Science & Technology of GW Detectors

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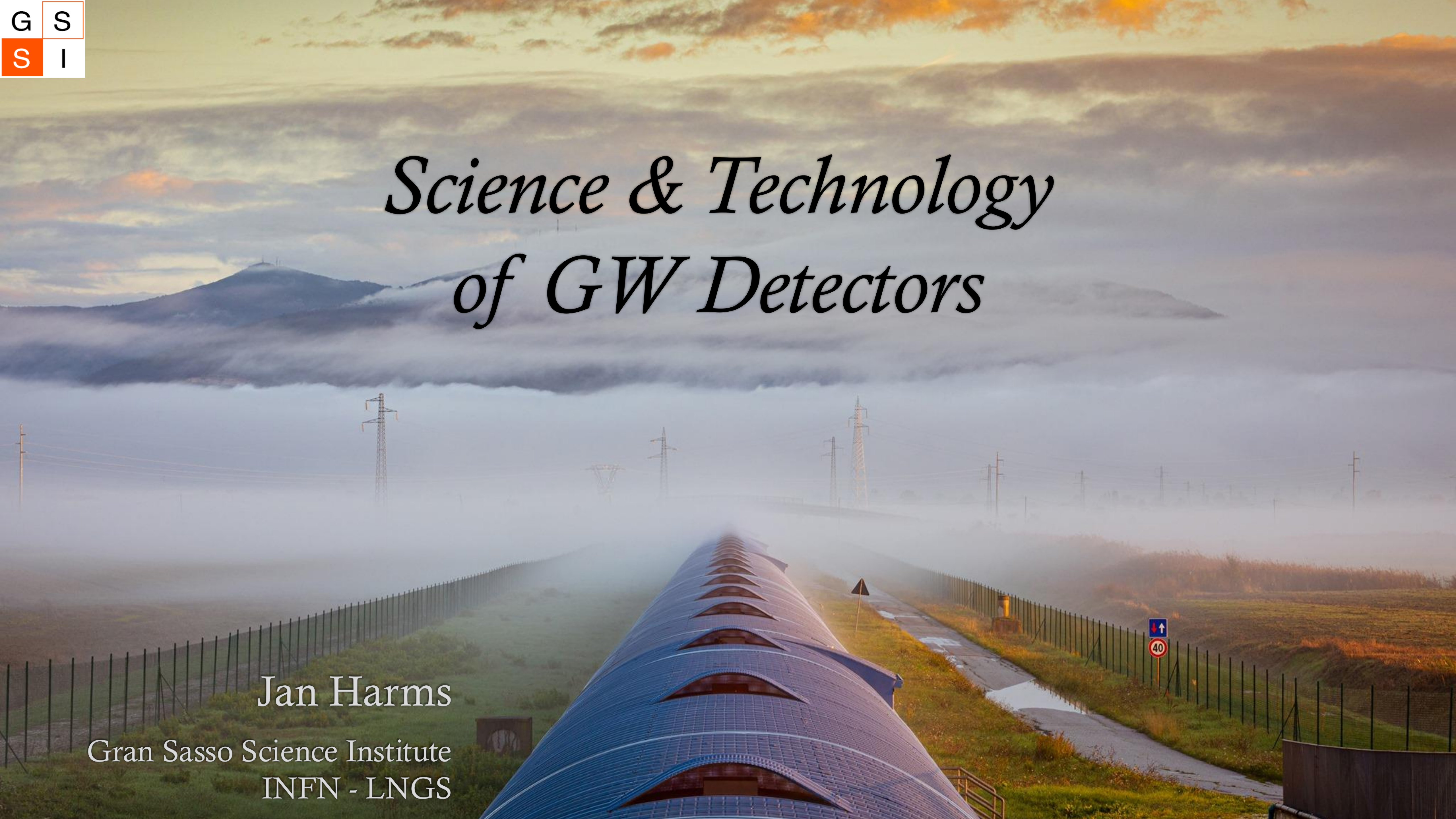
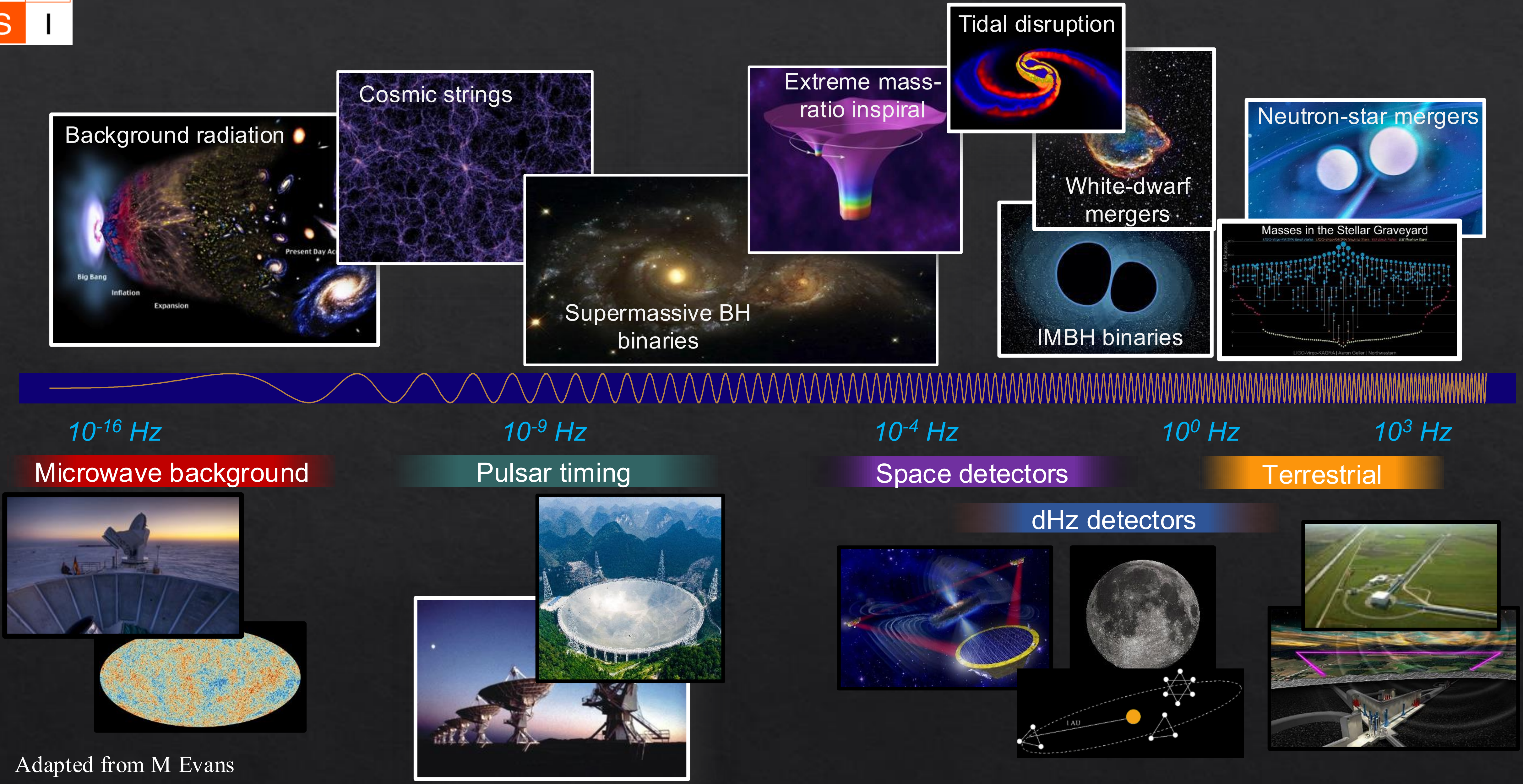
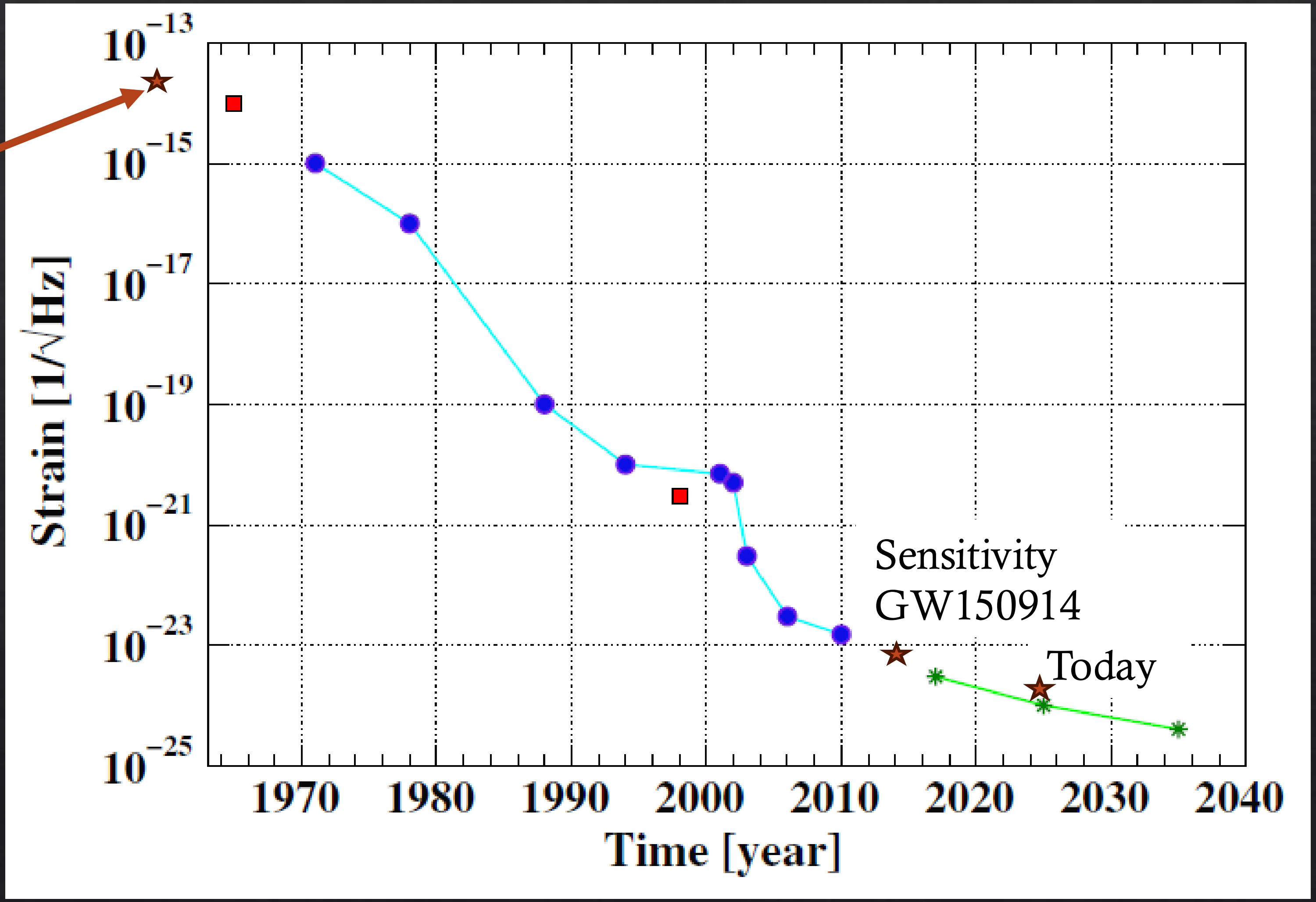




Adapted from M Evans

History of GW Detector Sensitivities

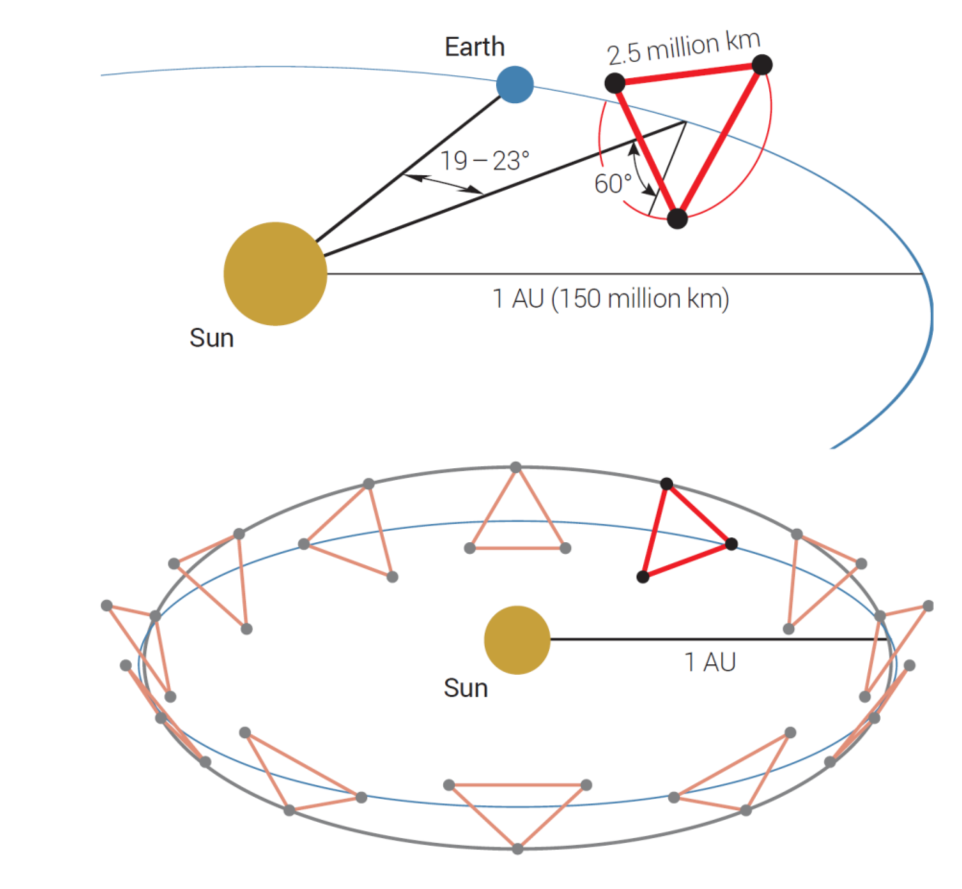
World's first GW measurement in 1961: Oscillations of Earth



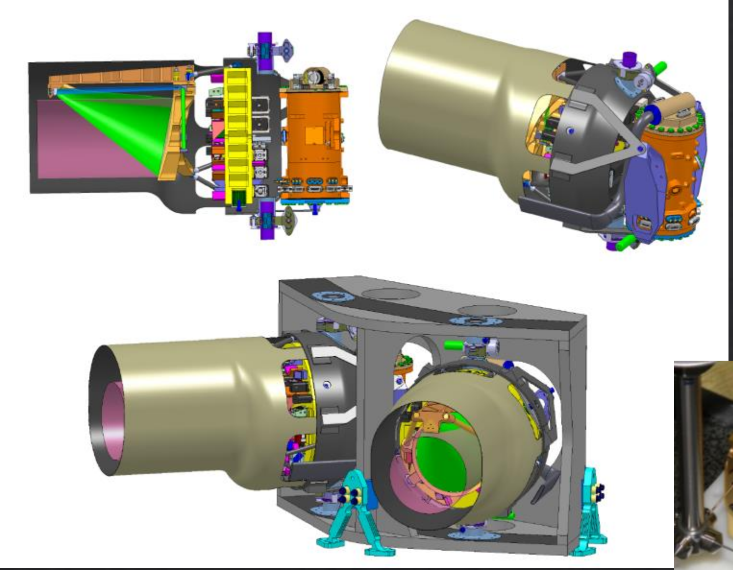
Adhikari, 2014

LISA: 0.1mHz – 0.1Hz
(and Taiji)

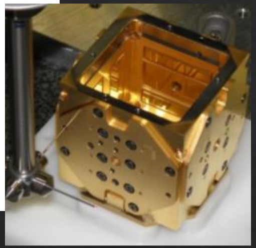
Earth-like orbit
(time-delay interferometry)



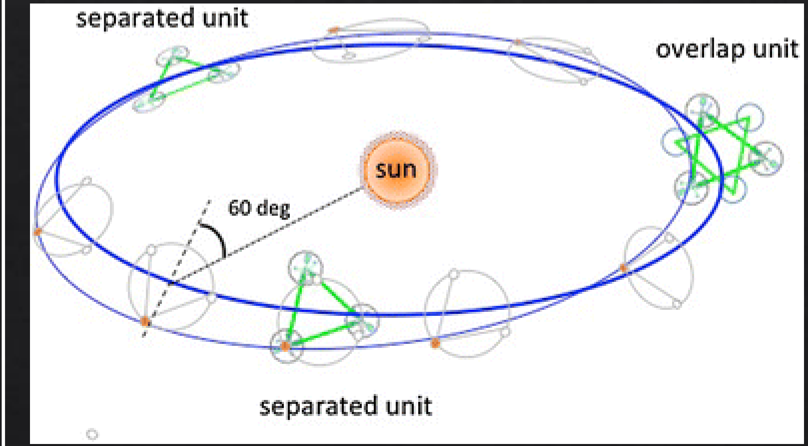
Payload
conceptual design



Drag-free control



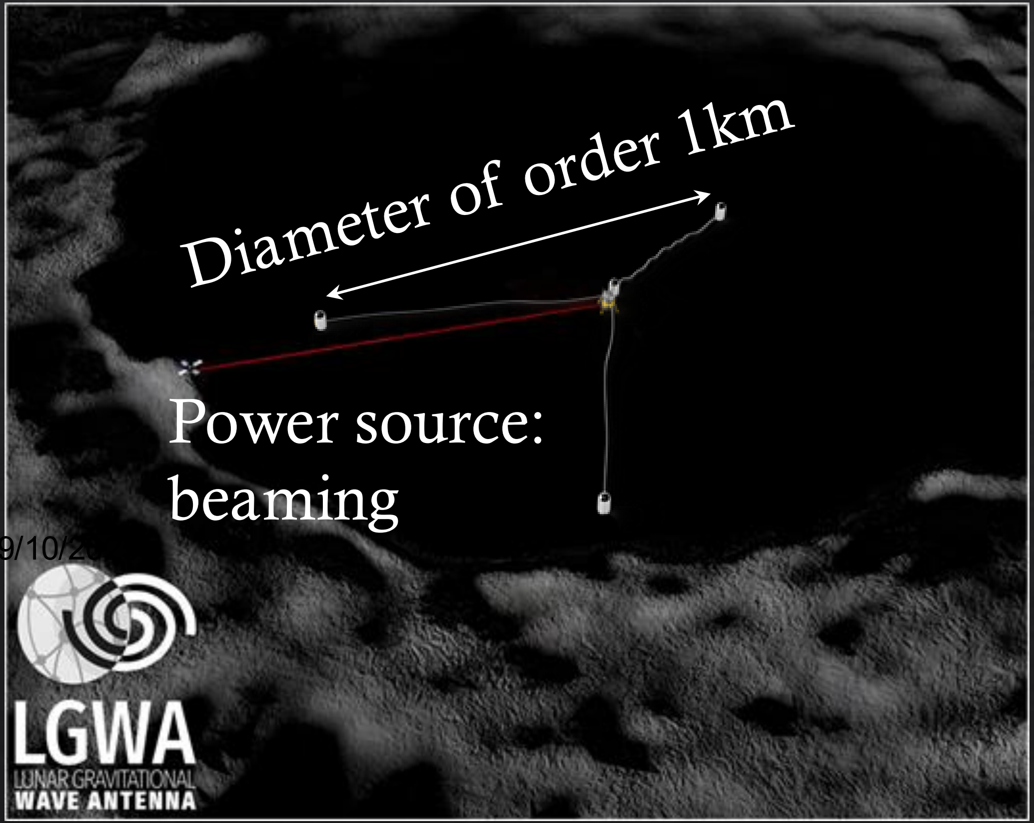
Proposal: adapt technology to higher frequencies



DECIGO
BBO
TianQin

LGWA: 1mHz – 1Hz

Deployment of sensor array inside a permanently shadowed region (PSR)



Lunar Surface Gravimeter deployed on the Moon with Apollo 17 in 1972

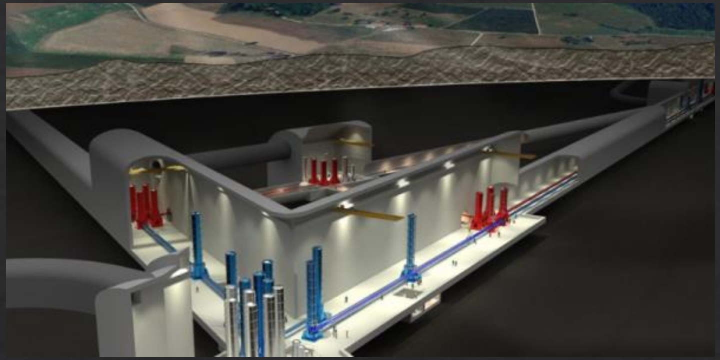
Measure oscillations of the Moon caused by GWs

Terrestrial: 3Hz – few kHz

Long-baseline laser interferometers with suspended test masses

LIGO India

Einstein Telescope



Cosmic Explorer

Incomplete List

- Levitated superconducting spheres
  - Effect on magnetic field (PRL 134, 181402, 2025)
  - Displacement readout with coil and SQUIDs (CQG 33 075003, 2016)
- Spin-nano-diamond (New J. Phys. 22, 083012, 2020)
- Torsion bars (PRL 105, 161101, 2010)
- Juggled interferometer (PRD 106, 042007, 2022)
- Jiggled interferometer (https://doi.org/10.48550/arXiv.2509.12095)
- Ring-accelerator detector (PRD 102, 122006, 2020)
- Binary resonance detector (PRL 128, 101103, 2022)
- Stellar resonances (MNRAS 408, 1742, 2010)
- Doppler tracking (CQG 19, 1767, 2002)
- Atom interferometers (EPJ Quantum Technology 7, 6, 2020)
- Frequency comb (https://doi.org/10.1117/12.3047830)
- Liquid Helium (New J. Phys. 19, 073023, 2017)
- Laser interferometer on the Moon (https://doi.org/10.48550/arXiv.2508.11631)
- Atomic-clock array (https://doi.org/10.48550/arXiv.2401.13668)

G S
S I

The Hierarchy of Detector Noise

Environmental noise
- Seismic
- Atmospheric
- Electromagnetic
- Radiation

Mitigation
- Location
- Isolation
- Noise cancellation
- Control

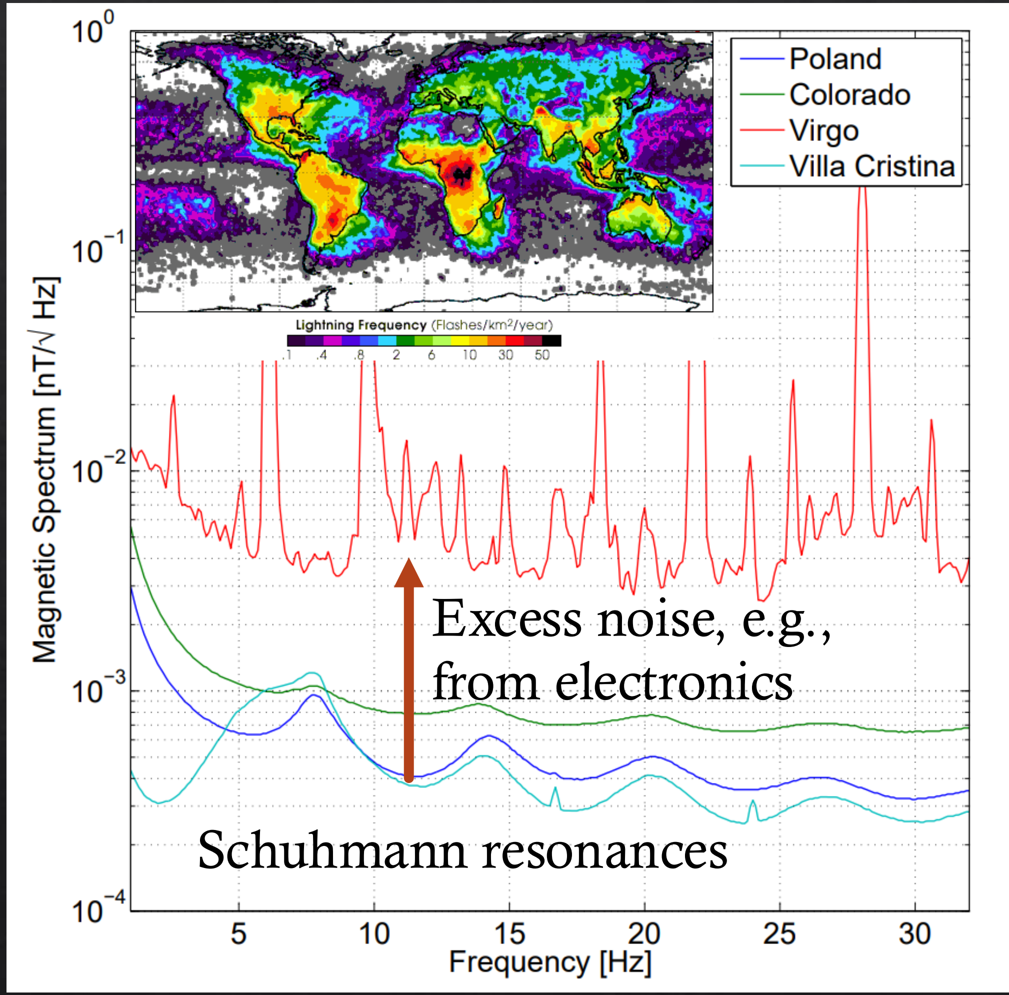
Intrinsic noise
- Thermal
- Sensing and control
- Engineering imperfections

Mitigation
- Lower and stabilize temperature
- Increase material quality
- Improve sensors
- Optimize control
- Stray light control

Quantum noise
- Vacuum fluctuations
- Back action

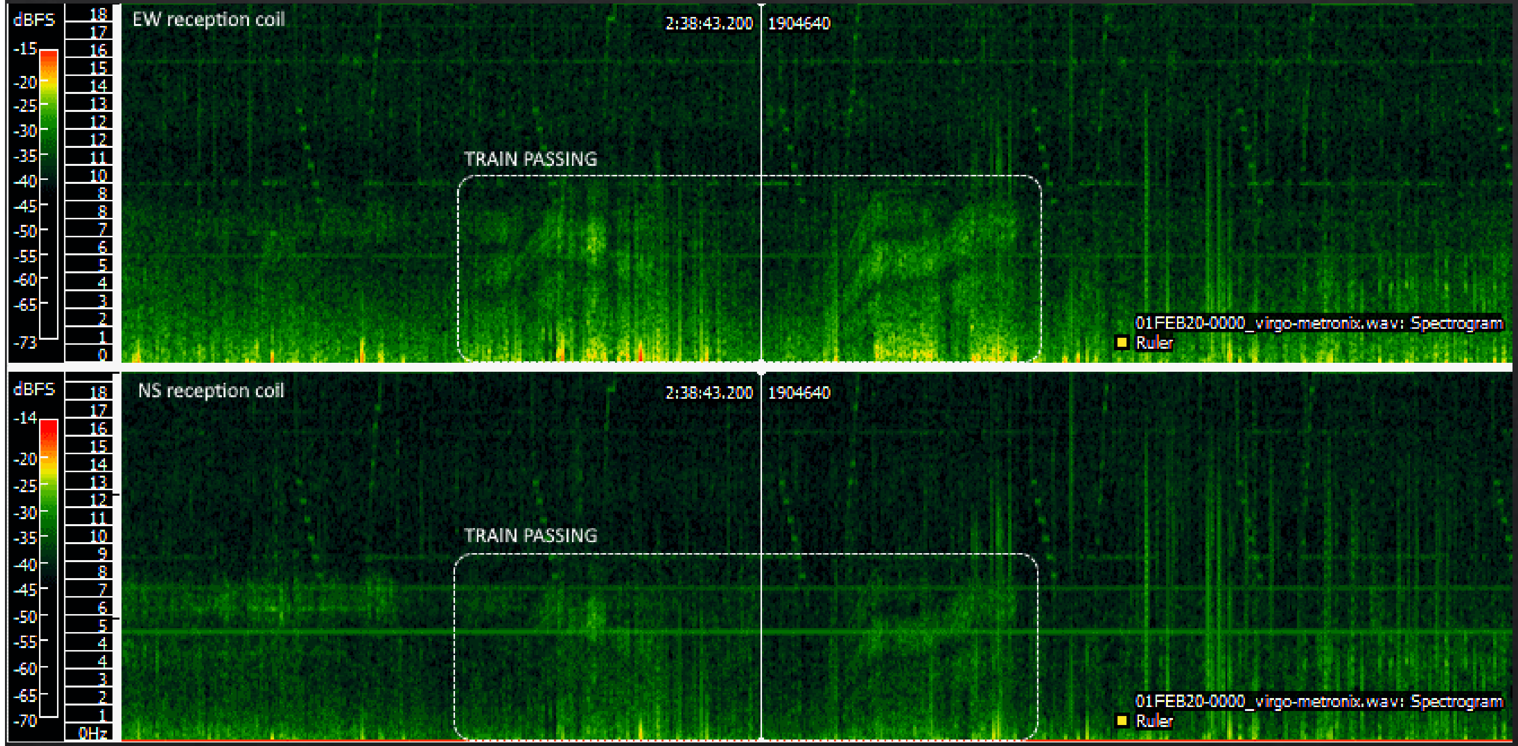
Mitigation
- Quantum-non-demolition
- Reduce decoherence
- Manipulate quantum state

Human-made EM Disturbances



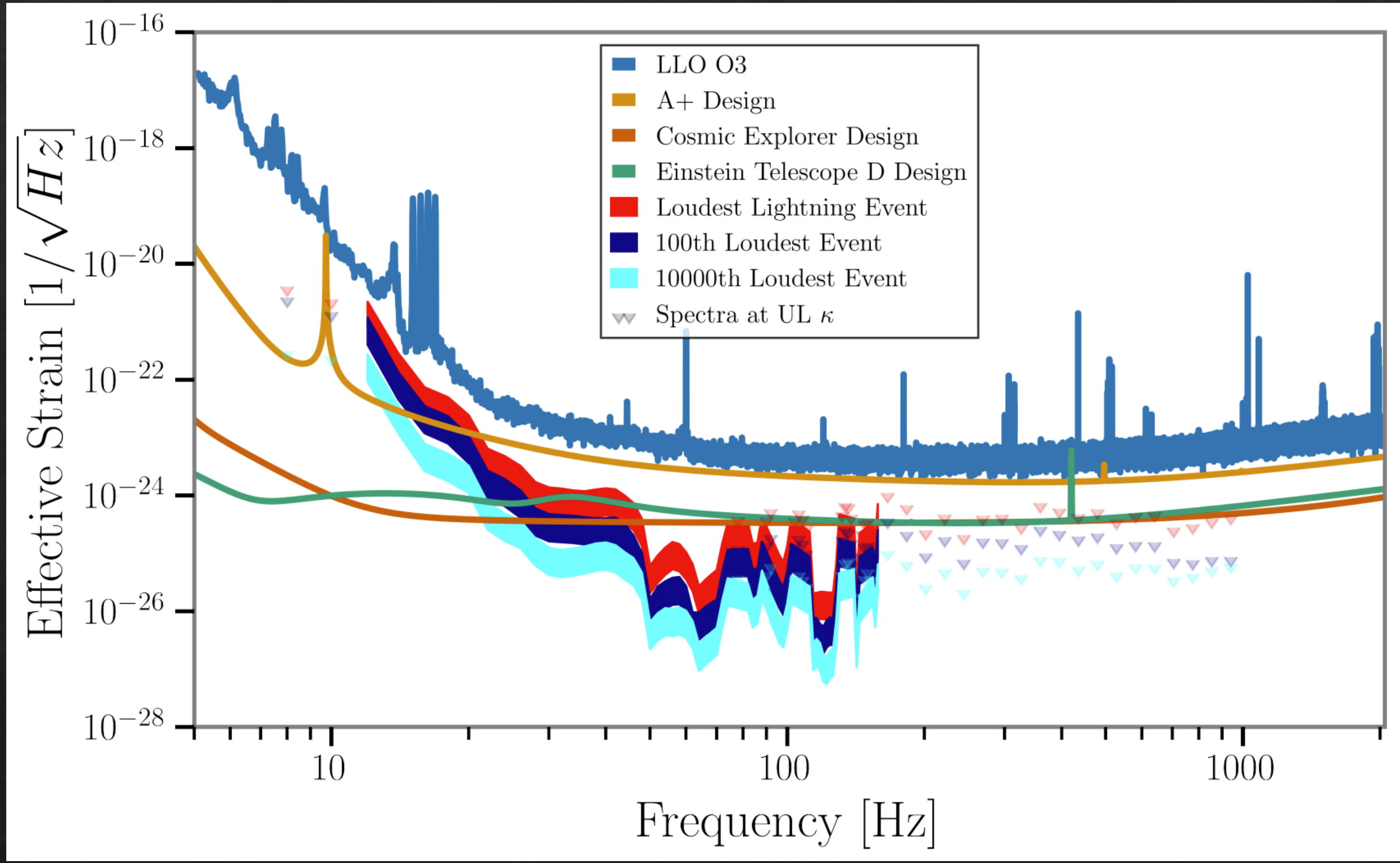
[Coughlin et al, 2016]

Measurement of magnetic field at Virgo

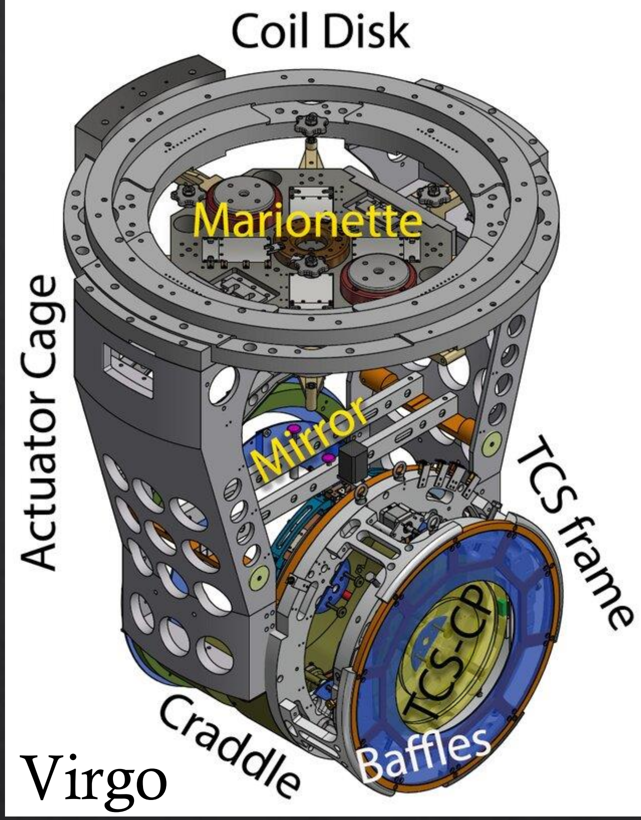


Magnetic Noise

Magnetic noise prediction for ET



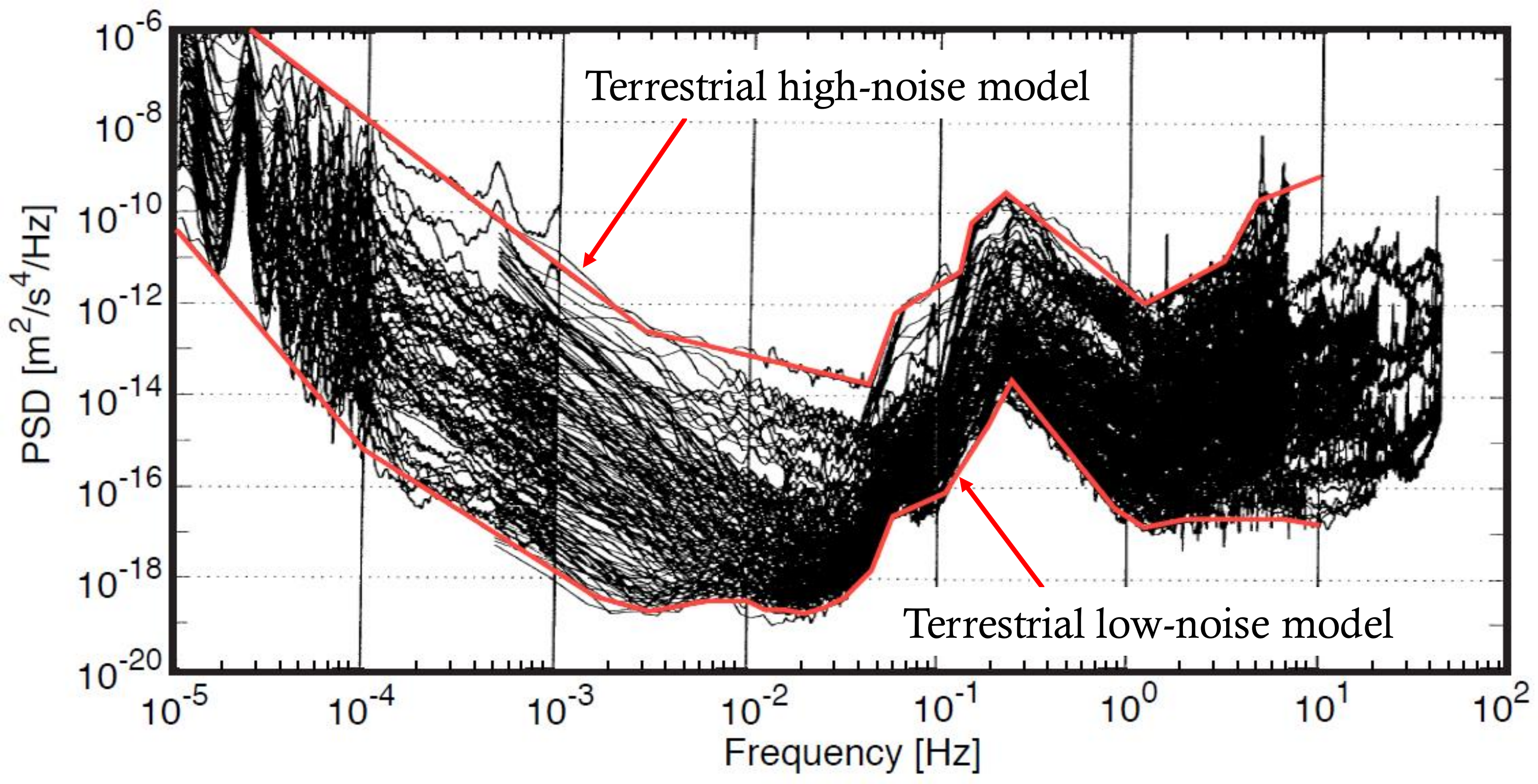
[Janssens et al, 2023](#)



Mitigation

a) Magnetic shielding
b) Reduction of magnetic susceptibility of certain components on the payload
c) Coherent noise cancellation

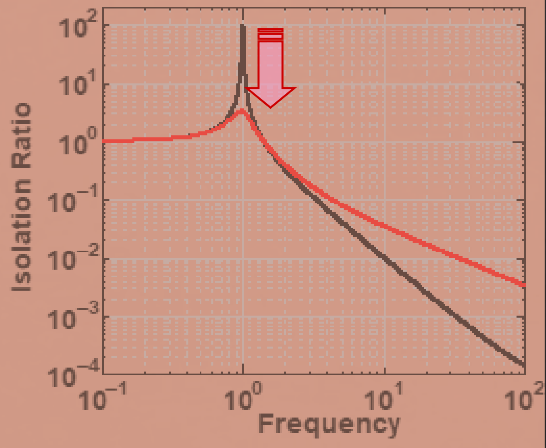
Seismic Background On Earth



Principles of Seismic Isolation

Damping

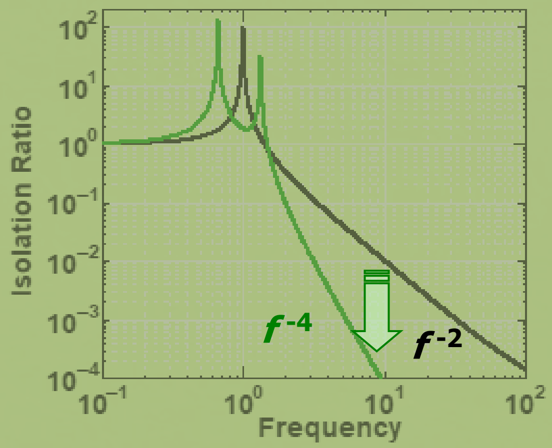
Lower peak height



Less isolation

Cascaded

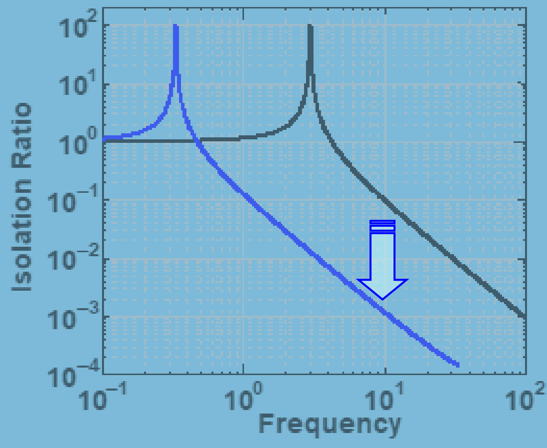
Steeper isolation curve



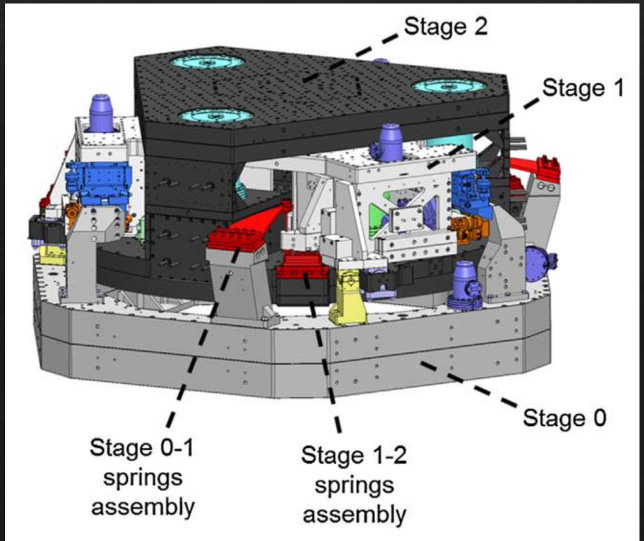
More peaks

Larger structure

Lower resonance frequency

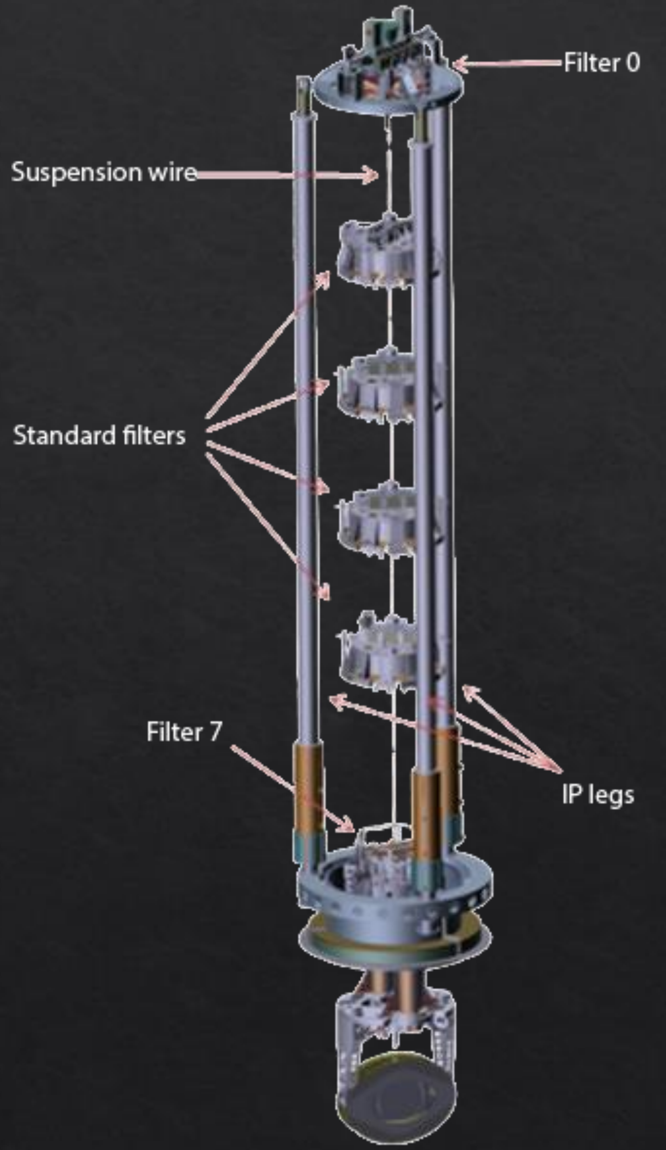


Difficult to realize

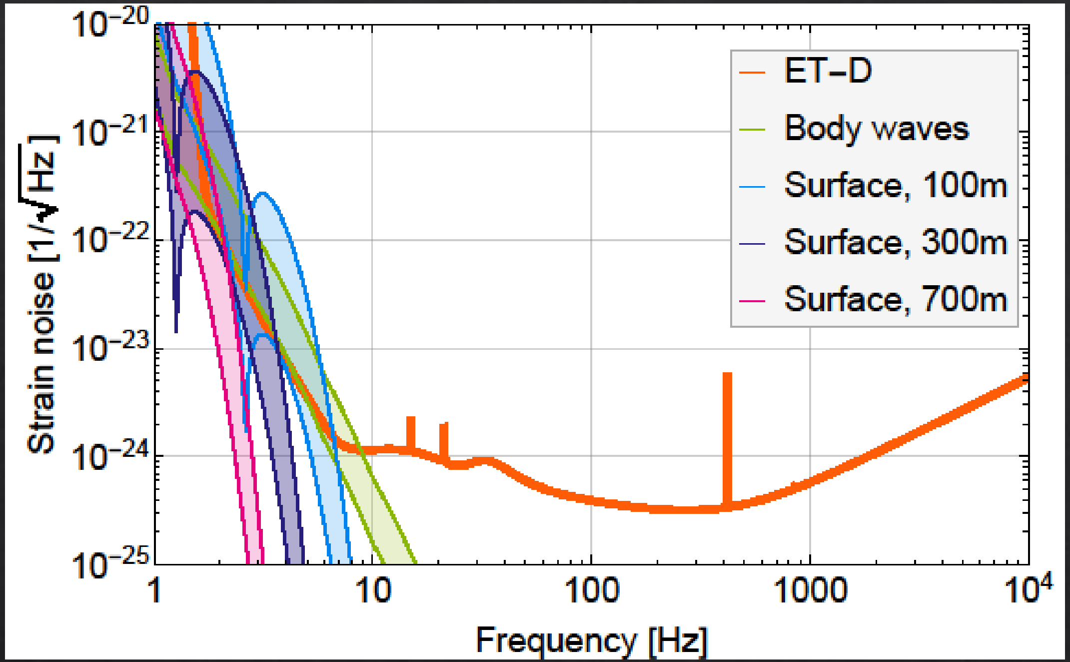


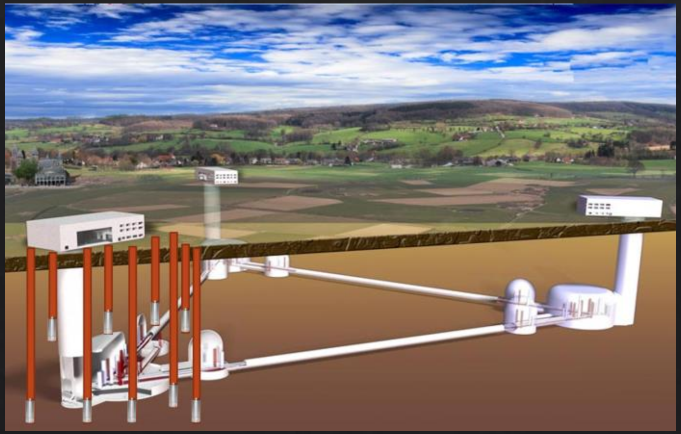
Active isolation:
LIGO BSC-ISI

Virgo Superattenuator



Seismic Newtonian Gravitational Noise





1) Density perturbation by a seismic field

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

2) Associated gravity perturbation

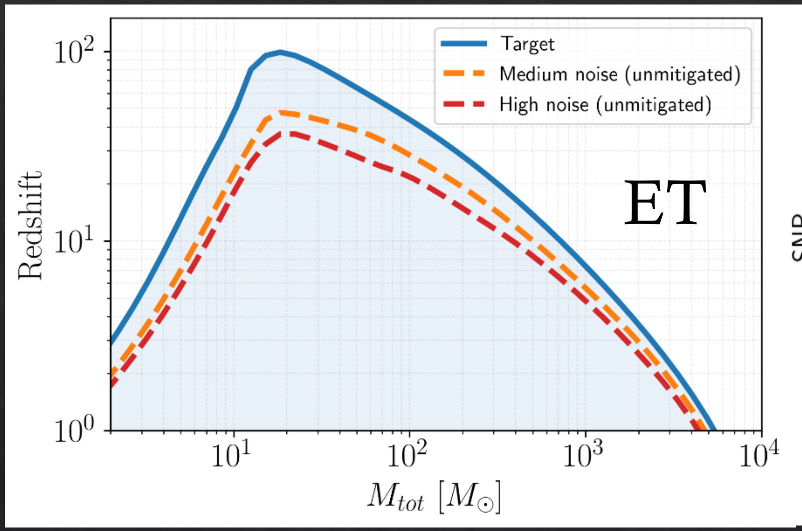
$$\delta\phi(\vec{r}_0,t) = G\int \mathrm{d}V\,\frac{\nabla\cdot\Big(\rho(\vec{r})\vec{\xi}(\vec{r},t)\Big)}{|\vec{r}-\vec{r}_0|}$$

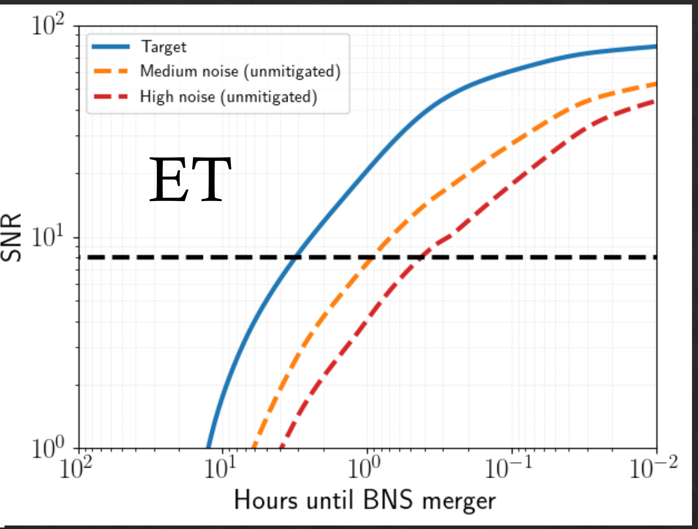
3) Solve for a specific seismic field

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

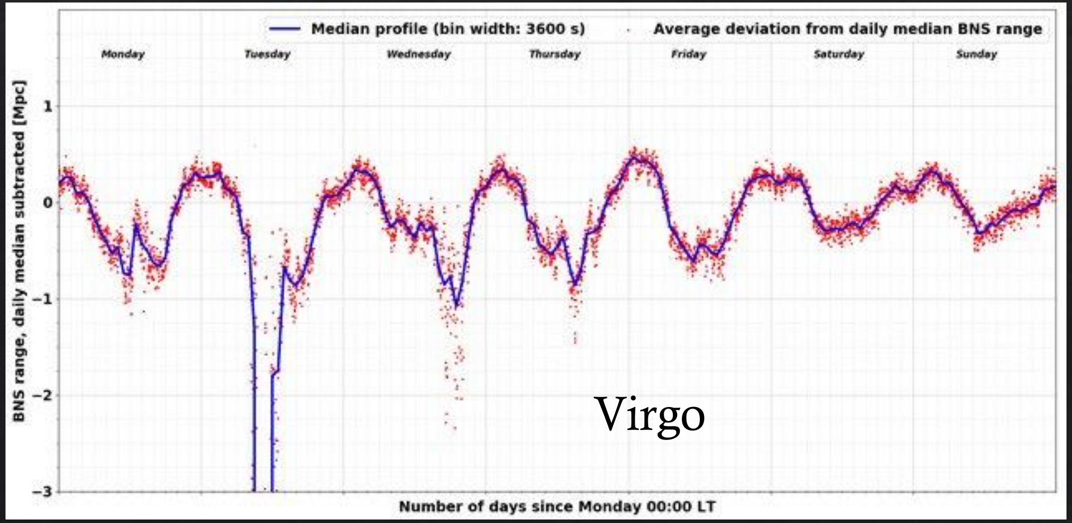
Impact of Elevated Low-f Noise

Varying levels of seismic Newtonian noise



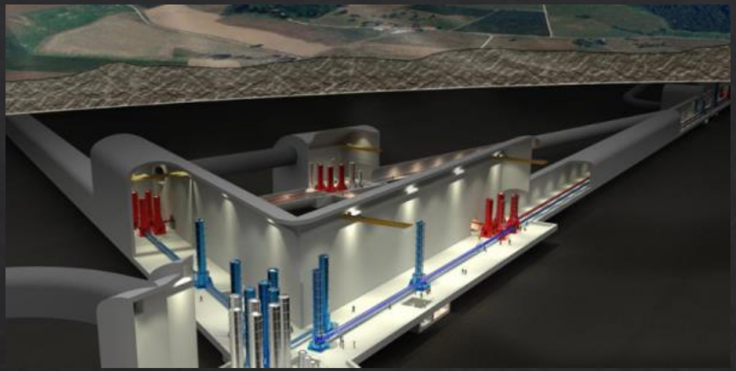


- Impacts detection range and parameter estimation
- Impacts pre-merger alert time



Diurnal variation of seismic noise causes diurnal variations of the detection range: demonstration of the continuous impact of the environment on detector performance

Infra, site, instrument, science: a consistent plan



underground

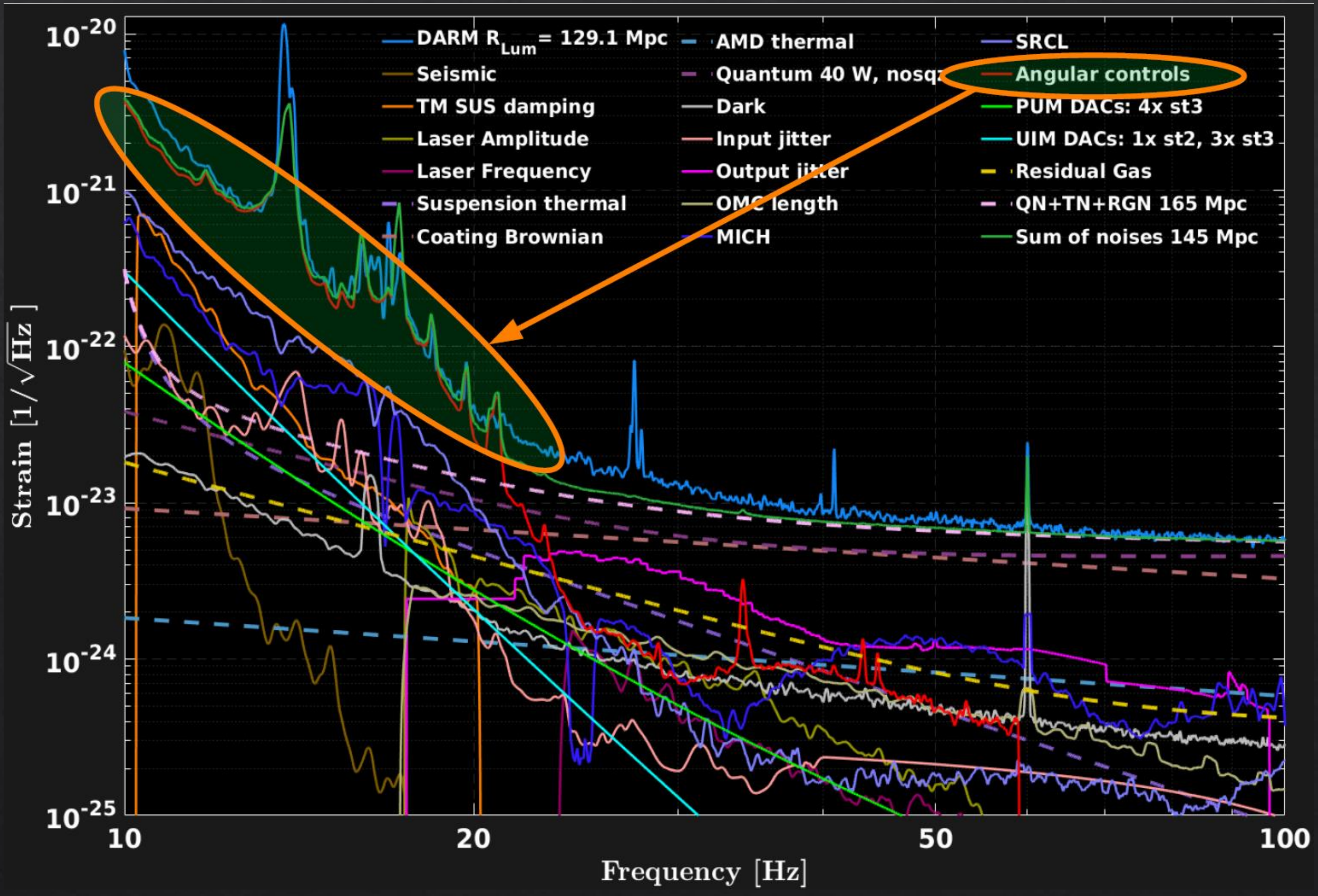
- lower environmental noise
- xylophone, cryogenics
- e.g., can observe higher-mass BBH and provide earlier warnings of BNS mergers

surface

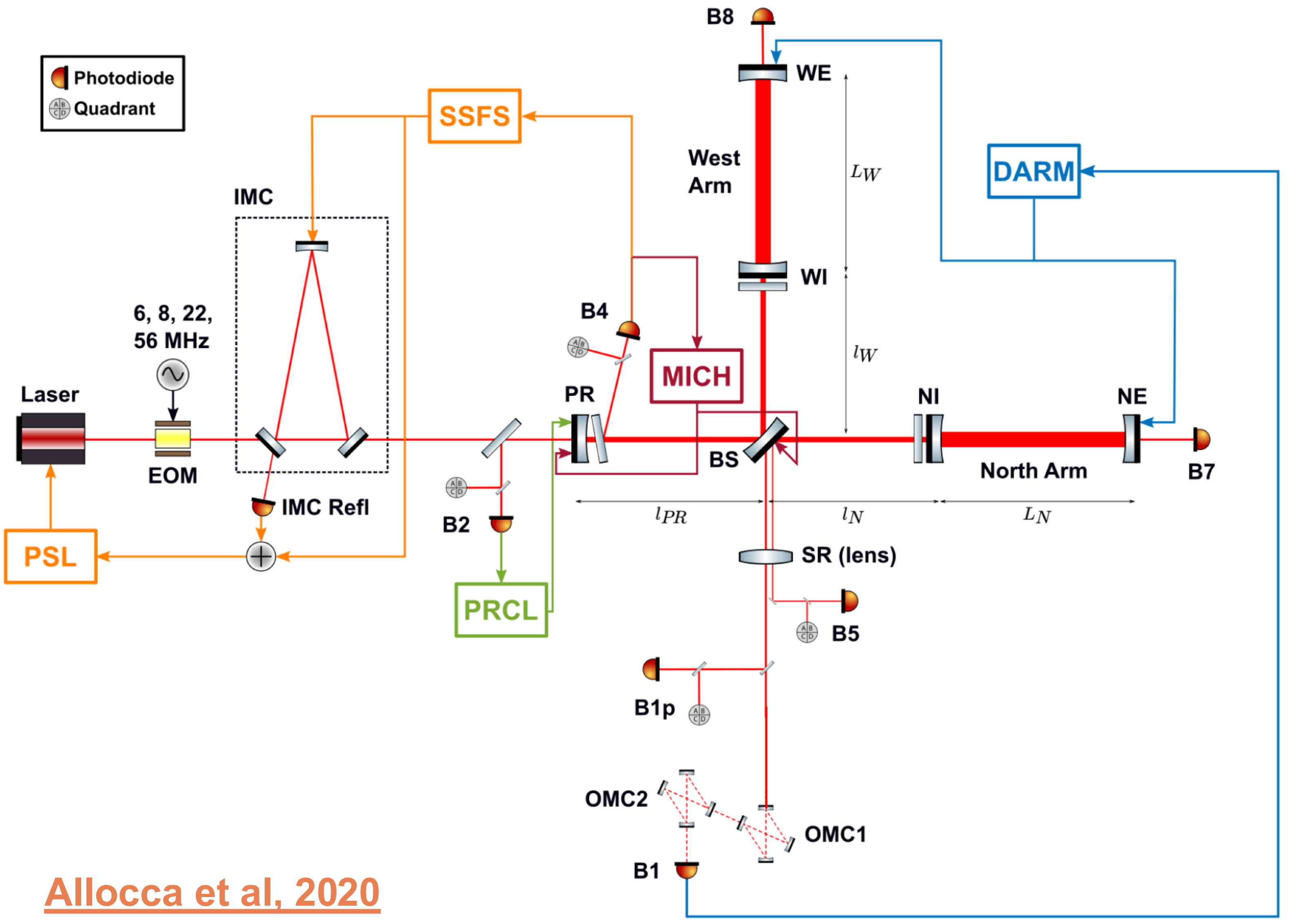
- higher environmental noise
- instrumental concept closer to LIGO detectors
- e.g., detects close to all BNS mergers in the observable universe

Noise from Detector Control

LIGO noise budget (2021)



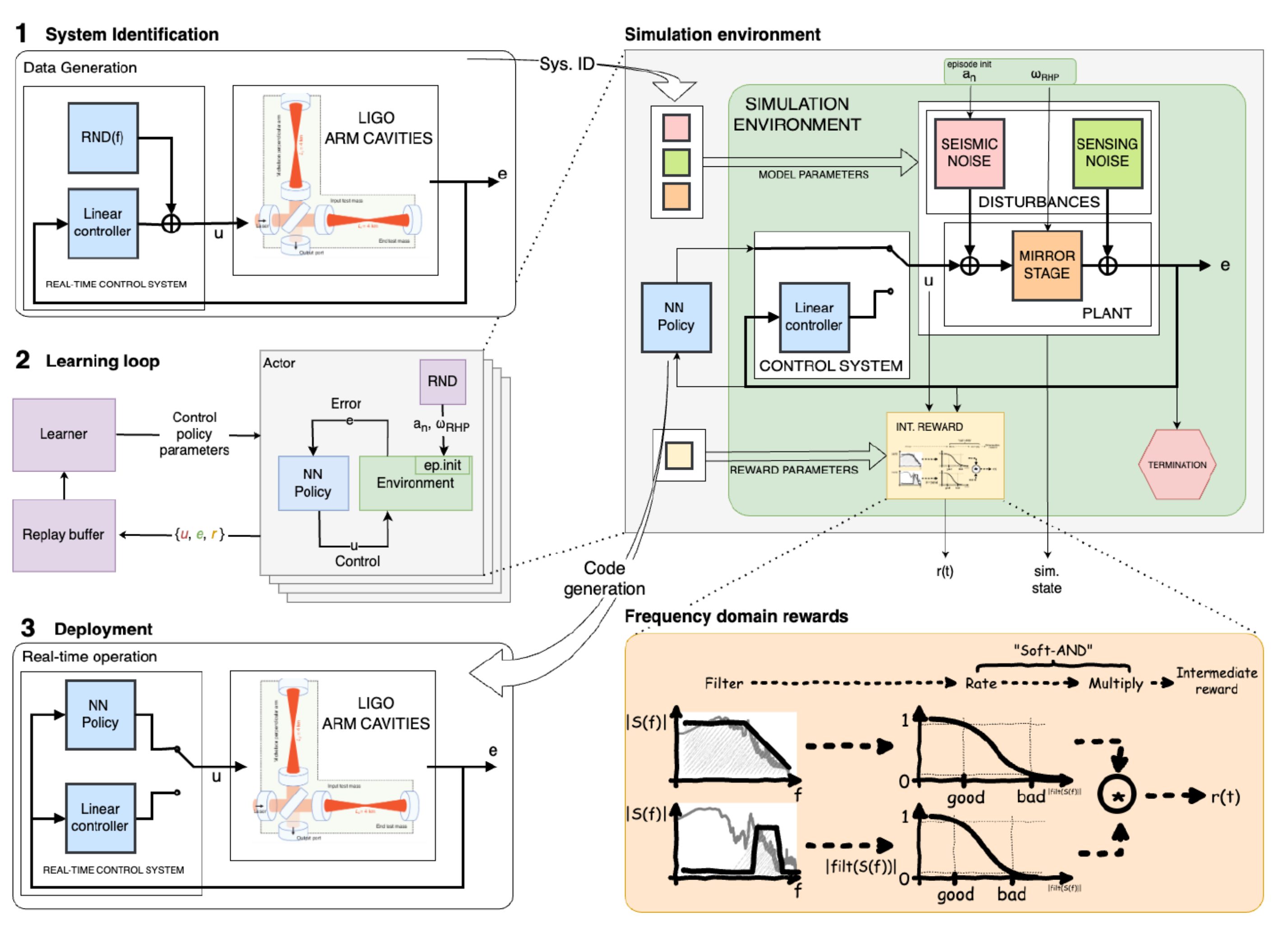
Detector Control



Allocca et al, 2020

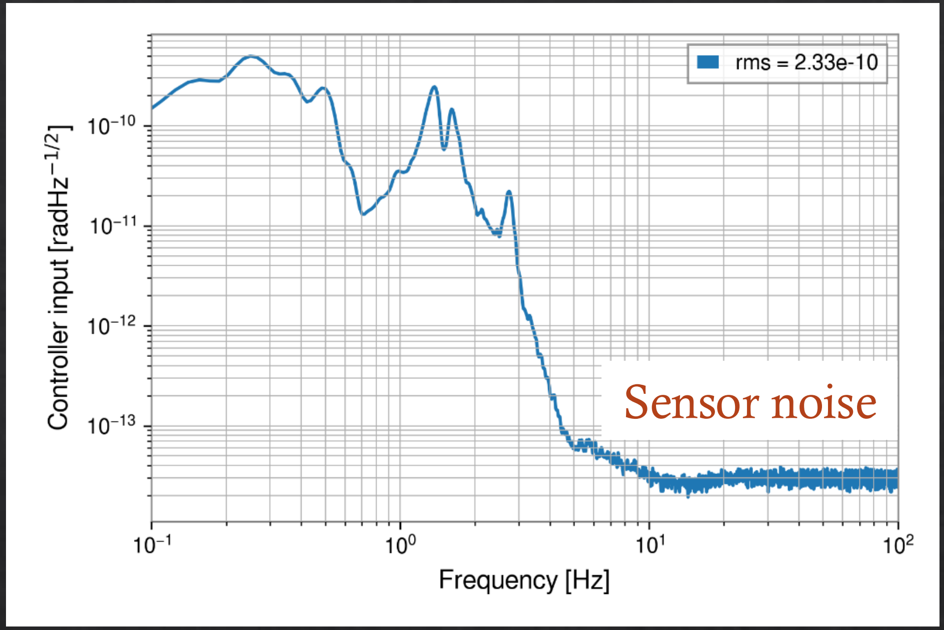
Angular Control

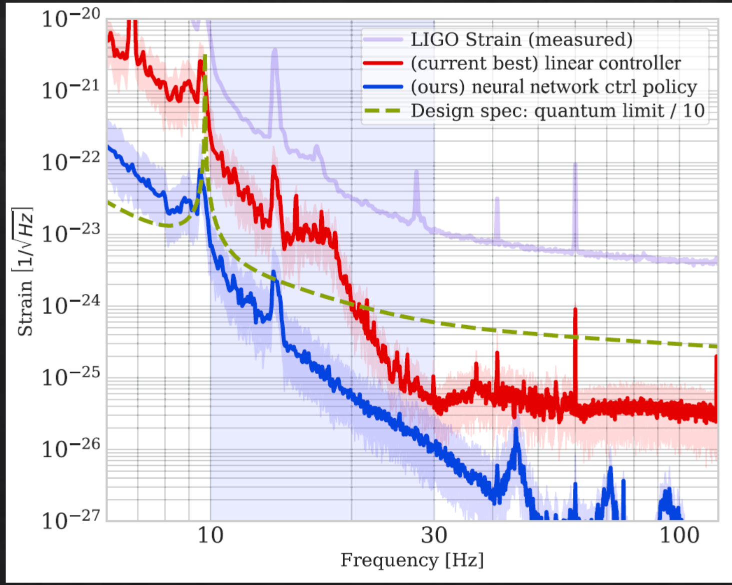
From conventional control to ML control



Science 389, 6764, 2025

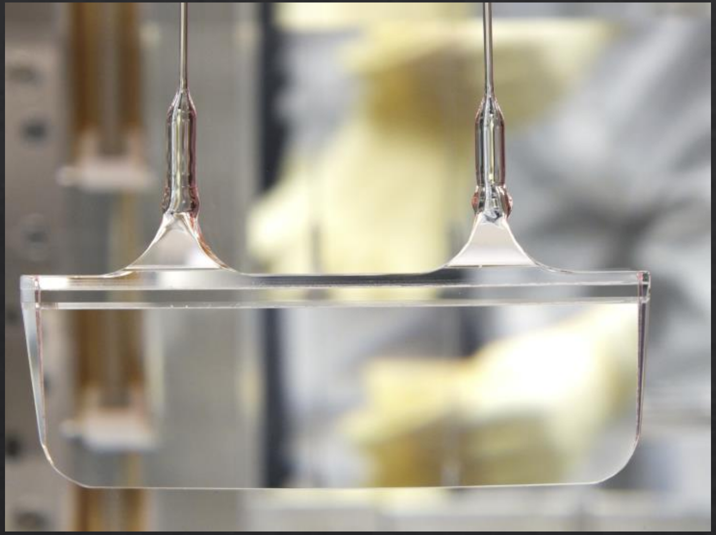
Measuring angular motion of a mirror

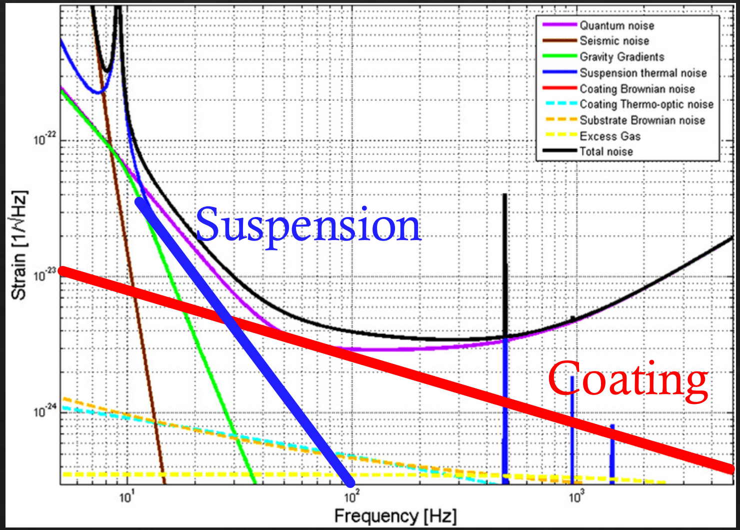




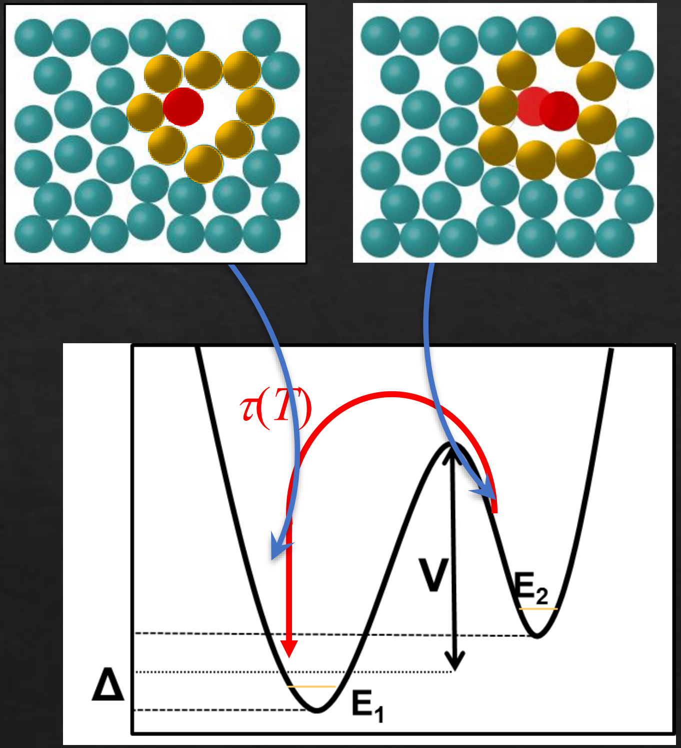
Thermal Noise

LIGO fibers welded to anchor on test mass





For example, reconfiguration of atoms in a solid

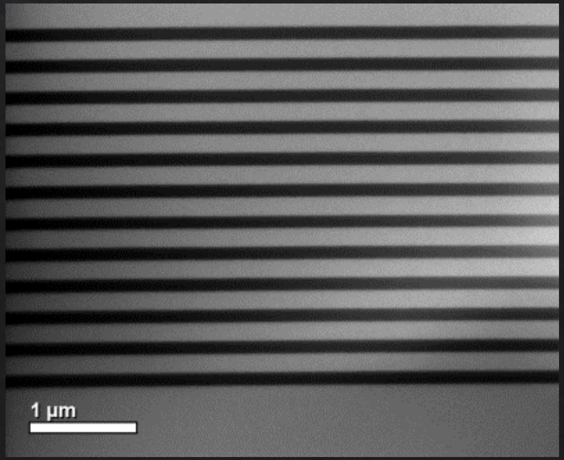


Fluctuation-dissipation theorem:
Thermal-noise spectrum proportional to dissipated power

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

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

Mirror coating stack



Quantum Noise

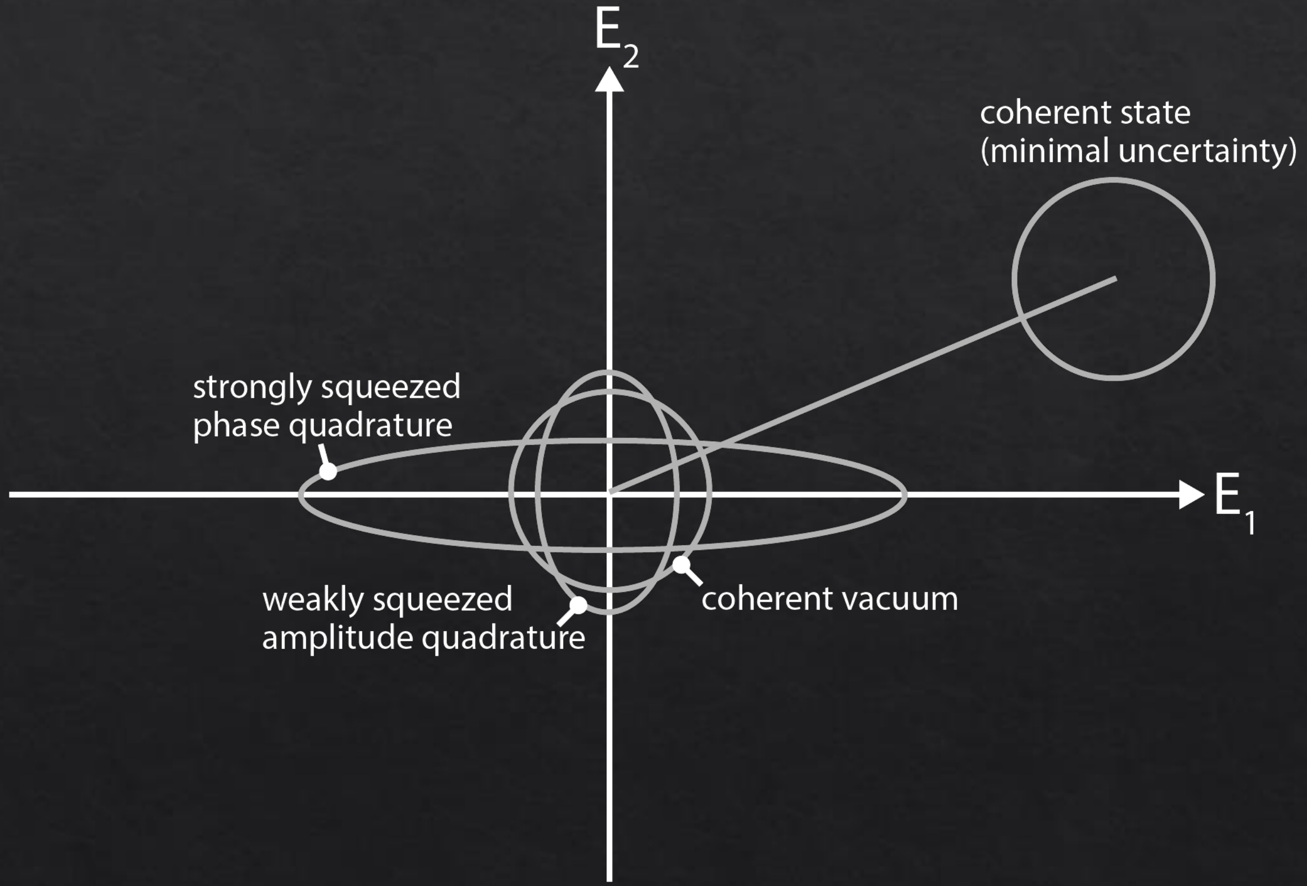
Heisenberg uncertainty principle

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

Fundamentally, we count photons

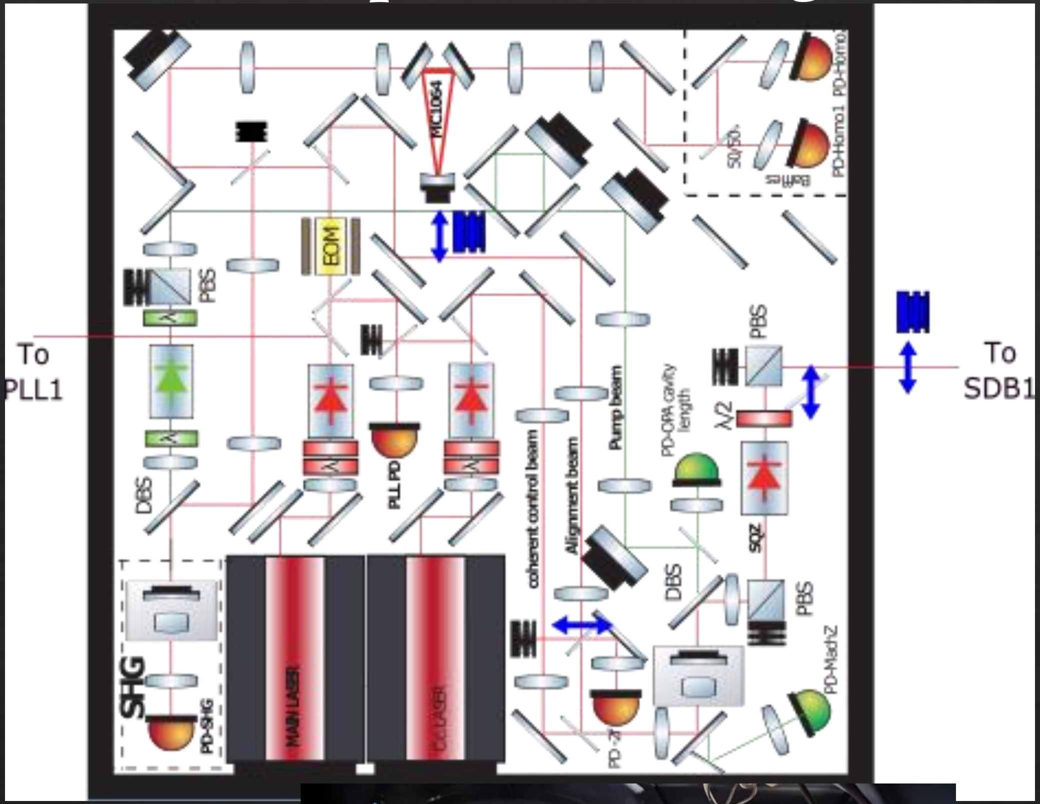
Quadratures of the EM field

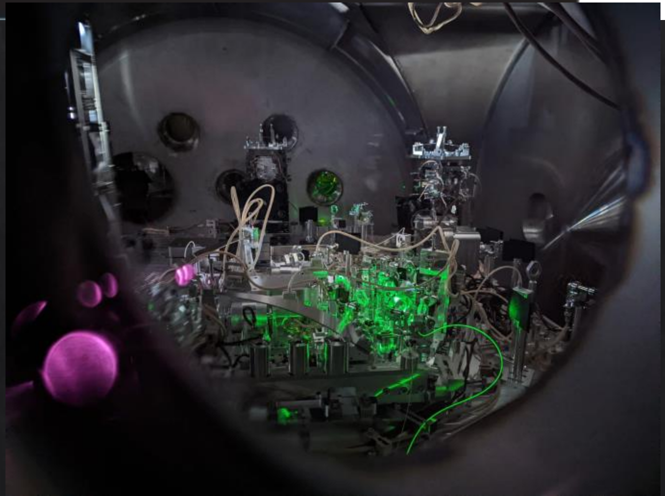
$$E(t) = E_1(t)\cos(\omega_0 t) + E_2(t)\sin(\omega_0 t)$$



Squeezed Light

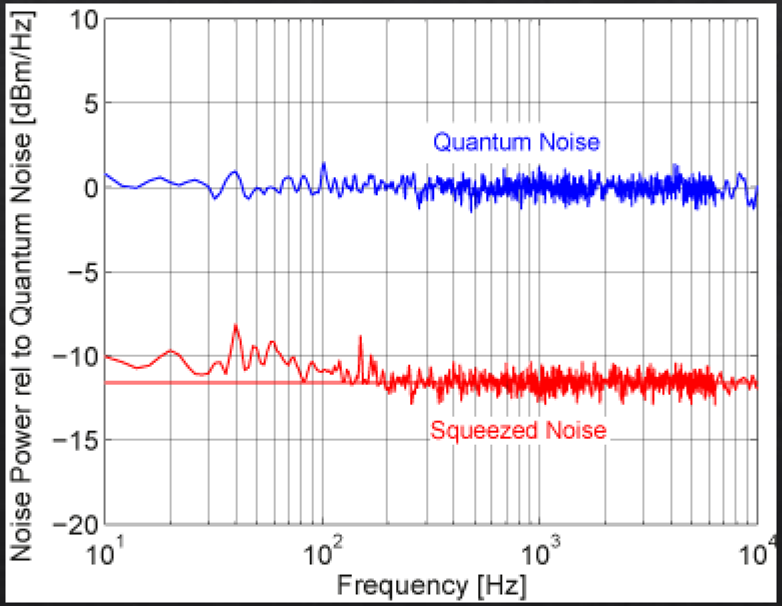
AEI squeezer at Virgo

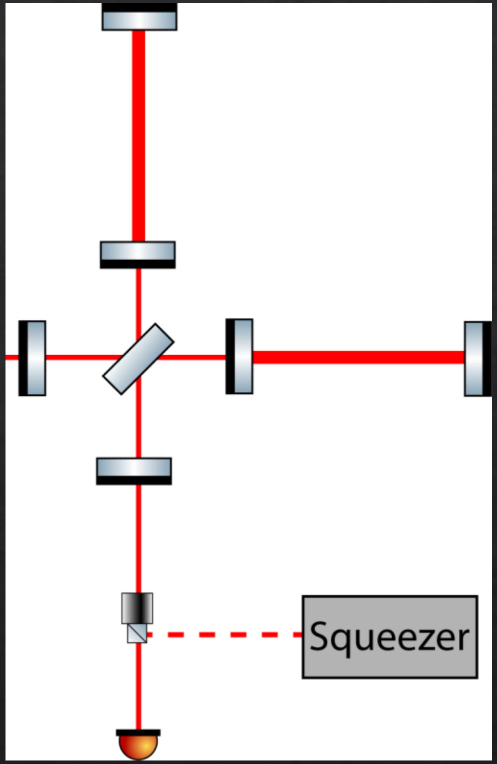




LIGO squeezer

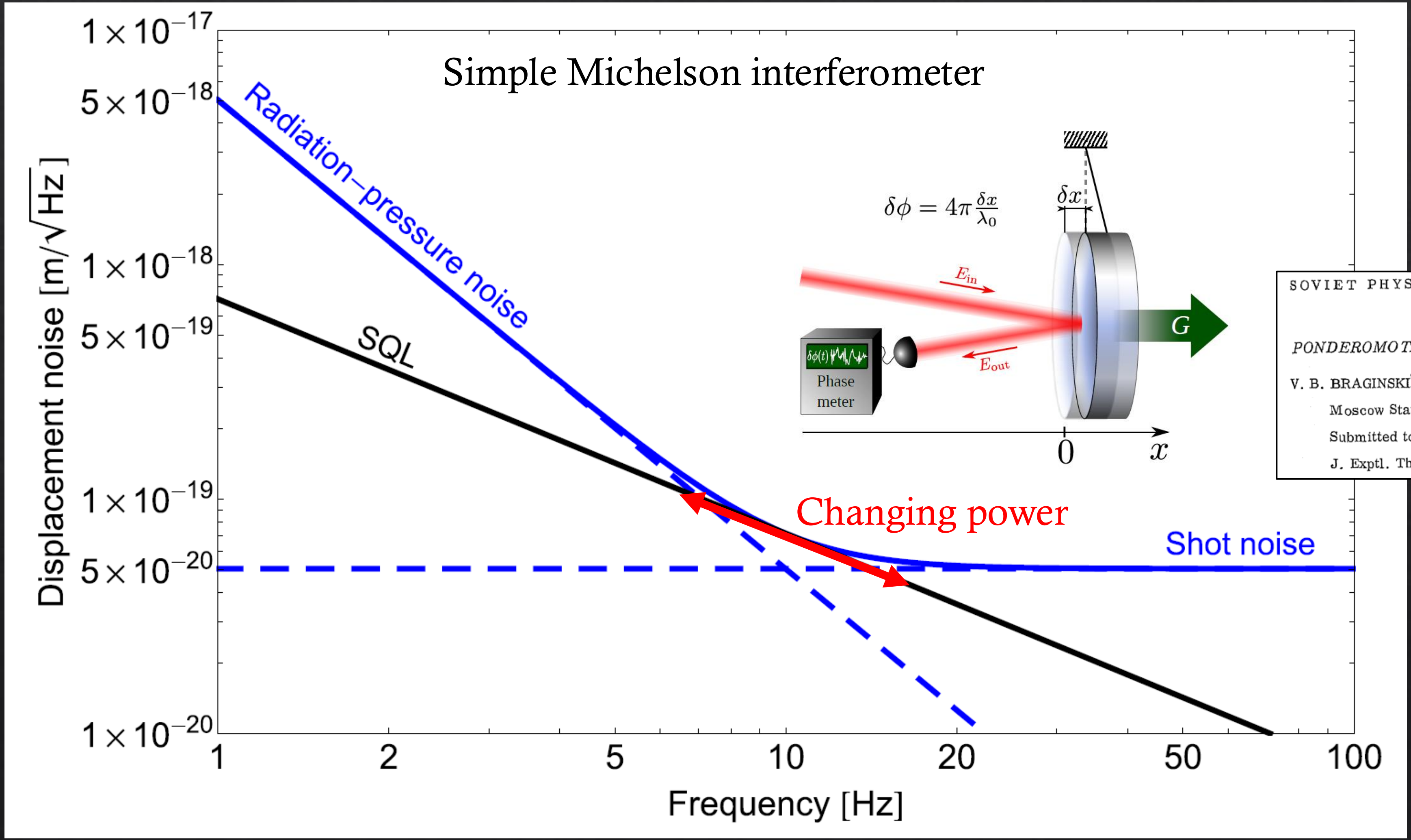
Quantum noise reduction at the output of a squeezer

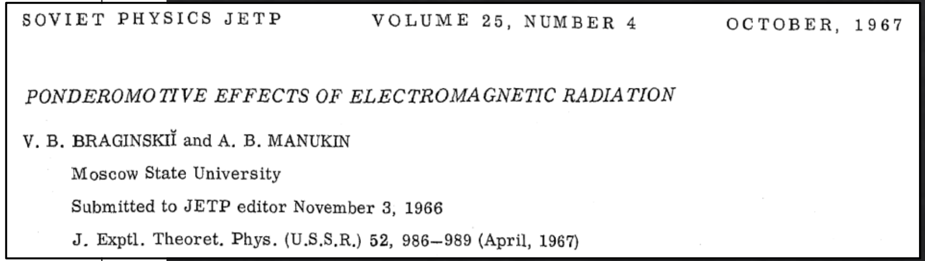




Optical losses reduce the gain from squeezing

Standard Quantum Limit




SOVIET PHYSICS JETP VOLUME 25, NUMBER 4 OCTOBER, 1967

PONDEROMOTIVE EFFECTS OF ELECTROMAGNETIC RADIATION

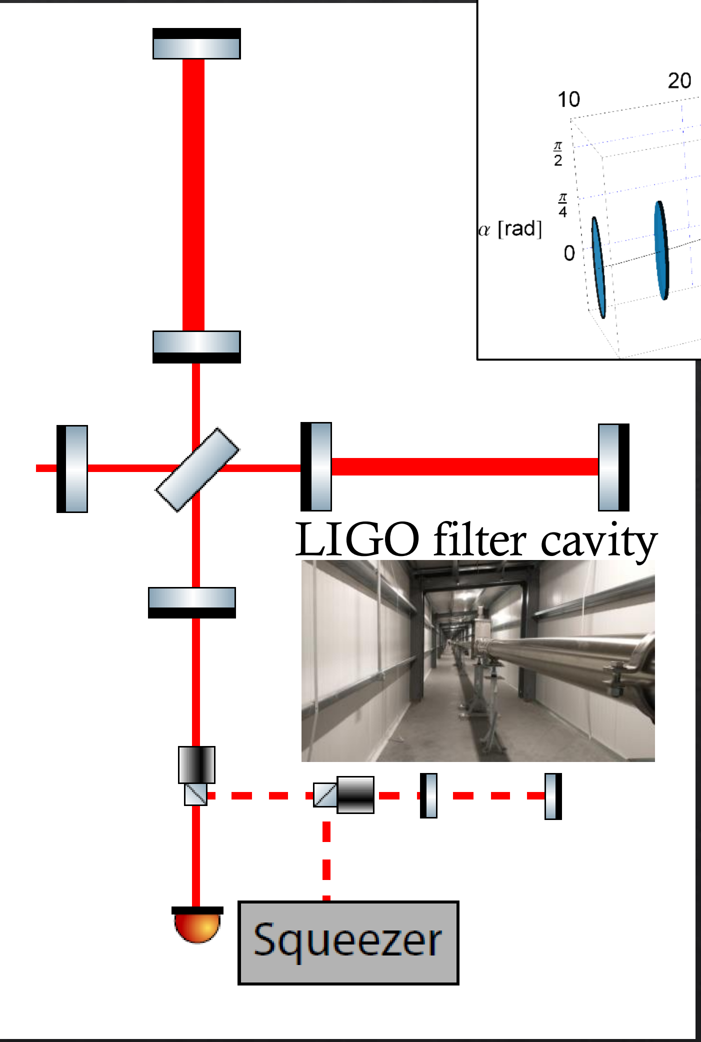
V. B. BRAGINSKIĬ and A. B. MANUKIN

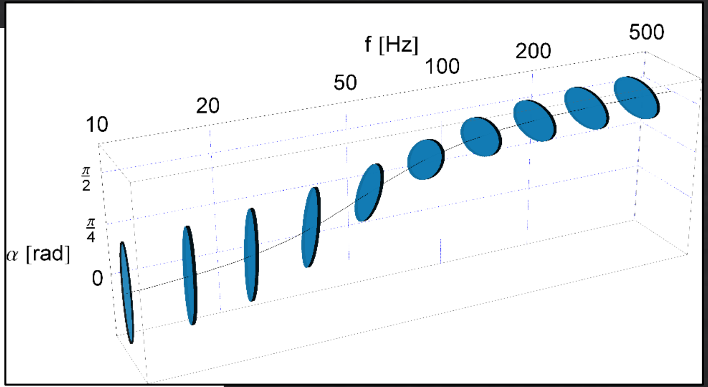
Moscow State University

Submitted to JETP editor November 3, 1966

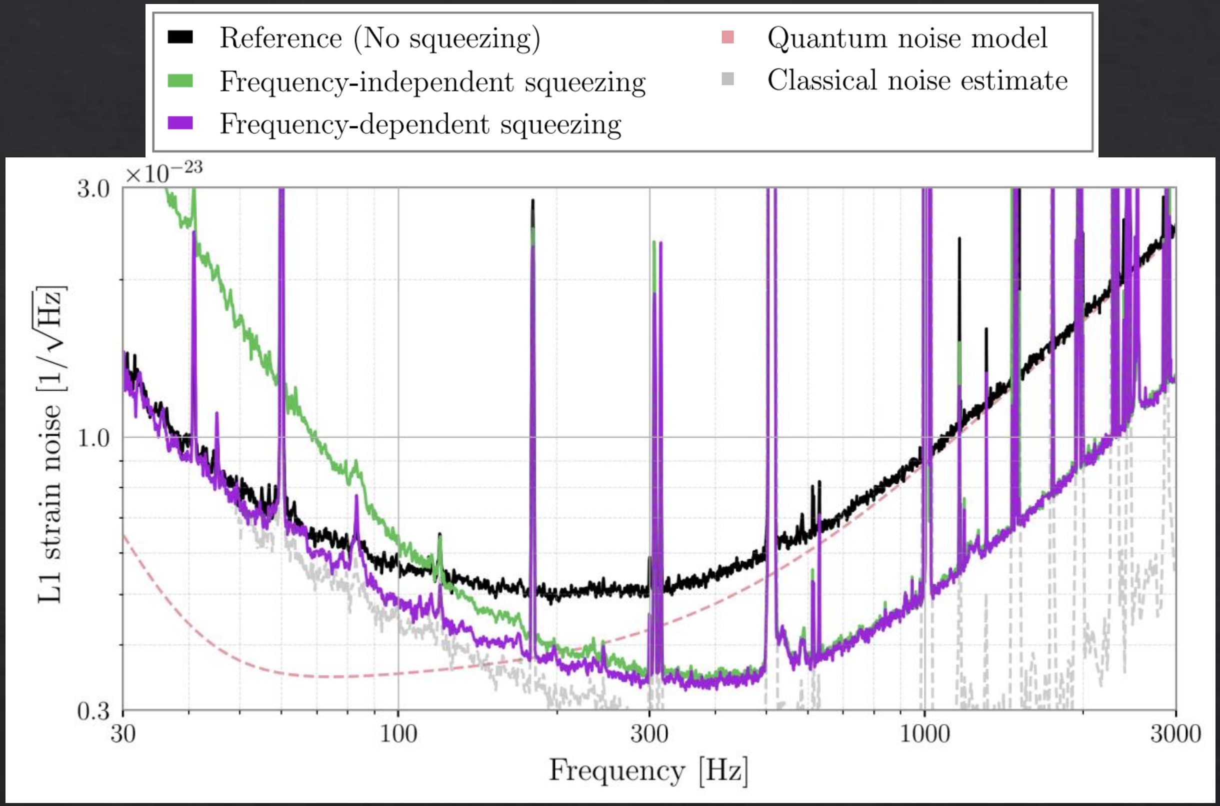
J. Exptl. Theoret. Phys. (U.S.S.R.) 52, 986–989 (April, 1967)

Frequency-dependent Squeezing





Rep. Prog. Phys. 82, 016905, 2019



PRX 13, 041021, 2023

- Requires long filter cavity
- Properties of the filter must be tuned to laser power inside interferometer
- More than one filter cavity is needed if one uses detuned signal extraction