Australian Government
Australian Research Council

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

Ground based interferometers: The Next Decades

David McClelland

Director, Centre for Gravitational Astrophysics

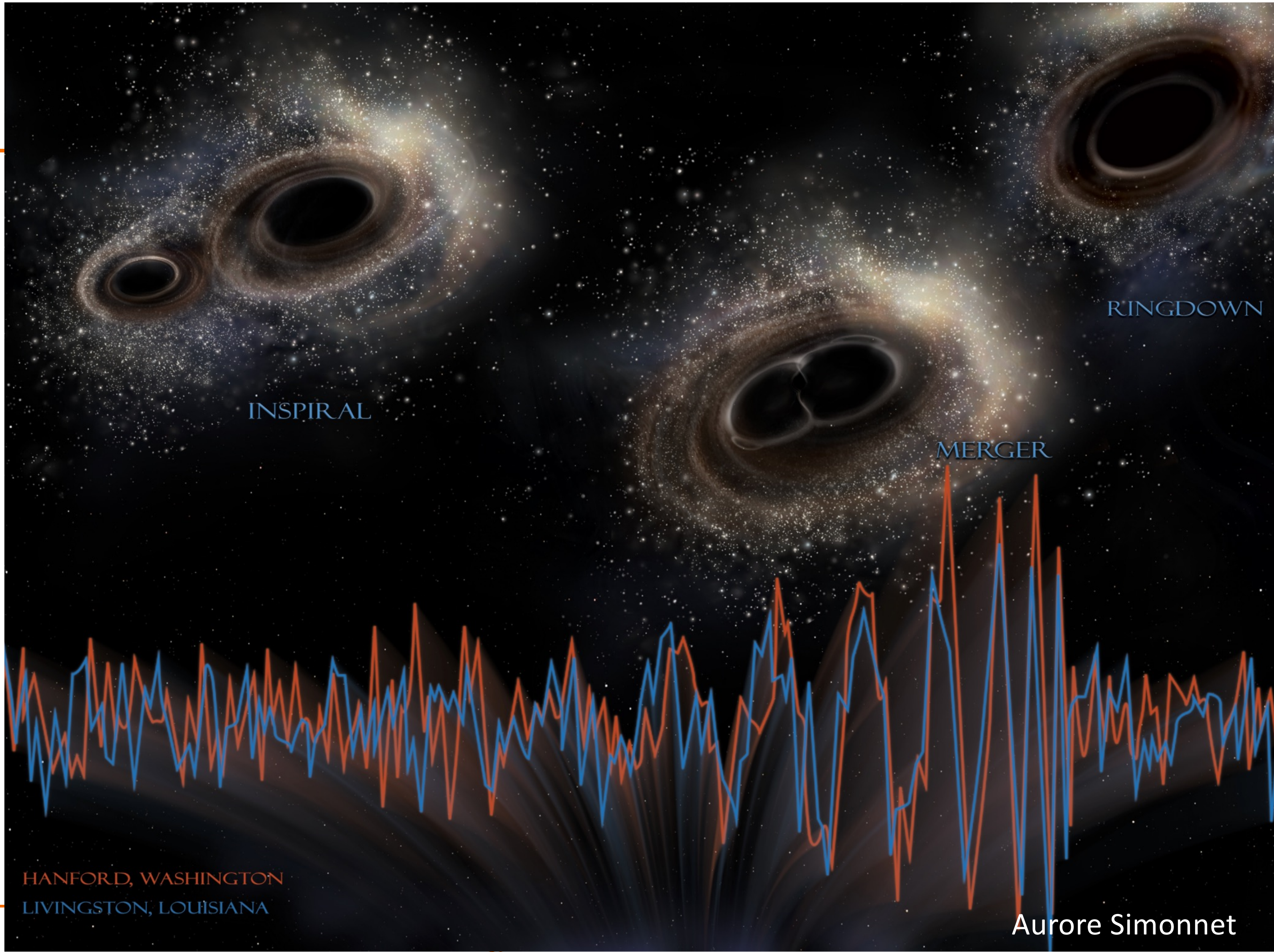
The Australian National University

https://cga.anu.edu.au

Acknowledgement Bram Slagmolen; OzGrav; LIGO Scientific Collaboration

SWINBURNE UNIVERSITY OF TECHNOLOGY
Australian National University
MONASH University
THE UNIVERSITY of ADELAIDE
THE UNIVERSITY OF MELBOURNE
THE UNIVERSITY OF WESTERN AUSTRALIA
AAO
CSIRO

GW150914 was the most powerful astrophysics event observed to that time



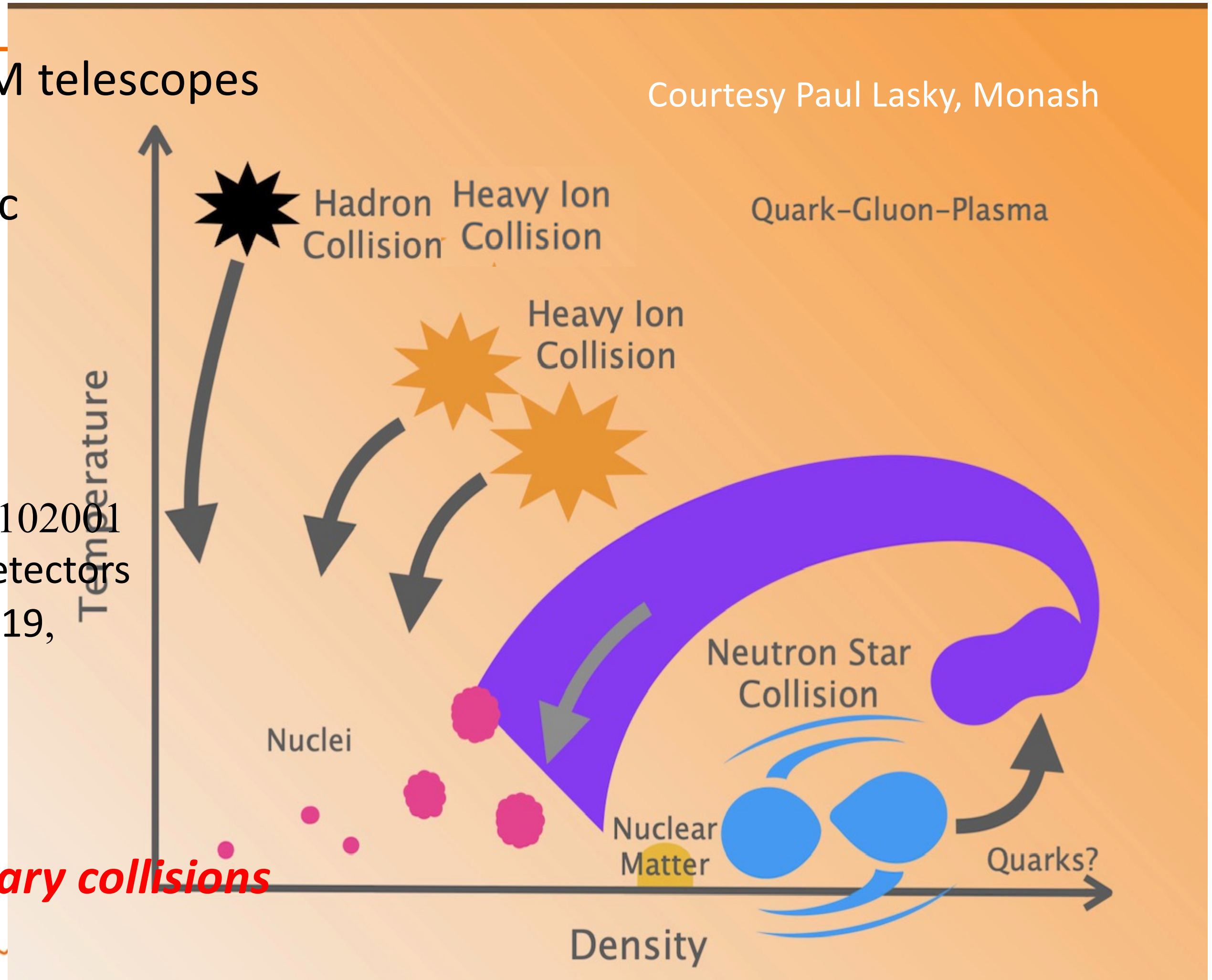
Gravitational waves, high energy physics and dark matter

- GW170817 had the most number of EM telescopes ever trained on a single event
  - origin of the heavy elements etc

- **Temperature vs density plot**

- **Dark matter searches**

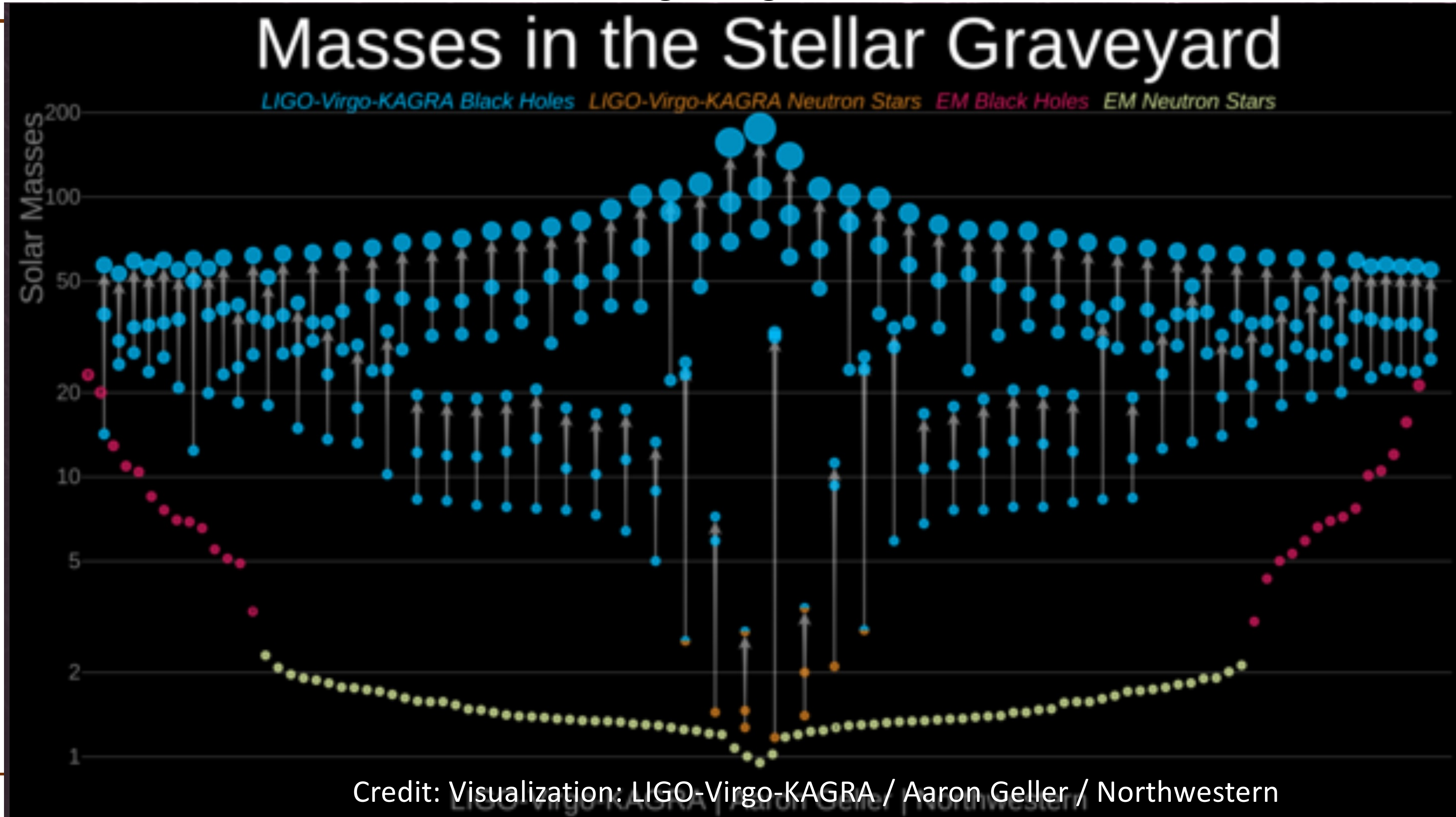
- GWs from dark matter interactions with black holes eg Abbott et al 2022,PRD 105, 102001
- direct influence of dark matter clouds on the detectors Abbot et al 2022a , via weak force, Grote et al 2019, Phys. Rev. Research 1, 033187 and superradiant growth of scalar, ultralight bosons (much less than 1 eV/c^2) around a spinning BH Sun and Spencer.; Laha yesterday



- *To date observed events have been binary collisions*
  - *more is anticipated!*

First 3 observing runs with the current GW network

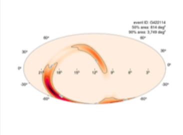
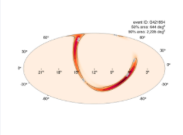
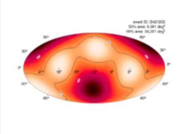
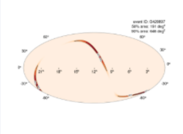
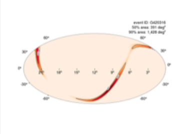
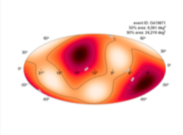
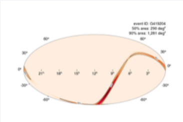
LIGO, Virgo, Kagra, GEO



Credit: Visualization: LIGO-Virgo-KAGRA / Aaron Geller / Northwestern

Observing Run 4 https://gracedb.ligo.org/superevents/public/O4/?page=2&showall=0

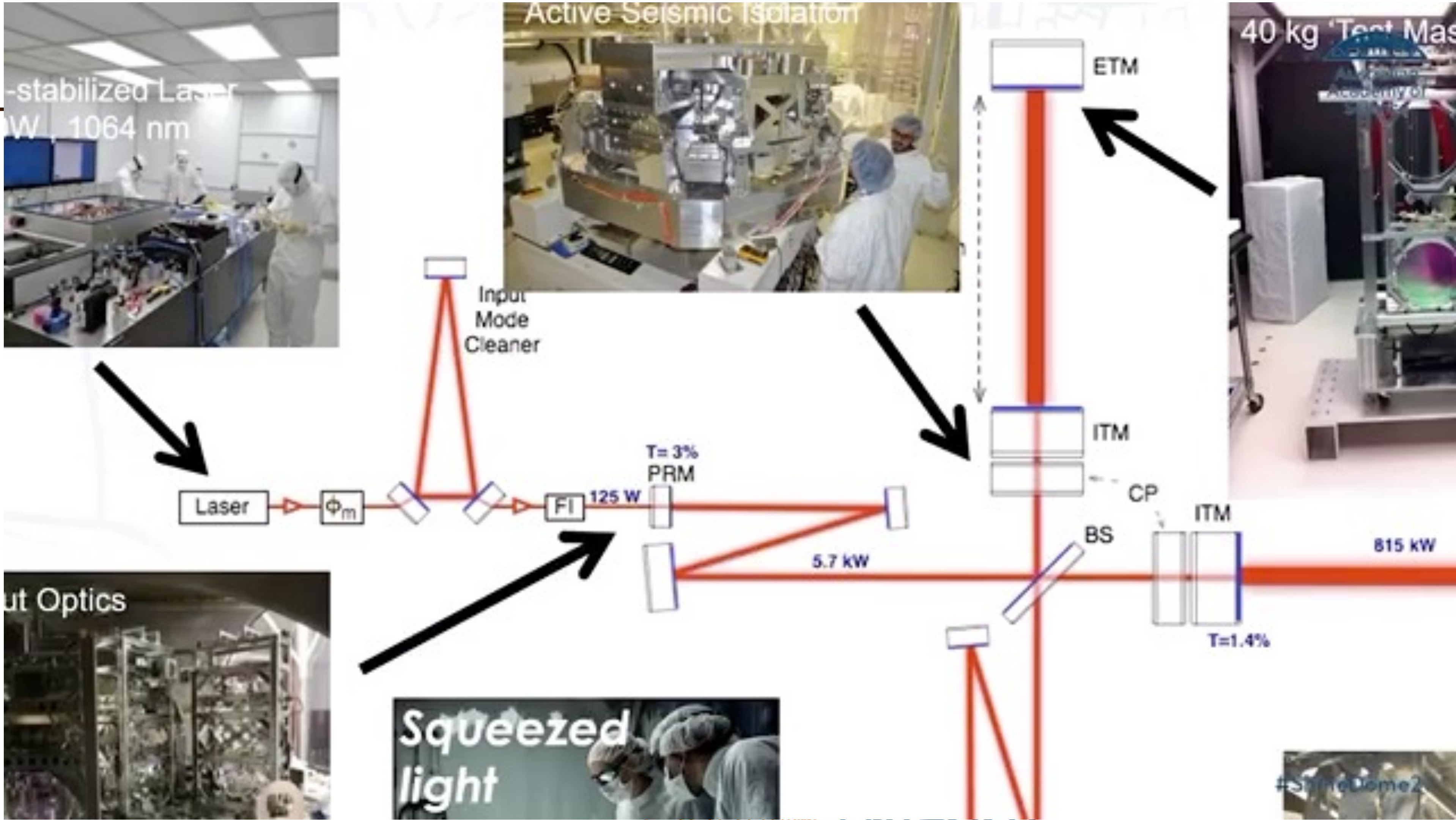
27 late May to early August 2023

S230806ak	BBH (>99%)	Yes	Aug. 6, 2023 20:40:41 UTC	GCN Circular Query Notices | VOE		1 per 10.711 years
S230805x	BBH (>99%)	Yes	Aug. 5, 2023 03:42:49 UTC	GCN Circular Query Notices | VOE		1 per 3.4497 years
S230802aq	BBH (90%), NSBH (6%), Terrestrial (3%)	Yes	Aug. 2, 2023 11:33:59 UTC	GCN Circular Query Notices | VOE		1 per 1.4226 years
S230731an	BBH (81%), NSBH (18%)	Yes	July 31, 2023 21:53:07 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years
			July 29, 2023 08:23:17 UTC	GCN Circular Query Notices | VOE		1 per 9.3389 years
S230726a	BBH (>99%)	Yes	July 26, 2023 00:29:40 UTC	GCN Circular Query Notices | VOE		1 per 8.2692e+05 years
S230723ac	BBH (87%), Terrestrial (13%)	Yes	July 23, 2023 10:18:34 UTC	GCN Circular Query Notices | VOE		1.6821 per year

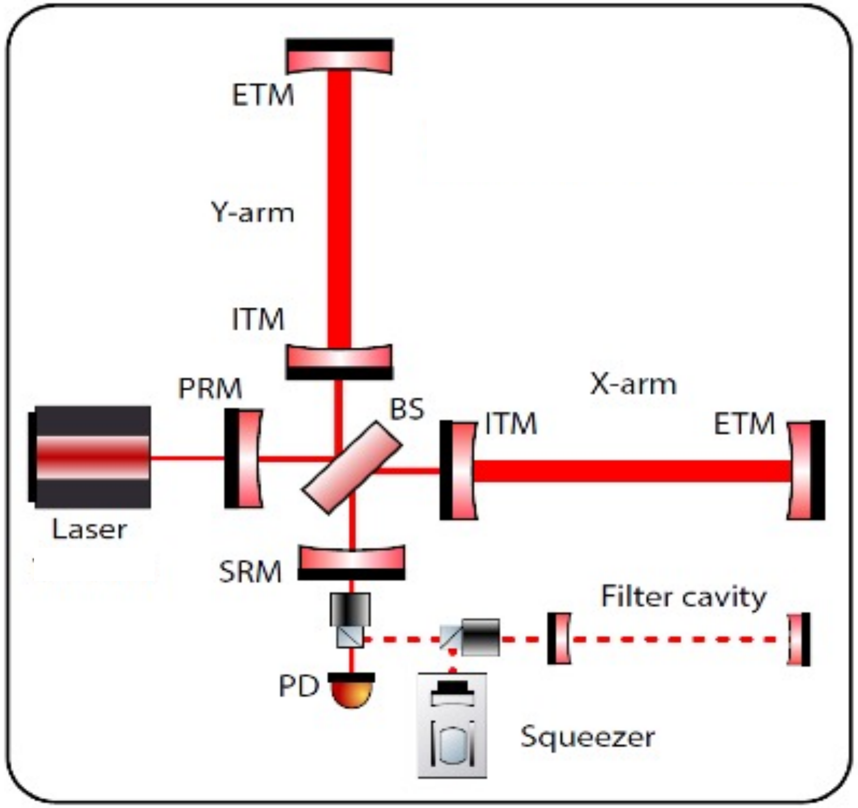
Gravitational Wave Events

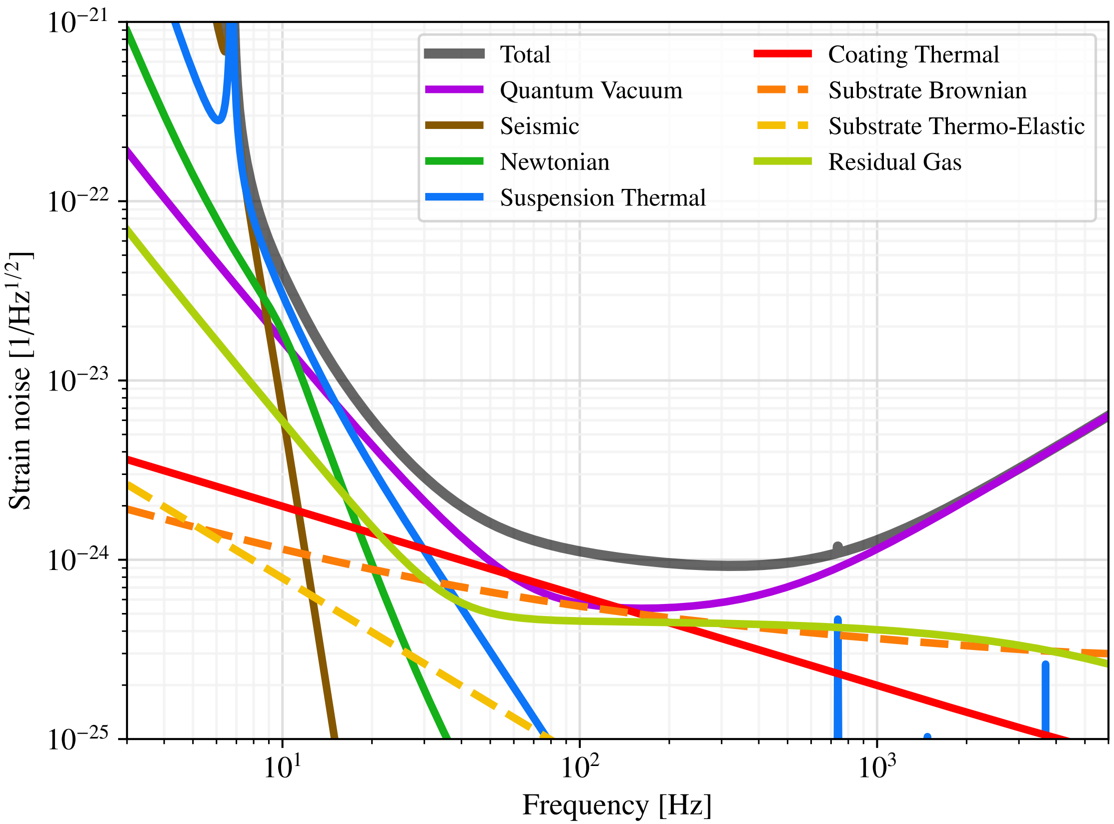
LIGO/Virgo/KAGRA GCN alerts

Designed for iPhone. Not verified for macOS.


-stabilized Laser
W , 1064 nm
Active Seismic Isolation
40 kg 'Test Mas
ETM
Input
Mode
Cleaner
ITM
T= 3%
PRM
CP
ITM
Laser
FI
125 W
BS
815 kW
5.7 kW
T=1.4%
ut Optics
Squeezed
light

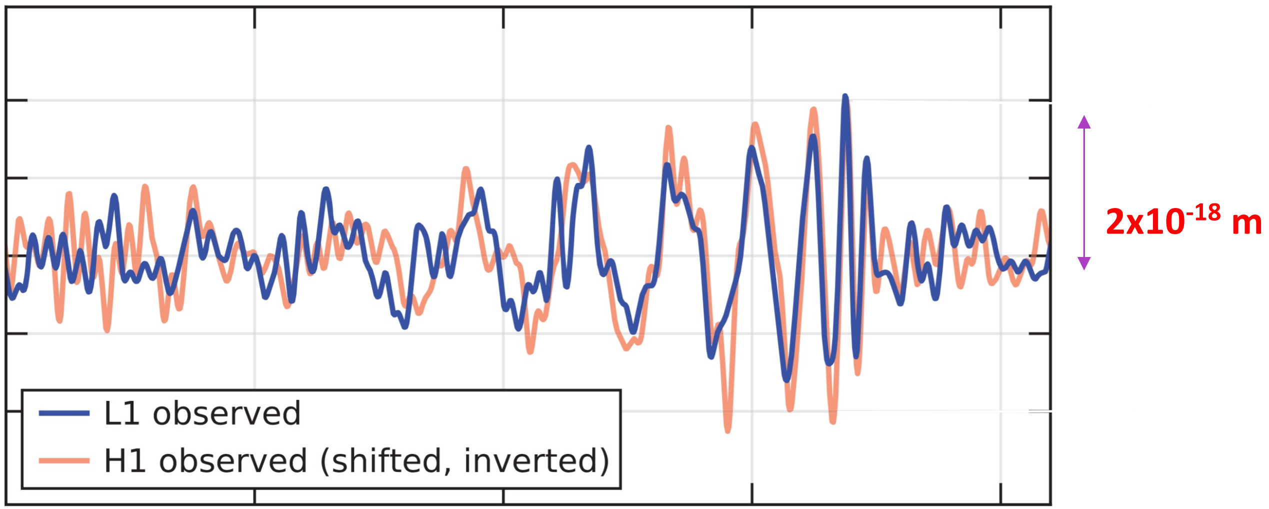
Standard Detector Layout and noise sources





Pinup for precision measurement and engineering!

B. P. Abbott *et al.*
(LSC, Virgo)
Phys. Rev. Lett. **116**,
061102, 2016



Effectively we have observed the separation between the **centres of mass of 40kg objects (10kg reduced mas) oscillate from 30Hz up to 240Hz with a peak amplitude of** ~ **2×10^{-18} m!**

Ultimately – Quantum Mechanics!

$$\Delta x \Delta p \geq \hbar / 2$$

Position measurement of free object:

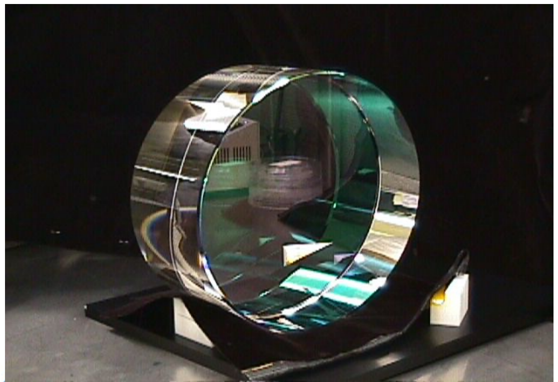
$$\Delta p \sim m\Delta \mathrm{v} \sim m\Delta x / \mathrm{t}$$

$$\Delta x \sim \sqrt{\frac{\hbar \, \mathrm{t}}{2m}}$$

So, 10kg ‘object’ in measurement time of 0.01 second:

$\Delta x_{SQL} \sim 2 \times 10^{-19}$m !

For the first time humans MAY see human-sized objects behave quantum mechanically! Science **372**, 1333-1336 (2021).



1980s: GW RESERCHERS LAUNCHED THE FIELD NOW KNOWN BROADLY AS QUANTUM INFORMATION -> WHY SUPPORTING FUNDAMENTAL RESEARCH IS CRUCIAL

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O4 - LIGO-Virgo-KAGRA

- The current O4 observing run covers all long baseline observatories (since 24 May 2023)
  - LIGO (H1/L1)
  - KAGRA
    - joined from the start of O4 for 4 weeks, after which it continued more commissioning work to improve performance
  - Virgo
    - had to delay joining the observing run due to instrument challenges earlier this year; now up

IMAGES NOT PUBLICALLY ACCESSIBLE

The Next Decade

Improving the performance 10-fold over current target performance.

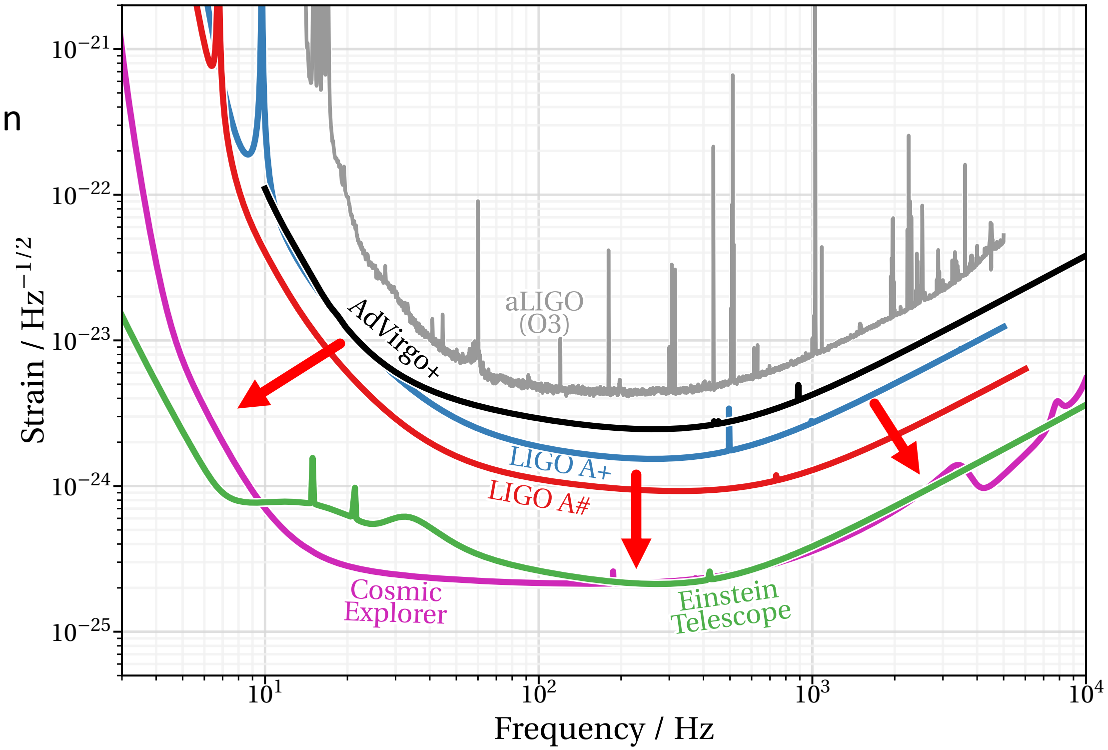
Few generations since the initial construction and operation of the ground based interferometric gravitational wave detectors

- Advanced LIGO/Advanced Virgo
- A+ LIGO / Virgo+ / LIGO-India
- A# / Virgo_nEXT

Currently we are generation 2 using some technologies predicted/planned for 2.5.

Third generation observatories

- New facilities
- New locations
- Incorporating lessons learned from current observatories



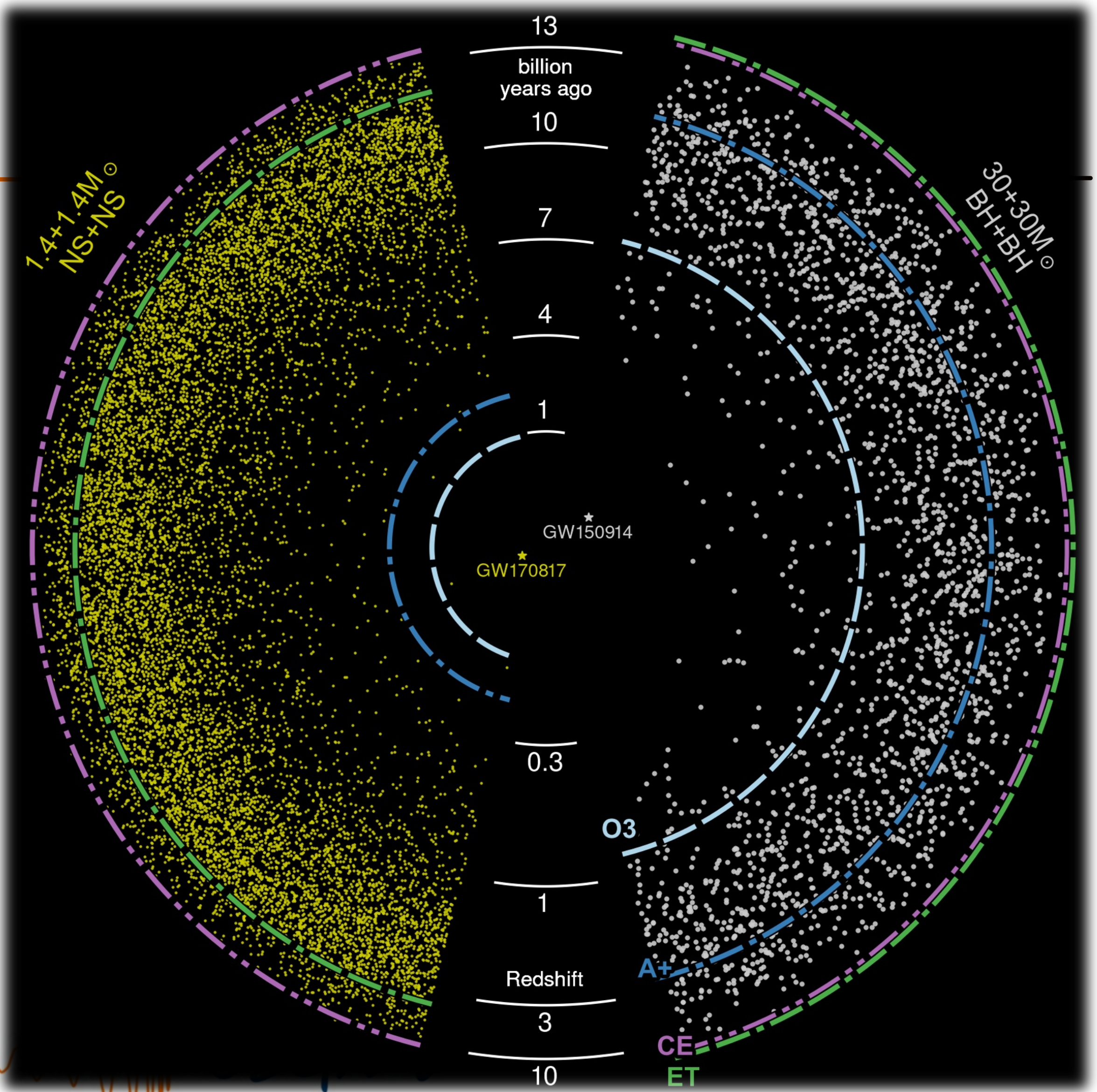
Kuns & Slagmolen

Next Generation (3G) Ground-based Observatories

Able to see astrophysical gravitational wave events out to almost the edge of the observable Universe.

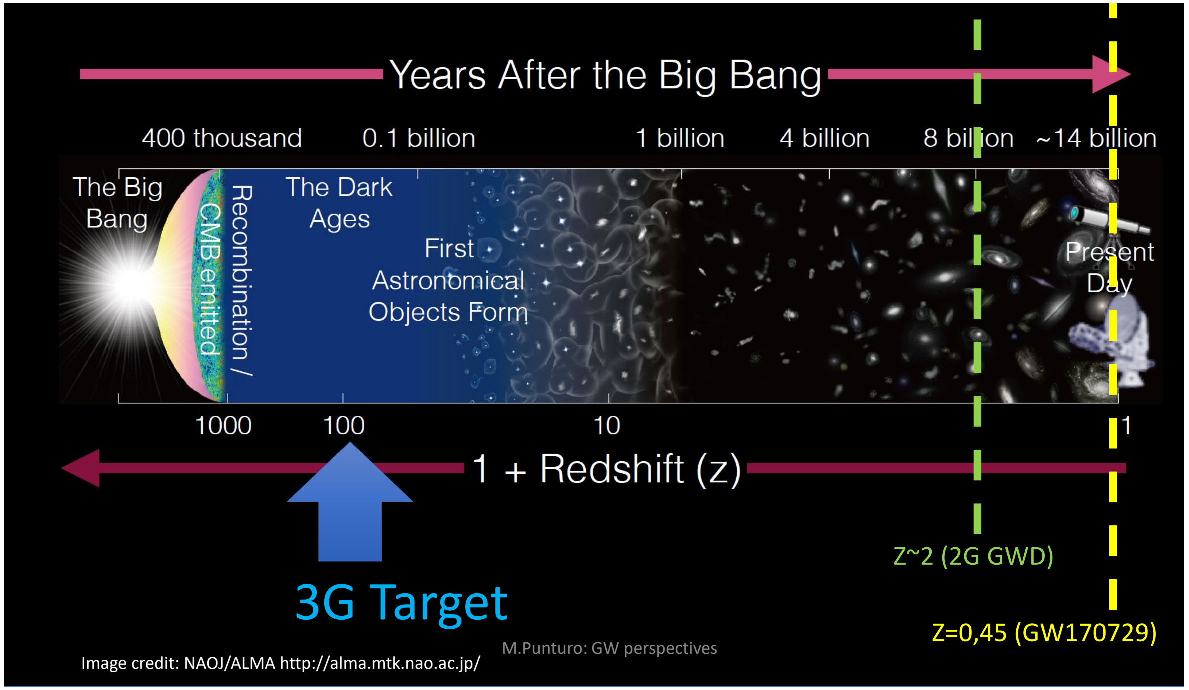
- Aim to see almost all BNS mergers
- To register most of 30+30M_{sol} mass black-hole mergers

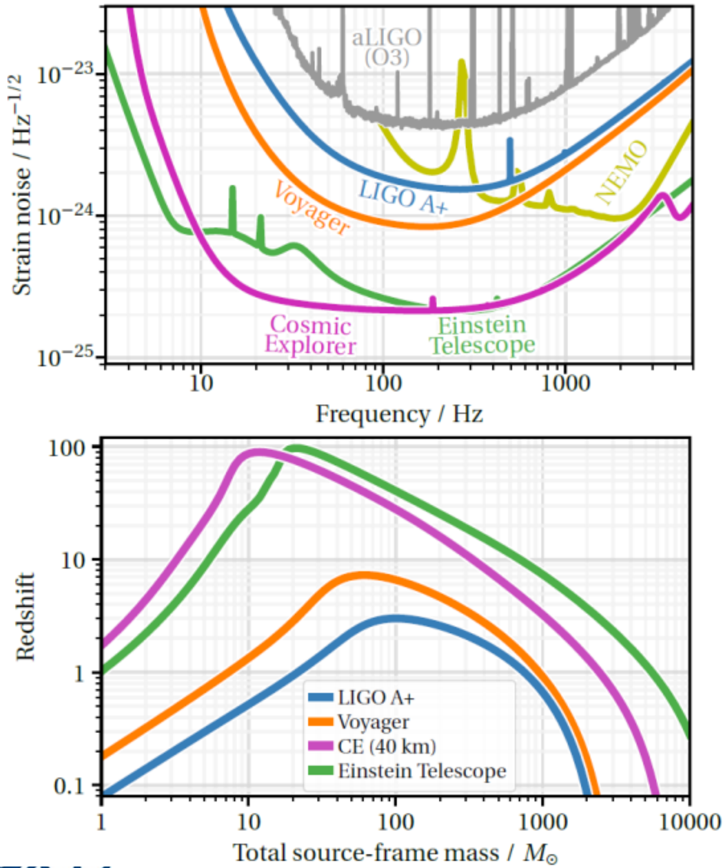
- Third generation observatories
  - 10x better performance across the whole frequency band



Kuns 2020 (https://dcc.cosmicexplorer.org/CE-T2000017), and Srivastava et al, "Science-driven tunable design of cosmic explorer detectors", The Astrophysical Journal, 931(1):22, 2022, https://doi.org/10.3847/1538-4357/ac5f04

Probing the Early Universe





Kuns 2020 (https://dcc.cosmicexplorer.org/CE-T2000017), and Srivastava et al, "Science-driven tunable design of cosmic explorer detectors", The Astrophysical Journal, 931(1):22, 2022, https://doi.org/10.3847/1538-4357/ac5f04

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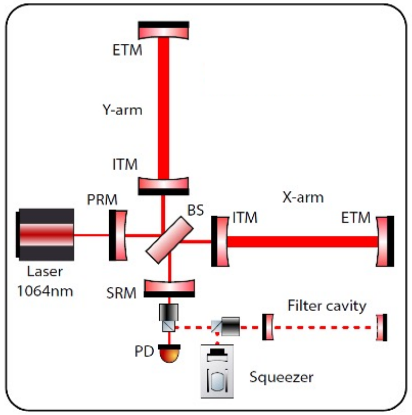
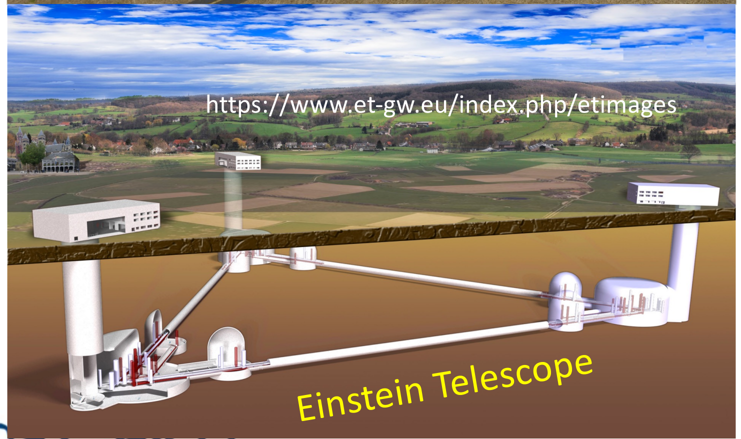
Next Generation Observatories

mid to late 2030s

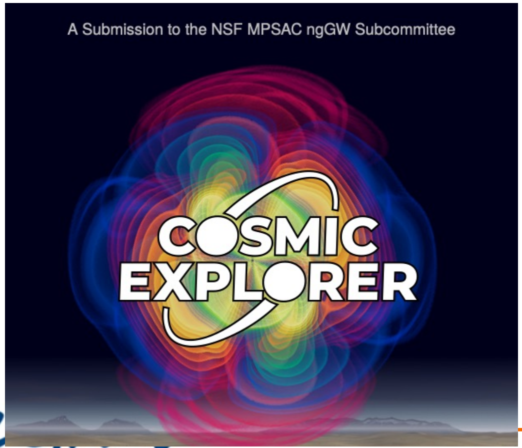
- Nominal configuration comparable to current detectors
  - Dual recycled Michelson Interferometer with arm cavities
  - Larger and heavier Test Masses in the arm cavities
- Cosmic Explorer
  - US based concept
- Einstein Telescope
  - European based proposal
- **Bridging concepts and proposals**
  - LIGO Voyager
  - NEMO





Cosmic Explorer

- Next-generation US-led gravitational wave observatory project
  - 40 km and 20 km L-shaped surface observatories
  - 10x better sensitivity compared to Advanced LIGO+
- Estimated operating in the mid-2030s
  - Initially scaled up A+ technology & enhancements
  - Flexible facilities allow building on R&D breakthroughs
- CE project submission to NSF's Next Generation Gravitational Wave Subcommittee
  - committee charged with to recommend on next-generation ground-based gravitational-wave science in the US

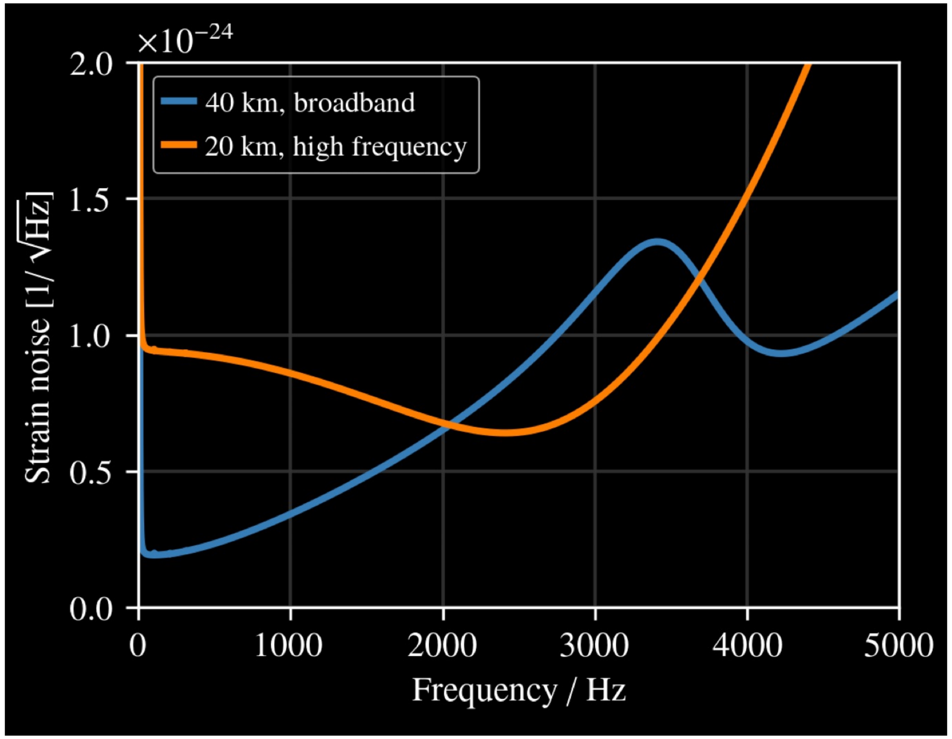


Design Motivation

Optimize science output while minimizing risk and complexity

Arm length

- 40 km detector with deep broadband sensitivity, from Hz - kHz (limited by free spectral range of 3.7 kHz)
- 20 km detector trades off sub-kHz sensitivity for better high-frequency (1-3 kHz) performance, neutron star post-mergers
- L-shape to reduce vacuum system cost (already 40% of cost); Long arms advantageous where surface feasible (North America, Australia?)



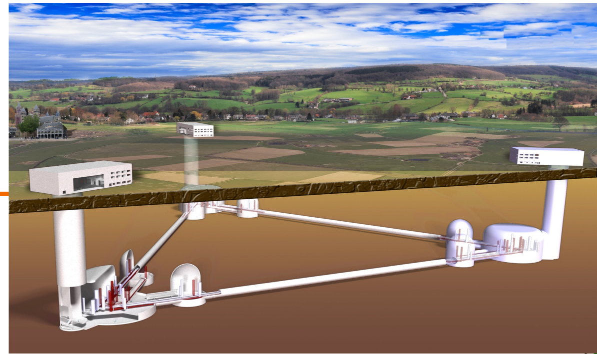
Number of detectors

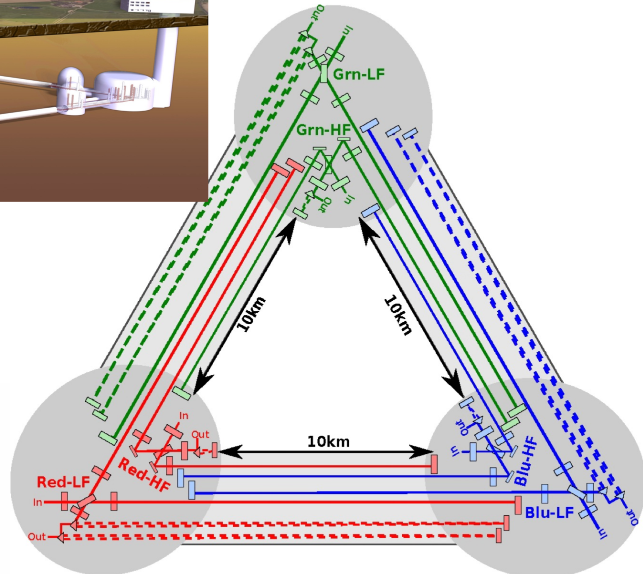
- Two widely separated CEs advantageous for source localization, polarization

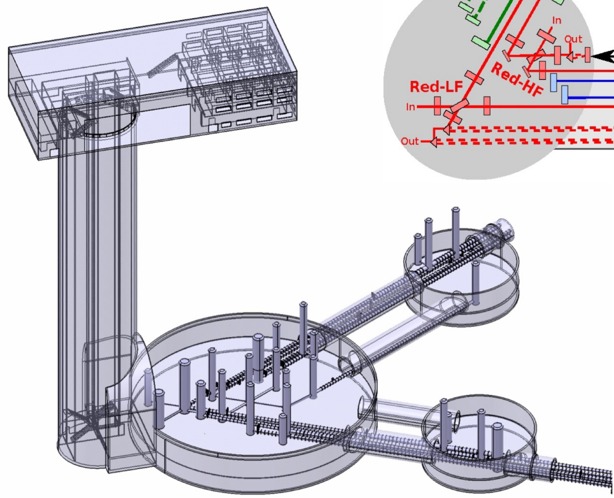
Srivastava et al, The Astrophysical Journal, 931(1):22, 2022, https://doi.org/10.3847/1538-4357/ac5f04

Einstein Telescope

- European based next generation gravitational wave observatory.
- Currently, Equilateral triangle
- Arm length 10 km
- 200-300m underground
- 3 ‘detectors’: Each detector consist of a low-frequency and high-frequency interferometer.
- Sense both polarisations, sensitive to low frequencies down to a few Hz







Promised major investments by Italy and The Netherlands depending on site location

https://www.et-gw.eu/index.php/etimages

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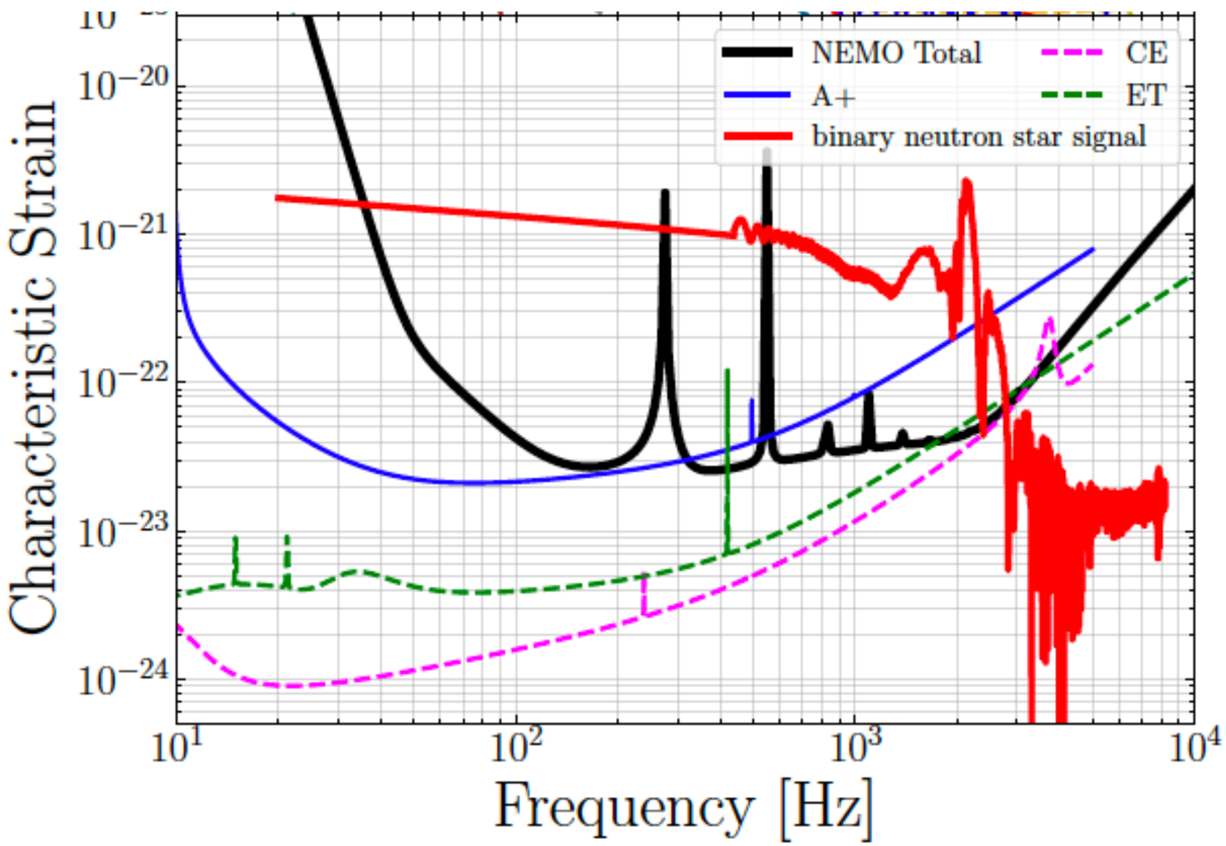
NEMO – Neutron start Extreme Matter Observatory (NEMO)

K. Ackley et al (OzGrav), “Neutron Star Extreme Matter Observatory: A kilohertz-band gravitational-wave detector in the global network”, PASA **37**, 45006 (2020).

- Detector looking at single events
- Increased sensitivity at kHz places significant constraints on NS Equation of State
- Trade off performance at lower frequencies
- Average number of post merger events detected with with NEMO increased to 1 – a few per year
- Potential to measure phase transitions in hot remnants : deconfined quarks, other exotica



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Optimum Global 3G Network