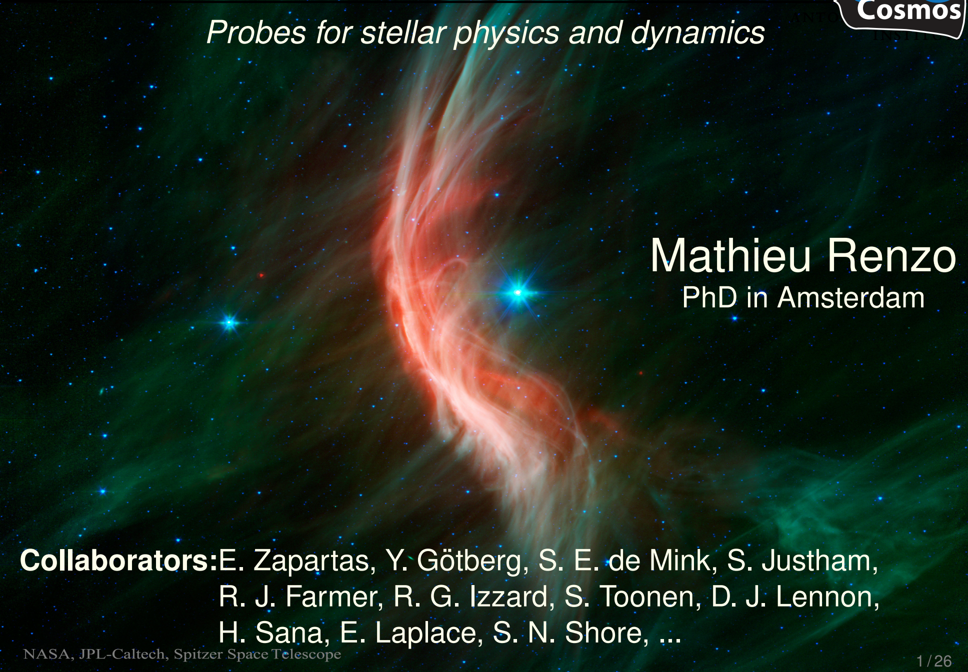
Massive Runaways:

Probes for stellar physics and dynamics

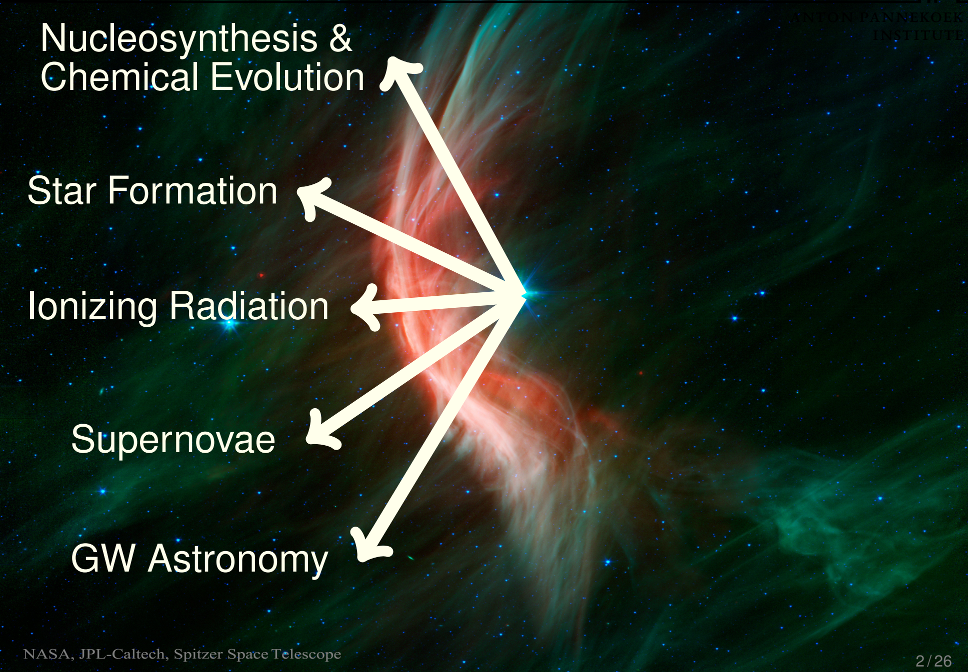


NASA, JPL-Caltech, Spitzer Space Telescope

Mathieu Renzo
PhD in Amsterdam

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

Why are massive stars important?



Nucleosynthesis & Chemical Evolution

Star Formation

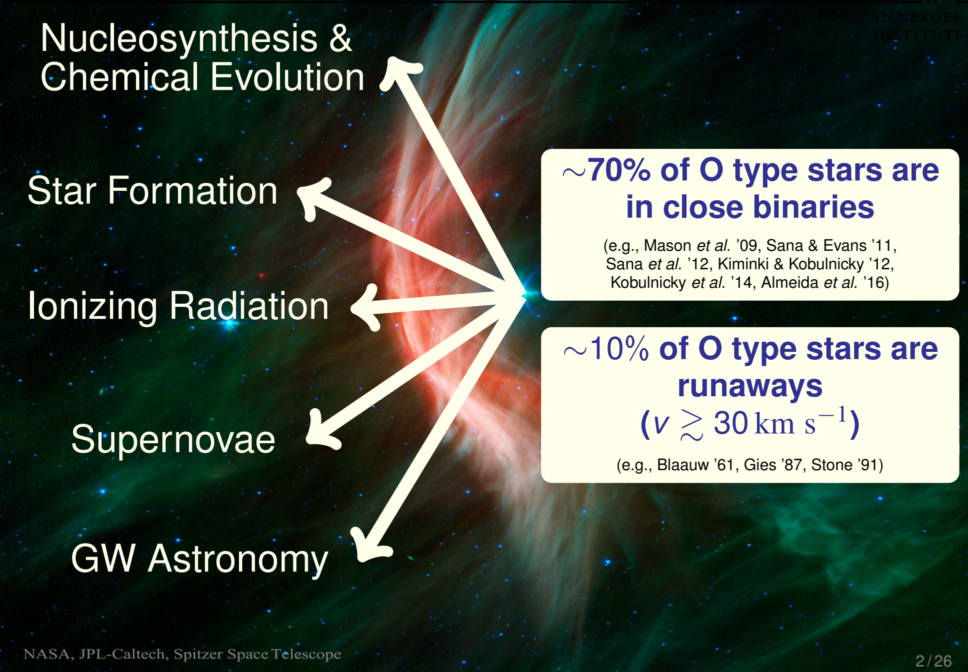
Ionizing Radiation

Supernovae

GW Astronomy

NASA, JPL-Caltech, Spitzer Space Telescope

Why are massive stars important?



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)

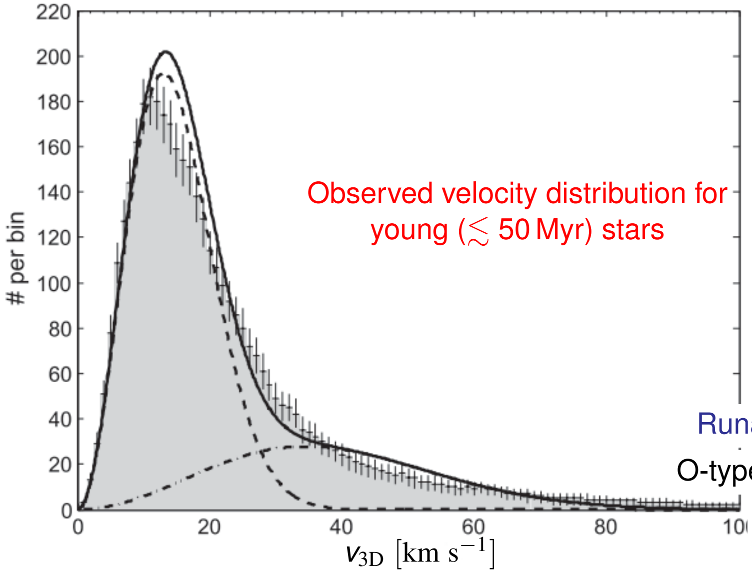
$\sim$10% of O type stars are runaways

($v \gtrsim 30\,\mathrm{km\ s^{-1}}$)

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

NASA, JPL-Caltech, Spitzer Space Telescope

What is a runaway star?



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

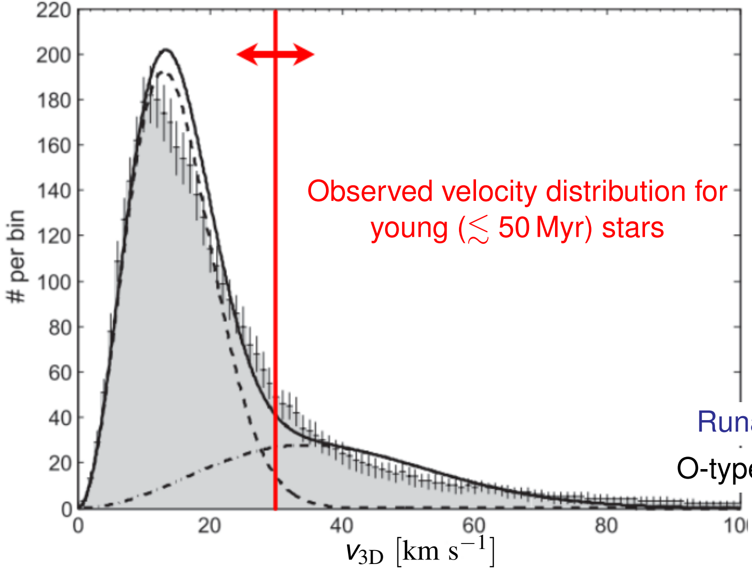
Runaway fraction

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

What is a runaway star?



Observed velocity distribution for young ($\lesssim 50\,\mathrm{Myr}$) 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

How to accelerate (massive) stars?

Dynamically ejected runaways

- Theory of N-body interactions
- Gaia DR2 reveals $\gtrsim 100\,M_{\odot}$ runaways from R136

Binary disruption

- The most common massive binary evolution path
- Velocity distribution of the “widowed” companions

Conclusions

Outline

Dynamically ejected runaways

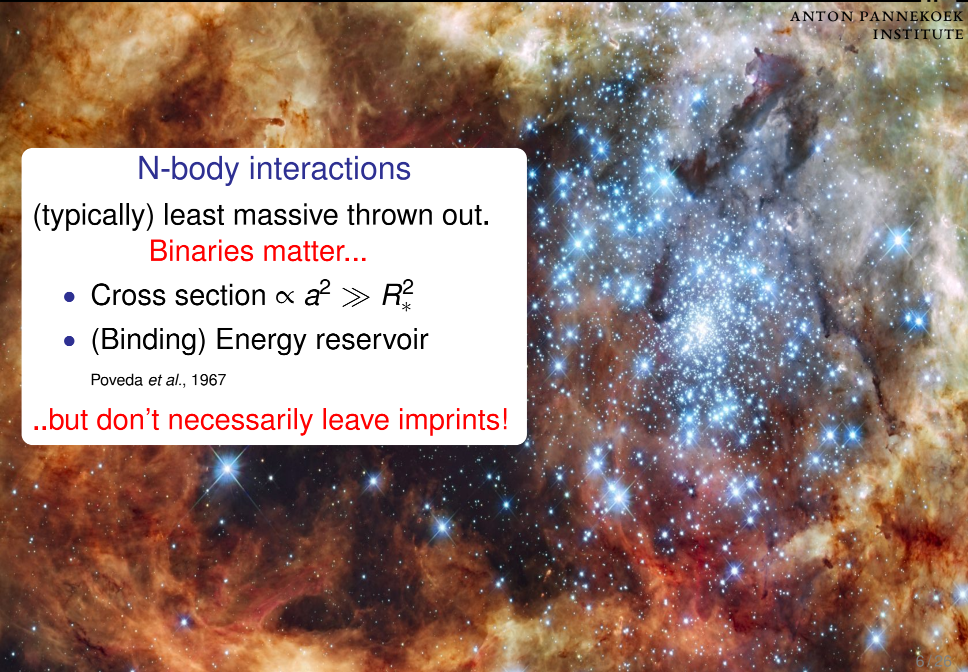
- Theory of N-body interactions
- Gaia DR2 reveals $\gtrsim 100\,M_{\odot}$ runaways from R136

Binary disruption

- The most common massive binary evolution path
- Velocity distribution of the “widowed” companions

Conclusions

Cluster ejection



N-body interactions

(typically) least massive thrown out.

Binaries matter...

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

Poveda *et al.*, 1967

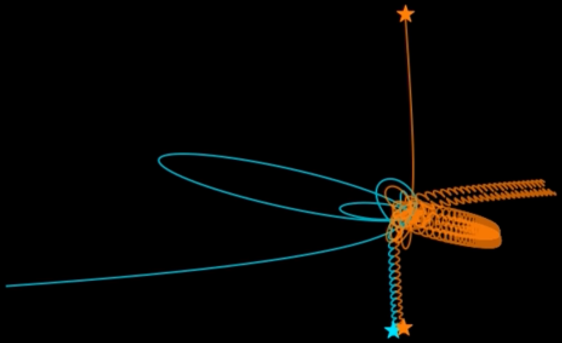
..but don't necessarily leave imprints!

Example of dynamical interaction

Credits: C. Rodriguez

Result of dynamical interaction

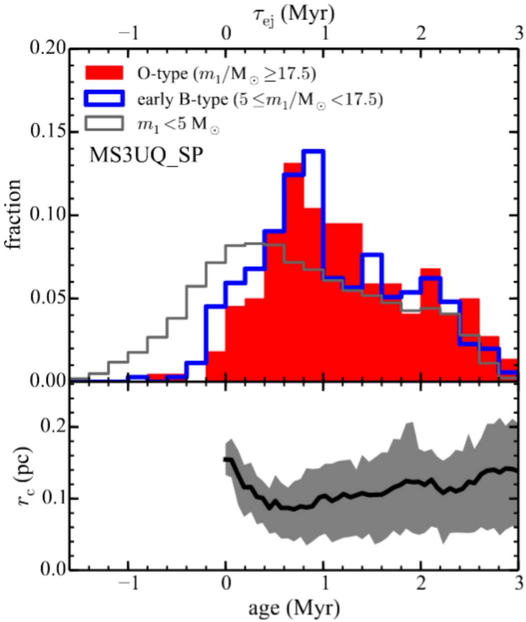
Fast runaway



Tighter and more massive binary

e.g., Fujii & Portegies-Zwart 11

Timing of ejection



Most ejections happen early
Before the first stellar
core-collapse

Chaotic Dynamics ⇒ **Very** sensitive to initial conditions

from Oh & Kroupa 16, see also, e.g., Poveda *et al.* 64, Fujii & Portegies-Zwart 11, Banerjee *et al.* 12, 14

Outline

Dynamically ejected runaways

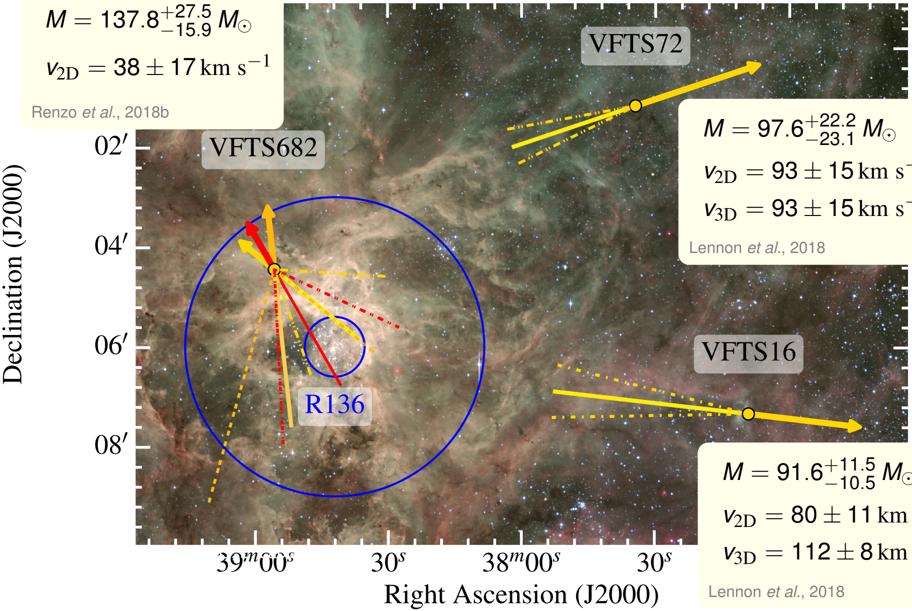
- Theory of N-body interactions
- Gaia DR2 reveals $\gtrsim 100\, M_\odot$ runaways from R136

Binary disruption

- The most common massive binary evolution path
- Velocity distribution of the “widowed” companions

Conclusions

The most massive runaways



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

$v_{2D} = 38 \pm 17\,\mathrm{km\ s^{-1}}$

Renzo *et al.*, 2018b

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

$v_{2D} = 93 \pm 15\,\mathrm{km\ s^{-1}}$

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

Lennon *et al.*, 2018

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

$v_{2D} = 80 \pm 11\,\mathrm{km\ s^{-1}}$

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

Lennon *et al.*, 2018

Lennon *et al.*, 2018, Renzo *et al.*, 2018b

Physics questions

Potential things we can learn

- **Which stars remain in the cluster/are ejected?**
  ⇒ Connection to multiple stellar populations?
- **How do clusters form?**
  ⇒ Monolithic collapse or multiple streams?
- **How does early cluster dynamics proceed?**
  ⇒ Formation of BBH progenitors?
- **Can we use stars outside the cluster to probe stellar physics in the cluster?**
  ⇒ No crowding issues
- **Efficiency of dynamical ejections**
  ⇒ What process dominates the runaway production?

Physics questions

Potential things we can learn

- **Which stars remain in the cluster/are ejected?**
  ⇒ Connection to multiple stellar populations?
- **How do clusters form?**
  ⇒ Monolithic collapse or multiple streams?
- **How does early cluster dynamics proceed?**
  ⇒ Formation of BBH progenitors?
- **Can we use stars outside the cluster to probe stellar physics in the cluster?**
  ⇒ No crowding issues
- **Efficiency of dynamical ejections**
  ⇒ What process dominates the runaway production?

Physics questions

Potential things we can learn

- **Which stars remain in the cluster/are ejected?**

  ⇒ Connection to multiple stellar populations?
- **How do clusters form?**

  ⇒ Monolithic collapse or multiple streams?
- **How does early cluster dynamics proceed?**

  ⇒ Formation of BBH progenitors?
- **Can we use stars outside the cluster to probe stellar physics in the cluster?**

  ⇒ No crowding issues
- **Efficiency of dynamical ejections**

  ⇒ What process dominates the runaway production?

Physics questions

Potential things we can learn

- **Which stars remain in the cluster/are ejected?**
  $\Rightarrow$ Connection to multiple stellar populations?
- **How do clusters form?**
  $\Rightarrow$ Monolithic collapse or multiple streams?
- **How does early cluster dynamics proceed?**
  $\Rightarrow$ Formation of BBH progenitors?
- **Can we use stars outside the cluster to probe stellar physics in the cluster?**
  $\Rightarrow$ No crowding issues
- **Efficiency of dynamical ejections**
  $\Rightarrow$ What process dominates the runaway production?

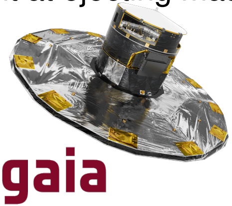
Physics questions

Potential things we can learn

- **Which stars remain in the cluster/are ejected?**
  ⇒ Connection to multiple stellar populations?
- **How do clusters form?**
  ⇒ Monolithic collapse or multiple streams?
- **How does early cluster dynamics proceed?**
  ⇒ Formation of BBH progenitors?
- **Can we use stars outside the cluster to probe stellar physics in the cluster?**
  ⇒ No crowding issues
- **Efficiency of dynamical ejections**
  ⇒ What process dominates the runaway production?

Hints from DR2...

Dynamical ejection seems very efficient at ejecting massive stars



Drew *et al.* 18, Renzo *et al.* 18b, Lennon *et al.* 18

How to accelerate (massive) stars?

Dynamically ejected runaways

- Theory of N-body interactions
- Gaia DR2 reveals $\gtrsim 100\,M_\odot$ runaways from R136

Binary disruption

- The most common massive binary evolution path
- Velocity distribution of the “widowed” companions

Conclusions

Outline

Dynamically ejected runaways

- Theory of N-body interactions
- Gaia DR2 reveals $\gtrsim 100\,M_\odot$ runaways from R136

Binary disruption

- The most common massive binary evolution path
- Velocity distribution of the “widowed” companions

Conclusions

Binary disruption

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

Spin up, pollution, and rejuvenation

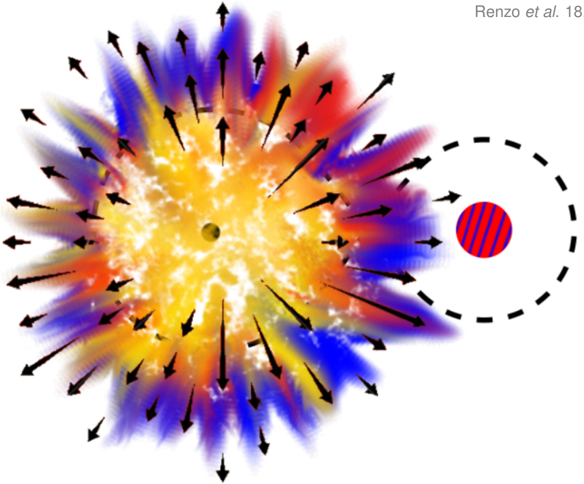
The binary disruption shoots out the accretor

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 massive 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

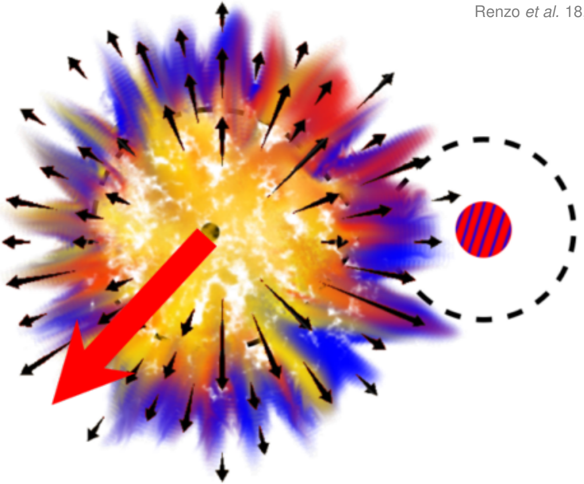
  (e.g., Shklovskii ’70, Janka ’16)

$$v_{\mathrm{dis}} \simeq v_{2,\mathrm{orb}}^{\mathrm{pre-SN}} = \frac{M_1}{M_1+M2}\sqrt{\frac{G(M_1+M2)}{a}}$$

What exactly disrupts the binary?

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

$$v_{\mathrm{dis}} \simeq v_{2,\mathrm{orb}}^{\mathrm{pre-SN}} = \frac{M_1}{M_1+M2}\sqrt{\frac{G(M_1+M2)}{a}}$$

Outline

Dynamically ejected runaways

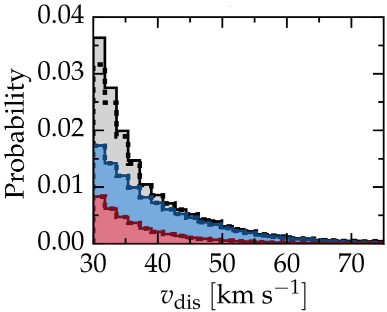
- Theory of N-body interactions
- Gaia DR2 reveals $\gtrsim 100\,M_\odot$ runaways from R136

Binary disruption

- The most common massive binary evolution path
- Velocity distribution of the “widowed” companions

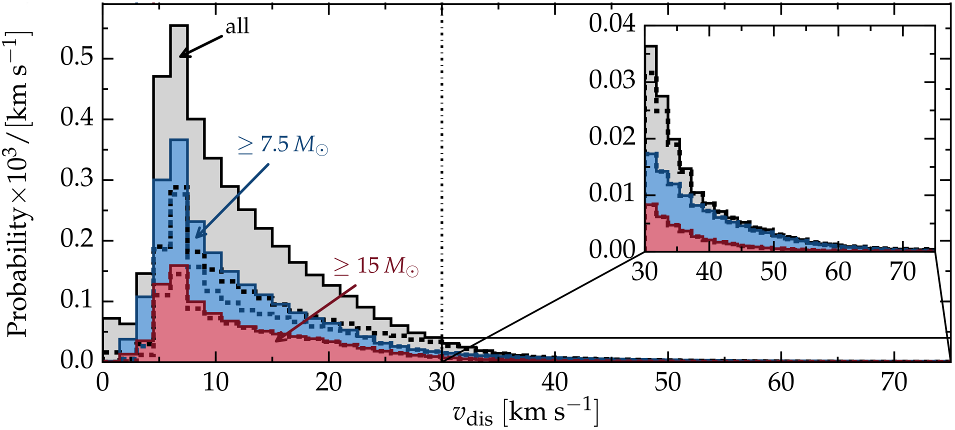
Conclusions

Velocity distribution: Runaways



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

Velocity distribution: Walkaways

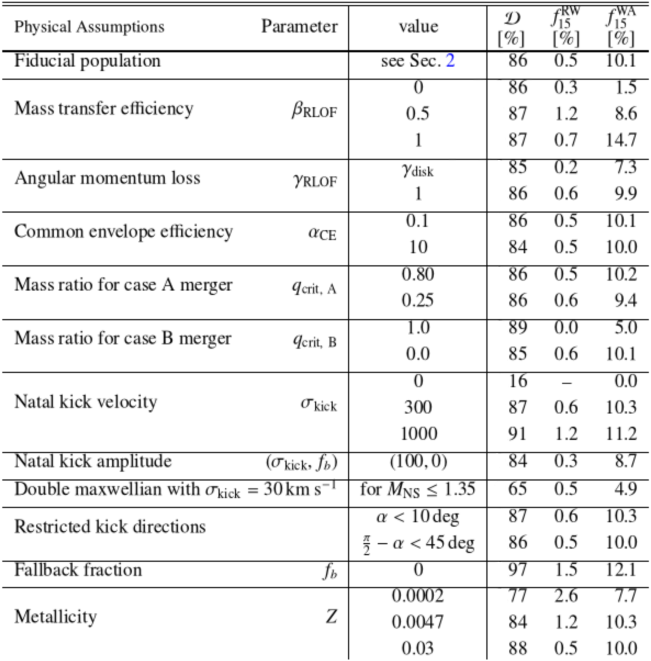


Take home points:

- 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

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

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
		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
(more runaways
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

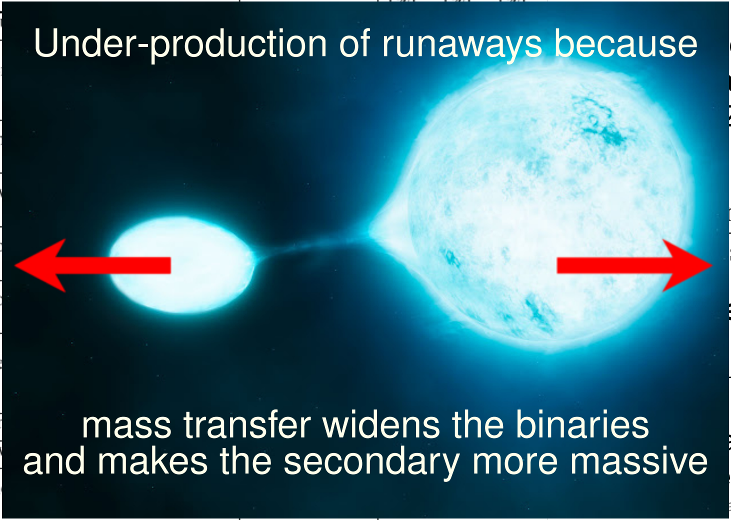
Hoogerwerf *et al.* '01

(but see also Jilinski *et al.* '10)

Renzo *et al.*, arXiv:1804.09164

Runaway fraction for O-type too low!

Physical Assumptions	Parameter	value	$\mathcal{D}$ [%]	f_{15}^{RW} [%]	f_{15}^{WA} [%]
Fiducial pop					
Mass transfe					
Angular mon					
Common env					
Mass ratio fo					
Mass ratio fo					
Natal kick ve					
Natal kick ar					
Double maxw					
Restricted ki					
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



Under-production of runaways because

mass transfer widens the binaries
and makes the secondary more massive

come
aways
Z)

naways
stars

ed:

- 20%

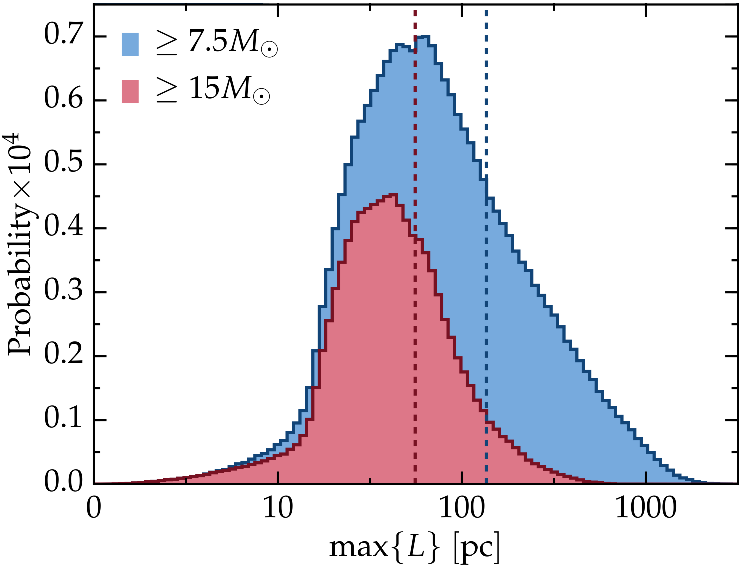
ays from
s

al. '01

(but see also Jilinski *et al.* '10)

Renzo *et al.*, arXiv:1804.09164

How far do they get?



“Distance traveled”

(No potential well)

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

Outline

Dynamically ejected runaways

- Theory of N-body interactions
- Gaia DR2 reveals $\gtrsim 100\,M_\odot$ runaways from R136

Binary disruption

- The most common massive binary evolution path
- Velocity distribution of the “widowed” companions

Conclusions

Summary of ejection mechanisms

Dynamical Interactions

- Happen early on, before SNe
- Can produce faster stars
- (Typically) least massive thrown out

...Binaries are still important! but might not leave signature

Binary SN disruption

- 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)

Take home points

Dynamical ejections

- Produce on average faster runaways
- Gaia DR2 hints at large efficiency of dynamical ejections
- Isolated star formation not required for VFTS16/72/682

  ⇒ Massive binary formed? Could evolve to binary BH?
- R136 extremely active in ejecting stars in its first 2 Myr

  ⇒ Implications for cluster formation?

Binary Disruption

- The vast majority of binaries are disrupted

  ⇒ X-ray binaries and GW sources are exceptions
- Over-produces “Walkaways”

  ⇒ Most runaways from dynamical ejections?

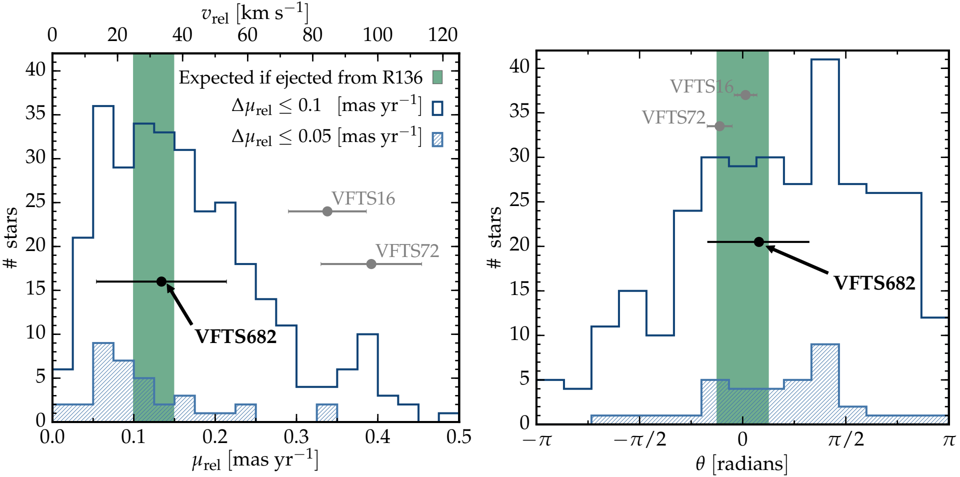
  ⇒ Biased pre-*Gaia* samples?
- Binarity leaves imprint on the ejected star
- Can be used to constrain BH kicks (statistically)

Outline

Backup slides

VFTS682: Concordant Picture?

ANTON PANNEKOEK
INSTITUTE

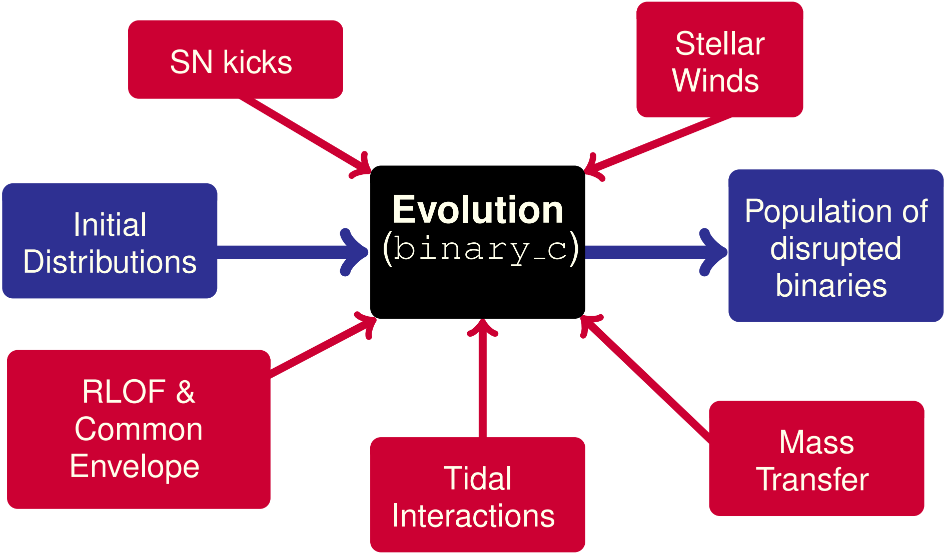


Large error bars compatible with no motion, but
best values fit with expectations for dynamical ejection

Renzo *et al.*, 2018b

Method: Population Synthesis

Fast ⇒ Allows statistical tests of the inputs & assumptions



SN kicks

Stellar Winds

Initial Distributions

Evolution (`binary_c`)

Population of disrupted binaries

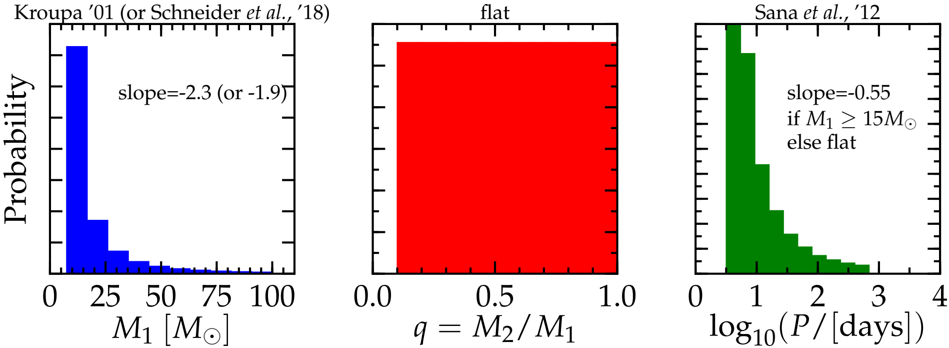
RLOF & Common Envelope

Tidal Interactions

Mass Transfer

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

Initial Distributions



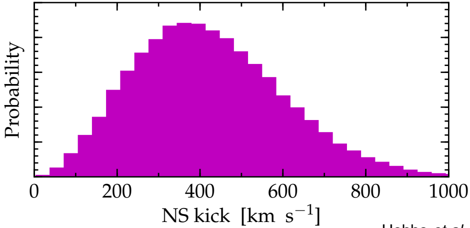
Kroupa ’01 (or Schneider *et al.*, ’18)

flat

Sana *et al.*, ’12

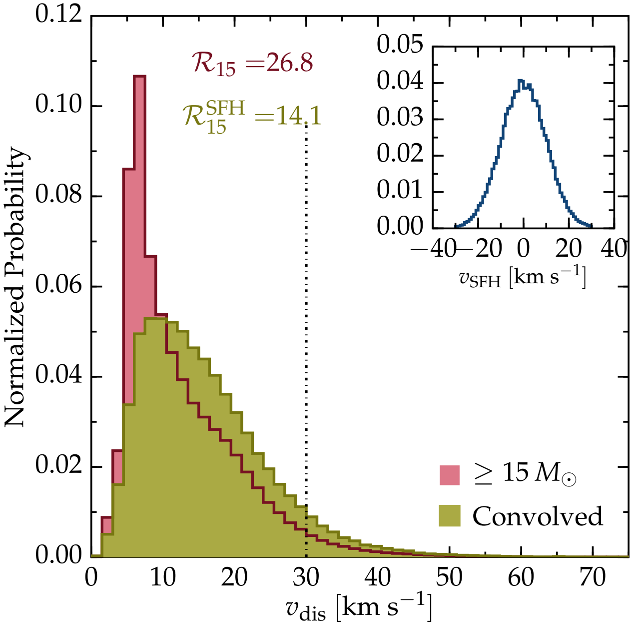
Maxwellian $\sigma_{v_{\mathrm{kick}}} = 265\,\mathrm{km\ s^{-1}}$ + Fallback rescaling

(from Fryer *et al.* ’12)



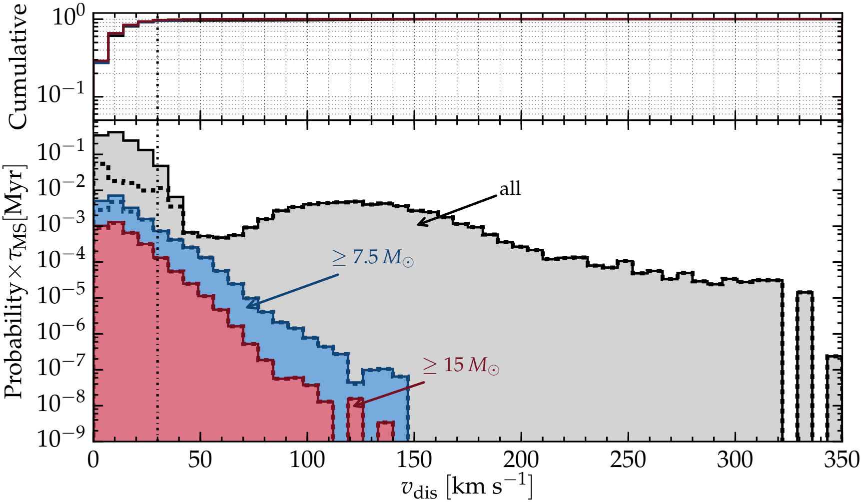
Hobbs *et al.* ’05

Star forming region velocity dispersion



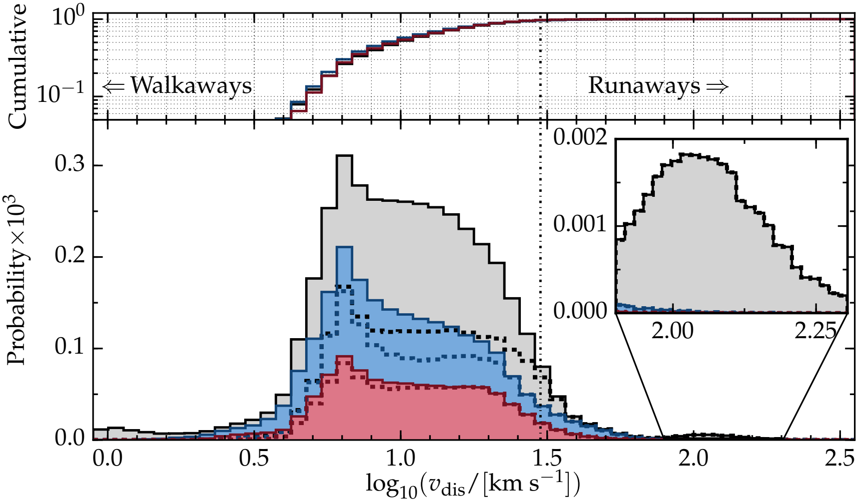
Renzo *et al.*, submitted, arXiv:1804.09164

Velocity distribution with lifetimes



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

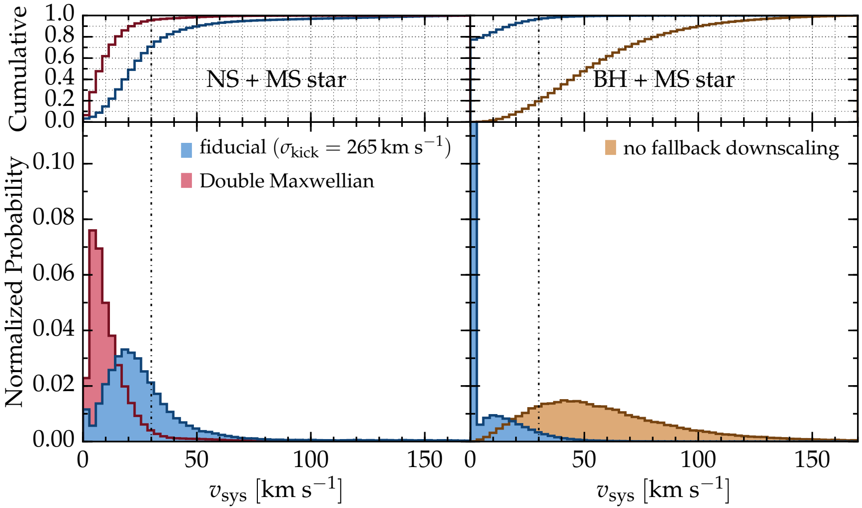
Velocity distribution log-scale



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

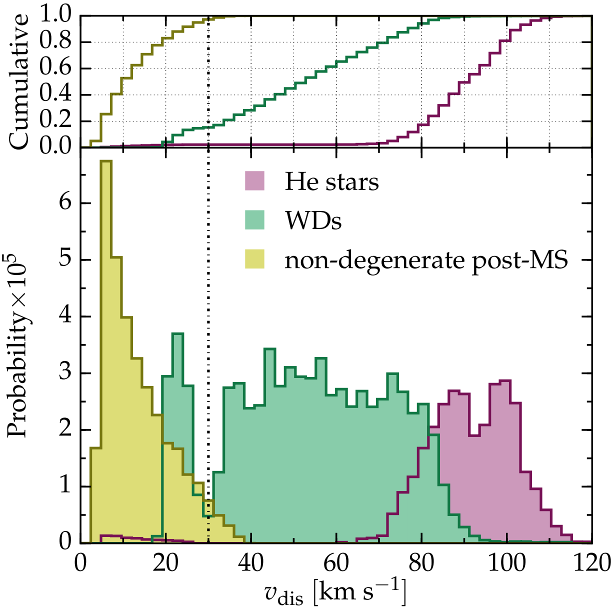
Velocity distribution bound binaries

ANTON PANNEKOEK
INSTITUTE



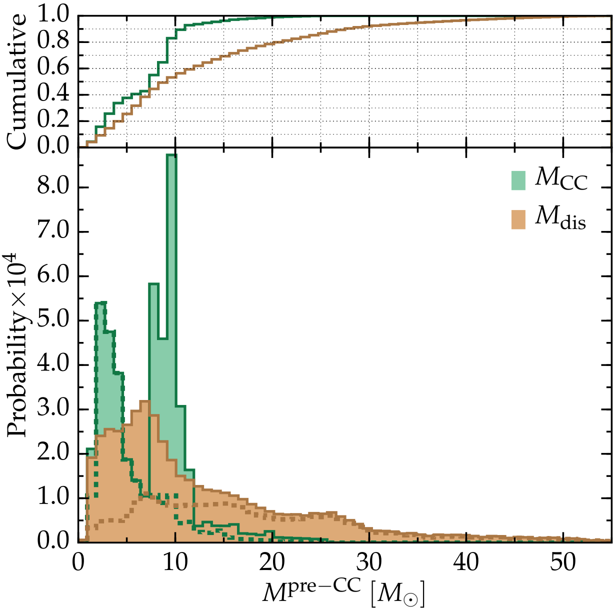
Renzo *et al.*, submitted, arXiv:1804.09164

Velocity post-main sequence stars



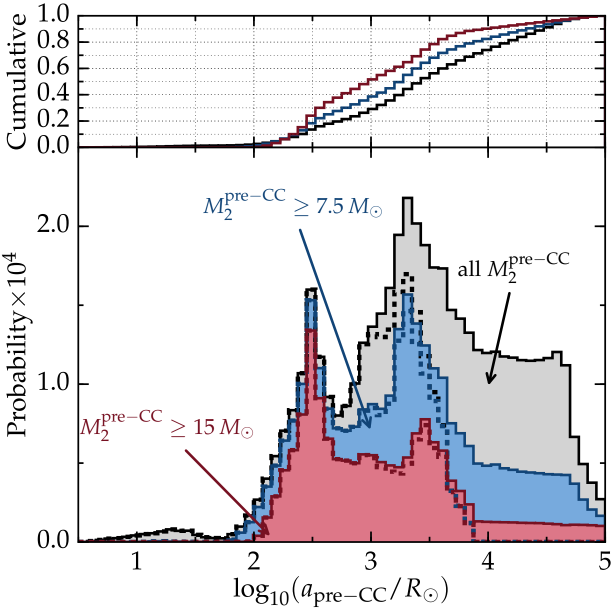
Renzo *et al.*, submitted, arXiv:1804.09164

pre-CC mass distribution



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

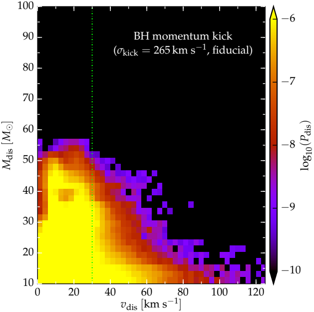
pre-CC separation distribution



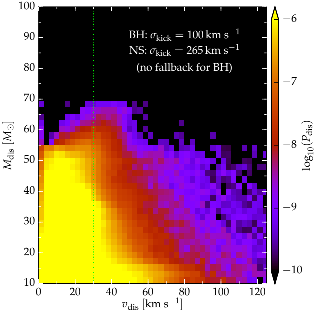
Renzo *et al.*, submitted, arXiv:1804.09164

Mass-velocity varying the natal kick

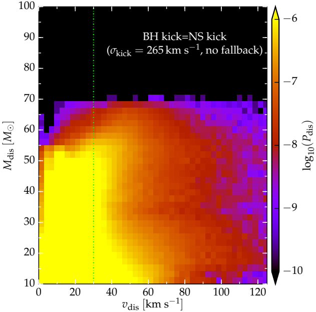
Fiducial
$\sigma_{\mathrm{kick}} = 265\,\mathrm{km\ s^{-1}}$



Intermediate BH kick
$\sigma_{\mathrm{kick}} = 100\,\mathrm{km\ s^{-1}}$



Large BH kicks
(no fallback)

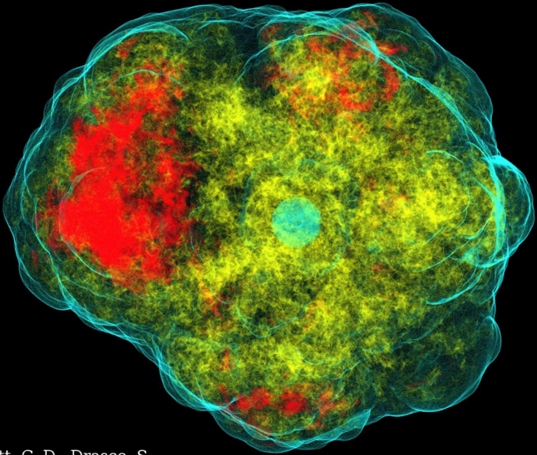


Renzo *et al.*, submitted, arXiv:1804.09164

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.

(potential) Physics lessons...

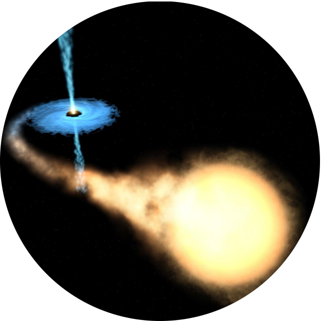
...from disrupted binaries

- BH kicks
- Binary evolution

Do BH receive natal kicks?

Spatial distribution of X-ray binaries

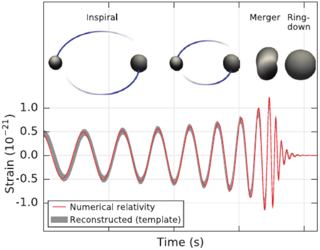
(e.g., Repetto *et al.* '12,'15,'16, Mandel '16)



Massive (and WR) runaways

(Dray *et al.* '05)

Disrupted binaries are "failed" GW sources!



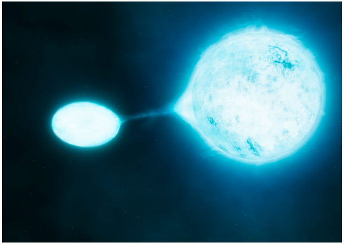
(potential) Physics lessons...

...from disrupted binaries

- BH kicks
- Binary evolution

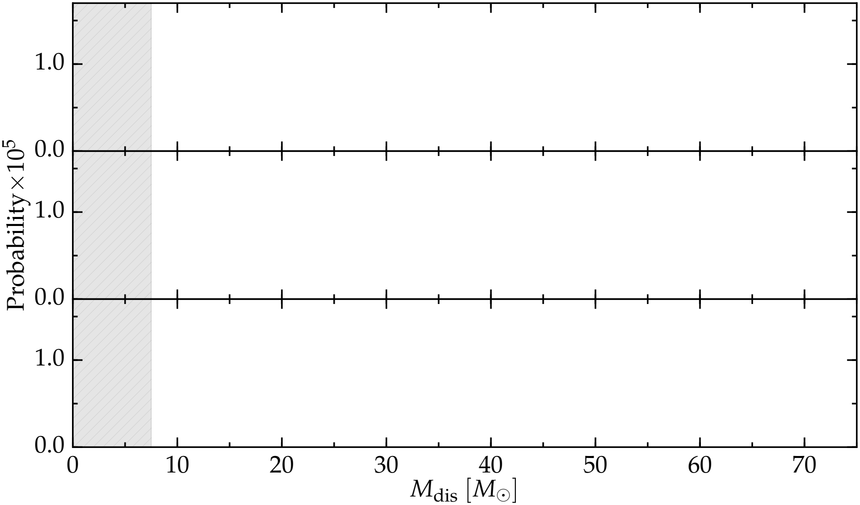
Constraints on binary physics

- Orbital evolution ⇔ pre-SN period
- Mass transfer efficiency ⇔ pre-SN M_2
- Angular momentum loss ⇔ isotropic re-emission, circumbinary disk, etc.



A way to constrain BH kicks with Gaia

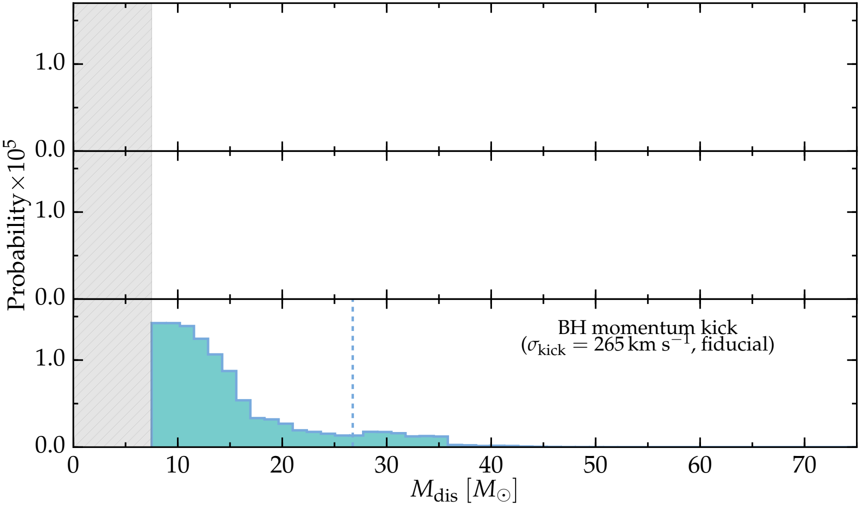
Massive runaways mass function ($v \geq 30\,\mathrm{km\ s^{-1}}$, $M \geq 7.5\,M_\odot$)



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

A way to constrain BH kicks with Gaia

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

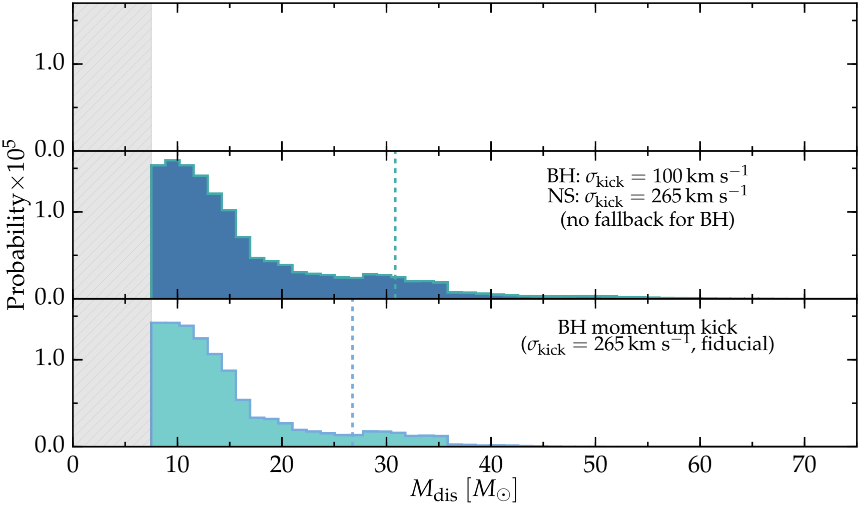


Renzo *et al.*, submitted, arXiv:1804.09164

A way to constrain BH kicks with Gaia

ANTON PANNEKOEK
INSTITUTE

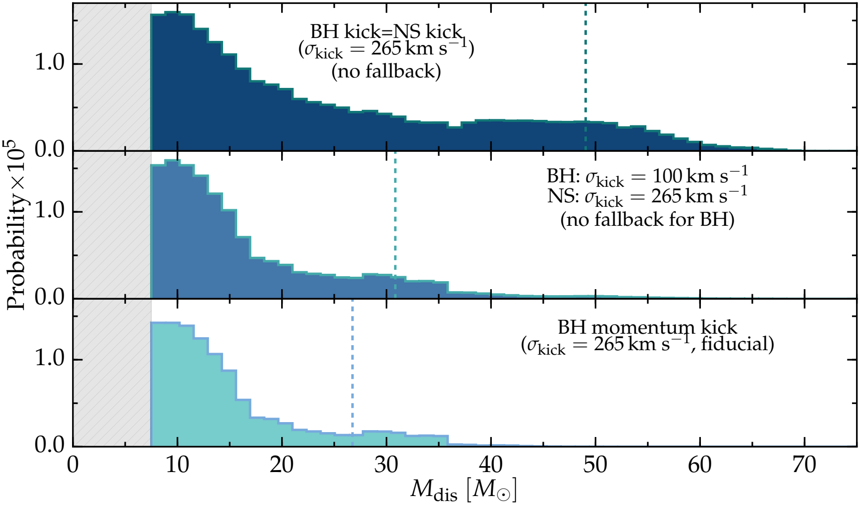
Massive runaways mass function ($v \geq 30\,\mathrm{km\ s^{-1}}$, $M \geq 7.5\,M_\odot$)



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

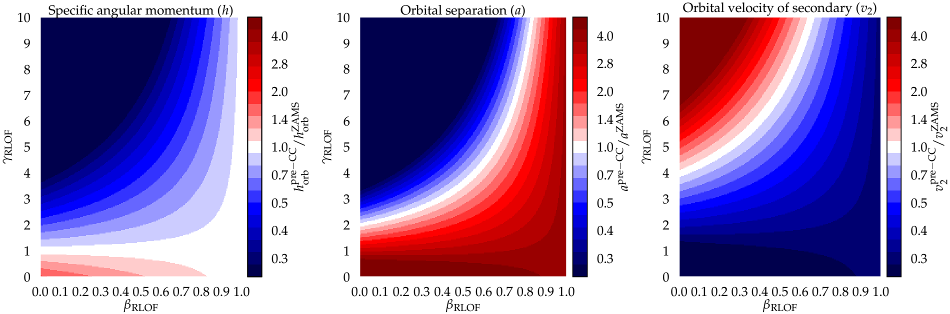
A way to constrain BH kicks with Gaia

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



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

Analytic calculations of orbital evolution



Assuming constant β_{RLOF}, γ_{RLOF}:

$$\beta_{\mathrm{RLOF}} \overset{\mathrm{def}}{=} \dot{M}_{\mathrm{acc}} / \dot{M}_{\mathrm{don}}$$
$$h \overset{\mathrm{def}}{=} \gamma_{\mathrm{RLOF}} \frac{J_{\mathrm{orb}}}{M_1+M_2}$$

In fiducial simulation β_{RLOF} depends on τ_{KH} of accretor

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