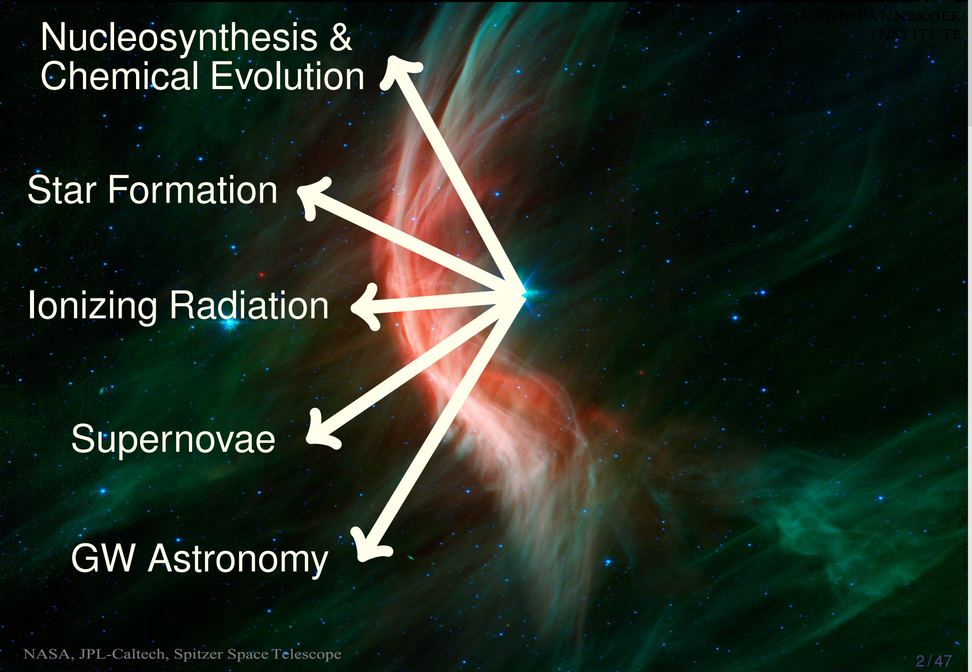
Standing blocks: – stand
– look
– welcome (open gesture)
– talk
say why you like things to convey enthiusiasm “I like massive stars because I like things that explode and where a lot of physics matters”
Hi everyone, today I would like to talk to YOU about Massive runaway stars, and on my title slide here I have an example. By massive star I mean stars that will collapse at the end of their evolution, and this here is zeta ophiuchi, which is a 20Msun star, so definitely we predict that it will form either a NS or a BH at the end of the evolution. Runaway stars are stars that are moving *fast*, and I will be more precise in a second. Here we see that this star is moving fast because its wind forms a bow shock when running in the interstellar material: this means that the velocity of the star is larger than the local speed of sound in the ISM.

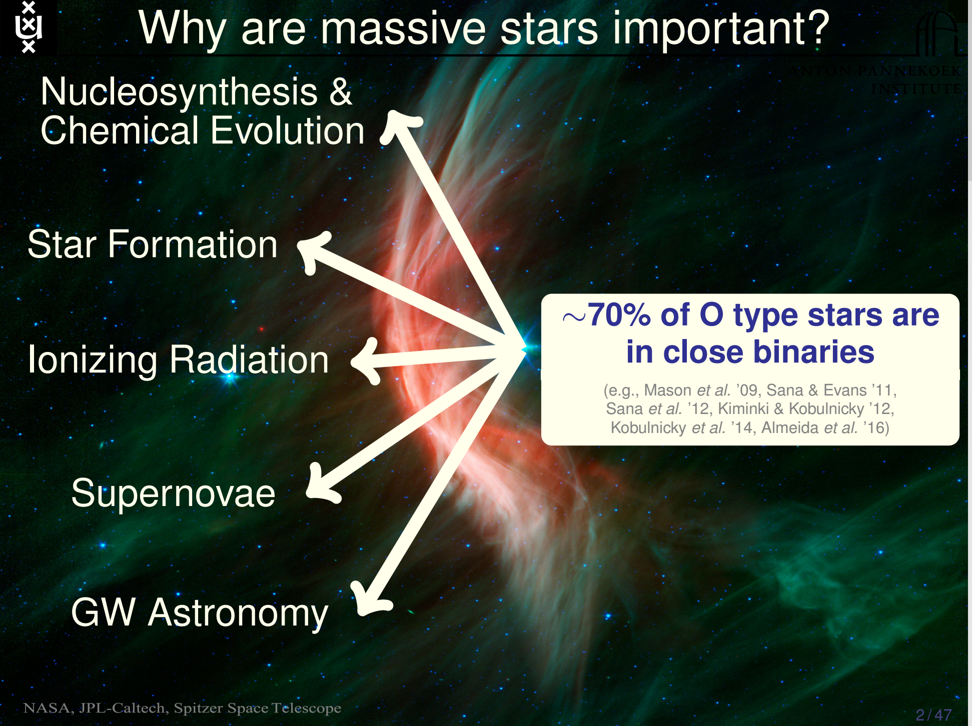
Why are massive stars important?



but before going into the runaway: Why should you care about massive stars? Massive stars are important for a variety of subfield of astrophysics because they have many way to interact with their environment and modify it. For example, they synthesize elements all the way to iron in their core, and although the heaviest elements will end up in the compact object they form at the end of their evolution, the lighter alpha-elements are released in the galaxy and drive the chemical evolution: THE OXYGEN WE BREATH AS BEEN SYNTHESIZED IN MASSIVE STARS.

They are powerful engines that stir the gas with their winds driving further star formation, but they can also sweep away the gas when they explode damping star formation: MASSIVE STARS ARE THE MAIN REGULATORS OF STAR FORMATION.

Their final collapse, at least sometimes leads to a SN explosion and forms a NS or BH, making massive stars the progenitors of the compact objects we can see in X-rays, radio but also gravitational waves.



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Outline

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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

Missing runaway "problem"?

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Ok, after this very brief intro on massive stars, here is what I want to walk you through:
* brief reminder on how we measure stellar velocities and give you a formal definition of runaway
* introduce YOU to 2 mechanisms active in nature to give to these stars their large velocity,
* naturally lead to the question of the relative efficiency of the two mechanisms.

Observations of stellar velocities

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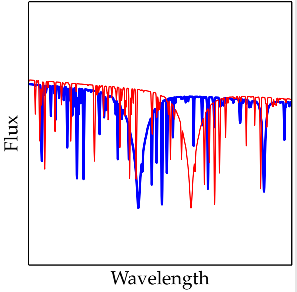
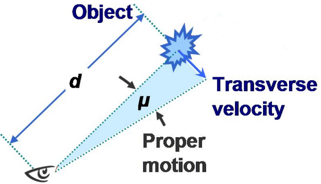
⇐ Bow shocks

Doppler shifts ⇒





⇐ Proper motions

(if distance known)

So how do we measure stellar velocities?
* special features of the stars (e.g. the bow shock on my title slide), but this requires the star to be rather nearby.
* component of the velocity ALONG OUR LINE OF SIGHT using Doppler shifts of the spectral lines in the spectrum.
* If the distance to the star is known, we can also measure the angular motion on the sky (so-called proper motion) and convert it into the other two components of the velocity.
Only combining radial velocity and proper motions we can reconstruct the THREEDIMENSIONAL velocity vector of a star.
We sometimes only have RV or pm, so not always easy to measure the threedimensional velocity ⇒ large uncertainties.

Observations of stellar velocities

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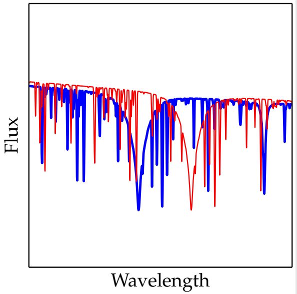
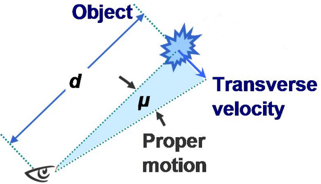
Doppler shifts ⇒





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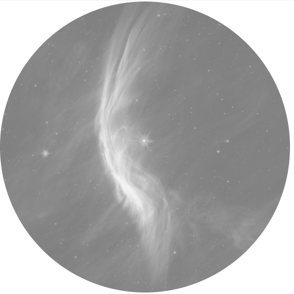

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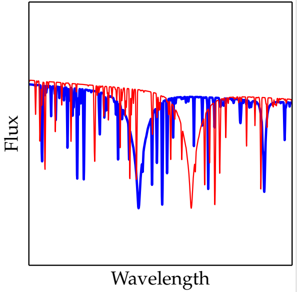

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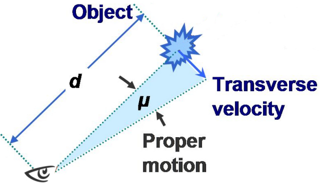

⇐ Proper motions

(if distance known)

=

v_{3D}

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We sometimes only have RV or pm, so not always easy to measure the threedimensional velocity ⇒ large uncertainties.

Gaia is giving proper motions and distances

movie from DR1

video

The European space agency satellite Gaia is providing distances and proper motions of over a billion stars in the galaxy. This animation shows a projection in the future of the kinematics of the galaxy from the FIRST gaia data release. The second contains so many stars that it's hard to see anything on this, and why I prefer to show something that is outdated. Gaia unfortunately is not an instrument targeting massive stars, so although it will have a complete sample for G-magnitude $\lesssim$20, its spectrograph is not providing radial velocities for massive stars.

What is a runaway star?

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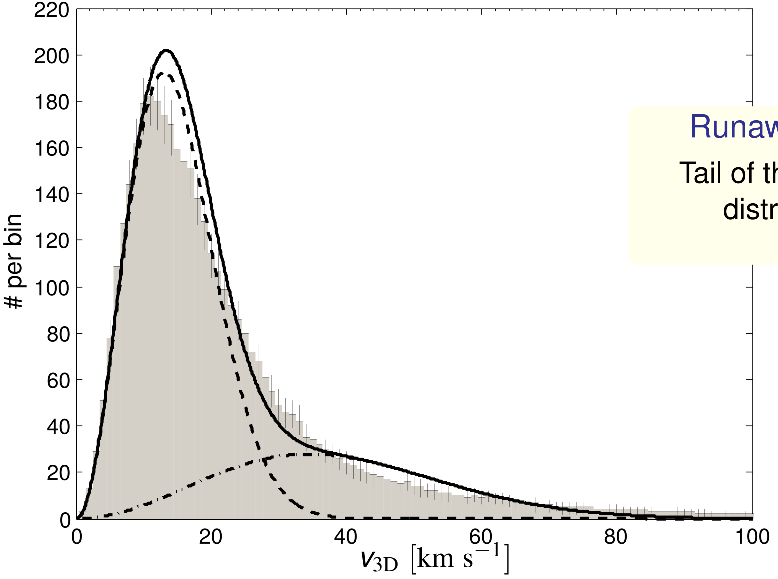


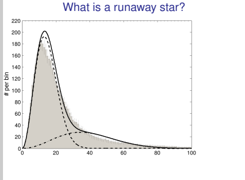
Runaway stars

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



Now, suppose you have the three-dimensional velocity vector for a bunch of stars, if you plot the velocity distribution, typically you find a bell curve with a thick tail. Adrian Blaauw in 1961 did this for each spectral type, and defined runaway stars as those in the TAIL of the velocity distribution. Now this requires having a full distribution and a definition of what the tail is, so for practical purposes

What is a runaway star?

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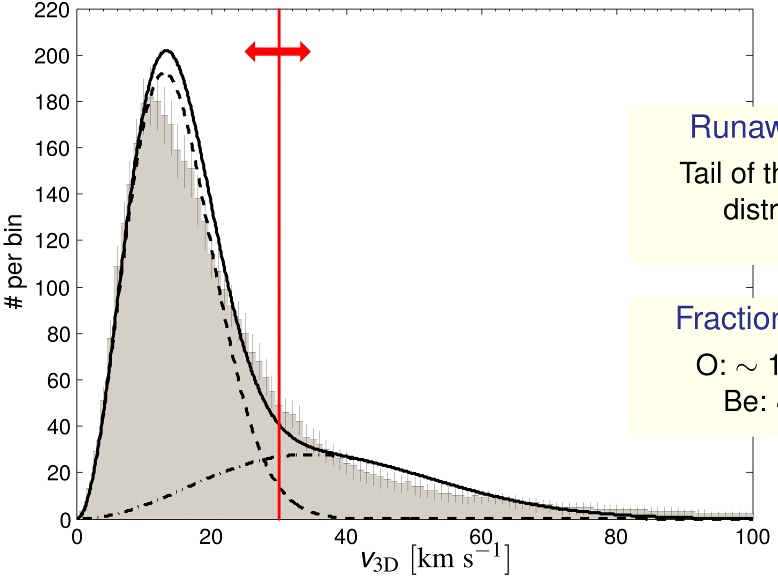

Runaway stars

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,

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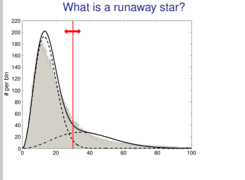

remember to say "O type", i.e. $\sim 20 M_\odot$ or more for people who don't know spectral types what is typically done is to ARBITRARILY draw a line to give an effective definition of what "tail" is: everything on the right is defined as a runaway star. Typical threshold (no physical meaning) are 30 or 40 *kms*.I use 30*kms*. For O type stars about 10-30% of stars are in the tail, and this is comparable to Be stars (and maybe slightly more than all early B-type stars), although these fractions are very uncertain because of the difficulty of measuring the 3 components of the velocity of a star and defining what is the tail of the distribution.

Note that HYPERvelocity star, with velocities larger than the escape velocity from the Galaxy have also been found, but these require different ejection mechanisms I will not touch upon.

Two ways to produce fast massive stars
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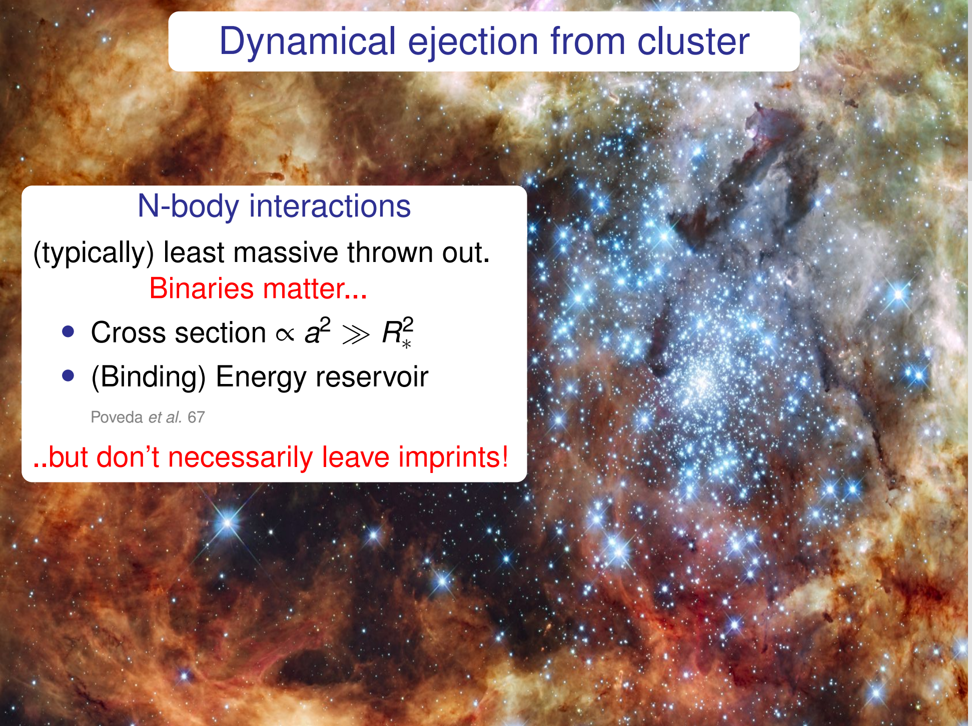
Binary SN disruption
The majority of massive binary are disrupted
Runaway X-ray binaries
Missing runaway "problem"?

How do we accelerate a massive star to make it become a runaway?
There are two mechanisms active in nature:
* dynamical ejections from dense stellar environments
* supernova explosion in a binary system
both are active in nature but we do not know the relative fraction
and I will compare these two and show you how we can use the end product, i.e. the runaway star, to study physical processes that matter for these processes.



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!

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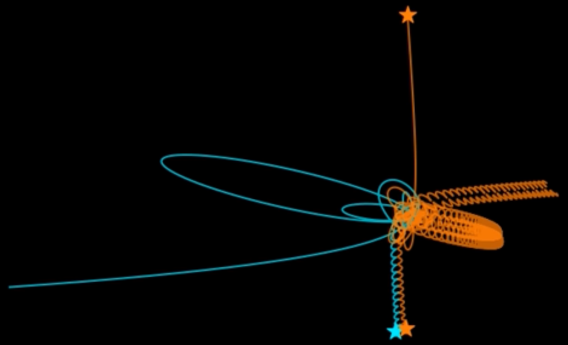
Poveda et al. 67
..but don't necessarily leave imprints!

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

Typical outcome of dynamical interactions

Timing of ejection

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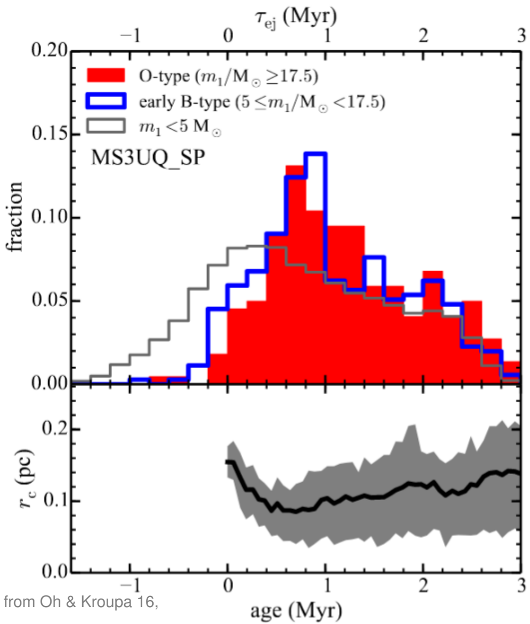


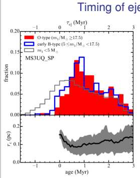
from Oh & Kroupa 16,

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



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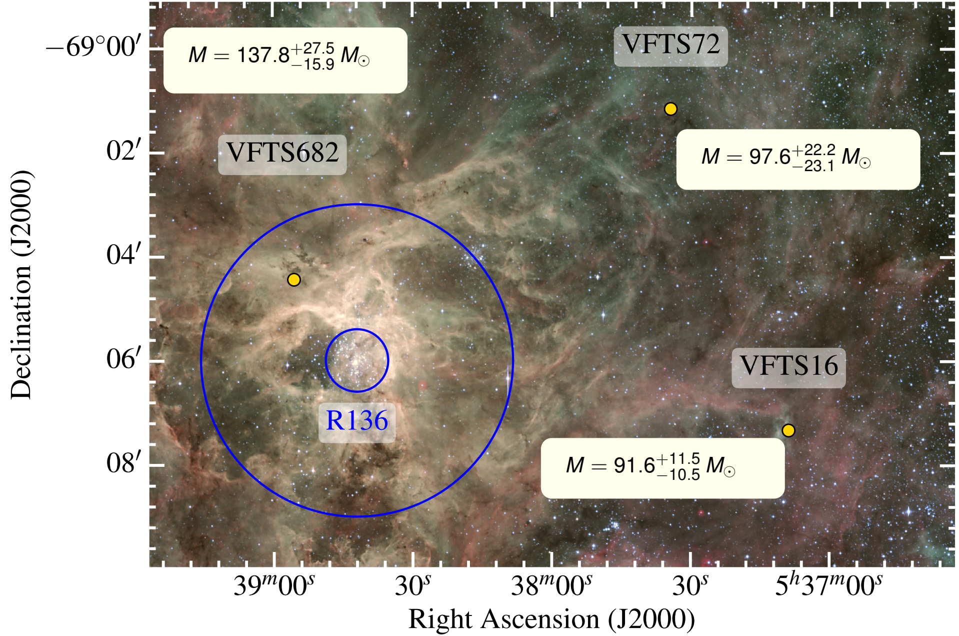
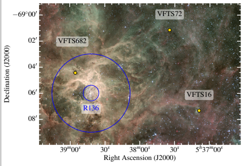
The most massive runaways known



Renzo *et al.* 19a

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



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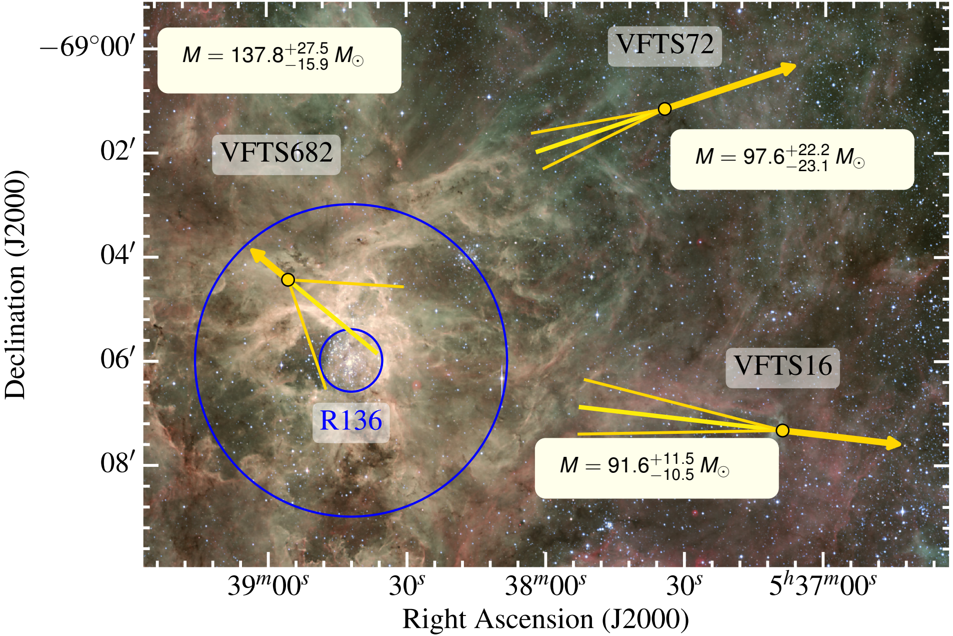

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2019-10-05

└Dynamical ejection from cluster
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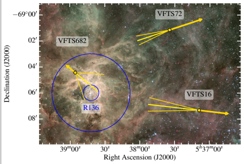

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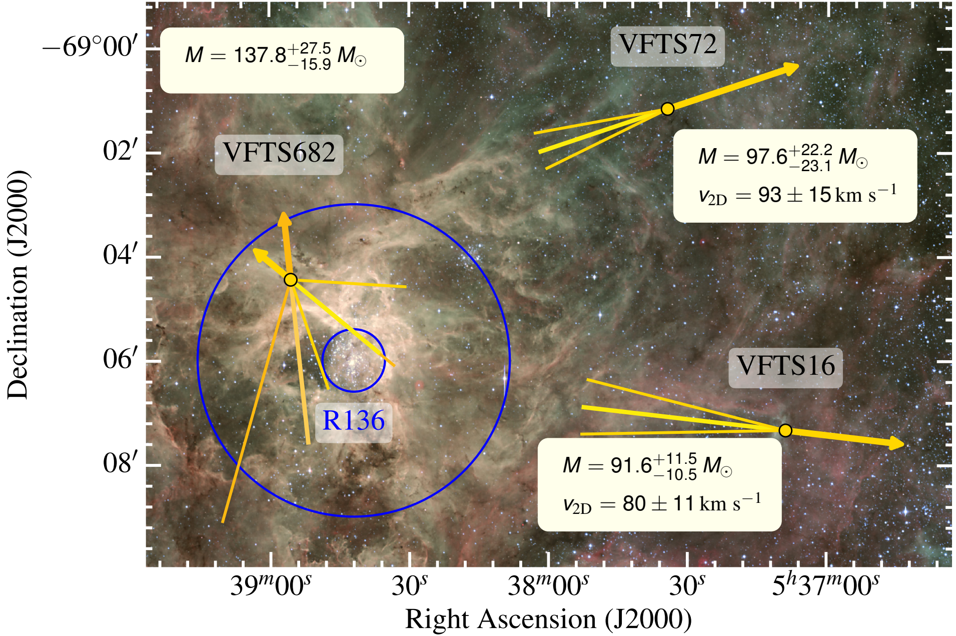

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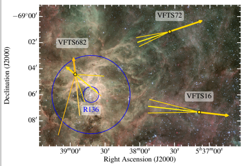

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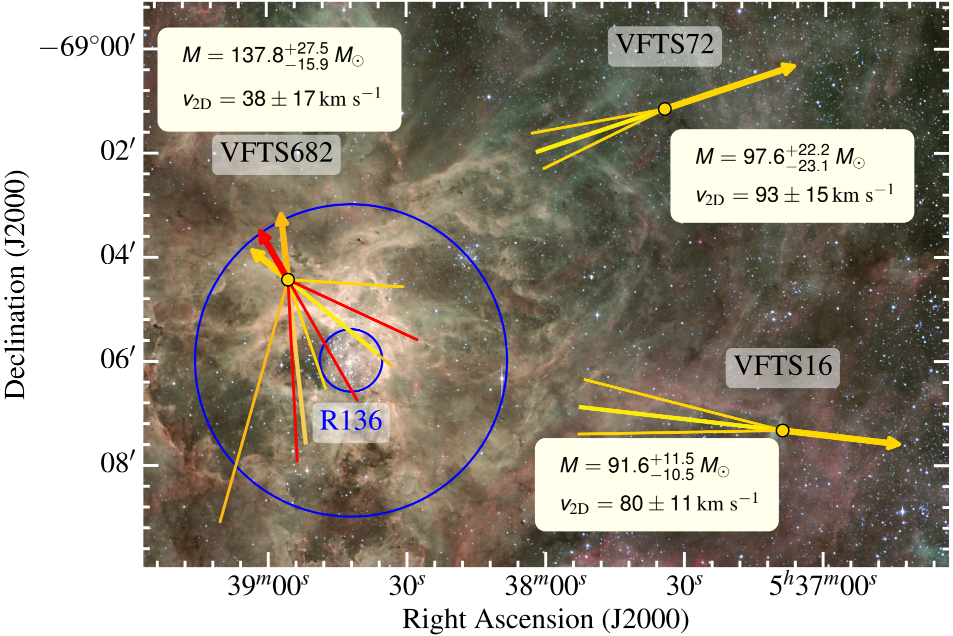

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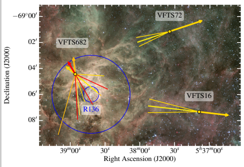

Summary of ejection mechanisms

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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

Summary of ejection mechanisms

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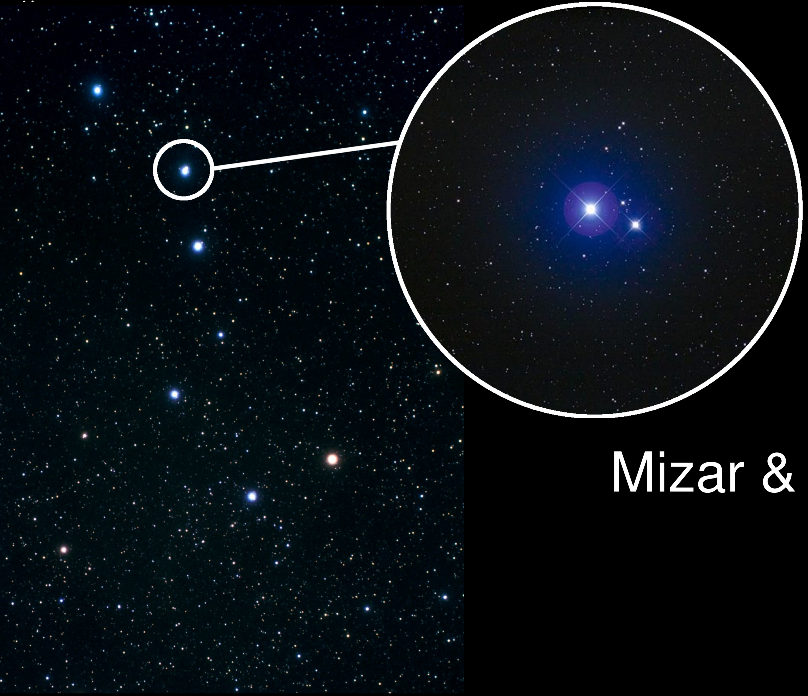
The big dipper

2019-10-05



Mizar & Alcor

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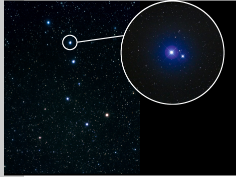
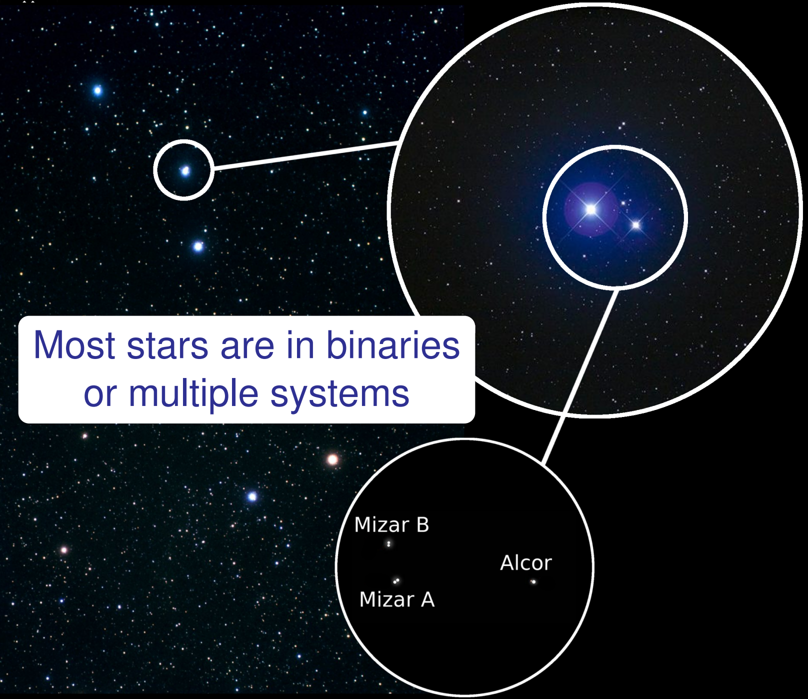
└Binary SN disruption

└The majority of massive binary are disrupted





Most stars are in binaries
or multiple systems

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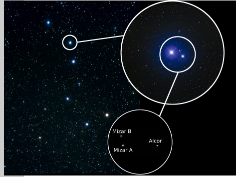

Most common massive binary evolution

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

2019-10-05

└Binary SN disruption
  └The majority of massive binary are disrupted
    └Most common massive binary evolution

Spin up, pollution, and rejuvenation

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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?

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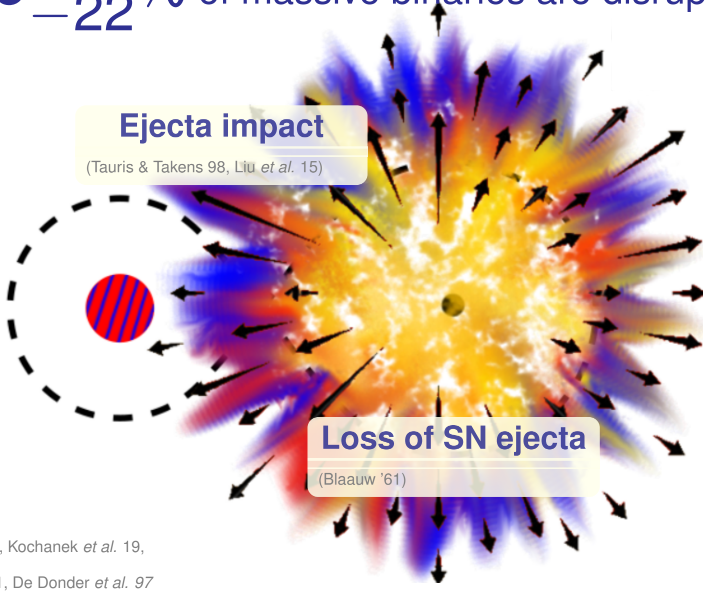
$86^{+11}_{-22}\%$ of massive binaries are disrupted



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

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

2019-10-05

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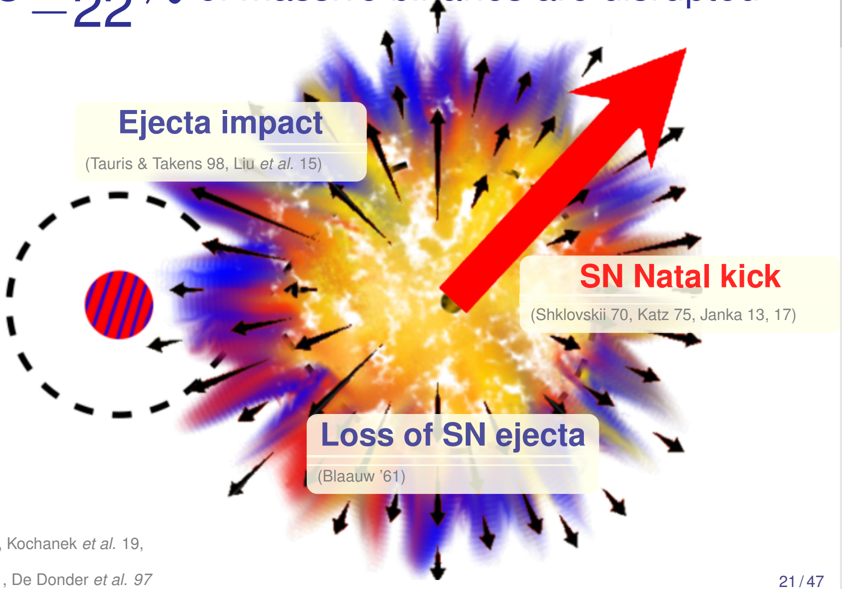

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2019-10-05

Binary SN disruption
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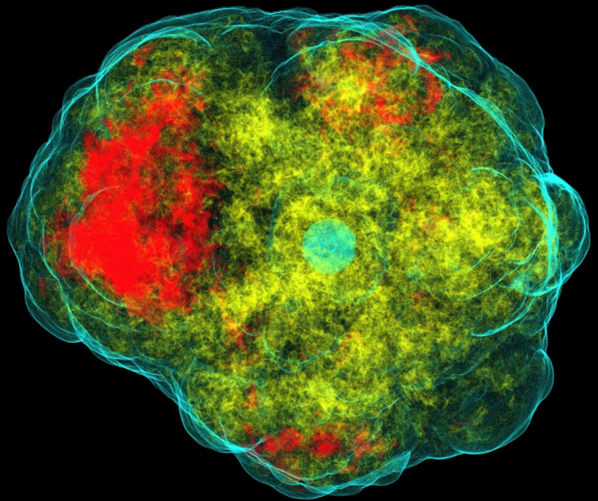
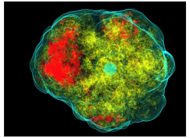
SN natal kick

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

Physically: ν emission and/or ejecta anisotropies



Credits: C. D. Ott, S. Drasco



What causes these natal kicks responsible for the binary disruption? From an observational point of view we know they exists because we see pulsars moving much faster than their parent O and early B type stars. From a theoretical perspective, we think that these kicks are due to asymmetries in the explosion dynamics, either in the neutrino flux that drives the explosion (although this is presently a bit disfavored) or because of the hydrodynamical instabilities in the explosion. For instance, here you see an entropy rendering of the core of an exploding 15Msun star, but for simplicity you can think of the color as the density. As you can see, this is not spherically symmetric: here you have a big red clump, which if it is denser, can gravitationally pull the proto-compact object (for up to a second) and as long as we have some ejecta in the other direction to conserve momentum, we can accelerate the proto compact object in the direction of the densest ejecta.

SN natal kick

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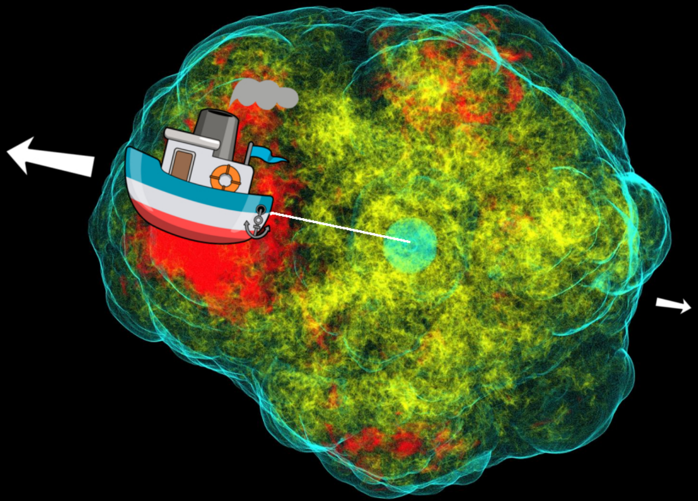

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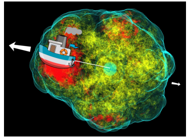

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Do BHs receive kicks?

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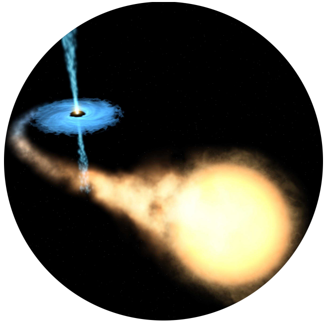
NO

⇒ most remain together with their widowed companion



YES

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

2019-10-05

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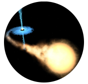

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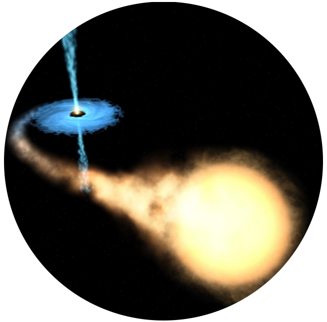
NO

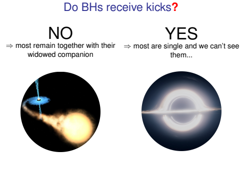
⇒ most remain together with their widowed companion



YES

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

...but we can see the widowed companion



A way to constrain BH kicks with Gaia

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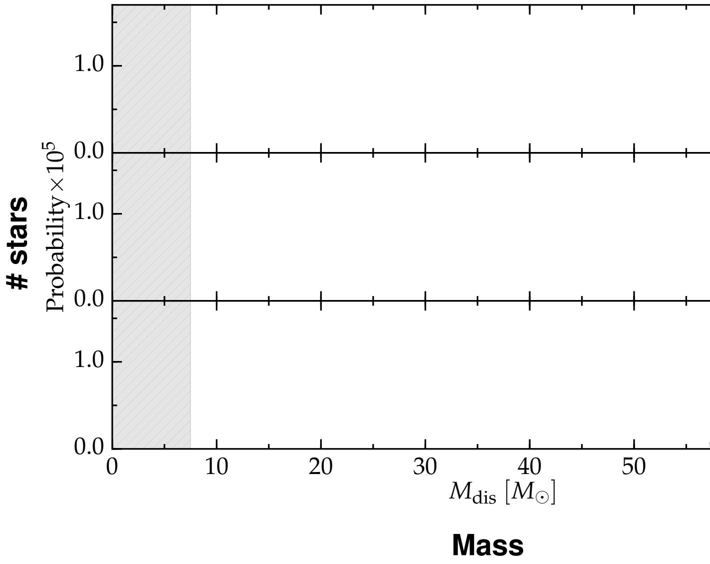
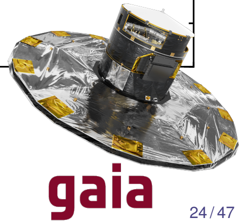
Massive runaways mass function ($v \geq 30\,\mathrm{km\ s^{-1}}$, $M \geq 7.5\,M_{\odot}$)





Renzo *et al.* 19b

2019-10-05

- Binary SN disruption
  - The majority of massive binary are disrupted
    - A way to constrain BH kicks with Gaia

A way to constrain BH kicks with Gaia

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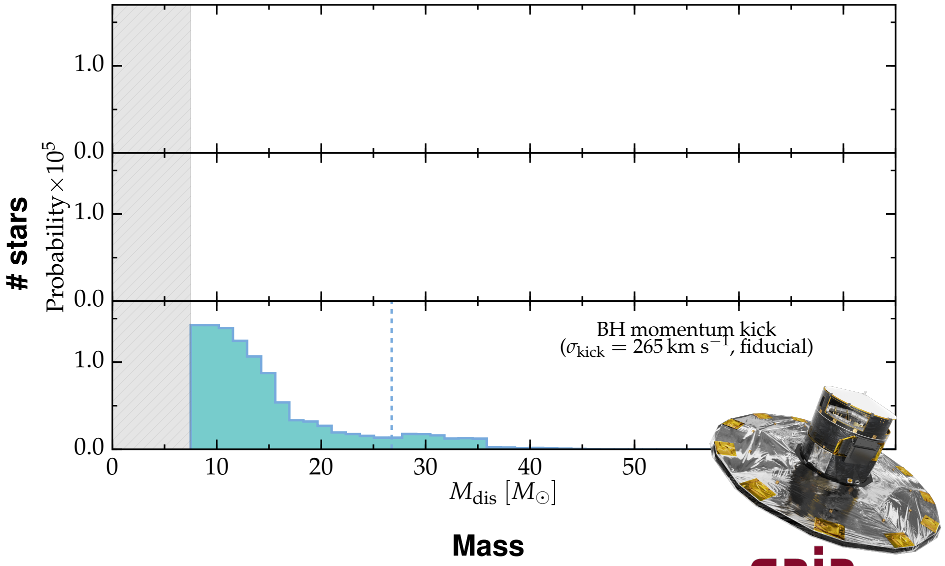

gaia

Renzo *et al.* 19b

2019-10-05

└Binary SN disruption
└The majority of massive binary are disrupted
└A way to constrain BH kicks with Gaia

A way to constrain BH kicks with Gaia

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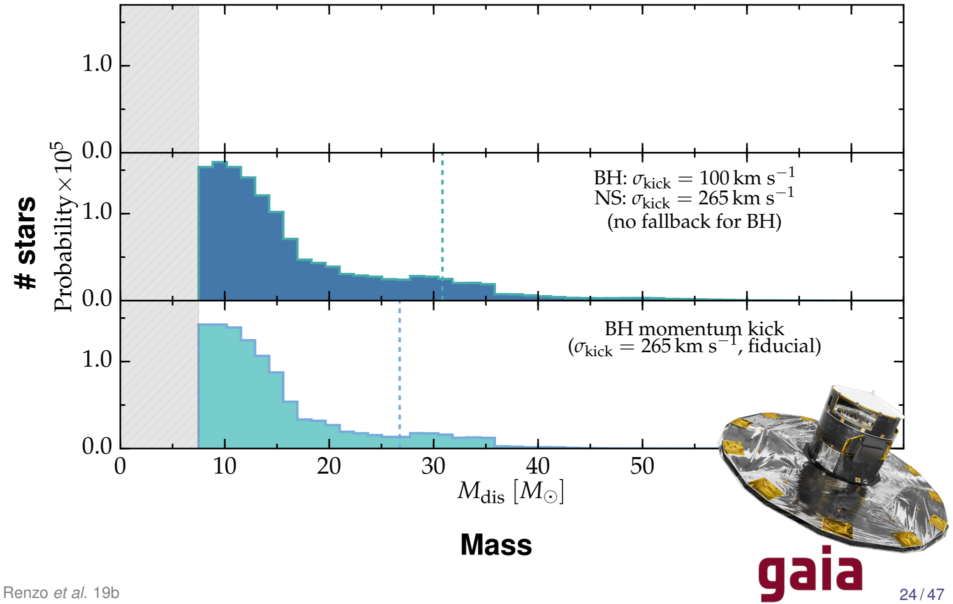

Renzo *et al.* 19b

2019-10-05

Binary SN disruption
The majority of massive binary are disrupted
A way to constrain BH kicks with Gaia

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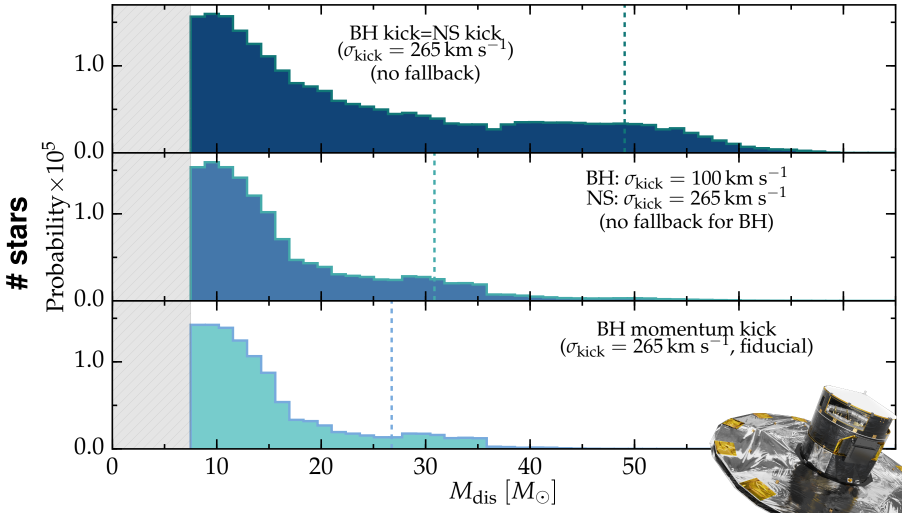

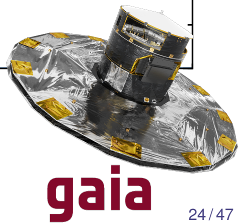

Renzo *et al.* 19b

2019-10-05

└Binary SN disruption
└The majority of massive binary are disrupted
└A way to constrain BH kicks with Gaia

A way to constrain BH kicks with Gaia

Kicks do not change companion velocity

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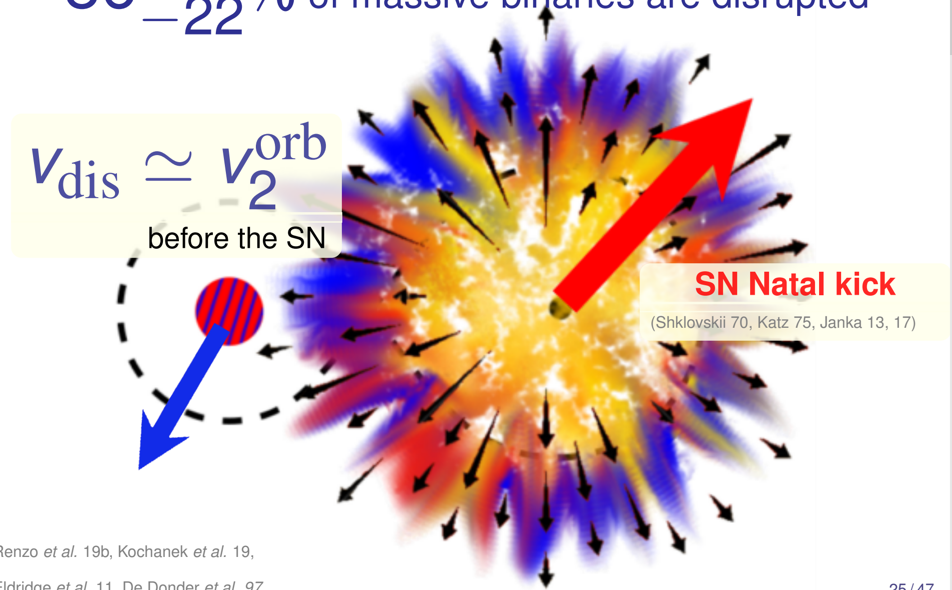
$86^{+11}_{-22}\%$ of massive binaries are disrupted



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

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

2019-10-05

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Kicks do not change companion velocity

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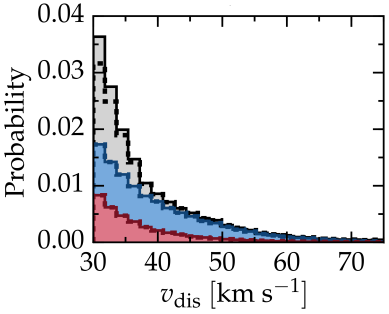
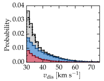


Renzo *et al.* 19b

Velocity distribution: **Runaways**



The first thing I want to draw your attention on is of course the velocity distribution of ejected widowed stars. Here you see the tail of the distribution above 30km/s (the typical threshold to define runaways). The three colors correspond to three lower mass cuts. The main thing to notice here is that *BINARIES HAVE A VERY HARD TIME PRODUCING MASSIVE RUNAWAYS FASTER THAN 60kms*.

Velocity distribution: **Walkaways**

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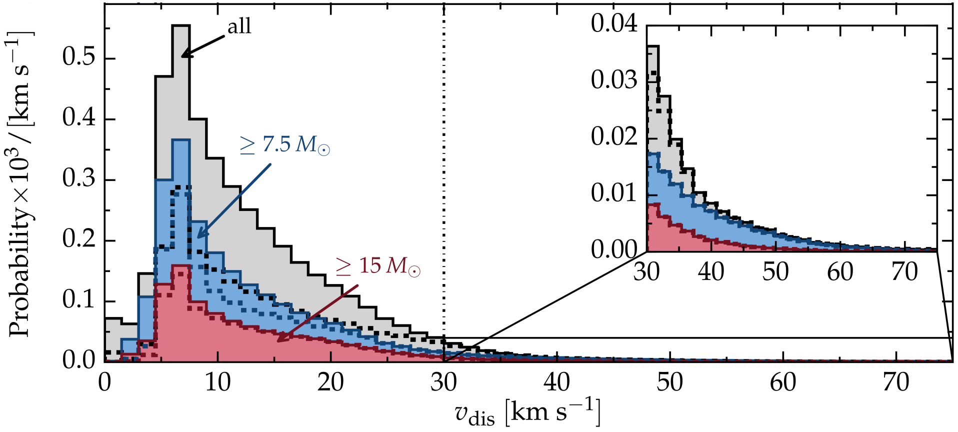
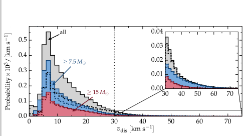


Renzo *et al.* 19b

2019-10-05

└Binary SN disruption
  └The majority of massive binary are disrupted
    └Velocity distribution: **Walkaways**



Take home points:

- Walkaways outnumber the runaways by $\sim 10\times$
- Binaries barely produce fast runaways
- All runaways from binaries are post-interaction objects

Velocity distribution: **Walkaways**

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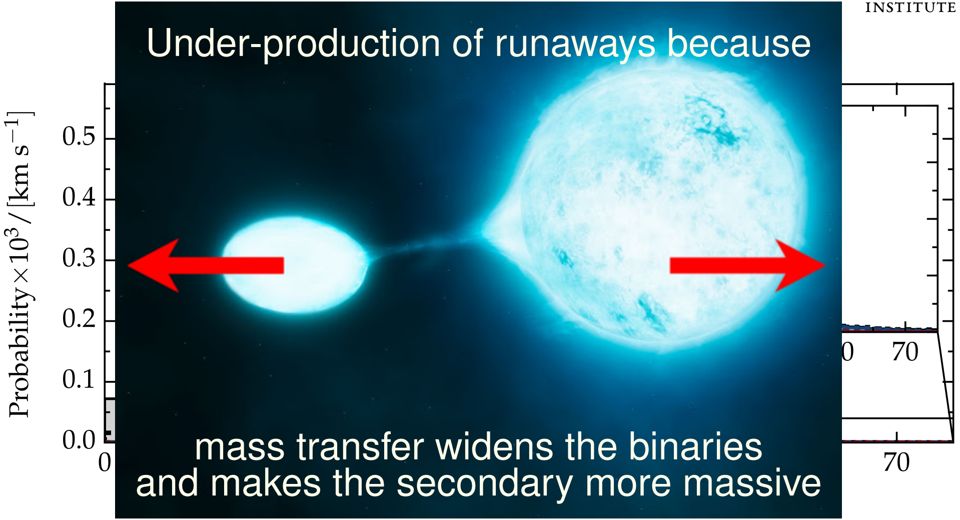
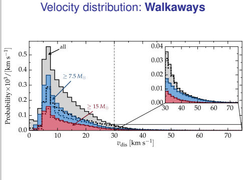


Renzo *et al.* 19b



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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

Missing runaway "problem"?

Outline

How to measure stellar velocities?
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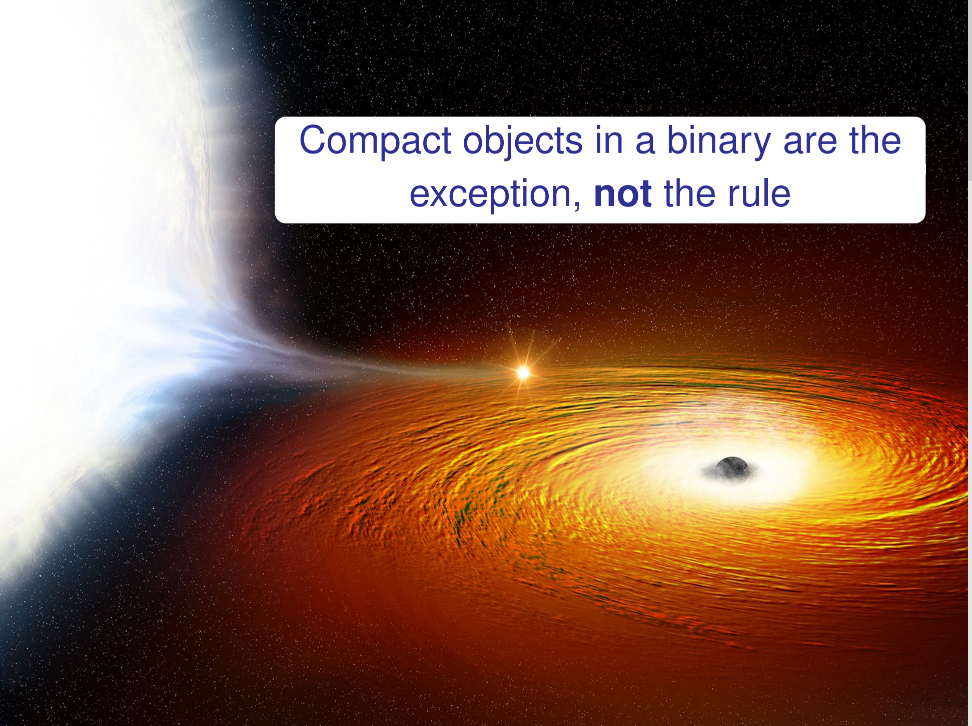

Compact objects in a binary are the exception, **not** the rule

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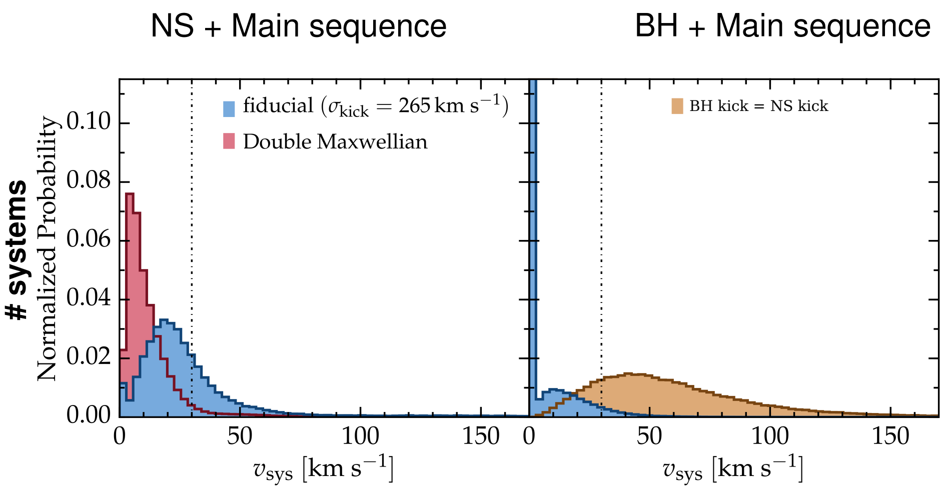
Post-SN velocity of surviving binaries



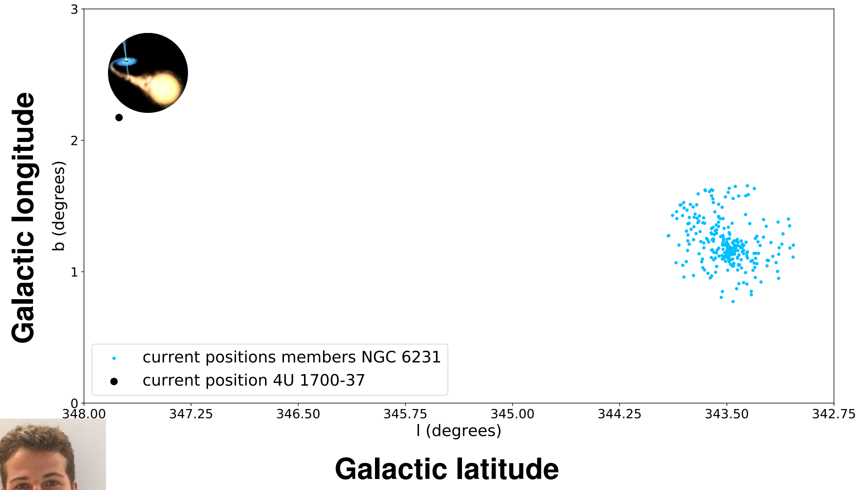
Velocity respect to the pre-explosion binary center of mass

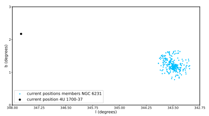
Renzo *et al.* 19b

2019-10-05

Post-SN velocity of surviving binaries

Preliminary: The case of 4U1700-37





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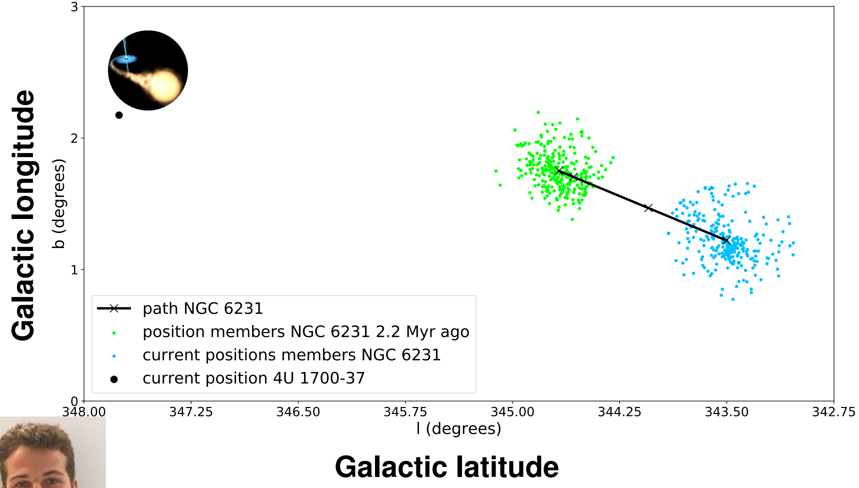
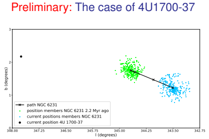


van der Meij *et al.* (incl. MR), in prep.

2019-10-05



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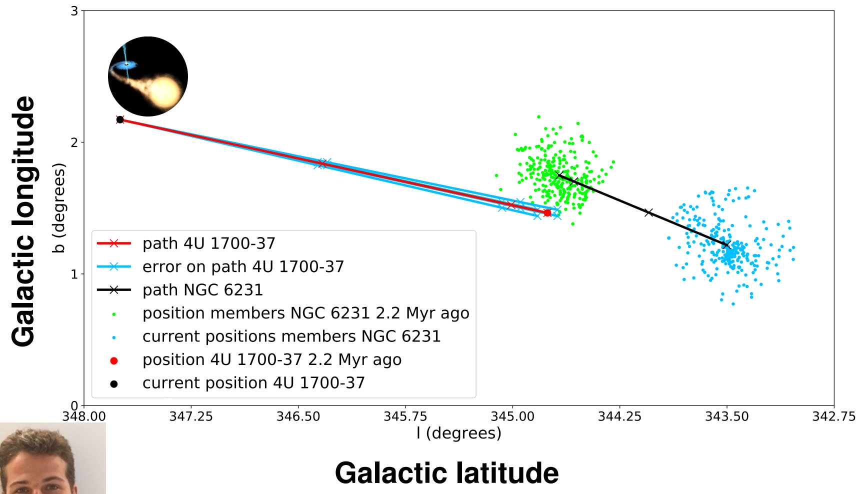

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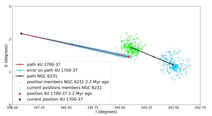

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Summary of ejection mechanisms

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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

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

  spin up, pollution, rejuvenation

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Relative efficiency **?**

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

Hoogerwerf *et al.* 01

2019-10-05

O type stars runaway fraction

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

Observational claims:

$\sim$ 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

Emphasize that numerator is regardless of ejection mechanism
Note the metallicity dependence of the theoretical runaway fraction If from the population synthesis theory side we are correct, than this discrepancy might be telling us that we are doing something wrong with the orbital evolution of the binaries, and we are predicting that we widen too much during RLOF (or maybe common envelope evolution happens more often?).

However, this is not necessarily a problem since: Jilinski et al. could not reproduce the result of Hoogerwerfer 01, and Gaia is suggesting a higher than previously thought dyamical ejection efficiency. This is a problem only if the majority of runaways come from binaries. Moreover, as you can see from the wide range claimed by observers, there is ambiguity in the definition of runaway: what minimum velocity do we require? In what reference frame are we measuring that velocity? The answer to these questions can change the observed fraction quite a lot. So this potential problem will need to be revisited when the

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~~$\sim$ 2 f... inaries~~

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

Emphasize that numerator is regardless of ejection mechanism

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Conclusions

Outline

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Backup slides

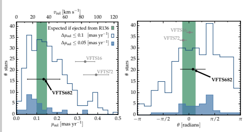
2019-10-05

└Backup Slides

└Outline

Outline

Backup slides



VFTS682: Concordant Picture?

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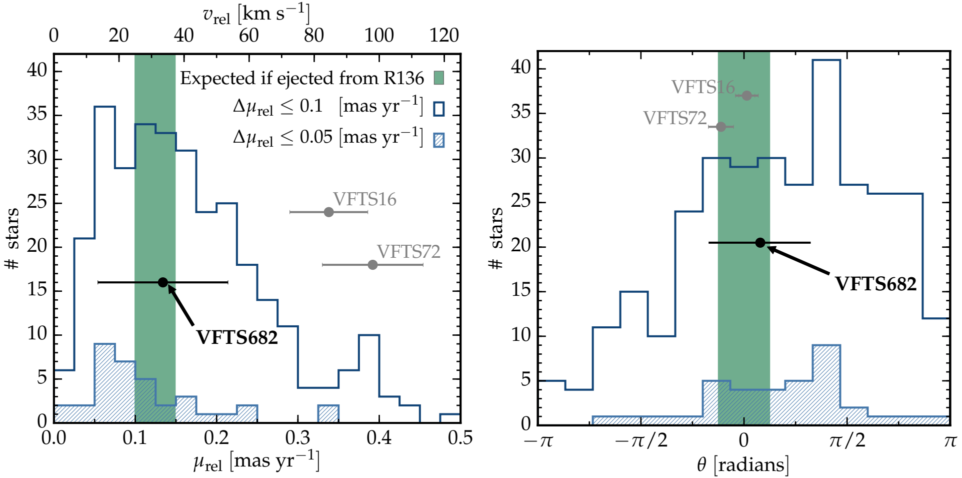

Large error bars compatible with no motion, but
best values fit with expectations for dynamical ejection

Renzo *et al.* 19a

Method: Population Synthesis

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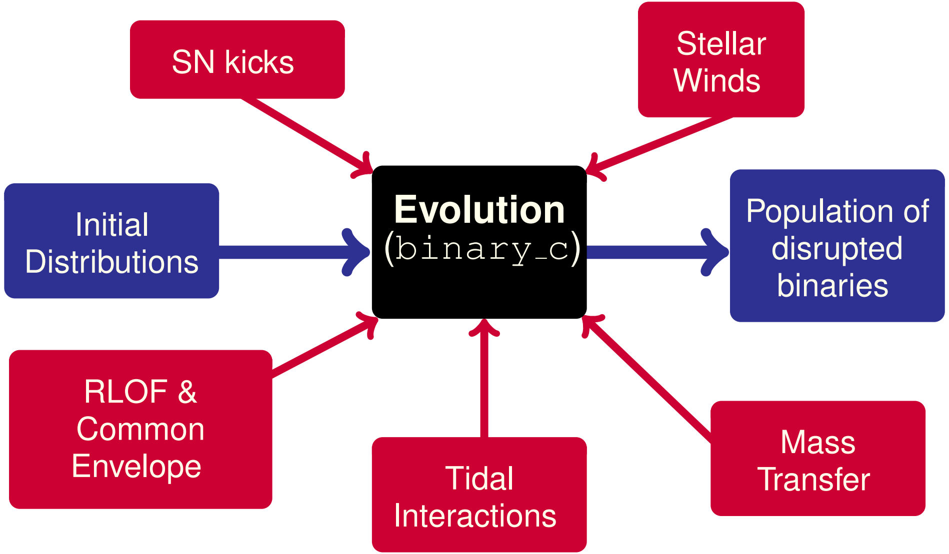
Fast ⇒ Allows statistical tests of the inputs & assumptions

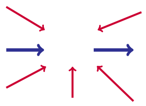


Izzard *et al.* '04, '06, '09; de Mink *et al.* '13

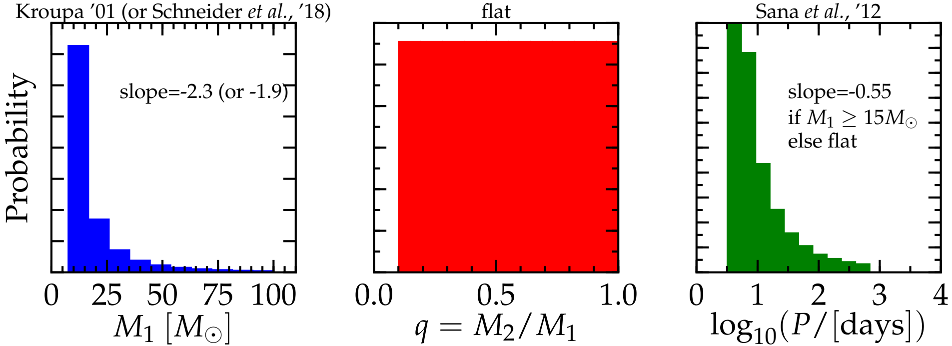
2019-10-05

└Backup Slides
└Population synthesis predictions
└Method: Population Synthesis

Method: Population Synthesis

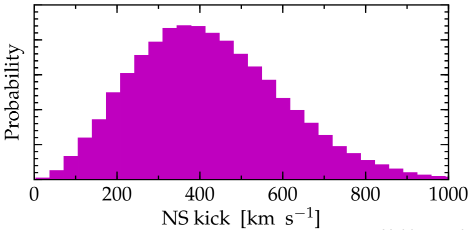


Izzard et al. '04, '06, '09; de Mink et al. '13



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

(from Fryer *et al.* '12)



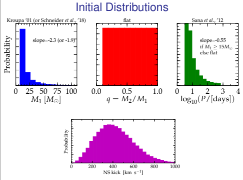
Hobbs *et al.* '05

2019-10-05

└ Backup Slides

└ Population synthesis predictions

└ Initial Distributions



Star forming region velocity dispersion

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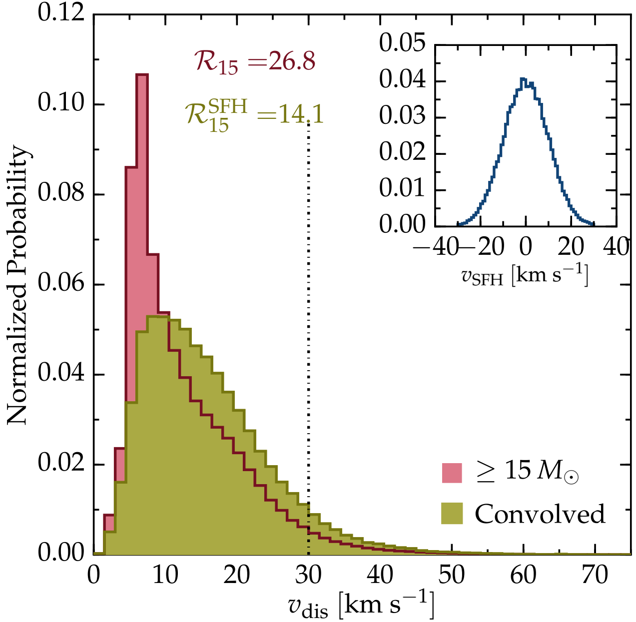
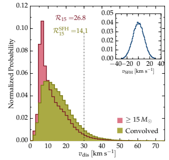


Renzo *et al.* 19b

2019-10-05



Velocity distribution log-scale

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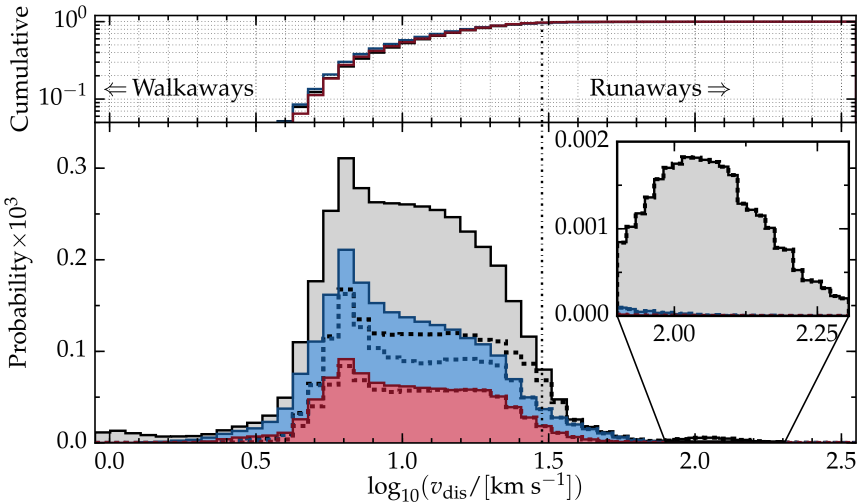
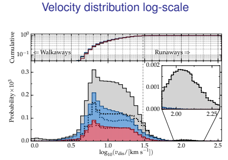


Renzo *et al.* 19b

2019-10-05

Backup Slides
Population synthesis predictions
Velocity distribution log-scale



Velocity post-main sequence stars

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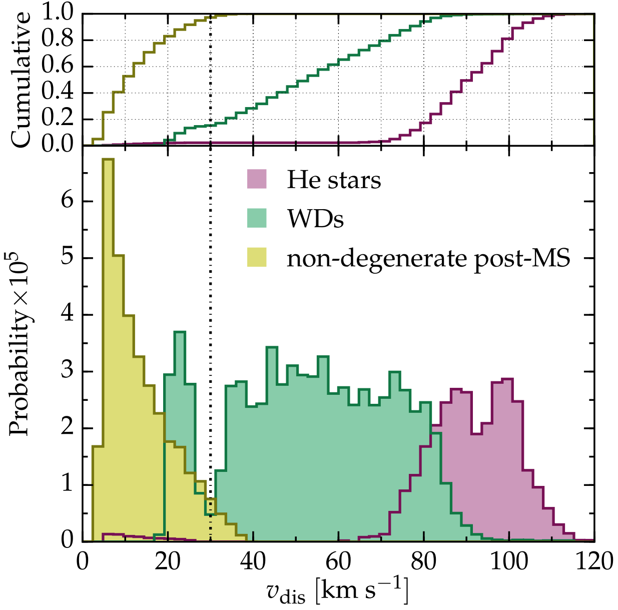

Renzo *et al.* 19b

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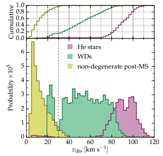

pre-CC mass distribution

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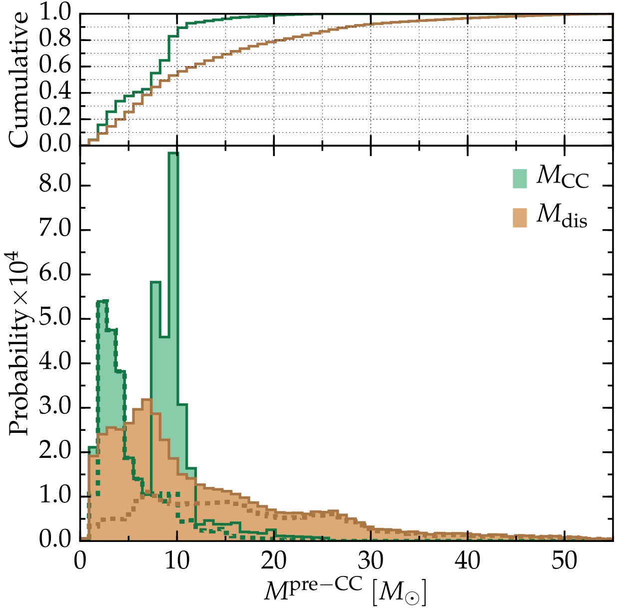
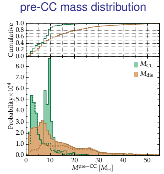


Renzo *et al.* 19b

2019-10-05

Backup Slides
Population synthesis predictions
pre-CC mass distribution



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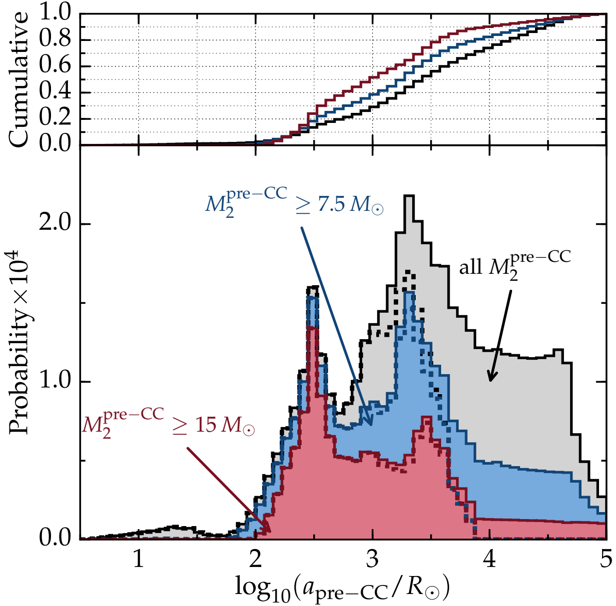
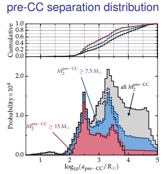


Renzo *et al.* 19b



Mass-velocity varying the natal kick

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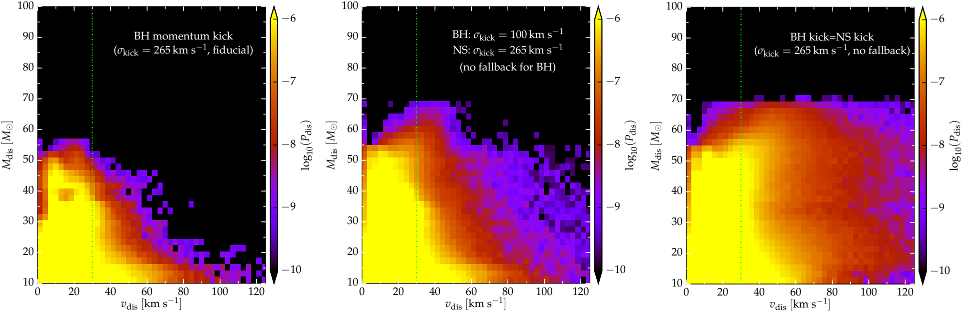
Fiducial	Intermediate BH kick	Large BH kicks
$\sigma_{\mathrm{kick}} = 265\,\mathrm{km\ s^{-1}}$	$\sigma_{\mathrm{kick}} = 100\,\mathrm{km\ s^{-1}}$	(no fallback)



Renzo *et al.* 19b

2019-10-05

Backup Slides
Population synthesis predictions
Mass-velocity varying the natal kick

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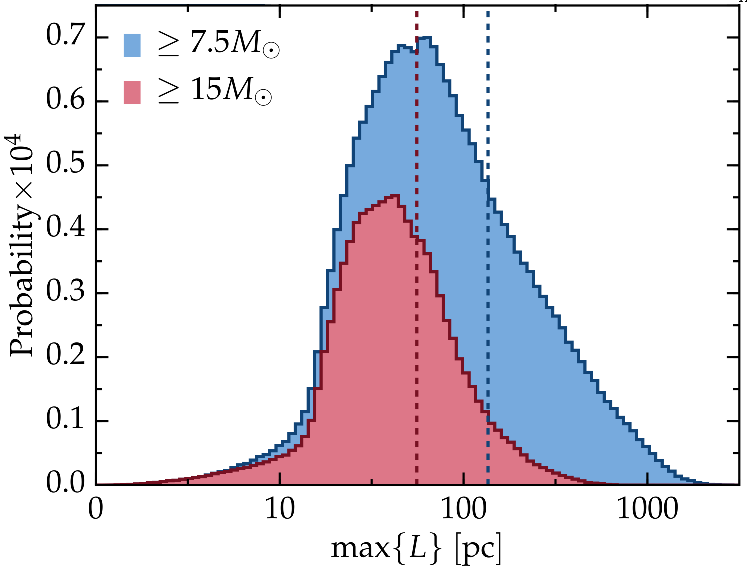

"Distance traveled"

(No potential well)

Renzo *et al.* 19b

2019-10-05