First gravitational wave detections : astrophysical implications and perspectives

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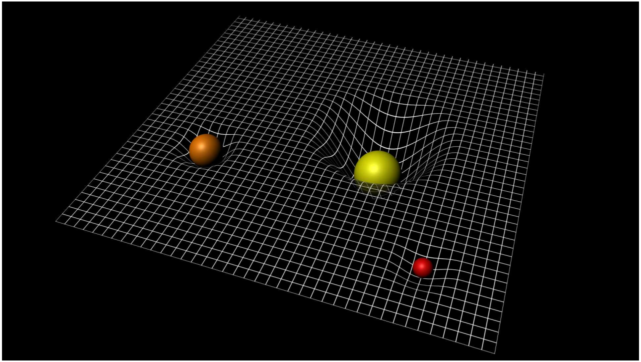
Institut d'astrophysique de Paris

Short history of gravitational wave astronomy

1915 : General relativity formulated by Einstein
1916 : Prediction of gravitational waves

Gravitational waves in General Relativity

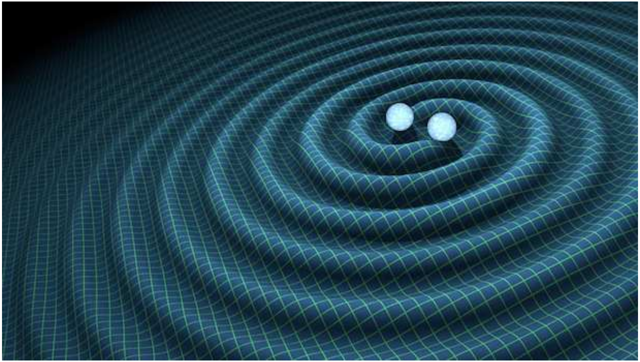
'Matter tells spacetime how to curve, spacetime tells matter how to move' (Wheeler)



Credit: ESA C. Carreau

Gravitational waves in General Relativity

- Produced by accelerating masses
- Propagate at the speed of light
- Weakly interacting



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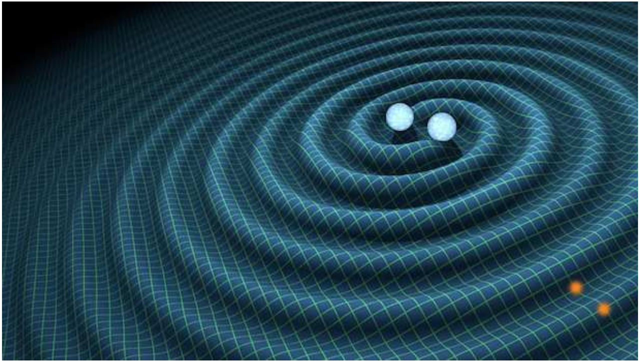

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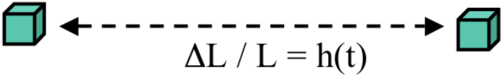
1960-1970 : First attempts to detect gravitational waves.
Prototype laser interferometers are built.

Typical strain amplitude

Using interferometers to detect GW (examples: LIGO, Virgo, LISA...)



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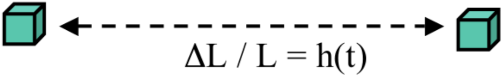

Strain from merging compact objects (black holes, neutron stars):

$$h = \frac{\Delta L}{L} \sim 10^{-20} \left(\frac{M}{M_\odot}\right) \left(\frac{Mpc}{D}\right)$$

$1 \text{ Mpc} = 3.1 \cdot 10^{19} \text{ km}$
$1\ M_\odot = 2 \cdot 10^{30} \text{ kg}$

$M \sim 30 M_\odot$ at $D \sim 400$ Mpc observed with LIGO:

$$L = 4 \text{ km} \rightarrow \Delta L \sim 3 \cdot 10^{-18} \text{ m}$$

Typical strain amplitude and frequency

Strain from merging compact objects (black holes, neutron stars):

$$h = \frac{\Delta L}{L} \sim 10^{-20} \left(\frac{M}{M_\odot}\right) \left(\frac{Mpc}{D}\right)$$

Typical frequency:

$$f \sim \frac{c}{2\pi R_S} \sim 10^4 \text{ Hz } \frac{M_\odot}{M}$$

$10 M_\odot$ at 100 Mpc $\rightarrow h \sim 10^{-21}$, $f < 10^3$ Hz

$10^6 M_\odot$ at 10^4 Mpc $\rightarrow h \sim 10^{-18}$, $f < 10^{-2}$ Hz

$10^9 M_\odot$ at 10^4 Mpc $\rightarrow h \sim 10^{-15}$, $f < 10^{-5}$ Hz

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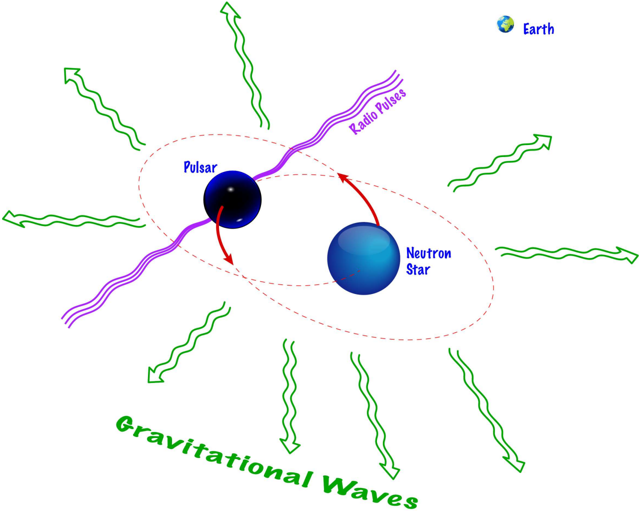
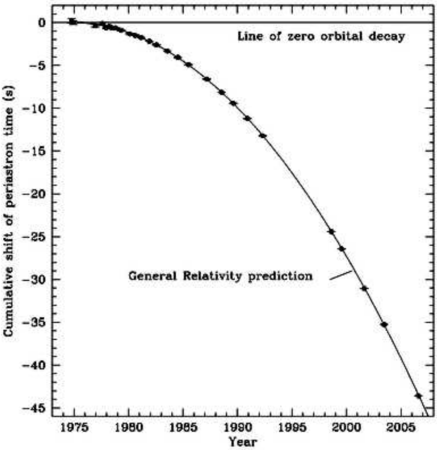
Hulse-Taylor binary pulsar



Hulse-Taylor binary pulsar

Orbit decays due to emission of gravitational waves



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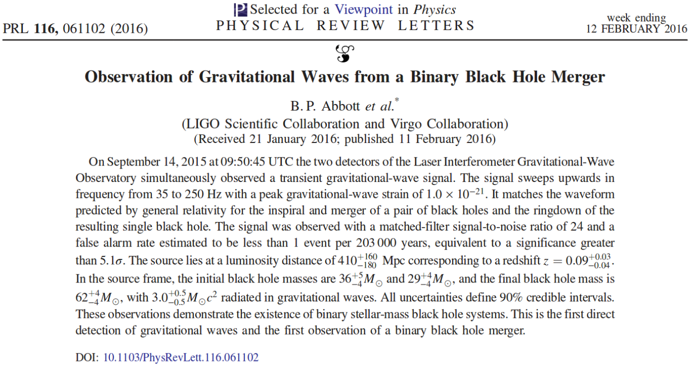
2015 : Advanced LIGO detects gravitational waves emitted by merging black holes

Gravitational waves are detected!



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

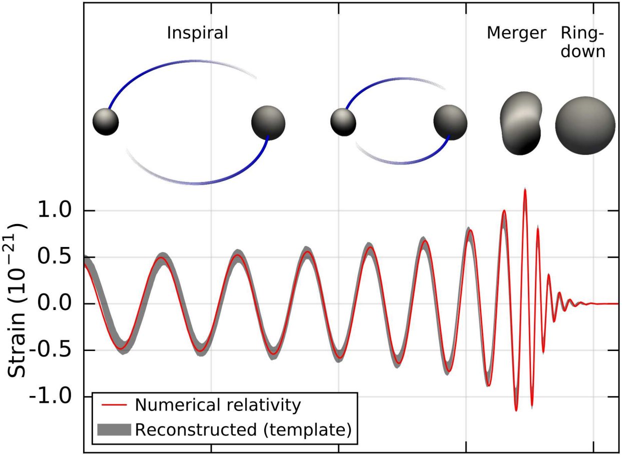
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

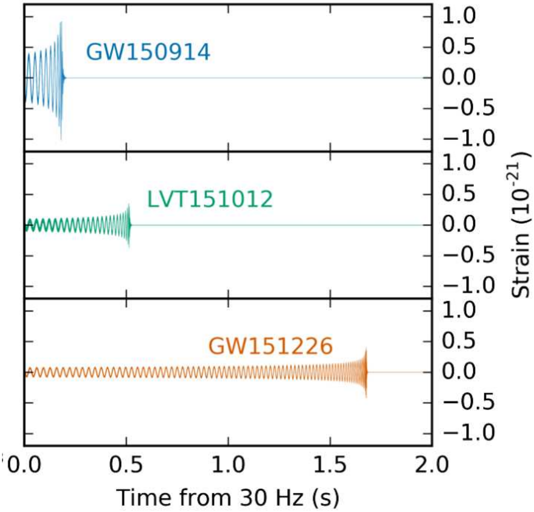
DOI: 10.1103/PhysRevLett.116.061102

Gravitational waves from binary black holes



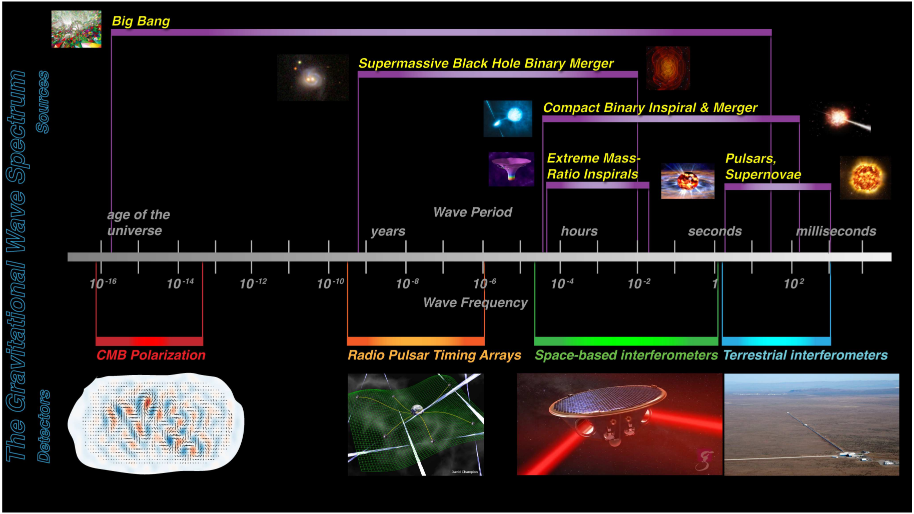
Abbott et al. PRL 116, 061102 (2016)

Gravitational waves from binary black holes



Abbott et al. Phys. Rev. X 6, 041015 (2016)

Spectrum of gravitational waves

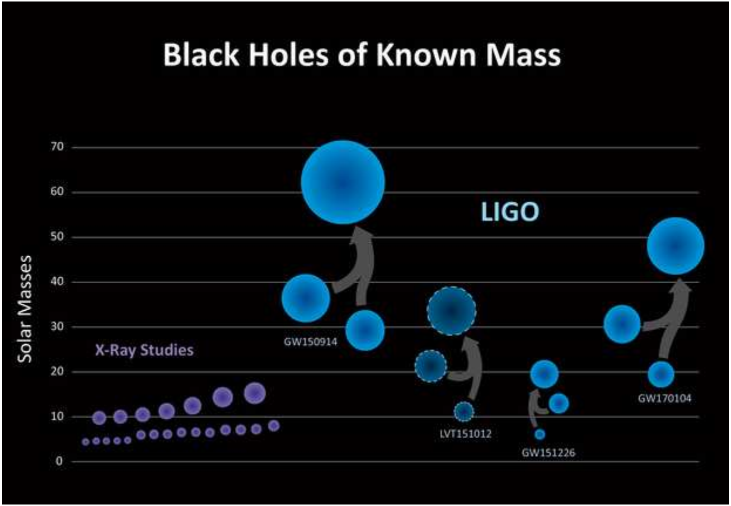


Astrophysics with gravitational waves

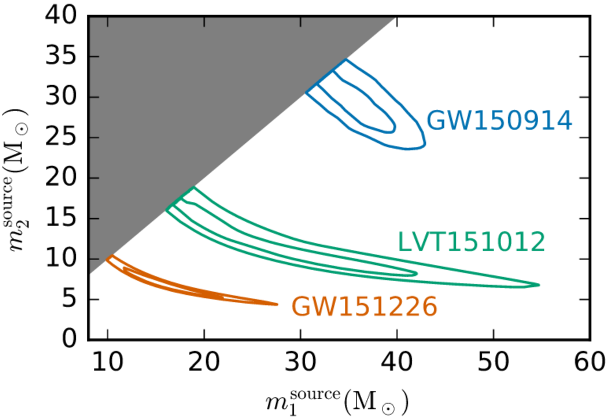
What can we learn about black hole formation?

Mass distribution of BHs

(LIGO/Virgo Collaboration [1606.04856])



Measuring BH properties: masses, spins, distances...



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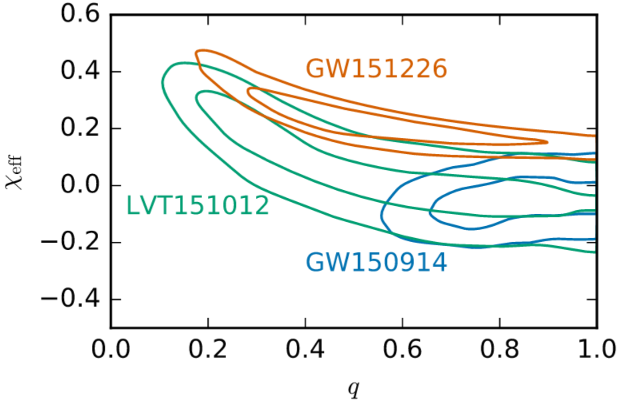

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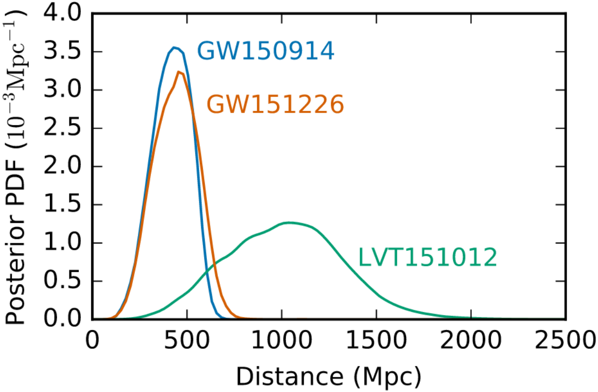
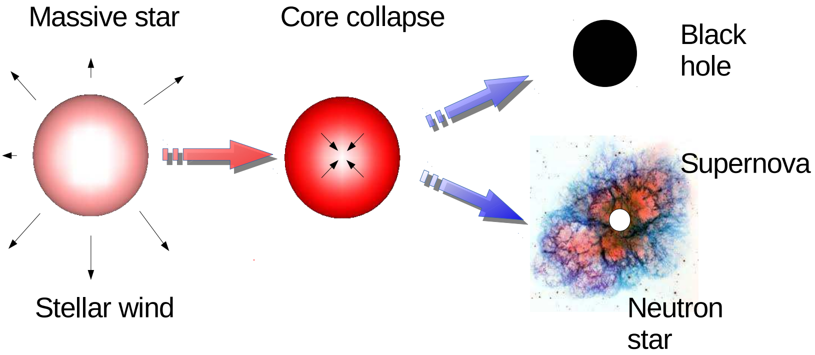


Abbott et al. Phys. Rev. X 6, 041015 (2016)

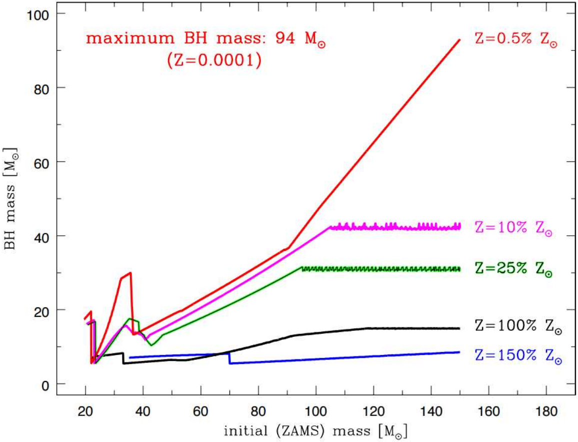
How do black holes form (1)

Standard scenario: massive stars ($M \gtrsim 20 M_\odot$) collapse to BHs after exhausting their nuclear fuel



How do black holes form (1)

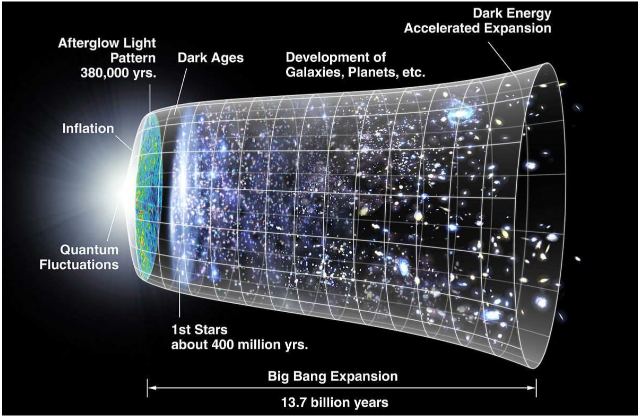
The mass of the black hole depends on the properties of the progenitor star: mass, chemical composition (metallicity), rotation...



[Belczynski et al. 2012]

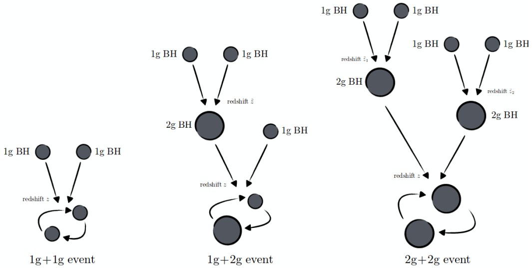
How do black holes form (1)

- Low metallicity → early cosmic times



How do black holes form (2)

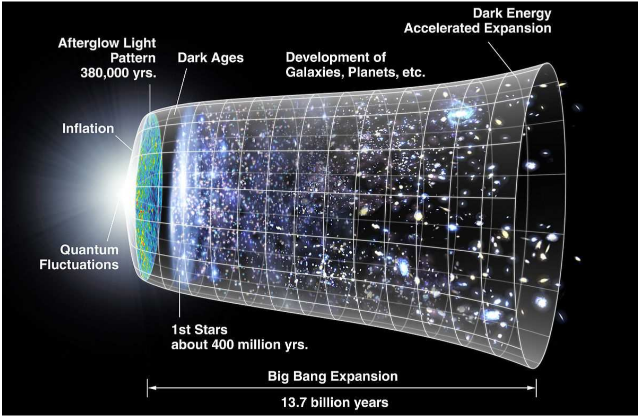
- Interactions in dense stellar environments



Gerosa & Berti (2017)

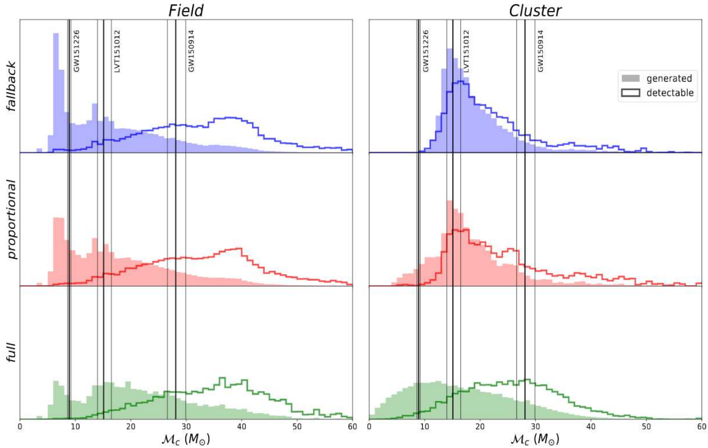
How do black holes form (3)

- Primordial BHs can form deep in the radiation-dominated era from extreme density fluctuations



Model selection: mass distribution

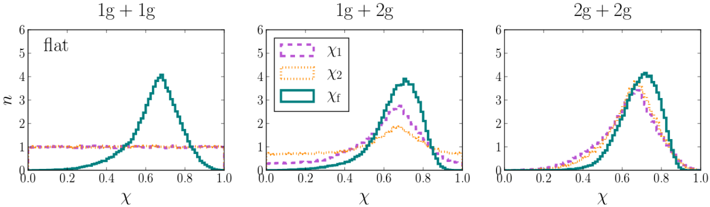
Need to account for observational bias



Zevin et al. (2017)

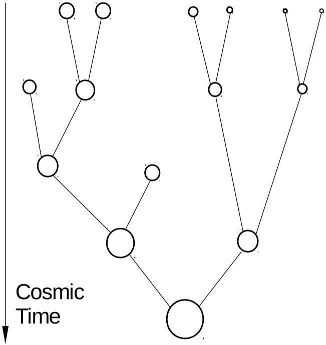
Model selection: spin distribution

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



Gerosa & Berti (2017)

Cosmological galaxy evolution model



- Merger tree of dark matter halos

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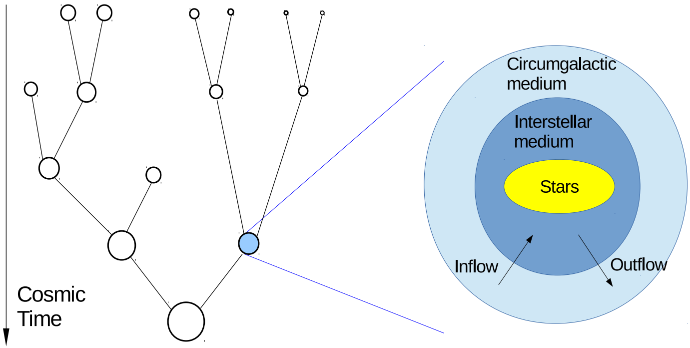

- Merger tree of dark matter halos

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

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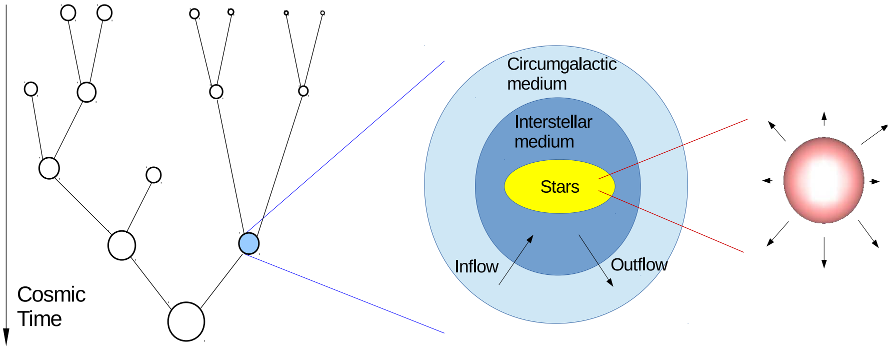

- Merger tree of dark matter halos

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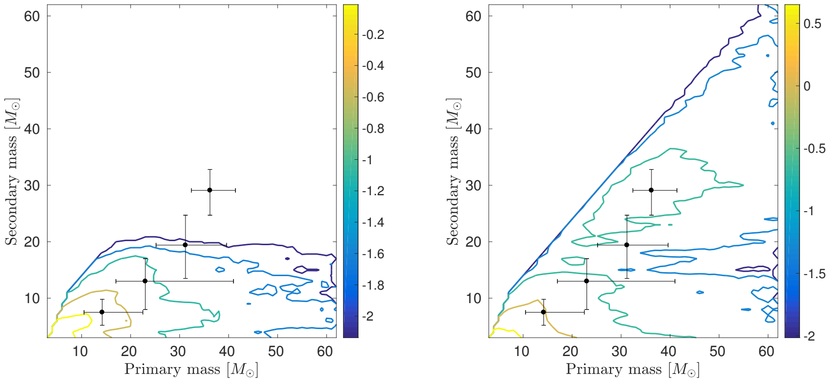
Detection rates: m_1 vs. m_2

Fixed explosion energy
Woosley & Weaver (1995)

Neutrino-driven explosion
Fryer et al. (2012)



Dvorkin et al. in prep

Summary

An exciting time for astrophysics:

- Gravitational wave astronomy is expected to provide constraints on:
    - Stellar evolution (winds...)
    - Supernova explosion mechanism
    - Binary systems
    - Stellar dynamics in dense environments (star clusters)
    - Primordial black holes

Summary

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  - Stellar dynamics in dense environments (star clusters)
  - Primordial black holes
- **Models are complex: will need many detections (~ 100) and sofisticated analysis tools**