Future Ground-Based GW Detectors

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Gainesville, FL

Overview

- Gravitational-wave Astronomy now
- Future gravitational-wave science
- Near- and long-term upgrades
  - LIGO A+ AdVirgo+, Kagra+
  - Einstein Telescope, Cosmic Explorer
- Technical challenges
- Organization and timeline

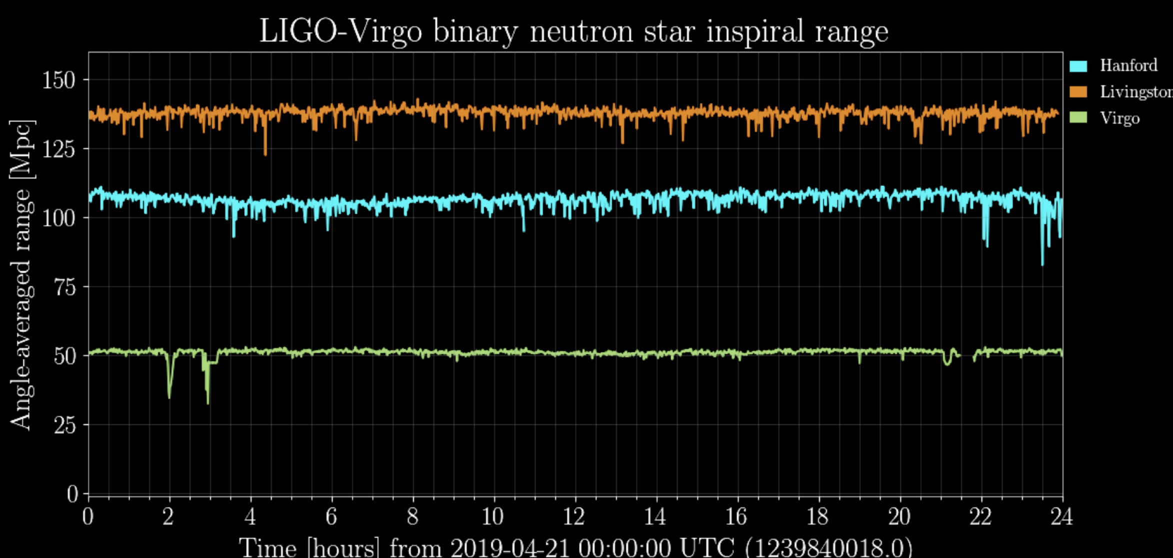
Gravitational-wave

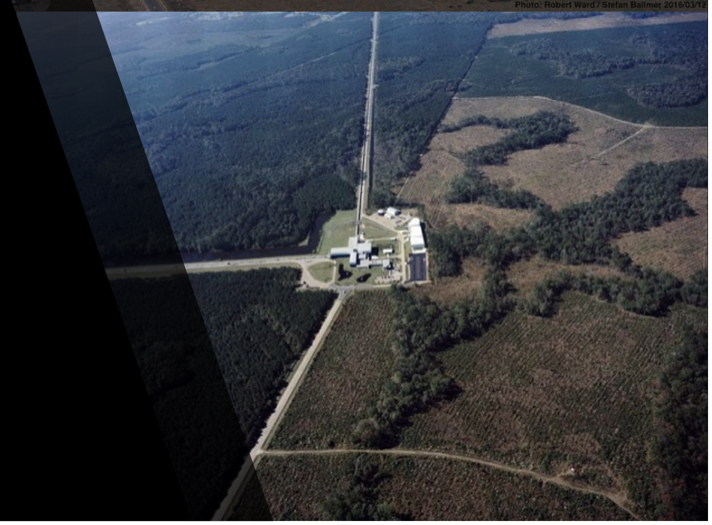
Astronomy

Now

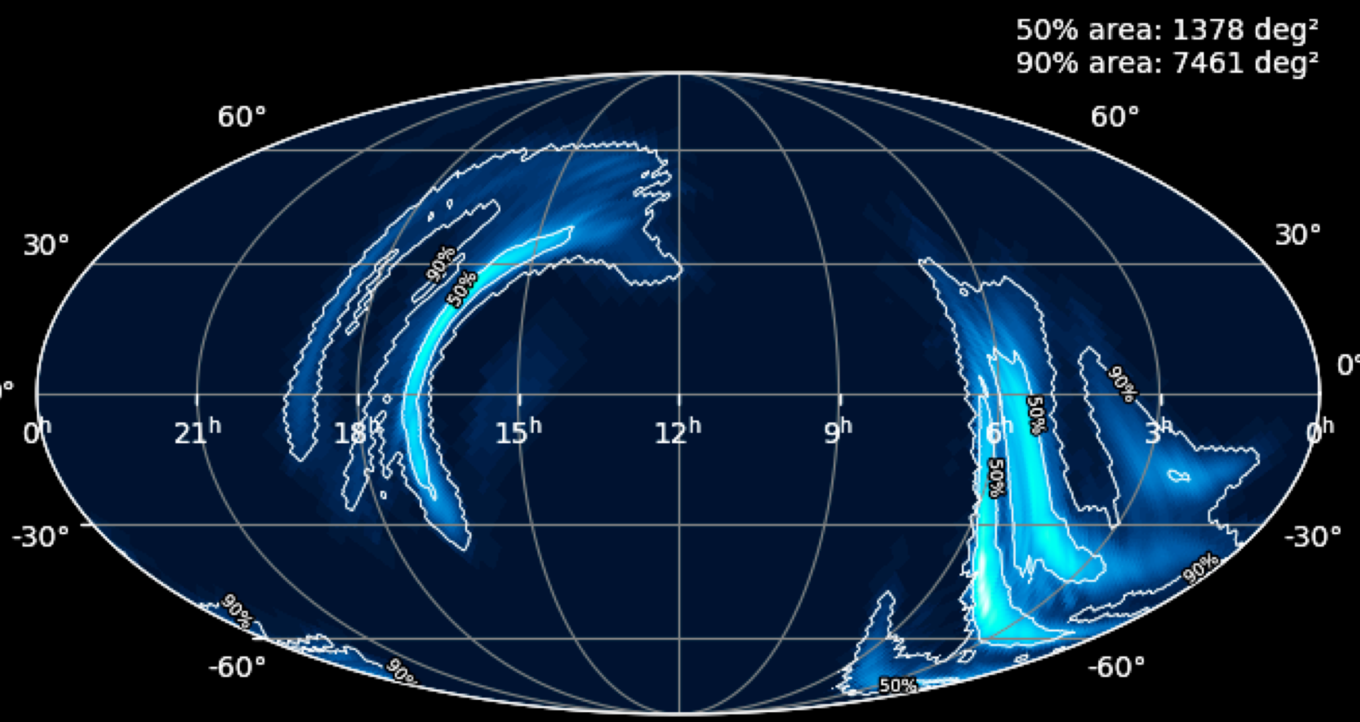
GW astronomy in full swing

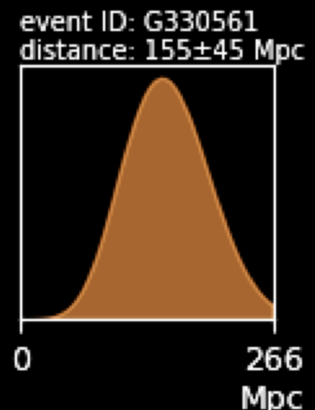
- Three km-scale detectors operational
  - LIGO Livingston ~140Mpc
  - LIGO Hanford ~105Mpc
  - Virgo ~ 55Mpc
- O3 run since April 1 2019
  - As of 4/24: 3 binary black hole merges





Just last week: BNS #2





Open alerts issued as GCN Circulars https://gcn.gsfc.nasa.gov
https://gracedb.ligo.org/superevents/S190425z/

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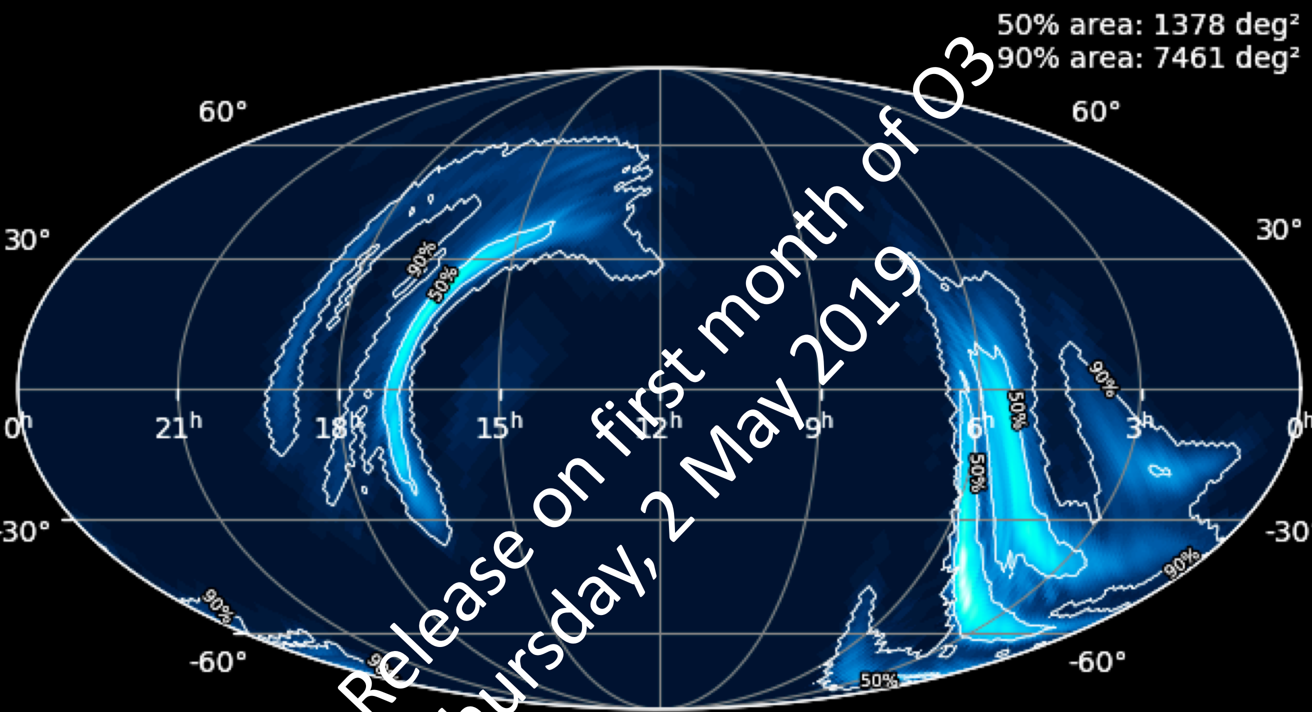

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https://gracedb.ligo.org/superevents/S190425z/

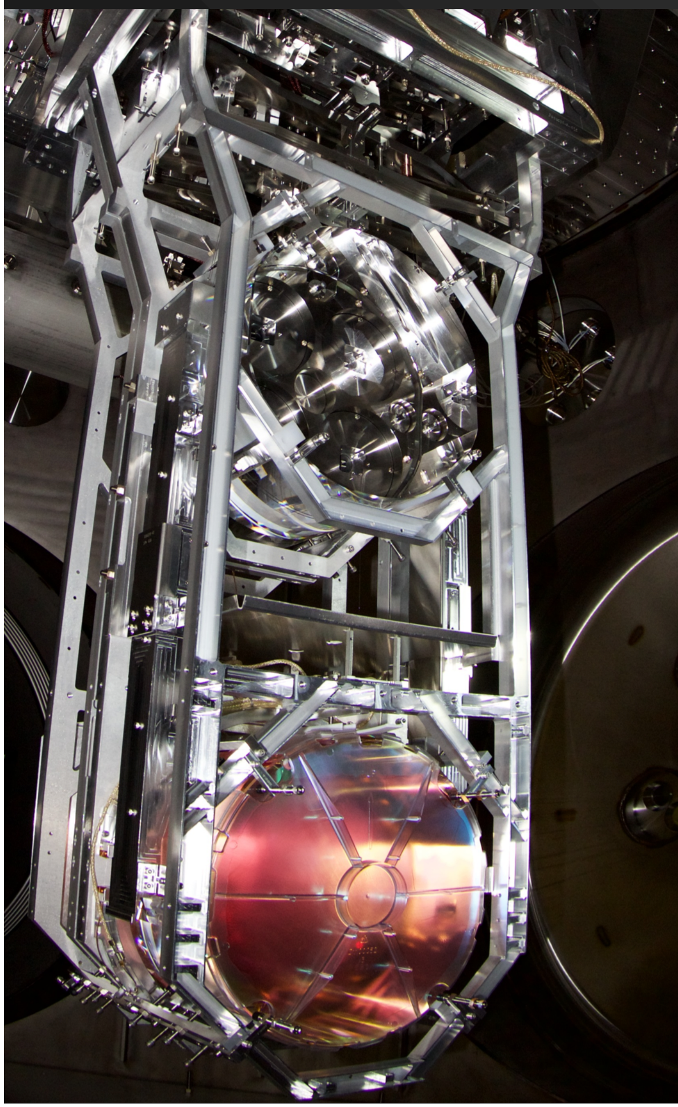
KAGRA

- Underground facility
- Cryogenic Sapphire test masses
- Locking full interferometer this summer
- Goal to join at the end of the O3 run

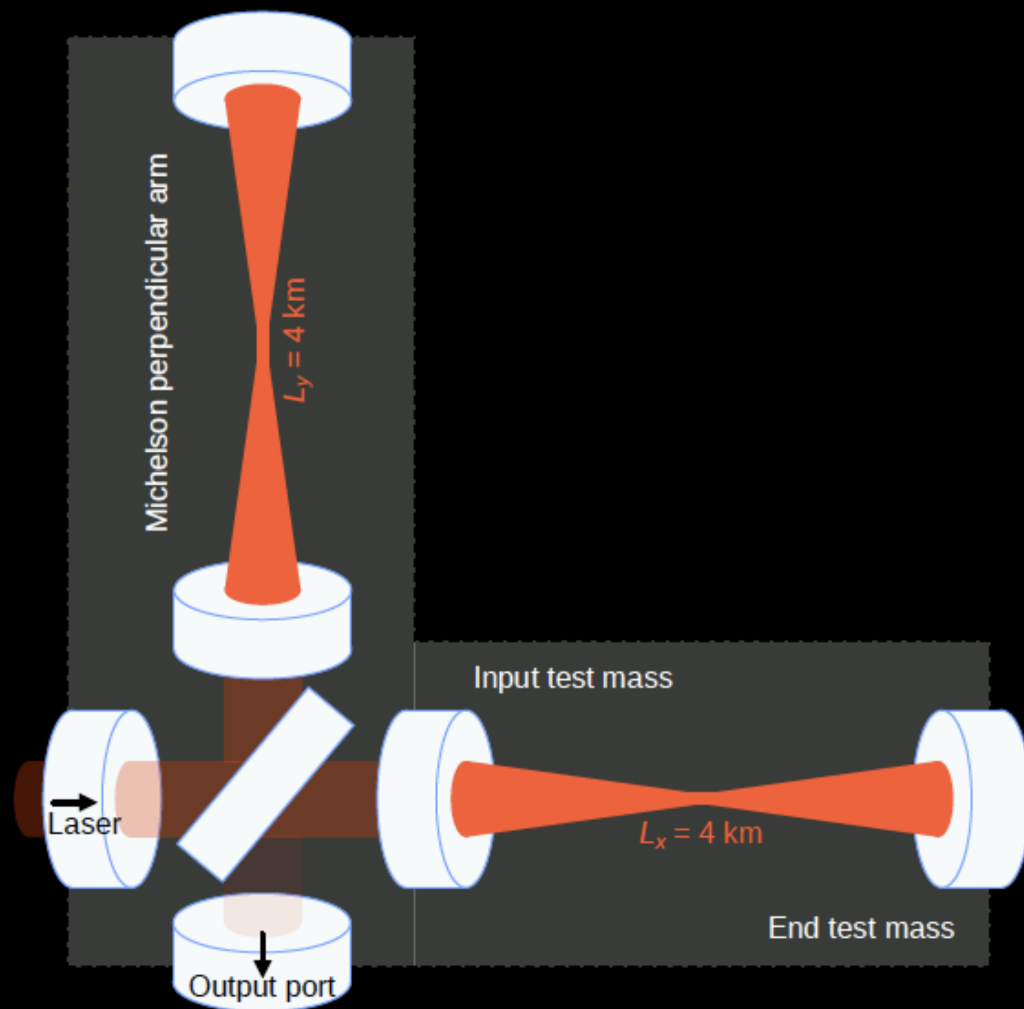
Today's detector network

A GW Interferometer in one slide

Quiet test mass



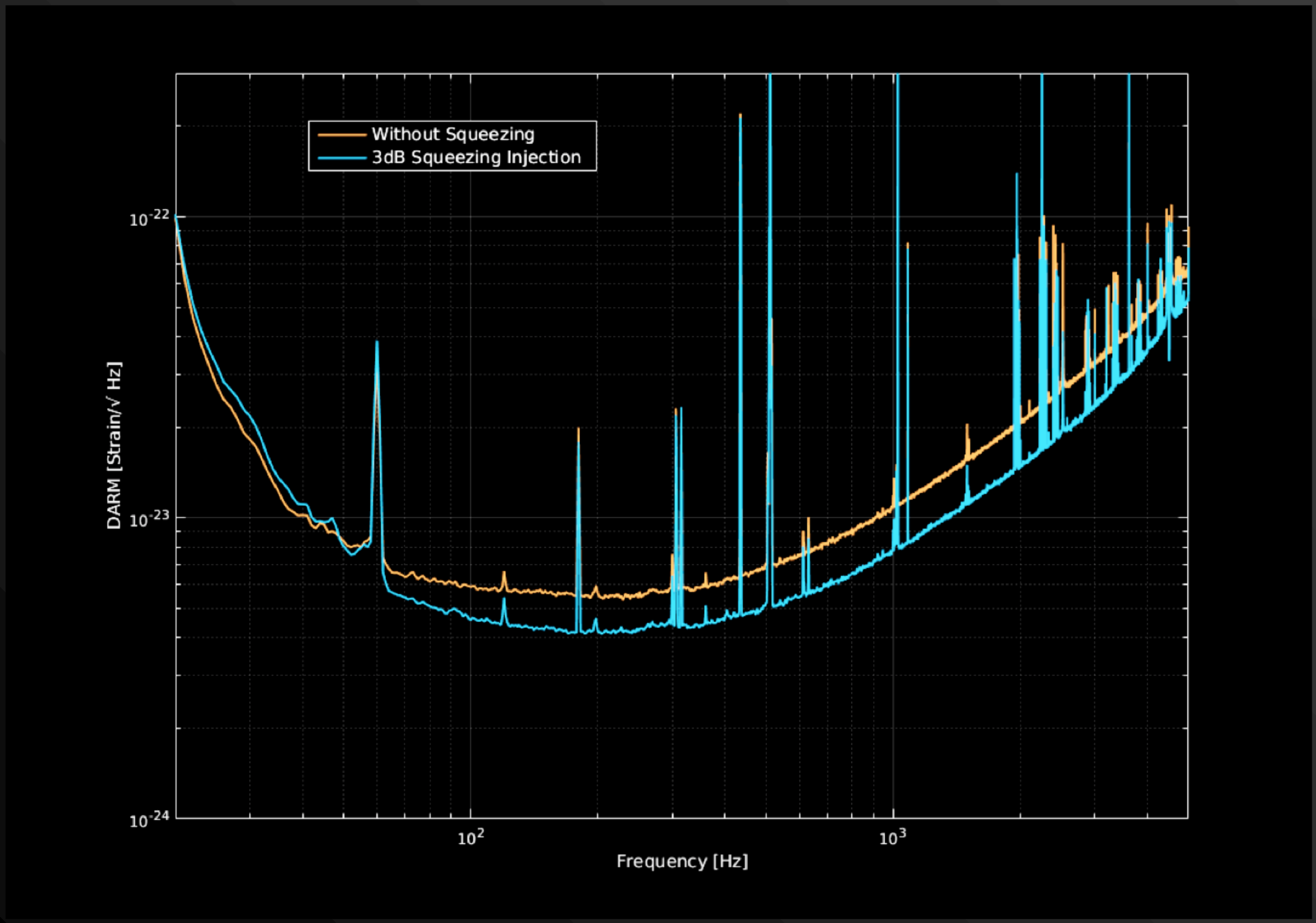
Interferometric readout



BP Abbott et al., Phys. Rev. Lett. **116**, 131103 (2016)

Vacuum Squeezing is now in use

LIGO Livingston detector in O3



Binary Neutron Stars range from ~125MPc to ~140MPc

What current detectors can reach

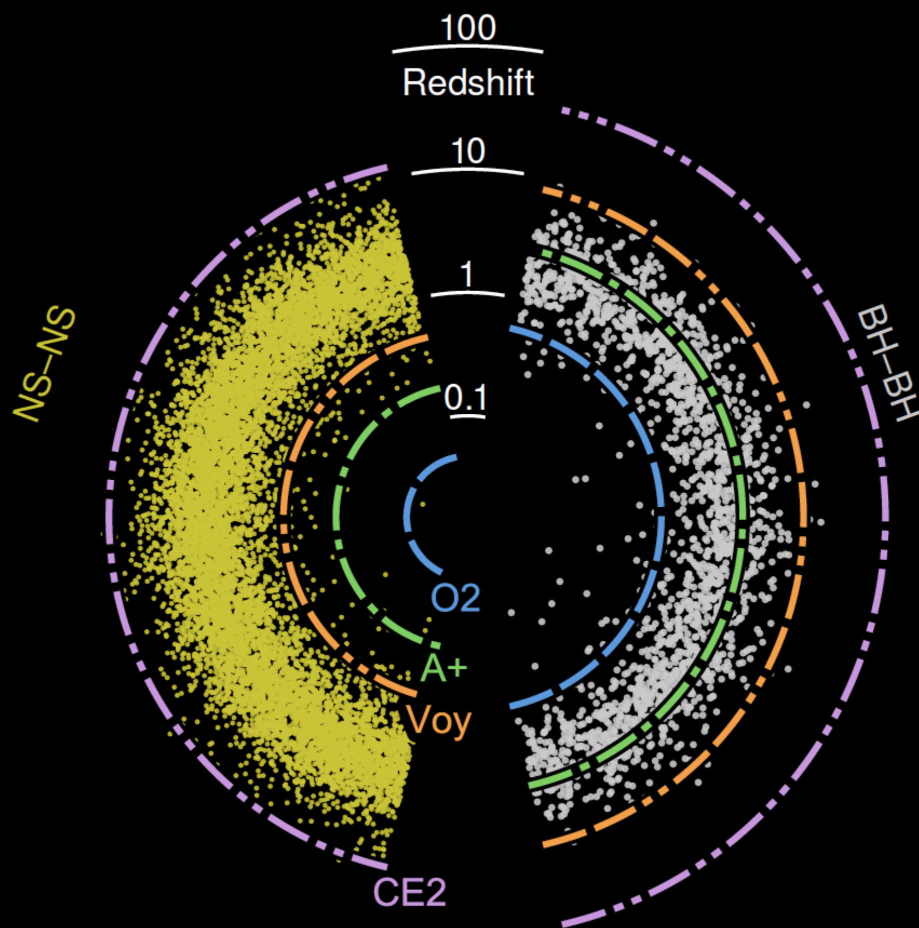
(at design sensitivity)

- GW merger events in the local universe
  - Black hole mergers: redshift $z \lesssim 2$
  - Neutron star mergers: redshift $z \lesssim 0.1$
- Most of the universe is still out-of-reach
  - At design at most O(1000)/yr detections per year
  - BH mergers: O(100 000)/yr in the universe
- Detected events relatively “noisy”
  - Typical Signal-to-noise ratio O(10)

What future detectors can reach

- High-redshift sources
  - Population III remnants merging at redshift $z \approx 10$
- High-fidelity source
  - Signal-to-noise ratio O(1000) for test of relativity and neutron star physics
- Large number of sources
  - Rare and exotic events
  - Population studies (a black hole merger every 5 minutes)

Compact binaries throughout the Universe

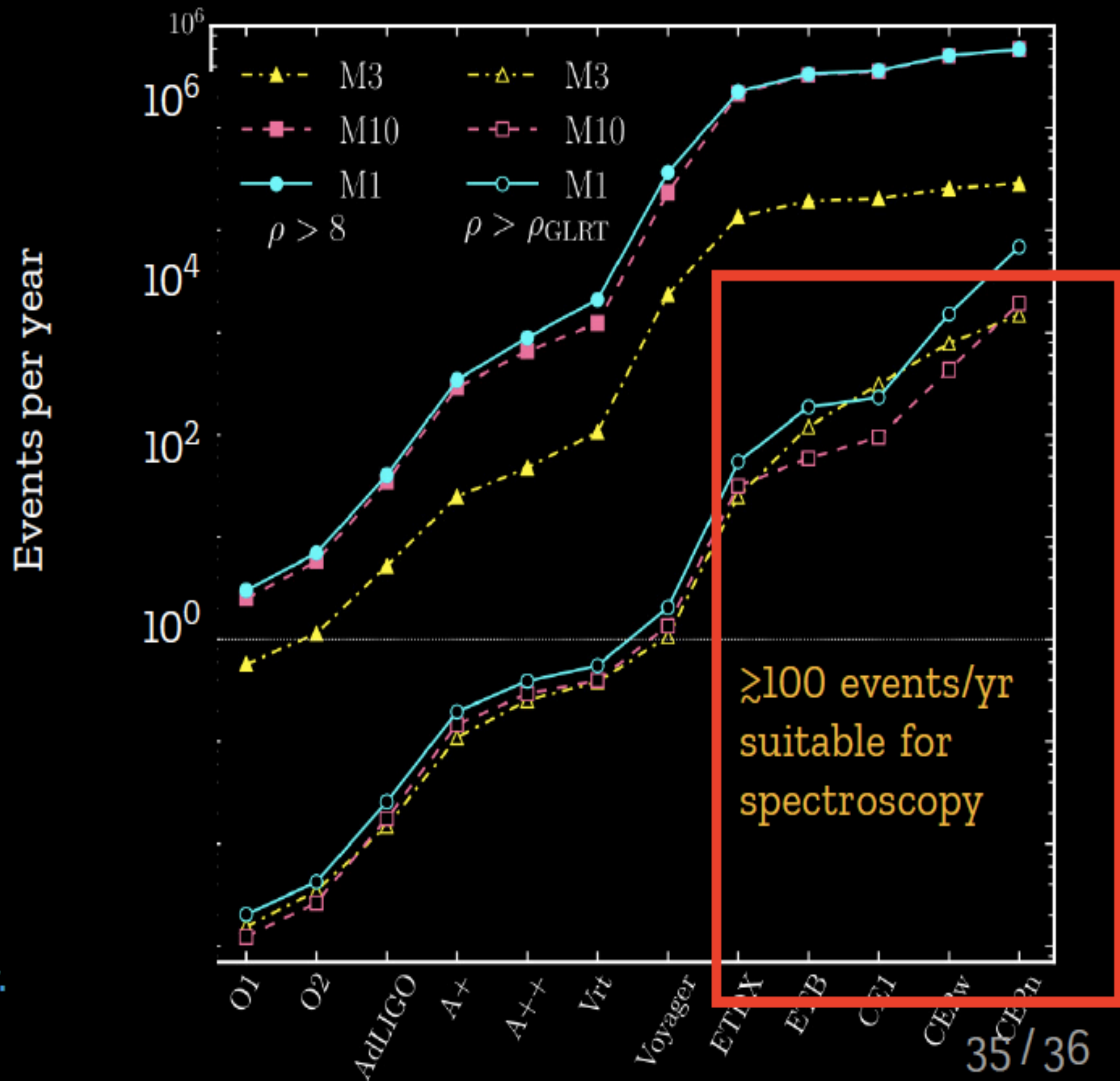


Hall/Vitale

https://dcc.ligo.org/LIGO-G1900803/public

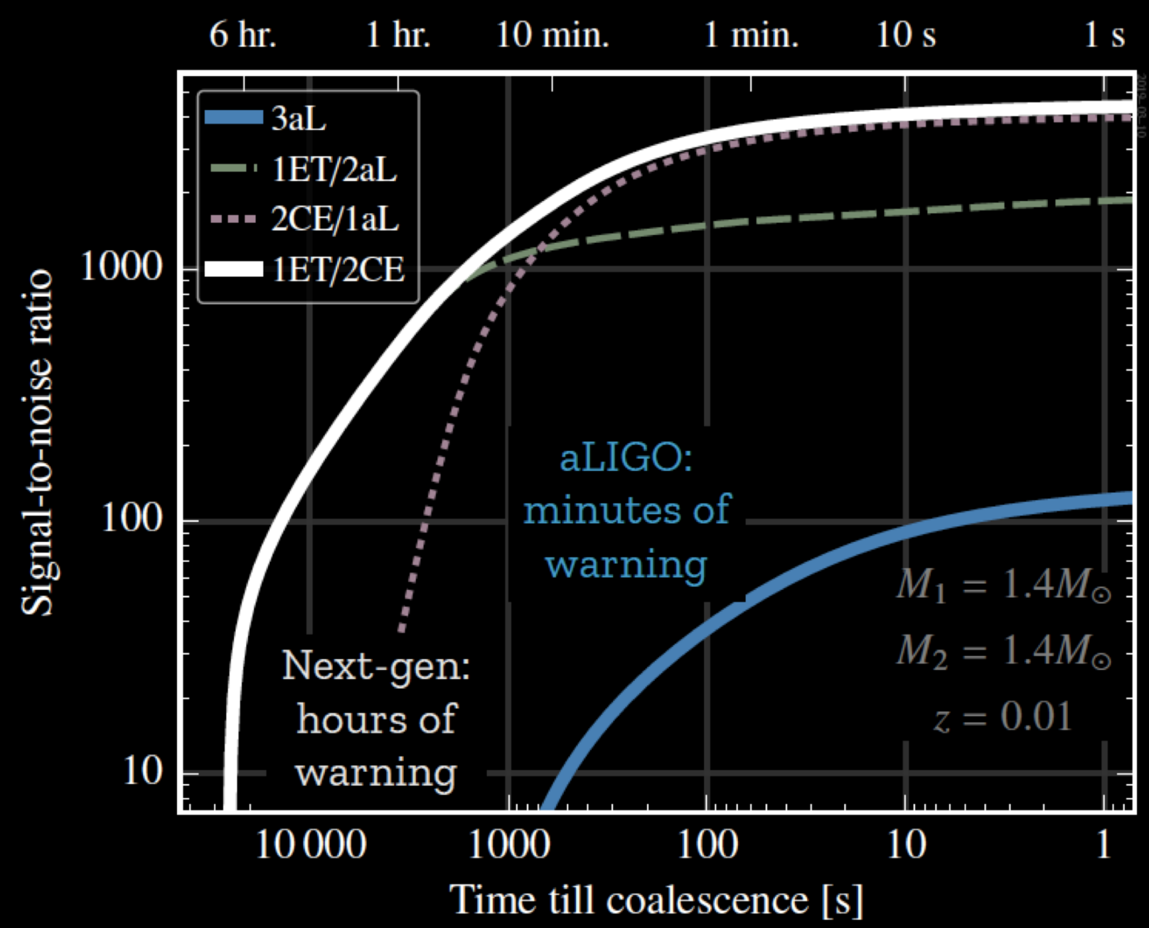
Tests of relativity

Look for deviations from Kerr geometry in the frequency spectrum of the ringdown signal



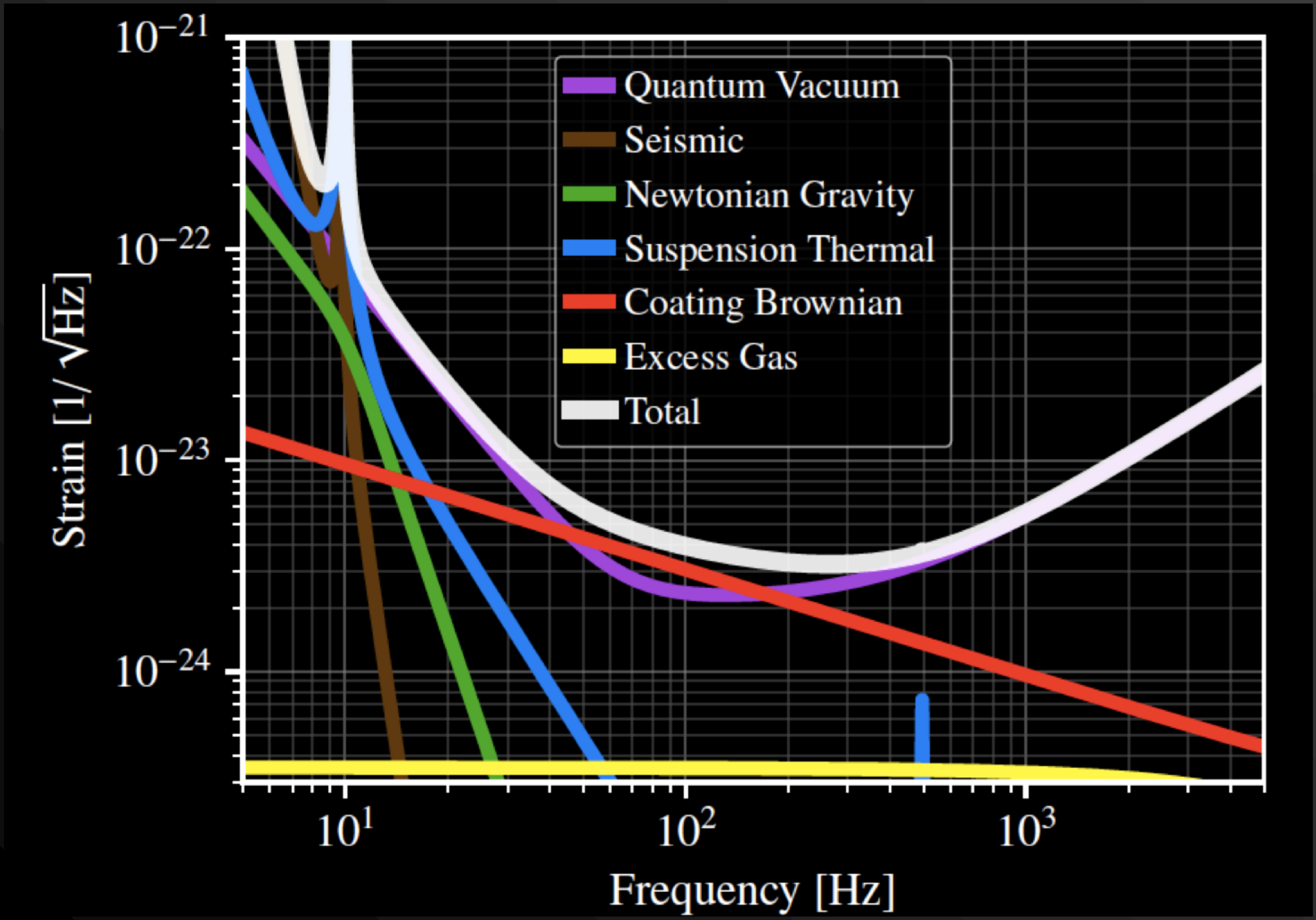
E Berti, A Sesana, et al., Phys. Rev. Lett. **117**, 101102 (2016)

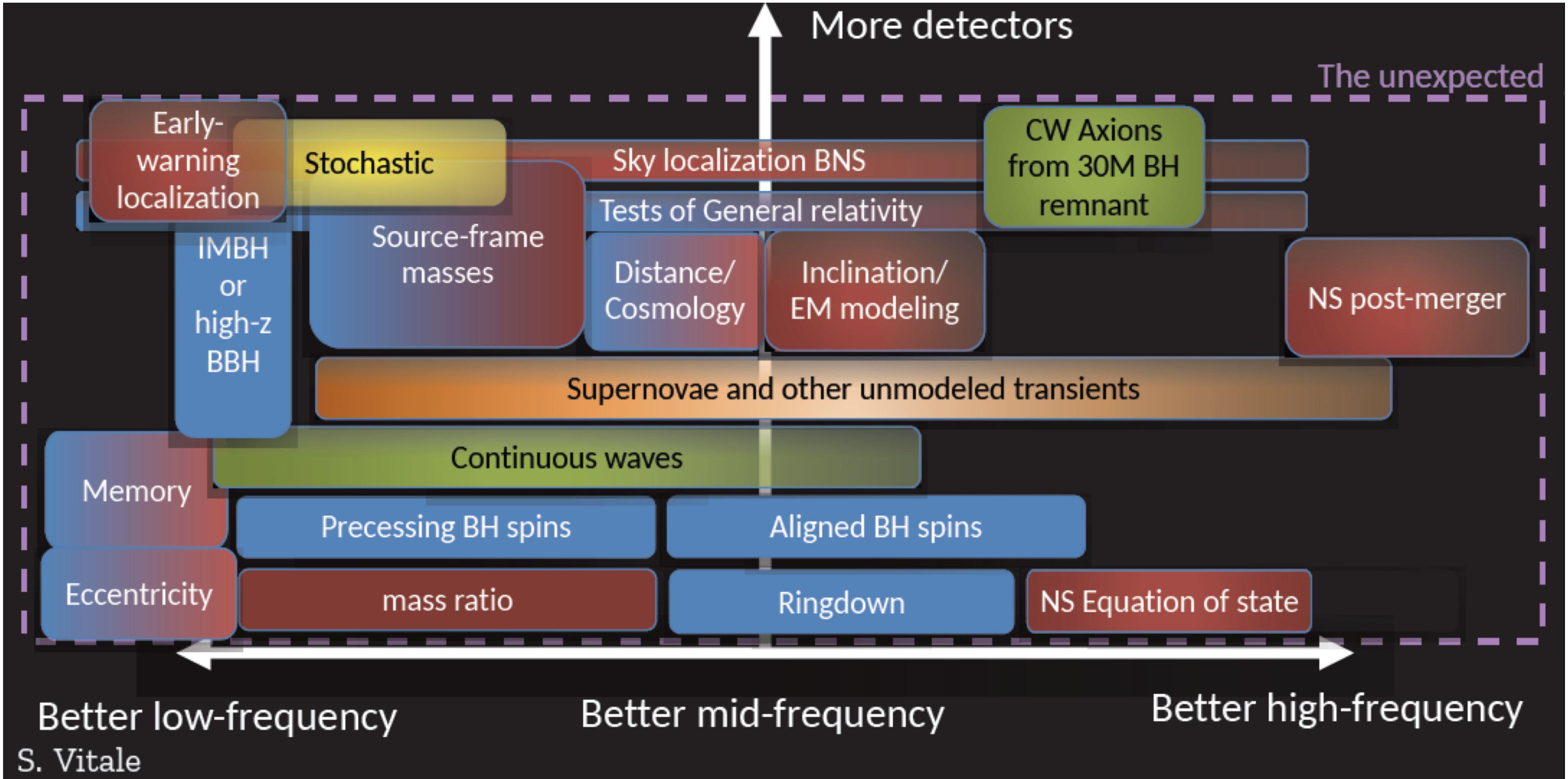
Early-warning capability



Future ground-based gravitational-wave detectors

The noise limits of Advanced LIGO

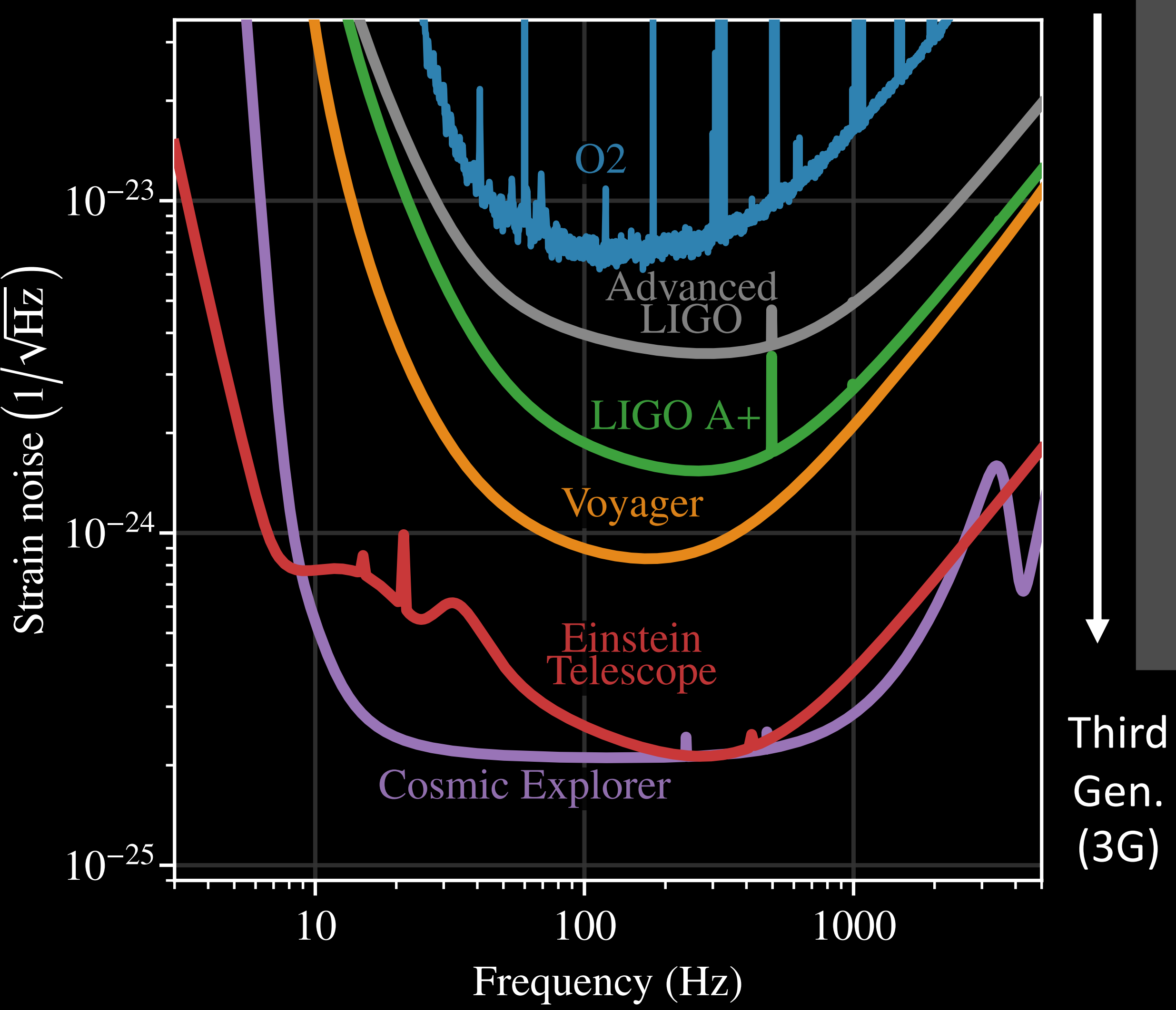




The Phase-Space of Detector Networks

https://dcc.ligo.org/LIGO-G1900660/public

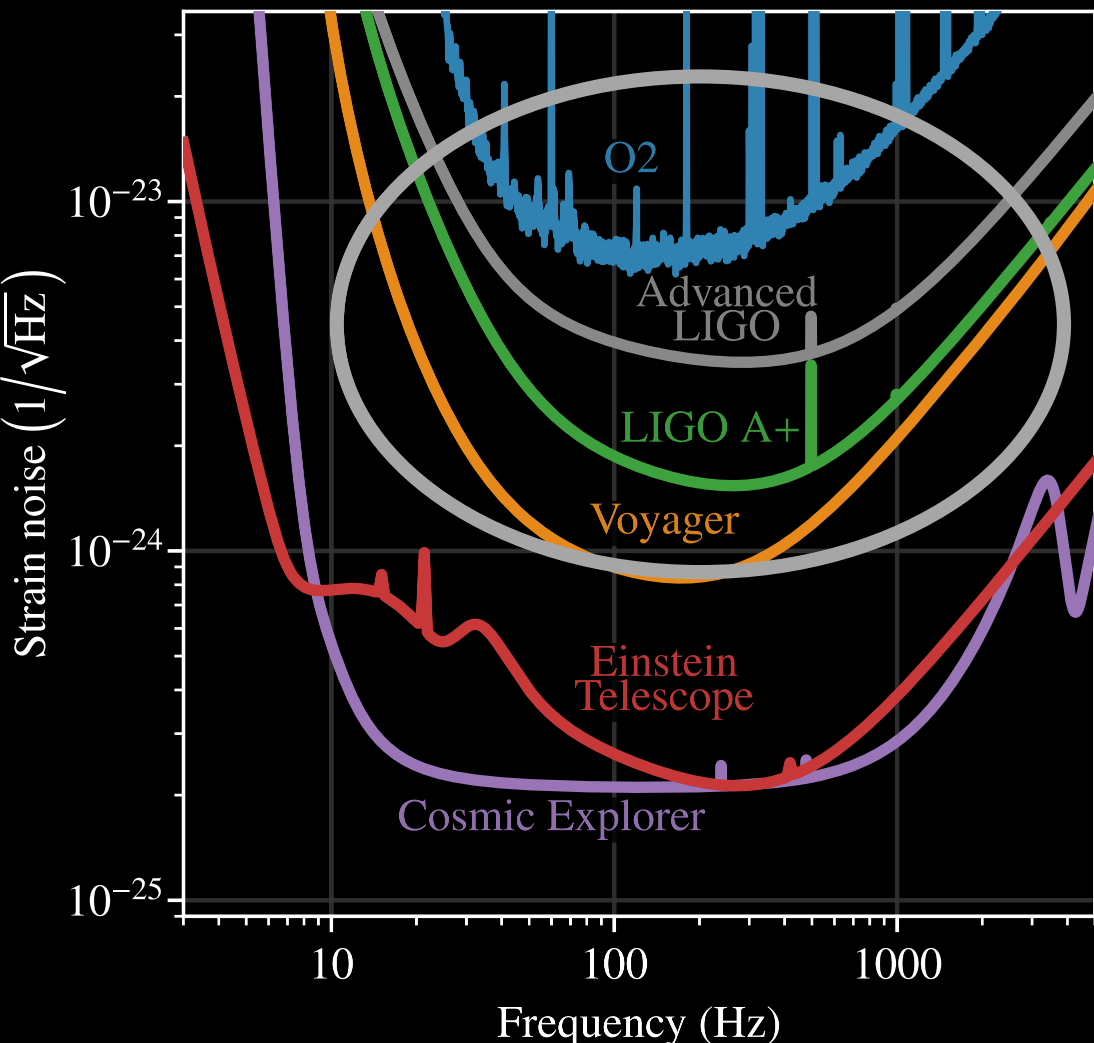
Sensitivity of Future Detectors



Two-step process…

Sensitivity of Future Detectors

2^{nd} Generation (2G)

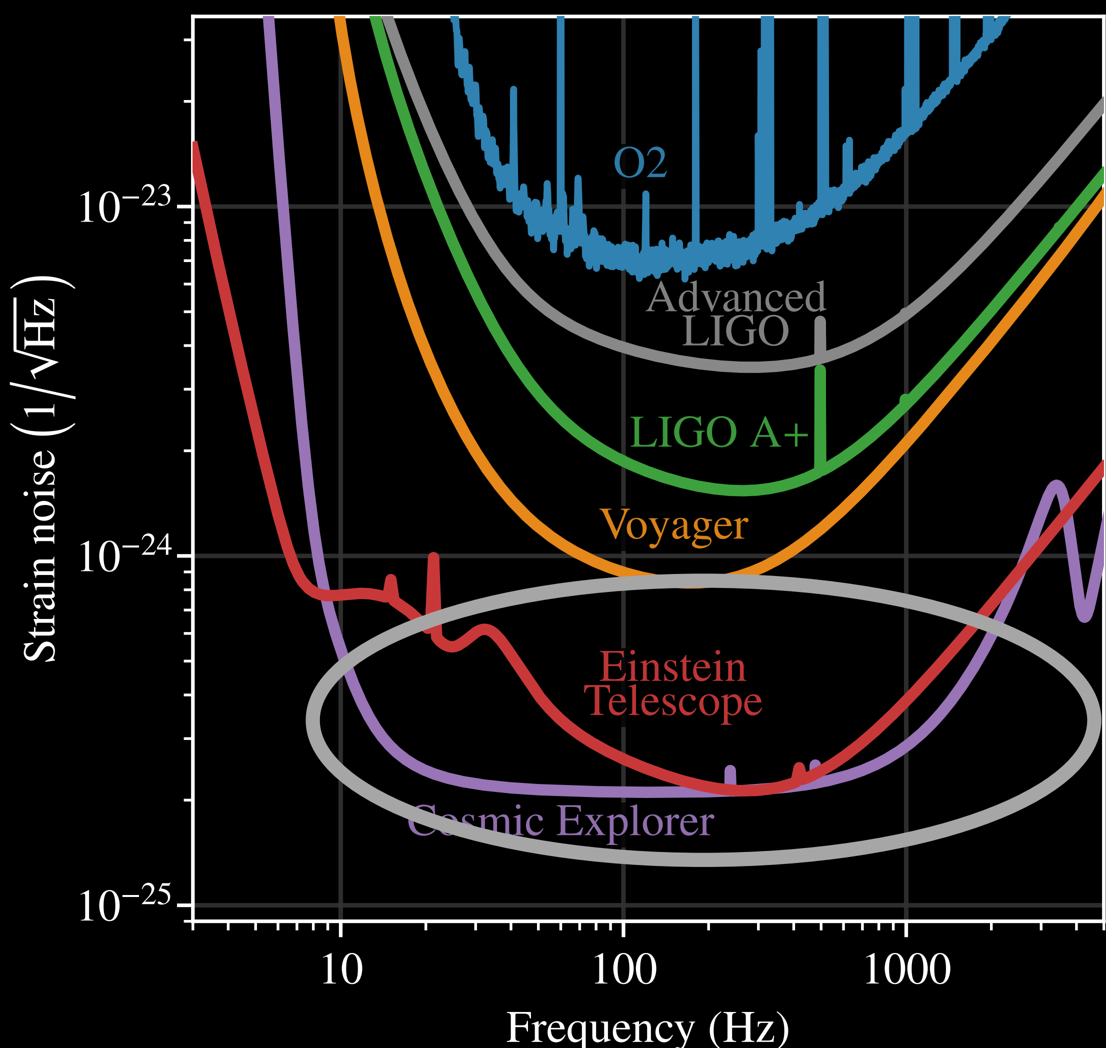


Third Gen. (3G)

1) Reduce noise (technology)

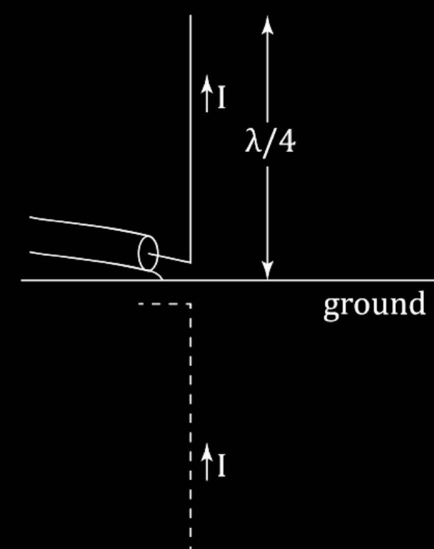
2nd Generation (2G)

Sensitivity of Future Detectors



Third Gen. (3G)

2) Match antenna size to signal



Near-term upgrades: A+ & AdVirgo+

~5 year time scale

Modest upgrades to aLIGO and AdVirgo:

- Better mirror coatings
- Frequency-dependent squeezing
- Heavier test masses*
- Suspension modifications*
- Newtonian noise subtraction*

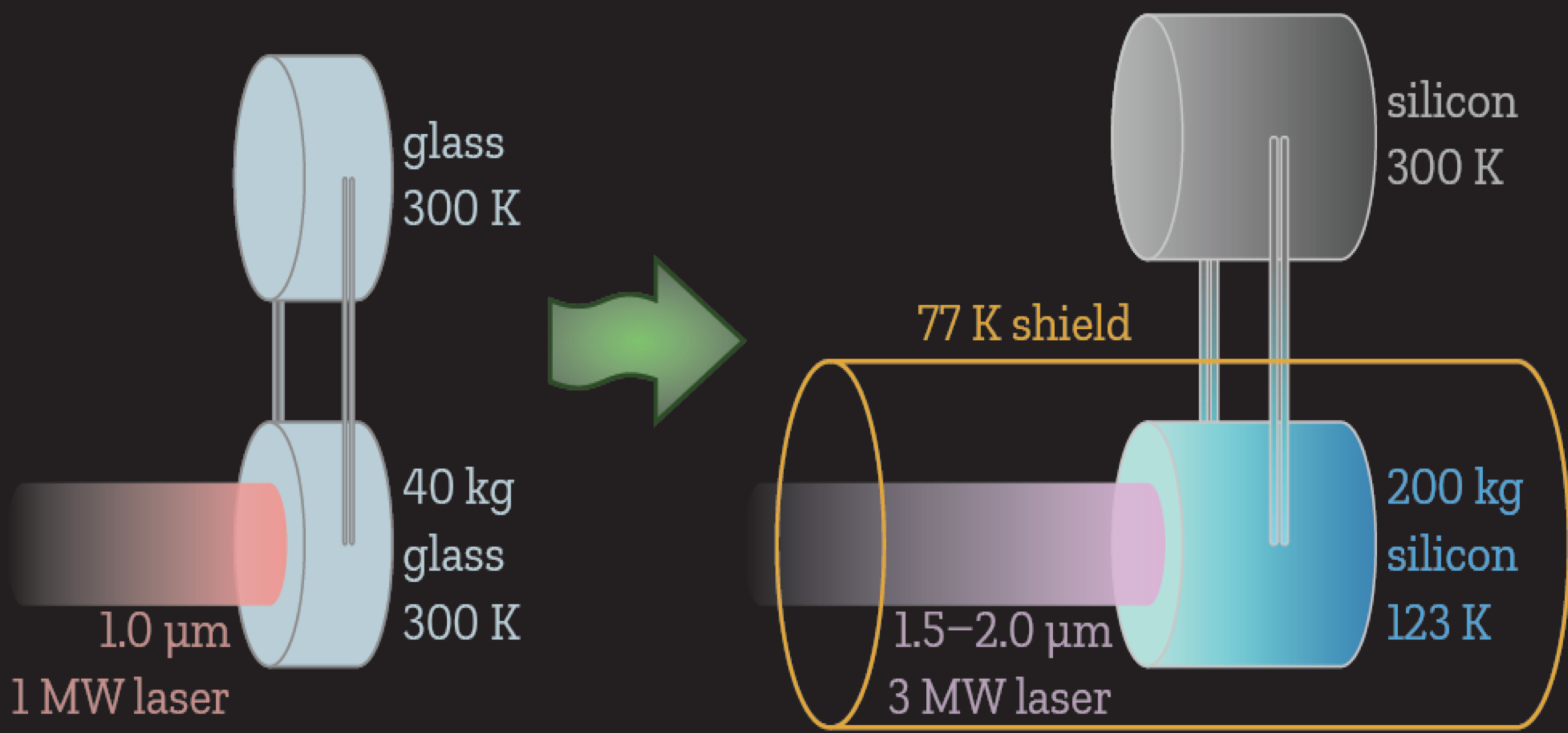
(*AdVirgo+ only)

~5× rate improvement for binary neutron stars

Also Kagra+: upgrades TBD

- Heavier masses, new materials, higher power, ...?

Voyager: A Cryogenic Upgrade

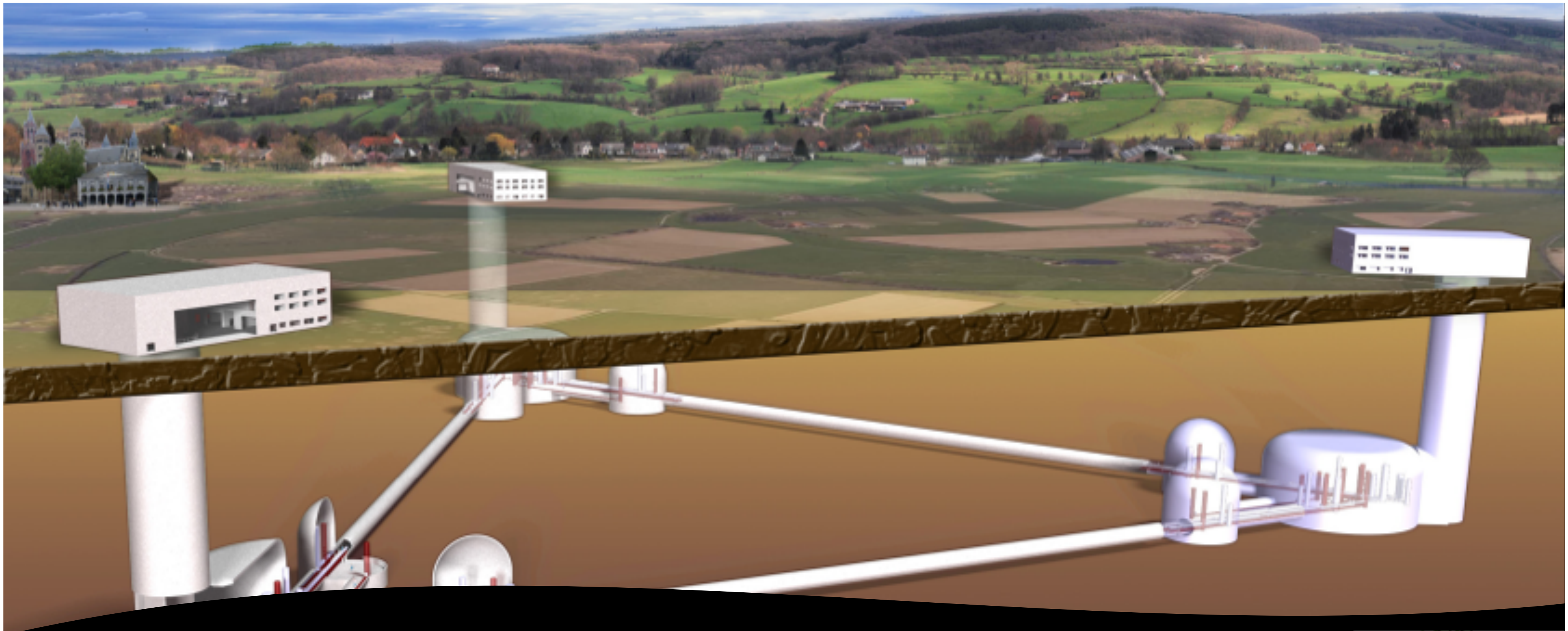


N Smith and R Adhkiari, *Cold voyage*, tech. rep. G1500312 (LIGO, 2015)

OzGrav High-Frequency Detector

https://www.ozgrav.org/

- Expand or build an Australian facility dedicated to high frequency detection
  - Neutron star equation of state, post-merger physics above ~1 kHz
- Don't worry about low-frequency noise
  - Removes many constraints on interferometer design and control scheme
- Currently in conceptual design
  - Cryogenics
  - Several megawatts of power + squeezing



Einstein Telescope

Facility:

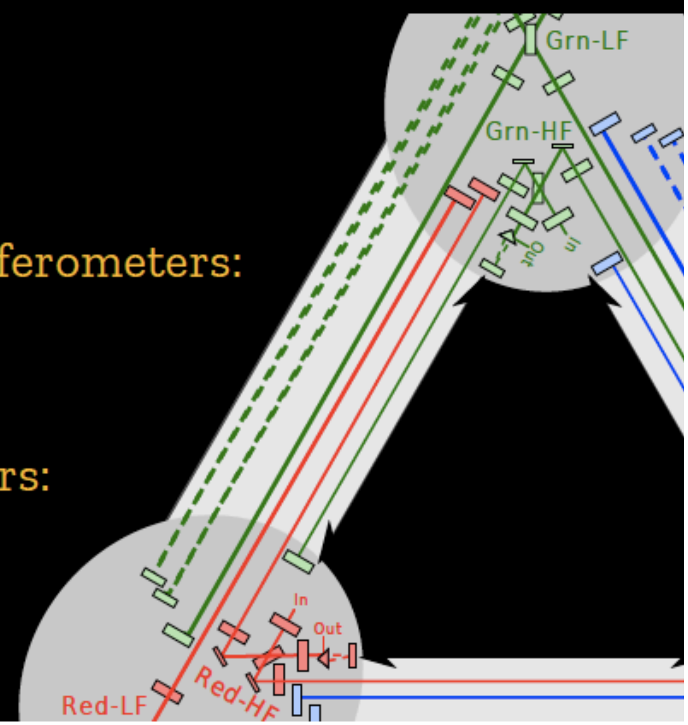
- 10-km triangle
- Underground in Europe

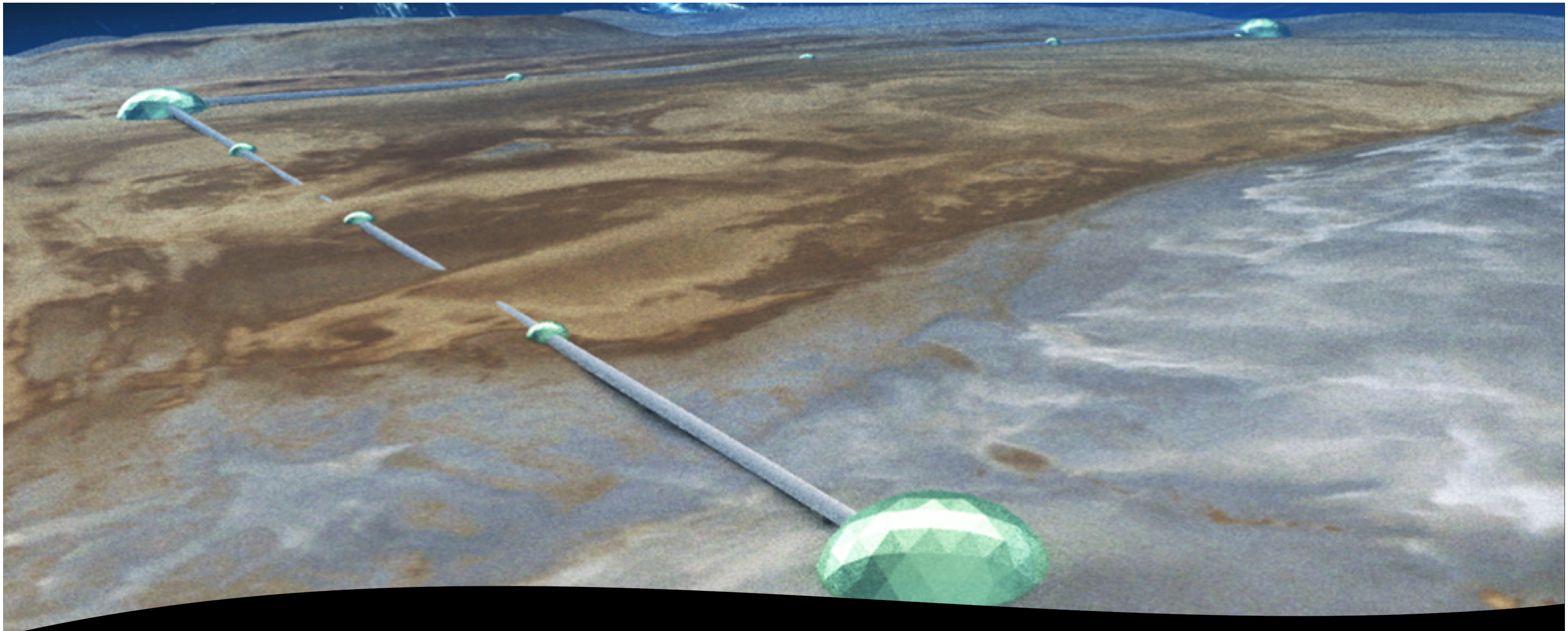
Three room-temperature interferometers:

- glass optics
- 1 μm laser

Three cryogenic interferometers:

- silicon or sapphire optics
- 10–20 K cryo
- 1.5 or 2 μm laser





Cosmic Explorer

Facility:

- 40 km L shape
- Surface or underground (TBD)

One interferometer:

- Stage 1: room-temperature glass with 1 μm lasers
- Stage 2: cryogenic silicon with 1.5 or 2 μm lasers

Network:

- Envisioned as part of a global network; e.g., two Cosmic Explorers and one Einstein Telescope


Example location:
Bonneville Salt Flats, Utah, USA

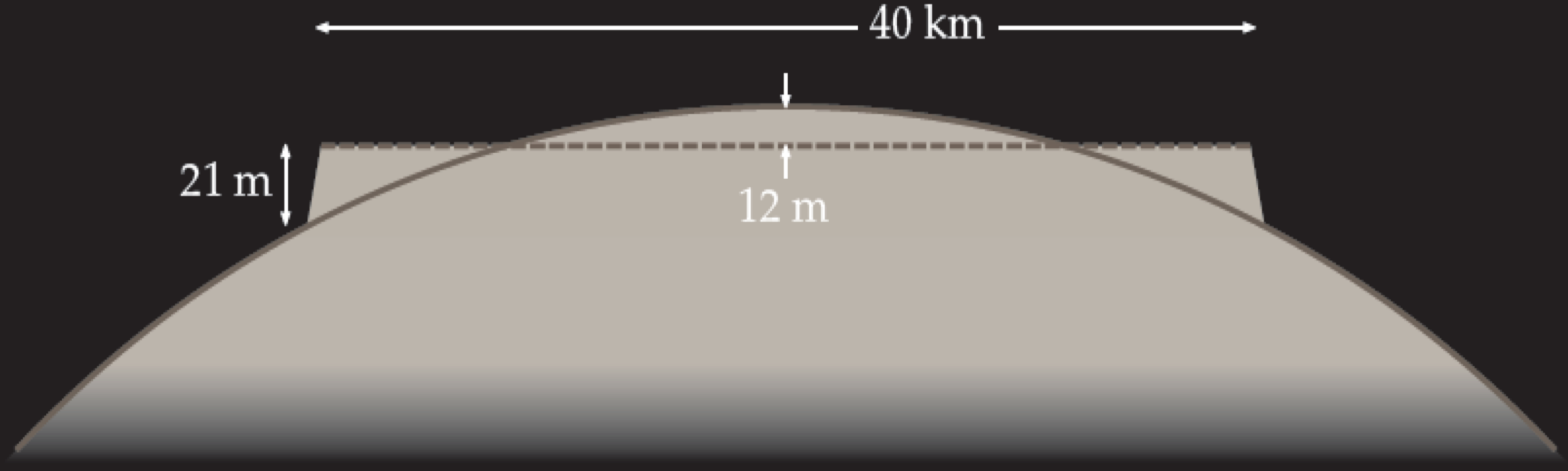
Technical challenges

Facility challenges

Building a new facility requires $\mathcal{O}(\$1\,\text{billion})$ with current technology

- Earthmoving, tunnelling
- Vacuum construction, bakeout

Some possible cost savings with novel vacuum systems or serendipitous sites



Low frequencies

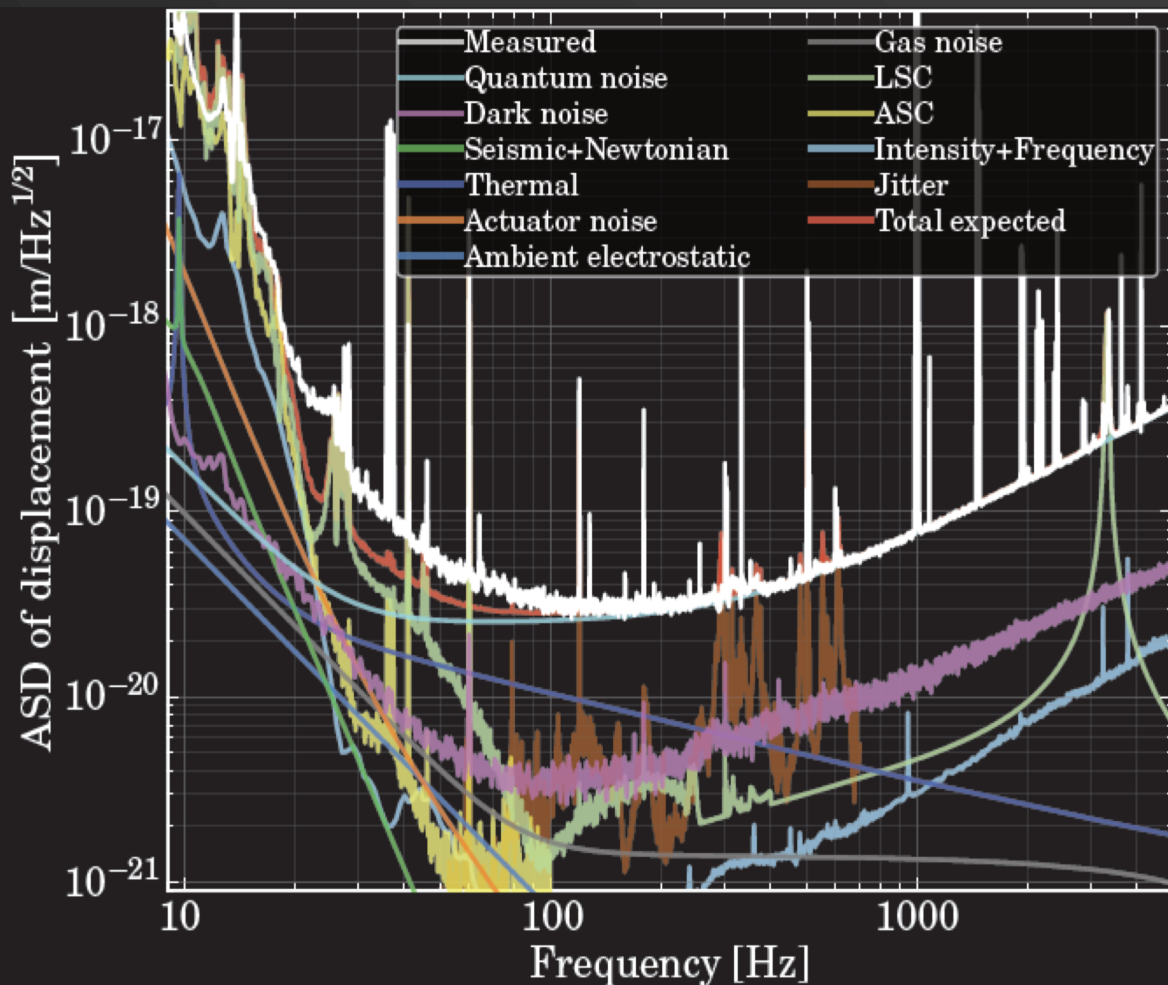
Low frequency is hard

- Control noises
- Geophysical noises
- Scattered light
- Mystery noises

aLIGO goal: 10 Hz

CE goal: 5 Hz

ET goal: 3 Hz



High Power + Strong Squeezing

Highest power demonstrated: ~250 kW (aLIGO)

Next-gen power requirement: 3 MW

10× power increase

Best squeezing demonstrated: 6 dB (GEO600)

Next-gen squeezing requirement: 10 dB

3× optical loss reduction

New materials + Wavelength

Most GW detector experience is with room-temperature glass and 1 µm lasers

Need to develop familiarity with cryogenic suspended silicon/sapphire

Need high-power lasers, high-efficiency photodetectors, etc. at new wavelengths

Need large pieces of high-quality silicon

Status

Organization

Timeline

Einstein Telescope

- European-led effort
- Design study 2008-2011
- Site studies in Limburg and Sardinia
- Maastricht Pathfinder Experiment (starting 7/2019)
  - Cryogenics
  - New wavelength
- Large-mass cryogenic prototyping at Virgo

Einstein Telescope timeline

2018–19	Formation of collaboration
2019–21	ESFRI roadmap
2021–22	Site selection
2023	Full technical design
2025	Excavation and construction begins
2032+	Instrument installation

A. Freise, LVC 21 Mar 2019

Cosmic Explorer

US-led effort

Design study underway now (2018–2021)

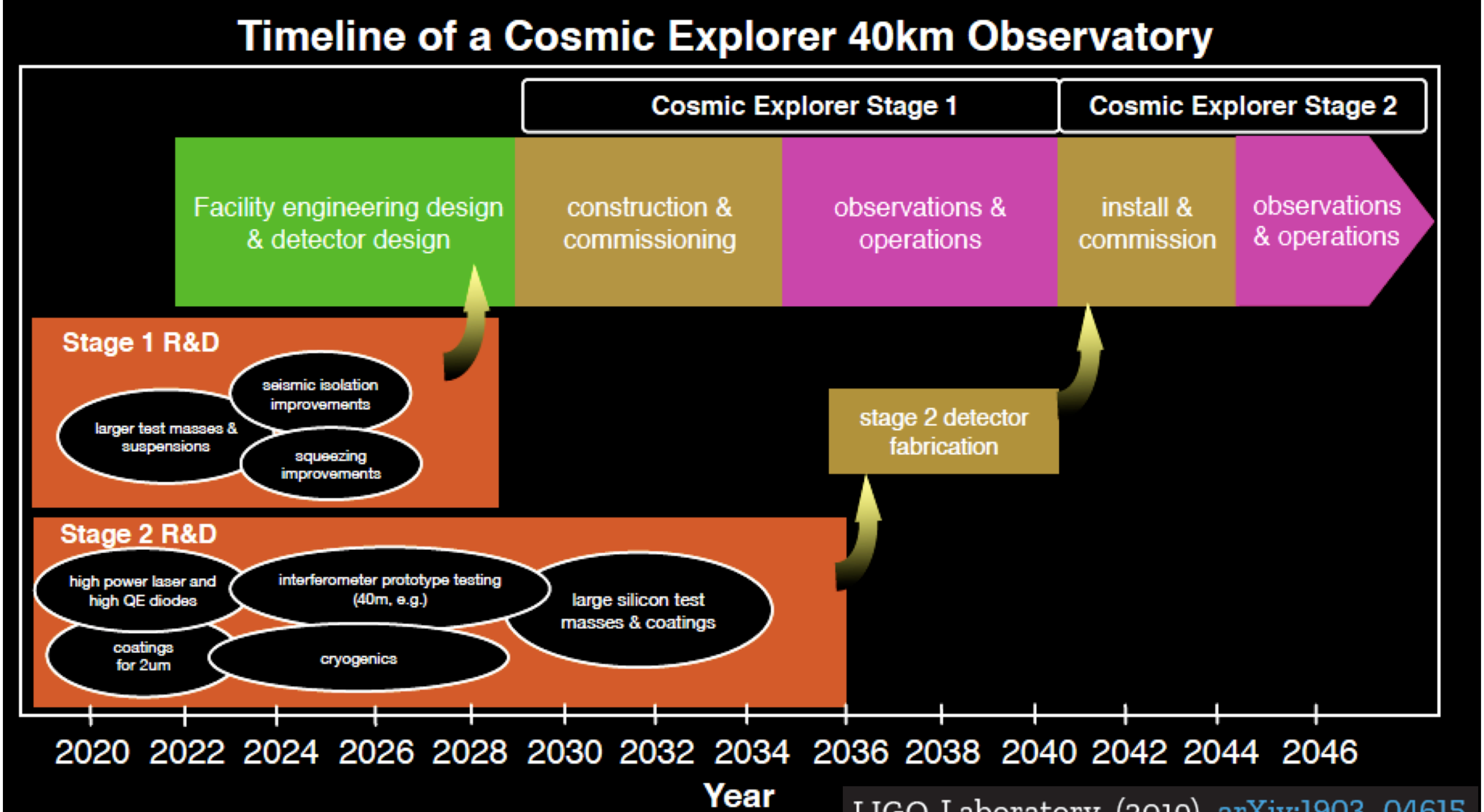
NSF-sponsored workshop on large ultrahigh-vacuum systems (Jan 2019)

Proceedings: https://dcc.ligo.org/LIGO-P1900072

Astro2020 Decadal Survey whitepaper:

https://arxiv.org/abs/1903.04615

Cosmic Explorer Timeline



LIGO Laboratory, (2019), arXiv:1903.04615

Coordination via GWIC

The Gravitational-Wave International Committee:
https://gwic.ligo.org/3Gsubcomm/

Astro2020 Decadal Survey whitepapers:

- Cosmology and early Universe
- Extreme gravity and fundamental physics
- Black hole binaries
- Multimessenger observations of neutron star binaries
- Multimessenger observations of supernovae and isolated neutron stars (magnetars, pulsars, ...)

Next-gen science book:

- ~100-page exhibition of next-generation gravitational-wave science
- Due out in next few months

Conclusion

Current detectors see local events

Terrestrial GW detectors that see the entire universe are possible

Planning for new generation detectors is underway


Thank you!