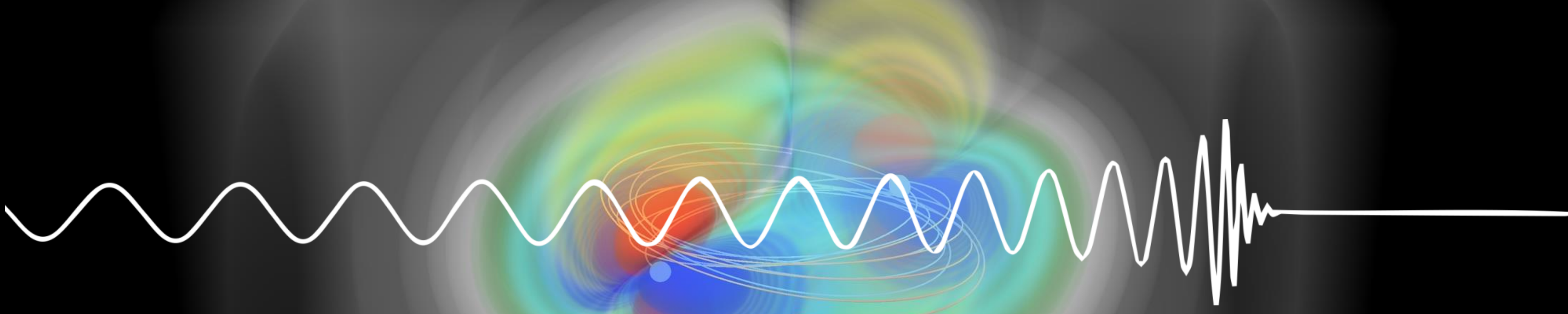
Gravitational waves with ground-based detectors

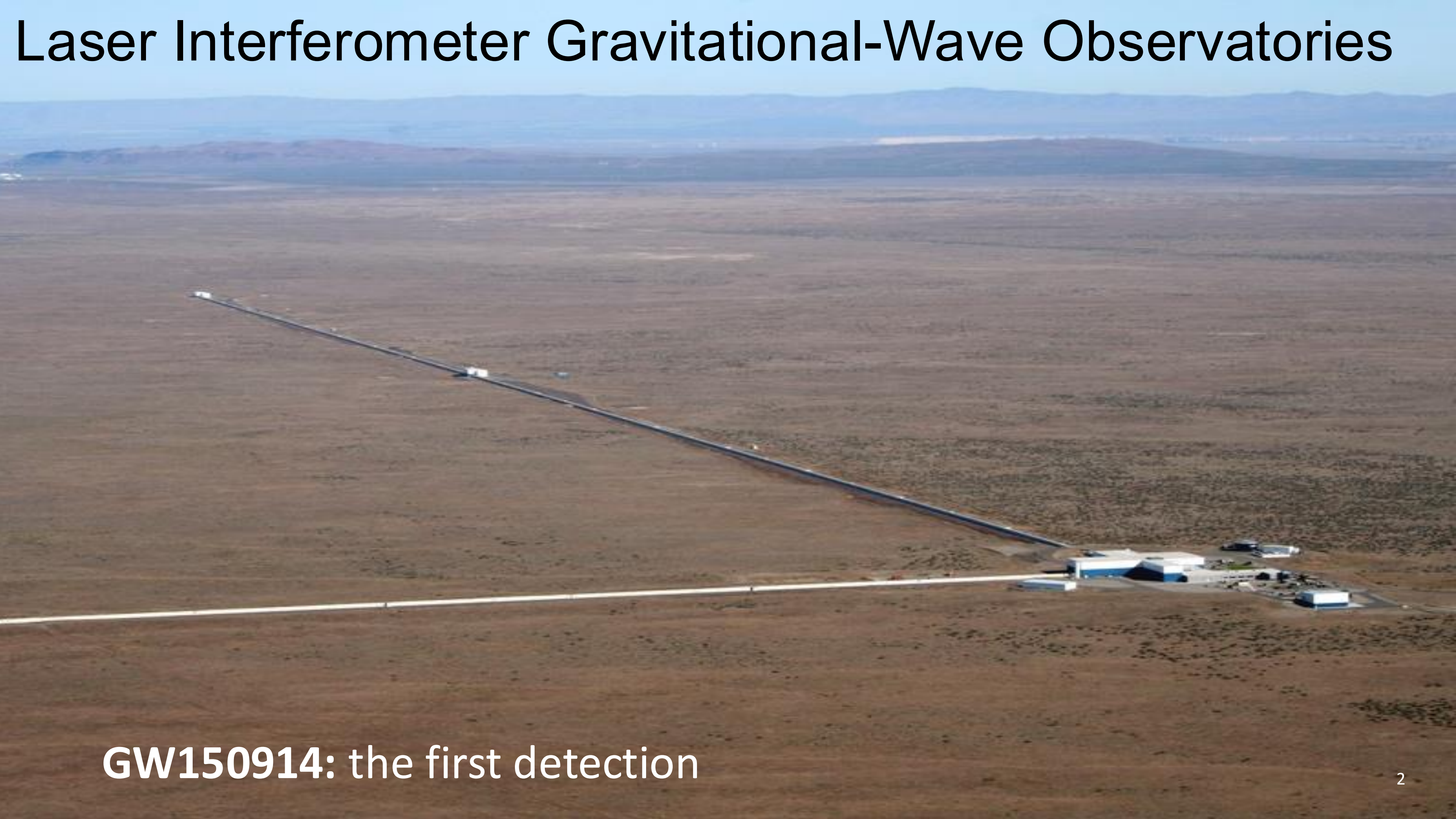
Alicia M Sintes



The 9th International Conference on
Advancements in **N**uclear **I**nstrumentation **M**easurement **M**ethods and their **A**pplications
ANIMMA 2025 Conference, June 10^{th} 2025
Hotel Meliá Valencia, Valencia, Spain

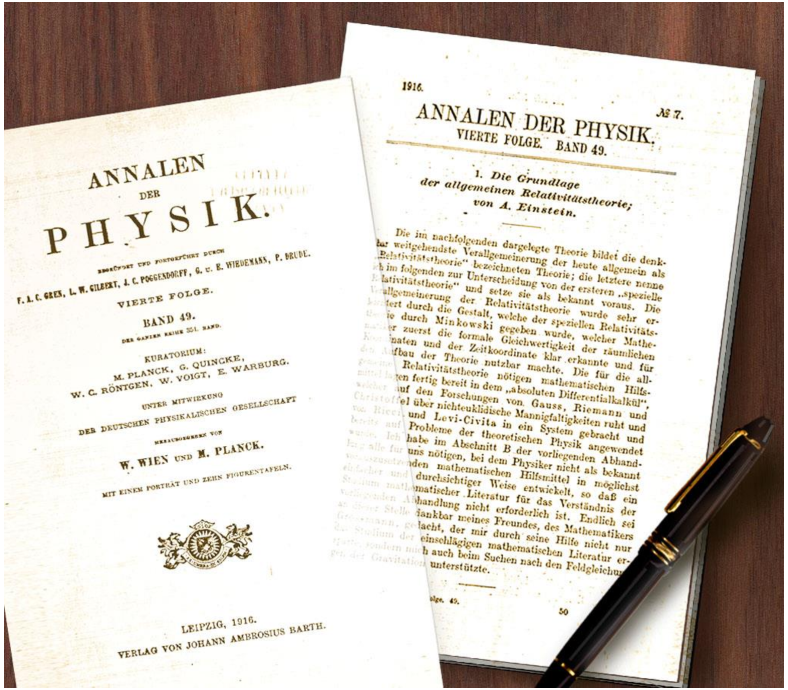
Universitat de les Illes Balears
IAC3 Institute of Applied Computing & Community Code.

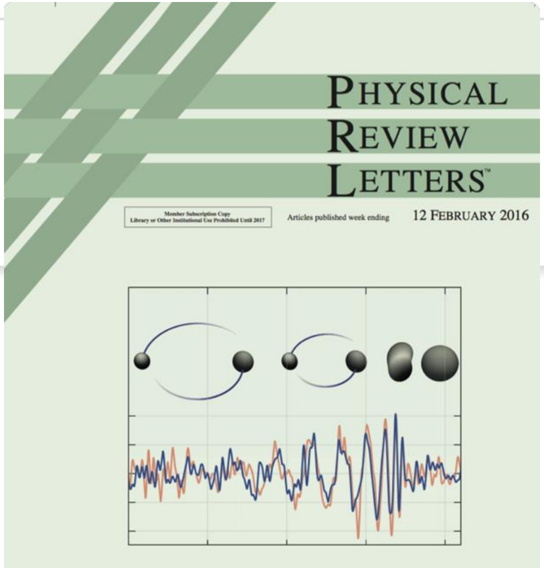
Laser Interferometer Gravitational-Wave Observatories



GW150914: the first detection

A century of General Relativity





Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

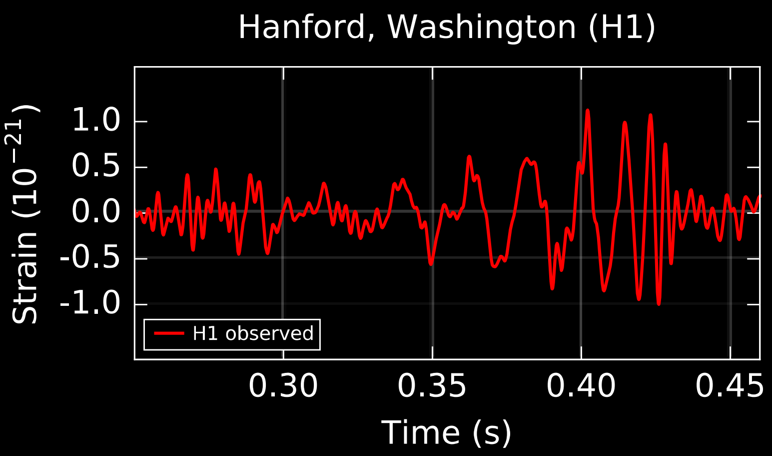
(Received 21 January 2016; published 11 February 2016)

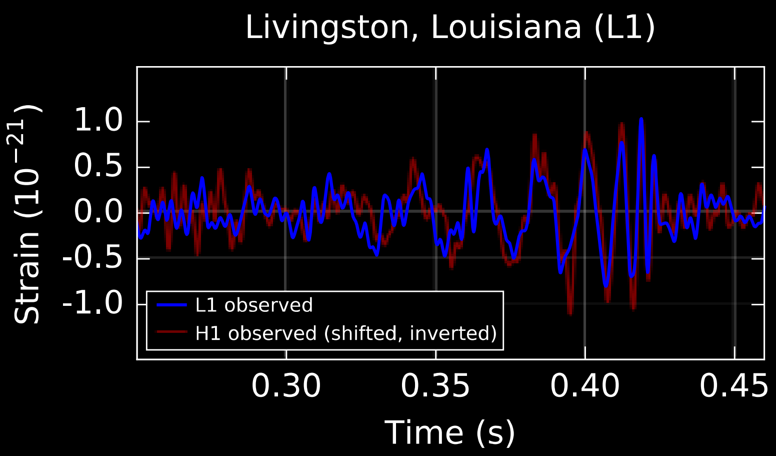
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

Observation of Gravitational Waves from a Binary Black Hole Merger (September 2015) - *GW150914*

Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger" Phys. Rev. Lett. 116, 061102 (2016)





A new window onto the Universe

The history of Astronomy: new bands of the EM spectrum opened --> major discoveries!

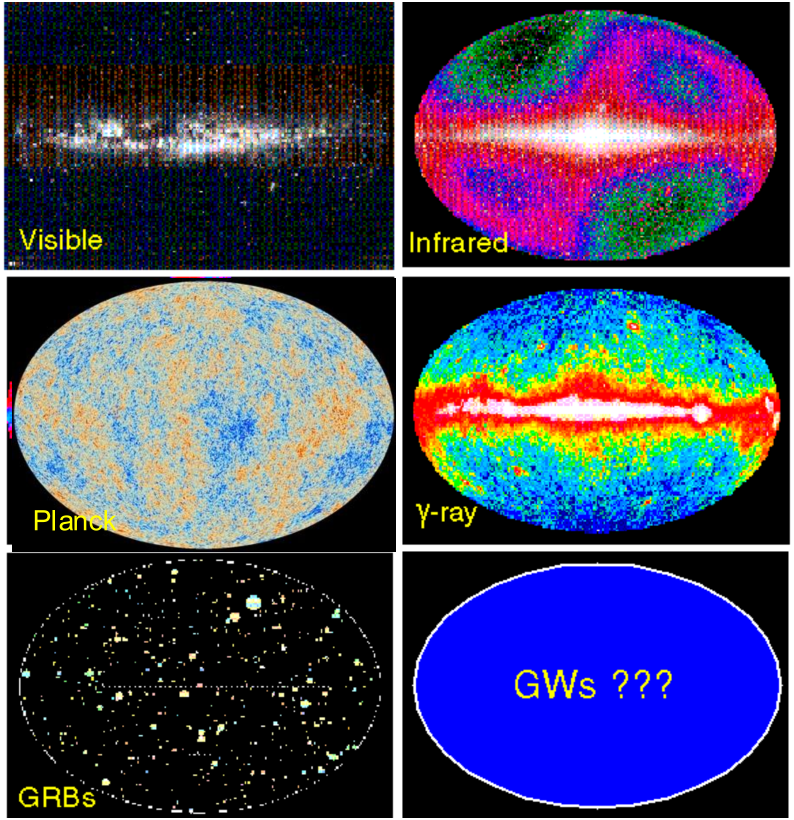
GWs aren’t just a new band, they’re a new spectrum, with very different and complementary properties to EM waves.

Distortions of space-time (not in space-time), propagating at the speed of gravity (light)

Generated by accelerating mass/energy, e.g., coherent motion of huge masses; not vibrations of electrons in atoms

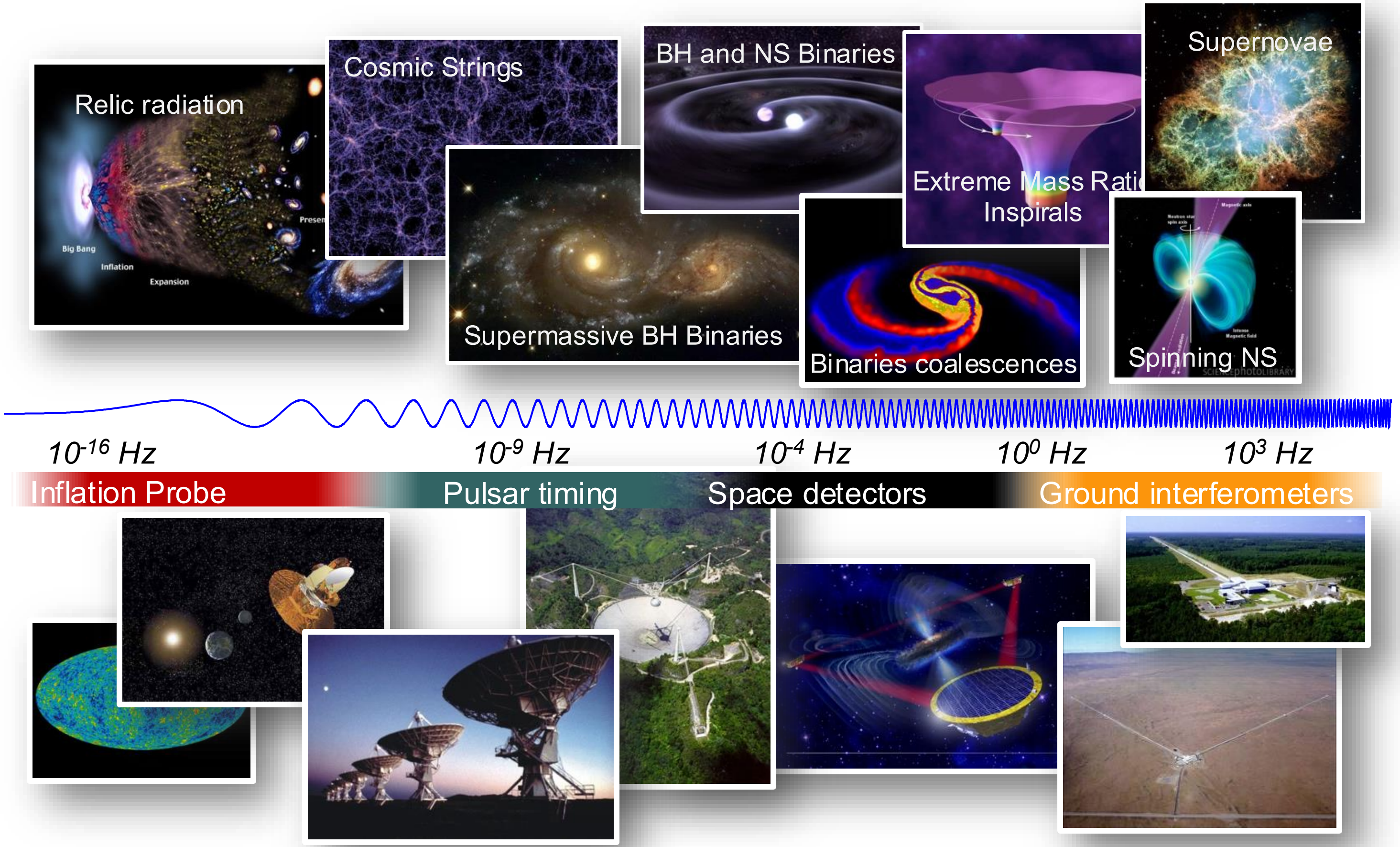
GWs are ~immune to scattering / obscuration / absorption… not immune to gravitational lensing

Detectors are rulers as opposed to buckets.
Sensitive to amplitude instead of power— signal falls off as 1/r.
Direct measure of Luminosity Distance

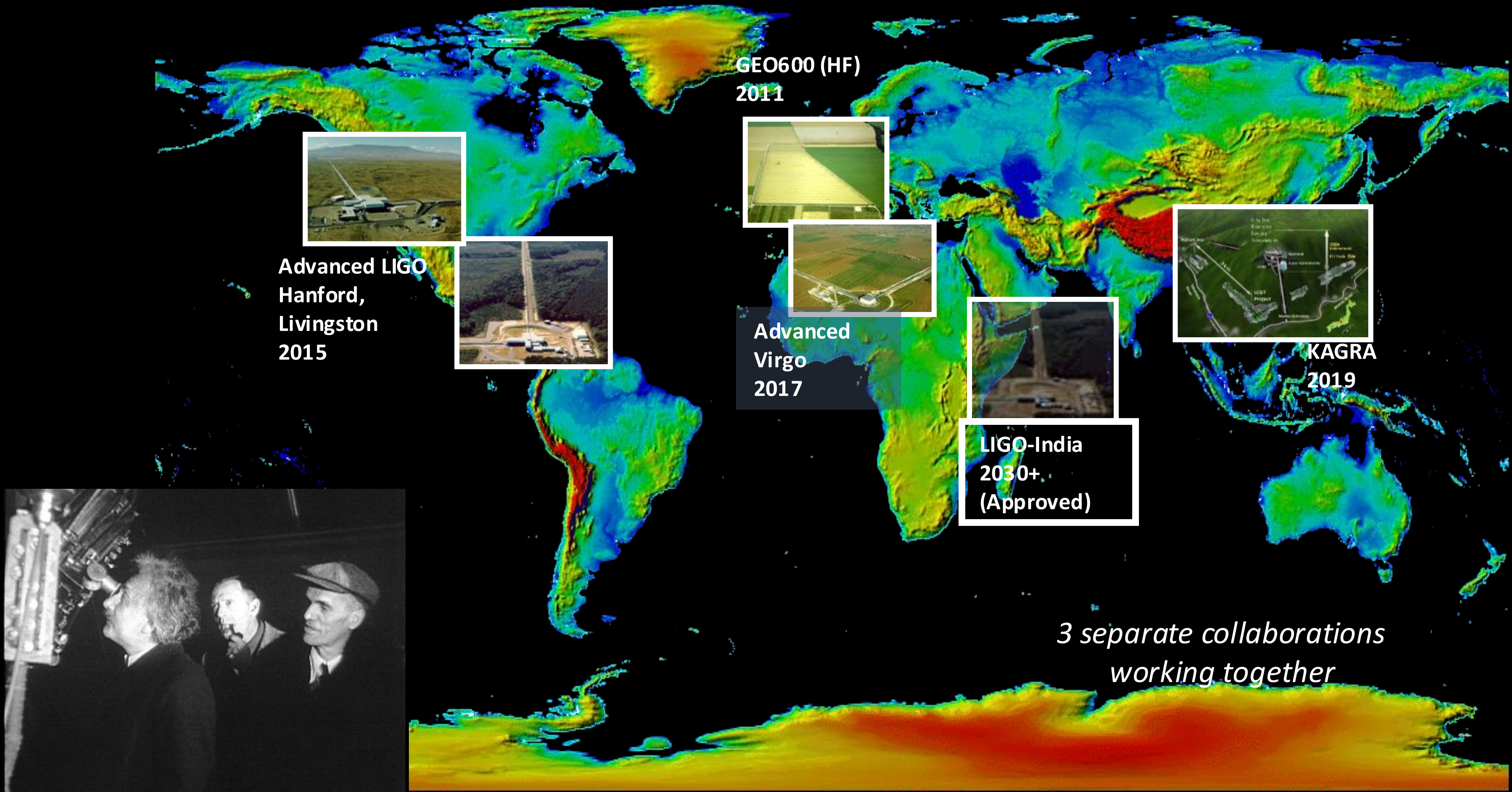


Gravitational waves offer a unique probe into some of the most extreme systems in the Universe. They originate from merging black holes; from binary stars orbiting at close to the speed of light; from supernovae, and from the Big Bang itself.

Gravitational Wave Spectrum



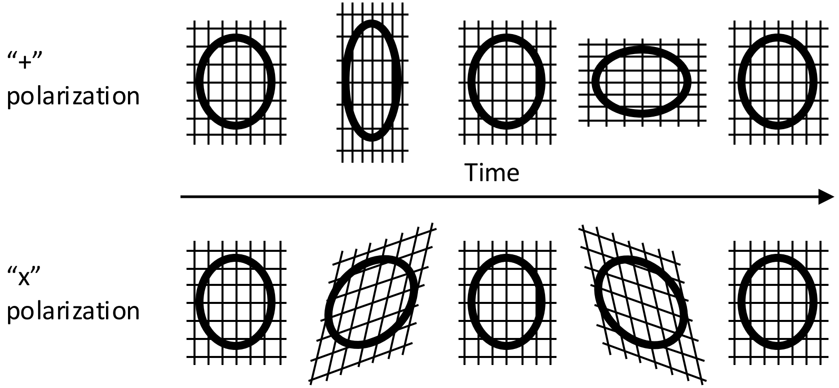
The growing network of advanced GW detectors

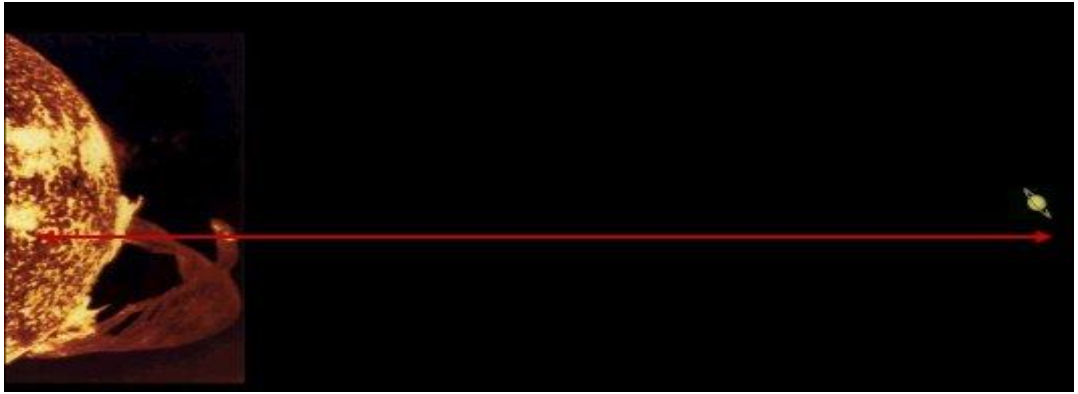


3 separate collaborations working together

How Small is the Stretching and Squeezing?

- The detection of gravitational radiation is technologically staggering.
- The effect of a gravitational wave is to change the distance between freely falling test masses.
- The amount of stretching and squeezing of space which is predicted to occur near the Earth due to events such as the coalescence of a pair of neutron stars within about 100 million light-years from Earth is about one part in 10^{22}.

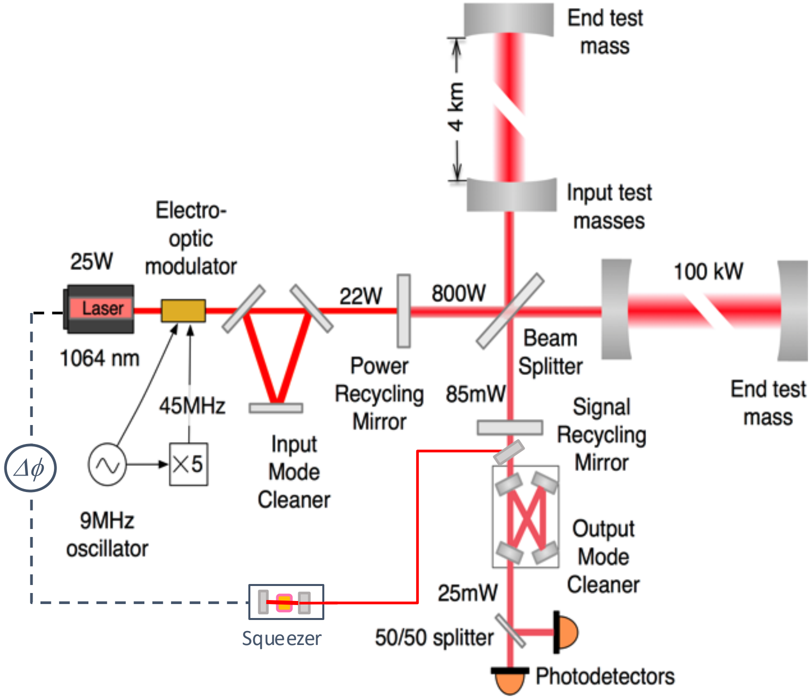




- Observing this fantastically tiny effect is equivalent to detecting the motion of Saturn if it were to move closer to the sun by the diameter of a single hydrogen atom!
- Detectors should measure displacements of a thousand of a proton.

Advanced LIGO: How Does It Really Work?

An Interferometer is a Gravitational- Wave Transducer



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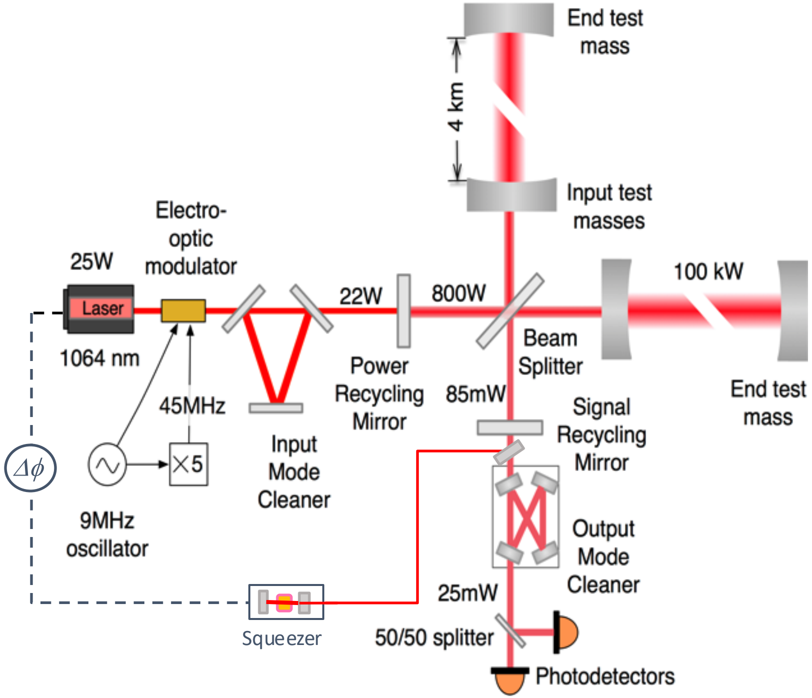

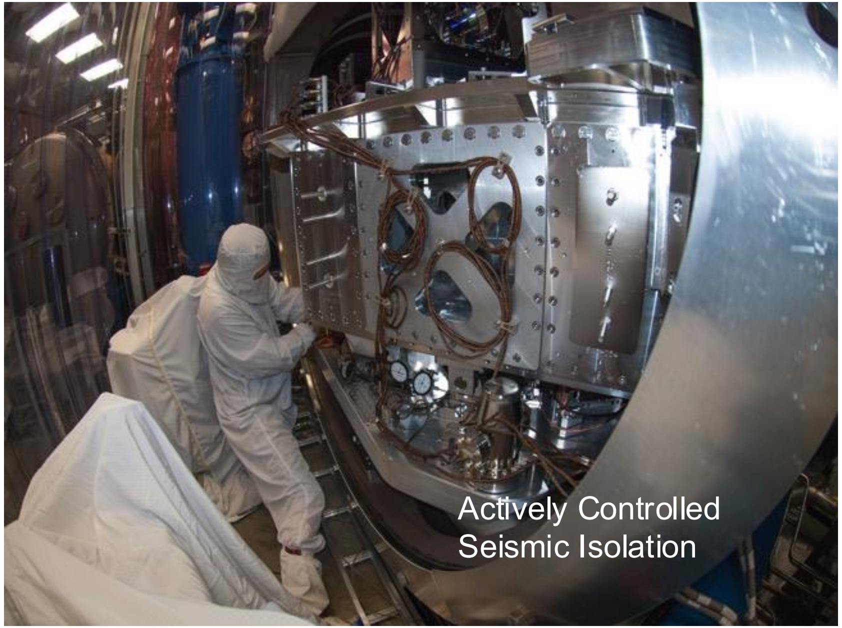

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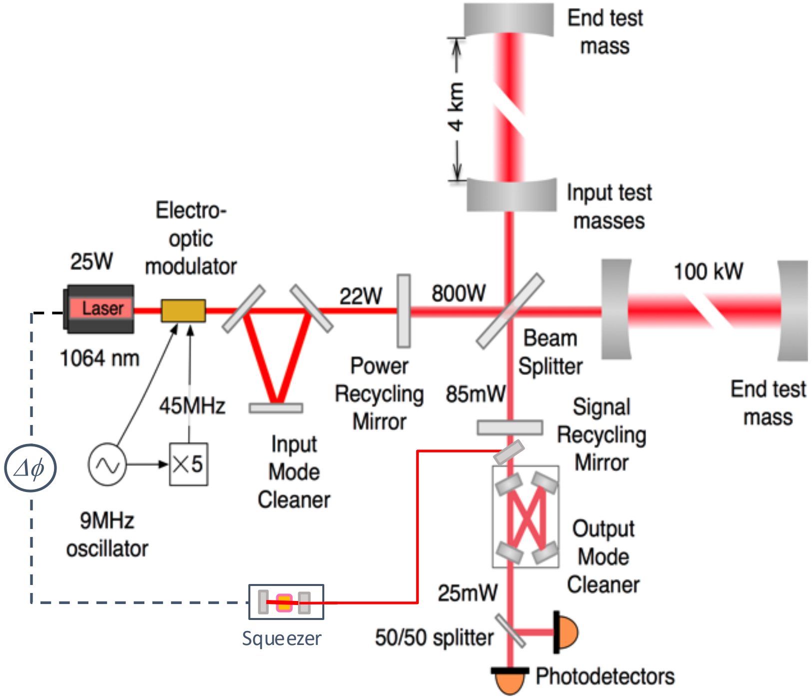
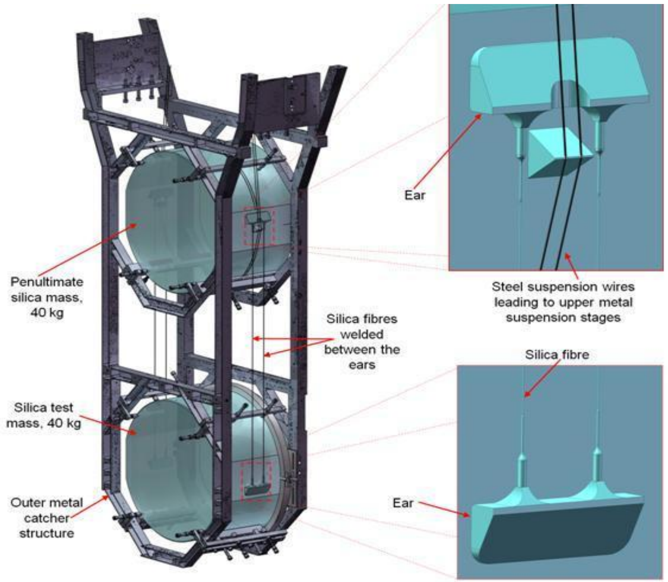


Quadruple Mirror Suspension



Advanced LIGO: How Does It Really Work?

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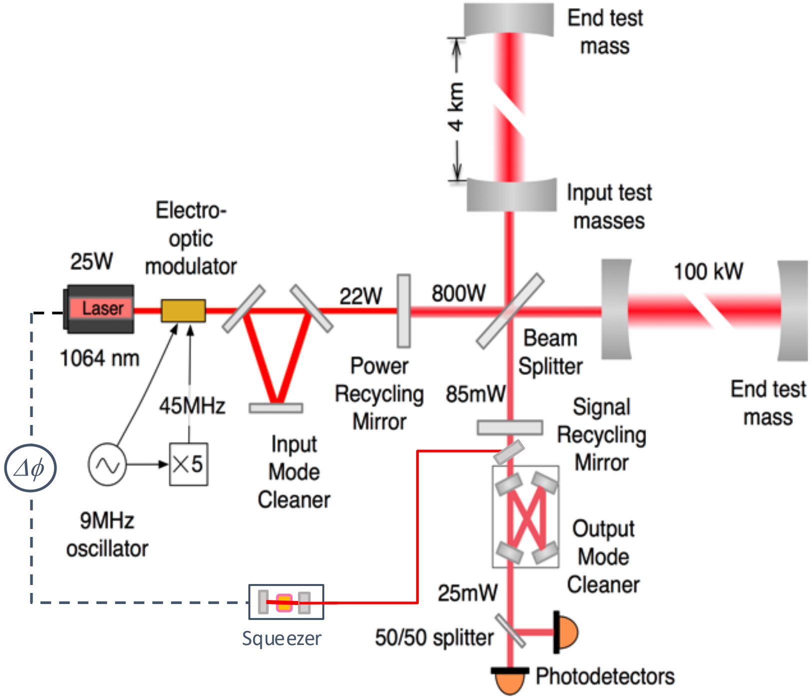
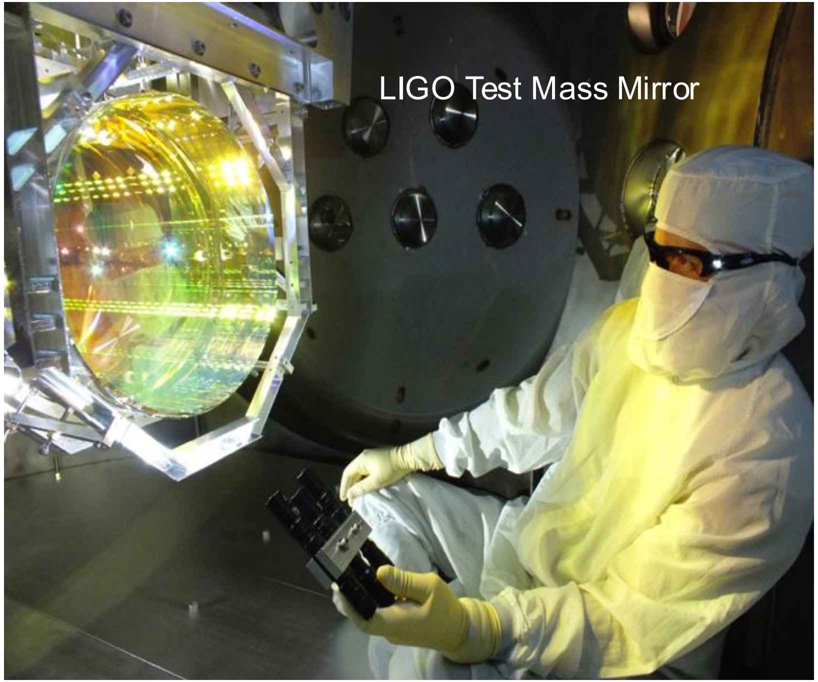


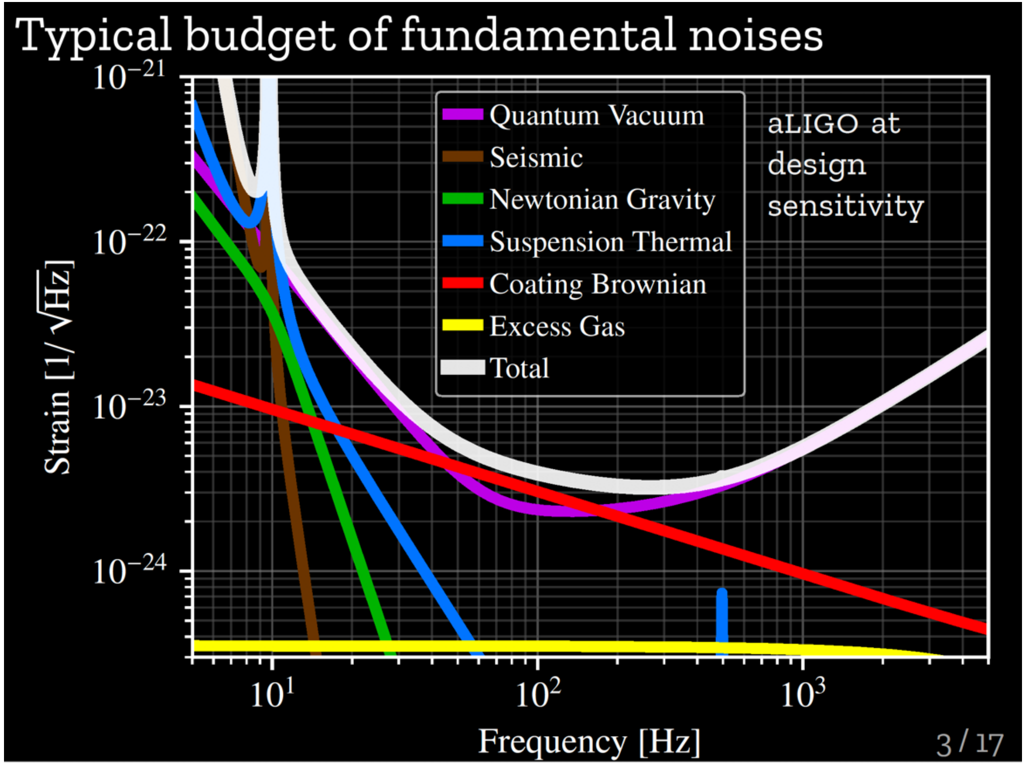


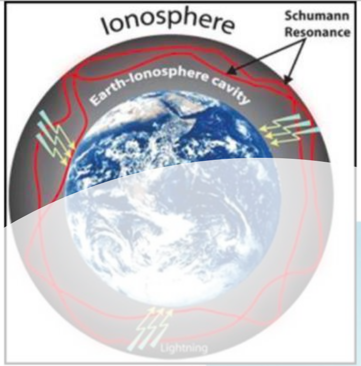
What Limits LIGO-Virgo-KAGRA Sensitivity?

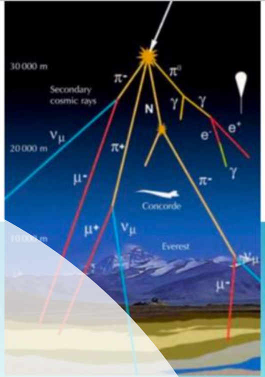
- **As designed….**
- Quantum noise – statistical nature of light – dominates at most frequencies
- Thermal noise – Brownian noise – dominates in a middle region
- Seismic noise, direct and via changing gravitational attraction – at low frequencies

- These noise sources don't grow with the arm length, but the signal does: **Length Matters**

- Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals

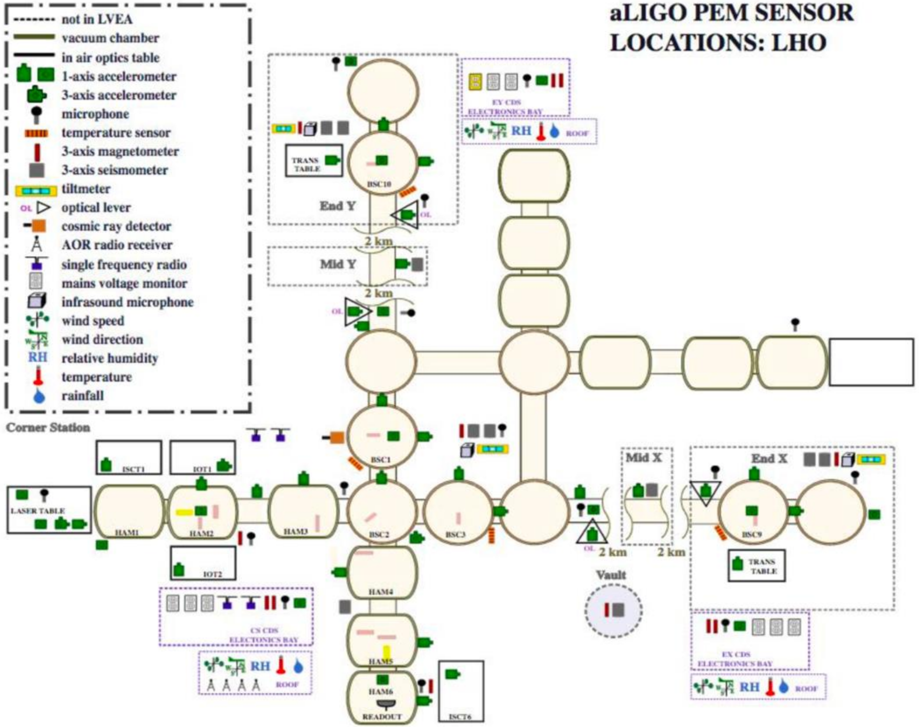


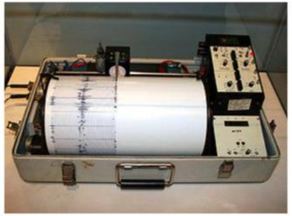


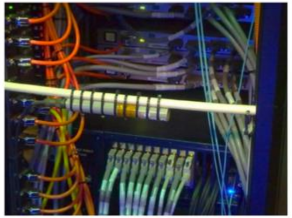


- wind,
- earthquakes,
- storms,
- geomagnetic fields,
- cosmics rays,
- density fluctuations in the ground and the atmosphere.

Environmental Monitoring

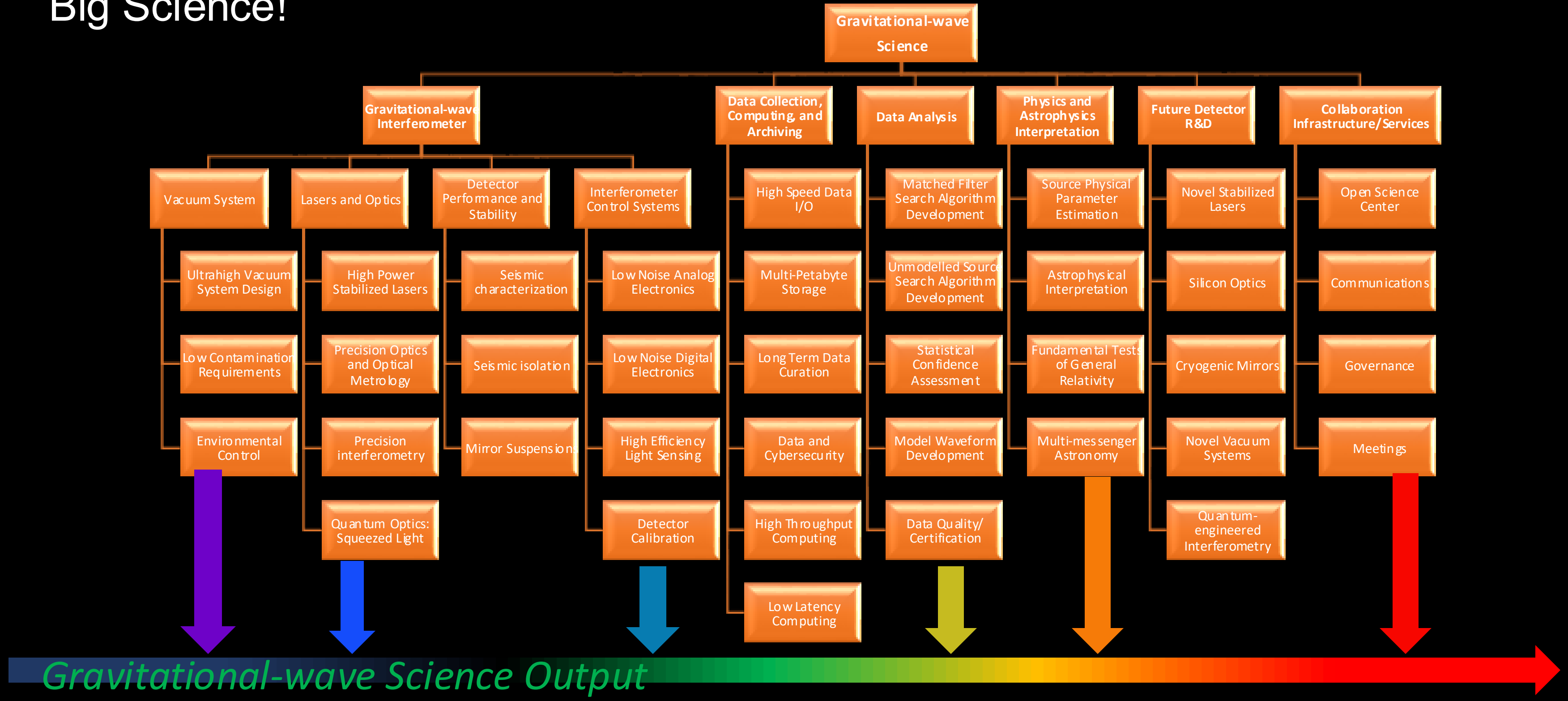






The Gravitational-Wave Science Ecosystem

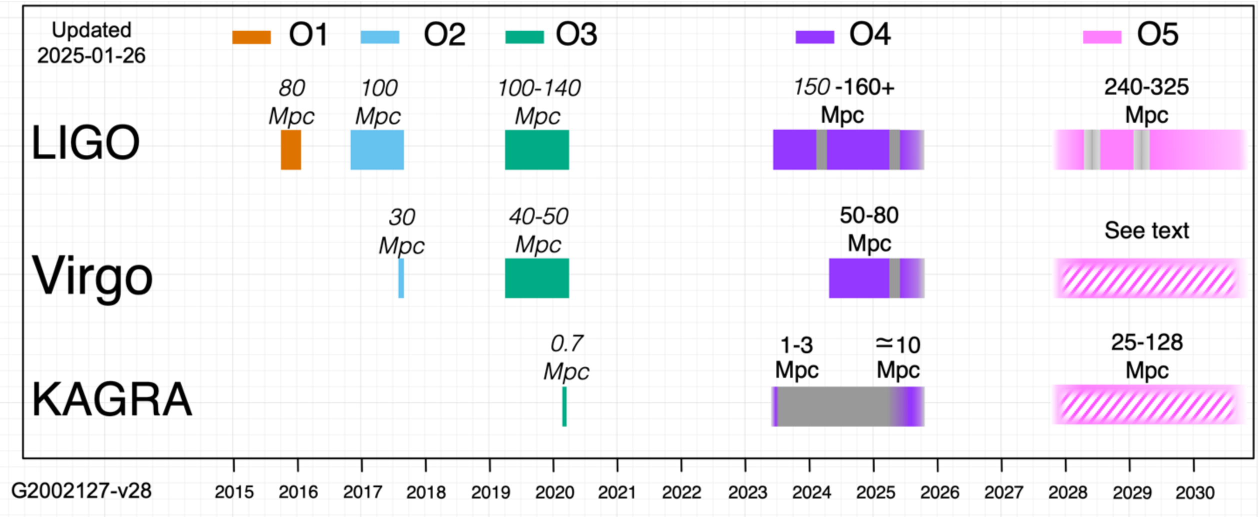
Gravitational Waves Science is
Big Science!



LVK current and future observing runs:

Important detector improvements between O3 and O4
- Higher laser power
- Frequency-dependent squeezing
- Noise reduction & duty cycle improvements
- + Improvements to processing of data for use by searches

Not comprehensive! These are just some highlights.



https://observing.docs.ligo.org/plan/

O4 observing run:
O4a: May 24th 2023- January 16th 2024
O4b: April 10th 2024- January 23rd 2025
O4c: January 24th 2025- November 18th 2025

- O4 break for maintenance and enhancement work + Engineering Run 16 (ER16) was from Jan 16 to April 10, 2024.
- 2nd Maintenance break from 1 April 2025 to 11 June 2025

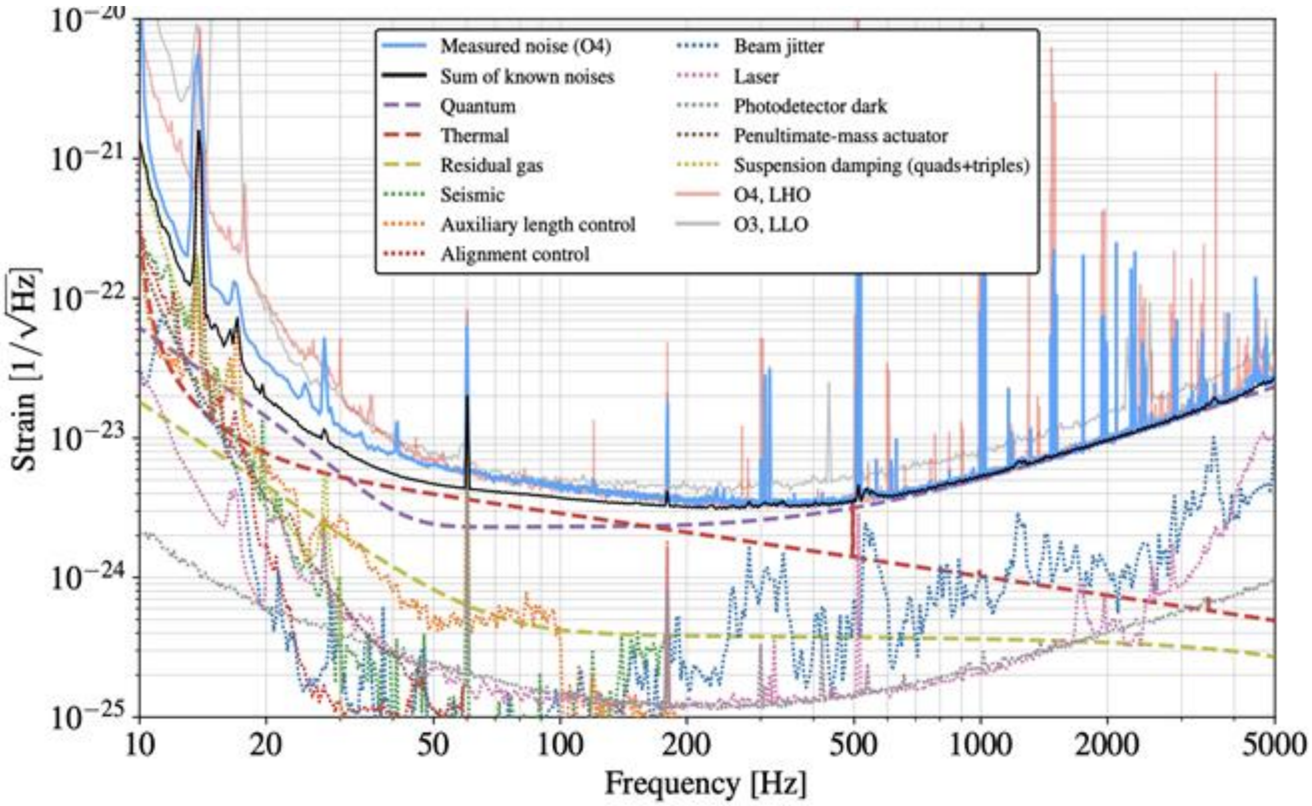
KAGRA delayed due to 7.6 magnitude earthquake on Jan 1, 2024

The GW network will continue improving in sensitivity…
….and thanks to that 1/r thing, make substantial improvements in sensitive volume…
- …which means more opportunity for multi-messenger events

O4a Noise budget

- Low frequency
  - Auxiliary control noise
  - Suspension damping
  - Unknown technical noise
- Mid frequency
  - Coating thermal noise
  - Unknown technical noise
- High frequency
  - Quantum noise
    - Frequency dependent squeezing (5-6dB)
  - Laser noise
    - Input beam jitter and frequency noise

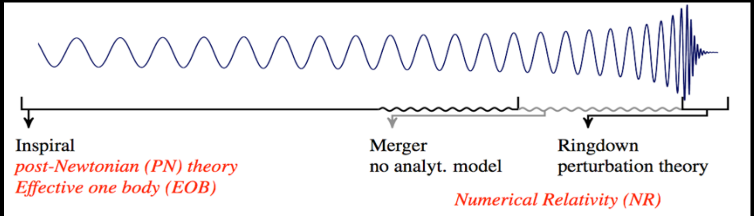
E. Capote, et.al. Phys. Rev. D 111, 062002



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

How do we identify the sources?

Compare with theoretical models of waveforms, calibrated to numerical solutions of the Einstein equations.



The GRAVITY group at UIB currently ranks among the leading national users of the BSC, the largest node of the RES. We have been using it since 2009 for numerical relativity simulations, and more recently for Bayesian parameter estimation in CBC signals, as well as for the search for CW signals generated by neutron stars in binary systems, employing a GPU-based implementation.

Impact of Gravitational Wave Detections On Our Understanding Of…

The Nature of Black Holes

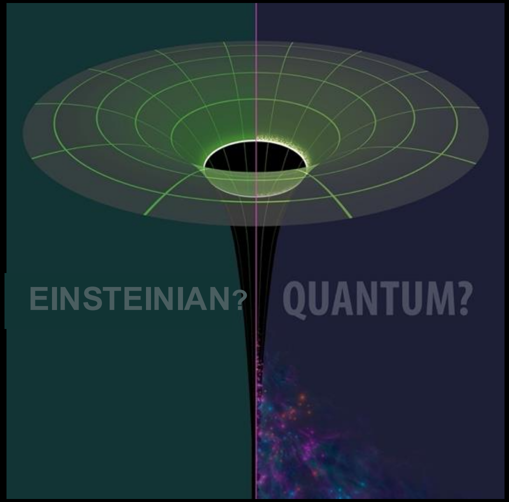


Image Credit: Robert Hurt, IPAC, Caltech

How Matter Behaves Under the Most Extreme Conditions in Nature

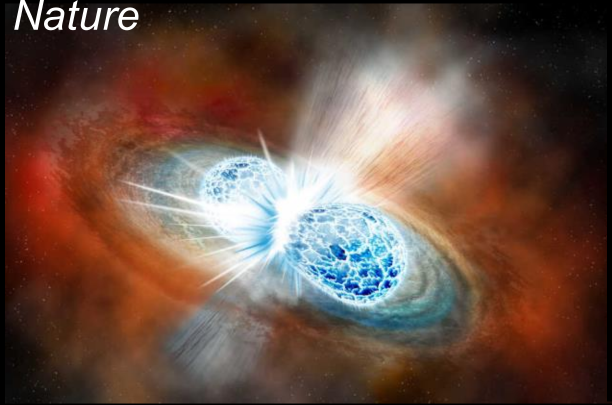


Image Credit: Robin Dienel/Carnegie Institution for Science

The Origin of Heavy Elements

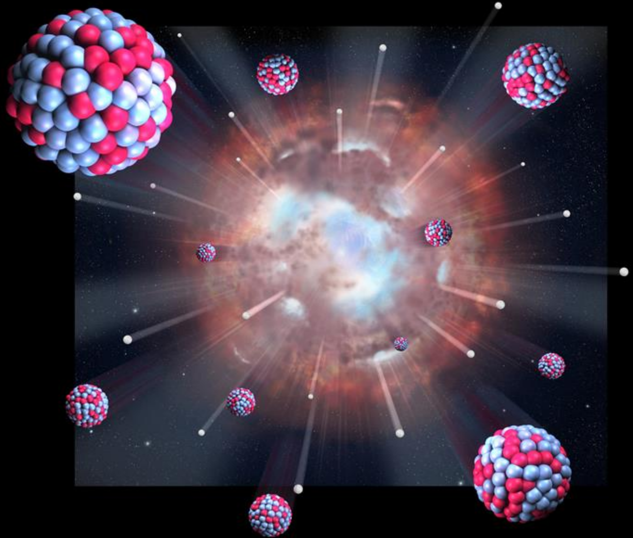


Image Credit: Akihiro Ikeshita/Naotsugu Mikami NAOJ

LIGO and Virgo (and KAGRA!) Haven't Yet Changed Our Thinking About …

How Supernovae Explode

Image Credit: JWST NIRcam/NASA,ESA,CSA

Continuously Emitting Neutron Stars

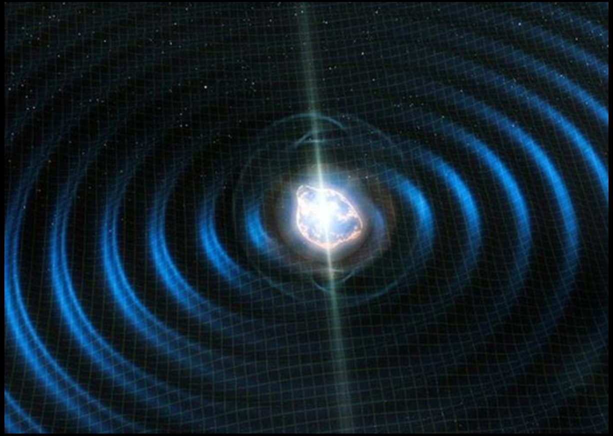
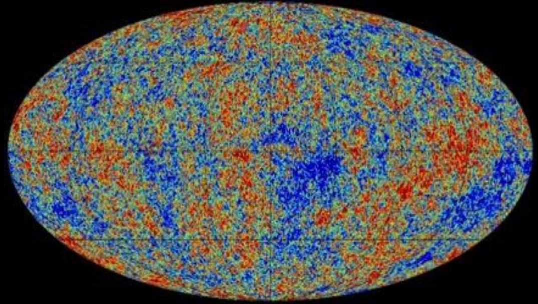


Image Credit: ScienceBlog

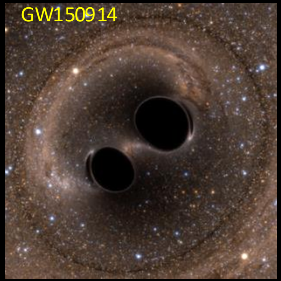
Astrophysical Stochastic Background

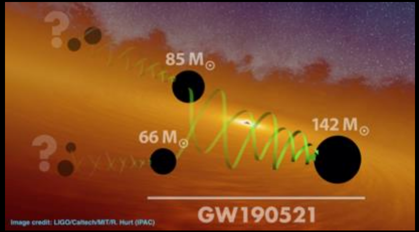


Credit: Planck Collaboration

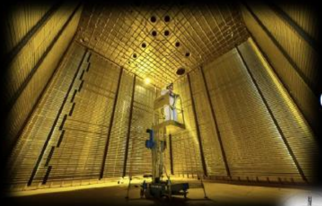
LIGO-Virgo **Greatest Hits 2015-2021:** What Ground-Based Gravitational Wave Detections Have Taught Us

- 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.

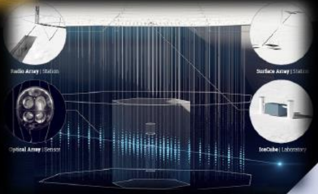




Multimessenger synergies



Galactic core-collapse supernova



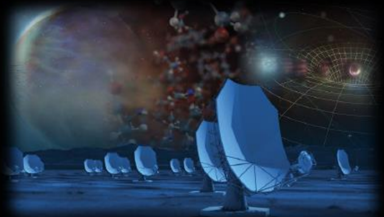
Gamma-ray bursts from neutron star mergers

Neutrino:
DUNE, NKM3Net, IceCube Gen2

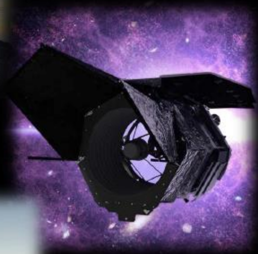
Radio:
ng VLA, SKA

X-ray/Gamma-ray:
Einstein Probe, Athena, THESEUS, HERMES

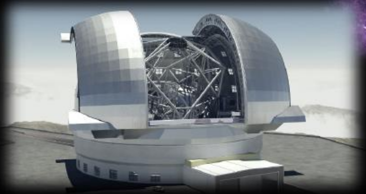
Optical/IR:
Nancy Grace Roman, ELTs, VRO LSST

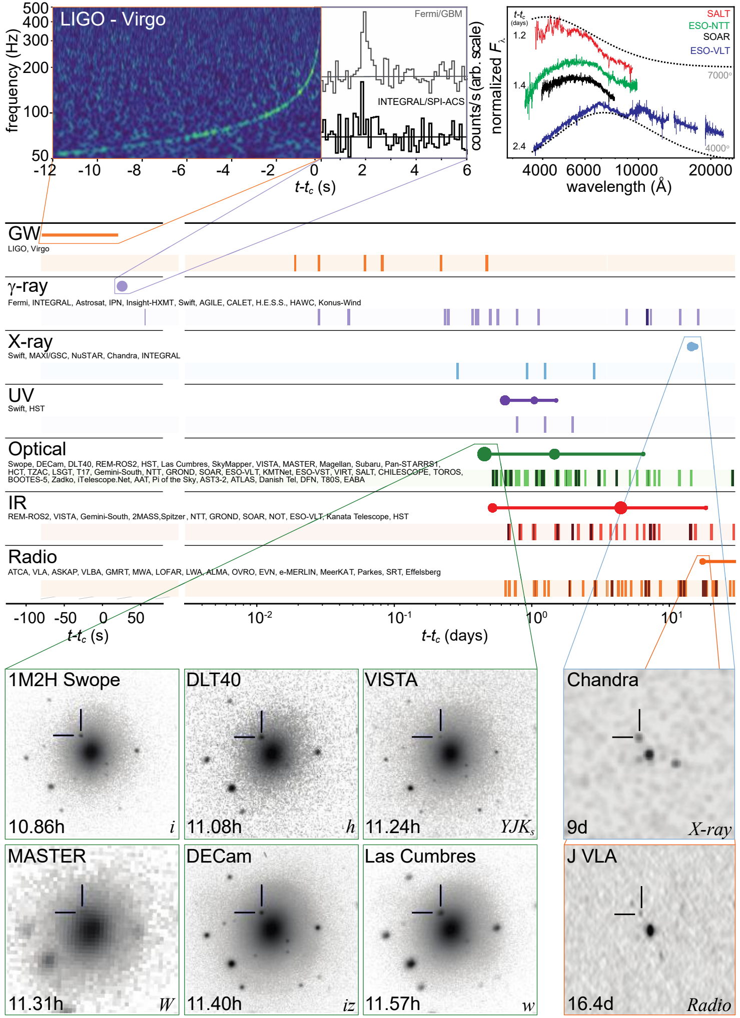


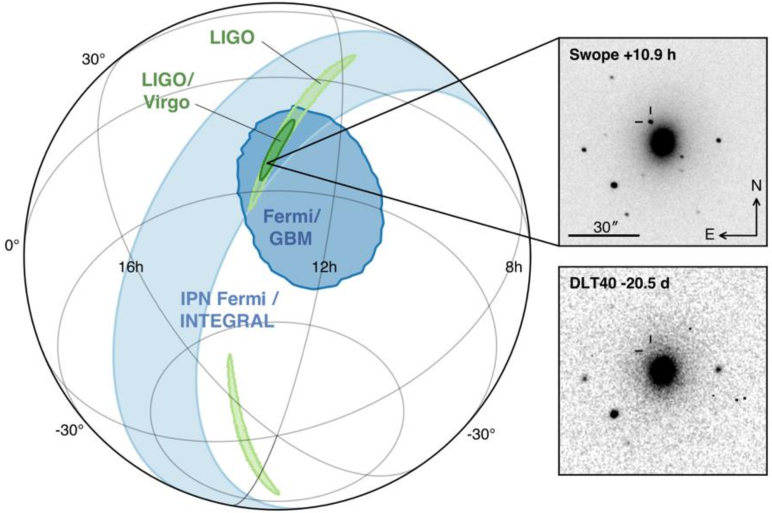
Elliptical, single, rapidly-rotating neutron stars



Kilonova, GRB afterglow







GW170917/GRB170817A :

"Multi-Messenger Observations of a Binary Neutron Star Merger"

B. Abbott et al., ApJL 848 (2017) L12

59-page "letter" (!). More than 3000 authors,~70 collaborations

First unambiguous EM counterpart to a GW source

- Gamma Ray transient classified as sGRB detected by *Fermi*-GBM 2s after inferred GW merger time.
- Host galaxy discovered by dedicated optical follow-up.
- "Whole of astronomy" broadband analysis of kilonova and host galaxy.

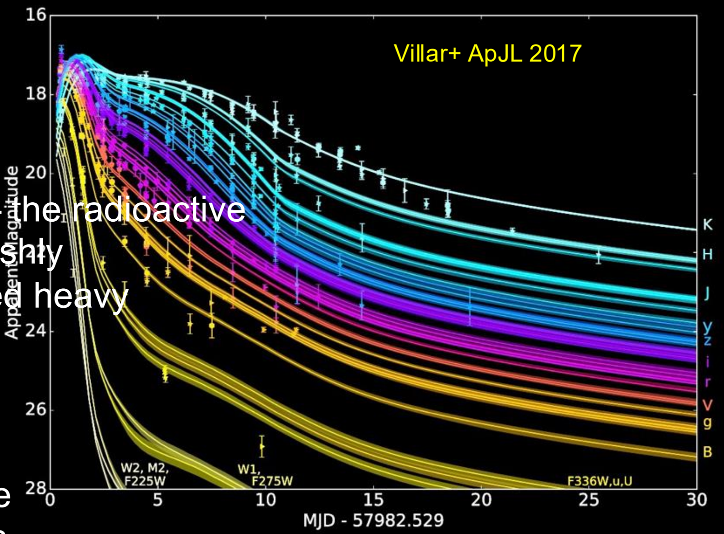
- **Vivid demonstration that joint observations are > sum of their parts.**

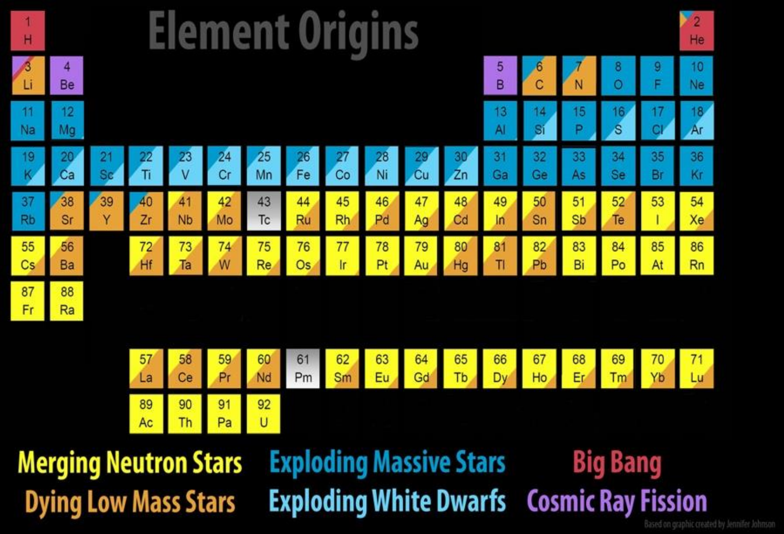
What we learned from GW170817

BNS mergers are the progenitors of some short gamma-ray burst –the most energetic electromagnetic explosions in the universe

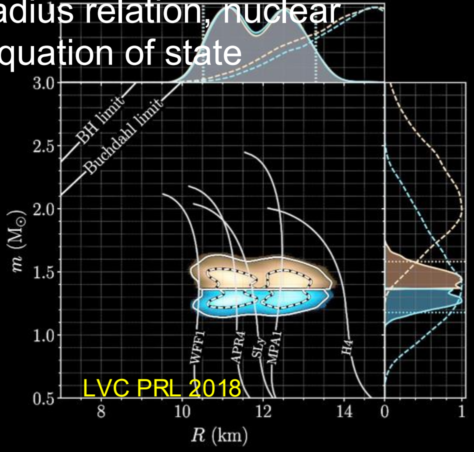
BNS mergers are the sites of heavy element nucleosynthesis, where most of the heavy elements are produced

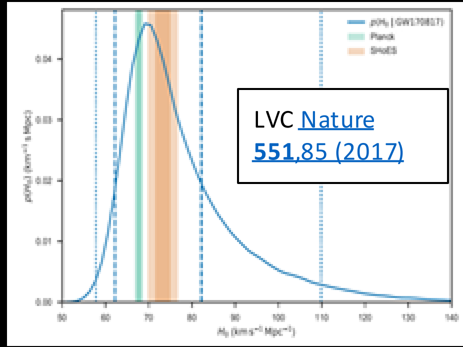
Kilonova – the radioactive glow of freshly synthesized heavy elements



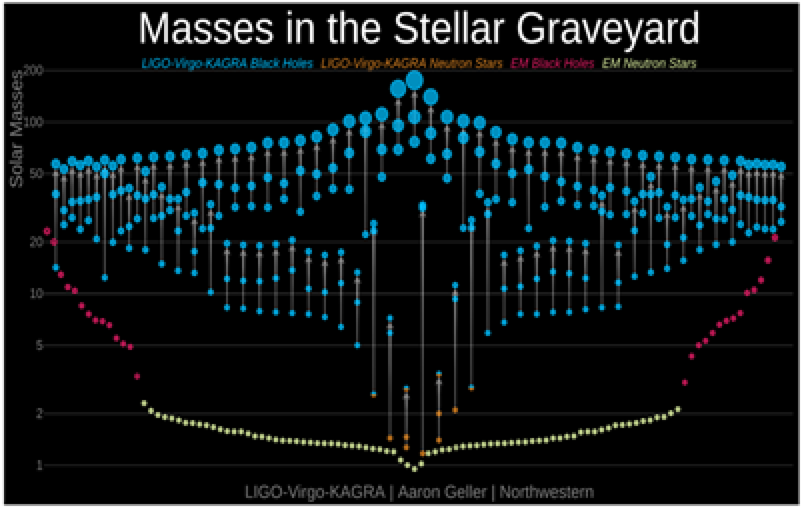


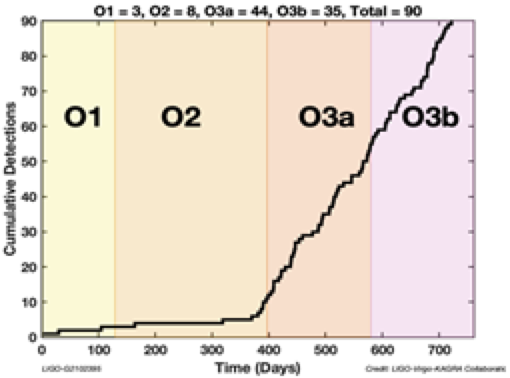
Constraints on the neutron star mass-radius relation, nuclear equation of state

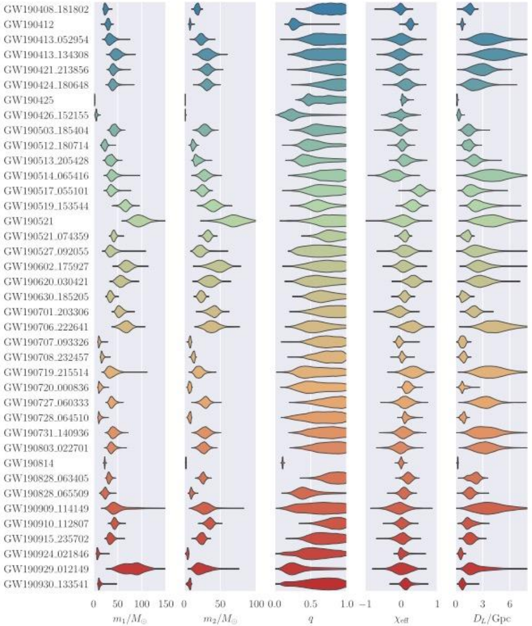




LVC [Nature 551,85 (2017)]





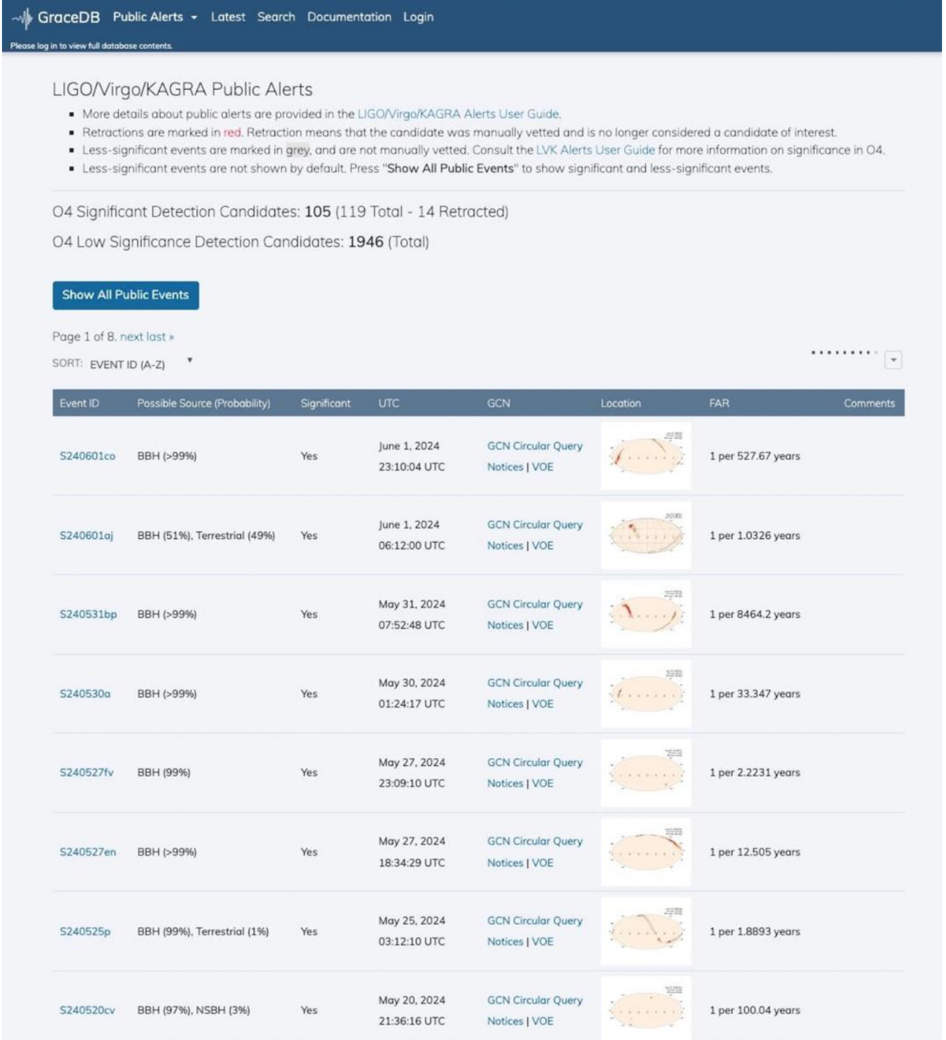


O3 campaign and beyond

O3 marked a phase change in GW astronomy, with public GW alerts in low latency and a lot of GW candidates!

- Wide range of masses
- most events: binary black holes
- redshifts up to ~0.8
- Spins:
  - Key signatures to discriminate BH populations: shed light on formation mechanism
  - Some events with clear indication of a net positive $X_{\rm eff}$

- No counterparts found in low latency
- But low mass candidates were poorly localized and/or poorly located on the sky



GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

LIGO/Virgo/KAGRA Public Alerts

- More details about public alerts are provided in the LIGO/Virgo/KAGRA Alerts User Guide.
- Retractions are marked in red. Retraction means that the candidate was manually vetted and is no longer considered a candidate of interest.
- Less-significant events are marked in grey, and are not manually vetted. Consult the LVK Alerts User Guide for more information on significance in O4.
- Less-significant events are not shown by default. Press "Show All Public Events" to show significant and less-significant events.

O4 Significant Detection Candidates: **105** (119 Total - 14 Retracted)

O4 Low Significance Detection Candidates: **1946** (Total)

Show All Public Events

Page 1 of 8. next last »

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S240601co	BBH (>99%)	Yes	June 1, 2024 23:10:04 UTC	GCN Circular Query Notices | VOE		1 per 527.67 years	
S240601aj	BBH (51%), Terrestrial (49%)	Yes	June 1, 2024 06:12:00 UTC	GCN Circular Query Notices | VOE		1 per 1.0326 years	
S240531bp	BBH (>99%)	Yes	May 31, 2024 07:52:48 UTC	GCN Circular Query Notices | VOE		1 per 8464.2 years	
S240530a	BBH (>99%)	Yes	May 30, 2024 01:24:17 UTC	GCN Circular Query Notices | VOE		1 per 33.347 years	
S240527fv	BBH (99%)	Yes	May 27, 2024 23:09:10 UTC	GCN Circular Query Notices | VOE		1 per 2.2231 years	
S240527en	BBH (>99%)	Yes	May 27, 2024 18:34:29 UTC	GCN Circular Query Notices | VOE		1 per 12.505 years	
S240525p	BBH (99%), Terrestrial (1%)	Yes	May 25, 2024 03:12:10 UTC	GCN Circular Query Notices | VOE		1 per 1.8893 years	
S240520cv	BBH (97%), NSBH (3%)	Yes	May 20, 2024 21:36:16 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years	

LVK- O4:

- Observing Run #4 (O4) started on May 24, 2023.
  O4a: May 24th 2023- January 16th 2024
  O4b: April 10th 2024- January 23rd 2025
  O4c: January 24th 2025- November 18th 2025

- O4 break for maintenance and enhancement work + Engineering Run 16 (ER16) was from Jan 16 to April 10, 2024.
- 2nd Maintenance break from 1 April 2025 to **11 June 2025**

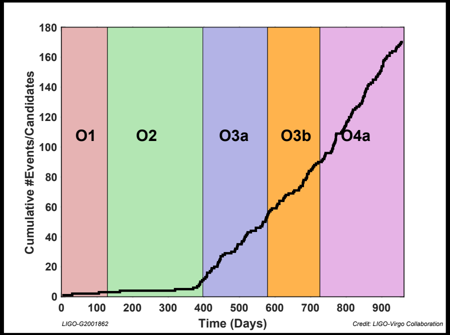
- You can always follow along with O4 Public Alerts here: https://gracedb.ligo.org/superevents/public/O4/

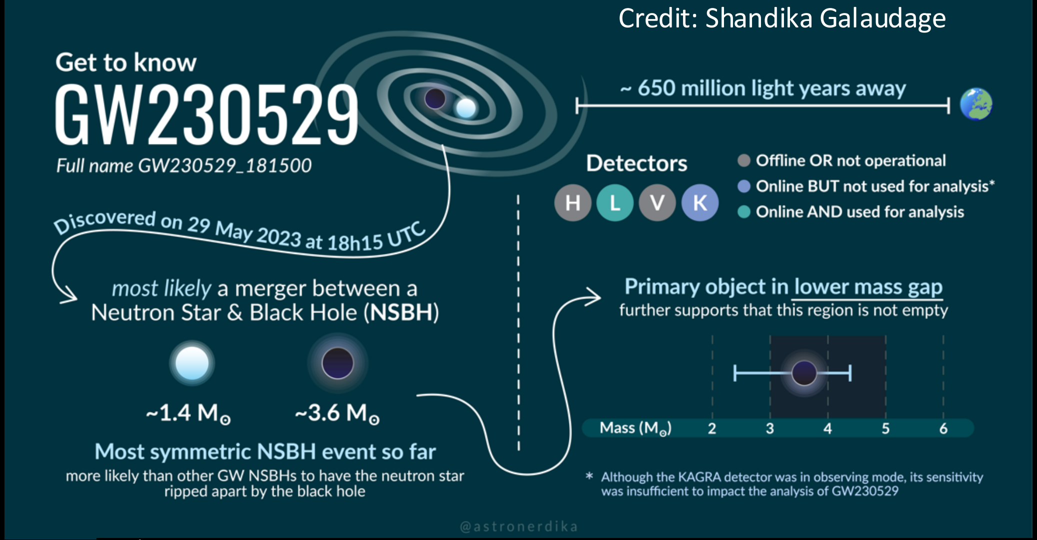
- As of April 1st 2025, there have been **203** O4 Significant Detection Candidates: 203 (228 Total - 25 Retracted)
- O4 Low Significance Detection Candidates: 3781 (Total)

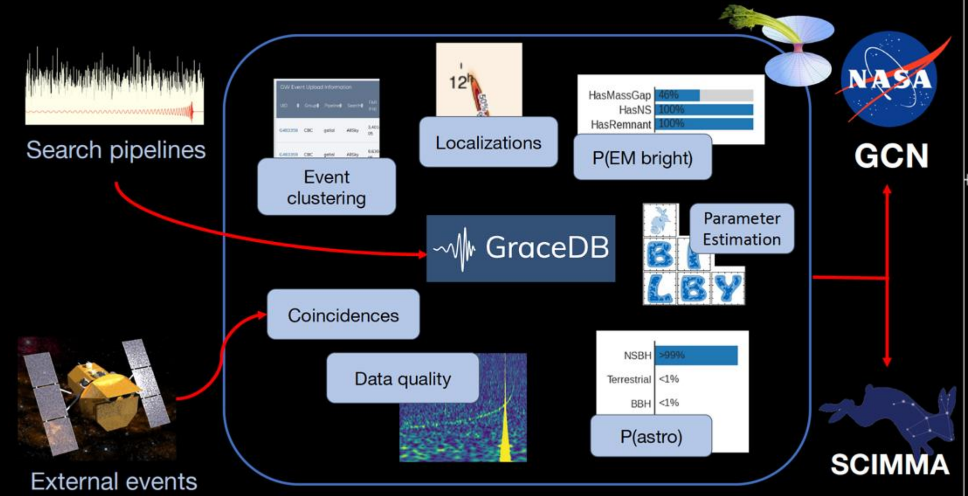
- Our first exceptional O4 gravitational wave detection (GW230529) was announced on April 5, 2024 (more info here: https://www.ligo.org/detections/GW230529.php).

- O5 is currently planned to start in 2028

First Results from O4 Observing Run

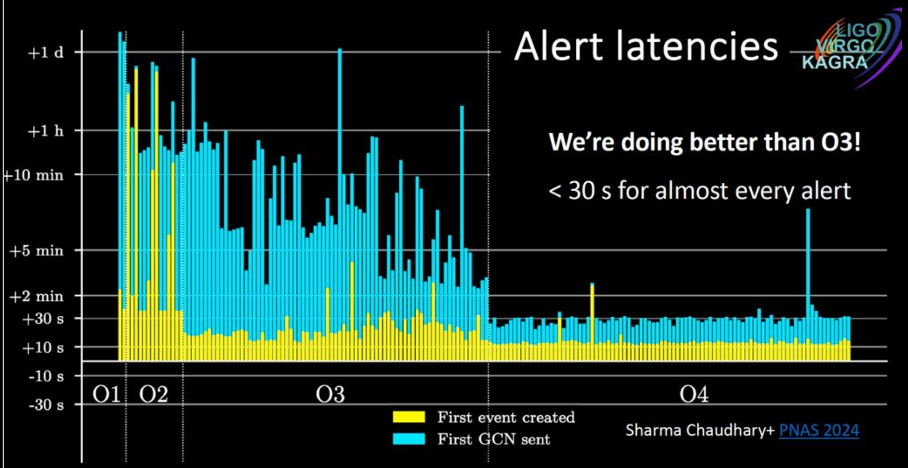






Slide credit: Geoffrey Mo, MIT

gwcelery.readthedocs.io/



e credit: Geoffrey Mo, MIT

Next Generation Observatories

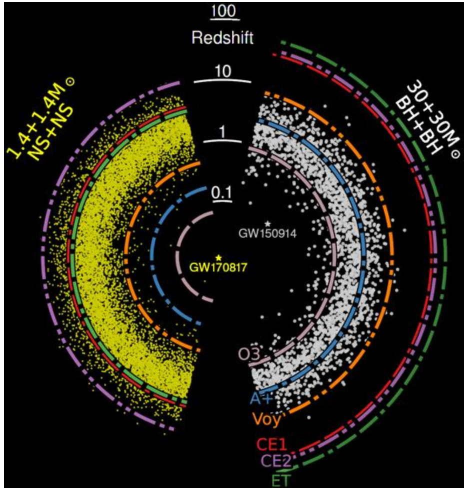
O5 will be "LIGO A+", significant further upgrades for Virgo and KAGRA too.

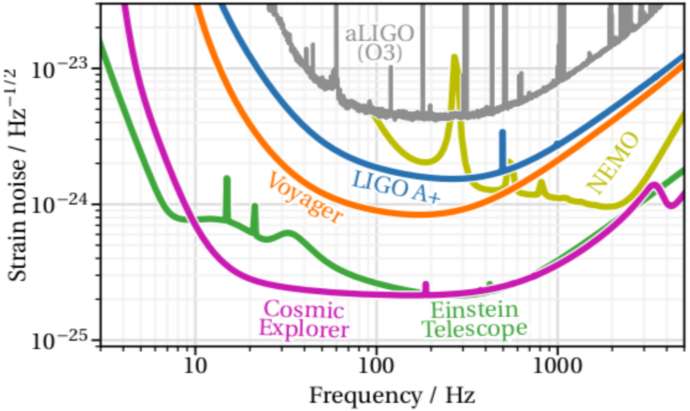
LIGO India is coming!

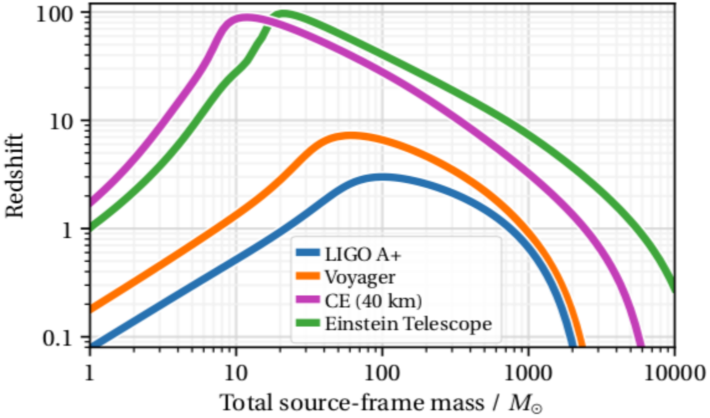
Next upgrade plan "LIGO A♯" [LIGO-T2200287]

3G detectors:

- Triangle configuration underground for Einstein Telescope.
- Two widely separated, L-shaped surface facilities in the US CE40 and CE20 for Cosmic Explorer
- Gain of a factor of 10 and lower frequency bound



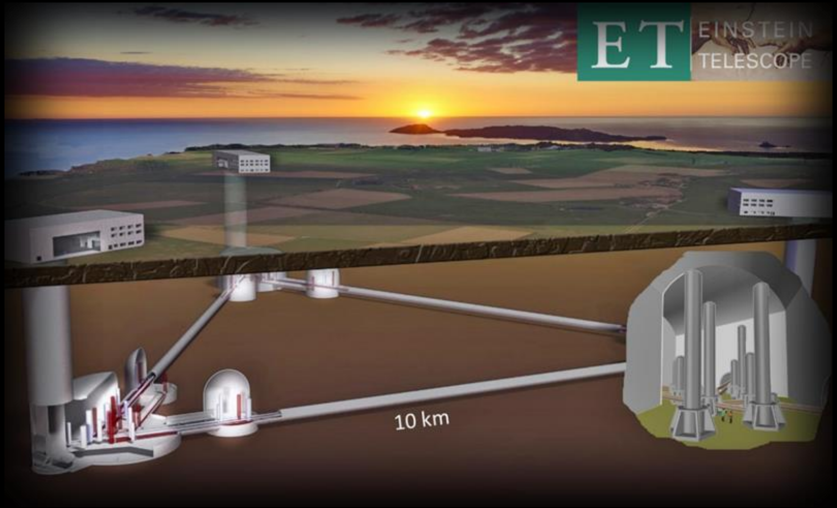




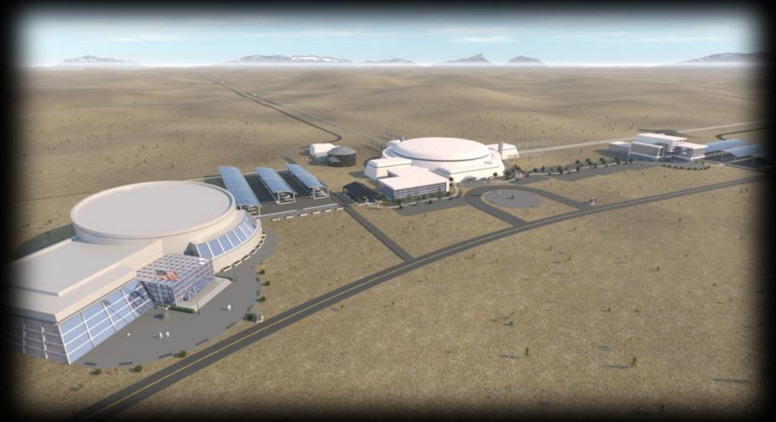
- New challenges (long-waveforms, overlapping signals, strong foreground, correlated noise)
- 3G observatories will detect **thousands of signals every day**
  - weak signals, loud mergers
  - BNS, NSBH, BBH, SN bursts, CW, …
- 3G detectors enable a ~complete census of BNS and BBH mergers

LIGO and Virgo (+ KAGRA + LIGO-India + Cosmic Explorer + Einstein Telescope) Will Change Our Thinking in the Future

LIGO-India: 2030+



Einstein Telescope (Europe): 2035+

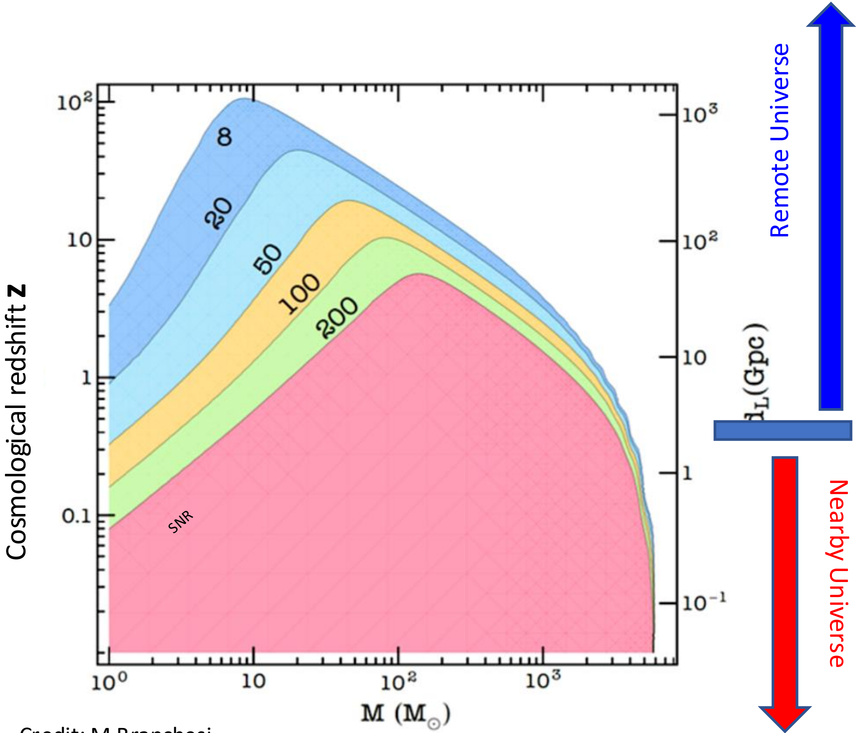


Cosmic Explorer (USA): 2035+

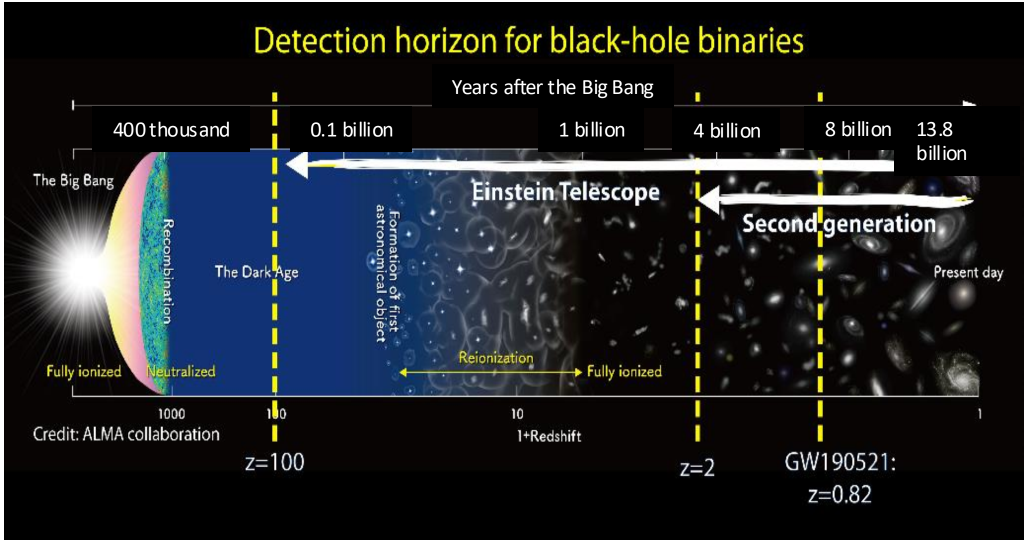
The next generation

ET/CE will be a new discovery machine:

- ET/CE will explore almost the entire Universe listening the gravitational waves emitted by black hole, back to the dark ages after the Big Bang



Credit: M.Branchesi



ET/CE will be a precision measurement observatory:

- ET/CE will detect, with high SNR, hundreds of thousands coalescences of binary systems of Neutron Stars per year, revealing the most intimate structure of the nuclear matter in their nuclei
- Robust statistics on GRB+BNS merger association, and how that correlates with orientation & distance
- BNS signals will be in band and detectable for O(100s) of seconds to several hours
- Advanced warning for EM follow-up (though localization will be rough)

ET/CE Science Case in a nutshell

ASTROPHYSICS

- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

FUNDAMENTAL PHYSICS AND COSMOLOGY

- **The nature of compact object**s
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

Acknowledgments

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