Explosions in massive binaries:
“widowed” stars and consequences for GW astronomy


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Why are massive stars important?

Nucleosynthesis & Chemical Evolution

Star Formation

Ionizing Radiation

Supernovae

GW Astronomy
Why are massive stars important?

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GW Astronomy

∼70% of O type stars will interact with a companion

(e.g., Mason et al. ’09, Sana & Evans ’11, Sana et al. ’12, Kiminki & Kobulnicky ’12, Kobulnicky et al. ’14, Almeida et al. ’17)
Masses in the Stellar Graveyard in Solar Masses

Credits: LIGO, F. Elavsky, Northwestern
Outline

BH or NS?
- Single stars winds impact on the core structure

Keep the stars together
- The most common evolution for massive binaries
- Constraints on BH kicks using runaway “widow”

The most massive (stellar) BHs
- (Pulsational) pair instability
- The BH mass distribution
  - Induced eccentricity
  - Post-pulsations BH spins

Conclusions
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Radiatively Driven Winds in One Slide

\[ \Delta p = \frac{h}{c} \left( \nu_i \cos(\theta_i) - \nu_f \cos(\theta_f) \right) \]

Problems: High Non-Linearity and Clumpiness
Clumpiness

Inhomogeneities:

\[ f_{cl} \overset{\text{def}}{=} \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \neq 1 \Rightarrow \dot{M} \neq 4\pi r^2 \rho v(r) \]
Clumpiness

Risk:
Possible overestimation of the wind mass loss rate

Inhomogeneities:

\[ f_{cl} \stackrel{\text{def}}{=} \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \neq 1 \Rightarrow \dot{M} = \eta \frac{4\pi r^2 \rho v(r)}{2} \]
Grid of $Z_\odot$ non-rotating models:

$$M_{\text{ZAMS}} = \{15, 20, 25, 30, 35\} \ M_\odot$$

$$\eta = \{1, \frac{1}{3}, \frac{1}{10}\}$$

Combinations of wind mass loss rates for “hot” ($T_{\text{eff}} \geq 15 \ [kK]$), “cool” ($T_{\text{eff}} < 15 \ [kK]$) and WR:

Impact on the final mass

Legend:

- $\eta = 0.1$
- $\times \eta = 0.33$
- $+ \eta = 1.0$

$\eta \rightarrow$ largest uncertainty

Renzo et al. '17
Impact on the final mass

\[ \eta = 0.1 \]
\[ \eta = 0.33 \]
\[ \eta = 1.0 \]

\( \eta \rightarrow \) largest uncertainty
“Explodability” & Compactness

\[ \xi_M(t) \overset{\text{def}}{=} \frac{M/M_\odot}{R(M)/1000 \text{ km}} \]

Single parameter to describe the core structure

e.g., O’Connor & Ott ’11,
Ugliano et al. ’12,
Sukhbold & Woosley ’14,
but see (for 3D explosions):
Ott et al. ’18,
Kuroda et al. ’18

\[ M = 2.5 M_\odot \]

not to scale!
Core structure at O depletion

\[ M_{\text{ZAMS}} = 25 \, M_\odot \] **MESA** models

\[ \log_{10}(\frac{(t_{\text{O depl}} - t)}{[\text{yr}]}) \]

Critical point:
Ne core/C shell burning

\[ T_c \geq 10^9 \, \text{K} \]
Post O burning evolution

Si shell burning

\[ \log_{10}( (t_{\text{pre-SN}} - t) / [\text{yr}] ) \]

\begin{align*}
15M_{\odot}, \eta = 1.0 \\
25M_{\odot}, \eta = 0.33 \\
30M_{\odot}, \eta = 0.33
\end{align*}

Renzo et al. '17
Post O burning evolution

Si shell burning $\rightarrow$

$\sim 30\%$ Uncertainty in $\xi_{2.5}^{\text{pre-SN}}$ for given $\eta$

Uncertainties in the wind impact the pre-SN core

$\log_{10}(\left((t_{\text{pre-SN}} - t)/[\text{yr}]\right))$

Log time to core-collapse
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Methods: Population Synthesis

Fast ⇒ Allows statistical tests of the inputs & assumptions

- SN kicks
- Stellar Winds
- Initial Distributions
- Population of disrupted binaries
- RLOF & Common Envelope
- Tidal Interactions
- Mass Transfer

Izzard et al. ’04, ’06, ’09; de Mink et al. ’13
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)
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$V_{\text{dis}} \sim V_{\text{pre-SN}}^{2,\text{orb}} = \frac{M_1}{M_1 + M_2} \sqrt{\frac{G(M_1 + M_2)}{a}}$

Most binaries produce a slow “walkaway” star
SN natal kick

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

Physically: $\nu$ emission and/or ejecta anisotropies

Credits: Ott, C. D., Drasco, S.
SN natal kick

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A way to constrain BH kicks with Gaia

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

Renzo et al., submitted, arXiv:1804.09164
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 momentum kick
\((\sigma_{\text{kick}} = 265 \text{ km s}^{-1}, \text{fiducial})\)

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

Renzo et al., submitted, arXiv:1804.09164
A way to constrain BH kicks with Gaia

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

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

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

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

Renzo et al., submitted, arXiv:1804.09164
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Radiation dominated:

\[ P_{\text{tot}} \sim P_{\text{rad}} \]

\[ M_{\text{He}} \gtrsim 32 \, M_\odot \]

Woosley 2017,
Marchant, Renzo et al. arXiv:1810.13412,
Renzo, Farmer et al., to be submitted
\Gamma_1 \overset{\text{def}}{=} \left( \frac{\partial \ln P}{\partial \ln \rho} \right)_s

\langle E_{\gamma} \rangle < \langle E_{\gamma} \rangle < E_{\text{Fermi}}

\langle E_{\gamma} \rangle < 2m_e c^2

\Gamma_1 < 4/3

\rho [\text{g cm}^{-3}] \quad \text{He core computed with MESA}

\nonumber M_{\text{He}} = 46 M_{\odot}, Z = 0.001

1. Pair production
\gamma \gamma \rightarrow e^+ e^-

\nonumber \frac{\partial \ln P}{\partial \ln \rho}

\nonumber \left( \frac{\partial \ln P}{\partial \ln \rho} \right)_s

\nonumber \Gamma_1

\nonumber \langle E_{\gamma} \rangle

\nonumber E_{\text{Fermi}}

\nonumber m_e c^2

\nonumber \text{non rel. } e^\pm

\nonumber \text{pressure support}
Thermal timescale

\[ \tau \propto \frac{GM_{\text{He}}^2}{RL_v}, \quad L_v \gg L \]

(Fraley 68)

1. Pair production
\[ \gamma\gamma \rightarrow e^+e^- \]

2. Softening of EOS triggers collapse
\[ \Gamma_1 < \frac{4}{3} \]
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\[ \gamma \gamma \rightarrow e^+ e^- \]

2. Softening of EOS triggers collapse
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3. Explosive (oxygen) ignition
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3. Explosive (oxygen) ignition

4a. Pulse with mass ejection

4b. PISN: complete disruption

1. Pair production
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2. Softening of EOS triggers collapse
\[ \Gamma_1 < \frac{4}{3} \]

3. Explosive (oxygen) ignition

4a. Pulse with mass ejection

4b. PISN: complete disruption

5. \( \nu \)-cooling and contraction

6. Entropy loss and fuel depletion stabilize the core

7. BH

Renzo, Farmer, et al., to be submitted
Example: $40 \, M_\odot$ He core

\begin{align*}
\log_{10}\{(t_{cc} - t)/[\text{yr}]\} & \quad \log_{10}(T_c/[\text{K}])
\end{align*}

Log Time to core-collapse

Renzo, Farmer et al., to be submitted
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The origin of very massive BHs

He core mass

$M_{\text{CO}} \left[ M_\odot \right]$
The origin of very massive BHs

Renzo, Farmer et al., to be submitted
The origin of very massive BHs

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The origin of very massive BHs

Renzo, Farmer et al., to be submitted
BH mass function

\[ \frac{dN}{dM_{BH}} \propto M_{BH}^{-2.35} \]

\[ q \geq 0.5 \]

(motivated by LVC 2016)
BH mass function

\[ \frac{dN}{dM_{\text{BH}}} \propto M_{\text{BH}}^{-2.35} \]

\[ q \geq 0.5 \]

(motivated by LVC 2016)

\[ M_{\text{chirp}} \overset{\text{def}}{=} \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} \left[ M_\odot \right] \]

\( dN/dM \times M_{\text{BH}}^{2.2} \)

LIGO/Virgo O3 will answer!

- Is there a gap?
  \[ \Rightarrow \mathcal{O}(10) \text{ binary BH detection} \]

- Where is the lower edge of the gap?
  \[ \Rightarrow \mathcal{O}(100) \text{ binary BH detection} \]

\[ \frac{dN}{dM_{\text{BH}}} \propto M_{\text{BH}}^{-2.35} \]

\[ q \geq 0.5 \]

(motivated by LVC 2016)


\[ M_{\text{chirp}} \overset{\text{def}}{=} \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} [M_\odot] \]

Chirp Mass
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PPI in a binary

\[ \Delta e = \frac{\Delta M}{M_1 + M_2 - \Delta M} \]
Two PPI in a binary

\[ \Delta e = \frac{\Delta M}{M_1 + M_2 - \Delta M} \]
Eccentricity distribution

\[ M_i \left( M_{\text{pre SN}}, M_{\text{BH}} \right) \ [M_\odot] \]

q=1

- 70 (50.3, 43.9)
- 82 (57.0, 37.3)
- 86 (59.2, 29.9)

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Spin down due to PPI ejecta

\[ a(M_f)/a(M_{\text{pre SN}}) \]

\[ M_i (M_{\text{pre SN}}) [M_\odot] \]

\[ M_f / M_\odot \]

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Conclusions
Take home points

- Uncertain wind mass loss rates influence the pre-SN core
  ⇒ systematic bias in SN initial conditions and outcome?

- The vast majority of binaries are disrupted
  ⇒ X-ray binaries and GW sources are exceptions

- Binarity leaves imprint on the ejected star

- “Widow” companions ejected constrain BH kicks

Simulations of Pulsational Pair Instability possible with MESA including self-consistently dynamical evolution

- can modify binary orbit and remnant spin
  ⇒ Signature on gravitational wave signals?

- determines BH masses below 2\textsuperscript{nd} gap
Take home points

• Uncertain wind mass loss rates influence the pre-SN core
  ⇒ systematic bias in SN initial conditions and outcome?

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Simulations of Pulsational Pair Instability possible with MESA including self-consistently dynamical evolution

• can modify binary orbit and remnant spin
  ⇒ Signature on gravitational wave signals?

• determines BH masses below 2\textsuperscript{nd} gap

Thank you!
Outline

Backup slides
Upper-limits in BH mass

\[ M_{\text{He}} = 48.5 \, M_\odot \]

Outgoing pulse wave

Infalling core

Mass lost in previous pulses

\[ v_{\text{esc}} \]

velocity [10^8 cm s^{-1}]

M [M_\odot]

[Diagram showing mass vs. velocity graph with various labeled points and regions, including mass limits and velocity scaling.]

\[ M_{\text{He}} = 48.5 \, M_\odot \]

Infalling core

Outgoing pulse wave

Mass lost in previous pulses

\[ v_{\text{esc}} \]
How many pulses?
- as a function of He core mass
Number of pulses

One pulse = One mass ejection

Renzo, Farmer et al., to be submitted
When do the pulsate?

- as a function of He core mass
Pulses timing

Log Time to core-collapse

$\log_{10} \left( \frac{t_{\text{CC}} - t}{\text{yr}} \right)$

$M_{\text{He}} [M_\odot]$
Pulses timing

\[
\log_{10} \left( \frac{t_{\text{CC}} - t}{|\text{yr}|} \right)
\]

Years-Months timescale

\[M_{\text{He}} [M_\odot]\]

Renzo, Farmer et al., to be submitted
How much mass is ejected \textit{per pulse}? How much mass is ejected \textit{in total}?

- as a function of He core mass
Mass lost per pulse

Renzo, Farmer et al., to be submitted
Total mass lost

- Graph showing the total mass lost as a function of $M_{\text{He}} [M_\odot]$.

- The $y$-axis represents the change in mass, $\Delta M_{\text{total}} [M_\odot]$.

- The $x$-axis represents the helium mass, $M_{\text{He}} [M_\odot]$.

- The graph indicates a trend where the total mass lost increases with the helium mass.

- Renzo, Farmer et al., to be submitted
How fast are the ejected shells?

- as a function of He core mass
Center of mass velocity

\[
\langle v \rangle \quad [\text{km s}^{-1}]
\]

\[
M_{\text{He}} \quad [M_\odot]
\]

Renzo, Farmer et al., to be submitted
Center of mass velocity

Progenitors of (some) SNIbn?

\[ \langle v \rangle \text{ [km s}^{-1}\text{]} \]

\[ M_{\text{He}} \text{ [M}_\odot\text{]} \]

Renzo, Farmer et al., to be submitted
Can the mass shell collide?

Woosley et al 07, Chen et al. 14, Woosley 17, Renzo, Farmer et al., to be submitted
Can the mass shells collide?

Distance to the star

\[ \log_{10} R \text{ [cm]} \]

Time to core-collapse

\[ \tau - \tau_{CC} \text{ [yr]} \]

Distance to the star

No self-interaction or potential well

\[ M_{\text{He}} = 40 M_\odot \]

Renzo, Farmer et al., to be submitted
Example: $40 \, M_\odot$ He core

![Graph showing the log time to core-collapse for a 40 $M_\odot$ He core. The graph plots $M_{\text{tot}}$ and $T_c$ against $\log_{10}\left(\frac{(t_{cc} - t)}{[\text{yr}]}\right)$, where $t_{cc}$ is the time to core-collapse. The inset shows a close-up of the transition region.](image)

Renzo, Farmer et al., to be submitted
Velocity distribution: Runaways

![Graph showing velocity distribution](image)

Probability

$v_{\text{dis}} \text{ [km s}^{-1}\text{]}$

Renzo et al., submitted, arXiv:1804.09164
Velocity distribution: Walkaways

Take home points:

- Walkaways outnumber the runaways by $\sim 10 \times$
- Binaries barely produce $v_{\text{dis}} \gtrsim 60$ km s$^{-1}$
- All runaways from binaries are post-interaction objects

Renzo et al., submitted, arXiv:1804.09164
Velocity distribution: Walkaways

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

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