How do black hole binaries form? Studying stellar evolution with gravitational wave observations

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with: Joe Silk, Elisabeth Vangioni, Jean-Philippe Uzan, Patrick Petitjean (IAP); Keith Olive (U Minnesota)

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Institut d'astrophysique de Paris

Outline

Gravitational waves from binary black holes

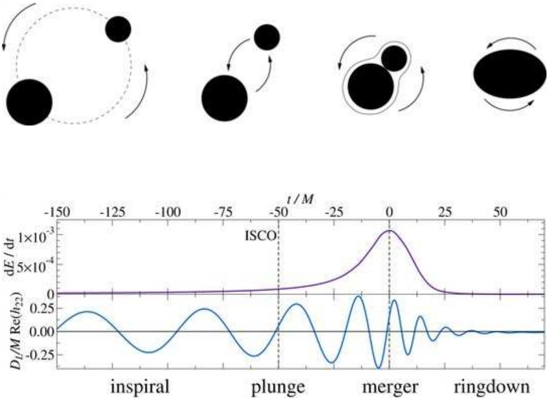


Image credit: A. Taracchini/AEI

Observing merging BHs with GW

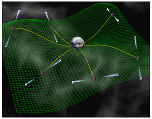
- Ground-based interferometers: LIGO, Virgo, KAGRA...
- Spaced-based interferometer LISA
- Pulsar Timing Arrays

Massive black hole binaries $(10^6 M_\odot \lesssim M \lesssim 10^9 M_\odot)$

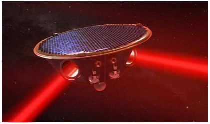
Stellar-mass black hole binaries $(M \lesssim 100 M_\odot)$

10^{-8} Hz 10^{-6} Hz 10^{-4} Hz 10^{-2} Hz 1 Hz 10^{2} Hz

Pulsar Timing Arrays
Parkes, NANOGrav, EPTA, SKA...



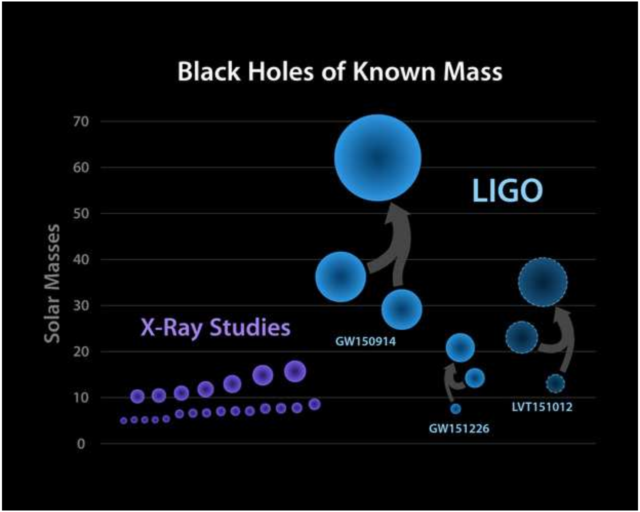
Space-based interferometer
LISA



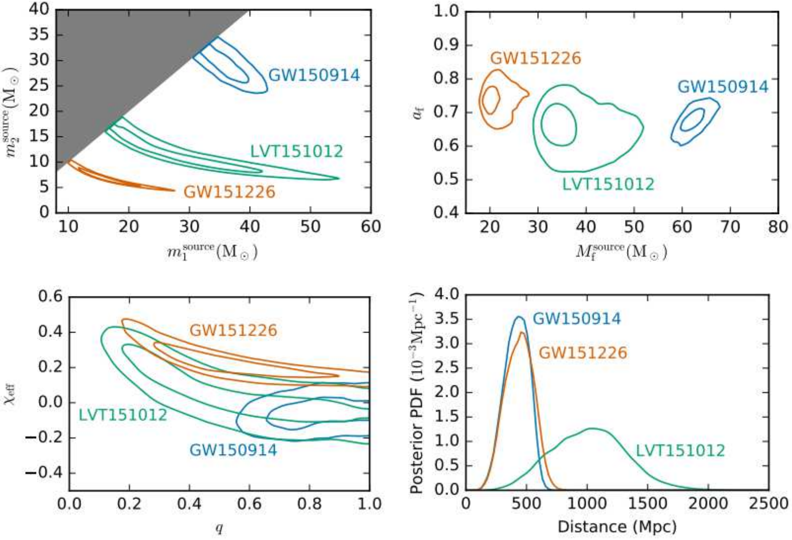
Ground-based interferometers
LIGO, Virgo, KAGRA

Astrophysics with gravitational waves

Starting to measure the BH mass distribution (LIGO/VIRGO Collaborations [1606.04856])



Astrophysics with gravitational waves

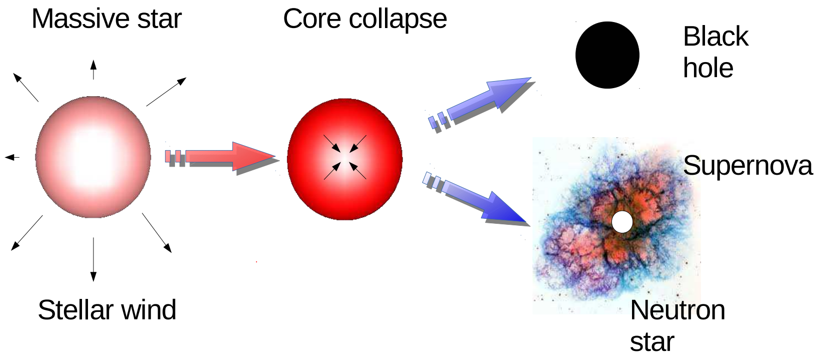


Astrophysics with gravitational waves

What can we learn about black hole formation?

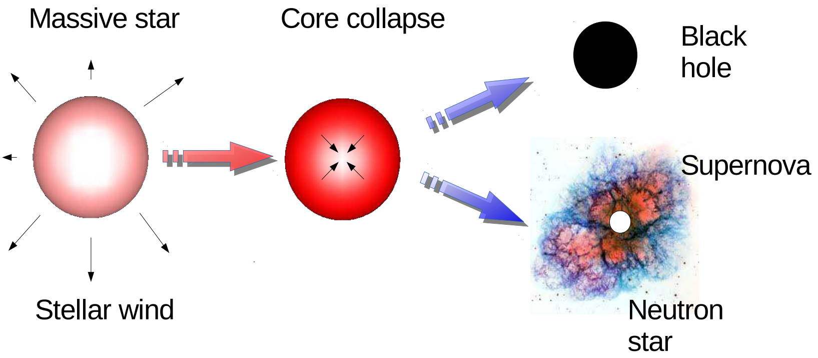
How to make a black hole

- Core collapse SN/direct collapse to a BH



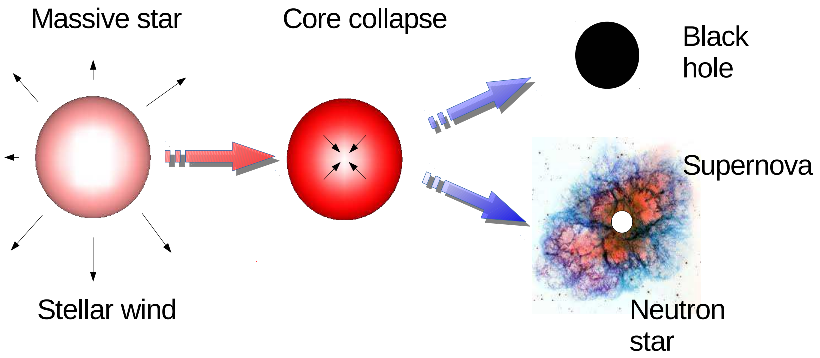
How to make a black hole

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



How to make a black hole

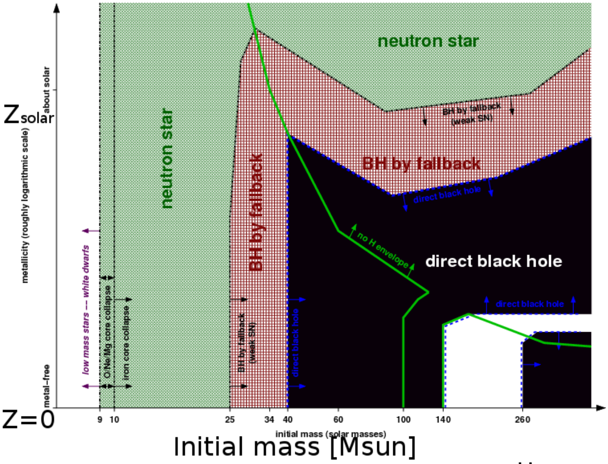
- Core collapse SN/direct collapse to a BH
    - Mass prior to core collapse: determined by stellar winds
    - Explosion mechanism
    - Electromagnetic signatures (SN; X-ray binaries)
      [see talk by Felix Mirabel]



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

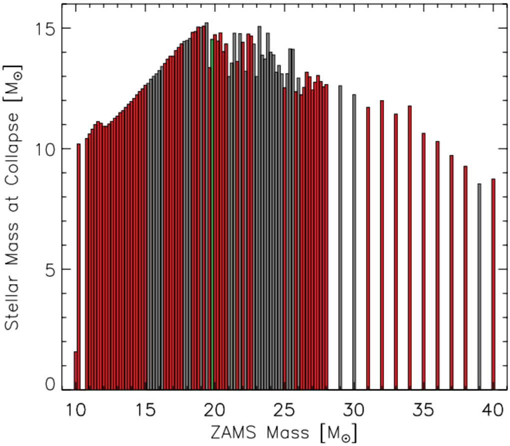
Which parameters determine the remnant mass?

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



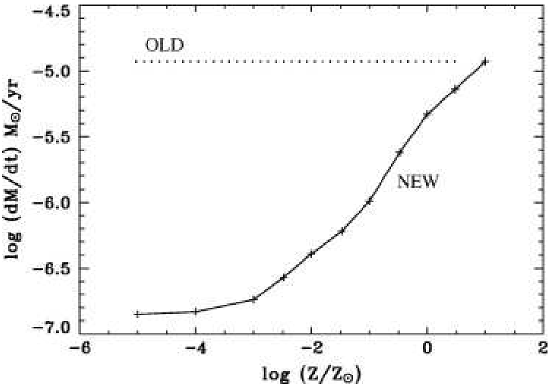
Heger et al. (2003)

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



Ugliano et al. (2012)

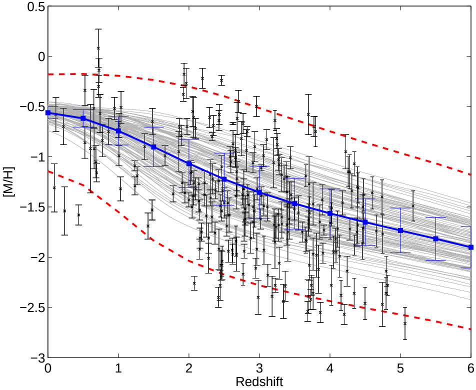
Mass prior to core collapse is determined by stellar winds



Vink (2008)

Cosmic metallicity evolution

Damped Ly-α systems data from Rafelski et al. (2012)

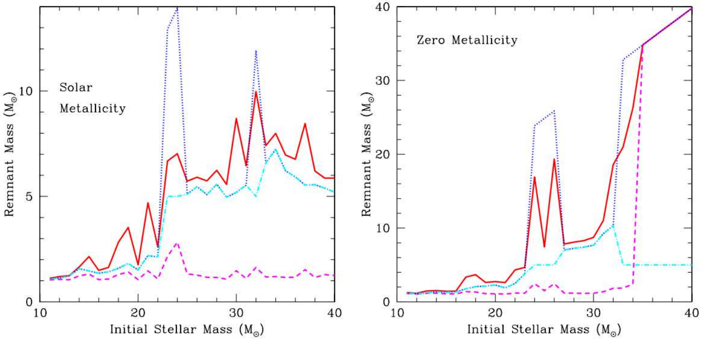


Dvorkin et al. (2015)

From massive stars to black holes

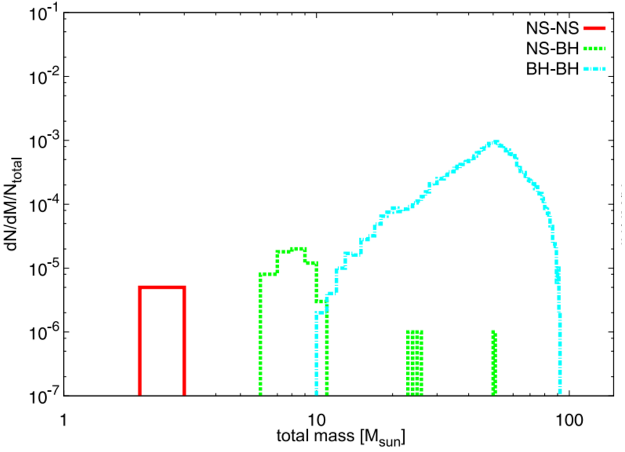
Woosley & Weaver (1995); Fryer et al. (2012); O'Connor & Ott (2011); Müller et al. (2012).....

Chemically homogeneous evolution; Marchant et al. (2016); De Mink & Mandel (2016)



Fryer et al. (2012)

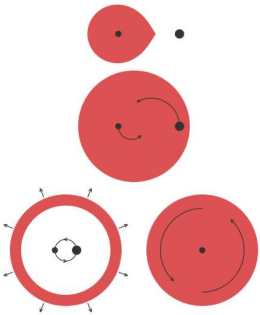
From massive stars to black holes: PopIII stars



Kinugawa et al. (2014)

From binary stars to binary BHs

- Common envelope evolution
  Podsiadlowski 2001; Ricket & Taam (2012)
- Natal kicks
  Bonnell & Pringle (1995); Fryer & Kusenko (2006); Dominik et al. (2012)

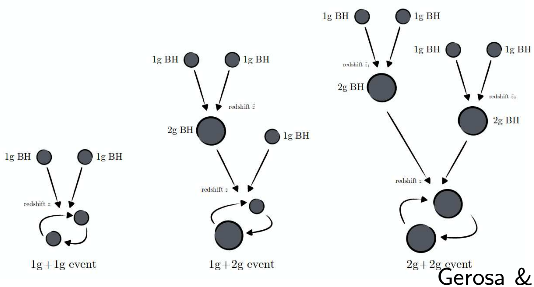


How to make a black hole

- Interactions in dense stellar environments

Rodriguez et al. (2015); Antonini & Rasio (2016); Mapelli (2016); O'Leary et al. (2016); Chatterjee et al. (2017); Gerosa & Berti (2017); Zaldarriaga et al. (2017); Fishbach et al. (2017); Park et al. (2017)

[see talk by Chunglee Kim]



Gerosa & Berti (2017)

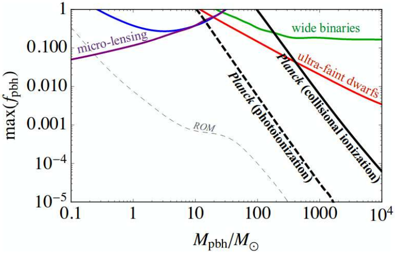
Primordial black holes

- Primordial BHs can form deep in the radiation-dominated era

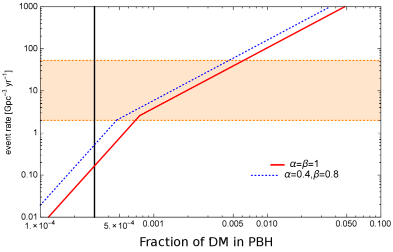
Bird et al. (2016); Sasaki et al. (2016); Nakama et al. (2017); García-Bellido (2017); Vuk et al. (2016)

[see talk by Letizia Sammut]

Ali-Haïmoud & Kamionkowski (2017)



Sasaki et al. (2016)



Observables vs. model parameters

What we can observe:

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

Observables vs. model parameters

What we can observe:

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

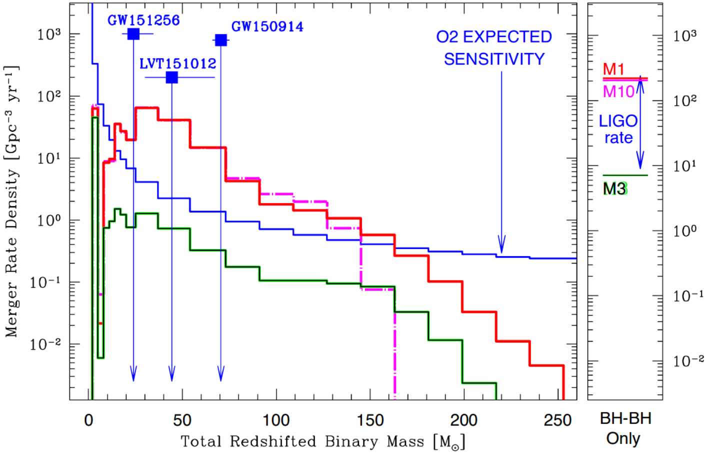
What we need to constrain:

- Black hole formation scenario
  - Isolated core collapse
  - Multiple mergers in dense environments
  - Primordial black holes
  - *Something else?*
- Specific model parameters (common envelope, natal kicks, ...)

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

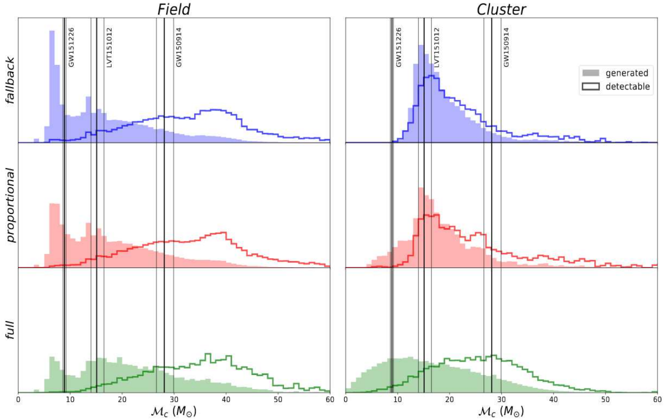
Mass distribution: model parameters



Belczynski et al. (2016)

Mass distribution: model selection

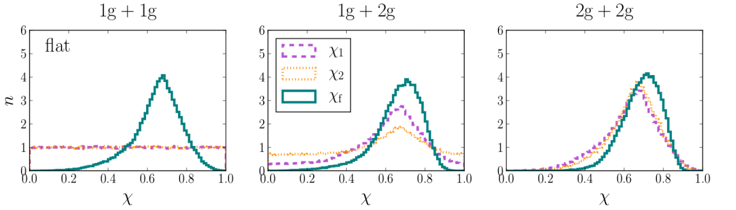
Need at least ~ 100 detections to measure the branching ratio field-cluster



Zevin et al. (2017)

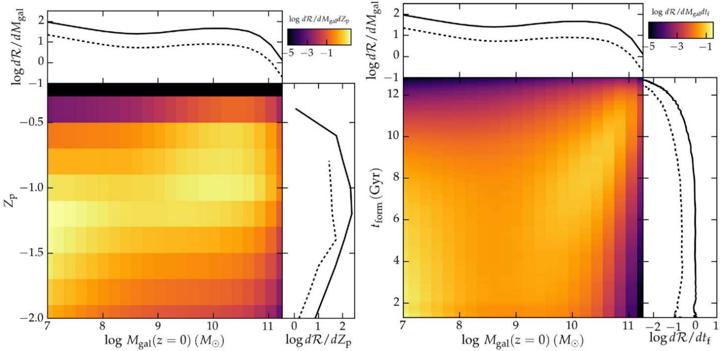
Spin distribution: model selection

After several mergers the effective spin converges to $\chi \sim 0.6 - 0.7$



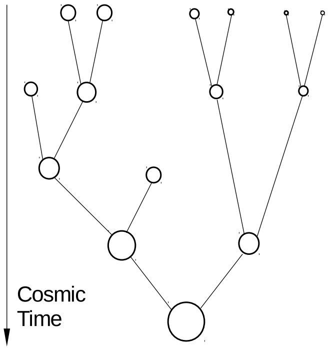
Gerosa & Berti (2017)

What are the host galaxies of BH mergers?



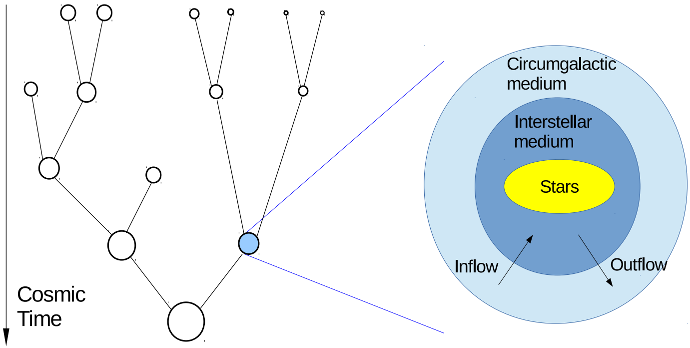
Lamberts et al. (2016)

Cosmological galaxy evolution model



- Merger tree of dark matter halos

Cosmological galaxy evolution model



- Merger tree of dark matter halos

- Star formation rate
- Metal yields in stars
- End product of massive stars

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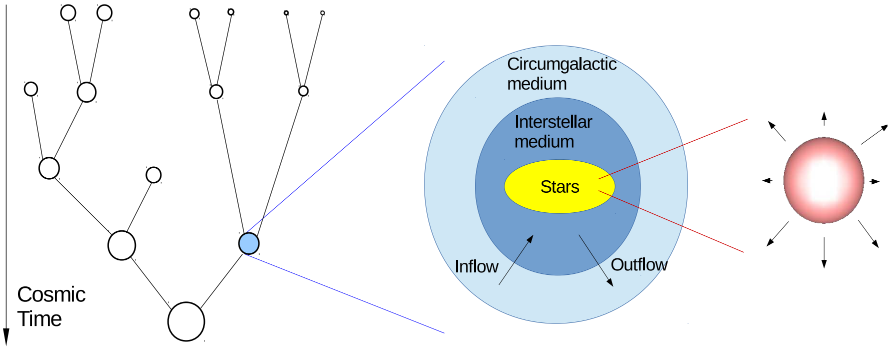

- Merger tree of dark matter halos

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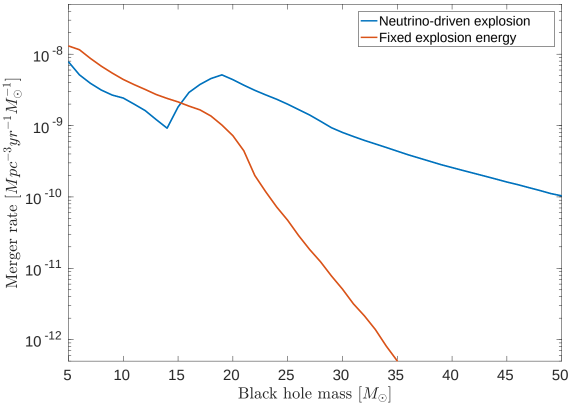
Merger rates vs. mass

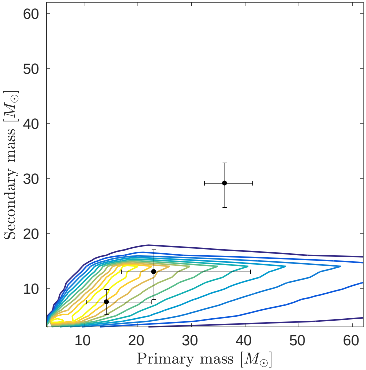
Woosley & Weaver (1995) vs. Fryer et al. (2012)



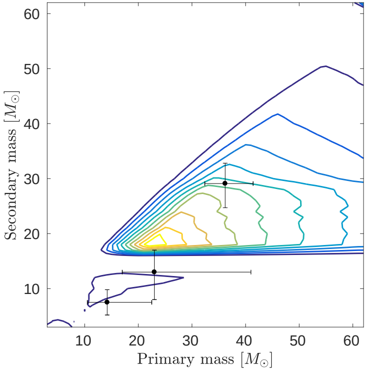
Dvorkin et al. (2016)

Detection rates: m_1 vs. m_2

Fixed explosion energy
Woosley & Weaver (1995)



Neutrino-driven explosion
Fryer et al. (2012)

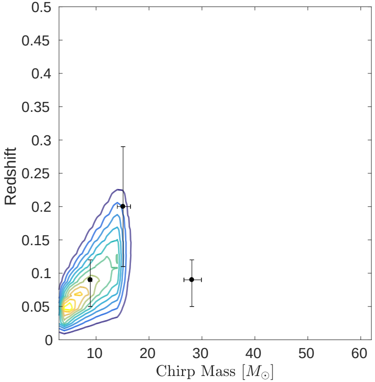


Dvorkin et al. in prep

Detection rates: M_{chirp} vs. z

Fixed explosion energy

Woosley & Weaver (1995)



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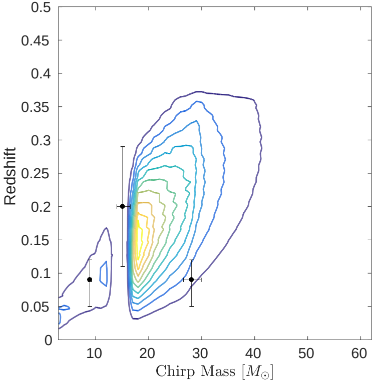

Dvorkin et al. in prep

Summary

An exciting time for astrophysics:

- Gravitational wave astronomy is expected to provide constraints on:
  - Stellar evolution (winds...)
  - SN explosion mechanism
  - Binary systems (common envelope...)
  - BH mergers in stellar clusters
  - *PopIII stars, primordial BHs, ...*

Summary

An exciting time for astrophysics:

- Gravitational wave astronomy is expected to provide constraints on:
  - Stellar evolution (winds...)
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  - BH mergers in stellar clusters
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- **Models are complex and involve various parameters: will need many detections (~ 100) and sofisticated analysis tools**

Additional slides

Stochastic gravitational wave background

- The background due to unresolved mergers of binary BHs

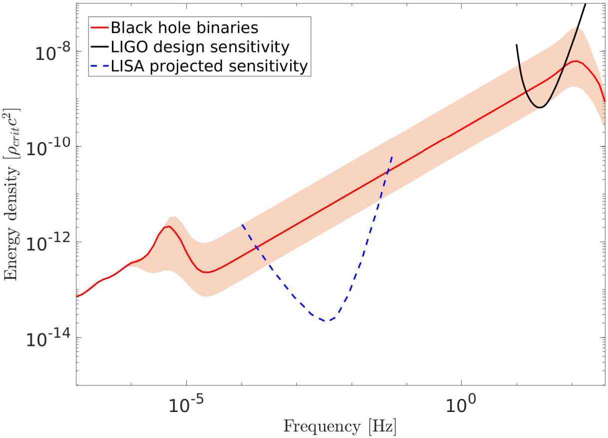
Stochastic gravitational wave background

- The background due to unresolved mergers of binary BHs
- Dimensionless density parameter (energy density in units of ρ_c per unit logarithmic frequency)

$$\Omega_{\rm gw}(f_o) = \frac{8\pi G}{3c^2 H_0^3} f_o \int dm_{bh} \int dz \frac{R_{\rm source}(z, m_{bh})}{(1+z)E_V(z)} \frac{dE_{\rm gw}(m_{bh})}{df}$$

$R_{\rm source}(z, m_{bh})$ is the merger rate, dE_{gw}/df is the emitted spectrum

Stochastic gravitational wave background



Dvorkin et al. (2016)