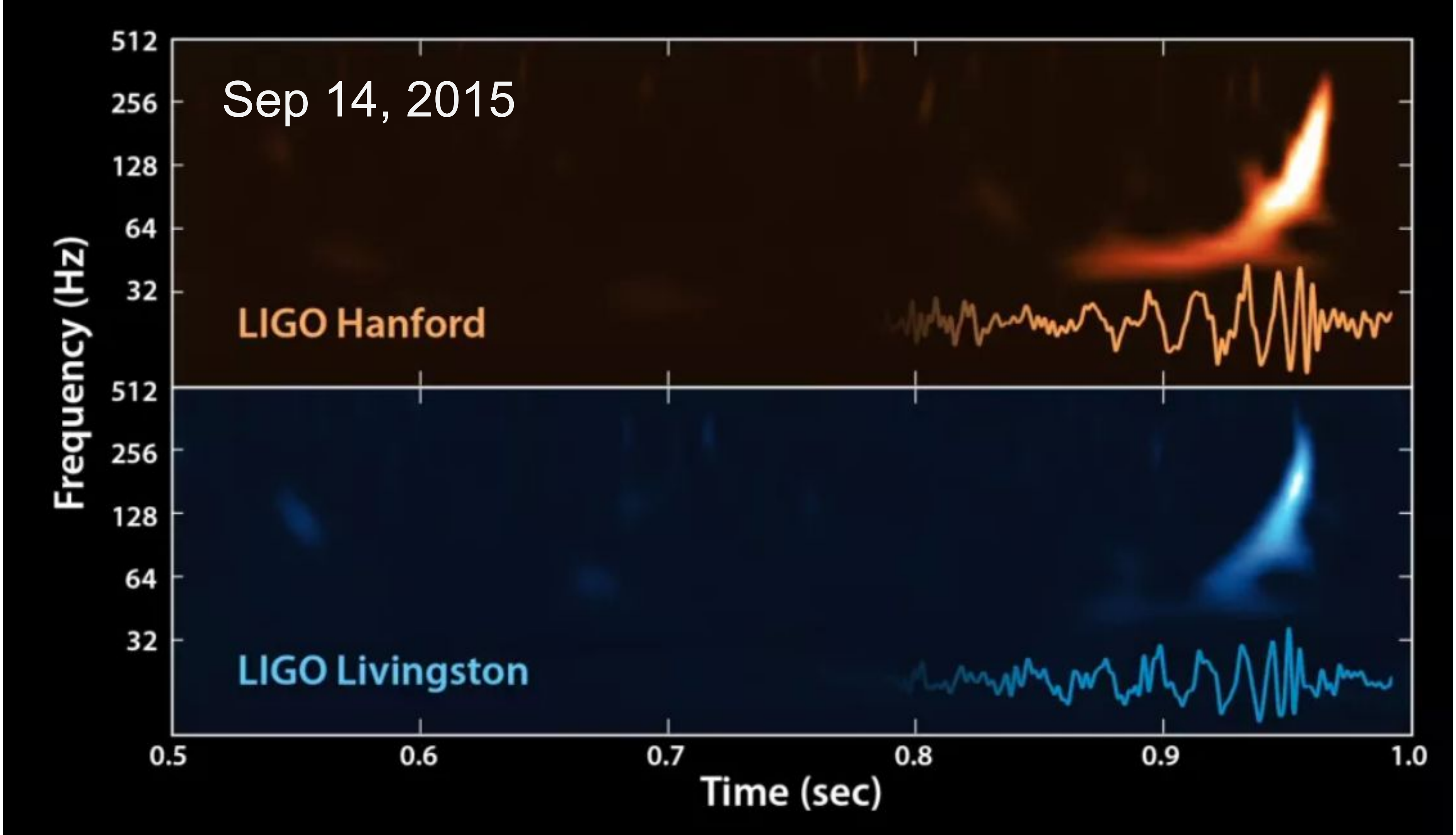
Counting Black Holes

The Cosmic Stellar Remnant Population and Implications for LIGO

Elbert, Bullock, and Kaplinghat (2018)


Sep 14, 2015
LIGO Hanford
LIGO Livingston
Frequency (Hz)
512
256
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512
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Time (sec)
0.5
0.6
0.7
0.8
0.9
1.0

We are pivoting from "GW *discovery* to GW *astronomy*"

Previous work:

Lamberts et al. (2016):
- GW 150914 likely formed in massive galaxy at $z \sim 1$
- Dwarf galaxy also possible

Belczynski et al. (2016):
- Massive black holes prefer low metallicity galaxies

Chatterjee et al. (2017):
- Massive black holes formed in globular clusters prefer massive, low metallicity clusters

What can we observe (about binary stellar mass black holes)?

Currently observable

- Rate
- BH Masses
- Spins

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Difficult but possible

- Distribution of host galaxy properties (SFR, galaxy mass, metallicity, etc.)
- Host galaxies of individual mergers

What can we predict (about binary stellar mass black holes)?

Assuming stellar population synthesis + merger "efficiency" + merger timescale:

As a function of BH mass:

- Rate
- Distribution of host galaxy masses / metallicities / SFRs
- Distribution of BBH *formation* redshifts

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Stellar population synthesis +

merger "efficiency" + merger timescale:

As a function of BH mass:

- Rate
- Distribution of host galaxy masses / metallicities / SFRs
- Distribution of BBH formation redshifts

How do we go about inferring these things?

Assume all black holes are from stellar evolution

Jean

Estimate N (black holes) as a function of BH mass & galaxy properties

Yashvi

Parameterize your ignorance about (1) the fraction that merge (2) the time it takes to merge

Kishalay

Compare predictions with observables to constrain parameters

What determines the black hole number density?

1. How massive must a star be to form a black hole?
2. How many progenitor stars exist in a galaxy?
3. What is the density of galaxies of a given total stellar mass?

Black hole masses will be denoted with $m_{\rm bh}$

Stellar masses will be denoted with $\mathcal{M}$

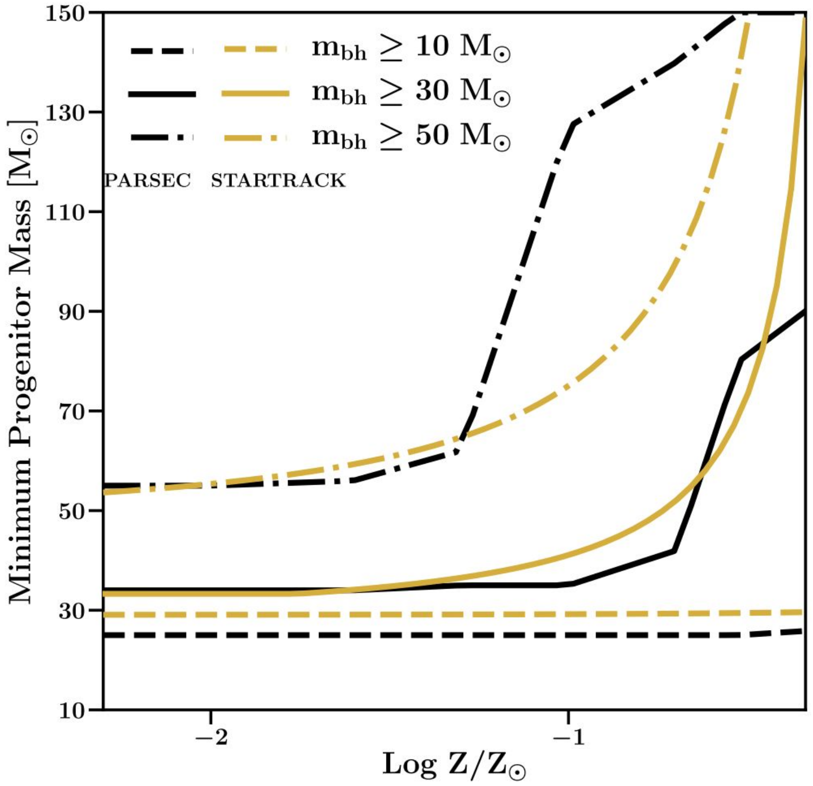
Total galaxy stellar masses will be denoted with $M_\star$

1. Minimum stellar mass to form a black hole

$$\mathcal{M}_{\rm min}(m_{\rm bh}, Z)$$

Note: strong dependence on metallicity

Fiducial values use PARSEC



2. How many progenitor stars exist in a galaxy?

Fraction of stars of a given metallicity which could form black holes > m_{bh}

Fiducially 150 $M_\odot$

$$\int_{\mathcal{M}_{\min}(m_{\rm bh},Z)}^{\mathcal{M}_{\rm u}} \xi(\mathcal{M}')\,{\rm d}\mathcal{M}'$$

Stellar IMF

Kroupa 2002

2. How many progenitor stars exist in a galaxy?

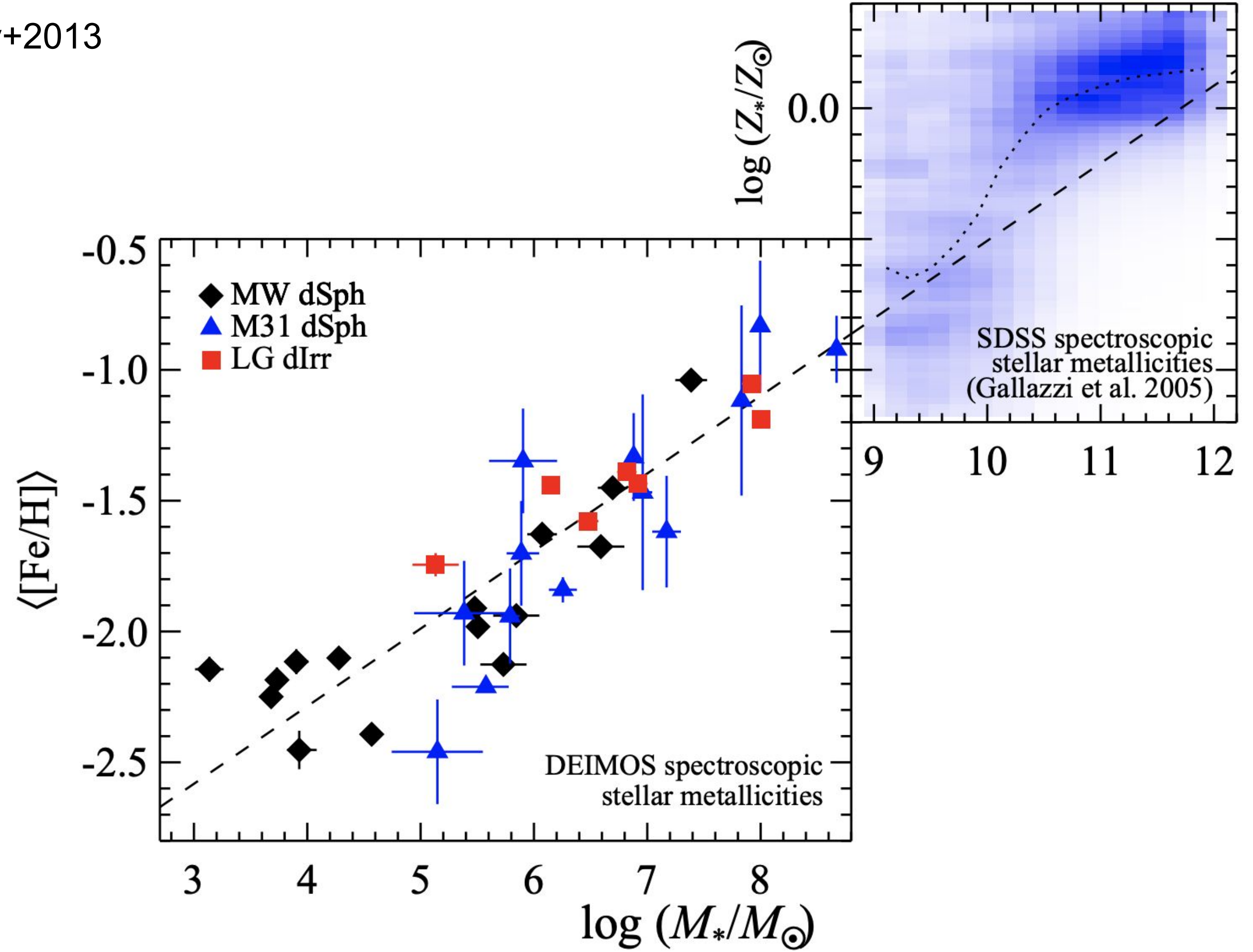
Fraction of stars with metallicity *Z* in a galaxy of mass M_*

$$\int \mathcal{P}(Z, M_\star) \int_{\mathcal{M}_{\min}(m_{\rm bh}, Z)}^{\mathcal{M}_{\rm u}} \xi(\mathcal{M}')\, \mathrm{d}\mathcal{M}' \mathrm{d}Z$$

Metallicity distribution function

Gallazzi+2005, Kirby+2013

Kirby+2013



MW dSph
M31 dSph
LG dIrr
⟨[Fe/H]⟩
log (M*/M⊙)
DEIMOS spectroscopic
stellar metallicities
log (Z*/Z⊙)
SDSS spectroscopic
stellar metallicities
(Gallazzi et al. 2005)
-0.5
-1.0
-1.5
-2.0
-2.5
0.0
3
4
5
6
7
8
9
10
11
12

2. How many progenitor stars exist in a galaxy?

Normalization

$$N_*(M_*) = \frac{M_*}{\int_{0.08\,M_\odot}^{\mathcal{M}_l(M_*)} \mathcal{M}'\xi(\mathcal{M}')d\mathcal{M}'}$$

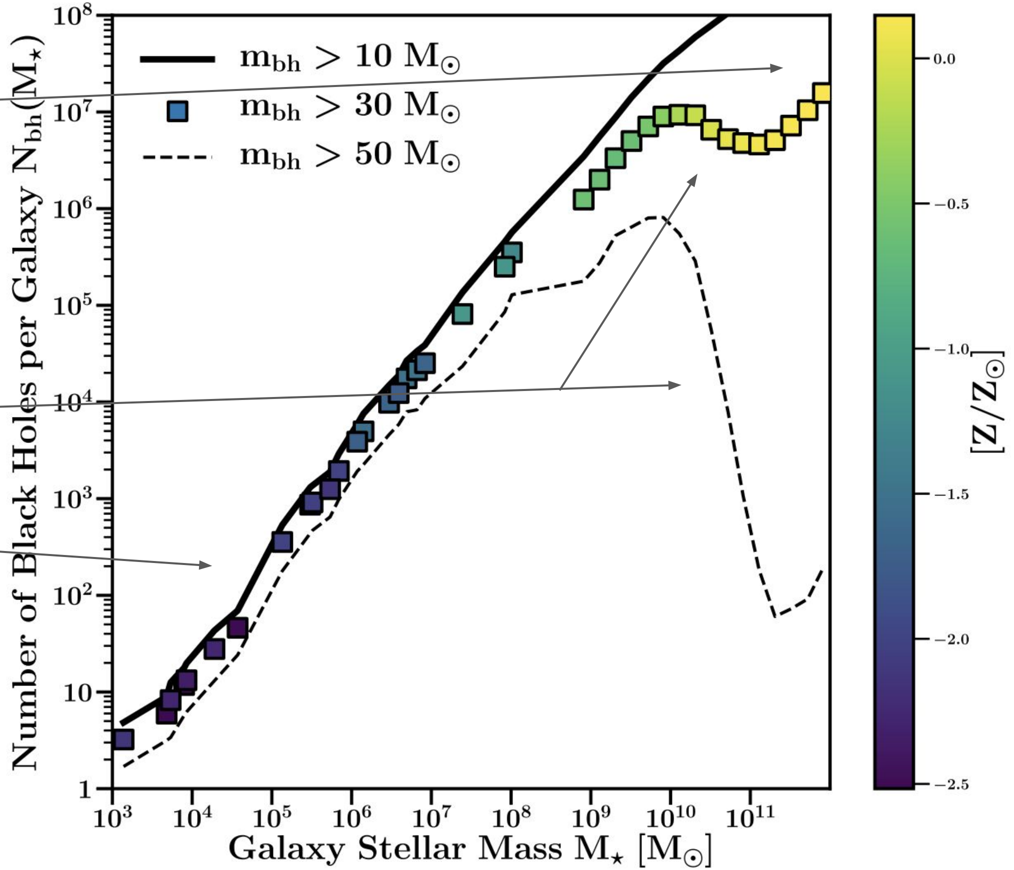
$$N_\star(M_\star)\int \mathcal{P}(Z, M_\star)\int_{\mathcal{M}_{\min}(m_{\rm bh},Z)}^{\mathcal{M}_{\rm u}} \xi(\mathcal{M}')\,\mathrm{d}\mathcal{M}'\mathrm{d}Z$$

The upper bound is the mass for which MS lifetime = average galaxy age (Behroozi, Wechsler & Conroy 2013)

MDF flattens

Metallicity effects kick in

Linear relation



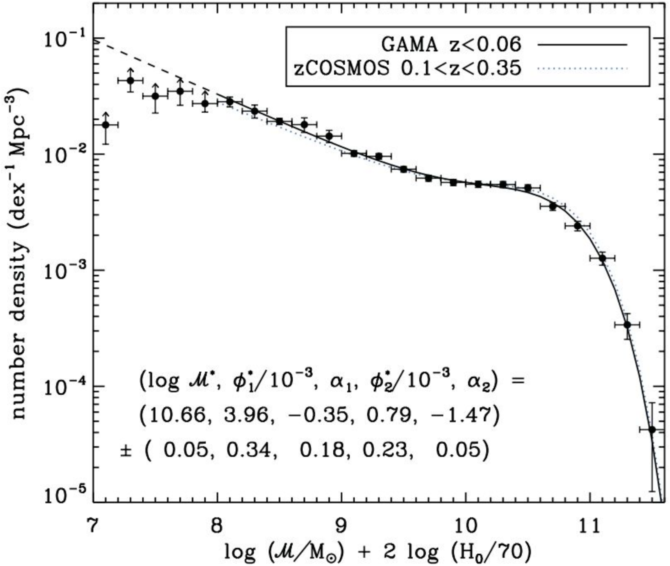
$$N_{\rm bh}(>m_{\rm bh}, M_\star) = N_\star(M_\star)\int \mathcal{P}(Z, M_\star)\int_{\mathcal{M}_{\rm min}(m_{\rm bh},Z)}^{\mathcal{M}_{\rm u}} \xi(\mathcal{M}')\,{\rm d}\mathcal{M}'{\rm d}Z$$

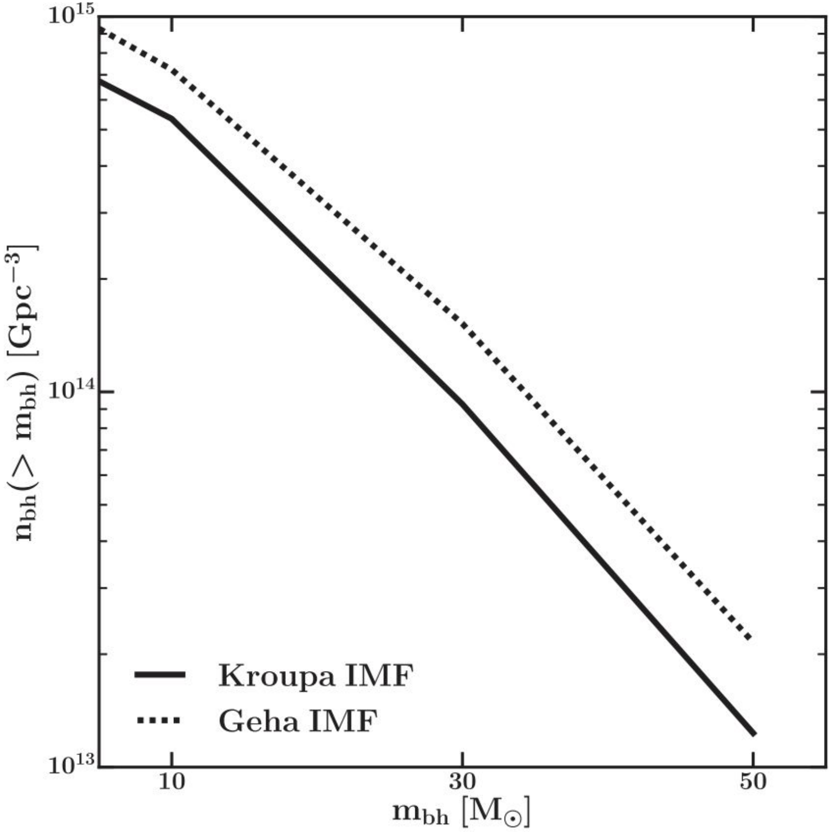
3. How many galaxies are there?

$$n_{\rm bh}(>m_{\rm bh}) = \int_{M_{\rm min}}^{\infty} \phi(M_\star)\, N_{\rm bh}(>m_{\rm bh}, M_\star)\, {\rm d}M_\star$$

Galactic Stellar Mass Function

Baldry et al. 2012, $M_{min} = 10^3\ M_\odot$



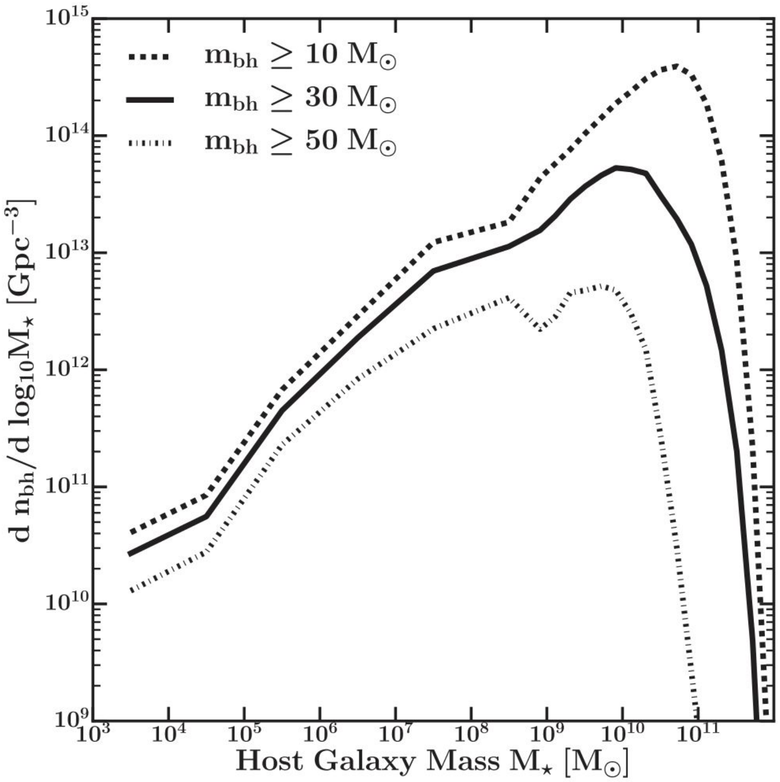


Lower mass black holes live in the most massive galaxies

High mass black holes live in dwarfs

Verification that this methodology is reasonable:

Applying the same equations to core collapse supernovae, they recover the observed number density within a factor of ~1.5



From BH number density to merger rate

Assumptions:

1. Mergers occur amongst binary pairs
   - ‘Binary black hole efficiency’ parameter : ϵ

$$n_{\rm bh}^{\rm pair}(>m_{\rm bh}) = \frac{1}{2}\,\epsilon\, n_{\rm bh}(>m_{\rm bh}).$$

   - Both BHs in a pair above same threshold mass i.e. $m_1, m_2 > m_{bh}$

2. Mergers occur after birth of binary pair over time-scale τ

Parameters to constrain : ϵ and τ

Epsilon magic

$$\epsilon \equiv f_{b\star} \times f_{m_1/m_2} \times f_{surv} \times f_t$$

Massive star binary fraction ~ **0.5**
Kobulnicky & Fryer (2007)

Fraction of massive binary systems with $m_1/m_2 = 0.9$ is ~ **0.1**
Sana et al. (2012)

Fraction of binary systems that survive as BH pair after stellar evolution ~ **0.1**
Belczynski et al.2016a

Fraction of BBH available to merge before present day
$f_t < 1$

Black hole merger rate density

- Formation rate density of BH pairs that can merge

$$\dot{n}_{\rm bh}^{\rm pair} = 0.5\,\epsilon\,\dot{n}_{\rm bh}$$

- Birth-rate density of BH
    - Assuming that it tracks the observed shape of global SFR density

$$\dot{n}_{\rm bh}(>m_{\rm bh}, t) = n_{\rm bh}(>m_{\rm bh})\,\frac{\psi(t)}{\int_0^{t_0}\psi(t')\mathrm{d}t'}$$

- Then for a distribution of merger times $\mathrm{P}(\tau') = \delta(\tau' - \tau)$

$$\mathcal{R} = \frac{1}{2}\,\epsilon\,\dot{n}_{\rm bh}(t_0 - \tau)$$

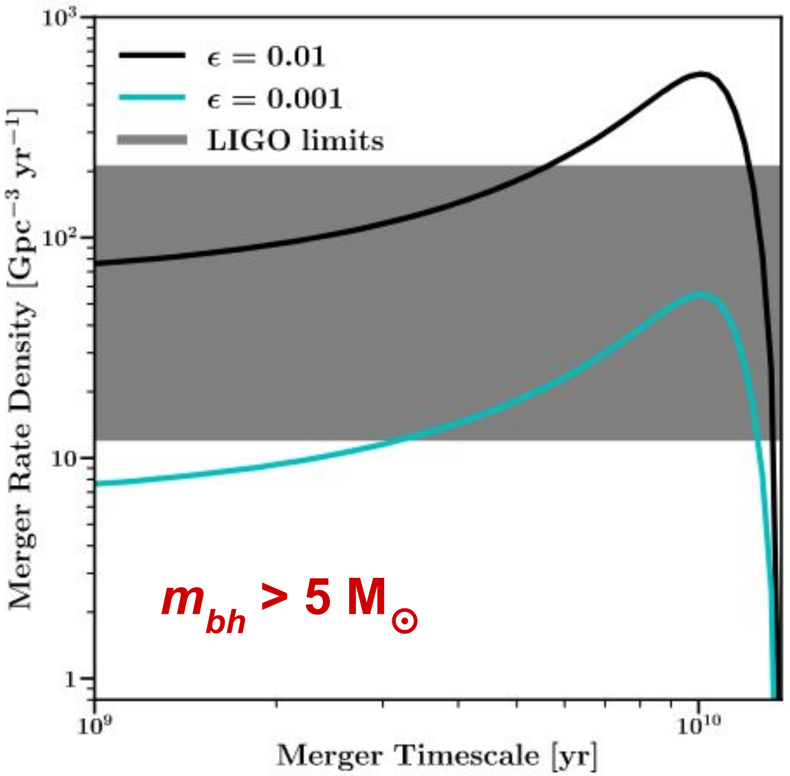
Predicted merger rate density

Gray region : 12 ≤ R ≤ 213 (Abbott et al., 2017)

Shorter τ (< 2 Gyr) needs larger ϵ (1%)

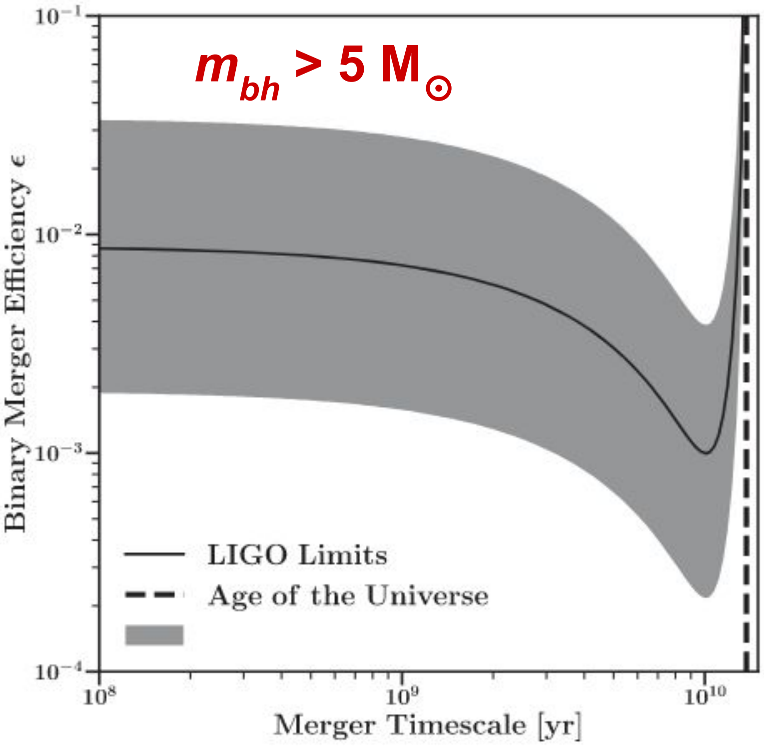
Longer τ (~10 Gyr) needs smaller ϵ (0.1%)

Similar agreement for $m_{bh} > 30\ M_\odot$



Degeneracy between τ and ϵ

$\epsilon \sim 0.2 - 3$ %
For $\tau < 2$ Gyr



$\epsilon \sim 0.02 - 0.4$ %
For $\tau \sim 10$ Gyr

NS-NS & Massive BH (>50 $M_\odot$) merger rates

From Abbott et al. (2016b)

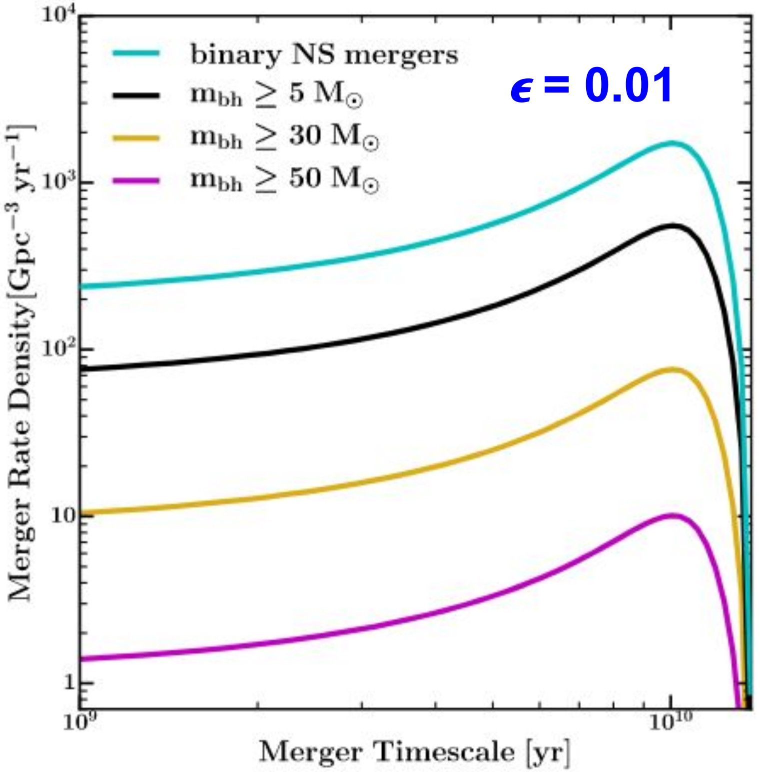
$$\mathcal{R}_{\rm NS} < 12\,600\ {\rm Gpc^{-3}\ yr^{-1}}.$$

From Kim, Kalogera & Lorimer(2006) & Enrico Petrillo, Dietz & Cavagli`a (2013)

$$\mathcal{R}_{\rm NS} \simeq 10^2 - 10^3\ {\rm Gpc^{-3}\ yr^{-1}}$$

Predicted rate density for m_{bh} > 50 $M_\odot$

$$\mathcal{R}_{50} \gtrsim 1\ (\epsilon/0.01)\ {\rm Gpc^{-3}\ yr^{-1}}$$



Breaking the degeneracy between τ and ϵ

Host galaxy populations of a statistical sample of mergers can constrain the delay times and merger efficiencies:

- Short delay times = Young and smaller star forming galaxies
- Long delay times = Old and larger quenched galaxies

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Number density of star formation

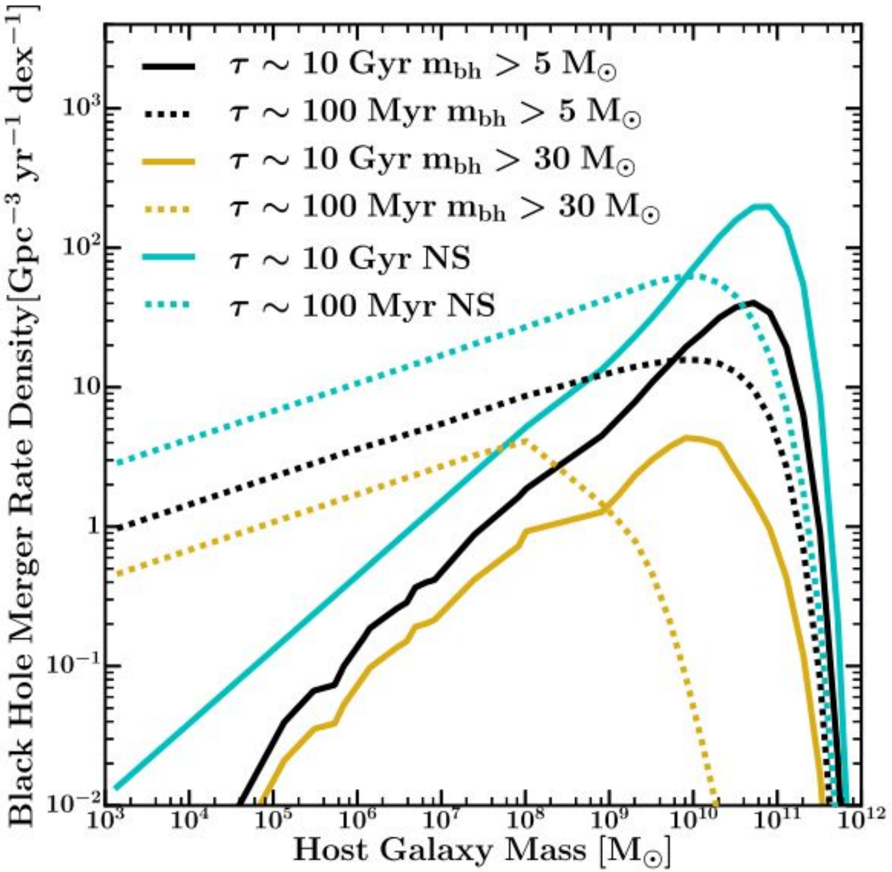
Galaxy mass function

$$\dot{n}_{\rm ns,0} = \int_{M_{\rm min}}^{\infty} \phi(M_\star) \int \frac{\dot{M}_\star(M_\star, Z_{\rm g})}{\bar{\mathcal{M}}} \mathcal{P}(Z_{\rm g}, M_\star) \int_{\mathcal{M}_{\rm min}^{\rm ns}}^{\mathcal{M}_{\rm max}^{\rm ns}} \xi(\mathcal{M}')\,{\rm d}\mathcal{M}'\,{\rm d}Z_{\rm g}\,{\rm d}M_\star.$$

Initial mass function

Metallicity distribution

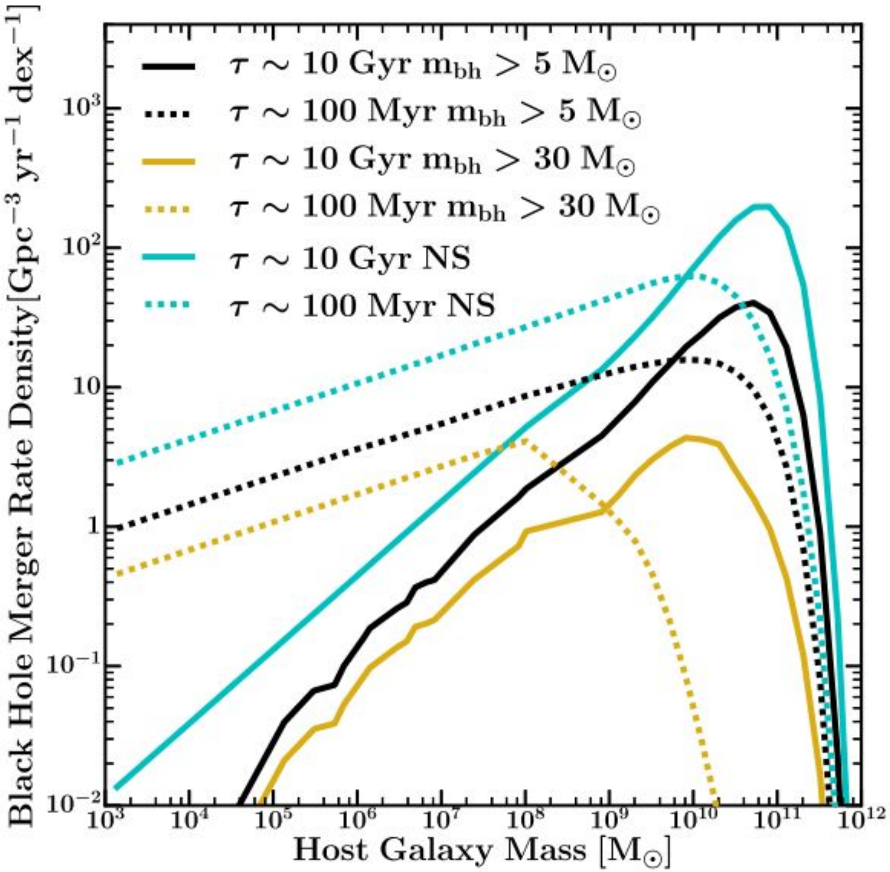
Merger rate as a function of host galaxy mass



Merger rate as a function of host galaxy mass

Shorter timescale mergers occur in lower mass galaxies on average (stars forming today)

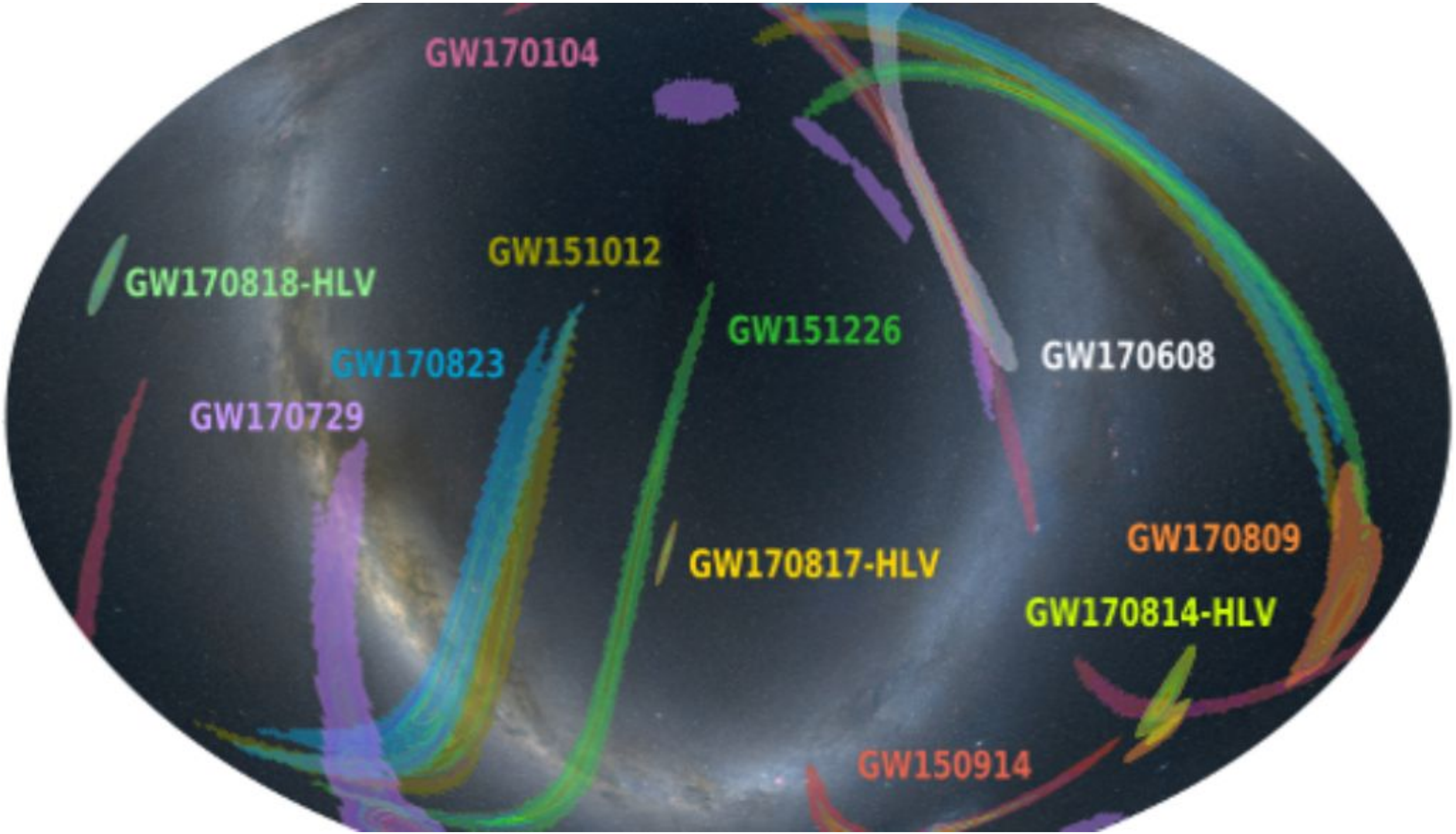
Strong effect for massive BHs since low metallicity only in low mass galaxies



47% of NS-NS mergers in dwarf galaxies for 100 Myr; Only 6% in dwarfs if 10 Gyr

51% of BBH mergers in dwarf galaxies, only 9% in dwarfs is 10 Gyr

The testing challenge: EM counterparts / localizations



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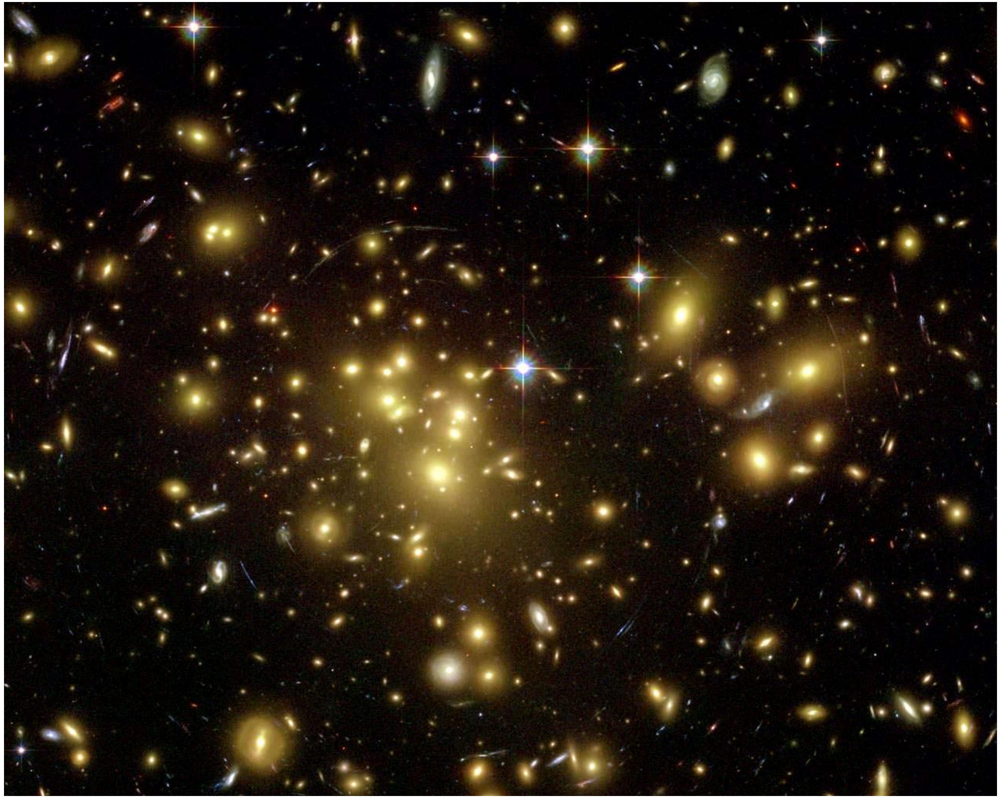

- Very massive galaxies preferentially hosted in giant clusters
- Even poorly localized association with clusters can test the fraction of BBH / BNS mergers in massive galaxies and constrain delay time and efficiencies.

What have we learned?

Estimate N (black holes) as a function of BH mass & galaxy properties

- $N_{BH} = 0.9 - 2 \times 10^{14}\ Gpc^{-3}$
- For galaxies < $10^{10}\ M_{\odot}$:
  - One >30 $M_{\odot}$ BH per 1000 $M_{\odot}$ of stars
- Plenty of massive BHs to merge

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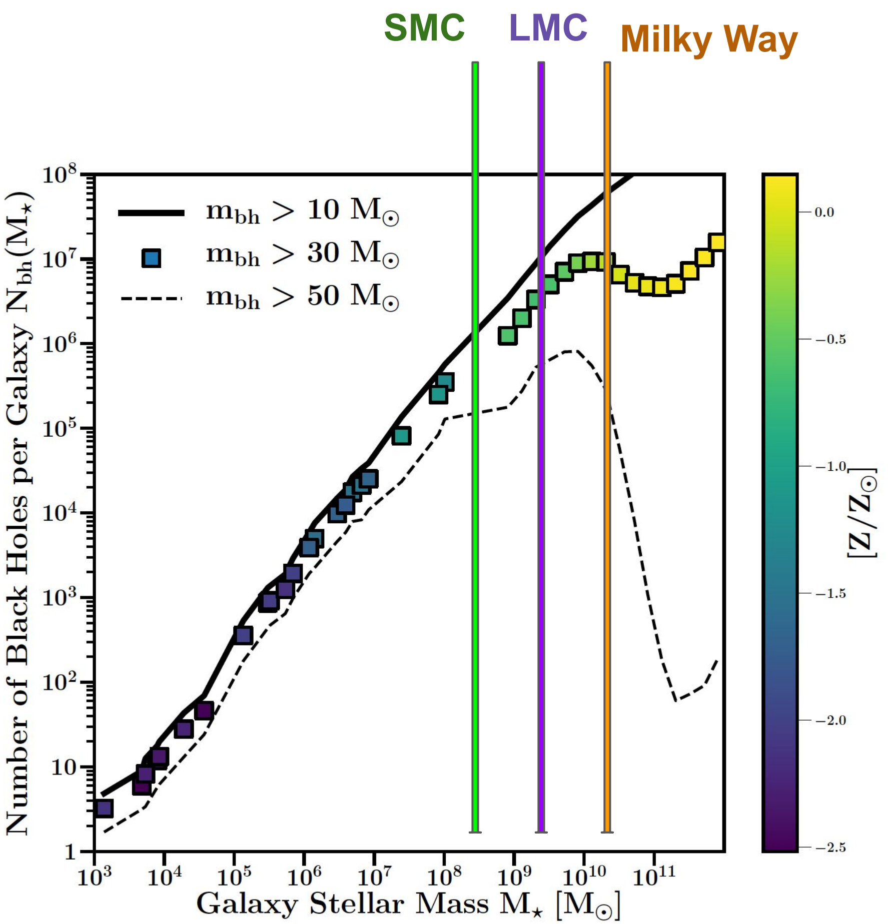
… especially in dwarf galaxies!

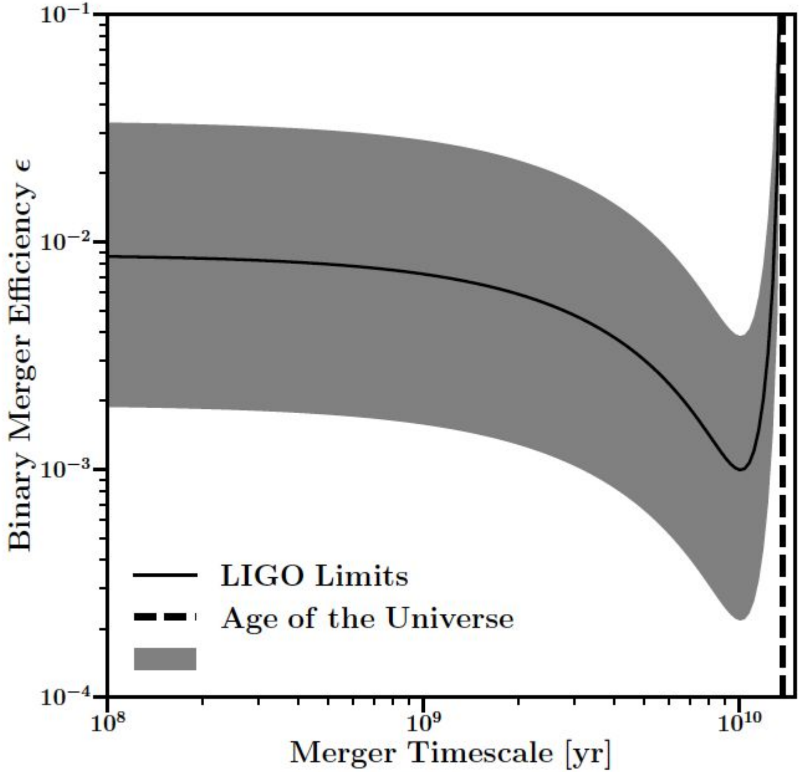


What have we learned?

Parameterize your ignorance about (1) the fraction that merge (2) the time it takes to merge

- Short merger timescales (< 5 Gyr) mean that ~1% of BH's are in binaries that merge

- Efficiency drops as merger timescales get longer, but spikes back up as it approaches a Hubble time



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Compare predictions with observables to constrain parameters

One possible way to break this degeneracy is to identify the host galaxy mass distribution for observed merger events. Small galaxies today have ongoing star formation, while larger galaxies tend to be quenched (e.g. Mannucci et al., 2010). Thus, binary mergers that occur soon after formation will more likely be seen in small galaxies. Mergers over timescales comparable to the age of the universe, however, will more closely track the overall stellar mass distribution. Most stars are in massive galaxies today (Baldry et al., 2012; Bernardi et al., 2013). Thus mergers detected locally that have take a long time to occur will be biased to reside within large galaxies.

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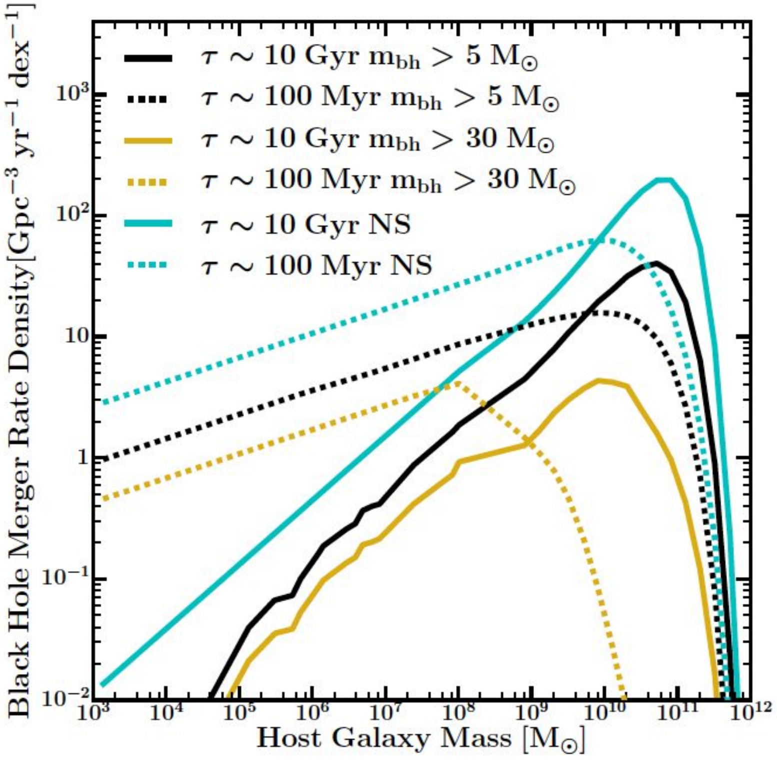

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2012; Lan et al., 2016). Scaling from the event-based rate derived for GW150914, we would therefore predict the rate for 50 $M_\odot$ black holes binary mergers to be $\mathcal{R}_{50} = 8^{+27}_{-6}$ Gpc^{3}yr^{-1}. This

Corresponding to ~56 per Gpc per year for > 30 solar masses

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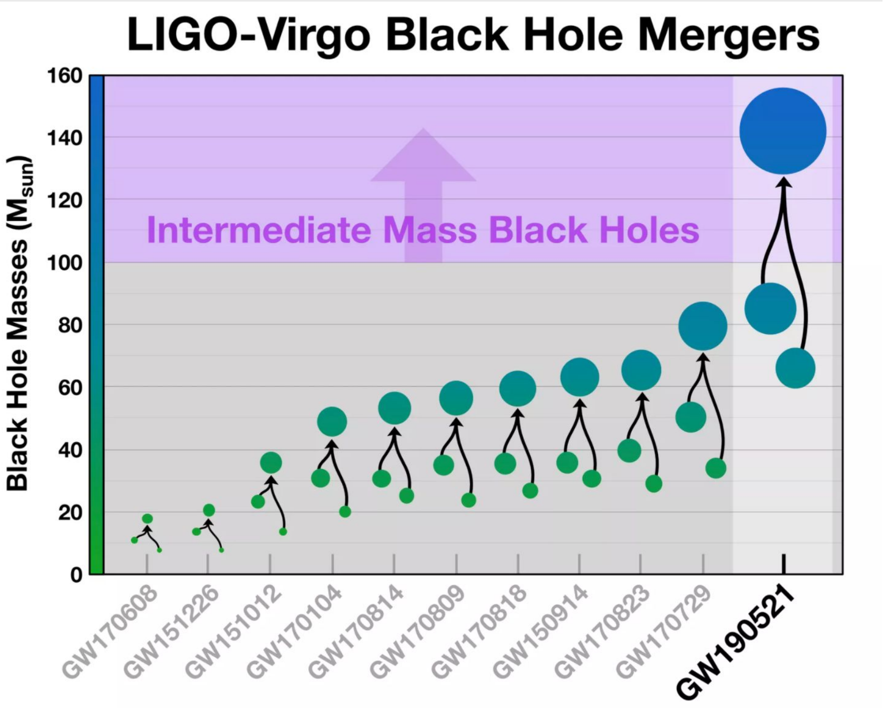
GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs

of marginal event candidates with an estimated false-alarm rate less than 1 per 30 days. From these results over the first two observing runs, which include approximately one gravitational-wave detection per 15 days of data searched, we infer merger rates at the 90% confidence intervals of $110 - 3840\ \mathrm{Gpc}^{-3}\ \mathrm{y}^{-1}$ for binary neutron stars and $9.7 - 101\ \mathrm{Gpc}^{-3}\ \mathrm{y}^{-1}$ for binary black holes assuming fixed population distributions and determine a neutron star–black hole merger rate 90% upper limit of $610\ \mathrm{Gpc}^{-3}\ \mathrm{y}^{-1}$.

Not bad, given O1 + O2 constraints.
However...

Assume all black holes are from stellar evolution

Though our approach is not well suited for ab initio calculations, it does provide fairly robust scalings because the uncertain/unknown parameters are reasonably constant for all compact objects in our calculations. For example, for any ϵ or τ, 50 $M_\odot$ black holes should have merger rate densities that are a factor of 7 ± 1 smaller than merger rates of binary 30 $M_\odot$ black holes (see Fig. 7). This range accounts for uncertainties in the faint end of the



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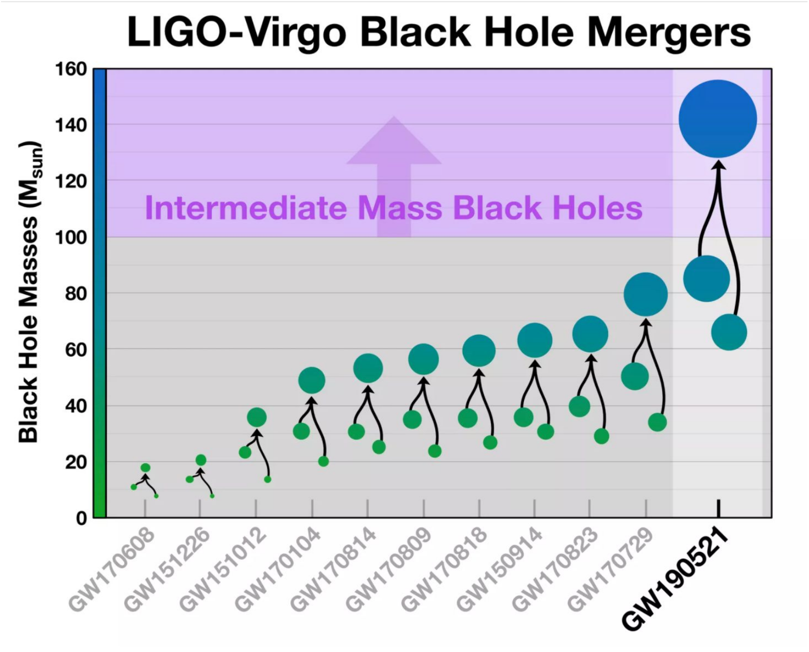
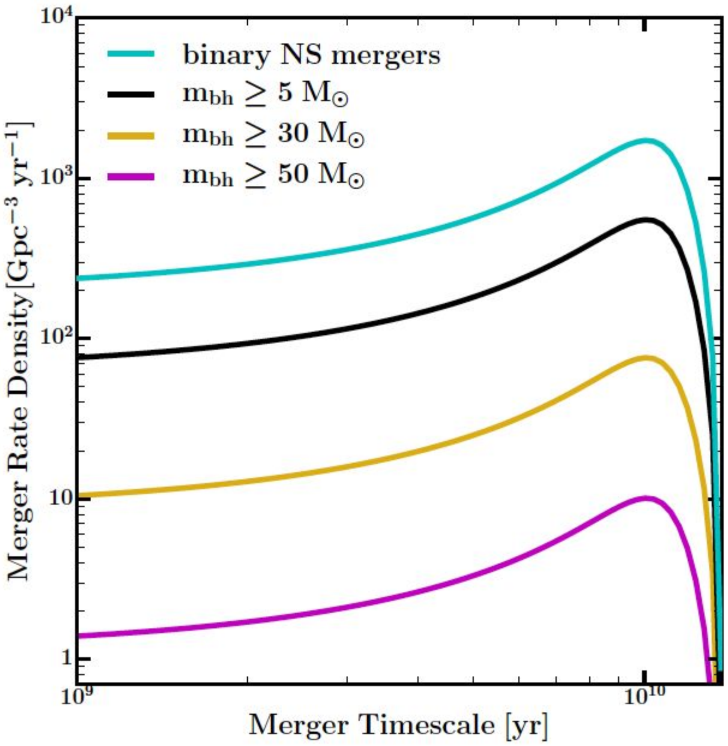


rate of mergers similar to GW190521 is $0.13^{+0.30}_{-0.11}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$



Rates aren't quite strong enough yet to challenge the stellar evolution assumption.

However, pair instability + other arguments (spins? asymmetry?) could be.

Questions?