Binary evolution and supernova kicks

Mathieu Renzo
The most common binary evolution path

Initial close binary

see outreach movie at
https://www.youtube.com/watch?v=qmfJNI0PXbo
The most common binary evolution path

Initial close binary → Orbit Widens

see outreach movie at
https://www.youtube.com/watch?v=qmfJNI0PXbo
The most common binary evolution path

Initial close binary

Orbit Widens

Stripped star + Accretor

see outreach movie at

https://www.youtube.com/watch?v=qmfJNI0PXbo
The most common binary evolution path

Initial close binary → Orbit Widens → Stripped star + Accretor → Core Collapse & Disruption

see outreach movie at https://www.youtube.com/watch?v=qmfJNI0PXbo
How common is “common”?

Binaries with
\[ M_{1}^{ZAMS} \geq 7.5 M_{\odot} \]
\[ q^{ZAMS} \geq 0.1 \]
\[ 0.15 \leq \log_{10}(P_{ZAMS}/\text{days}) \leq 5.5 \]

\[ 22^{+26}_{-9}\% \]

Stellar mergers

\[ 1 - \mathcal{D} = 14^{+22}_{-10}\% \]

Non mergers

\[ \mathcal{D} = 86^{+10}_{-22}\% \]

Non Disrupted (cf. Sec. 7)

\[ 36^{+42}_{-15}\% \]

NS companion

\[ 64^{+15}_{-42}\% \]

BH companion

Disrupted

\[ 25^{+8}_{-10}\% \]

Post-MS companion (cf. Sec. 5.3)

\[ 53^{+12}_{-46}\% \]

WD

\[ 25^{+23}_{-6}\% \]

He star

\[ 23^{+38}_{-20}\% \]

H-rich

\[ 5^{+14}_{-2}\% \]

Runaway \( v_{\text{dis}} \geq 30 \text{ km s}^{-1} \)

\[ 95^{+2}_{-14}\% \]

Walkaway \( v_{\text{dis}} < 30 \text{ km s}^{-1} \)

Renzo et al. 19b
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
What exactly disrupts the binary?

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

- **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
Kicks do not change companion velocity

\[ v_{\text{dis}} \sim v_{\text{orb}}^{2} \]

before the SN

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

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
BH kicks from the mass of runaways
A way to constrain BH kicks with Gaia

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

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

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A way to constrain BH kicks with Gaia

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

- BH: $\sigma_{\text{kick}} = 100 \text{ km s}^{-1}$
- NS: $\sigma_{\text{kick}} = 265 \text{ km s}^{-1}$
  (no fallback for BH)

BH momentum kick
($\sigma_{\text{kick}} = 265 \text{ km s}^{-1}$, fiducial)

Numerical results publicly available at::
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A way to constrain BH kicks with Gaia

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

- BH kick = NS kick ($\sigma_{\text{kick}} = 265 \text{ km s}^{-1}$) (no fallback)
- BH: $\sigma_{\text{kick}} = 100 \text{ km s}^{-1}$
- NS: $\sigma_{\text{kick}} = 265 \text{ km s}^{-1}$ (no fallback for BH)

BH momentum kick ($\sigma_{\text{kick}} = 265 \text{ km s}^{-1}$, fiducial)

Numerical results publicly available at:
http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66
Mass-velocity varying the natal kick

Fiducial

\( \sigma_{\text{kick}} = 265 \text{ km s}^{-1} \)

Intermediate BH kick

\( \sigma_{\text{kick}} = 100 \text{ km s}^{-1} \)

Large BH kicks (no fallback)

\( \sigma_{\text{kick}} = 265 \text{ km s}^{-1}, \text{ no fallback} \)

Numerical results publicly available at:
http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66
Kicks constraints from XRBs astrometry
Post-SN velocity of surviving binaries

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

\[ M \sim 2.5 M_\odot, \ M_* \sim 60 \pm 10 M_\odot, \ P \sim 3.4 \text{ days}, \ e \sim 0.22, \ \nu \sim 60 \text{ km s}^{-1} \]

Galactic longitude

Galactic latitude

- current positions members NGC 6231
- current position 4U 1700-37

M \sim 2.5 \, M_\odot, \quad M_\star \sim 60 \pm 10 \, M_\odot, \quad P \sim 3.4 \, \text{days}, \quad e \sim 0.22, \quad v \sim 60 \, \text{km s}^{-1}

**Preliminary: The case of 4U1700-37**

\[ M \approx 2.5 \, M_\odot, \quad M_\star \approx 60 \pm 10 \, M_\odot, \quad P \approx 3.4 \text{ days}, \quad e \approx 0.22, \quad v \approx 60 \, \text{km s}^{-1} \]

![Diagram showing Galactic latitude and longitude with data points and paths for 4U1700-37 and NGC 6231.](image_url)

Conclusions
Take home points

Natal kicks cause the disruption of $86^{+11}_{-22}\%$ of massive binaries

For disrupted binaries the kick acts only on compact object
⇒ walkaways outnumber the runaways;

If binary remains bound the kick changes the kinematics of the whole system;

Runaway mass distribution ⇒ constraints on BH kicks without seeing the collapse nor the BH.
Backup slides
Methods: Population Synthesis

Fast → Allows statistical tests of the inputs & assumptions

- SN kicks
- Stellar Winds
- Initial Distributions
- Synthetic Population (available online)
- RLOF & Common Envelope
- Tidal Interactions
- Mass Transfer
Initial Distributions

Kroupa '01 (or Schneider et al., '18)

slope = -2.3 (or -1.9)

Sana et al., '12

slope = -0.55
if $M_1 \geq 15M_\odot$
else flat

Maxwellian $\sigma_{v_{\text{kick}}} = 265 \text{ km s}^{-1} + \text{ Fallback rescaling}$
(from Fryer et al. '12)

Hobbs et al. '05

$\log_{10}(P/\text{[days]})$
Velocity distribution: Runaways

Velocity respect to the pre-explosion binary center of mass

Numerical results publicly available at:

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Velocity distribution: Walkaways

Velocity respect to the pre-explosion binary center of mass

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Velocity distribution: Walkaways

Under-production of runaways because mass transfer widens the binaries and makes the secondary more massive

Velocity respect to the pre-explosion binary center of mass

Numerical results publicly available at:
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Star forming region velocity dispersion

$$R_{15} = 26.8$$

$$R_{15}^{SFH} = 14.1$$

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

$M_{\text{pre-CC}}^2 \geq 15 \, M_\odot$

$M_{\text{pre-CC}}^2 \geq 7.5 \, M_\odot$

all $M_{\text{pre-CC}}^2$

$\log_{10}(a_{\text{pre-CC}}/R_\odot)$

Probability $\times 10^4$

Cumulative
How far do they get?

“Distance traveled”
(No potential well)

Renzo et al. 19b