INSTITUT D'ASTROPHYSIQUE DE PARIS
Unité mixte de recherche 7095 CNRS - Sorbonne Université

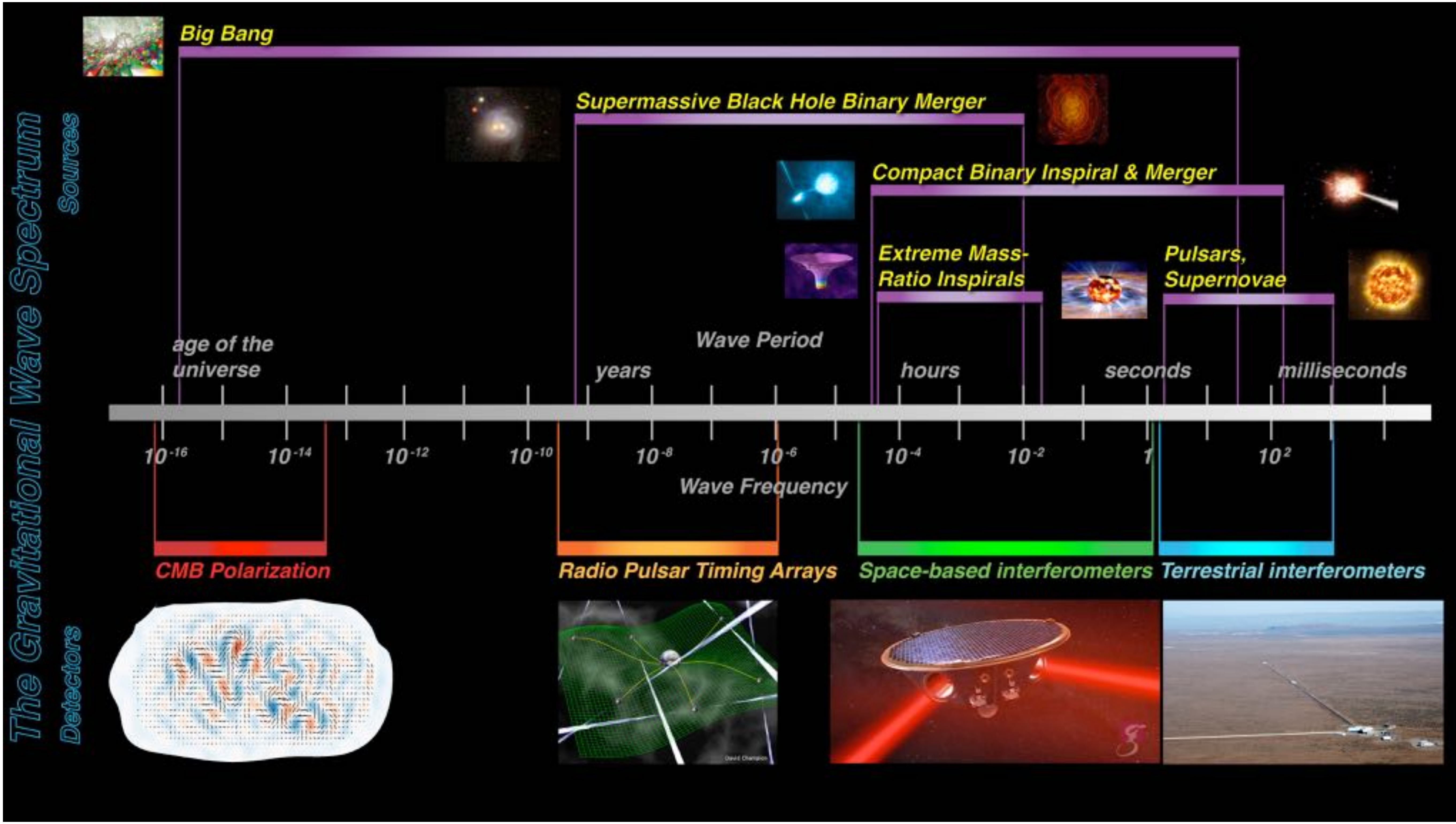
Stochastic gravitational-wave backgrounds from astrophysical sources

Irina Dvorkin

Institut d'Astrophysique de Paris

Sorbonne Université

First EuCAPT Annual Symposium, 6 May 2021

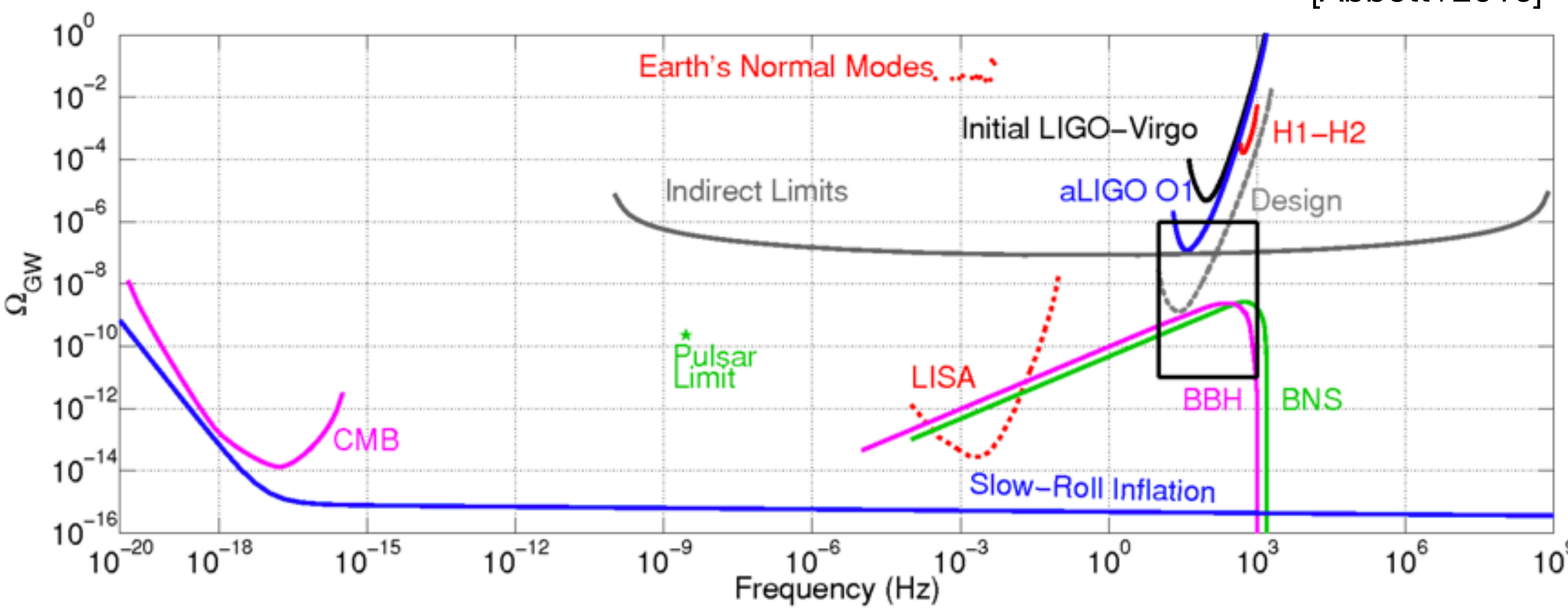

The Gravitational Wave Spectrum
Sources
Big Bang
Supermassive Black Hole Binary Merger
Compact Binary Inspiral & Merger
Extreme Mass-Ratio Inspirals
Pulsars, Supernovae
age of the universe
Wave Period
years
hours
seconds
milliseconds
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
Wave Frequency
CMB Polarization
Radio Pulsar Timing Arrays
Space-based interferometers
Terrestrial interferometers
Detectors

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

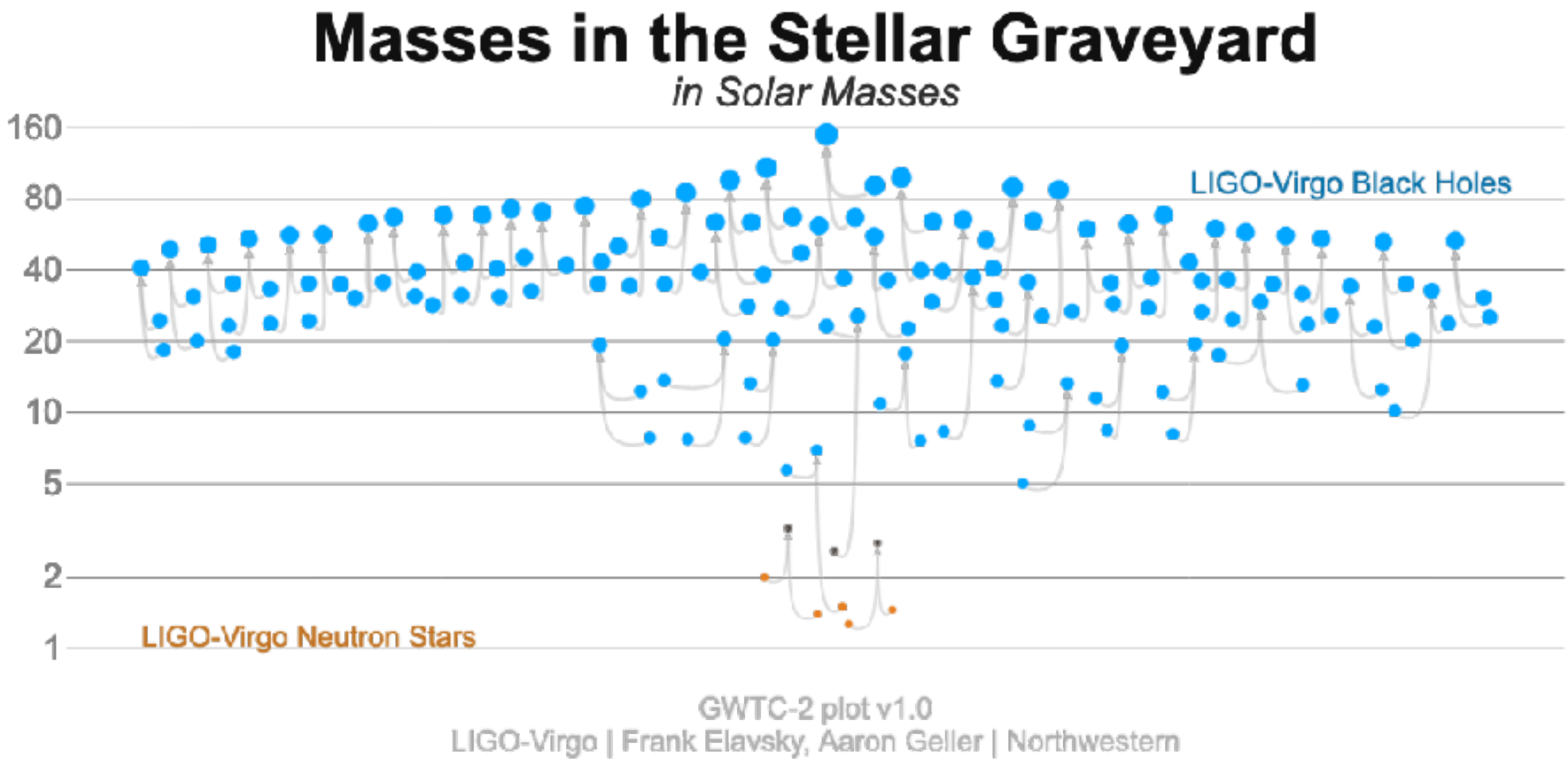
$$\hat{\Omega}_{\mathrm{GW}}(f) = \frac{1}{\rho_c}\frac{d\rho(f)}{d\ln f} = \frac{2\pi^2}{3H_0^2}f^2h_c^2(f)$$

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

[Abbott+2016]



High frequency: stellar-mass binaries



Local merger rates:

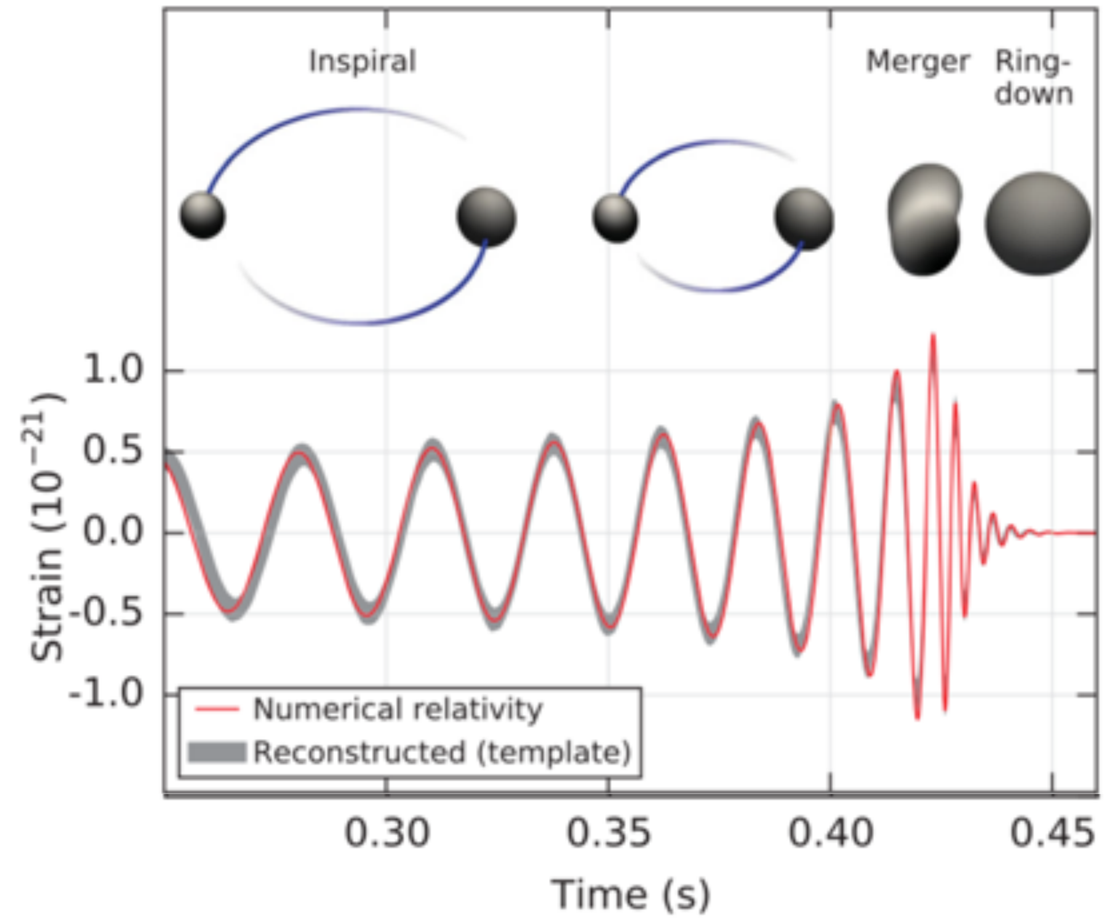
[LVK 2020]

$$\mathcal{R}_{\mathrm{BBH}} = 23.9^{+14.3}_{-8.6}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

$$\mathcal{R}_{\mathrm{BNS}} = 320^{+490}_{-240}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

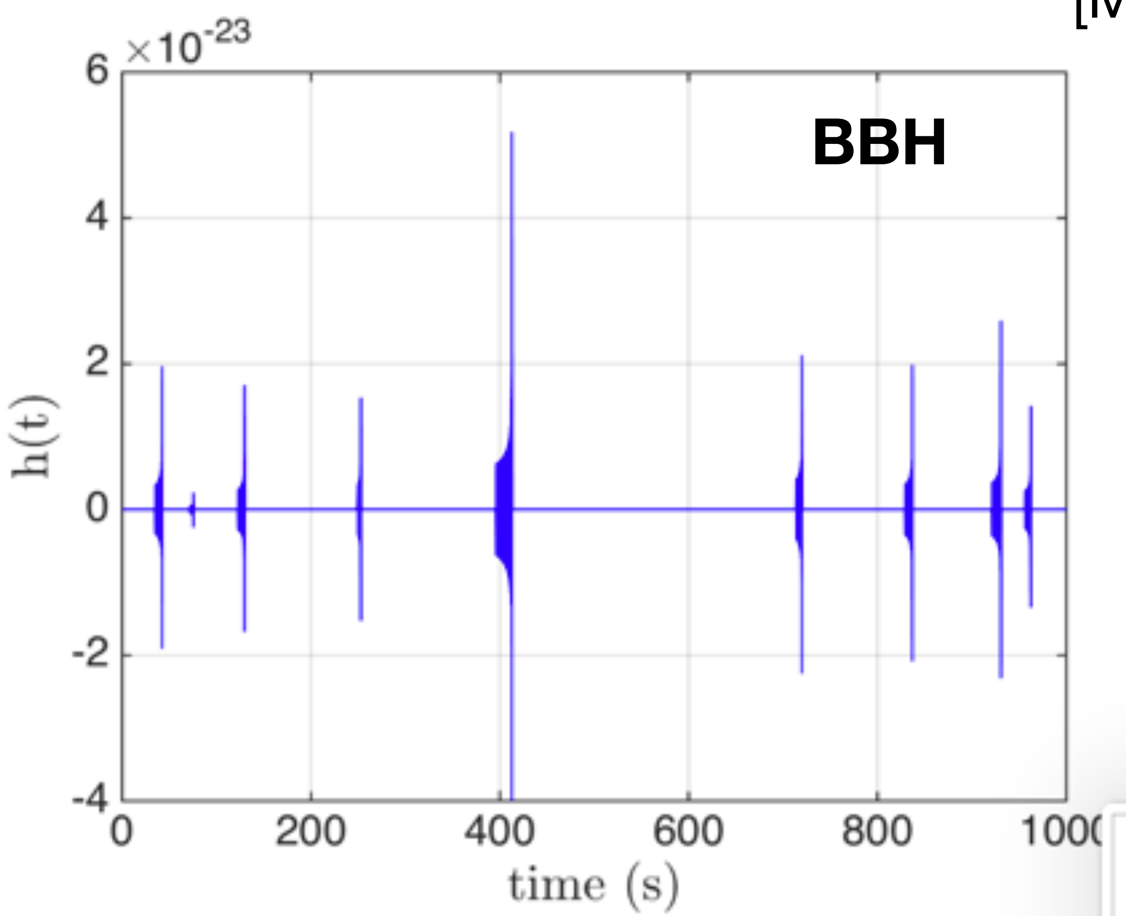
High frequency: stellar-mass binaries

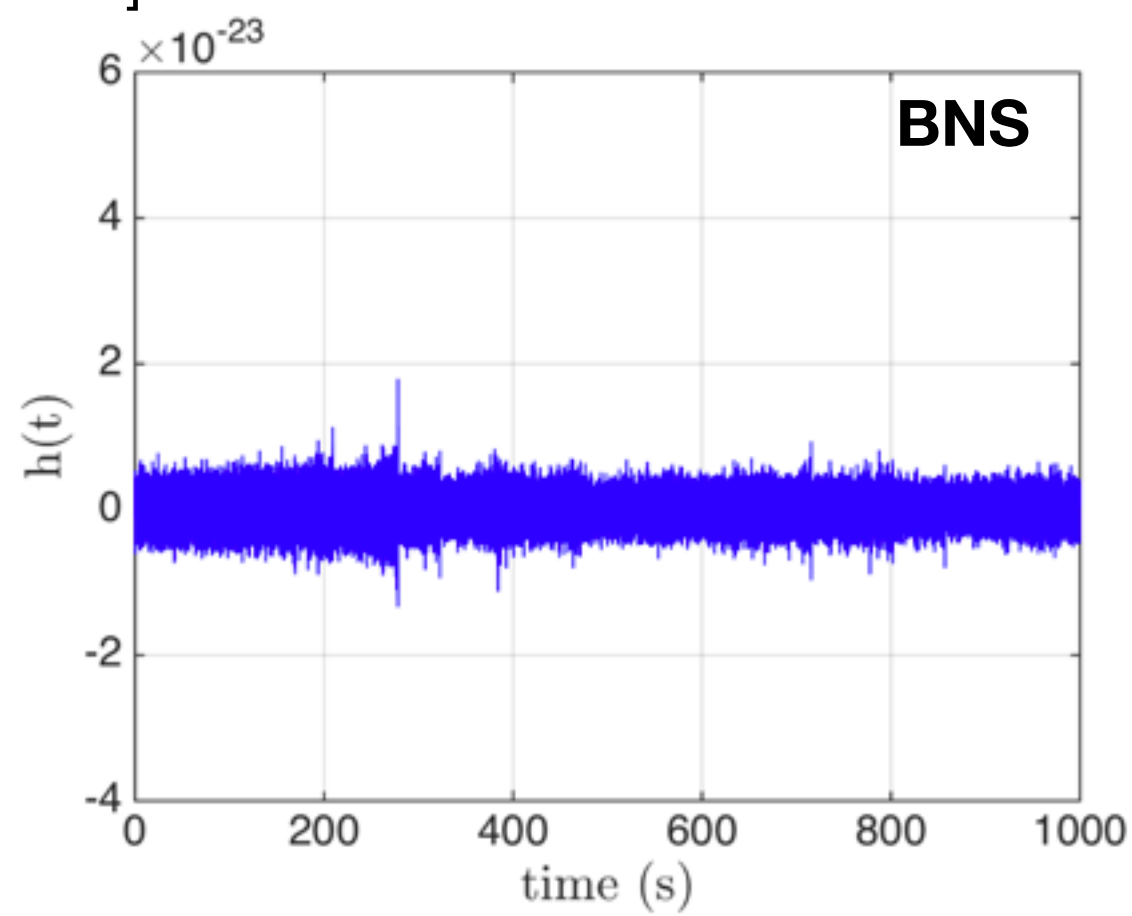
- Incoherent superposition of unresolved binaries creates a stochastic background
- Binary black holes: ‘popcorn noise’
- Binary neutron stars: signals overlap in time



[LVC 2015]

[Meacher+2015]



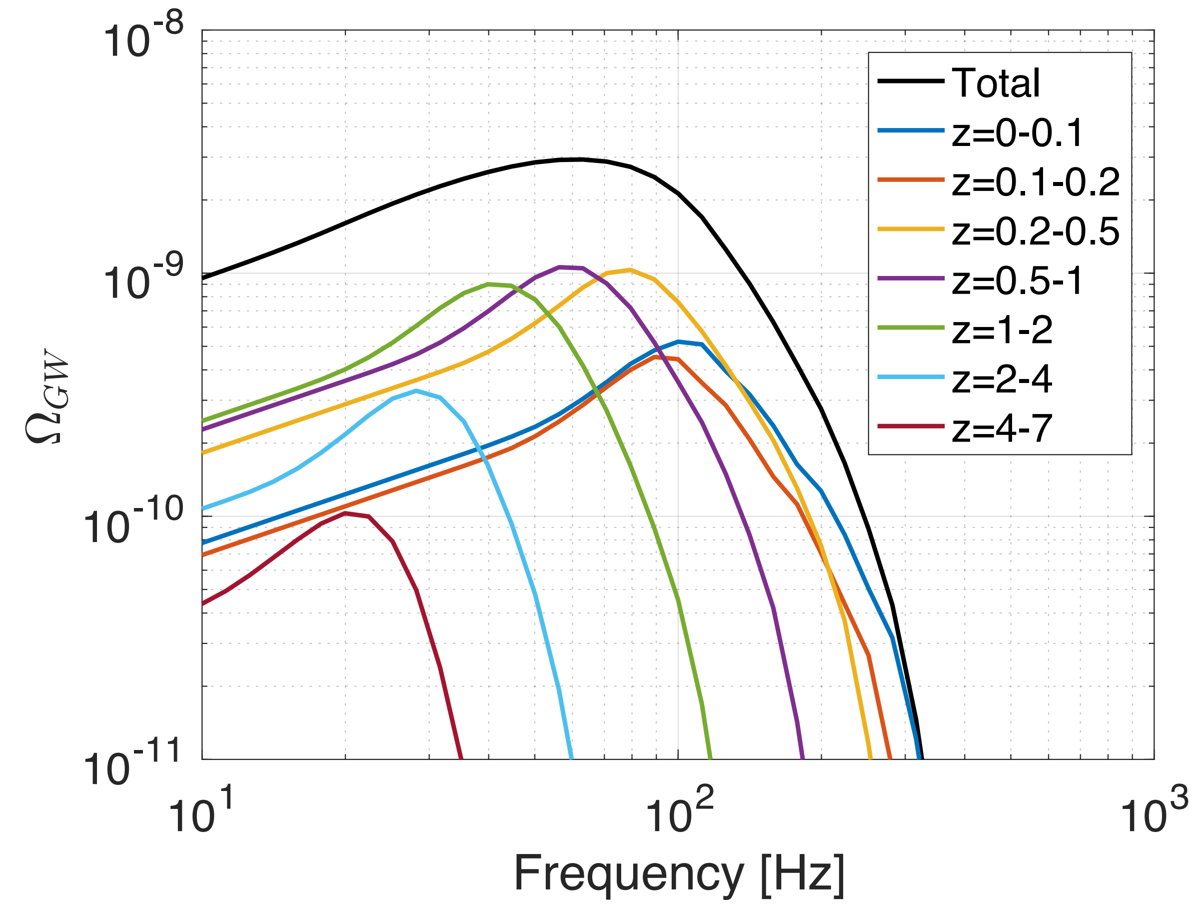


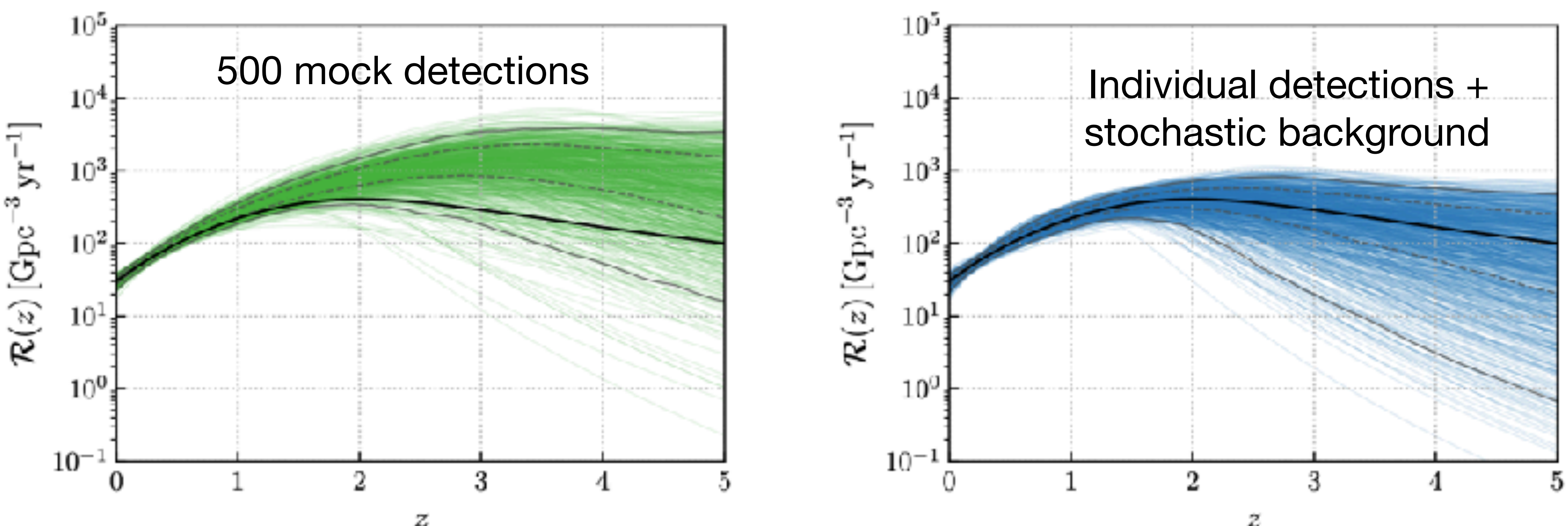
High frequency: stellar-mass binaries

- Energy density of the stochastic background:

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

- Probe of high-redshift source population

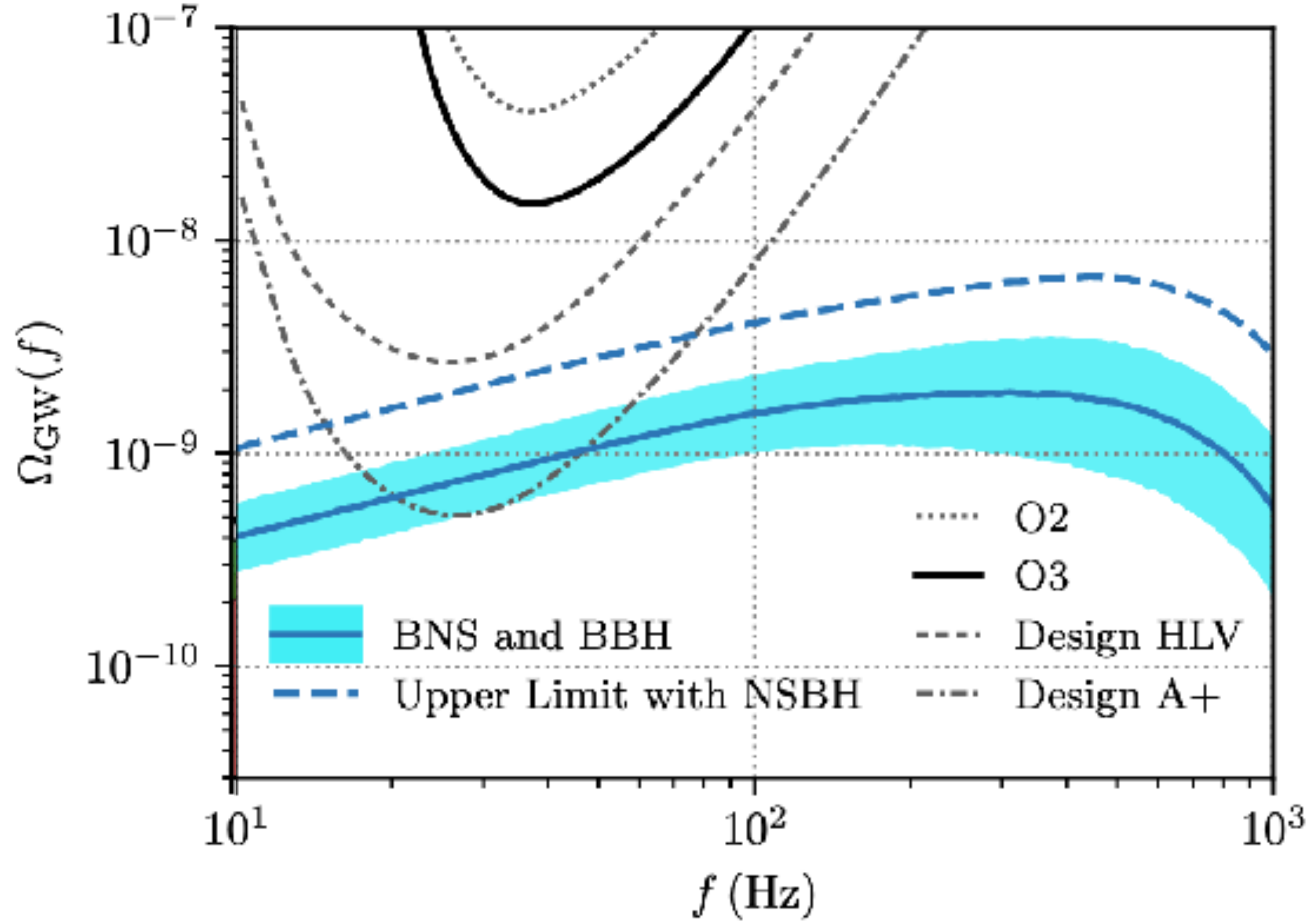


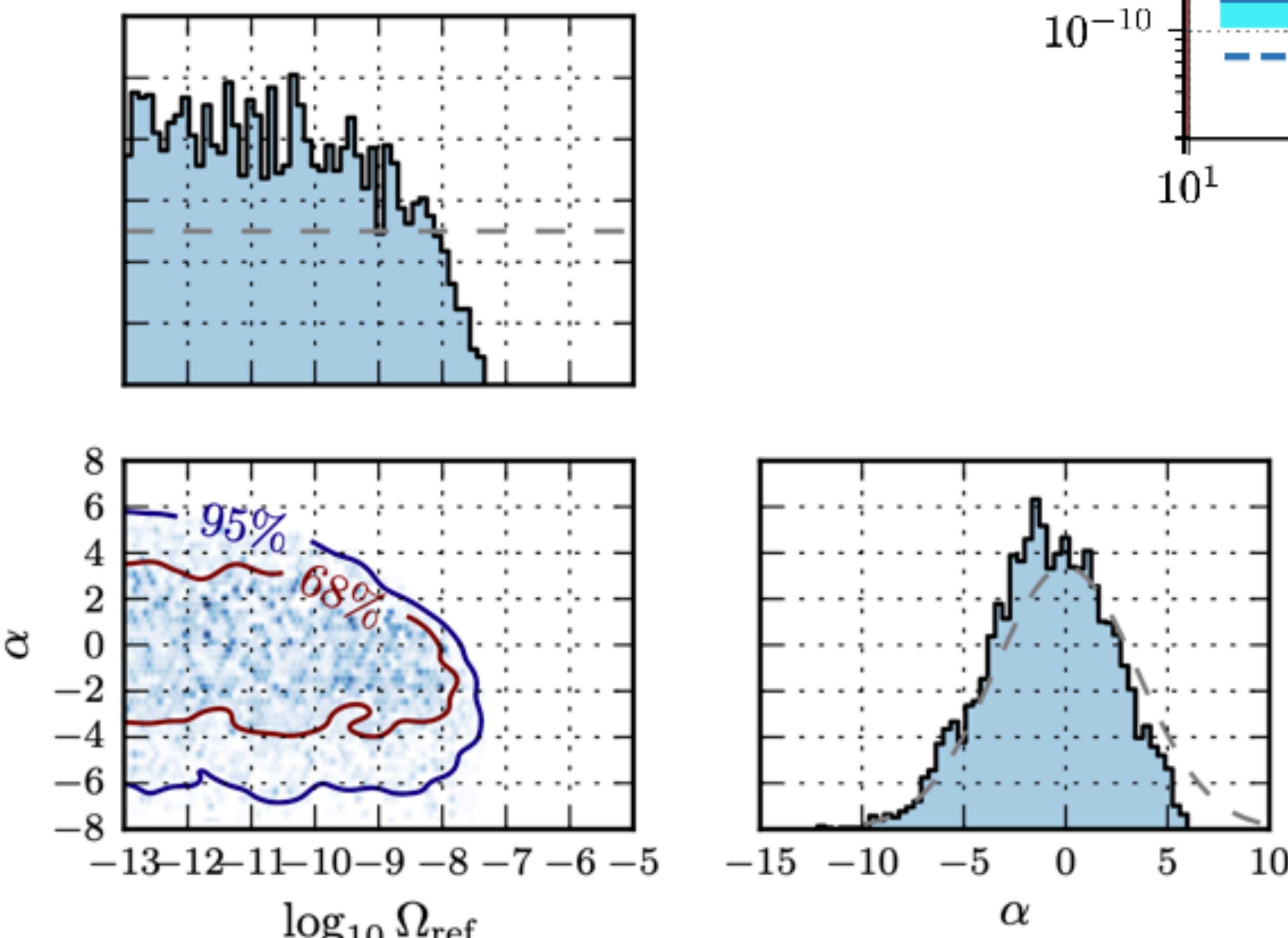


[Callister+2020]

 [LVK 2021]

- Upper limits from past runs consistent with expected signal
- Possible detection in the coming years: better sensitivity, more data…





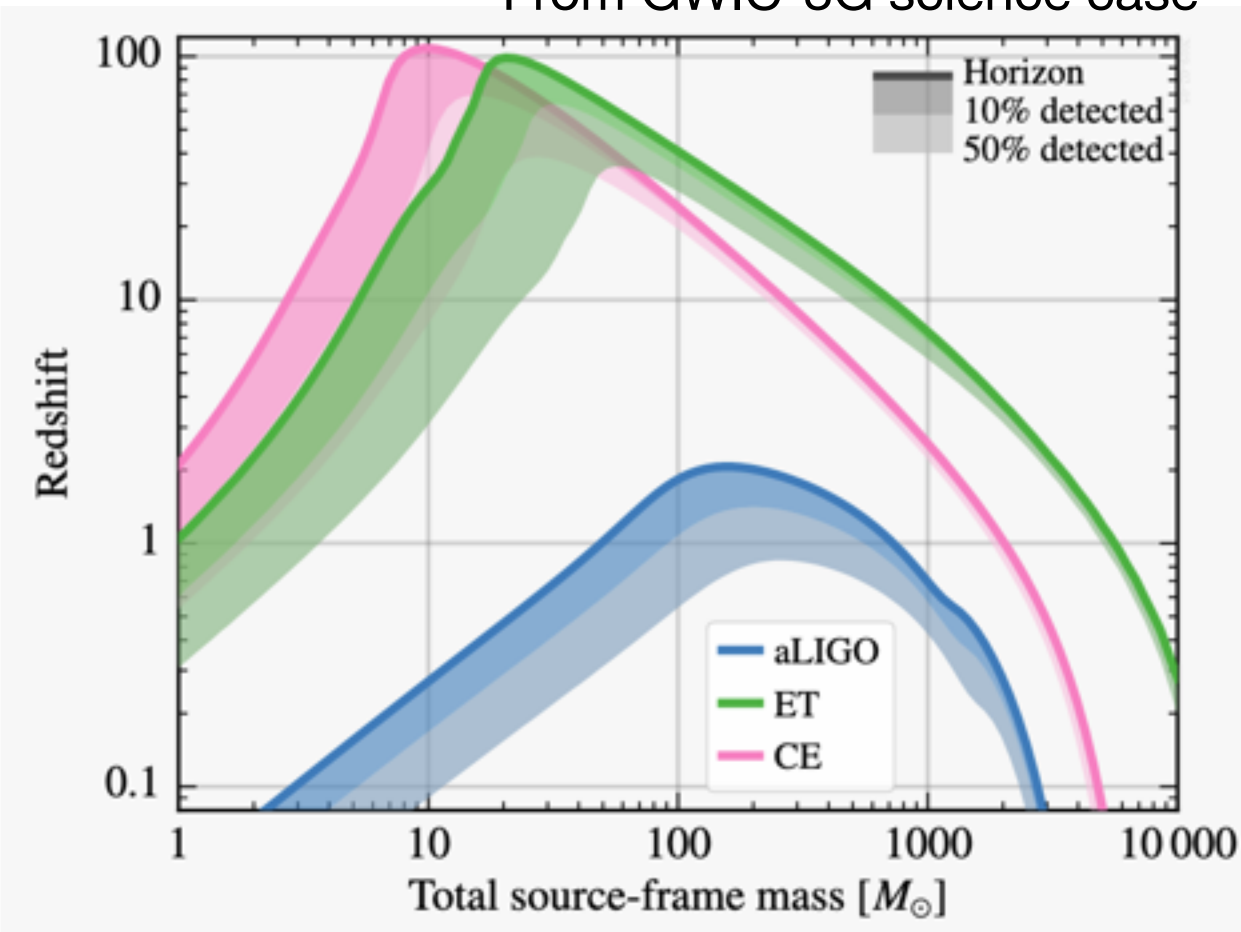
Power-law background:

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

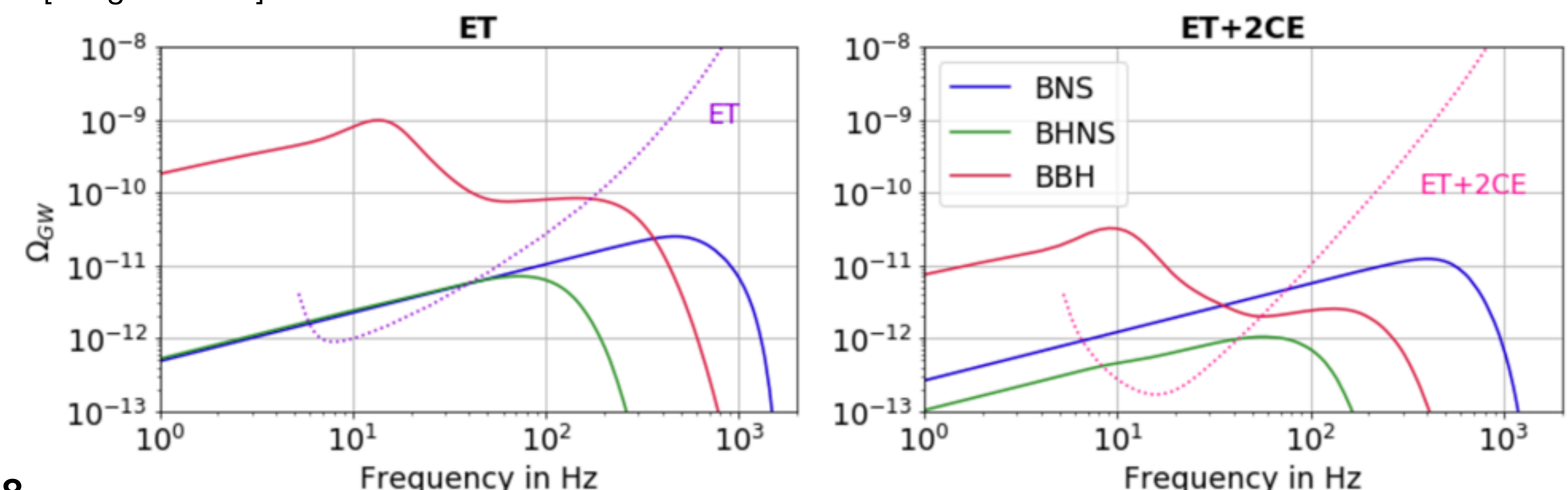
High frequency - next generation: stellar-mass binaries

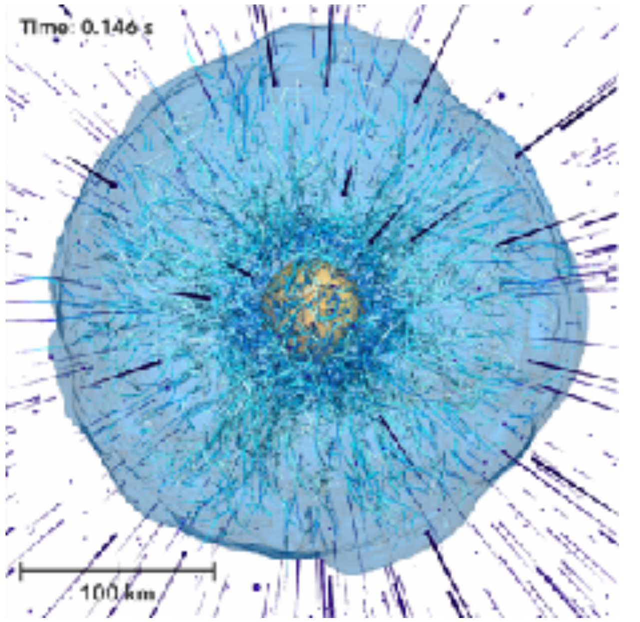
- 3G detectors will detect sources out to very high redshifts
- Fewer unresolved sources
- Better sensitivity
- Binary neutron stars: overlap in time

From GWIC-3G science case



[Perigois+2021]





[Burrows&Vartanyan 2021]

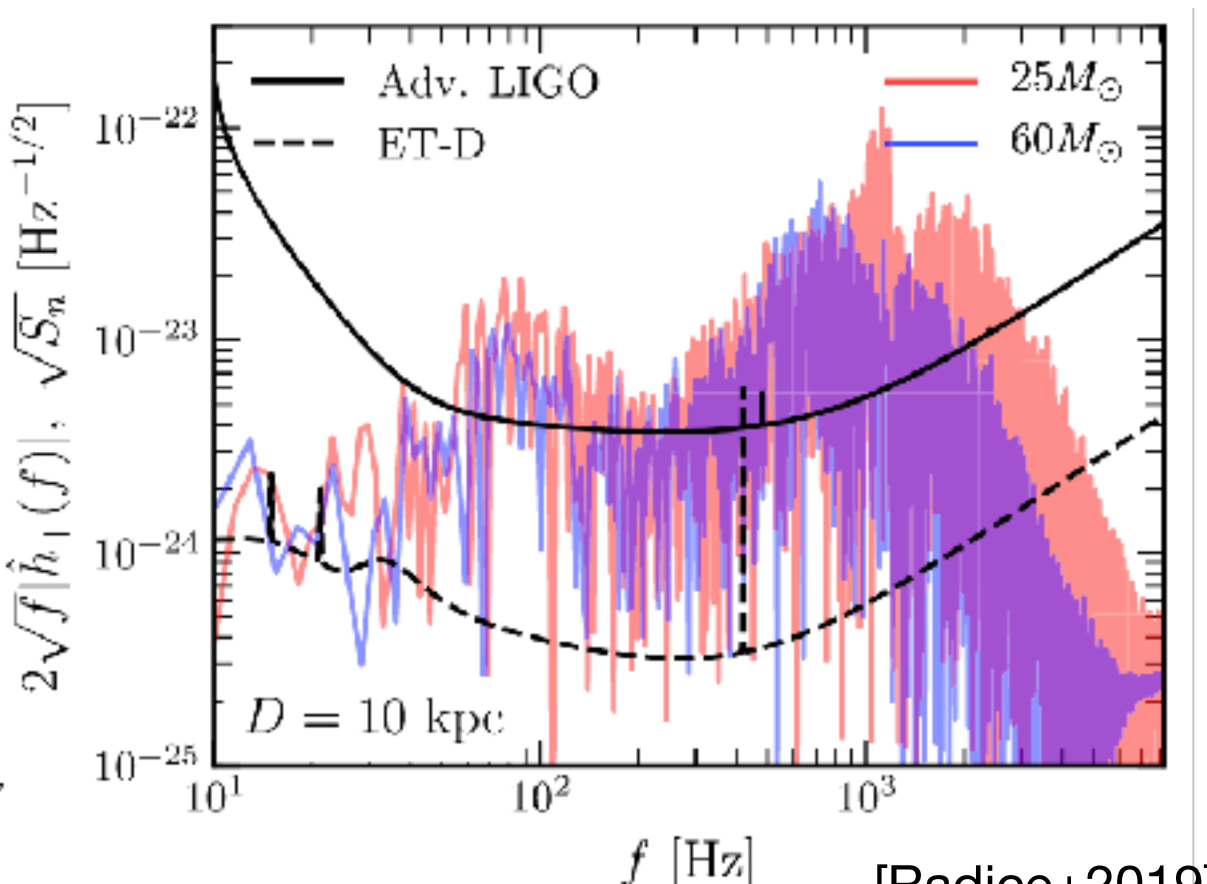
Generation of GW in the central region of the supernova

- Assymetrical flows (neutrino convection, hydro instabilities)
- Proto-neutron star oscillations and rotating non-axisymmetric shape
- Aspherical shock expansion

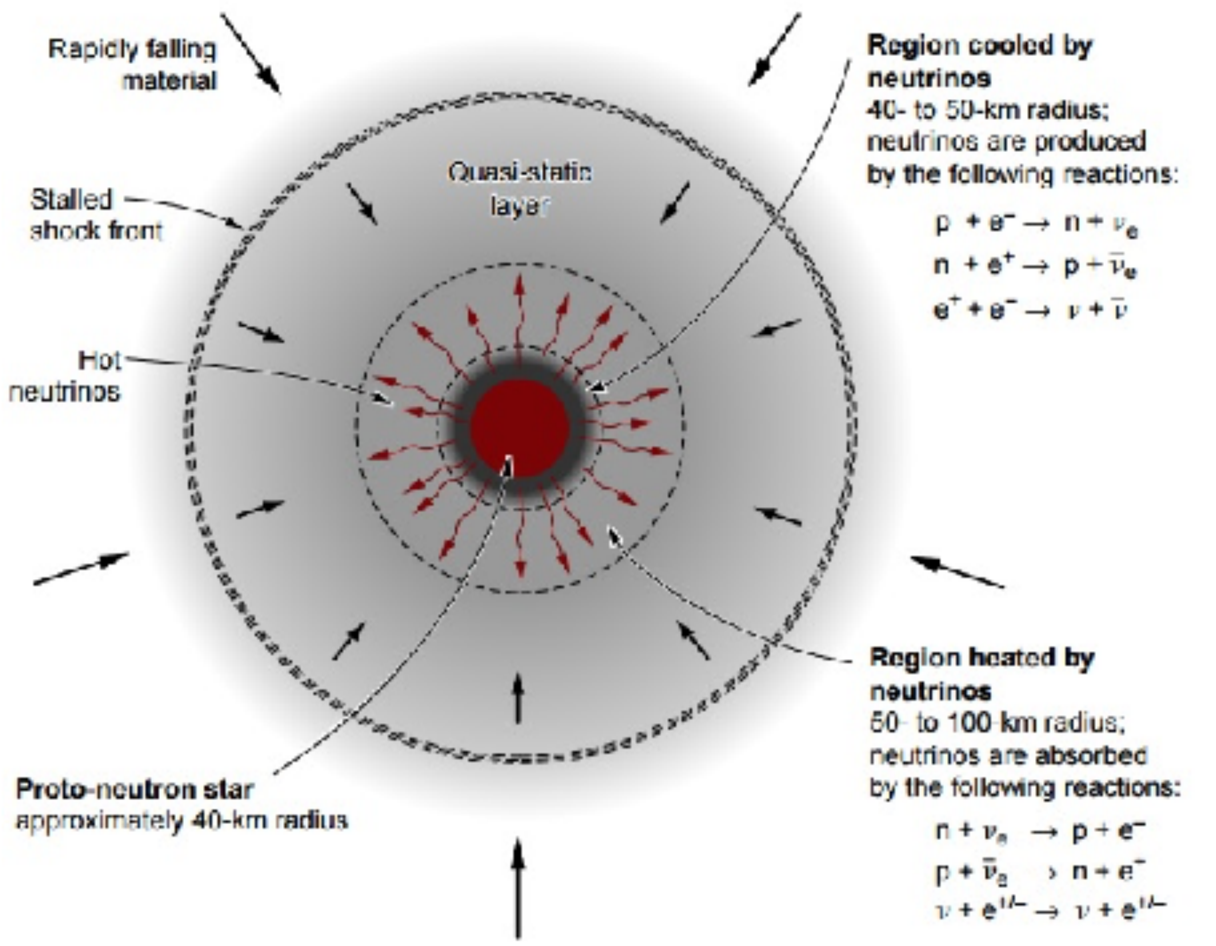
Unique information on:

- Mechanism of the central engine
- Dynamics that produced the explosion
- Structure of the inner region

- If a black hole forms: GW from ringdown



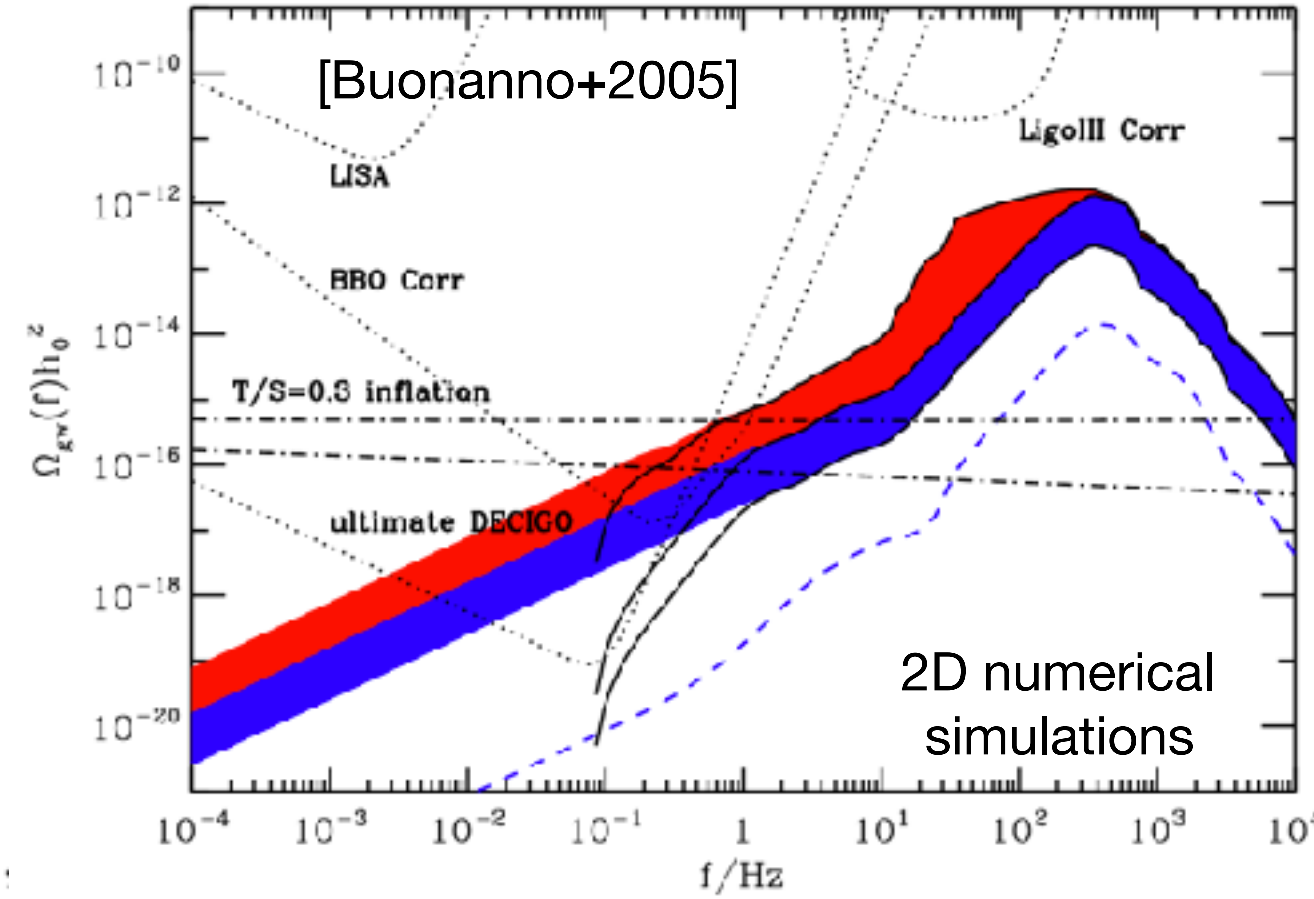
[Radice+2019]



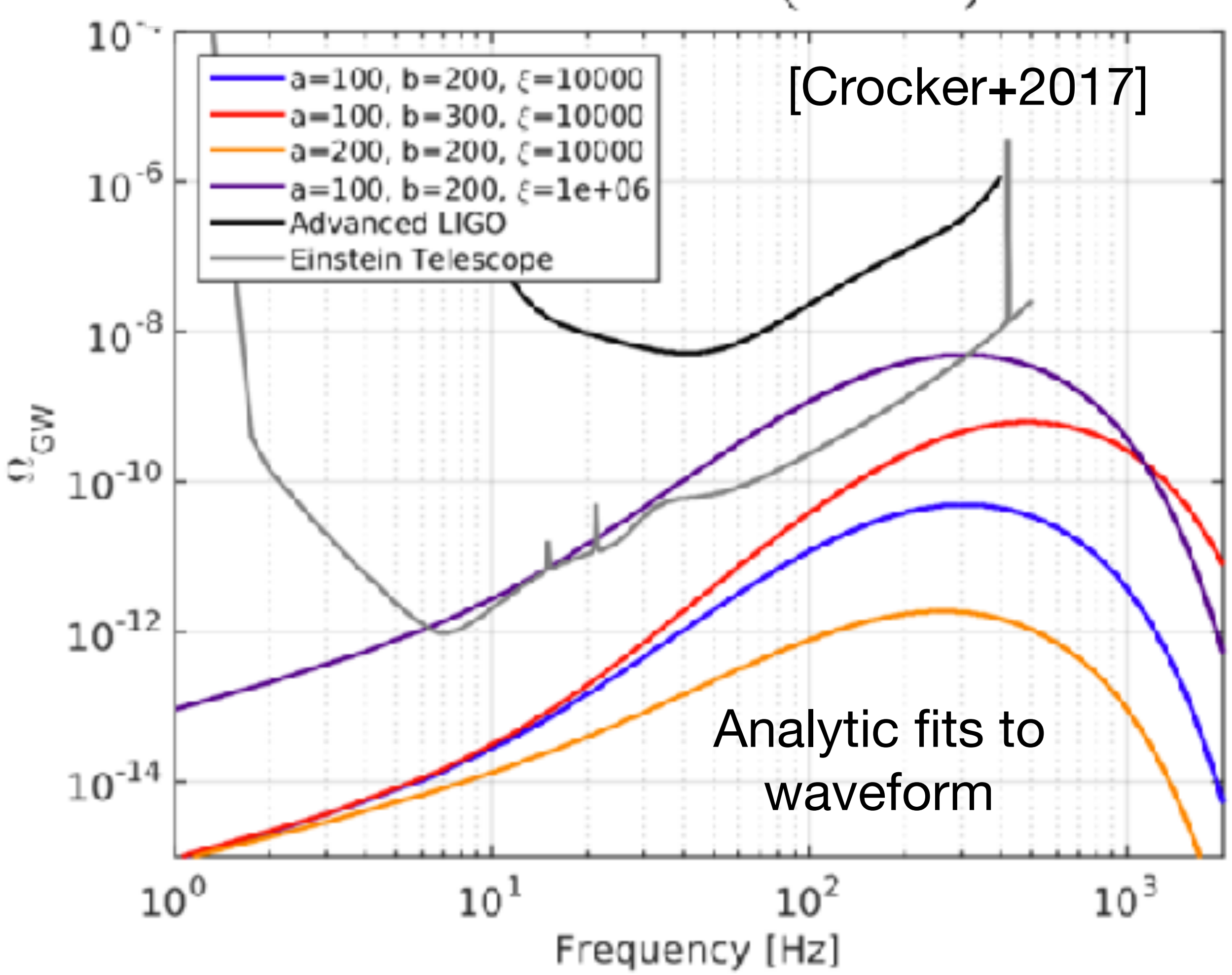
[Persival 2016]

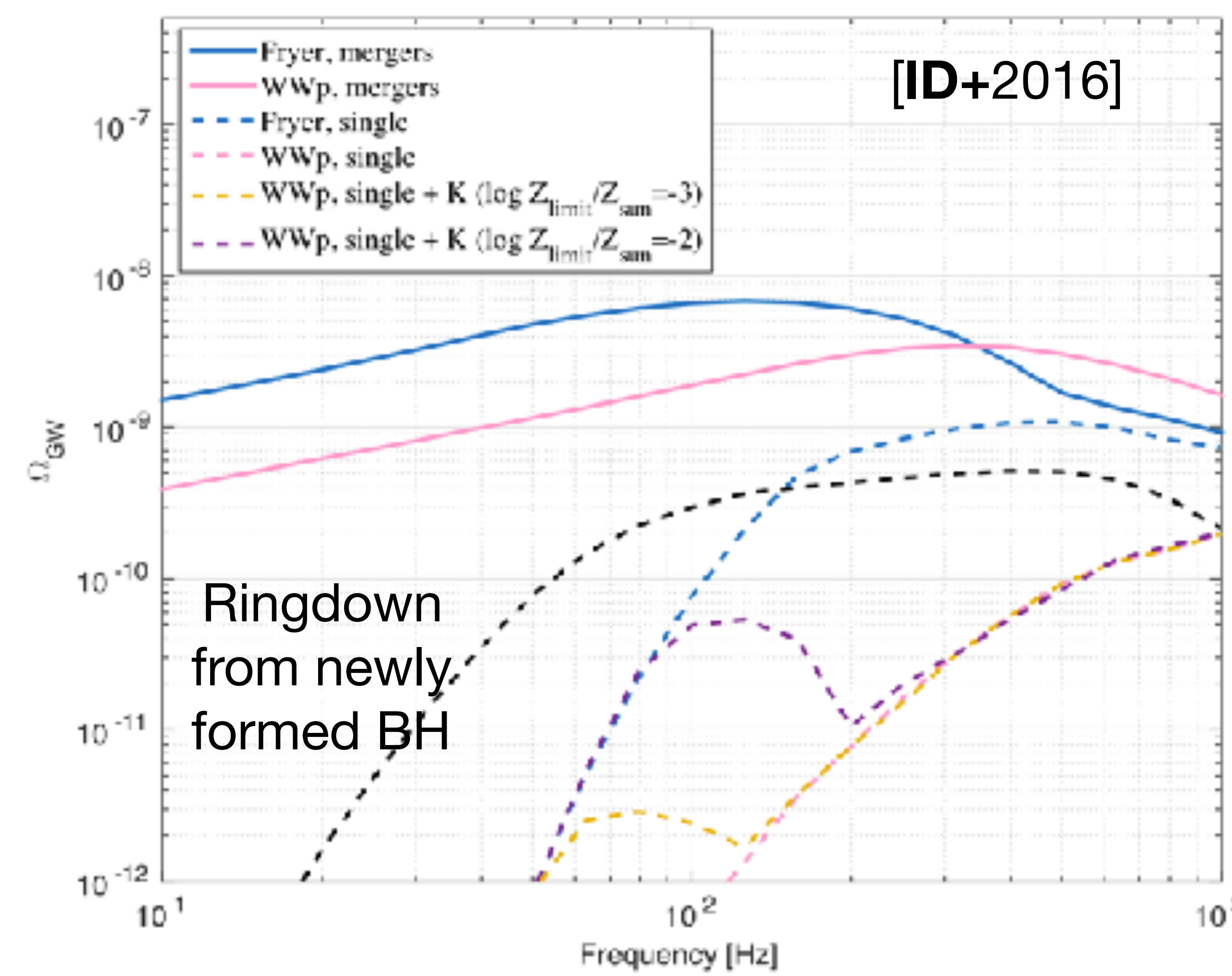
High frequency: collapsing stars

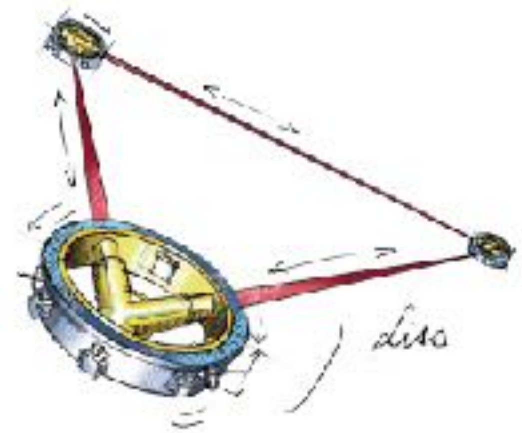
- Predictions for stochastic background difficult because of uncertainties in the waveform
- What is dependence on the progenitor?
- Does rotation influence the signal?

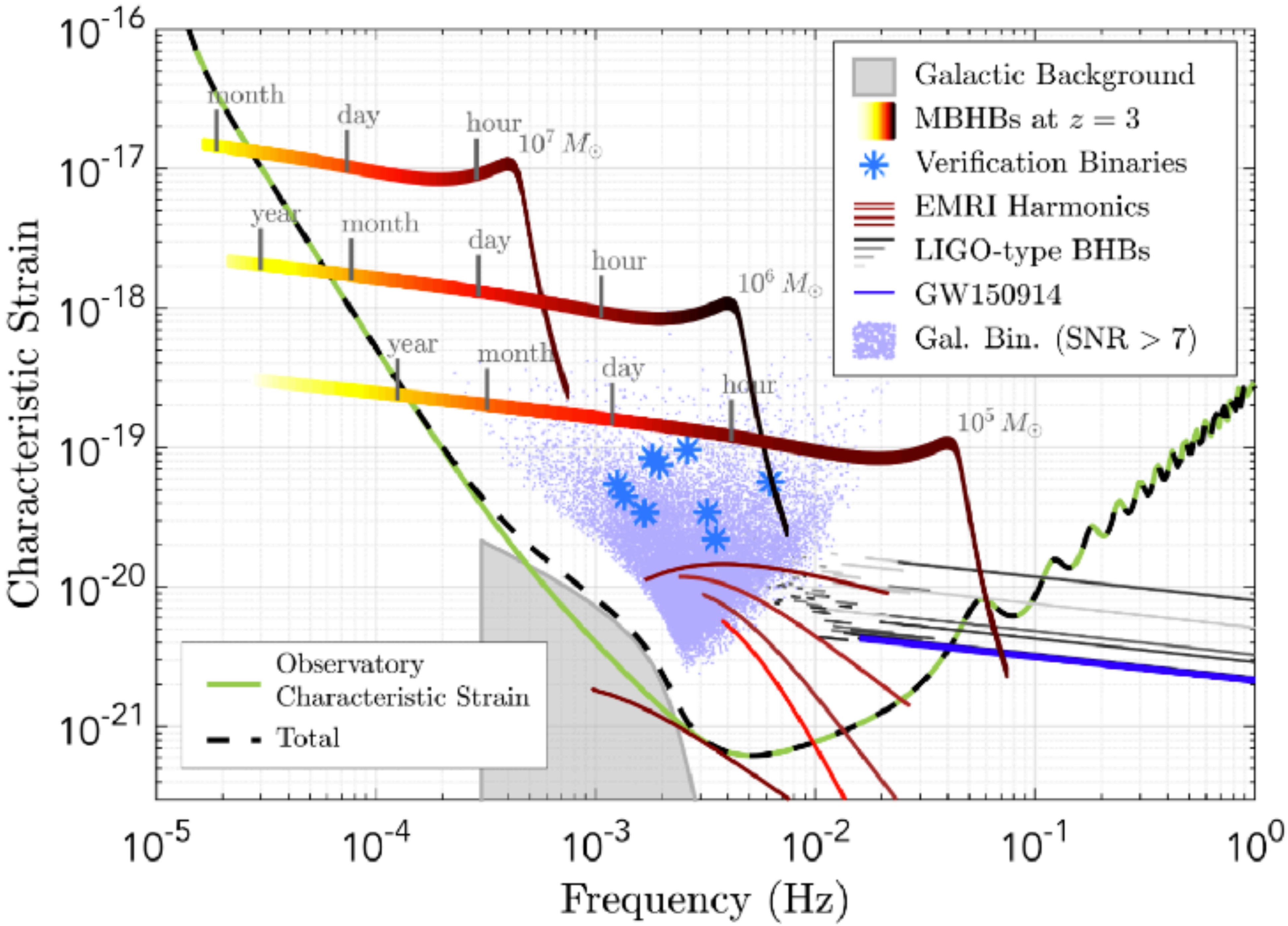


$$f_e|\tilde{h}(f_e)| = \frac{G}{\pi c^4 D} E_\nu \langle q \rangle \left(1 + \frac{f_e}{a}\right)^3 e^{-f_e/b},$$



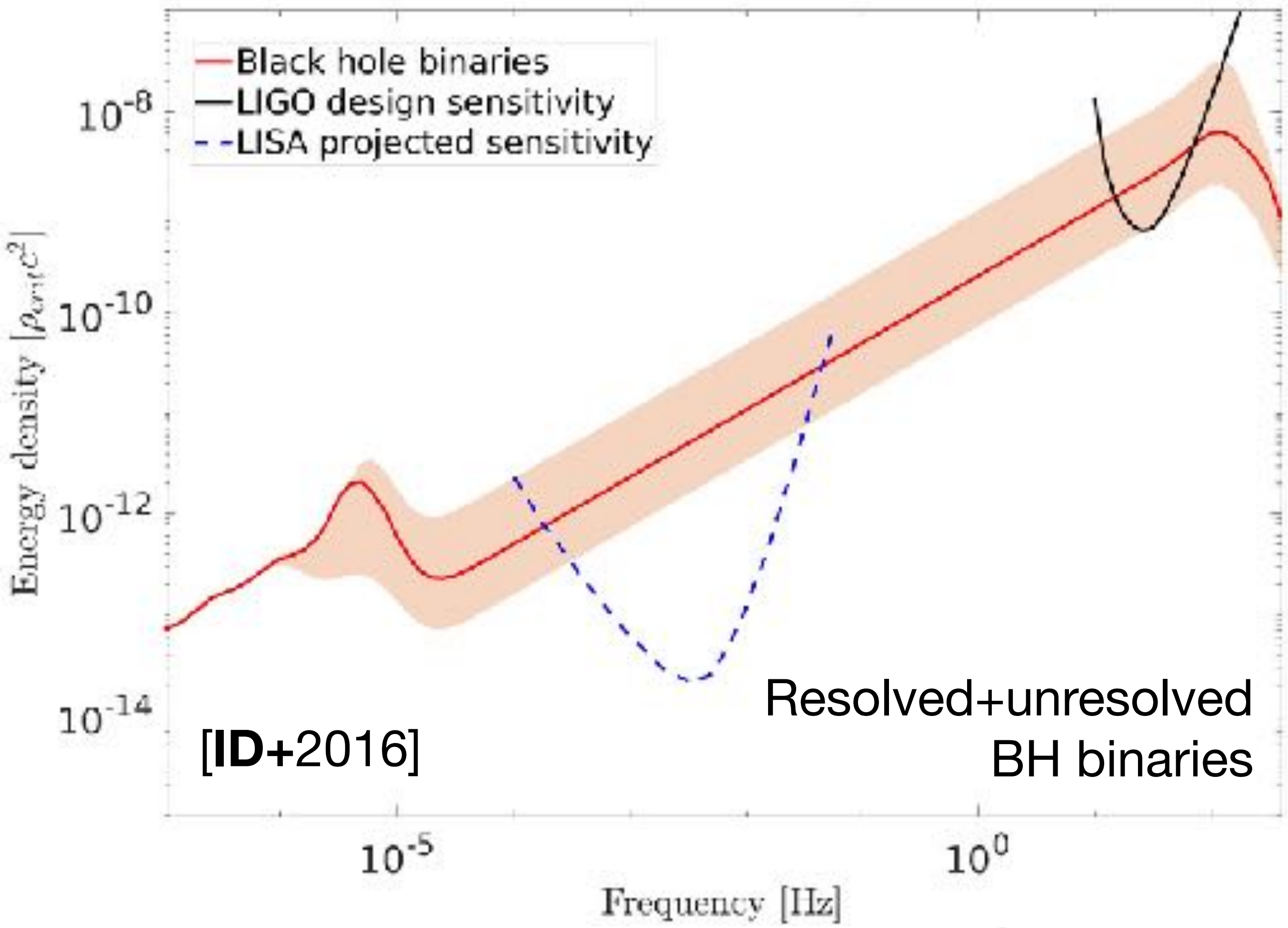






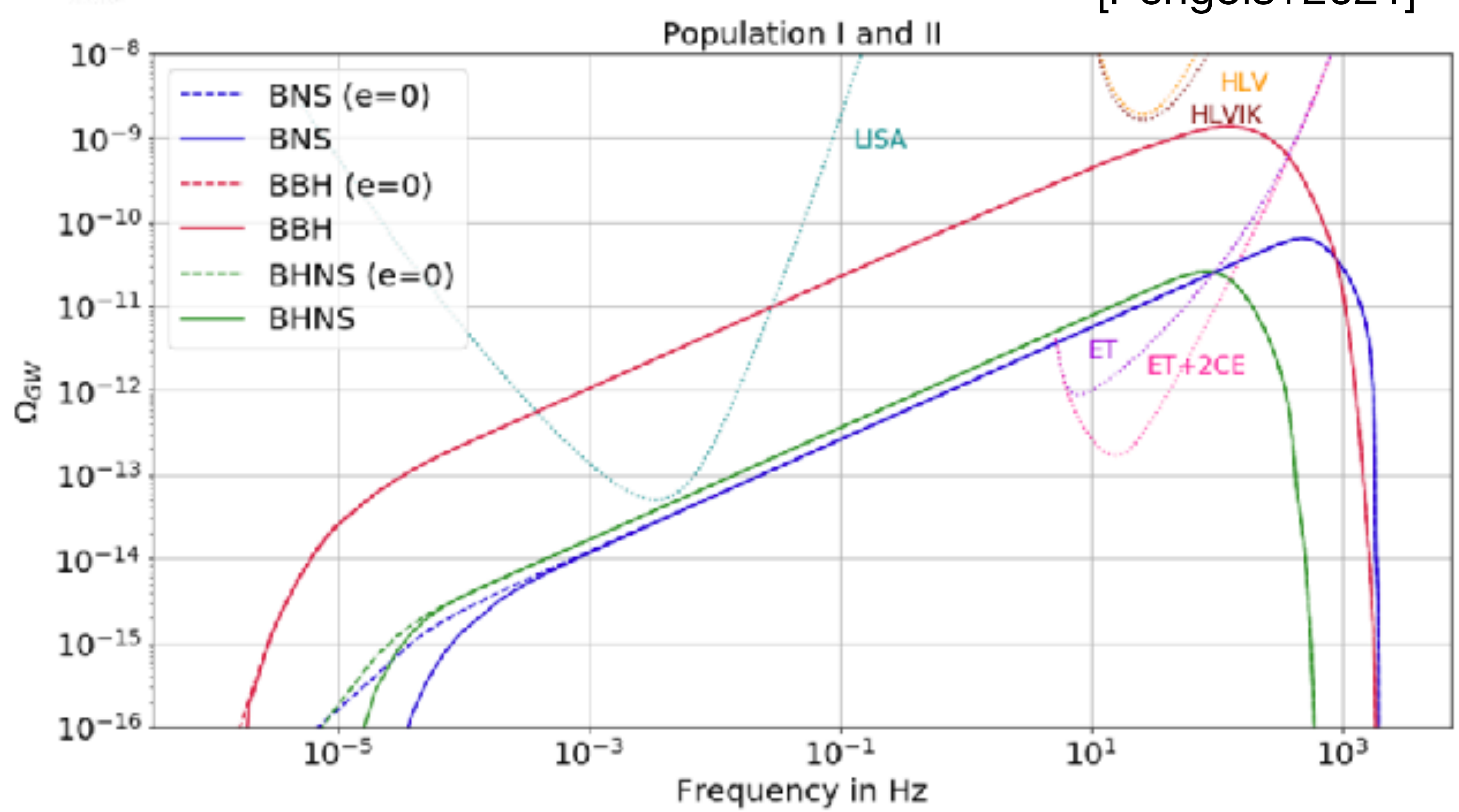
From LISA L3 Mission Proposal

Intermediate frequencies: stochastic backgrounds from stellar-mass binaries



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

[Perigois+2021]

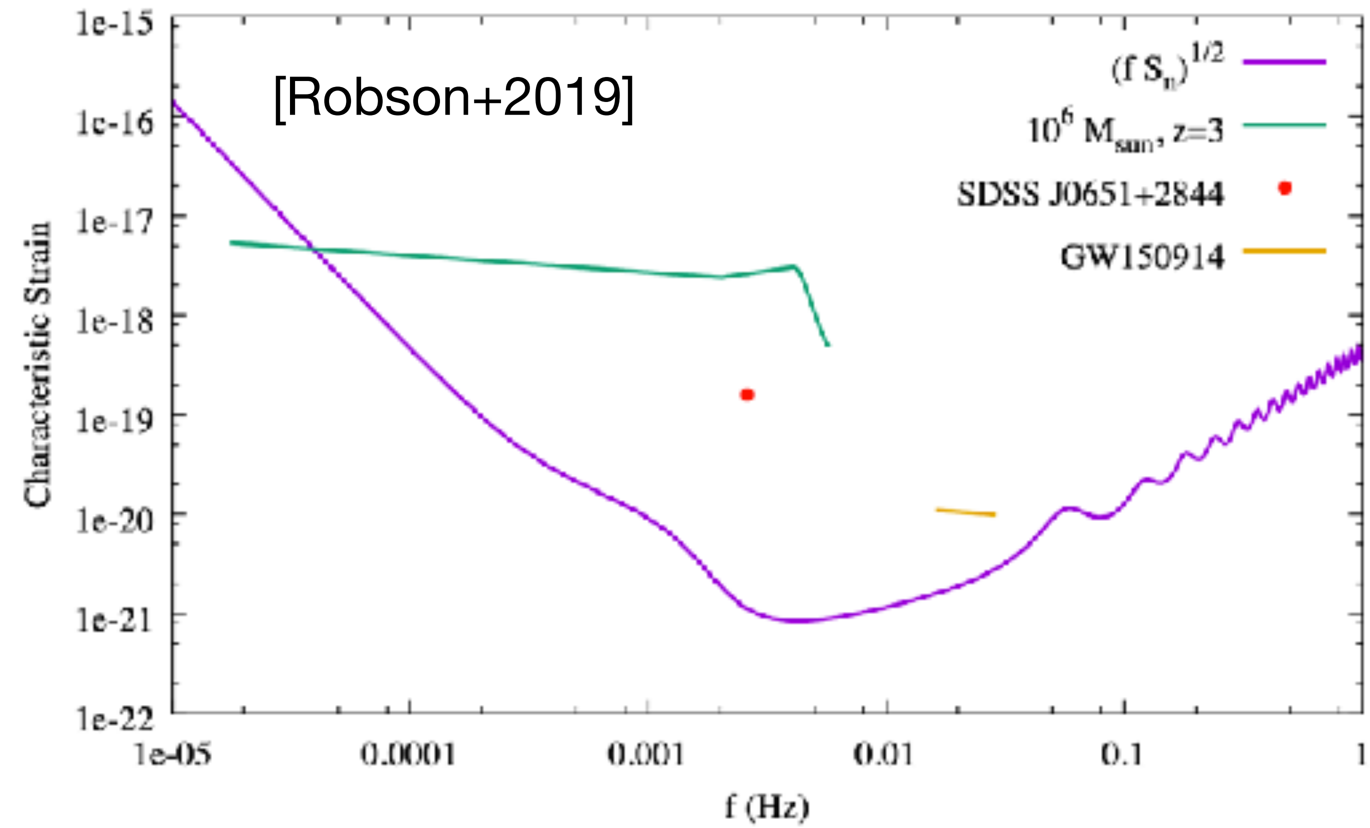


- Local rate measurements with LIGO/Virgo/Kagra will allow to provide precise models for LISA

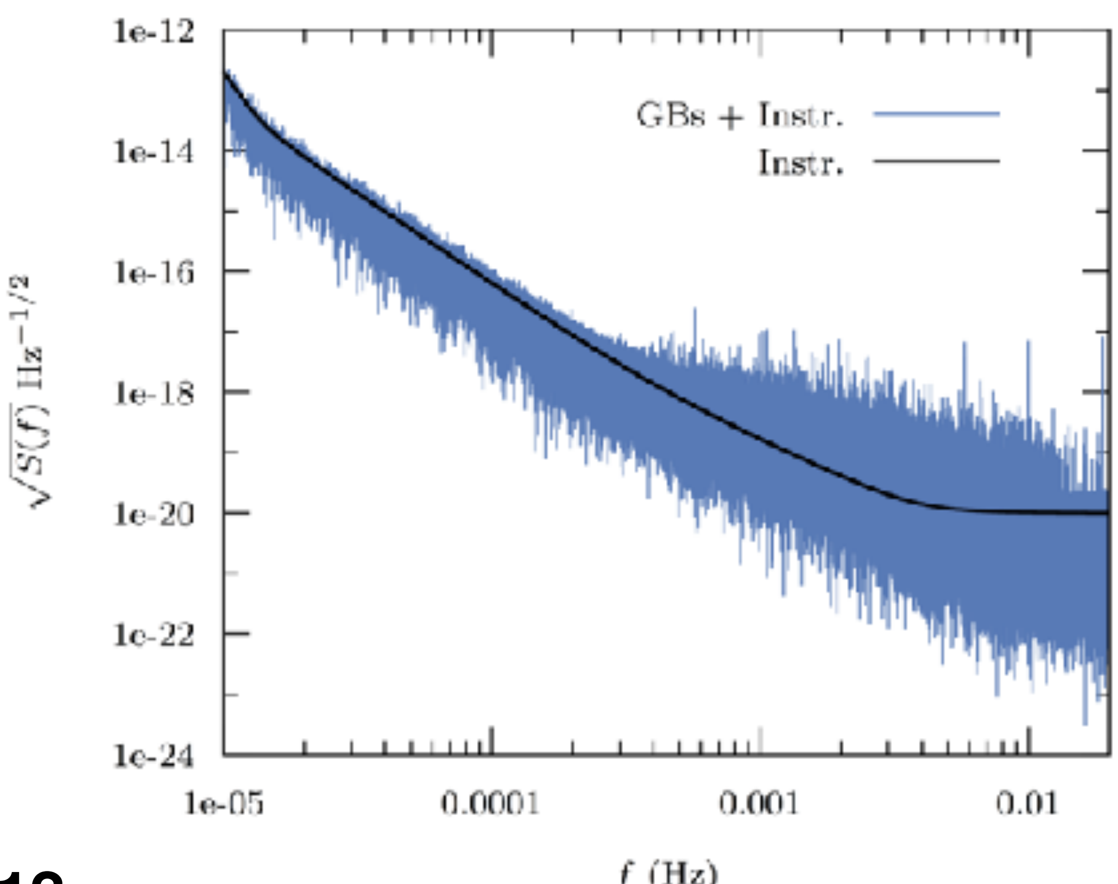
[see also Zhao&Lu 2020]

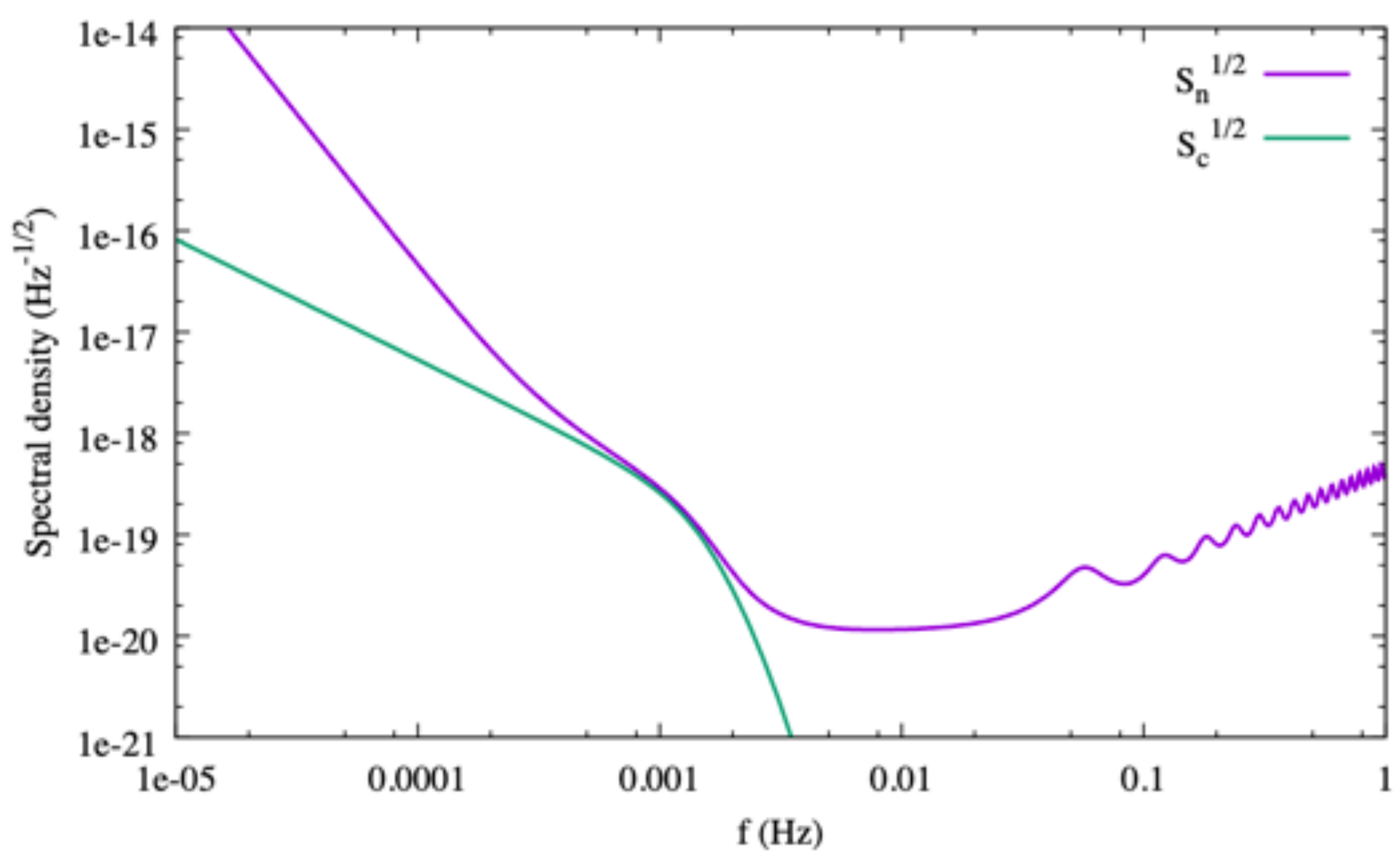
Intermediate frequencies: double white dwarfs

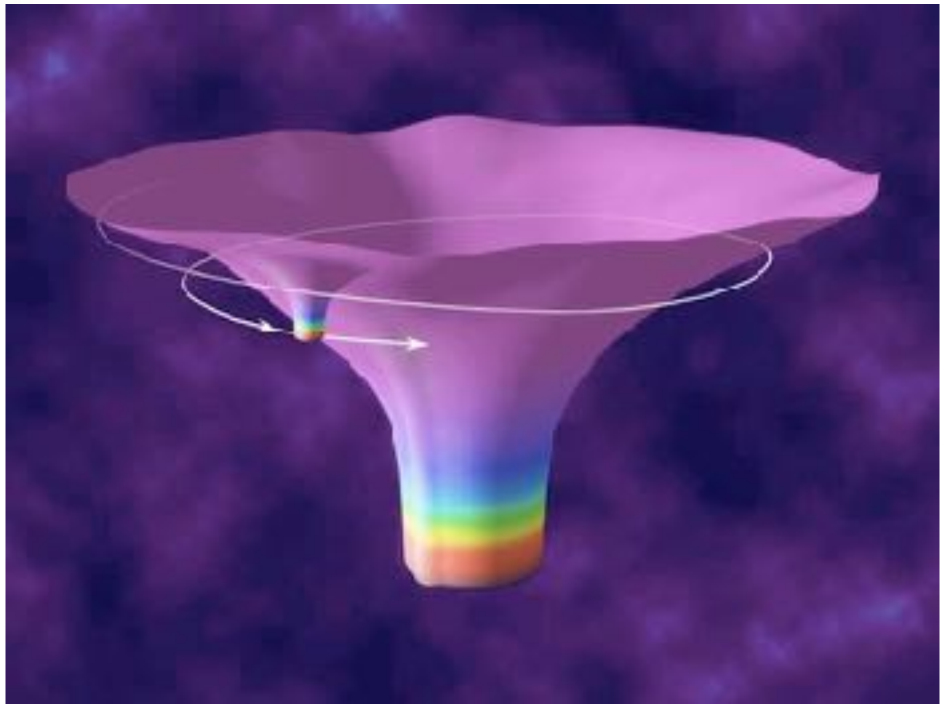
- 10^8 double white dwarfs in Milky Way
- Monochromatic sources in LISA band
- Confusion noise dominates instrument noise in the mHz band



[Robson & Cornish 2017]





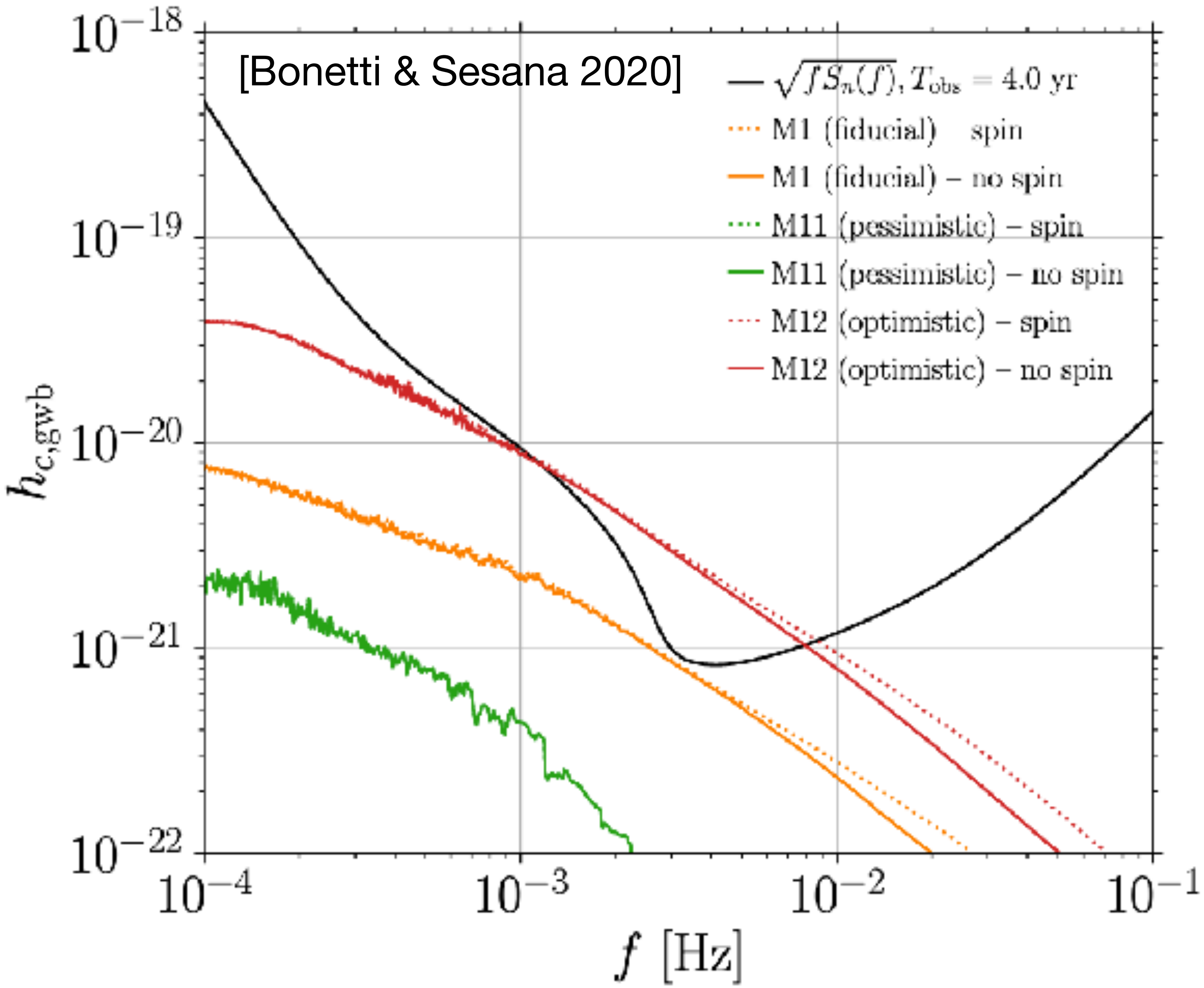


- Stellar-mass black holes orbiting massive black holes

$$M_{BH} \sim 10^5 - 10^7 M_\odot$$

$$m_{BH} \sim 10 - 50 M_\odot$$

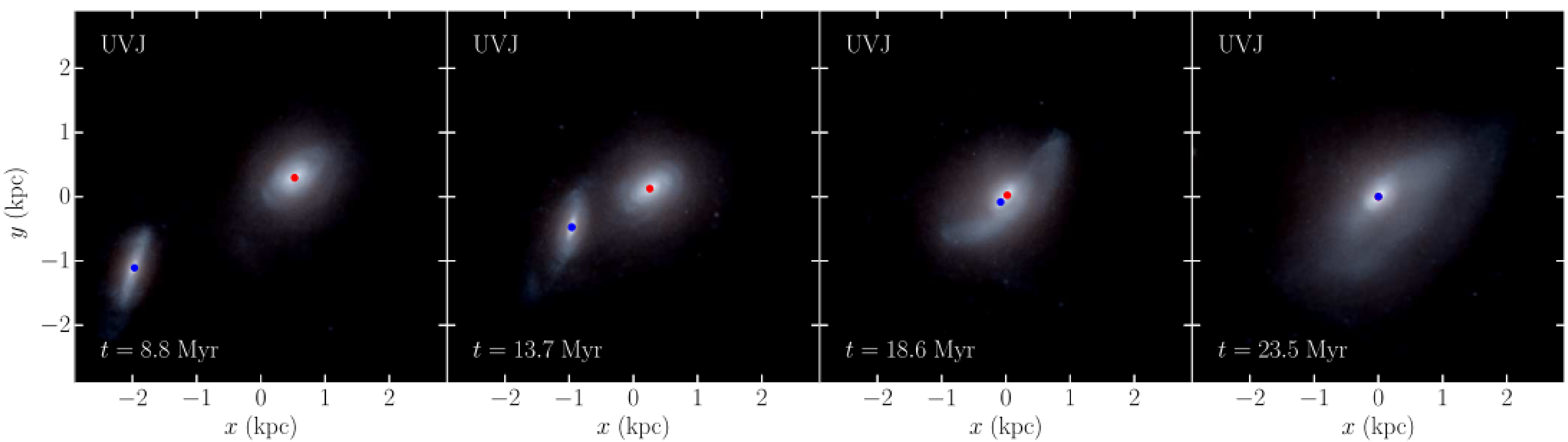
- Expected to form in dense galactic centers
- LISA detection rates: $1 - 10^4 \ yr^{-1}$ [Babak+2017]



Massive and super-massive black hole binaries

$$M_{BH} \sim 10^7 - 10^9 M_\odot$$

- Most galaxies have massive black holes in their centers
- When galaxies merge, their black hole can form a bound binary and eventually merge
- Key processes still unknown:
  - Seeds of massive black holes
  - Co-evolution with host galaxies
  - Interactions with surrounding gas and stars



[Khan et al. (2016)]

- Massive black hole binaries are prime target for LISA
- Large uncertainties in expected rates:

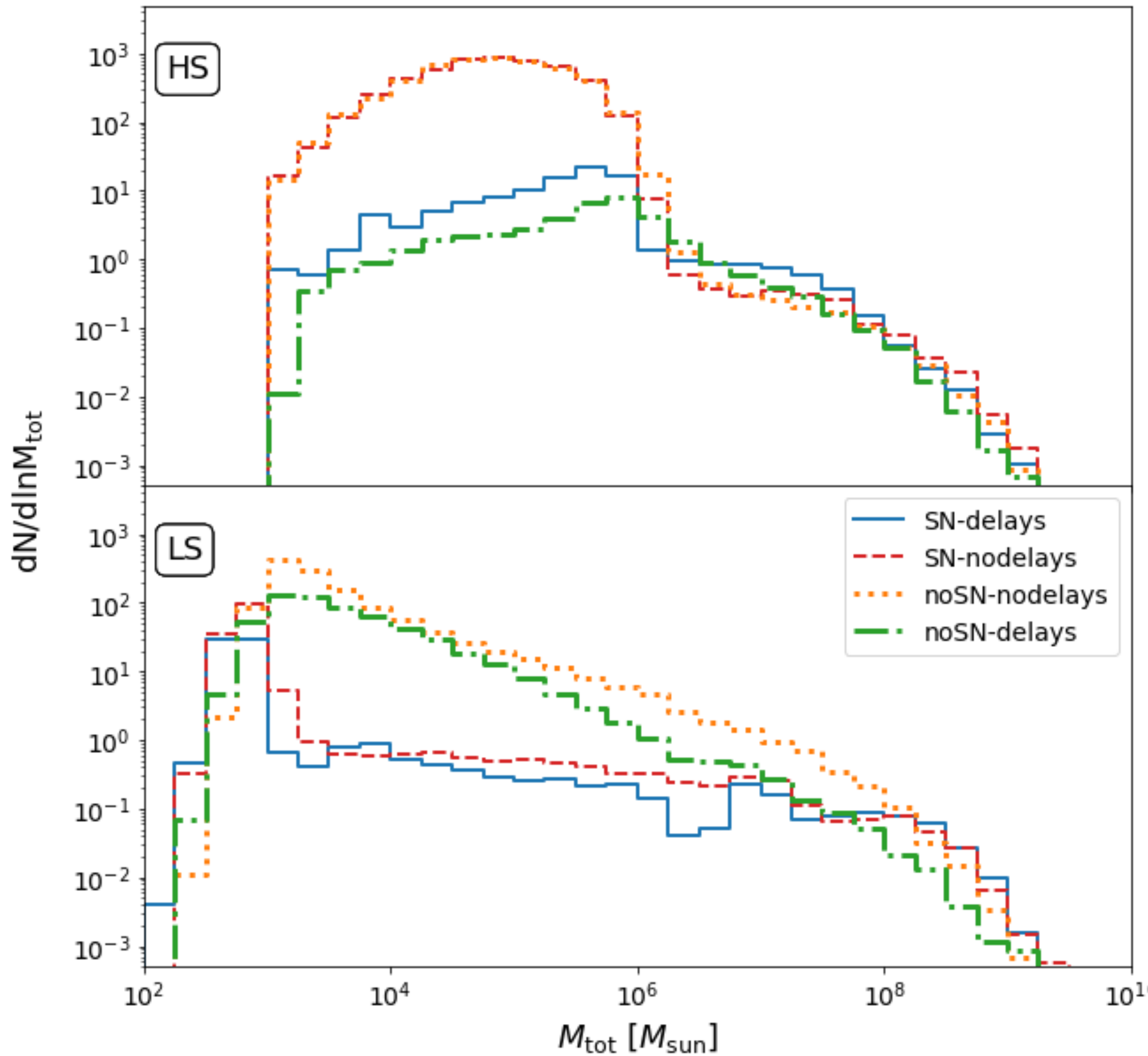
Semi-analytic models:

$$10 - 100\, yr^{-1}$$

Hydro simulations:

$$0.5 - 2\, yr^{-1}$$

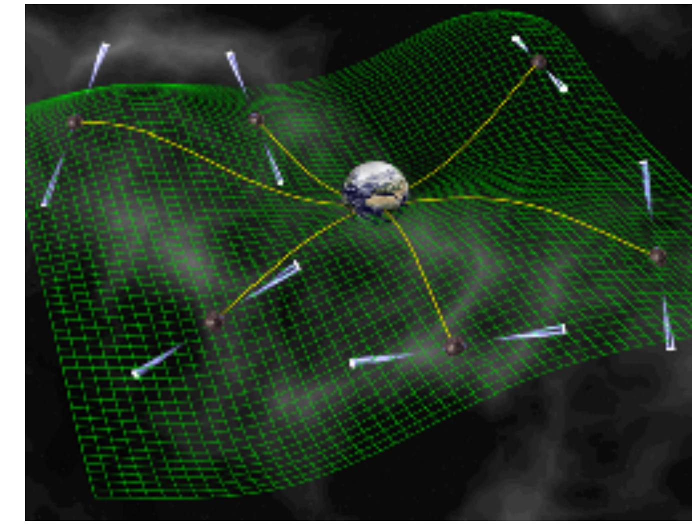
[e.g. Barausse 2012; Sesana+2014; Klein+2016; Dayal+2019; Bonetti+2019; Katz+2019; …]

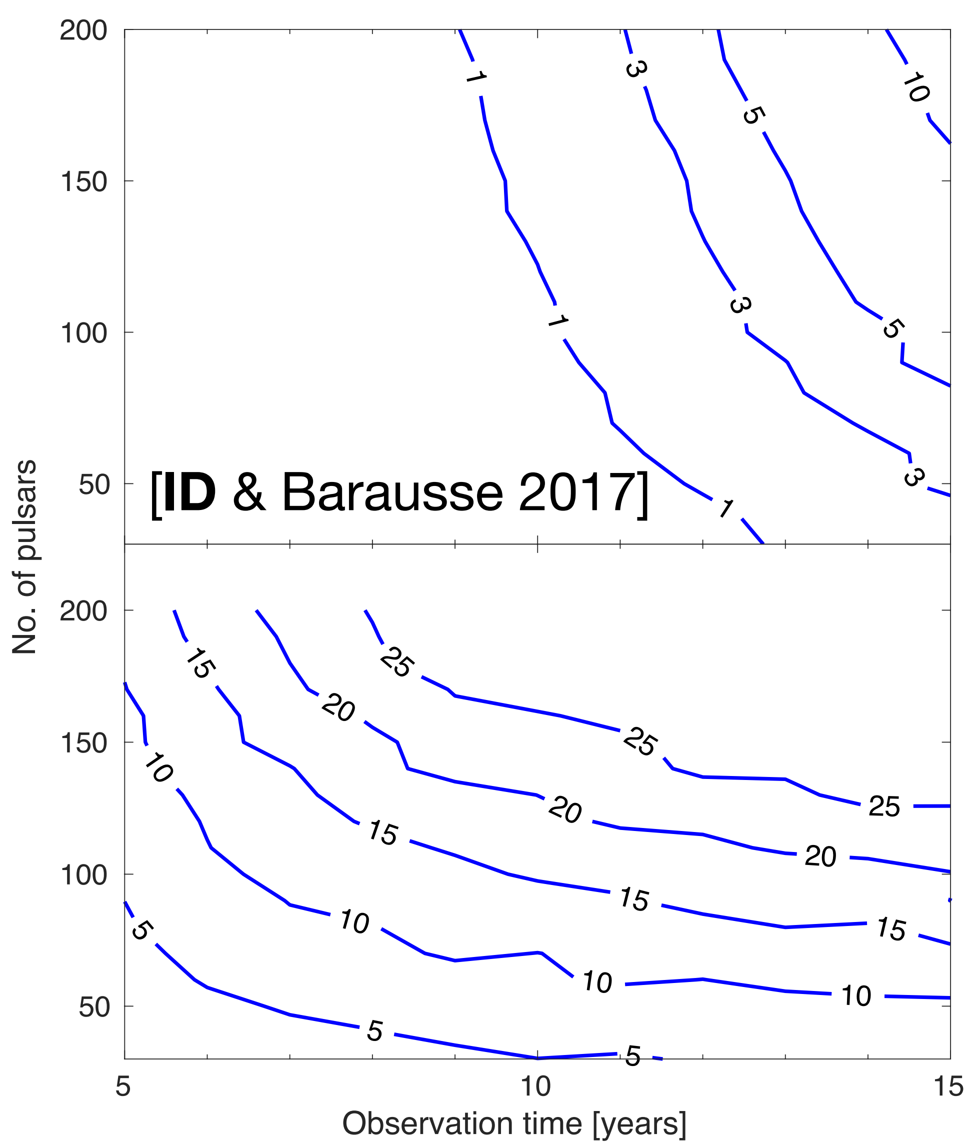


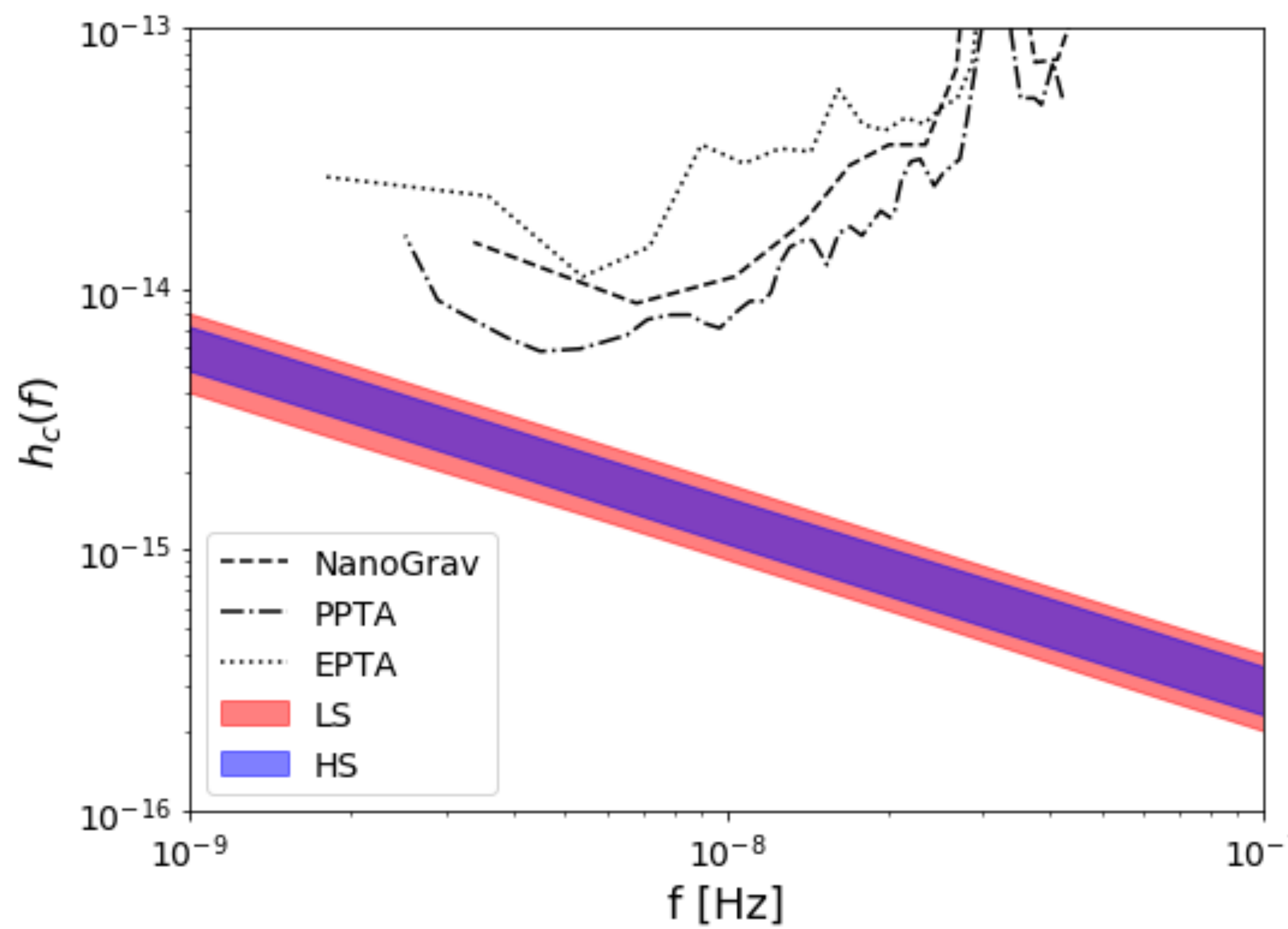
[Barausse, **ID**, Tremmel, Volonteri, Bonetti 2020]

- Super-massive binaries create a stochastic background in the nHz band which is less sensitive to differences between the models
- Very probable upcoming detection with pulsar timing arrays

[e.g. Wyithe&Loeb 2003; Sesana+2008; McWilliams+2014; Bonetti+2017; Kelly+2017; Sesana+2018; Chen+2019 …]

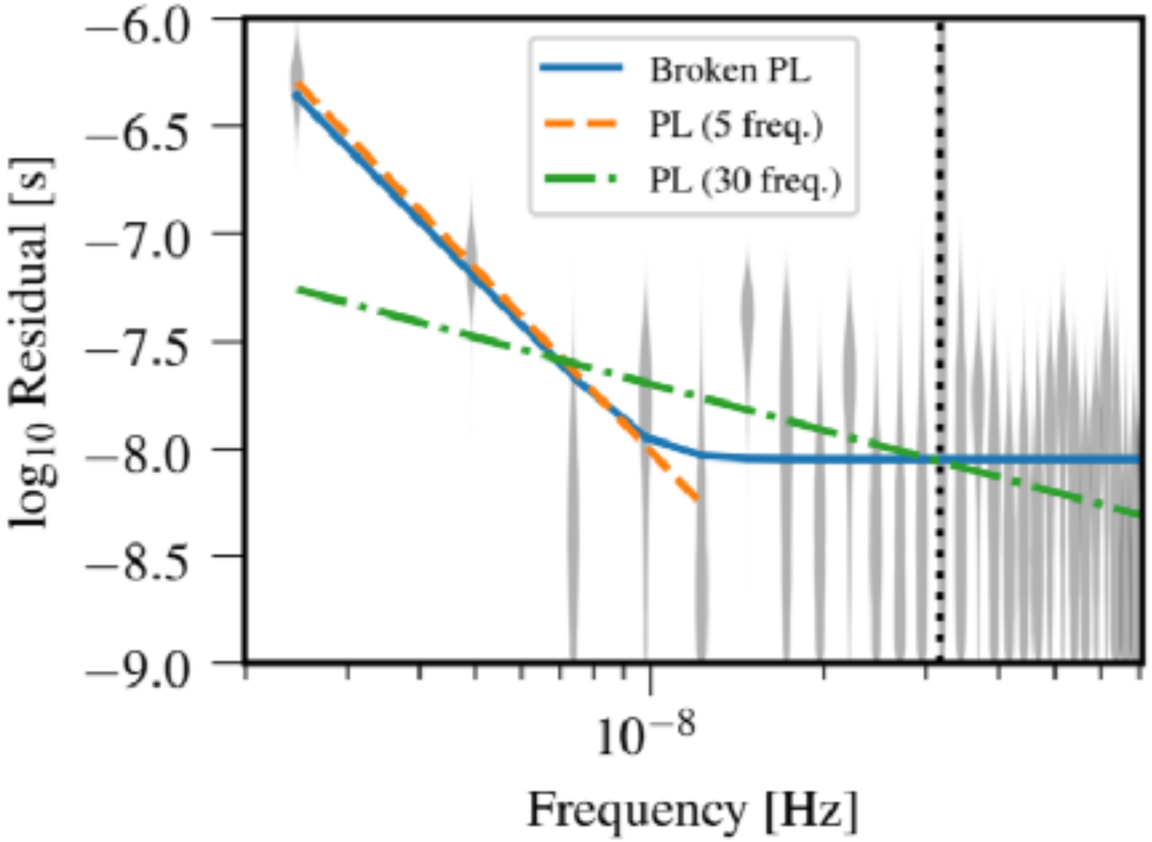


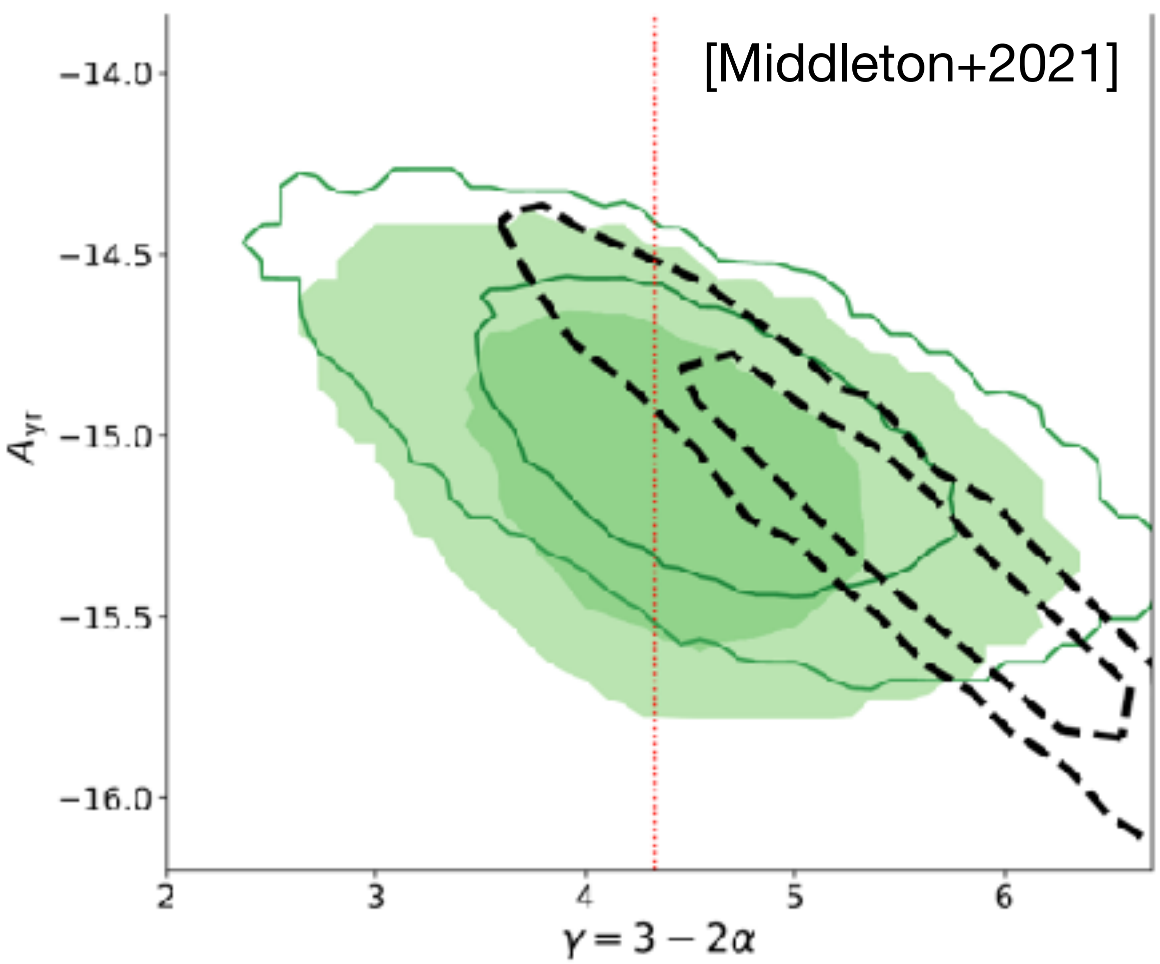




[Barausse, **ID**, Tremmel, Volonteri, Bonetti 2020]

[Arzoumanian+2020]



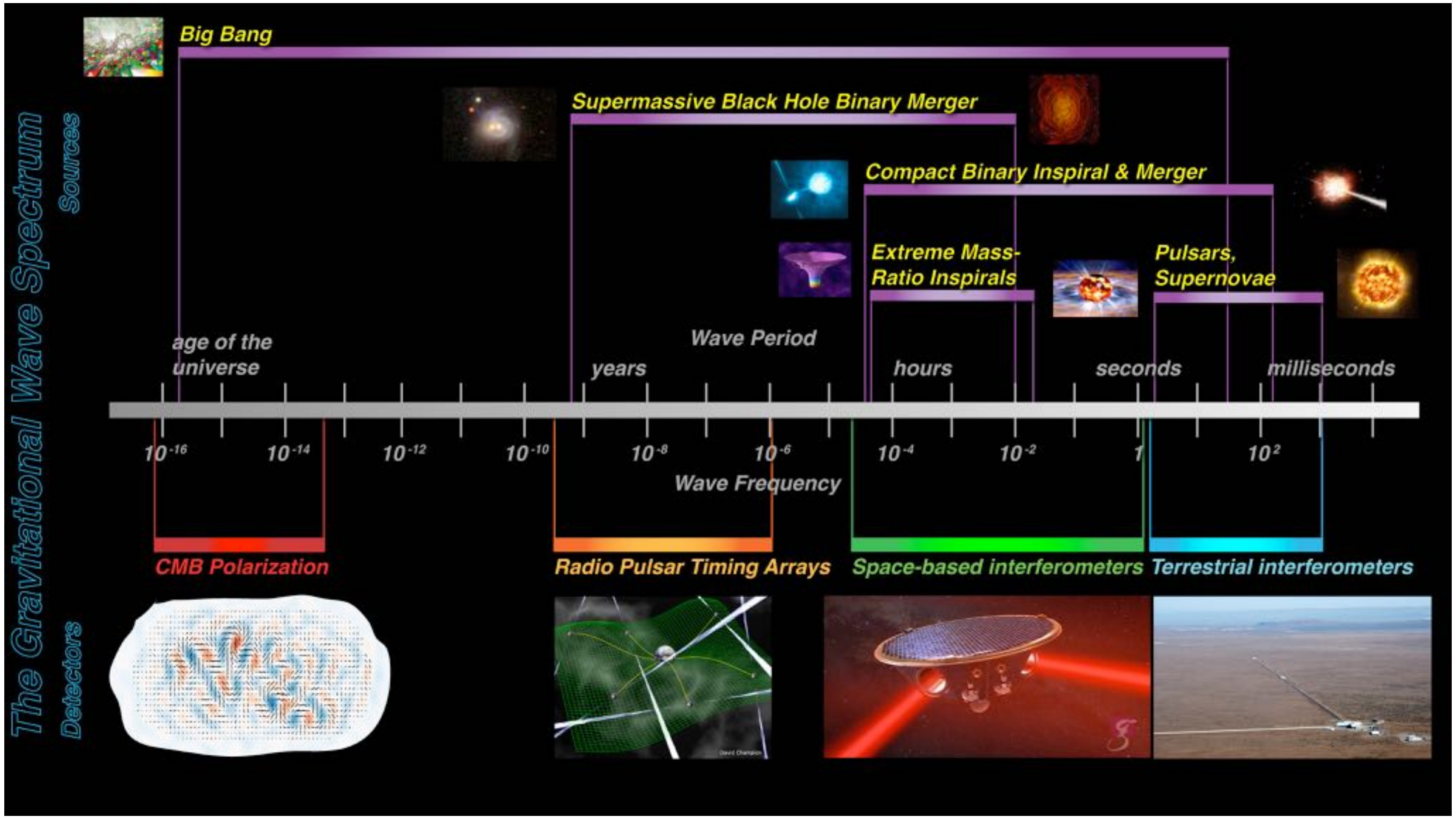


- Tentative detection of a correlated signal by the NANOGrav PTA
- Evidence for a common-spectrum process, but not the correlation expected from a GW signal
- In tension with previous upper limits
- Consistent with signal from black hole binaries
- Consistent with cosmological signals (primordial black holes, cosmic strings…)

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

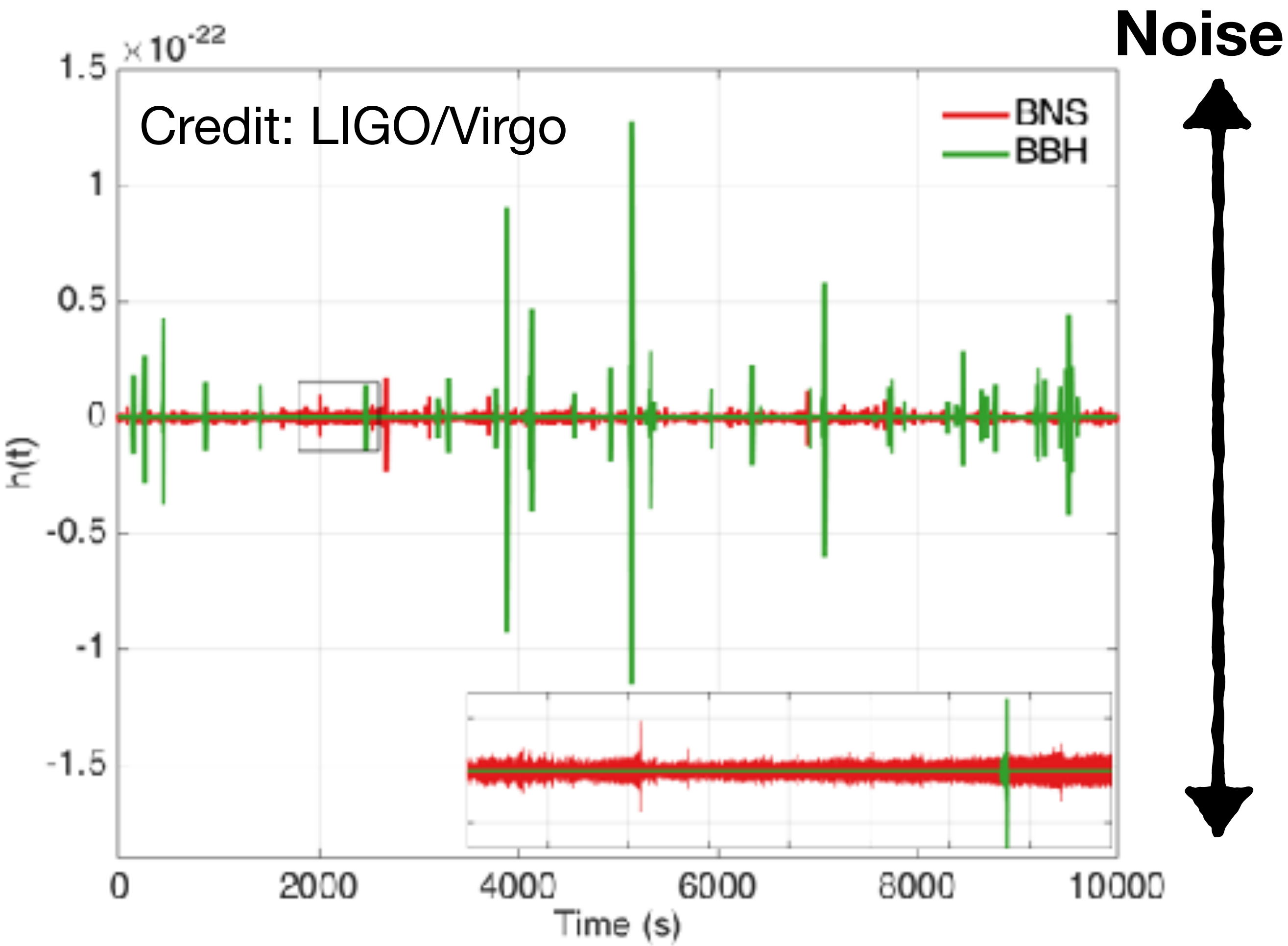
Conclusions

- Variety of astrophysical backgrounds across different frequencies
- Stochastic backgrounds are highly complementary to individual detections
- Tightening upper limits from LIGO/Virgo/Kagra
- Tentative detection of a common process by NANOGrav
- Expect a firm detection soon?…



Additional slides

Signal is stochastic and buried in noise!



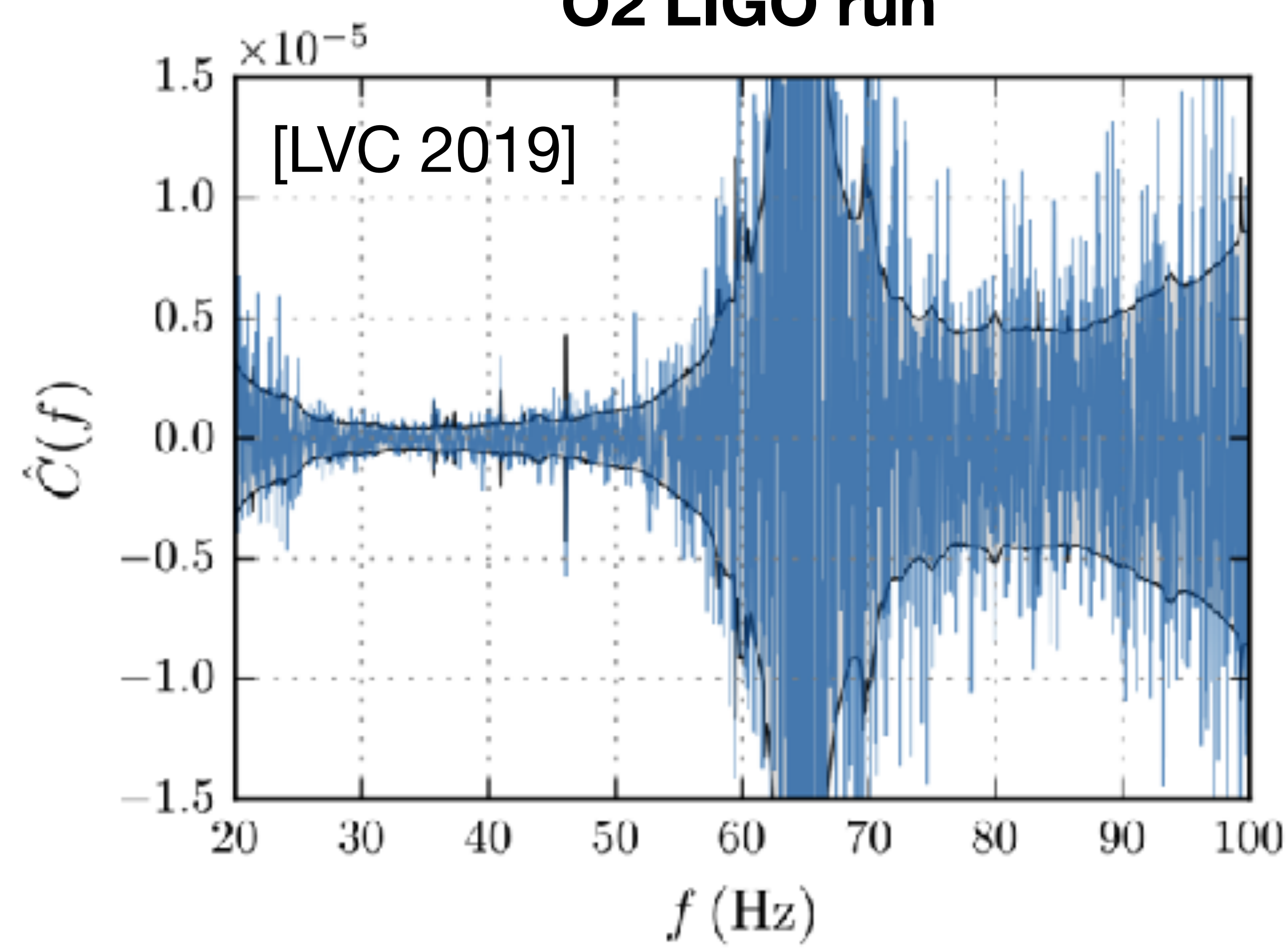
Noise can be correlated…

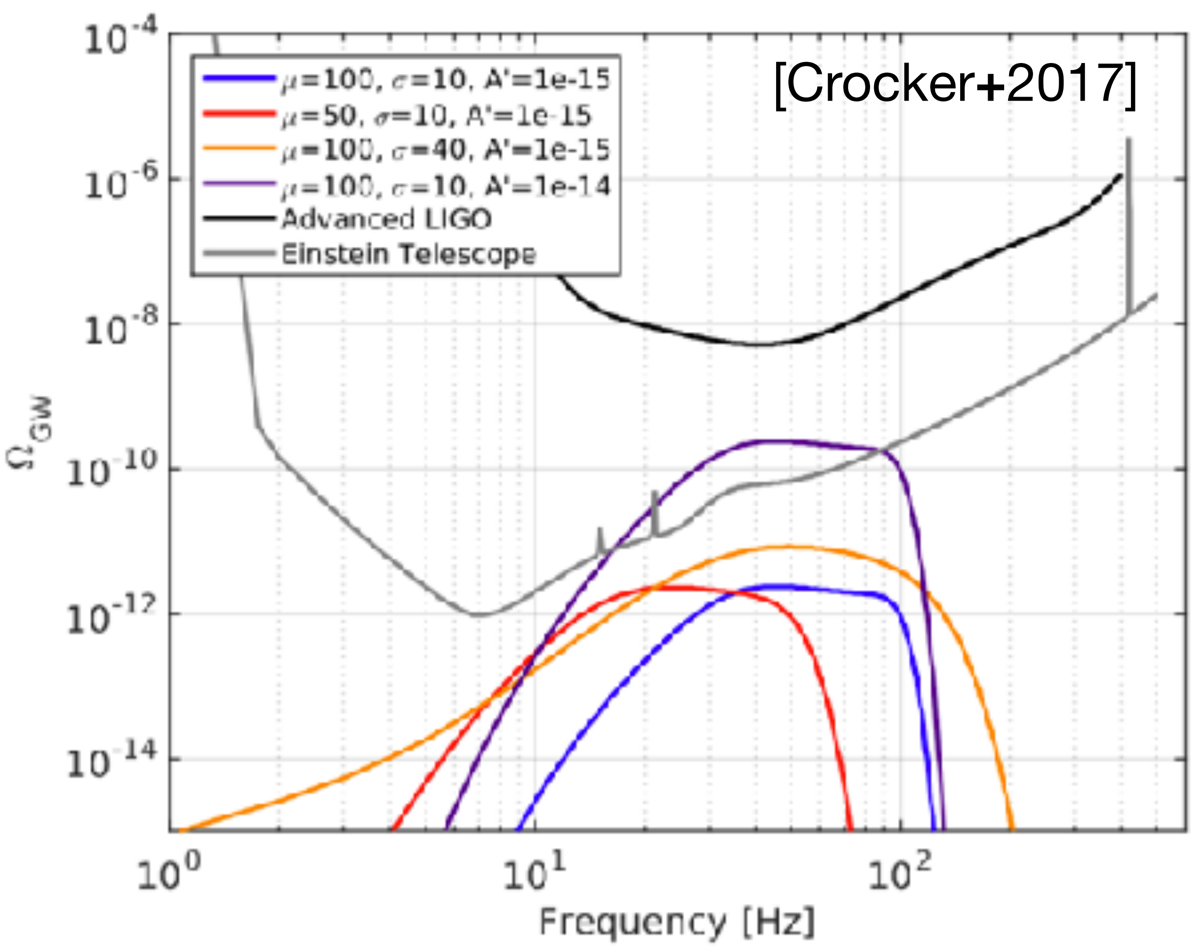
- Power/instrumental lines
- Signal injections
- Non-stationary noise (glitches)
- Schumann resonances

Cross-correlating outputs from two detectors and hoping noise is uncorrelated with the signal and between detectors

$$\hat{C}(f) = \frac{2}{T}\frac{\mathrm{Re}[\tilde{s}_1^\star(f)\tilde{s}_2(f)]}{\gamma_T(f)S_0(f)}$$

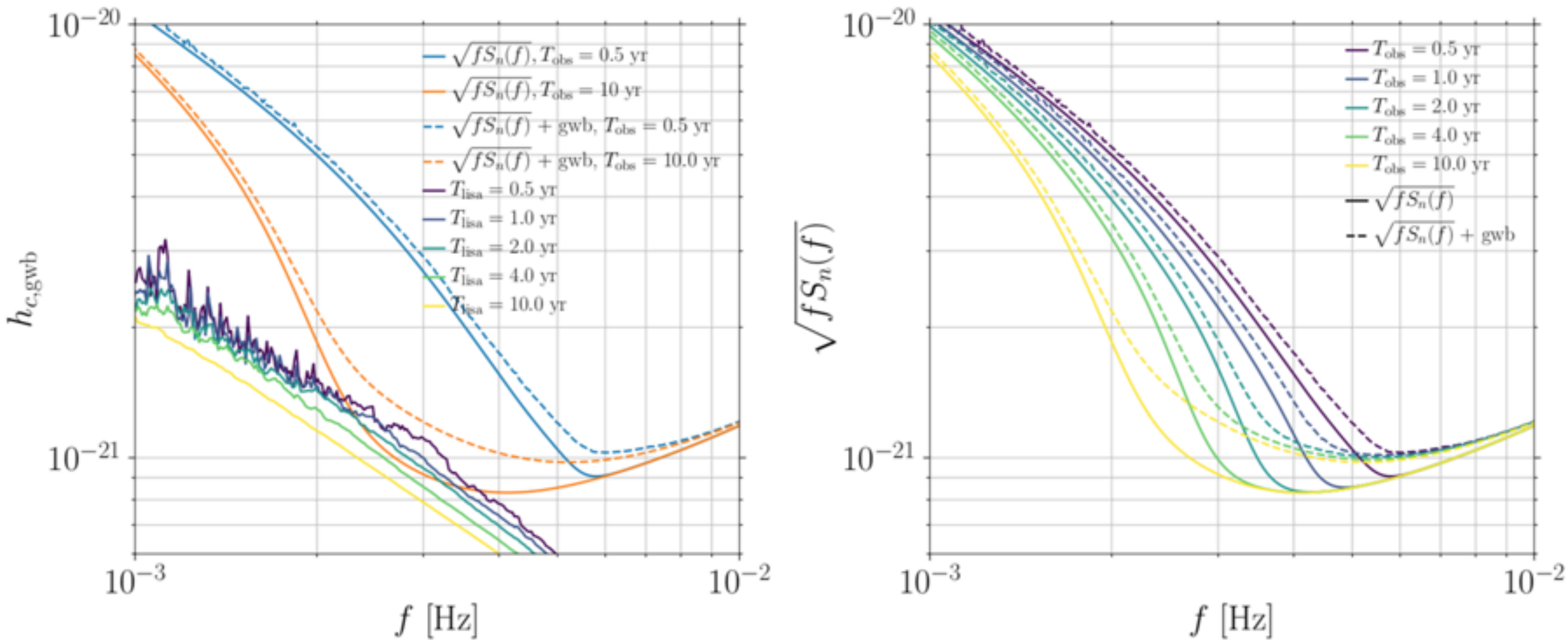
O2 LIGO run





[Crocker+2017]
μ=100, σ=10, A'=1e-15
μ=50, σ=10, A'=1e-15
μ=100, σ=40, A'=1e-15
μ=100, σ=10, A'=1e-14
Advanced LIGO
Einstein Telescope
Ω_{GW}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{0}
10^{1}
10^{2}
Frequency [Hz]

[Bonetti & Sesana 2020]



LISA White Paper