Gravitational Waves

Jan Harms

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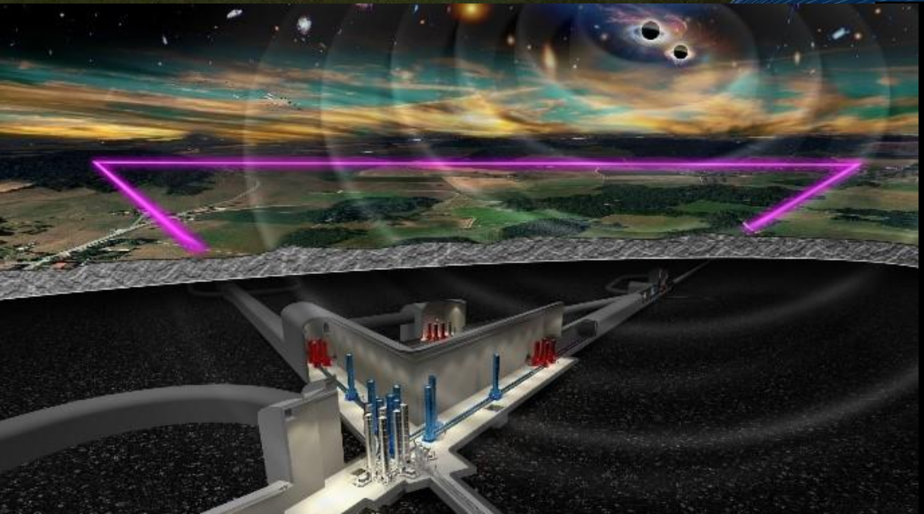
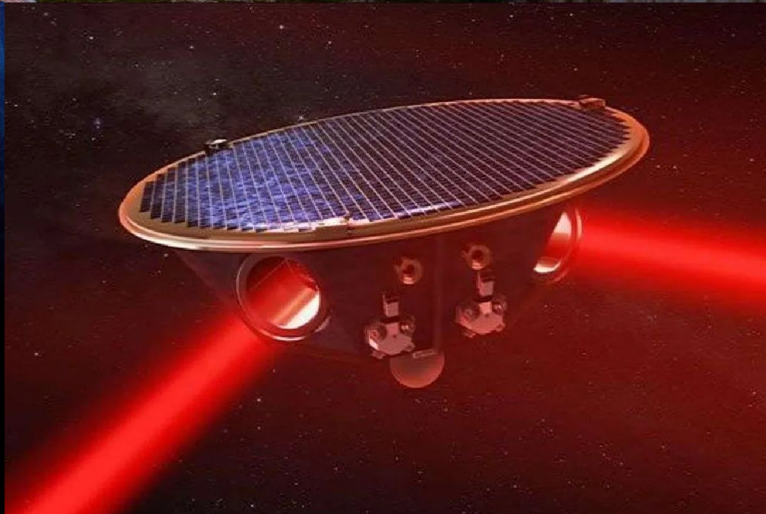
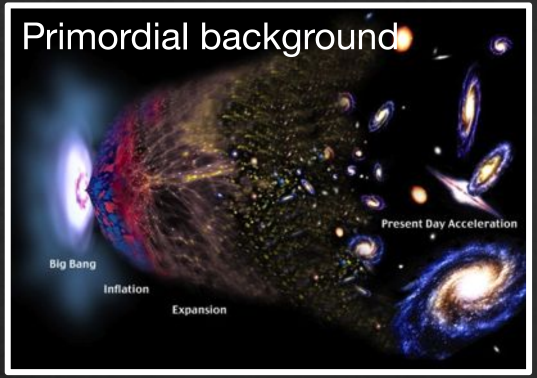
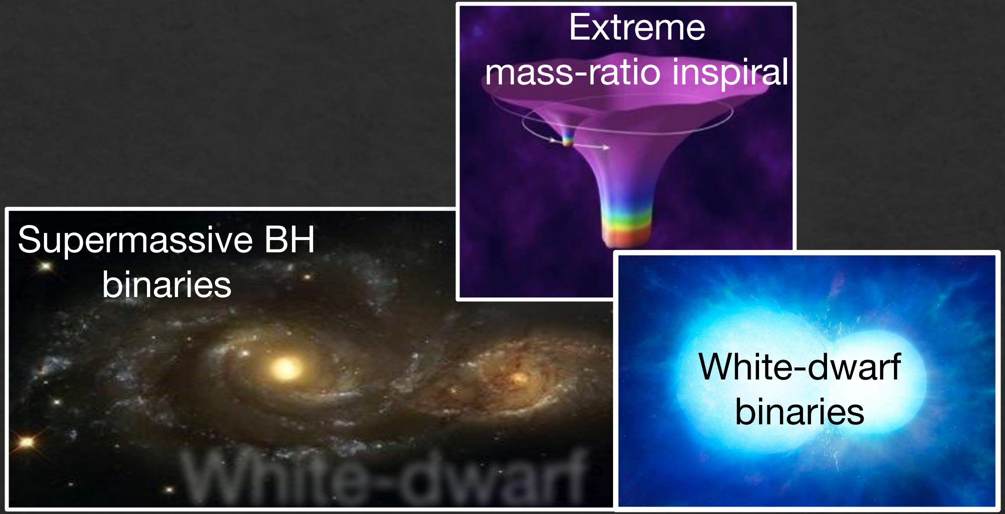
INFN - LNGS

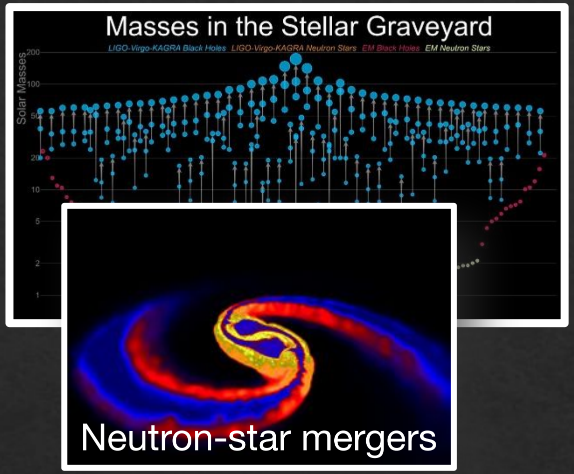


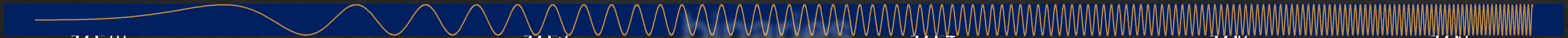


GW Observation Band









Hz Hz Hz Hz Hz

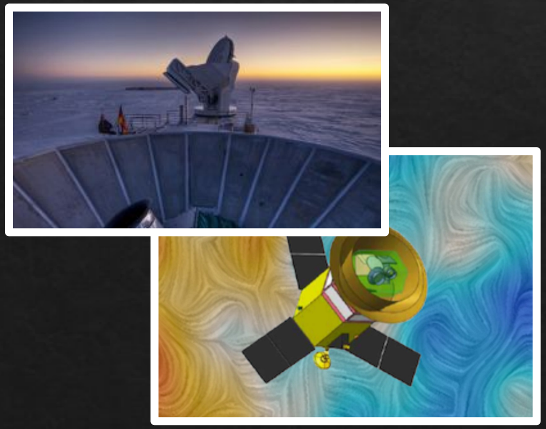
Microwave background

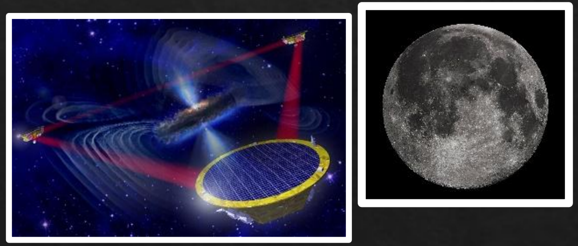
Pulsar timing

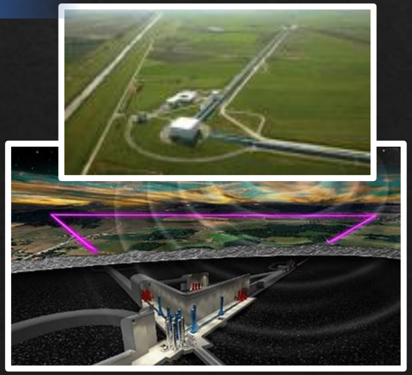
Space detectors

Terrestrial

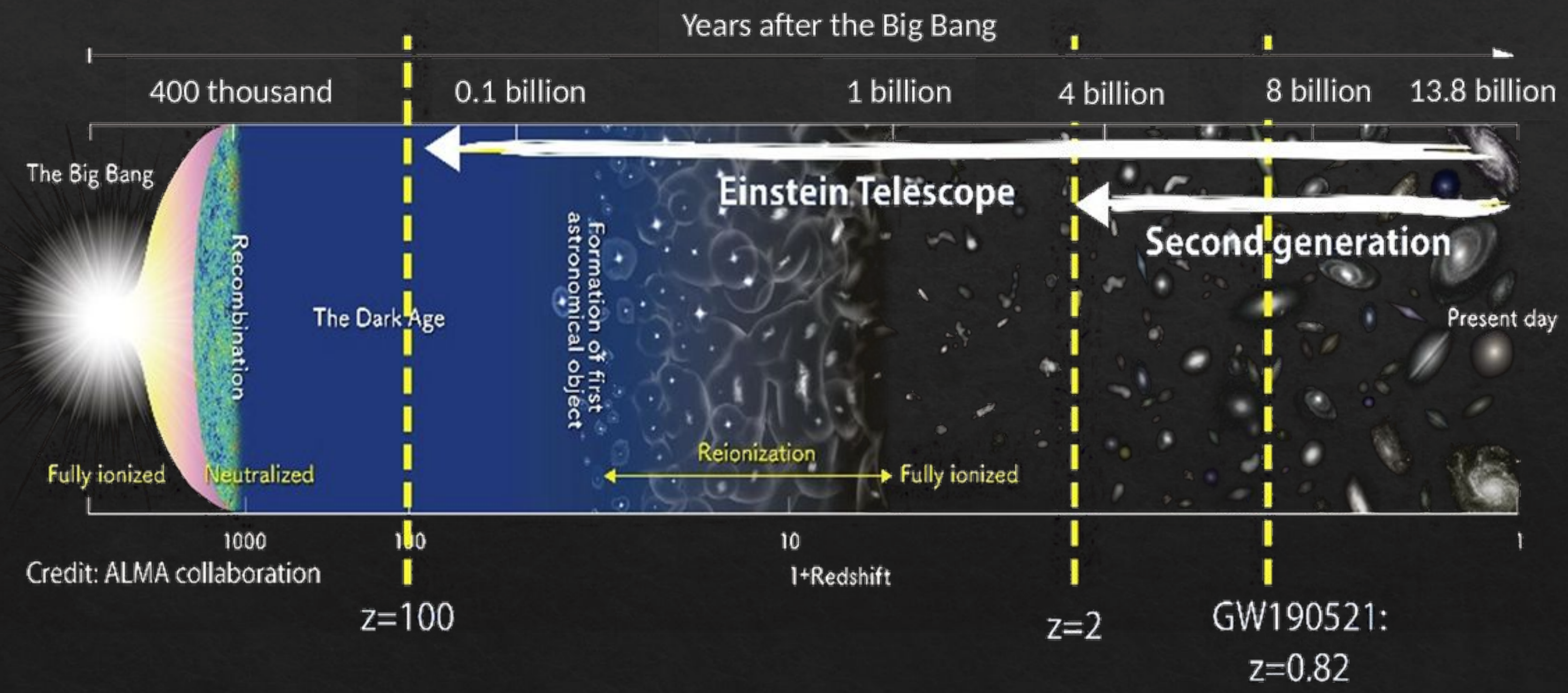
Missing link







Binary BH Detection Horizon



Detection Numbers

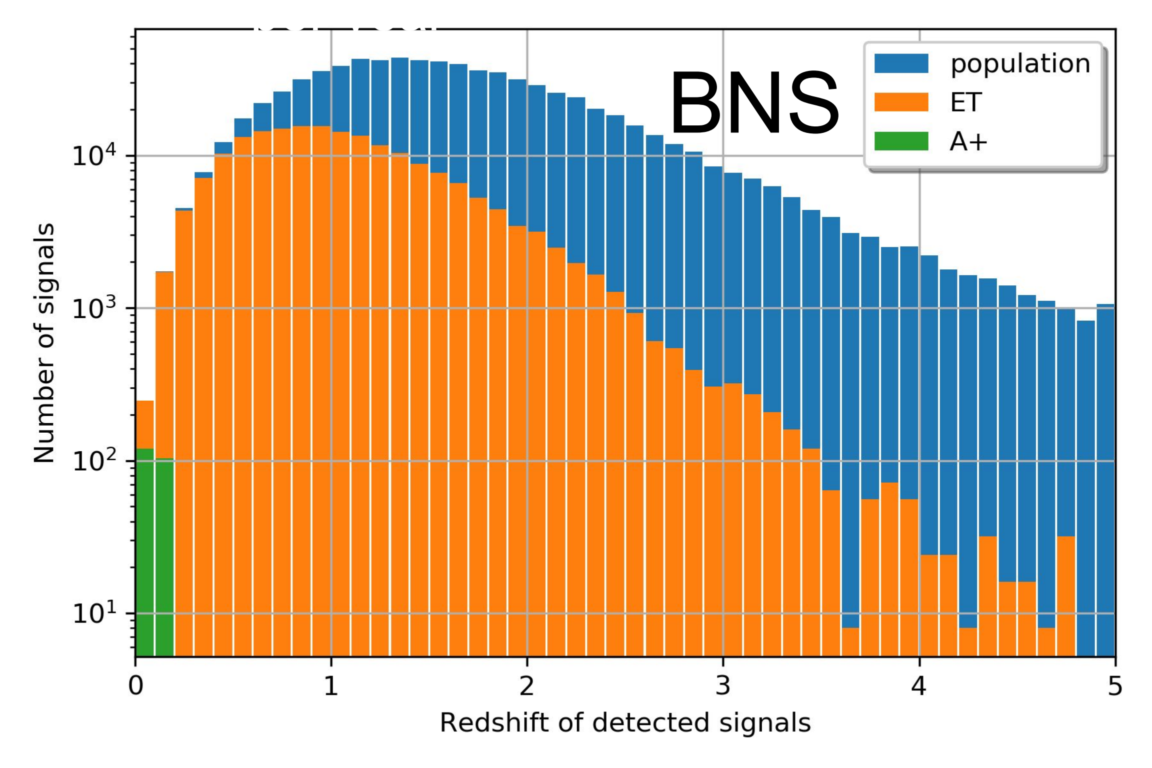
O1: 12.9.2015 – 19.1.2016

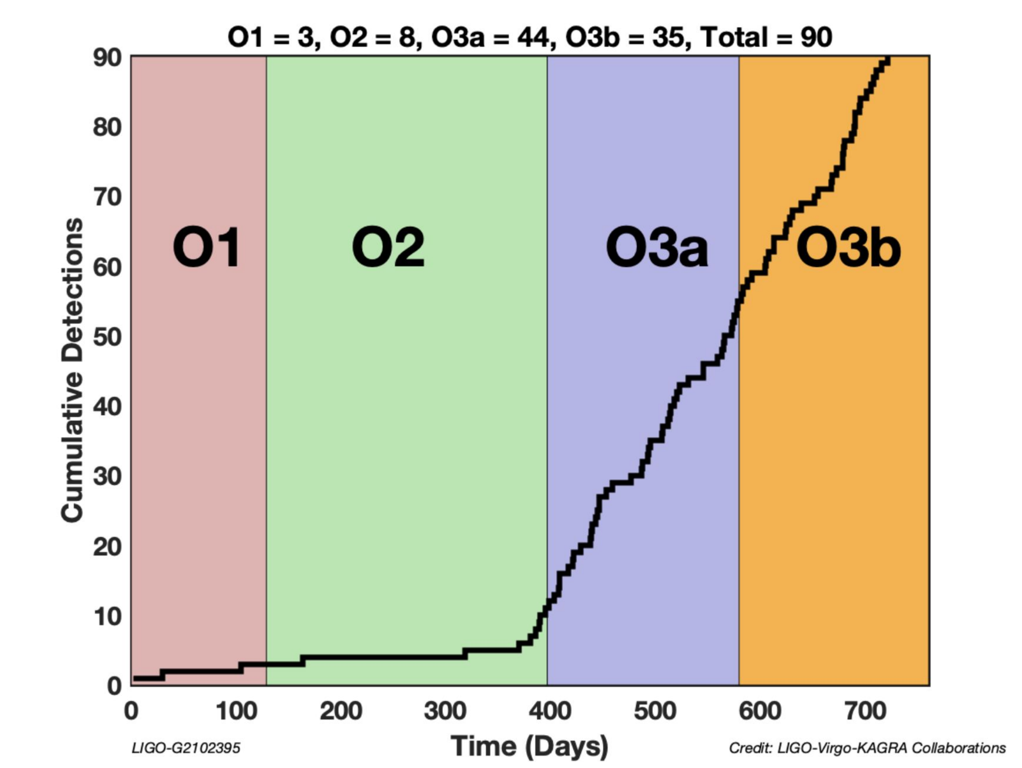
O2: 30.11.2016 – 25.8.2017

O3a: 1.4.2019 – 30.9.2019

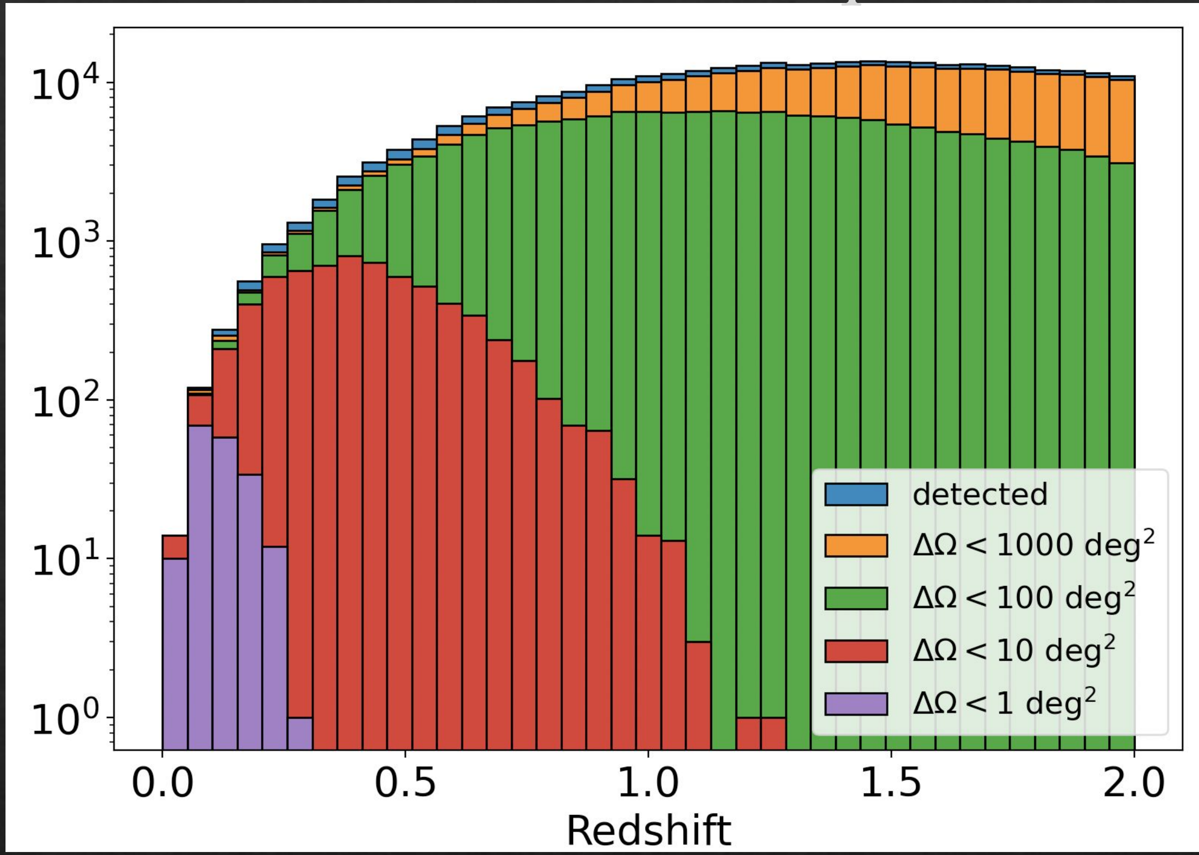
O3b: 1.11.2019 –

ET is expected see about 100000 BNS and 100000 BBH





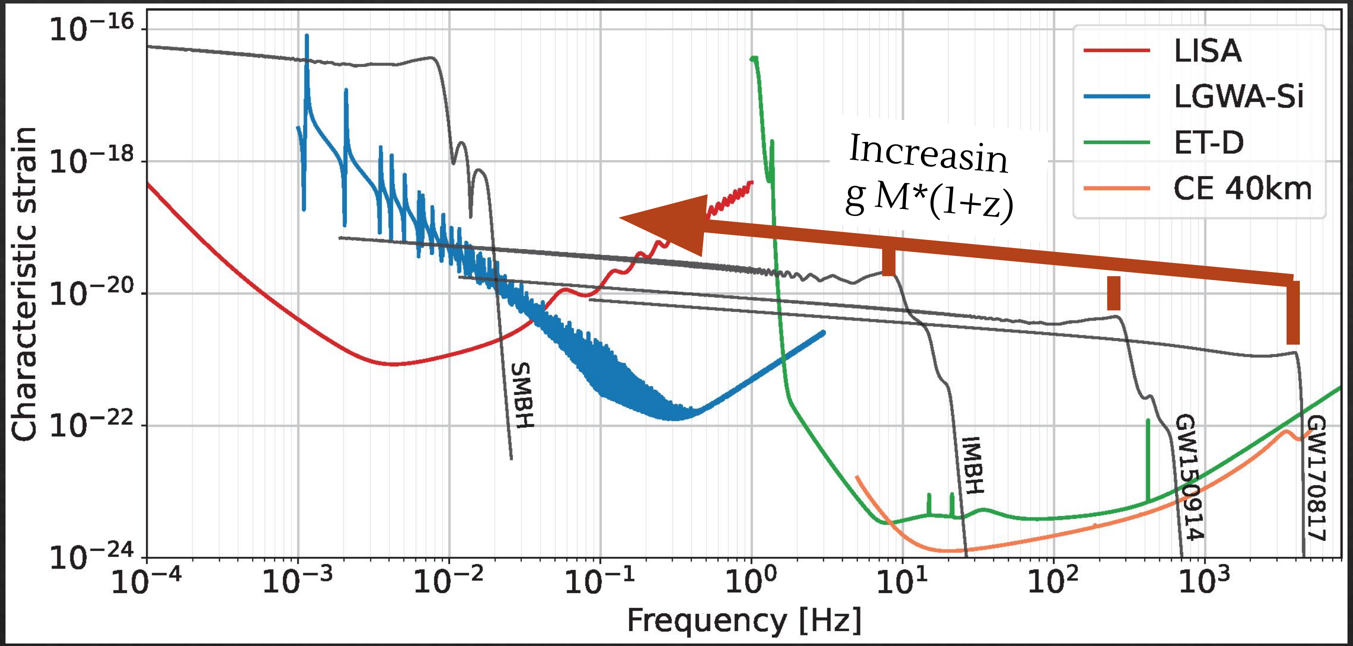
ET+CE Sky-localization Capabilities



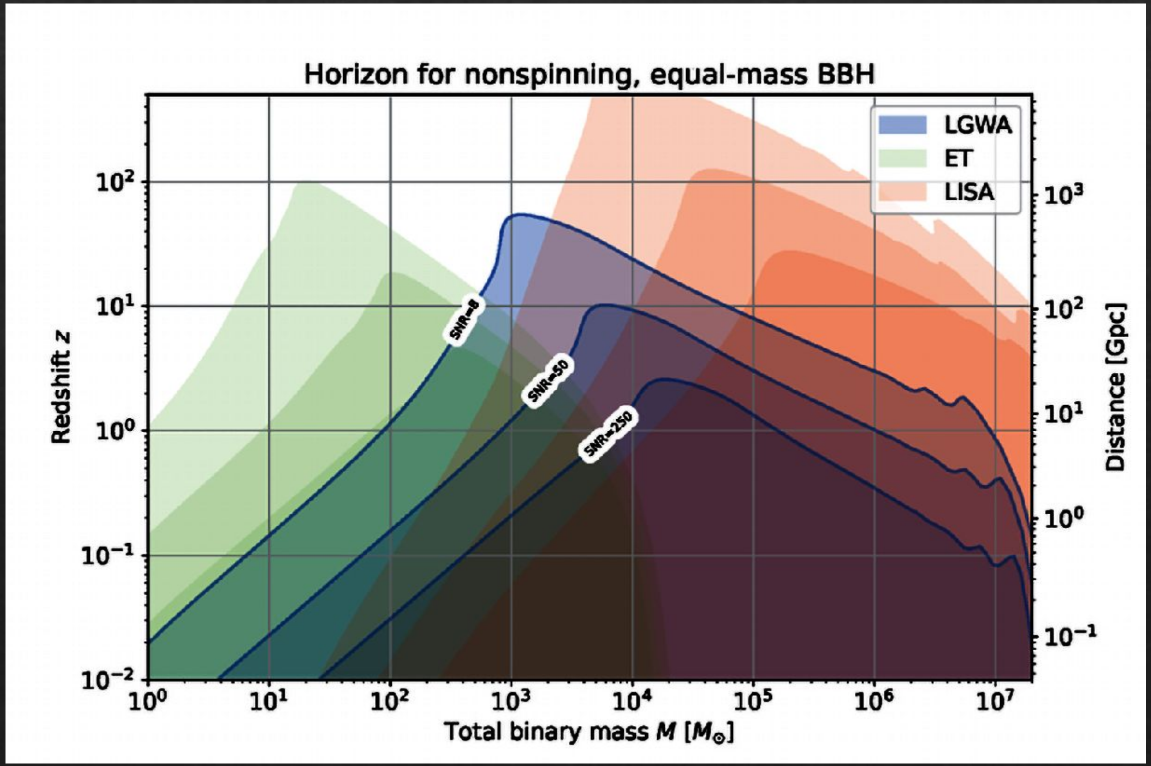
Cosmic Explorer
A proposed detector in the USA

- O(1000) detections per year with sky-localization (90% c.r.) < 10 sq. deg

Multiband Observations



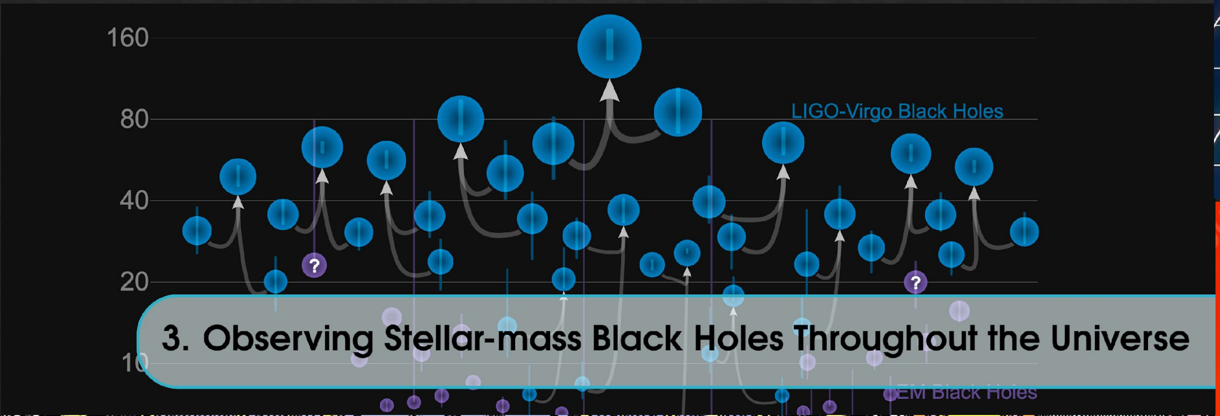
All planned/proposed future GW detectors would see signals from deep into the Dark Age of the Universe.

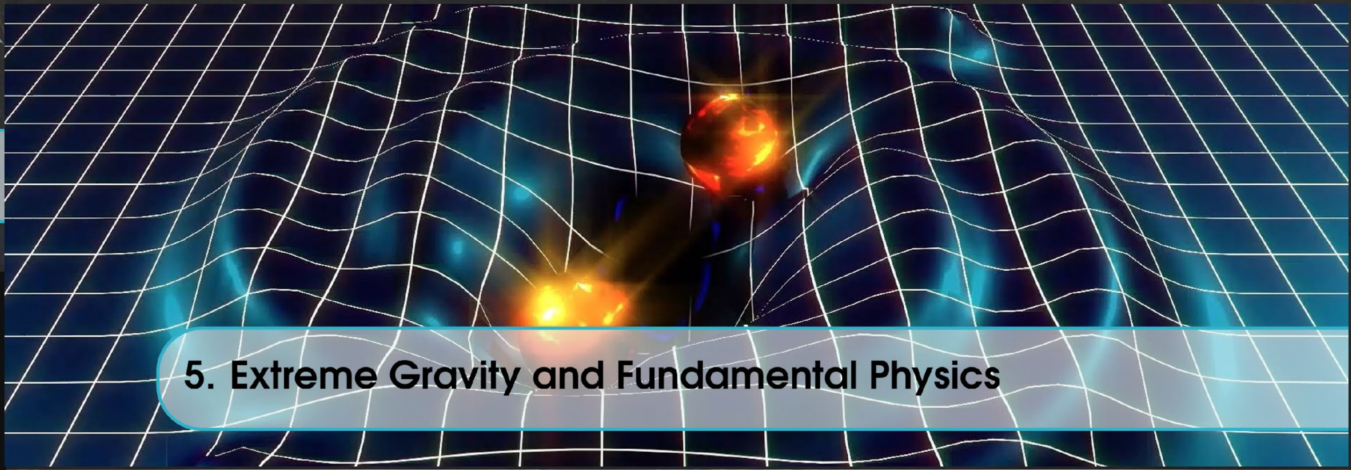


You can observe the same signal during different phases of its inspiral with different detectors (LISA, LGWA, ET / CE).

Multiband observations enable high-precision waveform analyses.

Science with Terrestrial GW Detectors



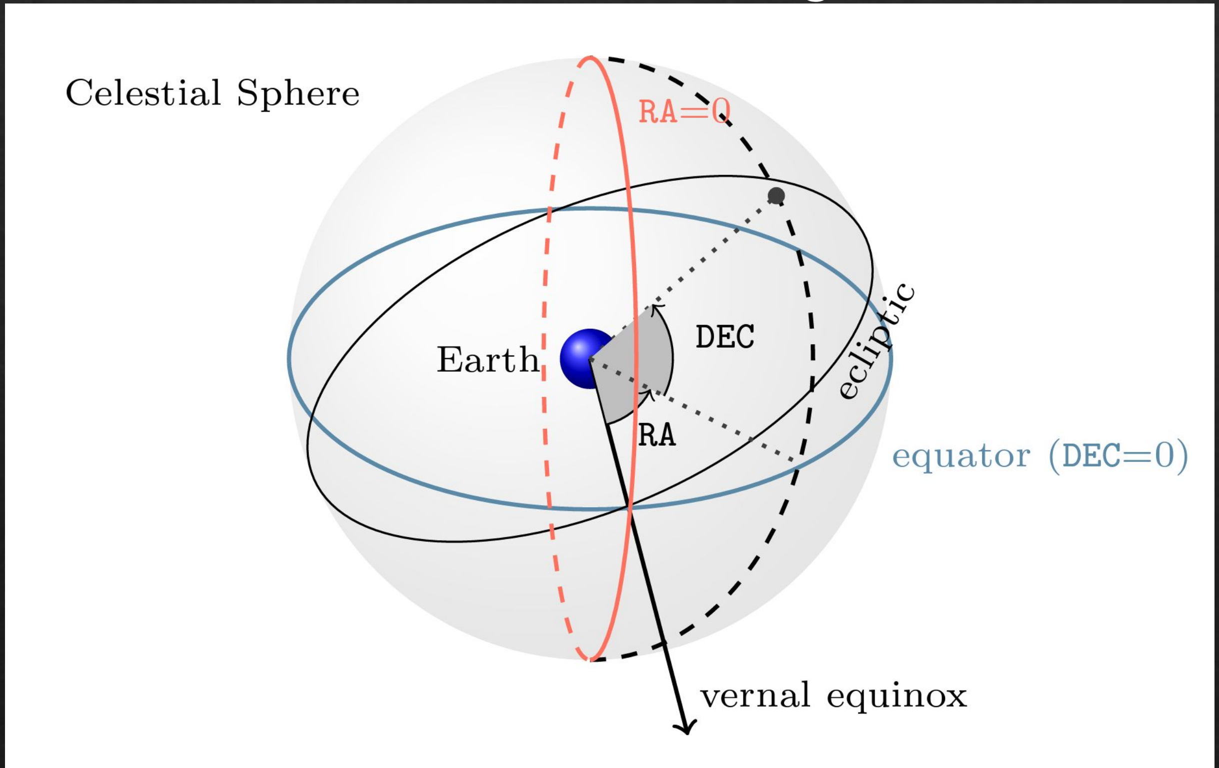


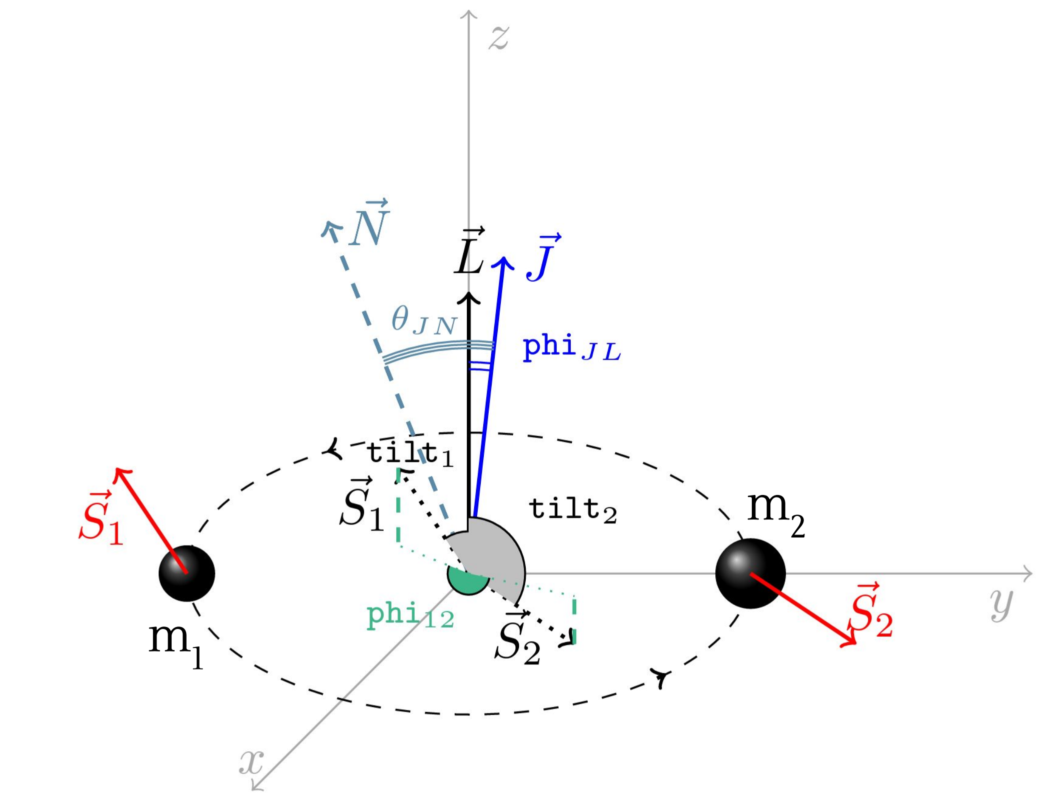
https://gwic.ligo.org/3Gsubcomm/docs/GWIC_3G_Science_Book.pdf

CBC Waveform Parameters

A BBH waveform has in total 16 parameters.

8 intrinsic: masses and spins
8 extrinsic: polarization and inclination angles, source location, orbital phase and eccentricity, merger time



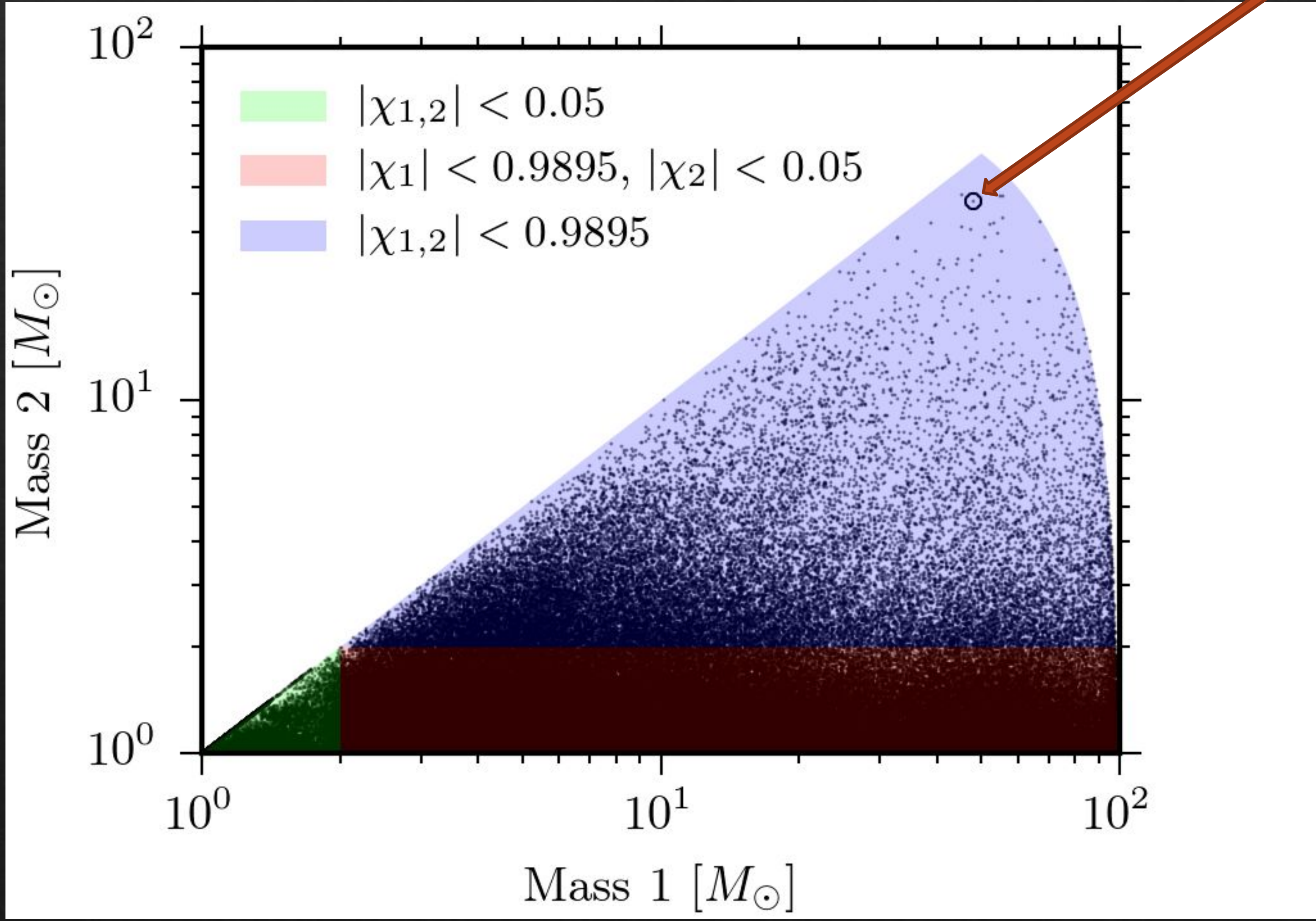


Dupletsa et al (2024)

Detecting a CBC: Matched Filtering

Example: template bank (in mass space) when GW150914 was discovered

Best match with GW150914



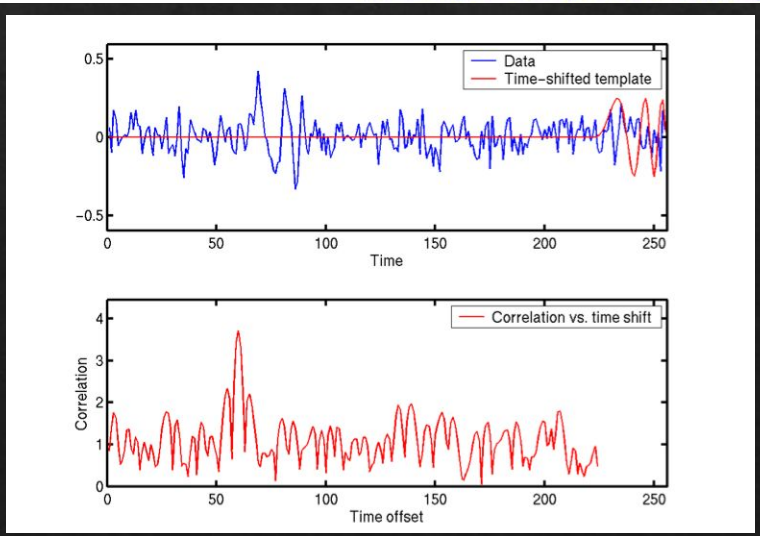
Matched filtering

FFT of data

Template; can be generated in frequency domain using stationary phase approximation

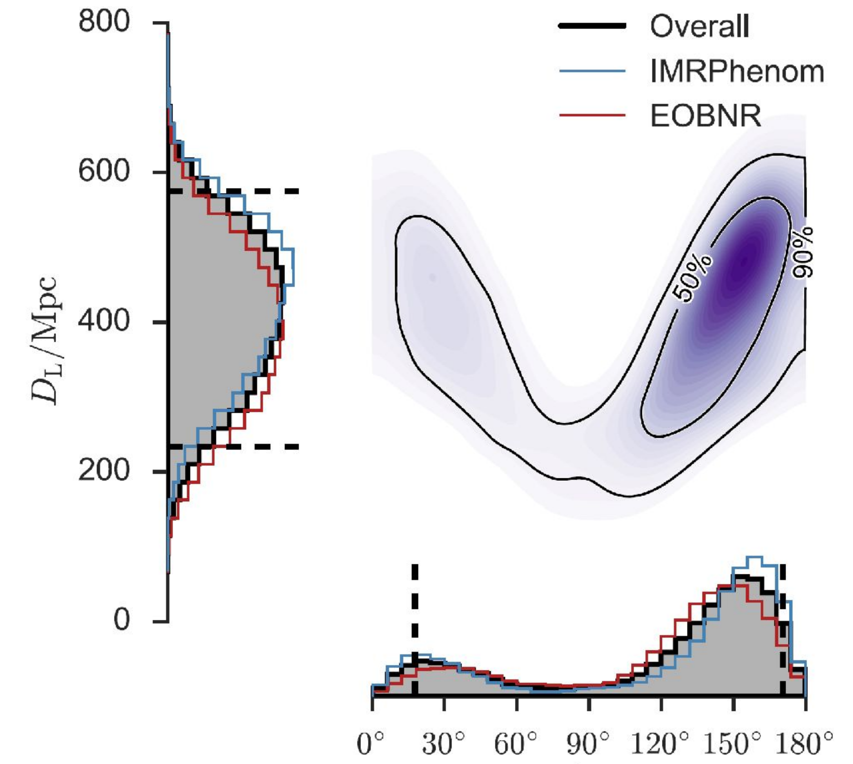
$$C(t) = 4\int_0^\infty \frac{\tilde{s}(f)\ \tilde{h}^*(f)}{S_n(f)}\ e^{2\pi i f t}\ df$$

Noise power spectral density



Bayesian Parameter Estimation

GW150914



PRL **116**, 241102 (2016)

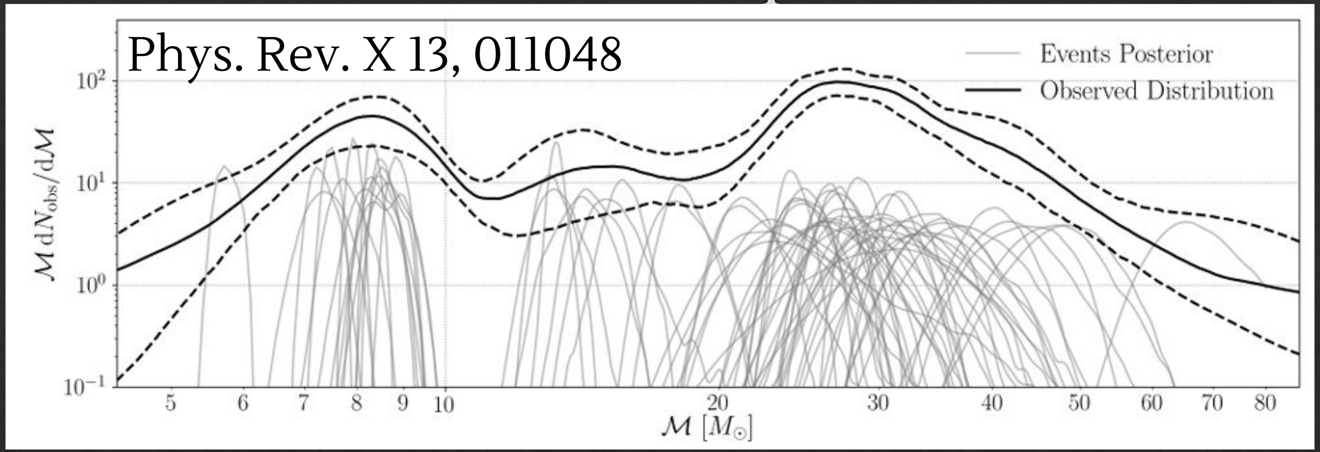
$$\underbrace{p(\theta|d)}_{\text{Posterior}} = \frac{\overbrace{p(d|\theta)}^{\text{Likelihood}}\ \overbrace{p(\theta)}^{\text{Prior}}}{\underbrace{p(d)}_{\text{Evidence}}}$$

Gaussian likelihood approximation:
Assume that detector noise is Gaussian

$$p(d|\theta) \propto \exp\left[-\frac{1}{2}\sum_k \langle h_k(\theta) - d_k | h_k(\theta) - d_k\rangle\right]$$

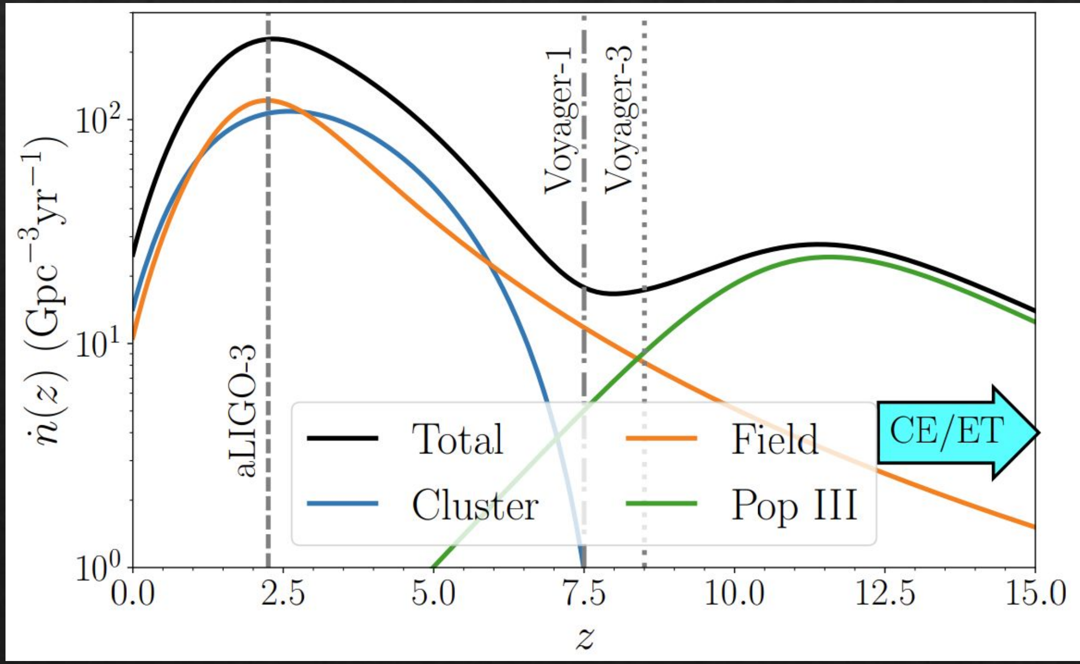
$$\langle a|b\rangle = 4\int_0^\infty \mathrm{d}f\, \frac{\Re(\tilde{a}(f)\tilde{b}^*(f))}{S(n;f)}$$

Black-hole Populations



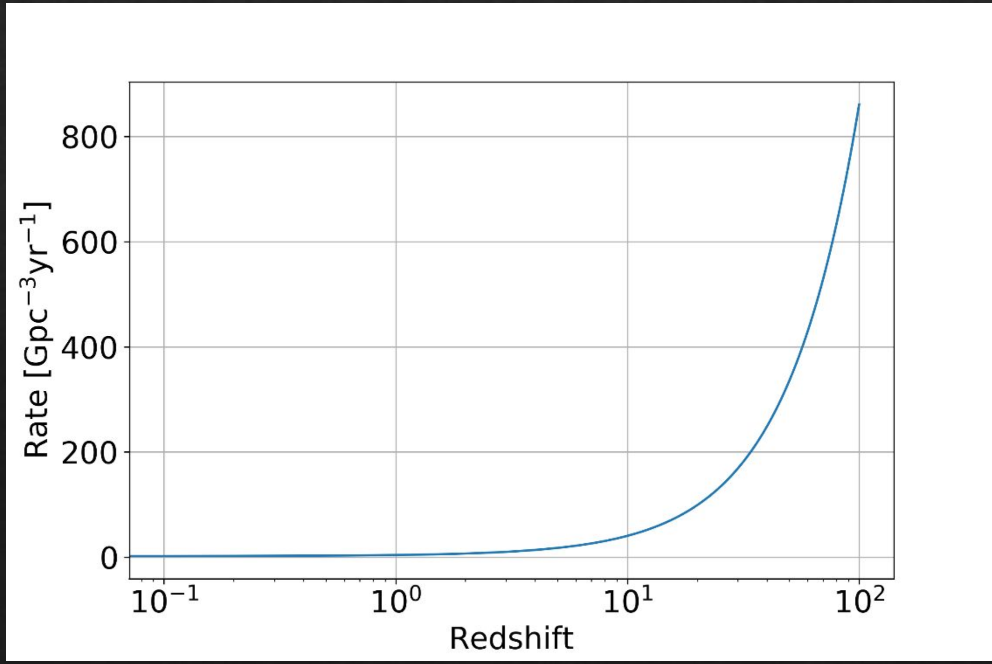
LVK, 2023

Precise population studies from 10^5 BBH mergers observed per year with ET/CE.



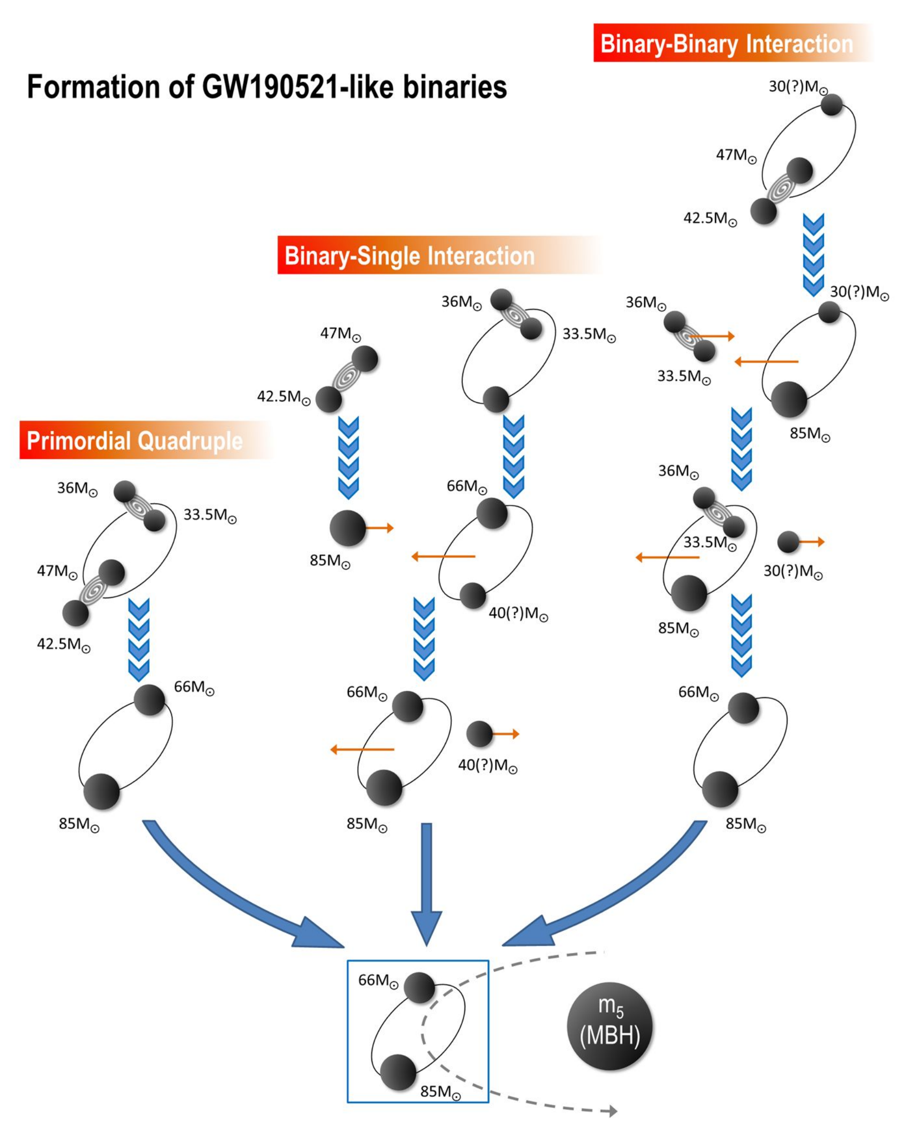
Ng et al, 2021

Is there a population of primordial black-holes?



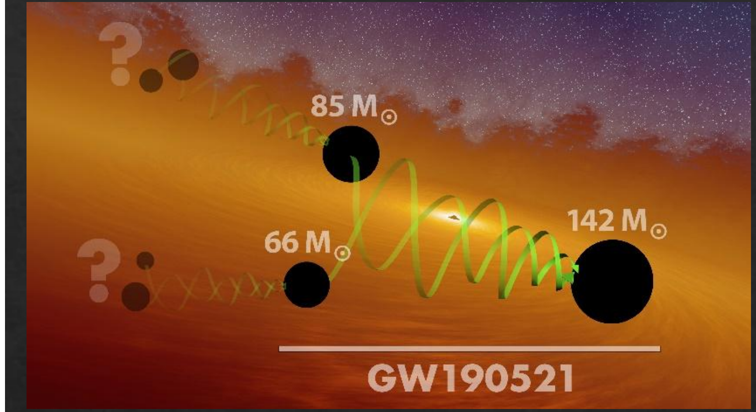
De Luca et al, 2020

Dynamical BH Interactions

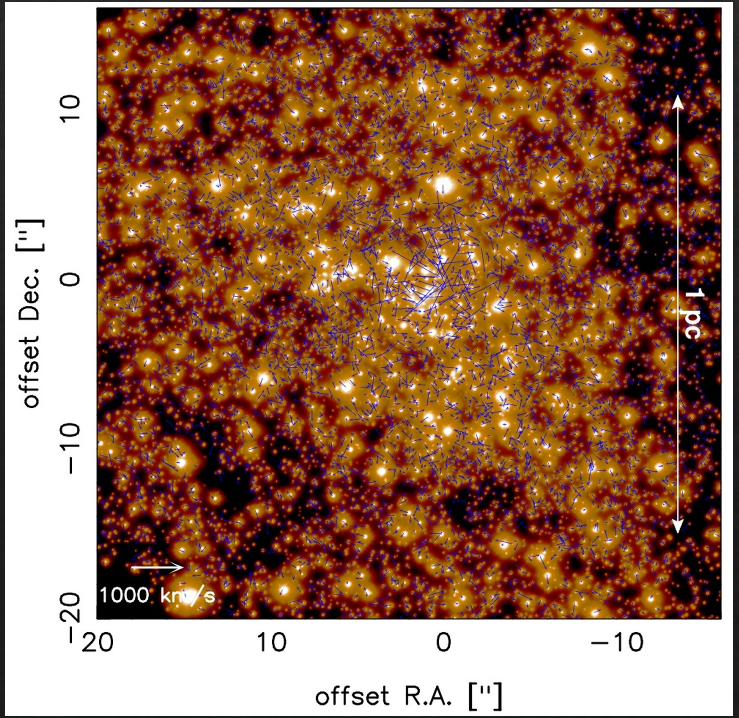


Lui/Lai, 2021

The cores of star clusters are expected tp have a high density of BHs facilitating dynamical BH interactions.

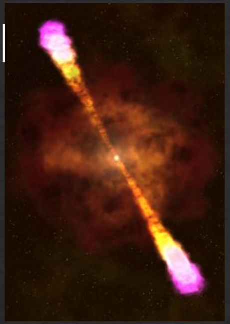


$$\rho > 10^5 M_\odot pc^{-3}$$



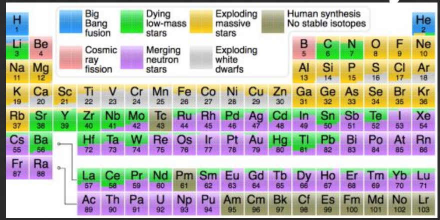
Science Of/With Neutron Stars

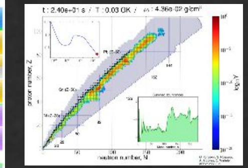
Relativistic astro



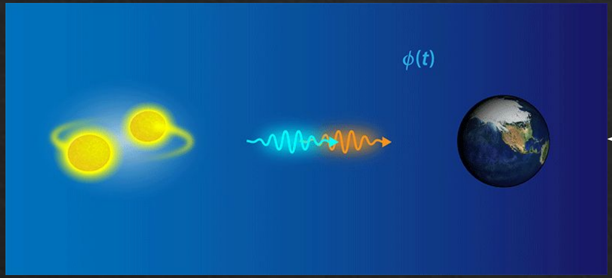
Radioactively powered transie

Nucleosynthes

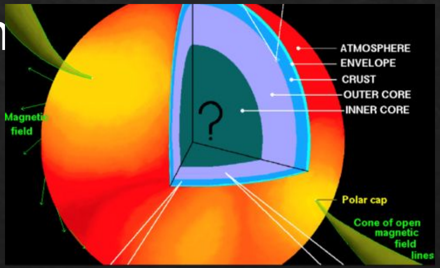




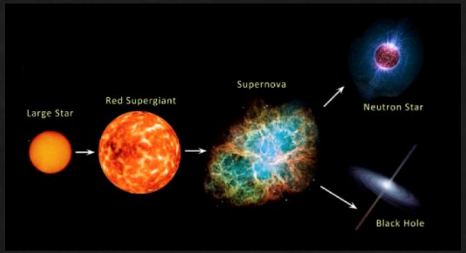
Testing general relativity



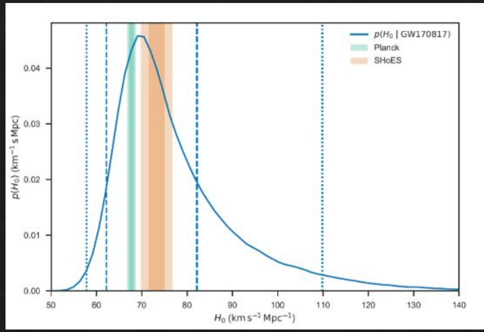
Nuclear matter ph



Compact-object formation and



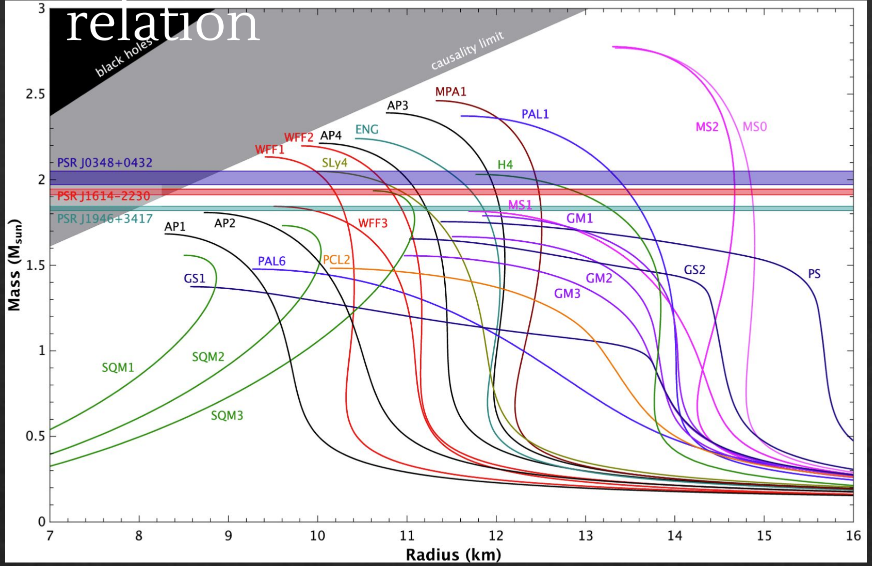
Cosmolog

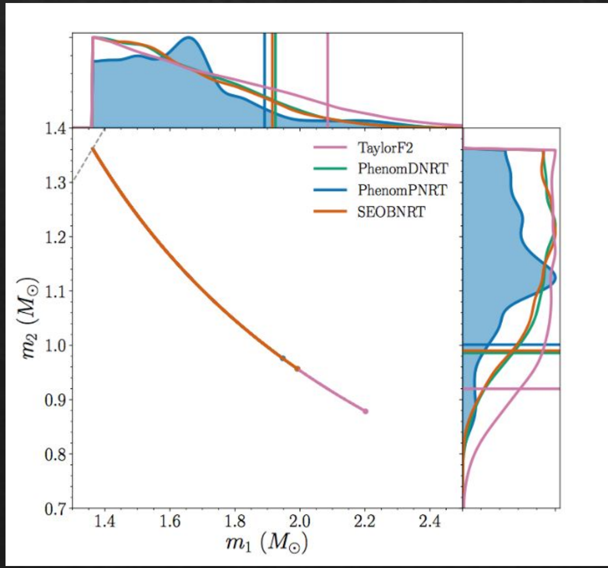


Credit: M Branchesi

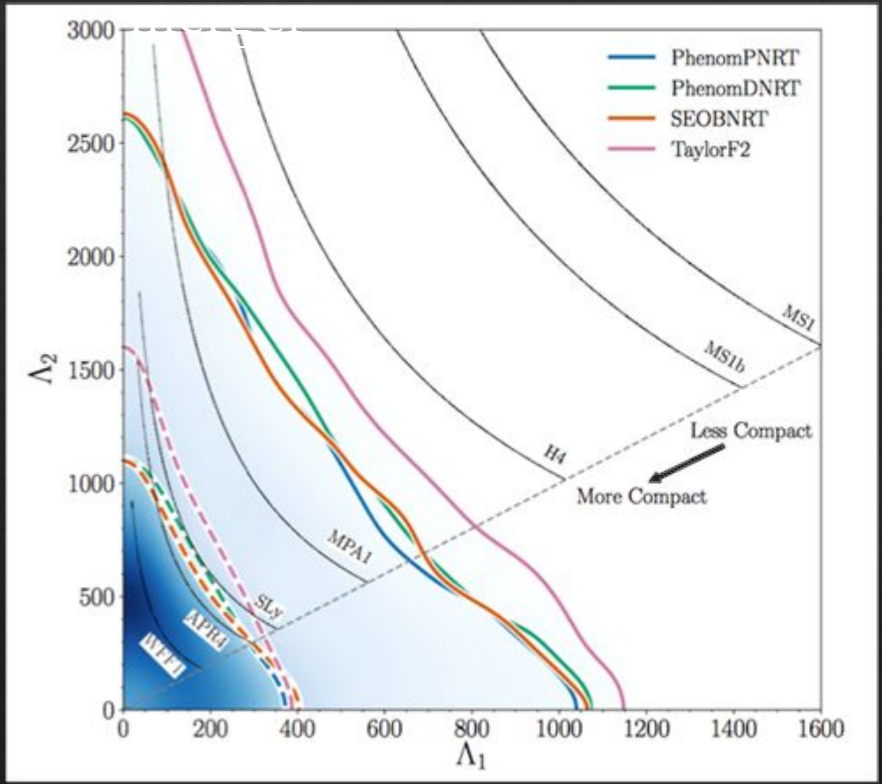
Neutron-star Equation of State

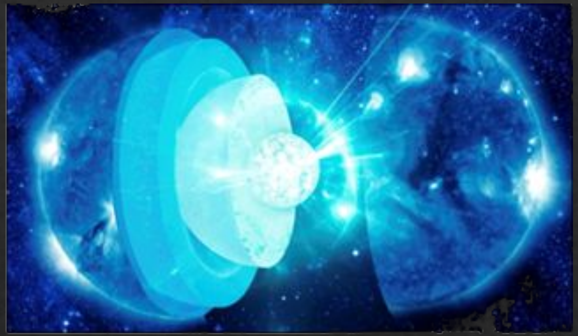
Intrinsic mass – NS radius relation





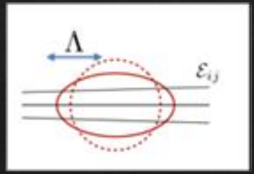
Observing deformations of neutron stars just before merger





TIDAL DEFORMABILITY

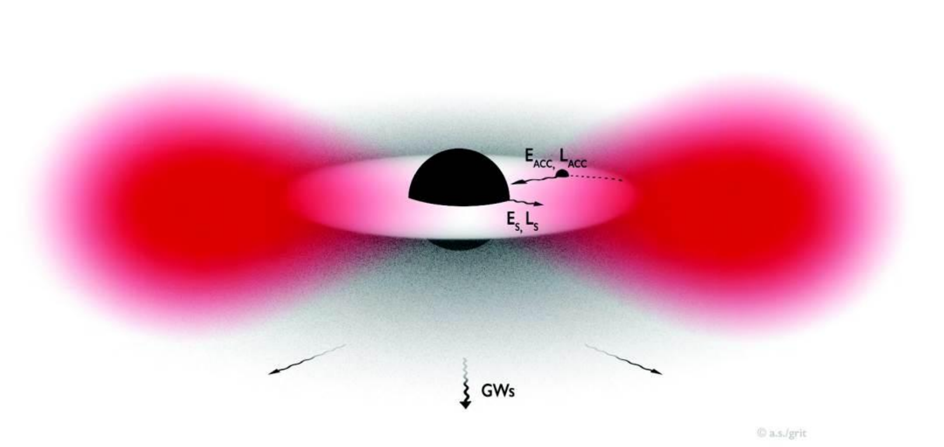
$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$



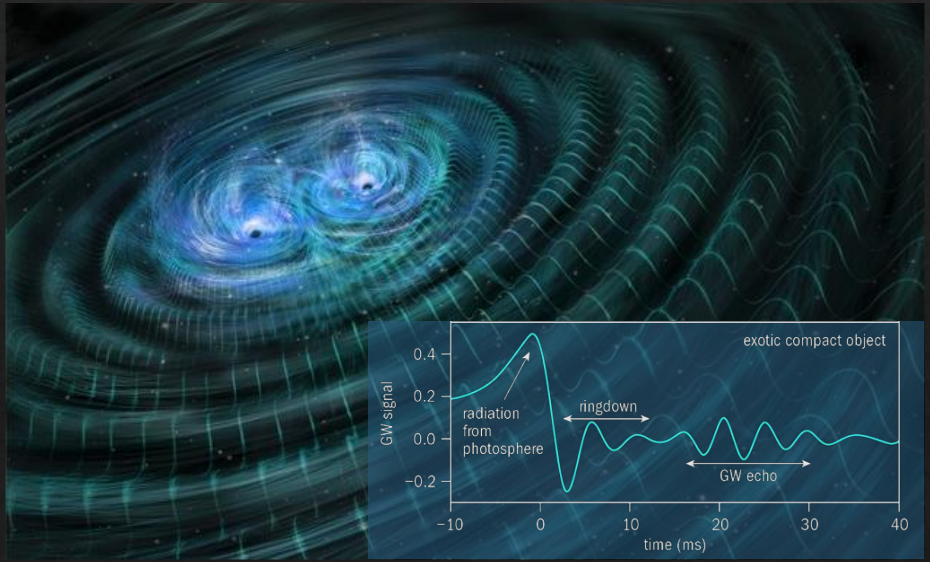
Individual BBH Signals: New Physics

Black holes: the ultimate engine of discovery
[cit Cardoso, 2020]

BH superradiance with light bosons

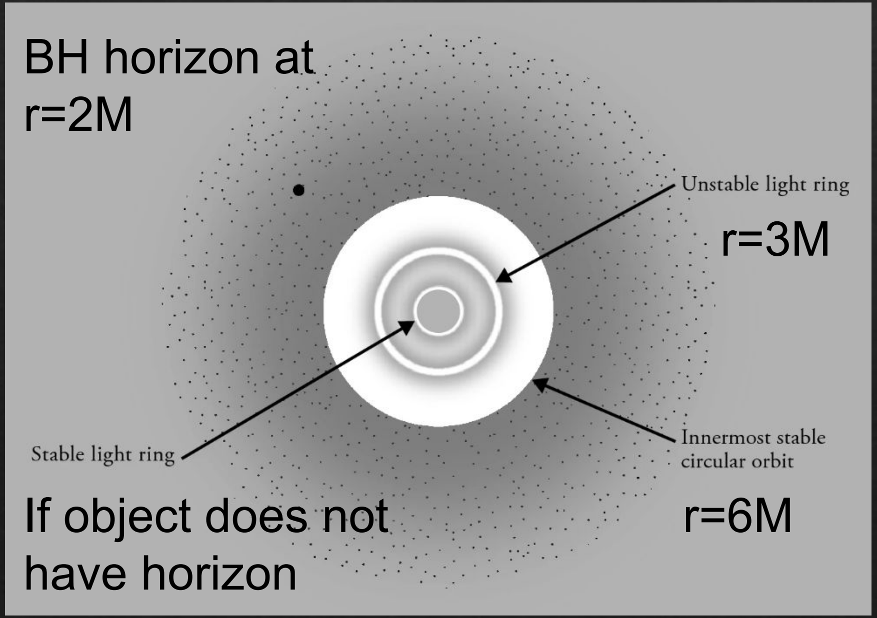


Quantum gravity: area discretization



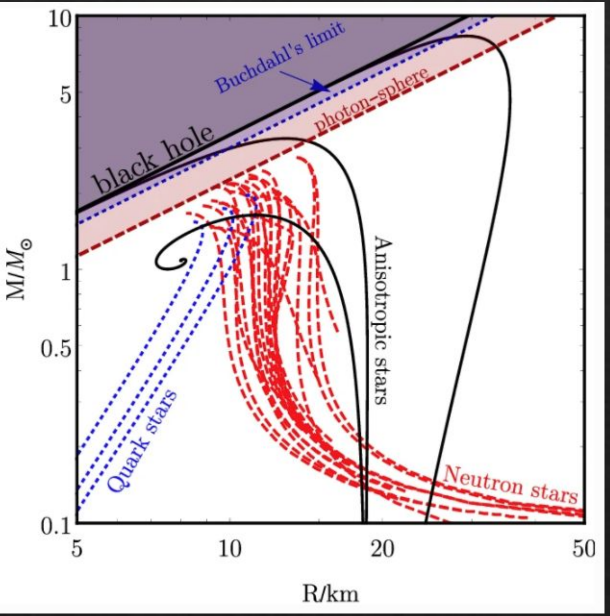
Agullo et al, 2021

Probing the structure of BH spacetime



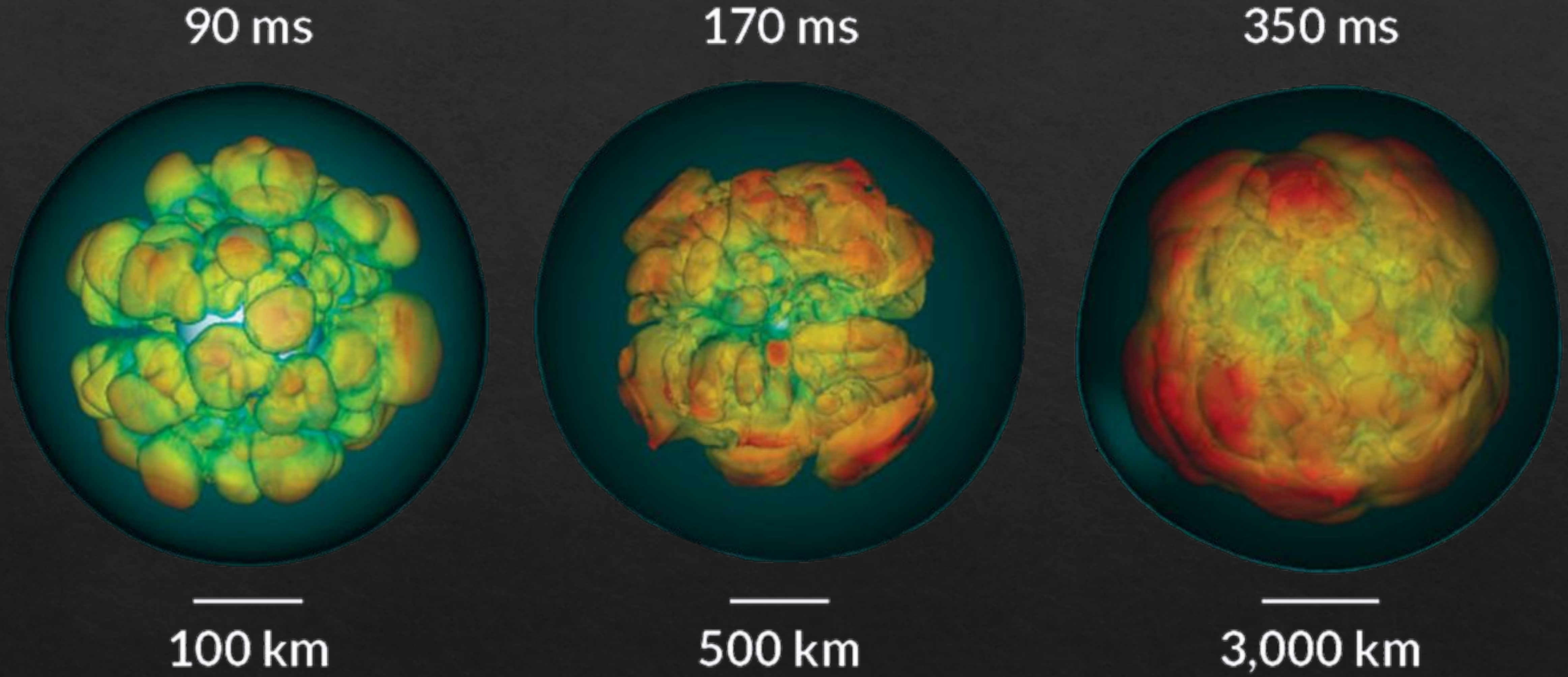
Cardoso, Pani, 2019

Exotic compact objects: Infer mass-radius relation



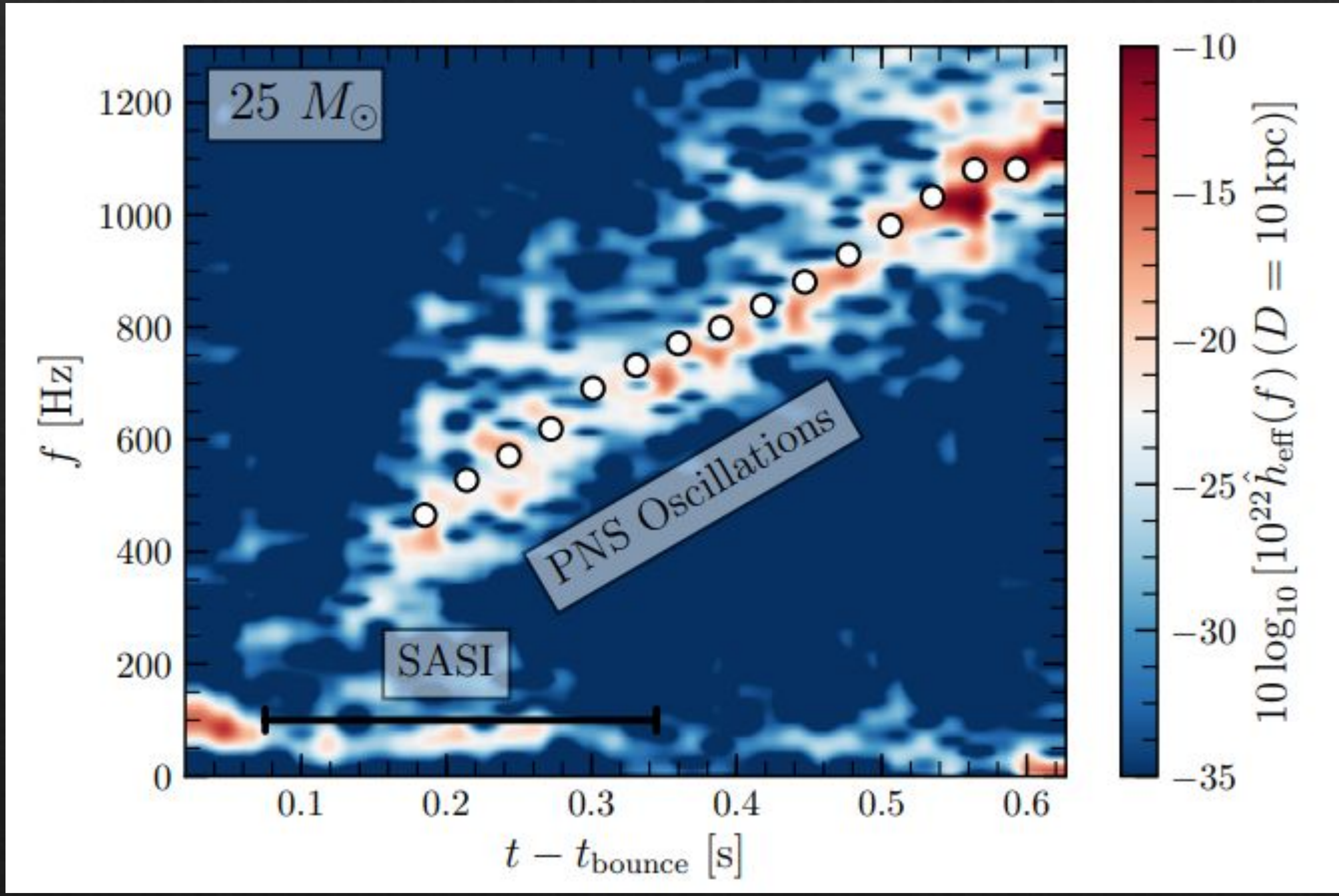
Cardoso, Pani, 2019

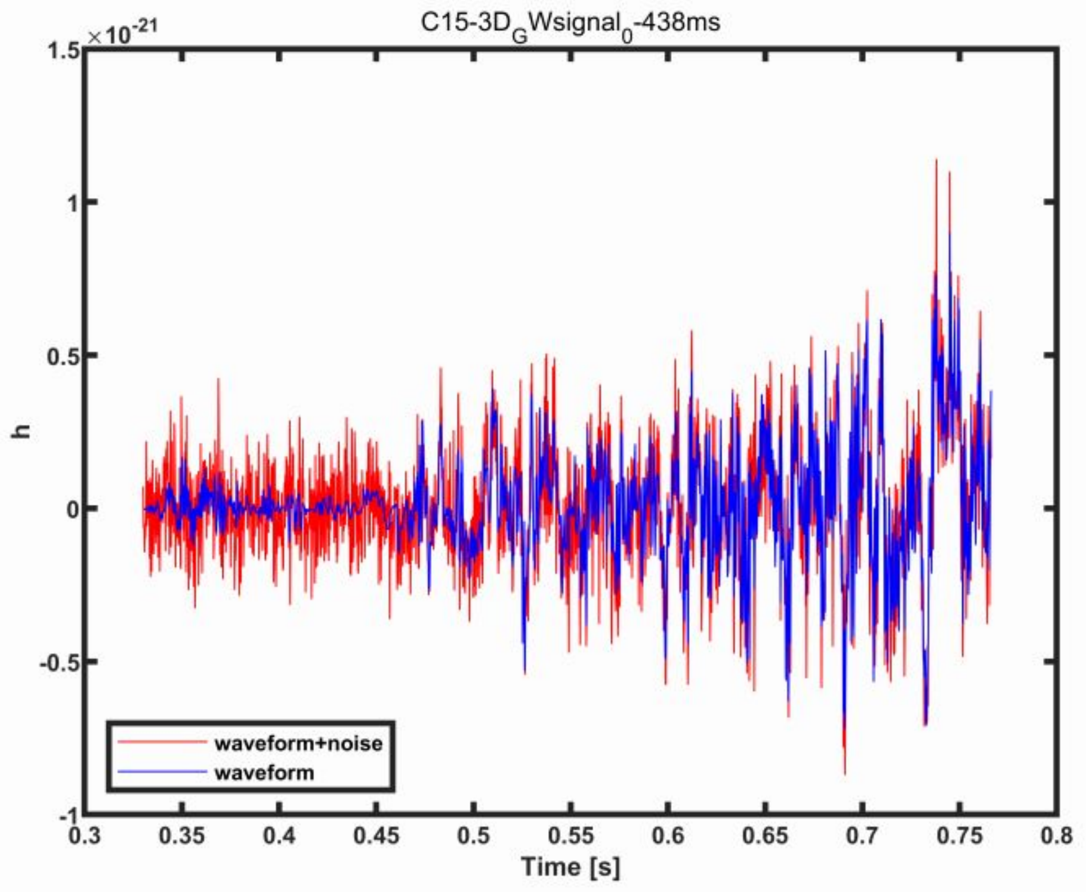
Core-Collapse Supernovae



GW signals from core-collapse SNe

Modeling of SN signals is an extremely complex problem and not yet fully understood.





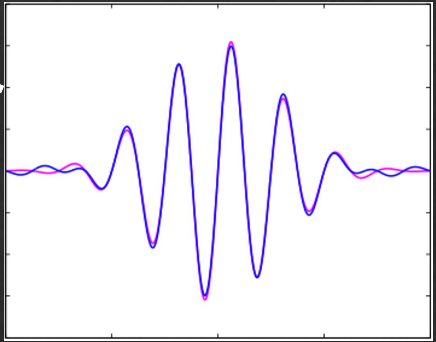
Coherent WaveBurst

wavelet transform

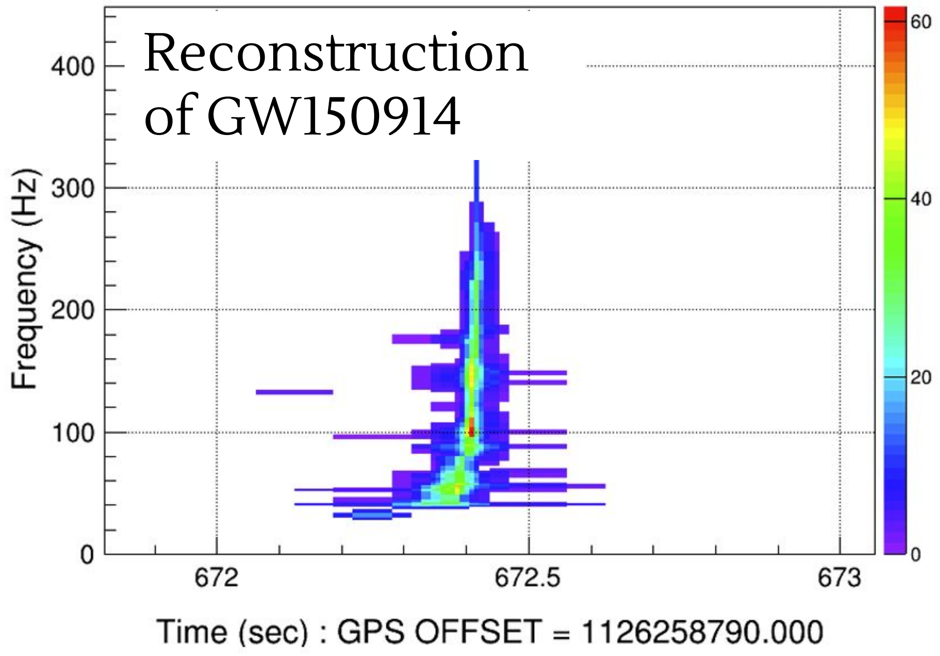
$$X(\tau,\phi,Q) = \int_{-\infty}^{+\infty} x(t)\, w(t-\tau,\phi,Q)\, e^{-i2\pi\phi t}\, dt$$

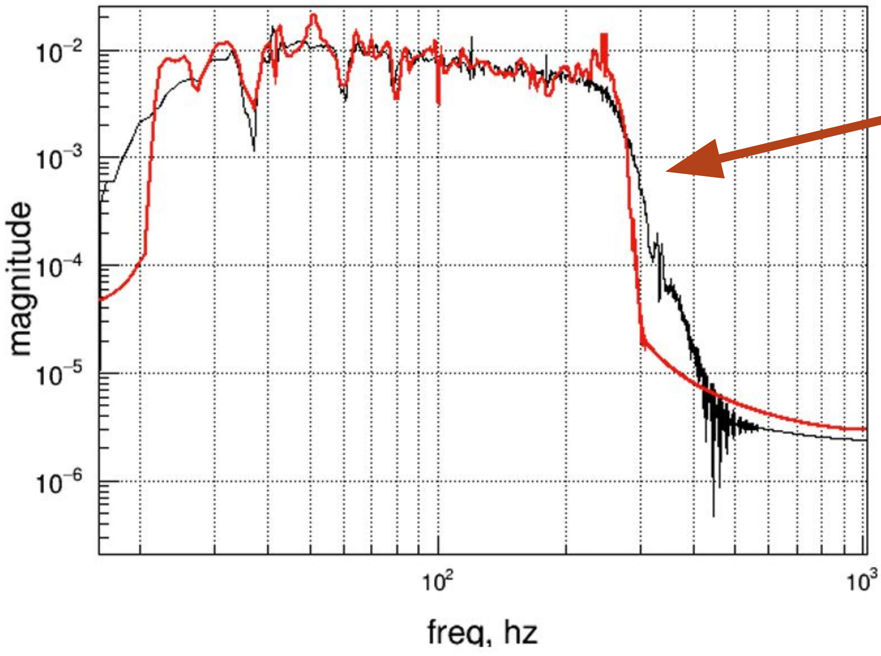
data

wavelet



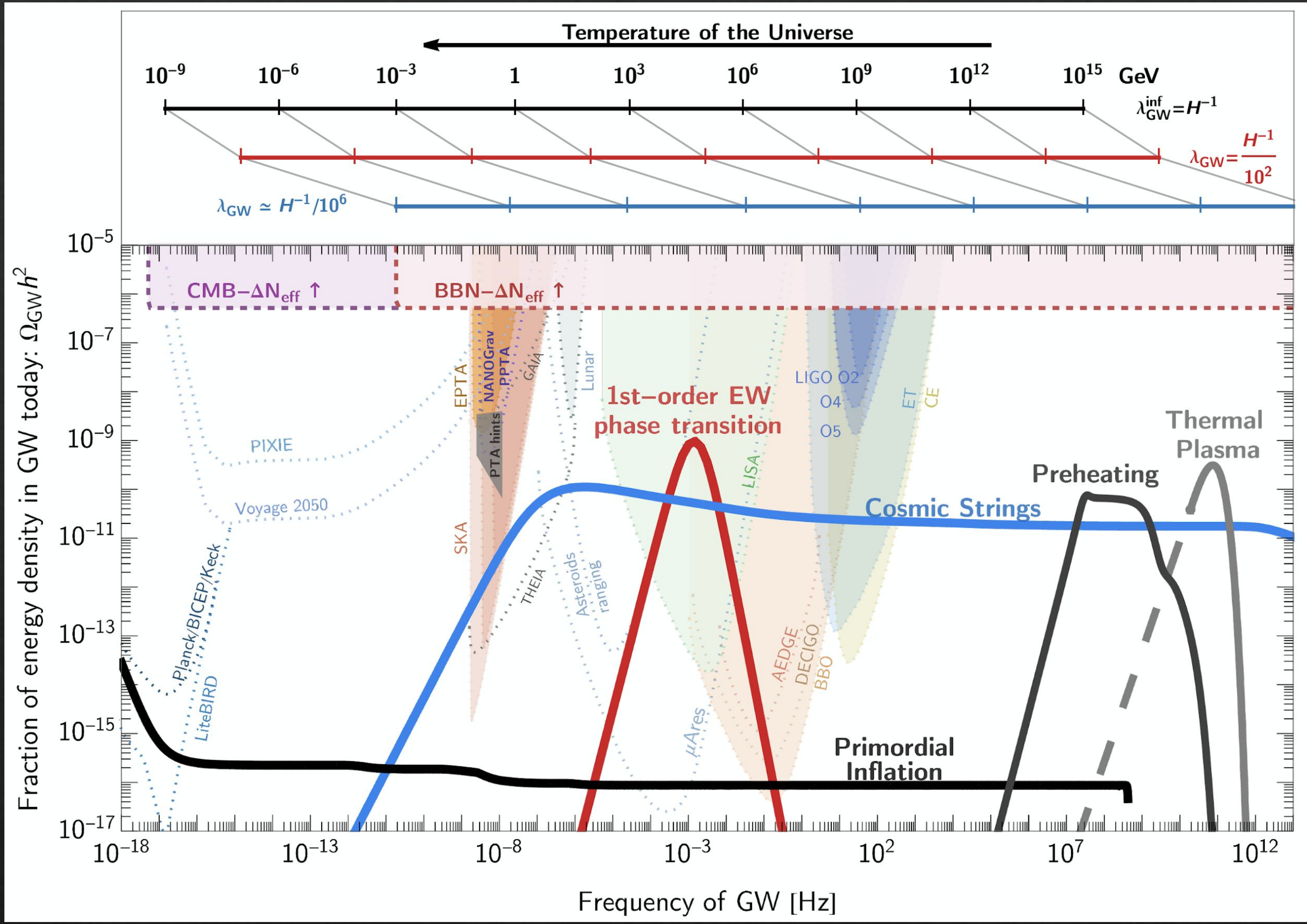
Likelihood 641 - dt(ms) [7.8125:250] - df(hz) [2:64] - npix 131





Comparison in frequency domain

Primordial GW Backgrounds



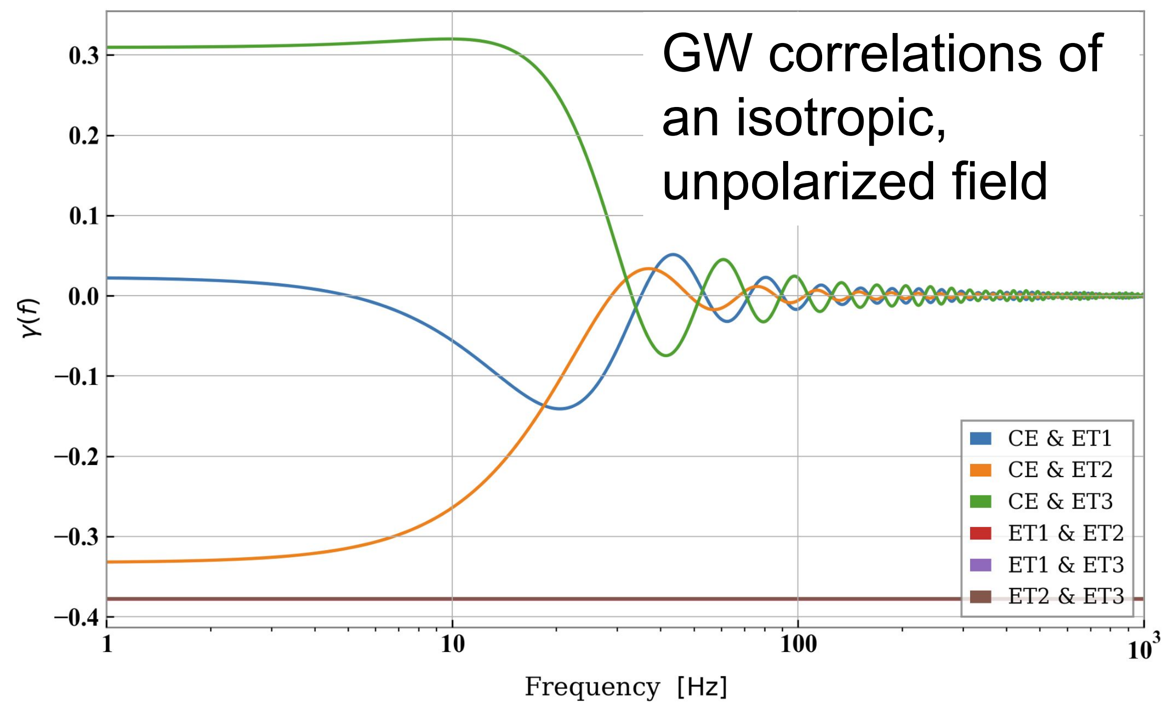
Simakachorn, 2022

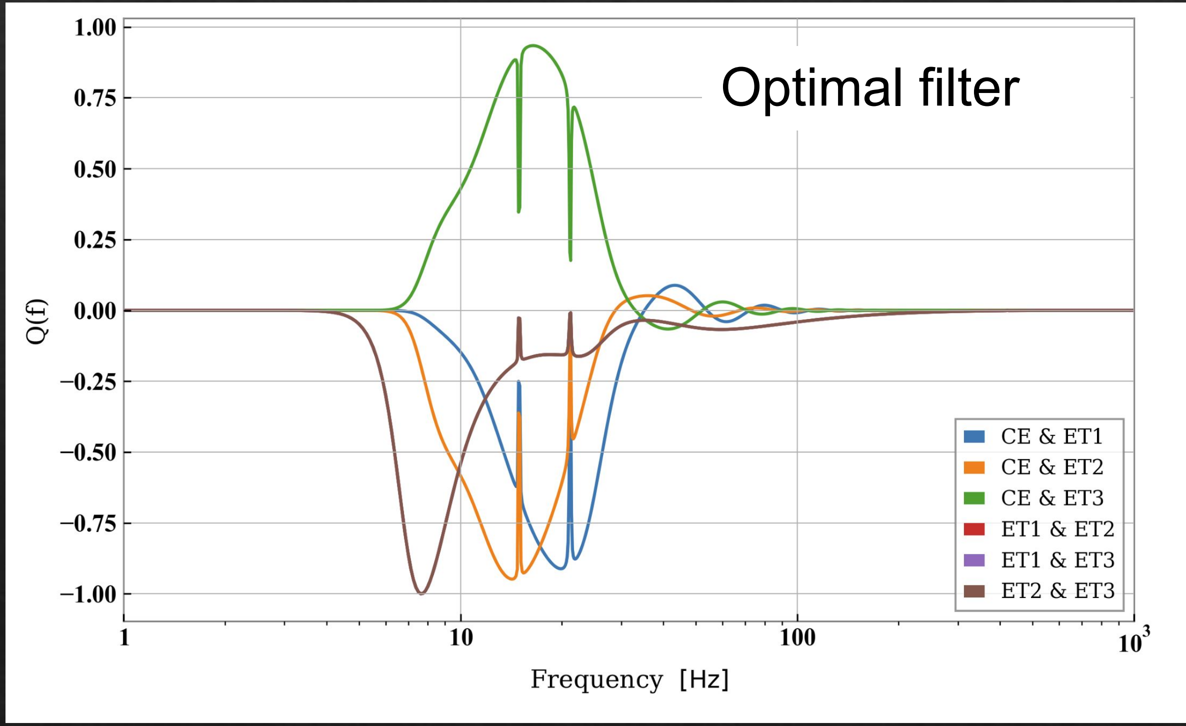
Observation of Stochastic Backgrounds

Correlate data between GW detectors!

$$C_{ij}(f) = S_{\rm GW}(f)\gamma_{ij}(f)$$

$$\langle \mathcal{C}_{ij}\rangle = \int_0^\infty \mathrm{d}f\,\langle C_{ij}(f)\rangle \tilde{Q}_{ij}(f)$$

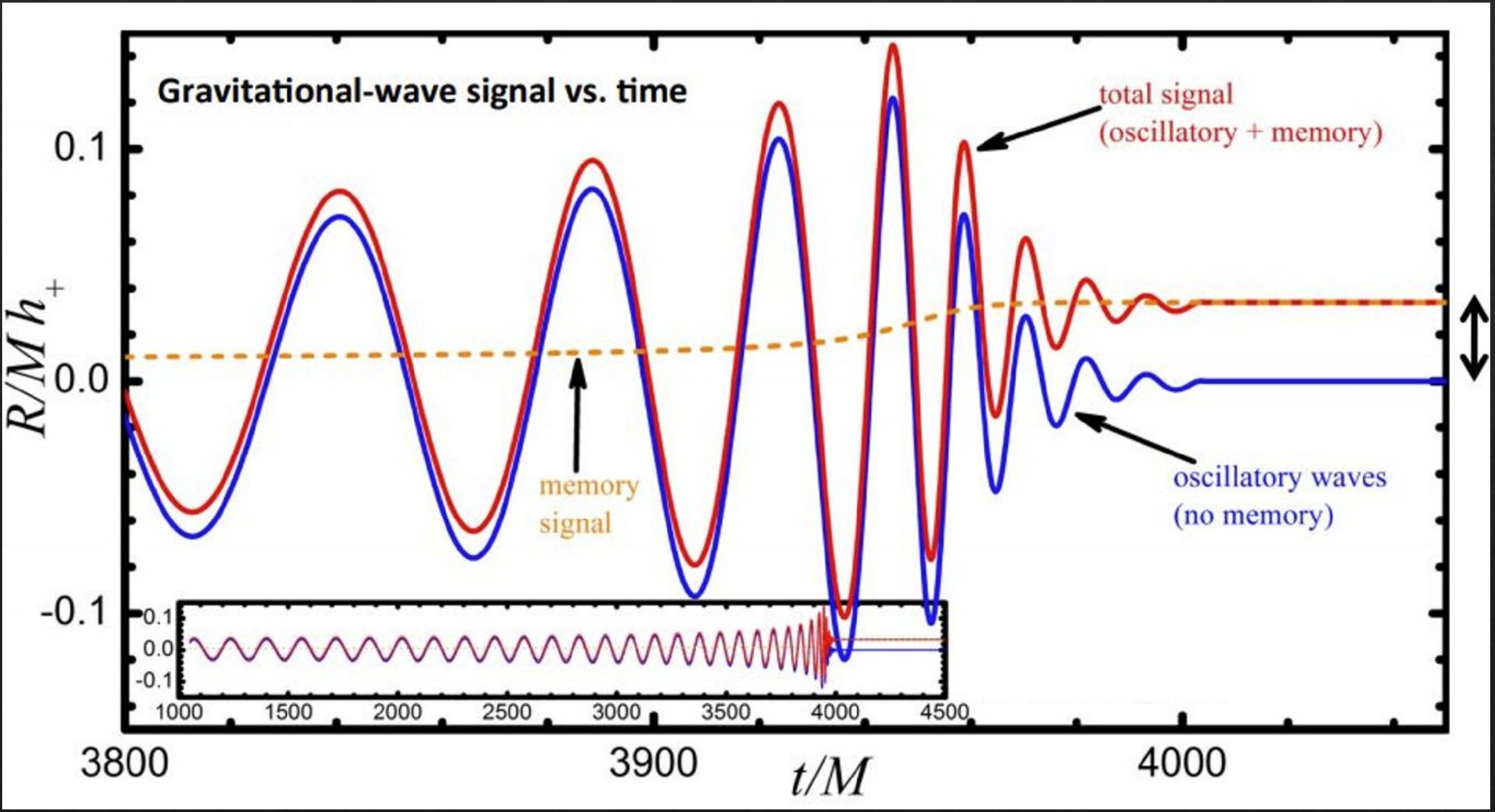




Gravitational-wave Memory

Time-integrated GW energy emitted into solid angle

Christodoulou memory effect: $$\Delta h_{jk}^{\mathrm{TT}} = \frac{4}{r}\int \frac{dE}{d\Omega'}\left[\frac{\xi^{j\prime}\xi^{k\prime}}{1-\cos\theta'}\right]^{\mathrm{TT}} d\Omega'$$

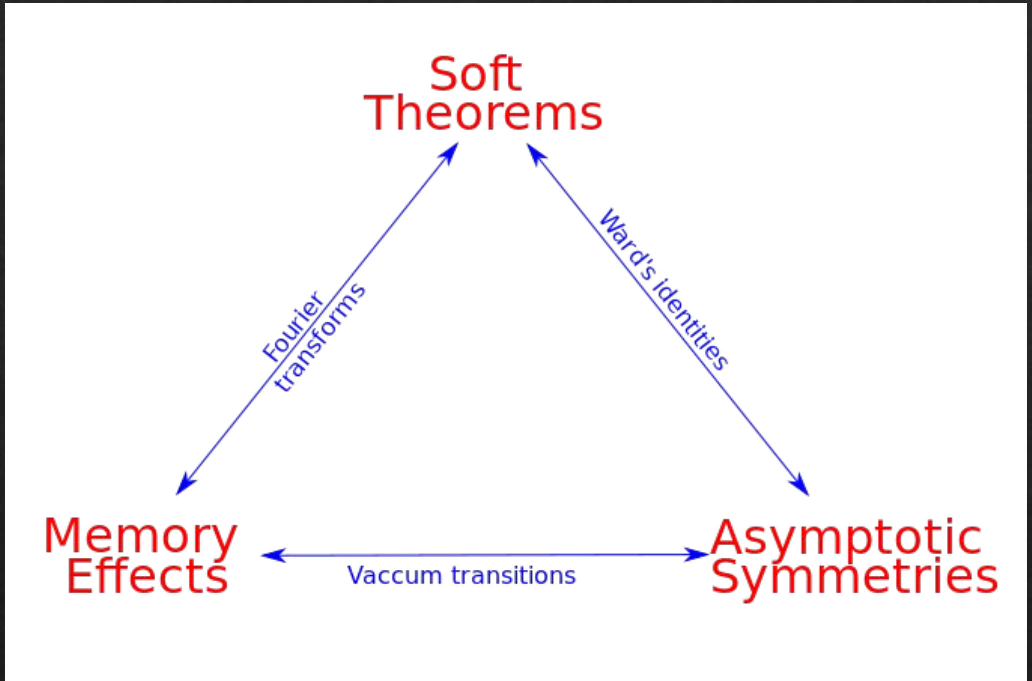


GWs leave a lasting deformation of spacetime behind them.

Deep connection to spacetime symmetries and quantum gravity.

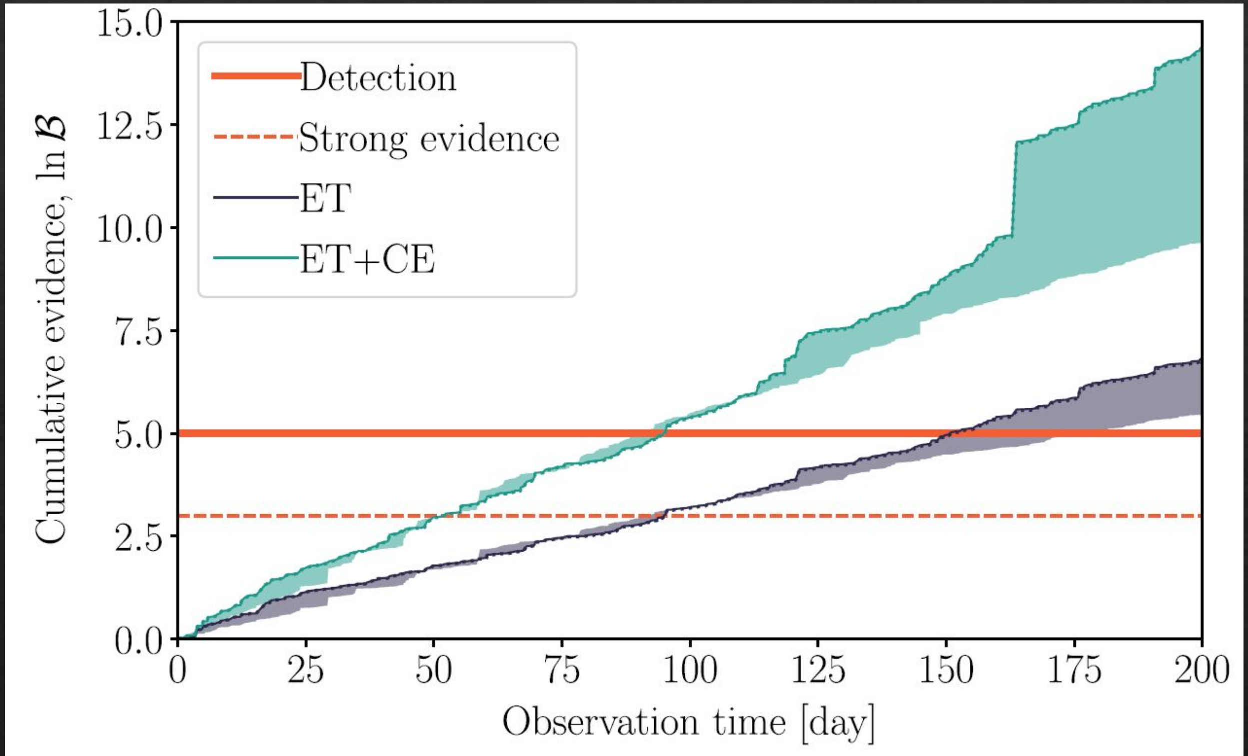
GW Memory: Exploring Fundamental Spacetime Symmetries

The infrared triangle



Pasterski–Strominger–Zhiboedov

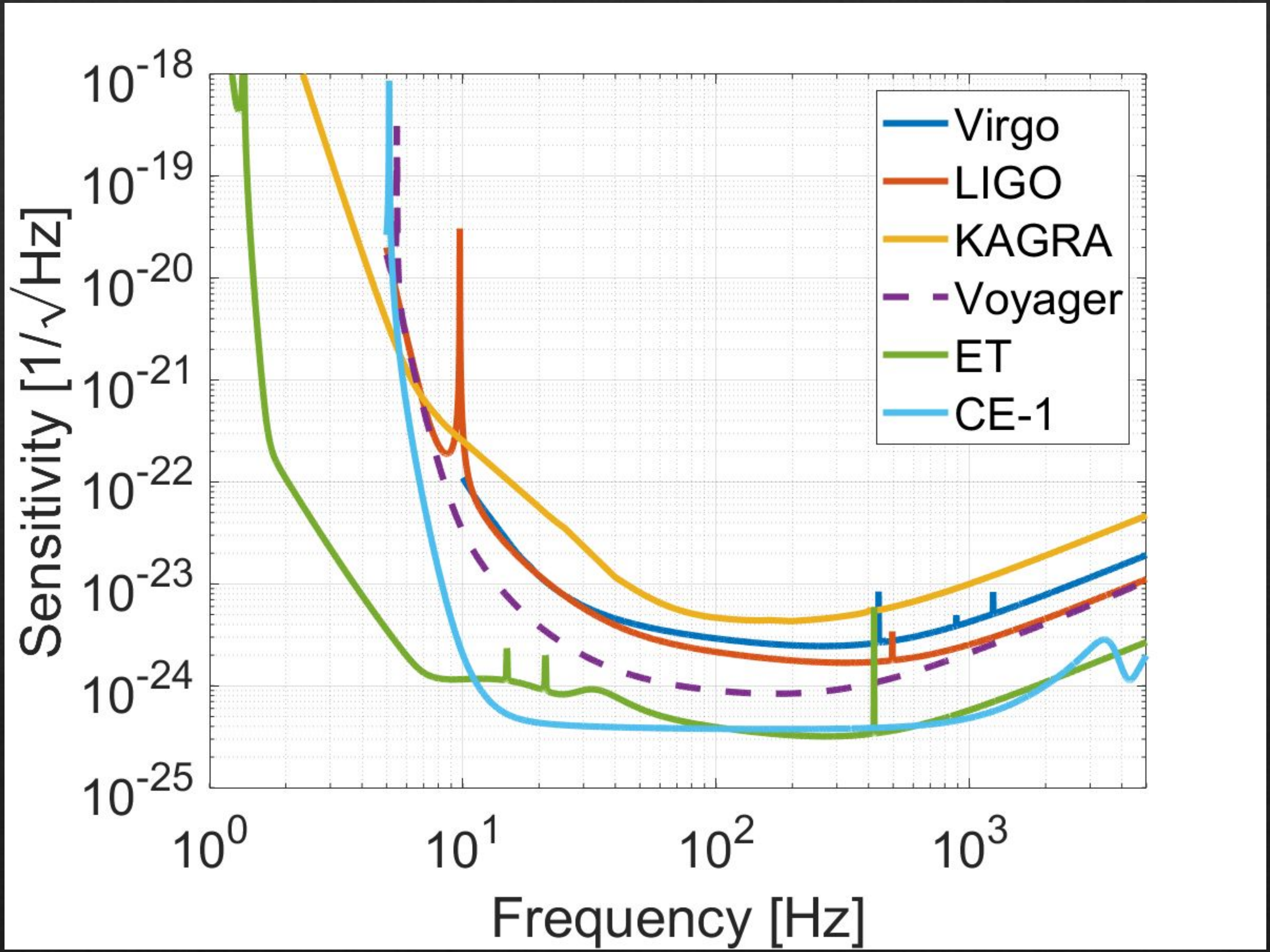
Bondi-Metzner-Sachs Symmetries



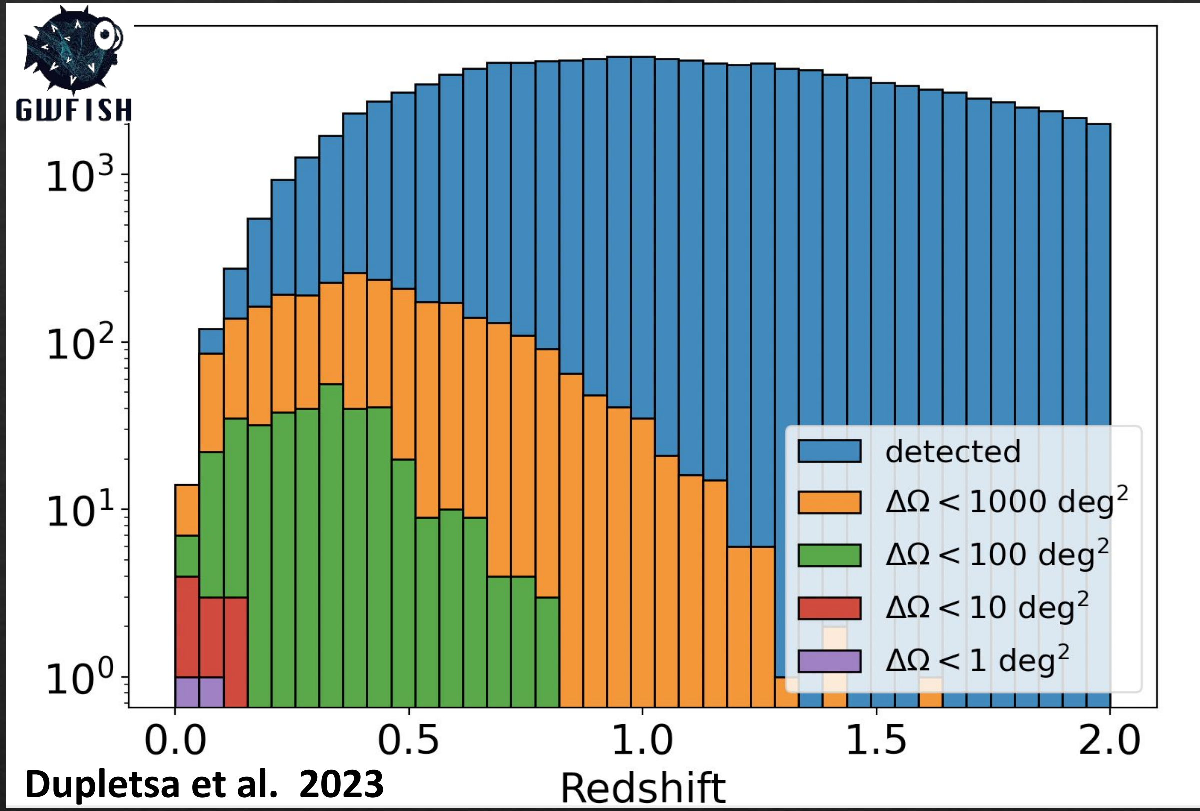
Goncharov et al, 2024

Fin
e

Targeted Strain Sensitivities



ET Sky-localization Capabilities



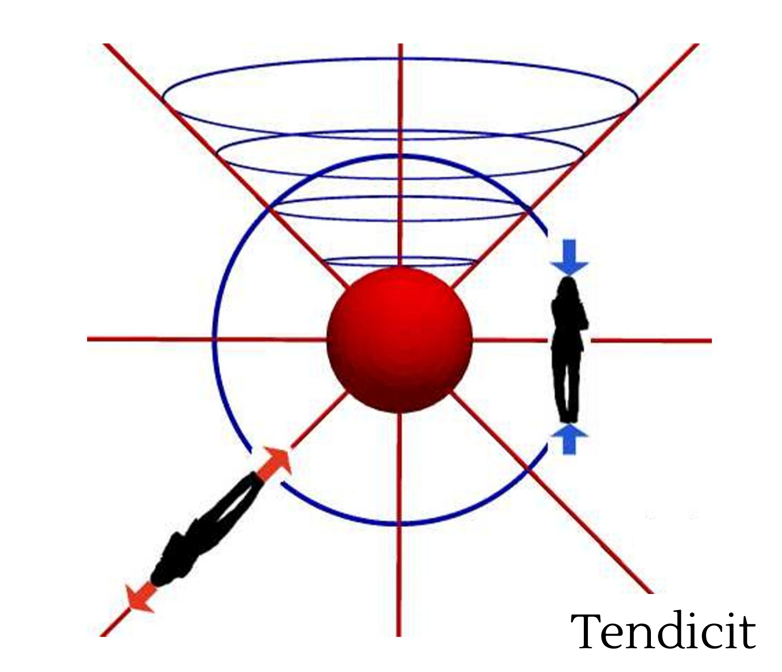
ET low frequency sensitivity makes it possible to localize BNS:

Modulation of signal amplitude and phase when observing it for many hours.

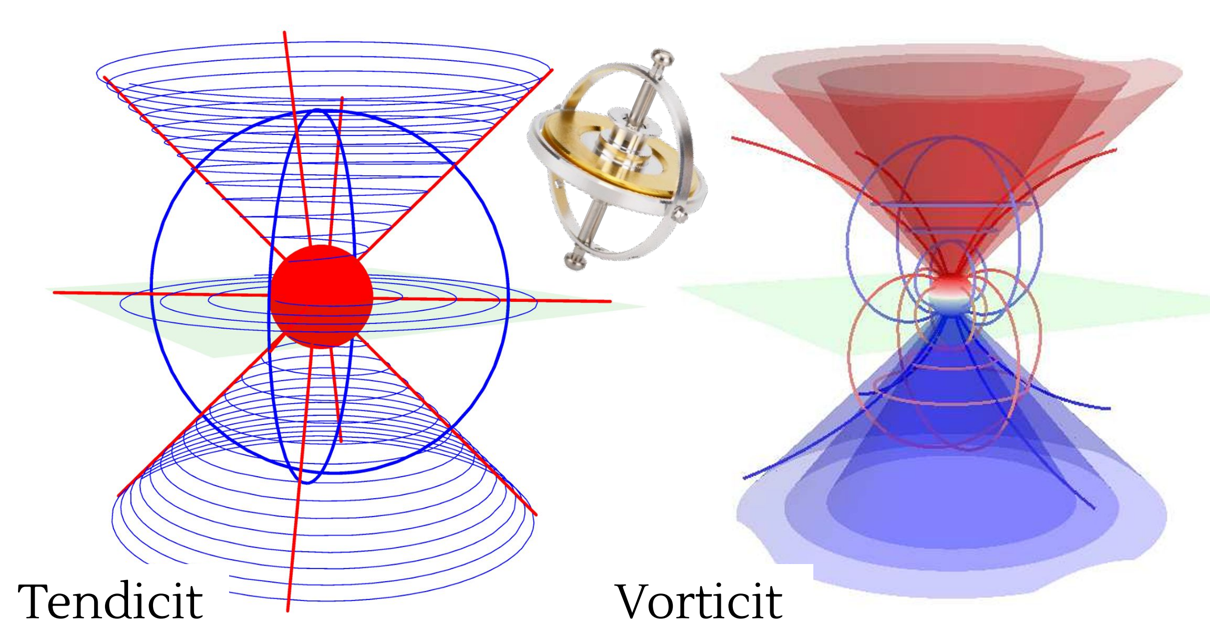
- O(100) detections per year with sky-localization (90% c.r.) < 100 sq. deg
- Early warning alerts!

Black-hole Spacetime

Non-rotating black hole



Slowly rotating black hole



Tendicity is derived from the tidal field:
Differential acceleration between freely-falling masses

Vorticity is derived from the frame-drag field:
Differential precession between freely-falling gyroscopes

Newtonian-noise Cancellation

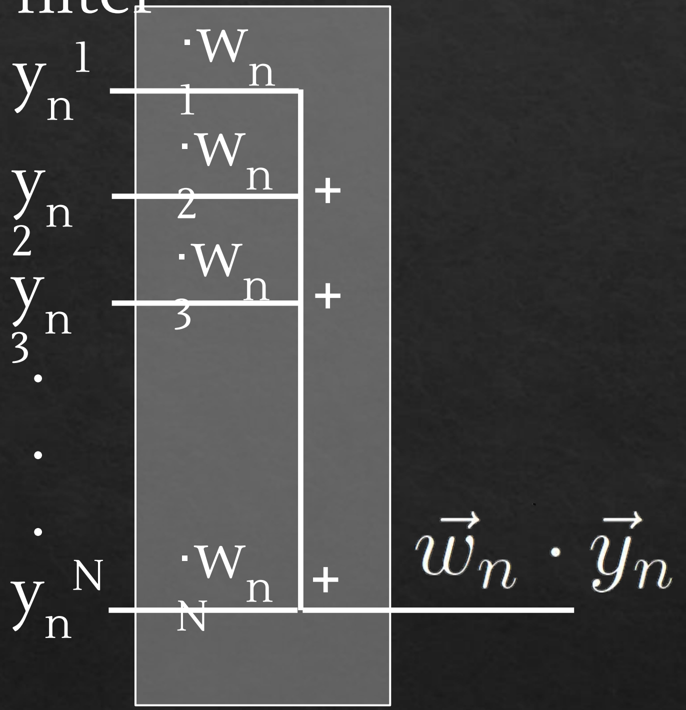
Wiener filter

$$\vec{w}_n = \langle x_n \vec{y}_n^{\dagger} \rangle \cdot \langle \vec{y}_n \vec{y}_n^{\dagger} \rangle^{-1}$$

Correlations between all inputs y

Correlations between inputs y and target

Linear discrete filter



Residual noise power after subtraction

$$\langle |\vec{w}_n \cdot \vec{y}_n - x_n|^2 \rangle$$

Assuming optimal sensor placement:
10 borehole seismometers per test mass