Massive stars as cosmic engines:

Commitment to companion(s), and implications for GW astronomy

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NASA, JPL-Caltech, Spitzer Space Telescope

Why are massive stars interesting?

Nucleosynthesis & Chemical Evolution

Star Formation

Ionizing Radiation

Supernovae

GW Astronomy

$L \propto M^{\alpha}$, $\alpha > 0$

NASA, JPL-Caltech, Spitzer Space Telescope

Why are massive stars interesting?

Nucleosynthesis & Chemical Evolution

Star Formation

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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, Almeida *et al.* '16)

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

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

NASA, JPL-Caltech, Spitzer Space Telescope

Different behaviors with $M_{\rm ZAMS}$ and/or $M_{\rm He}$

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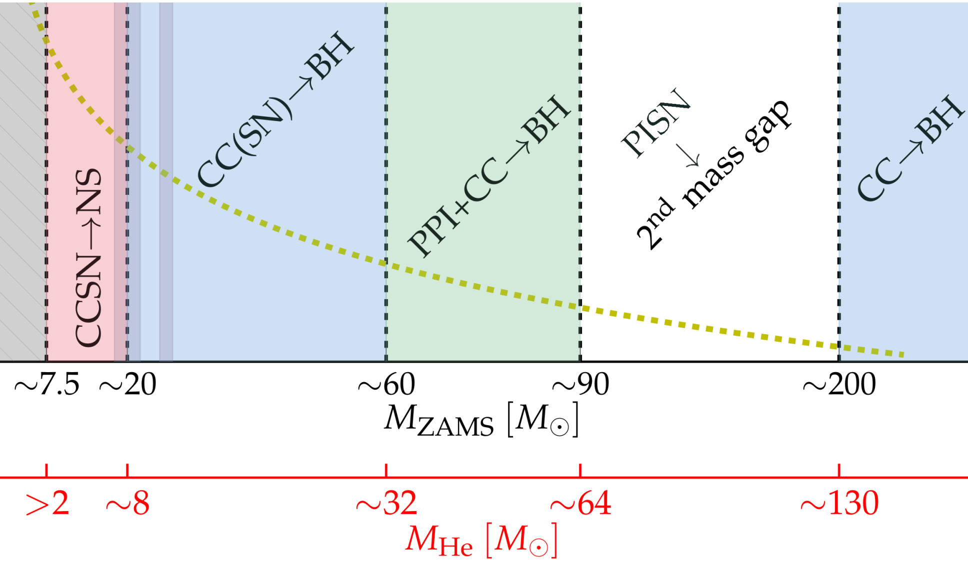
$\mathrm{IMF}(M) \propto M^{-2.3}$



cf. Woosley 2017

$M_{\rm He}$ governs the fate, determines $M_{\rm BH}$

Stellar winds: NS or BH?

- Line driving mechanism

Core Collapse in a Binary

- Massive “widowed” stars

Pulsational Pair Instability

- BH mass function above $\sim 30\, M_\odot$

Radiatively Driven Winds in One Slide

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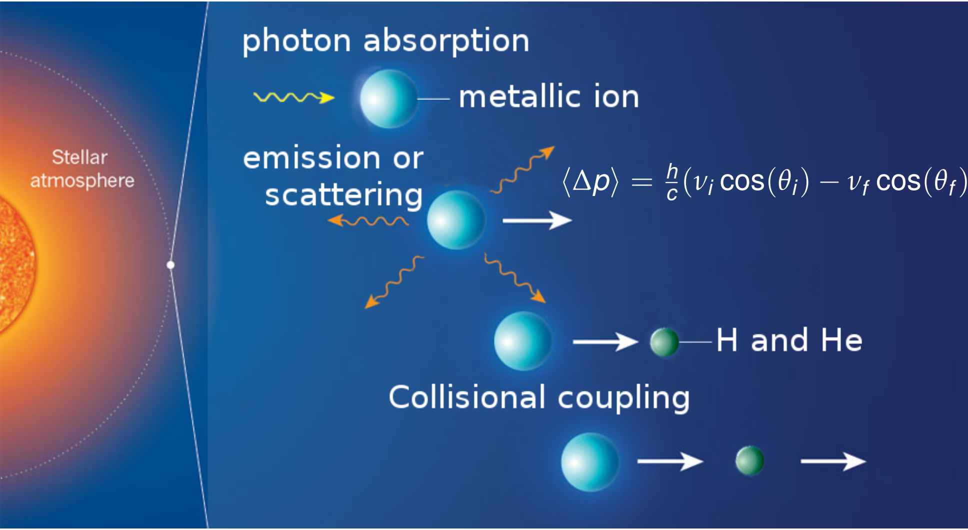


Problems: High Non-Linearity and Clumpiness

Clumpiness

Inhomogeneities:

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

Clumpiness

Risk:

Possible overestimation of the wind mass loss rate

Inhomogeneities:

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

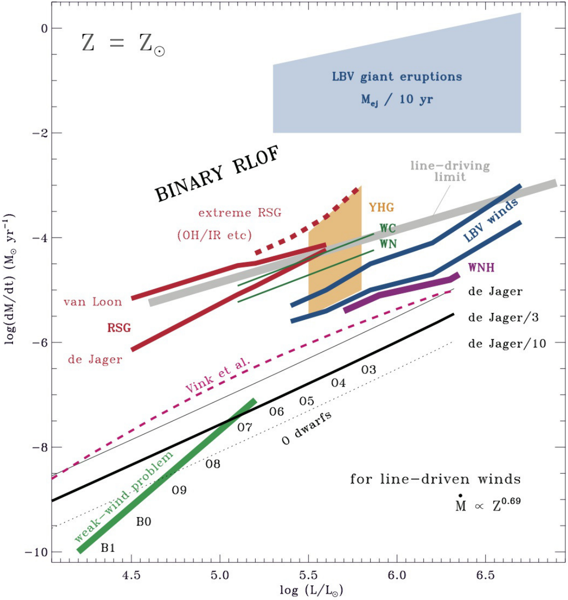


Figure: from N. Smith 2014, ARA&A, 52, 487

(Semi–)Empirical parametric models.

Efficiency factor:

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

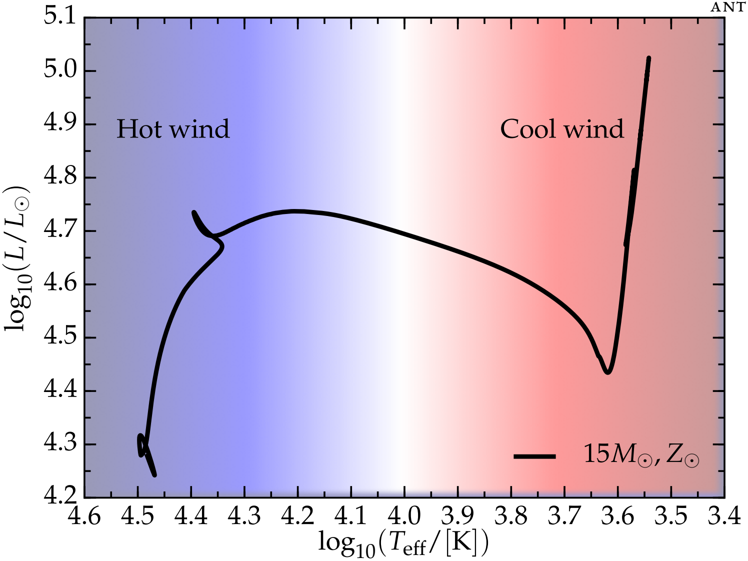
$$\Downarrow$$

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

η is a **free** parameter:

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

Combination of algorithms



WR wind $\Leftrightarrow X_s < 0.4$

Wind mass loss history

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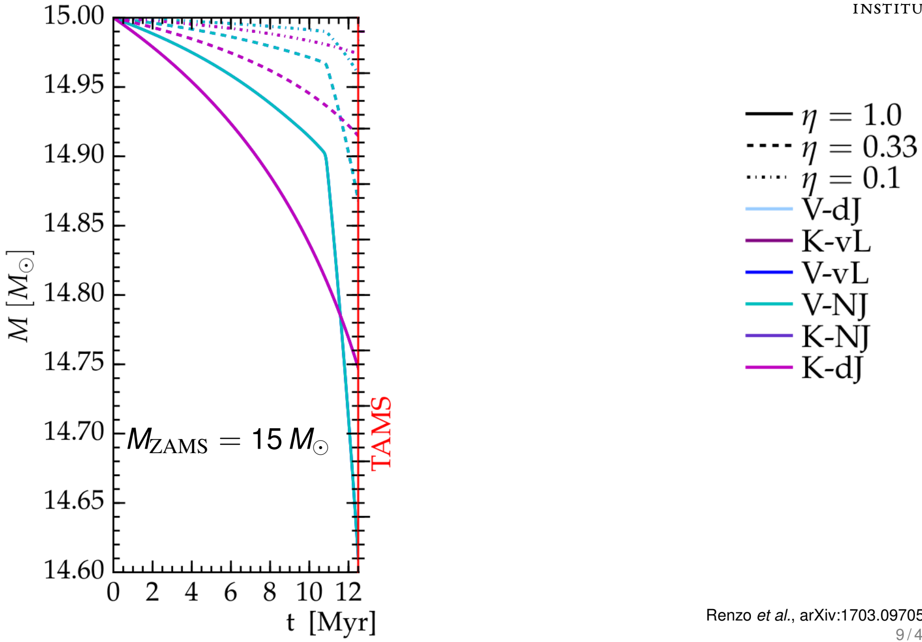
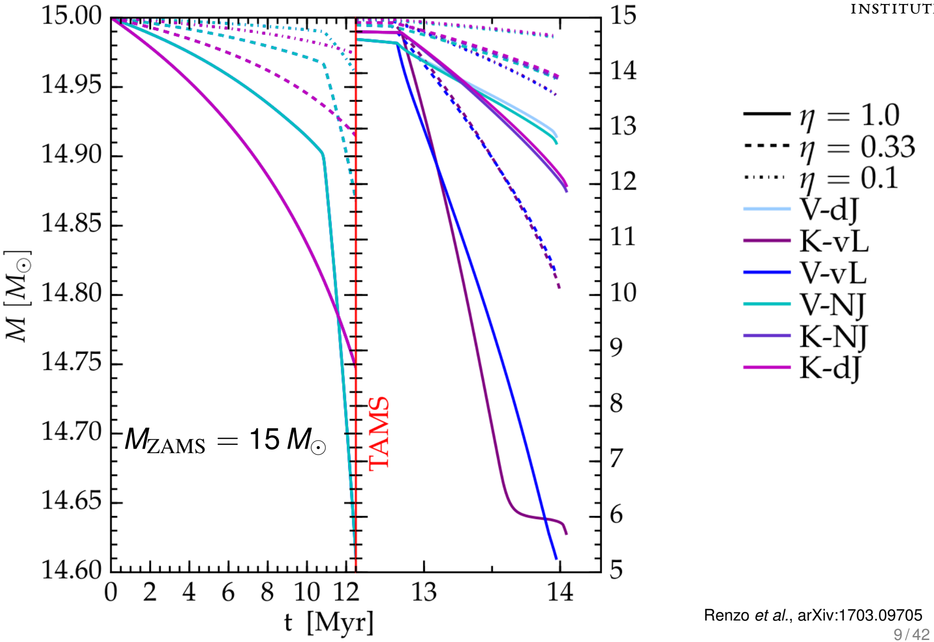


Renzo *et al.*, arXiv:1703.09705

Wind mass loss history



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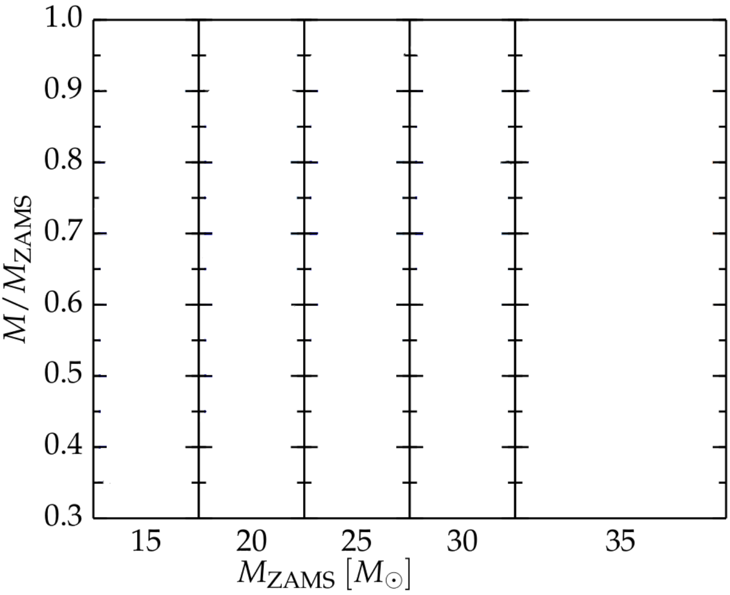
Impact on the final mass



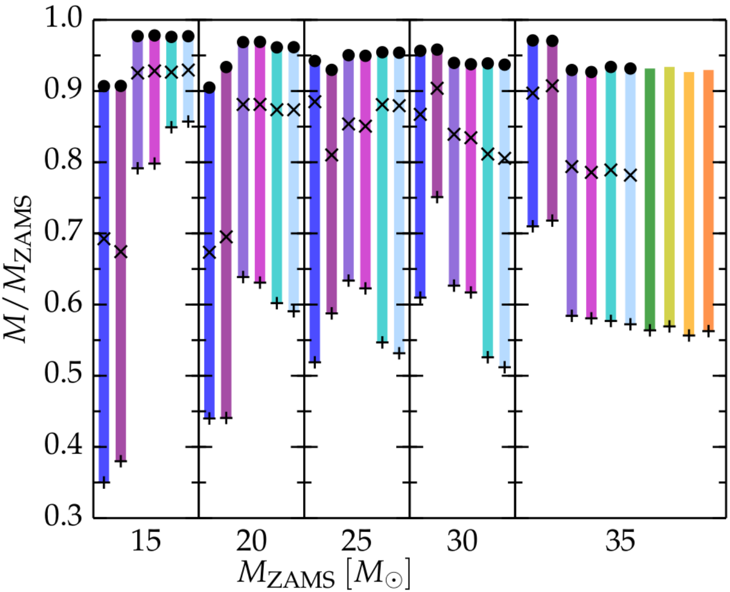
MESA

Legend:

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

Renzo *et al.*, arXiv:1703.09705

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.*, arXiv:1703.09705

Pre-explosion appearance

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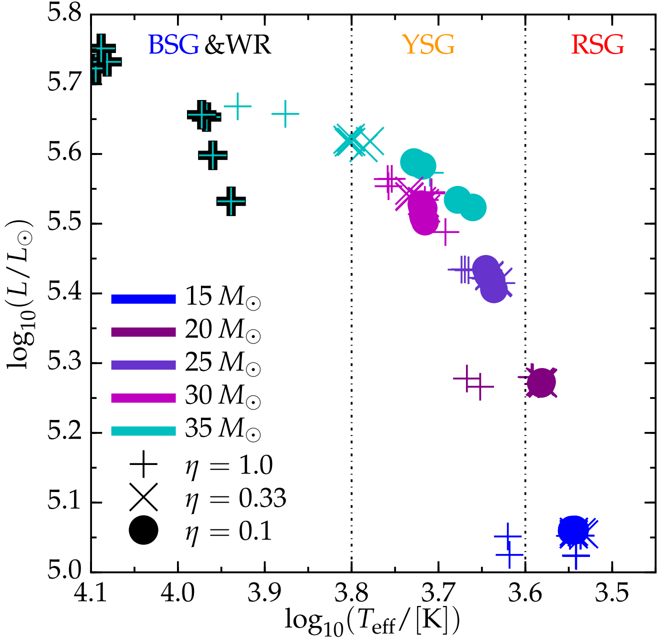


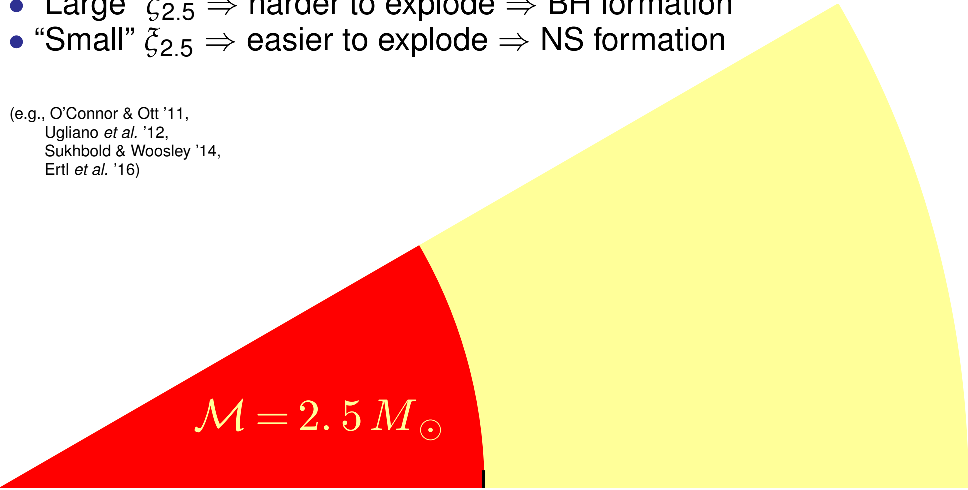
Renzo *et al.*, arXiv:1703.09705

“Explodability” & Compactness

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

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

(e.g., O’Connor & Ott ’11,
Ugliano *et al.* ’12,
Sukhbold & Woosley ’14,
Ertl *et al.* ’16)



not to scale!

$R(\mathcal{M})$

“Explodability” & Compactness

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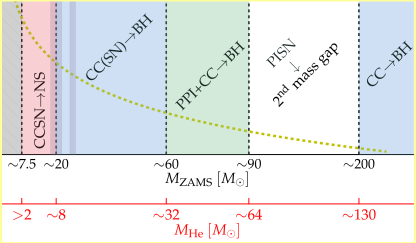
Caveat:
from 1D SN simulations



$\mathcal{M} = 2.5\, M_\odot$

$R(\mathcal{M})$

not to scale!

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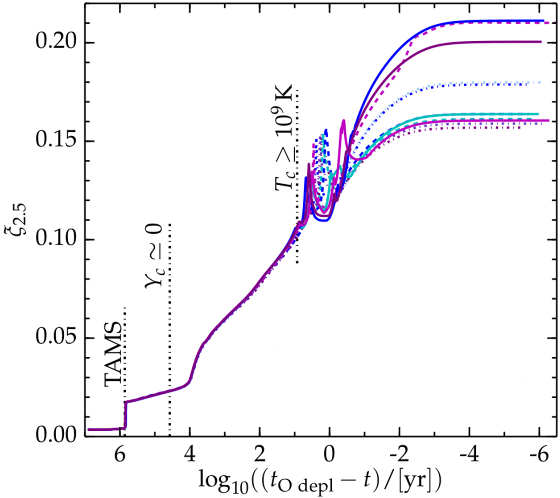
$M_{\mathrm{ZAMS}} = 25\,M_\odot$ MESA models



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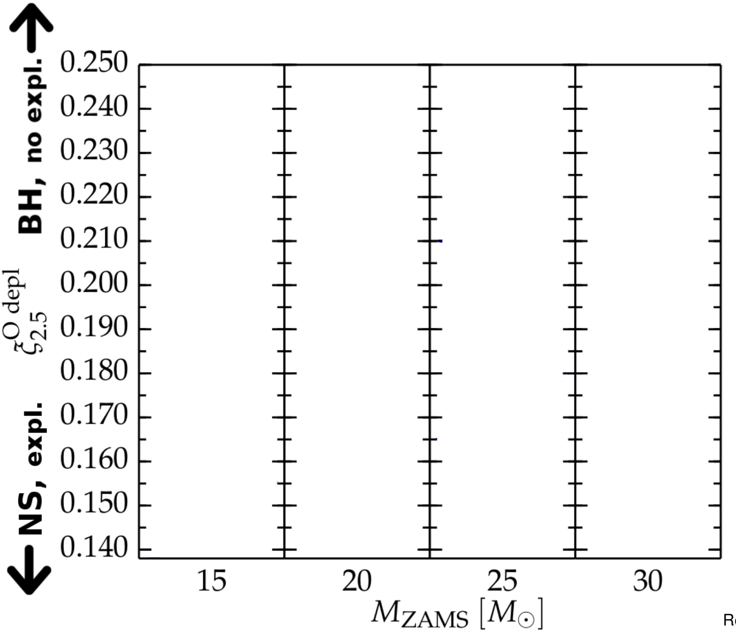
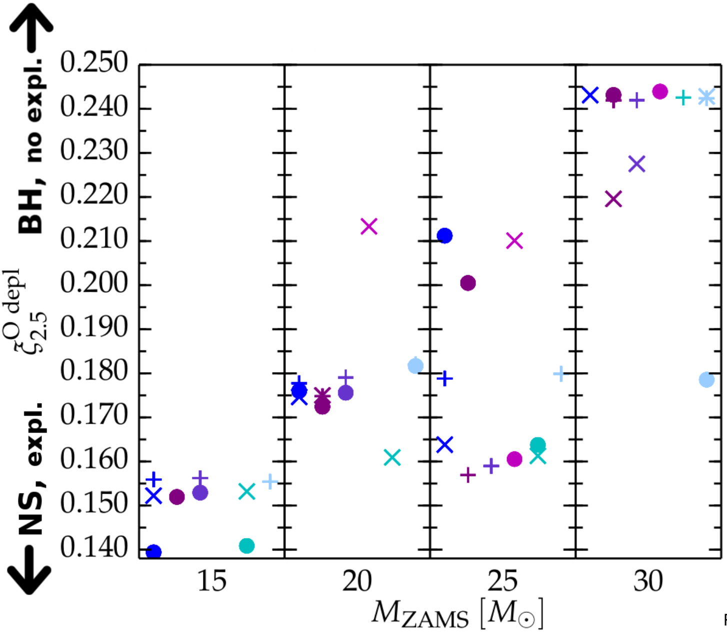
Critical point: Ne core burning/C shell burning

$\xi_{2.5}$ @ O depletion



Renzo *et al.*, arXiv:1703.09705

$\xi_{2.5}$ @ Oxygen Depletion



Legend:

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

Post O burning evolution

$\Downarrow$

Core contraction

$\Downarrow$

Amplification of the differences.

Renzo *et al.*, arXiv:1703.09705

Post O burning evolution

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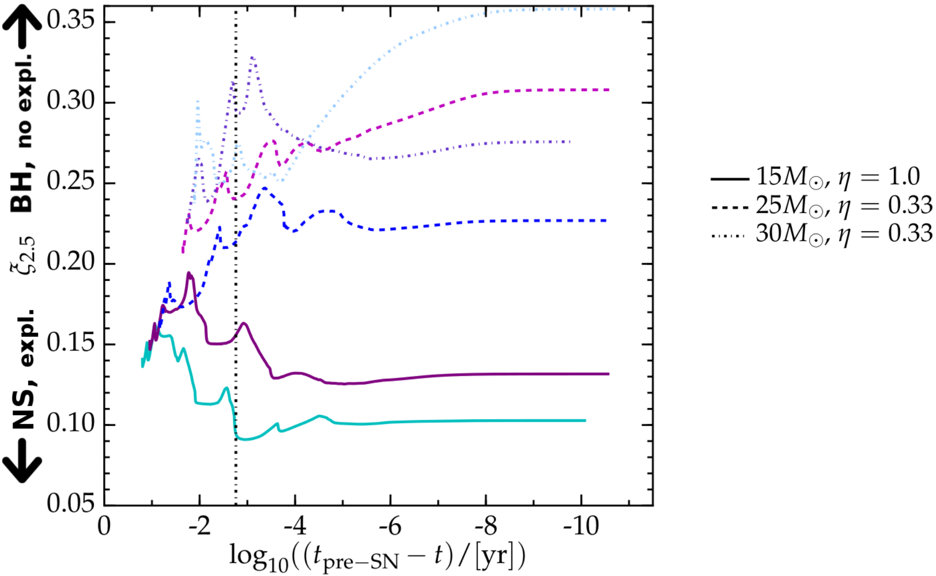
Si shell burning →

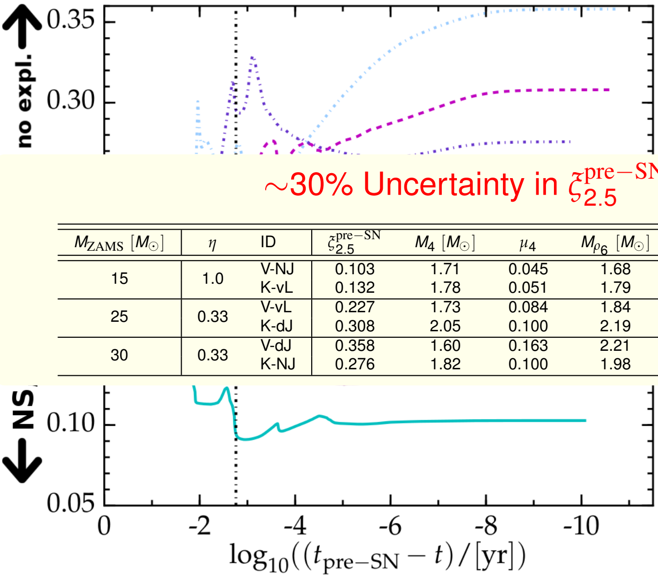


Time

Renzo *et al.*, arXiv:1703.09705

Post O burning evolution

Si shell burning →



∼30% Uncertainty in $\xi_{2.5}^{\mathrm{pre-SN}}$

M_{ZAMS} $[M_\odot]$	η	ID	$\xi_{2.5}^{\mathrm{pre-SN}}$	M_4 $[M_\odot]$	μ_4	M_{ρ_6} $[M_\odot]$	M_{CO} $[M_\odot]$	M_{Fe} $[M_\odot]$
15	1.0	V-NJ	0.103	1.71	0.045	1.68	2.91	1.39
		K-vL	0.132	1.78	0.051	1.79	3.07	1.50
25	0.33	V-vL	0.227	1.73	0.084	1.84	6.38	1.51
		K-dJ	0.308	2.05	0.100	2.19	6.40	1.63
30	0.33	V-dJ	0.358	1.60	0.163	2.21	7.98	1.56
		K-NJ	0.276	1.82	0.100	1.98	7.90	1.58

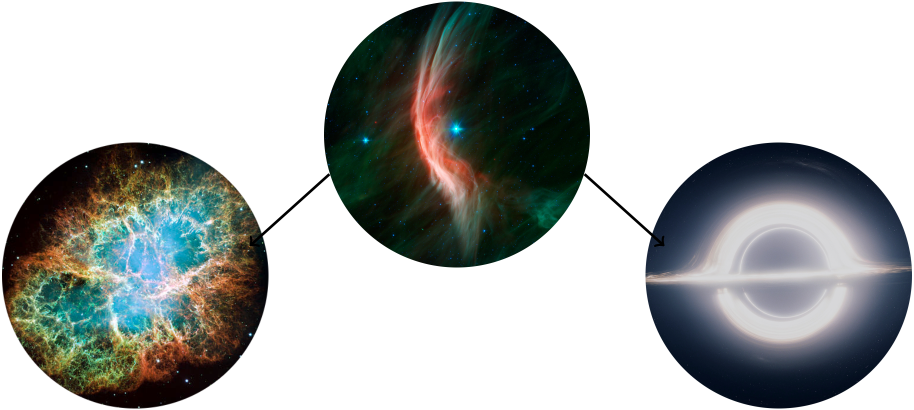
Time

Renzo *et al.*, arXiv:1703.09705

Take home points 1/3

Uncertainties in stellar winds:

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



Stellar winds: NS or BH?

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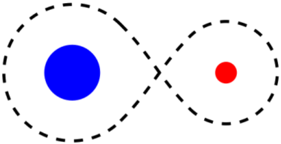
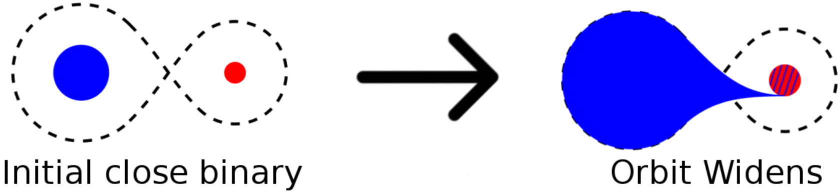
- BH mass function above $\sim 30\ M_{\odot}$

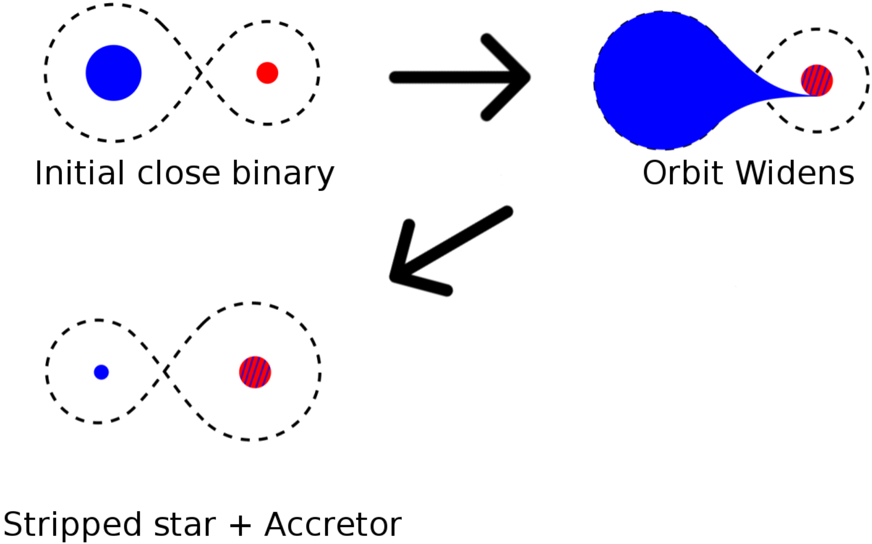


Initial close binary

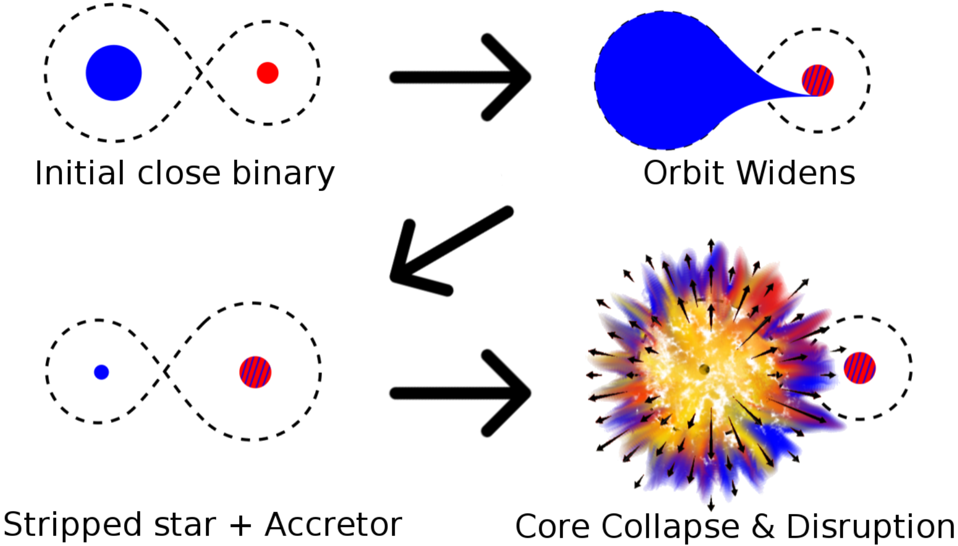
Binary disruption



Binary disruption



Binary disruption

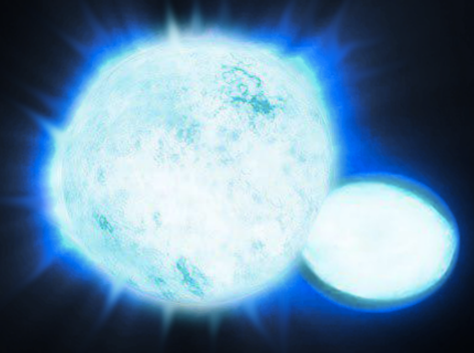


Spin up, pollution, and rejuvenation

Binary interactions modify the star to be ejected

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

What exactly disrupts the binary?
$\gtrsim$80% of binaries are disrupted



- Unbinding Matter

  (e.g., Blaauw '61)
- Ejecta Impact

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

  Tauris & Takens '98, Liu *et al.* '15)
- SN Natal Kick

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

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

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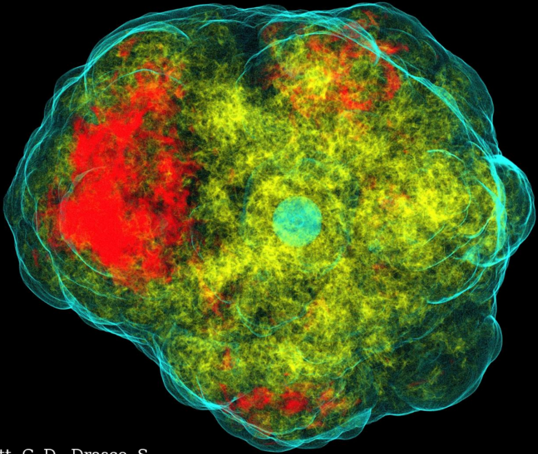
- SN Natal Kick

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

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

SN natal kick

ν emission and/or ejecta anisotropies



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

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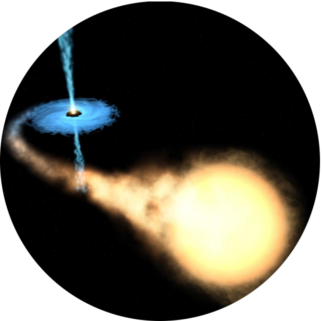
...from disrupted binaries

- BH kicks
- Binary evolution

Do BH receive natal kicks?

Spatial distribution of X-ray binaries

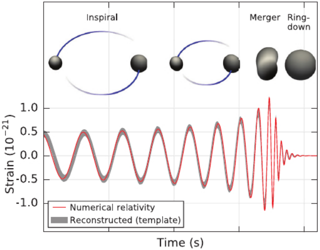
(e.g., Repetto *et al.* ’12,’15,’16, Mandel ’16)



Massive (and WR) runaways

(Dray *et al.* ’05)

Disrupted binaries are “failed” GW sources!



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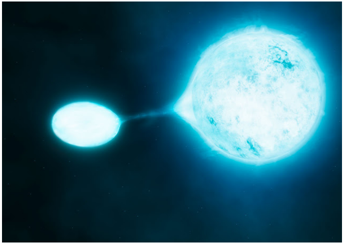
...from disrupted binaries

- BH kicks
- Binary evolution

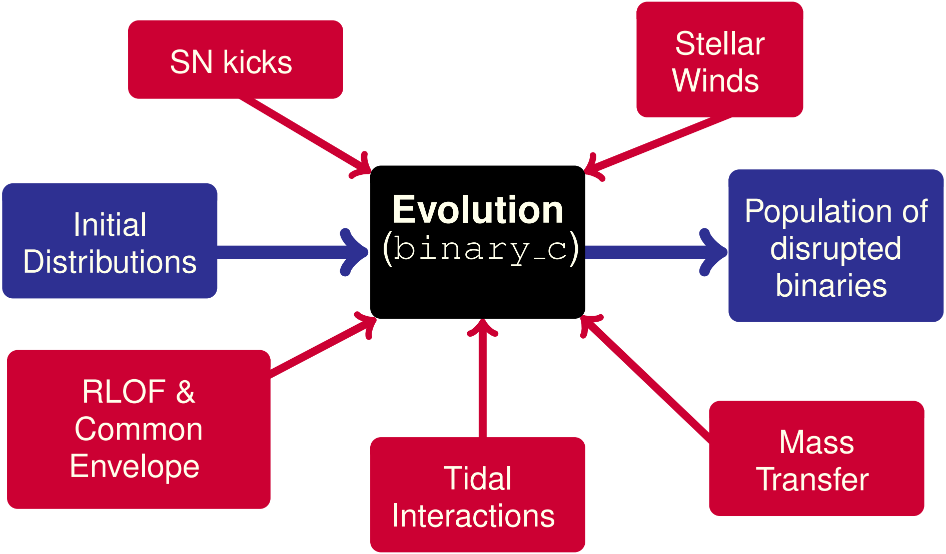
Constraints on binary physics

- Orbital evolution ⇔ pre-SN period
- Mass transfer efficiency ⇔ pre-SN M_2
- Angular momentum loss ⇒ isotropic re-emission, circumbinary disk, etc.



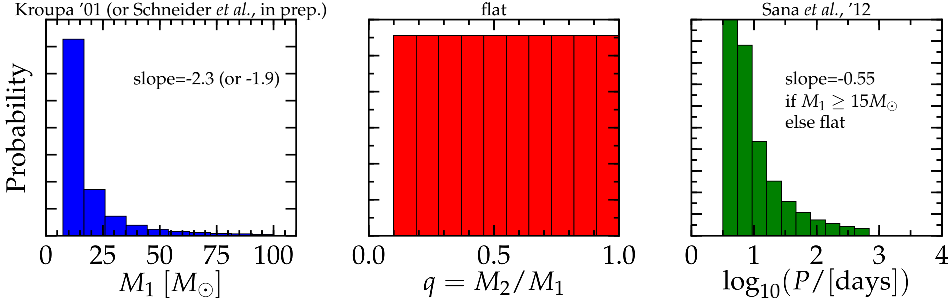
What I do: Population Synthesis

Fast ⇒ Allows statistical tests of the inputs & assumptions



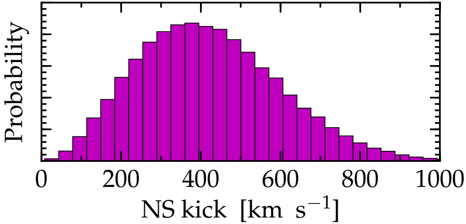
Izzard *et al.* ’04, ’06, ’09; de Mink *et al.* ’13

Initial Distributions



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

(from Fryer *et al.* '12)



Hobbs *et al.* '05

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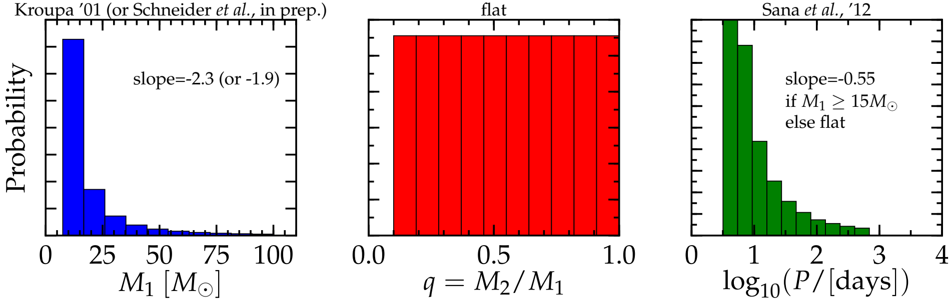

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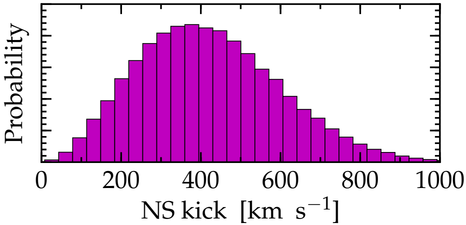
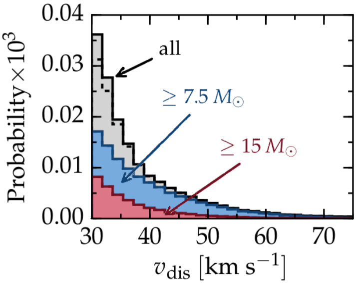
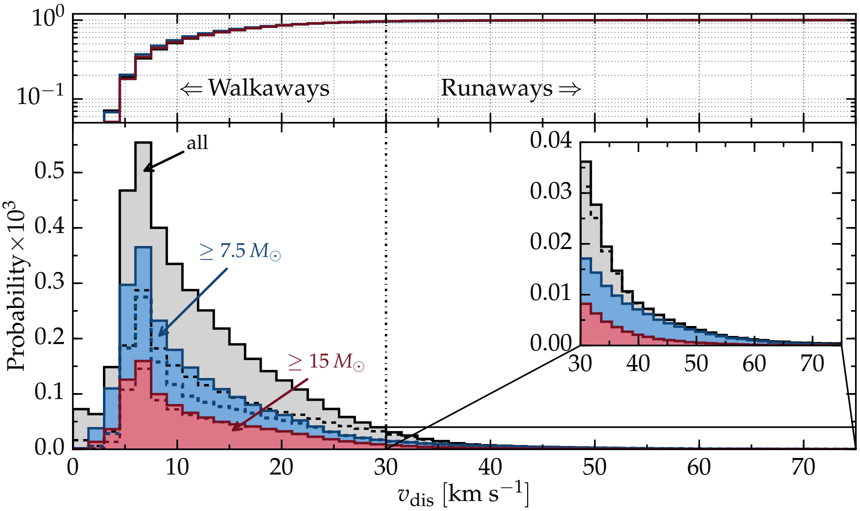


Hobbs *et al.* '05

Velocity distribution: Runaways

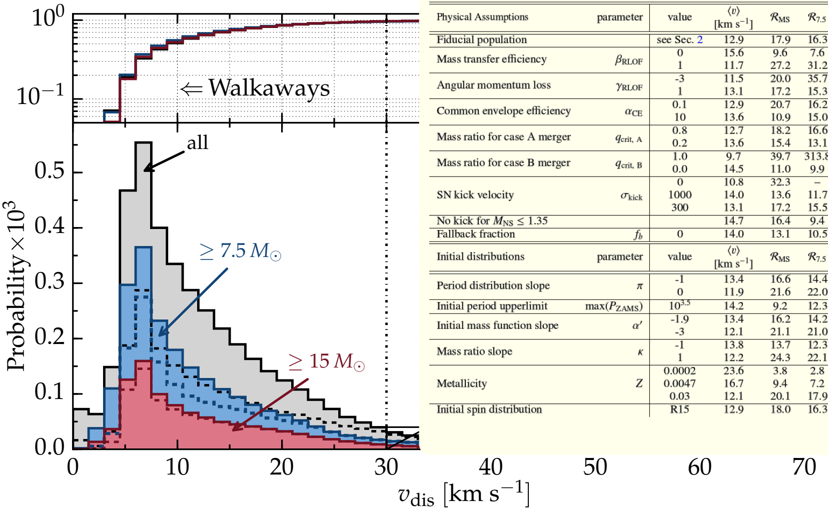


Velocity distribution: Walkaways



For each runaway there are ∼ 20 walkaways in the galaxy!

Velocity distribution: Walkaways



Can't get rid of them!

Physical Assumptions	parameter	value	$\langle v \rangle$ [km s^{-1}]	$\mathcal{R}_{\rm MS}$	$\mathcal{R}_{7.5}$	$\mathcal{R}_{15}$	$\mathcal{D}$
Fiducial population		see Sec. 2	12.9	17.9	16.3	17.2	0.84
Mass transfer efficiency	$\beta_{\rm RLOF}$	0	15.6	9.6	7.6	4.0	0.85
		1	11.7	27.2	31.2	17.4	0.84
Angular momentum loss	$\gamma_{\rm RLOF}$	-3	11.5	20.0	35.7	27.8	0.83
		1	13.1	17.2	15.3	16.8	0.84
Common envelope efficiency	$\alpha_{\rm CE}$	0.1	12.9	20.7	16.2	17.1	0.85
		10	13.6	10.9	15.0	17.2	0.82
Mass ratio for case A merger	$q_{\rm crit,\,A}$	0.8	12.7	18.2	16.6	18.1	0.84
		0.2	13.6	15.4	13.1	15.2	0.83
Mass ratio for case B merger	$q_{\rm crit,\,B}$	1.0	9.7	39.7	313.8	117.0	0.88
		0.0	14.5	11.0	9.9	15.5	0.82
SN kick velocity	$\sigma_{\rm kick}$	0	10.8	32.3	–	–	0.25
		1000	14.0	13.6	11.7	10.9	0.89
		300	13.1	17.2	15.5	16.3	0.85
No kick for $M_{\rm NS} \leq 1.35$			14.7	16.4	9.4	9.0	0.47
Fallback fraction	f_b	0	14.0	13.1	10.5	8.1	0.94
Initial distributions	**parameter**	**value**	**$\langle v \rangle$ [km s^{-1}]**	**$\mathcal{R}_{\rm MS}$**	**$\mathcal{R}_{7.5}$**	**$\mathcal{R}_{15}$**	**$\mathcal{D}$**
Period distribution slope	π	-1	13.4	16.6	14.4	15.0	0.86
		0	11.9	21.6	22.0	23.6	0.83
Initial period upperlimit	max($P_{\rm ZAMS}$)	$10^{3.5}$	14.2	9.2	12.3	16.9	0.80
Initial mass function slope	α'	-1.9	13.4	16.2	14.2	14.8	0.78
		-3	12.1	21.1	21.0	23.3	0.90
Mass ratio slope	κ	-1	13.8	13.7	12.3	13.4	0.84
		1	12.2	24.3	22.1	21.8	0.83
Metallicity	Z	0.0002	23.6	3.8	2.8	1.8	0.76
		0.0047	16.7	9.4	7.2	7.4	0.82
		0.03	12.1	20.1	17.9	20.7	0.85
Initial spin distribution		R15	12.9	18.0	16.3	17.2	0.84

For each runaway there are ∼ 20 walkaways in the galaxy!

30 Doradus

O-type runaways

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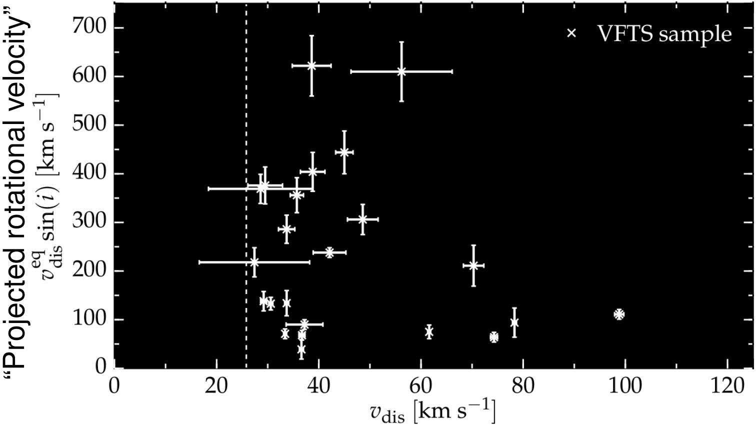
Largest homogeneous sample available to date



“Line of sight velocity”

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

O-type runaways

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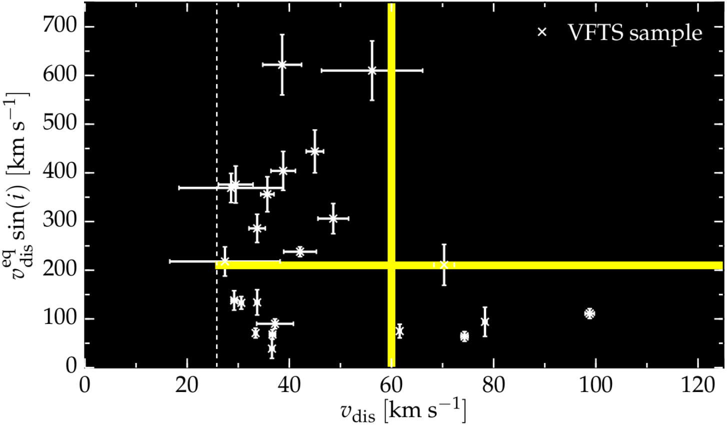
Largest homogeneous sample available to date

“Projected rotational velocity”



“Line of sight velocity”

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O-type runaways

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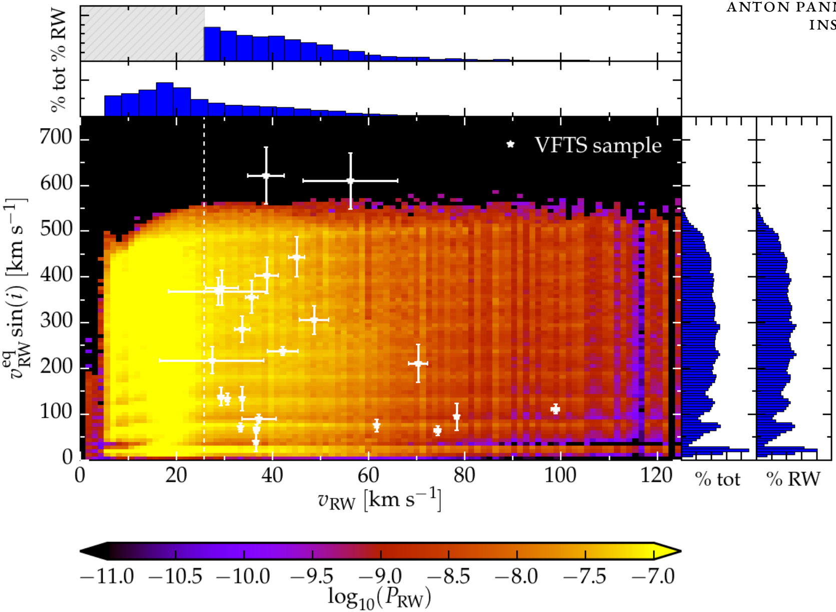

"$\log_{10}$(Number density)"

How to test BH kick physics?

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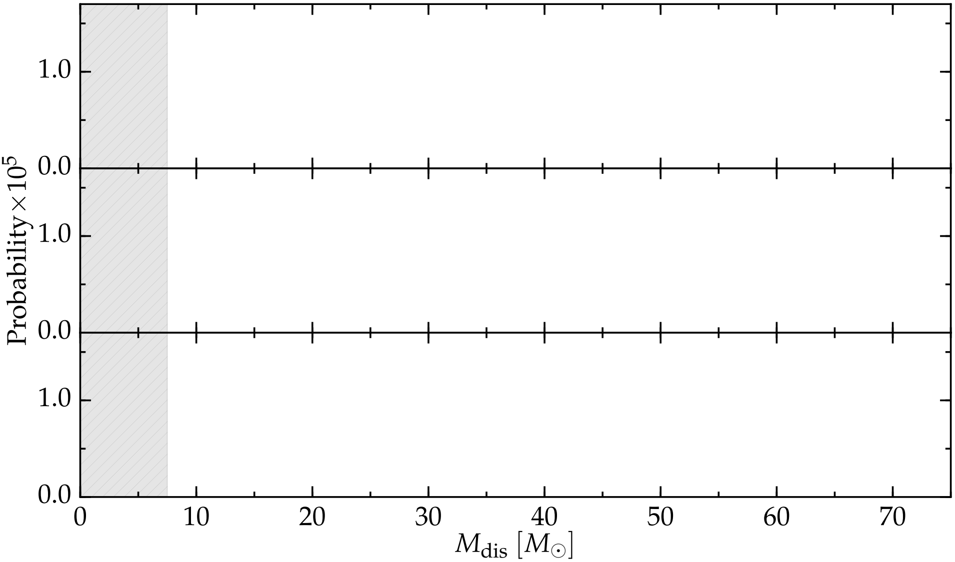

BH $\Leftrightarrow M_{\rm BH} \geq 2.5\,M_\odot$, Only $v \geq 30\,{\rm km\ s^{-1}}$ and $M_{\rm dis} \geq 7.5\,M_\odot$

(Massive) runaway mass function

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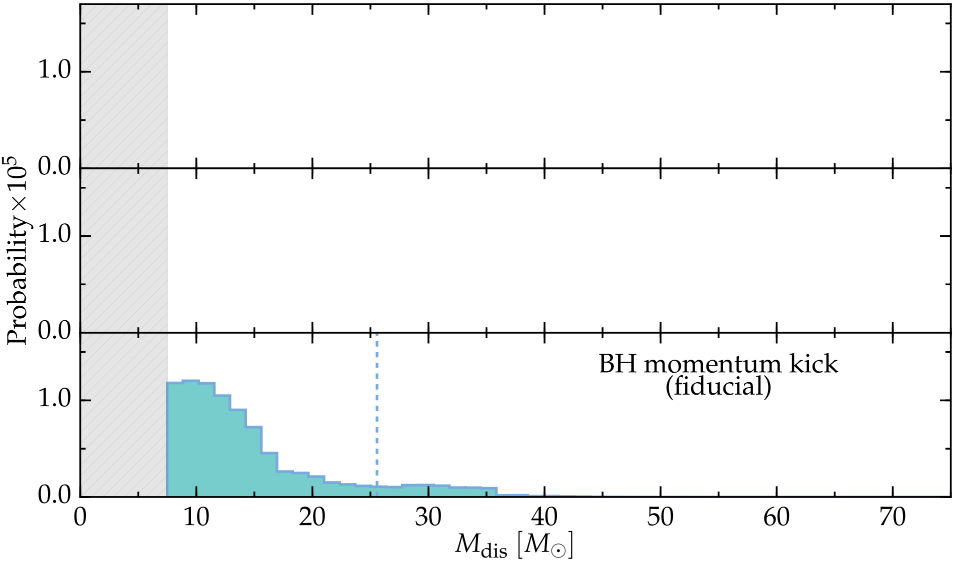
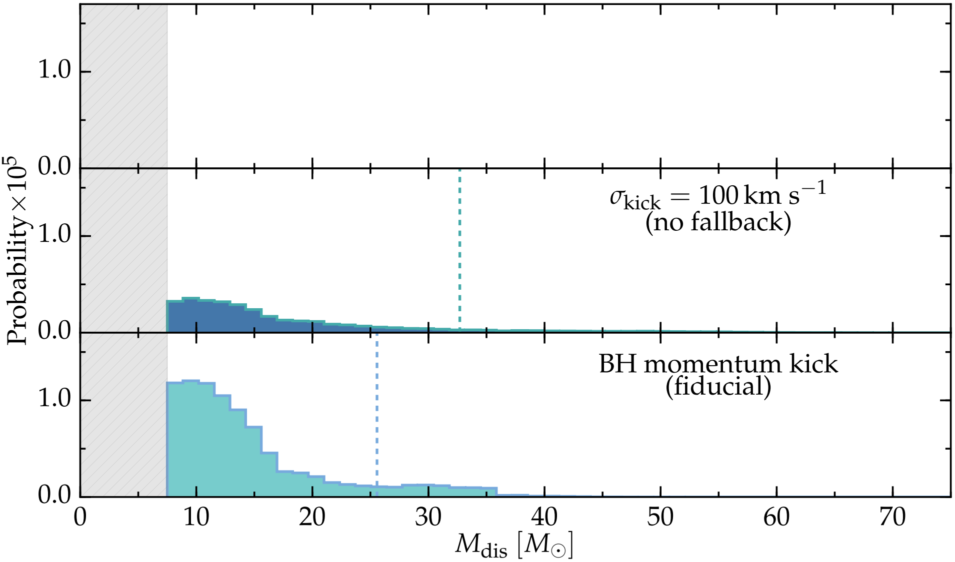


BH ⇔ $M_{\rm BH} \geq 2.5\,M_\odot$, Only $v \geq 30\,{\rm km\,s^{-1}}$ and $M_{\rm dis} \geq 7.5\,M_\odot$

(Massive) runaway mass function



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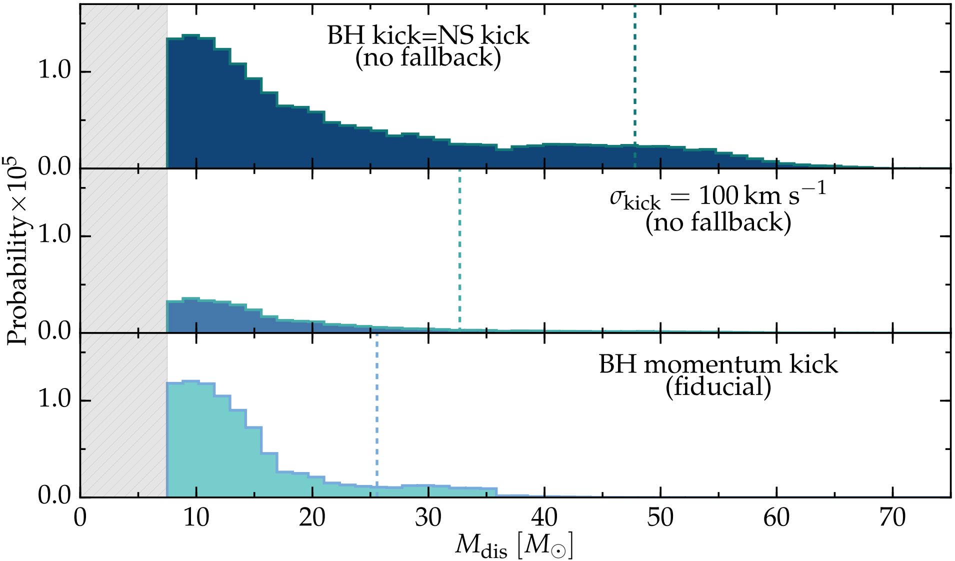

BH $\Leftrightarrow M_{\rm BH} \geq 2.5\,M_\odot$, Only $v \geq 30\,{\rm km\,s^{-1}}$ and $M_{\rm dis} \geq 7.5\,M_\odot$

Take home points 2/3

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

Massive walk/runaways stars...

(regardless of their final velocity)

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

Stellar winds: NS or BH?

- Line driving mechanism

Core Collapse in a Binary

- Massive “widowed” stars

Pulsational Pair Instability

- BH mass function above $\sim 30\,M_\odot$

Different behaviors with $M_{\rm ZAMS}$ and/or $M_{\rm He}$

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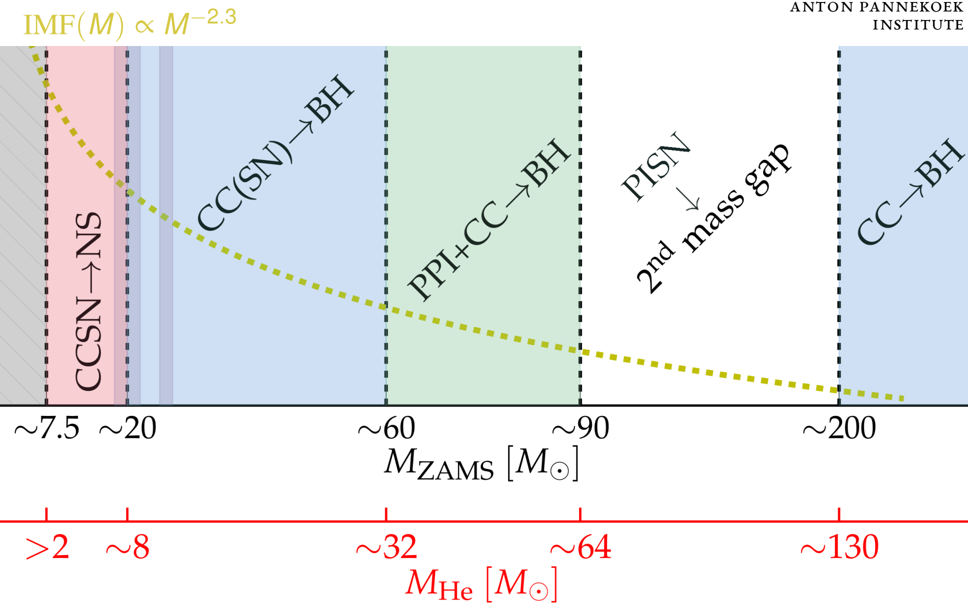


cf. Woosley 2017

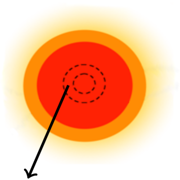
$M_{\rm He}$ governs the fate, determines $M_{\rm BH}$

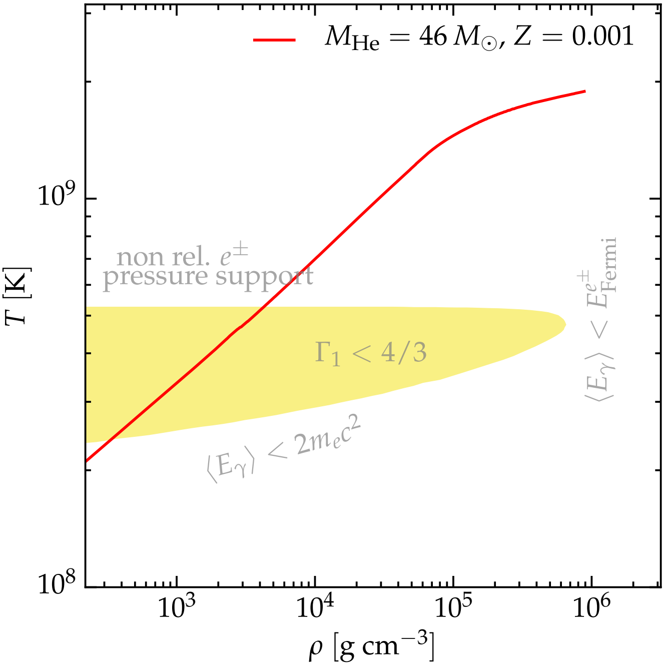
Radiation dominated:

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

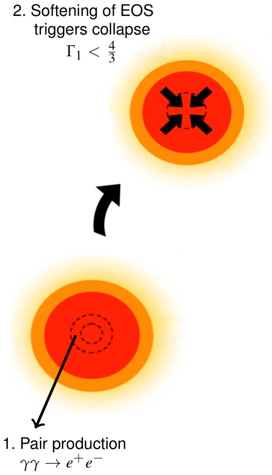
$M_{\mathrm{He}} \gtrsim 32\, M_\odot$

(Woosley 2017)

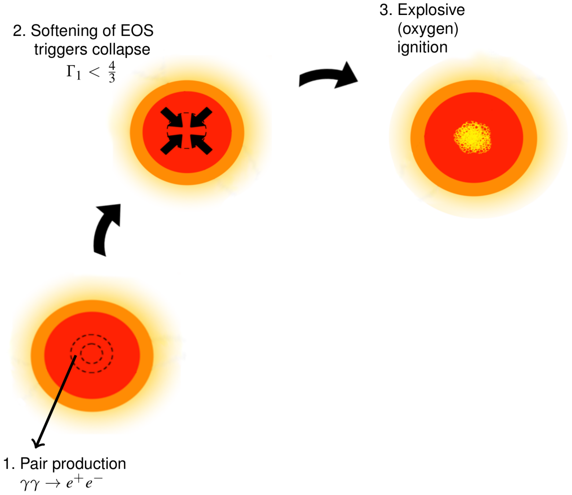




Preliminary calculations with MESA



2. Softening of EOS triggers collapse
$\Gamma_1 < \frac{4}{3}$
1. Pair production
$\gamma\gamma \to e^+e^-$


2. Softening of EOS triggers collapse
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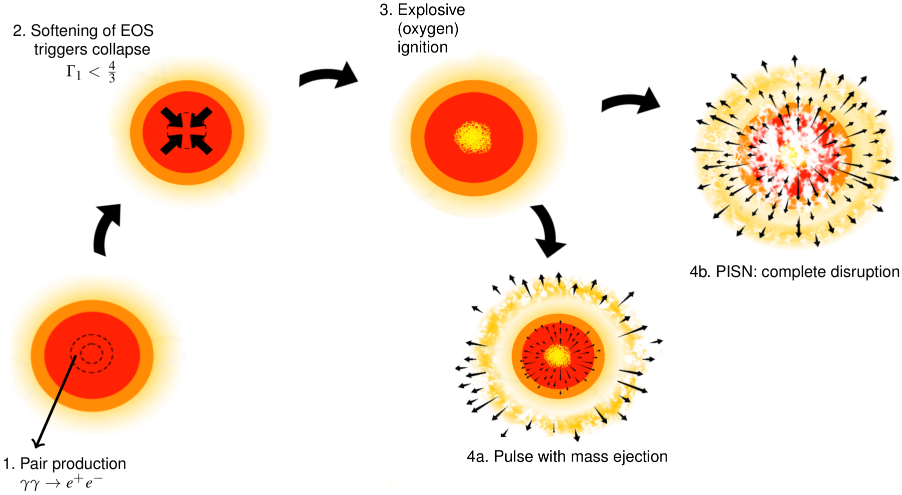
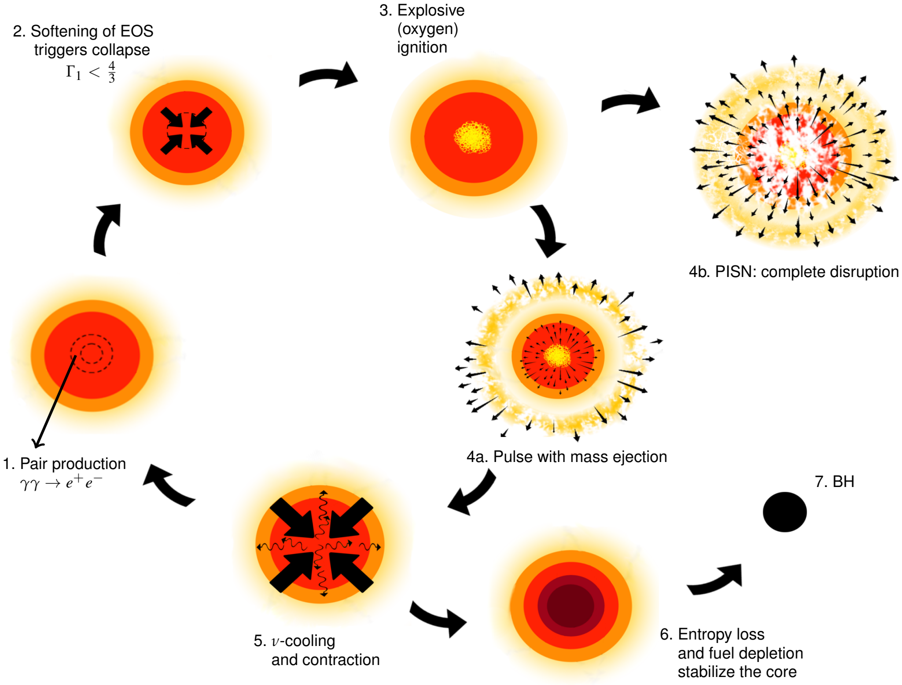
$\gamma\gamma \rightarrow e^+e^-$



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
$\gamma\gamma \rightarrow e^+e^-$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(oxygen)
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1. Pair production
$\gamma\gamma \rightarrow e^+e^-$
7. BH
5. ν-cooling
and contraction
6. Entropy loss
and fuel depletion
stabilize the core

PPISN mass loss history

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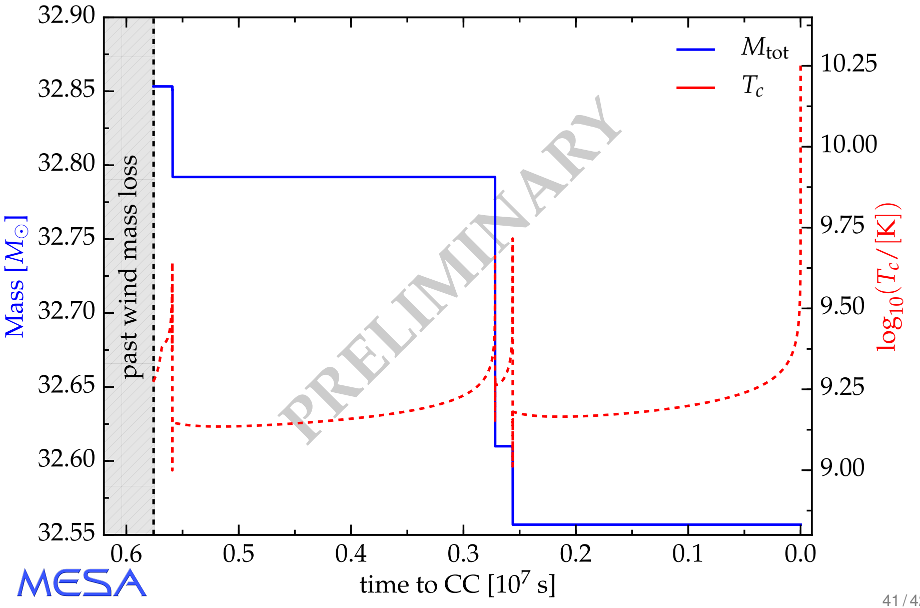
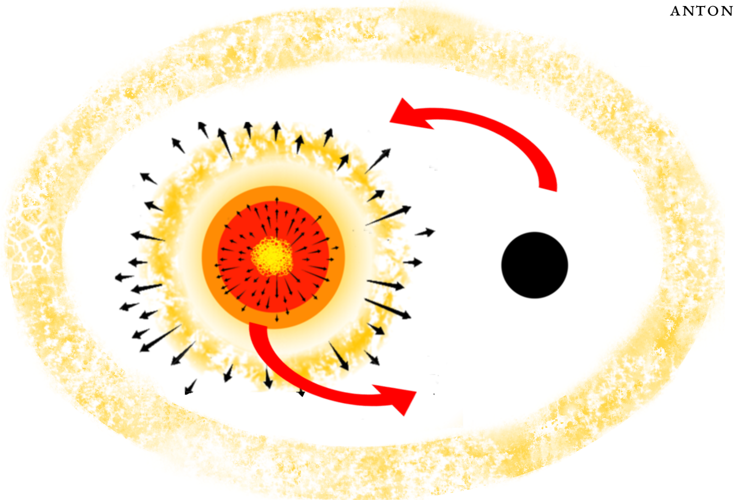
Example: $M_{He} = 46\,M_\odot$, $Z = 0.001$, no envelope



MESA

Take home point 3/3



- Can modify the BH mass function (2nd mass gap)
  - Creates circumbinary gas as late as possible
- How does the orbital parameter change because of the PPI?

Conclusions

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- Massive stars are important for their environment
  - Ionization (e.g., HII regions)
  - Star formation
  - Chemical evolution & Nucleosynthesis
- Their evolution is determined by:
  - Initial mass
  - Rotation
  - Presence of companion star(s)
- They produce BH and NS that can later become GW sources

Uncertainties are related to radiative and/or hydrodynamical processes on evolutionary timescales.

Conclusions

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Thanks!

Backup slides

Where do they die?

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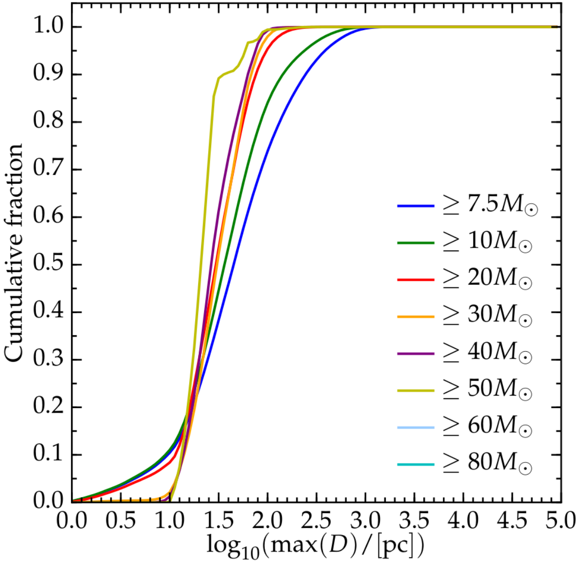

"Distance traveled"

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

30 Doradus Star Formation History

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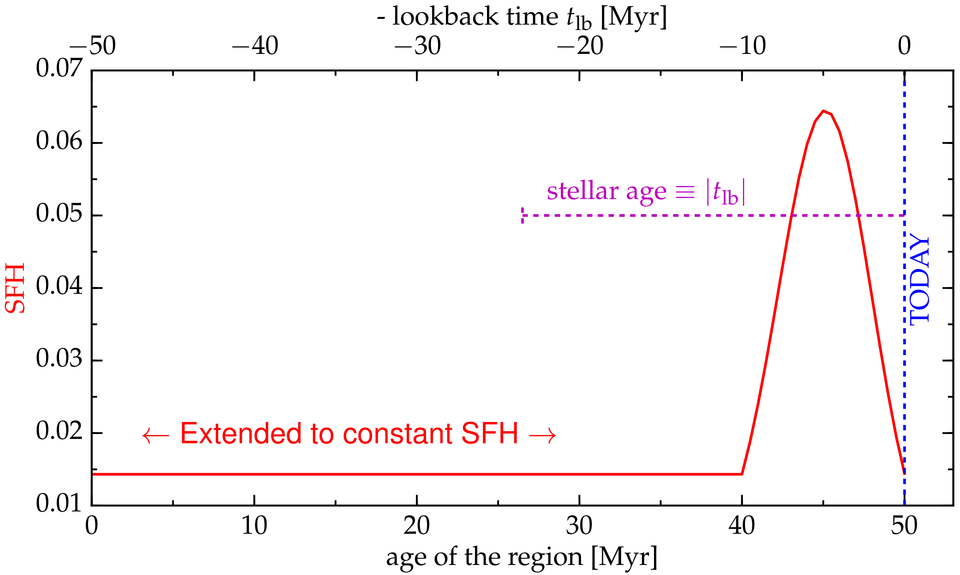
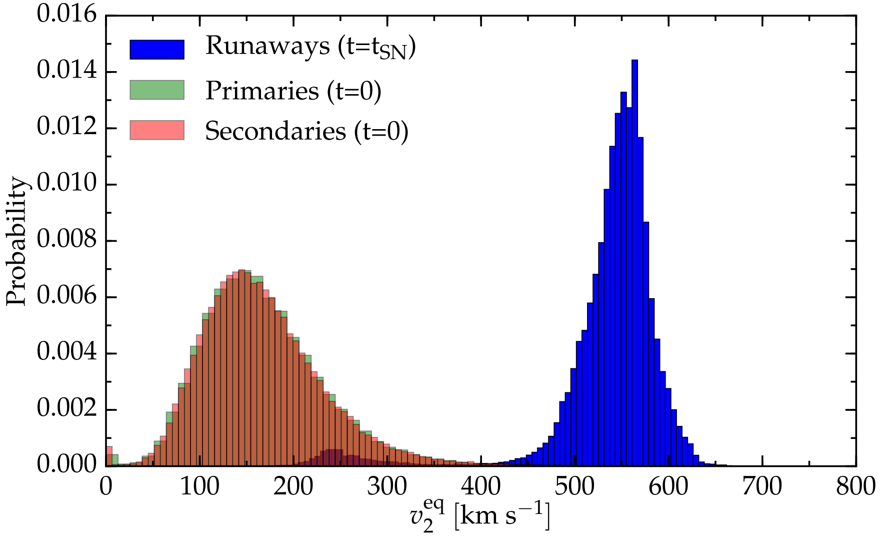
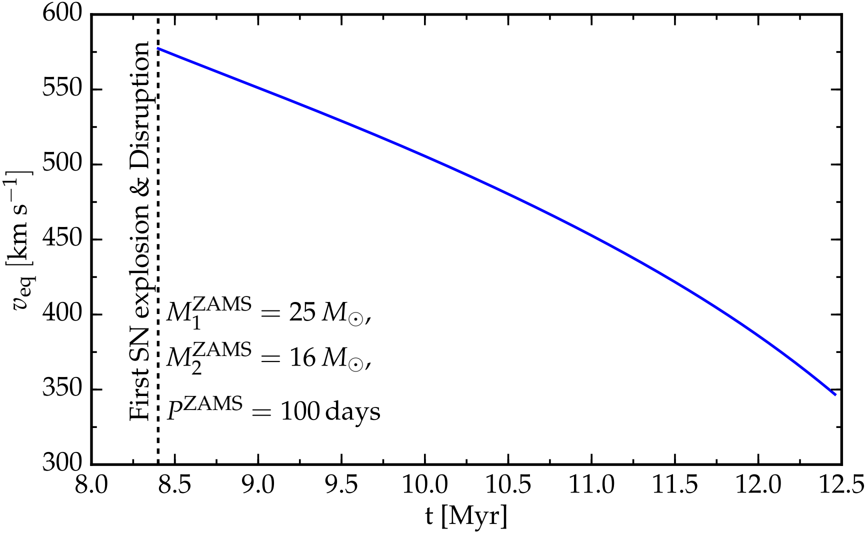


Initial Rotational Velocities

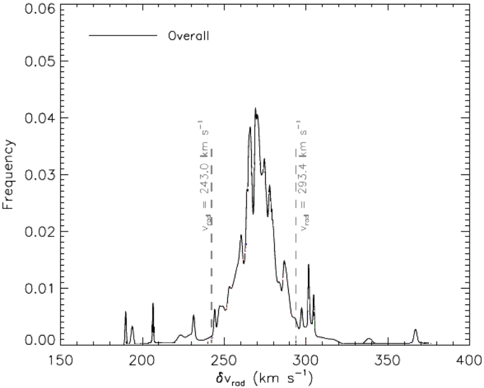


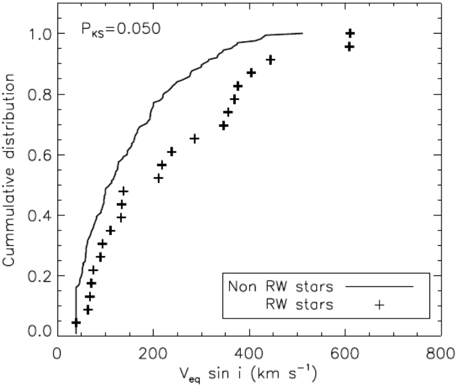
Rotation @ t=0 from O. Ramirez-Agudelo *et al.* '15

Spin Down: Winds



Properties of the RWs in 30 Dor





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

SN natal kicks

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Orbit from Tauris & Takens '98

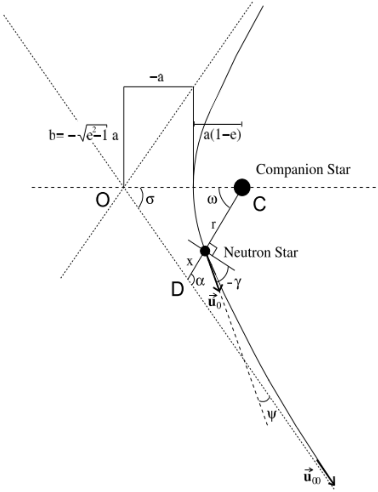


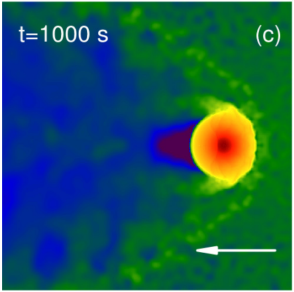
Fig. 2. Geometry of the orbital plane of a disrupted system ($e > 1$, $a < 0$) after an asymmetric supernova explosion. The reference frame is fixed on the companion star (C).

Fallback from Fryer *et al.* '12

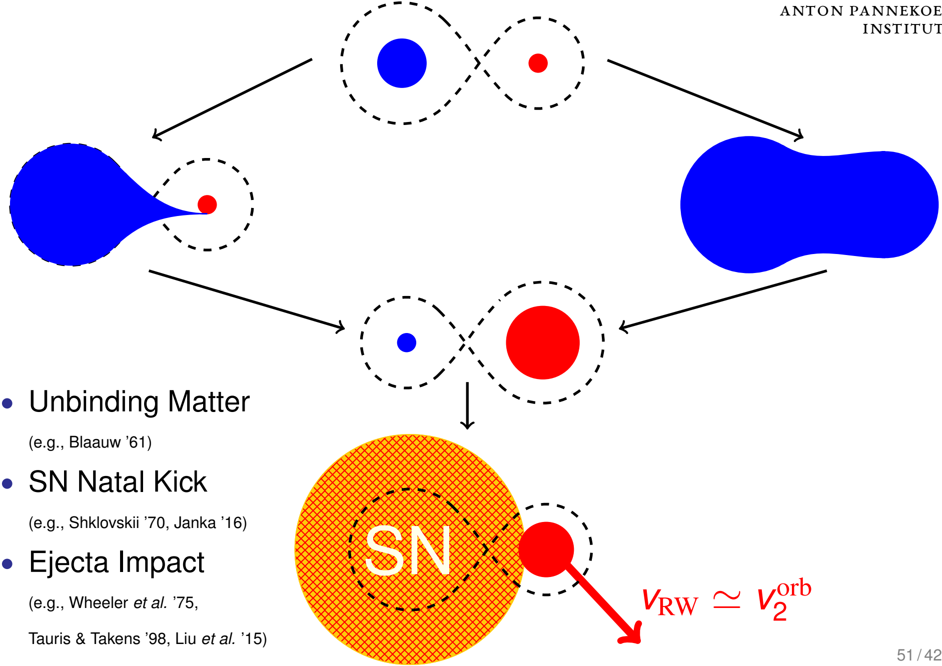
(Rapid SN mechanism)

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

Ejecta impact from Liu *et al.* '15



Binary Disruption



- Unbinding Matter

  (e.g., Blaauw '61)

- SN Natal Kick

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

- Ejecta Impact

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

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

Computing Advanced Burning Stages

- Initially small effect ⇒ $N_{\rm zones} \gtrsim 20\,000$
- Complex nuclear burning ⇒ $N_{\rm iso} \gtrsim 200$

$$M_{\rm Ch}^{\rm eff} \sim (5.83 M_\odot)\, Y_e^2 \left[1 + \left(\frac{s_e}{\pi Y_e}\right)^2\right]$$

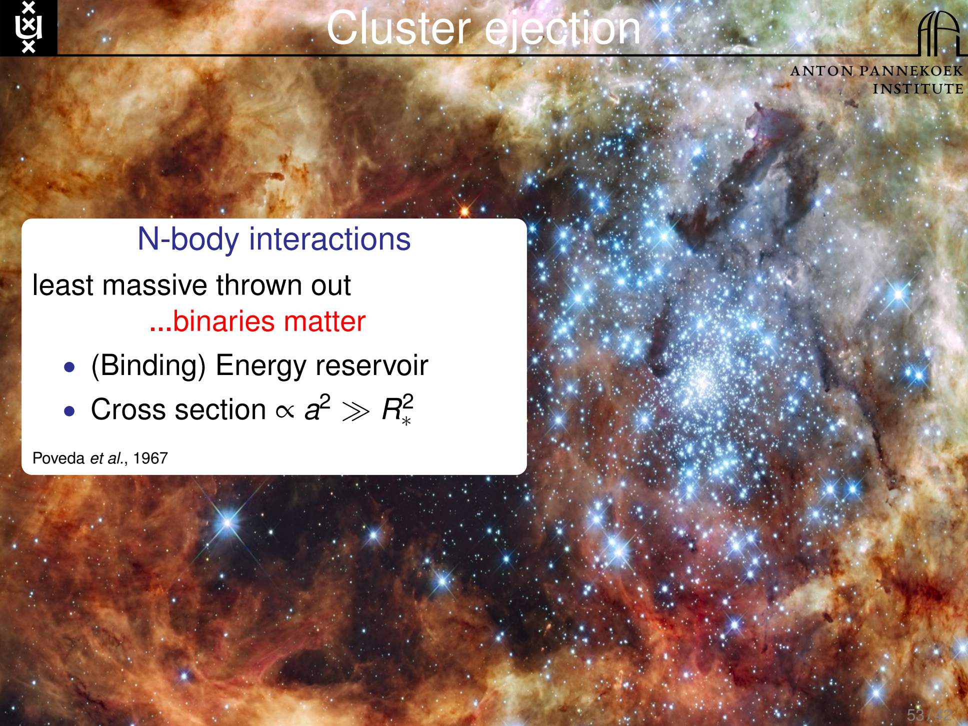
$$\texttt{approx21.net} \Rightarrow {}^{56}\mathrm{Fe} + 2e^- \rightarrow {}^{56}\mathrm{Cr} + 2\nu_e$$

$$Y_e(r=0) \equiv Y_e({}^{56}\mathrm{Cr}) = 0.428$$

Largest array size in MESA:

$$\mathcal{L} \sim (N_{\rm iso} + N_{\rm zones})^2 \sim ((N_{\rm iso} + 5) \cdot N_{\rm zones}) \cdot (3N_{\rm iso} + 9)$$

$\mathcal{L}$ is a `FORTRAN integer` ⇒ max{memory} = 17 Gb



Cluster ejection

N-body interactions

least massive thrown out

...binaries matter

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

Poveda *et al.*, 1967

MESA grid varying dM/dt

Grid of $Z_{\odot} = 0.019$, non-rotating stellar models:

- Initial mass:

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

- Efficiency:

$$\eta = \{1,\ \tfrac{1}{3},\ \tfrac{1}{10}\}\ ;$$

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

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.

Astrophysical implications...

...of disrupting binaries

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- Feedback
- Field contamination
- Massive Star Formation
- LBV

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- Feedback
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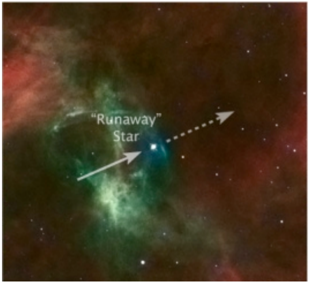
- Enhancement of massive stars feedback
  - Larger volume
  - Spatial spread of CCSN
    (e.g., Conroy & Kratter '12)
  - $\sim$20% increase in f_{esc}
    (e.g., Kimm & Cen '14)

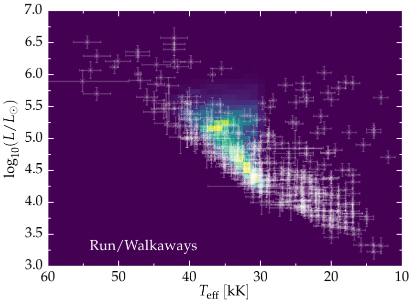


Astrophysical implications...

...of disrupting binaries

- Feedback
- Field contamination
- Massive Star Formation
- LBV

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



Astrophysical implications...

...of disrupting binaries

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- Feedback
- Field contamination
- Massive Star Formation
- LBV

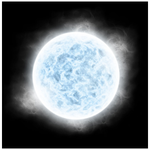
- Massive star formation
  - are isolated massive stars formed “in situ”?

    (e.g., Gavramadze *et al.* ’12)

...of disrupting binaries

- Feedback
- Field contamination
- Massive Star Formation
- LBV

- LBV phenomenon
  - Do LBV require binarity?



O-type

⇒

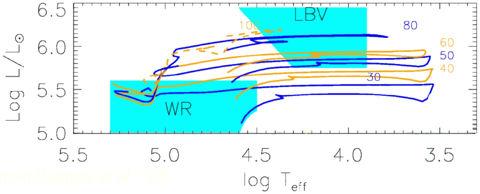
LBV

⇒

WR

"Conti scenario"

(e.g., Conti, '75, Maeder & Conti '94)



(Fig. adapted from Douglas *et al.*, '10)

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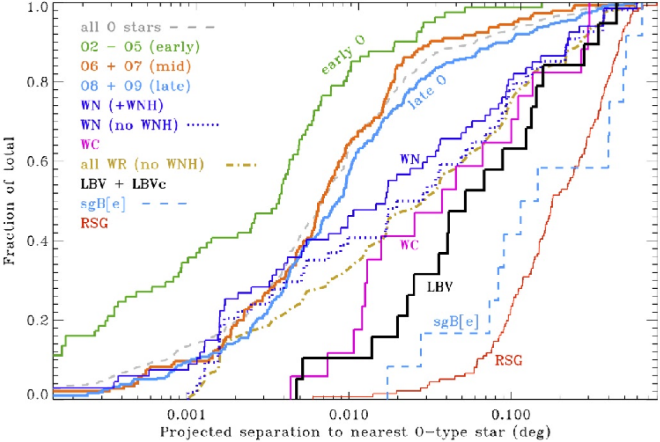
...of disrupting binaries

- Feedback
- Field contamination
- Massive Star Formation
- LBV

- LBV phenomenon
  - Do LBV require binarity?
    (e.g., Smith & Tombleson ’15, Smith ’16, Aghakhanlootakanloo *et al.* ’17)



Mass-rotation correlation

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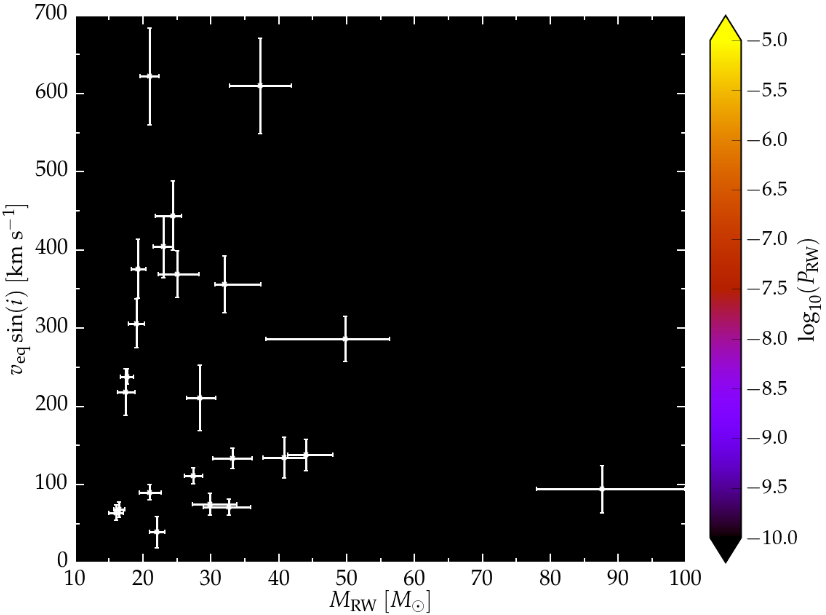
Runaways only



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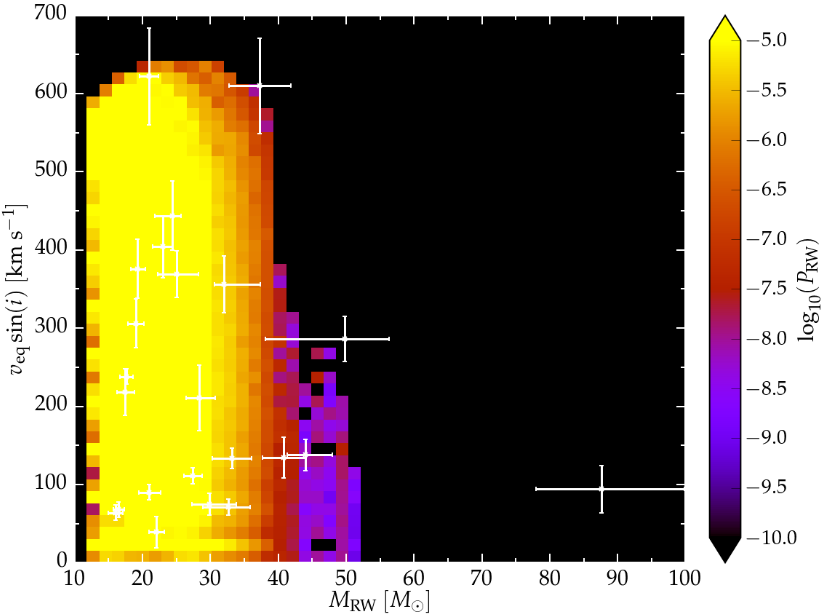

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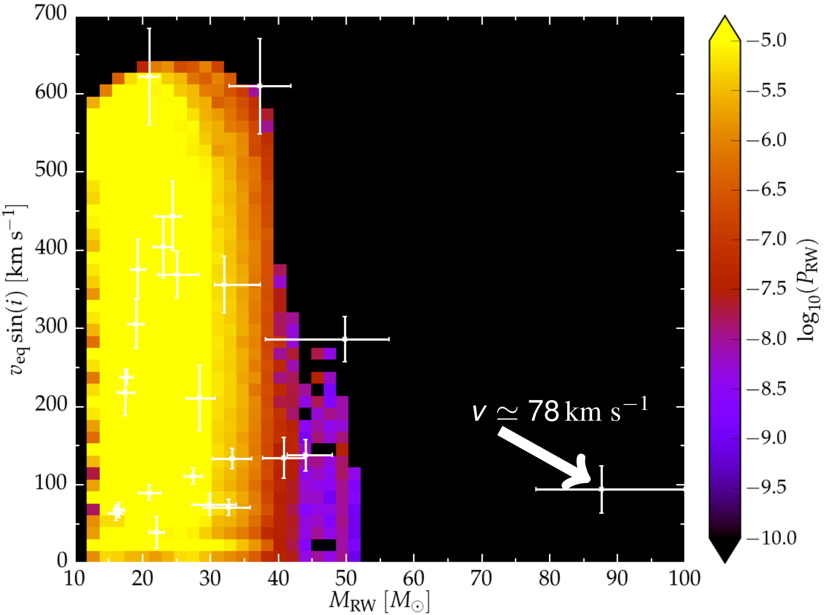
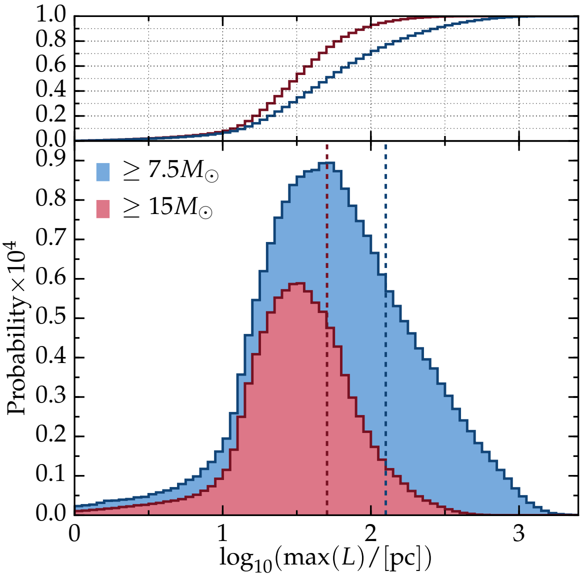


Where do they die?



"Distance traveled"

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

Where do they die?

Credits: ESA/Hubble & Nasa, A. Aloisi

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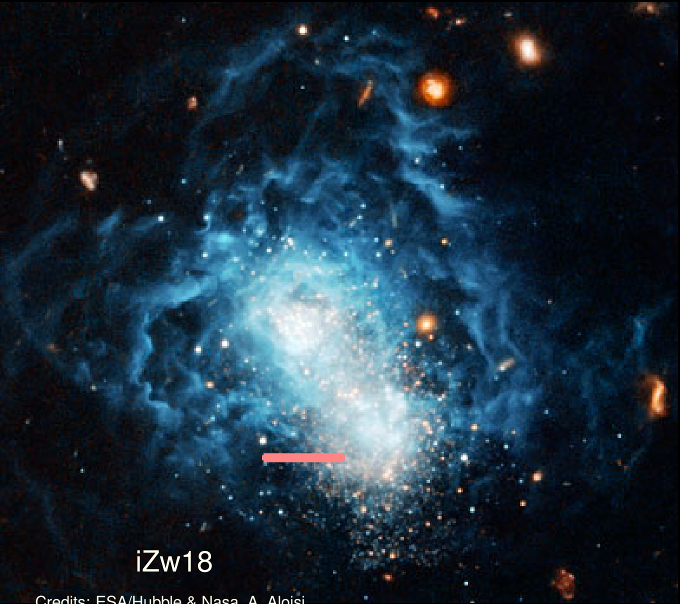

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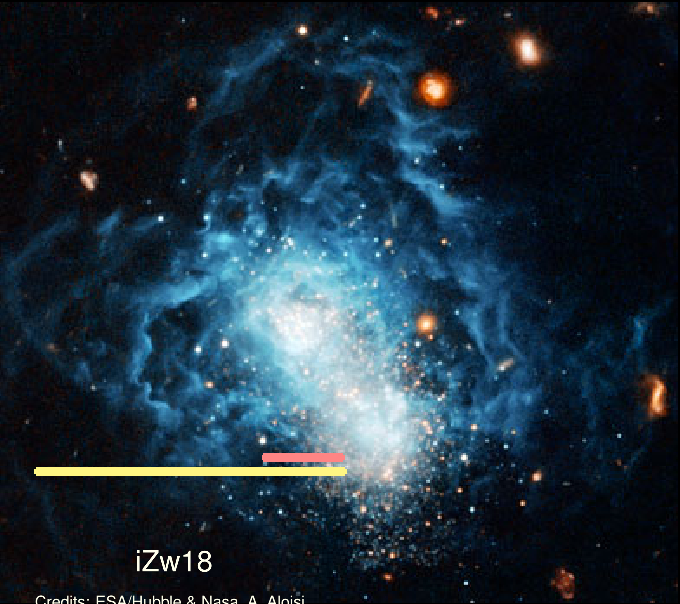
for $M \geq 7.5\,M_\odot$:

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

Where do they die?

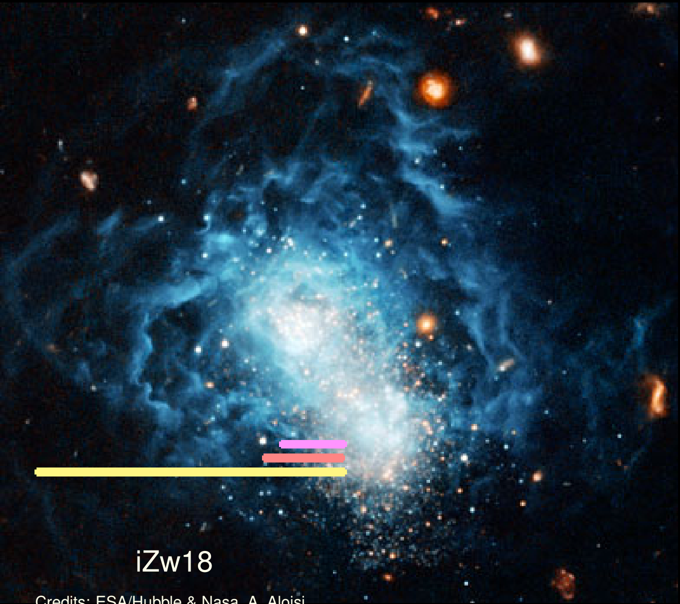


for $M \geq 7.5\,M_\odot$:

$\langle D \rangle$ = 128 pc

$\langle D_{\rm run} \rangle$ = 525 pc

Where do they die?



Credits: ESA/Hubble & Nasa, A. Aloisi

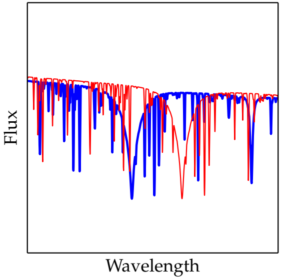
for $M \geq 7.5\,M_\odot$:

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

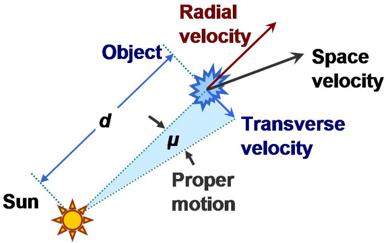
$\langle D_{\mathrm{run}} \rangle = 525\,\mathrm{pc}$

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

Line of sight velocity:
Doppler shifts ⇒



Transverse velocity:
Proper motions
(if distance known) ⇒



Gaia will give proper motions & distances

Wind Oservational Diagnostics

◂ Back

- P Cygni line profiles
- Optical and near UV lines (e.g. Hα)
- Radio and IR continuum excess
- IR spectrum of molecules (e.g. CO)
- Maser lines (for low density winds)

Assumptions commonly needed:

- Velocity structure: $v(r) \simeq \left(1 - \frac{r}{R_*}\right)^{\beta}$ with $\beta \simeq 1$
- Chemical composition and ionization fraction
- Spherical symmetry: $\dot{M} = 4\pi r^2 \rho v(r)$
- Steadiness and (often) homogeneity

$\dot{M}$ derived from fit of (a few) spectral lines.
No theoretical guaranties coefficients are constant.