Massive widowed stars:

Runaways and walkaways from binary disruptions

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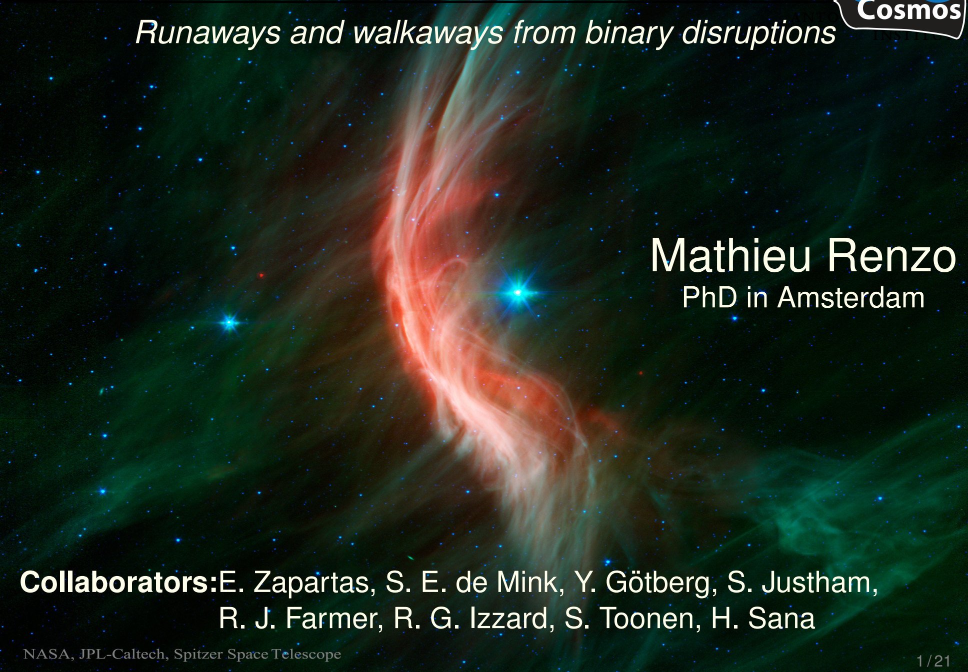
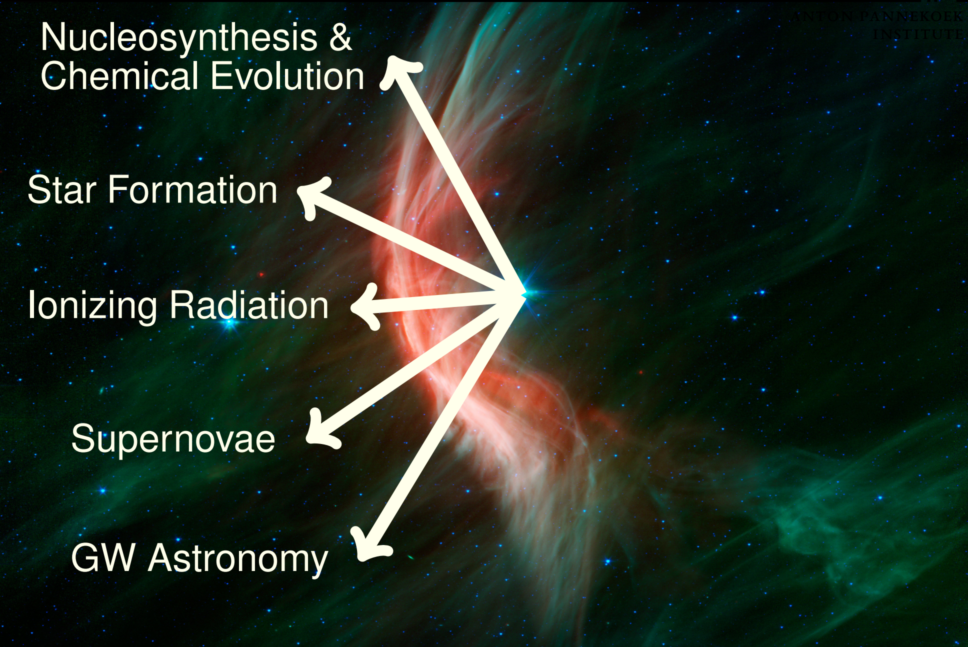
PhD in Amsterdam

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



NASA, JPL-Caltech, Spitzer Space Telescope

Why are they interesting?



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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)

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~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)

~10 walkaways for each O-type runaway

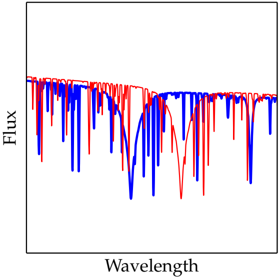
(e.g., de Donder *et al.* '97, Eldridge *et al.* '11, de Mink *et al.* '14, Renzo *et al.*, arXiv:1804.09164)

NASA, JPL-Caltech, Spitzer Space Telescope

Observations of stellar velocities

⇐ Bow shocks

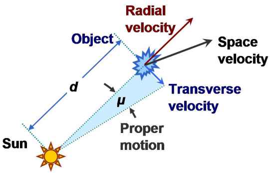
Doppler shifts ⇒



Proper motions

(if distance known)

⇓



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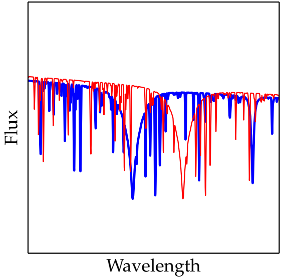

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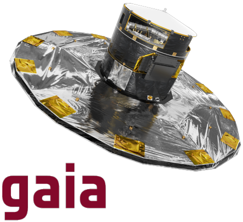

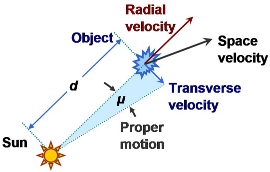

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How to measure stellar velocities?

Ejection Mechanisms

- Dynamical interactions
- Binary disruption

Methods

- Population synthesis

Results

- Velocity distribution
- Constraints on BH kicks from runaway mass function

Conclusions

Cluster ejection

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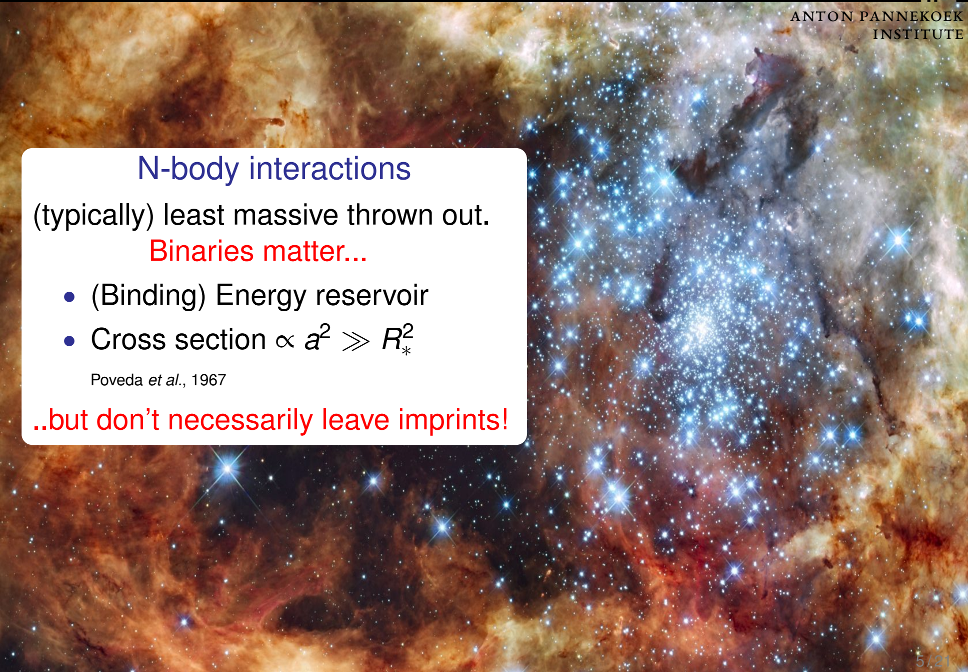

N-body interactions

(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!

VFTS682: Dynamically ejected runaway?

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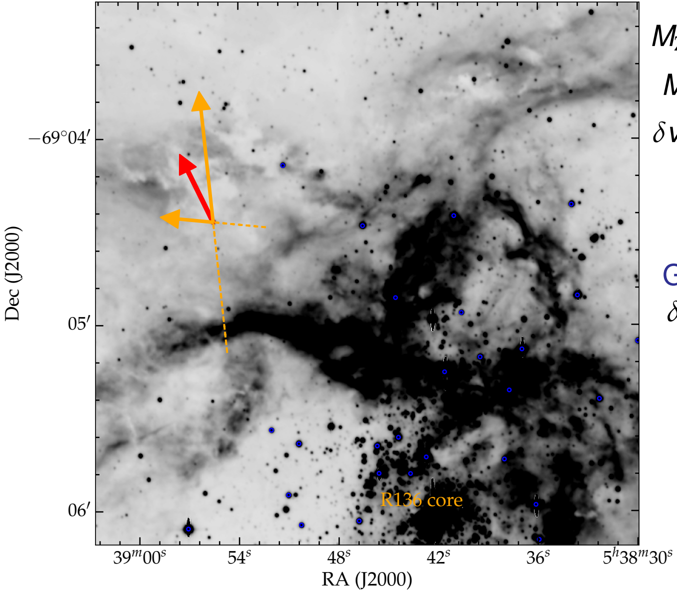
Very Preliminary!



Spectral analysis:

$$M_{\mathrm{ZAMS}} = 150.0^{+28.7}_{-17.4}\, M_{\odot}$$

$$M_{\mathrm{now}} = 137.8^{+27.5}_{-15.9}\, M_{\odot}$$

$$\delta v_{\mathrm{LOS}} \simeq 30 \pm 10\,\mathrm{km\ s^{-1}}$$

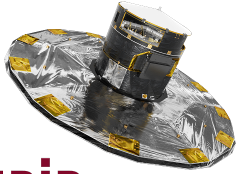
Evans *et al.*, ’11

Schneider *et al.*, ’18

Gaia DR2 astrometry:

$$\delta v_{\parallel} \simeq 34 \pm 17\,\mathrm{km\ s^{-1}}$$

Renzo *et al.*, in prep.



gaia

Outline

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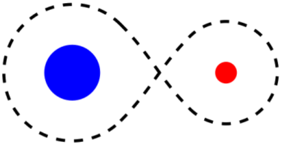
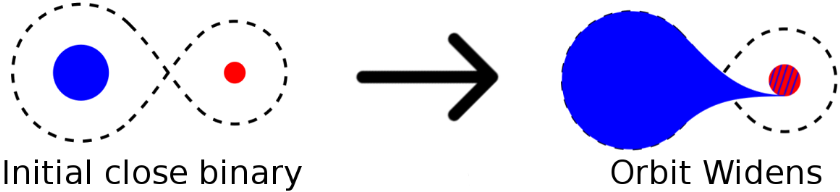
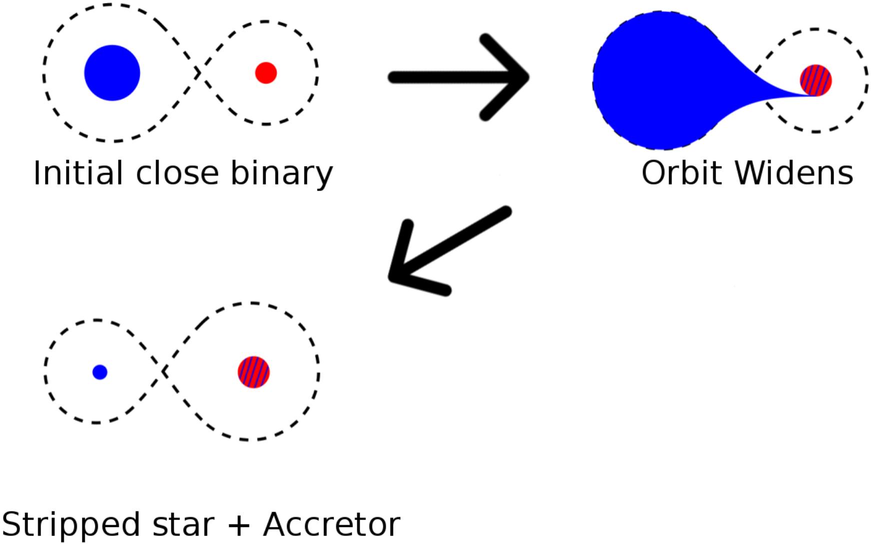


Initial close binary

Binary disruption



Binary disruption



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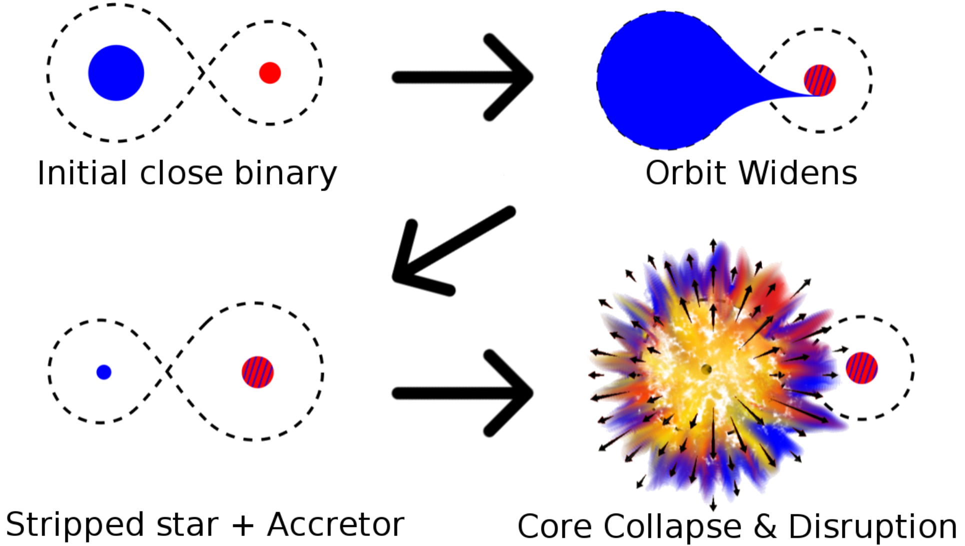

Spin up, pollution, and rejuvenation

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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?

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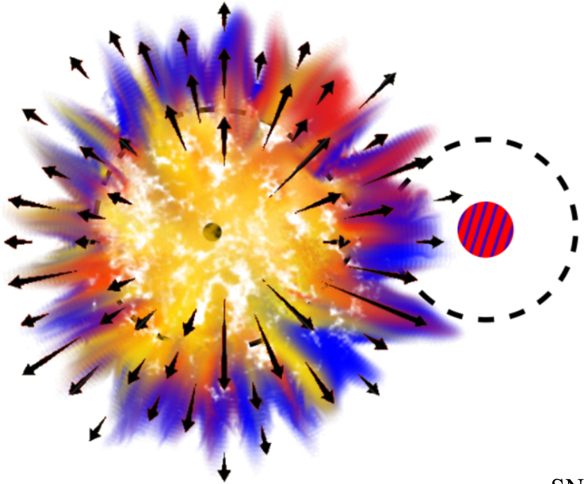
86^{+11}_{-9}% of binaries are disrupted



- 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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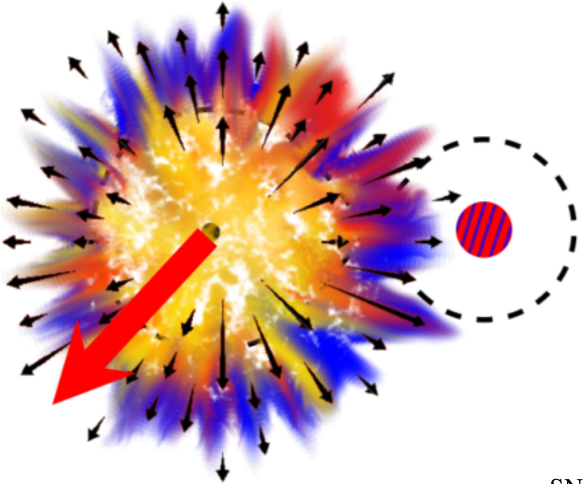

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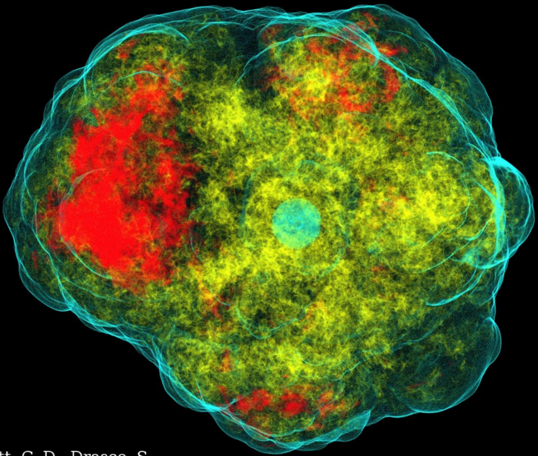
SN natal kick

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

Physically: ν emission and/or ejecta anisotropies



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

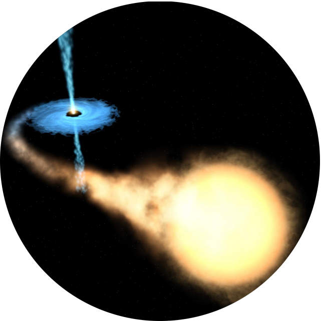
...from disrupted binaries

- BH kicks
- Binary evolution

Do BH receive natal kicks?

Spatial distribution of X-ray binaries

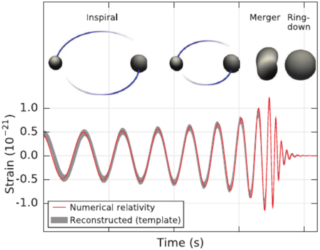
(e.g., Repetto *et al.* '12,'15,'16, Mandel '16)



Massive (and WR) runaways

(Dray *et al.* '05)

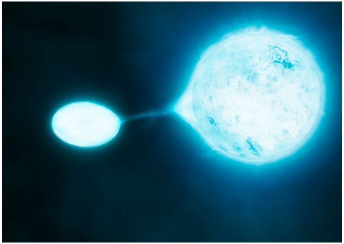
Disrupted binaries are "failed" GW sources!



- 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.



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What I do: Population Synthesis

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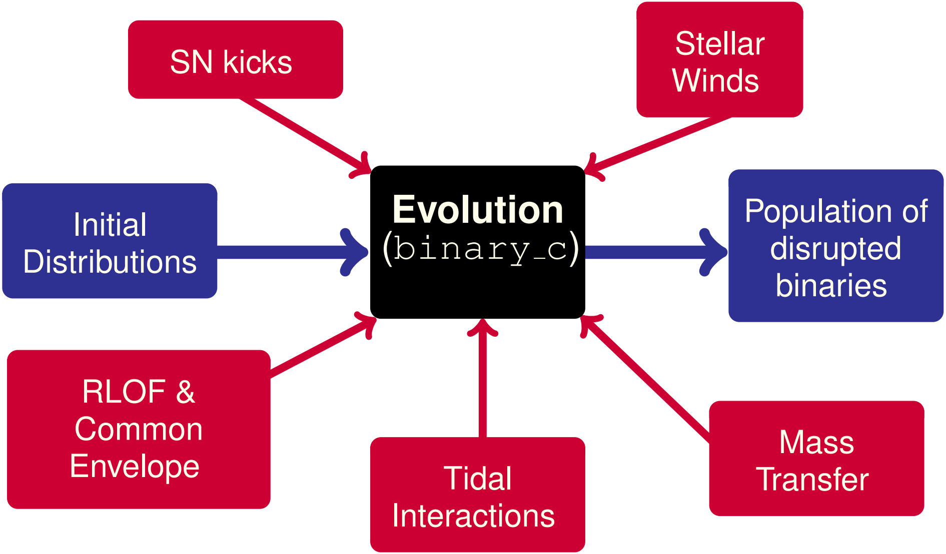
Fast ⇒ Allows statistical tests of the inputs & assumptions



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

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Velocity distribution: Runaways

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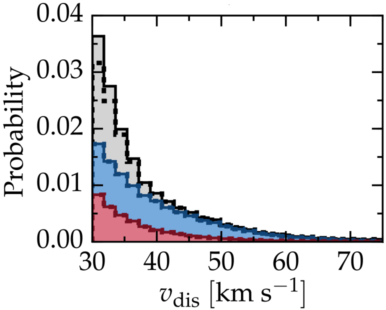
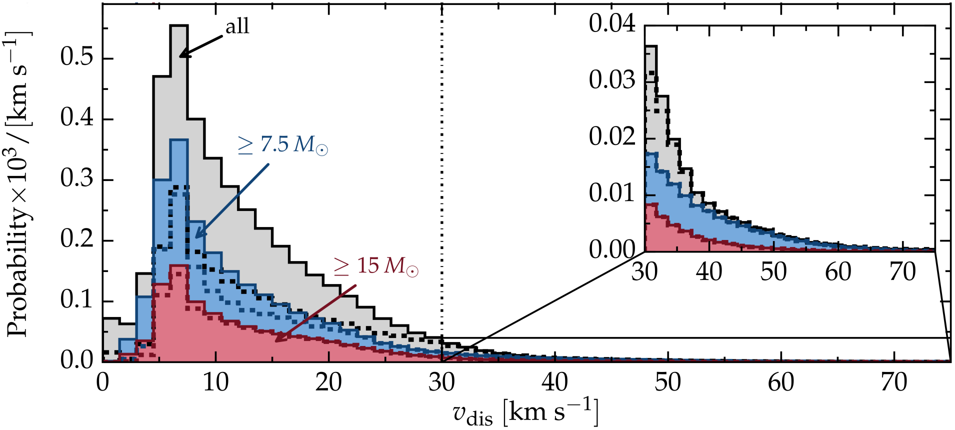


Velocity distribution: Walkaways



Take home points:

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

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

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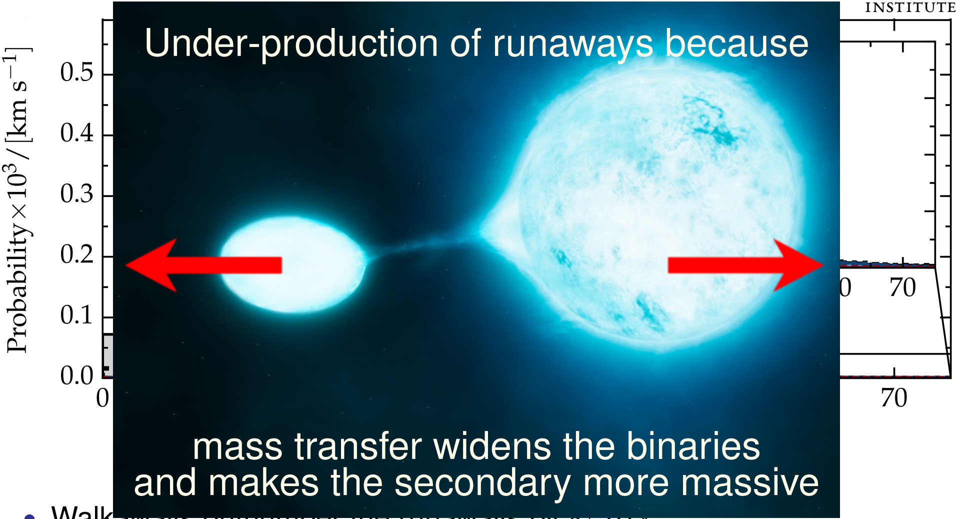

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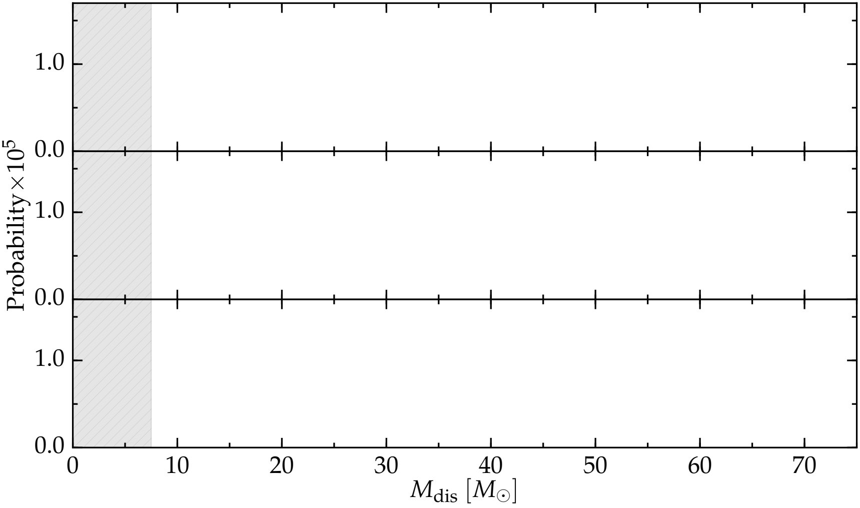
A way to constrain BH kicks

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



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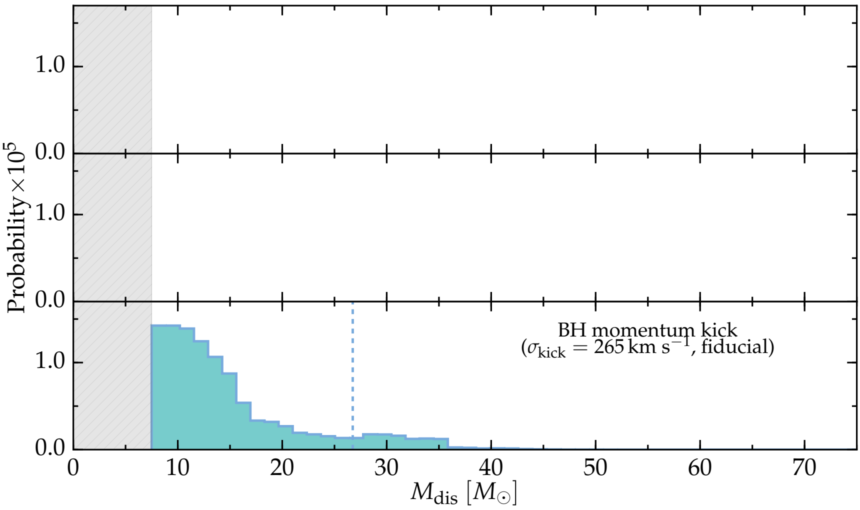

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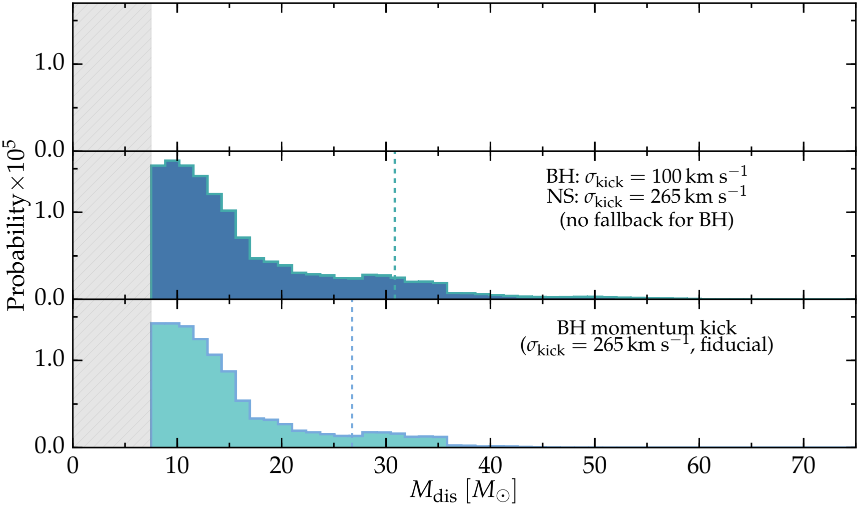

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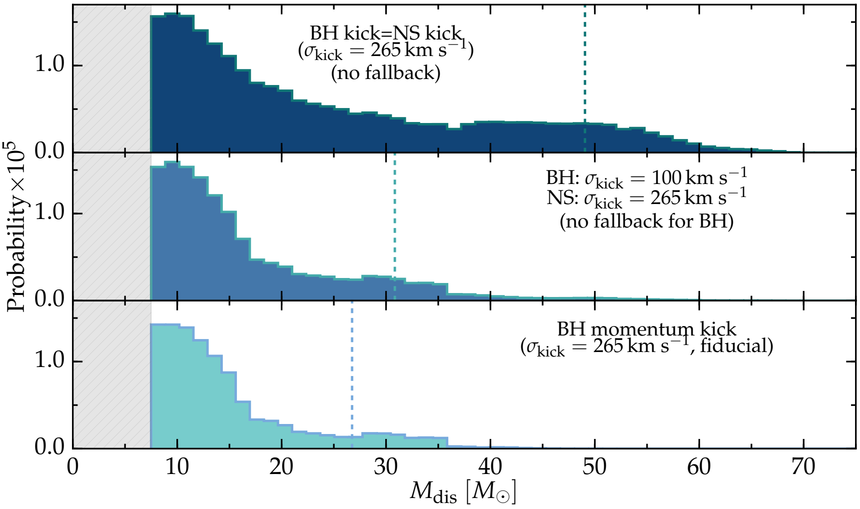

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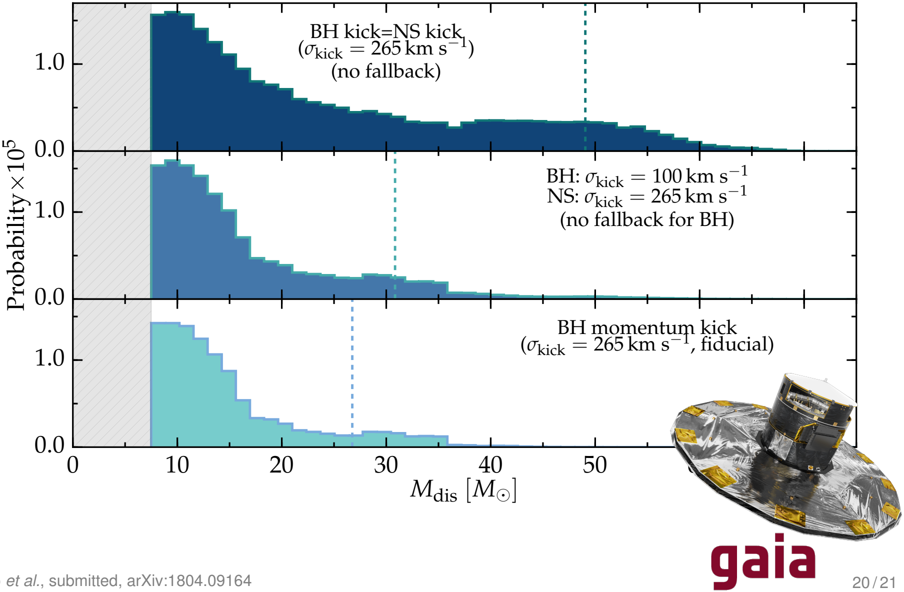

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Take home points

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- 86^{+11}_{-9}% **of binaries disrupted**
  $\Rightarrow$ X-ray binaries and GW sources are rare!
- **The vast majority produce slow "walkaways"**
  $\Rightarrow$ Contamination of single stars sample
  $\Rightarrow$ Spreading in space of stellar feedback
- **Runaway fraction for O-type stars lower than observed by $\sim$10$\times$**
  $\Rightarrow$ Other ejection mechanisms **?**
  $\Rightarrow$ overestimated in observations **?**

Very preliminary:

- **VFTS682 dynamically ejected massive runaway**
  $\Rightarrow$ The most massive stars in a cluster can be ejected early!

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Thank you!

Backup slides

Binary Supernova

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

Two ejection mechanisms

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Binary Supernova

- Ejects initially less massive star
- Requires SN kick
- Final $v \simeq v_2^{\rm orb}$
- 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

Runaway fraction for O-type too low!

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Physical Assumptions	Parameter	value	$\mathcal{D}$ [%]	$f_{15}^{\rm RW}$ [%]	$f_{15}^{\rm WA}$ [%]
Fiducial population		see Sec. 2	86	0.5	10.1
Mass transfer efficiency	$\beta_{\rm RLOF}$	0	86	0.3	1.5
		0.5	87	1.2	8.6
		1	87	0.7	14.7
Angular momentum loss	$\gamma_{\rm RLOF}$	$\gamma_{\rm disk}$	85	0.2	7.3
		1	86	0.6	9.9
Common envelope efficiency	$\alpha_{\rm CE}$	0.1	86	0.5	10.1
		10	84	0.5	10.0
Mass ratio for case A merger	$q_{\rm crit,\,A}$	0.80	86	0.5	10.2
		0.25	86	0.6	9.4
Mass ratio for case B merger	$q_{\rm crit,\,B}$	1.0	89	0.0	5.0
		0.0	85	0.6	10.1
Natal kick velocity	$\sigma_{\rm kick}$	0	16	–	0.0
		300	87	0.6	10.3
		1000	91	1.2	11.2
Natal kick amplitude	$(\sigma_{\rm kick}, f_b)$	(100, 0)	84	0.3	8.7
Double maxwellian with $\sigma_{\rm kick} = 30\,{\rm km\,s^{-1}}$		for $M_{\rm NS} \leq 1.35$	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)

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

Observed:

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

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

(Hoogerwerf *et al.* '01)

Renzo *et al.*, to be submitted

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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	$q_{\mathrm{crit,\ A}}$	0.80	86	0.5	10.2
		0.25	86	0.6	9.4
Mass ratio for case B merger	$q_{\mathrm{crit,\ B}}$	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	$(\sigma_{\mathrm{kick}}, f_b)$	(100, 0)	84	0.3	8.7
Double maxwellian with $\sigma_{\mathrm{kick}} = 30\,\mathrm{km\,s^{-1}}$		for $M_{\mathrm{NS}} \leq 1.35$	65	0.5	4.9
Restricted kick directions		$\alpha < 10\,\mathrm{deg}$	87	0.6	10.3
		$\frac{\pi}{2} - \alpha < 45\,\mathrm{deg}$	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)

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

Observed:

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

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

(Hoogerwerf *et al.* '01)

Renzo *et al.*, to be submitted

Runaway fraction for O-type too low!

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Physical Assumptions	Parameter	value	$\mathcal{D}$ [%]	f_{15}^{RW} [%]	f_{15}^{WA} [%]
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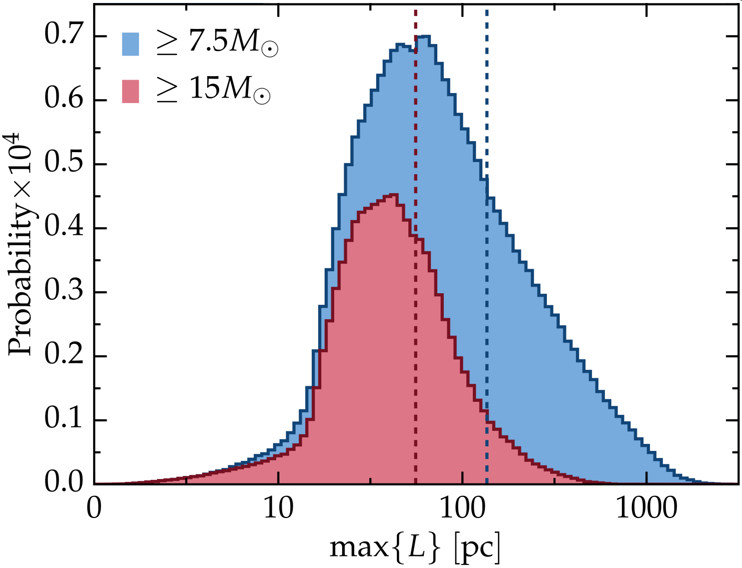
(Hoogerwerf *et al.* '01)

Renzo *et al.*, to be submitted

How far do they get?



"Distance traveled"
(No potential well)

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