A Massive Black Hole Binary Interpretation to the Nanohertz GW Background

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Jessie Runnoe, Joe Simon, Jeremy Wachter, David Wright, & NANOGrav et al.

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NANOGrav | chair, astrophysics working group

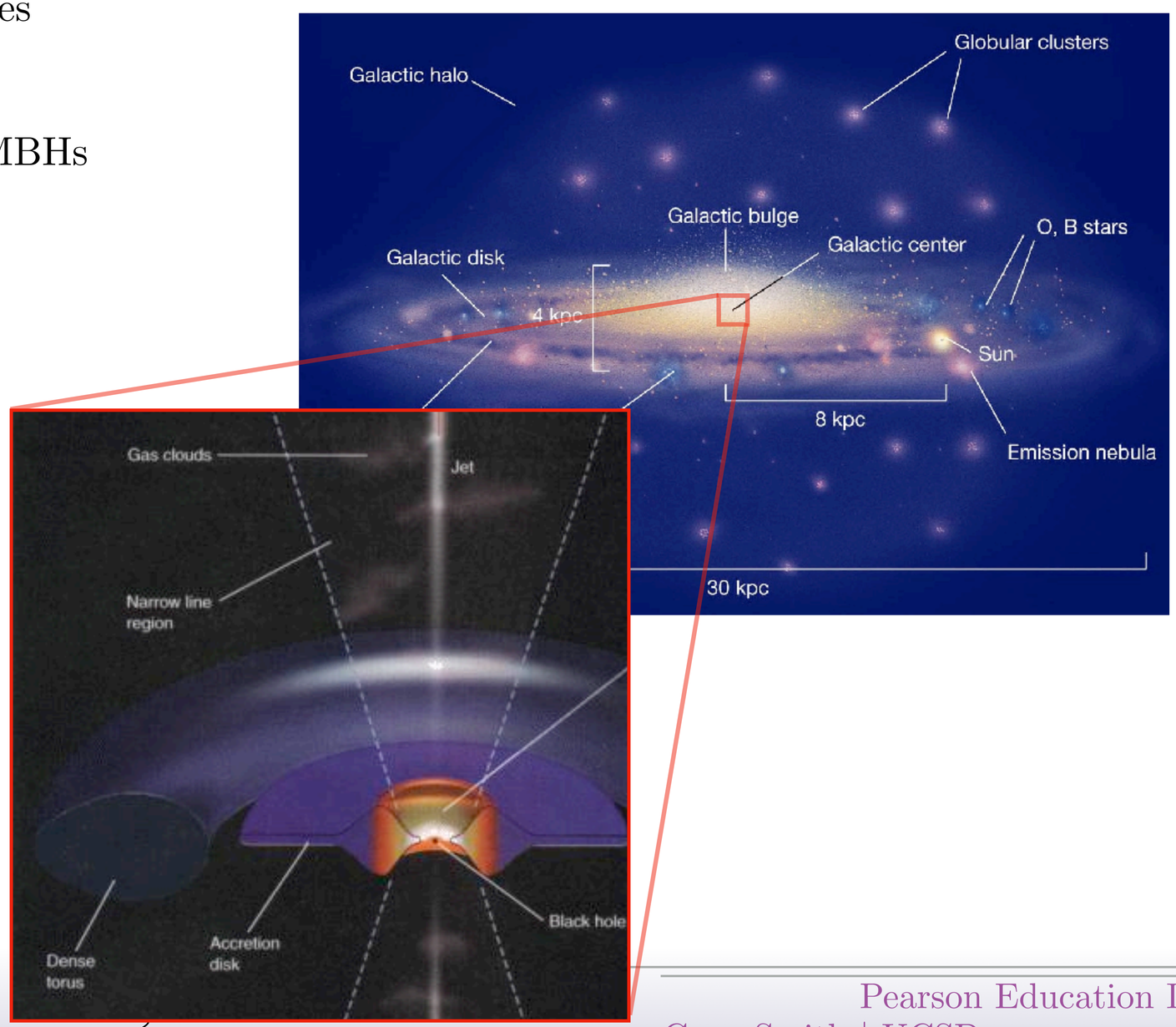
Massive Black Holes

- MBHs: occupy the center of ≈ all massive galaxies

$$M \to 10^5 - 10^{10} M_\odot$$

- active galactic nuclei (AGN): bright, accreting MBHs

$$L \to 10^{11} - 10^{15} L_\odot$$



Massive Black Holes & Active Galactic Nuclei

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- active galactic nuclei (AGN): bright, accreting MBHs

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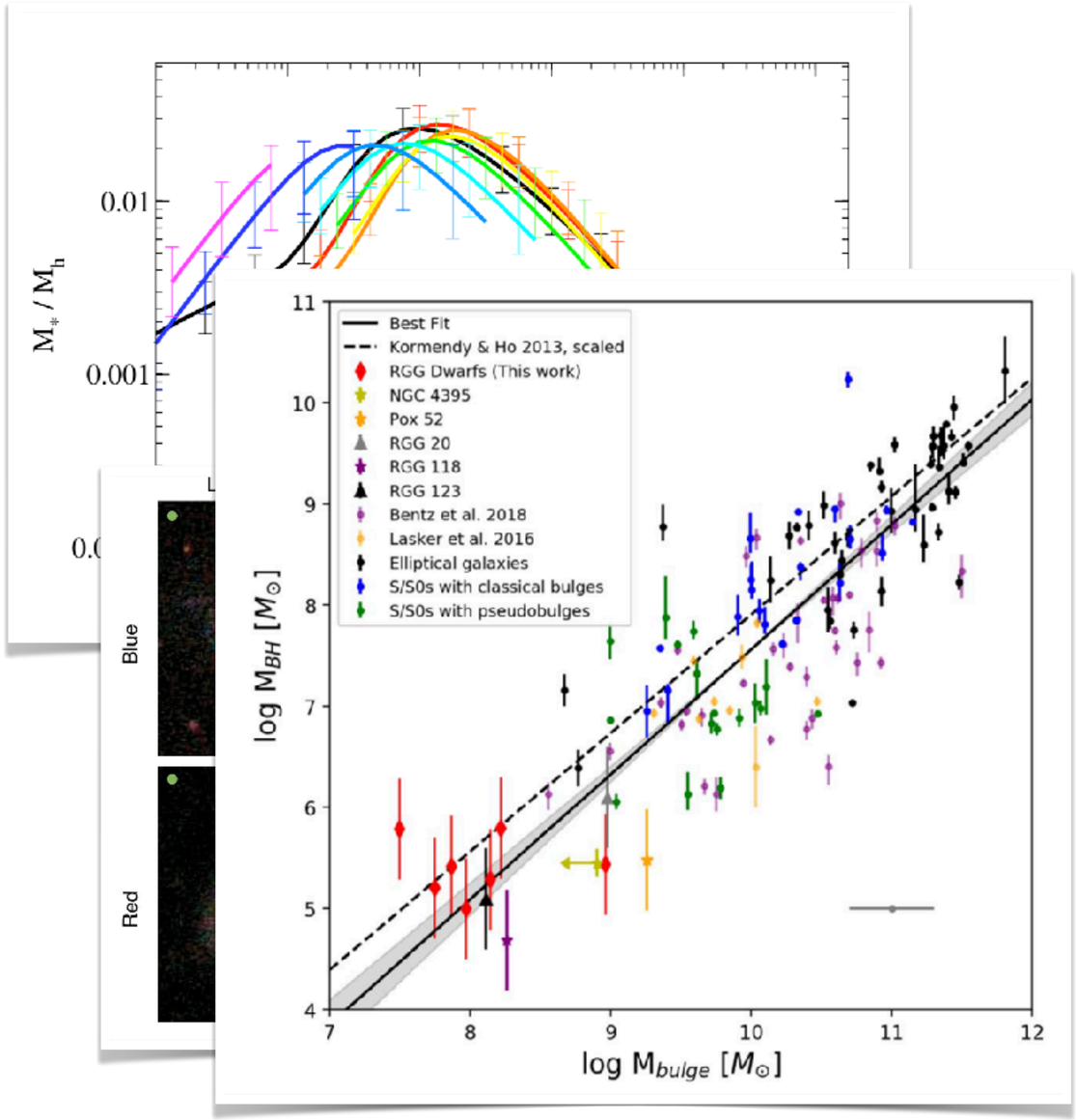
- responsible for "quenching" the most massive galaxies
- closely correlated with galaxy across all masses

- mostly mysterious
  - formation?
  - growth?
  - accretion?
  - feedback?



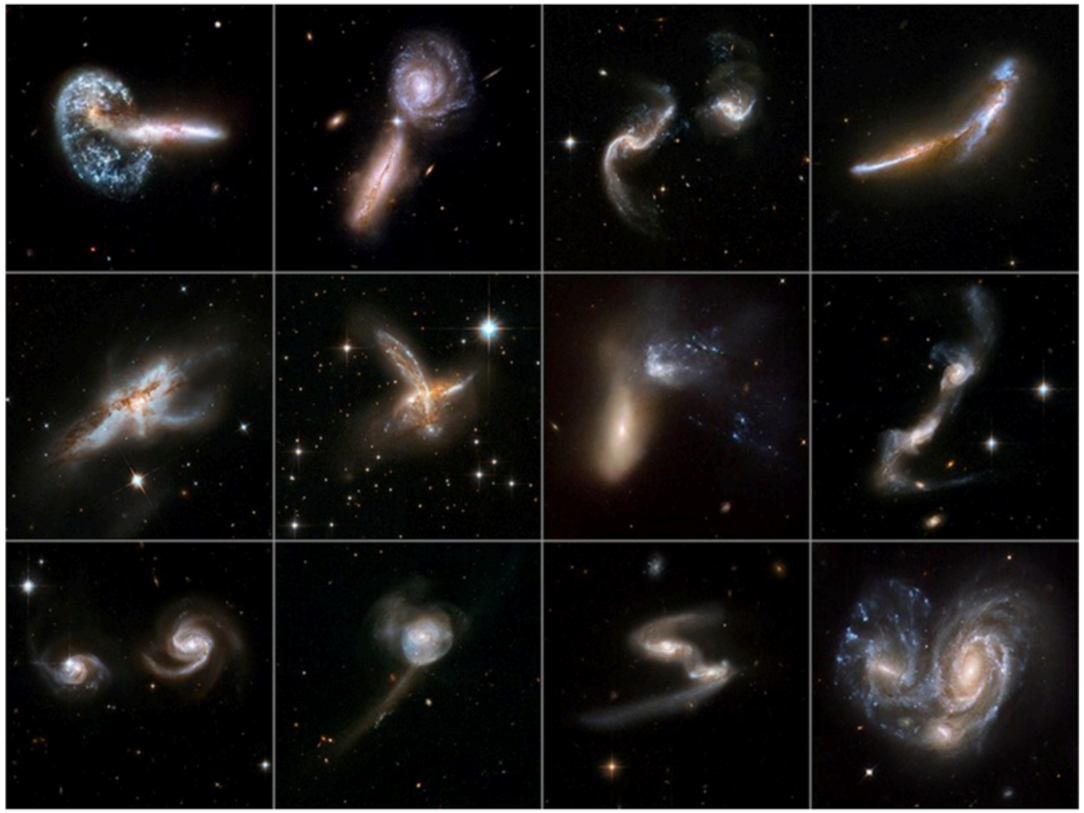
Behroozi et al. 2013

Tojeiro et al. 2013

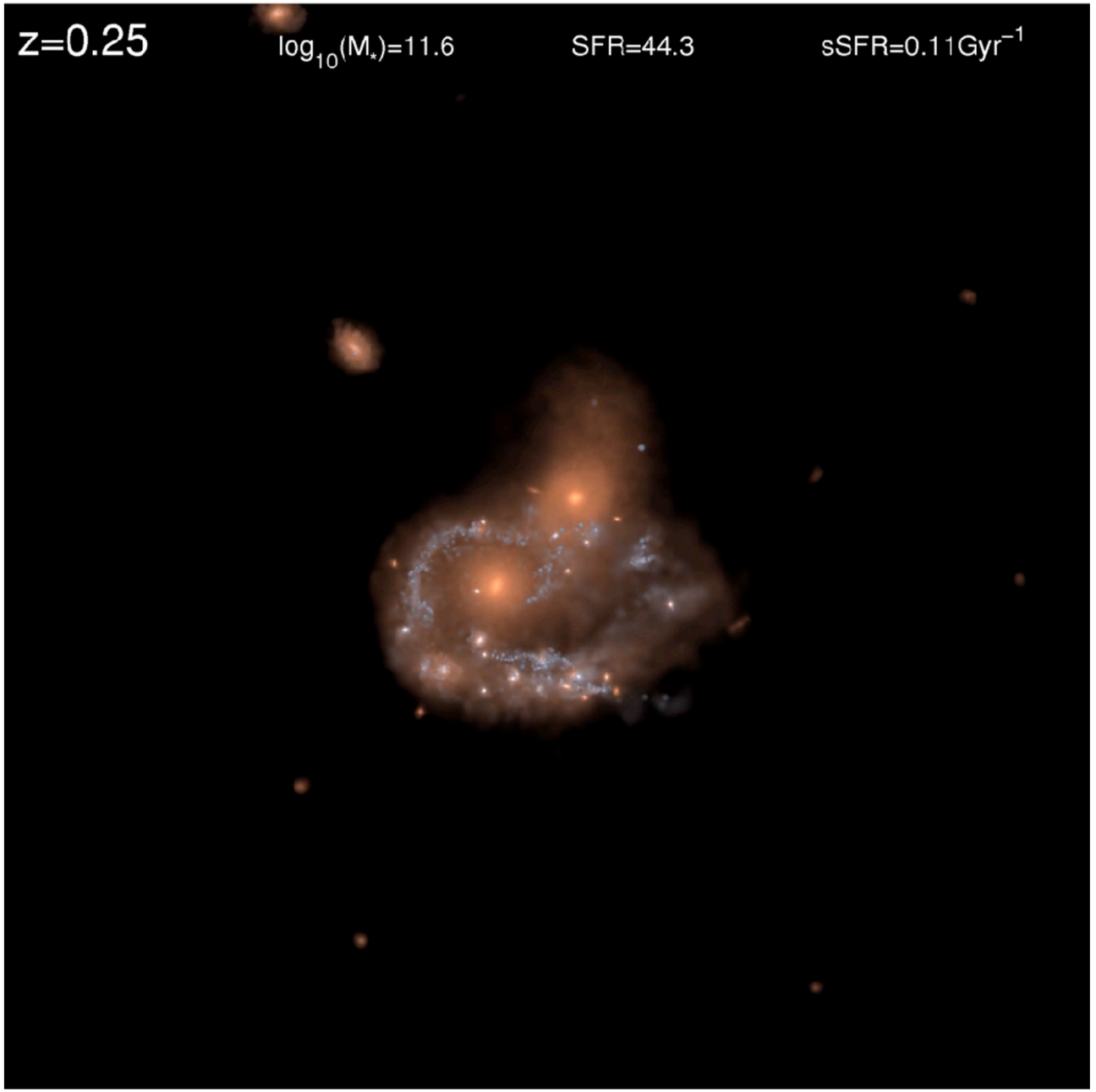
Schutte et al. 2019

Massive Black Holes Binaries

- Galaxy mergers – key to growth of massive galaxies



Examples of galaxy pairs found in this study – here are examples of detected systems which are within close proximity to each other Credit- C.Mundy C.Conselice et al



Massive Black Holes Binaries

- Galaxy mergers – key to growth of massive galaxies
  - "dual" MBHs in post-merger galaxy

    $r \sim 10^3$ pc $\qquad$ $t_{\rm GW} \sim 10^{17}$ Myr

Begelman, Blandford & Rees 1980

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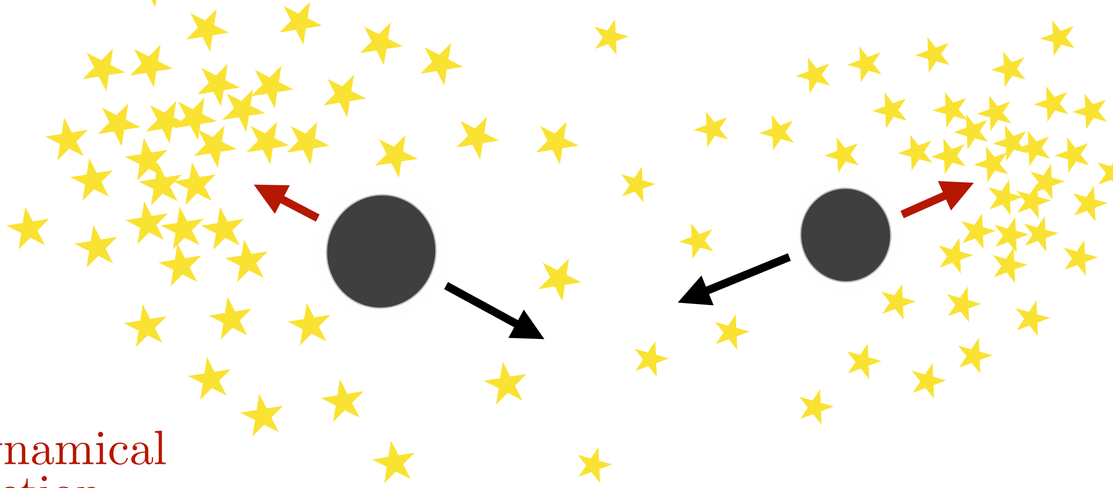
dynamical friction



- MBH sphere of influence

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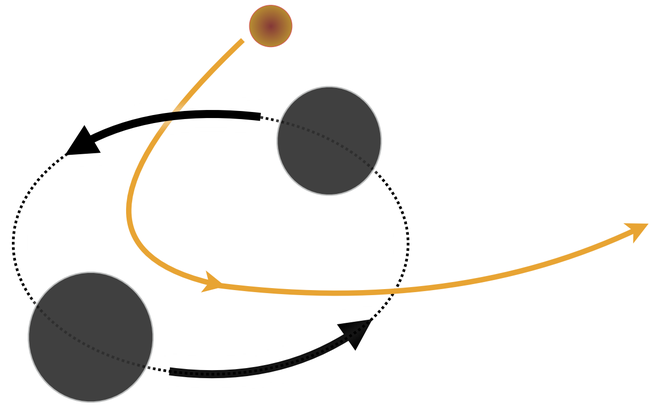

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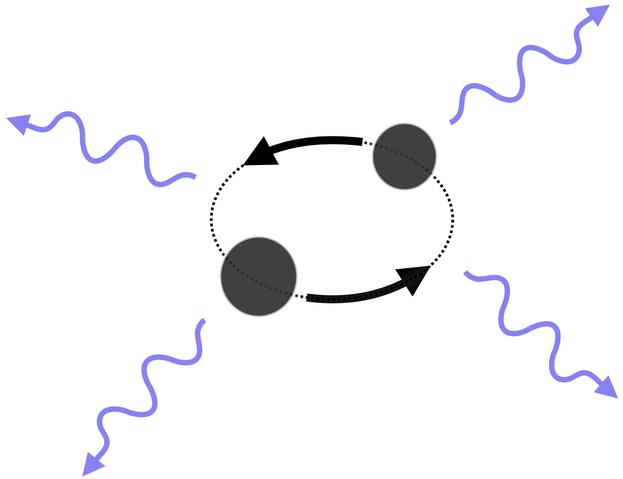

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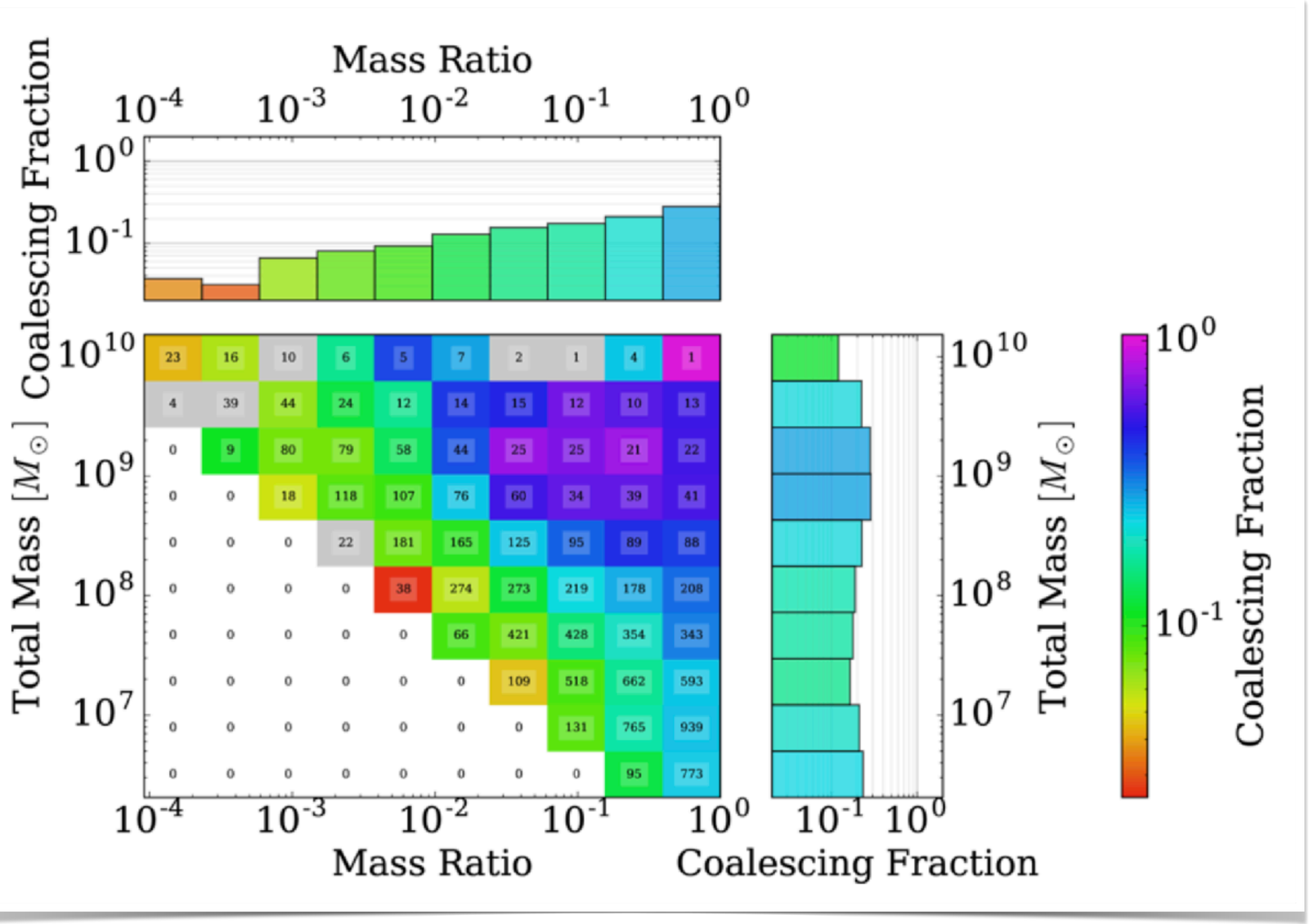

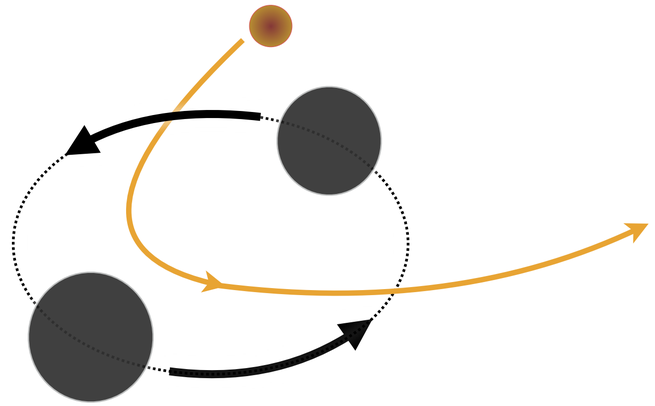

LZK+2017a

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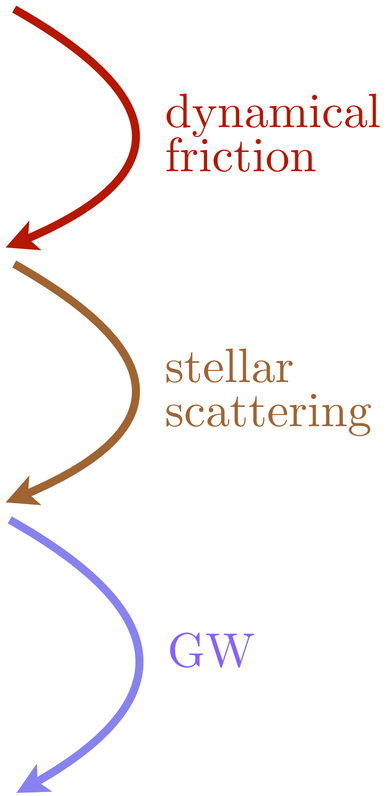
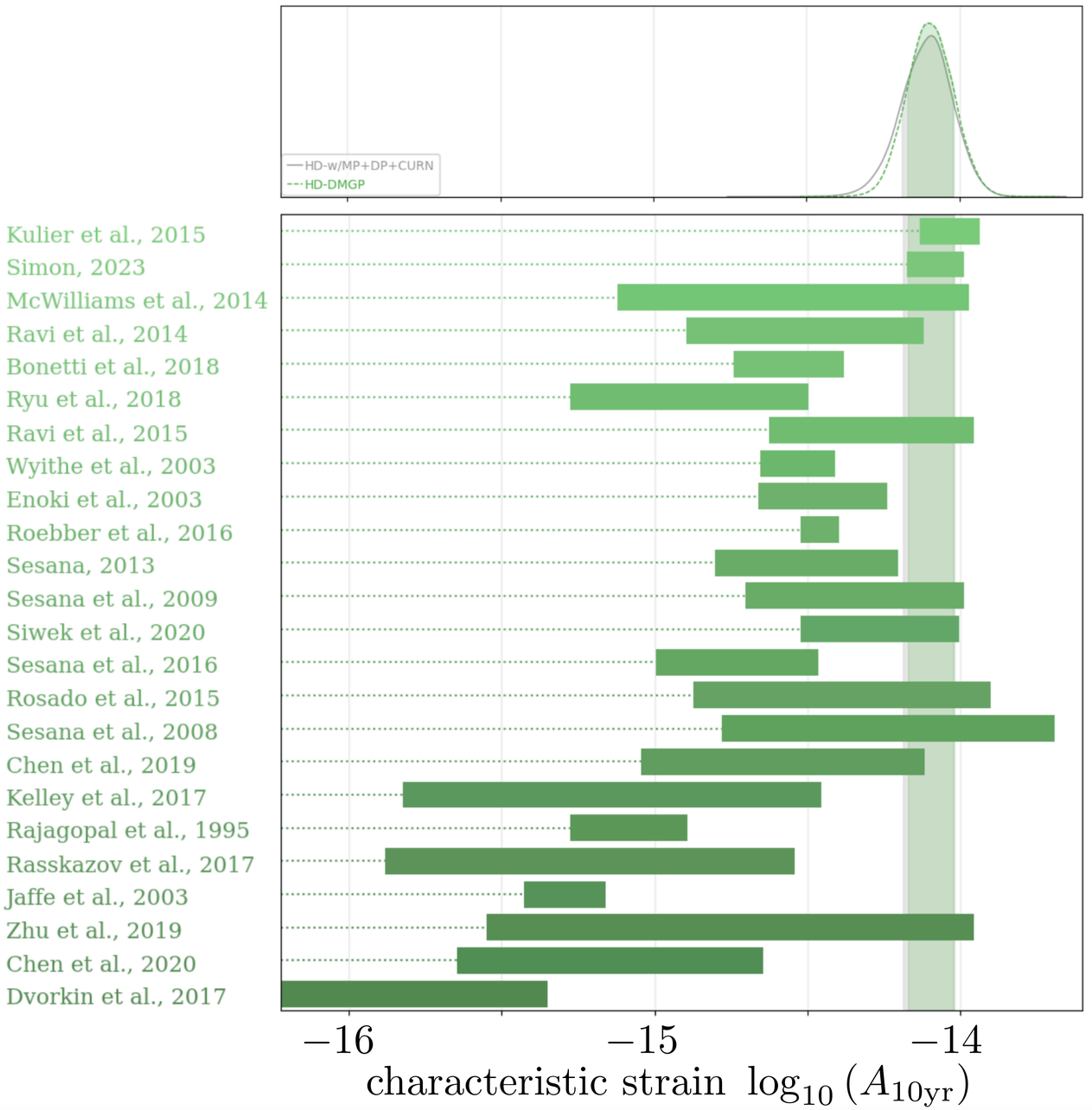


- rate of galaxy mergers?
- MBH masses? (M–Sigma / M–$M_{\rm bulge}$)
- very sensitive to initial conditions, cosmological distribution of galaxies
- tidal stripping is numerically challenging
  - ongoing galaxy evolution? (star bursts, AGN feedback)
  - triple MBH interactions?
- analytic approximations are bad
- numerically intractable
  - torques from circumbinary disks?
- easy!
  - GW recoils?

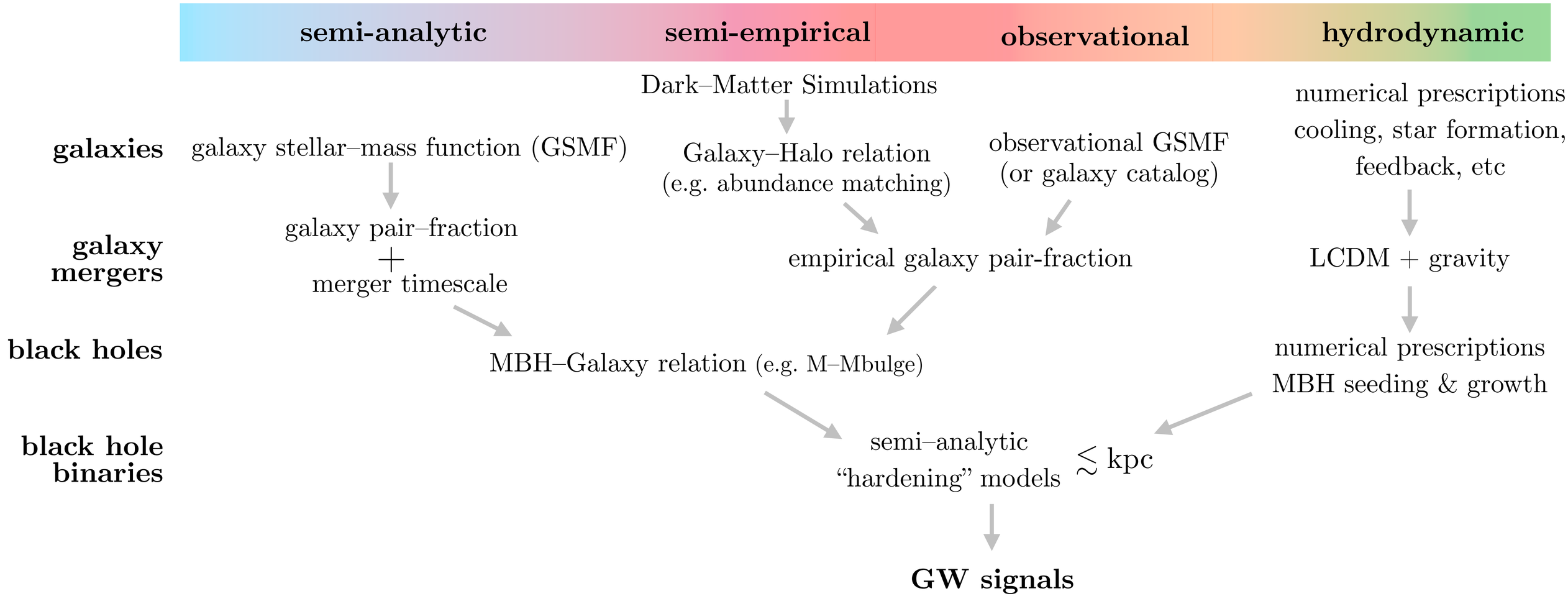
MBH Binary Population Synthesis

- wide range of predicted amplitudes



from Maria Charisi | Agazie+2023 (SMBH binaries)

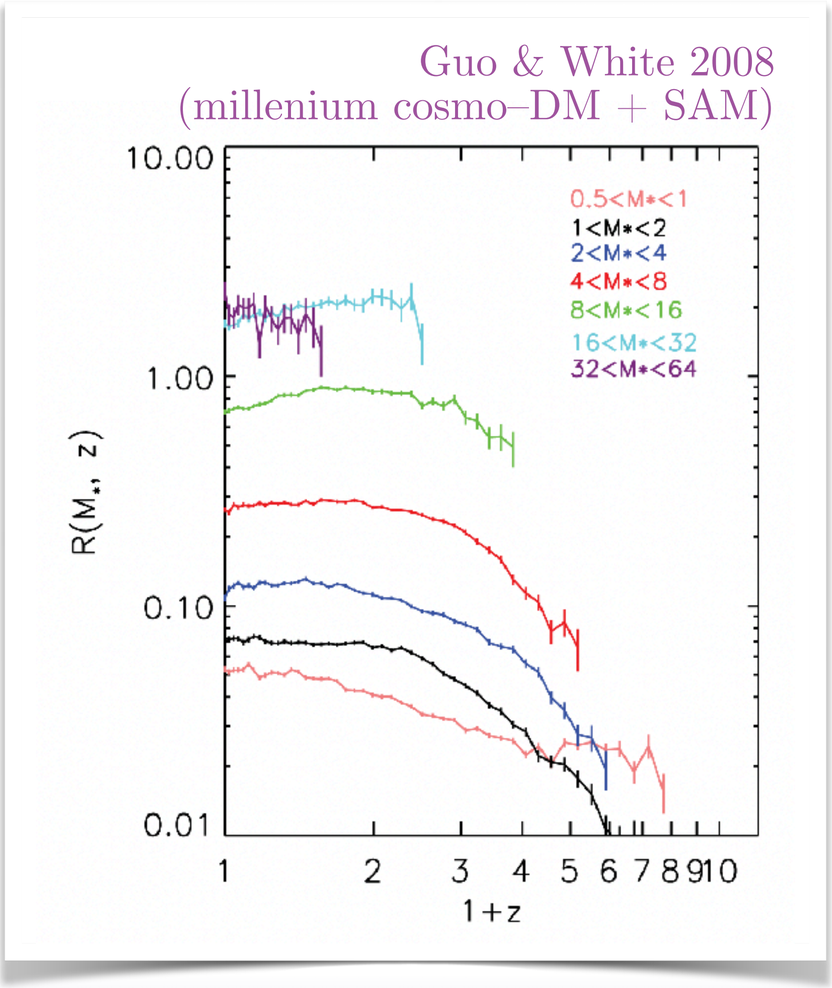
MBH Binary Population Synthesis



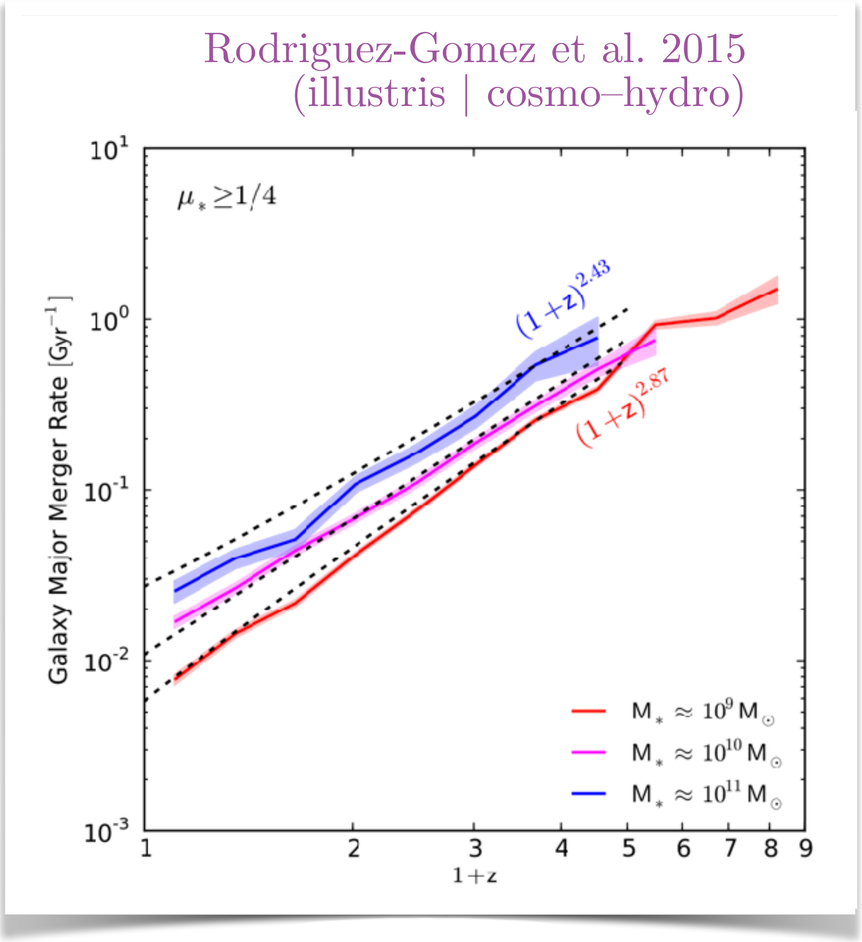
MBH Binary Population Synthesis

- differences between modeling assumptions can be significant
  e.g. galaxy–galaxy merger rates

Guo & White 2008
(millenium cosmo–DM + SAM)



Rodriguez-Gomez et al. 2015
(illustris | cosmo–hydro)



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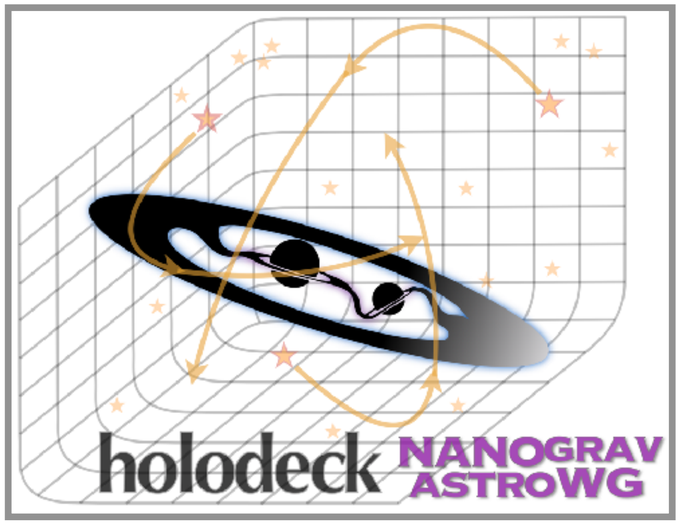
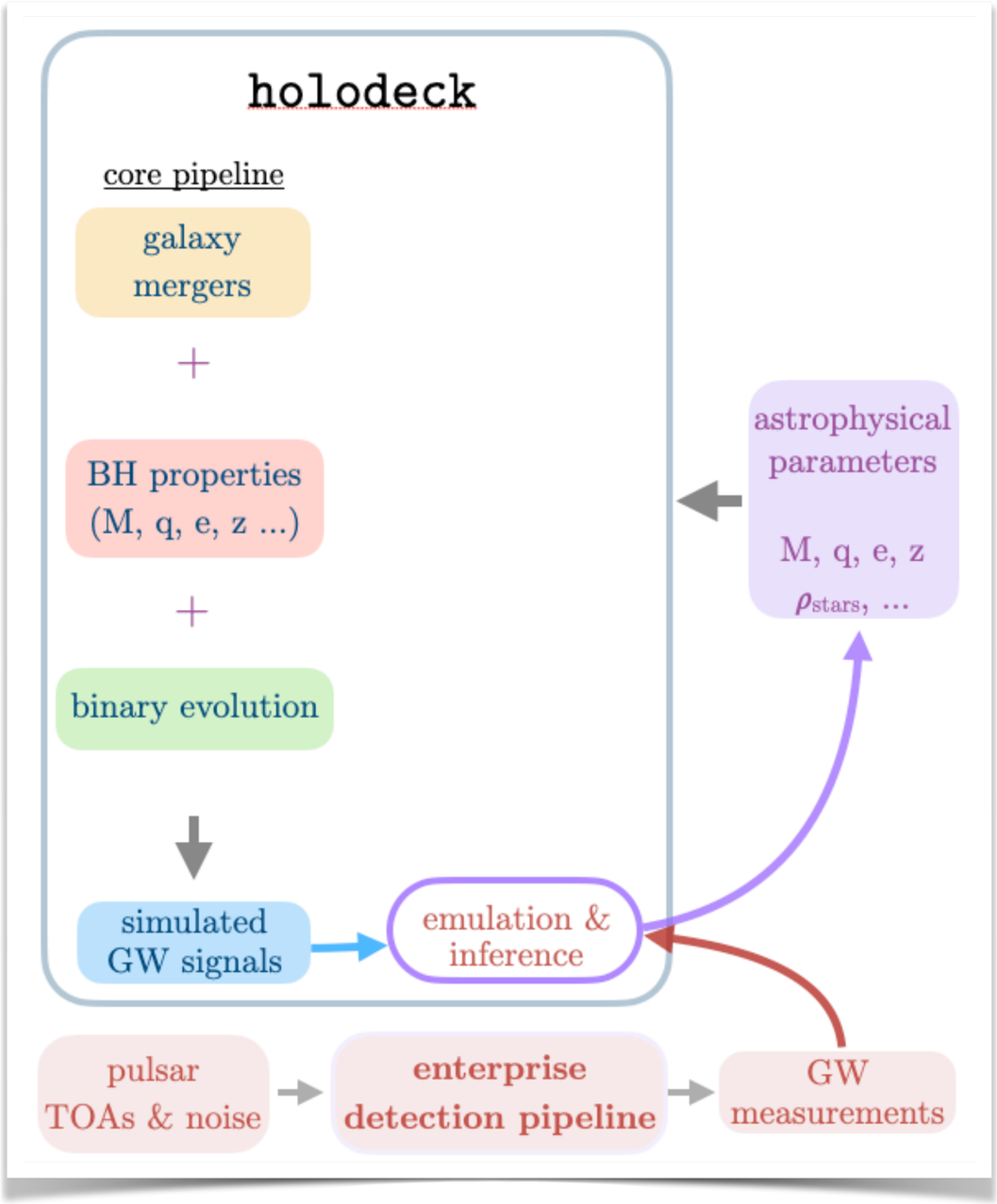


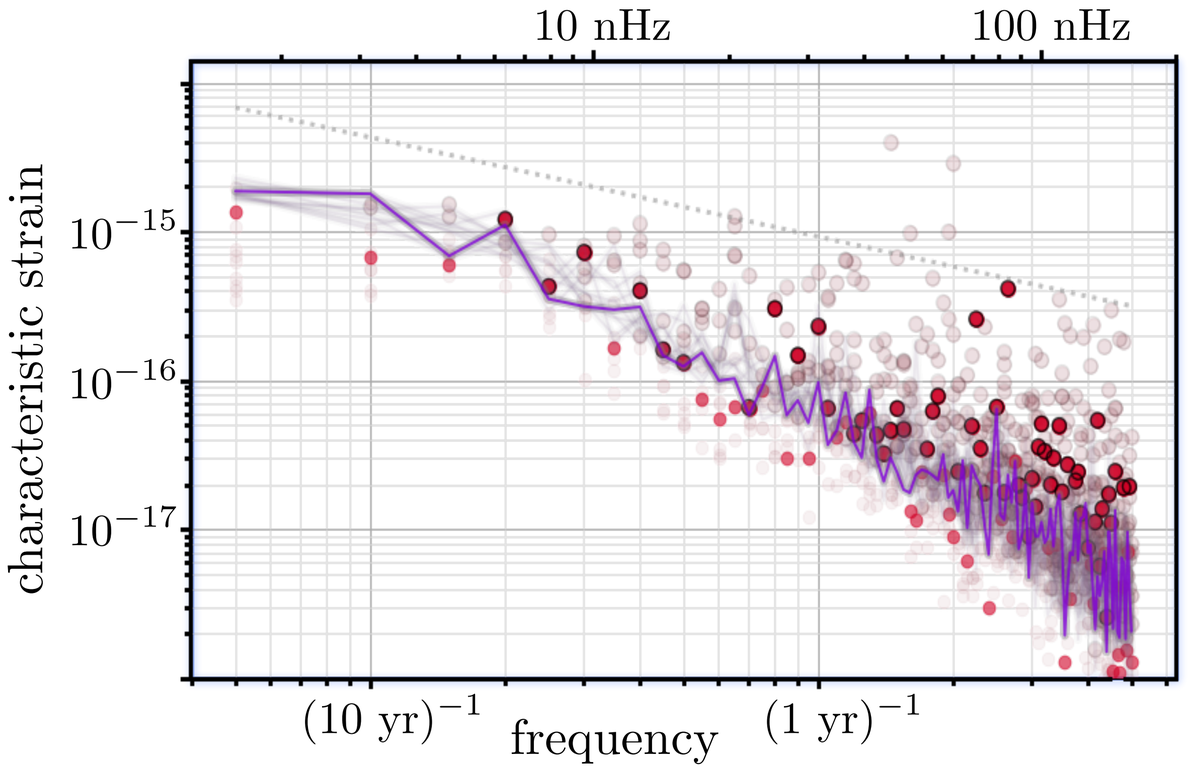
- interchangeably utilize multiple modeling approaches
  - cosmological hydro simulations
  - semi-analytic/semi-empirical models
  - observationally-based catalogs

- self-consistent binary evolution
  - comprehensive environmental interactions
  - eccentric orbits
  - discretized binary populations



GW Background

$$h_c^2(f) = \int h^2(f_r) \frac{d^4N}{dM\,dq\,dz\,d\ln f_r}\, dM\,dq\,dz$$



Rajagopal & Romani 1995; Phinney 2001; Jaffe & Backer 2003; Wyithe & Loeb 2003; Sesana 2008, 2010, 2013

LZK+2017a, 2017b, 2018

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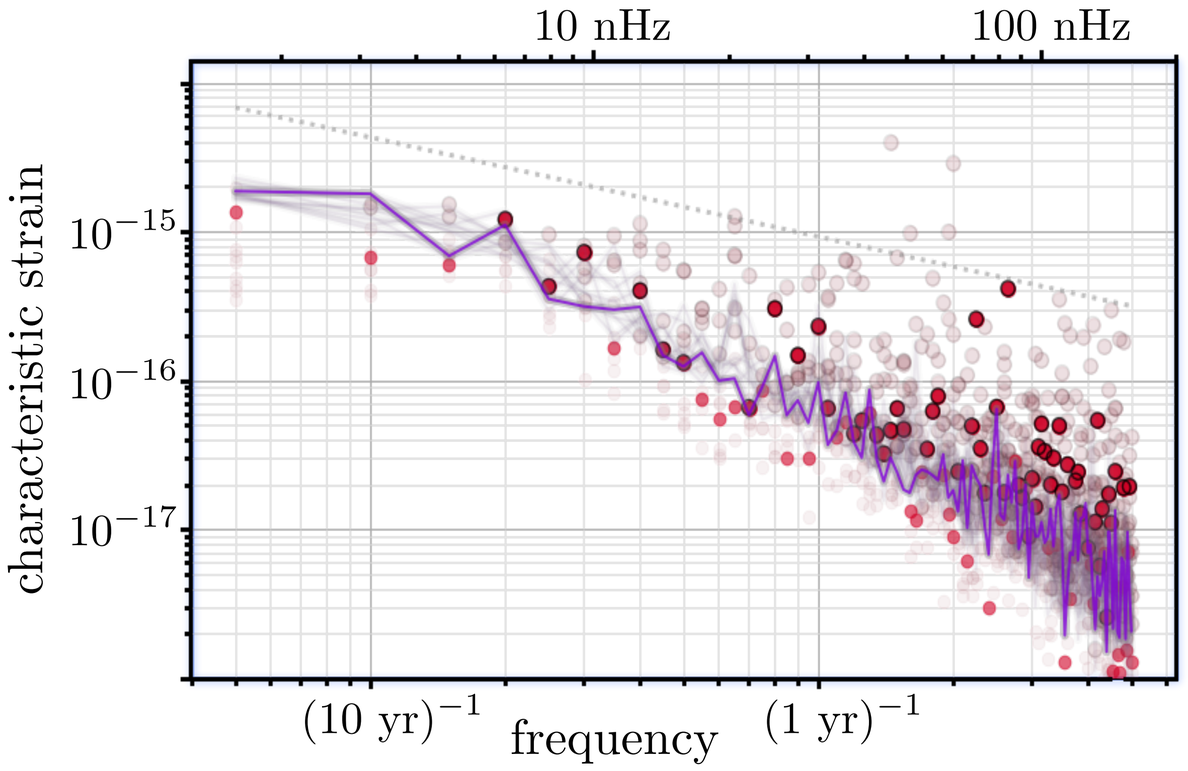

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GW Background

$$
\begin{aligned}
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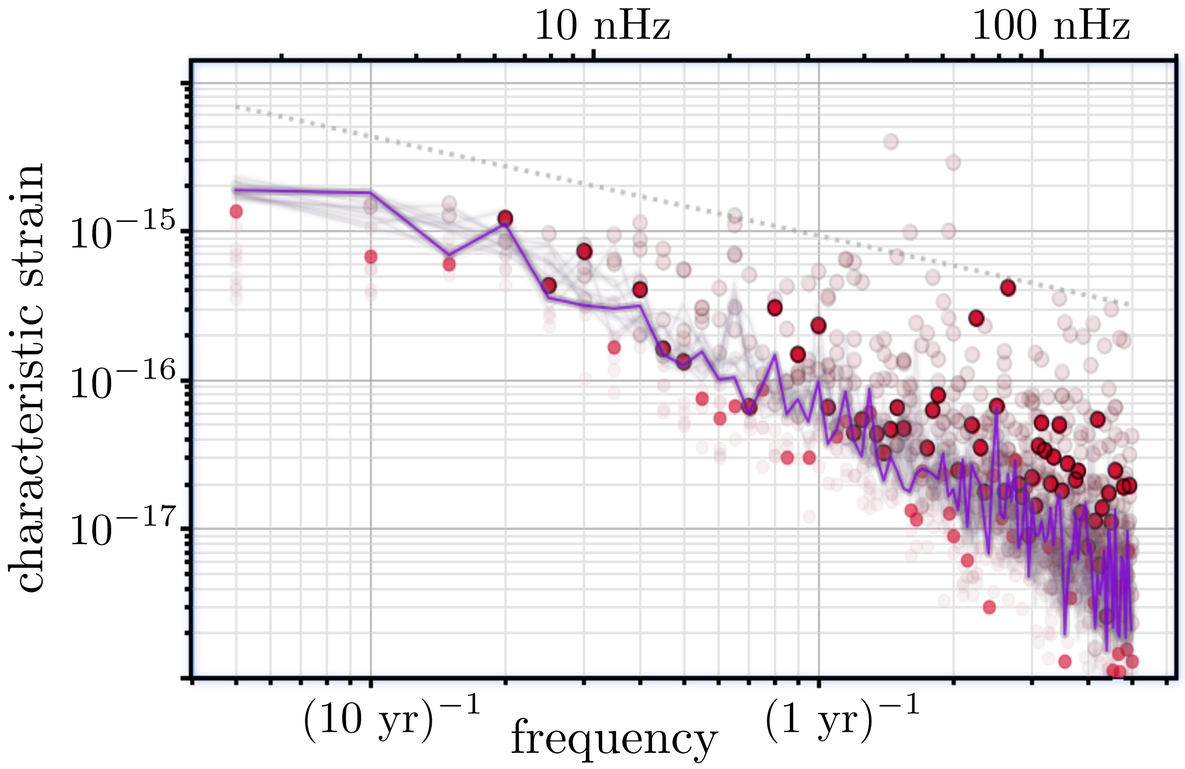
&= \int h^2(f_r) \frac{d^3n}{dM\,dq\,dz} \frac{dt}{d\ln f_r} \frac{dV}{dz} \frac{dz}{dt}\,dM\,dq\,dz \\
&= \int h^2(f_r)\,\frac{d^3n}{dM\,dq\,dz}\,\frac{f_r}{df_r/dt}\,4\pi c\,d_c^2\,(1+z)\,dM\,dq\,dz
\end{aligned}
$$



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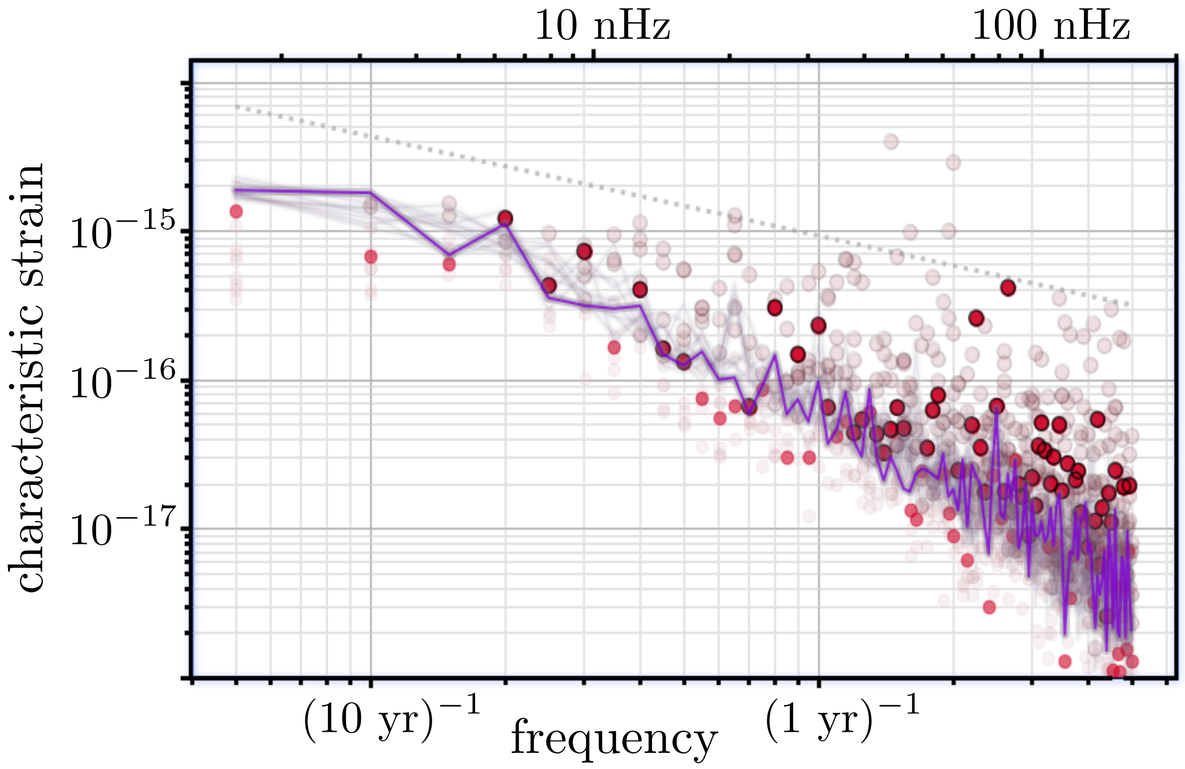

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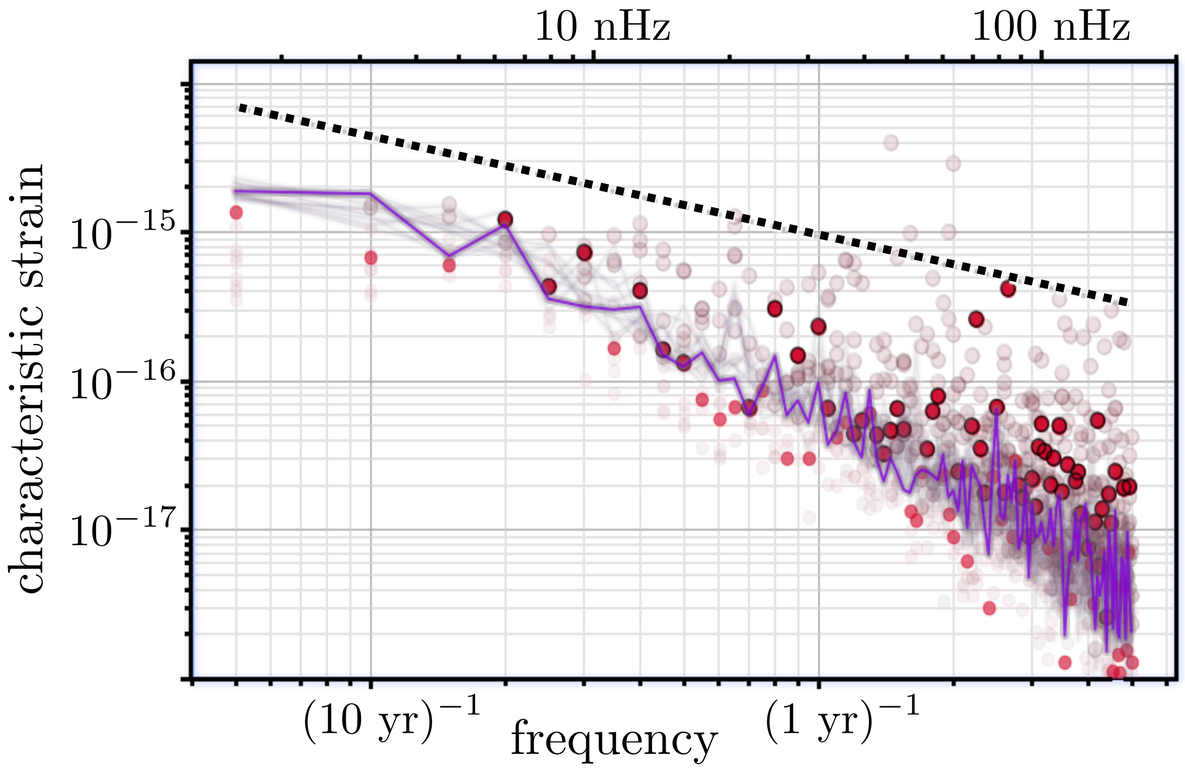
continuous GW–only

$$h_c(f) = A_0 \left(\frac{f}{f_0}\right)^{\gamma}$$

$$\gamma = -\frac{2}{3}$$

$$f_0 = 1\,\mathrm{yr}^{-1} \rightarrow A_0 \approx 10^{-15}$$



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population: continuous

evolution: GW–only

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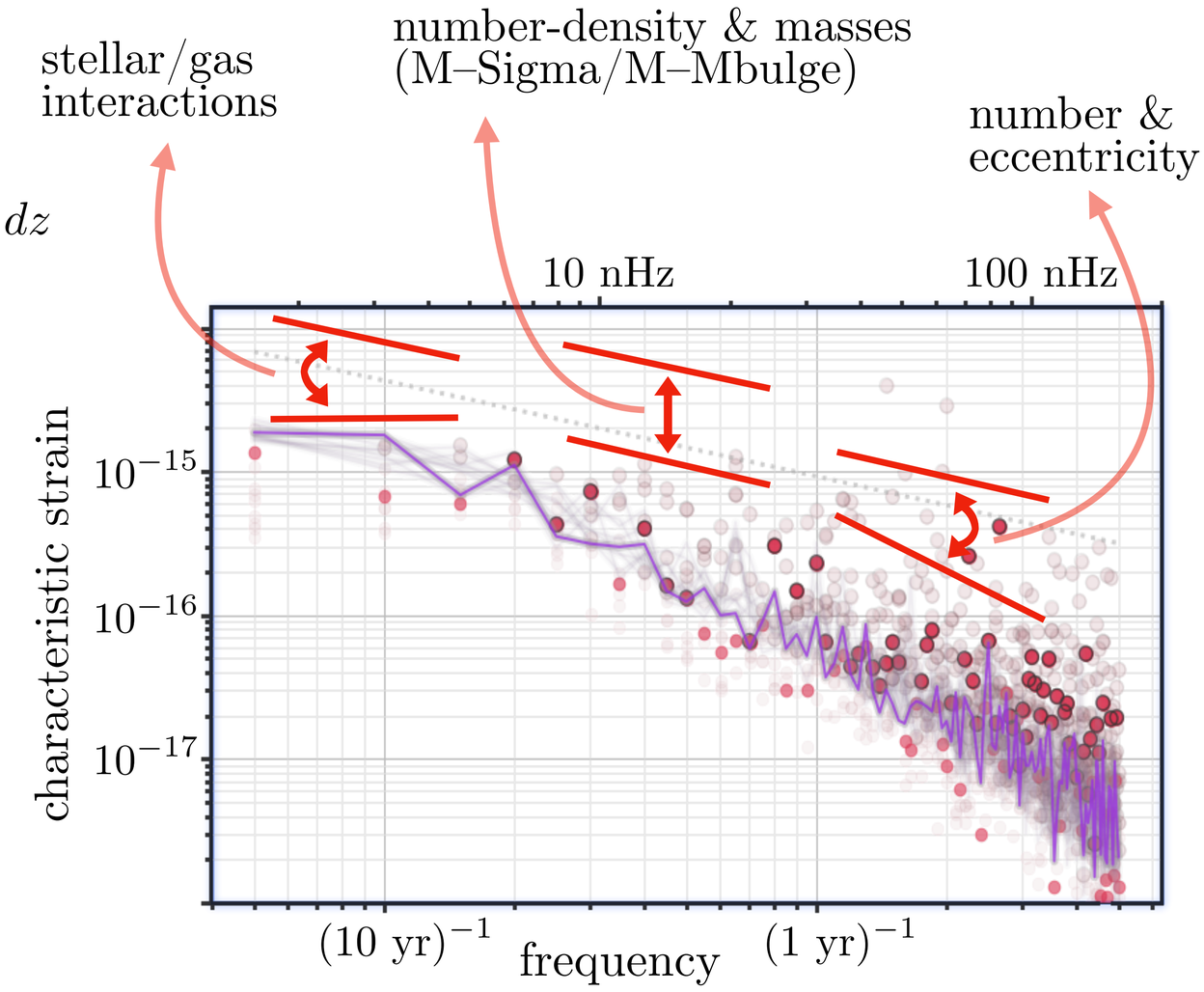

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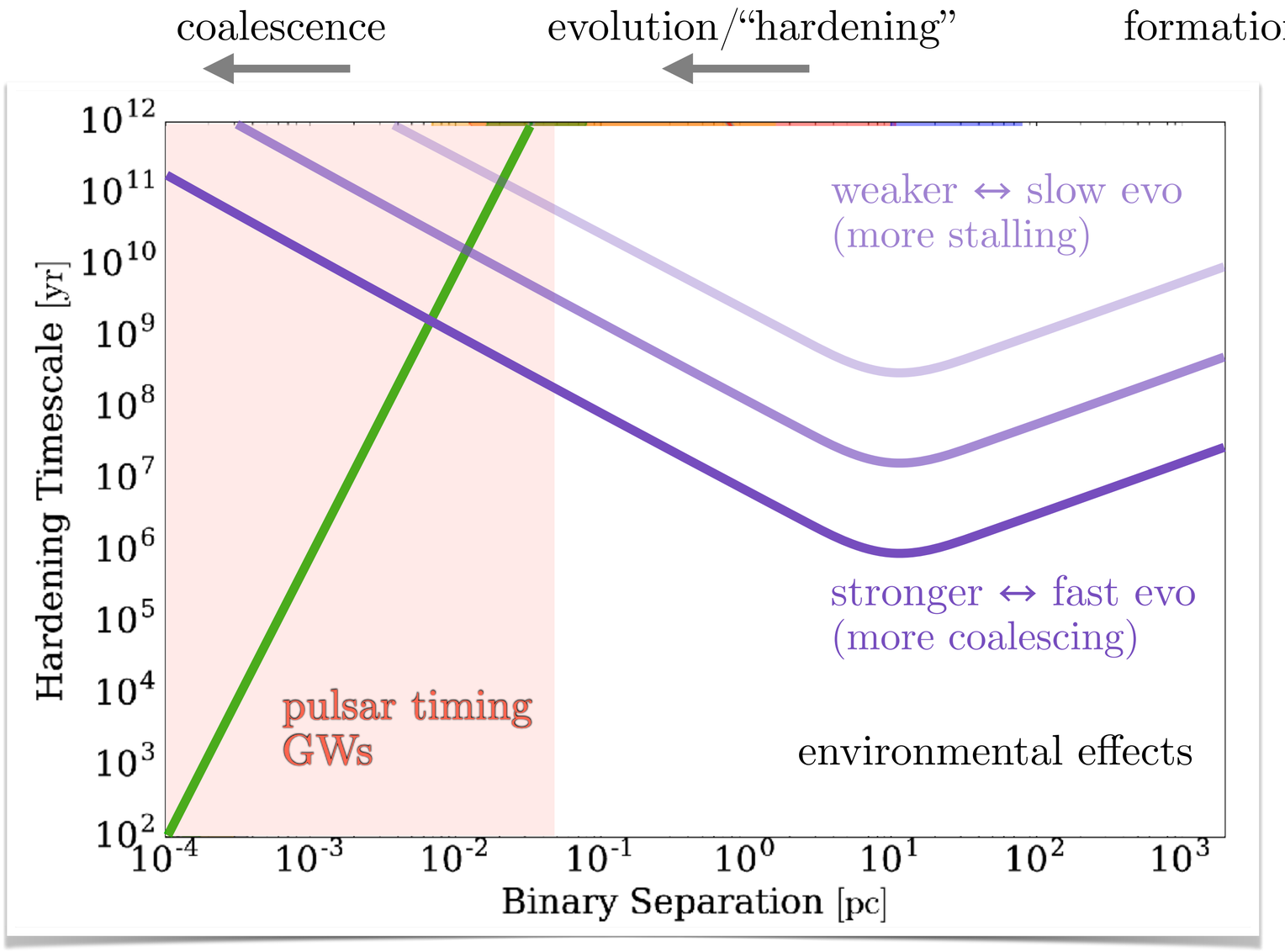
MBH Binary Evolution



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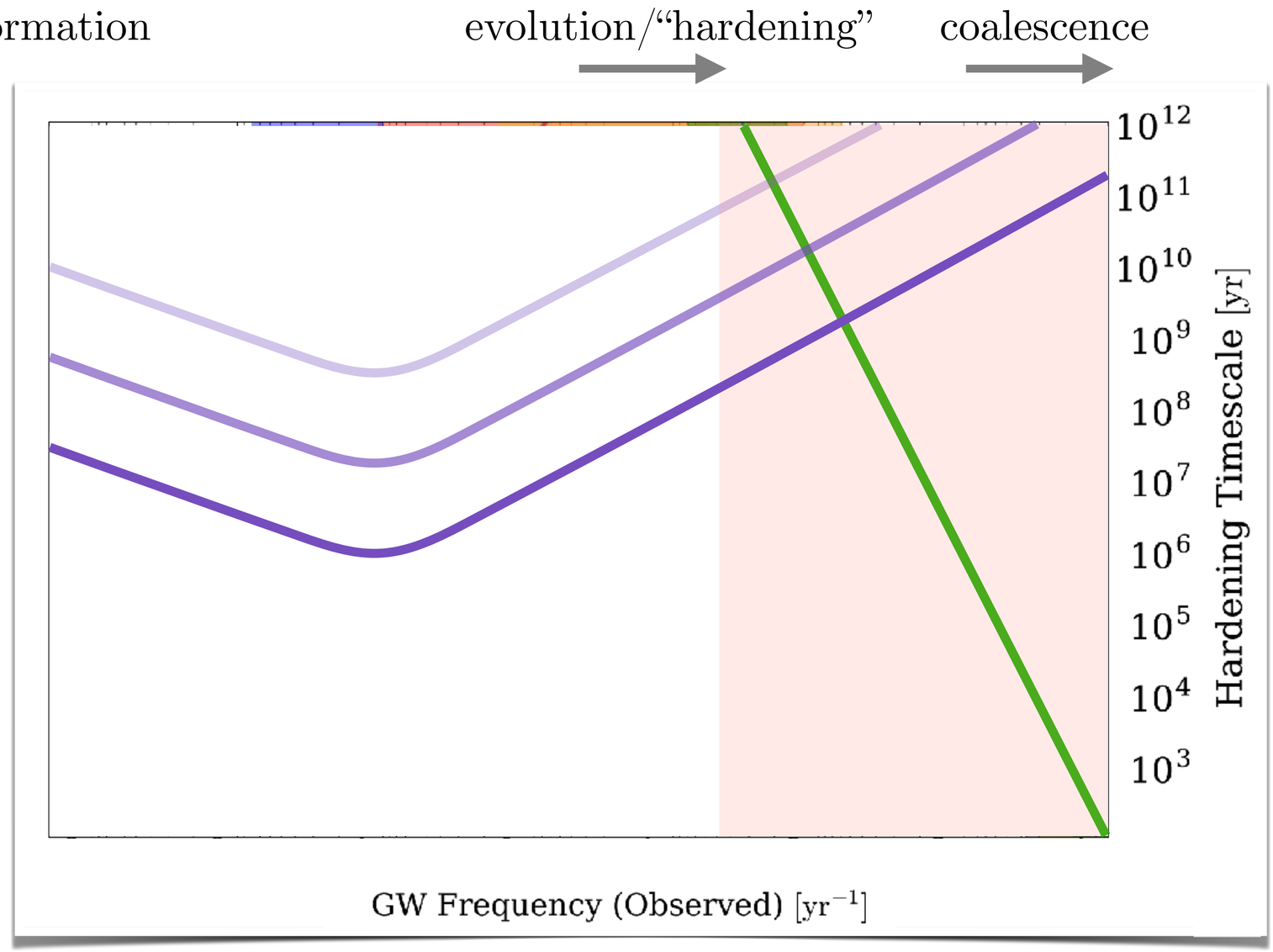

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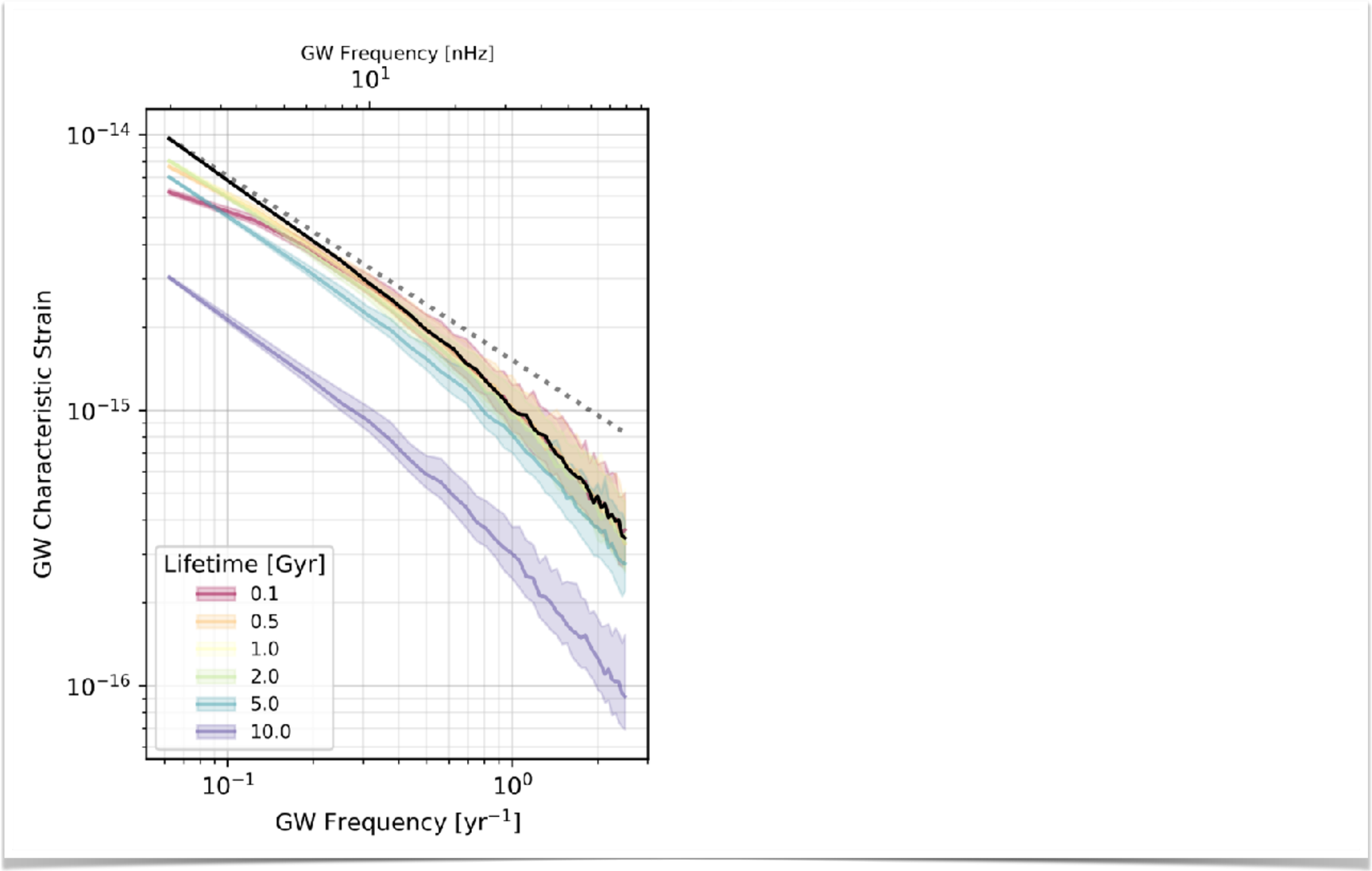
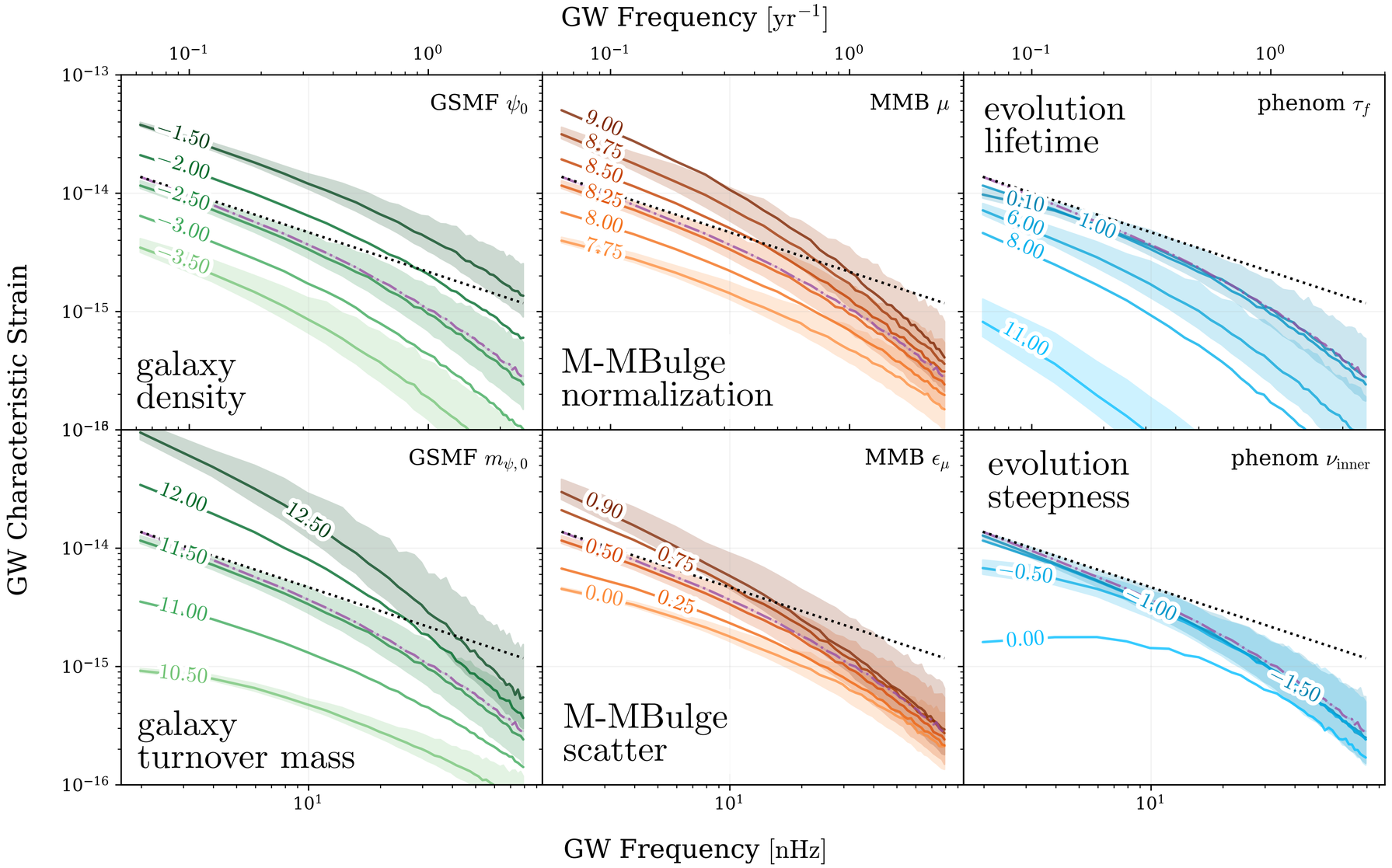


Agazie+2023 (SMBH binaries)

MBH Binary Landscape



from Kayhan Gültekin | Agazie+2023 (SMBH binaries)

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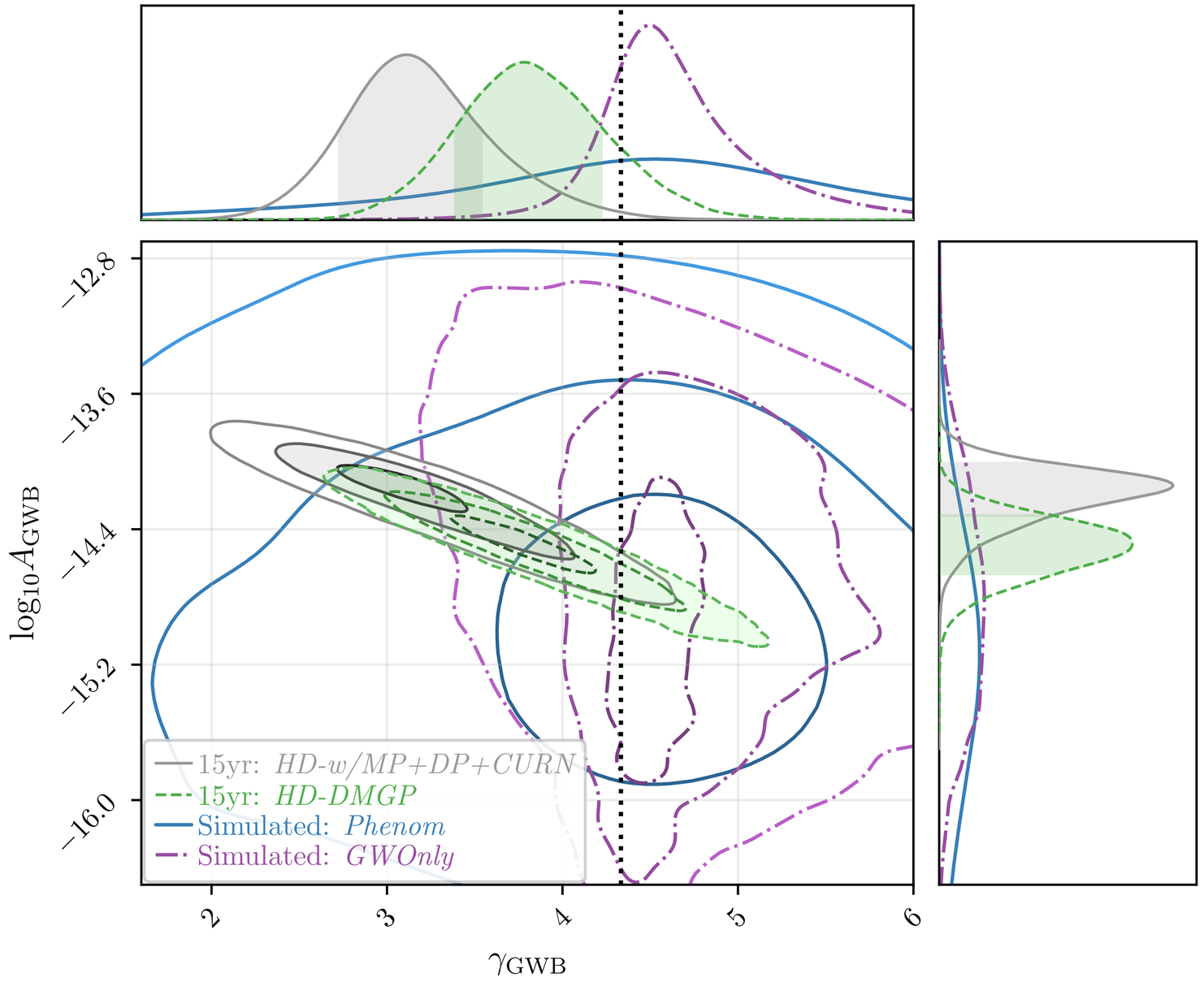
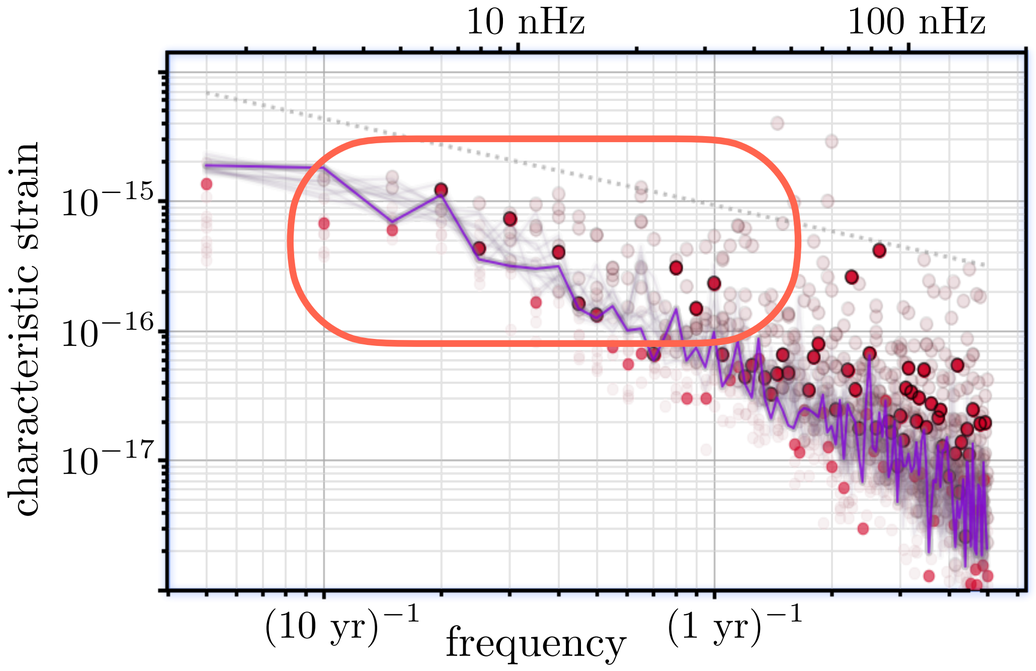


from Joe Simon | Agazie+2023g (SMBH binaries)

Single Binaries & Anisotropy



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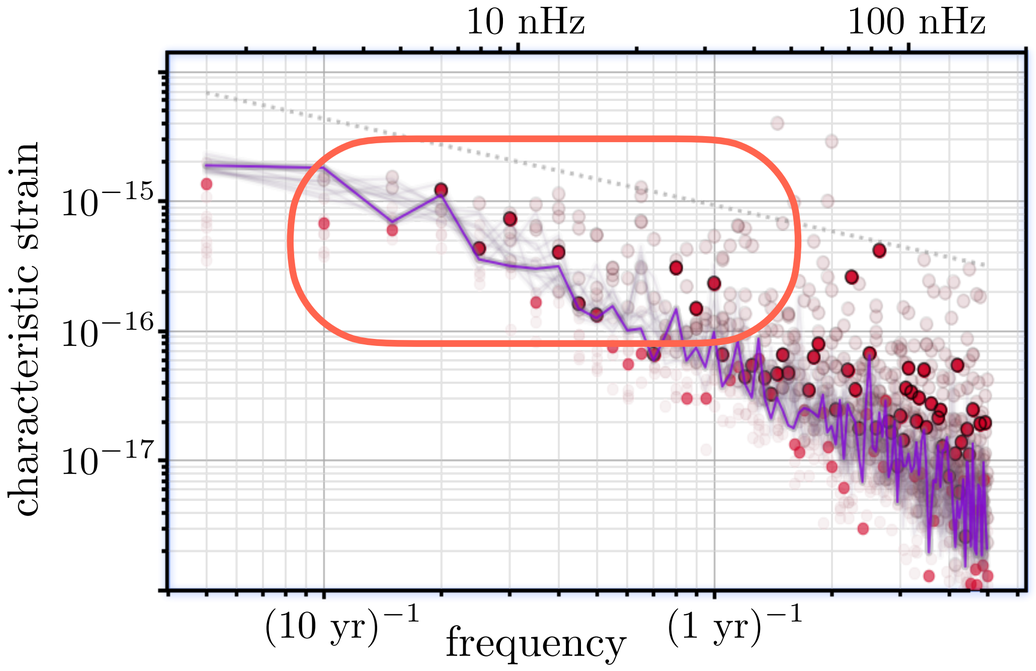

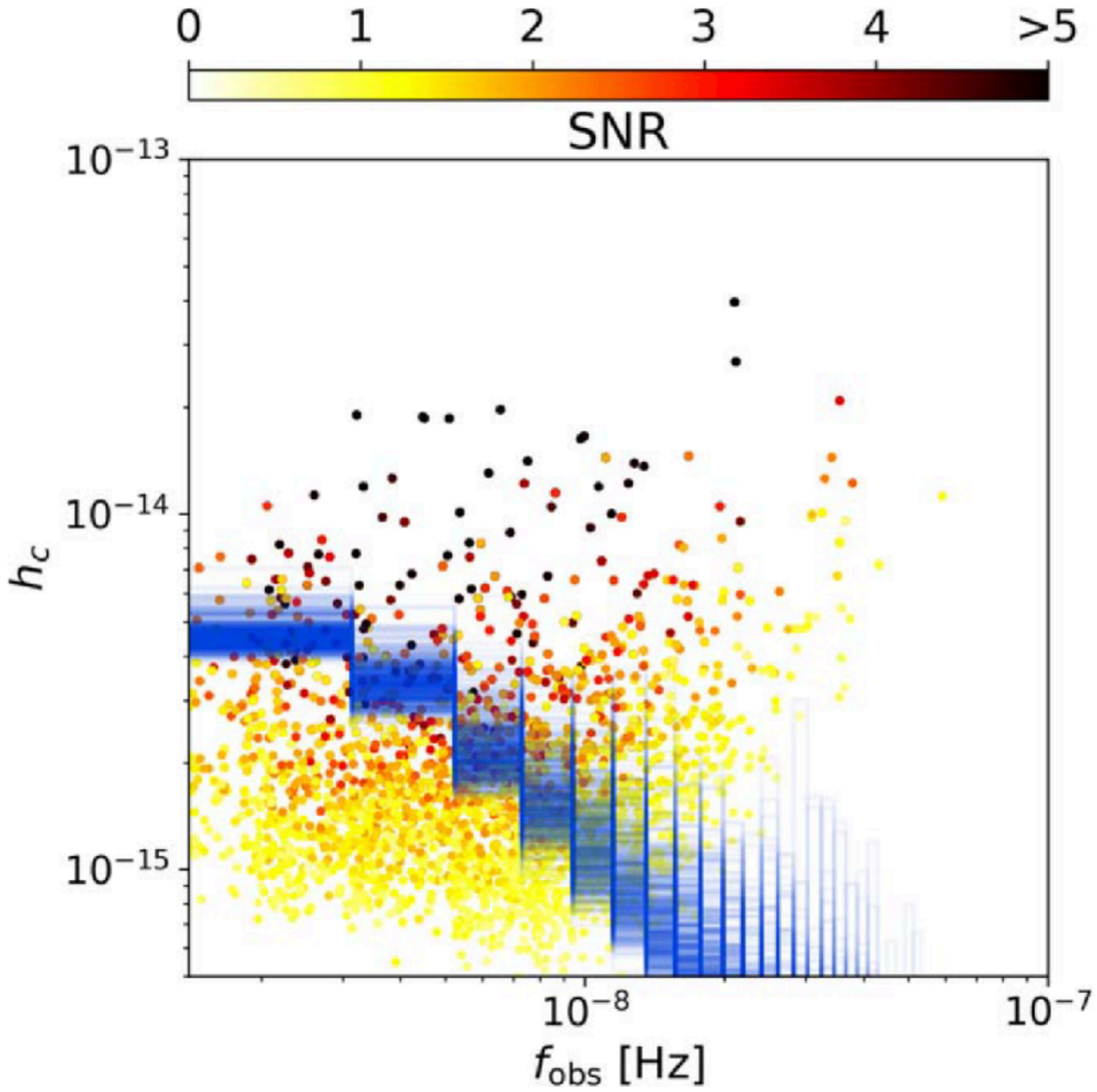

Bécsy, Cornish, LZK 2022
Bécsy+ *in prep*

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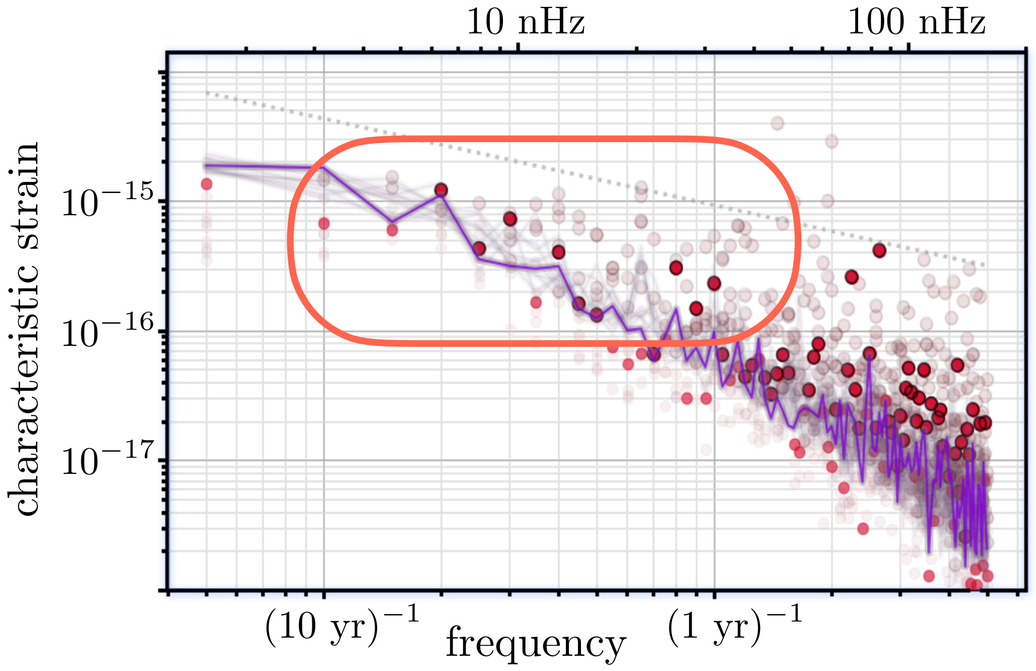

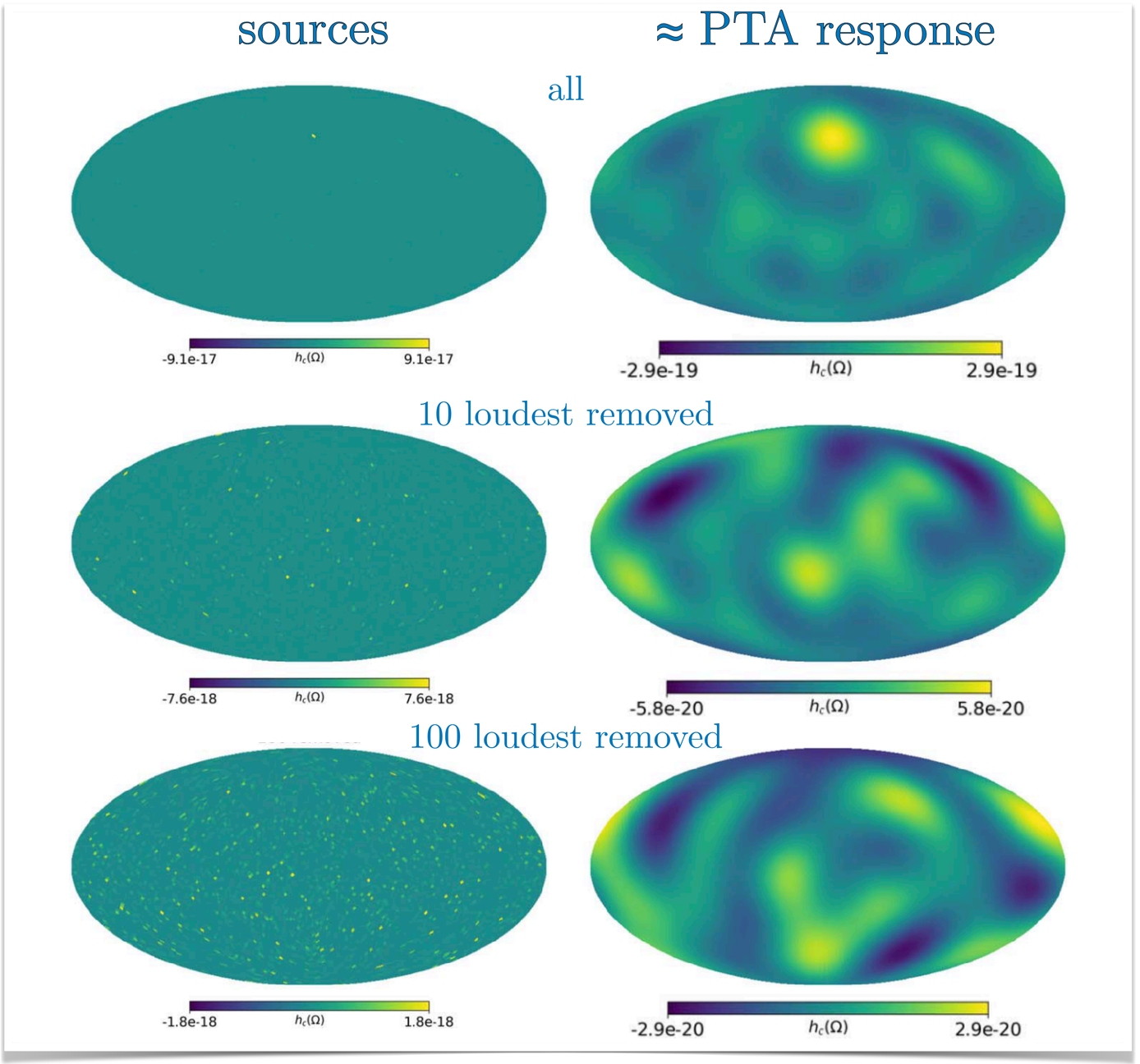

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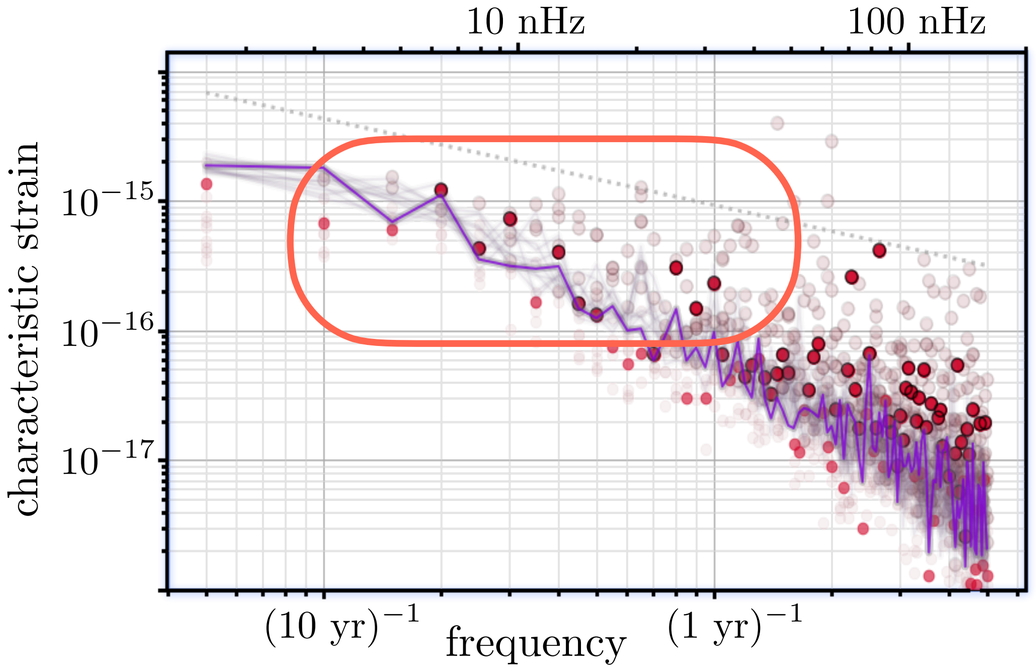

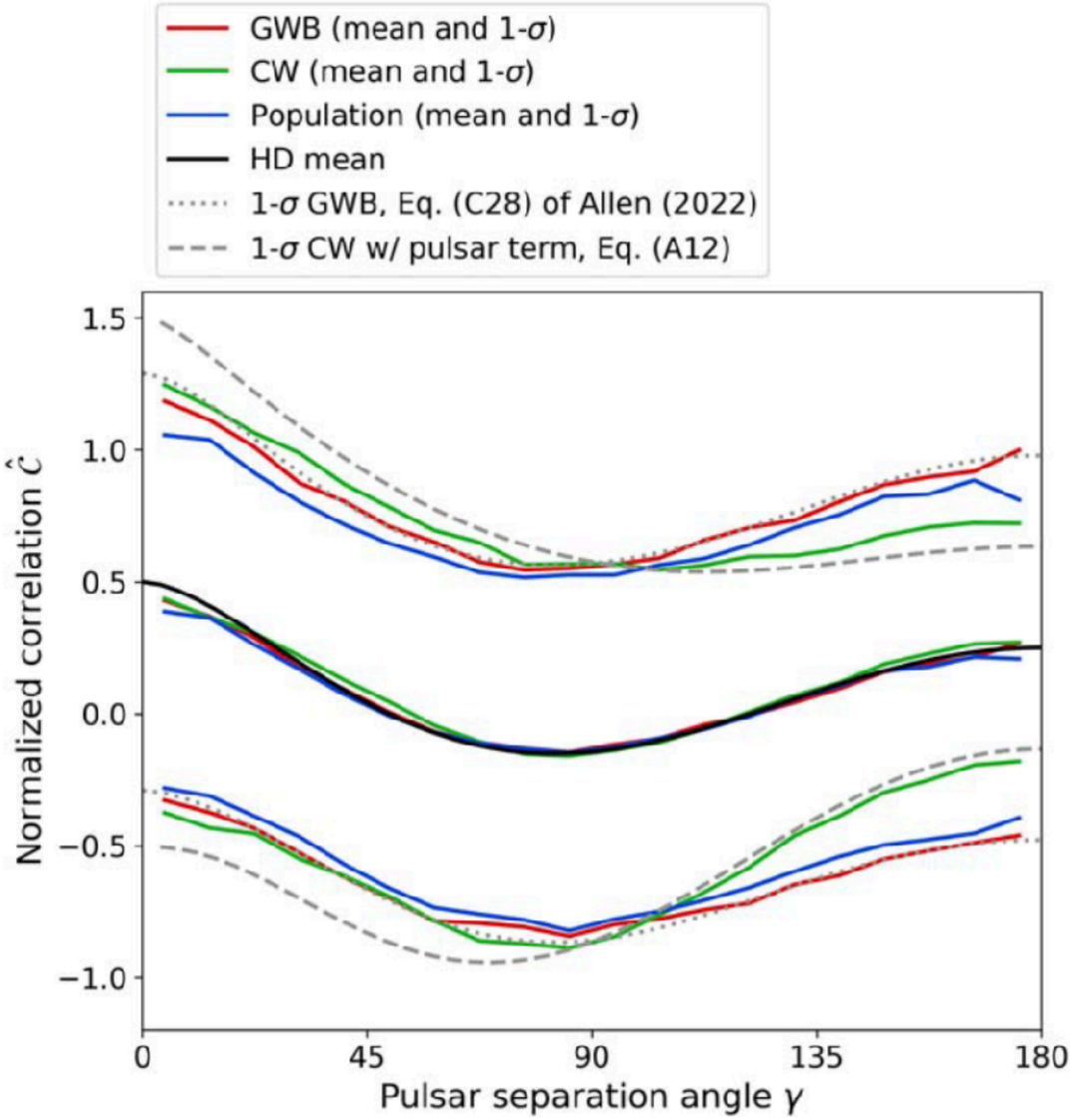

Bécsy, Cornish, LZK 2022
see also: Allen 2022

Single Binaries & Anisotropy

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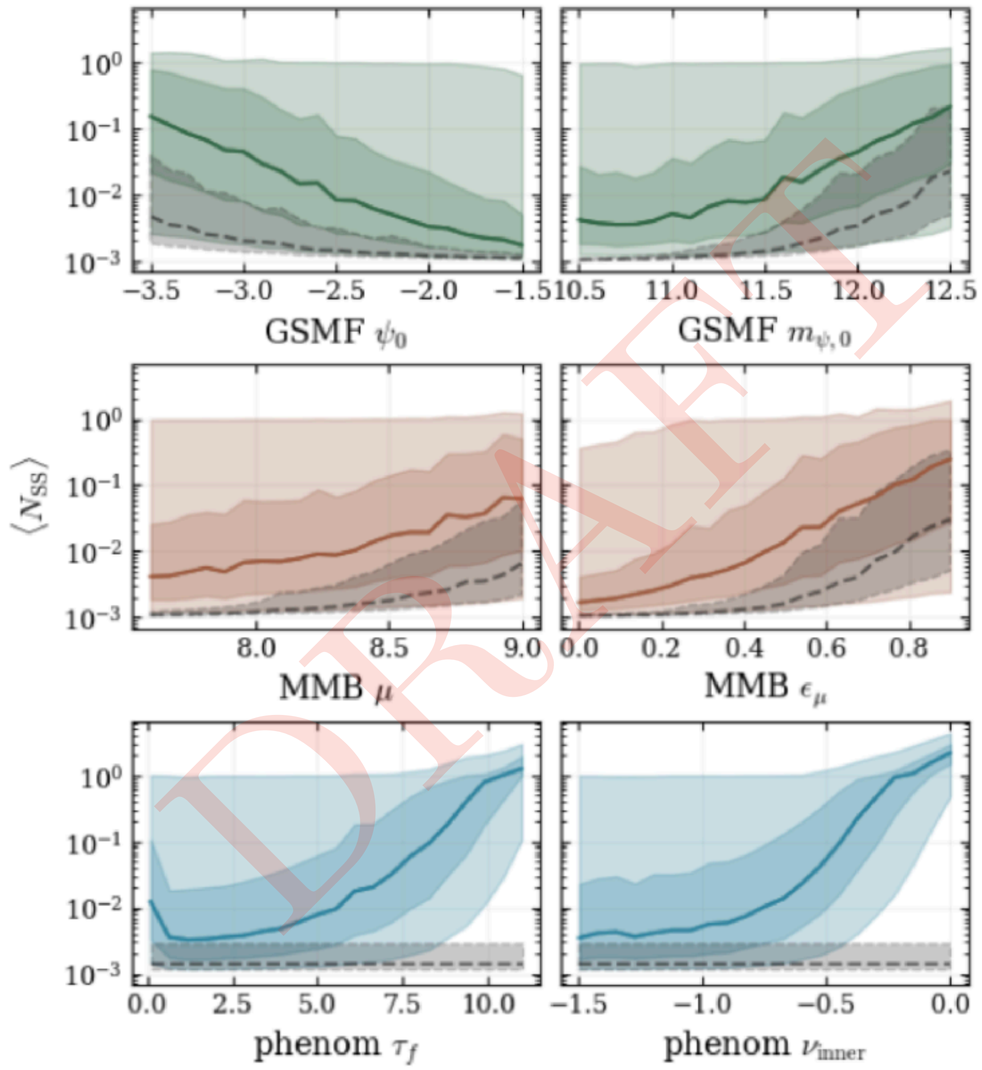

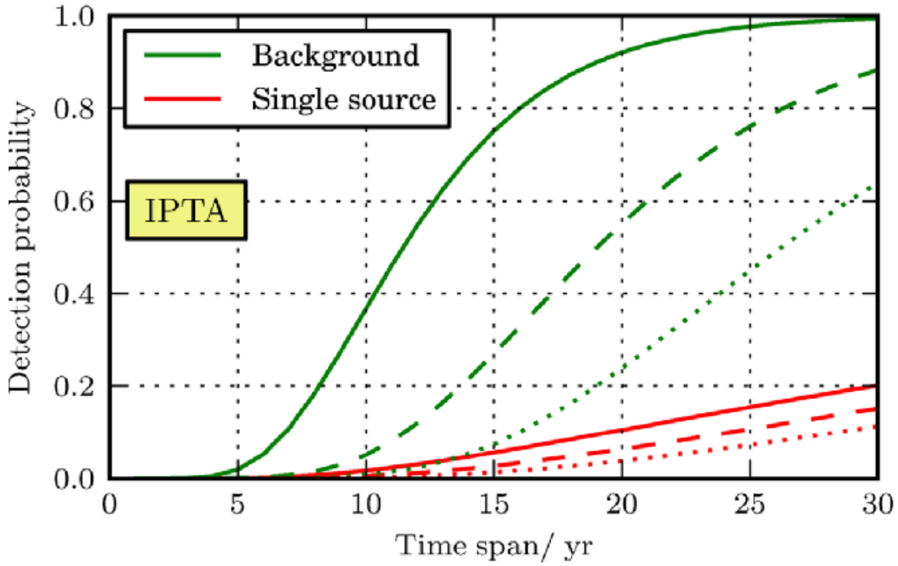

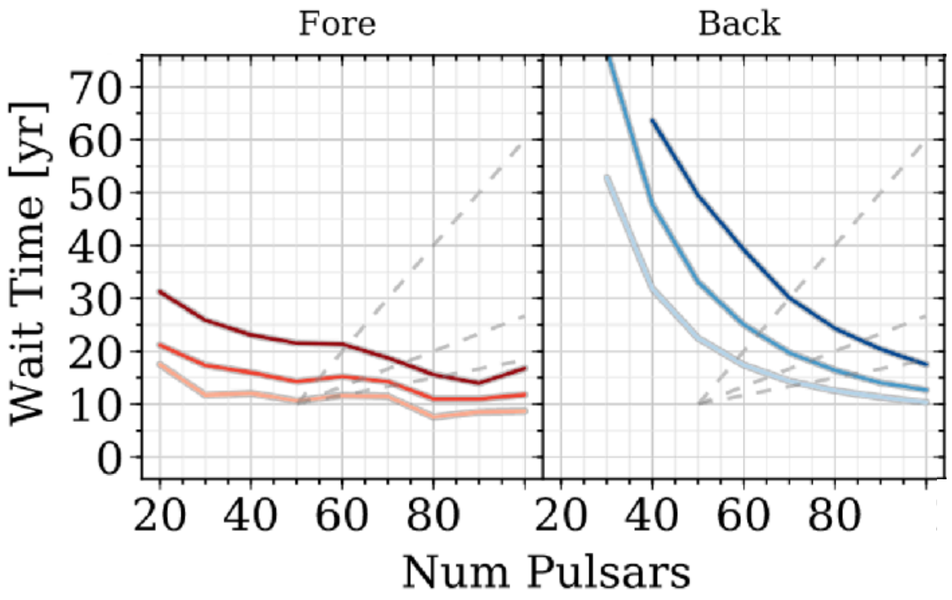

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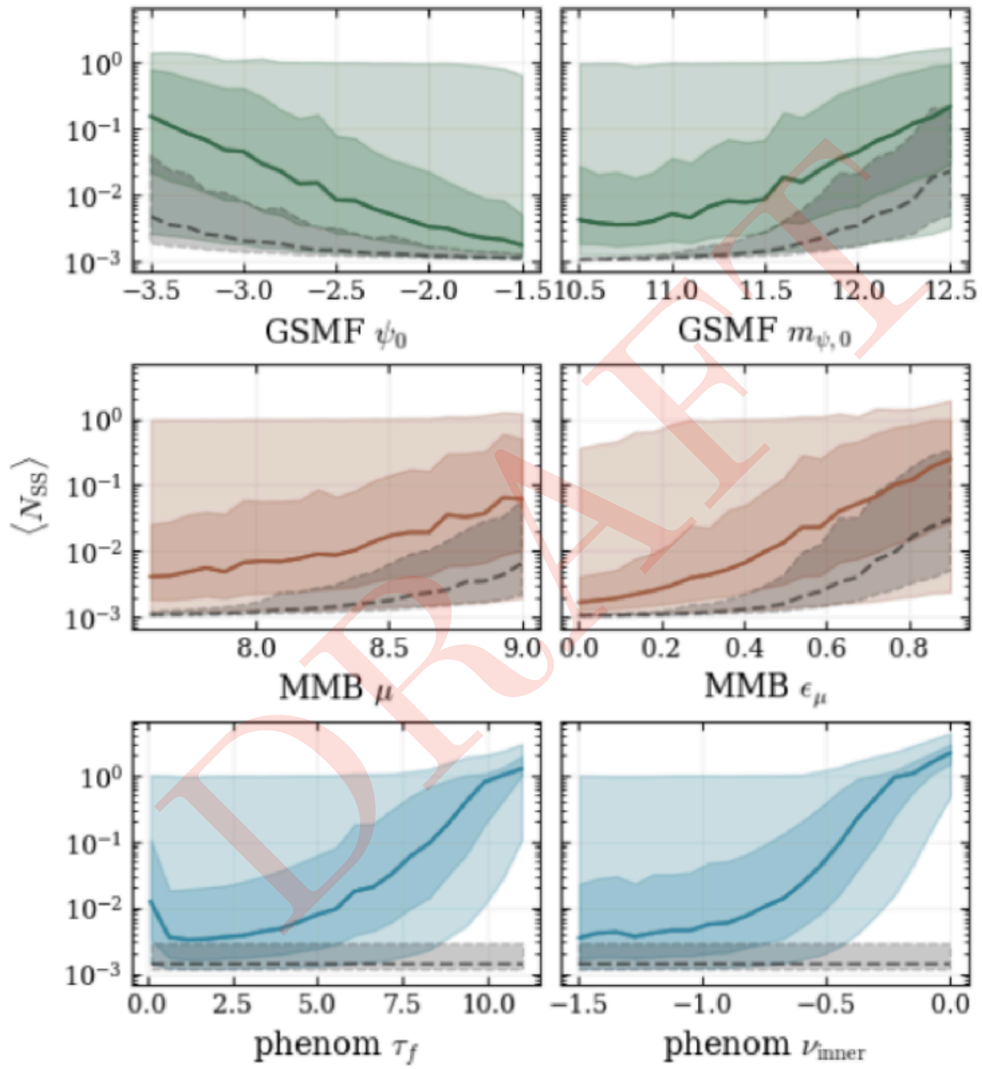
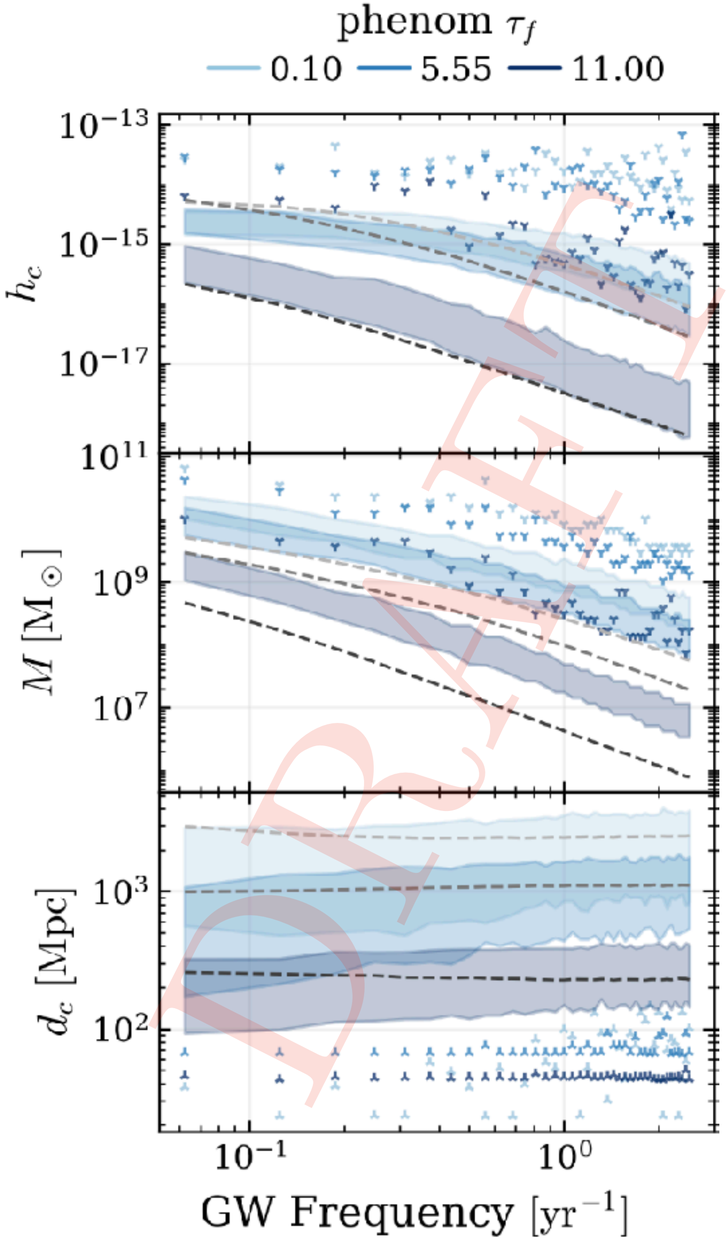
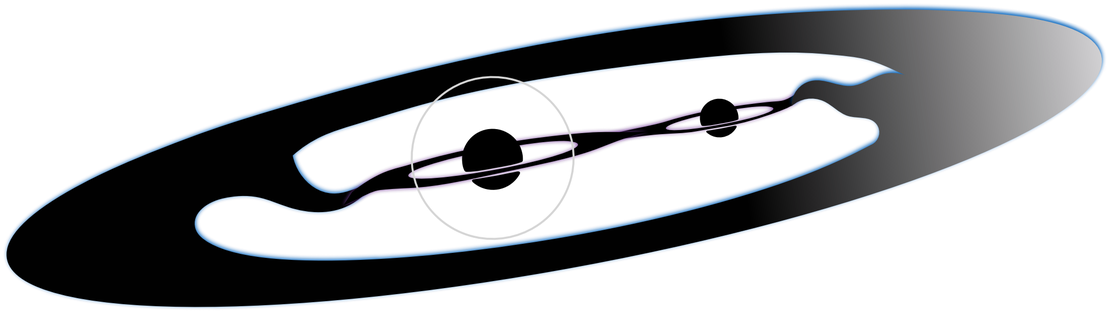


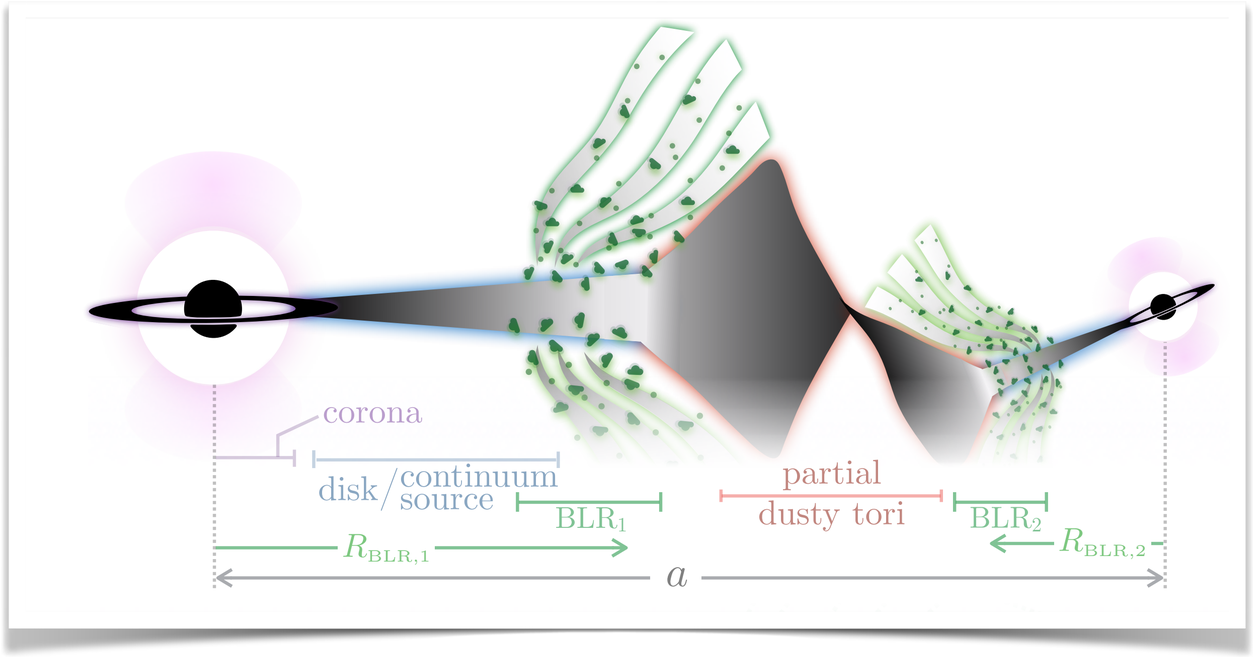


Emiko Gardiner, LZK+ *in prep*

Single Binaries & Anisotropy

- Electromagnetic Counterparts (zero confirmed to-date)
  reviews: Komossa (2006), Burke-Spolaor (2013),
  Bogdanovic (2015), De Rosa et al. (2019)
  - binary TDEs
  - photometric deficits
  - **periodic variability**
  - **kinematic/spectroscopic offsets**
  - **self–lensing**





LZK+2021, 2022b, LZK 2021

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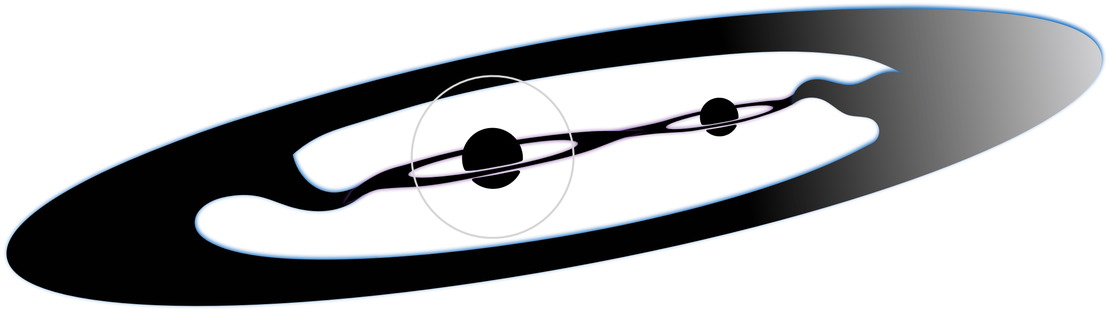
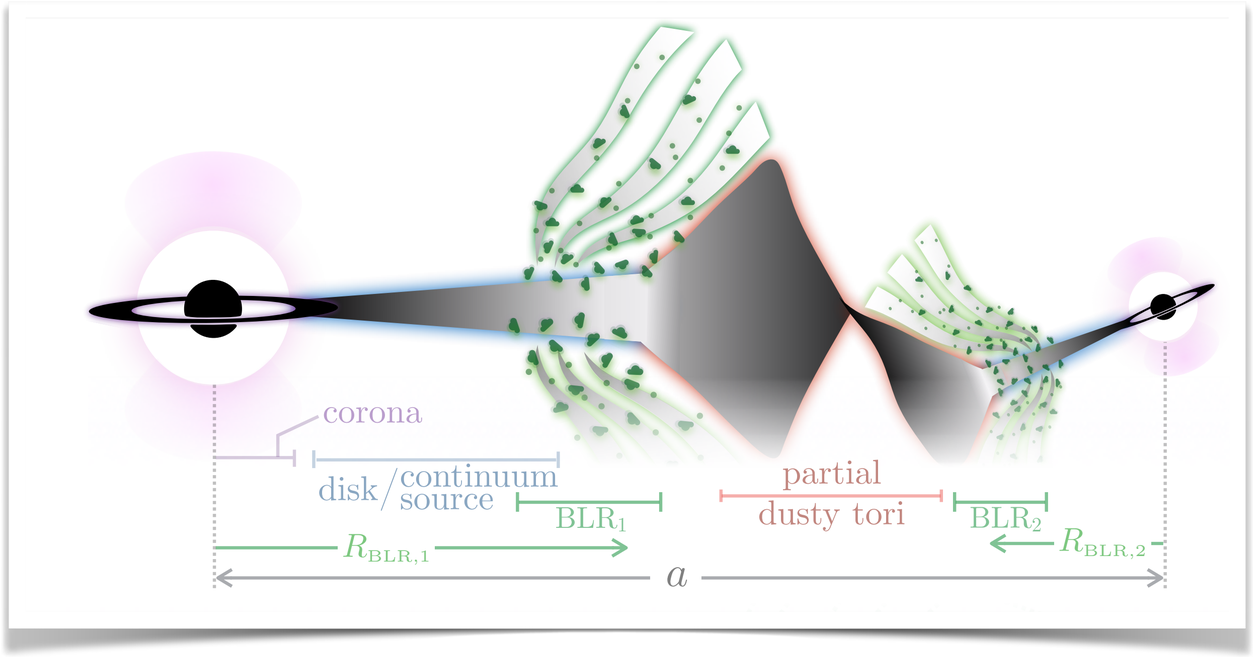


- Significant multi-messenger discovery space
  (see: NANOGrav white-paper | LZK+2022a)
  - MBH binaries + environments
  - accretion, jets & emission around binaries
  - MBH–galaxy co-evolution
  - cosmological probes (e.g. standard sirens)



LZK+2021, 2022b, LZK 2021

Thanks!

Maria Charisi, Emiko Gardiner, Kayhan Gültekin, William Lamb,
Jessie Runnoe, Joe Simon, Jeremy Wachter, David Wright, & NANOGrav et al.

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