Massive widowed stars:

Runaways and walkaways from binary disruptions

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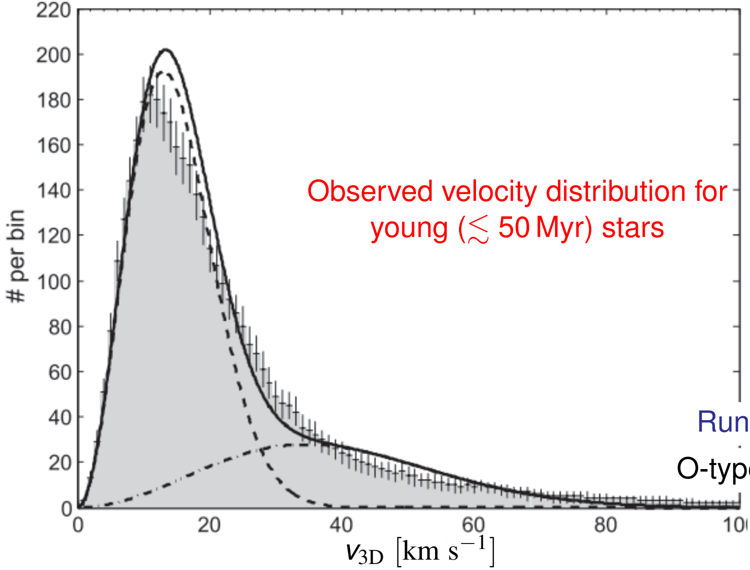
PhD in Amsterdam

Collaborators: E. Zapartas, S. E. de Mink, Y. Götberg, S. Justham, R. J. Farmer, R. G. Izzard, S. Toonen, H. Sana, E. C. Laplace

NASA, JPL-Caltech, Spitzer Space Telescope

What is a runaway star?



Observed velocity distribution for young ($\lesssim$ 50 Myr) stars

Runaway fraction

O-type: $\sim 10 - 20\%$

from Tetzlaff *et al.* 11,

see also Zwicky 57, Blaauw 61, 93, Gies & Bolton 86, Leonard 91, Renzo *et al.* 18, submitted, arXiv:1804.09164

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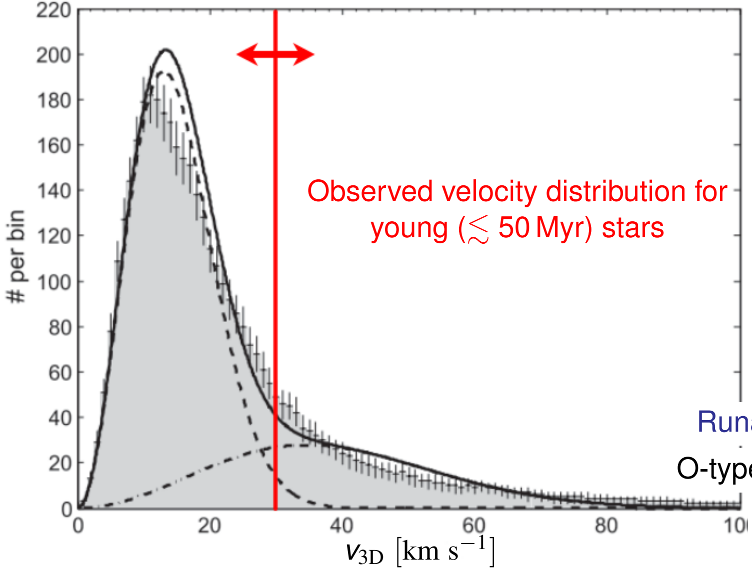

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Two ejection mechanisms

Dynamical interactions

- Extremely massive runaways in 30 Doradus

Binary disruption

- Velocity distribution of “widowed” companions
- BH kicks from massive runaway mass function

Cluster ejection

N-body interactions

(typically) least massive thrown out.

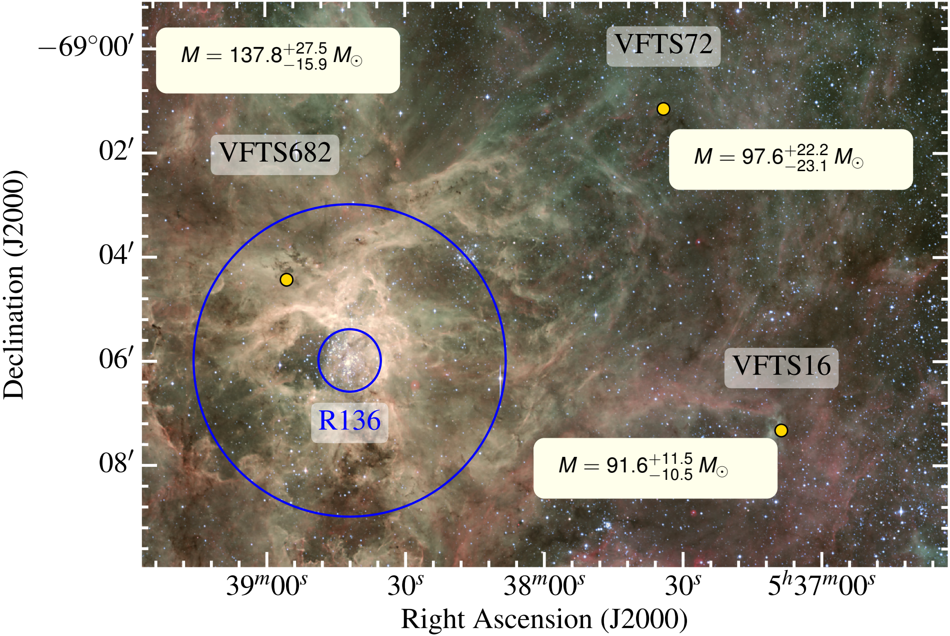
Binaries matter...

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

Poveda *et al.*, 1967

..but don't necessarily leave imprints!

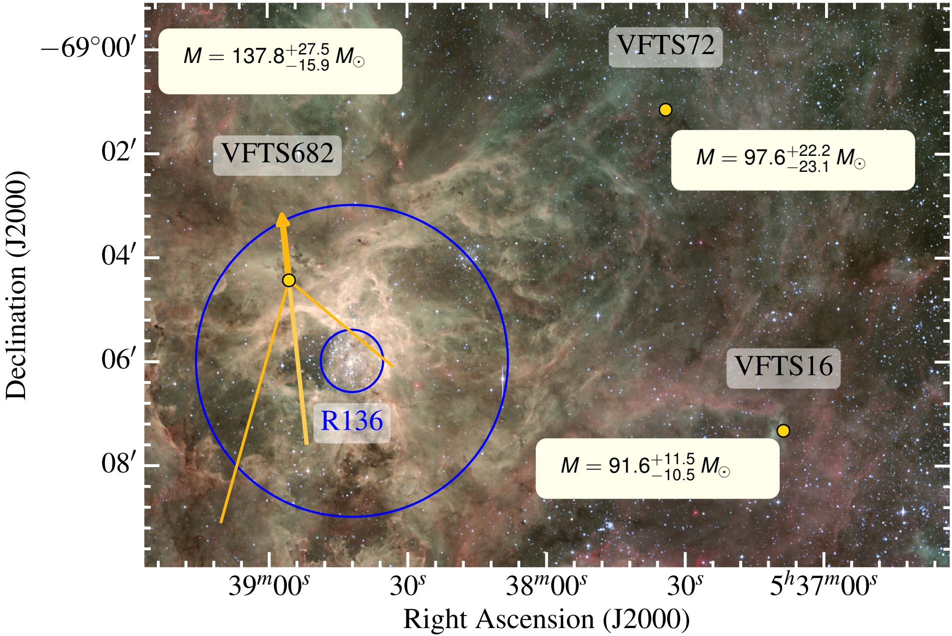
The most massive runaways known



Renzo *et al.*, submitted

Lennon *et al.*, accepted, arXiv:1805.08277

The most massive runaways known



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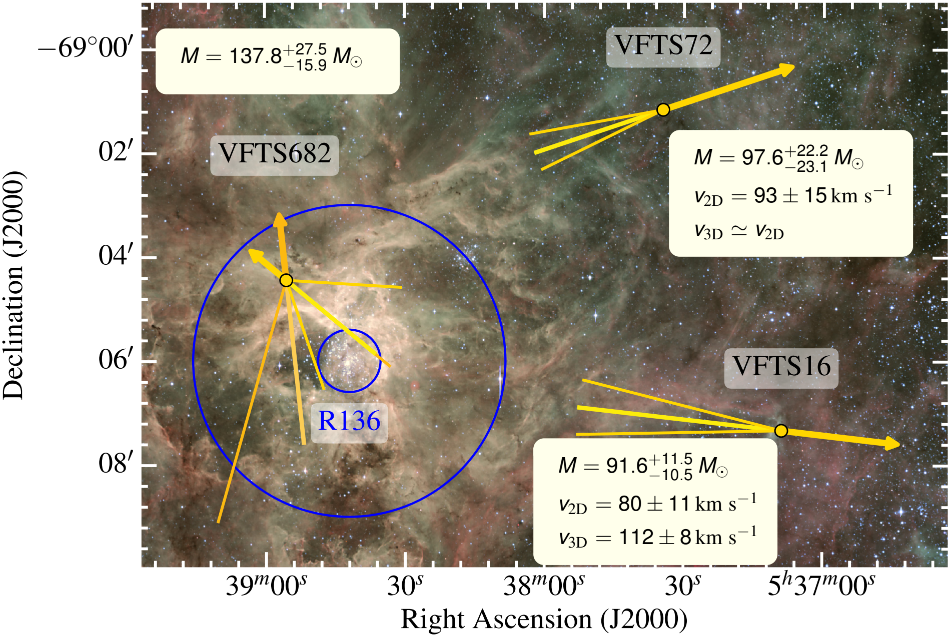

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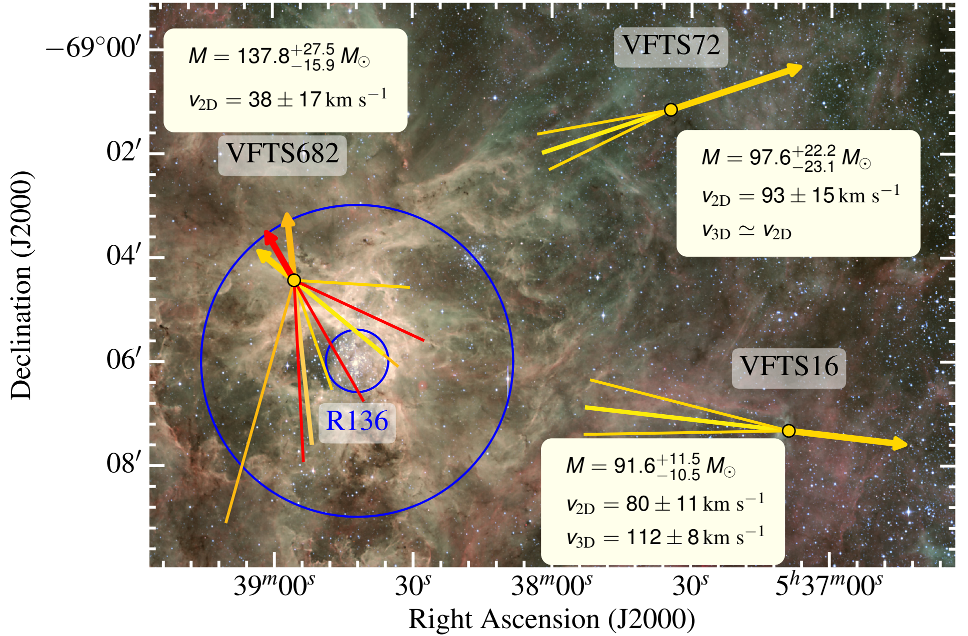

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Two ejection mechanisms

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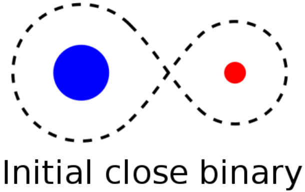
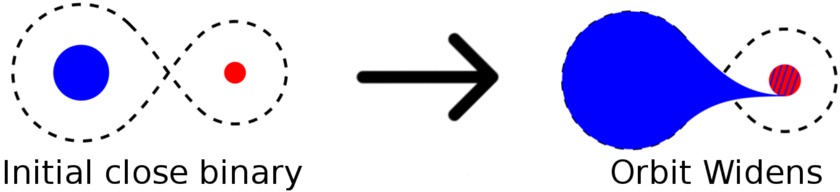


Most common evolutionary scenario for **massive binaries**

Binary disruption



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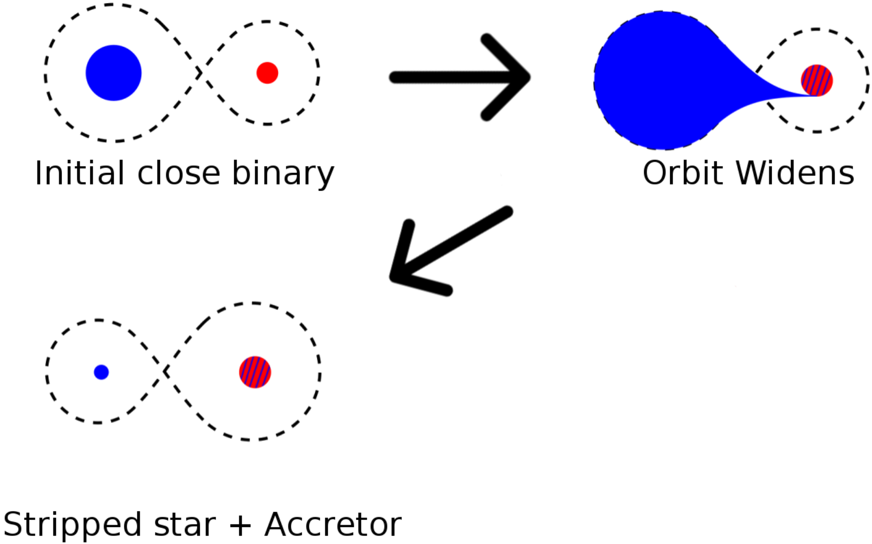

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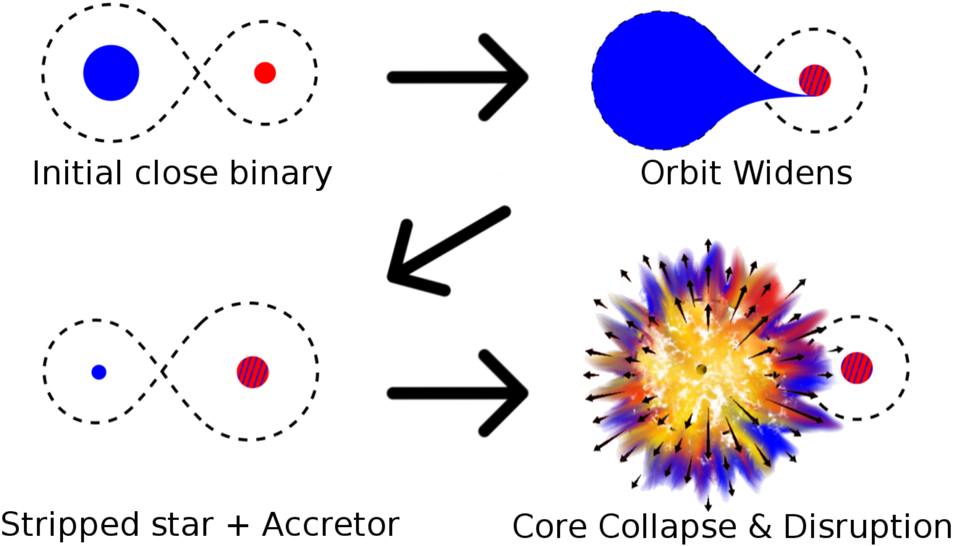

Most common evolutionary scenario for **massive binaries**

Spin up, pollution, and rejuvenation

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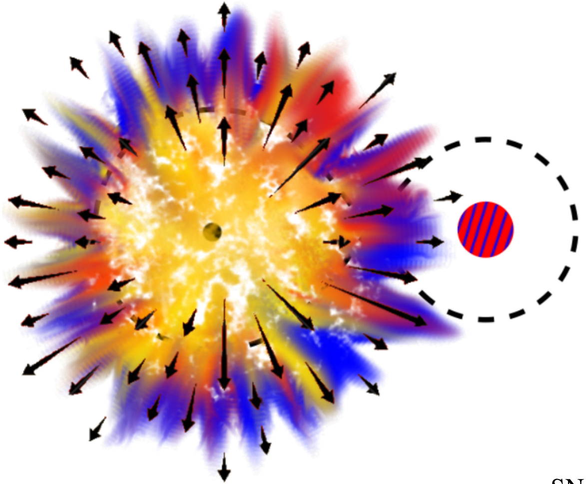
The binary disruption shoots out the accretor

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

What exactly disrupts the binary?

86^{+11}_{-9}% 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)

$$v_{\rm dis} \simeq v_{\rm 2,orb}^{\rm pre-SN}$$

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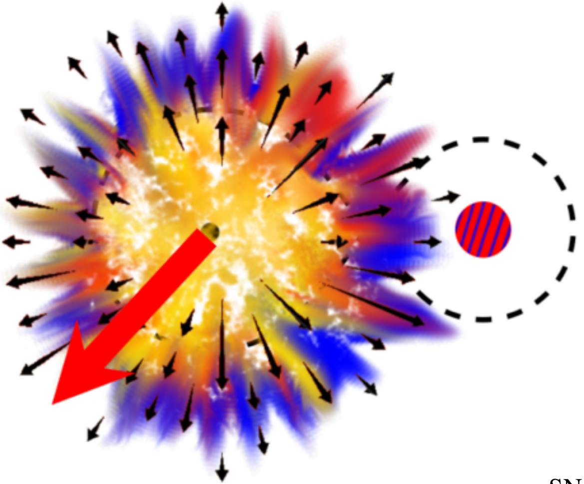

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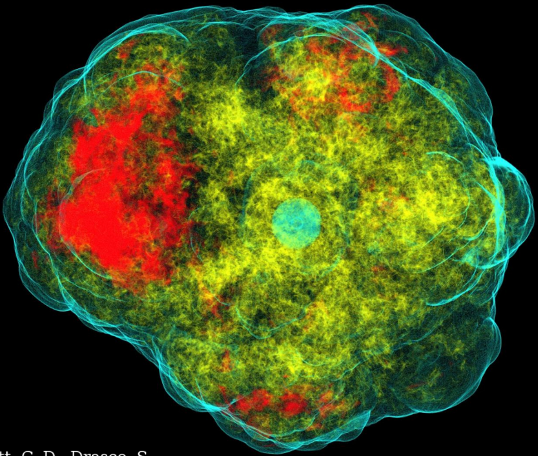
SN natal kick

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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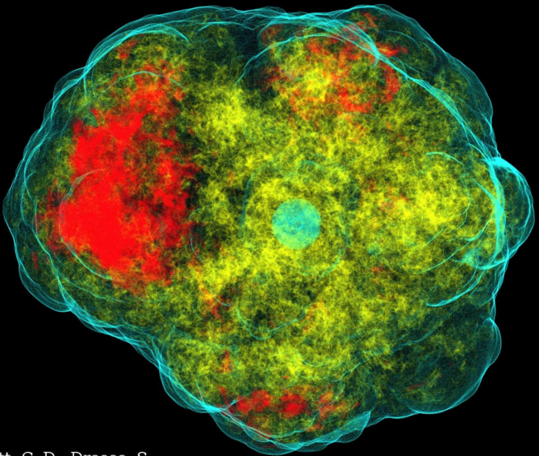

Credits: Ott, C. D., Drasco, S.

Do BH receive kicks?

What I do: Population Synthesis

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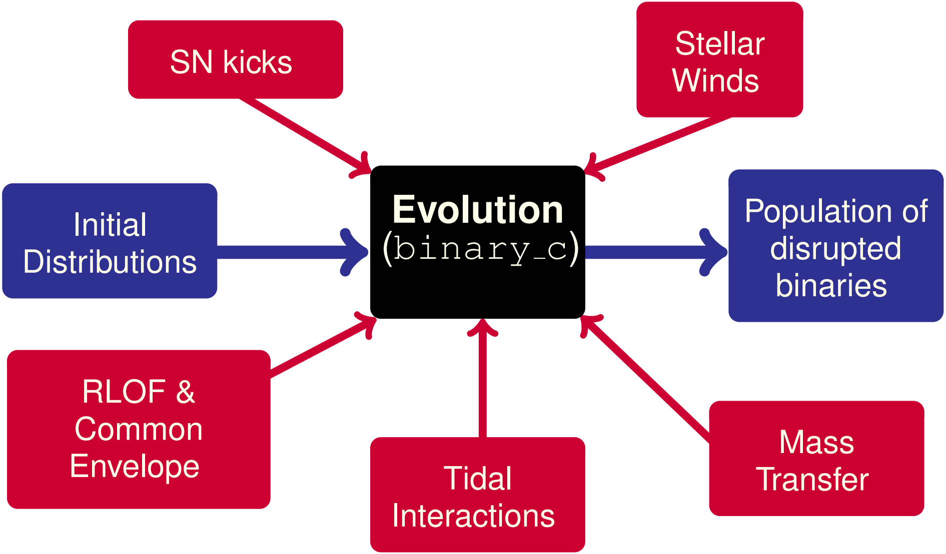
Fast ⇒ Allows statistical tests of the inputs & assumptions



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

Dynamical interactions

- Extremely massive runaways in 30 Doradus

Binary disruption

- Velocity distribution of “widowed” companions
- BH kicks from massive runaway mass function

Velocity distribution: Runaways

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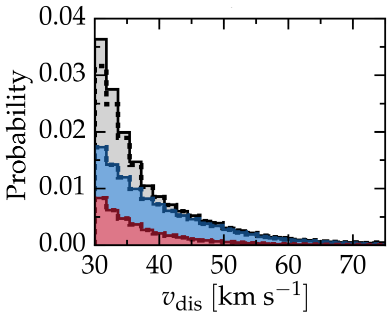
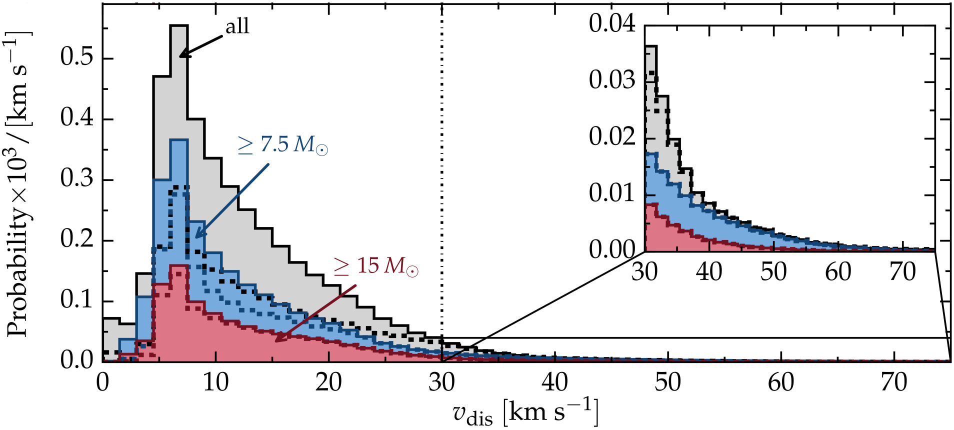
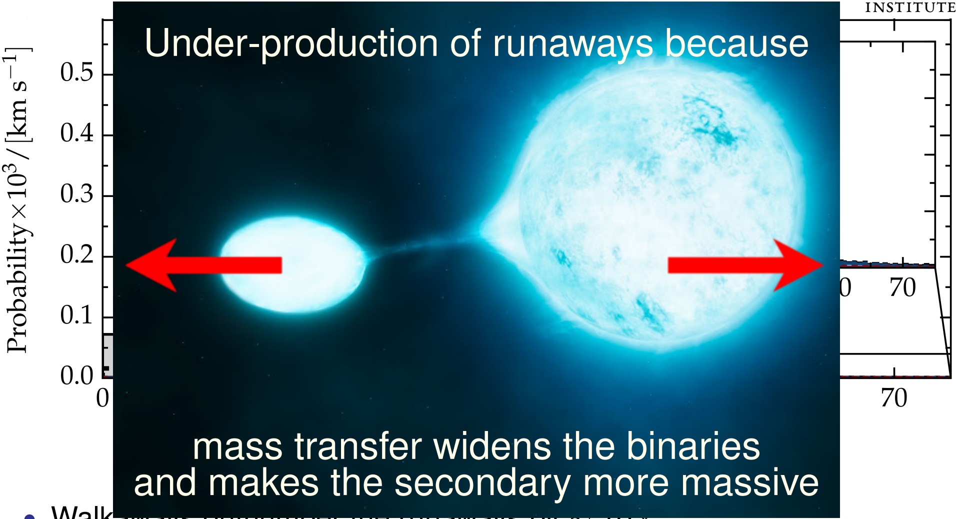




Take home points:

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

Velocity distribution: Walkaways



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A way to constrain BH kicks

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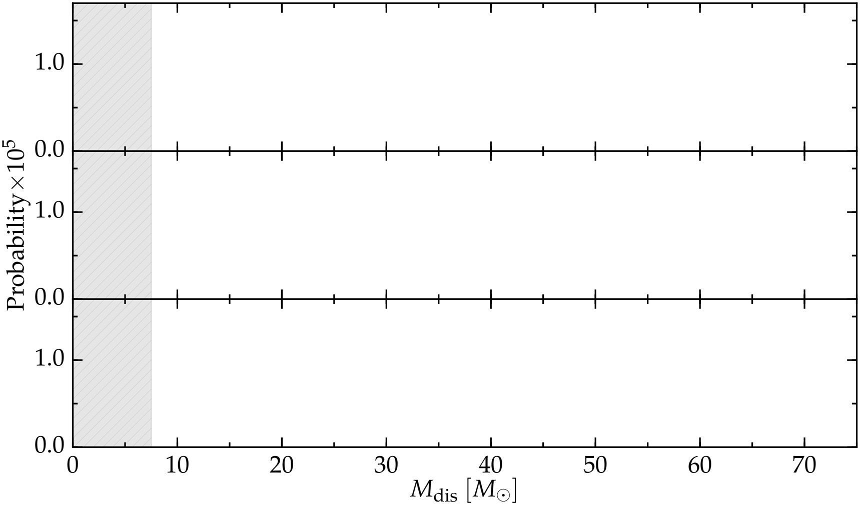
Massive runaways mass function ($v \geq 30\,\mathrm{km\ s^{-1}}$, $M \geq 7.5\,M_{\odot}$)



Mass of the runaway

A way to constrain BH kicks

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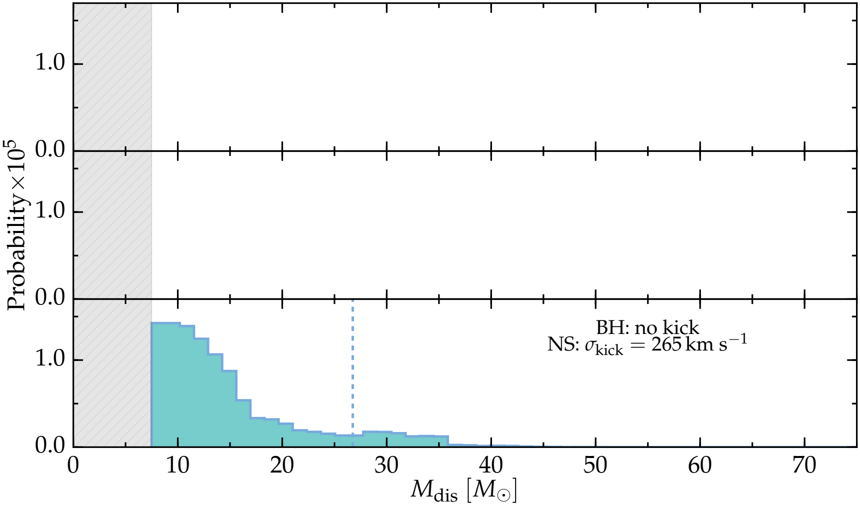

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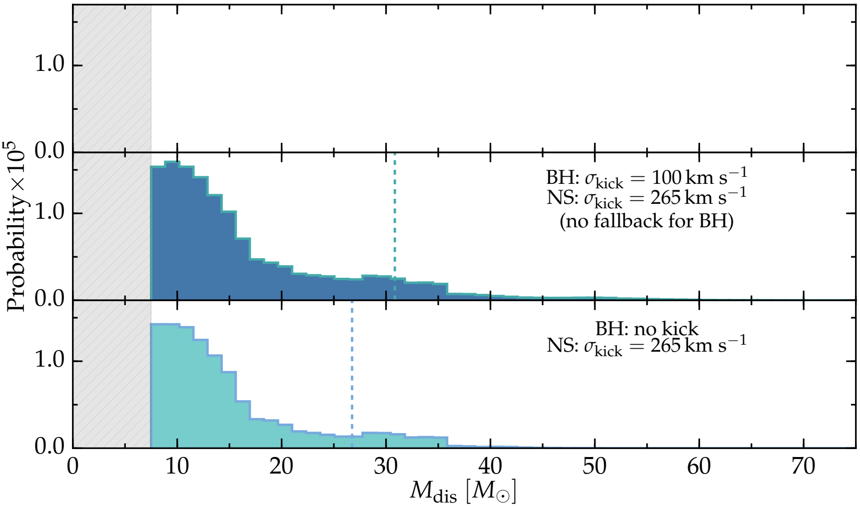

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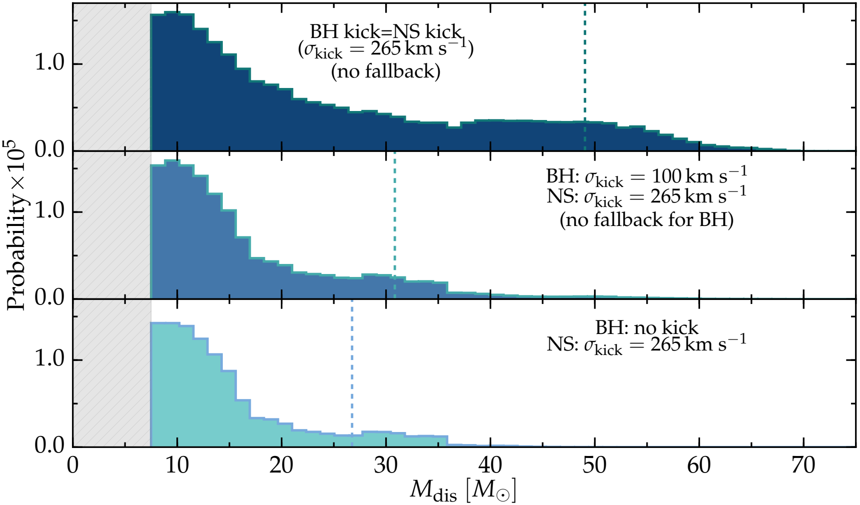

Mass of the runaway

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

A way to constrain BH kicks

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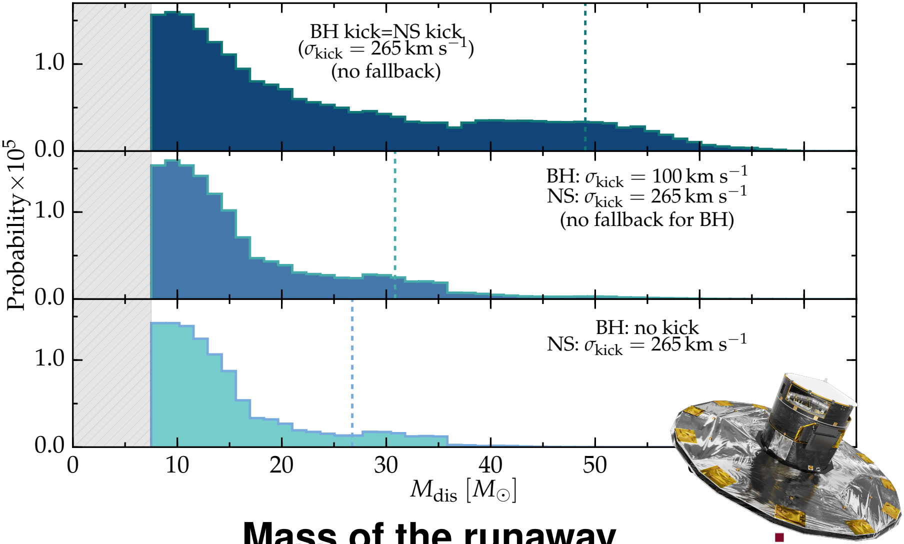

Mass of the runaway

gaia

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

Conclusions

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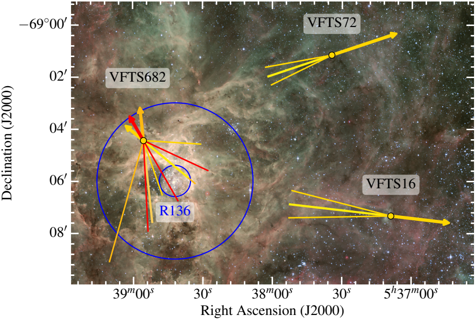
Binary Disruption

- 86^{+11}_{-9}% of binaries disrupted, most eject a **slow** walkaway
- **Observed runaway fraction** for O-type stars is $\times$**10 higher than binary populations can explain**
- ***Gaia* can constrain BH kicks** using the mass distribution of massive runaways



Dynamical ejections (?)

- ***Gaia* reveals the most massive runaways** known (up to $\sim$150 $M_\odot$)
- Extreme clusters can eject some of the most massive members
- Constraints on cluster formation and early dynamics

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Backup slides

Two ejection mechanisms

Binary Supernova

- Ejects initially less massive star
- Requires SN kick
- Final $v \simeq v_2^{\mathrm{orb}}$
- Leaves binary signature (fast rotation, He/N enhancement, lower apparent age)

Dynamical Ejection

- N-body interactions
- (Typically) least Massive thrown out

...Binaries are still important!

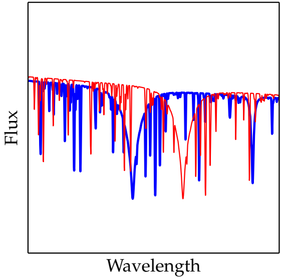
- (Binding) Energy reservoir
- Cross section $\propto a^2 \gg R_*^2$

but might not leave signature

Observations of stellar velocities

⇐ Bow shocks

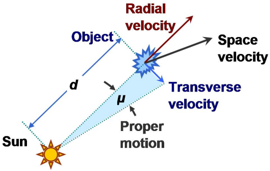
Doppler shifts ⇒



Proper motions

(if distance known)

⇓



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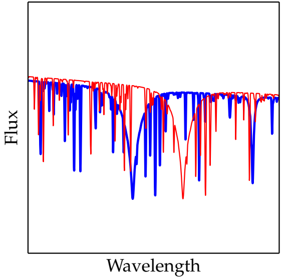

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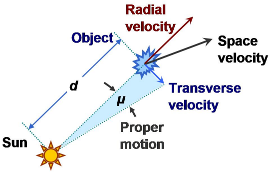
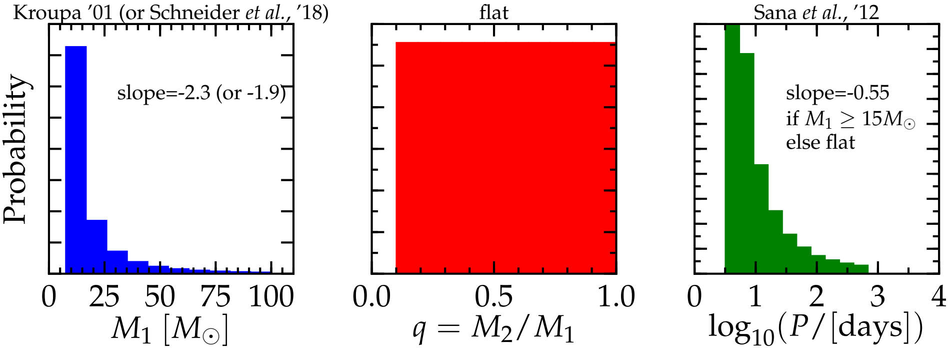
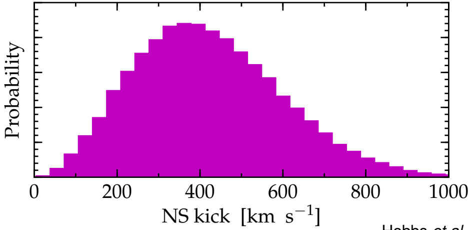




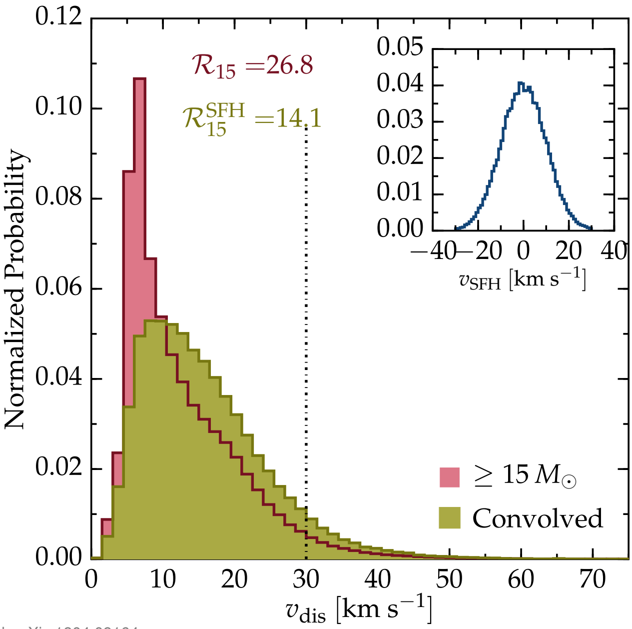
Maxwellian $\sigma_{v_\mathrm{kick}} = 265\,\mathrm{km\ s^{-1}}$ + Fallback rescaling

(from Fryer *et al.* '12)



Hobbs *et al.* '05

Star forming region velocity dispersion



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Velocity distribution with lifetimes

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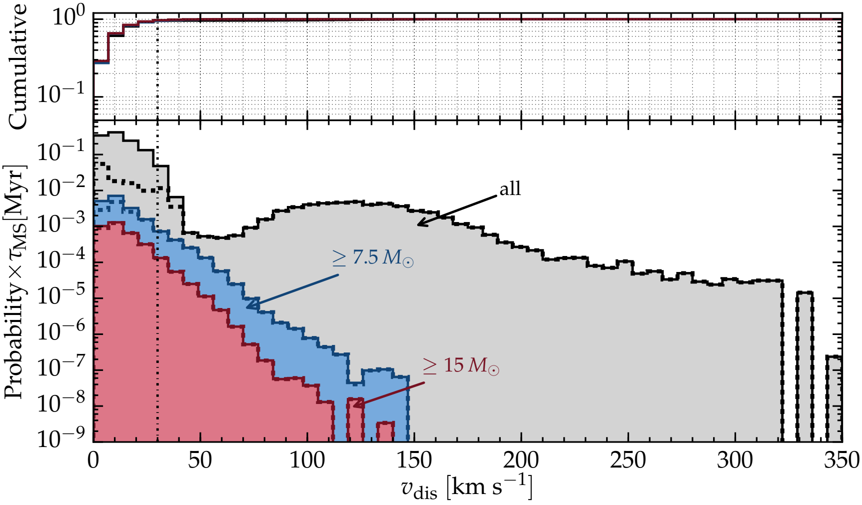

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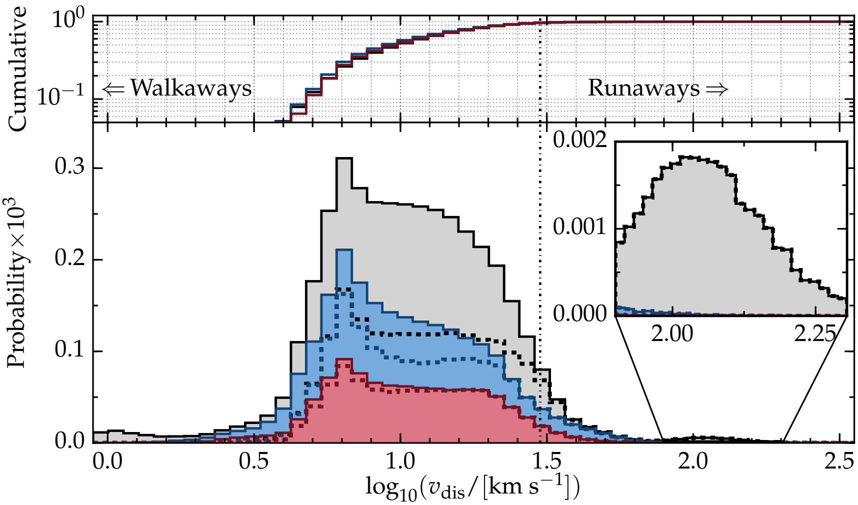
Velocity distribution log-scale



Velocity distribution bound binaries

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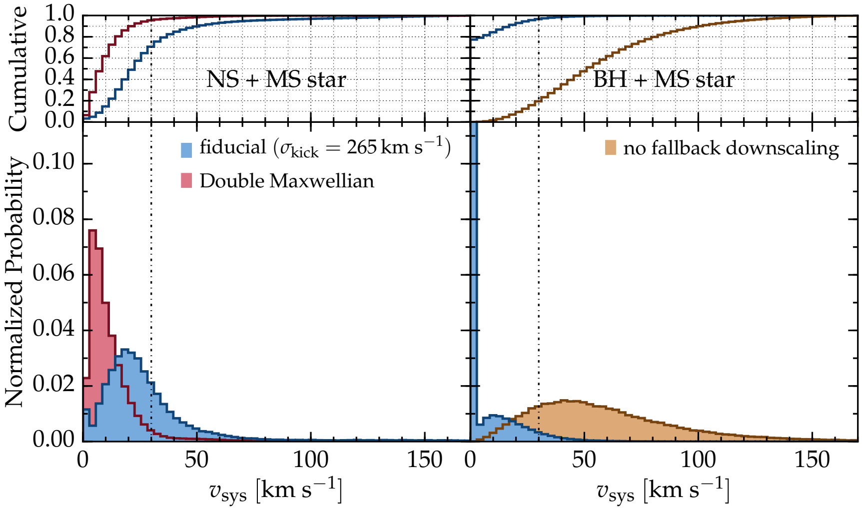

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Velocity post-main sequence stars

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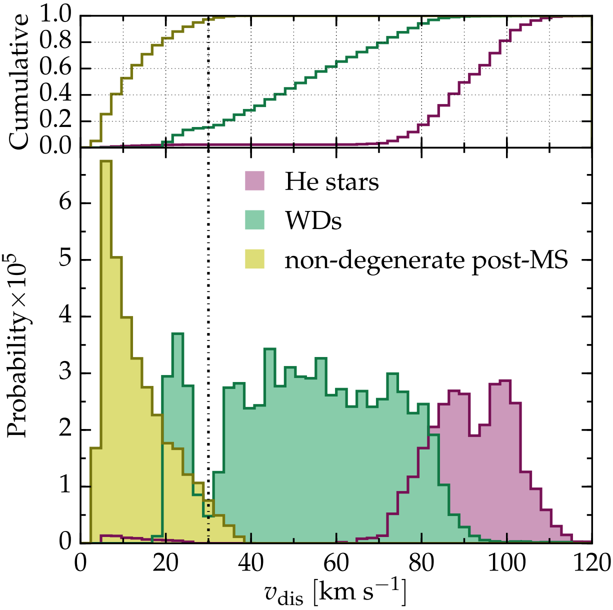

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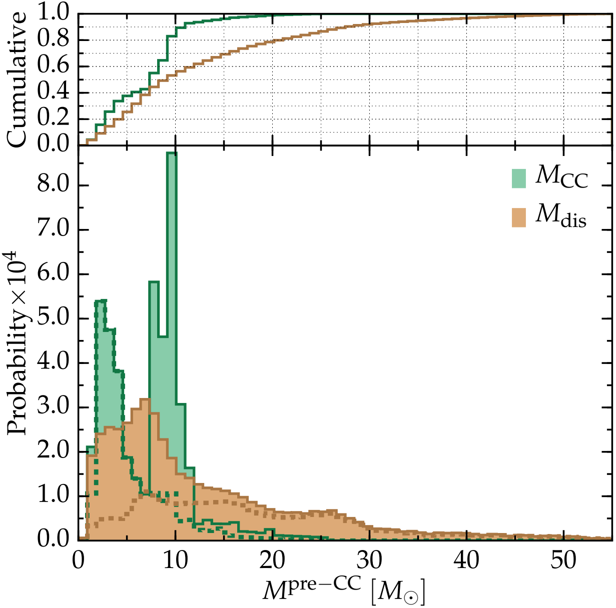
pre-CC mass distribution



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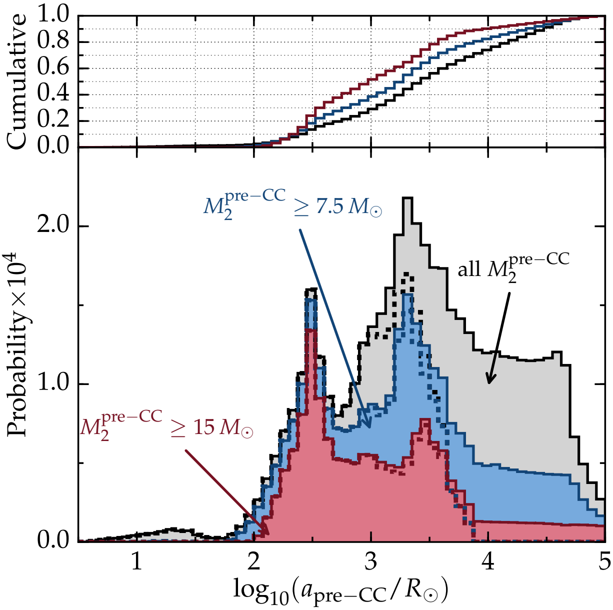

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Unprojected spin distribution

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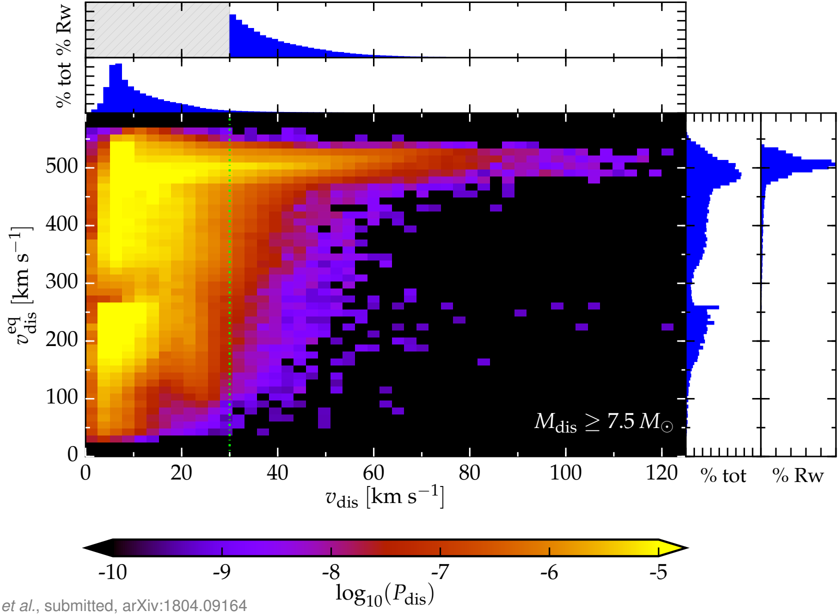

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How far do they get?

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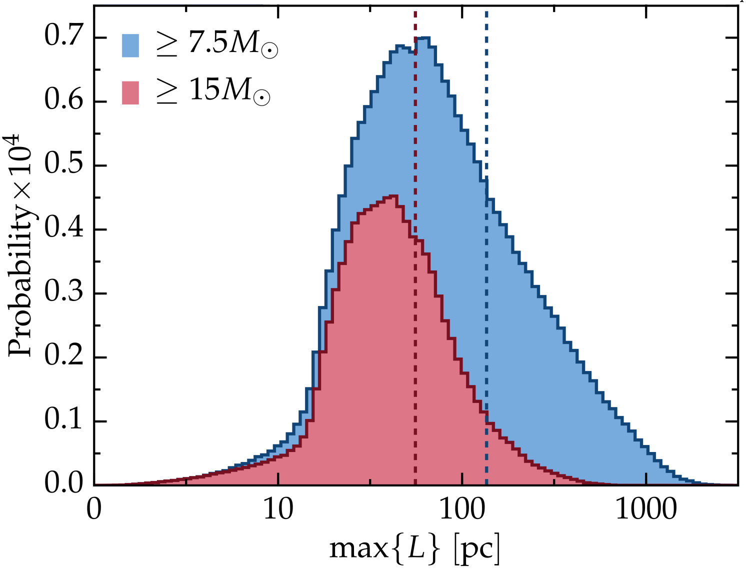

"Distance traveled"

(No potential well)

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

Runaway fraction for O-type too low!

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Physical Assumptions	Parameter	value	$\mathcal{D}$ [%]	f_{15}^{RW} [%]	f_{15}^{WA} [%]
Fiducial population		see Sec. 2	86	0.5	10.1
Mass transfer efficiency	β_{RLOF}	0	86	0.3	1.5
		0.5	87	1.2	8.6
		1	87	0.7	14.7
Angular momentum loss	γ_{RLOF}	γ_{disk}	85	0.2	7.3
		1	86	0.6	9.9
Common envelope efficiency	α_{CE}	0.1	86	0.5	10.1
		10	84	0.5	10.0
Mass ratio for case A merger	$q_{crit,\,A}$	0.80	86	0.5	10.2
		0.25	86	0.6	9.4
Mass ratio for case B merger	$q_{crit,\,B}$	1.0	89	0.0	5.0
		0.0	85	0.6	10.1
Natal kick velocity	σ_{kick}	0	16	–	0.0
		300	87	0.6	10.3
		1000	91	1.2	11.2
Natal kick amplitude	(σ_{kick}, f_b)	(100, 0)	84	0.3	8.7
Double maxwellian with $\sigma_{kick} = 30\,km\,s^{-1}$		for $M_{NS} \leq 1.35$	65	0.5	4.9
Restricted kick directions		$\alpha < 10\,deg$	87	0.6	10.3
		$\frac{\pi}{2} - \alpha < 45\,deg$	86	0.5	10.0
Fallback fraction	f_b	0	97	1.5	12.1
Metallicity	Z	0.0002	77	2.6	7.7
		0.0047	84	1.2	10.3
		0.03	88	0.5	10.0

Robust outcome
(but less bad at low Z)

$$f_{15}^{RW} \stackrel{def}{=} \frac{\#\ runaways}{\#\ stars}$$

Observed:

$$f_{15}^{RW} \simeq 10 - 20\%$$

$\sim\frac{2}{3}$ of runaways from binaries

Hoogerwerf *et al.* '01

but see also Jilinski *et al.* '10

Renzo *et al.*, submitted,

arXiv:1804.09164

VFTS682: Concordant Picture?

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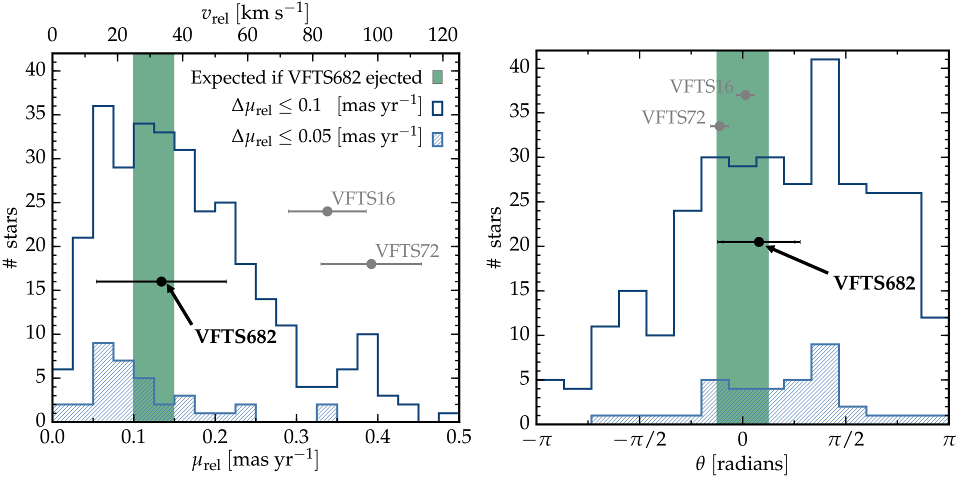

Large error bars compatible with no motion, but
best values fit with expectations for dynamical ejection

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, Tetzlaff *et al.* '11)

NASA, JPL-Caltech, Spitzer Space Telescope

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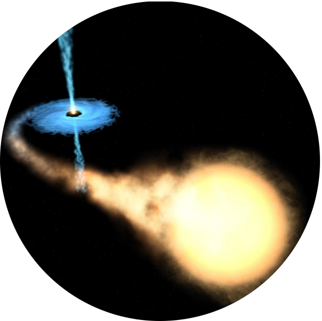
...from disrupted binaries

- **BH kicks**
- Binary evolution

Do BH receive natal kicks?

Spatial distribution of X-ray binaries

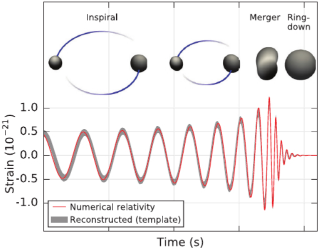
(e.g., Repetto *et al.* '12,'15,'16, Mandel '16)



Massive (and WR) runaways

(Dray *et al.* '05)

Disrupted binaries are "failed" GW sources!



- 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.