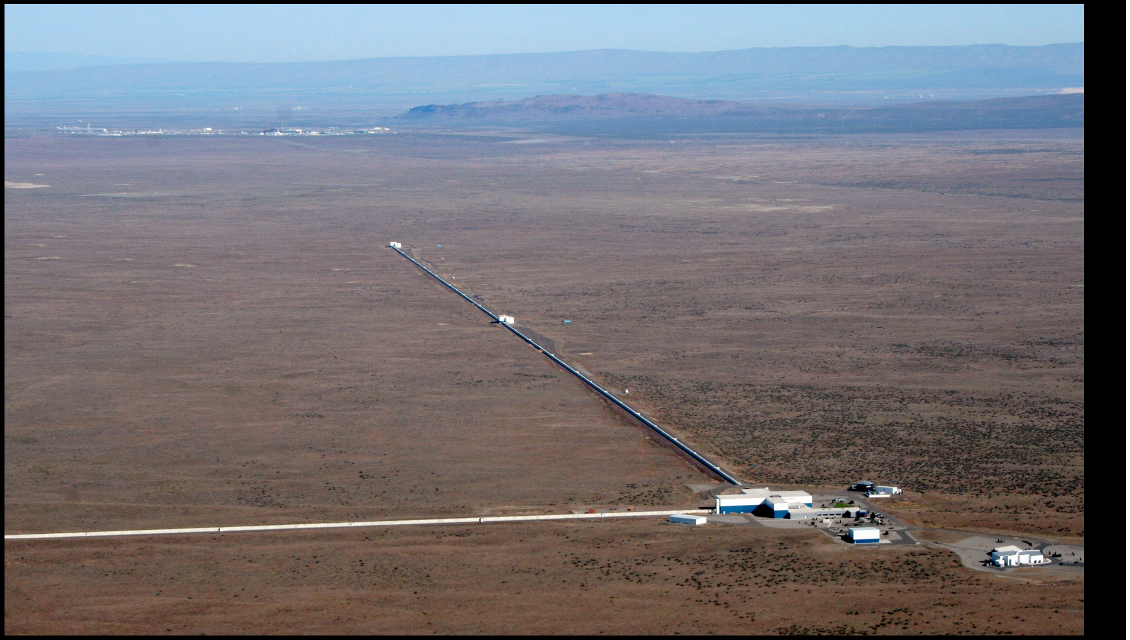
Present and Future Terrestrial GW Detectors



David Shoemaker

MIT Kavli Institute – LIGO Laboratory

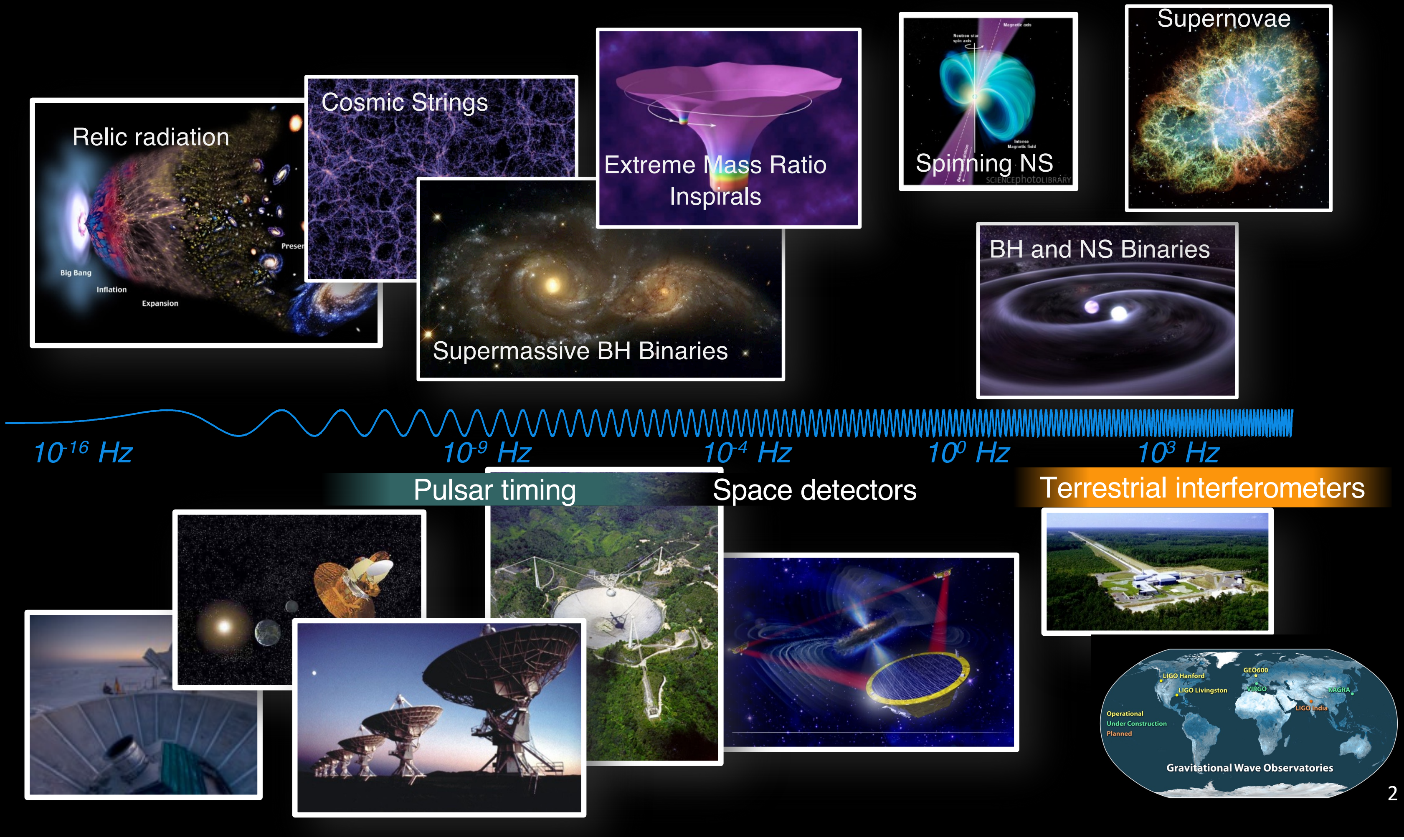
Slides from many CE and LIGO Collaborators!

ICGAC

3 July 2023

G2301273

The Gravitational Wave Spectrum



Relic radiation

Cosmic Strings

Extreme Mass Ratio Inspirals

Spinning NS

Supernovae

Supermassive BH Binaries

BH and NS Binaries

10^{-16} Hz

10^{-9} Hz

10^{-4} Hz

10^{0} Hz

10^{3} Hz

Pulsar timing

Space detectors

Terrestrial interferometers

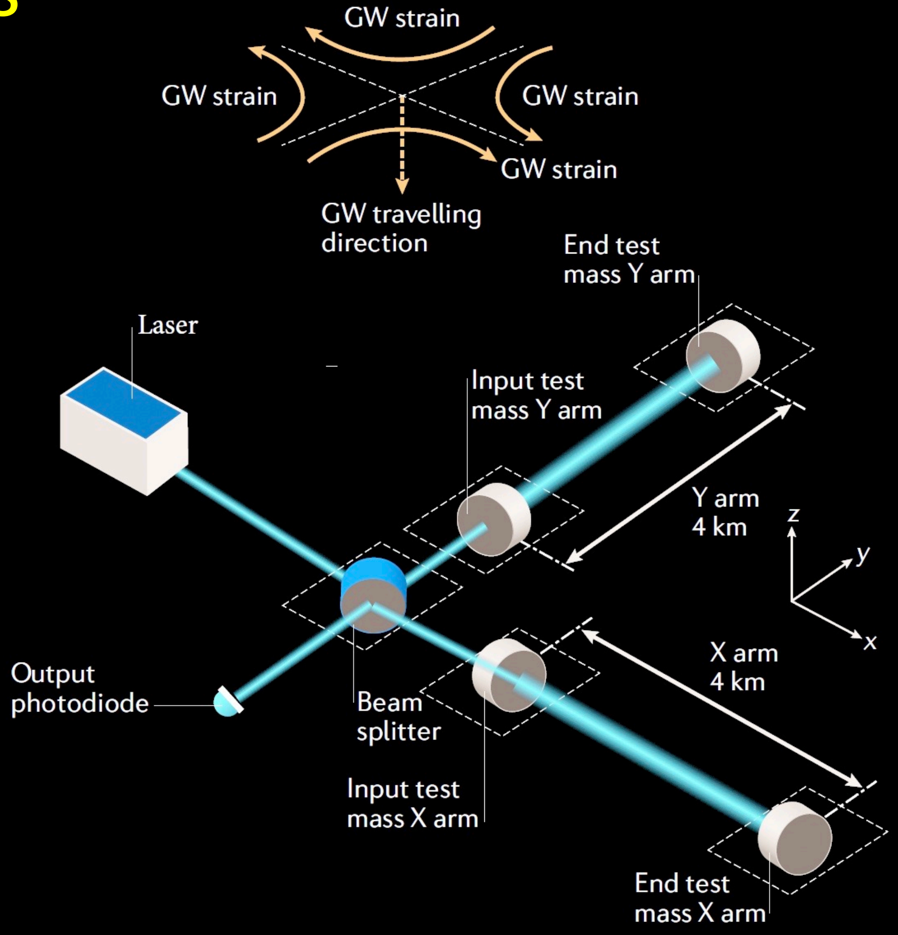
The Gravitational Wave Spectrum

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

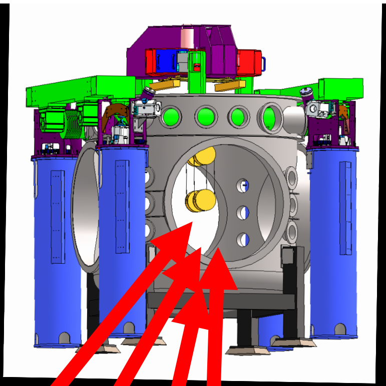
$$\Delta L = h_{\mathrm{GW}} \cdot L$$

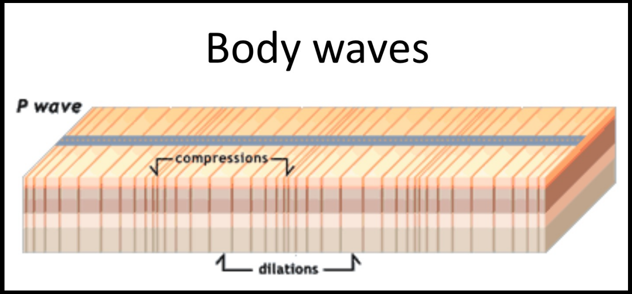
- Interference at the Beam splitter turns this into a light intensity variation, and a photodiode into an electrical signal
- Resolution of the readout limited by quantum effects
- **Physical motion of the mirrors due to local forces masks the minuscule changes in light path due to GWs**

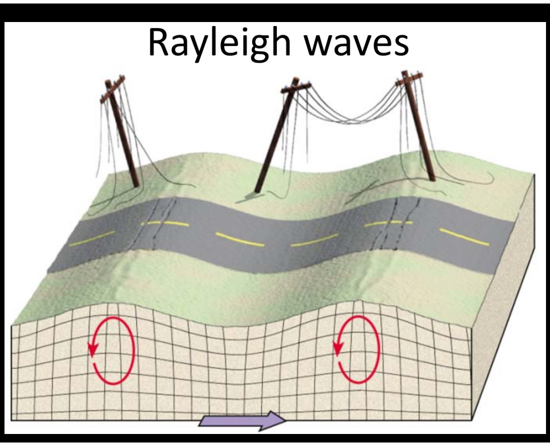


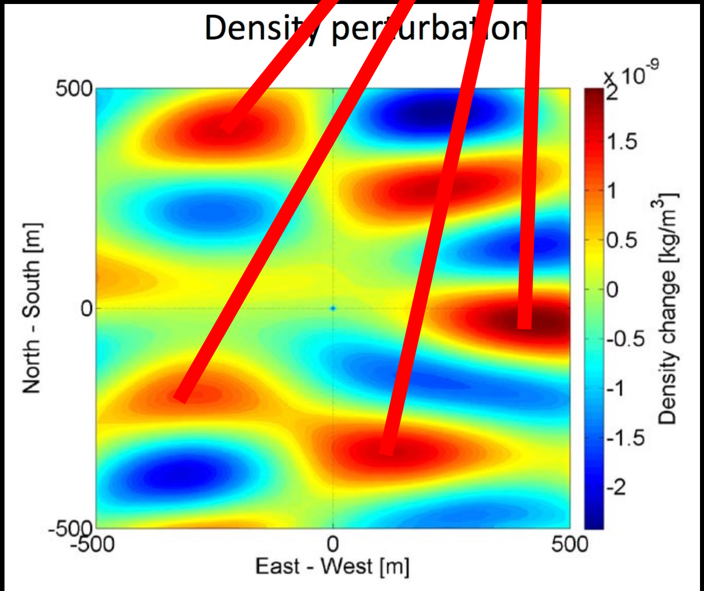
Newtonian background due to seismic environment

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







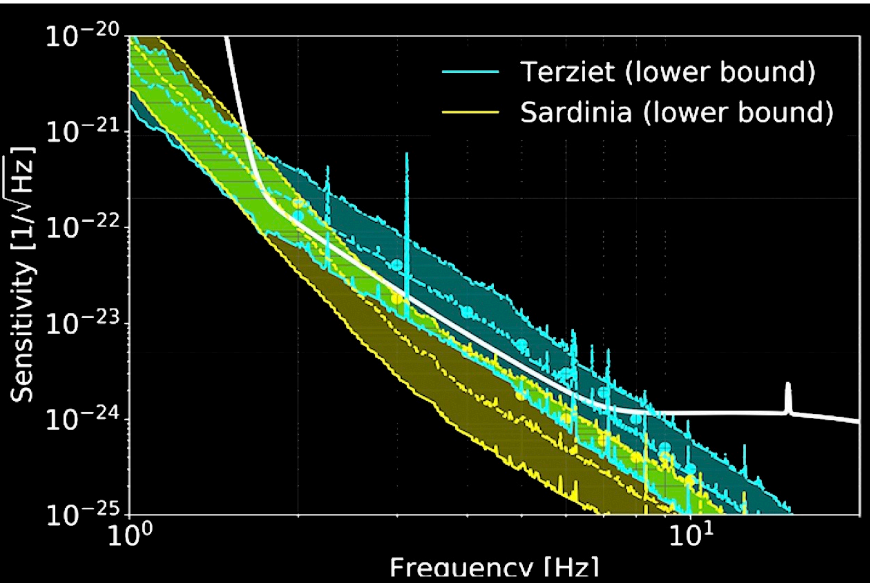


Density perturbations cause gravity perturbations.

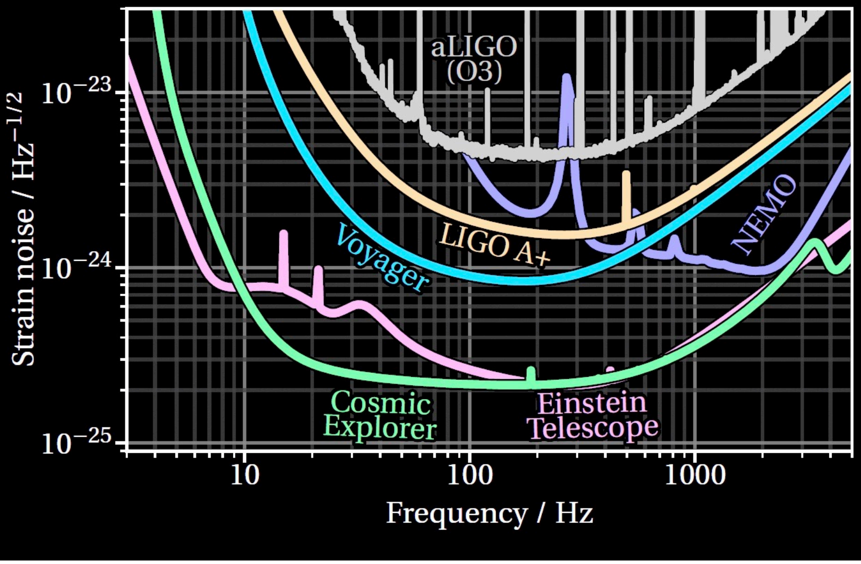
Images: J. Harms

Newtonian background creates a wall at a few Hz

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



Harms et al. 2022



Evans et al. 2023

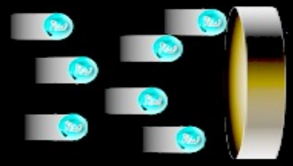
Practical limitations for Terrestrial Detectors

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

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

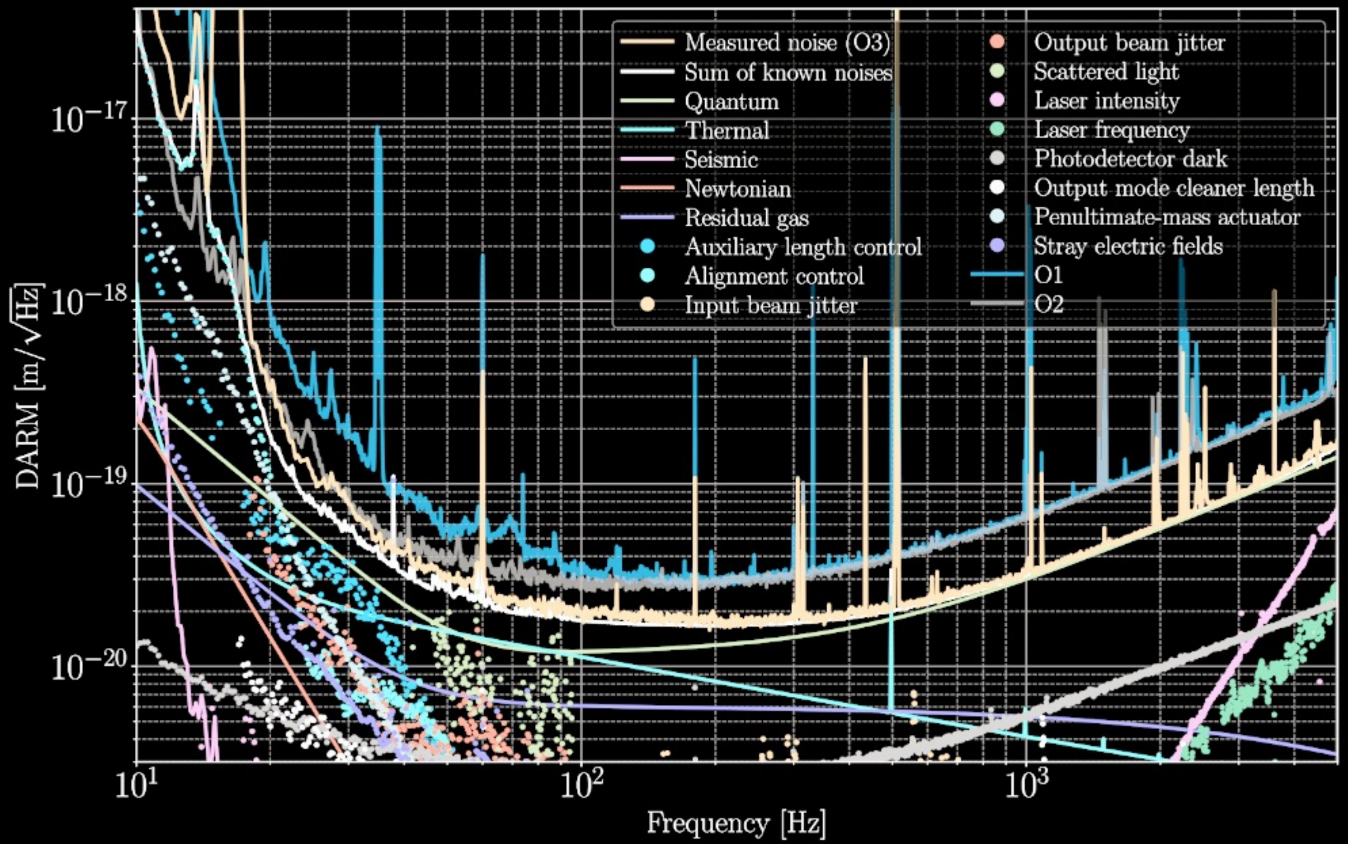
$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

- …but too much power, and the radiation pressure causes mirror motion which masks the GW
- Optimal power – naïve quantum limit
  - Working with ~50-100 W



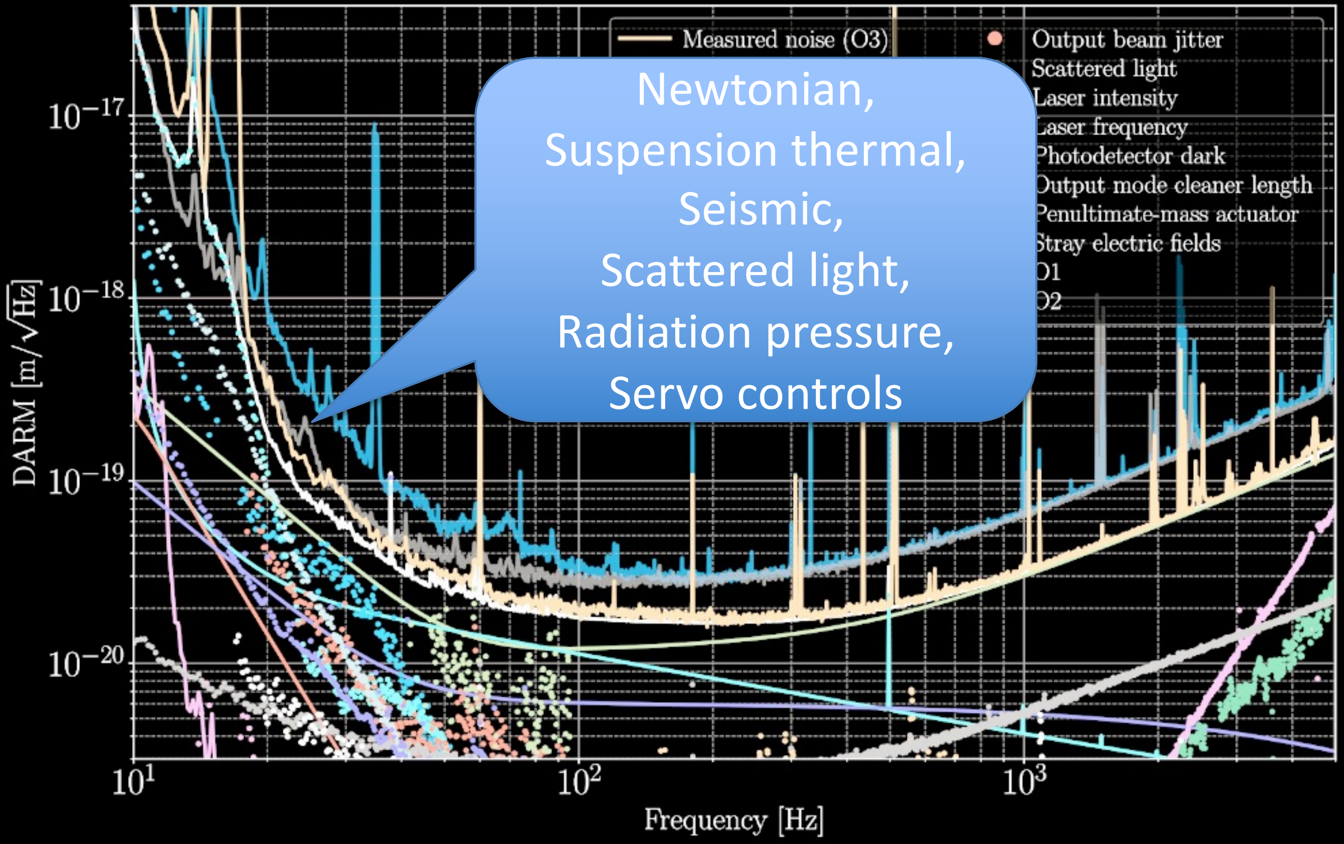
$$h_{\mathrm{rp}}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$

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

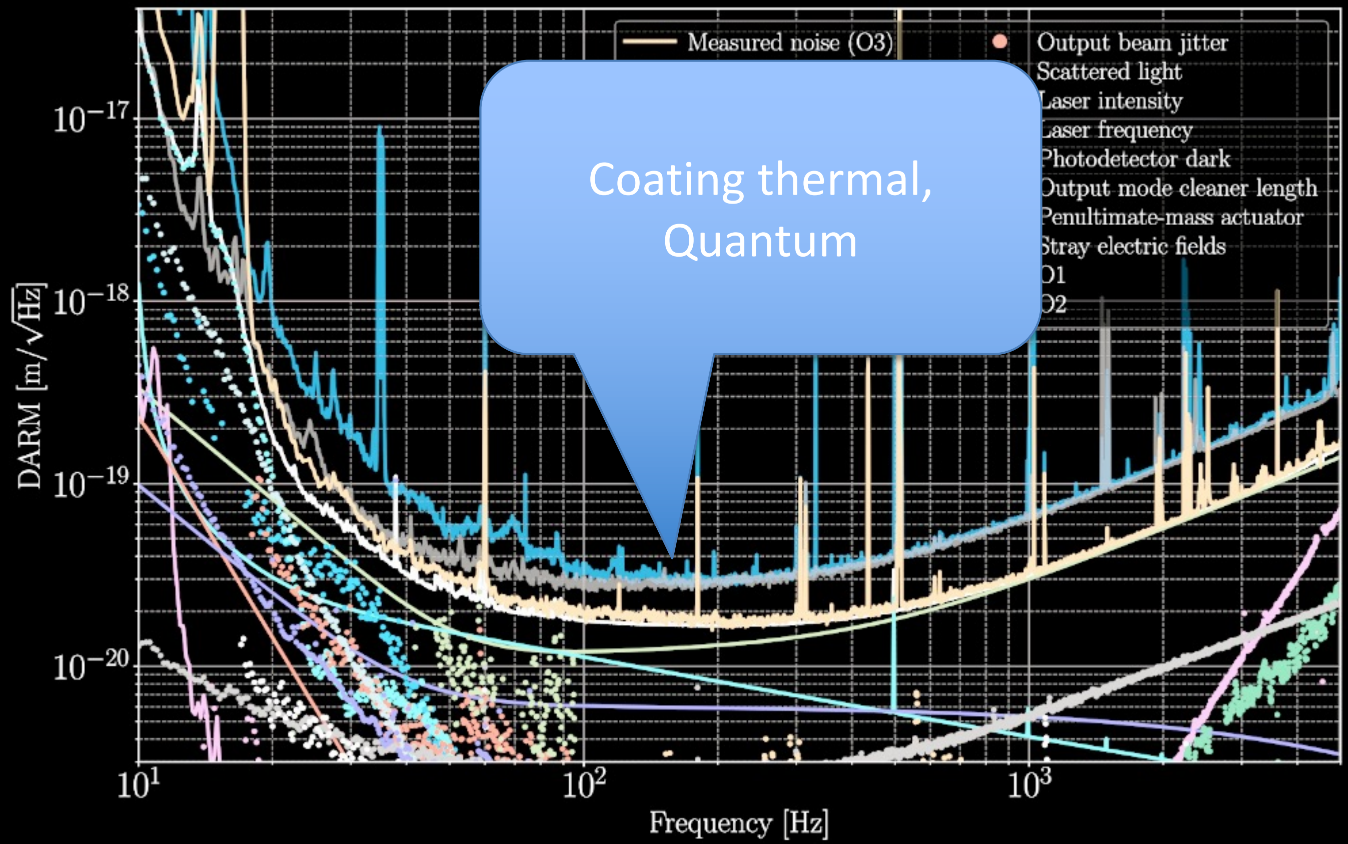
Many other technical noise sources…



Newtonian,
Suspension thermal,
Seismic,
Scattered light,
Radiation pressure,
Servo controls

Sensitivity and performance of the Advanced LIGO detectors in the third observing run
A. Buikema *et al.* Phys. Rev. D 102, 062003

Many other technical noise sources…

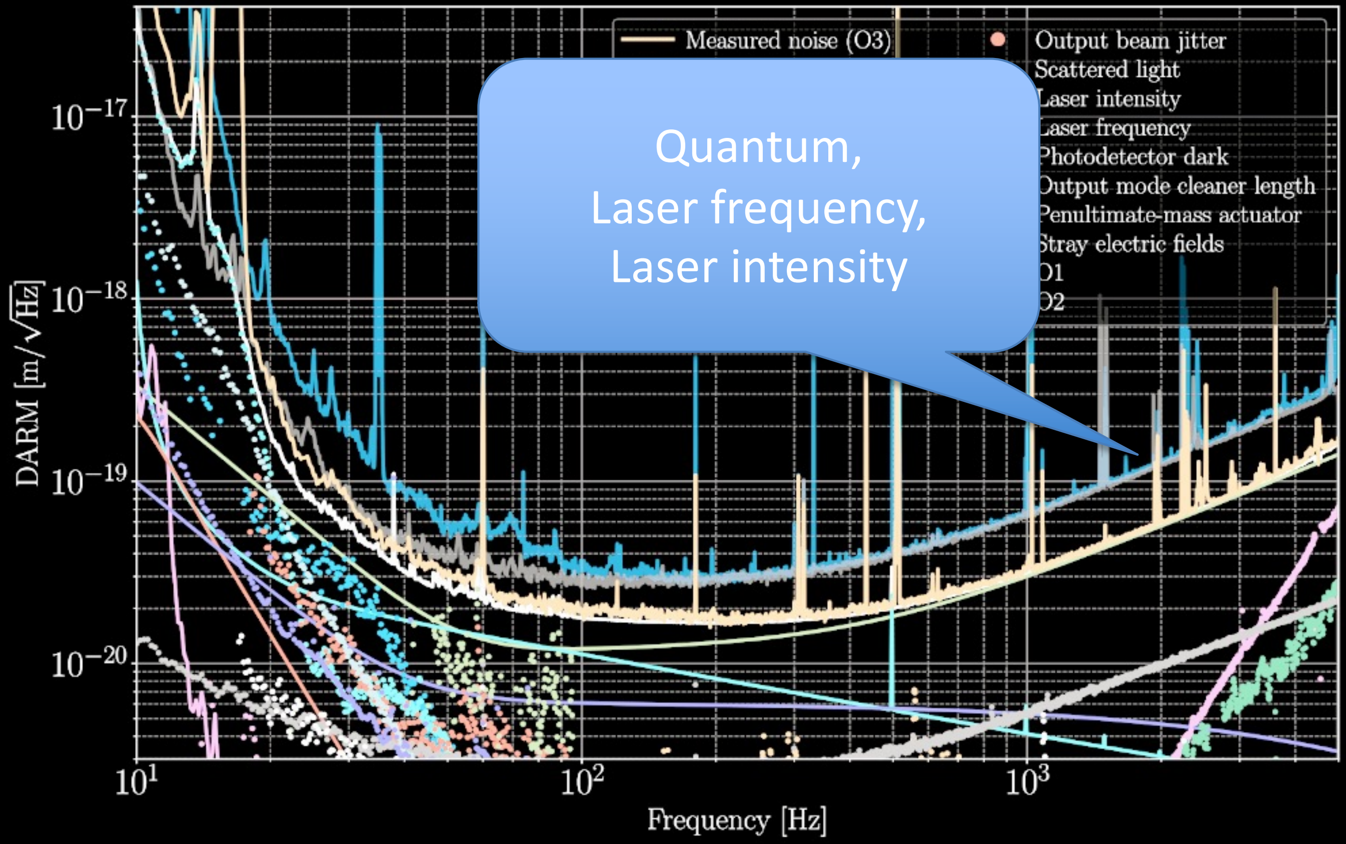


Coating thermal, Quantum

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

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

Many other technical noise sources…

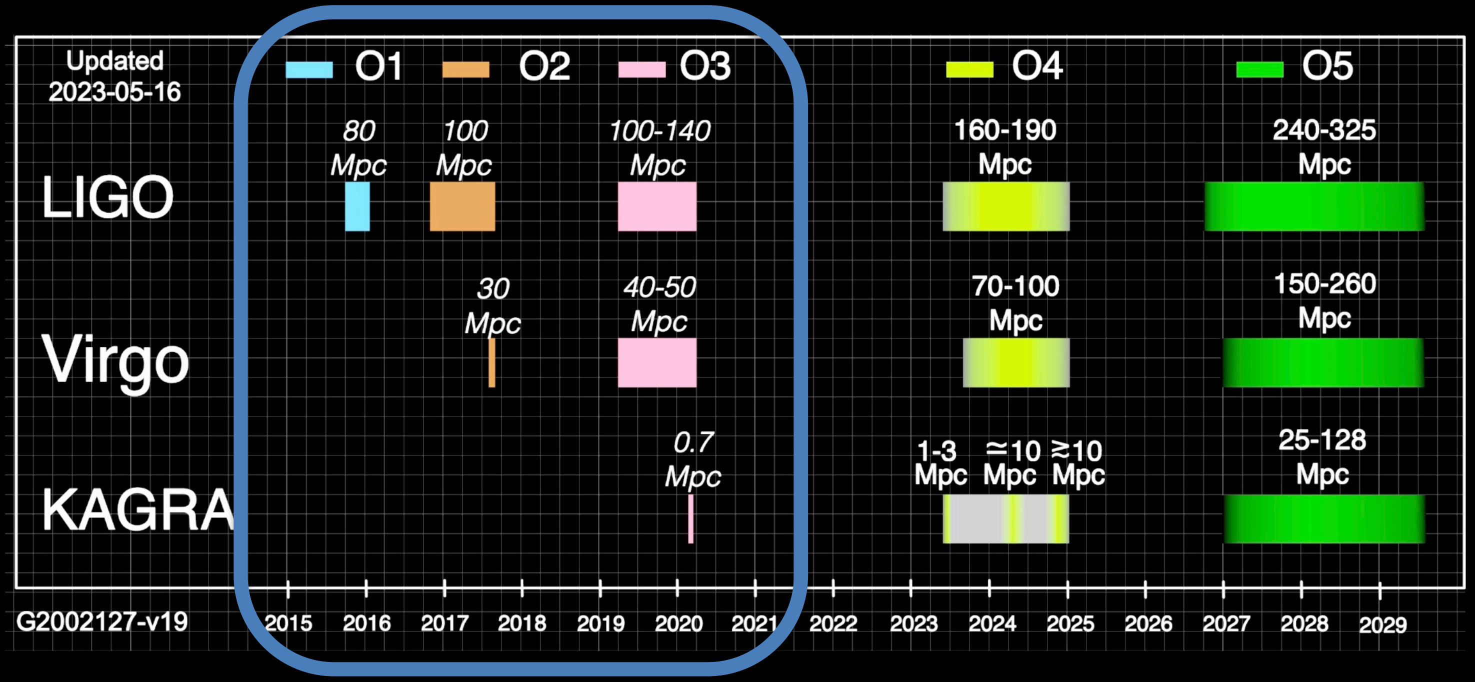


Quantum,
Laser frequency,
Laser intensity

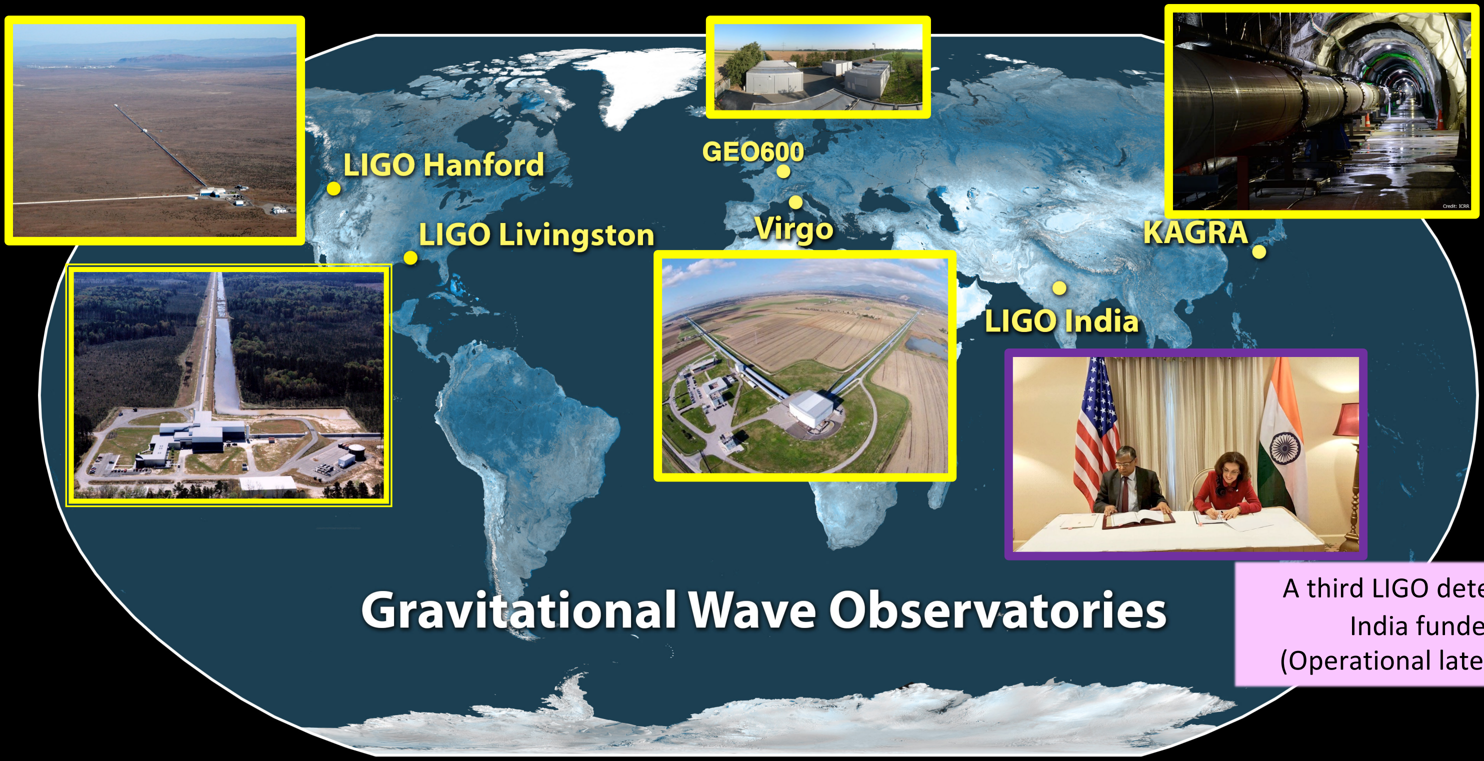
Sensitivity and performance of the Advanced LIGO detectors in the third observing run
A. Buikema *et al.* Phys. Rev. D 102, 062003

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



A third LIGO detector in India funded (Operational late 2020s)

Gravitational Wave Physics & Astrophysics

Observations

OBSERVING RUN
O1
2015 - 2016

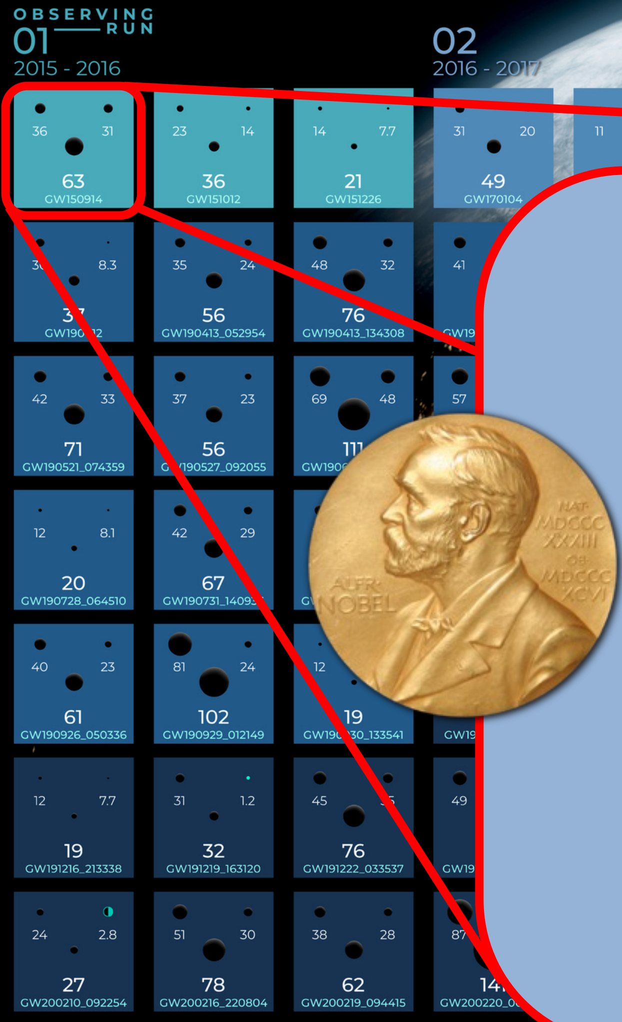
O2
2016 - 2017

O3a+b
2019 - 2020

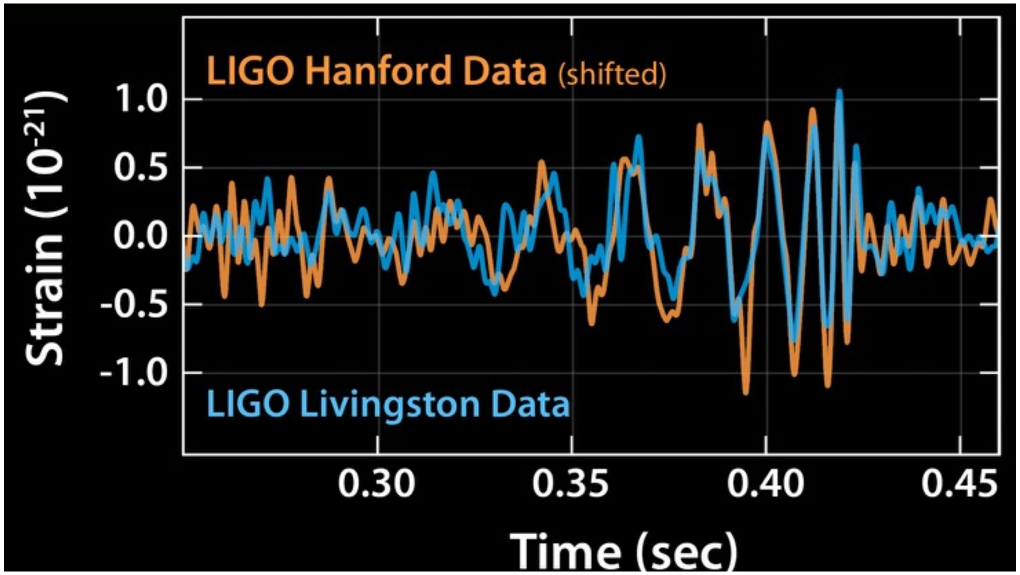
36 31 63 GW150914	23 14 36 GW151012	14 7.7 21 GW151226	31 20 49 GW170104	11 7.6 18 GW170608	50 34 80 GW170729	35 24 56 GW170809	31 25 53 GW170814	1.5 1.3 ≤ 2.8 GW170817	35 27 60 GW170818	40 29 65 GW170823	88 22 105 GW190403_051519	25 18 41 GW190408_181802
30 8.3 37 GW190412	35 24 56 GW190413_052954	48 32 76 GW190413_134308	41 32 70 GW190421_213856	2 1.4 3.2 GW190425	107 77 175 GW190426_190642	43 28 69 GW190503_185404	23 13 35 GW190512_180714	36 18 52 GW190513_205428	39 28 65 GW190514_065416	37 25 59 GW190517_055101	66 41 101 GW190519_153544	95 69 156 GW190521
42 33 71 GW190521_074359	37 23 56 GW190527_092055	69 48 111 GW190602_175927	57 36 87 GW190620_030421	35 24 56 GW190630_185205	54 41 90 GW190701_203306	67 38 99 GW190706_222641	12 8.4 19 GW190707_093326	18 13 30 GW190708_232457	37 21 55 GW190719_215514	13 7.8 20 GW190720_000836	12 6.4 17 GW190725_174728	38 29 64 GW190727_060333
12 8.1 20 GW190728_064510	42 29 67 GW190731_140936	37 27 62 GW190803_022701	48 32 76 GW190805_211137	23 2.6 26 GW190814	32 26 55 GW190828_063405	24 10 33 GW190828_065509	44 36 76 GW190910_112807	35 24 57 GW190915_235702	44 24 66 GW190916_200658	9.3 2.1 11 GW190917_114630	8.9 5 13 GW190924_021846	21 16 35 GW190925_232845
40 23 61 GW190926_050336	81 24 102 GW190929_012149	12 7.8 19 GW190930_133541	12 7.9 19 GW191103_012549	11 7.7 18 GW191105_143521	65 47 107 GW191109_010717	29 5.9 34 GW191113_071753	12 8.3 20 GW191126_115259	53 24 76 GW191127_050227	11 6.7 17 GW191129_134029	27 19 45 GW191204_110529	12 8.2 19 GW191204_171526	25 18 41 GW191215_223052
12 7.7 19 GW191216_213338	31 1.2 32 GW191219_163120	45 35 76 GW191222_033537	49 37 82 GW191230_180458	9 1.9 11 GW200105_162426	36 28 61 GW200112_155838	5.9 1.4 7.2 GW200115_042309	42 33 71 GW200128_022011	34 29 60 GW200129_065458	10 7.3 17 GW200202_154313	38 27 63 GW200208_130117	51 12 61 GW200208_222617	36 27 60 GW200209_085452
24 2.8 27 GW200210_092254	51 30 78 GW200216_220804	38 28 62 GW200219_094415	87 61 141 GW200220_061928	39 28 64 GW200220_124850	40 33 69 GW200224_222234	19 14 32 GW200225_060421	38 20 56 GW200302_015811	28 15 42 GW200306_093714	36 14 47 GW200308_173609	34 28 59 GW200311_115853	13 7.8 20 GW200316_215756	34 14 53 GW200322_091133

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

Slide: S. Fairhurst



GW150914: First Detection

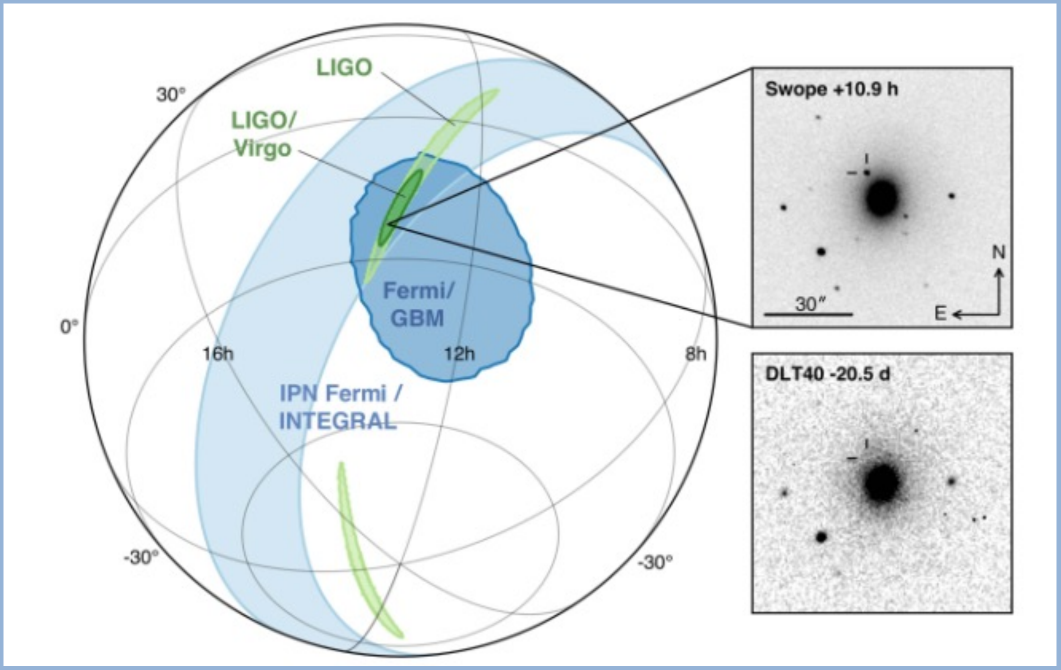


Abbott et al, "**Observation of Gravitational Waves from a Binary Black Hole Merger**", 2016

Image : Carl Knox (OzGrav, Swinburne Univers

Fairhurst

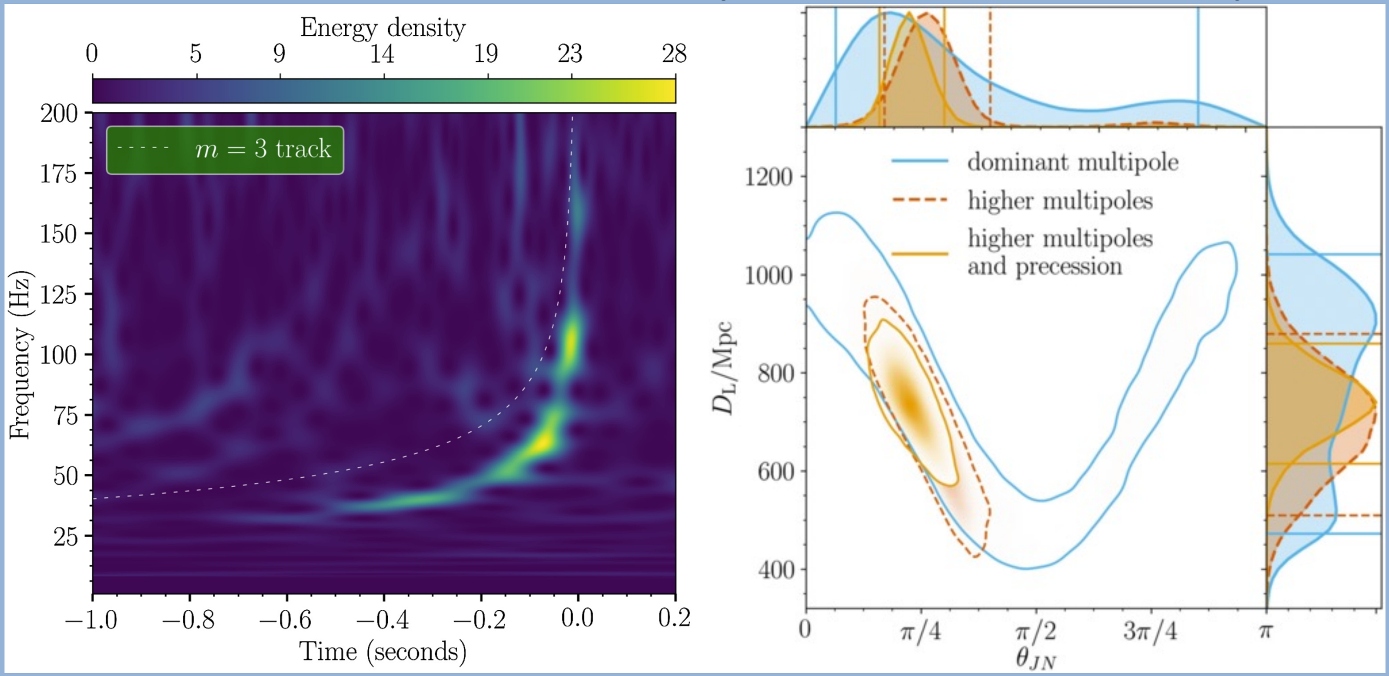
GW170817: Neutron Stars and Multi-messenger Observation



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

Slide: S. Fairhurst

GW190412: Unequal mass binary



One of the black holes ~4 times heavier than the other

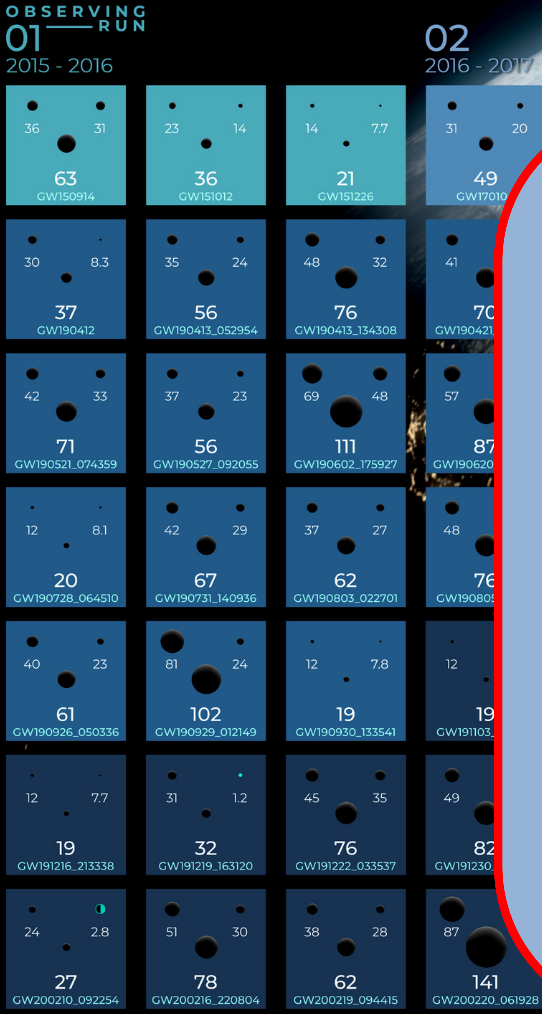
Slide: S. Fairhurst

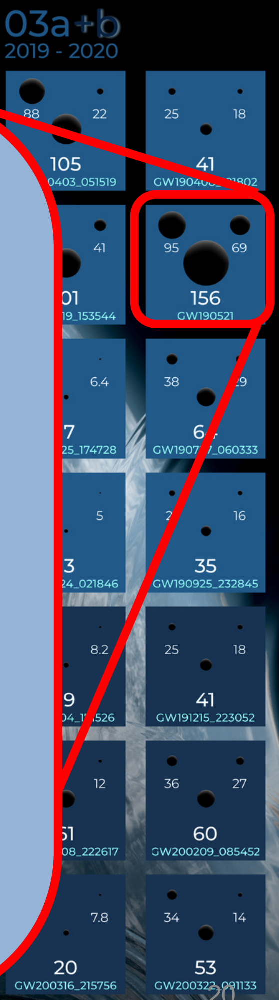
GW200105 and GW200115: Observation of Neutron Star Black Hole Mergers

First unambiguous observation of NS-BH system

Slide: S. Fairhurst

Observations





GW190521: A Black Hole in the Pair Instability Mass Gap

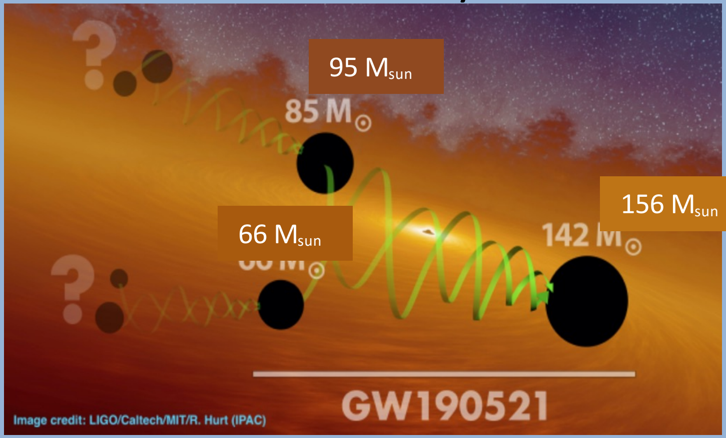


Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

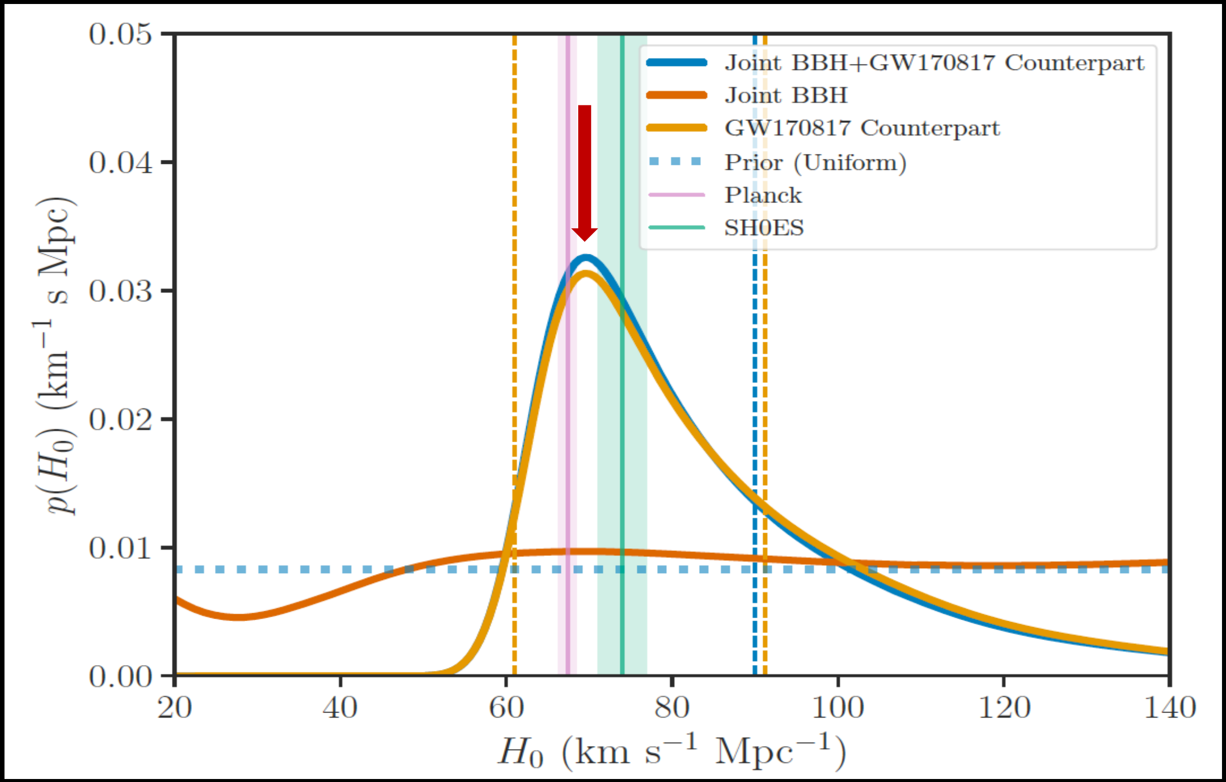
Evidence for a hierarchical merger?
Or perhaps dynamical capture?

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

Slide: S. Fairhurst

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

$$v_{Hubble}\,(\approx cz) = H_0 L_D(+v_p)$$



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.

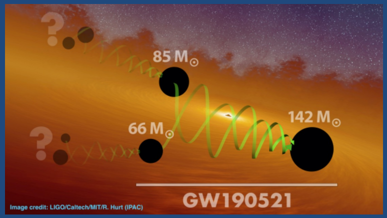
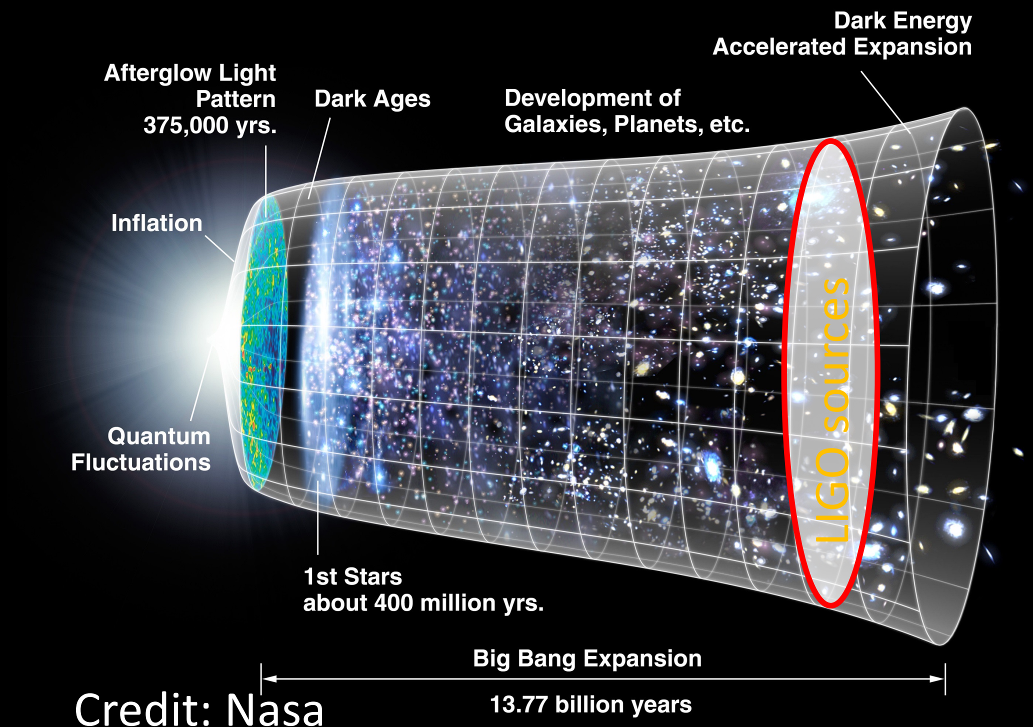
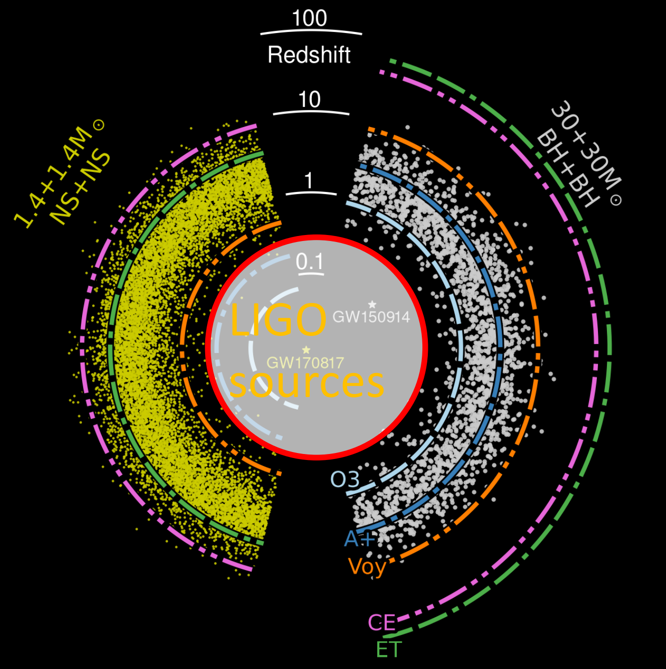


Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

Current Ground-based GW Detector 'Reach'



Credit: Nasa



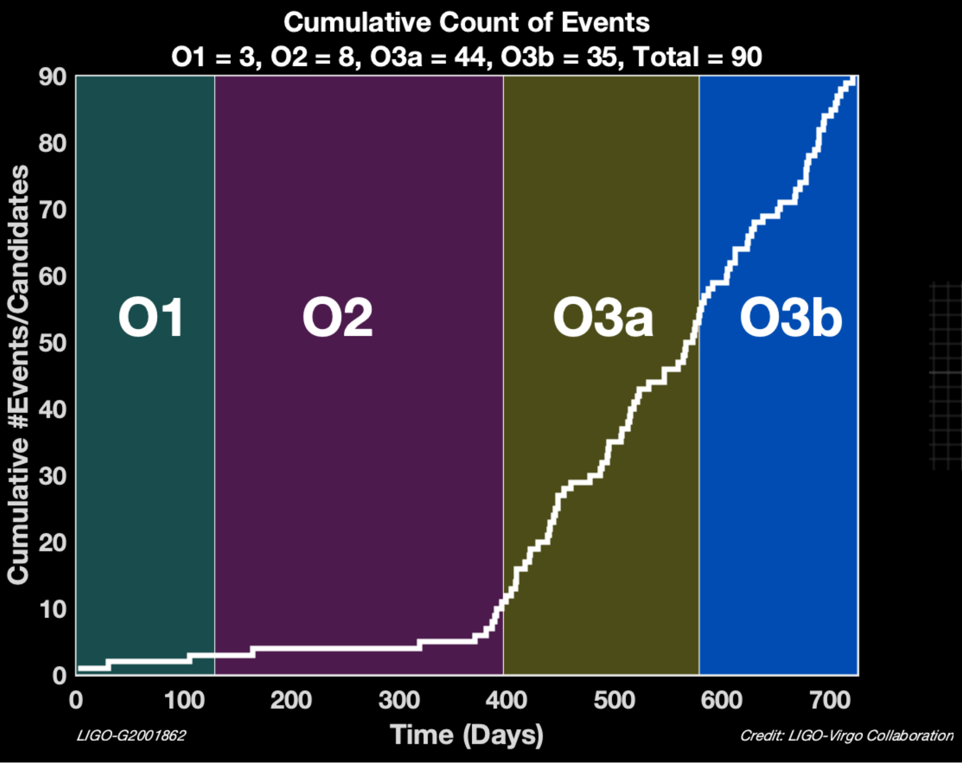
Cosmic Explorer Horizon Study

Slide: S. Ballmer

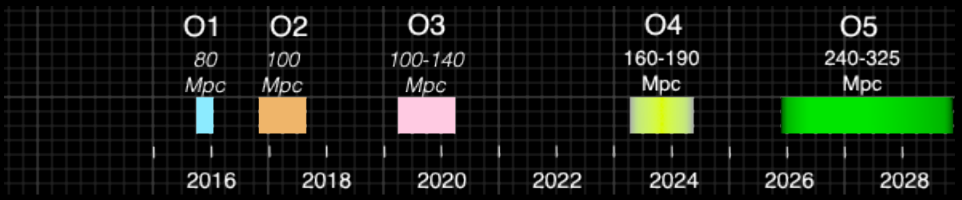
Sensitivity improvements boost signal rate

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

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



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



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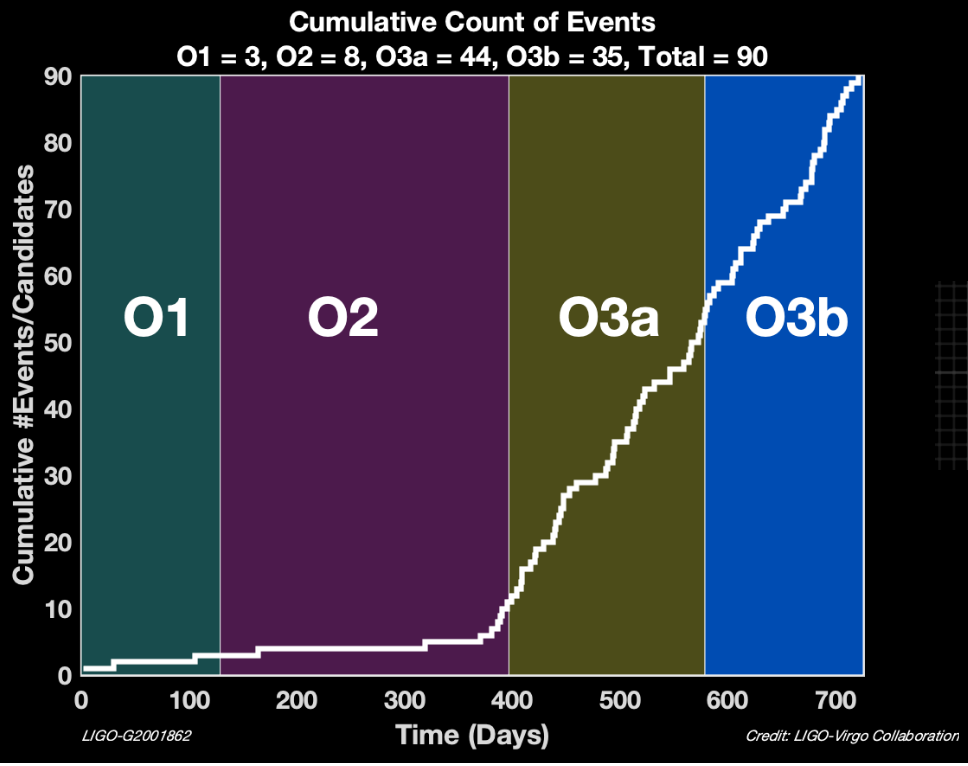
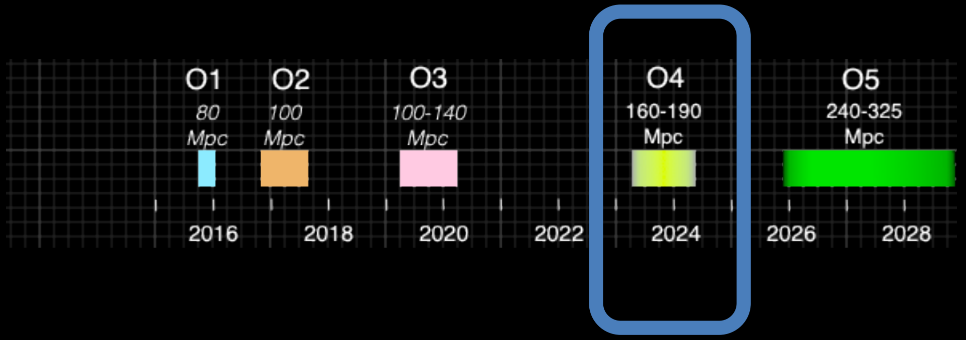

Cumulative Count of Events
O1 = 3, O2 = 8, O3a = 44, O3b = 35, Total = 90

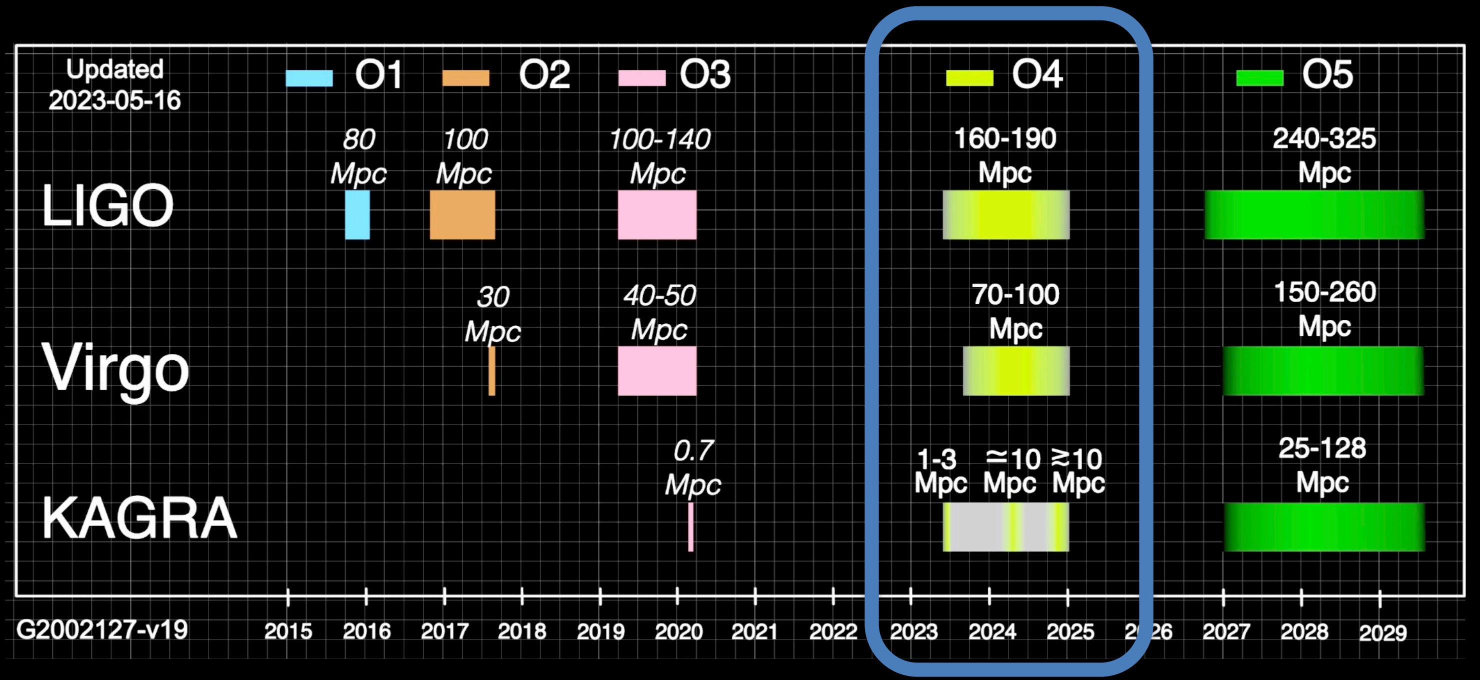
Credit: LIGO-Virgo Collaboration

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



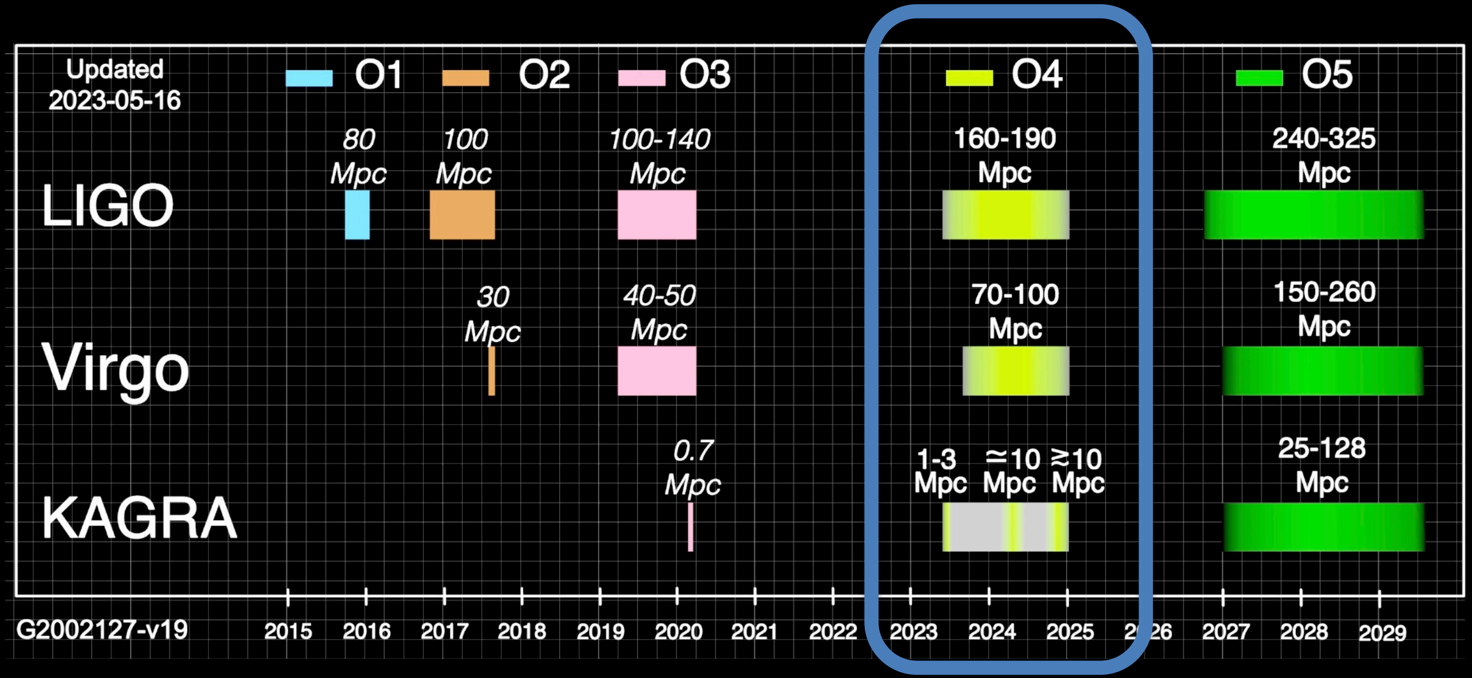
O4 started 24 May 2023

- 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



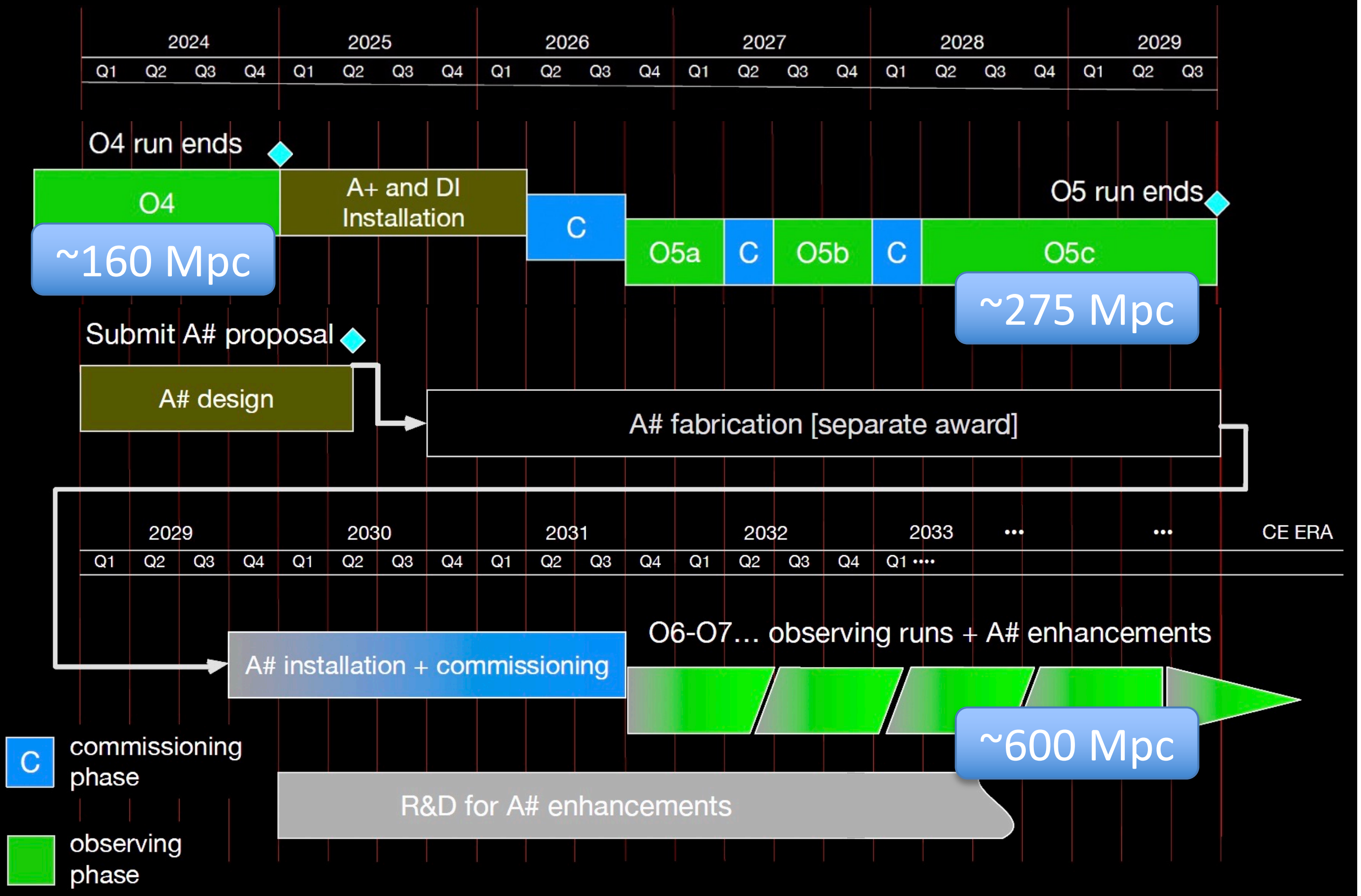
O4 started 24 May 2023

- 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 – 2x improvements

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



2024 2025 2026 2027 2028 2029

Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3

O4 run ends

O4

~160 Mpc

A+ and DI Installation

C

O5a

C

O5b

C

O5c

O5 run ends

~275 Mpc

Submit A# proposal

A# design

A# fabrication [separate award]

2029 2030 2031 2032 2033 ••• ••• CE ERA

Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 ••••

A# installation + commissioning

O6-O7… observing runs + A# enhancements

~600 Mpc

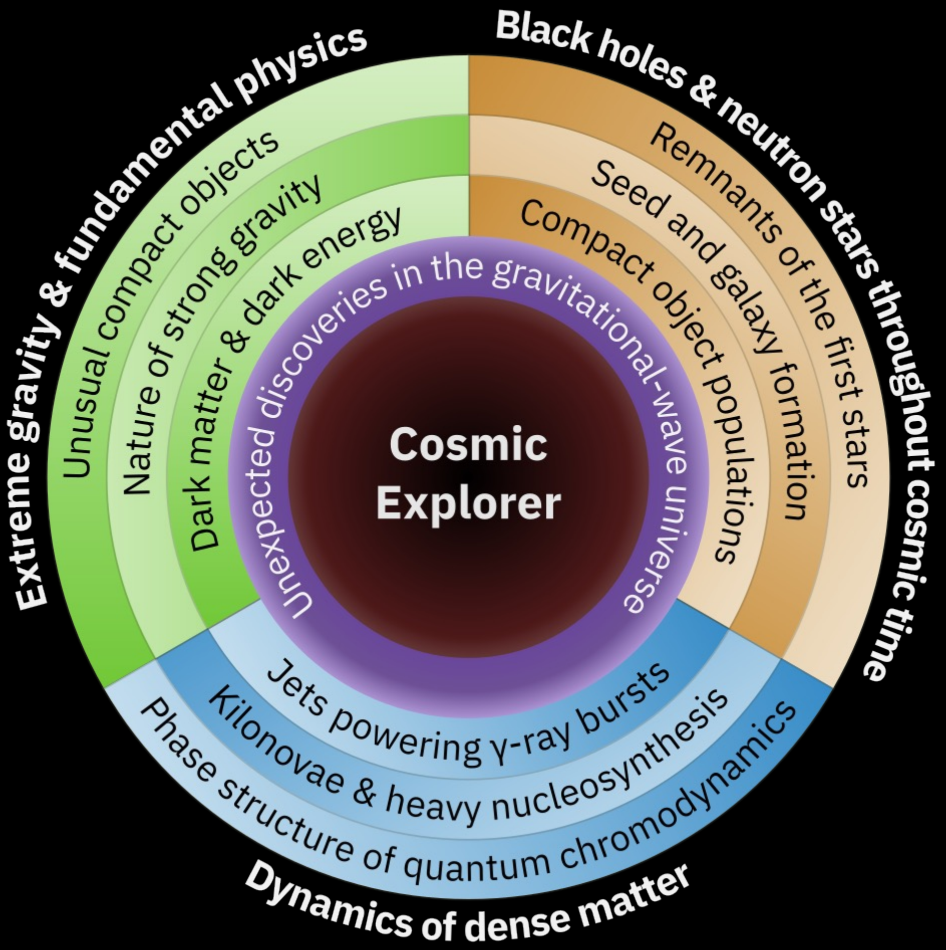
R&D for A# enhancements

C commissioning phase

🟩 observing phase

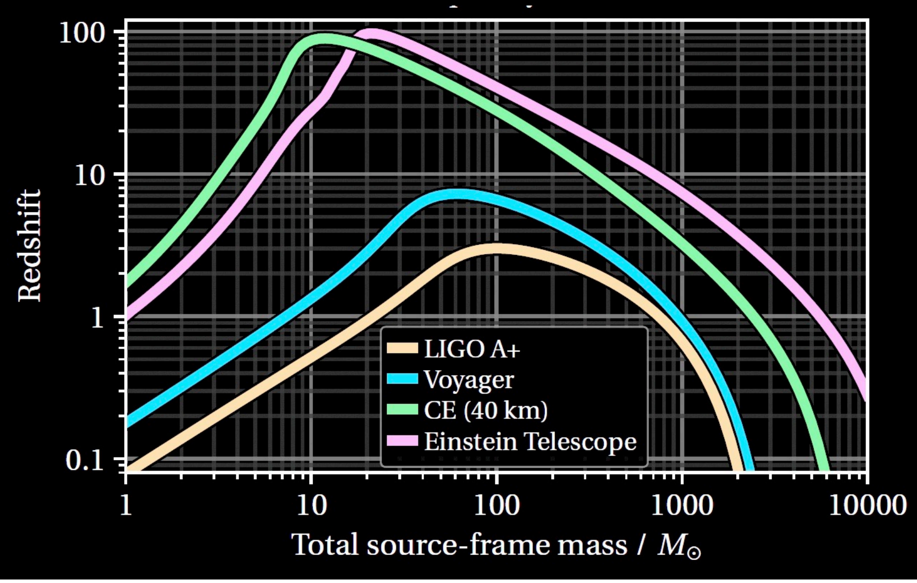
What could we do with ***10x*** better GW detectors?

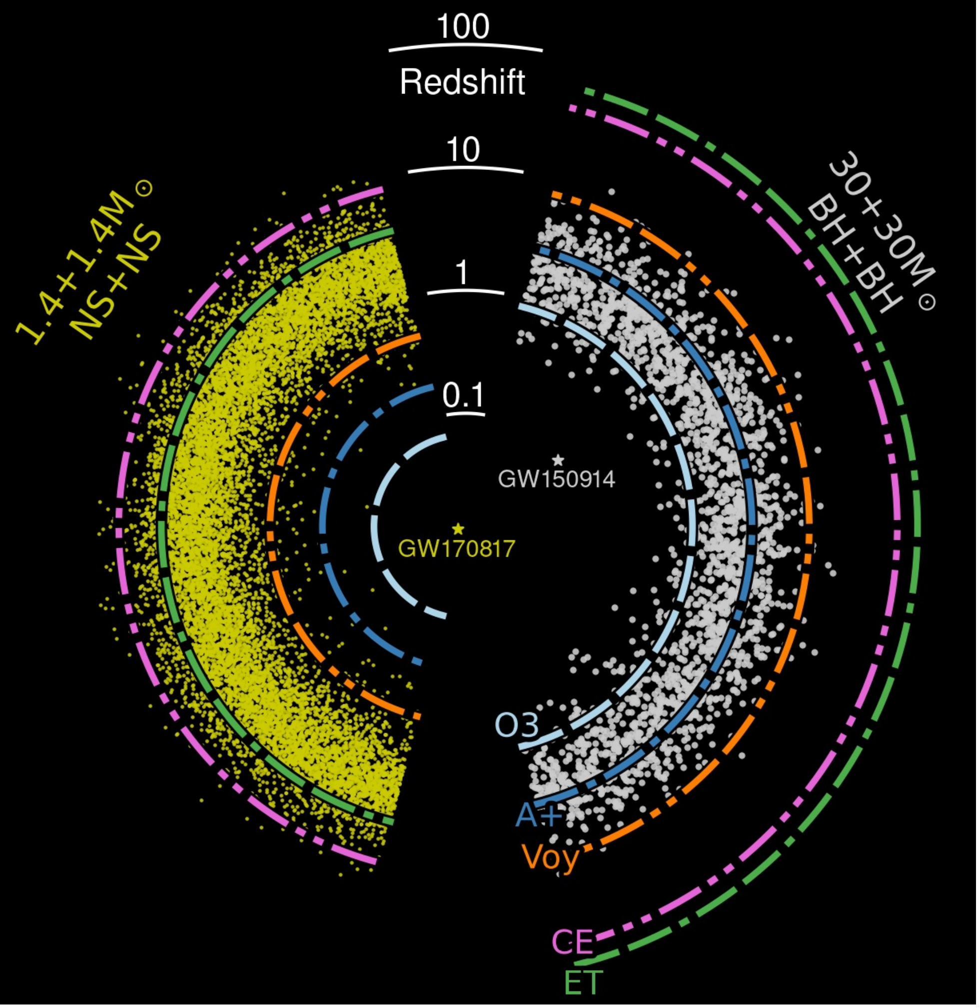
- Greater sensitivity will enable a qualitative growth in the number of observed sources
  (10x sensitivity →
  few 10^5 sources per year)
- It also increases the resolution of waveforms, enabling more stringent tests of GR and more detailed models of the coalescences
- Wider bandwidth can expose Neutron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

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

$\Delta L = h\,L$

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 λ_{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

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

Radiation Pressure Noise
while maintaining bandwidth

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

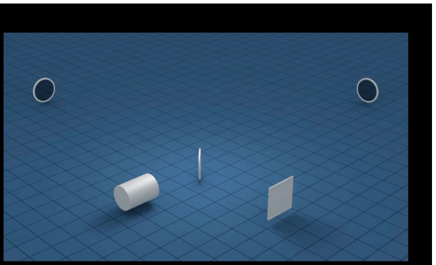
Coating Thermal Noise
loss angle dependence

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

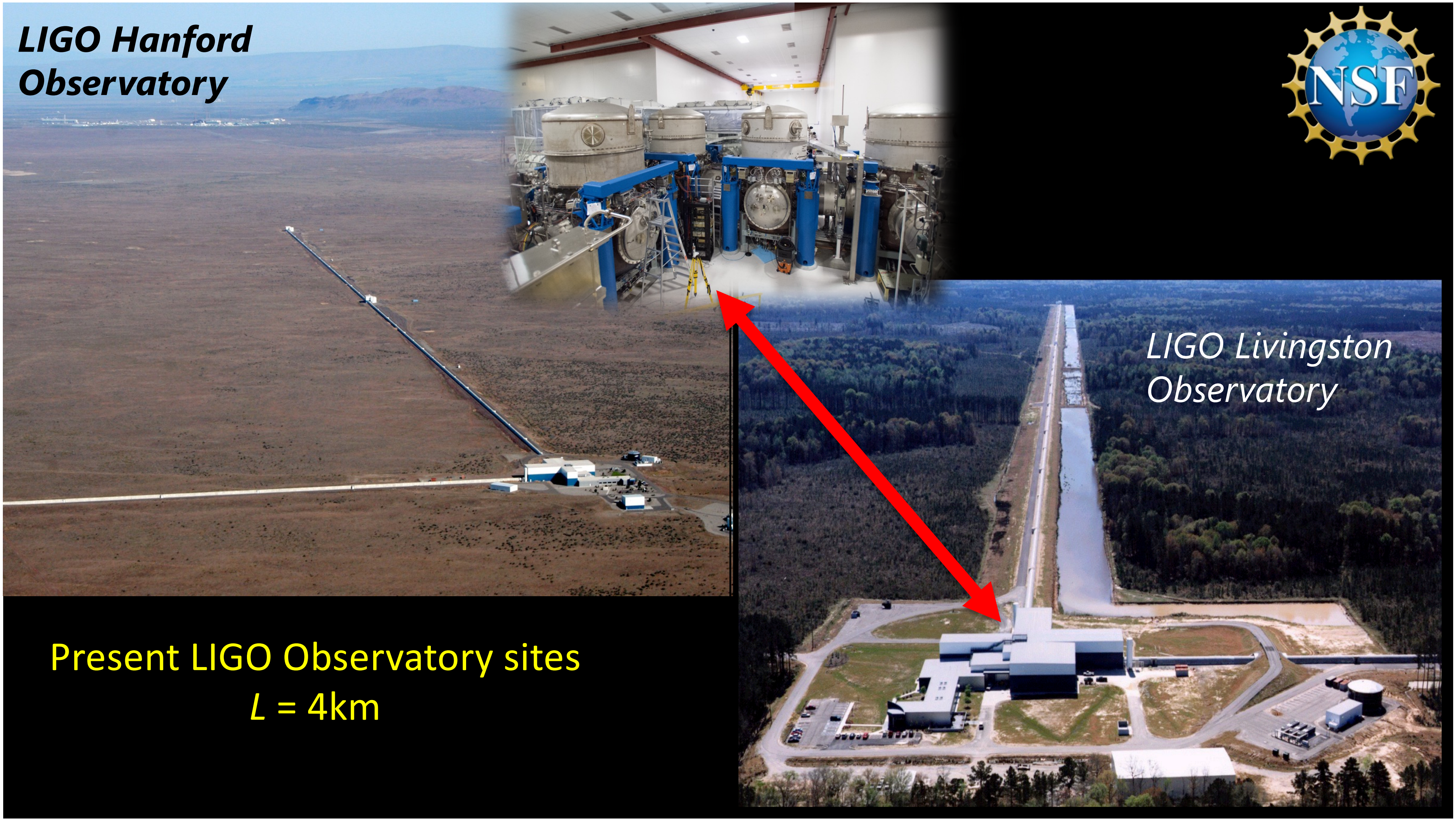
Residual Gas Noise
facility limit

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

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 → 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 (~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 (~10,000 m^2)



Present LIGO Observatory sites
L = 4km

COSMIC EXPLORER

Astro 2020
Decadal Survey on Astronomy and Astrophysics

The National Academies of SCIENCES ENGINEERING MEDICINE

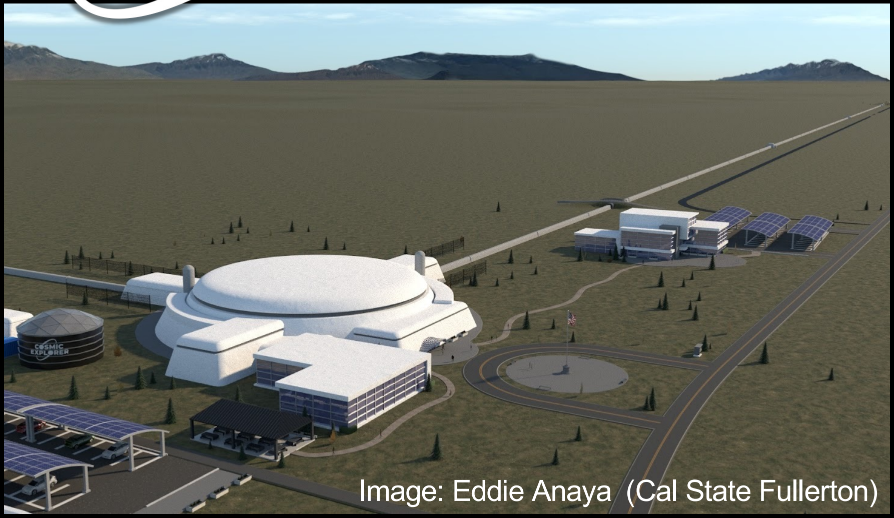
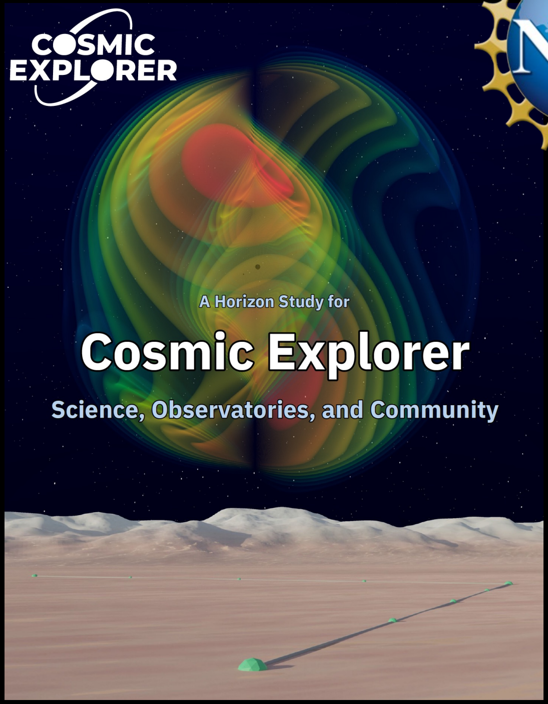


Image: Eddie Anaya (Cal State Fullerton)



COSMIC EXPLORER

A Horizon Study for

Cosmic Explorer

Science, Observatories, and Community

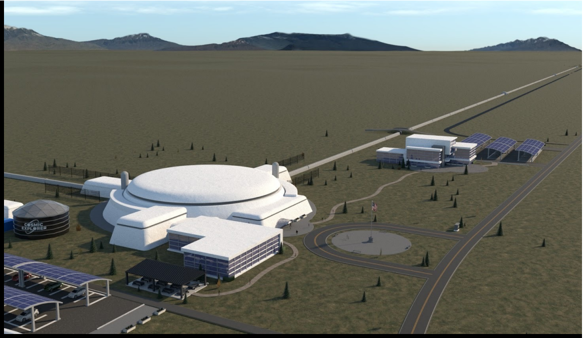
- US contribution to the next-gen Network (with Einstein Telescope – European project)
- LIGO-like concept for a single interferometer per site, on Earth’s surface
- CE is a larger, and more technically advanced version of LIGO:
  baseline of two widely separated observatories, **40km and 20km arms**

cosmicexplorer.org

CE Detector Design

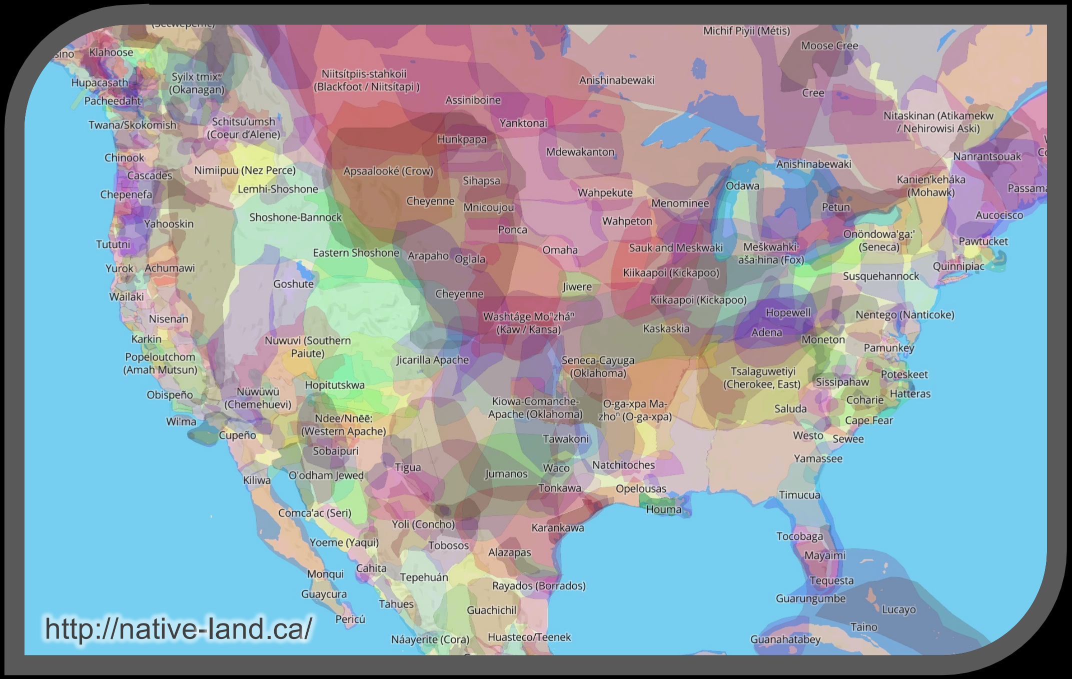
- LIGO is starting to plan upgrades to the LIGO 4km detectors for the 'Post-O5' epoch – ~2029 to the start of CE observing (*optimistically* 2035)
  - Room temperature, 1 micron light, fused silica optics, sputtered optical coatings, frequency dependent squeezed light..
- **Initial CE detectors will usetechniques 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 λ_{GW} is ideal for observing ~2kHz endgame of neutron-star mergers
  - 40km is optimized for absolute 'reach' to enable all in-scope binaries to be observed
- Sites separated by a continental baseline 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
  - Bad: increased coupling to surface 'seismic' noise, and thus Newtonian background – limits low-frequency sensitivity (~7Hz compared to ~5 Hz for ET)
  - Good: less expensive than tunneling; no complexity of underground work; future modifications of interferometer layout easier (no new caverns)
- *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.



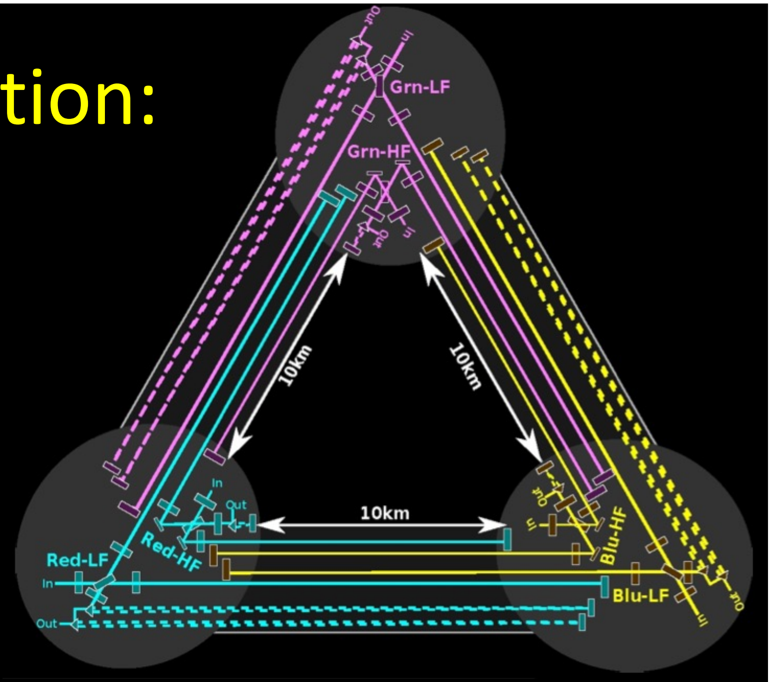
If you are not aware of issues surrounding TMT, please read arXiv:2001.00970 .

CE Status

- Conceptual Design is now underway
- CE Funding approved for this phase
    - International contributions (in-kind) – UK, Canada, Australia, Germany

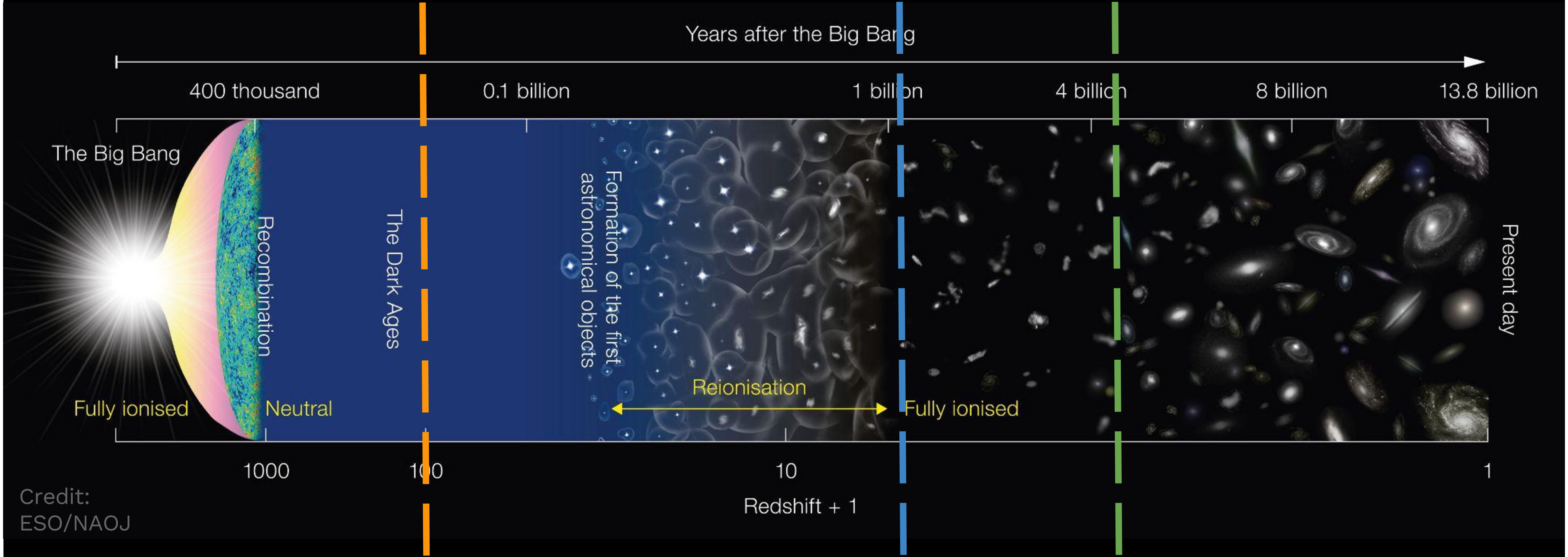
- **Goal: observatories by mid-2030’s**

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



Credit: ESO/NAOJ

Cosmic Explorer
and
Einstein Telescope

LIGO
~2033

LIGO
today

Slide: Kevin Kuns

The last page (at last!)

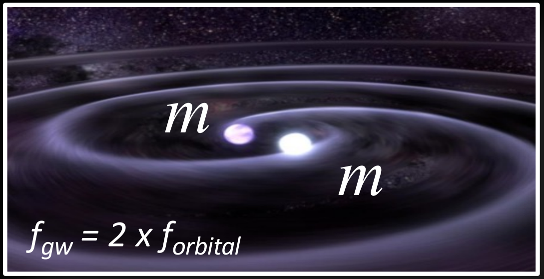
- Ground-based GW observation works, and LIGO, Virgo, and KAGRA observing together
- There are lots of sources yet to be observed
- Scaling laws show the technical feasibility of better detectors
- The US Concept, Cosmic Explorer
  - Two sites, one 40km, one 20km
  - Surface construction, LIGO Technology
- 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

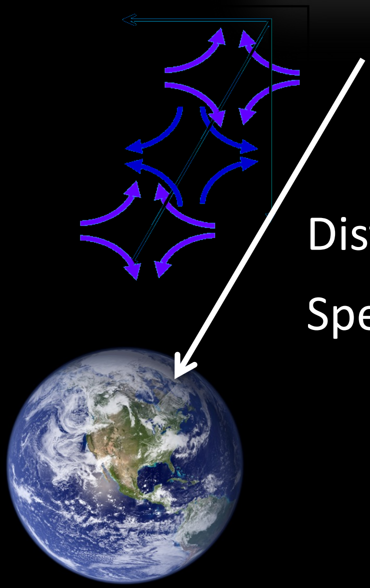
The future is bright for gravitational-wave astronomy!

Thank you!

Gravitational Wave Properties

Binary Coalescence of two compact objects





Distance r

Speed c

GW generation:
lowest order radiation is quadrupole

metric perturbation → h ; *quadrupole moment* → $\ddot{I}$

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

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

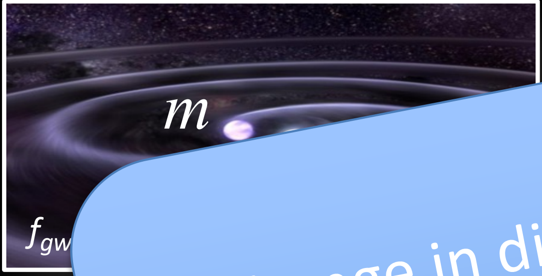
$$h = \frac{2\,G\,m}{c^4\,r}\,(2\pi\,f_{gw})^{2/3}$$

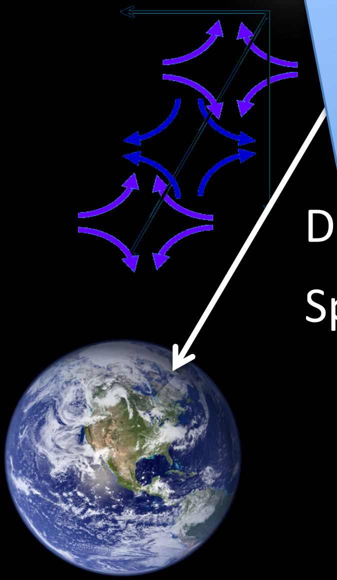
About once a week,
a wave passes with this characteristic strain:

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

Gravitational Wave Properties

Binary Coalescence of two compact objects





Di

Spe

GW

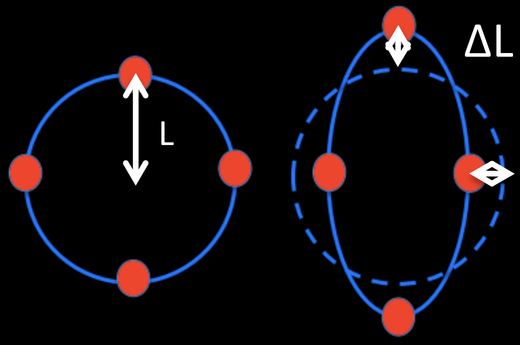
A change in distance from here to Alpha Centauri
(4 light-years distant)
of the thickness of a human hair
(10 microns)

$f_{gw})$ =

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

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

Stretching and squeezing of space-time



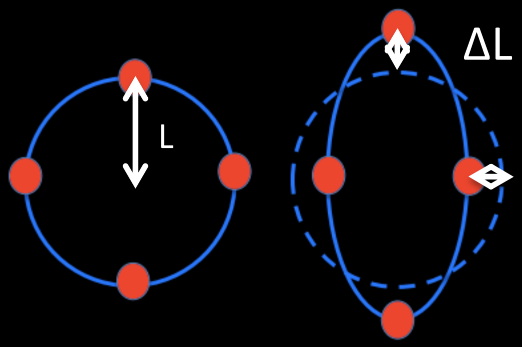
Amplitude of the gravitational wave strain is $h = \Delta L/L$

$\Delta L = h\, L$

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

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

Stretching and squeezing of space-time



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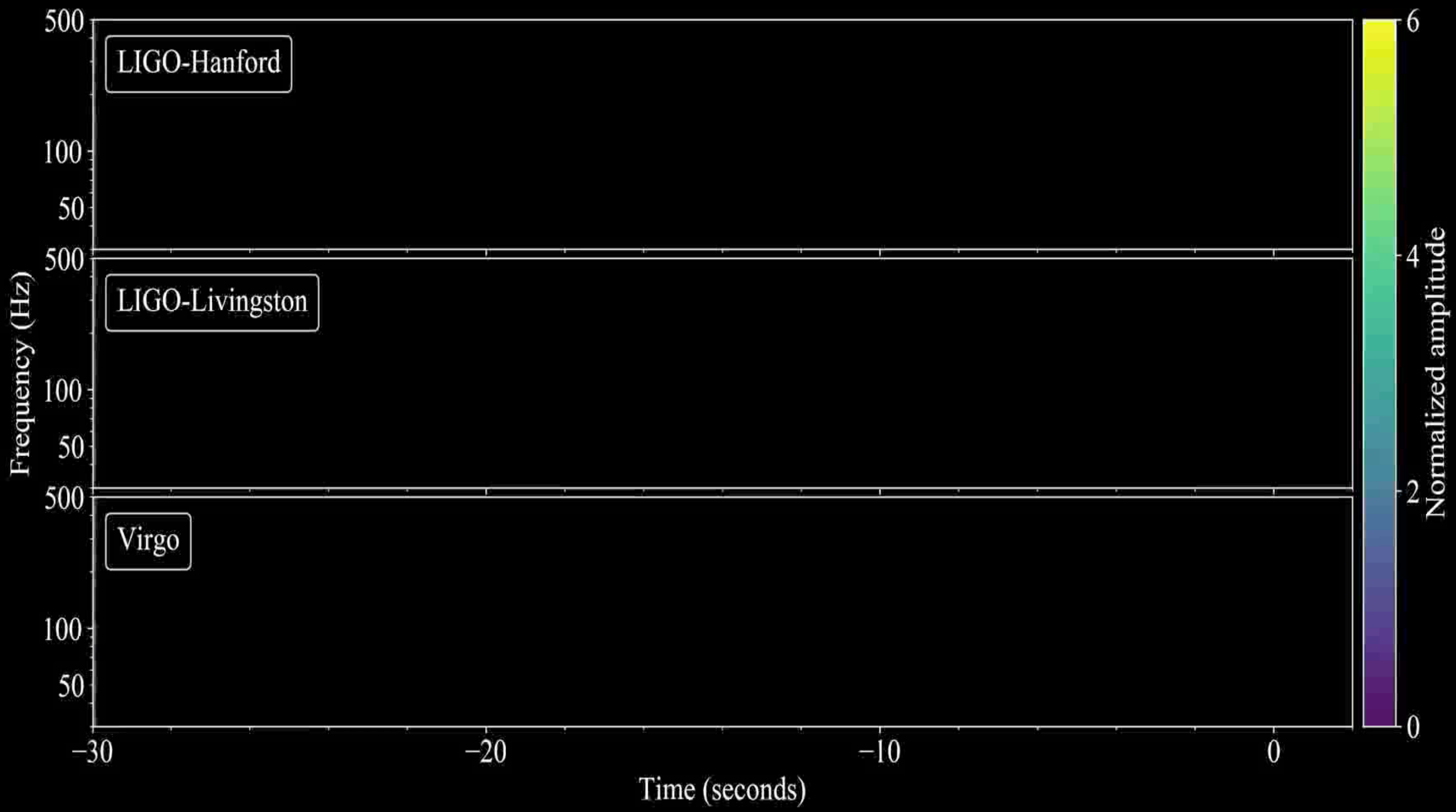
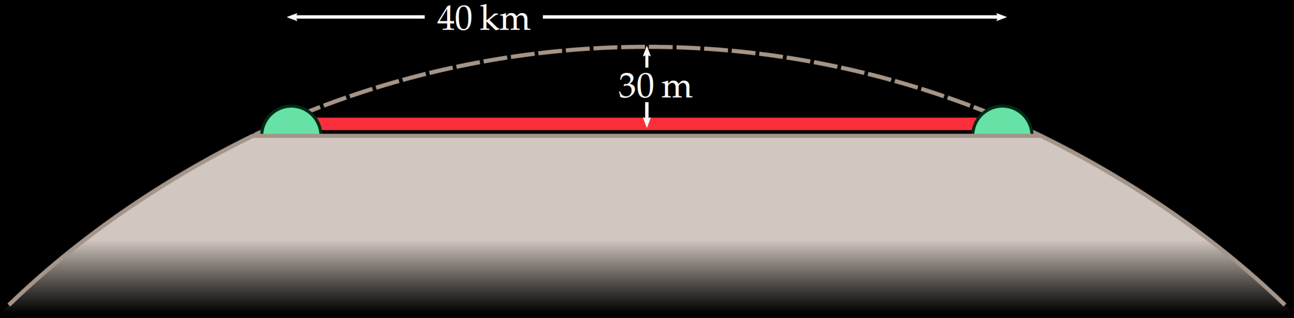
$$\sim 10^{-21} \text{ x } \sim 10^{3} = \boxed{\sim 10^{-18}\text{ m}}$$

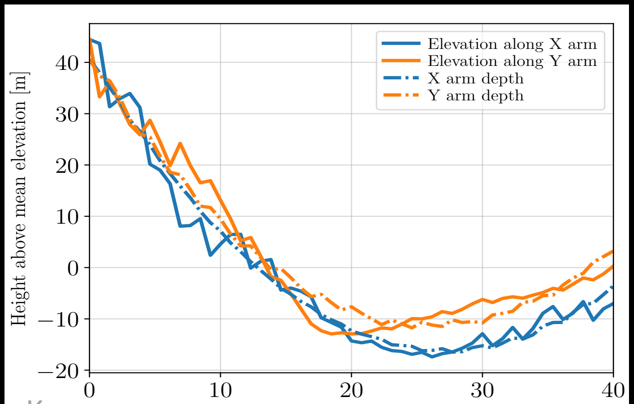
The binary neutron star signal, with and without the interferometer noise



40km CE



40 km
30 m



Elevation along X arm
Elevation along Y arm
X arm depth
Y arm depth
Height above mean elevation [m]
40
30
20
10
0
−10
−20
0
10
20
30
40
Distance from corner station [km]

Kuns

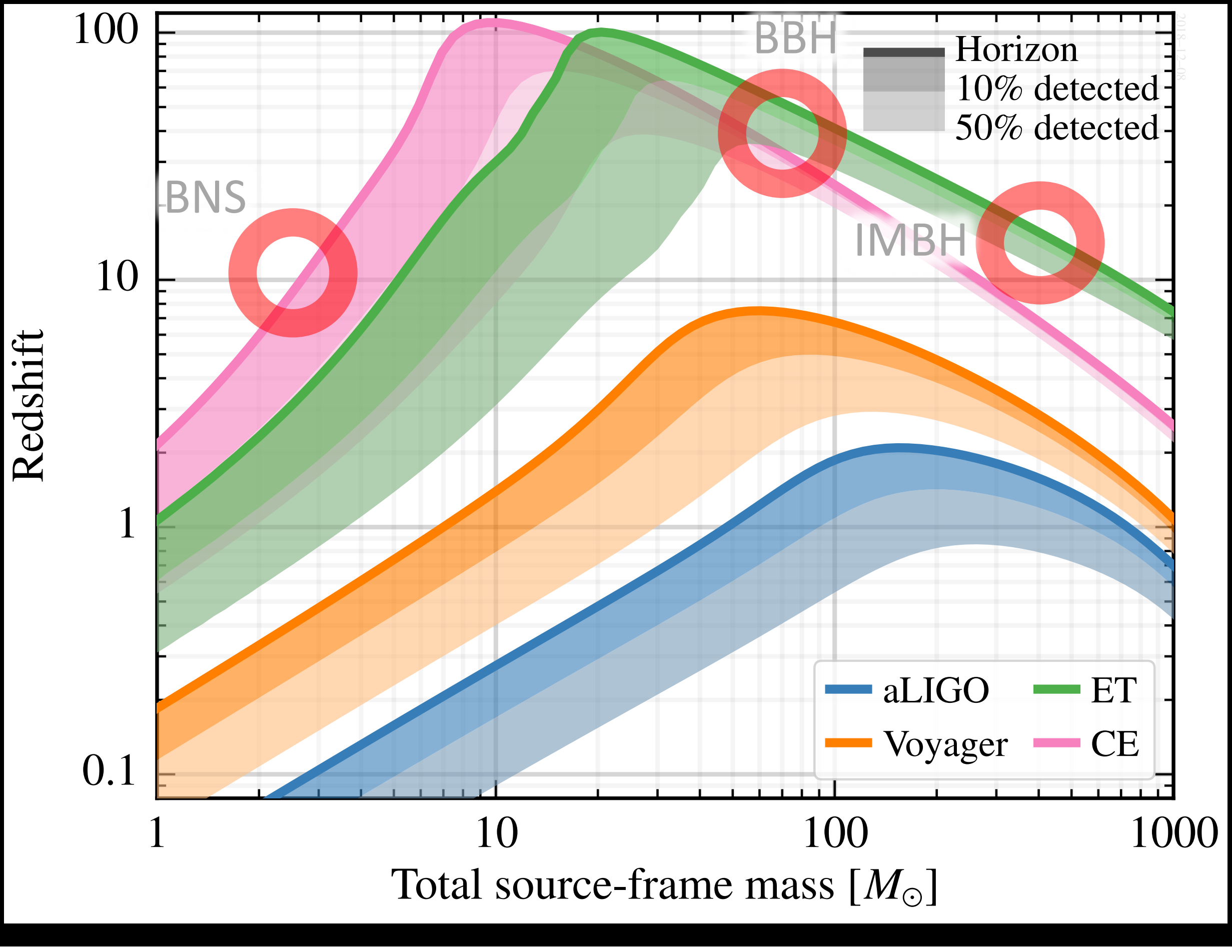
Why 40km?

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

$$\frac{c}{2L} = \frac{3\times10^{5}\,\frac{km}{s}}{2\,\times 40\;km} \simeq 4\;kHz$$

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?

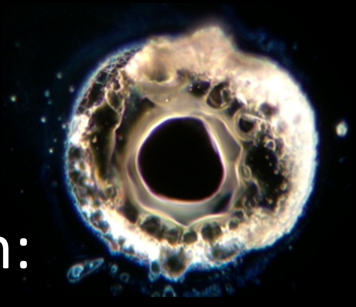


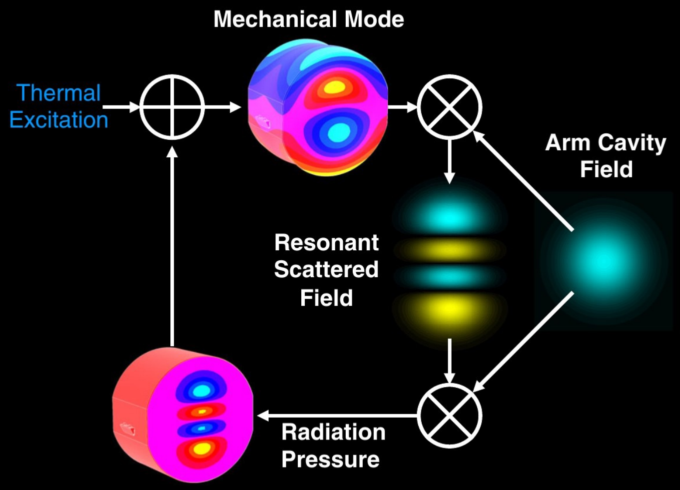
Noise improvements: reducing quantum noise

- 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)





Mechanical Mode

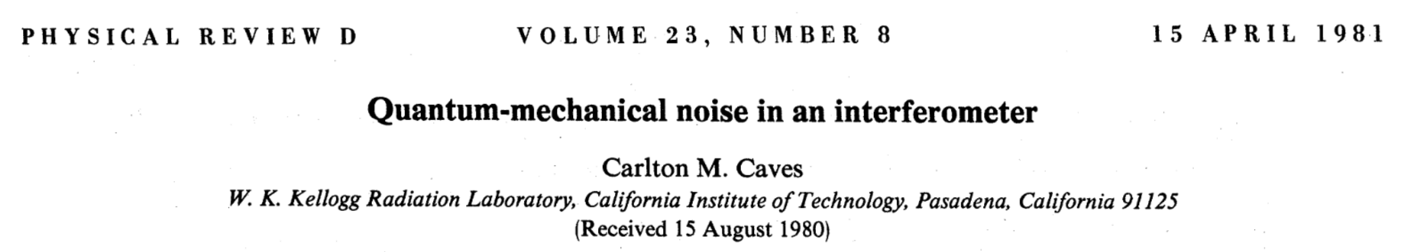
Thermal Excitation

Arm Cavity Field

Resonant Scattered Field

Radiation Pressure

- Complementary approach: squeezed states of vacuum

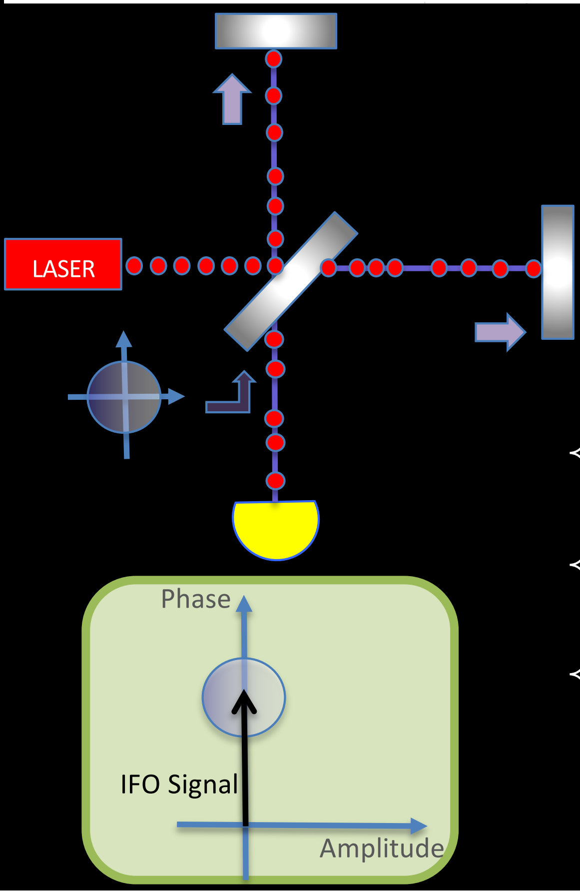


PHYSICAL REVIEW D VOLUME 23, NUMBER 8 15 APRIL 1981

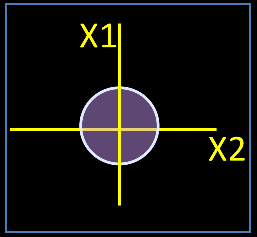
Quantum-mechanical noise in an interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

(Received 15 August 1980)



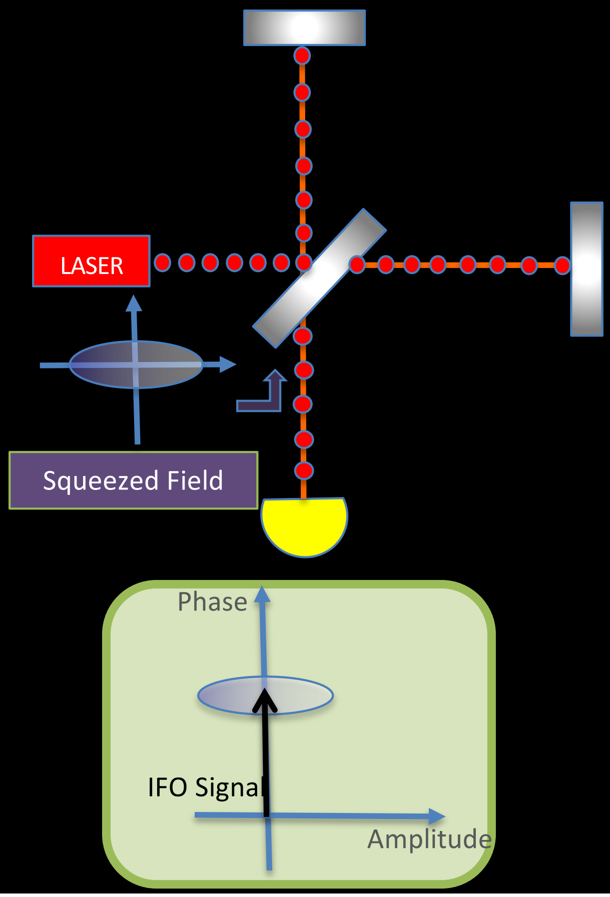
Zero-point energy
(vacuum) fluctuations



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

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

Replace regular vacuum with squeezed vacuum



✧ Reduce quantum noise by injecting squeezed vacuum: less uncertainty in one of the two quadratures

✧ Heisenberg uncertainty principle: if the noise gets smaller in one quadrature, it gets bigger in the other one

✧ One can choose the relative orientation between the squeezed vacuum and the interferometer signal (squeeze angle)

✧Squeezing is made by creating pairs of photons using an optical parametric oscillator

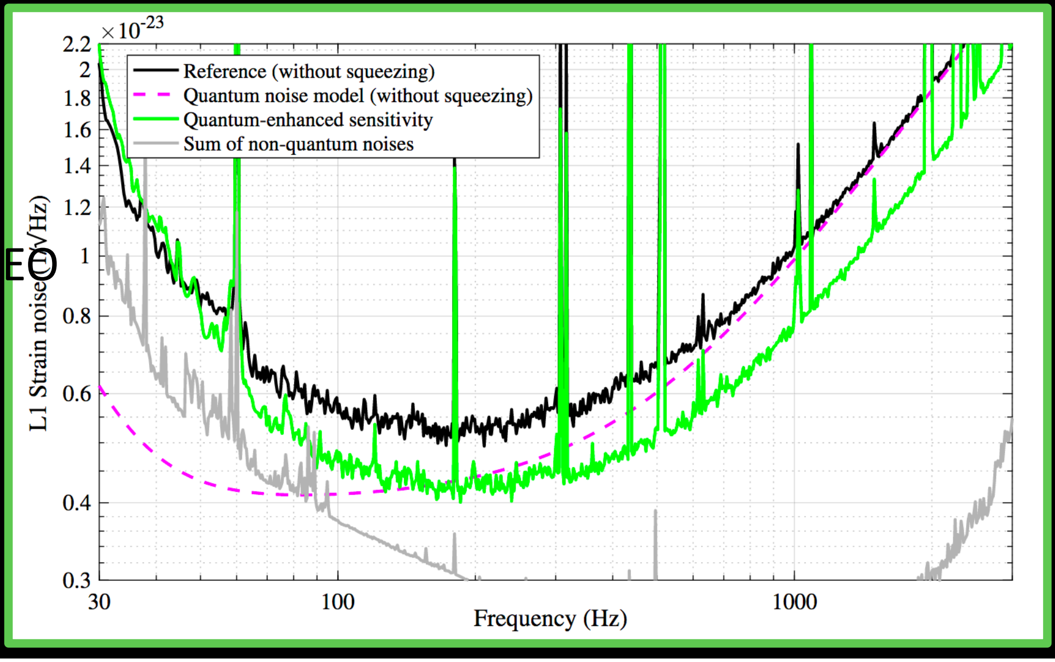
✧The pairs are quantum-mechanically entangled and have correlated arrival times at the detector

✧This reduces the randomness of the time distribution

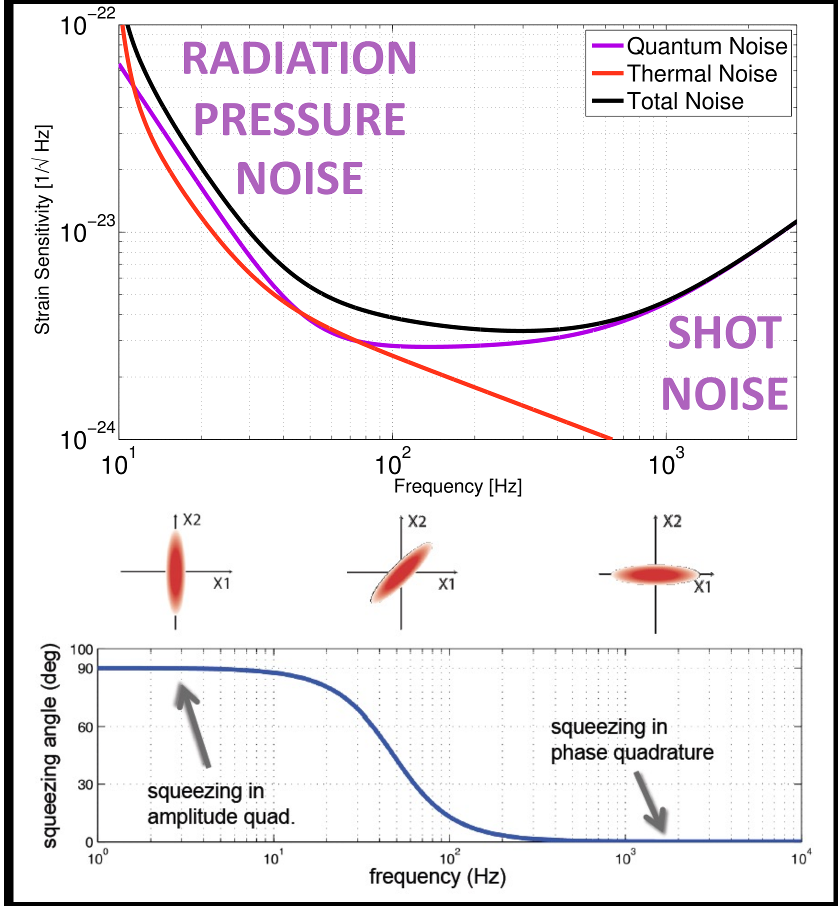
Squeezing performance in O3

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

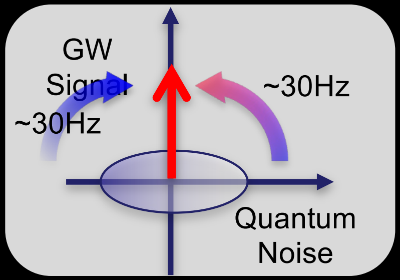
3 dB of squeezing observed at high frequency = 40% quantum noise reduction (in amplitude); observation of quantum radiation pressure noise in both detectors

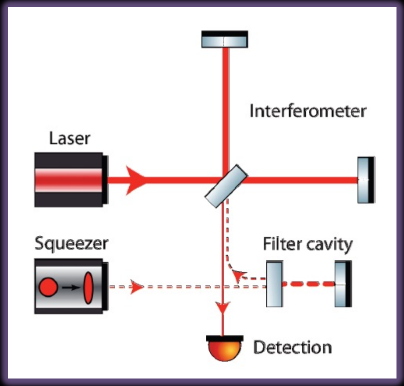


Frequency **Dependent** Squeezing for O4



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



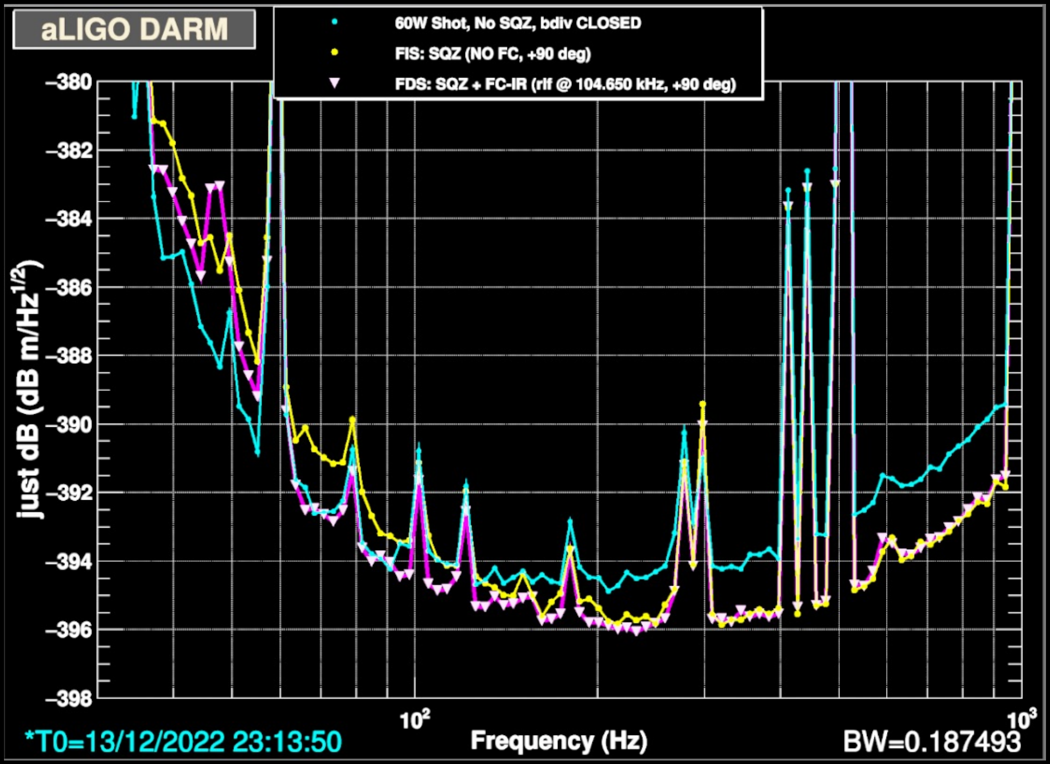


High finesse detuned **"filter cavity"** which rotates the squeezing angle as function of frequency

Credit: Antonio Pasqualetti

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

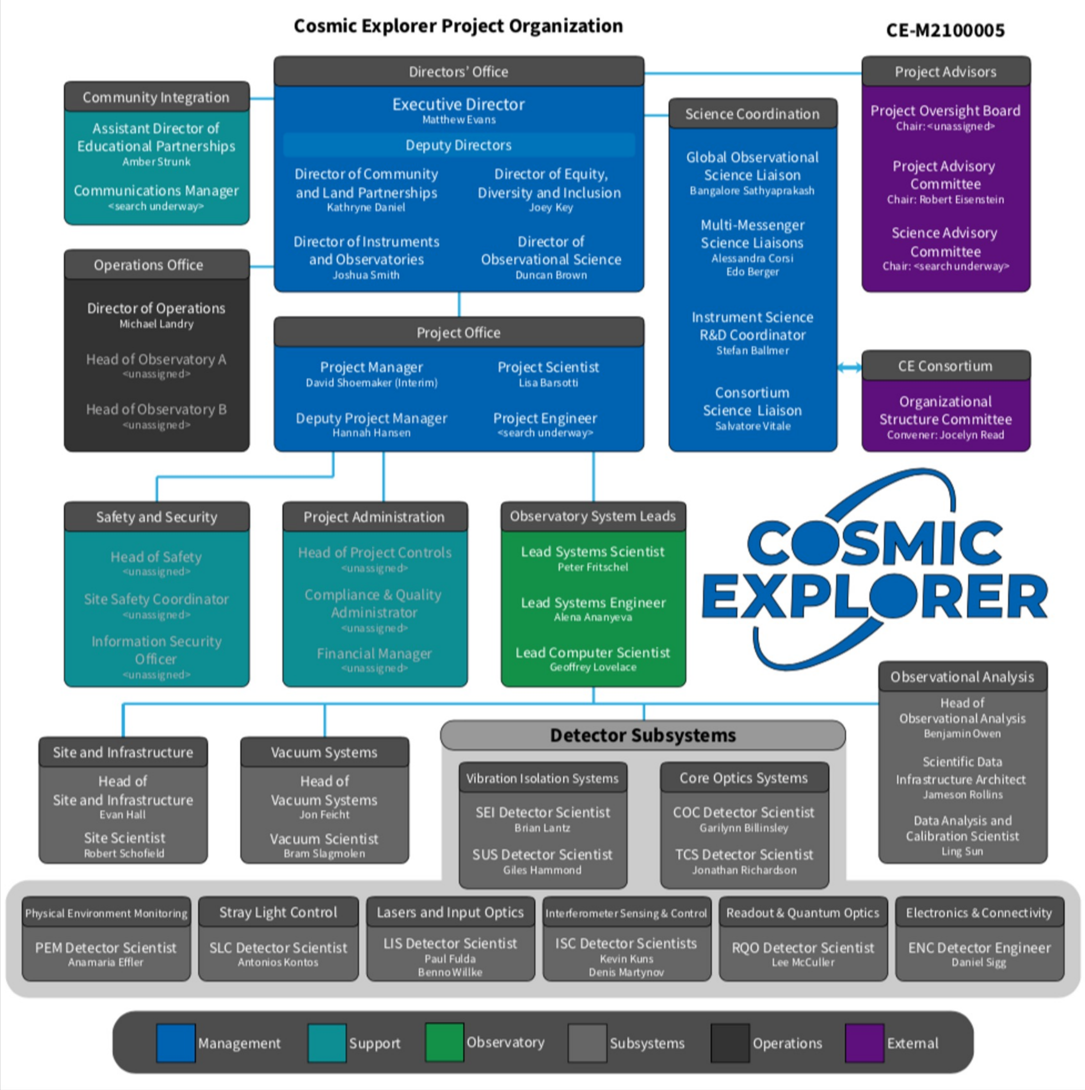
Initial results for Frequency Dependent Squeezing LIGO Hanford



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



Cosmic Explorer Project Organization

CE-M2100005

Community Integration
Assistant Director of Educational Partnerships
Amber Strunk
Communications Manager
<search underway>

Directors' Office
Executive Director
Matthew Evans
Deputy Directors
Director of Community and Land Partnerships
Kathryne Daniel
Director of Equity, Diversity and Inclusion
Joey Key
Director of Instruments and Observatories
Joshua Smith
Director of Observational Science
Duncan Brown

Science Coordination
Global Observational Science Liaison
Bangalore Sathyaprakash
Multi-Messenger Science Liaisons
Alessandra Corsi
Edo Berger
Instrument Science R&D Coordinator
Stefan Ballmer
Consortium Science Liaison
Salvatore Vitale

Project Advisors
Project Oversight Board
Chair: <unassigned>
Project Advisory Committee
Chair: Robert Eisenstein
Science Advisory Committee
Chair: <search underway>

Operations Office
Director of Operations
Michael Landry
Head of Observatory A
<unassigned>
Head of Observatory B
<unassigned>

Project Office
Project Manager
David Shoemaker (Interim)
Project Scientist
Lisa Barsotti
Deputy Project Manager
Hannah Hansen
Project Engineer
<search underway>

CE Consortium
Organizational Structure Committee
Convener: Jocelyn Read

Safety and Security
Head of Safety
<unassigned>
Site Safety Coordinator
<unassigned>
Information Security Officer
<unassigned>

Project Administration
Head of Project Controls
<unassigned>
Compliance & Quality Administrator
<unassigned>
Financial Manager
<unassigned>

Observatory System Leads
Lead Systems Scientist
Peter Fritschel
Lead Systems Engineer
Alena Ananyeva
Lead Computer Scientist
Geoffrey Lovelace

COSMIC EXPLORER

Observational Analysis
Head of Observational Analysis
Benjamin Owen
Scientific Data Infrastructure Architect
Jameson Rollins
Data Analysis and Calibration Scientist
Ling Sun

Site and Infrastructure
Head of Site and Infrastructure
Evan Hall
Site Scientist
Robert Schofield

Vacuum Systems
Head of Vacuum Systems
Jon Feicht
Vacuum Scientist
Bram Slagmolen

Detector Subsystems

Vibration Isolation Systems
SEI Detector Scientist
Brian Lantz
SUS Detector Scientist
Giles Hammond

Core Optics Systems
COC Detector Scientist
Garilynn Billinsley
TCS Detector Scientist
Jonathan Richardson

Physical Environment Monitoring
PEM Detector Scientist
Anamaria Effler

Stray Light Control
SLC Detector Scientist
Antonios Kontos

Lasers and Input Optics
LIS Detector Scientist
Paul Fulda
Benno Willke

Interferometer Sensing & Control
ISC Detector Scientists
Kevin Kuns
Denis Martynov

Readout & Quantum Optics
RQO Detector Scientist
Lee McCuller

Electronics & Connectivity
ENC Detector Engineer
Daniel Sigg

🟦 Management
🟩 Support
🟩 Observatory
⬜ Subsystems
⬛ Operations
🟪 External

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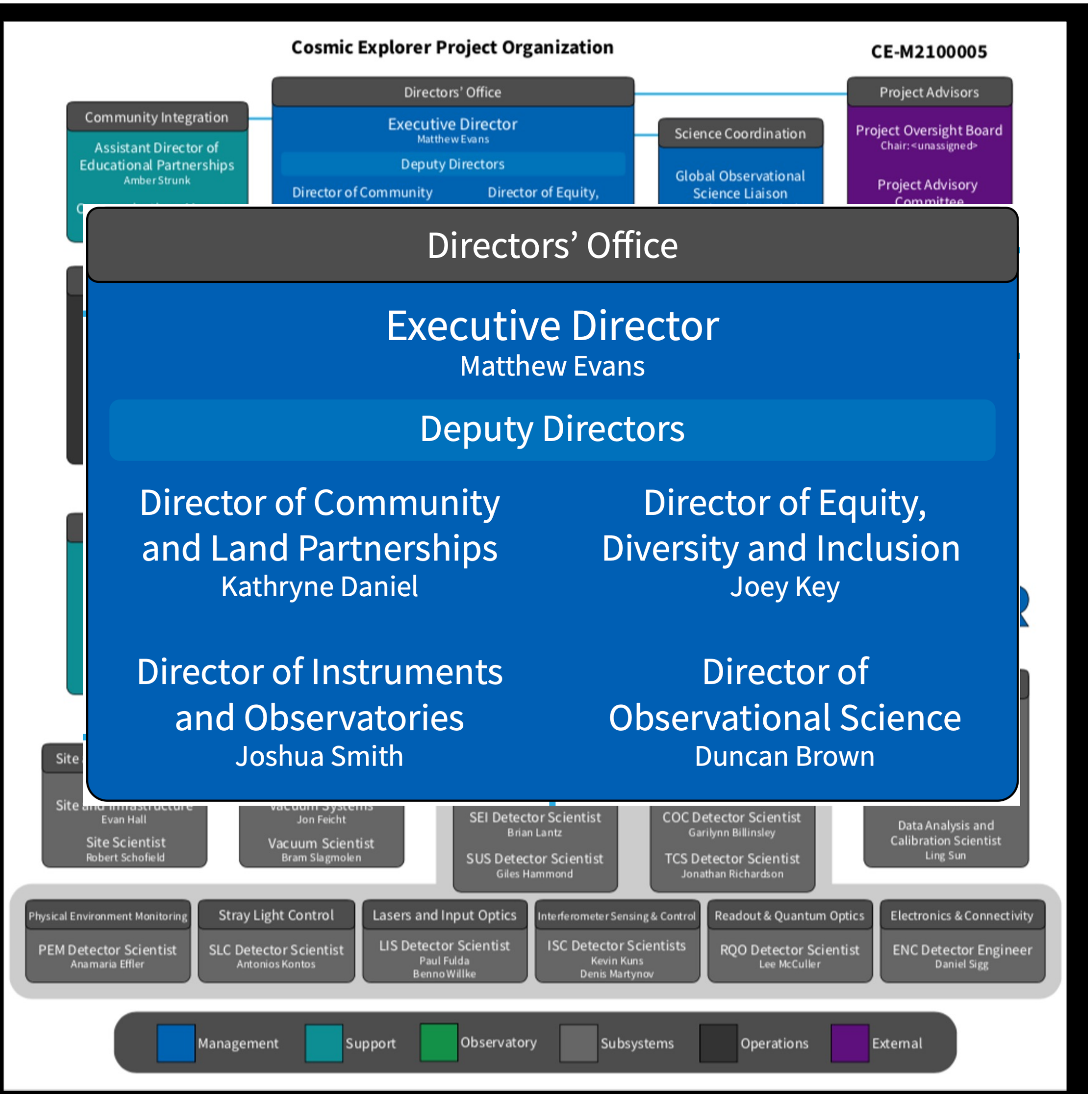

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