Massive runaway stars:

probes for stellar physics and dynamics

NASA, JPL-Caltech, Spitzer Space Telescope

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Collaborators:

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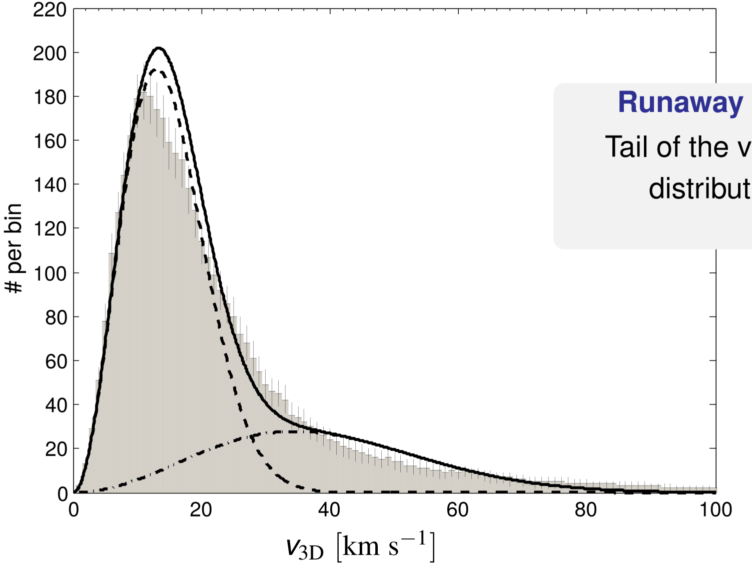
What is a runaway star?



Runaway stars

Tail of the velocity distribution

Blaauw 61

Hipparcos velocity distribution for young ($\lesssim$ 50 Myr) stars, Tetzlaff *et al.* 11,

see also Zwicky 57, Blaauw, 93, Gies & Bolton 86, Leonard 91, Renzo *et al.* 19a, 19b

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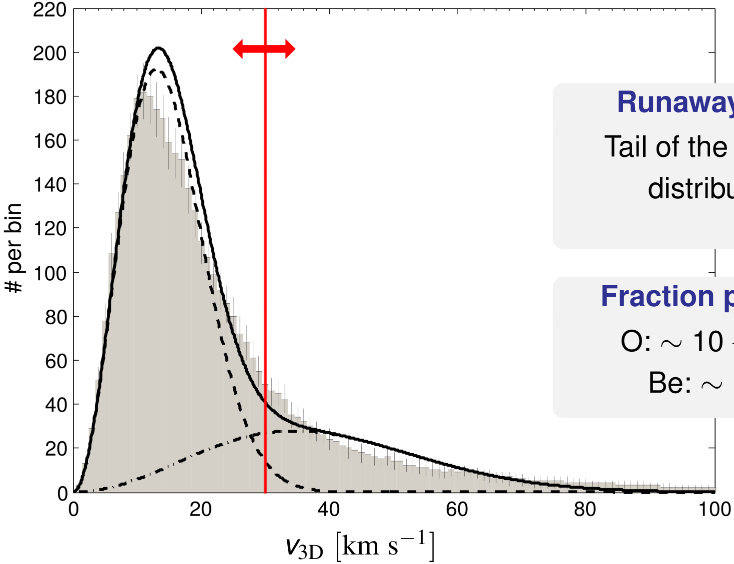


Runaway stars

Tail of the velocity distribution

Blaauw 61

Fraction per type

O: $\sim 10-20\%$

Be: $\sim 13\%$

Hipparcos velocity distribution for young ($\lesssim$ 50 Myr) stars, Tetzlaff *et al.* 11,

see also Zwicky 57, Blaauw, 93, Gies & Bolton 86, Leonard 91, Renzo *et al.* 19a, 19b

Two ways to produce fast massive stars

Binary supernova disruption

Dynamical ejection from cluster

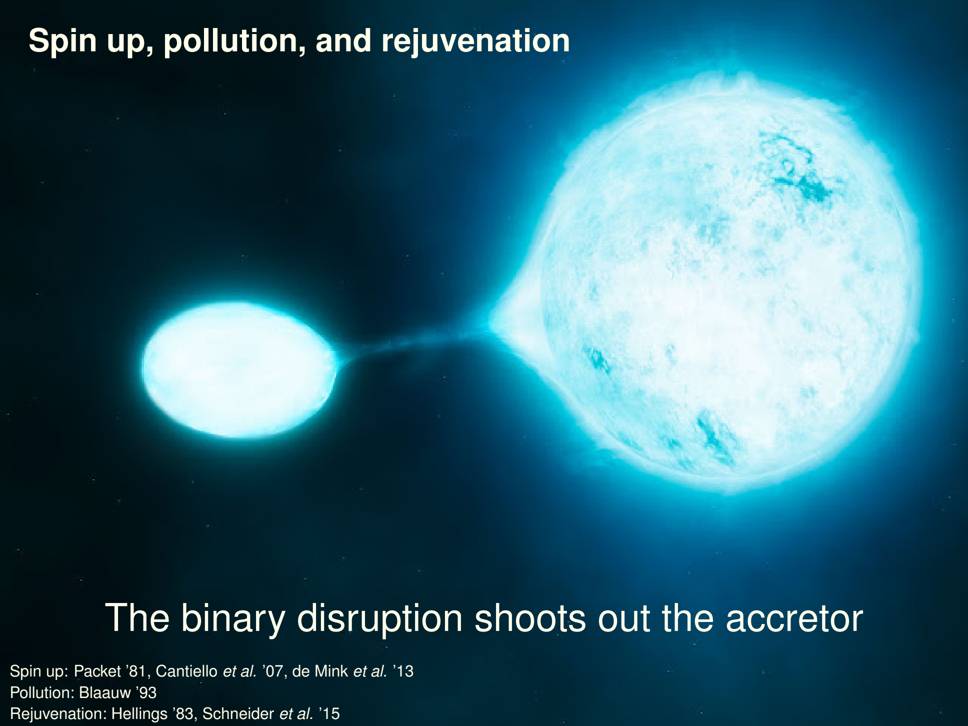
Massive runaway origins ...

... is there a problem ?

Most common massive binary evolution

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

Spin up, pollution, and rejuvenation

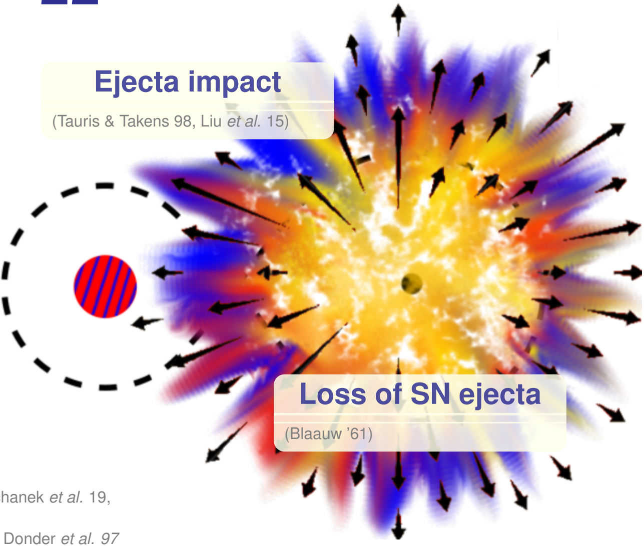


The binary disruption shoots out the accretor

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?

$86^{+11}_{-22}\%$ of massive binaries are disrupted



Ejecta impact

(Tauris & Takens 98, Liu *et al.* 15)

Loss of SN ejecta

(Blaauw '61)

Renzo *et al.* 19b, Kochanek *et al.* 19,

Eldridge *et al.* 11, De Donder *et al. 97*

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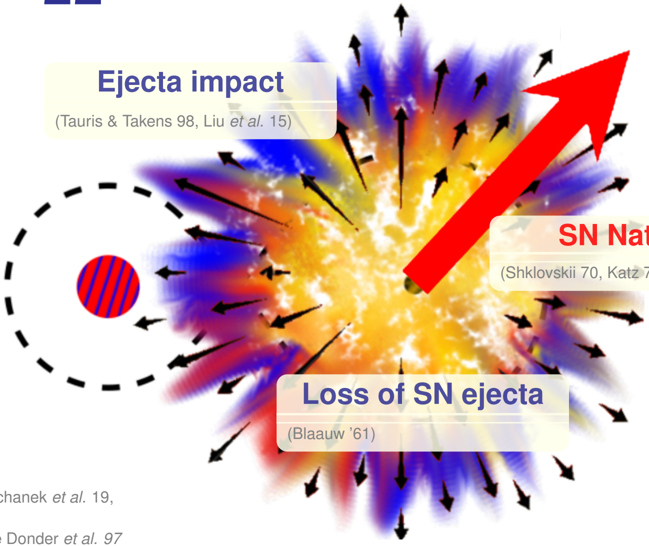


Ejecta impact

(Tauris & Takens 98, Liu *et al.* 15)

SN Natal kick

(Shklovskii 70, Katz 75, Janka 13, 17)

Loss of SN ejecta

(Blaauw '61)

Renzo *et al.* 19b, Kochanek *et al.* 19,

Eldridge *et al.* 11, De Donder *et al. 97*

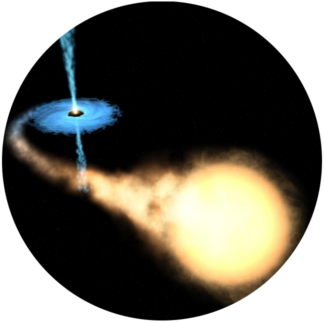
Do BHs receive kicks ?

NO

⇒ most remain together with their widowed companion

YES

⇒ most are single and we can’t see them...



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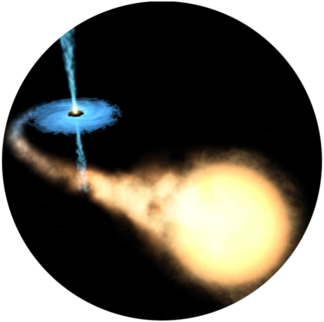
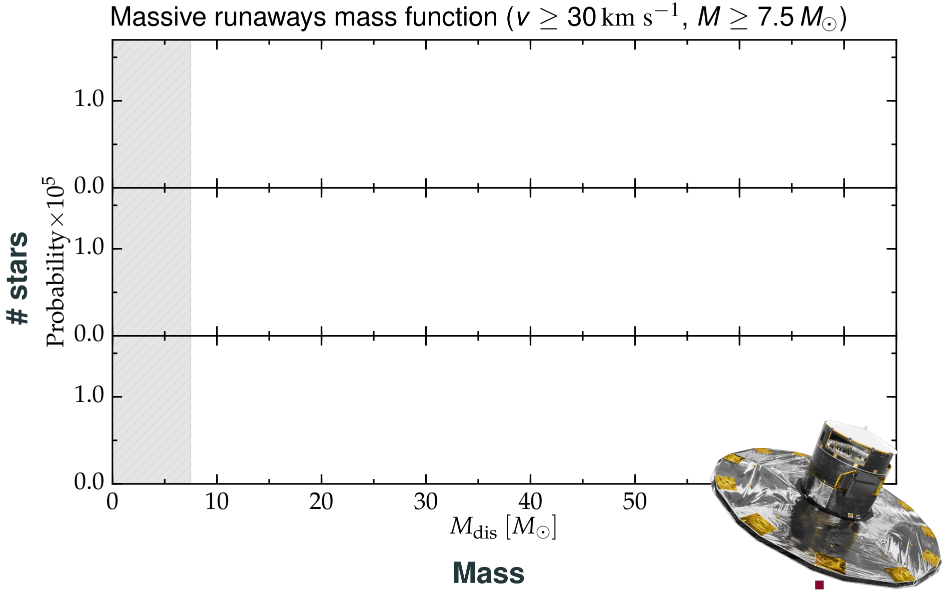


YES

⇒ most are single and we can't see them...

...but we can see the "widowed" companions

A way to constrain BH kicks with Gaia



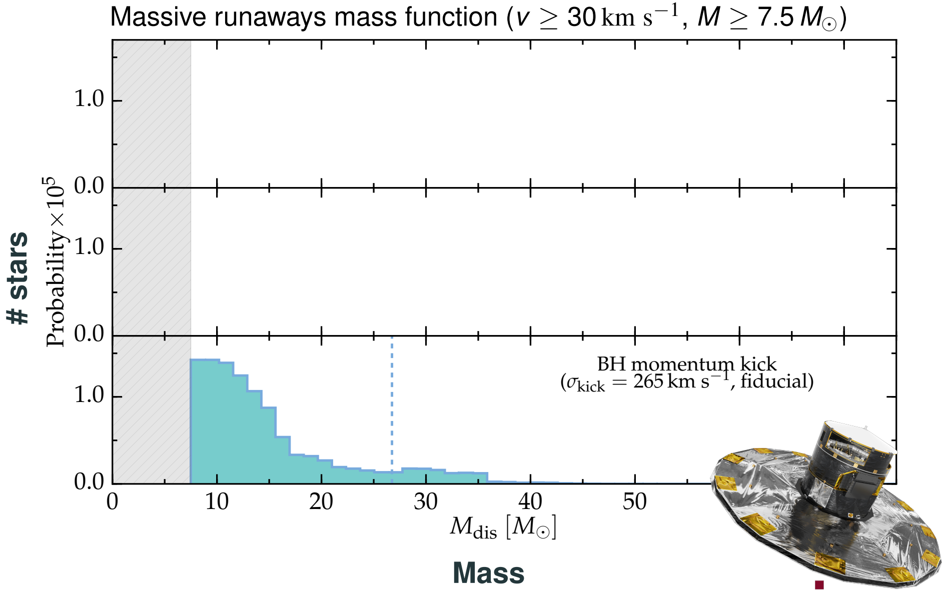
Numerical results publicly available at:

http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

Renzo *et al.* 19b

gaia

A way to constrain BH kicks with Gaia



Mass

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Renzo *et al.* 19b

gaia

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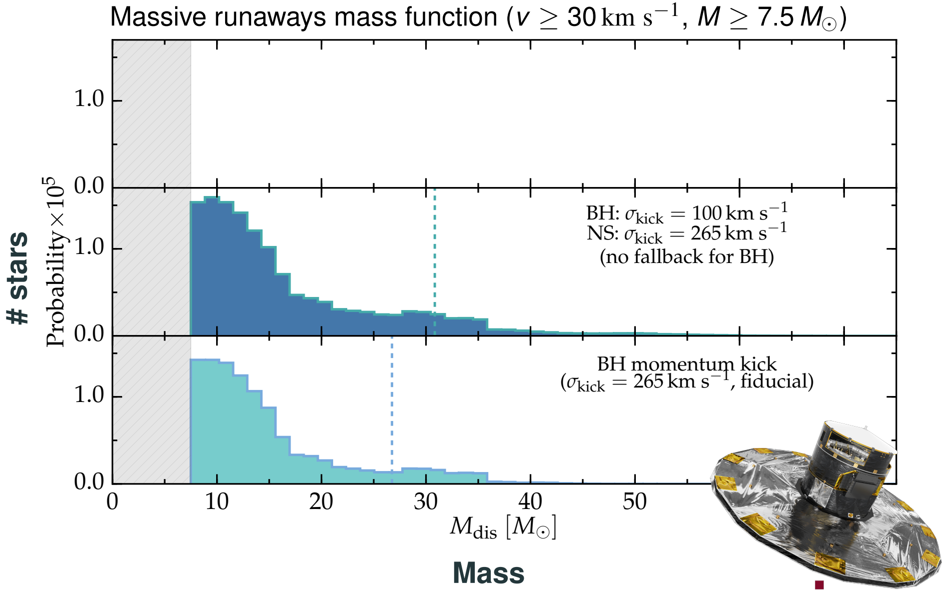

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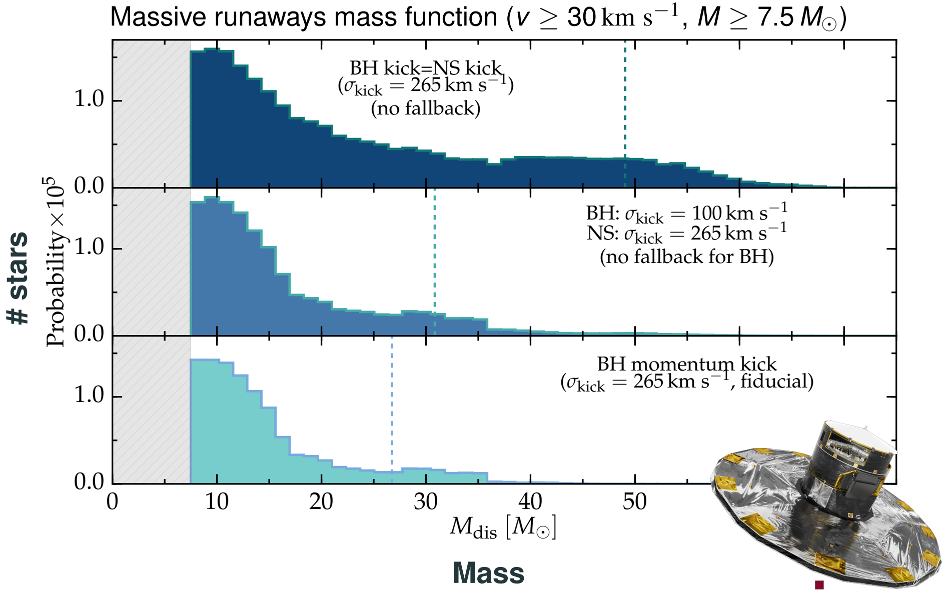

Massive runaways mass function ($v \geq 30\,\mathrm{km\,s^{-1}}$, $M \geq 7.5\,M_\odot$)

Numerical results publicly available at:

Renzo *et al.* 19b

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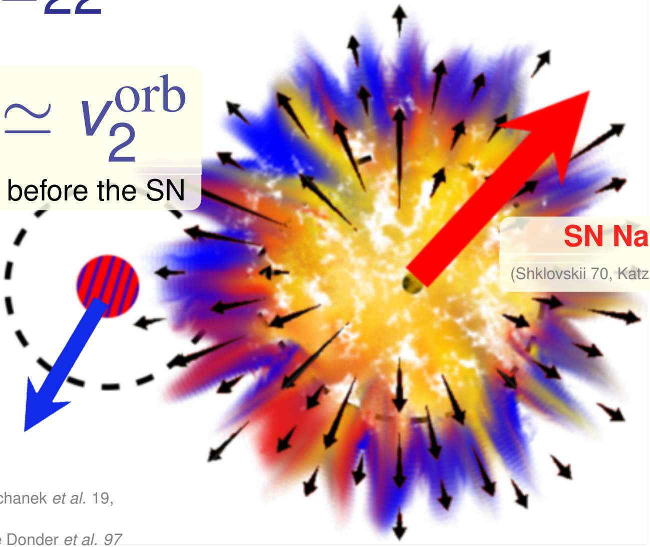
Kicks do not change companion velocity

$86^{+11}_{-22}\%$ of massive binaries are disrupted



$$v_{\mathrm{dis}} \simeq v_2^{\mathrm{orb}}$$

before the SN

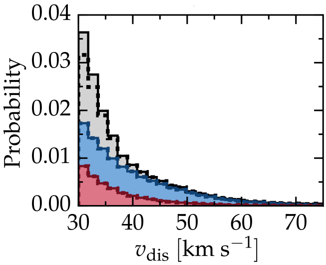
SN Natal kick

(Shklovskii 70, Katz 75, Janka 13, 17)

Renzo *et al.* 19b, Kochanek *et al.* 19,

Eldridge *et al.* 11, De Donder *et al.* 97

Velocity distribution: Runaways



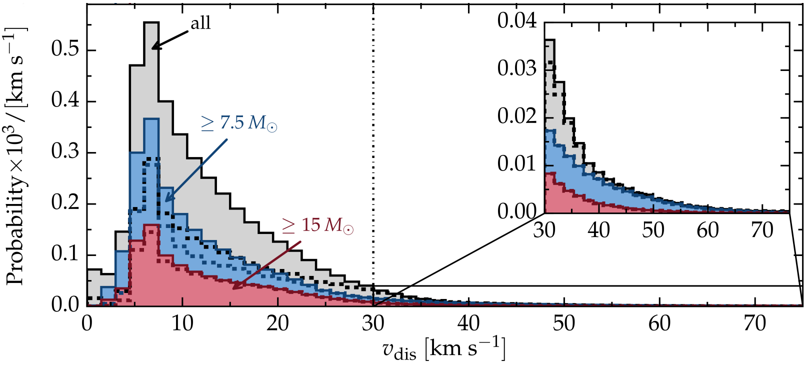
Velocity respect to the pre-explosion binary center of mass

Numerical results publicly available at:

http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

Renzo *et al.* 19b

Velocity distribution: Walkaways



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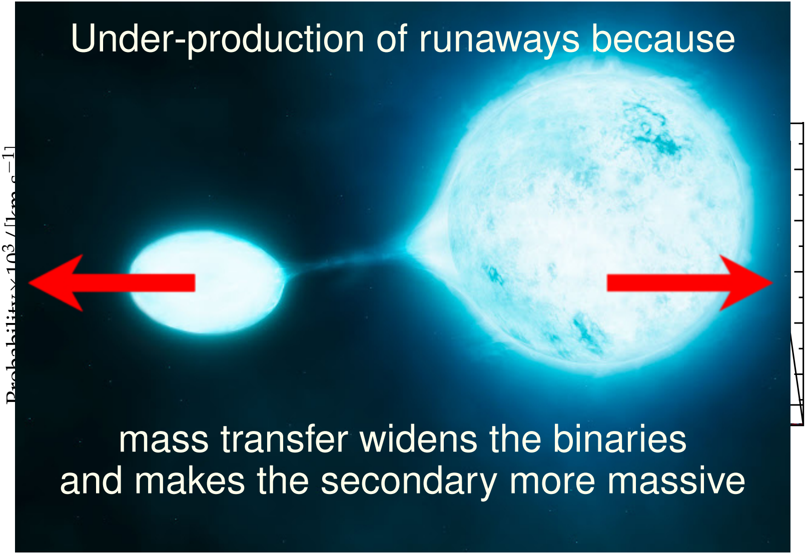

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Renzo *et al.* 19b

Summary of ejection mechanisms

Binary SN disruption

- Ejects initially less massive star
- Requires SN kick
- Final $v \simeq v_2^{\mathrm{orb}}$
- Most binaries are disrupted
- Leaves binary signature

  fast rotation, He/N enrichment,

  lower apparent age

Outline

Binary supernova disruption

Dynamical ejection from cluster

Massive runaway origins ...

... is there a problem ?

Dynamical ejection from cluster

N-body interactions

(typically) least massive thrown out.

Binaries matter...

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

Poveda *et al.* 67

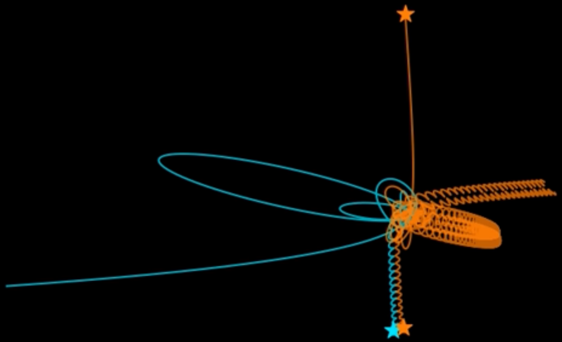
...but don't necessarily leave imprints!

Credits: C. Rodriguez

Typical outcome of dynamical interactions

Fast runaway

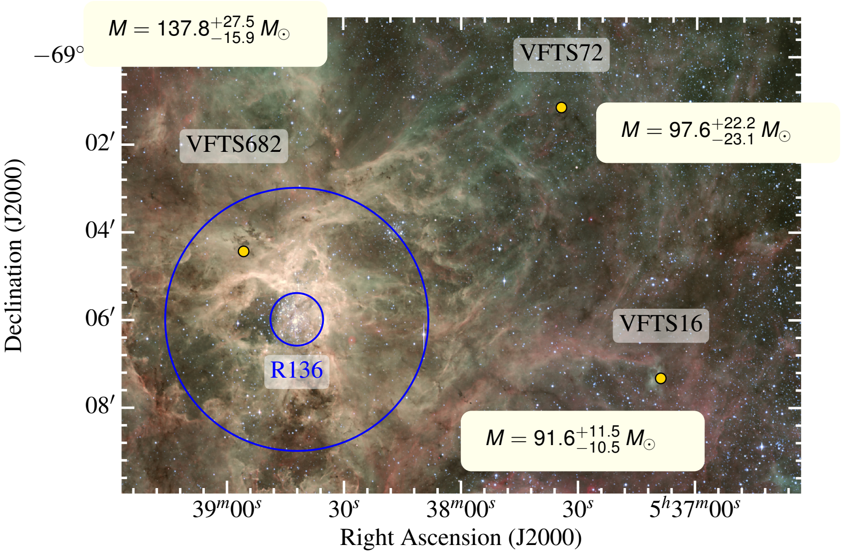
(the least massive of the three)



Tighter and more massive binary

e.g., Fujii & Portegies-Zwart 11

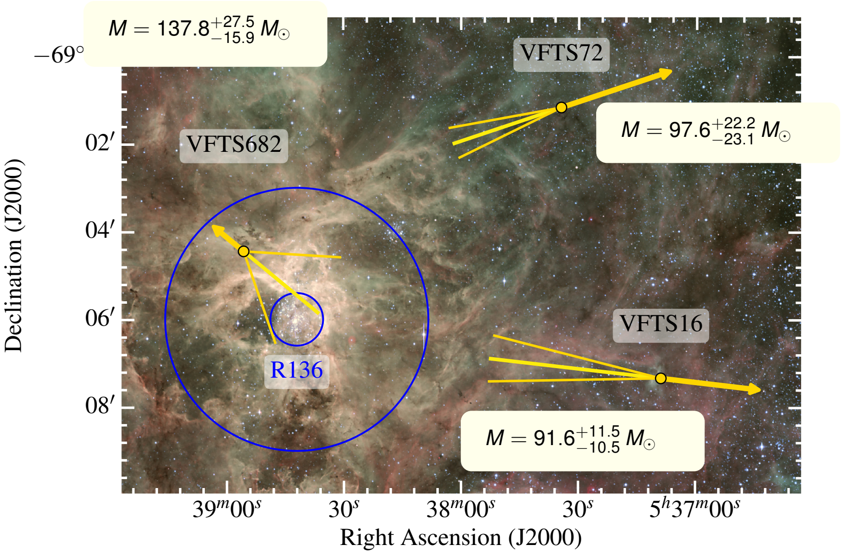
The most massive runaways known



Renzo *et al.* 19a

Lennon *et al.* (incl. MR), 18

The most massive runaways known



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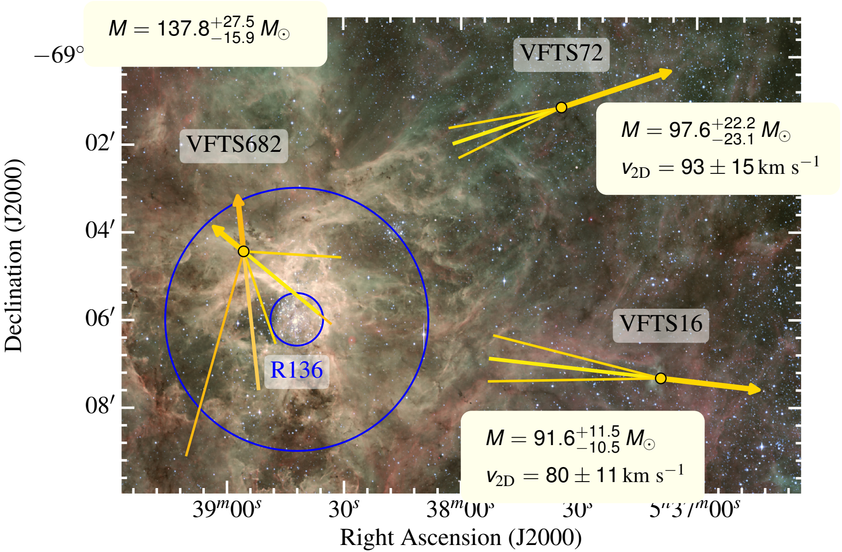

$M = 137.8^{+27.5}_{-15.9}\,M_\odot$

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

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

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

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

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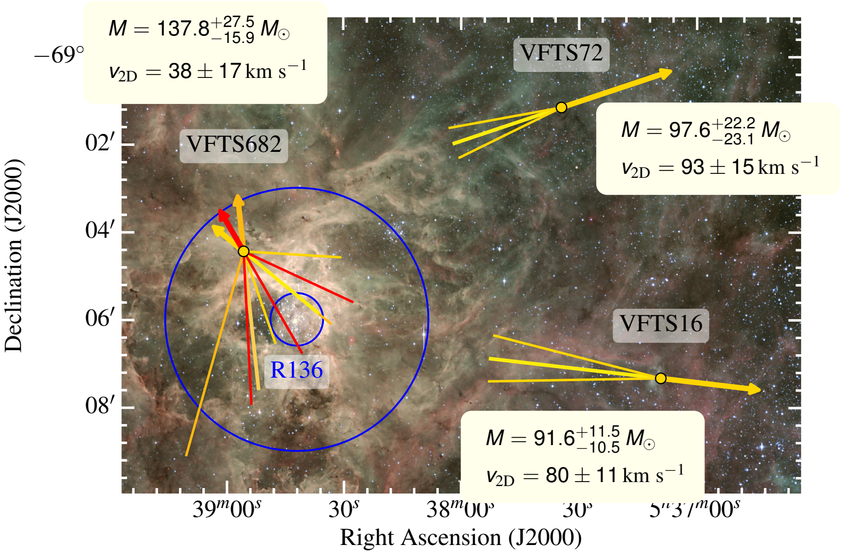

$M = 137.8^{+27.5}_{-15.9}\,M_\odot$

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

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

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

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Known ejection mechanisms

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fast rotation, He/N enrichment, lower apparent age

Cluster ejections

- Happen early on, before SNe
- Can produce faster stars
- Least massive thrown out
- *Gaia* hint: high efficiency dynamical ejection

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

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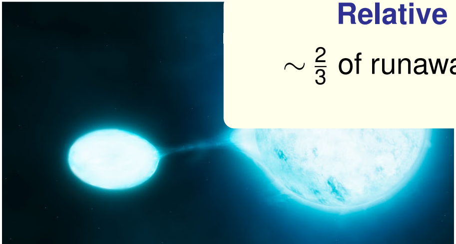
Relative efficiency ?

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

Hoogerwerf *et al.* 01



O type stars runaway fraction

$$\frac{\#\ \mathrm{runaways}}{\#\ \mathrm{all\ stars}} \simeq$$

Observational claims: (regardless of origin)

$\sim$ 10%

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

Hoogerwerf *et al.* 01

Theoretical consensus from binaries:

$0.5^{+2.1}_{-0.5}\%$

Renzo *et al.* 19b, De Donder *et al.* 97, Eldridge *et al.* 11, Kochanek *et al.* 19

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$$\frac{\#\ \text{runaways}}{\#\ \text{all stars}} \simeq$$

Observational claims: (regardless of origin)

$$\sim\ 10\%$$

~~$\sim$? binaries~~

Jilinski *et al.* 10

~~Hoogerwerf *et al.* 01~~

Theoretical consensus from binaries:

$$0.5^{+2.1}_{-0.5}\%$$

Renzo *et al.* 19b, De Donder *et al.* 97, Eldridge *et al.* 11, Kochanek *et al.* 19

Is it *really* a problem?

- **Frame of reference to measure *v***
- Biases in favor of runaways
- *Gaia* hint: high efficiency dynamical ejection
- Binary prediction sensitive to SFH

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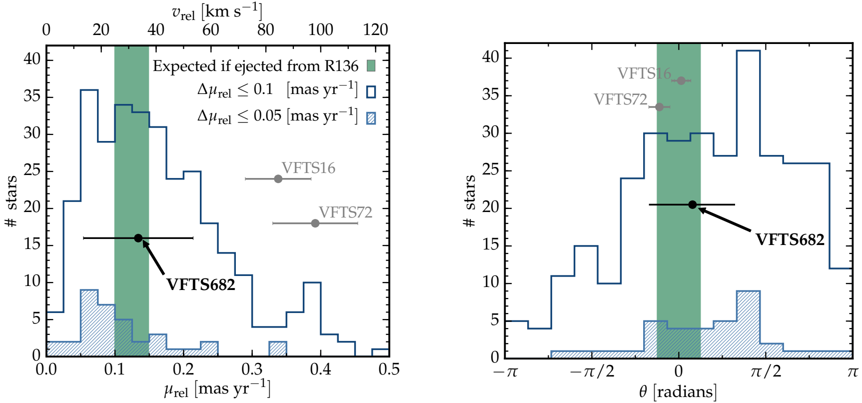
Backup slides

VFTS682: Concordant Picture?



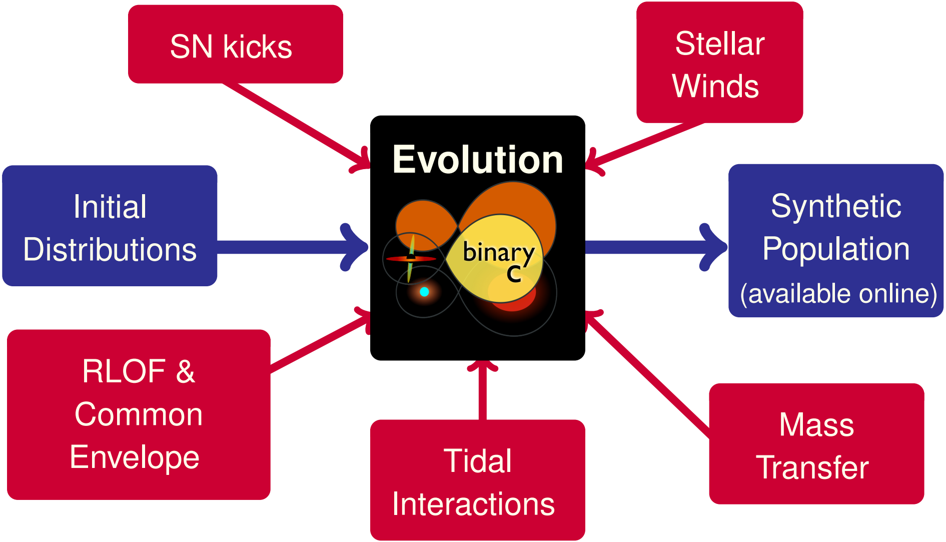
Large error bars compatible with no motion, but

best values fit with expectations for dynamical ejection

Renzo *et al.* 19a

Methods: Population Synthesis

Fast ⇒ Allows statistical tests of the inputs & assumptions



SN kicks

Stellar Winds

Initial Distributions

Evolution

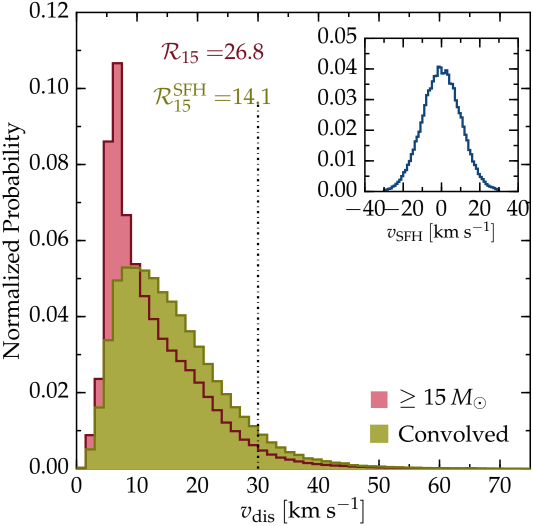
Synthetic Population (available online)

RLOF & Common Envelope

Tidal Interactions

Mass Transfer

Star forming region velocity dispersion

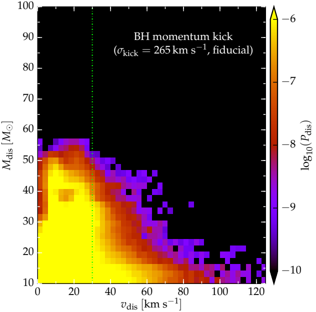


Renzo *et al.* 19b

Mass-velocity varying the natal kick

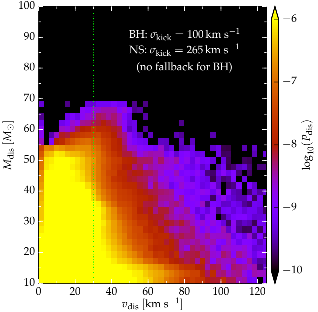
Fiducial

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

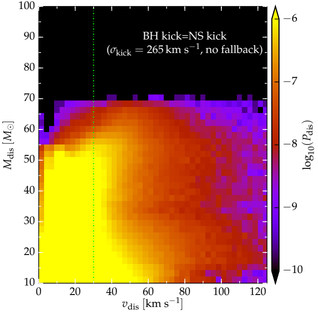


Intermediate BH kick

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

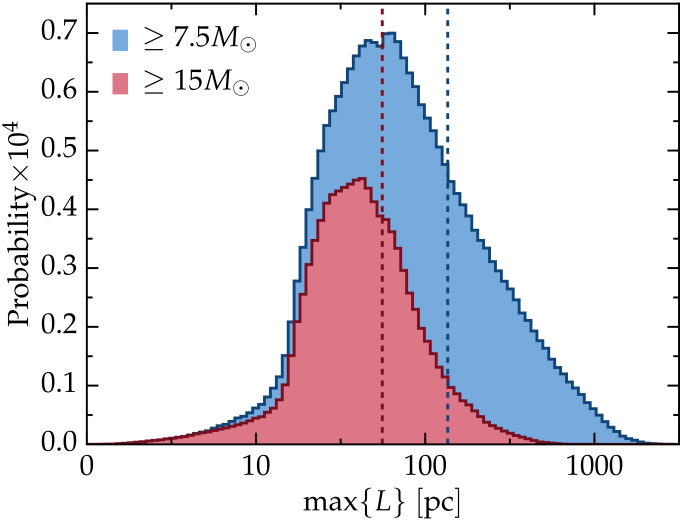


Large BH kicks
(no fallback)



Renzo *et al.* 19b

How far do they get?

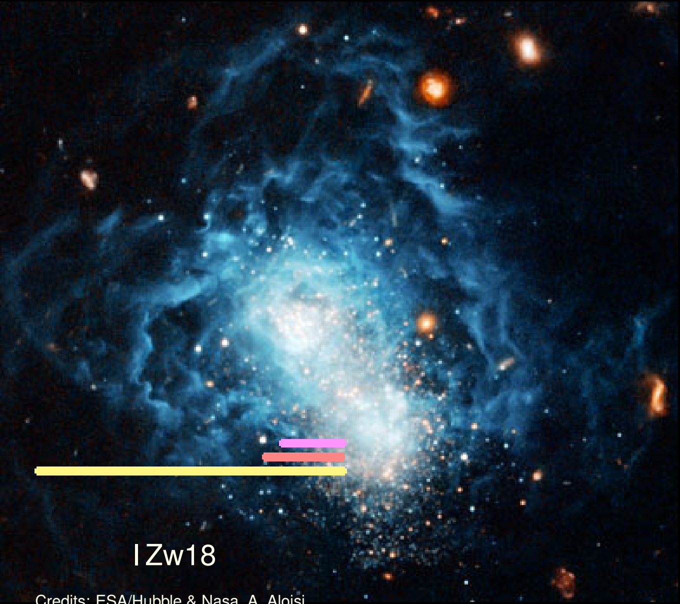


“Distance traveled”

(No potential well)

Renzo *et al.* 19b

Where do they die?



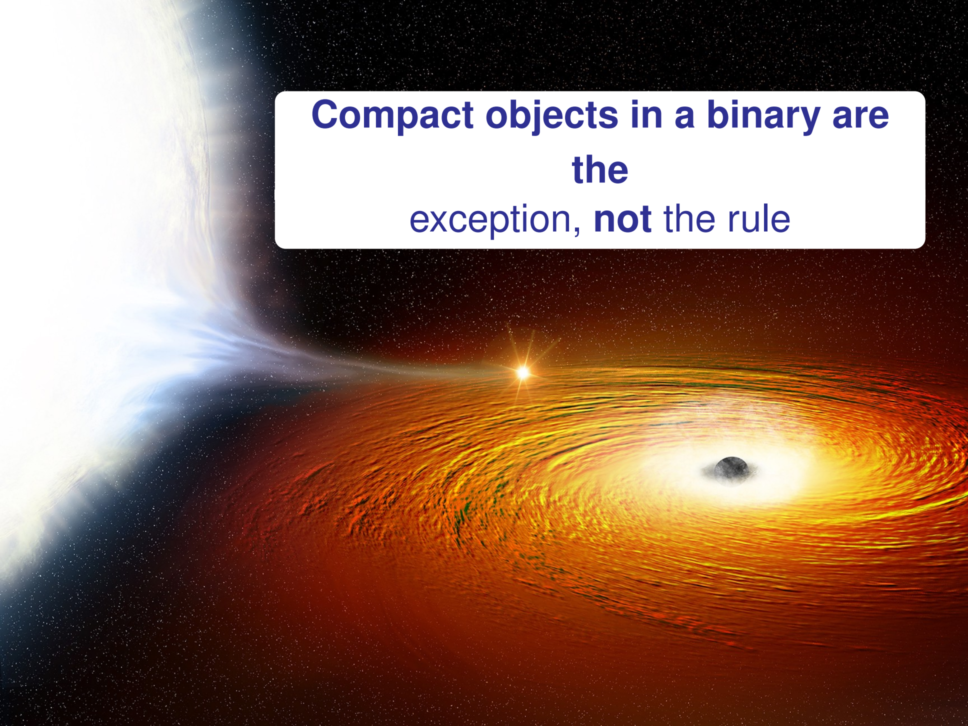
Credits: ESA/Hubble & Nasa, A. Aloisi

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

$\langle D \rangle = 128\,\mathrm{pc}$

$\langle D_\mathrm{run} \rangle = 525\,\mathrm{pc}$

$\langle D_\mathrm{walk} \rangle = 103\,\mathrm{pc}$

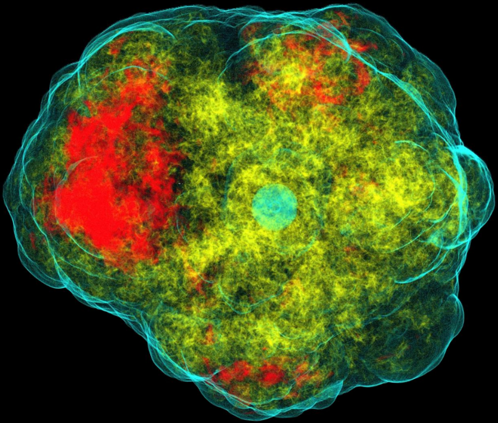


Compact objects in a binary are the exception, **not** the rule

SN natal kick

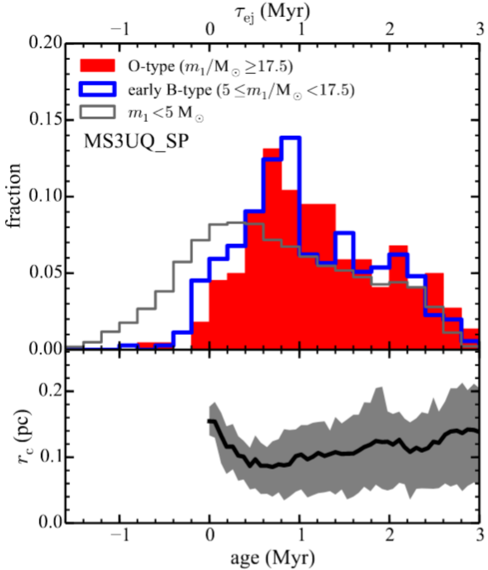
Observationally: $v_{\mathrm{pulsar}} \gg v_{\mathrm{OB-stars}}$

Physically: ν emission and/or ejecta anisotropies



Credits: C. D. Ott, S. Drasco

Timing of ejection



from Oh & Kroupa 16,

Most ejections happen early

Before the first stellar core-collapse

Very sensitive to initial conditions

see also, Poveda *et al.* 64, Fujii & Portegies-Zwart 11, Banerjee *et al.* 12, 14