Massive widowed stars:

Runaways and walkaways from binary disruptions

NASA, JPL-Caltech, Spitzer Space Telescope

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PhD in Amsterdam

Collaborators: S. E. de Mink, E. Zapartas, Y. Götberg, S. Justham, R. G. Izzard

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)

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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

Outline

Ejection Mechanisms

- Differences in resulting runaway stars

Methods

- Population synthesis

Results

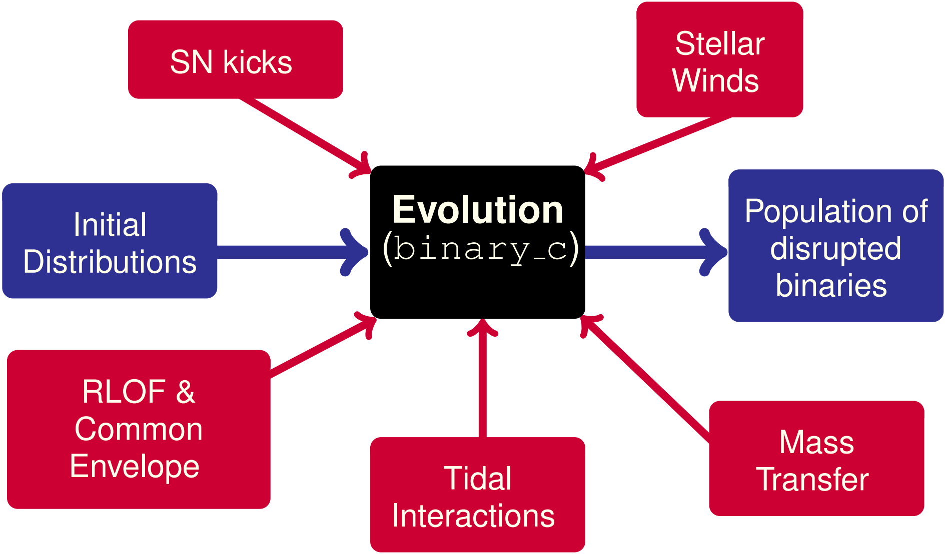
- Lessons from constant SFH
- **Preliminary**: reproducing 30 Doradus

Conclusions

- Back of the envelope estimates

What I do: Population Synthesis

Fast ⇒ Allows statistical tests of the inputs & assumptions



SN kicks

Stellar Winds

Initial Distributions

Evolution
`(binary_c)`

Population of disrupted binaries

RLOF & Common Envelope

Tidal Interactions

Mass Transfer

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

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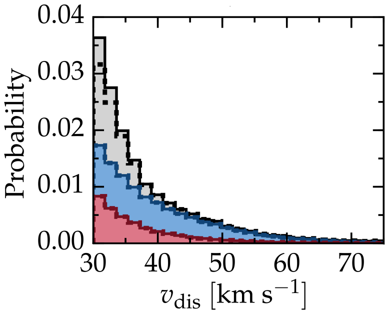
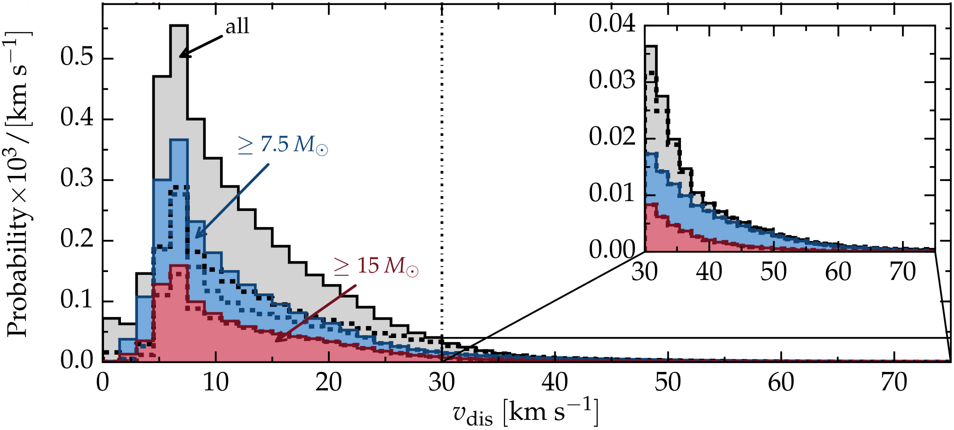
Velocity distribution: Runaways



Renzo *et al.*, to be submitted

Velocity distribution: Walkaways

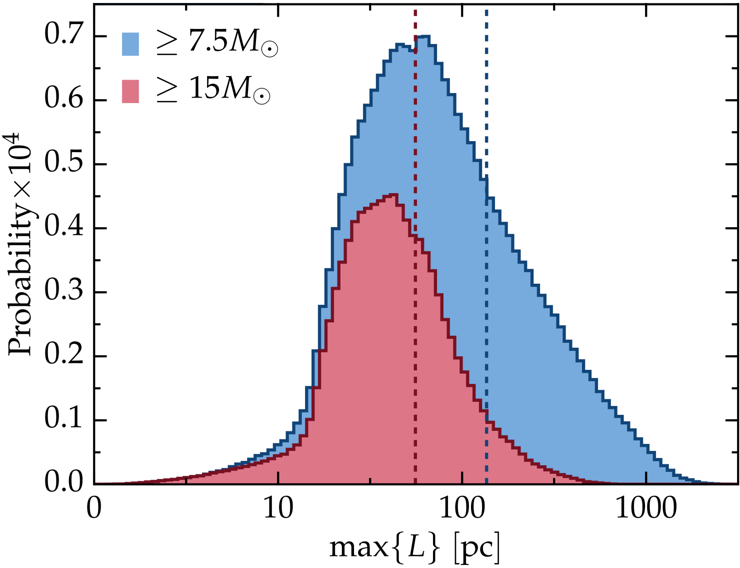


Take home points:

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

Renzo *et al.*, to be submitted

How far do they get?

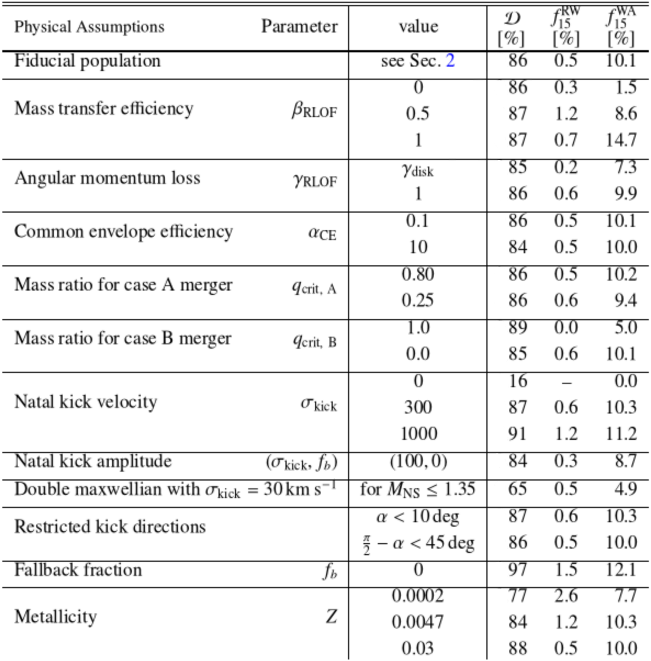


“Distance traveled”

(No potential well)

Renzo *et al.*, to be submitted

Runaway fraction for O-type too low!



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
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Natal kick velocity	σ_{kick}	0	16	–	0.0
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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)

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

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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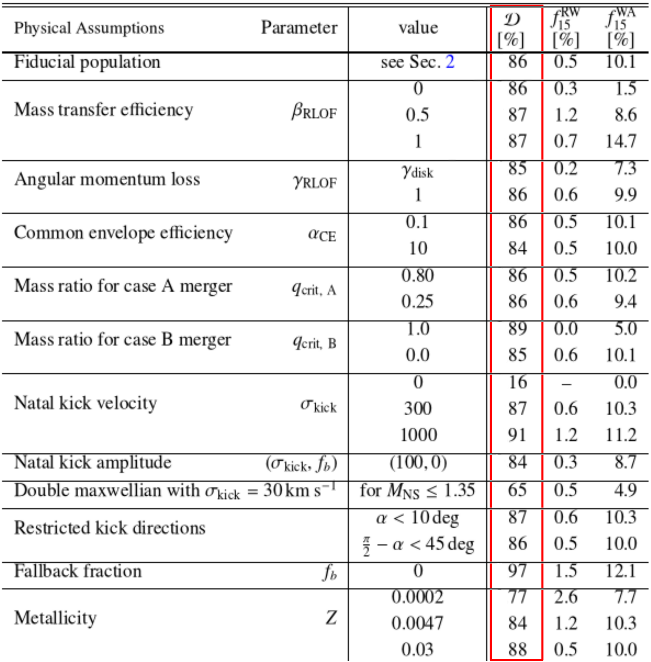

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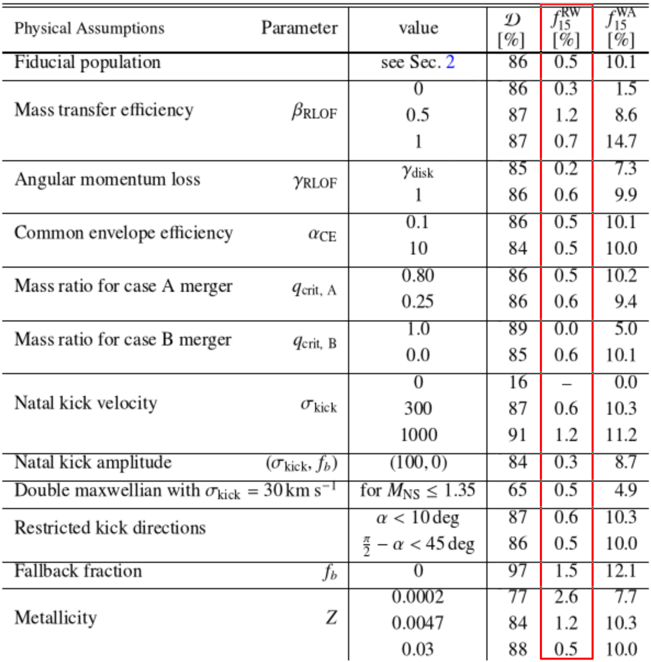

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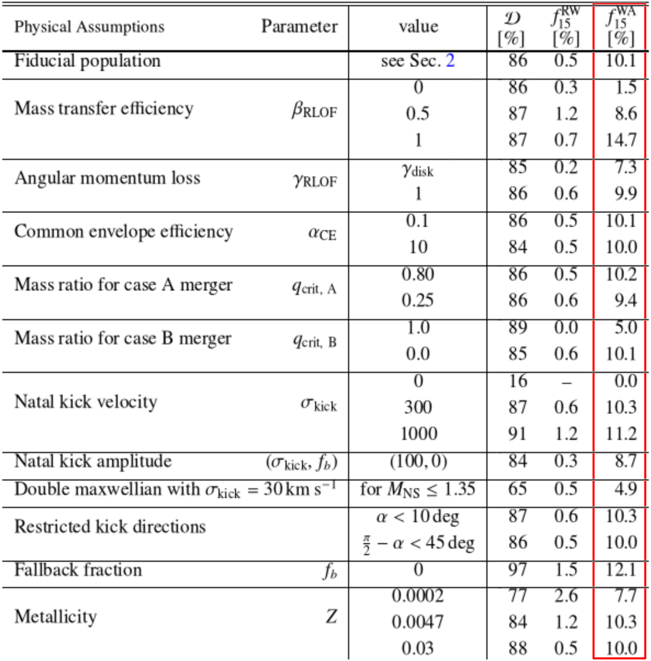

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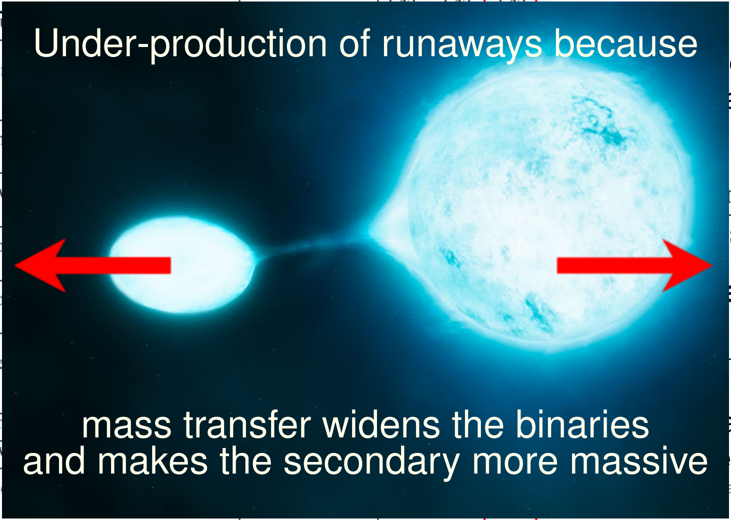

Under-production of runaways because

mass transfer widens the binaries
and makes the secondary more massive

come
at low Z)

naways
stars

ed:

- 20%

ays from
s
al. '01)

Renzo *et al.*, to be submitted

Outline

Ejection Mechanisms

- Differences in resulting runaway stars

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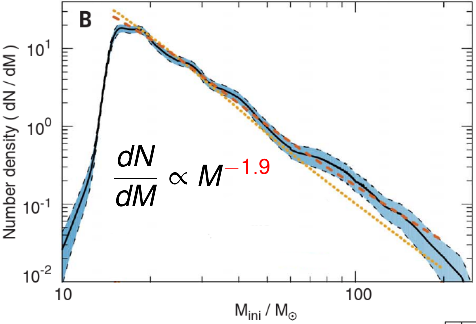
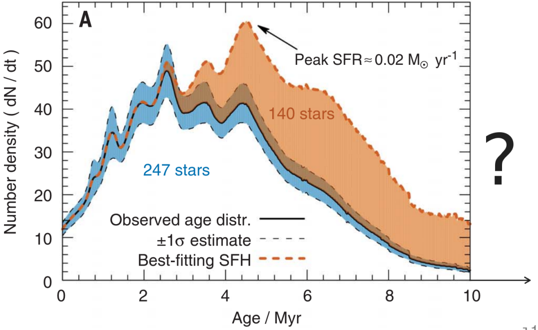
30 Doradus sample: IMF & SFH



$$\frac{dN}{dM} \propto M^{-1.9}$$



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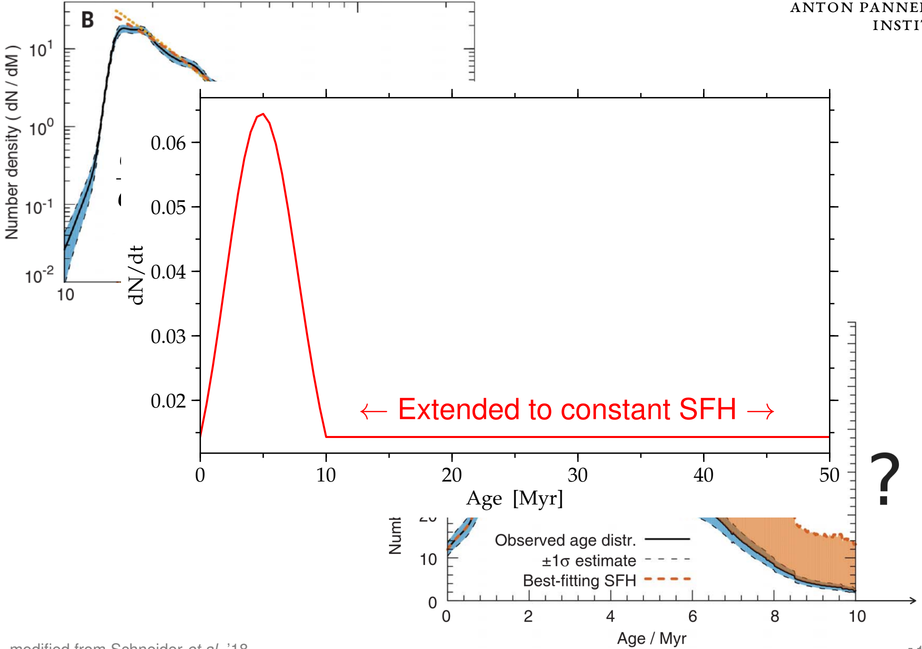
Schneider *et al.* '18

30 Doradus sample: IMF & SFH



modified from Schneider *et al.* ’18

30 Doradus sample: IMF & SFH

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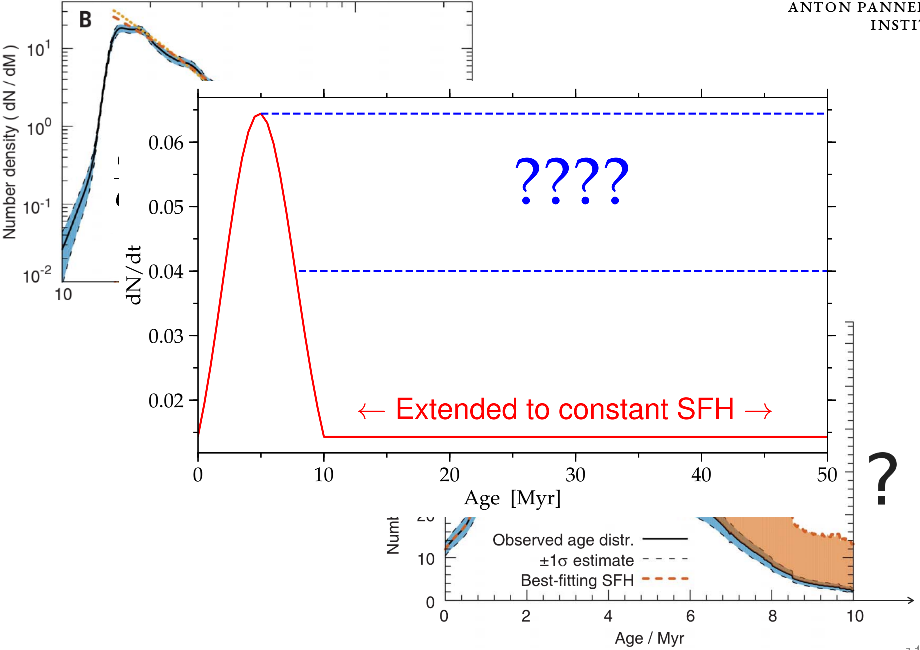

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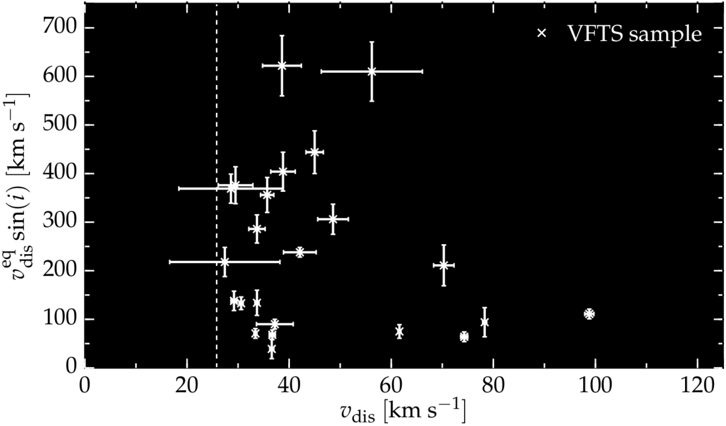
O-type runaways

Largest homogeneous sample available to date

“Rotational velocity”



“Line of sight velocity”

$$f_{15}^{\rm RW} \simeq \frac{23}{300} \simeq 8\%$$

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

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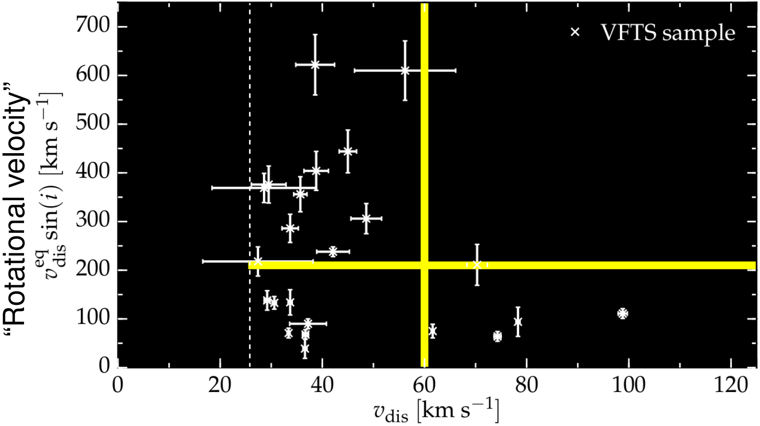

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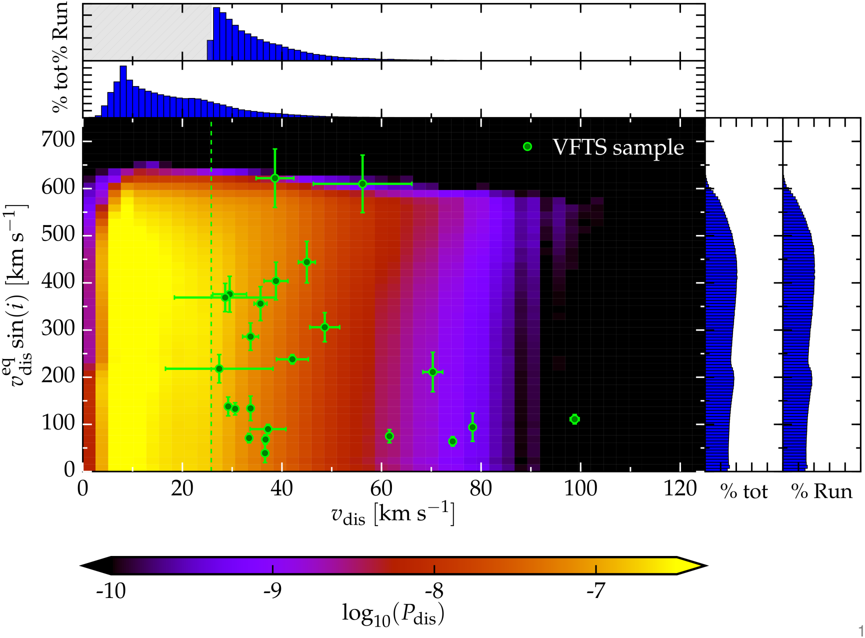

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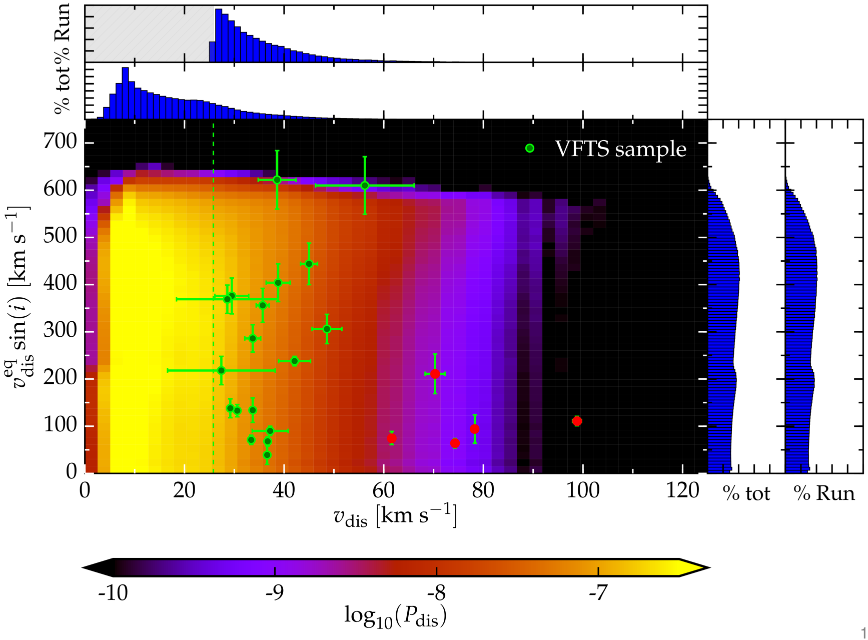
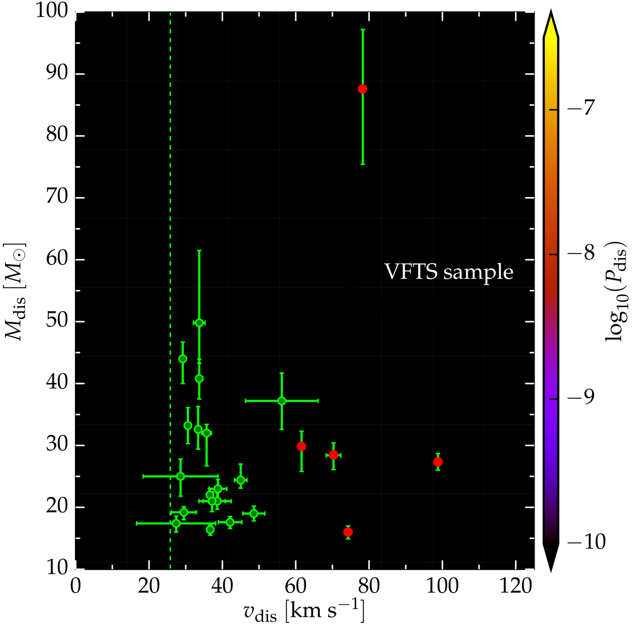


Mass-velocity distribution

“Mass of the runaway/walkaway”



“Logarithm of Probability”

“Line of sight velocity”

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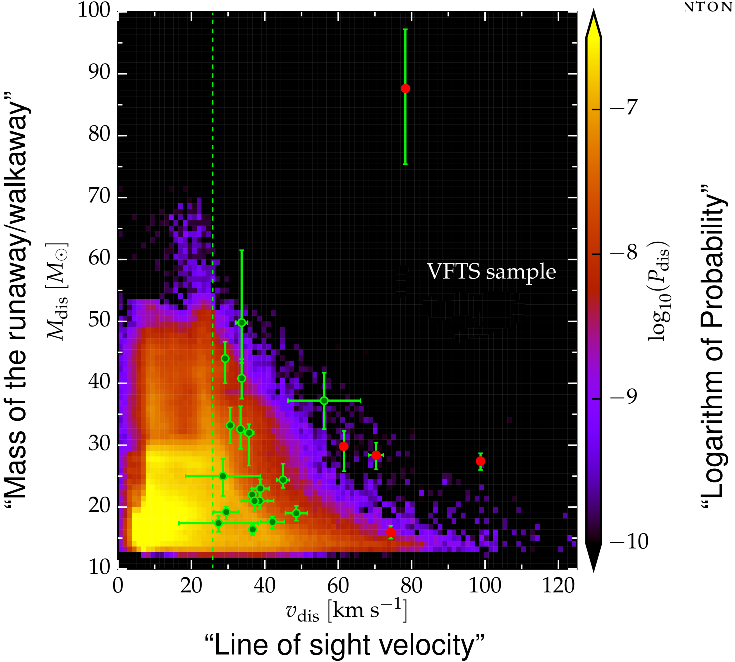

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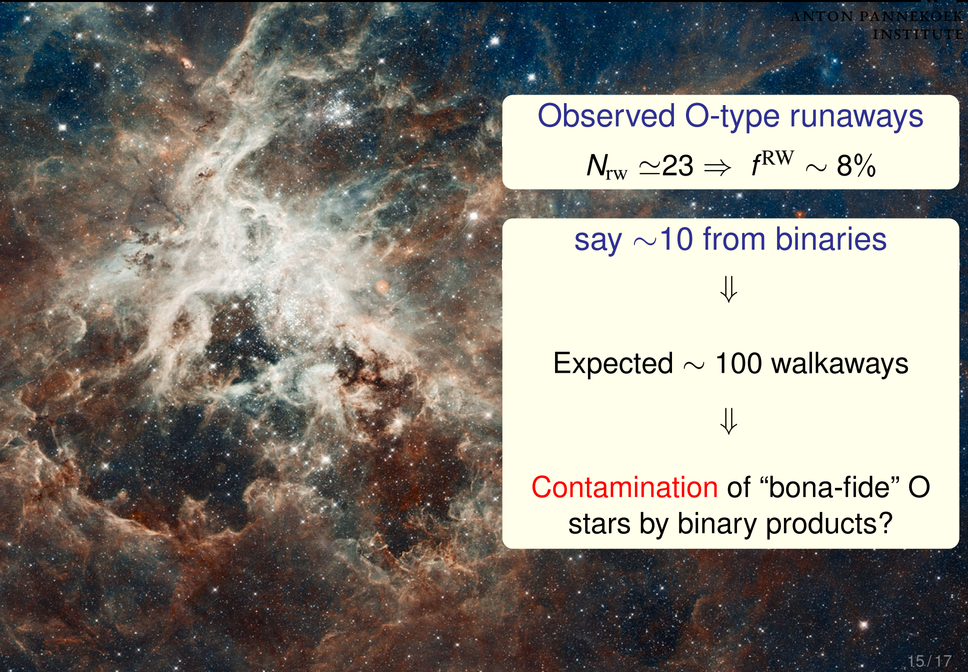
Preliminary estimates for 30 Doradus



Observed O-type runaways

$N_{\mathrm{rw}} \simeq 23 \Rightarrow\ f^{\mathrm{RW}} \sim 8\%$

say ∼10 from binaries

$\Downarrow$

Expected ∼ 100 walkaways

$\Downarrow$

Contamination of “bona-fide” O stars by binary products?

Preliminary estimates for 30 Doradus

Observed O stars

$N_{\mathrm{tot}} \simeq 300$

$\sim 10\,\% \simeq 30$ walkaways

$\Downarrow$

Contamination less dramatic

$\sim 1\,\% \simeq 3$ runaways

$\Downarrow$

Wrong RLOF and/or explosion physics?

Observed O-type runaways

$N_{\mathrm{rw}} \simeq 23 \Rightarrow f^{\mathrm{RW}} \sim 8\%$

say $\sim$10 from binaries

$\Downarrow$

Expected $\sim$ 100 walkaways

$\Downarrow$

Contamination of “bona-fide” O stars by binary products?

Conclusions

- $\sim$75% **of binaries disrupted by first SN**
- **The vast majority produce slow “walkaways”**
- **O-type runaway fraction lower by** $\sim$**10**$\times$

Future plans

Try to reproduce/predict **all** binary products in 30 Doradus
(Runaways, X-ray sources, # BHs, # NSs, etc.)

- Vary input physics and initial distributions
- Compare models (Bayesian approach)

Q: SFH beyond 10Myr ago?

Probability distribution within the error bars?

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Thank you!

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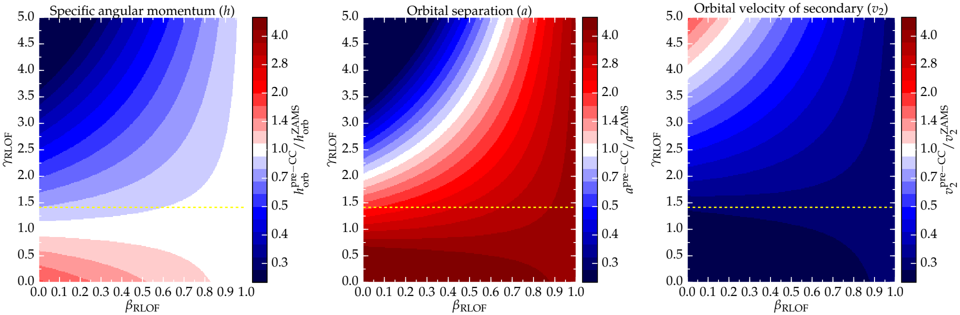
Backup slides

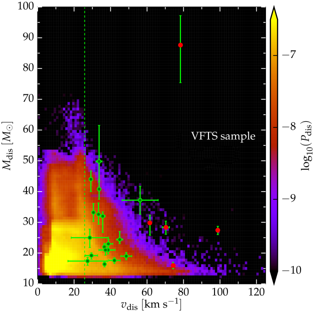
Analitical estimates



Hard to not widen the binary during interactions!

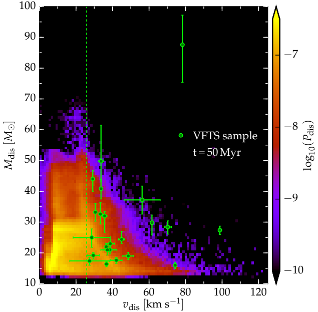
Mass-velocity varying the natal kick

$\sigma_{\rm kick} = 265\,{\rm km\ s^{-1}}$

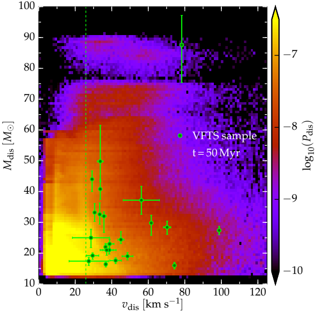


Double Maxwellian

$\sigma_{\rm kick} = (30,\ 265)\ {\rm km\ s^{-1}}$



Large BH kicks
(no fallback)



Bayesian comparison of different models

Q: What is the probability of drawing
the observed runaways from a synthetic population $\mathcal{M}$?

$$\log_{10}\left(\mathcal{L}_{\mathcal{M}}\right) \overset{\mathrm{def}}{=} \sum_{k=1}^{N_{\mathrm{rw}}} \log_{10}\left(P(v_{\mathrm{dis}}^{k}, v_{\mathrm{eq}}^{k}\sin(i)|\mathcal{M})\right)$$

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Bayes Factor $\mathcal{K}_{\mathcal{M}}$:

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Very preliminary!

- **Double Maxwellian kick**:

  (small kick for low mass NS)

  $\log_{10}\left(\mathcal{K}\right) \simeq -6.5 \cdot 10^{-5}$

- **No fallback scaling**:

  (large BH kicks, same as NS)

  $\log_{10}\left(\mathcal{K}\right) \simeq -0.08$

$\Longrightarrow$ Difficult to distinguish double and single Maxwellian

X-ray sources in 30 Doradus

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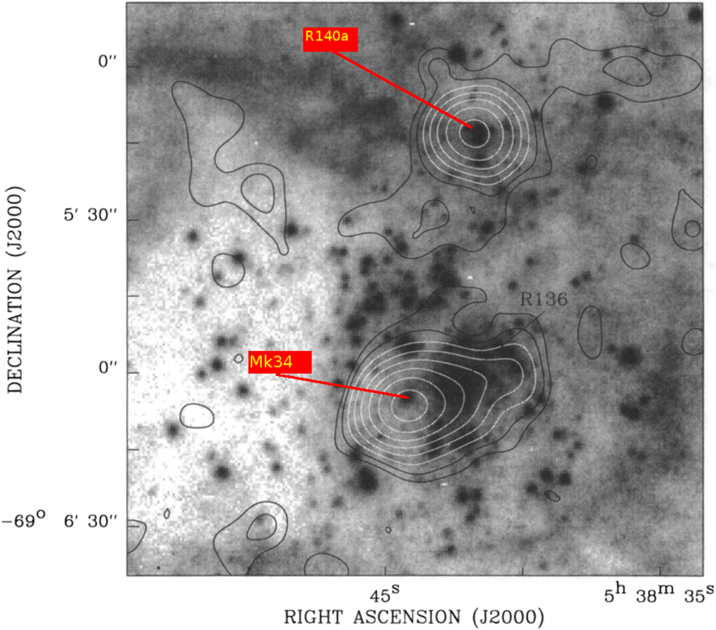

Wang, Q. D. ’95

Runaway age distribution

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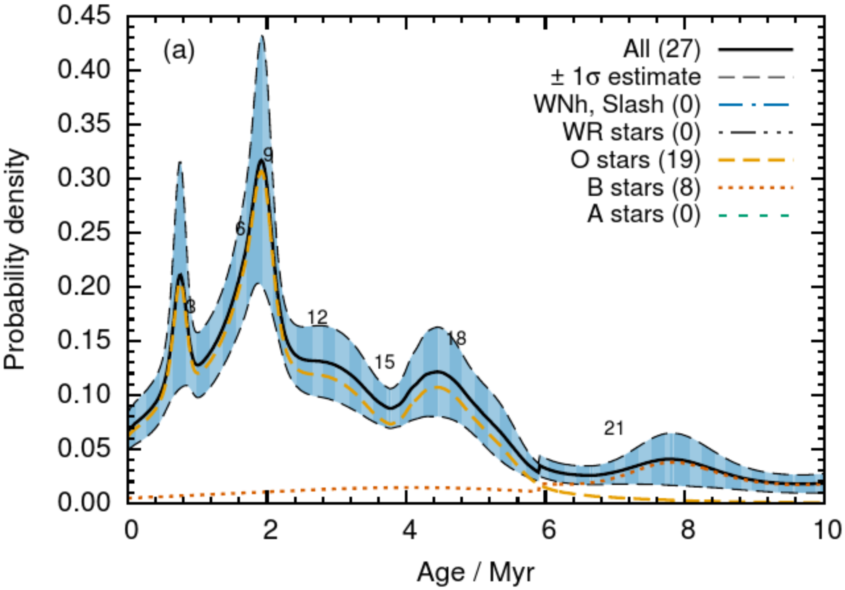
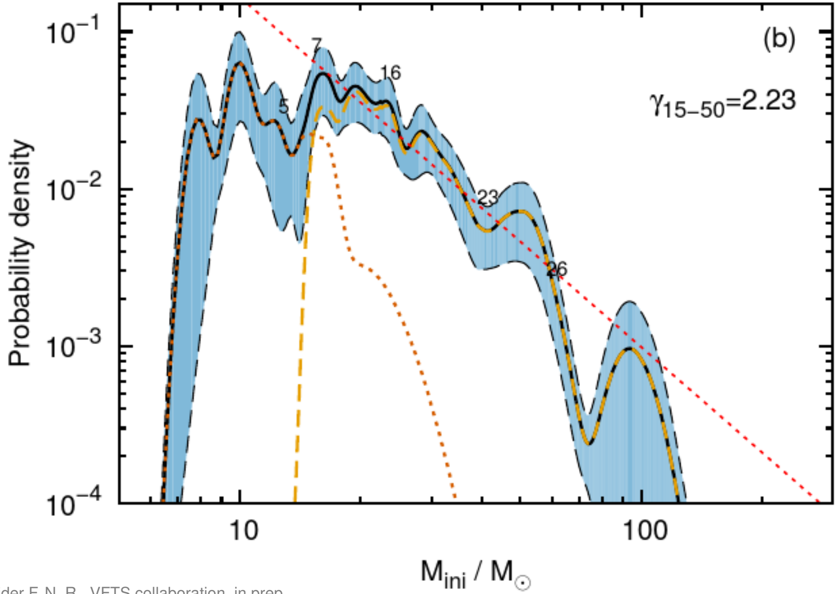


Schneider F. N. R., VFTS collaboration, in prep.

Runaways mass function



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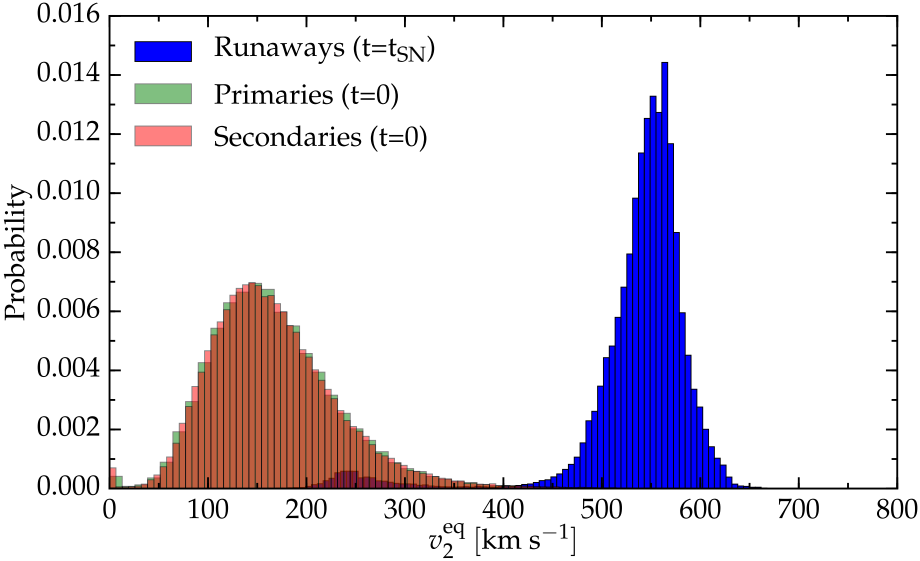
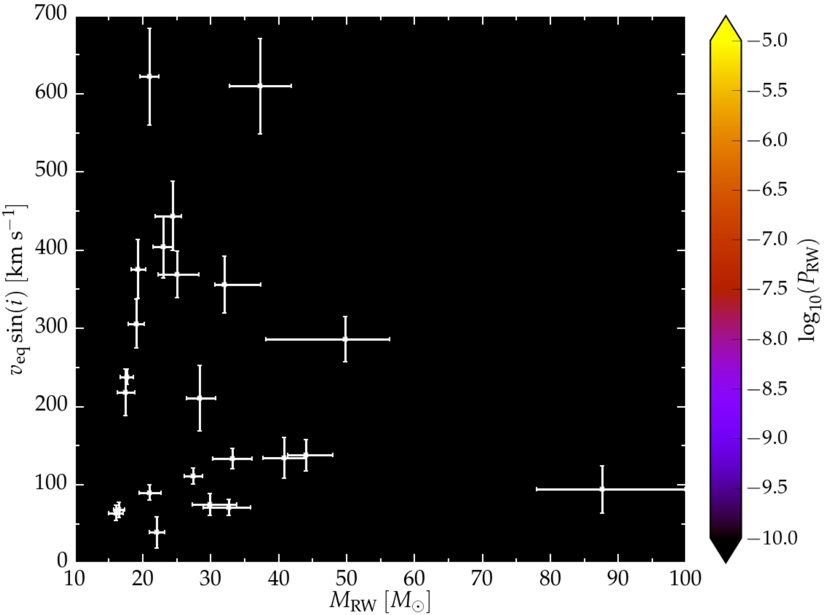
Rotation rate



Mass-rotation correlation

Runaways only



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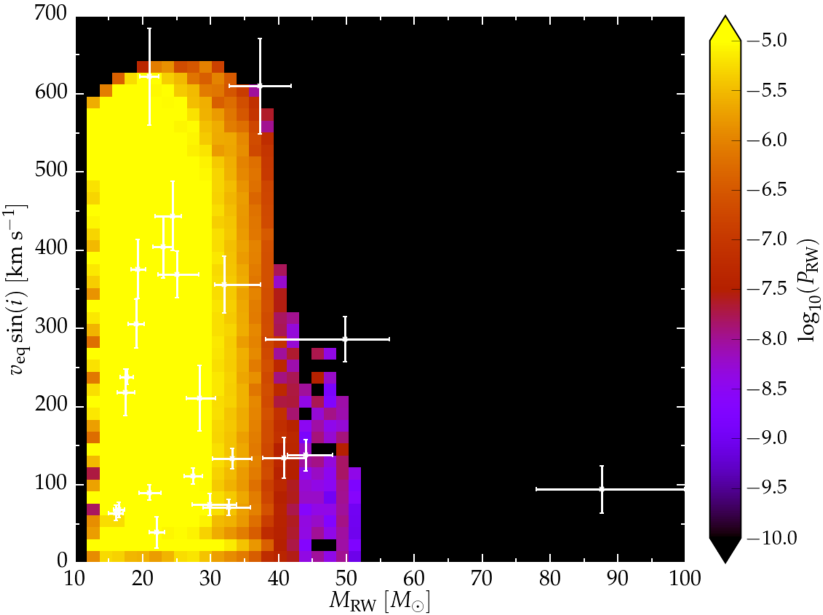

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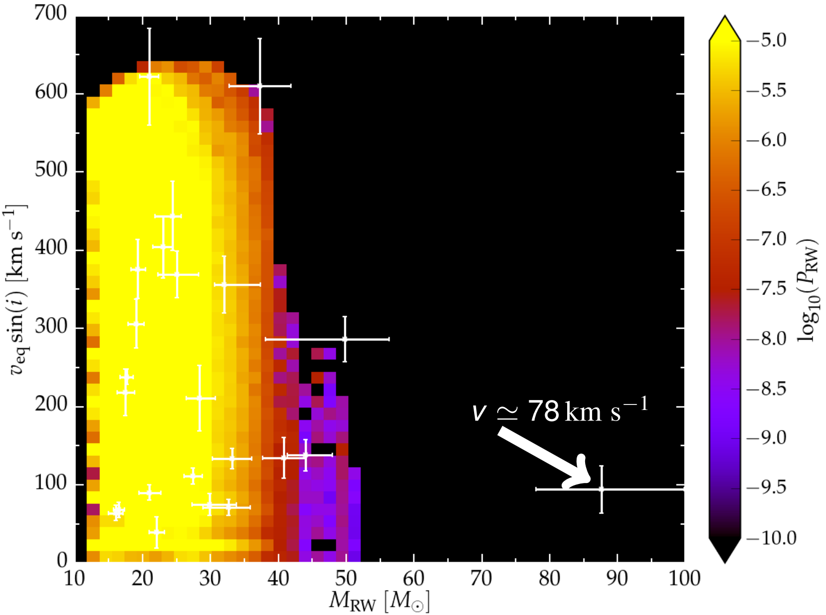
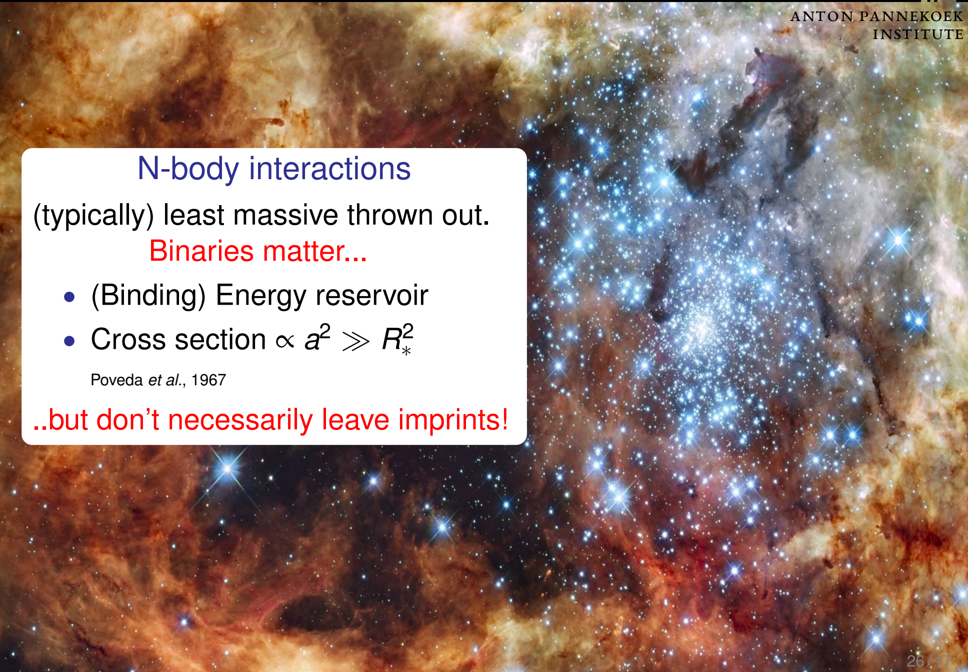


Cluster ejection



N-body interactions

(typically) least massive thrown out.

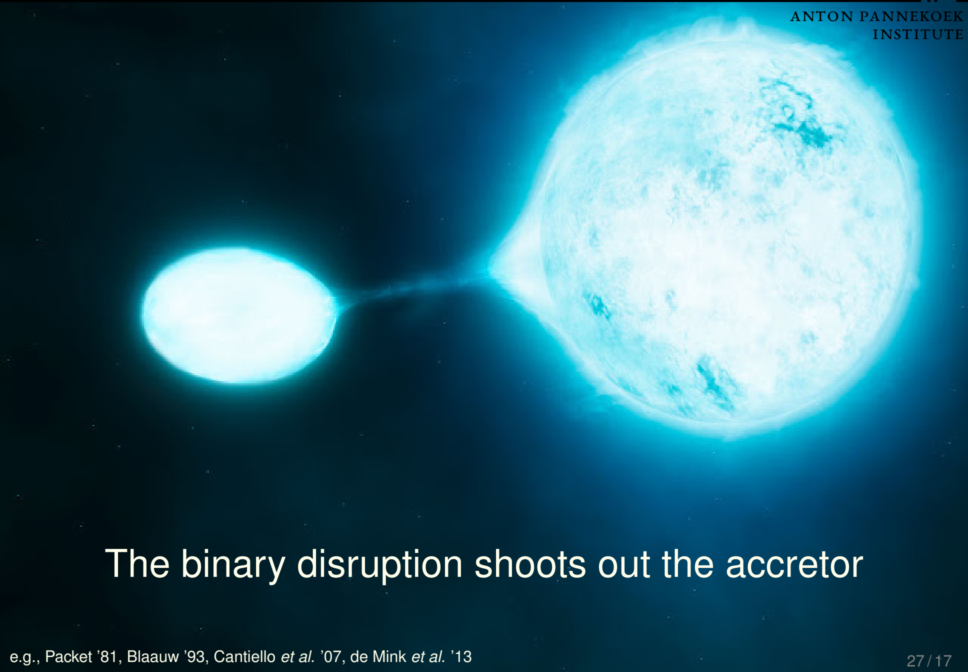
Binaries matter...

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

Poveda *et al.*, 1967

..but don’t necessarily leave imprints!

Spin up, pollution, and rejuvenation



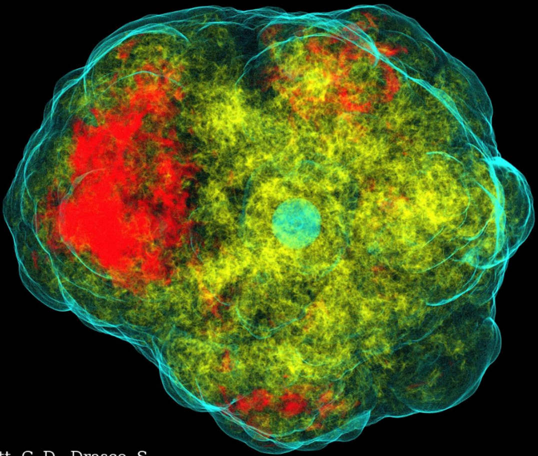
The binary disruption shoots out the accretor

e.g., Packet '81, Blaauw '93, Cantiello *et al.* '07, de Mink *et al.* '13

SN natal kick

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

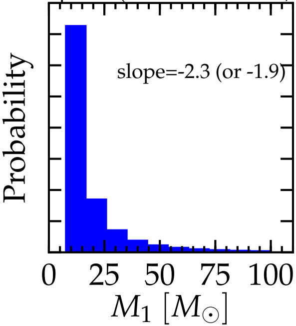
Physically: ν emission and/or ejecta anisotropies



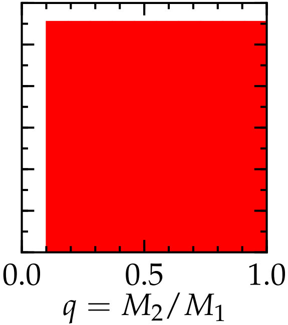
Credits: Ott, C. D., Drasco, S.

Fiducial Distributions

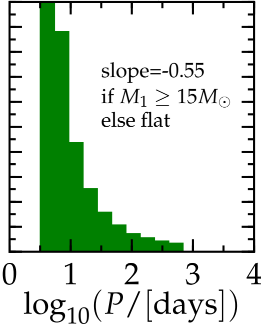
Kroupa ’01 (or Schneider *et al.*, ’18)



flat

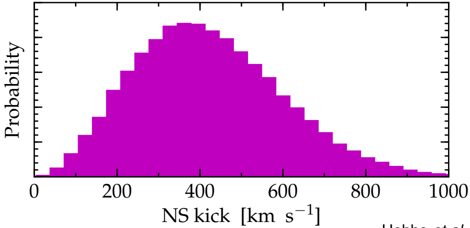


Sana *et al.*, ’12



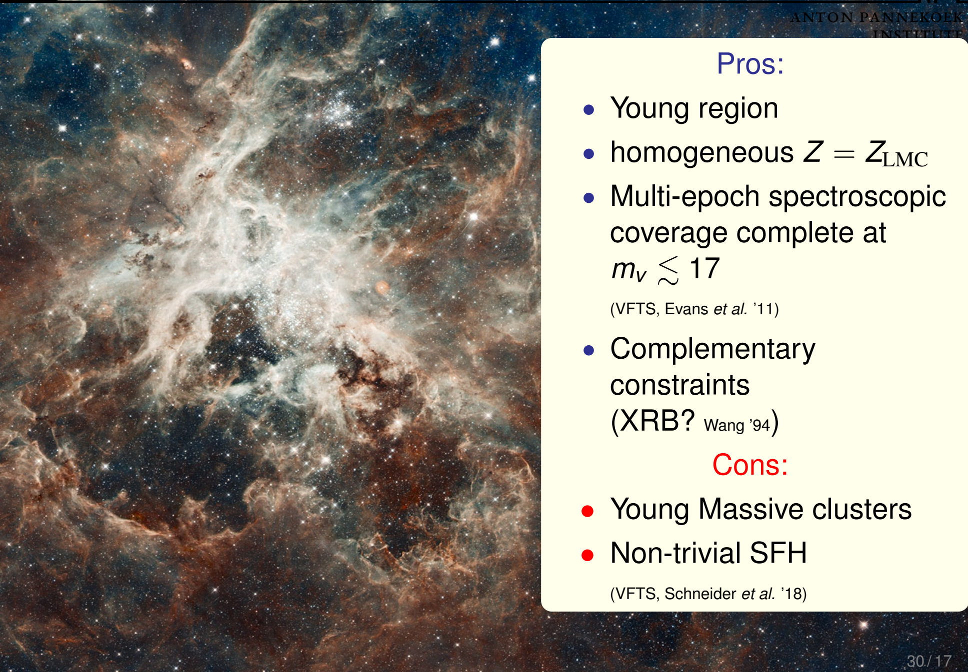
Maxwellian $\sigma_{v_{\mathrm{kick}}} = 265\,\mathrm{km\ s^{-1}}$ + Fallback rescaling

(from Fryer *et al.* ’12)



Hobbs *et al.* ’05

30 Doradus



Pros:

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

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

- Complementary constraints (XRB? Wang '94)

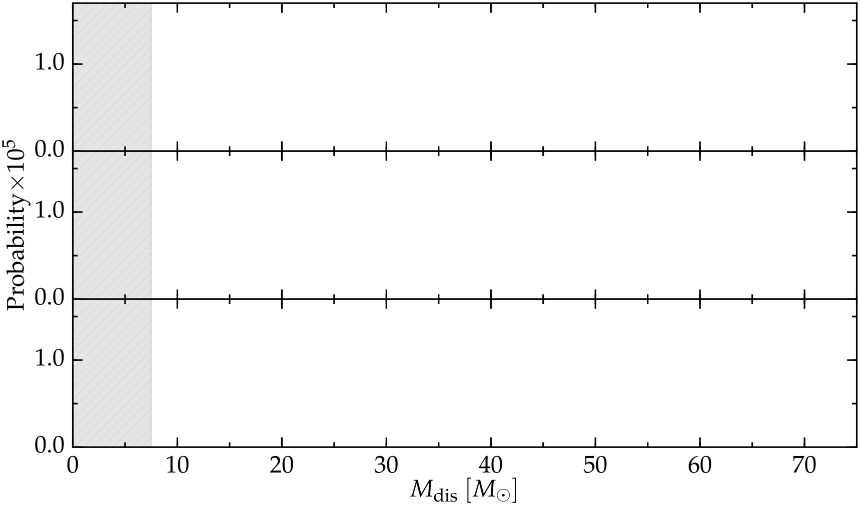
Cons:

- Young Massive clusters
- Non-trivial SFH

(VFTS, Schneider *et al.* '18)

A way to constrain BH kicks

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



Renzo *et al.*, to be submitted.

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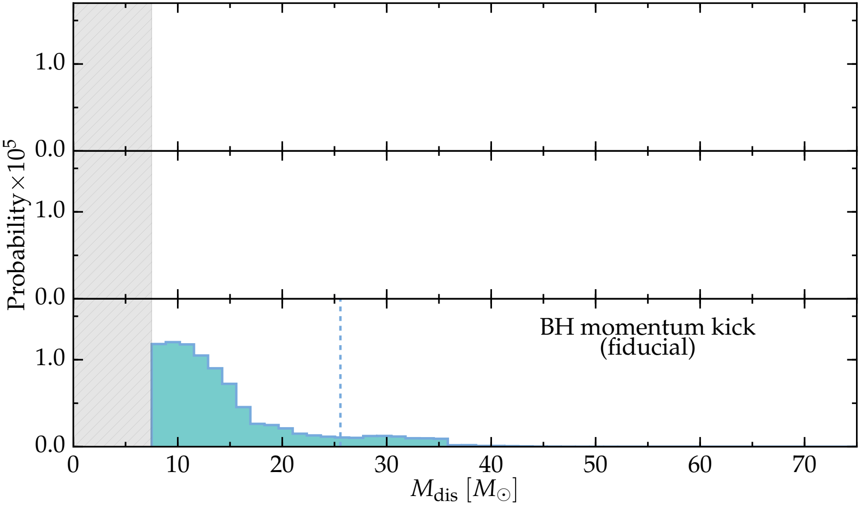

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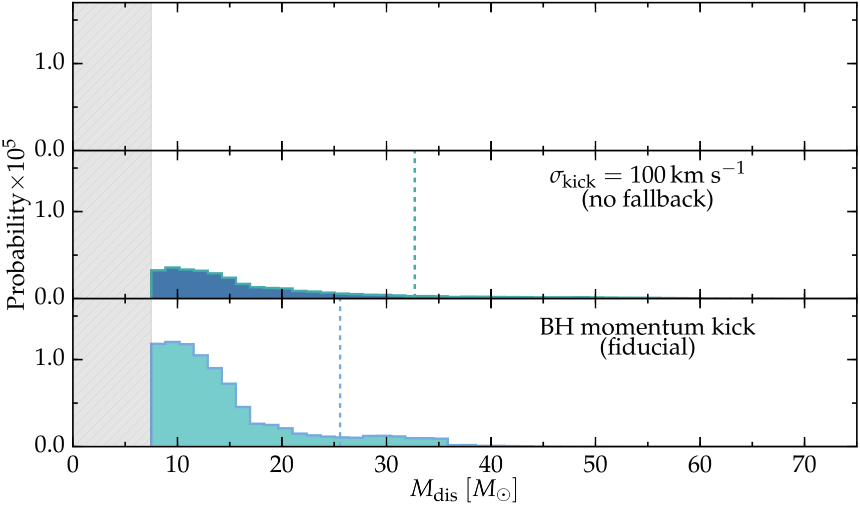

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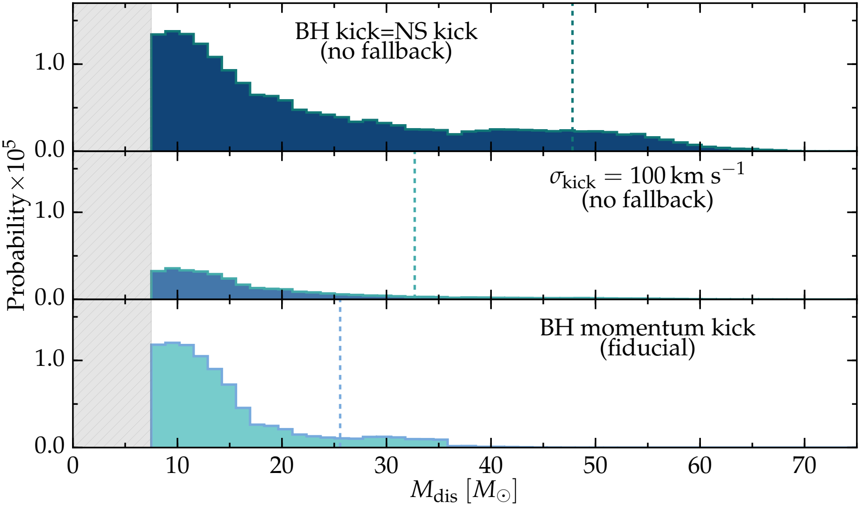

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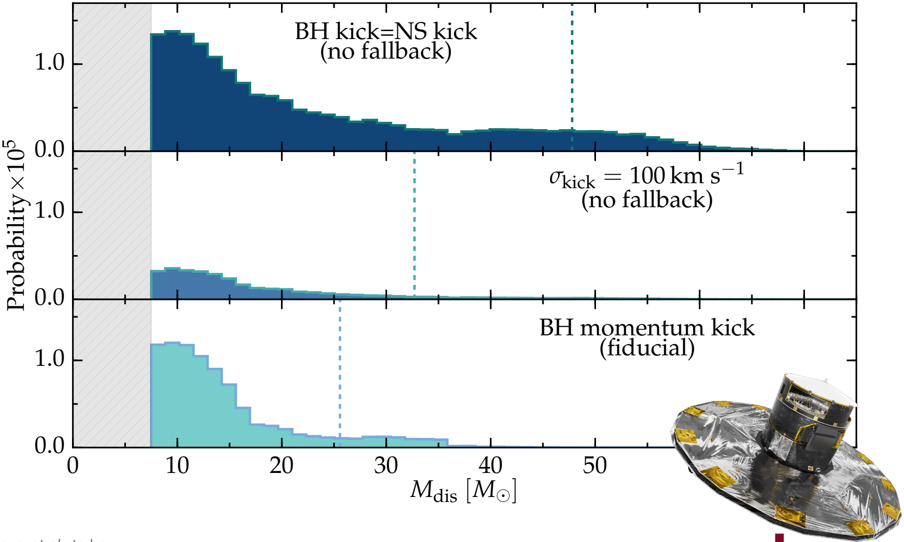

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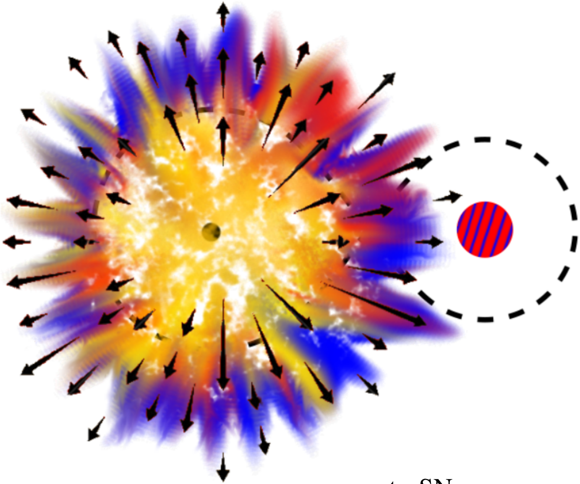
gaia

What exactly disrupts the binary?

$\gtrsim$75% 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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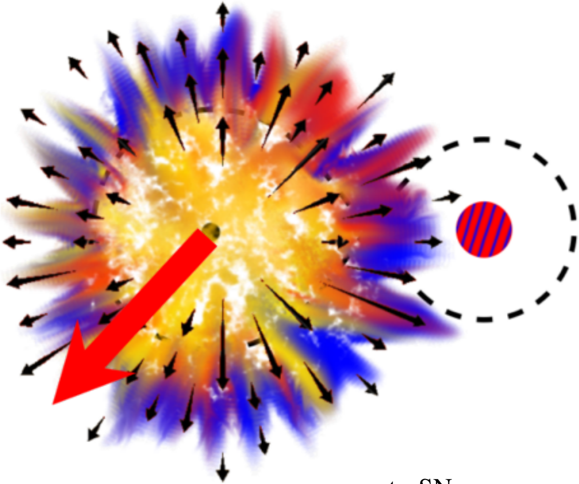

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$$v_2^{\mathrm{post-SN}} \simeq v_{2,\mathrm{orb}}^{\mathrm{pre-SN}}$$

(potential) Physics lessons...

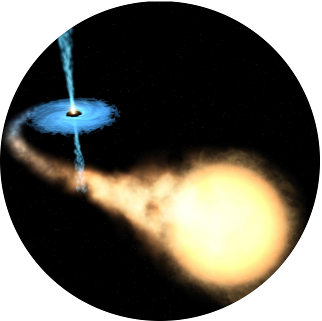
...from disrupted binaries

- BH kicks
- Binary evolution

Do BH receive natal kicks?

Spatial distribution of X-ray binaries

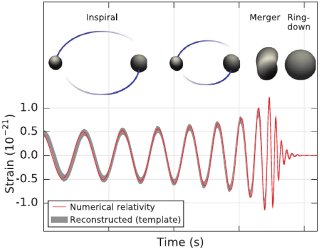
(e.g., Repetto *et al.* '12,'15,'16, Mandel '16)



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.