Prospects for the future of gravitational-wave observation

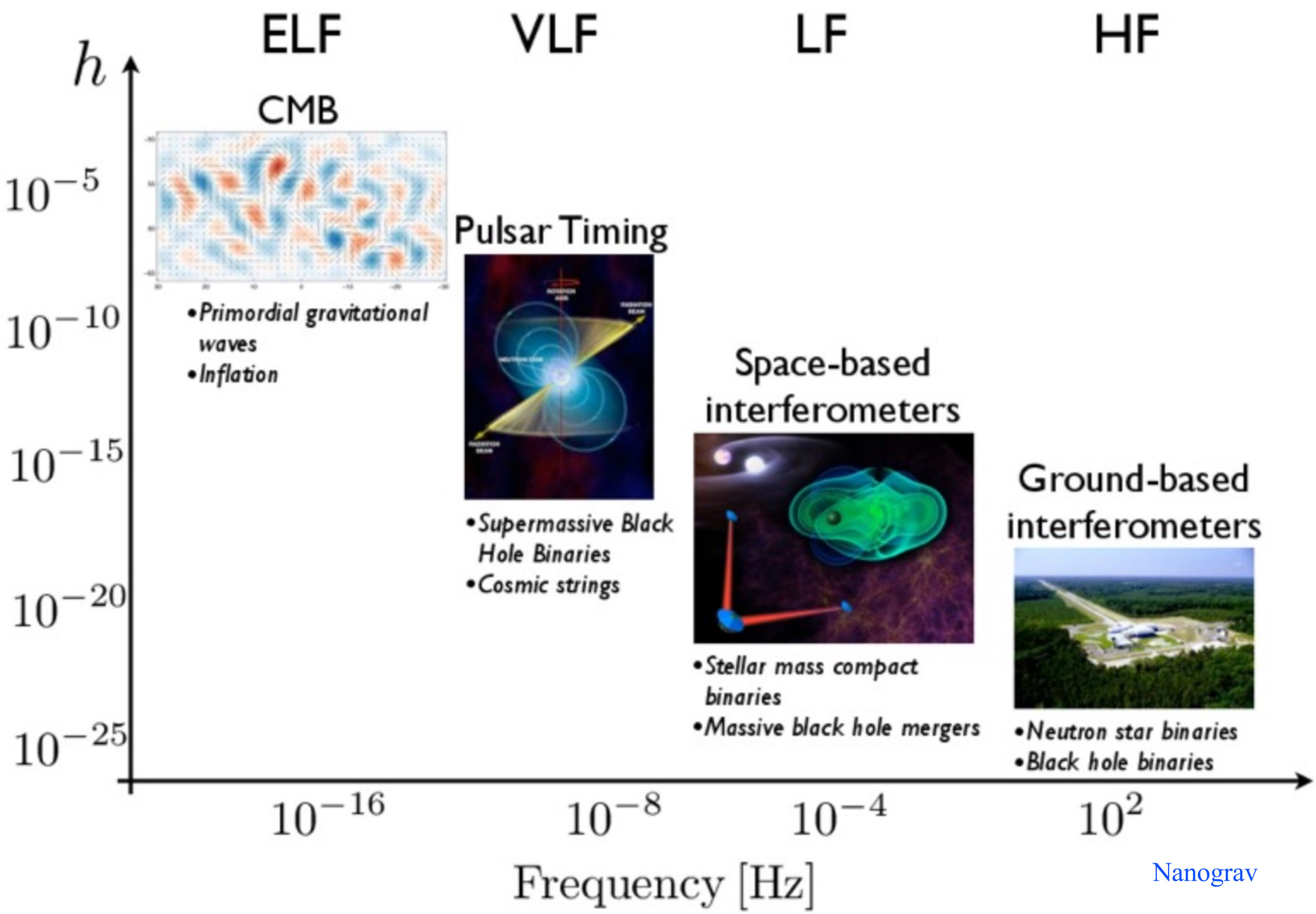
Réunion Groupement de Recherche "Ondes Gravitationnelles"
April Fool's day, 2021

David Shoemaker
MIT LIGO/LISA

Thanks to…

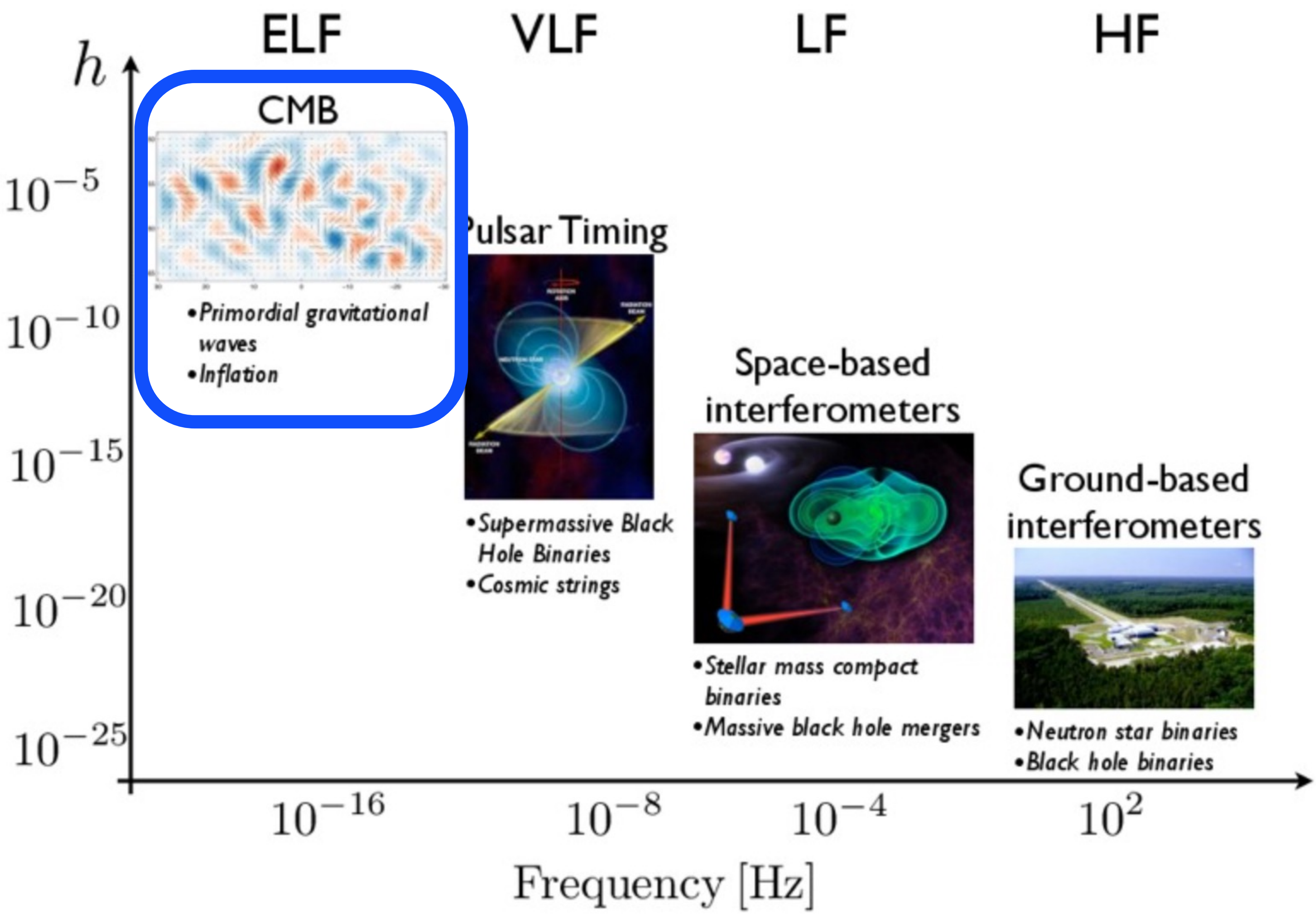
- The LIGO Lab – MIT, Caltech, Hanford and Livingston Observatories
- The LIGO Scientific Collaboration; Virgo and KAGRA
- NASA, and the LISA Consortium
- Pulsar Timing Array Collaborations
- GWIC – Gravitational-Wave International Committee
- The US National Science Foundation for extraordinary support and perseverance for LIGO

Detection methods, Projects



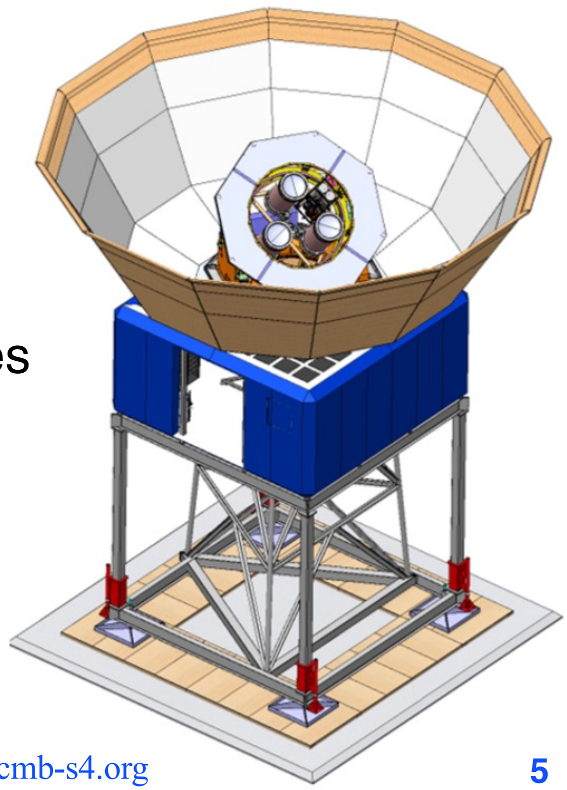
Nanograv

Detection methods, Projects



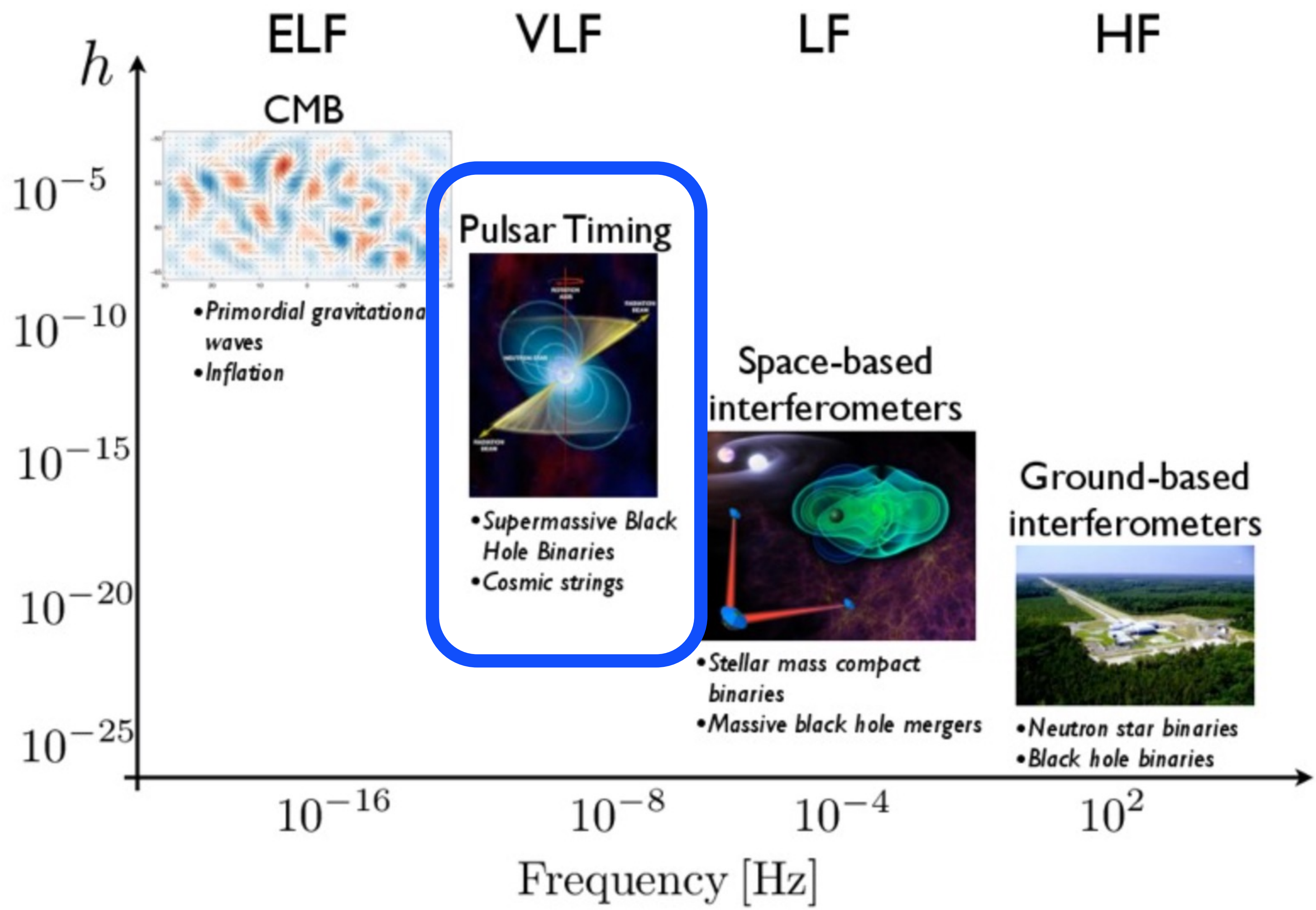
Primordial Stochastic Background search in the CMB

- Primordial gravitational waves are a prediction of cosmological inflation
- Leads to so-called B-mode polarization – a unique imprint on the CMB
- For the foreseeable future, precise measurements of CMB B-modes are our most likely way to detect these primordial gravitational waves
- In analogy to the Hulse-Taylor demonstration of GW emission, this search does not give the time series of $h(t)$ but rather an indirect indication
- CMB-S4 is the next-generation ground-based cosmic microwave background experiment; could make a factor 100 improvement in the measurement of the amplitude of tensor perturbations
- A total of 18 small aperture telescopes will measure odd-parity B-mode polarization fluctuations at degree scales
- Results from CMB-S4 anticipated in the late 2020's
  - » No guarantee of positive detections
  - » Very interesting target!



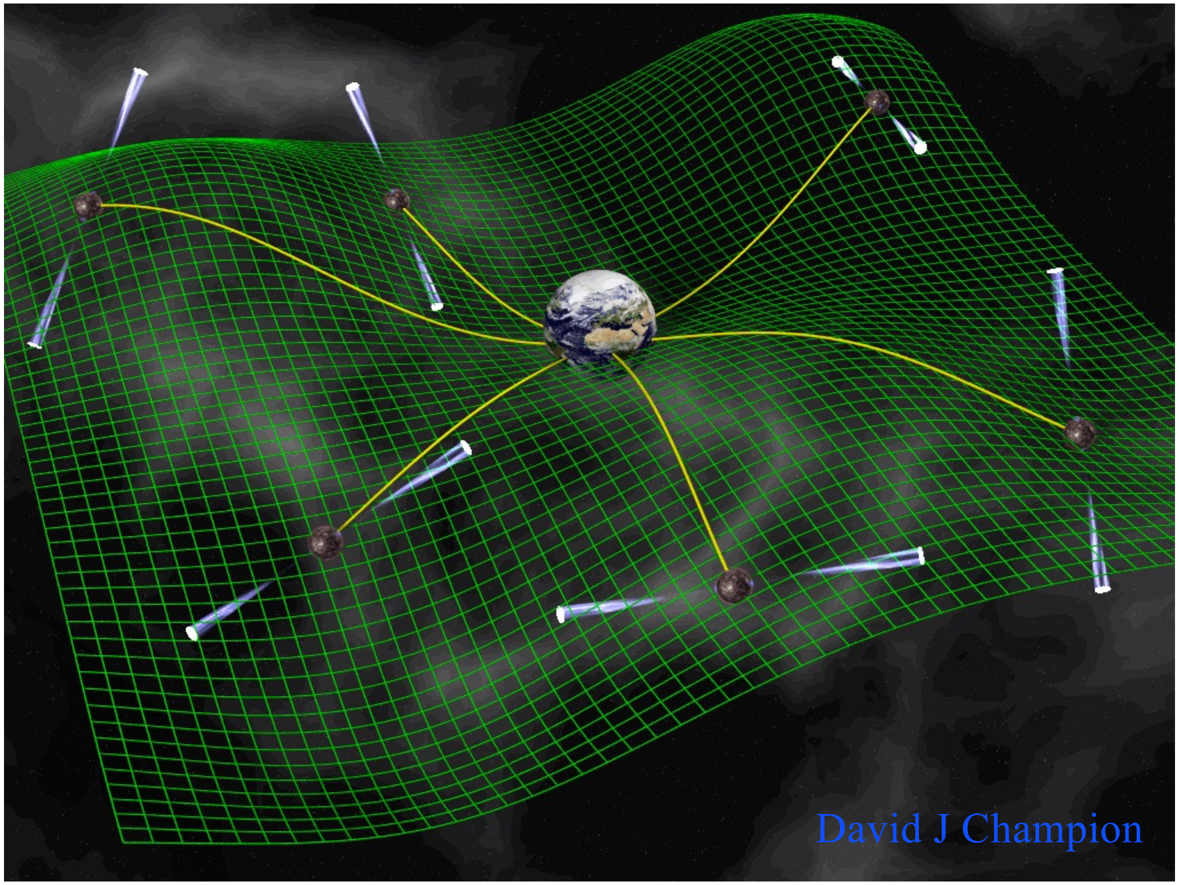
https://arxiv.org/abs/2008.12619, https://cmb-s4.org

Broad spectrum of GW sources

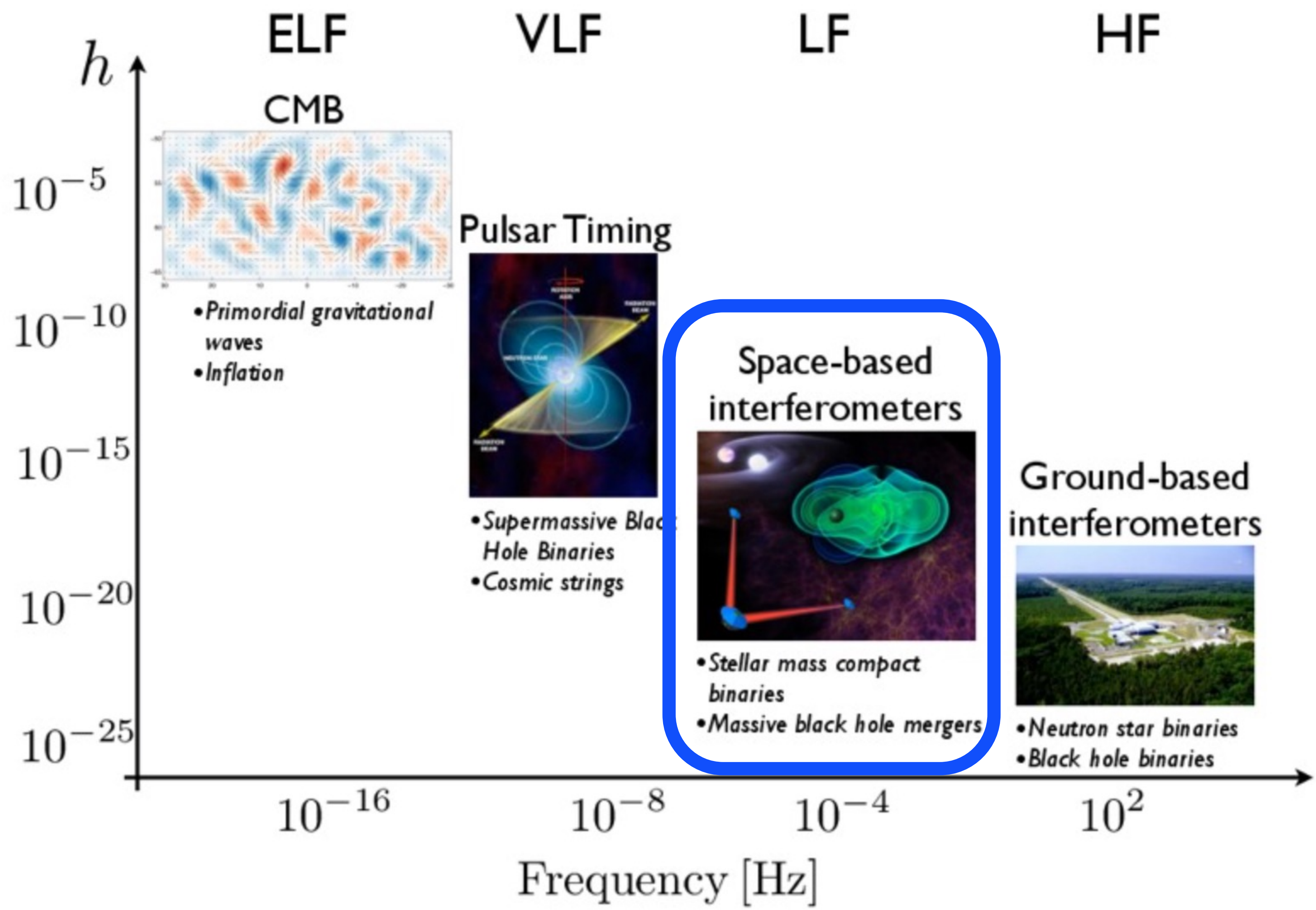


Pulsar Timing Arrays

- Pulsars: spinning Neutron Stars; magnetic fields lead to beamed EM emission
  - » Pulsars are extremely stable clocks, and are 'free test masses'
- Significant number have their 'beacons' pointing at Earth, received by an international array of radio telescopes – and team of researchers
- If a GW passes between us and the pulsar, the time-of-arrival of the clock pulse will be shifted
- Looking at a collection of pulsars scattered in space, unique signal corresponding to GWs can be inferred
- Sensitive to *very* massive BH
  - » ~10^7 - 10^{10} $M_\odot$
- Astrophysical stochastic background best candidate
- Some indication of a signal!
  - » arXiv:2005.06490
  - » Measurements continuing…



Broad spectrum of GW sources



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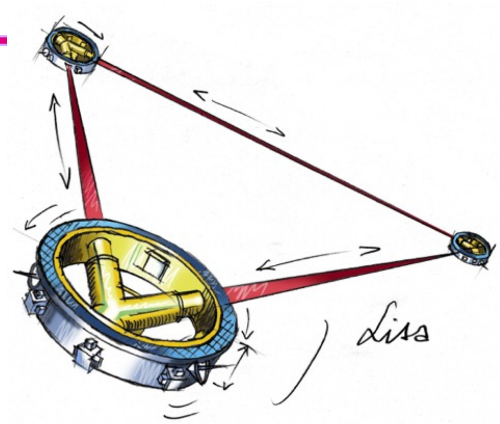
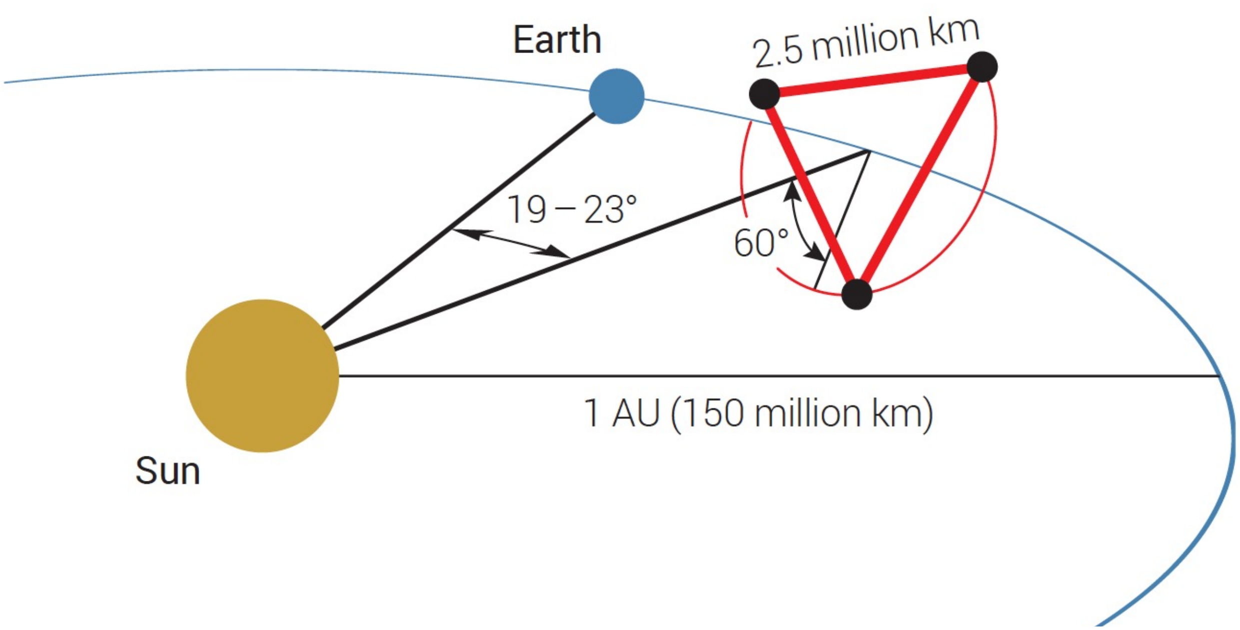
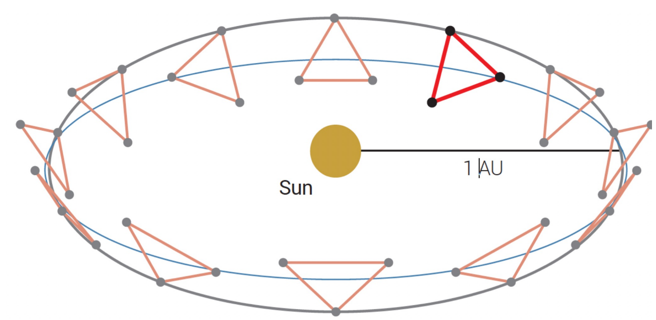
LISA, targeting super-massive Black Holes



- Place free masses in space; use interferometry to sense path length changes due to passing GW
- 2.5x10^6 km arms: best sensitivity 0.01 Hz, target masses to 10^6 solar masses
- 'Servo' the shield satellites to follow the test masses, protecting against solar wind etc.
- Orbit scans sky; sources last years, viewed from 2AU baseline

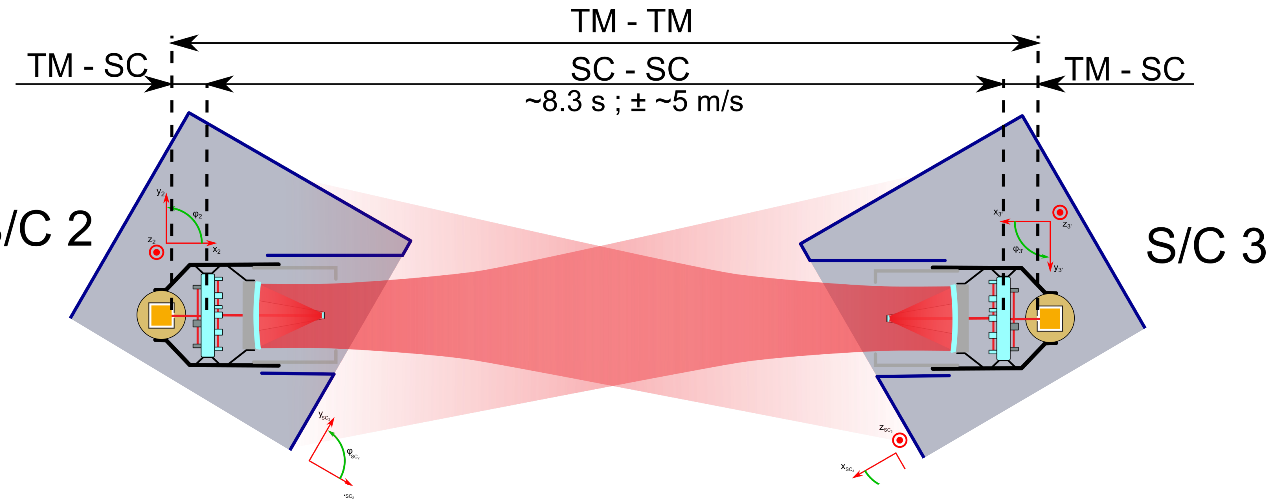




LISA L3 Mission Concept Proposal

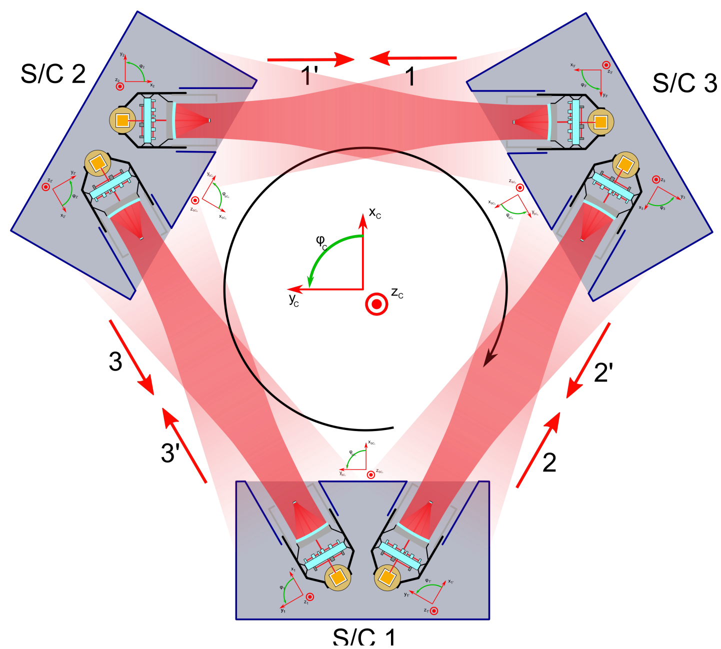
The measurement concept

- Test-mass to test-mass measurement is synthesized from:
- test-mass to spacecraft
- →spacecraft to spacecraft
- →→spacecraft to test-mass



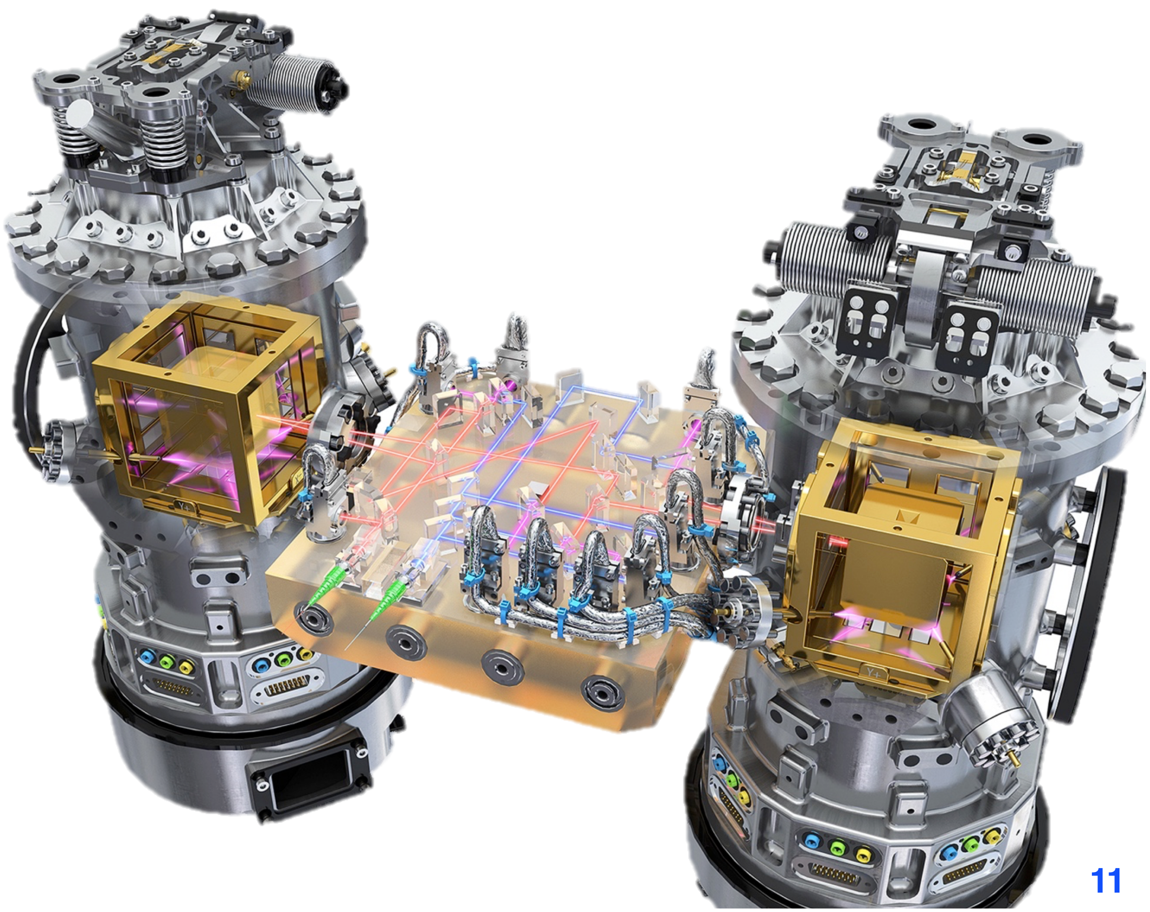
- 2 W broadcast, 10^{-10} W received
  - » *Not* LIGO-style interferometry!
  - » 6 independent lengths

- Combine 6 links on ground
- 'Time Delay Interferometry' to reconstruct GW waveform, suppress technical noise



LISA PathFinder

- LPF was two test masses, separated by and optical bench of some tens of cm; LISA uses the same test mass setup
- Sensors measure distance from test mass to the cage
- Low-force thrusters push on spacecraft to keep the cage equidistant from the test mass

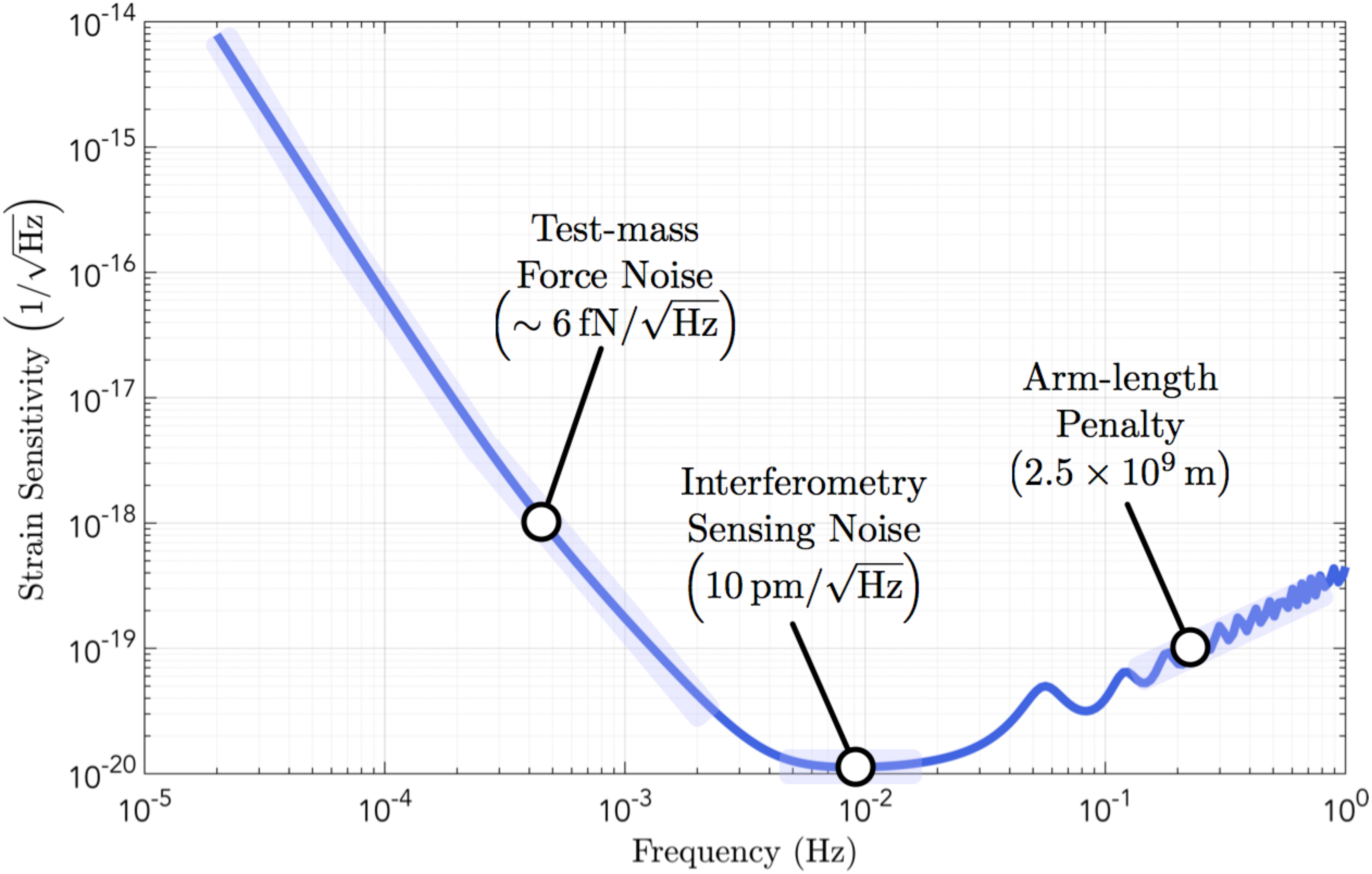


- Initial balancing is critical!
- The ‘gravitational attraction’* of the test mass to a paperclip would be fatal, causing the spacecraft to chase the paperclip to oblivion…

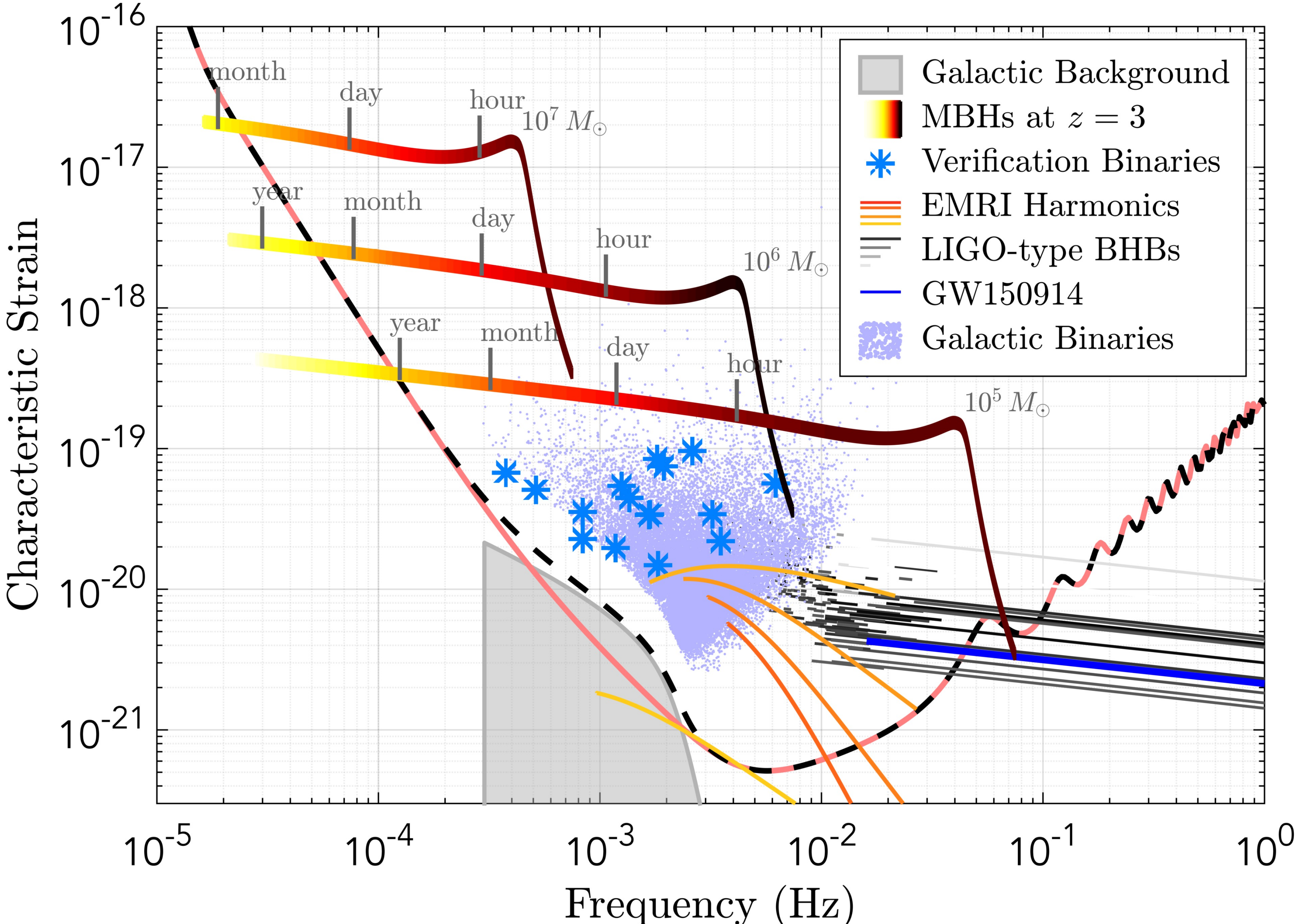
*‘gravitational attraction’ = warpage of spacetime

LISA Sensitivity curve

- Stray forces at low frequencies, shot noise at high frequency
- See the effect of GW wavelengths shorter than arms at HF



LISA Astrophysics



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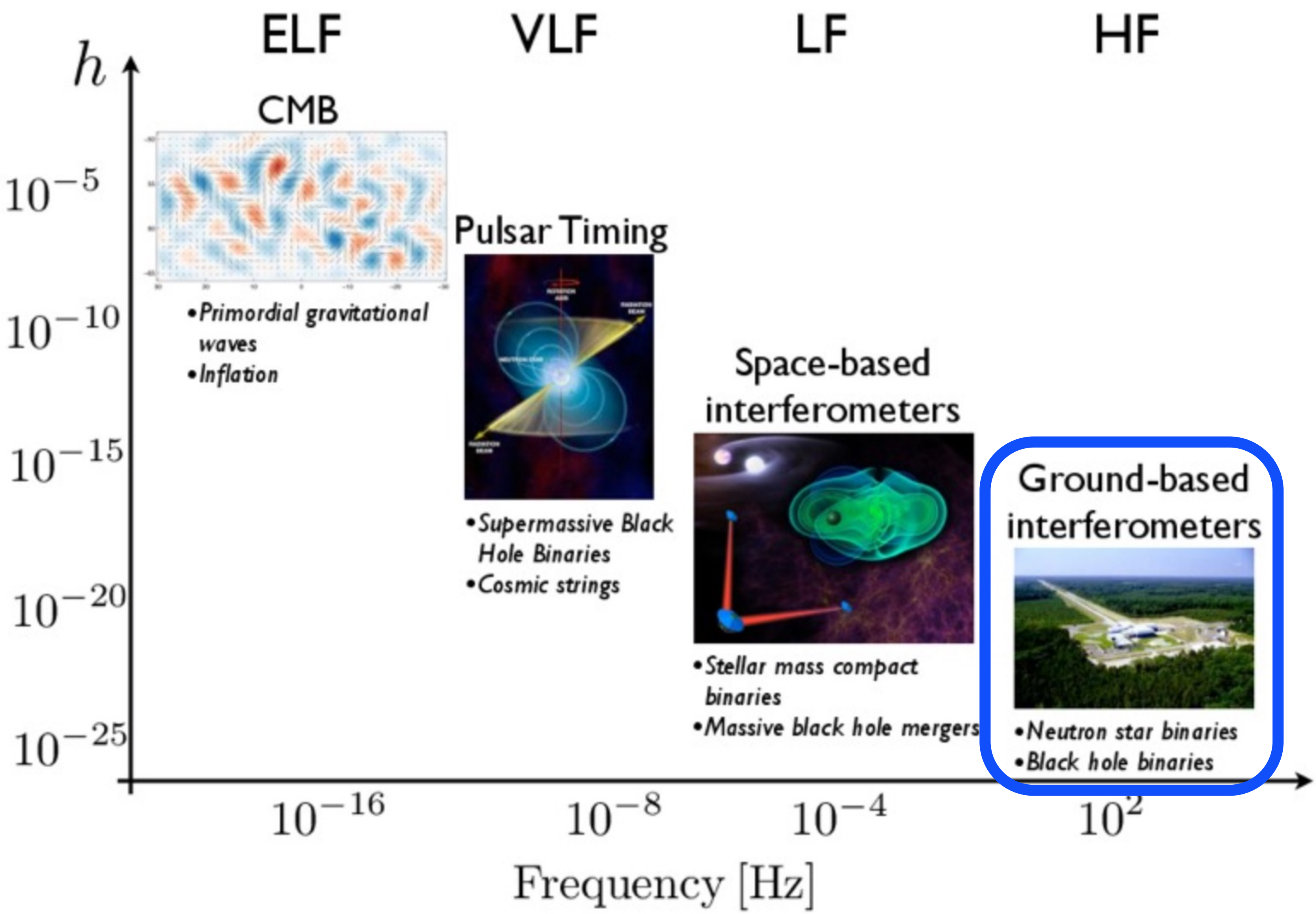
Credit: LISA L3 Mission Concept Proposal

LISA Status

- Approved ESA project; NASA also a partner in the mission
- LISA Consortium:
  - » Key expert group for observatory formulation and implementation
  - » Coordinating deliverables from ESA member nations
  - » Coordinating the development of scientific analysis of data
- Very active design and prototyping activity
- ESA funding competing studies for two possible prime contractors to lead the fabrication phase of the mission
- Production of 3 satellites, each with two transponders, a big production challenge
- Launch in mid-2030's; cruise to orbit ~18 months, commissioning ~6-12 months
- 6-year mission at 75% availability; extension to 10 years likely
- …seems far away, but there is lots of near-term exciting work to do that is pacing launch!

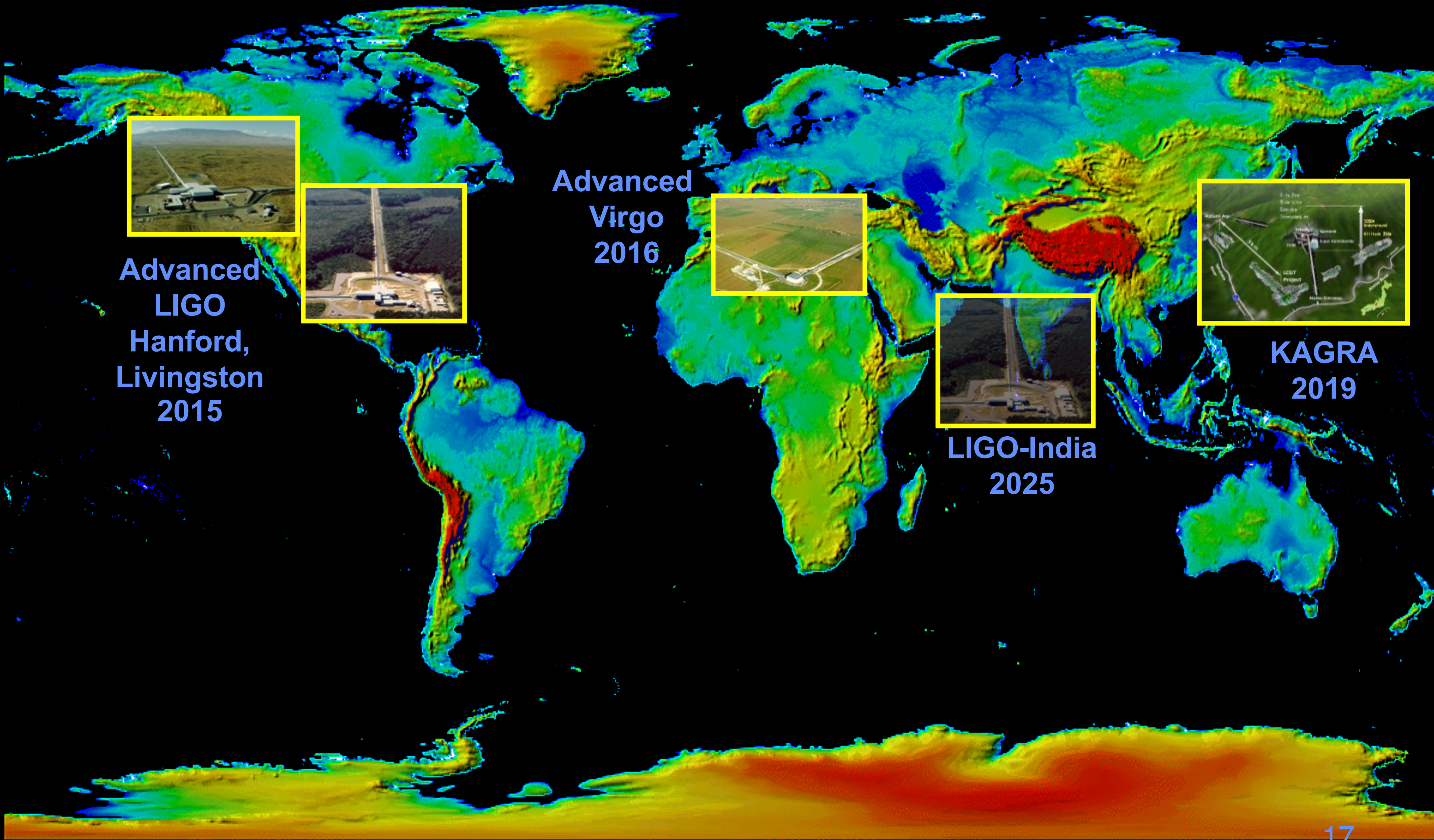
Detection methods, Projects



Ground-based Detector evolution

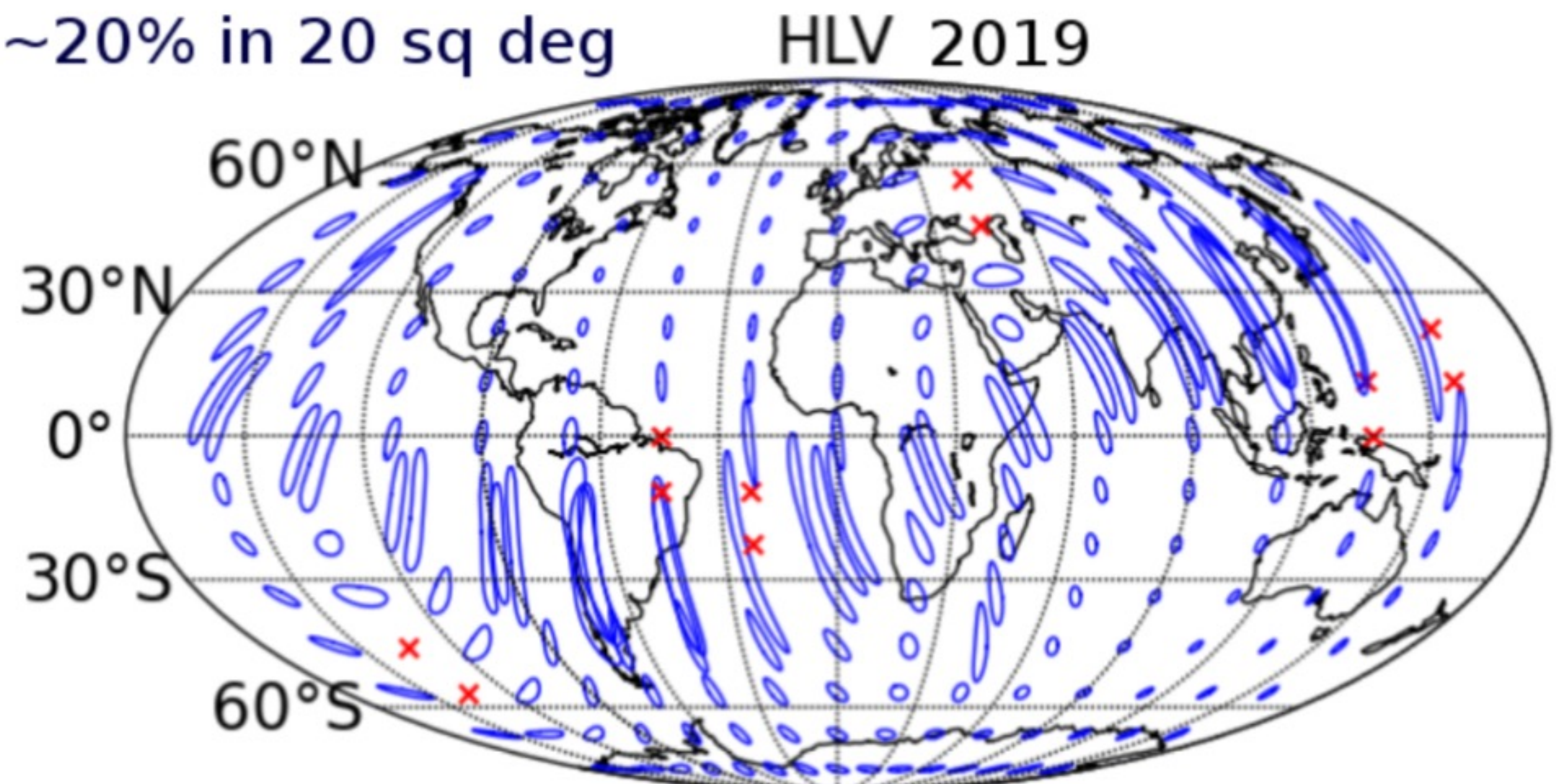
- Ground-based detectors to date are best-effort technically
  - Where were optical or radio telescopes, X-ray satellites, etc. 5 years after their first successful operation? That's where GW detectors are!
  - Seeking observational science enabled with what can be built now
  - Parallel development of future science-driven observatories/detectors
- **Can now envision a science-driven design**
  - Know infinitely more about rates and signals from (at least) binaries
  - Advances in theory offer more specific targets of value
  - Instrument science advancing to enable 'designer sensitivity'
- Two phases under consideration:
  - 'Post-O5' – how far can we get with the current 3-4 km Observatories?
    - How will the Network grow in the later 2020's?
  - Next Generation Observatories – what new facilities are needed?

The advanced GW detector network



2018-19 Sensitivity/configuration:

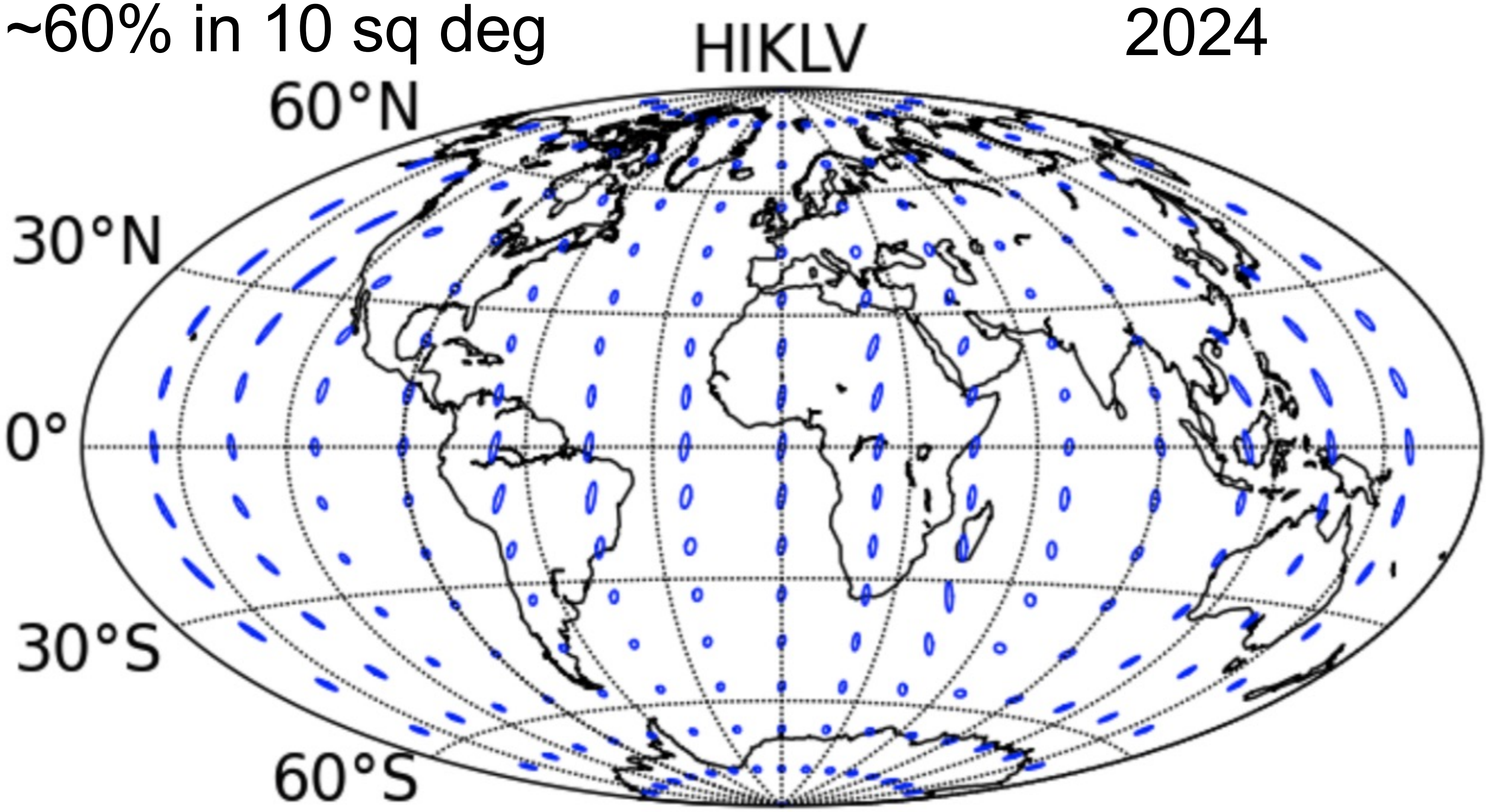
3 detectors
~1 signal per week



~2025 Sensitivity/configuration:

5 detectors (add India and Japan)
far improved source localization

~60% in 10 sq deg

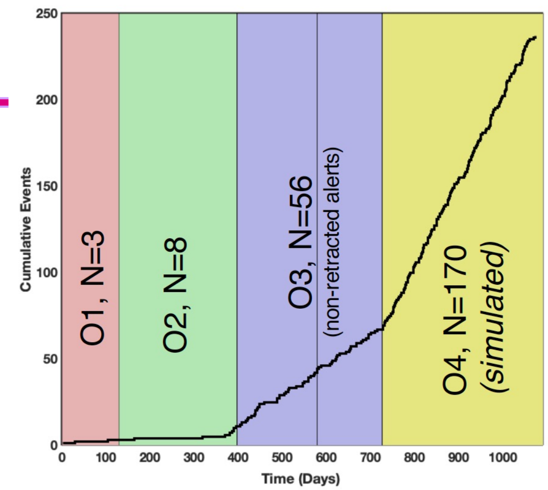


Sensitivity improvements are *very* well rewarded

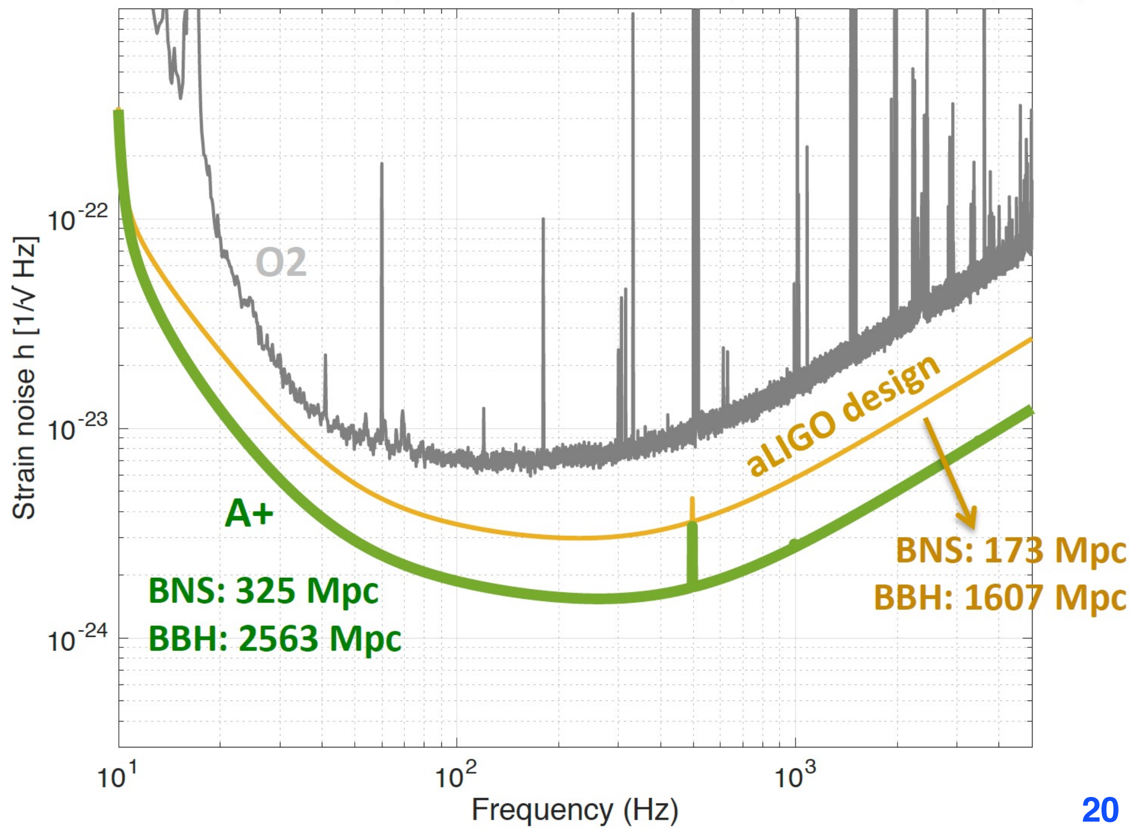
- LIGO 'A+' – Incremental changes to the Advanced LIGO design
  - » Similar changes planned for Virgo
- **Rough doubling of reach**
  - » **2^3 = 8 greater volume**
  - » **8x higher rate**
  - » 17-300 BBH/month
  - » 1-13 BNS/month
  - » 2-11 BNS x SGRB coincidences/year
- Population studies
- Hubble Constant
- …higher SNR for e.g., tests of GR

- Plan to be observing ~2024 (plus pandemic delay)

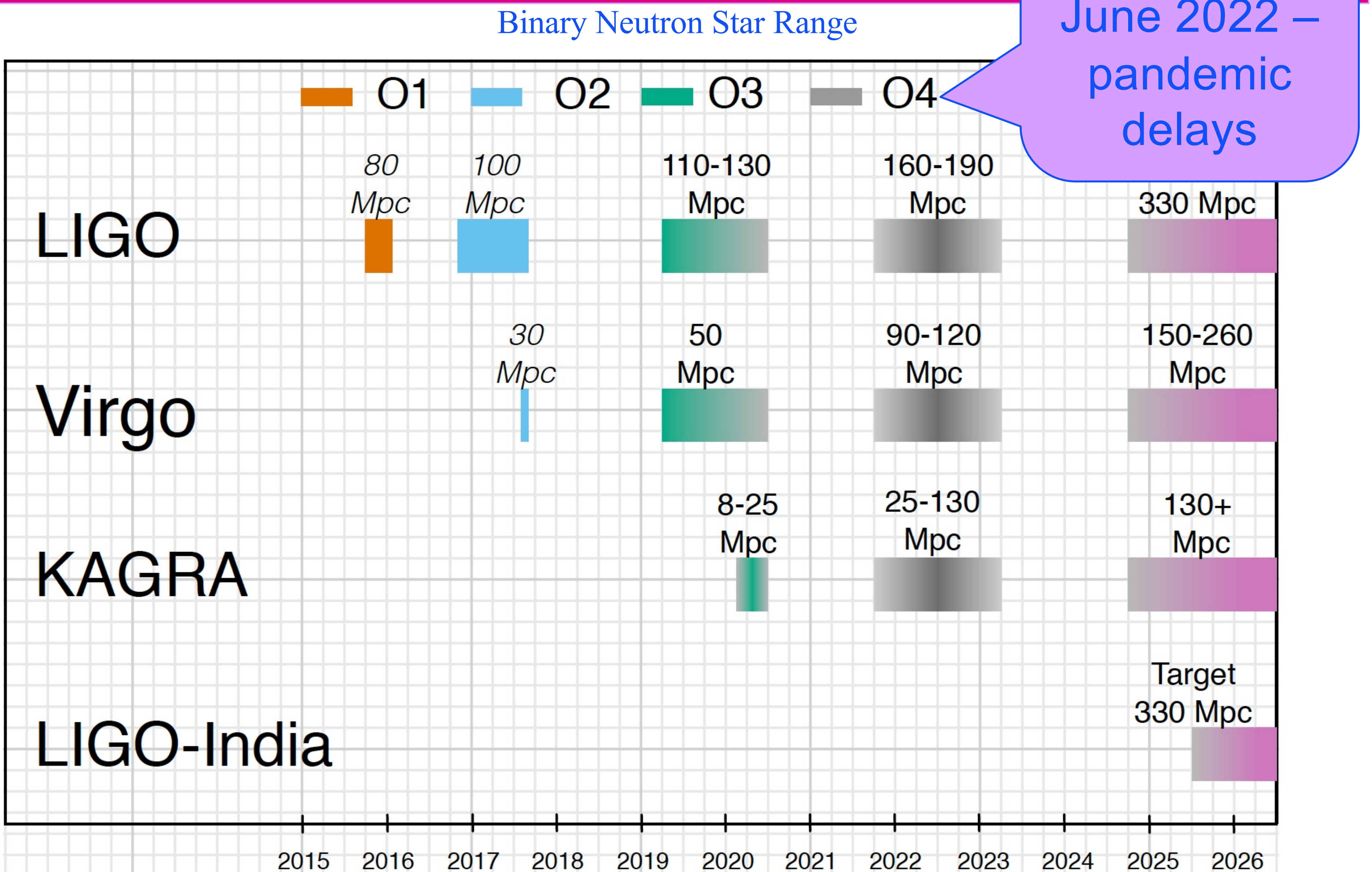
Simulated Event Stream for a one year duration O4 run



Projections toward aLIGO+ (Comoving Ranges: NSNS 1.4/1.4 $M_\odot$ and BHBH 20/20 $M_\odot$)



Planned Observing Timeline



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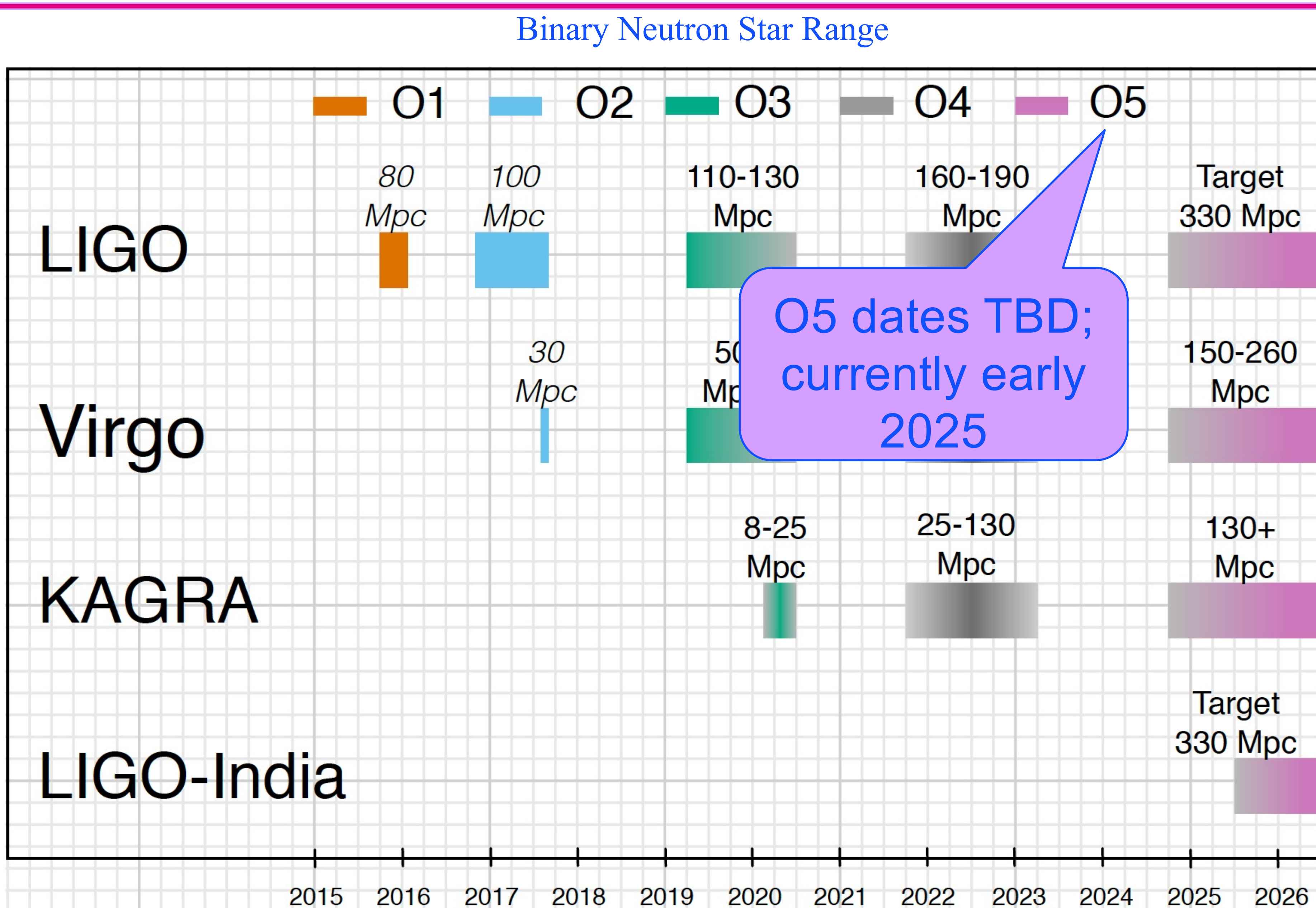
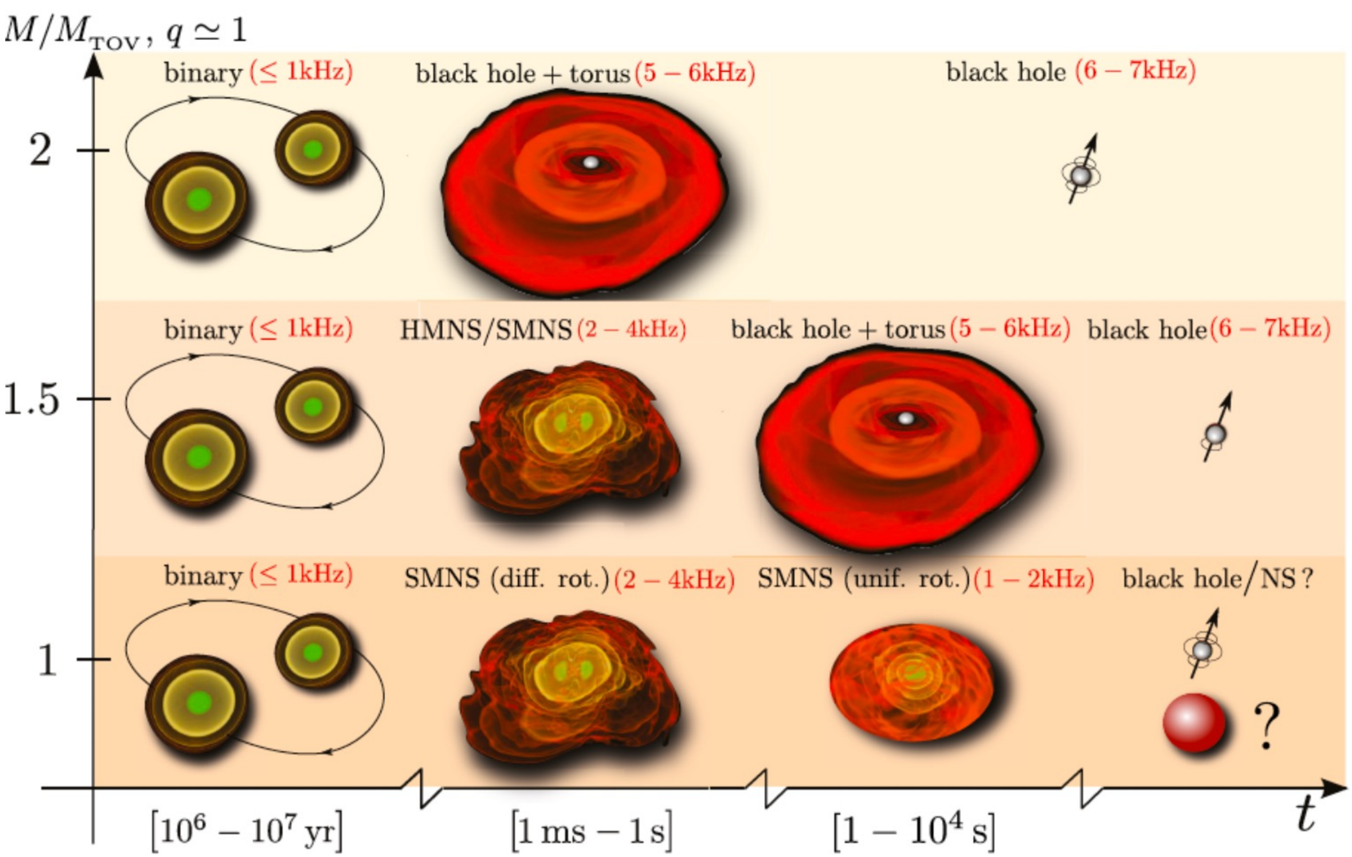


Designing instruments for Astrophysical goals

- Suppose we want to focus on the nuclear physics of Neutron Stars –



L. Baiotti, and L. Rezzolla (2017)

Merger remnants:

Hyper-massive neutron star (HMNS) or
Super-massive neutron star (SMNS)

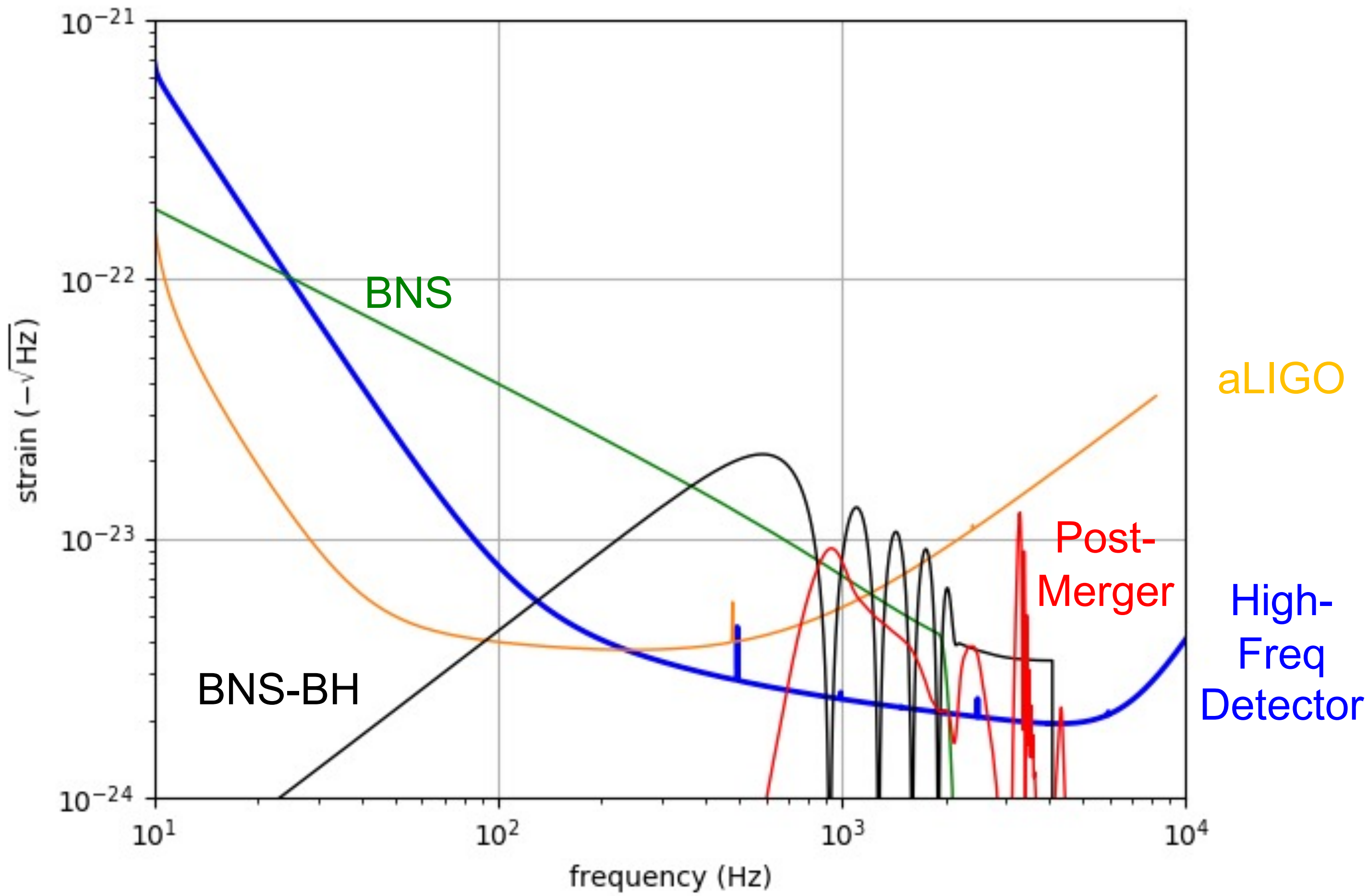
Oscillation mode (or GW) frequency is around 2kHz - 4kHz

Encoding rich information about equation of state (EOS) of hot, dense nuclear matter

Having EM counterpart (multi-messenger observation)

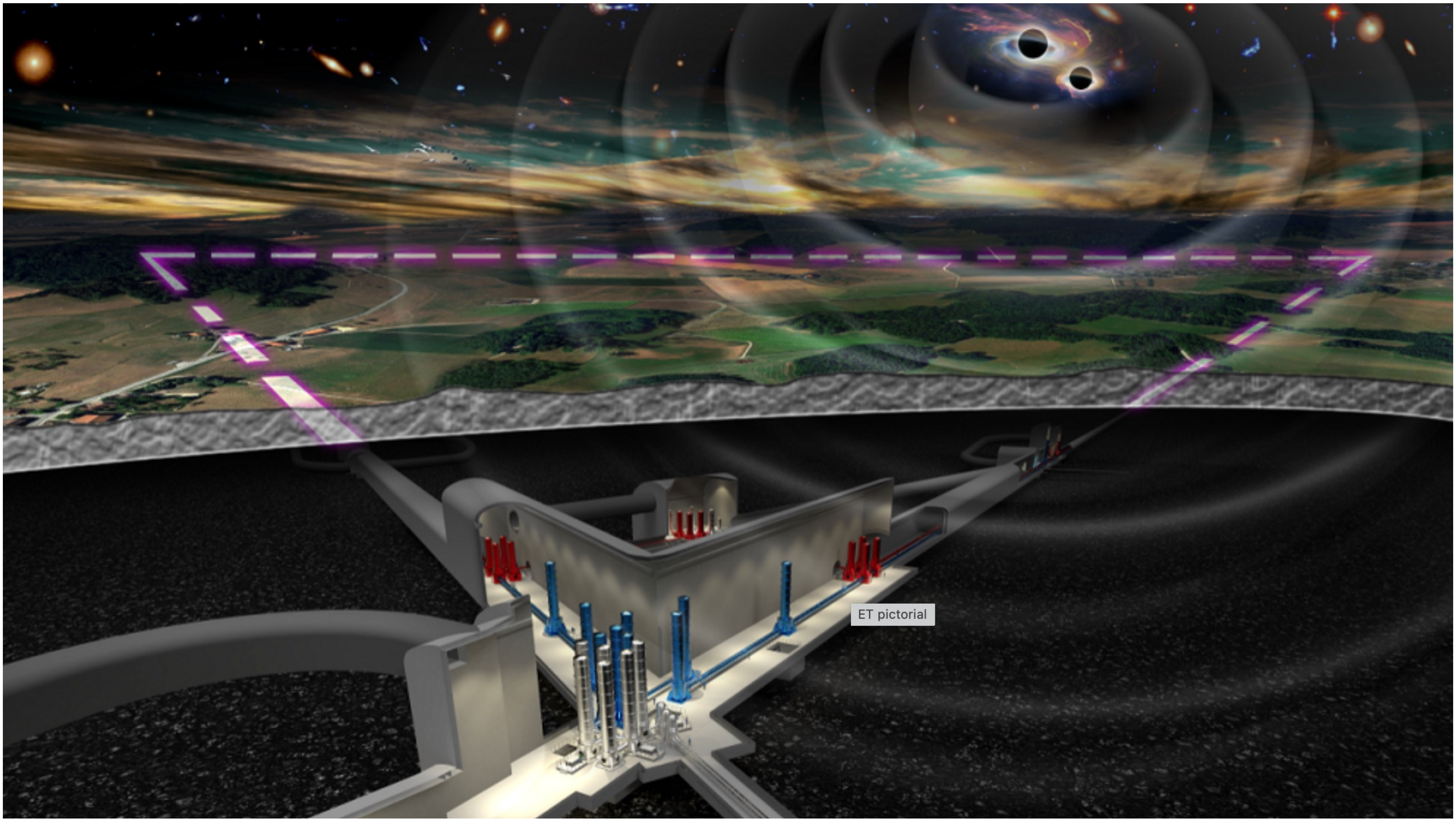
NEMO: A 'Neutron Star Explorer' – Possible evolution path for 3-4km

- Target the 1-5 kHz range
- Modest length requirements – 3-4 km
- Stressful on the optical design (high circulating power)
- …easy on the $1/f^{n}$ noise sources
- Australian future detector working group



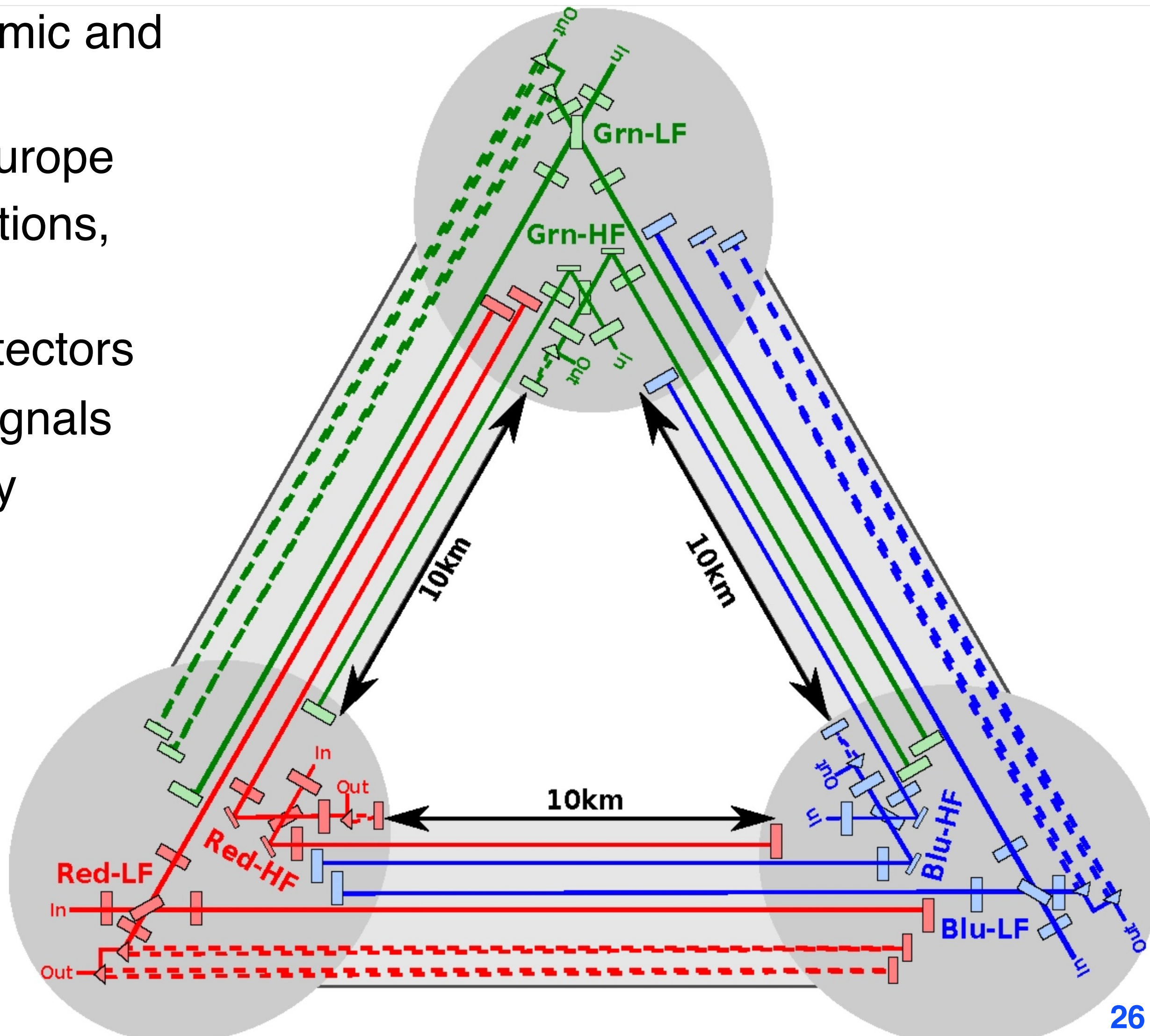
- 'Voyager' another interesting path for the current infrastructures
  - » Mild cryogenics, high laser power, aggressive 'squeezing'

Next Generation Observatories:
Einstein Telescope

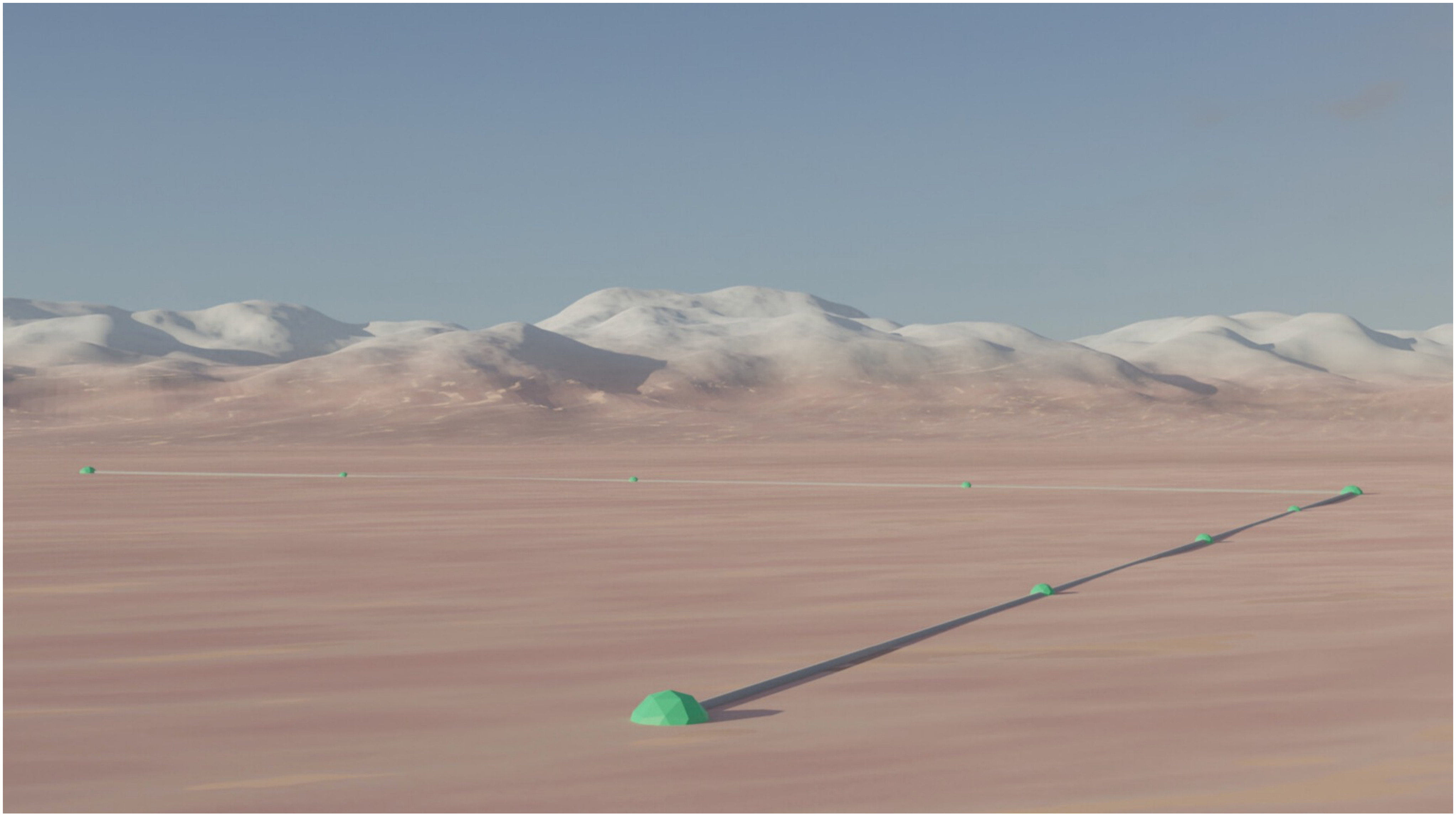


Einstein Telescope:
Underground multi-ifo Triangle

- 10km arms – philosophy is to stretch technologies to reduce external and internal test-mass motions
- Underground to reduce seismic and Newtonian noise
  - Also helps with site in Europe
- Triangular to give 2 polarizations, ‘null stream’
- High- and low-frequency detectors
  - High-power for NSNS signals
  - Cryogenic low-frequency for BHBH
- → Ed Porter’s talk

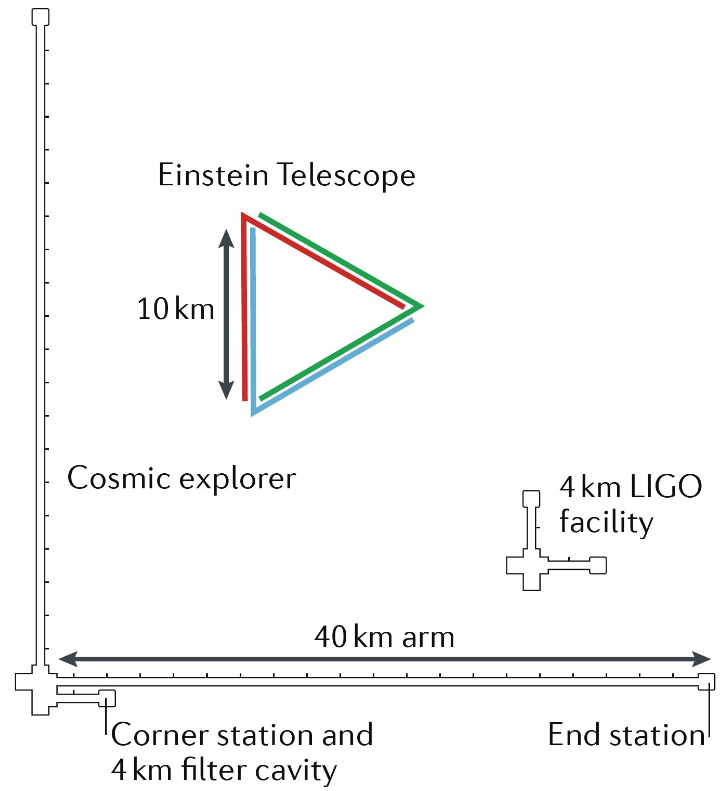


Next Generation Observatories: Cosmic Explorer



Cosmic Explorer:
Make arms 10x longer

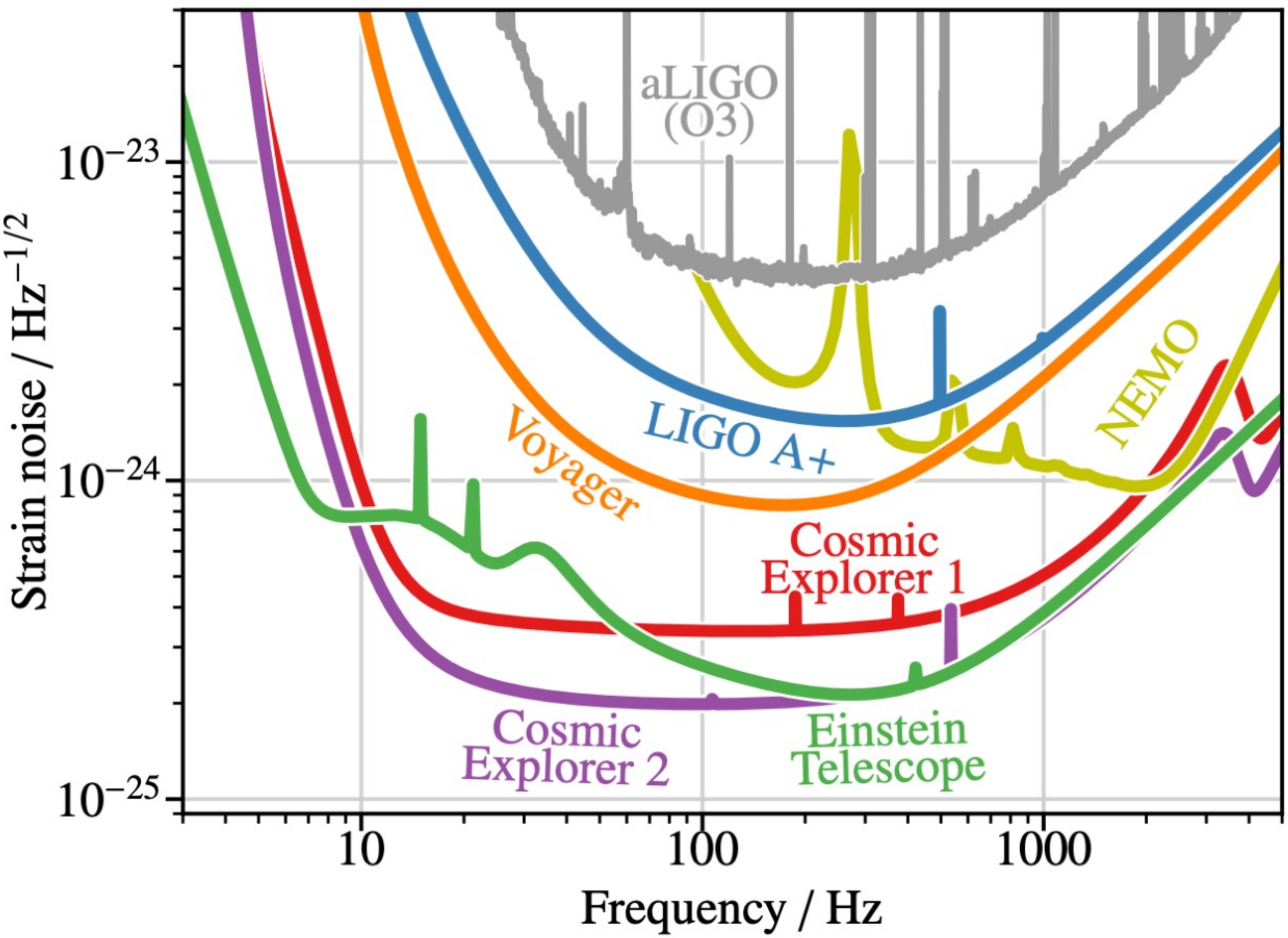
- Philosophy is the stretch the arms, and start with known technologies
- Signal $\Delta L = hL$ grows with length – *not* most noise sources
  - » Thermal noise, radiation pressure, seismic, Newtonian unchanged
  - » Coating thermal noise improves *faster* than linearly with length
- Concept offers sensitivity without new measurement challenges; start at room temperature, modest laser power, etc.
  - » Will install more challenging technologies when timely – Low initial risk is key
  - » Transfers challenges to vacuum, earthmoving
- Baseline of two detectors:
  - » 40km arms: maximize reach for cosmology
  - » 20km arms: focused on NSNS
- Have identified many possible sites
  - » Sagitta is 31 meters…
  - » Find 'bowls' which are in fact flat
    - – US; elsewhere, e.g., Australia

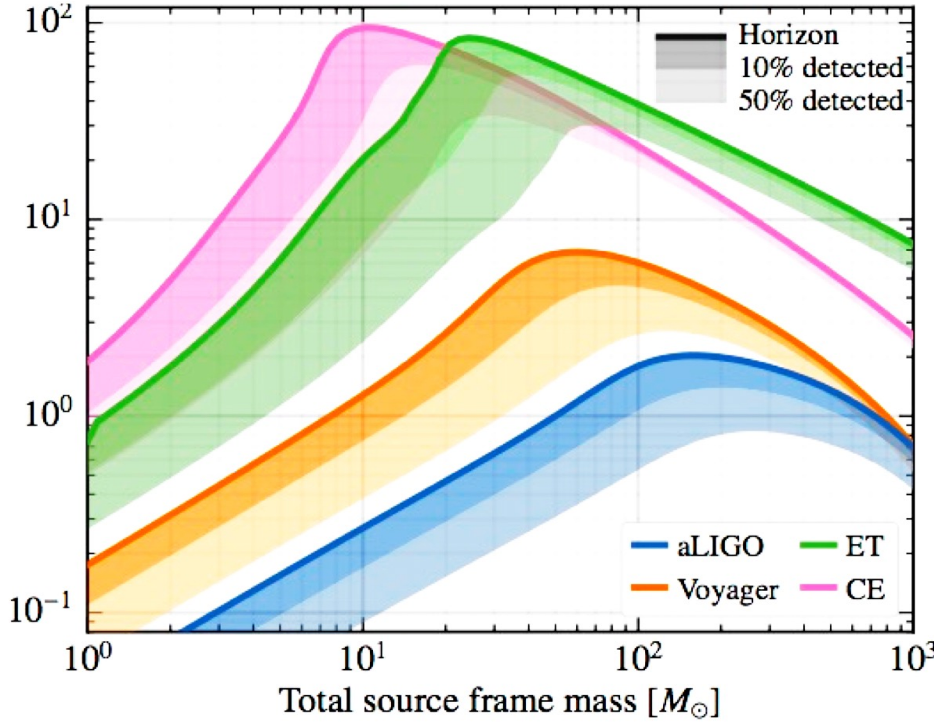


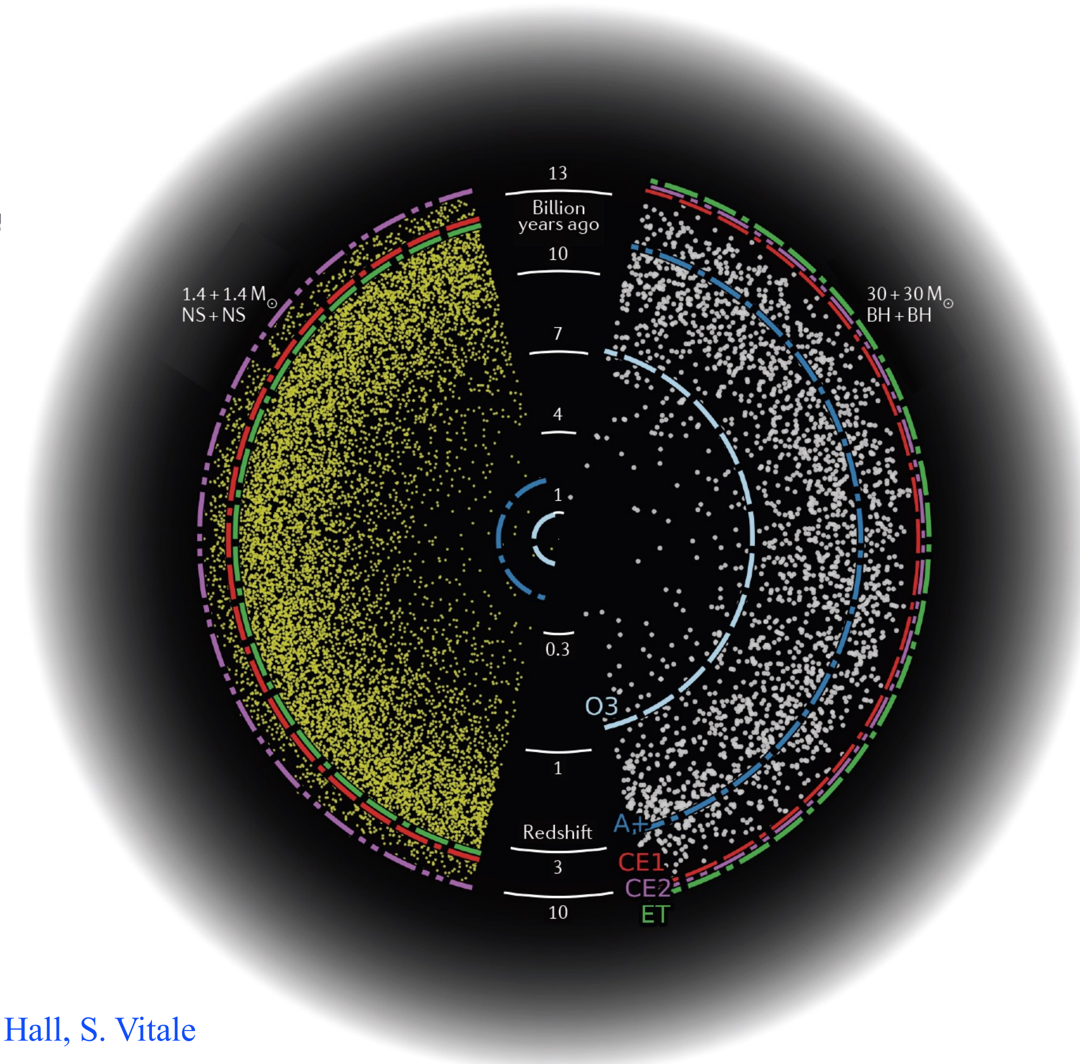
Cosmic Explorer

- Currently undertaking an initial 'Horizon Study' with NSF funding
  - What science is targeted?
  - What design does that dictate?
    - Looking at the possibility of a 40km for cosmology, and 20km for NS physics
  - What technologies to use?
    - Looking at an initial 'A+ on steroids' design, followed by more challenging technologies (cryogenics? Push fused silica to limits?)
  - How to make affordable?
    - Nobel-prize winning vacuum tube design…
  - How to raise consciousness of broad community?
    - Starting to plan a Dawn meeting in the Fall
- Completion of report in 2021 – Will be shared with the community for feedback
- Path forward in discussion with US National Science Foundation
- Maybe a review 'mid-decadal study' ~2025 for a detailed engineering study
- Timeline, governance, funding all fuzzy at present
  - hope to see a real start in the late 2020's

Sensitivity of ground-based detectors







Reach of Next Gen Observatories: All binaries in universe from 1-1000 $M_\odot$

E. Hall, S. Vitale

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Next Generation Observatories

- When could this new wave of ground instruments come into play?
- Appears 15 years from *t*=0 is a feasible baseline
  - Initial LIGO: 1989 proposal, and at design sensitivity 2005
  - Advanced LIGO: 1999 White Paper, GW150914 in 2015
- **Modulo funding, can envision 2030's**
- Should hope – and strive and plan – to have great instruments ready to 'catch' the end phase of binaries seen in space-based LISA
- Worldwide community working together on concepts and the best observatory configuration for the science targets, e.g.,
  - GWIC https://gwic.ligo.org/3Gsubcomm/documents.shtml
- Planning starting for a 'Dawn' meeting to discuss the path
  - likely with the focus on CE – less developed than ET at this time
  - Fall, and maybe even in person!

Two critical points

- **Crucial for all these endeavors: to expand the scientific community planning on exploiting these instruments far beyond the GR/GW enclave**
  - Costs are like TMT/GMT/ELT – needs a comparable audience
  - The initial detection by LIGO was seen as 'cool science'
  - GW170817 was seen as key to realizing the science of thousands of researchers; **localization**
  - **The network is critical to serving a big enough community**
- First Collaborations, now meta-collaborations: 'The LVK' – KAGRA, Virgo, and LIGO Scientific Collaborations all sharing data
  - The science that is possible is qualitatively greater
  - The sociology of a (mostly) non-competitive environment nurturing
- LISA and Pulsar Timing also in collaborations/consortia
- Now perhaps 3000 persons worldwide – and still short of hands to keep up with the current technology, data, and observational science flow
- **With a continuing globally collaborative effort, the field will succeed**

This meeting shows…

- Observational gravitational-wave detection is really a new messenger
- The (incredibly short) 5-year history of observations already enough to launch a new field
- Demonstrated by the richness of this meeting

	GR	Physics	Astro	MMA
Theory	✅	✅	✅	✅
Modeling	✅	✅	✅	✅
Observation	✅	✅	✅	✅
Analysis	✅	✅	✅	✅

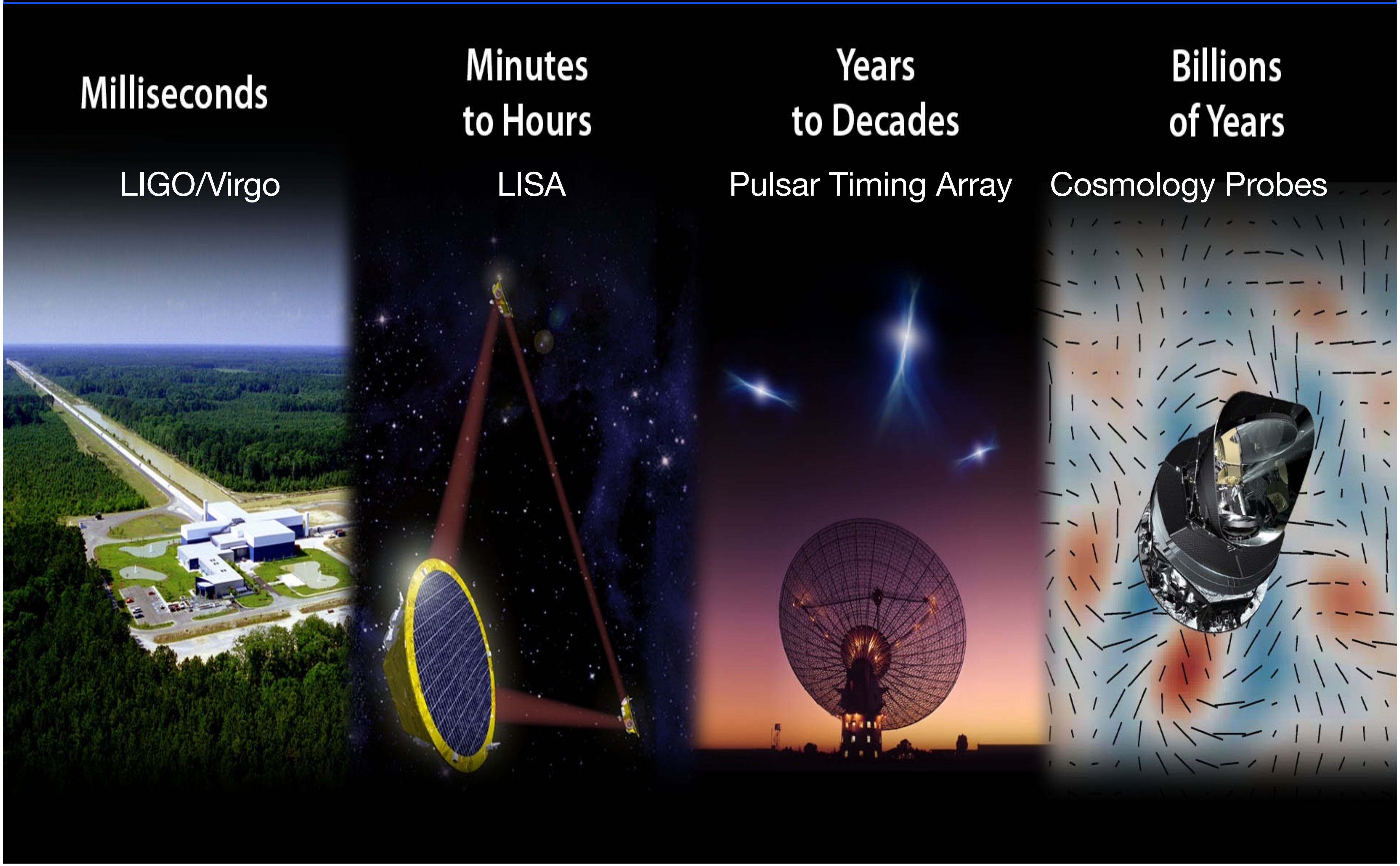
- Ever-growing network of detectors, with ever-growing sensitivity, promises to deliver new surprises in quantity and character

We are Experiencing

– and you are responsible for –

the birth of a new field

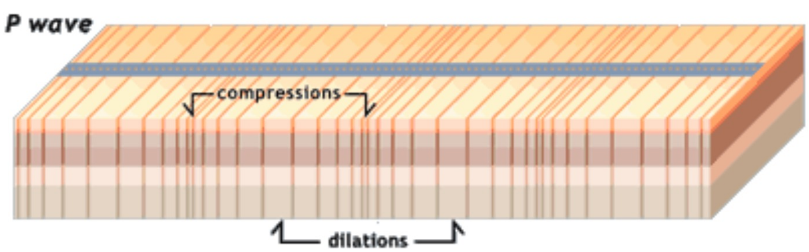
New instruments, New discoveries, New synergies



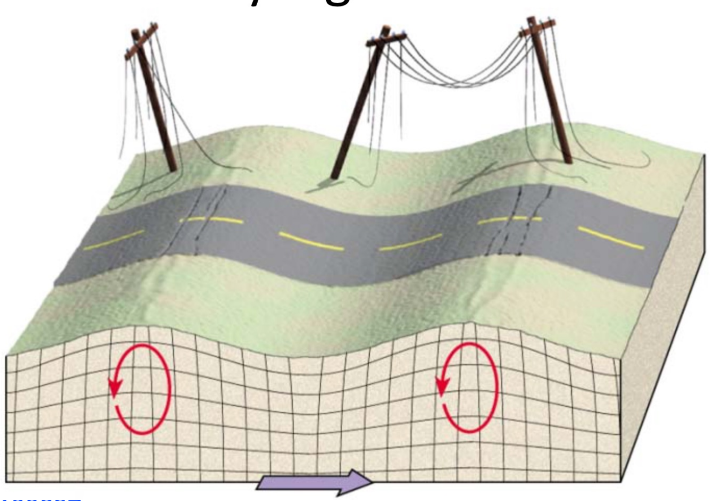
Measuring $\Delta L = 4 \times 10^{-18}$ m
Forces on test mass

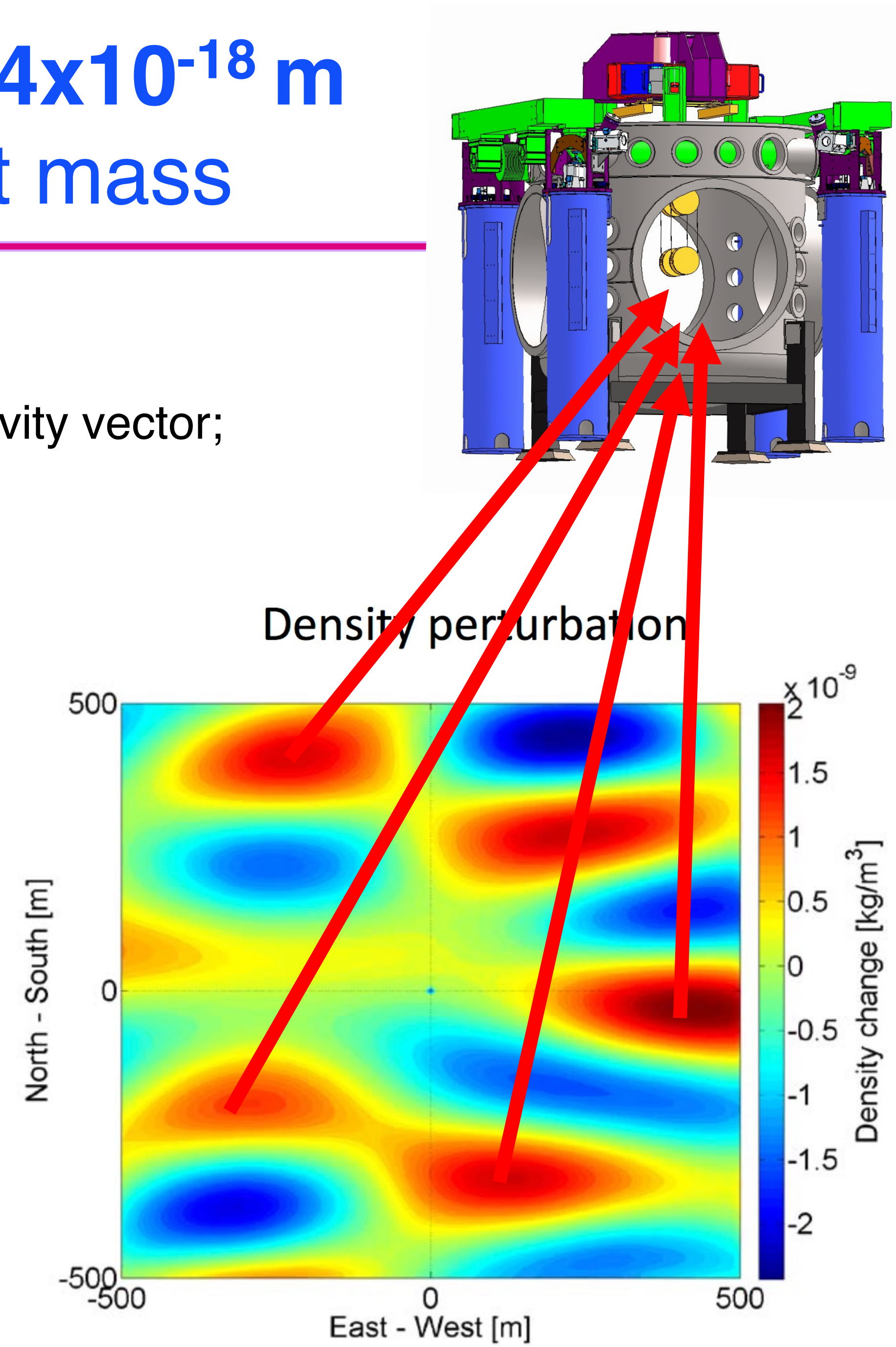
- Ultimate limit on the lowest frequency detectors on- or under-ground:
- **Newtownian background** – wandering net gravity vector; Forbiddingly large for ~3Hz and lower

Body waves



Rayleigh waves

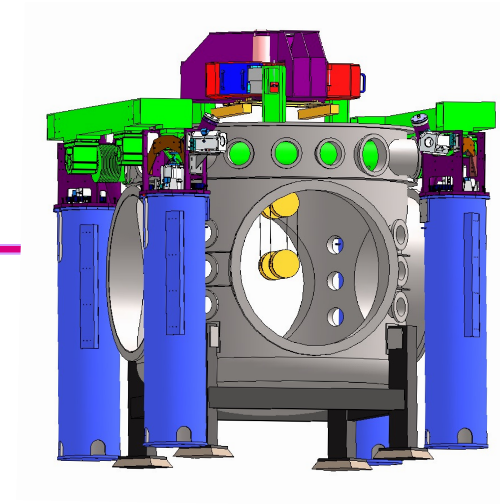




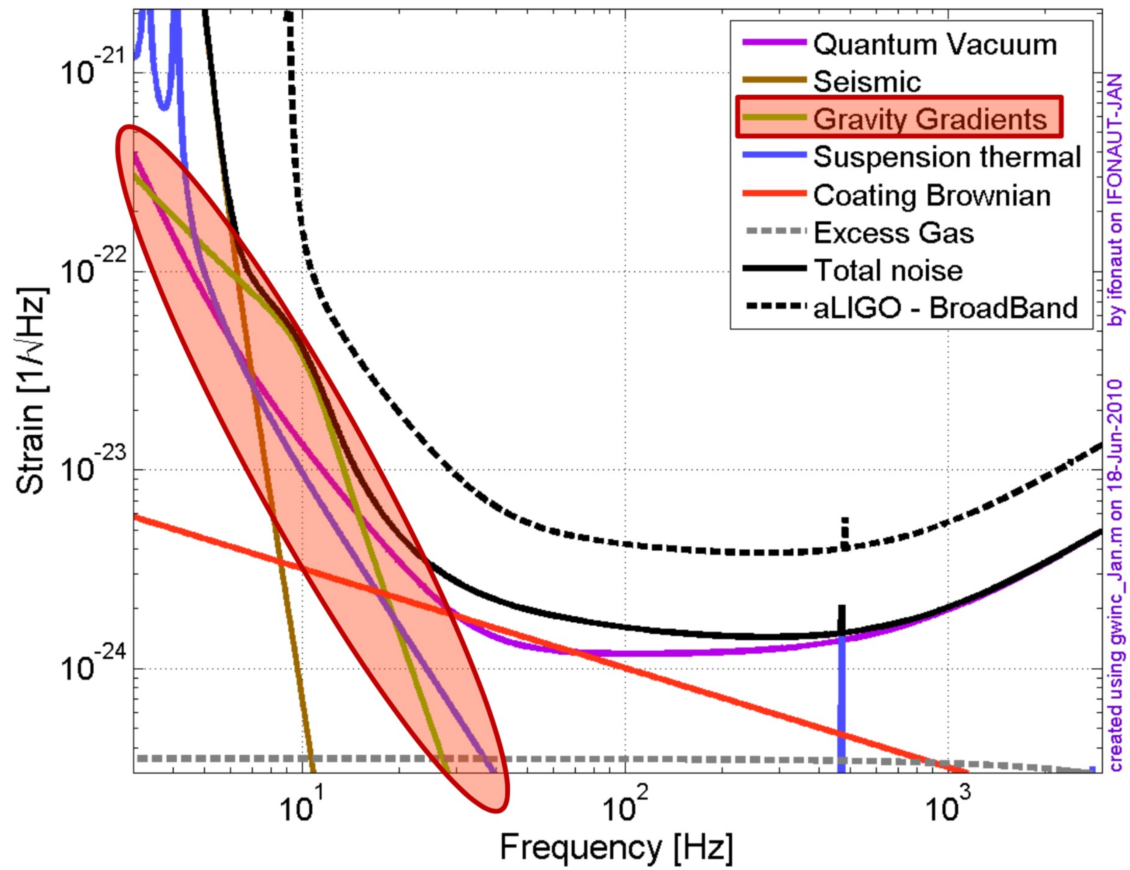
Density perturbations cause gravity perturbations.

Images: J. Harms

Measuring ΔL= 4x10^{-18} m
Forces on test mass



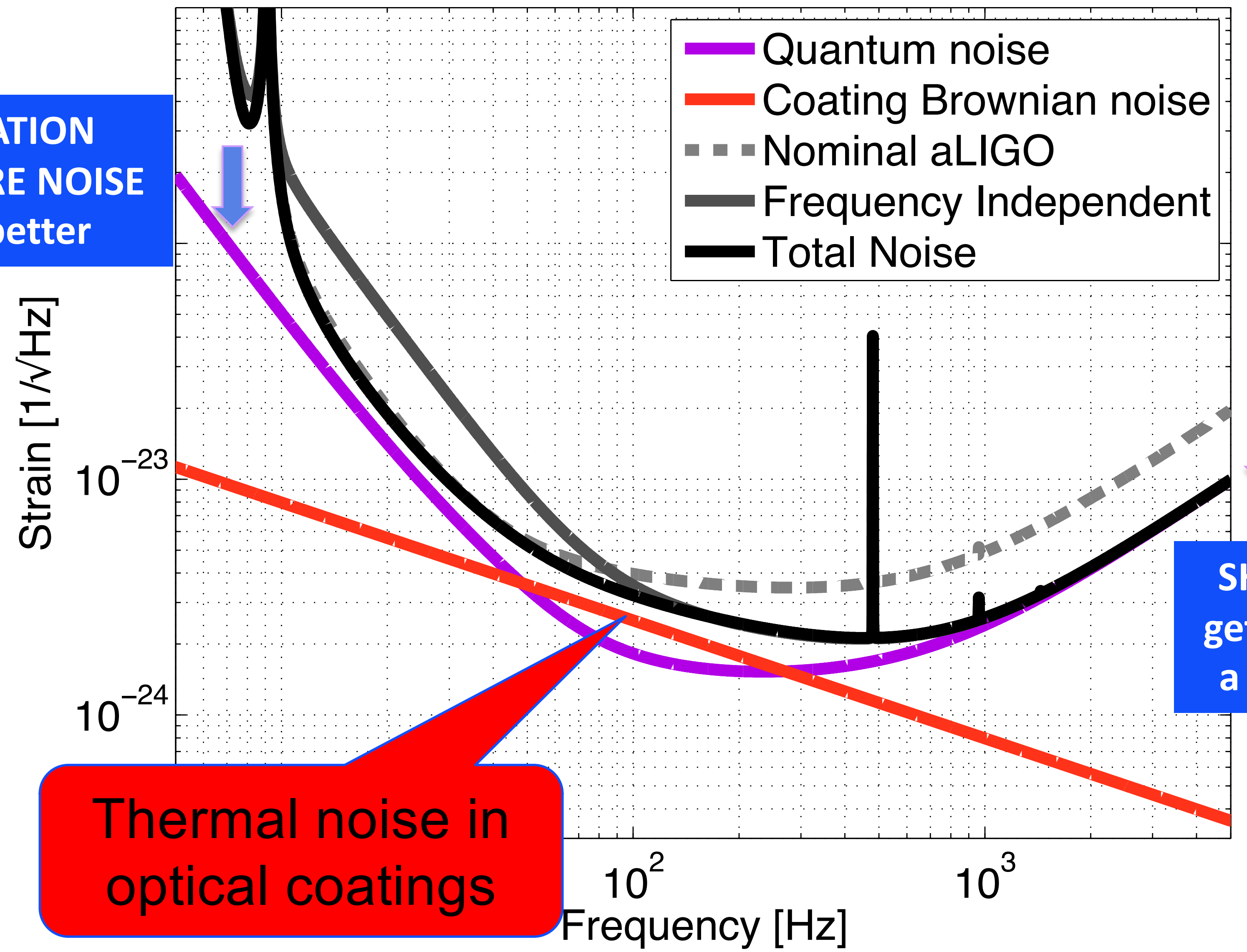
- Advanced LIGO (and Virgo) expect to be limited by this noise source –
  - After all technical noise sources beaten down
  - At low optical power (no radiation pressure noise)
  - In the 10-30 Hz range
- **We would *love* to be limited only by this noise source!**
- Want to go a bit lower? Go underground.
- Want to go much lower? Go to space.



Images: J. Harms

Frequency Dependent Squeezing

RADIATION PRESSURE NOISE gets better



SHOT NOISE gets better by a factor of 2

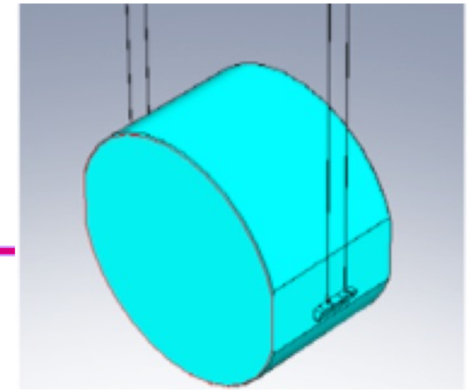
Thermal noise in optical coatings

➔ High frequency improvement, + 25% BNS-BNS range (200 → 250 Mpc)

M. Evans, Amaldi 11

Measuring Δ*L*= 4x10^{-18} m

Internal motion



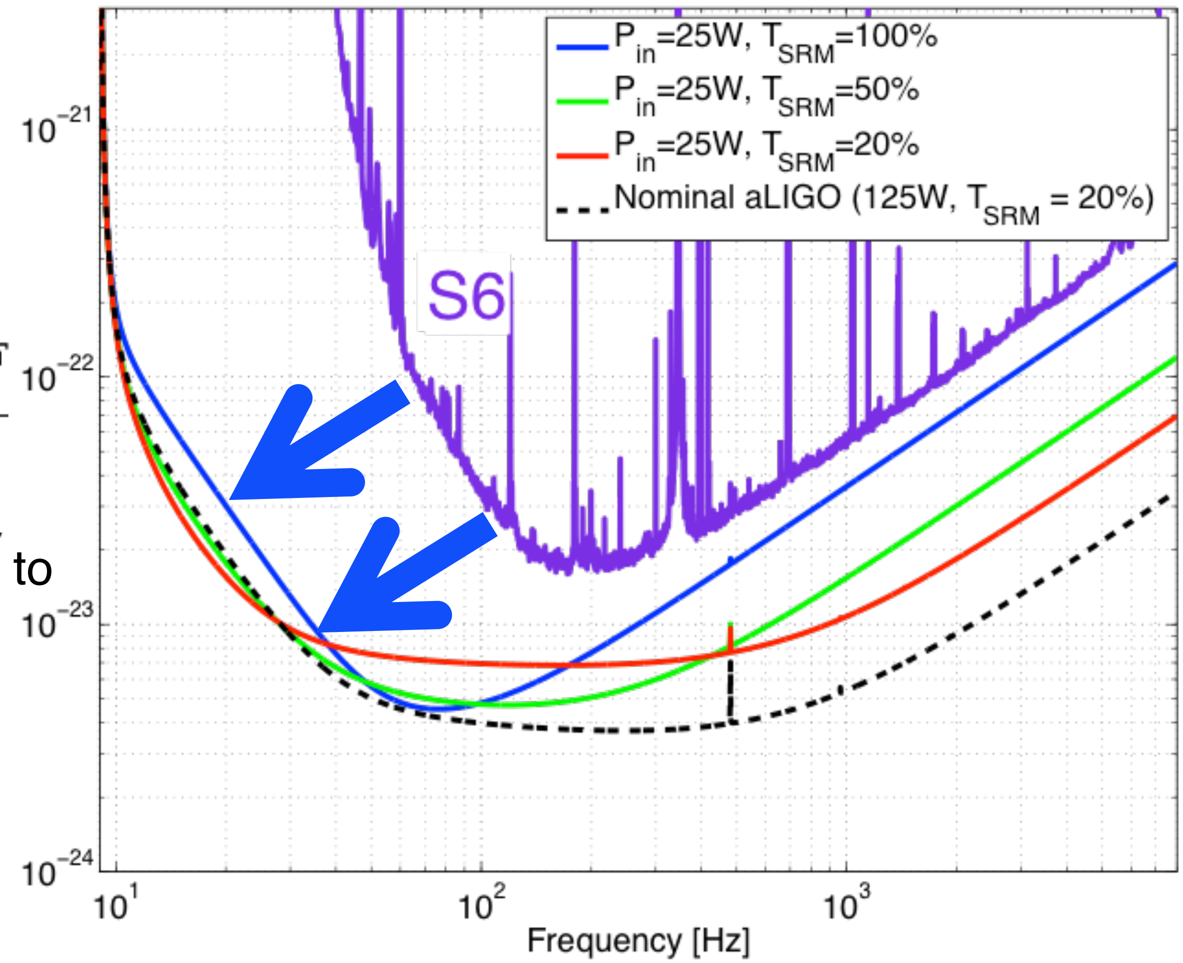
- **Thermal noise** – kT of energy per mechanical mode
- *Über die von der molekularkinetischen Theorie der Wärmegeforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen,* A. Einstein, 1905
- Simple Harmonic Oscillator:

$$x_{rms} = \sqrt{\left\langle (\delta x)^2 \right\rangle} = \sqrt{k_B T / k_{spring}}$$

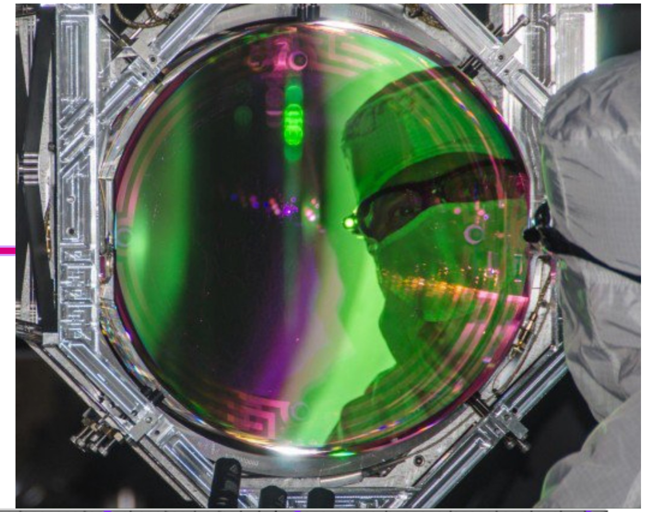
- Distributed in frequency according to real part of impedance $\Re(Z(f))$

$$\tilde{x}(f) = \frac{1}{\pi f}\sqrt{\frac{k_B T}{\Re(Z(f))}}$$

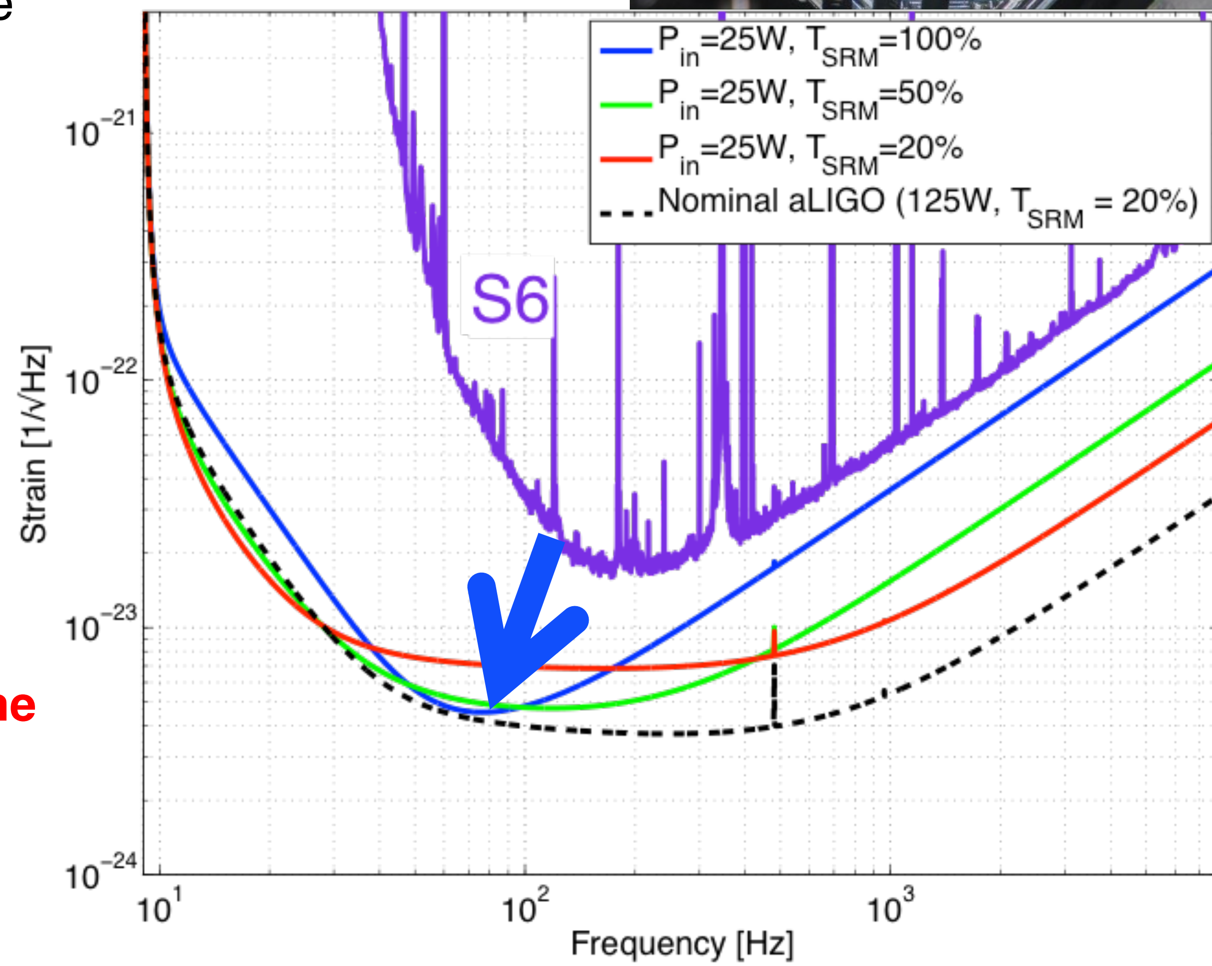
- **Low-loss materials, monolithic construction**



Measuring $\Delta L = 4\text{x}10^{-18}$ m
Internal motion



- In Advanced LIGO, the dielectric optical coating has a rather large loss tangent
  - Some 10^{-4} , compared to 10^{-8} for fused silica
- The Fluctuation-Dissipation theorem says this is where the greatest motion is found
- And: the coating is the surface that is sensed by the laser



- **This is the dominant limit in the critical 50-200 Hz band**

Civil Construction:
Beam Tube cover, foundation, earthmoving