Predictions from Improved Observational Measurements of the Galaxy Merger Rate and the Black Hole Mass Function

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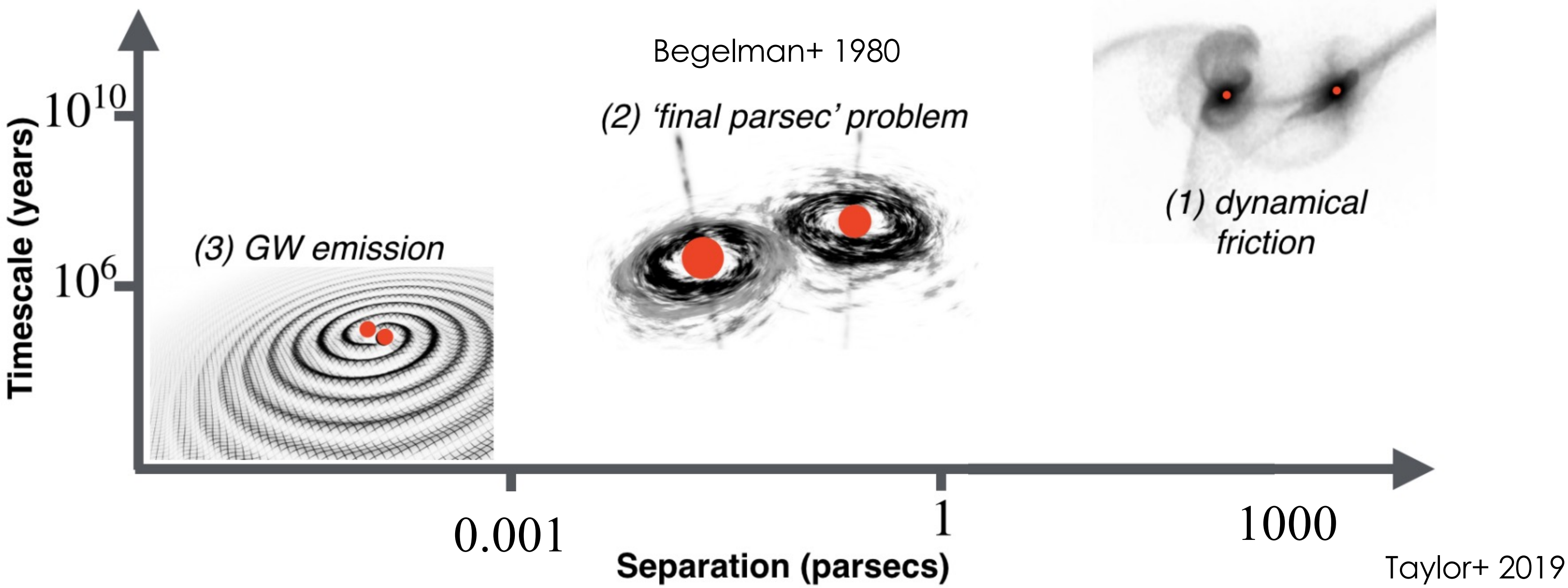
Gleaning Astrophysics from GWs

Galaxy merger rate + SMBH mass function + SMBH binary evolution

= Gravitational waves

The Unknown: SMBH Binary Evolution



For the SMBH binary evolution from ~pc to ~0.001 pc separation, unknowns are:

> SMBH binary timescale

> physics of SMBH binary evolution, including effects of stellar loss cone scattering and circumbinary gas disks (e.g., Kelley+ 2017)

Gleaning Astrophysics from GWs

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Our goal: use observationally-based estimates of galaxy merger rate and SMBH mass function to derive observationally-based constraints on SMBH binary evolution

Galaxy merger rate

Fractional galaxy merger rate is:

$$\mathcal{R}_{merge} = \frac{C_{merge}\ f_{pair}}{< T_{obs} >}$$

Observable:

f_{pair}, the galaxy close pair fraction

We are using SDSS galaxy pairs

Simulation-based:

C_{merge}, the correction factor to translate the number of galaxy pairs to the number of actual galaxy mergers

$<T_{obs}>$, the cosmologically-averaged observability timescale of merger

Galaxy merger rate

Hasn't this already been done? Yes, but due for some updates!

$$\mathcal{R}_{merge} = \frac{C_{merge}\ f_{pair}}{< T_{obs} >}$$

Our updates to the galaxy merger rate calculation:

1. Previous studies use a single number for the correction factor, derived from disk-disk merger simulations

We calculated the correction factor as a function of projected pair separation, velocity offset of the pairs, redshift, and galaxy stellar mass; derived from Illustris simulations (Ventou+ 2019)

Galaxy merger rate

Hasn't this already been done? Yes, but due for some updates!

$$\mathcal{R}_{merge} = \frac{C_{merge}\ f_{pair}}{< T_{obs} >}$$

Our updates to the galaxy merger rate calculation:

2. Previous studies use a single number for the observability timescale of a merger, derived from Millennium simulation

We calculated the observability timescale of a merger as a function of projected pair separation, velocity offset of the pairs, redshift, and galaxy stellar mass; derived from Illustris simulations (Snyder+ 2017)

Galaxy merger rate

Results!

Previous result:

$$\mathscr{R}_{merge} = 0.017 \text{ Gyr}^{-1}$$

Lotz+ 2011

Our updated result:

$$\mathscr{R}_{merge} = 0.036 \text{ Gyr}^{-1}$$

Simon, Comerford, & Nevin, in prep.

We find a galaxy merger rate that is a factor of 2 higher than previous estimates

This translates to an increase in the amplitude of GWs

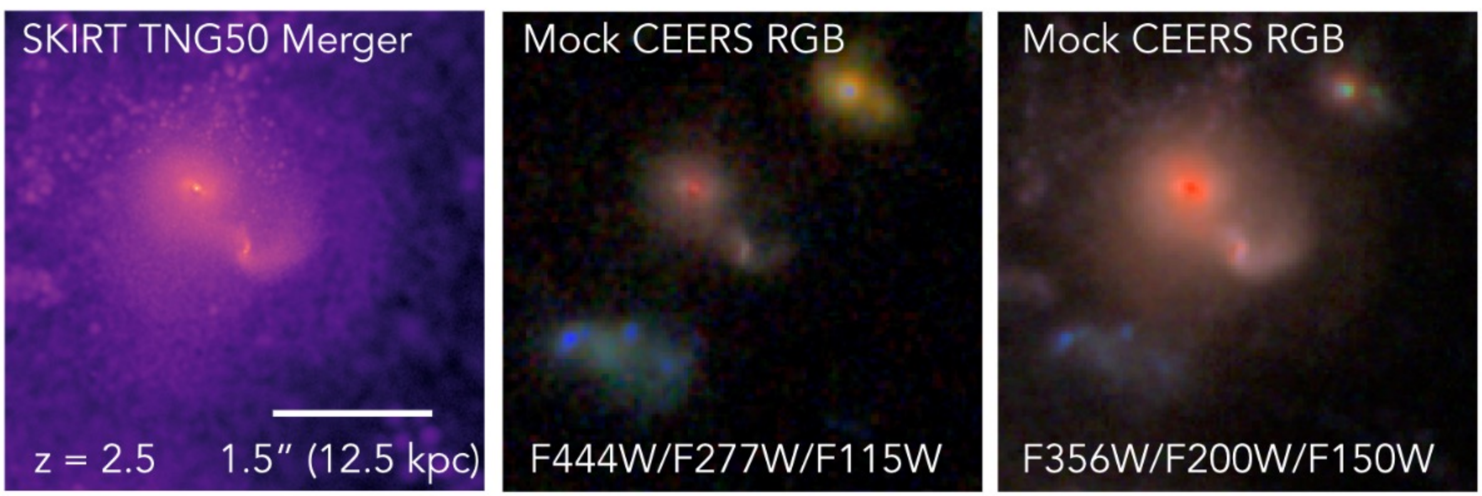
Galaxy merger rate

What about galaxy merger rate at higher z?

At high redshift: classify galaxy mergers in JWST/CEERS

Use machine learning to train galaxy merger identifications (e.g., Ackermann+ 2018, Snyder+ 2019)

Our approach: training set is galaxy mergers from IllustrisTNG cosmological simulations, processed to match JWST data



Schechter+ in prep.

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SMBH mass function

How to get SMBH masses?

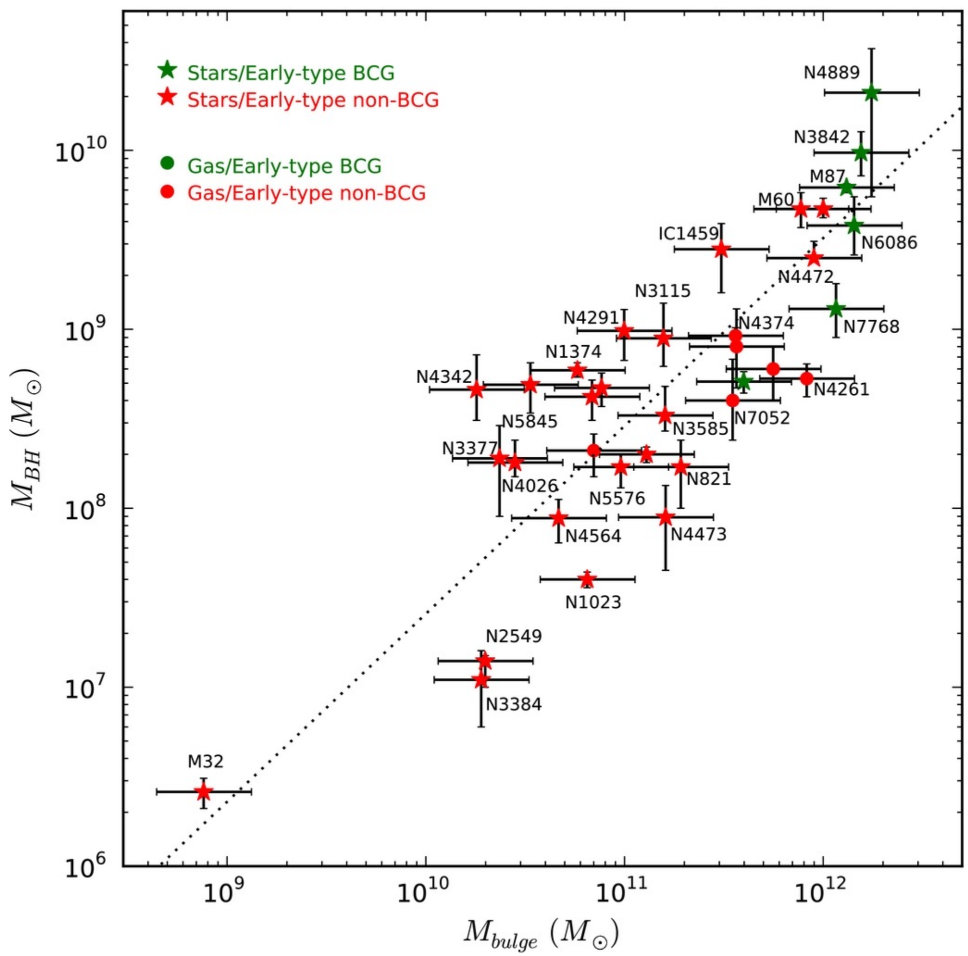
Dynamical SMBH mass measurements difficult beyond local Universe

So most frameworks use SMBH/galaxy scaling relations:

$M_{BH} - \sigma$

$M_{BH} - M_{bulge}$

But biases in SMBH masses have a large effect on inferred GWs (e.g., Sesana+ 2016)



McConnell & Ma 2013

SMBH mass function

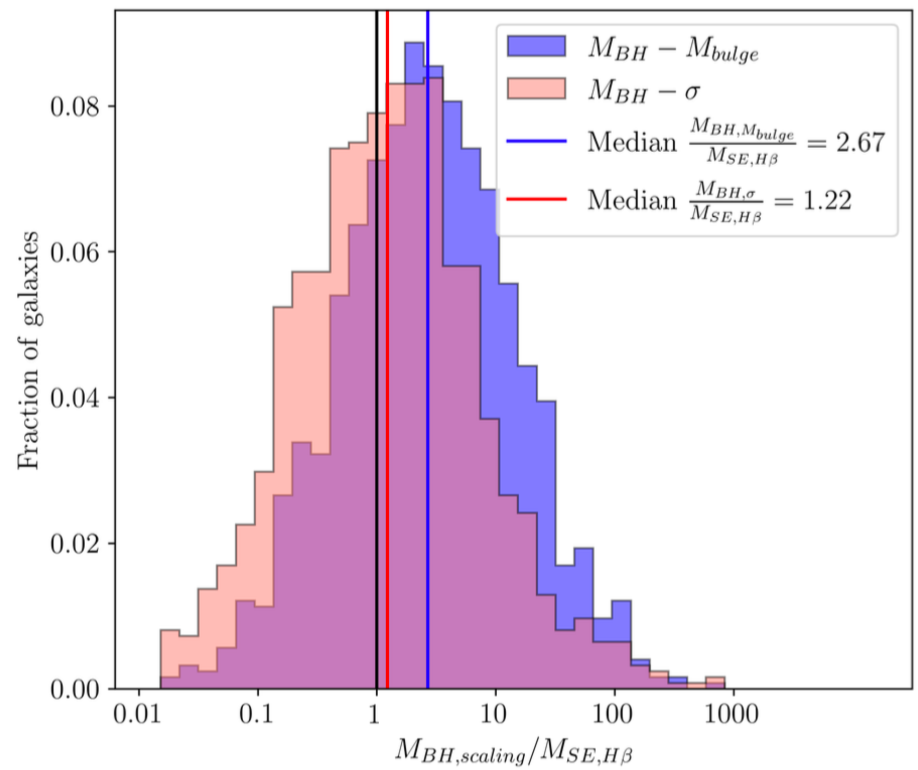
Biases in SMBH masses from scaling relations?

Infer a SMBH mass independent of scaling relations, using single-epoch (SE) virial relation for broad emission lines

Compare to SMBH masses from $M_{BH} - \sigma$ and $M_{BH} - M_{bulge}$

$M_{BH} - M_{bulge}$ biased to large SMBH masses, because it is based on massive elliptical galaxies

Using SMBH mass estimates that are too large will artificially increase amplitude of GWs



Huber, Simon, & Comerford 2024

SMBH mass function

What about SMBH masses at higher z?

$M_{BH} - \sigma$ difficult because of a lack of large, deep spectroscopic surveys of galaxies

Also difficult to do bulge-disk decompositions and get M_{bulge} at higher z

Can we assume total stellar mass is a good proxy for bulge mass?

Can we assume $M_{BH} - M_{bulge}$ extrapolates to higher z?

See, e.g., Volonteri & Reines 2016

Tying It All Together

Galaxy merger rate + SMBH mass function + SMBH binary evolution

= Gravitational waves

With GW observations from LISA, we can then infer:

SMBH binary evolution timescale, which is how long it takes after a galaxy merger for the resulting binary SMBH to produce gravitational waves at LISA frequencies

And constrain the physics of SMBH binary evolution, including effects of stellar loss cone scattering, circumbinary disks, differential accretion

Redshift evolution of galaxy merger rate and SMBH mass function still a large unknown