Pulsational Pair Instability
or why these black holes can’t come from stars

Mathieu Renzo
Radiation pressure dominated:

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

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

**Pair-instability SNe are the best understood supernovae**

$\Gamma_1 \equiv \left( \frac{\partial \ln P}{\partial \ln \rho} \right)_s$

He cores computed with MESA

Renzo, Farmer et al. 2020b
Collapse on thermal timescale

\[ \tau \propto \frac{G M_{\text{He}}^2}{R L_v}, \quad L_v \gg L \]

(Fraley 68)

Renzo, Farmer et al. 2020b
0. Evolved Massive He core

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

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

3. Explosive (oxygen) ignition
2. Softening of EOS triggers collapse
\[ \Gamma_1 < \frac{4}{3} \]

3. Explosive (oxygen) ignition

0. Evolved Massive He core

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

3. Explosive (oxygen) ignition

4a. Pair Instability supernova with complete disruption

0. Evolved Massive He core

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

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

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

3. Explosive (oxygen) ignition

4. Pair Instability supernova with complete disruption
   4a. Pair Instability supernova with complete disruption
   4b. Pulse with mass ejection

5. \( \nu \)-cooling

Renzo, Farmer et al. 2020b
0. Evolved Massive He core
1. Pair production \( \gamma \gamma \rightarrow e^+ e^- \)
2. Softening of EOS triggers collapse \( \Gamma_1 < \frac{4}{3} \)
3. Explosive (oxygen) ignition
4a. Pair Instability supernova with complete disruption
4b. Pulse with mass ejection
5. \( \nu \)-cooling
7. BH

Renzo, Farmer et al. 2020b
0. Evolved Massive He core

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

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

3. Explosive (oxygen) ignition

4a. Pair Instability supernova with complete disruption

4b. Pulse with mass ejection

4c. Photodisintegration instability and direct BH formation

5. \( \nu \)-cooling

7. BH
The pair-instability BH mass gap
The distribution of stellar BH masses

Renzo, Farmer, et al. 2020b
The distribution of stellar BH masses

GW190521.1

Some GW events missing!

PISN BH mass gap

CC

PPI + CC

Renzo, Farmer, et al. 2020b
Chirp mass distribution – weighted by LIGO’s sensitivity

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

\[ q \geq 0.5 \]

(motivated by LVC 2016)
How robust is this prediction?
Metallicity? Small effect

Focus on lower edge of the gap

\[ \sim 7\% \text{ shift over 2.5 orders of magnitude in } Z \]
Treatment of time-dependent convection? Not the edge

Matters for least massive PPI, not for the most massive BH

Renzo, Farmer et al. 2020a
Winds, mixing, $\nu$ physics? Also small effects

Farmer, Renzo et al. 2019
Can rotation move the gap? Barely...

Rotation can stabilize the core, but sufficient rotation only for very extreme assumptions...

- No core-envelope coupling
- Large initial rotation
- Low $Z$ ($\approx$ no winds)

Only $\sim 20\%$ shift of gap, $\lesssim 4\%$ for “realistic” core-envelope coupling
How robust is this prediction?

Does binarity move the gap?
Can isolated binary evolution “pollute” the gap?

With unlimited accretion, some binary BHs can enter the gap...

van Son et al., incl. MR, 2020
Can isolated binary evolution “pollute” the gap?

... but those entering the gap don’t merge within 13.7 Gyr

van Son et al., incl. MR, 2020
Can isolated binary evolution “pollute” the gap?

... but those entering the gap don’t merge within 13.7 Gyr

Mass accretion leads to orbital widening

With most optimistic assumptions:

- ≲ 1% systems with $M_{\text{tot}} \gtrsim 90 M_\odot$
- No systems with $M_{\text{tot}} > 100 M_\odot$

van Son et al., incl. MR, 2020
The only known large uncertainty

Nuclear reaction rates
The most important reaction $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction rate

Change in C/O ratio $\Rightarrow$ different C-shell behavior

GW can constrain nuclear rates with the gap...
...if other channels don’t pollute it too much

Farmer, Renzo et al. 2020, see also Takahashi 2018, Farmer, Renzo et al. 2019
Possible ways to bridge the gap
The speculative stellar merger scenario

Population synthesis assumptions *not quite* backed up by detailed models

- Mass loss during merger?
- Loss of envelope at core-collapse?
- Need dynamics to pair with 2nd BH

see Nadhezin 1980, Lovegrove & Woosley 2013

Requires nuclear cluster and/or AGN disk?
Beyond standard model physics

Photophilic axion: \( m_a \ll \text{keV}, Z = 10^{-5} \)

Other possibilities:
- dark photons
- other axions
- change \( G \)
- \( \nu \) magnetic moment
- extra dimensions

Effectively change the cooling during He core burning
Changes C/O ratio, \( \rho \)-structure, decrease \( P_{\text{rad}} / P_{\text{tot}} \)

Croon et al. 20a, see also Croon et al. 20b, Sakstein et al. 20
Conclusions
PISN are the theoretically best understood SNe although observationally elusive

- PISN BH mass gap very robust prediction
- BH formation after PPI poorly understood
- Binary effect seem small
- Populating the gap requires non-stellar (2\textsuperscript{nd} gen. +) BHs or new physics
Backup slides
The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ ends He core burning

More $^{12}\text{C} \rightarrow \text{C}$ shell burning delays $^{16}\text{O}$ ignition to higher $\rho$

![Diagram showing the stages of core burning and remnant formation](image_url)

(A) Reduced $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
- Helium shell
  - $\text{C/O} \approx 0.4$
- Center Carbon
- Off-center Carbon
- Explosive Oxygen
- Center Oxygen

(B) Median $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
- Helium shell
  - $\text{C/O} \approx 0.1$
- Center Carbon
- Off-center Carbon
- Explosive Oxygen
- Center Oxygen

(C) Enhanced $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
- Helium shell
  - $\text{C/O} \approx 0.001$
- Center Carbon
- Off-center Carbon
- Explosive Oxygen
- Center Oxygen

Core Collapse
Pulsations
Pair Instability SNe
No remnant

Farmer, Renzo et al. 2020
Convection during the pulses quenches the PPI mass loss

Renzo, Farmer et al. 2020a