COSMIC VARIANCE IN THE NANOHERTZ GRAVITATIONAL WAVE BACKGROUND

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with Gilbert Holder, Daniel Holz, and Michael Warren

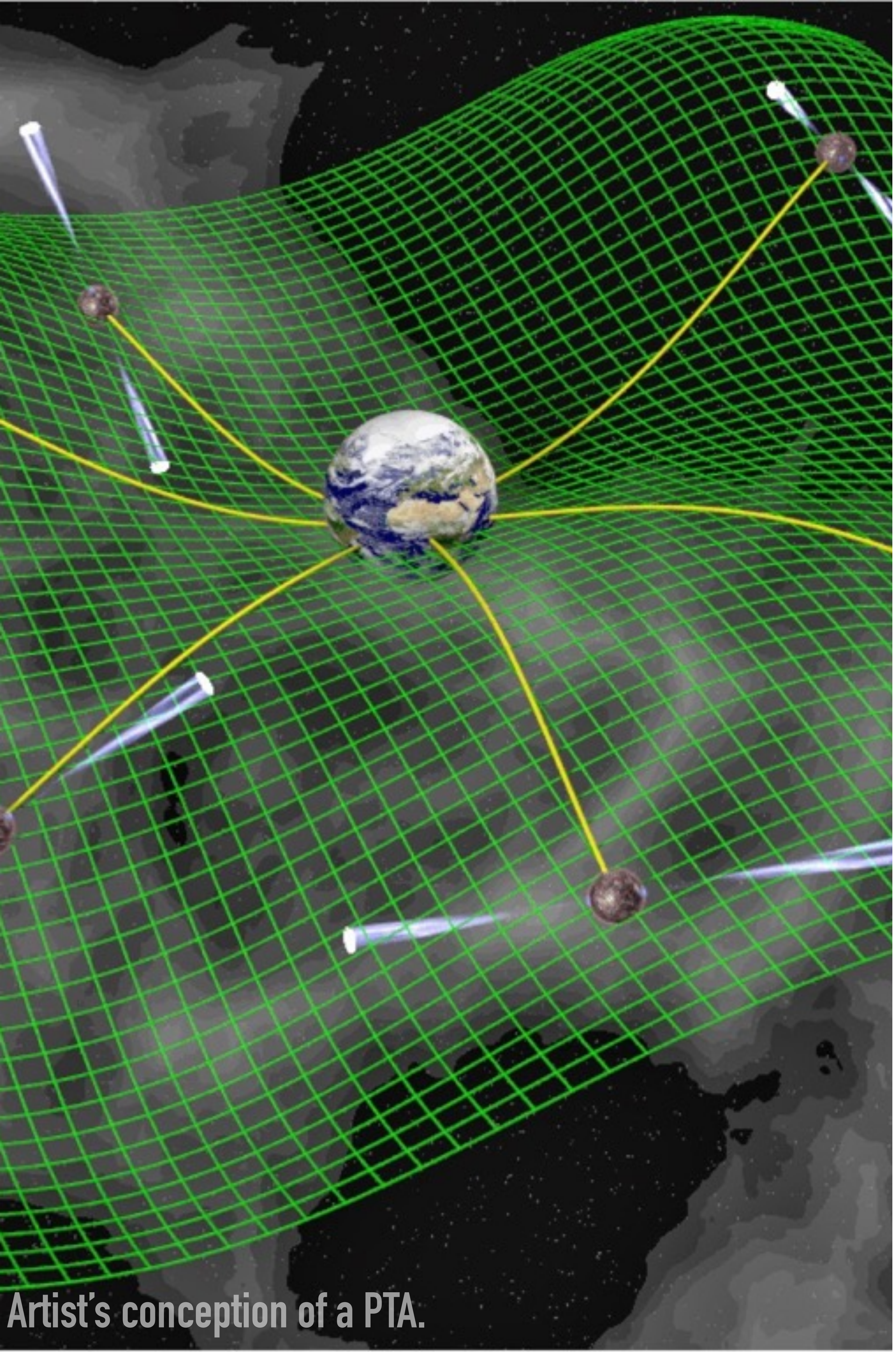
arXiv: 1508.07336
(revised version out soon)

McGill

NGC 6240: a merger remnant with SMBHs ~1 kpc apart.
Credit:

GWs FROM SMBH BINARIES

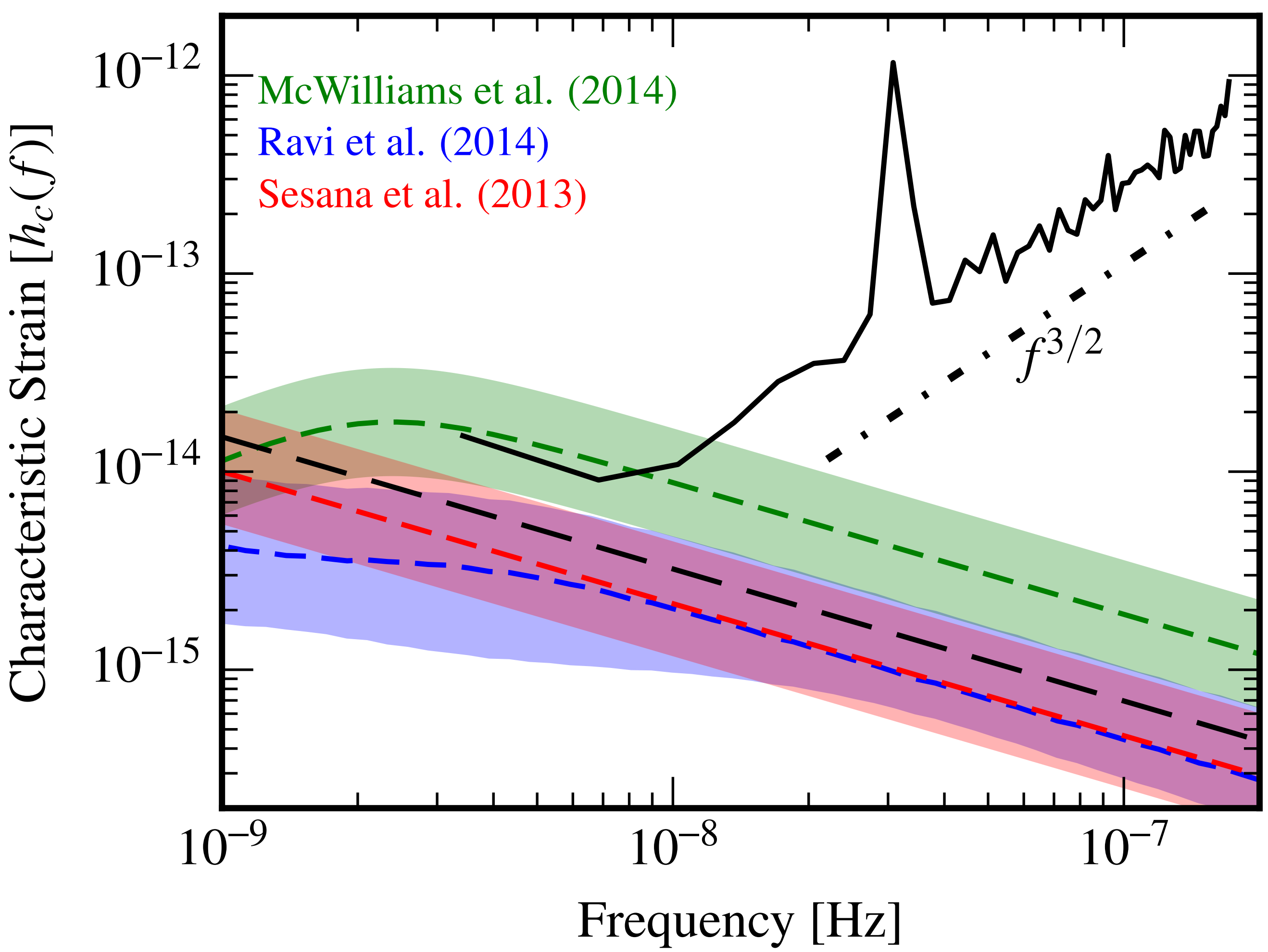
- **Supermassive black holes** ($M > 10^6\ M_\odot$) live at the centers of most galaxies.
- When galaxies merge, SMBHs may form **binaries**.
- If binaries become close enough ($\ll$1 pc) they will decay over millions of years by **gravitational wave emission**.
- Signal should be detectable by **pulsar timing arrays**.



PULSAR TIMING ARRAYS

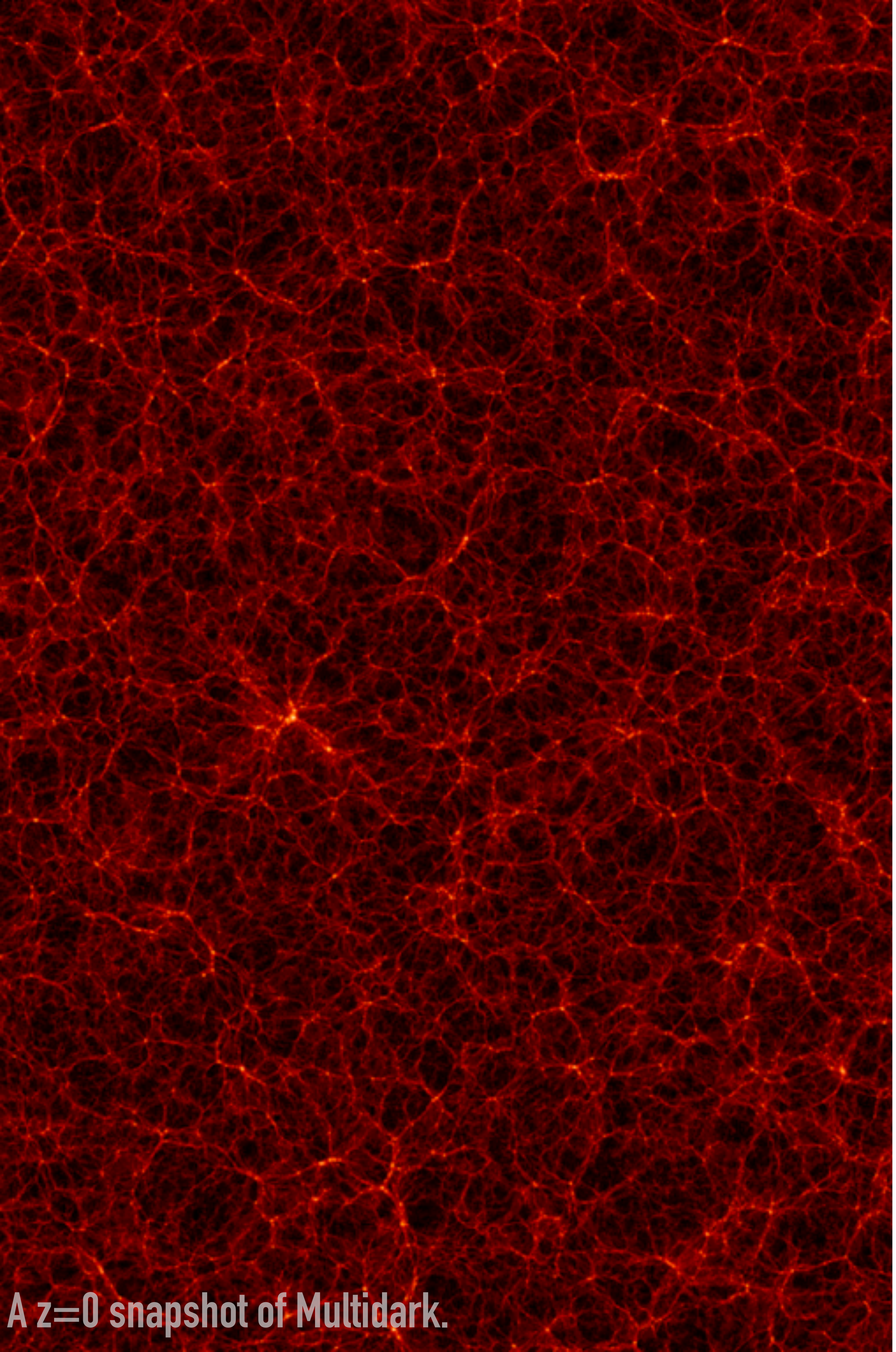
- Use precise timing of millisecond pulsars across the sky to **measure gravitational waves** passing the Earth.
- Sensitive to frequencies of order 1 to 100 nHz—times of years to decades.
- Primary expected signal: **stochastic, isotropic background** due to binary SMBHs at $z \lesssim 2$.
- Stringent **upper limits** starting to rule out models

THE nHz STOCHASTIC GRAVITATIONAL WAVE BACKGROUND



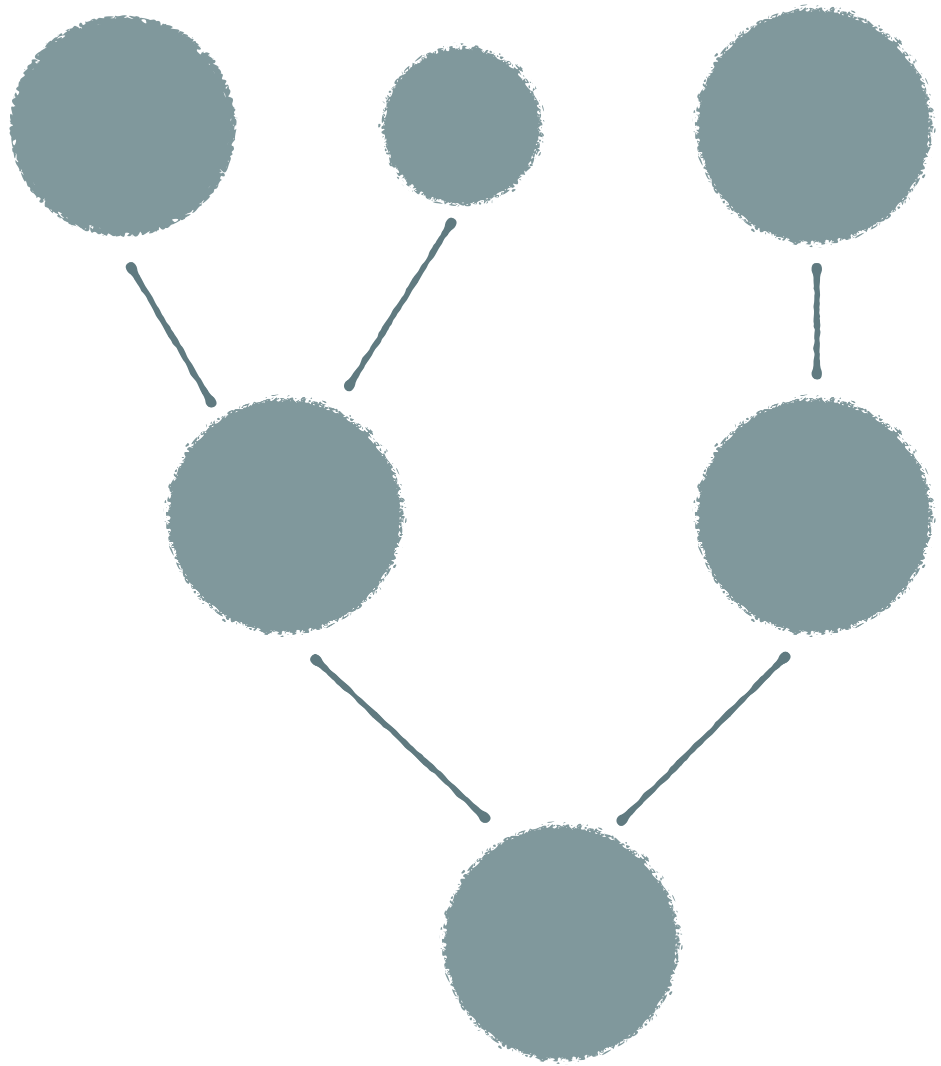
Arzoumanian et al. 2015

- Incoherent sum over **large number of sources**
- Almost no evolution on human timescales
- Canonical form: isotropic, **power law spectrum**
- Important unknowns:
  - **Formation rate of SMBH binaries** (sets amplitude)
  - Environmental coupling (could change shape)



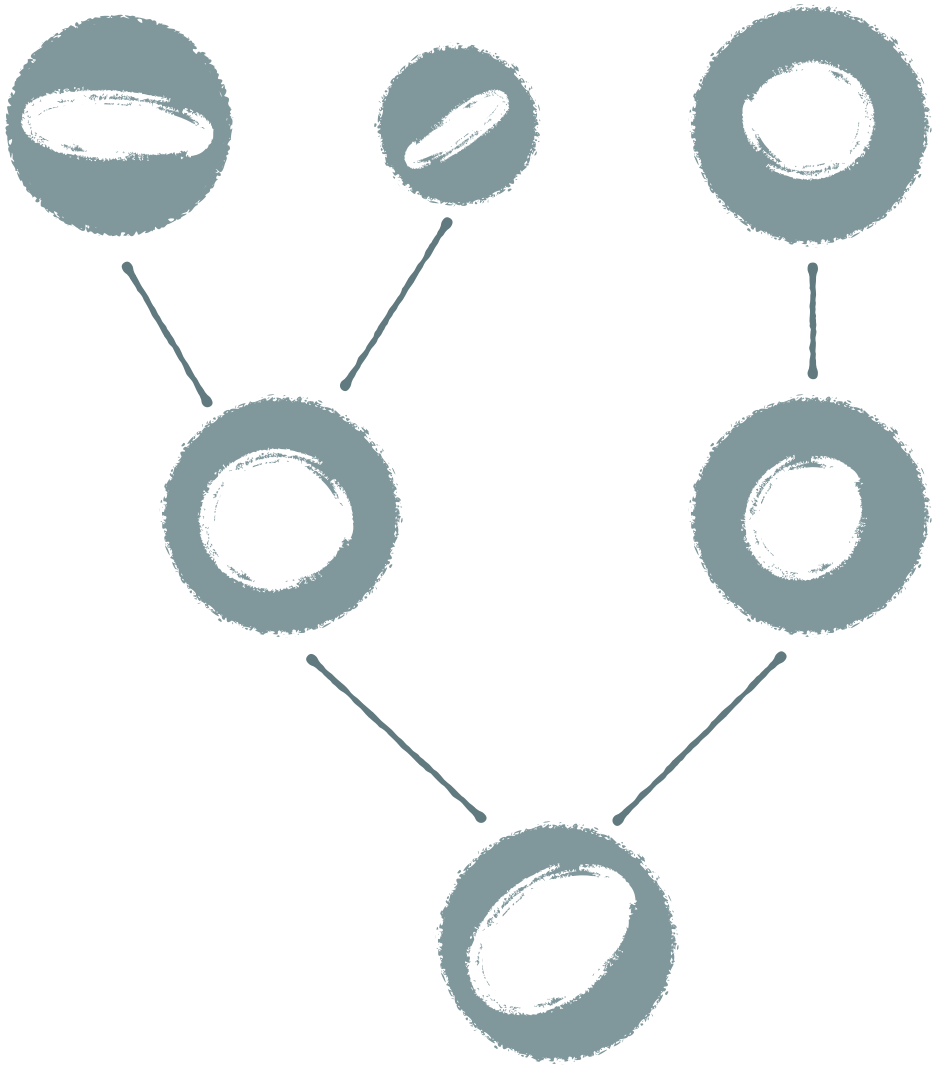
A NUMERICAL CALCULATION

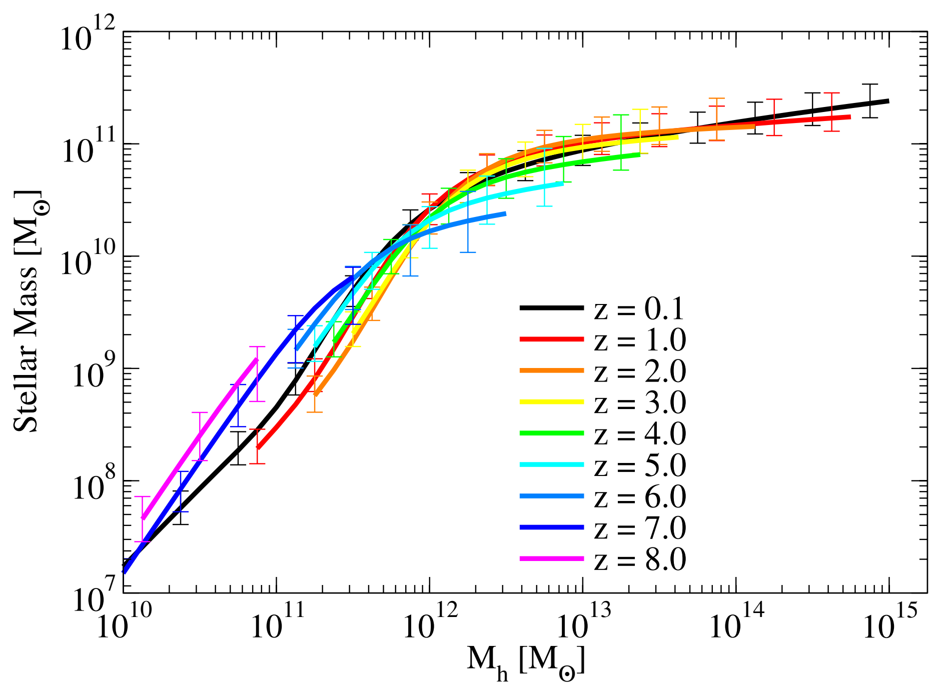
- Signal is from high redshift, massive sources, so we need **large number statistics**
- Use large dark matter **simulations**:
  - Multidark, Dark Sky
  - Box size: $(1\ \mathrm{Gpc/h})^3$
  - Cosmology: WMAP5, Planck
- Complementary to Millenium Simulation, empirical calculations



FROM HALOS TO GALAXIES

- From the dark matter simulations, we get **halo merger trees**:
  - List of dark matter halos with mass at snapshots in time
  - Halo evolutionary history
- We use stellar mass-halo mass scaling relations to assign galaxies of a given stellar mass to halos
- Assign galaxies to be either star-forming or quiescent





Behroozi et al. 2013

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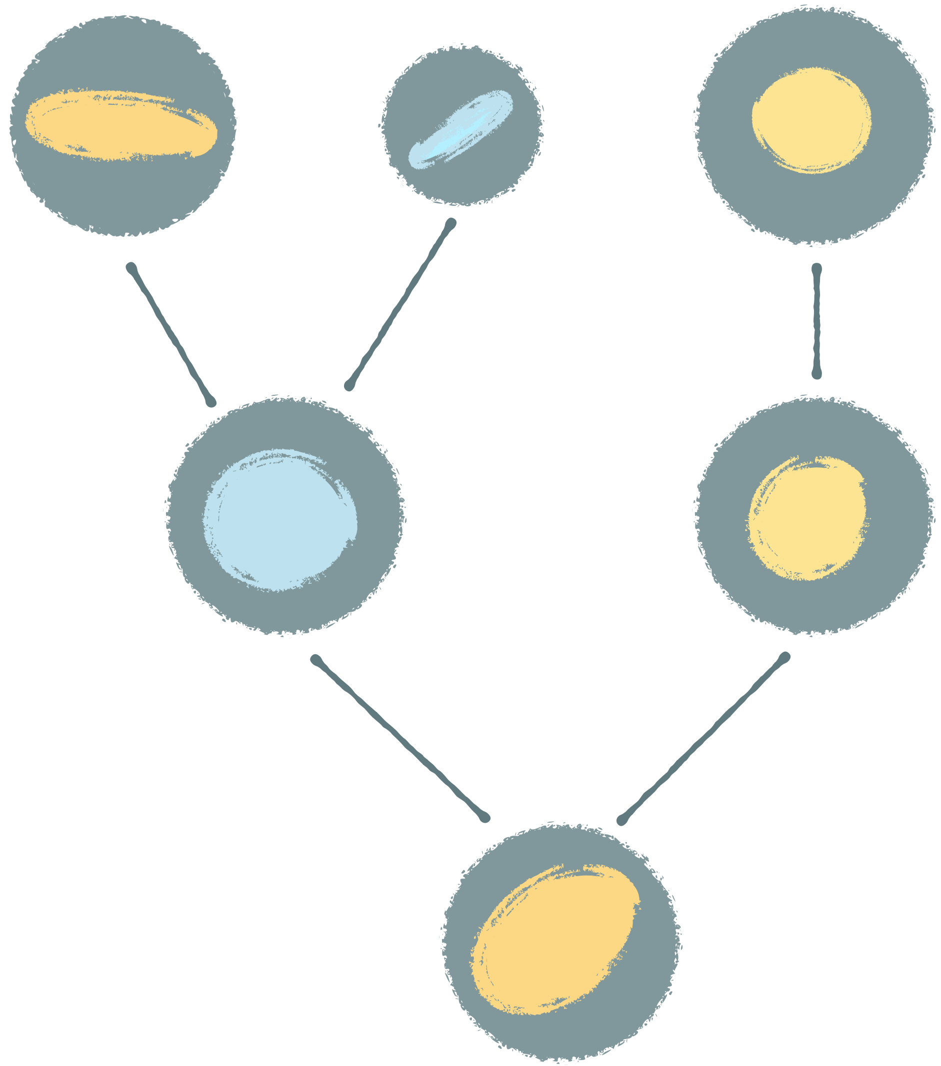

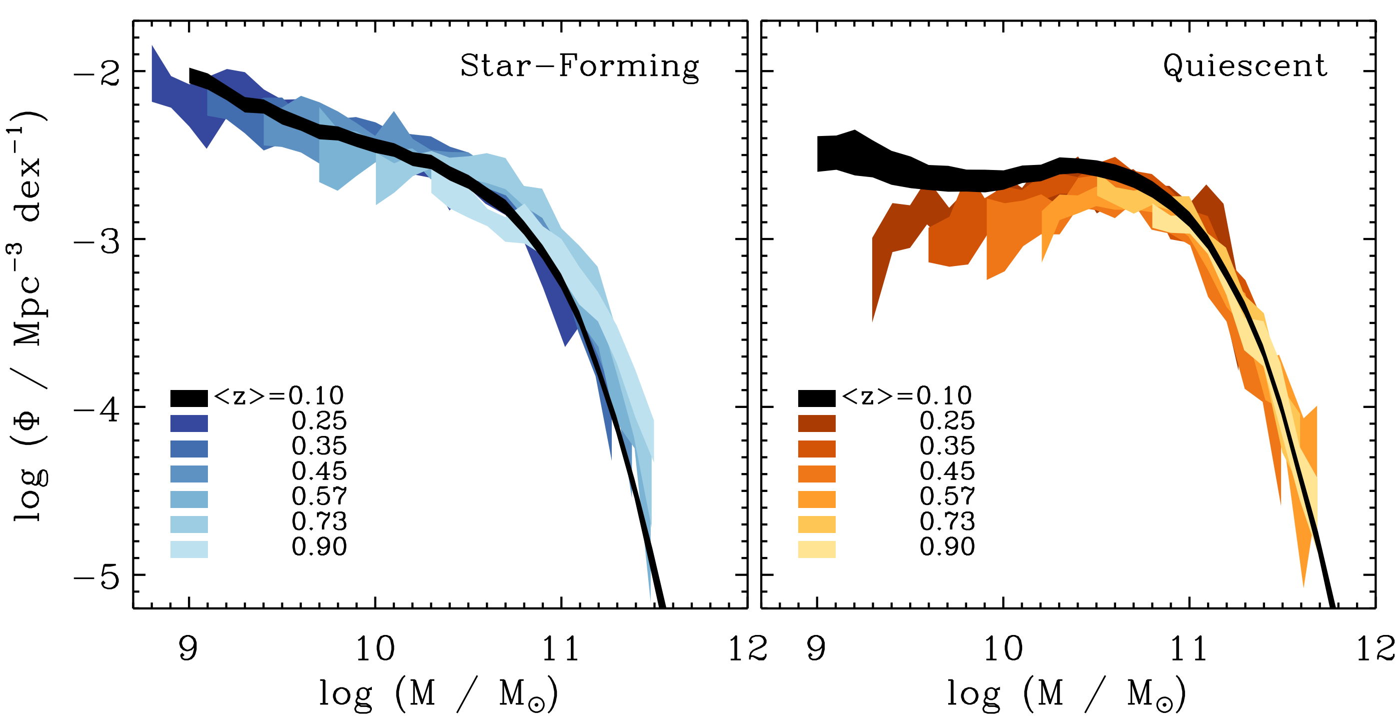

Moustakas et al. 2013

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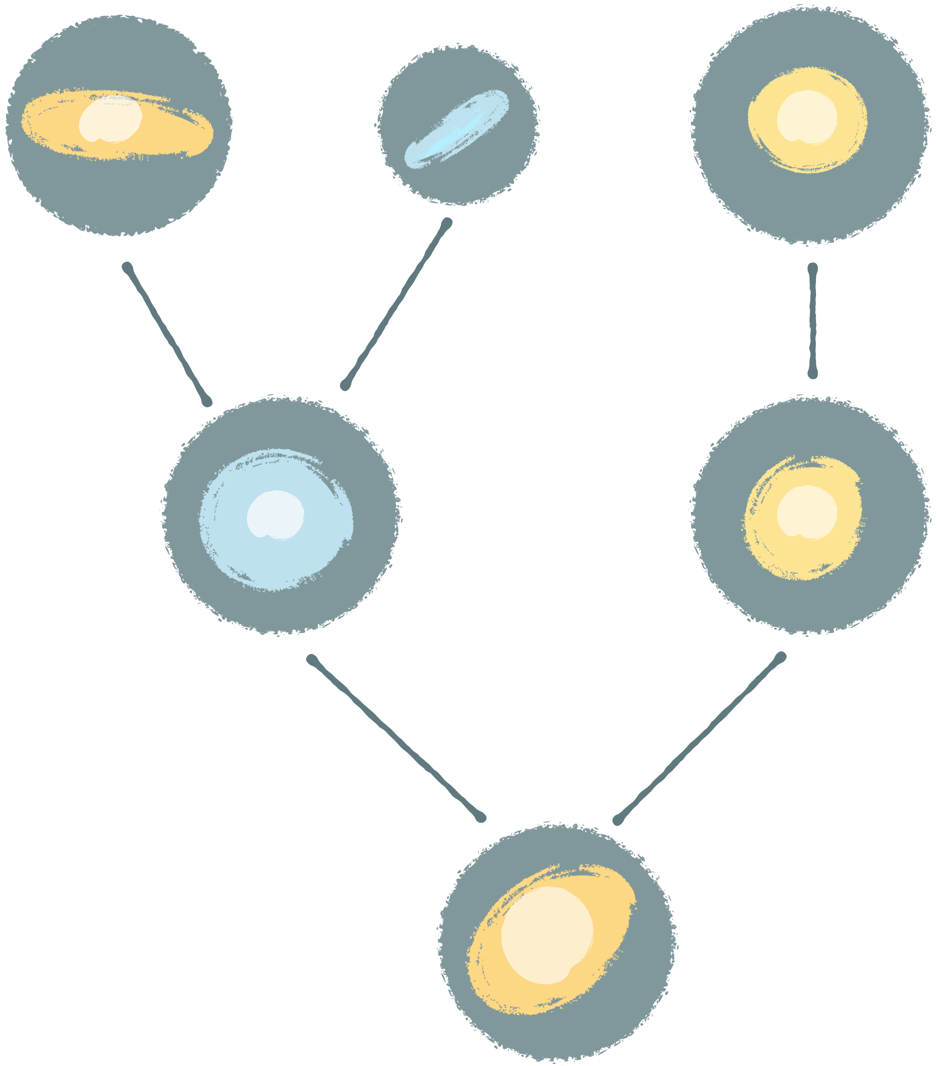
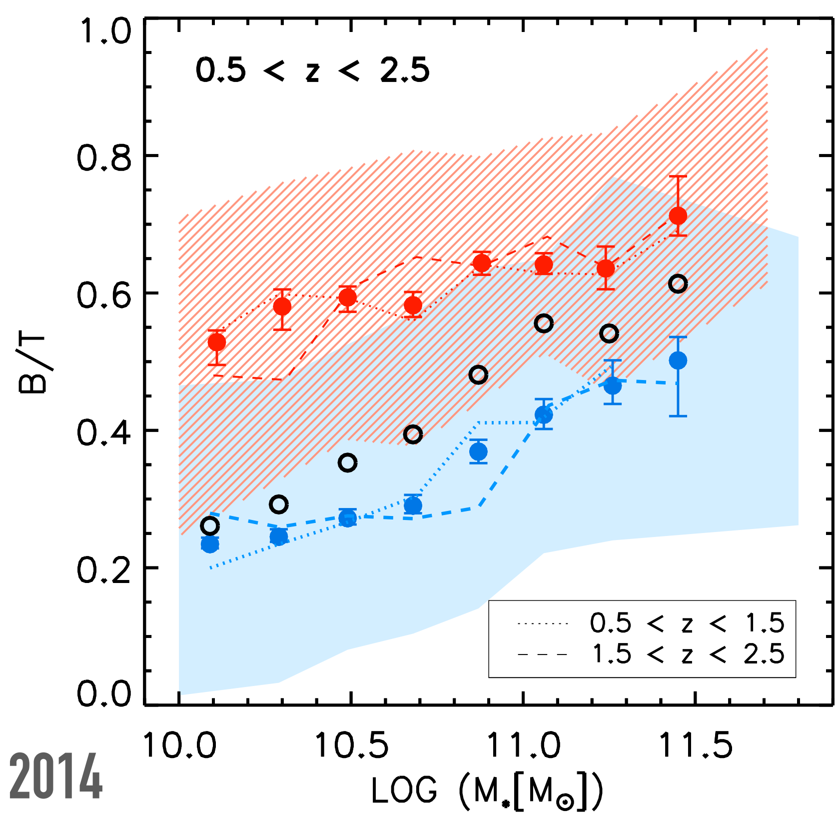
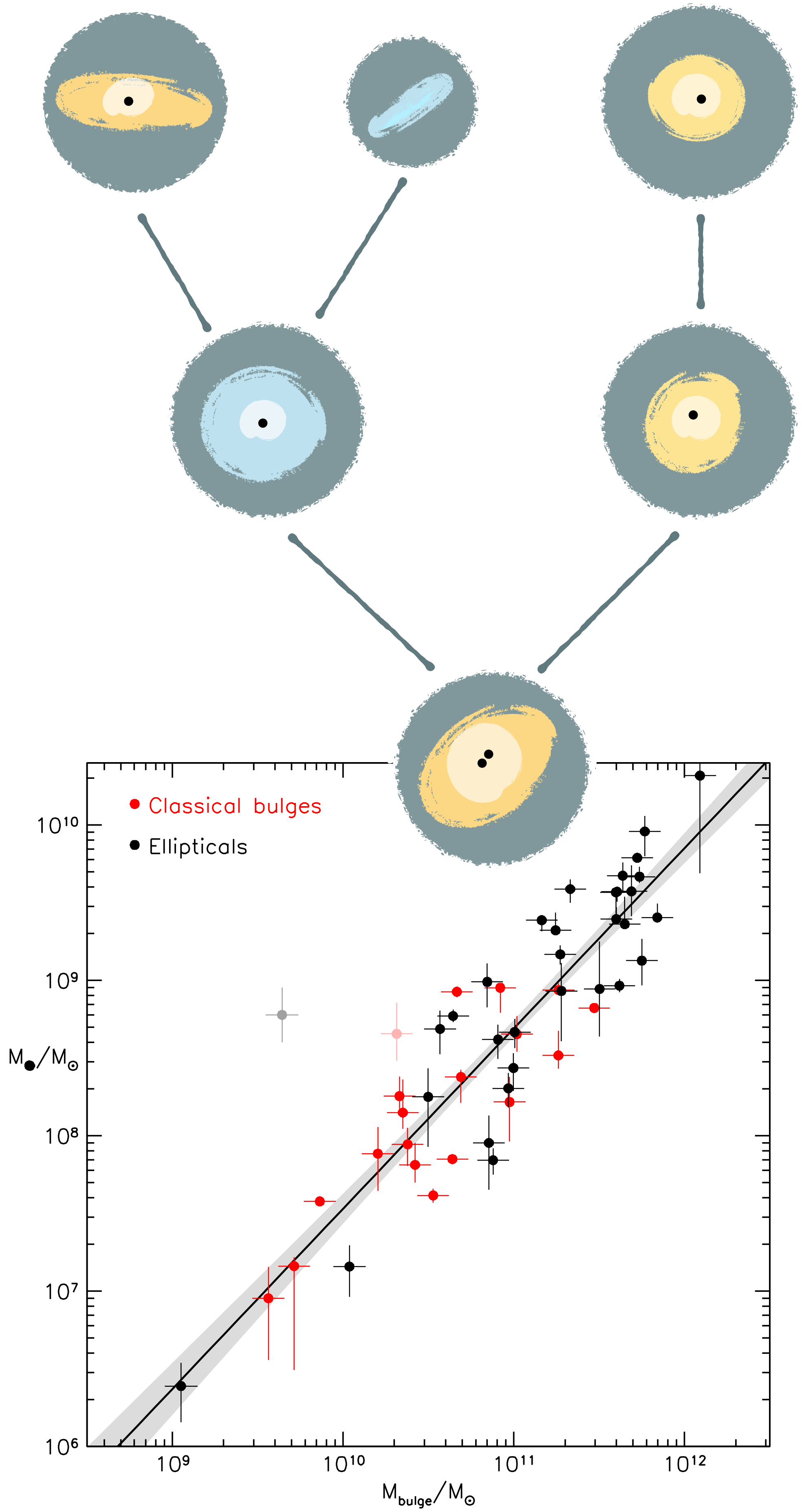




Lang et al. 2014

FROM GALAXIES TO BHS

- Calculate **galaxy bulge mass** according to stellar mass, population type
- Use BH-bulge mass scaling relations to populate galaxies with black holes
- Assume binaries form when the host halos merge
- Final result: distribution of binary black holes formed in each redshift interval



Kormendy & Ho 2013

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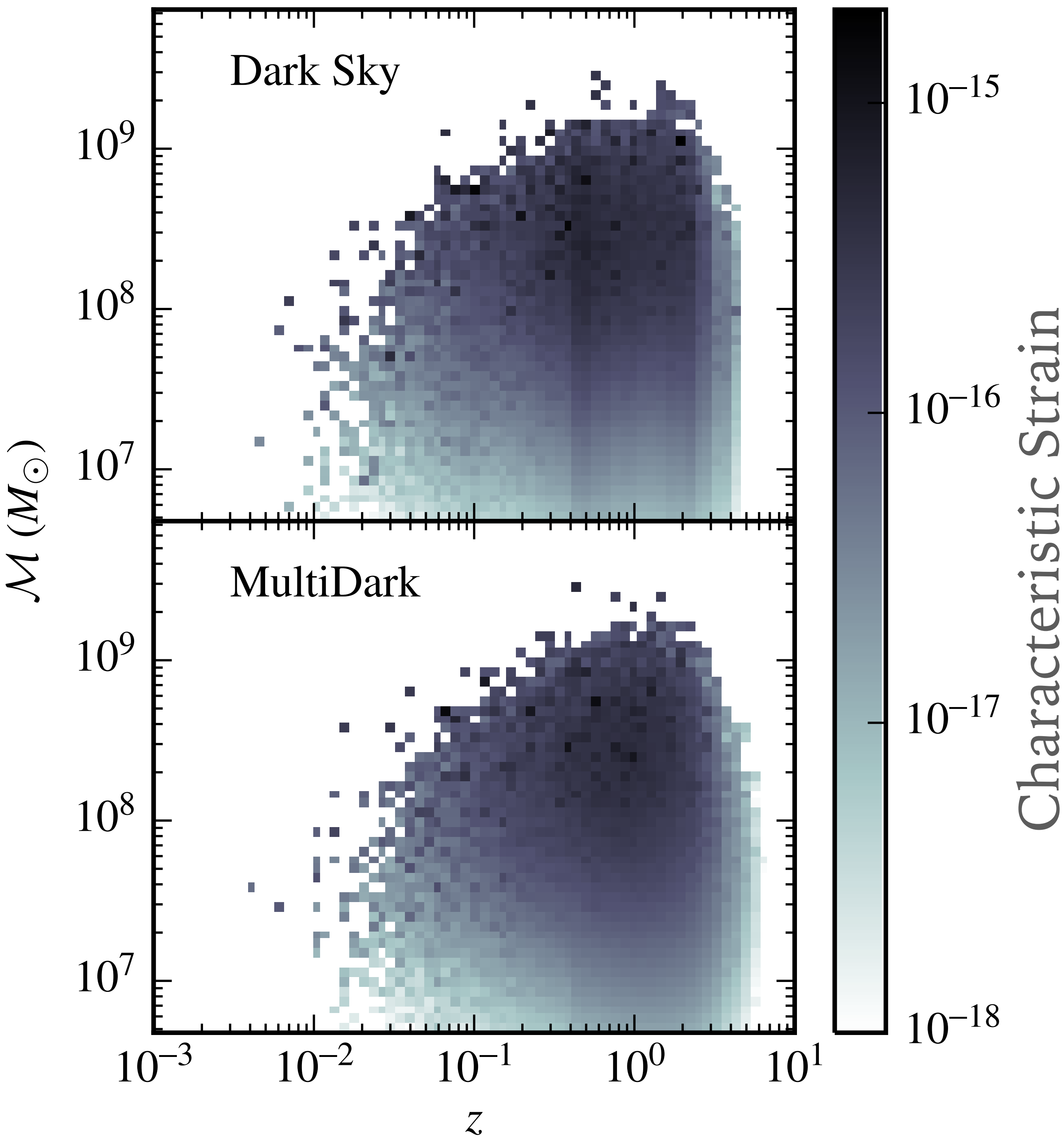
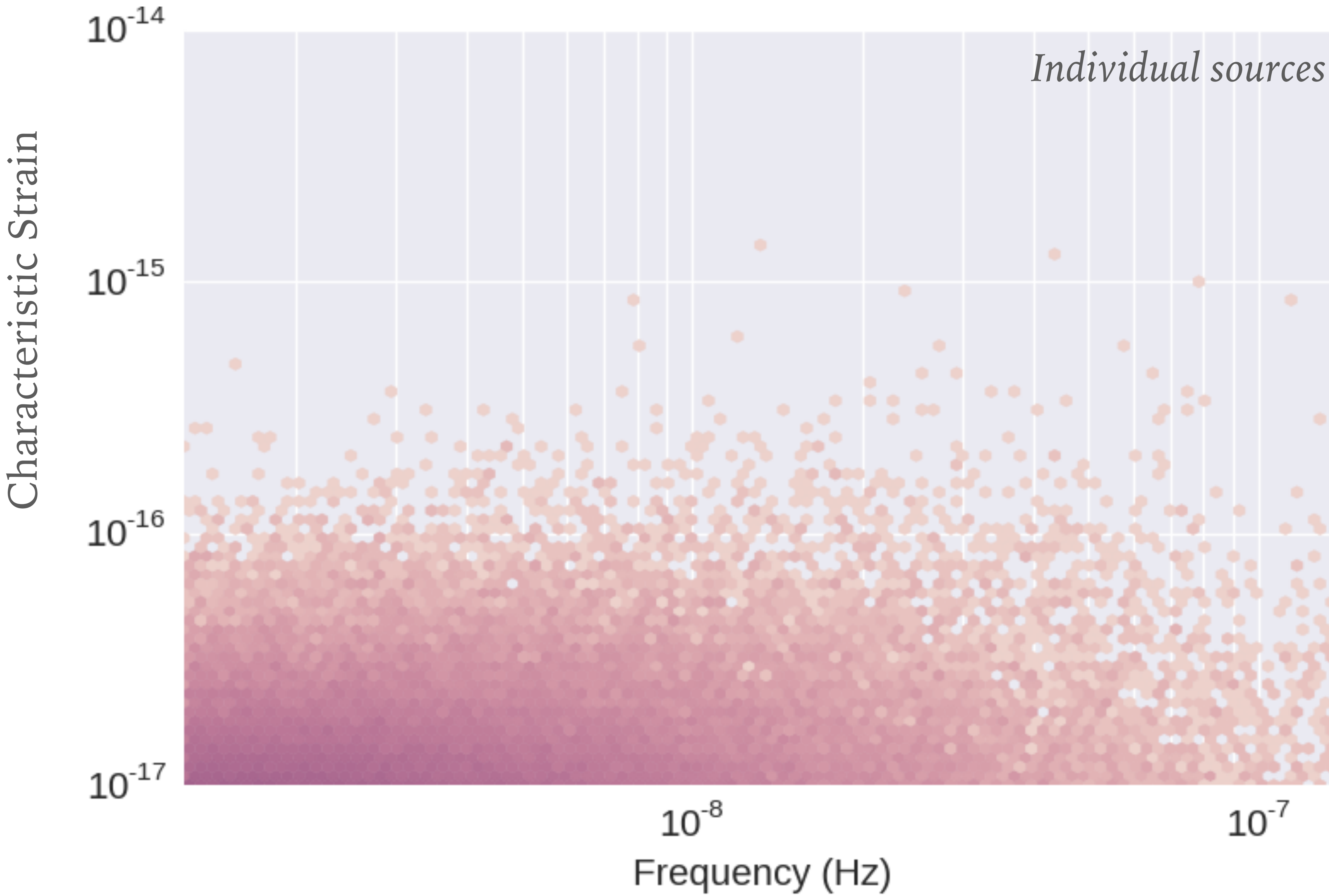


CALCULATING THE GWB

- Previous steps give us a **probability distribution** of binaries in mass, redshift
- Use Monte Carlo selection to simulate population of observed sources for many **realizations** of the universe
- Assume:
  - Keplerian circular binaries,
  - no environmental effects,
  - no stalling

REALIZATION-TO-REALIZATION VARIANCE IN THE SPECTRUM



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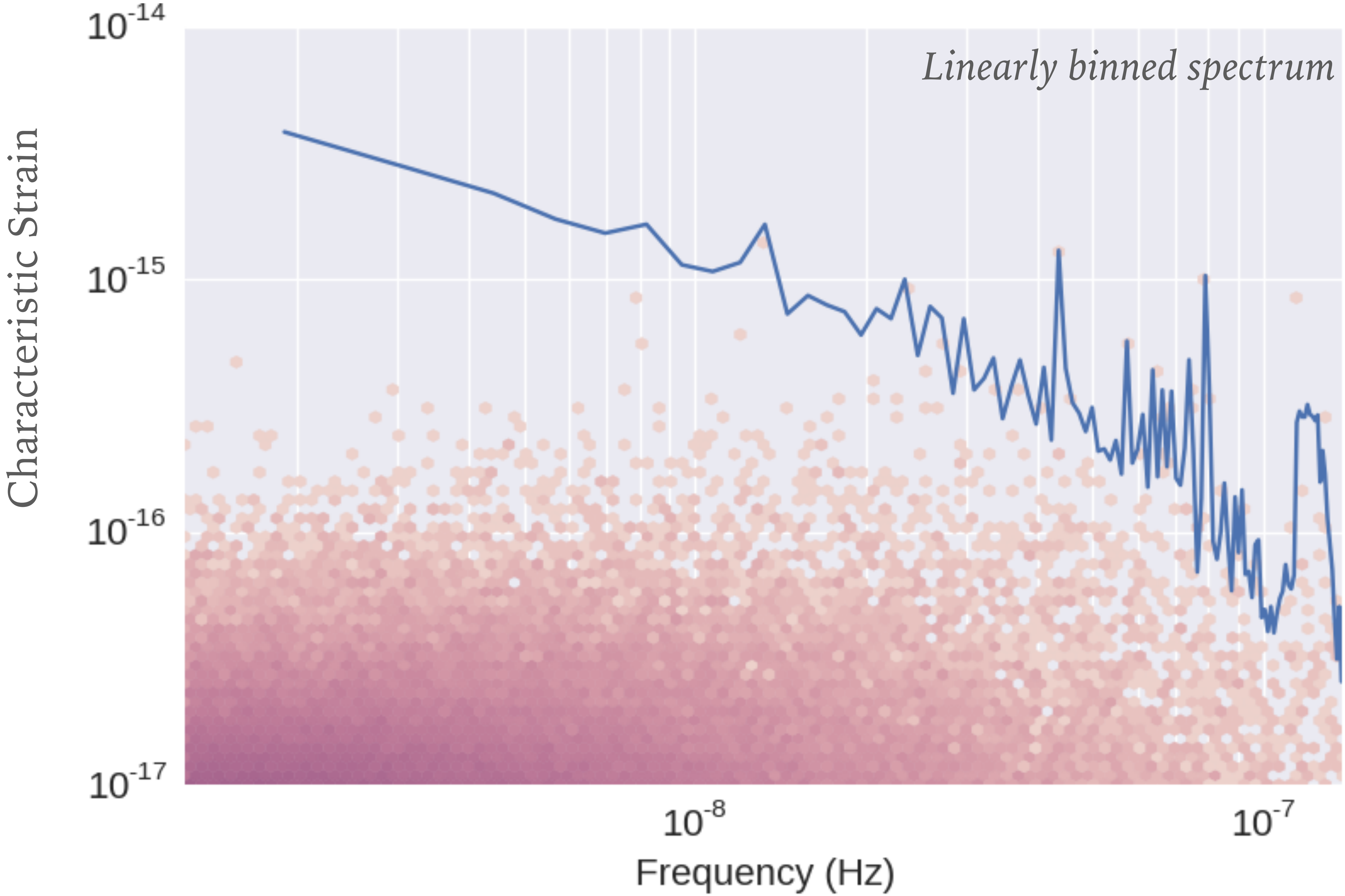

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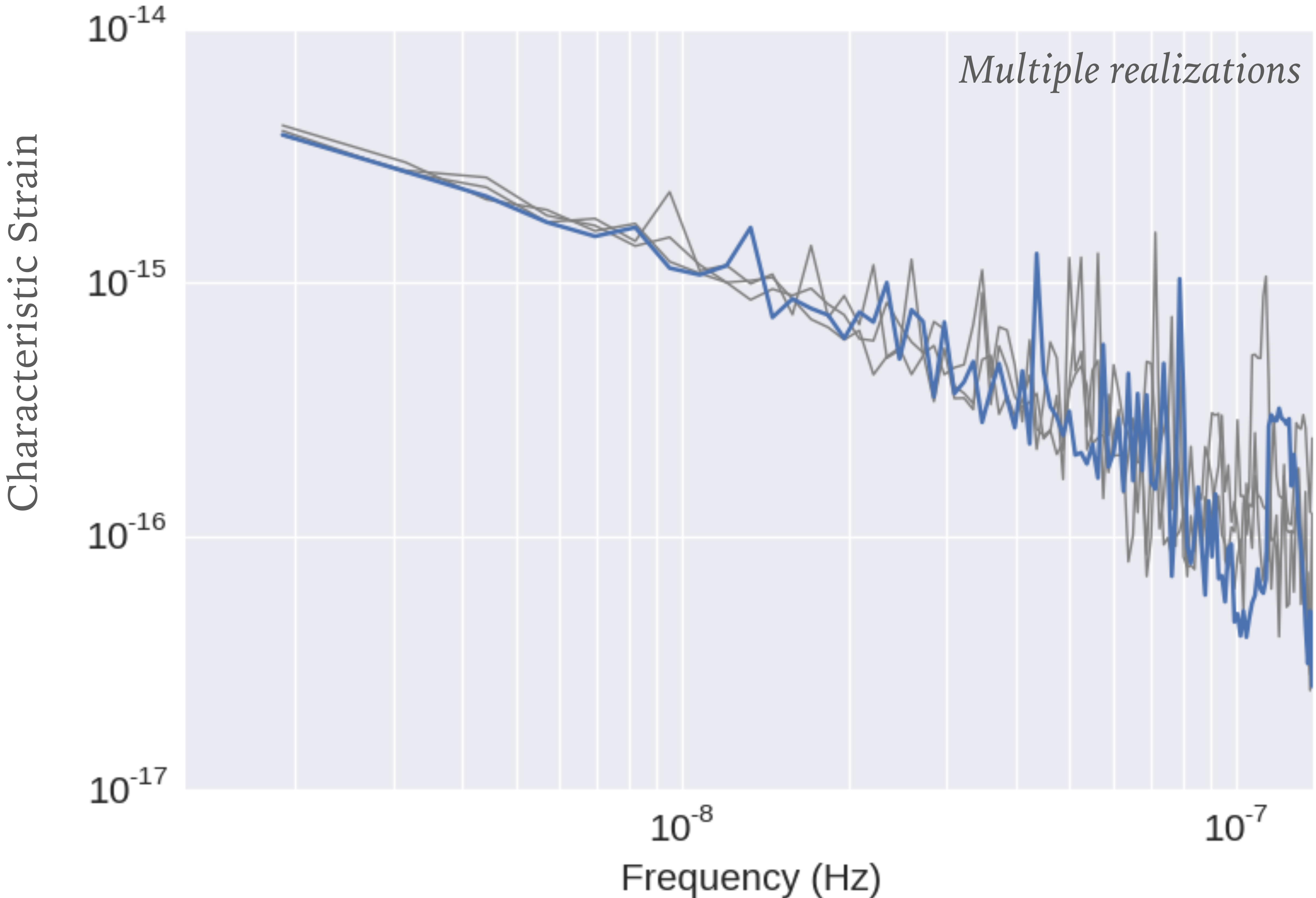

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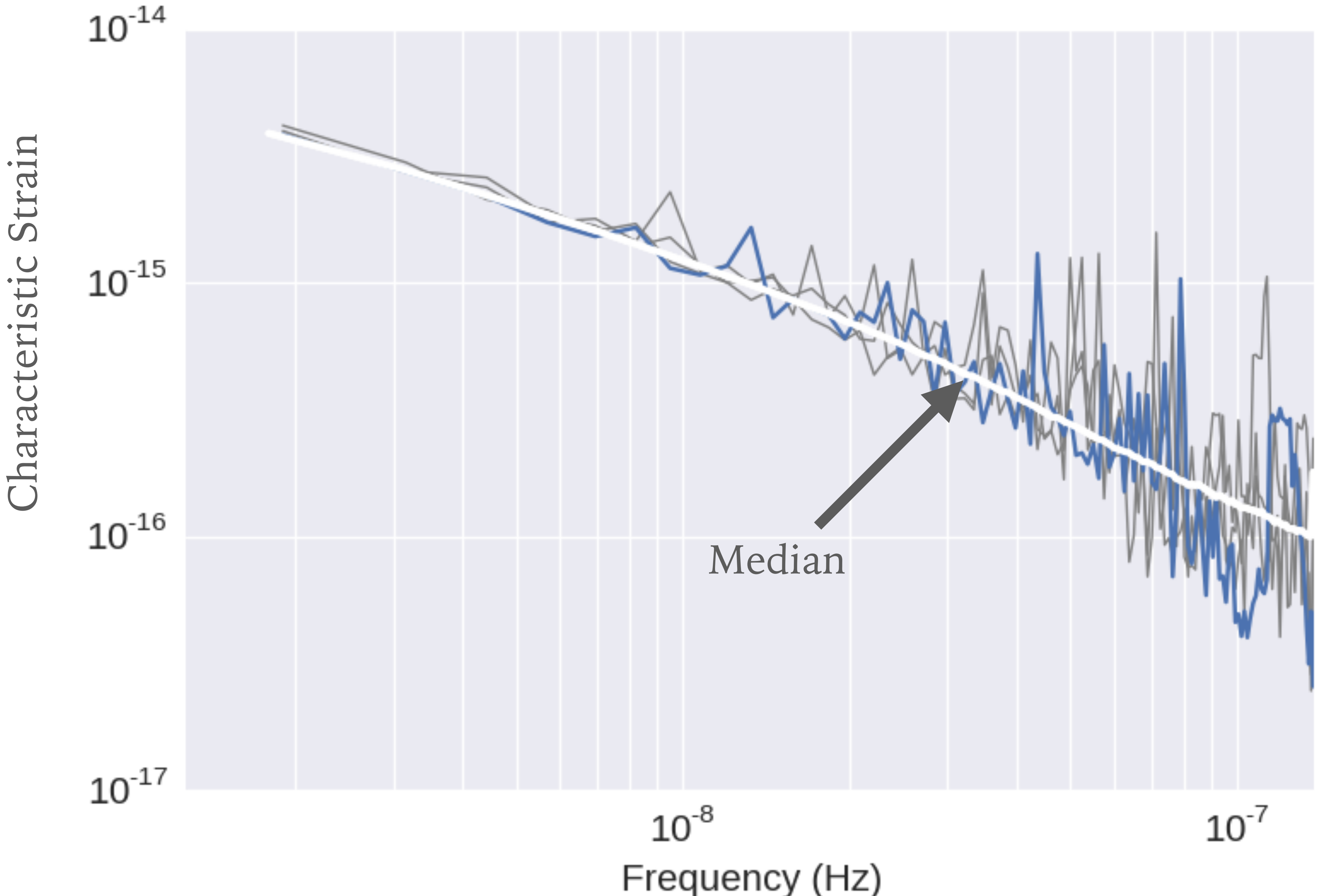

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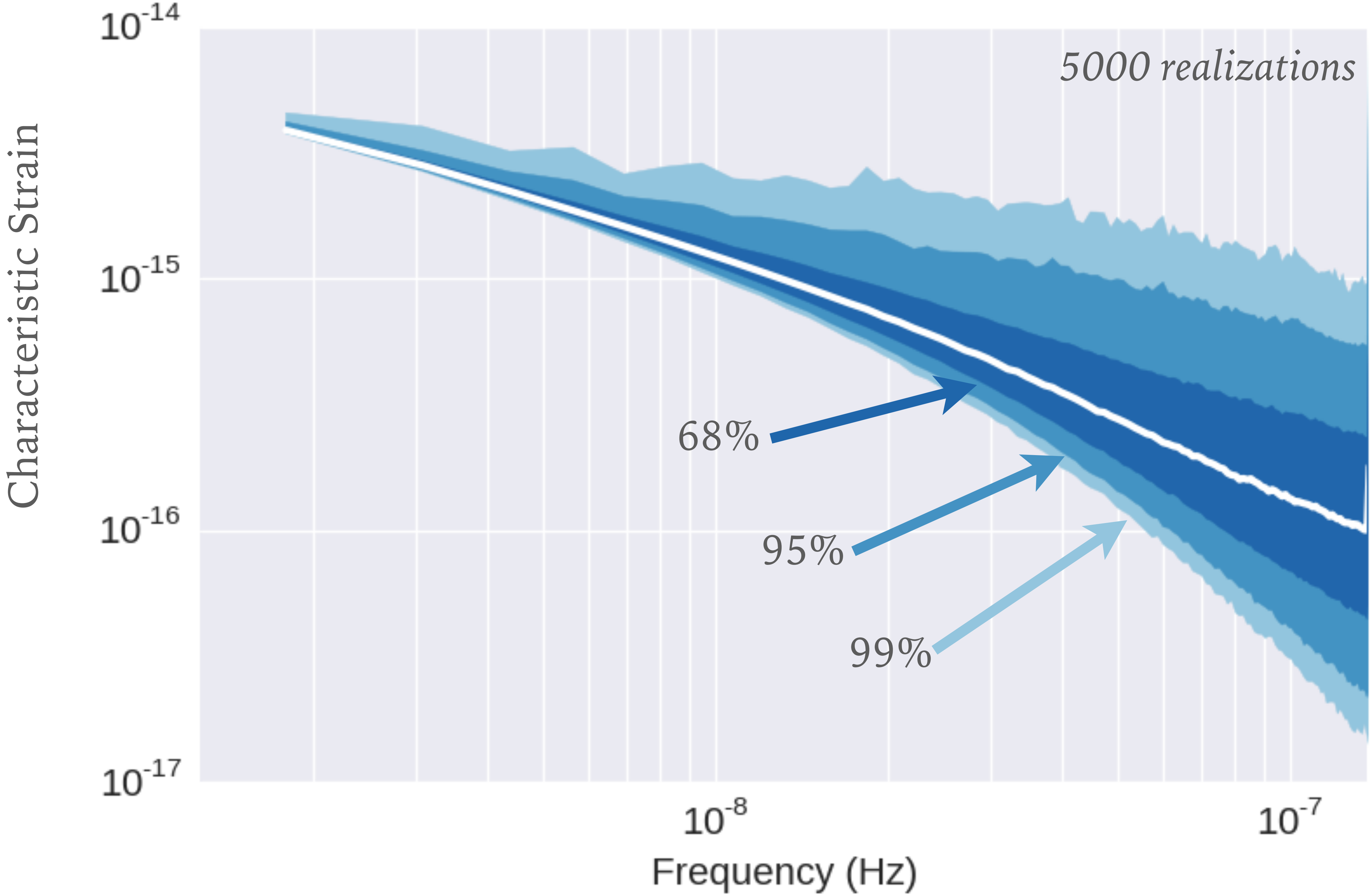

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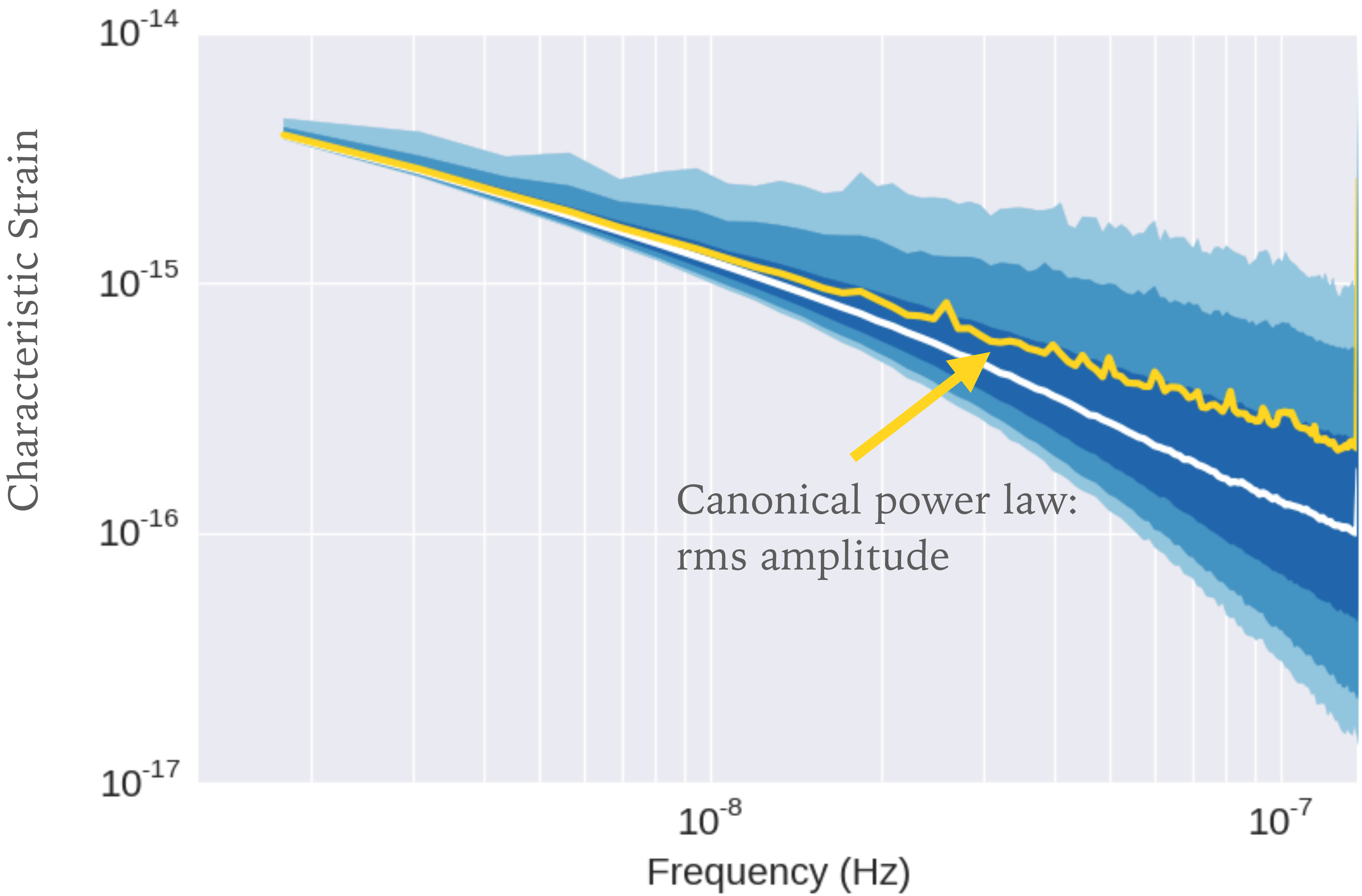
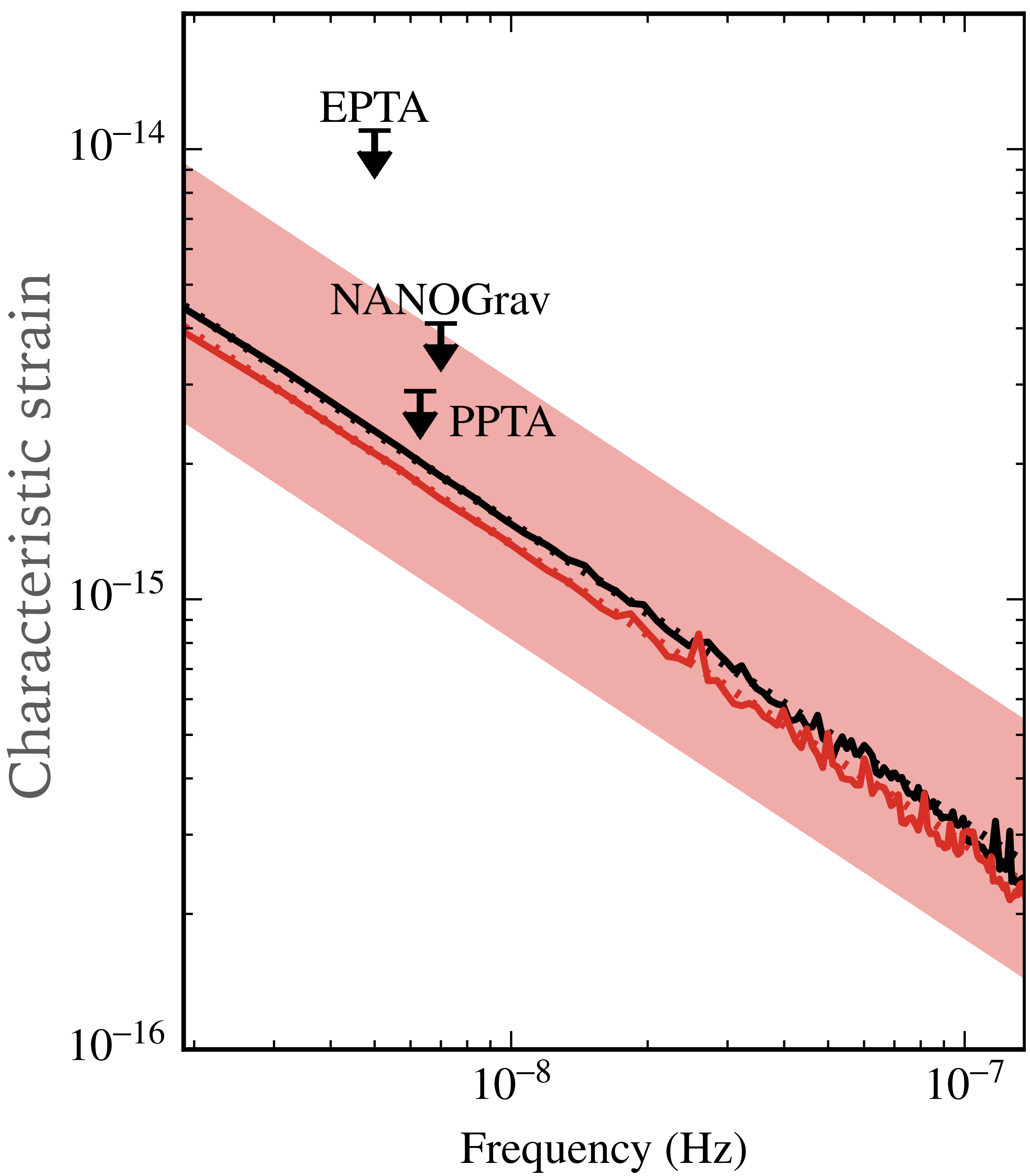
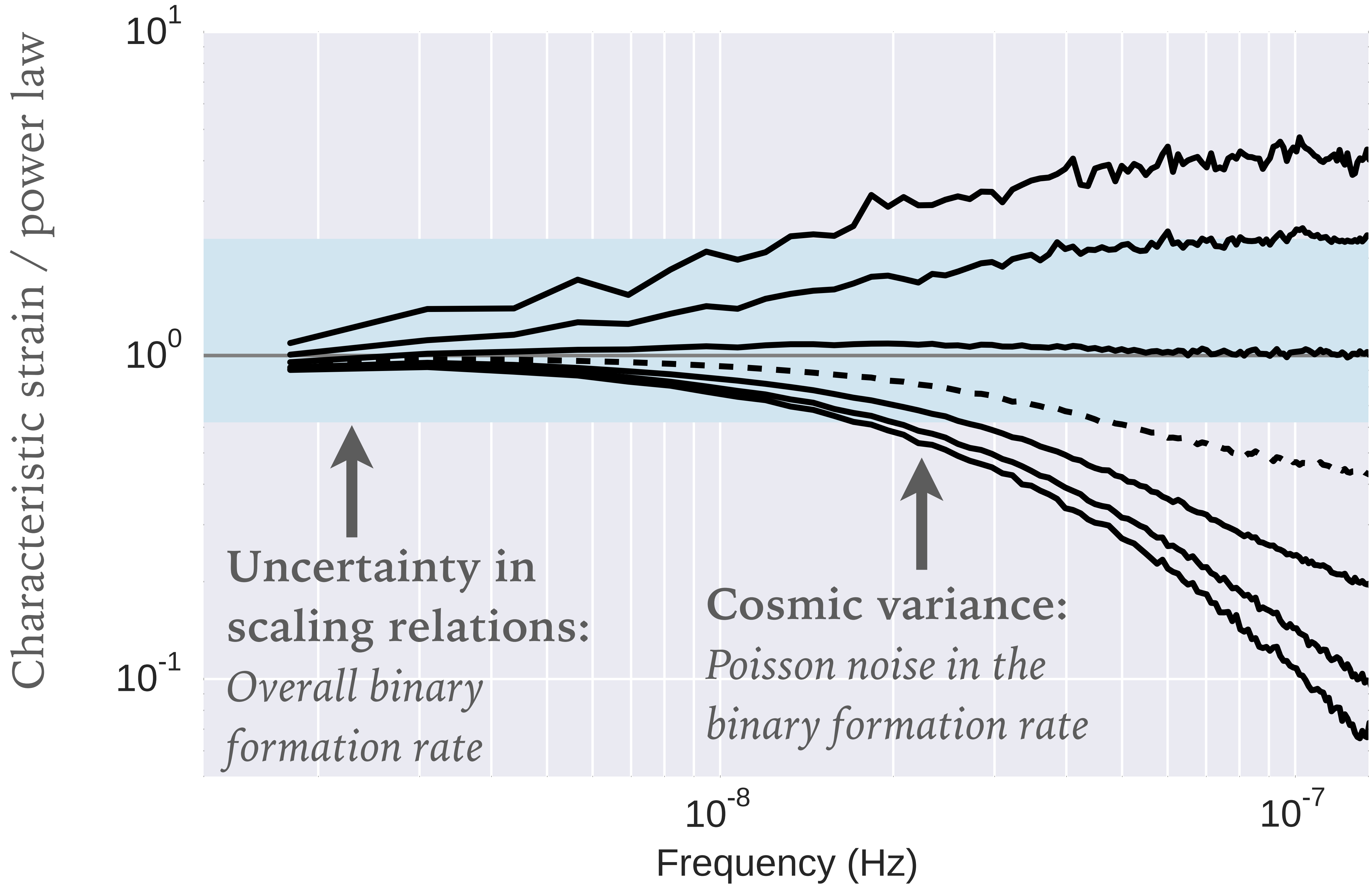




AMPLITUDE OF THE GWB

- Ensemble averaging gives the canonical power law spectrum ($A_{1yr} \approx 6x10^{-16}$)
- Varying **astrophysical** models gives a factor of 2 **uncertainty in the amplitude**
- Range is constrained by recent PTA upper limits

‘COSMIC’ VARIANCE VS ASTROPHYSICAL UNCERTAINTY



CONCLUSIONS

- Used large dark matter simulations to make numerical predictions for the stochastic gravitational wave background
- Amplitude similar to recent empirical approaches, range constrained by PTA upper limits
- **Two important forms of variance in the spectrum:**
  - **Astrophysical uncertainty**: in scaling relations merger rates, etc; produces **systematic offset** in the amplitude, frequency independent
  - **'Cosmic variance'**: result of Poisson noise in SMBHB mass function, frequency dependent—**dominates at high frequencies**
- Relation between this cosmic variance and anisotropy?
- Effect of the cosmic variance on spectra with a turnover?