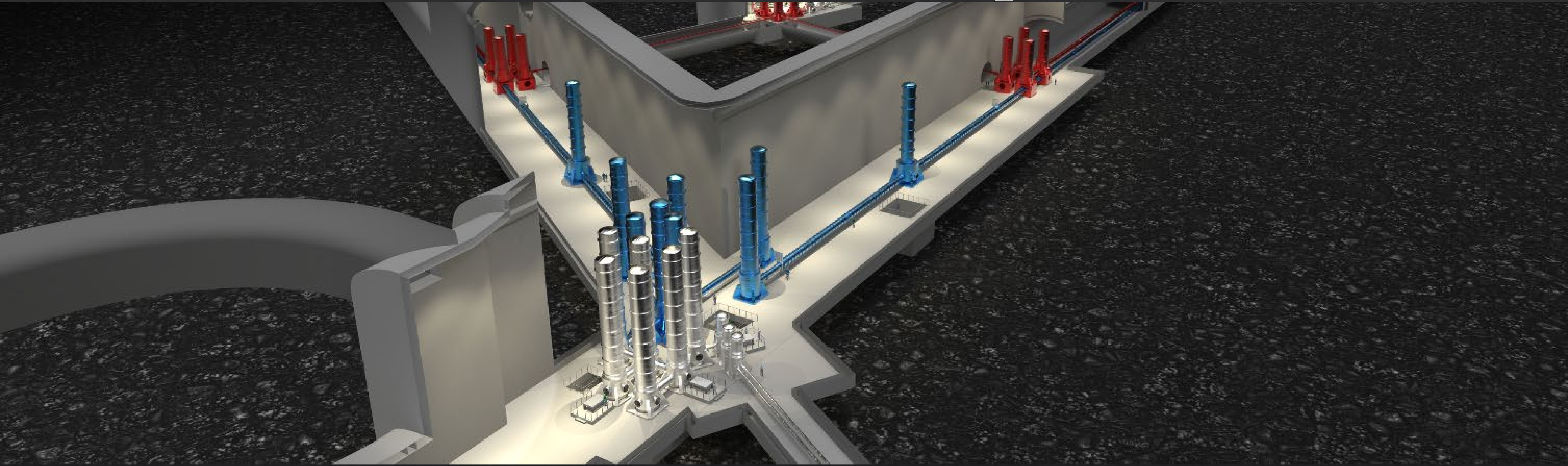
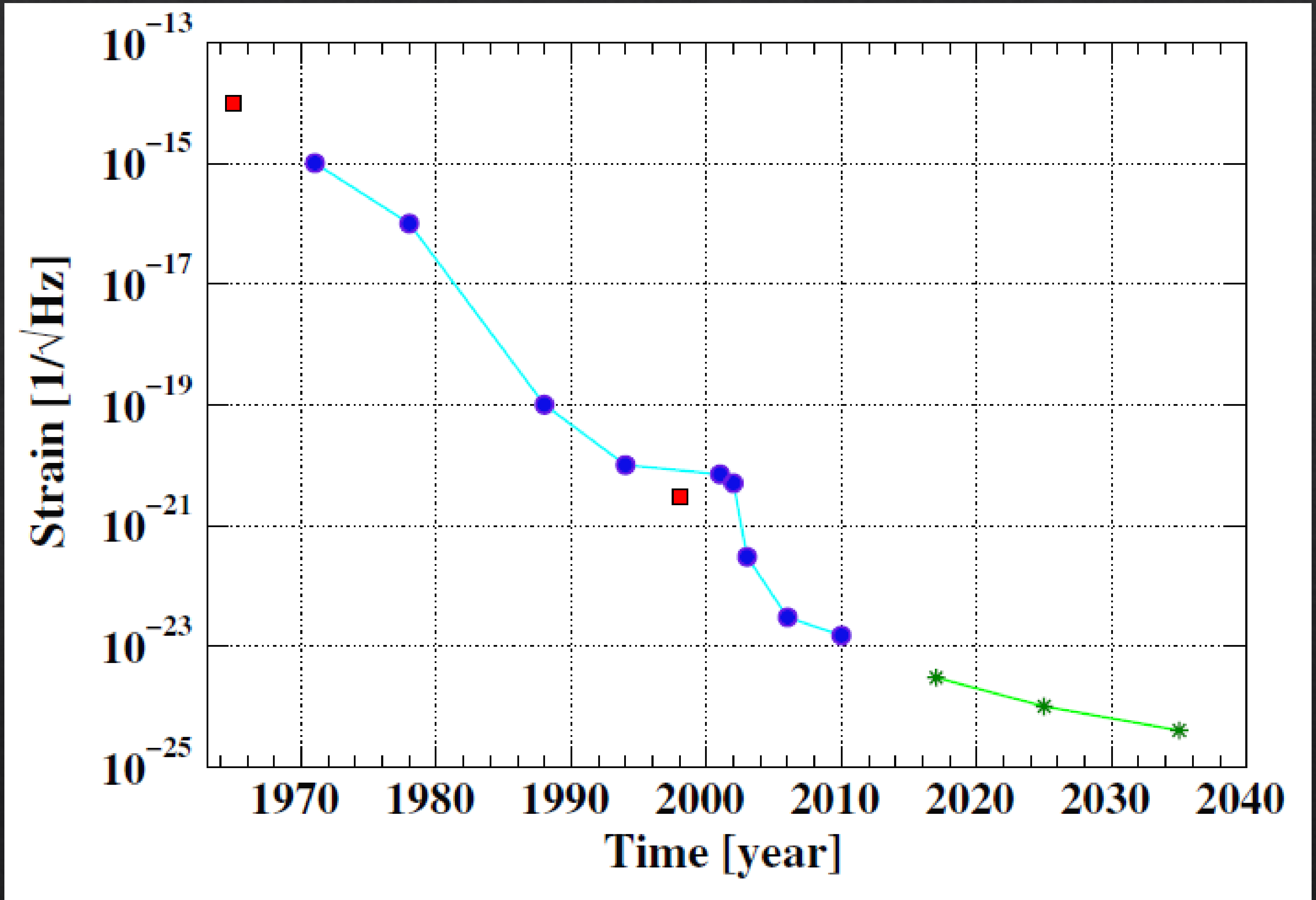
Einstein Telescope



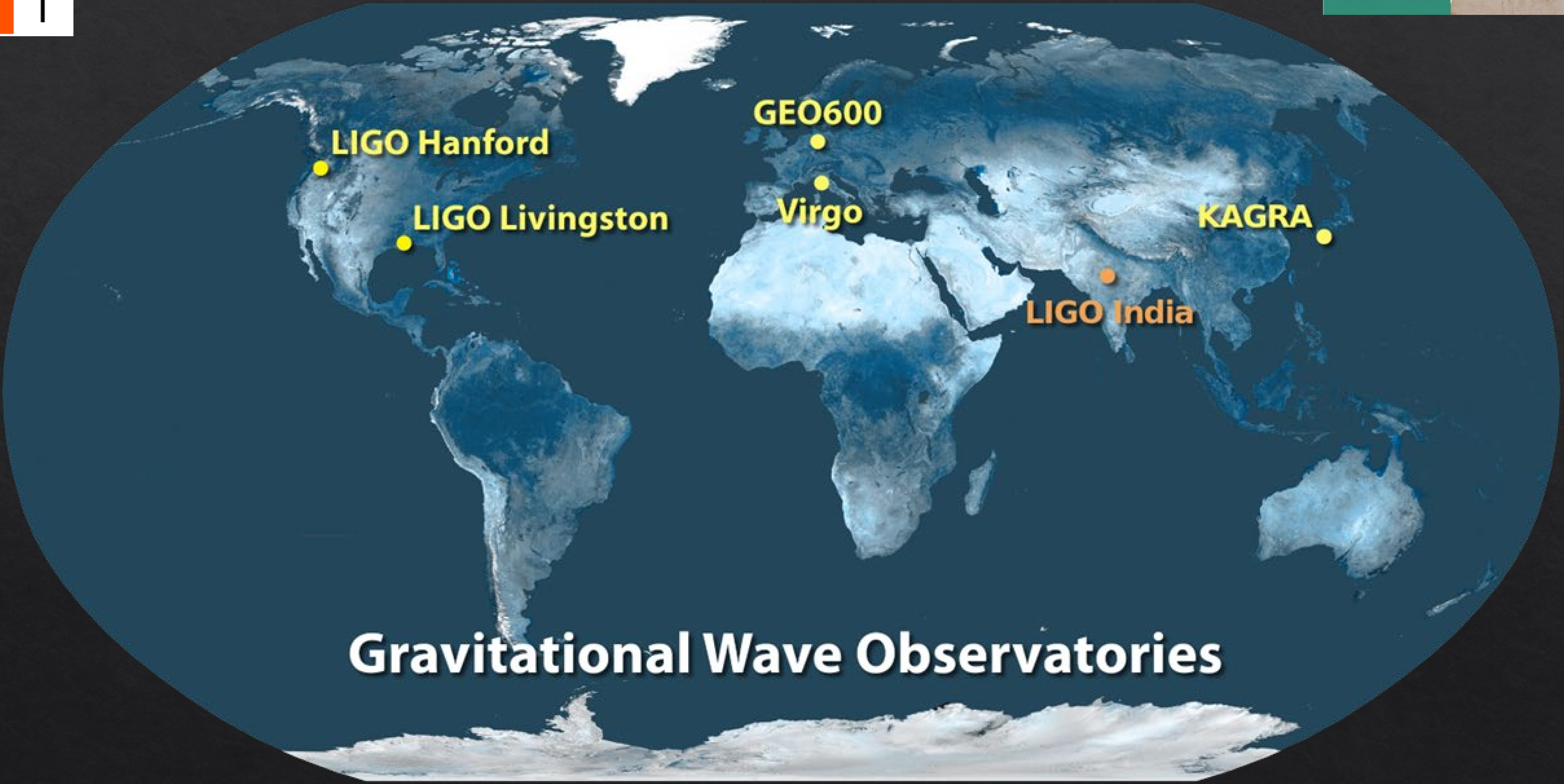
Jan Harms

Gran Sasso Science Institute
INFN - National Laboratory of Gran Sasso

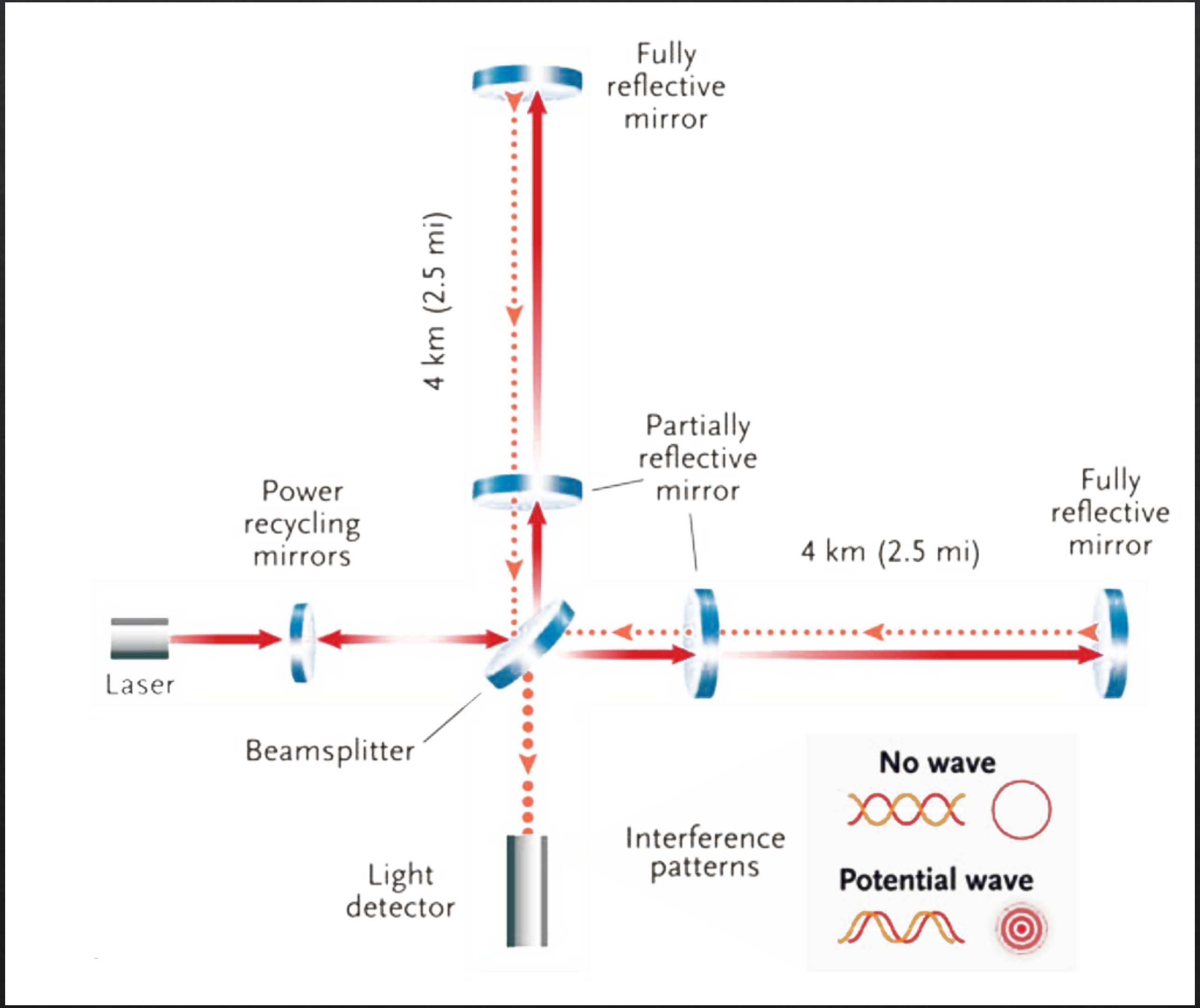
History of GW Detector Sensitivity

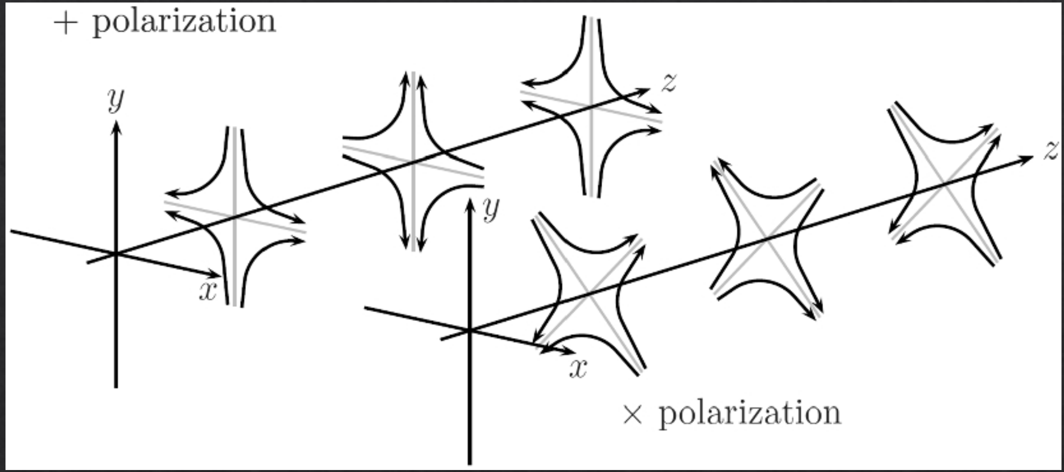


Adhikari, 2014


GEO600
LIGO Hanford
LIGO Livingston
Virgo
KAGRA
LIGO India
Gravitational Wave Observatories

Principle of GW Detection

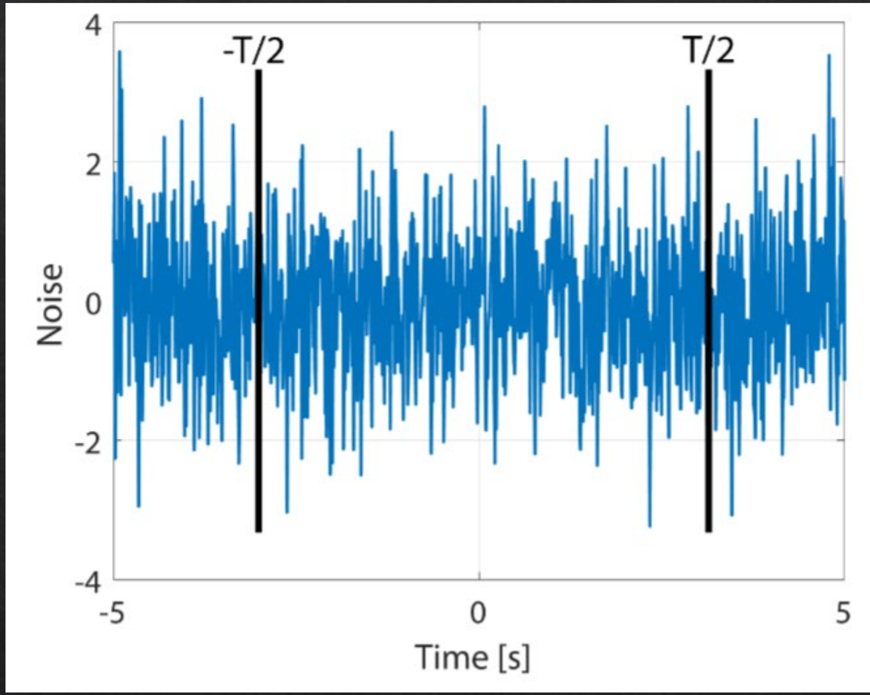




Gravitational waves change the distance between suspended test masses, which leaves an imprint on the phase of the laser beam.

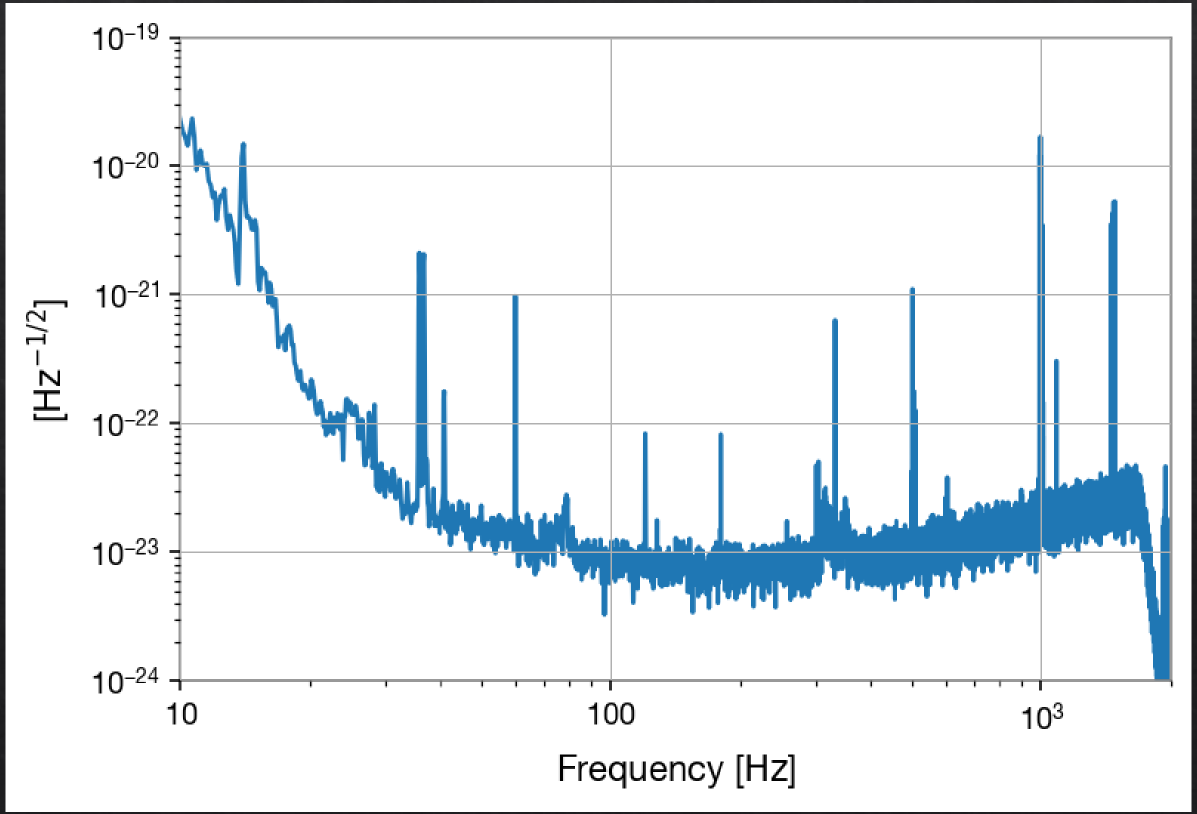
Power spectral density (PSD)

Time series



How to represent stationary noise in frequency domain?

Noise spectrum

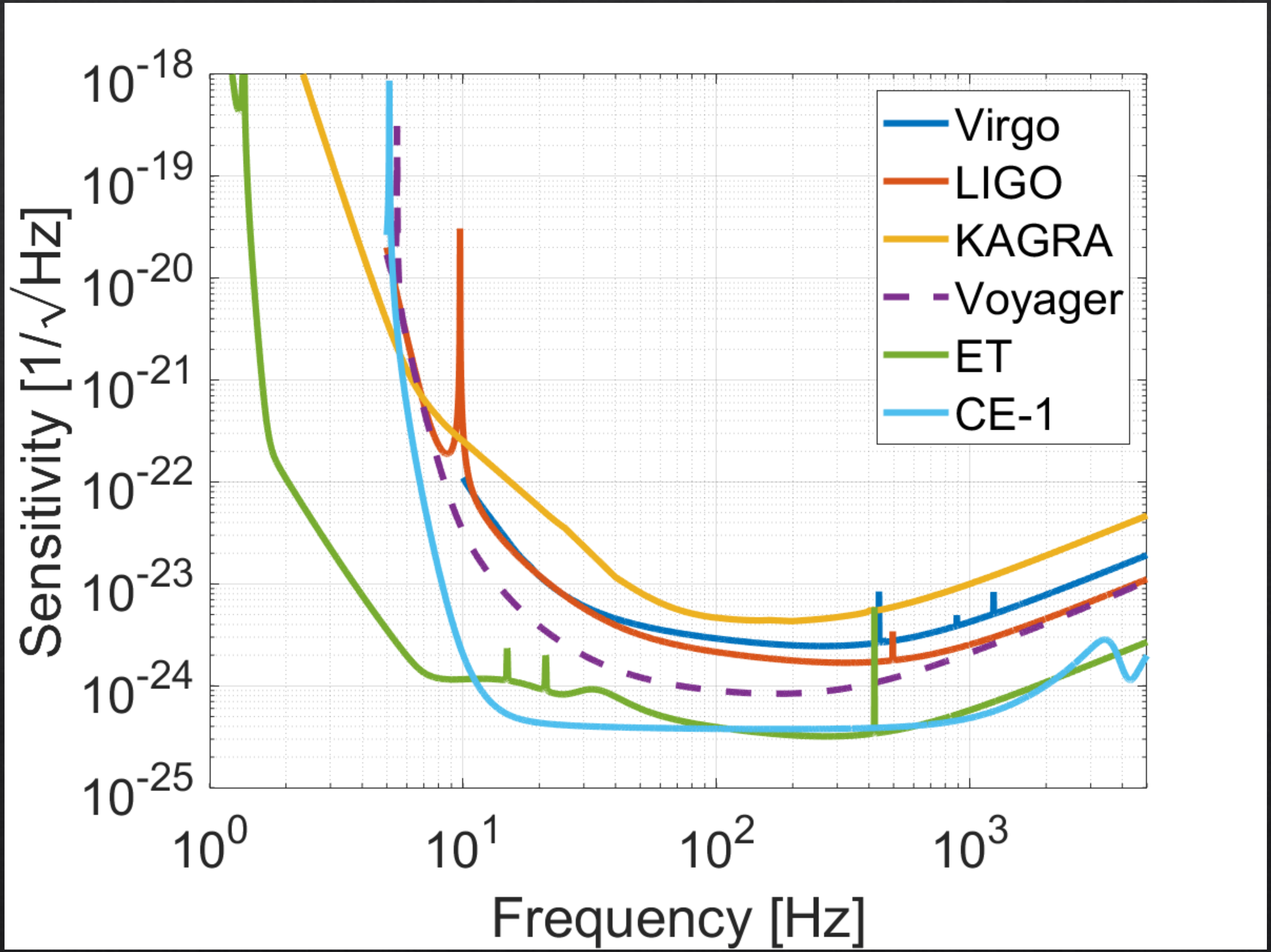


PSD

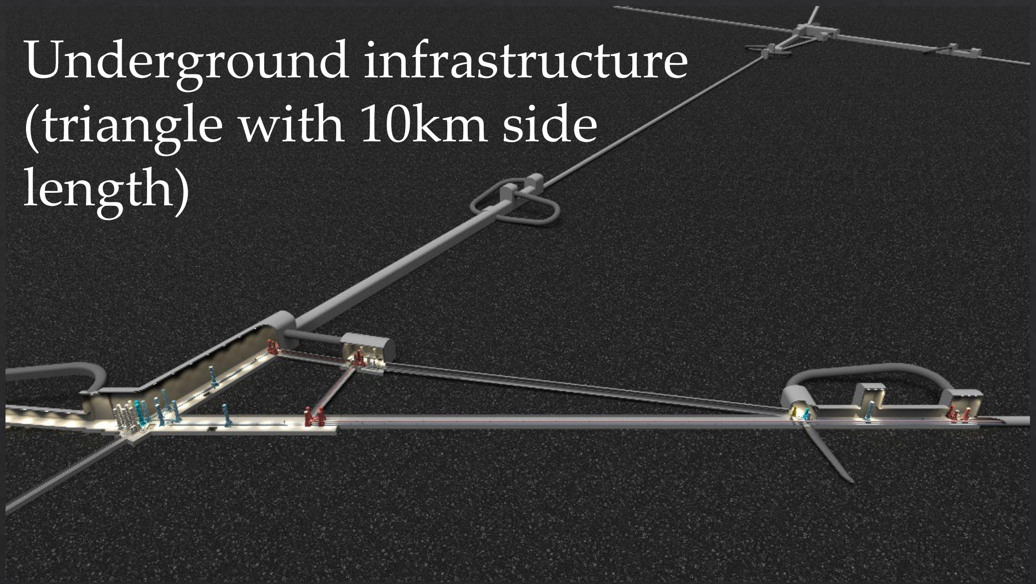
Finite-time Fourier transform

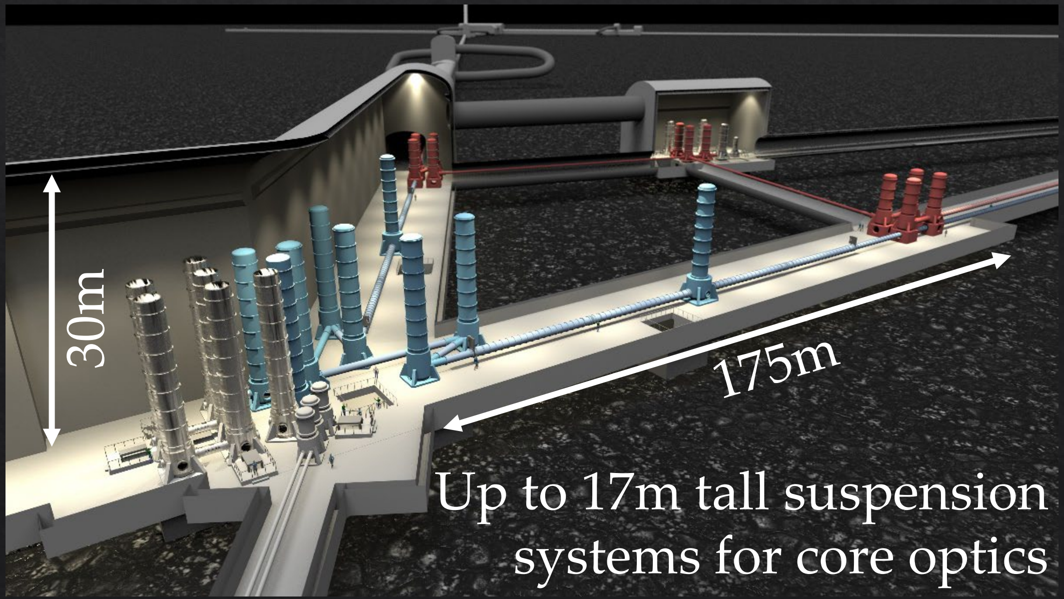
$$S(y;f) = \lim_{T\to\infty} \frac{2}{T} |\tilde{y}_T(f)|^2$$

Sensitivity Models

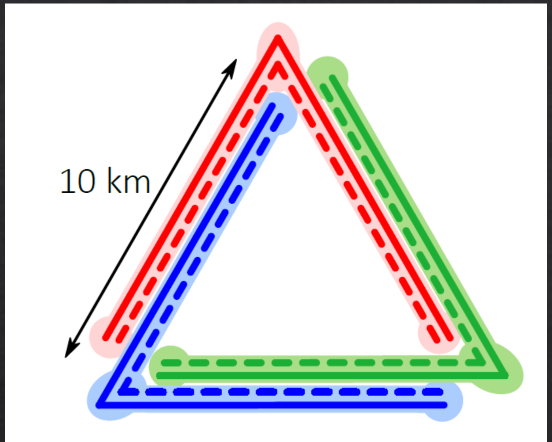


Einstein Telescope





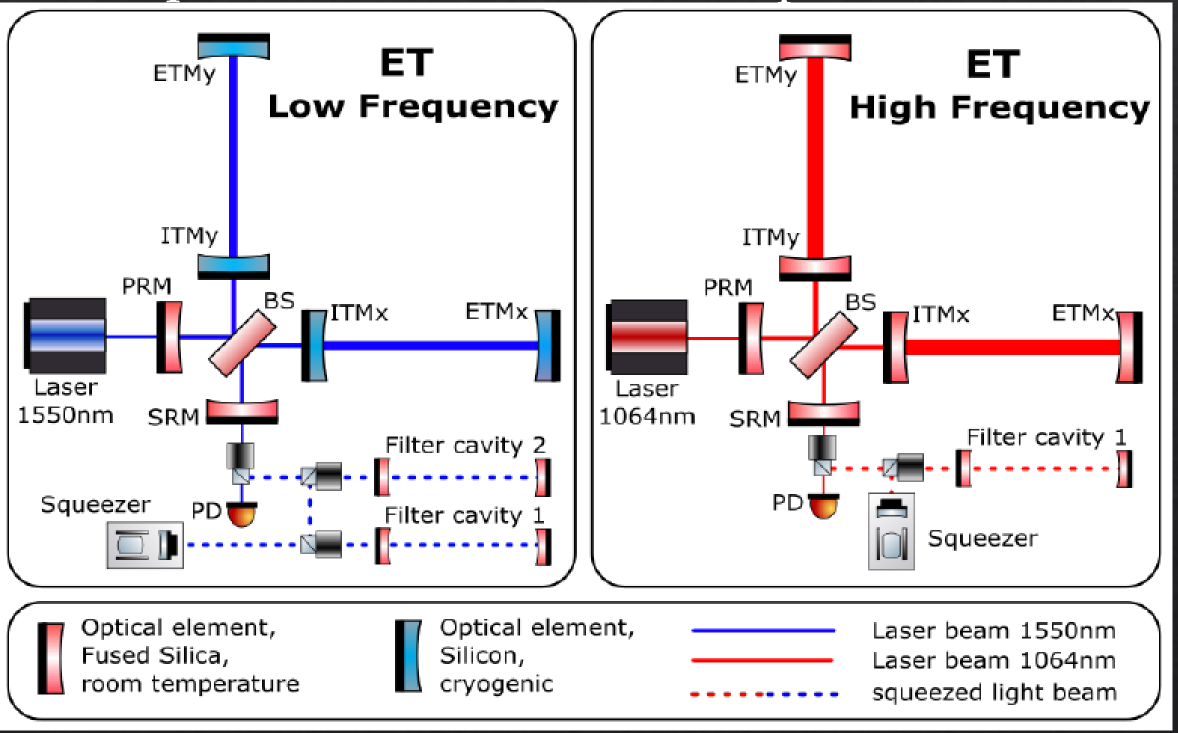
Einstein Telescope as Xylophone

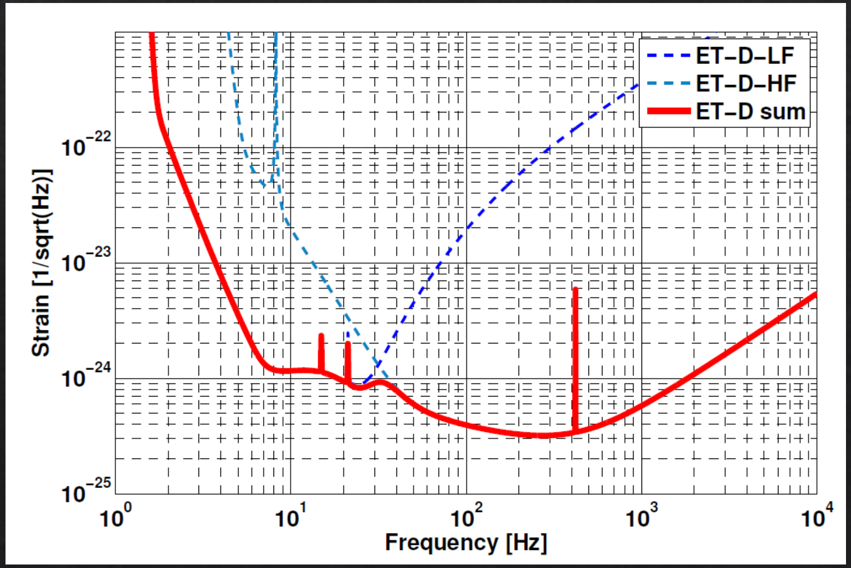


Each vertex is the center of a pair of interferometers, i.e., 6 interferometers in total.

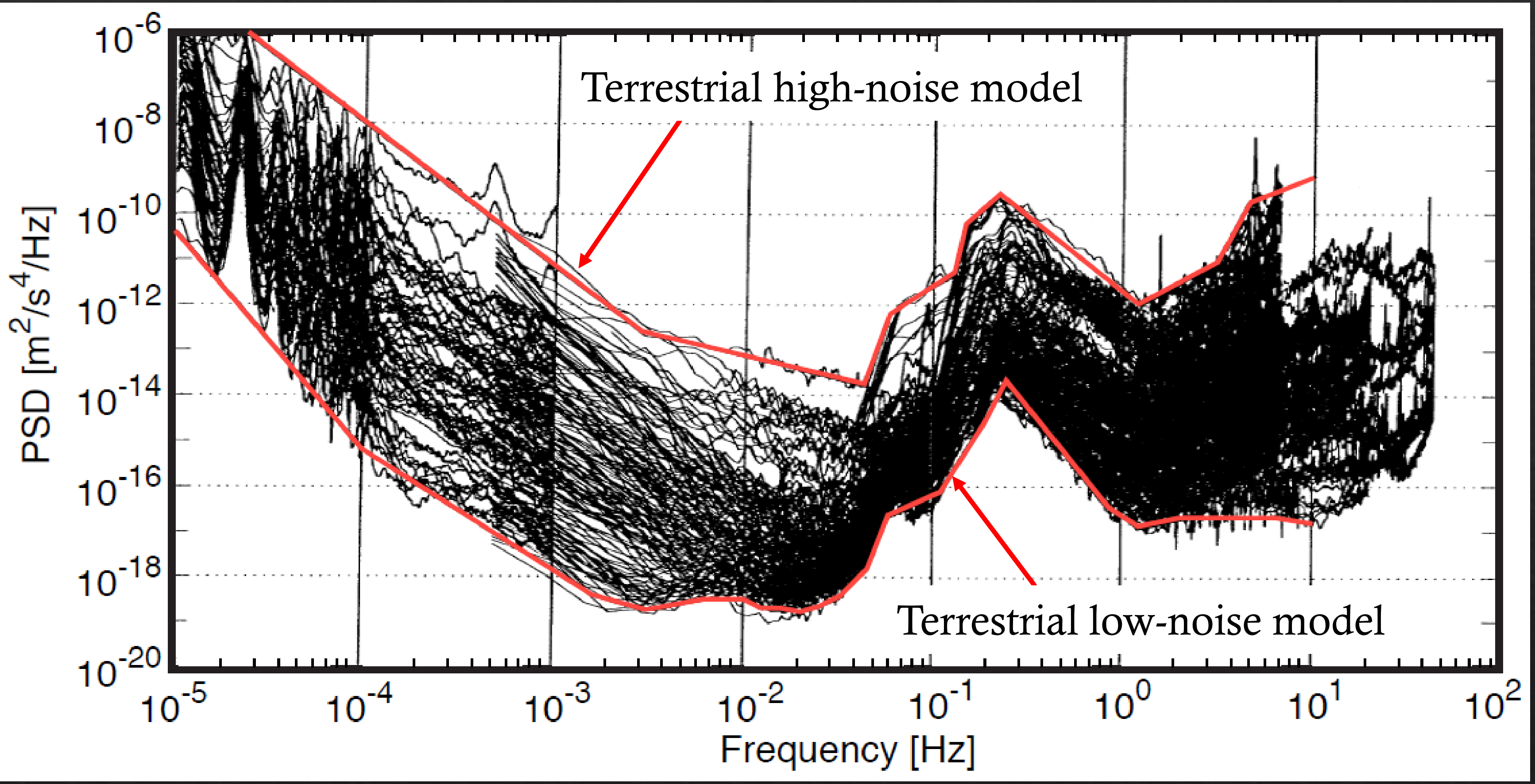
Power: 18kW
Temperature: 10-20K

Power: 3MW
Temperature: 290K





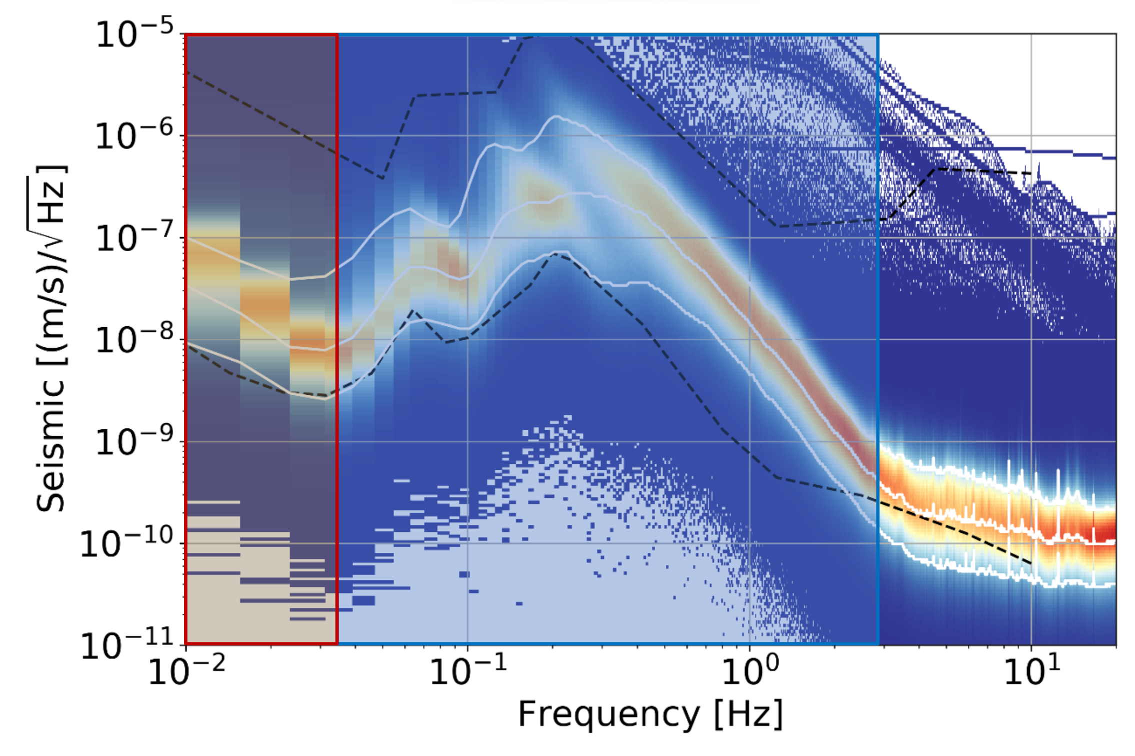
Seismic Background On Earth

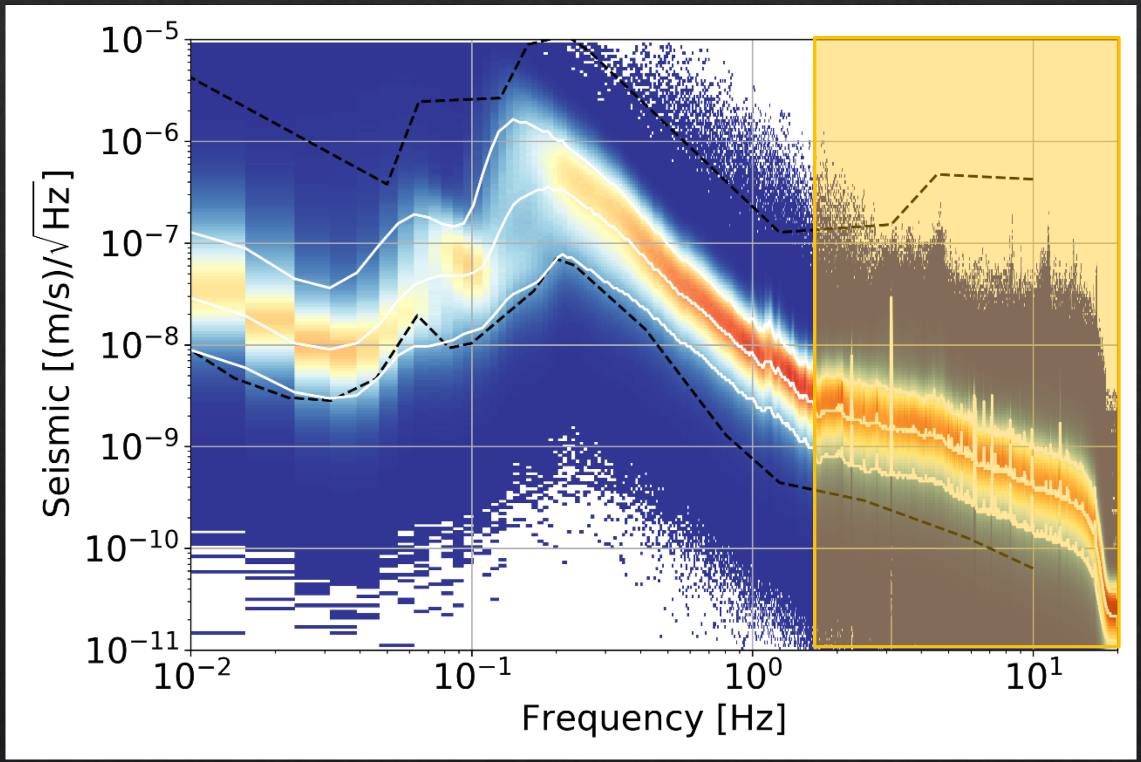


Seismic Noise at ET Candidate Sites

Sardinia

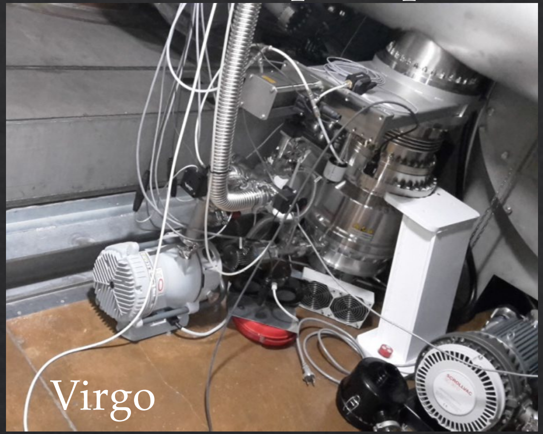
Euregio Meuse-Rhine





Detector Infrastructure

Vacuum pumps

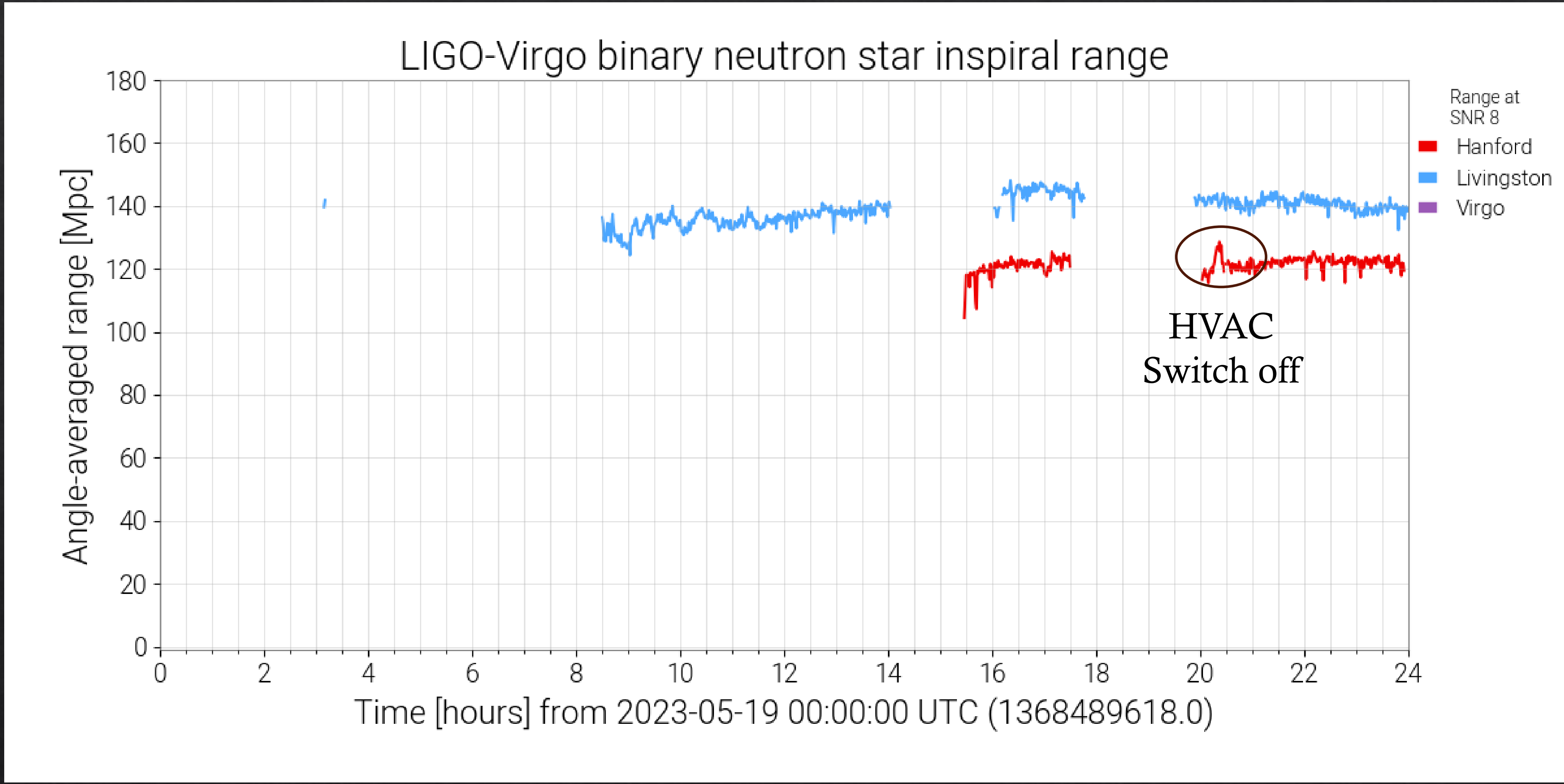


Tunnels and vacuum pipes

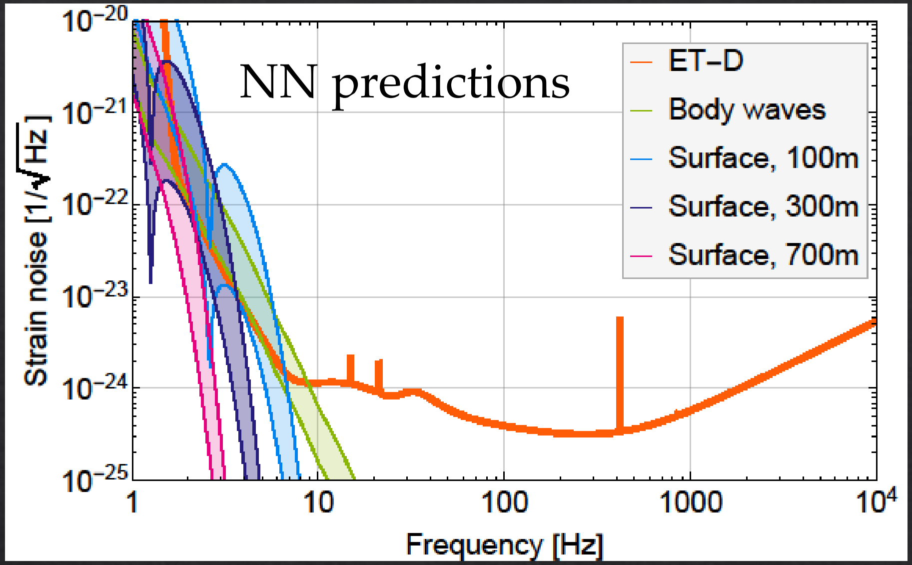
Ventilation

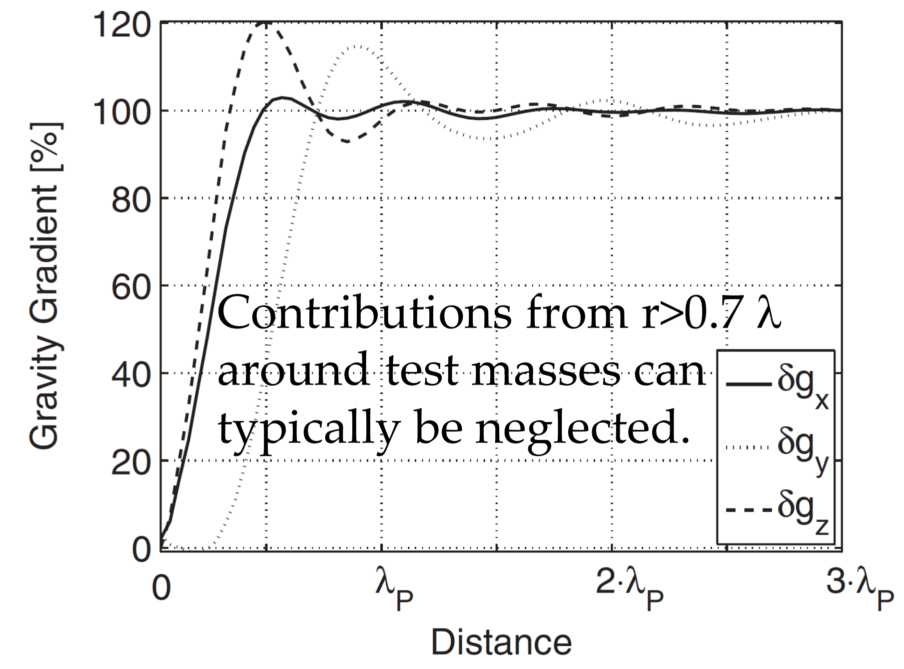
Cryocooler

HVAC: LIGO Hanford



Newtonian Gravitational Noise





1) Density perturbation by a seismic field

$$\delta\rho(\vec{r},t) = -\nabla\cdot\left(\rho(\vec{r})\vec{\xi}(\vec{r},t)\right)$$

2) Associated gravity perturbation

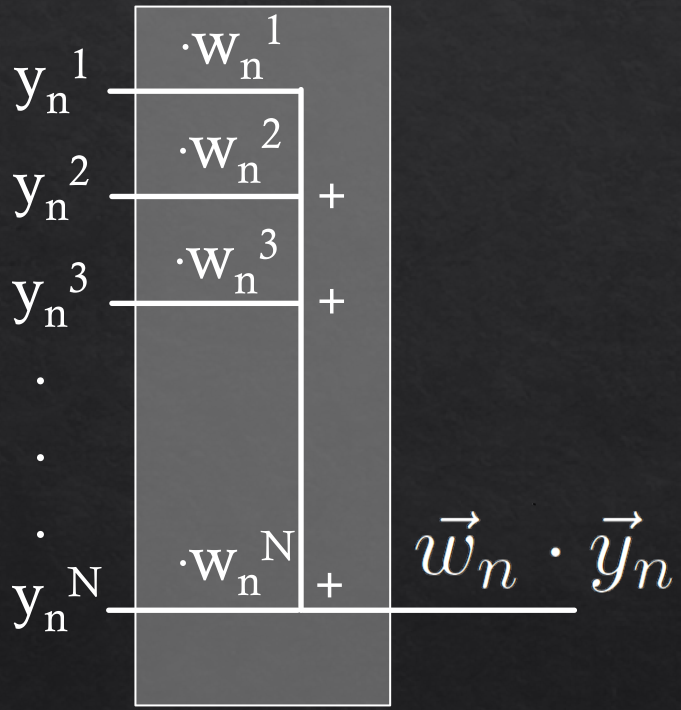
$$\delta\phi(\vec{r}_0,t) = G\int \mathrm{d}V\,\frac{\nabla\cdot\left(\rho(\vec{r})\vec{\xi}(\vec{r},t)\right)}{|\vec{r}-\vec{r}_0|}$$

3) Solve for a specific seismic field

$$\delta\vec{a}(\vec{r}_0,t) = \frac{4\pi G\rho}{3}\left(2\vec{\xi}^{\,\mathrm{P}}(\vec{r}_0,t) - \vec{\xi}^{\,\mathrm{S}}(\vec{r}_0,t)\right)$$

Newtonian-noise Cancellation

Linear discrete filter



Wiener filter

Correlations between all inputs y

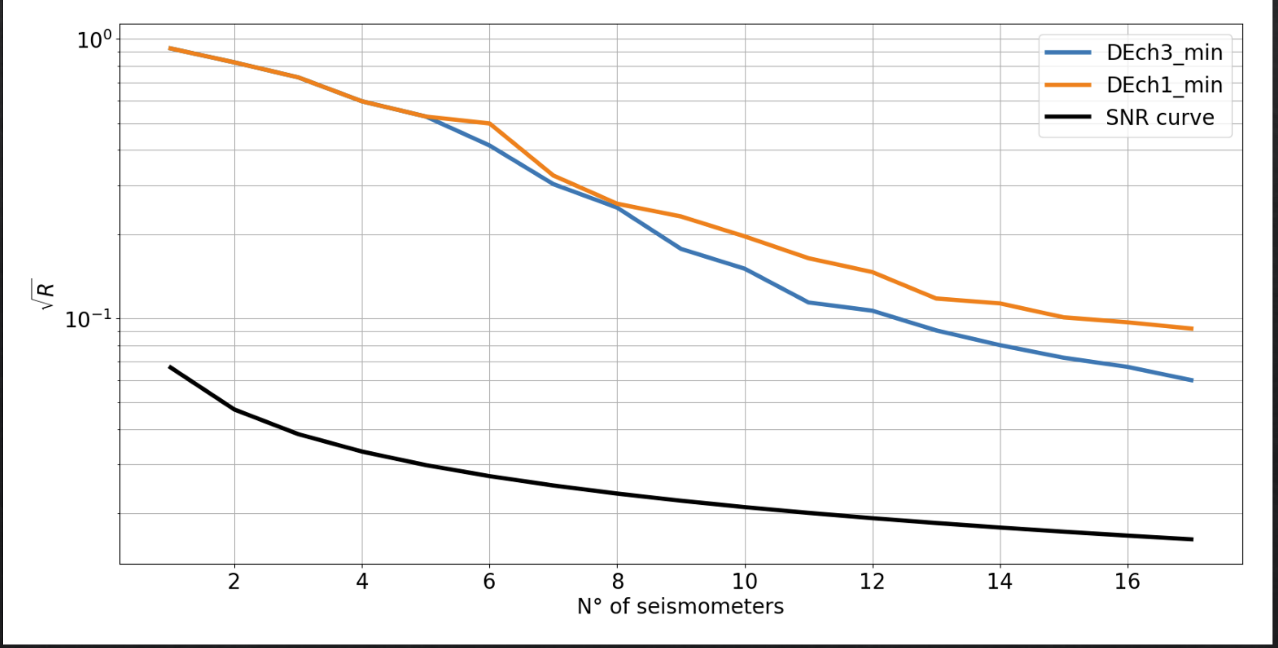
$$\vec{w}_n = \langle x_n \vec{y}_n^\dagger \rangle \cdot \langle \vec{y}_n \vec{y}_n^\dagger \rangle^{-1}$$

Correlations between inputs y and target x

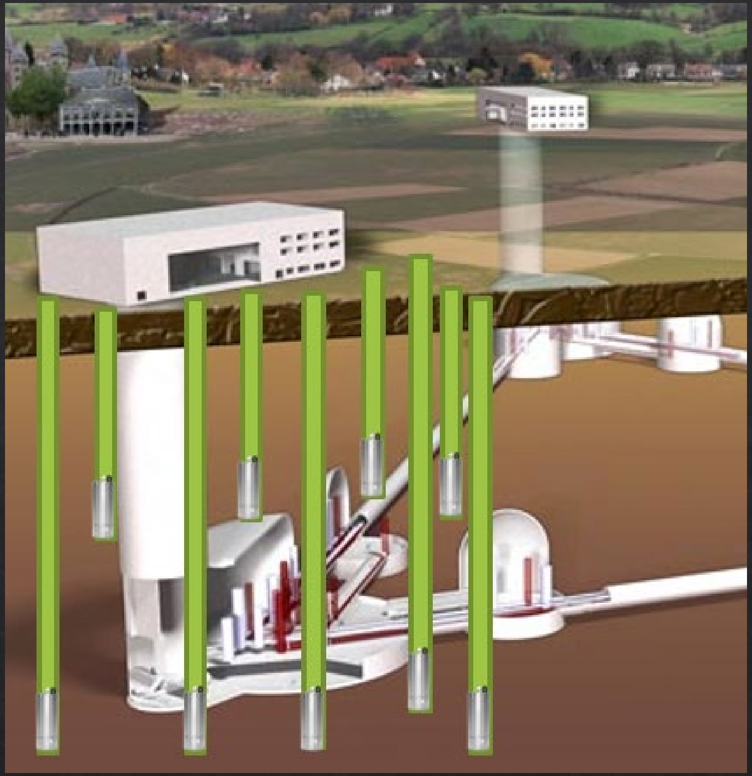
Residual noise power after subtraction

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

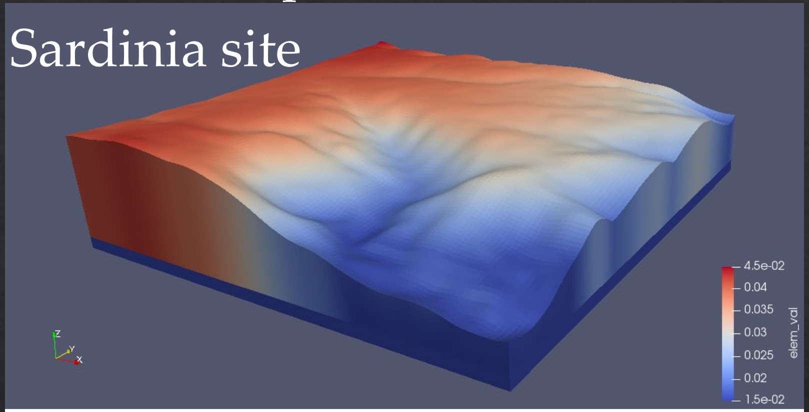
Assuming optimal sensor placement:
10 borehole seismometers per test mass

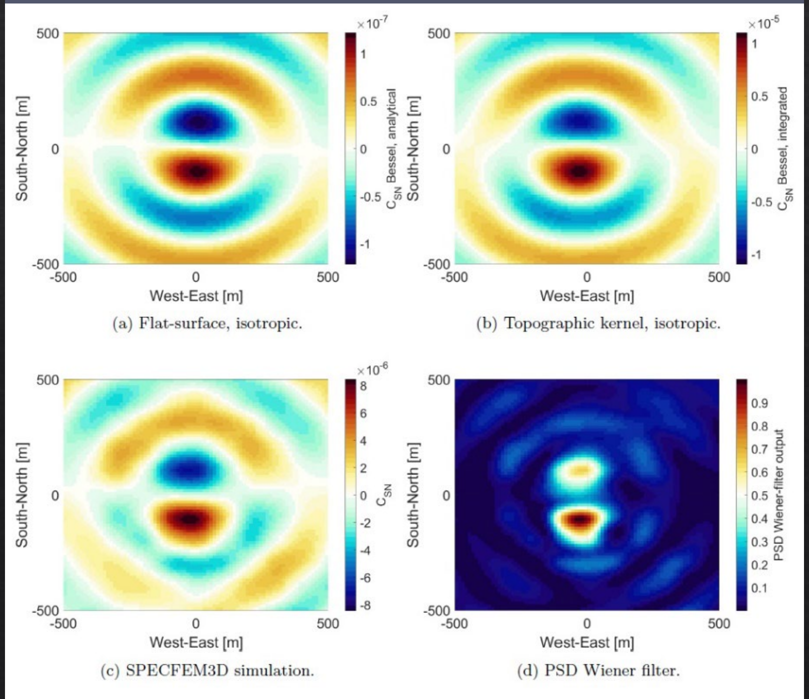


NNC System Design



Simulations + data for optimization



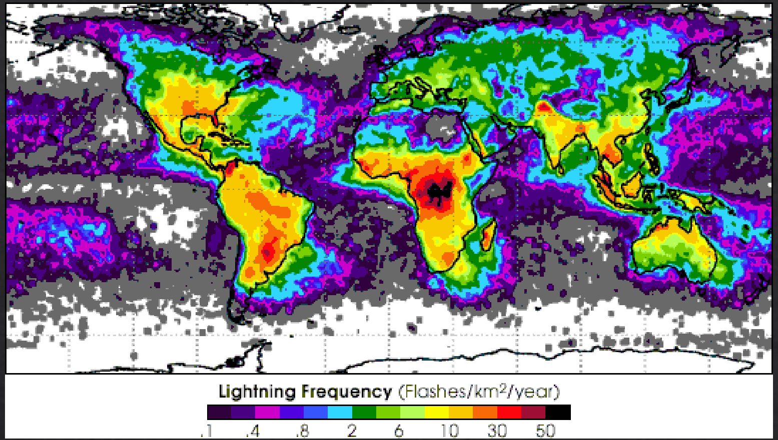


Open questions:

1) Where to place the sensors and how many?
2) How to design the noise-cancellation filter?
3) What types of seismic sensors should be used?

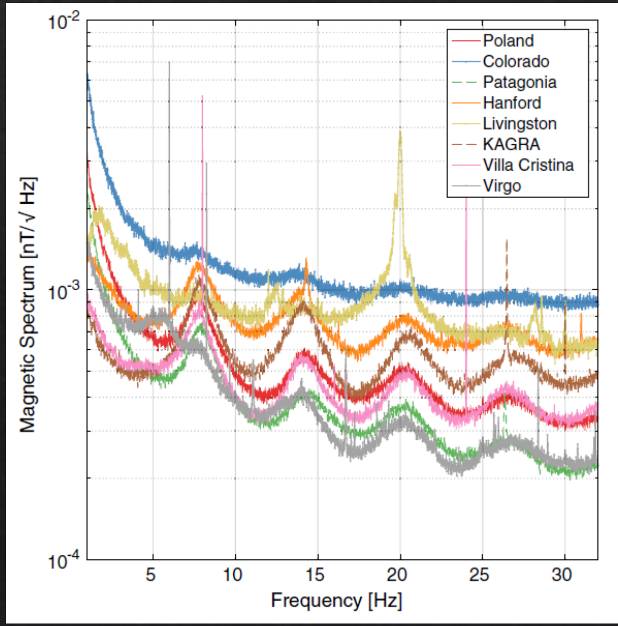
Magnetic Fluctuations

Magnetic disturbances can appear coherently in a global detector network.

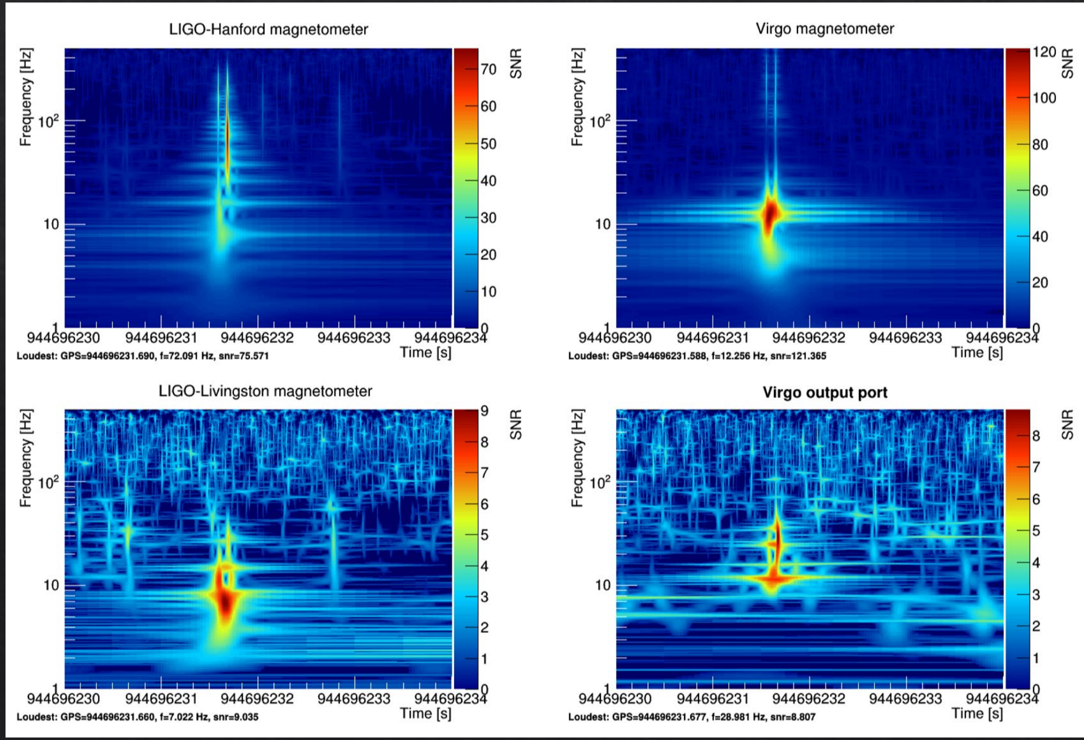


Globally coherent disturbances and noise

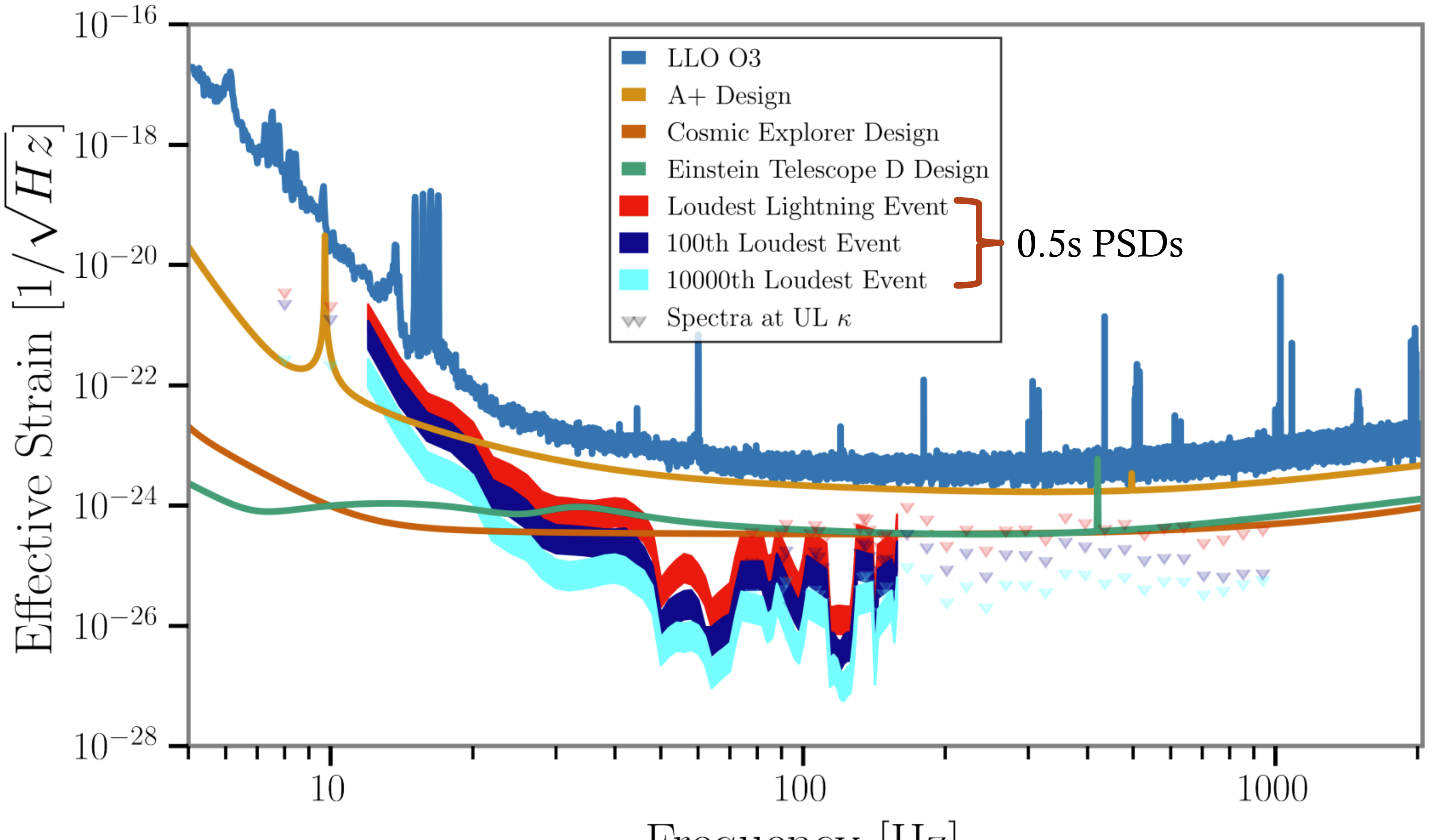
Schumann resonances



Lightning transient can be coincident



Magnetic Coupling



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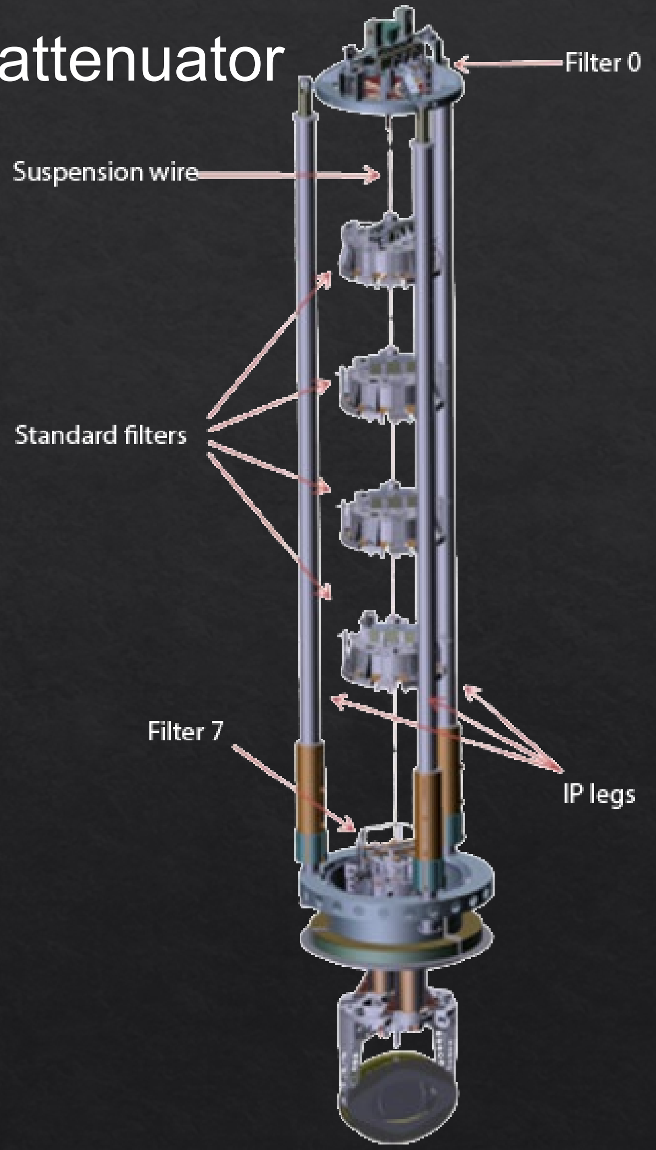
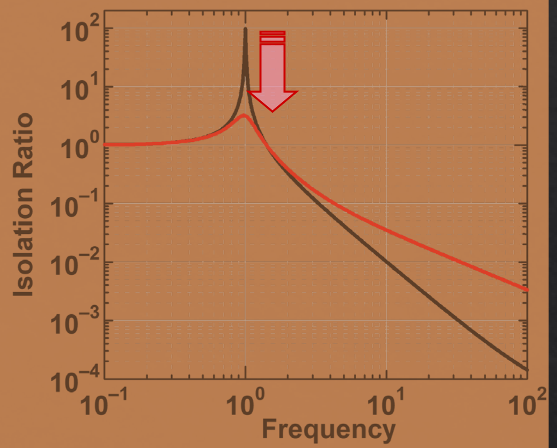
Principles of Seismic Isolation

Virgo Superattenuator



Damping

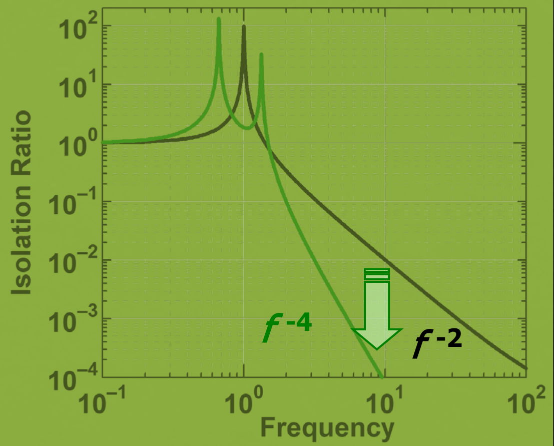
Lower peak height



Less isolation

Cascaded

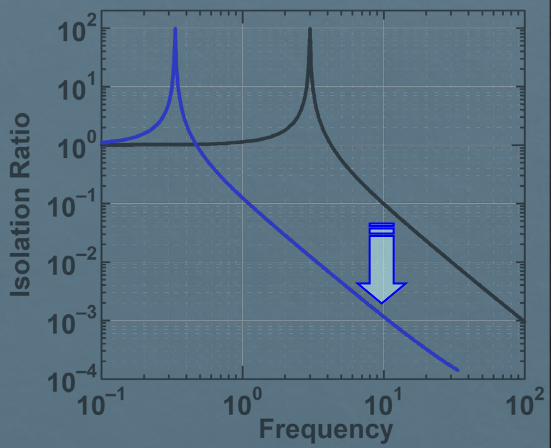
Steeper isolation curve



More peaks

Larger structure

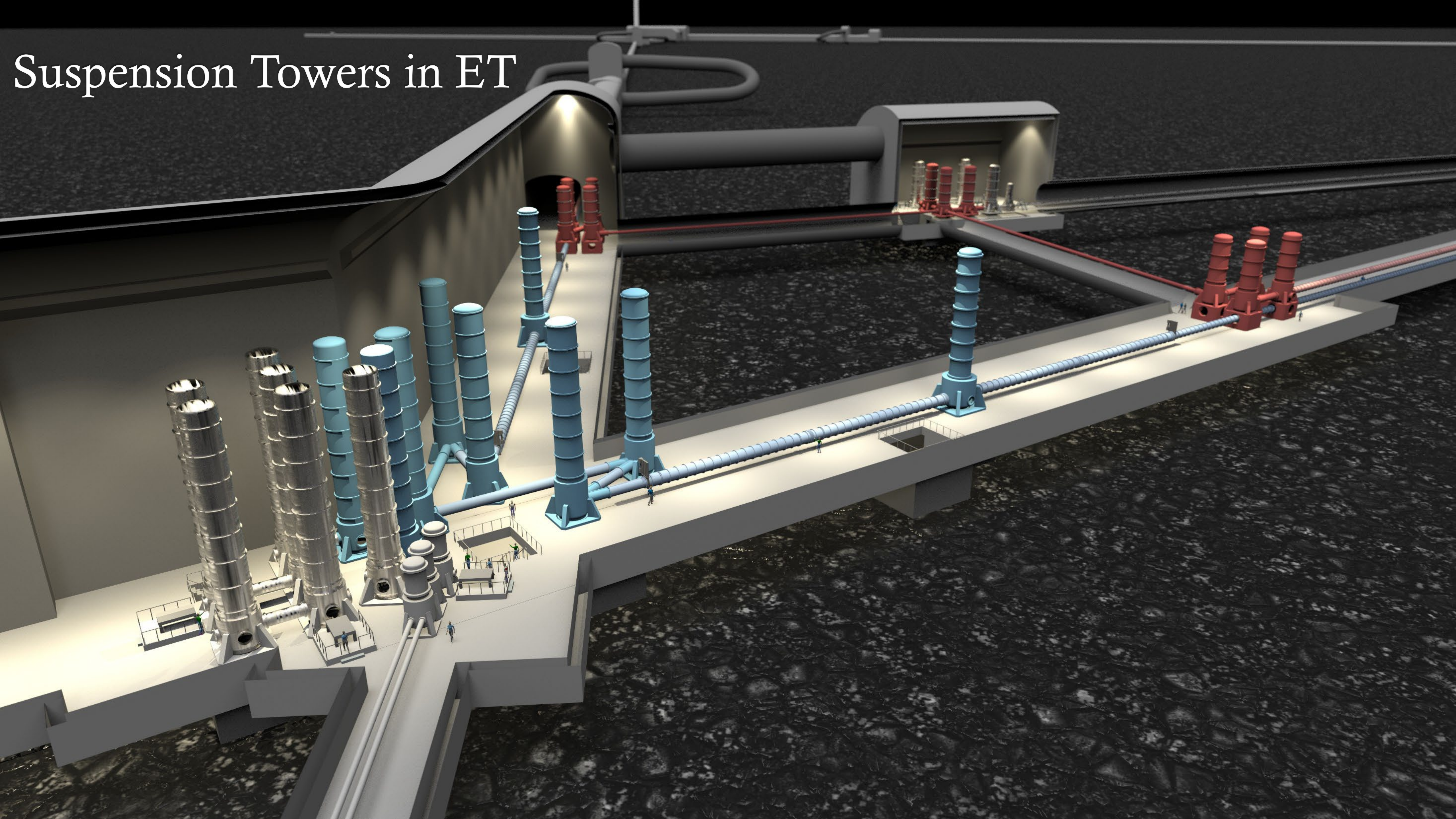
Lower resonance frequency



Difficult to realize

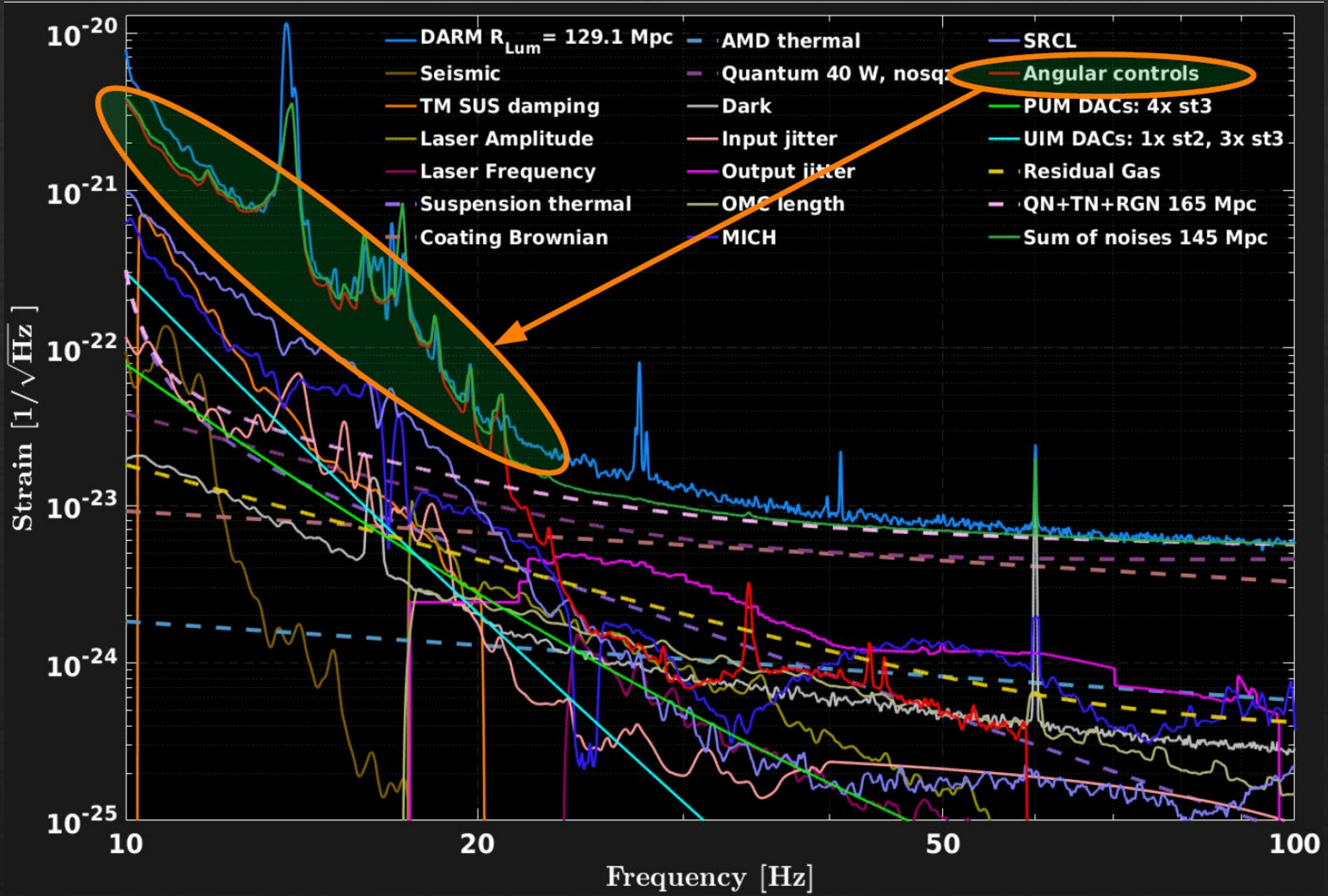
In pratice: use combination of these methods

Suspension Towers in ET



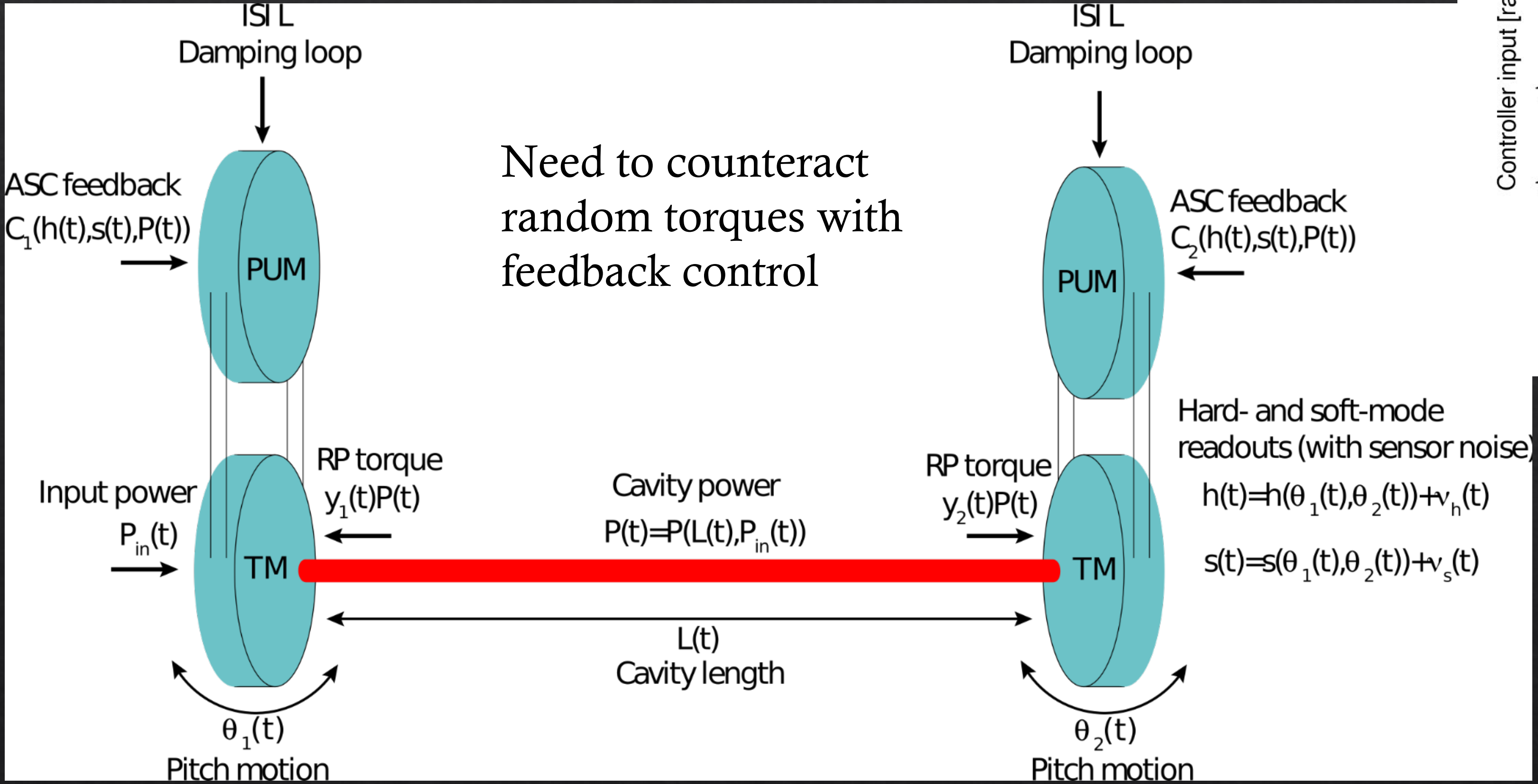
Noise from Detector Control

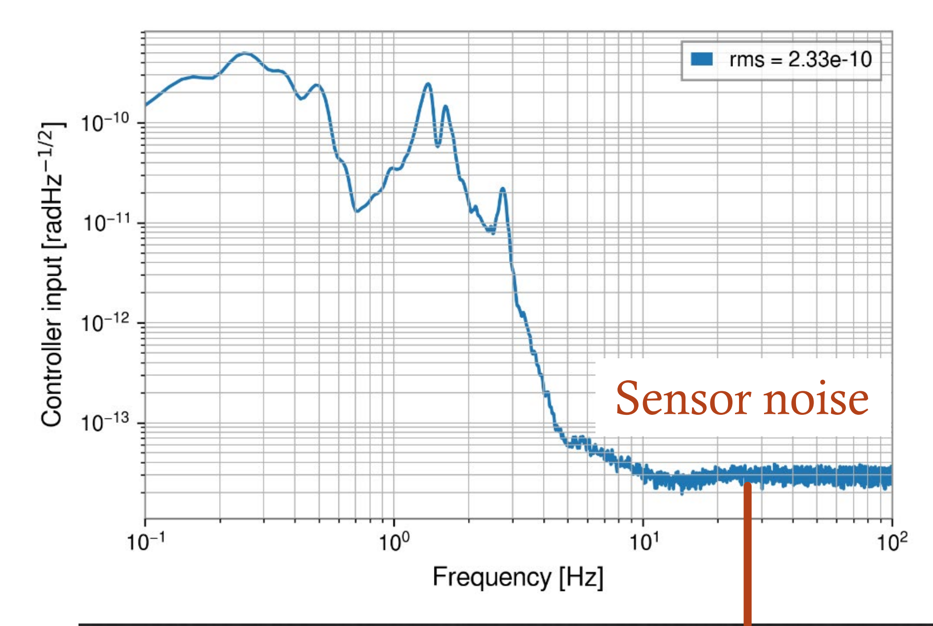
LIGO noise budget



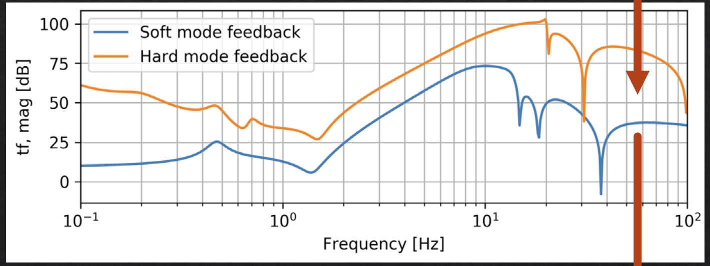
Angular Control

Torques continuously act on test masses:
Radiation pressure, noise from suspensions





Feedback filter

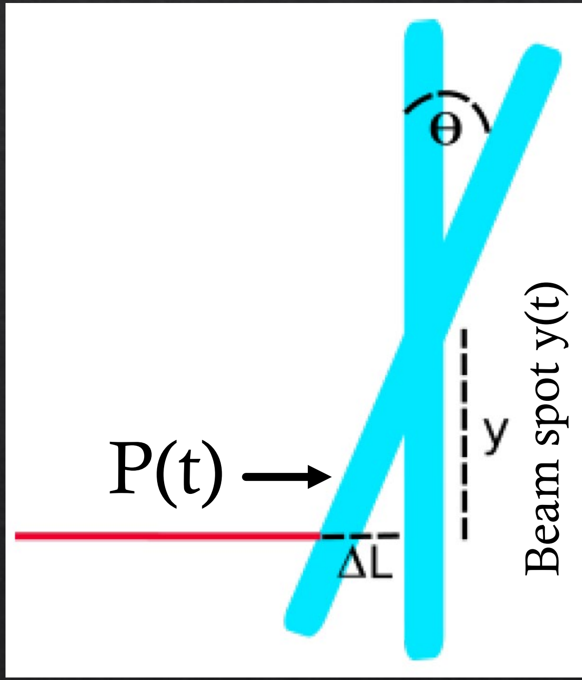


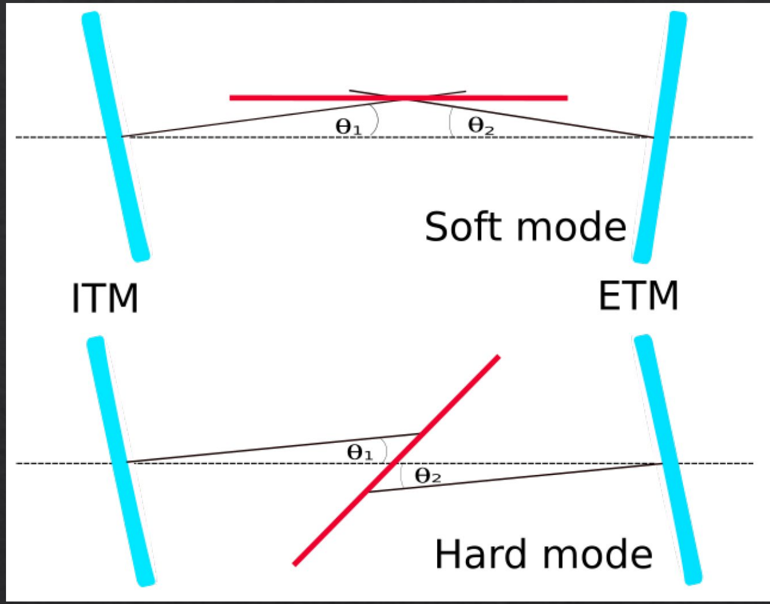
Back to suspensions and test masses

Angular Control: ET Strategy

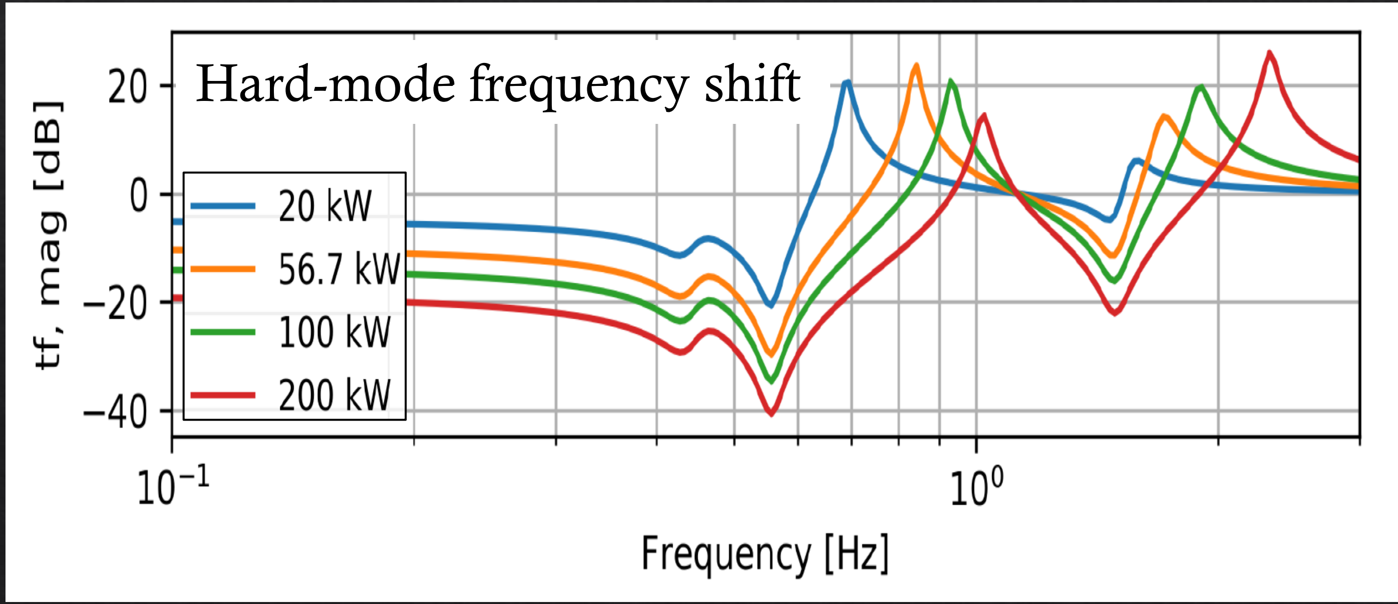
Radiation-pressure torque

$$\tau_{\mathrm{RP}}(t) = \frac{2P(t)}{c} y(t)$$





Optomechanical system

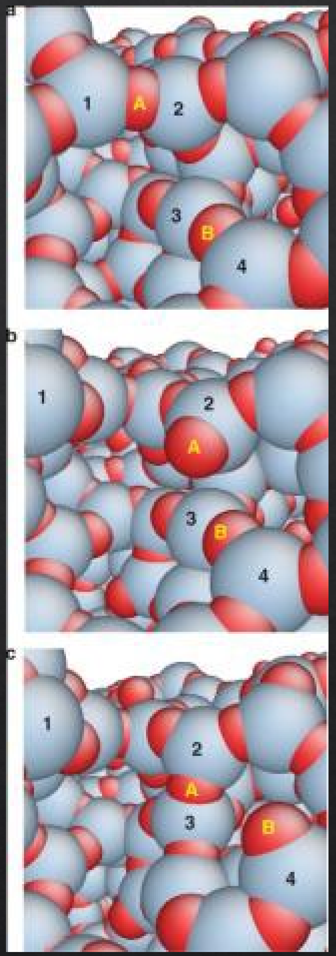


ET-LF: low power, high mass

Origin of Thermal Noise

Every dissipation mechanism leads to a coupling of the system to a thermal reservoir and thermal noise.

Brownian noise:
Many possible causes (for example, change in atomic bonds)



Thermo-elastic noise:
Irreversible heat flux across temperature gradients

Flexing fiber

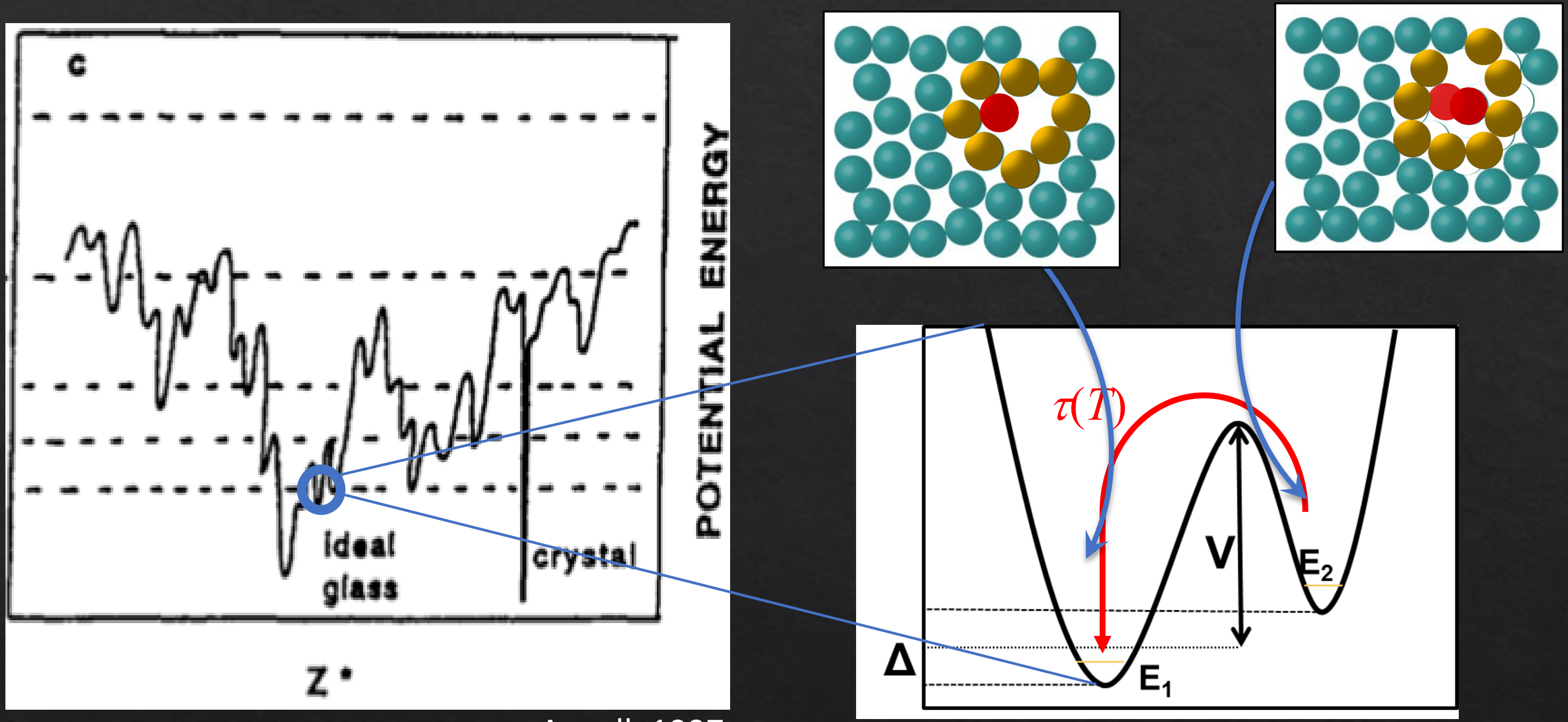
Fluctuation-dissipation theorem:
Thermal-noise spectrum proportional to mechanically dissipated power

$$S_x(\Omega) = \frac{8\pi kT}{\Omega^2}\frac{W_{\text{diss}}}{F_p^2}$$

$$W_{\text{diss}} \propto \frac{1}{Q}$$

Dissipation and Energy Landscape

"nearby" minima lead to tunneling *or* thermally-activated motion of groups of atoms



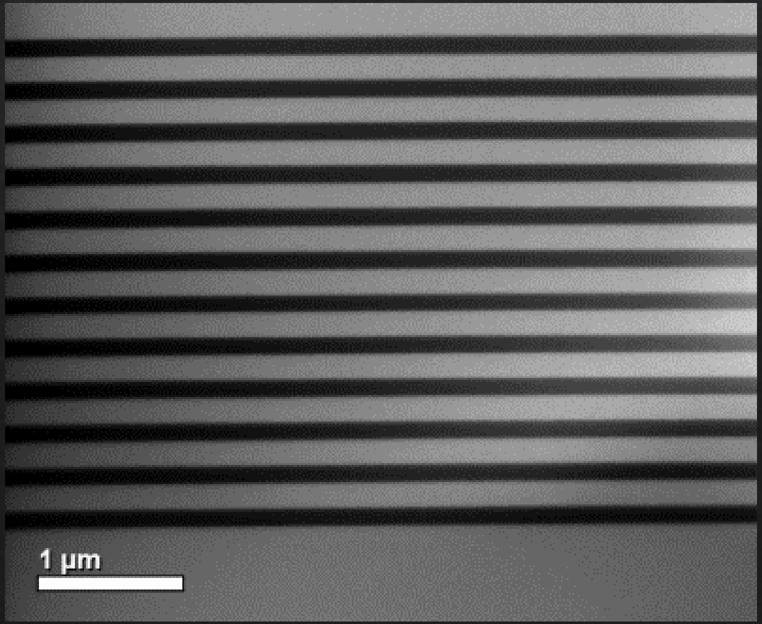
Angell, 1997

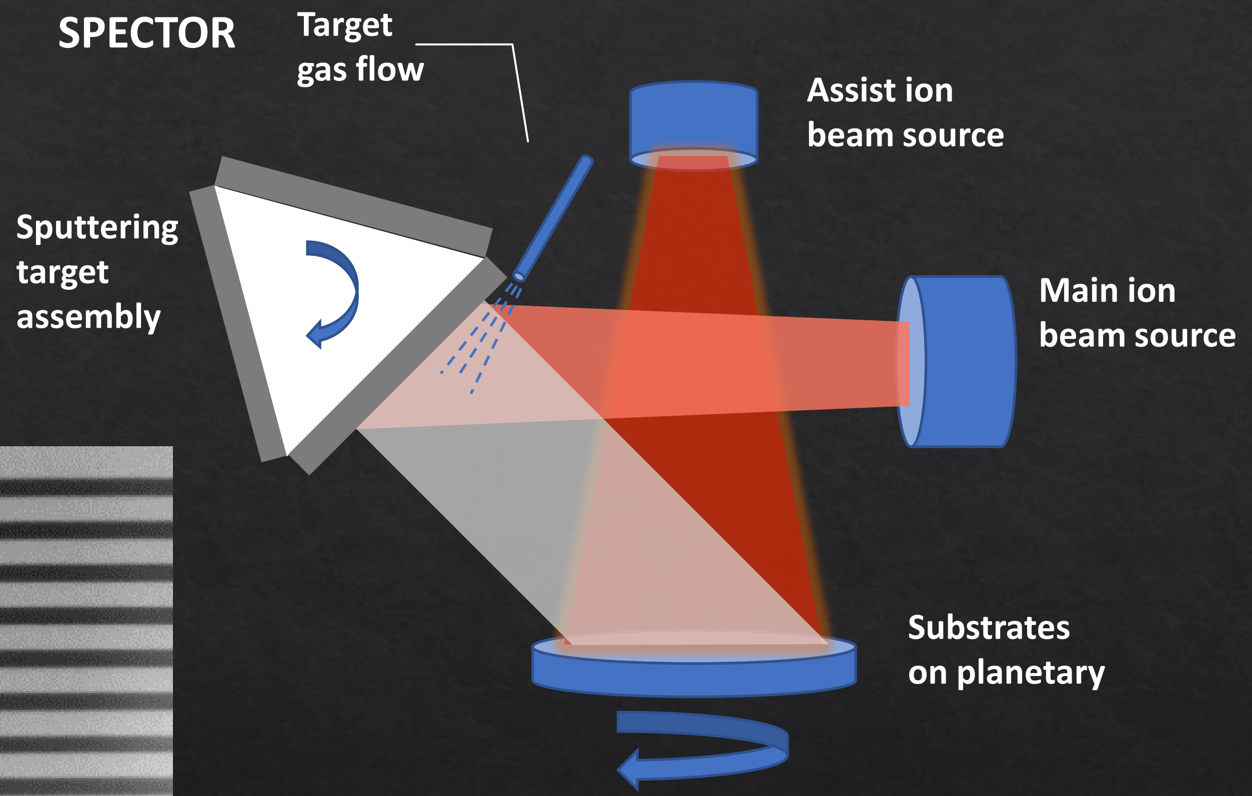
Two-level systems from neighboring energy minima in structural landscape:

- At low T, atomic structure **tunnels** between the ➢ μeV energy splitting $E_{1,2} \pm \Delta$
- At higher T, atomic motion is **thermally activated**, requiring $k_B T$ ~ barrier height V

Coating Deposition

Dielectric stacks grown by DIBS

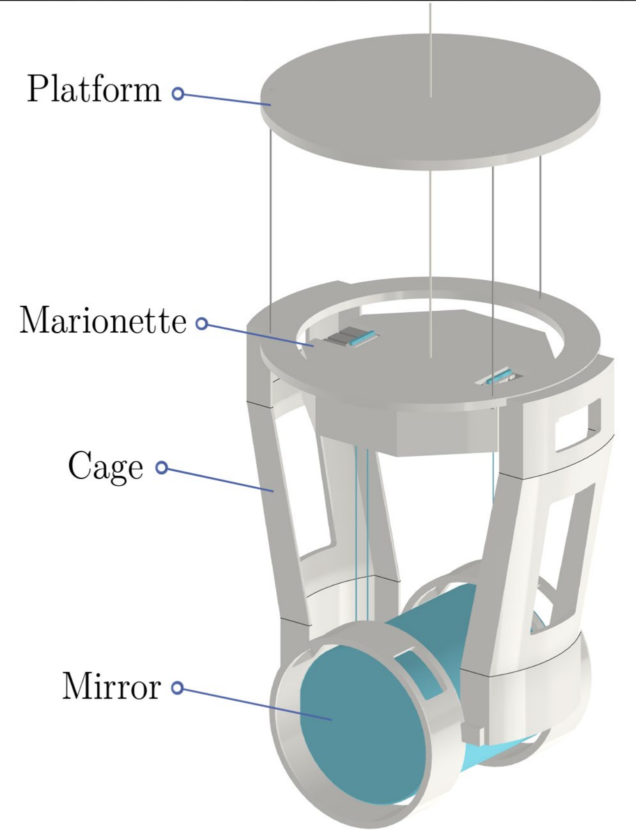




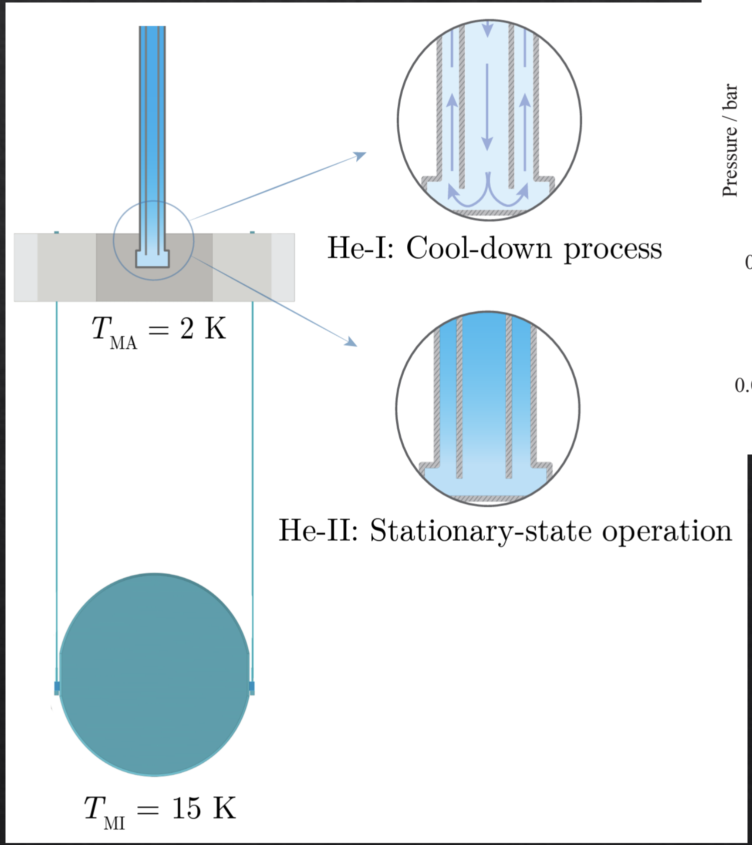
Dual ion-beam sputtering system

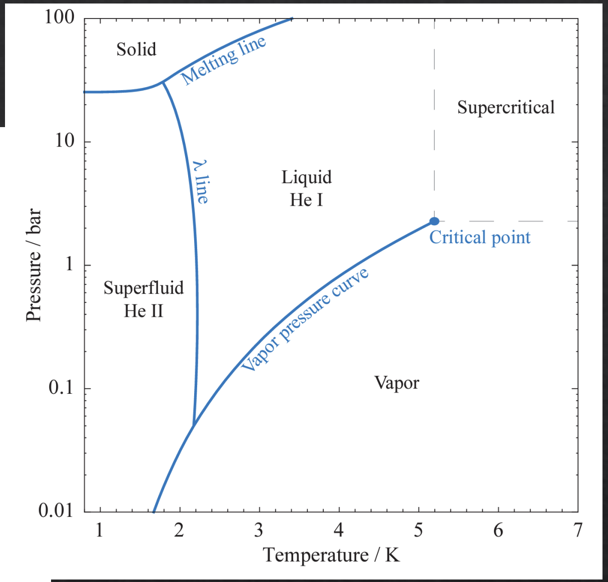
ET Cryogenic System

Cooling the ET-LF test masses is one of the biggest technological challenges of ET.

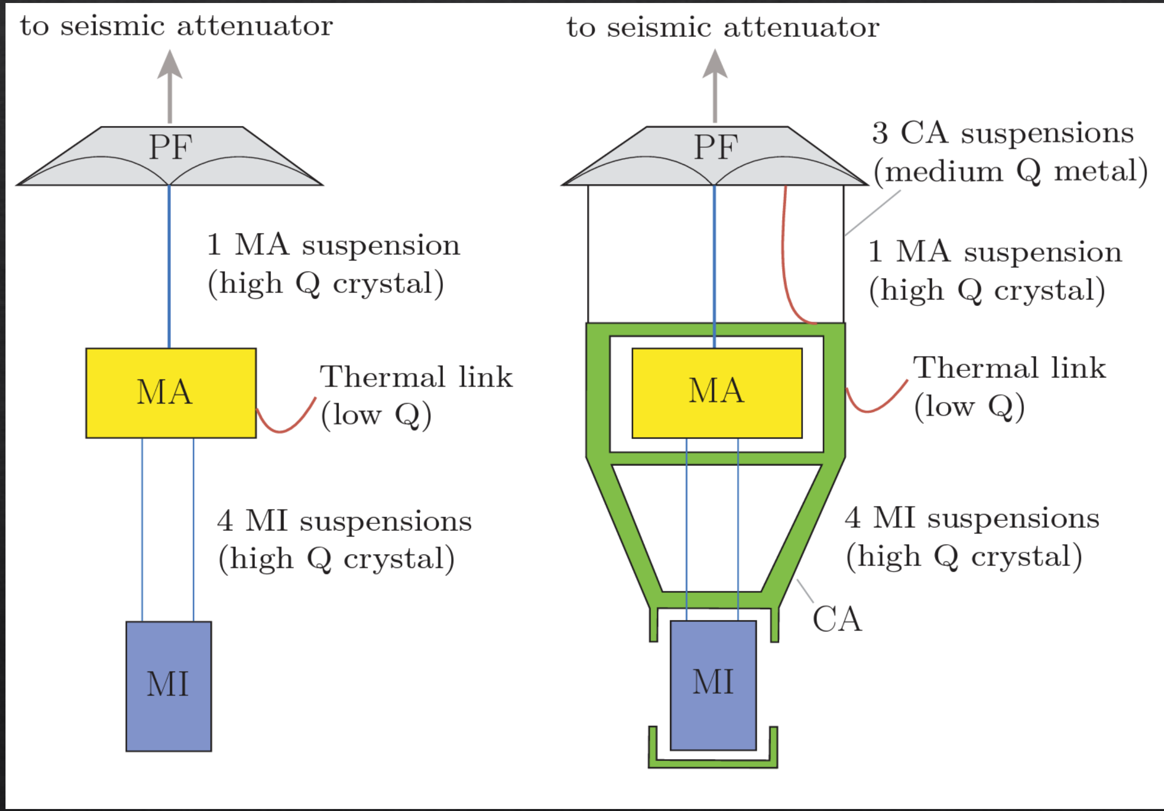


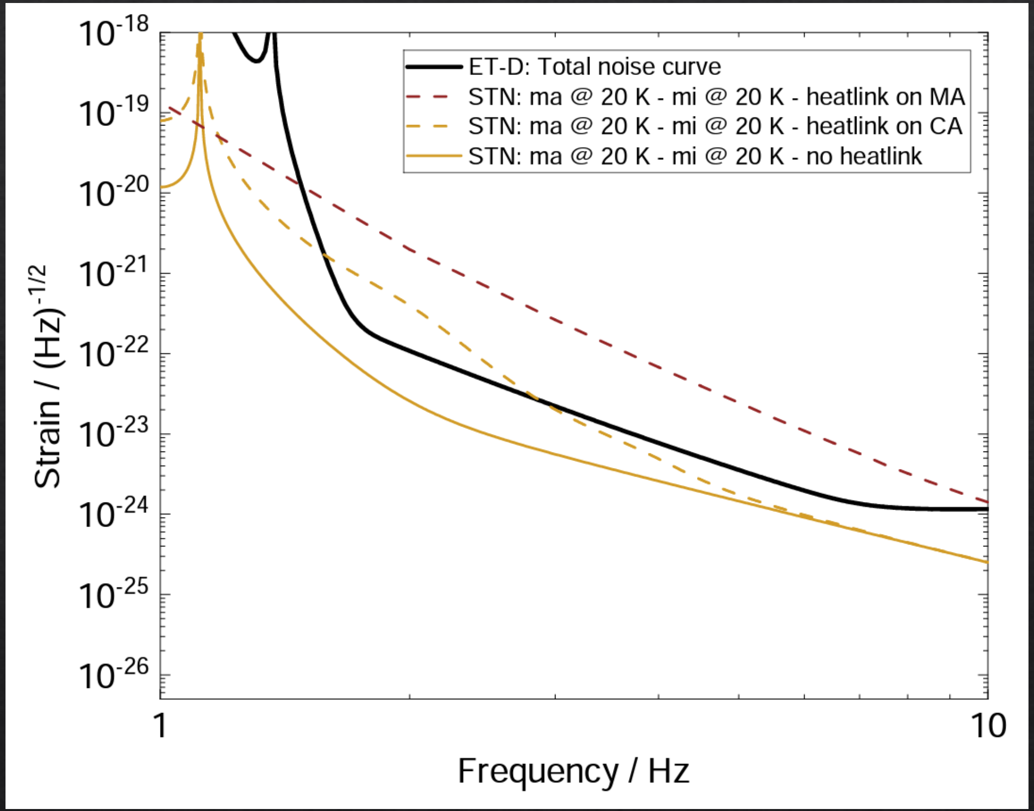
Conductive tube for initial He-I cool down, and stationary heat-transport with He-II is under investigation.





Suspension Thermal Noise





Quantum Noise

Heisenberg uncertainty principle

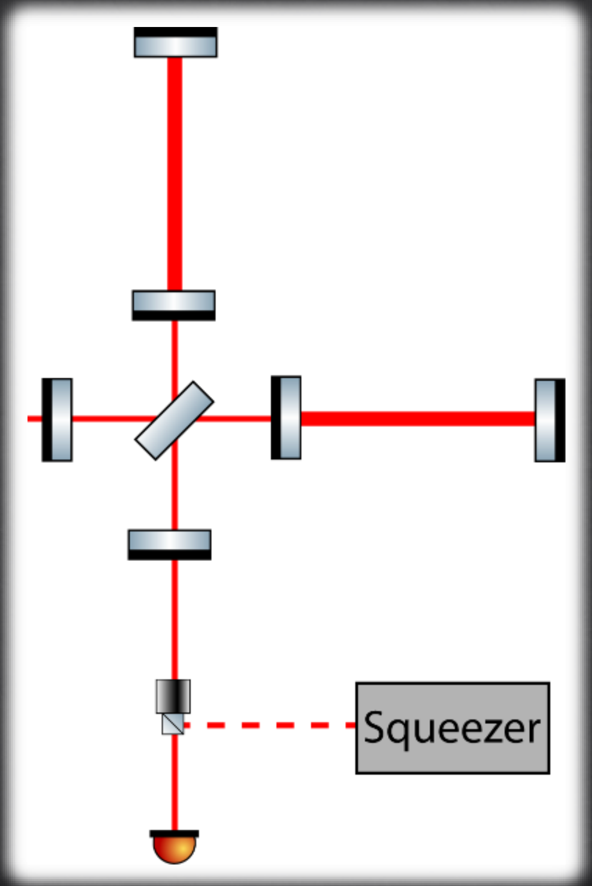
$$\Delta p \, \Delta x \geq \frac{\hbar}{2}$$

What are the position and momentum variables in the case of light?

Multiple answers, but for GW detectors, the conjugate variables are the quadratures of the EM field:

$$E(t) = E_1(t)\cos(\omega_0 t) + E_2(t)\sin(\omega_0 t)$$

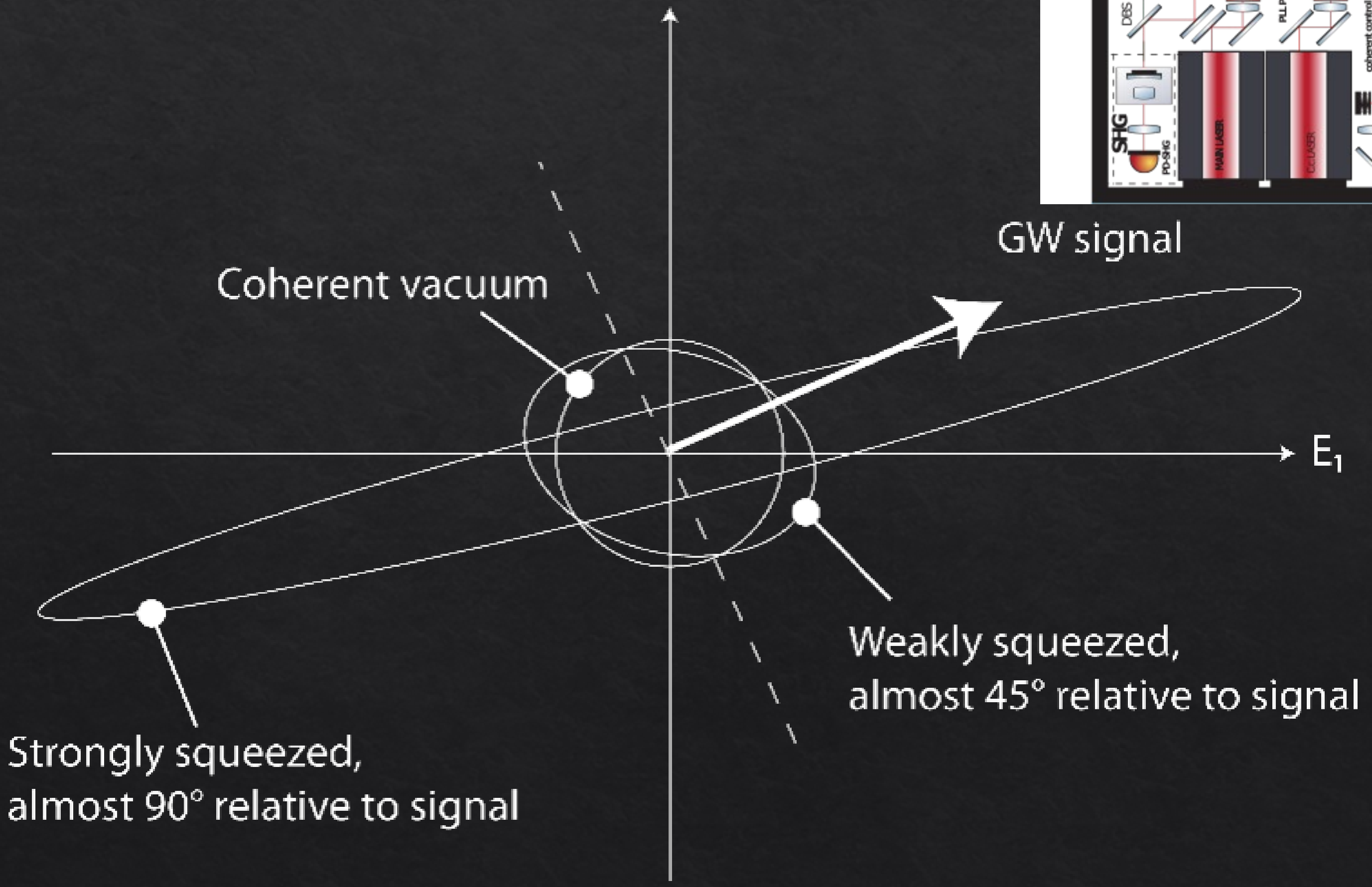
Fundamental measurement in ET: Counting photons



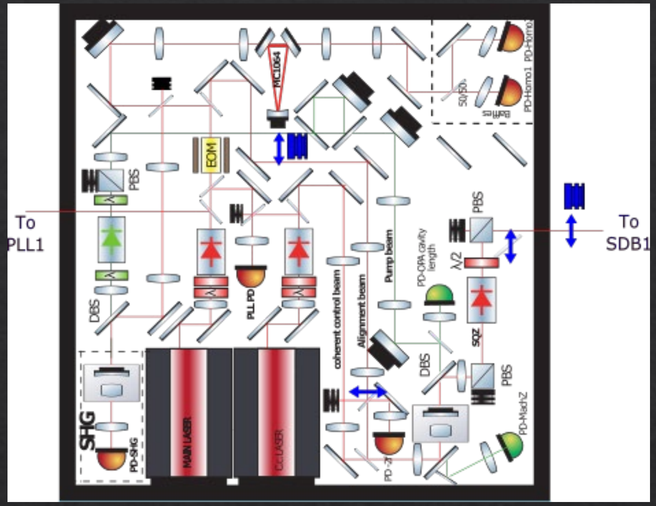
Caves: manipulate quantum state at the dark port.

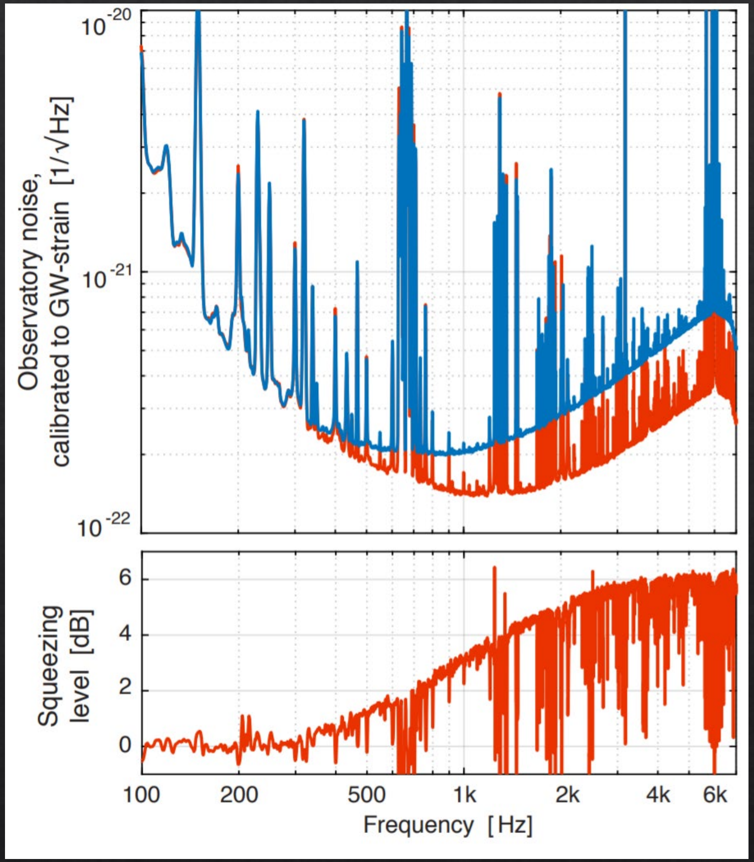
Squeezing

Coherent states and squeezed states both have minimal uncertainty.



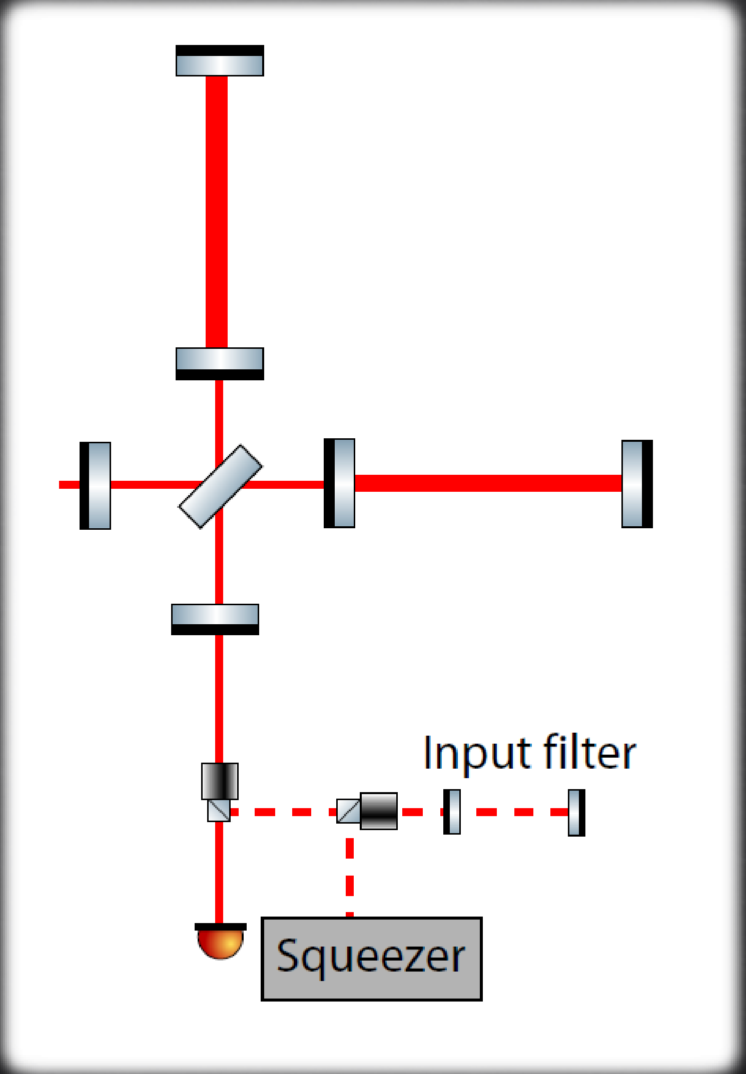
Squeezer developed at AEI Hannover



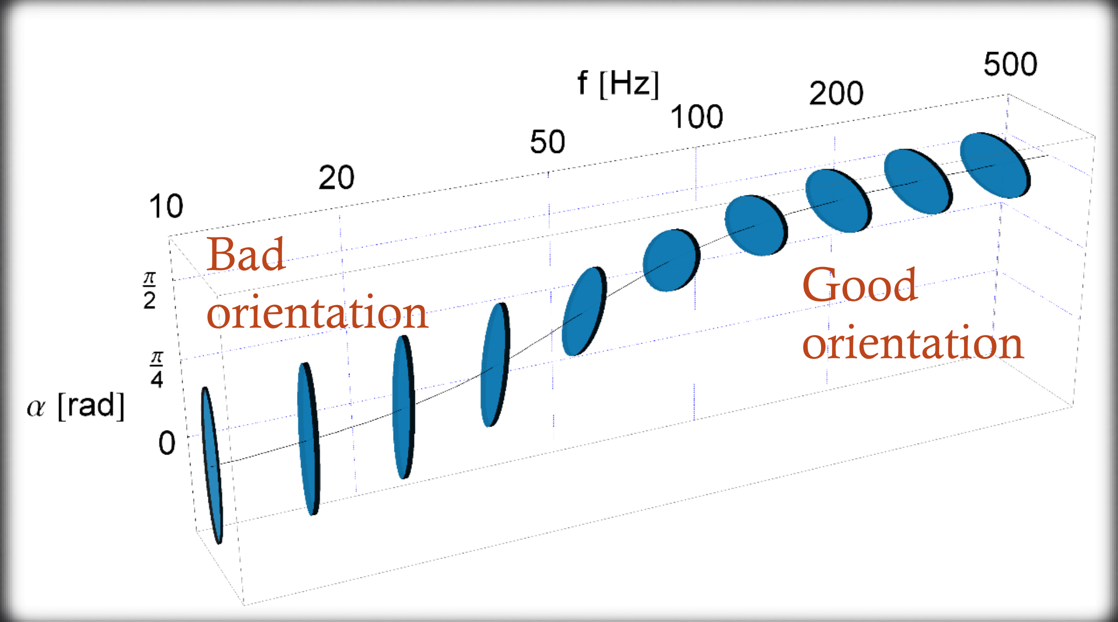


Lough et al 2020

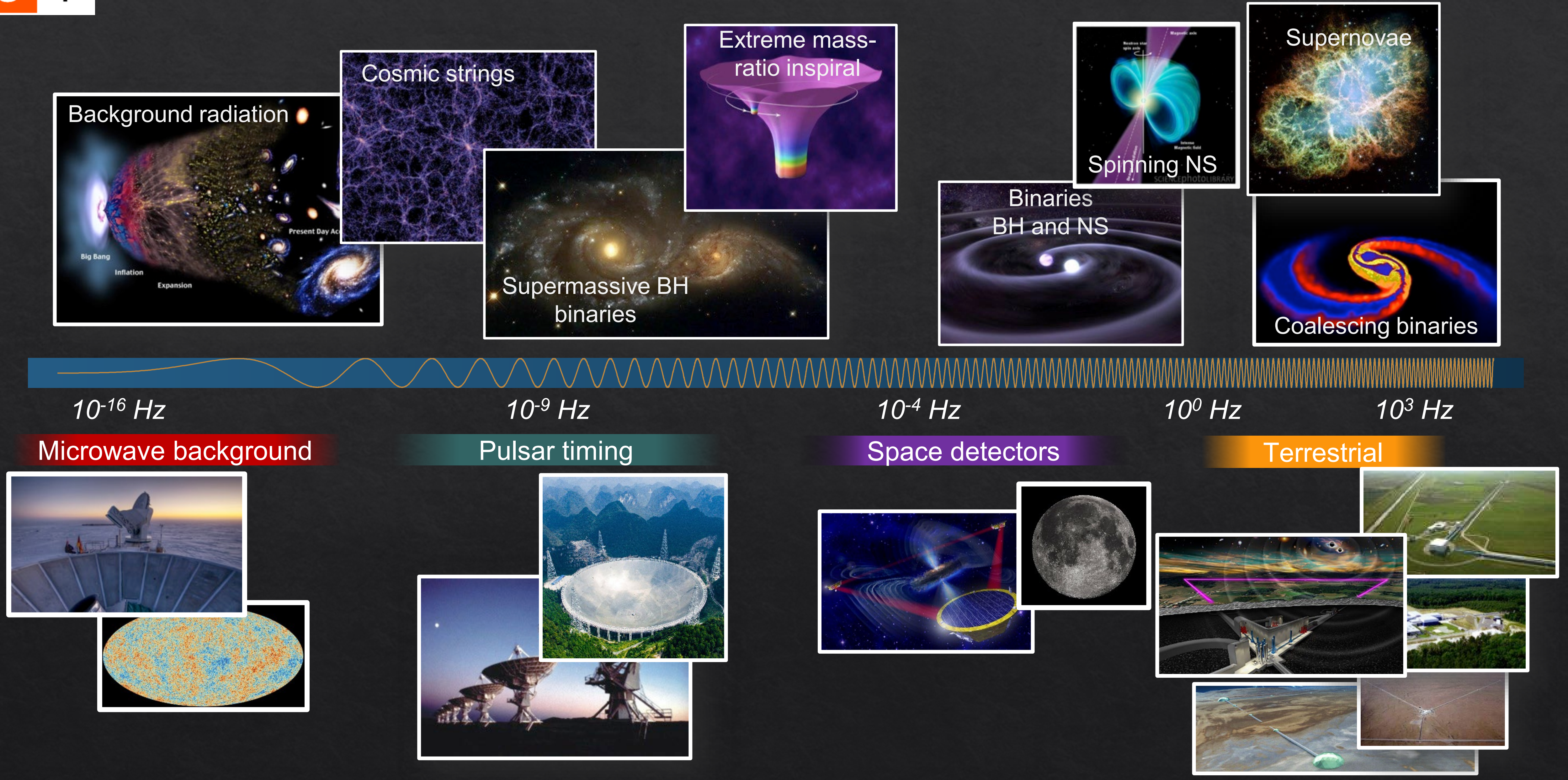
Quantum Filter



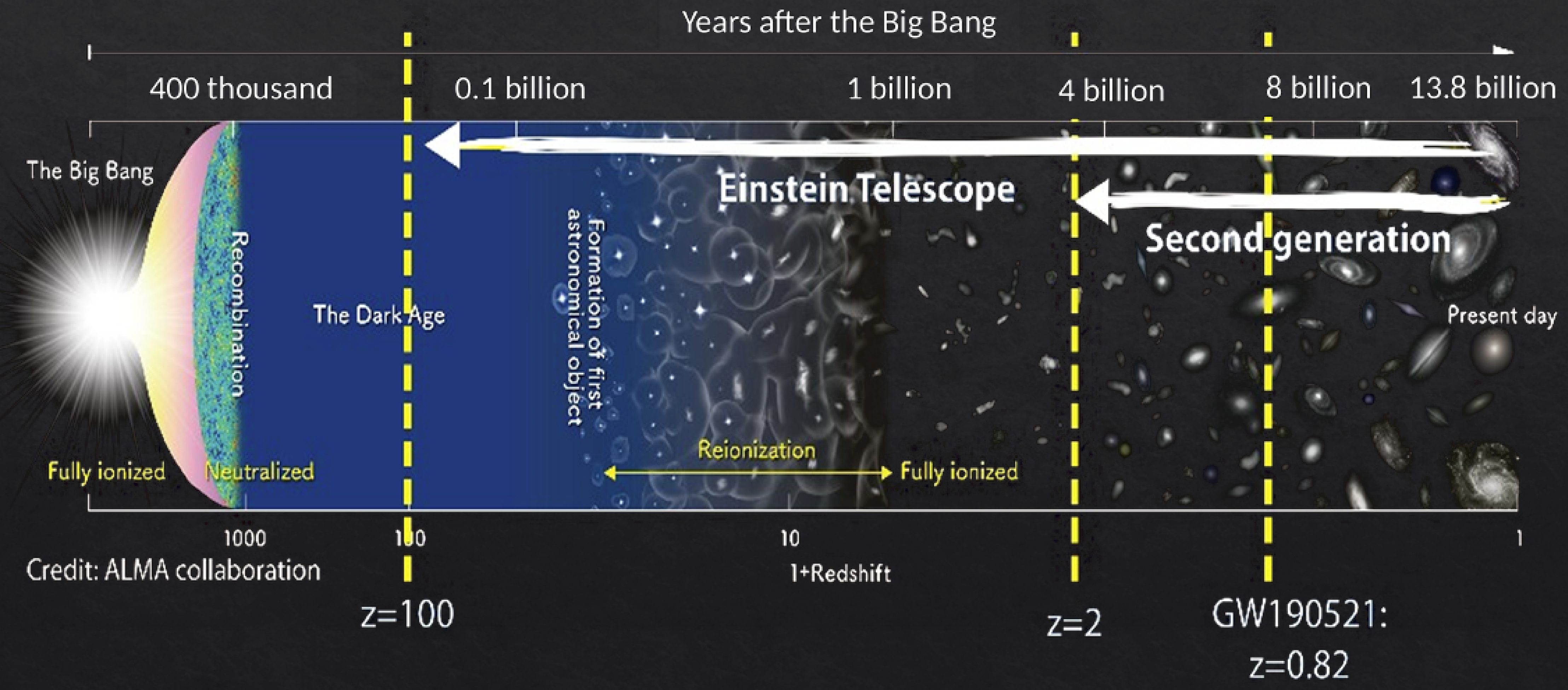
Squeezing ellipse gets rotated by the laser interferometer.



A filter is needed to compensate the rotation of the squeezing ellipse.

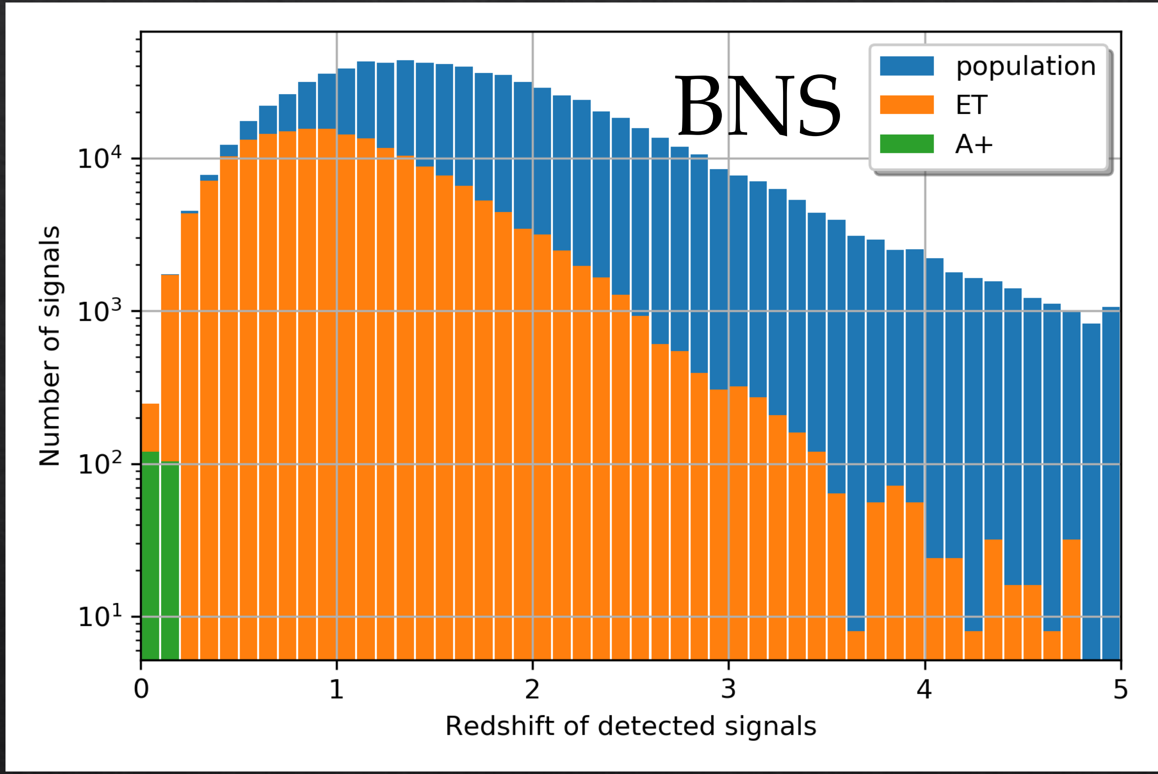

Background radiation
Big Bang
Inflation
Expansion
Cosmic strings
Supermassive BH binaries
Extreme mass-ratio inspiral
Binaries BH and NS
Spinning NS
Supernovae
Coalescing binaries
10^{-16} Hz
10^{-9} Hz
10^{-4} Hz
10^{0} Hz
10^{3} Hz
Microwave background
Pulsar timing
Space detectors
Terrestrial

Binary BH Detection Horizon

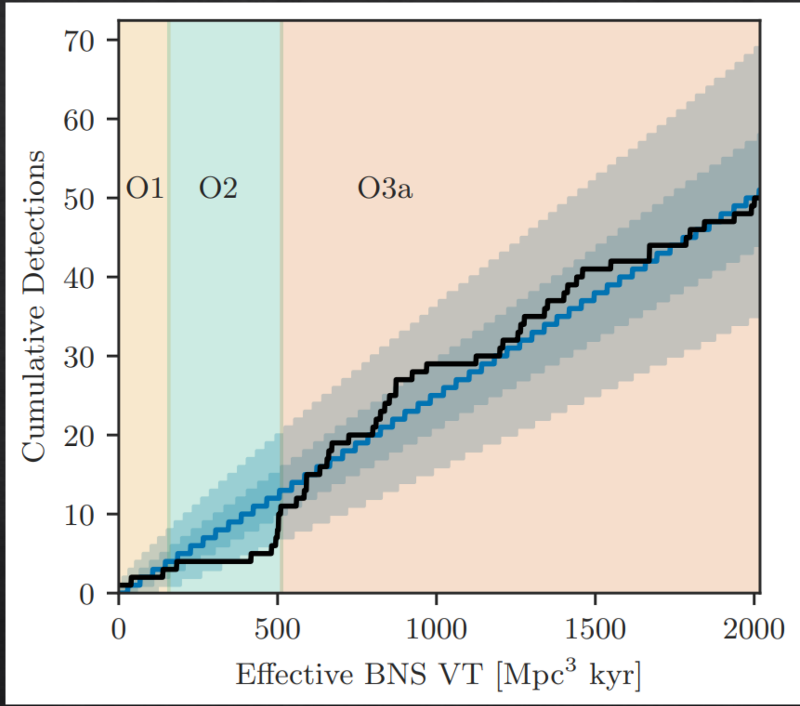


Detection Numbers

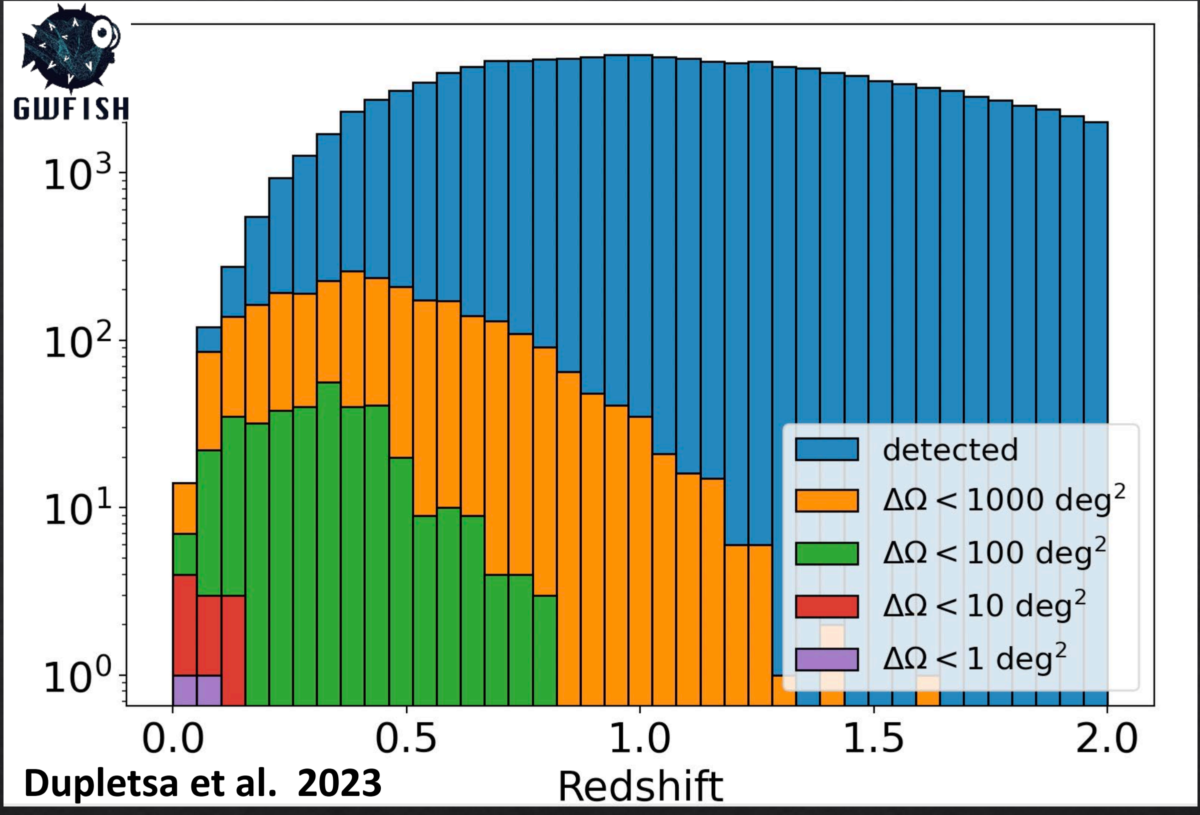
ET is expected see about 100000 BNS and 100000 BBH per year



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 – 26.3.2020



ET Sky-localization Capabilities



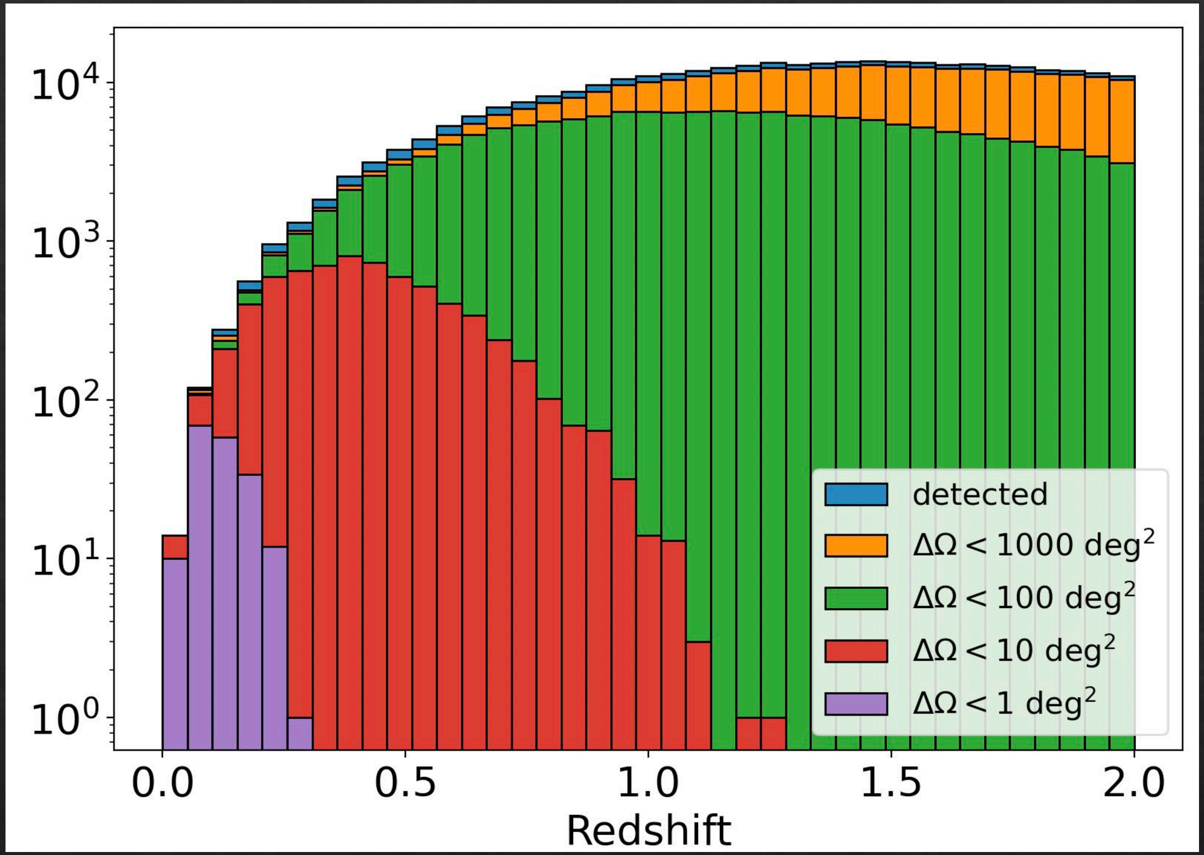
Dupletsa et al. 2023

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!

ET+CE Sky-localization Capabilities



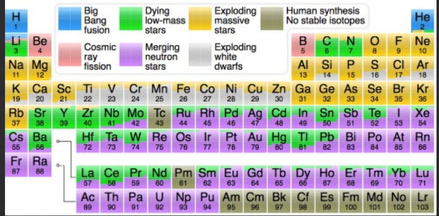
Cosmic Explorer
A proposed detector in the USA

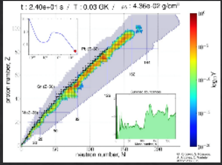
- O(1000) detections per year with sky-localization (90% c.r.) < 10 sq. deg

Science Of Neutron Stars

Radioactively powered transients

Nucleosynthesis

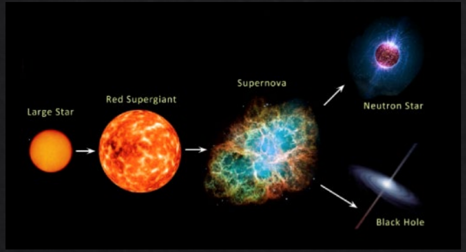




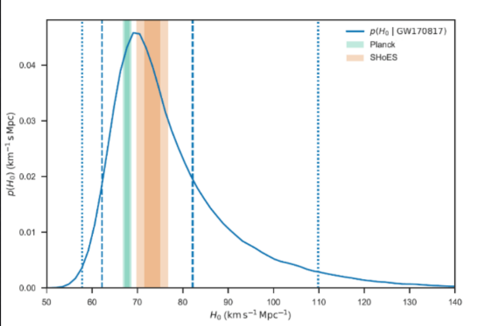
Relativistic astrophysics

Credit: M Branchesi

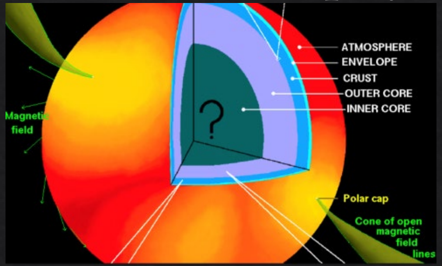
Compact-object formation and evolution



Cosmology

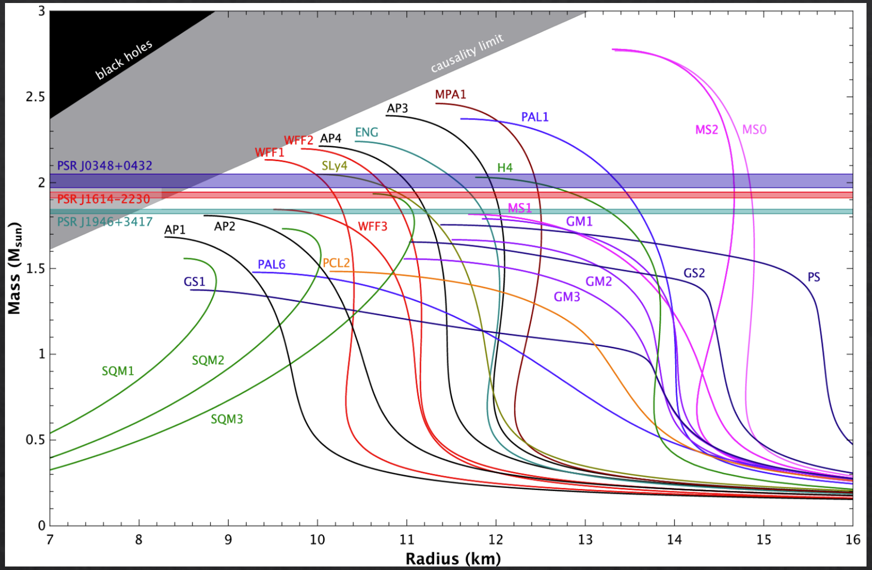


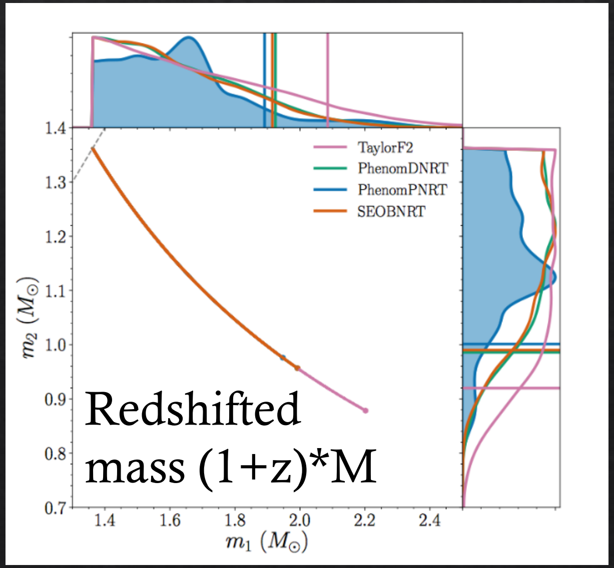
Nuclear matter physics



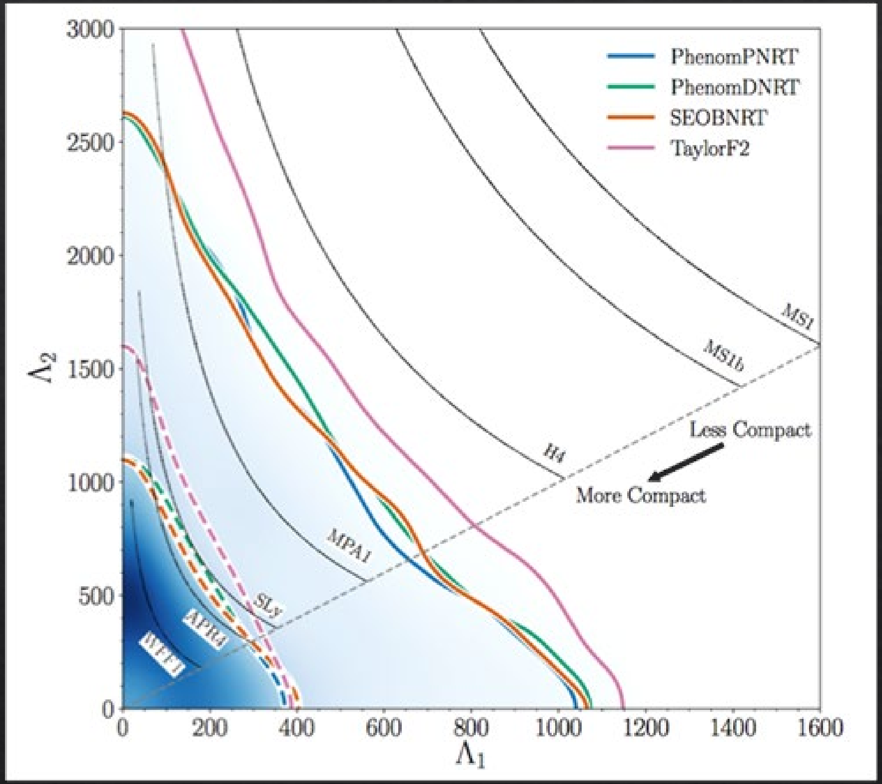
Neutron-star Equation of State

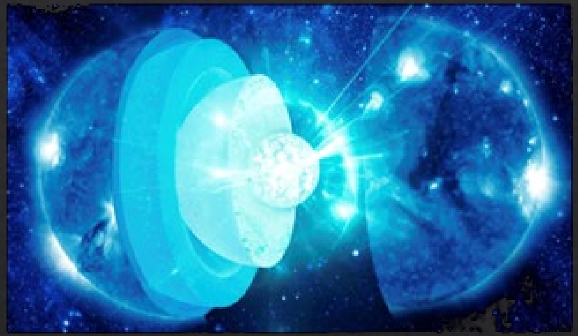
Intrinsic mass – NS radius relation





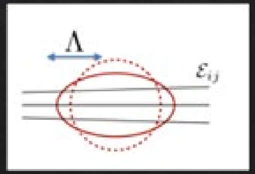
Observing deformations of neutron stars just before merger





TIDAL DEFORMABILITY

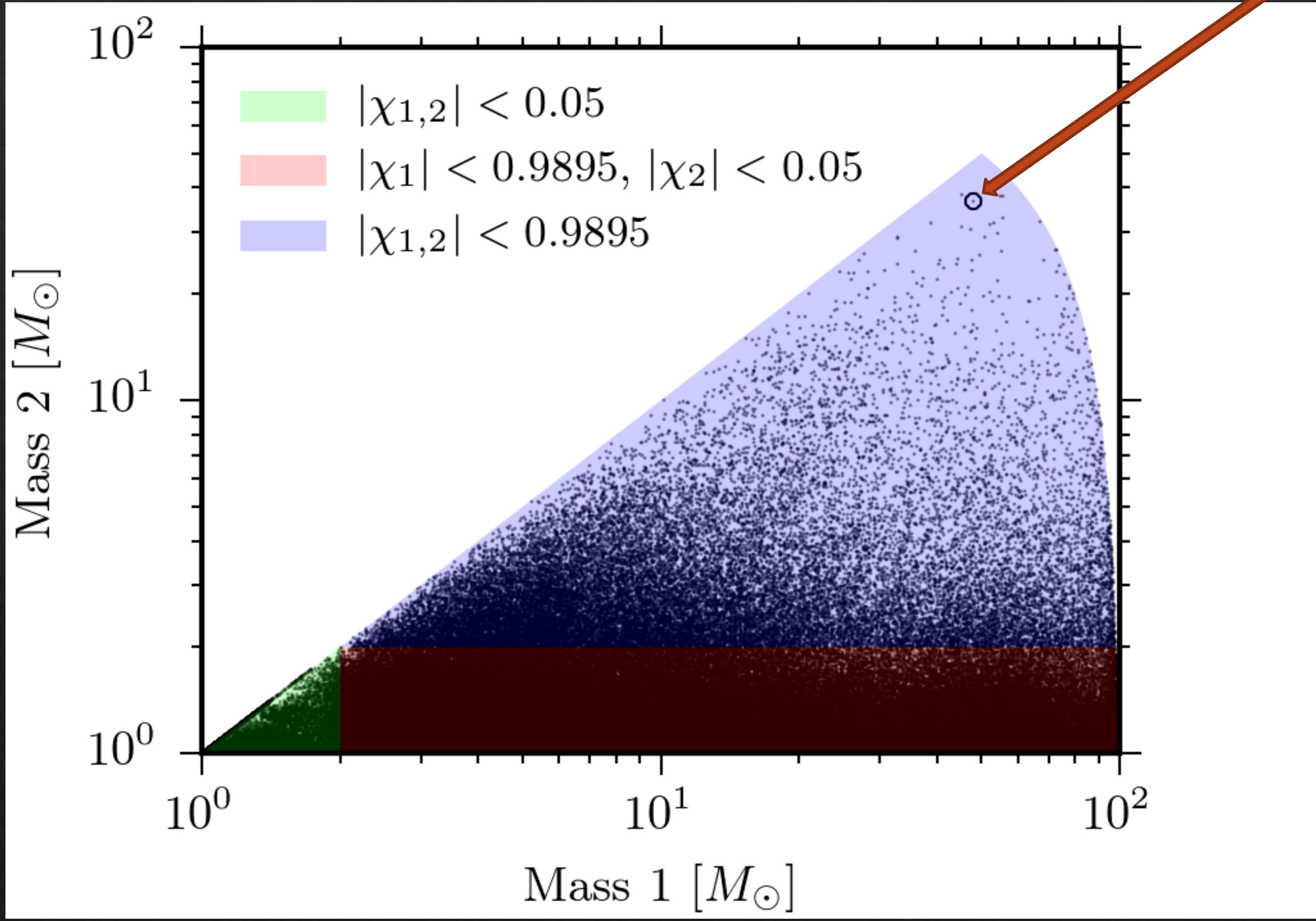
$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$



How to Detect a CBC: Matched Filtering

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

Best match with GW150914



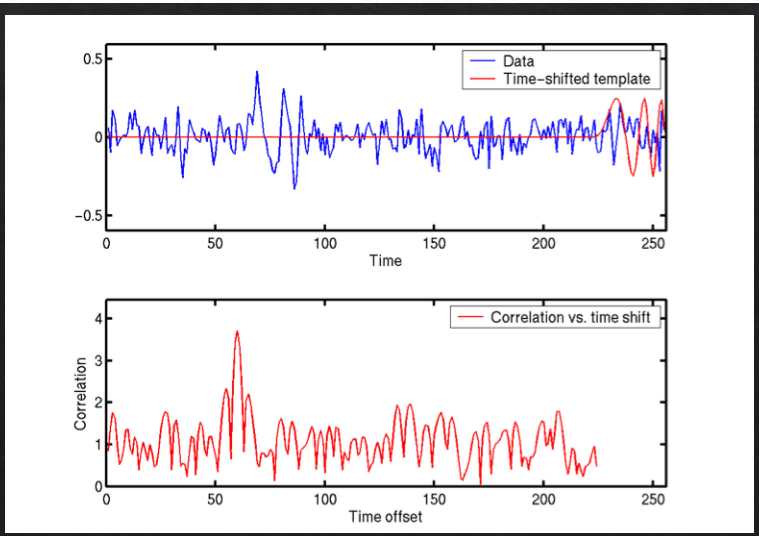
Matched filtering

FFT of data

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

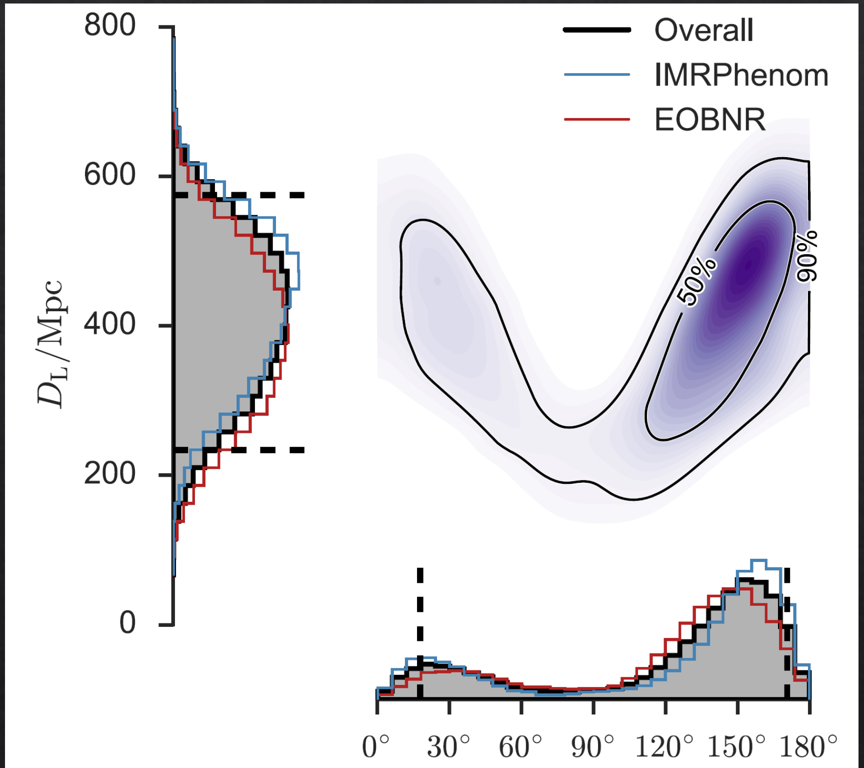
$$C(t) = 4\int_0^\infty \frac{\tilde{s}(f)\ \tilde{h}^*(f)}{S_n(f)}\ e^{2\pi i f t}\ df$$

Noise power spectral density



Bayesian Parameter Estimation

GW150914



PRL **116**, 241102 (2016)

Likelihood / Prior

$$p(\theta|d) = \frac{p(d|\theta)\,p(\theta)}{p(d)}$$

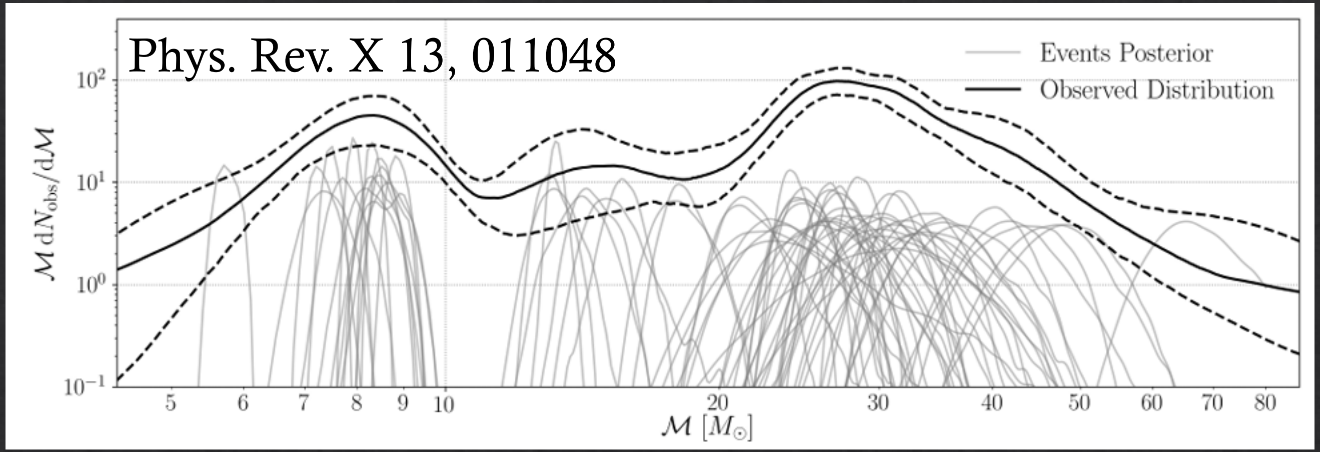
Posterior / Evidence

Gaussian likelihood approximation:
Assume that detector noise is Gaussian

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

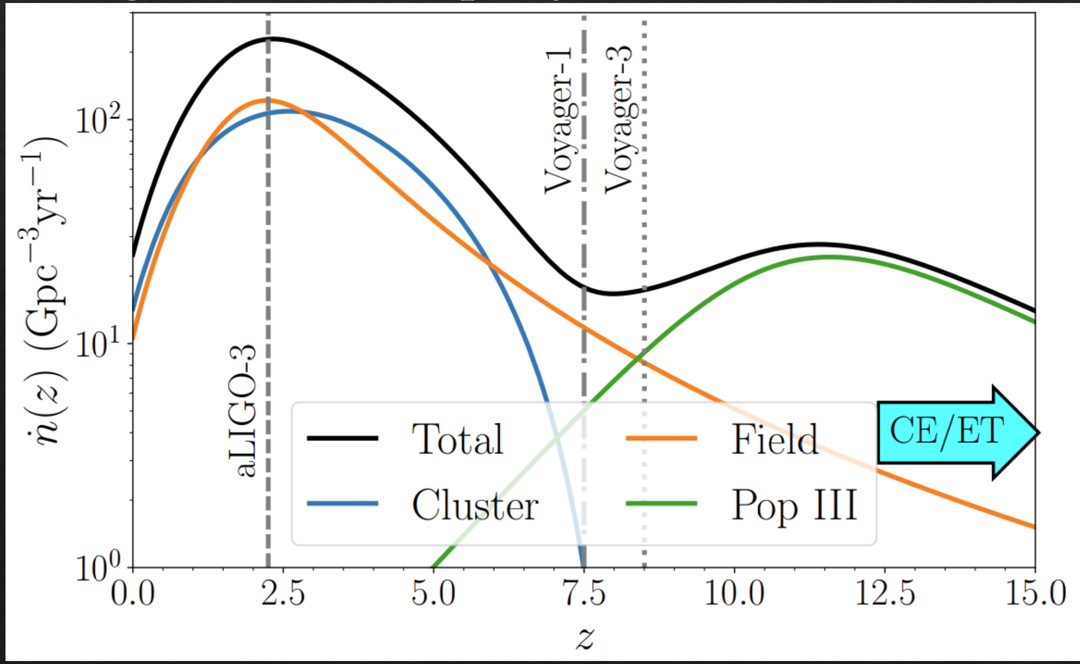
$$\langle a|b \rangle = 4\int_0^\infty \mathrm{d}f\, \frac{\Re(\tilde{a}(f)\tilde{b}^*(f))}{S(n;f)}$$

Black-hole Populations



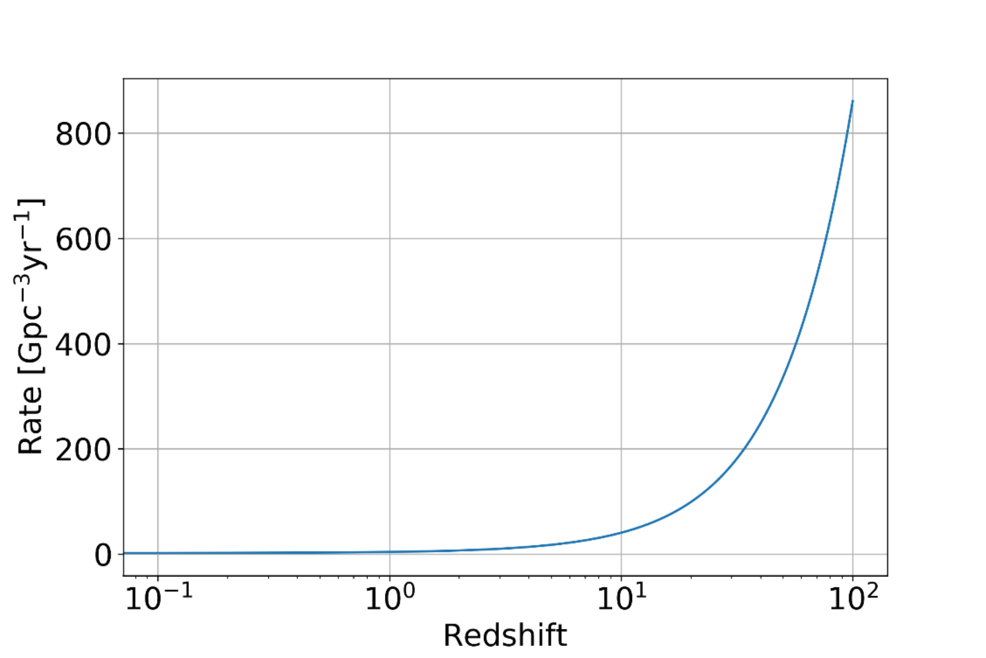
LVK, 2023

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



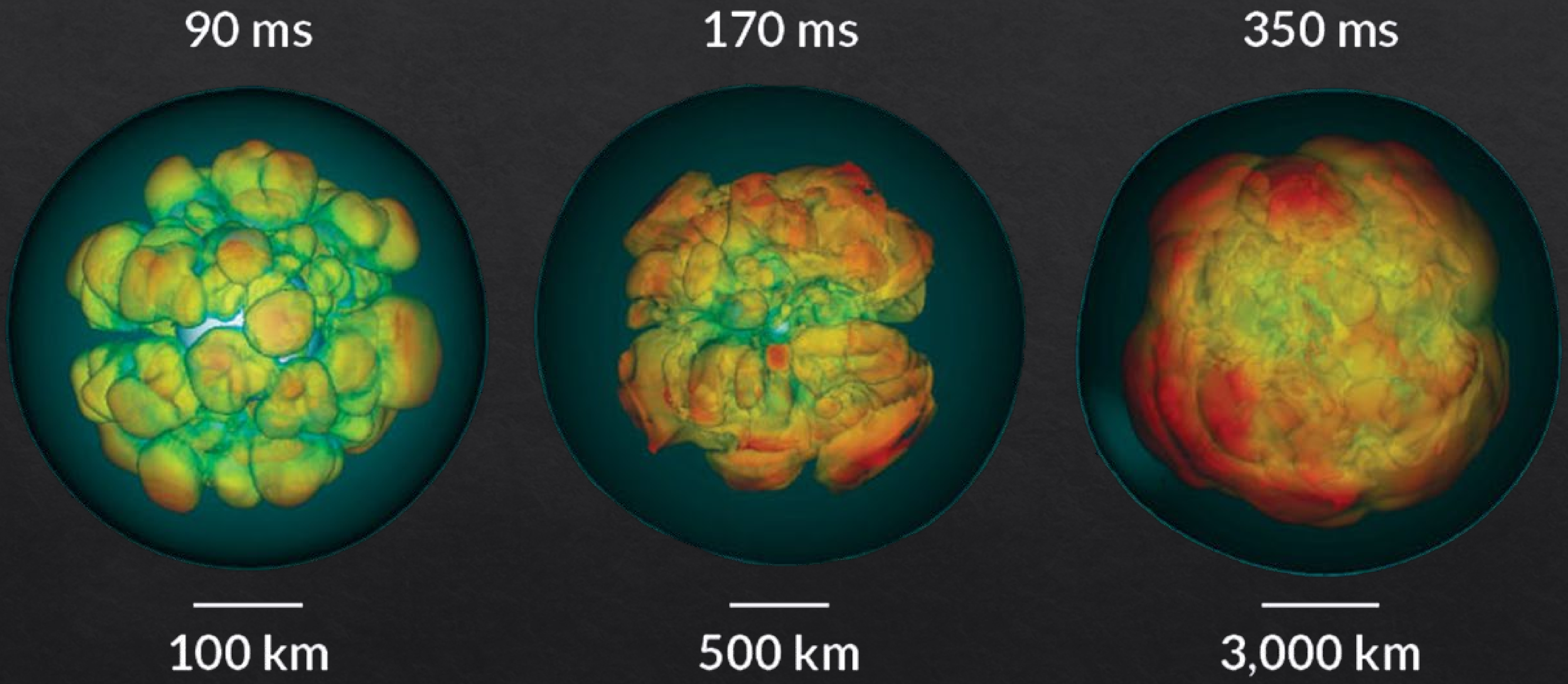
Ng et al, 2021

Is there a population of primordial black-holes?



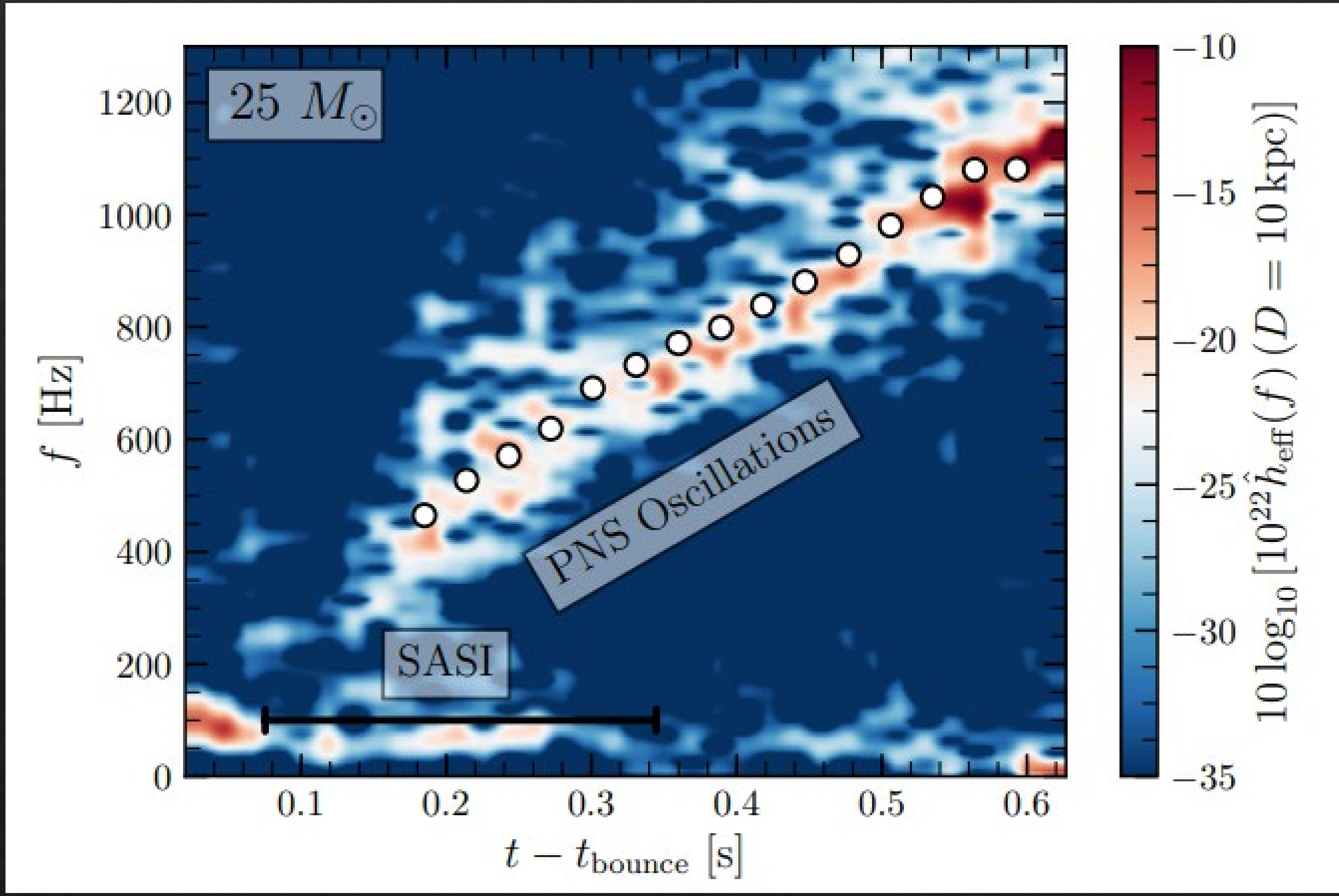
De Luca et al, 2020

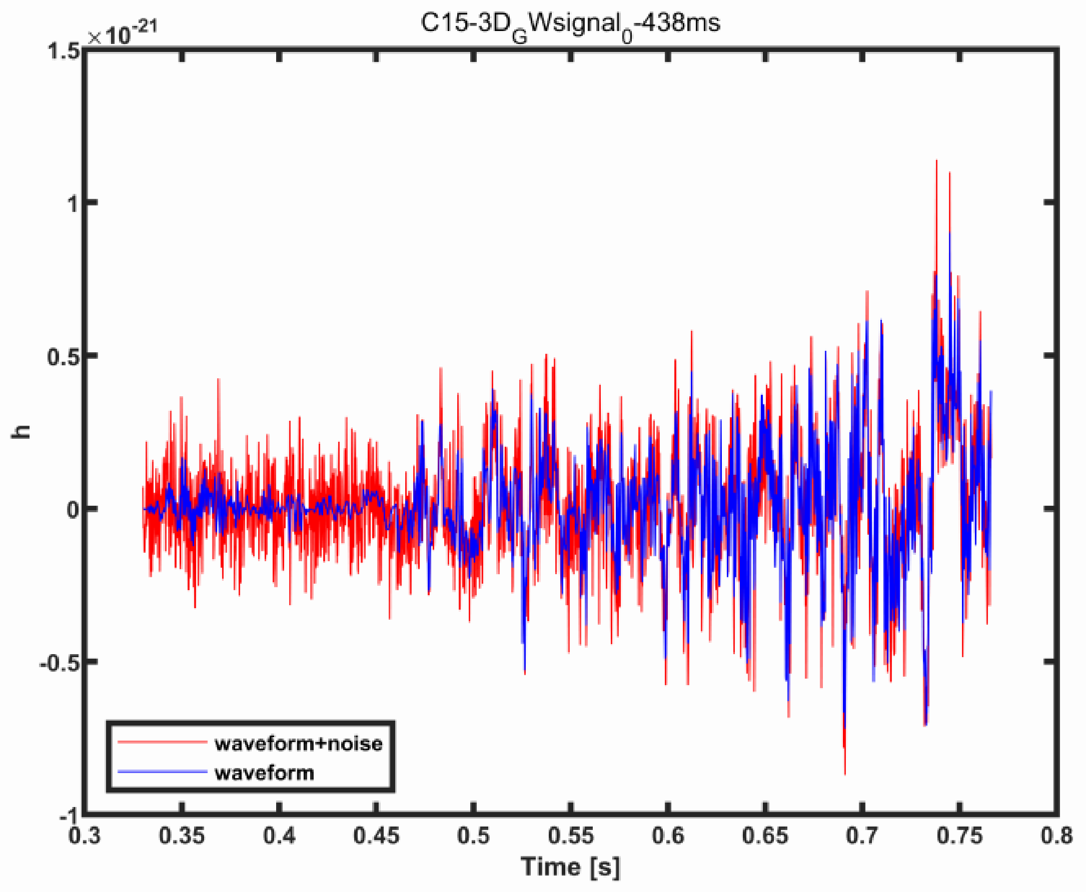
Core-Collapse Supernovae



GW signals from core-collapse SNe

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

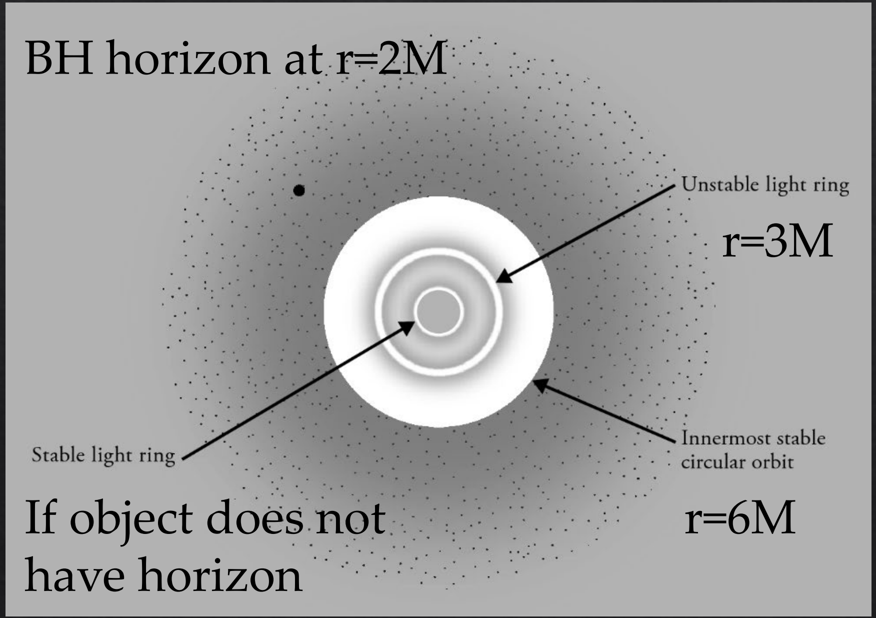




Individual BBH Signals: New Physics

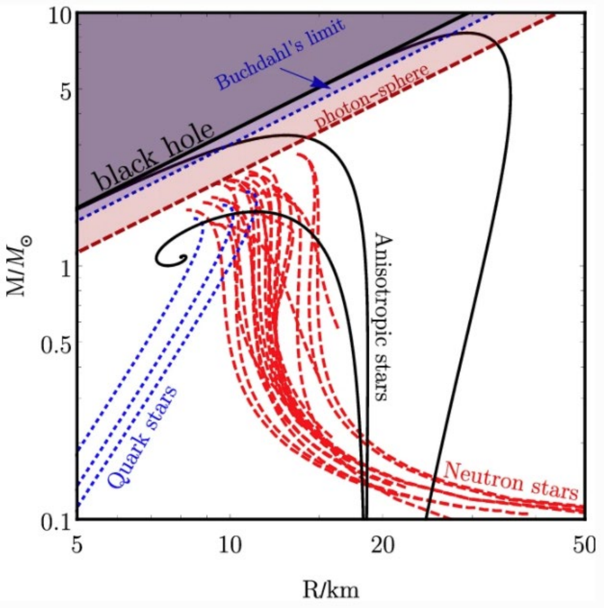
Black holes: the ultimate engine of discovery
[cit Cardoso, 2020]

Probing the structure of BH spacetime



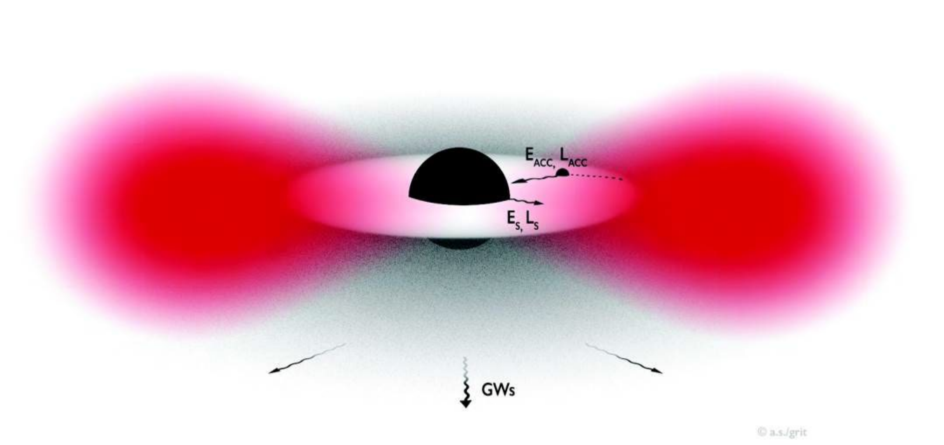
Cardoso, Pani, 2019

Exotic compact objects: Infer mass-radius relation

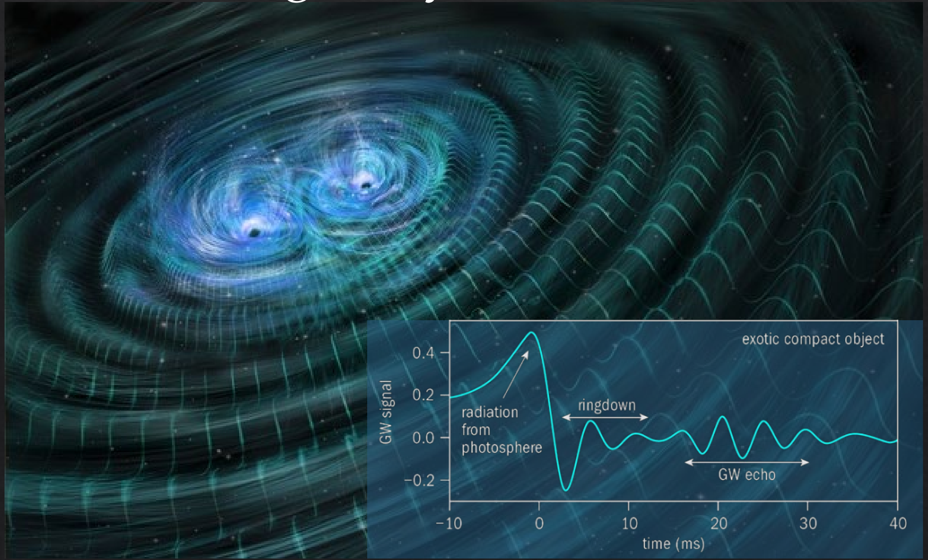


Cardoso, Pani, 2019

BH superradiance with light bosons



Quantum gravity: area discretization

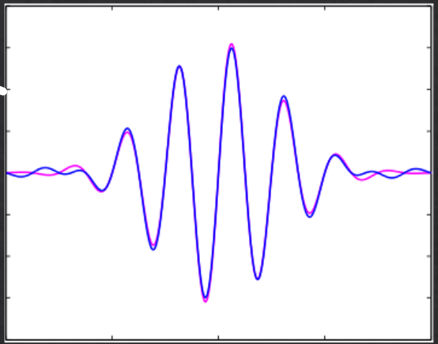


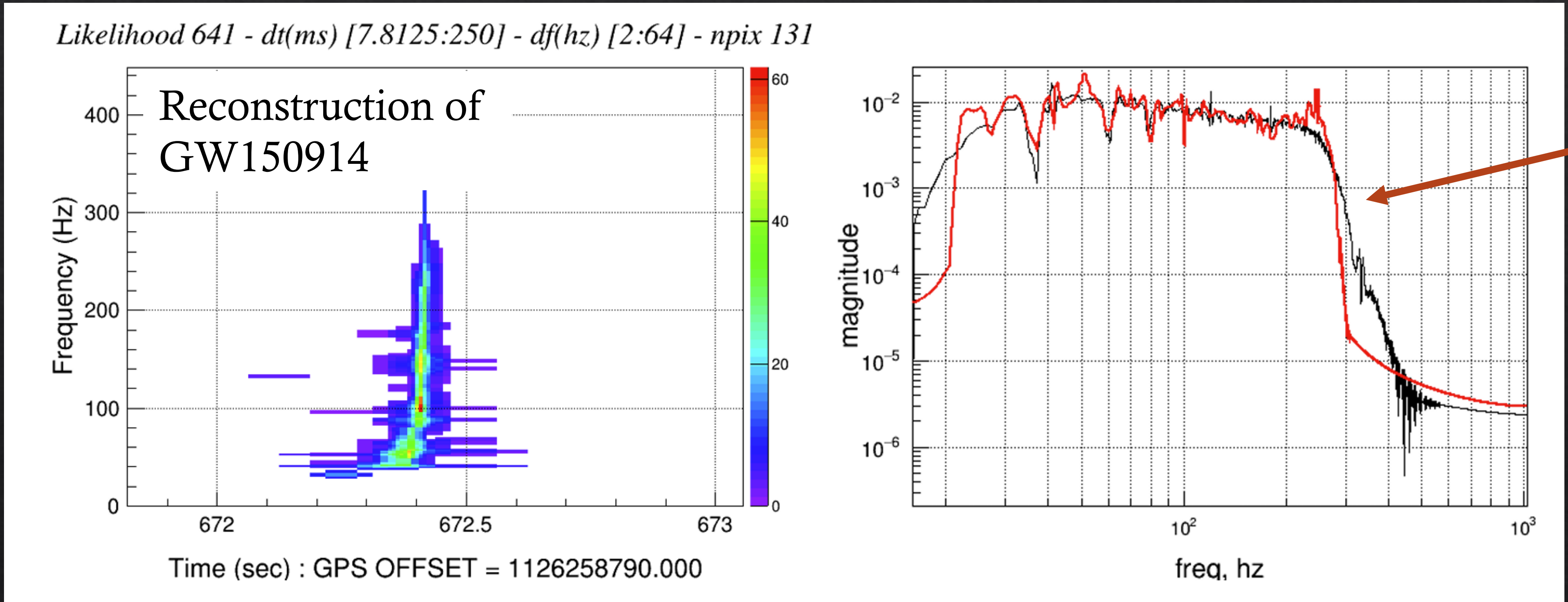
Agullo et al, 2021

Coherent WaveBurst

wavelet transform   data   wavelet

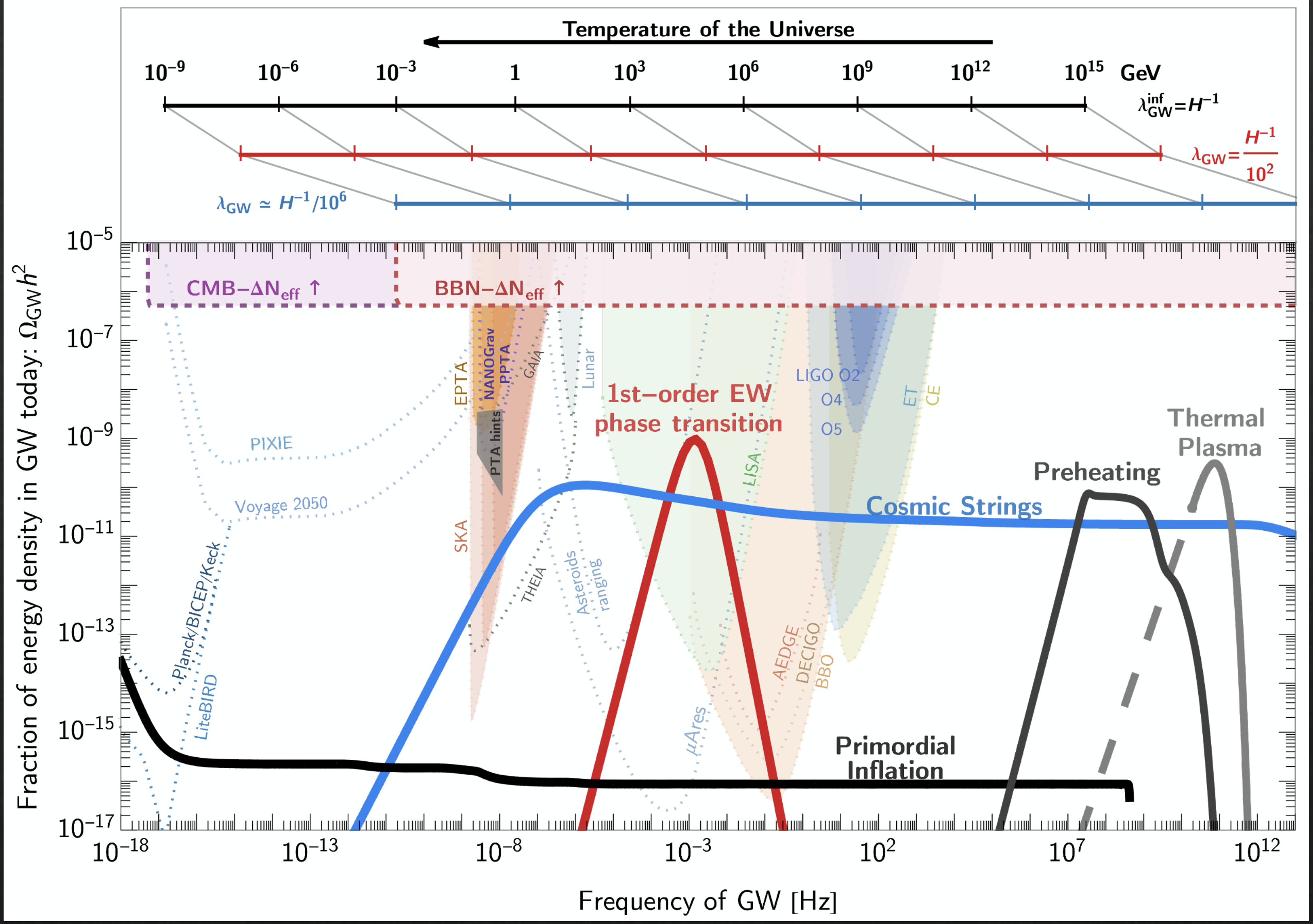
$$X(\tau,\phi,Q) = \int_{-\infty}^{+\infty} x(t)\, w(t-\tau,\phi,Q)\, e^{-i2\pi\phi t}\, dt$$





Comparison in frequency domain

Primordial GW Backgrounds



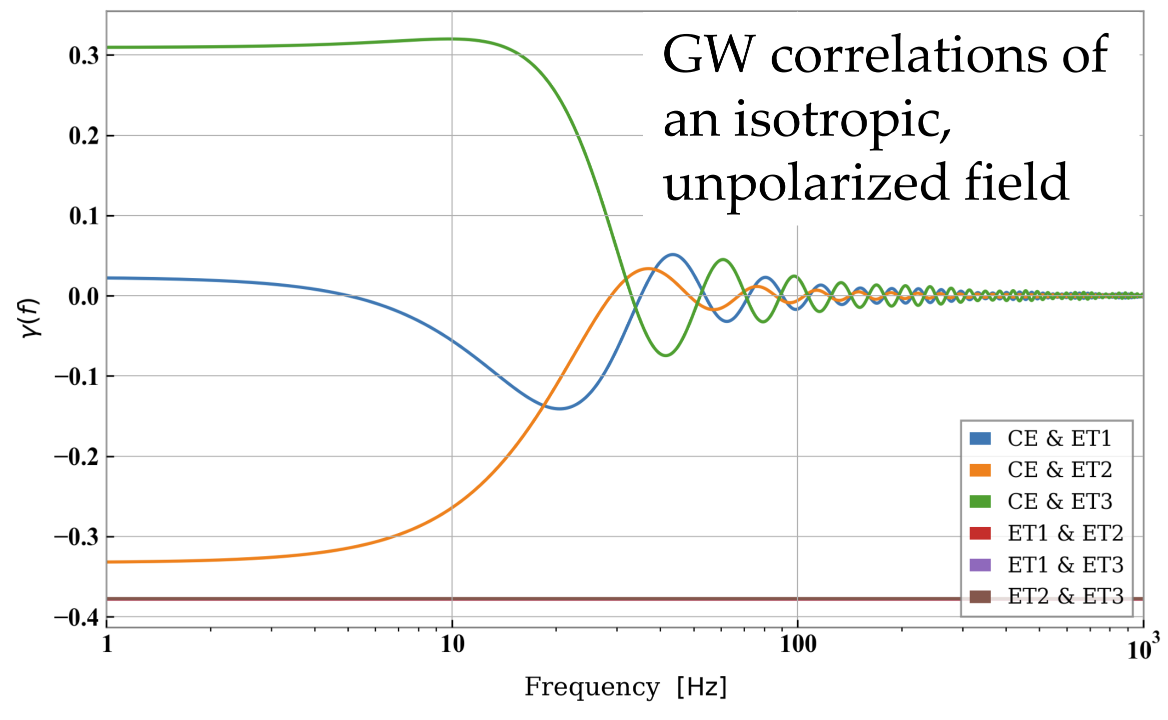
Simakachorn, 2022

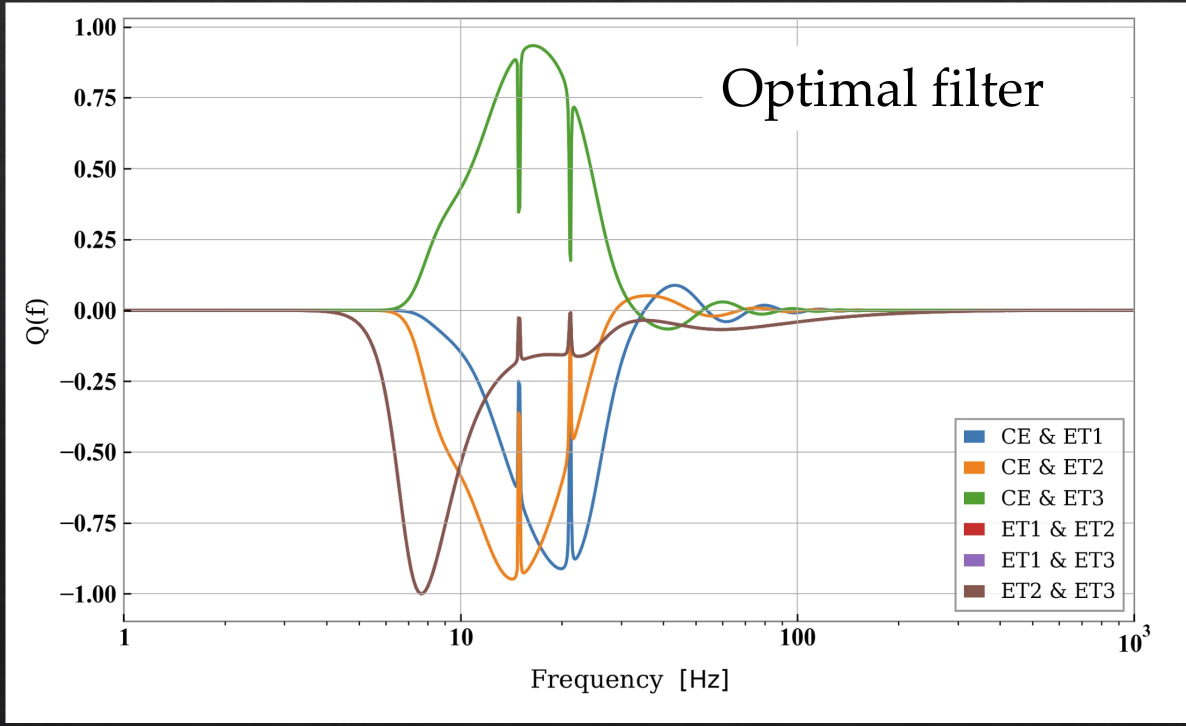
Observation of Stochastic Backgrounds

Correlate data between GW detectors!

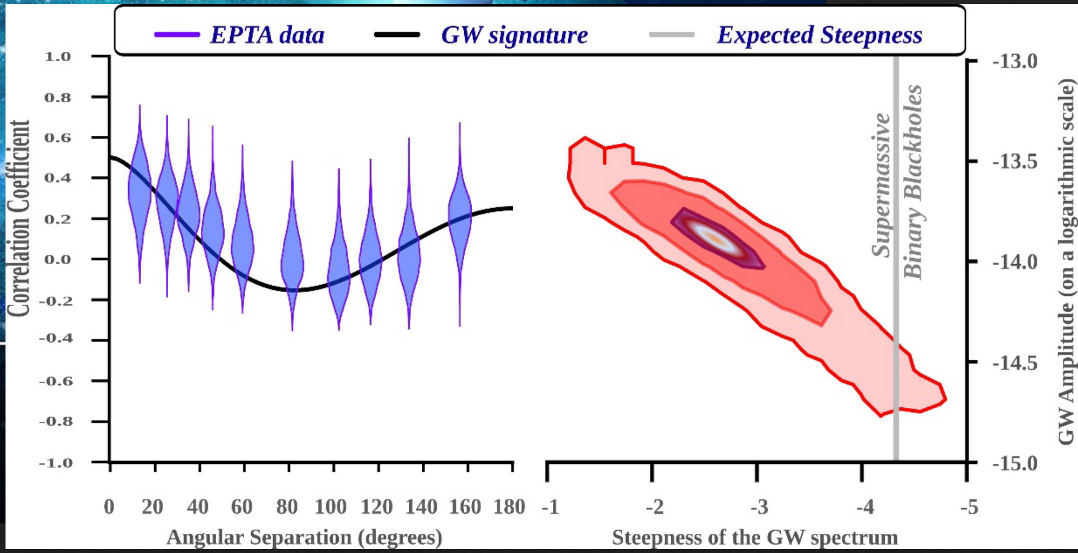
$$C_{ij}(f) = S_{\mathrm{GW}}(f)\gamma_{ij}(f)$$

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





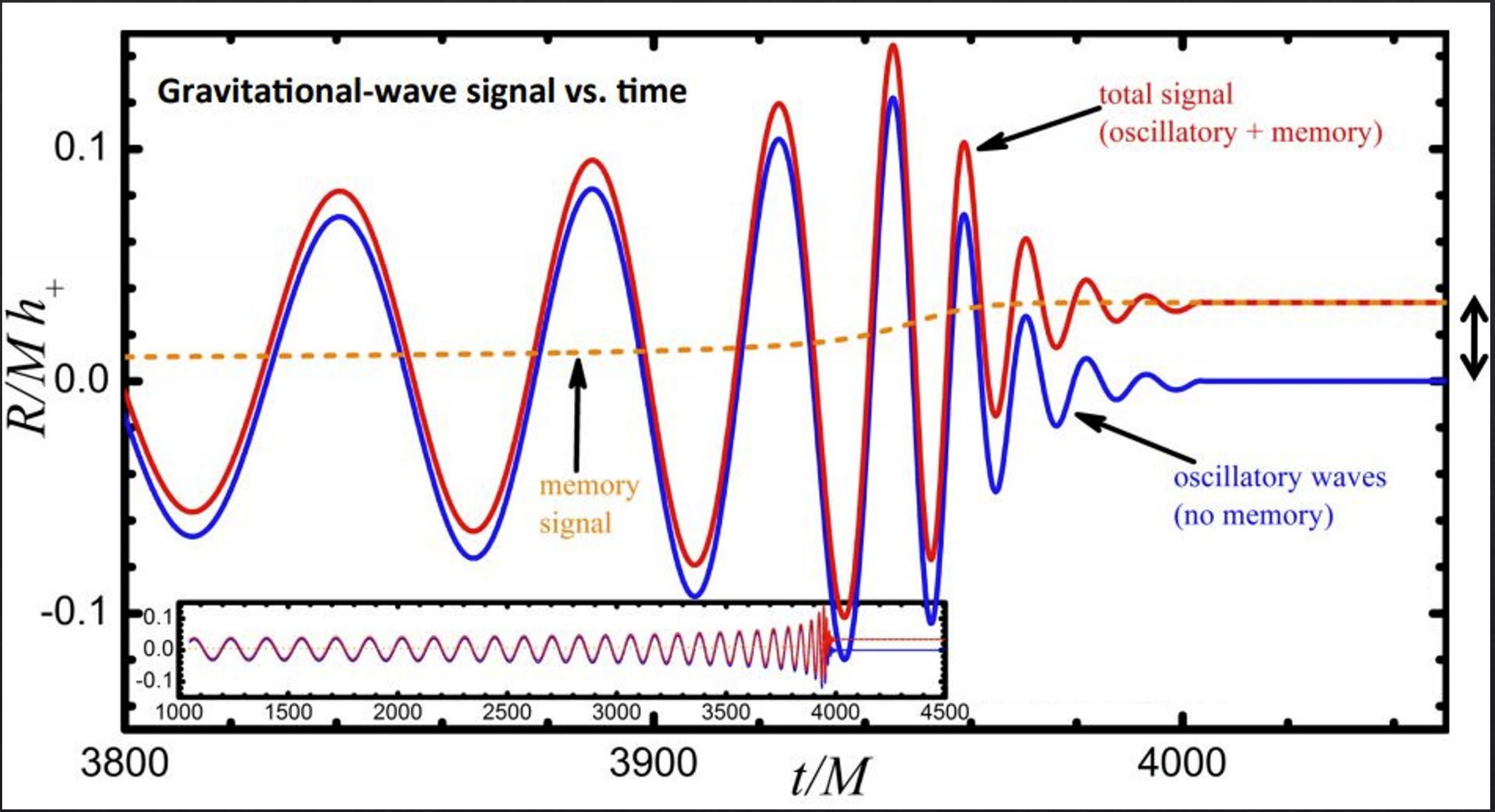
The News of the Day: PTAs



Gravitational-wave Memory

Time-integrated GW energy emitted into solid angle

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

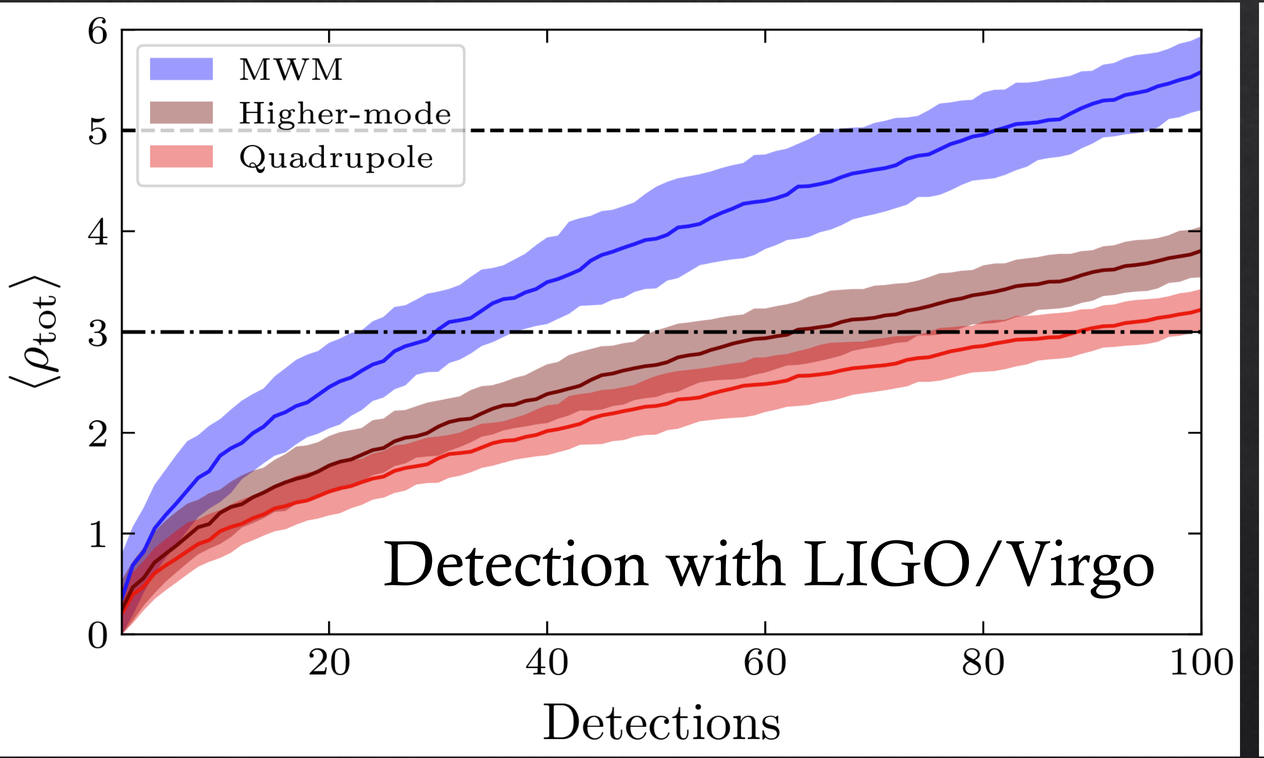


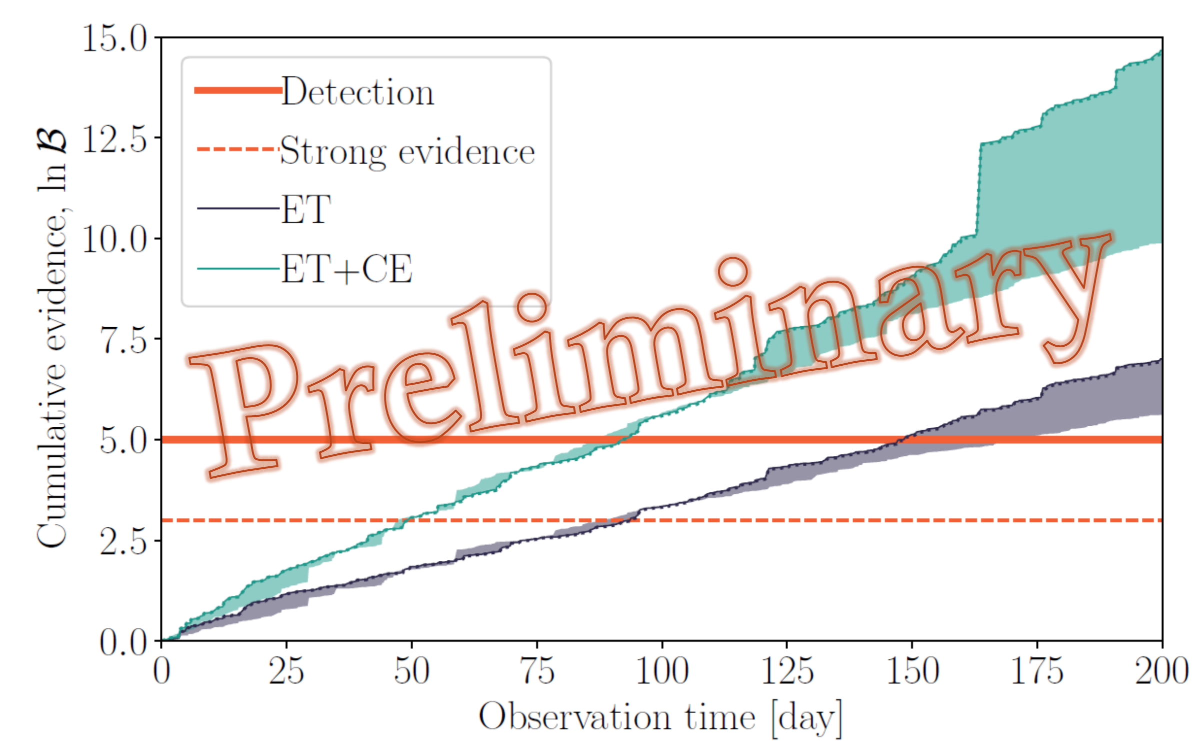
GWs leave a lasting deformation of spacetime behind them.

Deep connection to spacetime symmetries and quantum gravity.

GW Memory: Detection and Model Selection

Evidence of detection and for model selection is accumulated with increasing number of GW signals





Boersma et al, 2020