Gravitational Wave Observatories

Australian Institute of Physics Congress
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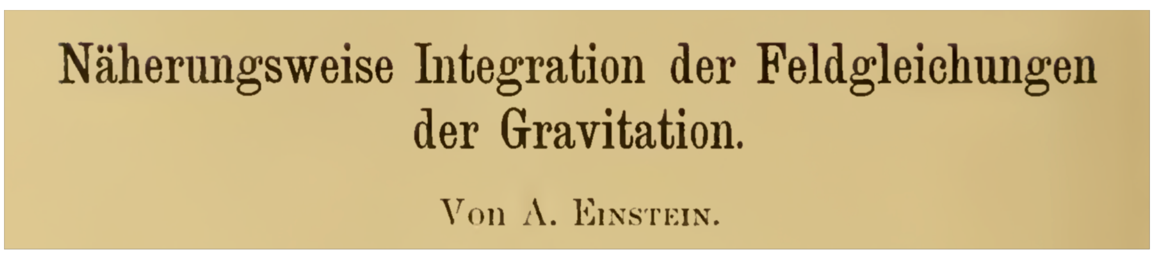
David Shoemaker
For the LIGO and Virgo Scientific Collaborations

Credits
Measurement results: LIGO/Virgo Collaborations,
PRL 116, 061102 (2016); Phys. Rev. Lett. 119, 161101 (2017);
Phys. Rev. Lett. 119, 141101 (2017); Phys. Rev. Lett. 118, 221101 (2017);
Phys. Rev. Lett. 116, 241103 (2016)
Simulations: SXS Collaboration; LIGO Laboratory
Localization: S. Fairhurst arXiv:1205.6611v1
Slides from (among others) L. Nuttal, P. Fritschel, L. Cadonati
Photographs: LIGO Laboratory; MIT; Caltech; Virgo

LIGO-G1802297

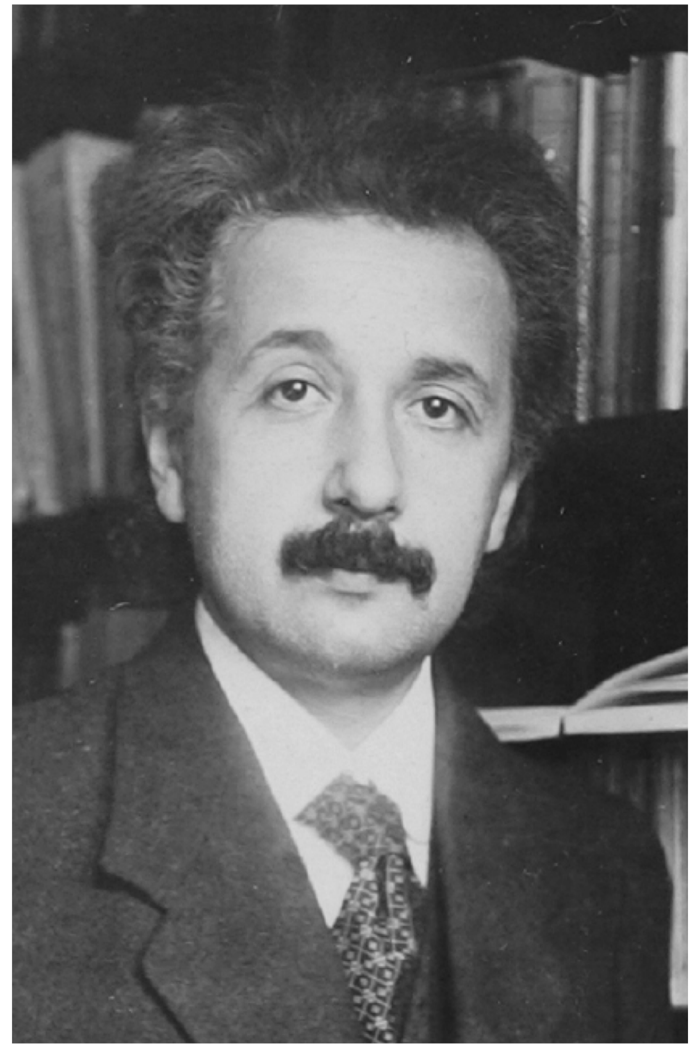
100 years ago

- Albert Einstein was evaluating and processing patent applications…
  - …for transmission of electric signals and electrical-mechanical synchronization of time
  - Musing on relative motion of electromagnetic transmitters and receivers
  - → Special Relativity, 1905
- …then dreaming of being in an elevator in space and asking if it is a pull on the cable or gravity...
  - → General Relativity, 1915
- Prediction of gravitational waves (GW) as a consequence of GR in **1916:** (ok, *right* in 1918)


Näherungsweise Integration der Feldgleichungen der Gravitation.

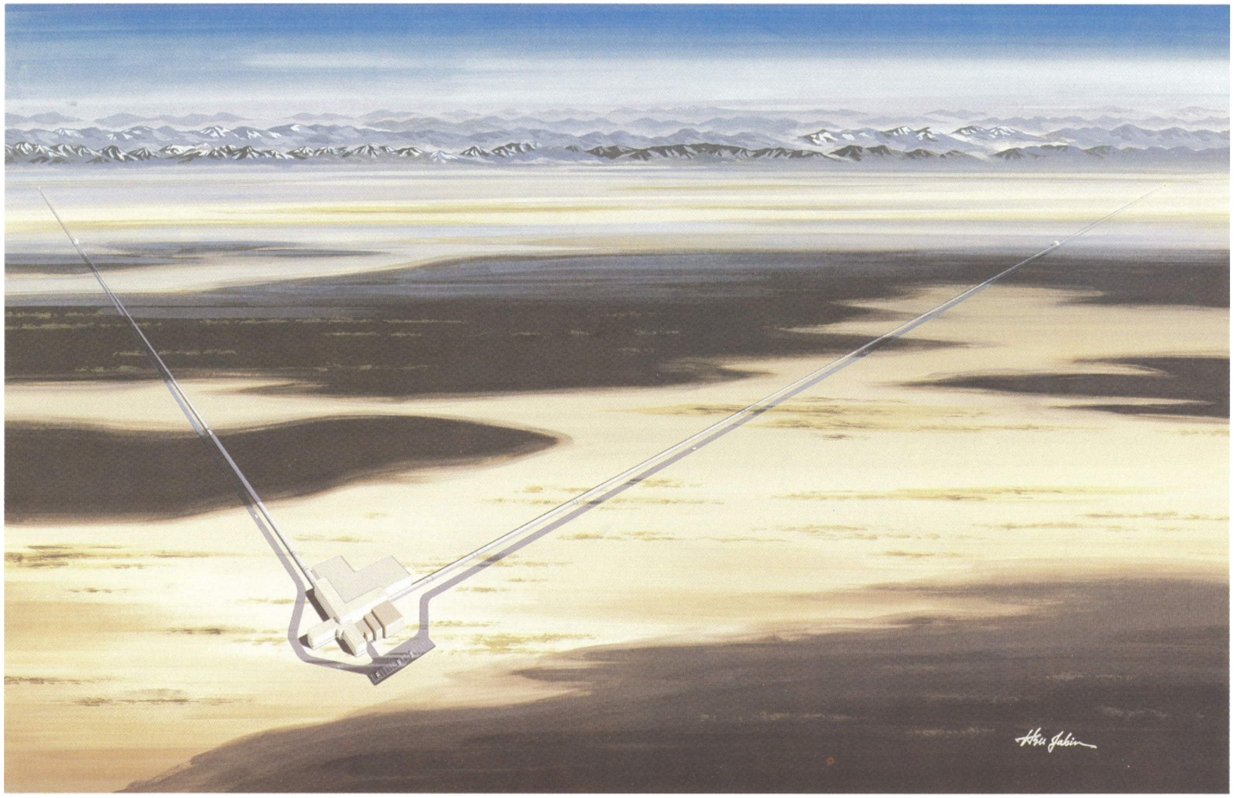
Von A. Einstein.

- Notes that it is of no practical interest as it will not be possible to detect such a small effect



1993

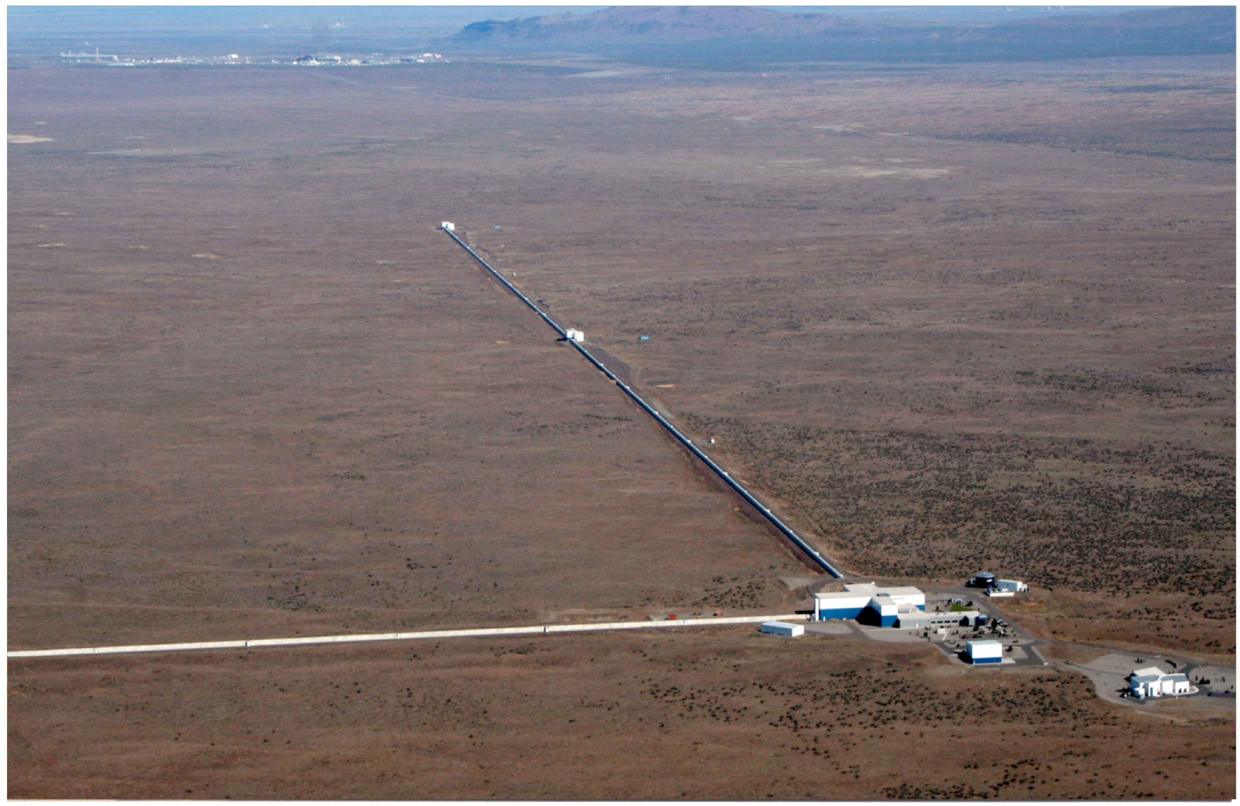
- Caltech and MIT propose to the NSF to establish Observatories
- Proposal states clearly that the initial detectors only have a chance of detections, and that upgraded detectors must be accommodated and foreseen
- Proposal cover art →



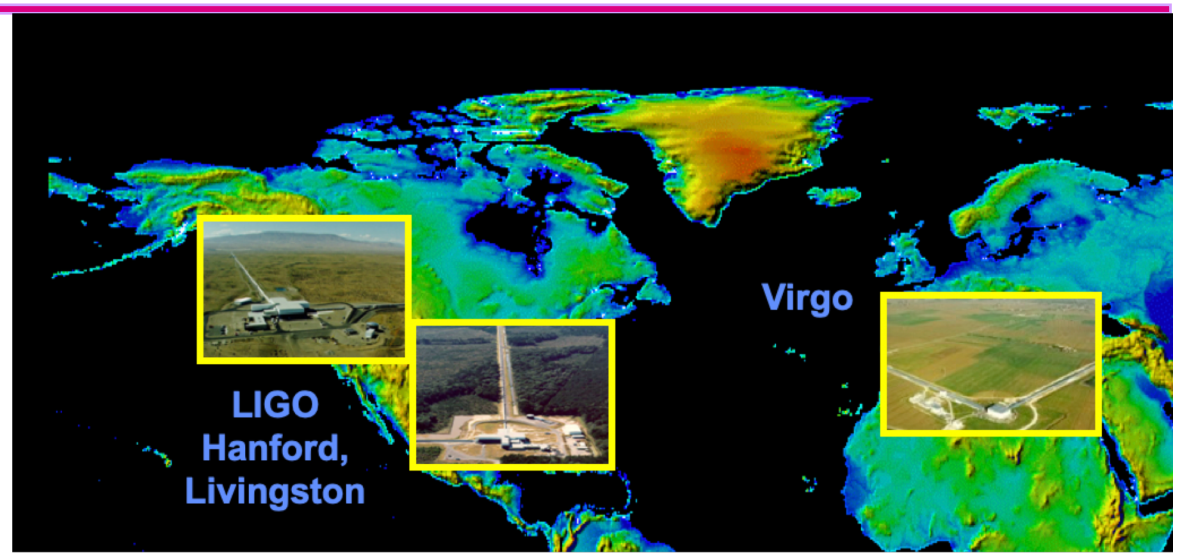
1995-2000

- Caltech and MIT Build two Observatories and Initial Detectors
- R&D starts on upgraded detectors

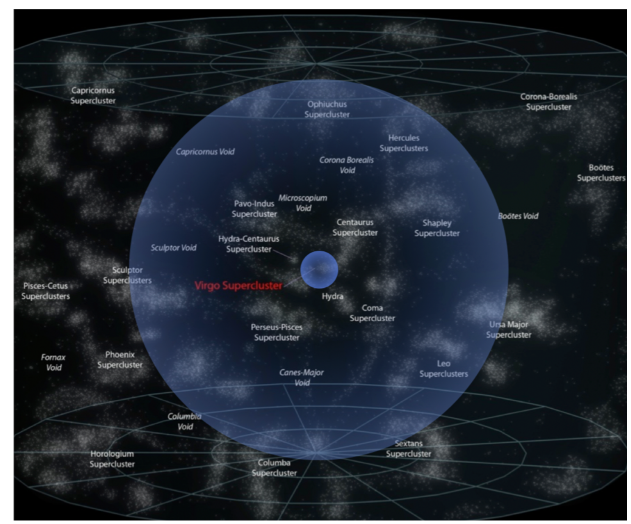
- Hanford Observatory→



2000-2015



- Virgo (French-Italian Collaboration) also builds an instrument
- Both instruments undergo ‘commissioning’ 2000-2005
- LIGO-Virgo Observed with the initial detectors 2005-2011
  - » saw no signals in 1+ years of observing
- In parallel, the LIGO Scientific Collaboration and Virgo advance R&D for 2nd generation detectors; LIGO Lab proposes in 2005
- Project start in 2008, completion in 2015
  - » on budget, on time
- Sensitivity target: 10x better in amplitude sensing
  - » We sense GW amplitude, which falls as $1/r$
  - » 10x reach → 10^3 more sources in reach

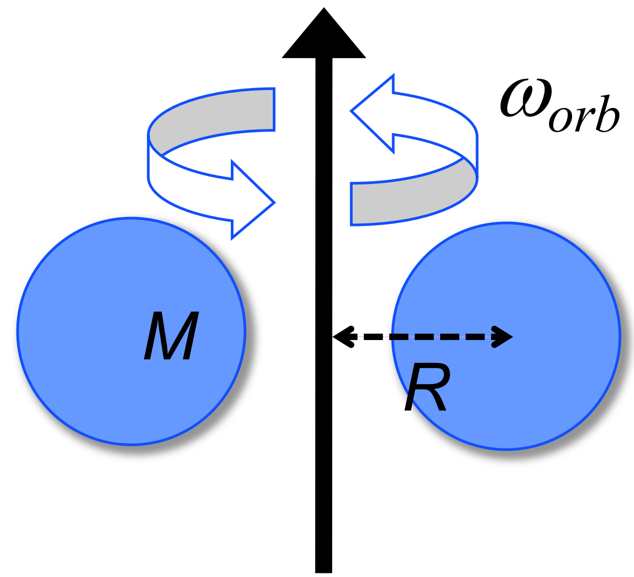


What are Gravitational Waves?

- GWs propagate at the speed of light (according to GR)
- Emitted from rapidly accelerating nonsymmetric mass distributions
- Creates a strain h in space

$$h = \frac{\Delta L}{L} \approx \frac{1}{r}\frac{G}{c^4}\ddot{I}$$

r = distance from the source to the observer



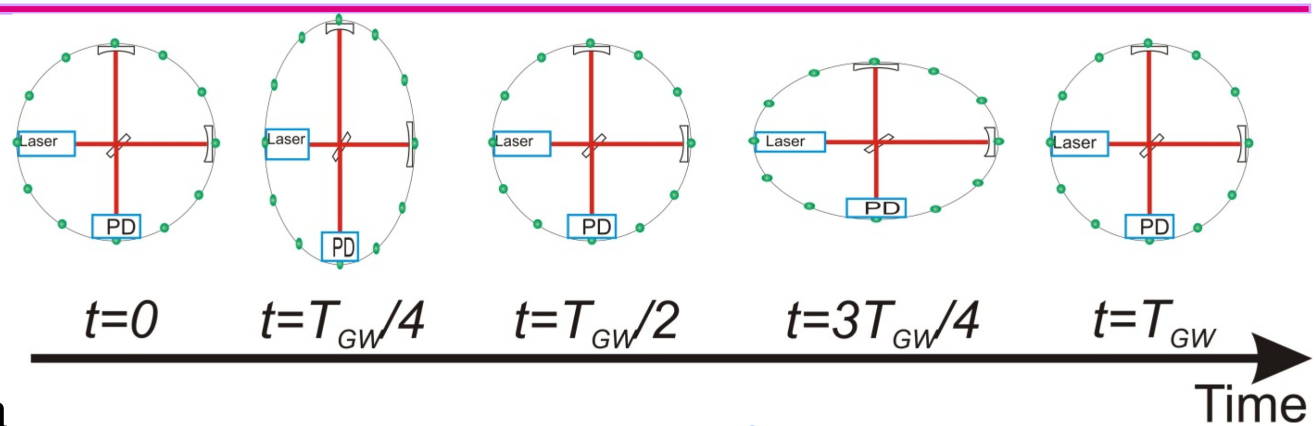
Rotating Dumbbell:

$$h \approx \frac{8GMR^2\omega_{orb}^2}{rc^4}$$

- Space is very stiff; h is ~10^{-21} for say Neutron Stars in Virgo Cluster
  - …or two ~30-solar-mass Black Holes at 420 Mpc...
- Measurable GWs can only be expected from the coherent bulk motion of matter in the highly relativistic regime

What is our measurement technique?

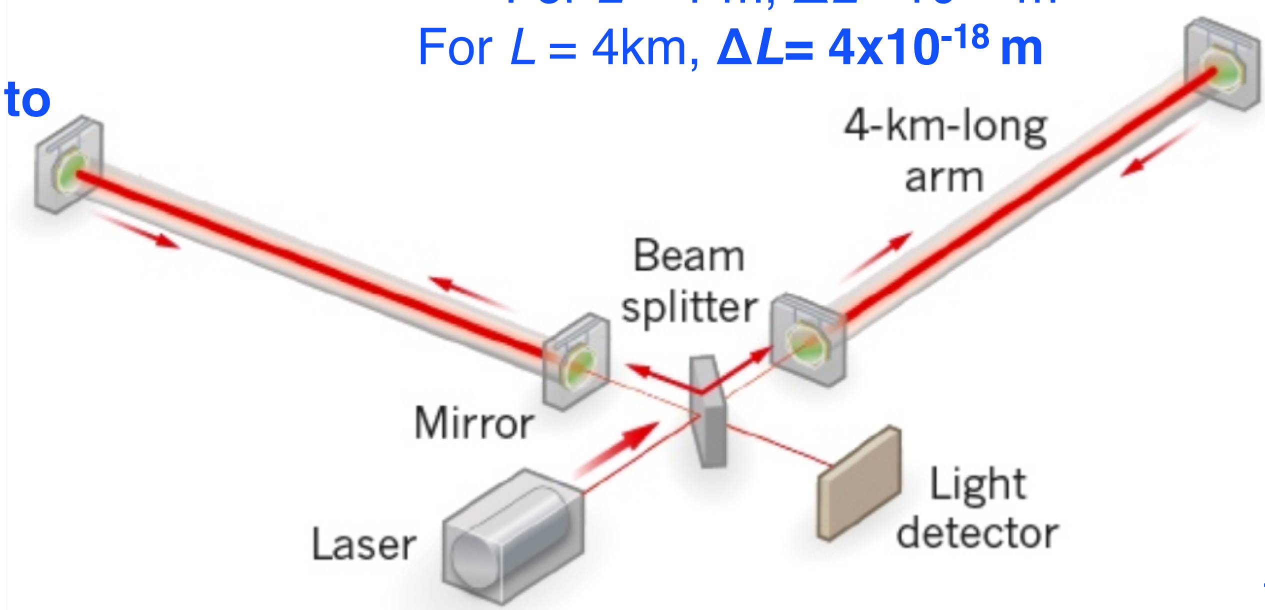
- Enhanced **Michelson interferometers**
- GWs modulate the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude



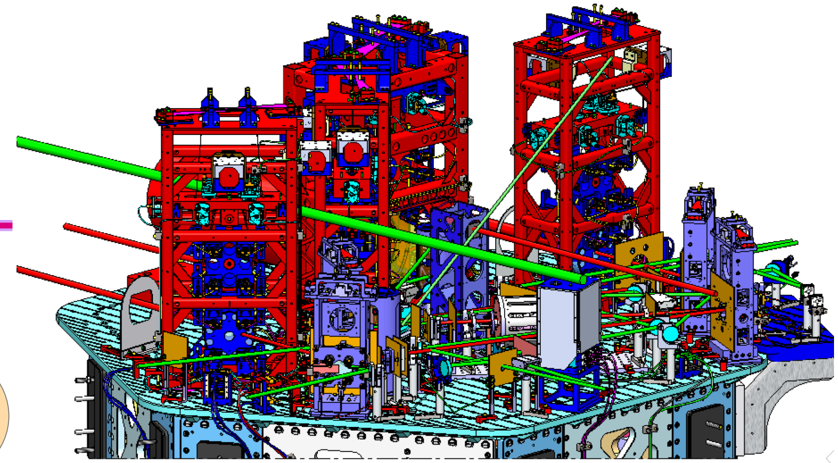
$$h \approx \frac{\Delta L}{L}$$

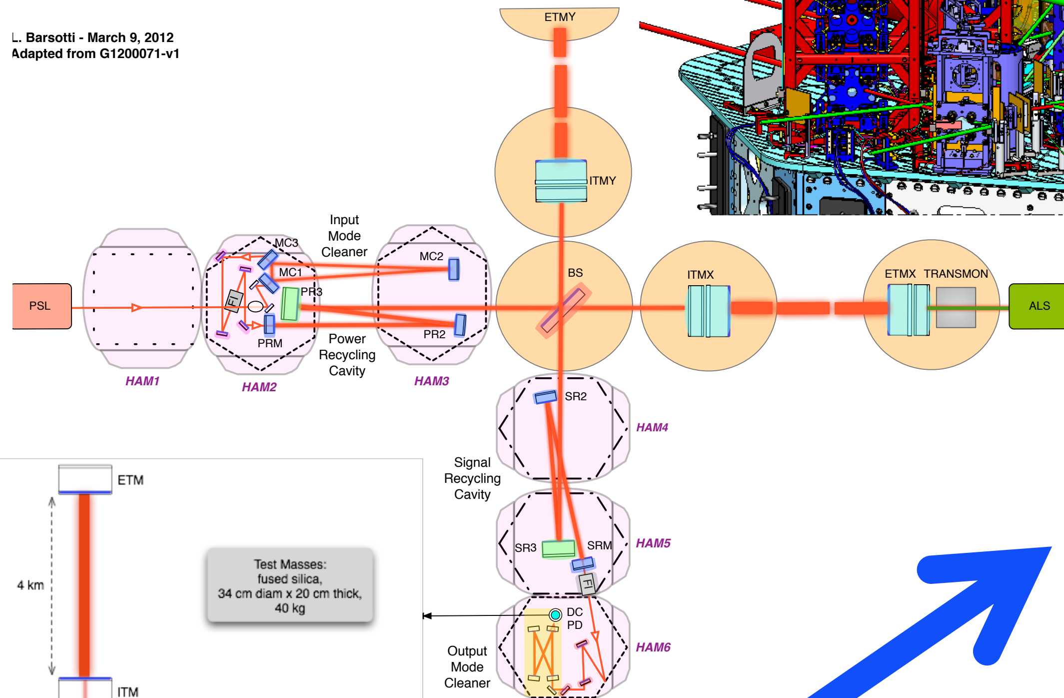
Magnitude of h at Earth:
Detectable signals h ~ 10^{-21}
(1 hair / Alpha Centauri)
For L = 1 m, $\Delta L = 10^{-21}$ m
For L = 4km, $\mathbf{\Delta L = 4 \times 10^{-18}}$ **m**

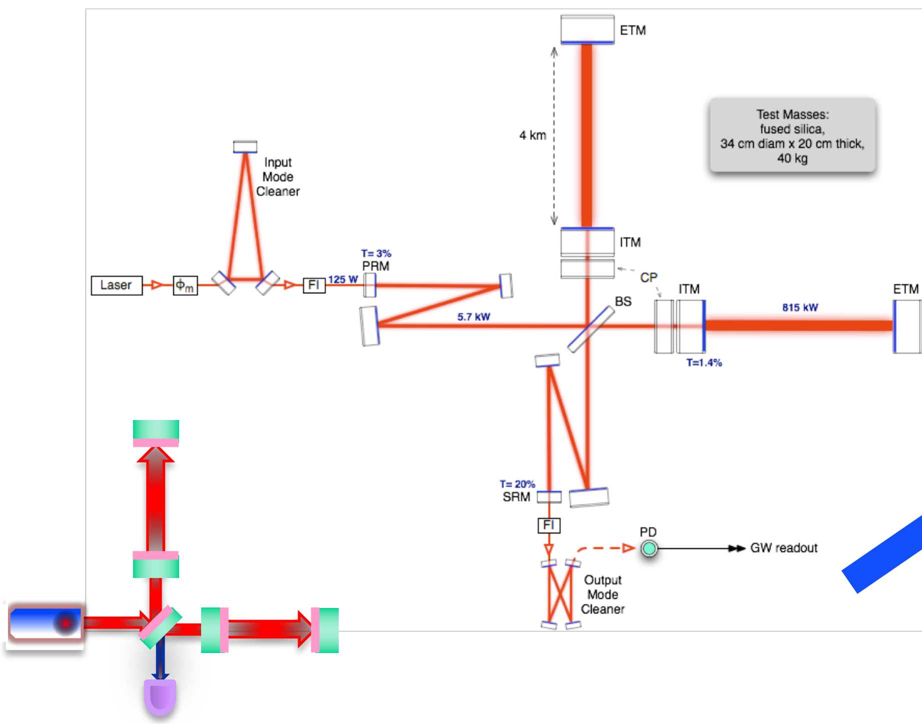
- **Arms are short compared to our GW wavelengths, so longer arms make bigger signals**
  → multi-km installations



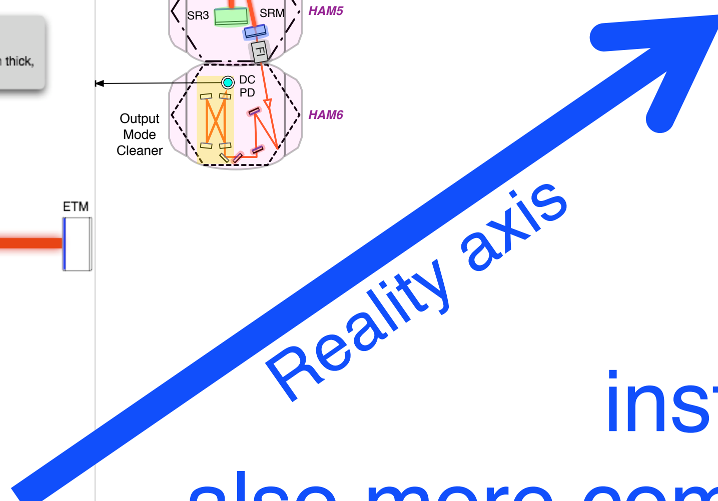
- Arm length limited by taxpayer noise….





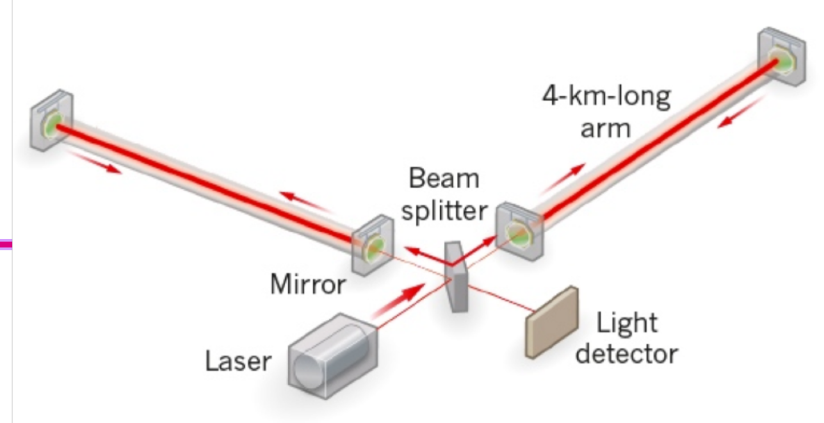


photodiode



The real instrument is also more complex than a simple Michelson…

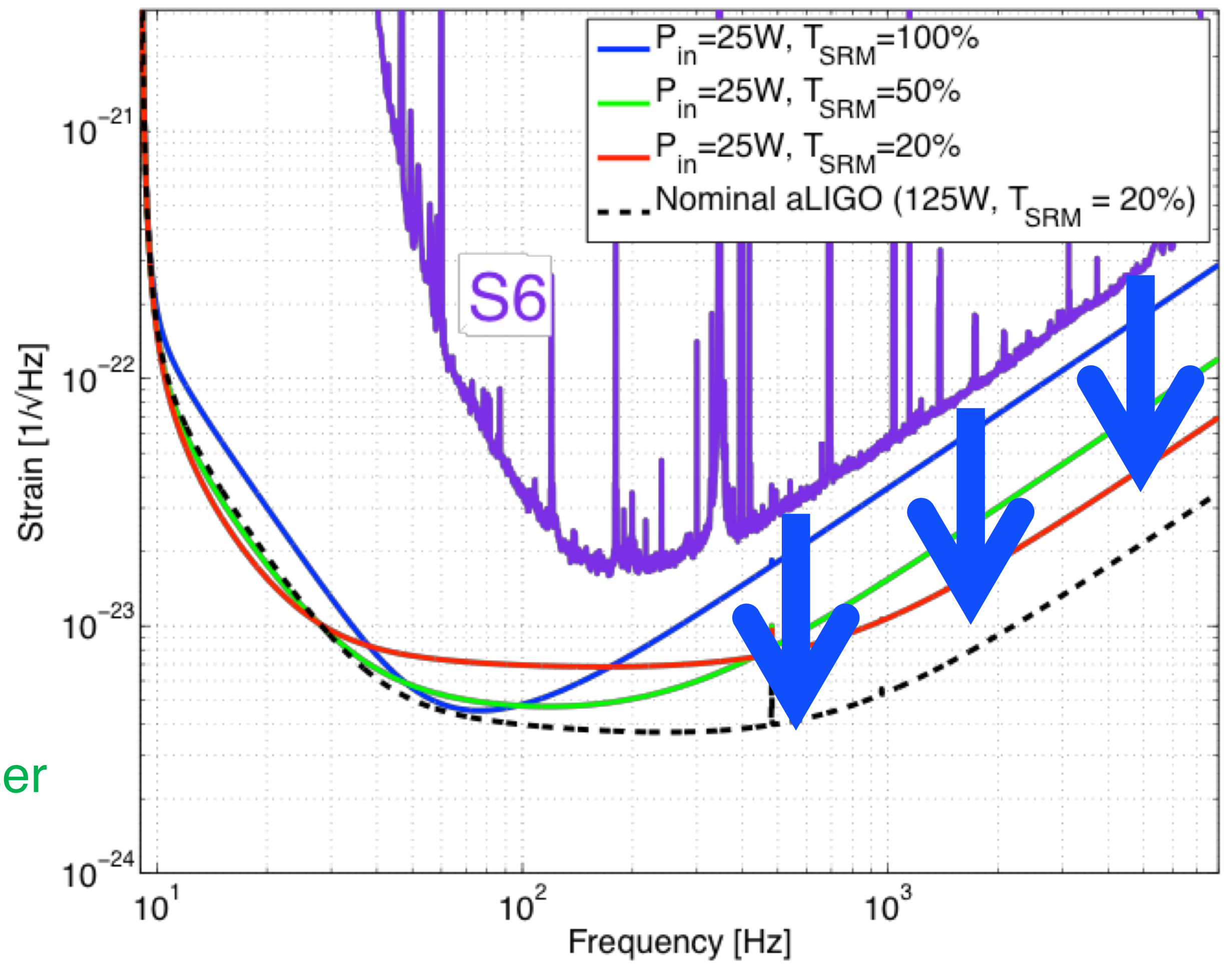
Measuring $\Delta L = 4 \times 10^{-18}$ m
Readout



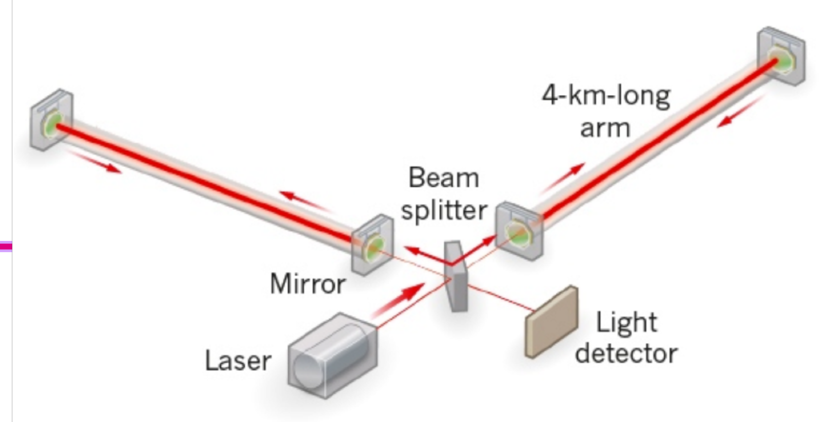
- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics)
- *Zum gegenwärtigen Stand des Strahlungsproblems*, A. Einstein, 1909
- Fringe Resolution at high frequencies improves as as (laser power)$^{1/2}$

$$h_{\rm sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

- OzGrav/UA a key partner in establishing the path to our laser solution, and monitoring mirror deformation from absorption



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



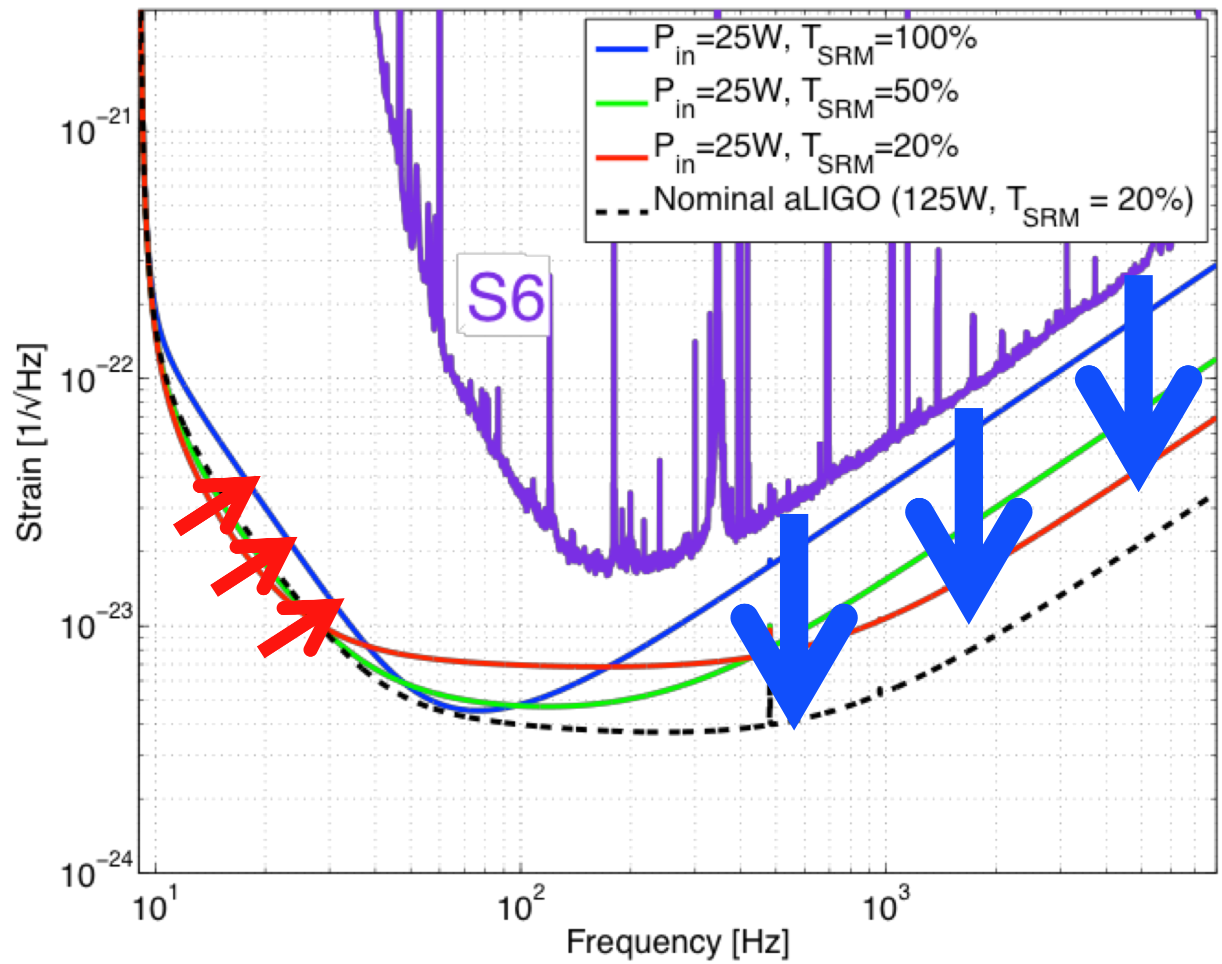
- Shot noise – ability to resolve a fringe shift due to a GW (counting statistics)

$$h_{\rm sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

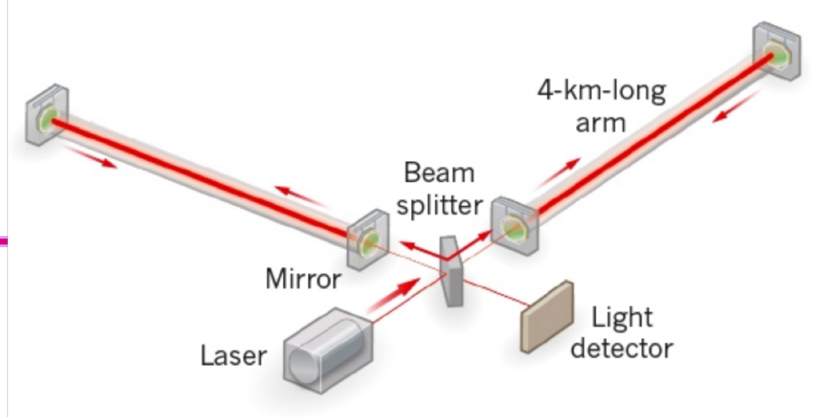
- **Radiation Pressure noise** – buffeting of test mass by photons increases low-frequency noise – use heavy test masses!

$$h_{\rm rp}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$

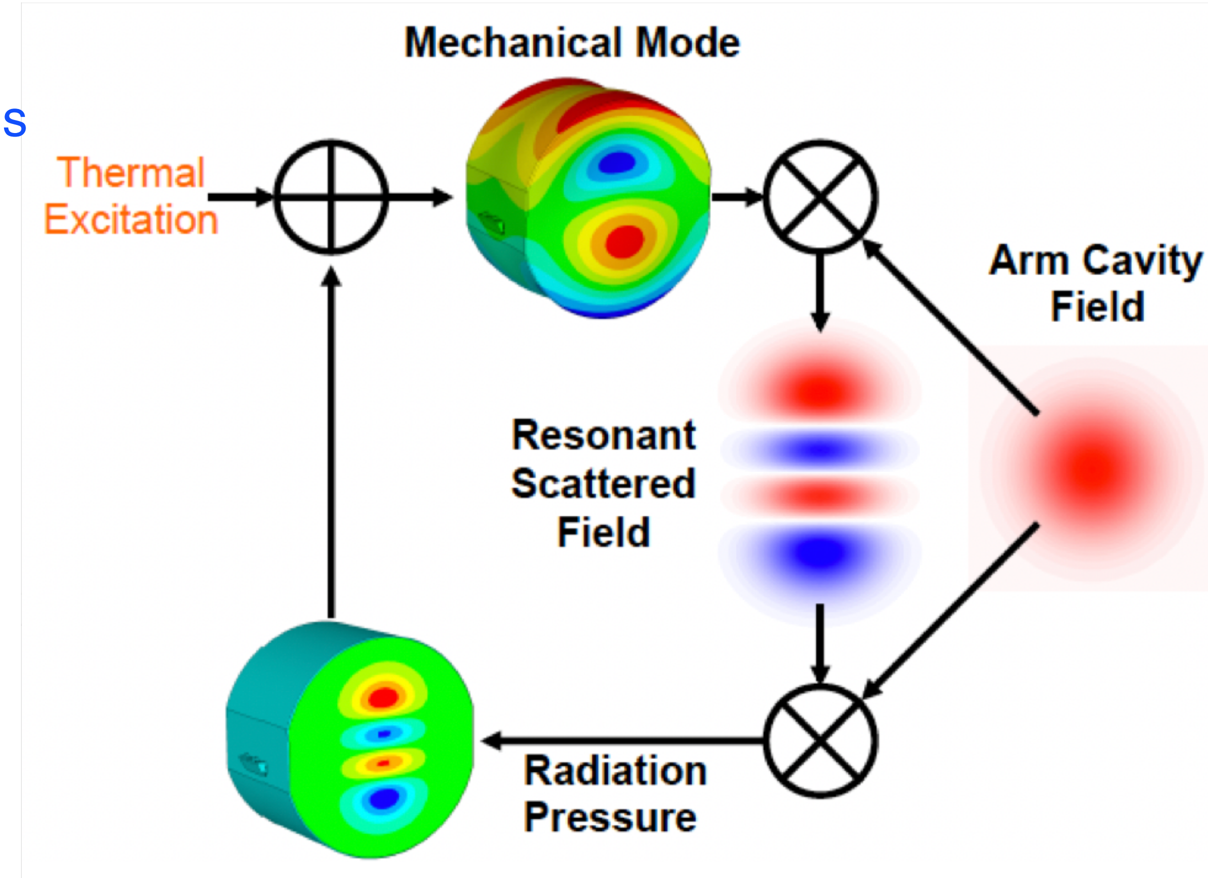
- **'Standard Quantum Limit'**
- OzGrav/ANU making 'squeezing' of light feasible, now being installed



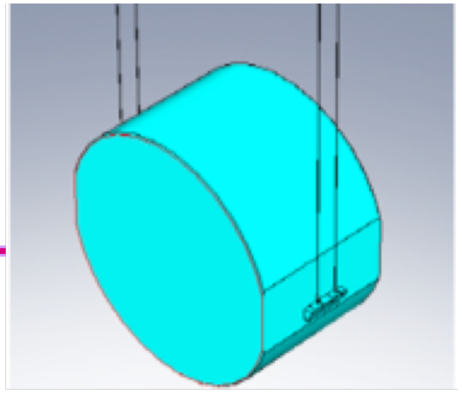
Parametric Instabilities



- Radiation pressure can excite test mass resonances
- Test mass resonances can match optical mode frequencies
- Runaway oscillations possible
- **Active and passive control scheme to suppress**
- OzGrav/UWA established quantitative basis, prototype tests



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



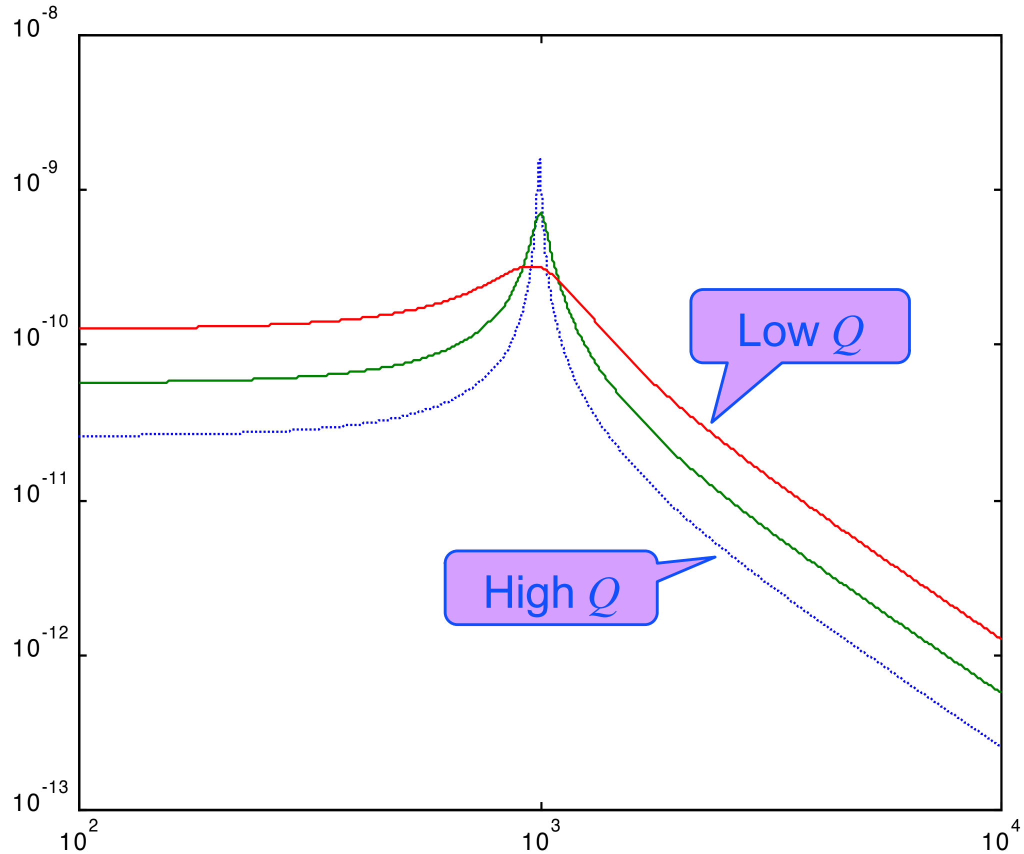
- **Thermal noise** – kT of energy per mechanical mode
- *Über die von der molekularkinetischen Theorie der Wärmegeforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen,* A. Einstein, 1905
- Simple Harmonic Oscillator:

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

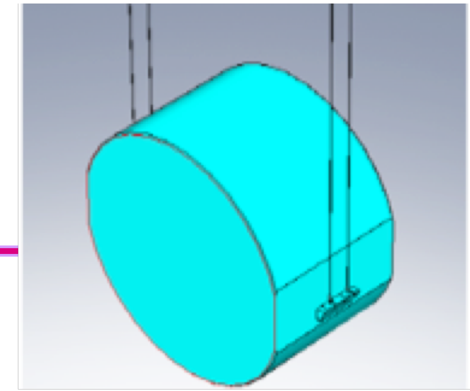
- Distributed in frequency according to real part of impedance $\Re(Z(f))$

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

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



Measuring Δ*L*= 4x10^{-18} m
Internal motion



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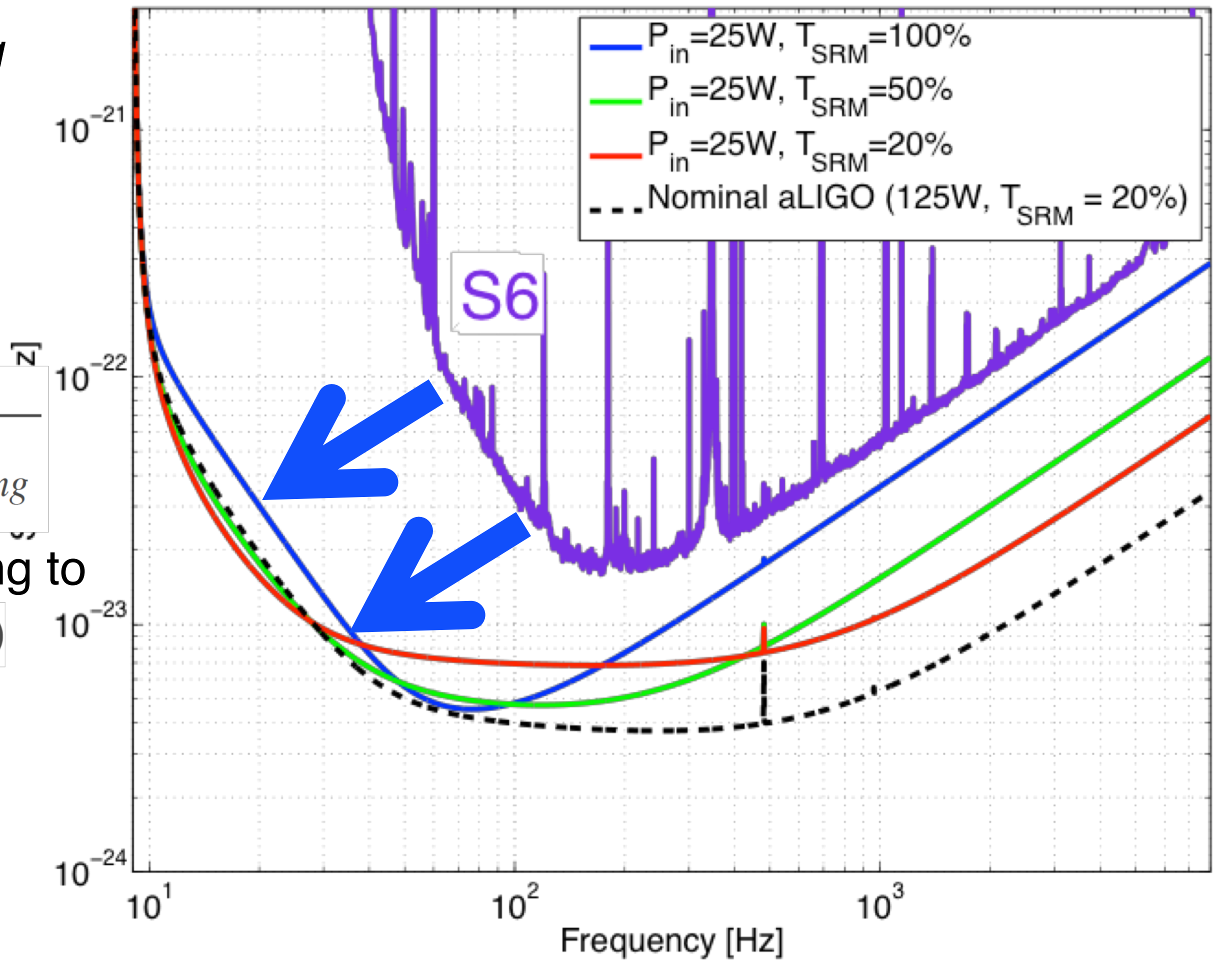
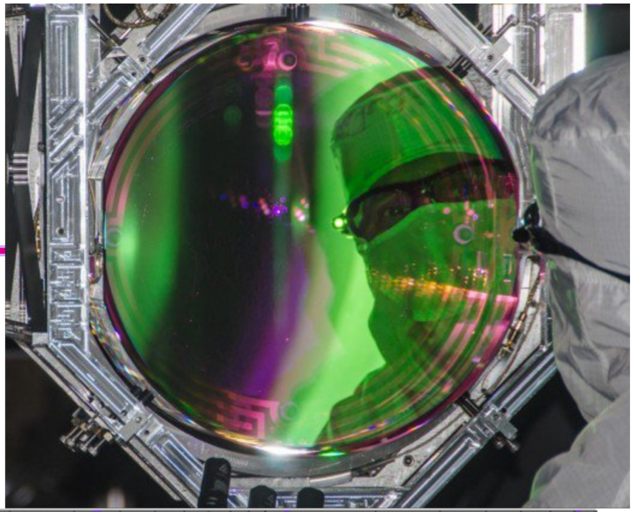
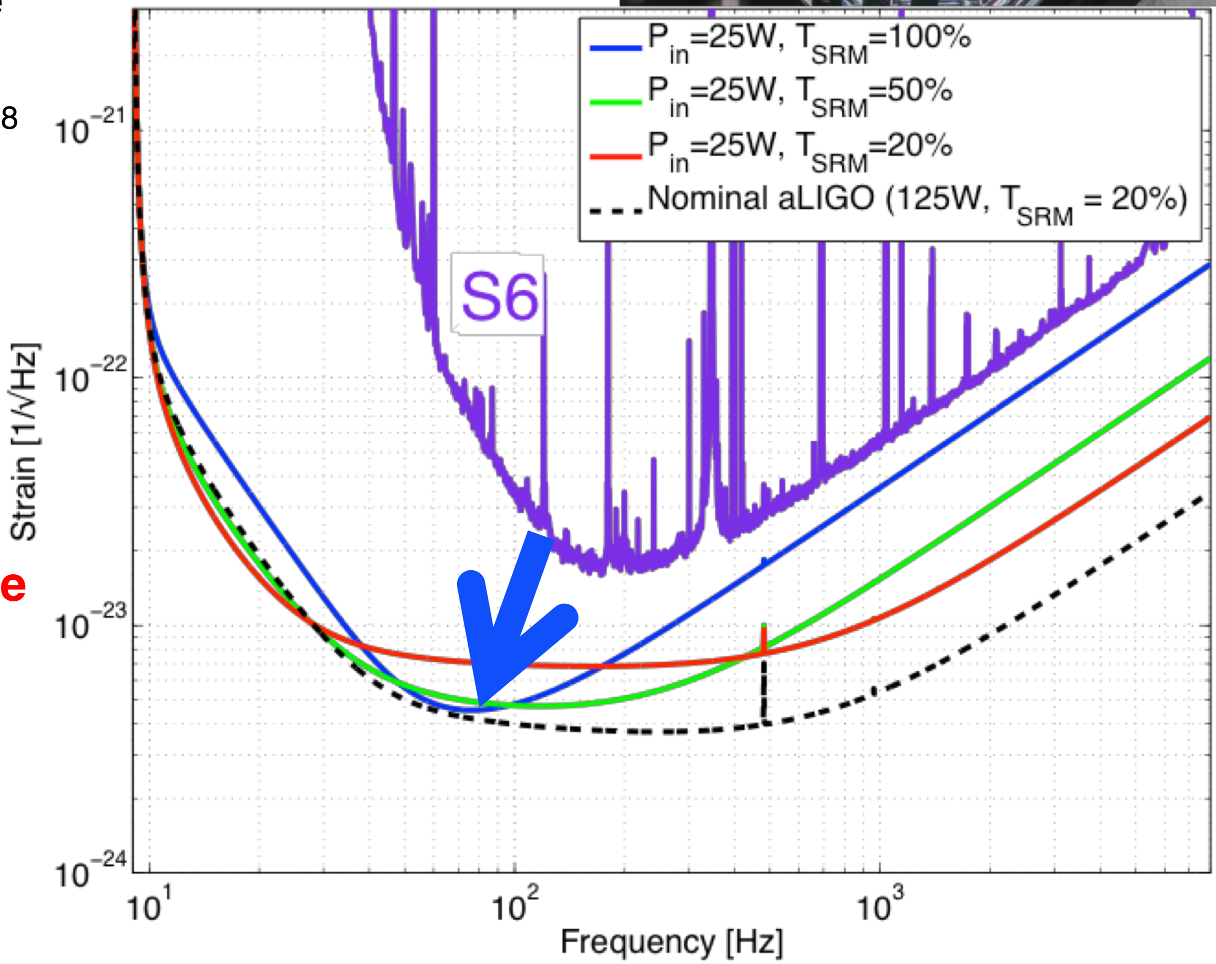


Measuring $\Delta L = 4 \times 10^{-18}$ m
Internal motion

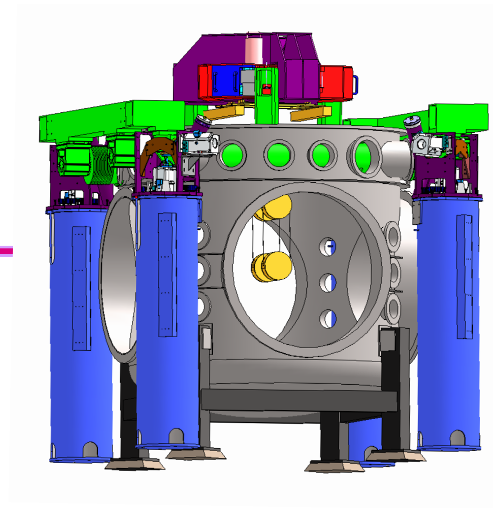


- In Advanced LIGO, the dielectric optical coating has a rather large loss tangent
  - Some 10^{-4} , compared to 10^{-8} for fused silica
- And: the coating is the surface that is sensed by the laser

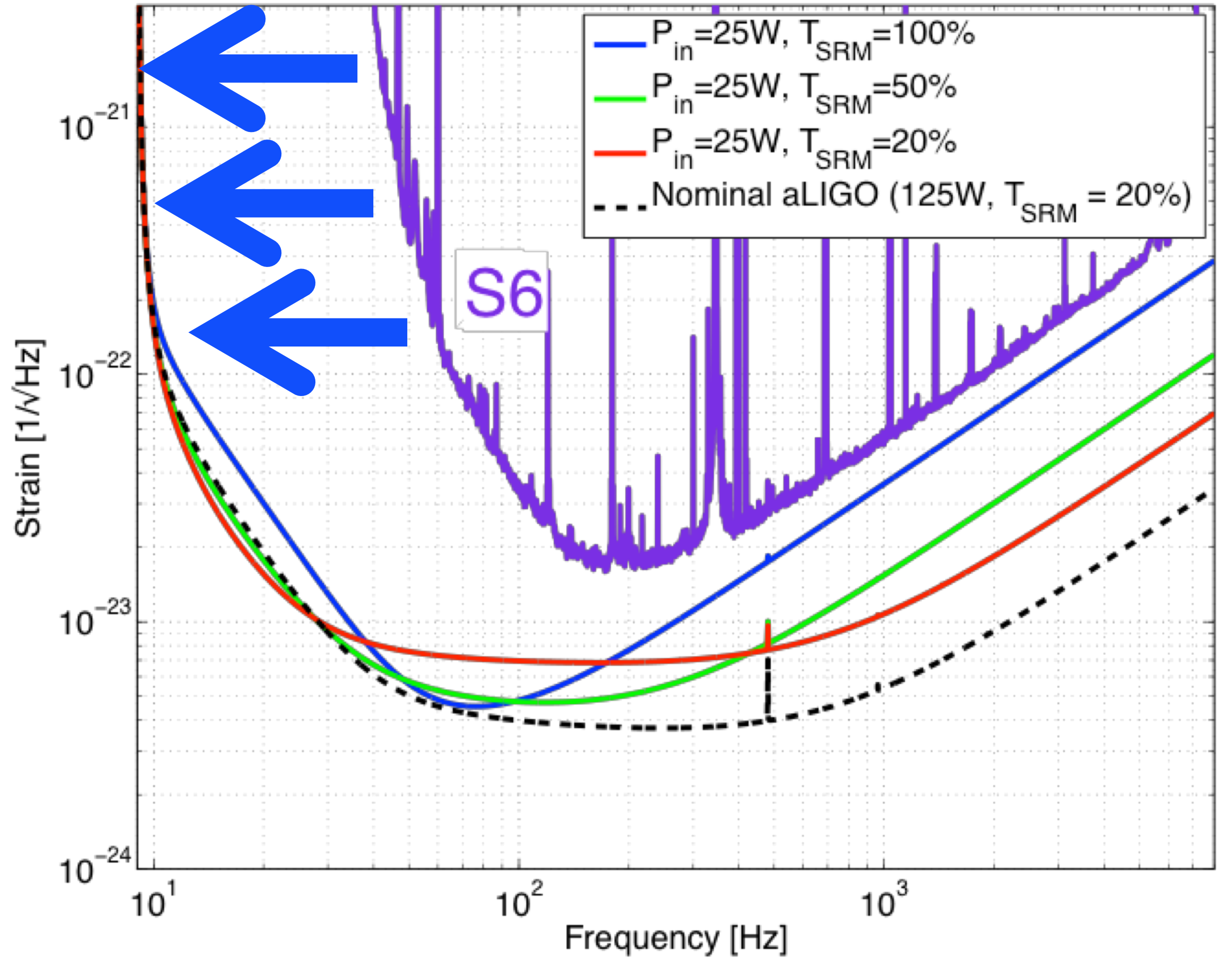


- **This is the dominant limit in the critical 50-200 Hz band**
- CSIRO helped develop and implement our coatings

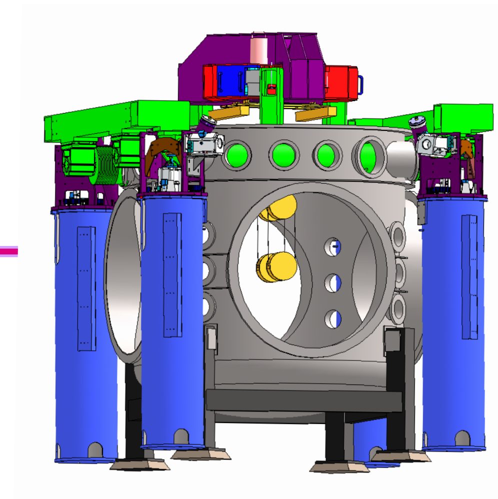
Measuring $\Delta L = 4 \times 10^{-18}$ m
Forces on test mass



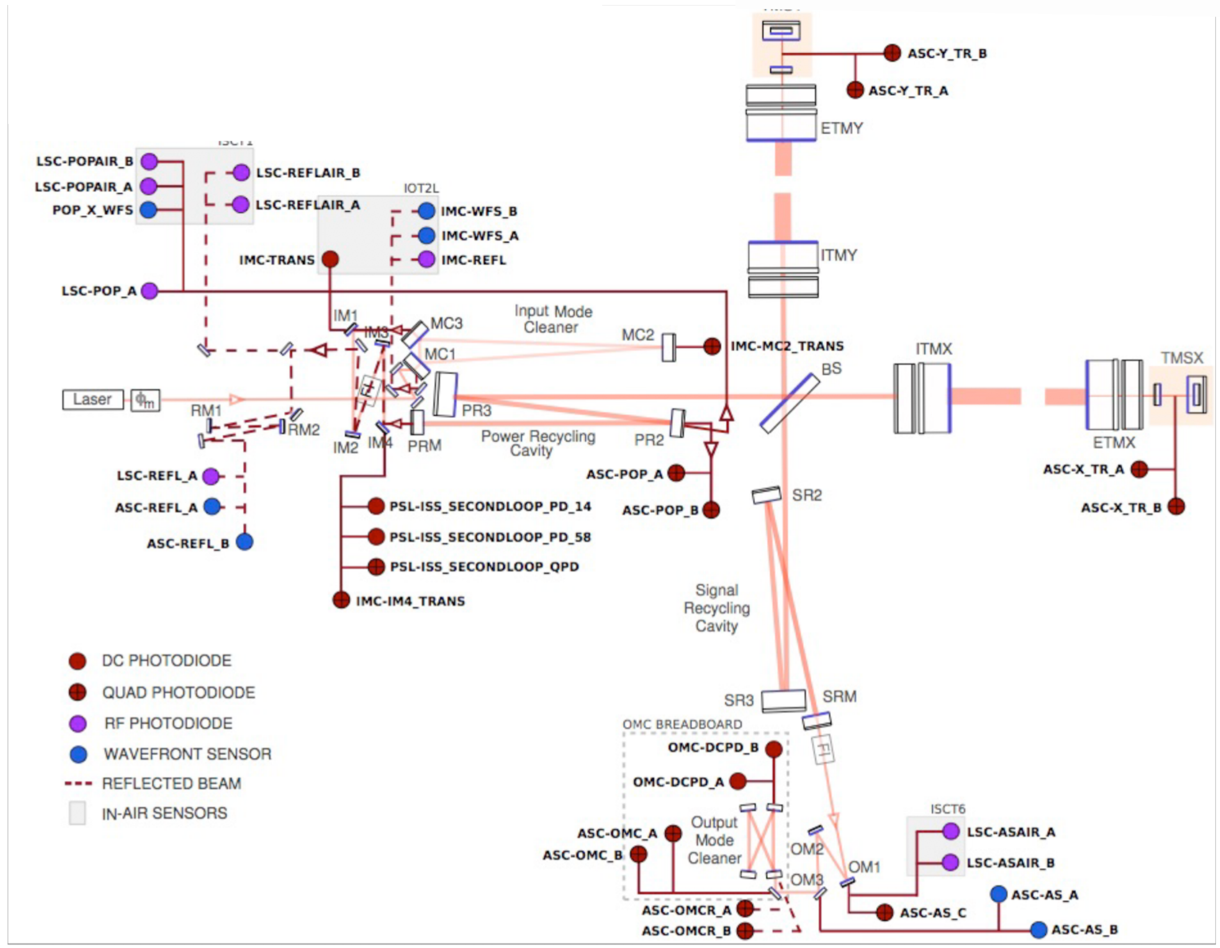
- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- aLIGO uses **active servo-controlled platforms, multiple pendulums**
- 3 layers, each of 6 degrees-of-freedom



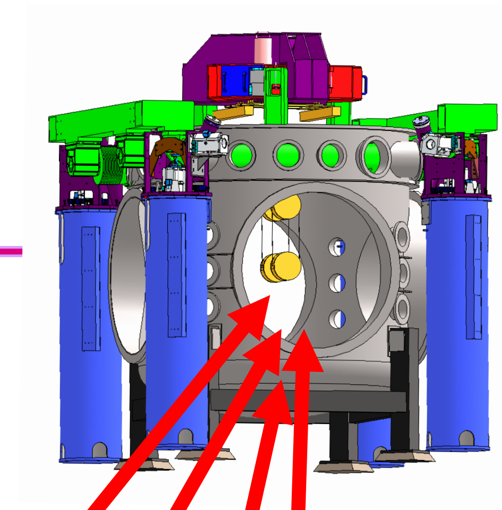
Keeping it all aligned



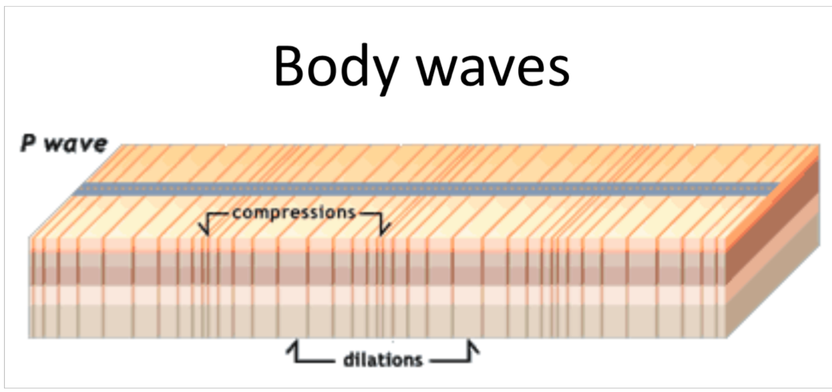
- **So…**
- 3 layers, each of 6 degrees-of-freedom
- 4 cavity optics – 'Test Masses'
- Beamsplitter, 'recycling' mirrors, filter cavities all suspended
- 4km baseline
- Micron motions at 1 Hz, 10^{-20} m at 20 Hz; dynamic range
- Microradian alignment
- Guided control to from micron to picometer motion, coupled cavities on resonance
- **Control system demands are extraordinary**
- OzGrav/ANU contributed key ideas and parts of initial 'bootstrapping'

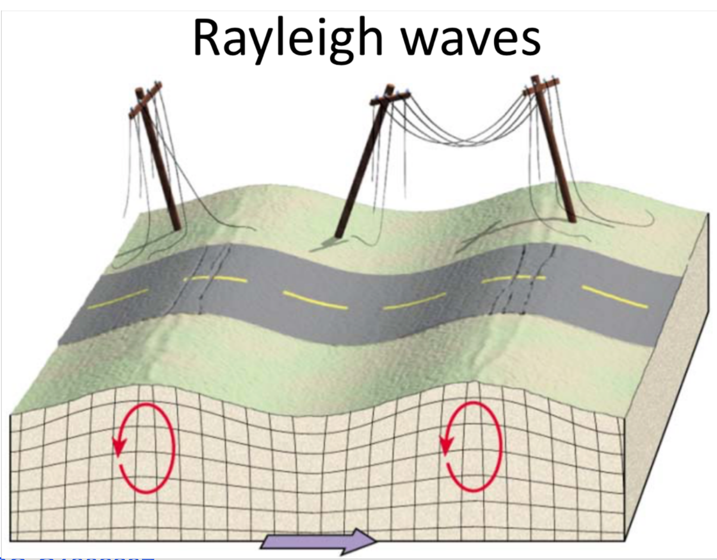


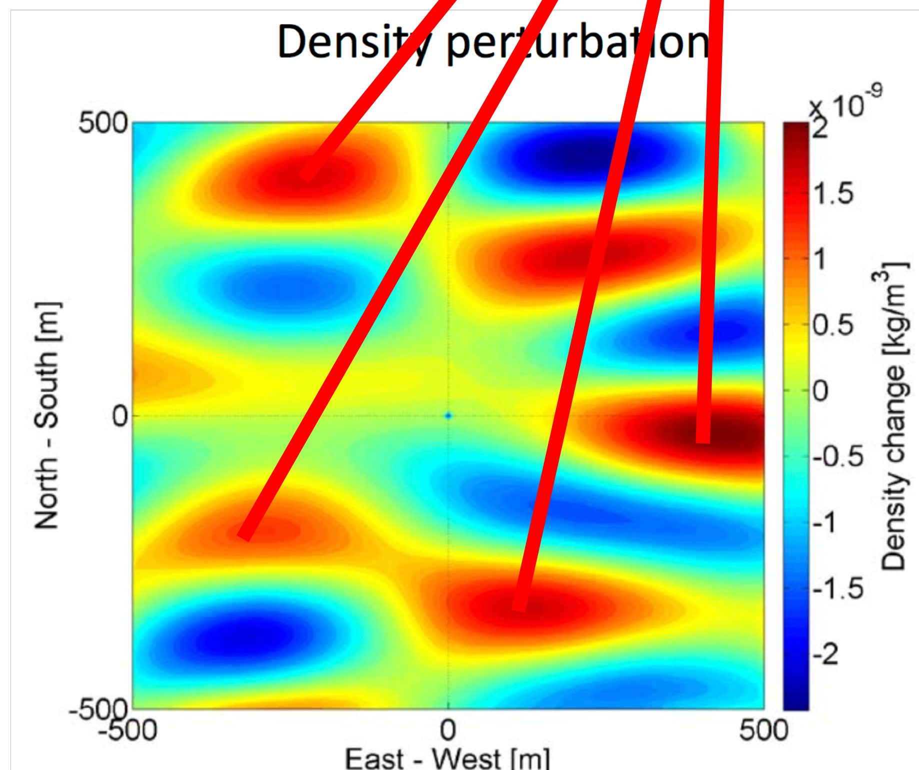
Measuring ΔL= 4x10^{-18} m
Forces on test mass



- Ultimate limit on the lowest frequency detectors on- or under-ground:
- Newtownian background – wandering net gravity vector; a limit in the 10-20 Hz band



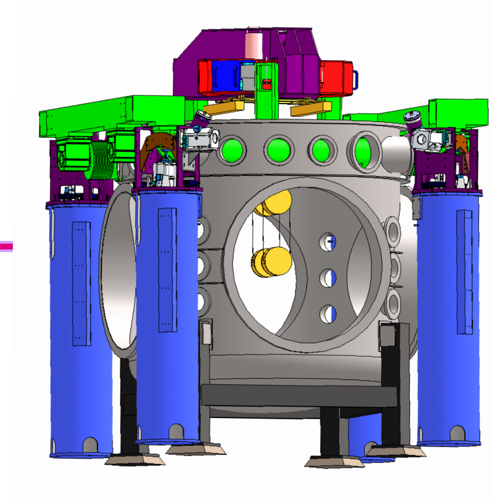




Density perturbations cause gravity perturbations.

Images: J. Harms

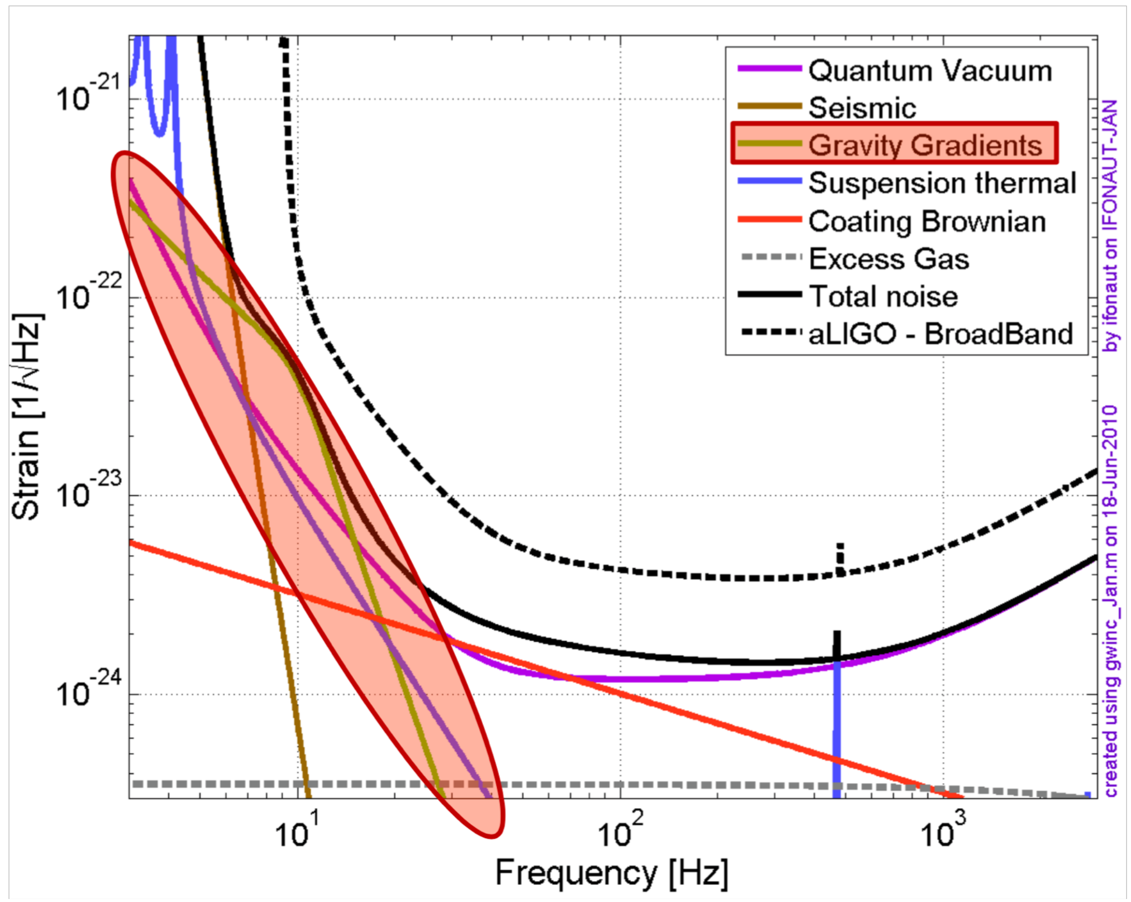
Measuring $\Delta L = 4x10^{-18}$ m
Forces on test mass



- 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

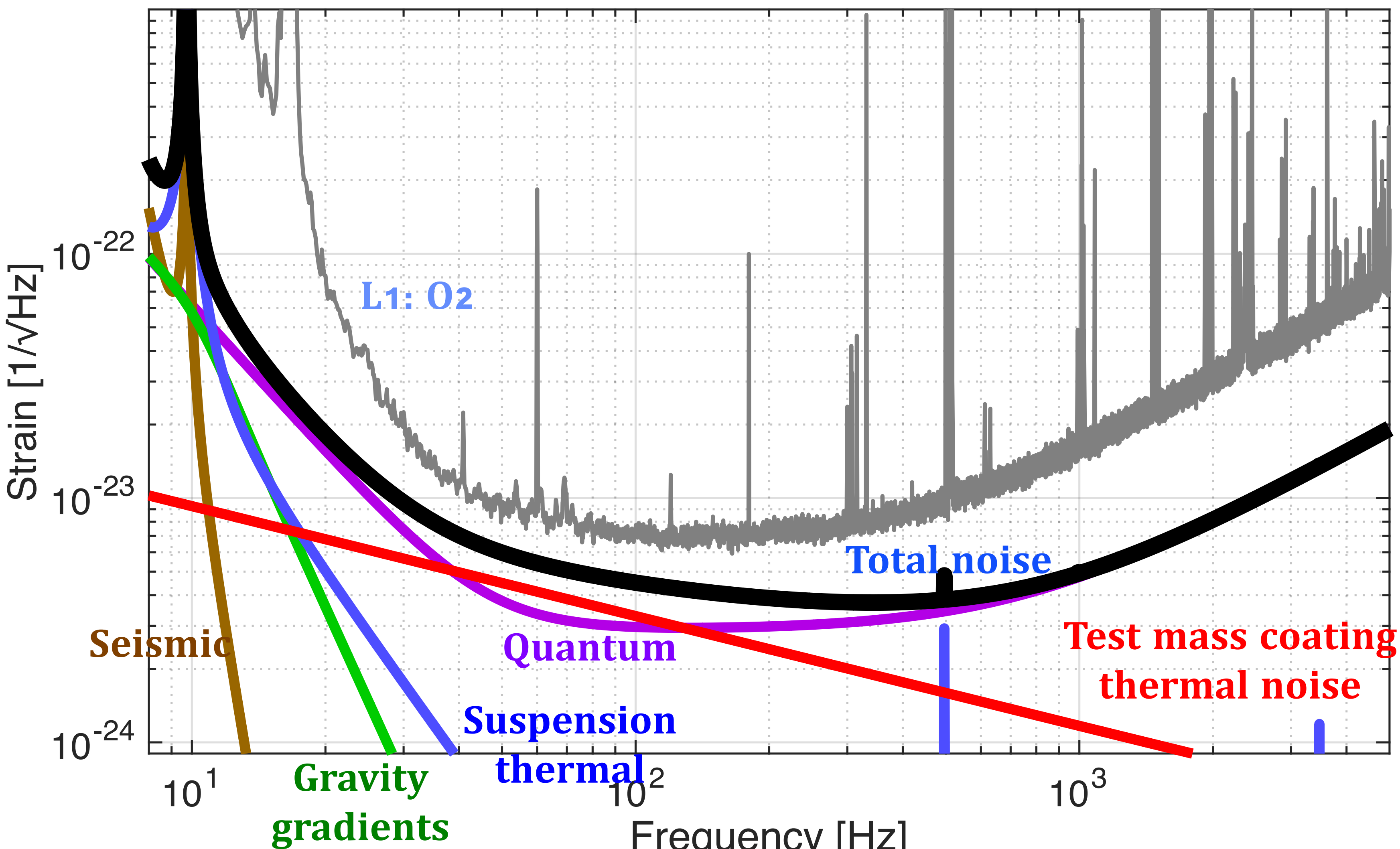
- **We would *love* to be limited only by this noise source!**

- Want to go a bit lower? Go underground.
- Want to go much lower? Go to space.

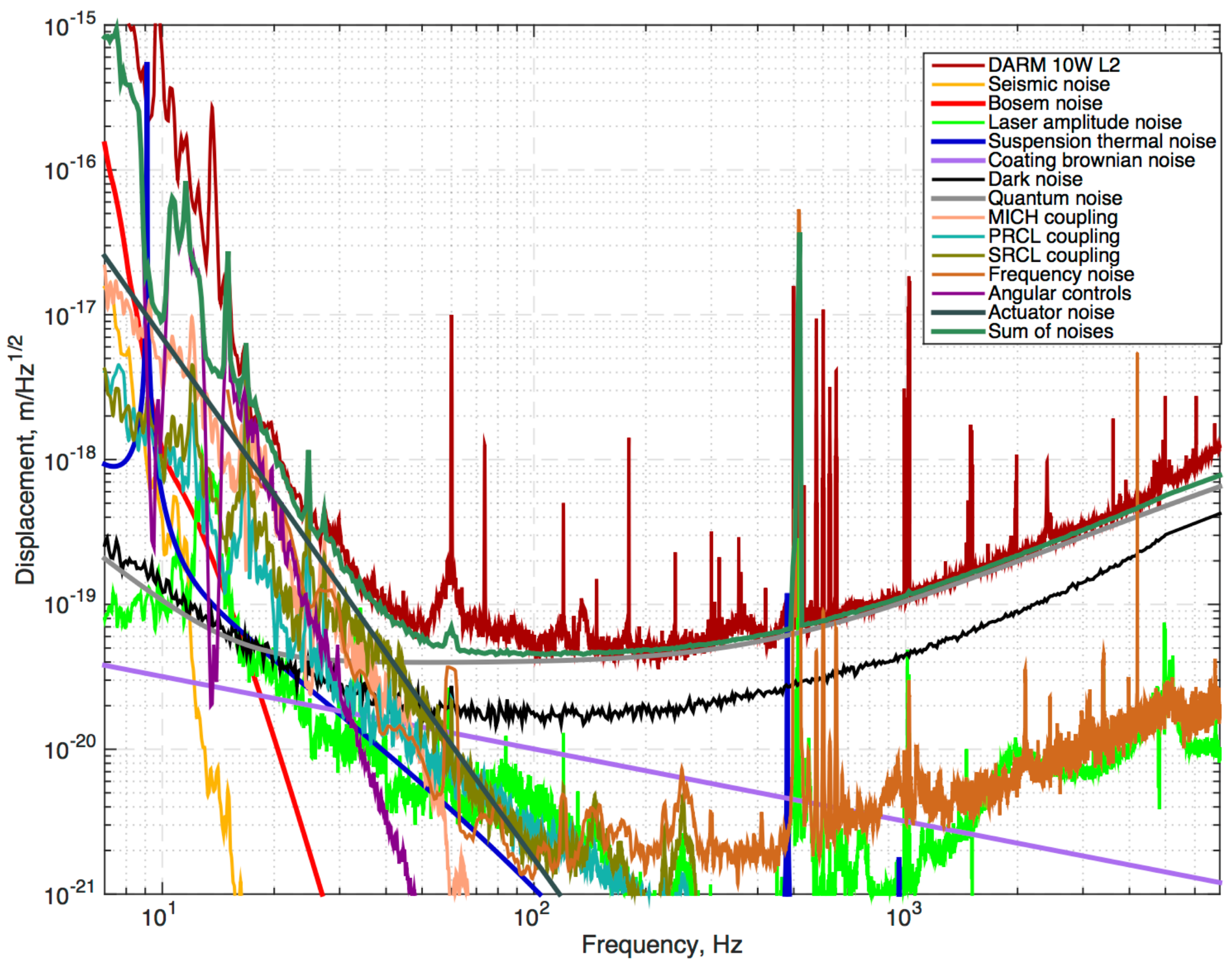


Images: J. Harms

Adv LIGO Target Design
Sensitivity, basic noise sources



Then there are the technical noise sources….



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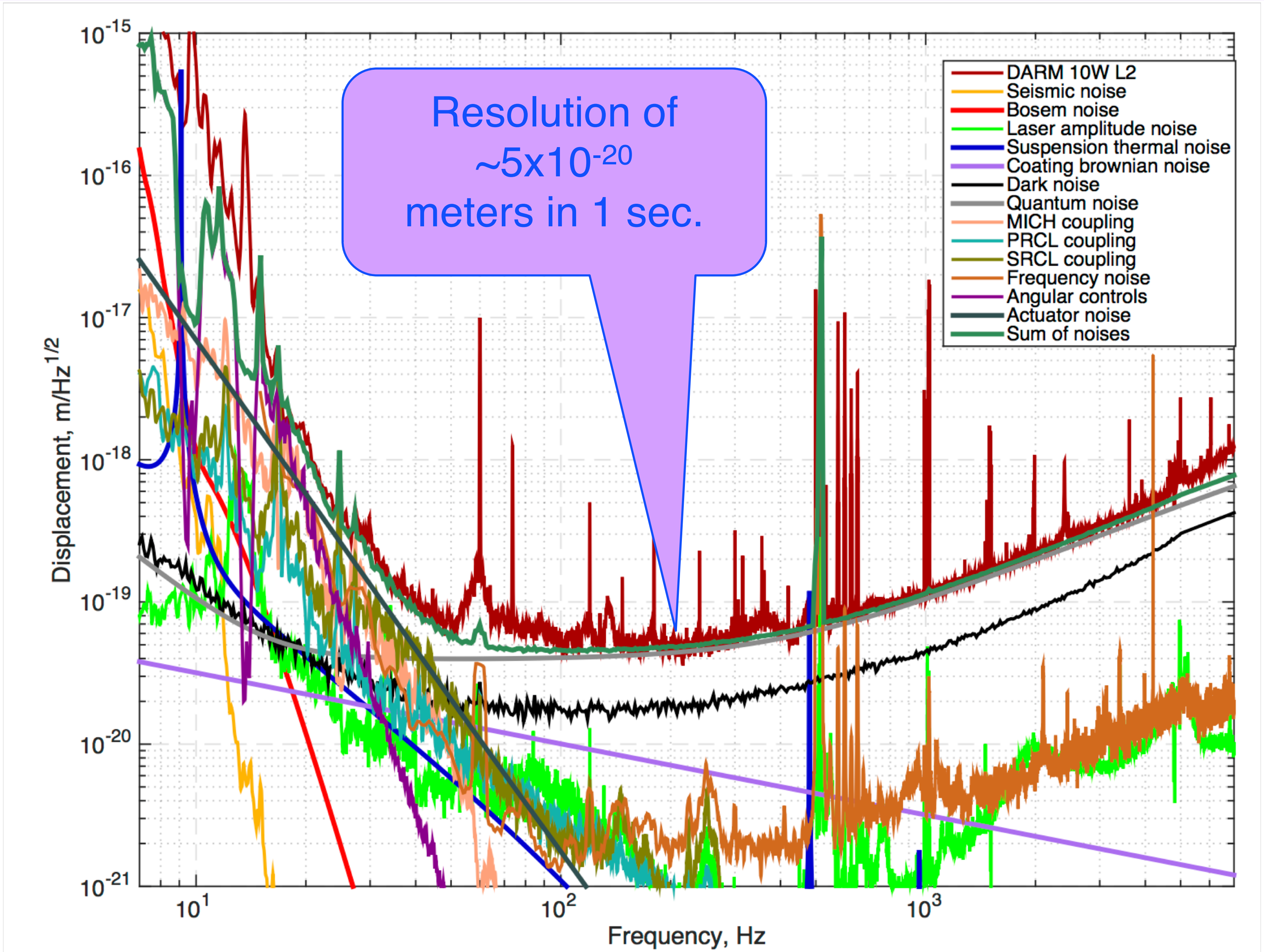
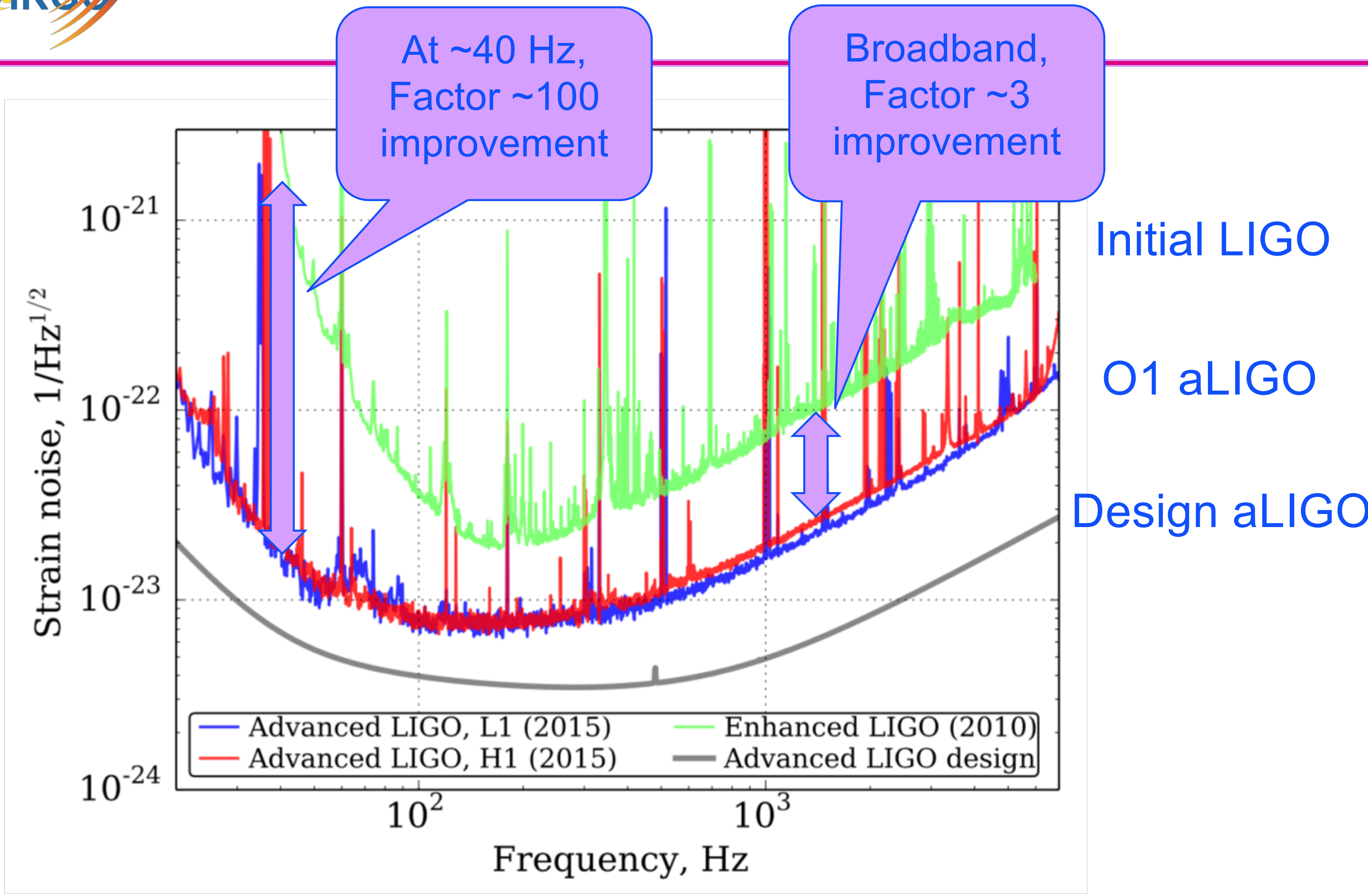
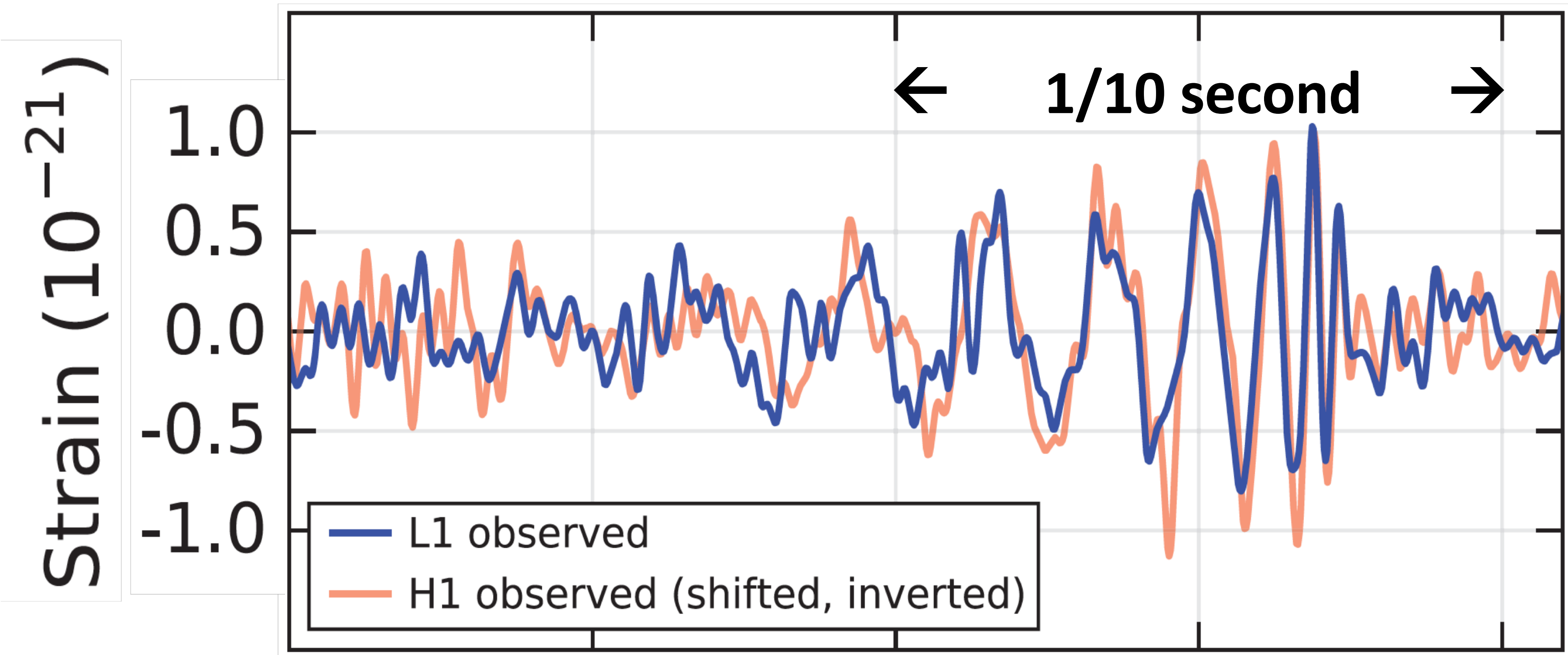


Sensitivity for first Observing runs



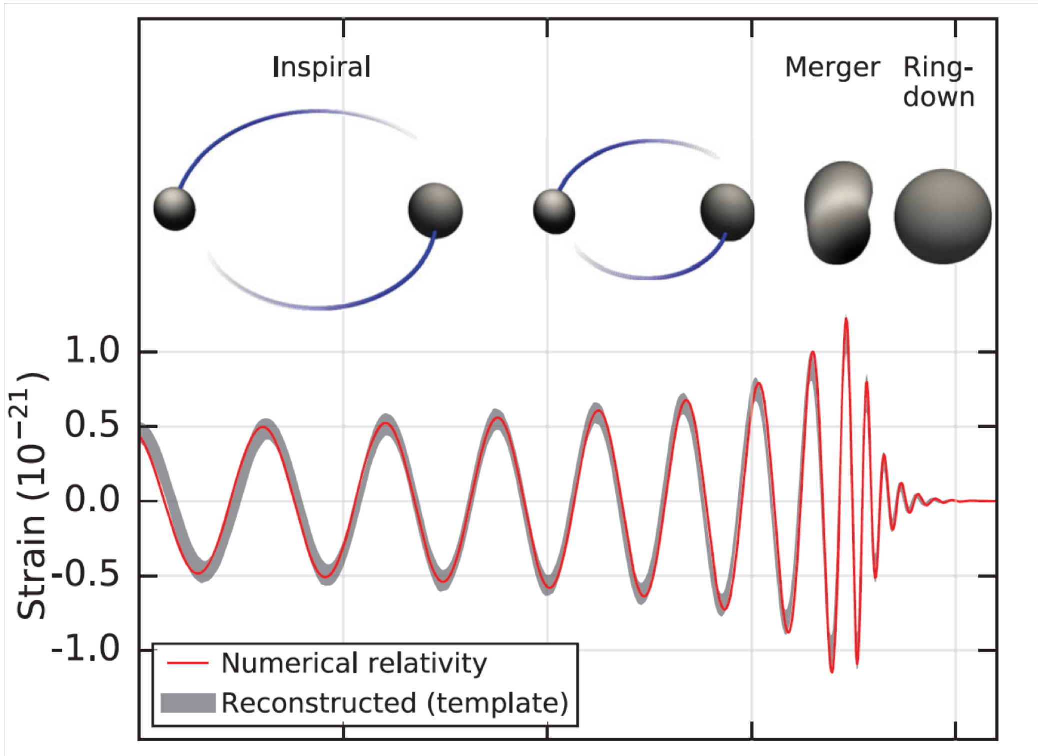
GW150914

The first GW detection



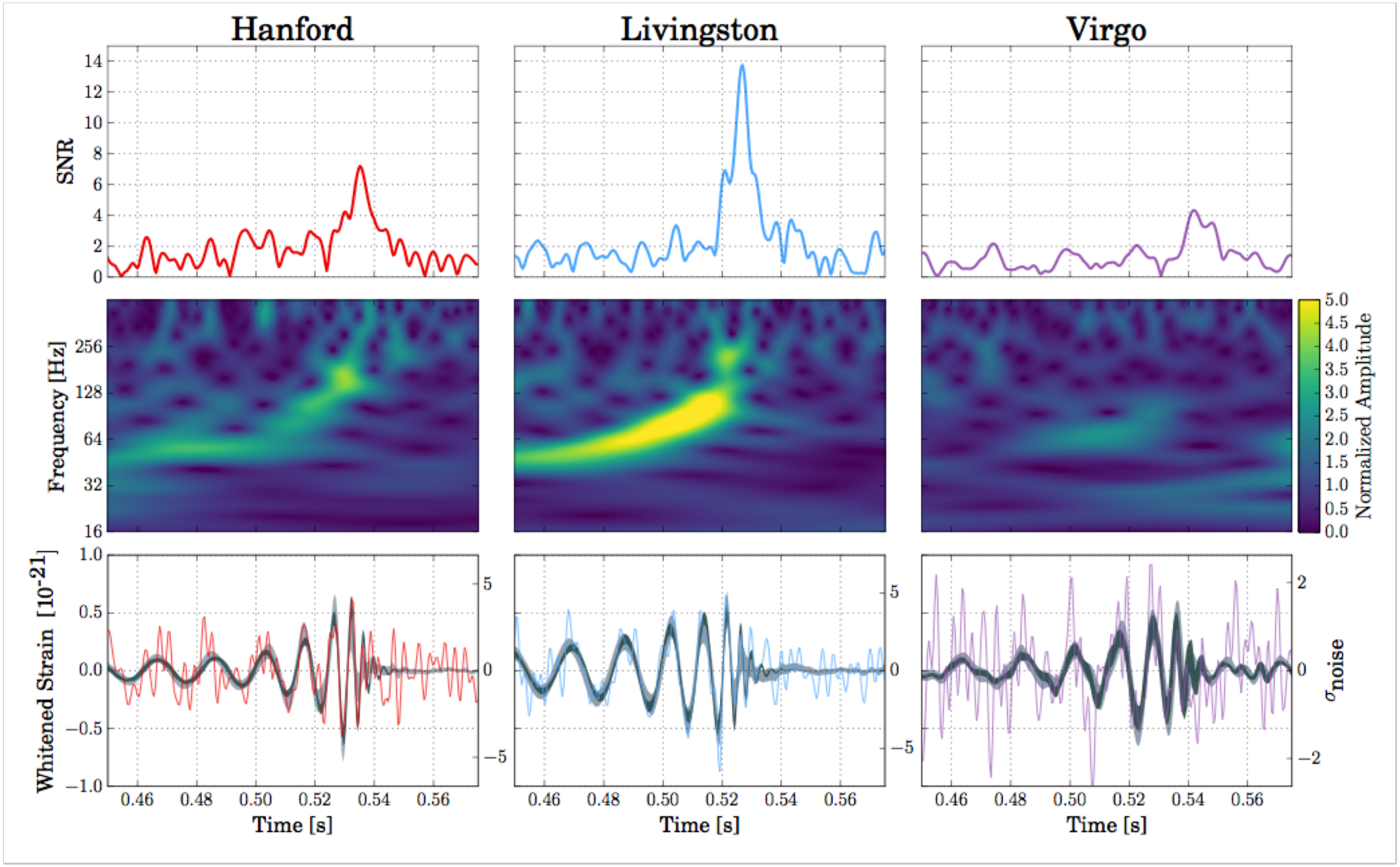
We measure *h(t)* – think 'strip chart recorder'

- The output of the detector is the (signed) strain as a function of time
- Earlier measurements of the pulsar period decay (Taylor/Hulse/Weisberg) measured energy loss from the binary system – a beautiful experiment
  - » radiation of gravitational waves confirmed to *remarkable* precision for 0^{th} post-Newtonian
- **LIGO can actually measure the change in distance between our own test masses, due to a passing space-time ripple**
  - » Instantaneous amplitude rather than time-averaged power
  - » Much richer information!



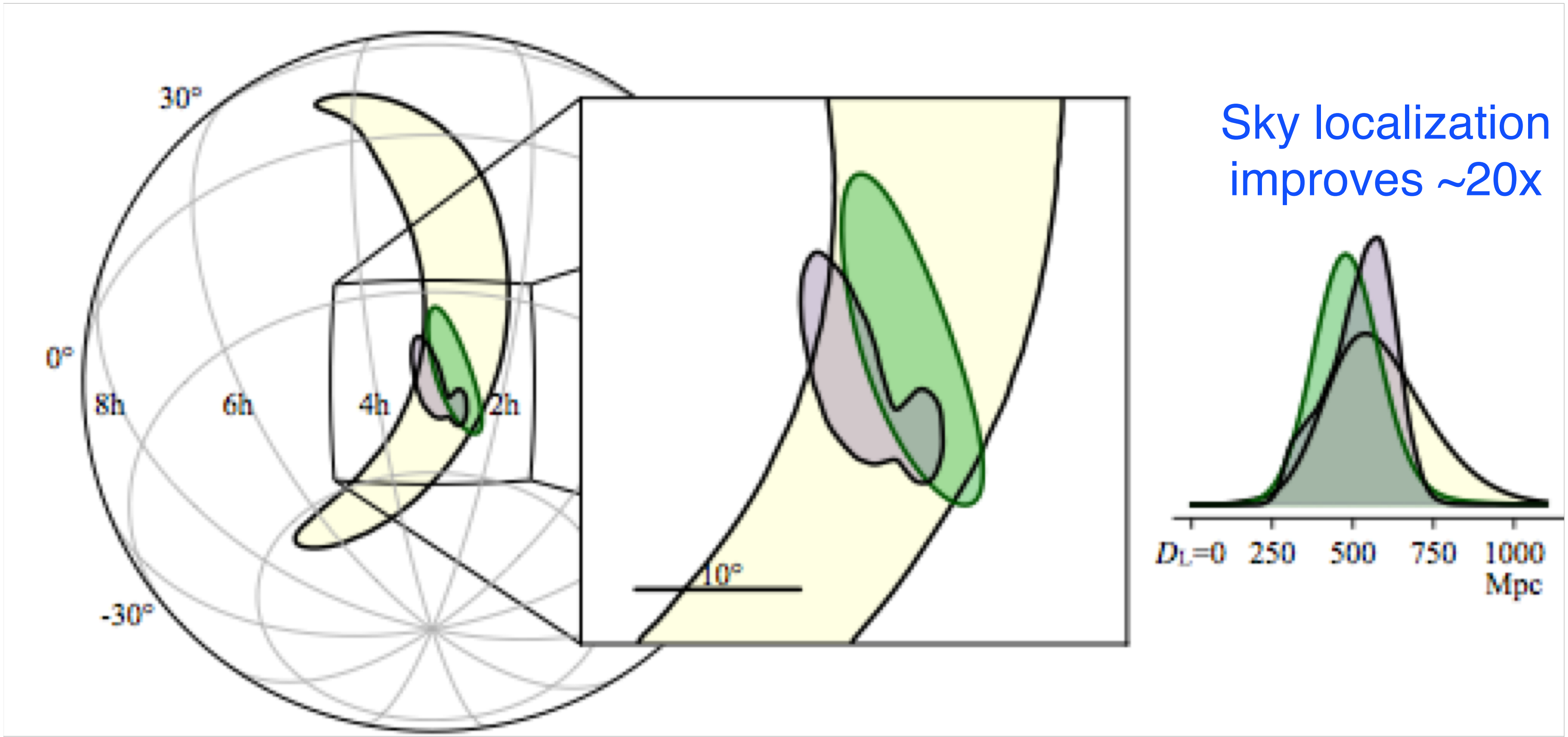
GW170814

The first GW signal observed by LIGO-Hanford, LIGO-Livingston and Virgo



B. P. Abbott et al., *A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence*, 2017, Phys. Rev. Lett., 119, 141101

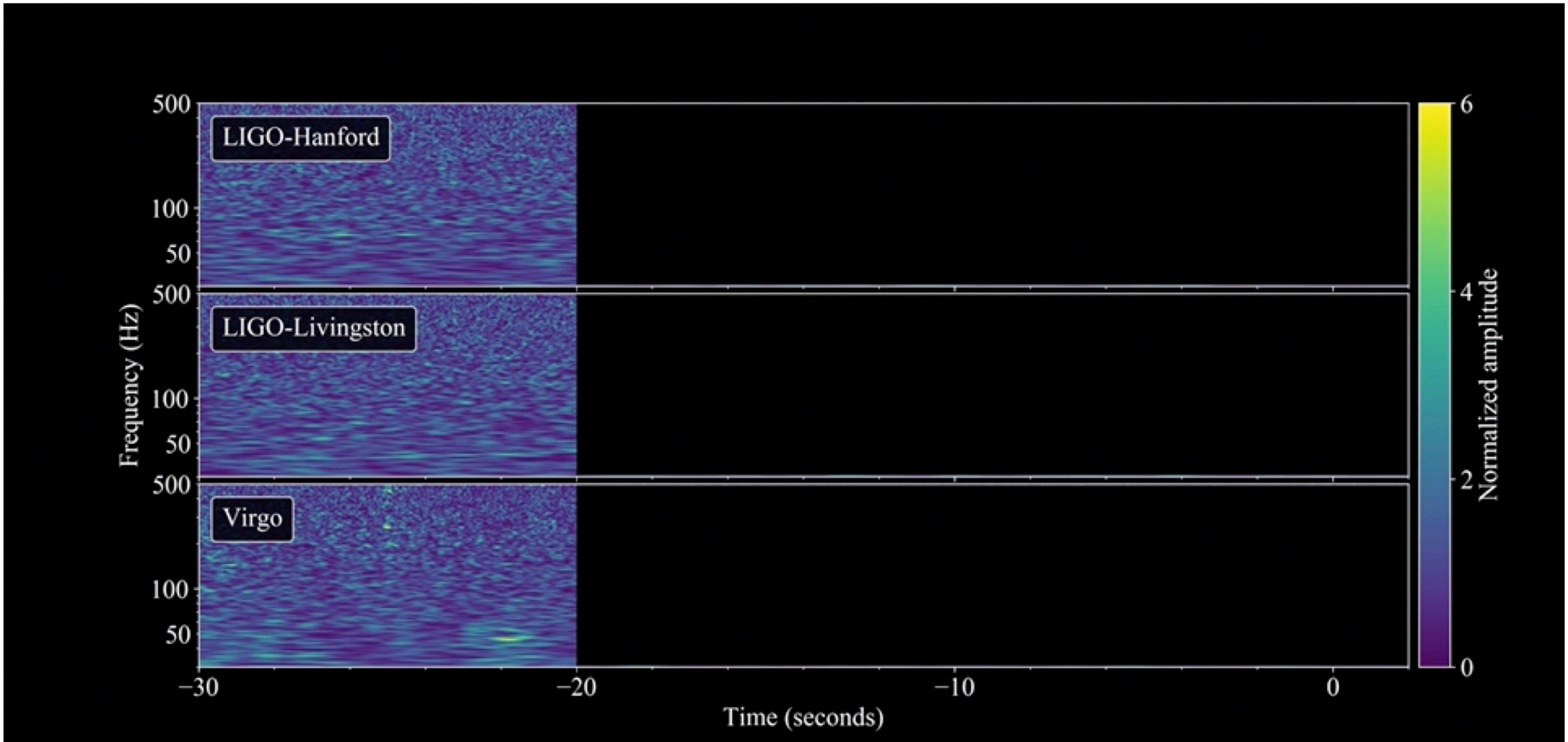
GW170814



Sky localization improves ~20x

Uncertainty in volume reduced ~34x

GW170817

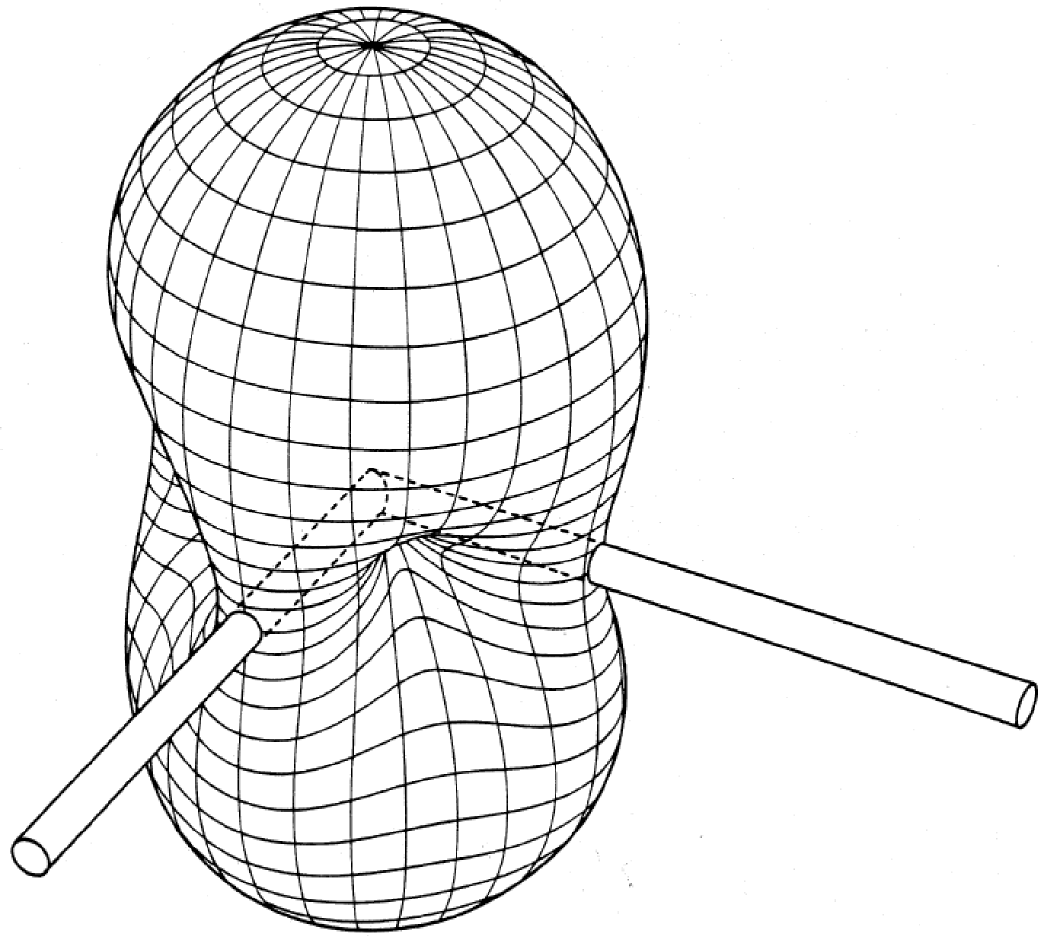


LIGO-Virgo/Geoffrey Lovelace, Duncan Brown, Duncan Macleod, Jessica McIver, Alex Nitz

https://doi.org/10.1103/PhysRevLett.119.161101

Antenna pattern for a single detector

- Maximal for overhead or underfoot source
- 1/2 for signals along one arm
- …and zero at 45 degrees

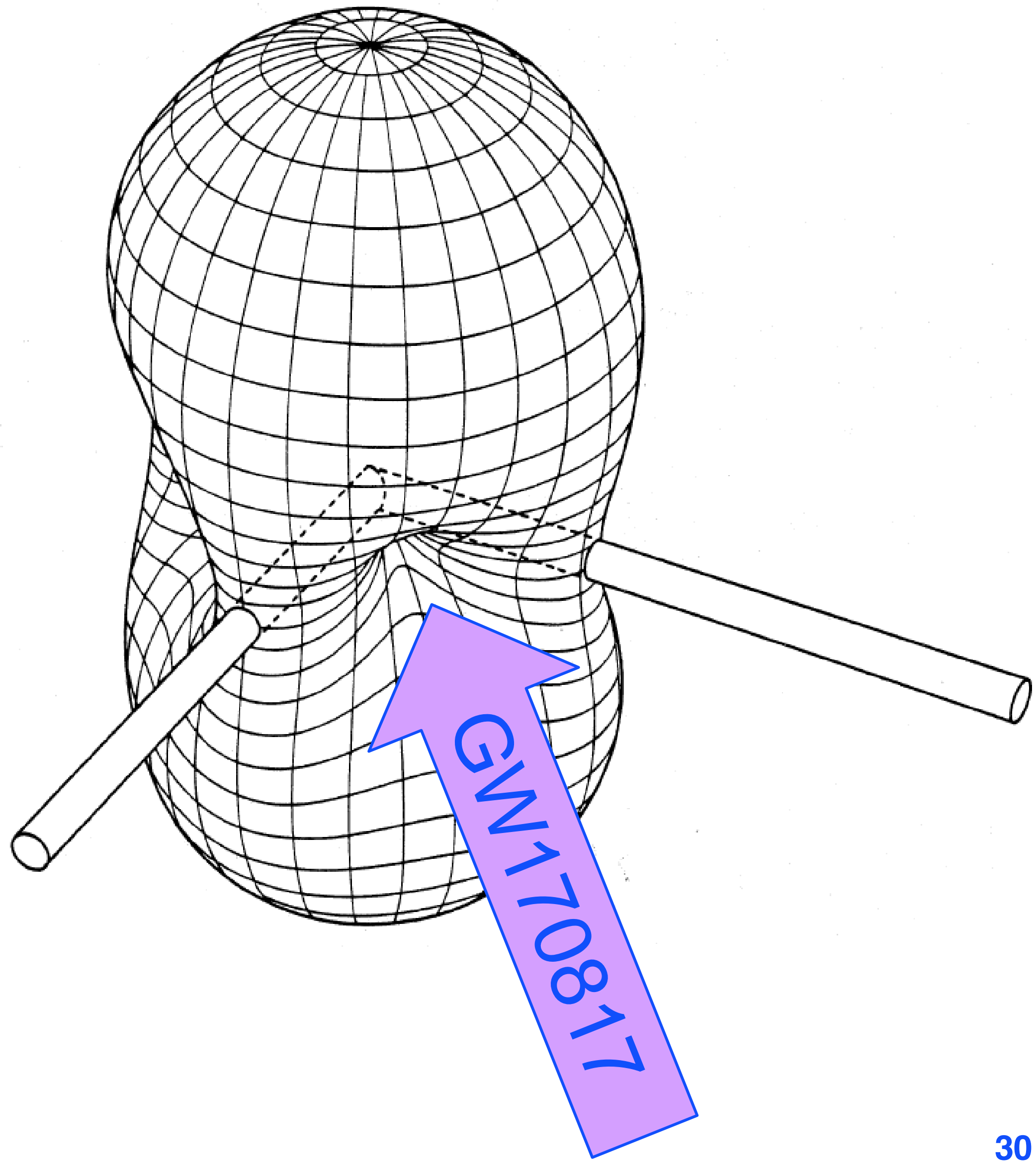


Antenna pattern for a single detector

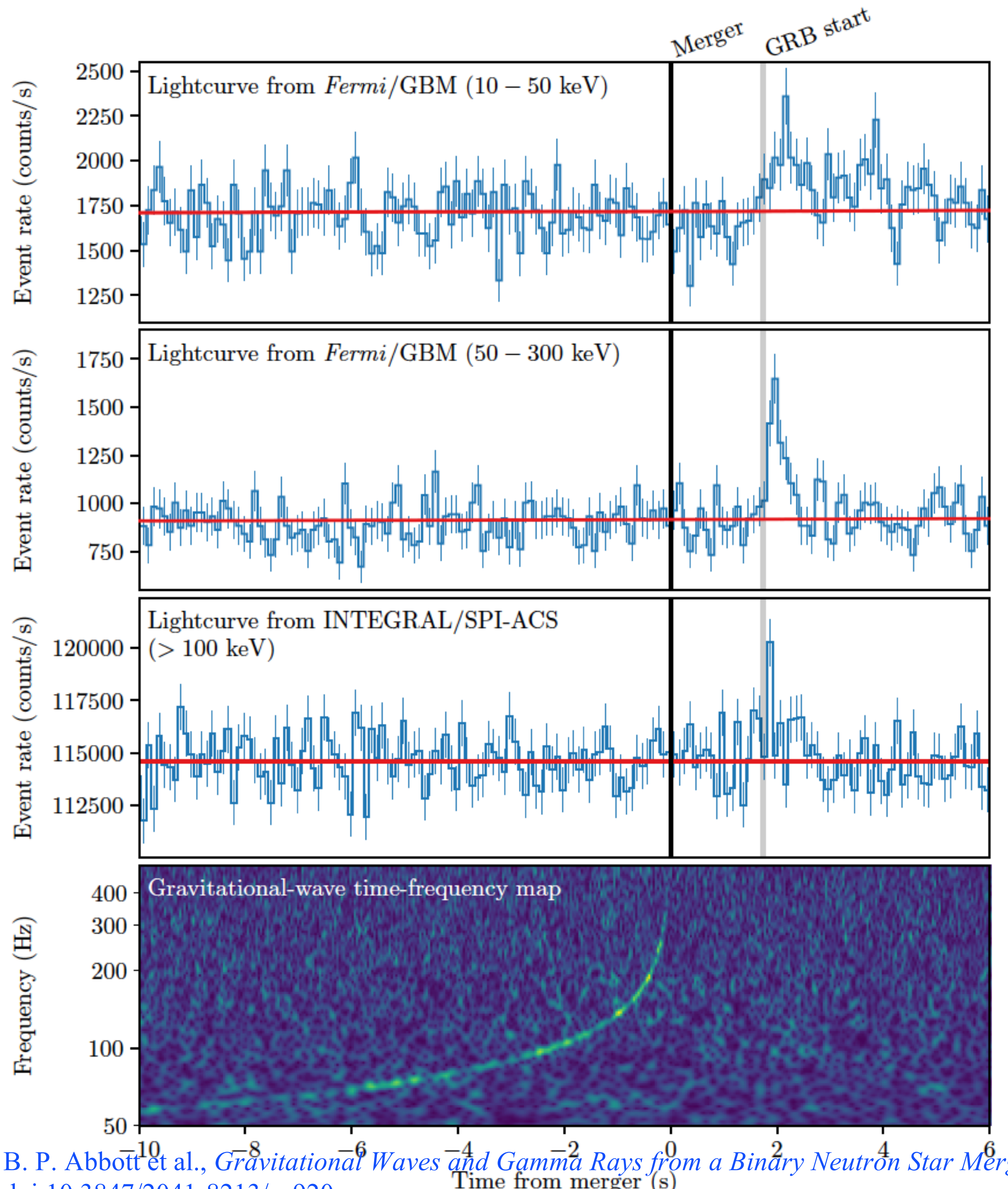
- Maximal for overhead or underfoot source
- 1/2 for signals along one arm
- …and zero at 45 degrees

- GW170817 fell on Virgo close to 45 degrees!

- Did no harm for localization. (GW170814 proved the detector was working, happily)



GRB 170817A



GRB 170817A occurs (1.74 ± 0.05) seconds after GW170817

It was autonomously detected in-orbit by Fermi-GBM (GCN was issued 14s after GRB) and in the routine untargeted search for short transients by INTEGRAL SPI-ACS

Probability that GW170817 and GRB 170817A occurred this close in time and with location agreement by chance is 5.0×10^{-8} (Gaussian equivalent significance of 5.3σ)

GWs and Photons travel at the same speed to one part in 10^{15}

BNS mergers are progenitors of (at least some) SGRBs

B. P. Abbott et al., *Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A*, 2017, ApJL in press.
doi:10.3847/2041-8213/aa920c

Multimessenger Observations

Approximate timeline:

GW170817 - August 17, 2017 12:41:04 UTC = $\mathbf{t_0}$

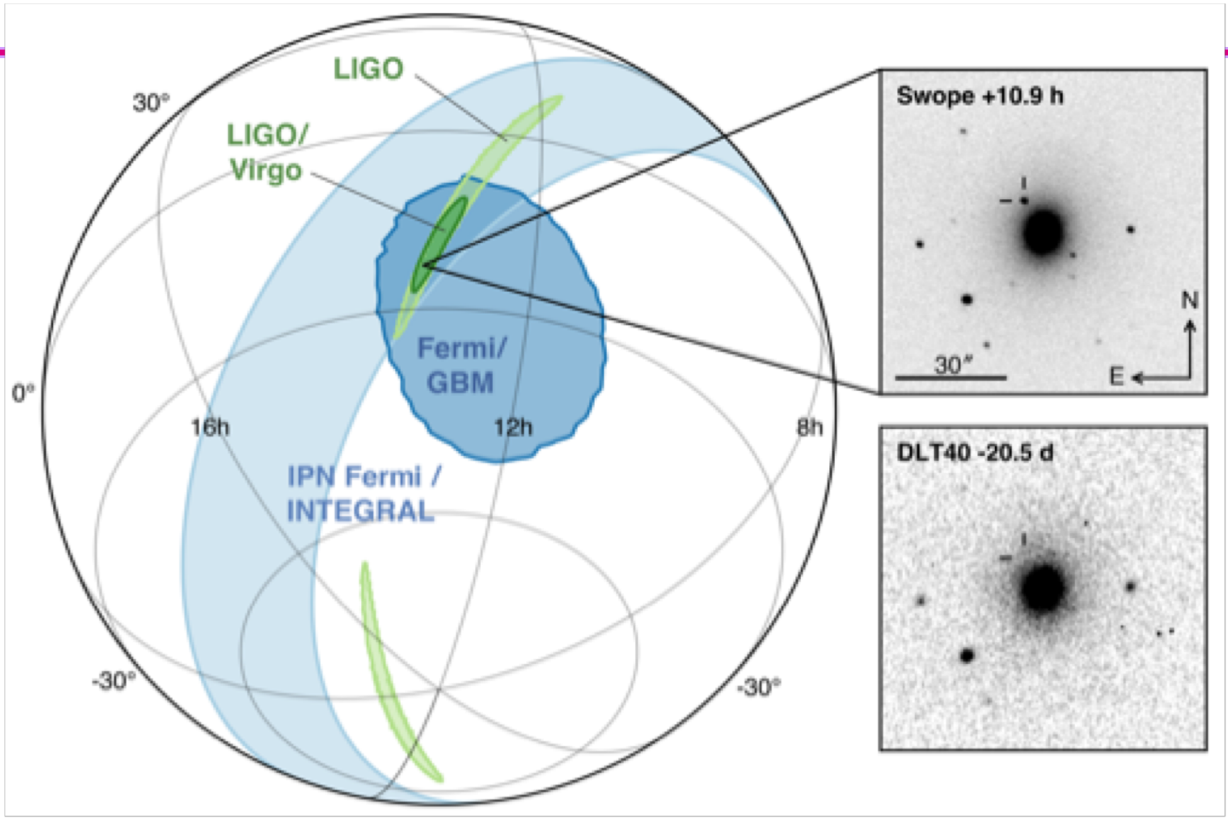
GRB 170817A
t_0 + 2 sec

LIGO signal found
t_0 +6 minutes

LIGO-Virgo GCN reporting BNS signal associated with the time of the GRB
t_0 +41 minutes

SkyMap from LIGO-Virgo
t_0 + 4 hours

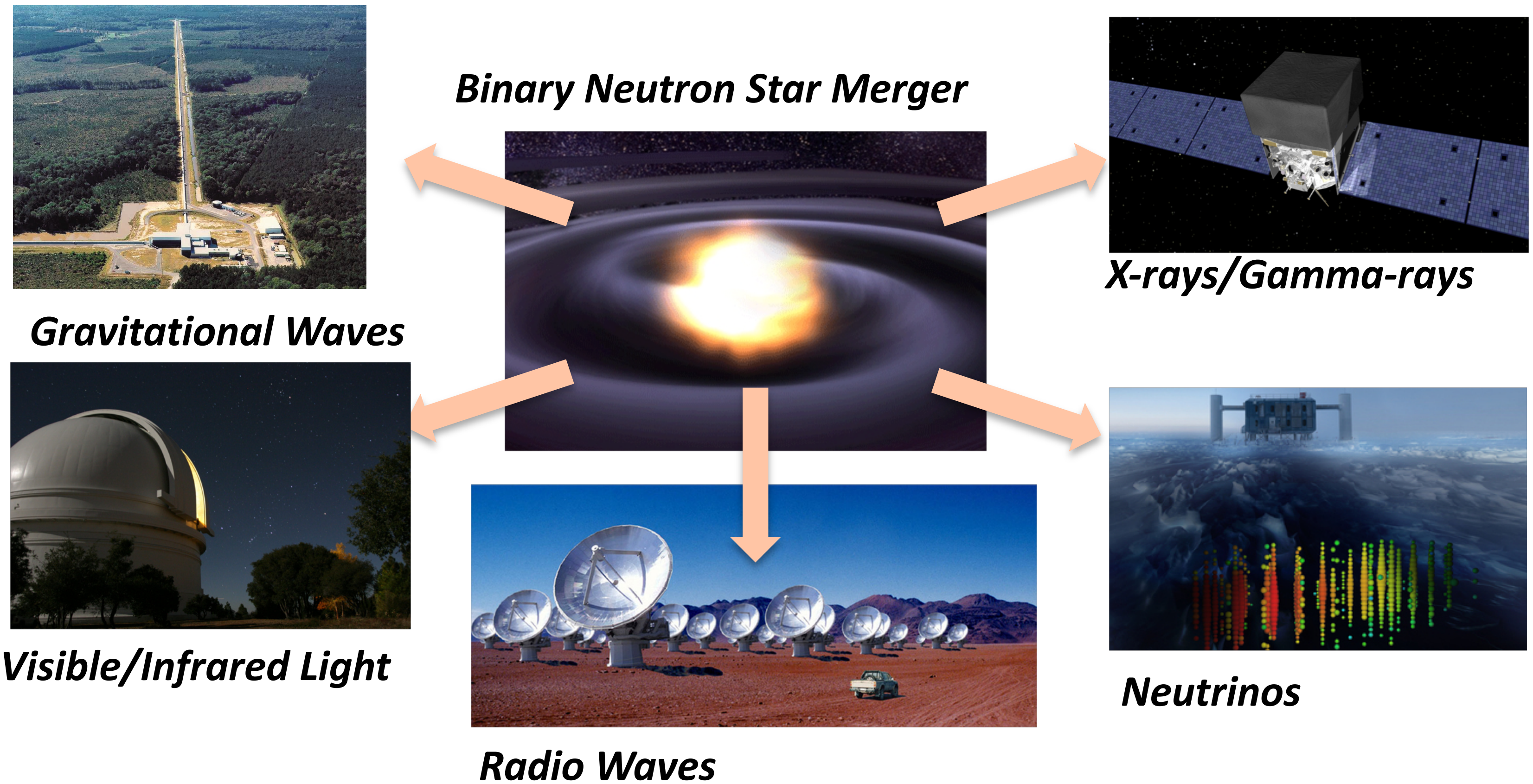
Optical counterpart found
t_0 + 11 hours



- The localisation region became observable to telescopes in Chile 10 hours after the event time (wait for nightfall!)
- Approximately 70 ground- and space- based observatories followed-up on this event

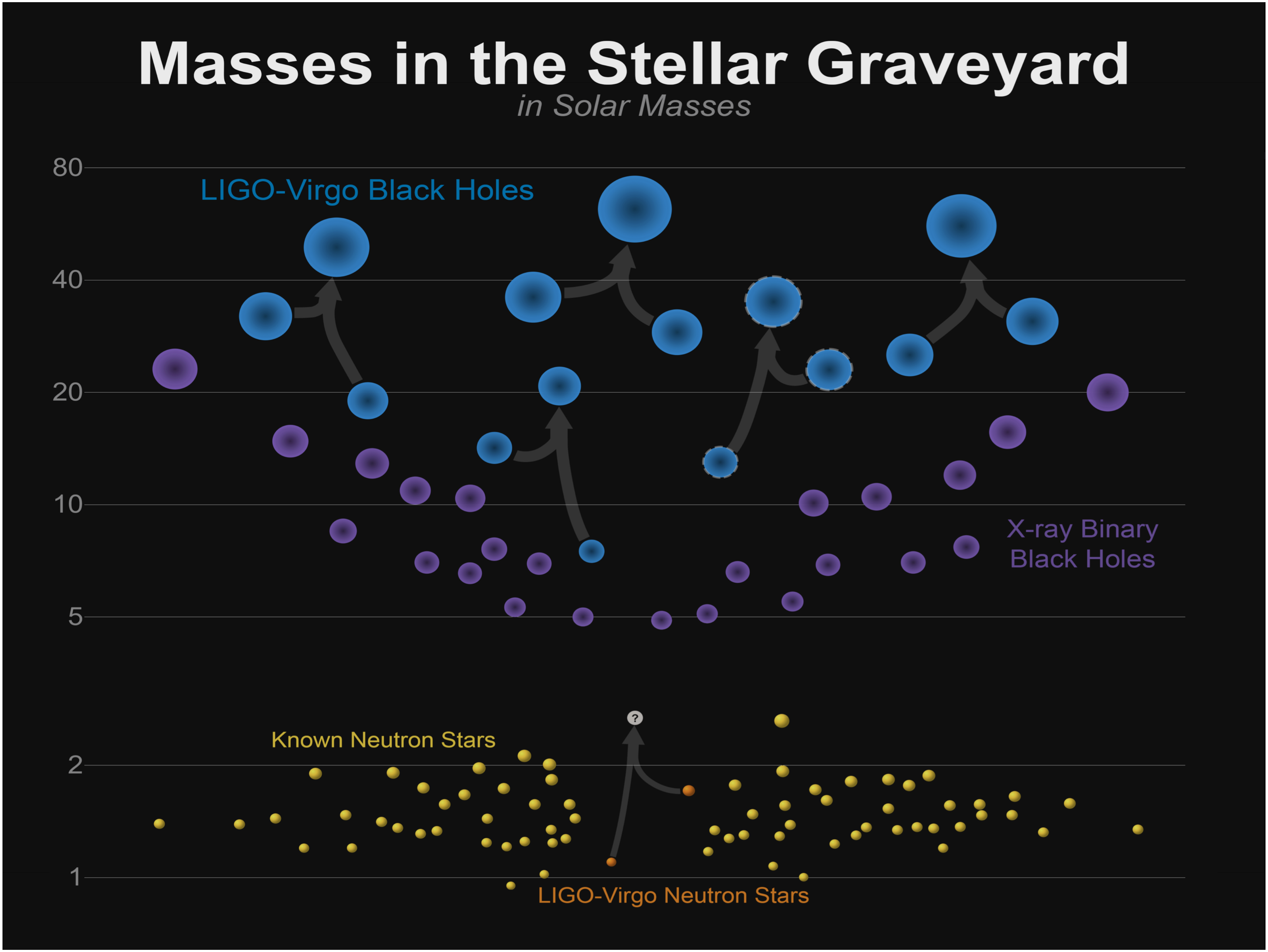
B. P. Abbott, *Multi-messenger Observations of a Binary Neutron Star Merger*, 2017, ApJL in press. doi:10.3847/2041-8213/aa91c9

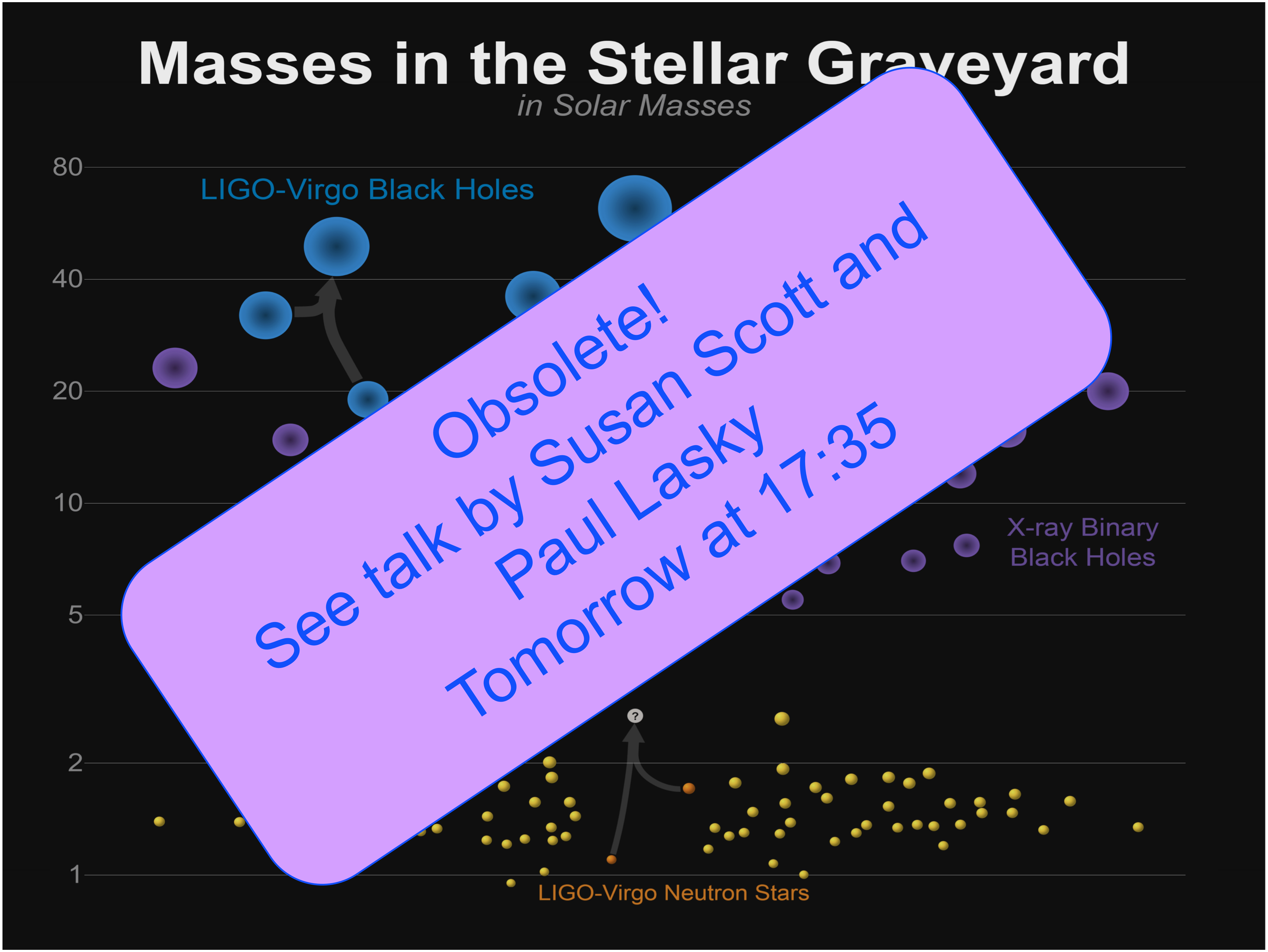
Multi-messenger Astronomy



LIGO and Virgo signed agreements with 95 groups for EM/neutrino followup of GW events

- ~200 EM instruments - satellites and ground based telescopes covering the full spectrum from radio to very high-energy gamma-rays
- Worldwide astronomical institutions, agencies and large/small teams of astronomers


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
X-ray Binary Black Holes
Known Neutron Stars
LIGO-Virgo Neutron Stars
?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X-ray Binary
Black Holes
LIGO-Virgo Neutron Stars
?
Obsolete!
See talk by Susan Scott and
Paul Lasky
Tomorrow at 17:35

LIGO Scientific Collaboration and Virgo Collaboration

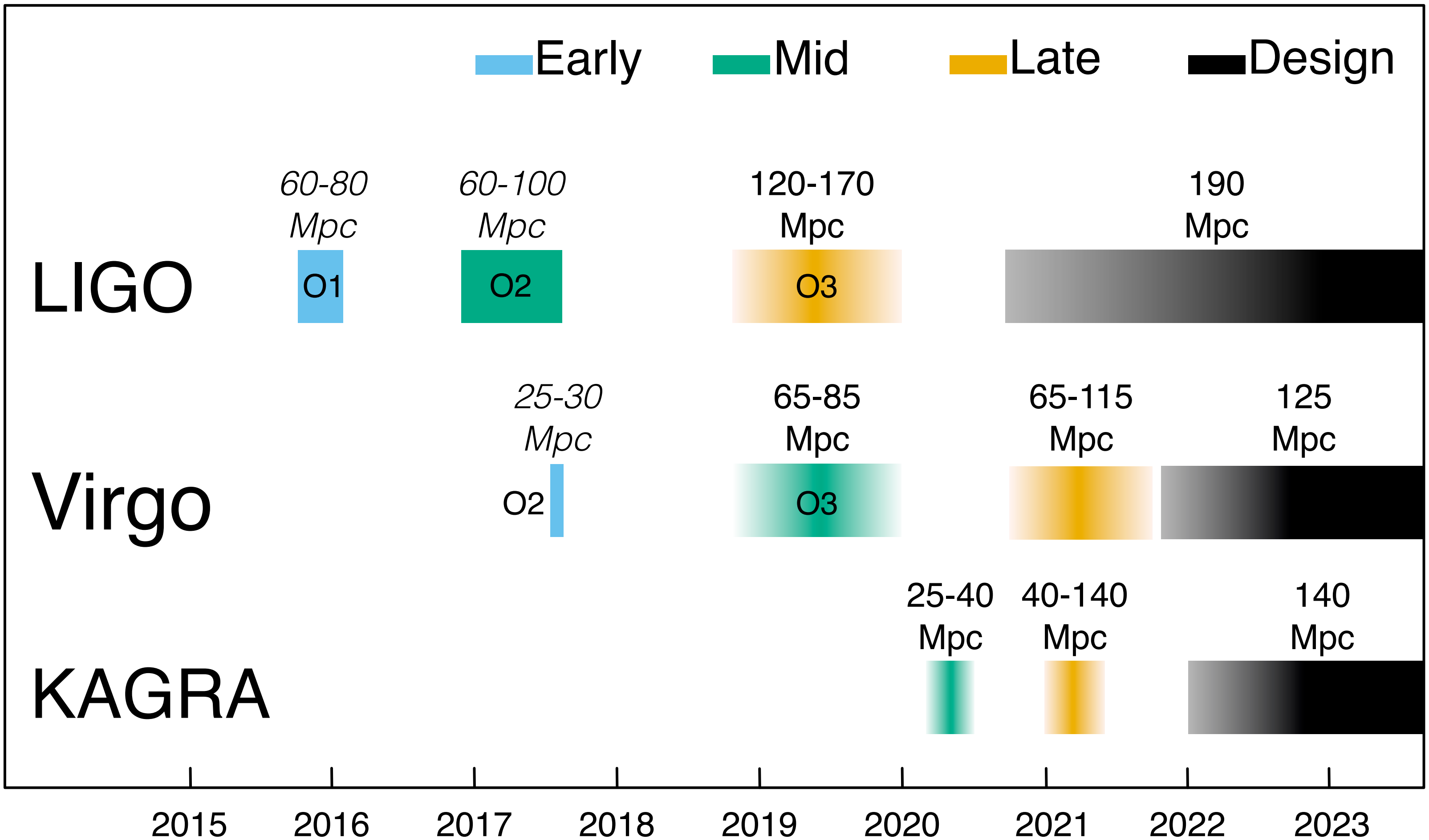
~1500 members, ~120 institutions, 21 countries

LIGO-G1802297

What does the future hold?

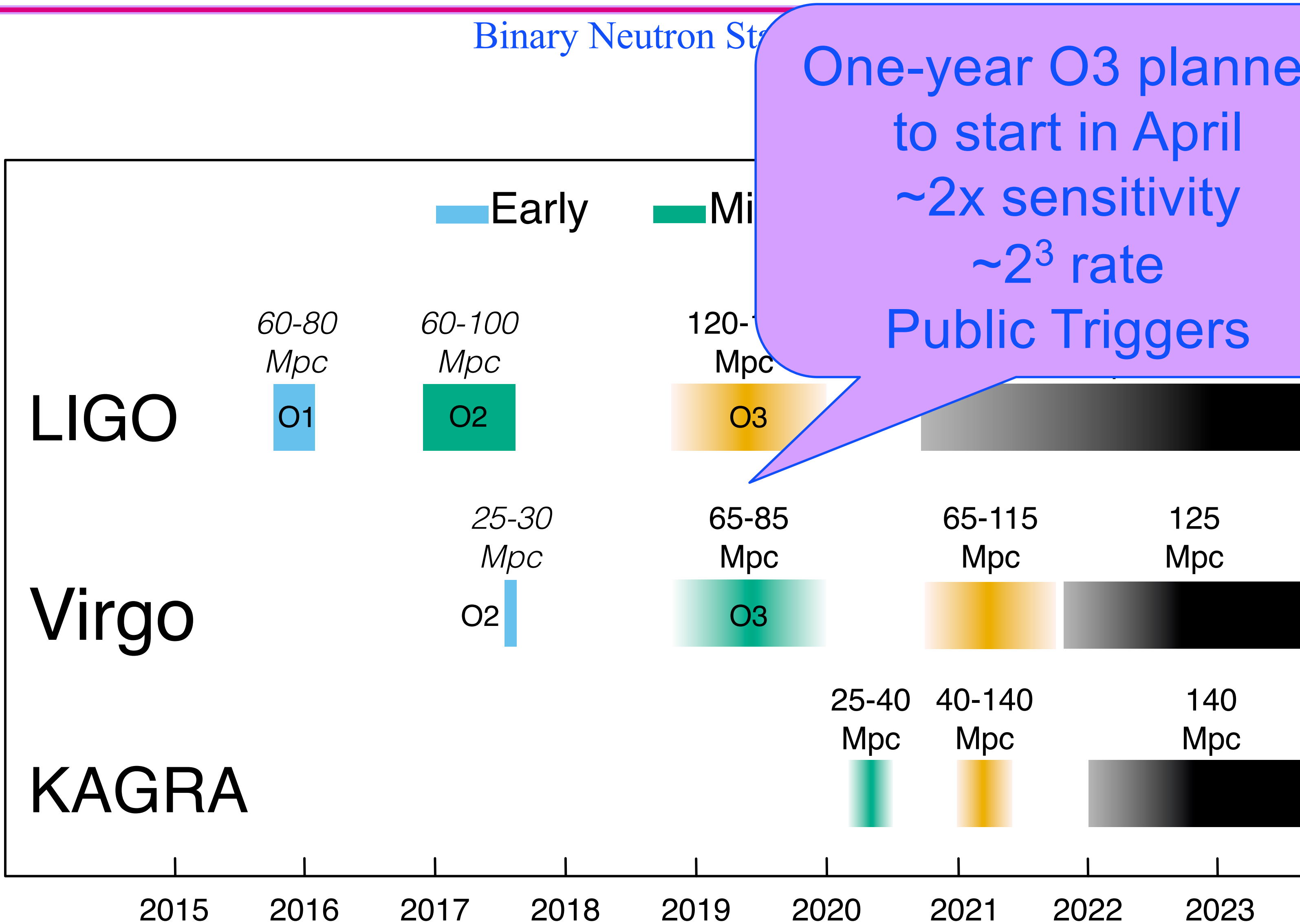
Planned Observing Timeline

Binary Neutron Star Range



B. P. Abbott et al., *Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA*, 2016, Living Rev. Relativity 19

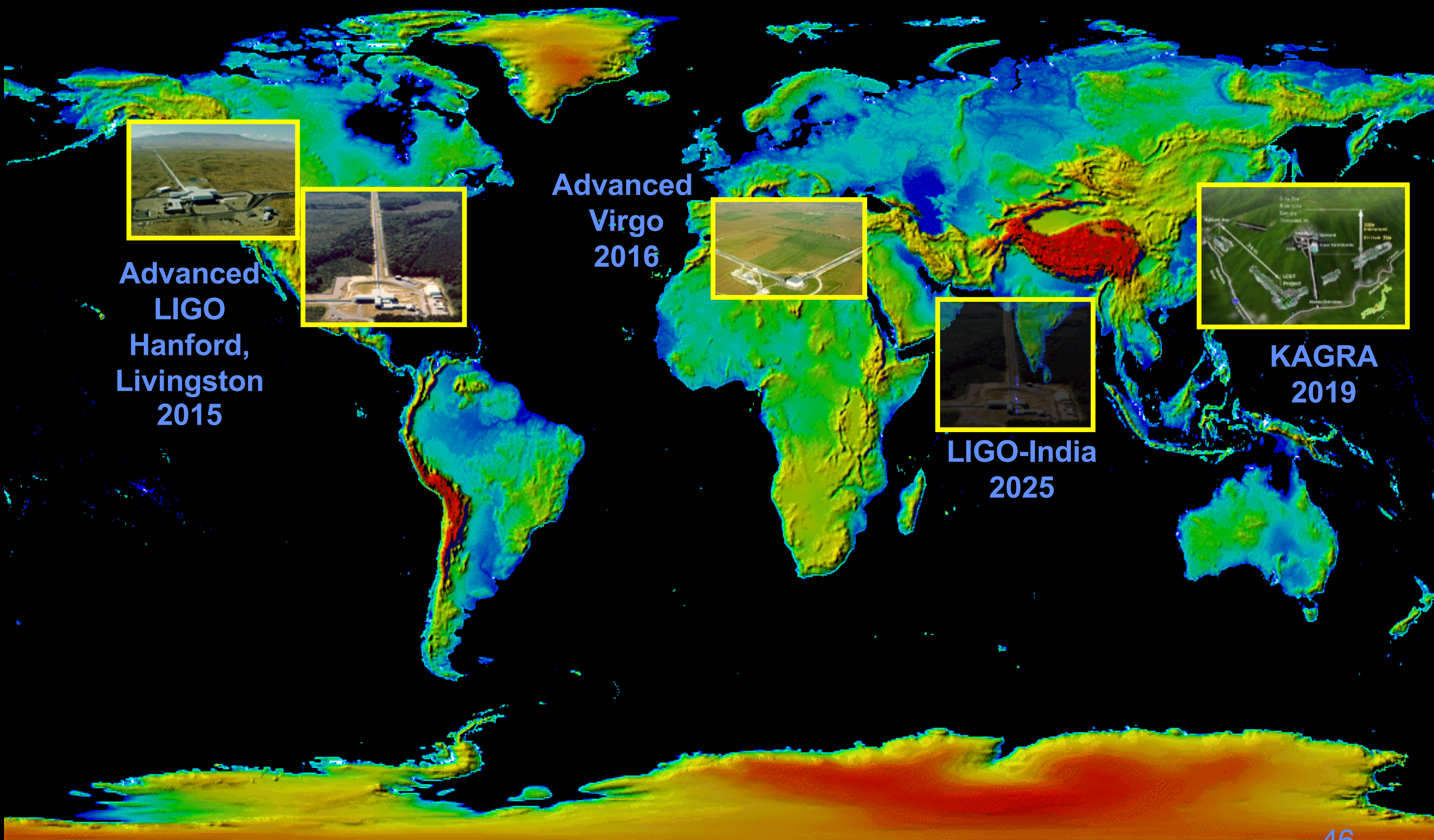
Planned Observing Timeline



One-year O3 planned to start in April
~2x sensitivity
$\sim 2^3$ rate
Public Triggers

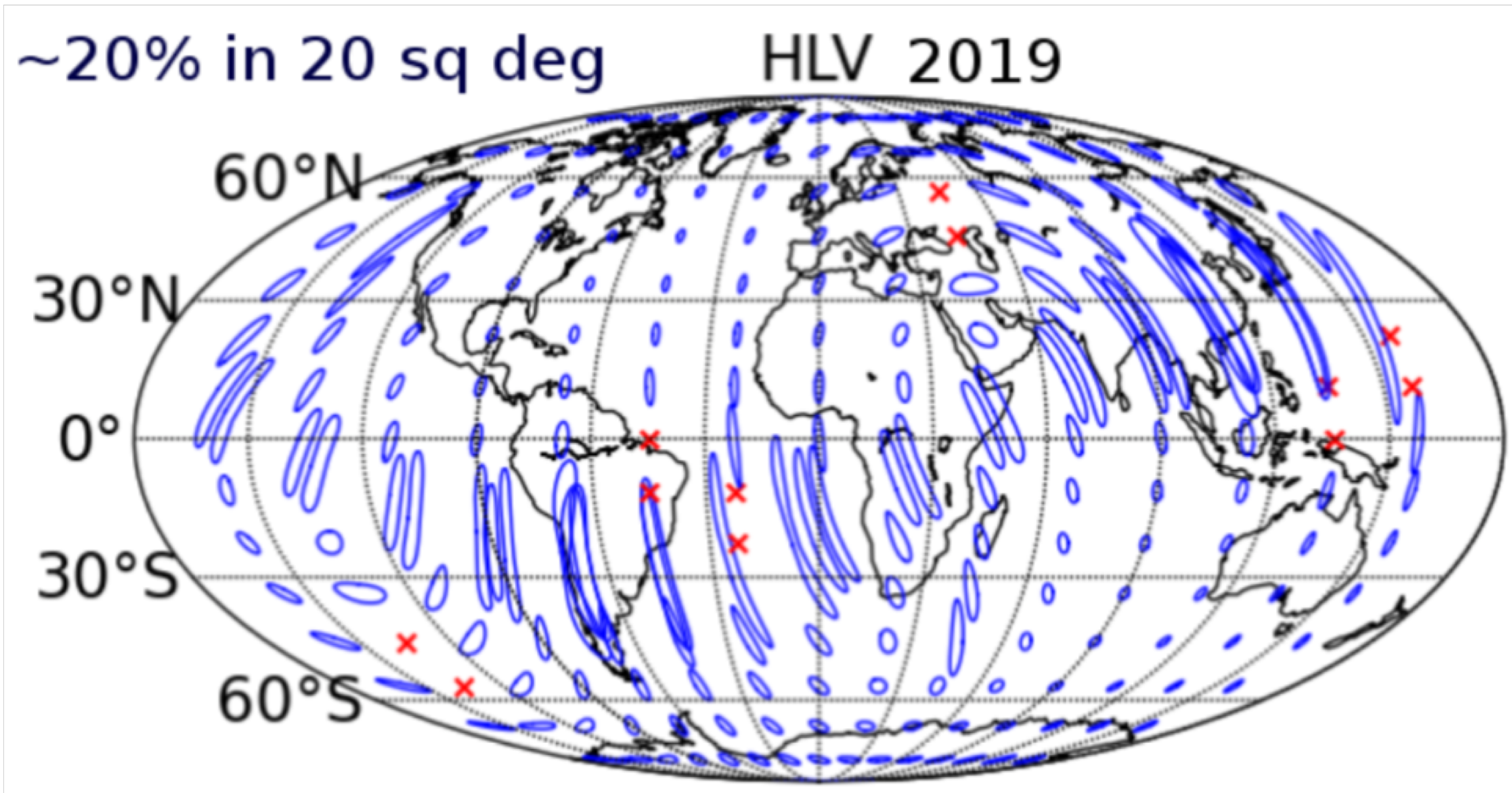
B. P. Abbott et al., *Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA*, 2016, Living Rev. Relativity 19

The advanced GW detector network



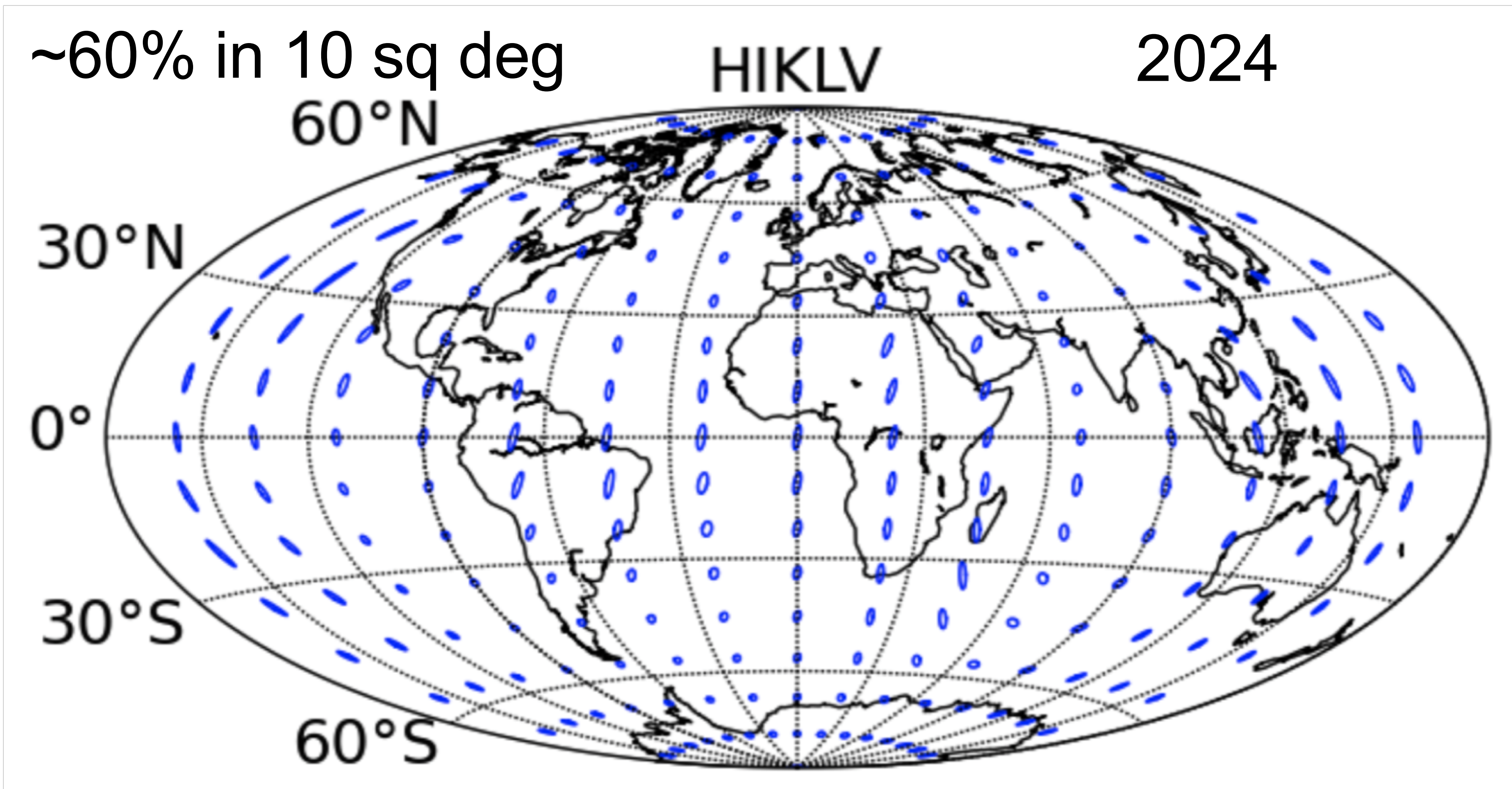
2018-19 Sensitivity/configuration:

3 detectors, perhaps
~1 signal per week



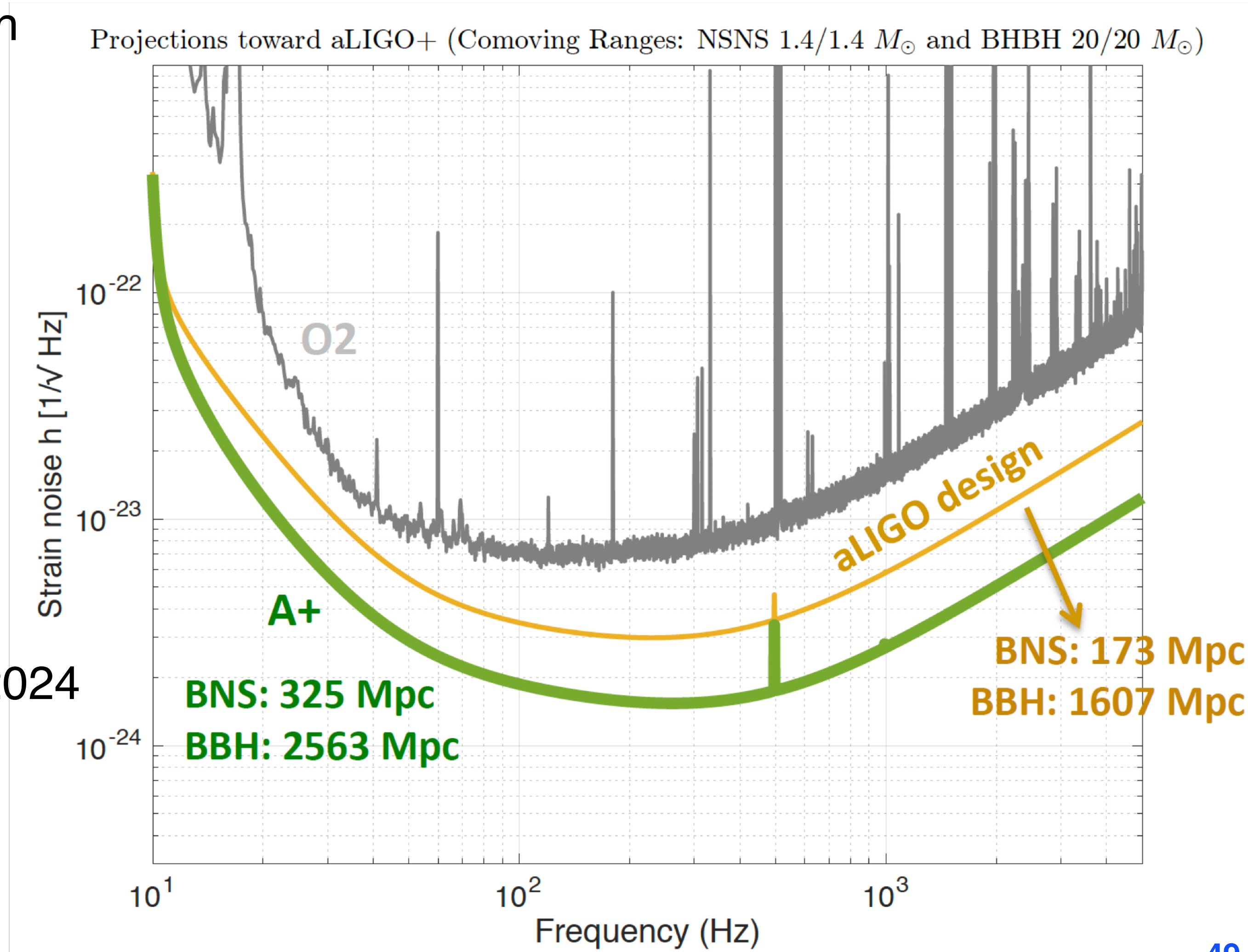
2025 Sensitivity/configuration:

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



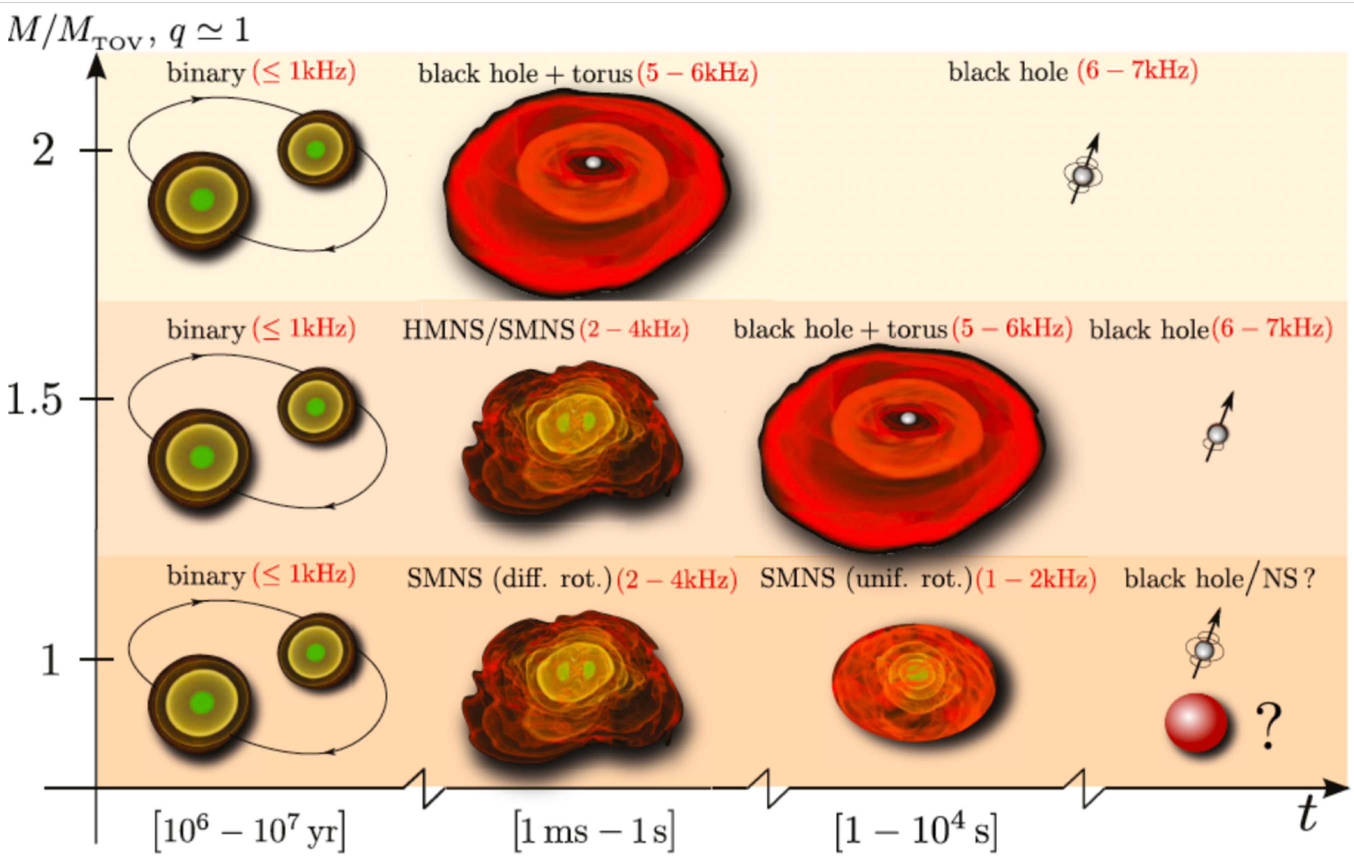
LIGO A+ Upgrade

- Incremental changes to the Advanced LIGO design
  - » Similar changes planned for Virgo
- Rough doubling of reach
  - » $2^3 = 8$ →
  - » 17-300 BBH/month
  - » 1-13 BNS/month
  - » 2-11 BNS x SGRB coincidences/year
- Population studies
- Hubble Constant
- Plan to be observing ~2024



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)

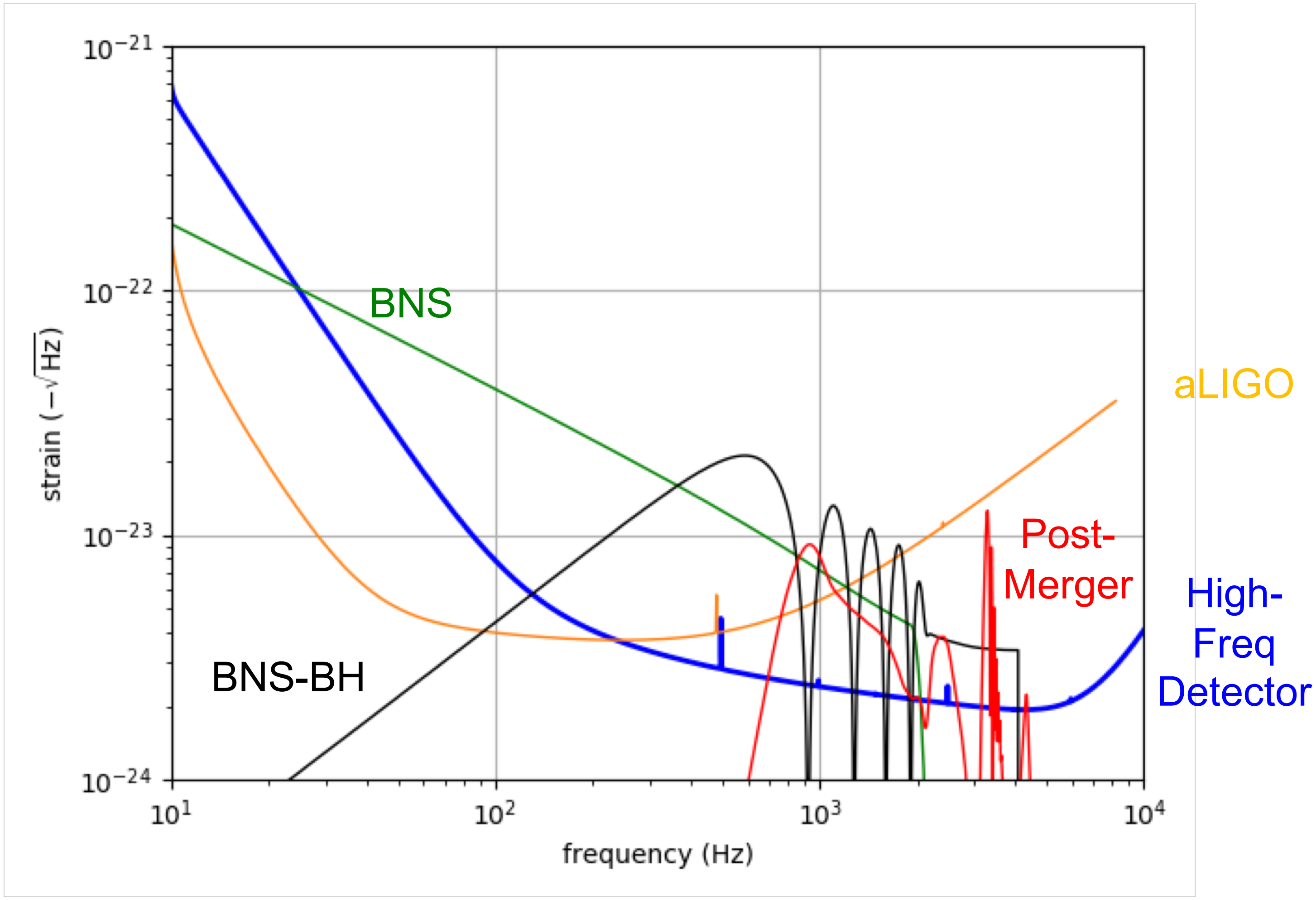
Oscillation mode (or GW) frequency is around 2kHz - 4kHz

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

Having EM counterpart (multi-messenger observation)

A ‘Neutron Star Explorer’

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

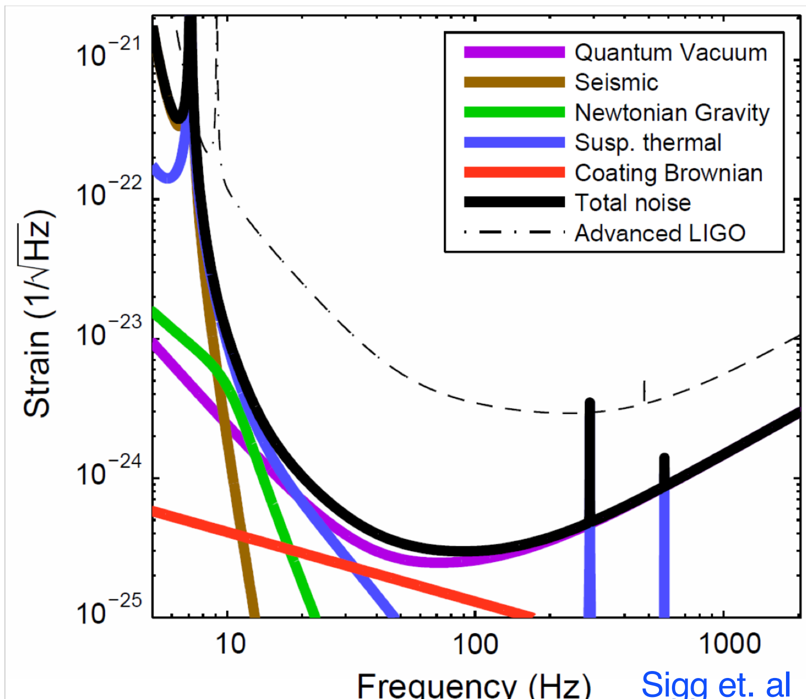


3G: Make Advanced LIGO 10x longer, 10x more sensitive, 1000x event rate

Signal grows with length – ***not*** most noise sources

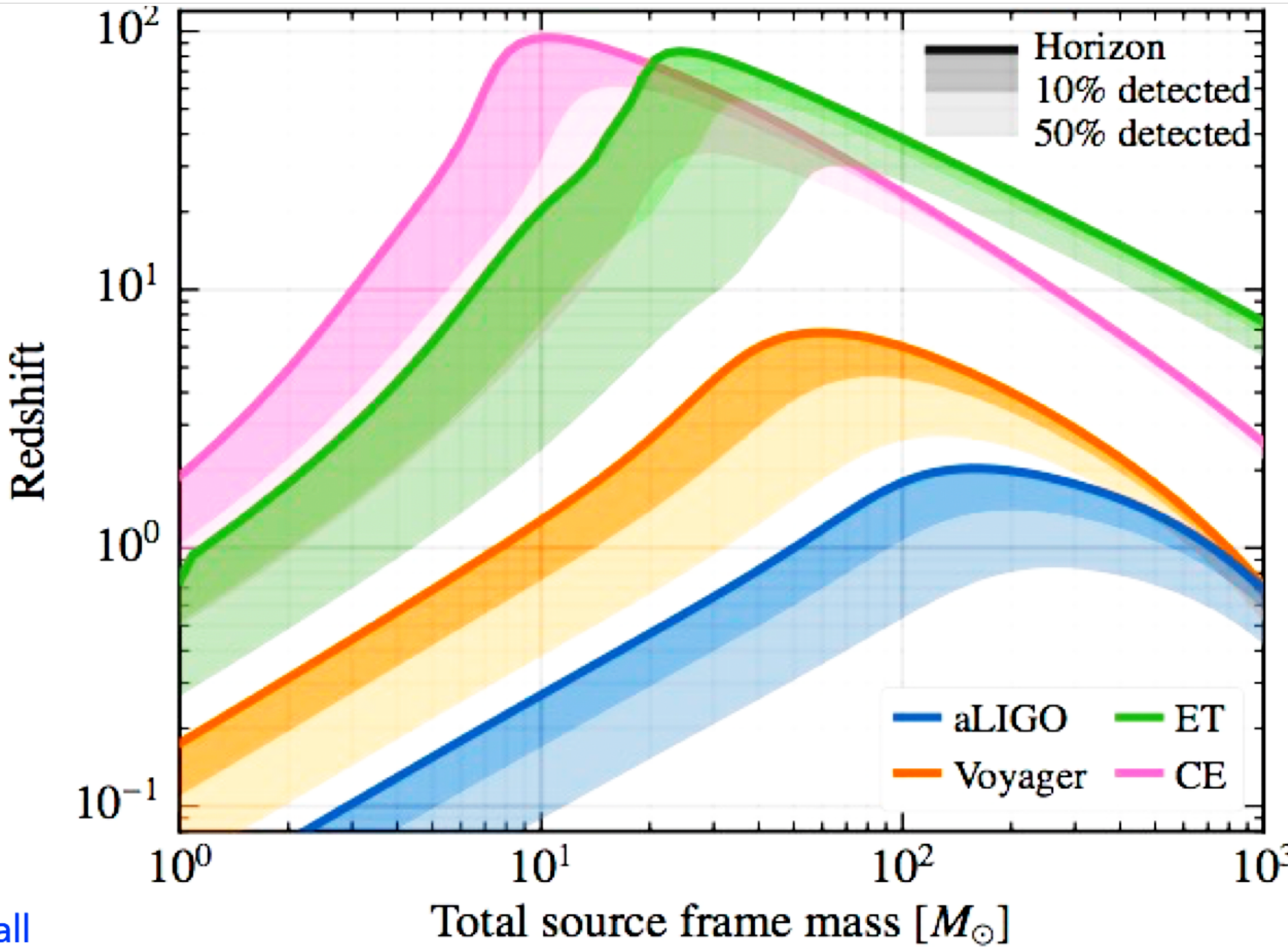
- Thermal noise, radiation pressure, seismic, Newtonian unchanged
- Coating thermal noise improves faster than linearly with length
- 40km surface Observatory ‘toy’ baseline
  - can still find sites, earthmoving feasible; costs another limit…
- Concept offers sensitivity without new measurement challenges; could start at room temperature, modest laser power, etc.

	Adv. LIGO	**40 km LIGO**
Arm length	4 km	40 km
Beam radius	6.2 cm	11.6 cm
Measured squeezing	none	5 dB
Filter cavity length	none	1 km
Suspension length	0.6 m	1 m
Signal recycling mirror trans.	20%	10%
Arm cavity circulating power	775 kW	
Arm cavity finesse	446	
Total light storage time	200 ms	2 s



Sigg et. al

Reach of 3G detectors for BH: Edge of the universe

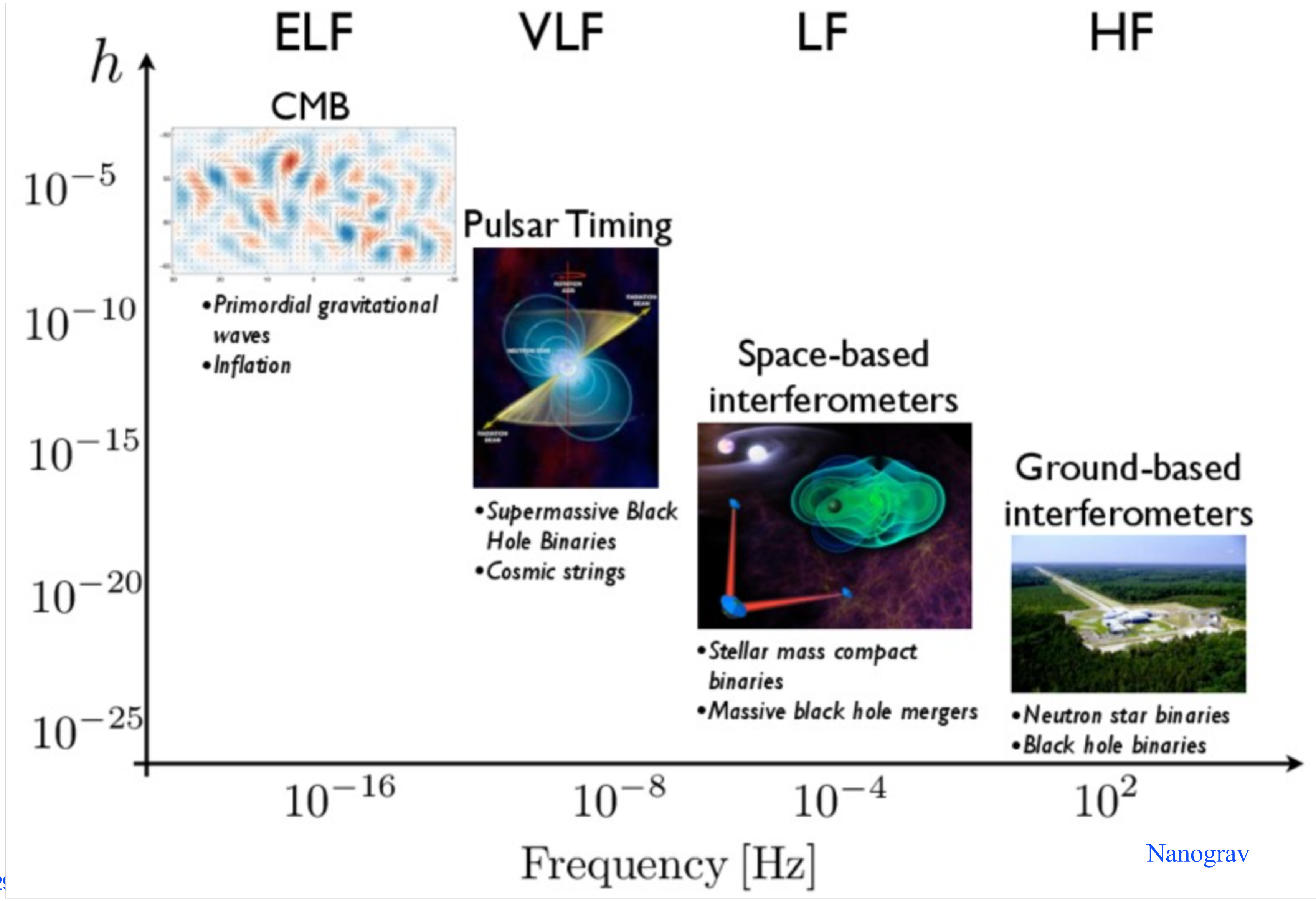


Evan Hall

3rd Generation

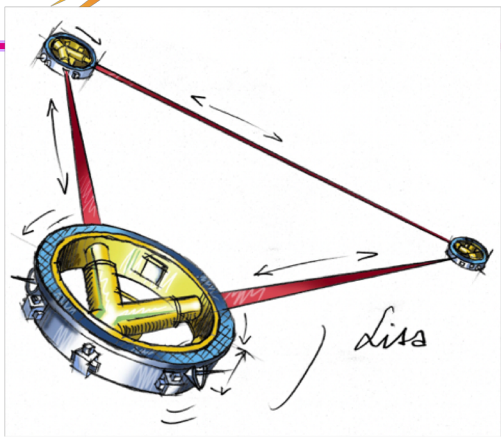
- When could this new wave of ground instruments come into play?
- Appears 15 years from *t*=0 is a feasible baseline
  - » Initial LIGO: 1989 proposal, and at design sensitivity 2005
  - » Advanced LIGO: 1999 White Paper, GW150914 in 2015
- **Modulo funding, could envision 2030's**
- Should hope – and 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
  - » GWIC – Gravitational-Wave International Committee '3G subcommittee' producing a careful study for early 2020
- **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
  - » Events like GW170817 help!

Broad spectrum of GW sources

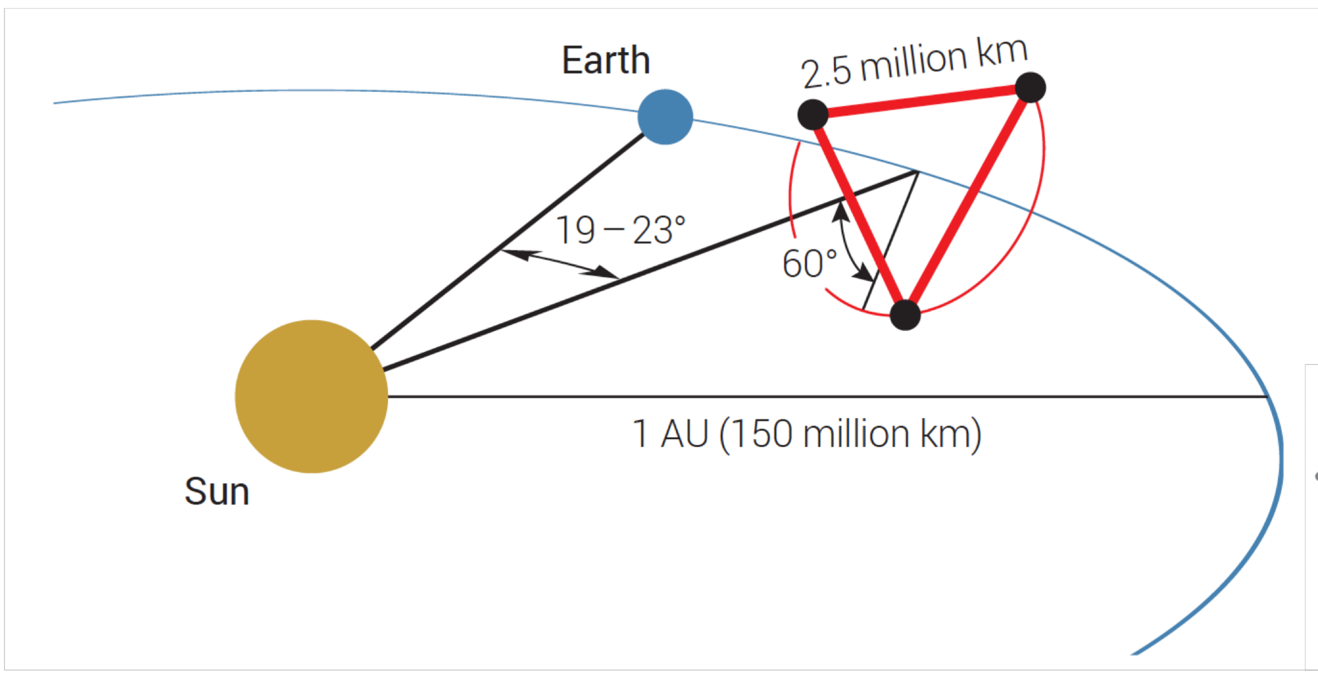


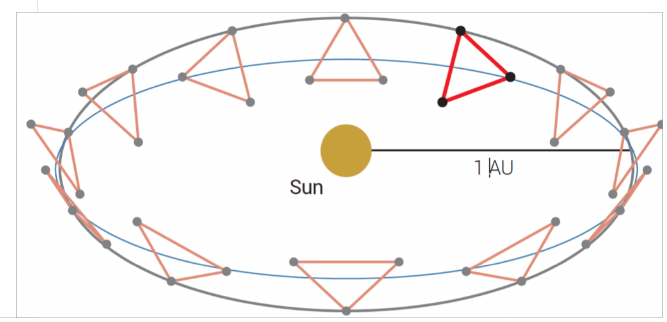
Nanograv

LISA, targeting super-massive Black Holes



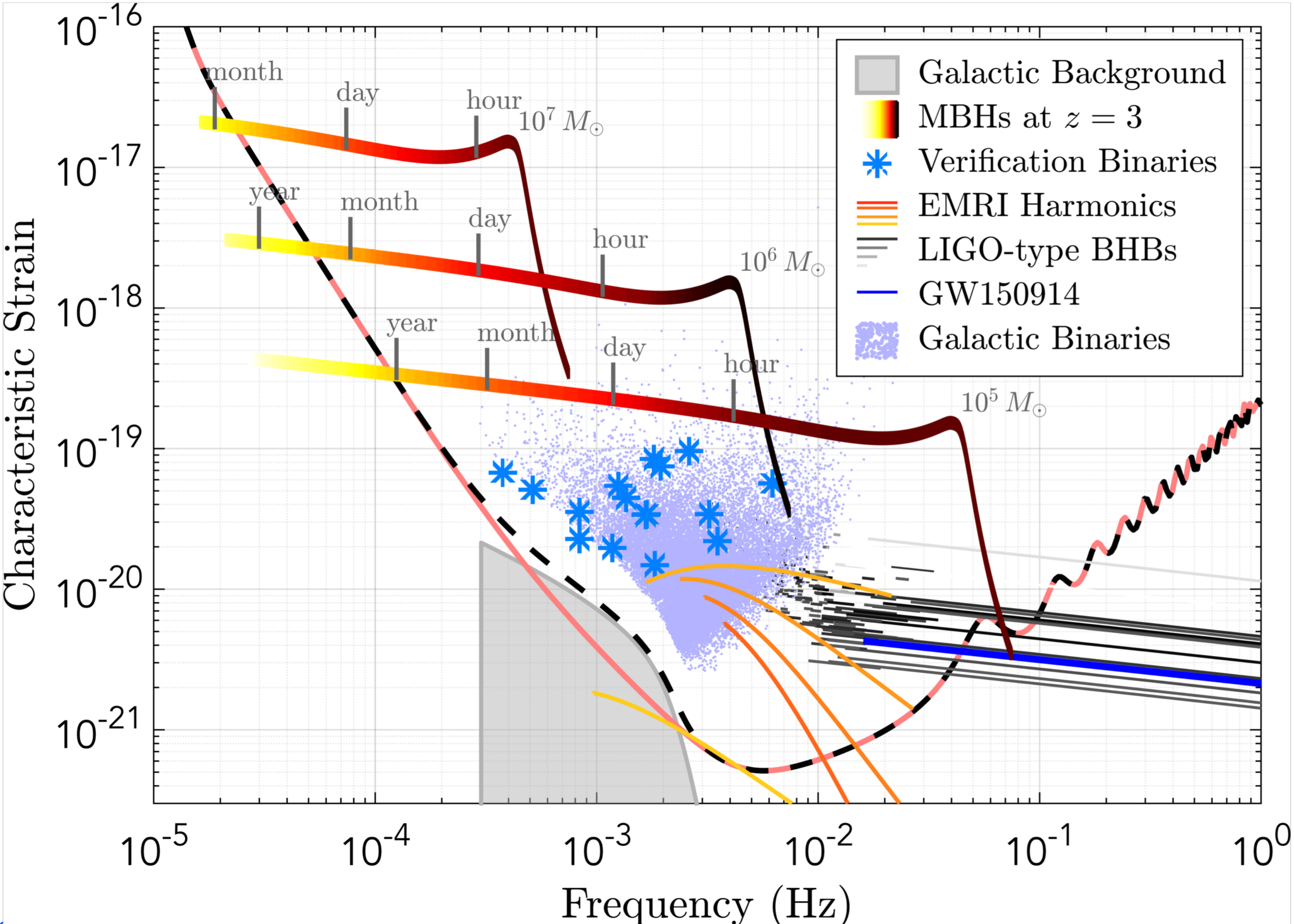
- 2.5x10^6 km arms: moves best sensitivity to 0.01 Hz, target masses to 10^6 solar masses
- 'Slave' the shield satellites to follow the test masses, protecting against solar wind etc.
- Orbit scans sky; sources last years, viewed from 2AU baseline
- Launch in the early 2030's





Credit: LISA L3 Mission Concept Proposal

LISA Astrophysics



Credit: LISA L3 Mission Concept Proposal

Just the beginning of a new field – new instruments, new discoveries, new synergies

Milliseconds	Minutes to Hours	Years to Decades	Billions of Years
LIGO/Virgo	LISA	Pulsar Timing Array	Cosmology Probes