Terrestrial GW Detectors, present and future

David Shoemaker

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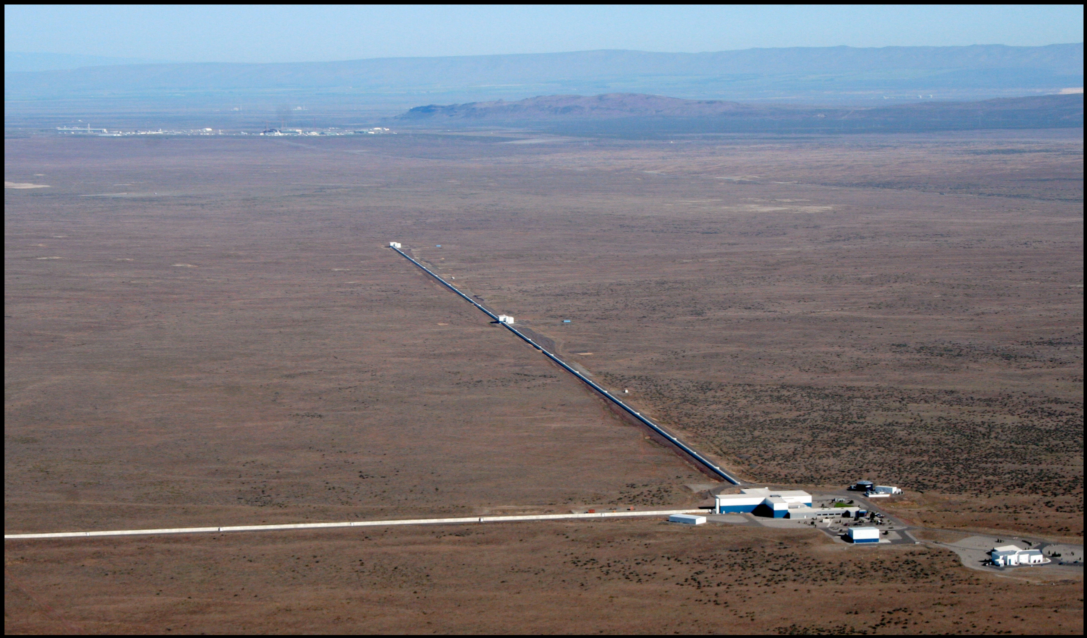
Slides from many CE and LIGO Collaborators!



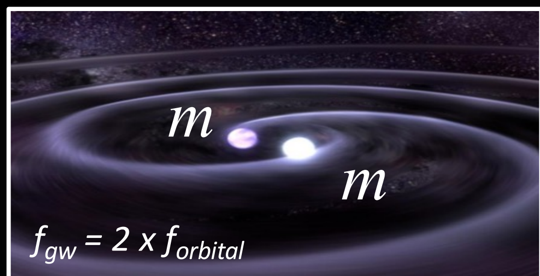
GWI 2025 Colloquium

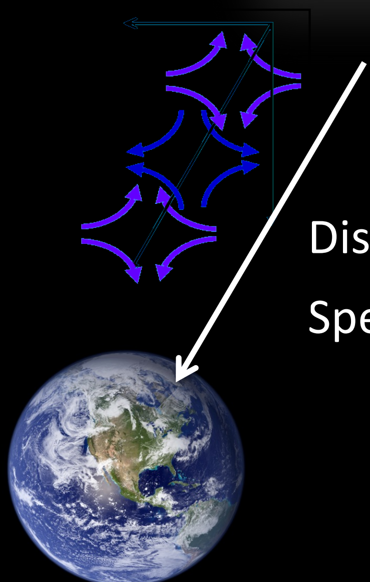
3 June 2025

CE-G2500043

Properties of GR's Gravitational Waves

Binary Coalescence of two compact objects





Distance r

Speed c

GW generation:
lowest order radiation is quadrupole

metric perturbation

$$h = \frac{2\,G}{c^4\,r}\,\ddot{I}$$

quadrupole moment

Two masses m in a circular orbit at a distance r create a periodic strain h in space

$$h = \frac{2\,G\,m}{c^4\,r}\,(2\pi f_{gw})^{2/3}$$

About once a week,
a wave passes with this characteristic strain:

$$1.5 \times 10^{-21}\left(\frac{m}{30 M_\odot}\right)\left(\frac{400\,\mathrm{Mpc}}{r}\right)\left(\frac{f_{gw}}{50\,\mathrm{Hz}}\right)^{2/3}$$

Gravitational Wave Properties

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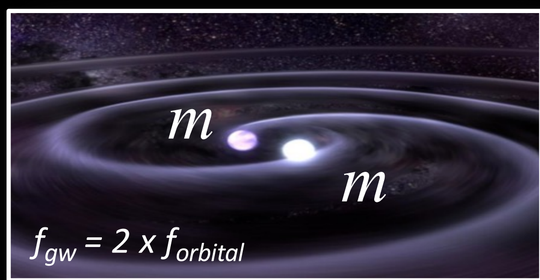

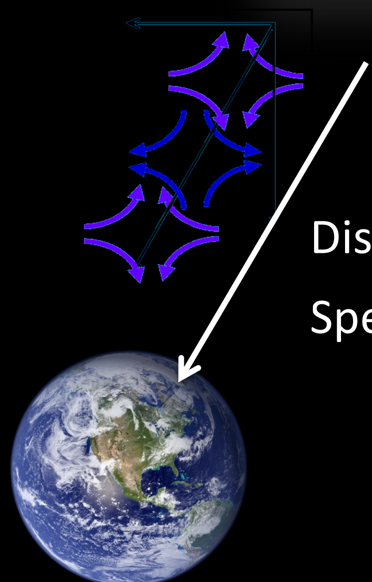

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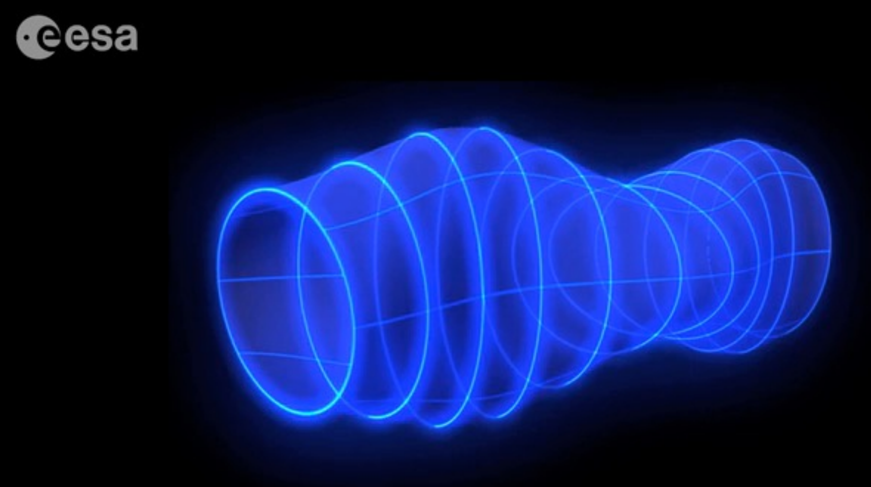
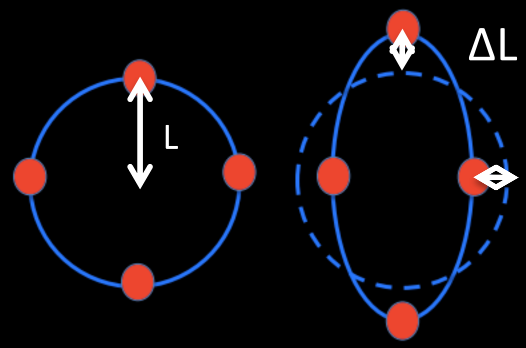
Stretching and squeezing of space-time





Amplitude of the gravitational wave strain is $h = \Delta L/L$

$\Delta L = h\, L$

Big L makes ΔL easier to measure; current detectors have $L = 4$ km, so from our two-mass example $\sim 10^{-21} \times \sim 10^{3} = \sim 10^{-18}$ m

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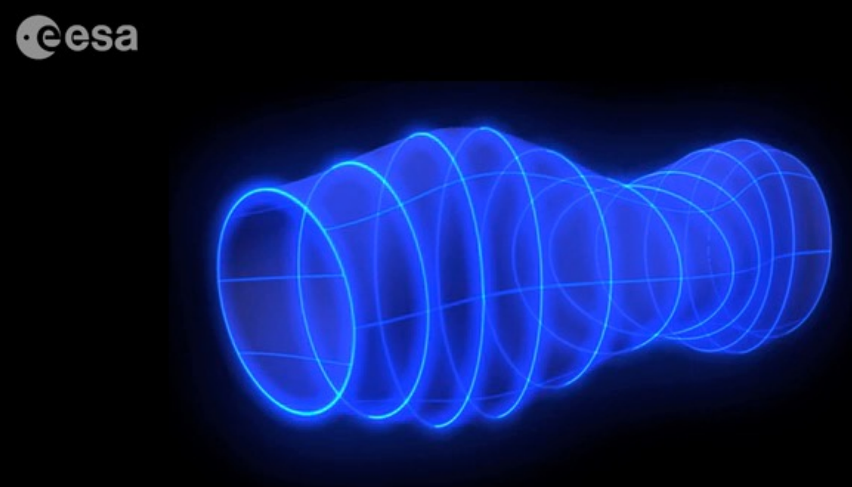

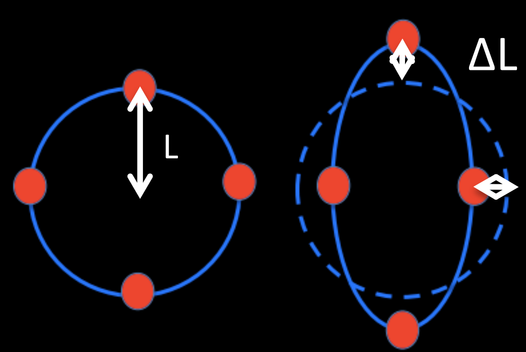

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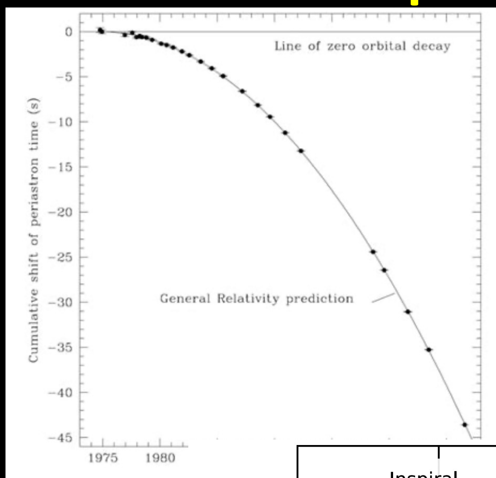
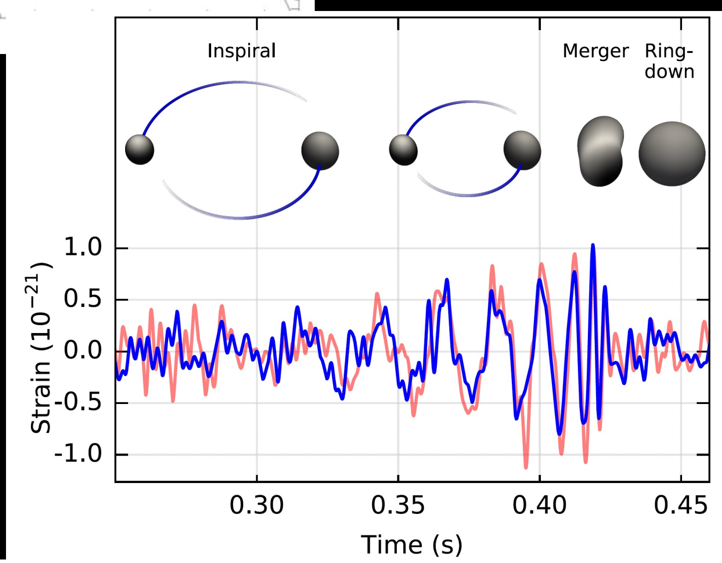
On September 14, 2015 at 09:50:45 UTC

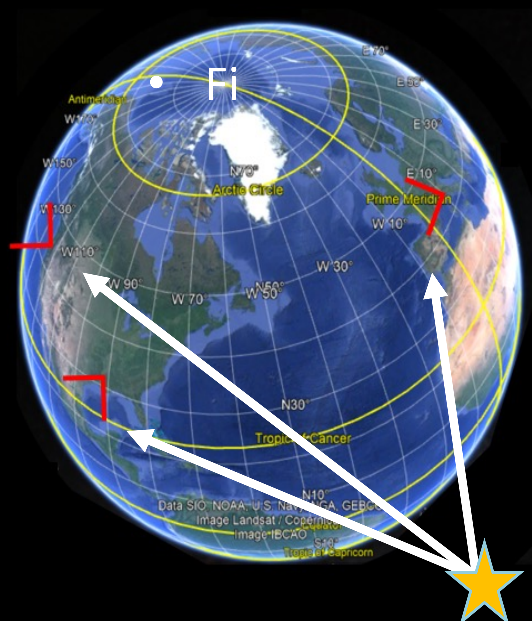




- First direct observation of the time-varying strain due to GWs
  - Hulse and Taylor deserved their Nobel!
- Two black holes, 36 $M_\odot$ and 29 $M_\odot$, merged merged 1.3 billion years ago to form a single black hole of 62 $M_\odot$
- As they merged, the equivalent of 3 $M_\odot$ was emitted in GW in ~0.2 sec
- Was seen in the two **LIGO** detectors separated by 3000 km, with a time difference consistent with the speed of light

GW150914

The VIRGO detector, located in Italy, joined LIGO in August 2017 – and we observed a Binary Neutron Star coalescence a few weeks later

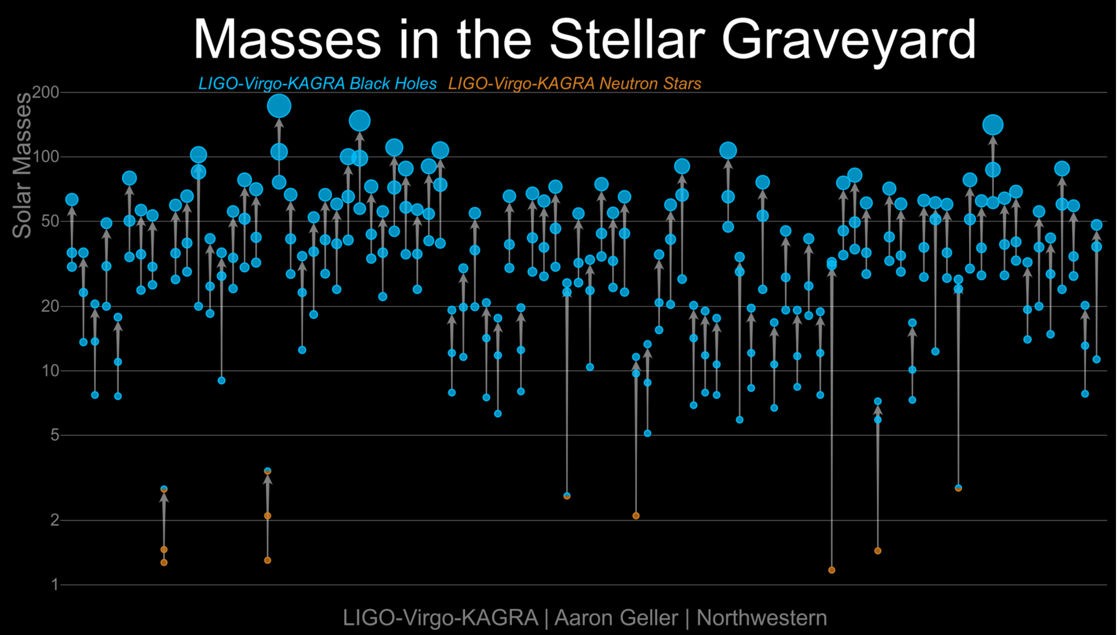


GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. LVC (2017) PRL 119, 161101

- Made first joint GW-EM source observation
- Linked short GRBs, binary neutron stars, kilonovae
- Independently measured the local Hubble constant
- Measured the speed of gravitational-wave propagation
- Made initial constraints on the neutron star equation of state
- Constrained the rate of binary neutron star mergers in the local Universe (and thus their production of heavy metals)

Astrophysics, Cosmology, Testing GR…

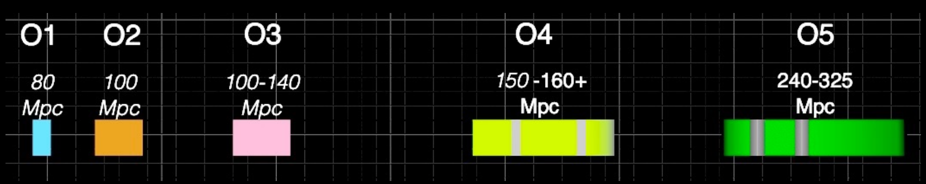
- Binaries: population studies of BH, NS
- Hubble tension resolution,
  other measures of large-scale space-time
- Nuclear physics – Neutron-star EOS
- Searches for deviations from GR
- Sub-solar BH of primordial origin
- Searches for Exotic matter
- Sources other than Binaries
  - Supernovae
  - Pulsars
  - Strings, Cusps, et alia
  - Stochastic backgrounds,
    both astrophysical and cosmological
- **Just getting started**

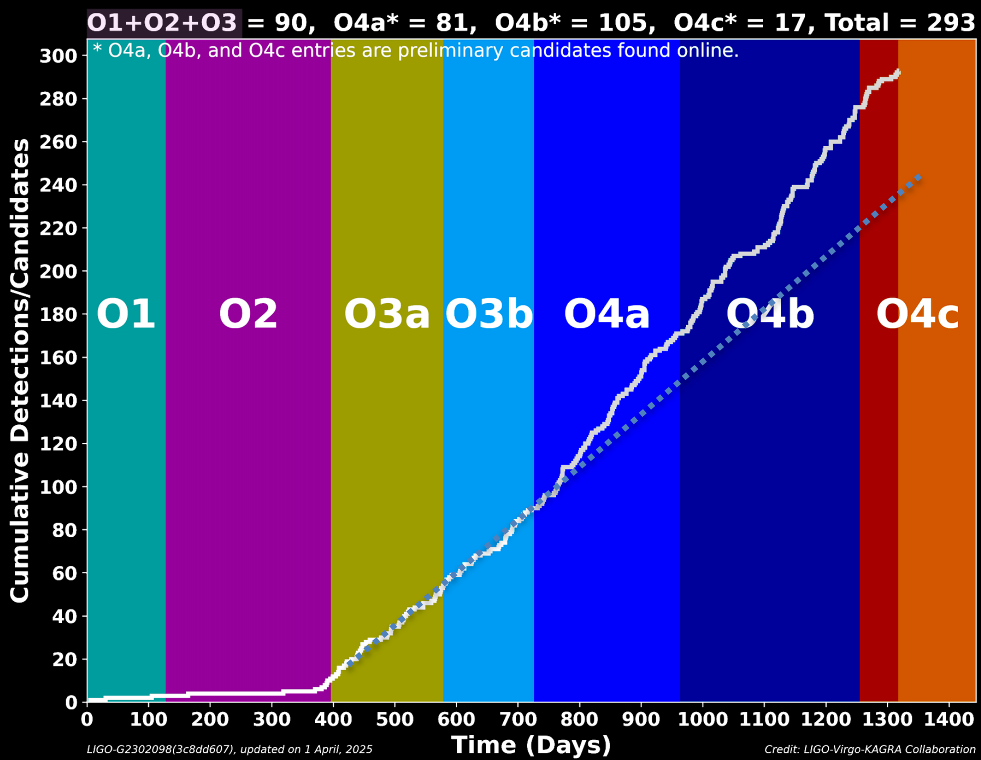


Sensitivity improvements boost signal rate

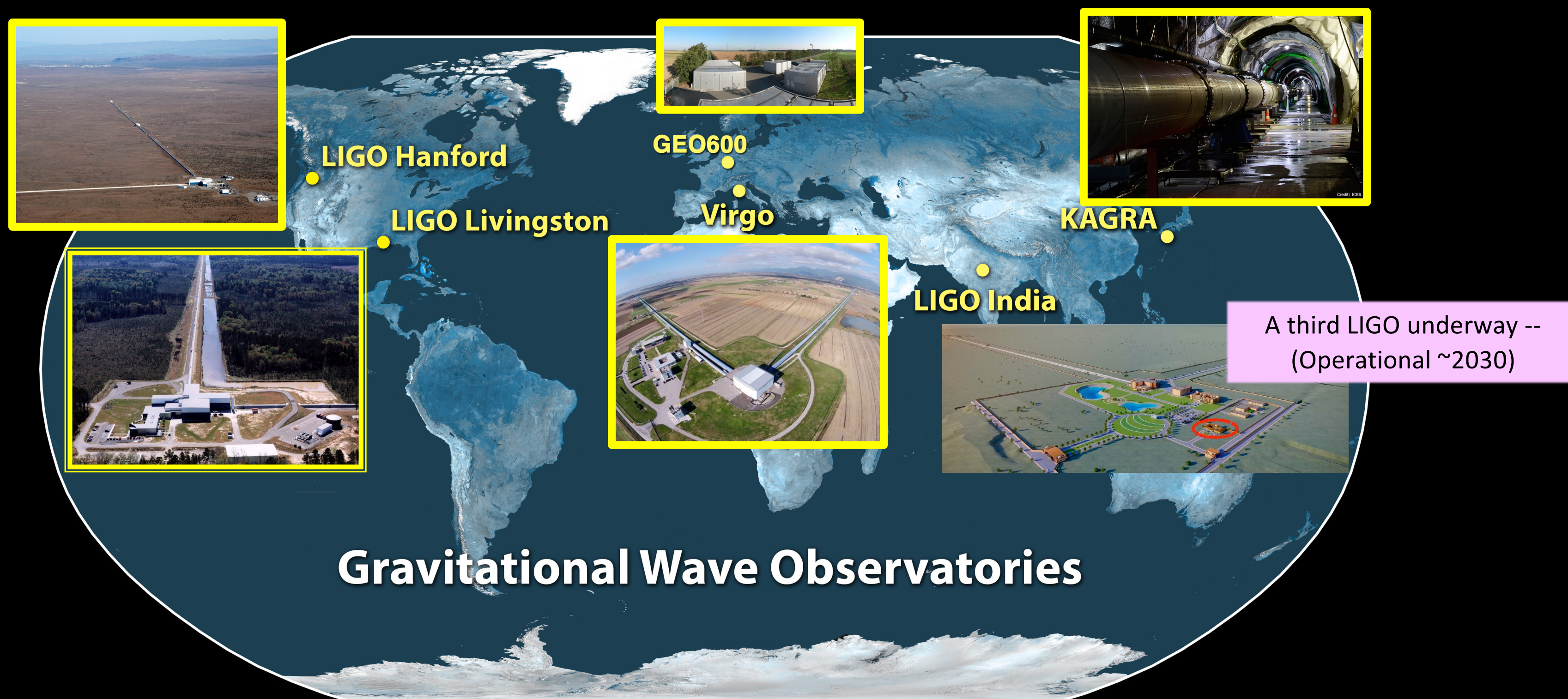
- Volume of space – and thus # of target sources – grows as ~(sensitivity)^3

- There are gaps for the upgrades… but so far we make up for it



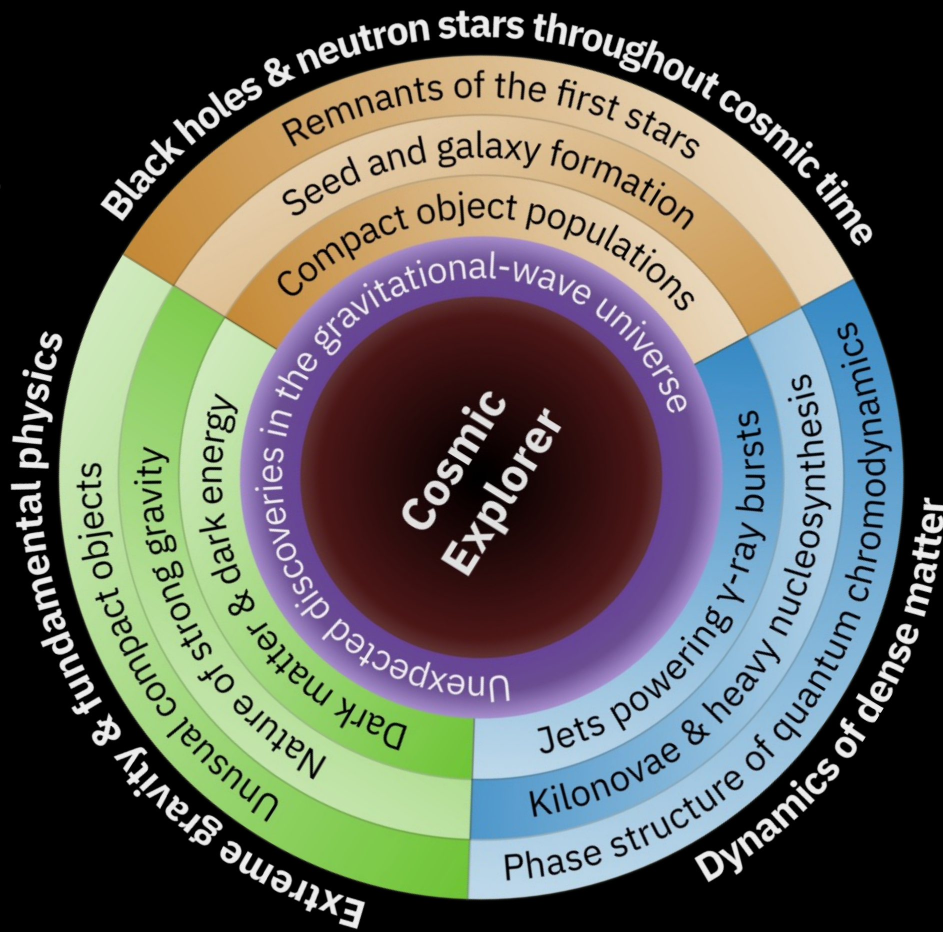


The current ground-based gravitational-wave world-wide network



What could we do with 10x better GW detectors?

- Event rate boost
  (10x sensitivity → 10^5 sources per year)
- Increases resolution of waveforms
  – tests of GR, BH Ringdown
  – Precise spin etc. measurements
- Wider bandwidth to expose Neutron star coalescence
  – dynamics of dense matter
- More Multi-Messenger Astrophysics
  – Where are those neutron stars….



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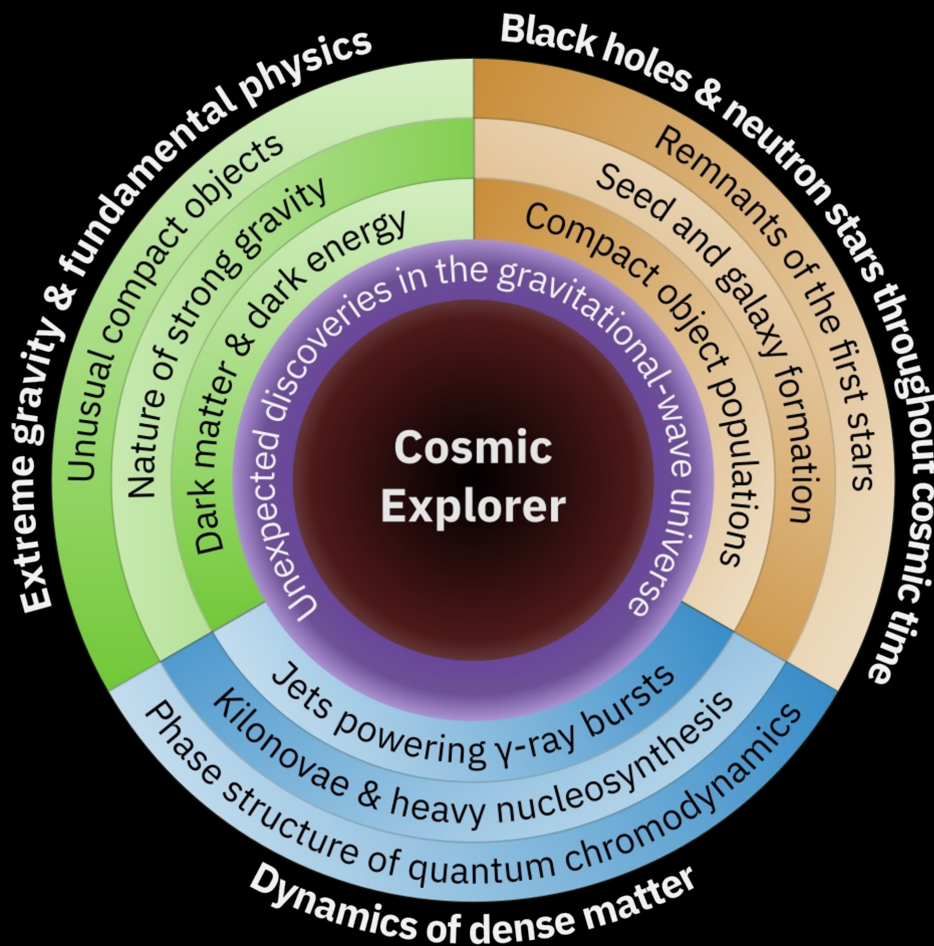

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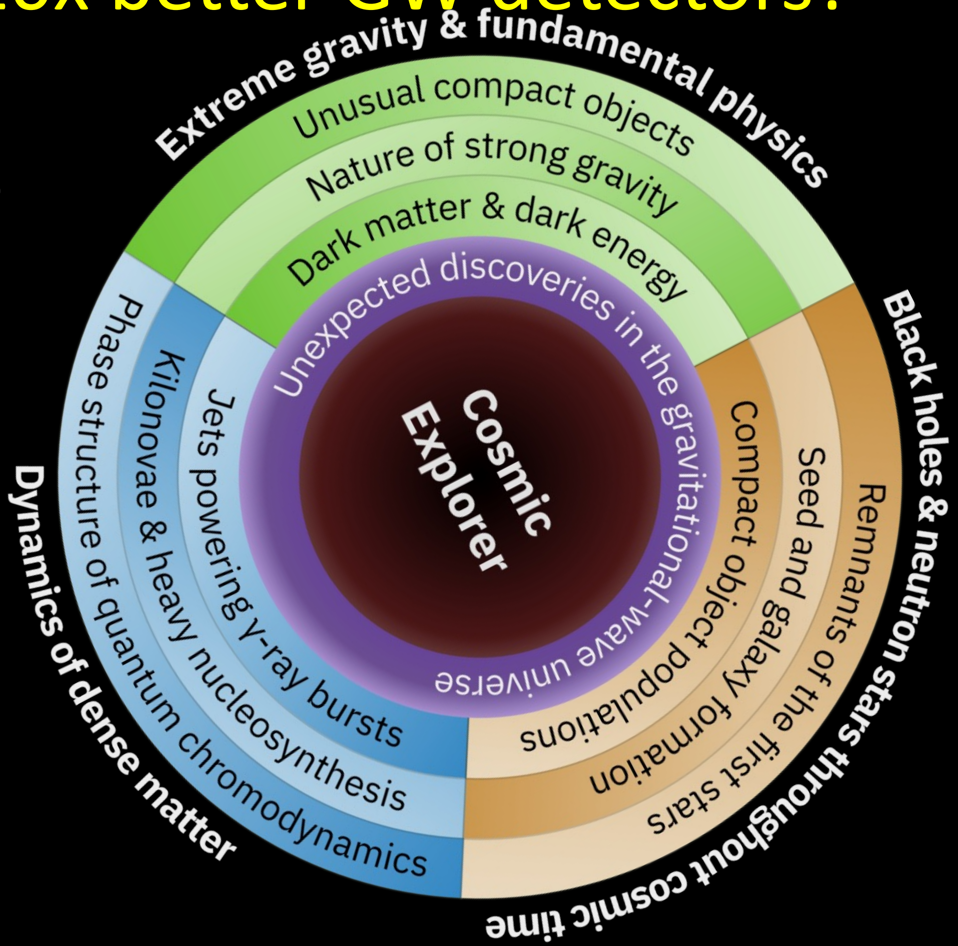
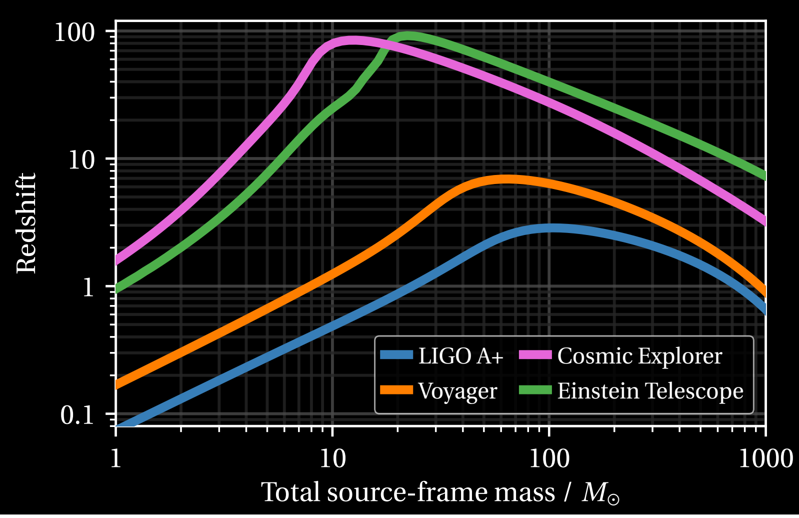
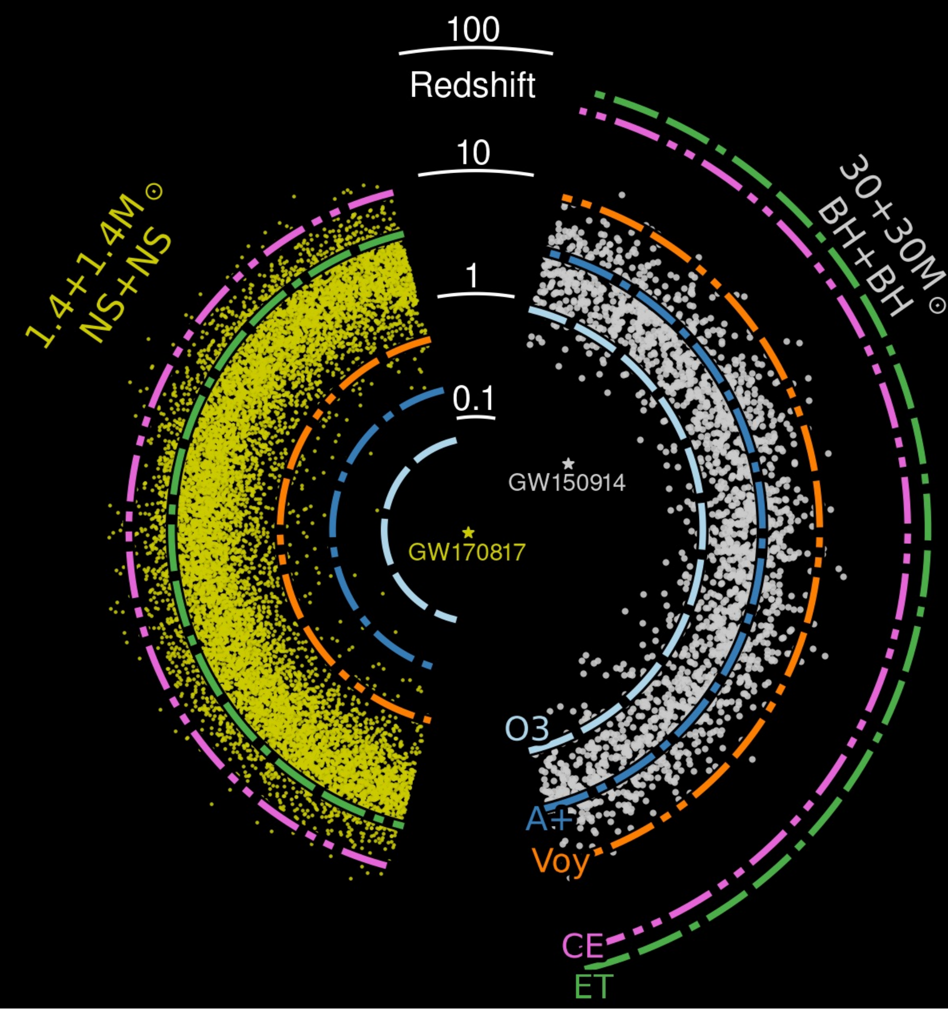


Black Holes and Neutron Stars throughout cosmic time

- The best understood source of gravitational wave emissions are compact binary systems.
- Can build a detector able see all binaries in a broad range of masses

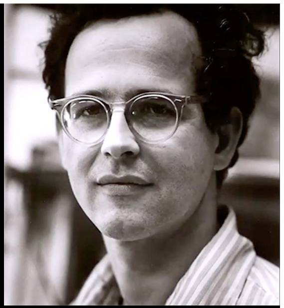




Even better detectors would deliver more science. How to build a such a 10x better detector?

- **Current detector concept**
- Scaling laws

Basic principle for detecting gravitational waves: a laser Michelson interferometer



Rai Weiss, early ‘70s

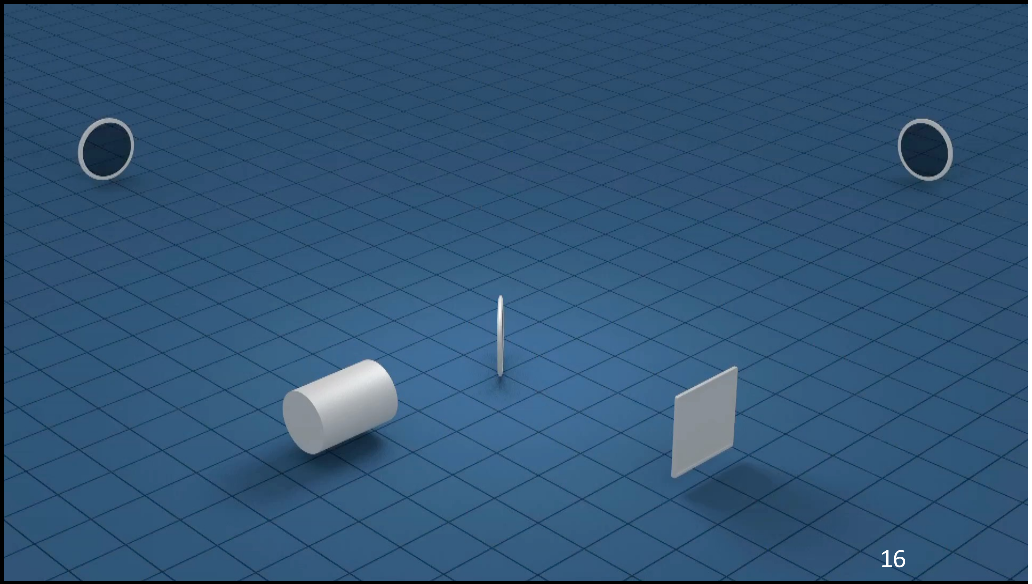
- A transducer from strain to light intensity → electrical signal

What determines the sensitivity of this detector?

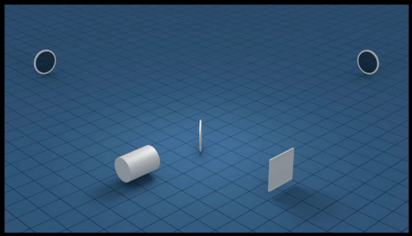
- **Distance over which strain is sensed**

$$\Delta L = h\, L$$

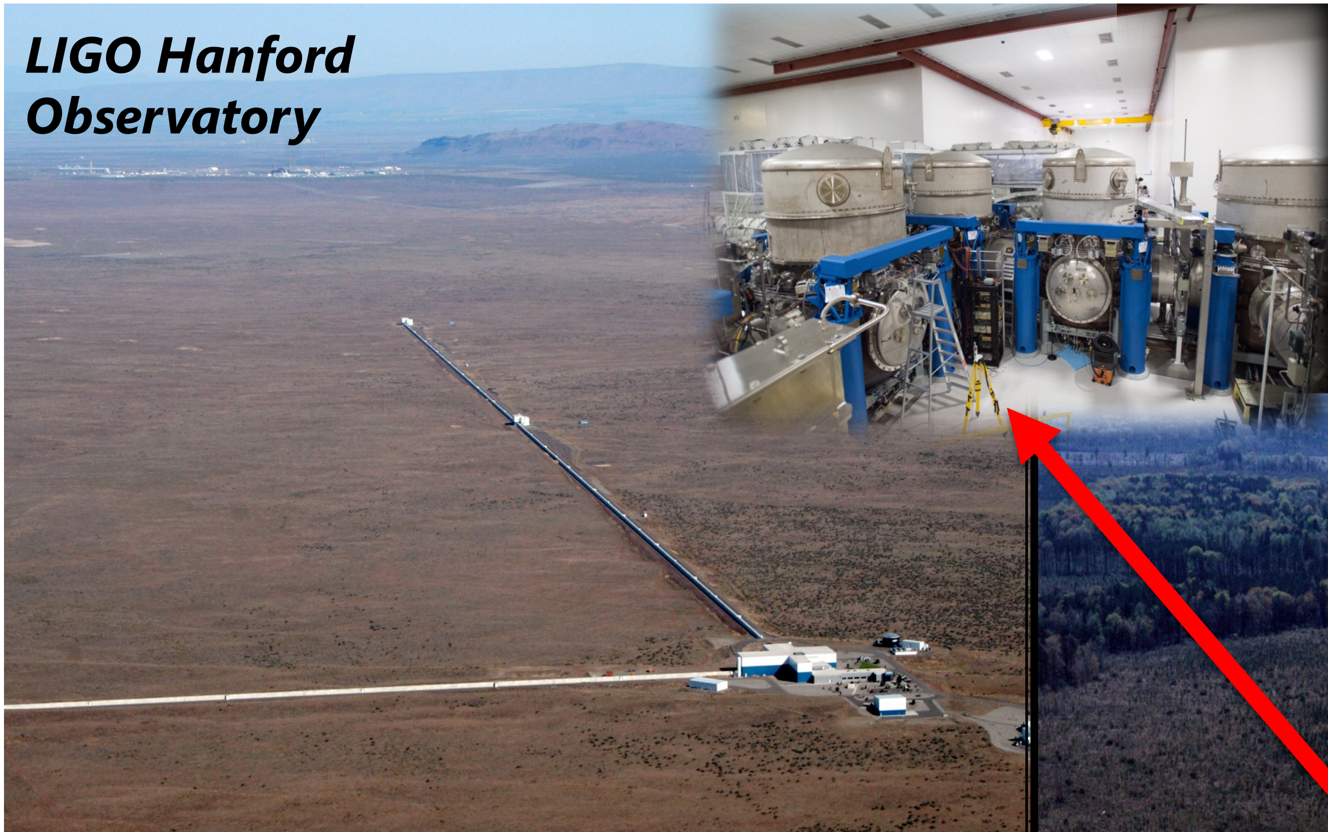
- Resolution of the optical sensing
- Stochastic forces making motion of mirrors, masking GWs



The Infrastructure for a realistic implementation



- Amplitude of the gravitational wave strain is $h = \Delta L/L \rightarrow \Delta L = h\, L$
- A sufficient length L of the arms is needed to bring the GW-induced strain to a measurable level (LIGO: 4km)
- Sensing laser light must travel in an excellent vacuum (LIGO: 10^{-9} Torr)
- The vacuum system diameter must accommodate a diffraction limited beam over 4km (LIGO: 1.2 m Diameter; → 10,000 m^3)
- The vacuum system must be *straight*, level, and protected from the human and natural environment (LIGO: earthmoving, concrete bed, aligned to several mm over 4km, and protected by a concrete cover)
- Corner and end buildings with particulate, temperature control; staff buildings; outreach/public science building (LIGO: 10,000 m^2)



Present LIGO Observatory sites

L = 4km

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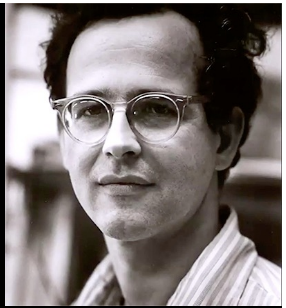

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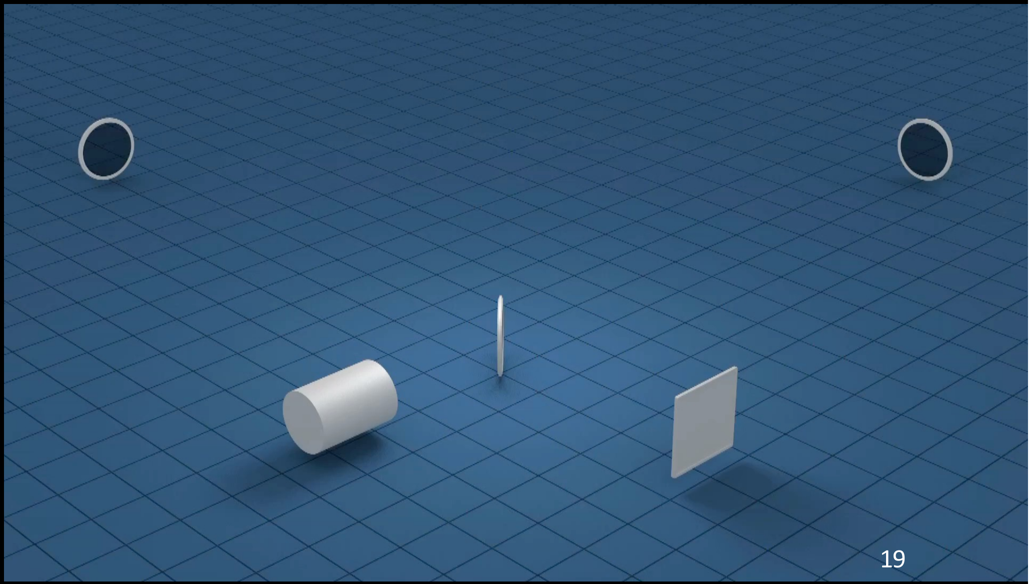


Resolution of the optical sensing

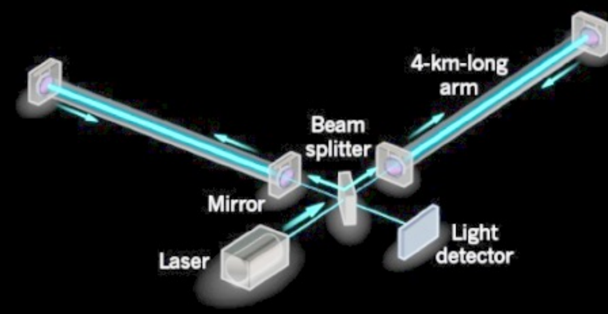
- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics; *A. Einstein, 1909*)

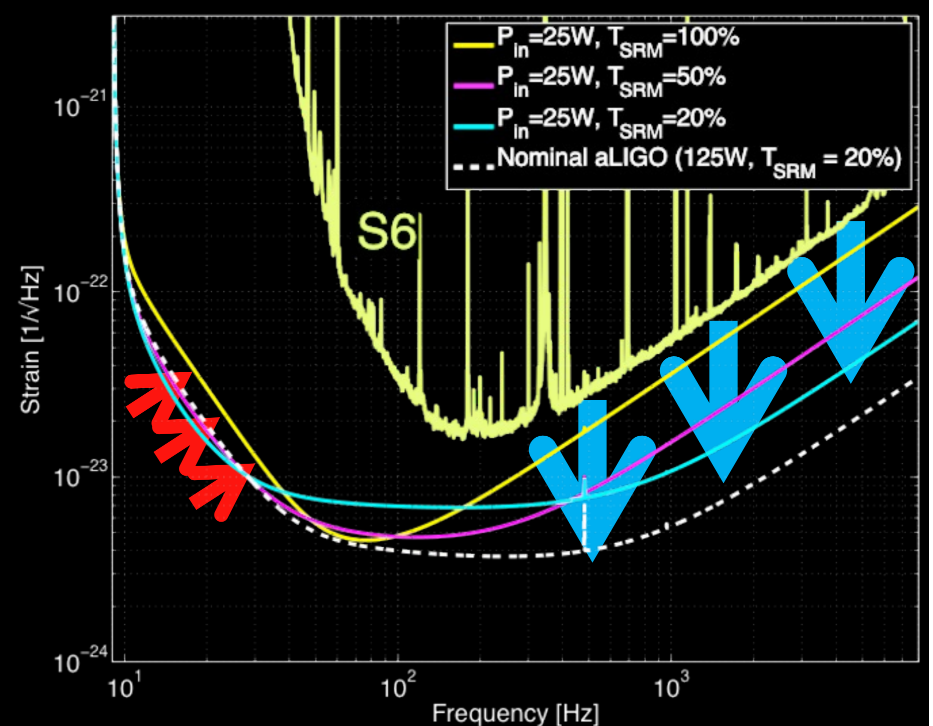
$$h_{\rm sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

- **Radiation Pressure noise** –buffeting of test mass by photons increases low-frequency noise – use heavy test masses!

$$h_{\rm rp}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$

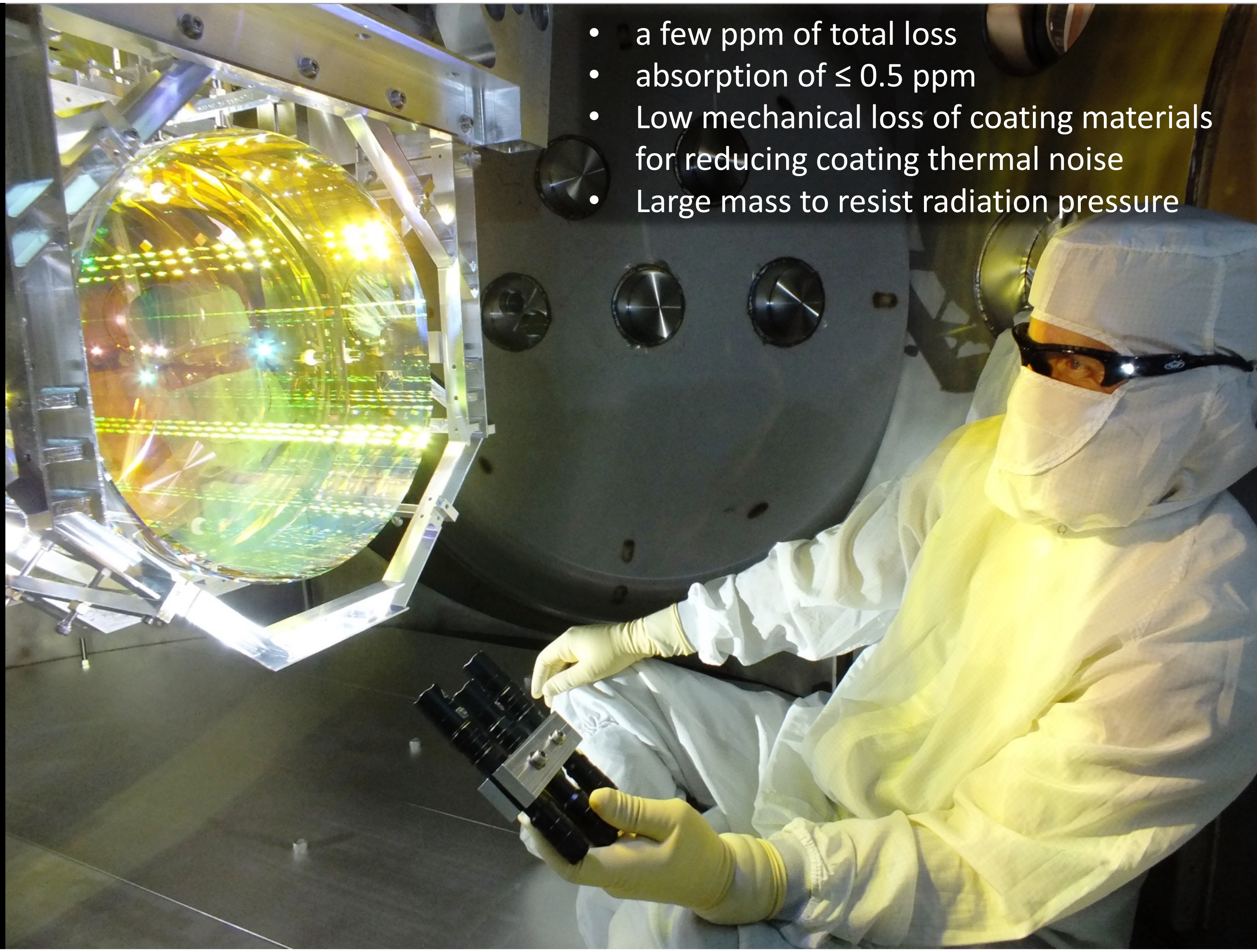
- **'Standard Quantum Limit'**





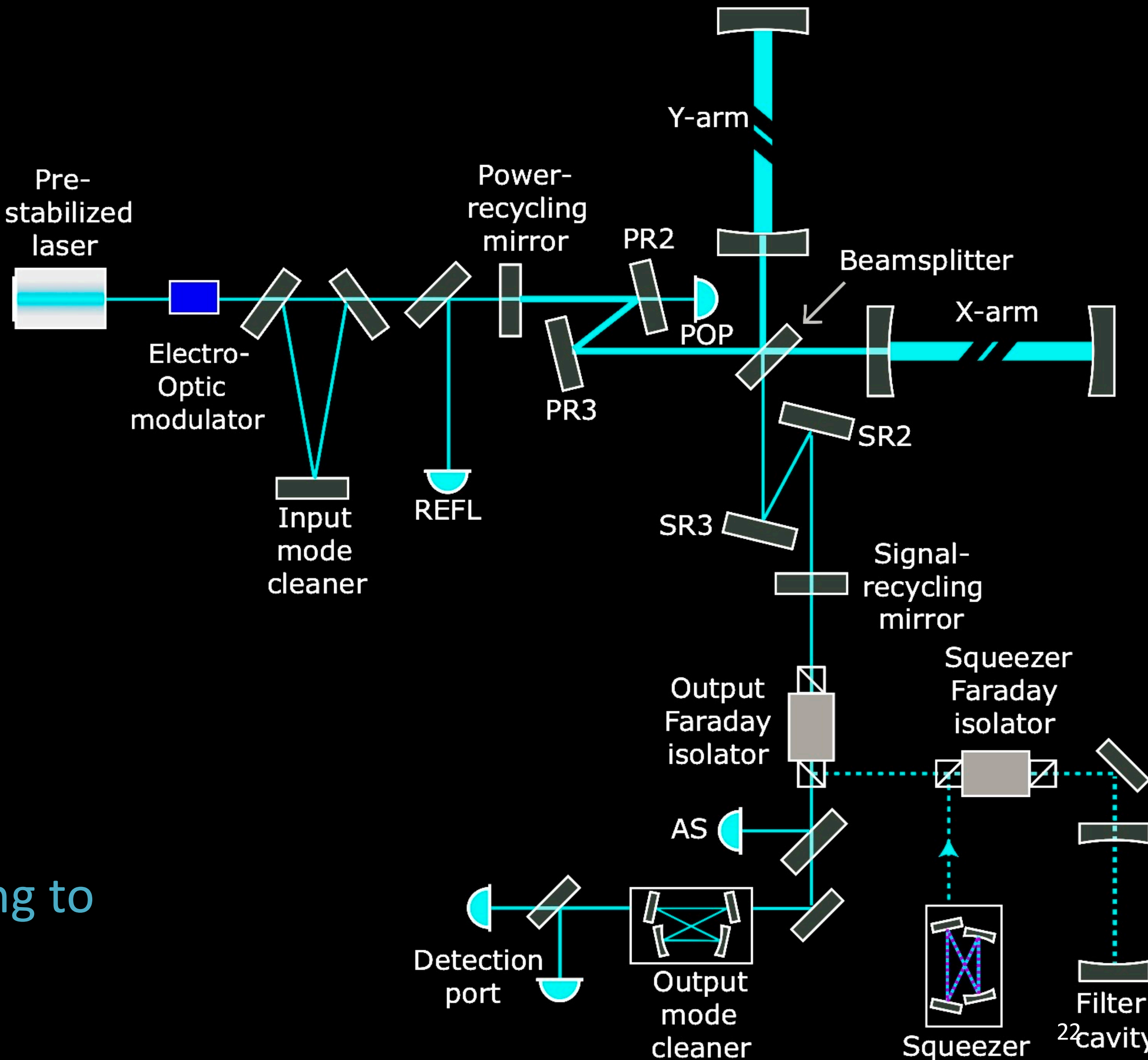
High Quality Optics

- a few ppm of total loss
- absorption of ≤ 0.5 ppm
- Low mechanical loss of coating materials for reducing coating thermal noise
- Large mass to resist radiation pressure



Optical schematic

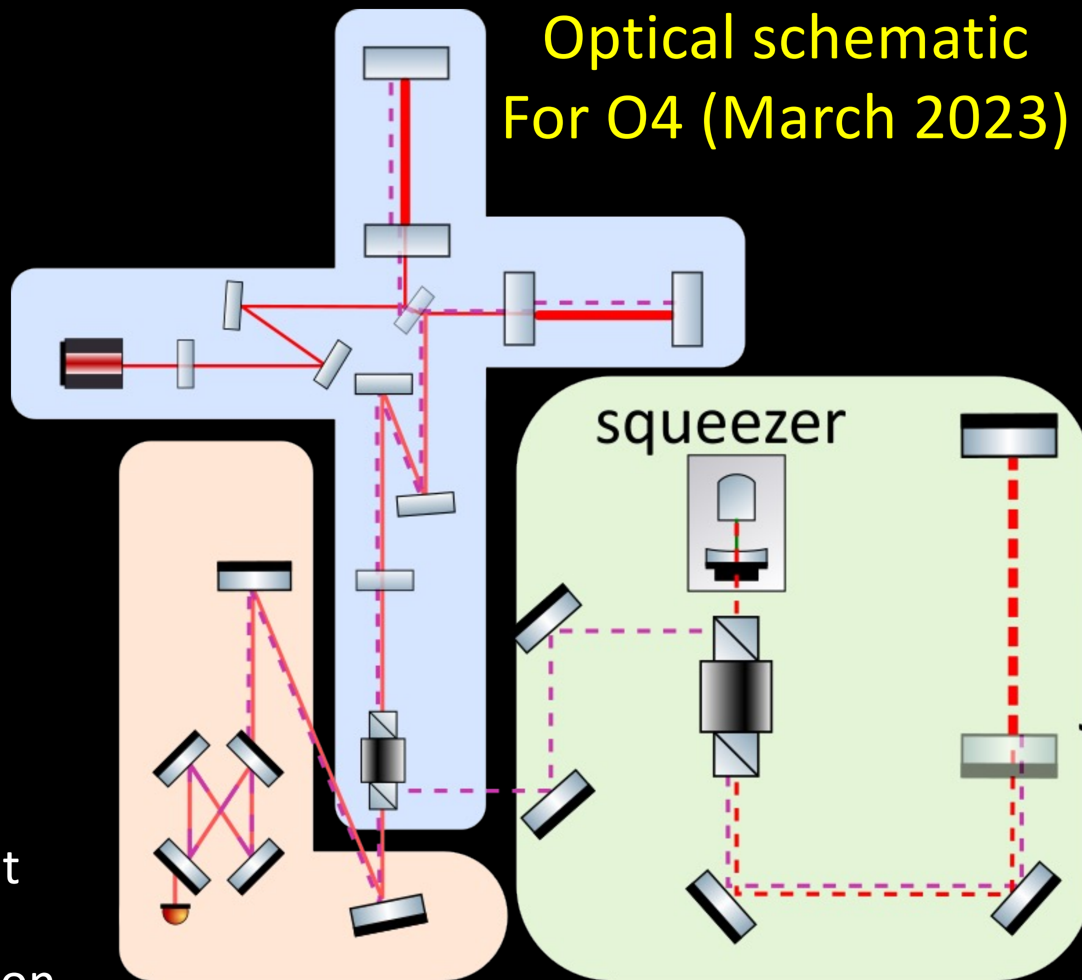
- Fabry-Perot cavities in arms to increase interaction time
- Coupled cavities to increase power, extract GW frequencies
- FP cavities in transmission to enforce TEM_{00} mode
- ~100 degrees-of-freedom to control!
- Frequency-dependent squeezing to manage quantum noise



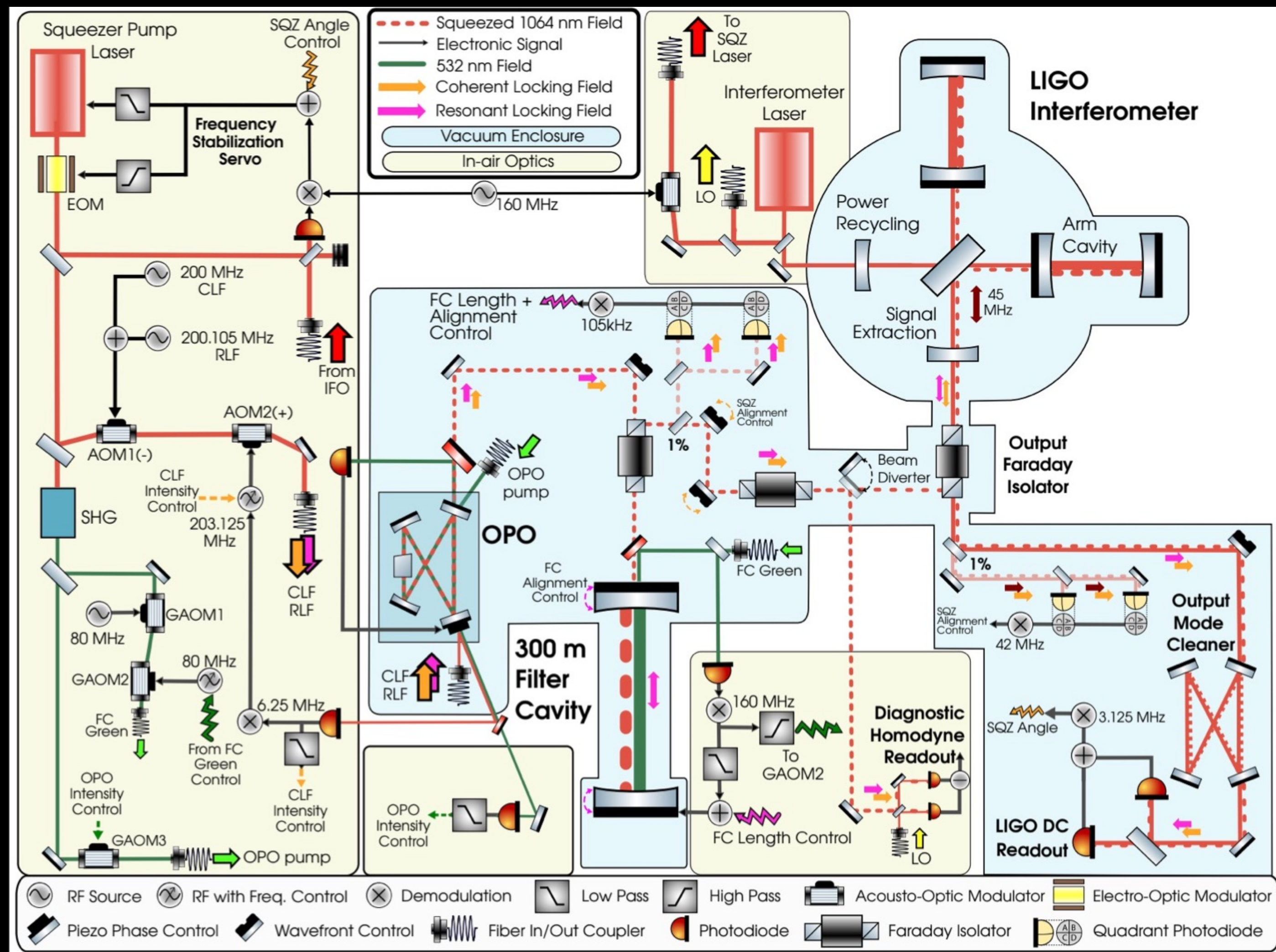
Squeezing

- Heisenberg Uncertainty Principle dictates that precise values of phase, and amplitude, of light cannot be known at the same time
- $\Delta X_{\text{phase}}\, \Delta Y_{\text{amp}} \leq h_{Heisenberg}/2$
- We can choose however to e.g., know the amplitude less well and look more closely at the phase
- 'Squeezed light' used in O3 to reduce shot noise at the expense of more radiation pressure noise
- For O4, adding 'Frequency Dependent Squeezing' to reduce high-frequency shot noise, and low-frequency radiation pressure noise

Optical schematic For O4 (March 2023)



That Squeezer in a bit more detail…



Ganapathy*,Jia*,Nakano*,Xu*,LIGO O4 instrument scientists,
Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing, PRX 13, 041021 (2023)

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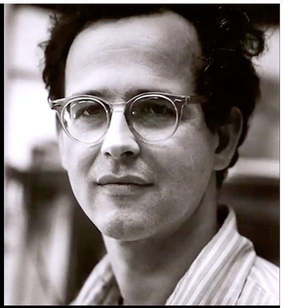

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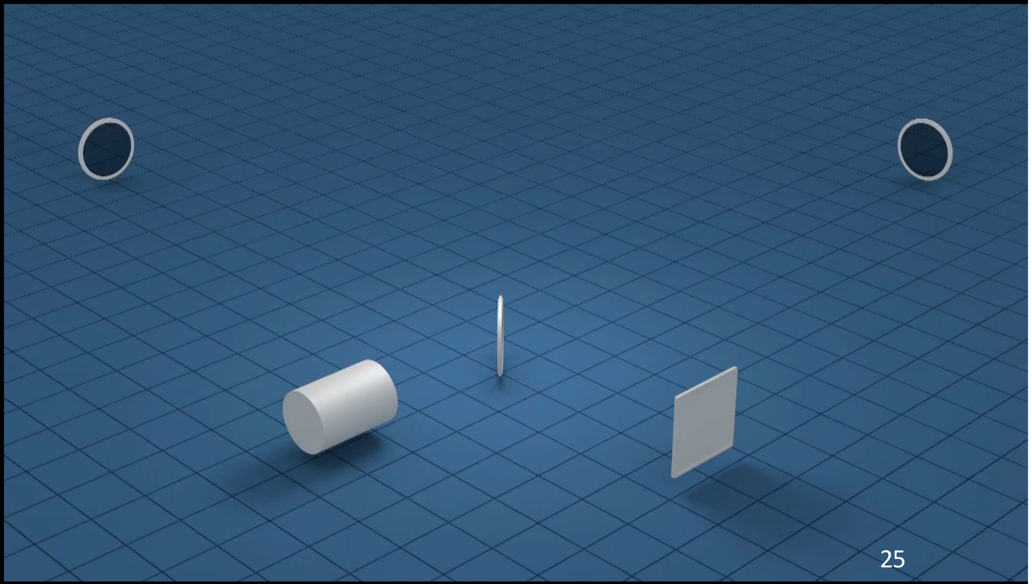
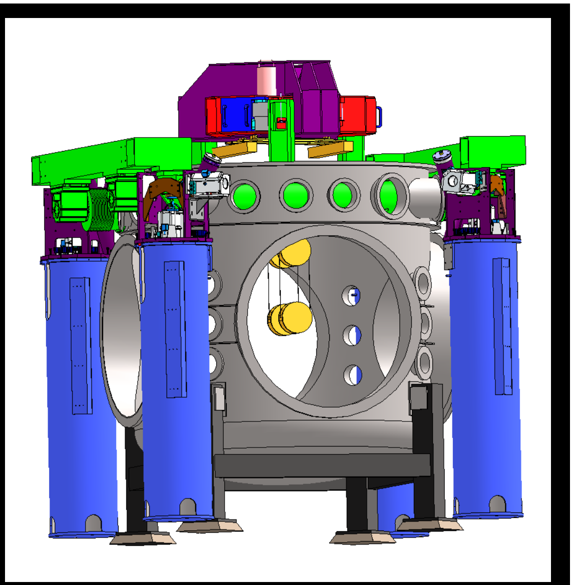


Stochastic force motion of mirrors



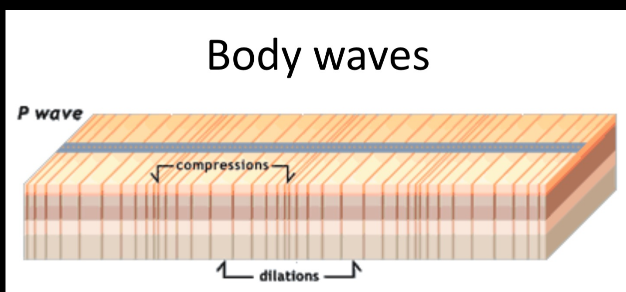
- Suppress physical transmission of (seismic etc.) motion from the outside via:
  - 3x6 degree-of-freedom servo controlled platforms
  - 4 pendulums in series, giving $((f_o/f)^2)^4$ isolation
  - Order of 10^{12} suppression of motion

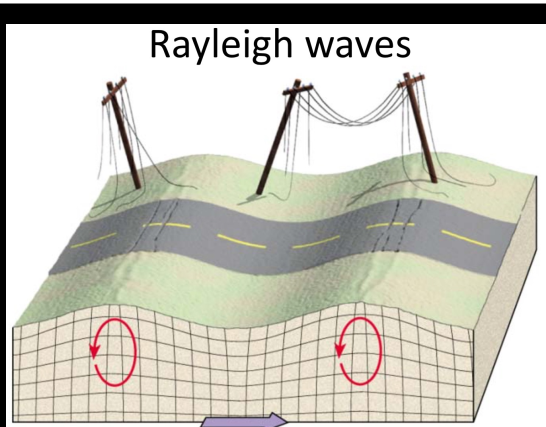
- Newtonian gravitational gradients due to seismic activity
  - Limit on lowest frequency for ground-based detectors….
    → go to space (LISA)

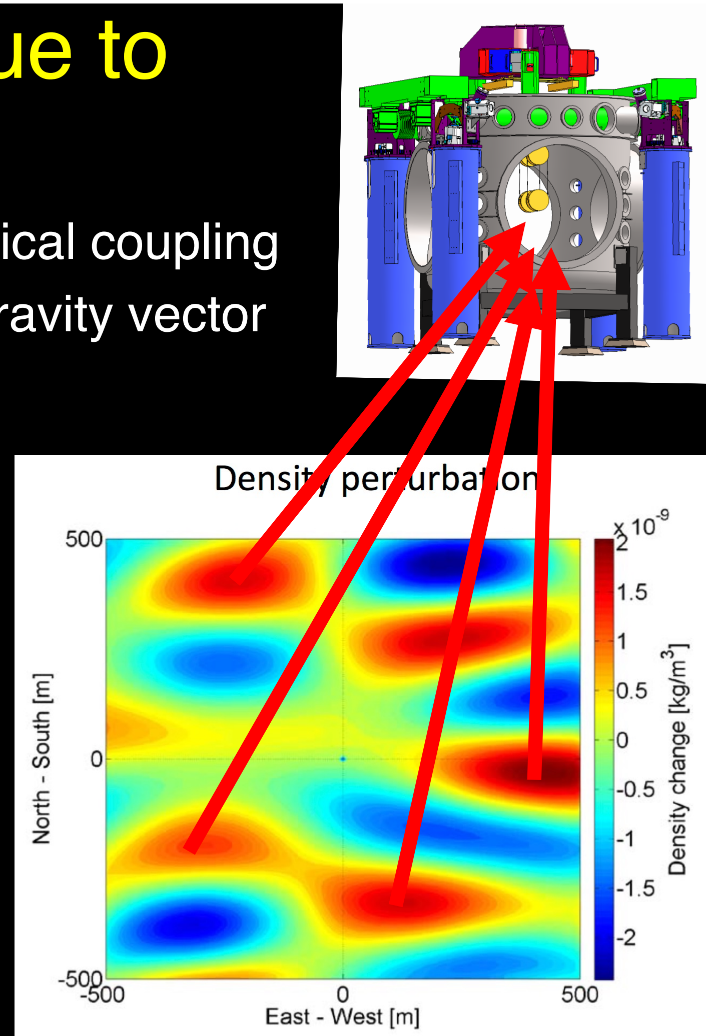
- Concentrate thermal noise in frequency bands to limit impact on GW range

Newtonian background due to seismic environment

- In principle, can eliminate all direct mechanical coupling
- Can not shield against the wandering net gravity vector





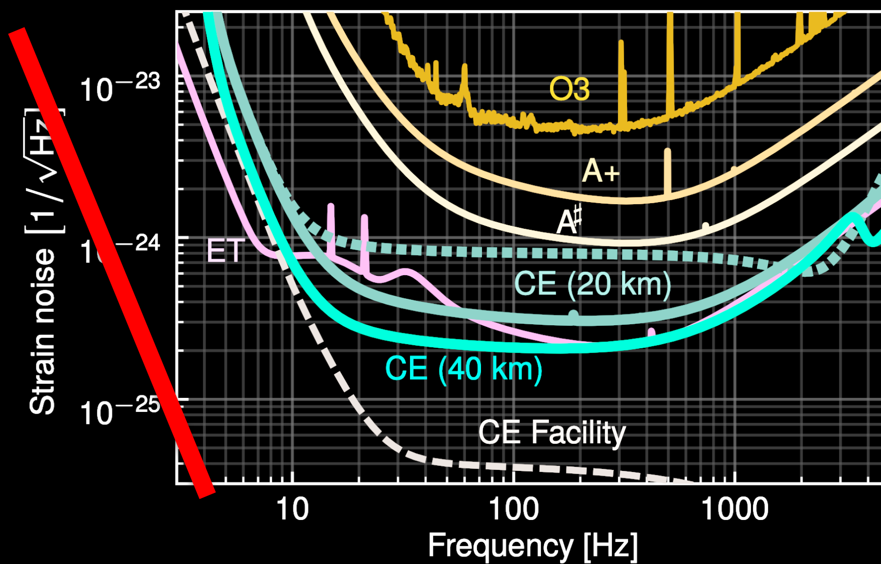


Density perturbations cause gravity perturbations.

Images: J. Harms

Newtonian background creates a wall at a few Hz

- Newtonian Background falls as ~ $1/f^5$
- Can reduce somewhat by moving underground
  - ET vs CE – more later on these two
- Can reduce somewhat with arrays of seismometers and subtraction of effect
- Forbiddingly large for ~3Hz and lower
- Ultimate limit on the lowest frequency detectors on- or under-ground
- And thus the largest BH masses detectable



Evans et al. 2023

Thermal Noise

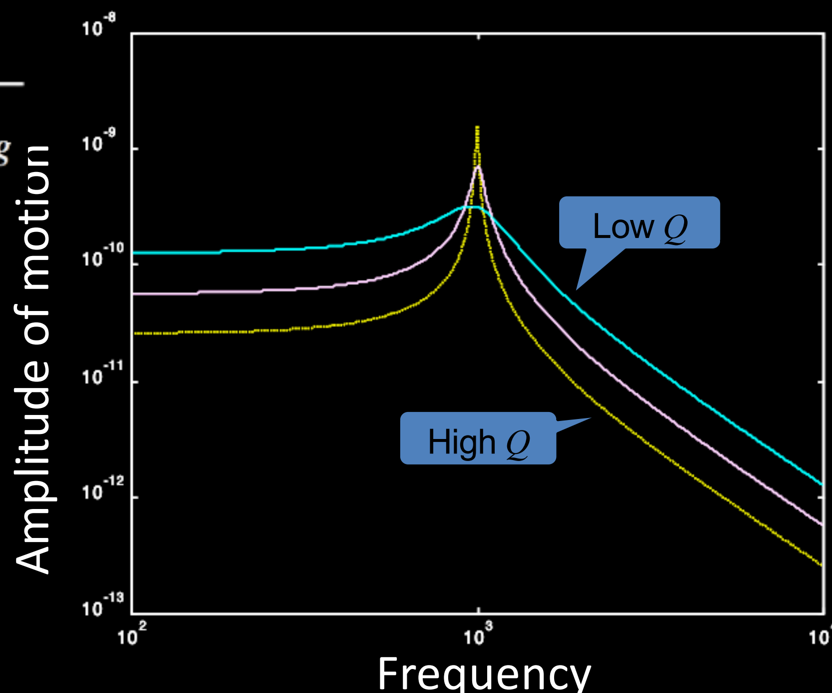
- **Thermal noise** – $k_B T$ of energy per mechanical mode (*A. Einstein, 1905*)
- Simple Harmonic Oscillator:

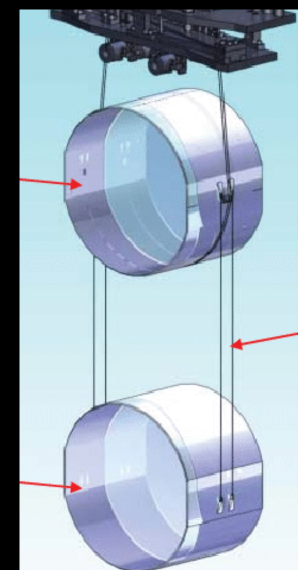
$$x_{rms} = \sqrt{\langle (\delta x)^2 \rangle} = \sqrt{k_B T / k_{spring}}$$

- Distributed in frequency according to real part of impedance $\Re(Z(f))$

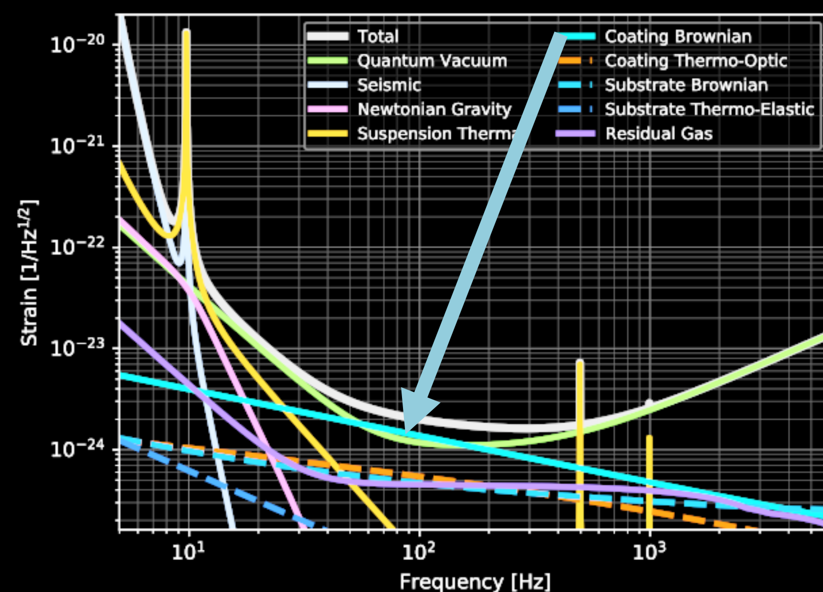
$$\tilde{x}(f) = \frac{1}{\pi f} \sqrt{\frac{k_B T}{\Re(Z(f))}}$$

- **Low-loss materials**
- **monolithic construction**





Mirror Coating thermal noise



- In in the best amorphous coatings, the dielectric optical coating has a rather large loss tangent
  - Some 10^{-4} , compared to 10^{-8} for fused silica
- The Fluctuation-Dissipation theorem says this is where the greatest motion is found
- And: the coating is the surface that is sensed by the laser
- **This is the dominant limit in the critical 50-200 Hz band**

coating elastic loss

$\phi \equiv \mathrm{Im}\,Y \,/\, \mathrm{Re}\,Y$

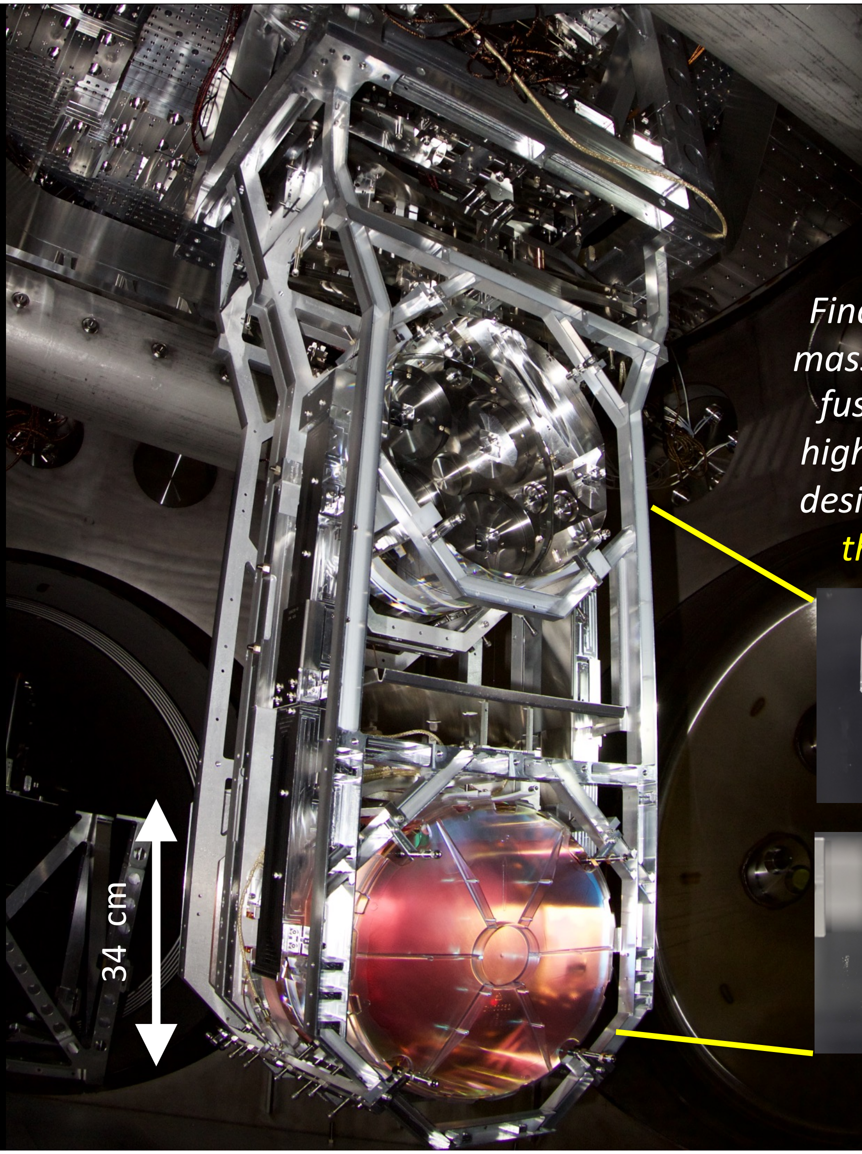
coating thickness

$$\left\langle \Delta x(f,T)^2 \right\rangle \approx \frac{2k_B T}{\pi^2 f}\frac{d}{w^2 Y}\phi(f)$$

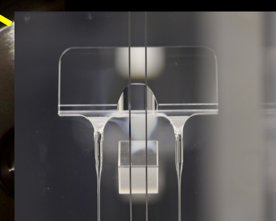
beam radius

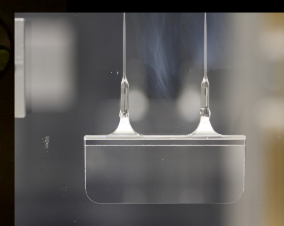
Y Levin *Phys. Rev. D* **57** 659 (1998)

Test Mass Suspension

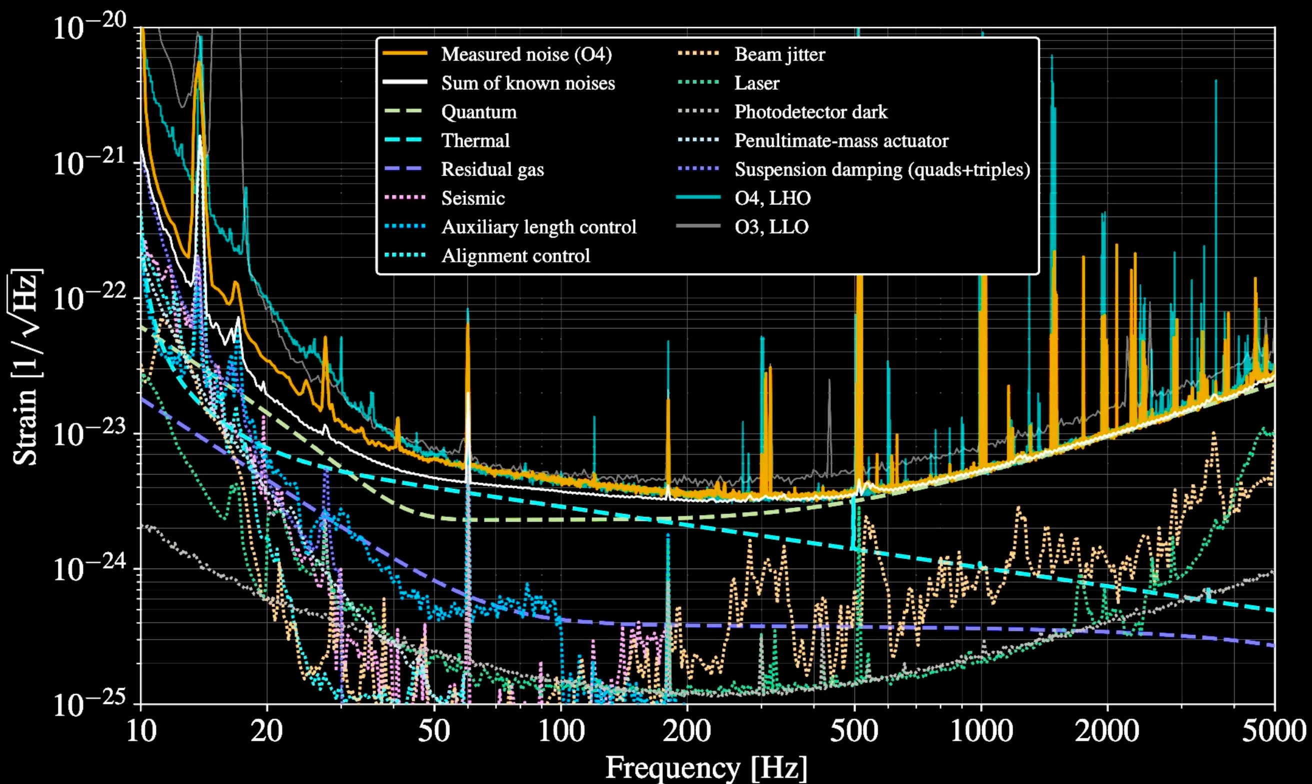


Final stage of test mass suspension all fused silica, very high quality factor, designed to reduce thermal noise





LIGO ‘Noise budget’



(b) Noise budget for the LIGO Livingston Observatory, as of October 2023.

PRD, **111**, 062002 (2025)

Even better detectors would deliver more science. How to build a such a 10x detector?

- Current concept
- Limitations to the sensitivity
- **Scaling laws**

Sensing noises scale with arm length at various powers of $1/L$ – all get better

Shot Noise
while maintaining bandwidth

$$\frac{h_{\mathrm{shot}}}{h_{0\,\mathrm{shot}}} = \sqrt{\frac{2\,\mathrm{MW}}{P_{\mathrm{arm}}}}\sqrt{\frac{\lambda}{1.5\,\mu\mathrm{m}}}\left(\frac{3}{r_{\mathrm{sqz}}}\right)\sqrt{\frac{40\,\mathrm{km}}{L_{\mathrm{arm}}}}$$

Radiation Pressure Noise
while maintaining bandwidth

$$\frac{h_{\mathrm{RPN}}}{h_{0\,\mathrm{RPN}}} = \sqrt{\frac{P_{\mathrm{arm}}}{2\,\mathrm{MW}}}\sqrt{\frac{1.5\,\mu\mathrm{m}}{\lambda}}\left(\frac{3}{r_{\mathrm{sqz}}}\right)\left(\frac{40\,\mathrm{km}}{L_{\mathrm{arm}}}\right)^{3}$$

Coating Thermal Noise
loss angle dependence

$$\frac{h_{\mathrm{CTN}}}{h_{0\,\mathrm{CTN}}} = \sqrt{\frac{T}{123\,\mathrm{K}}}\sqrt{\frac{\phi_{\mathrm{eff}}(T)}{5\times10^{-5}}}\left(\frac{40\,\mathrm{km}}{L_{\mathrm{arm}}}\right)^{3/2}$$

Residual Gas Noise
facility limit

$$\frac{h_{\mathrm{gas}}}{h_{0\,\mathrm{gas}}} = \sqrt{\frac{p_{\mathrm{gas}}}{4\times10^{-7}\,\mathrm{Pa}}}\sqrt{\frac{40\,\mathrm{km}}{L_{\mathrm{arm}}^{3/2}}}$$

B P Abbott *et al* 2017
CQG **34** 044001

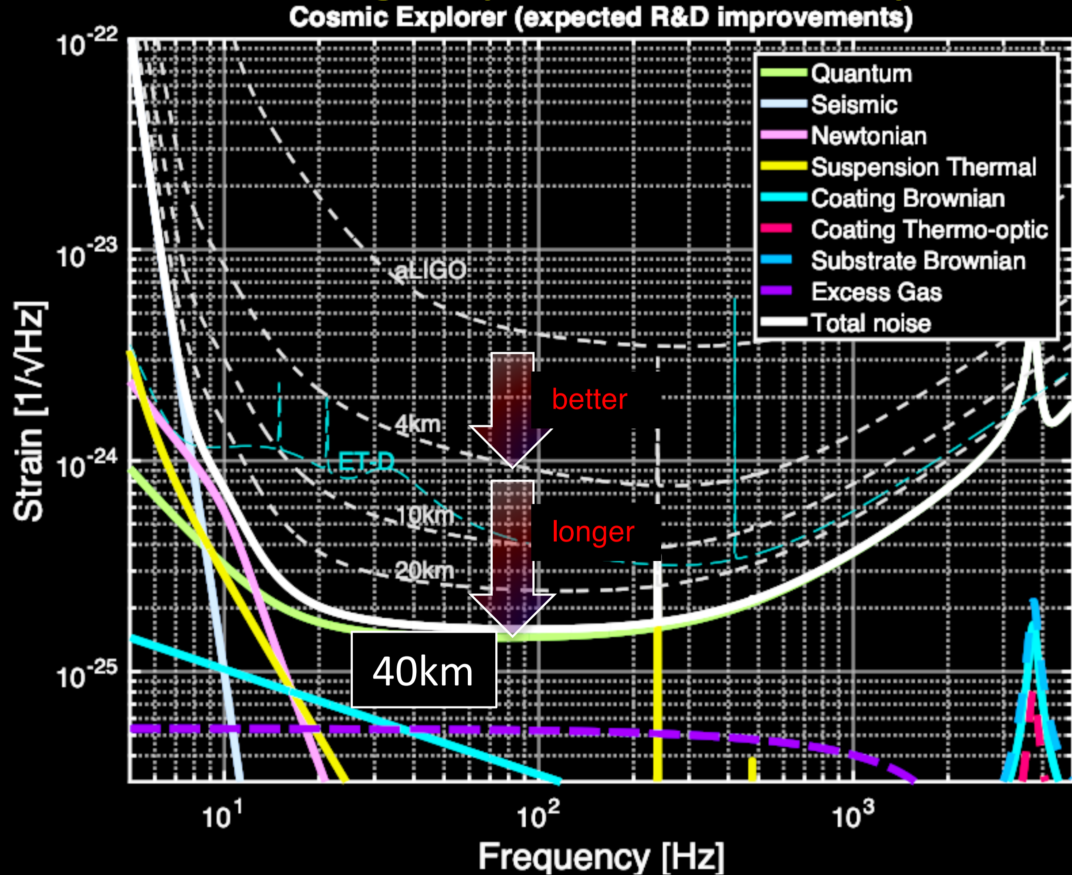
$\Delta L = h\,L$

Noise due to stochastic forces is independent of armlength

- Seismic noise; acoustic coupling
- Varying direction of Newtonian gravity
- Thermal noise motion (pendulum, substrate, coating)

- …and the change in optical pathlength for a given GW-induced strain becomes larger, so SNR improves linearly with length
  - Up to 1/2 λ_{GW} – giving an optimal length for a given signal

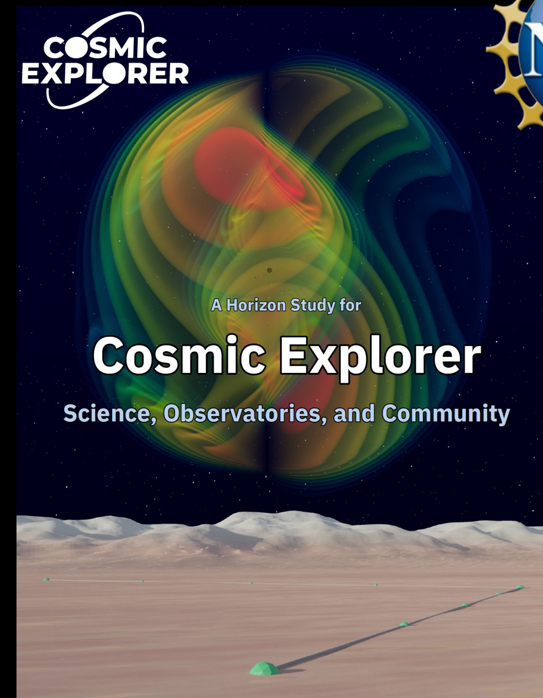
Scaling Up… an example



Exploring the sensitivity of next generation gravitational wave detectors (2017) CQG 34, 044001

COSMIC EXPLORER

Astro 2020
Decadal Survey on Astronomy and Astrophysics
The National Academies of SCIENCES ENGINEERING MEDICINE



NSF

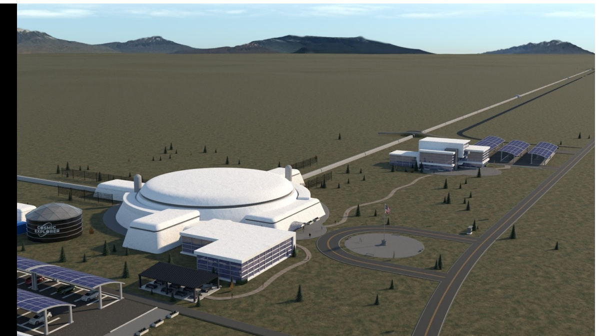
- US contribution to the next-gen Network
- LIGO-like concept for a single interferometer per site, on Earth’s surface
- CE is a larger, and more technically advanced version of LIGO:
  baseline of two widely separated observatories, 40km and 20km arms

cosmicexplorer.org

CE Detector Design

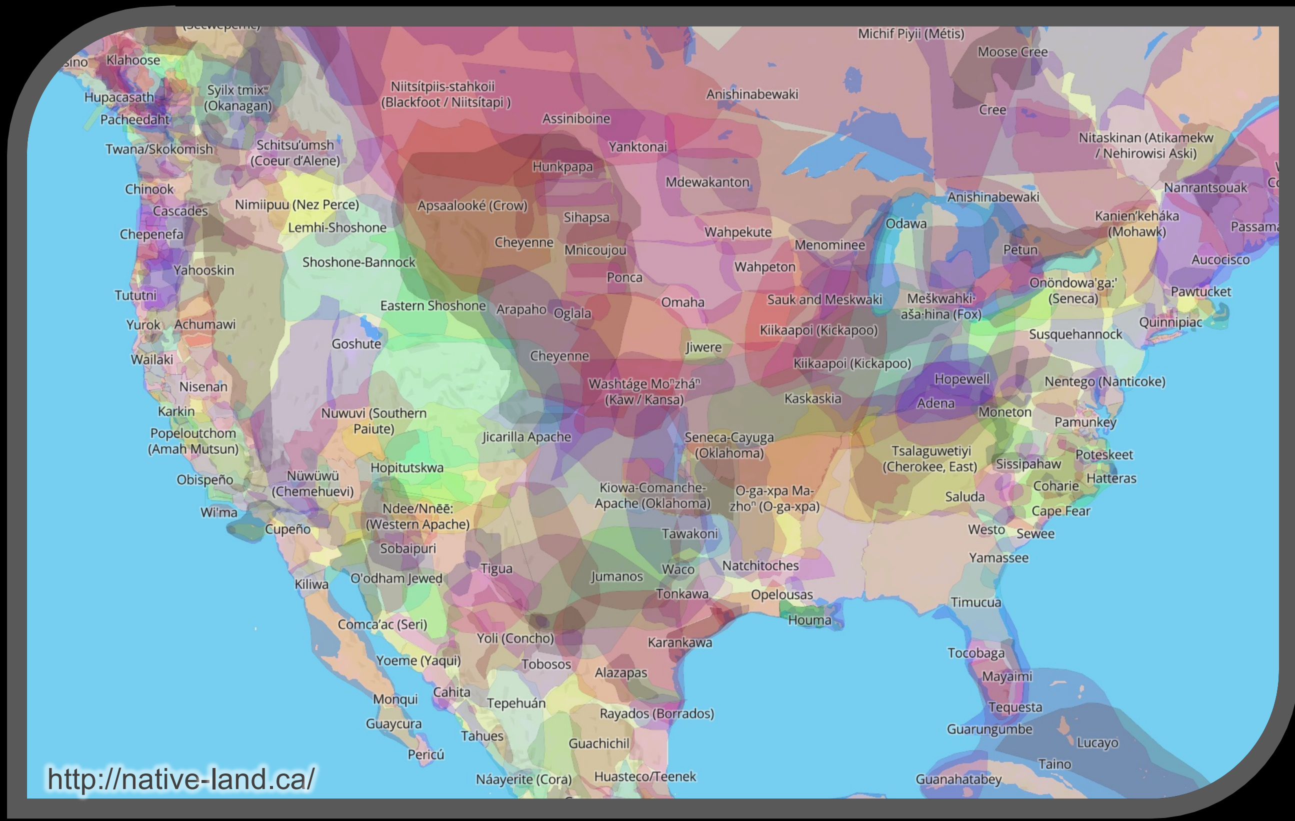
- LIGO is starting to plan upgrades to the LIGO 4km detectors for the 'Post-O5' epoch – ~2029 to the start of CE observing (*optimistically* 2035)
- Initial CE detectors will use all the techniques of this LIGO Post-O5 upgrade
  - Move from a 4km baseline to a 40km baseline
- **Low risk** – no significant advances in the detector are needed
  - Some work on bigger masses, suspensions, lower-loss optics
- Much like LIGO, later upgrades to CE are expected

CE Infrastructure



- Baseline of 40km and 20km observatories
  - 20km is ideal for observing ~2kHz endgame of neutron-star mergers
  - 40km is optimized for absolute ‘reach’ to enable all in-scope binaries to be observed
- Sites separated by a continental baseline
  - Hope that ET in Europe will be built; expect that data will be shared
- Working on less expensive vacuum systems (dominates the cost)
- Single interferometric detector per site
- Earth’s surface construction
  - Good: less expensive than tunneling; no complexity of underground work; future modifications of interferometer layout easier (no new caverns)
  - Bad: increased coupling to surface ‘seismic’ noise, and thus Newtonian background – limits low-frequency sensitivity (~7Hz compared to ~5 Hz for ET)
- *Geographically* suitable sites can be found in the US (and Canada, Australia…)

No matter where we build Cosmic Explorer,
the history of the land will play a **pivotal role** in this project.

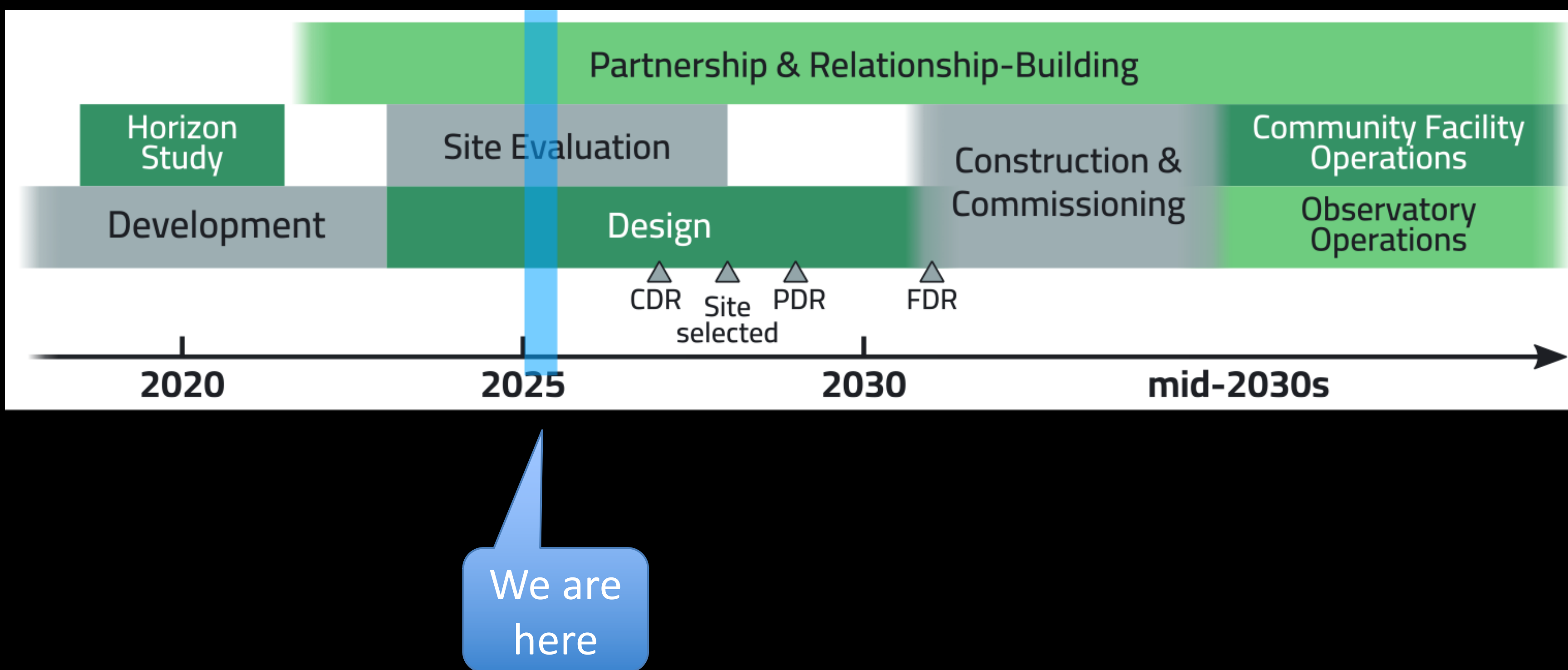


If you are not aware of issues surrounding TMT, please read arXiv:2001.00970 .

CE Status

- Conceptual Design is now underway
- CE Funding is being sought for this phase
  - Working with the NSF; their model is multiple smaller awards
  - International contributions (in-kind) – UK, Germany currently
- CE Project Phase Funding
  - Order of $\$2\times10^9$ for the two-detector baseline
  - Hope that the NSF continues to see GWs as a compelling topic
  - DOE, private funding, in-kind or other international support all sought
- Key participant in the future network: CE, ET, LIGO-India

Cosmic Explorer Timeline
…assuming funding

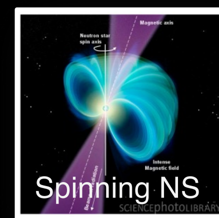


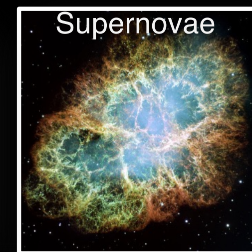
The last page (at last!)

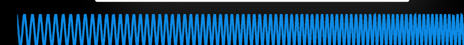
- Ground-based GW observation works
- There are lots of sources yet to be observed
- Scaling laws show the technical feasibility of better detectors
- The US Concept, Cosmic Explorer is our proposal for a Next-Gen GW detector
  - Top-down observational science prioritization
  - bottom-up technology study
- The biggest challenges appear to be in
  - finding resources to build Cosmic Explorer
  - building relationships with host communities
- **CE needs very broad community support to merit the investment**

Why stop there?

The Gravitational Wave Spectrum

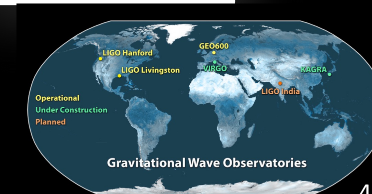




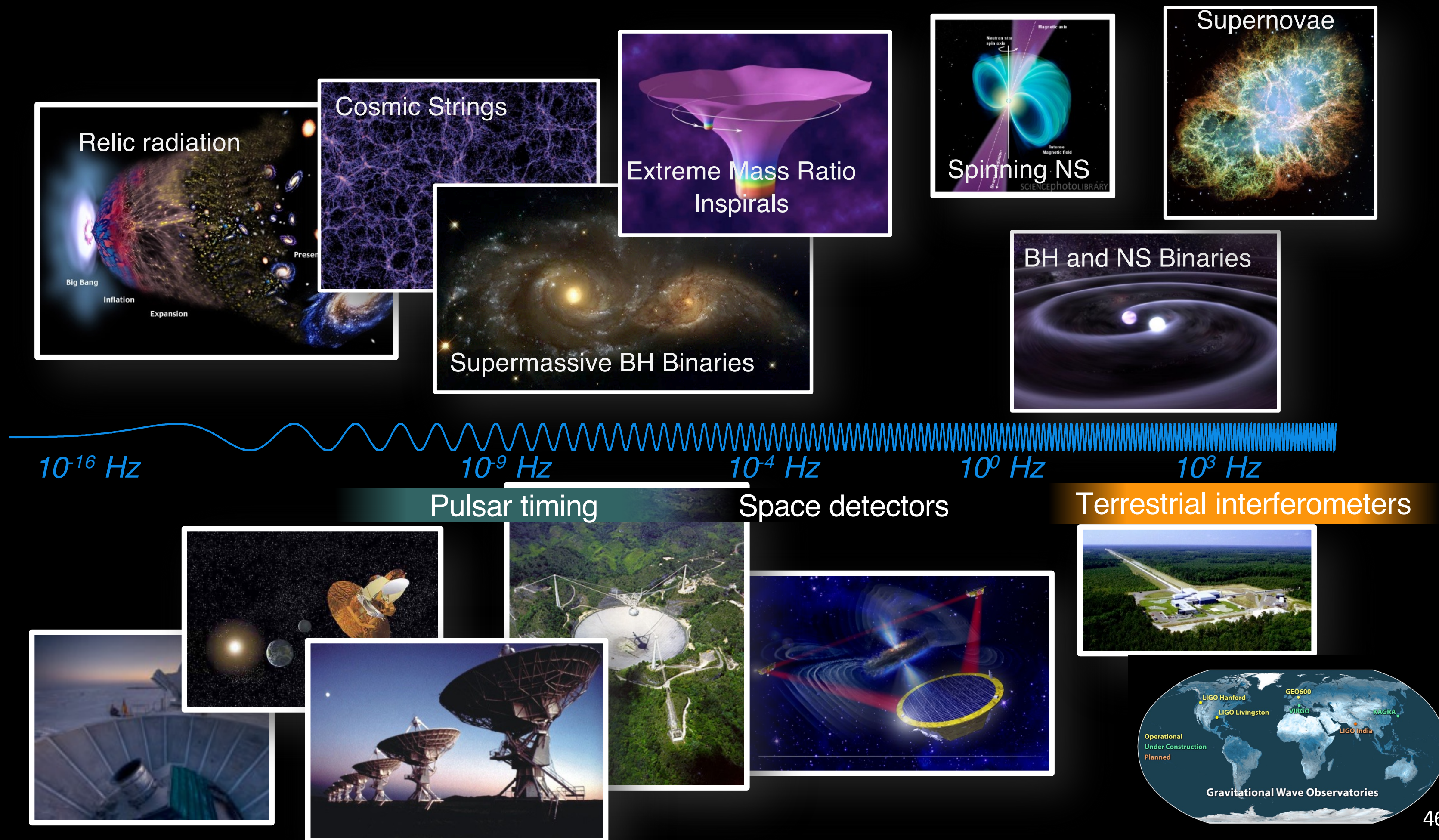


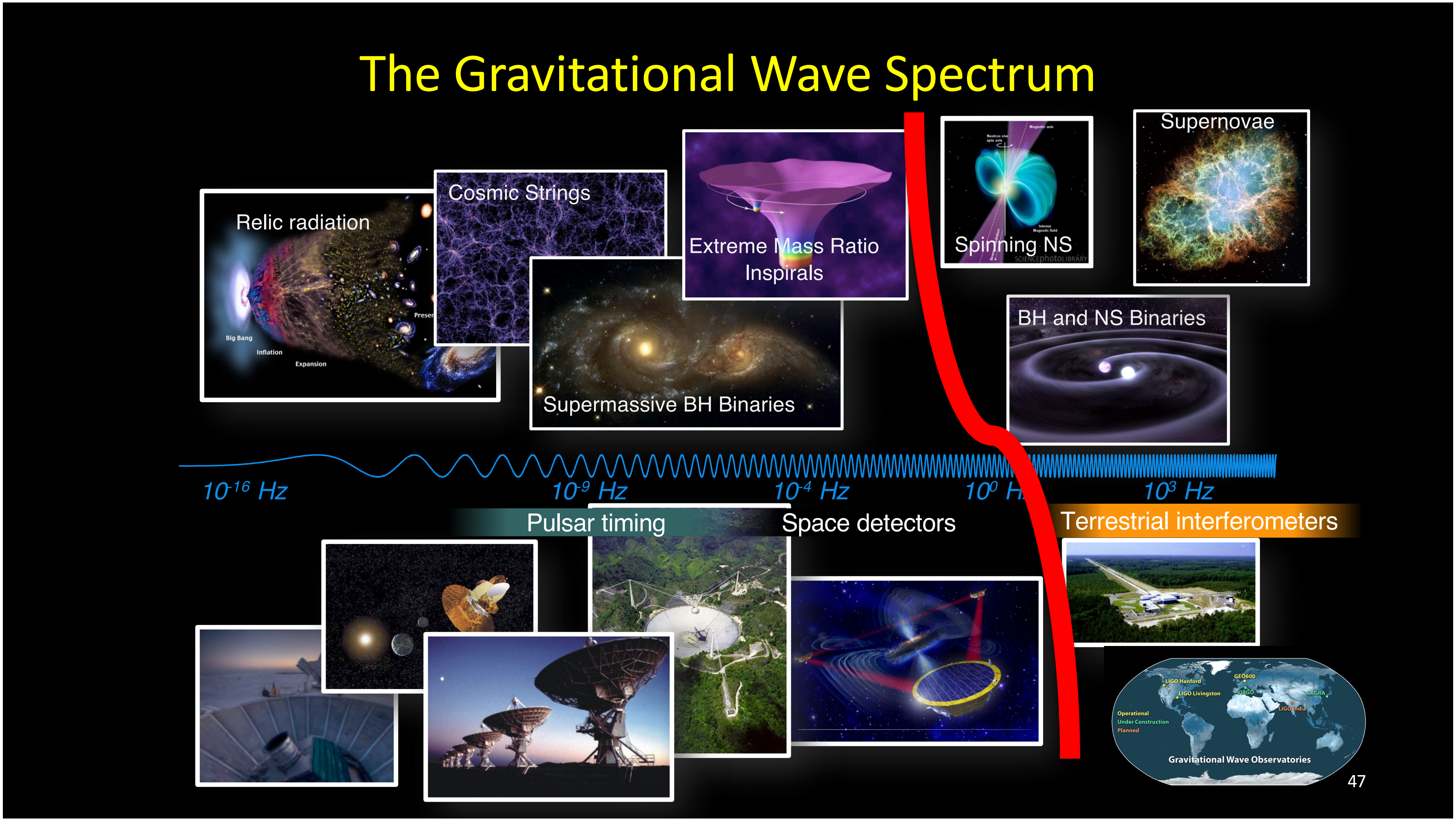
10^0 Hz 10^3 Hz

Terrestrial interferometers

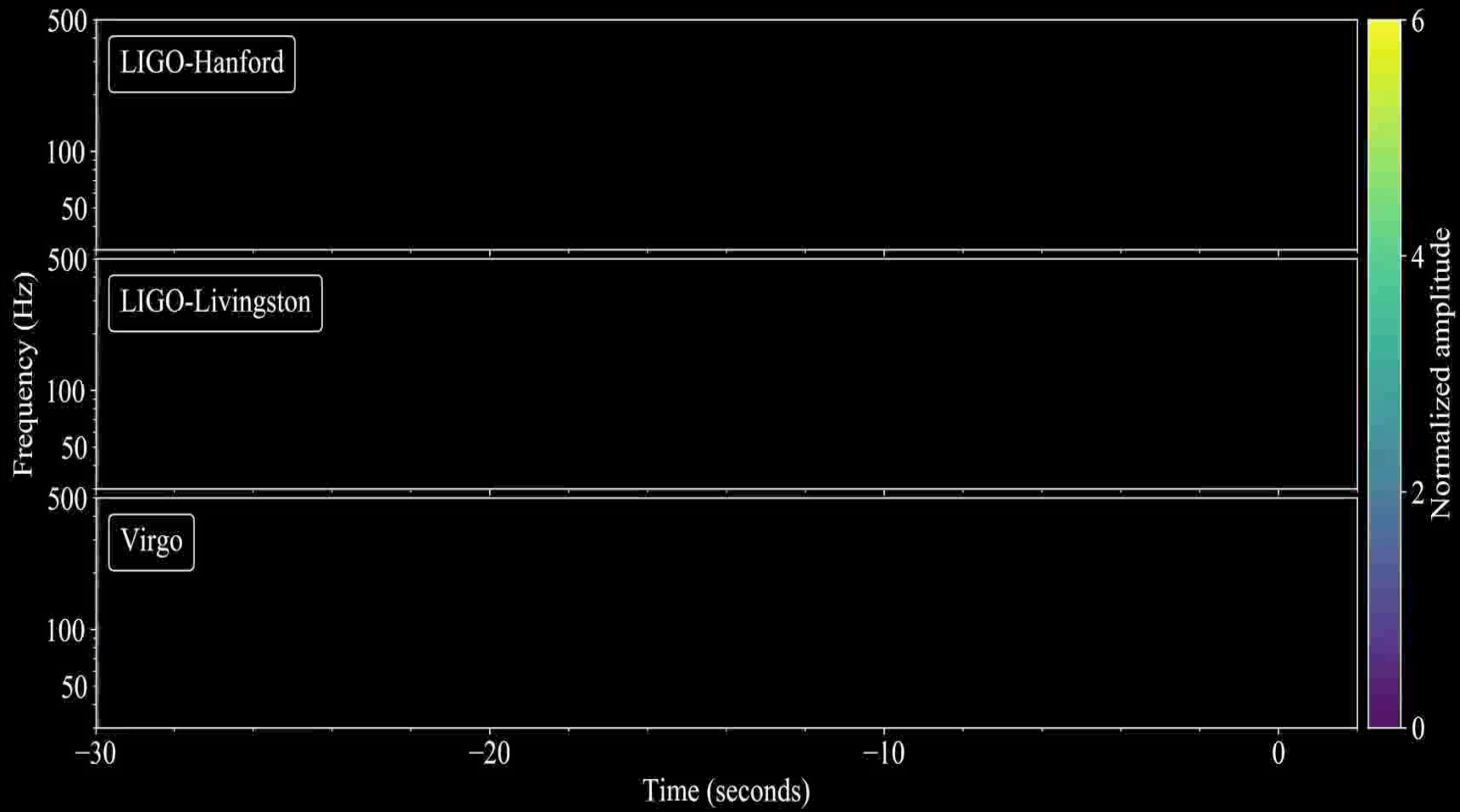


The Gravitational Wave Spectrum




The Gravitational Wave Spectrum
Relic radiation
Big Bang
Inflation
Expansion
Cosmic Strings
Extreme Mass Ratio Inspirals
Supermassive BH Binaries
Spinning NS
Supernovae
BH and NS Binaries
10^{-16} Hz
10^{-9} Hz
10^{-4} Hz
10^{0} Hz
10^{3} Hz
Pulsar timing
Space detectors
Terrestrial interferometers
LIGO Hanford
LIGO Livingston
GEO600
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories
47

The binary neutron star signal, with and without the interferometer noise



Einstein Telescope

Underground; in Sardinia or near NL-B-D border

Six detectors arranged in a triangle

⇒ sense both GW polarizations

⇒ “null stream” for consistency checks

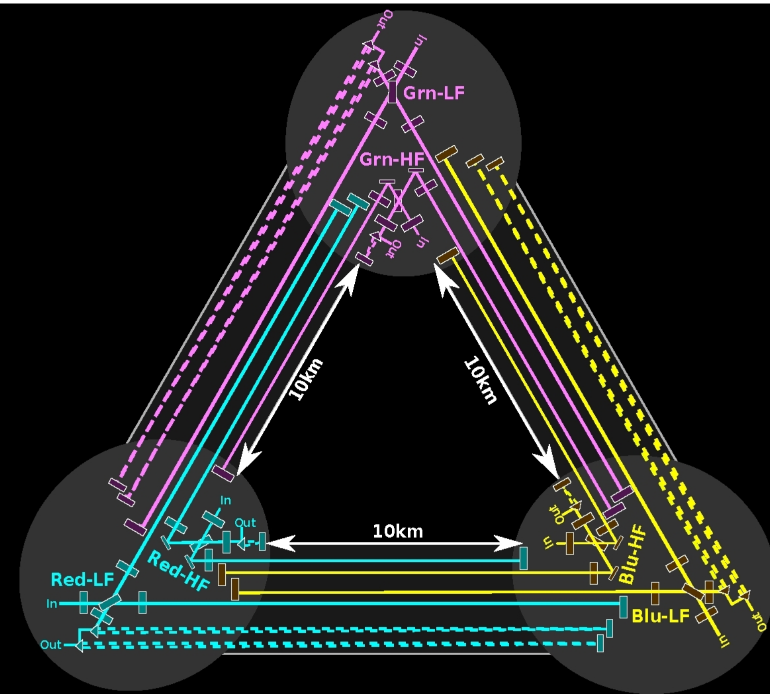
Observe down to a few hertz and have deep bucket using “xylophone” detectors with large masses, freq-dep squeezing

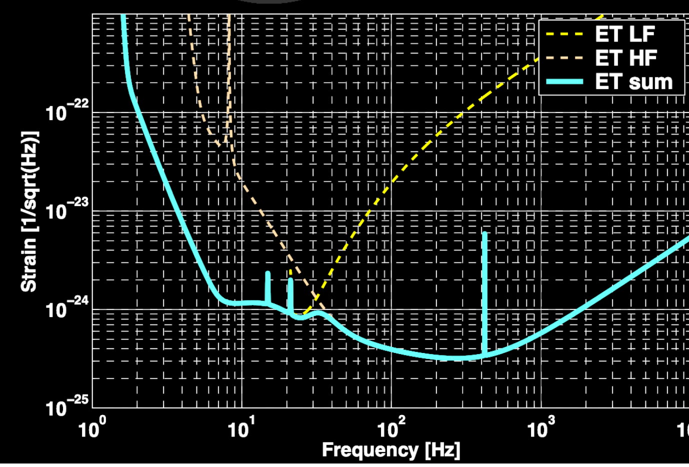
⇒ low frequency: cryogenic silicon

⇒ high frequency: high power, room temp

ET Design Report published 2011, updated in 2020

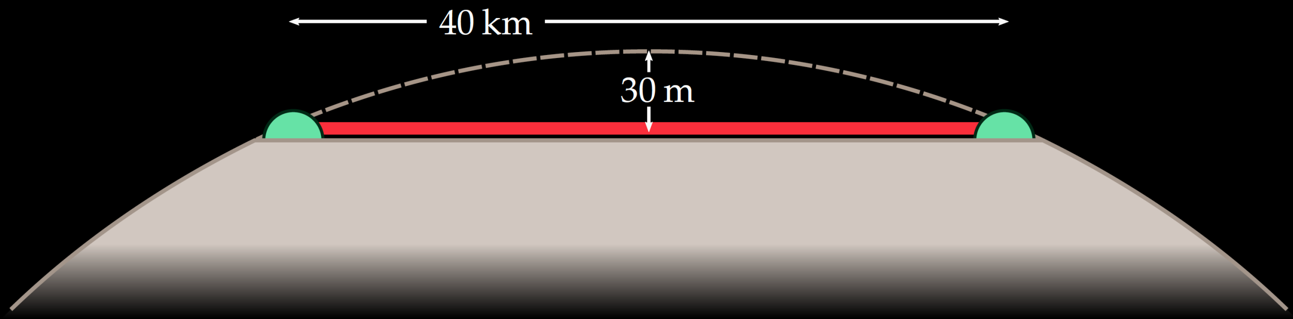
In 2021, ET was included in the roadmap of the European Strategic Forum for Research Infrastructures (ESFRI).



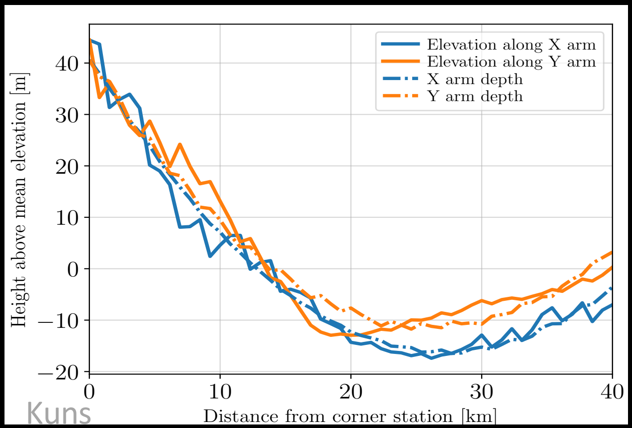


X

40km CE



40 km
30 m



Elevation along X arm
Elevation along Y arm
X arm depth
Y arm depth
Height above mean elevation [m]
Distance from corner station [km]
Kuns

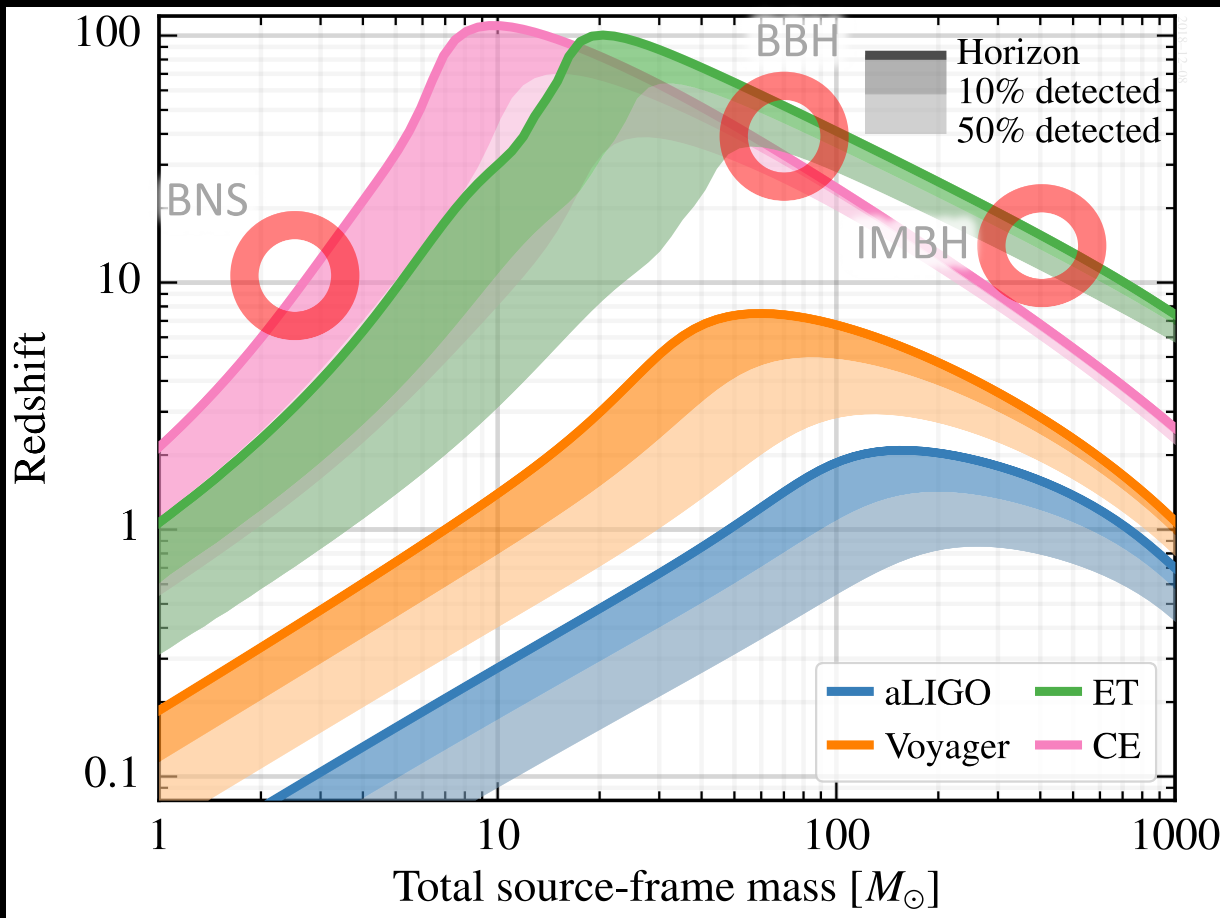
Why 40km?

- Broadly speaking, the sensitivity of these instruments improves with length
- The bandwidth is, however, limited to roughly

$$\frac{c}{2L} = \frac{3\times10^5 \frac{km}{s}}{2\times40\ km} \simeq 4\ kHz$$

so making a detector longer than 40km would compromise its access to interesting astrophysics (i.e., post-merger signals and supernovae).

What can CE do?



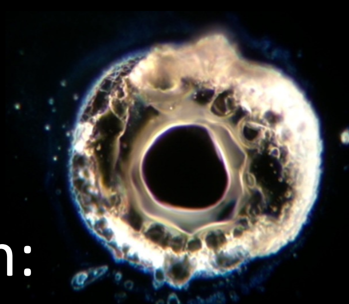
Noise improvements: reducing quantum noise

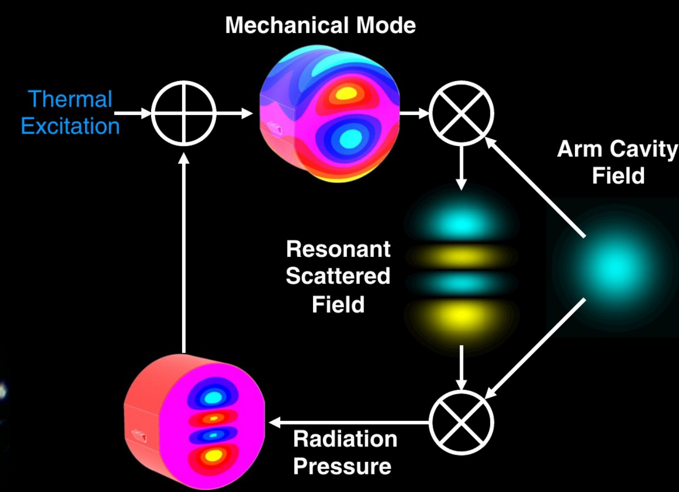
- Increasing the laser power in the arms

  O1,O2 (100kW) → O3 (200kW) → goal is 400 kW for O4
- Not easy!

  - You need a high power laser first..
  - Mirror radii must remain within a few meters of the ~2 kilometer nominal value
  - Control issues: angular control and parametric instabilities
  - ``Point absorbers”

    Applied Optics Vol. 60, Issue 13 pp. 4047-4063 (2021)



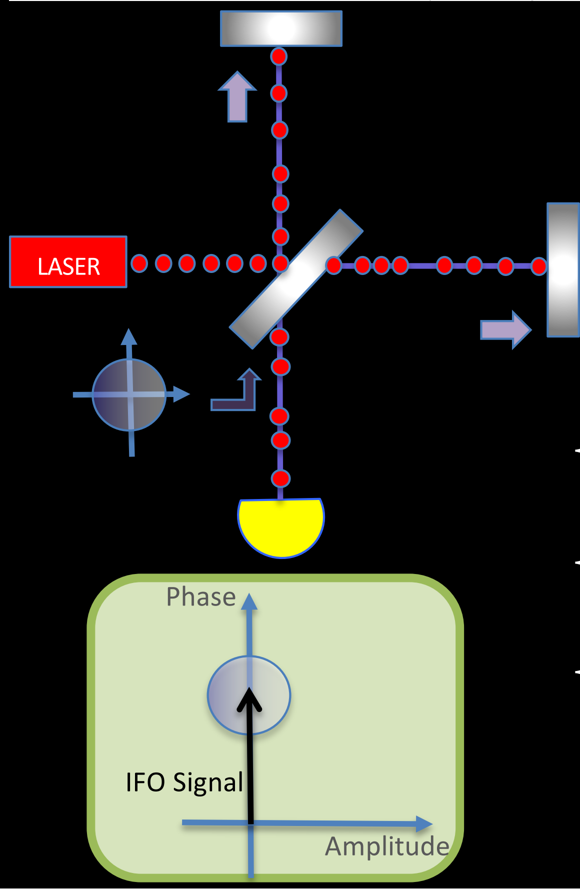


- Complementary approach: squeezed states of vacuum

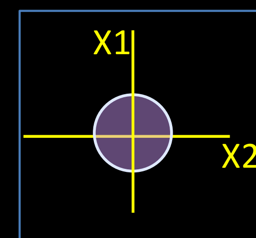
PHYSICAL REVIEW D VOLUME 23, NUMBER 8 15 APRIL 1981

Quantum-mechanical noise in an interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 15 August 1980)



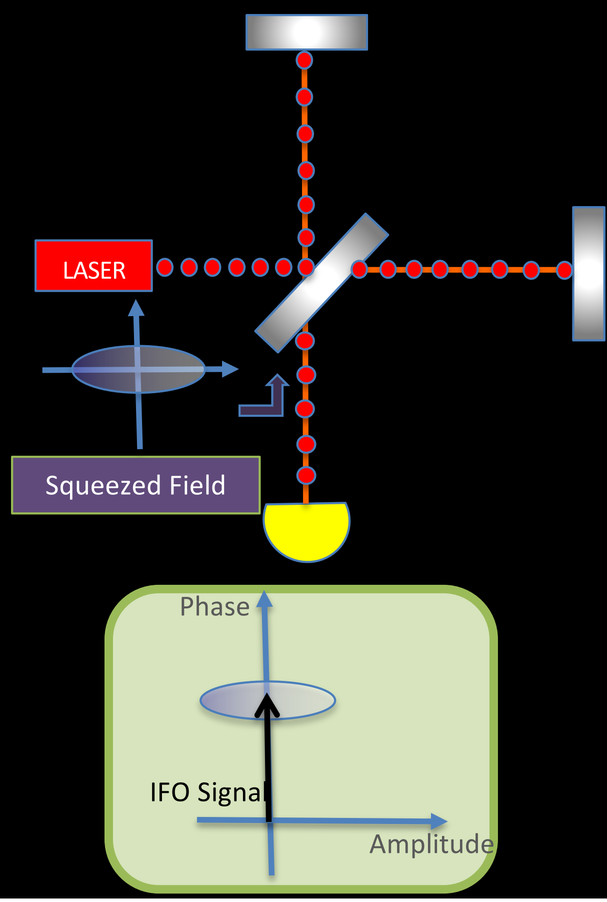
Zero-point energy
(vacuum) fluctuations



$$\Delta X_1 \, \Delta X_2 \geq 1$$

- When average amplitude is zero, the variance remains
- Heisenberg uncertainty principle, quadratures associated with **amplitude** and **phase**
- They enter the interferometer from all the open ports of the interferometer, but the ones which matter are the one **entering from the anti-symmetric port**!

Replace regular vacuum with squeezed vacuum

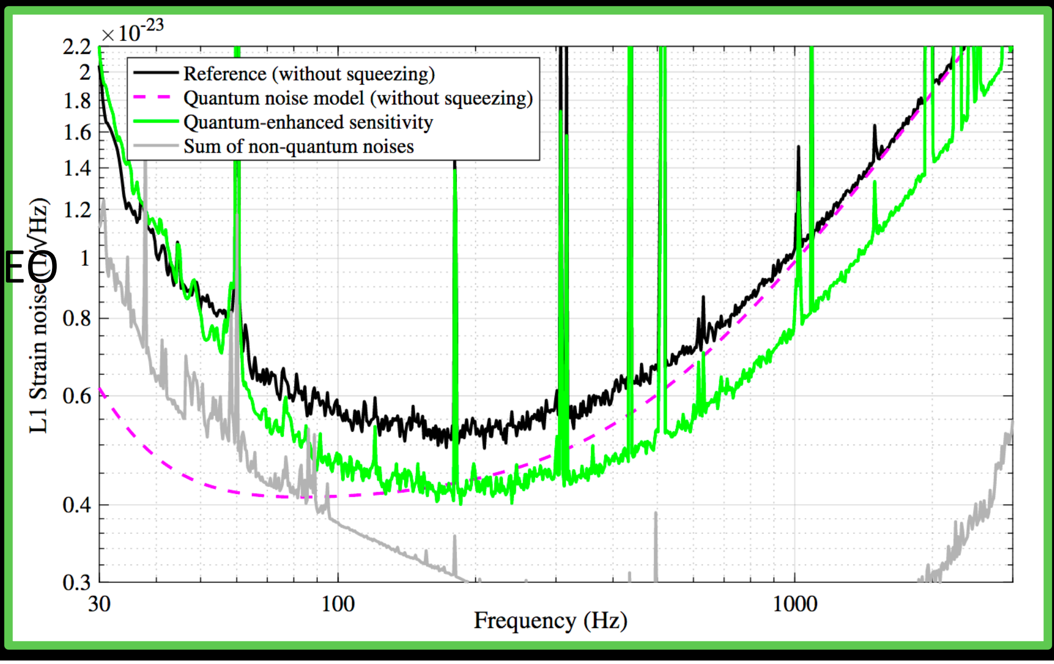


✧ Reduce quantum noise by injecting squeezed vacuum: less uncertainty in one of the two quadratures
✧ Heisenberg uncertainty principle: if the noise gets smaller in one quadrature, it gets bigger in the other one
✧ One can choose the relative orientation between the squeezed vacuum and the interferometer signal (squeeze angle)
✧Squeezing is made by creating pairs of photons using an optical parametric oscillator
✧The pairs are quantum-mechanically entangled and have correlated arrival times at the detector
✧This reduces the randomness of the time distribution

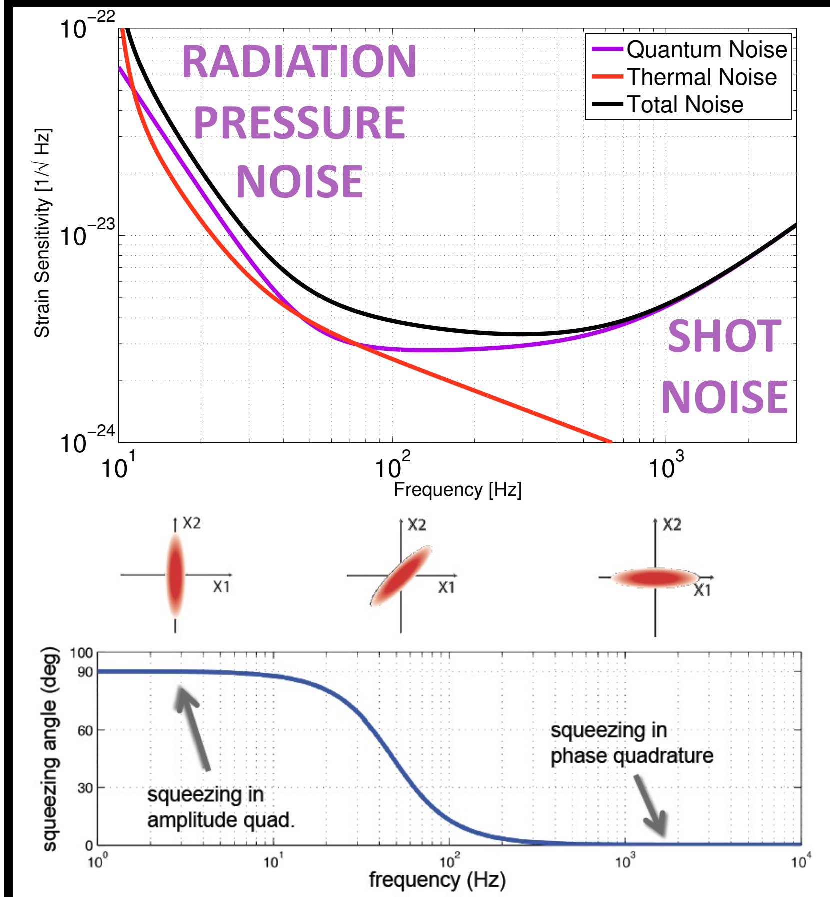
Squeezing performance in O3

PhysRevLett.123.231107 *Nature 583, pages 43–47 (2020)*

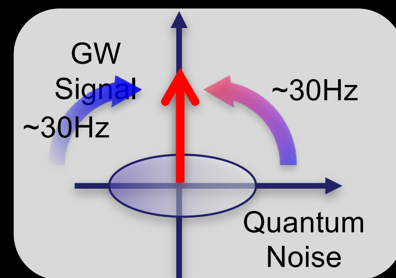
3 dB of squeezing observed at high frequency = 40% quantum noise reduction (in amplitude); observation of quantum radiation pressure noise in both detectors

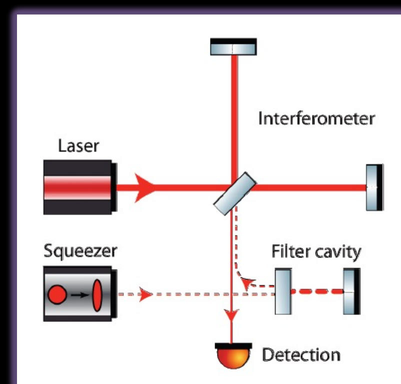


Frequency **Dependent** Squeezing for O4



Kimble et al., Phys. Rev. D 65**(2) 022002** 2001





High finesse detuned **"filter cavity"** which rotates the squeezing angle as function of frequency

Highlight from Virgo:
300 m filter cavity already built and locked and characterized, commissioning in progress