Distribution

(Fishbach & Holtz 2017)



Chirp Mass

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)

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Outline

BH or NS?

- Single stars winds impact on the core structure

Keep the stars together

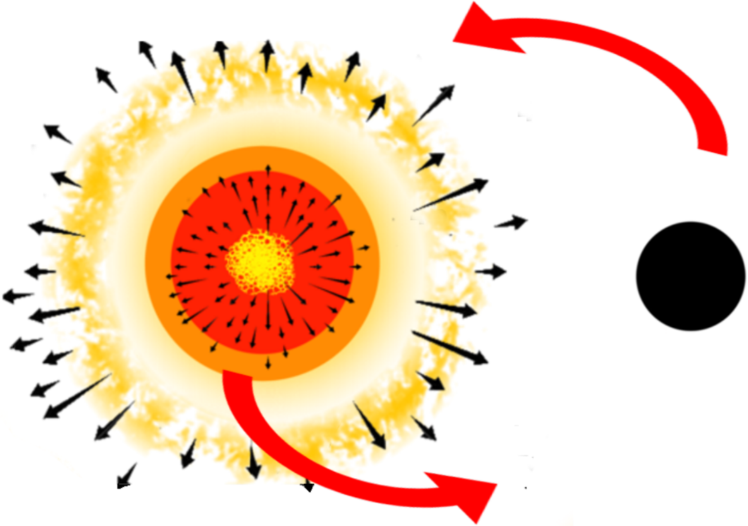
- The most common evolution for massive binaries
- Constraints on BH kicks using runaway “widow”

The most massive (stellar) BHs

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

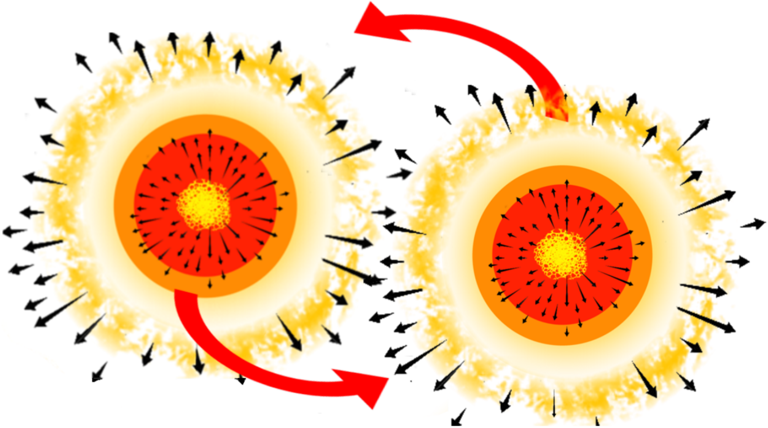
Conclusions

Post common envelope PPI



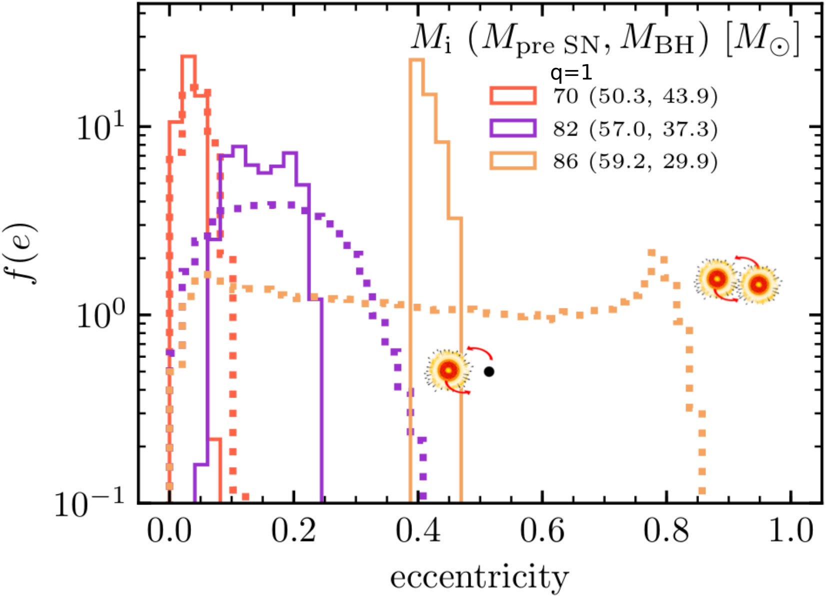
$$\Delta e = \frac{\Delta M}{M_1 + M_2 - \Delta M}$$

Two PPI in a binary



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

Eccentricity distribution



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

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Conclusions

Take home points

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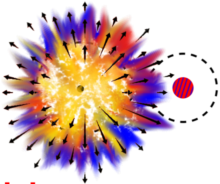
- **Uncertain wind mass loss rates influence the pre-SN core**

  ⇒ systematic bias in SN initial conditions and outcome?

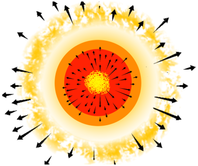


- **The vast majority of binaries are disrupted**

  ⇒ 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**

  ⇒ Signature on gravitational wave signals?
- **determines BH masses below PISN gap**

Take home points

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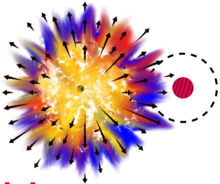

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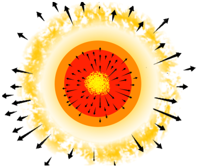


- **can modify binary orbit and remnant spin**

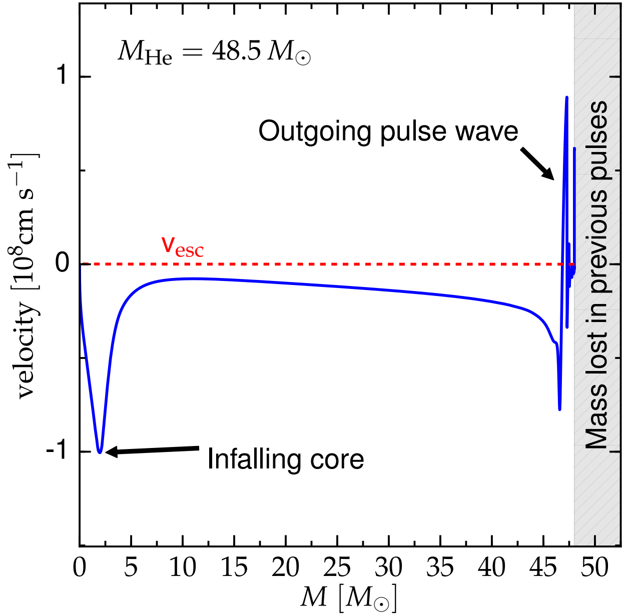
  ⇒ Signature on gravitational wave signals?
- **determines BH masses below PISN gap**

Thank you!

Outline

Backup slides

Upper-limits in BH mass



MESA grid of He PPI models

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How many pulses?

- as a function of He core mass

Number of pulses

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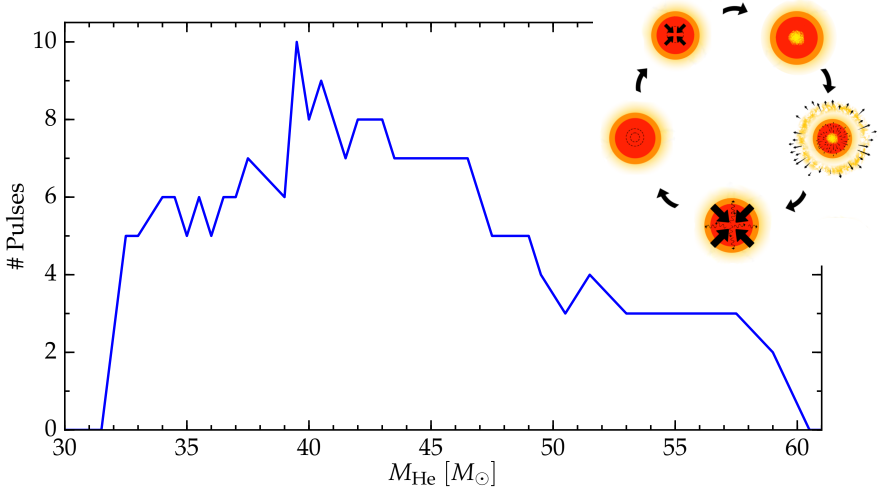

One pulse = One mass ejection

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

MESA grid of He PPI models

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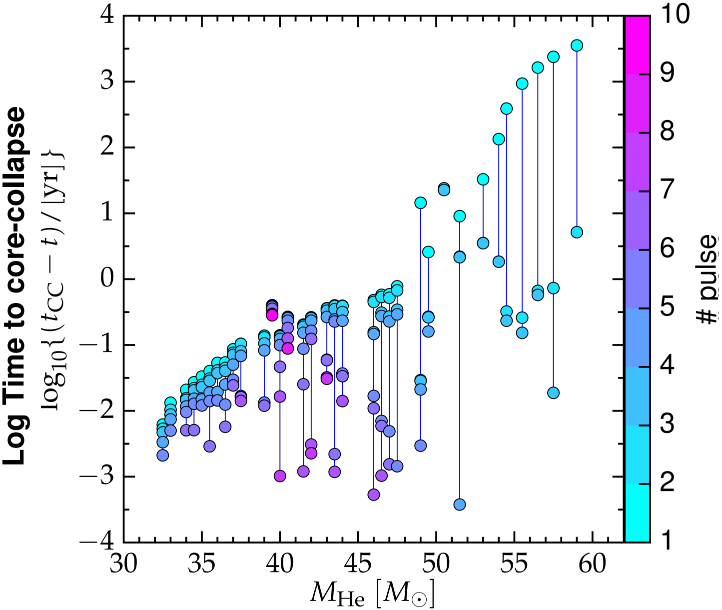
When do the pulsate?

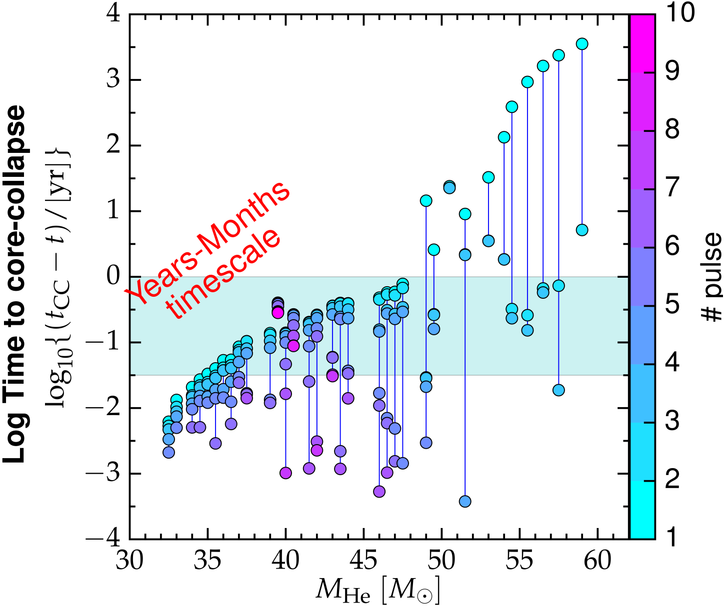
- as a function of He core mass

Pulses timing



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

Pulses timing



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

MESA grid of He PPI models

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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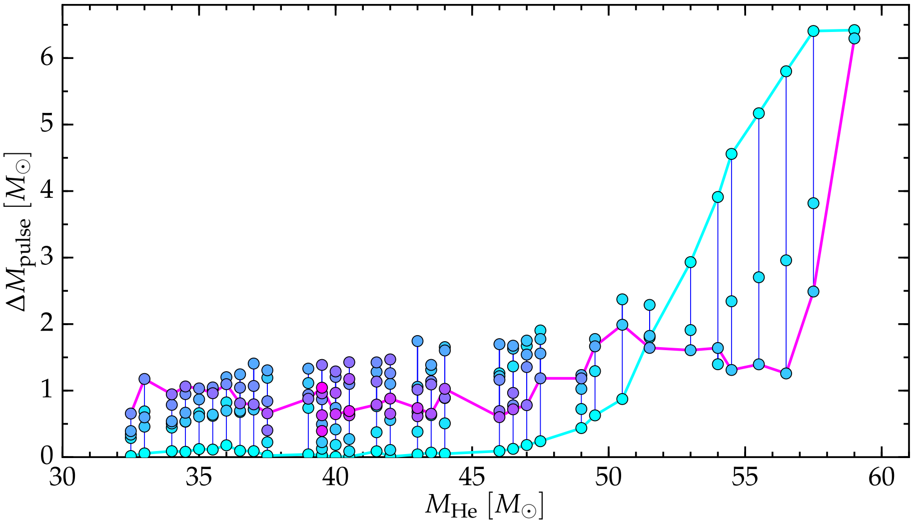
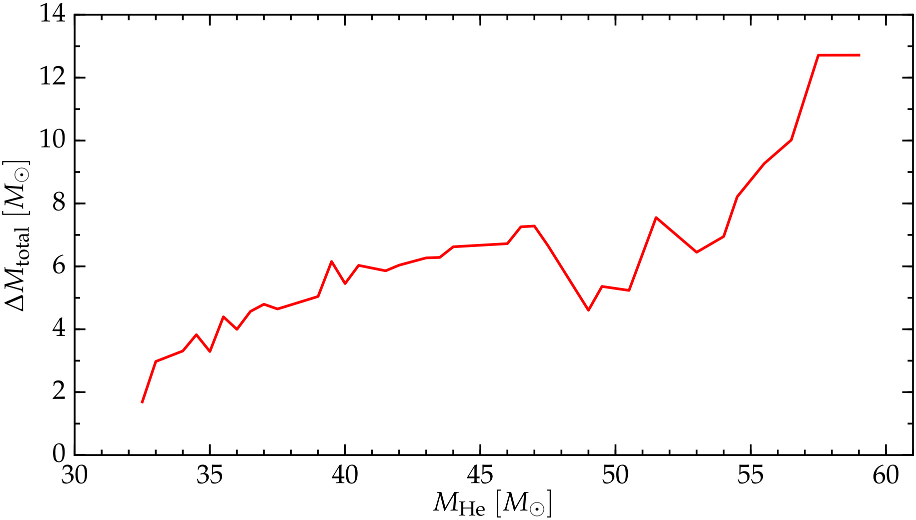


Renzo, Farmer *et al.*, to be submitted

Total mass lost



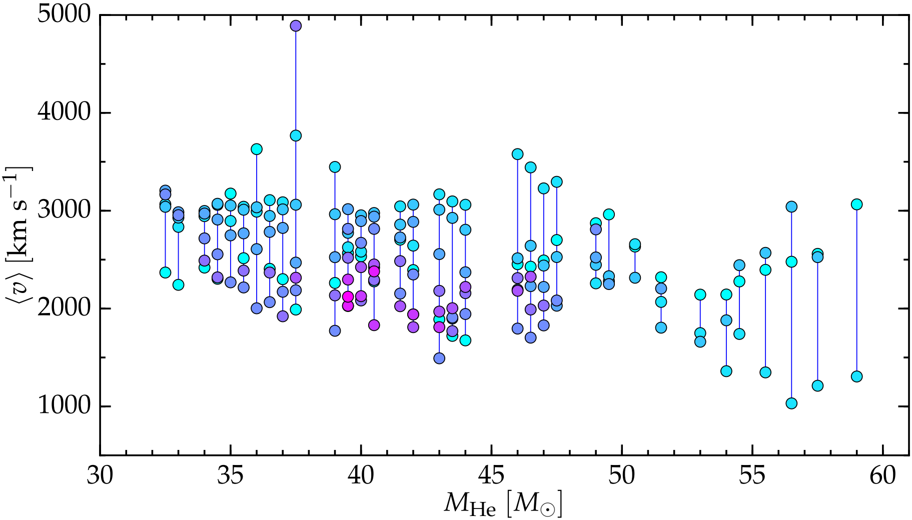
Renzo, Farmer *et al.*, to be submitted

MESA grid of He PPI models

How fast are the ejected shells?

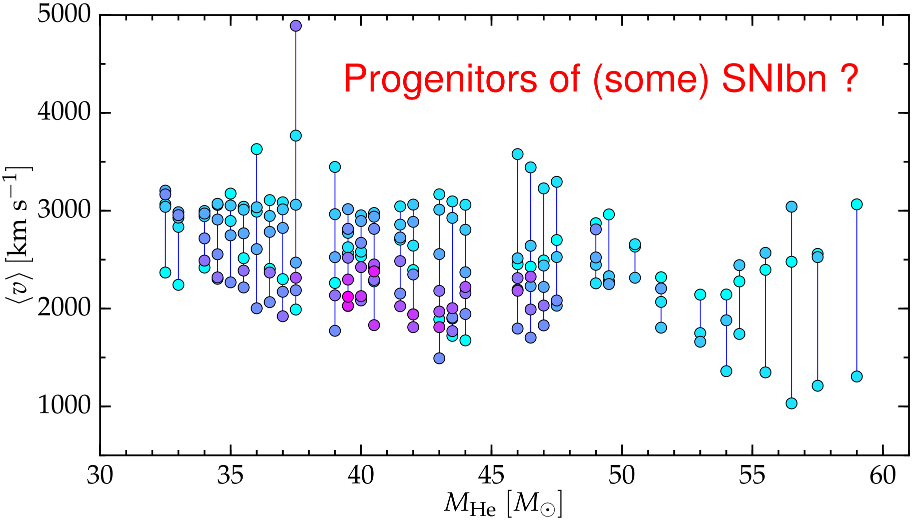
- as a function of He core mass

Center of mass velocity



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

Center of mass velocity



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

Can the mass shell collide?

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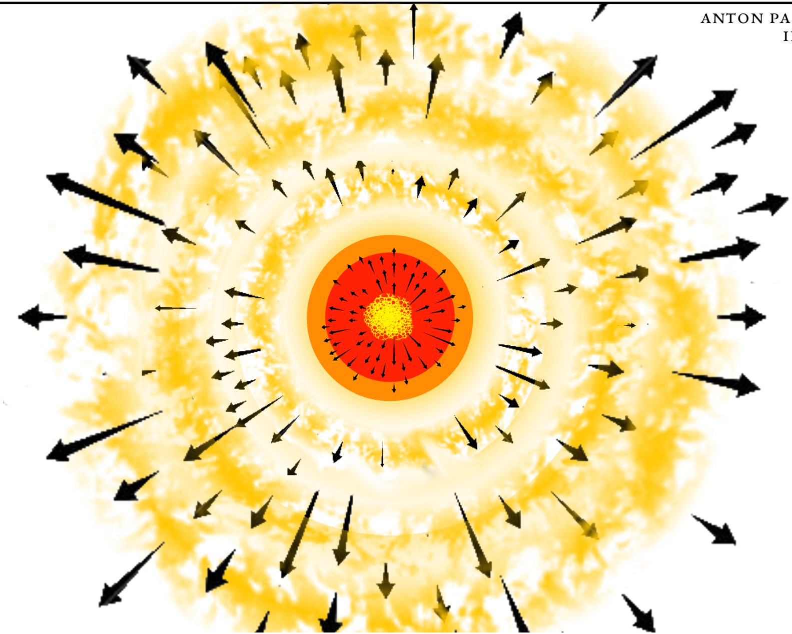

Woosley *et al* 07, Chen *et al.* 14, Woosley 17, Renzo, Farmer *et al.*, to be submitted

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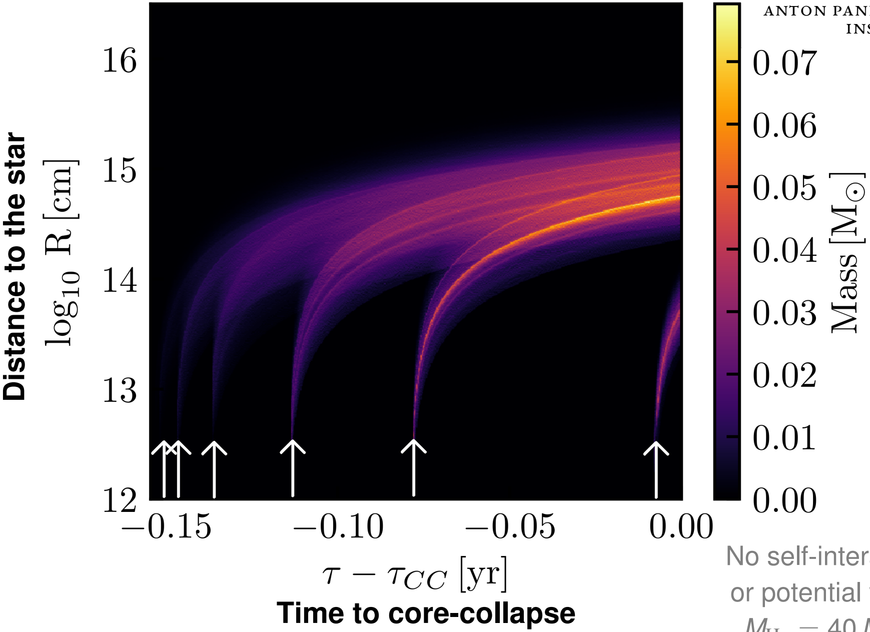
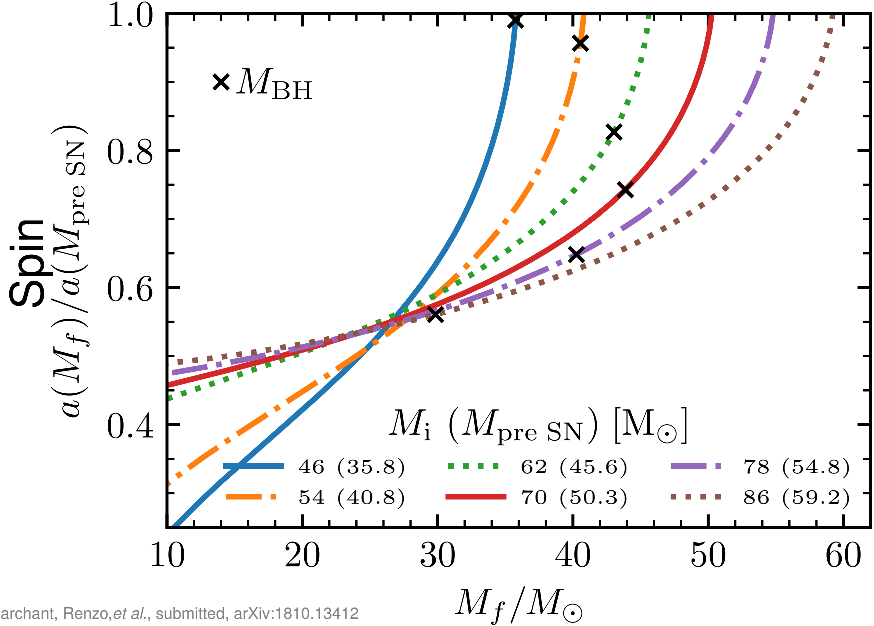


No self-interaction
or potential well
$M_{\mathrm{He}} = 40\,M_\odot$

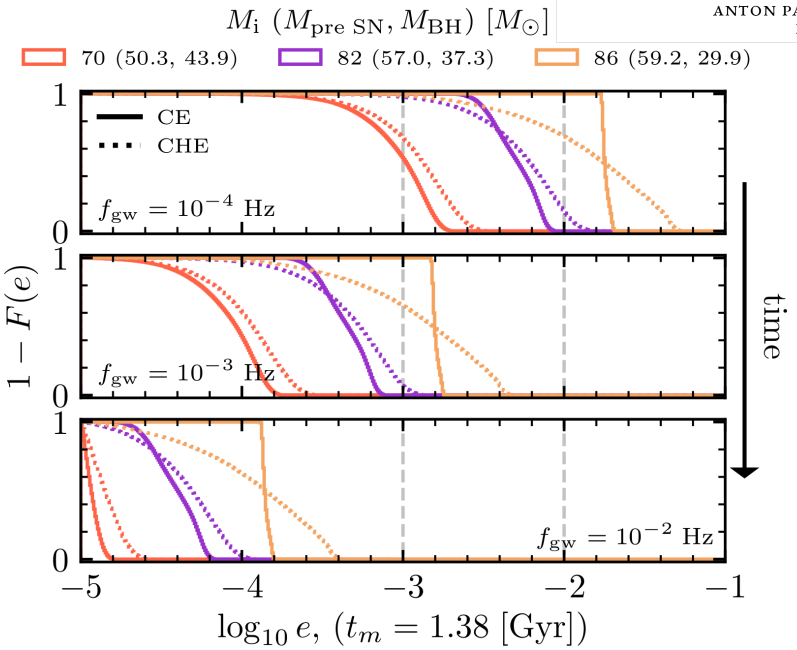
Renzo, Farmer *et al.*, to be submitted

Spin down due to PPI ejecta



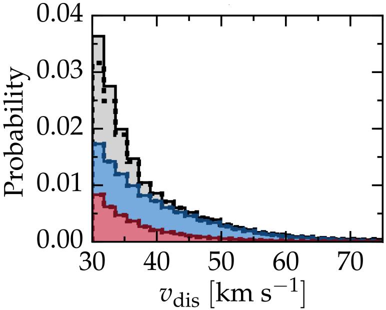
Marchant, Renzo, *et al.*, submitted, arXiv:1810.13412

GW circularization



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

Velocity distribution: Runaways



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

Velocity distribution: Walkaways

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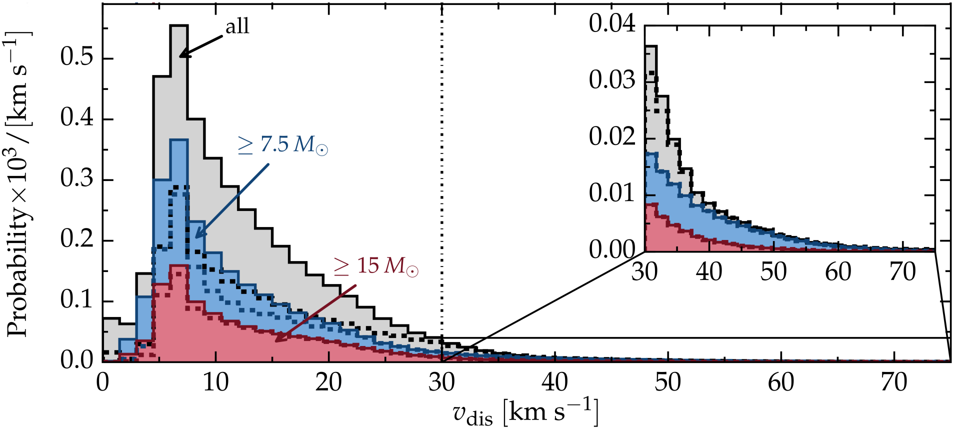
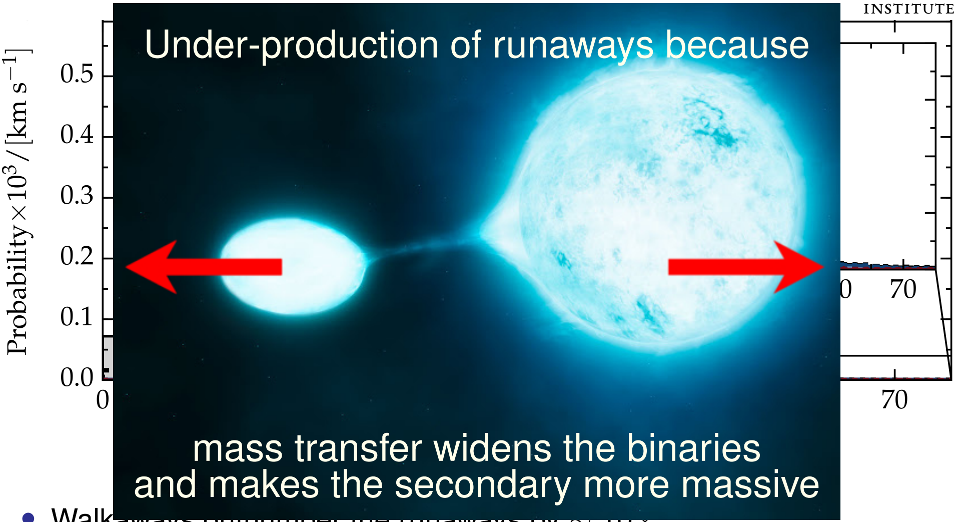


Take home points:

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

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

Velocity distribution: Walkaways



Under-production of runaways because

mass transfer widens the binaries
and makes the secondary more massive

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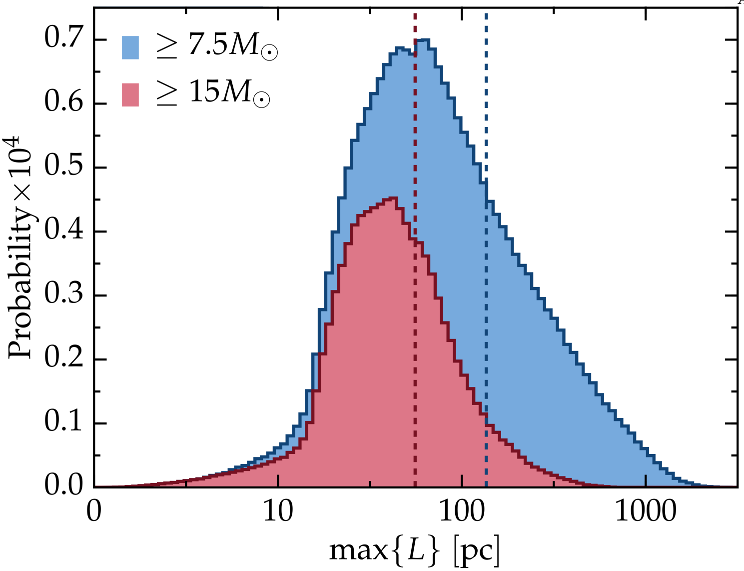
Renzo *et al.*, accepted, arXiv:1804.09164

How far do they get?



“Distance traveled”

(No potential well)

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