Massive widowed stars:

Runaways and walkaways from binary disruptions

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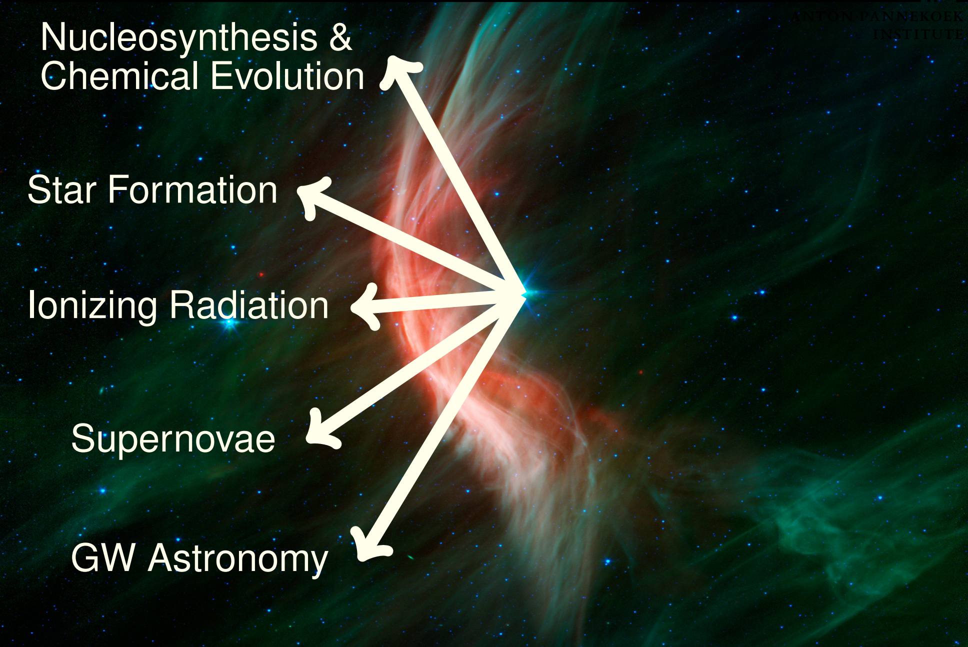
Collaborators: S. E. de Mink, E. Zapartas, Y. Götberg, F. R. N. Schneider, R. G. Izzard, H. Sana

Why are they interesting?



NASA, JPL-Caltech, Spitzer Space Telescope

Why are they interesting?

- Nucleosynthesis & Chemical Evolution
- Star Formation
- Ionizing Radiation
- Supernovae
- 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

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

Preliminary:

~20 walkaways for each O-type runaway

(e.g., Renzo *et al.*, in prep, de Mink *et al.* '14)

NASA, JPL-Caltech, Spitzer Space Telescope

Outline

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How to measure stellar velocities?

Astrophysical implications

How to make fast stars?

- Dynamical ejection
- Binary disruption

Methods: population synthesis

Preliminary results

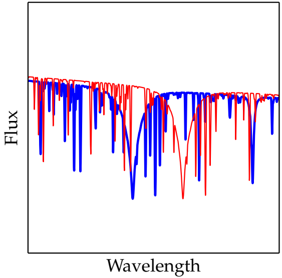
- O-type runaways in 30 Doradus
- Walkaways in the Milky Way

Conclusions

Observations of stellar velocities

⇐ Bow shocks

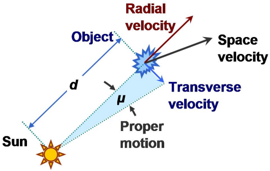
Doppler shifts ⇒



Proper motions

(if distance known)

⇓



Gaia will give proper motions & distances

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Astrophysical implications...

...of disrupting binaries

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- Field contamination
- Massive Star Formation
- LBV

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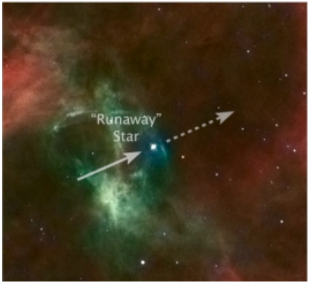
- Enhancement of massive stars feedback
  - Larger volume
  - Spatial spread of CCSN (e.g., Conroy & Kratter '12)
  - ~20% increase in f_{esc} (e.g., Kimm & Cen '14)



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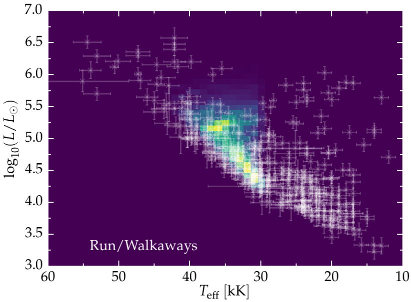
- Feedback
- Field contamination
- Massive Star Formation
- LBV

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



Astrophysical implications...

...of disrupting binaries

- Feedback
- Field contamination
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- LBV

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

(e.g., Gavramadze *et al.* '12)

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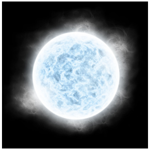
- Feedback
- Field contamination
- Massive Star Formation
- LBV

- LBV phenomenon
  - Do LBV require binarity?


O-type

⇒

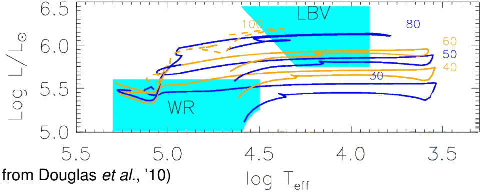

LBV

⇒


WR

“Conti scenario”

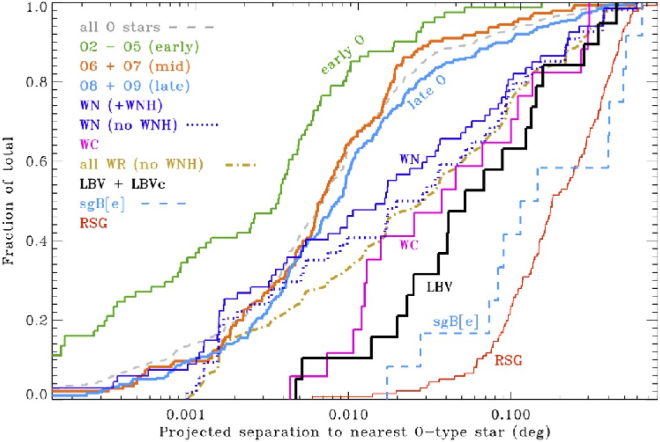
(e.g., Conti, ’75, Maeder & Conti ’94)



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

- Feedback
- Field contamination
- Massive Star Formation
- LBV

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



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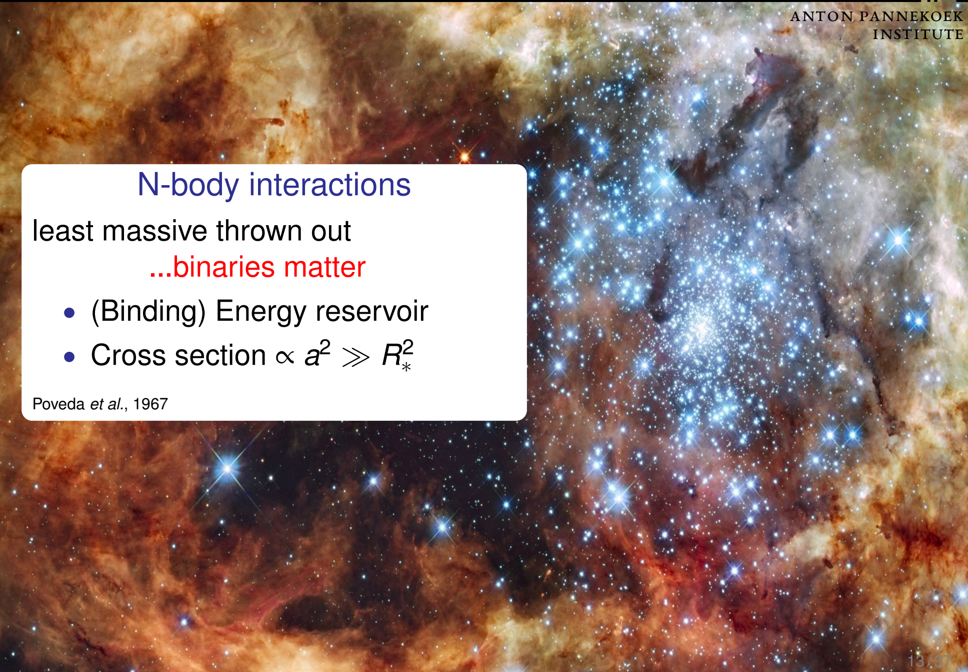

Cluster ejection

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N-body interactions

least massive thrown out

...binaries matter

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

Poveda *et al.*, 1967

Binary disruption

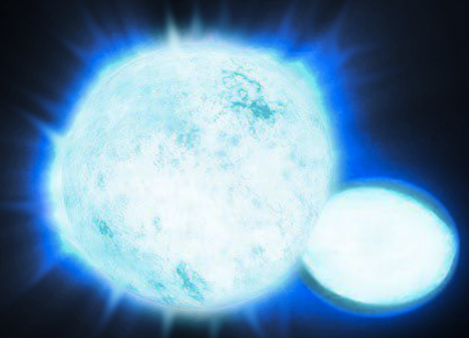
Credits: ESO, L. Calçada, M. Kornmesser, S.E. de Mink

Spin up, pollution, and rejuvenation

The binary disruption shoots out the accretor

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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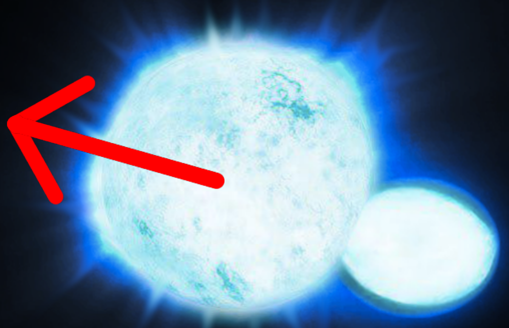

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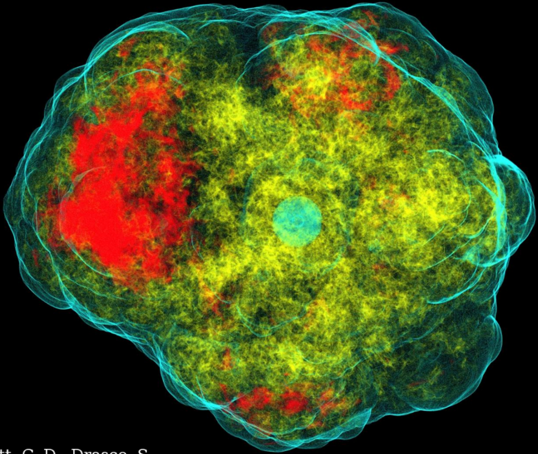
$$v_2^{\mathrm{post-SN}} \simeq v_{2,\mathrm{orb}}^{\mathrm{pre-SN}}$$

SN natal kick

ν emission and/or ejecta anisotropies



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

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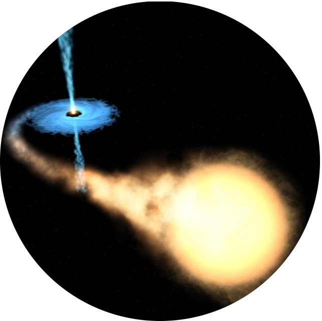
...from disrupted binaries

- **BH kicks**
- Binary evolution

Do BH receive natal kicks?

Spatial distribution of X-ray binaries

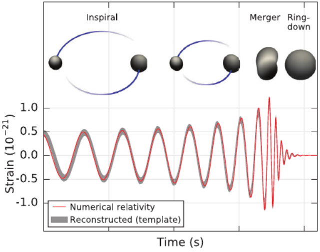
(e.g., Repetto *et al.* '12,'15,'16, Mandel '16)



Massive (and WR) runaways

(Dray *et al.* '05)

Disrupted binaries are "failed" GW sources!

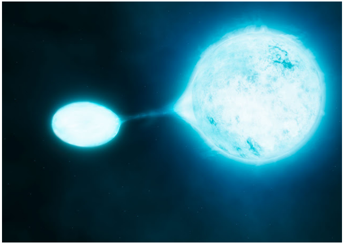


...from disrupted binaries

- 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.



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What I do: Population Synthesis

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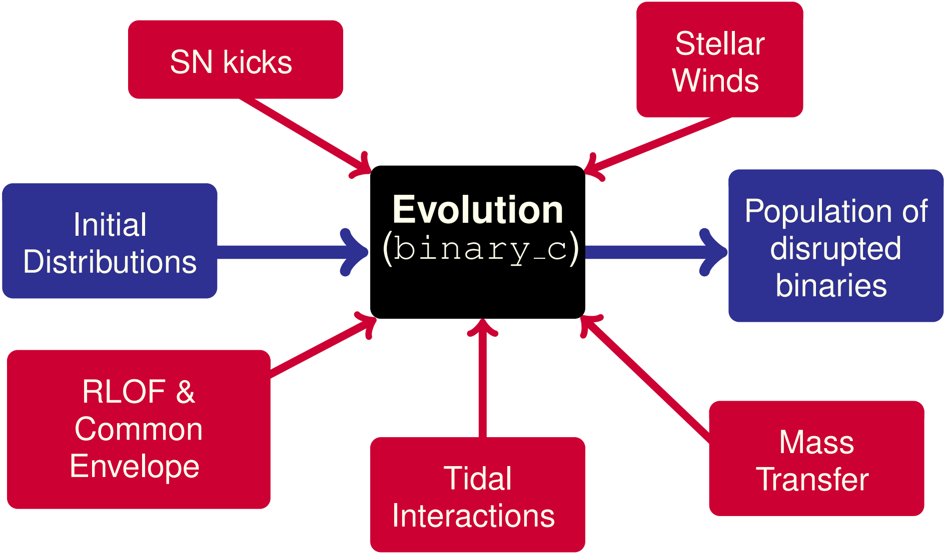
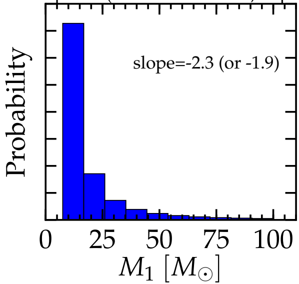
Fast ⇒ Allows statistical tests of the inputs & assumptions

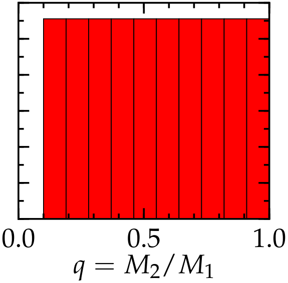


Izzard *et al.* ’04, ’06, ’09; de Mink *et al.* ’13

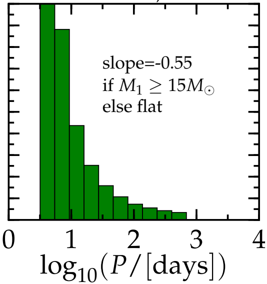
Kroupa '01 (or Schneider *et al.*, in prep.)



flat

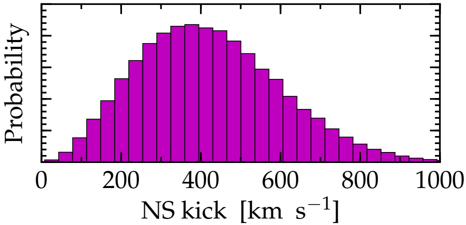


Sana *et al.*, '12



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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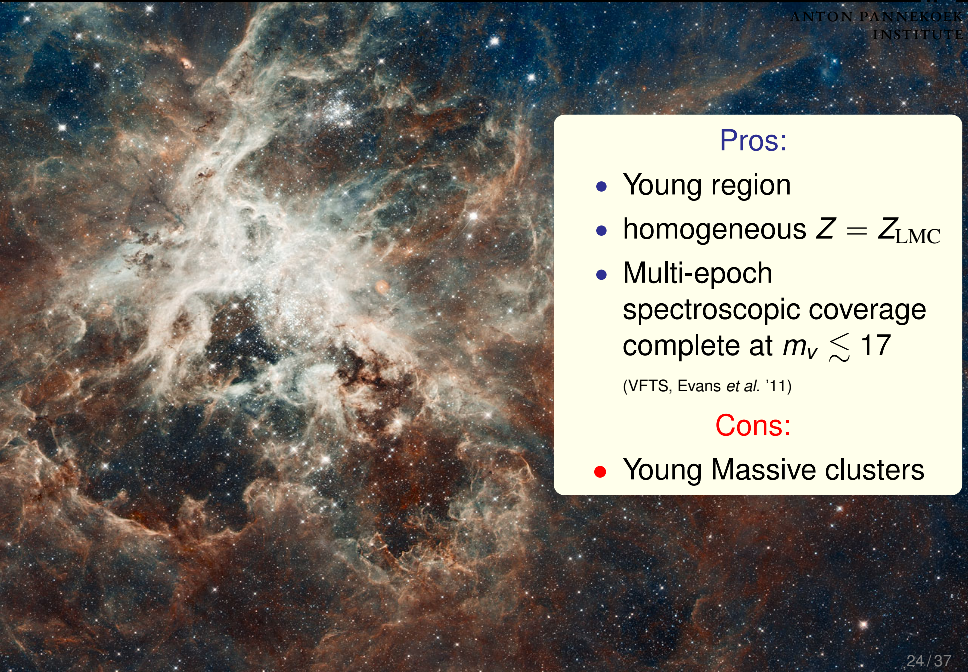
30 Doradus



Pros:

- Young region
- homogeneous $Z = Z_{\rm LMC}$
- Multi-epoch spectroscopic coverage complete at $m_v \lesssim 17$

(VFTS, Evans *et al.* '11)

Cons:

- Young Massive clusters

O-type runaways

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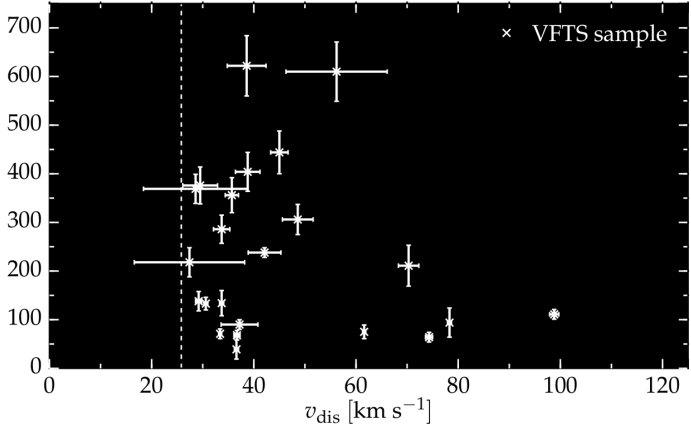
Largest homogeneous sample available to date

“Rotational velocity”



“Line of sight velocity”

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

O-type runaways

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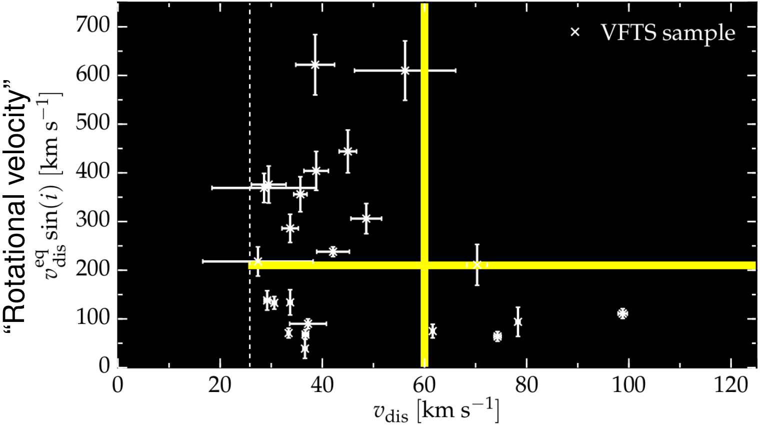

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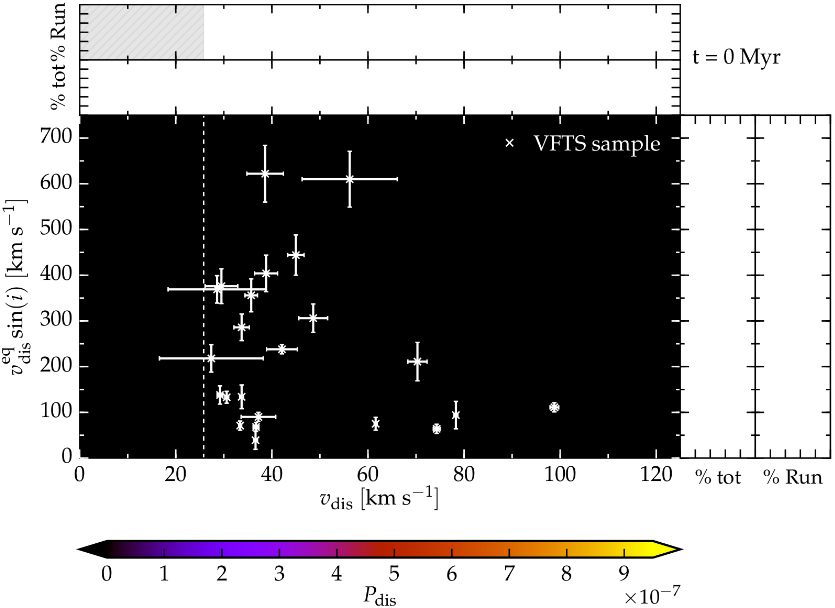

Mass-rotation correlation

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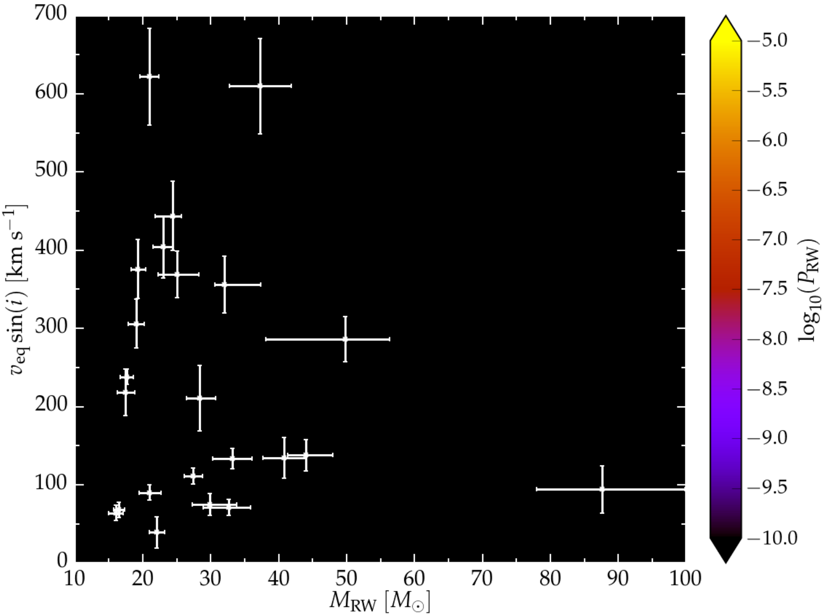
Runaways only



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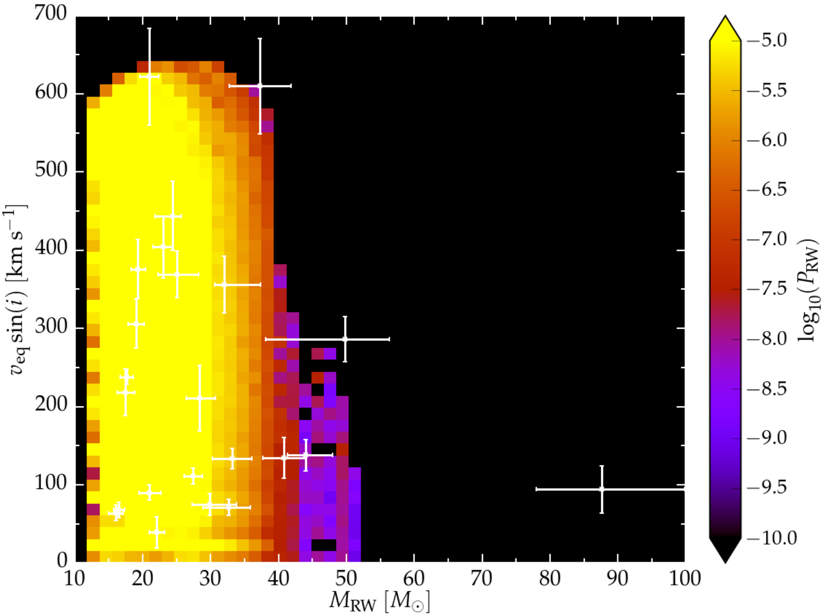

Mass-rotation correlation

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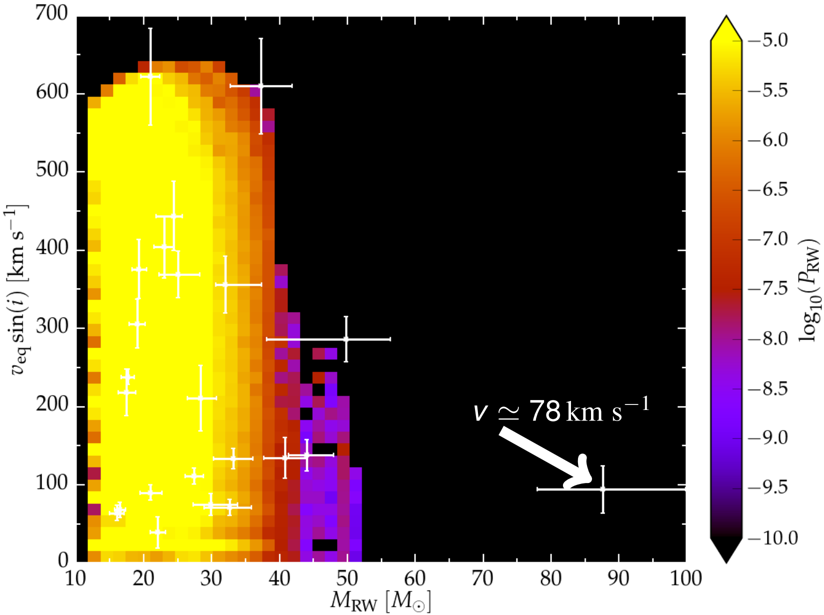

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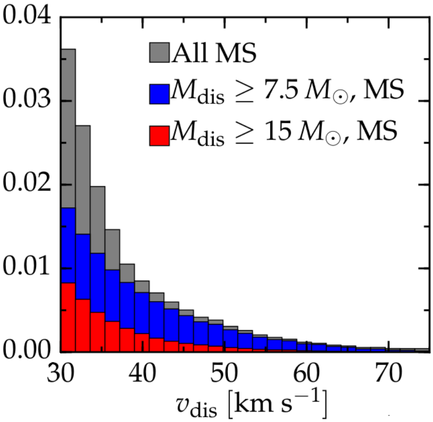
Velocity distribution: Runaways

Runaways ⇒



Velocity distribution: Walkaways

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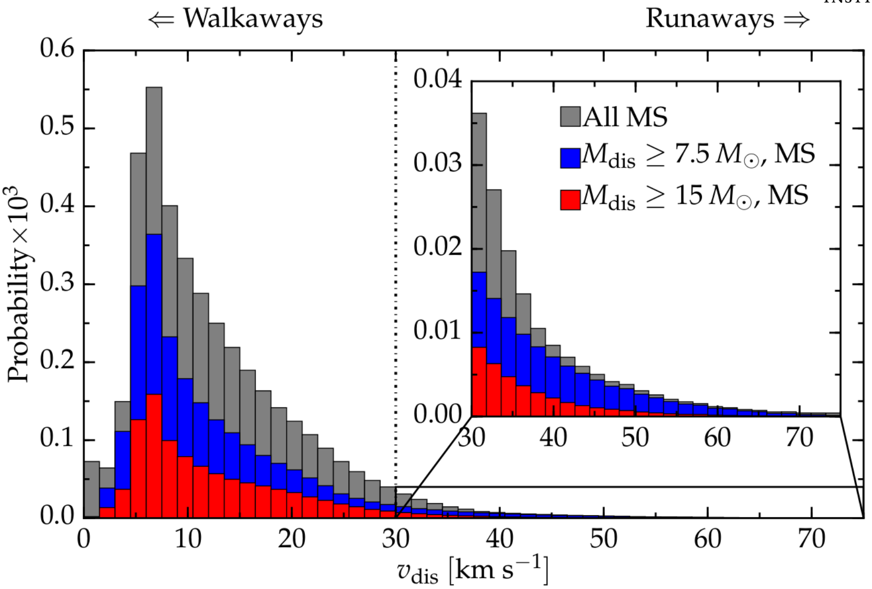
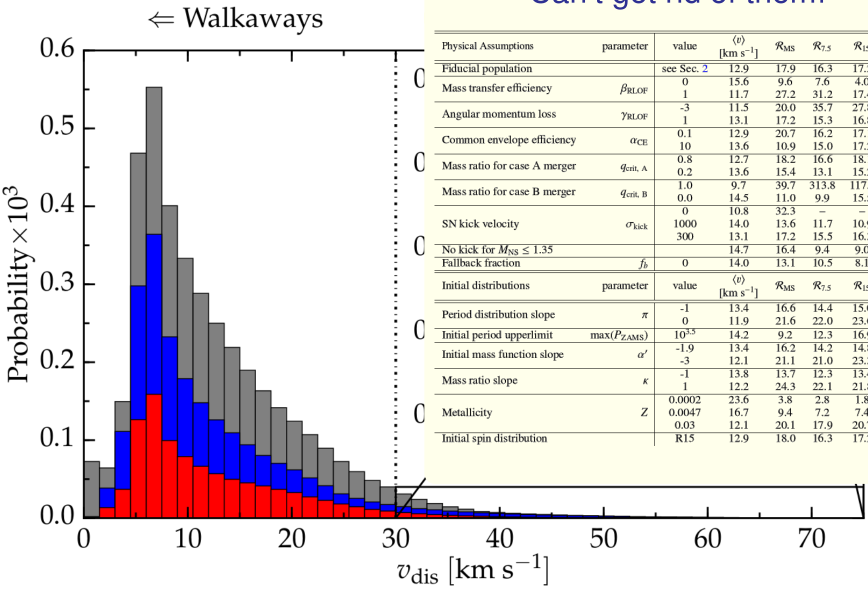


For each runaway there are ∼ 20 walkaways in the galaxy!

Velocity distribution: Walkaways

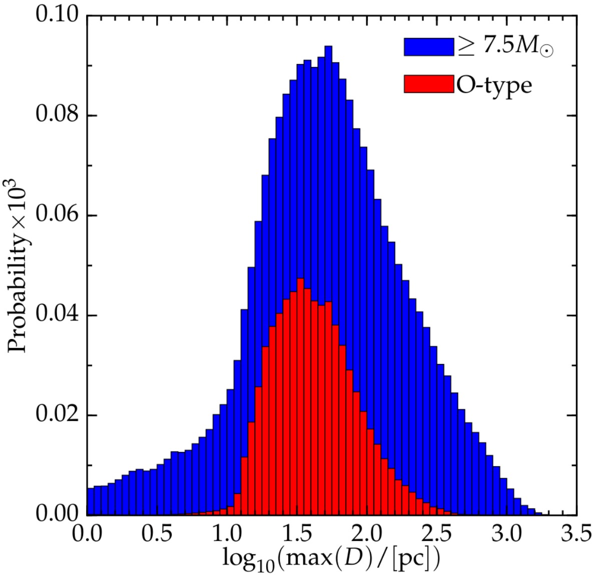


Can't get rid of them!

Physical Assumptions	parameter	value	$\langle v \rangle$ [km s^{-1}]	$\mathcal{R}_{MS}$	$\mathcal{R}_{7.5}$	$\mathcal{R}_{15}$	$\mathcal{D}$
Fiducial population		see Sec. 2	12.9	17.9	16.3	17.2	0.84
Mass transfer efficiency	β_{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	γ_{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	α_{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	$q_{crit, A}$	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	$q_{crit, B}$	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	σ_{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 $M_{NS} \leq 1.35$			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}]**	**$\mathcal{R}_{MS}$**	**$\mathcal{R}_{7.5}$**	**$\mathcal{R}_{15}$**	**$\mathcal{D}$**
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	$\max(P_{ZAMS})$	$10^{3.5}$	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!

Where do they die?



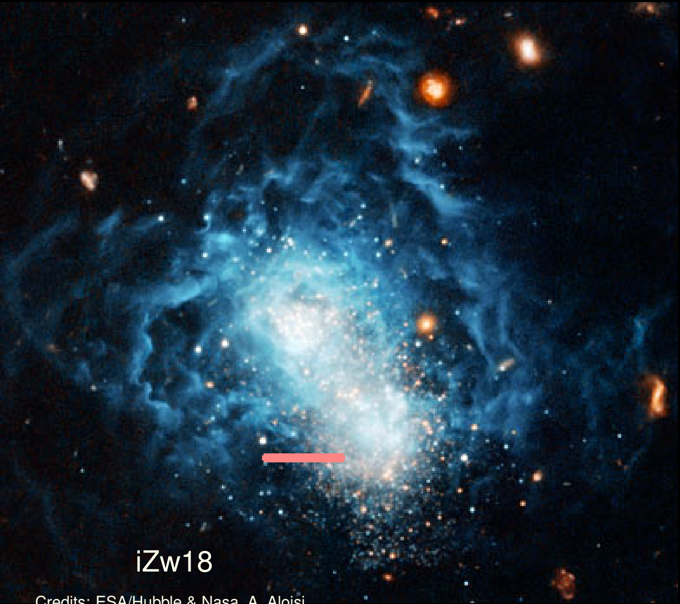
"Distance traveled"

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

Where do they die?

Credits: ESA/Hubble & Nasa, A. Aloisi

Where do they die?



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

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

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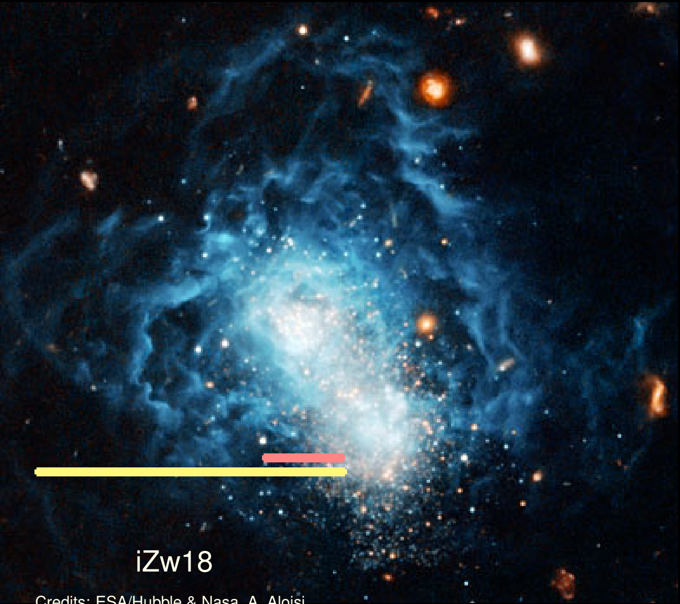

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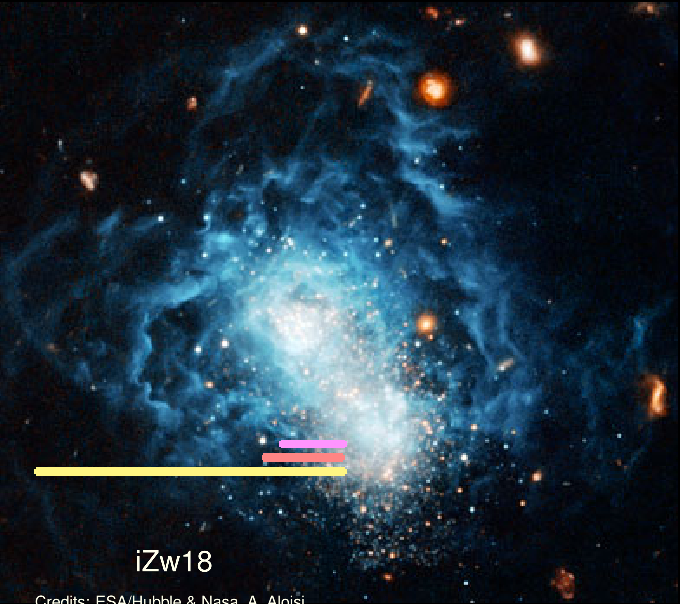
for $M \geq 7.5\,M_\odot$:

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

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

Where do they die?



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

$\langle D \rangle = 128$ pc

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

$\langle D_{\rm walk} \rangle = 103$ pc

How to test BH kick physics?

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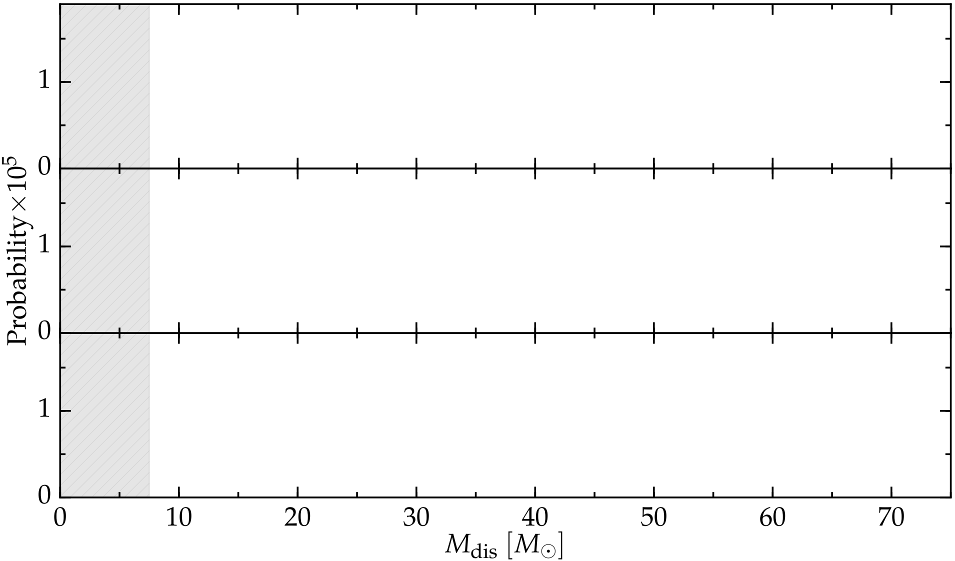

BH ⇔ $M_{\rm BH} \geq 2.5\,M_\odot$, Only $v \geq 30\,{\rm km\,s^{-1}}$ and $M_{\rm dis} \geq 7.5\,M_\odot$

(Massive) runaway mass function

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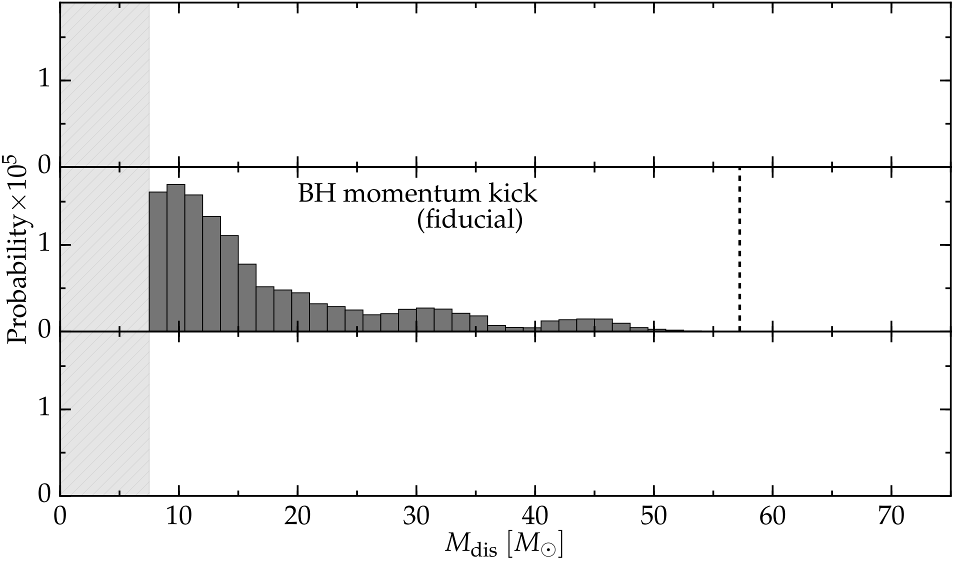

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(Massive) runaway mass function

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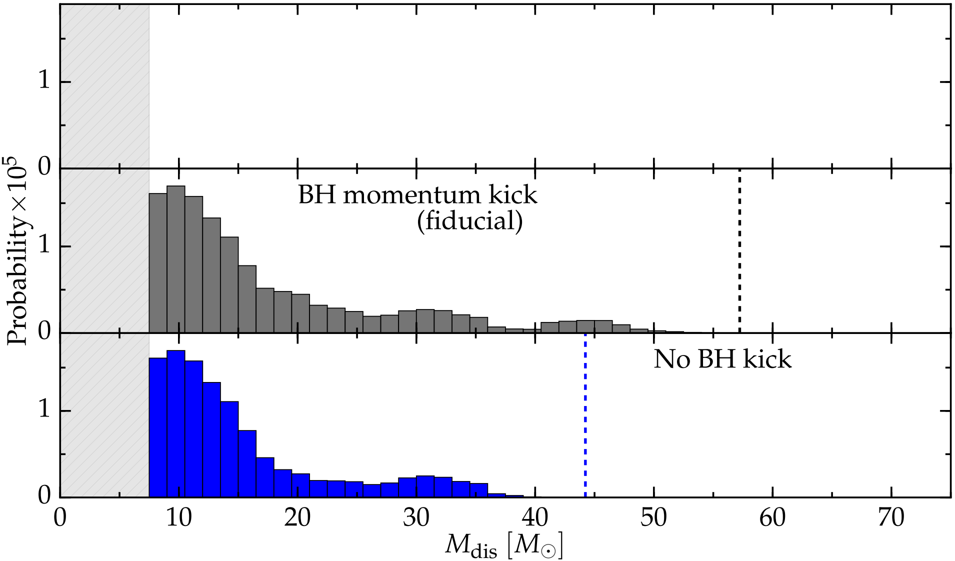

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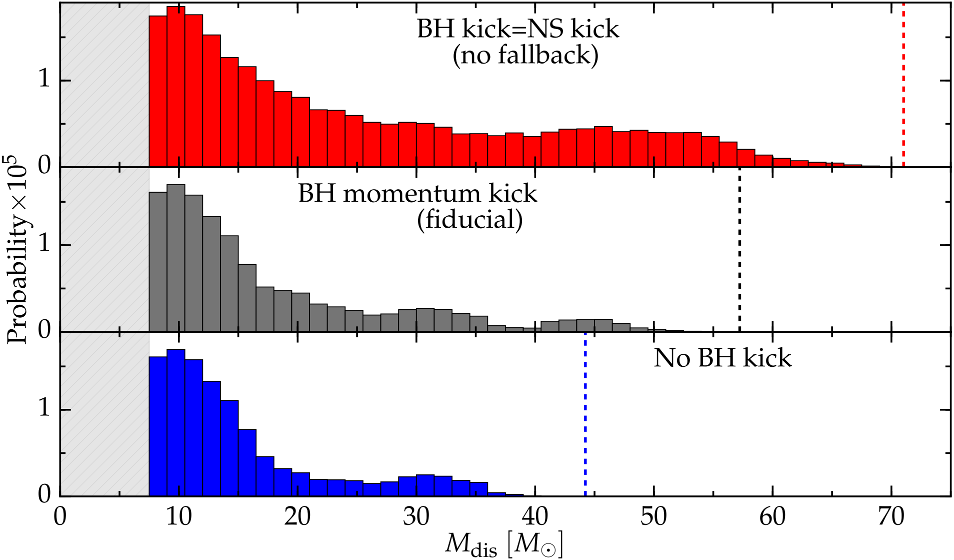

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$\sim$ 80% **of binaries disrupted by first SN**

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

Conclusions

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$\sim$ 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

Thank you!

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Backup slides

Where do they die?

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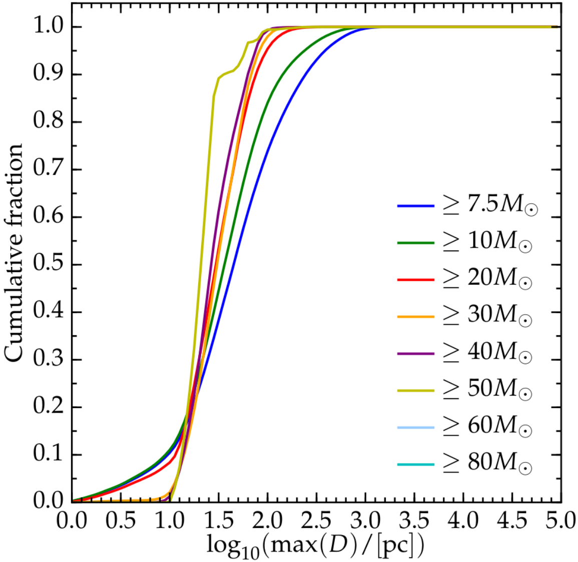
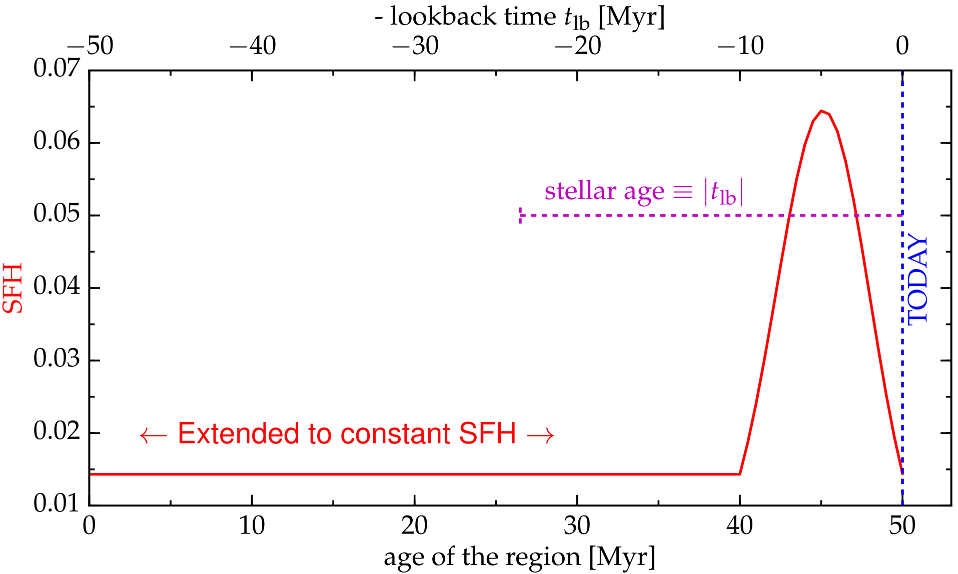


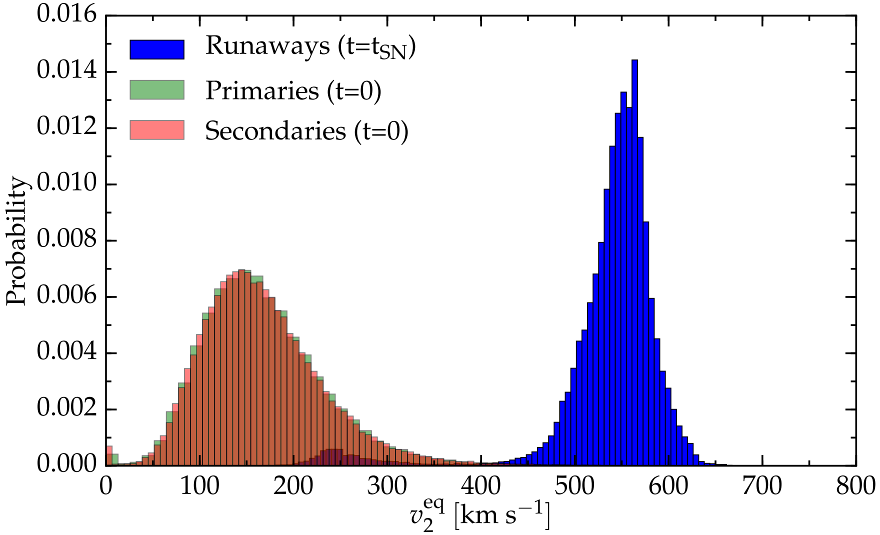
"Distance traveled"

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

30 Doradus Star Formation History

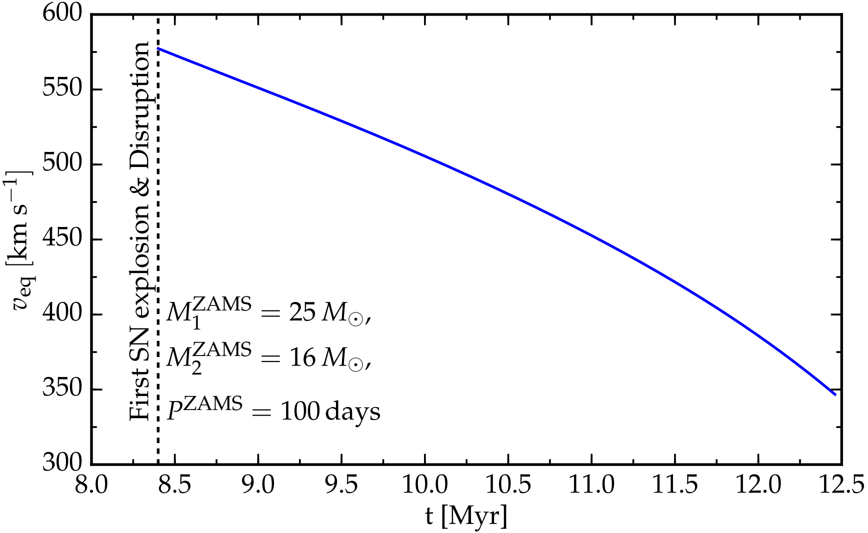


Initial Rotational Velocities

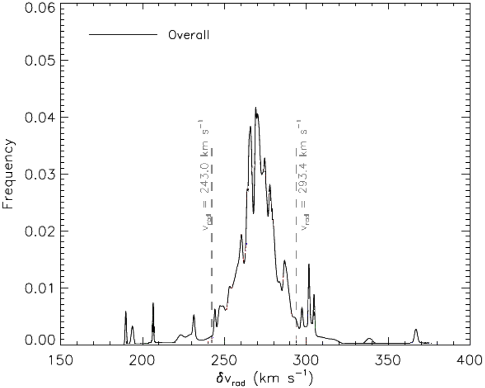


Rotation @ t=0 from O. Ramirez-Agudelo *et al.* ’15

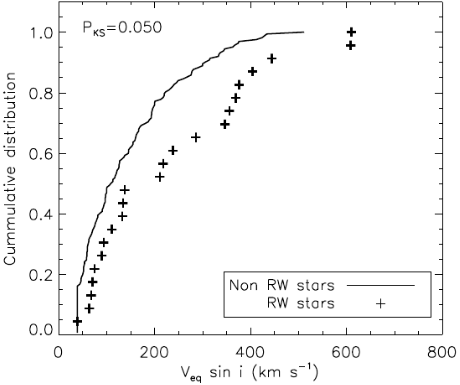
Spin Down: Winds



Line of Sight Velocities



Rotational Velocities



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

Soon proper motions!

SN natal kicks

Orbit from Tauris & Takens '98

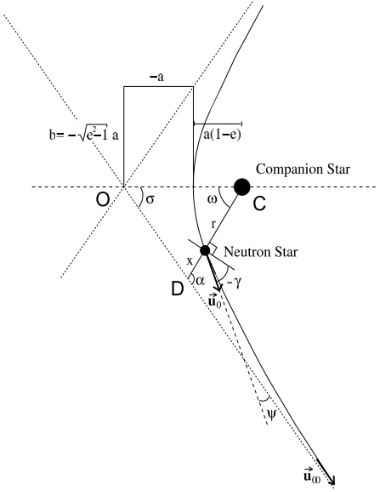


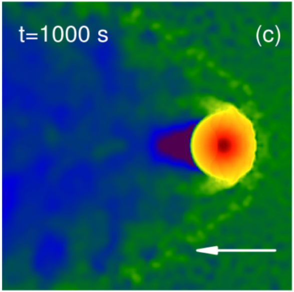
Fig. 2. Geometry of the orbital plane of a disrupted system ($e > 1$, $a < 0$) after an asymmetric supernova explosion. The reference frame is fixed on the companion star (C).

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



SN kick directions 1/2

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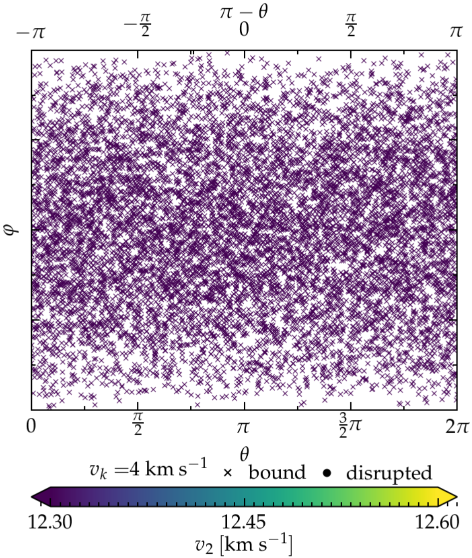
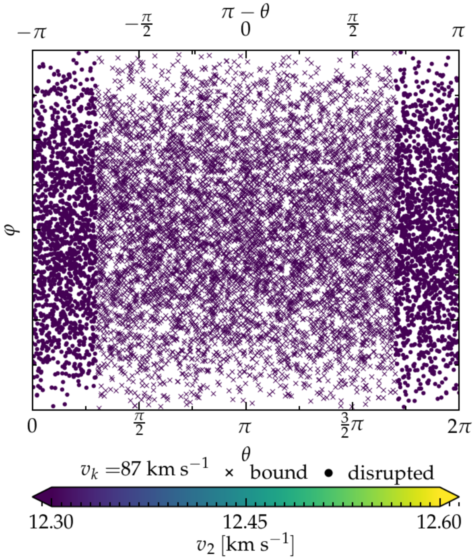
$20\,M_\odot + 15\,M_\odot$ on $P_{\mathrm{ZAMS}} = 100$ days $\Rightarrow v_2^{\mathrm{pre-SN}} \simeq 12.55\,\mathrm{km\ s^{-1}}$





SN kick directions 2/2

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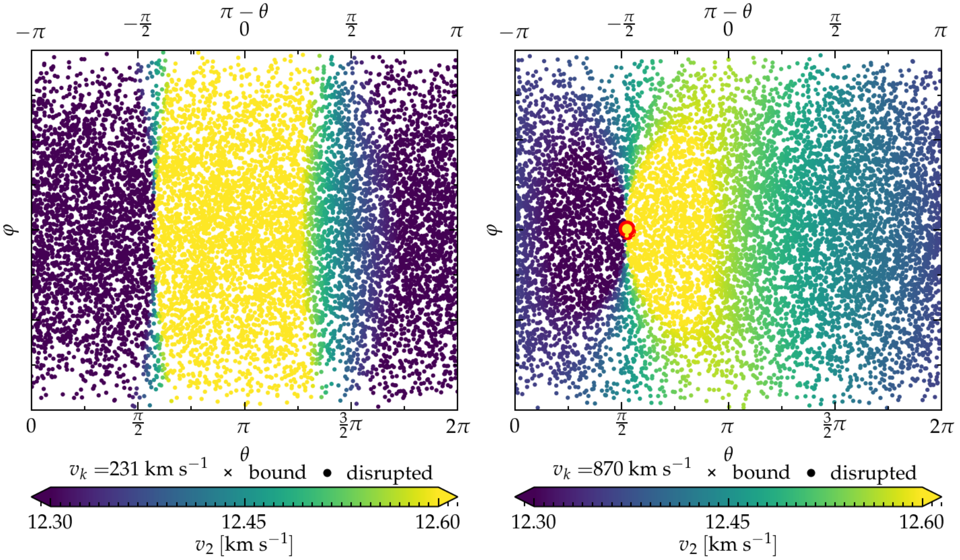
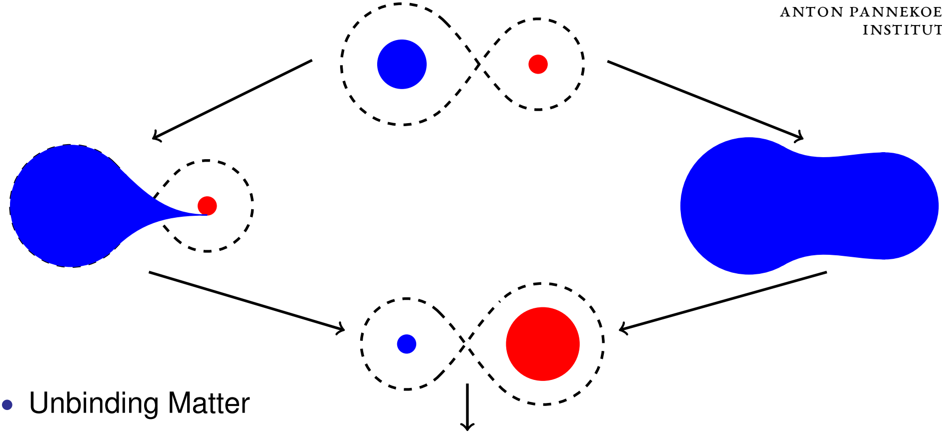
$20\,M_\odot + 15\,M_\odot$ on $P_{\mathrm{ZAMS}} = 100\,\mathrm{days} \Rightarrow v_2^{\mathrm{pre-SN}} \simeq 12.55\,\mathrm{km\ s^{-1}}$



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)