Current and Future Gravitational Wave Detectors

Artist: Eddie Anaya (Cal State Fullerton)

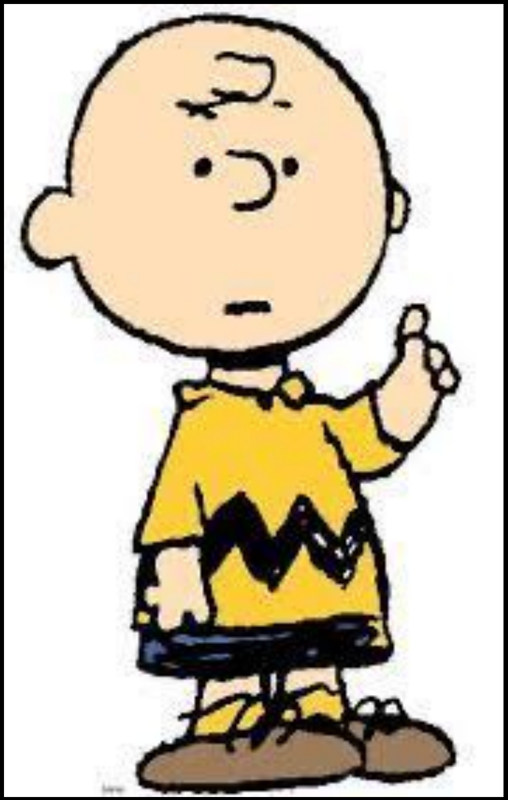
Santa Cruz, CA, July 21/22
Stefan Ballmer


Sorry for the virtual presence…
DELTA
DELTA

Please do interrupt me with question

- This is your talk

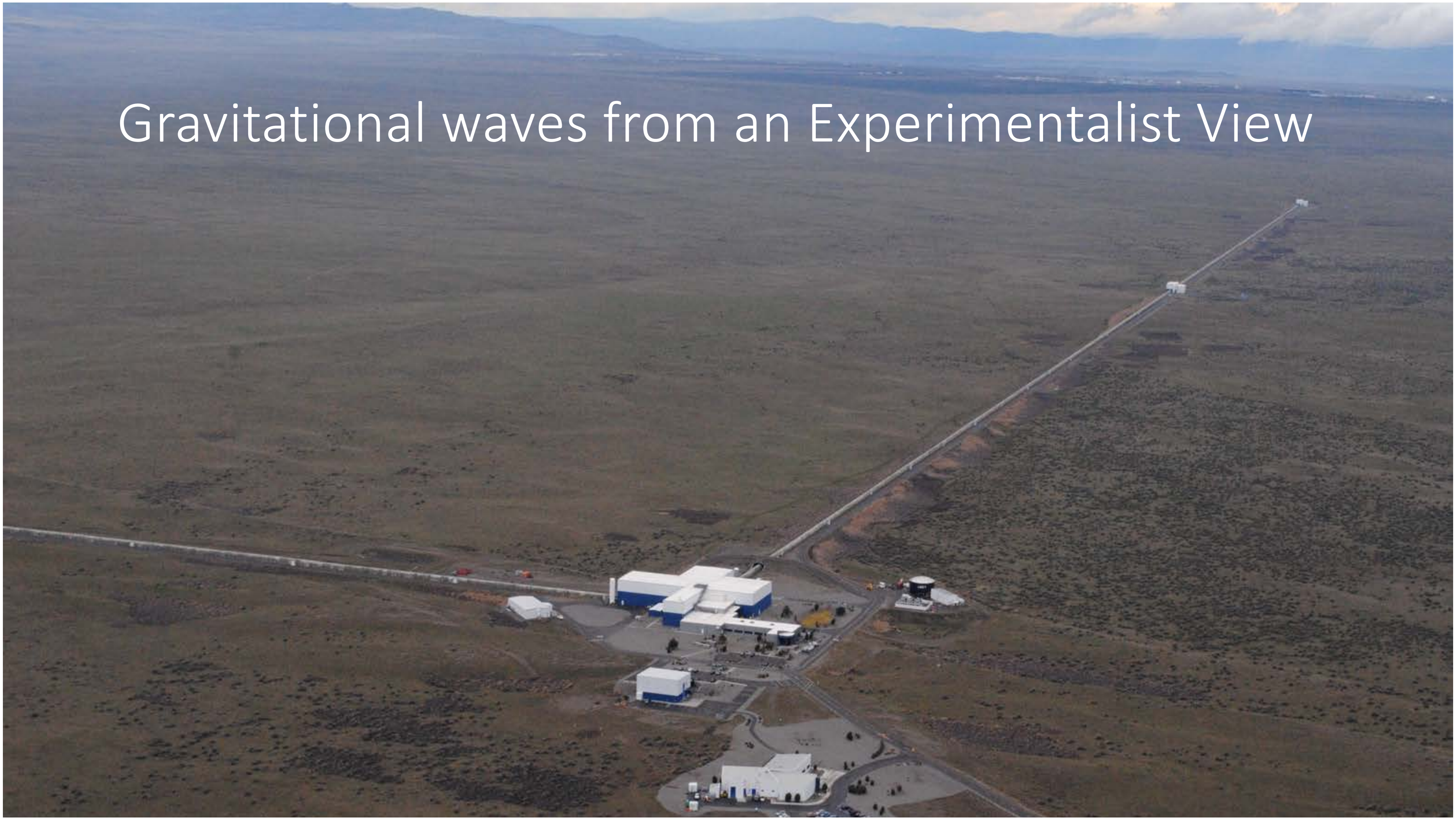
- Zoom makes it hard enough
  So don’t hesitate to speak up!



Outline

- Day 1
  - Gravitational waves from an Experimentalist View
    - History of the field
  - How can you measure them in principle?
    - Scale of effect
    - How to read out such small motions (Classical Shot Noise)
    - How to isolate all other large motion (Seismic isolation, Newtonian noise, Thermal Noise)
  - How is Advanced LIGO doing in O4?
- Day 2
  - Key Technologies for the Future
    - Beyond Quantum Noise (Quantization of EM field, squeezing)
  - Cosmic Explorer: the Next-generation of US GW detectors
- Will not talk about sources
  - See presentations from Jim Lattimer and Neil Cornish for that

Gravitational waves from an Experimentalist View



SITZUNGSBERICHTE 1916.

XXXIII.

DER

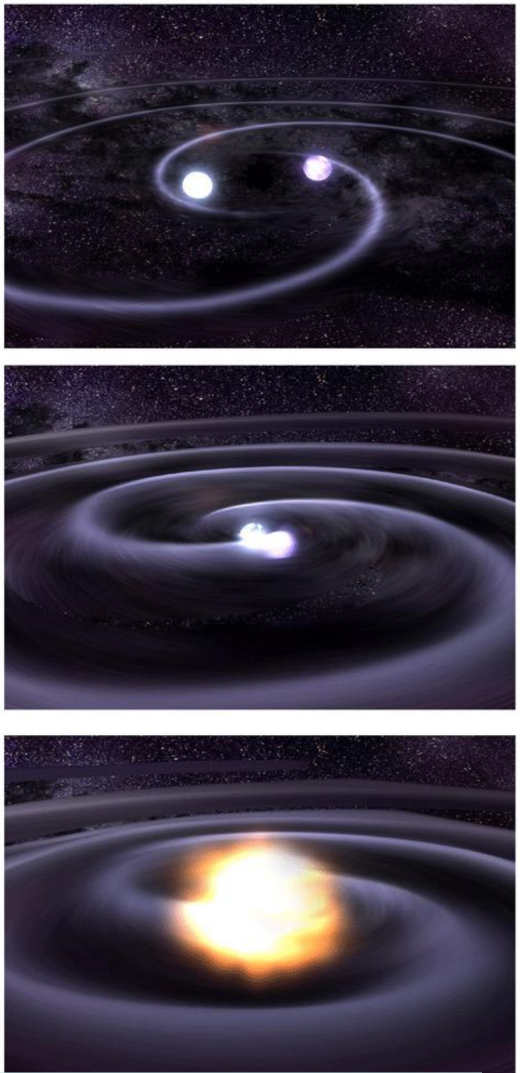
KÖNIGLICH PREUSSISCHEN

AKADEMIE DER WISSENSCHAFTEN.

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

“Approximate integration of the field equations of gravitation”



NASA/Dana Berry, Sky Works Digital

Gravitational Waves Quadrupole Formula

"Curvature of Space-Time" "Matter"

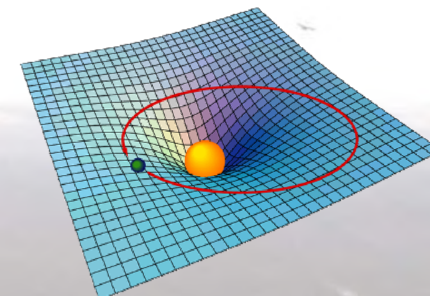
$$G_{\mu\upsilon} = \frac{8\pi G}{c^4} T_{\mu\upsilon}$$

Linearize

$$-\frac{1}{2}\Box\tilde{h}_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Emitting source

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



I: Quadrupole moment of source

Über Gravitationswellen.

Von A. Einstein.

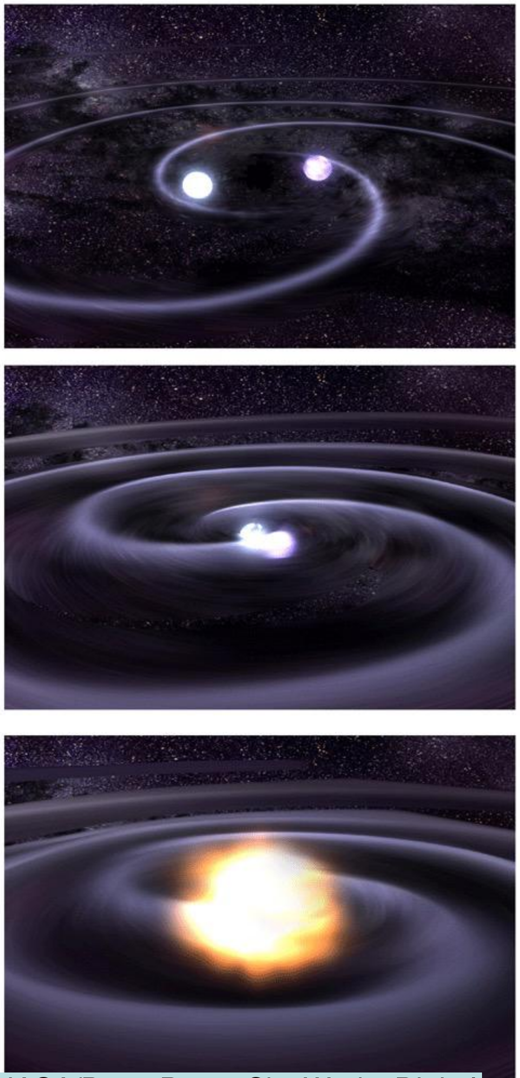
(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

"… is disfigured by a regrettable calculation error… "

Signal Amplitude

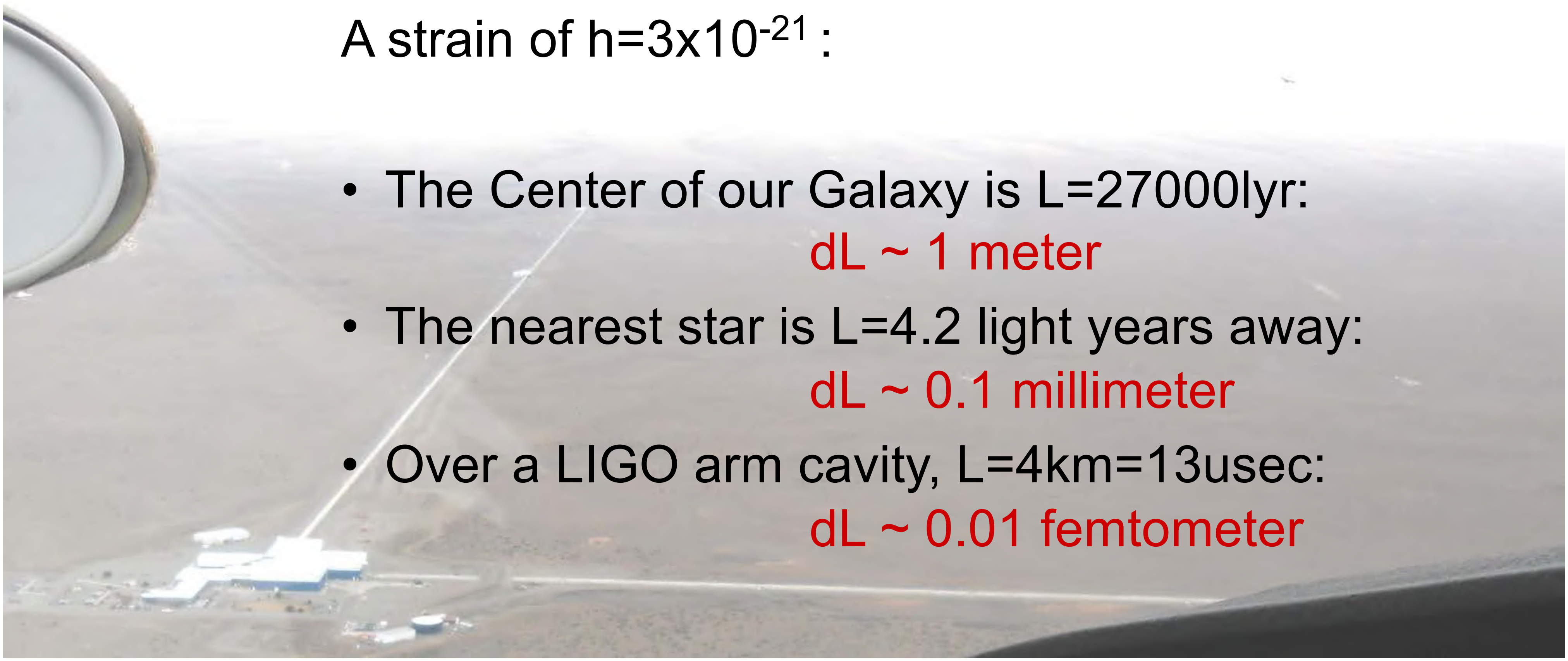

NASA/Dana Berry, Sky Works Digital

- For 2 1.4M_{Sun} Neutron stars, at 1 Mpc (3 million light years):

$$h = \frac{dL}{L} \approx 3 \times 10^{-21}$$

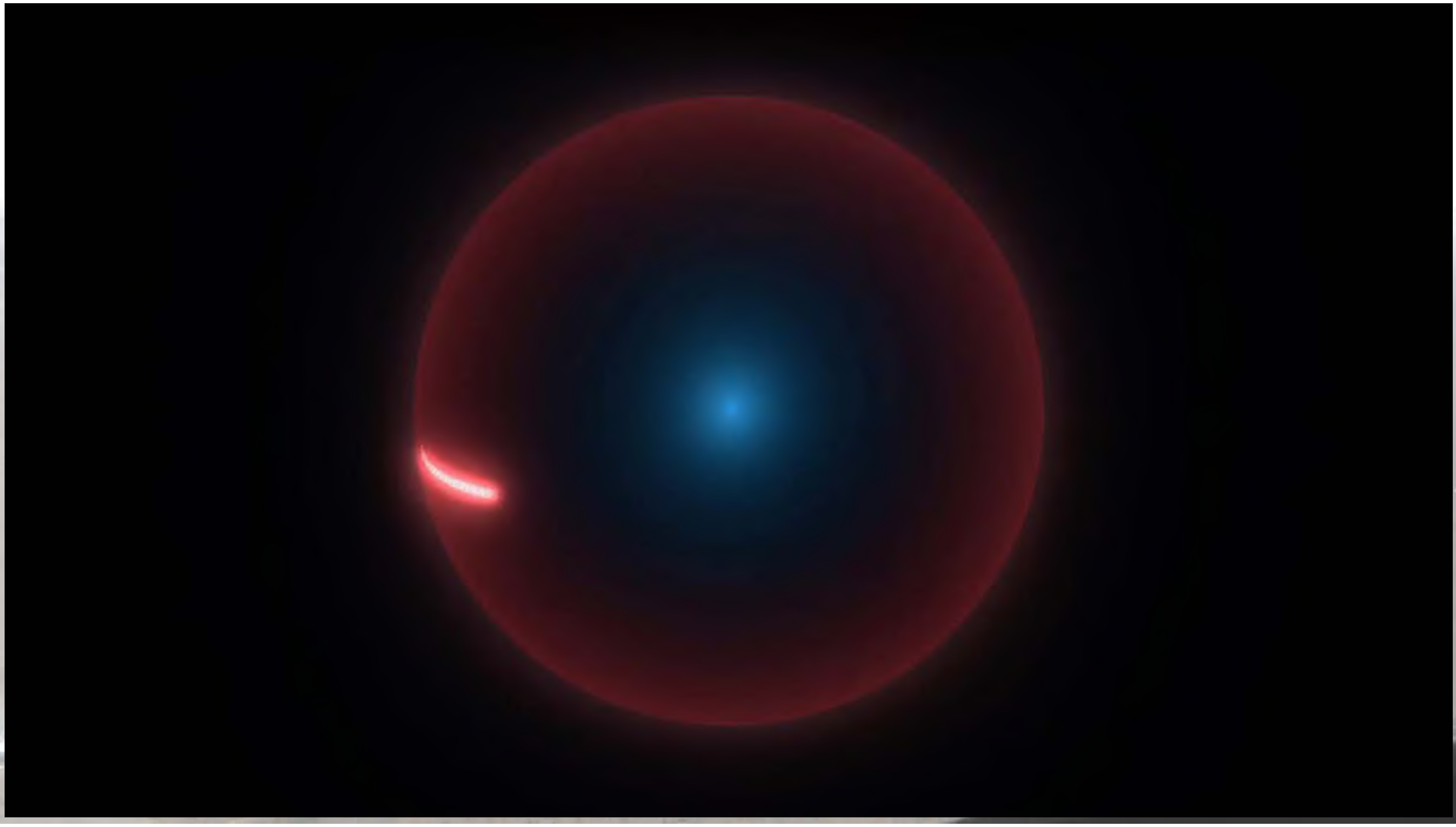
Signal Amplitude

A strain of $h=3x10^{-21}$:



- The Center of our Galaxy is L=27000lyr:
  dL ~ 1 meter
- The nearest star is L=4.2 light years away:
  dL ~ 0.1 millimeter
- Over a LIGO arm cavity, L=4km=13usec:
  dL ~ 0.01 femtometer

Signal Amplitude



Before 1957

"… in all imaginable cases A must have a practically vanishing value.

ein. Man erhält aus ihm also die Ausstrahlung A des Systems pro Zeiteinheit durch Multiplikation mit $4\pi R^2$:

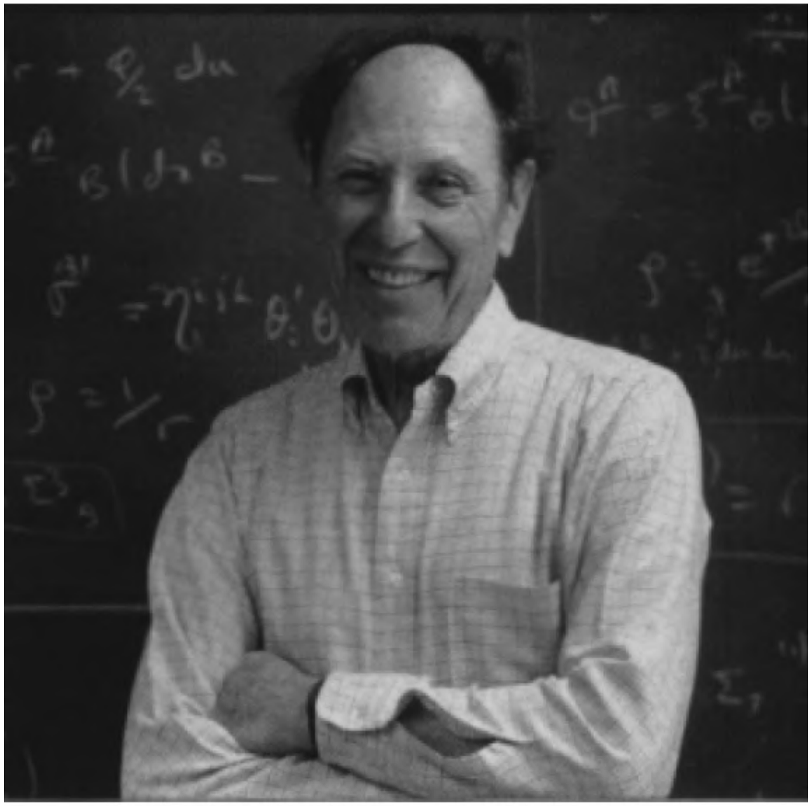
$$A = \frac{\varkappa}{24\pi} \sum_{\alpha\beta} \left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3} \right)^2 . \qquad (21)$$

Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

Josh Goldberg in 1957

Josh was working at Wright Patterson AFB. In addition to his own research (searching for anti-gravity?), he was the funding officer for the USAF's support for research in relativity.

Josh made it possible for relativity to thrive worldwide.



Josh Goldberg, Syracuse University

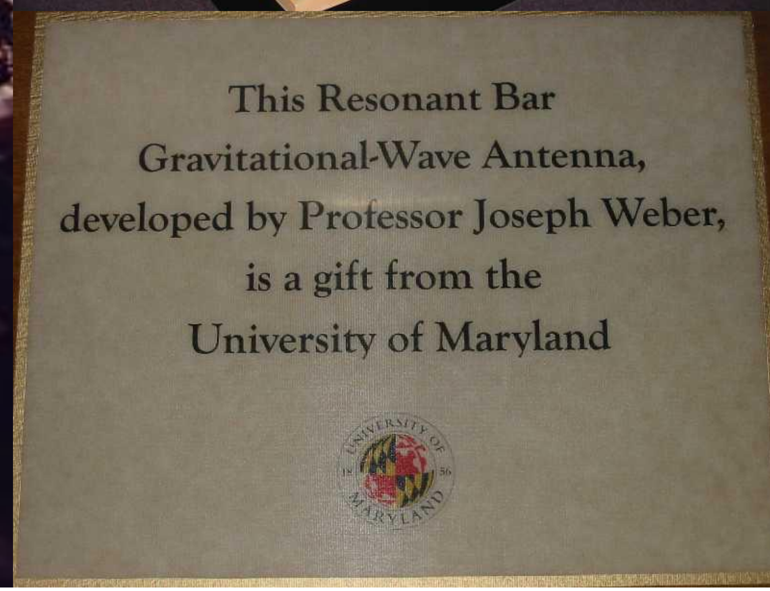
The Chapel Hill Conference

In January 1957, Josh sponsored the Conference on the Role of Gravitation in Physics, a.k.a. the Chapel Hill Conference, a.k.a. GR1. The organizers were Bryce and Cecile DeWitt. 44 of the world's leading relativists attended.

Much of the future of gravitational physics was launched then. (Numerical relativity was prefigured in a remark by Charles Misner.)

The "gravitational wave problem" was solved there, and the quest to detect gravitational waves was born.


1960s and '70s:
First gravitational wave detectors
By Joseph Webber


This Resonant Bar
Gravitational-Wave Antenna,
developed by Professor Joseph Weber,
is a gift from the
University of Maryland

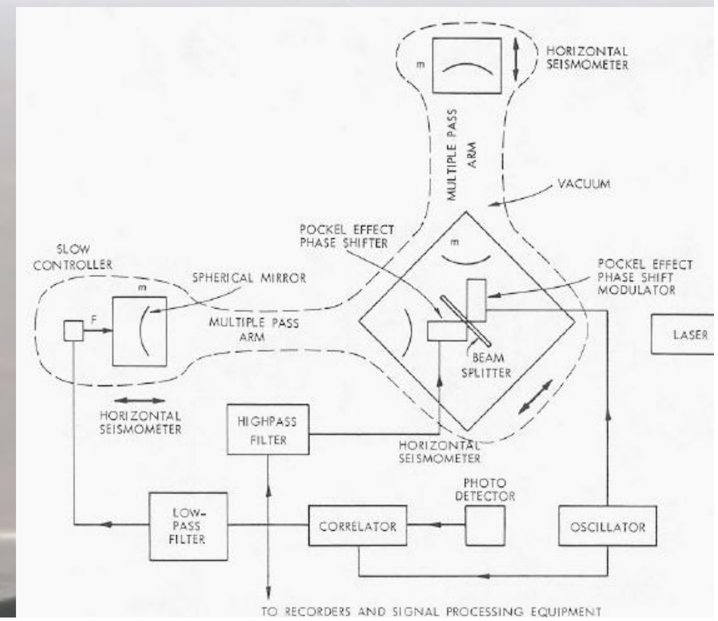
1972: Gravitational Wave Antenna

- Electromagnetically coupled broad-band gravitational wave antenna, R.Weiss, MIT RLE QPR 1972

- Use a laser to compare the length of the interferometer arms!

1972

2017



MIT Research Laboratory of Electronics Quarterly Progress Report 1972

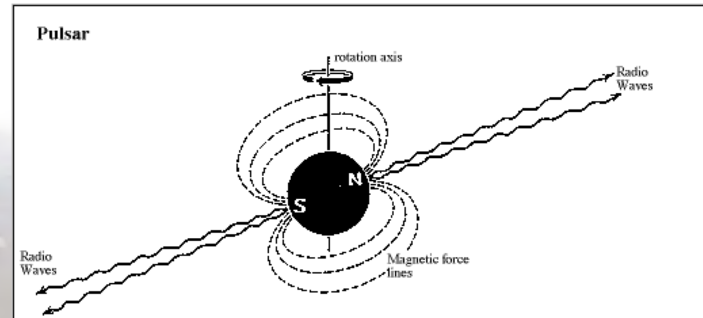
The discovery of the pulsars may have uncovered sources of gravitational radiation which have extremely well-known frequencies and angular positions. The fastest known pulsar is NP 0532, in the Crab Nebula, which rotates at 30.2 Hz. The gravitational flux incident on the Earth from NP 0532 at multiples of 30.2 Hz can be 10^{-6} erg/cm^2/s at most. This is

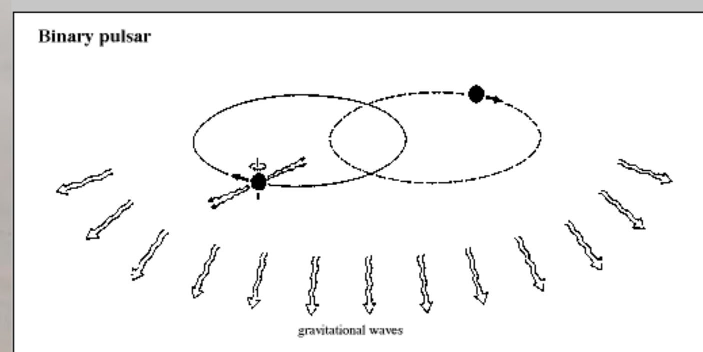
The antenna arms can be made as large as is consistent with the condition that the travel time of light in the arm is less than one-half the period of the gravitational wave that is to be detected. This points out the principal feature of electromagnetically coupled antennas relative to acoustically coupled ones such as bars; that an electromagnetic antenna can be longer than this acoustic counterpart in the ratio of the speed of light to the speed of sound in materials, a factor of 10^5. Since it is not the strain but rather the differential displacement that is measured in these gravitational antennas, the proposed antenna can offer a distinct advantage in sensitivity relative to bars in detecting both broadband and single-frequency gravitational radiation. A significant improvement in thermal noise can also be realized.

Relativistic Binary Pulsar B1913+16

R. A. Hulse J. H. Taylor

- First binary Pulsar
  - Spinning neutron star with radio beacon
- Discovered in 1974
- Loses energy by radiating gravitational waves



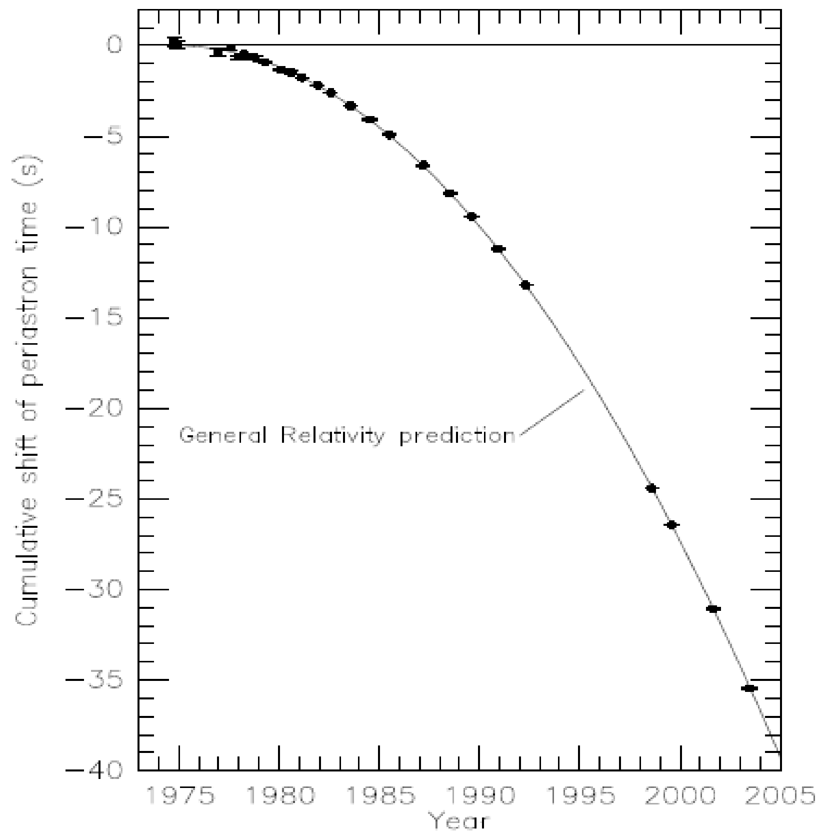


KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES
1993

Relativistic Binary Pulsar B1913+16

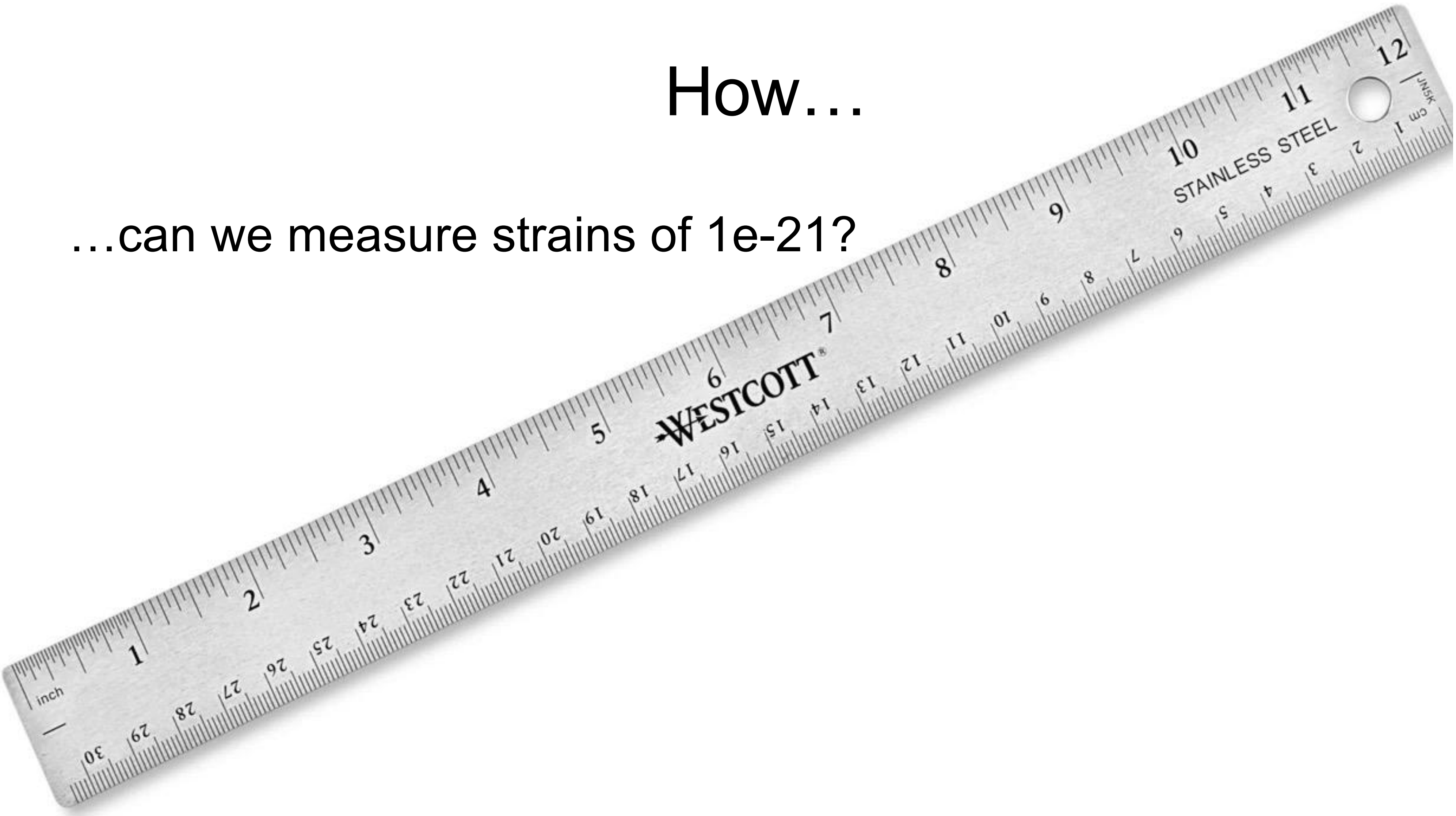
- Nobel prize in 1993
- Orbital parameters measured for 30yr!
- Energy loss agrees with GW emission
- Standard source for GW observatories
  - Merges in 300Myr

Weisberg, Taylor, arXiv:astro-ph/0407149



How…

…can we measure strains of 1e-21?



The wave's field

- "Ripples in Space-Time"

Amplitude:

dL/L = h

- Measureable effect:
  - Stretches/contracts distances perpendicular to propagation

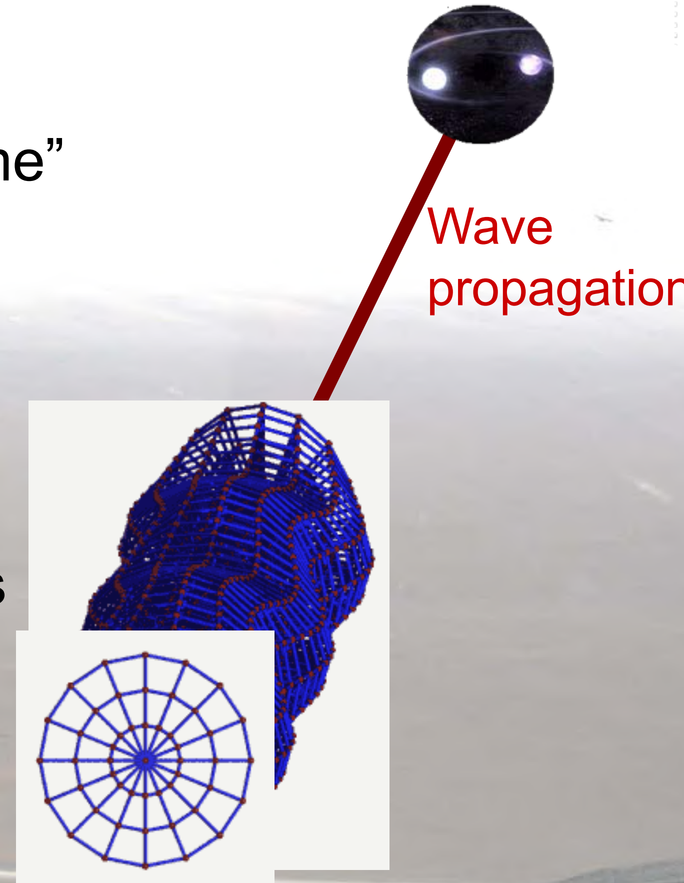


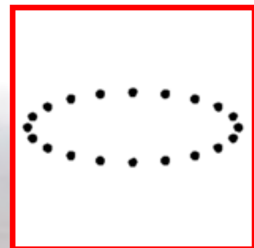
Image credit: Markus Pössel,
Einstein Online **Vol. 02** (2006), 1008

LIGO

The wave’s field

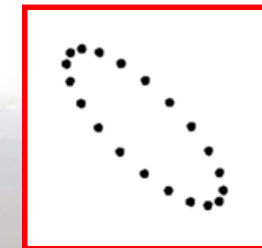
SYRACUSE UNIVERSITY · FOUNDED A·D· 1870 · SUOS CULTORES SCIENTIA CORONAT

- 2 polarizations:



+ polarization

$$ds^2 = (1+h)dx^2 + (1-h)dy^2$$

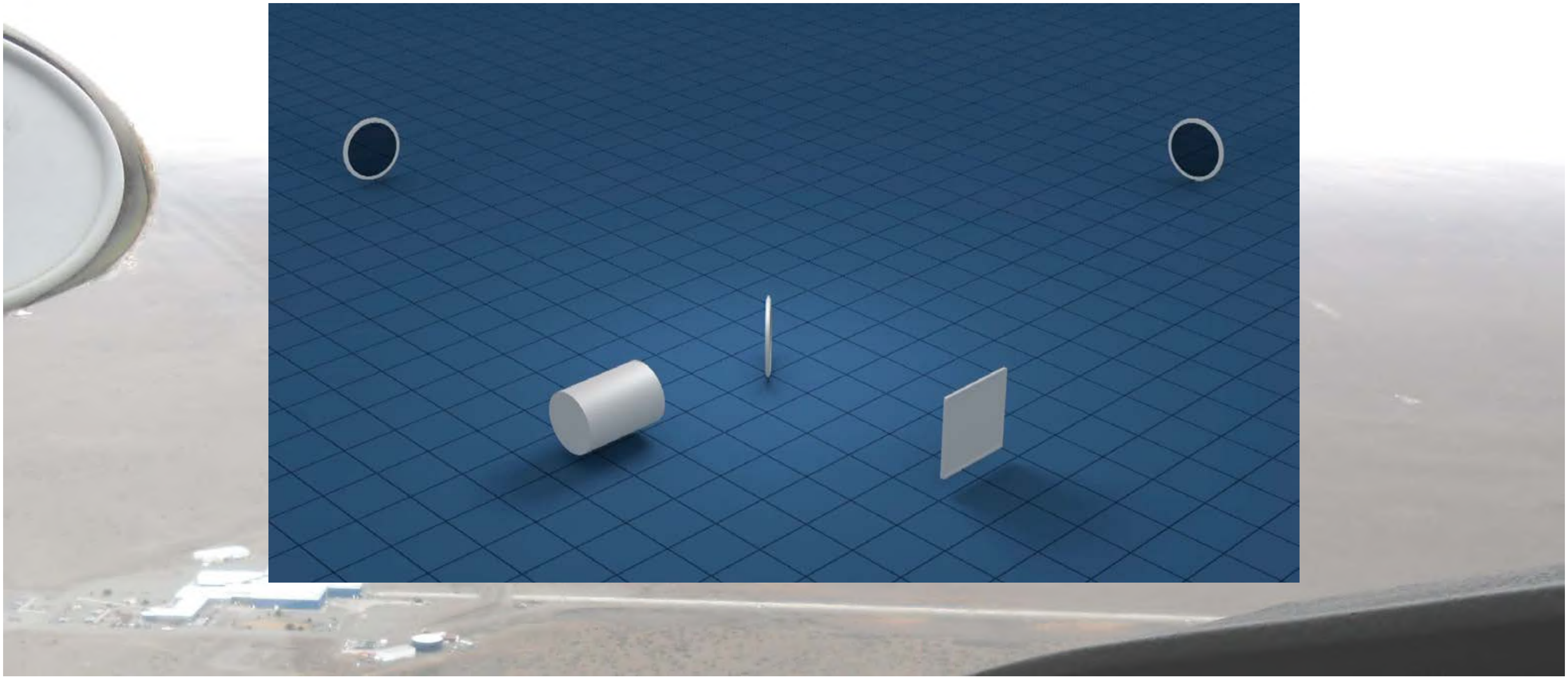


x polarization

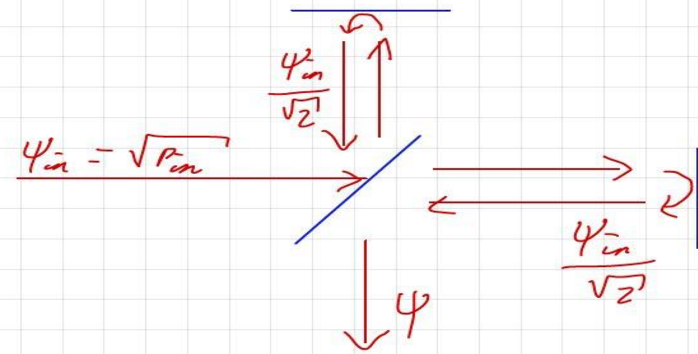
$$ds^2 = dx^2 + dy^2 + 2h dx dy$$

- Note:
  Test particle remain at rest - only their separation changes!

The interferometer



Michelson interferometer shot noise



$$\psi = \frac{\psi_{in}}{2}\left(e^{ik\Delta L} - e^{-ik\Delta L}\right)$$

$$= i\,\psi_{in}\,\sin k\Delta L$$

$$P = |\psi|^2 = P_{in}\,\sin^2 k\Delta L = P_{in}\,\frac{1-\cos 2k\Delta L}{2}$$

Differential Arm Length (DARM):

$$\Delta L = L_x - L_y$$

- $2k\Delta L = 0 \pmod{2\pi} \Rightarrow$ Dark fringe (A)
  $2k\Delta L = \frac{\pi}{2} \pmod{2\pi} \Rightarrow$ Half fringe (B)
  $2k\Delta L = \pi \pmod{2\pi} \Rightarrow$ Bright fringe (C)
  Somewhere else (D)

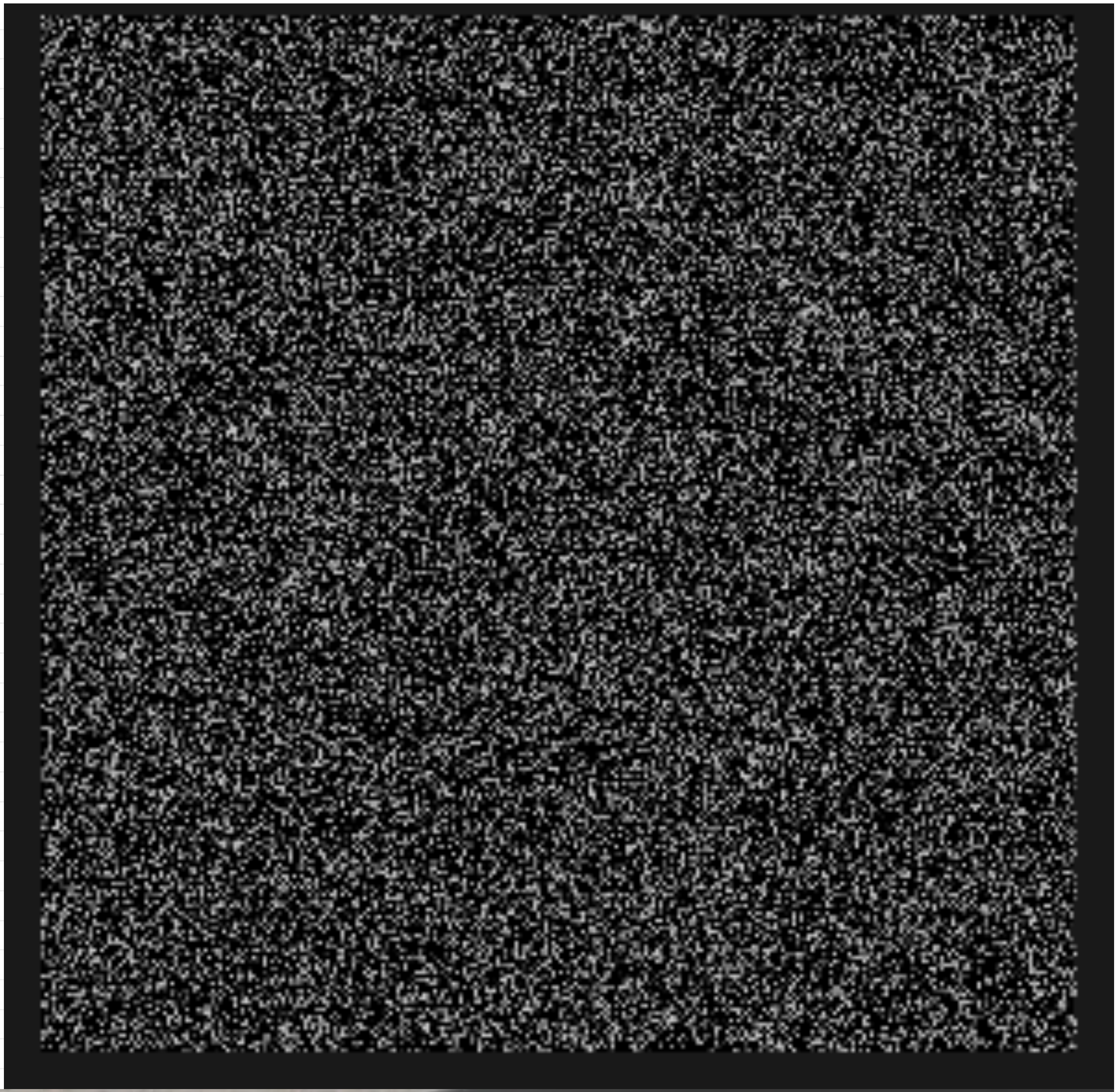
Where should we operate?

- $\frac{dP}{d\Delta L} = P_{in}\,k \cdot \sin 2k\Delta L$

$$= P_{in}\,k \cdot 2 \cdot \sin k\Delta L \cdot \cos k\Delta L$$

Measuring Power

- Interferometer translates length fluctuations into laser power fluctuations
- What is the limit on how precisely we can measure laser power?
- Light is quantized
    - Shot noise!



Shot noise (classical)

Random photon arrival times t_j :

Pulse train p(t):

$$p(t) = \sum_{j=1}^{N} A\,\delta(t - t_j)$$

N: Number of quanta

A: Unit of quanta

T: observation time

$$n := \langle p(t) \rangle = \frac{NA}{T} \quad \text{rate} \begin{cases} \text{Watts} \\ \text{Ampere} \\ \text{quanta/sec} \end{cases}$$

Note: Fourier transform of δ-function $\propto e^{-i2\pi f t_j}$

t_i are random ==> phases are random and will average out ==> power spectrum will be white $S_p(f) = \text{const}(\text{in } f)$

Auto-correlation function:

$$R_{pp}(\tau) := \frac{1}{T}\int_{-T/2}^{T/2} dt\; p(t)\,p(t+\tau) = \frac{1}{T}\sum_{j=1}^{N}\sum_{k=1}^{N} A^2\,\delta(t_j - t_k + \tau)$$

Power spectral density is the Fourier transform of the Auto-correlation function:

$$S_{pp}^{2\text{-sided}}(f) = \int R_{pp}(\tau)\, e^{-2\pi i f \tau}\, d\tau = \frac{A^2}{T}\sum_{j=1}^{N}\sum_{k=1}^{N} e^{-2\pi i f (t_j - t_k)}$$

$$= \frac{A^2}{T}\Bigg[\underbrace{\sum_{j=1}^{N} e^{0}}_{N} + \sum_{j=1}^{N}\sum_{\substack{k=1 \\ k\neq j}}^{N} \underbrace{e^{-2\pi i f (t_j - t_k)}}_{\Downarrow\, t_j \text{ random} \;\to\; 0}\Bigg] = \frac{A^2 N}{T} = n\,A$$

One-sided PSD (only positive frequencies):

$$S_{pp}^{1\text{-sided}}(f) = 2\,n\,A$$

$\Longrightarrow$

Amplitude Spectral Density:

$$S_{p}^{1\text{-sided}}(f) = \sqrt{2\,n\,A}$$

⇒ Quanta shot noise: $S_n(f) = \sqrt{2\, n \quad 1}$ n : Rate $\left(\frac{\text{quanta}}{\text{sec}}\right)$

Laser power shot noise: $S_P(f) = \sqrt{2\, P\, h\nu}$ P : Power (Watt)

Photo current shot noise: $S_I(f) = \sqrt{2\, I\, e}$ I : Current (Ampere)

Shot noise

$$S_P(f) = \sqrt{2 P h\nu} = \sqrt{2 P_{in} h\nu}\ \sin k\delta L$$

$$= S_L(f) = S_P(f)\,\frac{d\delta L}{dP} = \frac{\sqrt{2 P_{in} h\nu}\ \sin k\delta L}{P_{in}\, k \cdot \sin 2k\delta L}$$

$$= \frac{\lambda}{\pi}\sqrt{\frac{2h\nu}{P_{in}}}\cdot\frac{1}{\cos k\delta L}$$

$k = \frac{2\pi}{\lambda}$

Wave length is the meter stick

$\nu \propto \frac{1}{\lambda}$

$\Rightarrow$ Scales with $\sqrt{\lambda}$

Scales with $P_{in}^{-\frac{1}{2}}$

Operate close to the dark fringe

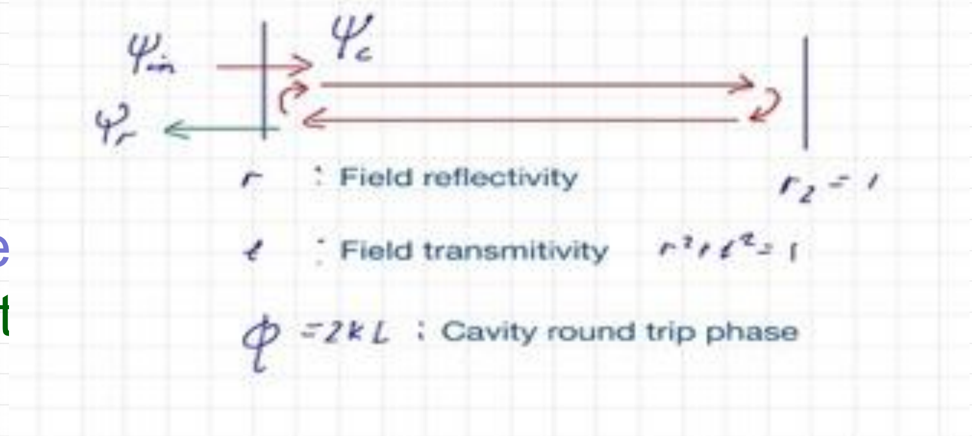
Arm Length

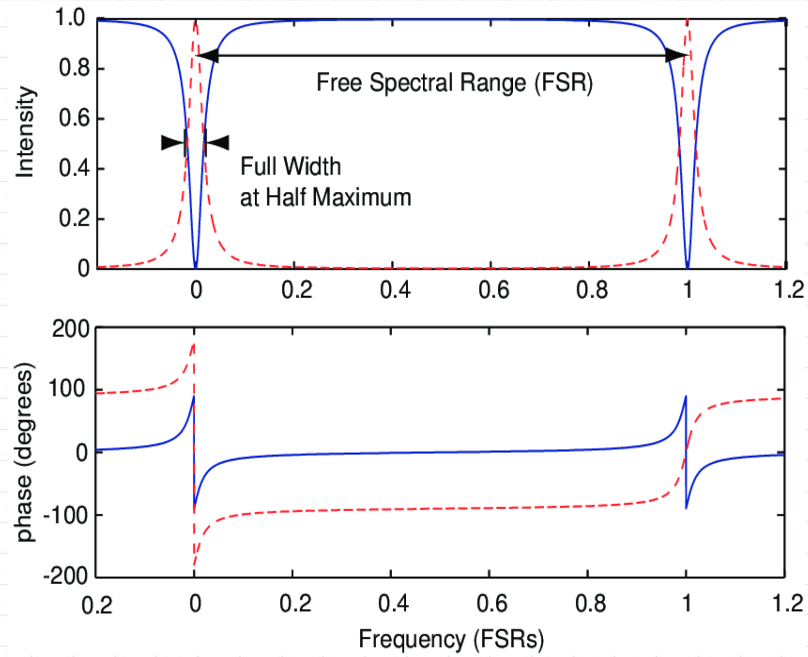
- At DC: dx = L h
- But h(t) changes ➔if L is too long, the interrogation time is too long, and we start averaging. Roughly at L=λ/4
- At 100Hz: λ/4 = 750km
- At 1kHz: λ/4 =   75km
- No easy way to adjust effective length

Arm Cavities

- Instead of extremely long arm we can use a partially reflective input mirror (ITM) in the arm
  ➔ Fabry-Perot cavities

- Enhances phase sensitivity
- Allows for shorter arms
- Interrogation time set by input mirror (and signal extraction mirror…)
- But increases mirror thermal noise (more on that later)





Fabry-Perot arm cavities

$$\Psi_c = r e^{i\phi}\Psi_c + t\,\Psi_{in}$$
$$\Psi_r = t e^{i\phi}\Psi_c - r\,\Psi_{in}$$

Laser field:

r : Field reflectivity $\quad r_2 = 1$

t : Field transmitivity $\quad r^2 + t^2 = 1$

$\phi = 2kL$: Cavity round trip phase

$$\Rightarrow \Psi_c = \frac{t}{1 - r e^{i\phi}}\,\Psi_{in}$$

$\phi \sim 0$:

$$\Psi_r = \frac{t^2 \cdot (1 + i\phi)}{1 - r - i r \phi}\,\Psi_{in} - r\,\Psi_{in}$$
$$= \frac{1-r^2}{1-r}\,\frac{1 + i\phi}{1 - i\frac{r}{1-r}\phi}\,\Psi_{in} - r\,\Psi_{in}$$
$$\sim (1+r)\left[1 + i\phi\left(\frac{1}{1-r}\right)\right]\Psi_{in} - r\,\Psi_{in}$$
$$= \left(1 + i\phi\,\frac{1+r}{1-r}\right)\Psi_{in}$$
$$\sim e^{i\frac{1+r}{1-r}\phi}\,\Psi_{in}$$

$\Rightarrow$ Phase enhancement by:

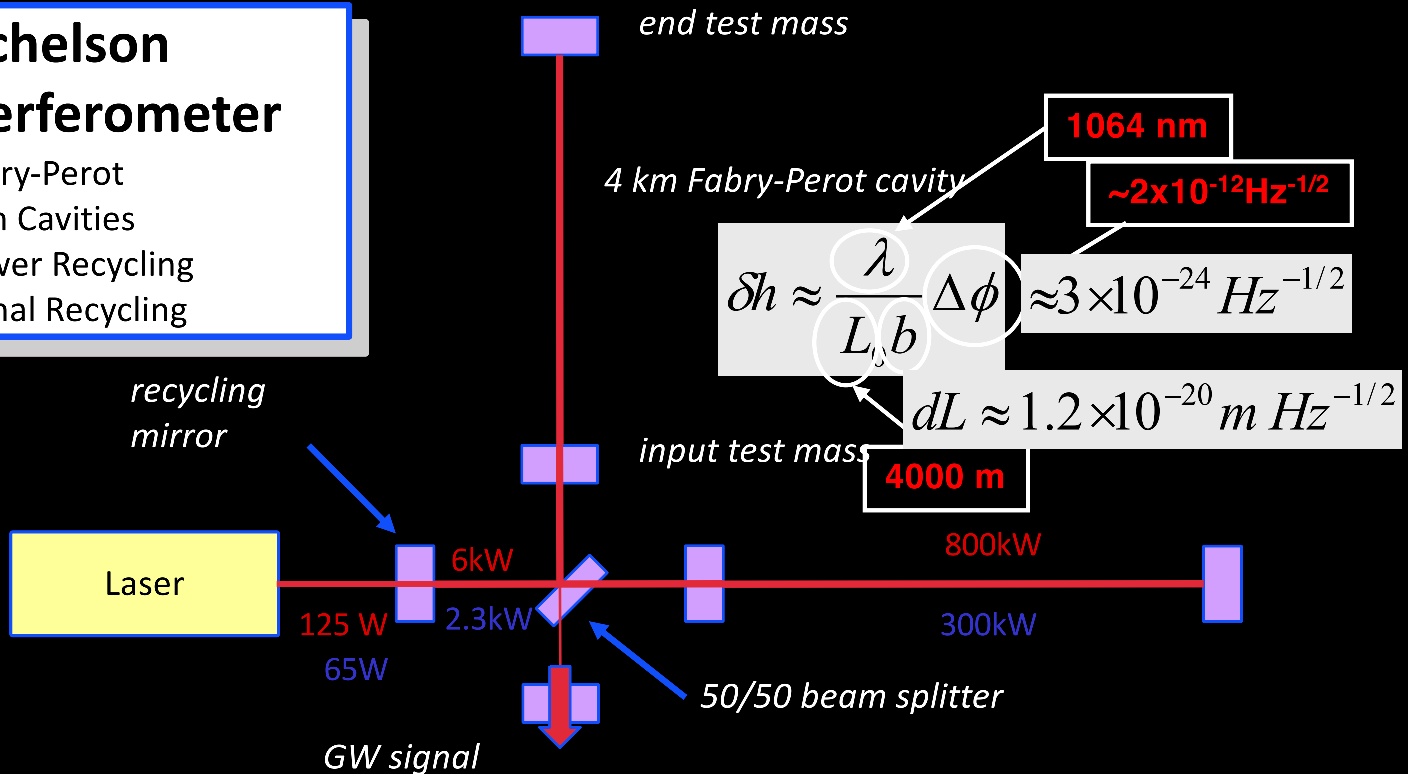
$$\measuredangle\left(\frac{\Psi_r}{\Psi_{in}}\right) = \frac{1+r}{1-r}\,\phi$$

$$\underset{\text{AdvLIGO}}{\simeq} 280\,\phi$$

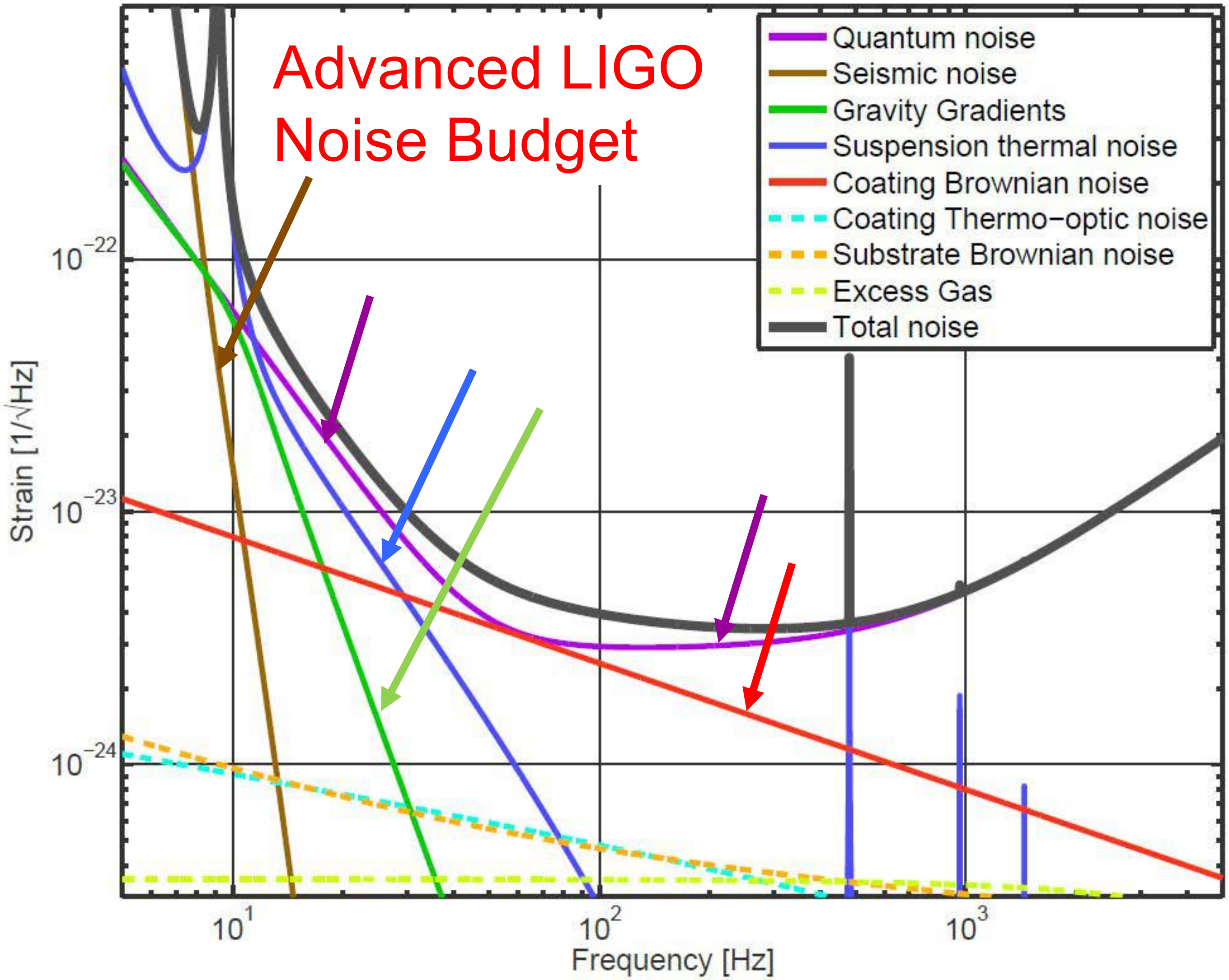
Interferometer Sensitivity

Michelson Interferometer

+ Fabry-Perot Arm Cavities
+ Power Recycling
+ Signal Recycling

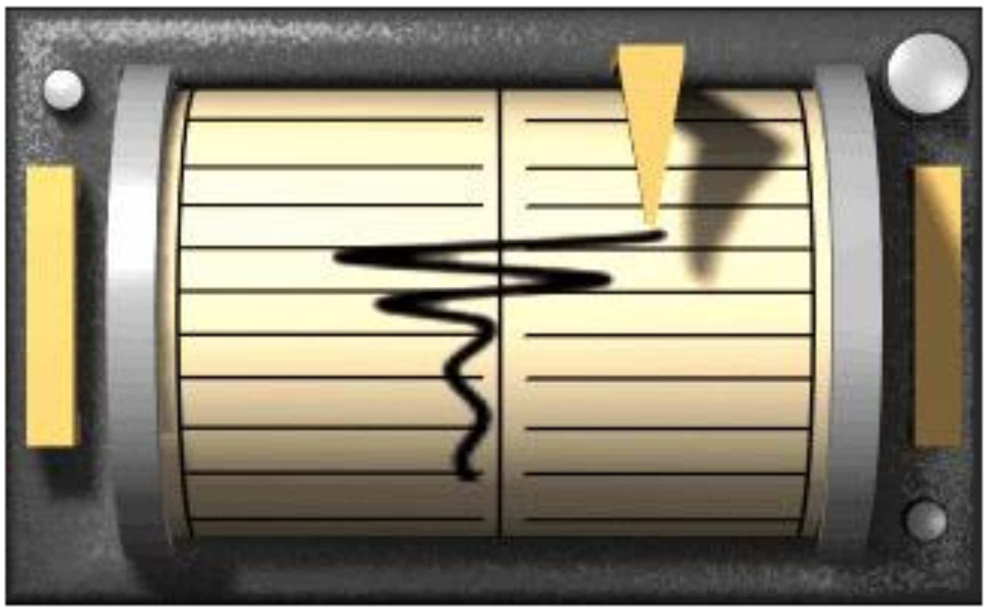


(Numbers: Red: for aLIGO design)
(Blue: for aLIGO 2022)


Advanced LIGO
Noise Budget
Quantum noise
Seismic noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo−optic noise
Substrate Brownian noise
Excess Gas
Total noise
Strain [1/√Hz]
10^−22
10^−23
10^−24
10^1
10^2
10^3
Frequency [Hz]

How…

…do we isolate from any other motion?

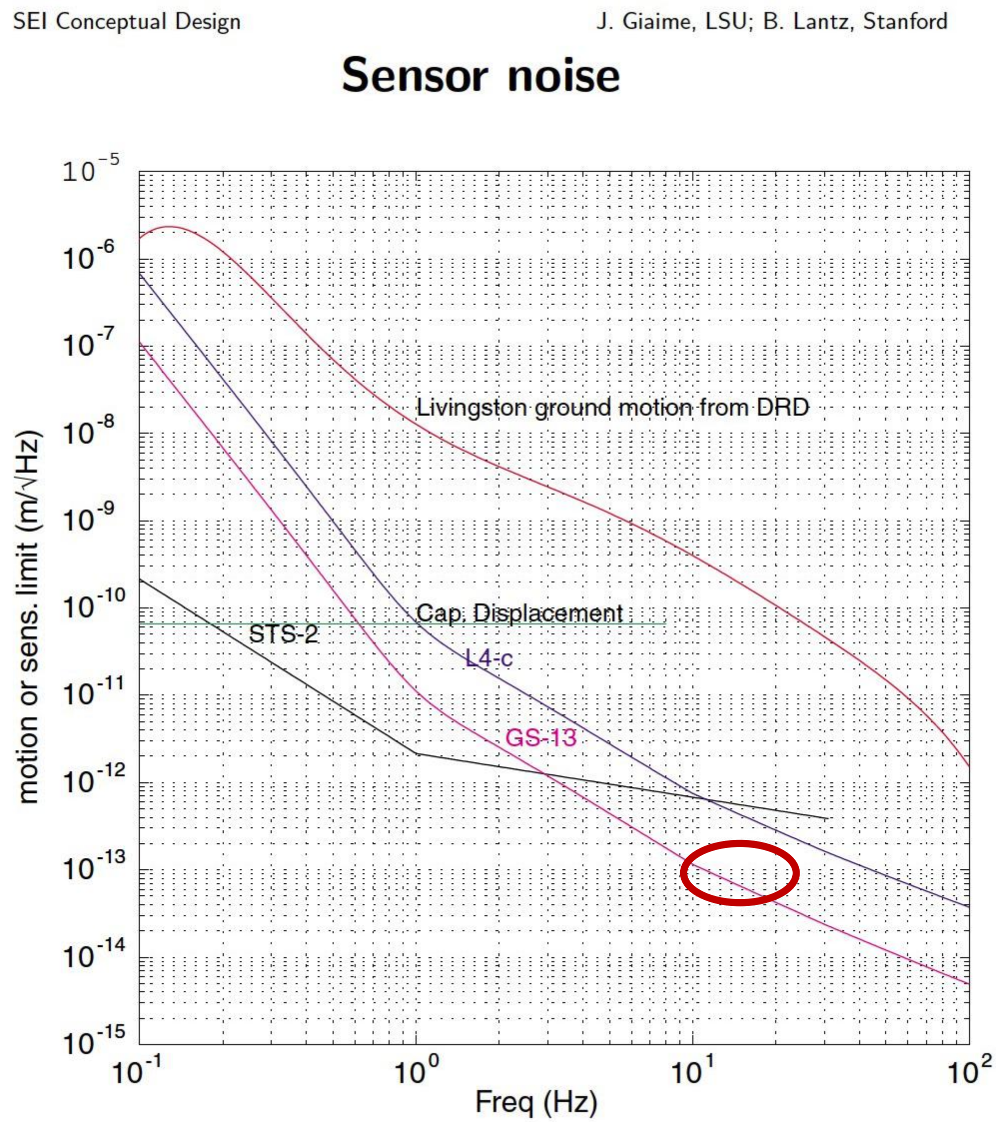


Seismic Noise

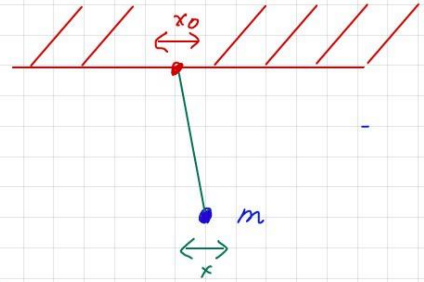
Ground Motion

Active insolation system

- Reach accelerometer sensor noise in observation band
- Make the platform follow the ground at low frequencies using displacement sensors



Pendulum Suspensions



Damped harmonic oscillator

$$m\ddot{x} + \gamma\dot{x} + kx = F$$
$$-\omega^2 m x + i\omega\gamma x + kx = F$$

Force F Is zero, but suspension point x_0 Is moving:

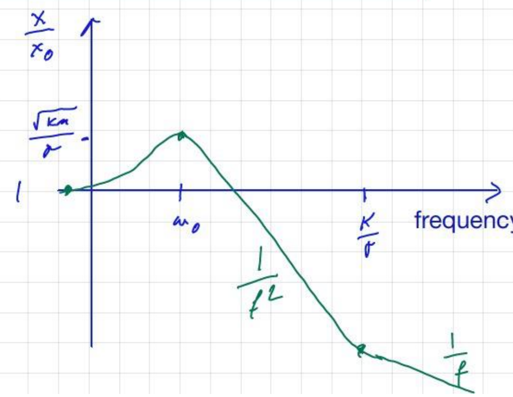
$$\Rightarrow -\omega^2 m x + i\omega\gamma(x - x_0) + k(x - x_0) = 0$$
$$(-\omega^2 m + i\omega\gamma + k)x = (i\omega\gamma + k)\,x_0$$
$$\Rightarrow \frac{x}{x_0} = \frac{i\omega\gamma + k}{k - \omega^2 m + i\omega\gamma}$$

$$1 + \frac{k}{i\omega\gamma} = 1 - i\frac{\sqrt{km}}{\gamma}$$

For $\omega >> \omega_0 \equiv \sqrt{\frac{k}{m}}$ $\quad \frac{x}{x_0} \sim -\left(\frac{\omega_0}{\omega}\right)^2 \Rightarrow \frac{1}{f^2}$ suppression of external noise

But $\omega < \frac{k}{\gamma}$

Small damping γ required, otherwise isolation $\frac{1}{f}$



Quad-Pendulum Suspensions

We can do better than $\frac{1}{f^2}$: Hang Pendulum from pendulum, etc (4 timed for Advanced LIGO)

$\Rightarrow$ Coupled system, four resonance frequencies, choose masses wisely.

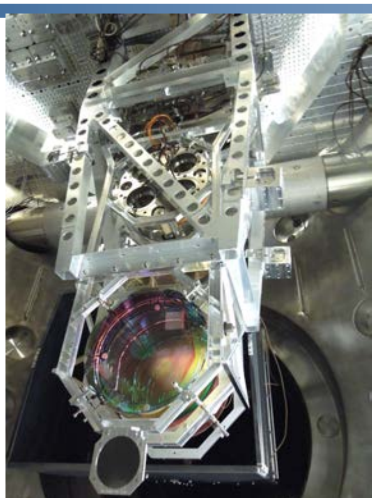
Above highest resonance $\Rightarrow$ transfer function $\frac{x}{x_0}$ drops off as $\frac{1}{f^8}$

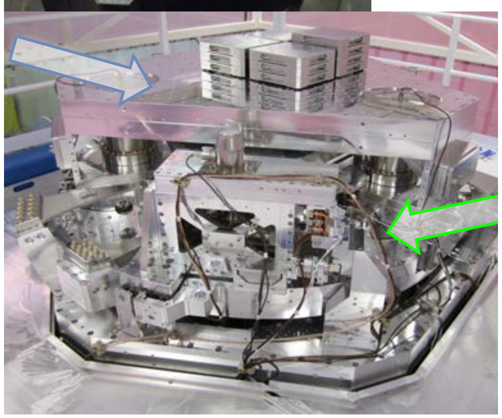
- Suspension platform motion (from active seismic isolation): $\sim 2 \cdot 10^{-13} \frac{m}{\sqrt{Hz}}$ @ 15 Hz

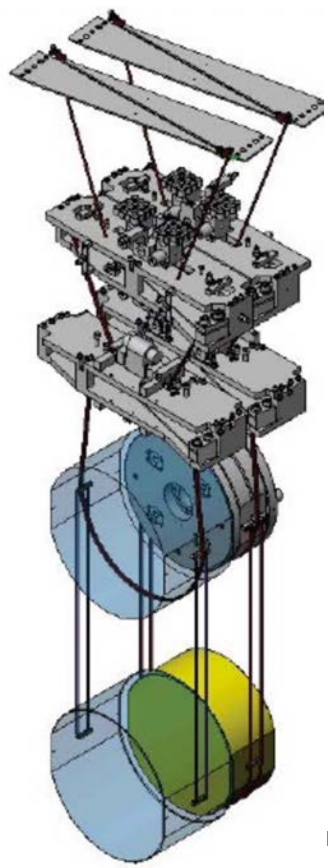
Target noise floor: $\sim 4 \cdot 10^{-20} \frac{m}{\sqrt{Hz}}$ @ 15 Hz

Highest resonance frequency: $\Rightarrow \sim 2.3$ Hz

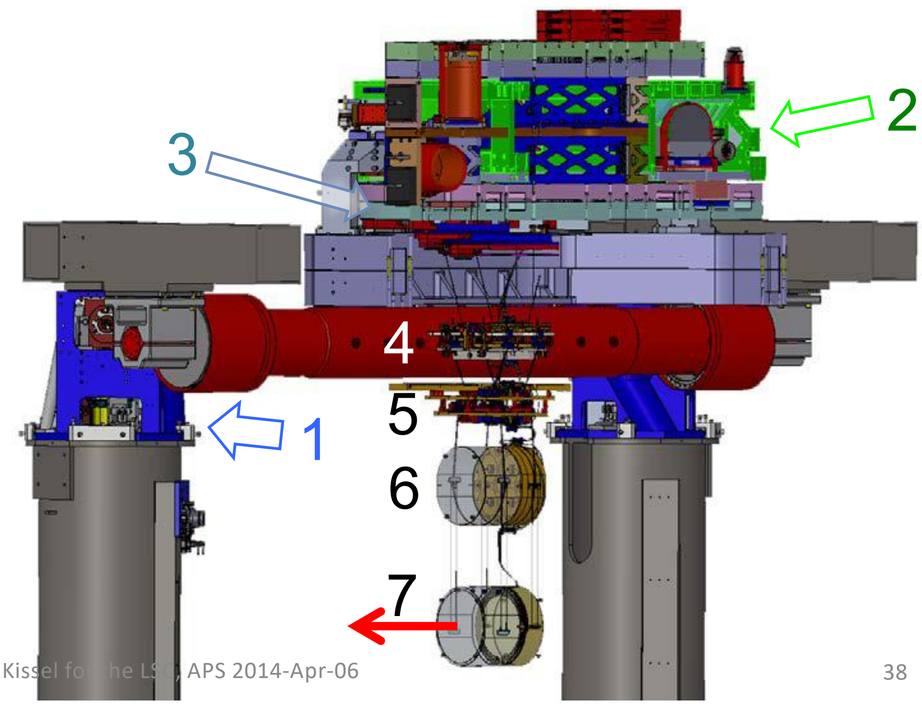
The Advanced LIGO Detectors
Seismic Isolation



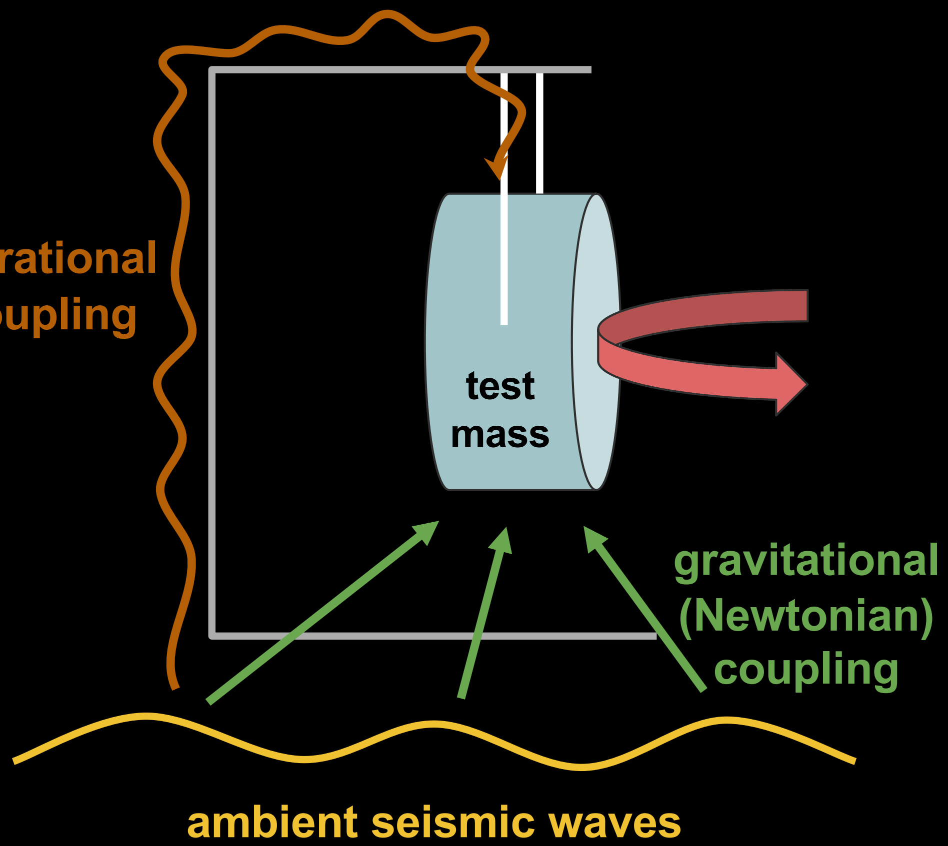




Internal Seismic Isolation (ISI) on top
Quadruple Pendulum below



Newtonian Noise: Bypassing the Isolation System

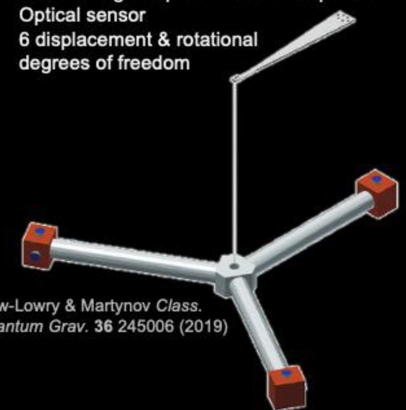


Vibrational coupling can be filtered or suppressed

Gravitational coupling cannot be shielded
- couples as $1/f^2$
- steeper drop-off from source coherence

Novel seismometers, e.g.:

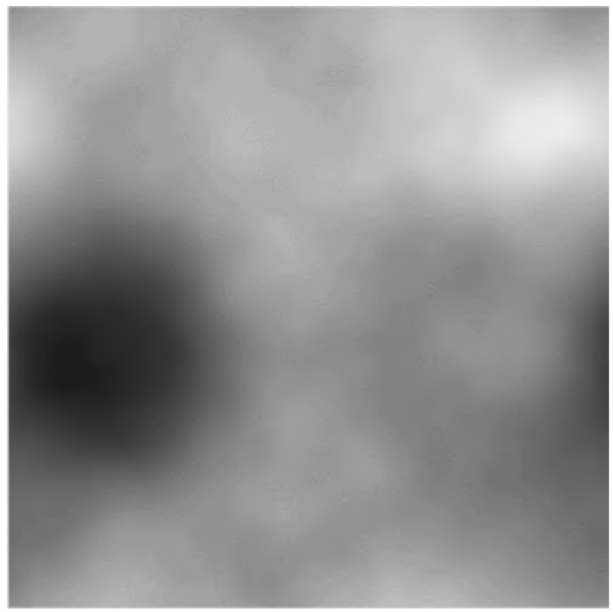
- Monolithic glass proof mass & suspension
- Optical sensor
- 6 displacement & rotational degrees of freedom



Mow-Lowry & Martynov *Class. Quantum Grav.* **36** 245006 (2019)

How…

…do we isolate from any other motion?



Thermal Noise

Thermal Noise - Basics

- Fluctuation-dissipation theorem: It's the loss!
  - Equipartition theorem.:

$$\frac{1}{2}m\langle\dot{x}^2\rangle = \frac{k_B T}{2}$$

vs.

$$m\ddot{x} + \gamma\,\dot{x} + kx = F_{\text{noise}}$$

Thermal Noise: Fluctuation Dissipation Theorem Motivation

Damped harmonic oscillator $m\ddot{x} + \gamma\dot{x} + kx = F$

Assume F=0 $\Rightarrow$ x(t) damps out. Energy conservation?

Equipartition theorem: $\frac{1}{2} m \langle \dot{x}^2 \rangle = \frac{k_B T}{2} \Rightarrow \langle \dot{x}^2 \rangle = \frac{k_B T}{m}$

Contradiction! F cannot be zero. It has to be non-zero, but random!

Express RMS velocity as integral of its power spectrum:

$$\langle \dot{x}^2 \rangle \equiv \int_0^\infty S_{\dot{x}\dot{x}}(f)\,df \overset{!}{=} \frac{4 k_B T}{4m}$$

Can we generalize the inverse mass, and express it as an integral over frequencies???

Introduce impedance Z, via $Z\dot{x} = F$

For damped harmonic oscillator: $Z = i\omega m + \gamma + \frac{k}{i\omega}$

Indeed we have:

$$\frac{1}{4m} = \int_0^\infty \mathrm{Re}(Z^{-1})\,df = \int_0^\infty \frac{\gamma}{\gamma^2 + \left(2\pi f m - \frac{k}{2\pi f}\right)^2}\,df$$

$$\Rightarrow \int_0^\infty S_{\dot{x}\dot{x}}(f)\,df = 4 k_B T \int_0^\infty \mathrm{Re}(Z^{-1})\,df$$

Thermal Noise: Fluctuation Dissipation Theorem

This equation holds for the integrated at all frequencies:

$$S_{\dot{x}\dot{x}}(f) = 4 k_B T \, Re\left(Z^{-1}\right)$$

Velocity Power Spectral Density (1-sided)

Temperature of the heat bath

Real part of the inverse of the mechanical impedance

- Holds for all (mechanical) systems coupled to a heat bath.
- The physical coupling responsible for damping the motion also has to work in reverse, driving the system.
- Can be generalized to multiple mechanical degrees of freedom, cross-power-spectra, etc.

- Note:
- x and F are a pair of conjugate thermodynamic variables. Indeed the FD theorem can me generalized for any pair of conjugate TD variables: (Pressure,Volume), (Temperature,Entropy), (Chem. potential, Particle N)
- Every pair of TD variables generates statistically independent thermal noise.

Fluctuation Dissipation Theorem - Other Forms

Displacement Fluctuation Power Spectrum

$$S_{xx}(f) \equiv \langle x\, x^{+} \rangle = \frac{1}{-i \cdot i}\, \frac{1}{\omega^2} \underbrace{\langle \dot{x}\, \dot{x}^{+} \rangle}_{S_{\dot{x}\dot{x}}(f)}$$

$$S_{\dot{x}\dot{x}}(f) = 4 k_B T \; Re\left(Z^{-1}\right)$$

$$\Rightarrow \; S_{xx}(f) = \frac{4 k_B T}{\omega^2}\, Re\left(Z^{-1}\right)$$

Force Fluctuation Power Specrum

$$S_{FF}(f) \equiv \langle F\, F^{+} \rangle = \langle Z\, \dot{x}\, \dot{x}^{+} Z^{+} \rangle$$

$$= 4 k_B T \;\; Z\, Re\left(Z^{-1}\right) Z^{+}$$

$$= 4 k_B T \cdot \frac{1}{2}\left(Z Z^{-1} Z^{+} + Z Z^{-1\,+} Z^{+}\right)$$

$$= 4 k_B T \;\; Re\left(Z\right)$$

$$\Rightarrow \; S_{FF}(f) = 4 k_B T \; Re\left(Z\right)$$

$\Longrightarrow$ $S_{FF}(f)$ is white $\Leftrightarrow$ $\gamma = Re\, Z$ Is independent of frequency

Thermal Noise - Basics

- Fluctuation-dissipation theorem: It's the loss!
  - Equipartition theorem.:

$$\frac{1}{2} m \langle \dot{x}^2 \rangle = \frac{k_B T}{2} \quad \text{vs.} \quad m\ddot{x} + \gamma\,\dot{x} + kx = F_{\text{noise}}$$

- Fluctuation-dissipation theorem

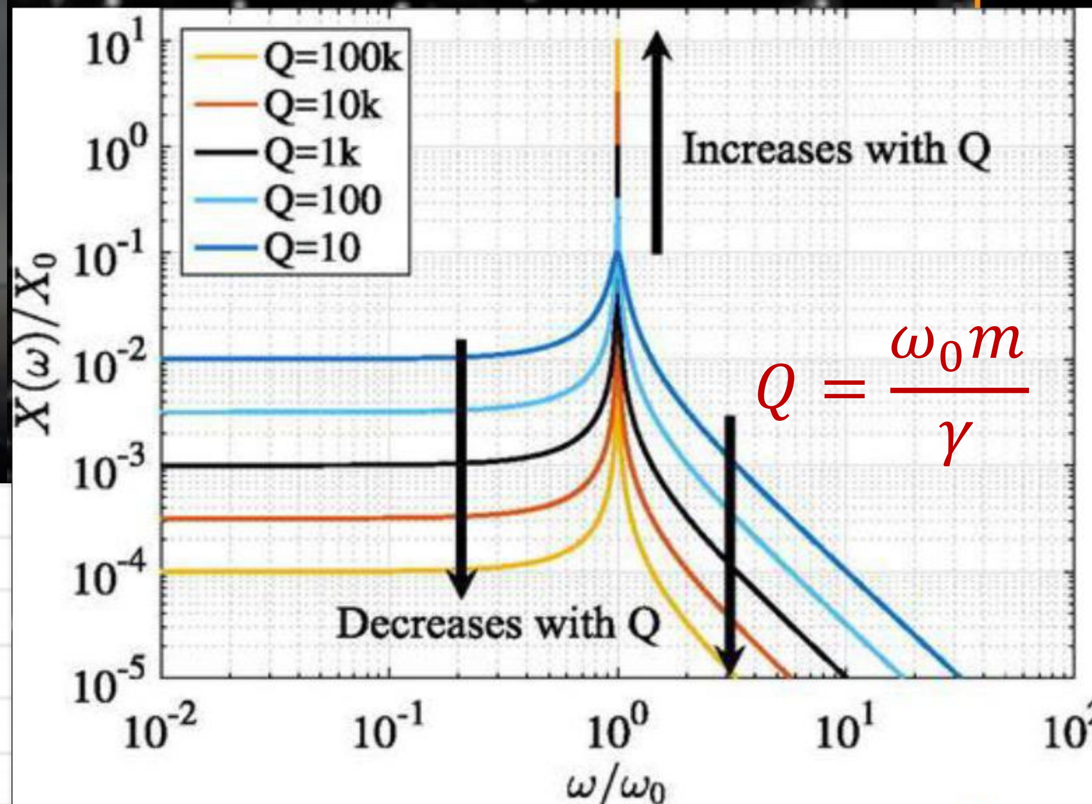
$$S_{vv}(f) = 4k_B T \frac{P_{\text{diss}}(f)}{\langle \mathrm{F}^2 \rangle}$$

  - The energy loss per cycle (normalized by the driving force squared) is proportional to the velocity power spectrum

Thermal Noise

$$S_{xx}(f) = \frac{4k_B T}{\omega^2}\,\frac{\gamma}{\gamma^2 + \left(\omega m - \frac{k}{\omega}\right)^2}$$

Miller et al., Applied Physics Reviews 5, 041307 (2018)



$$Q = \frac{\omega_0 m}{\gamma}$$

Rutger Saly, YouTube, "We filmed Brownian motion, random movement of particles in water…"

Thermal Noise: Design Implications

Damped harmonic oscillator

$$S_{xx}(f) = \frac{1}{\omega^2} S_{\dot{x}\dot{x}}(f) = \frac{4k_BT}{\omega^2} \frac{\gamma}{\gamma^2 + \left(\omega m - \frac{k}{\omega}\right)^2}$$

Off-resonance ($\left|\omega m - \frac{k}{\omega}\right| \gg \gamma$)

- Above resonance frequency: $S_{xx}(f) = \frac{4k_BT}{\omega^4 m^2}\gamma$ — Example: Gas damping
- Below resonance frequency: $S_{xx}(f) = \frac{4k_BT}{k^2}\gamma$

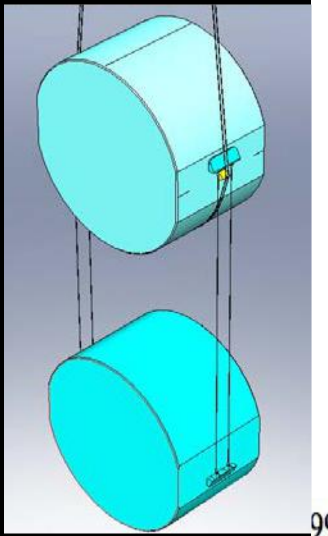
For structural damping: $\gamma = 0$, but $k = \tilde{k}(1+i\varphi)$ — φ: Mechanical loss angle $\Rightarrow k \to \tilde{k}$, $\gamma \to \frac{k\varphi}{\omega}$

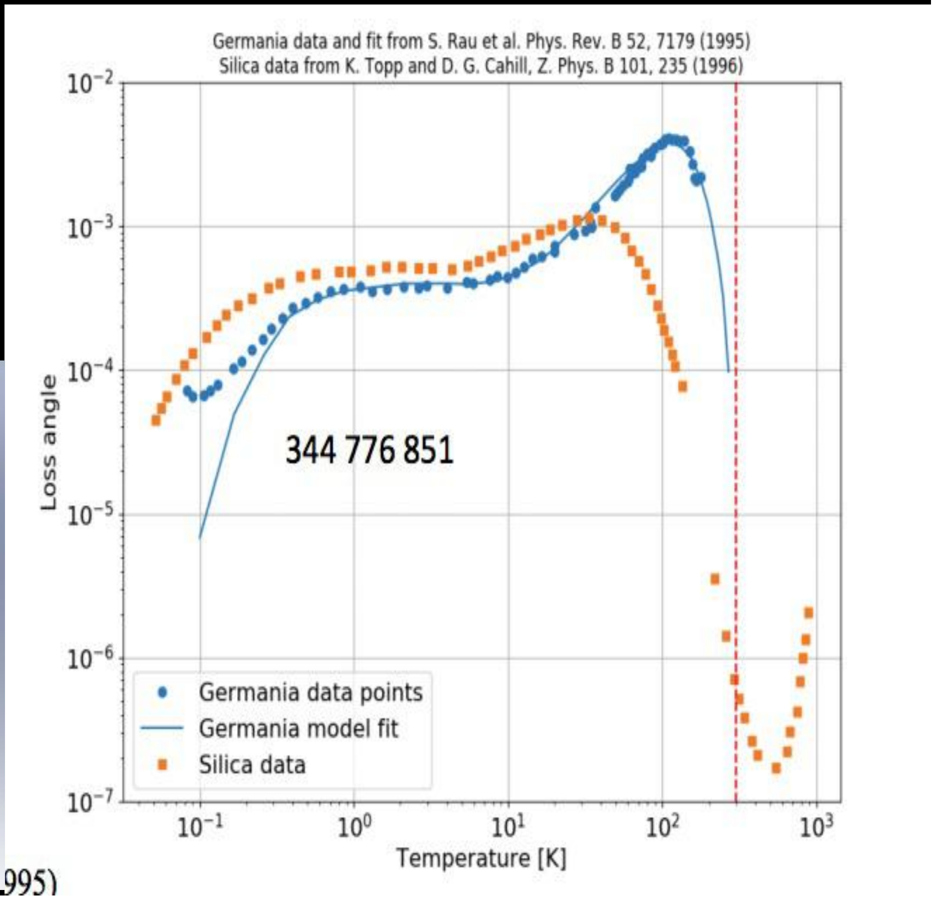
- Above resonance frequency: $S_{xx}(f) = \frac{4k_BT}{\omega^5 m^2}\tilde{k}\varphi$ — Example: suspension thermal noise
- Below resonance frequency: $S_{xx}(f) = \frac{4k_BT}{\omega k}\varphi$ — Example: coating thermal noise

We need to minimize mechanical damping!

Suspension Thermal Noise

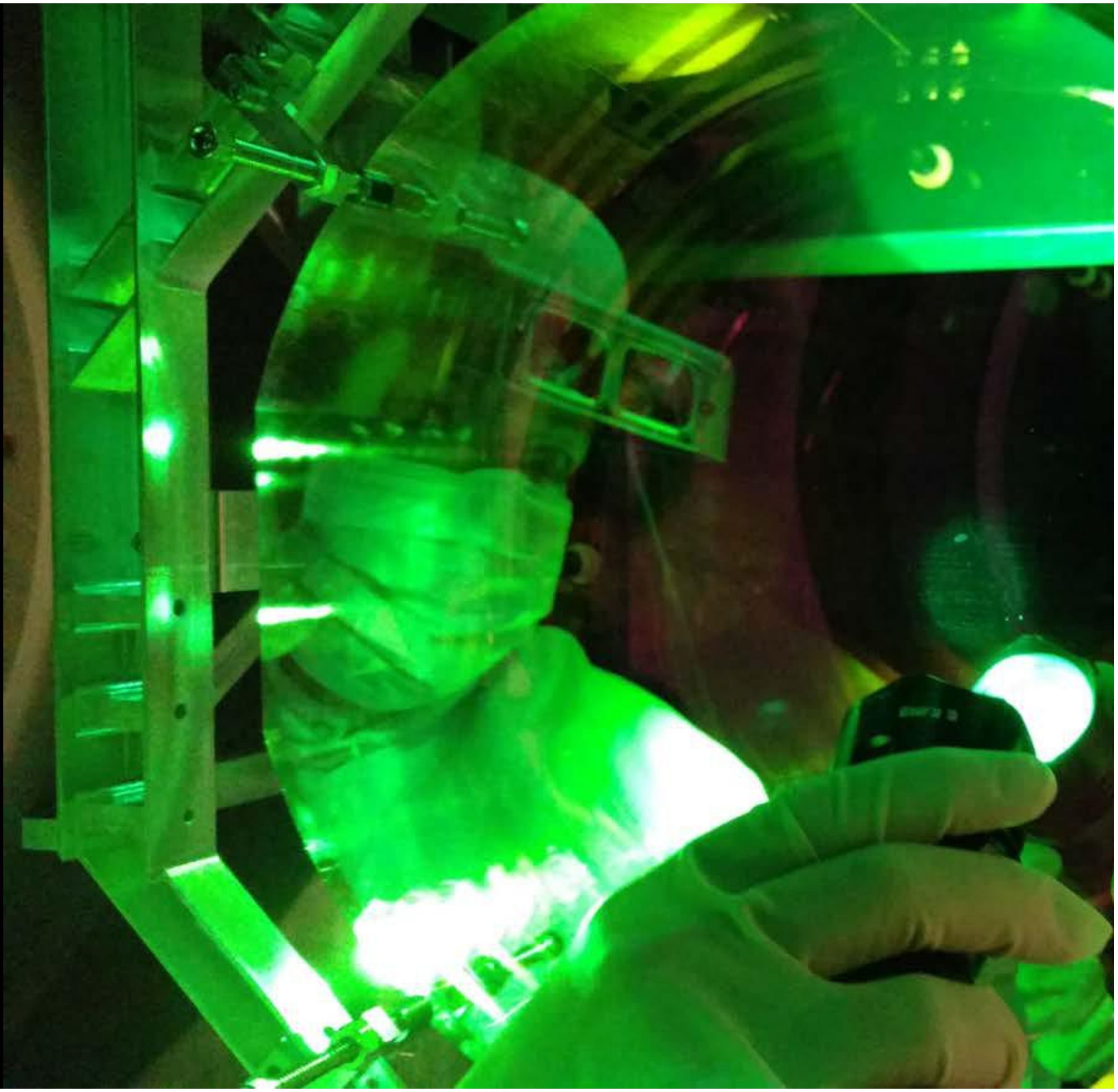
- Dominated by last suspension stage
  - Thermal noise from upper stages filtered by remaining suspension stages
- Most potential energy stored by gravity
  ➔ mechanical loss diluted
- SiO2 has extraordinary low mechanical loss at room temperature!
  ➔ Monolithic bottom stage





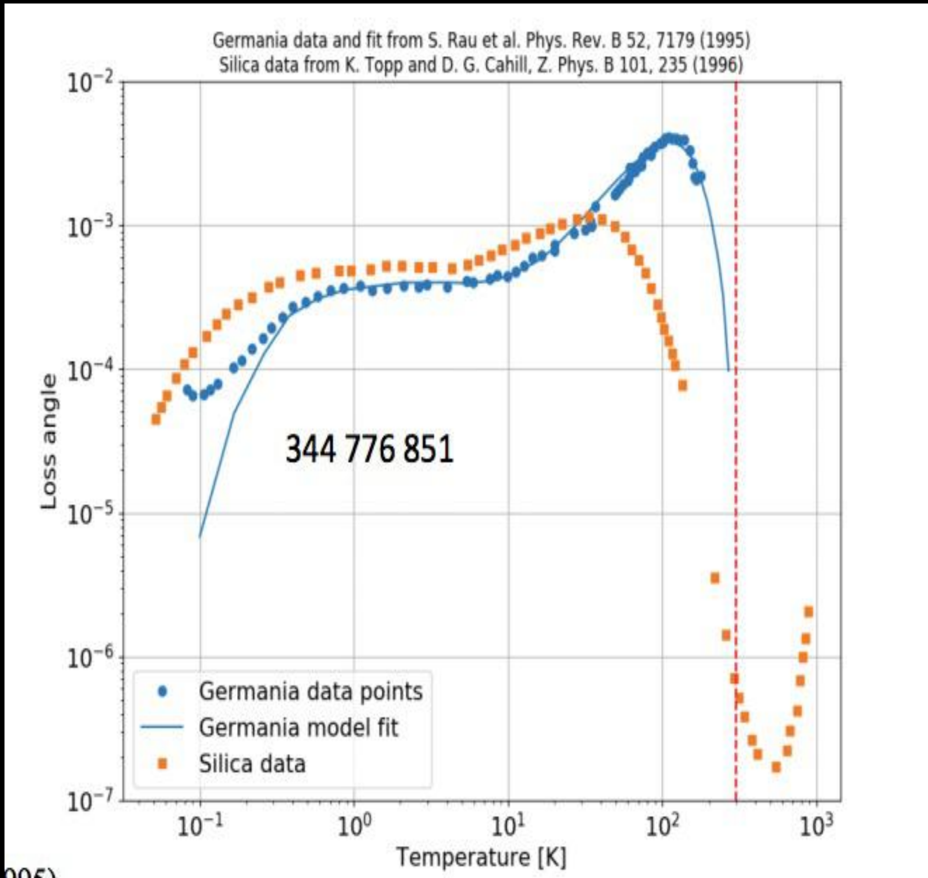
Coating Thermal Noise

- Dielectric Mirror Coating dominates mechanical loss (TiO_2-doped Ta_2O_5 SIO_2)
- Mirror coating interacts directly with laser light, no extra filtering possible
- Need better coating material!



$TiO_2:GeO_2$ / SiO_2 coatings

- Germania (GeO_2) has loss angle ~4e-5
  - similar to Silica (SiO_2)
  - much lower than Tantala (Ta_2O_5)
- But:
  - Refractive index of Germania 1.6
  - 2.1 for Tantala
  - 1.45 for Silica
- Can achieve ~30% thermal noise amplitude reduction
- Candidate for A+ upgrade

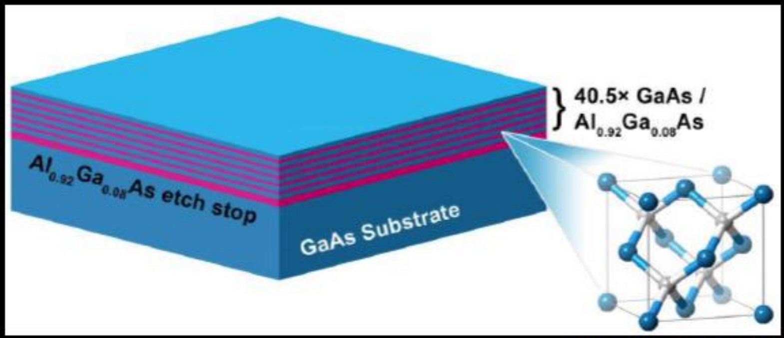


995)

Crystalline AlGaAs coatings

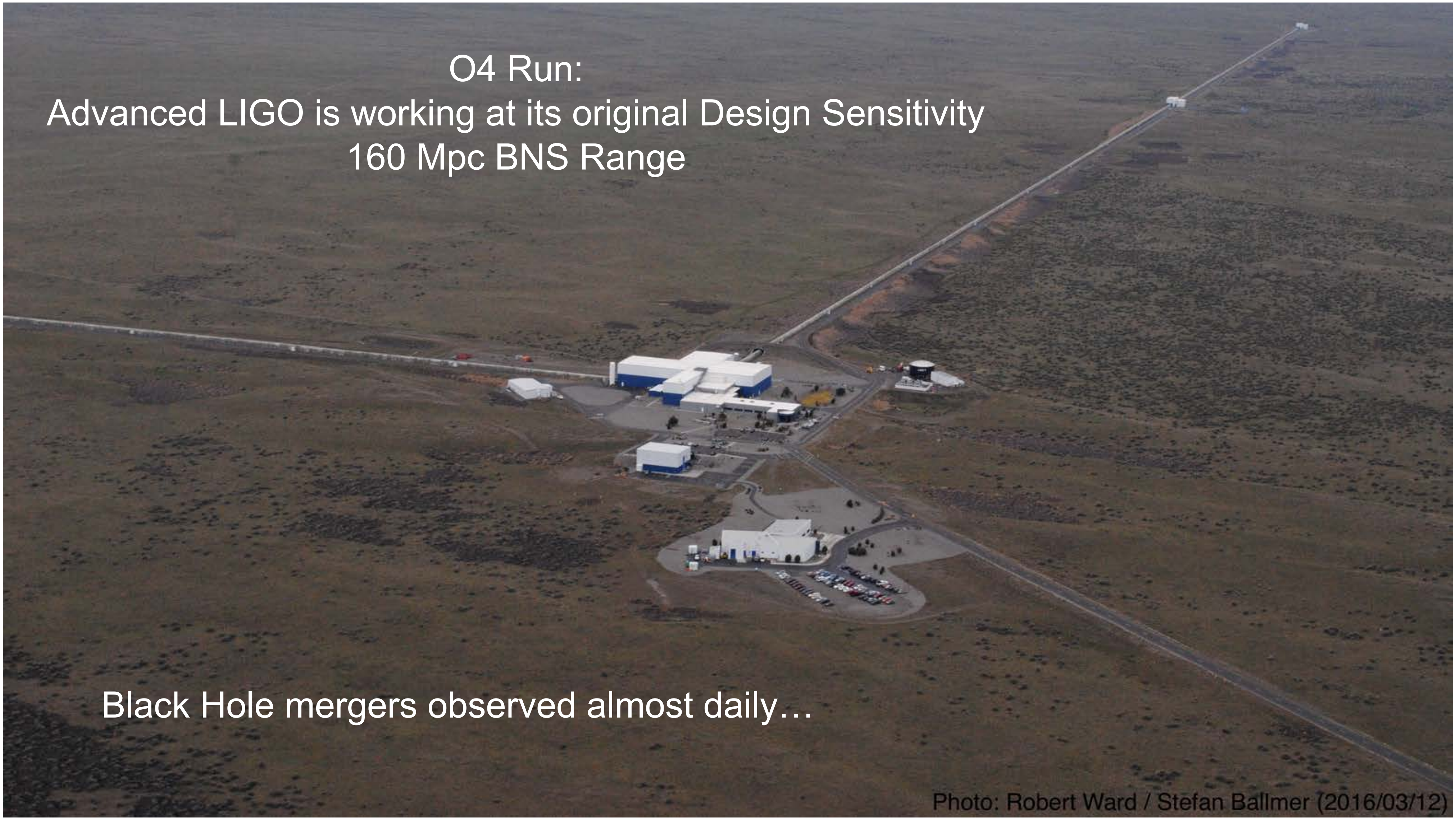
- The crystal is grown via Molecular Beam Epitaxy (MBE) on a single-crystal GaAs wafer.
- Alternating the Al alloy composition forms a Bragg reflector from layers of $Al_{0.92}Ga_{0.08}As$ (n=2.89) and GaAs (n=3.30).
- Limited to $\lambda > 870\text{nm}$

G. Cole 2013



https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=14069

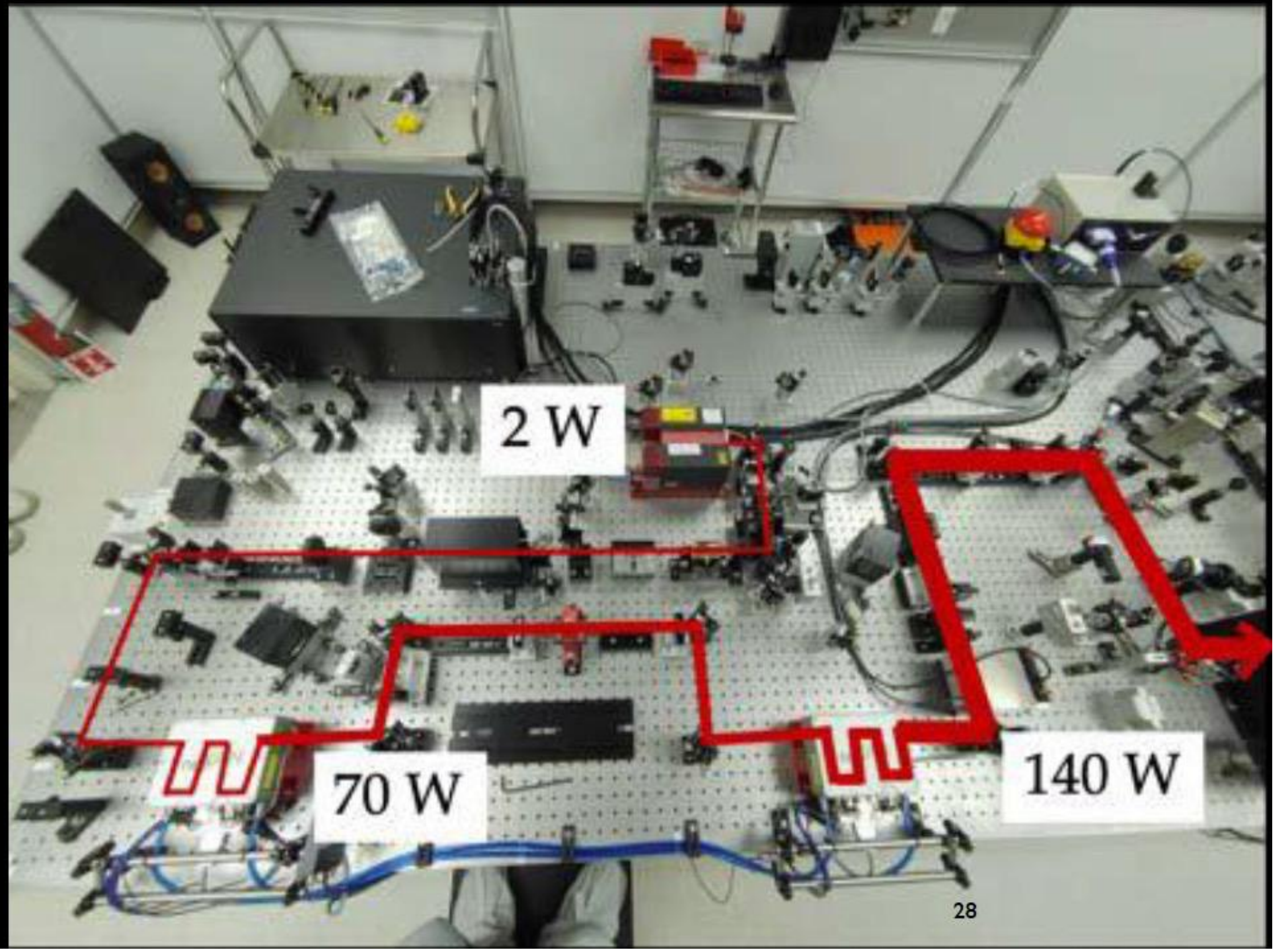
Satoshi Tanioka
Steve Penn


O4 Run:
Advanced LIGO is working at its original Design Sensitivity
160 Mpc BNS Range
Black Hole mergers observed almost daily…
Photo: Robert Ward / Stefan Ballmer (2016/03/12)

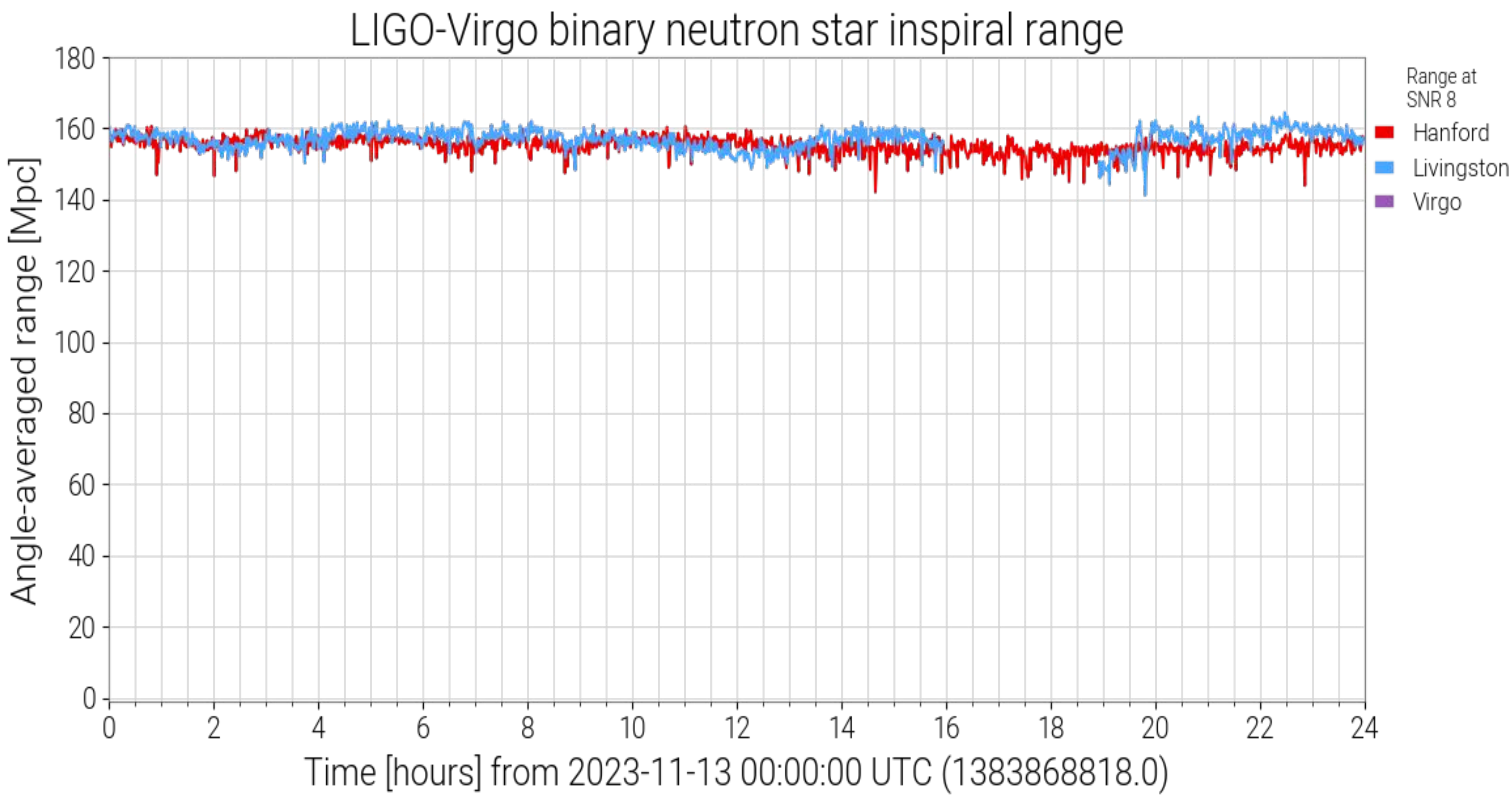
Credit: LIGO

Pre-Stabilized Laser

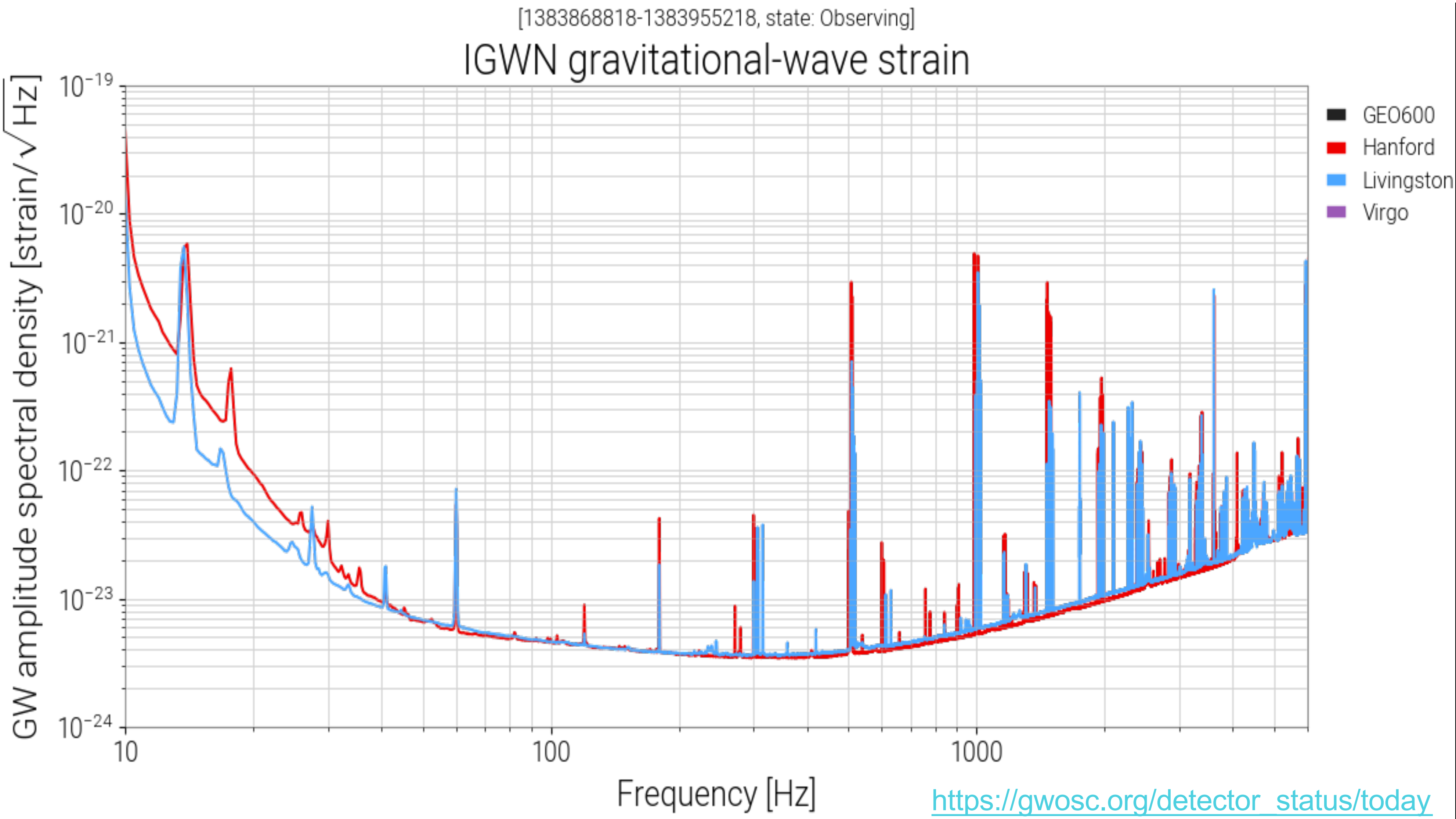
- 2W NPRO seed laser, 2 neoVAN-4S-HP amplification stages
- Delivers 110W to vacuum system



Credit: Elenna Capote and LIGO



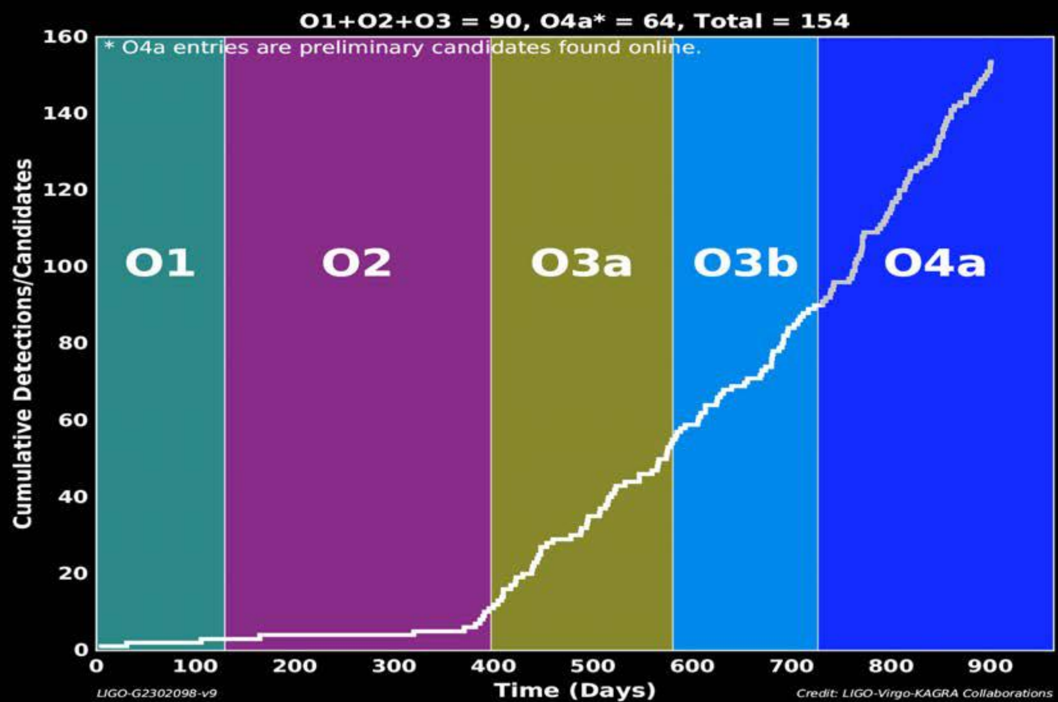
https://gwosc.org/detector_status/today



https://gwosc.org/detector_status/today

O4 Events

- https://gracedb.ligo.org/superevents/public/O4



Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S231114n	BBH (>99%)	Nov. 14, 2023 04:32:11 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years	
S231113bw	BBH (96%), Terrestrial (4%)	Nov. 13, 2023 20:04:17 UTC	GCN Circular Query Notices | VOE		1 per 2.3265 years	
S231113bb	BBH (96%), Terrestrial (4%)	Nov. 13, 2023 12:26:23 UTC	GCN Circular Query Notices | VOE		1.7663 per year	
S231112ag	BBH (>99%)	Nov. 12, 2023 11:02:03 UTC	GCN Circular Query Notices | VOE		1 per 2.9871e+06 years	RETRACTED
S231110g	BBH (97%), Terrestrial (3%)	Nov. 10, 2023 04:03:20 UTC	GCN Circular Query Notices | VOE		1 per 1.6429 years	
S231108u	BBH (>99%)	Nov. 8, 2023 12:51:42 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years	
S231104ac	BBH (>99%)	Nov. 4, 2023 13:34:18 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years	
S231102w	BBH (>99%)	Nov. 2, 2023 07:17:36 UTC	GCN Circular Query Notices | VOE		1 per 5.4281e+14 years	
S231030av	BNS (93%), NSBH (6%), Terrestrial (1%)	Oct. 30, 2023 12:51:11 UTC	GCN Circular Query Notices | VOE		1.3301 per year	RETRACTED
S231029y	BBH (>99%)	Oct. 29, 2023 11:15:08 UTC	GCN Circular Query Notices | VOE		1 per 146.45 years	
S231028bg	BBH (>99%)	Oct. 28, 2023 15:30:06 UTC	GCN Circular Query Notices | VOE		1 per 4.1513e+22 years	
S231020bw	BBH (>99%)	Oct. 20, 2023 18:05:09 UTC	GCN Circular Query Notices | VOE		1 per 91.785 years	
S231020ba	BBH (91%), NSBH (8%)	Oct. 20, 2023 14:29:47 UTC	GCN Circular Query Notices | VOE		1 per 25.01 years	
S231014r	BBH (99%)	Oct. 14, 2023 04:05:32 UTC	GCN Circular Query Notices | VOE		1 per 3.0666 years	
S231008ap	BBH (>99%)	Oct. 8, 2023 14:25:21 UTC	GCN Circular Query Notices | VOE		1 per 20.718 years	

Observations

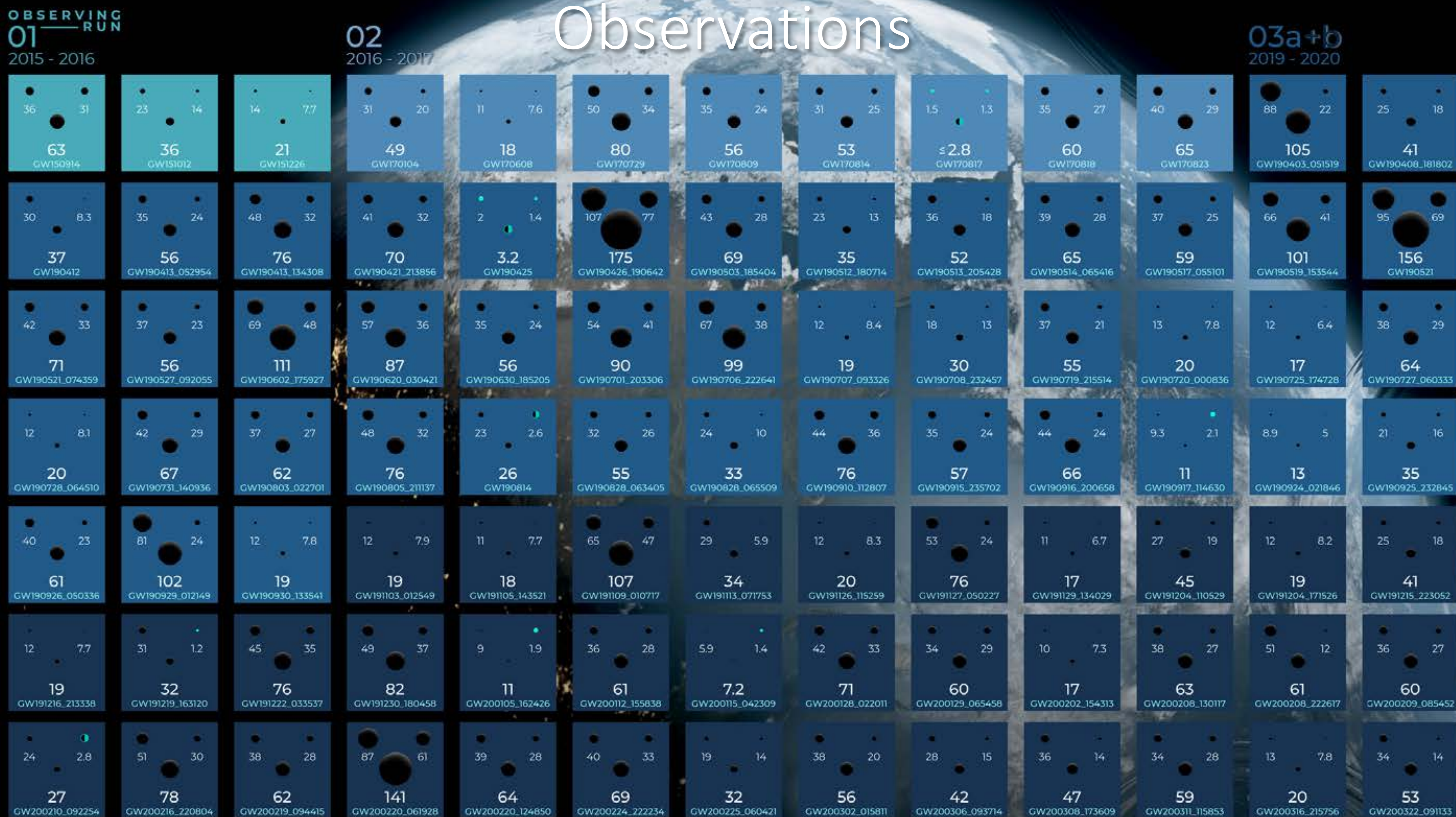
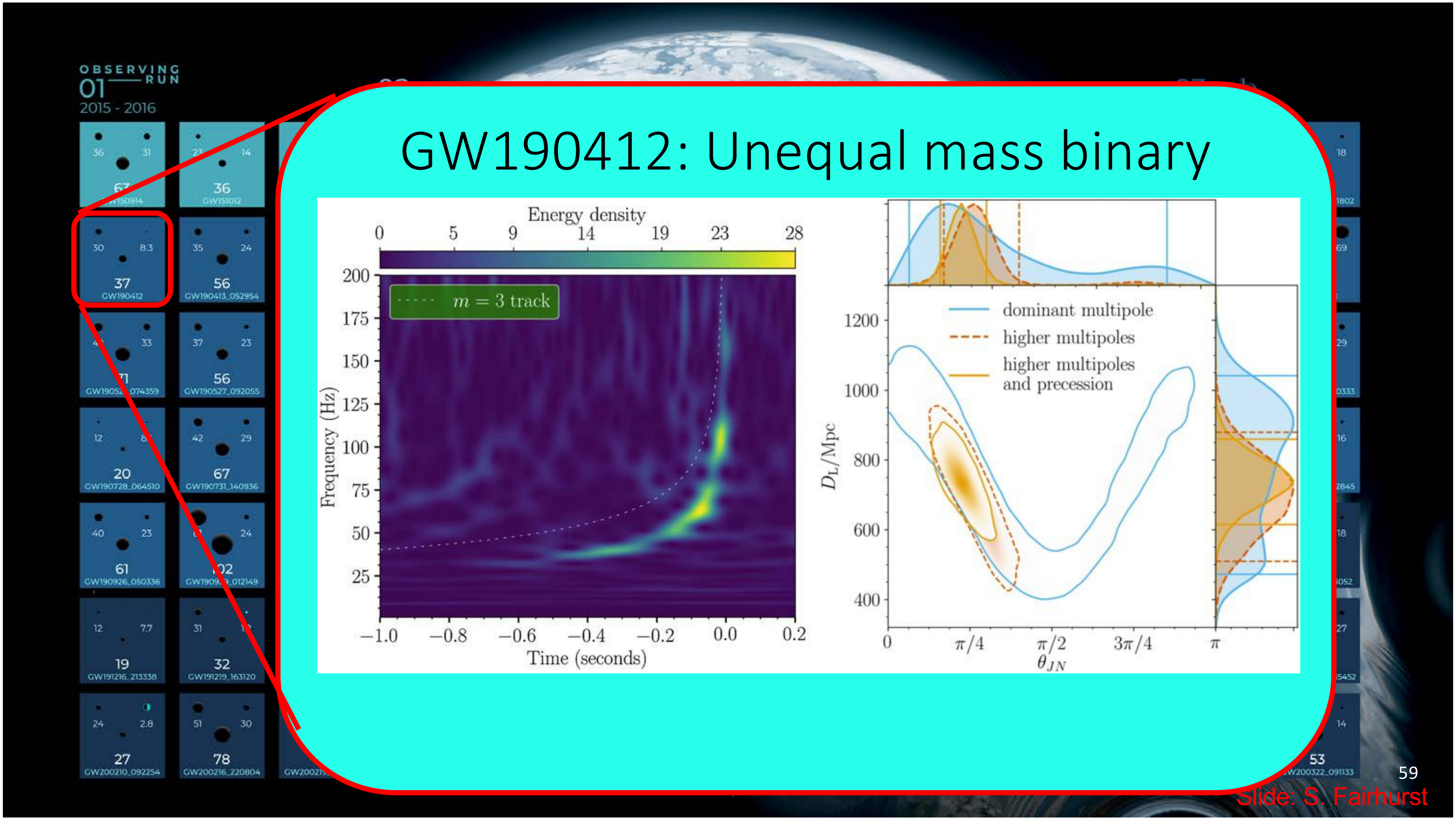


Image credit "Carl Knox (OzGrav, Swinburne University of Technology)"

Slide: S. Fairhurst



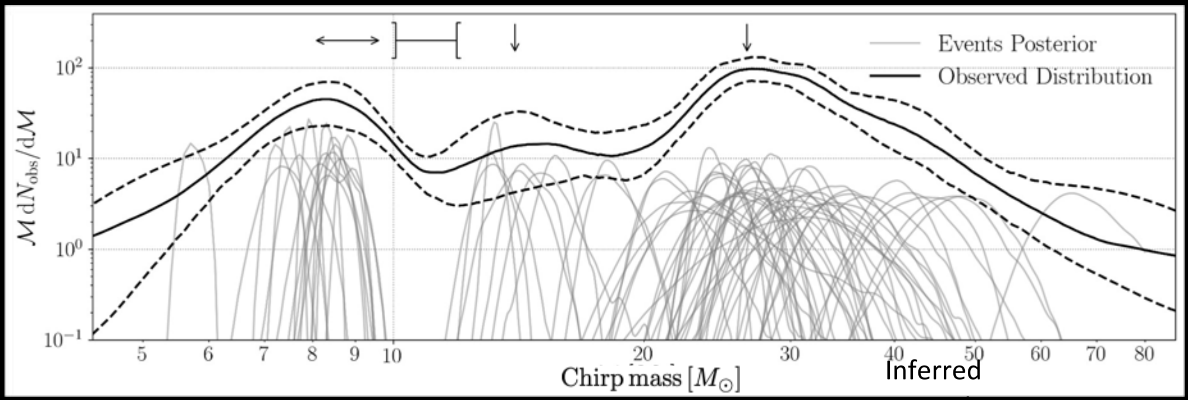
OBSERVING RUN
01
2015 - 2016
GW190412: Unequal mass binary
Energy density
m = 3 track
Frequency (Hz)
Time (seconds)
dominant multipole
higher multipoles
higher multipoles and precession
D_L/Mpc
θ_{JN}
59
Slide: S. Fairhurst

Features in the Black Hole mass spectrum

Observations clustered in chirp mass

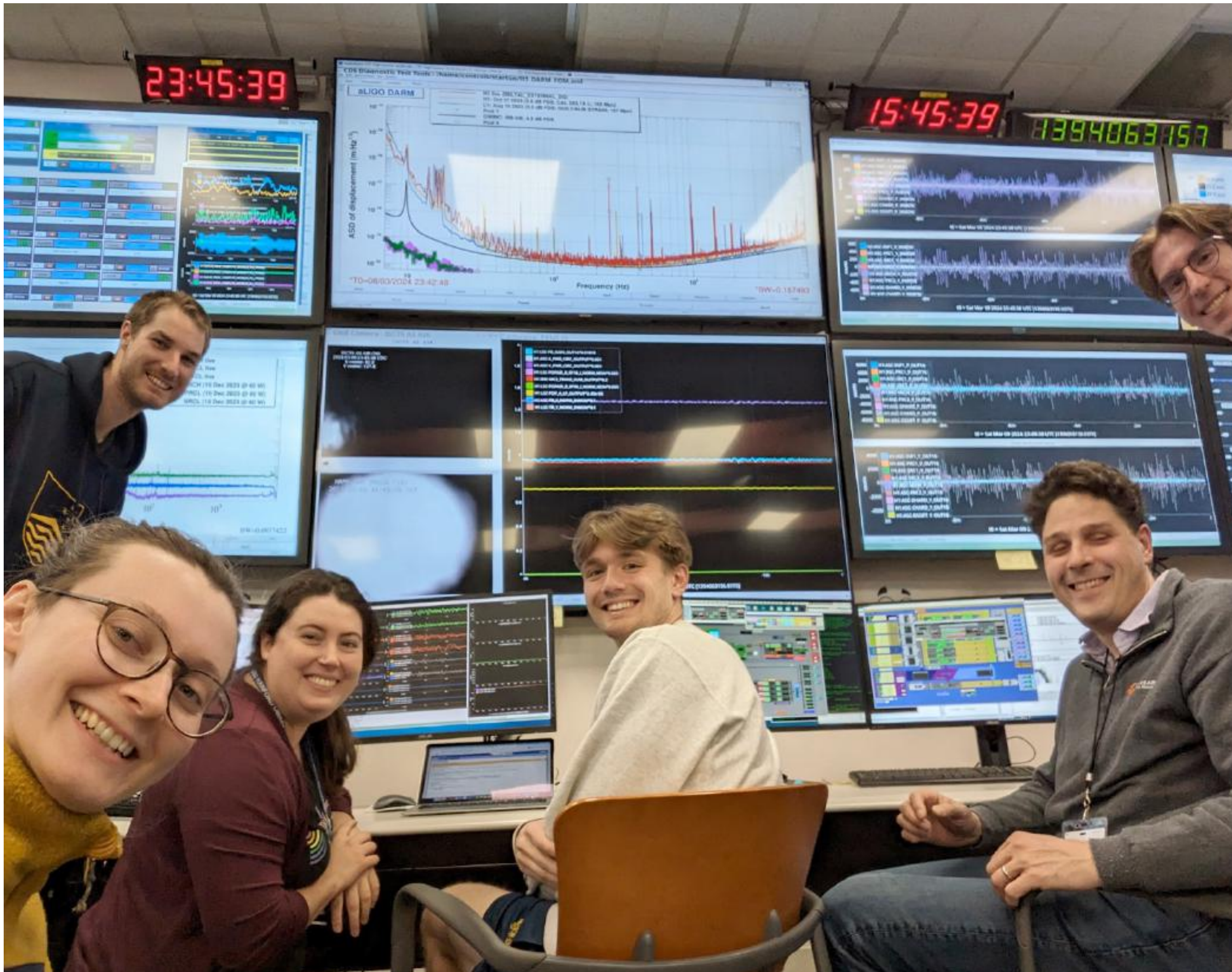
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

- Chirp mass is the combination of masses which is best measured



- **Over-density** between 8M$_\odot$ and 10M$_\odot$ and around 26M$_\odot$.
- A **weaker feature** present at around 14M$_\odot$
- **Absence** of mergers with chirp masses between 10M$_\odot$ and 12M$_\odot$.

Credit: S. Fairhurst



Syracuse University team in the Hanford Control Room (3/9/2024)

O4 Commissioning Break

- LIGO Hanford Output Mode Cleaner
- LIGO Livingston End Test Mass cleaning
- Squeezer path work
- New scattered light baffles and baffle dampeners
- Resume observations Apr 3rd

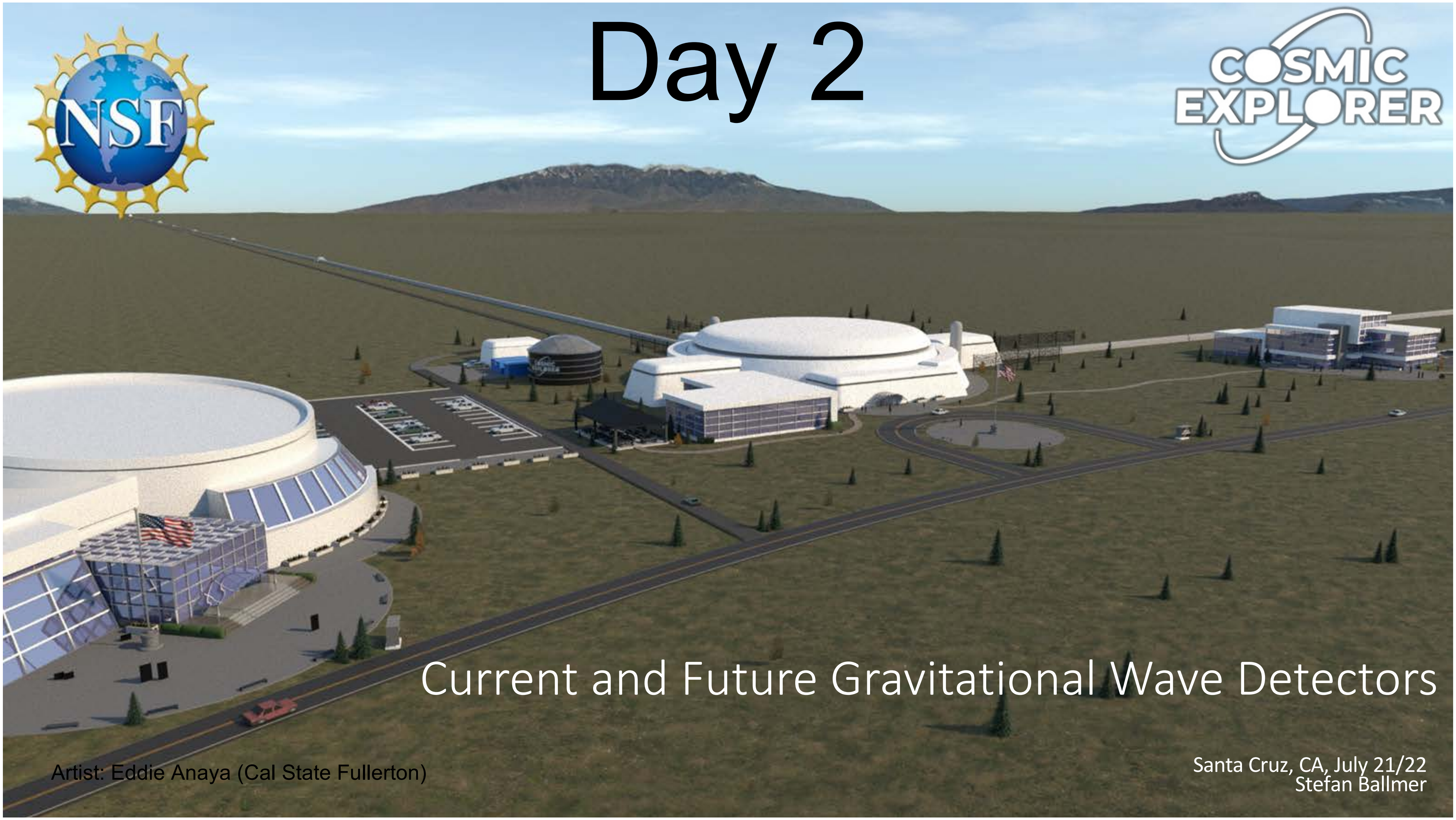
Where do we go from here?

“Recently, we have waded a little out to sea, enough to dampen our toes or, at most, wet our ankles. The water seems inviting. The ocean calls.”

Carl Sagan

That’s for tomorrow…

Day 2



Current and Future Gravitational Wave Detectors

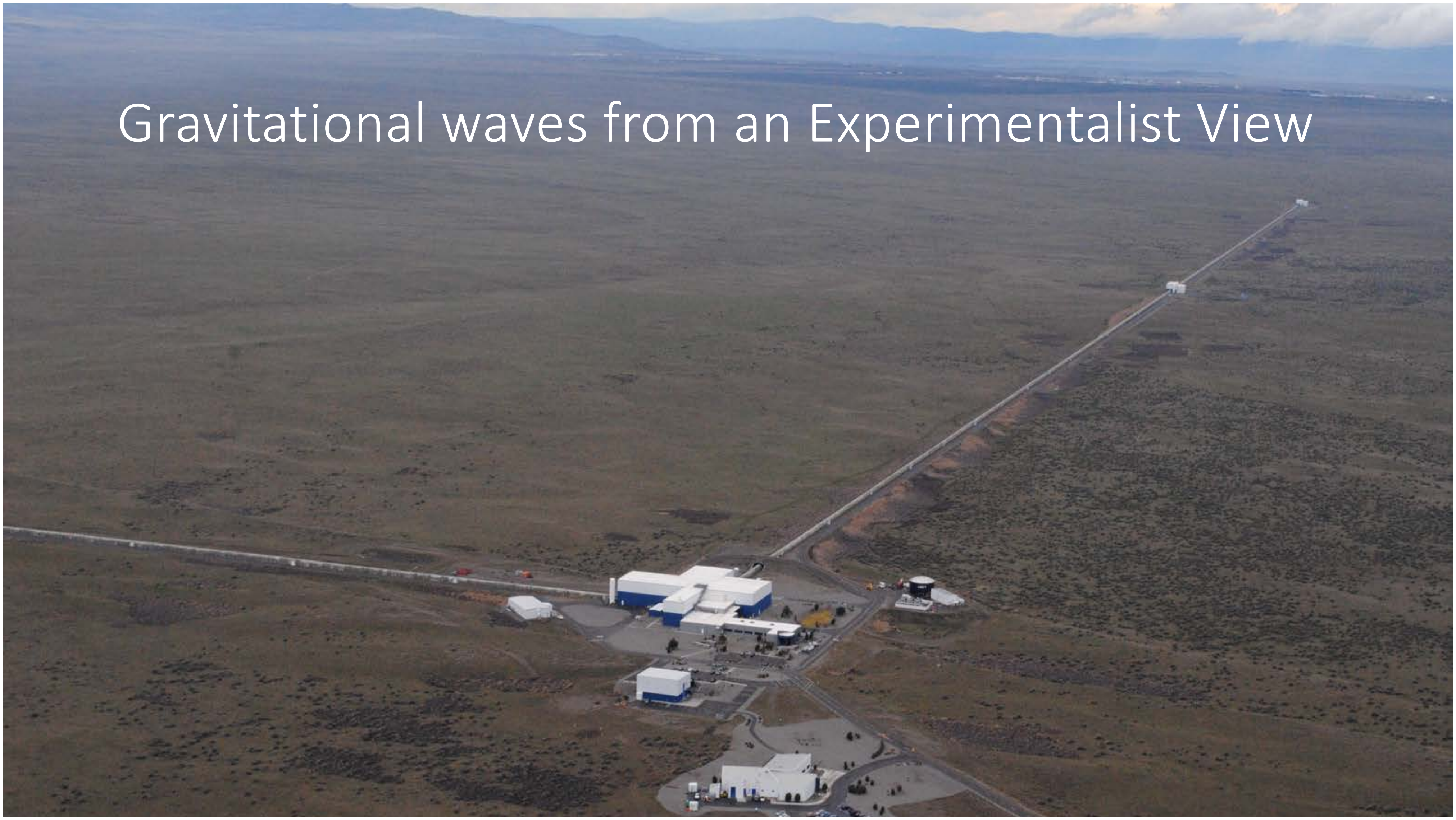
Artist: Eddie Anaya (Cal State Fullerton)

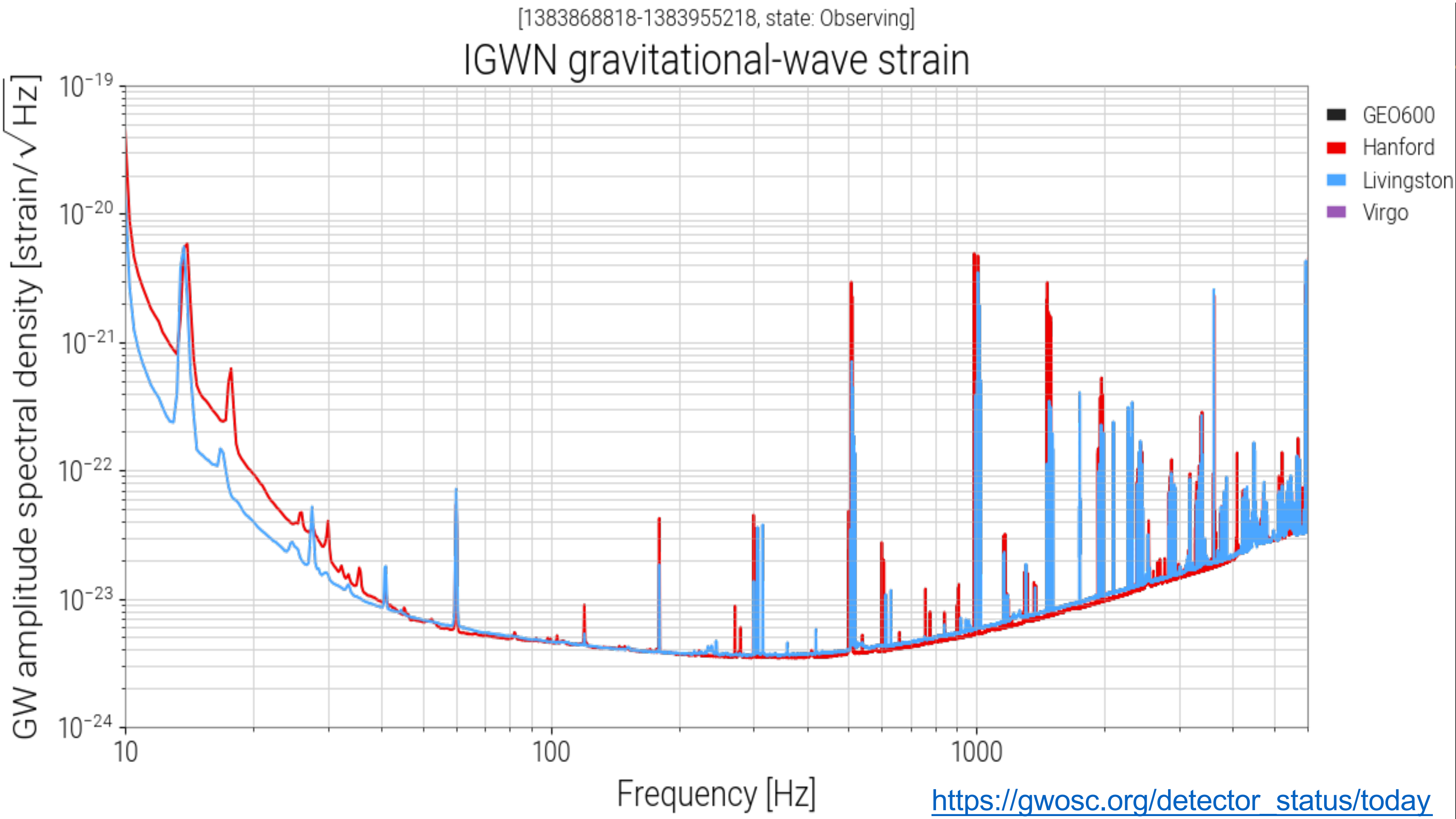
Santa Cruz, CA, July 21/22
Stefan Ballmer

Outline

- Day 1
  - Gravitational waves from an Experimentalist View
    - History of the field
  - How can you measure them in principle?
    - Scale of effect
    - How to read out such small motions (Classical Shot Noise)
    - How to isolate all other large motion (Seismic isolation, Newtonian noise, Thermal Noise)
  - How is Advanced LIGO doing in O4?
- Day 2
  - Key Technologies for the Future
    - Beyond Quantum Noise (Quantization of EM field, squeezing)
  - Cosmic Explorer: the Next-generation of US GW detectors
- Will not talk about sources
  - See presentations from Jim Lattimer and Neil Cornish for that

Gravitational waves from an Experimentalist View





https://gwosc.org/detector_status/today

LIGO

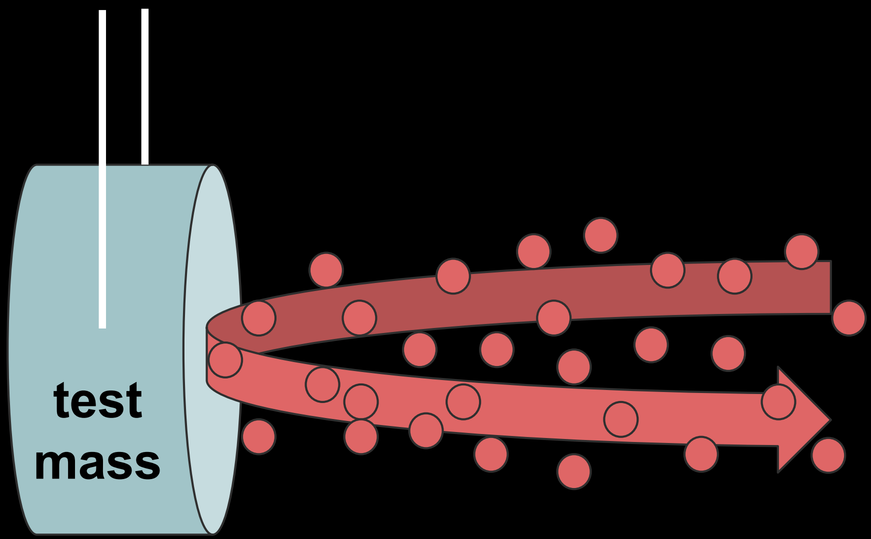
How…

…do we surpass…

Quantum Noise

Shot Noise
&
Radiation Pressure Noise

Quantum noises



Shot noise
(photon counting on detector)
⇒ ***need high optical power***

Radiation pressure noise
(photon momentum)
⇒ ***need heavy test masses***

Classical:

Classical Radiation Pressure Noise

Recall classical shot noise: $S_{PP}(f) = 2 P h\nu$; $S_P = \sqrt{2 P h\nu}$

Force on fully reflecting mirror: $F = \frac{2P}{c}$

⟹ Classical radiation pressure noise: $S_F = \frac{2 S_P}{c} = \frac{2}{c}\sqrt{2 P h\nu}$

But:

Any power fluctuations (classical ↗ usually much bigger! and quantum) are entering from the input side

They will get enhanced in cavity (but filtered above cavity pole

They should be common in both arms……. And cancel completely?????

Quantization of Maxwell Equation

Maxwell equation $c=1,\ \varepsilon_0=1,\ \mu_0=1$

$$\dot{\vec{E}} = \vec{\nabla}\times\vec{B}$$
$$\dot{\vec{B}} = -\vec{\nabla}\times\vec{E}$$

$\Rightarrow$ Interpret at collection of harmonic oscillators, one at each frequency $\omega_0 \equiv k$

For simplicity, assume plane wave, $\vec{k} \parallel \hat{z}$, $\vec{E} \parallel \hat{x}$, $\vec{B} \parallel \hat{y}$

Switch to scalar amplitudes
$$\dot{E} = -B'$$
$$\dot{B} = -E'$$

But for plane wave we know $E=B$ …… and they are in phase….. what is going on?

Two Quadratures:
$$E = E_{10}\cos(kz-\omega t) + E_{20}\sin(kz-\omega t)$$
$$= \mathrm{Re}\left(\underbrace{(E_{10}+iE_{20})\,e^{i\omega t}}\,e^{-kz}\right)$$
$$=: \mathrm{Re}\left(\underbrace{X(t)}\,e^{-ikz}\right)$$

complex field amplitude $X = X_1 + iX_2$

"Phasor"

Note: Maxwell equation respects quadratures.

Define: $\langle f \rangle := \frac{2}{L}\int_{-L/2}^{L/2} \cos kz \; f(t,z)\, dz$

Introduce position and momentum

$$x := \langle E \rangle \qquad \Rightarrow \dot{x} = p$$

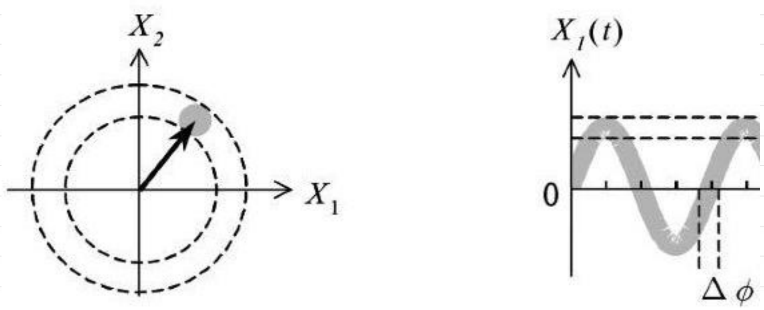
$$p := \langle -B' \rangle \qquad \dot{p} = \langle -\dot{B}' \rangle = \langle E'' \rangle = \langle -k^2 E \rangle = -k^2 x$$

(integrate by parts twice)

$$\boxed{\begin{aligned} \dot{x} &= p \\ \dot{p} &= -k^2 x \end{aligned}} \quad \& \quad \begin{aligned} x &= X_1 \\ p &= -k X_2 \end{aligned} \quad \Rightarrow X \equiv X_1 + iX_2 = x - i\frac{p}{k}$$

$$\dot{X} = ik X$$

Can be quantized just like mechanical harmonic oscillator!



Quantization of Maxwell Equation

So far we didn't pay attention to the normalization of the field χ :

$$\Rightarrow \quad H = \hbar\omega\left(\chi^\dagger \chi\right)$$

Note: this is volume dependent…
But we won't need the details.

vs

$$H = \frac{1}{2} m \dot{x}^2 + \frac{p^2}{2m} \quad \text{with} \quad \Delta x \Delta x \geq \frac{\hbar}{2}$$

$$\Rightarrow \quad \boxed{\Delta \chi_1 \, \Delta \chi_2 \geq \frac{1}{4}}$$

Normalization for Experimentalists

Compare to classical shot noise! (unsqueezed, $\Delta\psi_1 = \Delta\psi_2$)

$$P = |\psi|^2 = |\psi_0 + \delta\psi_1 + i\delta\psi_2|^2 = |\psi_0|^2 + 2\psi\,\delta\psi_1$$

$$= P + 2\sqrt{P}\,\delta\psi_1$$

$$S_{pp}^{2\text{-sided}} \equiv \langle P P^+ \rangle = 4P\langle \delta\psi_1^2 \rangle = 4P\Delta\psi_1^2 \overset{!}{=} P\hbar\omega$$

$\Rightarrow$ we need to recover shot noise!

2 sided

$$\Delta\psi_1^2 = \frac{1}{4}\hbar\omega \left[\frac{\text{Watt}}{\text{Hz}}\right]$$

but only $\delta\psi_1$ matters!

$$\Rightarrow \Delta\psi_1 \cdot \Delta\psi_2 \geq \frac{1}{4}\hbar\omega$$

$$S_{pp}^{1\text{-sided}} \equiv \langle P P^+ \rangle = 4P\langle \delta\psi_1^2 \rangle = 4P\Delta\psi_1^2 \overset{!}{=} 2P\hbar\omega$$

1-sided

$$\Delta\psi_1^2 = \frac{1}{2}\hbar\omega \left[\frac{\text{Watt}}{\text{Hz}}\right]$$

Coherent State I (Fox 7.5)

- Quantum mechanical equivalent to classical monochromatic EM wave is coherent state $|\alpha>$
- For linearly polarized mode in cavity volume V, $\alpha = X_1 + iX_2$
- Can separate into amplitude and phase $\alpha = |\alpha| e^{i\phi}$ with $|\alpha| = \sqrt{X_1^2 + X_2^2}$ and $X_1 = |\alpha| \cos\phi$ and $X_2 = |\alpha| \sin\phi$, α can be represented with phasor length $|\alpha|$, angle ϕ
- Coherent state is a minimum uncertainty state so $\Delta X_1 = \Delta X_2 = \dfrac{1}{2}$ (shaded circle)
- Relating with $E_{\text{classical}} = \bar{n}\hbar\omega$, find $|\alpha| = \sqrt{n}$

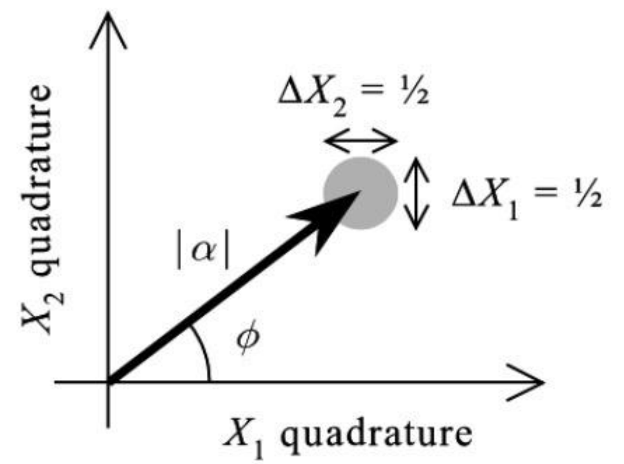


Fig. 7.5 Phasor diagram for the coherent state $|\alpha\rangle$. The length of the phasor is equal to $|\alpha|$, and the angle from the X_1-axis is the optical phase ϕ. The quantum uncertainty is shown by a circle of diameter 1/2 at the end of the phasor.

Mark Fox, Quantum Optics

Shot Noise (Fox 7.6)

- Average phasor length α, circle diameter is $1/2$, length of phasor uncertain between $(\alpha + 1/4)$ and $(\alpha - 1/4)$
- $\Delta n = (|\alpha| + 1/4)^2 - (|\alpha| - 1/4)^2 = |\alpha| = \sqrt{\bar{n}}$
  - coherent states have Poissonian photon statistics and shot noise (from light's quantum uncertainty)
- For large $|\alpha|$, phase uncertainty is $\Delta\phi = \dfrac{1/2}{\sqrt{\bar{n}}}$
- These give number-phase uncertainty of light, $\Delta n \Delta \phi \geq \dfrac{1}{2}$

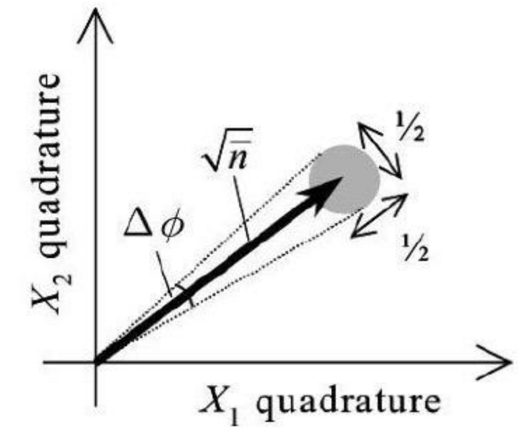


Fig. 7.6 The uncertainty circle of a coherent state $|\alpha\rangle$ introduces both photon number and phase uncertainty. Note that the phase uncertainty $\Delta\phi$ is only well-defined when $|\alpha| = \sqrt{\bar{n}} \gg 1$.

Mark Fox, Quantum Optics

Vacuum Field I (Fox 7.4)

- Zero-point energy of QHO is $(1/2)\hbar\omega$
- Quantum optics: this energy from randomly fluctuating field called vacuum field (present everywhere)
- Equating zero-point energy of QHO to time-averaged energy of E and B fields gives, $E_{\text{vac}} = \sqrt{\dfrac{\hbar\omega}{2\epsilon_0 V}}$
- Uncertainties in the two quadratures equal the minimum allowed, minimum uncertainty state $\Delta X_1^{\text{vac}} = \Delta X_2^{\text{vac}} = \dfrac{1}{2}$

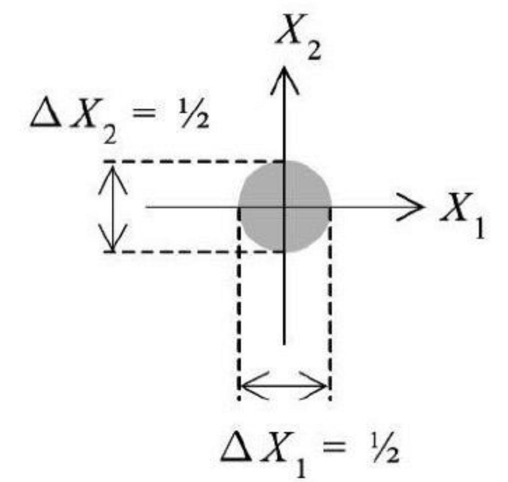
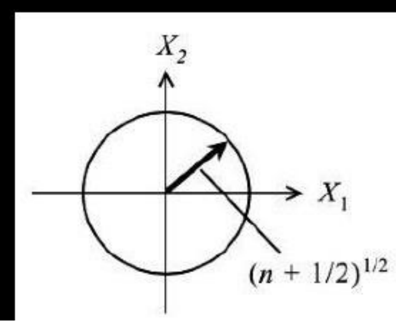


Fig. 7.4 Phasor diagram for the vacuum state. The uncertainties in the two field quadratures are identical, with $\Delta X_1 = \Delta X_2 = 1/2$. Note that this figure is essentially the same as Fig. 7.3(a) except that the uncertainty circle is displaced to the origin to account for the zero classical field of the vacuum.

Mark Fox, Quantum Optics

Squeezed States (Fox 7.7)

- Can squeeze the uncertainty circle of vacuum or coherent state into ellipse of same area: quadrature-squeezed state
- Phase squeezed light allows interferometric measurements with greater precision
- Amplitude squeezed light allows lower amplitude noise
    - has sub-Poissonian statistics
- Could squeeze along any angle
- Could also make photon number state where $\Delta n = 0$ and phase is completely undefined!



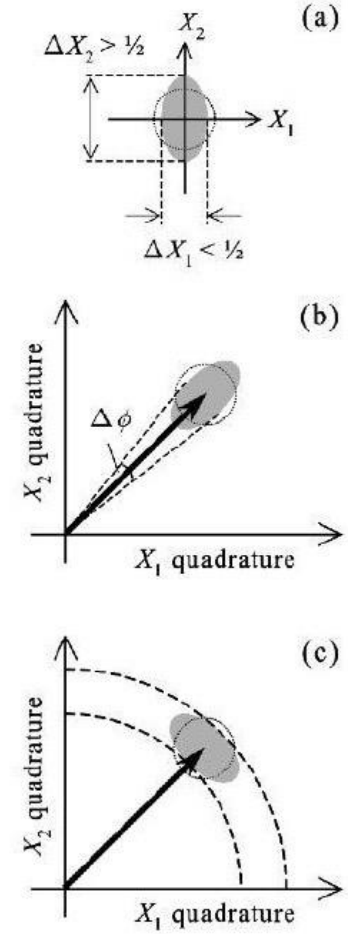


Fig. 7.8 Quadrature squeezed state (a) Squeezed vacuum. (b) Phas squeezed light. (c) Amplitude-squeeze light. The dotted circle in each of th diagrams shows the quadrature uncer tainty of the vacuum/coherent state

Michelson interferometer quantum noise

Shot Noise

$$\psi = \frac{\psi_{in}}{2}\left(e^{ik\Delta L} - e^{-ik\Delta L}\right) + \frac{\phi_{in}}{2}\left(e^{ik\Delta L} + e^{-ik\Delta L}\right)$$

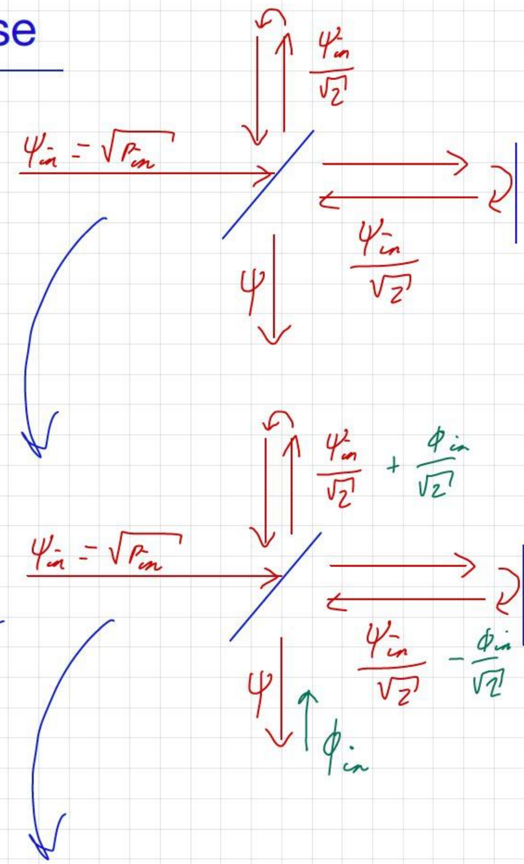
$$= i\,\psi_{in}\sin k\Delta L + \phi_{in}\cos k\Delta L$$

near fringe: $\psi = \phi_{in} + ik\Delta L\,\psi_{in}$

$$P = |\psi|^2 = (k\Delta L)^2 P_{in} - 2\,\mathrm{Im}\left(k\Delta L\,\phi_{in}\psi_{in}^*\right) + |\phi|^2$$

$$\delta P = 2k^2\Delta L\,\delta L - 2k\Delta L\,\mathrm{Im}\,\phi_{in}\psi_{in}^*$$

$$= 2k\Delta L\left(k\,\delta L - \mathrm{Im}\left(\phi_{in}\psi_{in}^*\right)\right)$$



$\mathrm{Im}\left(\phi_{in}\psi_{in}^*\right)$ Is shot noise quadrature

Radiation Pressure Noise

$$F = \frac{2(P_x - P_y)}{c}$$

$$P_{x,y} = \left| \frac{\varphi_{in}}{\sqrt{2}} \pm \frac{\phi_{in}}{\sqrt{2}} \right|^2 = \frac{1}{2} P_{in} \pm Re(\varphi_{in}^* \phi_{in})$$

$$F = \frac{4\, Re(\varphi_{in} \phi_{in})}{c}$$

$Re\,(\phi_{in} \varphi_{in}^*)$ Is radiation pressure noise quadrature

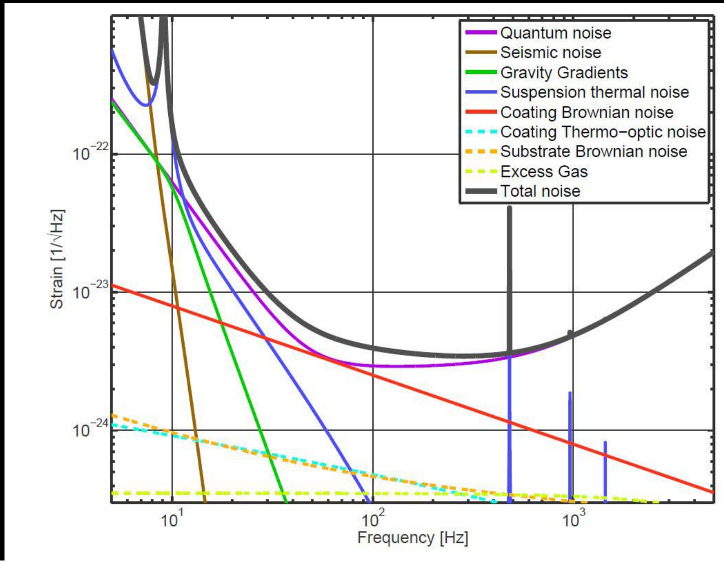
How to calculate quantum noise in any interferometer

- Calculate optical input-output relations for all ports of the interferometer (dark port, bright port)
- Send in normal vacuum state at every port:

  $\frac{1}{2}\hbar\omega$ in each quadrature

  ○

- Propagate to the output.



Quantum Power Spectral Density and Two-photon Squeezing

Amplitude quadrature ↓ ; Phase quadrature ↙

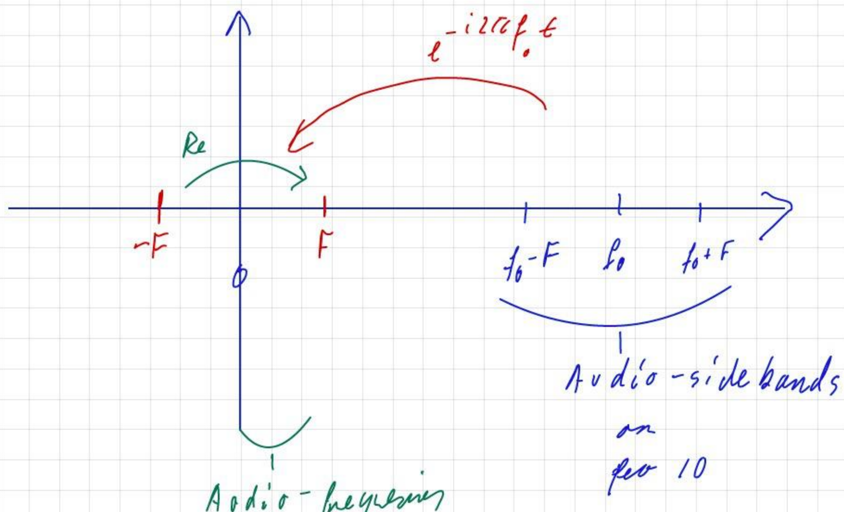
$$\Psi = \Psi_0 + \delta\Psi_1 + i\,\delta\Psi_2$$

↑ carrier ; ↖ ↗ fluctuations at all frequencies

$$P = |\Psi|^2 = |\Psi_0|^2 + 2\,\mathrm{Re}\left(\Psi_0^* \,\delta\Psi_1\right) = |\Psi_0|^2 + 2\,\mathrm{Re}\,\Psi_0^* \int df\, \delta\Psi_1(f)$$

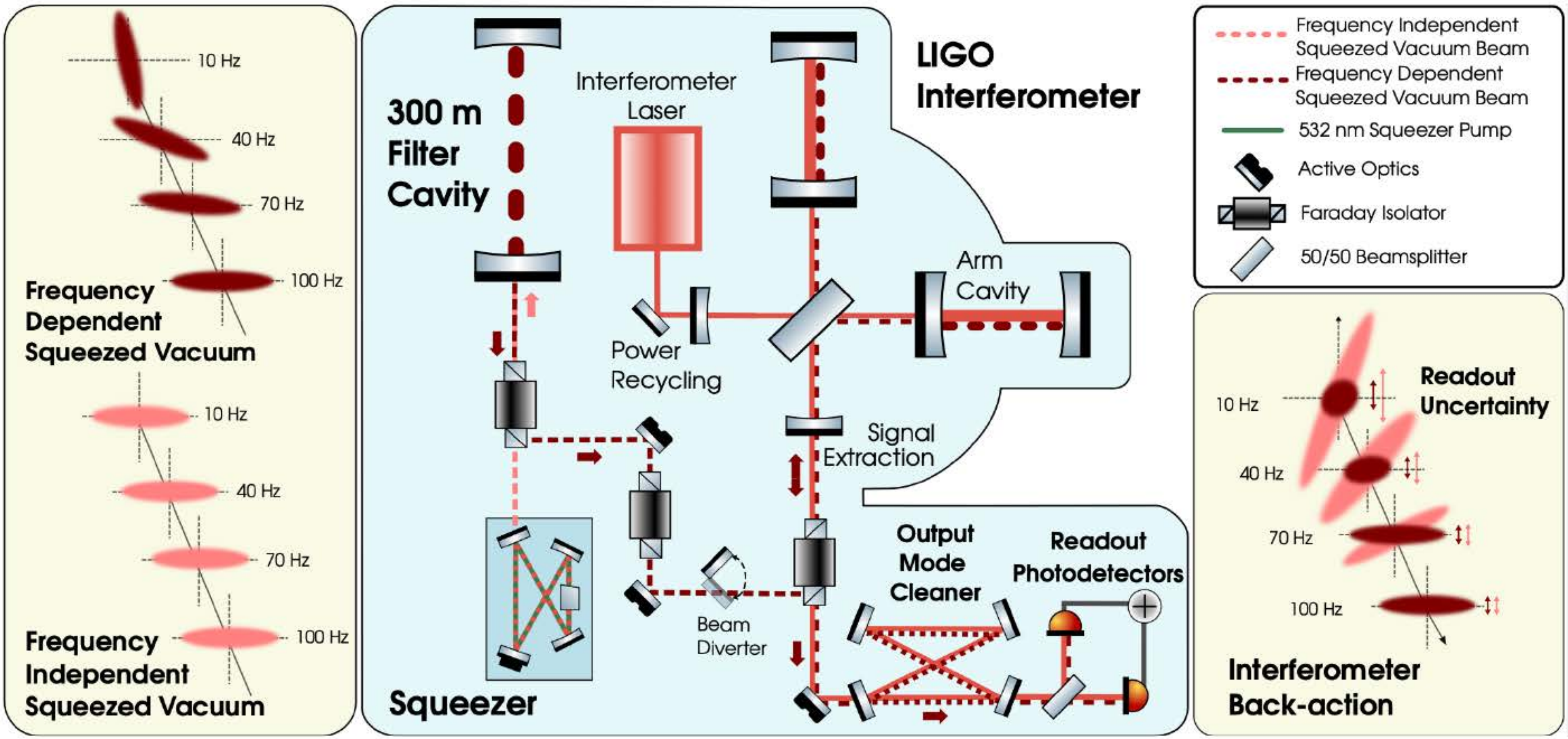
$\sim e^{-2\pi i f_0 t}$

base-bands



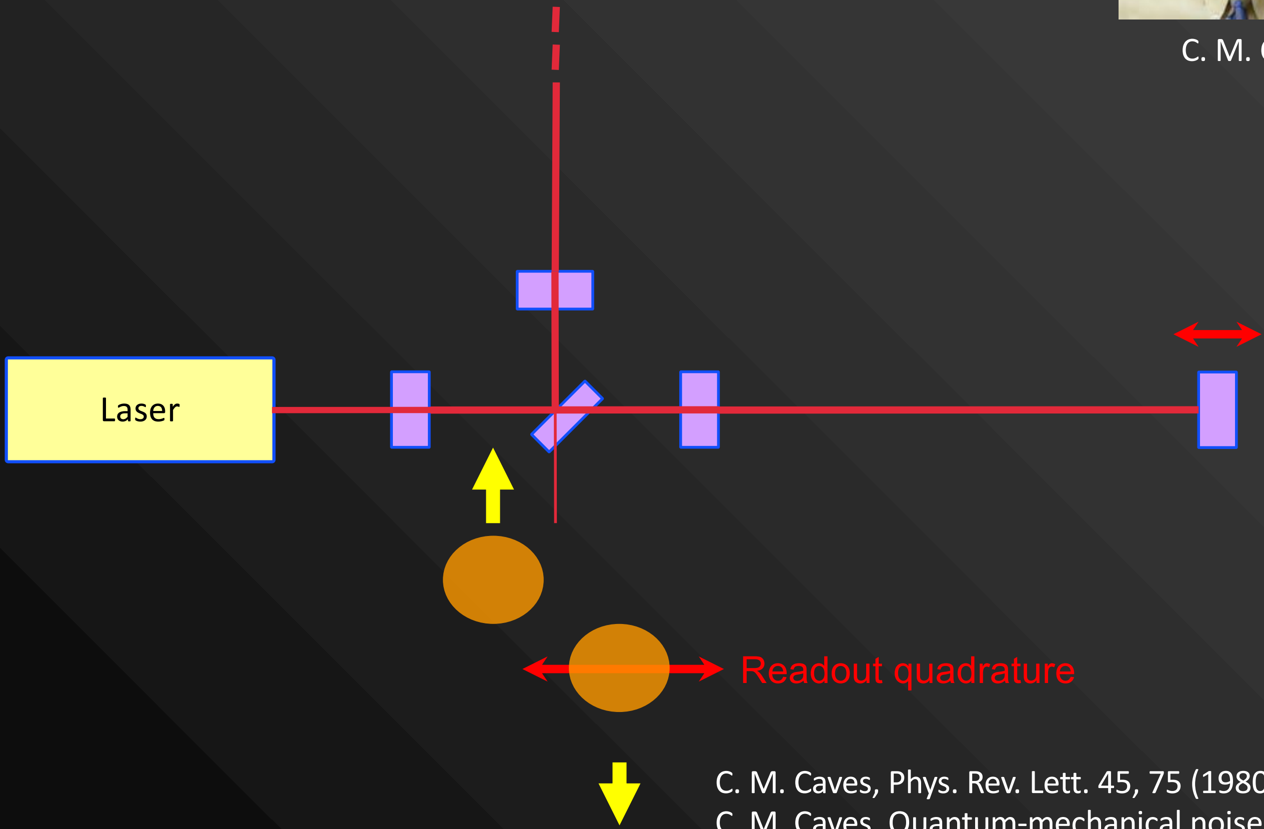
Dhruva Ganapathy
Vicky Xu

Frequency Dependent Squeezing



Beyond Quantum Noise

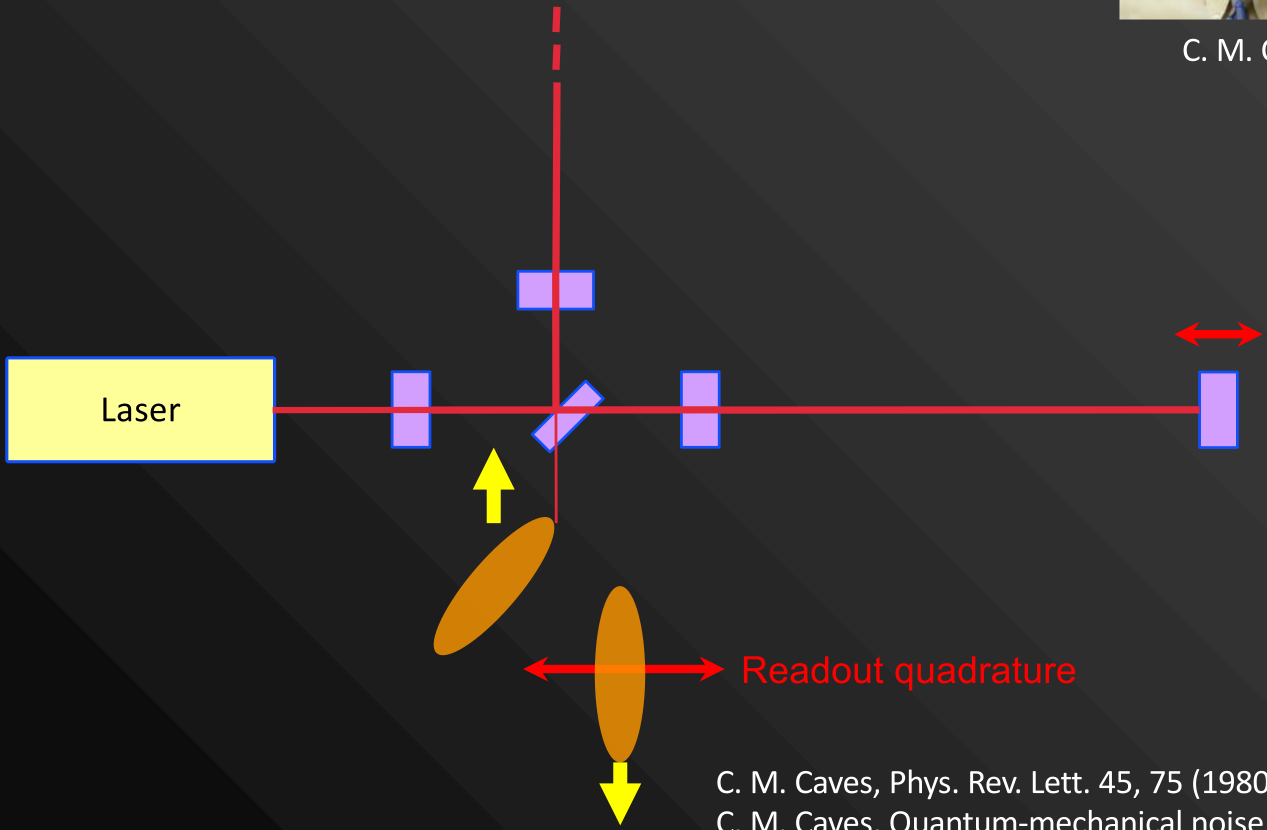
C. M. Caves



C. M. Caves, Phys. Rev. Lett. 45, 75 (1980).
C. M. Caves, Quantum-mechanical noise in an interferometer. Phys. Rev. D 23, p. 1693 (1981).

Beyond Quantum Noise

C. M. Caves

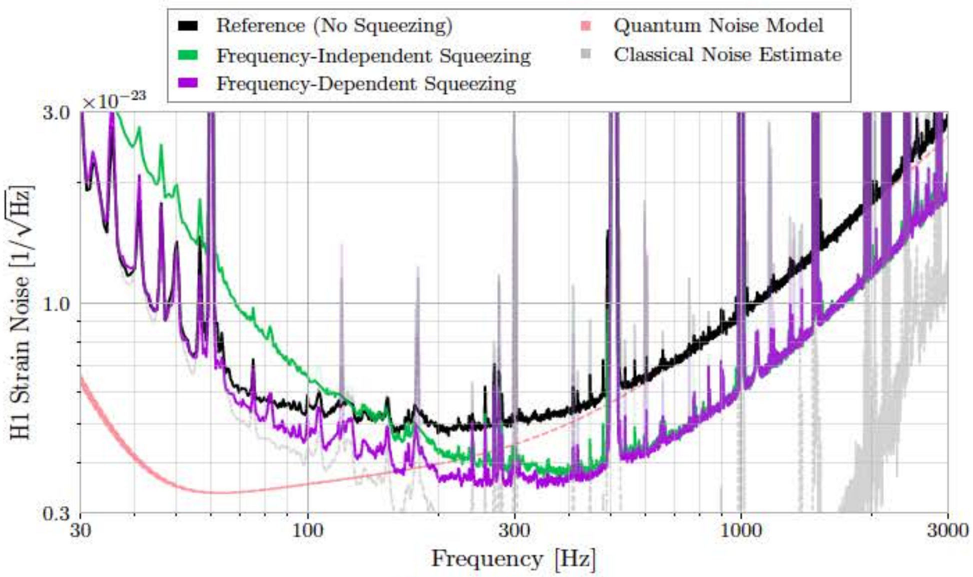


C. M. Caves, Phys. Rev. Lett. 45, 75 (1980).
C. M. Caves, Quantum-mechanical noise in an interferometer. Phys. Rev. D 23, p. 1693 (1981).

Key Pieces of LIGO A+ done: Freq. Dep. Squeezing in O4!

Dhruva Ganapathy
Vicky Xu

Frequency Dependent Squeezing in O4



H1

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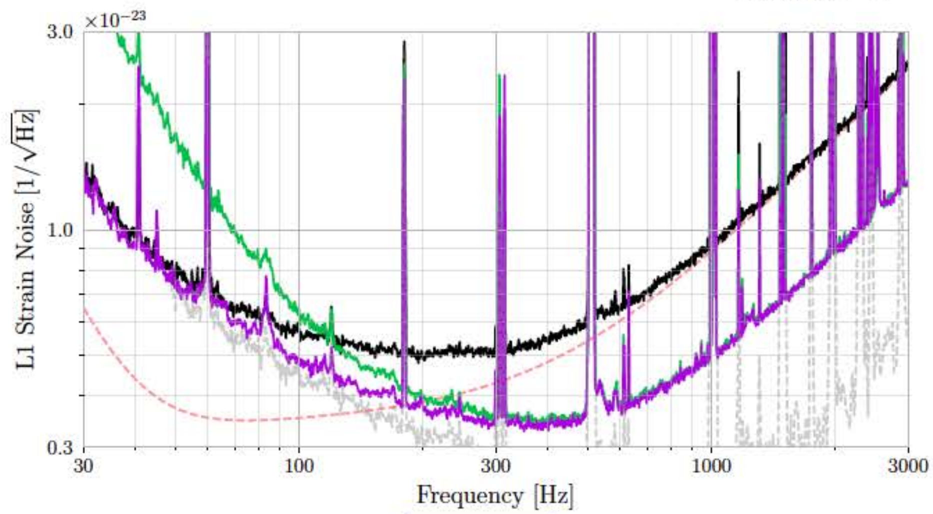
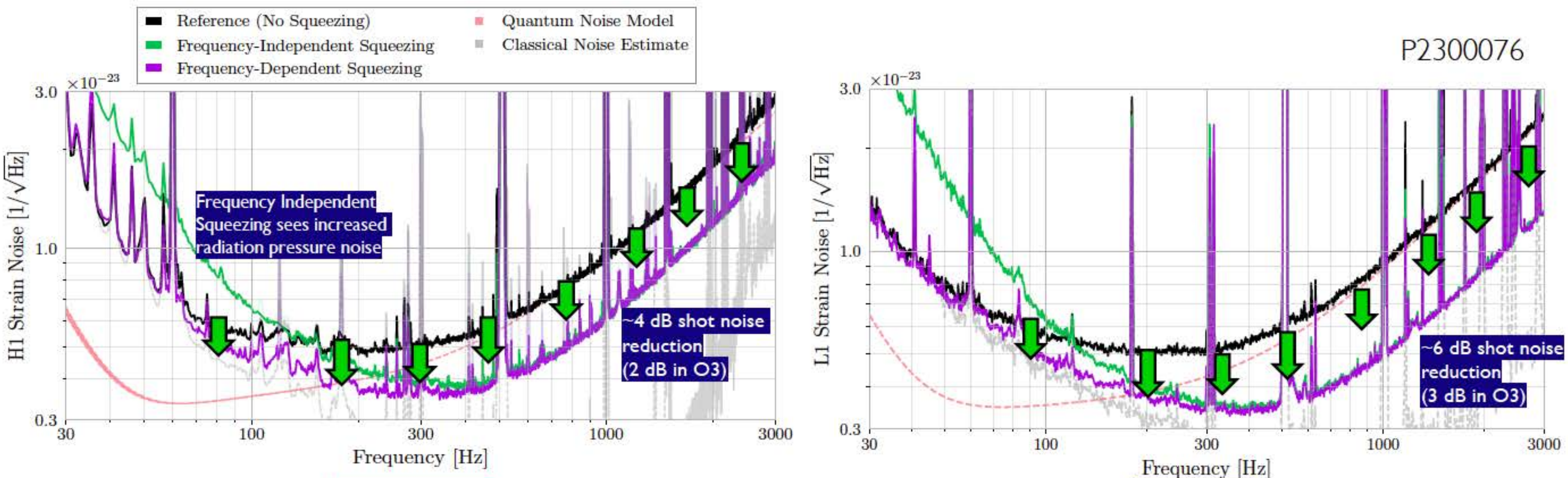


L1

Dhruva Ganapathy
Vicky Xu

Frequency Dependent Squeezing in O4



H1

L1

Where do we go from here?

“Recently, we have waded a little out to sea, enough to dampen our toes or, at most, wet our ankles. The water seems inviting. The ocean calls.”

Carl Sagan

COSMIC EXPLORER

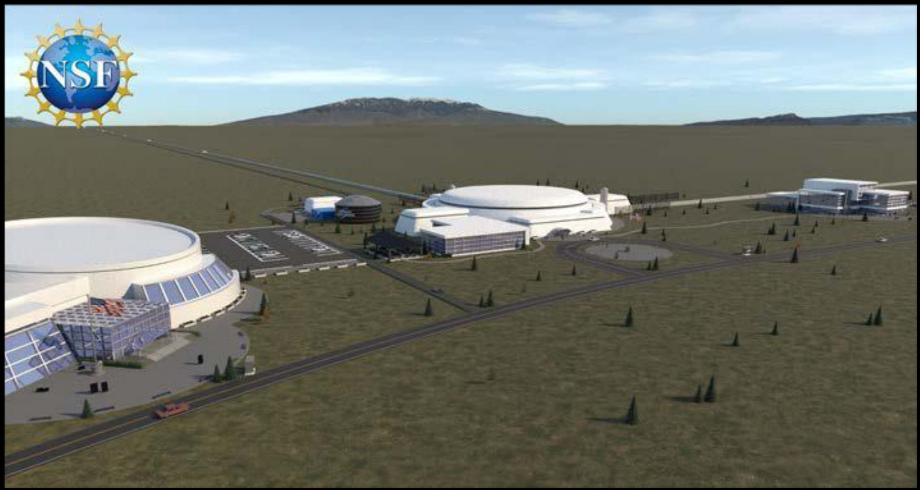
Cosmic Explorer

Stefan Ballmer

The US Vision for Gravitational-Wave Astrophysics

- Next-Generation Gravitational-Wave Observatory
  - 40 km and 20 km L-shaped surface observatories
  - 10x sensitivity of today's observatories
  - Global network together with European Einstein Telescope

- Enables access to
  - Stellar to intermediate mass mergers throughout Cosmic Time
  - Dynamics of Dense Matter
  - Extreme Gravity

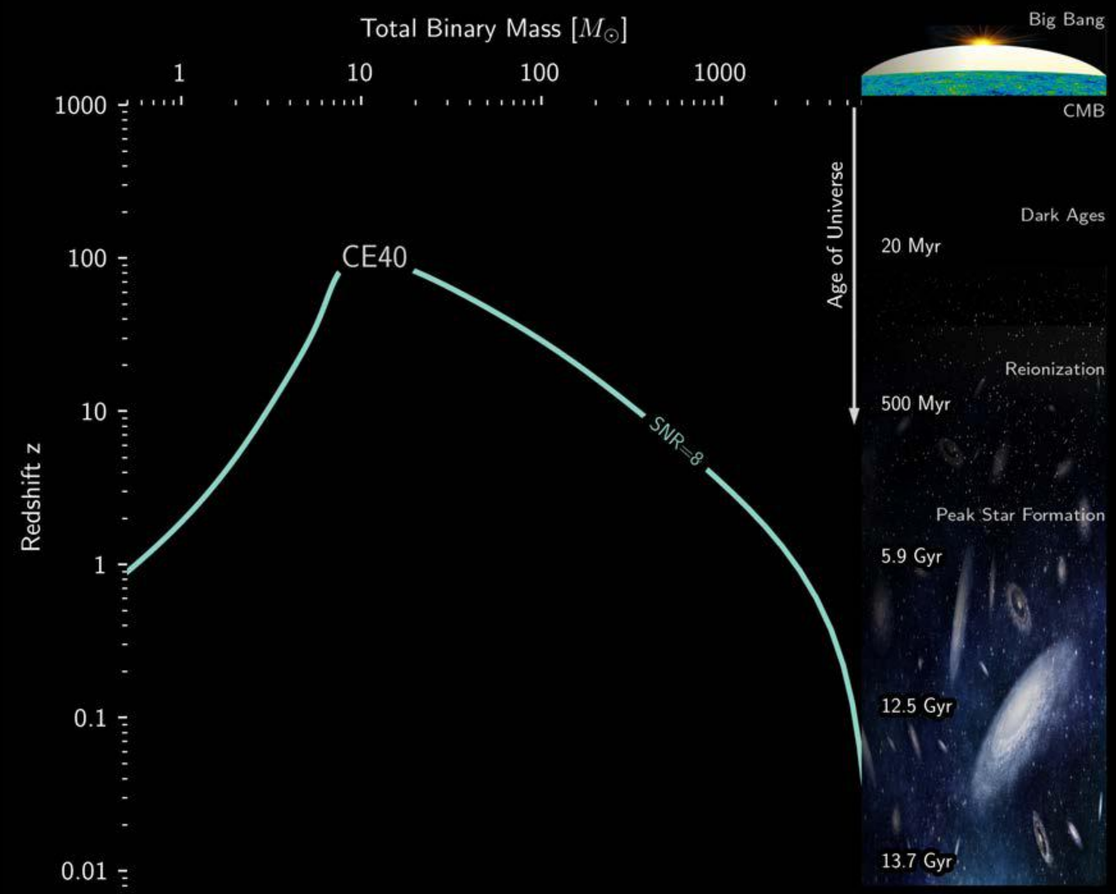


https://cosmicexplorer.org

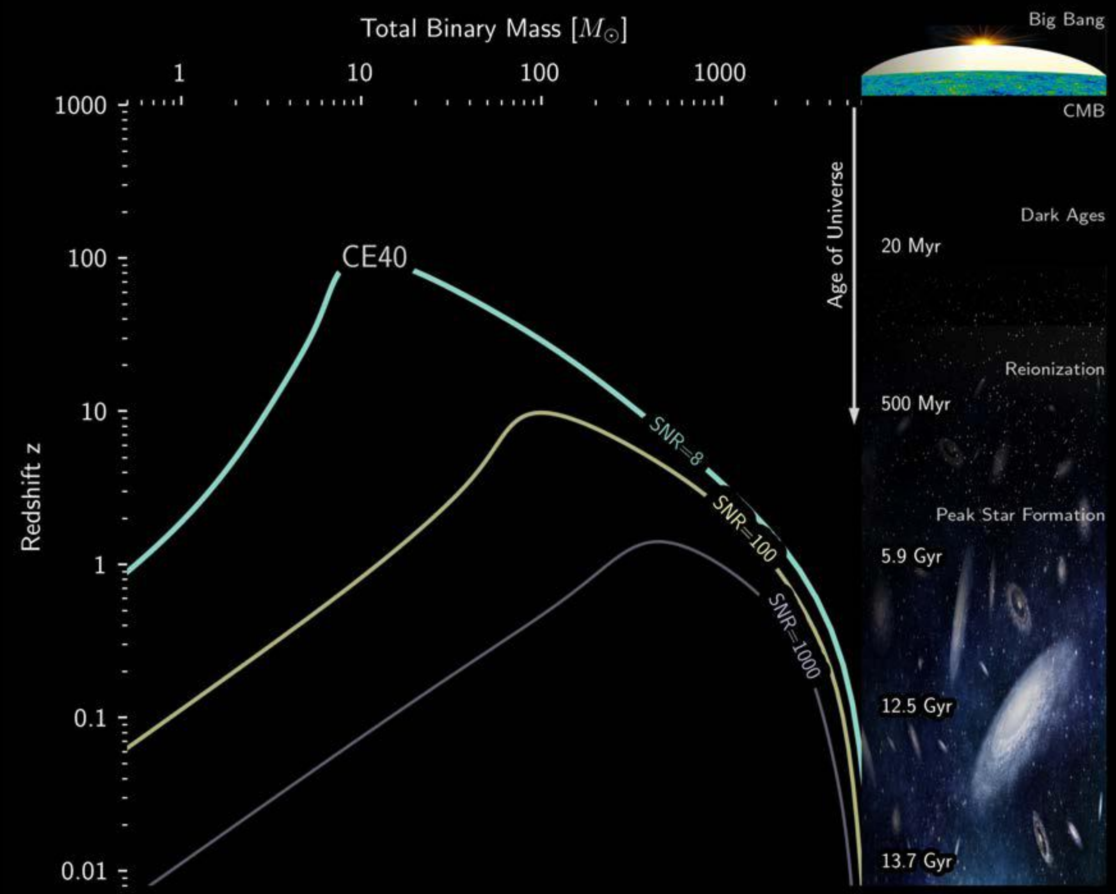
Artist: Eddie Anaya (Cal State Fullerton)

90

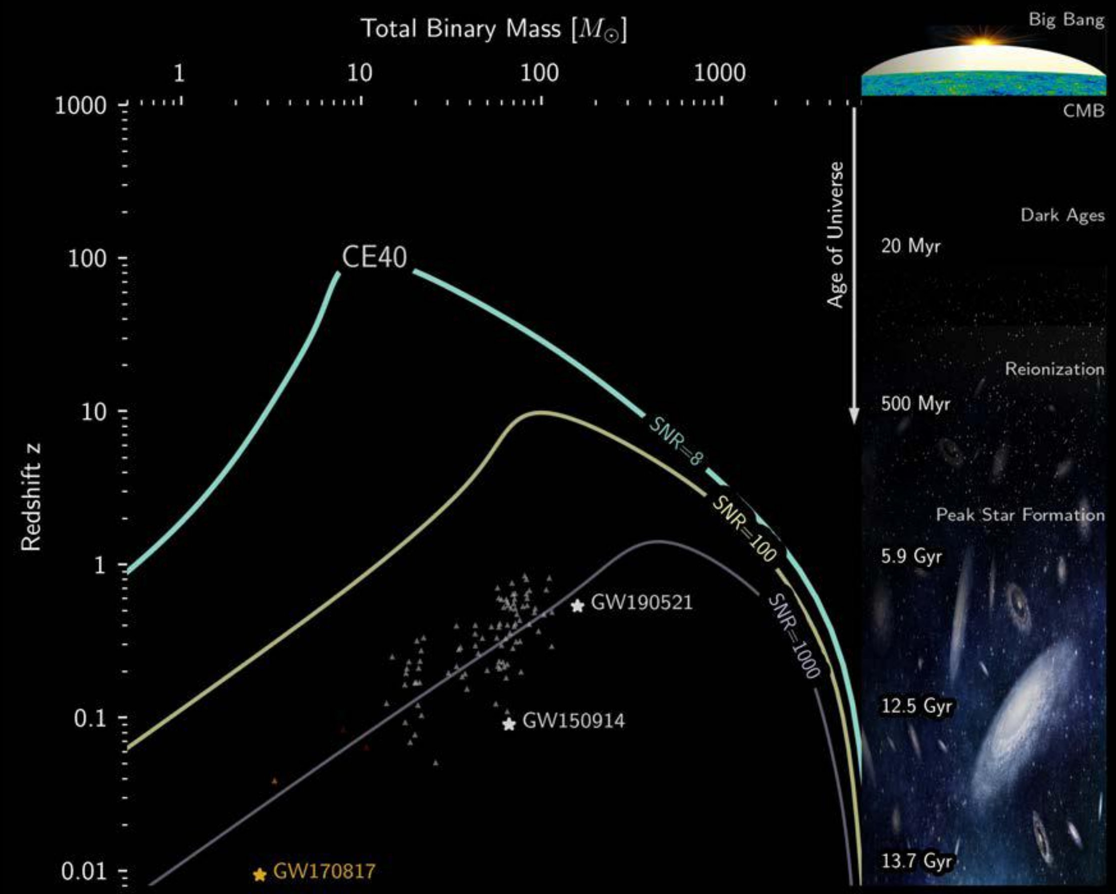
Reaching the Far Shores of the Cosmic Ocean



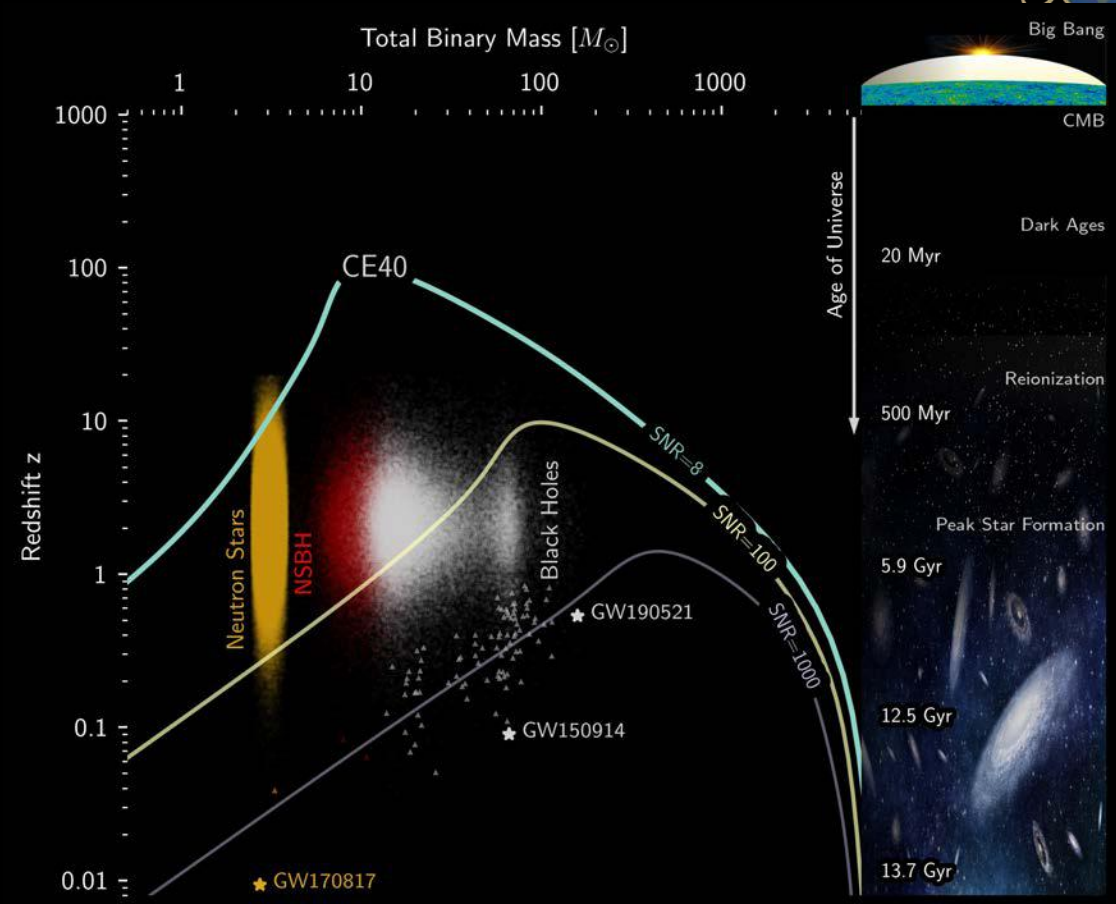
Reaching the Far Shores of the Cosmic Ocean



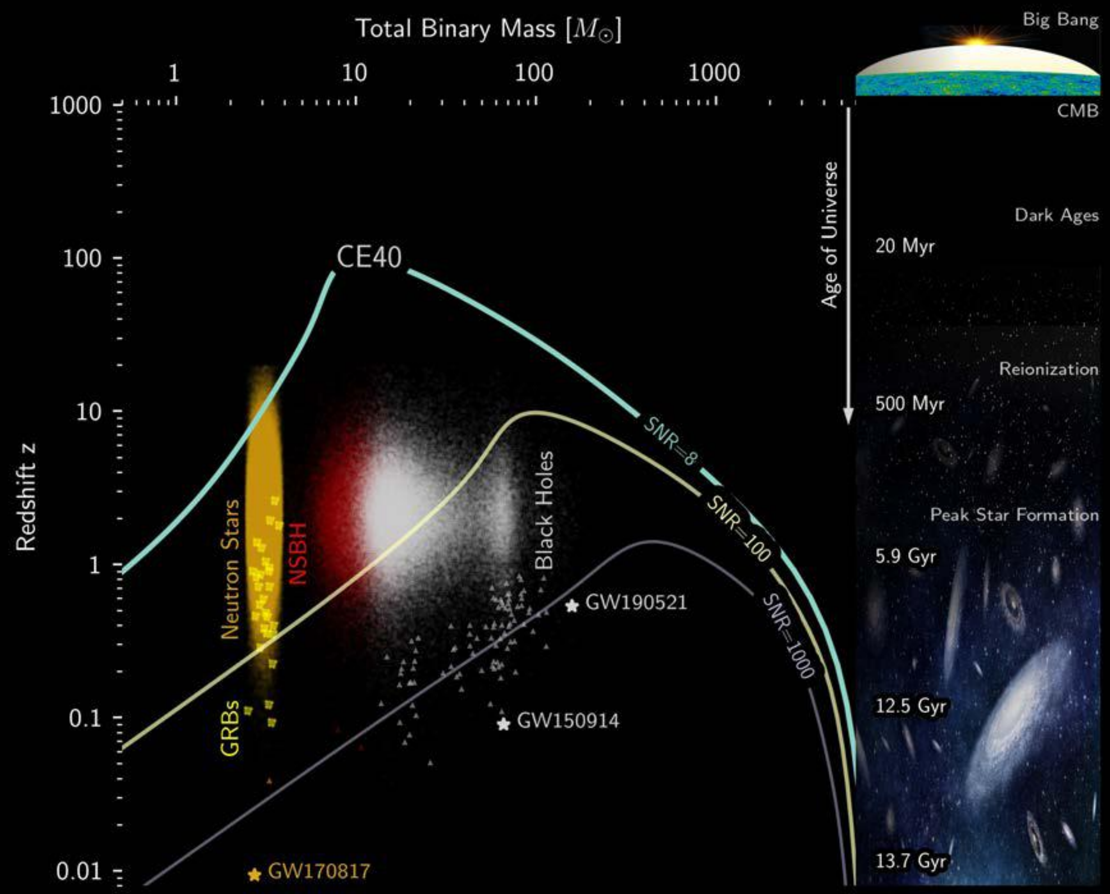
Reaching the Far Shores of the Cosmic Ocean



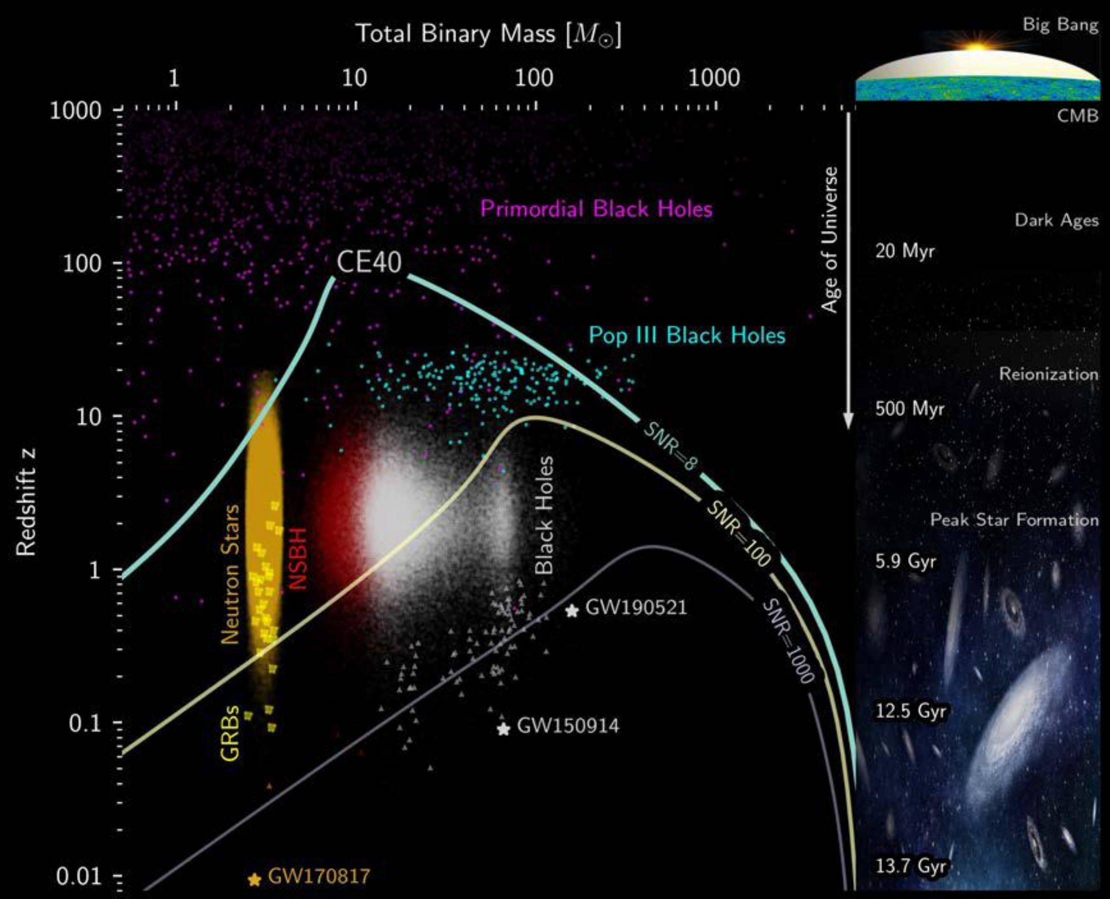
Reaching the Far Shores of the Cosmic Ocean



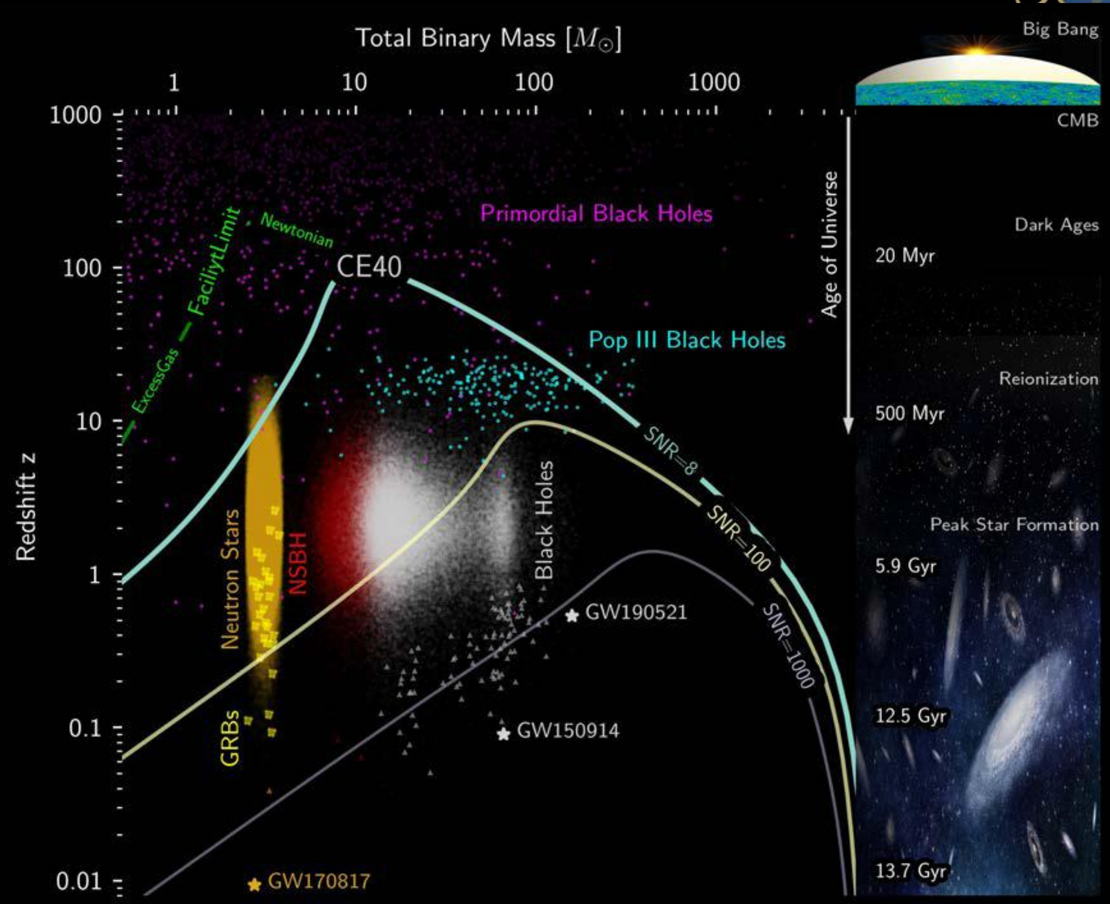
Reaching the Far Shores of the Cosmic Ocean



Reaching the Far Shores of the Cosmic Ocean



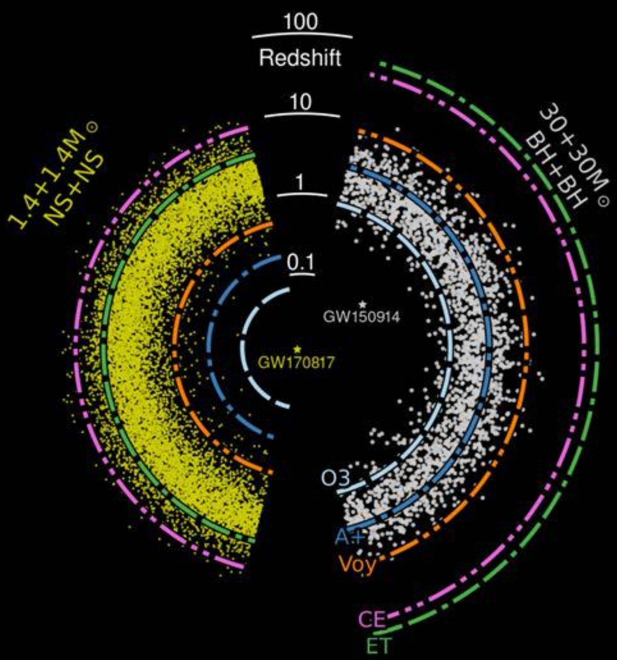
Reaching the Far Shores of the Cosmic Ocean



Credit: Alex Nitz

Cosmology with Cosmic Explorer

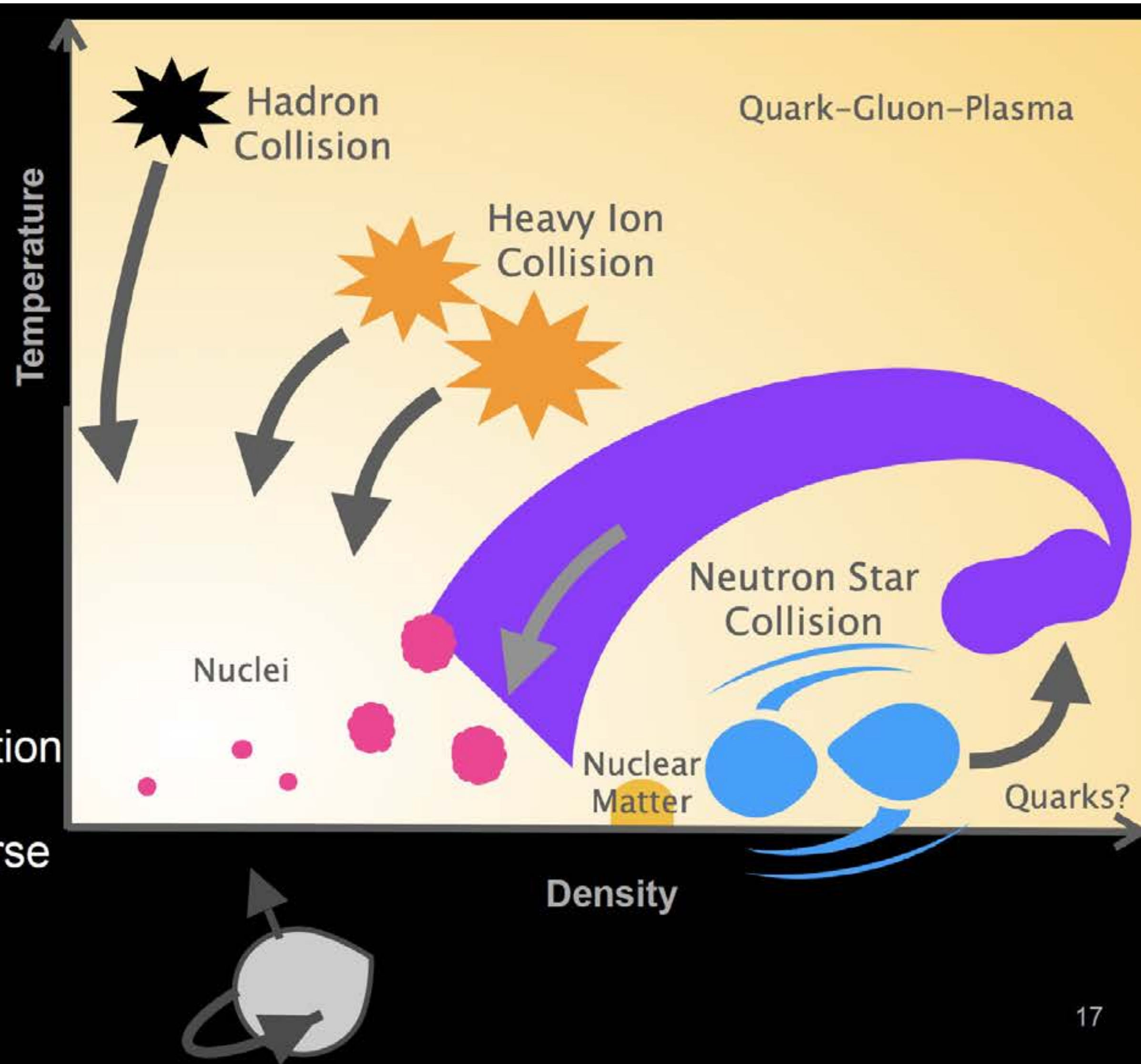
- Expected event rate
  - O(1e5) BHBH merger annually
  - O(1e6) NSNS mergers annually
- Across redshifts up to O(30)
  - Sky localization from detector network
- The full Cosmic Explorer data set is a treasure trove for structure formation studies



Dynamics of dense matter

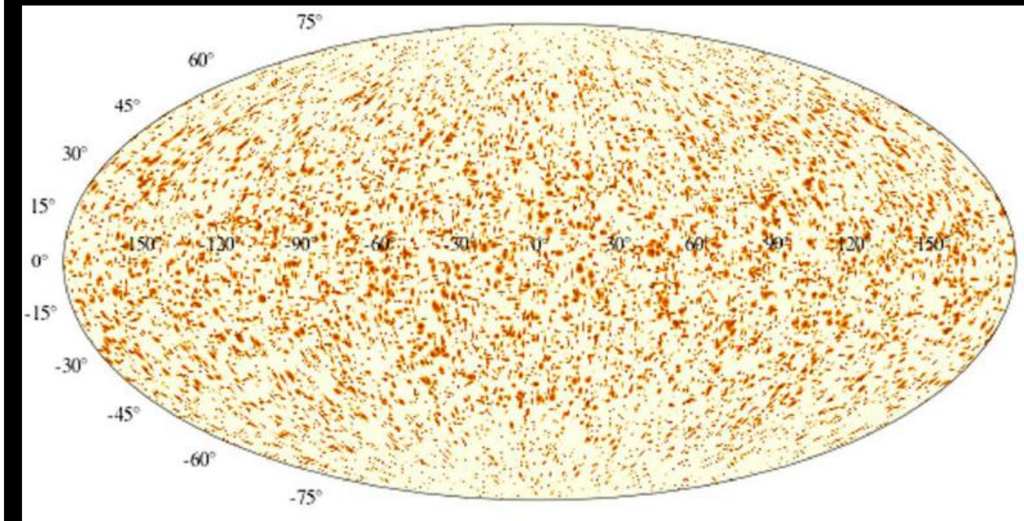
How does matter behave under the most extreme conditions in the universe?

- Neutron star structure, composition
- New phases of dense matter
- Chemical evolution of the universe
- Gamma-ray bursts and jets

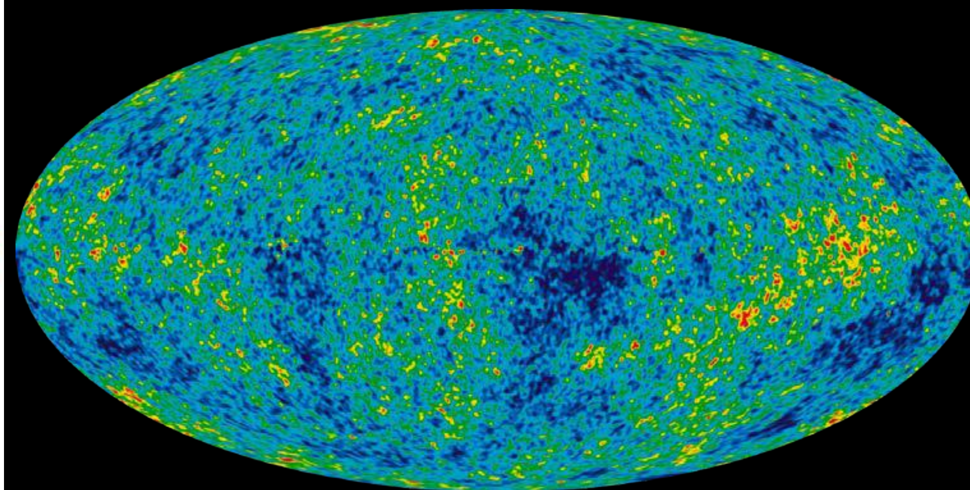


Slide: P Landry, Figure: P Landry, J Read

Detecting Baryon Acoustic Oscillations



Combined posterior field 1year 3G detector network



CMB - WMAP

$$\theta \sim \frac{r_s}{(1+z)D_A(z)}$$

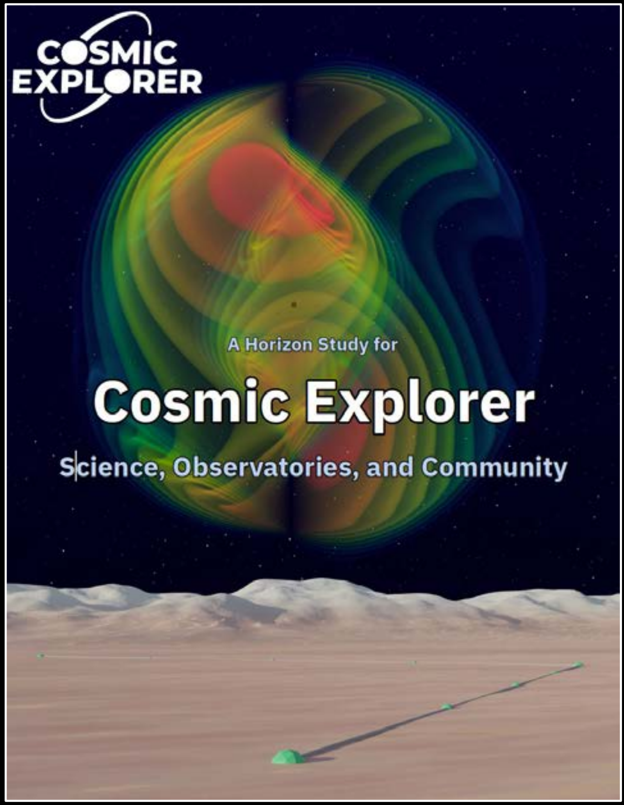
Sumit Kumar

https://iopscience.iop.org/article/10.3847/1538-4357/ac5e34

Cosmic Explorer Updates

- Horizon Study for more information available at:
  - https://arxiv.org/abs/2109.09882
  - https://cosmicexplorer.org

- CE is as envisioned an NSF-funded Project
  - Initial design funding for 3 years at ~ USD 9M…
  - Institutions involved (alphabetically):
    Caltech, CSU Fullerton, **MIT (lead)**, Syracuse University, University of Arizona, University of California Riverside, University of Florida, University of Minnesota, University of Oregon



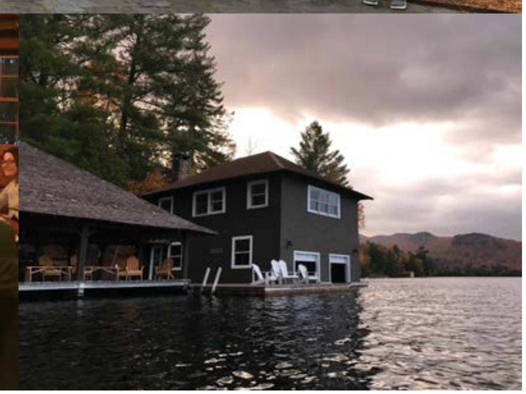
Design and Hardware for Cosmic Explorer

Overview of CE Design and Research Activities

- Funded NSF awards:
  - "Launching the Cosmic Explorer Conceptual Design"
  - "Collaborative Research: Identifying and Evaluating Sites for Cosmic Explorer"
  - "Cosmic Explorer Optical Design"
  - "Enabling Megawatt Optical Power in Cosmic Explorer"
  - "Local Gravity Disturbances and Next-Generation Gravitational-Wave Astrophysics."
  - "Cosmic Explorer: Research and Conceptual Designs for Scattered-Light Mitigation."
- Other related funded awards partly supporting Cosmic Explorer:
  - Observational Science (consortium driven)
  - Vacuum system research
  - Center for Coatings Research
  - Suspension design (A#)

CE Retreat, Minnowbrook, NY, Oct 15-19, 2023

- Workshop to kick off design work for Cosmic Explorer
  - Site search for Cosmic Explorer
  - Optical and Thermal design
  - Project management and international collaborations

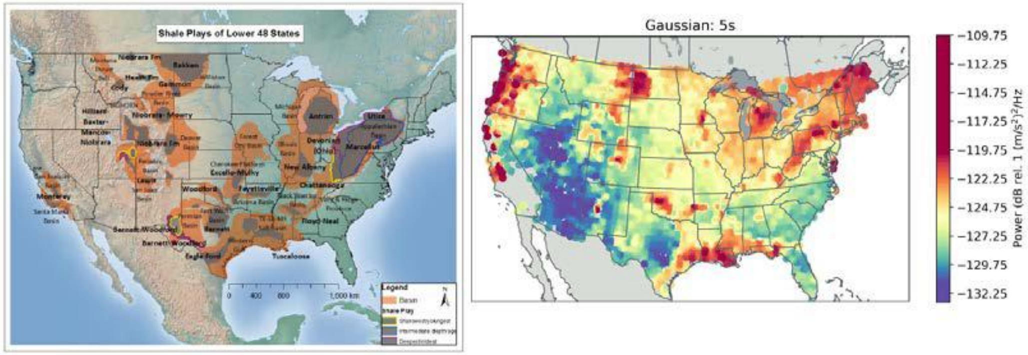


Identifying and Evaluating Sites for Cosmic Explorer

- Identification and evaluation of the most promising locations for CE observatories while developing protocols
- Many considerations:
    - Site Topography
    - Seismicity
    - Land ownership and Indigenous People Partnership
    - Long-term suitability and Economic Impact

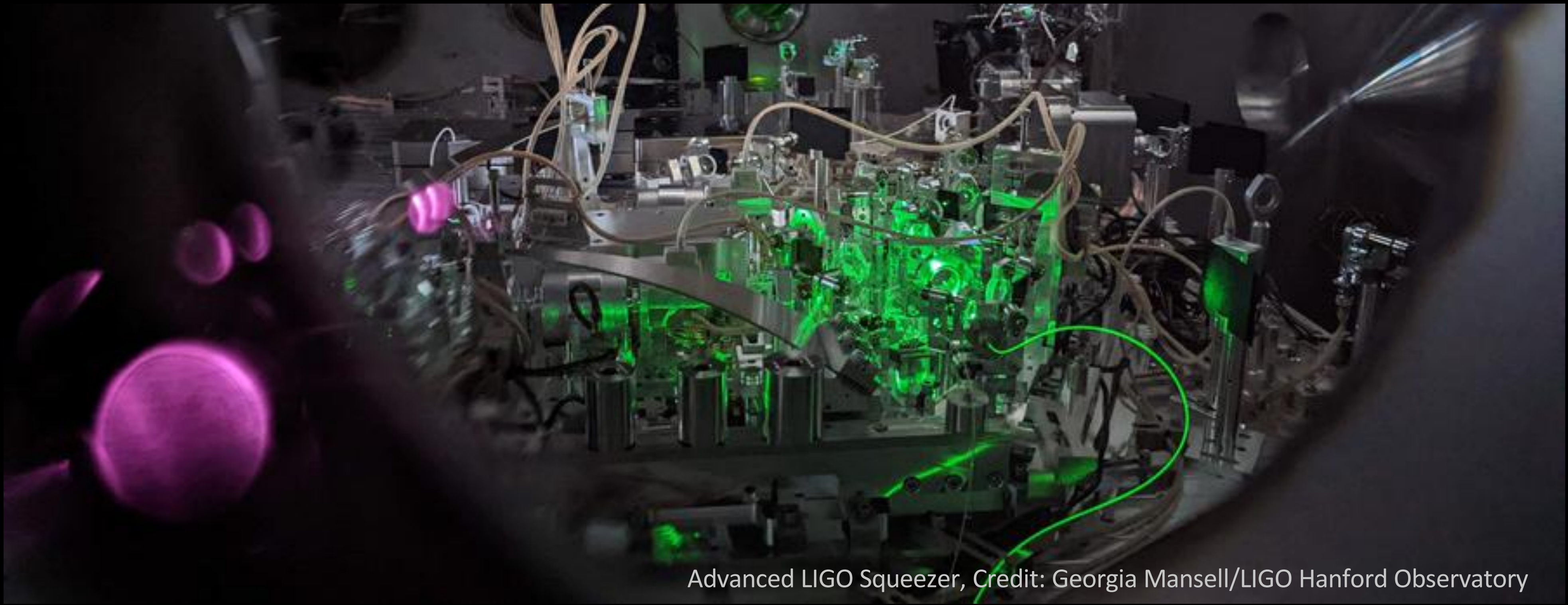
- Initial candidate site selection in progress

0.2 Hz energy compared to basin locations



Sedimentary Basin Seismic Response
Joshua Russell, Syracuse University

Cosmic Explorer Optical Design



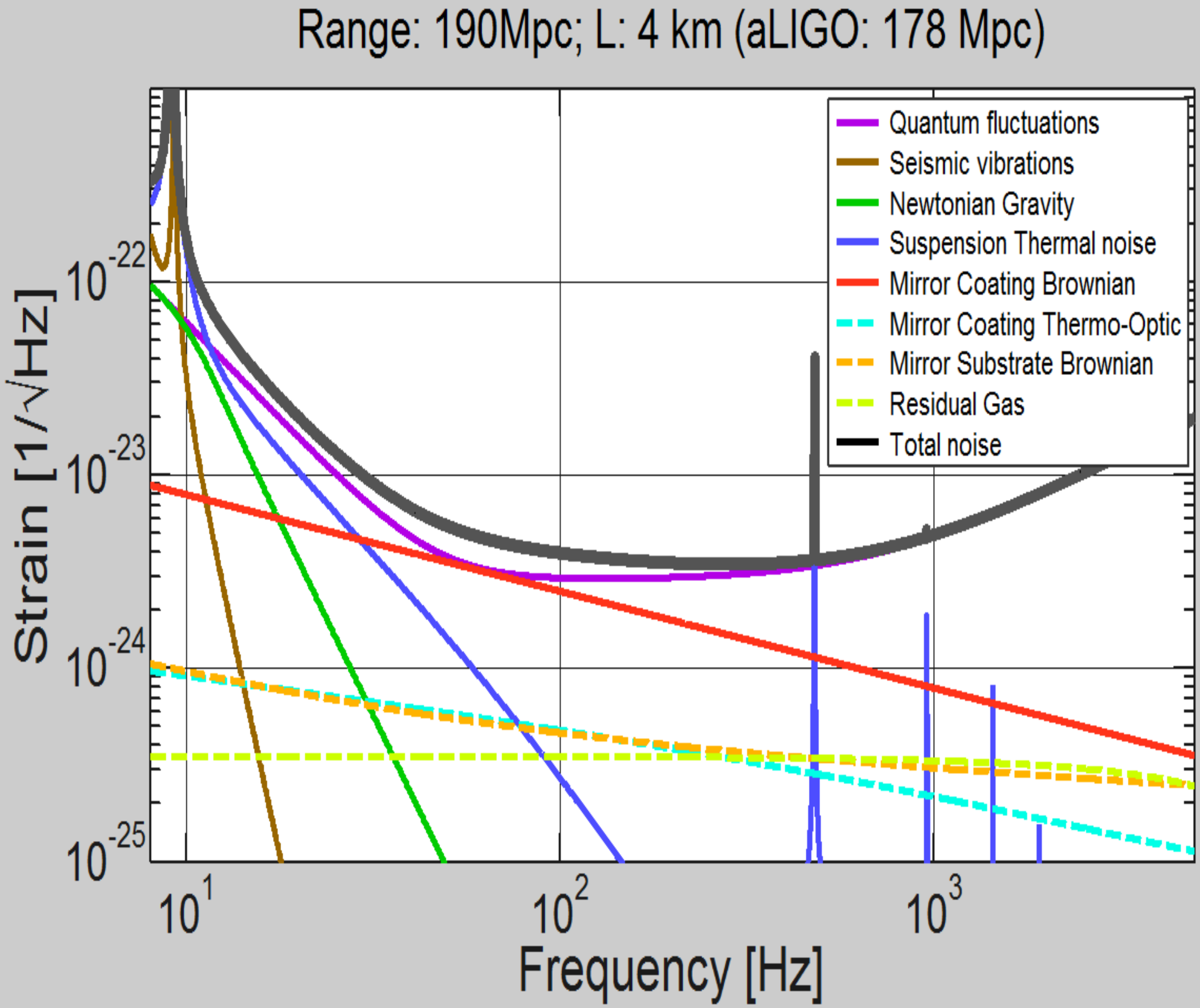
Advanced LIGO Squeezer, Credit: Georgia Mansell/LIGO Hanford Observatory

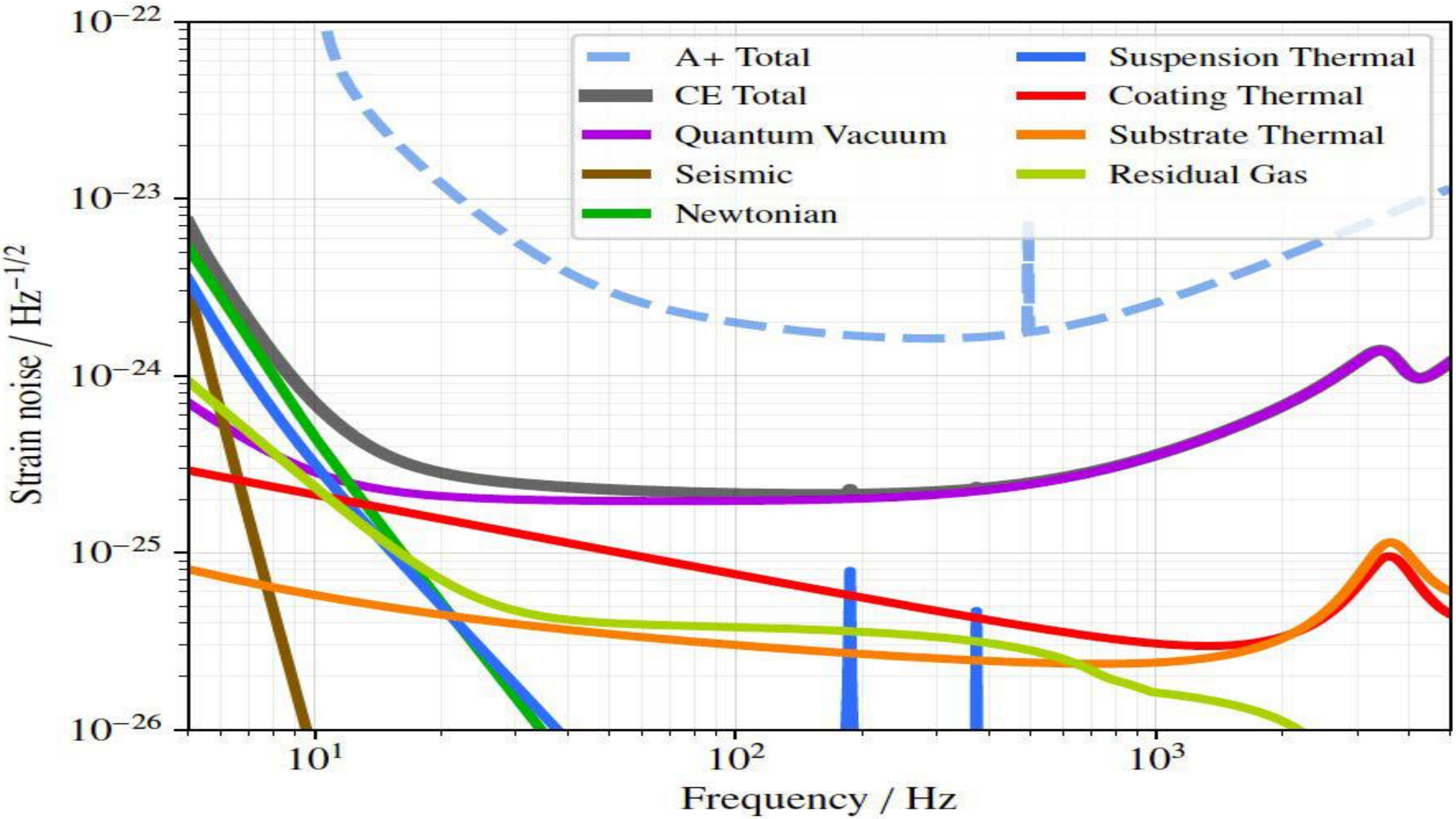
GWADW 2013

Talk on final day
May 24, 2013

Advanced LIGO noise budget

Scaled to longer arm length




A+ Total
CE Total
Quantum Vacuum
Seismic
Newtonian
Suspension Thermal
Coating Thermal
Substrate Thermal
Residual Gas
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
Strain noise / $Hz^{-1/2}$
10^{1}
10^{2}
10^{3}
Frequency / Hz

Large Test masses

320 kg ultra-pure glass:
Reduce thermodynamic fluctuations and heat-induced deformation

Research into fabrication techniques & metrology

Metal-oxide thin-film coatings:
Turn test mass into a mirror with reflectivity >99.995%

Configuration changes compared to Advanced LIGO

- Longer arm cavities (4km→40km)
- Larger test masses (m=40kg, ø=34cm →m=320kg, ø=70cm)
- 2nd input mode cleaner for frequency stabilization (arXiv:2107.14349)
- Scaled filter cavity (compared to A+)
- Homodyne readout (same as A+)
- Larger vacuum system (cost-critical)

Cosmic Explorer: Why Not Just Scale up LIGO Design?

- Unique challenges arise from a 10x longer arm length (CE-G2300033)
  - Minimum beam size for 40 km arms is ~12 cm. For < 1 ppm clipping loss on ITMs, require ~70 cm ITMs. Beamsplitter should be √2 bigger* (at 45° AOI). 1 m diameter unfeasible?

    ➡ Consider alternate layouts with a different beamsplitter location
- Signal Extraction Cavity (SEC) resonance approaches detection band with 40 km or 20 km arms

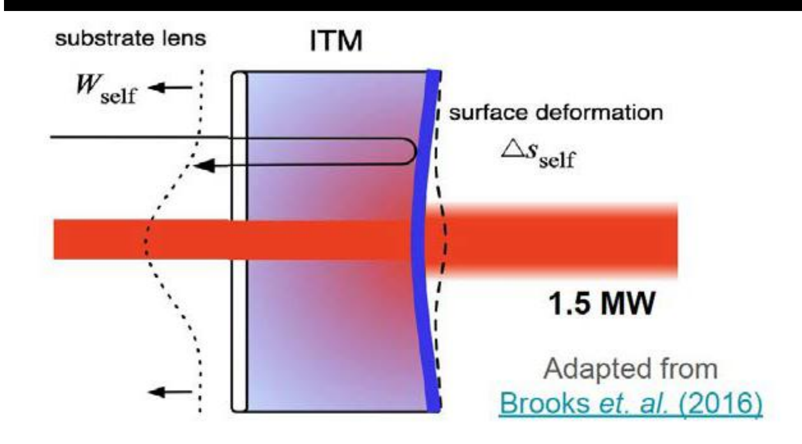
    ➡ SEC length must be < 200 m (40 km arms) or < 90 m (20 km arms)
- FSR of 40 km arms is 3.75 kHz. With same arm finesse, DARM pole is 10x lower

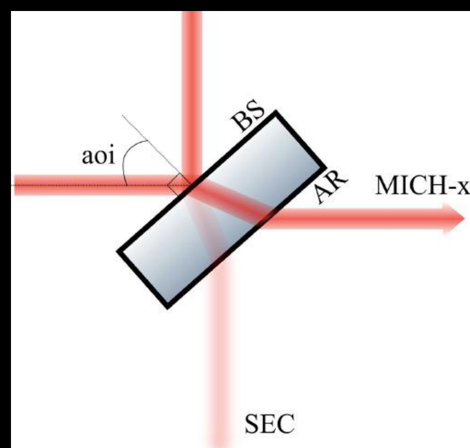
    ➡ Need 10x higher SEC finesse to recover same bandwidth

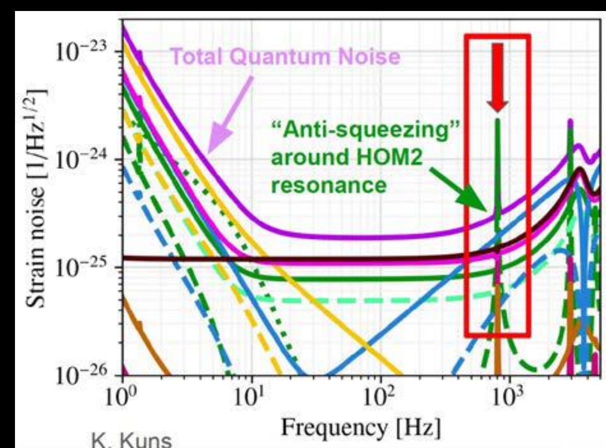
Cosmic Explorer: Why Not Just Scale up LIGO Design?

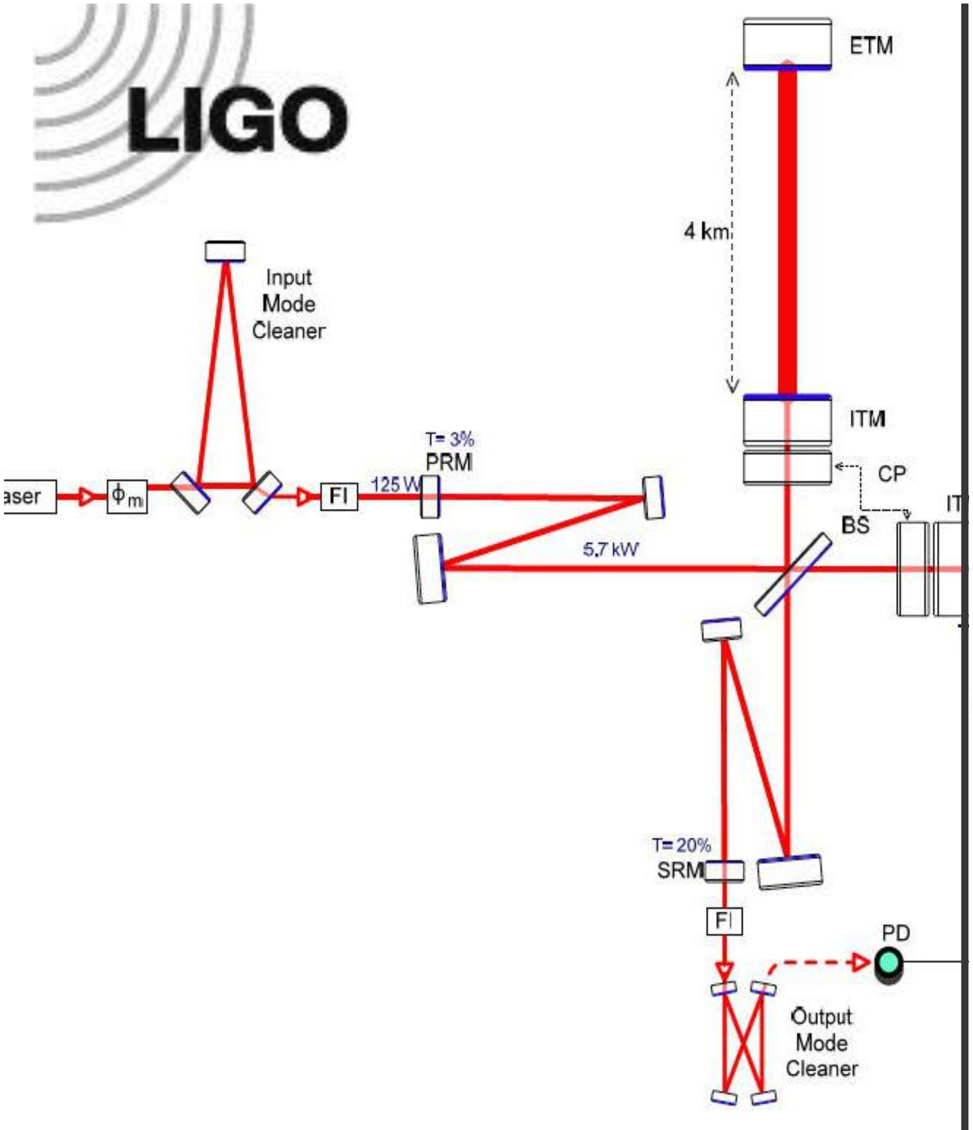
- With a 10x lower arm cavity FSR, nearly all higher-order mode (HOM) resonances will lie in the observation band

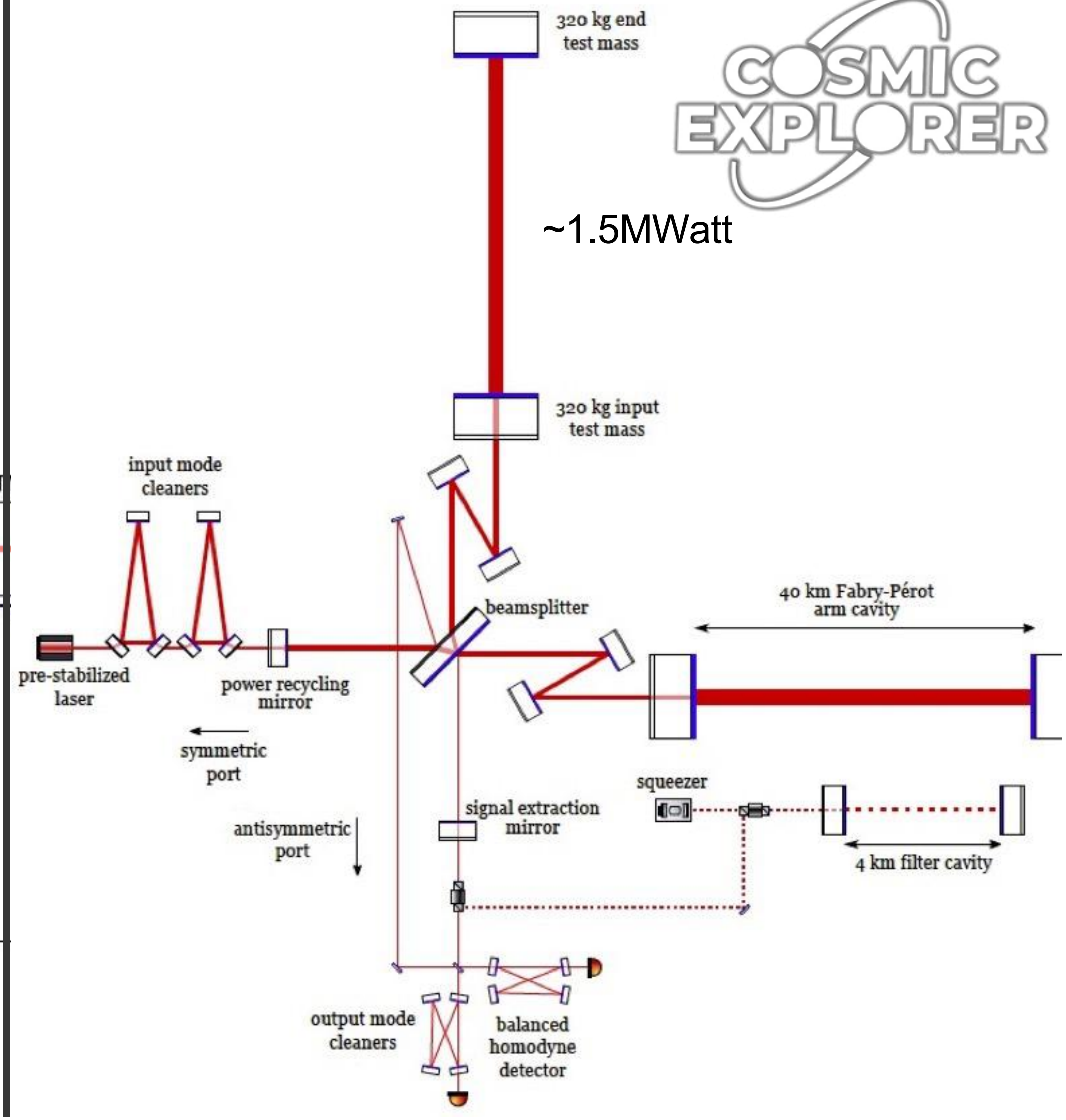
➥ Precision mode-matching is critical to suppress noise couplings, squeezing loss, and squeezing angle mis-rotation around the frequencies of these resonances



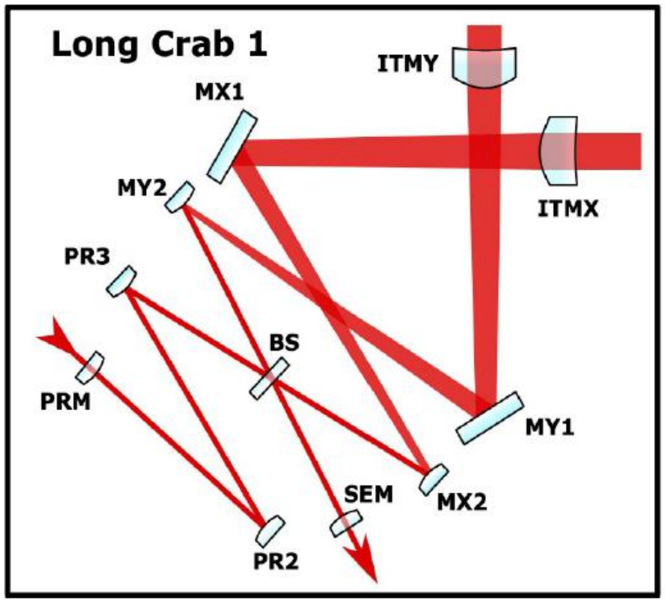




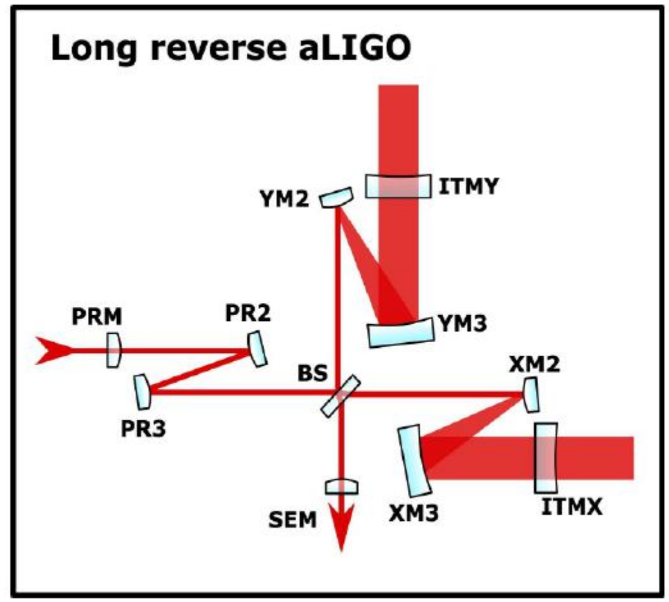

ETM
4 km
Input
Mode
Cleaner
ITM
CP
T= 3%
PRM
125 W
FI
5,7 kW
BS
T= 20%
SRM
FI
PD
Output
Mode
Cleaner


320 kg end
test mass
~1.5MWatt
320 kg input
test mass
input mode
cleaners
beamsplitter
40 km Fabry-Pérot
arm cavity
pre-stabilized
laser
power recycling
mirror
symmetric
port
squeezer
antisymmetric
port
signal extraction
mirror
4 km filter cavity
output mode
cleaners
balanced
homodyne
detector

"Leading" CE Interferometer Topologies (Preliminary)

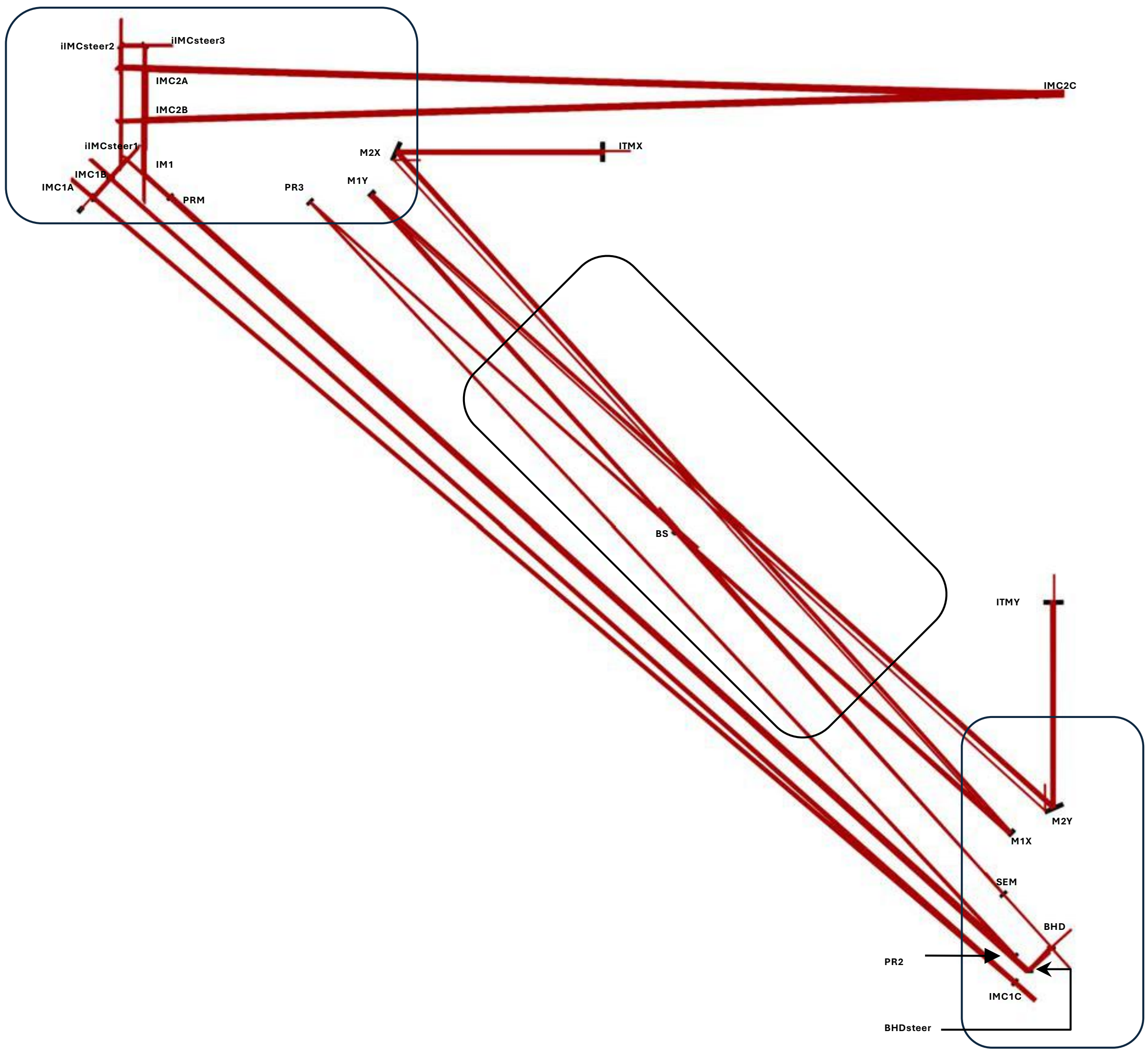


- ~1° beamsplitter AOI
- Static lens polished onto ITM AR surface



- 45° beamsplitter AOI
- Lower-risk option, *if* beamsplitter thermal lensing is manageable

More to scale



Cosmic Explorer Technology Challenges

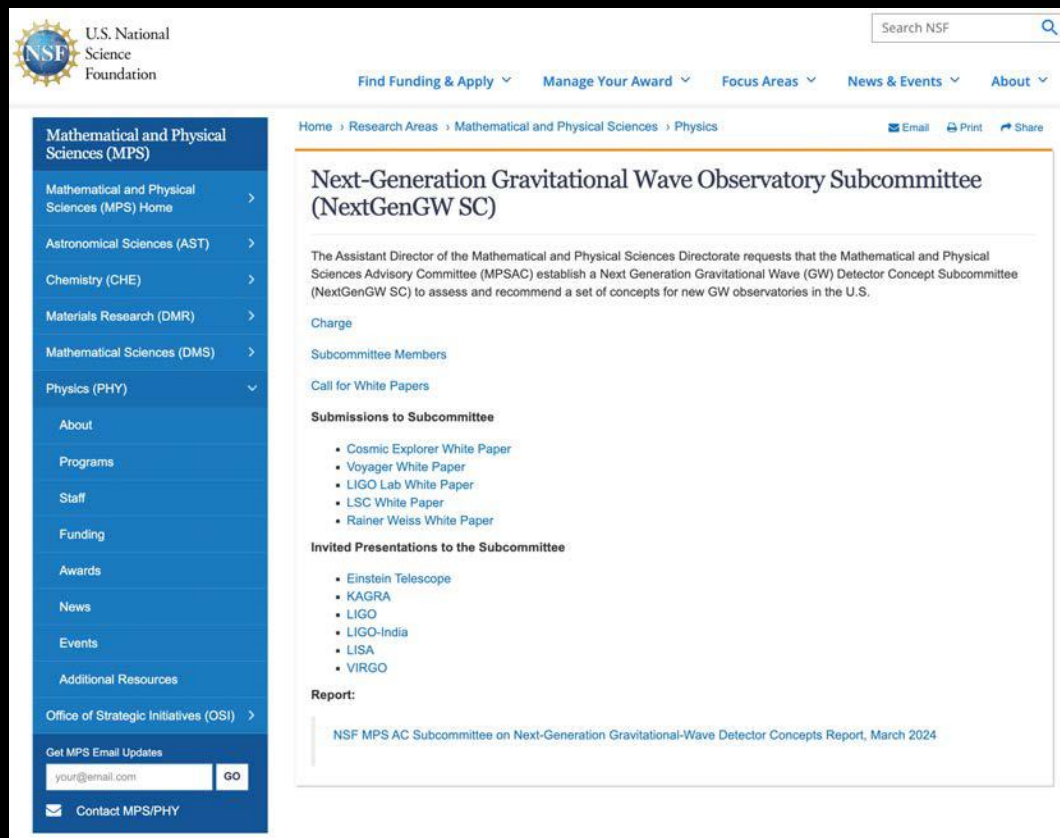
- Large Optics
- Coatings (Thermal noise, Absorption)
- Squeezing (application)
- **Suspensions and seismic isolation syste**
- Vacuum system


The Road Ahead

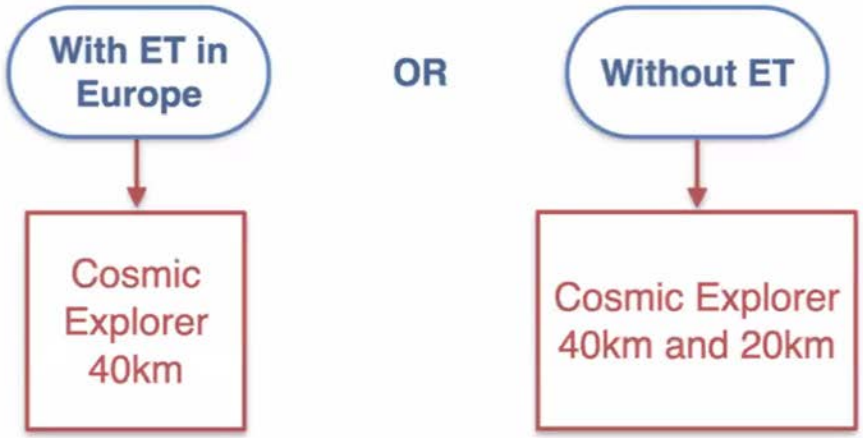
Next-Generation Gravitational Wave Observatory Subcommittee (NextGenGW SC)

- Established by the NSF
- Committee home page with membership: https://www.nsf.gov/mps/phy/nggw.jsp
- Charge:
  - "… Based on this survey, a recommended list of GW detection network configurations that will deliver a detector with sensitivity an order of magnitude greater than the LIGO A+ design…."
  - https://www.nsf.gov/mps/advisory/subcommittee_charges/mpsac-nggw-charge_signed.pdf
- Call for White Papers:
  - Addressing"… science motivation and key science objectives, technical description of the proposed concept(s) and how different aspects are associated with key science, current and new technologies needed, risks, timelines, and approximate cost assessment, any synergies or dependencies on other multi-messenger facilities. …"
  - https://www.nsf.gov/mps/phy/nggw/WhitePaperCall2.pdf
- Cosmic Explorer White Paper submitted: https://arxiv.org/abs/2306.13745
- Report is now published

Report available on home page:
https://www.nsf.gov/mps/phy/nggw.jsp



ngGW Subcommittee Recommendations



- aLIGO facilities to be phased out by the time the CE wide-band sensitivity (of one or two detectors) is better than that of the aLIGO detectors.
- The availability of the LIGO-India detector in the network is important for MMA and, in fact, critically important in the absence of ET. The absence of LIGO-India cannot be balanced by keeping the aLIGO detectors operational.

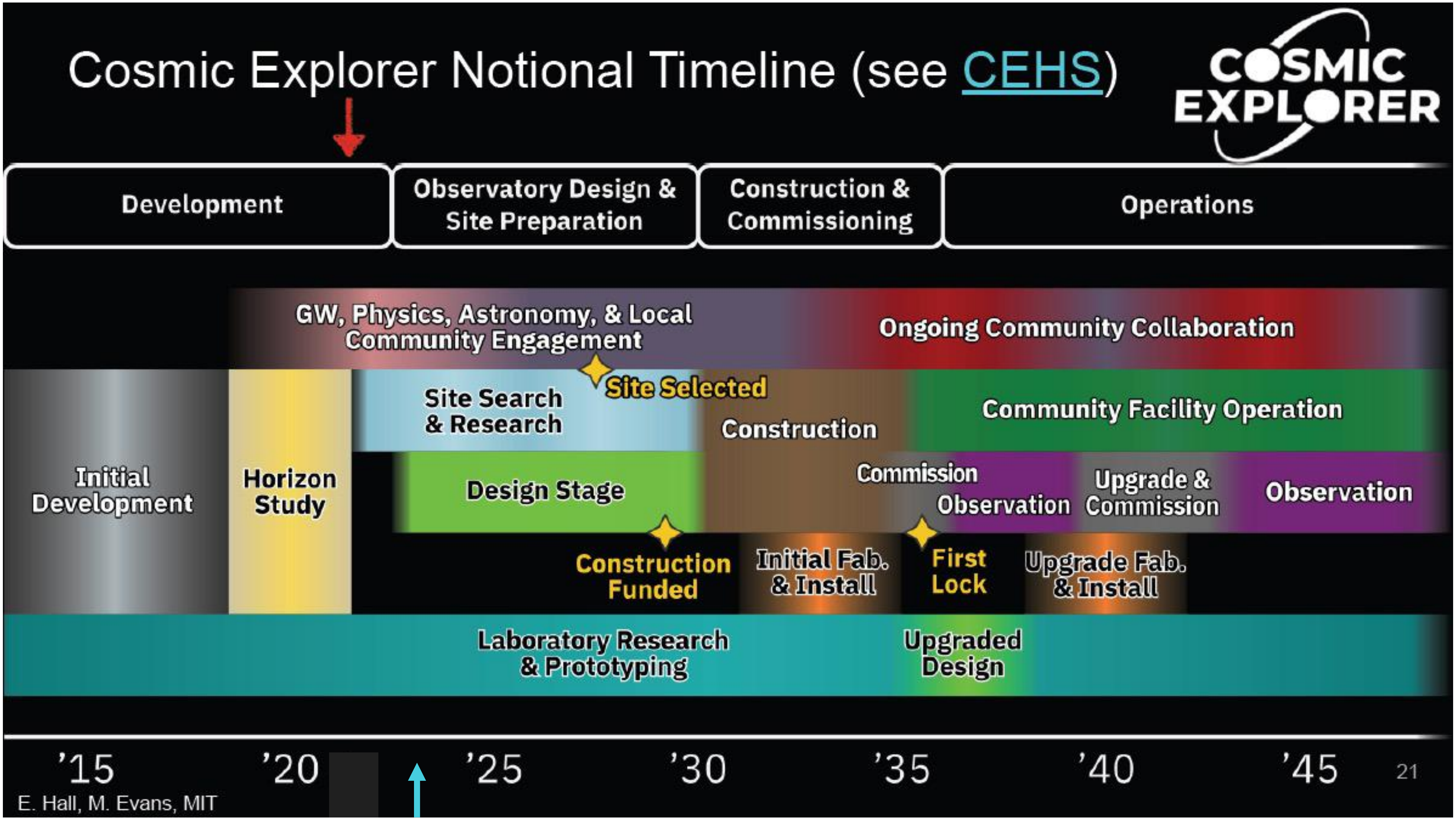
ngGW Subcommittee Report to MPSAC, March 2024

ngGW Subcommittee Recommendations

Recommended list of GW detection network configurations that will deliver sensitivity an order of magnitude greater than the aLIGO A+ design.

- **CE40**, **ET**, **LIGO-India** (Network #1)
- **CE40**, **ET** (Network #2)
- **CE40**, **CE20**, **LIGO-India** (Network #3)
- **CE40**, **CE20** (Network #4)

ngGW Subcommittee Report to MPSAC, March 2024



Cosmic Explorer Notional Timeline (see CEHS)
COSMIC EXPLORER
Development
Observatory Design & Site Preparation
Construction & Commissioning
Operations
GW, Physics, Astronomy, & Local Community Engagement
Ongoing Community Collaboration
Site Selected
Initial Development
Horizon Study
Site Search & Research
Construction
Community Facility Operation
Design Stage
Commission
Observation
Upgrade & Commission
Observation
Construction Funded
Initial Fab. & Install
First Lock
Upgrade Fab. & Install
Laboratory Research & Prototyping
Upgraded Design
'15
'20
'25
'30
'35
'40
'45
21
E. Hall, M. Evans, MIT

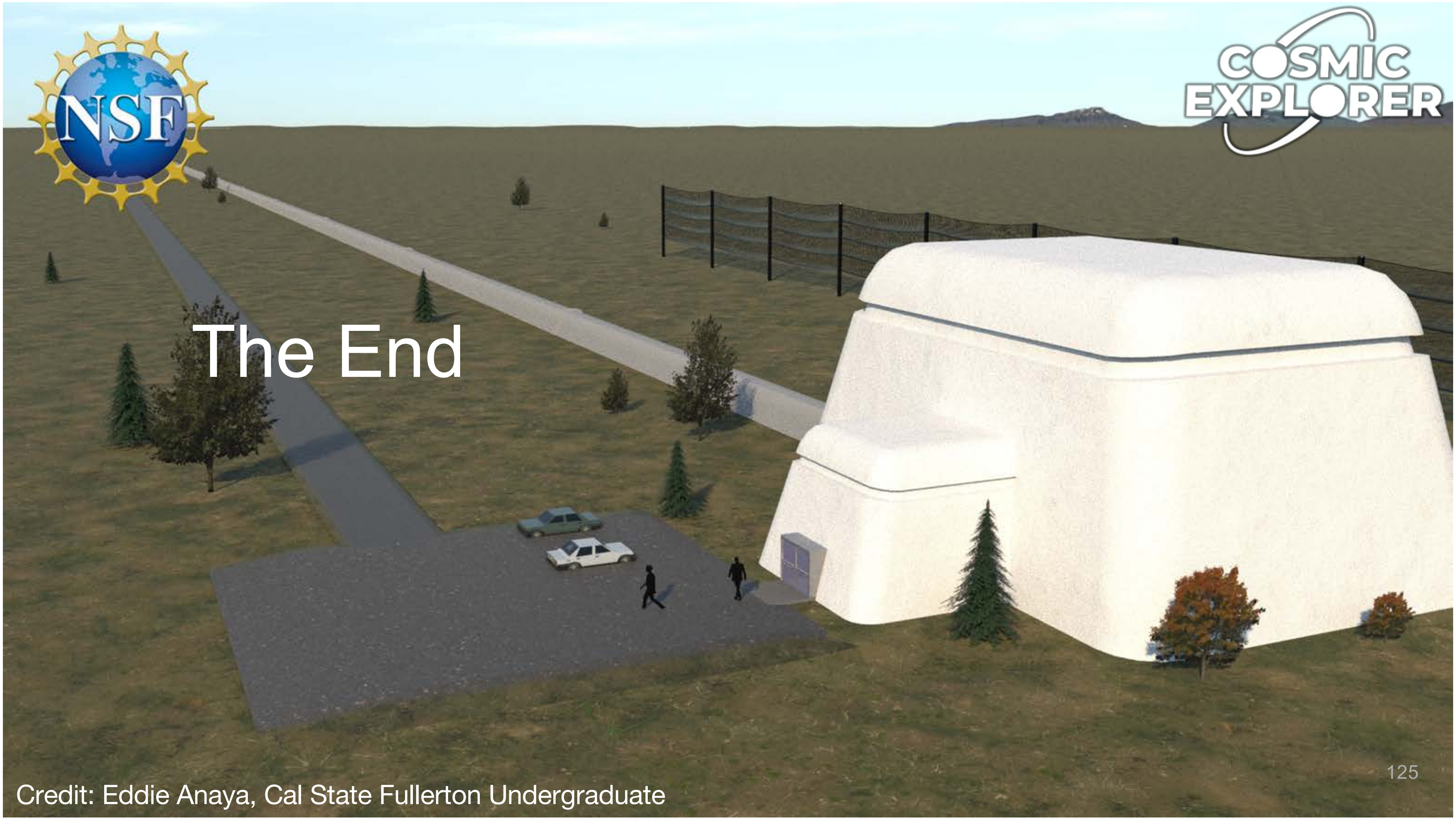
Take-away points

- GW astronomy is here, and we are staring to understand the actual source population.

- Advanced LIGO design works extraordinary well
  - Limiting: - Quantum noise
    - Coating Thermal noise
    - Power handing due to point absorbers

- US effort for designing the next-generation observatories is underway. Based on proven technology, but some R&D is needed.
  - Quantum sensing (optical squeezing, …)
  - Large optics and coatings
  - Vacuum technology
  - …


Thank you for the invite!



Credit: Eddie Anaya, Cal State Fullerton Undergraduate