Coming soon: Advanced LIGO

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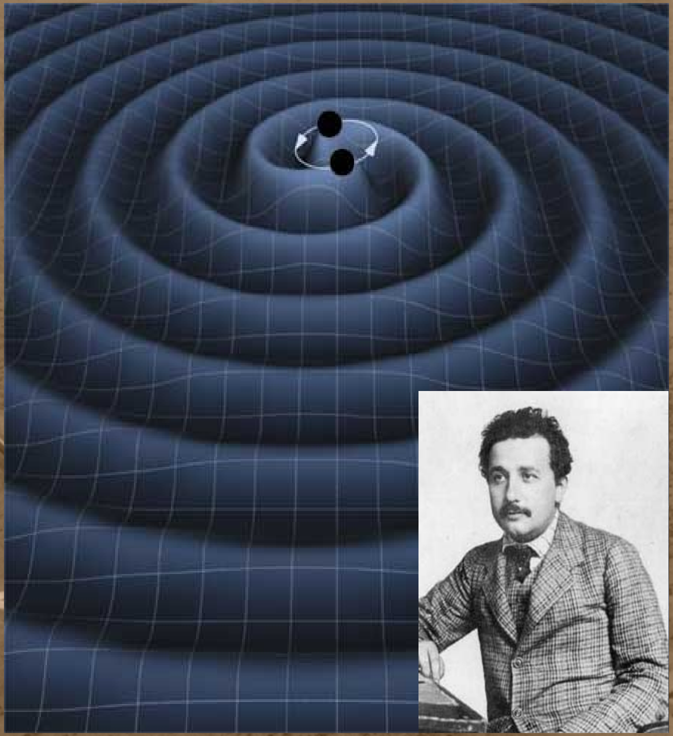
LIGO-G1400110-v1

A gravitational wave is a propagating disturbance of the space-time

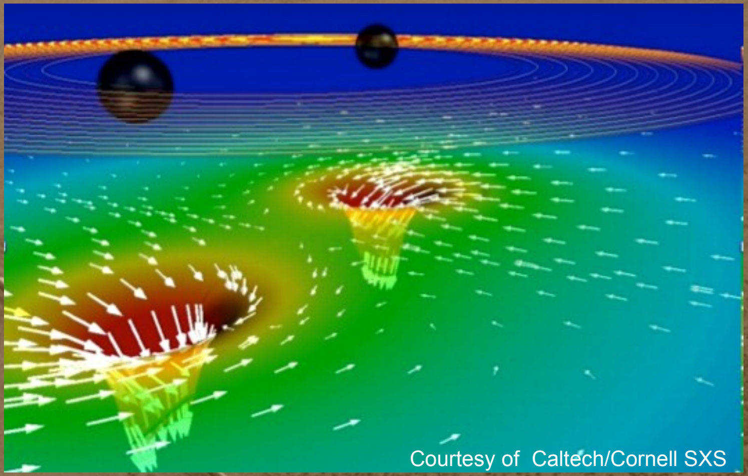
When masses move rapidly, the space-time becomes stirred by their motion:

Gravitational waves start traveling outward with the speed of light



Sources of gravitational waves

- ♦ Coalescing binary neutron stars or black holes



Courtesy of Caltech/Cornell SXS

- ♦ Spinning neutron stars
- ♦ Gravitational bursts (e.g. supernovae)
- ♦ Big bang gravitational echo

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Courtesy of NASA/HST/STScI

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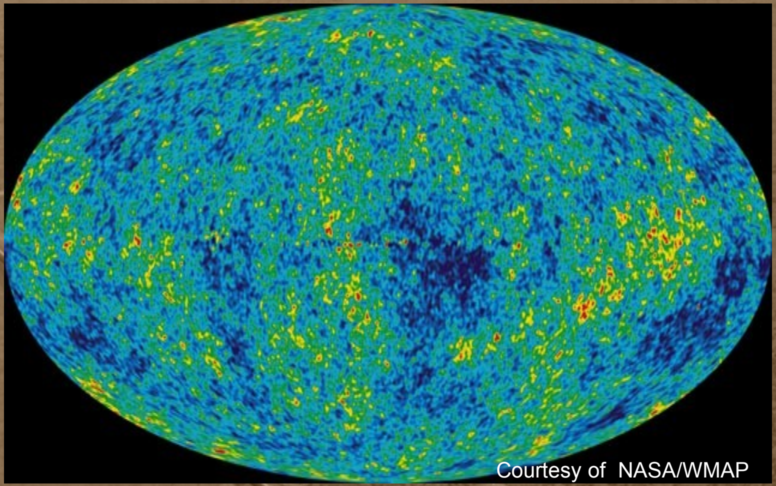
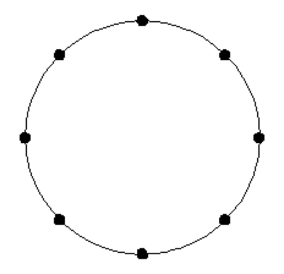


Courtesy of NASA/WMAP

What is the effect of a gravitational wave?

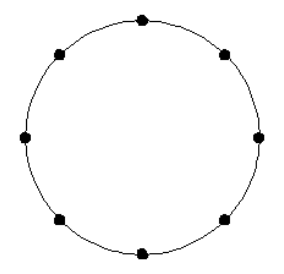
“+” polarization:

$$h_+(t-z) = h^{TT}_{xx} = -h^{TT}_{yy}$$



“x” polarization:

$$h_\times(t-z) = h^{TT}_{xy} = h^{TT}_{yx}$$



But…gravitational waves are tiny!

For a coalescing compact object into a black hole:

$$f \sim \frac{1}{M} \sim 10^4 \text{ Hz} \left(\frac{M_\odot}{M}\right)$$

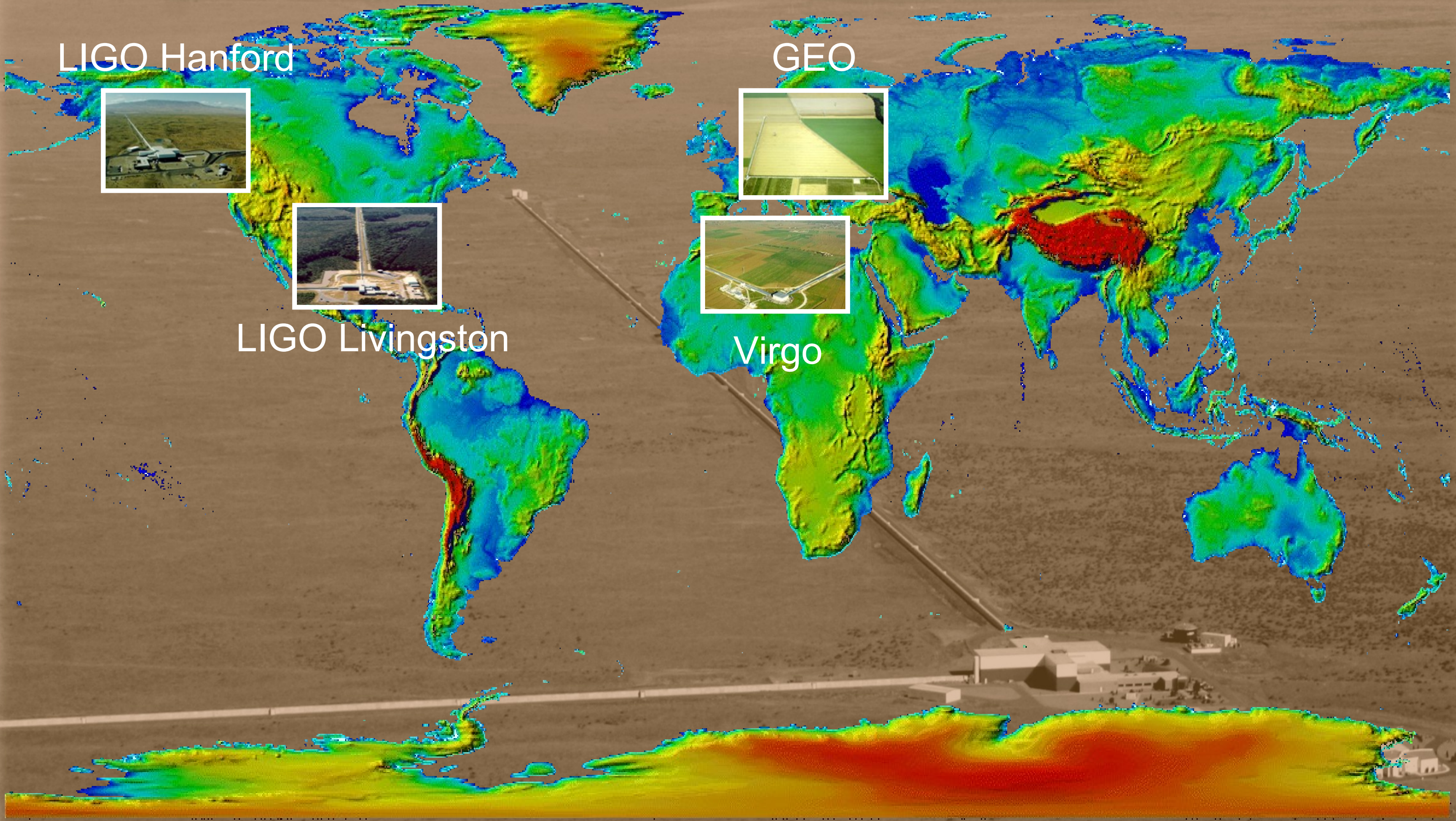
$$h \sim \epsilon^{1/2} \frac{M}{r} \sim 10^{-21} \left(\frac{\epsilon}{0.01}\right)^{1/2} \left(\frac{M}{M_\odot}\right) \left(\frac{10 \text{ Mpc}}{r}\right)$$

Distance Earth-Sun (1.5 x 10^7 km)….

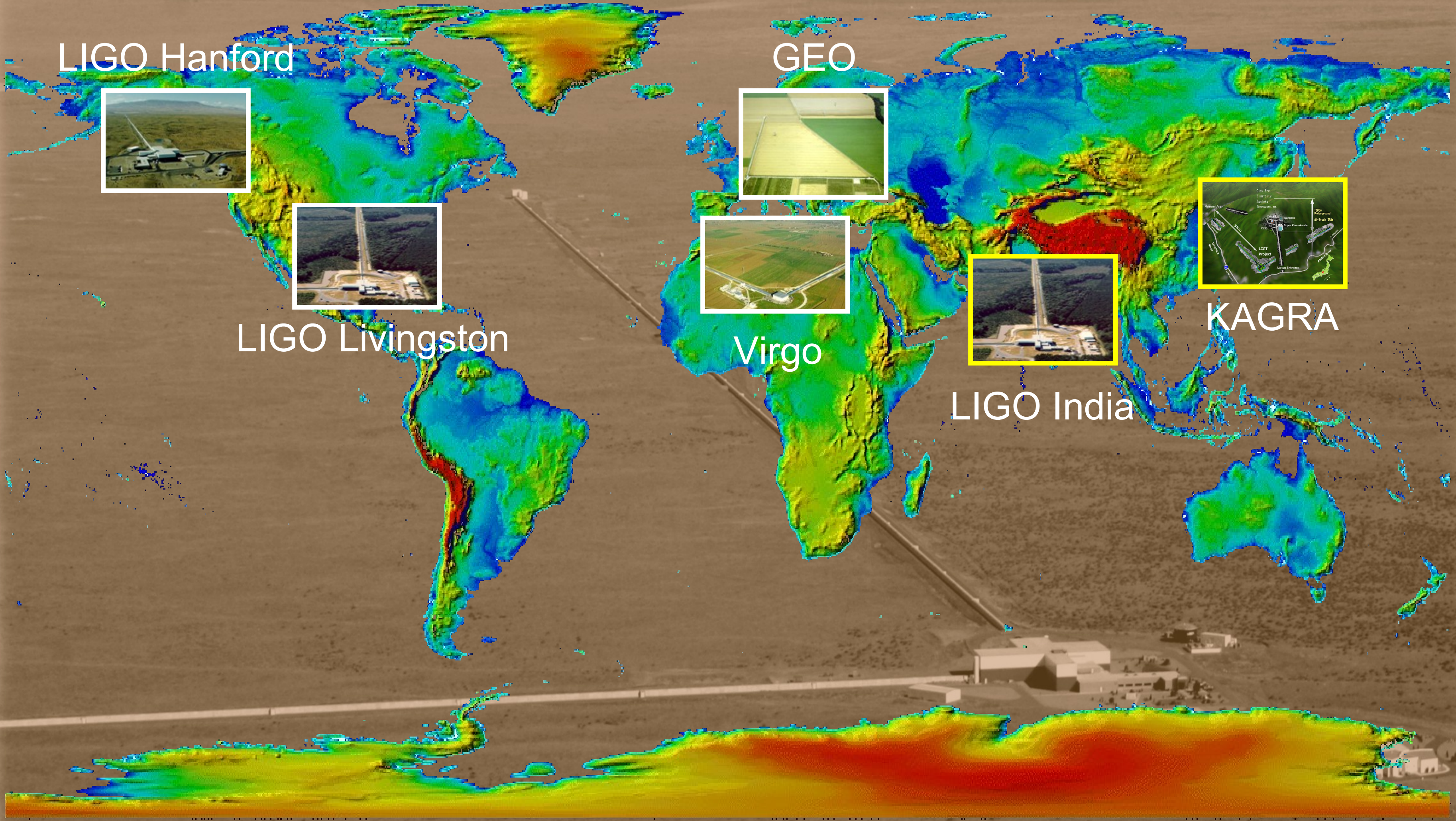
…stretches by a fraction of an atom!

What do we need to detect them?

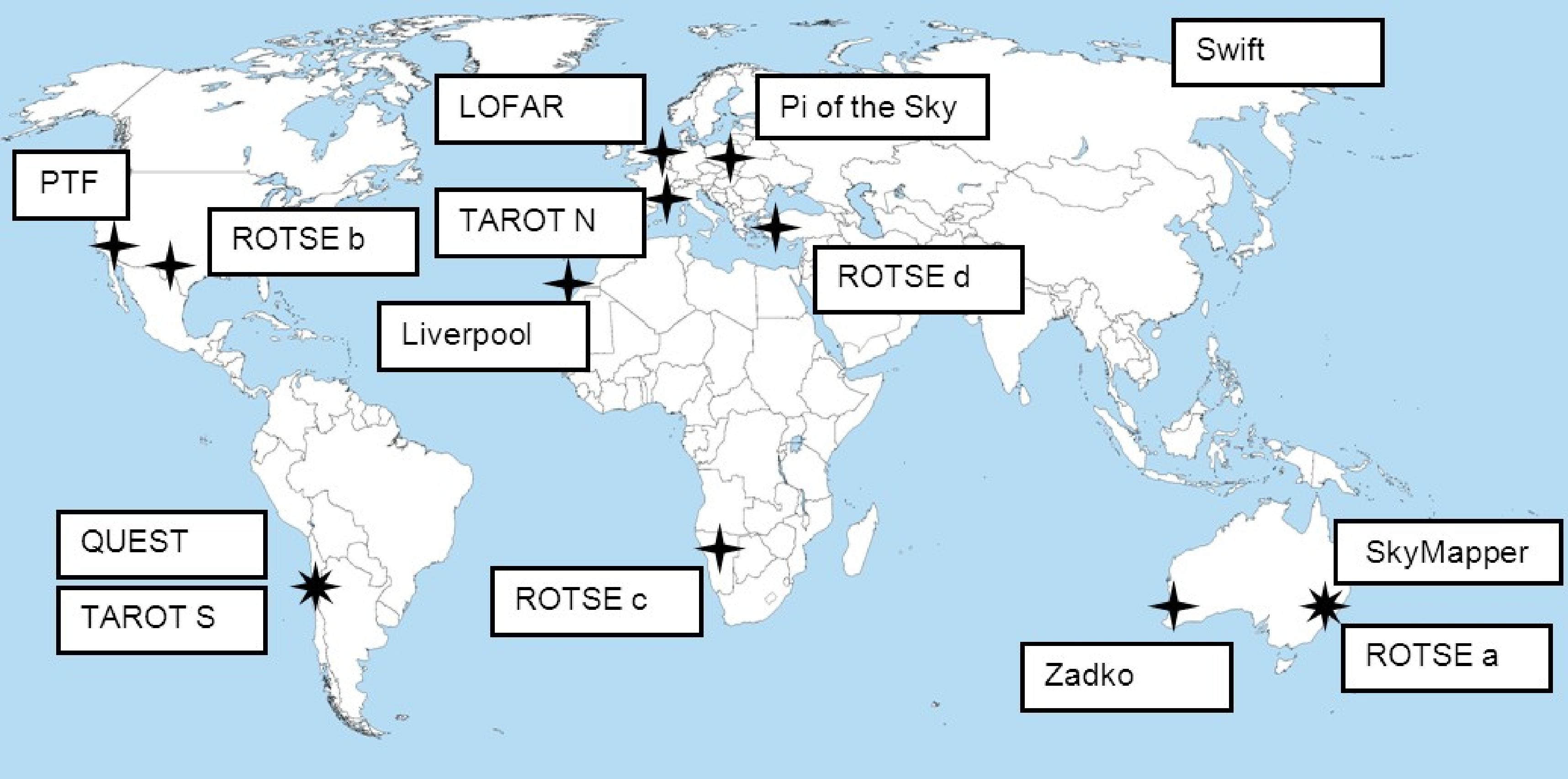
A detector network



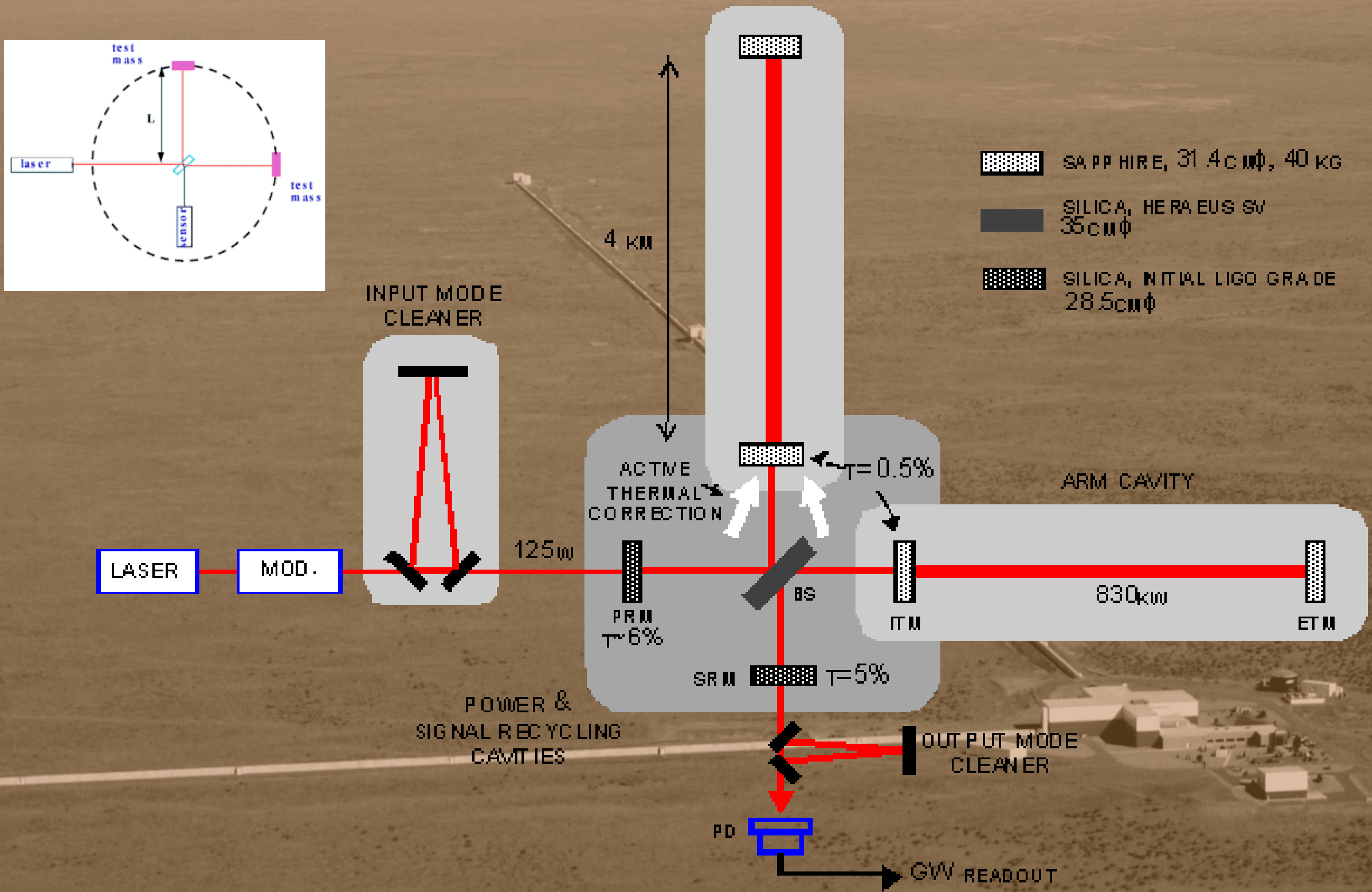
(An even better detector network)

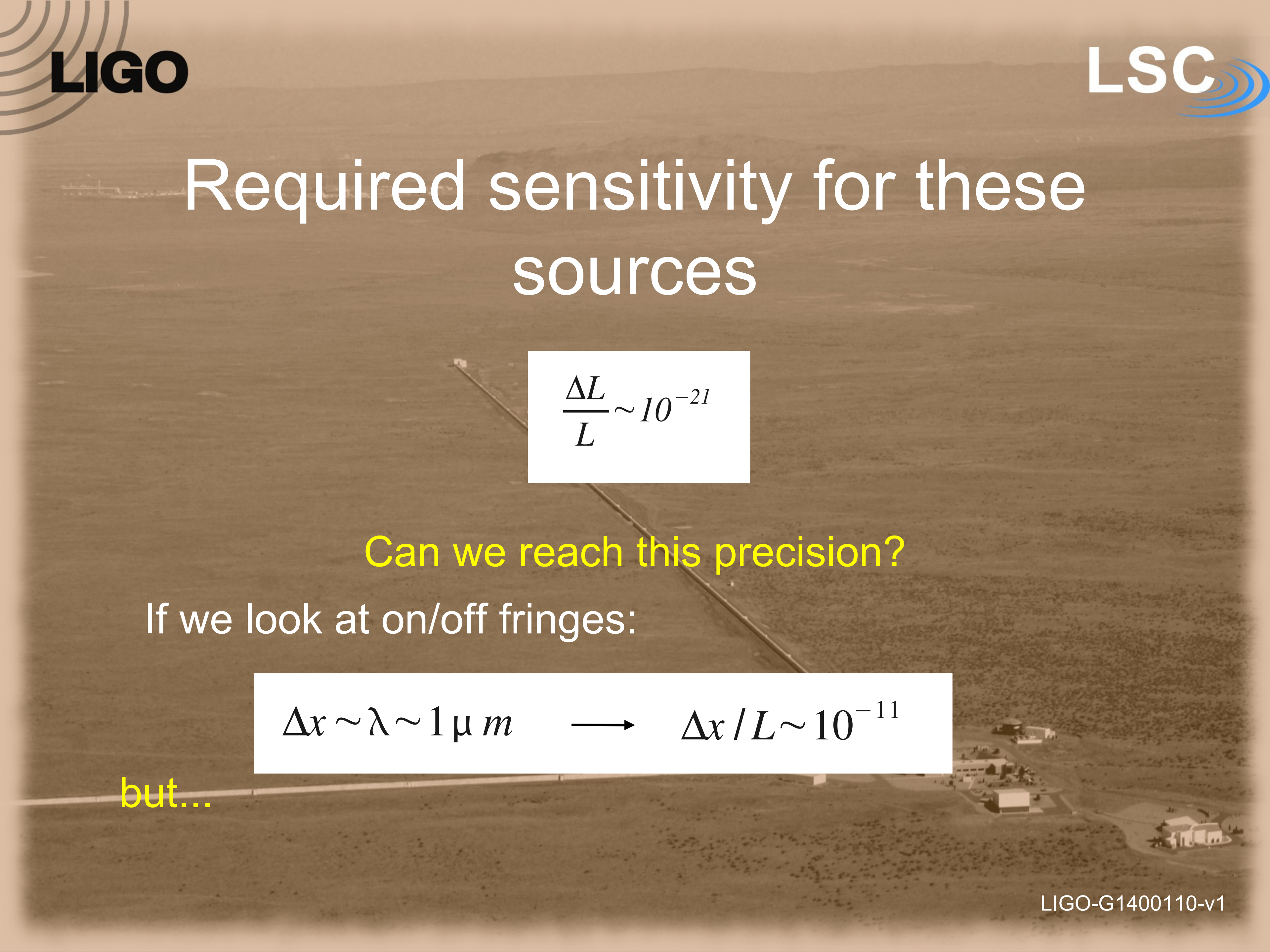


Astronomy observing partners



An extremely sensitive detector





Required sensitivity for these sources

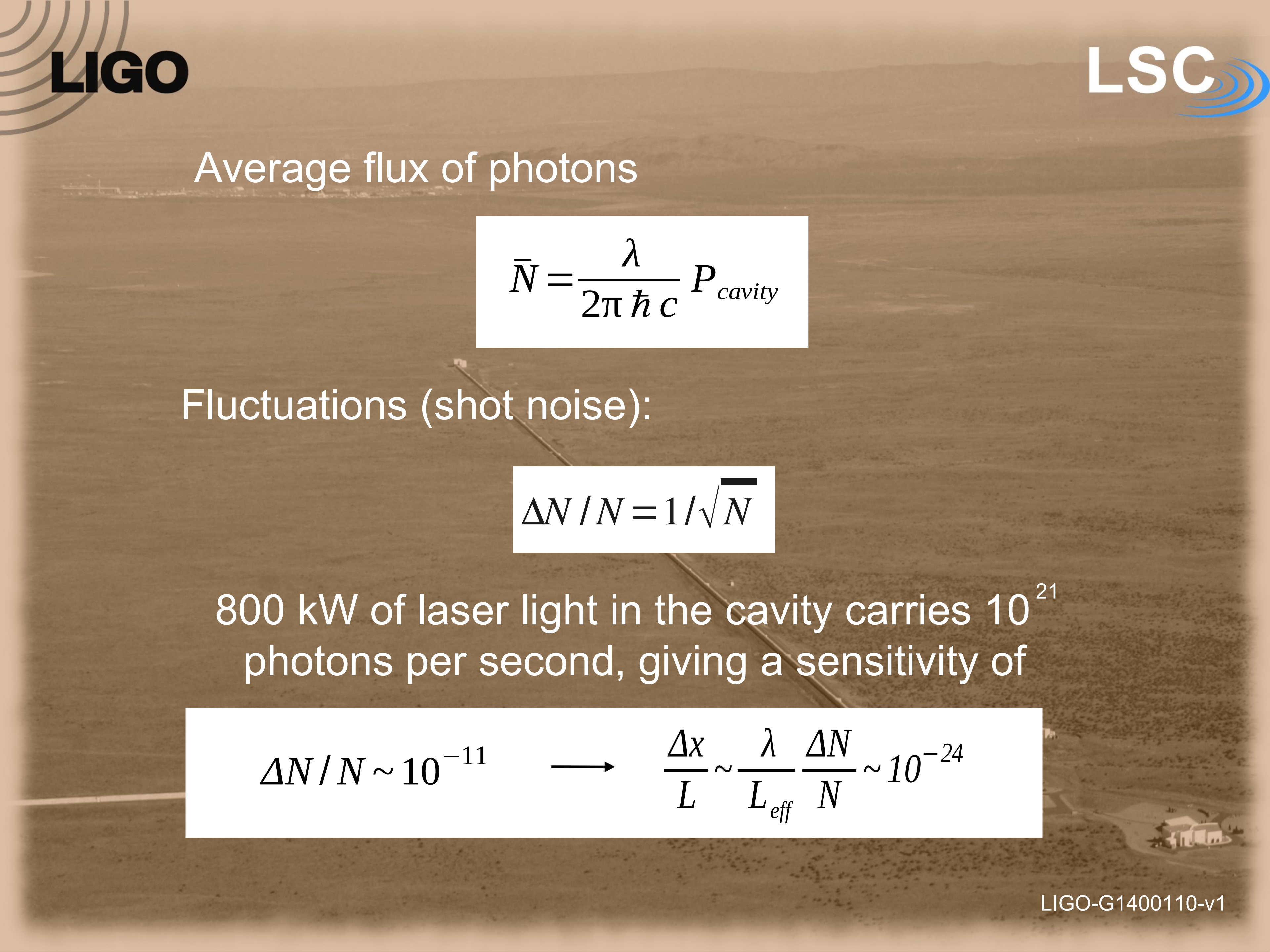
$$\frac{\Delta L}{L} \sim 10^{-21}$$

Can we reach this precision?

If we look at on/off fringes:

$$\Delta x \sim \lambda \sim 1\,\mu m \quad \longrightarrow \quad \Delta x / L \sim 10^{-11}$$

but...



Average flux of photons

$$\bar{N} = \frac{\lambda}{2\pi \hbar c} P_{cavity}$$

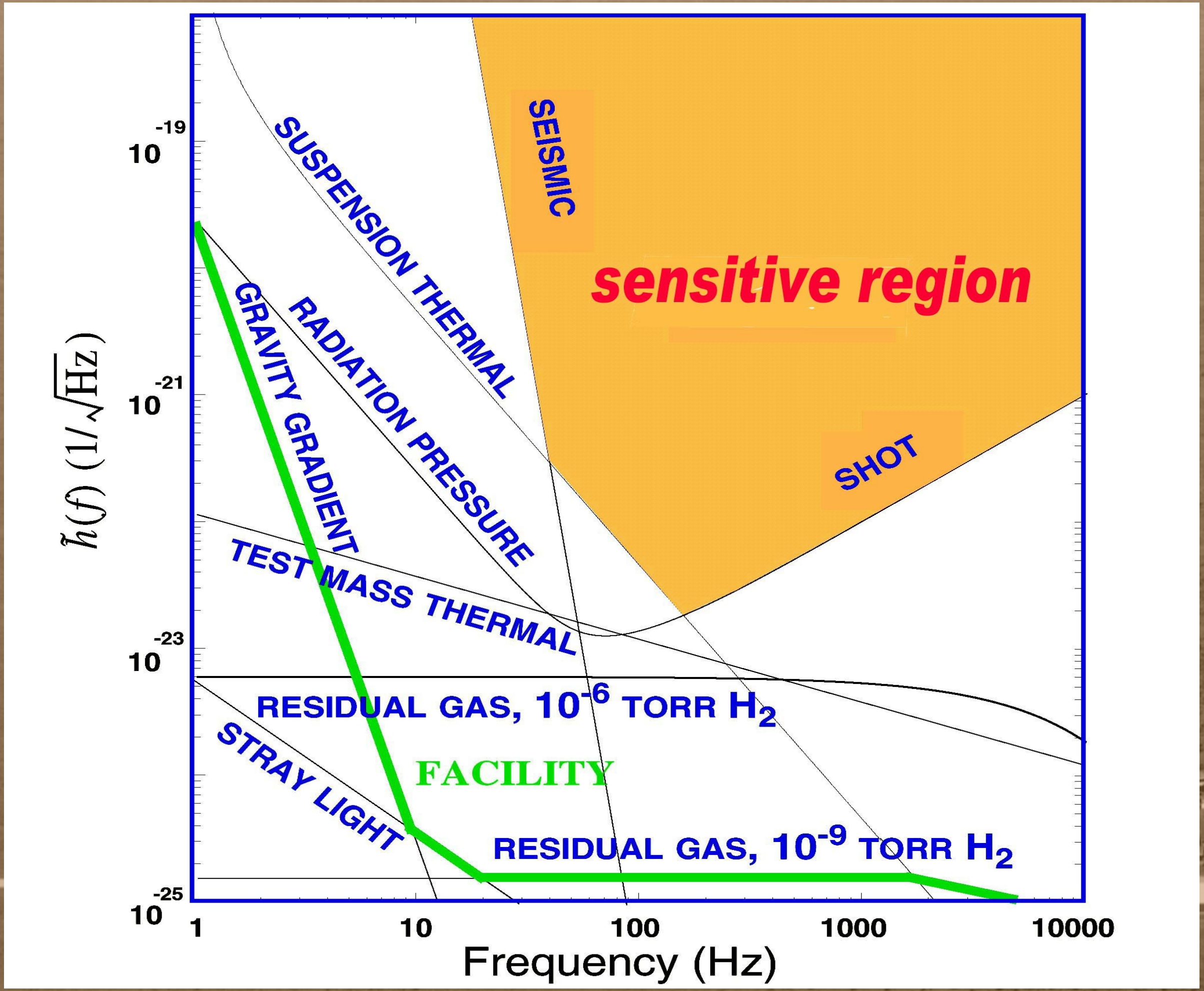
Fluctuations (shot noise):

$$\Delta N / N = 1 / \sqrt{\bar{N}}$$

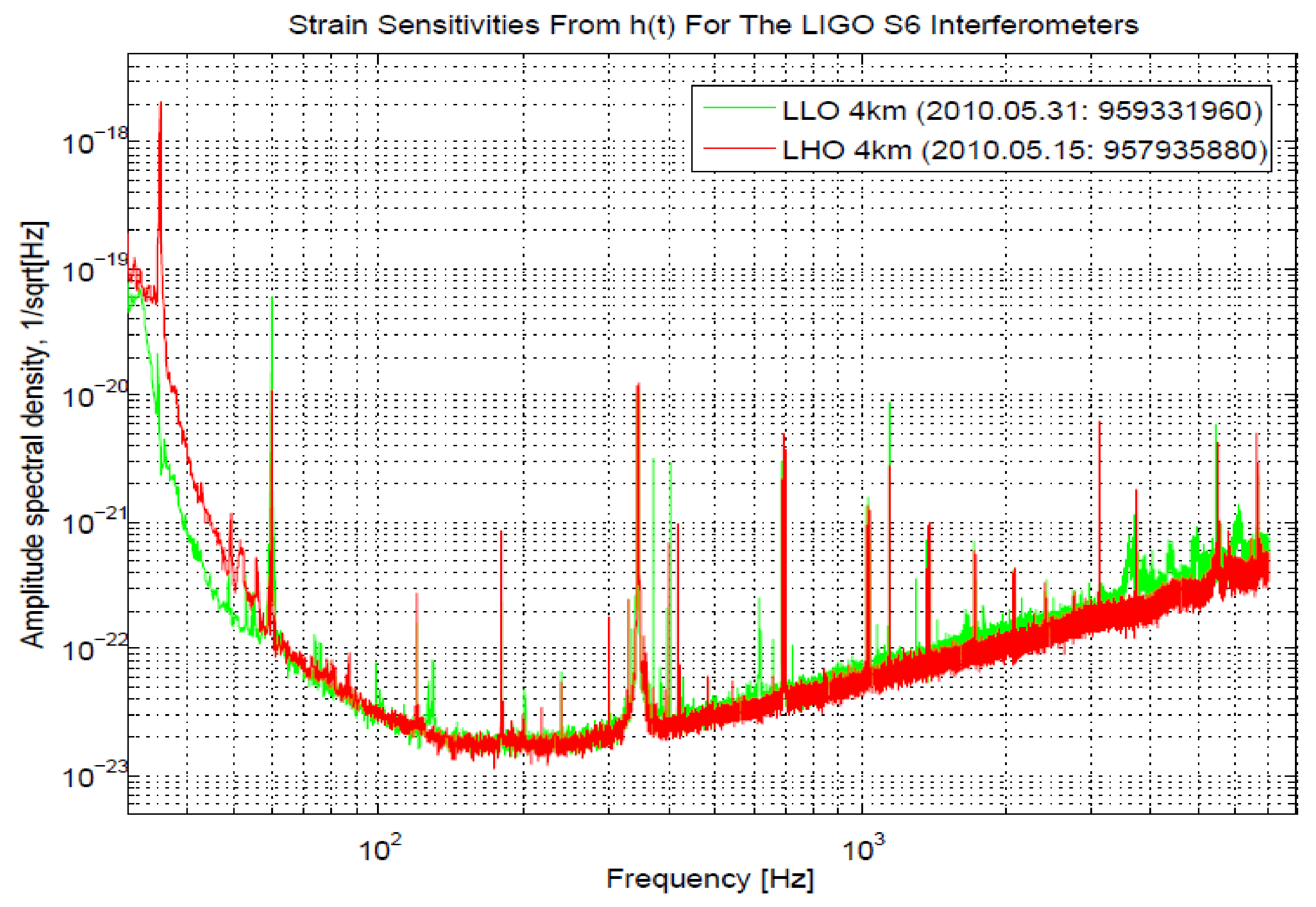
800 kW of laser light in the cavity carries 10^{21} photons per second, giving a sensitivity of

$$\Delta N / N \sim 10^{-11} \quad \longrightarrow \quad \frac{\Delta x}{L} \sim \frac{\lambda}{L_{eff}} \frac{\Delta N}{N} \sim 10^{-24}$$

Initial LIGO design sensitivity



Initial LIGO actual sensitivity



Latest Initial LIGO runs

LIGO S5 run: Nov 2005 – Oct. 2007
(last 5 months → Virgo VSR1 run) → results published

LIGO S6 run: July 2009 – Oct. 2010
(VSR2 first 6 months, VSR3 after Aug 2010)
→ flagship analyses completed

Phys. Rev. D 85, 082002 (2012) [12 pages]

Search for gravitational waves from low mass compact binary coalescence in LIGO's sixth science run and Virgo's science runs 2 and 3

Download: PDF (795 kB) Export: BibTeX or EndNote (RIS)

J. Abadie *et al.* (LIGO Scientific Collaboration, Virgo Collaboration)
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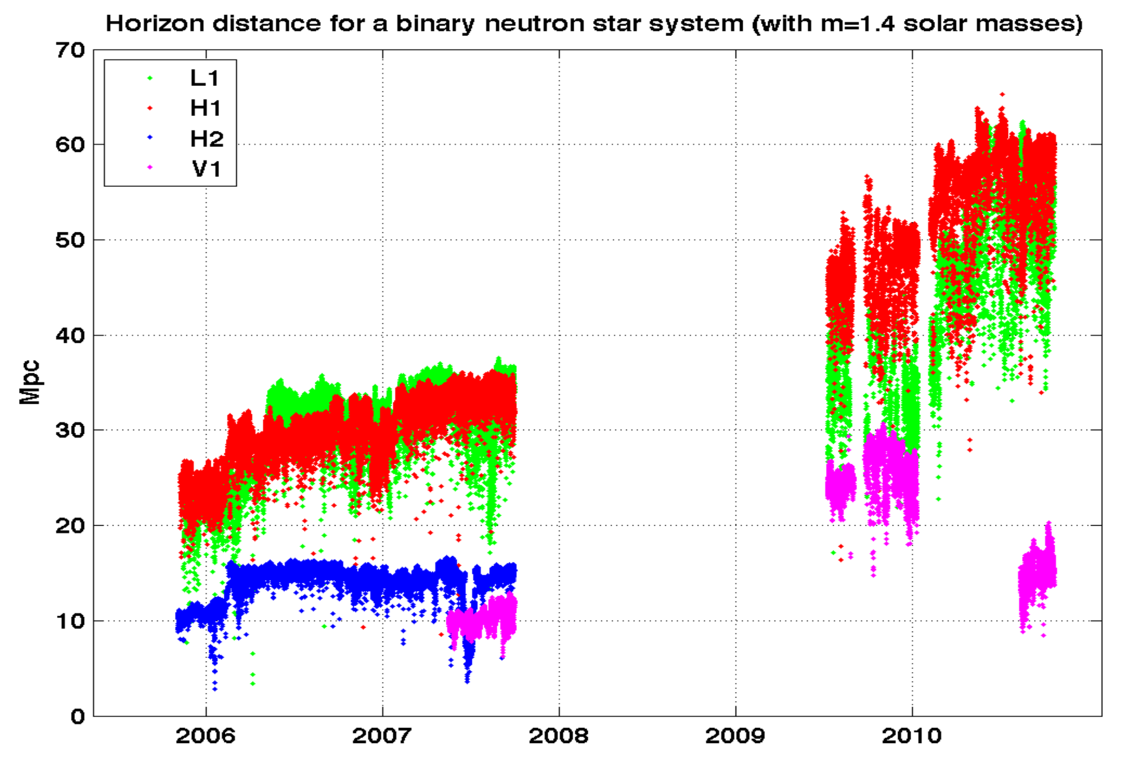
SWIFT **FOLLOW-UP OBSERVATIONS OF CANDIDATE GRAVITATIONAL-WAVE TRANSIENT EVENTS**

Initial LIGO inspiral range



So far…

Design detector ✓

Build detector ✓

Run detector ✓

Reach design sensitivity ✓

Detect gravitational waves ✗ Why?

Expected initial LIGO (CBC) detection rates

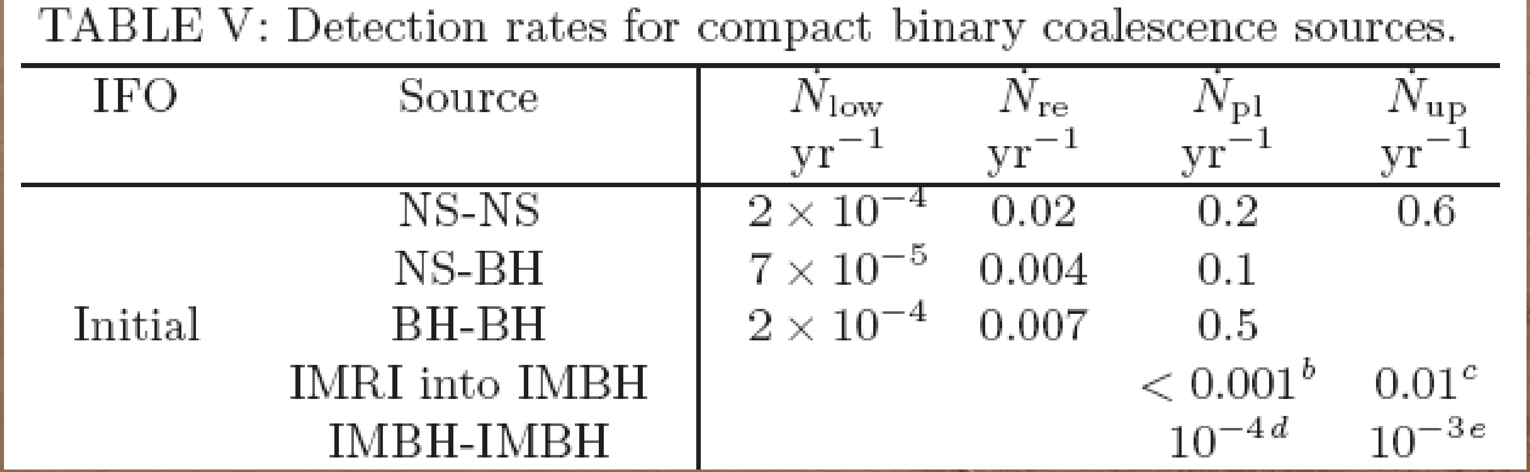


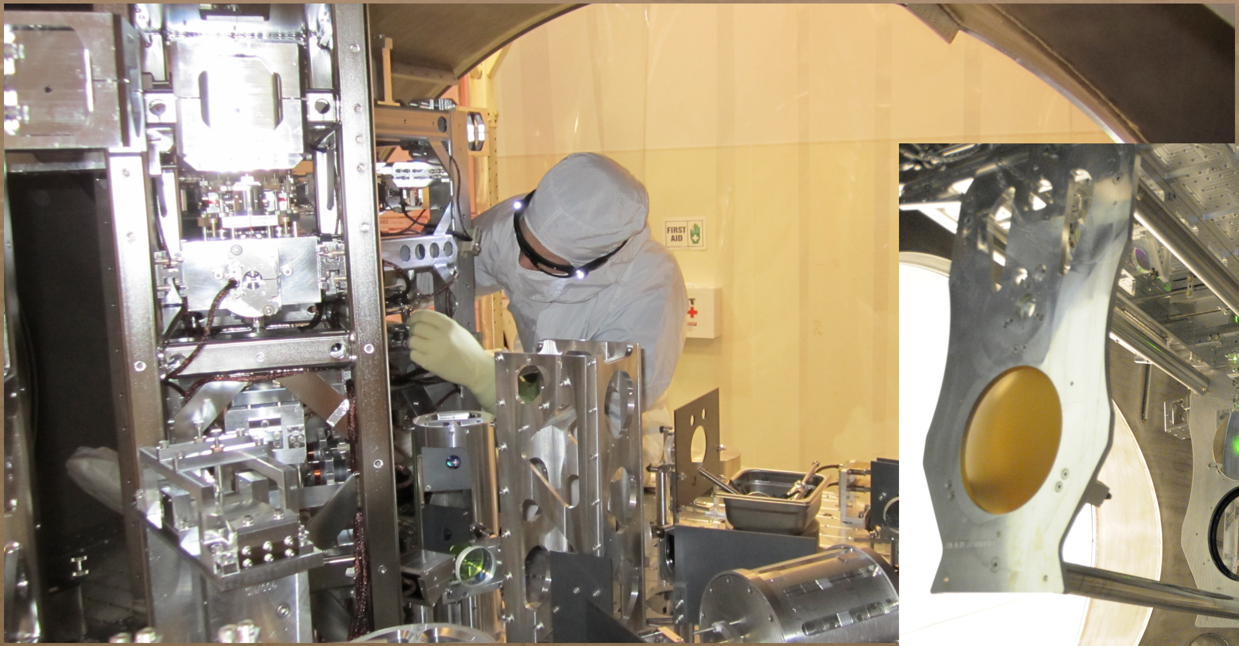
TABLE V: Detection rates for compact binary coalescence sources.

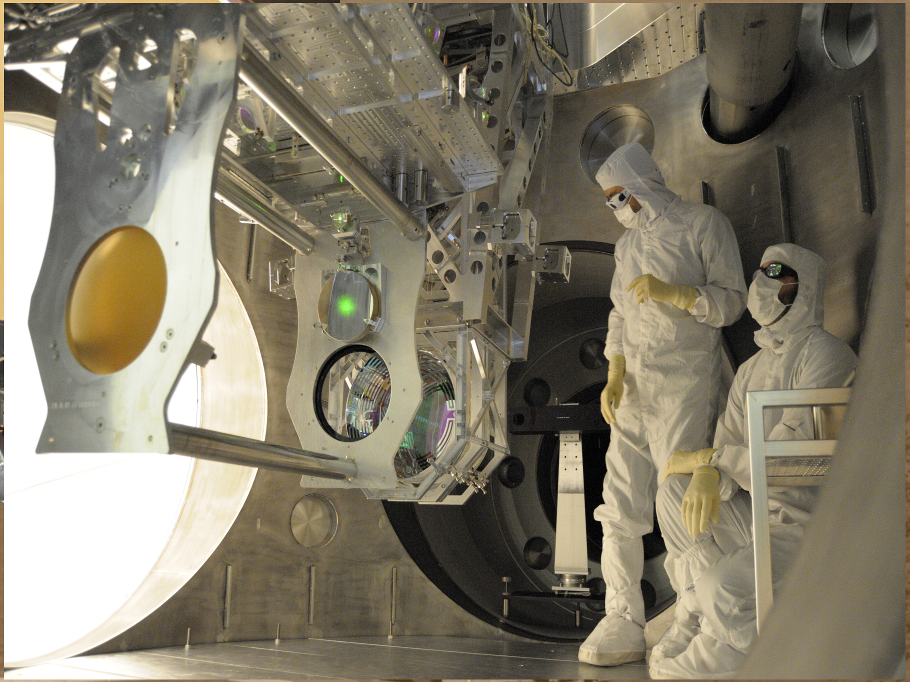
IFO	Source	$\dot{N}_{\rm low}$ $\rm yr^{-1}$	$\dot{N}_{\rm re}$ $\rm yr^{-1}$	$\dot{N}_{\rm pl}$ $\rm yr^{-1}$	$\dot{N}_{\rm up}$ $\rm yr^{-1}$
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^{b}$	0.01^{c}
	IMBH-IMBH			10^{-4d}	10^{-3e}

LIGO Scientific and Virgo Collaborations,“Predictions for the Rates of Compact Binary Coalescences Observable by Ground-based Gravitational-wave Detectors” Class. Quantum Grav. 27 (2010) 173001

So, what’s next?

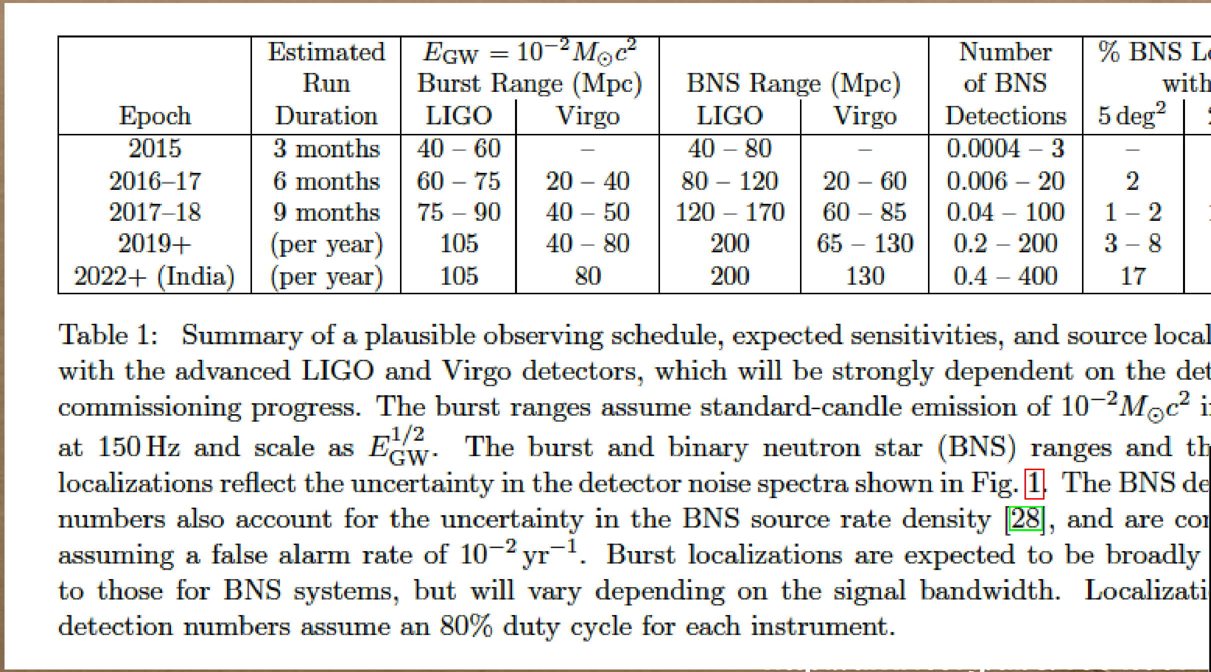
Advanced detectors





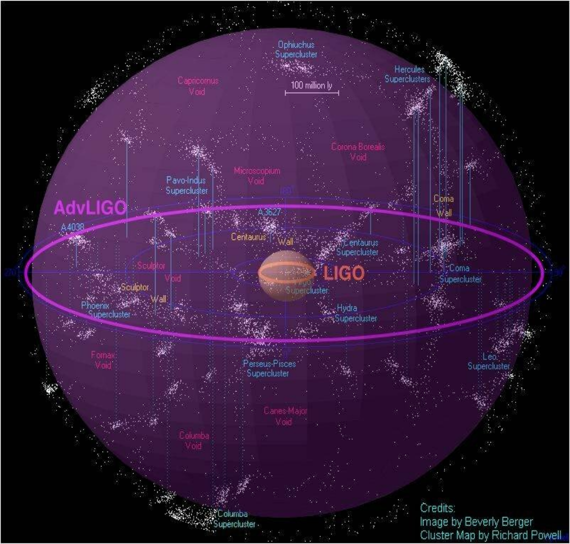
Built on the experience gained from the first generation detectors

Detection rates of advanced detectors



Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Table 1: Summary of a plausible observing schedule, expected sensitivities, and source localization with the advanced LIGO and Virgo detectors, which will be strongly dependent on the detectors' commissioning progress. The burst ranges assume standard-candle emission of $10^{-2} M_\odot c^2$ in GWs at 150 Hz and scale as $E_{\rm GW}^{1/2}$. The burst and binary neutron star (BNS) ranges and th- BNS localizations reflect the uncertainty in the detector noise spectra shown in Fig. 1. The BNS de numbers also account for the uncertainty in the BNS source rate density [28], and are co assuming a false alarm rate of $10^{-2}\,{\rm yr}^{-1}$. Burst localizations are expected to be broadly to those for BNS systems, but will vary depending on the signal bandwidth. Localizati detection numbers assume an 80% duty cycle for each instrument.



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

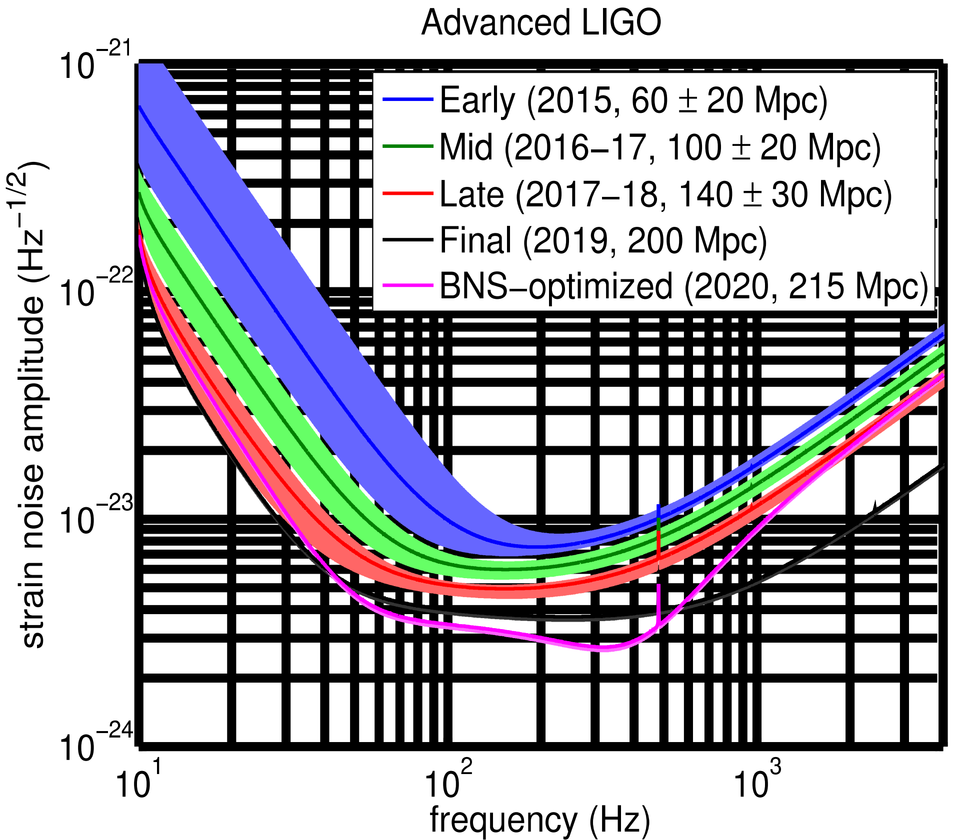
Neutron Star Binaries:

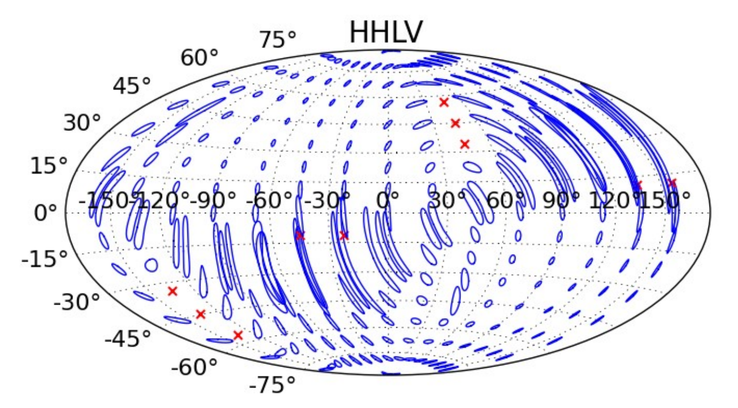
Initial LIGO: ~15 Mpc → rate ~1/50yrs

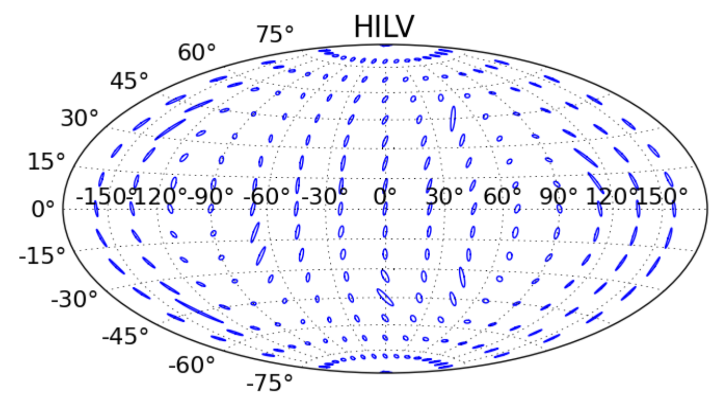
Advanced LIGO: ~ 200 Mpc

→ *"Realistic rate" ~ 40/year*

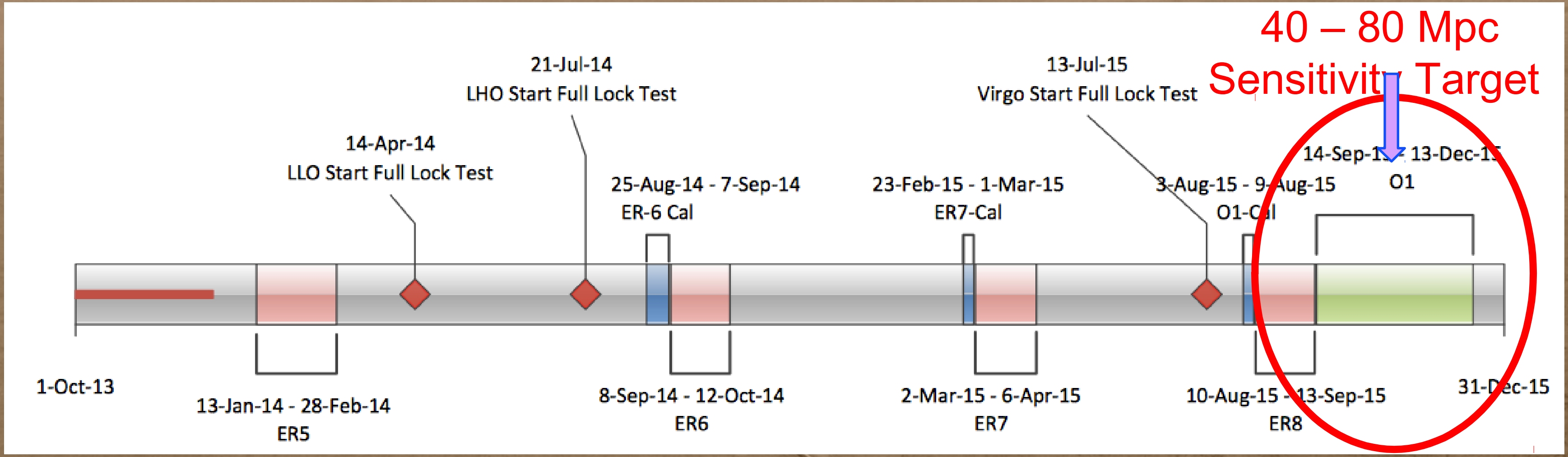
Expected Advanced LIGO sensitivity





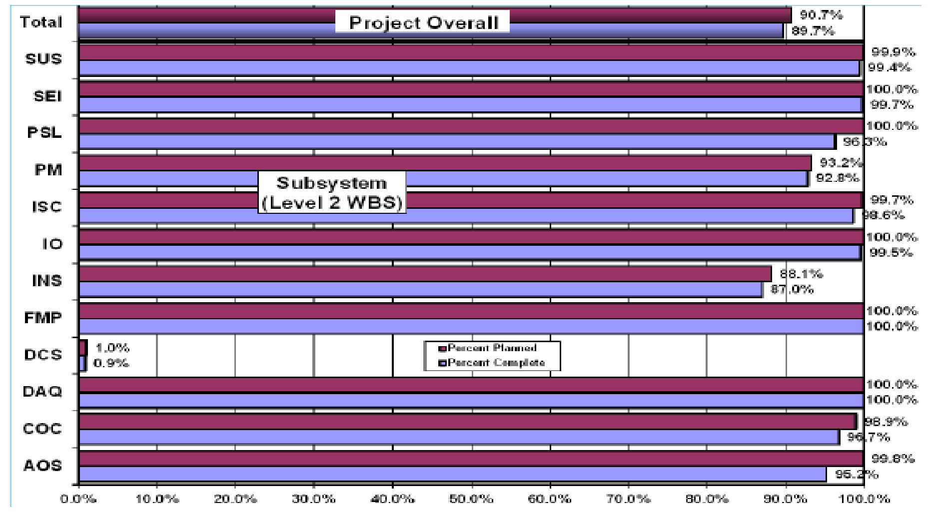


Advanced LIGO schedule



Removal of iLIGO detector and installation of aLIGO ongoing since October 2010

So far, everything as planned!

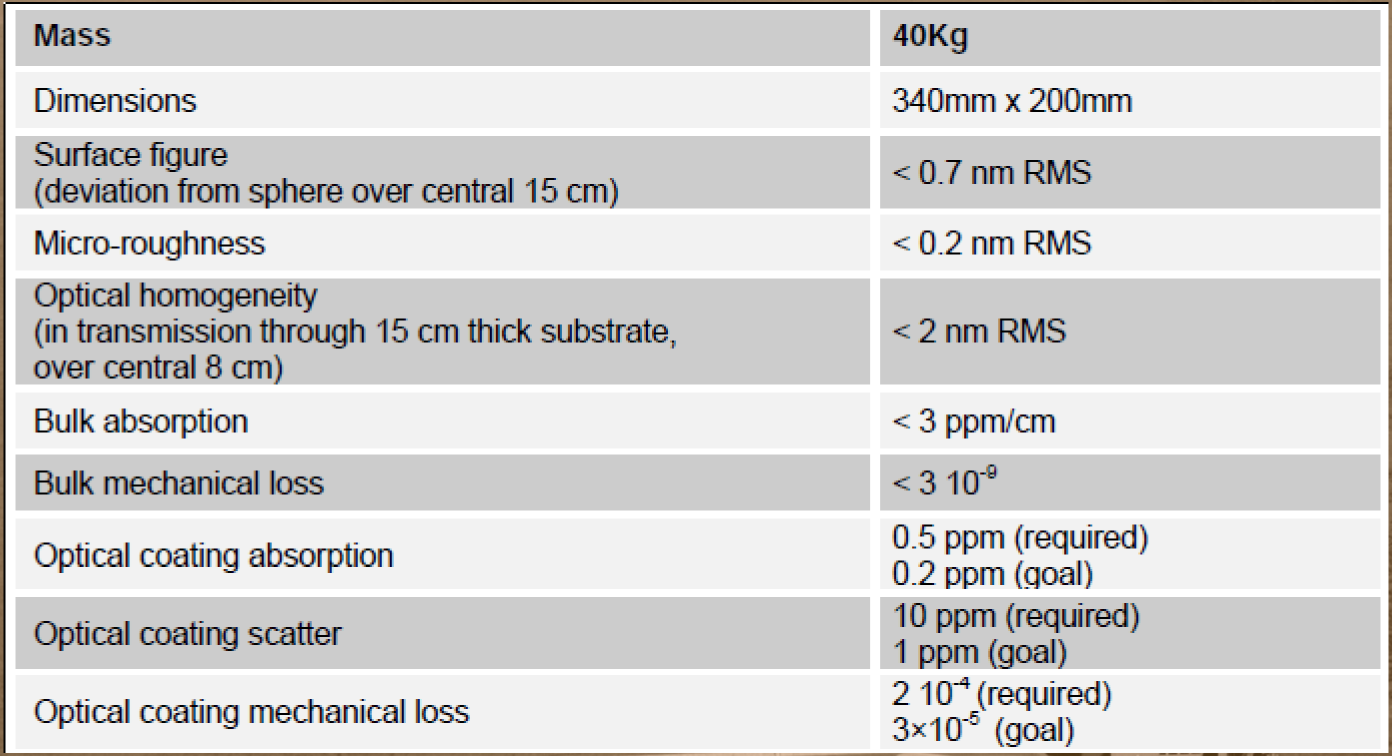


Initial LIGO vs Advanced LIGO

	Initial LIGO	Advanced LIGO
Input laser power	10 W	180 W
Laser power in arm cavities	~10 kW	850 kW
Beam size	4 cm	6 cm
Mirror mass	11 kg	40 kg
Mirror diameter	25 cm	34 cm
Mirror suspensions	Single Pendulum, steel wire	Quadruple pendulum, fused silica
Seismic isolation system	5 stage passive	3 stage active, 4 stage passive

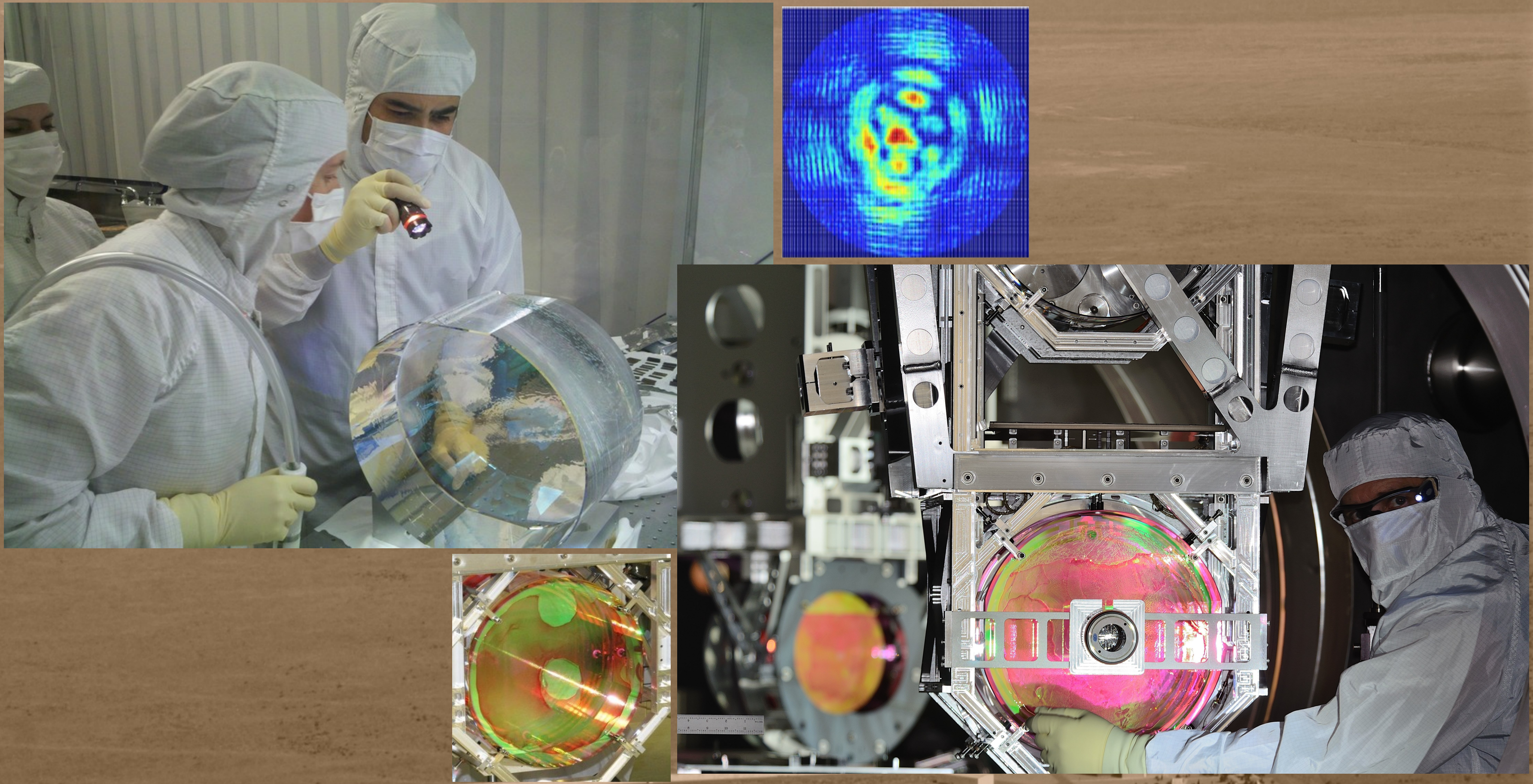
Vacuum equipment

Core optics parameters

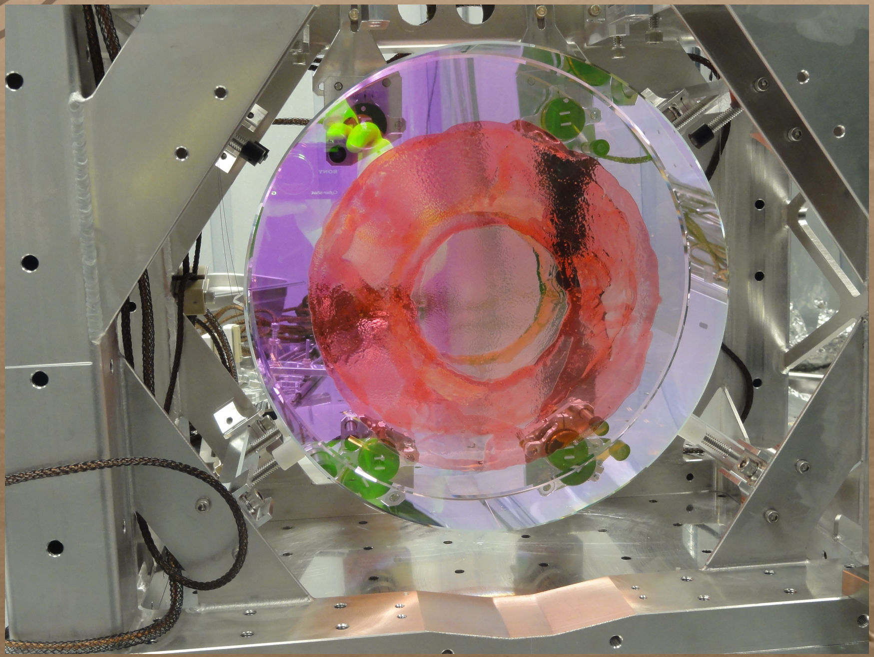


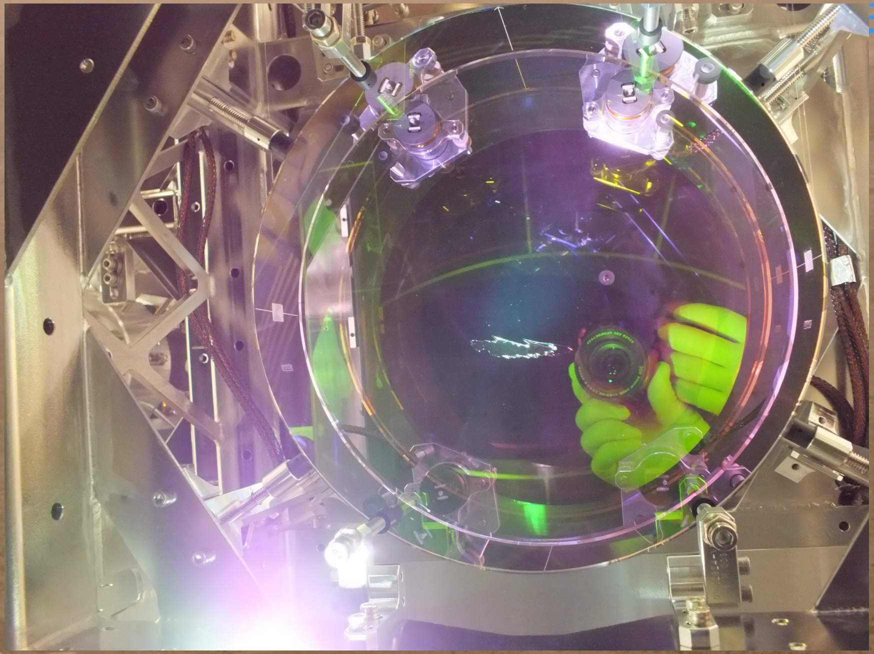
Mass	**40Kg**
Dimensions	340mm x 200mm
Surface figure (deviation from sphere over central 15 cm)	< 0.7 nm RMS
Micro-roughness	< 0.2 nm RMS
Optical homogeneity (in transmission through 15 cm thick substrate, over central 8 cm)	< 2 nm RMS
Bulk absorption	< 3 ppm/cm
Bulk mechanical loss	$< 3\ 10^{-9}$
Optical coating absorption	0.5 ppm (required) 0.2 ppm (goal)
Optical coating scatter	10 ppm (required) 1 ppm (goal)
Optical coating mechanical loss	$2\ 10^{-4}$ (required) 3×10^{-5} (goal)

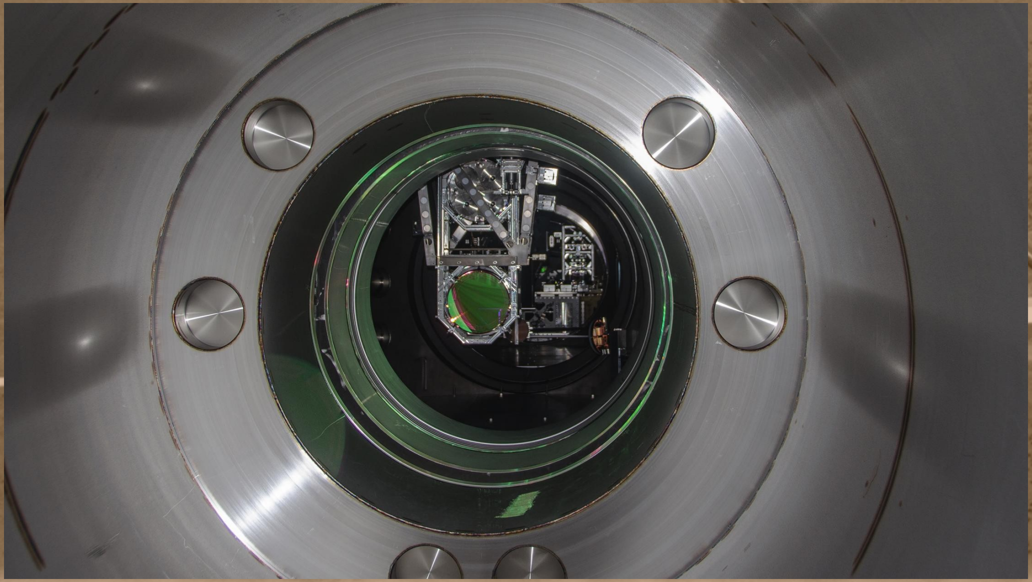
Core optics



Low absorption fused silica (surface < 0.7 nm RMS, micro-roughness < 0.2 nm RMS, 34 cm diameter 20 cm thickness, 40 kg mass)





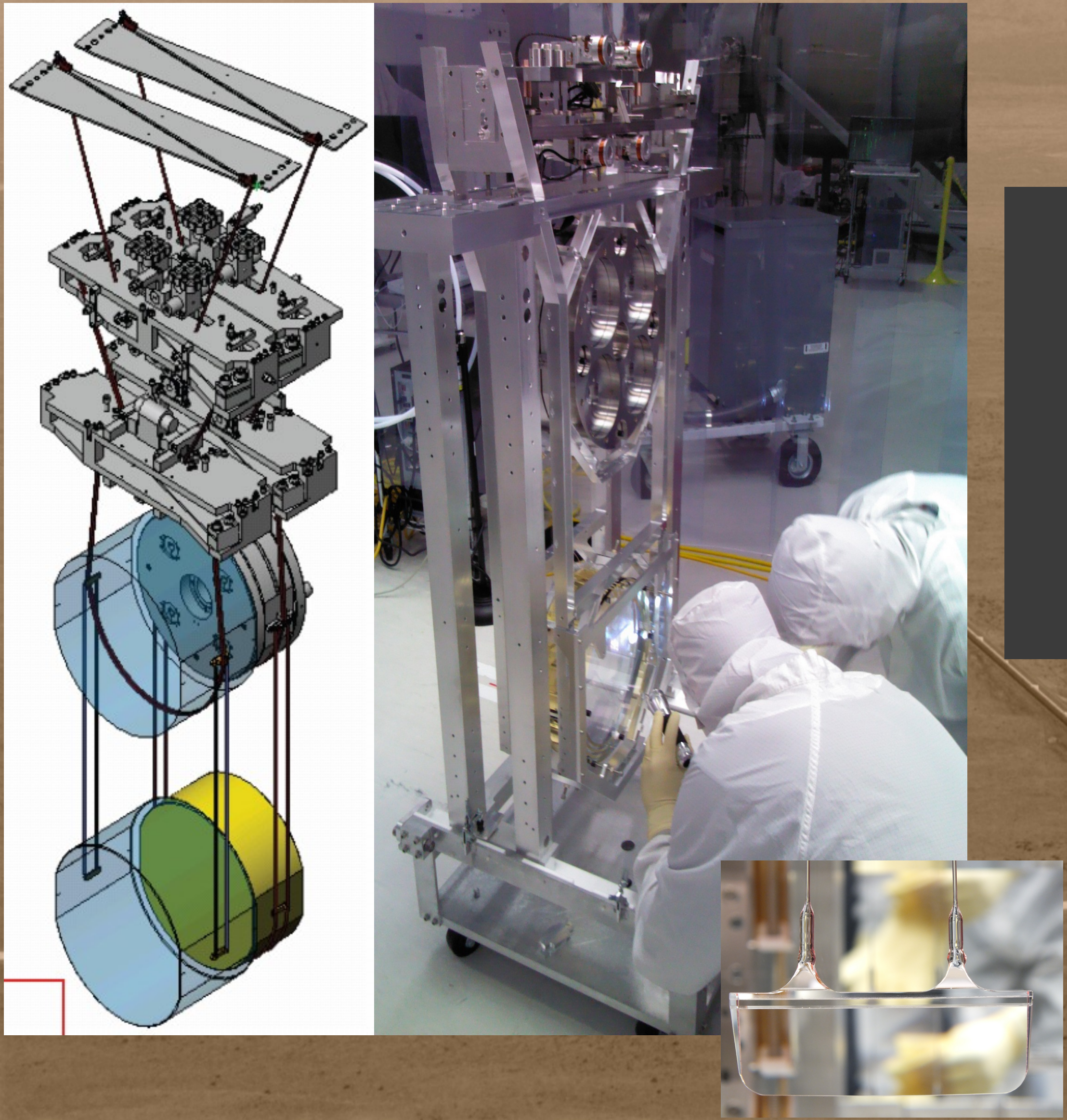


View from beam tube

Test mass suspension parameters

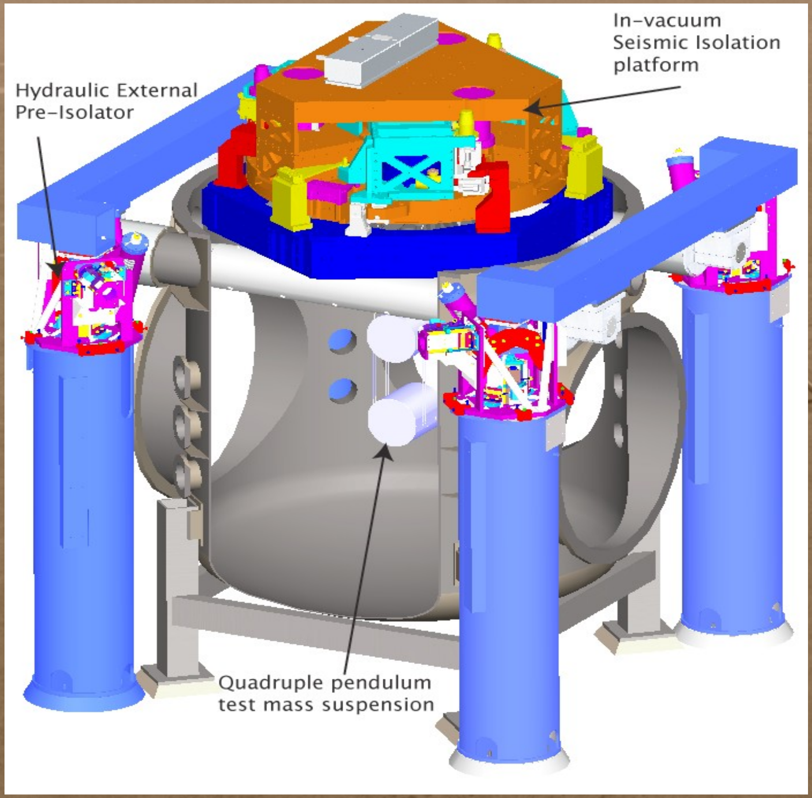
Suspension Parameter	Value
Test mass	40 kg, silica
Penultimate mass	40 kg, silica (lower quality)
Top and upper intermediate masses	22 kg each, stainless steel
Test mass suspension fiber	Fused silica tapered fiber
Upper mass suspension fibers	Steel
Approximate suspension lengths	0.6 m test mass, 0.3, 0.3 m intermediate stages, 0.4 m top
Vertical compliance	Trapezoidal cantilever springs
Optic-axis transmission at 10 Hz	$\sim 2 \times 10^{-7}$
Test mass actuation	Electrostatic (acquisition and operation)
Upper stages of actuation; sensing	Magnets/coils; incoherent occultation sensors

Suspensions



Suspended by fused silica tapered fibers attached with hydroxy-catalysis bonds

Seismic isolation system

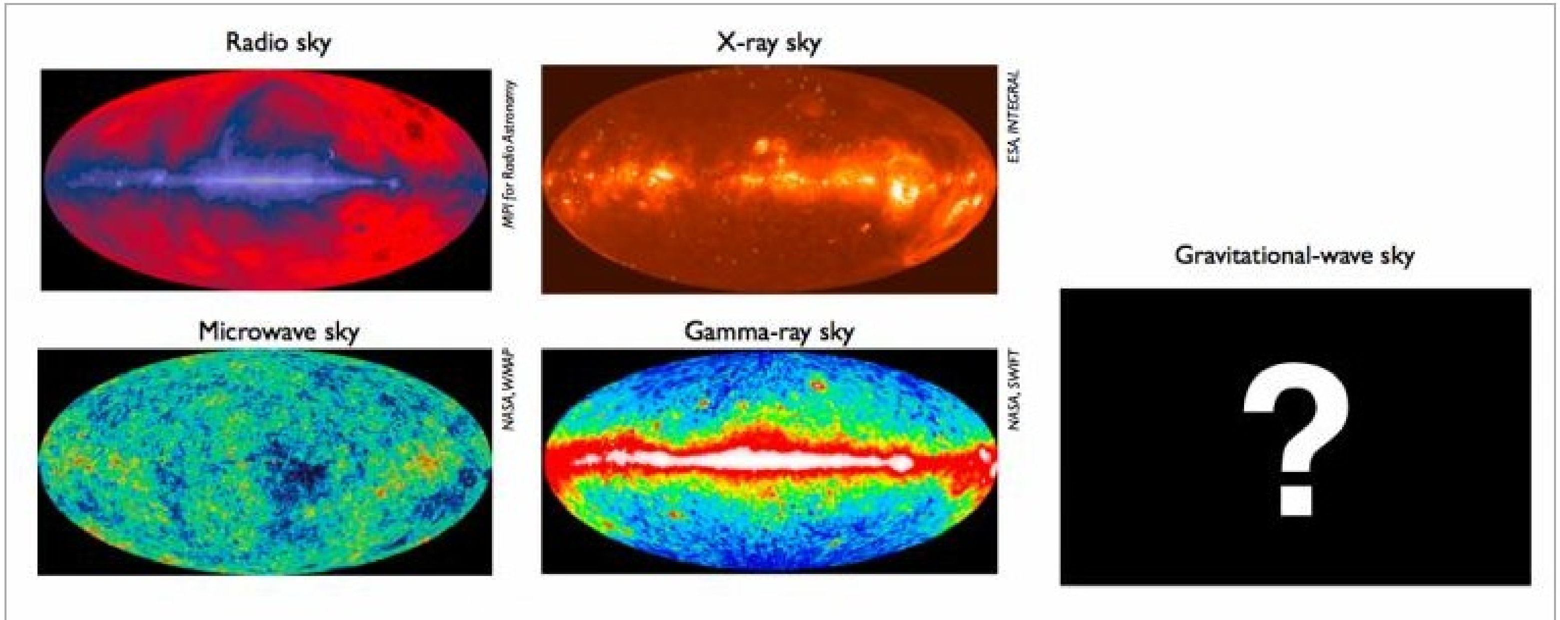


Hydraulic external (to the vacuum) pre-isolator stage and in-vacuum 2-stage active seismic isolation platform give horizontal attenuation > 10^{-10} at 10 Hz

Pre-Stabilized Laser

Input laser power of 180 W. Stored cavity powers 850 kW.

Advanced detectors will open a new window on the universe



Different windows to the Universe.

Stay tuned!

Thanks to Gaby Gonzalez, Matthew Heintze, Brian O’Reilly, Dave Reitze, David Shoemaker and the whole LIGO collaboration for building the LIGO detectors and letting me plagiarize their presentations.