A numerical calculation of the gravitational wave signal in the low frequency regime produced by binary supermassive black holes

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Supermassive black holes (SMBHs)

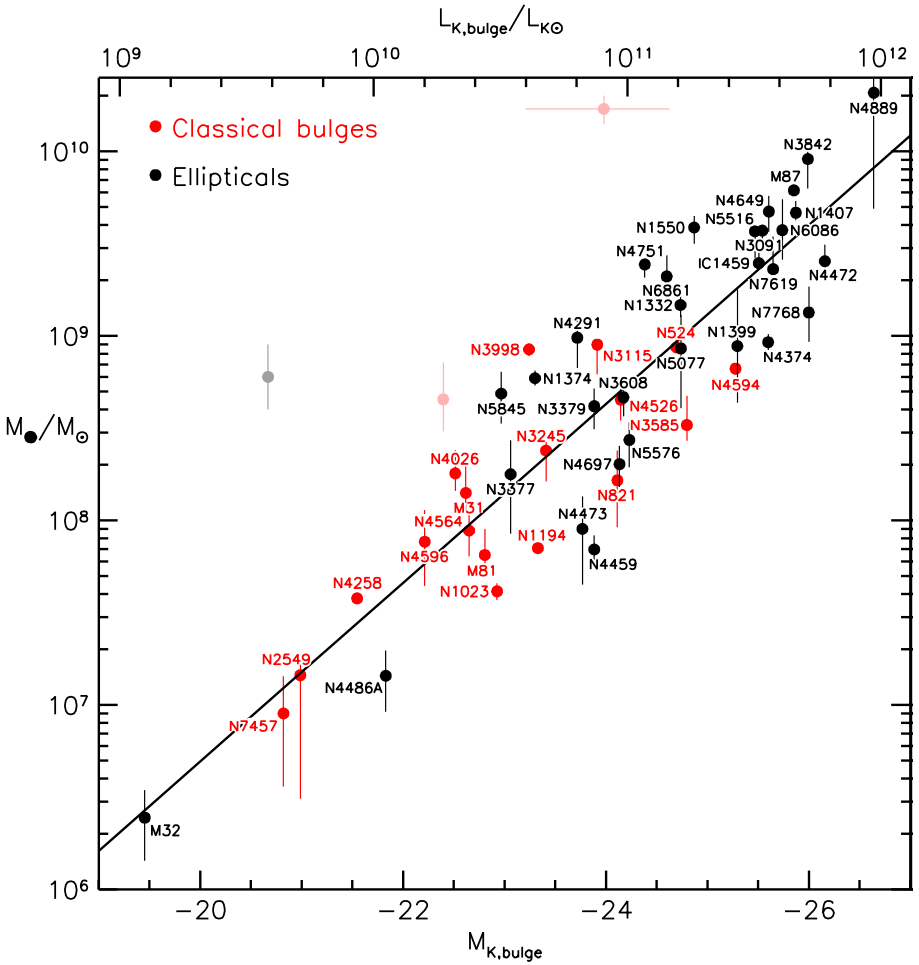


Figure: $M_{\rm BH}$–$L_{\rm bulge}$ scaling relation
Kormendy & Ho 2013

- Black holes which have a mass $\gtrsim 10^6 M_\odot$
- Found at the centers of most galaxies at $z = 0$
- Quasars at $z \lesssim 7$
- Masses correlate remarkably closely with the properties of their host galaxies
- Famous scaling relations: $M_{\rm BH}$–σ and $M_{\rm BH}$–$L_{\rm bulge}$

Do galaxy mergers produce SMBH binaries?

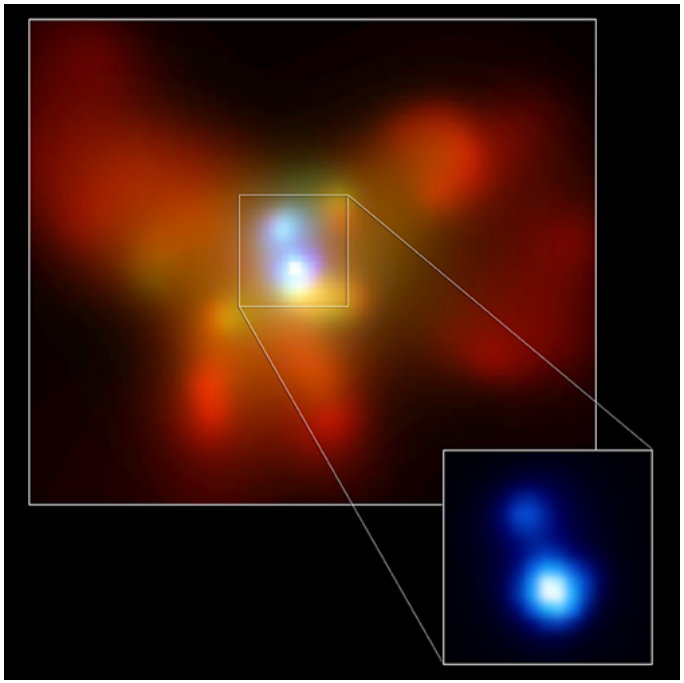


Figure: NGC 6240, the result of a galaxy merger, with two active black holes at its center.
Credit: NASA/CXC/MPE/S.Komossa et al.

- Large galaxies experience many mergers over their lifetimes.
- When two galaxies merge, the SMBHs fall to the center of the remnant through dynamical friction.
- The final parsec problem: can they get close enough to form a binary?
- We don't see a lot of galaxies with two SMBHs a parsec apart.
- Could be solved for galaxies with non-spherical symmetry or in gas-rich mergers.

Binary SMBHs produce gravitational radiation

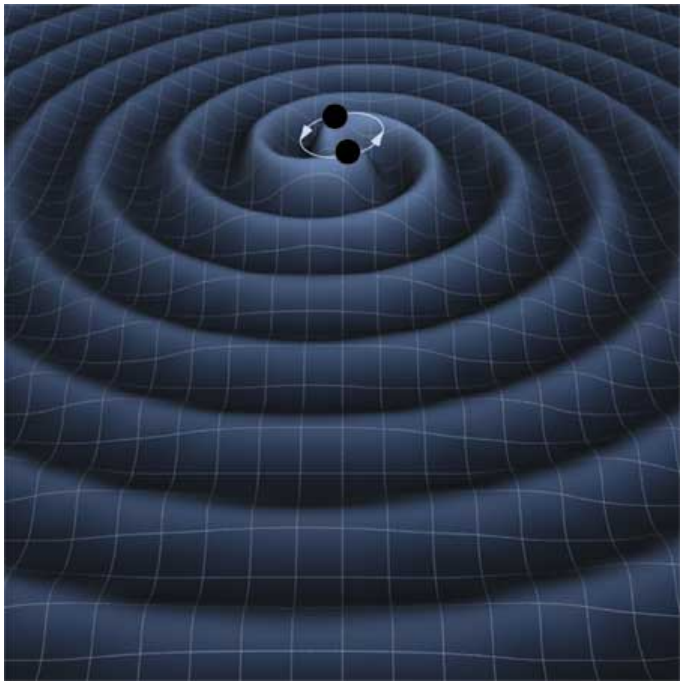


Figure: Artist's conception of binary black holes emitting gravitational radiation.
Credit: T. Carnahan (NASA GSFC)

- If sufficiently tight binaries form, they will emit gravitational waves at twice their orbital frequency.
- This emission tightens the binary: after ~ 100 Myr, the black holes will merge.
- Observed gravitational wave amplitude ('strain') is a function of:

Separation	(orbital frequency)
Chirp mass	$M_{\text{chirp}} = \mu^{3/5} M^{2/5}$
Distance	to the observer

The gravitational wave background from SMBH binaries

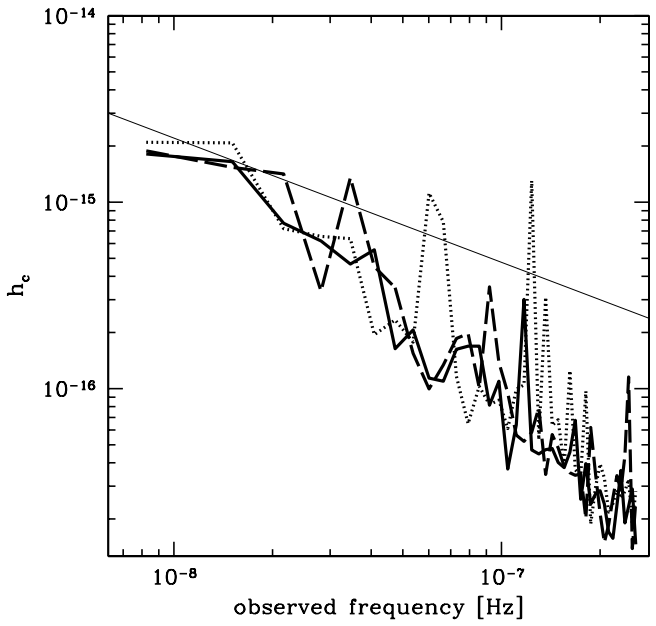
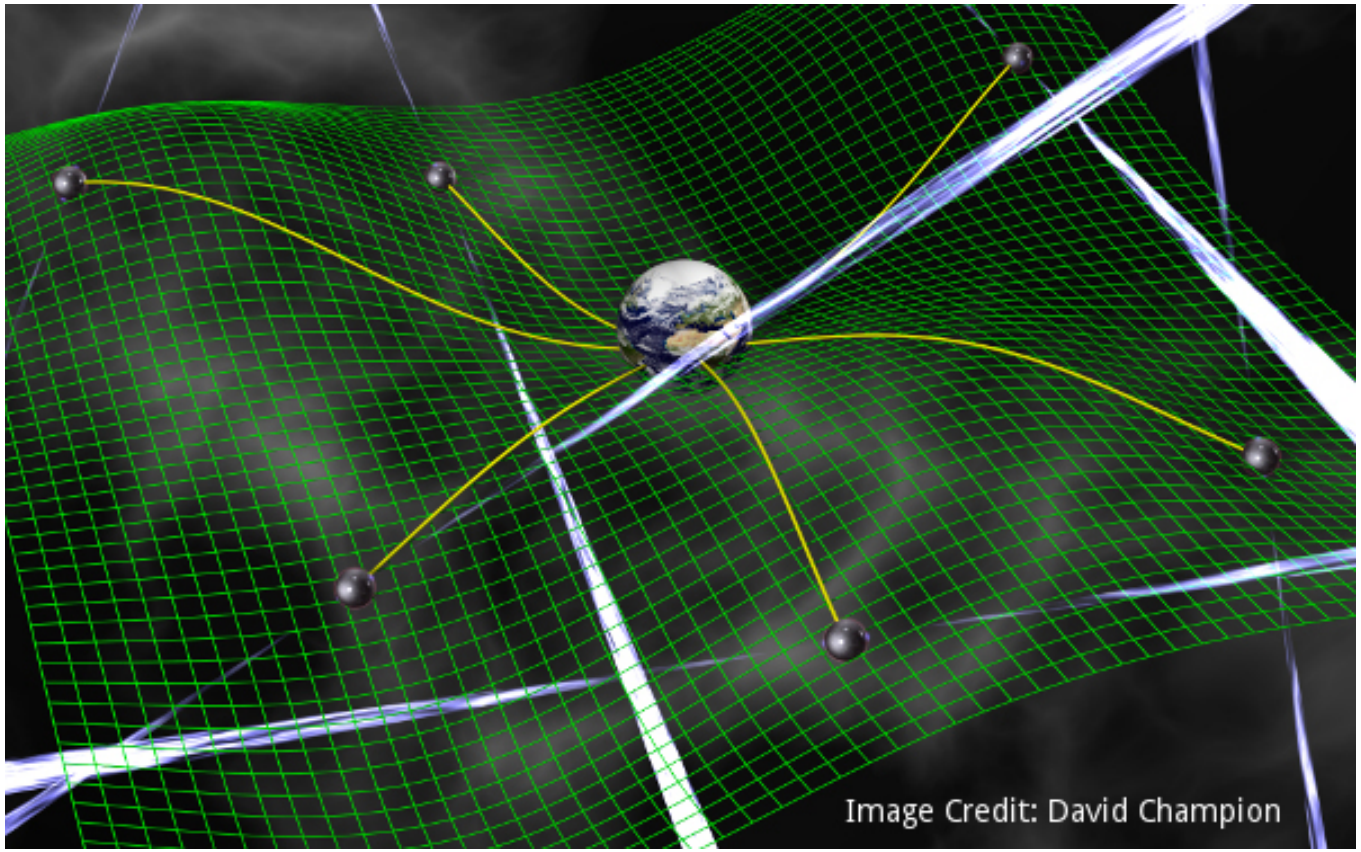


Figure: A 2/3 power law vs. more realistic signals.
Sesana et al. 2008

- Due to their orbital periods, binaries should emit a lot of gravitational waves at frequencies between $\sim 10^{-9}$ Hz and $\sim 10^{-7}$ Hz.
- The characteristic signal produced by SMBH binaries is an incoherent sum of the strains from all sources.
- It is traditionally represented as a 2/3 power law, but the reality is more complicated.

Pulsar Timing arrays

PTAs look for slight variations in the periods of millisecond pulsars to see if gravitational waves are passing the earth.



PTAs will measure low-frequency gravitational waves

Pulsar timing arrays are sensitive to nHz frequencies.

$\Longrightarrow$ Sensitive to the SMBH binary gravitational wave background.

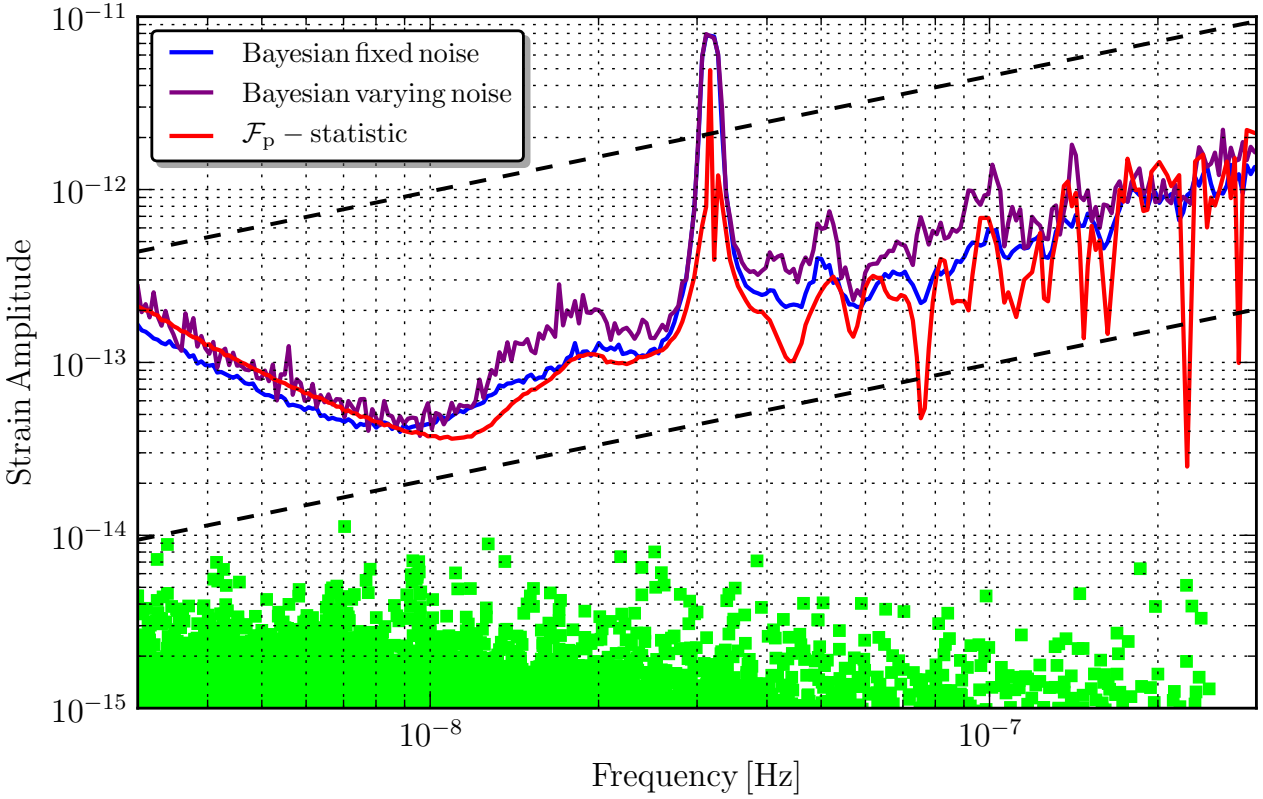


Figure: NANOgrav pulsar timing array sensitivity.
Arzoumanian et al. 2014

Large-scale dark matter simulations

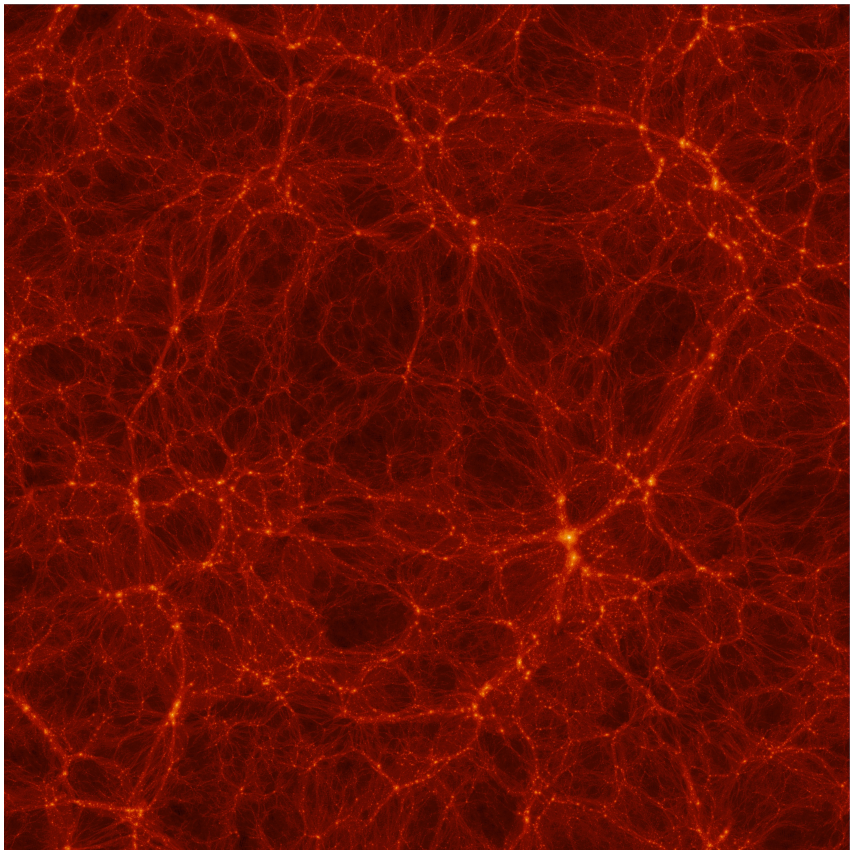


Figure: A snapshot of the Bolshoi simulation at $z = 0$.
Credit: Stefan Gottlober (AIP)

We use halo merger trees from:

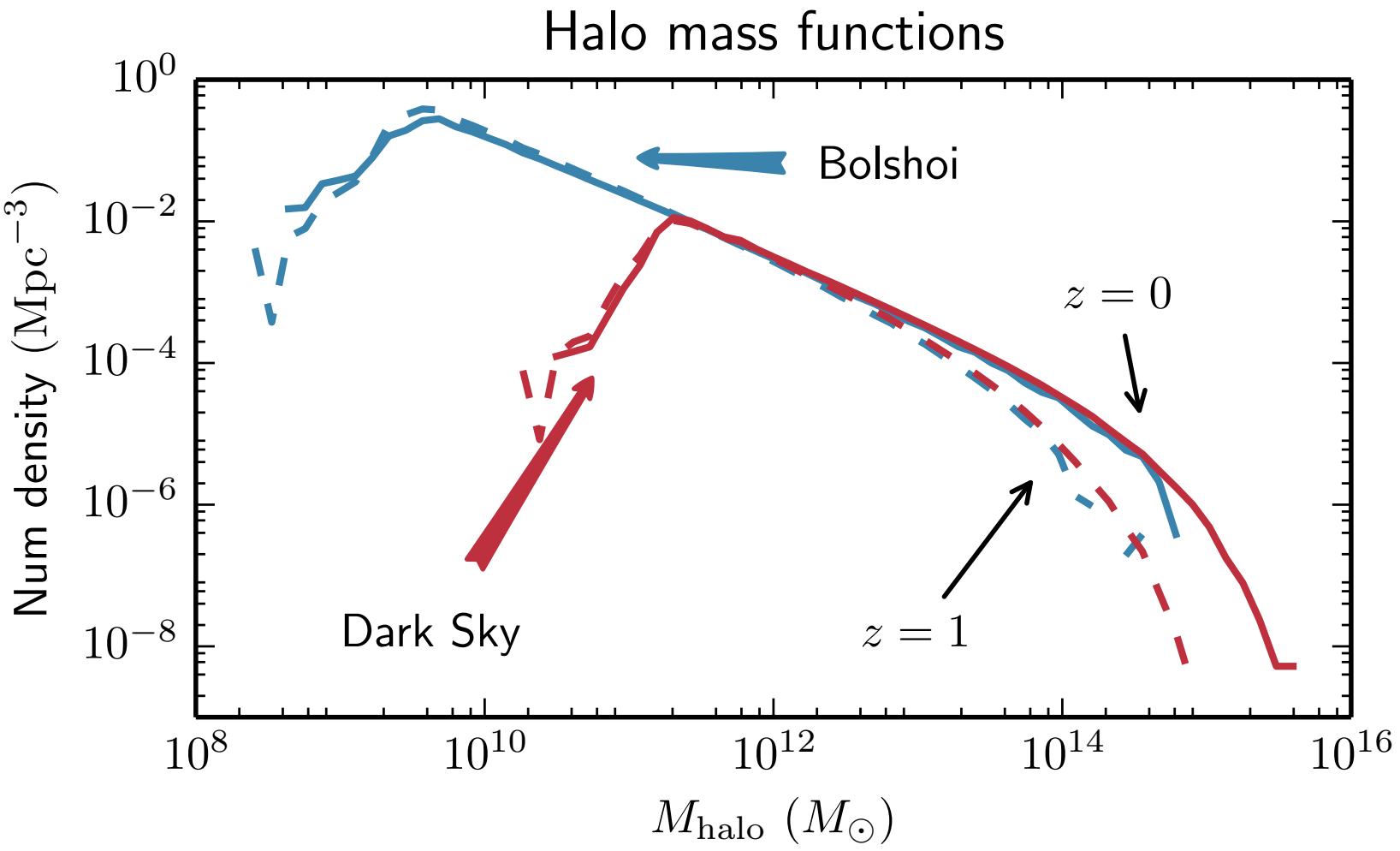
Bolshoi — Klypin et al. 2011

- 250 Mpc/h box size
- WMAP5 cosmology
- 10^8 $M_\odot$/h mass resolution

Dark Sky — Warren 2013

- 1000 Mpc/h box size
- Planck cosmology
- 10^{10} $M_\odot$/h mass resolution

Dark matter halos



Placing galaxies in halos

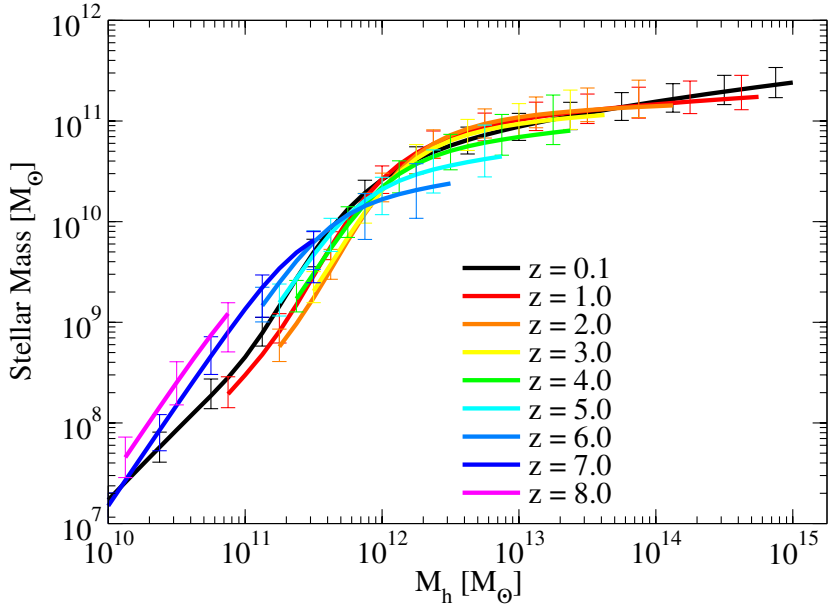


Figure: Empirically calibrated stellar mass–halo mass relation.
Behroozi et al. 2013

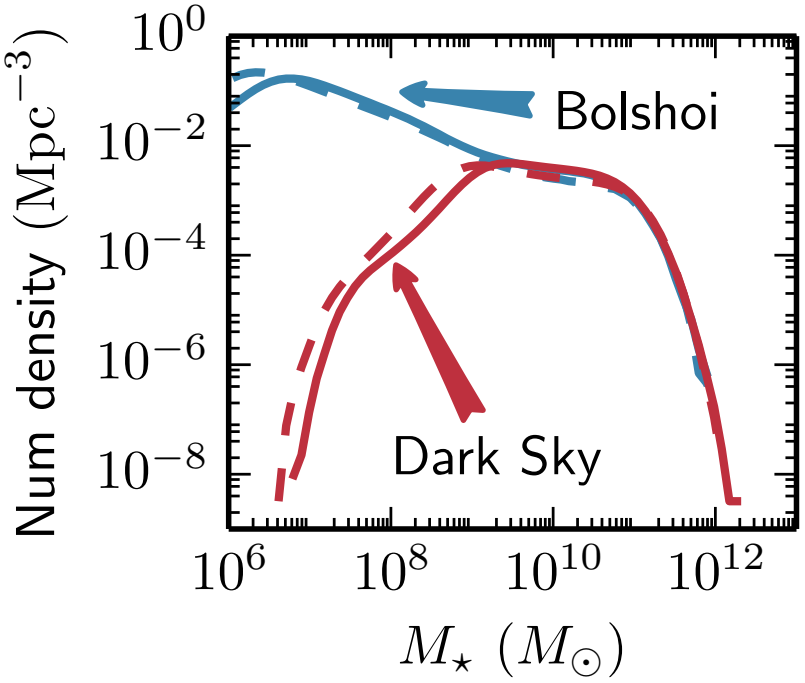


Figure: Resulting stellar mass functions.

Placing black holes in galaxies

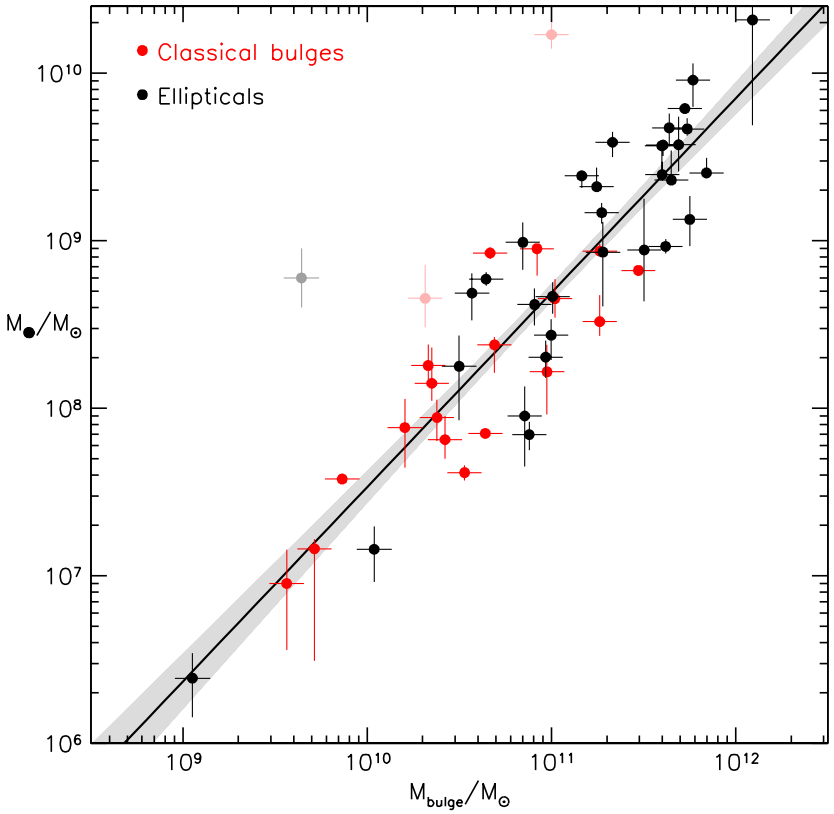


Figure: Relation between galaxy bulge mass and black hole mass.
Kormendy & Ho 2013

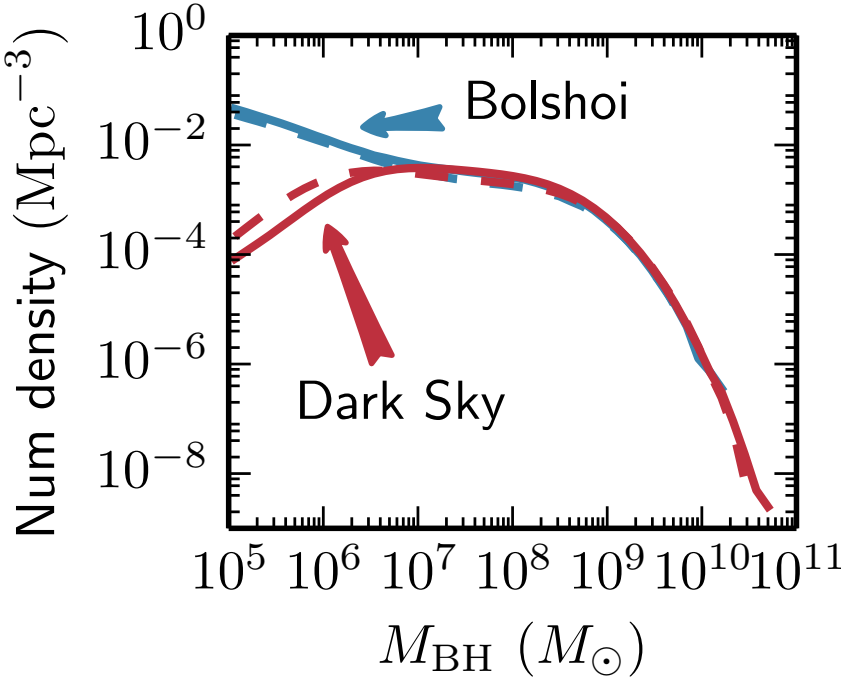


Figure: Resulting black hole mass functions.

Binary black holes

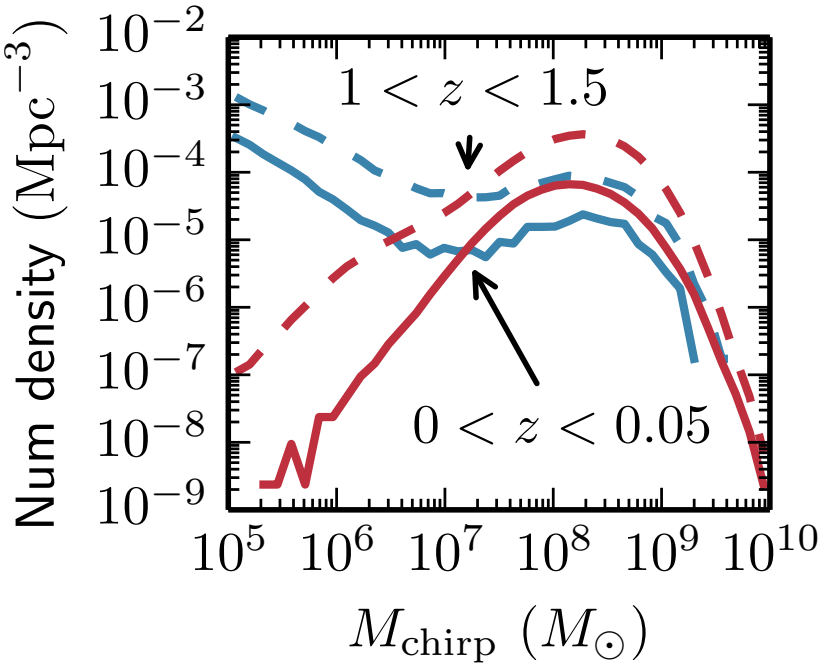


Figure: Binary SMBH mass functions

Putting it all together:

- Halos are populated with galaxies.
- Galaxies are populated with black holes.
- The simulation tells us which halos merge.

From this, we can determine the population of SMBH binaries born between each redshift snapshot.

Constructing a representative sample of 'observed' binaries

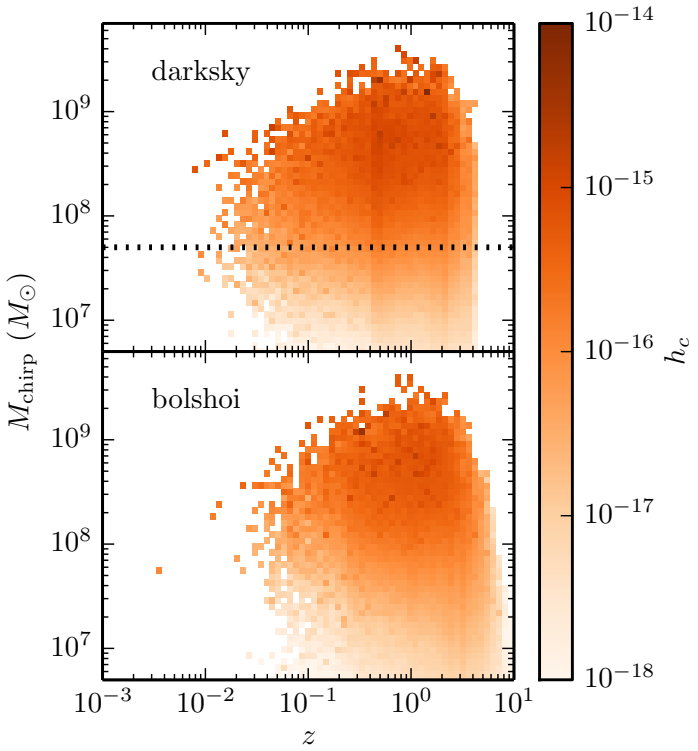


Figure: The strain for a single population of binaries.

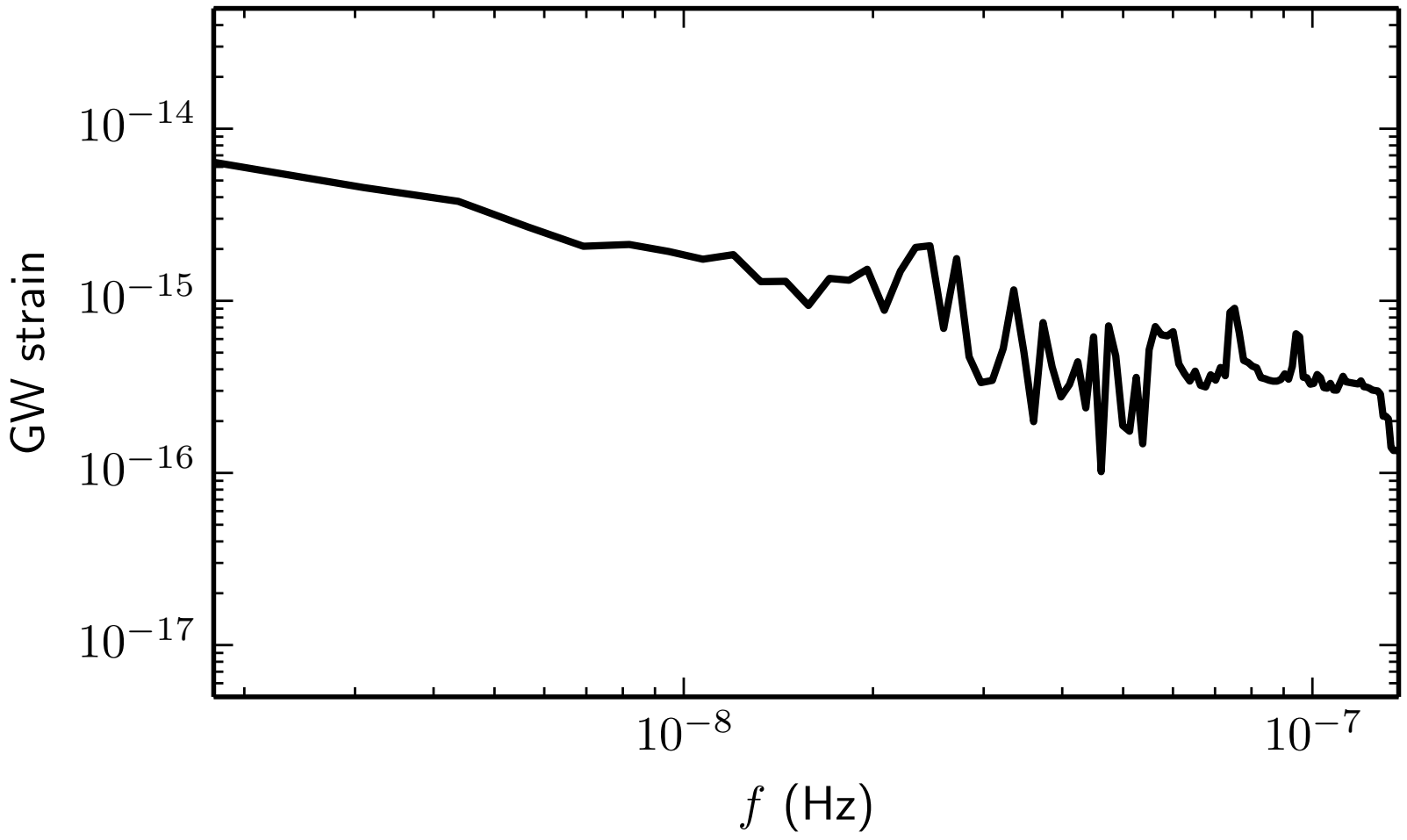
- Begin with the population of SMBH binaries derived for each simulation within a redshift slice.
- Transform the population in each simulation box to the population we expect to see on the sky.
- Draw binaries from this population:

  Chirp Mass of the binary
  Frequency (separation)
  Distance from the observer

- Calculate the resulting gravitational wave signal for this population!

What does the gravitational wave backgound look like?

Example: Bolshoi



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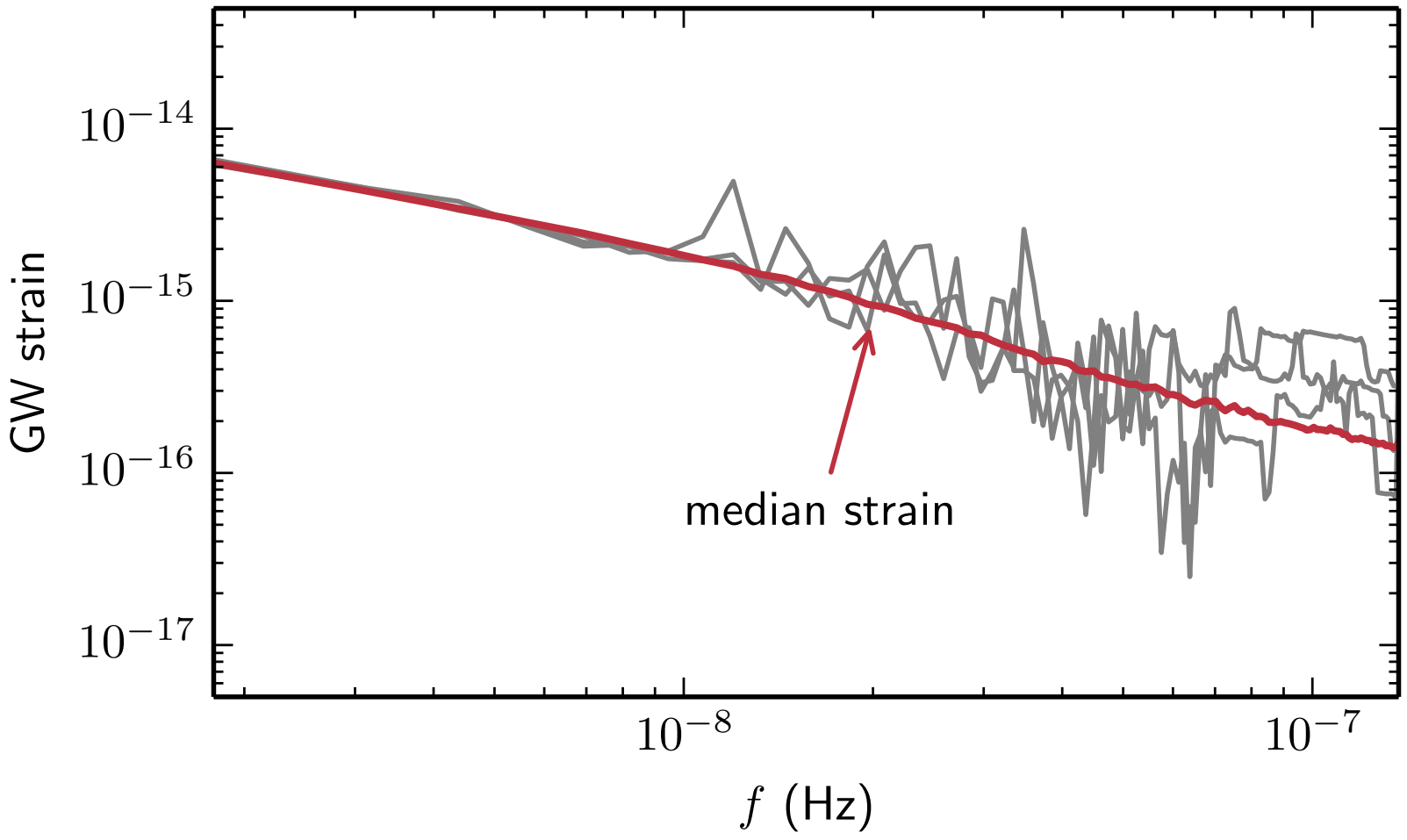

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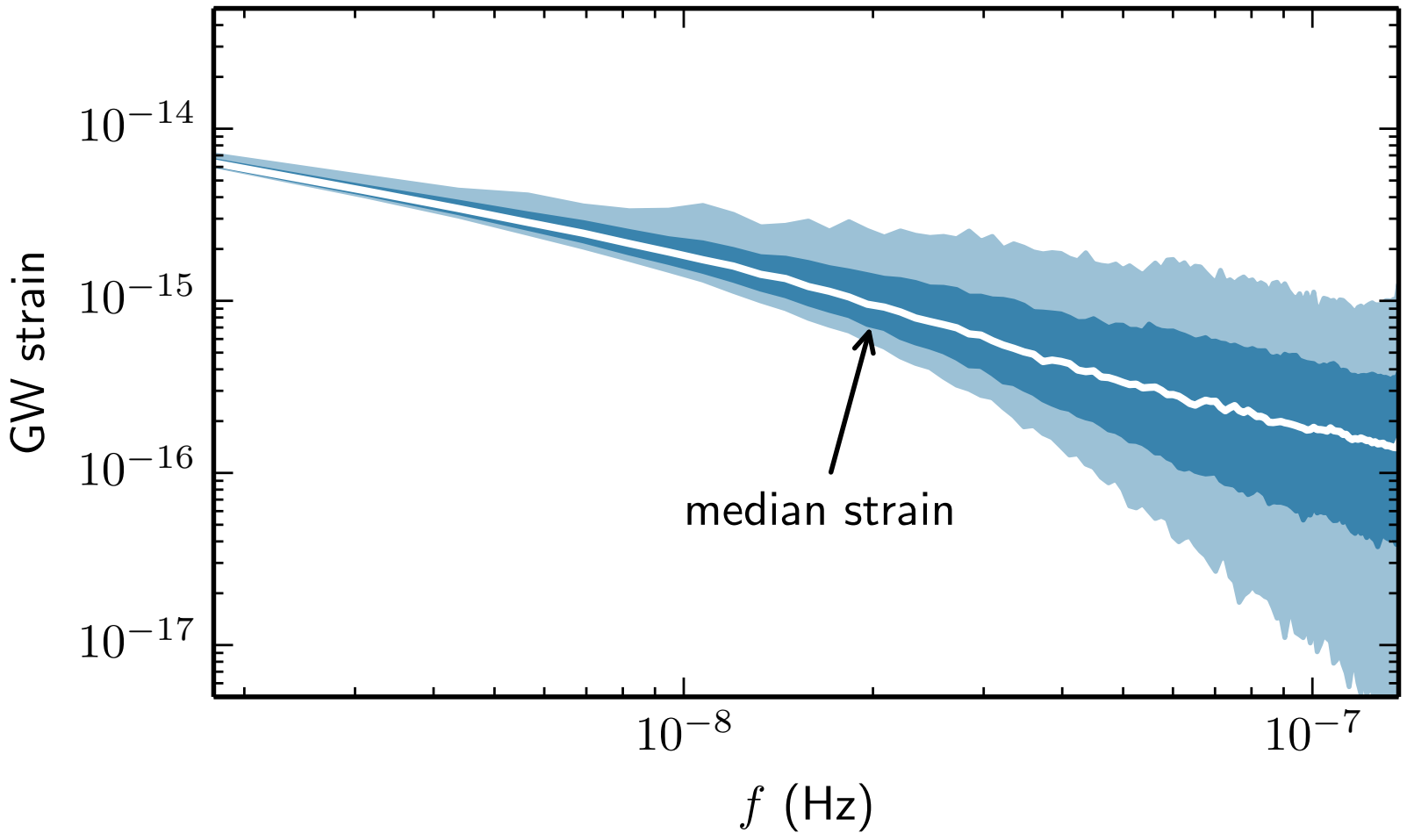

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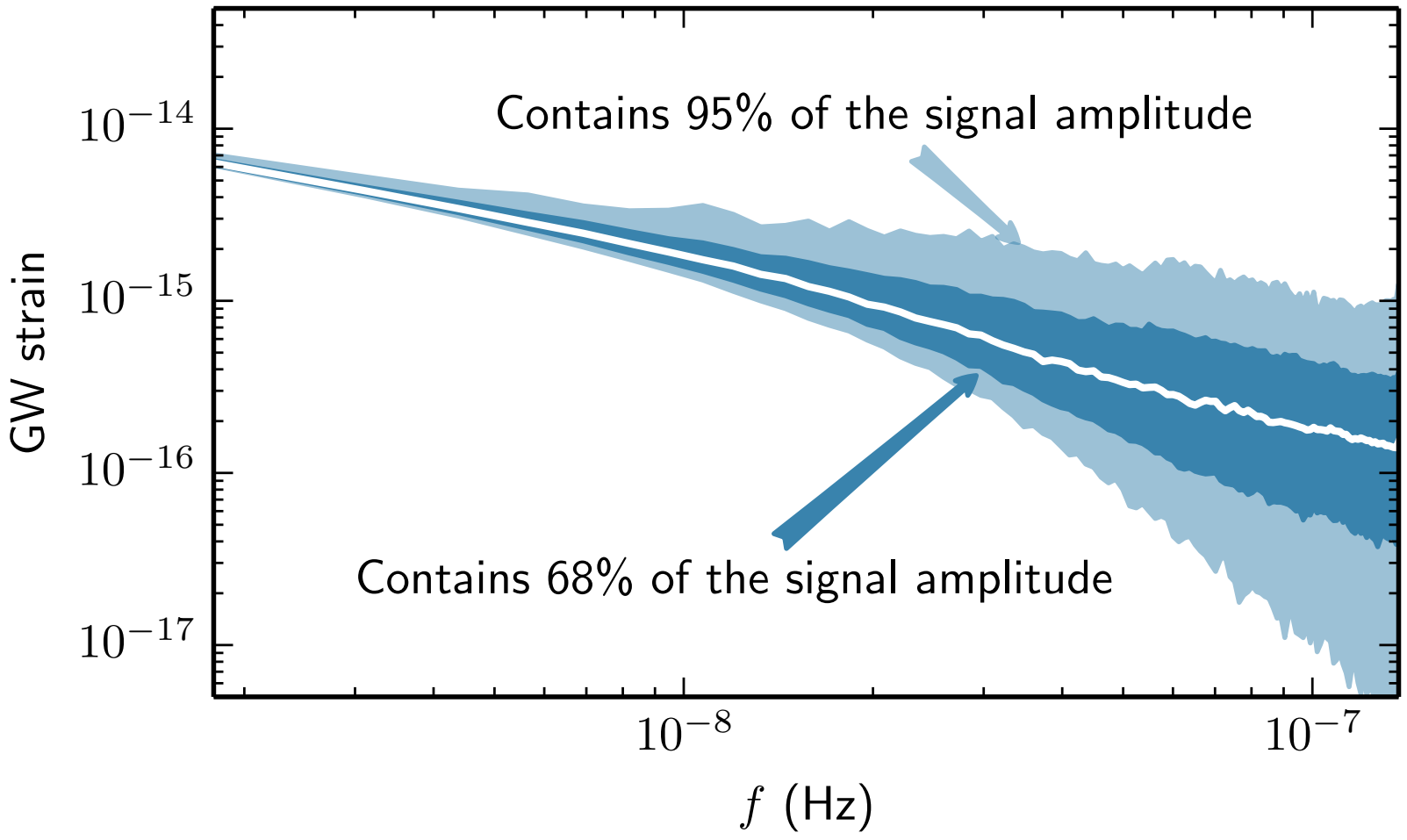

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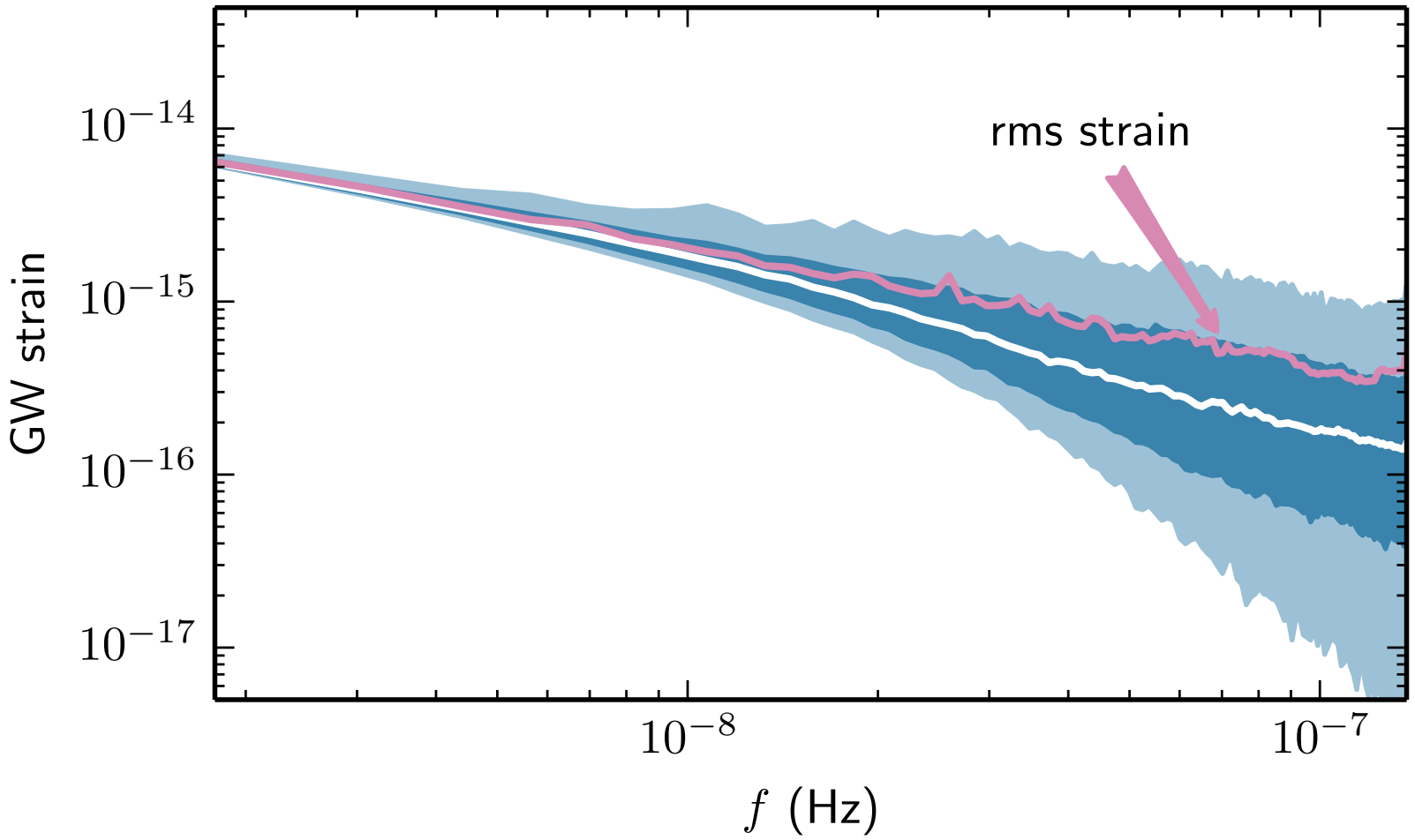

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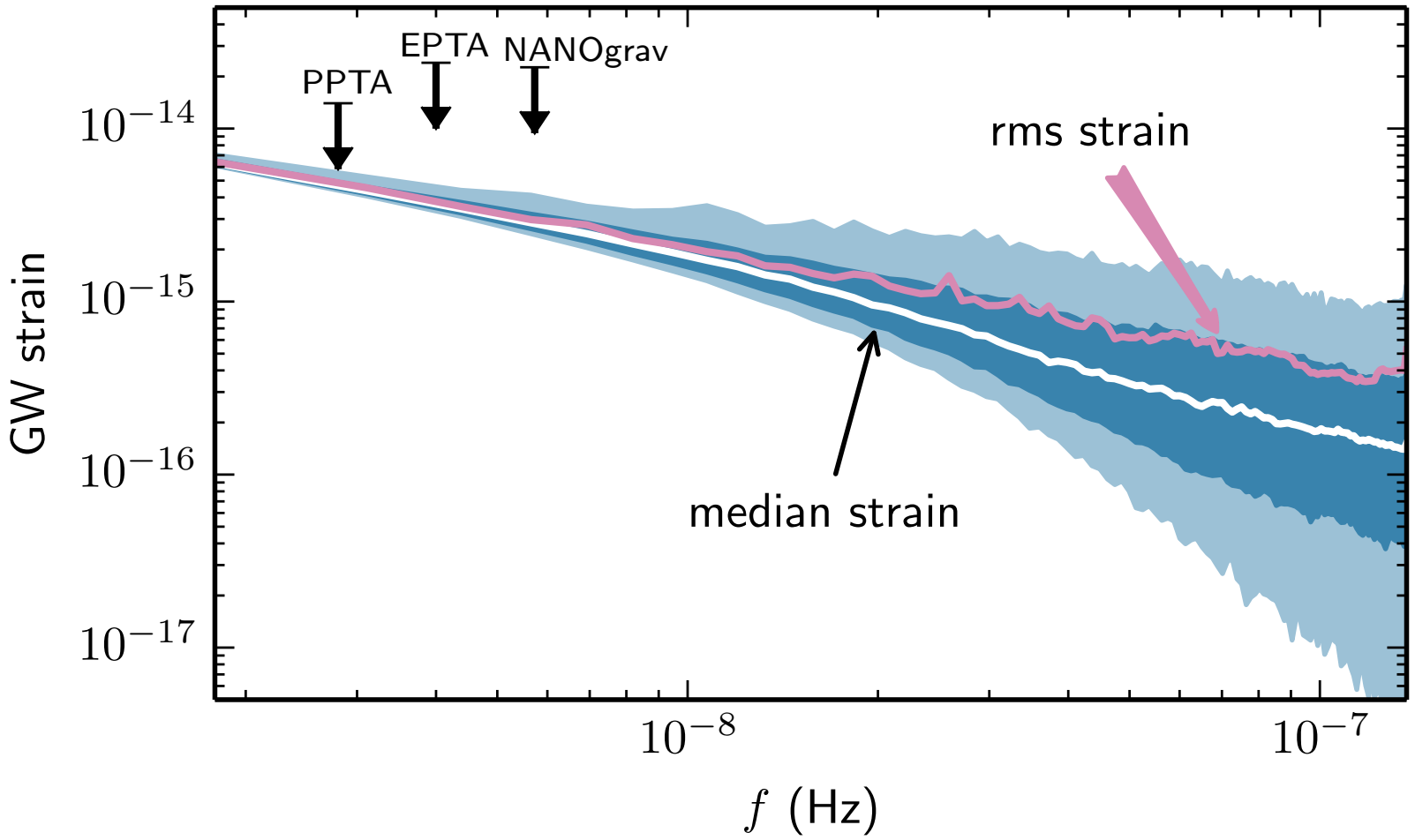


Amplitude of the signal

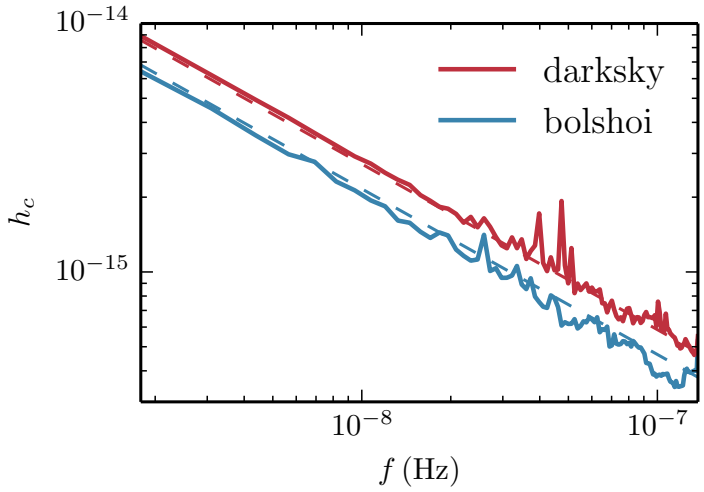
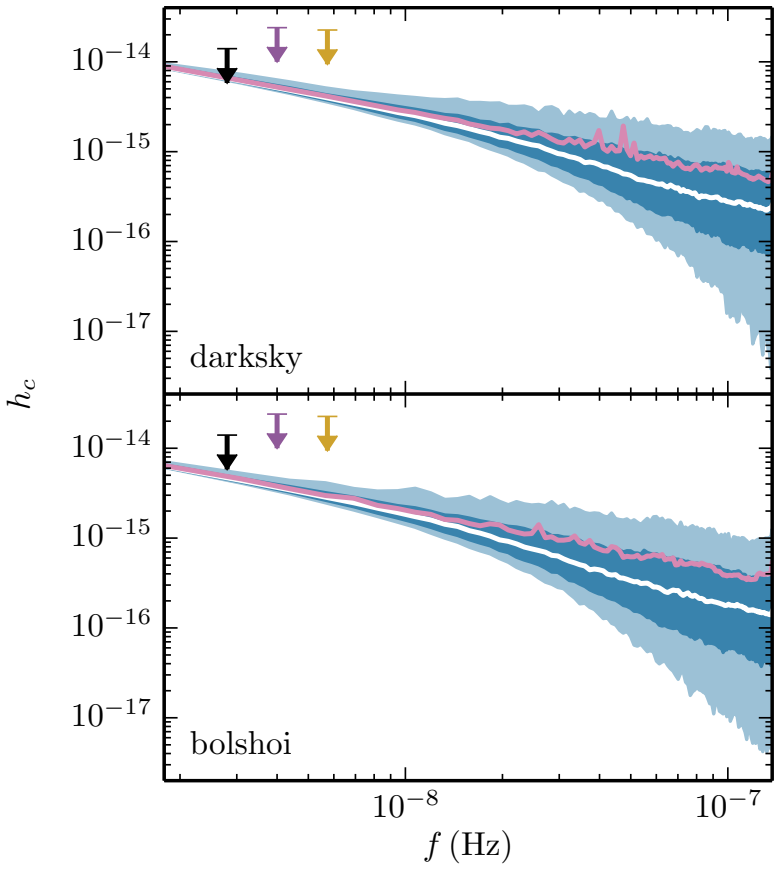


Figure: The rms amplitudes for each simulation, compared to a 2/3 power law.

- The rms strain closely resembles the expected 2/3 power law.
- Its amplitude is a factor of 2–3 lower than the current upper limits.
- Consistent with predictions from 'empirical' models (Sesana 2013, Ravi+ 2014).
- We see a $\sim 25\%$ difference between simulations, including the effect of different cosmologies.
- Variance due to astrophysics is somewhat larger (Sesana 2013).

Scatter in the signal



- No single realization of the gravitational wave spectrum will look like a power law.
- Scatter increases with frequency: at low frequencies, a single realization of the strain will be close to the rms signal; at high frequencies it will be much smaller with occasional individual bright sources.

Conclusions

- As a result of galaxy mergers, a large population of supermassive black hole binaries is expected to exist.
- This population is difficult to probe with conventional astrophysics, and is a poorly understood aspect of galaxy evolution.
- BUT: a strong source of gravitational waves out to $z \sim 1$.
- Should be detectable by pulsar timing arrays soon!