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Stochastic gravitational-wave backgrounds from astrophysical sources

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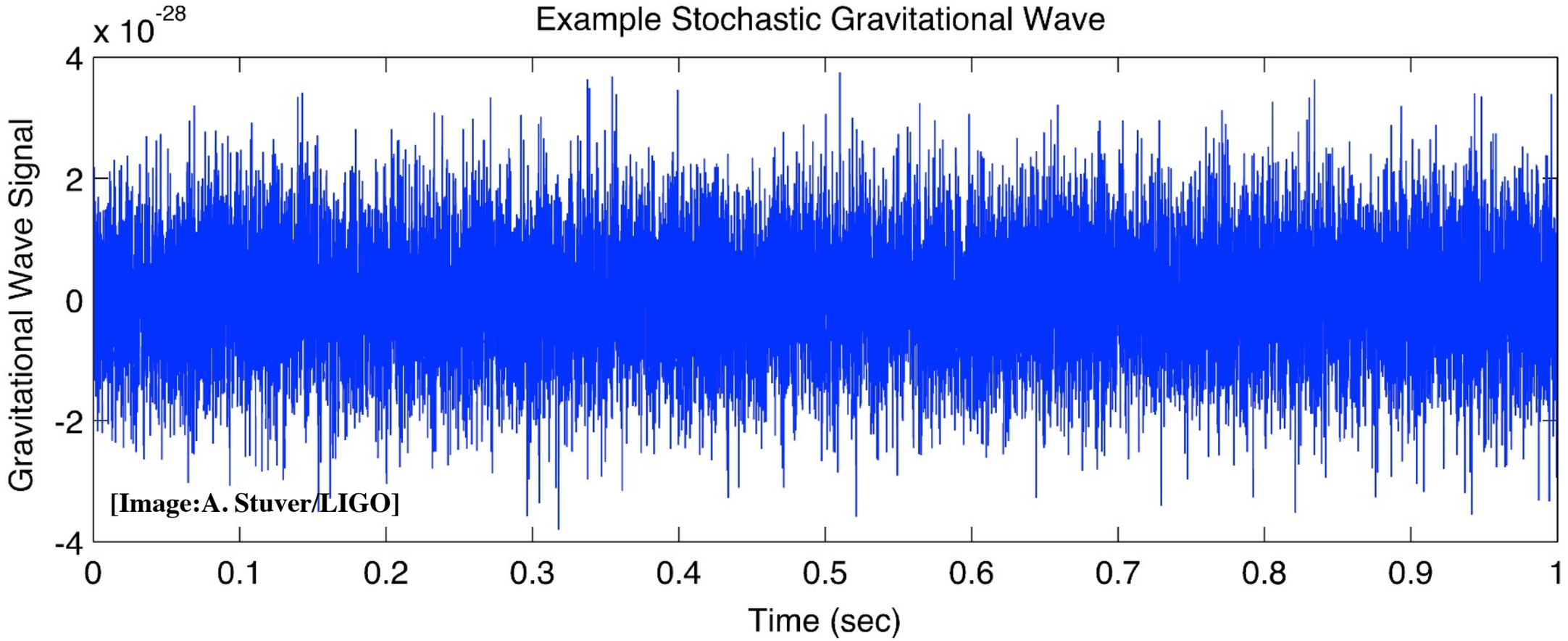
Intro: Stochastic gravitational-wave backgrounds

- **Cosmological**: intrinsically stochastic signal
  - Inflation
  - First order phase transitions
  - Cosmic strings

- **Astrophysical**: incoherent superposition of unresolved sources
  - Individual sources too faint
  - Individual sources overlap in time (confusion noise)

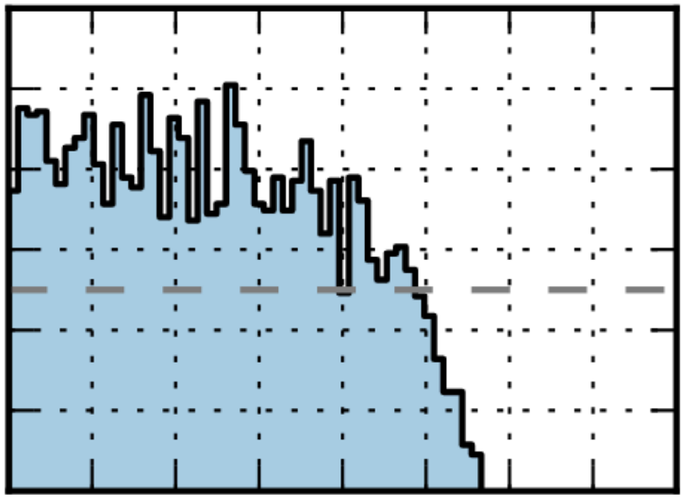


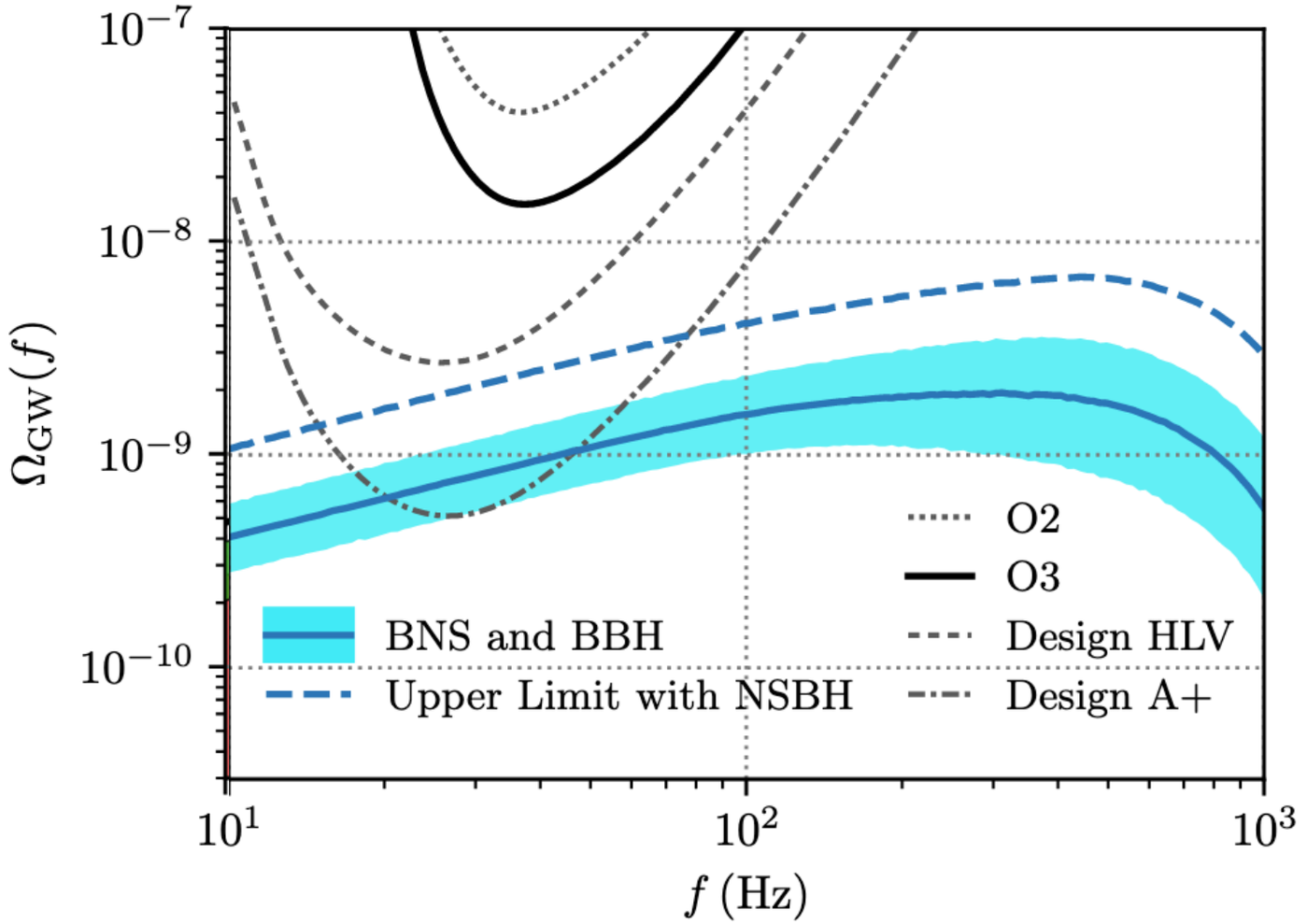
Current upper limits: LIGO/Virgo O1+O2+O3

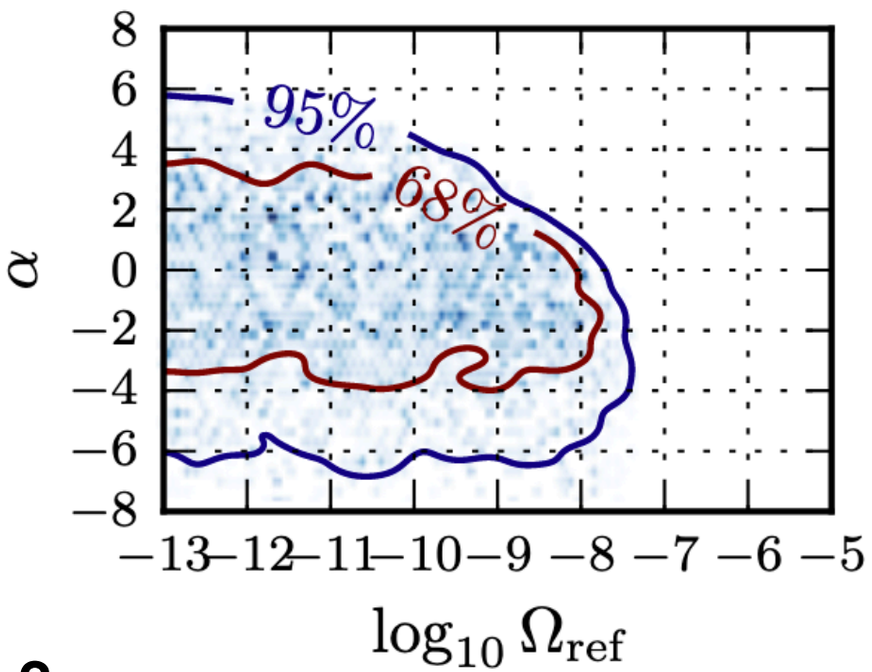
[LVK 2021]

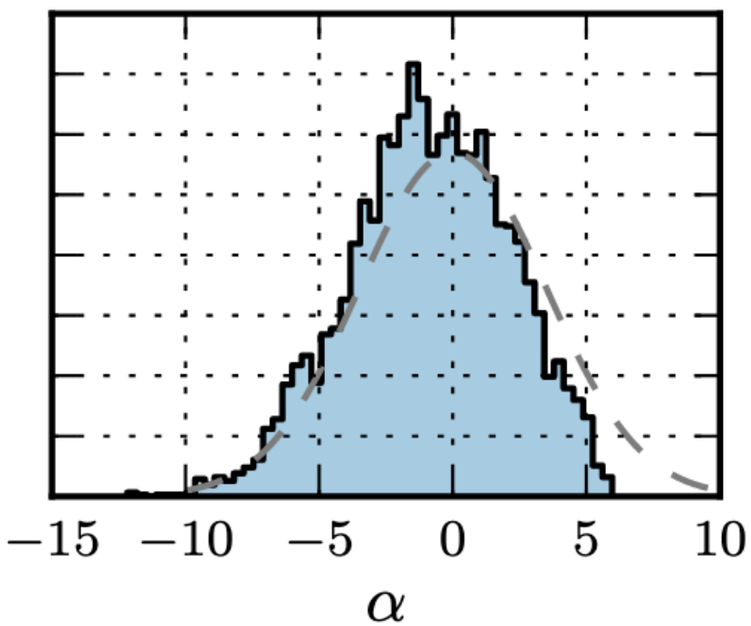
Power-law background:

$$\Omega_{\rm GW}(f) = \Omega_{\rm ref} \left(\frac{f}{f_{\rm ref}} \right)^{\alpha}$$









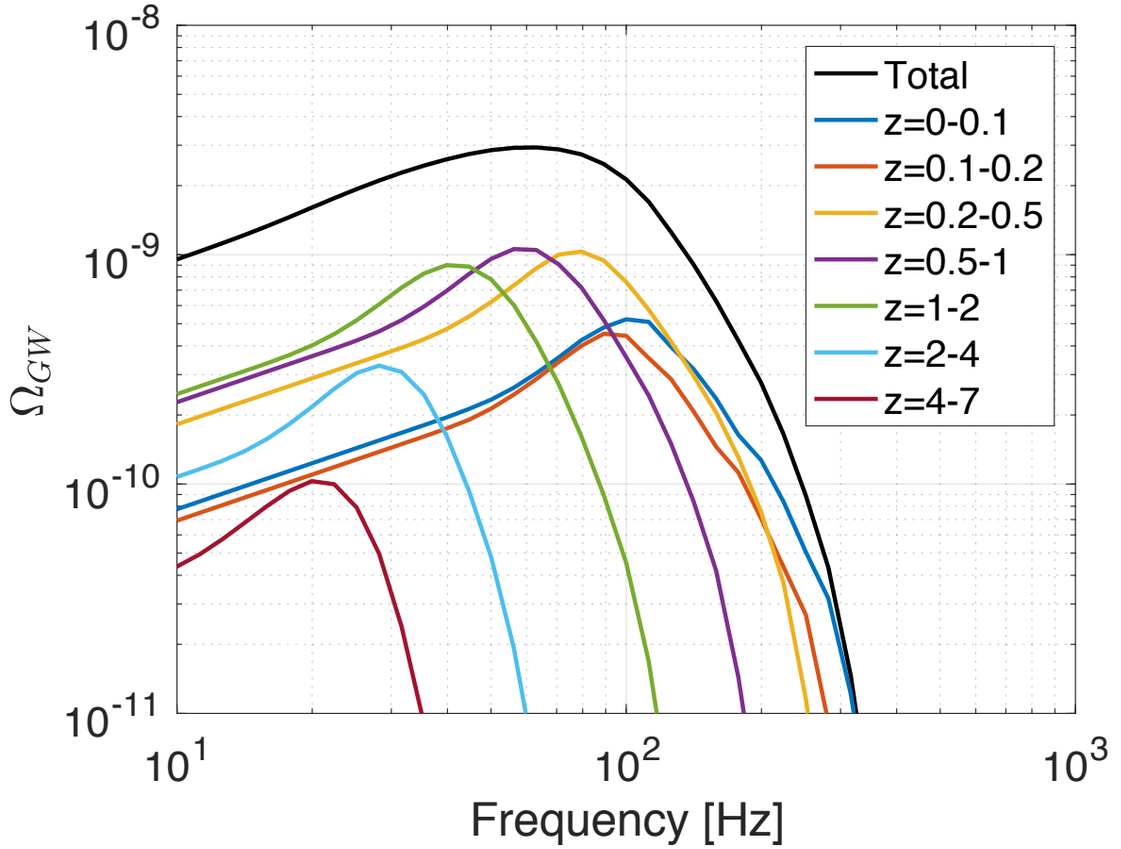
High frequency: stellar-mass binaries

- Energy density of the stochastic background:

$$\Omega_{\rm GW}(f;\theta_k) = \frac{f}{\rho_c H_0}\int_0^{z_{\rm max}} dz \frac{R_m(z;\theta_k)\frac{dE_{\rm GW}}{df}(f_s;\theta_k)}{(1+z)E(\Omega_M,\Omega_\Lambda,z)}$$

- Probe of high-redshift source population

Models from [Cusin, **ID**, Pitrou, Uzan (2019)]



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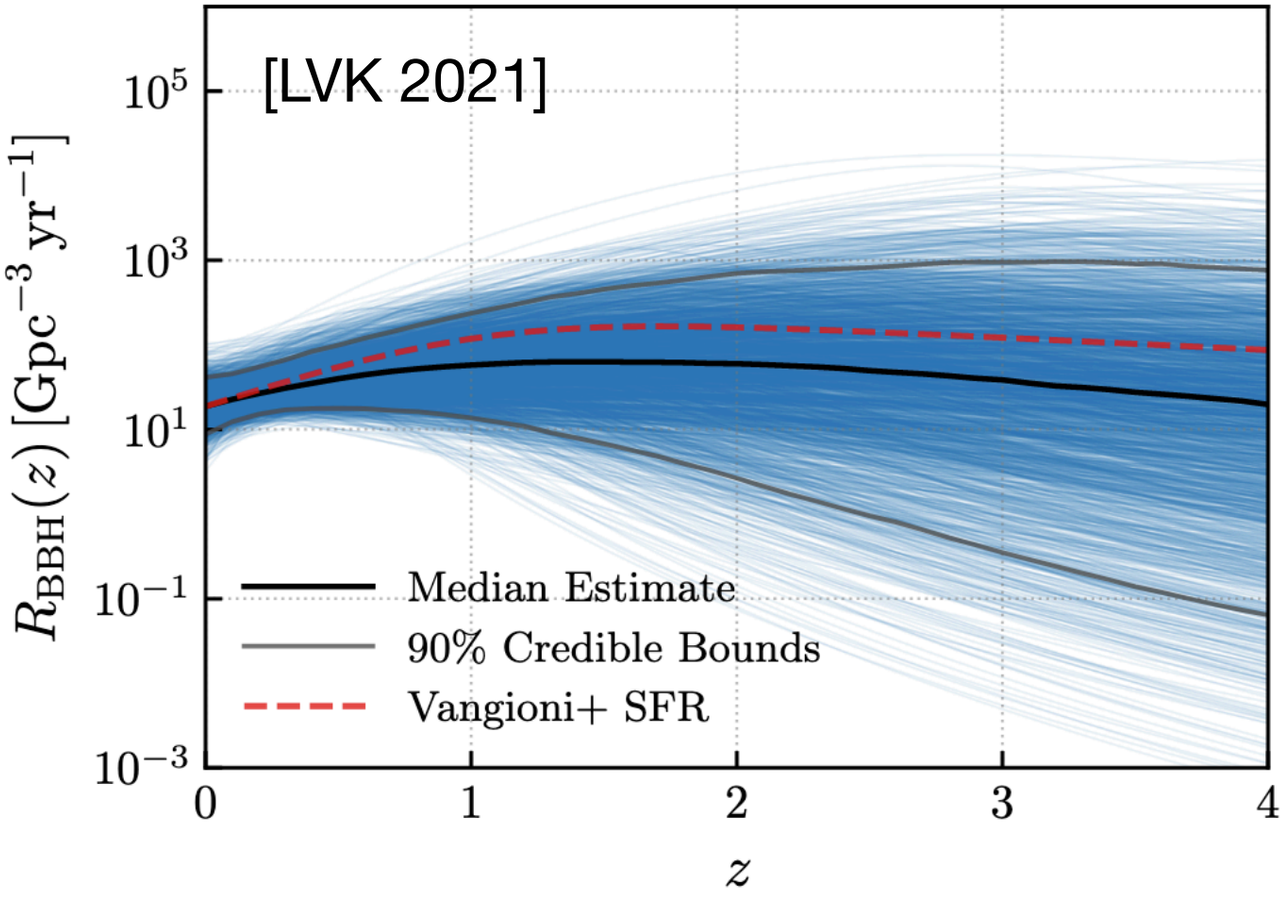

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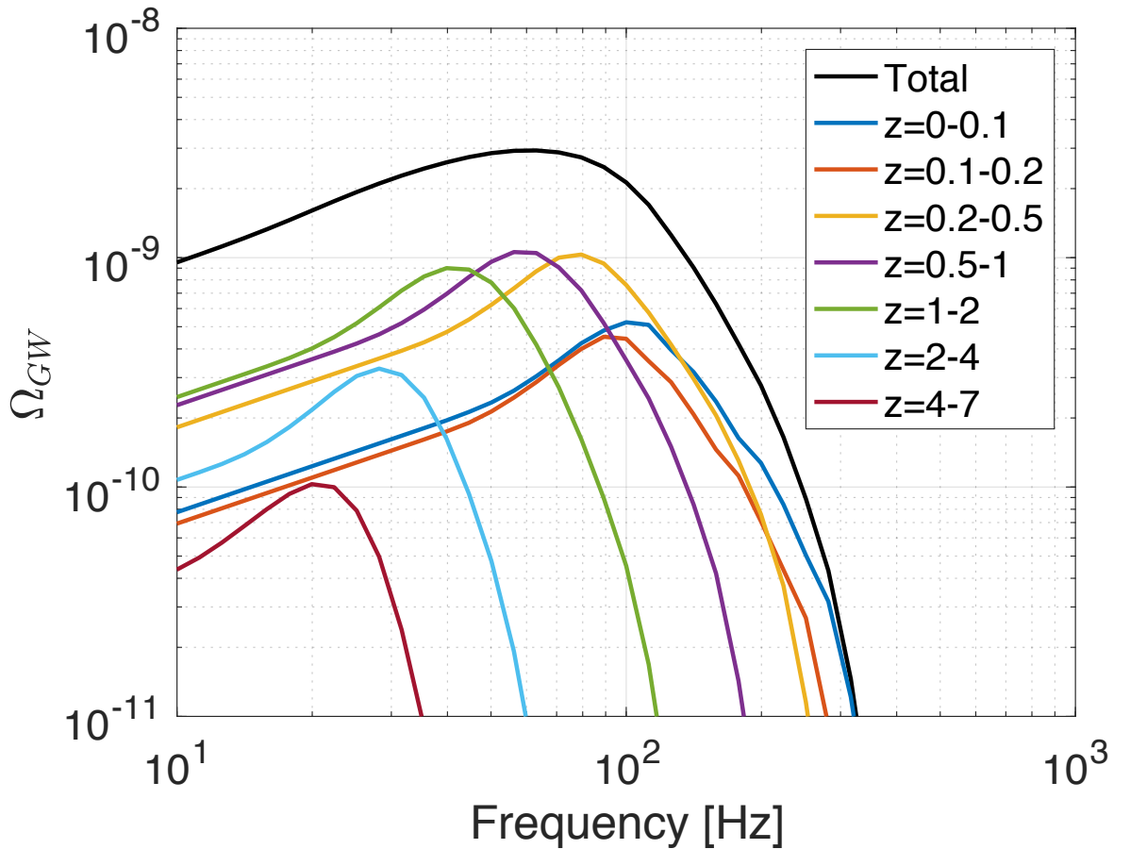
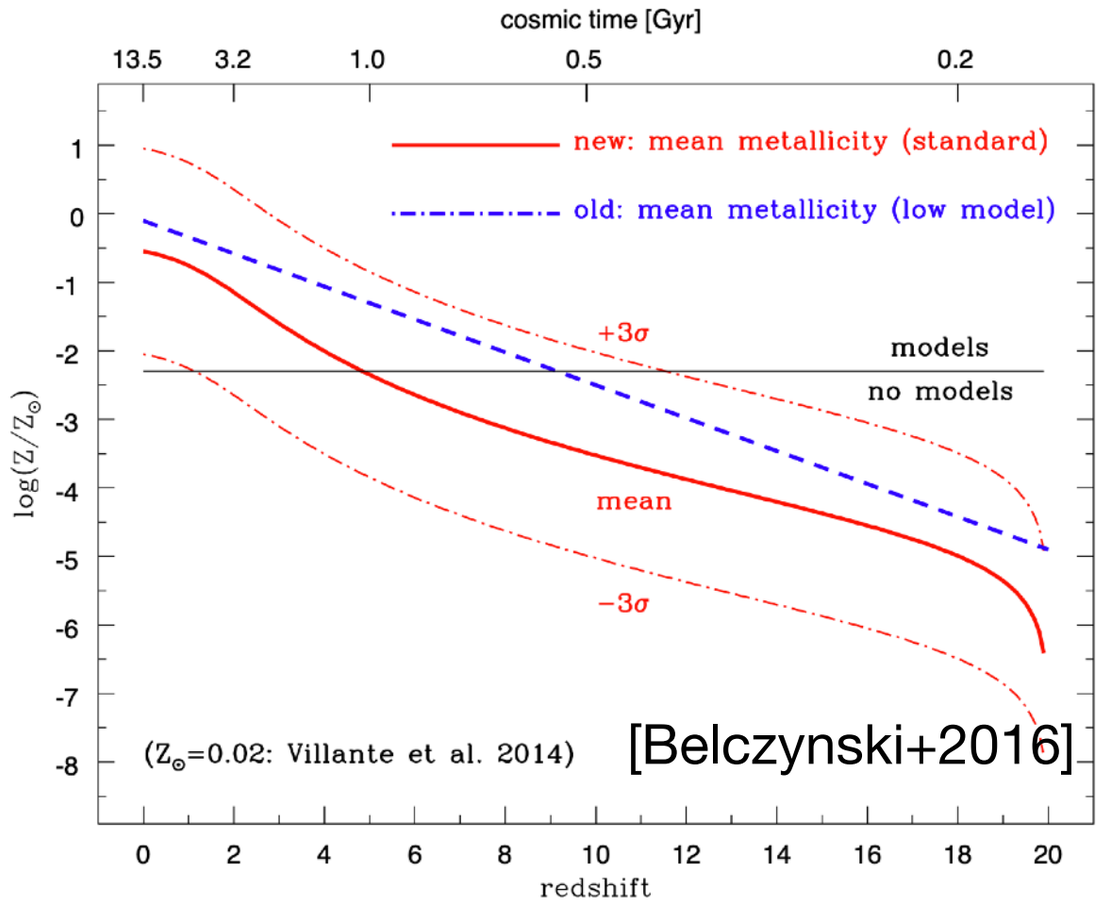


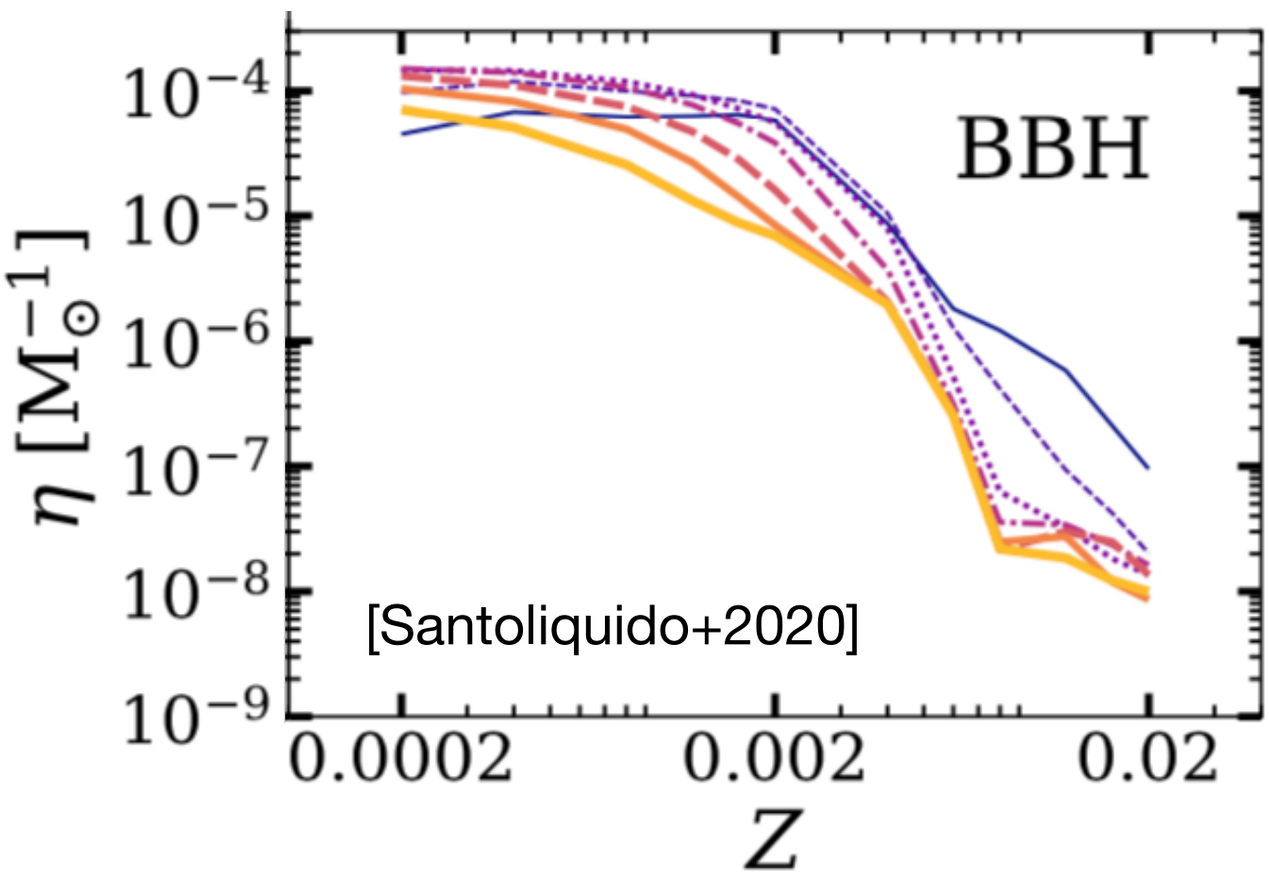
- Non-detection of stochastic background constrains high-z merger rate

See [Callister+2020]

High frequency: stellar-mass binaries

- Black hole mass depends on metallicity of progenitor star
  - High metallicity -> strong winds -> low BH mass
  - Metallicity evolves with time





- Metallicity evolves with time
  - Galactic mass-metallicity relation

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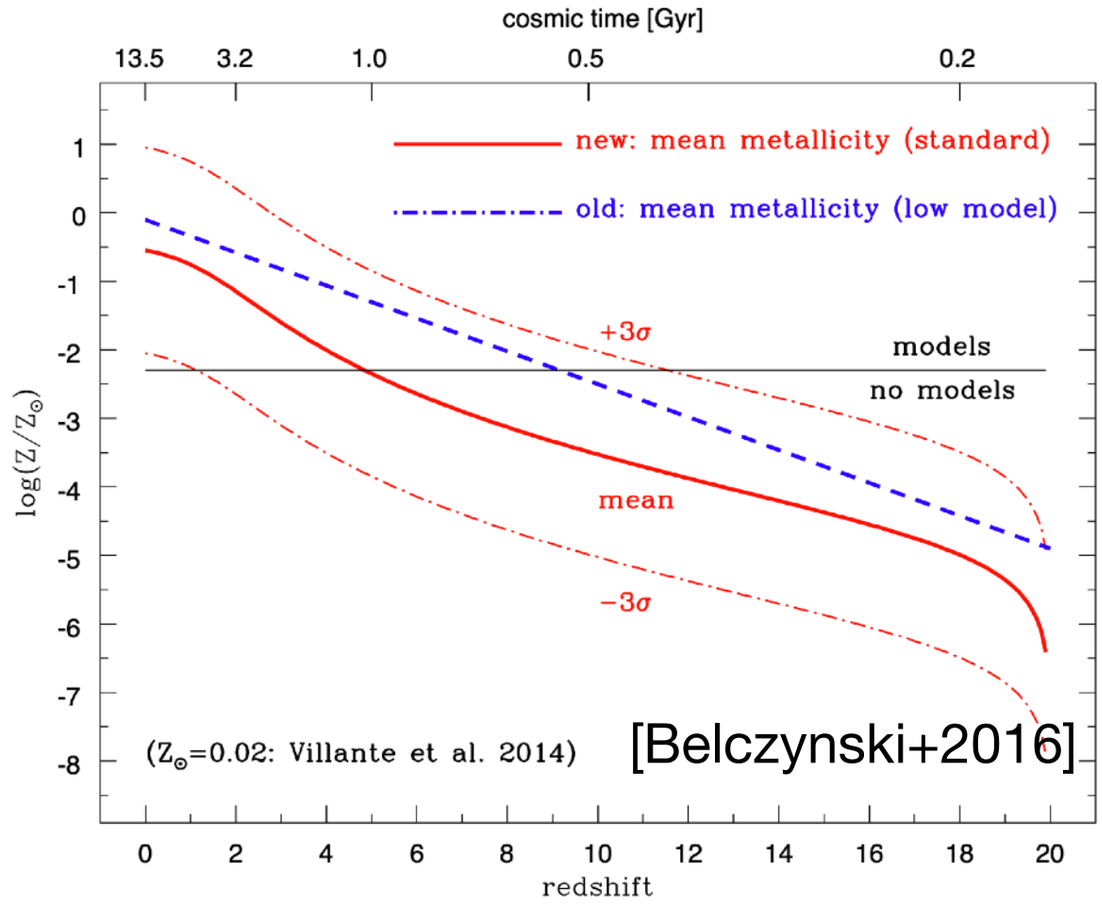
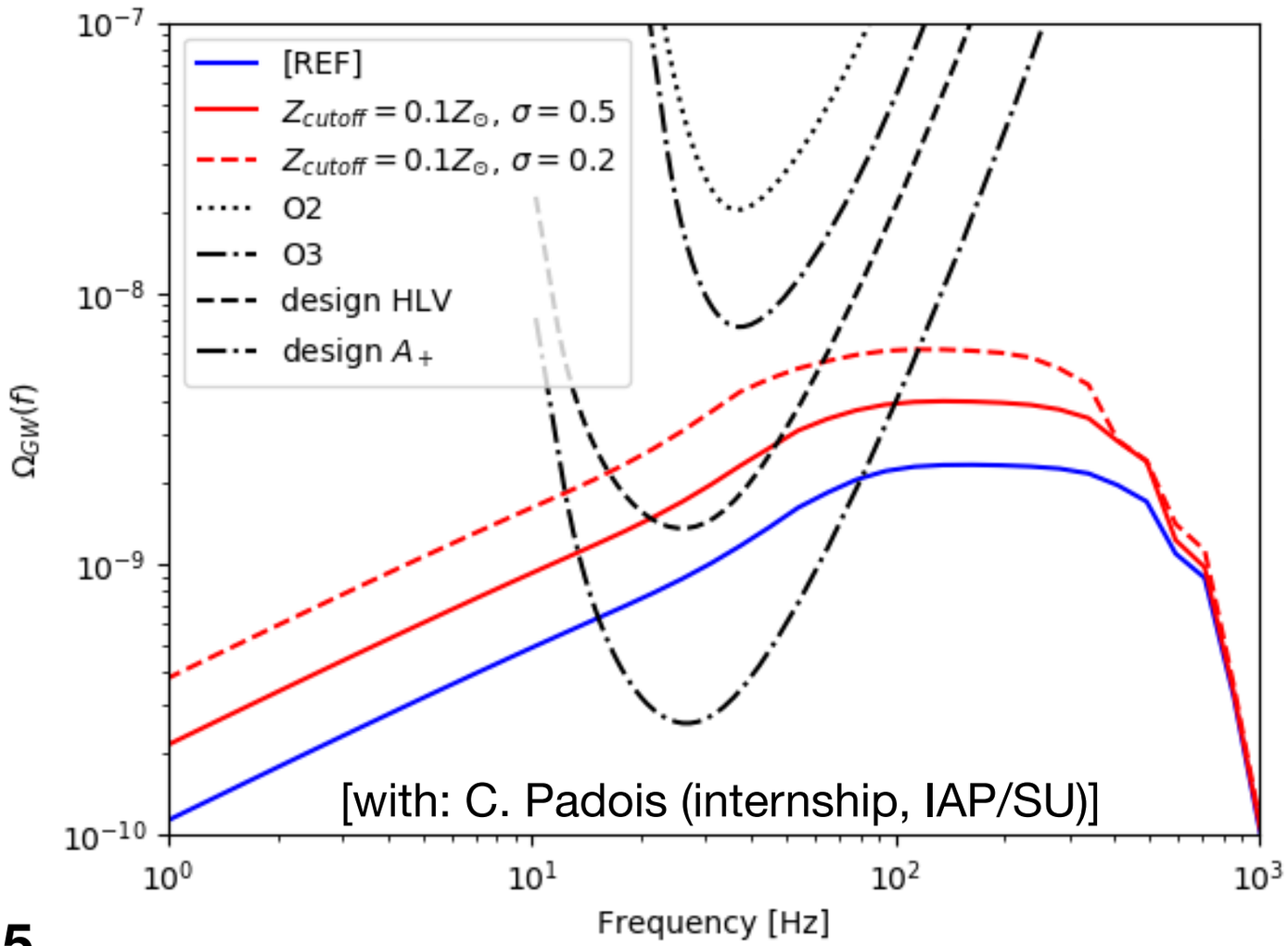
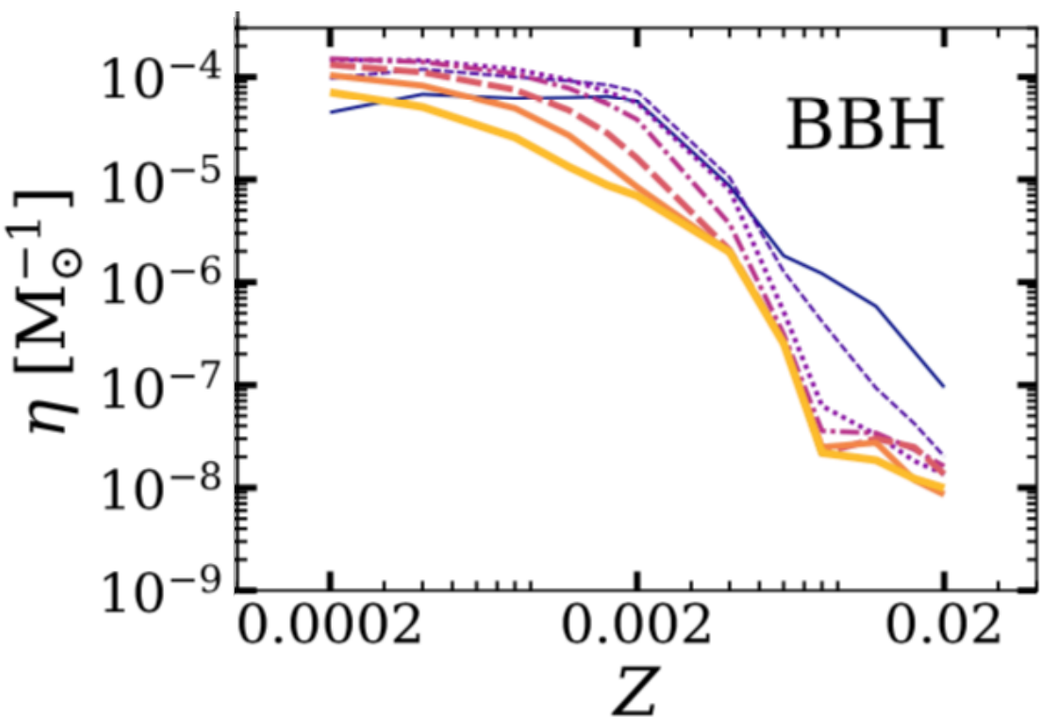


[Belczynski+2016]



[Santoliquido+2020]



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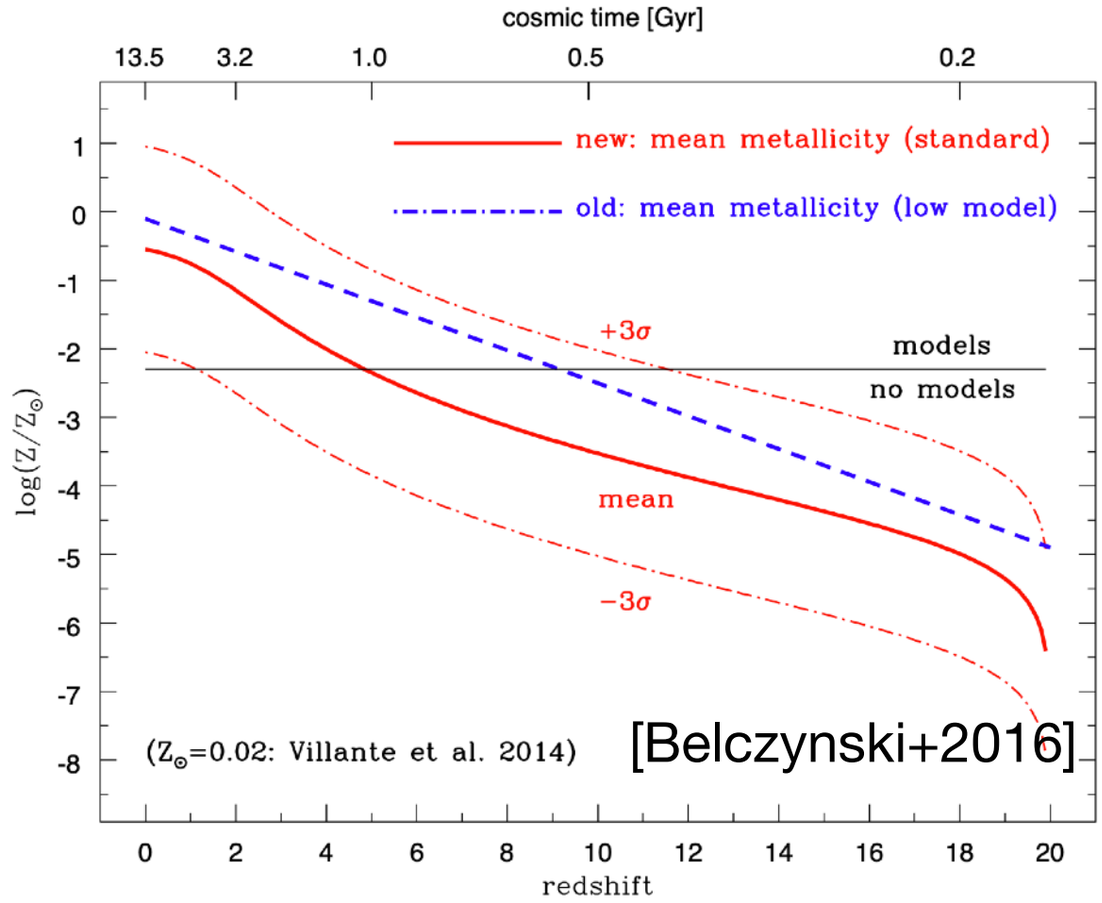

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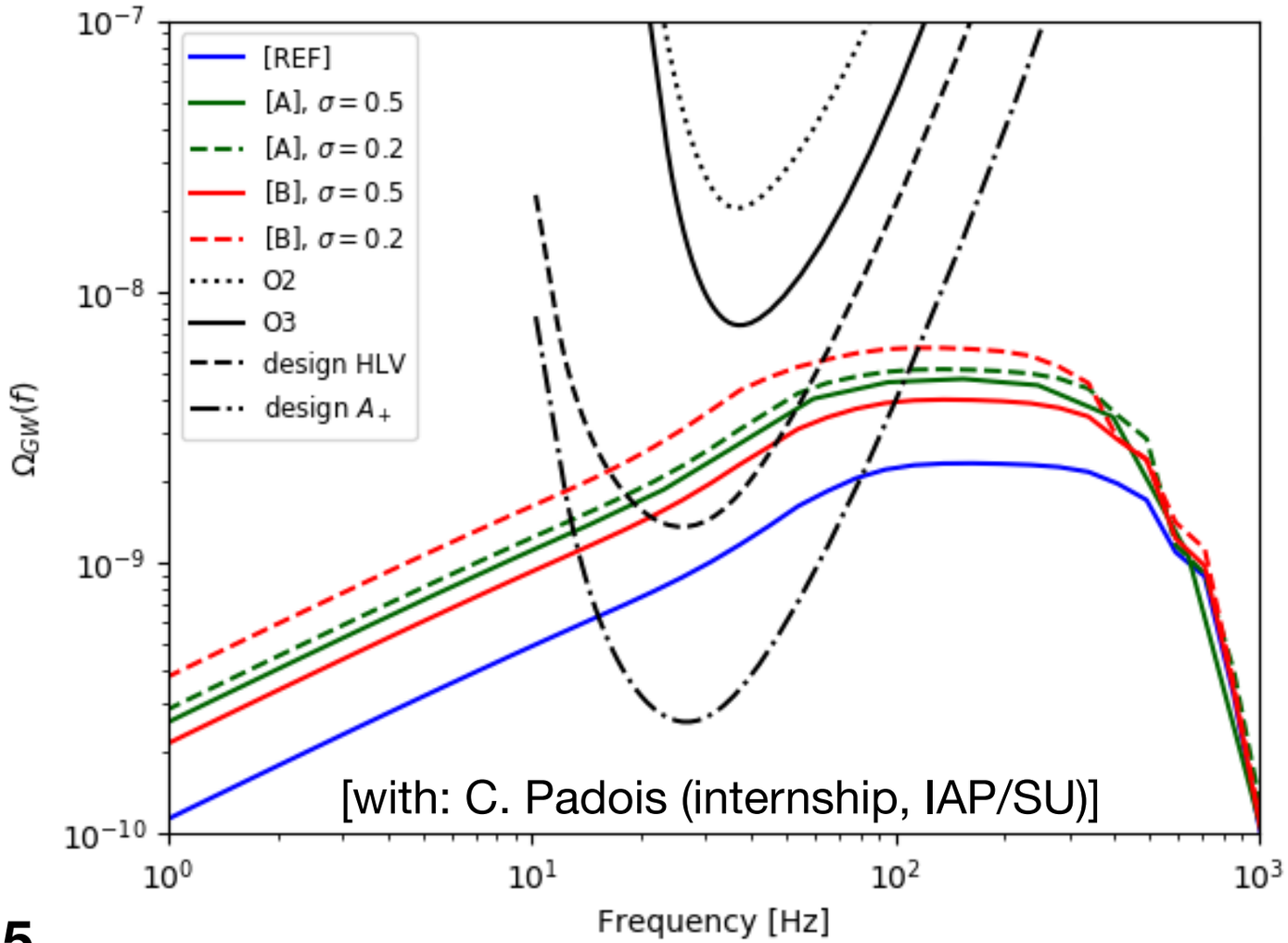

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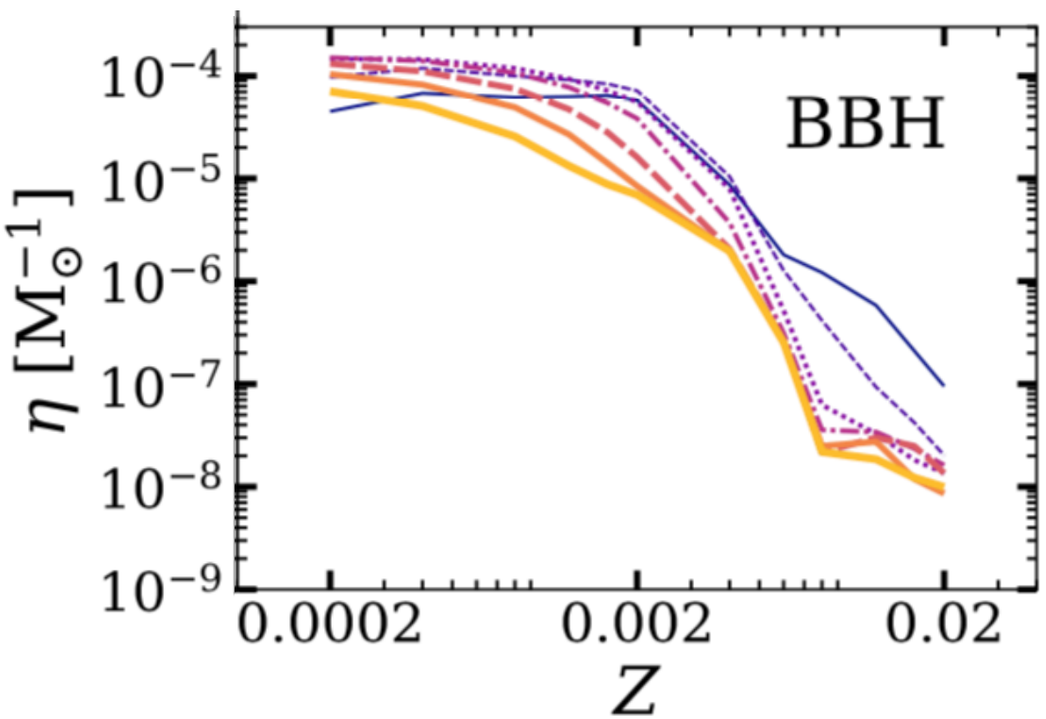
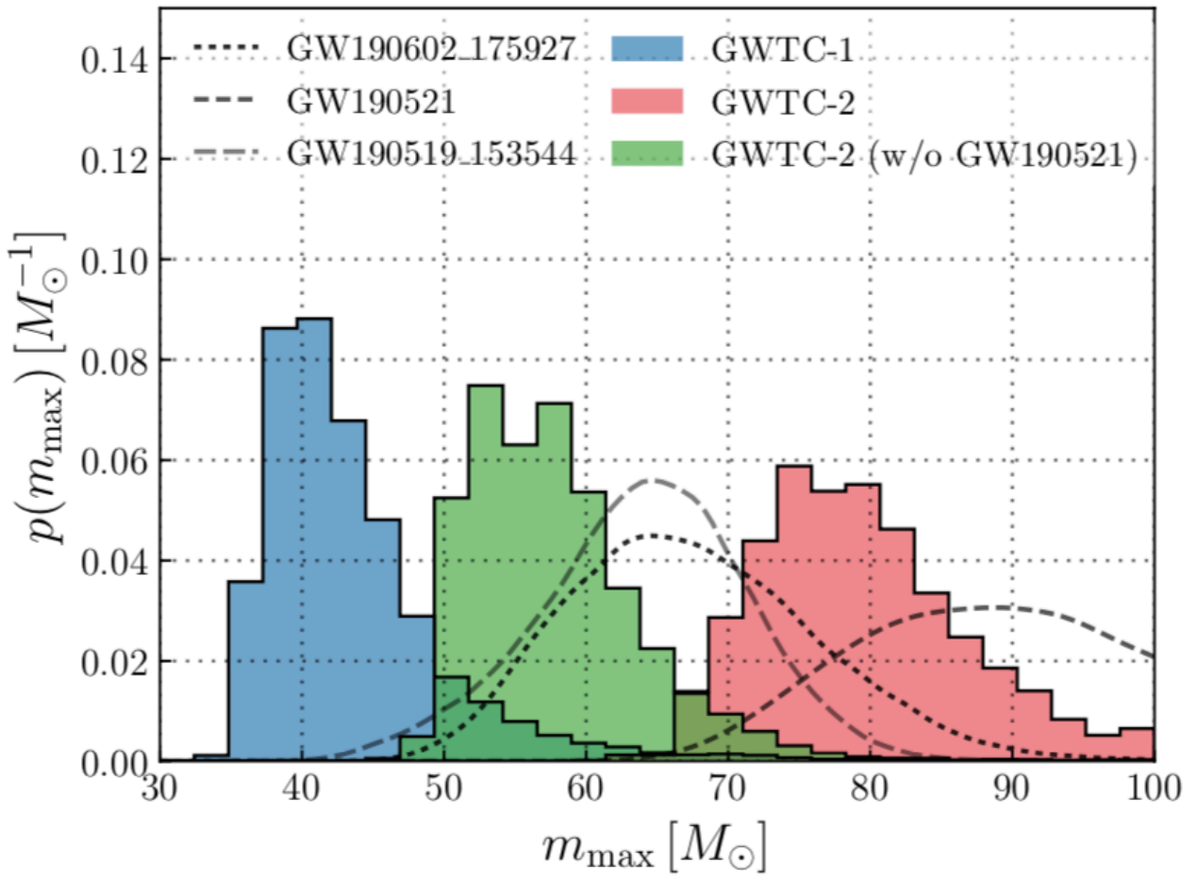


Intermediate frequencies: stellar-mass binaries

[LVC, GWTC-2 implications]

- O3a catalogue: evidence for BHs in the PISN mass gap **GW190521:** $85M_\odot + 66M_\odot$



Intermediate frequencies: stellar-mass binaries

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- One of the possible explanations: PopIII remnants (metal-free)

  [e.g. Kinugawa+2014; Hartwig+2016; Belczynski+2017; Liu&Bromm+2021…]

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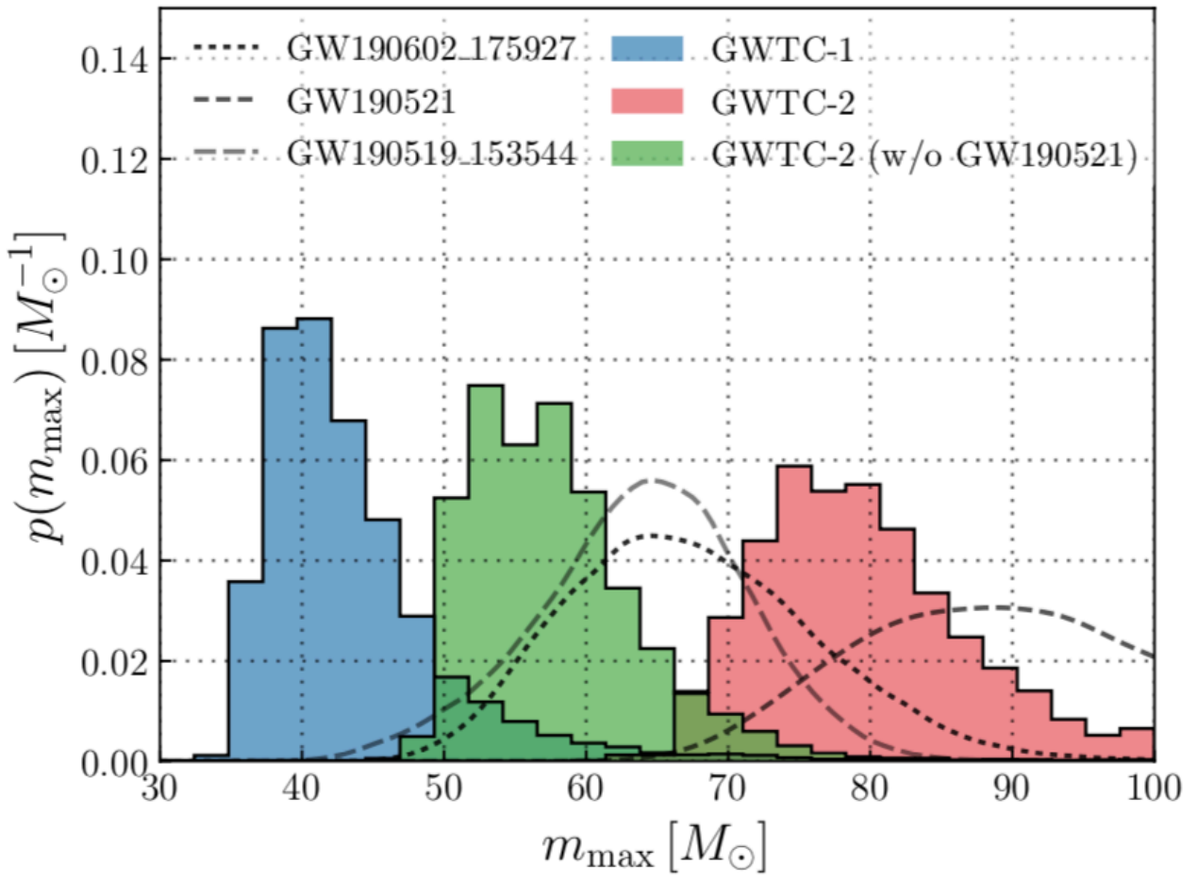

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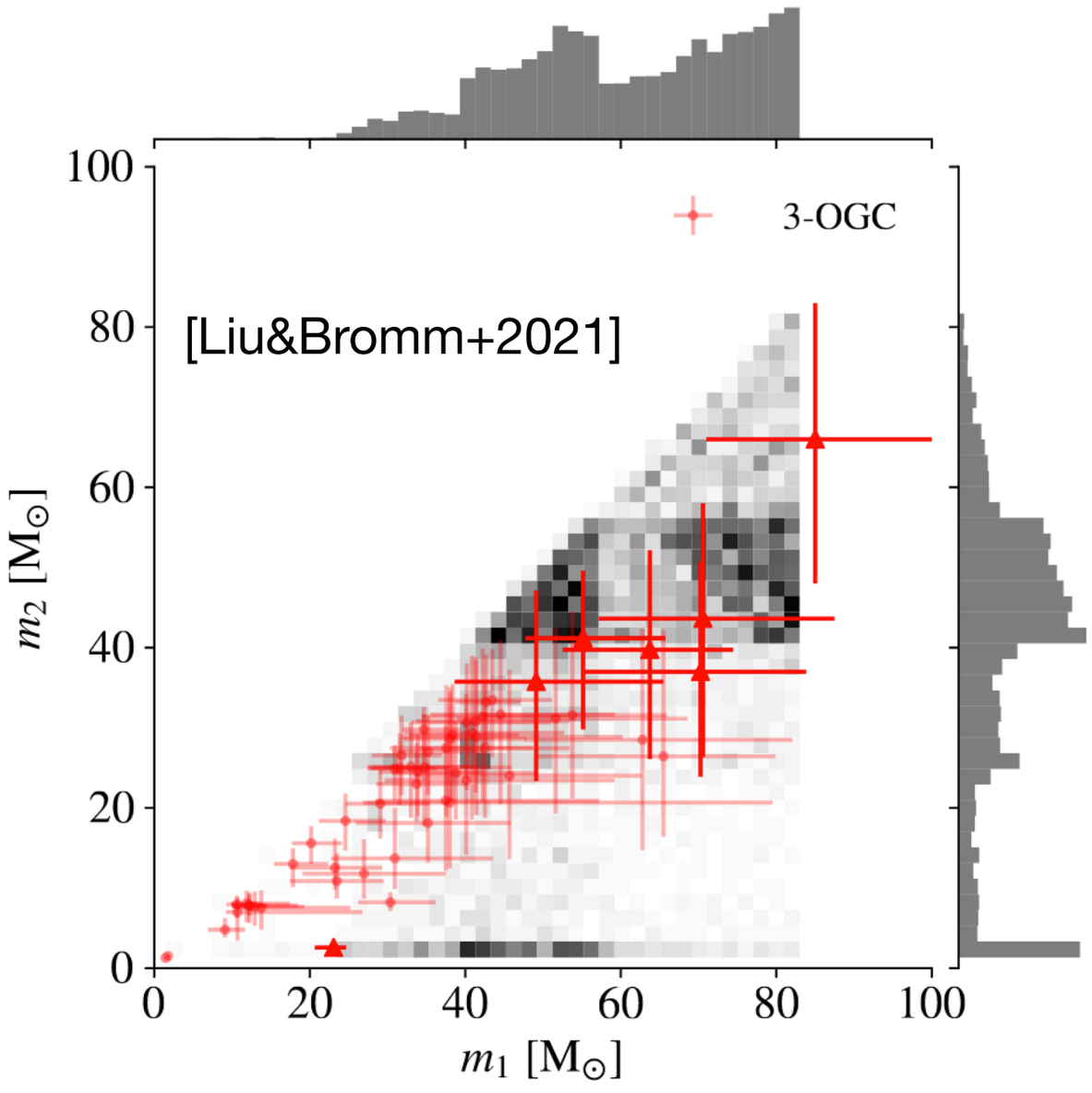

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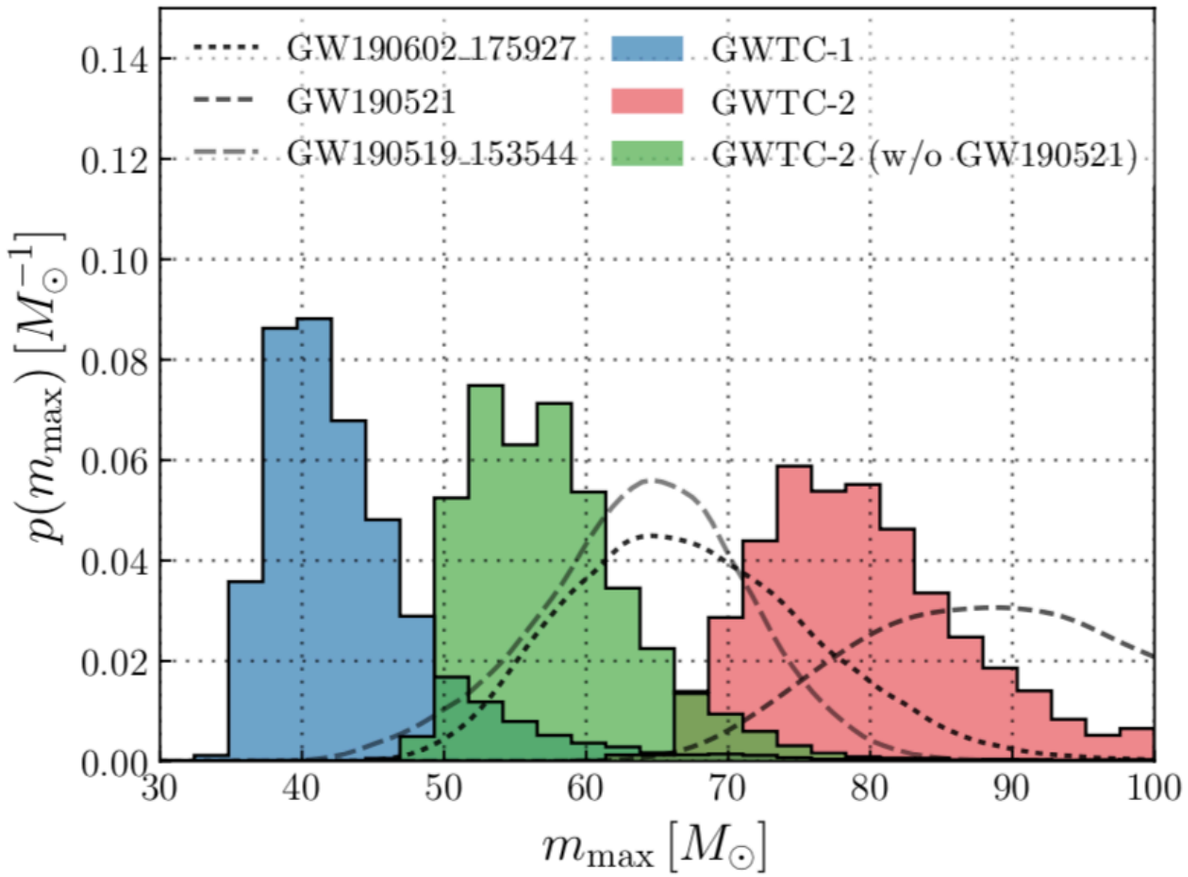
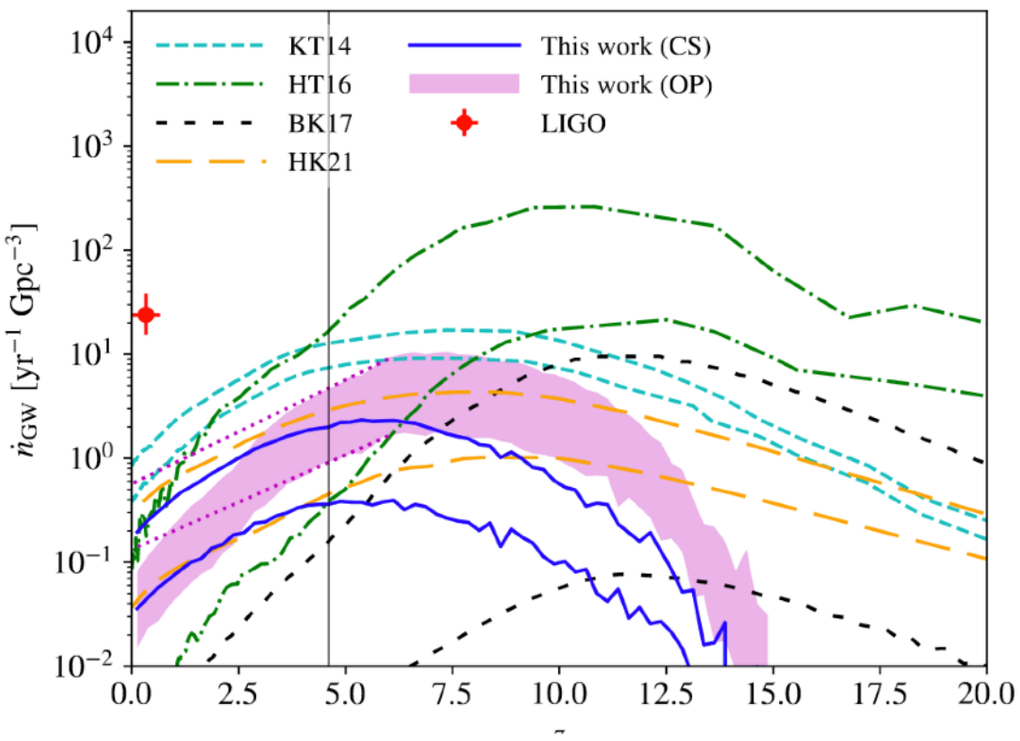
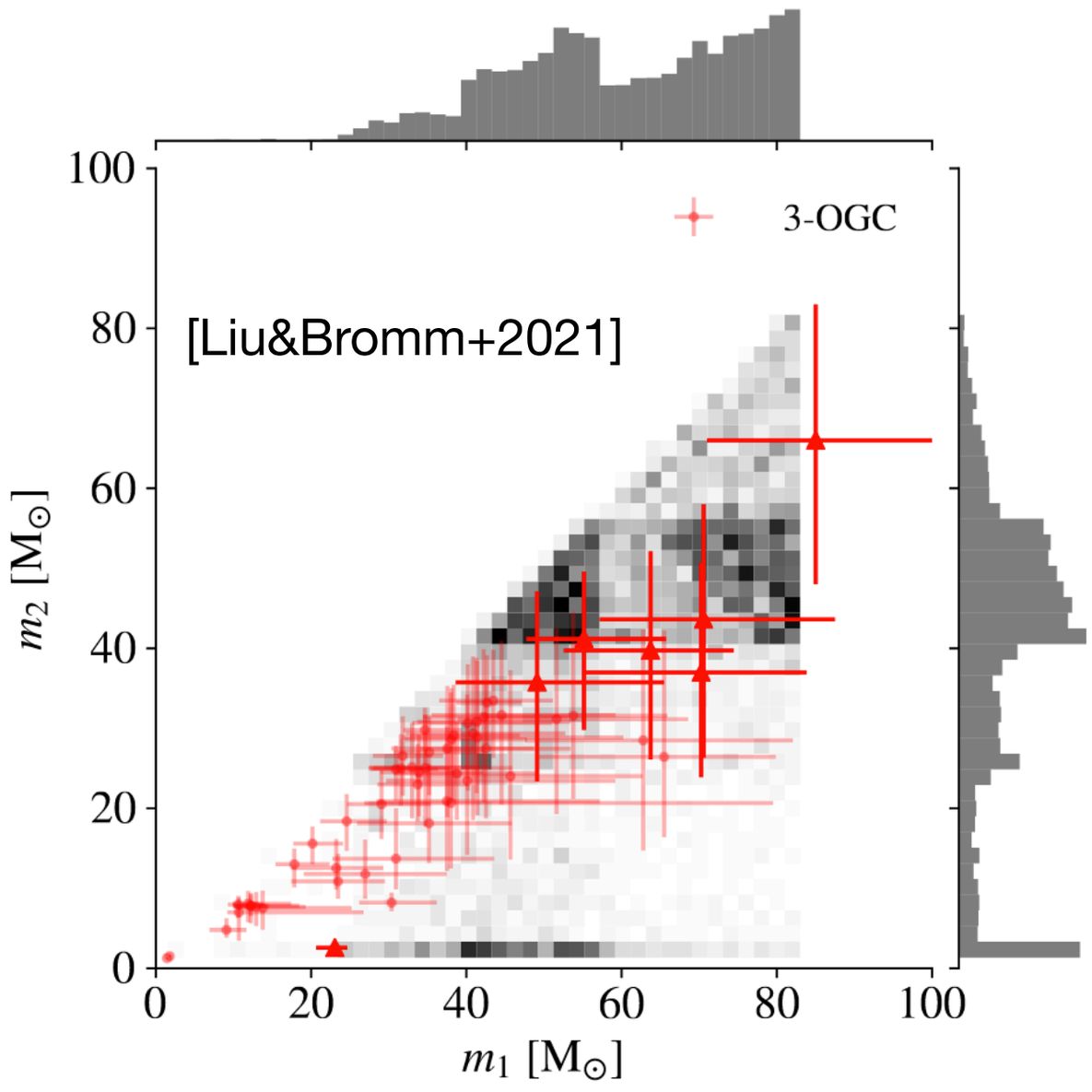
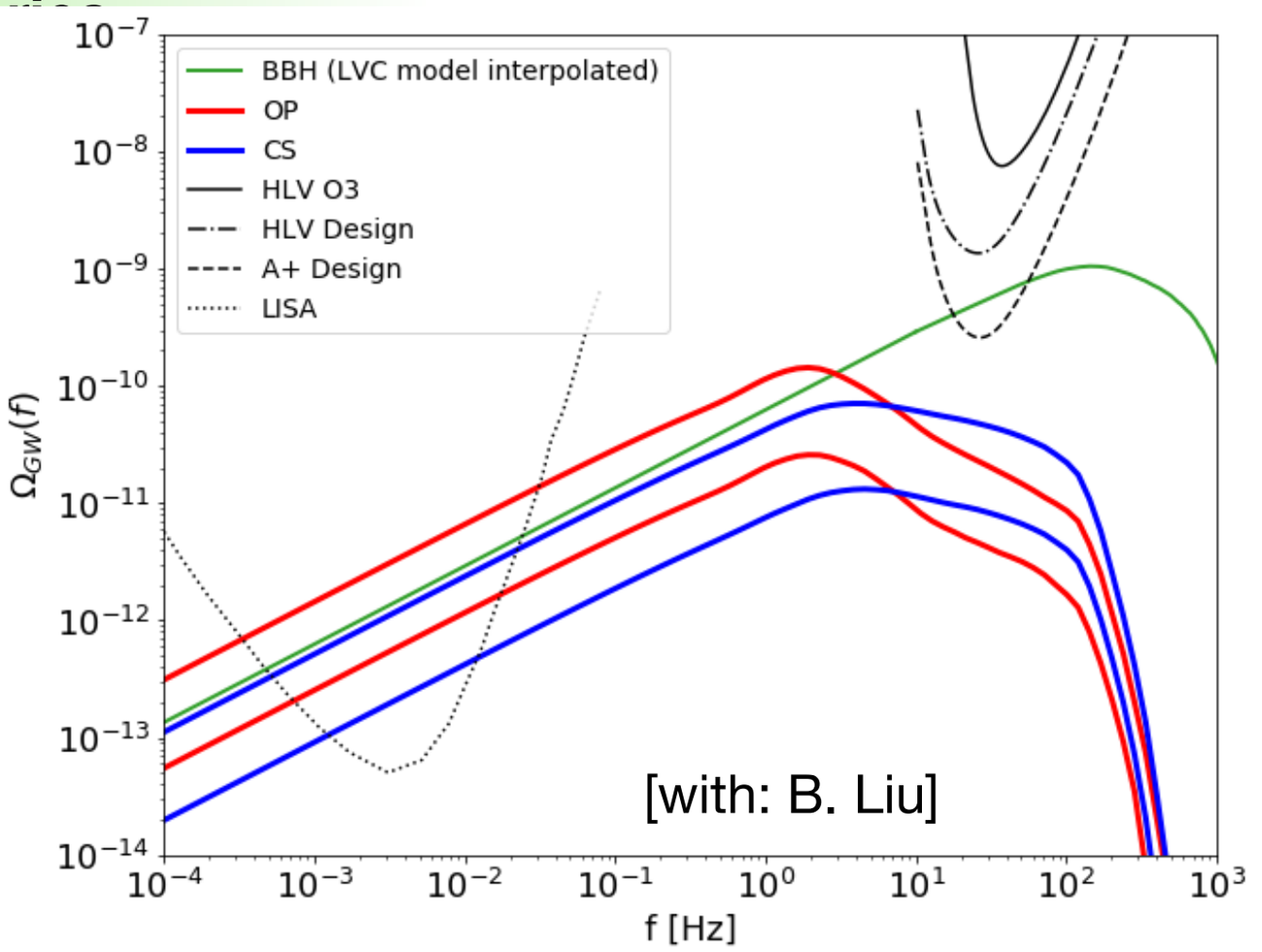


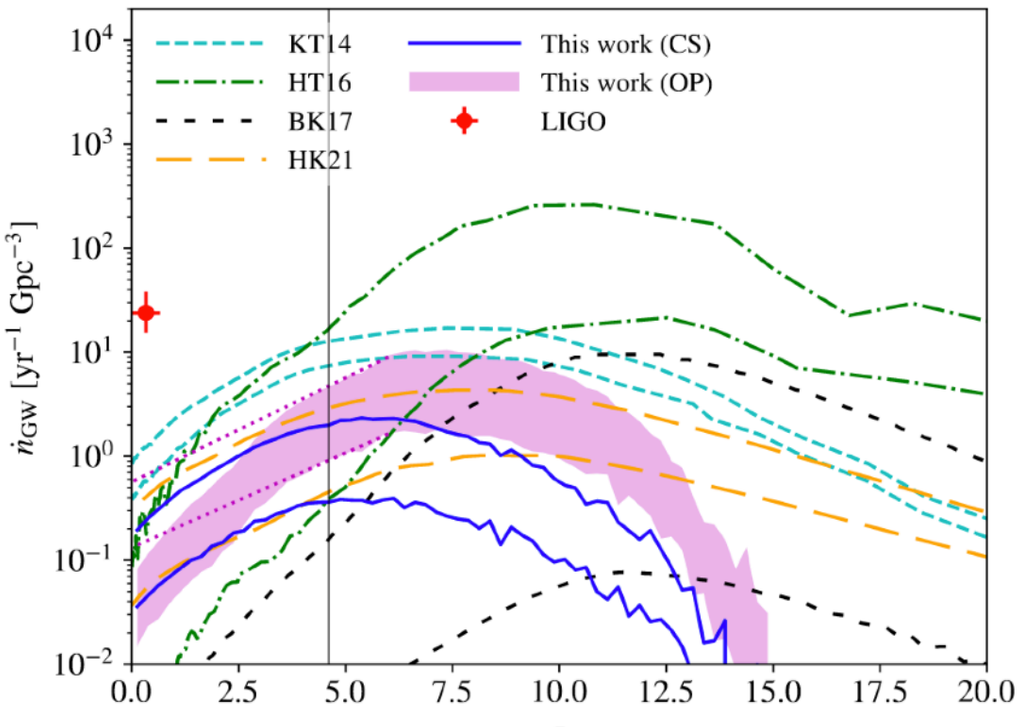


Intermediate frequencies: stellar-mass bina

- O3a catalogue: evidence for BHs in the PISN mass gap
- One of the possible explanations: PopIII remnants (metal-free)
- Contribution to background at low frequencies







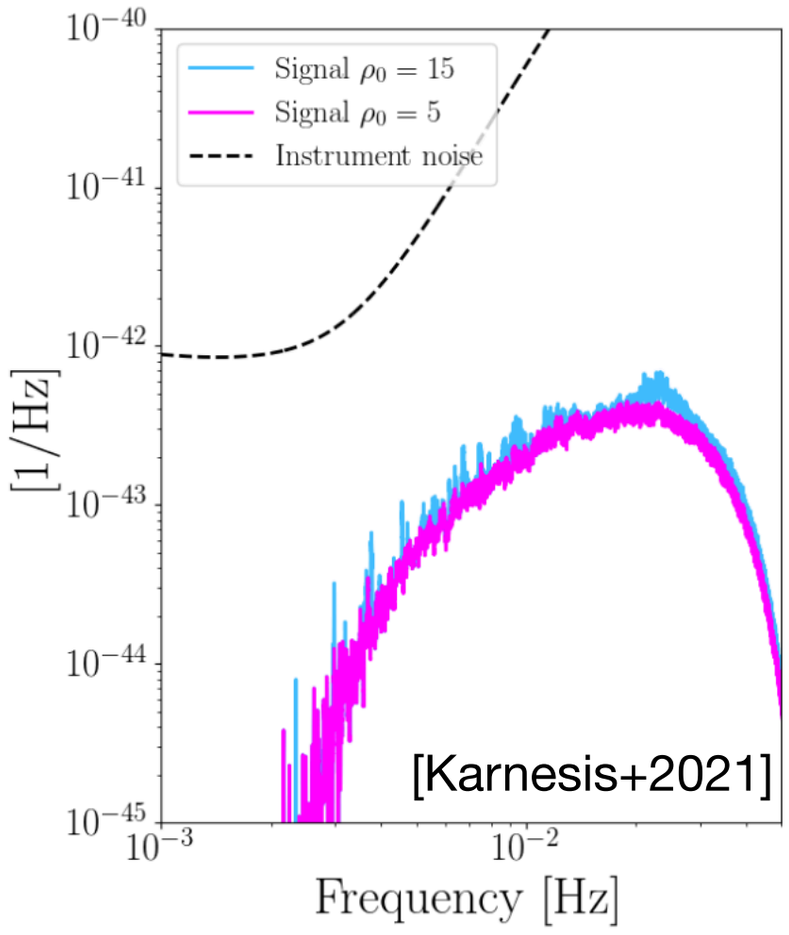
Intermediate frequencies: stochastic backgrounds from stellar-mass binaries

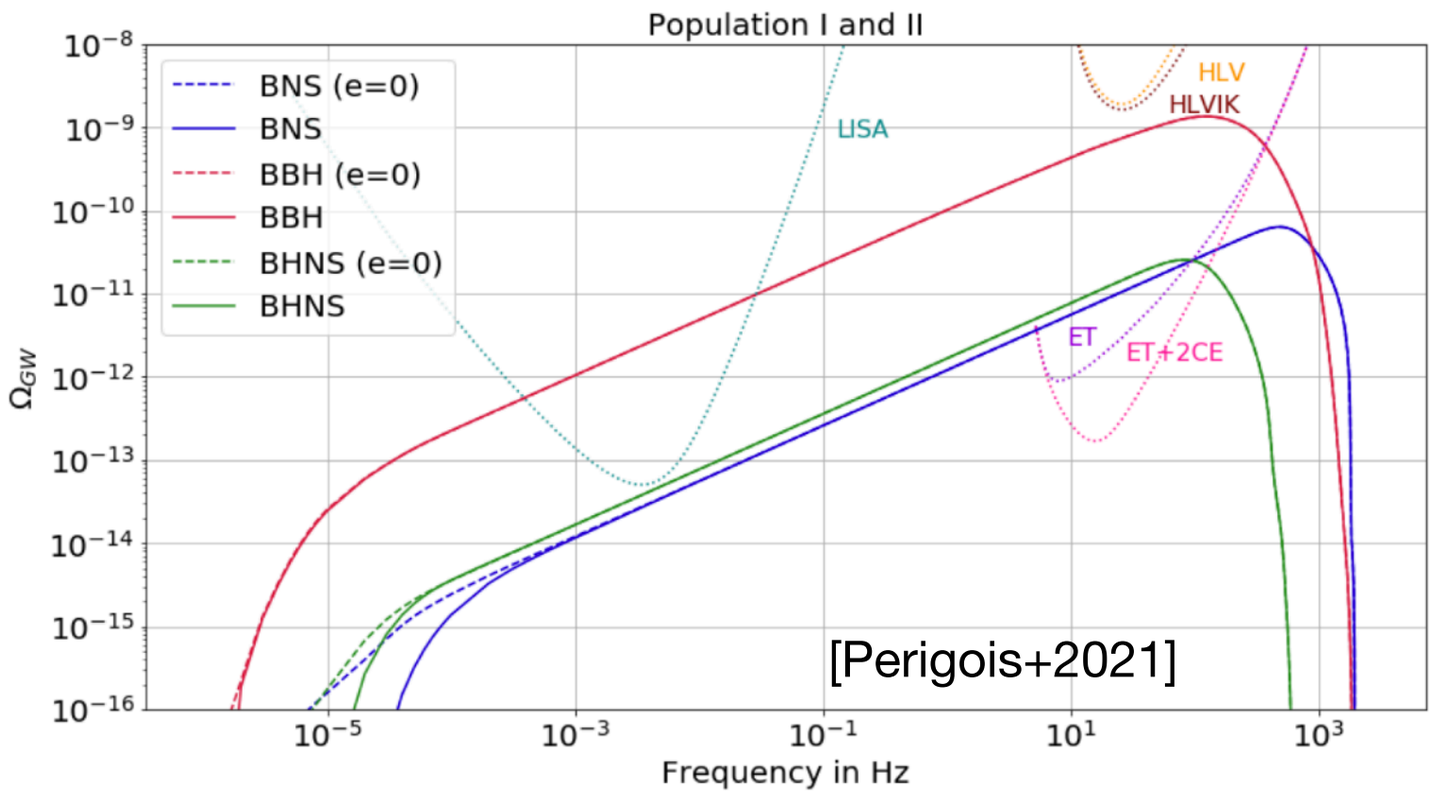
- Stochastic background from stellar-mass binary black holes: foreground for cosmological signals!

[**ID+**2016; Cusin, **ID**+2019, Perigois+2021,…]

- Will need to separate astrophysical and cosmological backgrounds

[Biscoveanu+2020; Karnesis+2021; Boileau+2021]

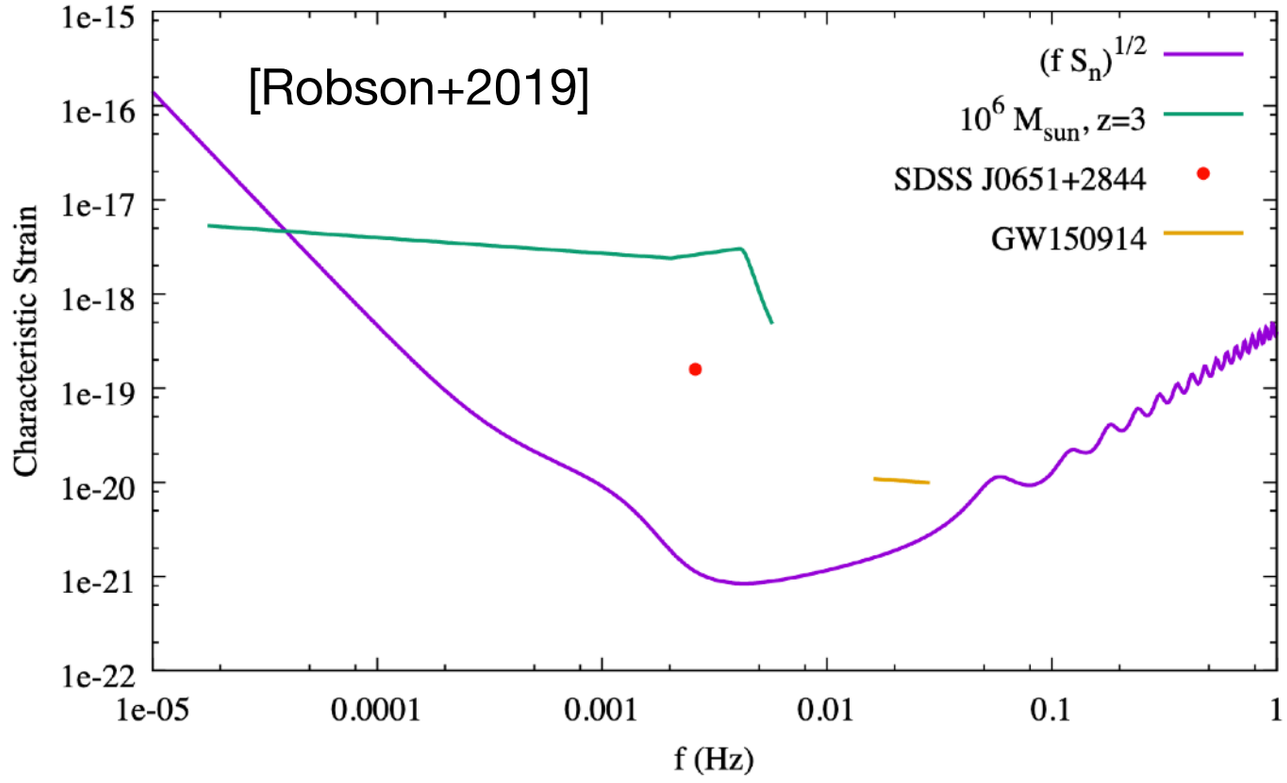




Intermediate frequencies: confusion noise

Galactic binaries

- 10^8 double white dwarfs in Milky Way
- Monochromatic sources in LISA band
- Confusion noise dominates instrument noise in the mHz band



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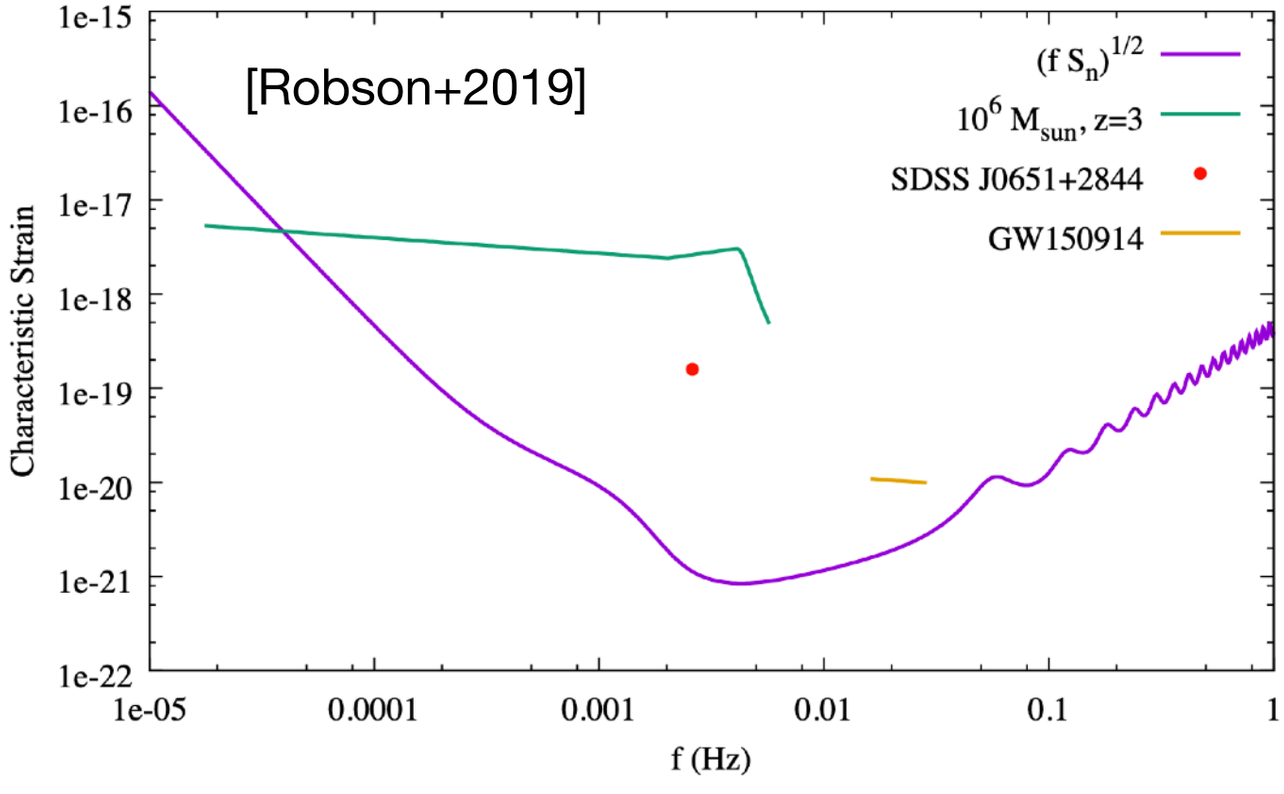
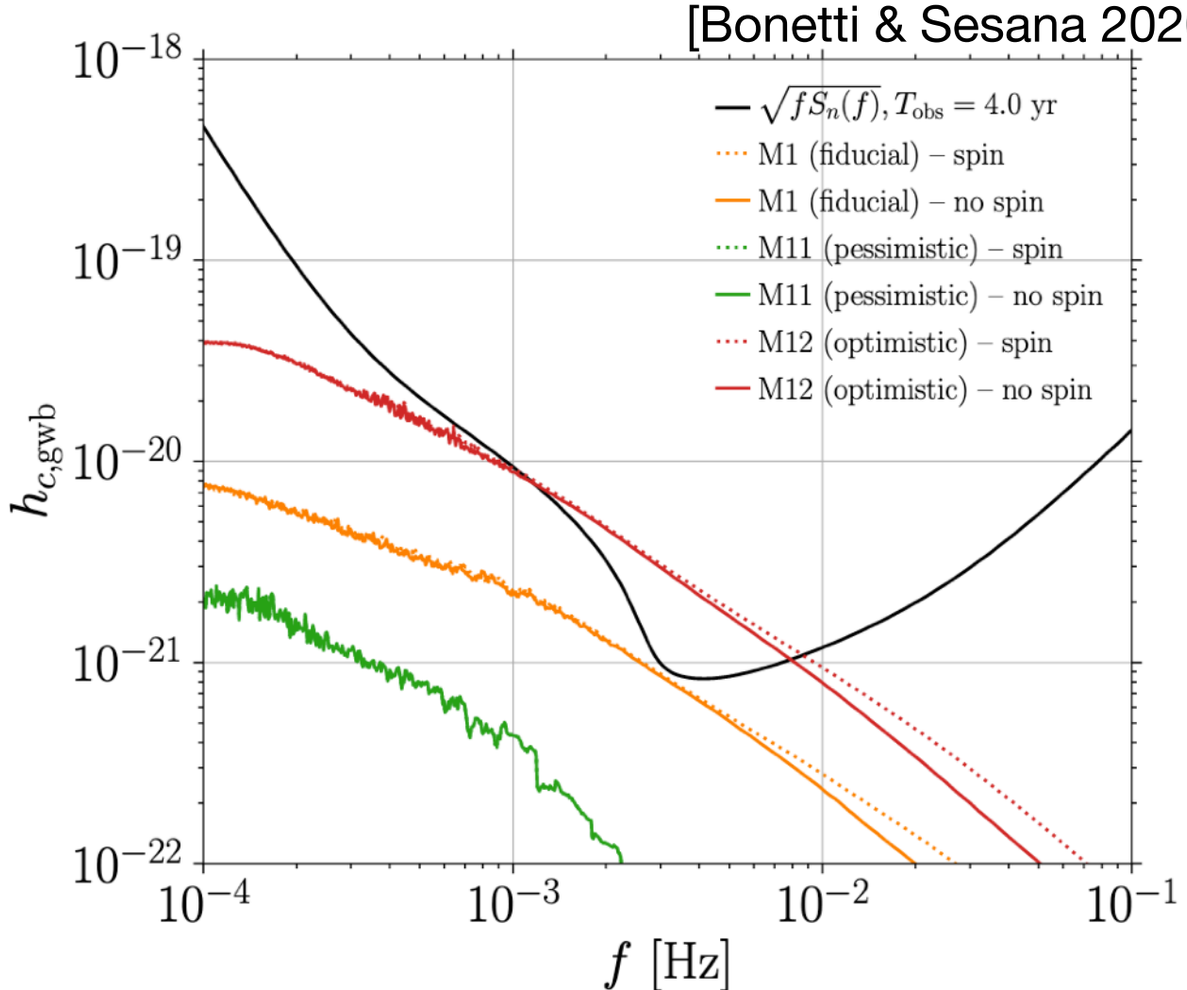


Extreme mass-ratio inspirals

- Stellar-mass black holes orbiting massive black holes
- Expected to form in dense galactic centers
- LISA detection rates: $1 - 10^4\ \ yr^{-1}$

[Babak+2017]

[Bonetti & Sesana 2020]



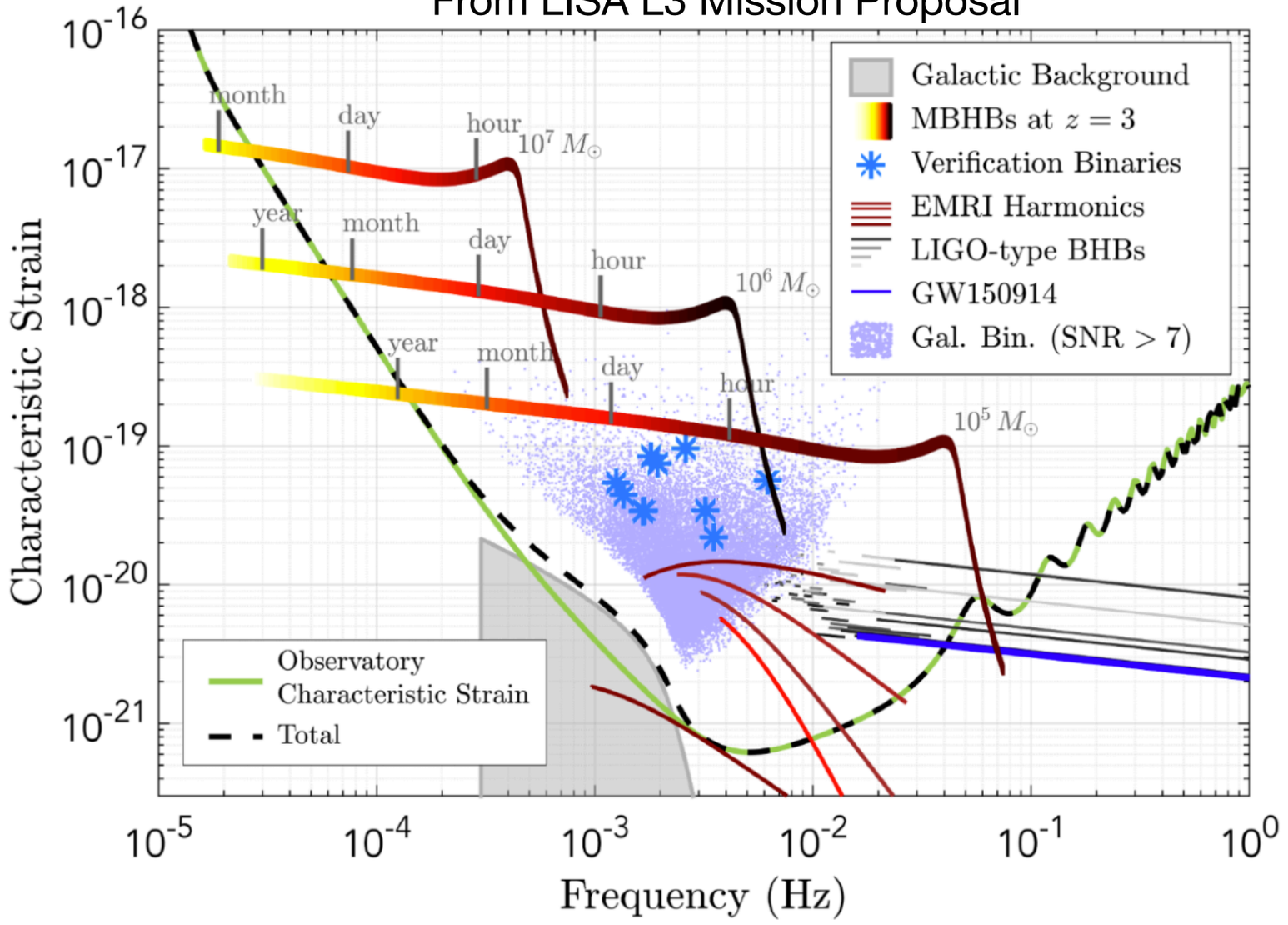
Massive black hole binaries

- Massive BH binaries: primary targets for LISA

$$M_{BH} \sim 10^5 - 10^9 M_\odot$$

[e.g. Barausse 2012; Sesana+2014; Klein+2016; Dayal+2019; Bonetti+2019; Katz+2019; …]

From LISA L3 Mission Proposal

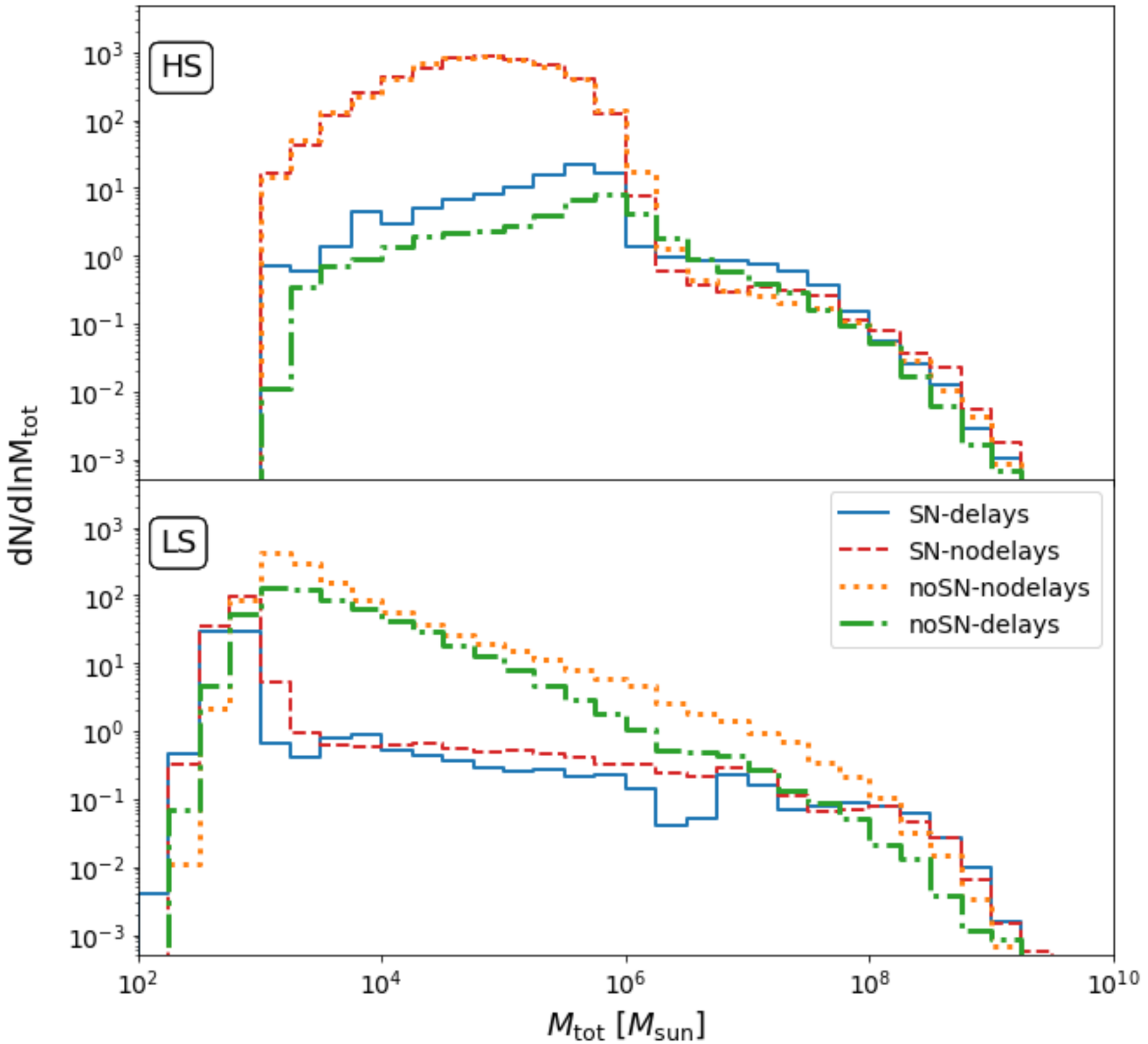


* **Key processes still unknown:**
  * Seeds of massive black holes
  * Co-evolution with host galaxies
  * Interactions with surrounding gas and stars

Redshifts of MBH binaries detectable with LISA

[Barausse, **ID**, Tremmel, Volonteri, Bonetti 2020]

- Detection rates: **4-6 per year** in the most 'pessimistic' case
- High-mass seed models not affected by SN feedback
- SN feedback decreases the merger rate in low-mass galaxies
- kpc-scale wandering decreases the merger rate in high-mass galaxies



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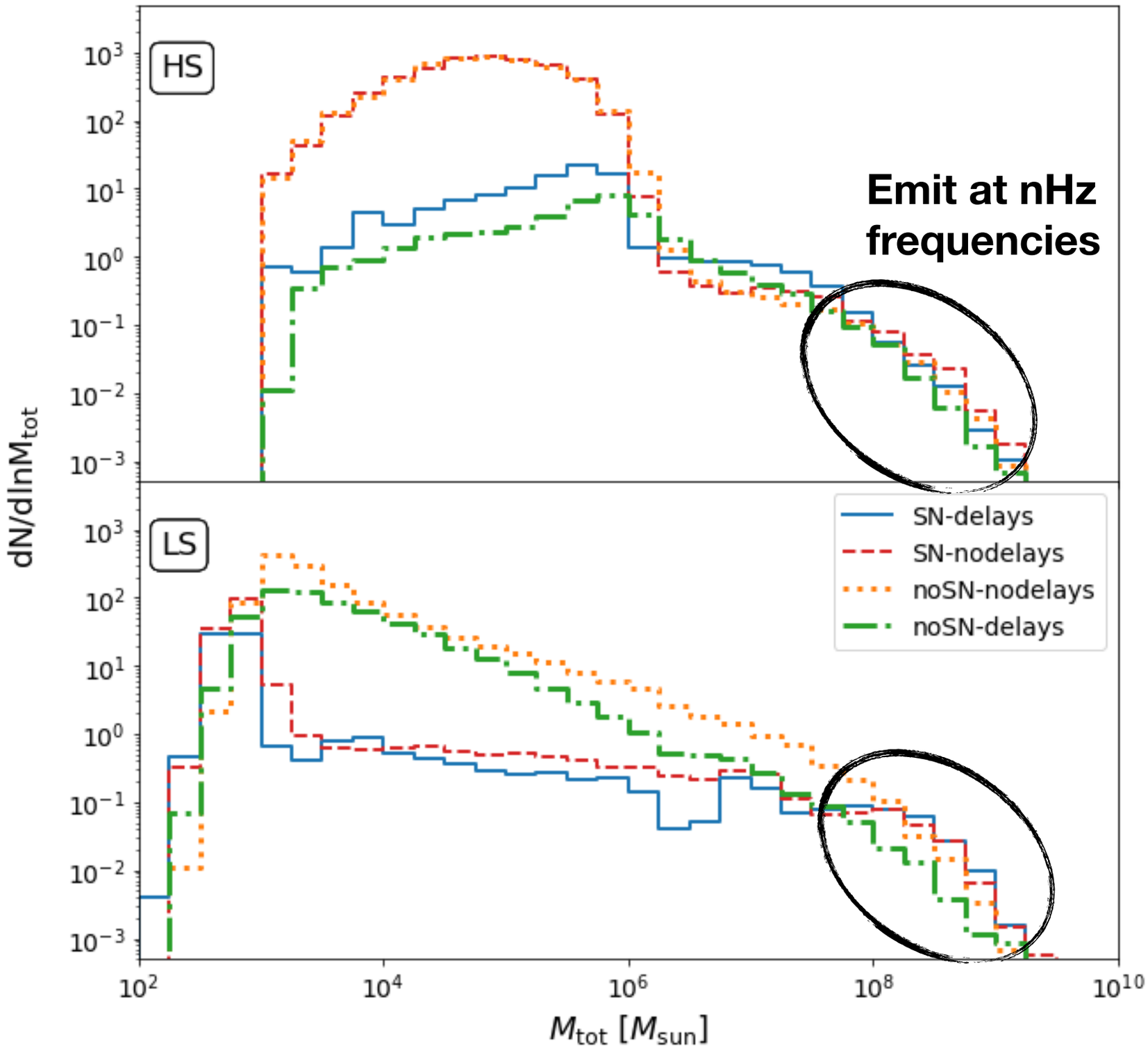
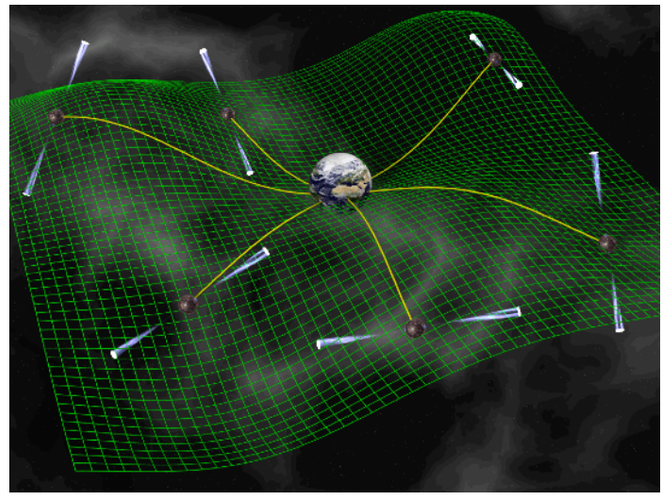
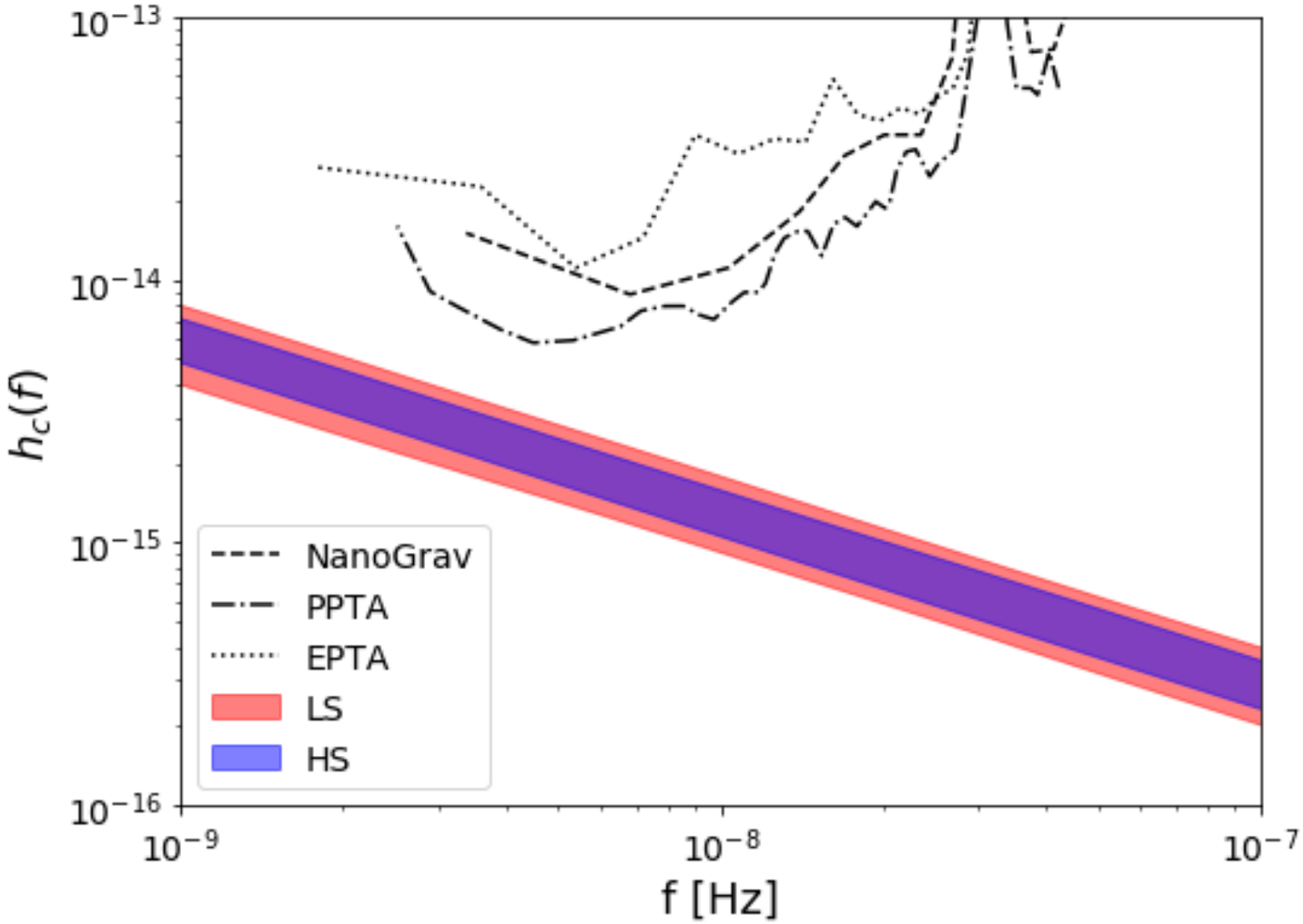


Low frequencies: super-massive black hole binaries



- Super-massive binaries create a stochastic background in the nHz band which is less sensitive to differences between the models

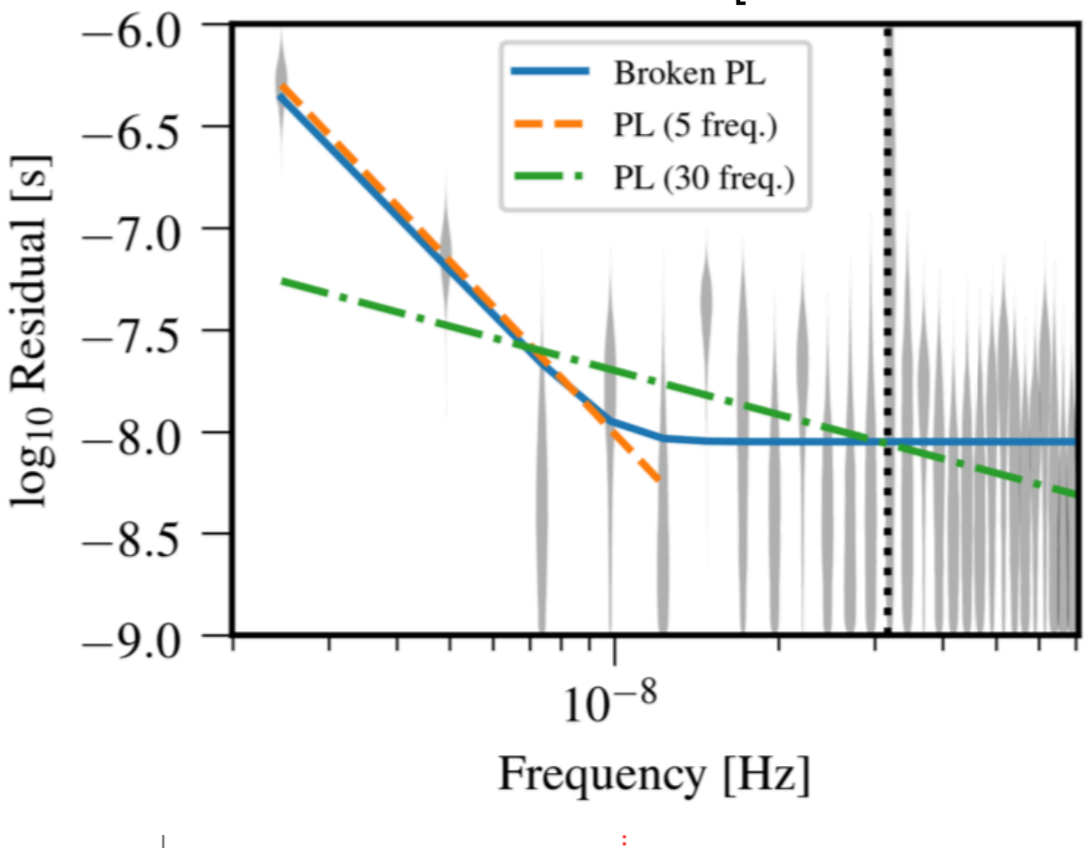
[e.g. Bonetti+2017; Kelly+2017; **ID** & Barausse 2017; Sesana+2018; Chen+2019 …]

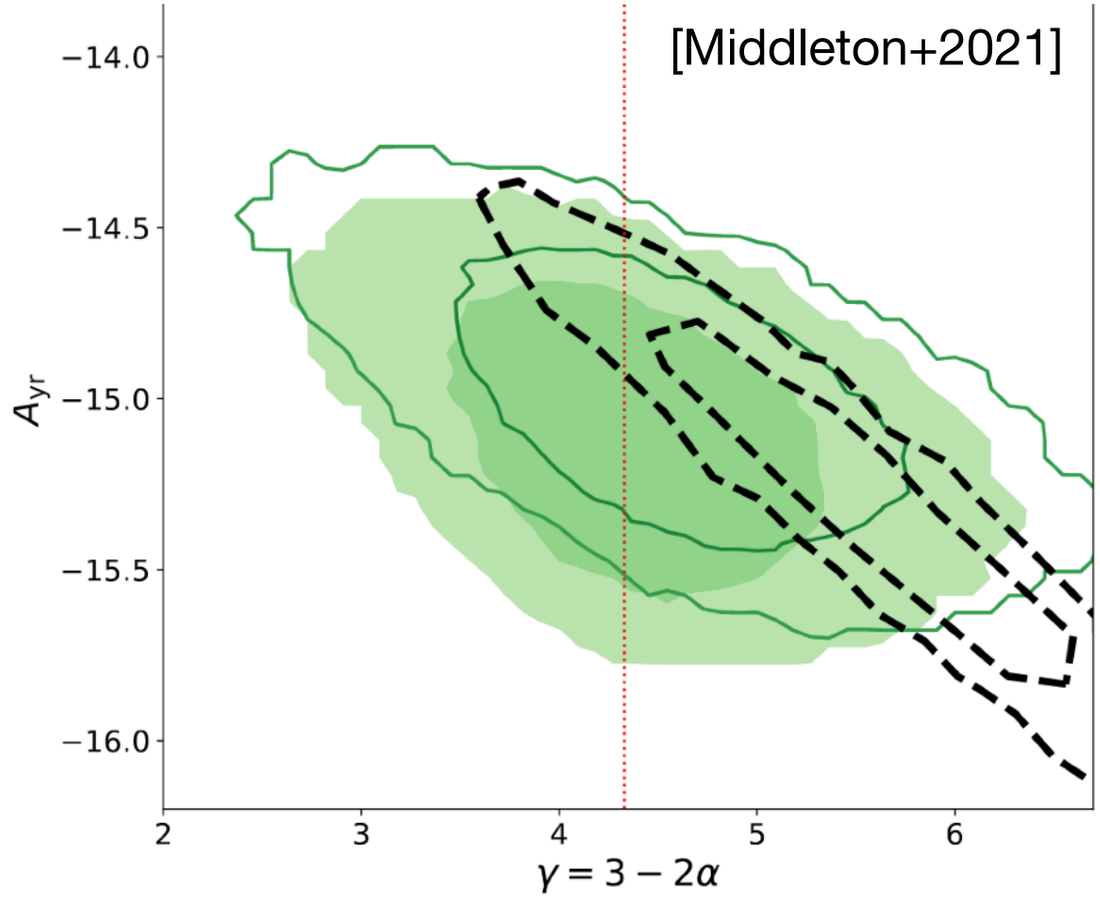


[Barausse, **ID**, Tremmel, Volonteri, Bonetti 2020]

Low frequency: Pulsar Timing Arrays

[Arzoumanian+2020]





- Tentative detection of a correlated signal by the NANOGrav PTA

  [see Goncharov+2021 for Parkes analysis]

- Evidence for a common-spectrum process, but not the correlation expected from a GW signal
- Consistent with signal from black hole binaries
- Consistent with cosmological signals (primordial black holes, cosmic strings…)

  [e.g. De Luca+2021; Vaskonen&Veermäe 2021; Ellis&Lewicki 2021; Blasi+2021; Nakai+2021; Ratzinger&Schwaller 2021; Addazi+2020]

Stochastic backgrounds: conclusions

- Variety of astrophysical backgrounds across different frequencies
- Highly complementary to individual detections (explore high redshifts)
- Expect a detection soon?…
  - Tightening upper limits from LIGO/Virgo/Kagra
  - Tentative detection of a common process by Pulsar Timing Arrays
- Future: LISA, 3G detectors…

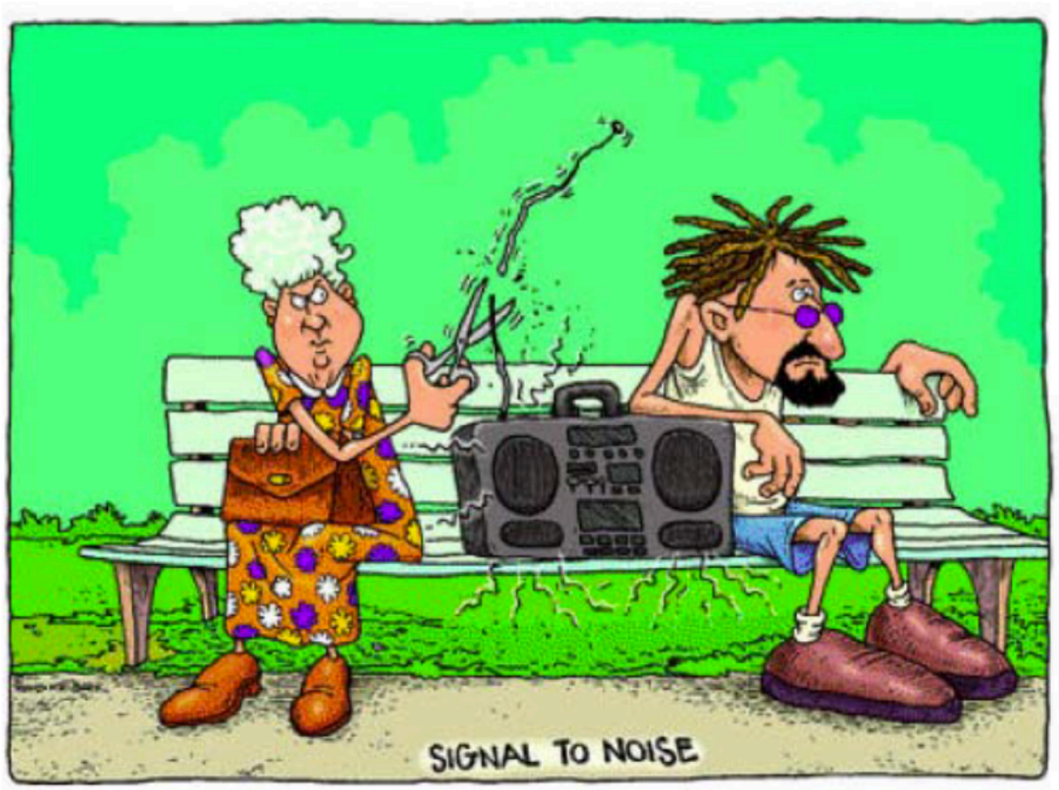


FIG. 1: Whether noise is a nuisance or a signal may depend on whom you ask. (Cartoon by Rand Kruback. Used with permission of Agilent Technologies.)