Massive Runaways:

Probes for stellar physics and dynamics

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NASA, JPL-Caltech, Spitzer Space Telescope

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How to measure stellar velocities?

Runaway definition

Ejection Mechanisms

- Dynamical interactions
  - Binary disruption
- SN kicks and binary evolution

Runaway stars from Gaia DR2

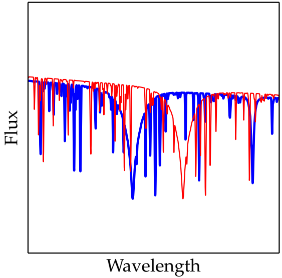
- Dynamical ejections (?)
- What can we learn from the Galactic population

Conclusions

Observations of stellar velocities

⇐ Bow shocks

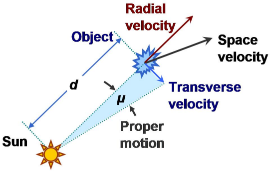
Doppler shifts ⇒



Proper motions

(if distance known)

⇓



Observations of stellar velocities

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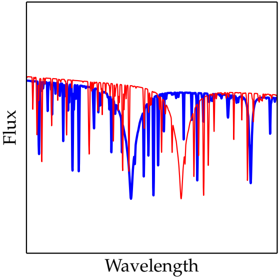

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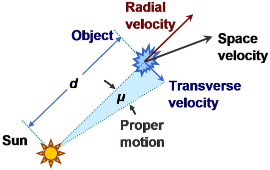

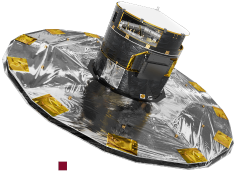

gaia

Gaia will give proper motions & distances

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What is a runaway?

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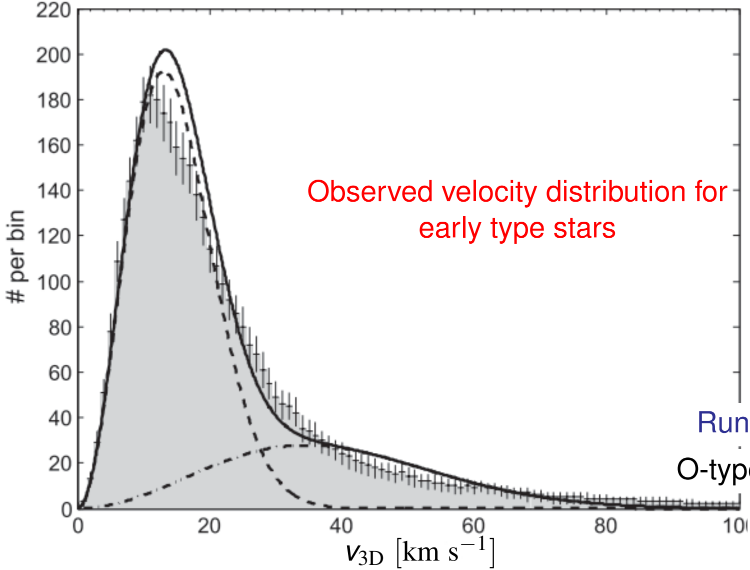

Runaway fraction

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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Cluster ejection

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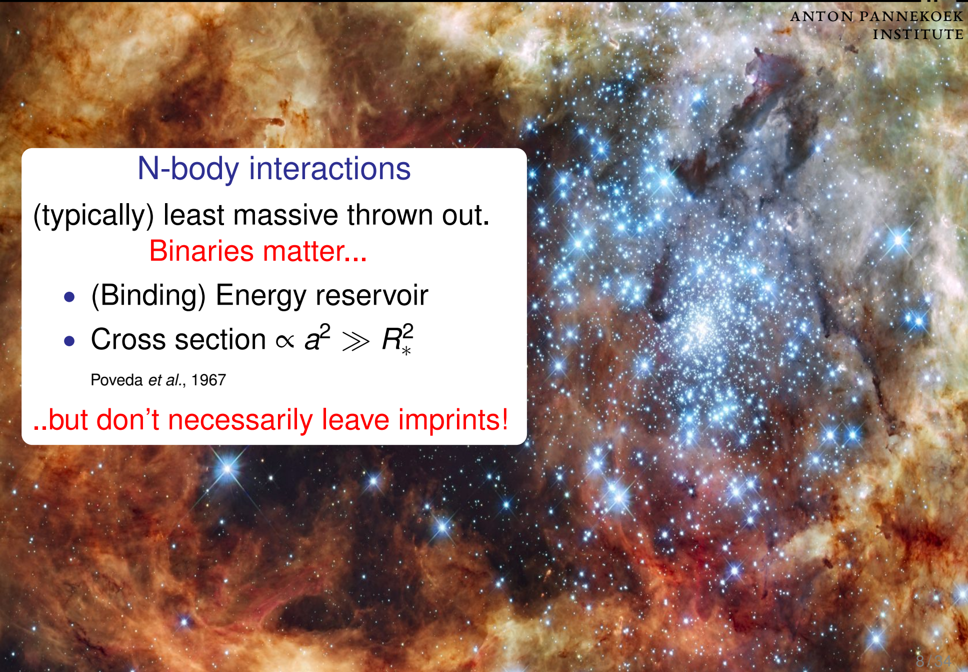

N-body interactions

(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!

Example of dynamical interaction

Credits: C. Rodriguez

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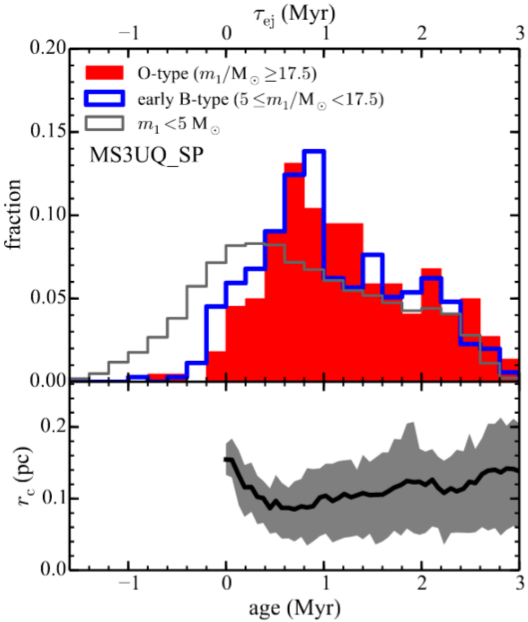

Most ejections happen early

Before the first stellar core-collapse

Typical τ_{ej} smaller than τ_*

from Oh & Kroupa 16, see also, e.g., Poveda *et al.* 64, Fujii & Portegies-Zwart 11, Banerjee *et al.* 12

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Binary disruption

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

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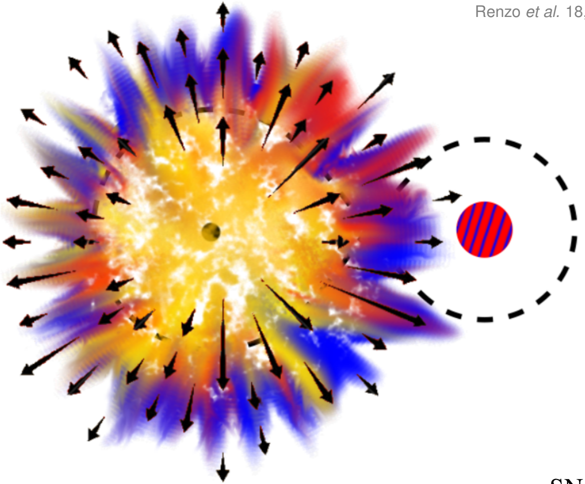
86^{+11}_{-9}% of binaries are disrupted

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)

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

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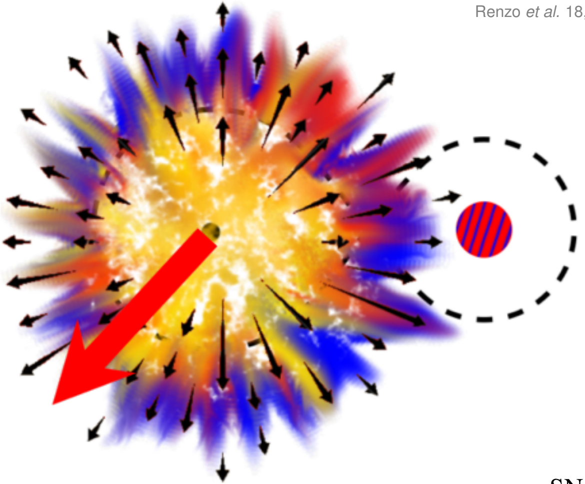

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Summary of ejection mechanisms

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

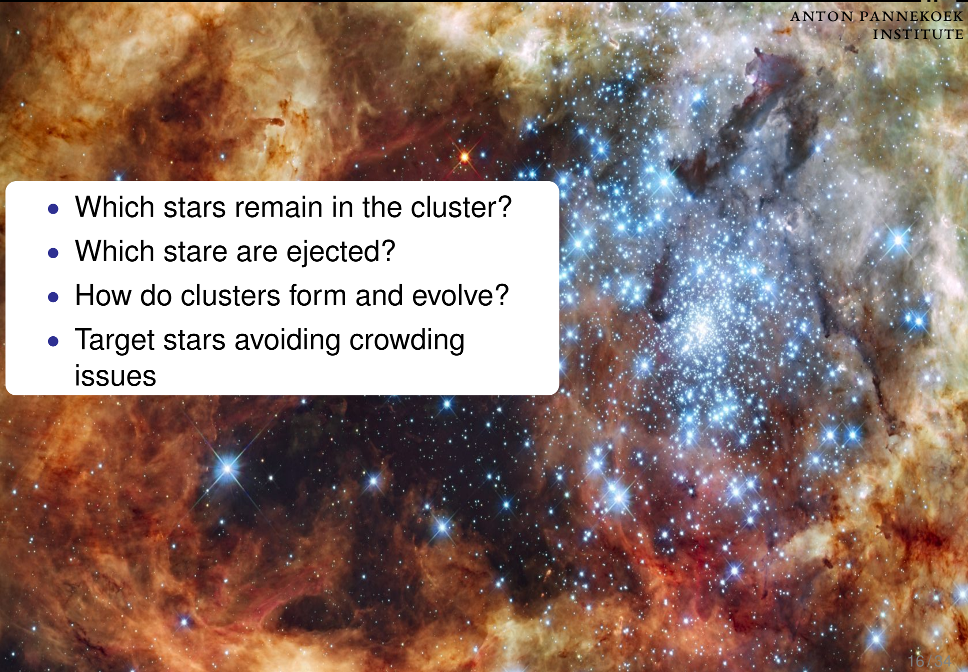
- N-body interactions
- (Typically) least Massive thrown out

...Binaries are still important!

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

but might not leave signature

Cluster Evolution



- Which stars remain in the cluster?
- Which stare are ejected?
- How do clusters form and evolve?
- Target stars avoiding crowding issues

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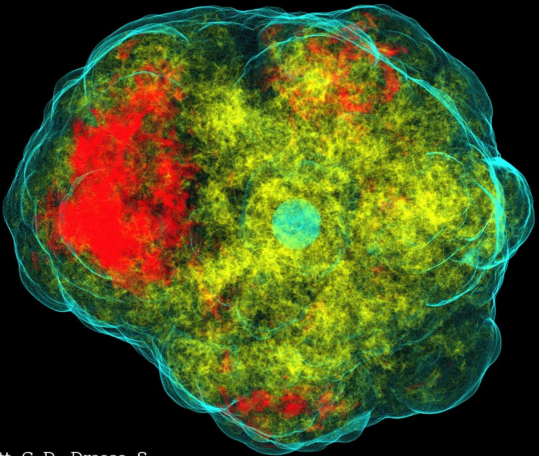
SN natal kick

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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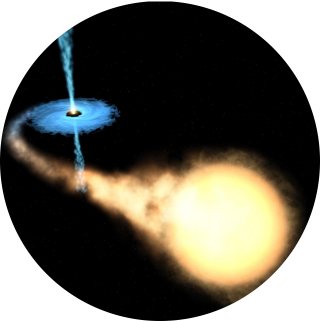
...from disrupted binaries

- **BH kicks**
- Binary evolution

Do BH receive natal kicks?

Spatial distribution of X-ray binaries

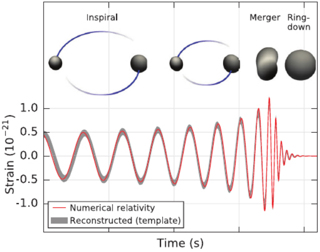
(e.g., Repetto *et al.* '12,'15,'16, Mandel '16)



Massive (and WR) runaways

(Dray *et al.* '05)

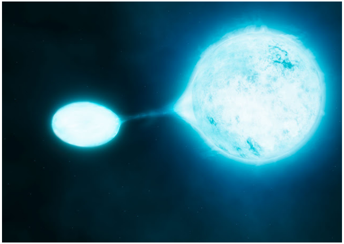
Disrupted binaries are "failed" GW sources!



- 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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Gaia DR2 reveals extreme runaways

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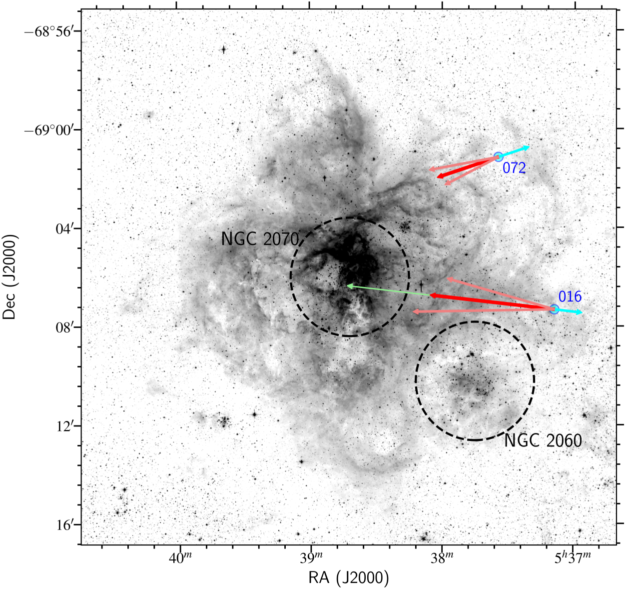

VFTS 16

$M = 91.6^{+11.5}_{-10.5}\,M_\odot$

age = 0.7 ± 0.1 Myr

$\tau_{\rm kin} = 1.50 \pm 0.21$ Myr

$v_{\rm projected} = 80 \pm 11$ km s^{-1}

$v_{\rm 3D} = 112 \pm 8$ km s^{-1}

VFTS 72

$M = 97.6^{+22.2}_{-23.1}\,M_\odot$

age = $0.4^{+0.8}_{-0.4}$ Myr

$\tau_{\rm kin} = 0.9 \pm 0.15$ Myr

$v_{\rm projected} = 93 \pm 15$ km s^{-1}

$v_{\rm 3D} = 93 \pm 15$ km s^{-1}

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

VFTS682: Dynamically ejected runaway?

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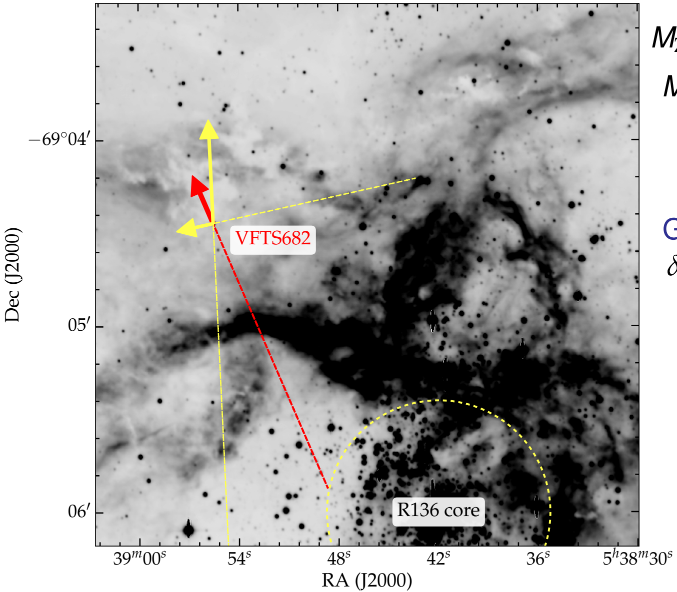
Very Preliminary!



Spectral analysis:

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

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

Evans *et al.*, '11

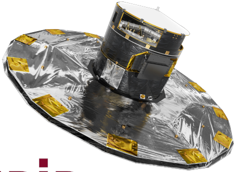
Schneider *et al.*, '18

Gaia DR2 astrometry:

$$\delta v_{\|} \simeq 32 \pm 21\,\mathrm{km\ s^{-1}}$$

$$\tau_{\mathrm{kin}} = 0.9 \pm 0.6\,\mathrm{Myr}$$

Renzo *et al.*, in prep.



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VFTS682: Concordant Picture?

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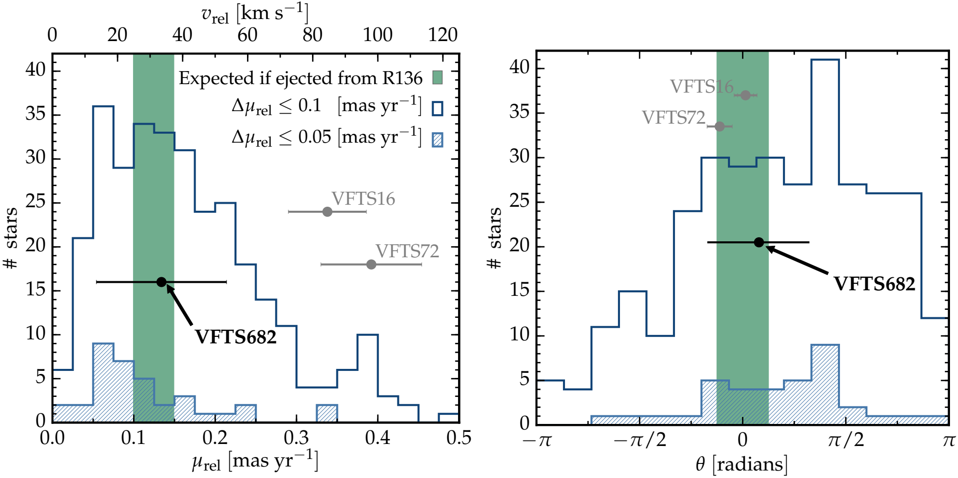
Very Preliminary!



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

Renzo *et al.*, in prep.

Implications of ejection of $\gtrsim 100\,M_\odot$ stars

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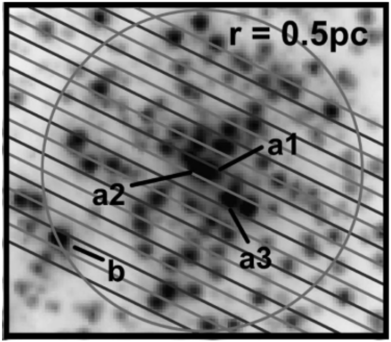
How massive are the stars that caused the scattering?

R136a1: $M_{\rm now} = 315^{+60}_{-50}\,M_\odot$

R136a2: $M_{\rm now} = 195^{+35}_{-30}\,M_\odot$

R136a3: $M_{\rm now} = 180^{+30}_{-30}\,M_\odot$

...



Crowther *et al.* 16

R136 hosts the most massive stars known to date:
did they form through dynamical mergers?

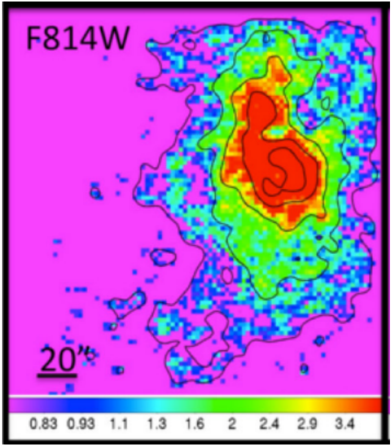
Spectroscopic evidence: de Koter *et al.* 97, Crowther *et al.* 10, 16,

N-body simulations: Fujii & Portegies-Zwart 11, Banerjee *et al.* 12

How did the cluster form?

- Monolithic collapse?
- Merger of substructures?
- Influence on N-body dynamics?

cf. Oh & Kroupa 16



Sabbi *et al.* 12

$\tau_{\mathrm{R136}} \lesssim 2\,\mathrm{Myr} < \min\{\text{stellar lifetime}\}$:

No SNe yet, dynamical ejections very early on!

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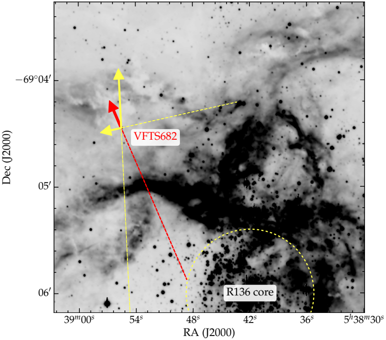
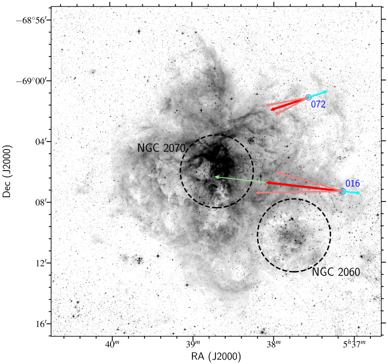
Can massive stars form in isolation?



Renzo *et al.*, in prep.



Lennon *et al.* 18, arXiv:1805.08227

Isolated formation not required for VFTS16 and 72

Less clear for 682, but possibly not needed.

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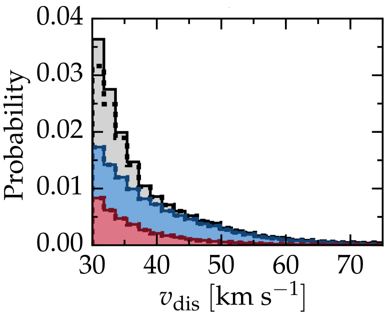
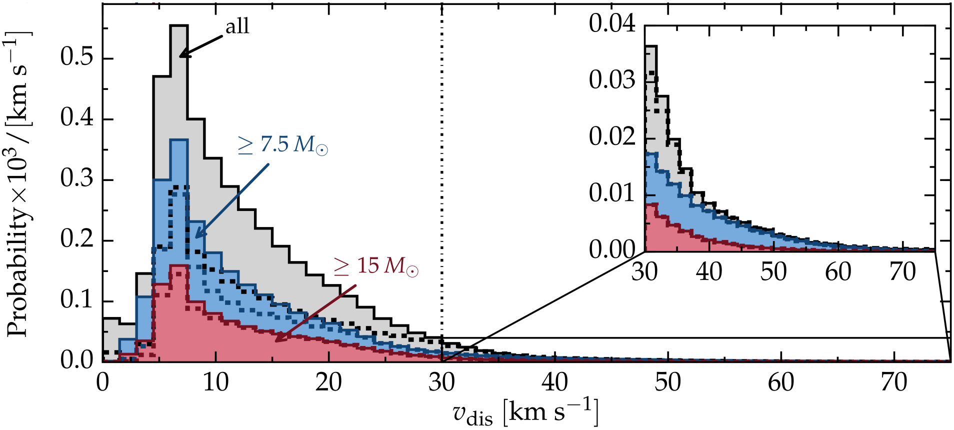
Velocity distribution: Runaways



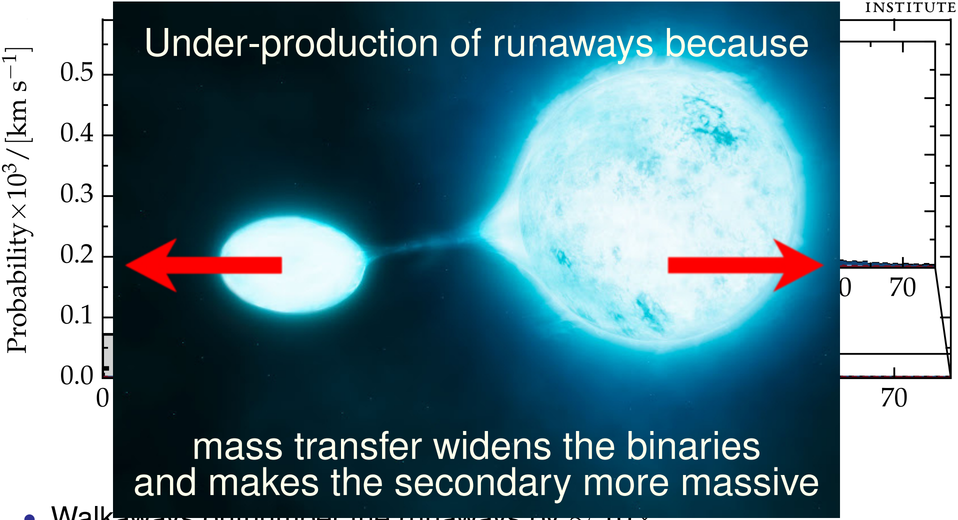
Velocity distribution: Walkaways



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

Velocity distribution: Walkaways



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

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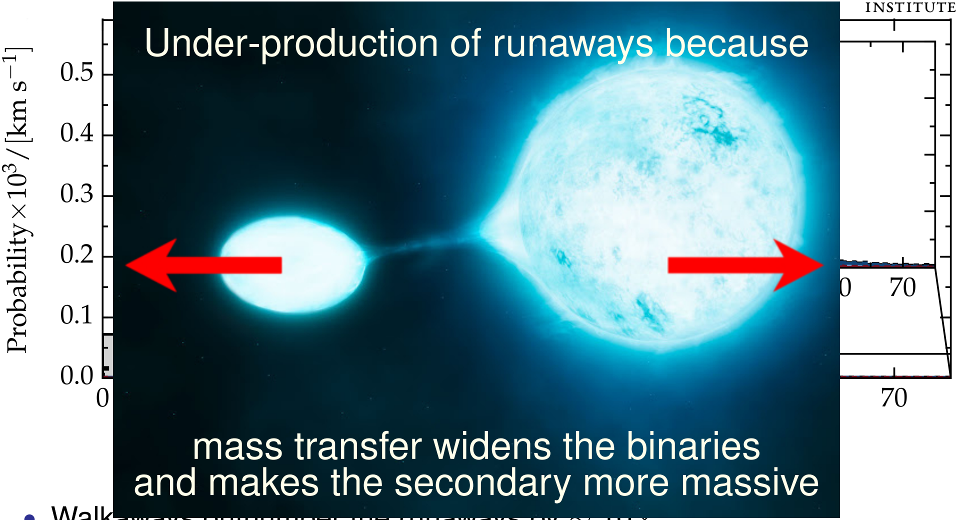

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A way to constrain BH kicks

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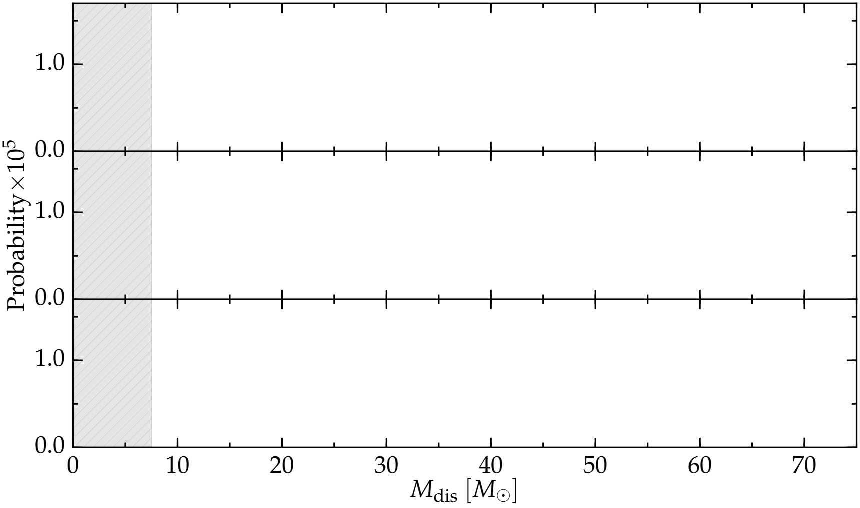
Massive runaways mass function ($v \geq 30\,\mathrm{km\,s^{-1}}$, $M \geq 7.5\,M_\odot$)



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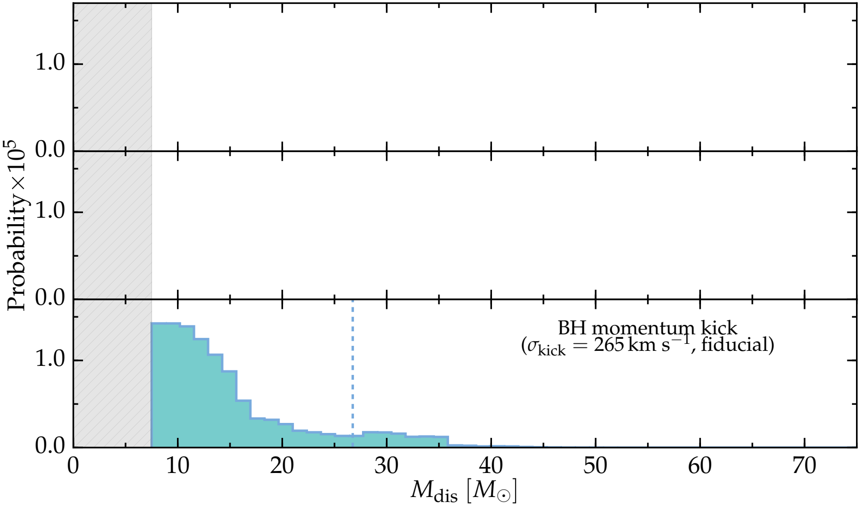

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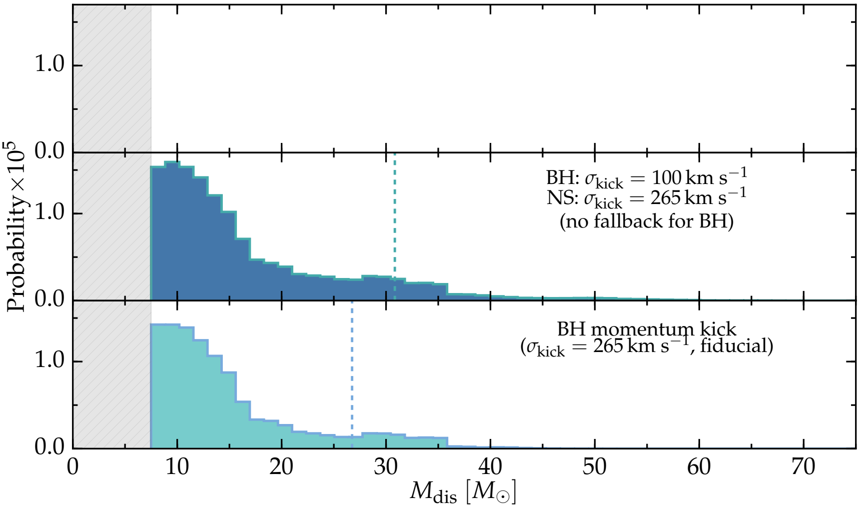

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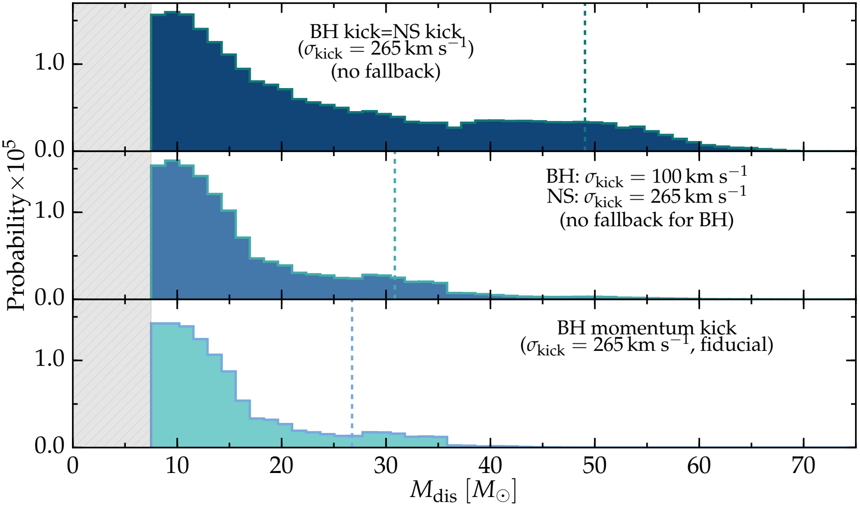

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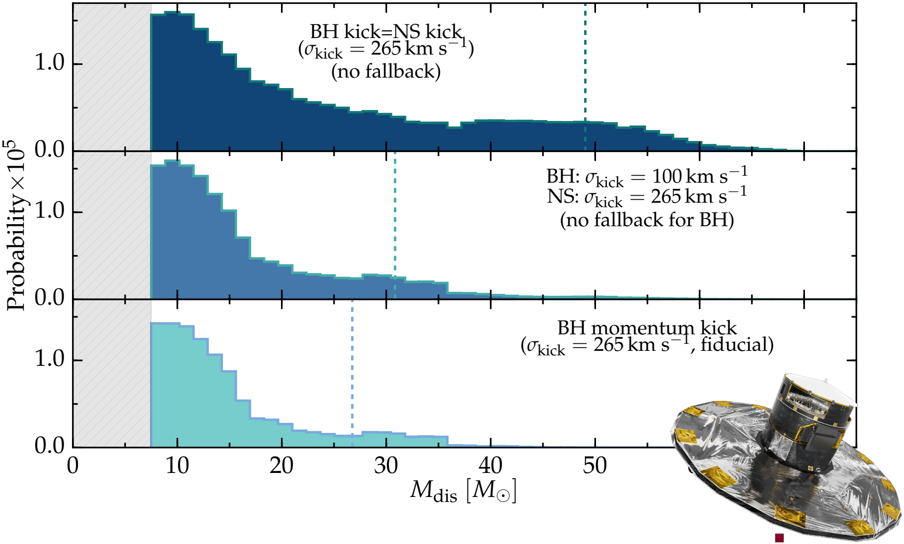

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Dynamical ejections

- Produce on average faster runaways
- *Gaia* DR2 confirms ejection of $\gtrsim 100\,M_\odot$ stars
- VFTS682: isolated star formation cannot be ruled out, but seems consistent with ejection from R136
  $\Rightarrow$ Massive "bully binary" as GW progenitor?
- R136 extremely active in ejecting stars in its first 2 Myr
  $\Rightarrow$ implications for formation?

Binary SNe

- Disrupts the vast majority of binaries
  $\Rightarrow$ X-ray binaries and GW sources are exceptions
- Over-produces "Walkaways"
- Binarity leaves imprint on the ejected star
- Can be used to constrain BH kicks (statistically)

Backup slides

What I do: Population Synthesis

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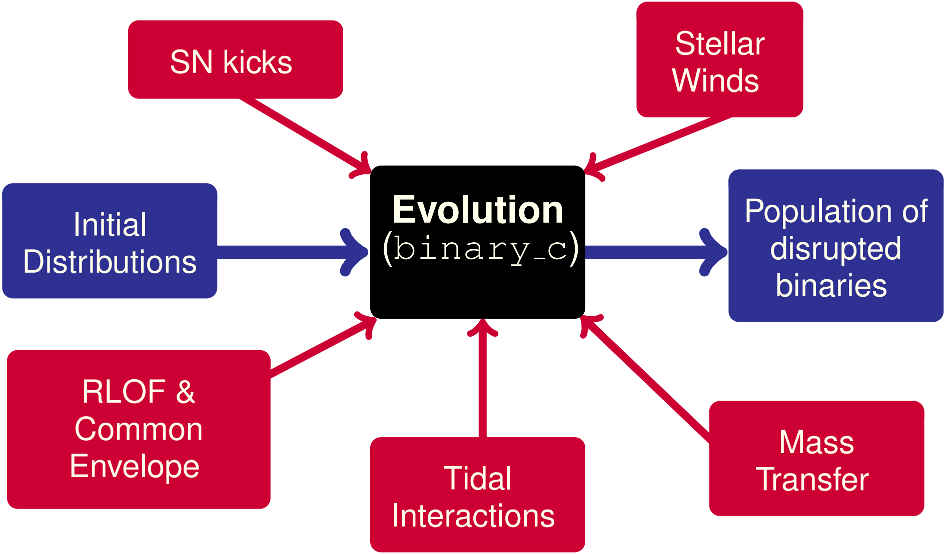
Fast ⇒ Allows statistical tests of the inputs & assumptions



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

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	$q_{\mathrm{crit,\ A}}$	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

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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	$\mathcal{D}$ [%]	$f_{15}^{\rm RW}$ [%]	$f_{15}^{\rm WA}$ [%]
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
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How far do they get?

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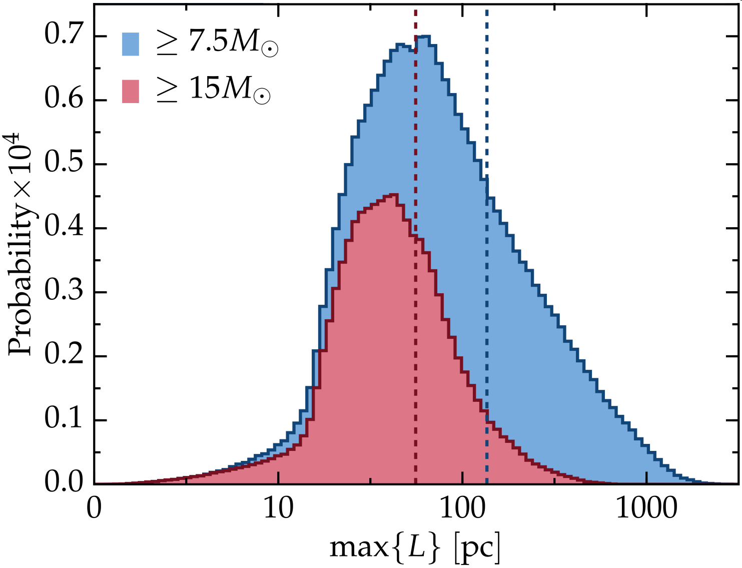

Renzo *et al.*, submitted,

arXiv:1804.09164

“Distance traveled”

(No potential well)

Star forming region velocity dispersion