

**LIGO**

**COSMIC  
EXPLORER**



# Present and Future Terrestrial GW Detectors

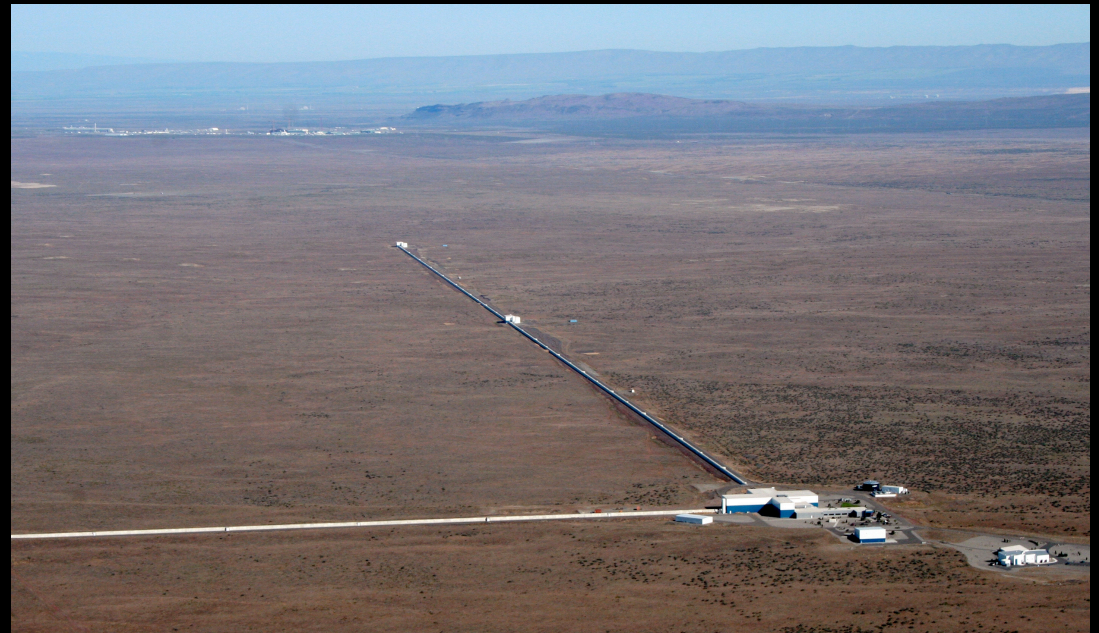
David Shoemaker

MIT Kavli Institute – LIGO Laboratory

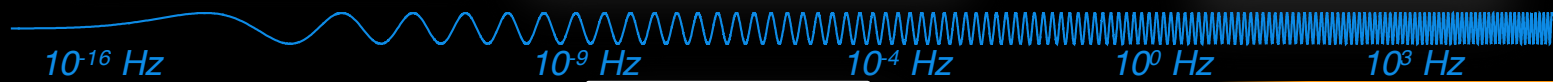
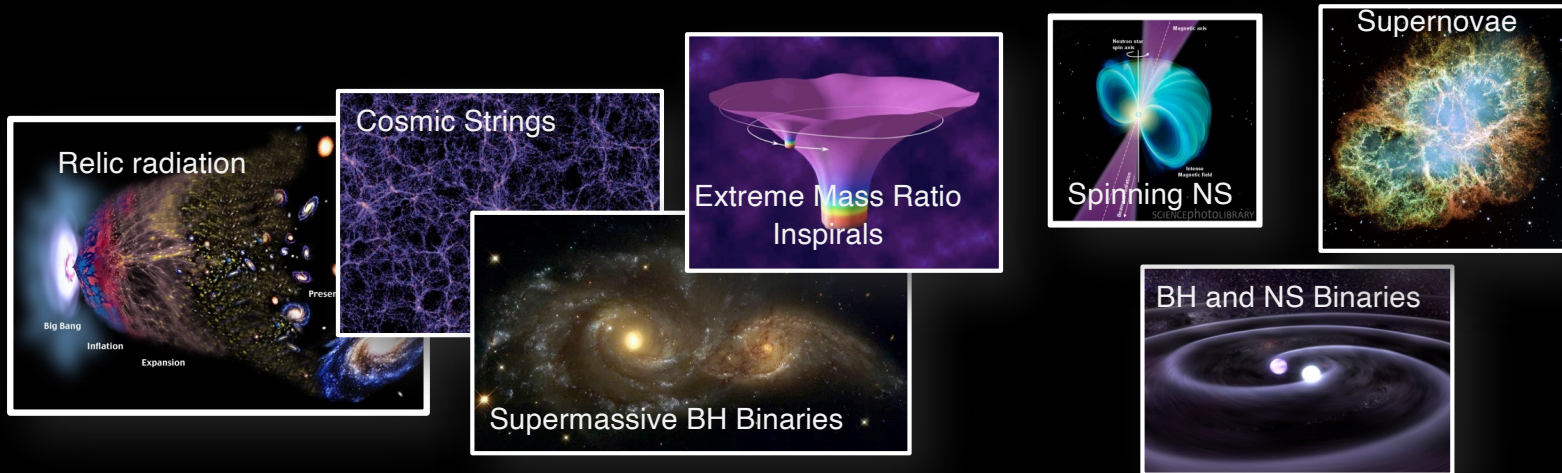
Slides from many CE and LIGO Collaborators!

**ICGAC**

3 July 2023  
**G2301273**



# The Gravitational Wave Spectrum

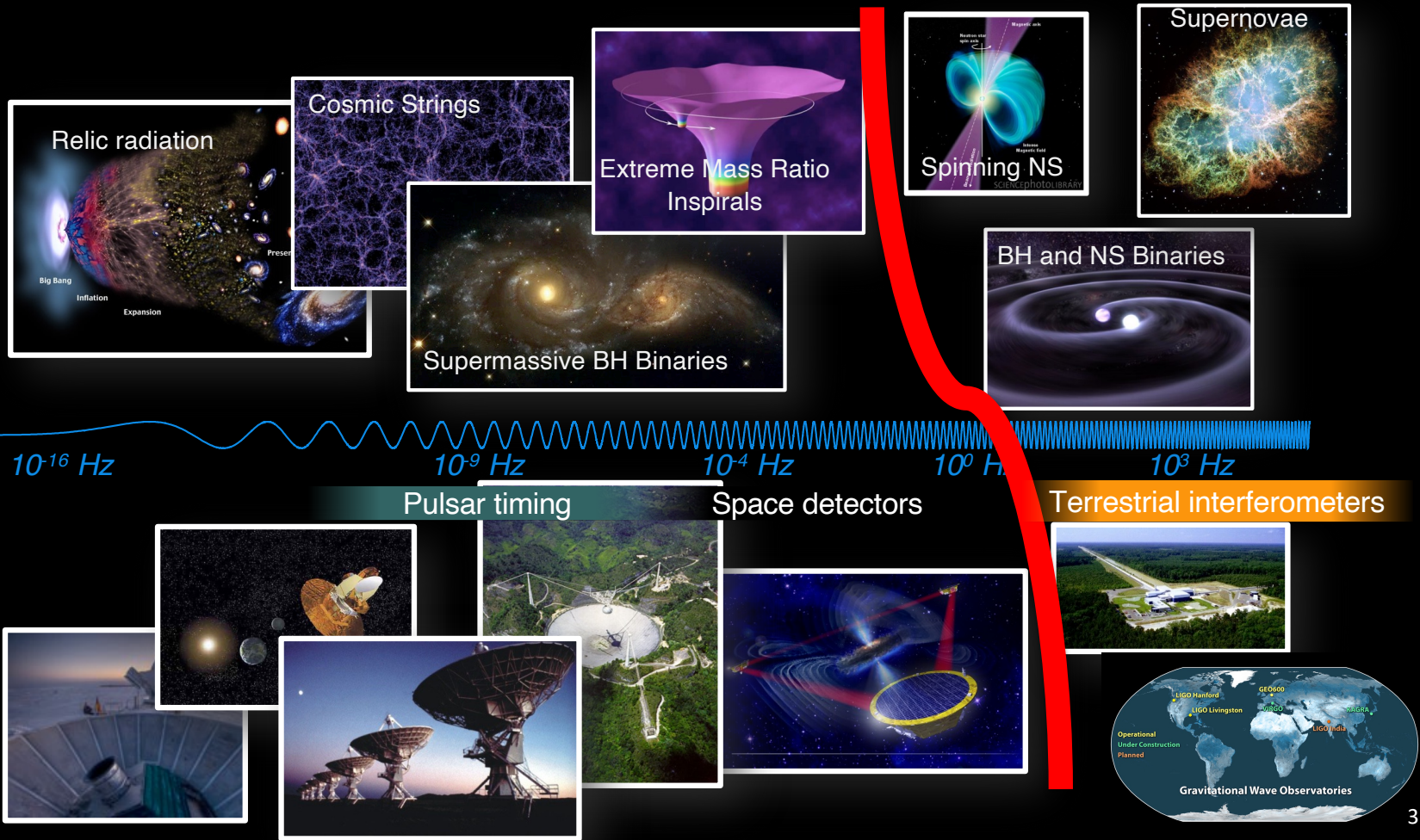


**Pulsar timing**      **Space detectors**      **Terrestrial interferometers**





# The Gravitational Wave Spectrum

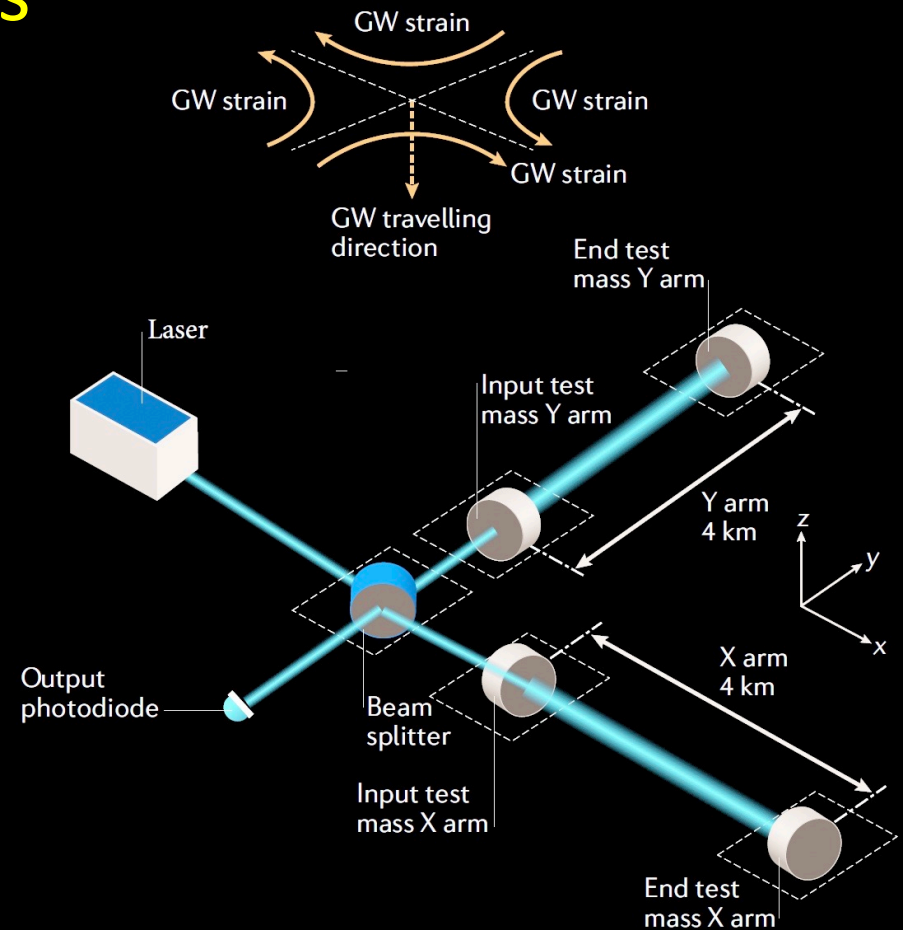


# Why are terrestrial detectors limited to $f > \sim 1$ Hz?

- Passing GW shortens the light path for one arm, lengthens for the other – and then vice-versa

$$\Delta L = h_{\text{GW}} \cdot L$$

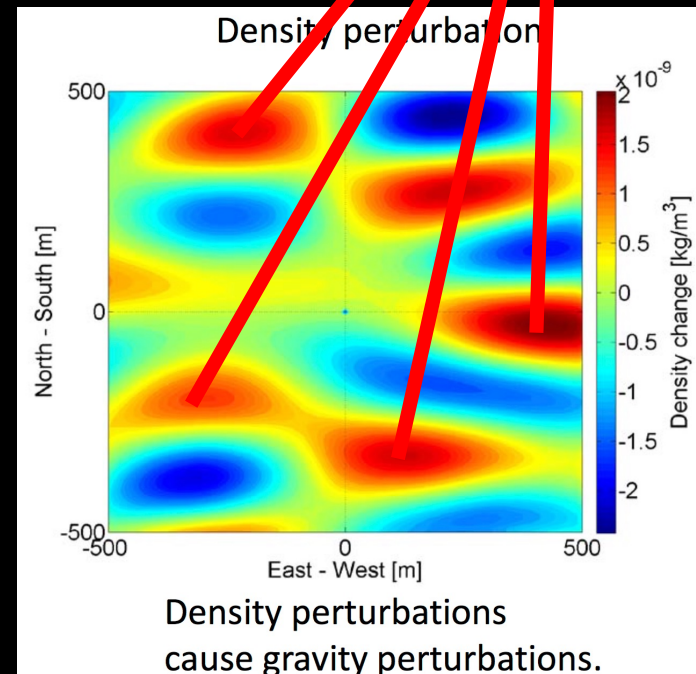
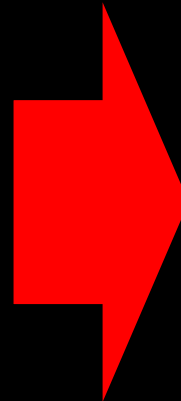
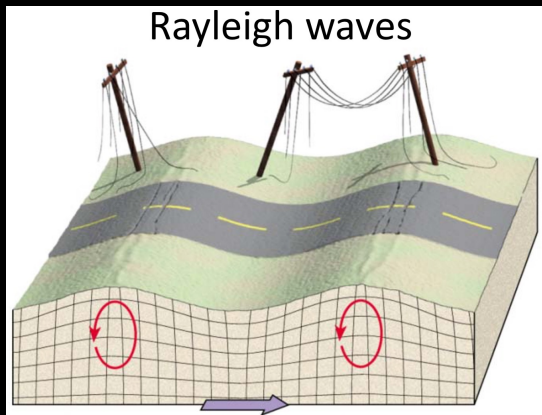
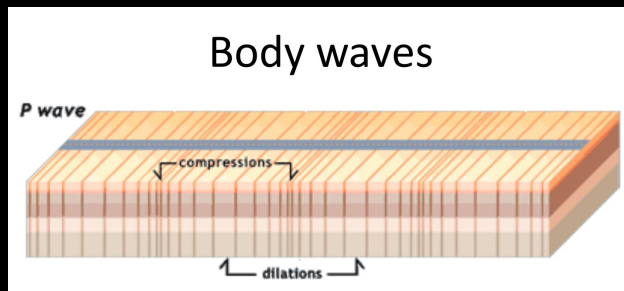
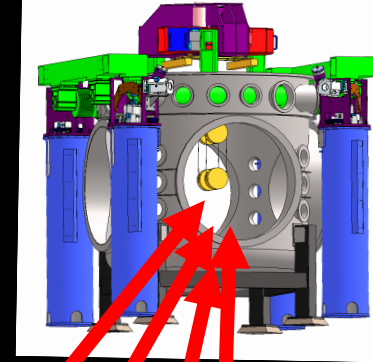
- Interference at the Beam splitter turns this into a light intensity variation, and a photodiode into an electrical signal
- Resolution of the readout limited by quantum effects
- **Physical motion of the mirrors due to local forces masks the minuscule changes in light path due to GWs**





# Newtonian background due to seismic environment

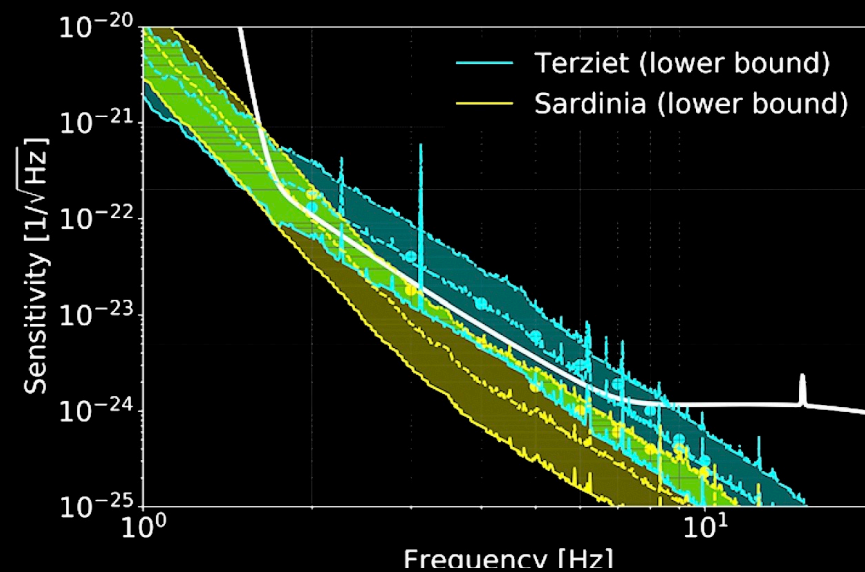
- In principle, can eliminate all direct mechanical coupling
- Can not shield against the wandering net gravity vector



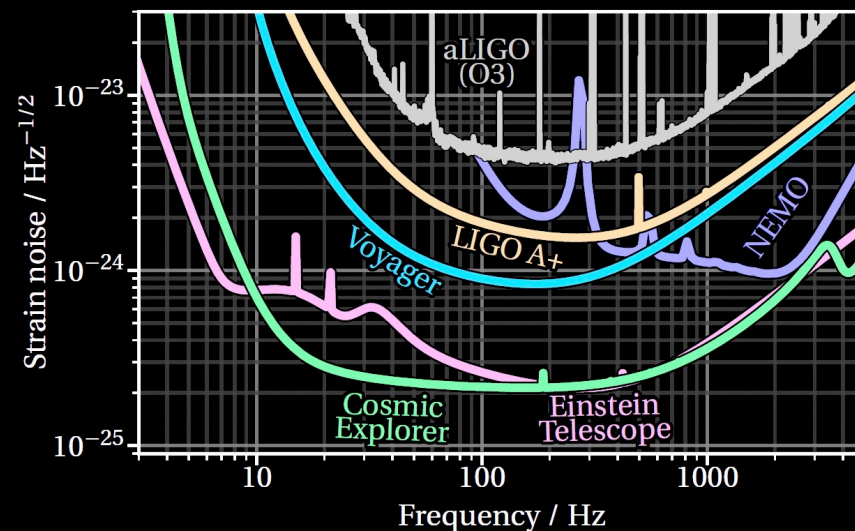
Density perturbations cause gravity perturbations.

# Newtonian background creates a wall at a few Hz

- Newtonian Background falls as  $\sim 1/f^5$
- 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  $\sim 3\text{Hz}$  and lower
- **Ultimate limit on the lowest frequency detectors on- or under-ground**
- **And thus the largest BH masses detectable**



Harms et al. 2022



Evans et al. 2023

# Practical limitations for Terrestrial Detectors

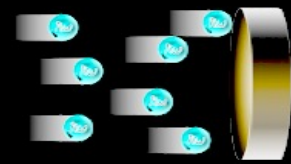
- Arm length  $L$  – currently in short-antenna limit; path-length shift  $\Delta L$  from a given strain grows with interferometer arm length. Maximize  $L$ !
  - $\Delta L = h_{\text{GW}} \cdot L$
  - LIGO 4km, Virgo and KAGRA 3km

- Optical resolution – limited by photon Poisson counting statistics; maximize laser power  $P$

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

- ...but too much power, and the radiation pressure causes mirror motion which masks the GW

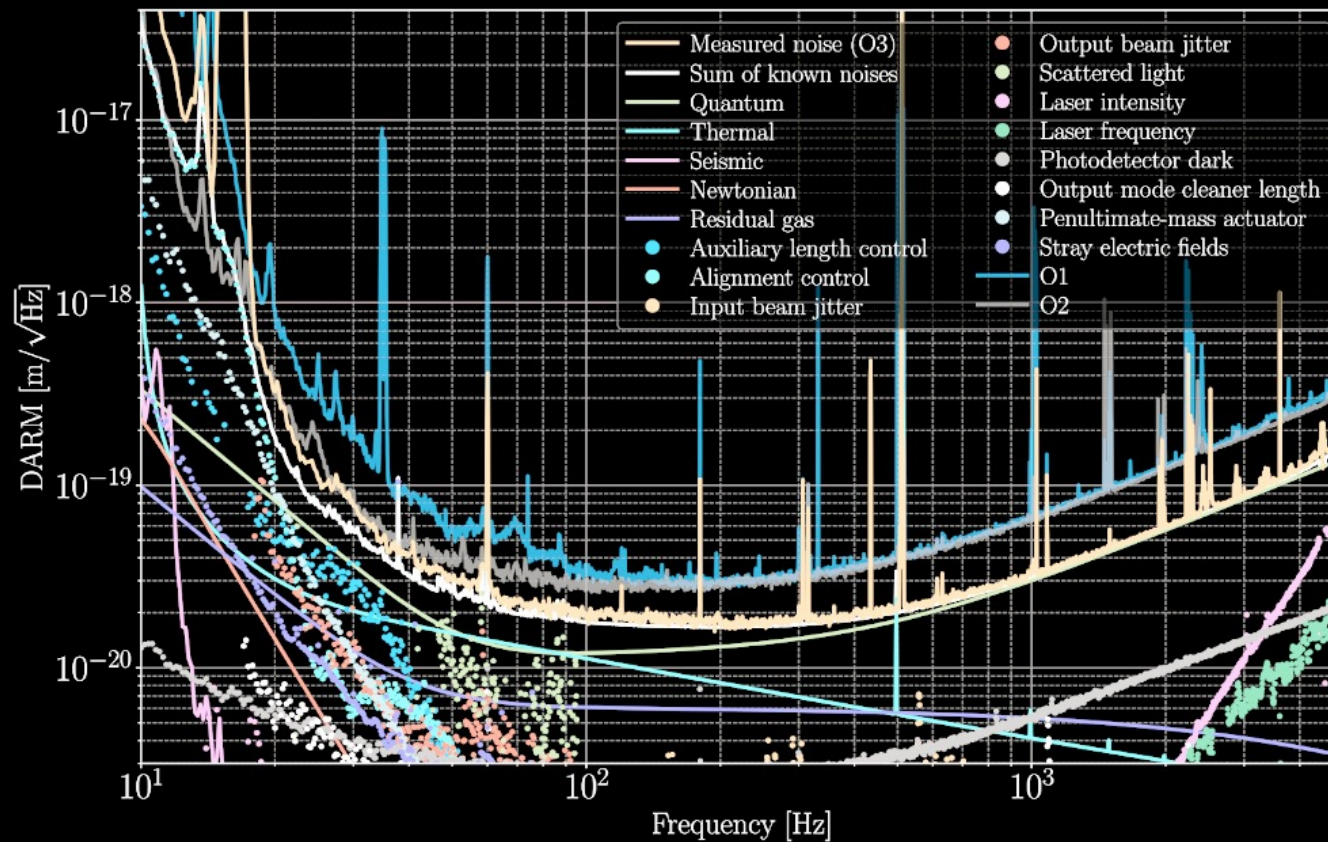
- Optimal power – naïve quantum limit
  - Working with  $\sim 50$ -100 W



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



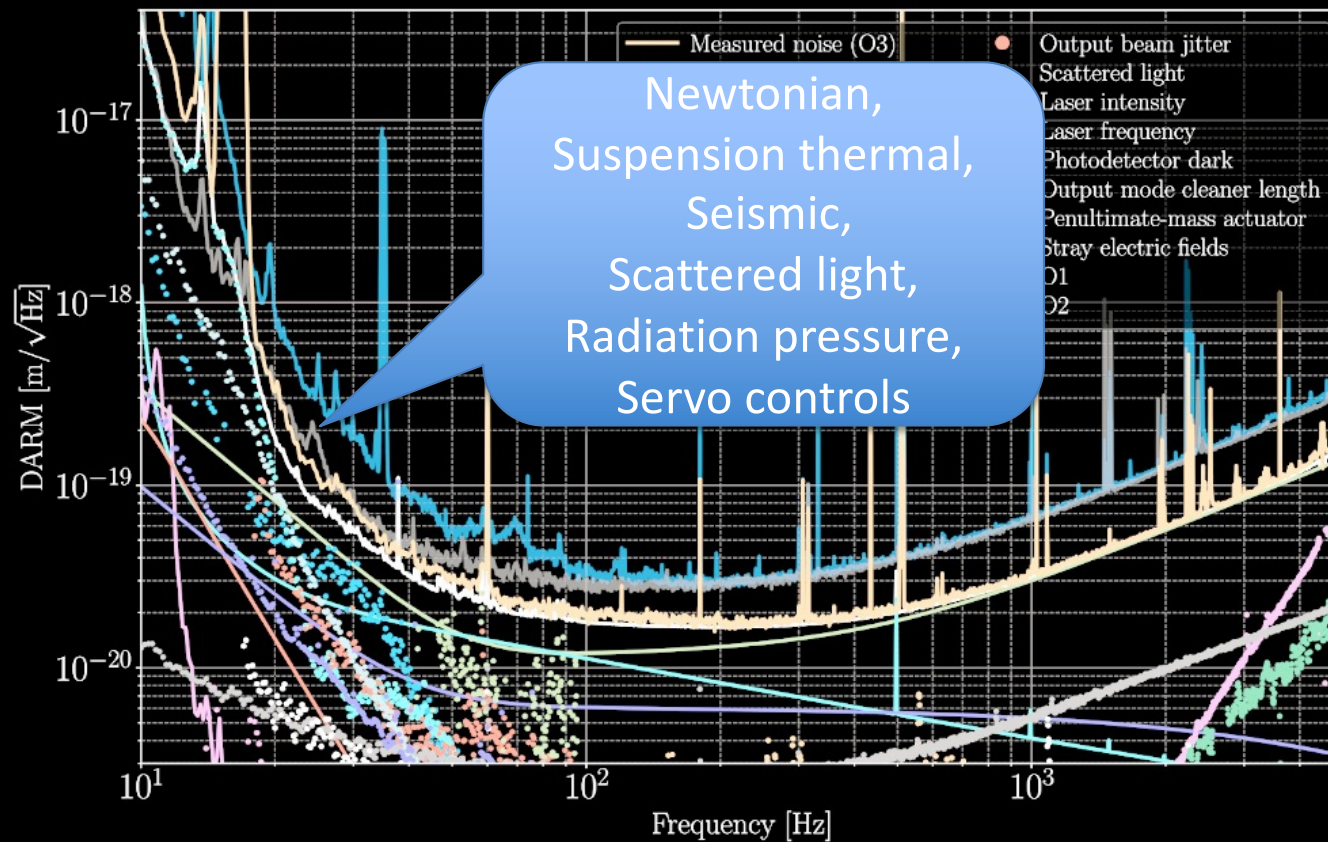
# Many other technical noise sources...



Sensitivity and performance of the Advanced LIGO detectors in the third observing run

A. Buikema *et al.* *Phys. Rev. D* 102, 062003

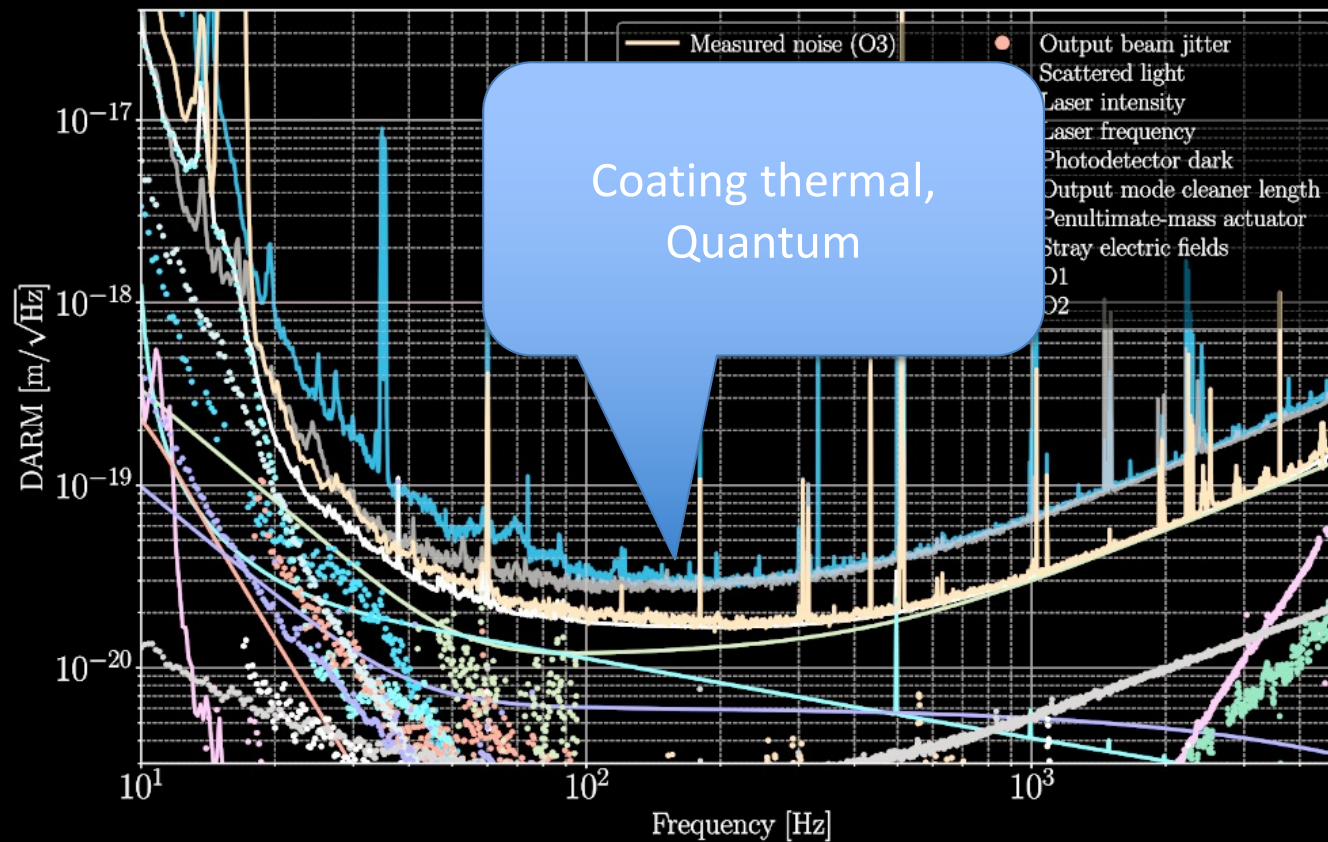
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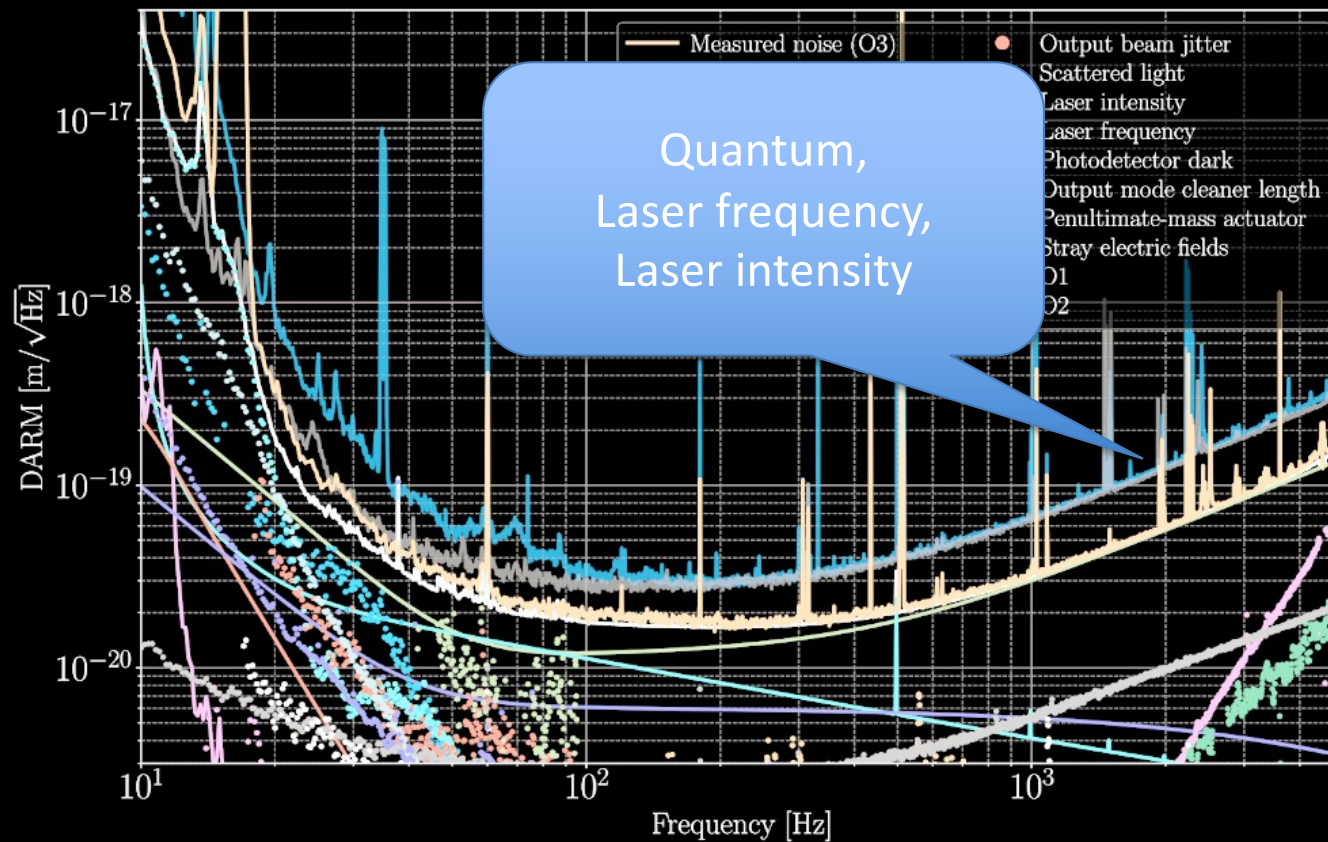


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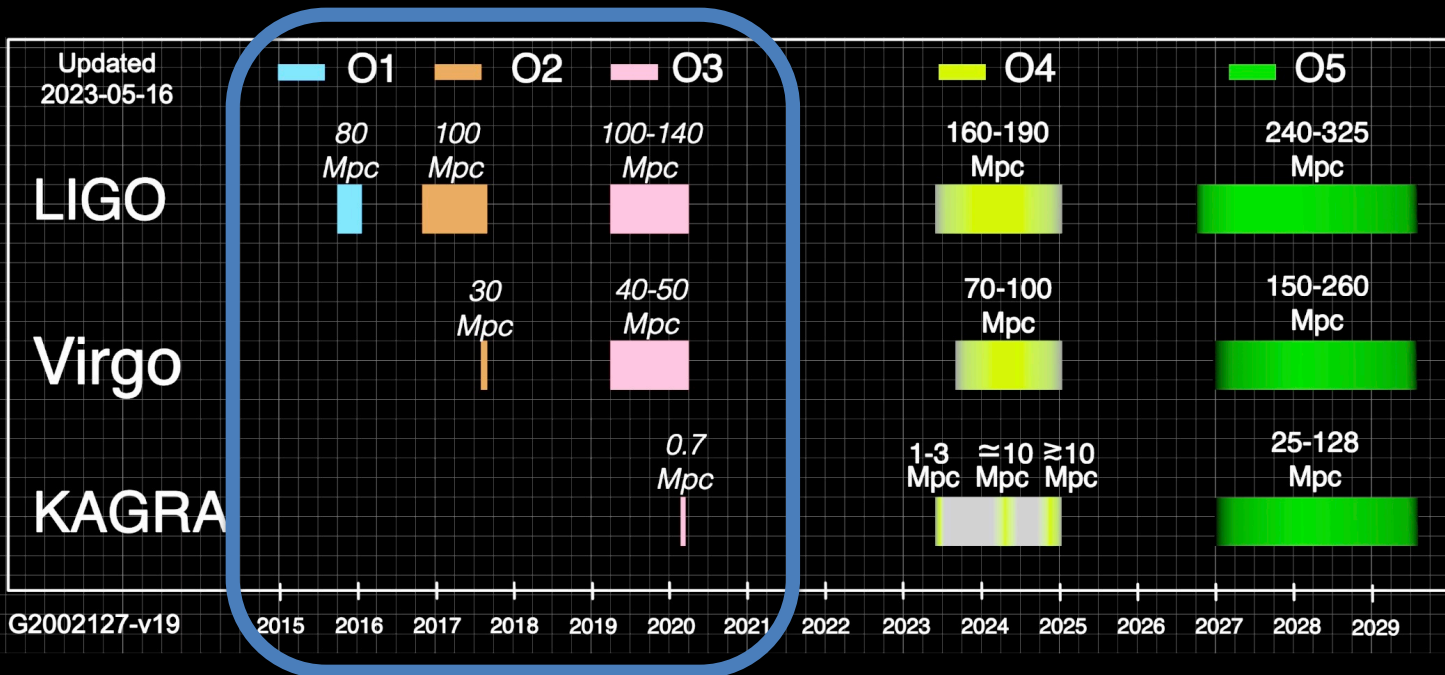


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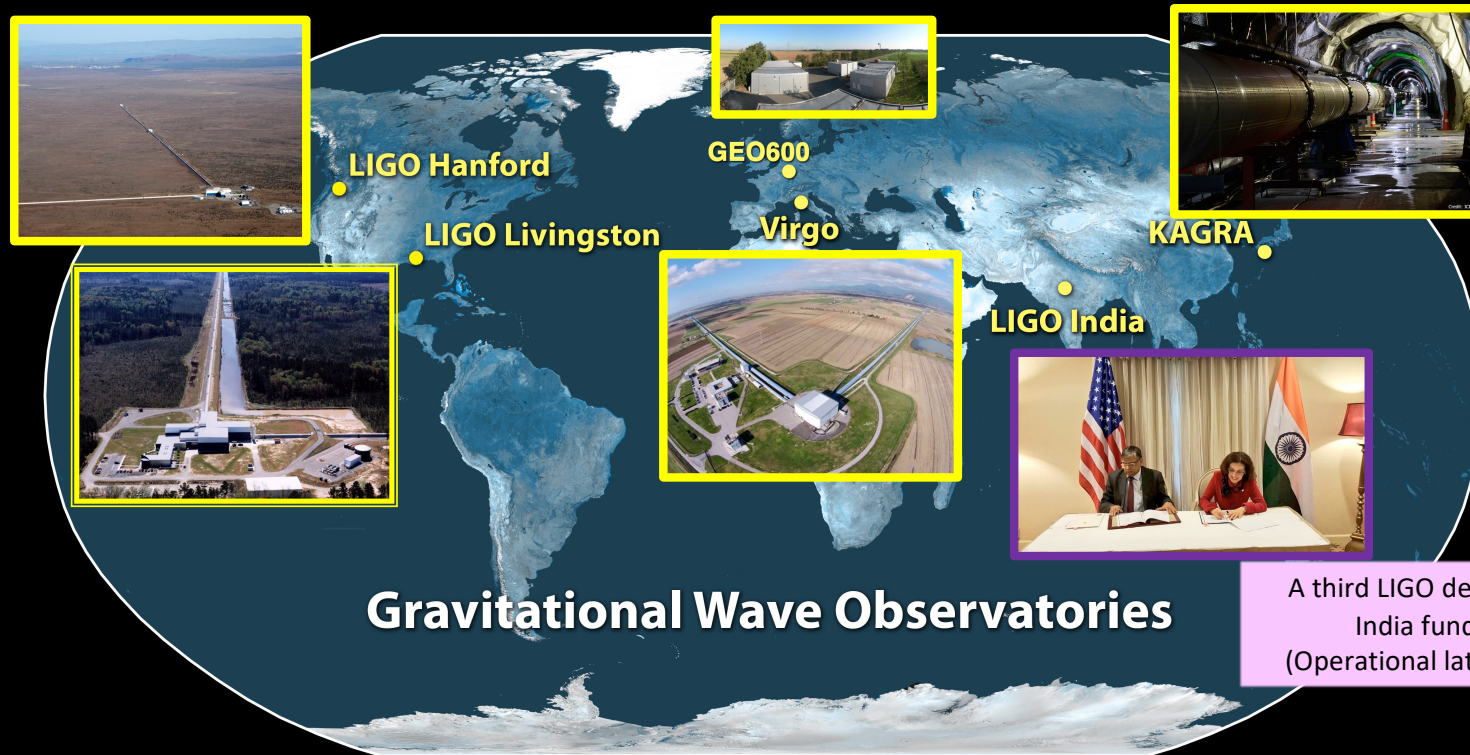
A. Buikema *et al.* Phys. Rev. D 102, 062003

# Good enough to start the new observational discipline of Gravitational Wave Astronomy

- What have we seen so far?



# The ground-based gravitational-wave world-wide network in 2023





# *Gravitational Wave Physics & Astrophysics*

OBSERVING  
01  
2015 - 2016

02  
2016 - 2017

# Observations

03a+b  
2019 - 2020

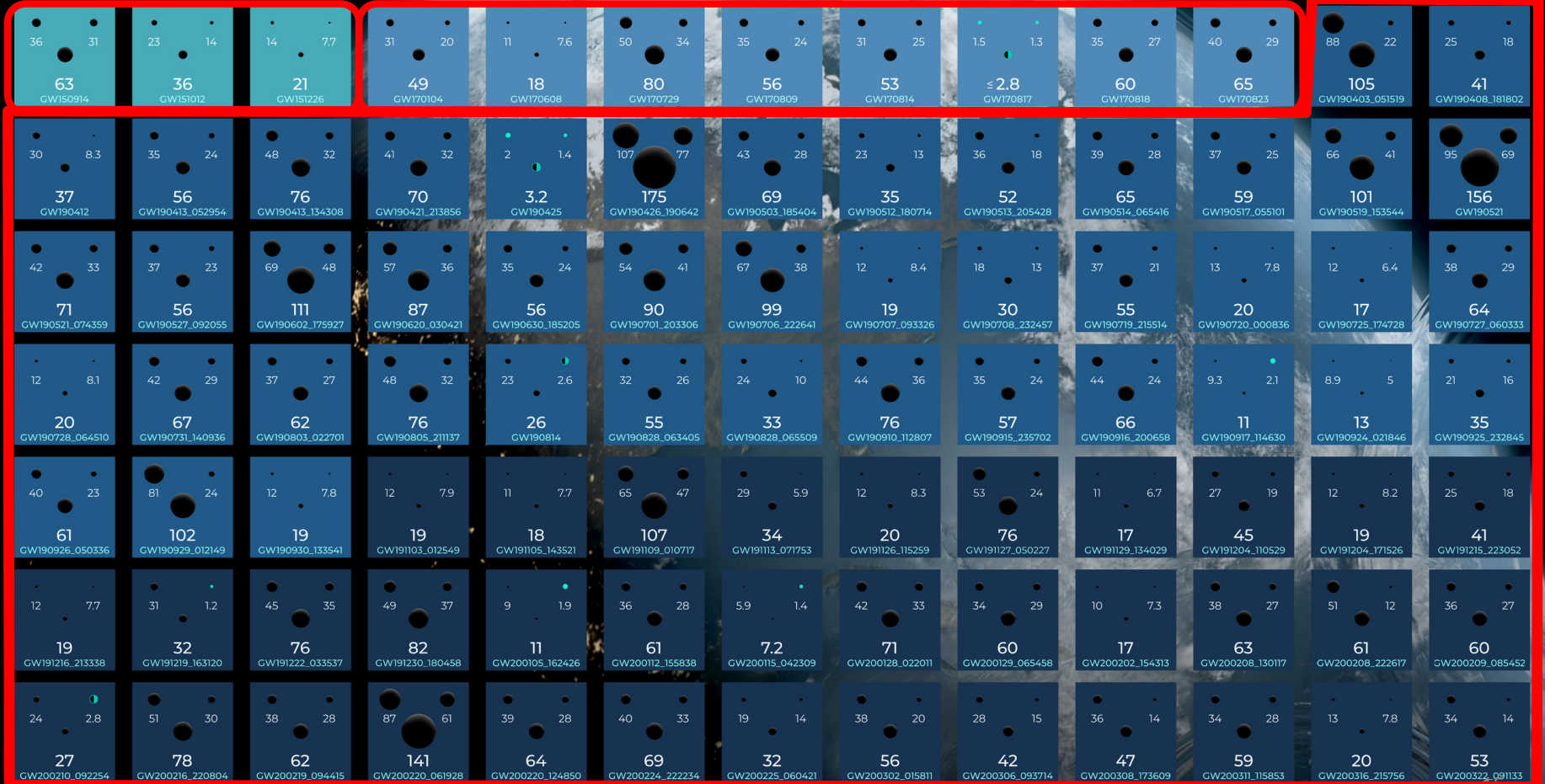


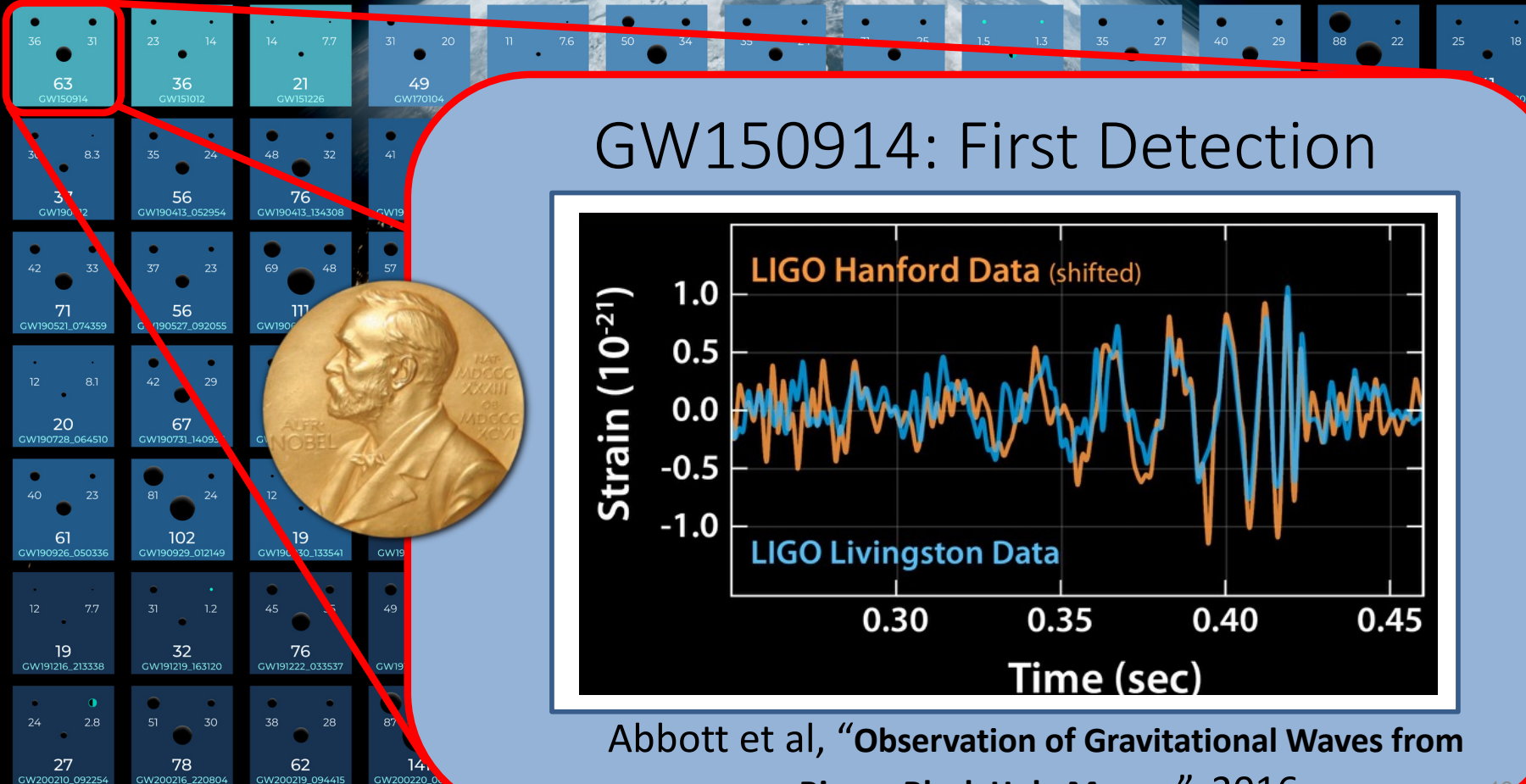
Image : Carl Knox (OzGrav, Swinburne University of Technology)

Slide: S. Fairhurst

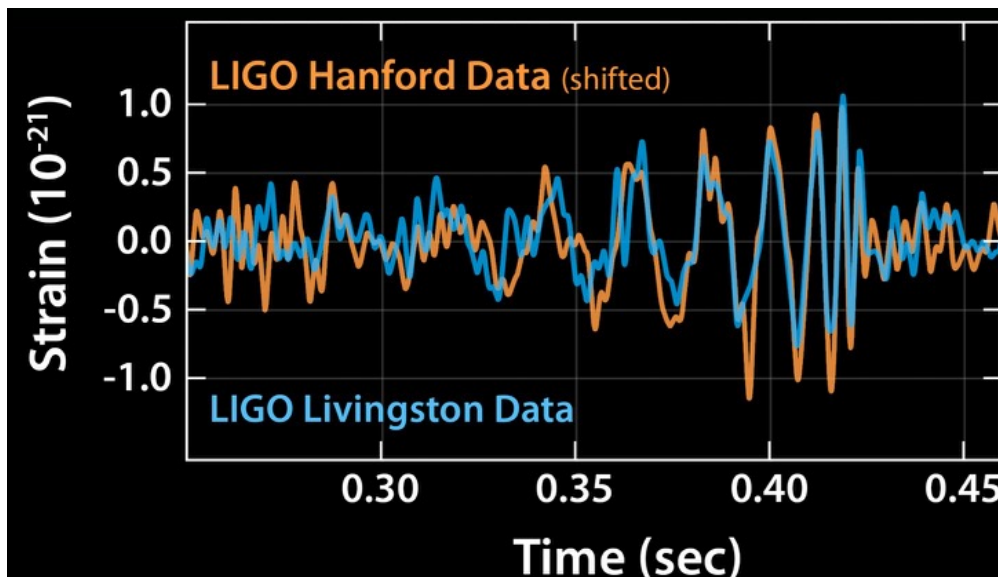
OBSERVING RUN  
01  
2015 - 2016

02  
2016 - 2017

03a+b  
2019 - 2020

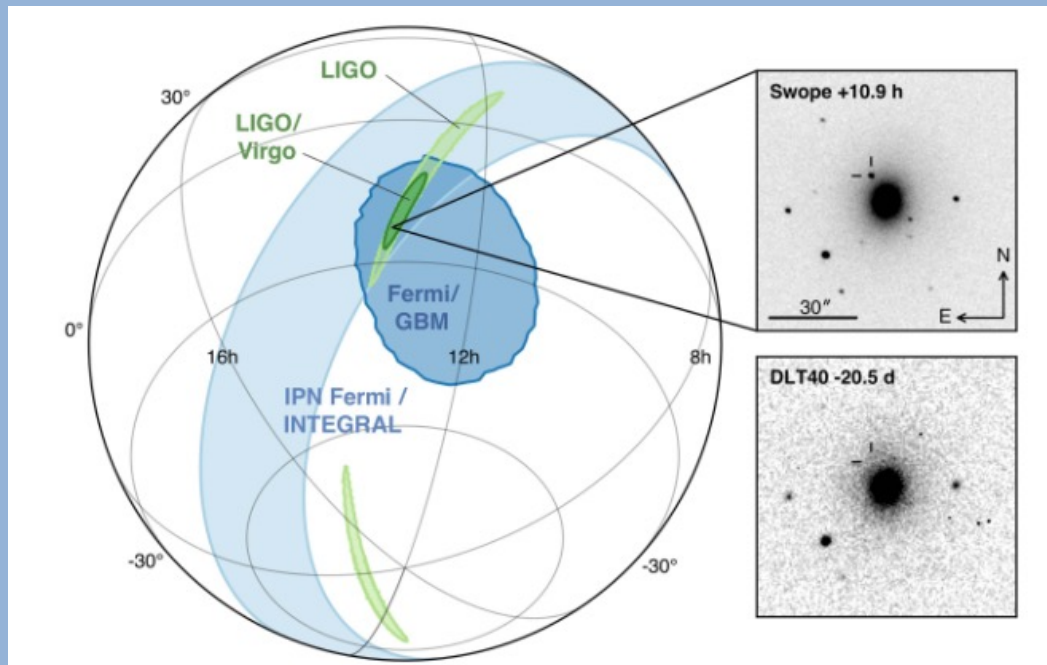


## GW150914: First Detection



Abbott et al, "Observation of Gravitational Waves from a Binary Black Hole Merger", 2016

# GW170817: Neutron Stars and Multi-messenger Observation



From Abbott et al, "Multi-Messenger Observations of a Binary Neutron Star Merger", 2017

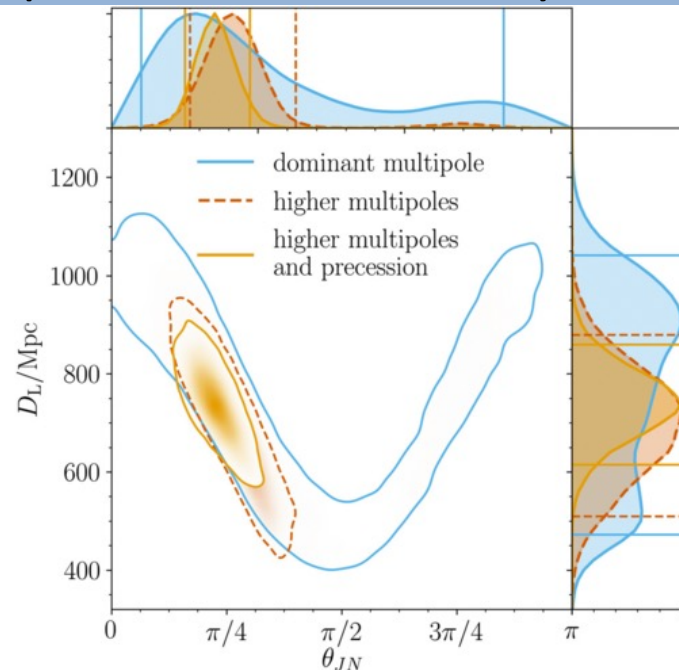
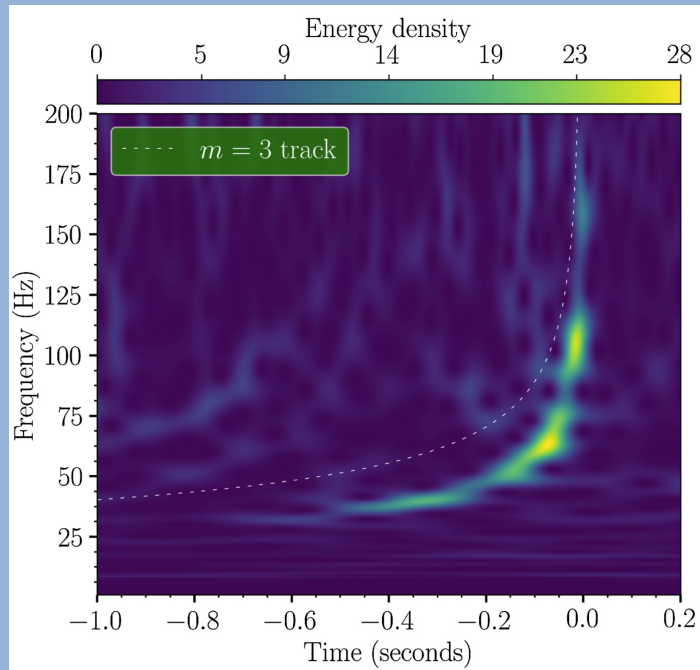


03a+b  
2019 - 2020





# GW190412: Unequal mass binary



One of the black holes 3.75 times heavier than the other

# GW200105 and GW200115: Observation of Neutron Star Black Hole Mergers

First unambiguous observation  
of NS-BH system

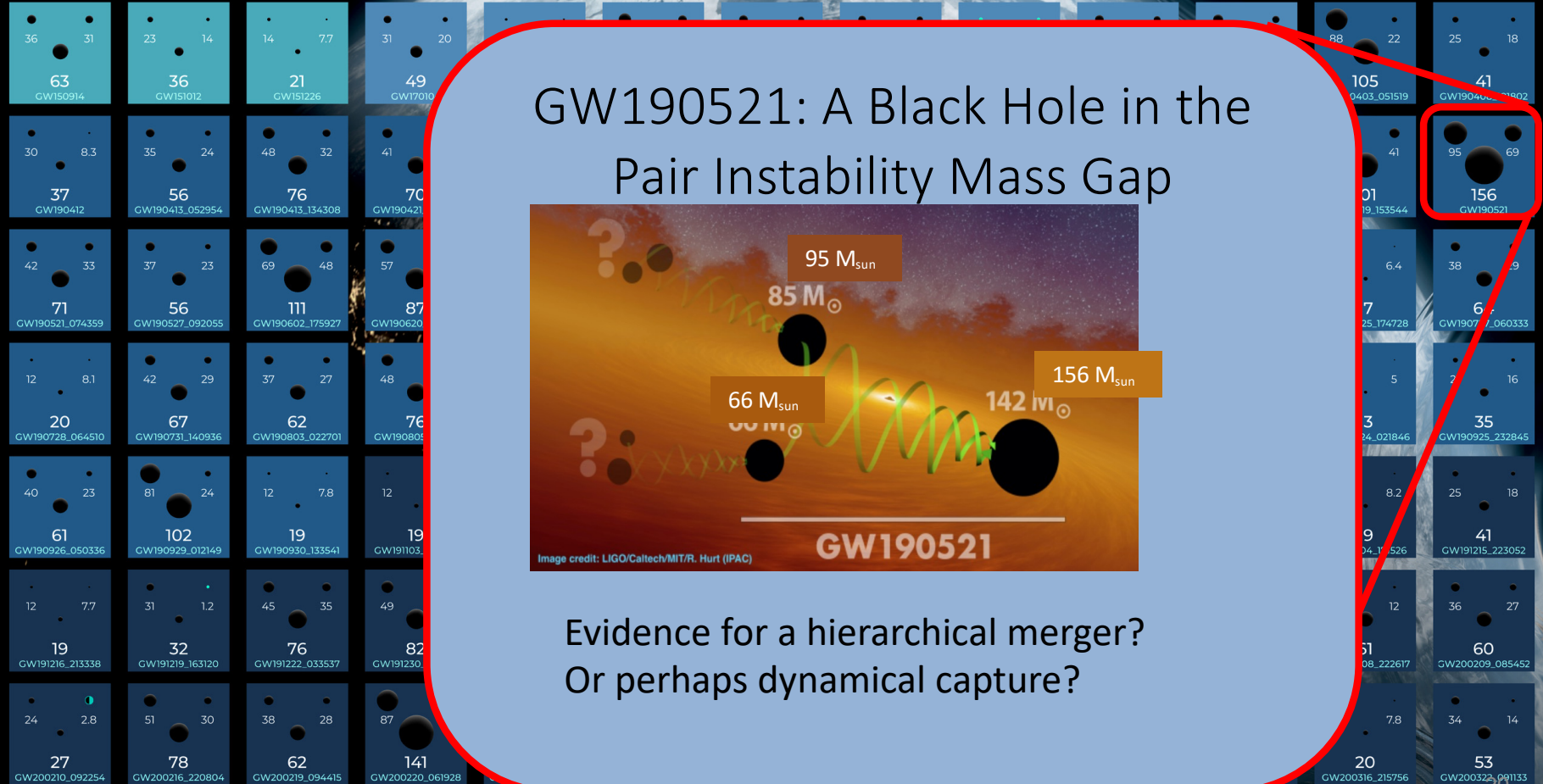


# Observations

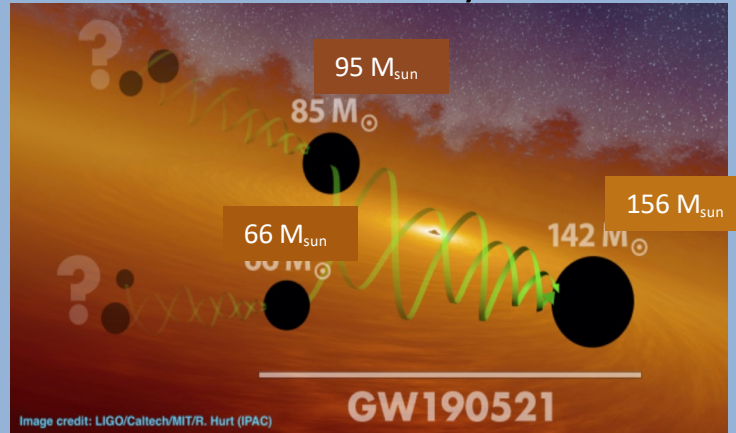
OBSERVING RUN  
01  
2015 - 2016

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03a+b  
2019 - 2020



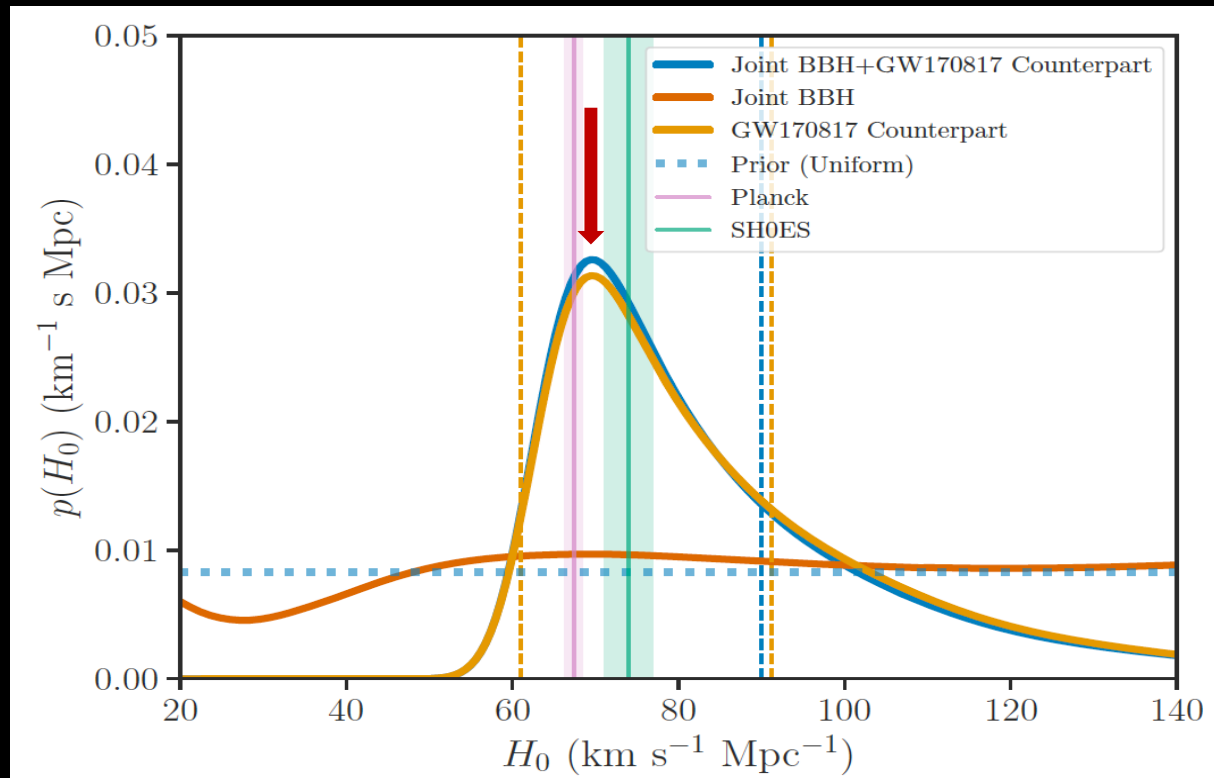
## GW190521: A Black Hole in the Pair Instability Mass Gap



Evidence for a hierarchical merger?  
Or perhaps dynamical capture?

# Measuring the Hubble Constant Using Gravitational-wave 'Standard Sirens'

$$v_{\text{Hubble}} (\approx cZ) = H_0 L_D (+v_p)$$



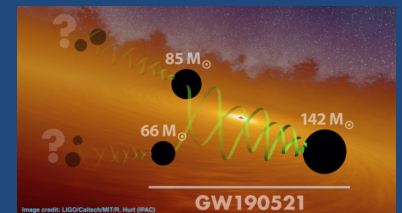
B. F. Schutz, "Determining the Hubble Constant from Gravitational Wave Observations", [Nature](#) 323, 310–311 (1986).

B. P. Abbott, et al., "A gravitational-wave standard siren measurement of the Hubble constant", [Nature](#) 551, 85–88 (2017).

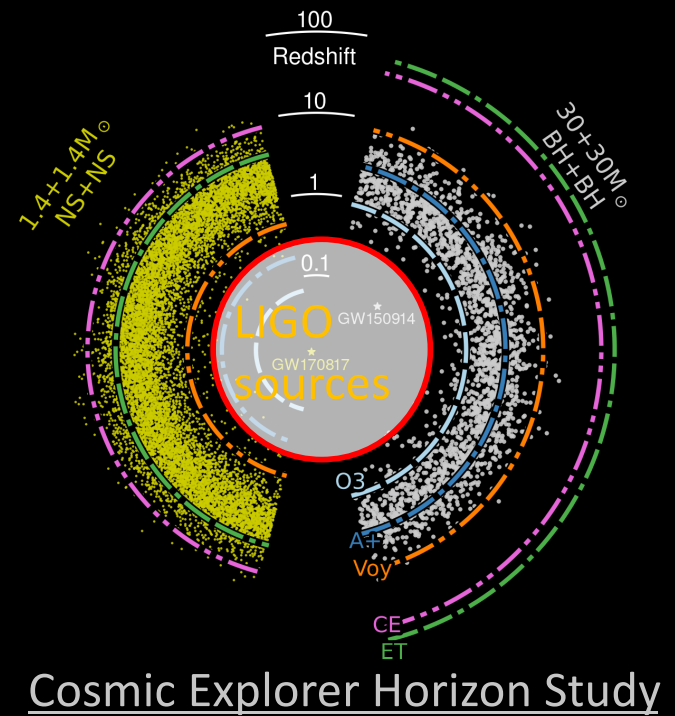
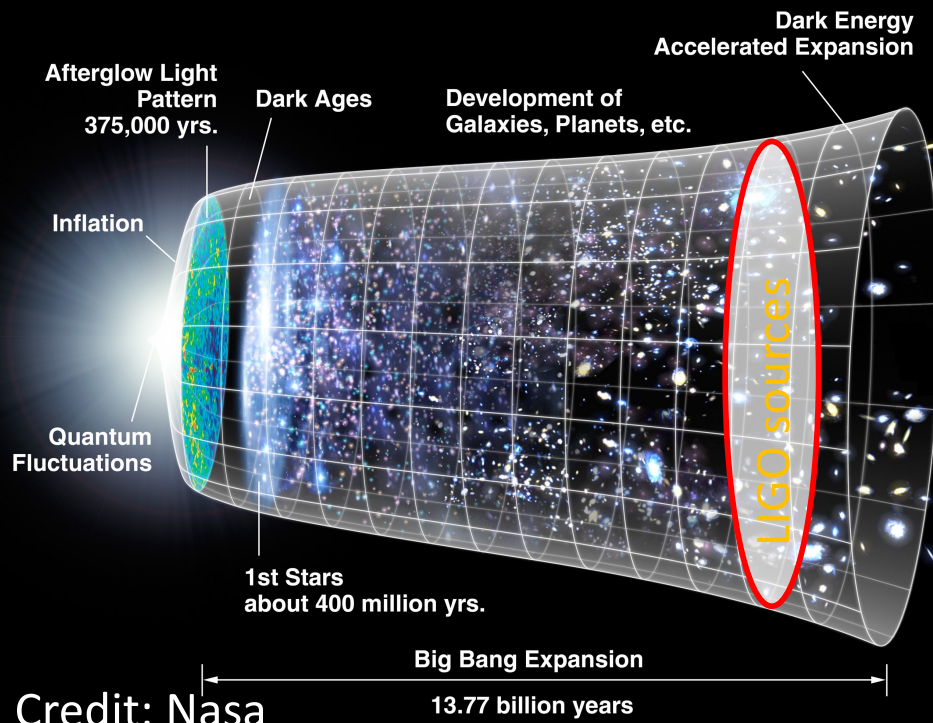


# LIGO-Virgo Fundamental Results 2015-2021: What Ground-Based Gravitational Wave Detections Have Taught Us

- **O1:** Gravitational waves from astrophysical sources can be measured.
- **O1:** Binary black hole (BBH) systems exist.
- **O2:** Binary neutron stars (BNS) are progenitors of short gamma ray bursts.
- **O2:** BNS mergers produce kilonovae, which produce heavy elements.
- **O2:** The speed of gravitational waves equals the speed of light.
- **O2:** The Hubble-Lemaître constant can be measured using EM-bright GW ‘sirens’.
- **O2 – O3:** The Hubble-Lemaître constant can be measured using dark GW ‘sirens’.
- **O3:** Black holes with masses in the (pulsational) pair instability gap exist.
- **O3:** Black hole – neutron star systems exist.
- **O3:** Compact objects exist in the  $2 - 3 M_{\odot}$  mass range.
- **O1-O3:** Astrophysical black holes are Kerr black holes
- **O1 – O3:** General relativity is valid in the high curvature, high field regime.
- **O1 – O3:** Intermediate black holes and stellar mass black holes with mass  $> 20 M_{\odot}$  exist.



# Current Ground-based GW Detector 'Reach'



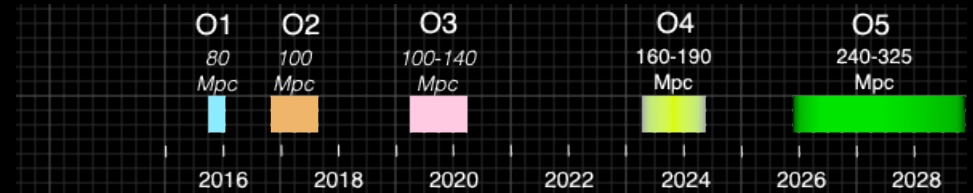
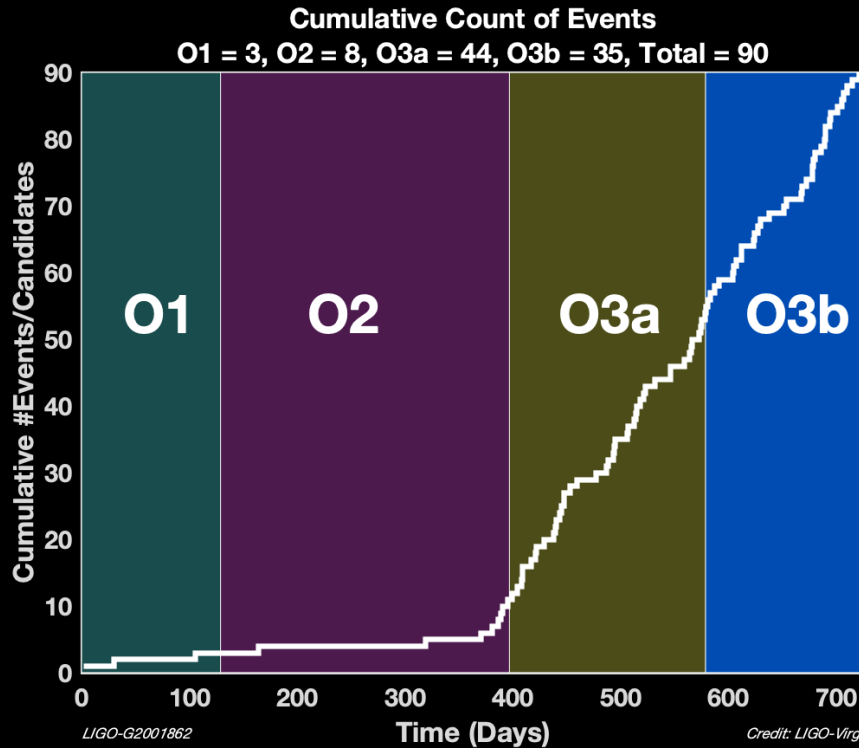
Slide: S. Ballmer

# Sensitivity improvements boost signal rate

- Volume of space accessible – and sources – grows as  $\sim(\text{sensitivity})^3$

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

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

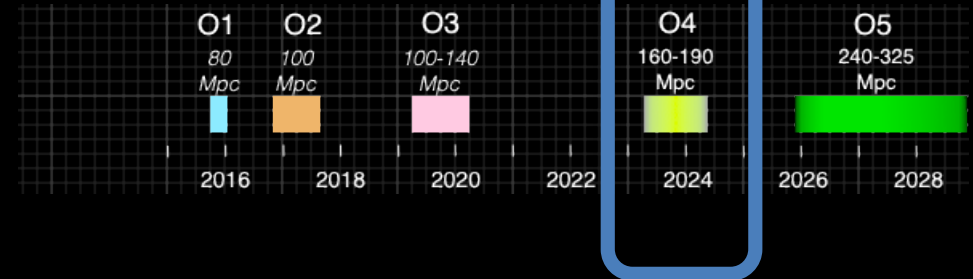
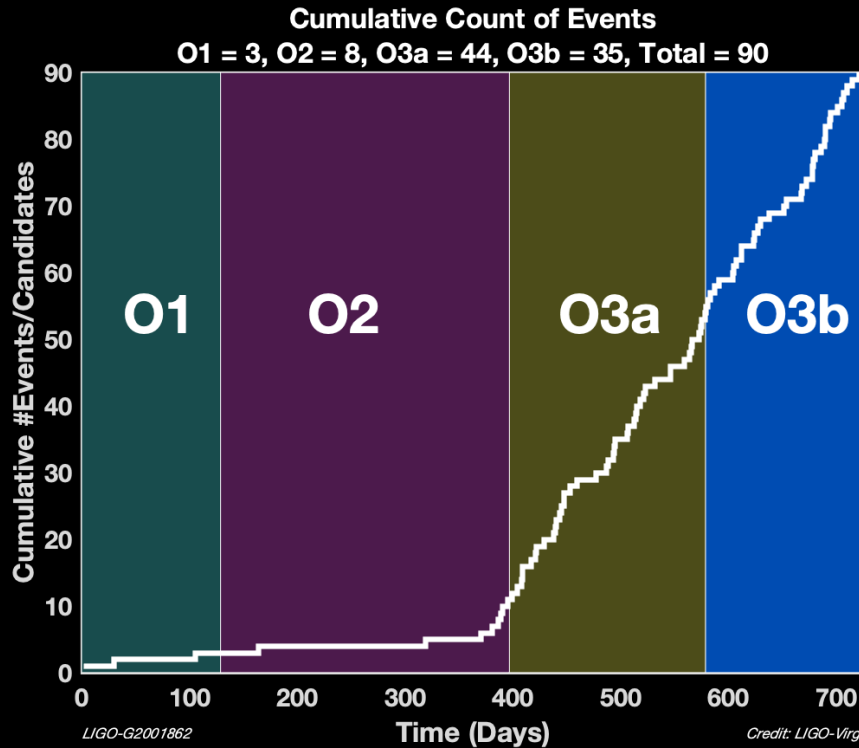


# Sensitivity improvements boost signal rate

- $r_{\text{reach}} \propto 1/h_{\text{sensitivity}}$
- Volume of space accessible – and sources – grows as  $\sim(\text{sensitivity})^3$

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

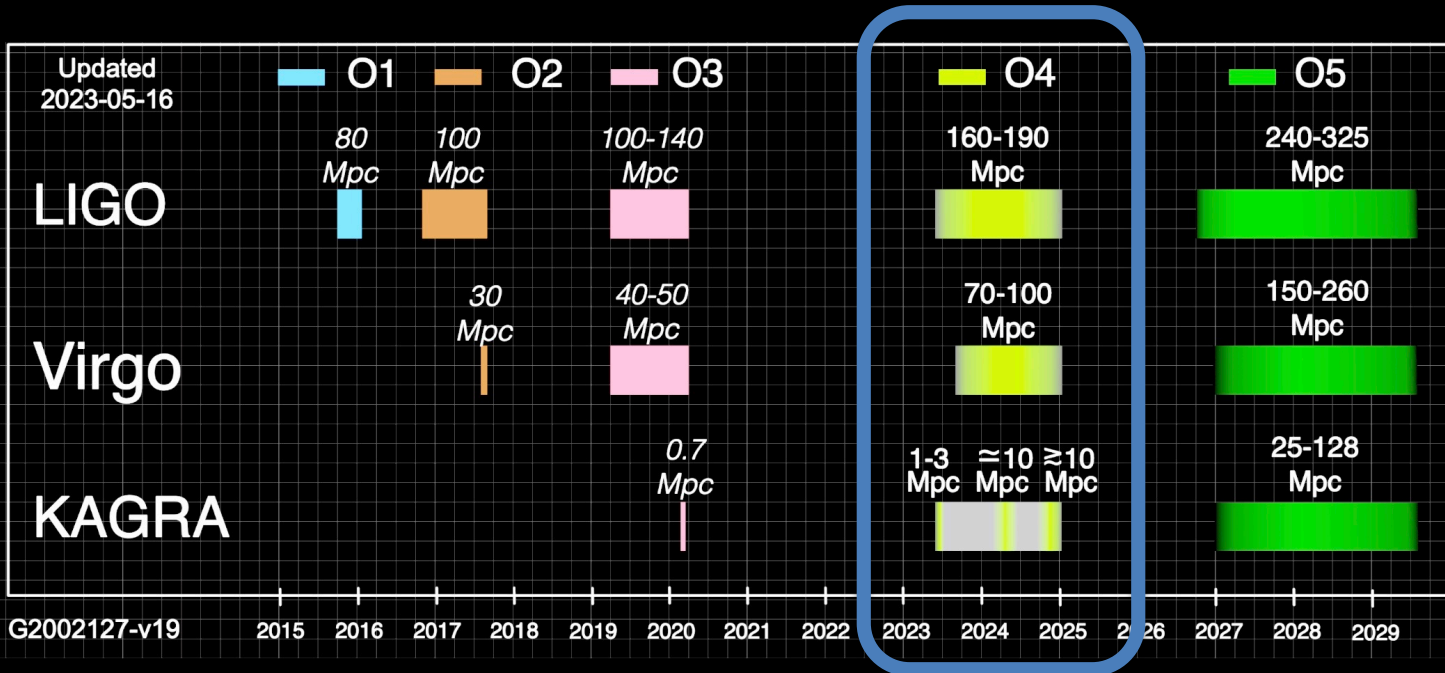
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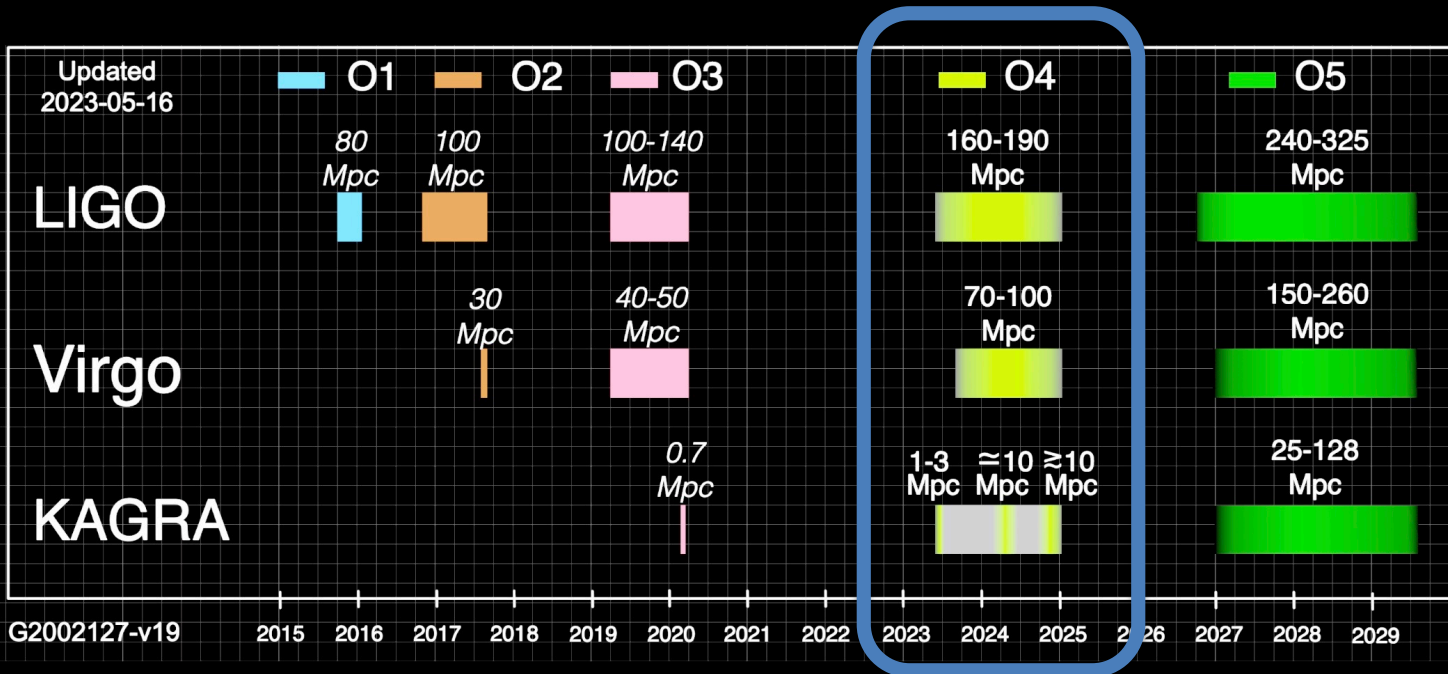
# O4 started 24 May 2023

- Significant delay from original planning – COVID primary cause
- Starting without Virgo due to technical problems; hope to join in Fall '23
- KAGRA still commissioning, with plans to join late in the run



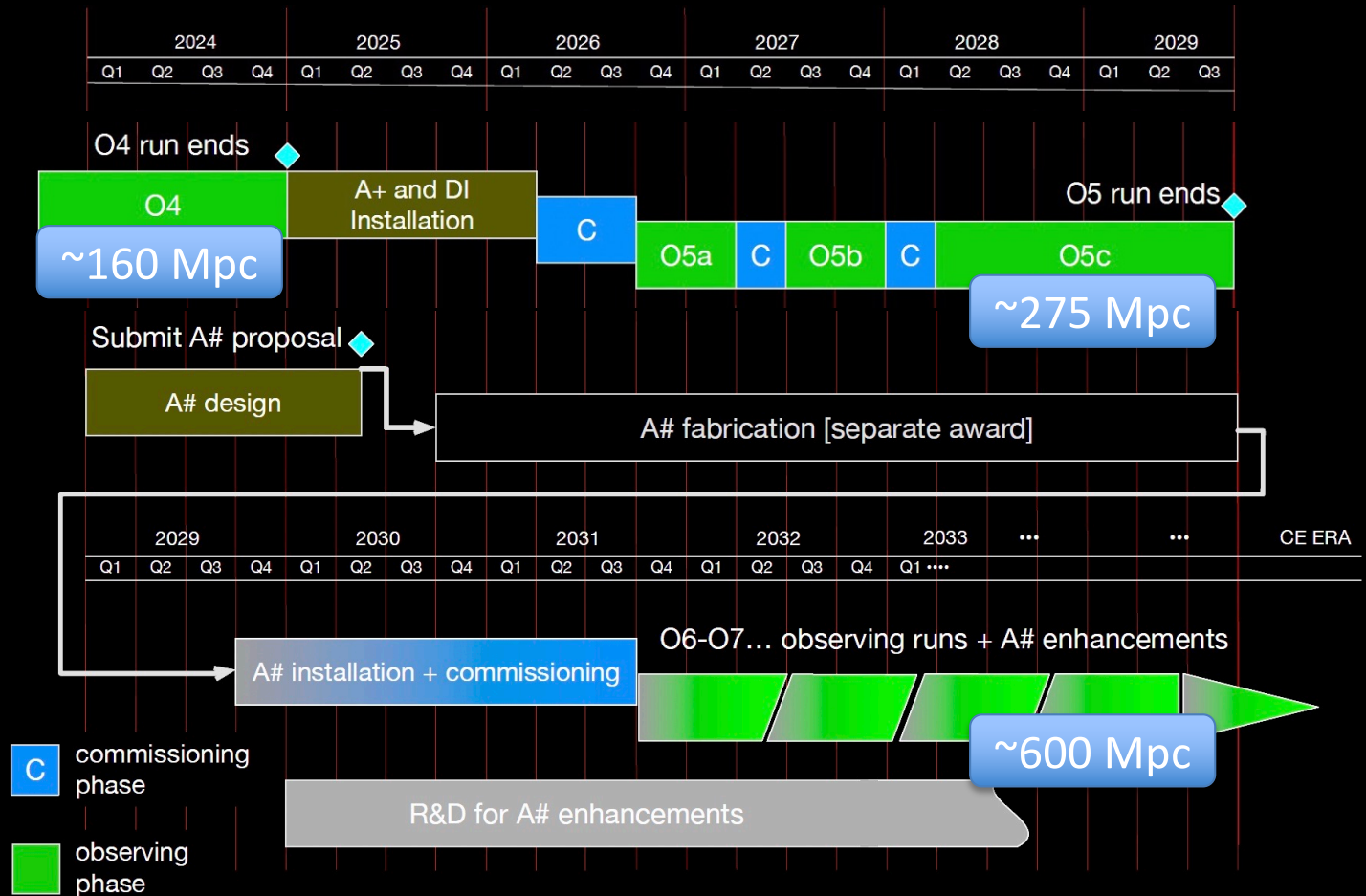
# O4 started 24 May 2023

- Many event triggers sent out, range of likely binary systems represented
- No EM/particle coincidences to date (and very poor localization...)
- Eagerly awaiting Virgo!



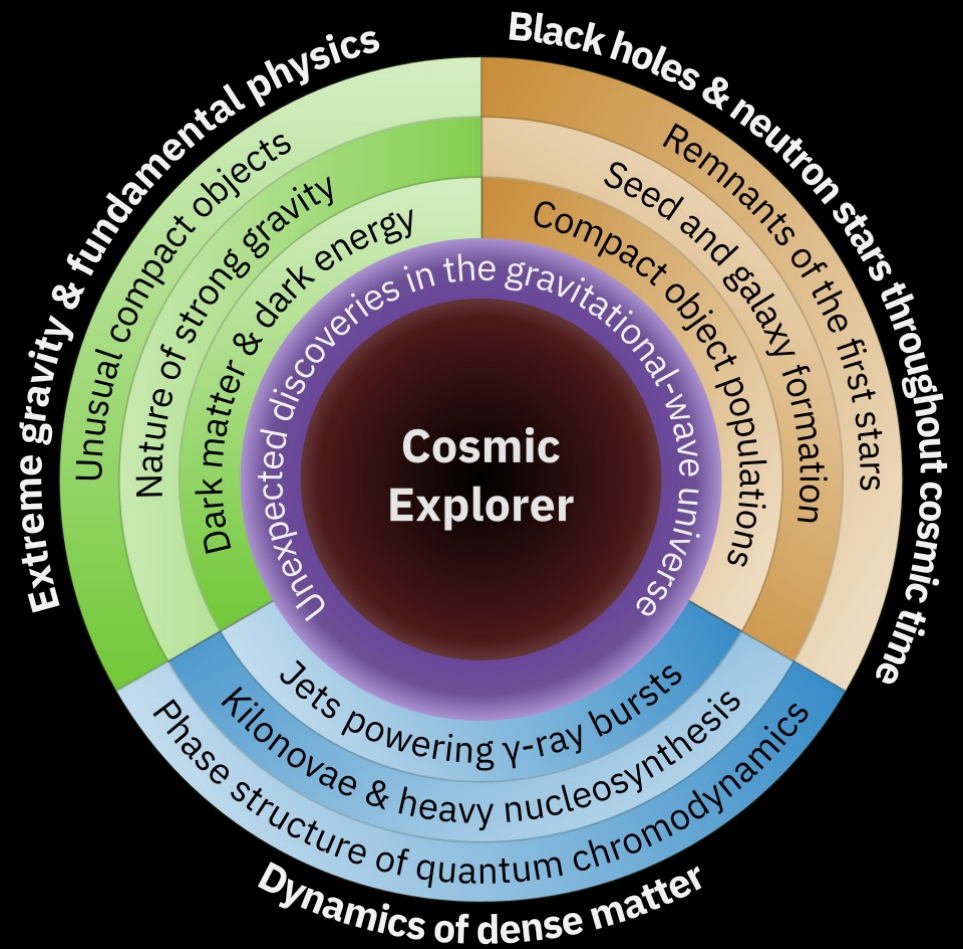
# Notional Plans for the current 4km observatories

- Best guess for LIGO
- Virgo similar
- Gives improving performance and continuous operation to ~2040



# What could we do with 10x better GW detectors?

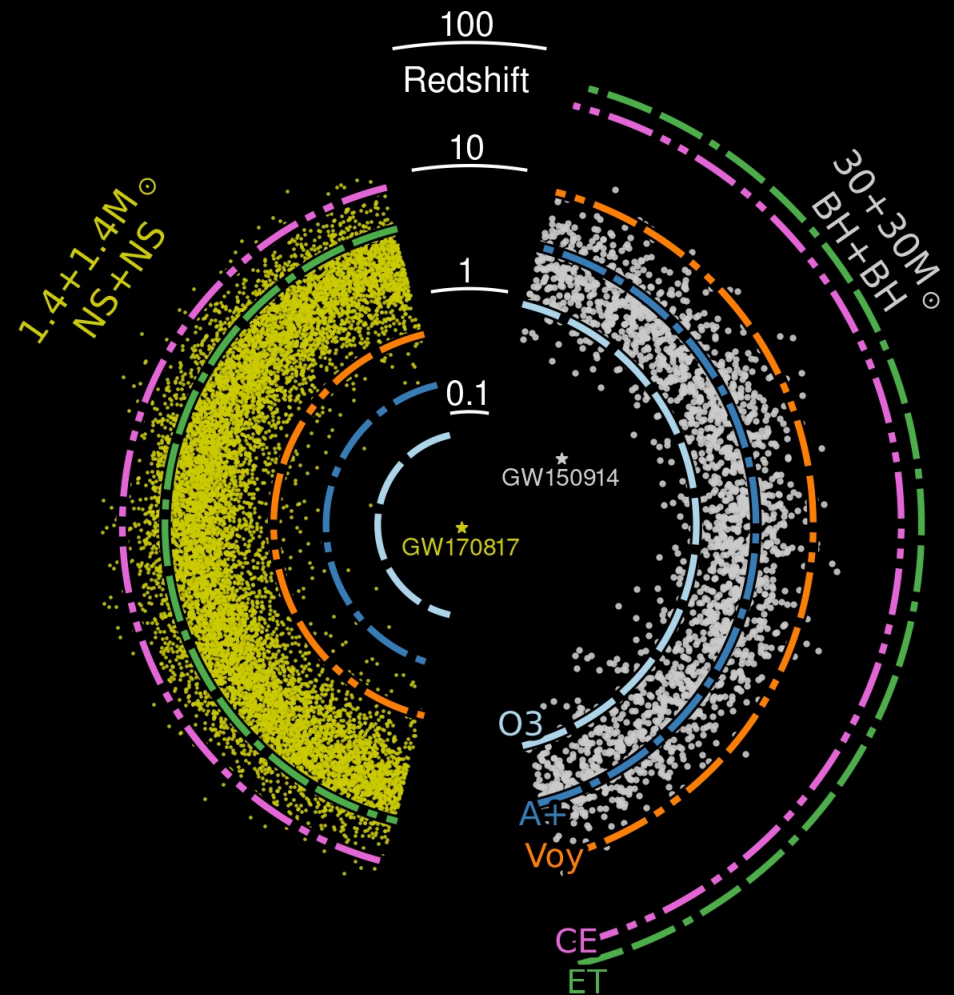
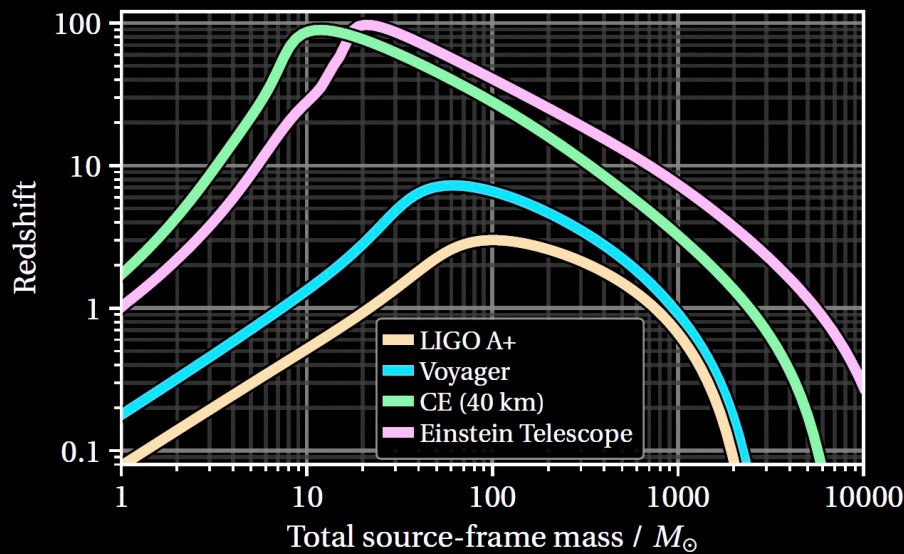
- Greater sensitivity will enable a qualitative growth in the number of observed sources (10x sensitivity → few  $10^5$  sources per year)
- It also increases the resolution of waveforms, enabling more stringent tests of GR and more detailed models of the coalescences
- Wider bandwidth can expose Neutron star coalescence and thus dynamics of dense matter





# 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?

Make it 10x longer → 10x larger signal

$$\Delta L = h_{\text{GW}} \cdot L$$

$$\Delta L = h L$$

## Noise due to stochastic forces is independent of armlength

- The Newtonian Background is the same for 4 or 40km, but the signal is 10x larger
- Also unchanged:
  - Thermal noise motion (pendulum, substrate, coating)
  - Magnetic and electrostatic dynamic forces
- ...Up to  $L = 1/2 \lambda_{\text{GW}}$  – giving an optimal length for a given signal

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

Shot Noise  
while maintaining bandwidth

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

Radiation Pressure Noise  
while maintaining bandwidth

$$\frac{h_{\text{RPN}}}{h_{0\text{RPN}}} = \sqrt{\frac{P_{\text{arm}}}{2 \text{ MW}}} \sqrt{\frac{1.5 \mu\text{m}}{\lambda}} \left(\frac{3}{r_{\text{sqz}}}\right) \left(\frac{320 \text{ kg}}{m_{\text{TM}}}\right) \left(\frac{40 \text{ km}}{L_{\text{arm}}}\right)^{3/2},$$

Coating Thermal Noise  
loss angle dependence

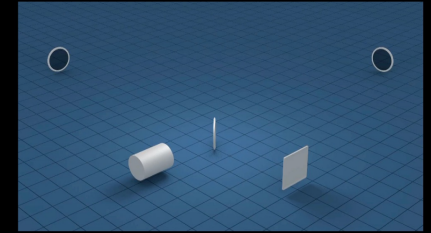
$$\frac{h_{\text{CTN}}}{h_{0\text{CTN}}} = \sqrt{\frac{T}{123 \text{ K}}} \sqrt{\frac{\phi_{\text{eff}}(T)}{5 \times 10^{-5}}} \left(\frac{40 \text{ km}}{L_{\text{arm}}}\right)^{3/2}$$

Residual Gas Noise  
facility limit

$$\frac{h_{\text{gas}}}{h_{0\text{gas}}} = \sqrt{\frac{p_{\text{gas}}}{4 \times 10^{-7} \text{ Pa}}} \sqrt{\frac{40 \text{ km}}{L_{\text{arm}}^{3/2}}}$$

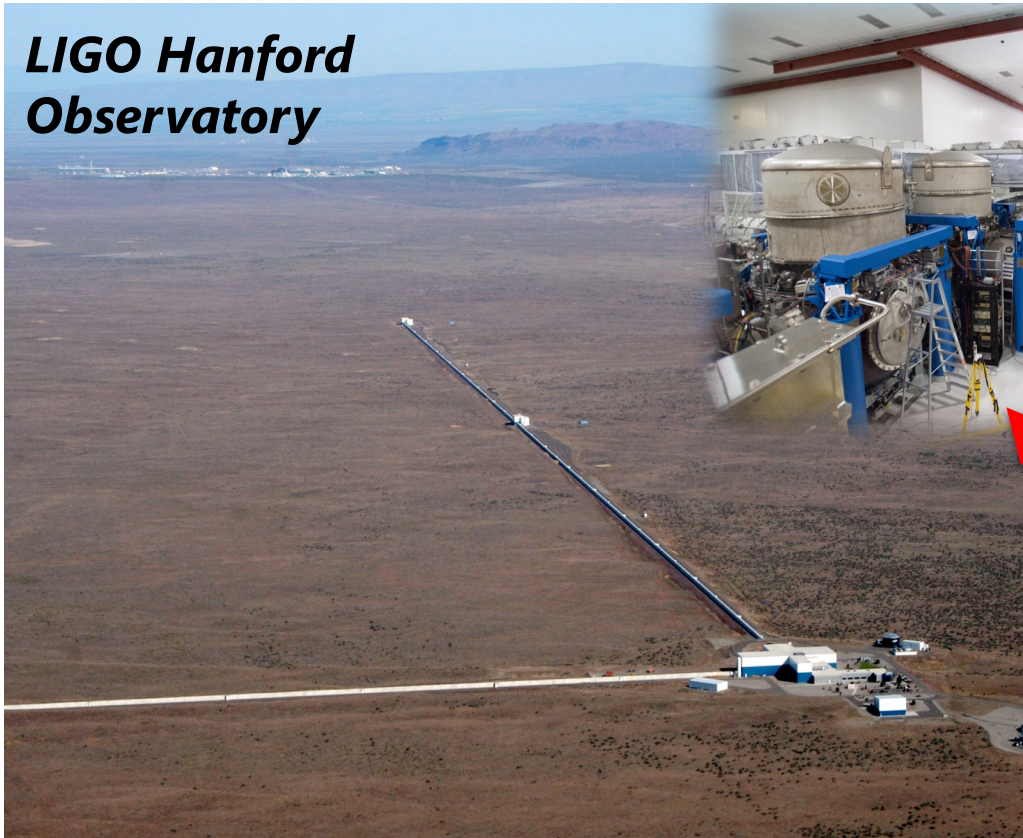


# The Infrastructure for a realistic implementation



- A sufficient length  $L$  of the arms is needed to bring the GW-induced strain to a measurable level (4km  $\rightarrow$  40km)
- Sensing laser light must travel in an excellent vacuum ( $10^{-9}$  Torr)
- The vacuum system diameter must accommodate a diffraction limited beam over 4 or 40km ( $\sim 1$  m Diameter)
- The vacuum system must be *straight*, level, and protected from the human and natural environment (earthmoving, concrete bed, aligned to several mm over 4 or 40km, and protected by a concrete cover)
- Corner and end buildings with particulate, temperature control; staff buildings; outreach/public science building ( $\sim 10,000$  m<sup>2</sup>)

**LIGO Hanford  
Observatory**



**Present LIGO Observatory sites  
 $L = 4\text{km}$**

**LIGO Livingston  
Observatory**





# COSMIC EXPLORER

Astro 2020

Decadal Survey on Astronomy and Astrophysics

The National Academies of SCIENCES ENGINEERING MEDICINE

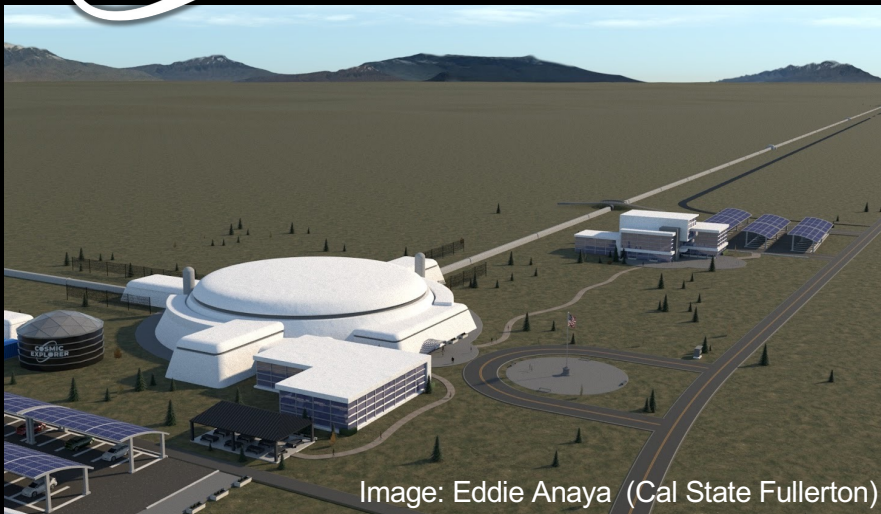
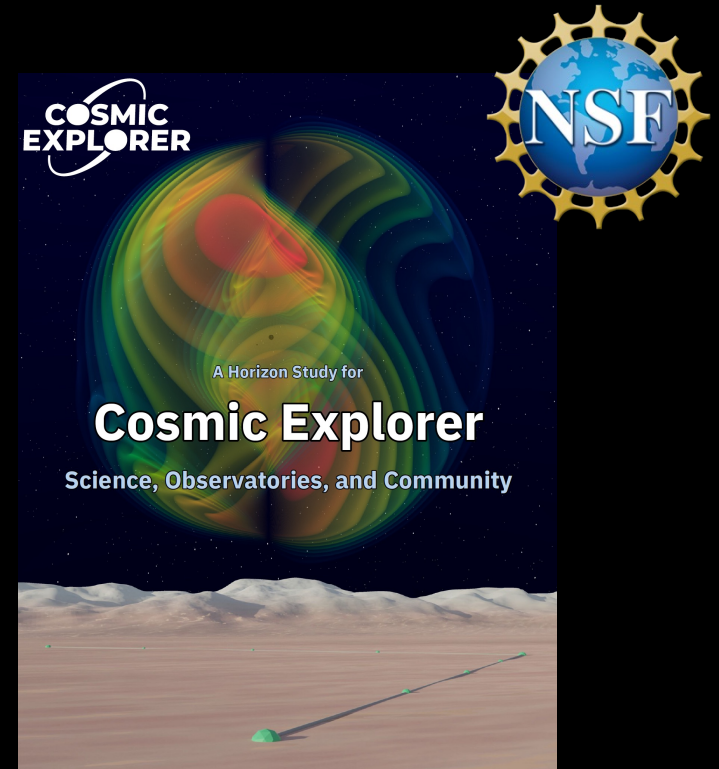


Image: Eddie Anaya (Cal State Fullerton)



- US contribution to the next-gen Network (with Einstein Telescope – European project)
- 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](http://cosmicexplorer.org)

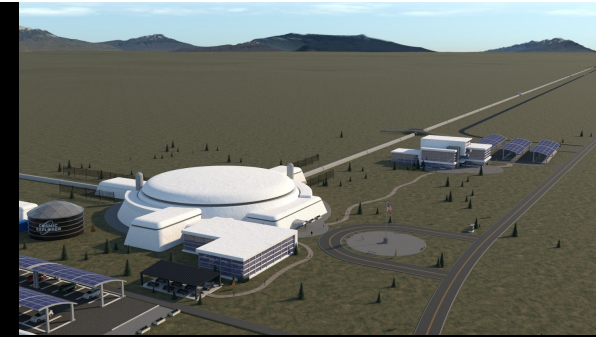
# CE Detector Design

- 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)
  - Room temperature, 1 micron light, fused silica optics, sputtered optical coatings, frequency dependent squeezed light..
- **Initial CE detectors will use techniques of this LIGO Post-O5 upgrade**
- **Low risk** – no significant advances in the detector are needed
  - Some work on bigger masses, suspensions, lower-loss optics
- (Later CE upgrades can include all insights from CE, ET, quantum sensing...)

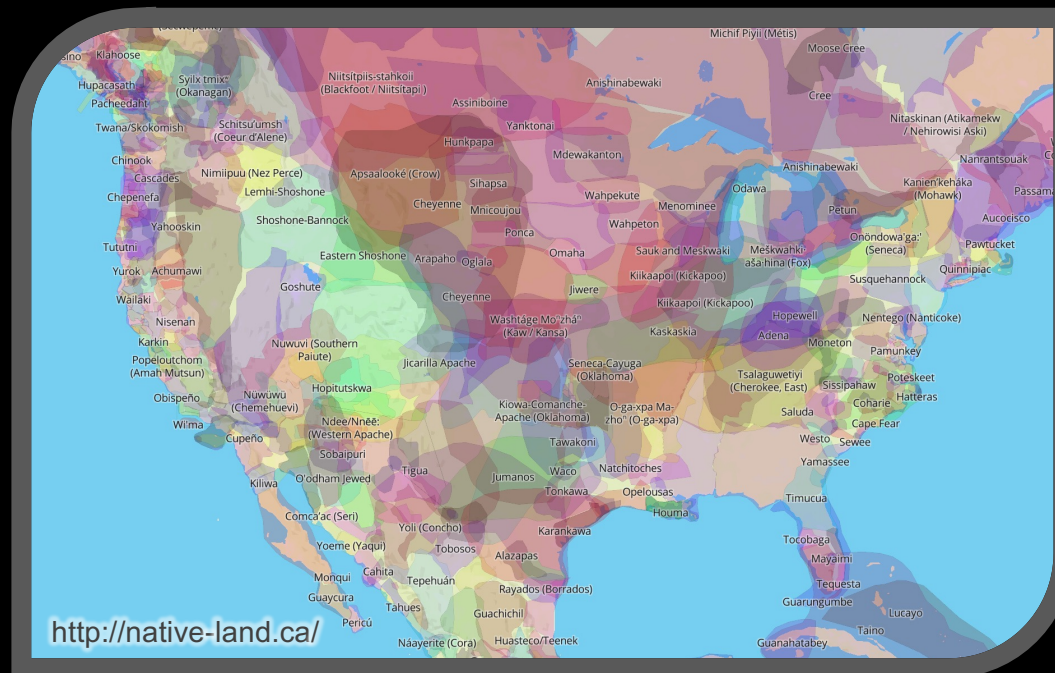


# CE Infrastructure

- Baseline of 40km and 20km observatories
  - 20km =  $1/2 \lambda_{\text{GW}}$  is ideal for observing  $\sim 2\text{kHz}$  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 for position information
  - 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 ( $\sim 7\text{Hz}$  compared to  $\sim 5\text{Hz}$  for ET)
- *Geographically* suitable sites can be found in the US (and Canada, Australia...)



- The history of the land will play a **pivotal** role in this project.
- We have the **opportunity**, and obligation, to work with Indigenous Peoples
- We will build synergistic relationships and respect their land, their culture, and their sovereignty.



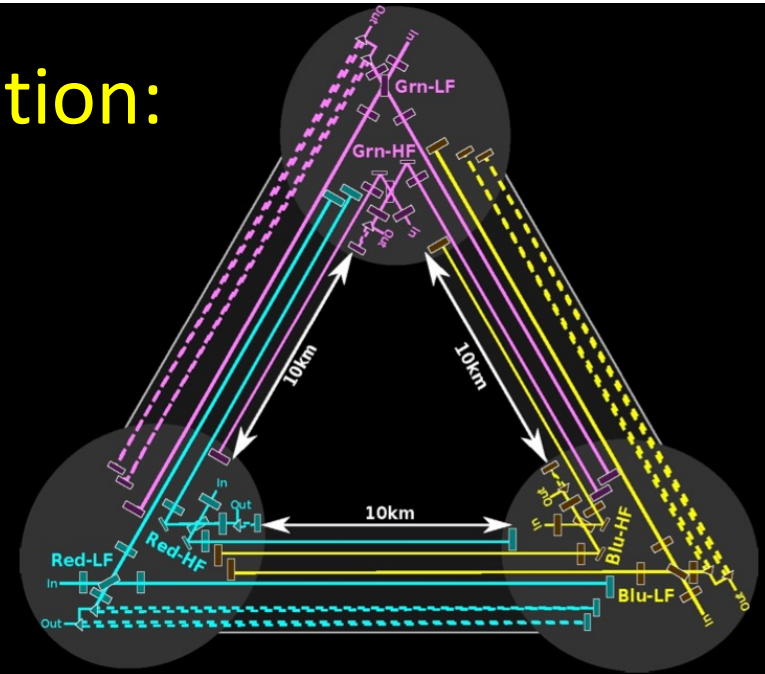
If you are not aware of issues surrounding TMT, please read [arXiv:2001.00970](https://arxiv.org/abs/2001.00970) .

# CE Status

- Conceptual Design is now underway
- CE Funding approved for this phase
  - International contributions (in-kind) – UK, Canada, Australia, Germany
- **Goal: observatories by mid-2030's**

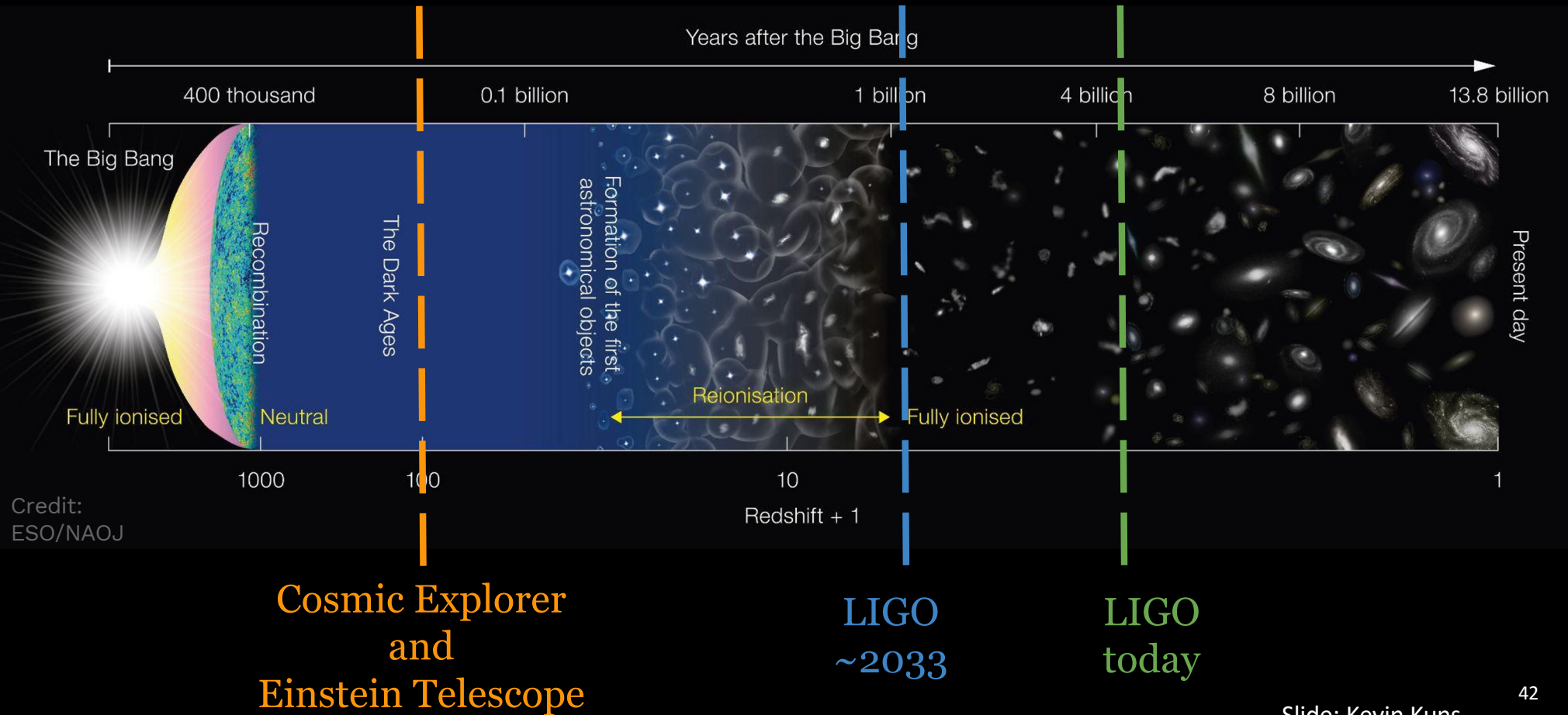
# European Vision for the next generation: Einstein Telescope

- ET Design: underground, triangular, 3 detectors consisting of two interferometers each (high frequency + low frequency ‘xylophone’)
  - Cryogenic test masses, longer wavelengths for LF operation
  - Underground infrastructure designed for future upgrades
- Possible sites:
  - Euregio Meuse-Rhine
  - Sardinia, Italy
  - (possibly) Saxony, Germany
- Current envisioned timeframe:
  - Construction to begin in 2026
  - Science operations to begin in 2035
- Status:
  - ET is a fully recognized European Project on European Strategy Forum for Research Infrastructures (ESFRI) Roadmap → a key step in getting the project funding lined up.
  - ET Project Organization and relevant Boards have been established
  - ET Pathfinder facility in Maastricht, Netherlands under construction
  - Site evaluation well underway





# Reach of present and future instruments



## The last page (at last!)

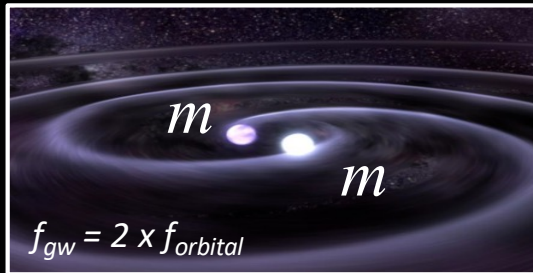
- Ground-based GW observation works, and LIGO, Virgo, and KAGRA observing together
- There are lots of sources yet to be observed
- Scaling laws show the technical feasibility of better detectors
- The US Concept, Cosmic Explorer
  - Two sites, one 40km, one 20km
  - Surface construction, LIGO Technology
- The European Concept, Einstein Telescope
  - Underground triangle multiple-interferometer approach
  - Pushes detector technology with high power, low temperatures
- Both eager to participate in Multi-Messenger Astrophysics

**The future is bright for gravitational-wave astronomy!**

Thank you!

# Gravitational Wave Properties

Binary Coalescence of two compact objects



GW generation:  
lowest order radiation is quadrupole

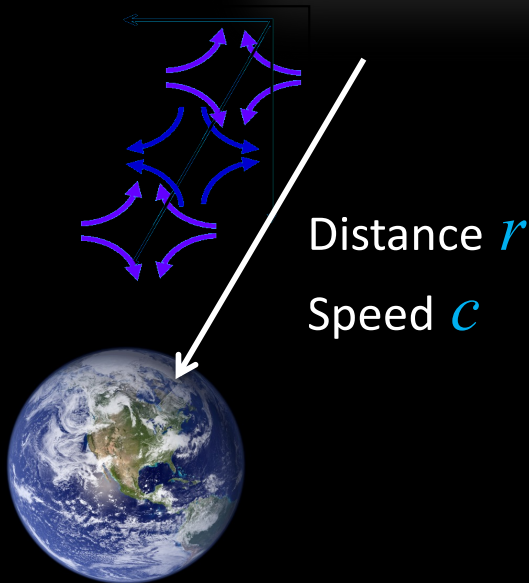
metric perturbation  $\rightarrow$   $h = \frac{2G}{c^4 r} \ddot{I}$   $\leftarrow$  quadrupole moment

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

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

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

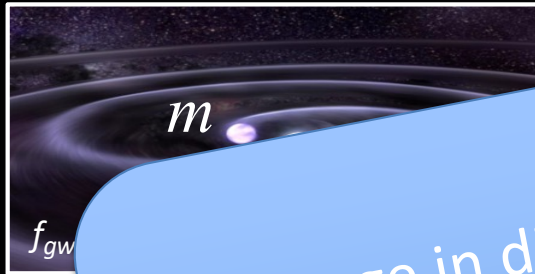
$$1.5 \times 10^{-21} \left( \frac{m}{30M_{\odot}} \right) \left( \frac{400 \text{ Mpc}}{r} \right) \left( \frac{f_{gw}}{50 \text{ Hz}} \right)^{2/3}$$



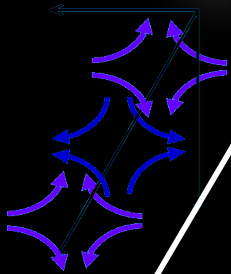


# Gravitational Wave Properties

Binary Coalescence of two compact objects



A change in distance from here to Alpha Centauri  
 (4 light-years distant)  
 of the thickness of a human hair  
 (10 microns)



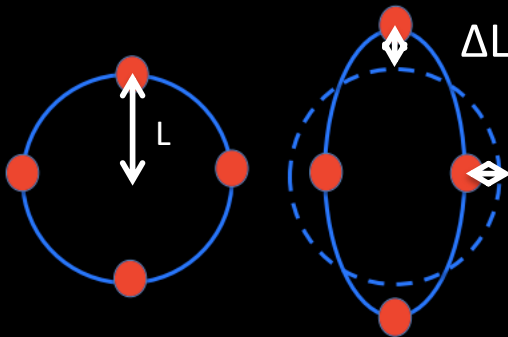
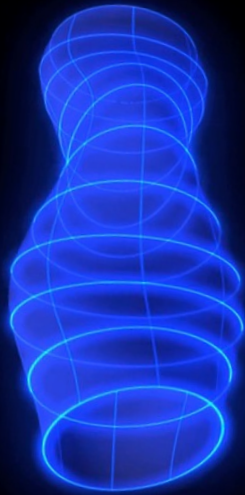
Distance  
 Speed

About once a week,

a wave passes with this characteristic strain:

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

# Stretching and squeezing of space-time



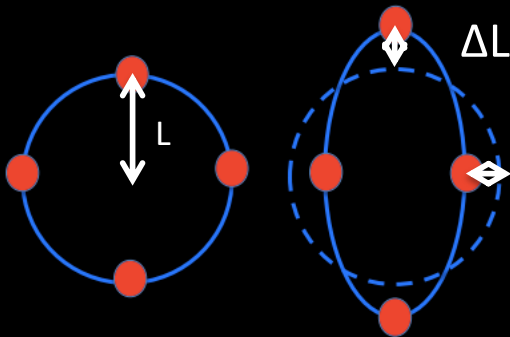
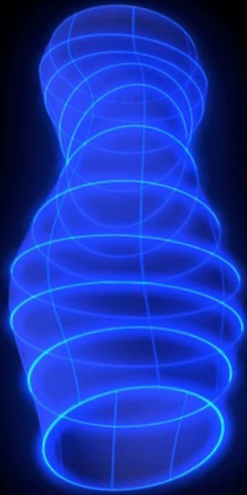
Amplitude of the gravitational wave strain is  $h = \Delta L/L$

$$\Delta L = h L$$

Big  $L$  makes  $\Delta L$  easier to measure; current detectors have  $L = 4$  km, so from our two-mass example

$$\Delta L \sim 10^{-21} \times 10^3 = \sim 10^{-18} \text{ m}$$

# Stretching and squeezing of space-time



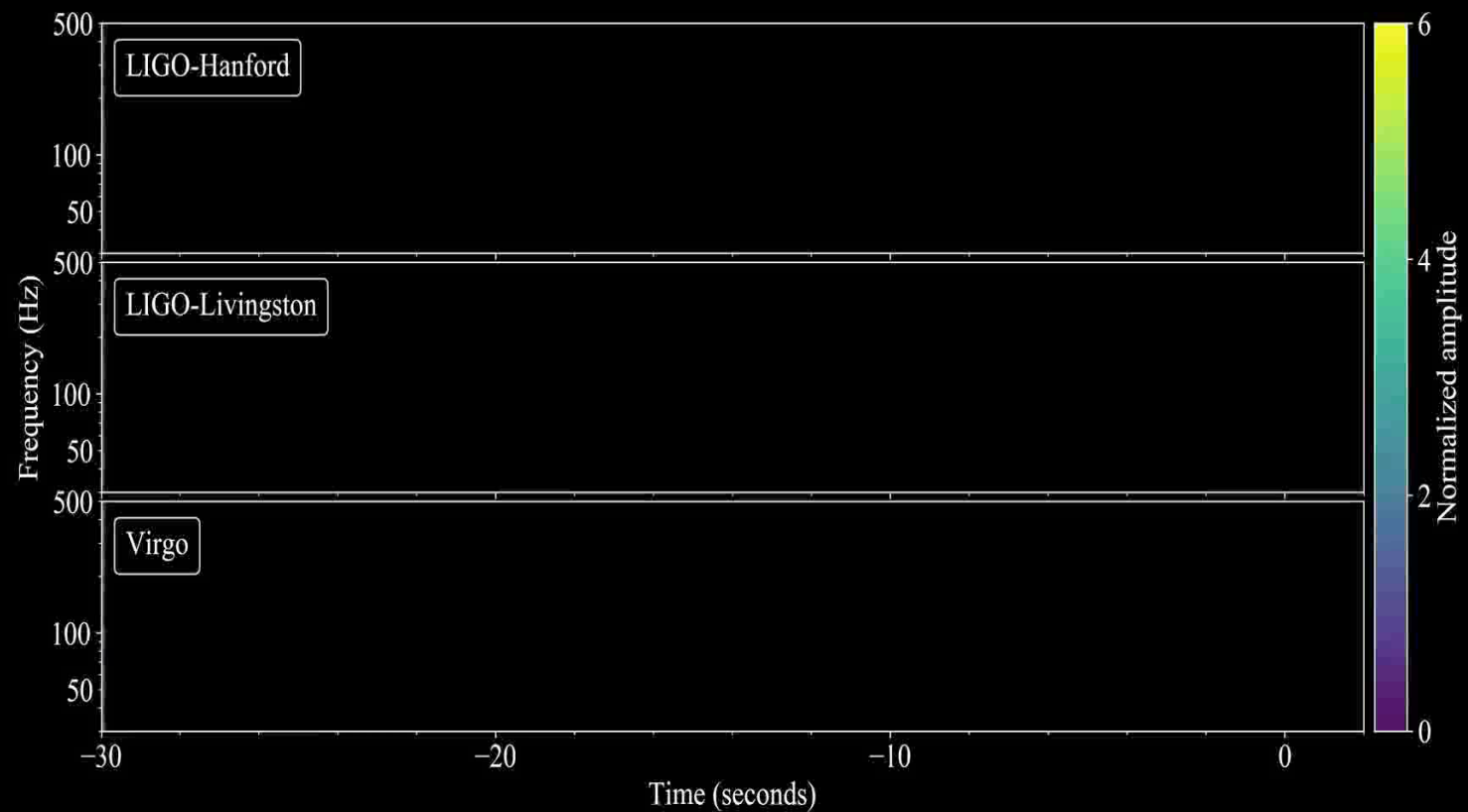
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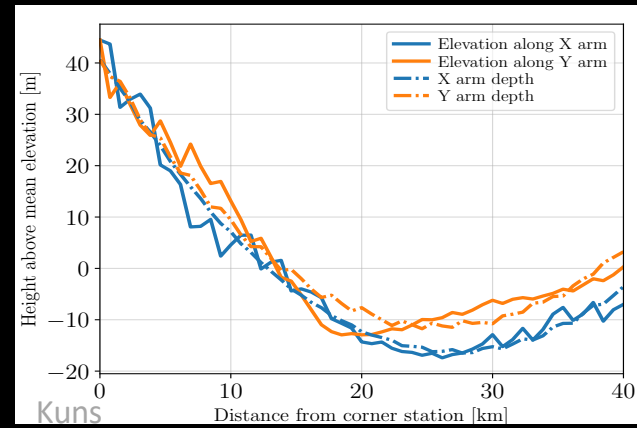
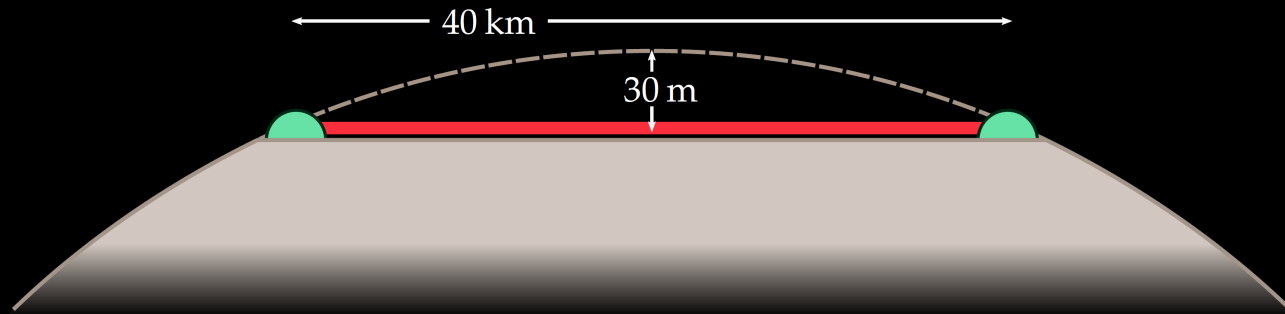
$$\sim 10^{-21} \times \sim 10^3 = \sim 10^{-18} \text{ m}$$

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





# 40km CE



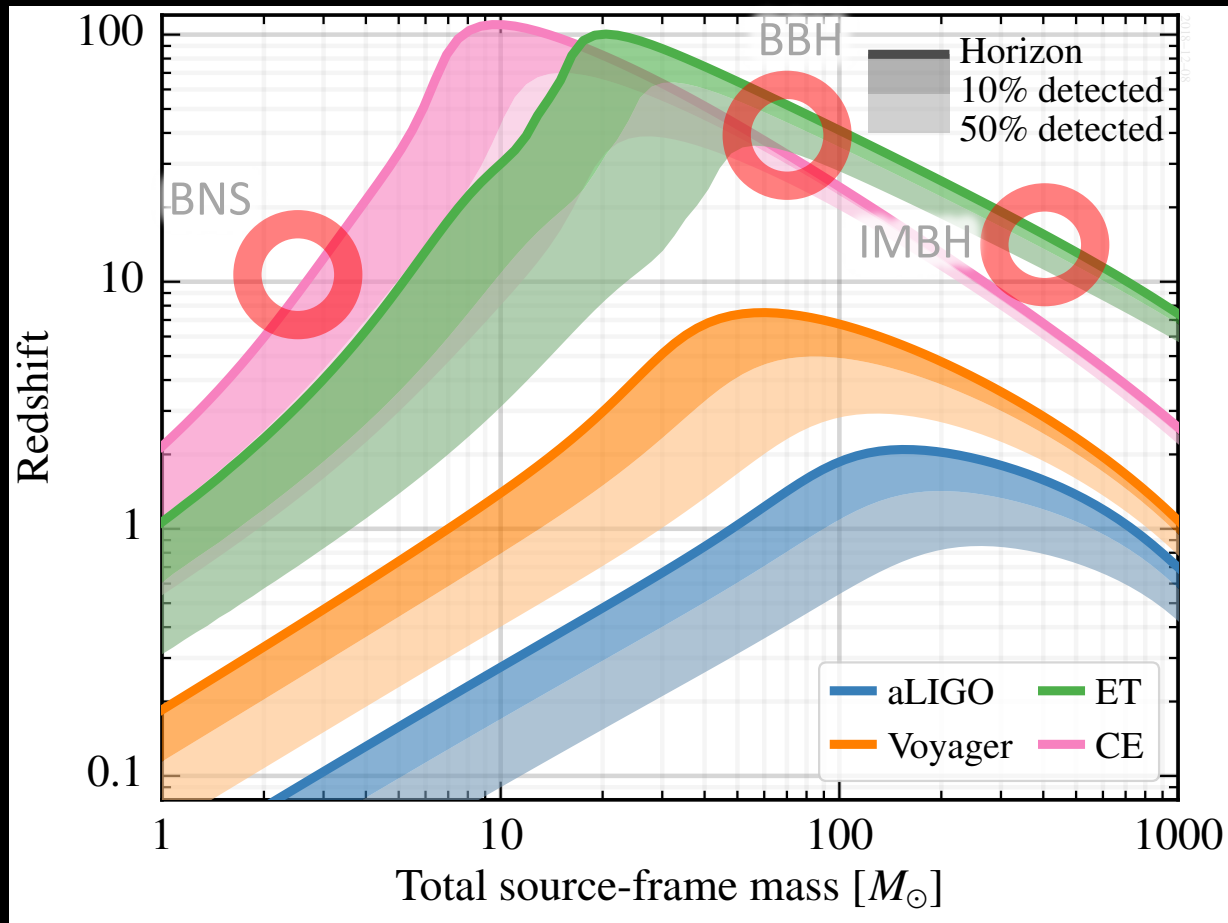
## Why 40km?

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

$$\frac{c}{2L} = \frac{3 \times 10^5 \frac{km}{s}}{2 \times 40 km} \simeq 4 kHz$$

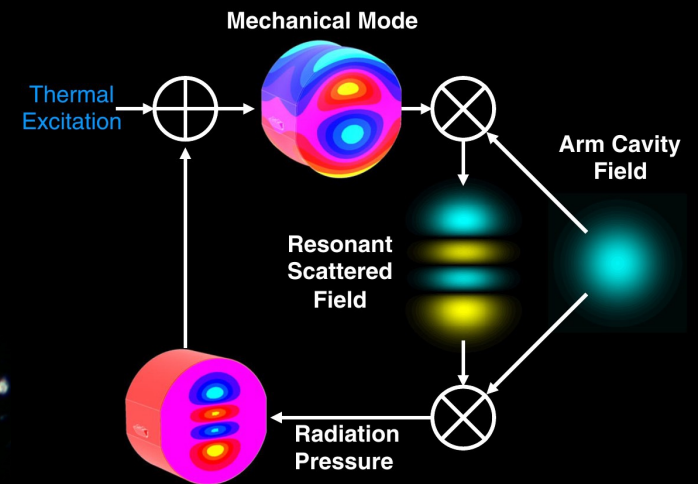
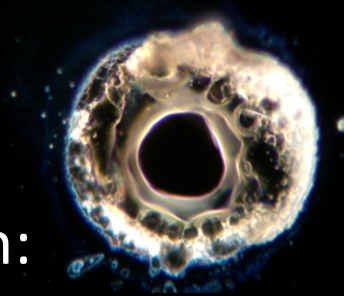
so making a detector longer than 40km would compromise its access to interesting astrophysics (i.e., post-merger signals and supernovae).

# 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 \(2021\)](#)



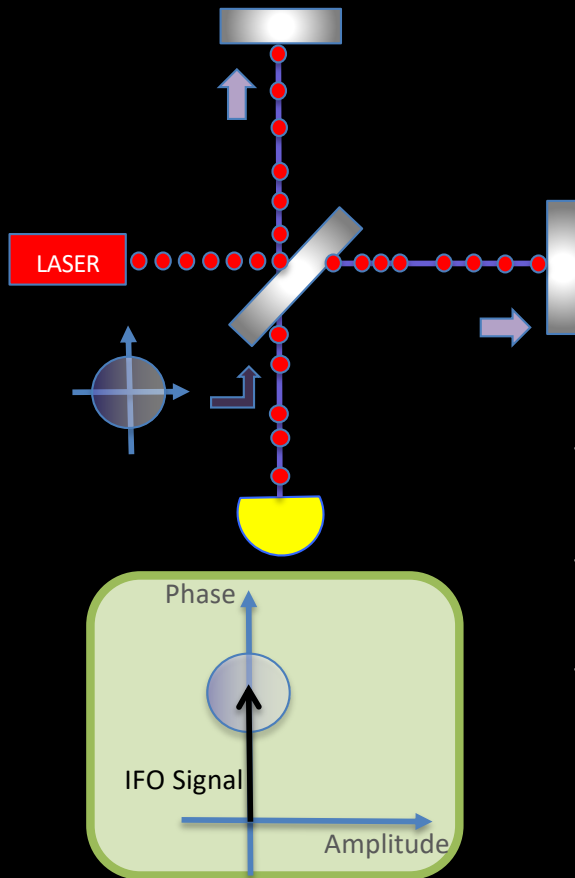
- Complementary approach:  
**squeezed states of vacuum**

**Quantum-mechanical noise in an interferometer**

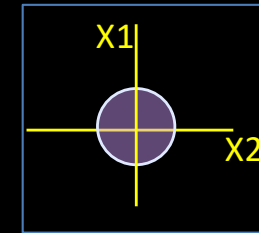
Carlton M. Caves

*W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125*

(Received 15 August 1980)



Zero-point energy  
(vacuum) fluctuations

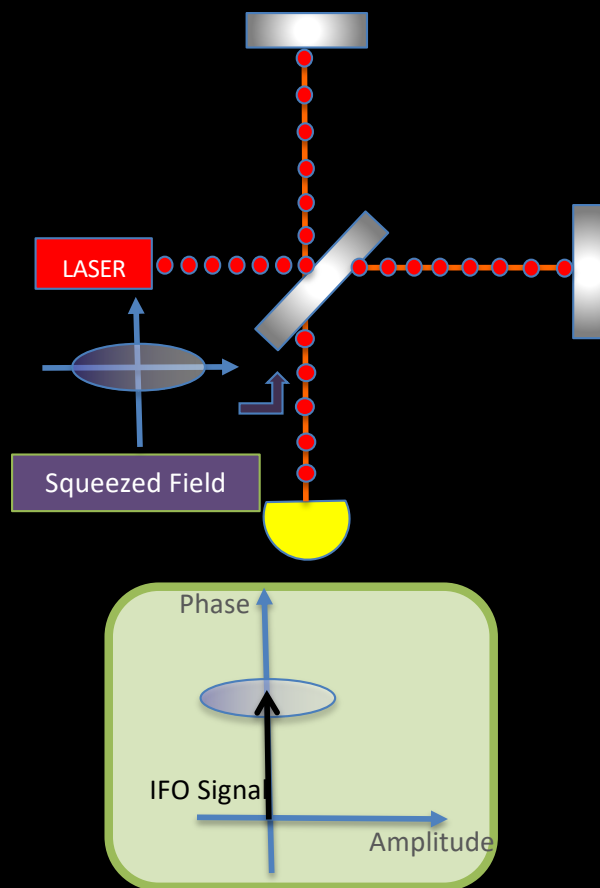


$$\Delta X_1 \Delta X_2 \geq 1$$

- ✧ 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

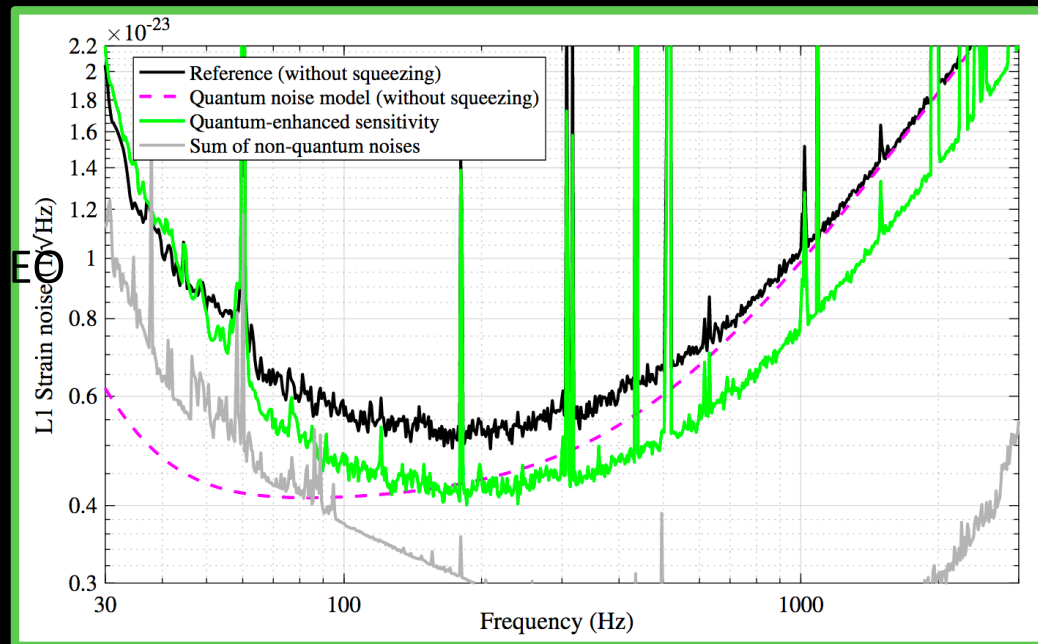


- ✧ Reduce quantum noise by injecting squeezed vacuum: less uncertainty in one of the two quadratures
- ✧ Heisenberg uncertainty principle: if the noise gets smaller in one quadrature, it gets bigger in the other one
- ✧ One can choose the relative orientation between the squeezed vacuum and the interferometer 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

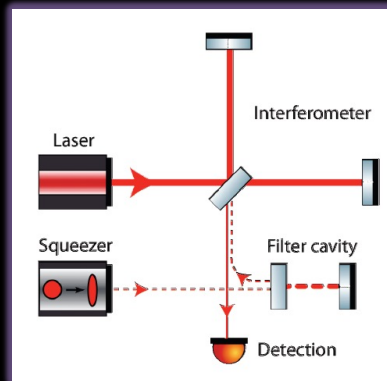
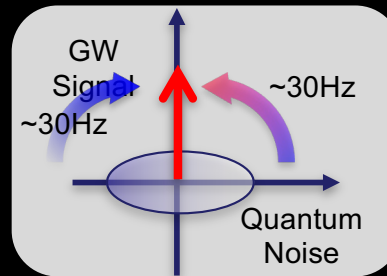
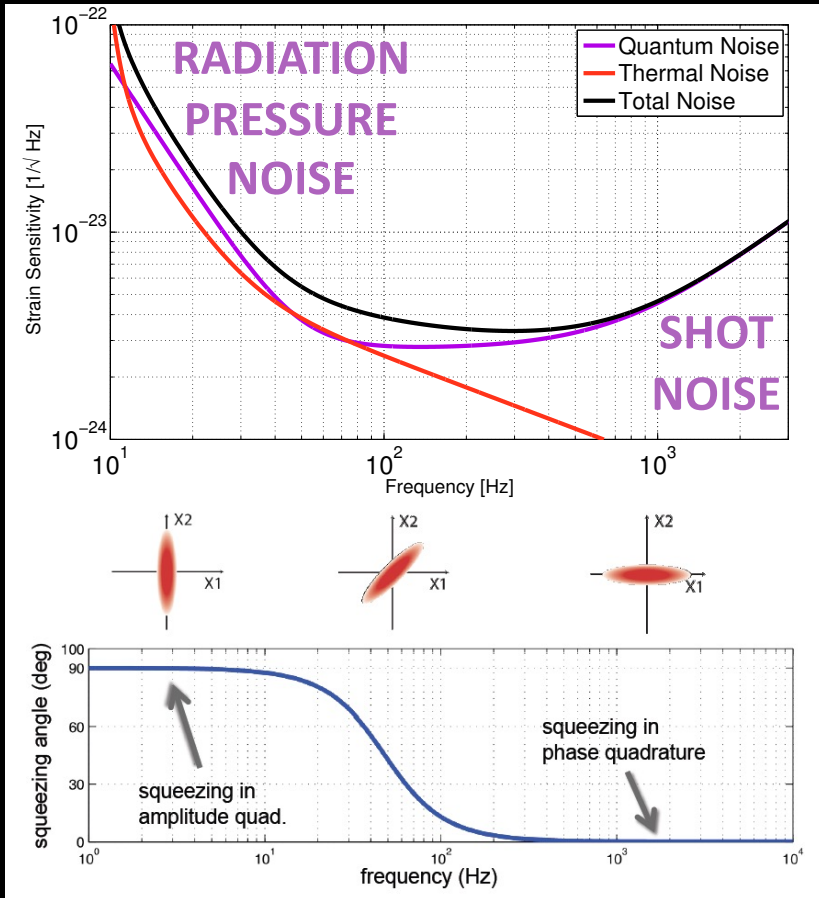
# Squeezing performance in O3

[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



High finesse detuned “filter cavity” which rotates the squeezing angle as function of frequency

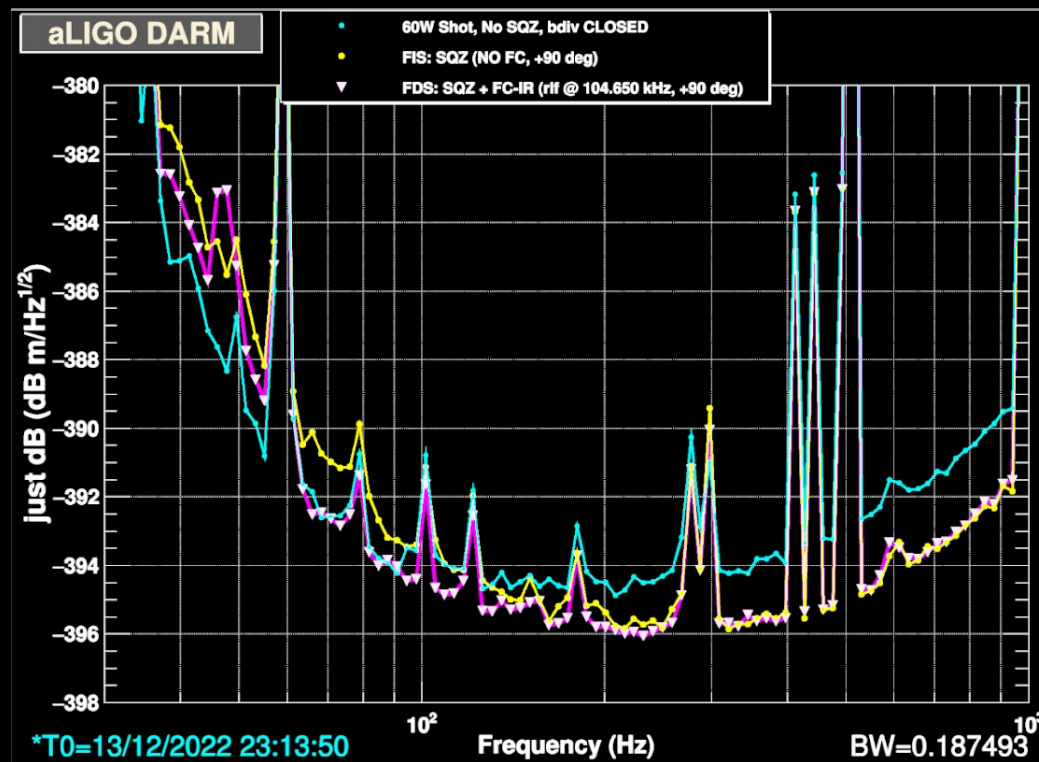


Credit: Antonio Pasqualetti

Highlight from Virgo:  
300 m filter cavity already built and locked and characterized, commissioning in progress 57

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

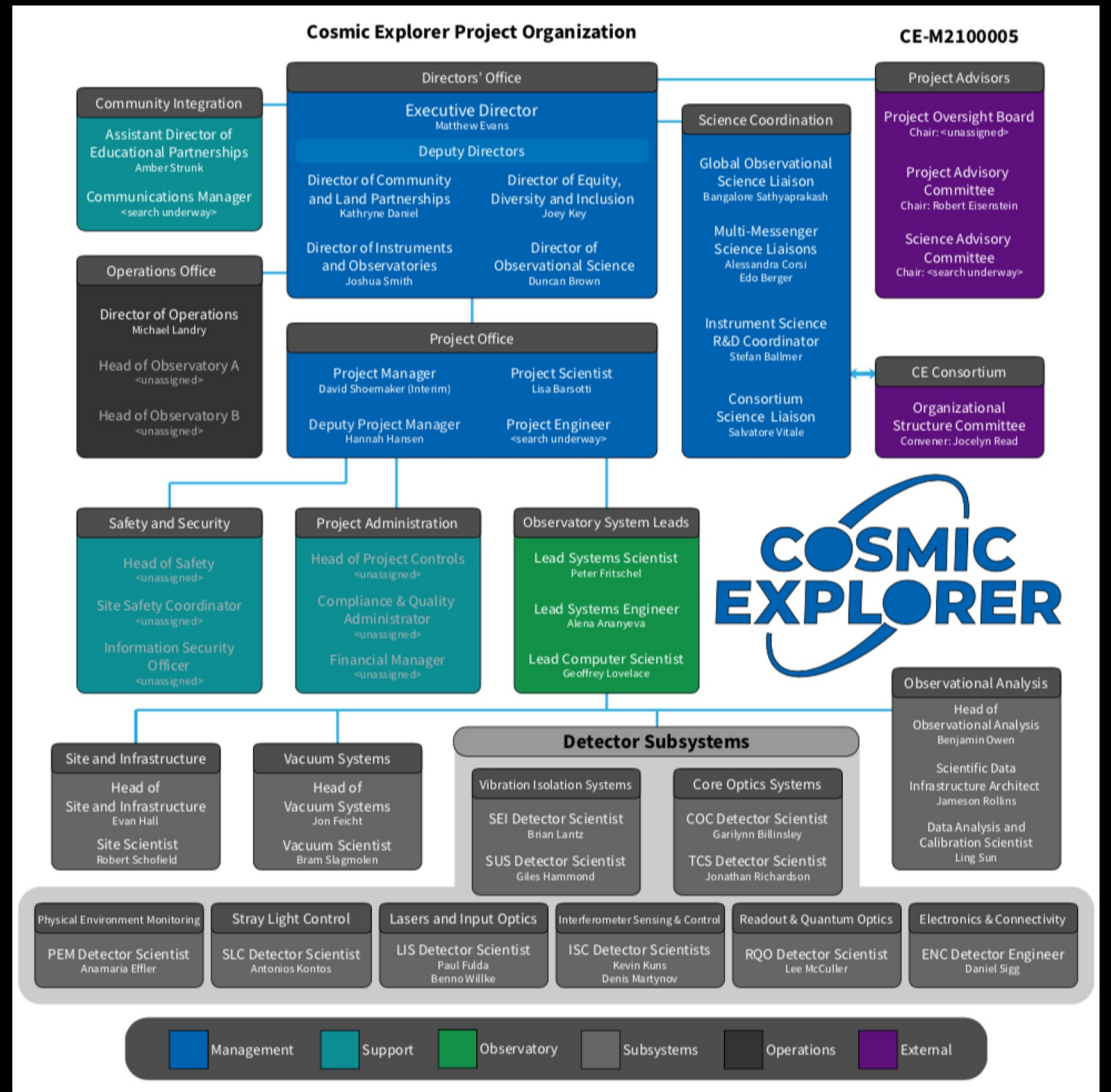
# Initial results for Frequency Dependent Squeezing LIGO Hanford



# The Cosmic Explorer Project Organization today

Team members from

MIT  
 Cal State Fullerton  
 Syracuse  
 Penn State  
 Caltech  
 University of Washington Bothell  
 University of Oregon  
 University of Florida  
 Texas Tech University  
 University of Arizona  
 Bard College  
 Stanford  
 Harvard  
 UC Riverside  
 The Australian National University  
 Albert Einstein Institute  
 University Birmingham  
 University of Glasgow





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 UC Riverside  
 The Australian National University  
 Albert Einstein Institute  
 University Birmingham  
 University of Glasgow

