Exploring stellar evolution with gravitational-wave observations

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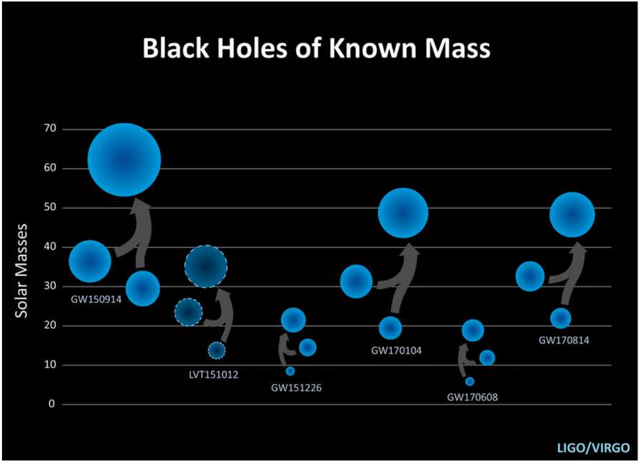
Dark Matters, 13 December 2017

ID, Uzan, Vangioni, Silk [astro-ph/1709.09197]

Max-Planck-Institut
für Gravitationsphysik
(Albert-Einstein-Institut)

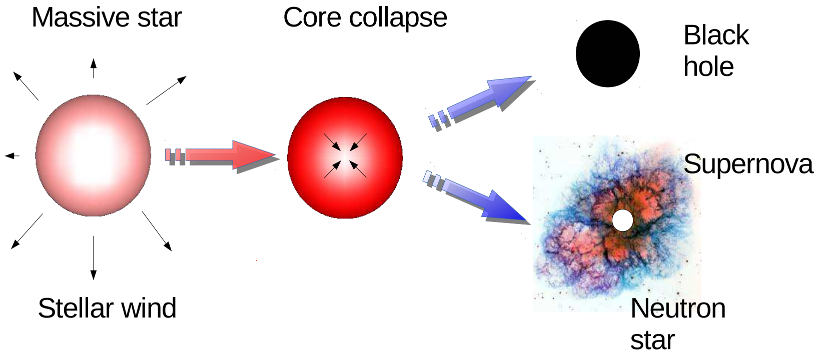
Astrophysics with gravitational waves

Starting to measure the BH mass distribution



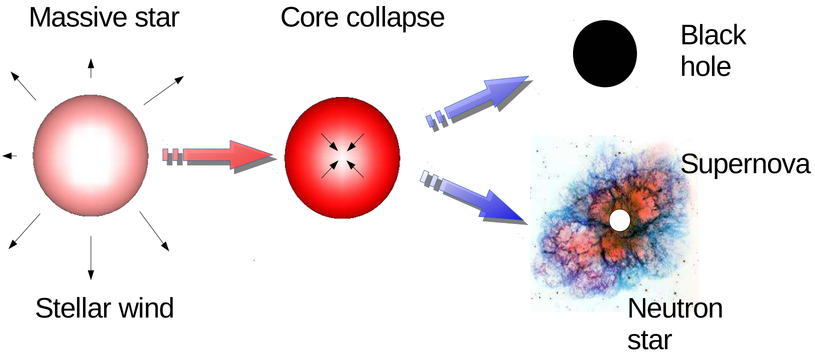
How to make a stellar-mass black hole

- Core collapse SN/direct collapse to a BH



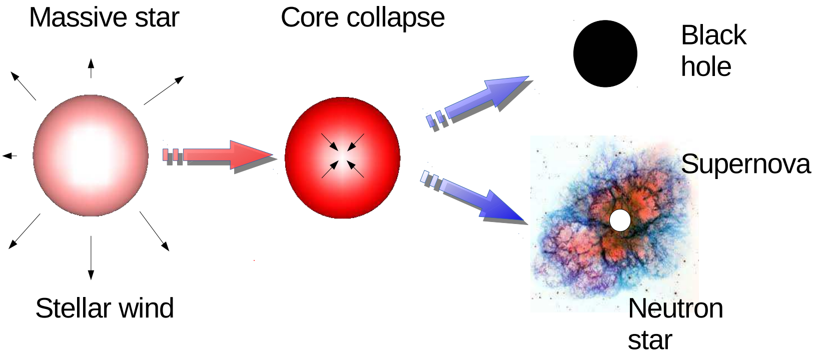
How to make a stellar-mass black hole

- Core collapse SN/direct collapse to a BH
  - Mass prior to core collapse: determined by stellar winds



How to make a stellar-mass black hole

- Core collapse SN/direct collapse to a BH
  - Mass prior to core collapse: determined by stellar winds
  - Explosion mechanism

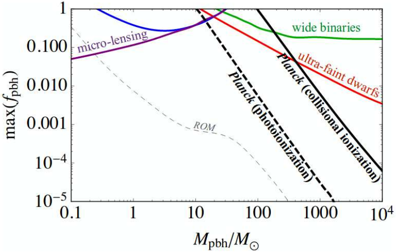


Primordial black holes

- Primordial BHs can form deep in the radiation-dominated era or early in the matter-dominated era

Bird et al. (2016); Sasaki et al. (2016); Nakama et al. (2017); García-Bellido (2017); Vuk et al. (2016); Carr et al. (2017)

Ali-Haïmoud & Kamionkowski (2017)



$M_{BH} = f(M_{initial}, Z, ?)$

Which parameters determine the remnant mass?

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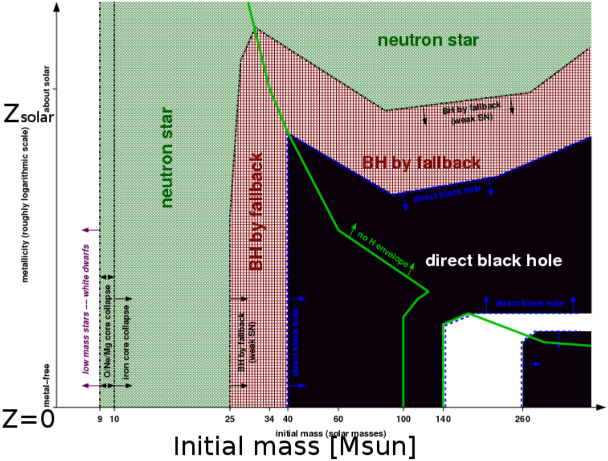

Heger et al. (2003)

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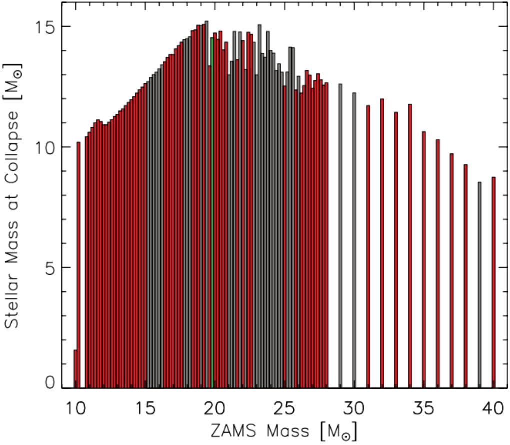
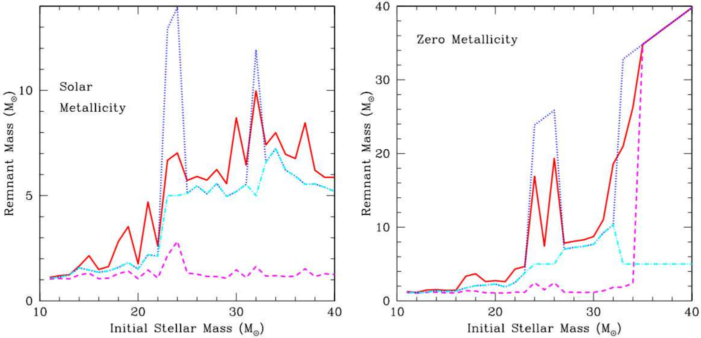


Ugliano et al. (2012)

From massive stars to black holes

Woosley & Weaver (1995); Fryer et al. (2012); Dominik et al. (2012); Limongi (2017)
Chemically homogeneous evolution; Marchant et al. (2016); De Mink & Mandel (2016)



Fryer et al. (2012)

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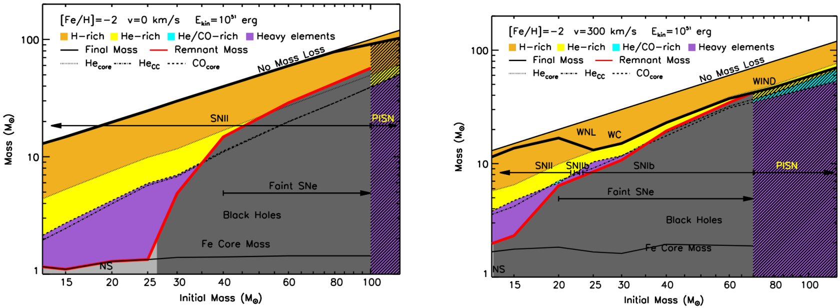

Limongi (2017)

Observables vs. model parameters

What we can observe:

- Masses
- Spins
- Redshift z
- *Sky location*

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What we need to constrain:

- Black hole formation scenario
    - Isolated core collapse
    - Multiple mergers in dense environments
    - Primordial black holes
    - *Something else?*
- Specific model parameters

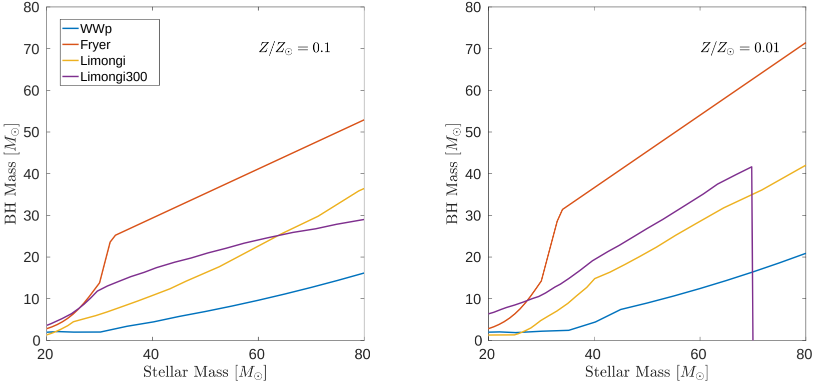
Model ingredients

- Galaxy evolution, star formation rate, stellar mass distribution
- Stellar evolution, formation of binary black holes, merger rate
- Description of merger - GW waveform
- Instrument sensitivity

Model ingredients

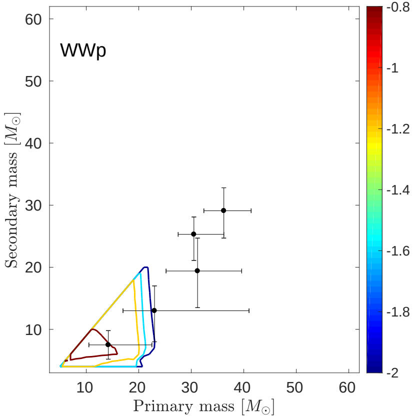
- Galaxy evolution, star formation rate, stellar mass distribution
  → Semi-analytic model [Daigne et al. (2006); Dvorkin et al. (2015)]
- Stellar evolution, formation of binary black holes, merger rate
  → Input models [Woosley & Weaver (1995); Fryer et al. (2012); Limongi (2017)]
- Description of merger - GW waveform
  → PhenomB waveform [Ajith et al. (2011)]
- Instrument sensitivity
  → LIGO O1 run

Initial mass-remnant mass relation

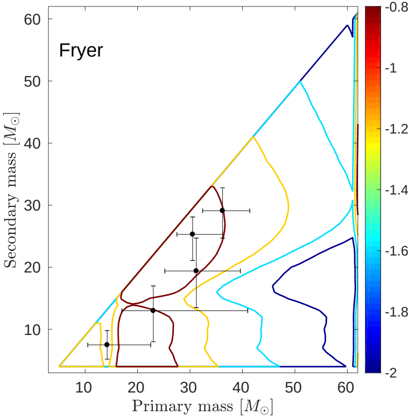


Detection rates [events per yr per $M_\odot^2$]

Fixed explosion energy



Neutrino-driven explosion



Dvorkin et al. (2017)

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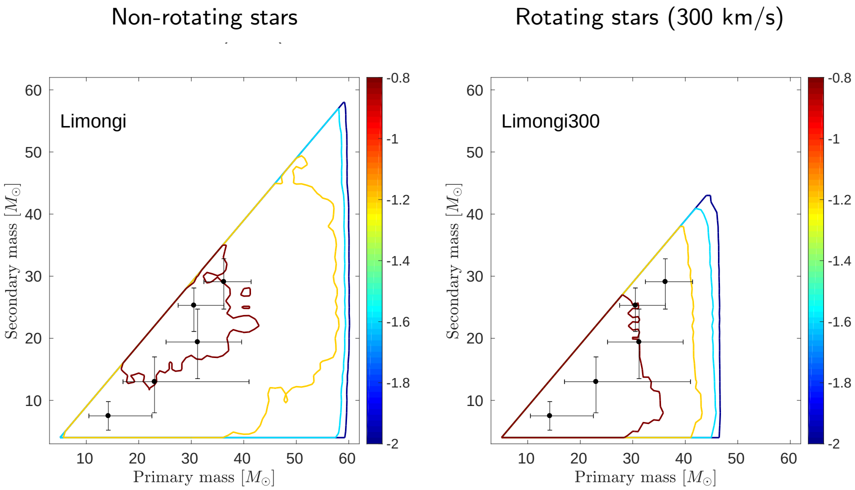
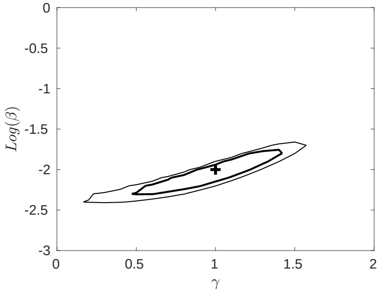


Dvorkin et al. (2017)

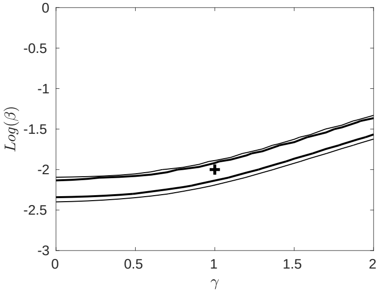
Constraining model parameters - Preliminary

Just 2 free parameters (β, γ):
β : fraction of BHs that are in binaries that merge within a Hubble time
delay time distribution slope $P_d \sim t^{-\gamma}$
with $\sim$ 1400 detections

Fryer et al. (2012)



Limongi (2017)



Dvorkin et al. in prep

Summary

An exciting time for astrophysics:

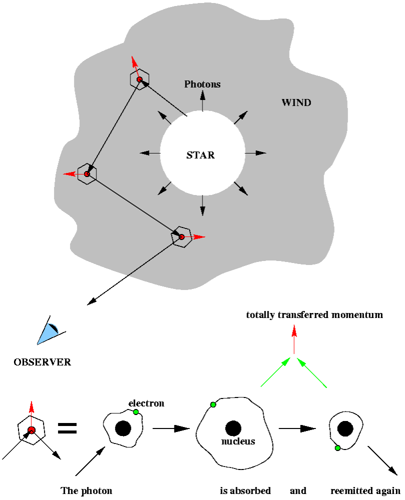
- New tool to study stellar evolution...
  - SN explosion mechanism, winds
  - Binary systems (common envelope phase)
  - PopIII stars, primordial BHs, *something else?*
- Need many more detections and more sophisticated analysis tools to explore the entire parameter space

Additional slides

Mass prior to core collapse is determined by stellar winds

- Winds are driven by radiation pressure
- Many metals (O, Fe, Si, C) have transition lines for which the atmosphere is optically thick
- Mass-loss rates can reach $\sim 10^{-5} M_{\odot}/\mathrm{yr}$
- Lifetime of $\sim 20 - 30 M_{\odot}$ stars: a few $\sim 10^6$ yr

The principle of radiatively driven winds



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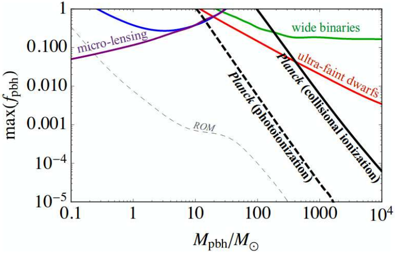

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