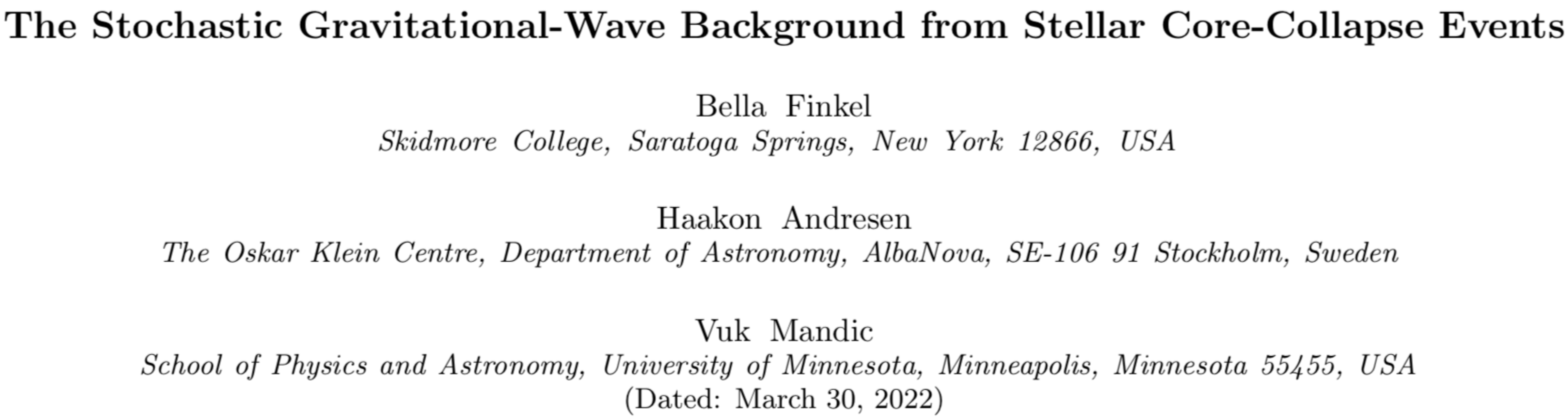
General Intro on GW stochastic backgrounds

and



The Stochastic Gravitational-Wave Background from Stellar Core-Collapse Events

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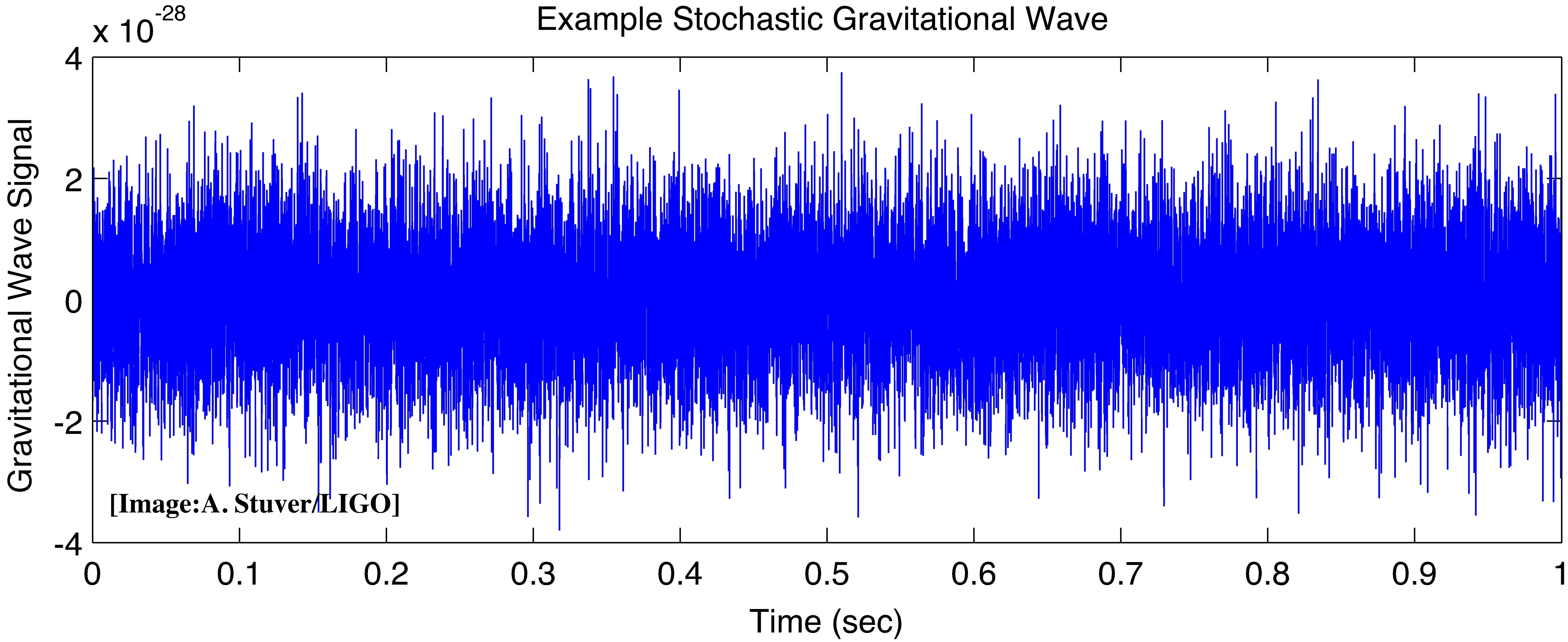
Introduction: Stochastic gravitational-wave backgrounds

- **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)



[Image:A. Stuver/LIGO]

Introduction: Stochastic gravitational-wave backgrounds

- If the background is stationary and Gaussian: fully specified by second moment

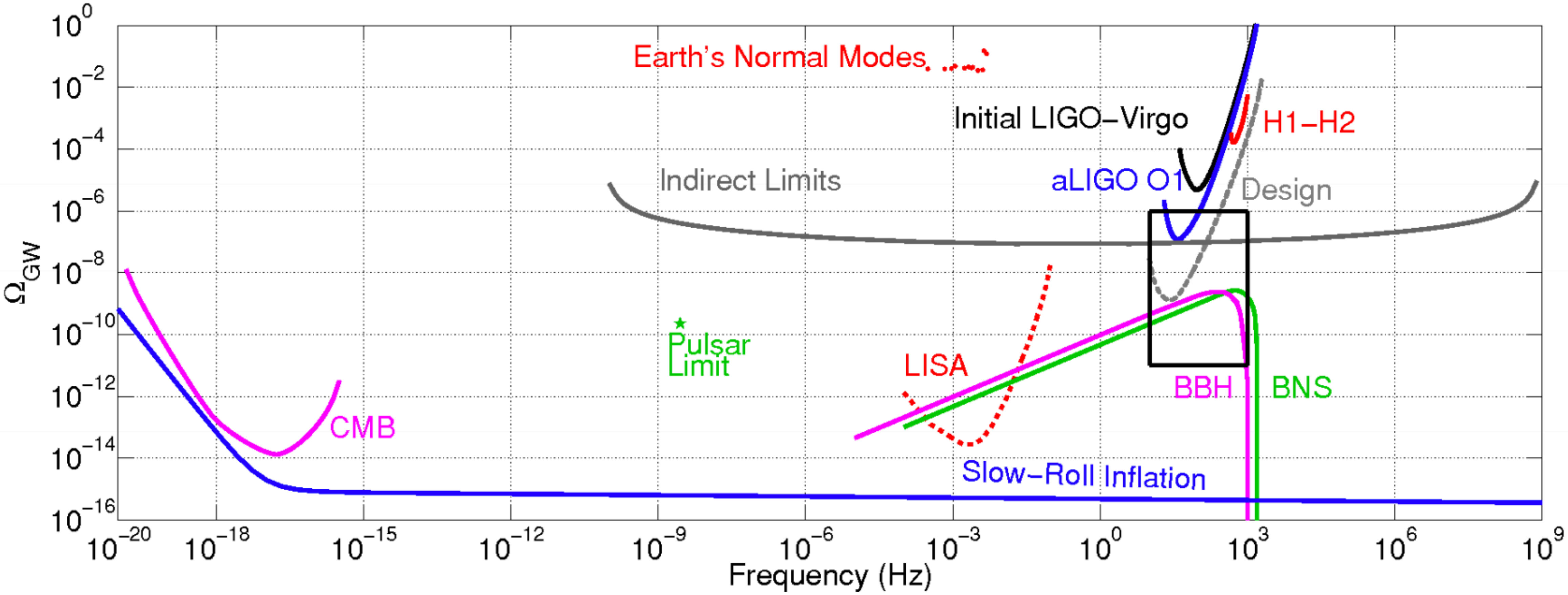
  (here assuming isotropy)

$$\boxed{\langle h_A^*(f,\hat{\Omega})\, h_{A'}(f',\hat{\Omega}')\rangle} = \frac{3H_0^2}{32\pi^3}\,\delta^2(\hat{\Omega},\hat{\Omega}')\,\delta_{AA'}\,\delta(f-f')\;|f|^{-3}\boxed{\Omega_{\rm gw}(|f|)}$$

- Relation with energy density:

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

[Abbott+2016]



Detection methods

- GW signal *h* much fainter than noise $s_i = h_i + n_i$
- Cross-correlating outputs from two detectors and hoping noise is uncorrelated with the signal and between detectors

$$< s_1 s_2 > = < h_1 h_2 > + < h_1 n_2 > + < h_2 n_1 > + < n_1 n_2 >$$

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$$< s_1 s_2 > = < h_1 h_2 > + < \cancel{h_1 n_2} > + < \cancel{h_2 n_1} > + < \cancel{n_1 n_2} >$$

- Noise: $\sigma^2 = < n_1 n_1 > < n_2 n_2 >$

- Signal to noise ratio: $SNR = \frac{\mu}{\sigma} = \frac{< h_1 h_2 >}{\sqrt{< n_1^2 > < n_2^2 >}} \propto \frac{\Omega_{gw}}{\sqrt{P_1 P_2}}$

P1, P2 : Detector power spectral density

Detection methods

- In LIGO-Virgo: data divided into segments of T=192 sec
- Cross-correlation statistic between detectors I and J:
- Expectation value: $\langle \hat{C}^{IJ}(f) \rangle = \Omega_{\rm GW}(f)$

Data I

Data J

$$\hat{C}^{IJ}(f) = \frac{2}{T} \frac{\mathrm{Re}[\tilde{s}_I^{\star}(f)\tilde{s}_J(f)]}{\gamma_{IJ}(f) S_0(f)}$$

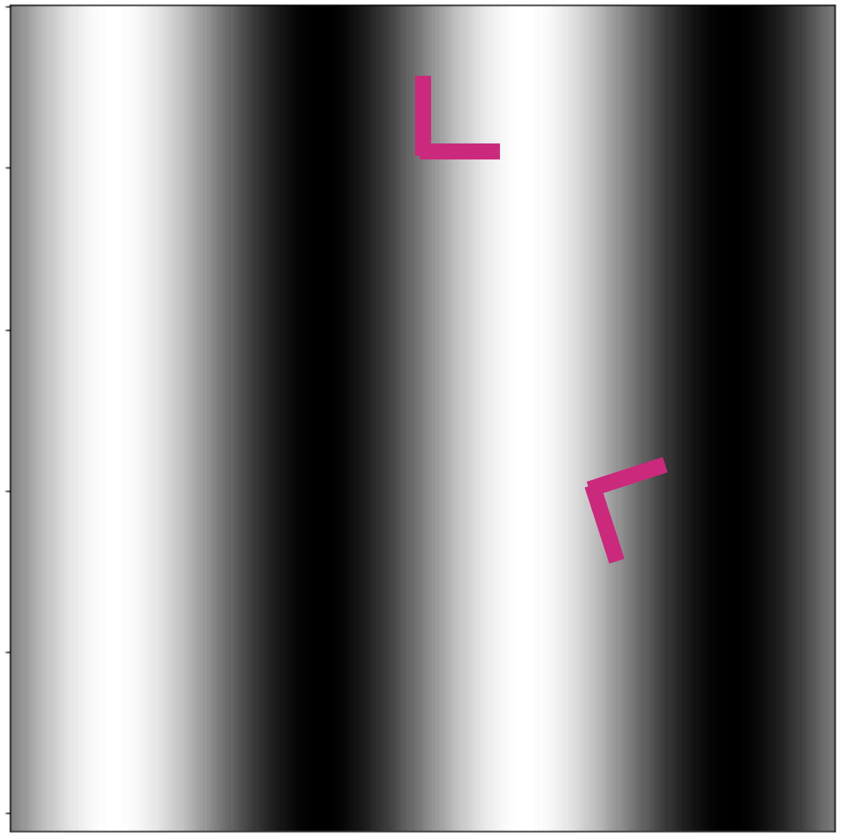
Overlap reduction function

Optimal SNR:

Overlap reduction function

$$\mathrm{SNR} = \frac{3H_0^2}{10\pi^2}\sqrt{2T}\left[\int_0^{\infty} df \sum_{i=1}^{n}\sum_{j>i} \frac{\gamma_{ij}^2(f)\Omega_{\rm GW}^2(f)}{f^6 P_i(f) P_j(f)}\right]^{1/2}$$

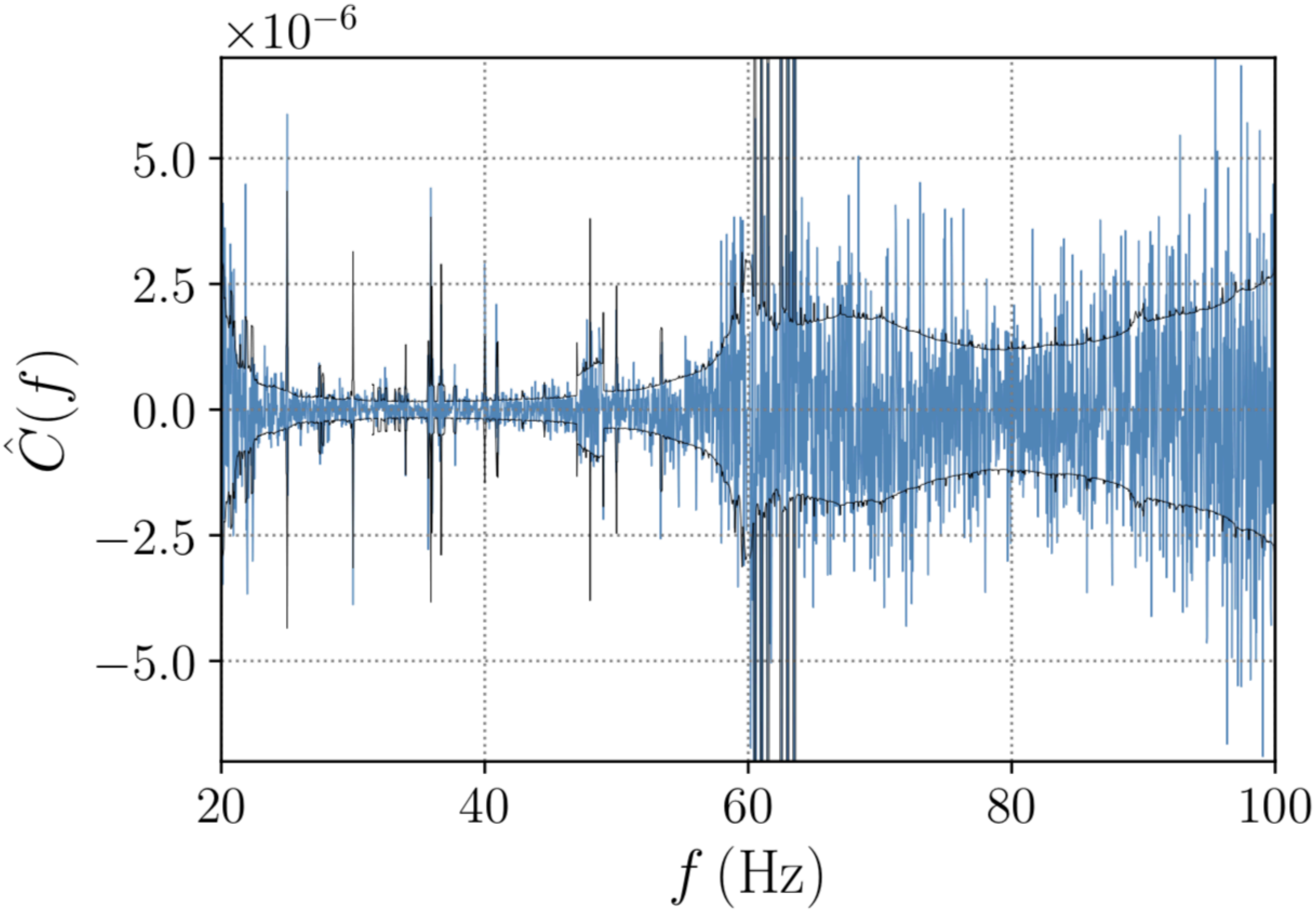
Detector noise



Upper limits

[LVK 2021]

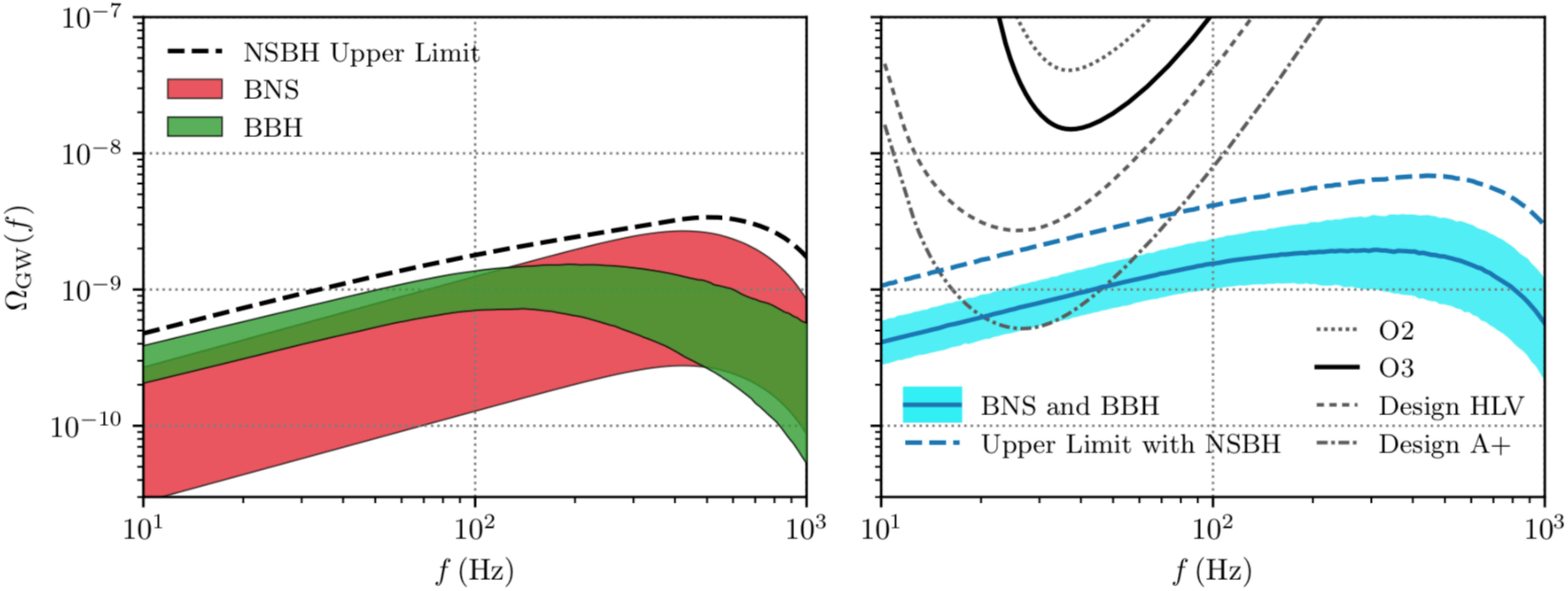
Data consistent with uncorrelated Gaussian noise



Stochastic background from merging compact binaries

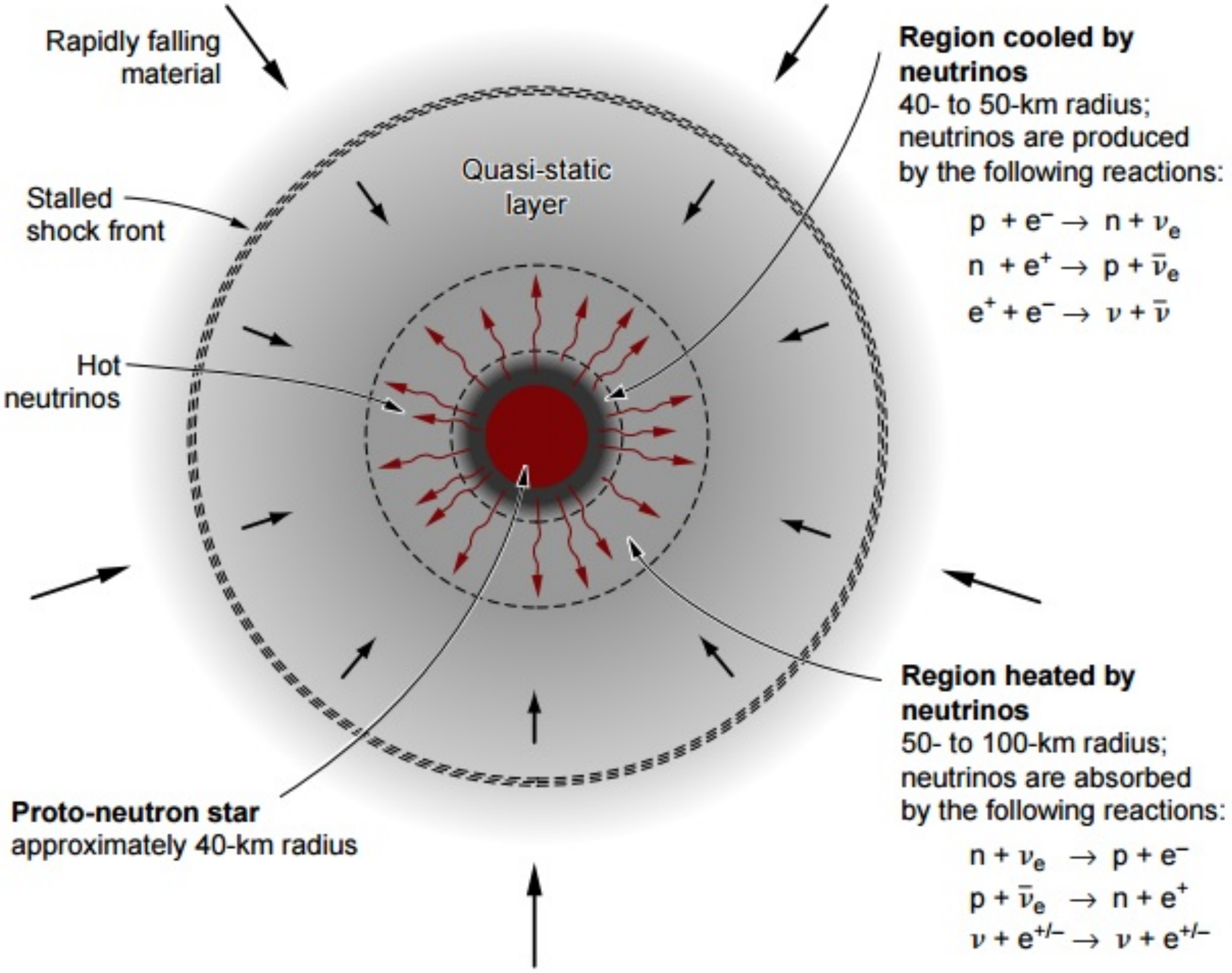
[LVK 2021]

- BBH/BNS local merger rate and mass distribution from O1+O2+O3a catalogue
- Expect detection with design sensitivity or A+



Gravitational waves produced during stellar collapse

- Main contribution: **Proto-neutron star oscillations** (above 300 Hz)
- Low-frequency (below 300 Hz) from SASI (standing accretion shock instability)



[Persival 2016]

Finkel et al. 2022:

- Calculate the contribution of all CCSN to stochastic background
- Use GW signal from 3D simulations

Stochastic background:

$$\Omega_{\rm GW}(f) = \frac{f}{\rho_c H_0} \int_0^{z_{\rm max}} {\rm d}z \frac{R(z)\frac{{\rm d}E_{\rm GW}}{{\rm d}f_e}(f_e)}{(1+z)E(\Omega_m, \Omega_\Lambda, z)}, \qquad (2)$$

Rate of CCSN follows SFR:

$$R(z) = \lambda_{\rm CC} R_*(z), \qquad (3)$$

Fraction of stars that collapse (using Salpeter IMF):

$$\lambda_{\rm CC} = \int_{8{\rm M}_\odot}^{\infty} \phi(m){\rm d}m \approx 0.007\ {\rm M}_\odot^{-1}. \qquad (4)$$

SFR:

$$R_*(z) = \nu \frac{p e^{q(z-z_m)}}{p - q + q e^{p(z-z_m)}}, \qquad (5)$$

Finkel et al. 2022:

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GW spectrum:

$$\frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}f} = \frac{c^3}{16\pi G}(2\pi f)^2 \int r^2 \langle (\tilde{h}_{\times}^{\mathrm{TT}})^2 + (\tilde{h}_{+}^{\mathrm{TT}})^2 \rangle \mathrm{d}\Omega, \quad (11)$$

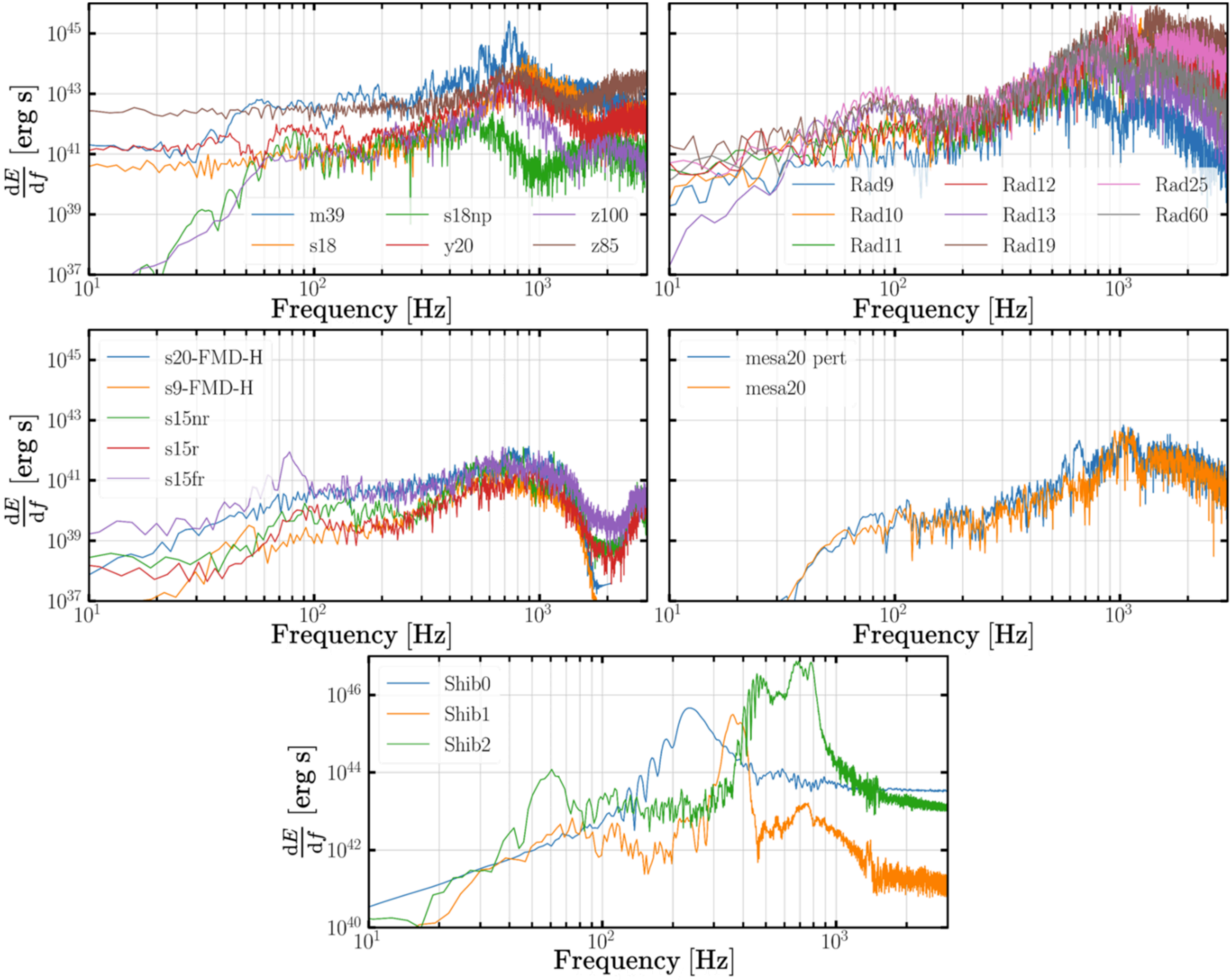
Direction-dependent
GW strain

Integral over a
spherical shell

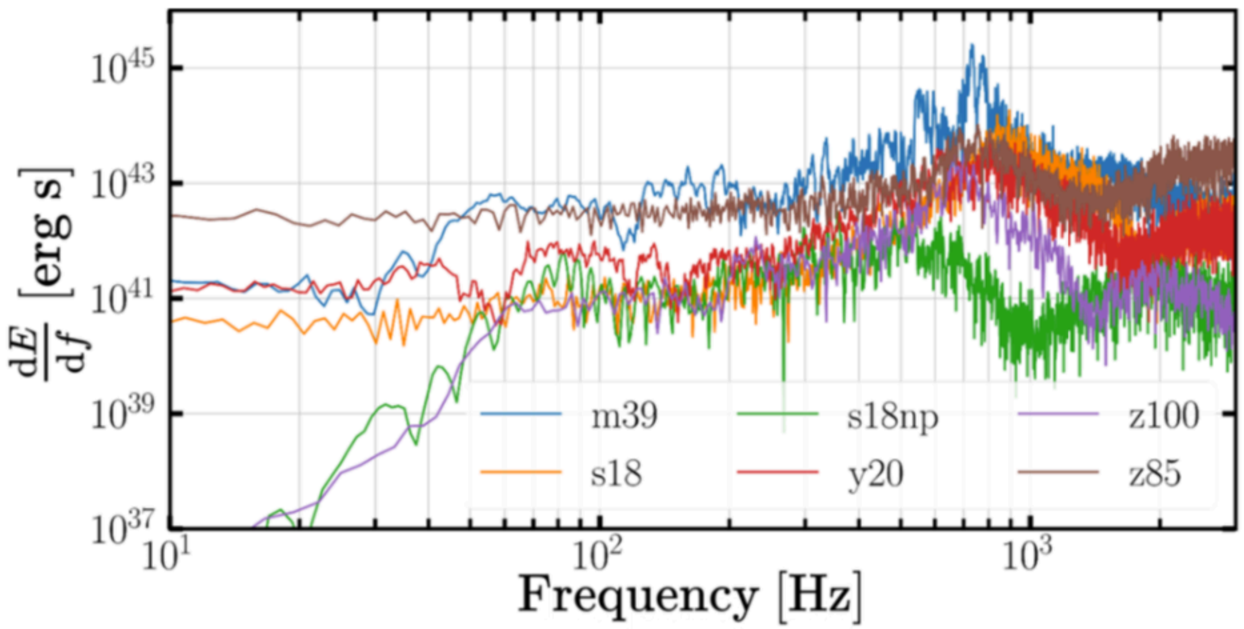
✱ Need angular information, most simulations do not provide it!

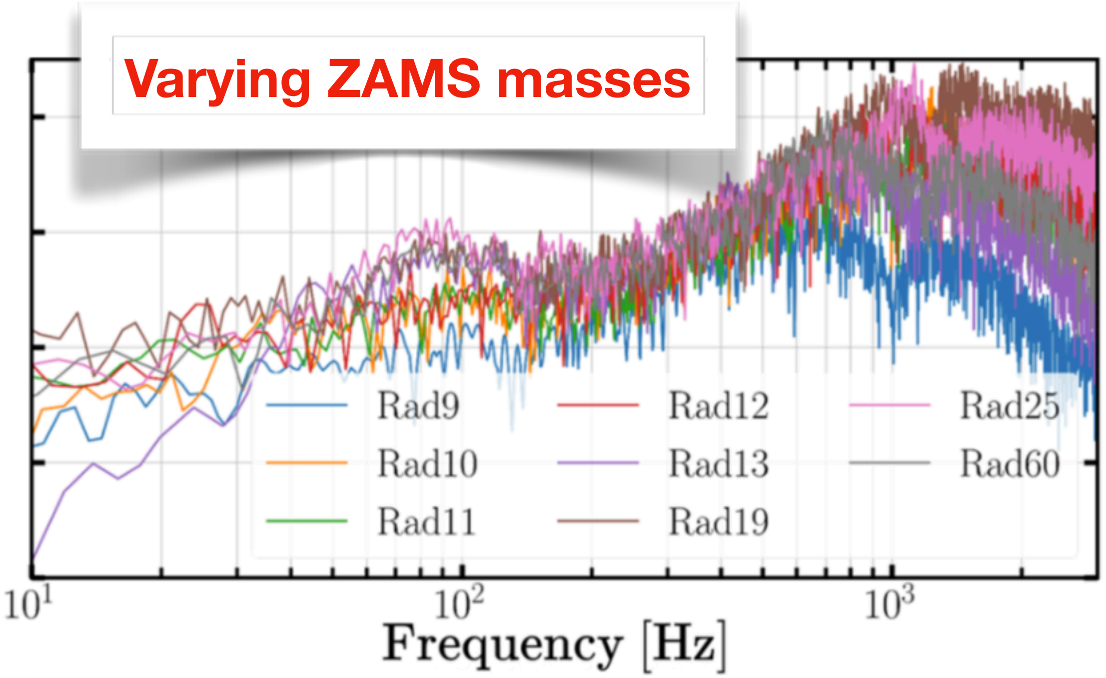
Model name	ZAMS mass, type	Numerical code	EoS	Notes	Reference
m39	39 $M_\odot$, Wolf-Rayet star	CoCoNuT-FMT [64]	LS220	Rotating, Exploding	[60]
s18np	18 $M_\odot$, giant		LS220	SASI	
y20	20 $M_\odot$, Wolf-Rayet star		LS220	Exploding	
s18	18 $M_\odot$, giant		LS220	Exploding	[57]
z100	100 $M_\odot$		SFHx	SASI	
z85	85 $M_\odot$		SFHx	Exploding, SASI	[63]
Rad9	9 $M_\odot$	Fornax [65]	SFHo	Exploding	[58]
Rad10	10 $M_\odot$		SFHo	Exploding	
Rad11	11 $M_\odot$		SFHo	Exploding	
Rad12	12 $M_\odot$		SFHo	Exploding	
Rad13	13 $M_\odot$		SFHo		
Rad19	19 $M_\odot$		SFHo	Exploding	
Rad25	25 $M_\odot$		SFHo	Exploding, SASI	
Rad60	60 $M_\odot$		SFHo	Exploding	
s9-FMD-H	9 $M_\odot$, giant	Aenus-Alcar [66, 67]	SFHo	Exploding	[62]
s20-FMD-H	20 $M_\odot$, giant		SFHo		
s15nr	15 $M_\odot$	Prometheus-Vertex [68]	LS220	SASI	[56]
s15r	15 $M_\odot$		LS220	SASI	
s15fr	15 $M_\odot$		LS220	Rotating, Exploding, SASI	
mesa20-pert	20 $M_\odot$, giant	FLASH [69]	SFHo	SASI	[55]
mesa20	20 $M_\odot$, giant		SFHo	SASI	
Shib0	70 $M_\odot$	[70]	LS220	SASI	[71]
Shib1	70 $M_\odot$		LS220	Rotating, low-$T/\|W\|$ instability	
Shib2	70 $M_\odot$		LS220	Rotating, low-$T/\|W\|$ instability	

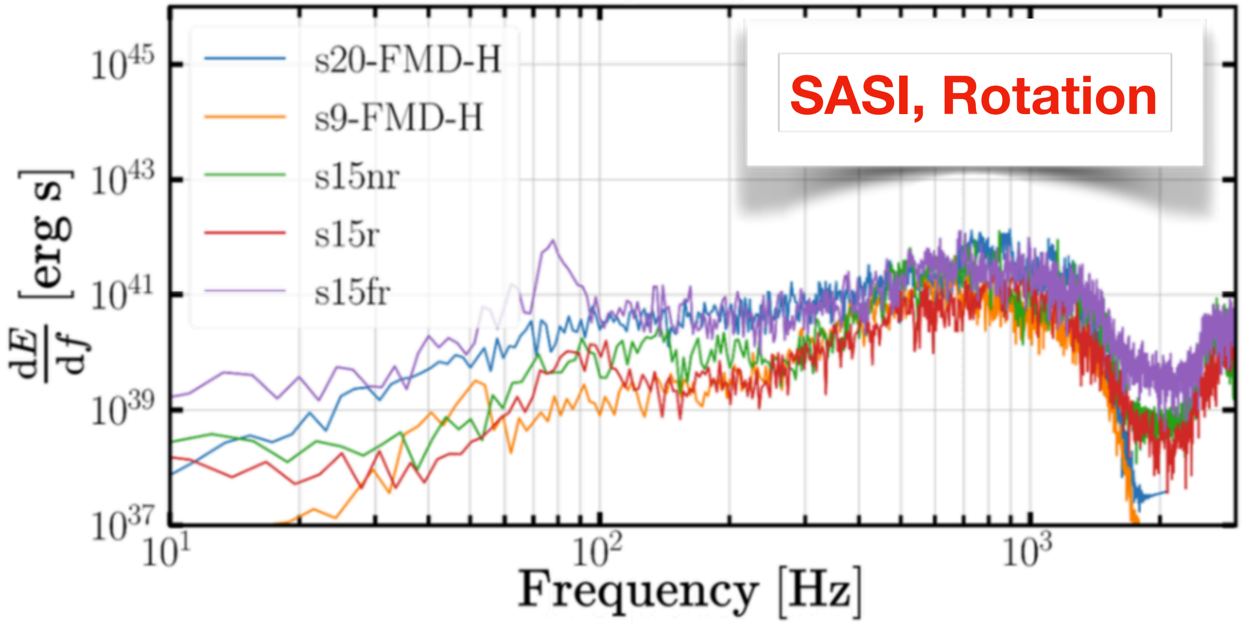
TABLE I: Simulations from which we calculate the SGWB. The high-density nuclear equations of state (EoS) include SFHo & SFHx [72] and that of Lattimer & Swesty [73] with bulk incompressibility of K = 220 MeV (LS220).

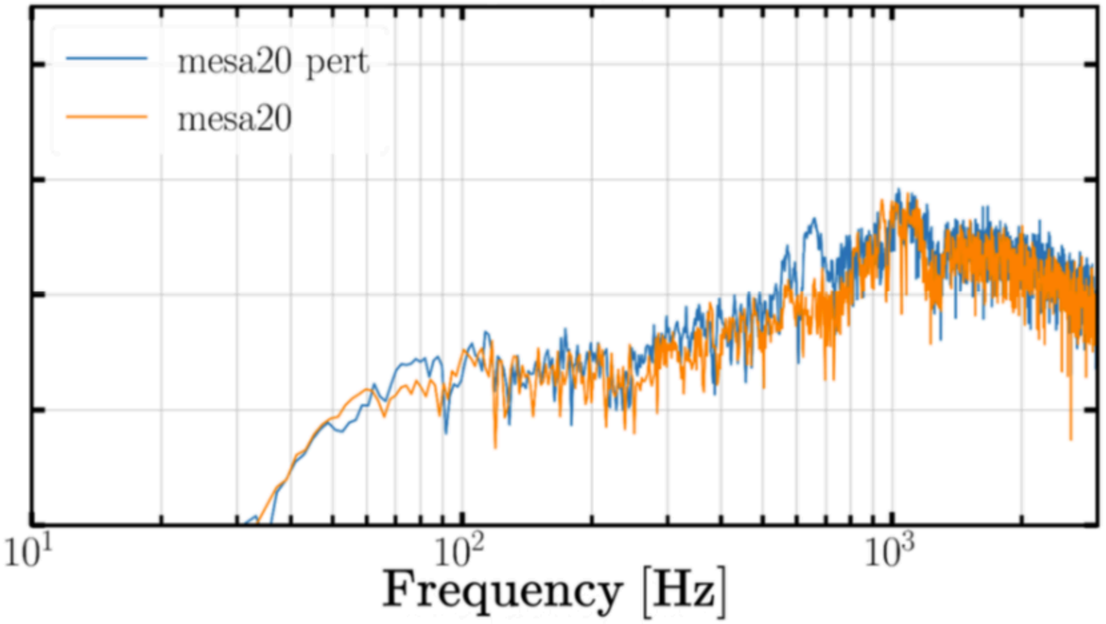


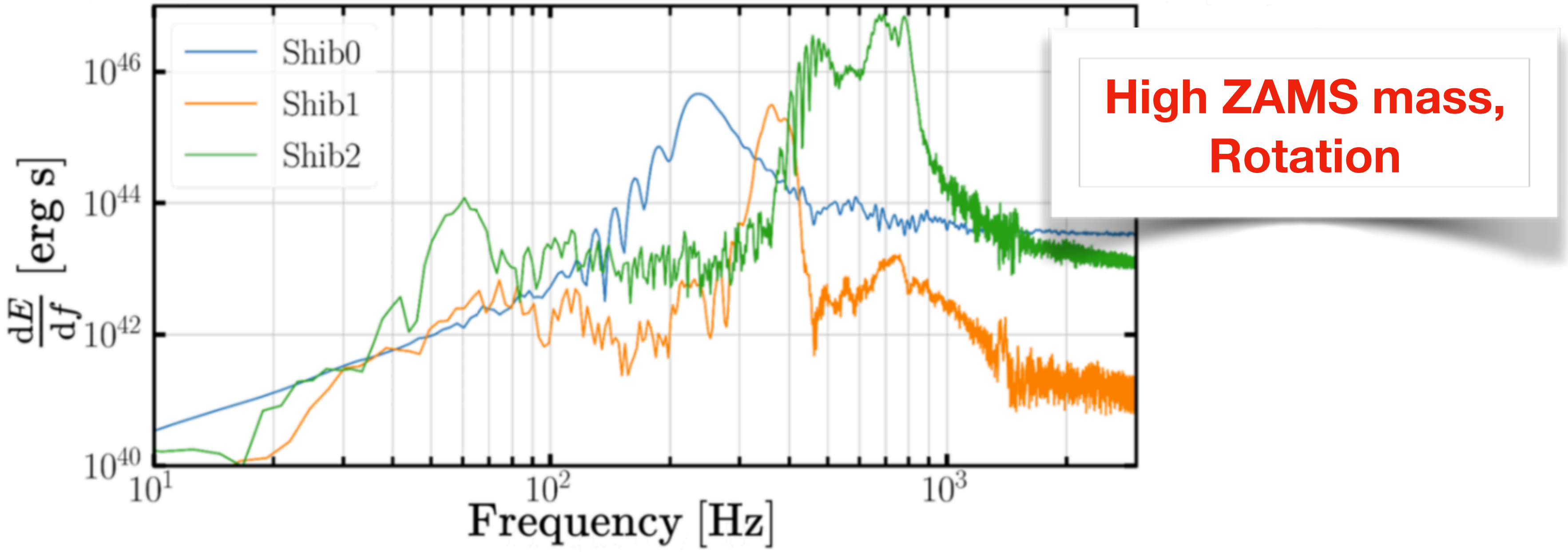
$\frac{dE}{df}$ [erg s]
10^{37}
10^{39}
10^{41}
10^{43}
10^{45}
10^{1}
10^{2}
10^{3}
Frequency [Hz]
m39
s18
s18np
y20
z100
z85
Rad9
Rad10
Rad11
Rad12
Rad13
Rad19
Rad25
Rad60
s20-FMD-H
s9-FMD-H
s15nr
s15r
s15fr
mesa20 pert
mesa20
Shib0
Shib1
Shib2
10^{40}
10^{42}
10^{44}
10^{46}

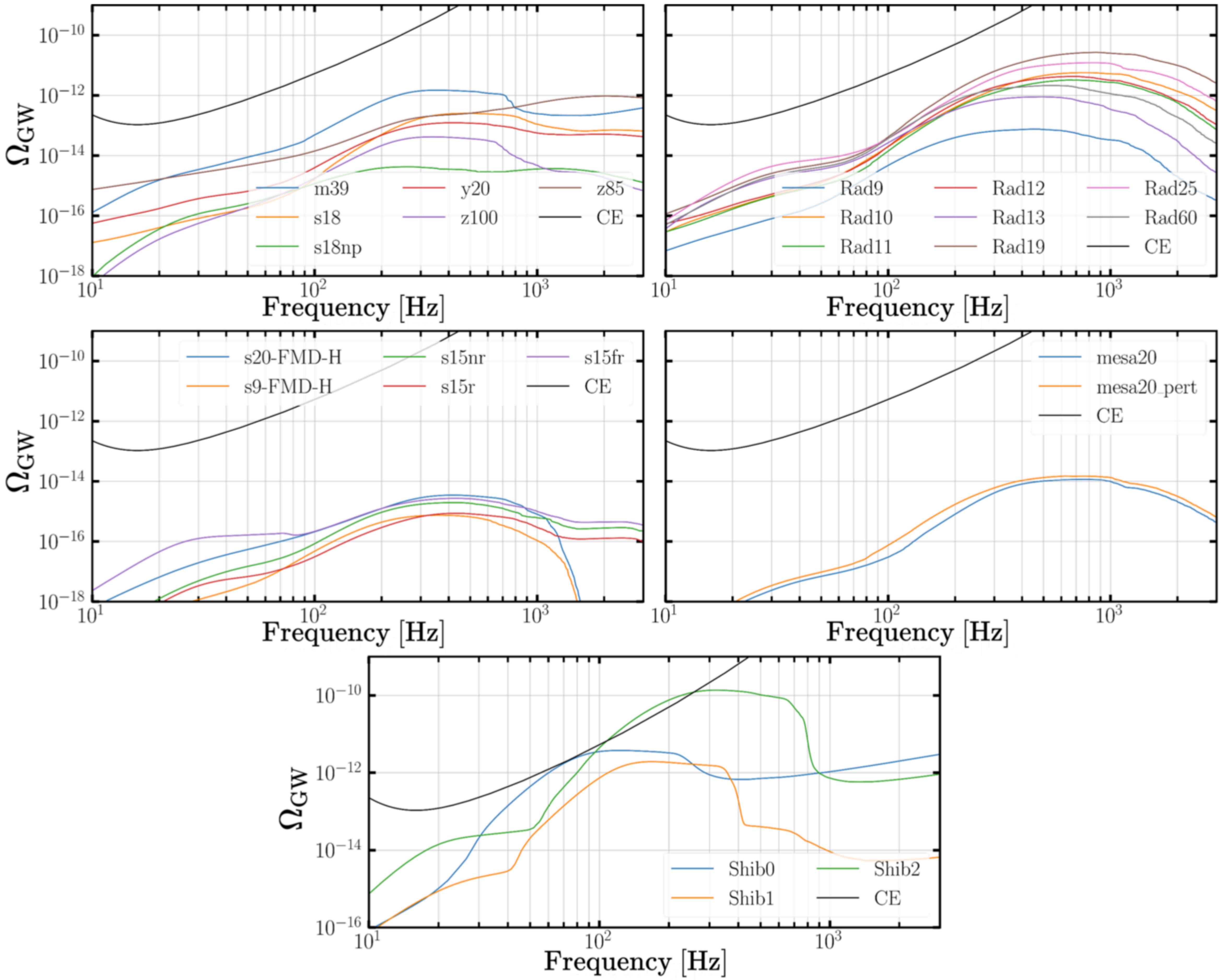



Varying ZAMS masses


SASI, Rotation




High ZAMS mass, Rotation



Ω_{GW}
Frequency [Hz]
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{1}
10^{2}
10^{3}
m39
y20
z85
s18
z100
CE
s18np
Rad9
Rad12
Rad25
Rad10
Rad13
Rad60
Rad11
Rad19
CE
s20-FMD-H
s15nr
s15fr
s9-FMD-H
s15r
CE
mesa20
mesa20_pert
CE
Shib0
Shib2
Shib1
CE

Finkel et al. 2022: conclusions

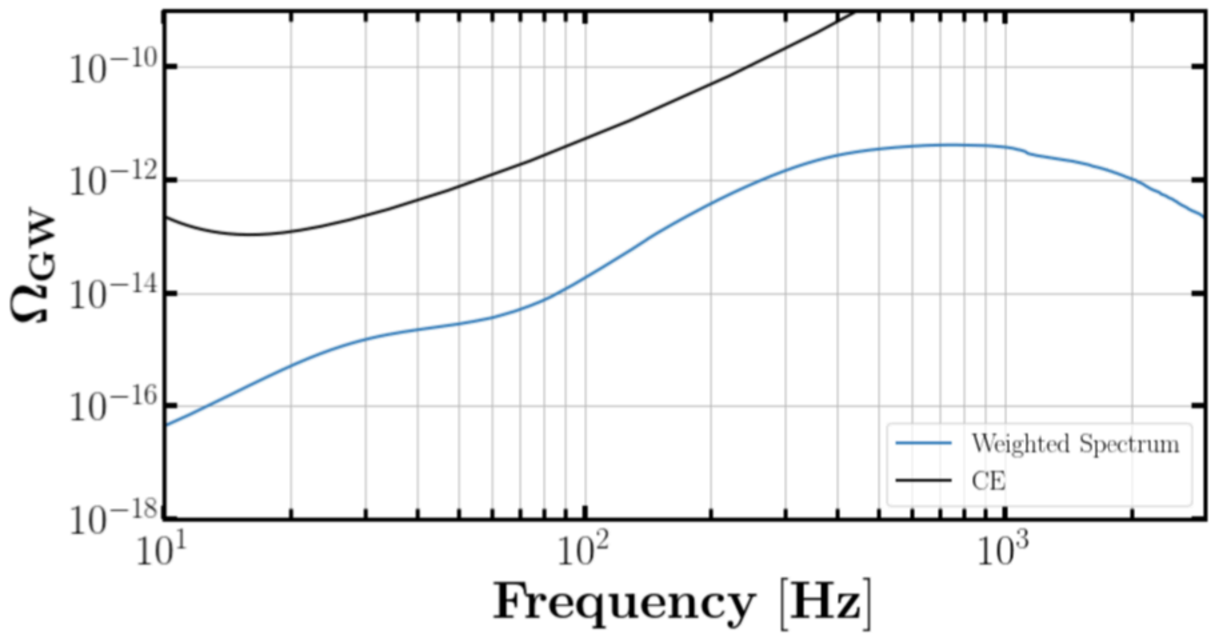
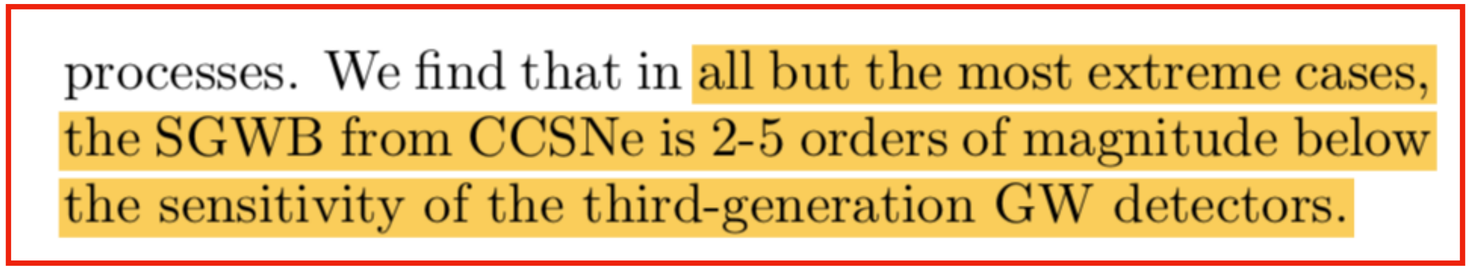


FIG. 3: Averaged $\Omega_{\rm GW}$ including the contributions of the non-rotating progenitors and excluding Shib0 weighted by the abundance of the stellar progenitor in the stellar population as given by the Salpeter IMF (c.f. Eq. 12).

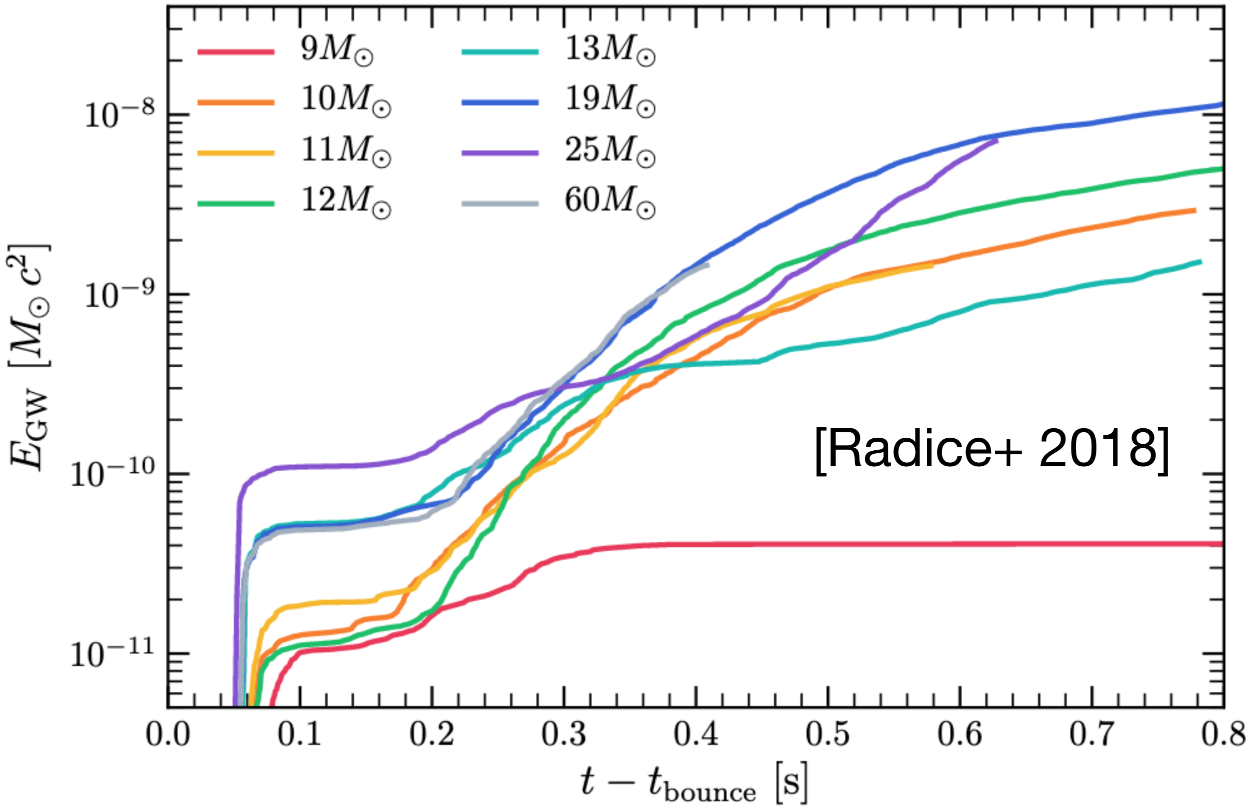


processes. We find that in all but the most extreme cases, the SGWB from CCSNe is 2-5 orders of magnitude below the sensitivity of the third-generation GW detectors.

Finkel et al. 2022: conclusions

Caveats:

- Most simulations were terminated while the system was still emitting GW
- Anisotropic neutrino emission from PNS not included
- Asymmetries due to magnetic fields not included



[Radice+ 2018]

On the positive side:

- Cosmological signal is expected to be much stronger, will not be masked by CCSN !