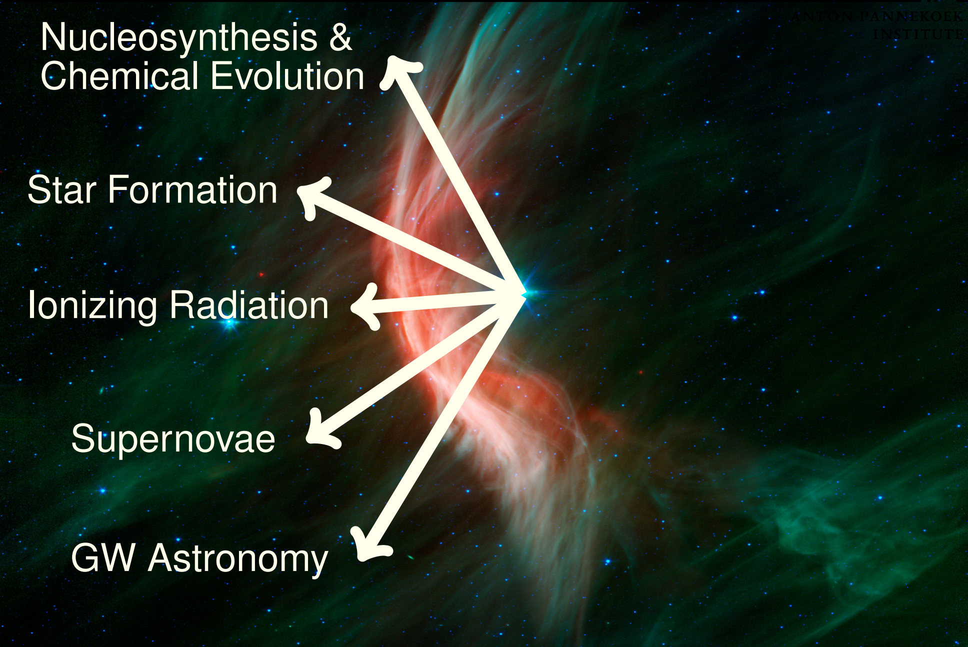
Explosions in massive binaries:

"widowed" stars and consequences for GW astronomy

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, D. J. Lennon, H. Sana, S. N. Shore

Why are massive stars important?



NASA, JPL-Caltech, Spitzer Space Telescope

Why are massive stars important?

Nucleosynthesis & Chemical Evolution

Star Formation

Ionizing Radiation

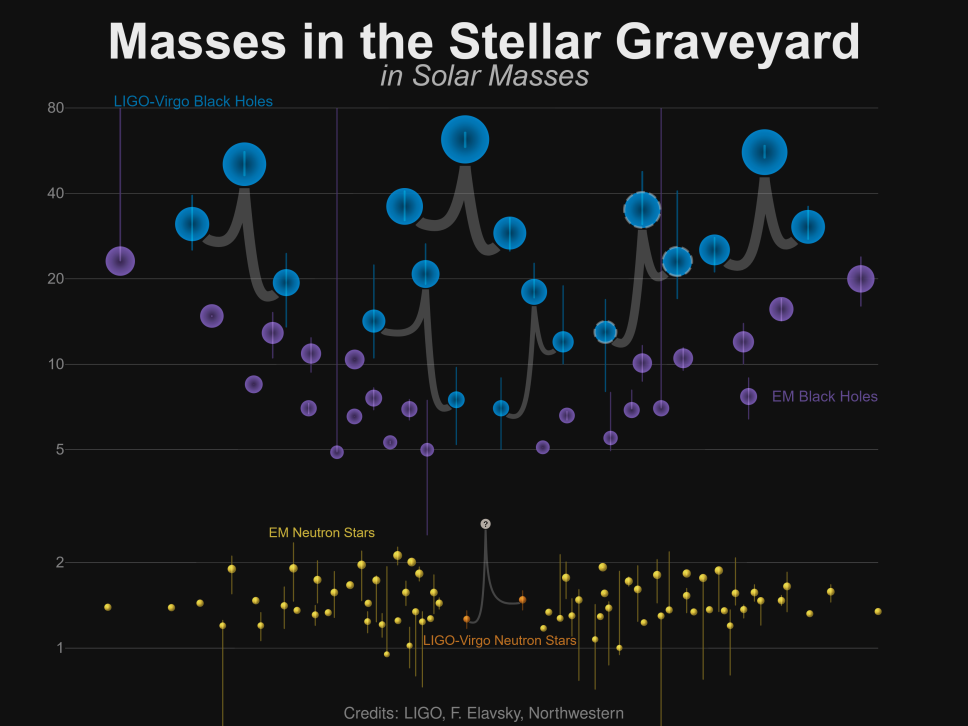
Supernovae

GW Astronomy

∼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
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
80
40
20
10
5
2
1
?
Credits: LIGO, F. Elavsky, Northwestern

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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
- Post-pulsations BH spins

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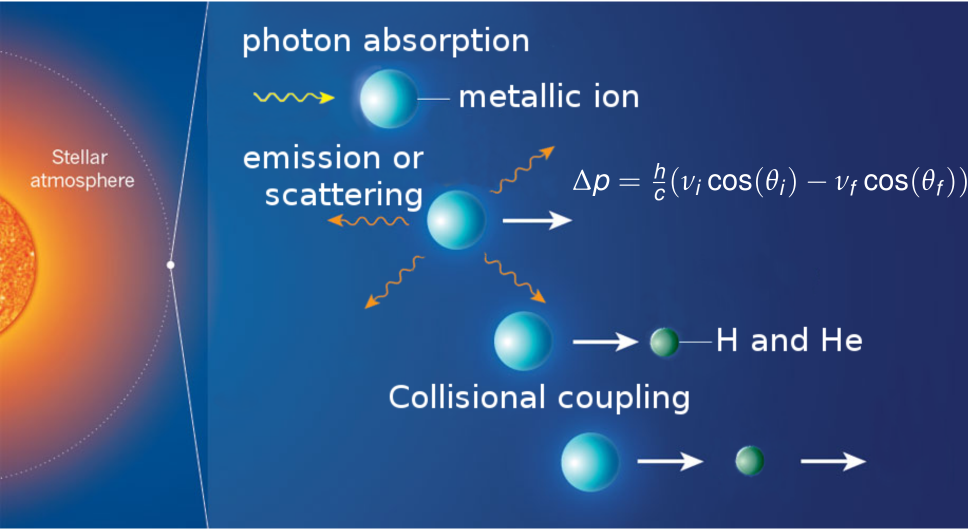
Radiatively Driven Winds in One Slide



Problems: High Non-Linearity and Clumpiness

Clumpiness

Inhomogeneities:

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

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Risk:

Possible overestimation of the wind mass loss rate

Inhomogeneities:

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

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

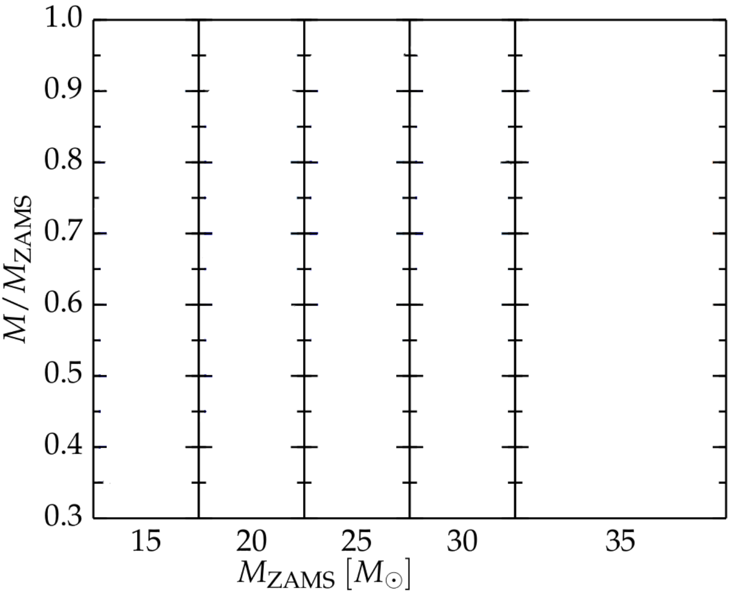
$$M_{\rm ZAMS} = \{15,\ 20,\ 25,\ 30,\ 35\}\ M_\odot$$

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

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

Impact on the final mass



MESA

Legend:

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

$\eta \rightarrow$ largest uncertainty

Impact on the final mass

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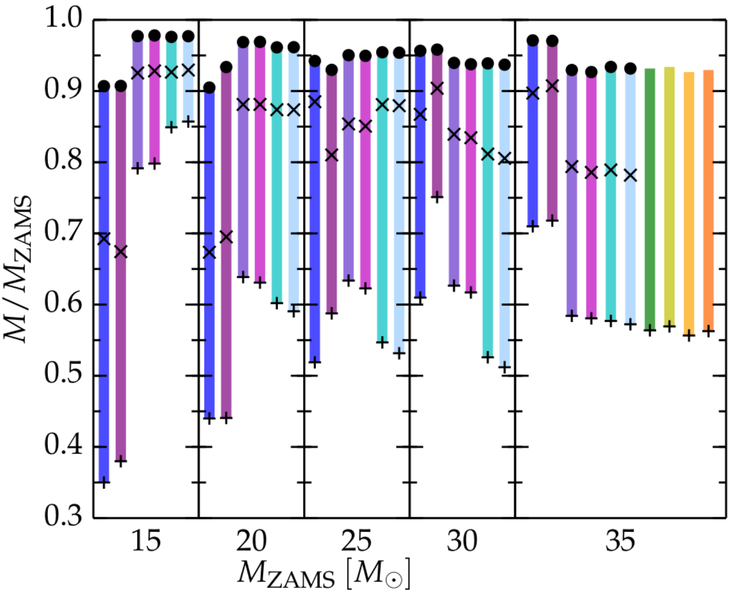

MESA

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Renzo *et al.* '17

Pre-explosion appearance

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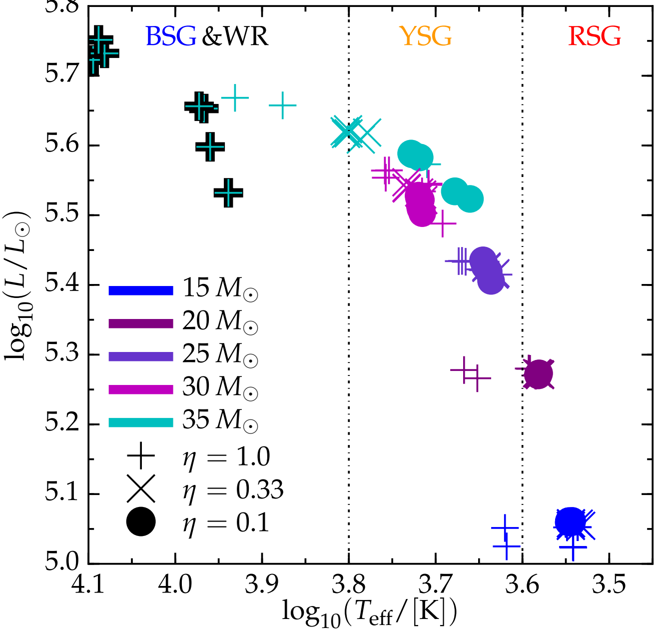


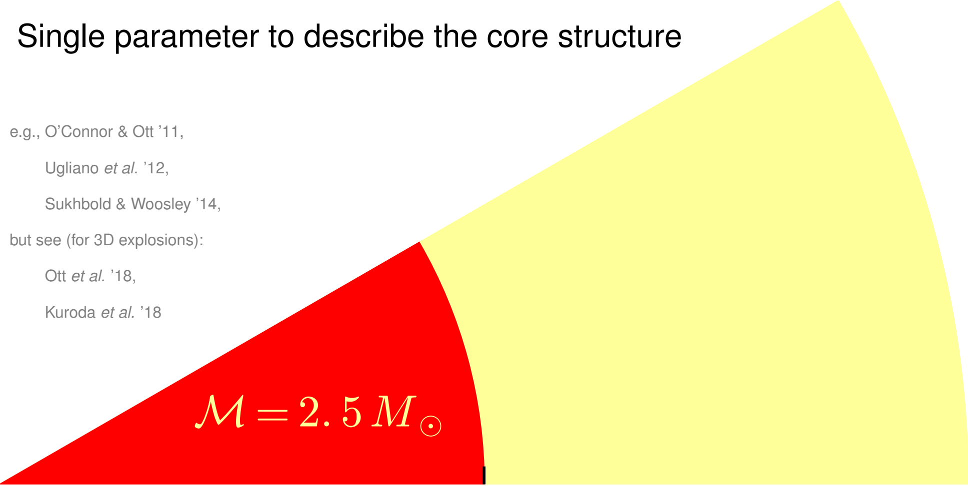
Renzo *et al.* '17

“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

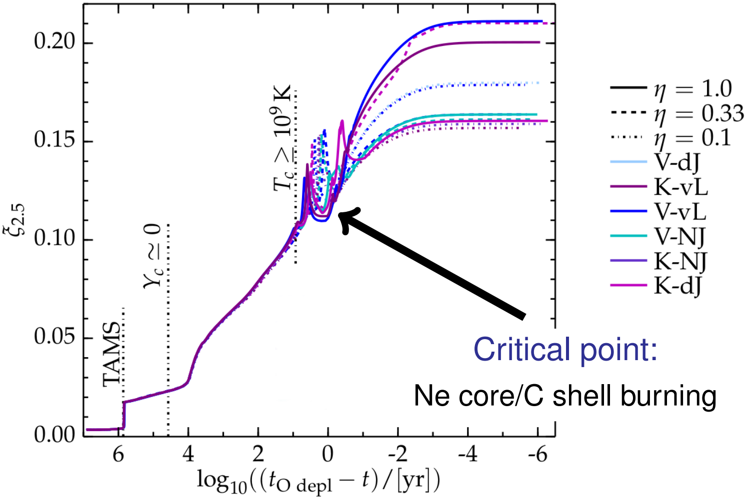
e.g., O’Connor & Ott ’11,
Ugliano *et al.* ’12,
Sukhbold & Woosley ’14,
but see (for 3D explosions):
Ott *et al.* ’18,
Kuroda *et al.* ’18



not to scale!

Core structure at O depletion

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



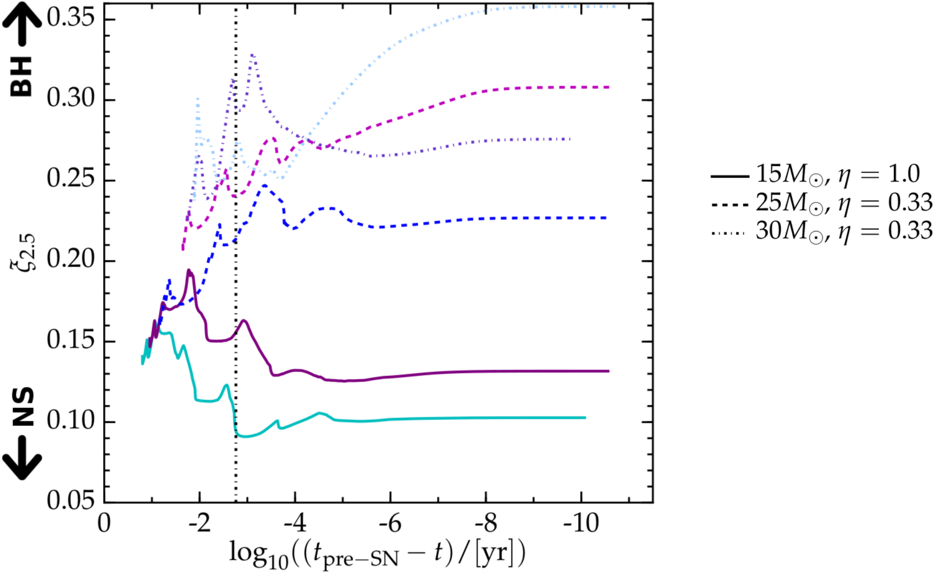
Critical point:

Ne core/C shell burning

Log time to O depletion

Post O burning evolution

Si shell burning →



Renzo *et al.* '17

Log time to core-collapse

Post O burning evolution

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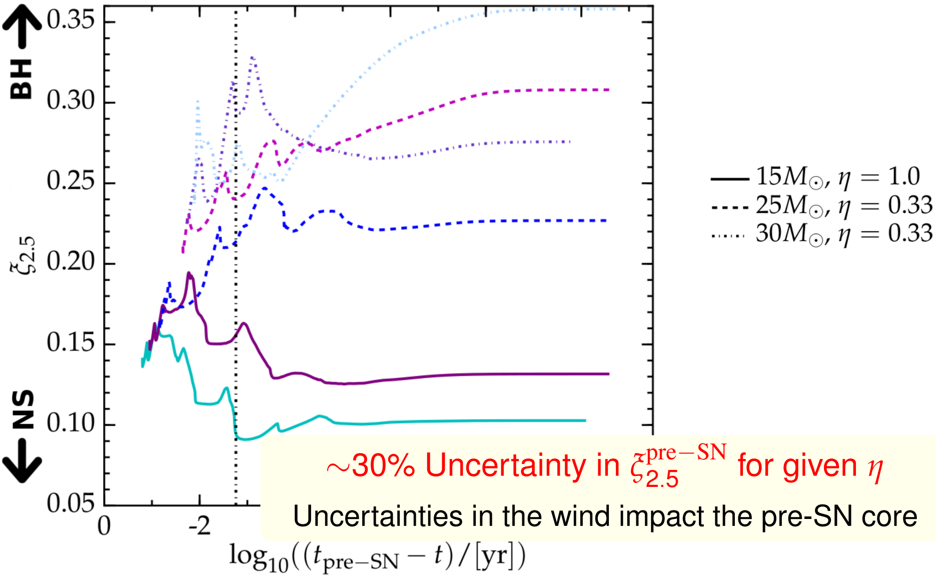
Si shell burning →



~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

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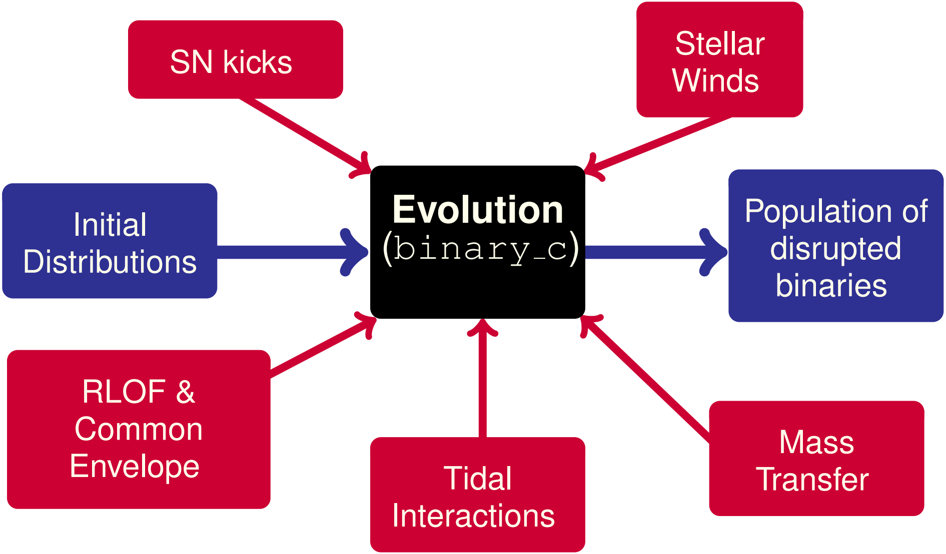
Fast ⇒ Allows statistical tests of the inputs & assumptions



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

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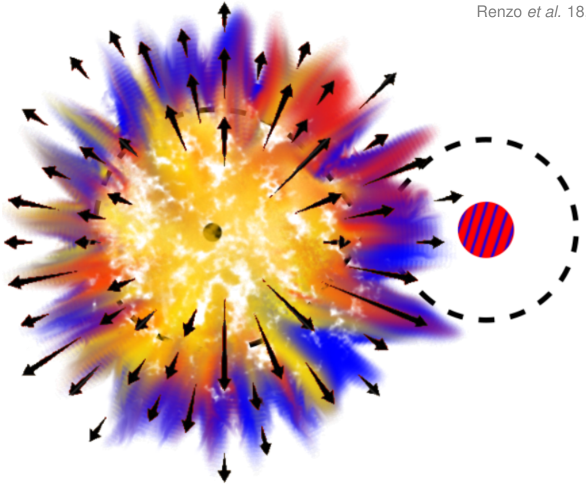
86^{+11}_{-9}% of massive binaries are disrupted

Renzo *et al.* 18, arXiv:1804.09164



- 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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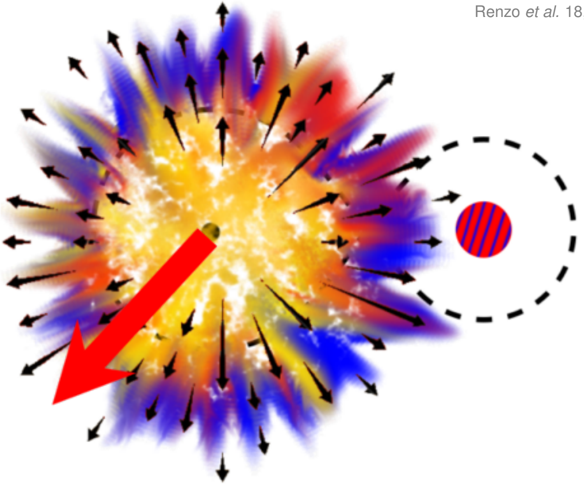

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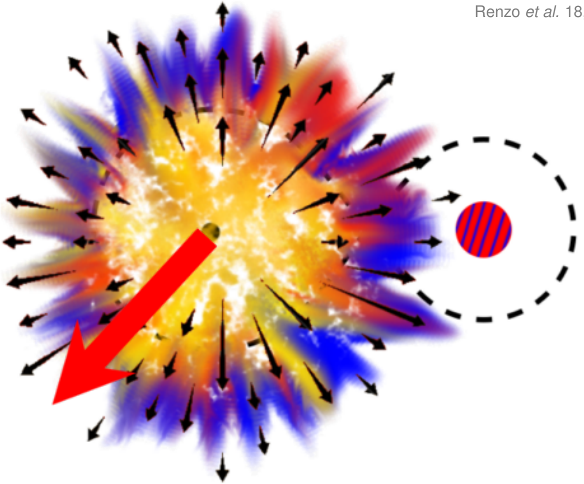

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  (e.g., Shklovskii '70, Janka '16)

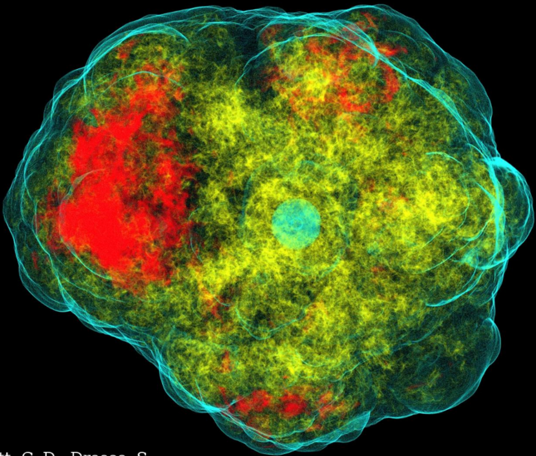
$$v_{\mathrm{dis}} \simeq v_{2,\mathrm{orb}}^{\mathrm{pre-SN}} = \frac{M_1}{M_1+M2}\sqrt{\frac{G(M_1+M2)}{a}}$$

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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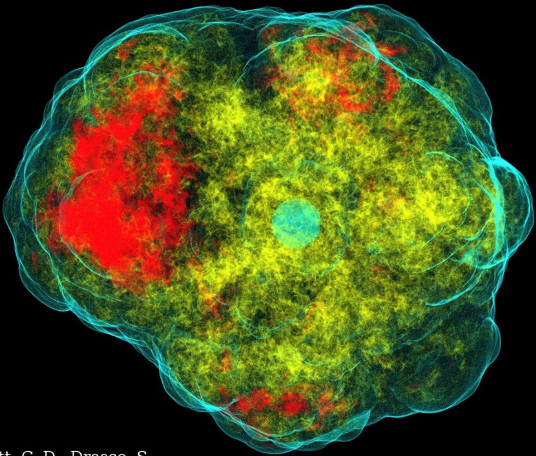

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BH kicks?

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A way to constrain BH kicks with *Gaia*

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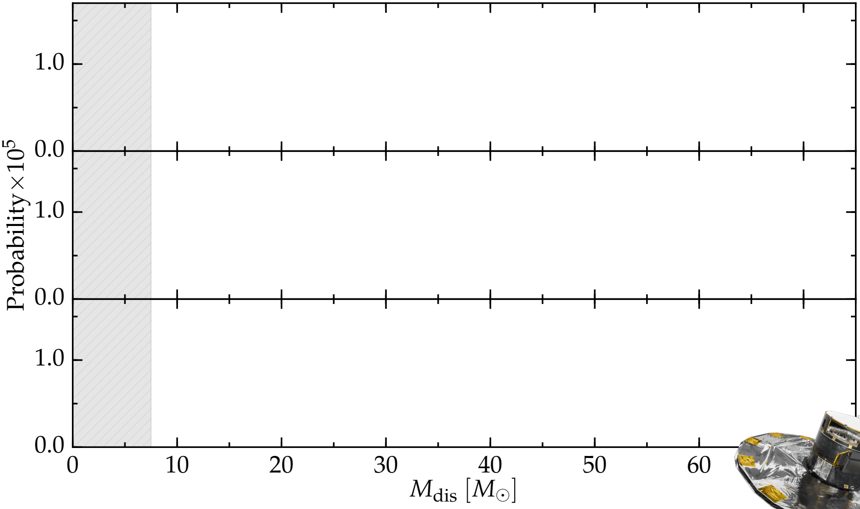
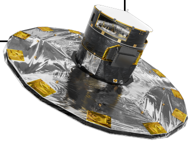
Massive runaways mass function ($v \geq 30\,\mathrm{km\ s^{-1}}$, $M \geq 7.5\,M_\odot$)





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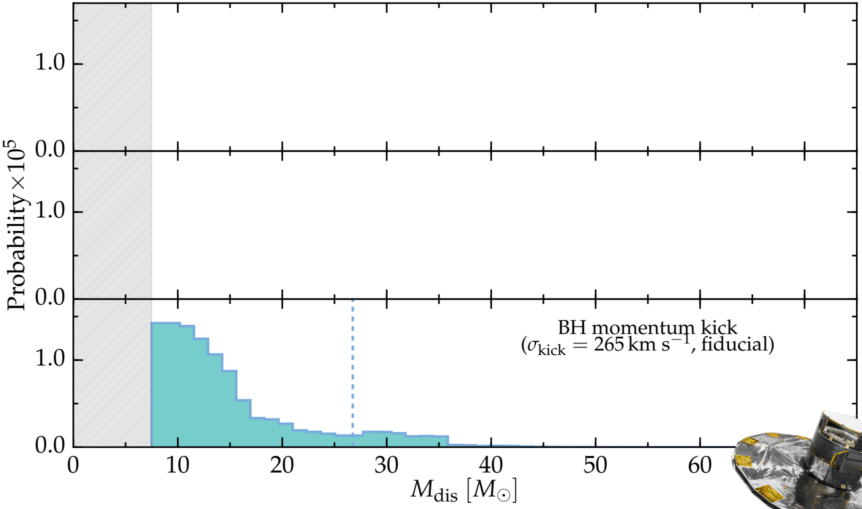

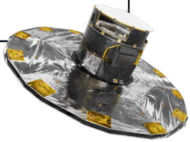

gaia

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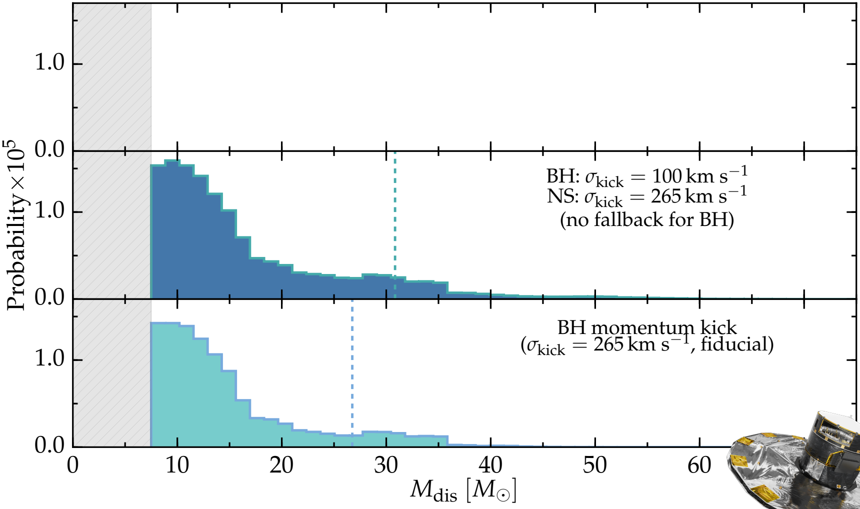

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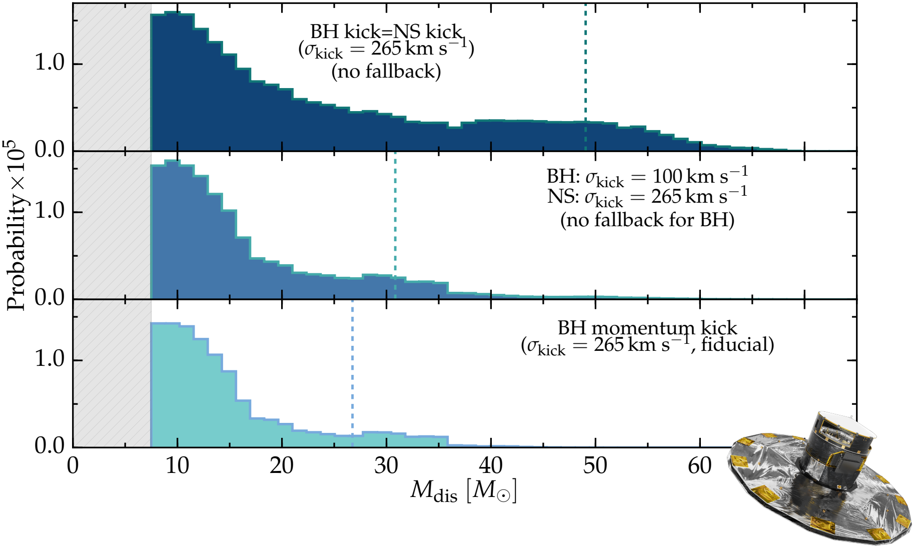

gaia

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Radiation dominated:

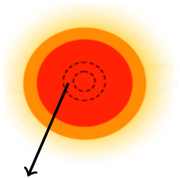
$$P_{\mathrm{tot}} \simeq P_{\mathrm{rad}}$$

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

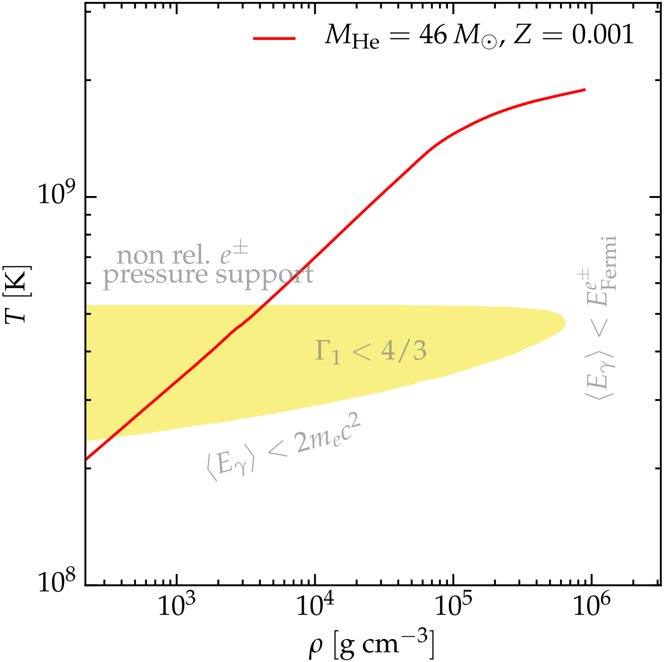
Woosley 2017,

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

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

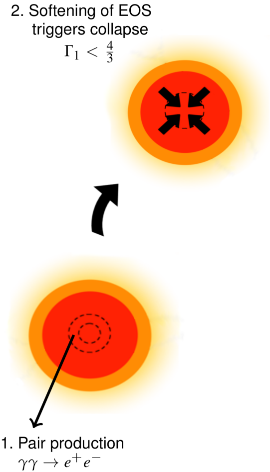


$$\Gamma_1 \stackrel{\mathrm{def}}{=} \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$$



He core computed with MESA

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

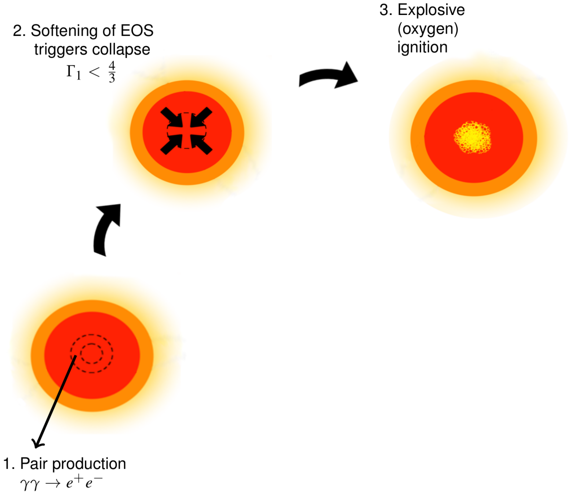


Thermal timescale

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

(Fraley 68)

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



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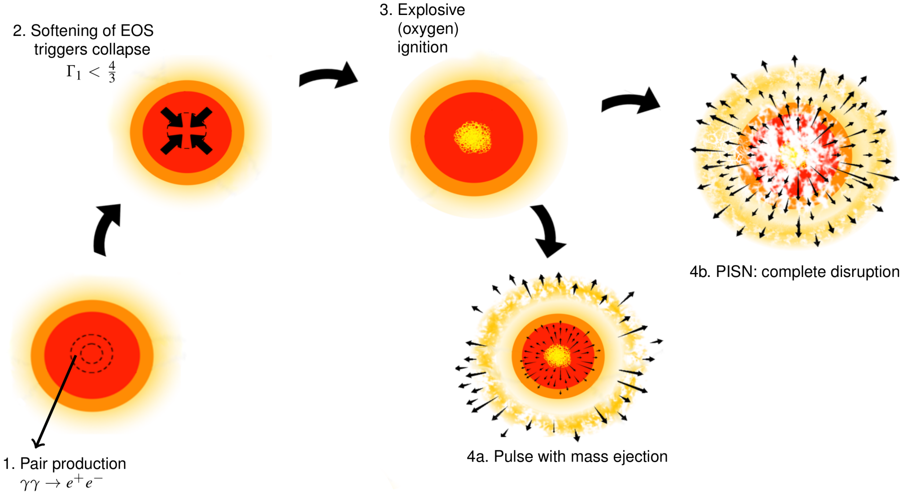

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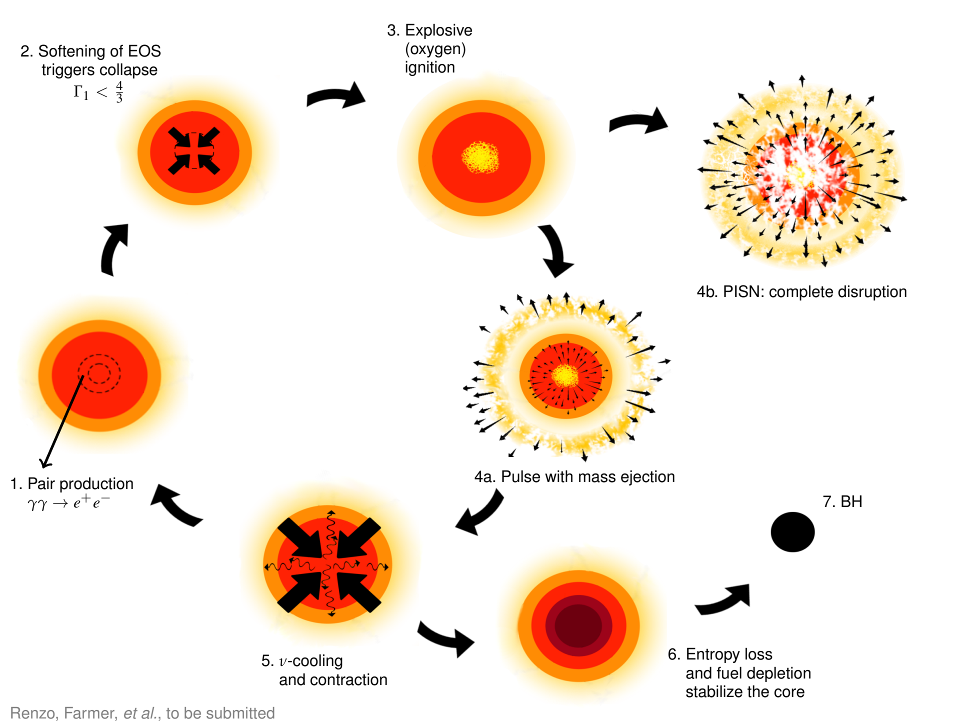
2. Softening of EOS
triggers collapse
$\Gamma_1 < \frac{4}{3}$
3. Explosive
(oxygen)
ignition
4b. PISN: complete disruption
4a. Pulse with mass ejection
1. Pair production
$\gamma\gamma \rightarrow e^+e^-$
7. BH
5. ν-cooling
and contraction
6. Entropy loss
and fuel depletion
stabilize the core
Renzo, Farmer, *et al.*, to be submitted

Example: 40 $M_\odot$ He core

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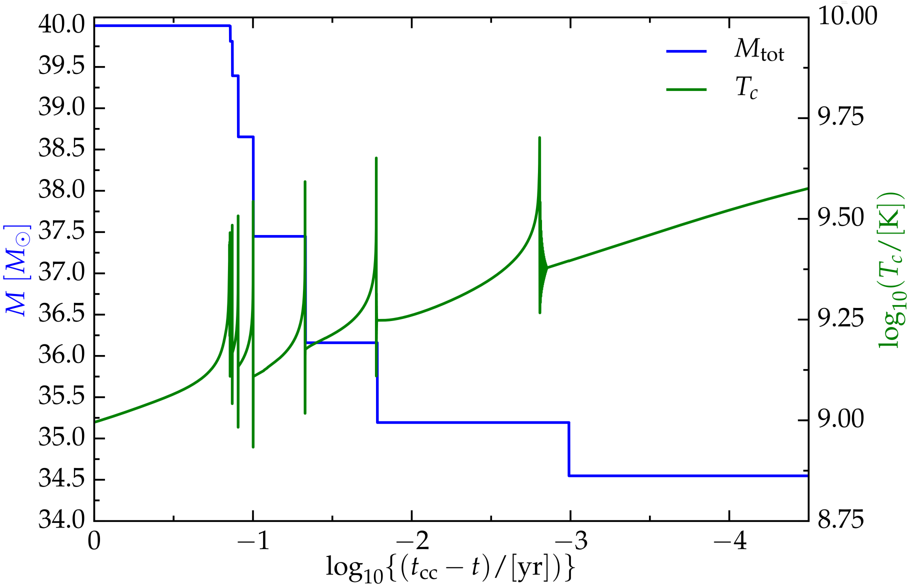

Log Time to core-collapse

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

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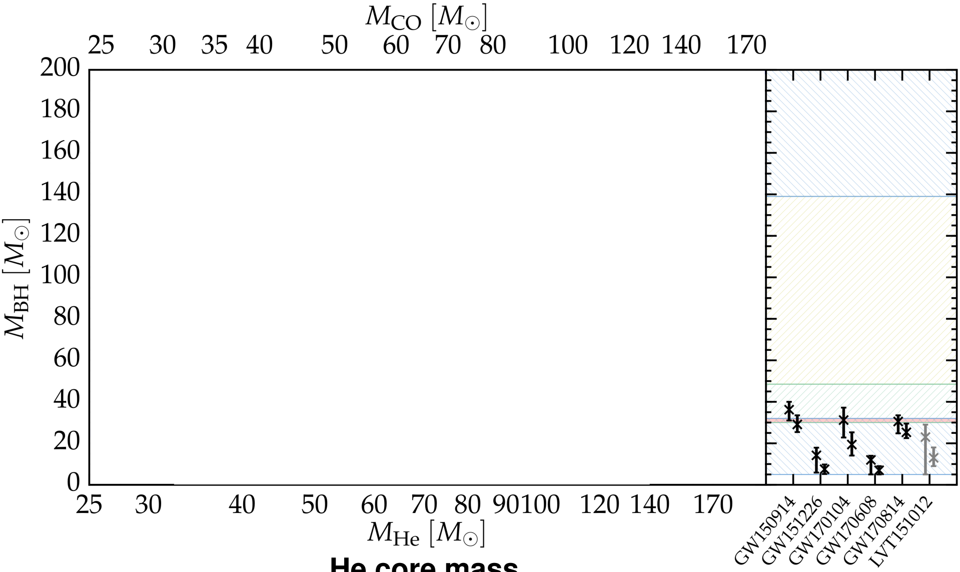
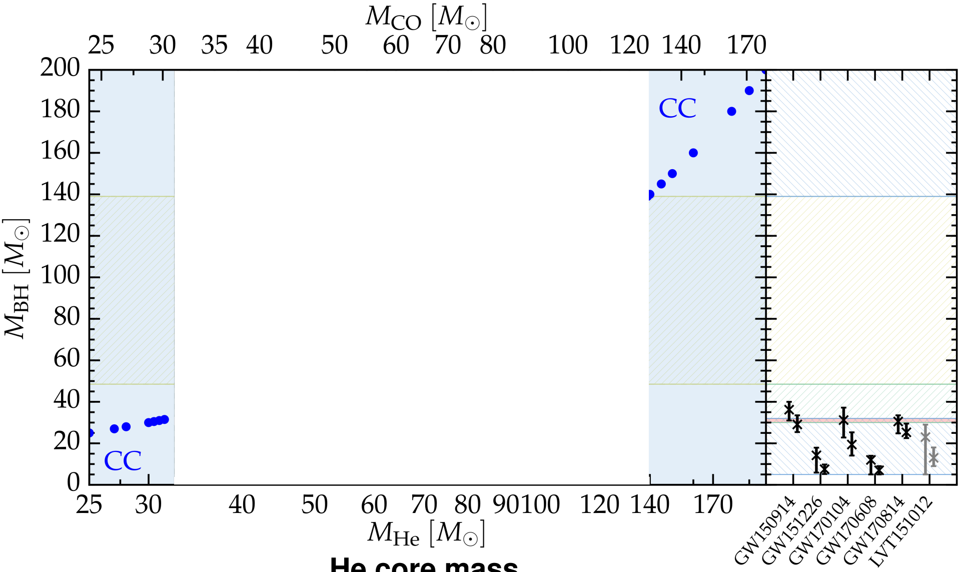


He core mass

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

The origin of very massive BHs



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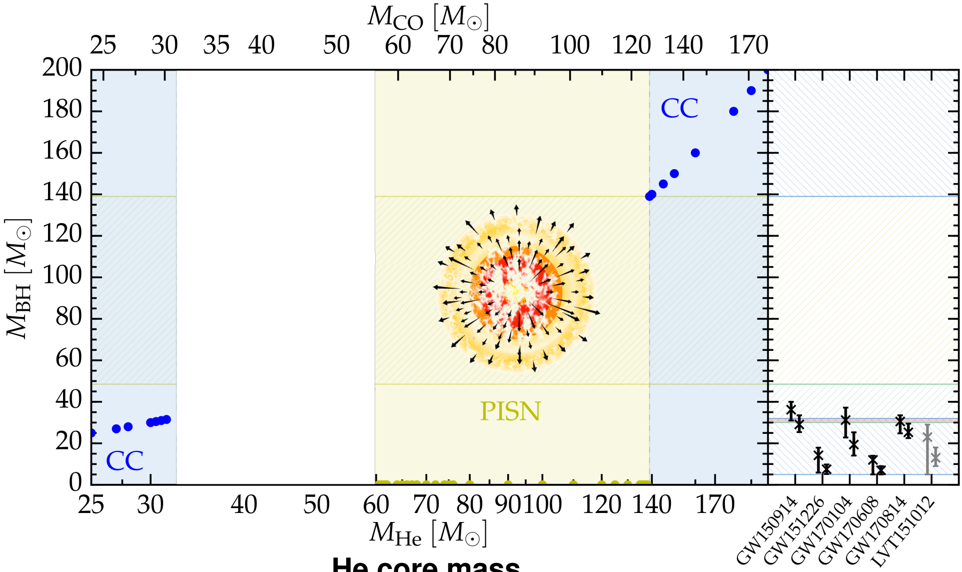

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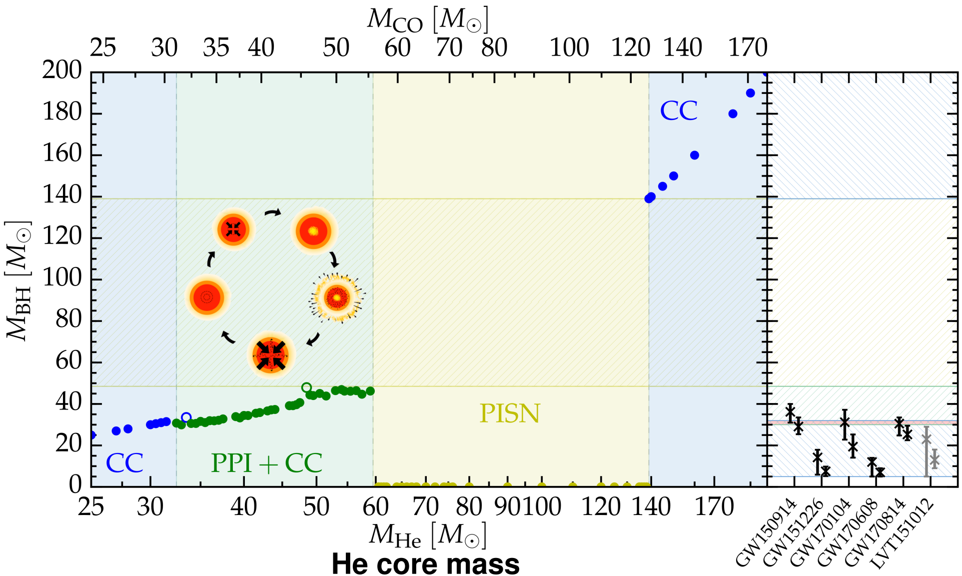

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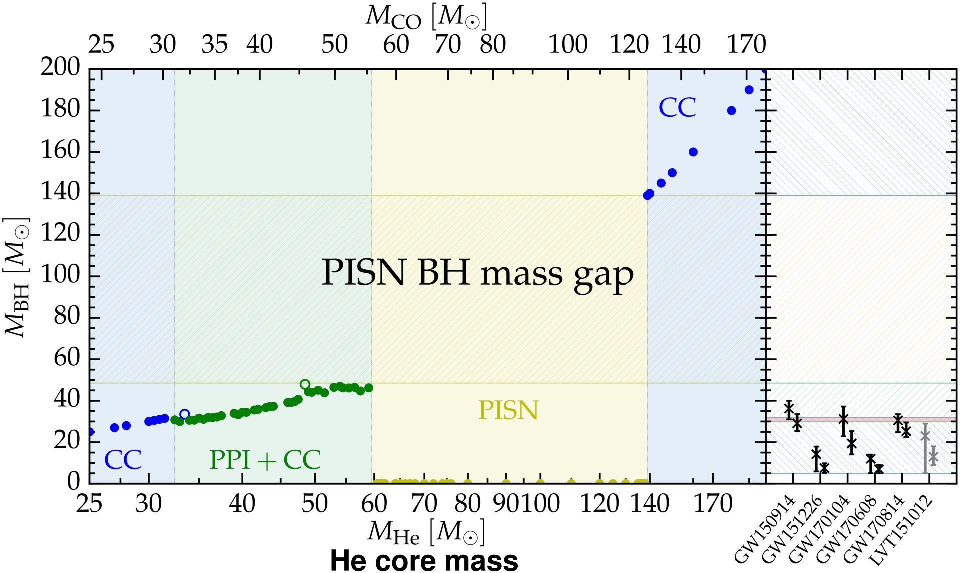

He core mass

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

BH mass function

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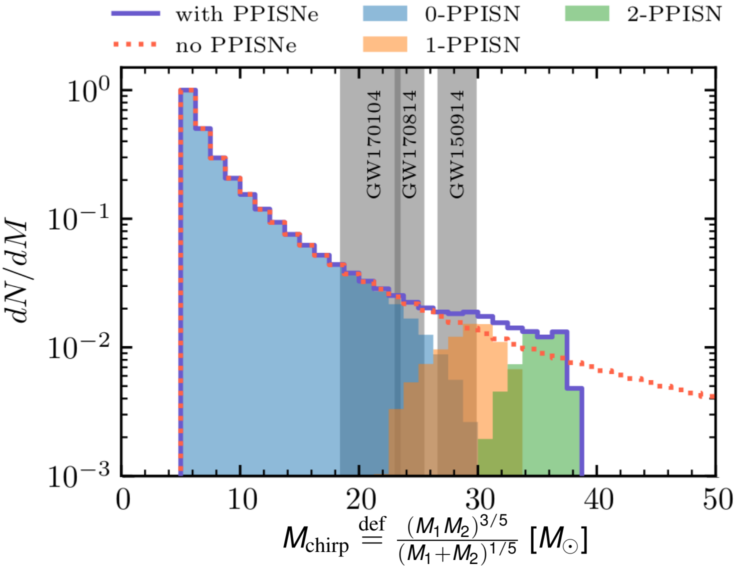


Chirp Mass

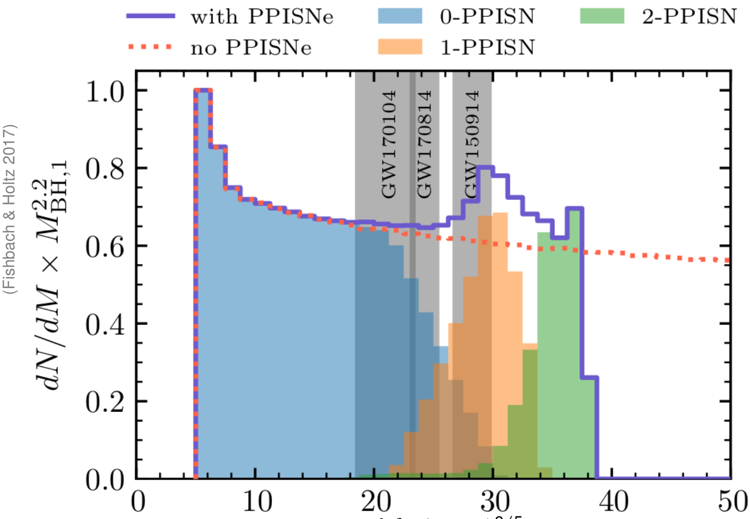
$$\frac{dN}{dM_{\rm BH}} \propto M_{\rm BH}^{-2.35}$$

$$q \geq 0.5$$

(motivated by LVC 2016)

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

BH mass function



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

Chirp Mass

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

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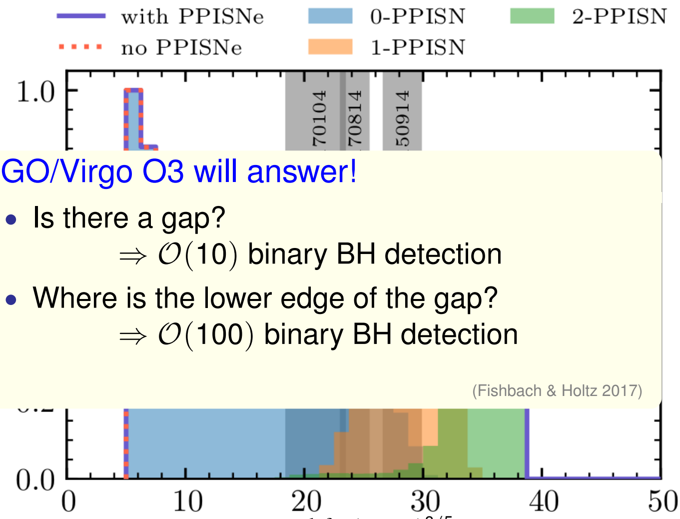

$M_{\rm chirp} \stackrel{\rm def}{=} \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}}\ [M_\odot]$

Chirp Mass

(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)

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

$$q \geq 0.5$$

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PPI in a binary

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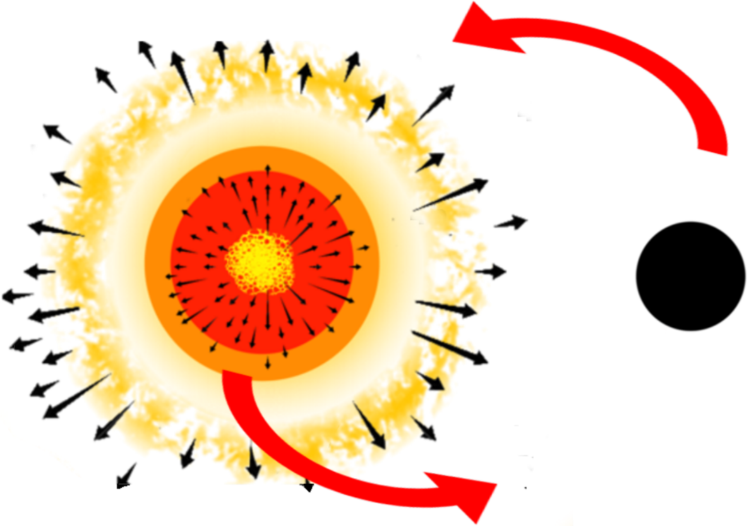

$$\Delta e = \frac{\Delta M}{M_1 + M_2 - \Delta M}$$

Two PPI in a binary

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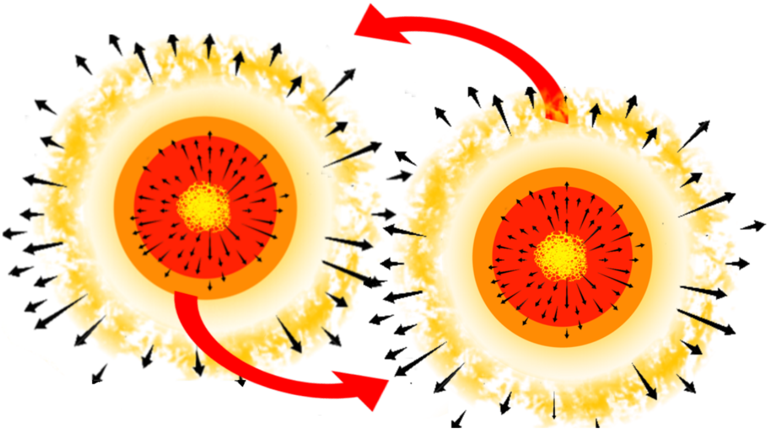

$$\Delta e = \frac{\Delta M}{M_1 + M_2 - \Delta M}$$

Eccentricity distribution

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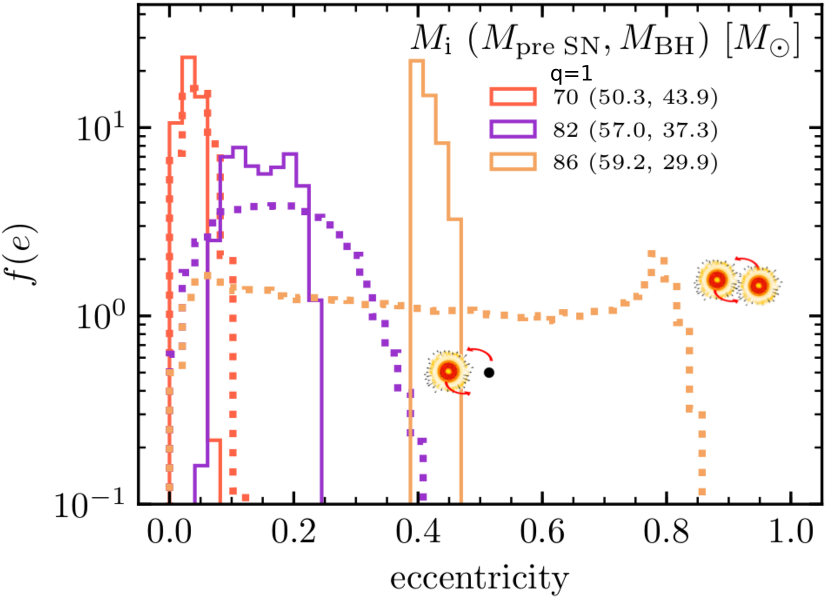

Marchant, Renzo, *et al.*, submitted, arXiv:1810.13412

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BH or NS?

- Single stars winds impact on the core structure

Keep the stars together

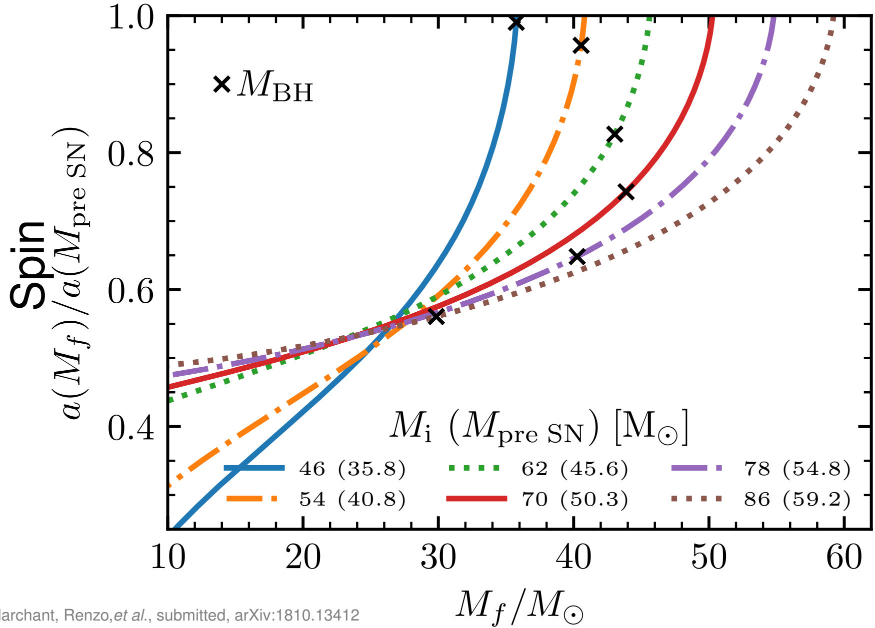
- The most common evolution for massive binaries
- Constraints on BH kicks using runaway “widow”

The most massive (stellar) BHs

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

Conclusions

Spin down due to PPI ejecta



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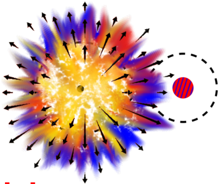
Conclusions

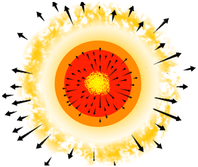
Take home points

- **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 2^{nd} gap**

Take home points

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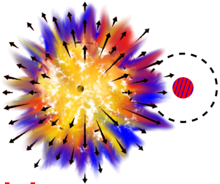

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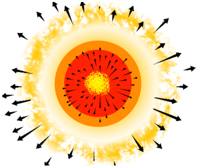

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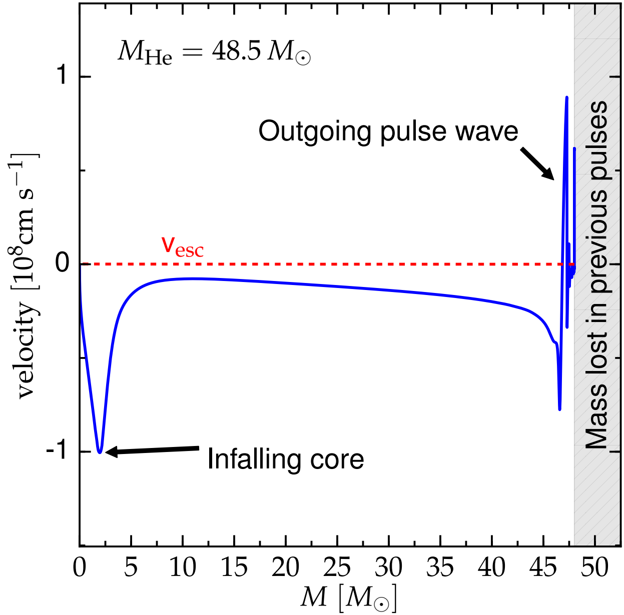
Thank you!

Backup slides

Upper-limits in BH mass



How many pulses?

- as a function of He core mass

Number of pulses

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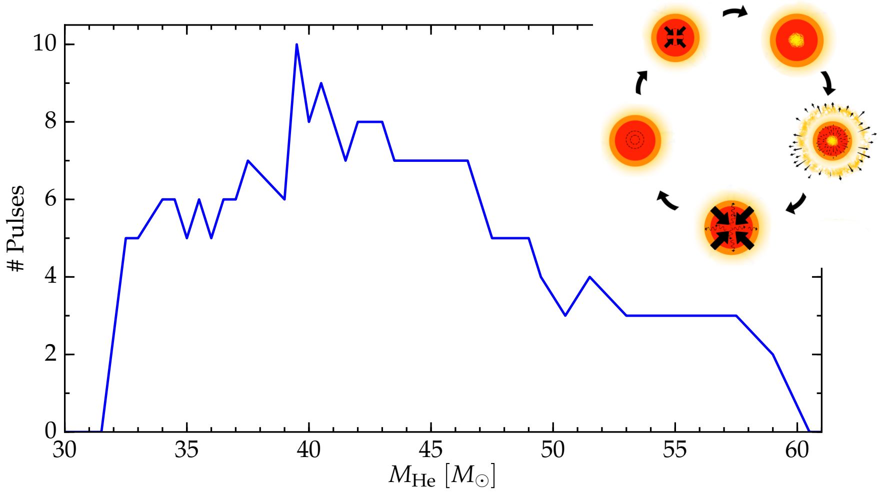

One pulse = One mass ejection

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

When do the pulsate?

- as a function of He core mass

Pulses timing

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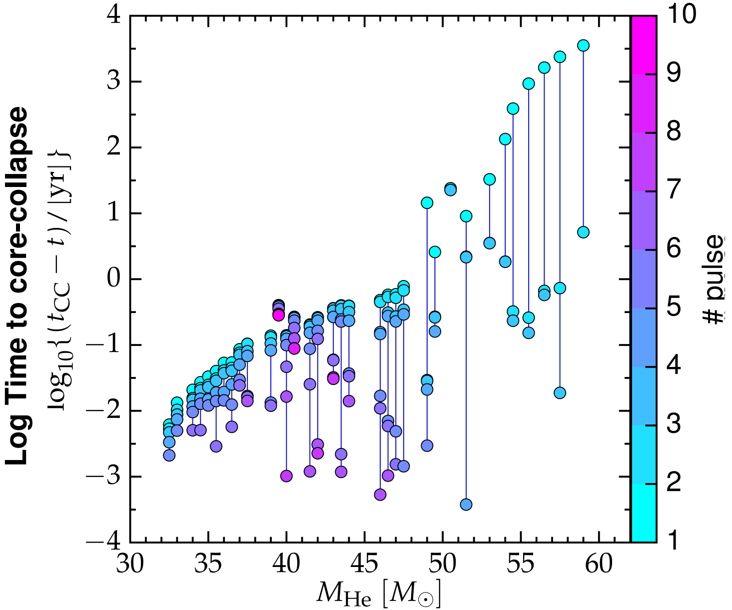

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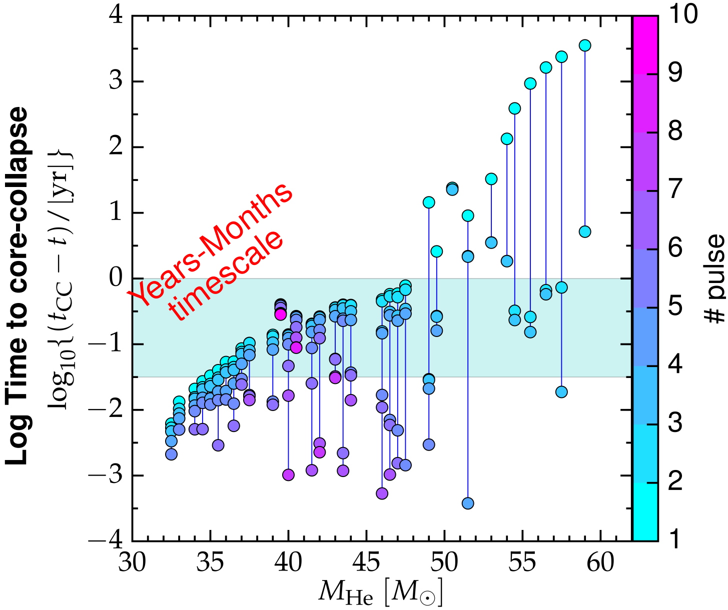
Pulses timing



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

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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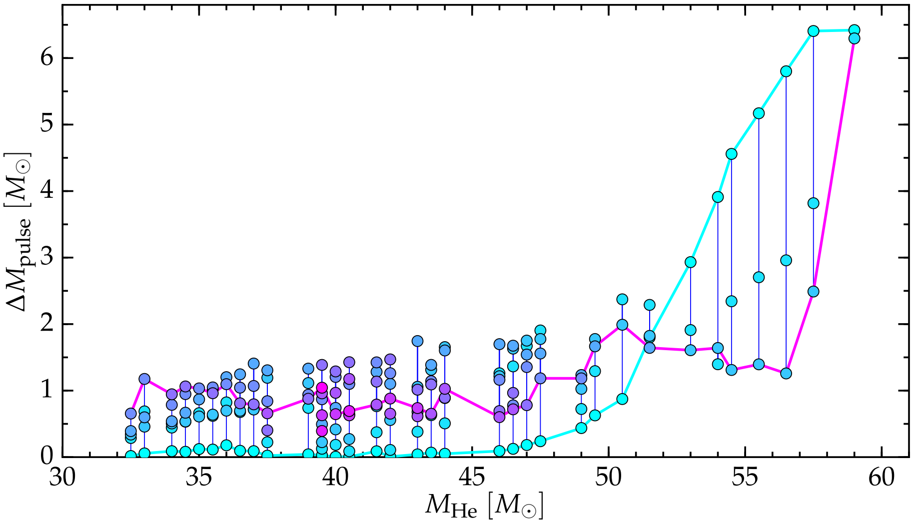
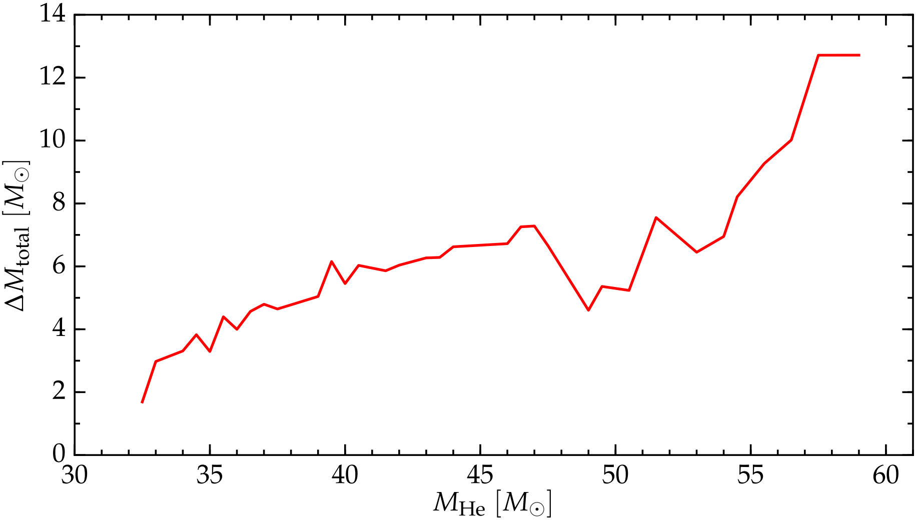


Renzo, Farmer *et al.*, to be submitted

Total mass lost



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How fast are the ejected shells?

- as a function of He core mass

Center of mass velocity

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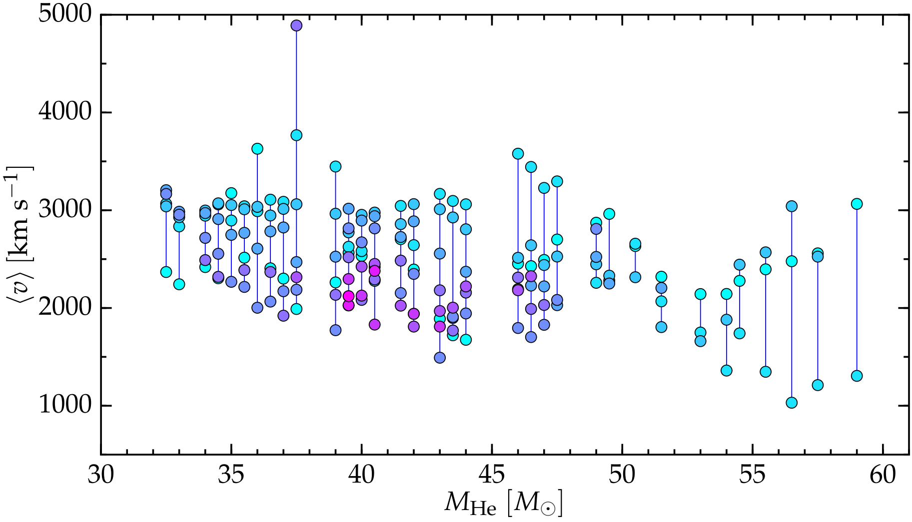

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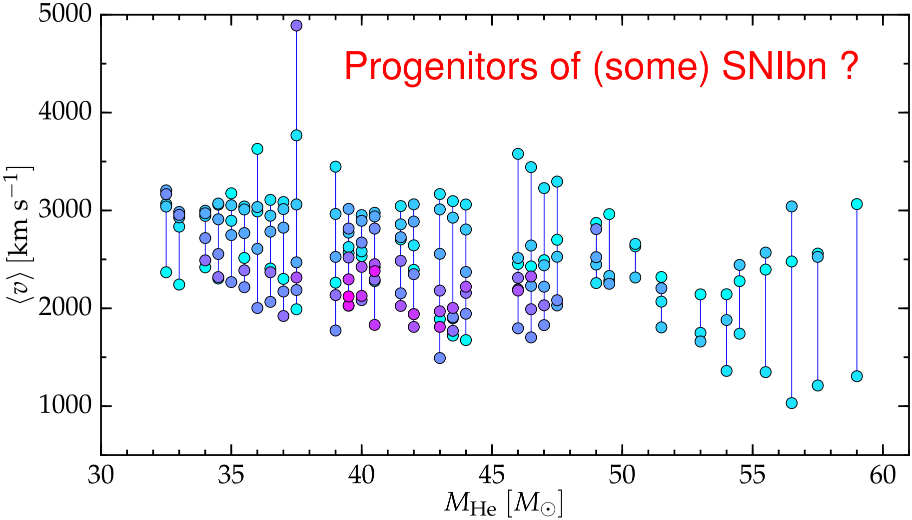

Renzo, Farmer *et al.*, to be submitted

Can the mass shell collide?

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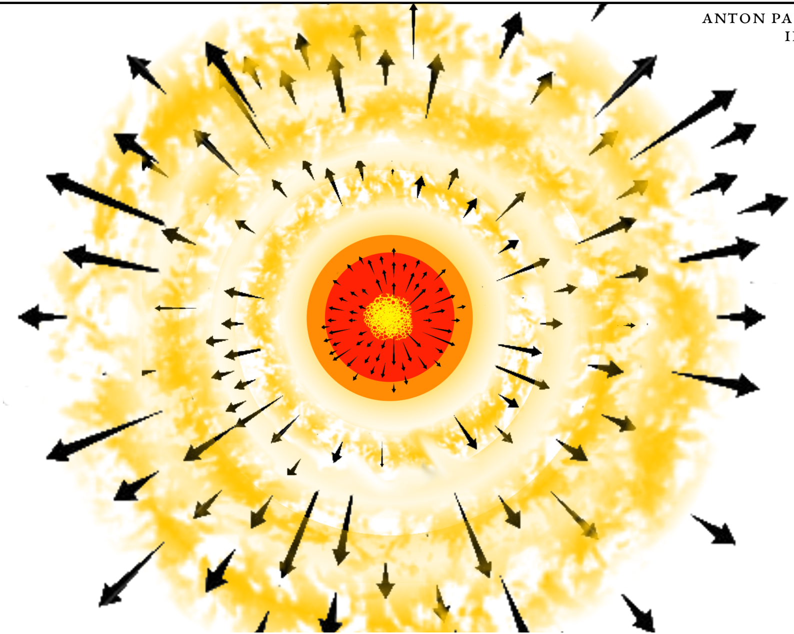

Woosley *et al* 07, Chen *et al.* 14, Woosley 17, Renzo, Farmer *et al.*, to be submitted

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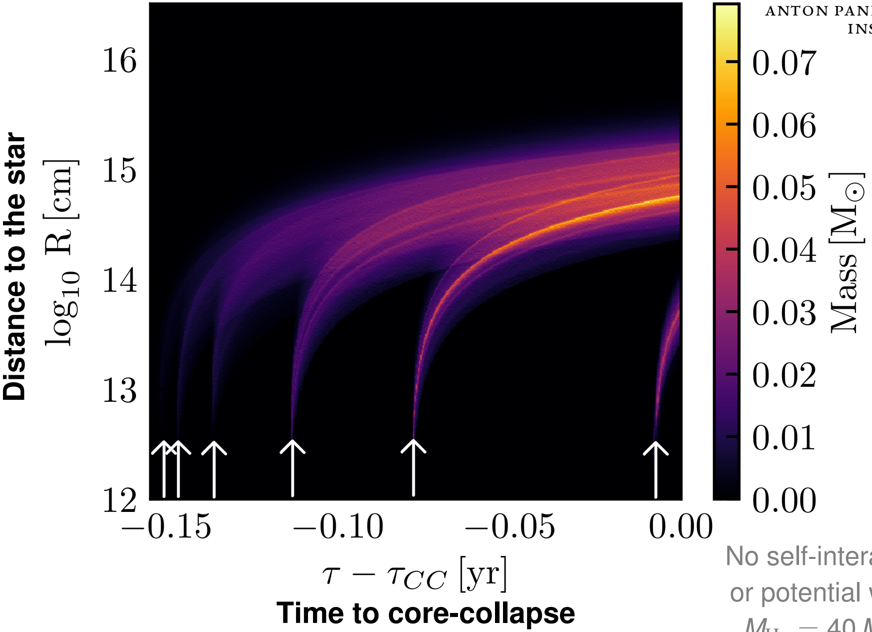

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No self-interaction or potential well

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

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

Example: 40 $M_\odot$ He core

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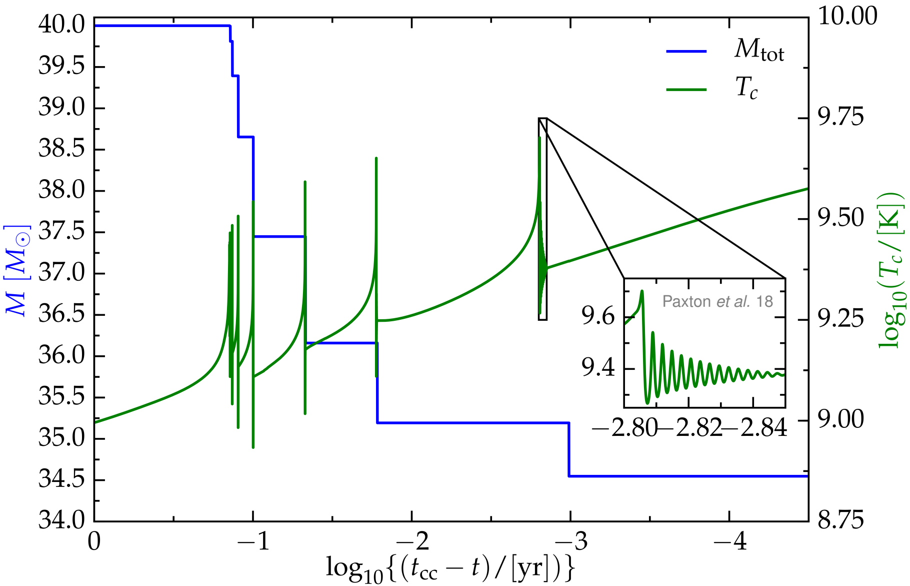

Log Time to core-collapse

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

Velocity distribution: Runaways

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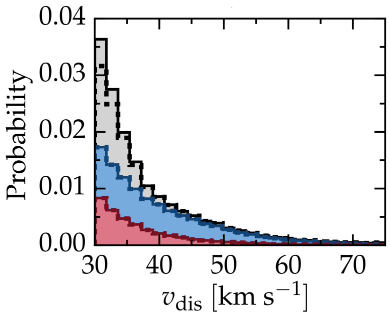

Renzo *et al.*, submitted, arXiv:1804.09164

Velocity distribution: Walkaways

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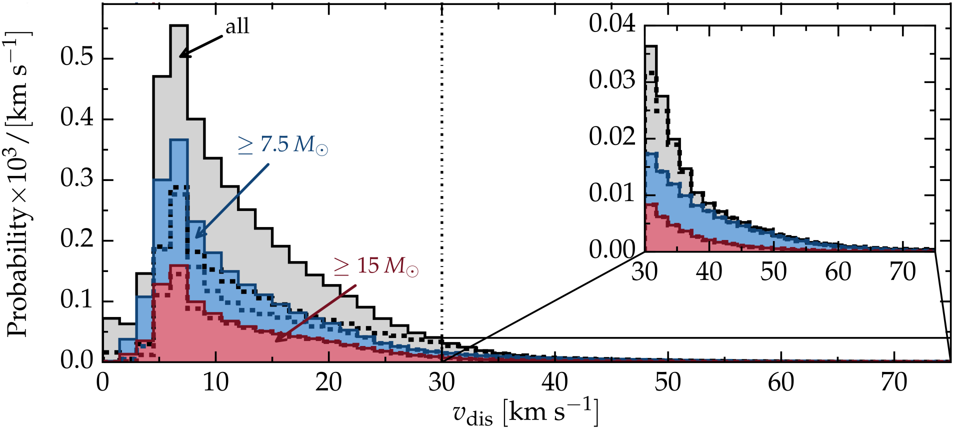

Take home points:

- 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.*, submitted, arXiv:1804.09164

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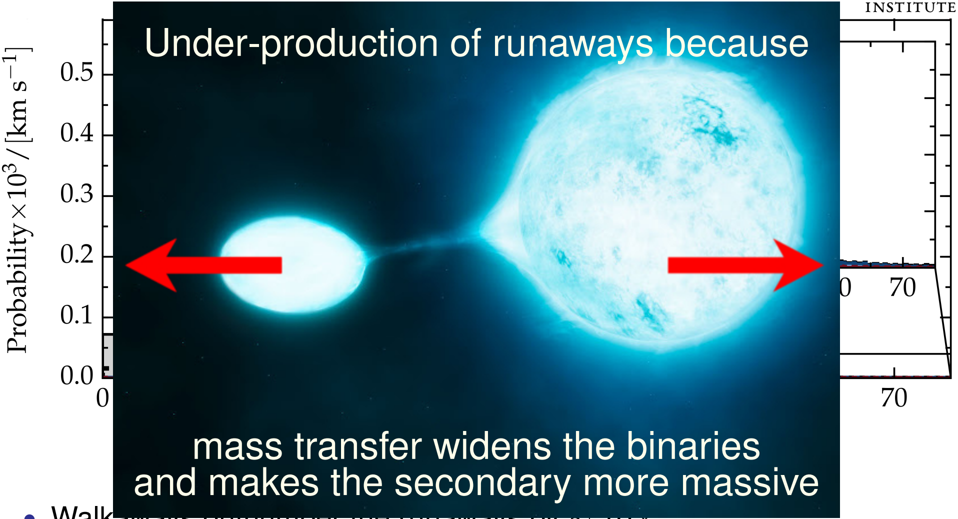

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