Formation and Evolution of BHs in Star Clusters

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Outline

1. My research in a nutshell

2. The BH mass spectrum (single stellar evolution)

3. The BH mass spectrum (binary stellar evolution)

4. Conclusions
Overview of my research

AIM
To study the formation pathways of compact-object binaries that merge within a Hubble time

FINAL GOAL
To provide theoretical models to interpret present and forthcoming GW sources

MOTIVATION
The formation and evolution of (merging) compact-object binaries is very uncertain

How/where massive stellar BHs ($\gtrsim 25M_\odot$) form?
Understanding black holes: ingredients

- **Stellar Evolution**
  - (progenitors evolution)

- **Stellar Dynamics**
  - (N-body simulations)

- **Superova Explosion**
  - (Compact object mass)
BH mass spectrum: physical processes

Stellar evolution $\rightarrow$ stellar winds

Stars lose mass

$\frac{dM}{dt} \propto Z^{0.85}$

✅ Mass-loss depends on **mass** and **metallicity**

✅ The amount of mass-loss for massive stars can be **conspicuous**

Supernova explosion

BHs form after supernovae

✅ Very **complex and uncertain**. It depends on: final mass of the star, fallback, compactness...

✅ $M_{\text{final}} \gtrsim 30M_\odot$: the SN explosion may fail $\rightarrow$ **direct collapse** $\rightarrow$ massive black hole
BH mass spectrum: physical processes

Stellar evolution ➔ stellar winds

Stars lose mass

Mass-loss depends on mass and metallicity

\[ \frac{dM}{dt} \propto Z^{0.85} \]

The amount of mass-loss for massive stars can be conspicuous

Supernova explosion ➔ BHs form after supernovae

Very complex and uncertain. It depends on: final mass of the star, fallback, compactness...

\[ M_{\text{final}} \geq 30M_\odot \]: the SN explosion may fail ➔ direct collapse ➔ massive black hole
The SEVN code

*Stellar EVolution for N-body*

- **Up-to-date Stellar Evolution**
- **Up-to-date SN models** (5 models)
- **Versatile approach**
  - a. CO-based criteria
  - b. Compactness-based criteria
- **Ready for N-body sims**
  - Starlab
  - HiGPUs-RX
- **SEVN is publicly available**
  - [http://web.pd.astro.it/mapelli/SEVN.tar.gz](http://web.pd.astro.it/mapelli/SEVN.tar.gz)

- **Stellar evolution through look-up tables.**
  - a. Versatile approach.
  - b. Default: tables from the PARSEC code (Bressan+ 2012, Chen+ 2015)

- **Several up-to-date SN explosion models**
  - a. CO-based criteria
  - b. Compactness-based criteria

- **Already coupled with some N-body codes**

- **MS +, 2018, in preparation**
The BH mass spectrum

Massive (> 30M⊙) stellar black holes:

- Low metallicity
- Direct collapse

- MS, Mapelli, Bressan, 2015, MNRAS, 451, 4086 (Fig. 6)
- Abbott+ 2016 ApJL, 818, L22 (Fig. 1)
The effect of pair-instability SNe

Pulsational- and pair-instability SNe are missing in most population-synthesis codes

What about black-hole binaries?

*MS+, 2018, in preparation*

• Major upgrade to the SEVN code: binary stellar evolution

• We follow the BSE prescriptions (Hurley+ 2002), with few important updates.

• Preliminary results: population synthesis simulations of $10^7$ binary systems at:
  • different metallicity $z \in [10^{-4}; 6 \times 10^{-2}]$;
  • different initial $a$ and $e$ (Sana+, 2012);
  • Kroupa IMF $[10; 150] M_\odot$
The BH mass spectrum

MS+, 2018, *in preparation*

----- Single stellar evolution

![Graphs showing the BH mass spectrum with normalized density.](image)
The distribution of BH masses

MS+, 2018, in preparation

![Graphs showing the distribution of black hole masses](image-url)
Merging BH binaries

MS+, 2018, in preparation

- GW150914
- GW170608
- GW170814
- GW151226
- GW170104

Normalized density

Z = 2.0E-2
Z = 1.0E-4
Conclusions

1. Massive stellar BHs can form at low metallicity via direct collapse

2. Major upgrade of the SEVN code (binary stellar evolution):
   1. The mass distributions of double BHs from single and binary stellar evolution calculations are remarkably similar;
   2. Massive ($\gtrsim 60M_\odot$) single BHs can form at all metallicities;
   3. BH binaries with massive BHs ($\gtrsim 40M_\odot$) do form in our simulations but they do not merge.