Present and future lessons in stellar physics from gravitational waves

Mathieu Renzo
Outline

Future: LISA detection of GW from a Galactic common envelope

Present: LIGO/Virgo BH masses and pulsational pair instability
Prospects of gravitational-waves detections from common-envelope evolution with LISA

Mathieu Renzo, T. Callister, K. Chatziioannou, L. van Son, C. M. F. Mingarelli, M. Cantiello, K. E. S. Ford, B. McKernan, and G. Ashton

arXiv:2102.00078
LISA can see Galactic double white dwarfs formed via common envelope formation.

![Graph showing characteristic strain versus frequency with LIGO/Virgo and PTA signals identified.]

Robson et al. 2019
Common Envelope Evolution

Is *not* GW-driven!
But GW passively trace the dynamics
Common envelope evolution in one slide

a. Mass transfer becomes dynamically unstable
Common envelope evolution in one slide

Example from Ivanova et al. 13b
Common envelope evolution in one slide

Example from Ivanova et al. 13b
Common envelope evolution in one slide

Example from Ivanova et al. 13b

Plunge-in might be detectable

Loud but short and rare

Renzo, Callister et al. 21

a. Mass transfer becomes dynamically unstable

b. Loss of corotation between the cores and the envelope

c. Dynamical plunge-in

\[ \log_{10}(R/R_\odot) \]

\[ m=1.1 \, M_\odot \]

\[ m=0.6 \, M_\odot \]

\[ m=0.48 \, M_\odot \]

\[ m=0.485 \, M_\odot \]

\[ m=0.482 \, M_\odot \]

\[ \text{Time [yr]} \]

\[ \text{Characteristic Strain} \]

\[ 10^{-25} \]

\[ 10^{-20} \]

\[ 10^{-15} \]

Ginat et al. 2020

LISA

BBO
Common envelope evolution in one slide

Example from Ivanova et al. 13b
Common envelope evolution in one slide

Example from Ivanova et al. 13b
Common envelope evolution in one slide

Example from Ivanova et al. 13b
How many sources do we expect?

\[ N_{\text{CE}} = R_{\text{CE,init}} \times \Delta t_{\text{CE}} \]
How many sources do we expect? $N_{CE} = R_{CE,\text{init}} \times \Delta t_{CE}$

$R_{CE,\text{init}} = 0.18^{+0.02}_{-0.09} \ (0.06^{+0.03}_{-0.02})$

c.f. LRN rate $\sim 0.3 \ \text{yr}^{-1}$

Kochaneck et al. 14, see also Howitt et al. 20
How many sources do we expect? \( N_{CE} = R_{CE, \text{init}} \times \Delta t_{CE} \)

\[
R_{CE, \text{init}} = (0.18^{+0.02}_{-0.09})(0.06^{+0.03}_{-0.02})
\]

c.f. LRN rate \( \sim 0.3 \text{ yr}^{-1} \)

Kochaneck et al. 14, see also Howitt et al. 20

Duration (in band) is very uncertain

\( \Delta t_{CE} \sim 10^{-2} - 10^5 \text{ years} \)

(e.g., Meyer & Meyer-Hofmeister 79, Fragos et al. 19, Igoshev et al. 20, Chamandy et al. 20, Law-Smith et al. 20)

\[ 0 \lesssim N_{CE} \lesssim 1000 \]
Could we detect something?
Could we see it? An answer not relying on a specific model

\begin{align*}
\log_{10}(a/\left[ R_\odot \right]) & \\
\log_{10}(\dot{f}_{GW}/\left[ s^{-2} \right]) & \\
\log_{10}(f_{GW}/\left[ Hz \right]) & \\
\log_{10}(|\dot{f}_{GW}|/\left[ s^{-2} \right]) & \\
\end{align*}

\[ M_{\text{core}} = 0.5 \, M_\odot, \quad M_2 = 0.3 \, M_\odot, \]
\[ D = 3 \, \text{kpc},\ \ T = 5 \, \text{years}, \]

averaged over orientation and sky location

Renzo, Callister et al. 21
Could we see it? An answer not relying on a specific model

\[
\log_{10}(a/[R\odot])
\]

\[
\log_{10}(|\dot{f}_{GW}|/[s^{-2}])
\]

GW Emission

\[
M_{\text{core}} = 0.5 M\odot, \ M_2 = 0.3 M\odot, \ D = 3 \text{ kpc}, \ T = 5 \text{ years}, \text{ averaged over orientation and sky location}
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Renzo, Callister et al. 21
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\[
\log_{10}\left(\frac{a}{R_\odot}\right)
\]

\[
\log_{10}\left(\frac{\dot{f}_{GW}}{[\text{Hz}]}\right)
\]

\[
\log_{10}\left(\frac{|\dot{f}_{GW}|}{[s^{-2}]}\right)
\]

Gas Drag (No Feedback)
GW Emission

\[
M_{\text{core}} = 0.5 M_\odot, \ M_2 = 0.3 M_\odot, \ D = 3 \text{ kpc}, \ T = 5 \text{ years}, \n\]

averaged over orientation and sky location

Renzo, Callister et al. 21
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\[
\frac{M_{\text{core}}}{M_\odot} = 0.5, \quad \frac{M_2}{M_\odot} = 0.3, \quad D = 3\text{ kpc}, \quad T = 5\text{ years},
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$log_{10}(a/[R_\odot])$

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$M_{\text{core}} = 0.5 \, M_{\odot}, \, M_2 = 0.3 \, M_{\odot}, \, D = 3 \, \text{kpc}, \, T = 5 \, \text{years}, \, \text{averaged over orientation and sky location}$
Would we recognize GWs from common envelope?
“Stealth bias” assuming GR in vacuum: chirp mass

Renzo, Callister et al. 21
“Stealth bias” assuming GR in vacuum: chirp mass

“Braking index”

\[ n = \frac{f \ddot{f}}{\dot{f}^2} \]

\[ n_{GR} = \frac{11}{3} \]

\[ \log_{10}(f_{GW}/[\text{Hz}]) \]

\[ \log_{10}(|\dot{f}_{GW}|/[\text{s}^{-2}]) \]

\[ \ddot{f}_{GW} \text{ Measurable} \]

\[ \dot{f}_{GW} \text{ Measurable} \]

\[ \text{vacuum GR} \]
“Stealth bias” assuming GR in vacuum: chirp mass

“Braking index”

\[ n = \frac{f \dddot{f}}{f^2} \]

\[ n_{\text{GR}} = \frac{11}{3} \]

EM counterparts:

- Optical/IR transients (Blagorodnova et al. 20)
- “weird” red giant star (Clayton et al. 17)

Renzo, Callister et al. 21
Can LISA see common-envelope events? Maybe!

- $\sim$ One CE-begin per 10 yr
- $0 \lesssim N_{\text{CE}} \lesssim 1000$
- if stalls at short separation they might be detectable

Direct window on the inside

If non-detection
- stalls at large separation
- stalling phase is short

Renzo, Callister et al. 21

https://github.com/tcallister/LISA-and-CE-Evolution
Future: LISA detection of GW from a Galactic common envelope

Present: LIGO/Virgo BH masses and pulsational pair instability
Gravitational wave mergers offer an unprecedented view on massive BHs

Abbott et al. 2020b
Part 1: Life and death of the most massive black-hole progenitors

Abbott et al. 2020b
Part 2: Making forbidden black holes?

Abbott et al. 2020b
Part 1: Life and death of the progenitors of BHs $\lesssim 45 M_\odot$

(Pulsational) pair instability evolution
Pair-production happens in the interior\textsuperscript{†} after carbon depletion

\textsuperscript{†} can be off-center
Simulating the He core captures the important dynamics

H-rich envelope can be lost to:

• winds
• binary interactions
• first pulse

He cores computed with **MESA**
Isolated binary evolution removes the H-envelope anyways

**Common envelope (CE)**

- $a_i \sim 1000 R_\odot$
- Stable mass transfer
- Explosion in wide binary
- CE ejection
- $a \lesssim 60 R_\odot$, $e = 0$
- Explosion in very close binary
- Merger

**Chemically homogeneous evolution (CHE)**

- $a_i \lesssim 60 R_\odot$
- Explosion in very close binary
- Explosion in very close binary
- Merger

Marchant, Renzo et al. 2019
Pair-instability SNe are the best understood supernovae

Radiation pressure dominated:

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

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

\[ \gamma \gamma \rightarrow e^+ e^- \]
0. Evolved Massive He core

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

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

3. Explosive (oxygen) ignition

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3. Explosive (oxygen) ignition

4a. Pair Instability supernova with complete disruption

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4b. Pulse with mass ejection

5. $\nu$-cooling
0. Evolved Massive He core

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4a. Pair Instability supernova with complete disruption

4b. Pulse with mass ejection

5. \( \nu \)-cooling

7. BH

Renzo, Farmer et al. 2020b
Resulting stellar BH masses

\[ M_{\odot} \sim 125 \]

\[ M_{\odot} \sim 45 \]
Weak dependence on primordial metallicity

Focus on lower edge of the gap

\[ \Delta \max \{ M_{\text{BH}} \} \sim 7\% \]
over 2.5 orders of magnitude

Comparable or smaller effects:
resolution, winds, overshooting, neutrino cooling, \[a_{\text{MLT}}\], etc..

Farmer, Renzo et al. 2019, see also Woosley & Heger 2021
Weak dependence on primordial metallicity

Focus on lower edge of the gap

$\Delta \max\{M_{\text{BH}}\} \sim 7\%$

over 2.5 orders of magnitude

Comparable or smaller effects:
resolution, winds, overshooting, neutrino cooling, $\alpha_{\text{MLT}}$, etc..

$max(M_{\text{BH}})$ below the gap robust &
$\sim$ constant throughout the Universe
$
\downarrow$

Standardizable siren?

Farmer, Renzo et al. 2019, see also Woosley & Heger 2021
The dominant uncertainty is the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate

Change in $^{12}\text{C}/^{16}\text{O}$ ratio

↓

different C-shell behavior and CO core mass

The lower edge of the gap can give GW constrain on nuclear rates...

...if 2nd + generations don’t pollute it too much

The feature at $\sim 40 M_\odot$ suggests PPI happens in nature

Abbott et al. 2020b, Talbot & Thrane 2018
The feature at $\sim 40 M_\odot$ suggests PPI happens in nature.

97.1$^{+1.7}_{-3.4}$% have $m_1 < 45 M_\odot$

How to form the others?
Part 2: Making forbidden BHs?

The “stellar merger” scenario
The “stellar merger scenario”

- Make a star with a small core and oversized envelope to avoid PPISN
- Collapse it to a BH in the gap
- Pair it in a GW source with dynamics
Four challenges of the “stellar merger scenario”

- Mass loss (and rejuvenation)? Assumed zero
- Wind and eruptions? Assumed zero
- Loss of envelope at core-collapse? Because of $\nu$ losses – Assumed zero
  see Nadhezin 1980, Lovegrove & Woosley 2013
- Need dynamics to pair with 2nd BH?
  Requires nuclear cluster and/or AGN disk?
Part 2: Making forbidden BHs?

Oversimplified MESA mergers
Merger model: the pre-merger stars

\[ Z = 2 \times 10^{-4} \]

\[ Z = 2 \times 10^{-4} \]

Renzo, Cantiello et al. 20
Merger model: composition of the merger

\[ Z = 2 \times 10^{-4} \]

Star 1
58 \( M_\odot \)

Star 2
42 \( M_\odot \)

Merger
99 \( M_\odot \)

\( ^1\)H
\( ^4\)He

Renzo, Cantiello et al. 20
Merger products are He-rich and blue $\Rightarrow$ envelope instabilities?

Very massive stars are hardly stable
- $\sim 10^5$ years in S Dor instability strip
- reach core-collapse as BSG
- LBV eruptions, helped by He opacity?

Jiang et al. 18

Renzo, Cantiello et al. 20
Merger products are He-rich and blue \( \Rightarrow \) envelope instabilities?

Very massive stars are hardly stable
- \( \sim 10^5 \) years in S Dor instability strip
- reach core-collapse as BSG
  \[ \Downarrow \]
- LBV eruptions, helped by He opacity?

Jiang et al. 18

\begin{align*}
\text{log}_{10}(T_{\text{eff}}/ [K]) & \quad 4.2 \quad 4.4 \quad 4.6 \quad 4.8 \\
\text{log}_{10}(L/L_\odot) & \quad 6.1 \quad 6.2 \quad 6.3 \quad 6.4 \quad 6.5 \quad 6.6 \quad 6.7
\end{align*}

Renzo, Cantiello et al. 20

\( \eta \) Car
Part 2: Making forbidden BHs?

Envelopes fate at BH formation
Do BHs form via a failed, weak, or full blown SN explosion?

\[ \Delta E_\nu \sim 10^{53} \text{ erg} \]

Possible causes for mass ejection at BH formation:

- \( \nu \)-driven shocks
  Nadhezin 1980, Lovegrove & Woosley 2014, Fernandez et al. 2018,
  Ivanov & Fernandez 2021

- Jets and disk wind
  (even without net rotation)
  Gilkis & Soker 2014, Perna et al. 2018, Quataert et al. 2019

- (weak) fallback powered explosion

see also Adams et al. 2017 for possible EM counterpart to BH formation
Accretion disks and $\nu$-driven shocks remove little mass for BSG

$$M_{\text{BH},0} \approx M_{\text{core}} - \frac{E_{\nu}}{c^2}$$

MESA $\rightarrow$ GR1D+FLASH

Fernández et al. 2018

$M_{\text{BH},0}$ is the initial mass of the black hole, $M_{\text{core}}$ is the core mass, $E_{\nu}$ is the energy of the neutrino, and $c$ is the speed of light.

Credits: R. Fernández

Can convective random motion cause disk formation and collapsar?

\[
\dot{j}_{\text{rand}} = \frac{H_{\rho} \nu_{\text{conv}}}{\sqrt{4\pi}}
\]

\text{c.f. Gilkis & Soker et al. 14, Quataert et al. 19}
Can convective random motion cause disk formation and collapsar?

\[ \dot{j}_{\text{rand}} = \frac{H_p v_{\text{conv}}}{\sqrt{4\pi}} \]

Not enough in non-rotating models
But the merger process might inject AM
Conclusions
Future: LISA might detect Galactic CE
(or rule out existing models with non-detections)
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(or rule out existing models with non-detections)

Present:
GW detections of BBHs...
...provide first \textit{uncontroversial} evidence for PPI
**Future:** LISA might detect Galactic CE
(or rule out existing models with non-detections)

**Present:**
GW detections of BBHs...

...provide first uncontroversial evidence for PPI

⇒ require **dynamics** and, if merging stars, un perturbed core & full envelope fallback

but better stellar merger models needed
Backup slides
Dynamical phases are **loud but short** and thus rare

Requires massive donor star

Ginat et al. 2020
Rate of common-envelope initiation with pre-CE separation

\[ \text{Initiation rate } R_{CE,\text{init}} \left[ \text{yr}^{-1} \right] \]

- \( q_c = 0.1 \)
- \( q_c = 1 \)
- \( q_c = 2 \)

Clayes et al. 14

\( Z = 0.002 \)

Clayes et al. 14, indip. dist

all CE
both post MS

\[ \min(a_{\text{pre-CE}}) \left[ R_\odot \right] \]

\[ \min(M_{\text{GW emitting}}) \left[ M_\odot \right] \]
“Stealth bias” assuming GR in vacuum: chirp mass & distance

“Braking index” \( n = \frac{\ddot{f}}{\dot{f}^2} \Rightarrow n_{GR} = \frac{11}{3} \)
Most common envelope events cross the LISA band

\[ M_{\text{GW emitting}} = M_{\text{core}} + M_{\text{WD}} \ [M_\odot] \]

Post-CE separation

Pre-CE separation

\( \alpha = 1, \ \lambda = 0.3 \)

\( M_{\text{WD}} = 0.3 M_\odot \)

\( M_{\text{WD}} = 1.4 M_\odot \)

LISA frequency range

arXiv:2102.00078
The estimated radiation-driven mass loss is not significant

\[
\dot{M} = \frac{L - L_{\text{Edd}}}{v_{\text{esc}}^2}
\]

\(L > L_{\text{Edd}}\) only for few 100 years

(higher \(Z \Rightarrow \) higher \(\kappa \Rightarrow \) higher \(\dot{M}\))

Renzo, Cantiello et al. 20
Filling the PISN BH mass gap
### Filling the PISN BH mass gap

#### Move the gap

- decrease by $\sim 2.5\sigma$ the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  
  Farmer et al. 20, Belczynski 20

- beyond standard model physics  
  Choplin *et al.* 17, Croonet *et al.* 20a,b, Sakstein *et al.* 20,  
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## Avoid pair-instability

- stellar merger scenario
  - Spera & Mapelli 2019, di Carlo *et al.* 19, 20a, 20b, Renzo *et al.* 20c
- decrease overshooting (in pop. III)
  - Farrell *et al.* 20, Kinugawa *et al.* 20, Vink *et al.* 20
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### Multiple generations of BBH mergers

- in clusters
  
  Fragione et al. 20, Liu & Lai 20

- in nuclear clusters
  
  Perna et al. 19

- in AGN disks
  
  McKernan et al. 12, Bartos et al. 17, Stone et al. 19
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**“Impostor” GW events:** High eccentricity merger? Lensing?