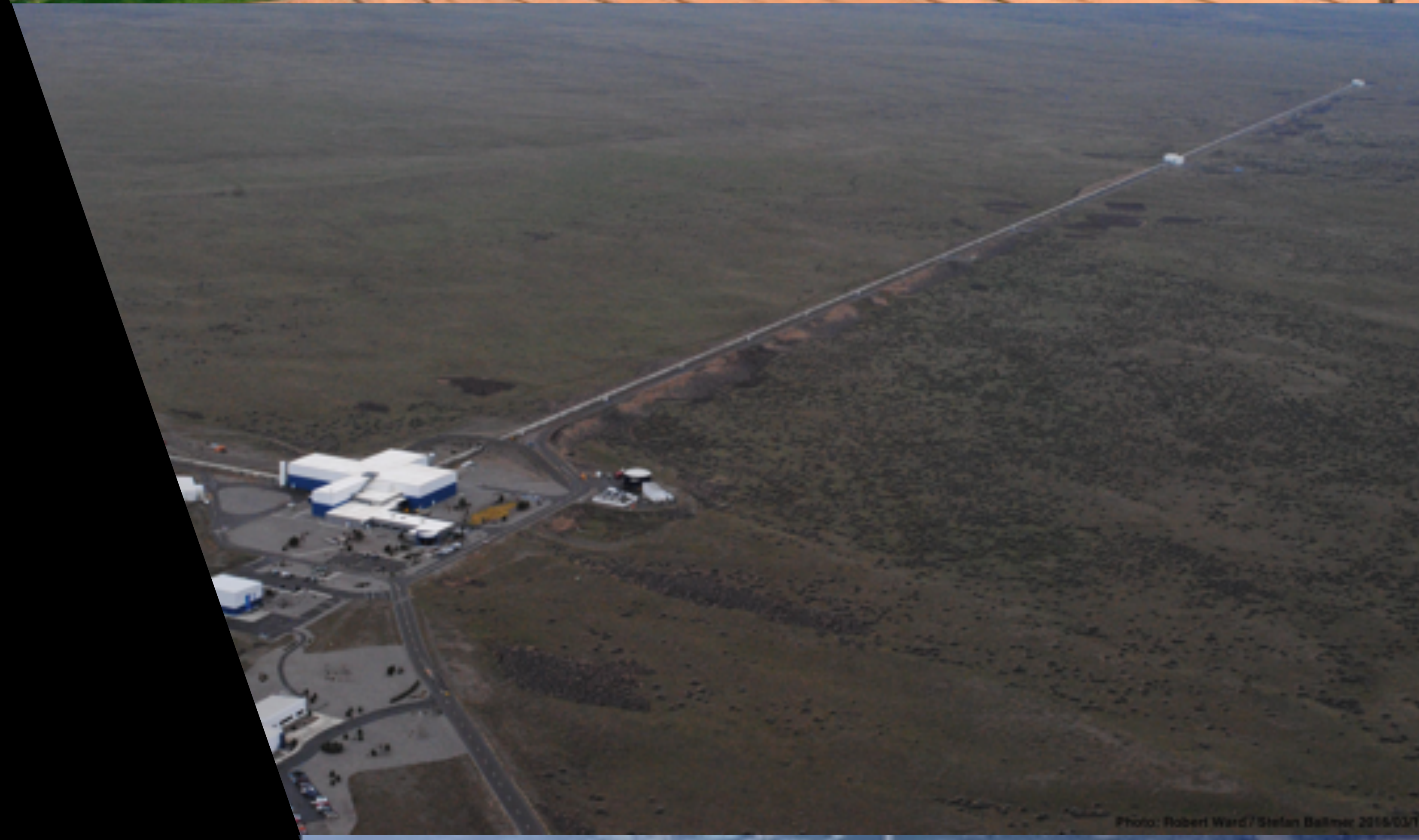
Syracuse University

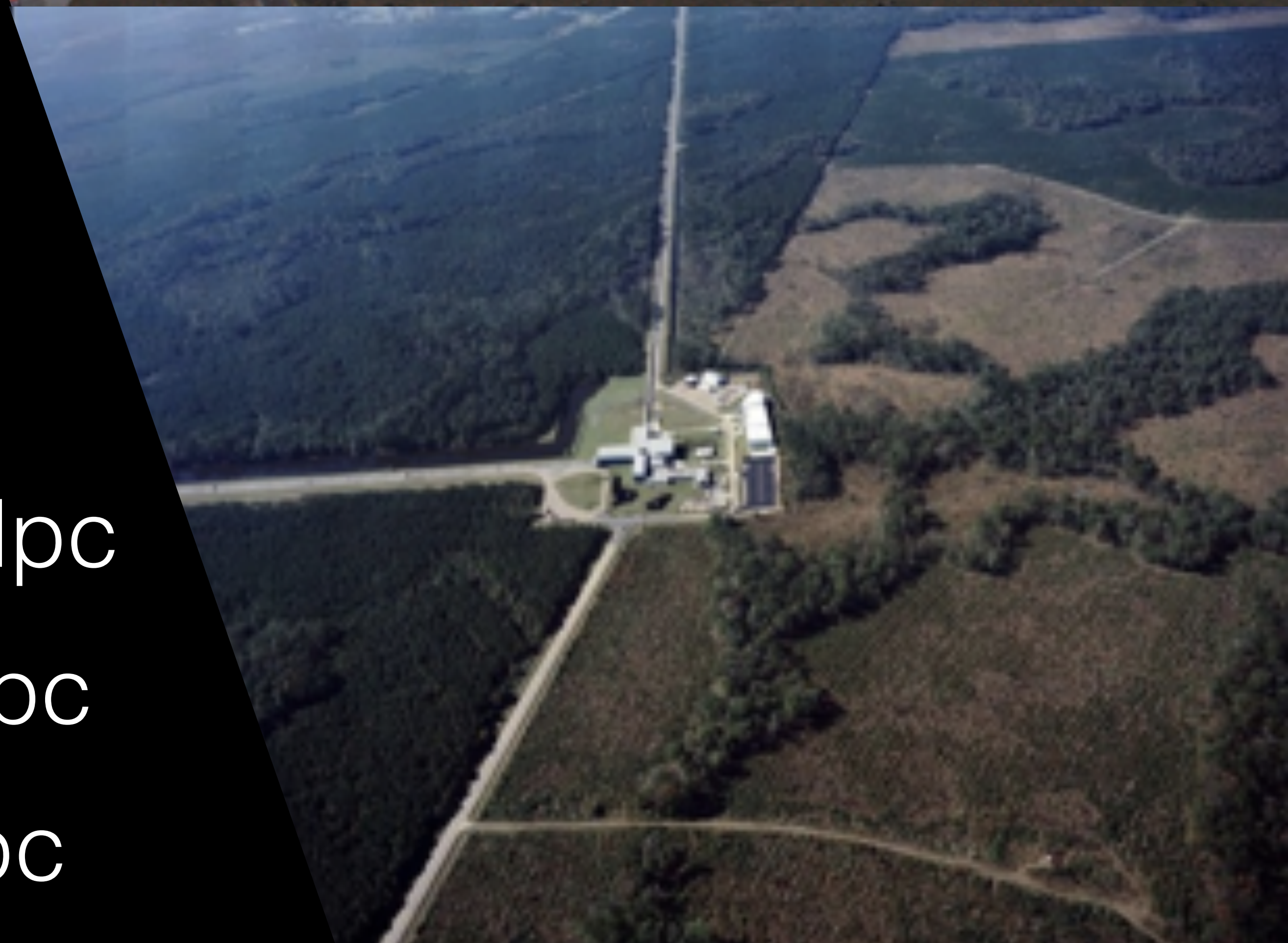
Towards Third-Generation Gravitational-Wave Detectors

Duncan Brown

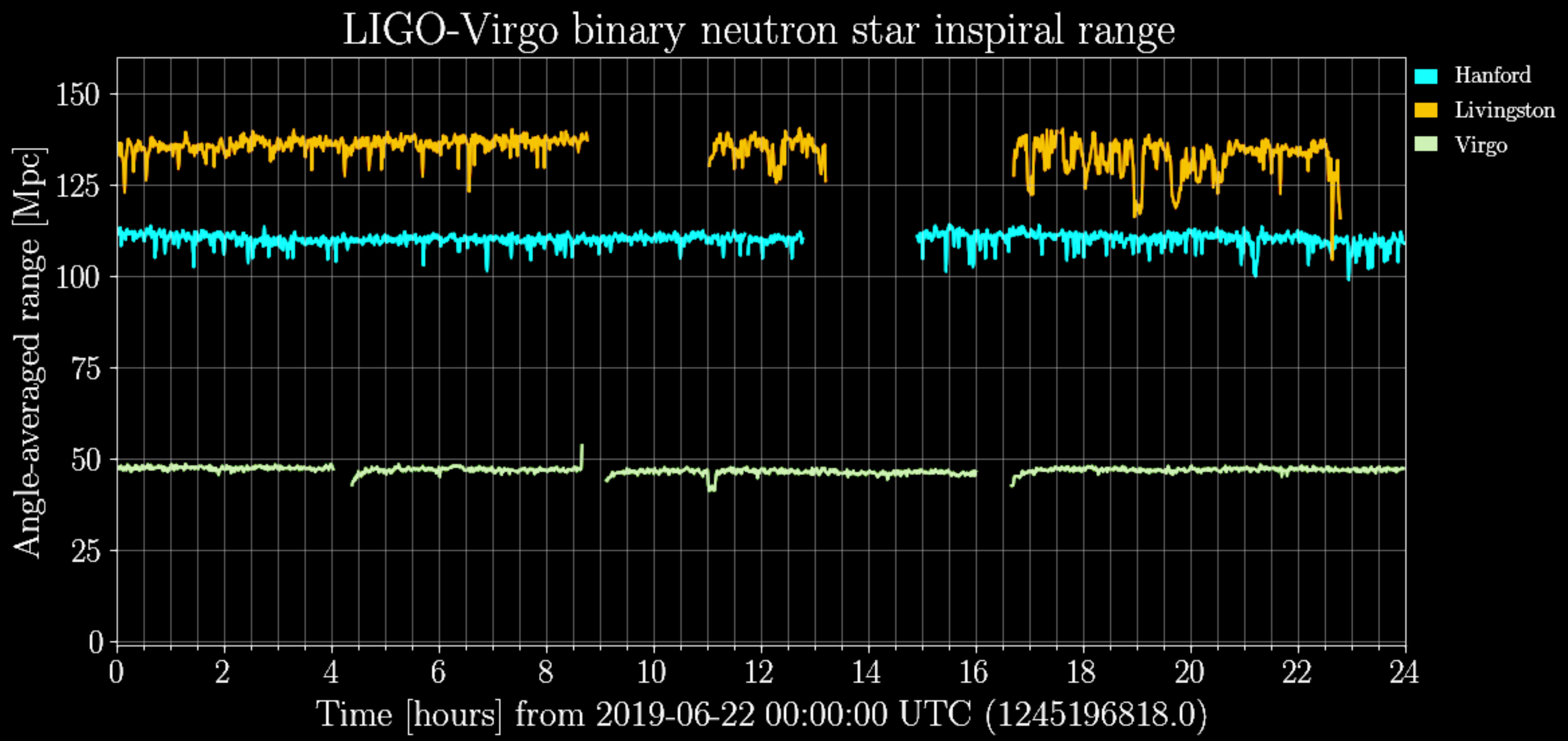
on behalf of the Cosmic Explorer Team

Gravitational-wave astronomy is in full swing with second-generation detectors: Advanced LIGO and Virgo





Three kilometer-scale detectors operational



LIGO Livingston ~ 130 Mpc

LIGO Hanford ~110 Mpc

Virgo ~ 50 Mpc

https://www.gw-openscience.org/detector_status/today/

KAGRA

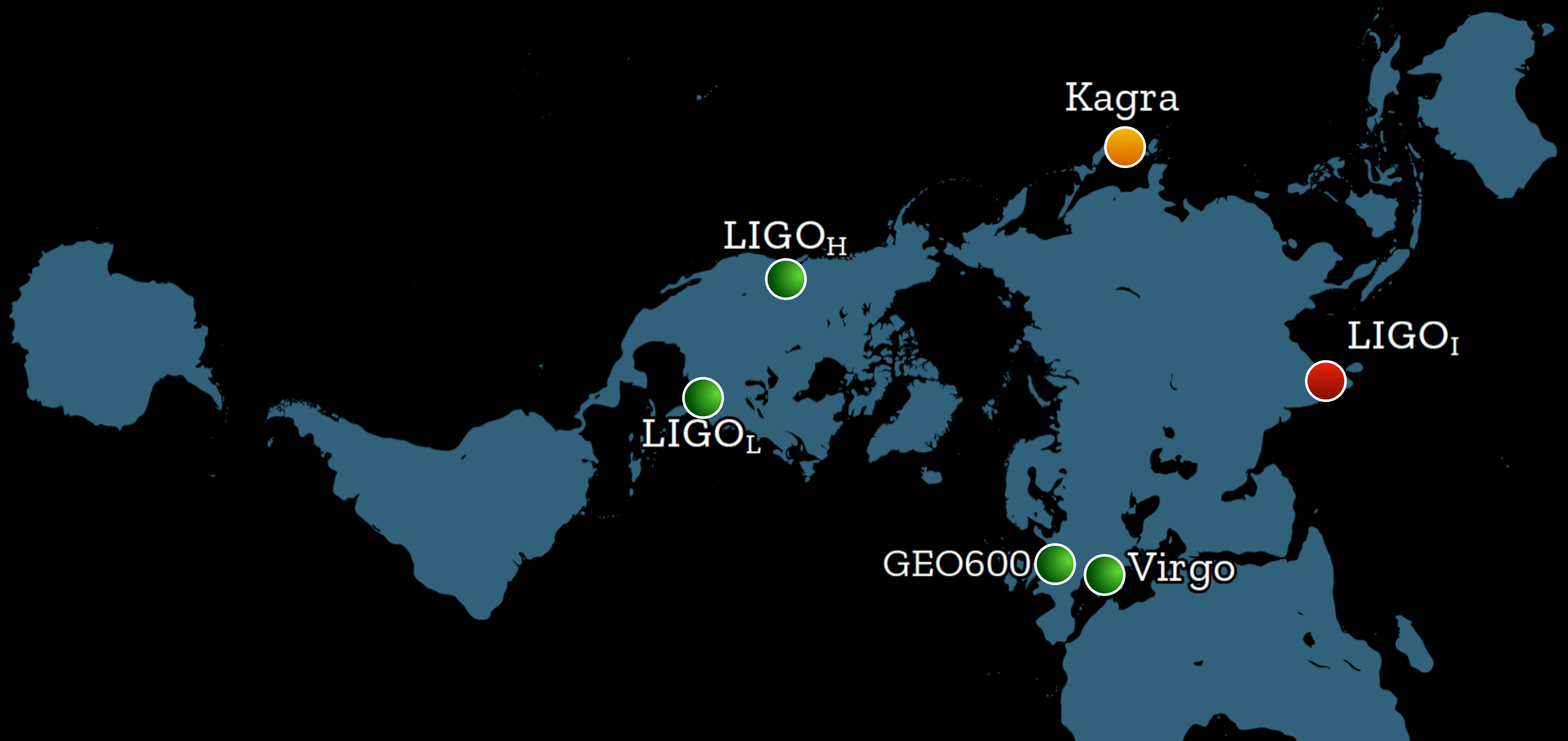
Underground facility

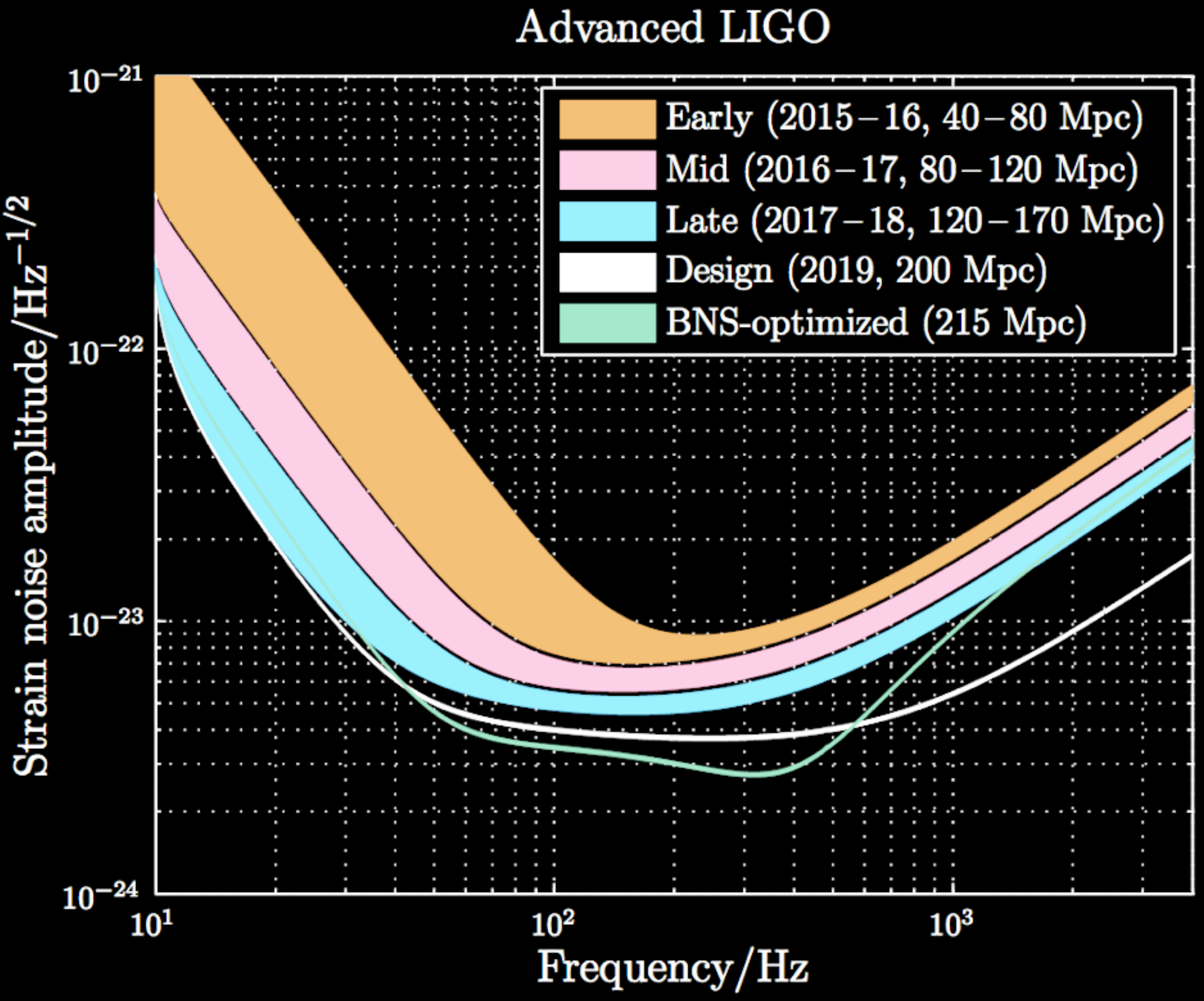
Cryogenic sapphire test masses

Locking full interferometer this summer

Goal to join at the end of the O3 run

Current and near-future network





Early and **Mid**: O1 and O2

13 BBH mergers

1 BNS merger

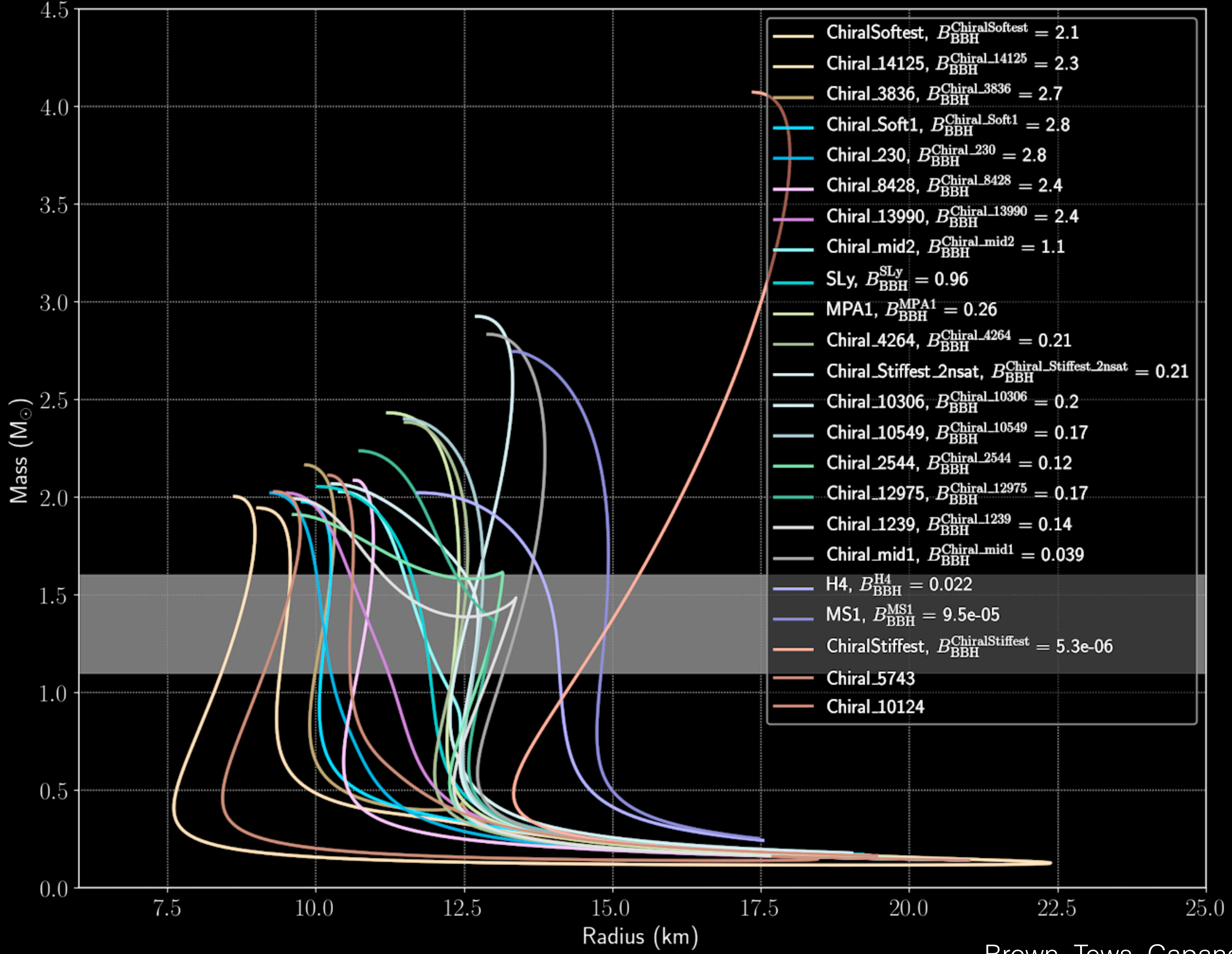
Abbott et al. (arXiv:1811.12907)
Venumadhav et al. (arXiv:1904.07214)

Late: O3

Design: O4+

Detection every day!

Abbott,..., DAB, et al. Living Reviews in Relativity **21**:3 (2018)



GW170817 has ruled out the stiffest equations of state, but not yet detected tidal deformability

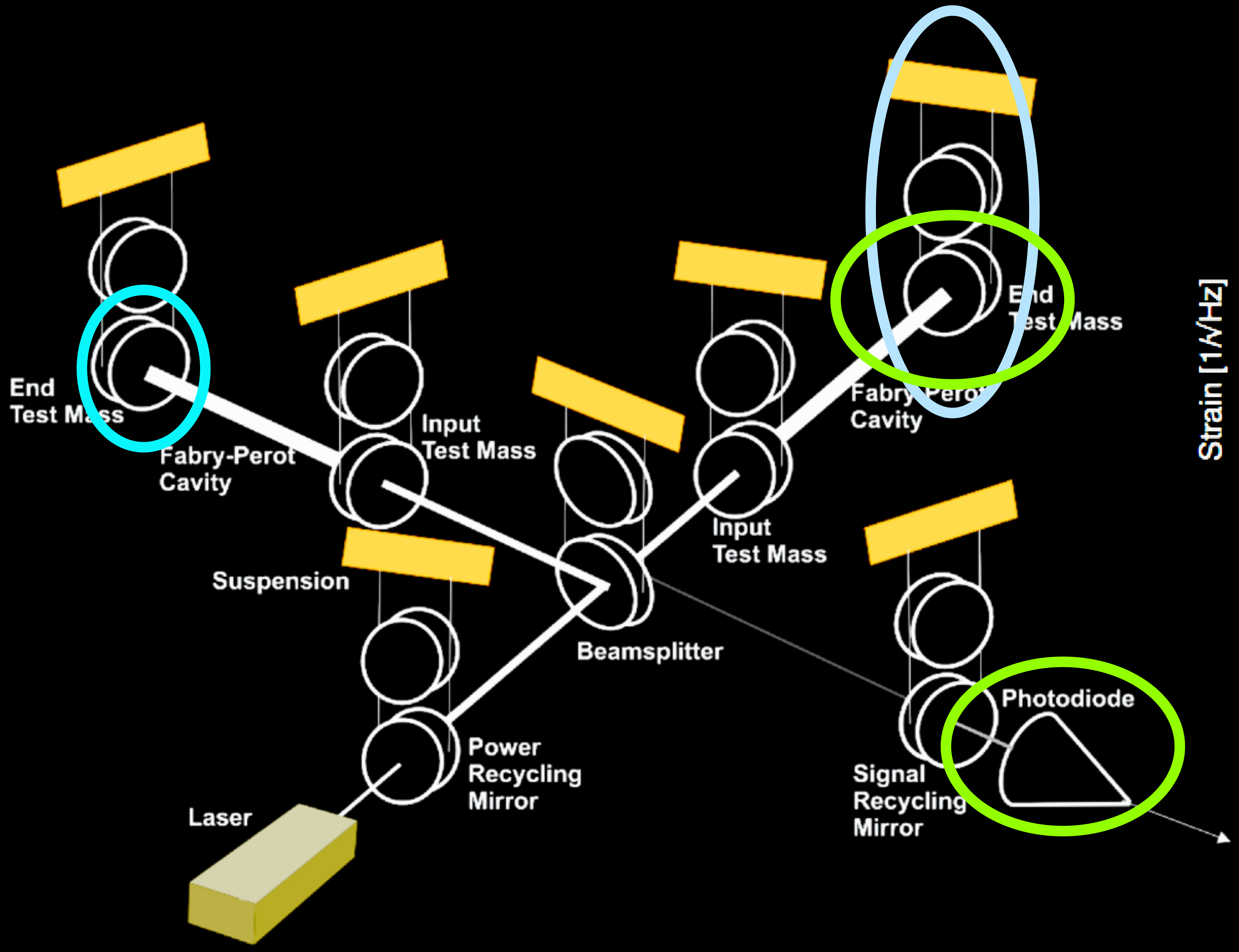
Post-merger signals undetectable by 2G

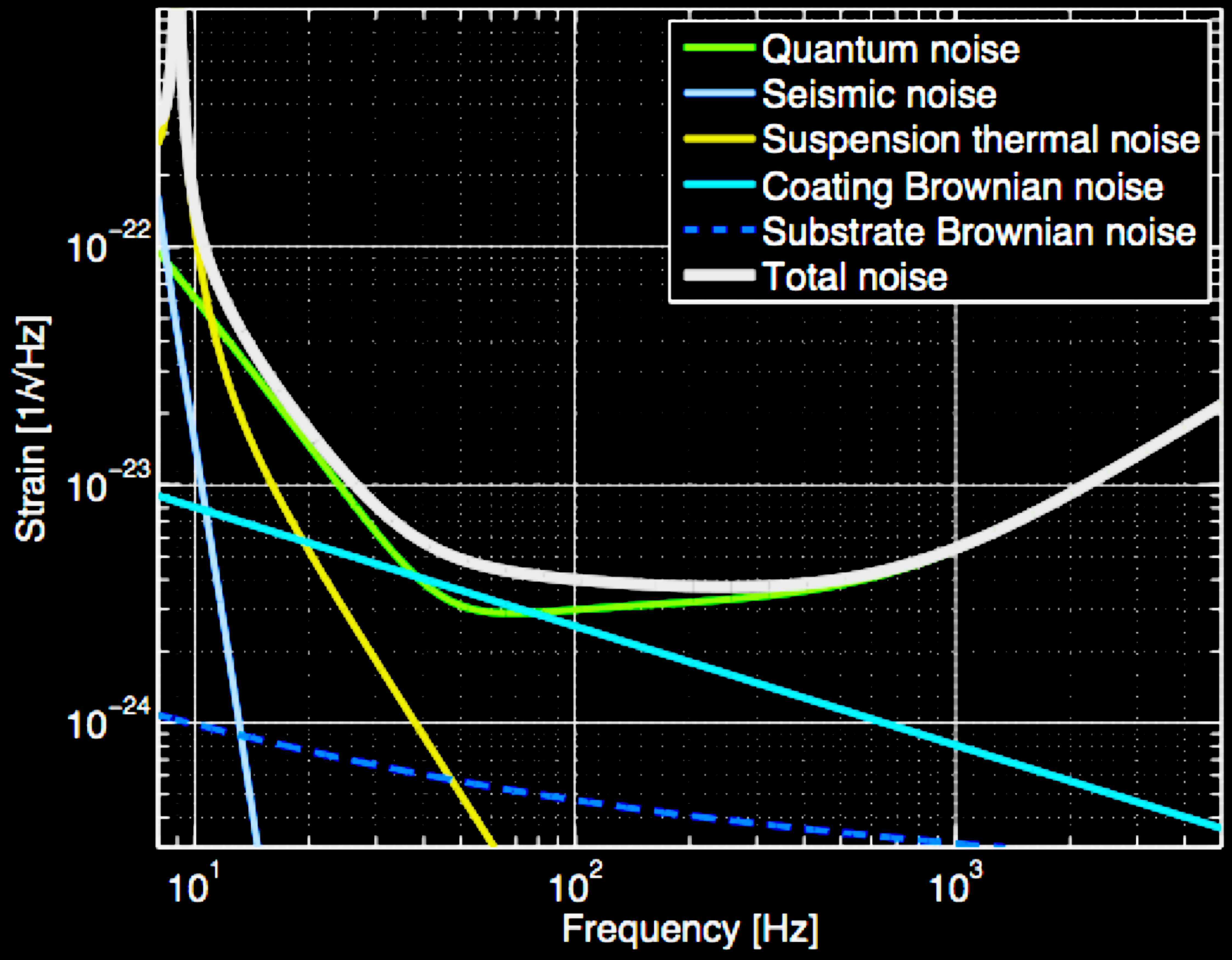
Brown, Tews, Capano, De, Reyes, DAB, Krishnan, Reddy in prep

What 2G Detectors Can See

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

What limits Advanced LIGO?



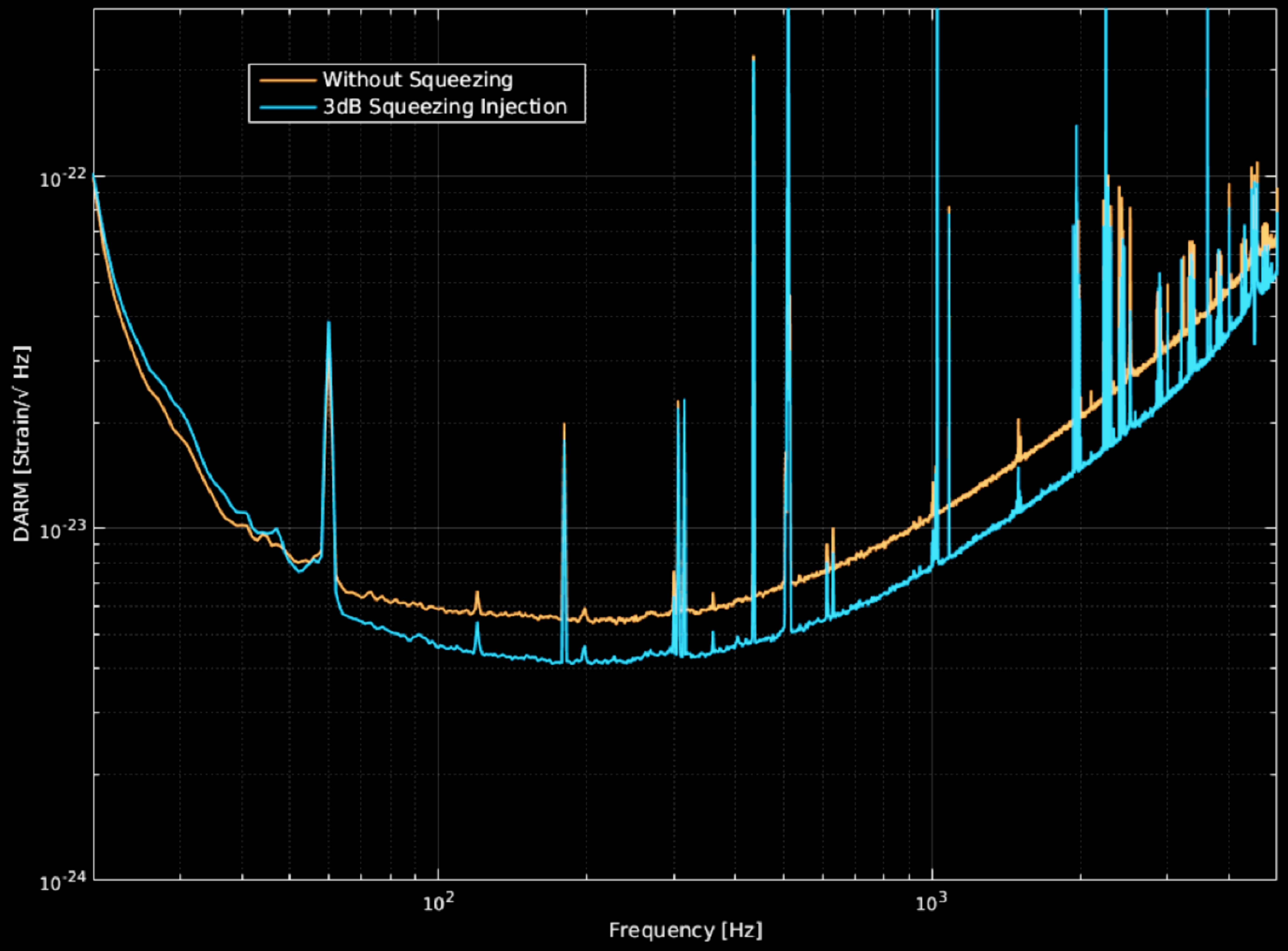


Aasi,..., DAB, et al. CQG **32** 074001 (2015)

Reducing Quantum Noise

- Shot noise and radiation pressure form the standard quantum limit
- Higher power in the arms decreases shot noise but increases radiation pressure
- Larger mirrors react less to impulses
- Squeezing can help one (or both using an extra cavity!)

Vacuum squeezing now in use



LIGO Livingston in O3

BNS range increases from ~125 Mpc to ~ 140 Mpc

Barsotti/aLIGO

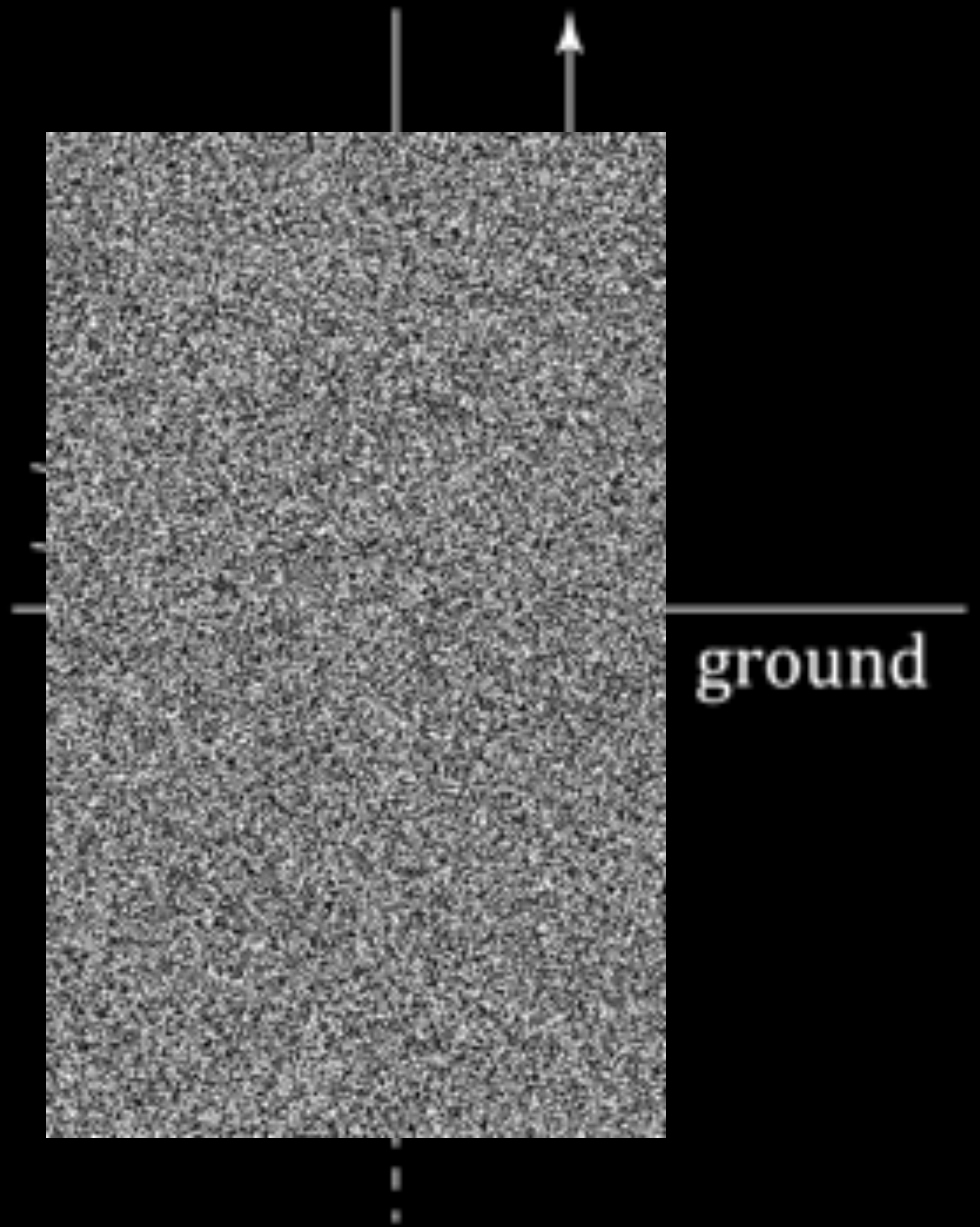
Near-term upgrades: A+ & AdVirgo+

- Five year time scale: modest improvements to aLIGO and AdVirgo
  - Better mirror coatings, frequency dependent squeezing, heavier test masses*, suspension modifications*, Newtonian noise subtraction*

    *AdVirgo+ only
  - ~ 5x rate improvement for binary neutron stars
- KAGRA upgrades also on the horizon

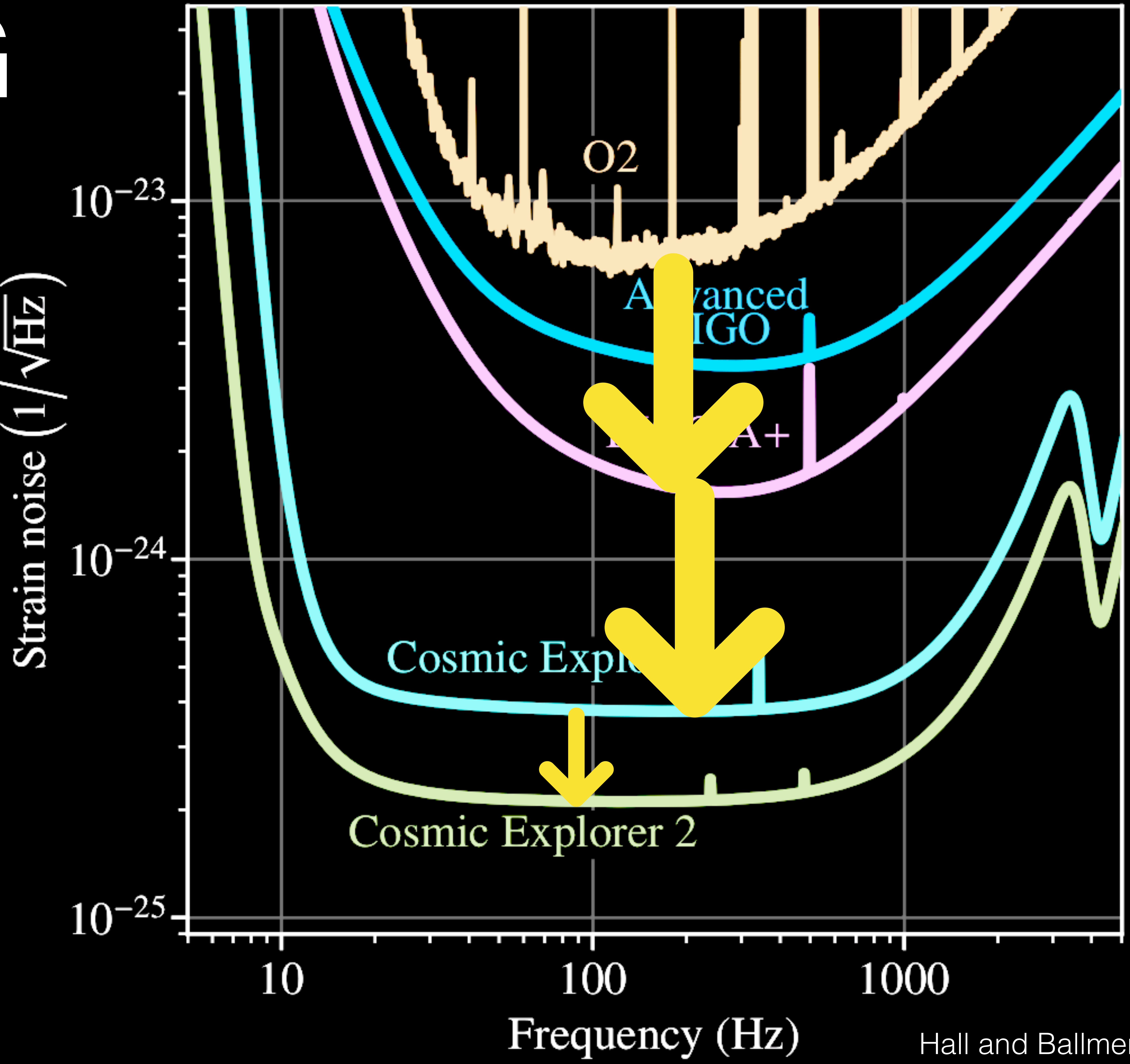
https://www.nsf.gov/awardsearch/showAward?AWD_ID=1834382

From 2G to 3G



Reduce noise (technology)

Match antennae size to signal



Hall and Ballmer

What about Voyager?

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

What about Voyager?

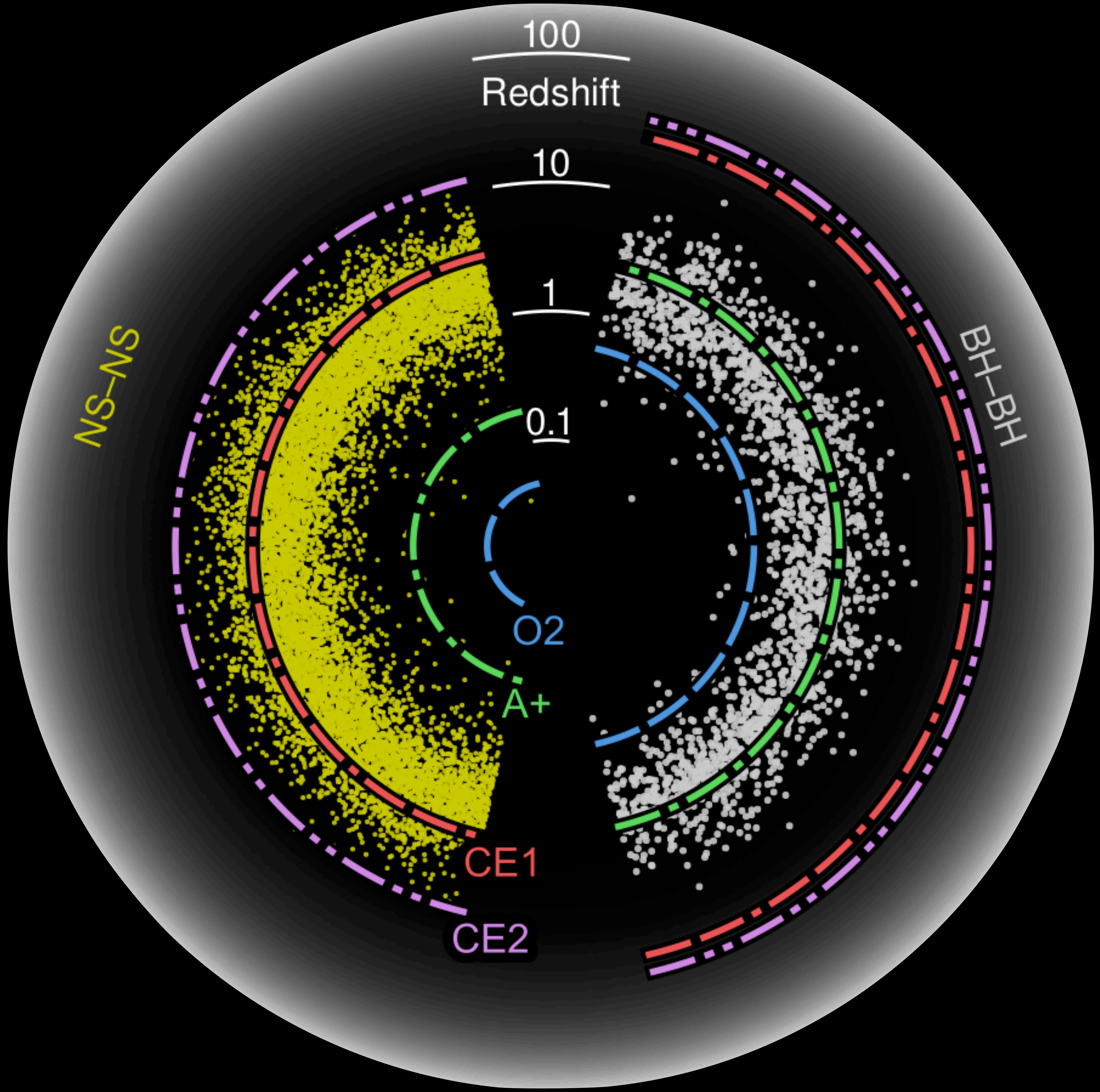
- LIGO Laboratory has not yet converged on a post a+ timeline for the 4 km facilities
- Should Voyager be installed:
  - ...as soon as the technology is ready?
  - ...or when the disruption to the global network will be minimal?
- Hinges on several unknowns:
  - When will Voyager technology be ready?
  - Which detectors will be online after 2025 and with what sensitivity?
  - How many facilities would be upgraded to Voyager?
  - Is a funding available that would not significantly delay Cosmic Explorer?

Einstein Telescope

Cosmic Explorer

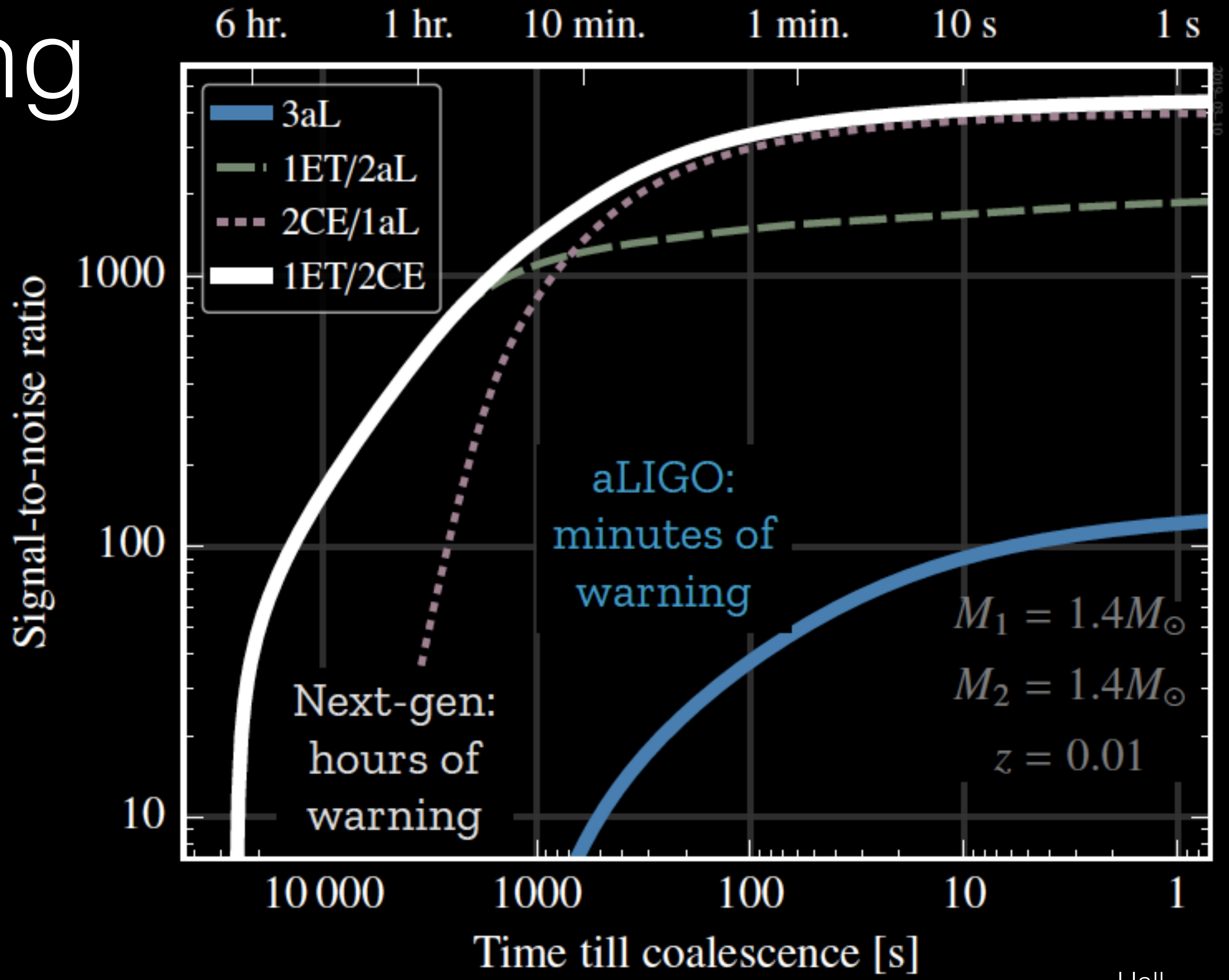
GWIC arXiv:1903.09260

Binary mergers throughout cosmic time



Hall/Vitale arXix:1903.04615

Early warning for BNS mergers

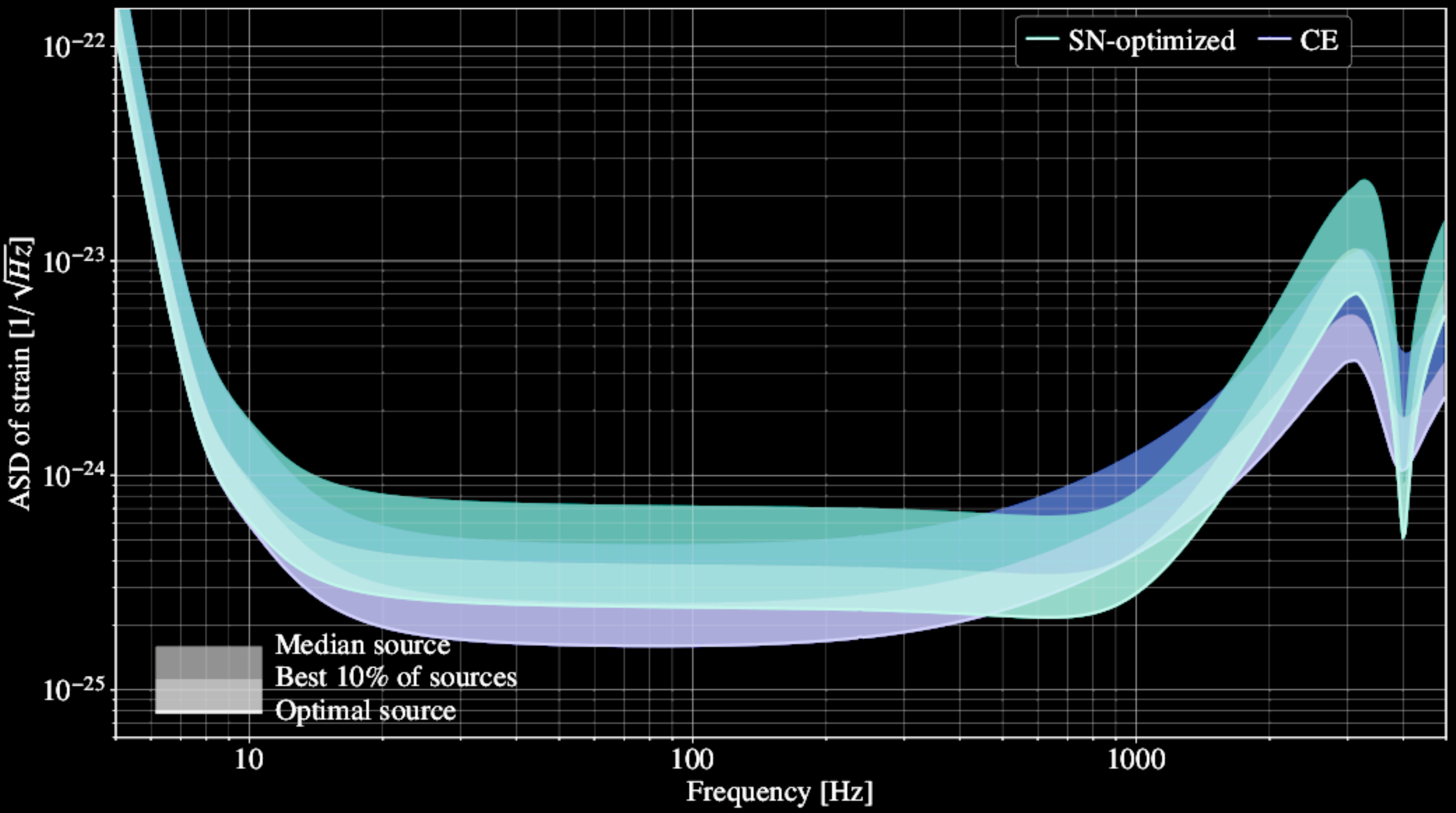


Hall

What 3G Detectors Can See

- Observe every binary black hole merger in the universe
- Direct detection of BBH at high redshift
- Precision exploration of cold dense matter in neutron stars
- Behavior of hot dense matter in post-merger signatures
- High-fidelity detections, finding the "odd ball" mergers
- Precision tests of General Relativity, possible exploration of new physics

Supernovae in 3G



70 kpc at SNR 8

95 kpc at SNR 8

c.f. DUNE

"4G" may get 1 Mpc

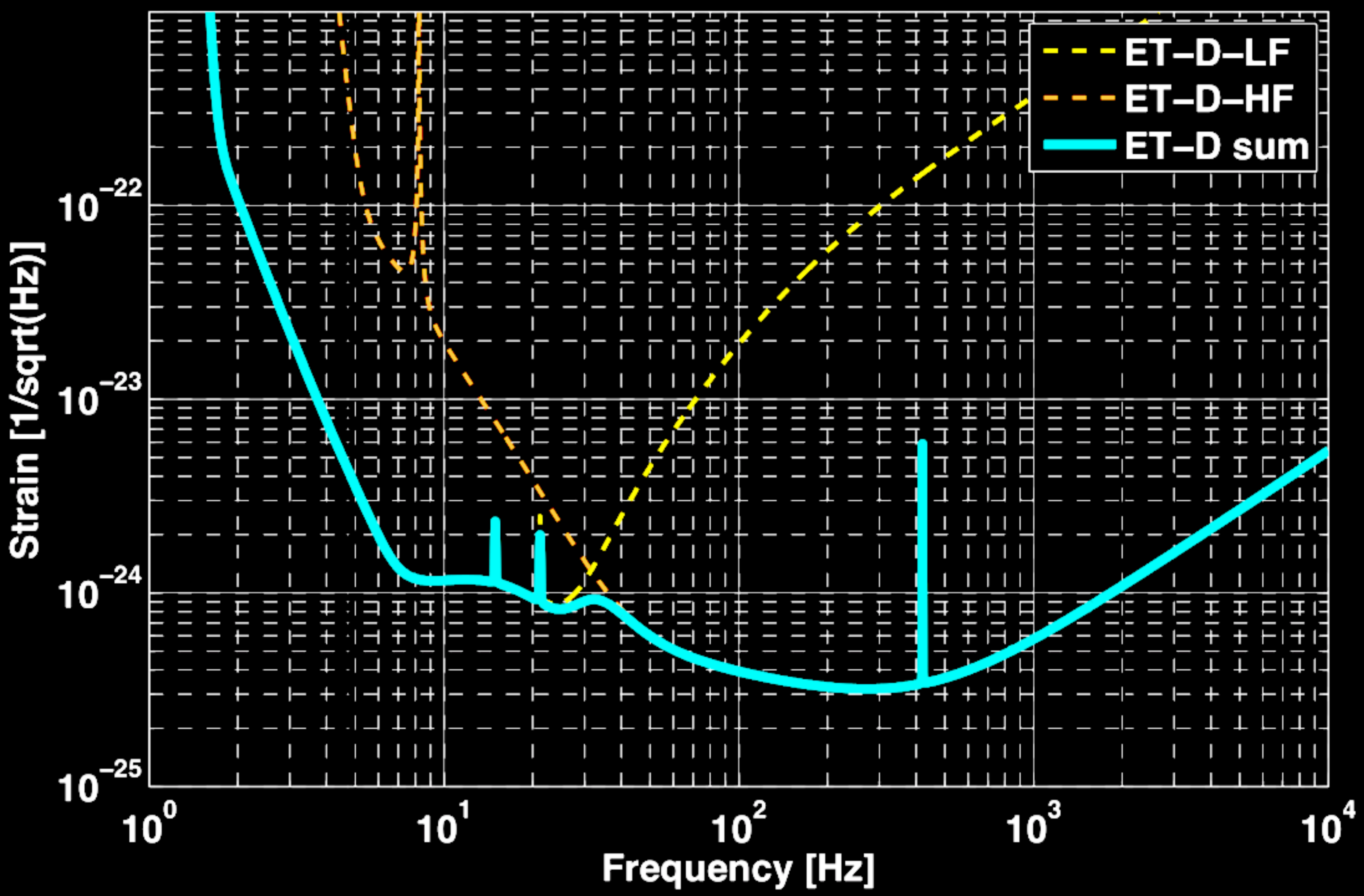
Srivastava, Ballmer, DAB, Afle, Burrows, Radice, Vartanyan arXiv:1906.00084

Einstein Telescope

- 2011 conceptual design, 10x range of advanced detectors, ~1B Euro cost
- Facility: 10.3km-long tunnels, 25m high vertex rooms, 100-200m underground, 20+year lifetime
- Three nested detectors, each with two interferometers
- Triangle geometry: equal sensitivity for both polarizations and more isotopic sensitivity

ET Design Study, ET-0106C-10

Xylophone Configuration



- ET-HF (30-10000Hz):
  - 200kg fused silica optics at room temperature
  - 3MW 1064nm light and phase squeezing
- ET-LF (1.5-30Hz)
  - 211kg silicon mirrors at 10K
  - 16kW 1550nm light and amplitude squeezing
  - Superattenuators

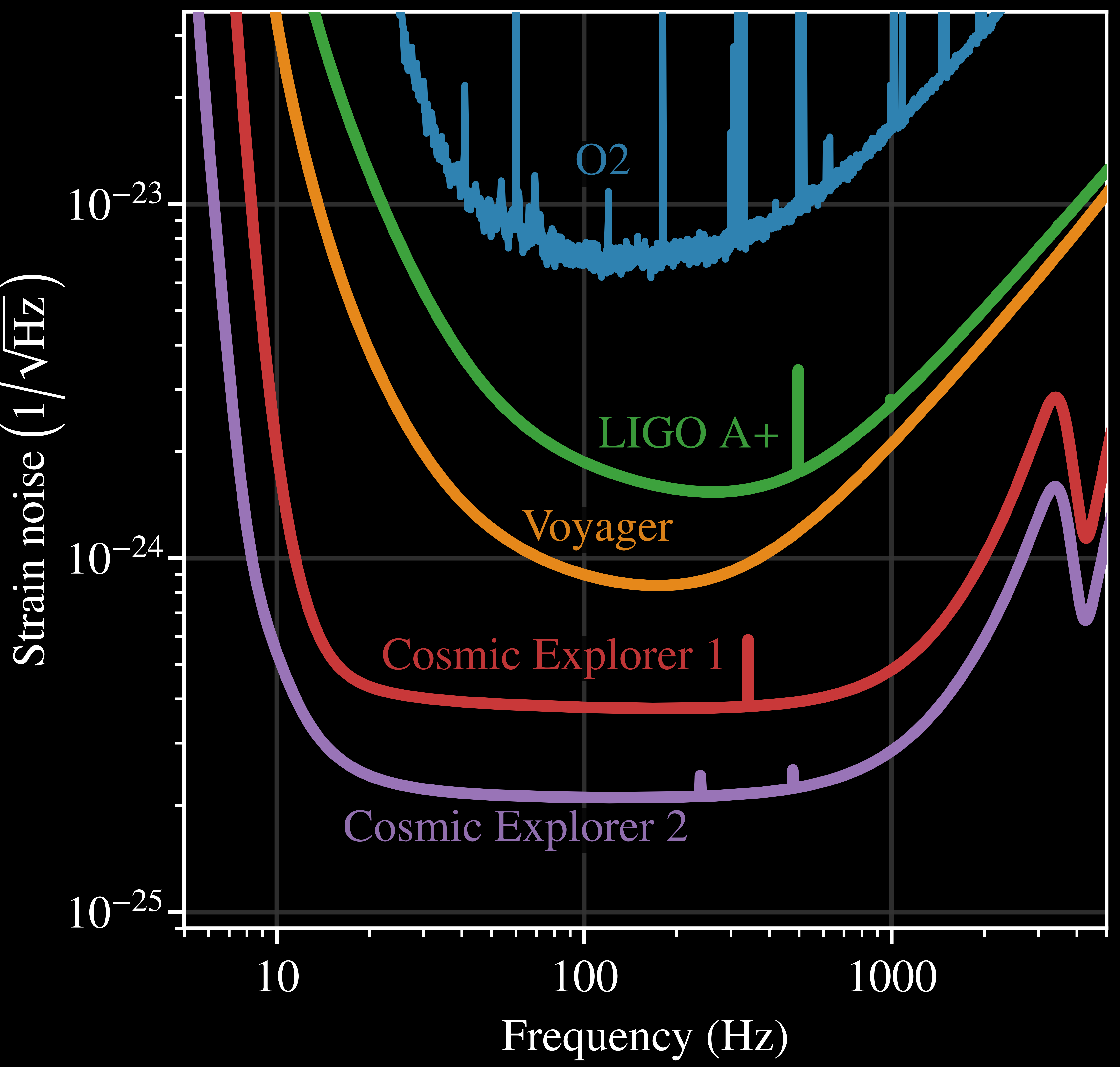
ET Design Study, ET-0106C-10

Cosmic Explorer

- Facility: 40km L-shaped detector on Earth's surface
- One interferometer in faculty
- 14cm wide laser beams, 2 MW laser
- R&D progress needed in optical coatings, quantum noise, thermal compensation
    - Year ~ 2030 and ~ 1B USD

CE1 and CE2: two-stage approach

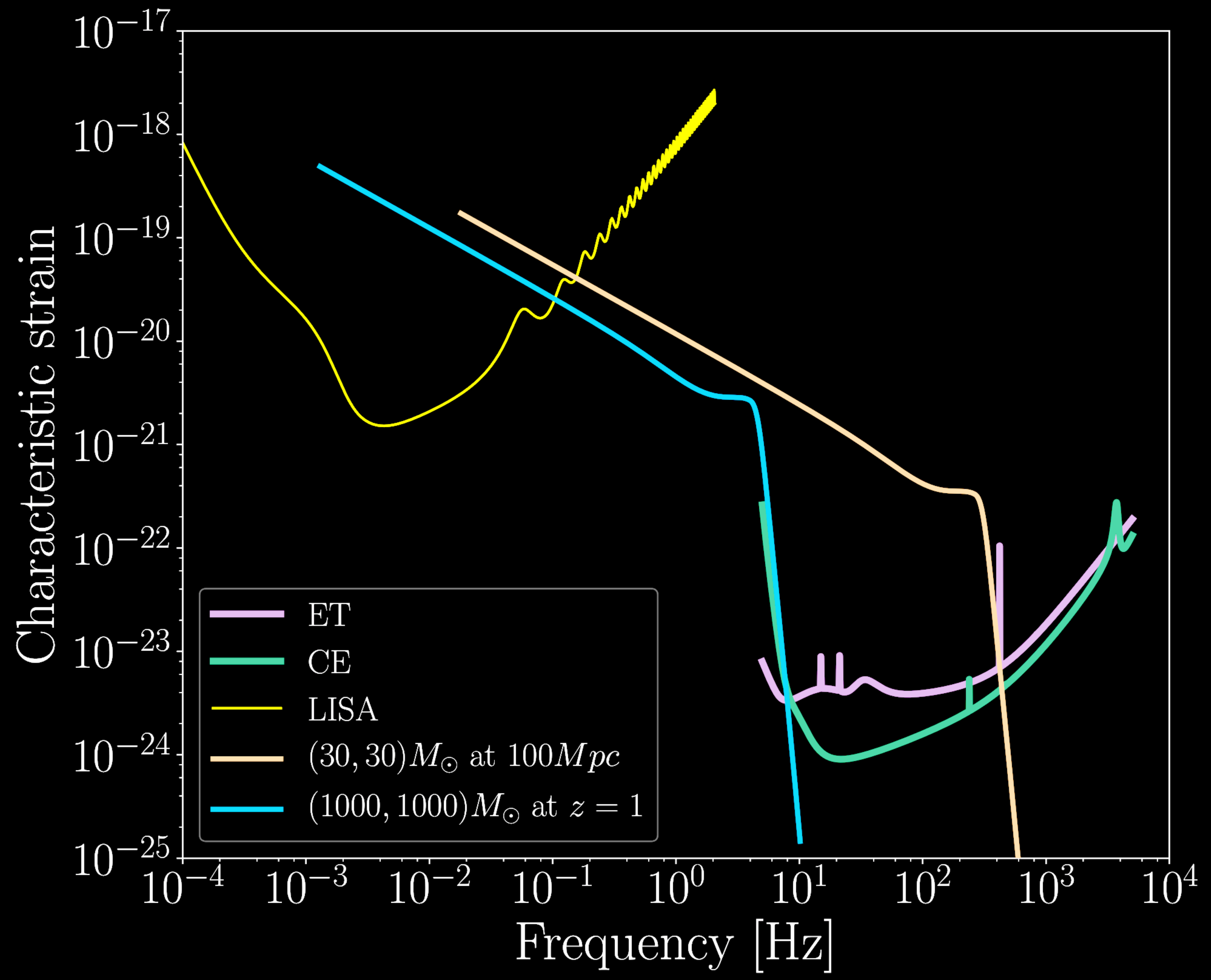
	CE1 2030s, à la aLIGO	CE2 2040s, à la Voyager
Wavelength	1.0 µm	1.5 to 2.0 µm
Temp.	293 K	123 K
Material	glass	silicon
Mass	320 kg	
Coating	silica/tantala	silica/aSi
Spot size	12 cm	14 to 16 cm
Suspension	1.2 m fibers	1.2 m ribbons
Arm power	1.4 MW	2.0 to 2.3 MW
Squeezing	6 dB	10 dB

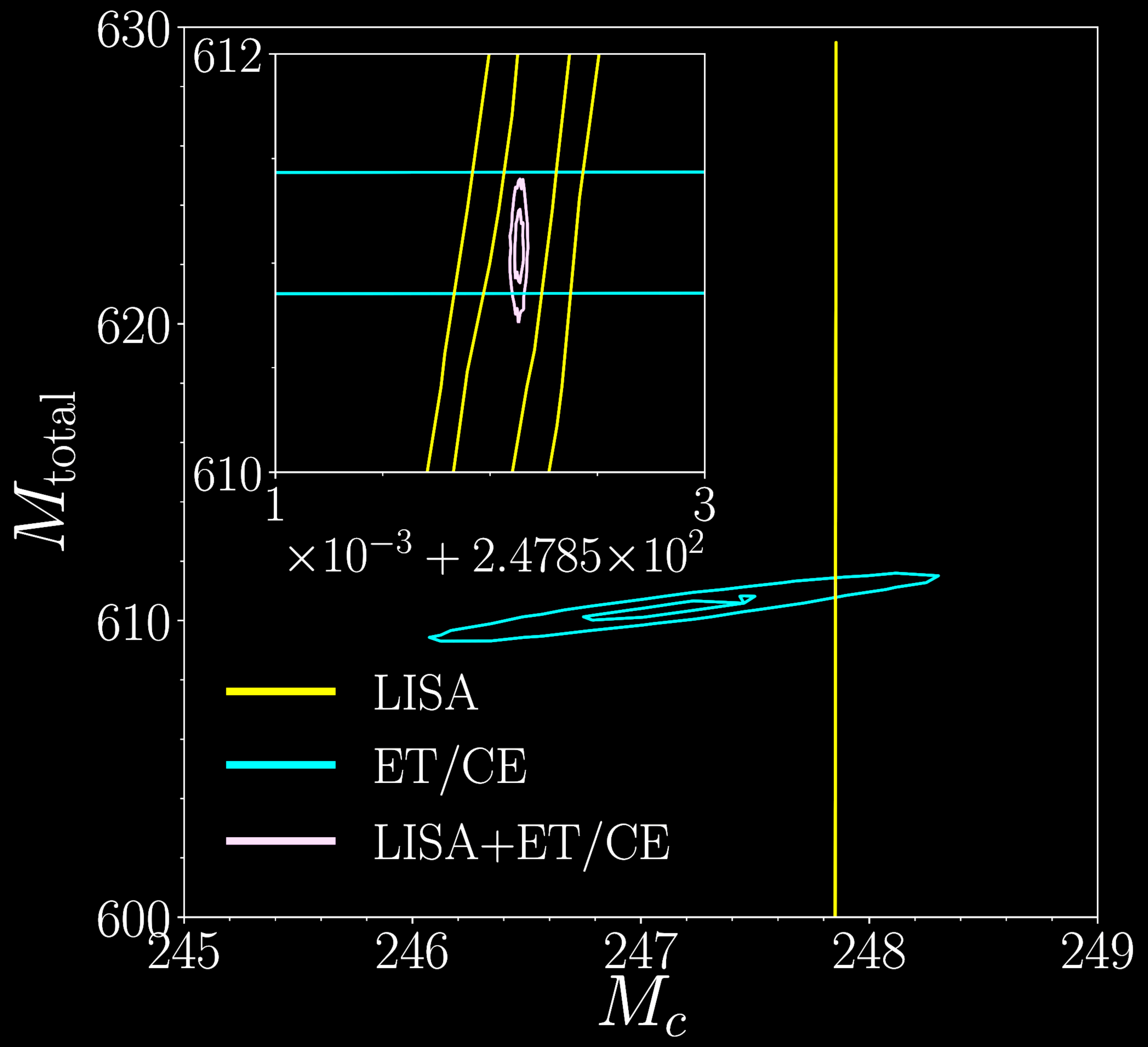


ET and CE are complimentary

- 1 x ET + 2 x CE would be awesome, but expensive
- Community is exploring the scientific benefits of various network configurations
- Other possible detectors:
  - OzGrav High Frequency Interferometer currently in conceptual design
  - Ignoring low-frequency simplifies things a lot, but still lots of physics

Multi-band with LISA

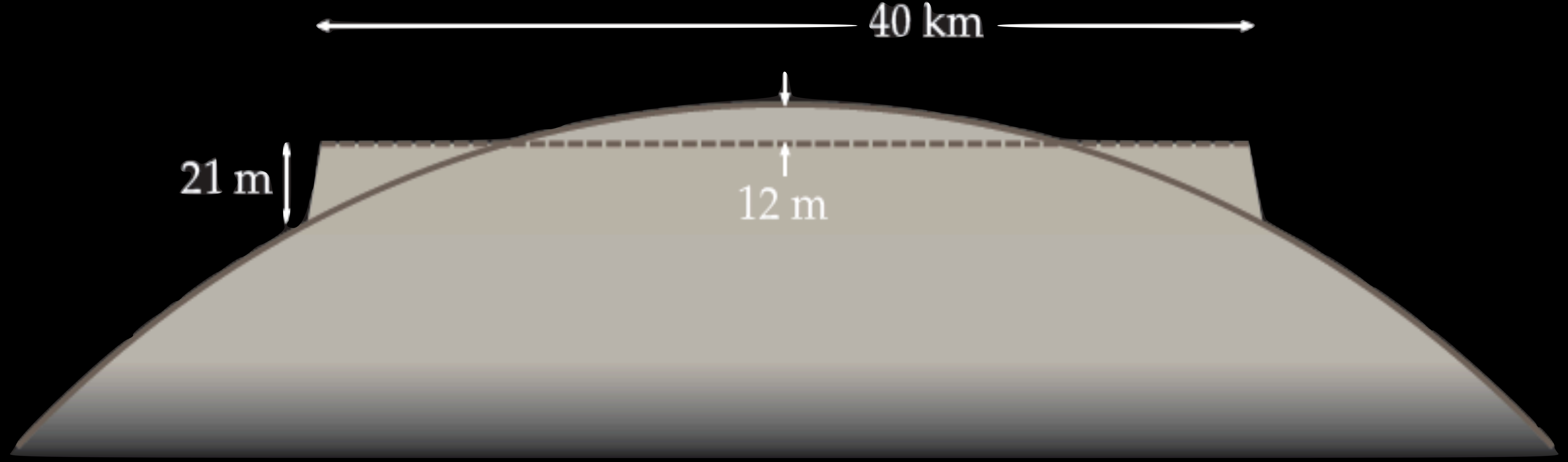




Cutler et al. arXiv:1903.04069

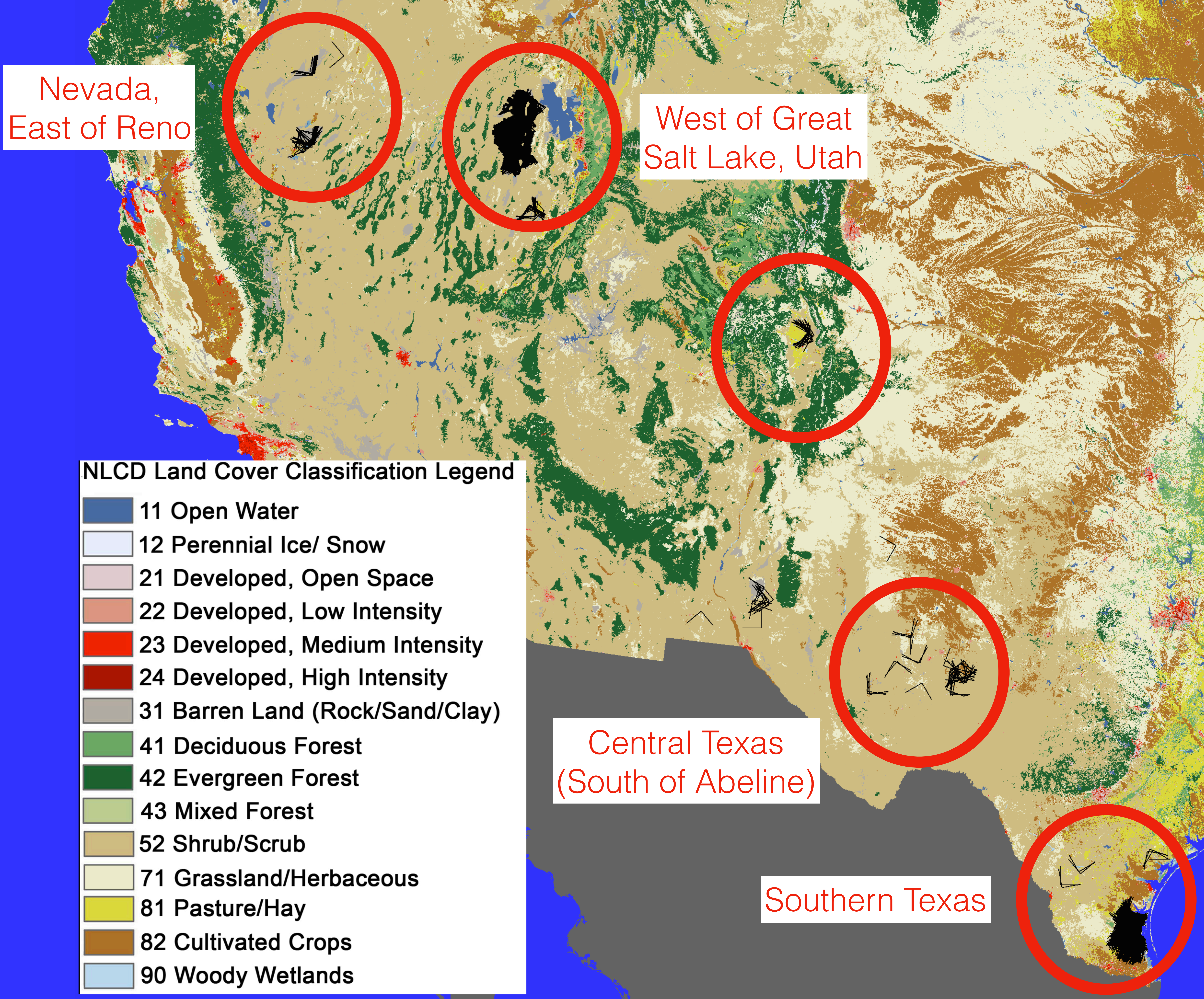
Facility Challenges

- Building a new facility requires ~ $1 billion with current technology
  - Earth moving, tunnelling.
  - Vacuum construction, beam-tube bake out
- Possible cost savings with novel vacuum systems or serendipitous sites



Example location: Bonneville Salt Flats, Utah, USA

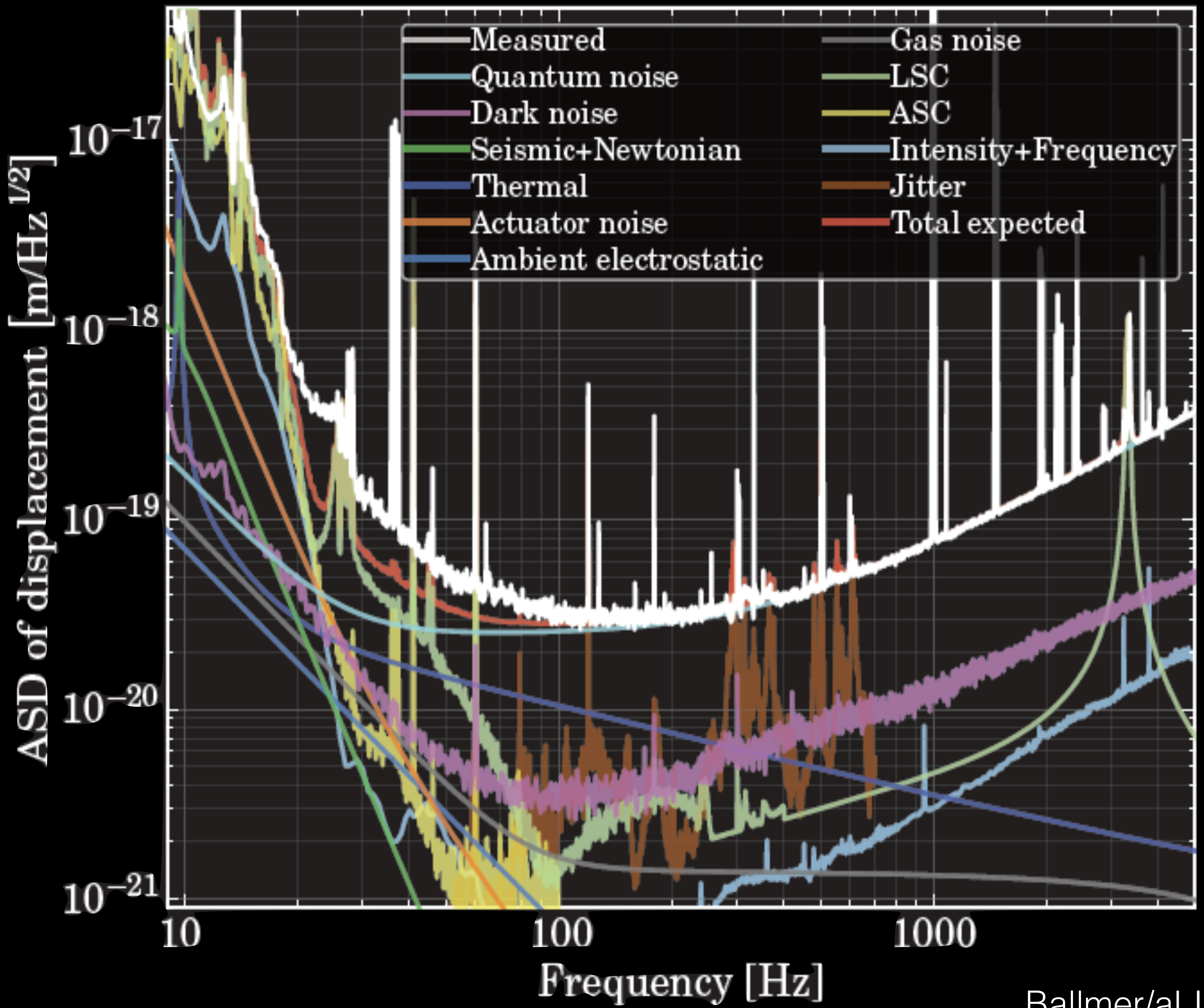
Potential 40 km sites in US



Evans and Hall

Low Frequency is Hard

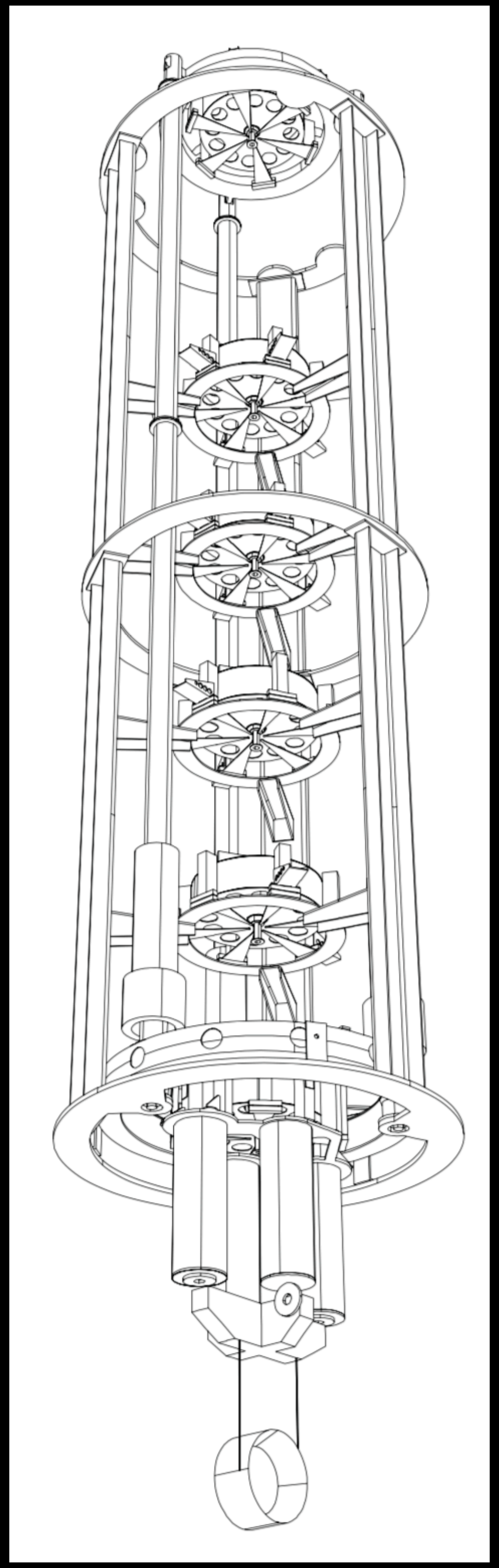
- Lots of noise sources:
  - Control noises
  - Geophysical noises
  - Scattered light
  - Mystery noises
- Ambitious goals:
  - aLIGO 10Hz, CE 5Hz, ET 3 Hz



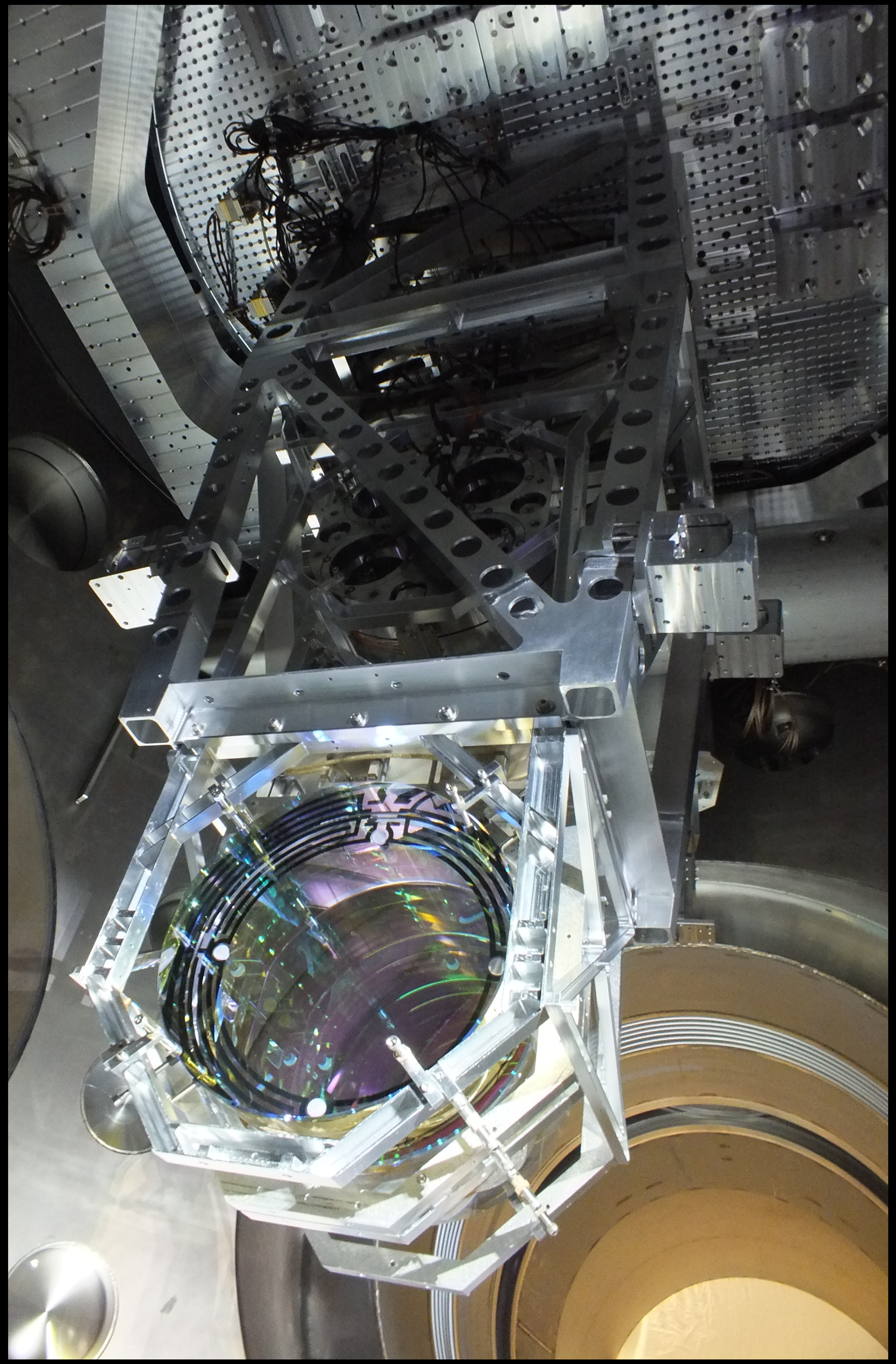
Ballmer/aLIGO

Reducing Mirror Motion

- Suspend mirrors from multiple pendulums
- Apply multiple-stage active isolation and tiered control
- Reduce wind and surface waves through building shape or depth
- Cancel gravity noise by sensing it with seismometer array



Virgo



LIGO

High Power and Strong Squeezing

- Highest power demonstrated so far ~ 250 kW (aLIGO)
- 3G power requirements: 3 MW
    - 10x power increase
- Best squeezing demonstrated: 6 dB (GEO600)
- 3G requirement: 10 dB
    - 3x optical loss reduction

New Materials and New Wavelengths

- Most detector experience is with room-temperature glass and 1064 nm lasers
- Need to develop familiarity with cryogenic suspended sapphire or silicon
- Need high-power lasers, high-efficiency photodetectors, etc. at new wavelengths
- Need large pieces of high-quality silicon for core optics

Where are we now?

GWIC 3G White Papers

- Coordination via Gravitational Wave International Committee
  - Cosmology and early Universe arXiv:1903.09260
  - Extreme gravity and fundamental physics arXiv:1903.09221
  - Black hole binaries arXiv:1903.09220
  - Multimessenger observations of neutron star binaries arXiv:1903.09277
  - Multimessenger observations of supernovae and isolated neutron stars (magnetars, pulsars, ...) arXiv:1903.09224
- Science book coming soon

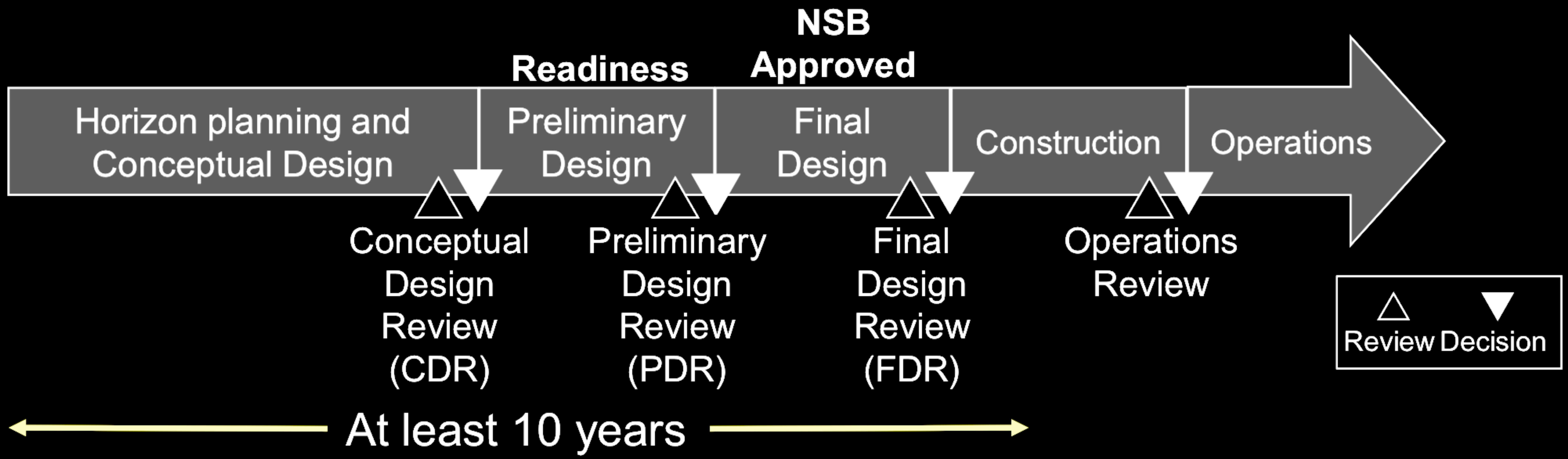
Einstein Telescope

- 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

Cosmic Explorer

- US-funded effort
- Horizontal design study funded by NSF
  - MIT (Evans, Vitale), Syracuse (Ballmer, Brown), Caltech (Adhikari, Chen), Fullerton (Lovelace, Read, Smith), Penn State (Sathyaprakash)
  - Collaborating with LIGO Lab on Astro2020 APC White Paper
  - Deliverable is Cosmic Explorer White Paper for community
- NSF-sponsored workshop on large ultra-high vacuum systems
  - https://dcc.ligo.org/cgi-bin/DocDB/ShowDocument?docid=P1900072

The US MREFC Process



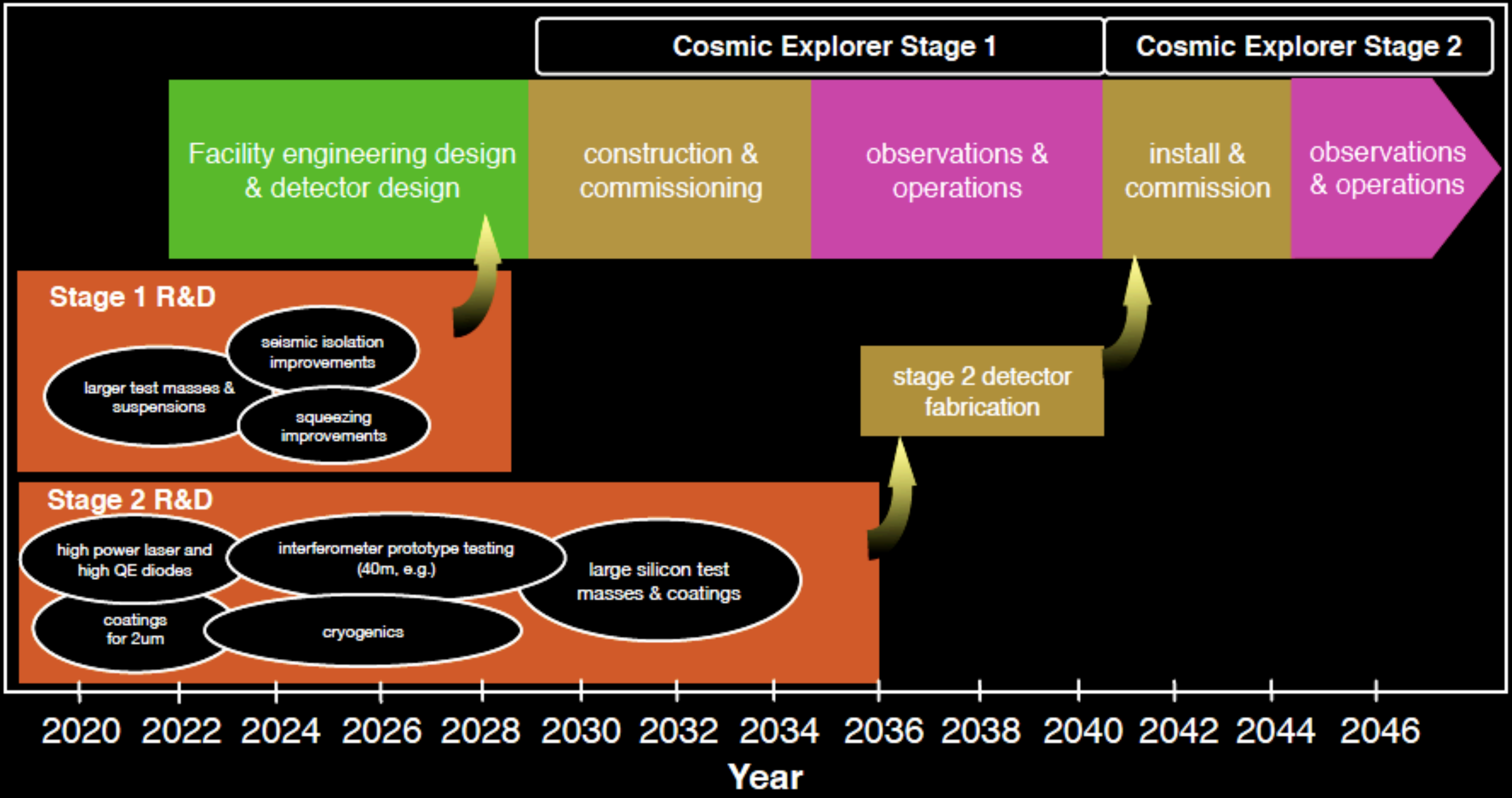
Marronetti, Dawn Meeting 2019

Towards Cosmic Explorer

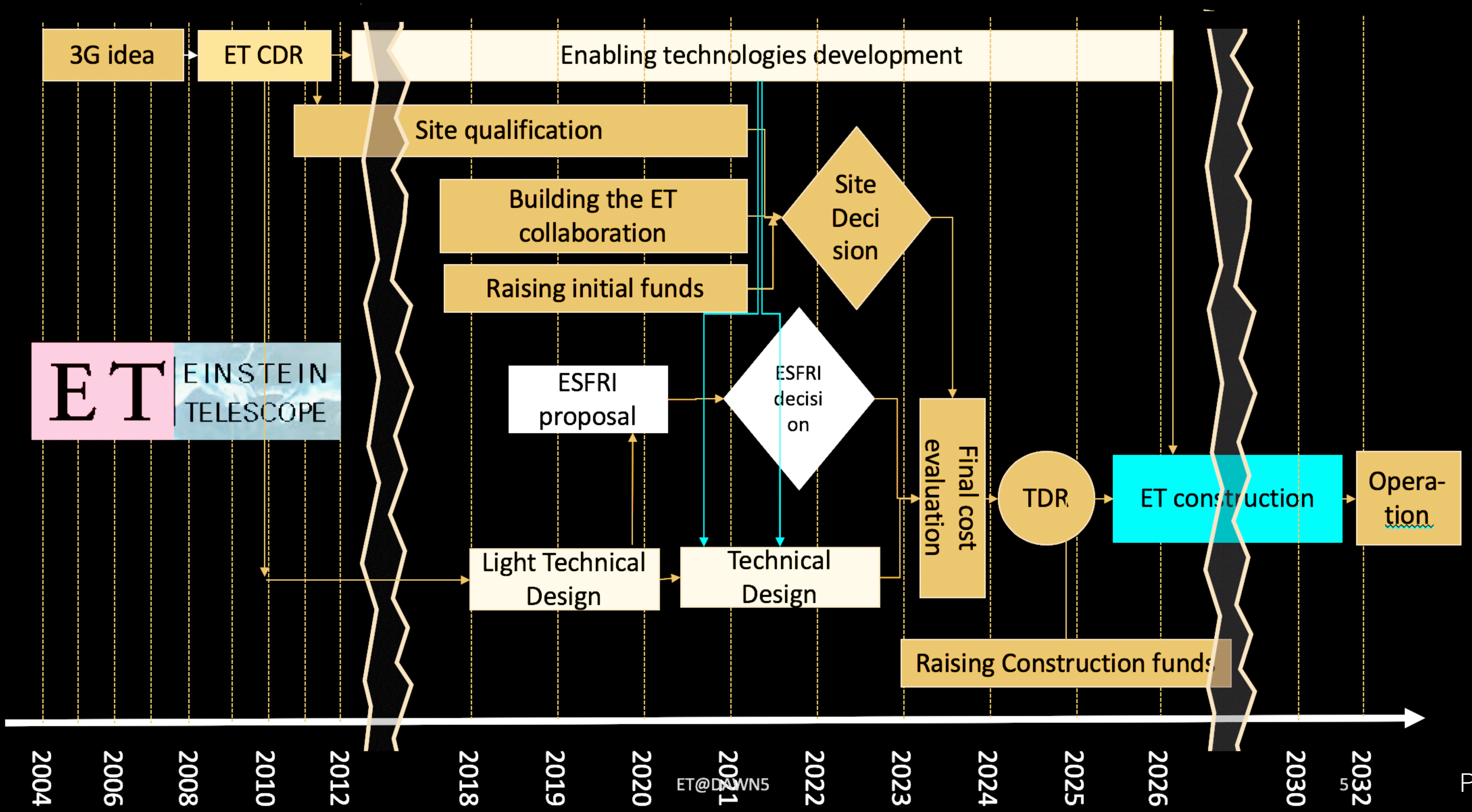
- Horizon planning (3G Design NSF award in 2018) leading to Cosmic Explorer White Paper (3 years)
- Community endorses the CE White Paper (0.5 years)
- NRC report based on CE White Paper and GWIC reports (1.5 years?)
- NSF MPS Advisory Committee subcommittee reviews NRC report (0.5 years)
  - Physics Division develops written plan for MPS approval
  - NSF Director makes a decision to authorize Conceptual Design funding
- Conceptual Design period (2-3 years)
- Preliminary Design period (2-3 years)
- NSF approves submission to NSB (0.5 years)
- Final Design period (2-3 years)
  - NSB prioritization
  - OMB/Congress budget negotiations
- Congress appropriates MREFC funding (2030-35) **Total 12-15 years**

Marronetti, Dawn Meeting 2019

Timeline of a Cosmic Explorer 40km Observatory



Einstein Telescope



Punturo Dawn 2019

Engaging the Community

- Investing in a 3G detector is a big undertaking for the science community
- Need input beyond from beyond the existing gravitational-wave community
- US Cosmic Explorer team currently discussing how to get input from wider community... we would like to get something set up soon!
  - LISA-like lightweight science consortium?

Conclusion

- Current detectors see the local universe
- Terrestrial detectors that see the entire universe are within reach
- Planning for third-generation detectors is underway