Massive widowed stars:

Runaways and walkaways from binary disruptions

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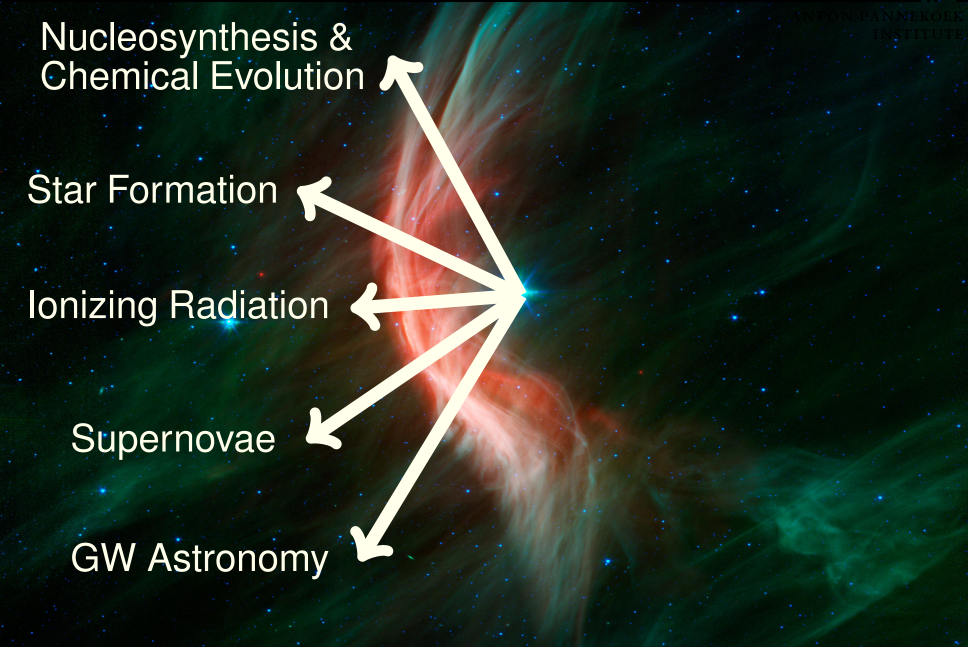
NASA, JPL-Caltech, Spitzer Space Telescope

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}}$)

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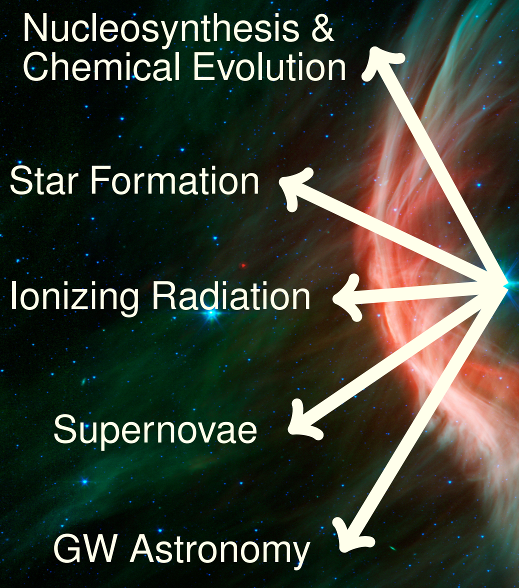

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$\sim$10% of O type stars are runaways ($v \gtrsim 30\,\mathrm{km\ s^{-1}}$)

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

Preliminary:

$\sim$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

ANTON PANNEKOEK INSTITUTE

How to measure stellar velocities?

How to generate widowed stars?

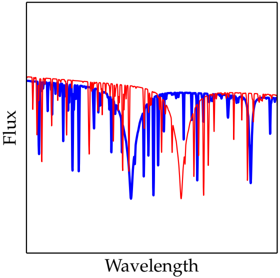
Methods: population synthesis

Preliminary results

Conclusions

⇐ Bow shocks

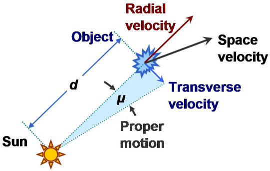
Doppler shifts ⇒



Proper motions

(if distance known)

⇓



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Binary disruption

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

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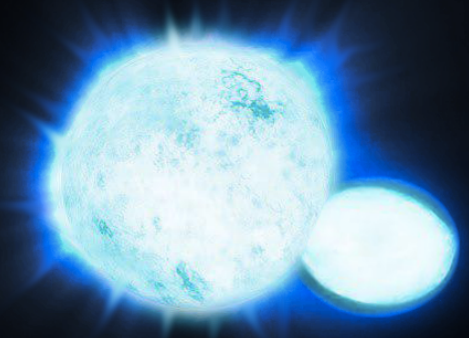
Spin up, pollution, and rejuvenation

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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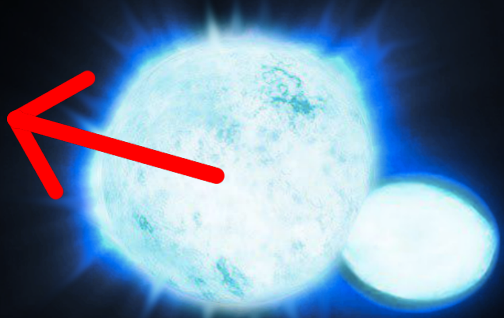

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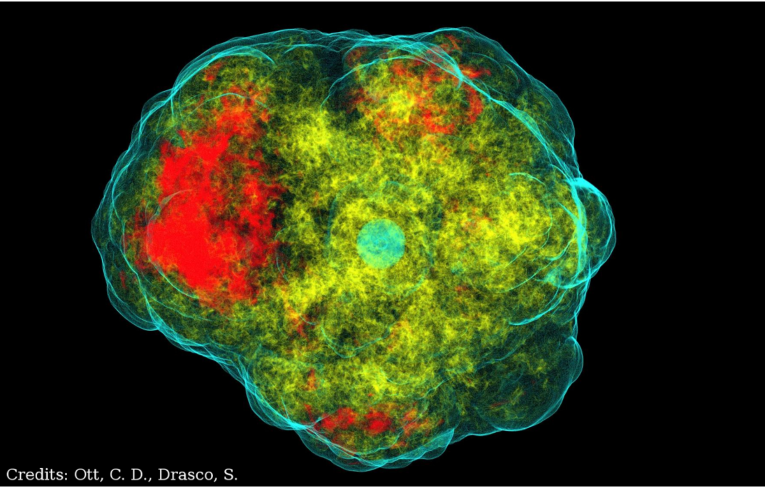
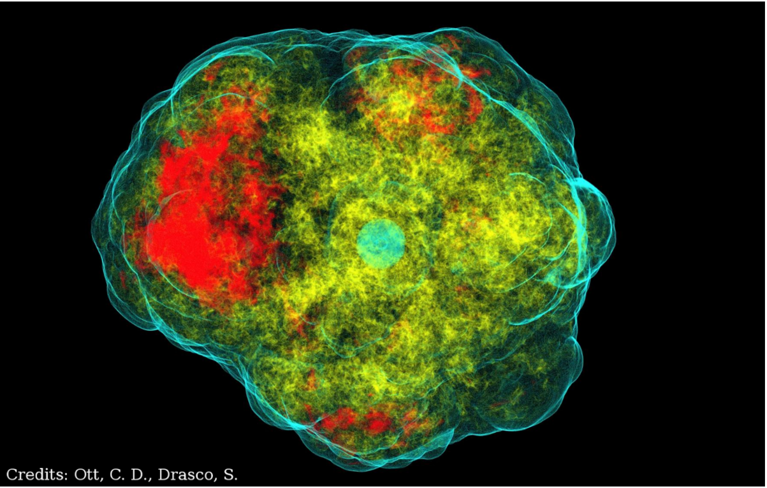
SN natal kick



ν emission and/or ejecta anisotropies

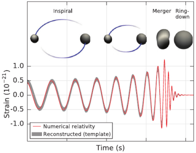
SN natal kick

do BH receive a kick?

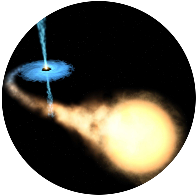


ν emission and/or ejecta anisotropies

Runaways



Gravitational Waves



XRBs

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What I do: Population Synthesis

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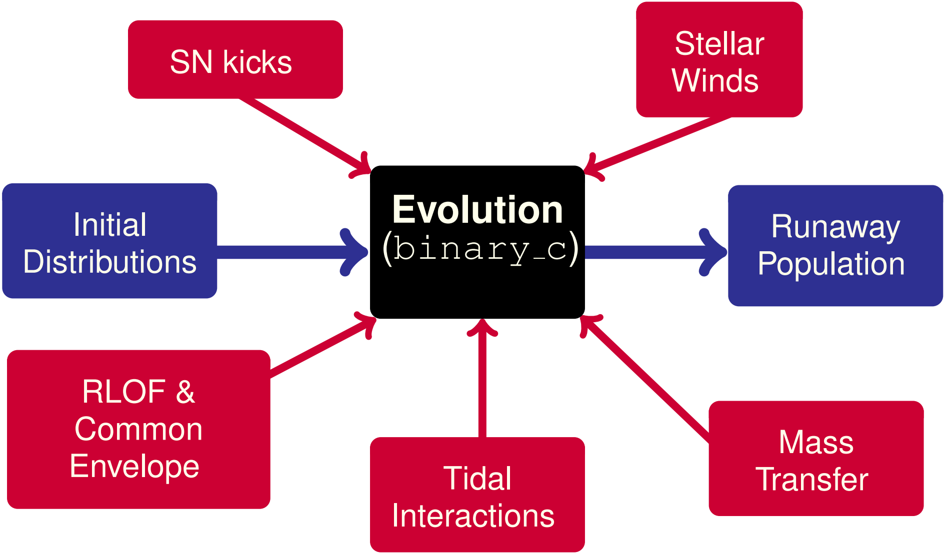
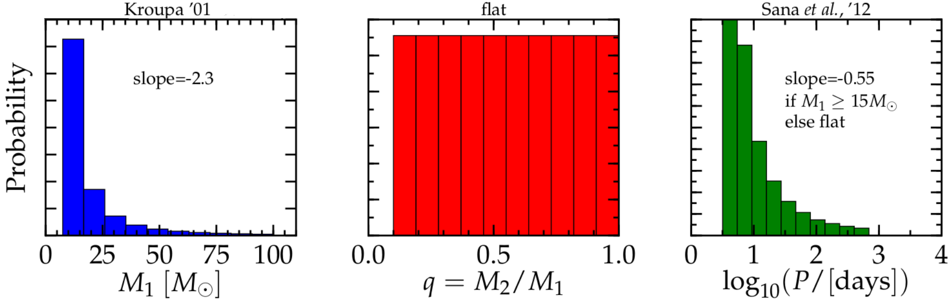
Fast $\Rightarrow$ Allows statistical tests of the inputs & assumptions



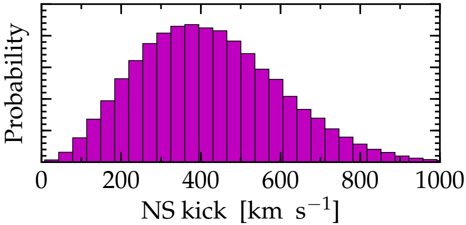
Izzard *et al.* ’04, ’06, ’09; de Mink *et al.* ’13

Initial Distributions



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

(from Fryer *et al.* '12)



Hobbs *et al.* '05

Velocity distribution: Runaways

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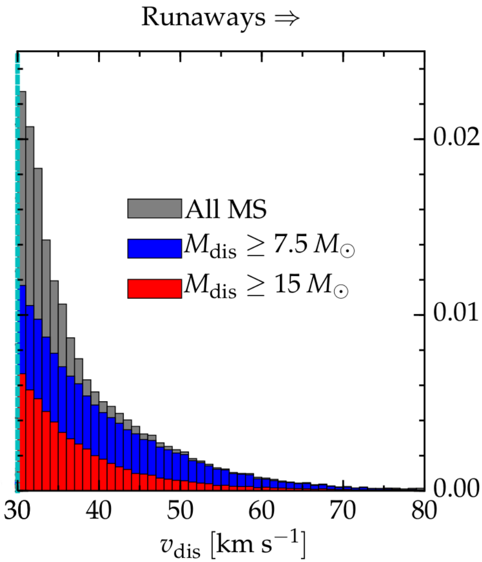

Velocity distribution: Walkaways

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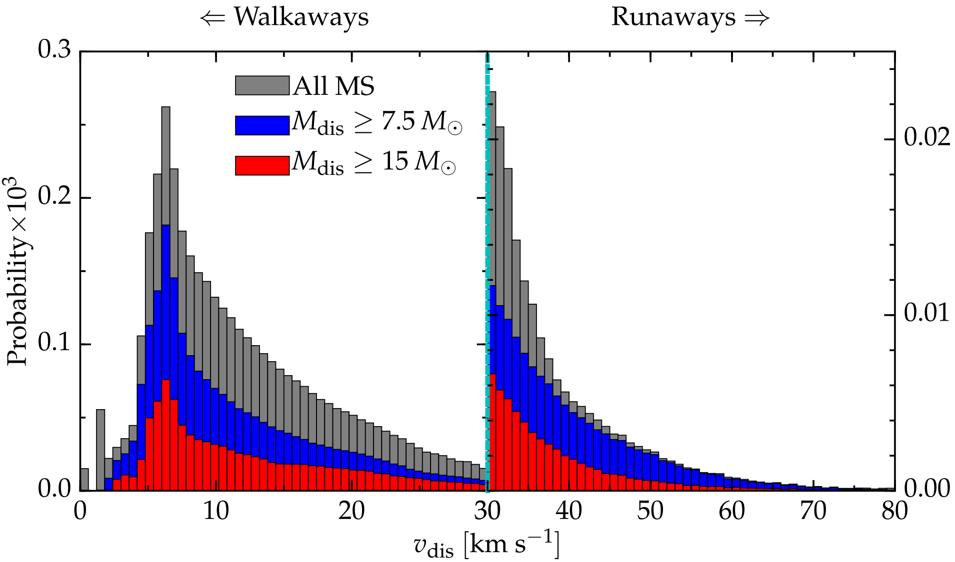
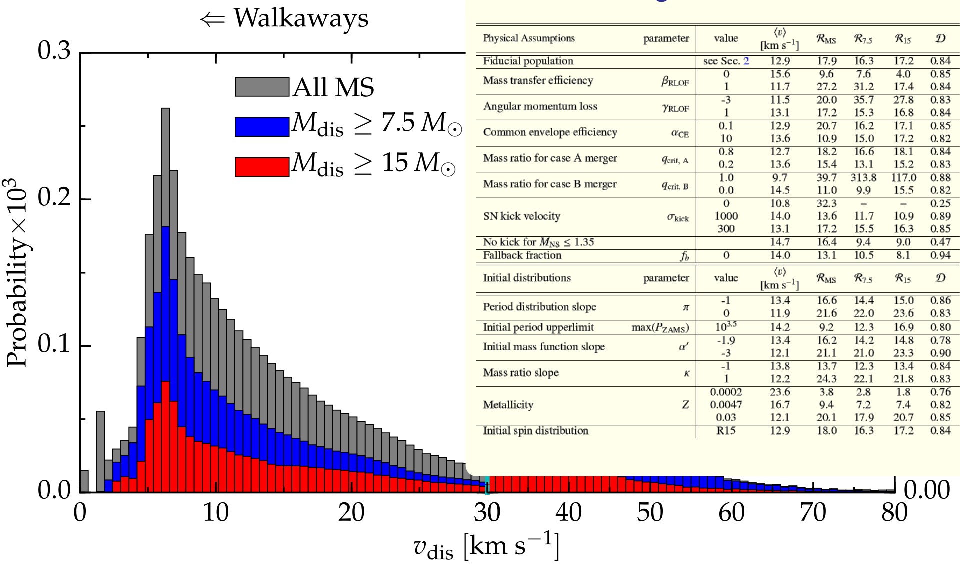


For each runaway there are ∼ 20 walkaways in the galaxy!

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?

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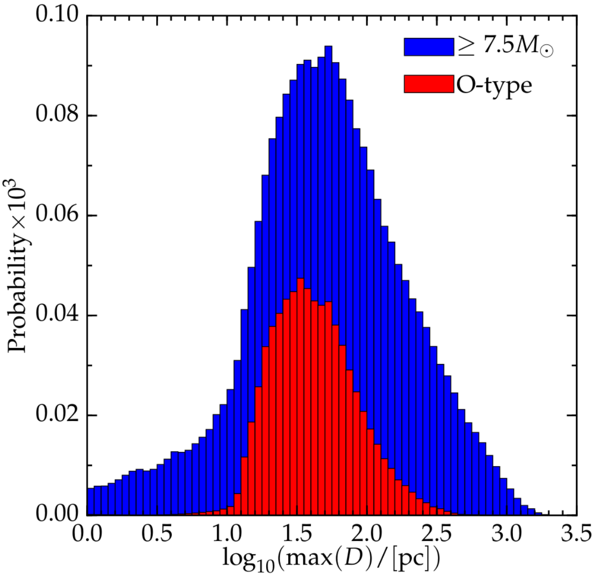


"Distance traveled"

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

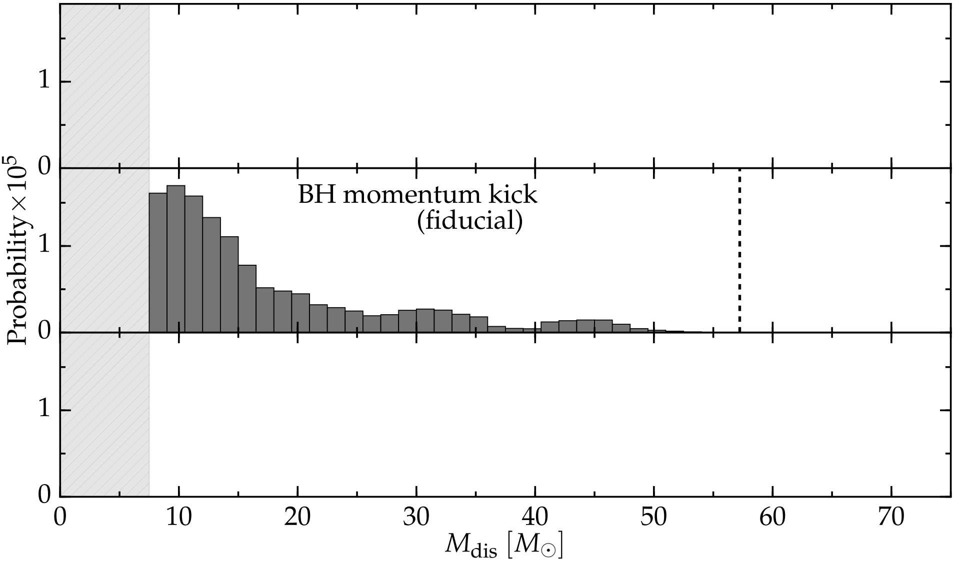
for $M \geq 7.5\,M_\odot$:

$\langle D \rangle$ = 128 pc

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

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

(Massive) runaway mass function



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

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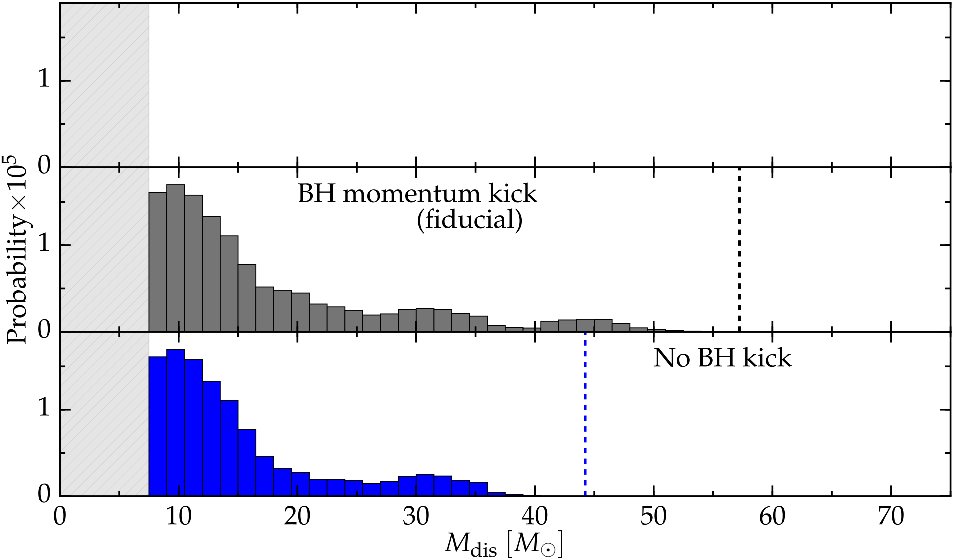

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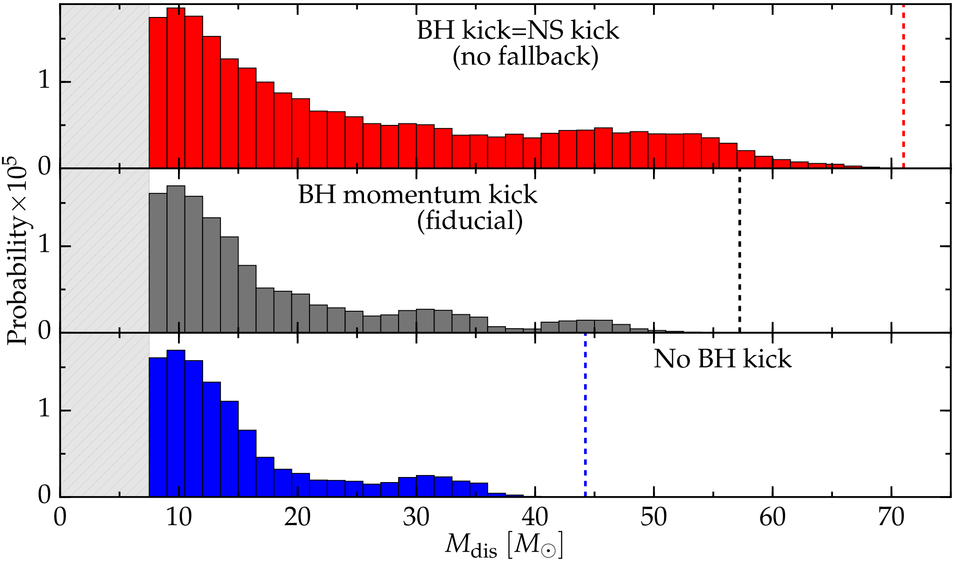

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$\sim$ 80% **of binaries disrupted by first SN**

Massive walk/runaways stars...

(regardless of their final velocity)

- ...carry info on previous binary evolution
- ...can be used to learn about companion explosion
- ...enhance the massive stars feedback

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Thank you!

Backup slides

Where do they die?

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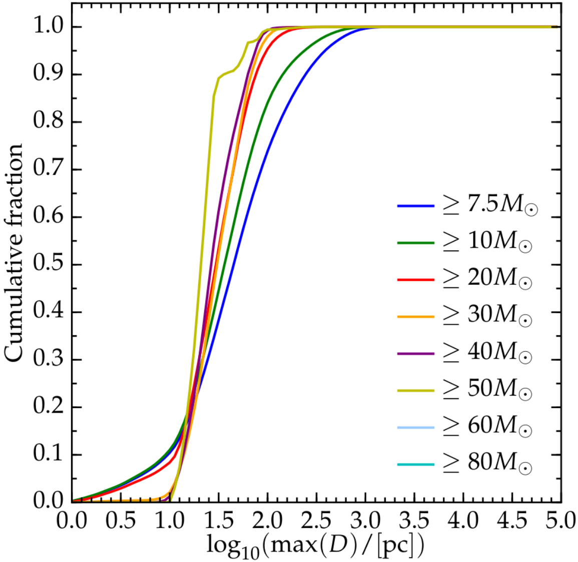

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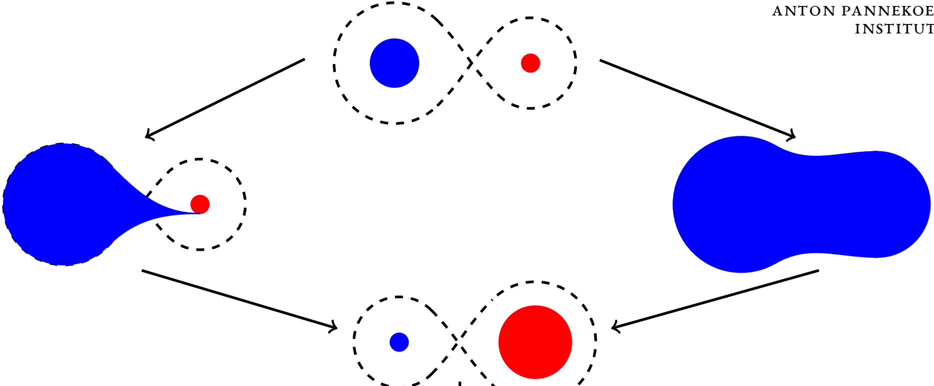
Binary disruption



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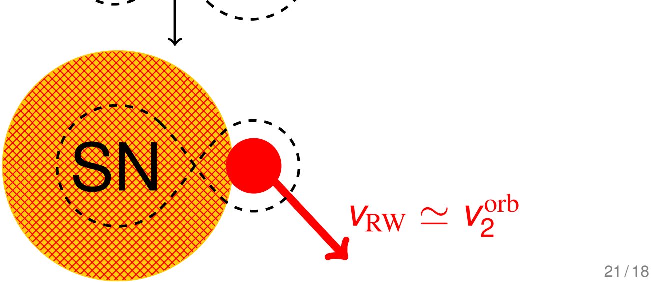
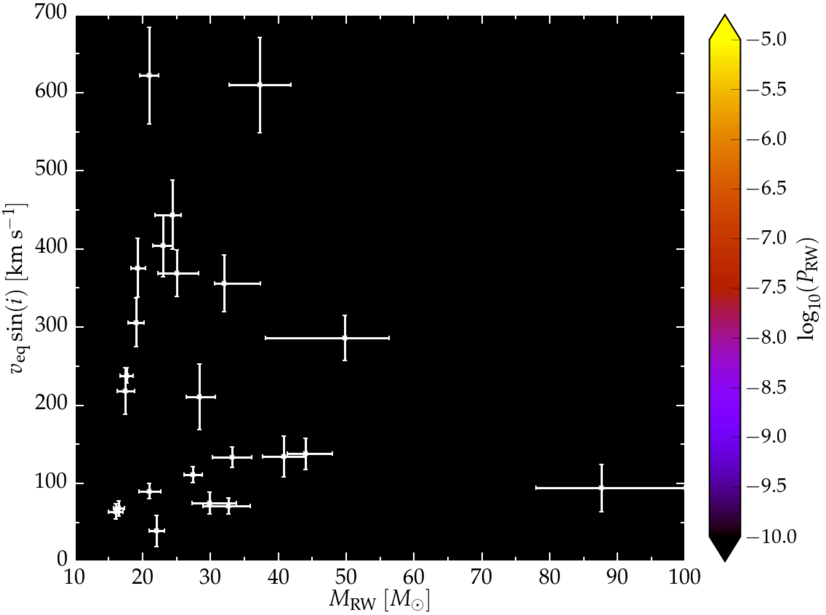
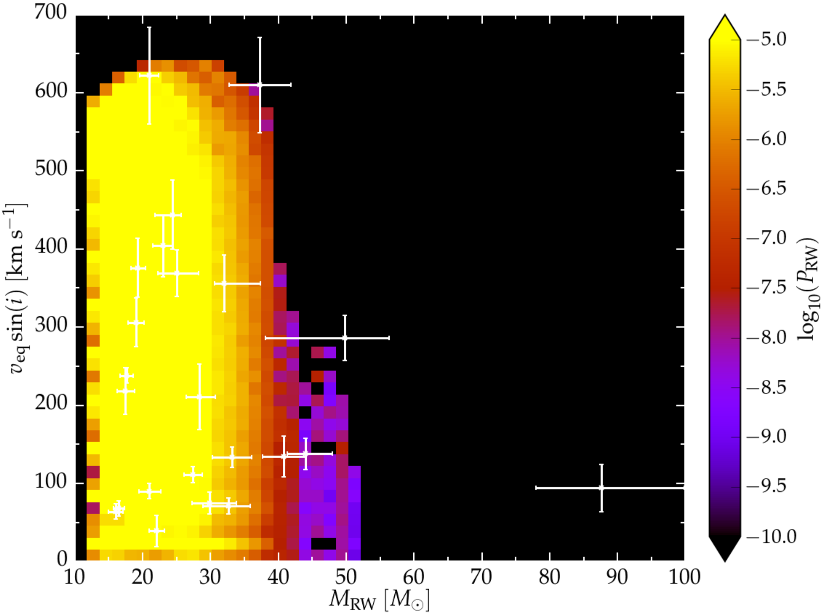


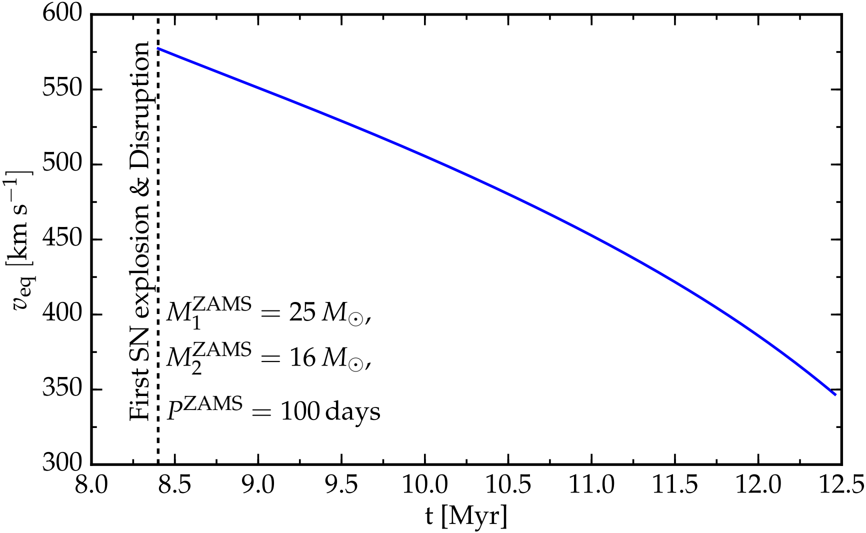
Mass-rotation correlation 1/2



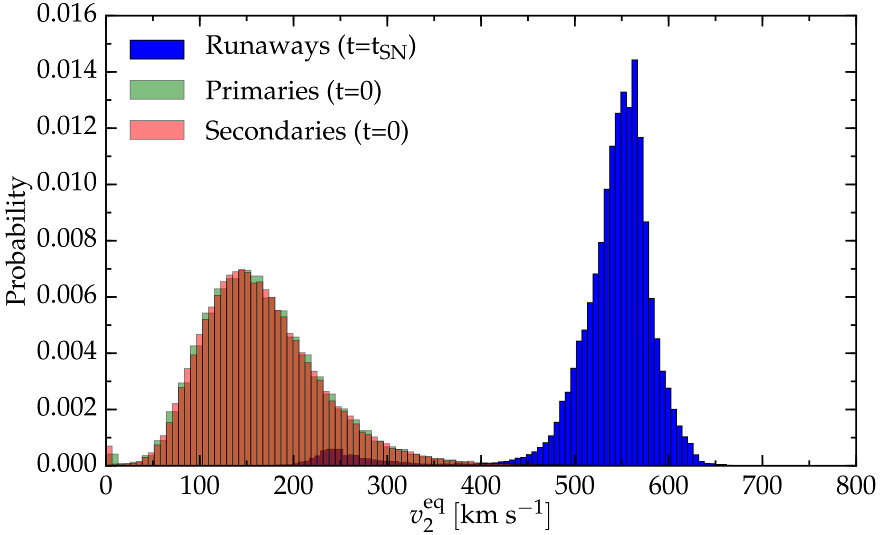
Mass-rotation correlation 2/2



Spin Down: Winds



Initial Rotational Velocities



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

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Orbit from Tauris & Takens '98

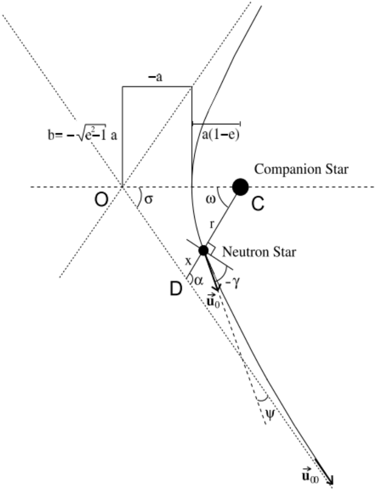


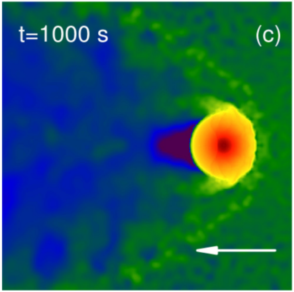
Fig. 2. Geometry of the orbital plane of a disrupted system ($e > 1$, $a < 0$) after an asymmetric supernova explosion. The reference frame is fixed on the companion star (C).

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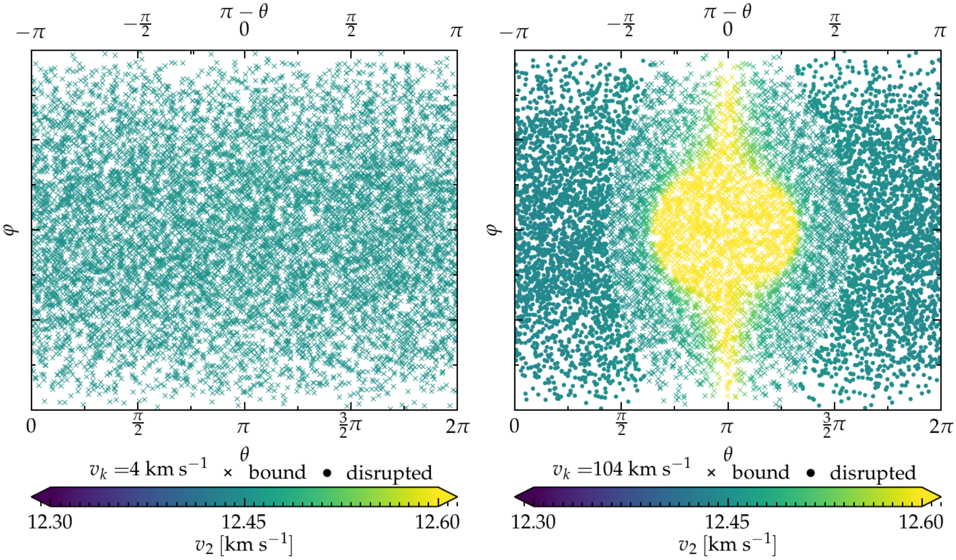
$20\,M_\odot + 15\,M_\odot$ on $P_{\rm ZAMS} = 100$ days $\Rightarrow v_2^{\rm pre-SN} \simeq 12.55\,{\rm km\ s^{-1}}$



SN kick directions 2/2

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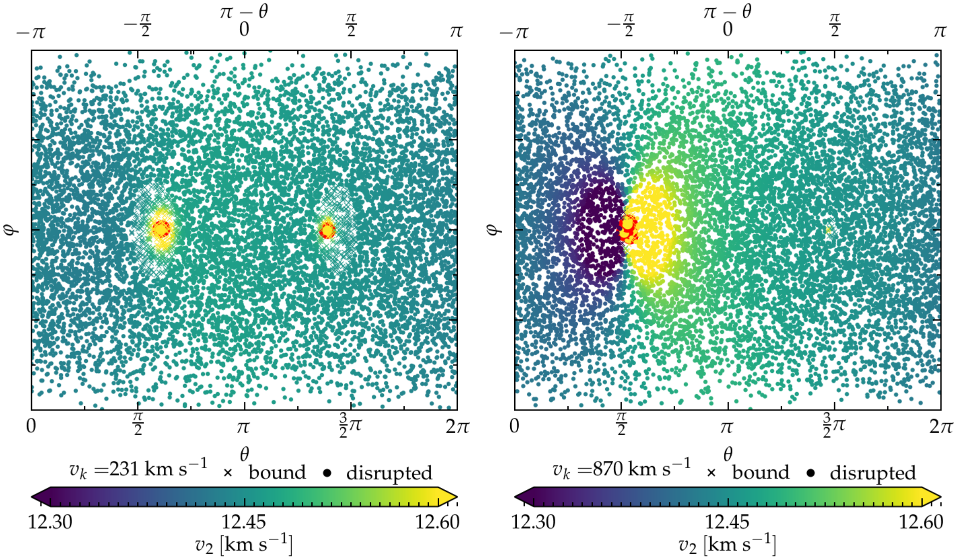

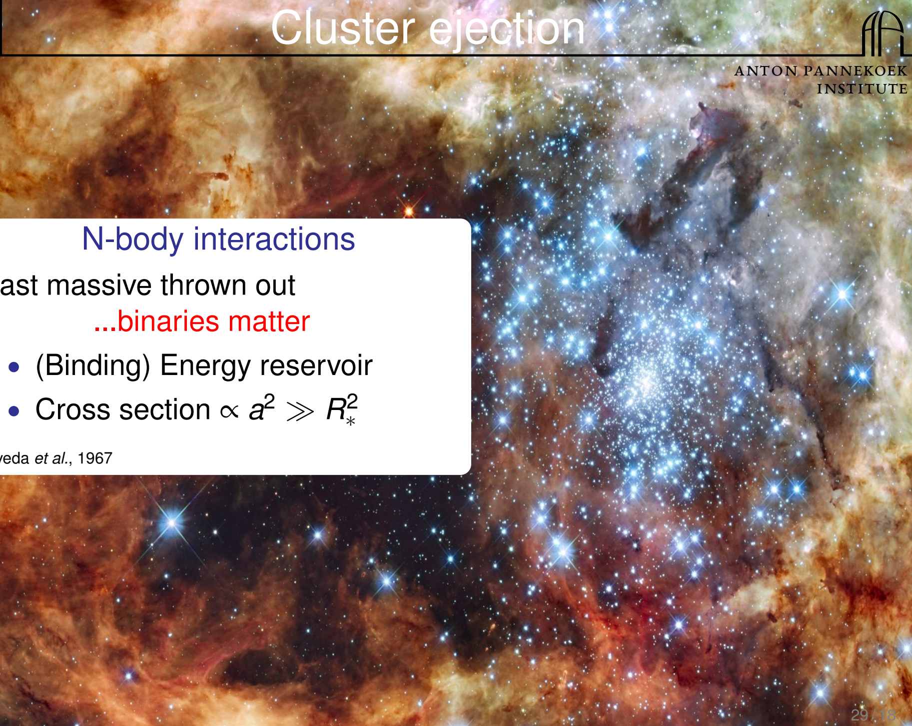

N-body interactions

least massive thrown out

...binaries matter

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

Poveda *et al.*, 1967