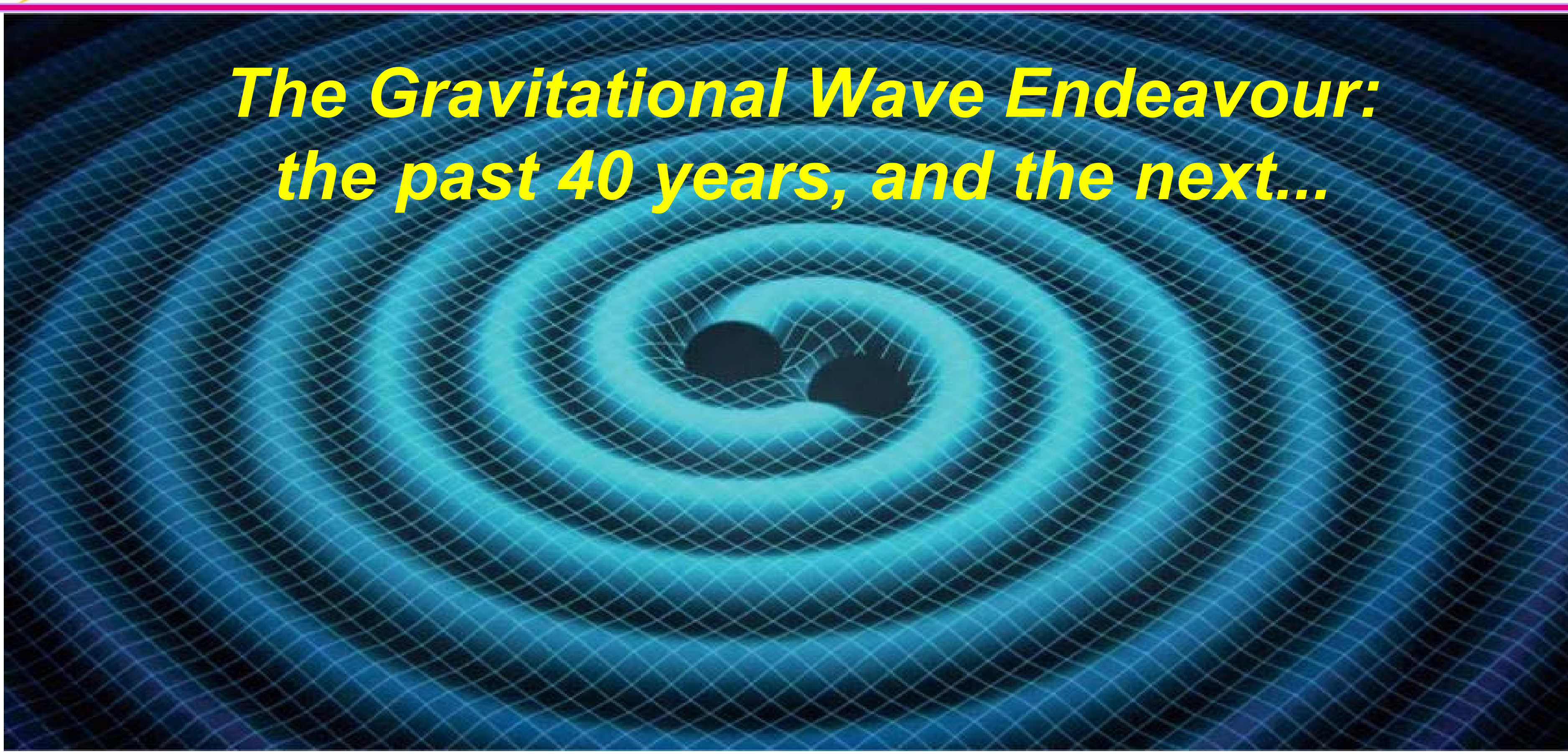
The Gravitational Wave Endeavour: the past 40 years, and the next...



Stan Whitcomb

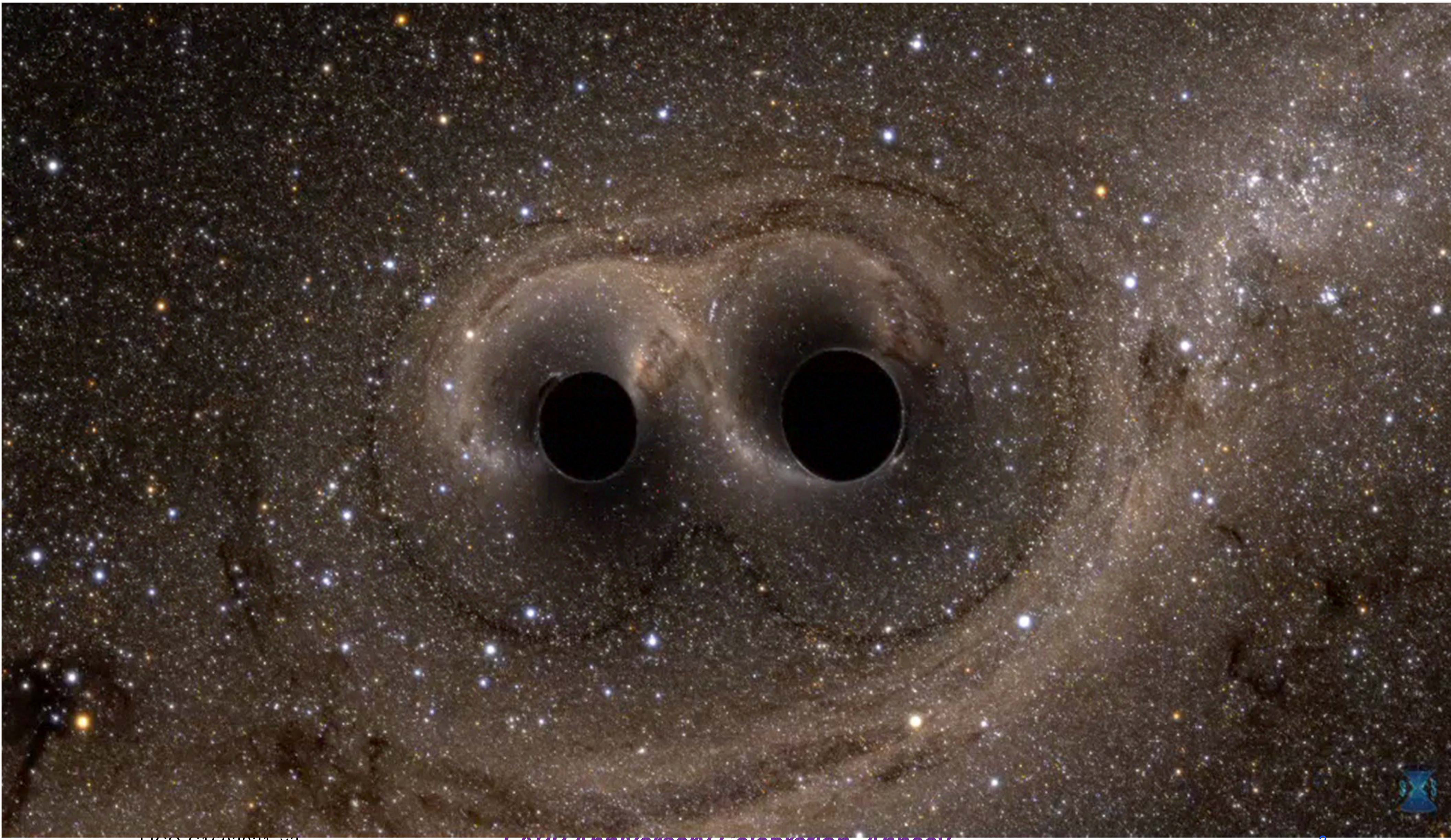
For the LIGO Scientific Collaboration and the Virgo Collaboration

LAPP Anniversary Celebration, Annecy

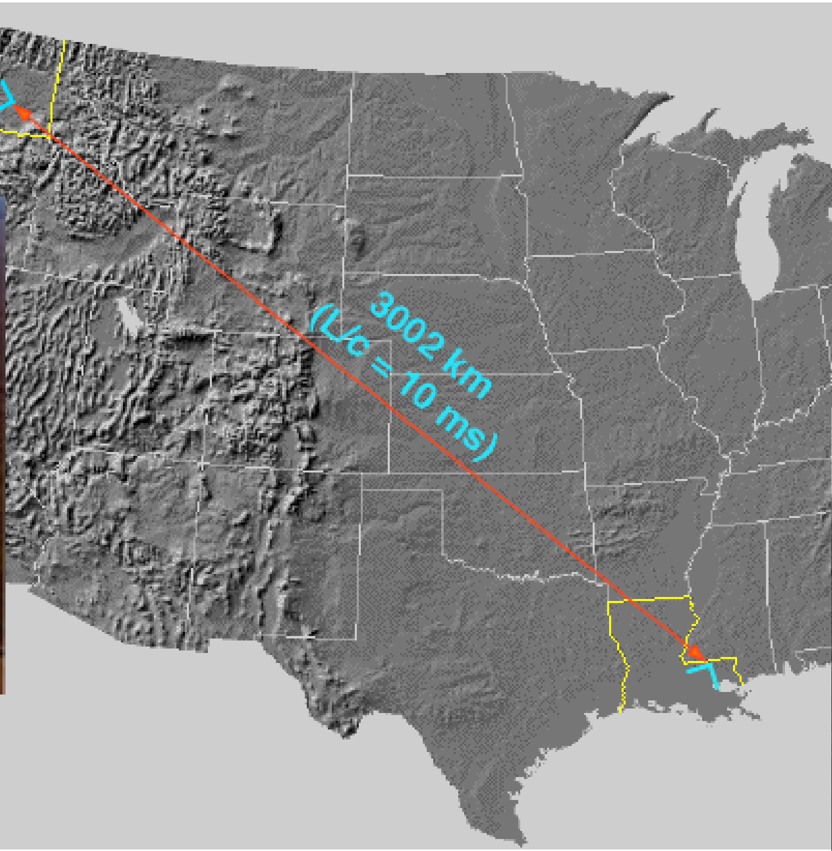
14 October 2016

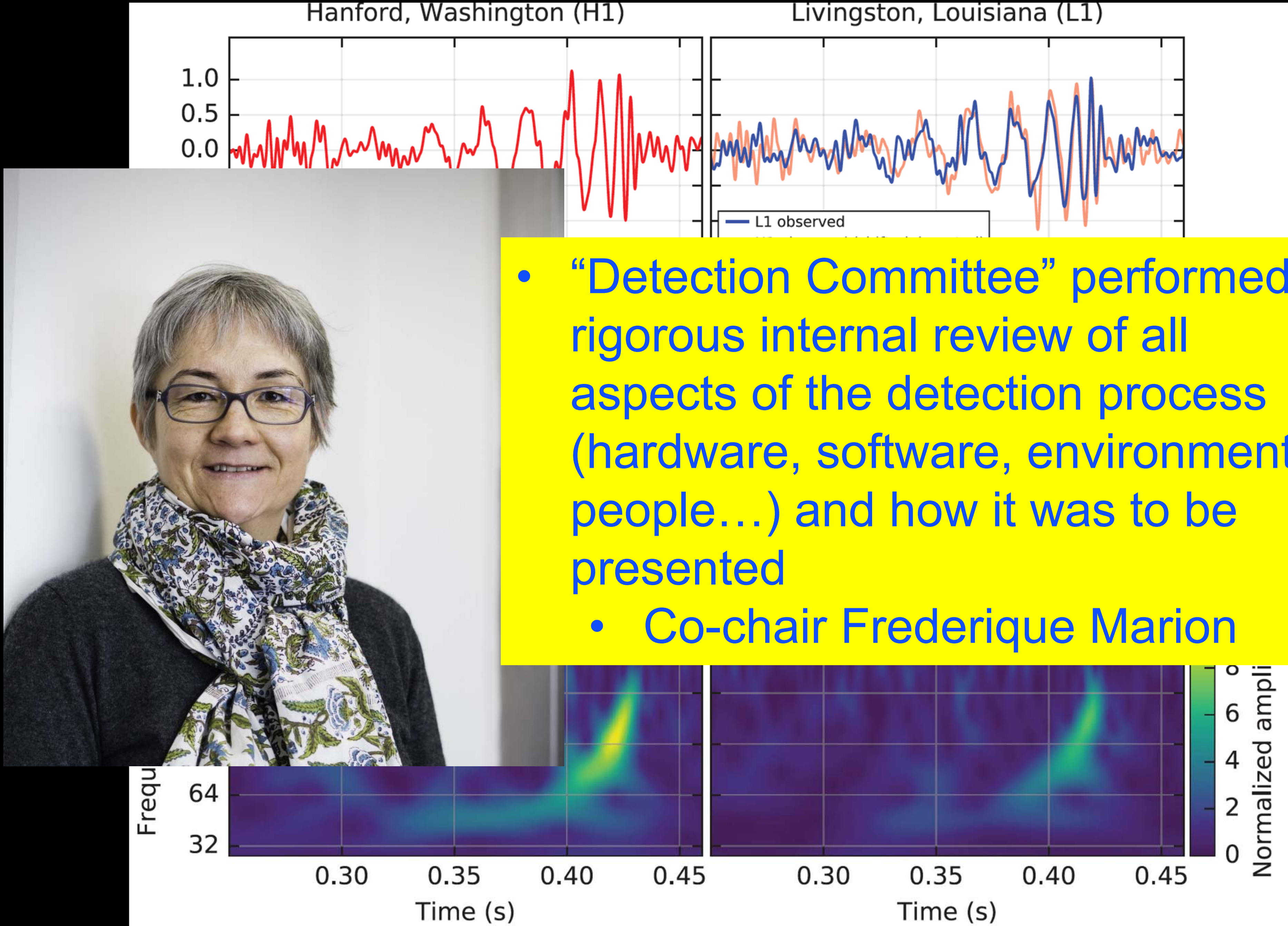
LIGO-G1602021-v2

1.3 Billion years ago, in a distant galaxy…



Then on 14 September 2015, at the LIGO sites…





- "Detection Committee" performed rigorous internal review of all aspects of the detection process (hardware, software, environment, people…) and how it was to be presented
  - Co-chair Frederique Marion

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)

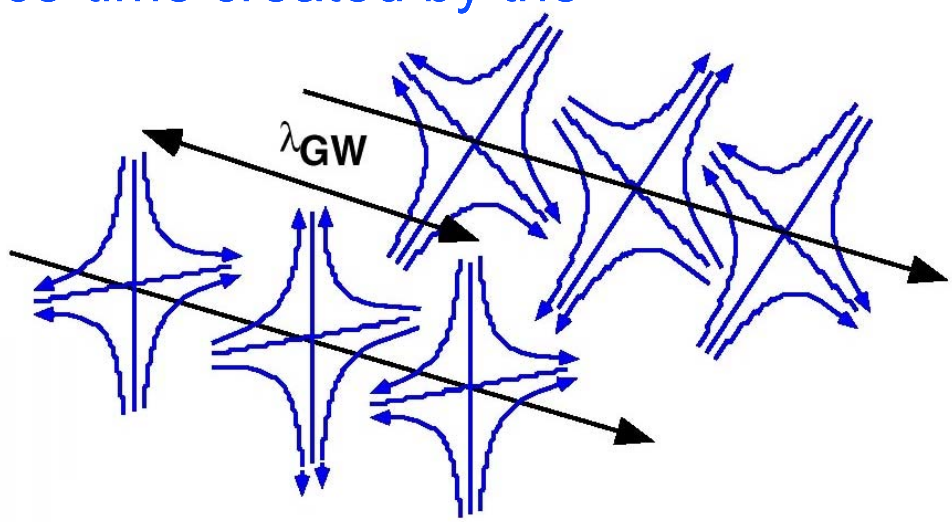
Outline/Points of Emphasis

- History
  - » What are the physical effects of a gravitational wave?
  - » Why is this appropriate for a particle physics lab?
- Detectors
  - » How do they work?
  - » Challenges
- The Future
  - » Detector and Network Development
  - » Future Physics and Astronomy

Gravitational Wave Basics

- Einstein (in 1916) first derived gravitational waves in his General Theory of Relativity
  - » Necessary consequence of Special Relativity with its finite speed for information transfer
  - » Most distinctive departure from Newtonian theory
- Time-dependent distortions of space-time created by the acceleration of masses
  - » Propagate away from the sources at the speed of light
  - » Pure transverse waves
  - » Two orthogonal polarizations

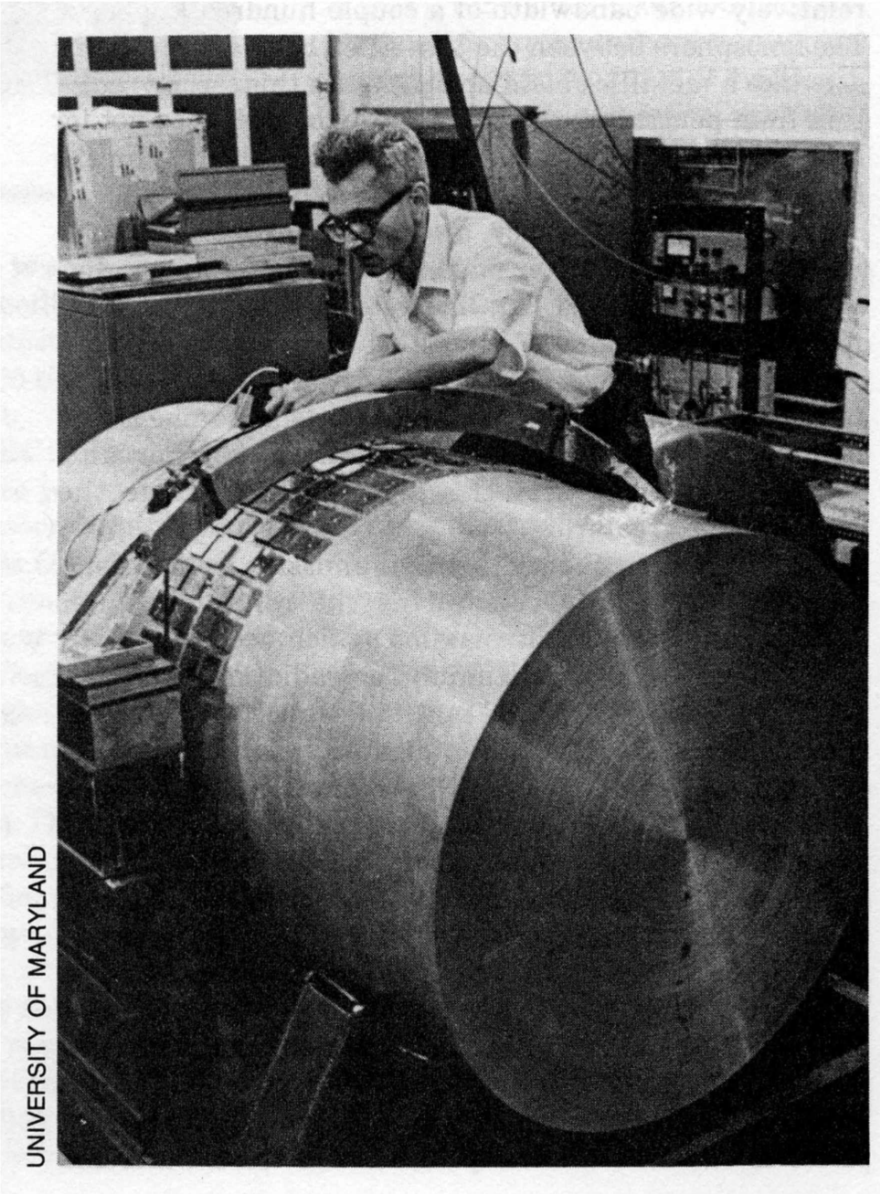
$$h = 2\Delta L / L$$



- Weakness of gravity means there is no feasible way to generate detectable gravitational waves, must rely on astrophysical sources

The First Detectors

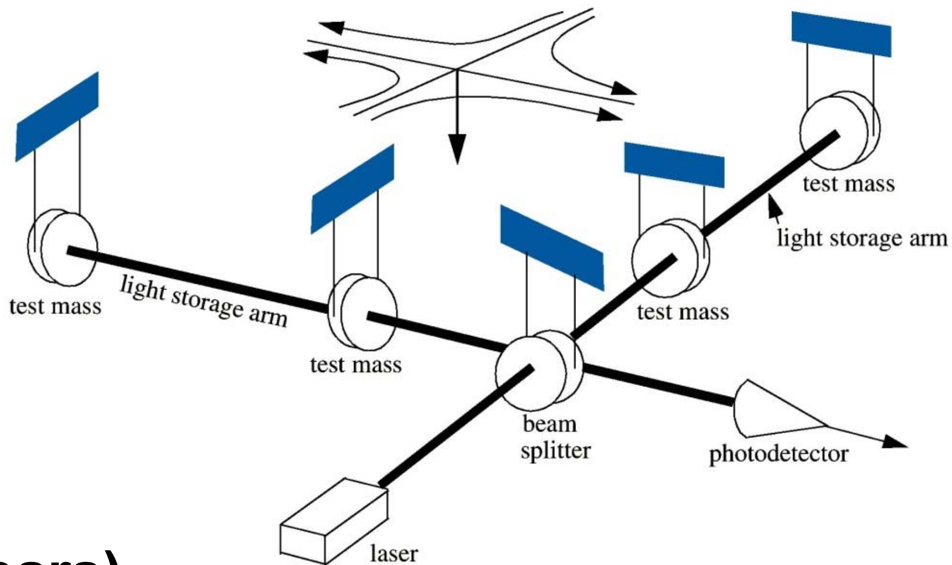
- Einstein's view that the waves would never have any practical role in physics prevailed until the early 1960's
- Joseph Weber conceived and built his first bar detectors
  - » Announced in 1969 that he had seen evidence for gravitational waves
- At least 19 different bar detectors (in 8 countries) were built and used in searches
  - » None were able to confirm Weber's claim
- Weber's work triggered wide interest
  - » Theoretical studies of sources
  - » Alternate methods of detection



In the mid-1970s, a New Method of Detecting GWs with Interferometry

$$\Delta L = hL / 2$$

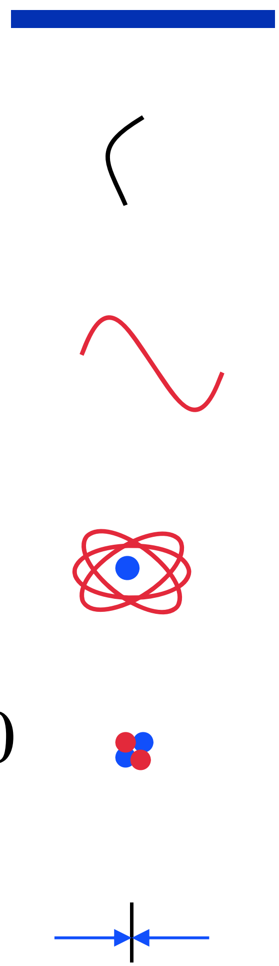
Suspended mirrors act as "freely-falling" test masses in horizontal plane for frequencies $f >> f_{pend}$



For a 3-4 km long detector,
$h \sim 10^{-22} - 10^{-21}$
$\Rightarrow \Delta L \sim 10^{-18}$ m
(~1/1000 diameter of proton)

Inherently broadband (unlike bars),
Terrestrial bandwidth 10 Hz - 10 kHz,
determined by "unavoidable" noise
(at low frequencies) and expected maximum
source frequencies (high frequencies)

How Small is 10^{-18} Meter?



One meter

÷10,000 — **Human hair ~ 10^{-4} m (0.1 mm)**

÷100 — **Wavelength of light ~ 10^{-6} m**

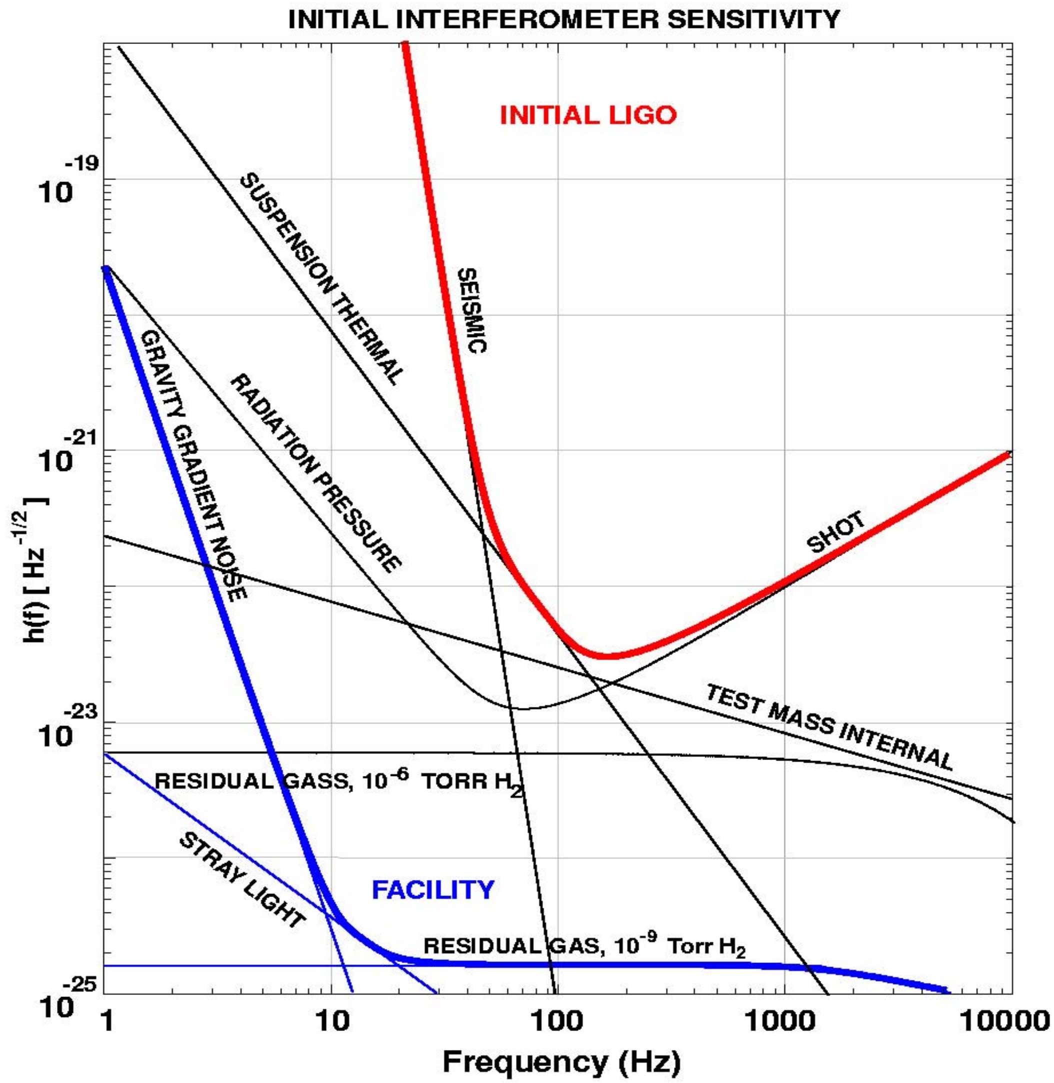
÷10,000 — **Atomic diameter 10^{-10} m**

÷100,000 — **Nuclear diameter 10^{-15} m**

÷1,000 — **GW detector 10^{-18} m**

10^{-12}

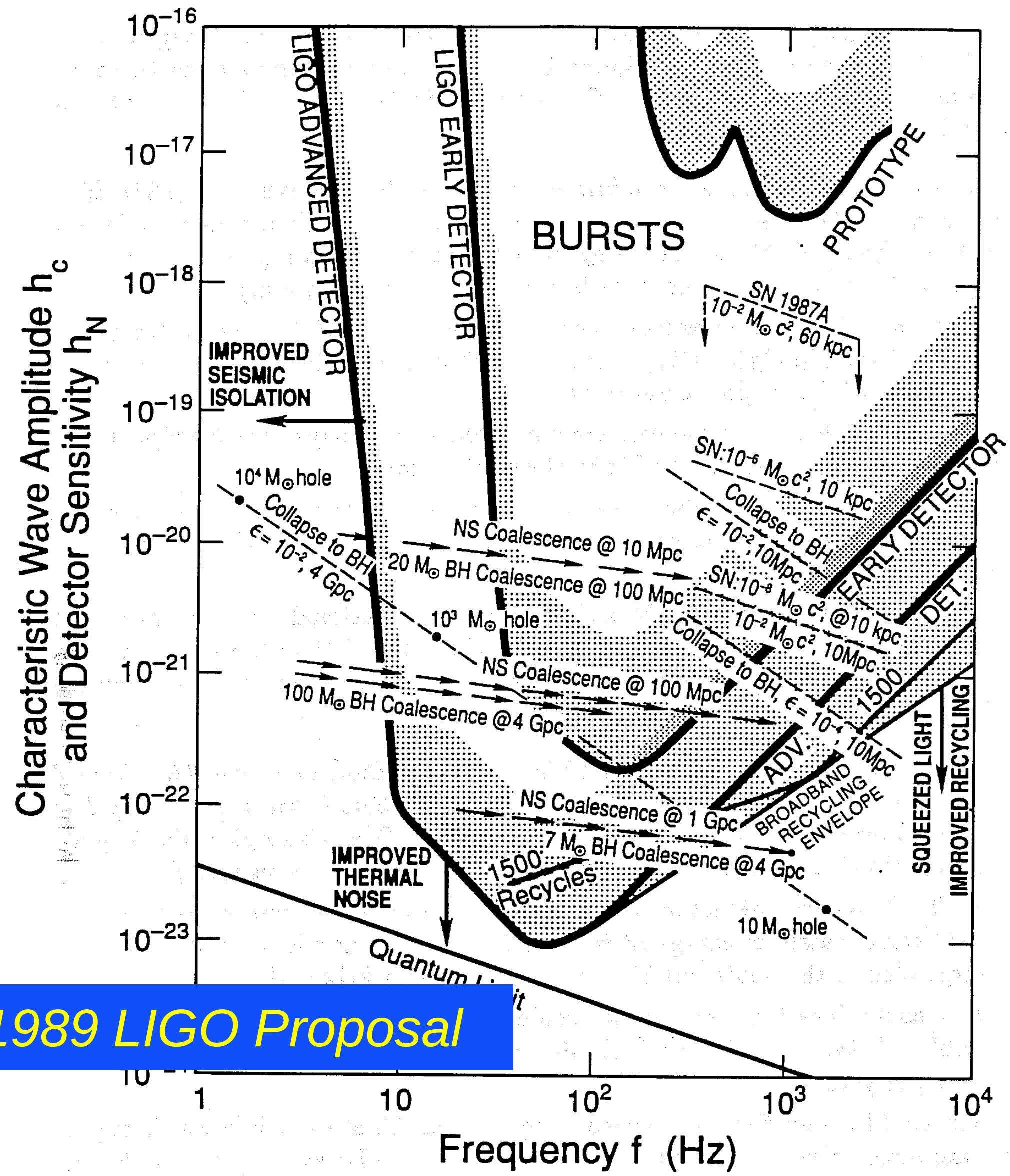
1980's: Developed Understanding of Noise Sources and Designed Large Facilities



- Strain sensitivity <3x10^{-23} 1/Hz$^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

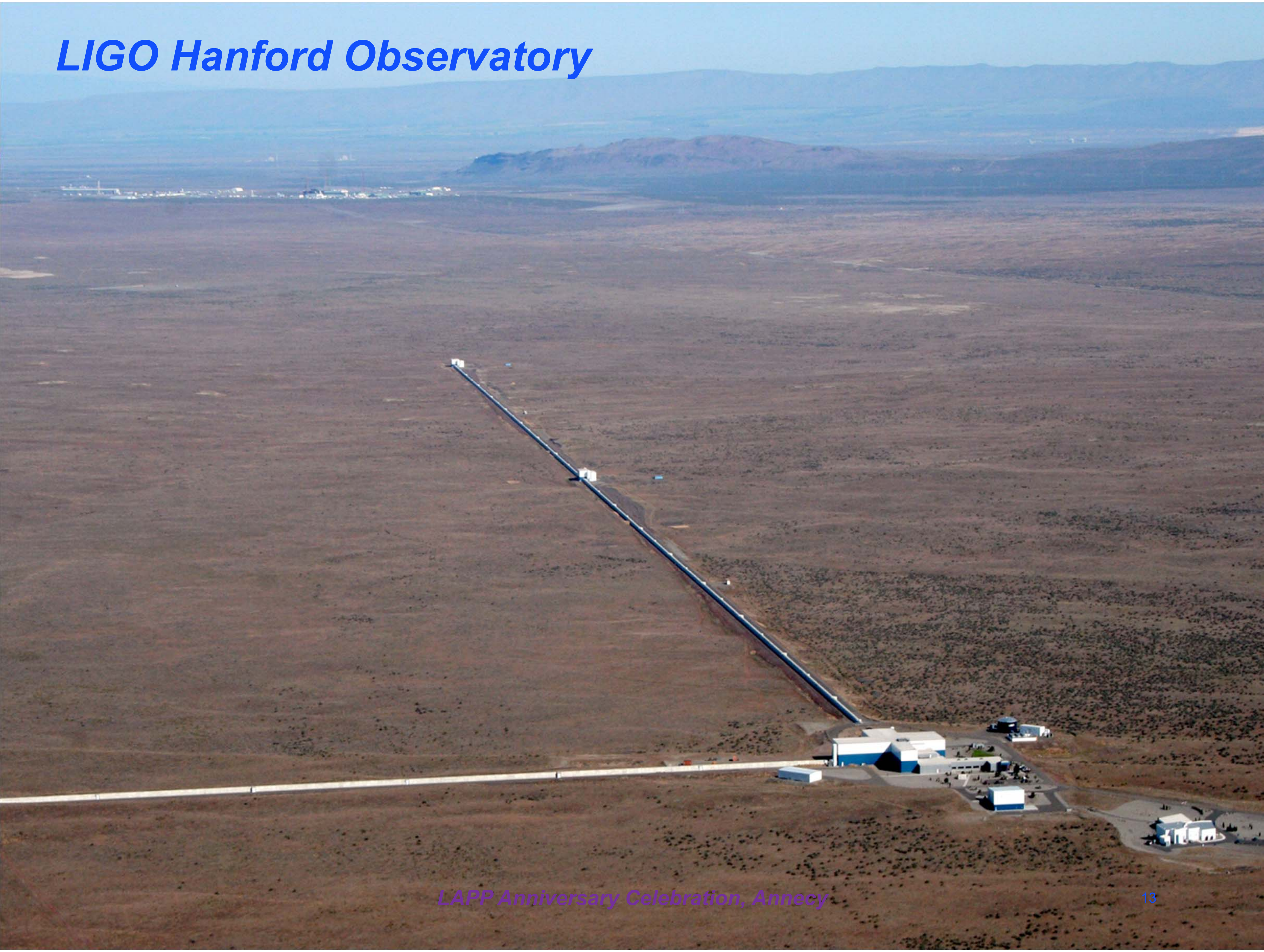
~1990: Full-Scale Construction Proposals in US, UK, Germany, Italy, France

- Bold proposals, considering the cost and timescale for success
- Recognized that detectors would evolve and improve
- *Remarkable* vision and braveness of laboratory directors, university leaders, and government funding agencies



1989 LIGO Proposal

LIGO Hanford Observatory

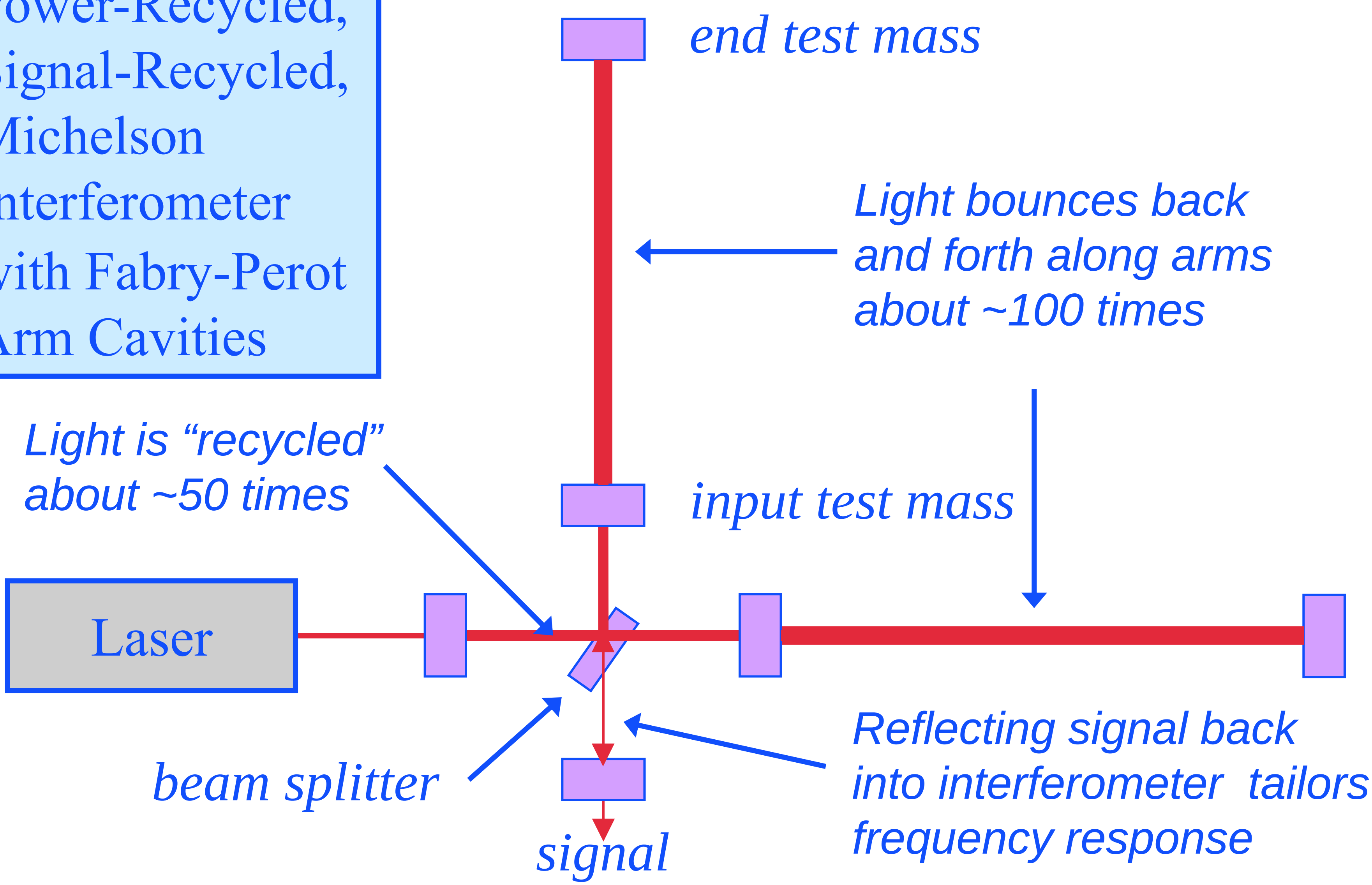


The Virgo Interferometer

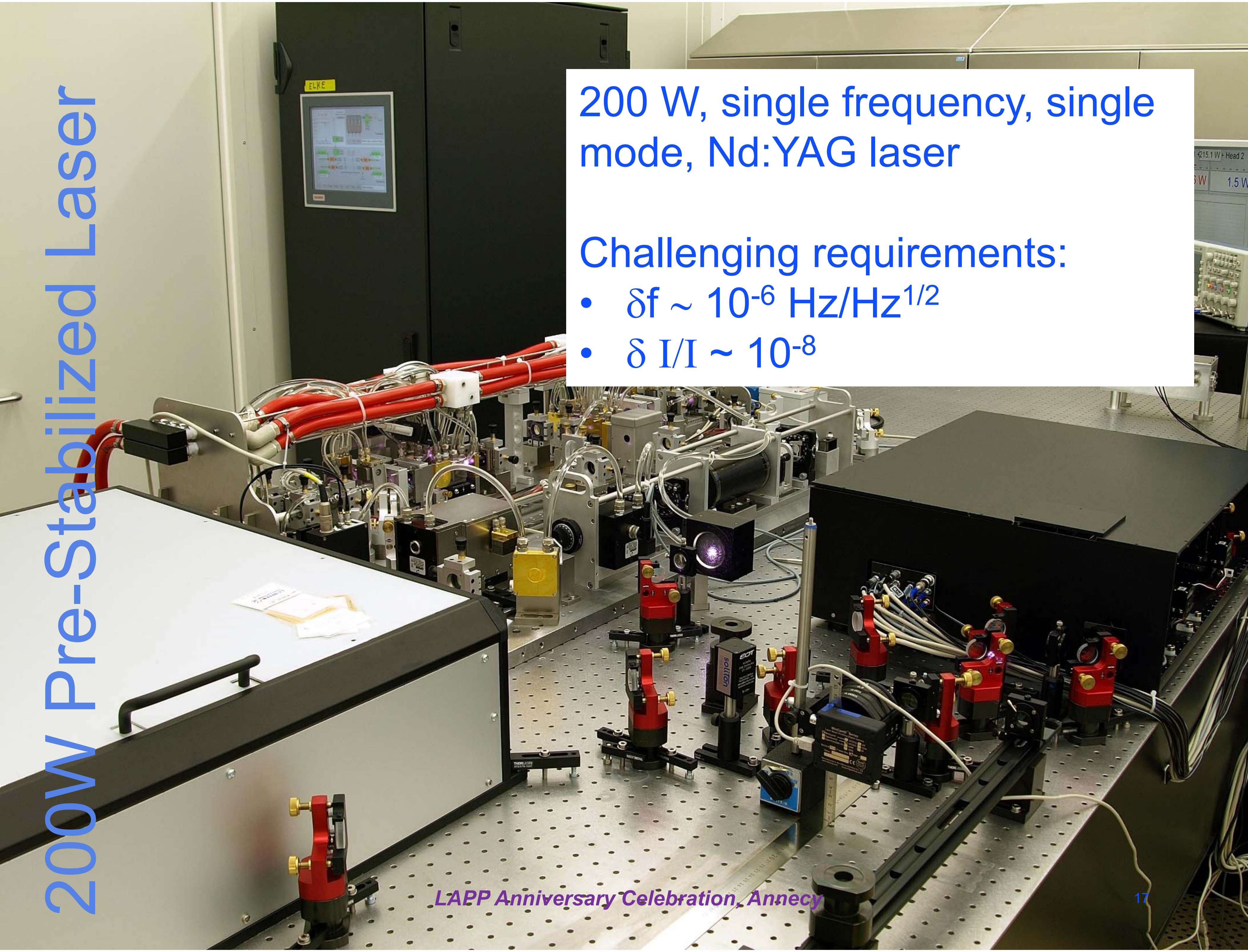
The Detectors

Basic (LIGO/Virgo) Interferometer Configuration

Power-Recycled, Signal-Recycled, Michelson Interferometer with Fabry-Perot Arm Cavities



200W Pre-Stabilized Laser

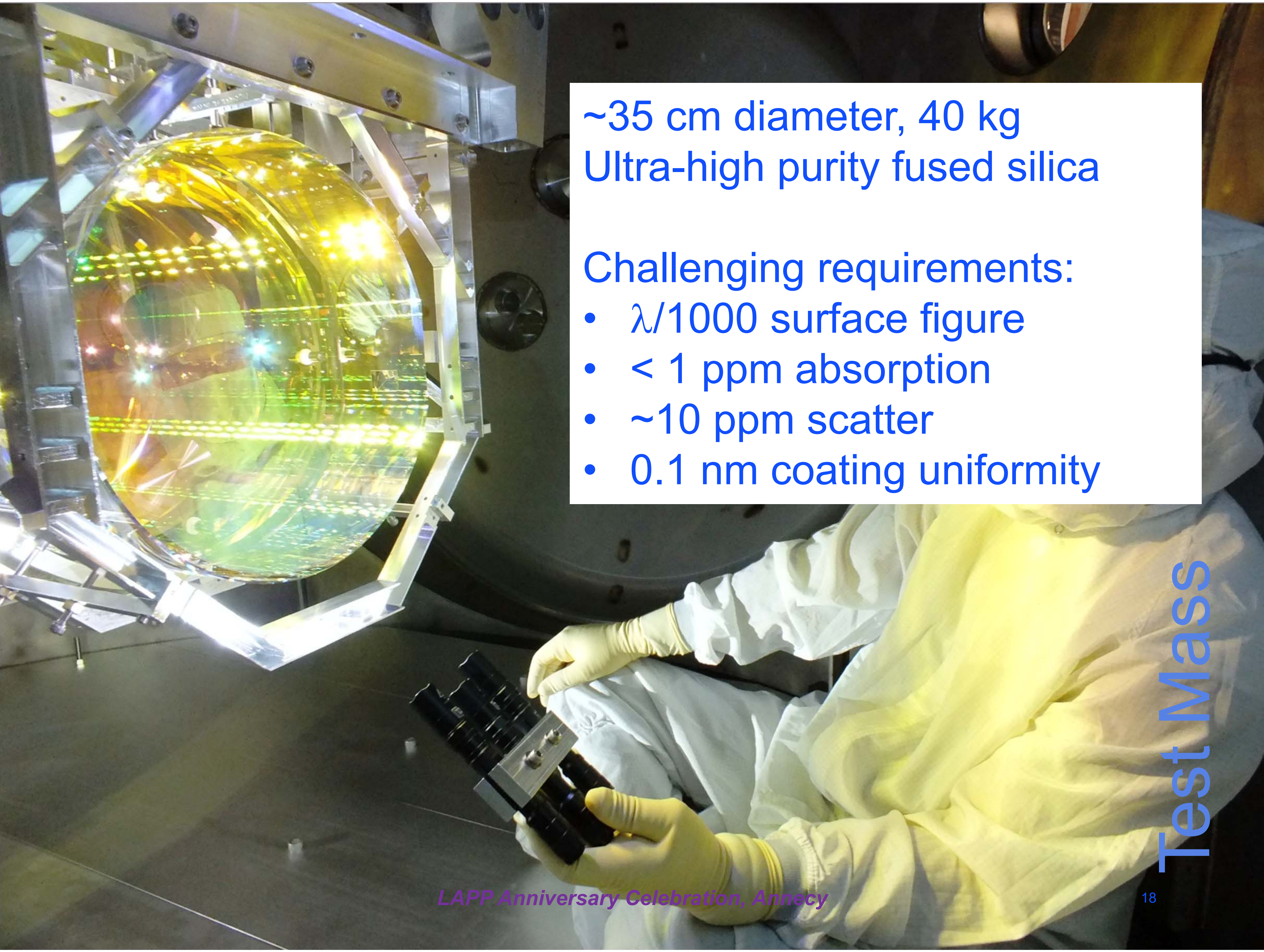


200 W, single frequency, single mode, Nd:YAG laser

Challenging requirements:

- $\delta f \sim 10^{-6}$ Hz/Hz$^{1/2}$
- $\delta I/I \sim 10^{-8}$

Test Mass



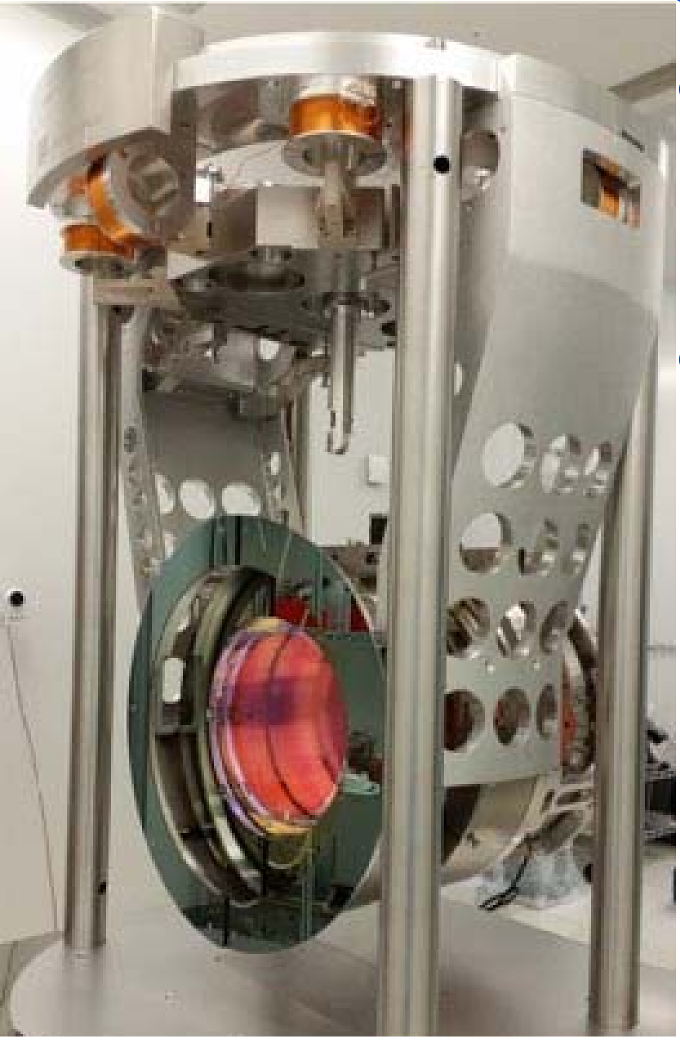
~35 cm diameter, 40 kg
Ultra-high purity fused silica

Challenging requirements:

- $\lambda/1000$ surface figure
- < 1 ppm absorption
- ~10 ppm scatter
- 0.1 nm coating uniformity

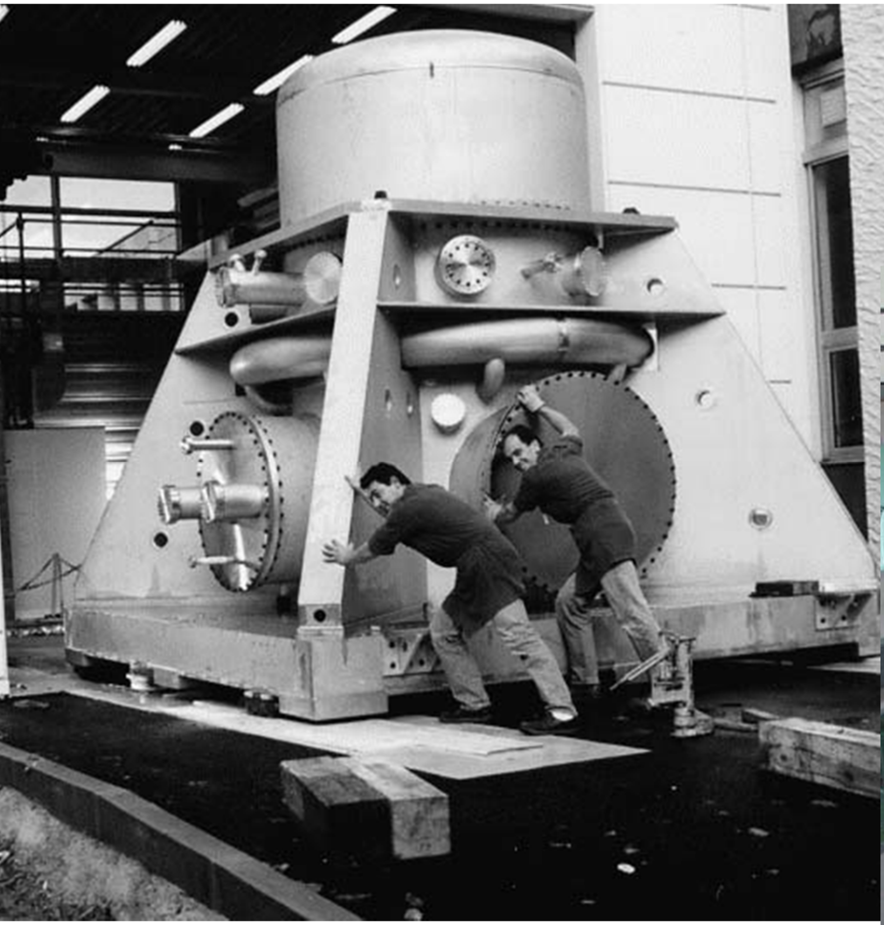
Mirror Suspension

- Multi-stage isolation system for attenuating ground noise



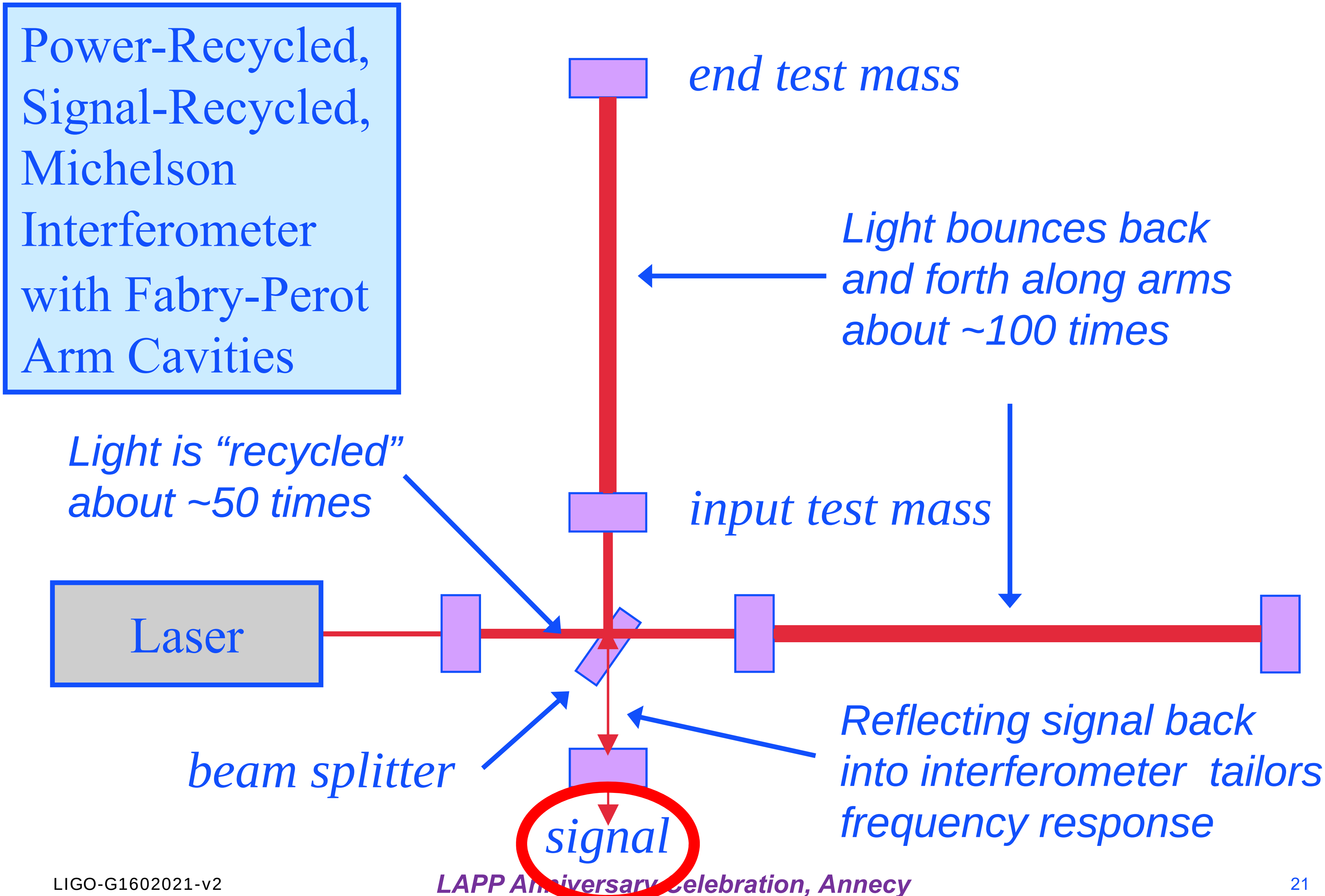
- Completely eliminates all ground motion
- Low thermal noise final suspension stage

Vacuum Chambers

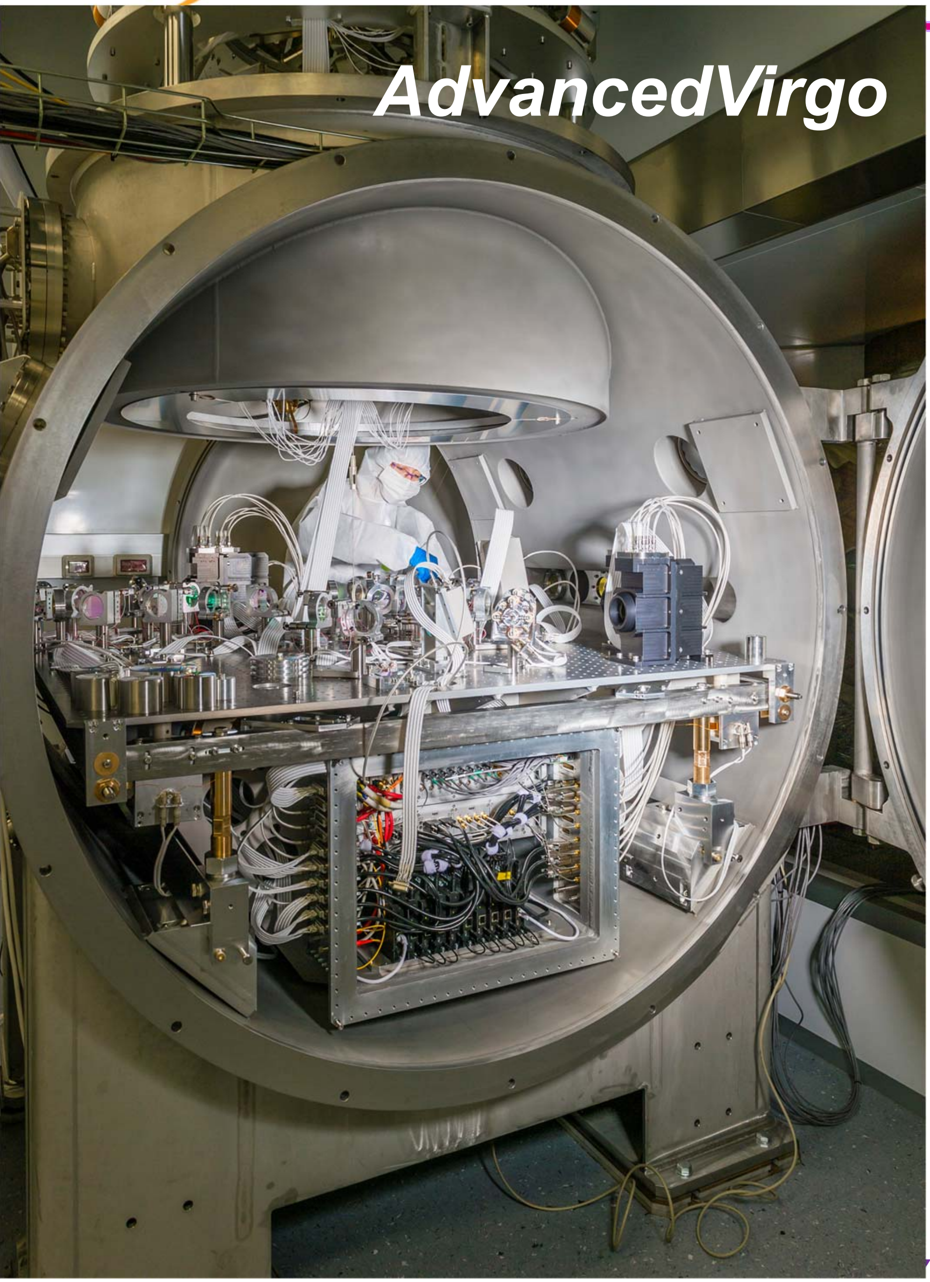


- Provided to Virgo by LAPP
  - » Along with mirror installation procedures and fixtures

Schematic Interferometer vs. Real Interferometer

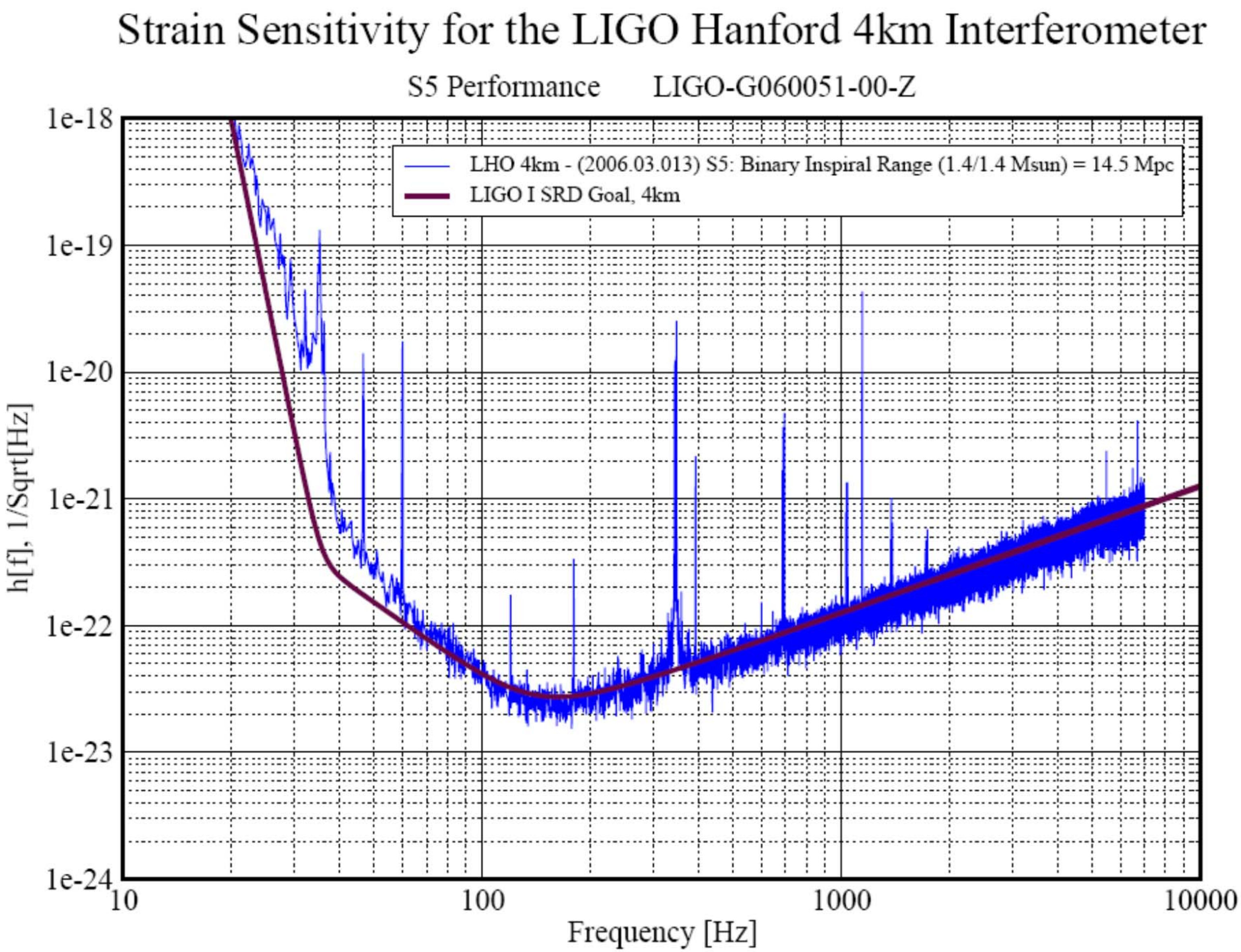


Detection Bench



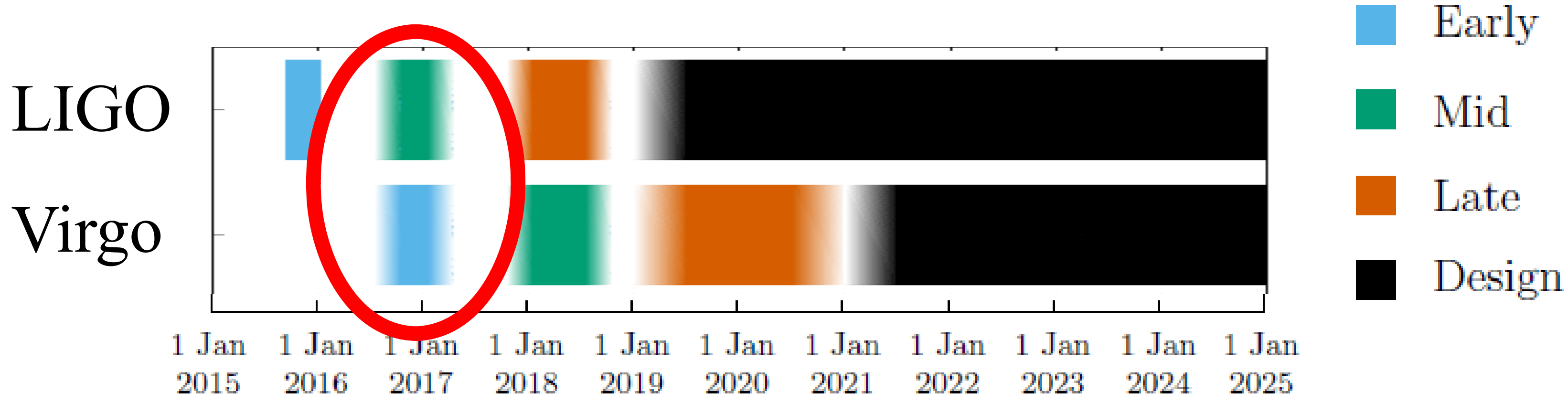
- Filters and conditions light to eliminate contaminating noise
- Ultra-low scatter, high efficiency
- Supplied by LAPP

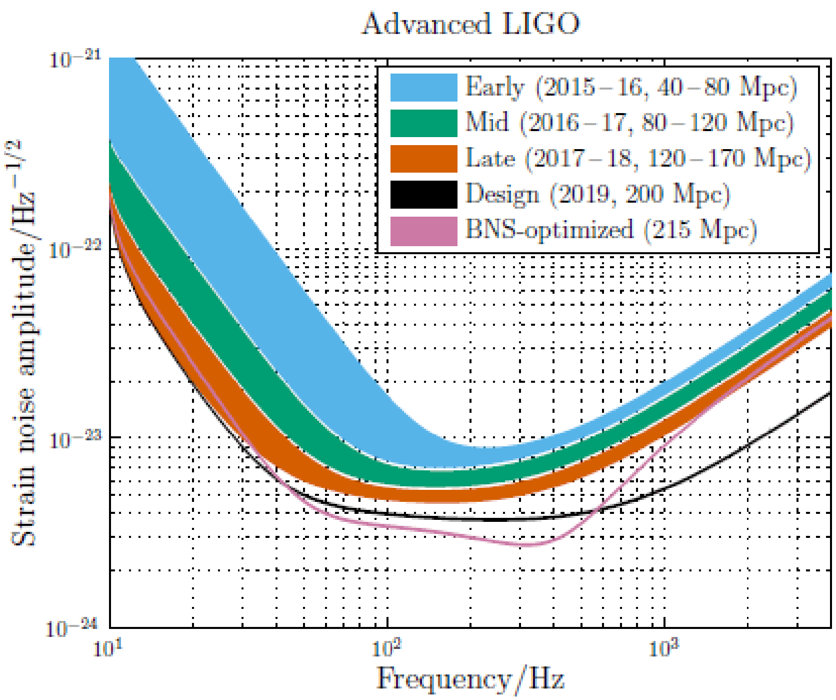
Initial LIGO Sensitivity Closely Matches Prediction

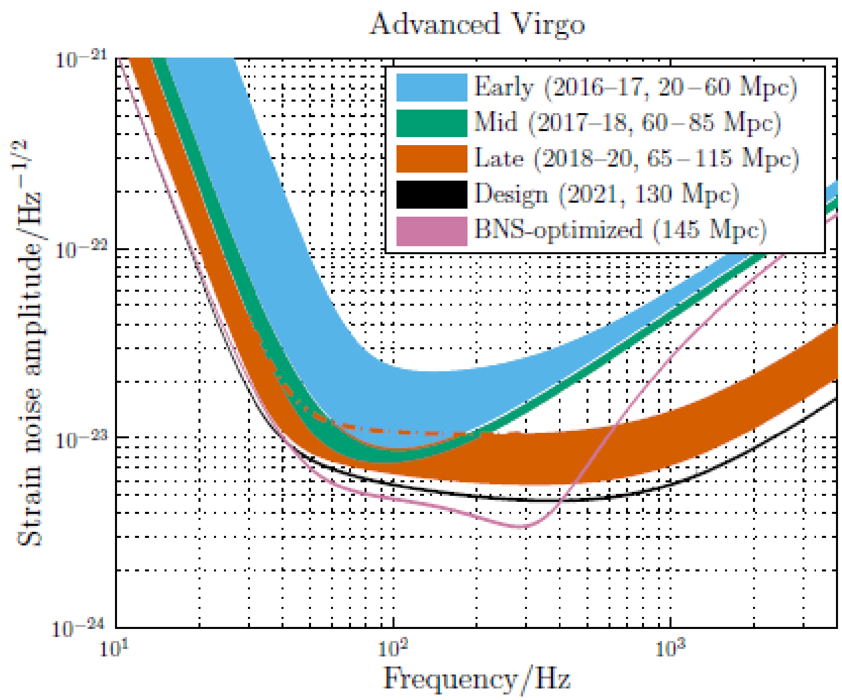


What Can We Expect from the Next Forty Years?

Soon! The Next Observing Run



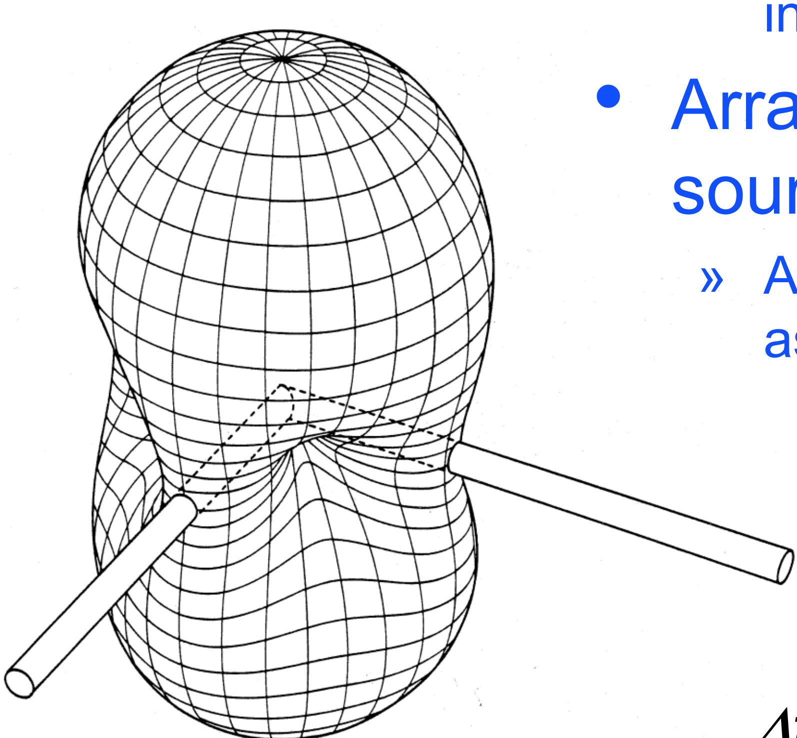




Living Rev. Relativity 19 (2016), 1

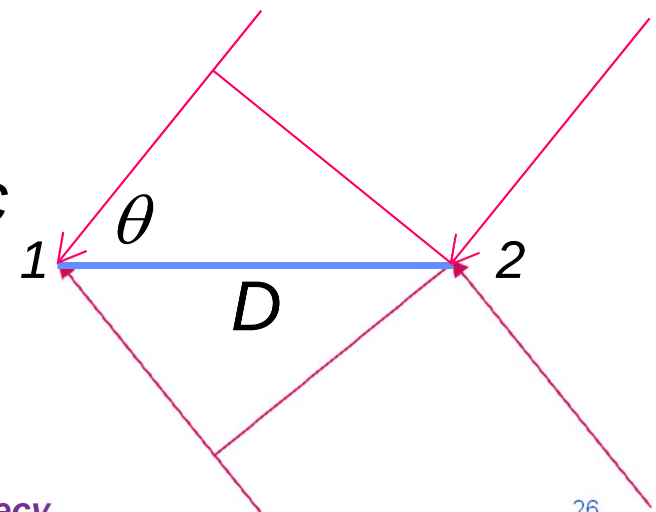
Source Localization Requires a Global Array of GW Detectors

- Detectors are nearly omni-directional
  - » Individually they provide almost no directional information
- Array working together can determine source location
  - » Analogous to “aperture synthesis” in radio astronomy

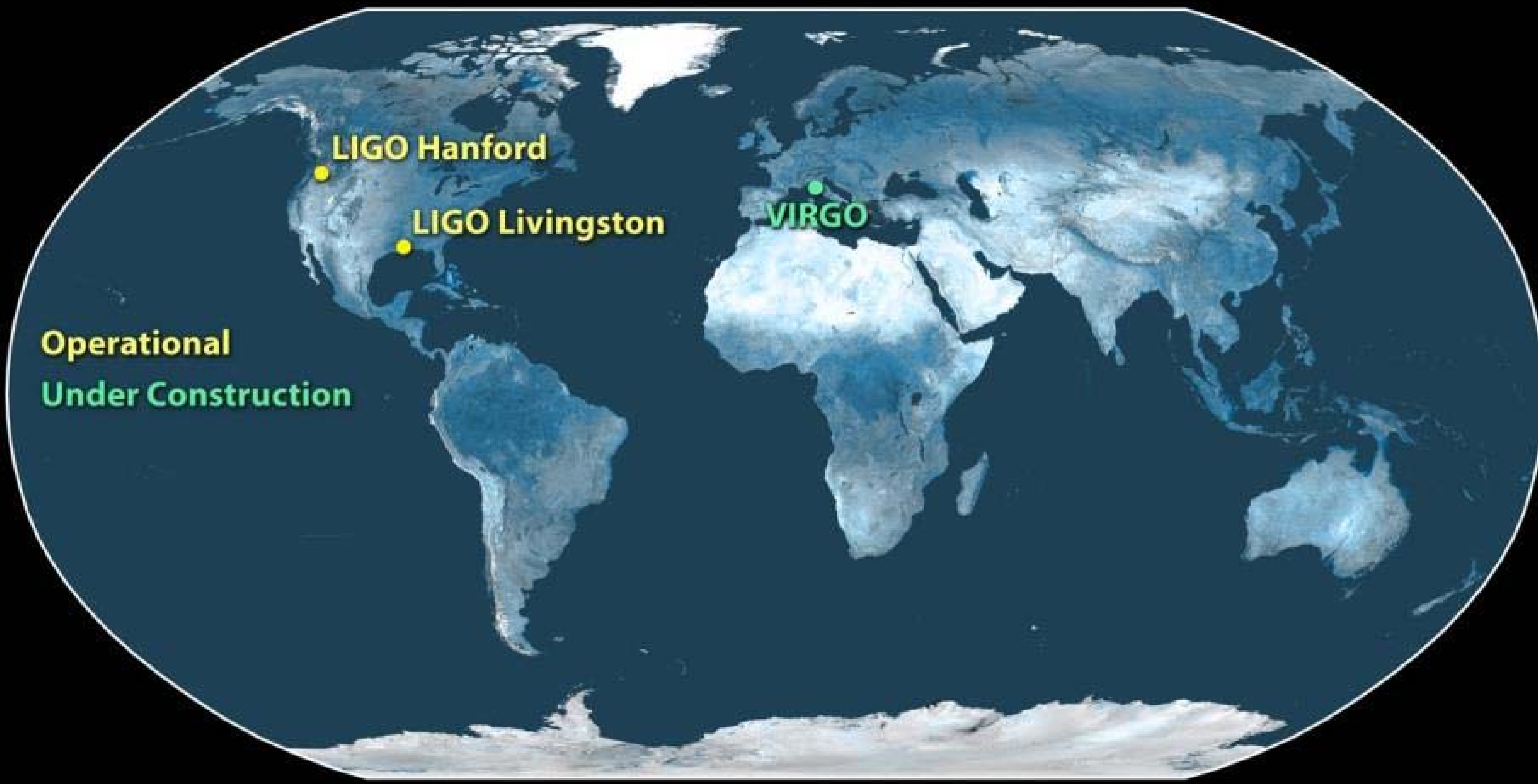


- Accuracy tied to diffraction limit

$\Delta t = (D \cos \theta)/c$



LIGO-Virgo Network



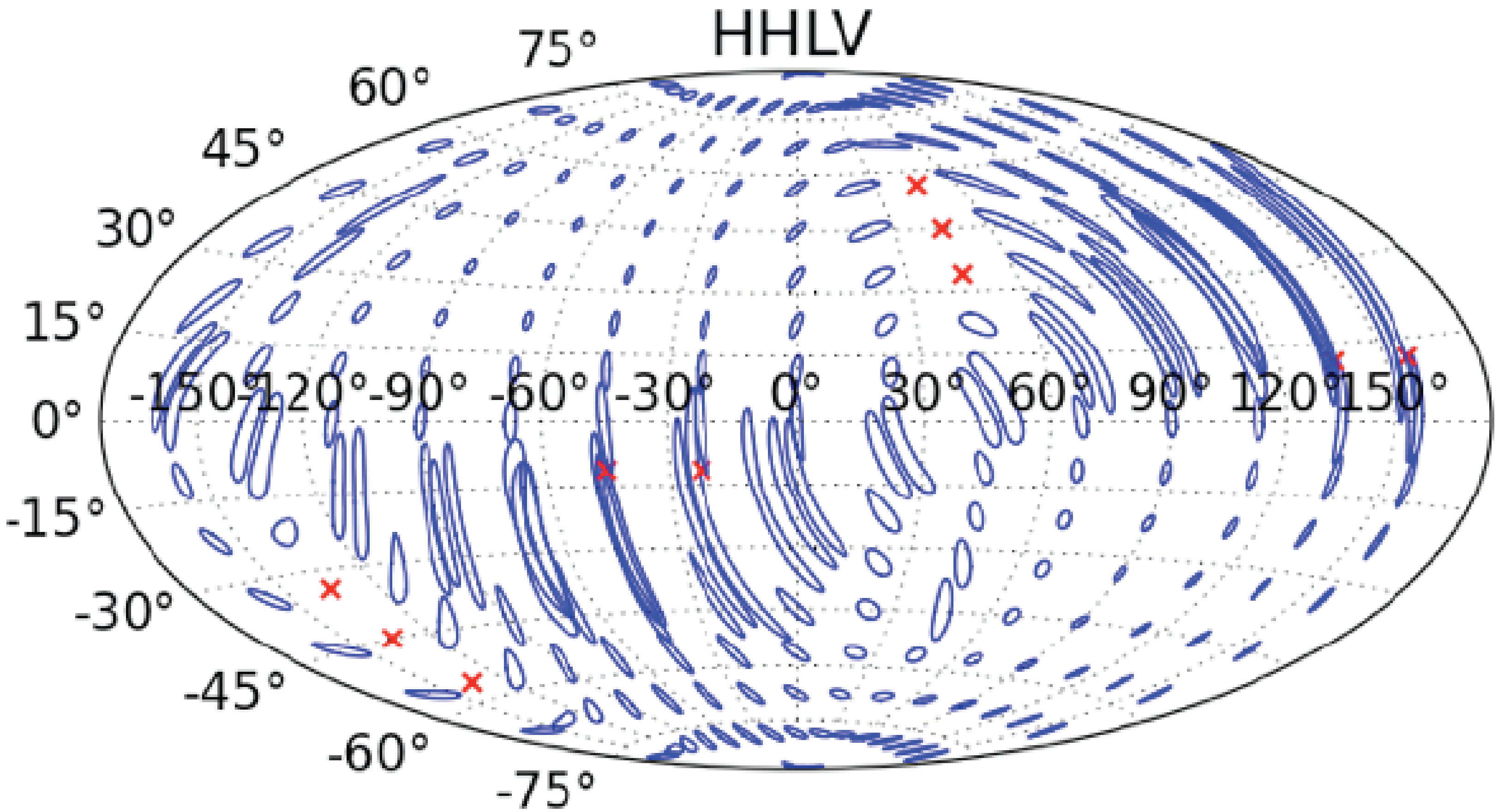
Localization Capability: LIGO-Virgo Working Together

HHLV

- LIGO, Virgo began as independent, competing Projects
- International collaboration was anticipated, but clearly put off to the future
- In 2005, Virgo and LIGO negotiated ground-breaking data-sharing agreement
  - » Complete merger of Data Analysis efforts

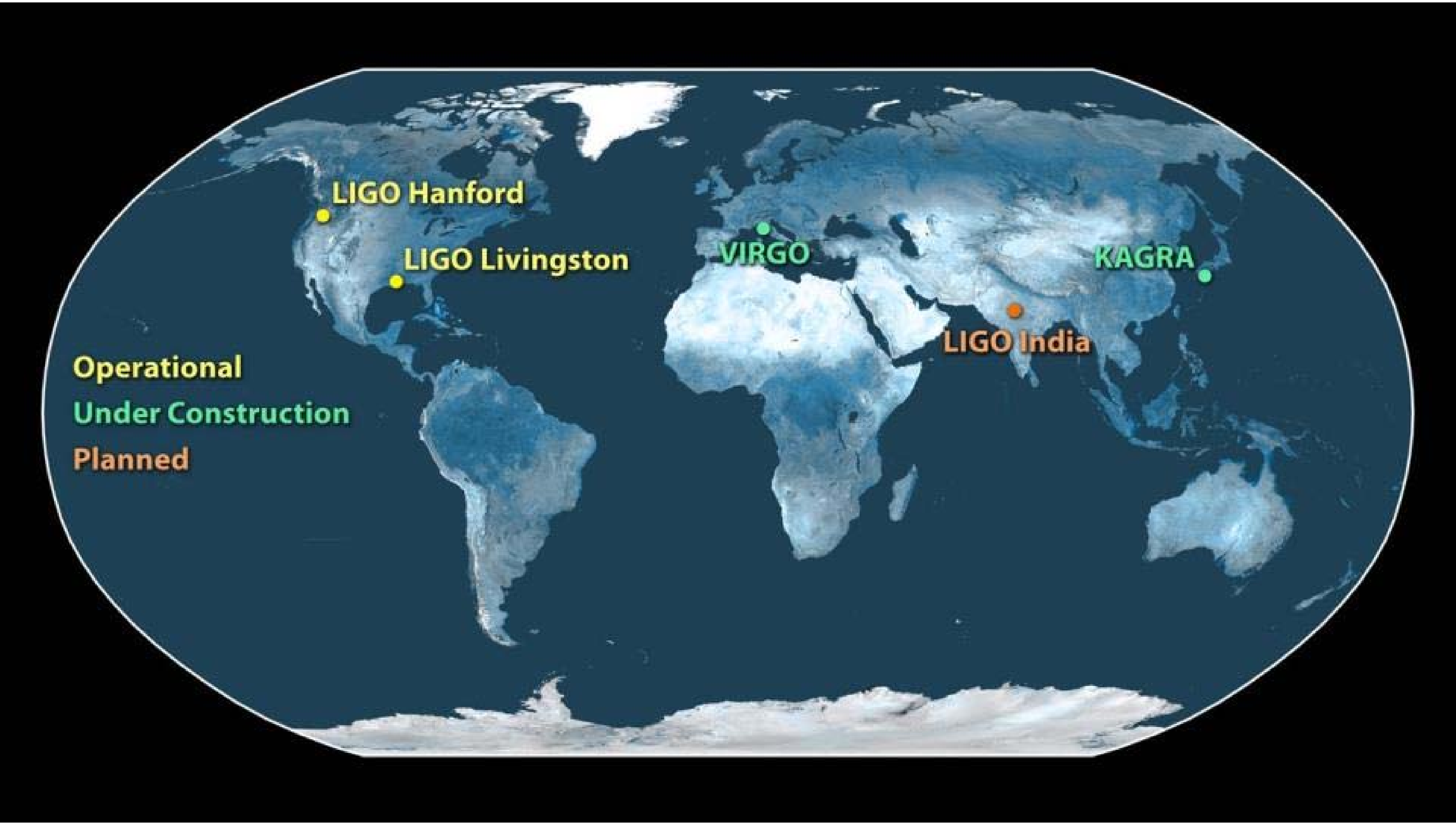
S. Fairhurst, "Improved source localization with LIGO India", J. Phys.: Conf. Ser. ***484*** *012007*

Localization Capability: LIGO-Virgo Working Together

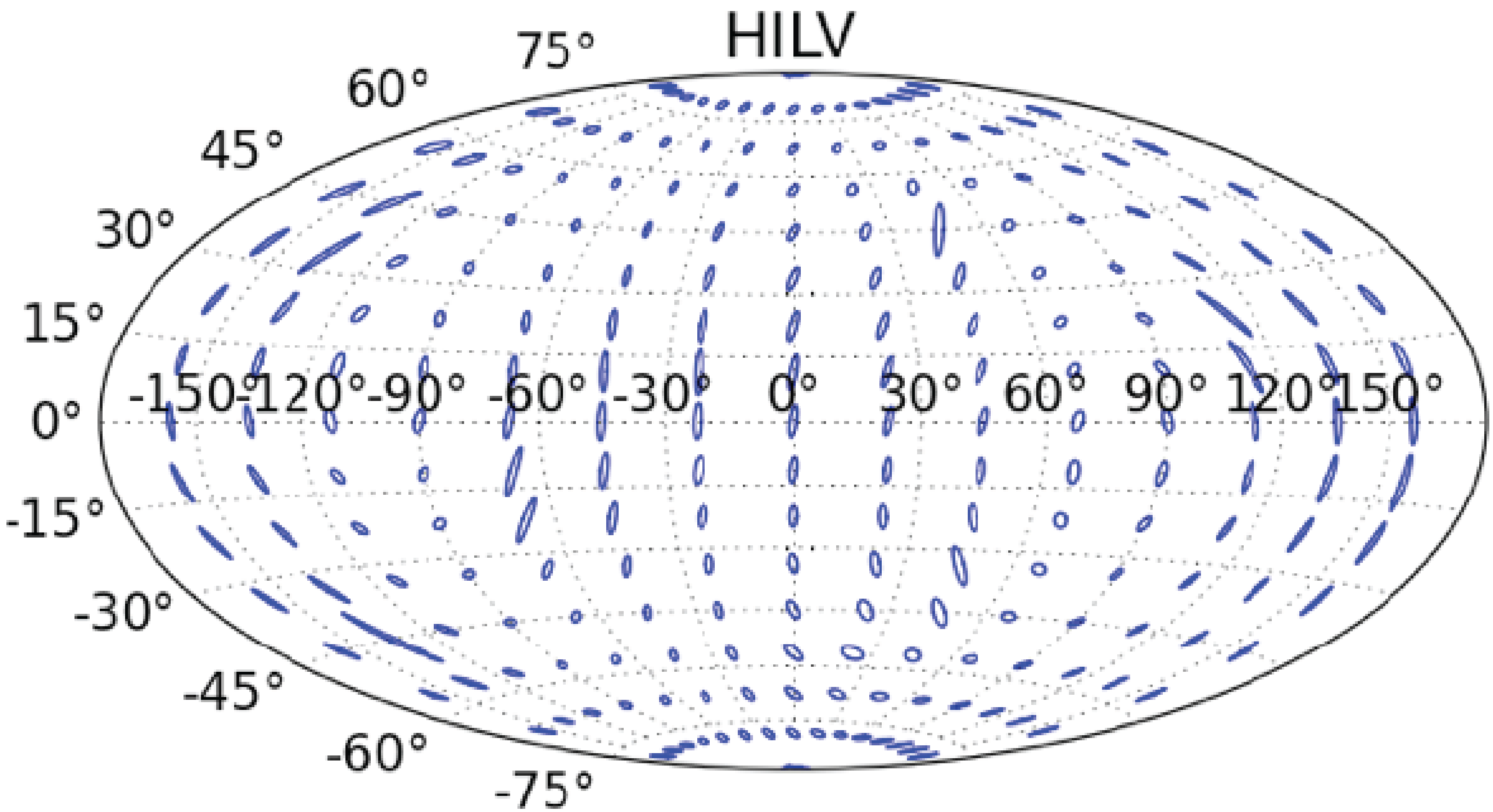


S. Fairhurst, "Improved source localization with LIGO India", J. Phys.: Conf. Ser. **484** 012007

The Global Network

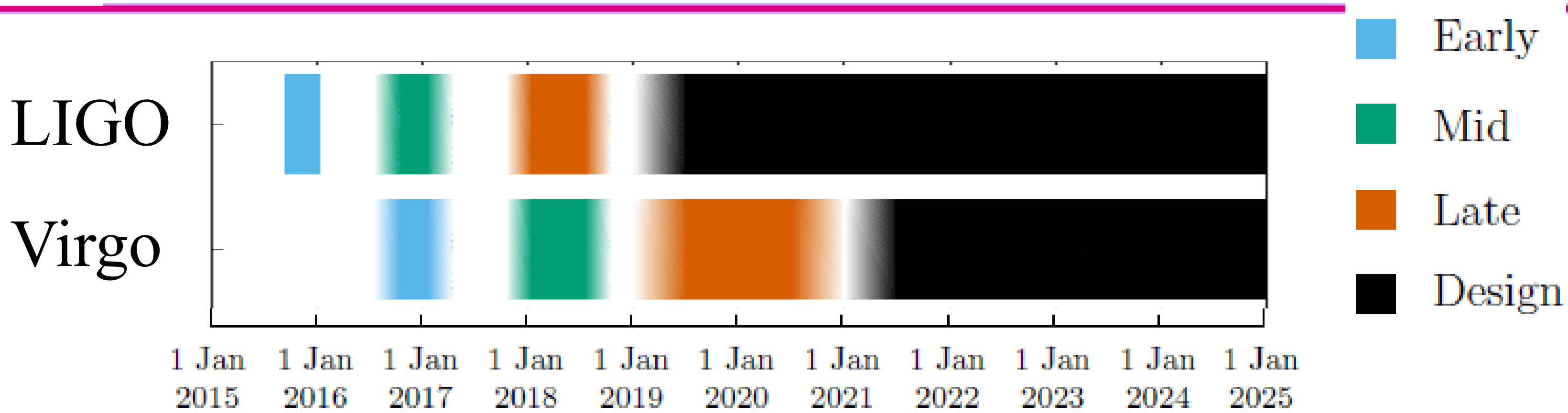


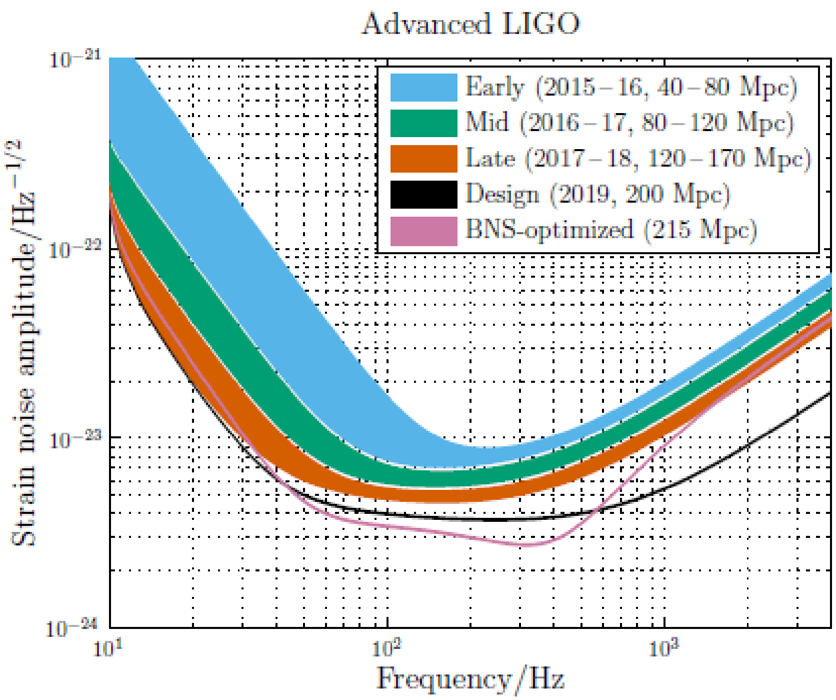
Localization Capability: LIGO-Virgo plus LIGO-India

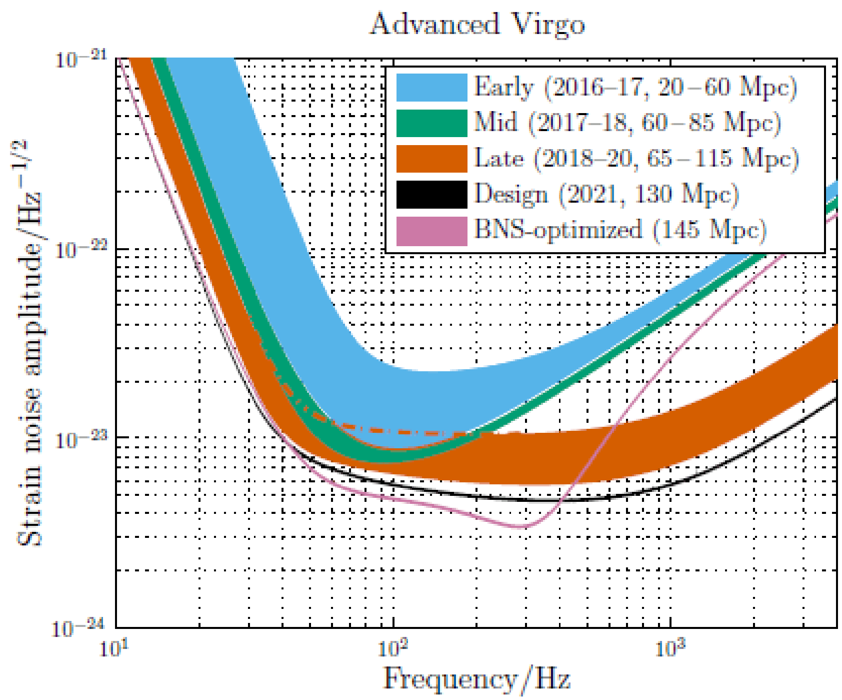


S. Fairhurst, "Improved source localization with LIGO India", J. Phys.: Conf. Ser. ***484*** *012007*

Future Observing Runs







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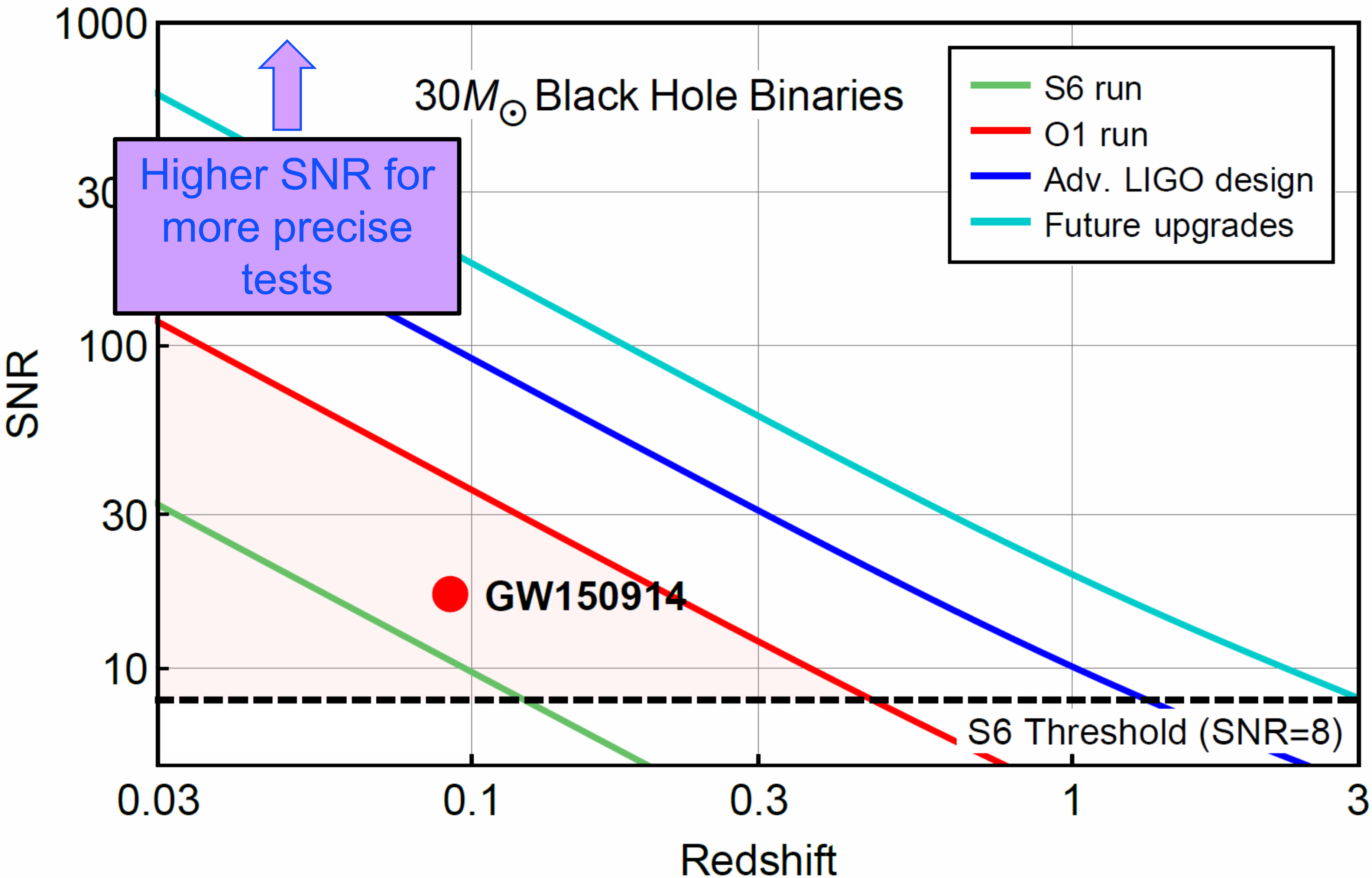
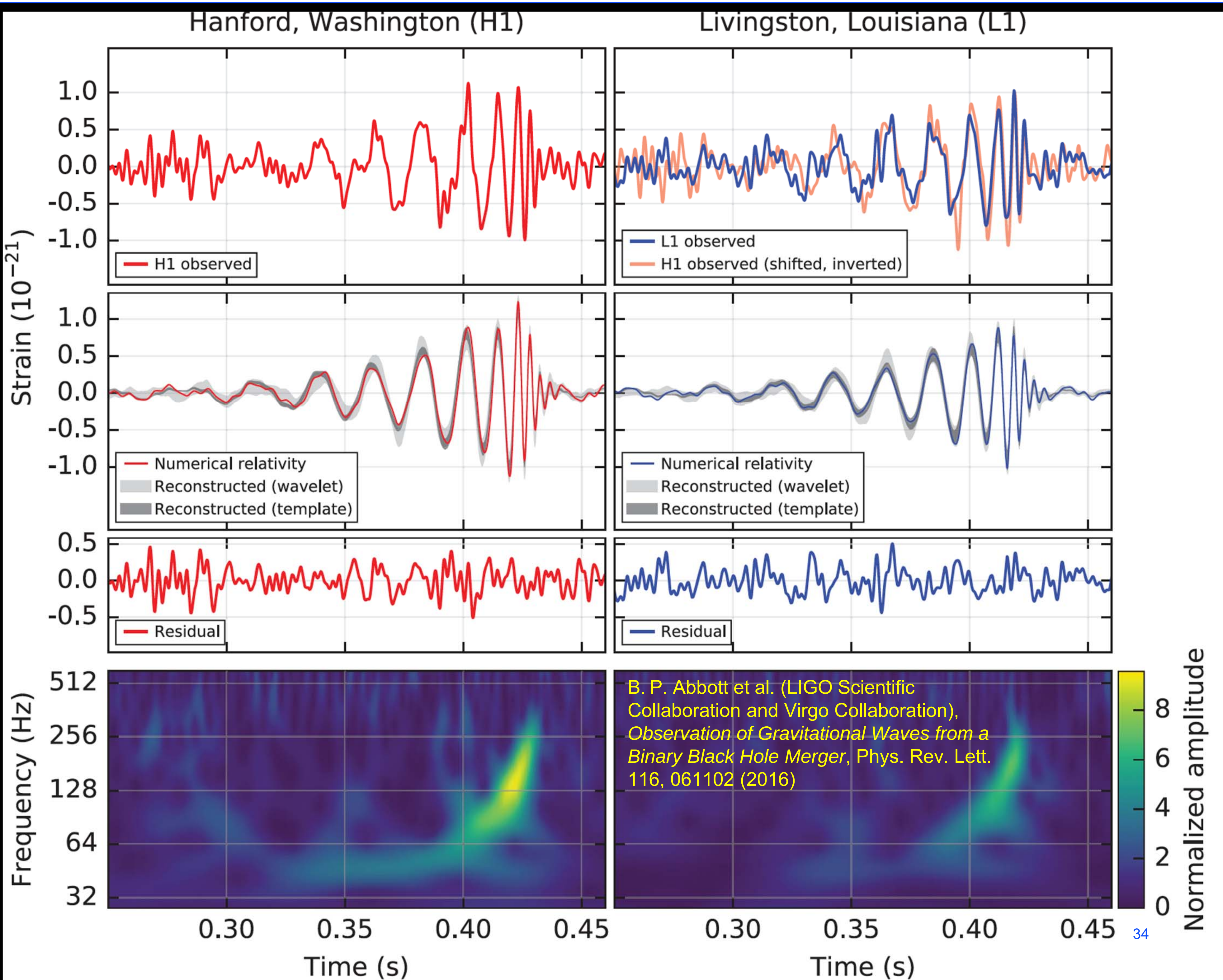
Scientific Prospects for Advanced LIGO

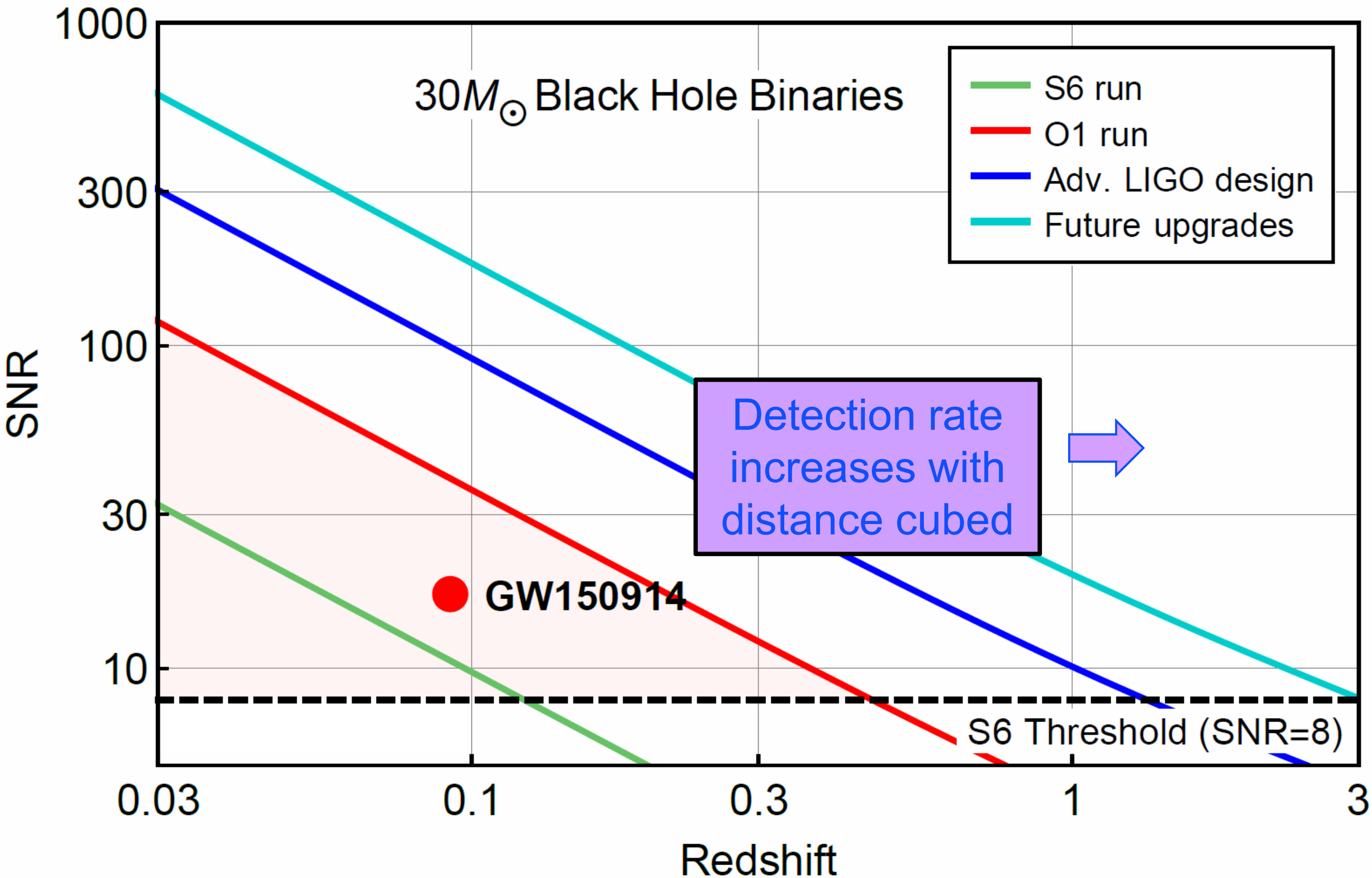



Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized amplitude
Time (s)
B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)

Source Parameters determined from Waveform

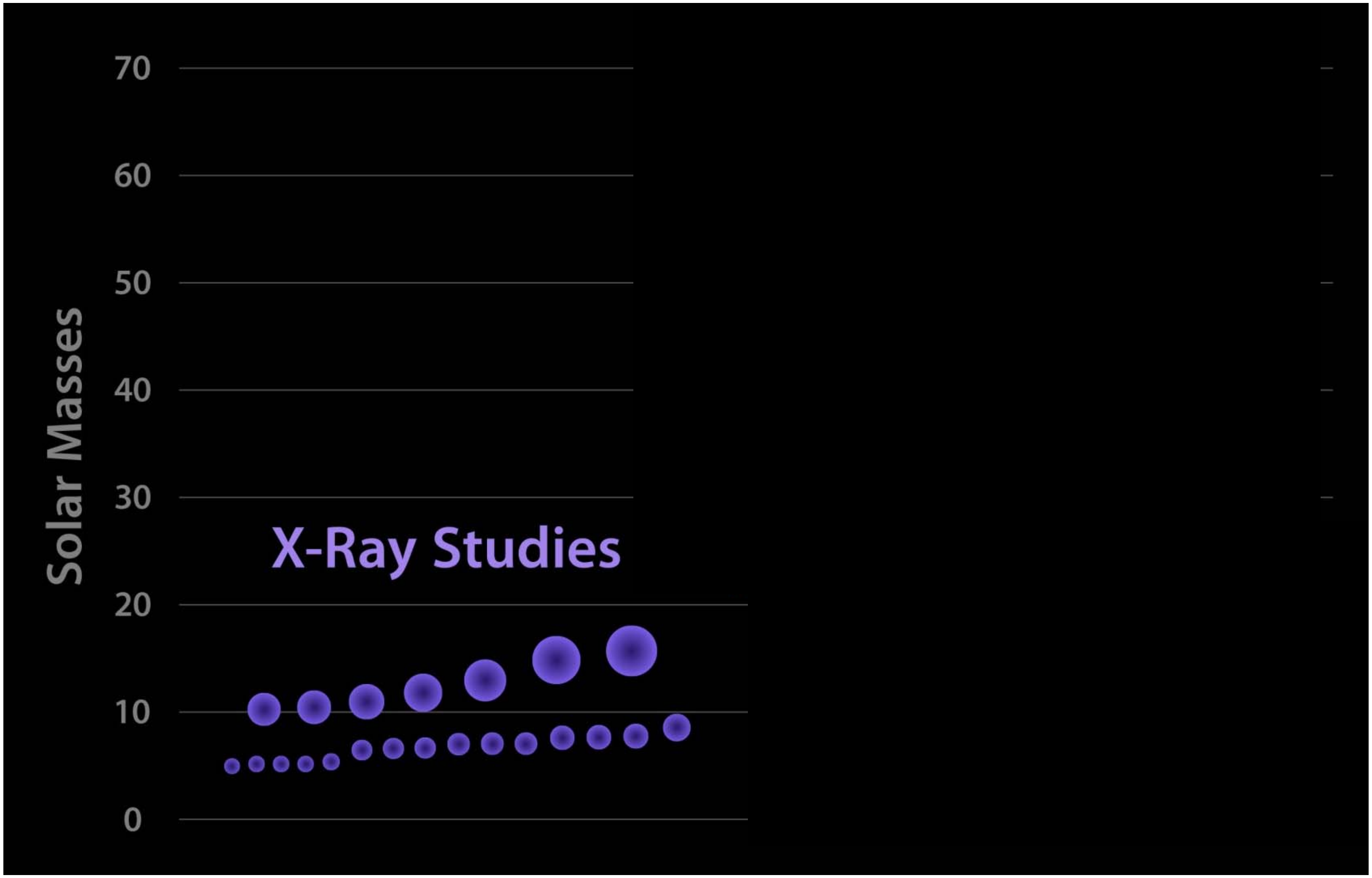
Parameter	Value	90% Error	Unit
Primary black hole mass	36	$^{+5}_{-4}$	$M_\odot$
Secondary black hole mass	29	$^{+4}_{-5}$	$M_\odot$
Final black hole mass	62	$^{+4}_{-4}$	$M_\odot$
Total radiated energy	3.0	$^{+0.5}_{-0.5}$	$M_\odot$
Final black hole spin	0.67	$^{+0.05}_{-0.07}$	
Luminosity distance	410	$^{+160}_{-190}$	Mpc
Source redshift z	0.09	$^{+0.03}_{-0.04}$	

Scientific Prospects for Advanced LIGO



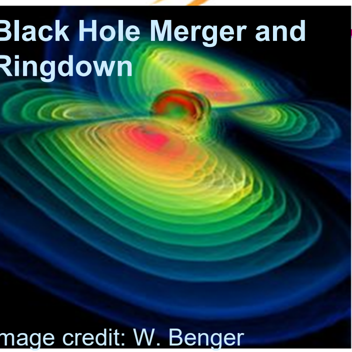
Census of Black Holes in the Universe

- Previously known black holes (X-ray binary systems)



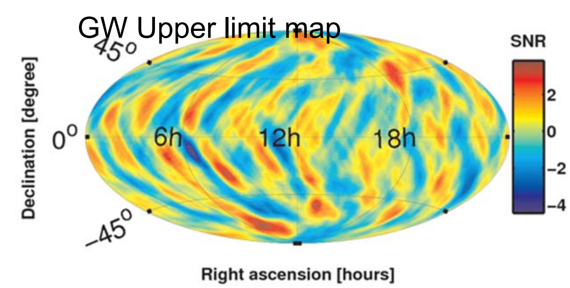
LIGO & Caltech Press Office

Further Questions in Physics and Astronomy



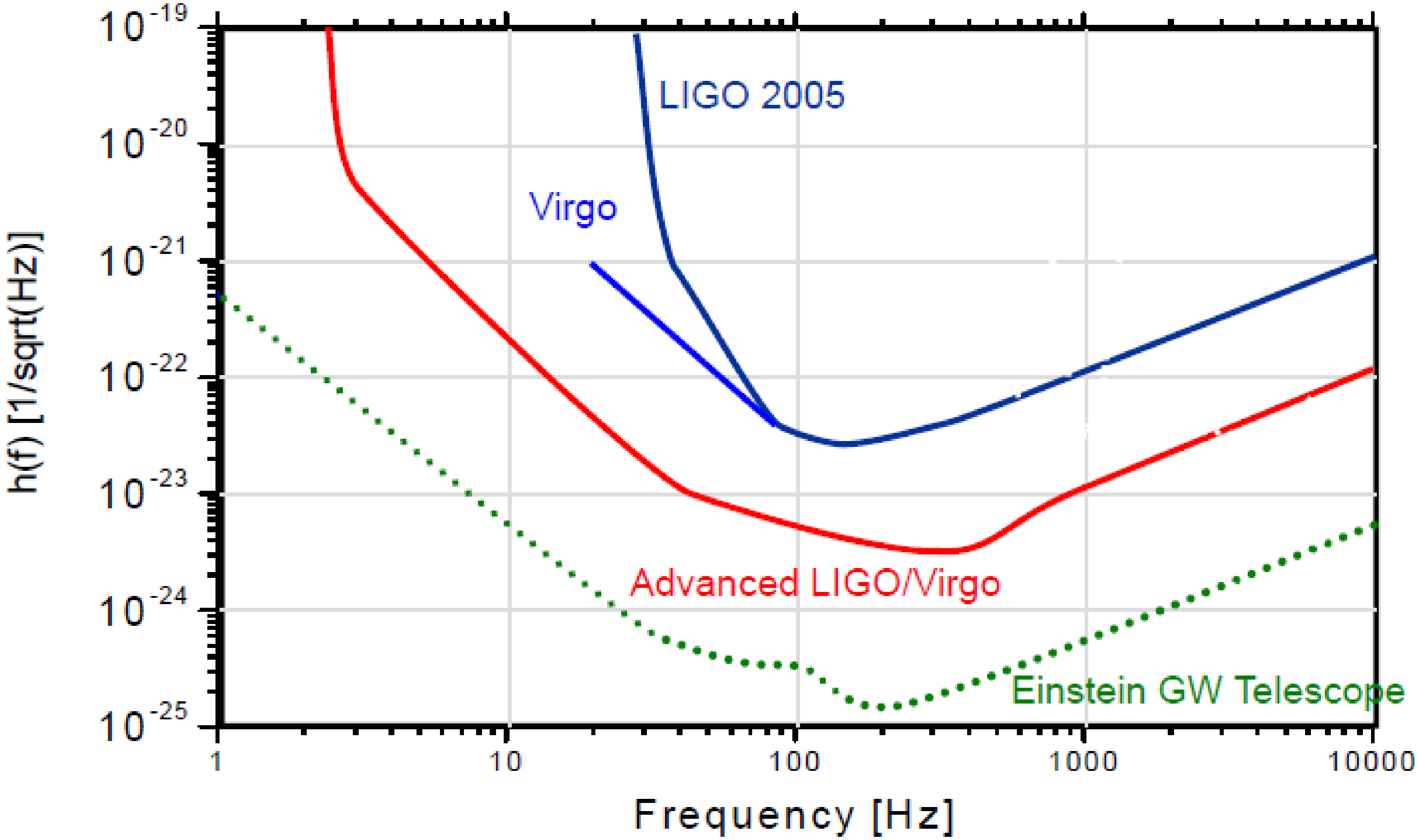
- Is General Relativity the correct theory of gravity?
  - » Wave propagation speed (delays in arrival time of bursts)
  - » Spin of the graviton (polarization of radiation)
  - » Are black holes really characterized by only mass and spin?

- Nuclear physics—neutron stars
  - » How does matter behave under extreme conditions?
  - » Determine the matter equation of state at nuclear densities
- Astrophysics, Astronomy, Cosmology
  - » What is the supernova mechanism in core-collapse of massive stars?
  - » How bumpy are neutron stars?
  - » Do compact binary mergers cause GRBs?
  - » Are there unexpected gravitational wave sources?
  - » Can we observe a stochastical background of GWs?
  - » Can binary inspirals be used as "standard sirens" to measure the local Hubble parameter?



Future Detectors

- Advanced LIGO/Virgo are not the end!
- Another factor of 10 in sensitivity is technologically possible

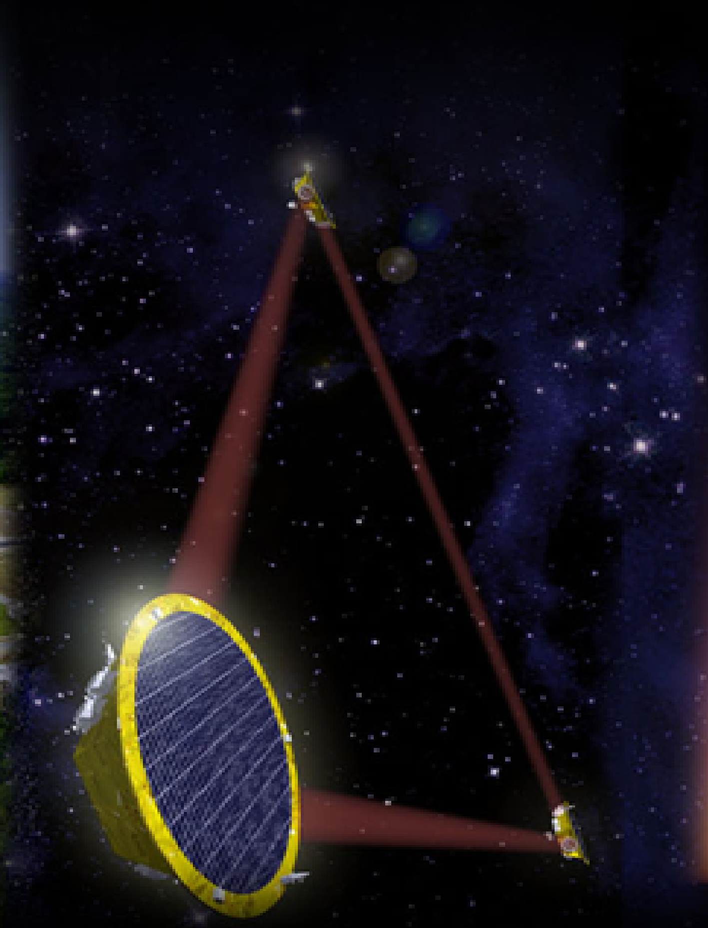


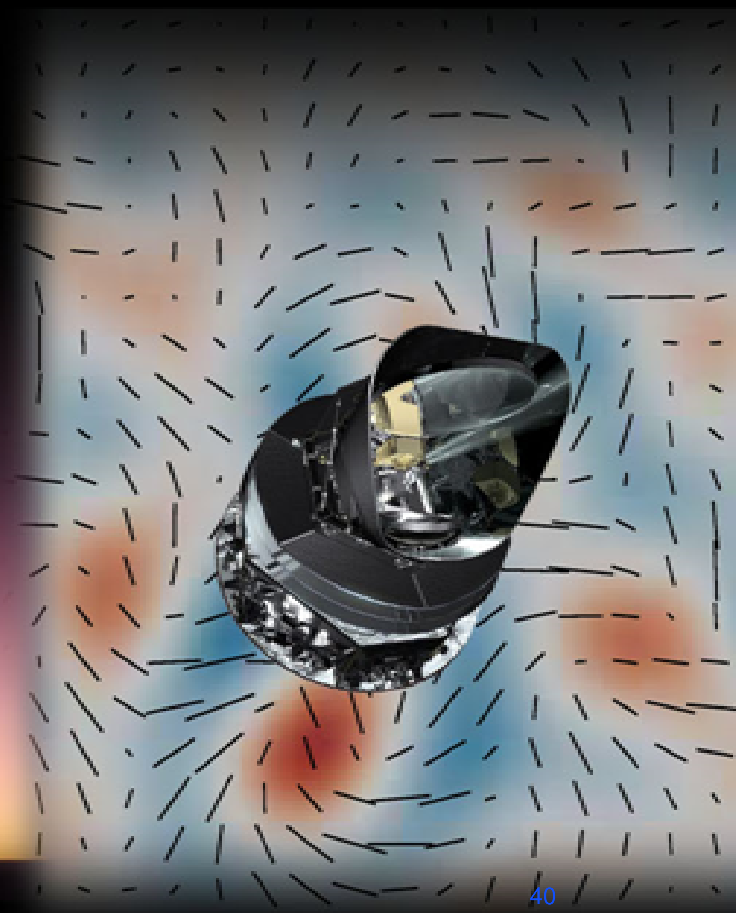
Gravitational Wave Spectrum

Minutes to Hours

Years to Decades

Billions of Years





Thank you!