Massive runaways stars:

Probes for stellar physics and dynamics

Mathieu Renzo

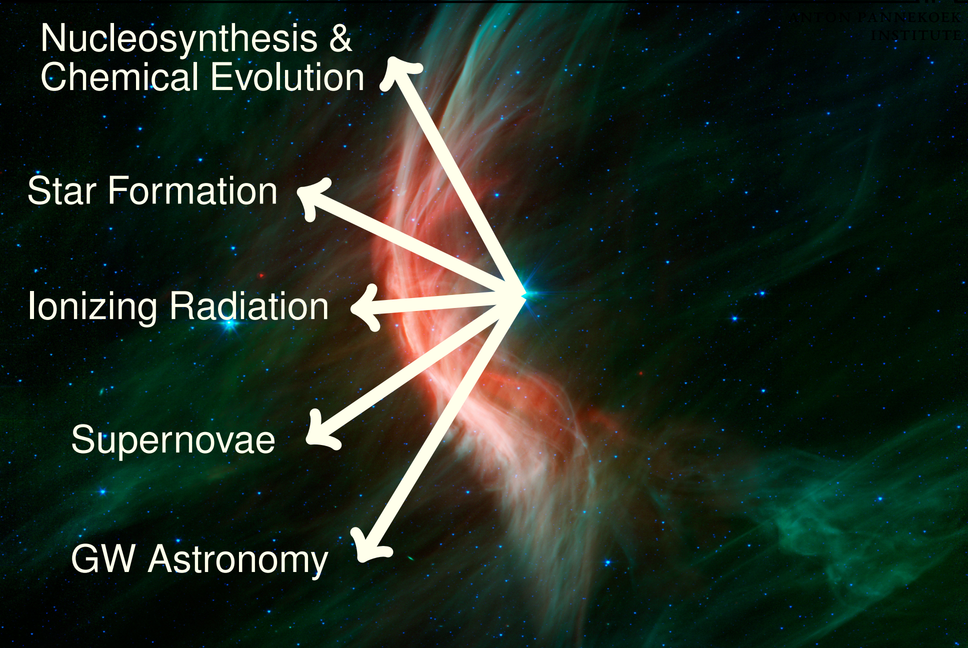
Amsterdam ⇒ Flatiron, NY

Collaborators:

E. Zapartas, S. E. de Mink, Y. Götberg, S. Justham, R. J. Farmer, R. G. Izzard, S. Toonen, D. J. Lennon, H. Sana, E. Laplace, S. N. Shore, V. van der Meij, ...

NASA, JPL-Caltech, Spitzer Space Telescope

Why are massive stars important?



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)

NASA, JPL-Caltech, Spitzer Space Telescope

Outline

ANTON PANNEKOEK
INSTITUTE

How to measure stellar velocities?

Runaway definition

Dynamical ejection from cluster

Extremely massive runaways in 30 Doradus

Binary SN disruption

The majority of massive binary are disrupted

Runaway X-ray binaries

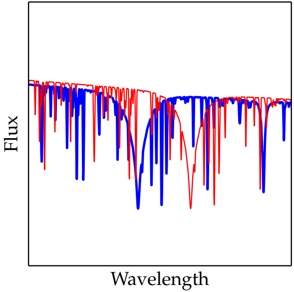
Massive runaway origins ...

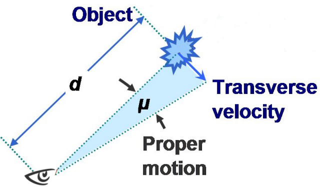
... is there a problem ?

Observations of stellar velocities

⇐ Bow shocks

Doppler shifts ⇒

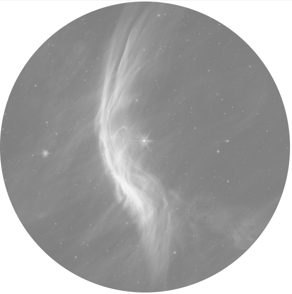




⇐ Proper motions

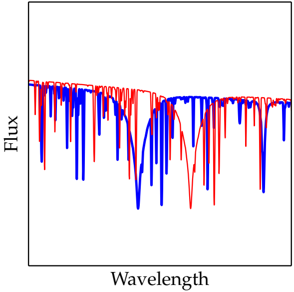
(if distance known)

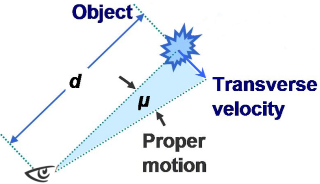
Observations of stellar velocities



⇐ Bow shocks

Doppler shifts ⇒



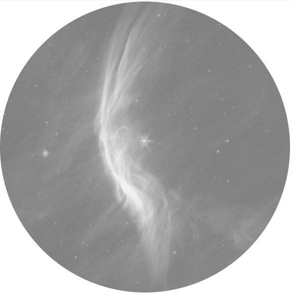


⇐ Proper motions

(if distance known)

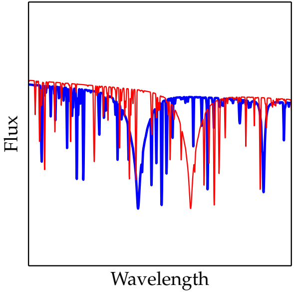
Observations of stellar velocities

ANTON PANNEKOEK INSTITUTE

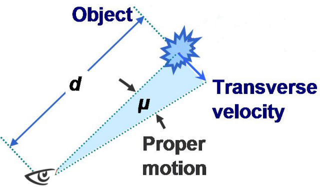


⇐ Bow shocks

Doppler shifts ⇒



+



⇐ Proper motions

(if distance known)

=

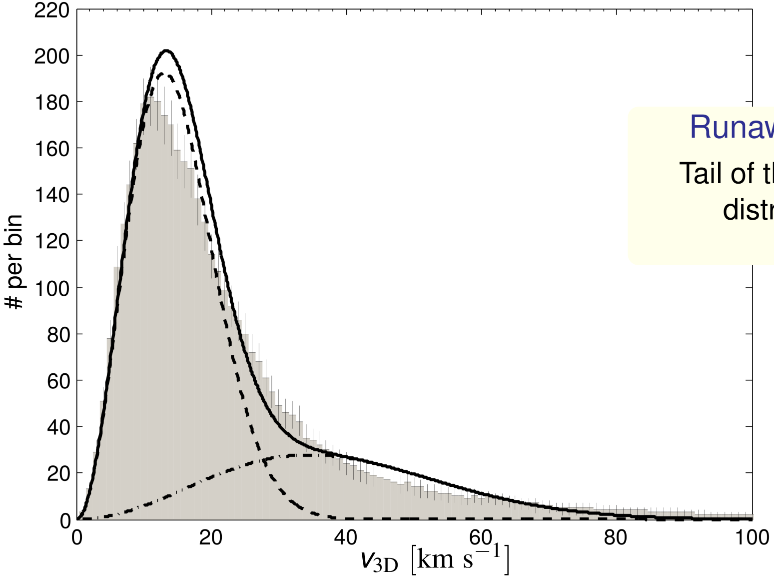
V_{3D}

Gaia is giving proper motions and distances

movie from DR1

What is a runaway star?

ANTON PANNEKOEK INSTITUTE



Runaway stars

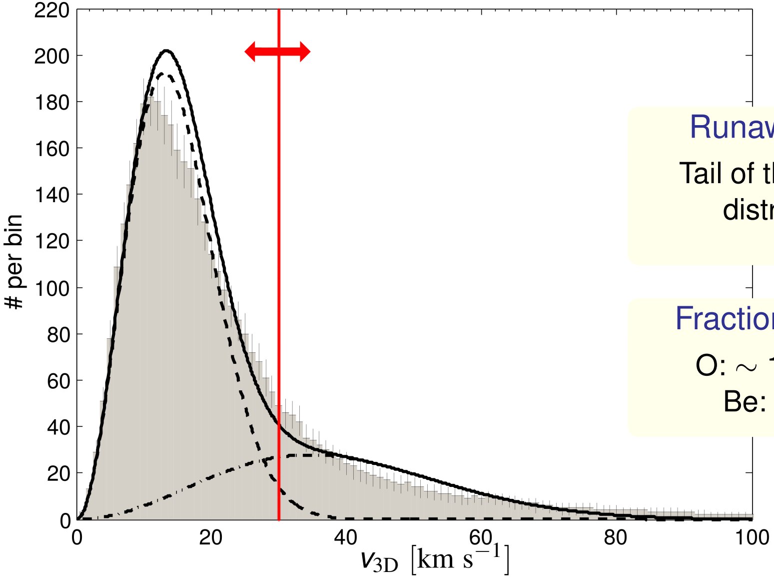
Tail of the velocity distribution

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

What is a runaway star?



ANTON PANNEKOEK INSTITUTE

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

How to measure stellar velocities?

Runaway definition

Dynamical ejection from cluster

Extremely massive runaways in 30 Doradus

Binary SN disruption

The majority of massive binary are disrupted

Runaway X-ray binaries

Massive runaway origins ...

... is there a problem ?

Dynamical ejection from cluster

N-body interactions

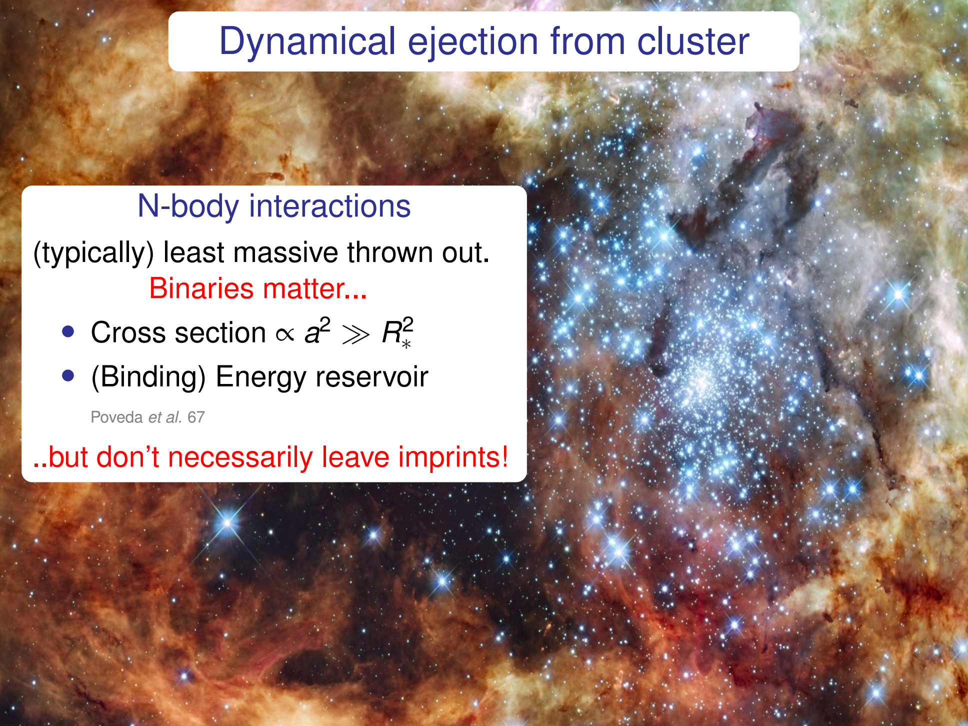
(typically) least massive thrown out.

Binaries matter...

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

Poveda *et al.* 67

..but don't necessarily leave imprints!

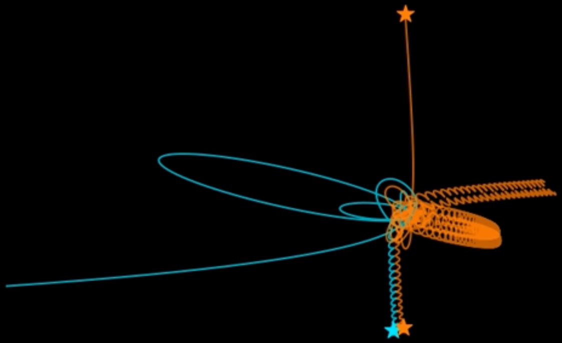


Example of dynamical interaction

Credits: C. Rodriguez

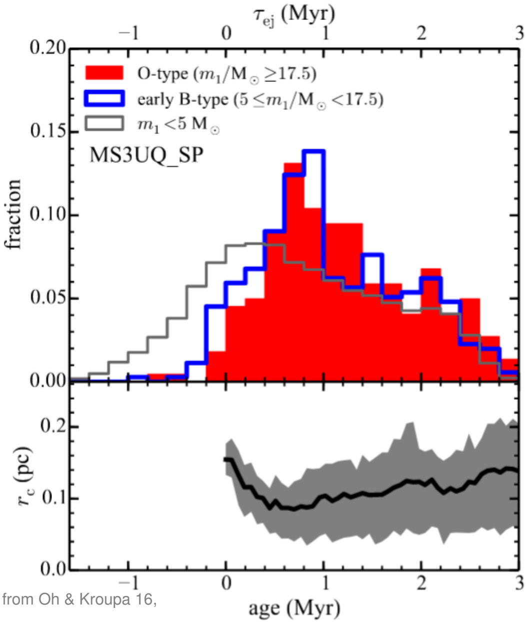
Typical outcome of dynamical interactions

Fast runaway



Tighter and more massive binary

e.g., Fujii & Portegies-Zwart 11



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

Outline

How to measure stellar velocities?

Runaway definition

Dynamical ejection from cluster

Extremely massive runaways in 30 Doradus

Binary SN disruption

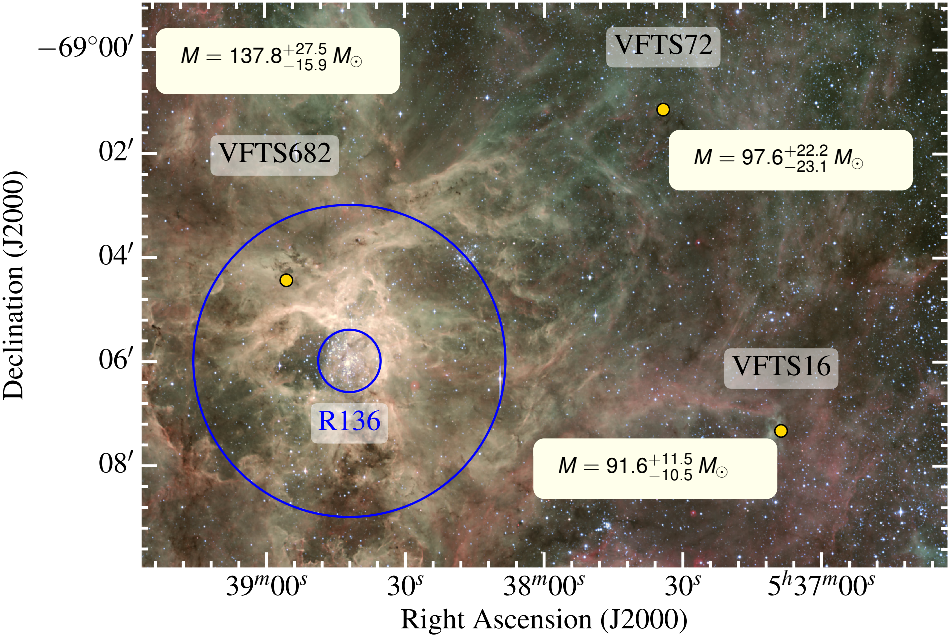
The majority of massive binary are disrupted

Runaway X-ray binaries

Massive runaway origins ...

... is there a problem ?

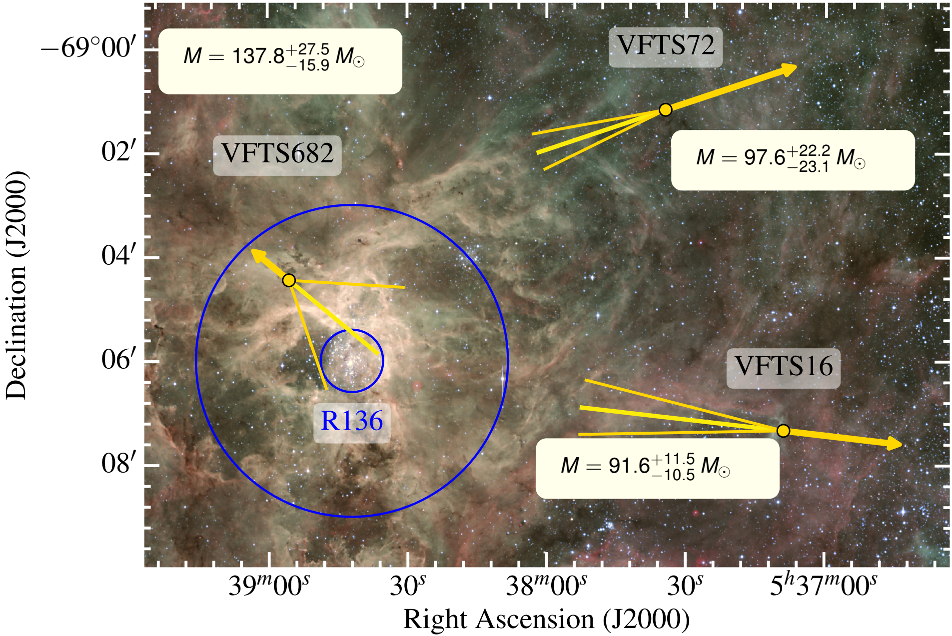
The most massive runaways known



Renzo *et al.* 19a

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

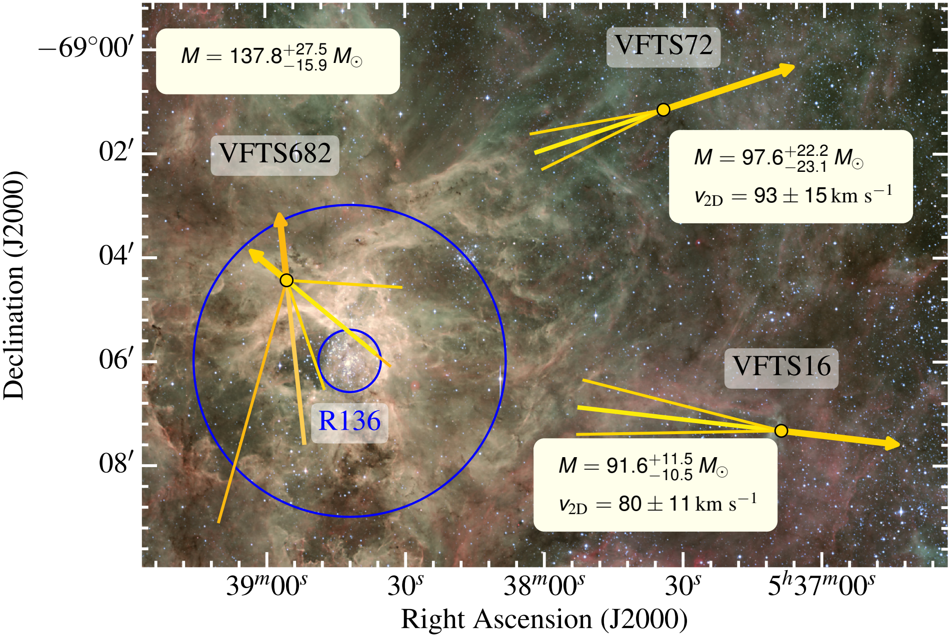
The most massive runaways known



Renzo *et al.* 19a

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

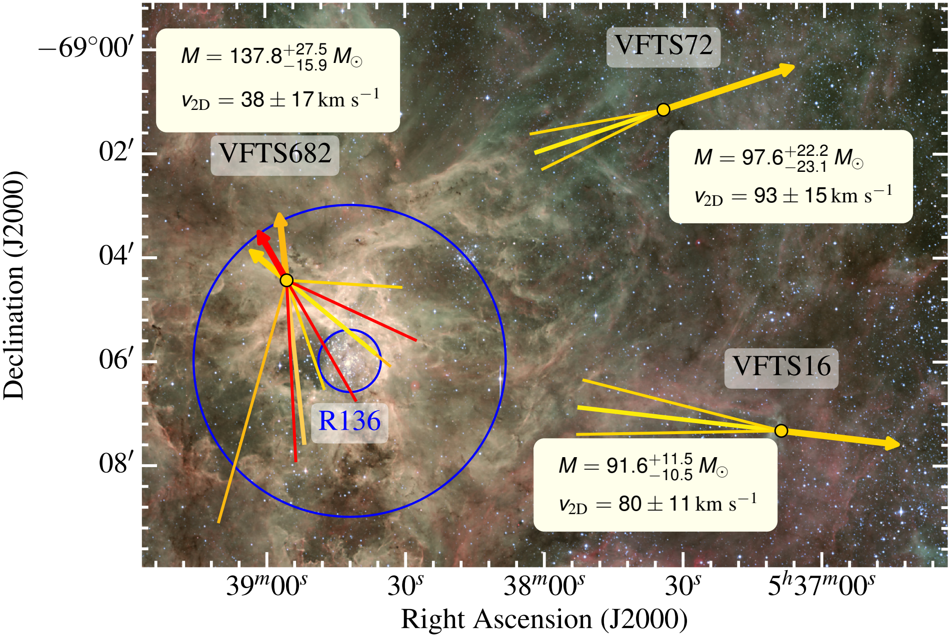
The most massive runaways known



Renzo *et al.* 19a

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

The most massive runaways known



Renzo *et al.* 19a

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

Summary of ejection mechanisms

ANTON PANNEKOEK INSTITUTE

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

Outline

ANTON PANNEKOEK INSTITUTE

How to measure stellar velocities?

Runaway definition

Dynamical ejection from cluster

Extremely massive runaways in 30 Doradus

Binary SN disruption

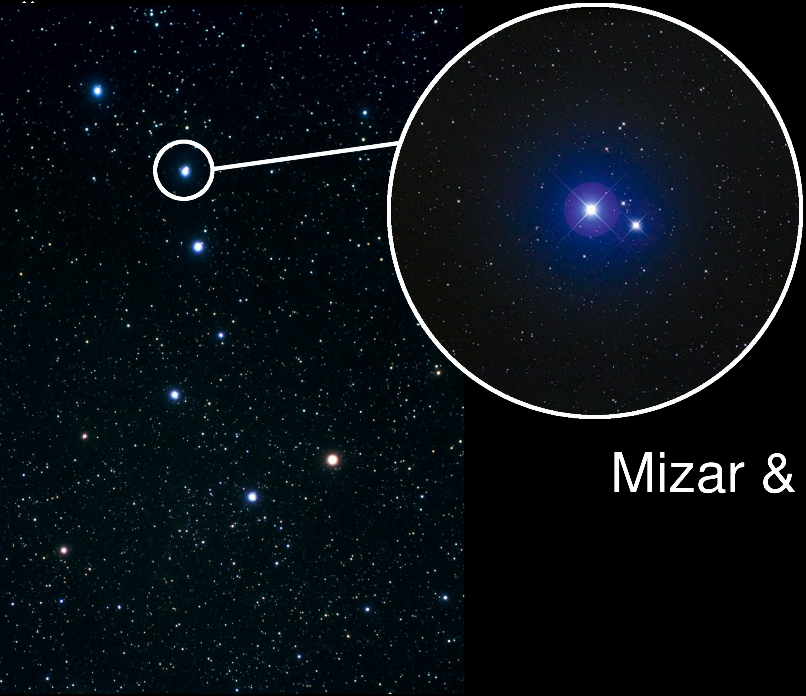
The majority of massive binary are disrupted

Runaway X-ray binaries

Massive runaway origins ...

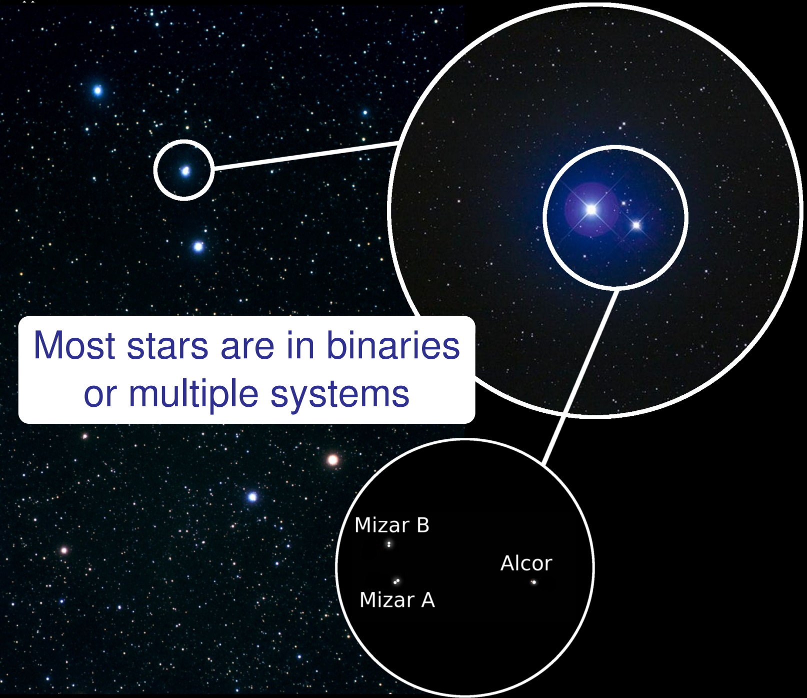
... is there a problem ?

The big dipper



Mizar & Alcor

Most stars are in binaries or multiple systems



Most common massive binary evolution

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

Spin up, pollution, and rejuvenation

ANTON PANNEKOEK INSTITUTE

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?

ANTON PANNEKOEK INSTITUTE

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

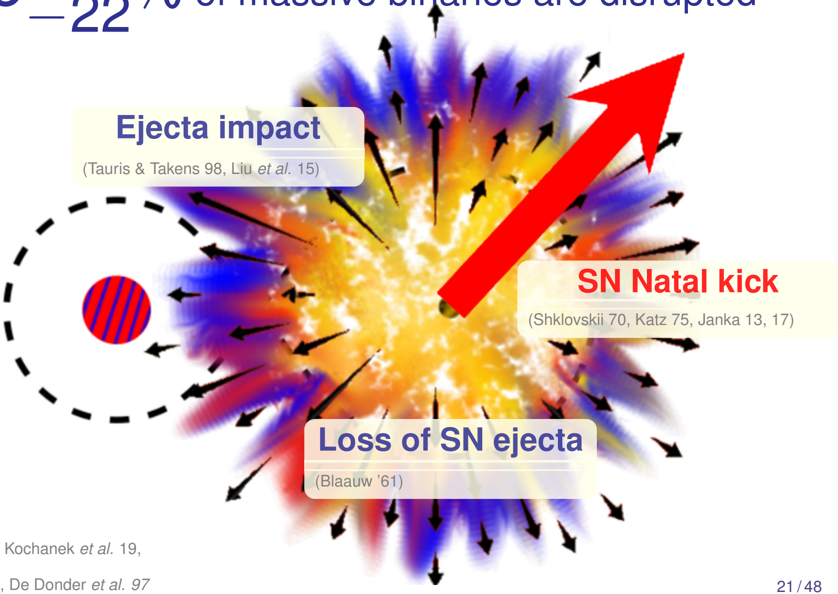
Renzo *et al.* 19b, Kochanek *et al.* 19,

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

What exactly disrupts the binary?

ANTON PANNEKOEK INSTITUTE

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



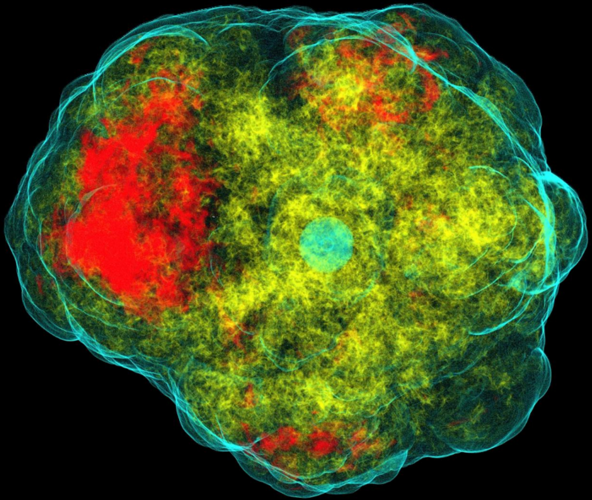
Renzo *et al.* 19b, Kochanek *et al.* 19,

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

SN natal kick

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

Physically: ν emission and/or ejecta anisotropies

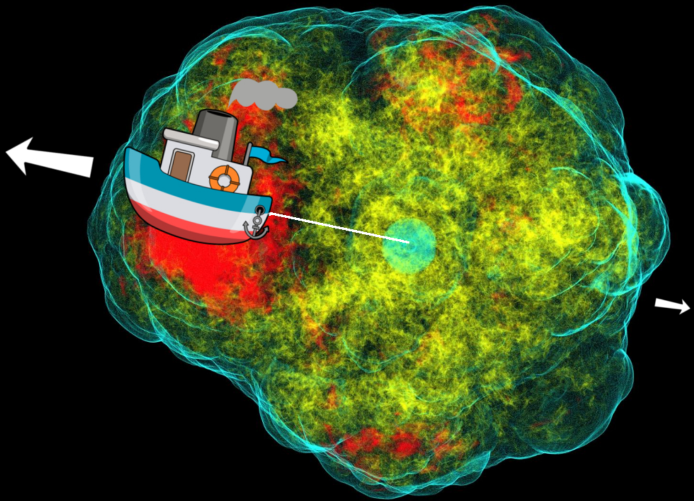


Credits: C. D. Ott, S. Drasco

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

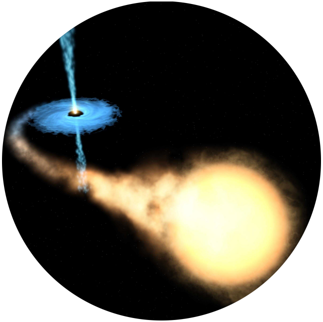
Do BHs receive kicks?

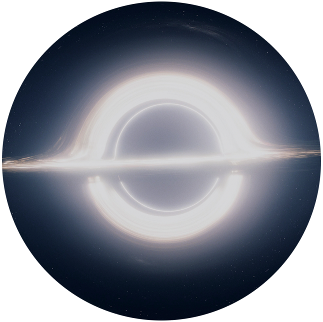
NO

⇒ most remain together with their widowed companion

YES

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



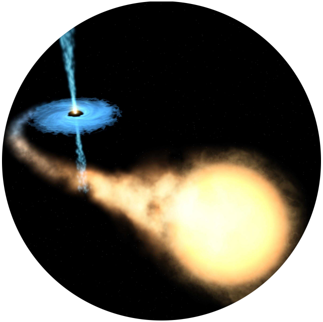


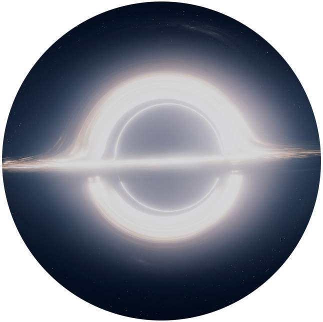
NO

⇒ most remain together with their widowed companion

YES

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



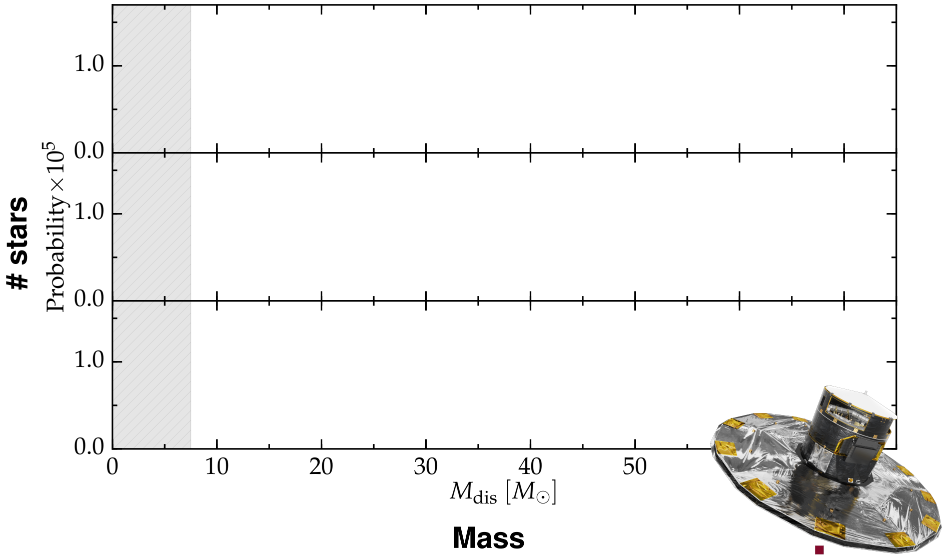


...but we can see the "widowed" companions

A way to constrain BH kicks with Gaia

ANTON PANNEKOEK INSTITUTE

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

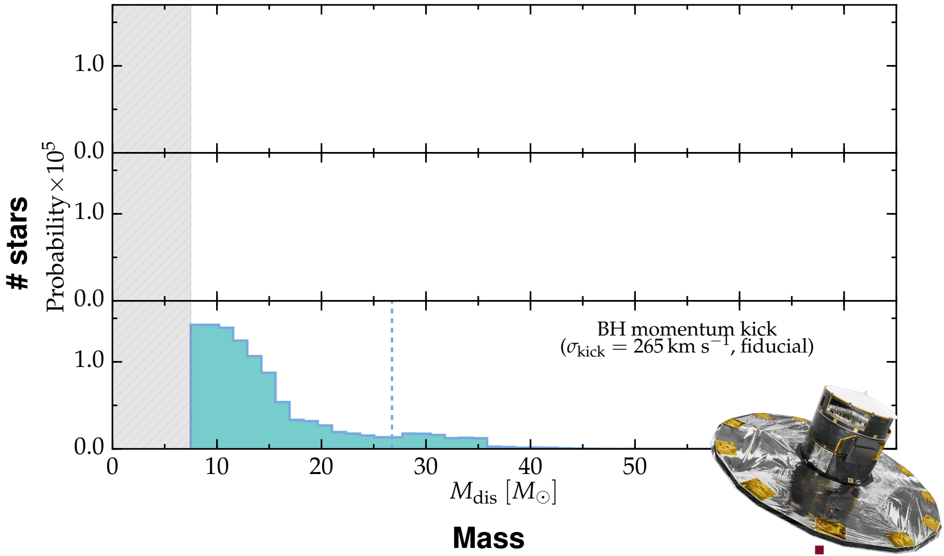


Numerical results publicly available at::
http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

A way to constrain BH kicks with Gaia

ANTON PANNEKOEK INSTITUTE

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



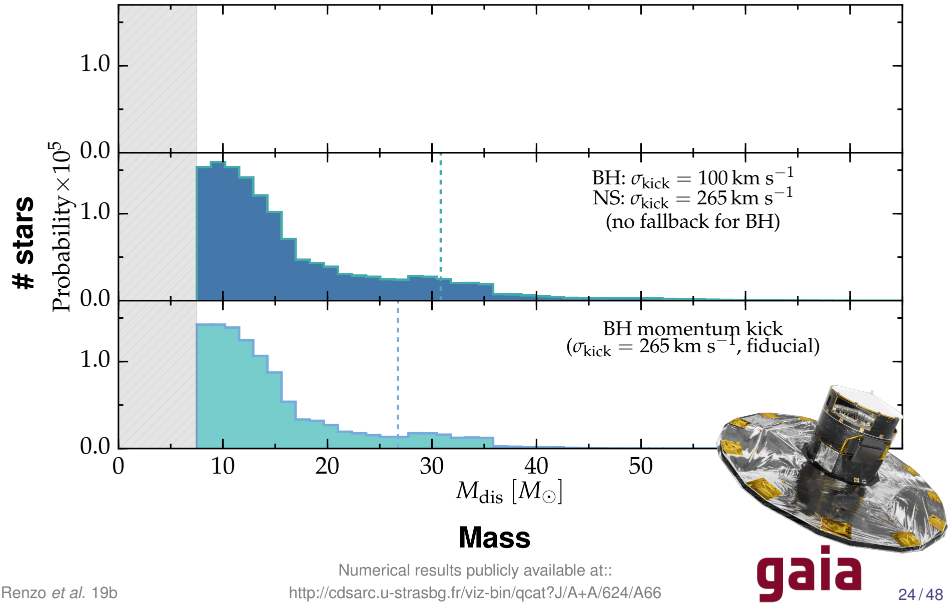
gaia

Numerical results publicly available at::
http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

A way to constrain BH kicks with Gaia

ANTON PANNEKOEK INSTITUTE

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

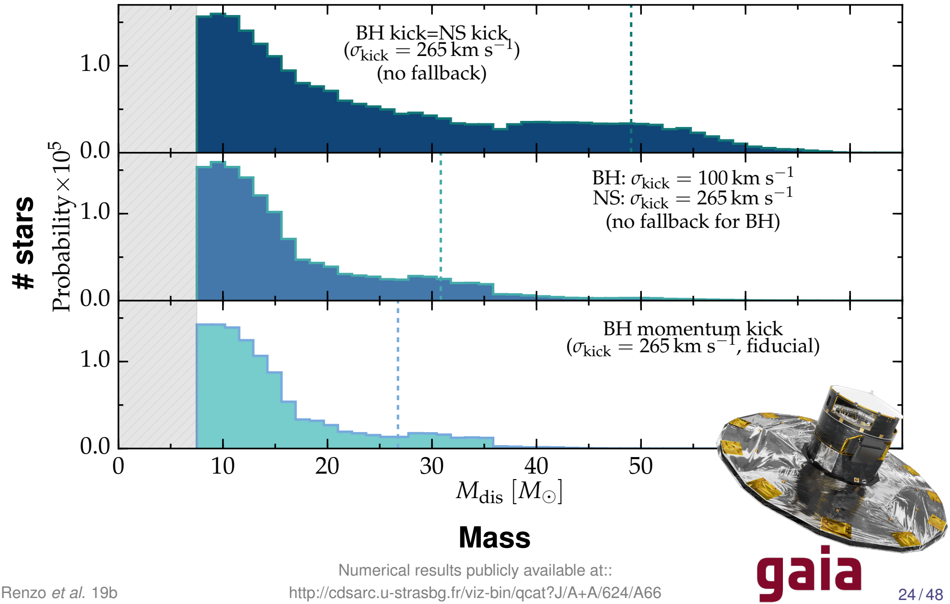


Numerical results publicly available at::
http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

Renzo *et al.* 19b

ANTON PANNEKOEK INSTITUTE

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



Numerical results publicly available at::
http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

Renzo *et al.* 19b

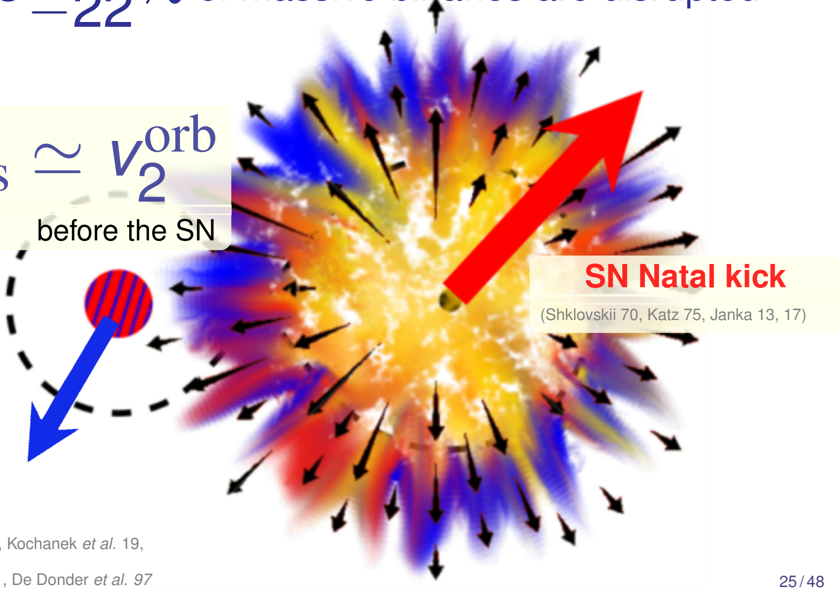
Kicks do not change companion velocity

ANTON PANNEKOEK INSTITUTE

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

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

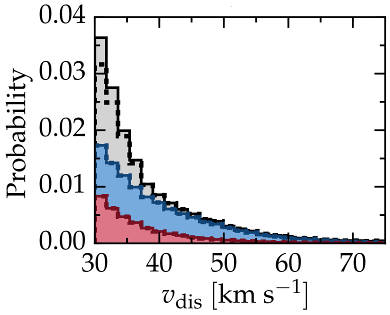
before the SN



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

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

Velocity distribution: **Runaways**

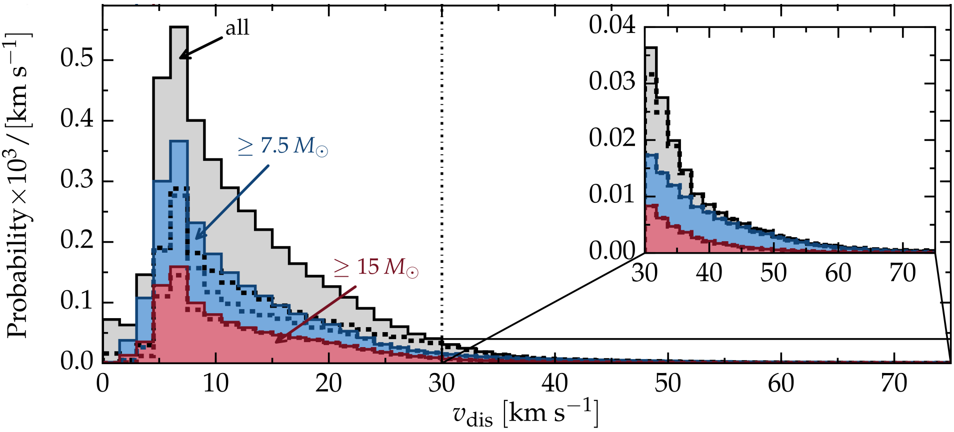


Velocity respect to the pre-explosion binary center of mass

Numerical results publicly available at::
http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

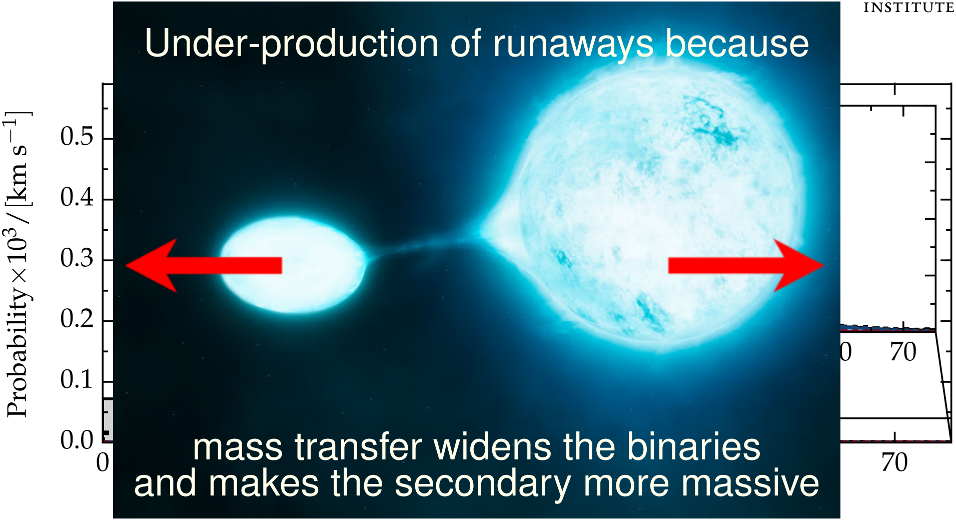
Velocity distribution: **Walkaways**

ANTON PANNEKOEK INSTITUTE



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



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

How to measure stellar velocities?

Runaway definition

Dynamical ejection from cluster

Extremely massive runaways in 30 Doradus

Binary SN disruption

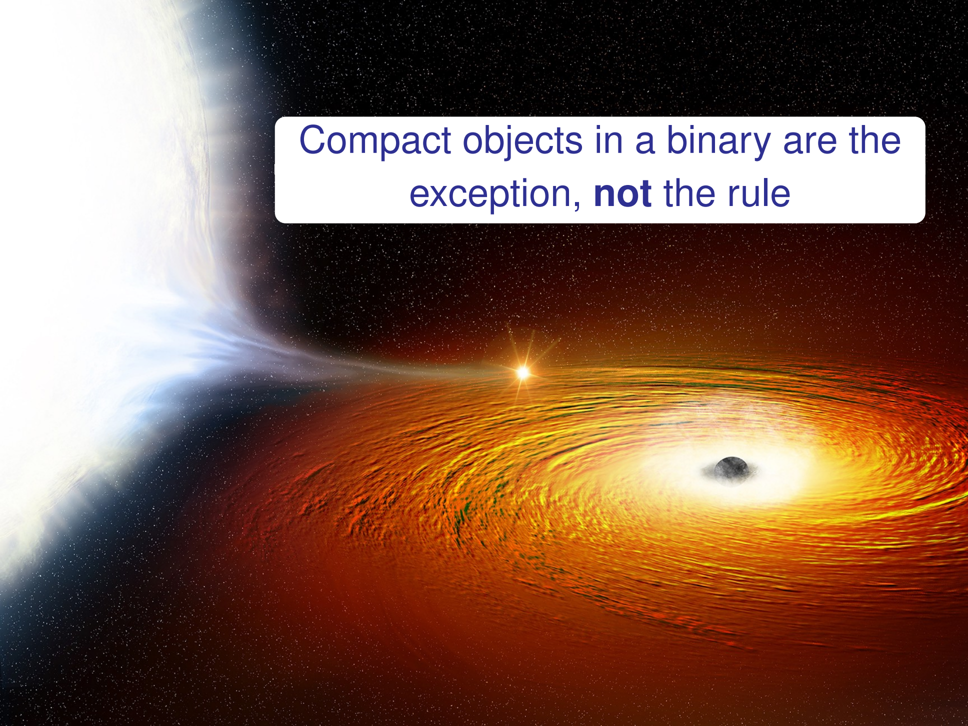
The majority of massive binary are disrupted

Runaway X-ray binaries

Massive runaway origins ...

... is there a problem ?

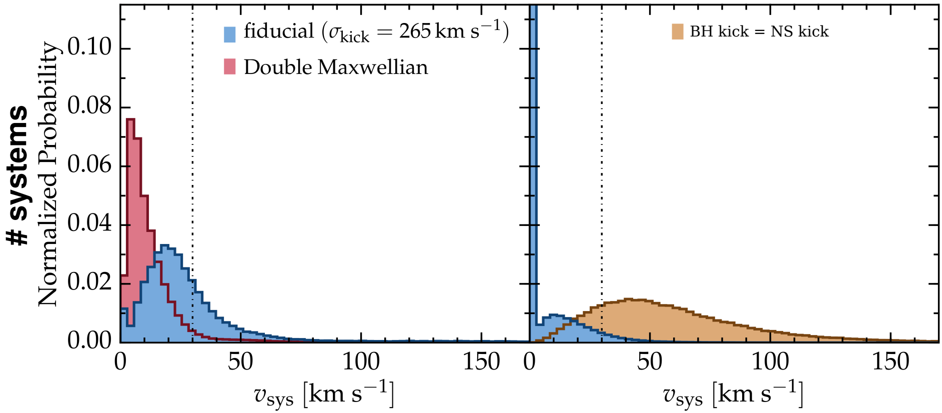
Compact objects in a binary are the exception, **not** the rule



ANTON PANNEKOEK INSTITUTE

NS + Main sequence

BH + Main sequence



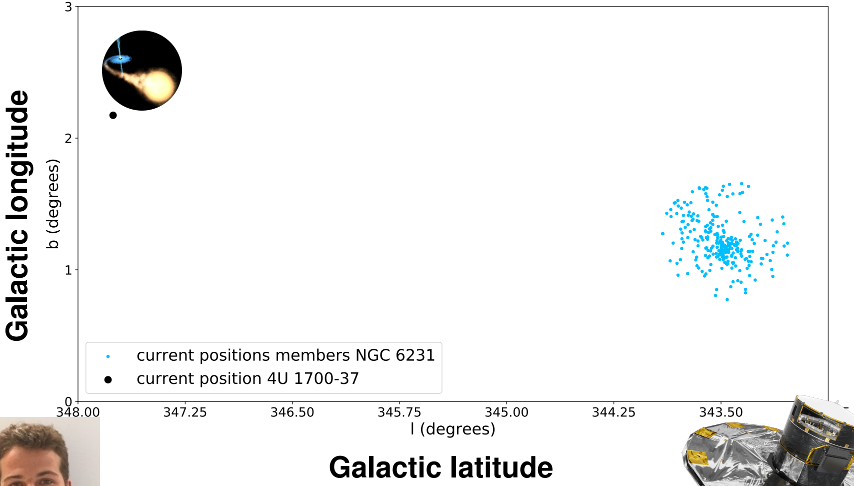
Velocity respect to the pre-explosion binary center of mass

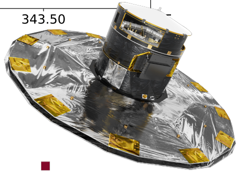
Numerical results publicly available at:
http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

Renzo *et al.* 19b

Preliminary: The case of 4U1700-37

$M \simeq 2.5\,M_\odot\ ,\ M_* \simeq 60 \pm 10\,M_\odot\ ,\ P \simeq 3.4\,\mathrm{days}\ ,\ e \simeq 0.22\ , v \simeq 60\,\mathrm{km\ s^{-1}}$





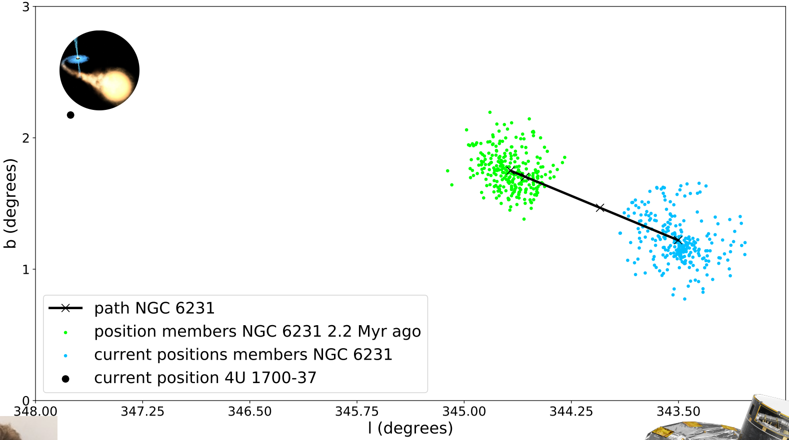
gaia

van der Meij *et al.* (incl. MR), in prep.

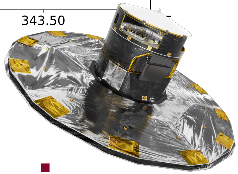
Preliminary: The case of 4U1700-37

$M \simeq 2.5\, M_\odot$, $M_* \simeq 60 \pm 10\, M_\odot$, $P \simeq 3.4\,\mathrm{days}$, $e \simeq 0.22$, $v \simeq 60\,\mathrm{km\ s^{-1}}$

Galactic longitude



Galactic latitude



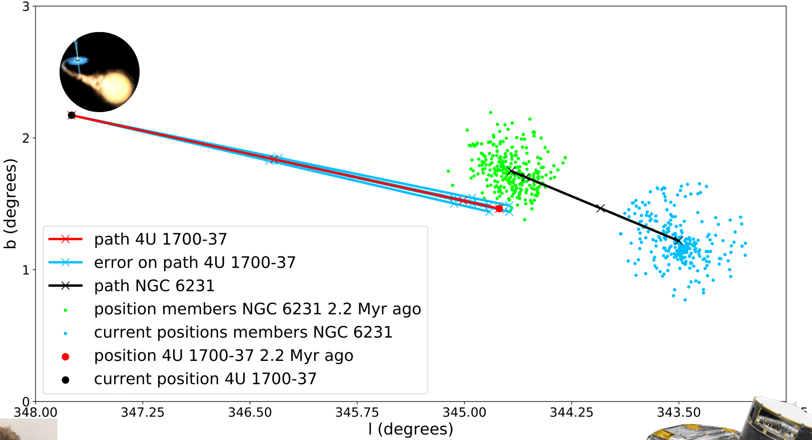
gaia

van der Meij *et al.* (incl. MR), in prep.

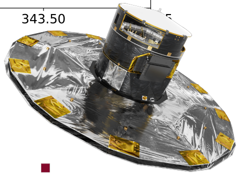
Preliminary: The case of 4U1700-37

$M \simeq 2.5\,M_\odot\ ,\ M_* \simeq 60 \pm 10\,M_\odot\ ,\ P \simeq 3.4\,\mathrm{days}\ ,\ e \simeq 0.22\ , v \simeq 60\,\mathrm{km\ s^{-1}}$

Galactic longitude



Galactic latitude



gaia

How to measure stellar velocities?

Runaway definition

Dynamical ejection from cluster

Extremely massive runaways in 30 Doradus

Binary SN disruption

The majority of massive binary are disrupted

Runaway X-ray binaries

Massive runaway origins ...

... is there a problem ?

ANTON PANNEKOEK INSTITUTE

How to measure stellar velocities?

Runaway definition

Dynamical ejection from cluster

Extremely massive runaways in 30 Doradus

Binary SN disruption

The majority of massive binary are disrupted

Runaway X-ray binaries

Massive runaway origins ...

... is there a problem ?

Known ejection mechanisms

ANTON PANNEKOEK
INSTITUTE

Cluster ejections

- Happen before SNe
- Can produce high v
- Least massive thrown out
- *Gaia* hint: high efficiency

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

Binary SN disruption

- Most binaries are disrupted
- Determined by SN kick
- Ejects accretor
- $v \simeq v_2^{\rm orb}$ typically slow
- Leaves binary signature

spin up, pollution, rejuvenation

Known ejection mechanisms

ANTON PANNEKOEK INSTITUTE

Cluster ejections

- Happen before SNe
- Can produce high v
- Least massive thrown out
- *Gaia* hint: high efficiency

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

Binary SN disruption

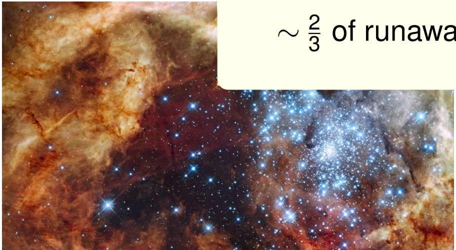
- Most binaries are disrupted
- Determined by SN kick
- Ejects accretor
- $v \simeq v_2^{\rm orb}$ typically slow
- Leaves binary signature

spin up, pollution, rejuvenation

Relative efficiency ?

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

Hoogerwerf *et al.* 01



O type stars runaway fraction

ANTON PANNEKOEK
INSTITUTE

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

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

O type stars runaway fraction

ANTON PANNEKOEK INSTITUTE

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

Observational claims: (regardless of origin)

$\sim\ 10\%$

~~∼ 2 fr~~ ~~ies~~

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

Conclusions

Summary of ejection mechanisms

Cluster ejections

- Happen before SNe
- Can produce high v
- Least massive thrown out
- *Gaia* hint: high efficiency

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

Binary SN disruption

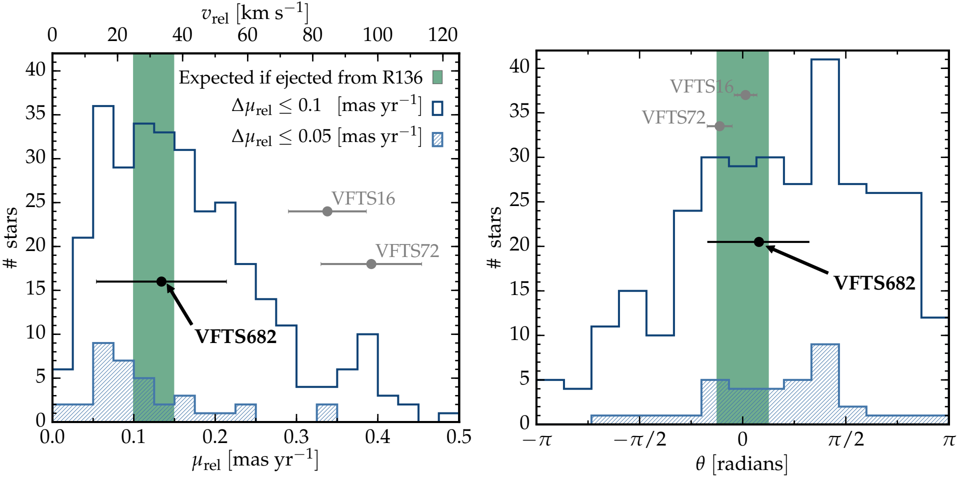
- Most binaries are disrupted
- Determined by SN kick
- Ejects accretor
- $v \simeq v_2^{\mathrm{orb}}$ typically slow
- Leaves binary signature

spin up, pollution, rejuvenation

Backup slides

VFTS682: Concordant Picture?

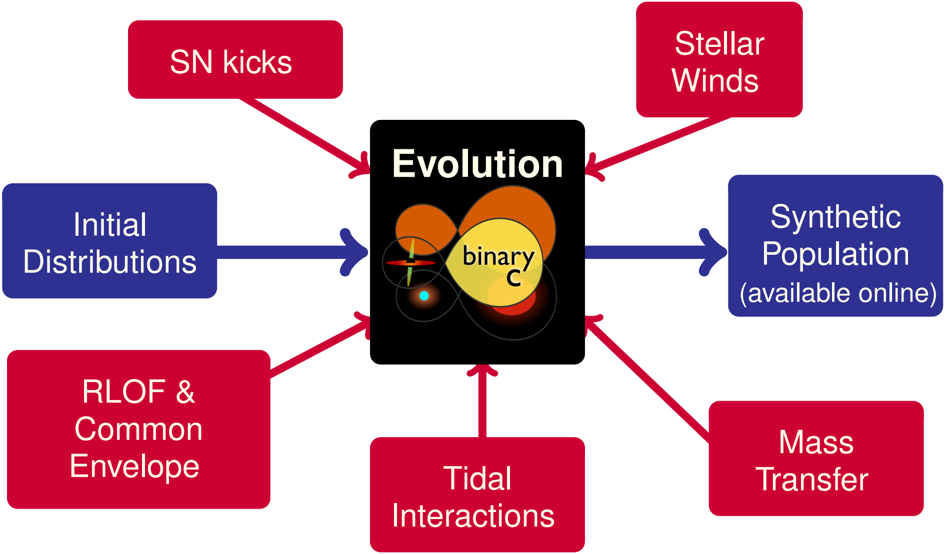
ANTON PANNEKOEK INSTITUTE



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

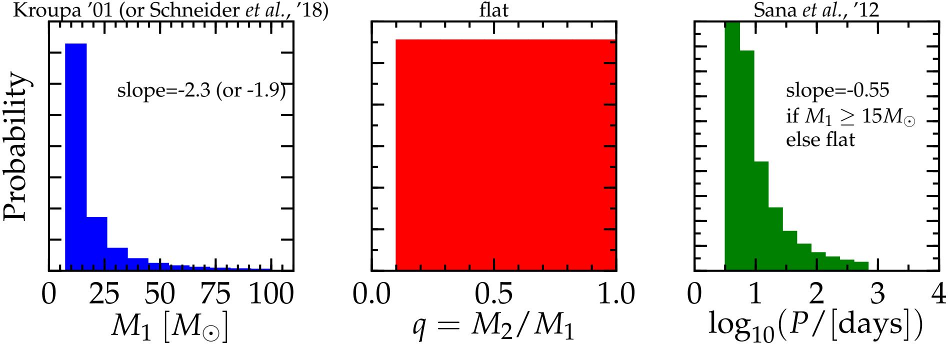
Methods: Population Synthesis

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



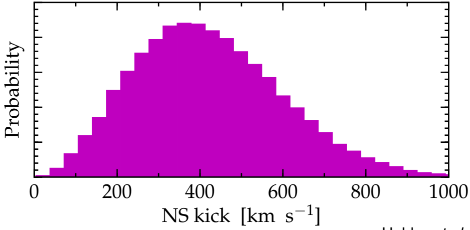
Izzard *et al.* 04, 06, 09, 18; de Mink *et al.* 13; Schneider *et al* 15

Initial Distributions



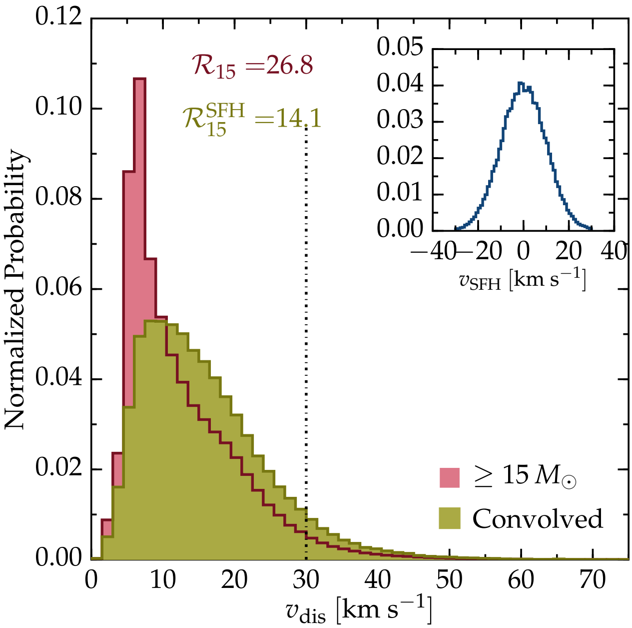
Maxwellian $\sigma_{v_{\mathrm{kick}}} = 265\,\mathrm{km\ s^{-1}}$ + Fallback rescaling

(from Fryer *et al.* '12)

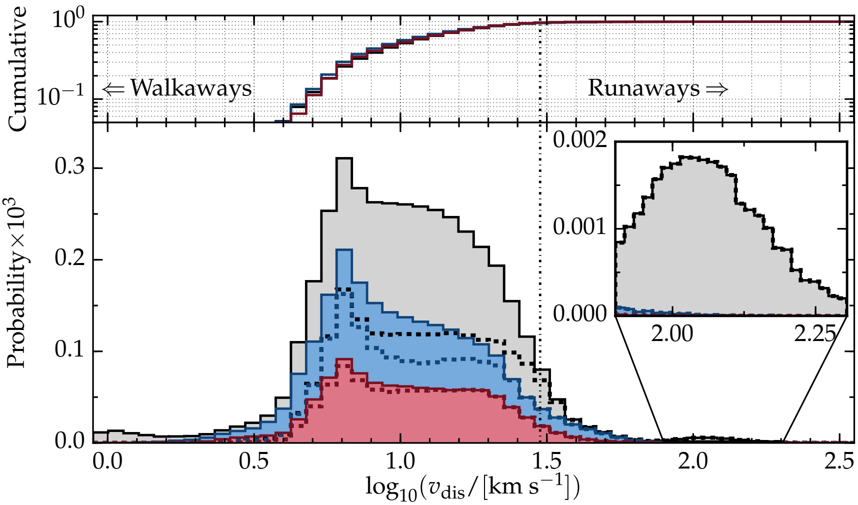


Hobbs *et al.* '05

Star forming region velocity dispersion

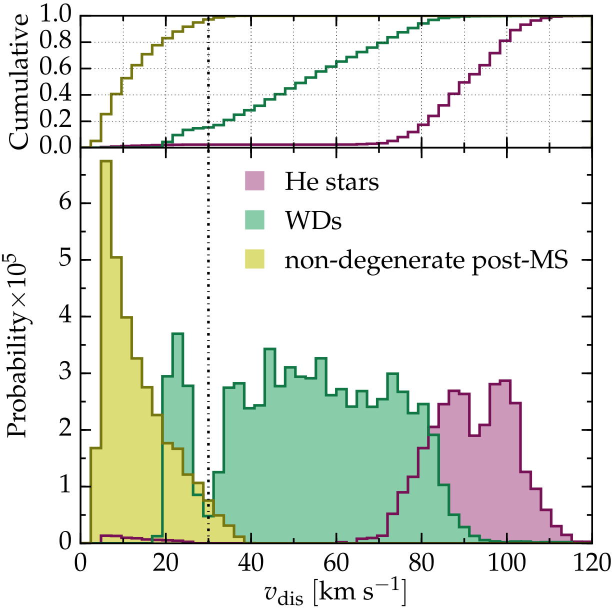


Renzo *et al.* 19b



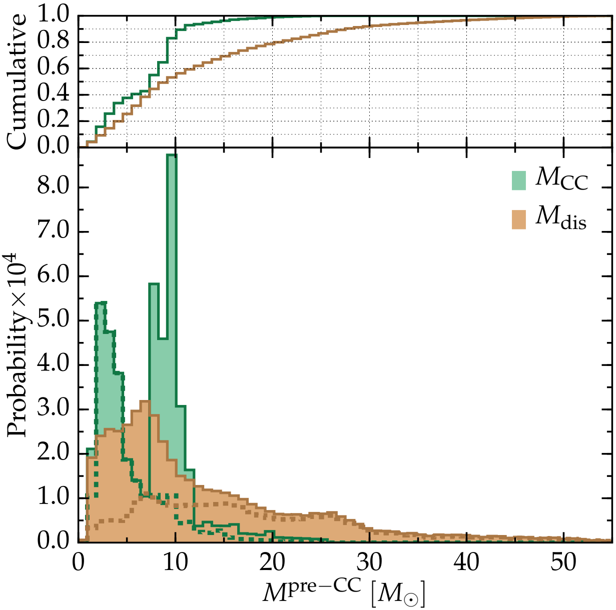
Renzo *et al.* 19b

Velocity post-main sequence stars



Renzo *et al.* 19b

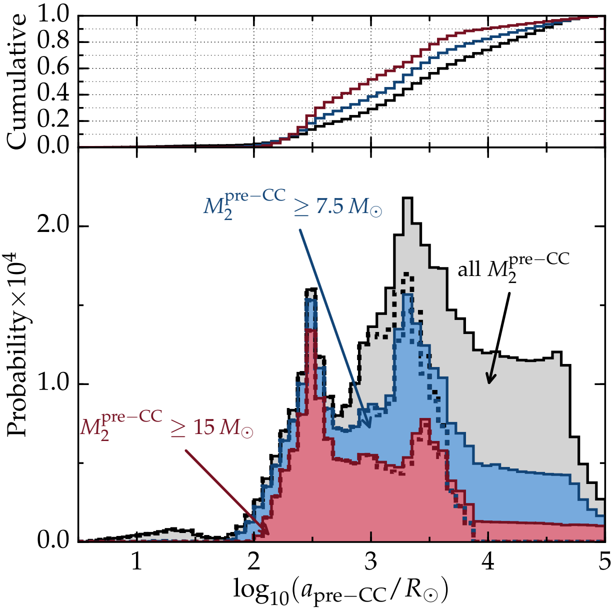
pre-CC mass distribution



Renzo *et al.* 19b

pre-CC separation distribution

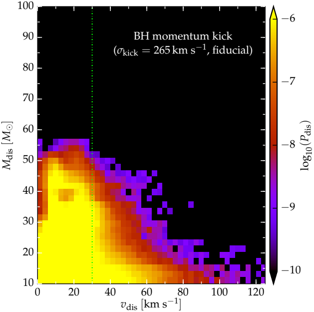
ANTON PANNEKOEK INSTITUTE



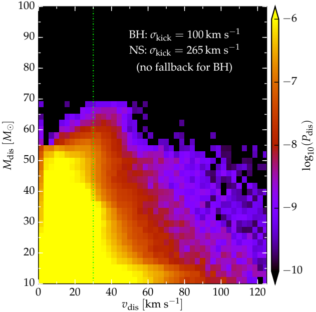
Mass-velocity varying the natal kick

ANTON PANNEKOEK INSTITUTE

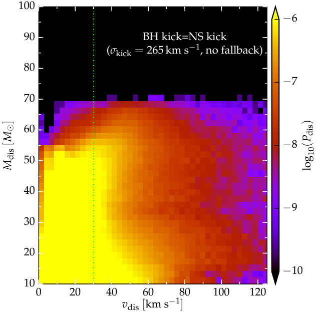
Fiducial
$\sigma_{\mathrm{kick}} = 265\,\mathrm{km\ s^{-1}}$



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

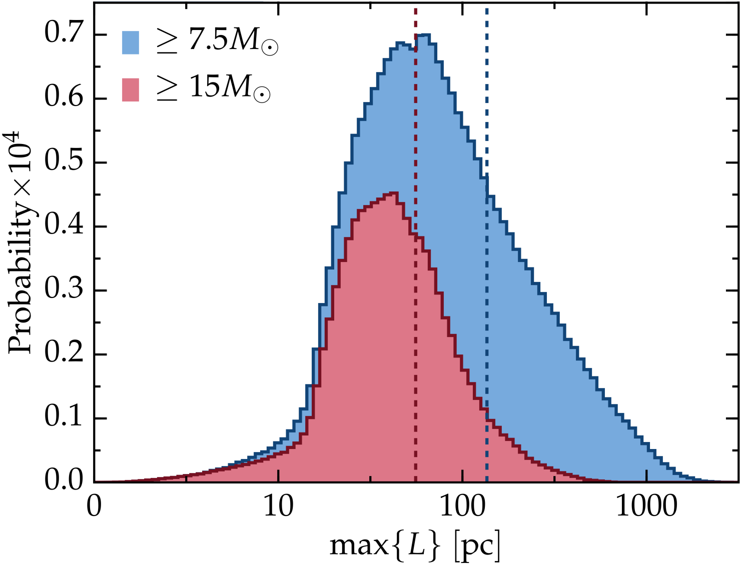


Large BH kicks
(no fallback)



Renzo *et al.* 19b

ANTON PANNEKOEK INSTITUTE



“Distance traveled”

(No potential well)

Renzo *et al.* 19b