AMALDI
RESEARCH CENTER

Gravitational Waves: A Revolution in the Way We Study the Universe

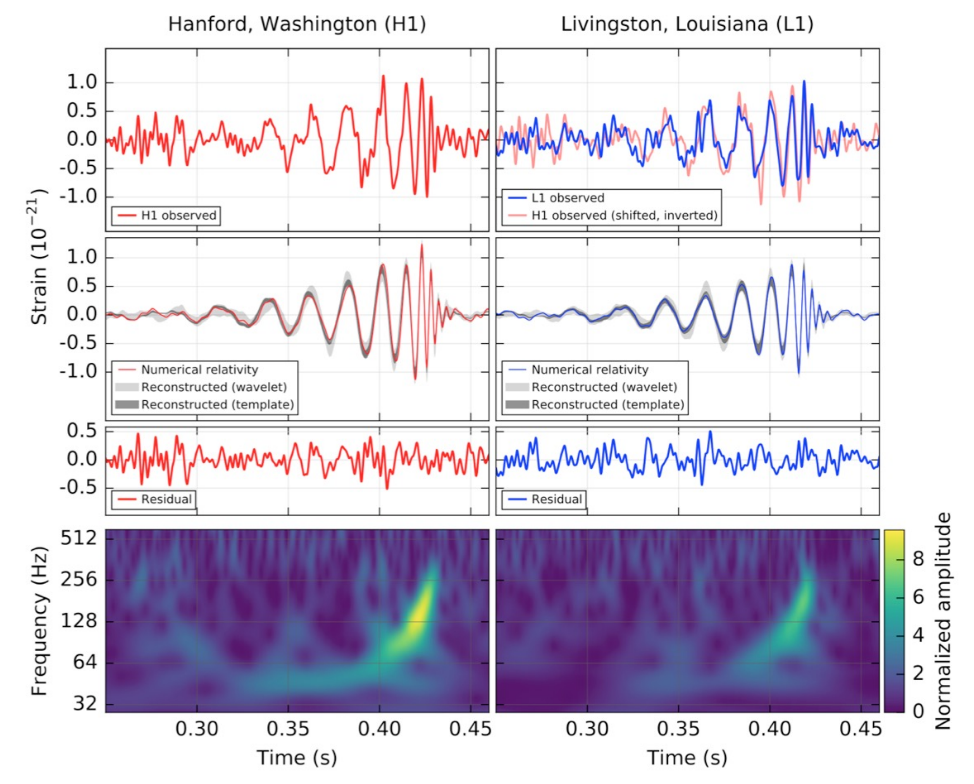
Irene Di Palma
University of Rome
La Sapienza and INFN
Irene.DiPalma@uniroma1.it

Image Credit: Aurore Simmonet/SSU

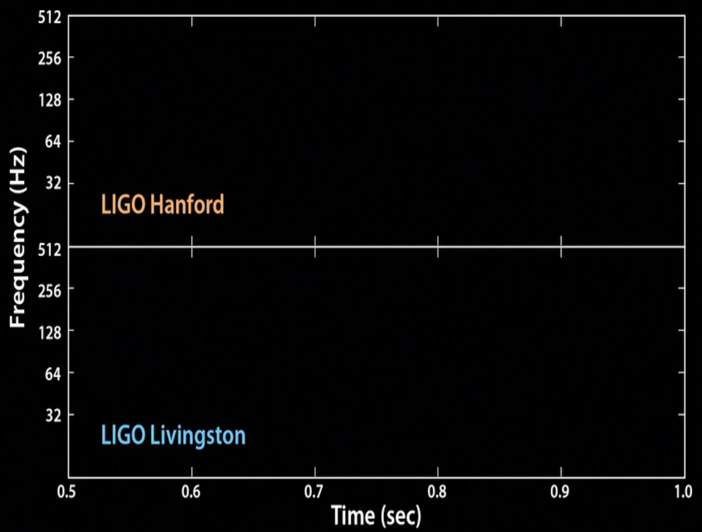
Schedule for the week

- ***Monday:*** Gravitational Waves: basic and data analysis
- ***Tuesday:*** Interferometric detectors of Gravitational Waves
- ***Wednesday:*** 90 Gravitational Wave detections: what did we learn?
- ***Thursday:*** Multimessenger probes
- ***Hands-on session:*** Gravitational Wave Open Science Center

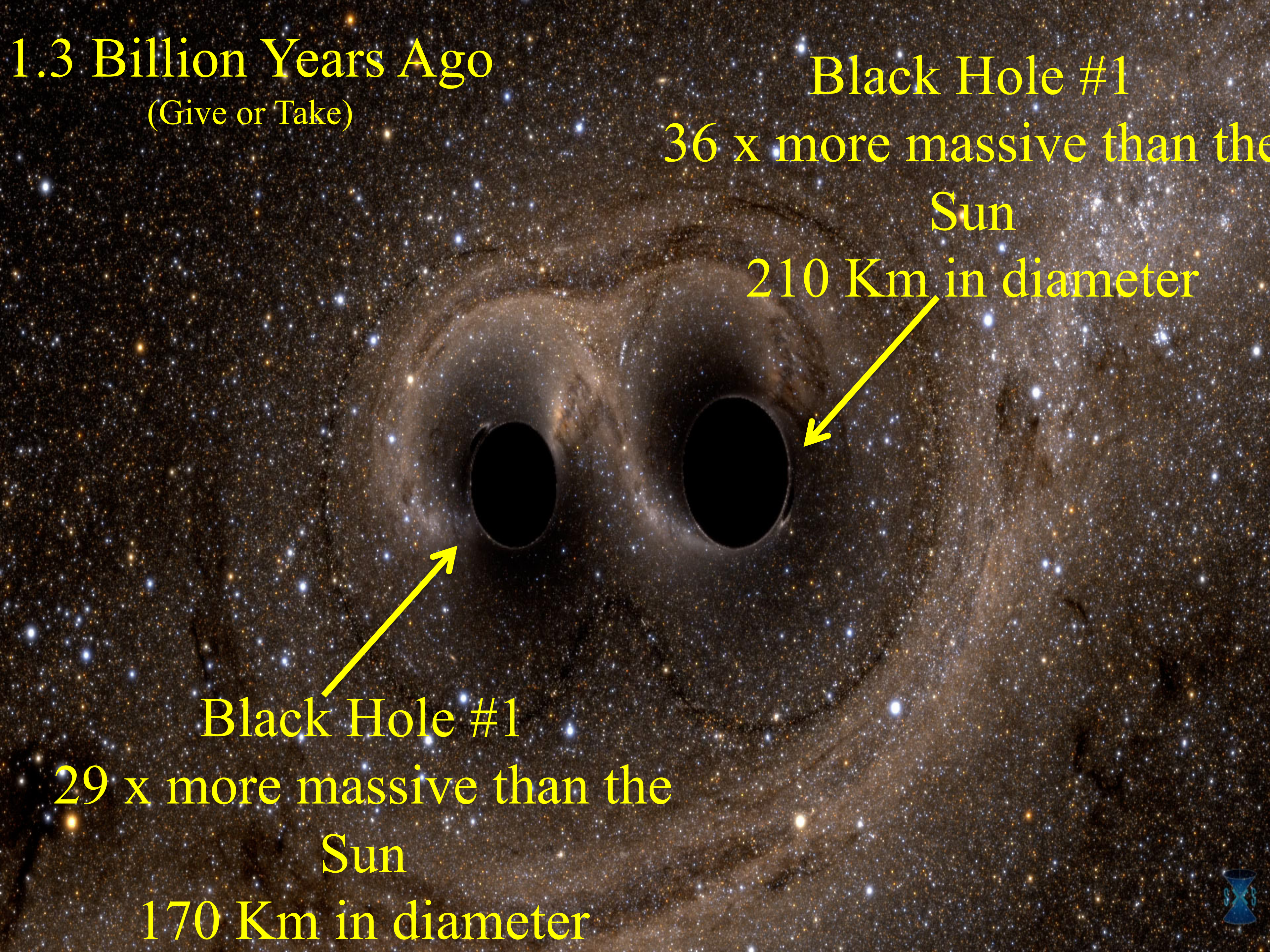
GW150914: The First Binary Black Hole Merger




Andy Bohn, François Hébert, and William Throwe, SXS Collaboration



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)



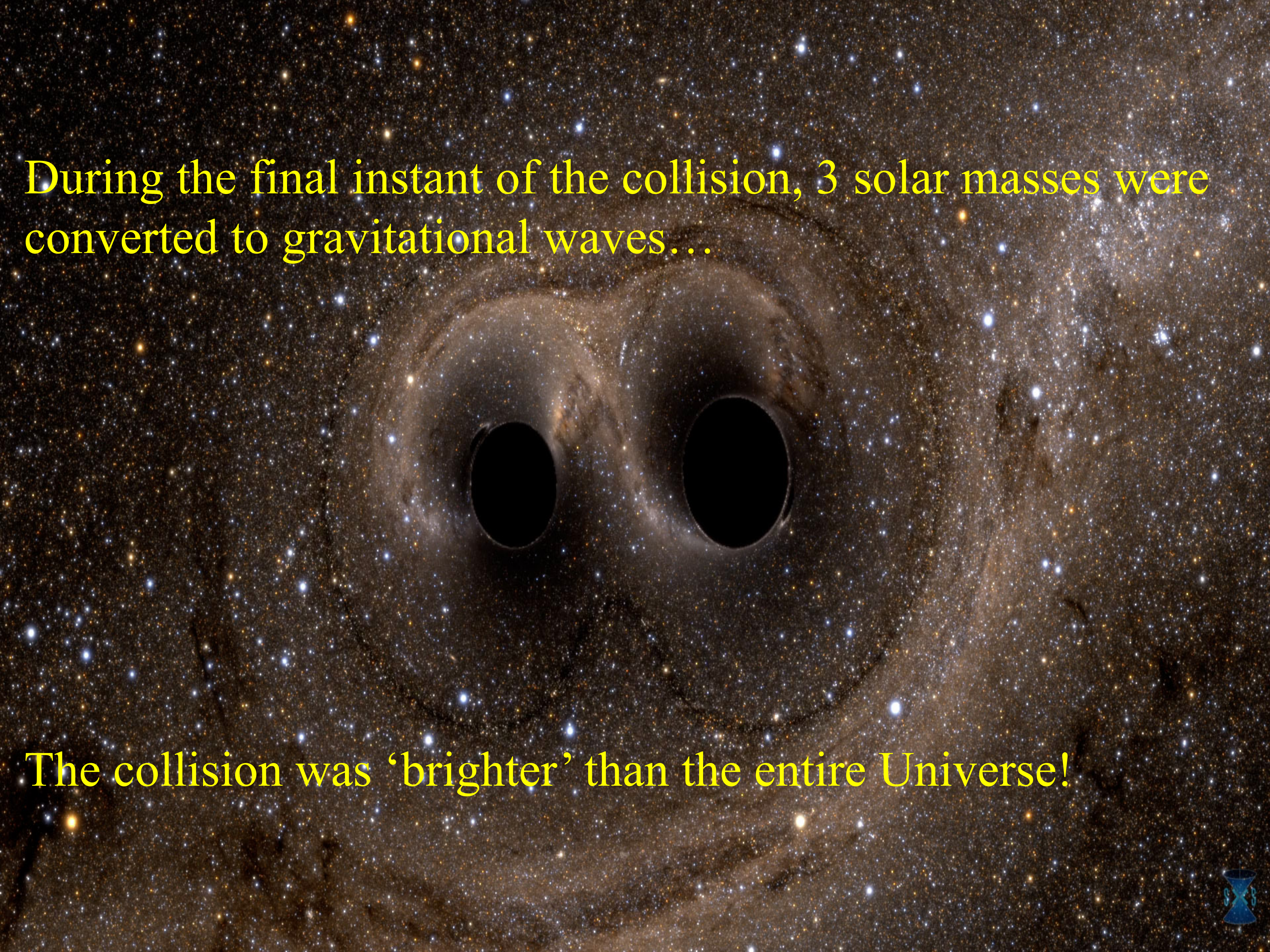
1.3 Billion Years Ago

(Give or Take)

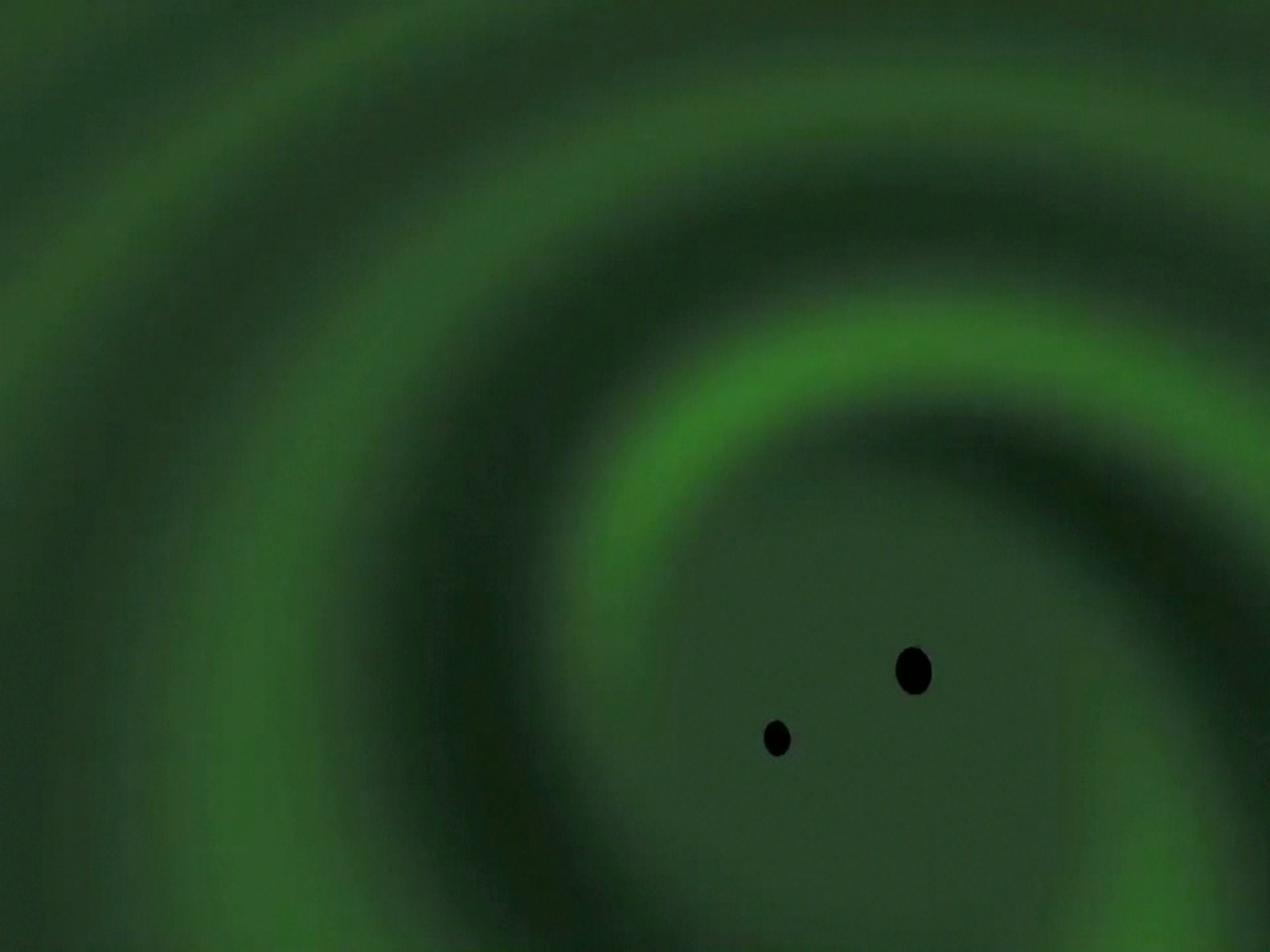
Black Hole #1
36 x more massive than the
Sun
210 Km in diameter

Black Hole #1
29 x more massive than the
Sun
170 Km in diameter

During the final instant of the collision, 3 solar masses were converted to gravitational waves…



The collision was ‘brighter’ than the entire Universe!



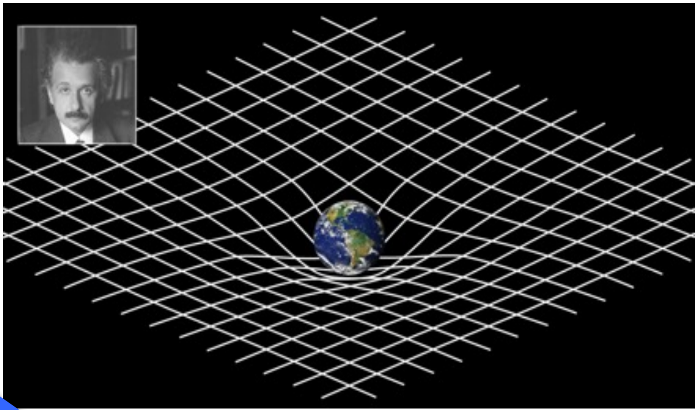
General Relativity and Gravitational Waves

Einstein field tensor

General Relativity: Einstein Field Equations

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Stress-energy-momentum tensor



~ 10^{-43}

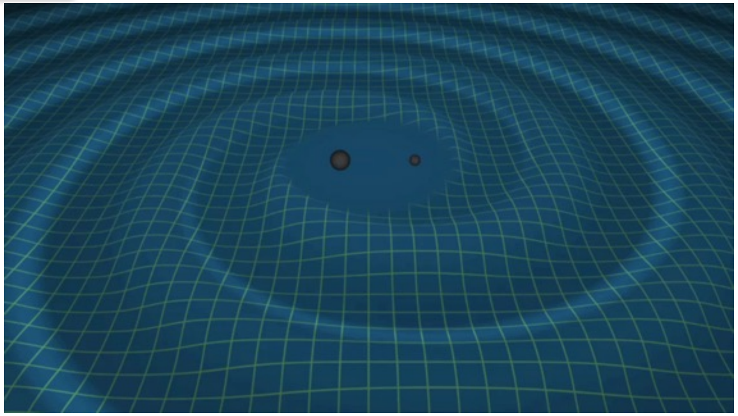
Weak field approximation -- space-time is slightly perturbed from flat space-time:

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$$

Free Space:
$T_{\mu\nu} = 0$

Wave equation for $h_{\mu\nu}$!

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h_{\mu\nu} = 0$$



A. Einstein, *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften* (Berlin,1916), 688696; *Sitzungsberichte der Kniglich Preussischen Akademie der Wissenschaften* (Berlin, 1918), 154167.

Gravitational Waves

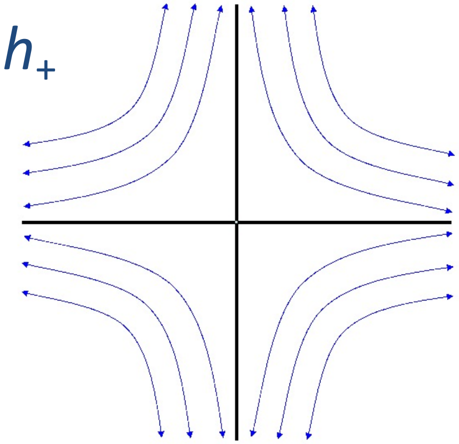
Solution for an outward propagating wave in z-direction:

$$\boxed{h(t,z) = h_{\mu\nu} e^{i(\omega t - kz)} = h_+(t - z/c) + h_\times(t - z/c)}$$

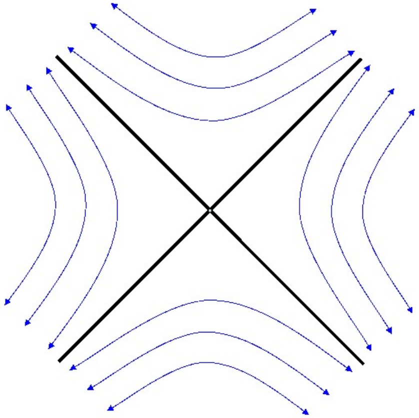
$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

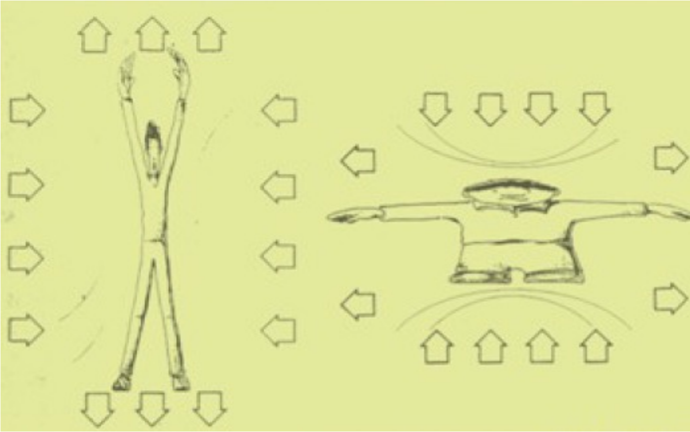
Physically, *h* is a *strain*: ΔL/L

h_+



h_x





Basic Analysis Concepts

The output of a gravitational wave detector is a time series $s(t)$ that includes instrument noise $n(t)$ and the response to the gravitational wave signal $h(t)$:

$$s(t) = F^{+}(t)h_{+}(t) + F^{\times}(t)h_{\times}(t) + n(t).$$

The instrument response is a convolution of the antenna patterns $F^{+}, F^{\times}$ with the two gravitational wave polarizations $h_{+}, h_{\times}$.

The information contained in the time series is usually represented in the Fourier domain as a strain amplitude spectral density, $h(f)$. This quantity is defined in terms of the power spectral density $S_s(f) = \tilde{s}^*(f)\tilde{s}(f)$ of the Fourier transform of the time series

$$\tilde{s}(f) = \int_{-\infty}^{\infty} e^{-2\pi i f t}\, s(t)\, dt.$$

A commonly used quantity for sensitivity curves is the square root of the PSD or the amplitude spectral density

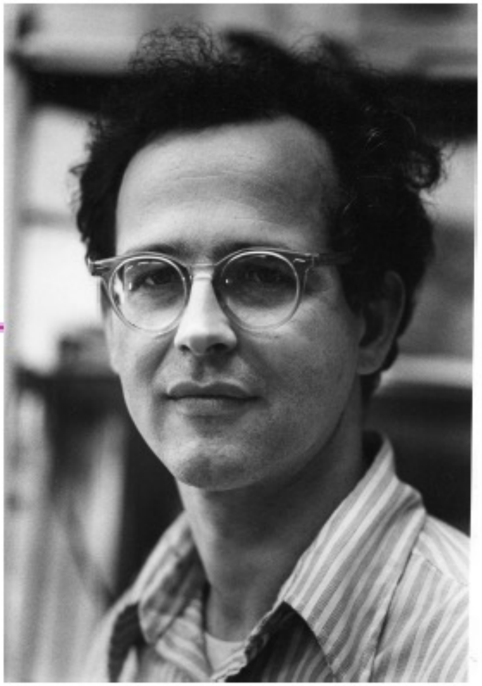
$$\sqrt{S_s\,(f)} = h_n(f) f^{-1/2}$$

General Relativity and Gravitational Waves

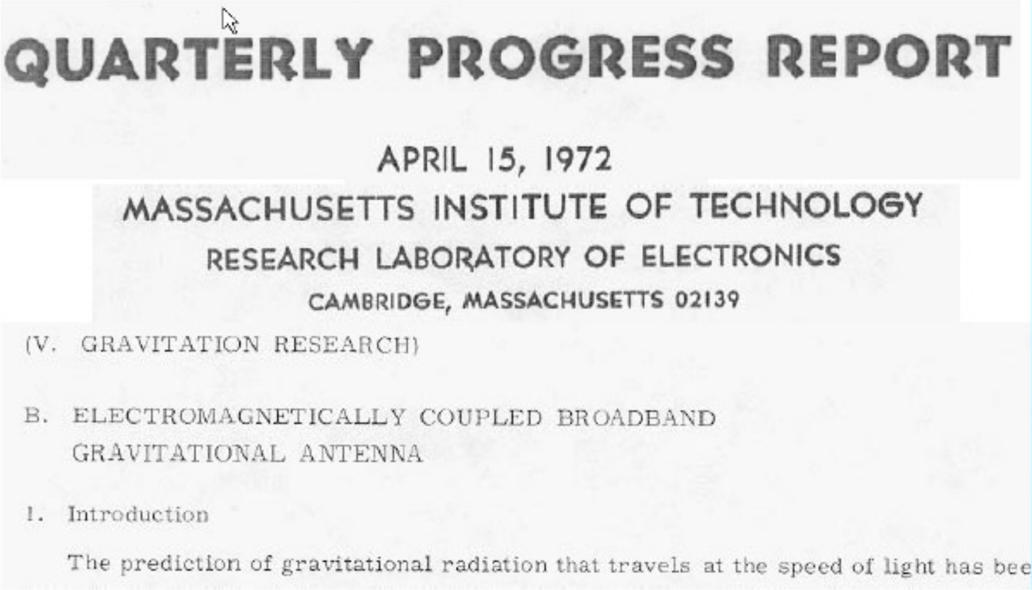
- Predictions from GR allow us to search for gravitational waves from compact binary mergers using large numbers of waveform templates
- LIGO-Virgo noise features present challenges for identification of gravitational-wave signals
- Current searches rely on matched-filtering, with signal tests to account for non-Gaussianities
- Also use unmodelled searches to catch the unexpected
- We have found lots already - let’s find more!

From G1101133 by D.H.Shoemaker

In the beginning



- Rai Weiss of MIT was teaching a course on GR in the late ‘60s
- Wanted a good homework problem for the students
- Why not ask them to work out how to use laser interferometry to detect gravitational waves?
- …led to the instruction book we have been following ever since



QUARTERLY PROGRESS REPORT

APRIL 15, 1972

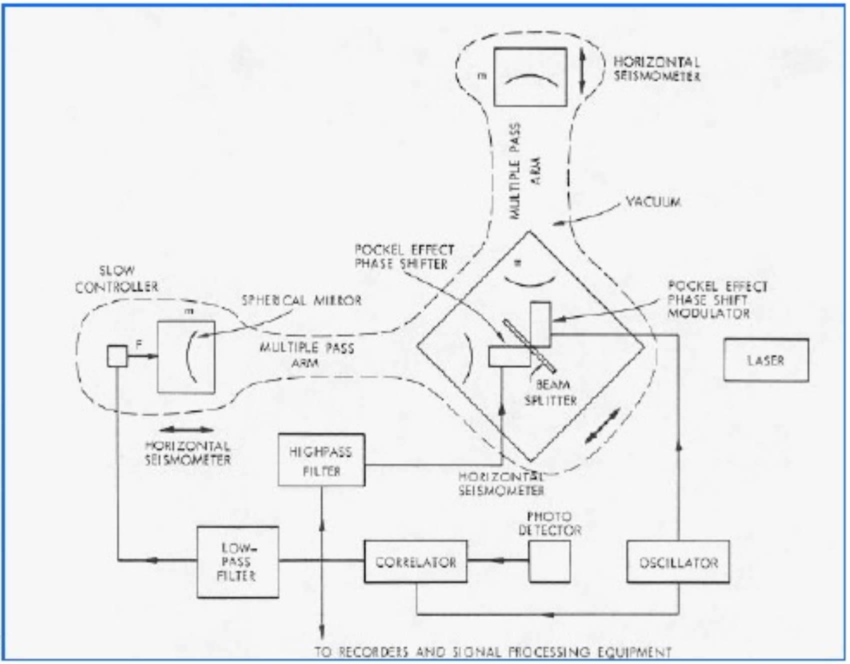
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
RESEARCH LABORATORY OF ELECTRONICS
CAMBRIDGE, MASSACHUSETTS 02139

(V. GRAVITATION RESEARCH)

B. ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

1. Introduction

The prediction of gravitational radiation that travels at the speed of light has bee




Drever

LIGO Chronology

idea to realization ~ 15 years


Weiss

Real size R&D for the real detection

Journey for the new astronomy

1970s		Feasibility studies and early work on laser interferometer gravitational-wave detectors
1979		National Science Foundation (NSF) funds Caltech and MIT for laser interferometer R&D
1984		Development of multiple pendulum Advanced LIGO Concept
1989	**December**	**Construction proposal for LIGO submitted to the NSF ($365M as of 2002)**
1990	May	National Science Board approves LIGO construction proposal
1994	July	Groundbreaking at Hanford site
1999		LIGO Scientific Collaboration White Paper on a Advanced LIGO interferometer concept
2000	October	Achieved "first lock" on Hanford 2-km interferometer in power-recycled configuration
2002	August	First scientific operation of all three interferometers in S1 run
2003		**Proposal for Advanced LIGO to the NSF ($205 NSF + $30 UK+German**
2004	October	Approval by NSB of Advanced LIGO
2005	**November**	**Start of initial LIGO Science run, S5, with design sensitivity**
2008	April	Advanced LIGO Project start
2009	July	Science run ("S6") starts with enhanced initial detectors
2014	May	Advanced LIGO Livingston first two-hour lock
2015	March	Advanced LIGO all interferometers accepted
2015	September	Advanced LIGO observation run 1 scheduled


Vogt

Initial LIGO events
Advanced LIGO events
R&D of aLIGO using iLIGO facility

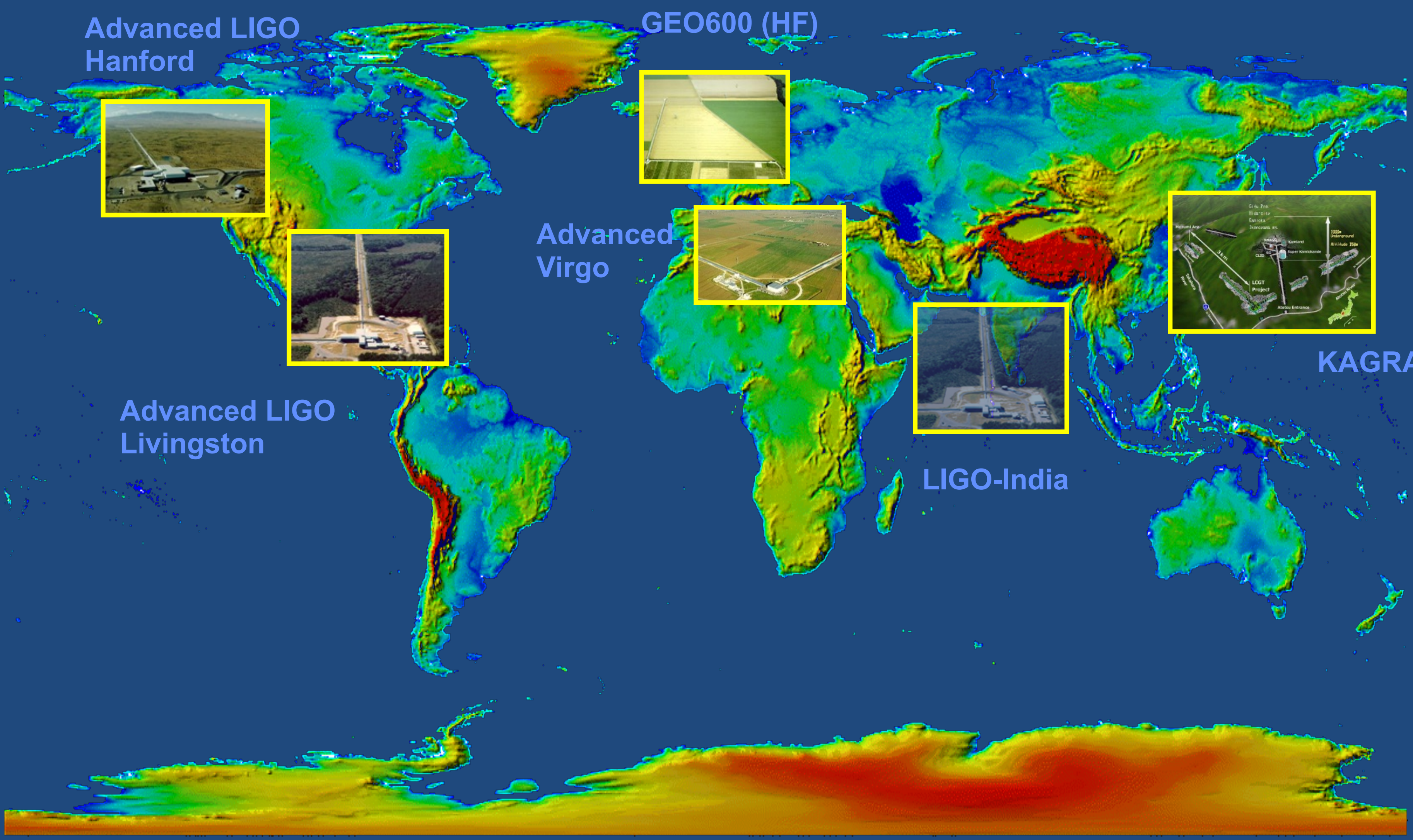

Thorn


Executive producer & consultant of movie "Intersteller"

The Initial and Enhanced GW detector network

- The three Initial LIGO detectors completed five science observation runs (S1-S5) from 2002-2007.
- Virgo's VSR1 was conducted in 2007, jointly with LIGO's S5, which operated at design sensitivity for 2 years.
- Two "Enhanced LIGO" detectors conducted S6 during 2009-2010, jointly with Virgo VSR2 and (enhanced) VSR3.
- Many different searches were done with these data, but no gravitational wave signals were found; upper limits are still above plausible expectations.
- Two Advanced LIGO detectors are now taking data since September 14th 2015.
- The Advanced Virgo started the data acquisition in August 2017, joining the second observation run of LIGO.

The Advanced GW Detector Network



Advanced LIGO Hanford

GEO600 (HF)

Advanced Virgo

KAGRA

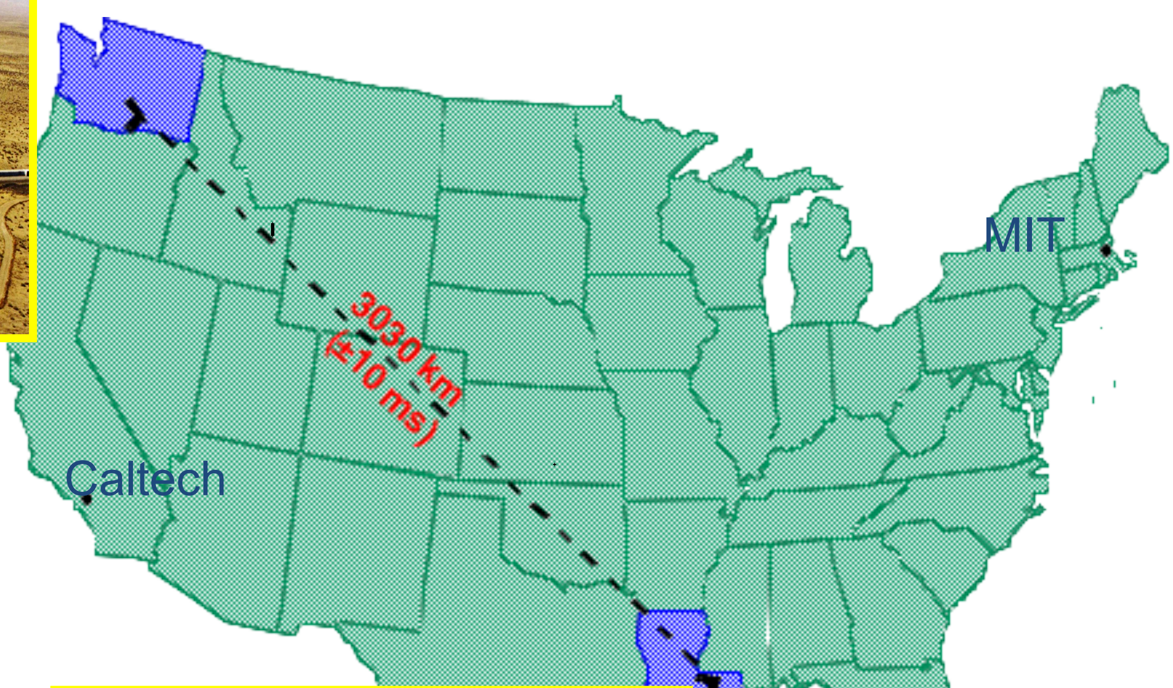
Advanced LIGO Livingston

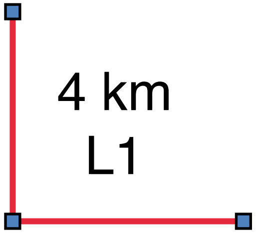
LIGO-India

LIGO: Laser Interferometer Gravitational-wave Observatory

Hanford, WA

4 km (H1)
+ 2 km (H2)





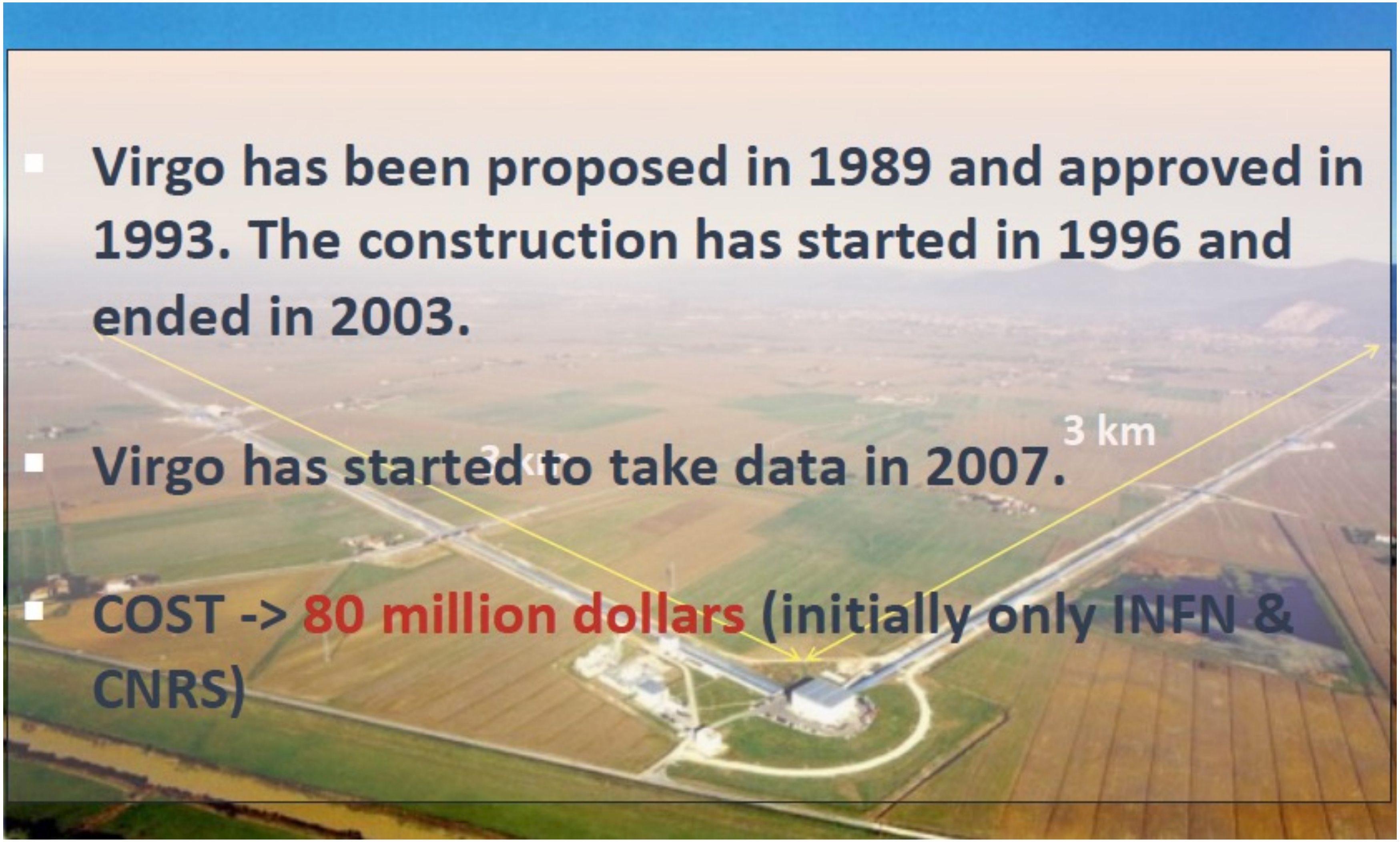
4 km
L1

Livingston, LA

Despite a few difficulties, science runs started in 2002.

Virgo Interferometer

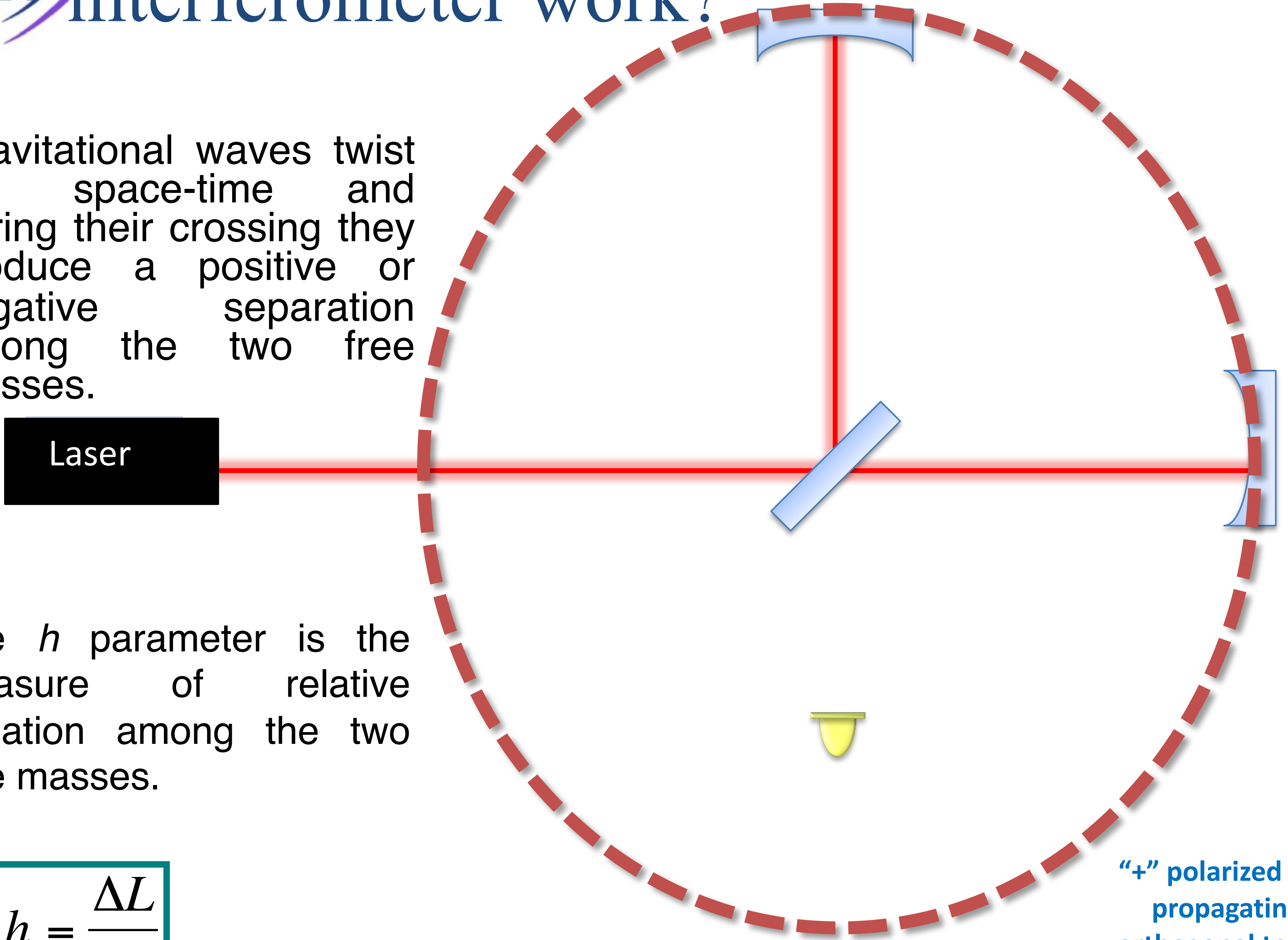
Virgo Interferometer



- Virgo has been proposed in 1989 and approved in 1993. The construction has started in 1996 and ended in 2003.
- Virgo has started to take data in 2007.
- COST -> 80 million dollars (initially only INFN & CNRS)

How does an interferometer work?

- Gravitational waves twist the space-time and during their crossing they produce a positive or negative separation among the two free masses.

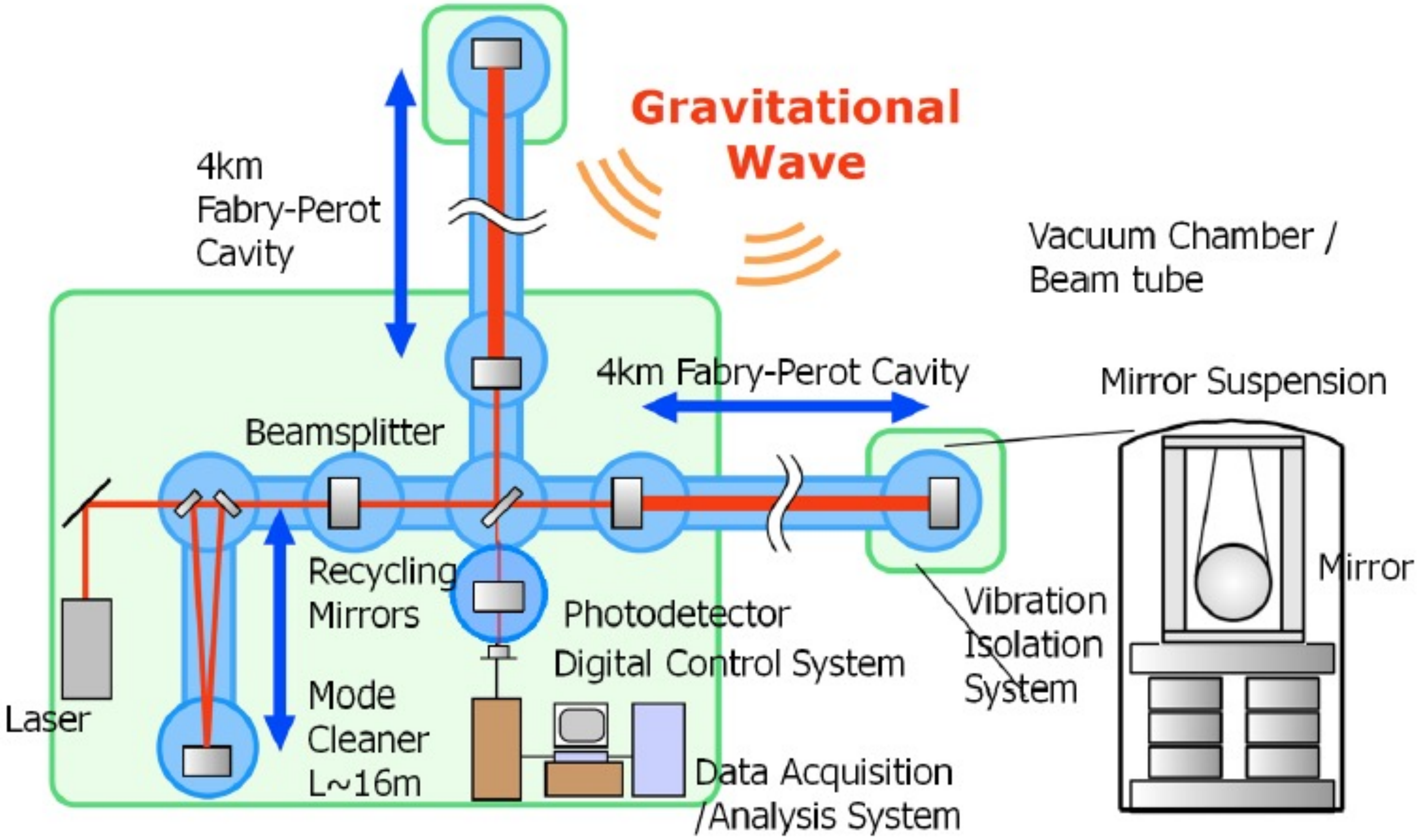


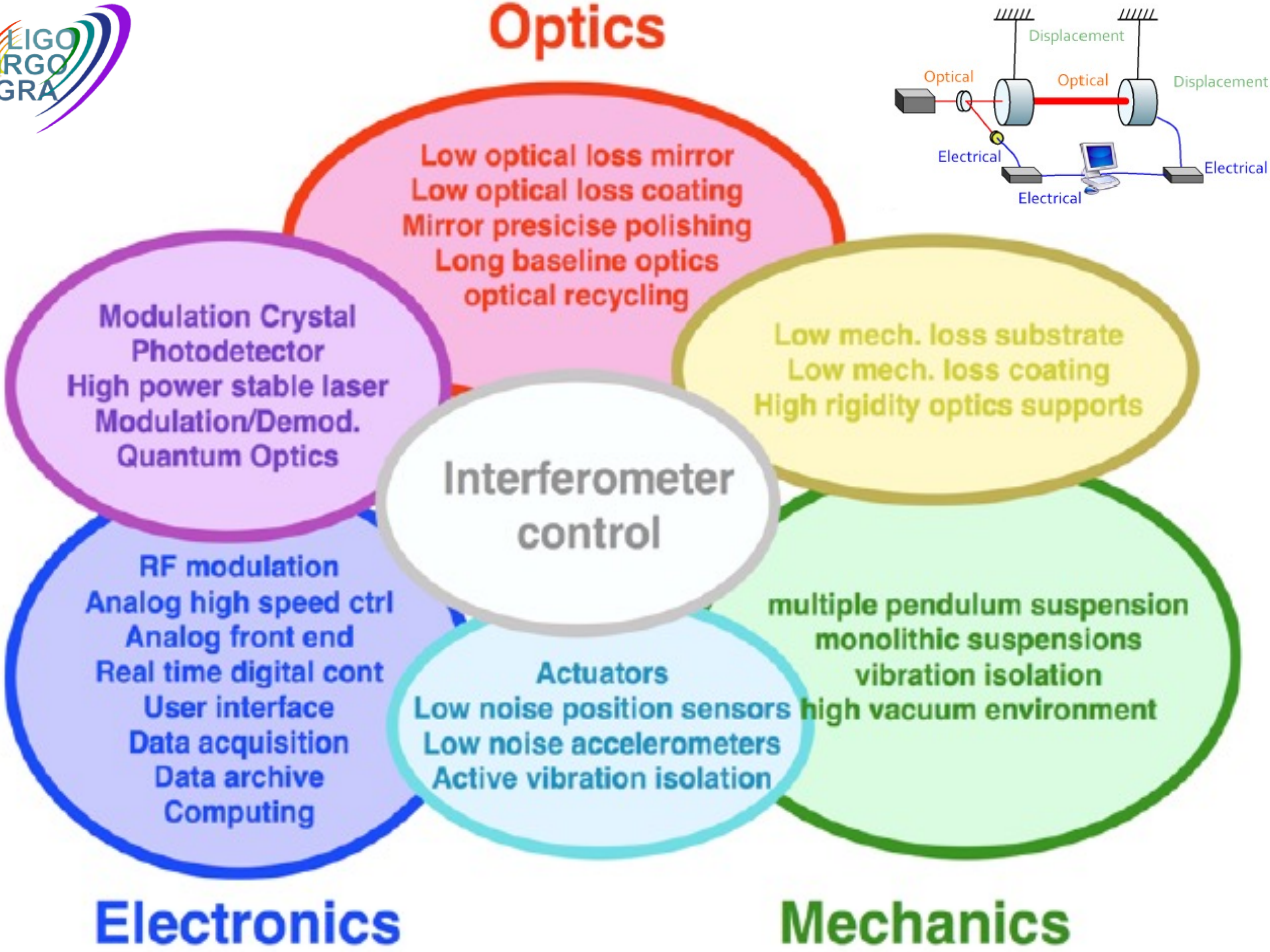
- The *h* parameter is the measure of relative variation among the two free masses.

$$\boxed{h = \frac{\Delta L}{L}}$$

“+” polarized GW propagating orthogonal to the screen

Interferometric detection of GWs





Optics

Low optical loss mirror
Low optical loss coating
Mirror presicise polishing
Long baseline optics
optical recycling

Modulation Crystal
Photodetector
High power stable laser
Modulation/Demod.
Quantum Optics

Low mech. loss substrate
Low mech. loss coating
High rigidity optics supports

Interferometer control

RF modulation
Analog high speed ctrl
Analog front end
Real time digital cont
User interface
Data acquisition
Data archive
Computing

Actuators
Low noise position sensors
Low noise accelerometers
Active vibration isolation

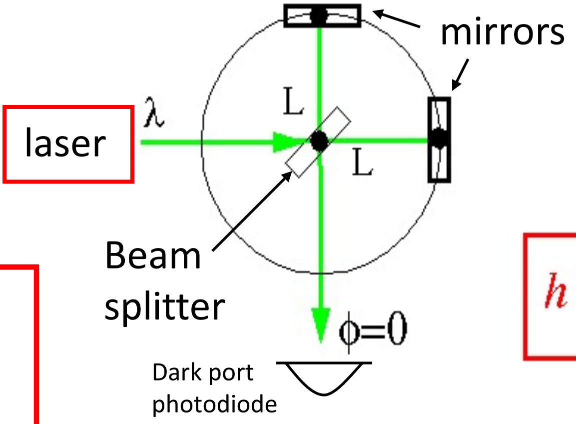
multiple pendulum suspension
monolithic suspensions
vibration isolation
high vacuum environment

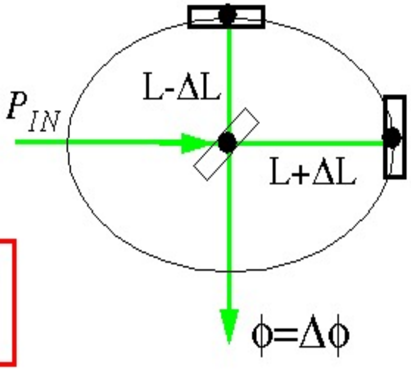
Electronics

Mechanics

Interferometric detection of GWs

GW acts on freely falling masses:



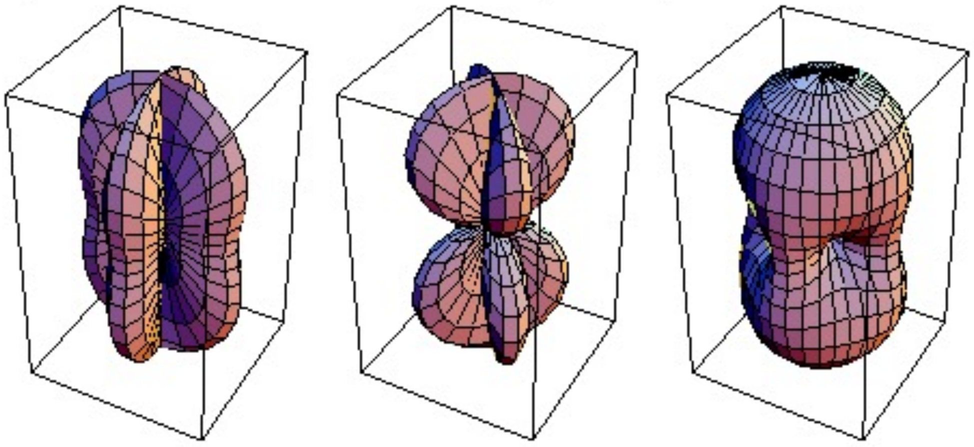


$$\boxed{h = \frac{\Delta L}{L}}$$

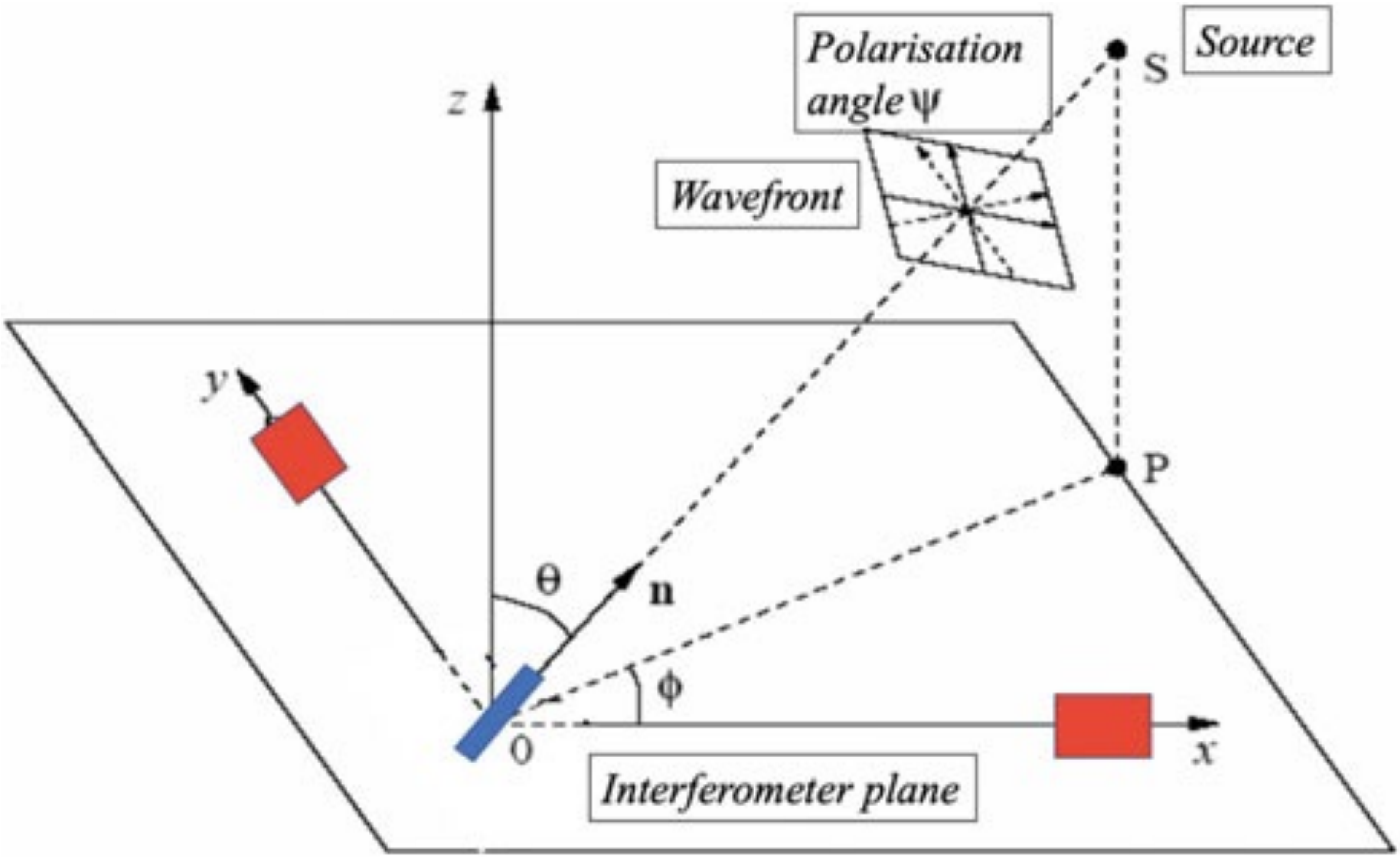
$$P_{out} = P_{in} \sin^2(2k\Delta L)$$

For fixed ability to measure *ΔL*, make *L* as big as possible!

Antenna pattern: (not very directional!)



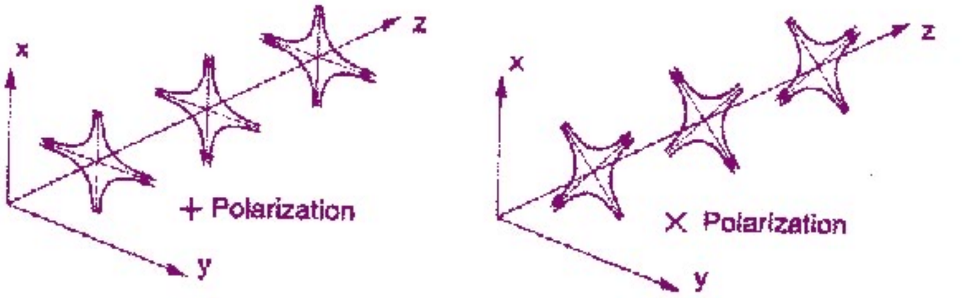
+ polarization × polarization unpolarized



The coordinate systems used to compute the GW antenna pattern of a Michelson interferometer: the origin is set at the beamsplitter, the arms lie along the x and y axes, the source is identified by two polar angles θ and ϕ

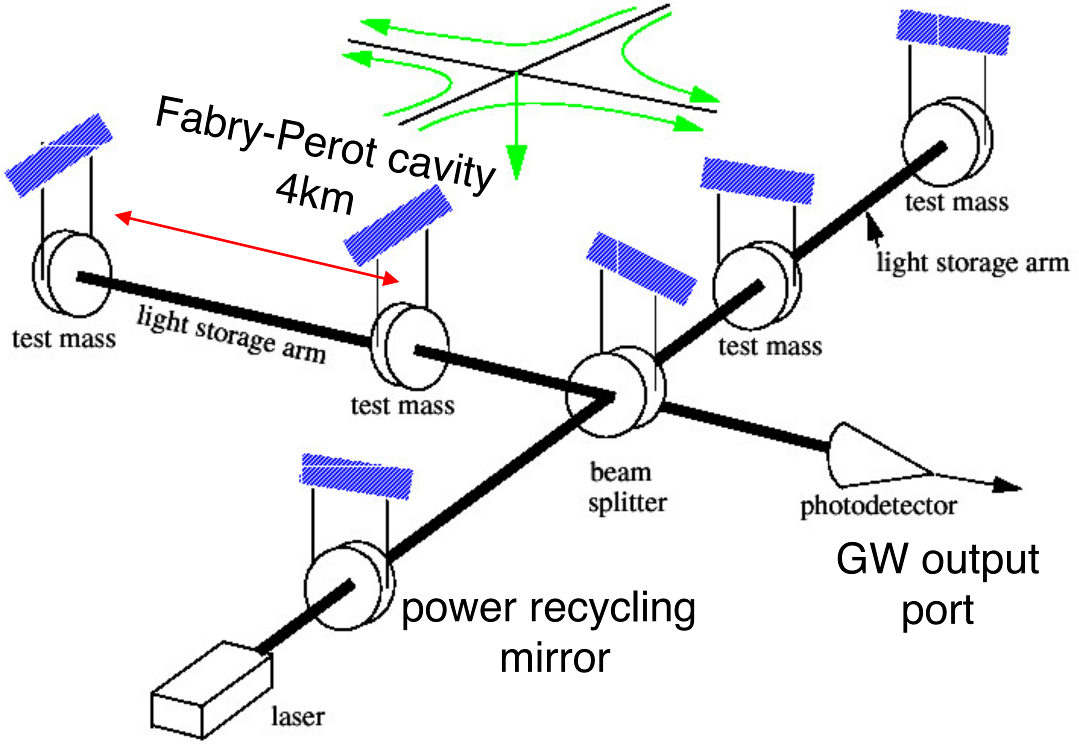
Interferometric GW detectors

- Quadrupolar radiation pattern



- Michelson interferometer
  “natural” GW detector
- Suspended mirrors
  in “free-fall”
- Broad-band response
  ~50 Hz to few kHz
- Waveform detector
  e.g., chirp reconstruction

- **$h = \Delta L / L$**
  Goal: get $h \leq 10^{-22}$;
  can build $L =$ 4 km;
  must measure
  $\Delta L = h\,L \leq 4\times10^{-19}$ m



GW detector at a glance

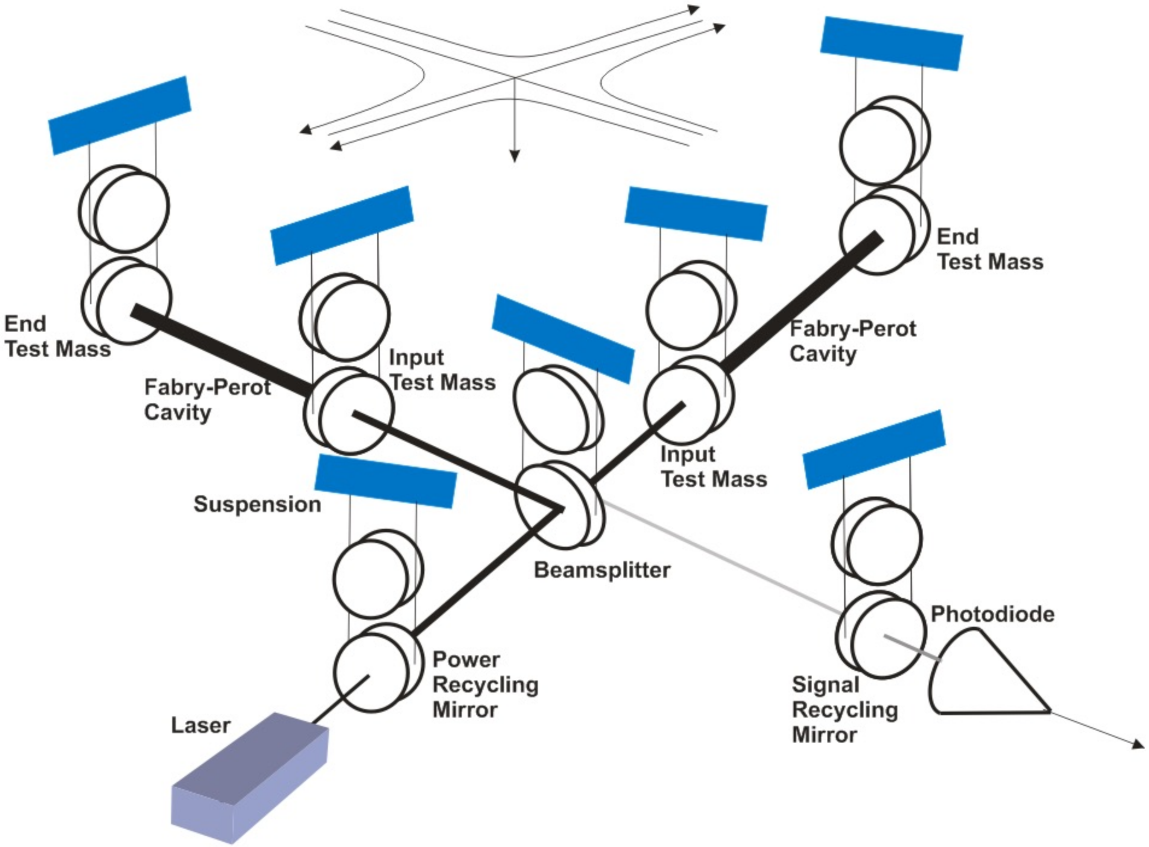
Attacking fundamental limits (quantum, thermal, environmental) to precision measurement

Seismic motion -- ground motion due to natural and anthropogenic sources

Thermal noise -- vibrations due to finite temperature

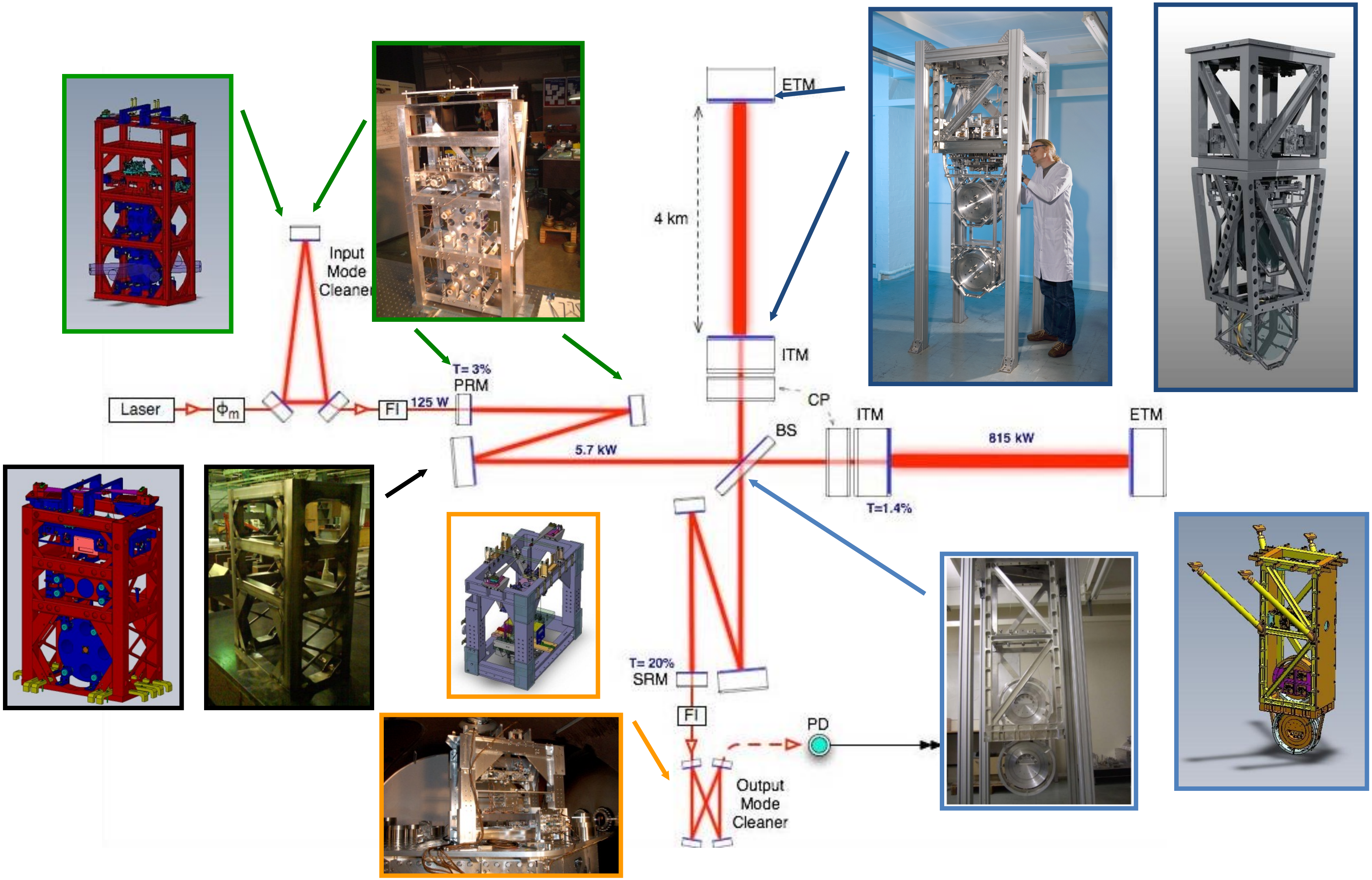
$$h = \Delta L / L$$

want to get h $\leq 10^{-22}$; can build L = 4 km; must measure $\Delta L = h L \leq 4\times10^{-19}$ m



Shot noise -- quantum fluctuations in the number of photons detected

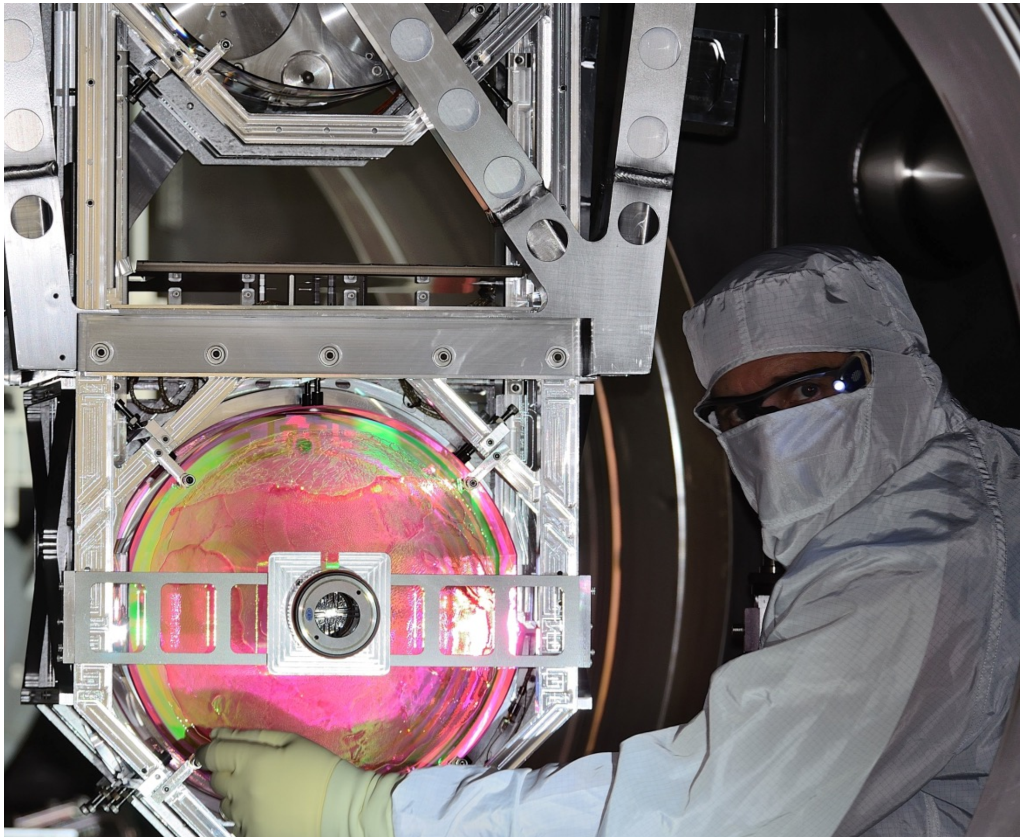
Advanced LIGO Suspensions

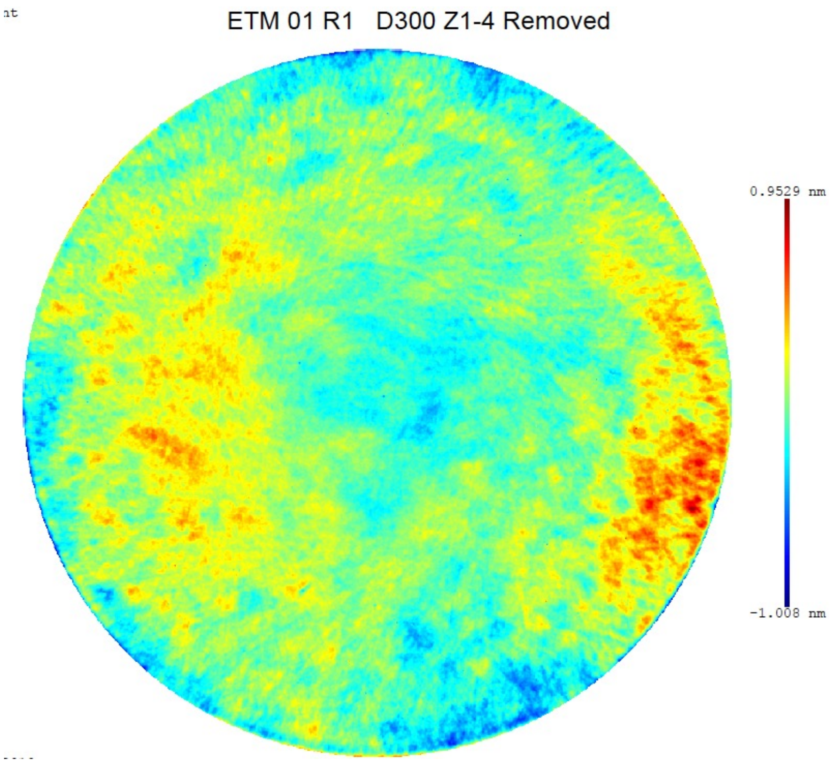


Advanced LIGO Pre-stabilized Laser

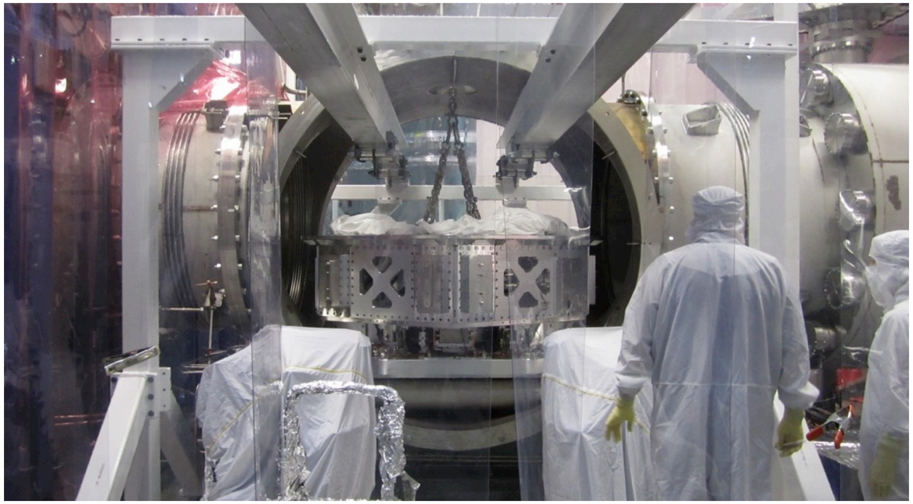
Advanced LIGO Core Optics

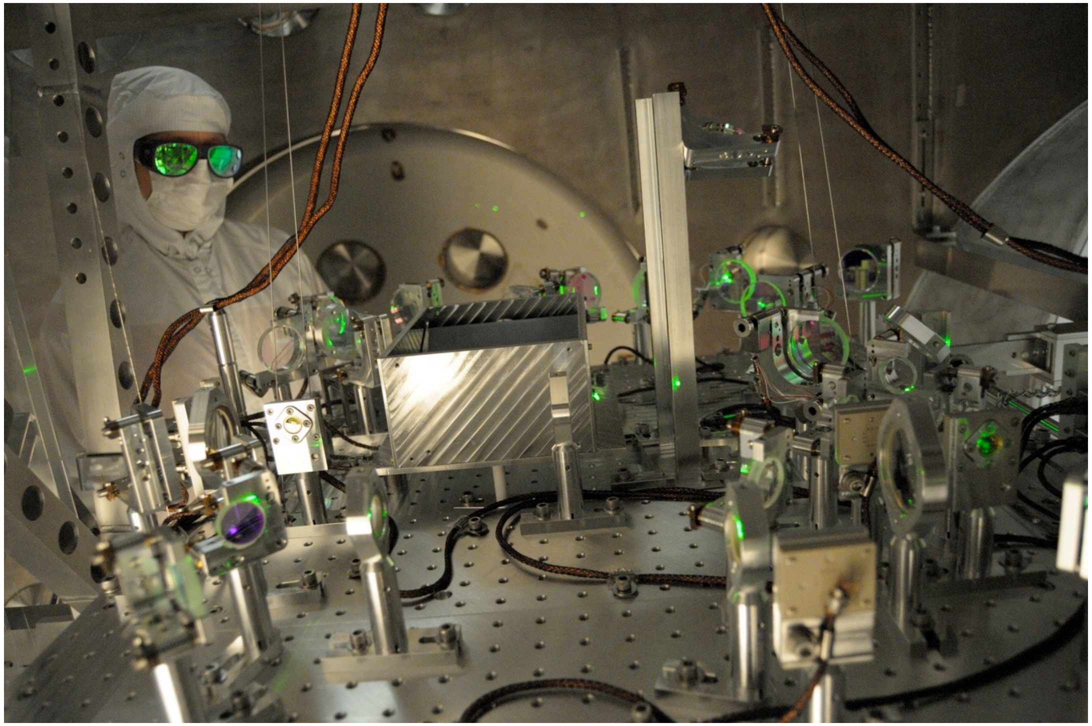
- 40 kg masses, 38 cm in diameter, and figured to 0.15 nm rms
- Optical coatings are challenging!





Advanced LIGO Installation





Advanced LIGO Detectors: optical layout

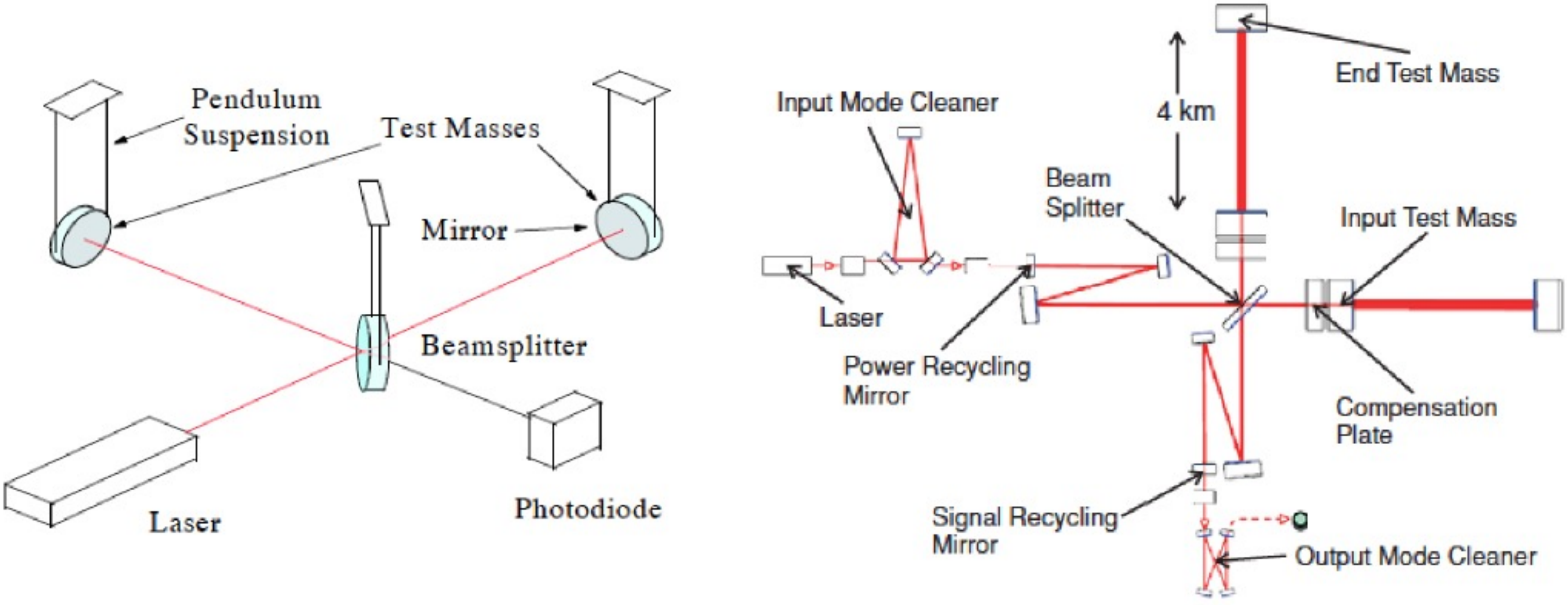
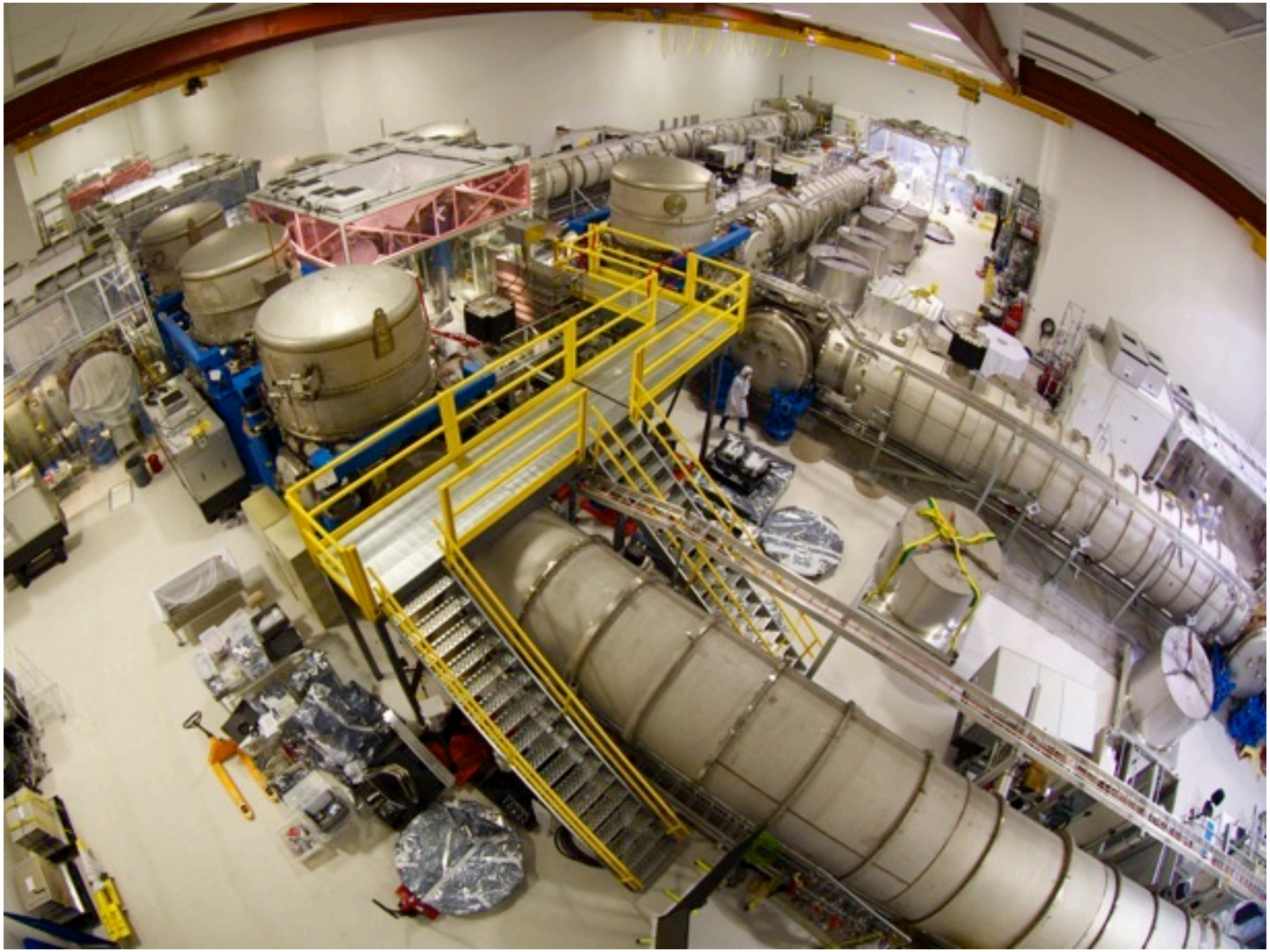


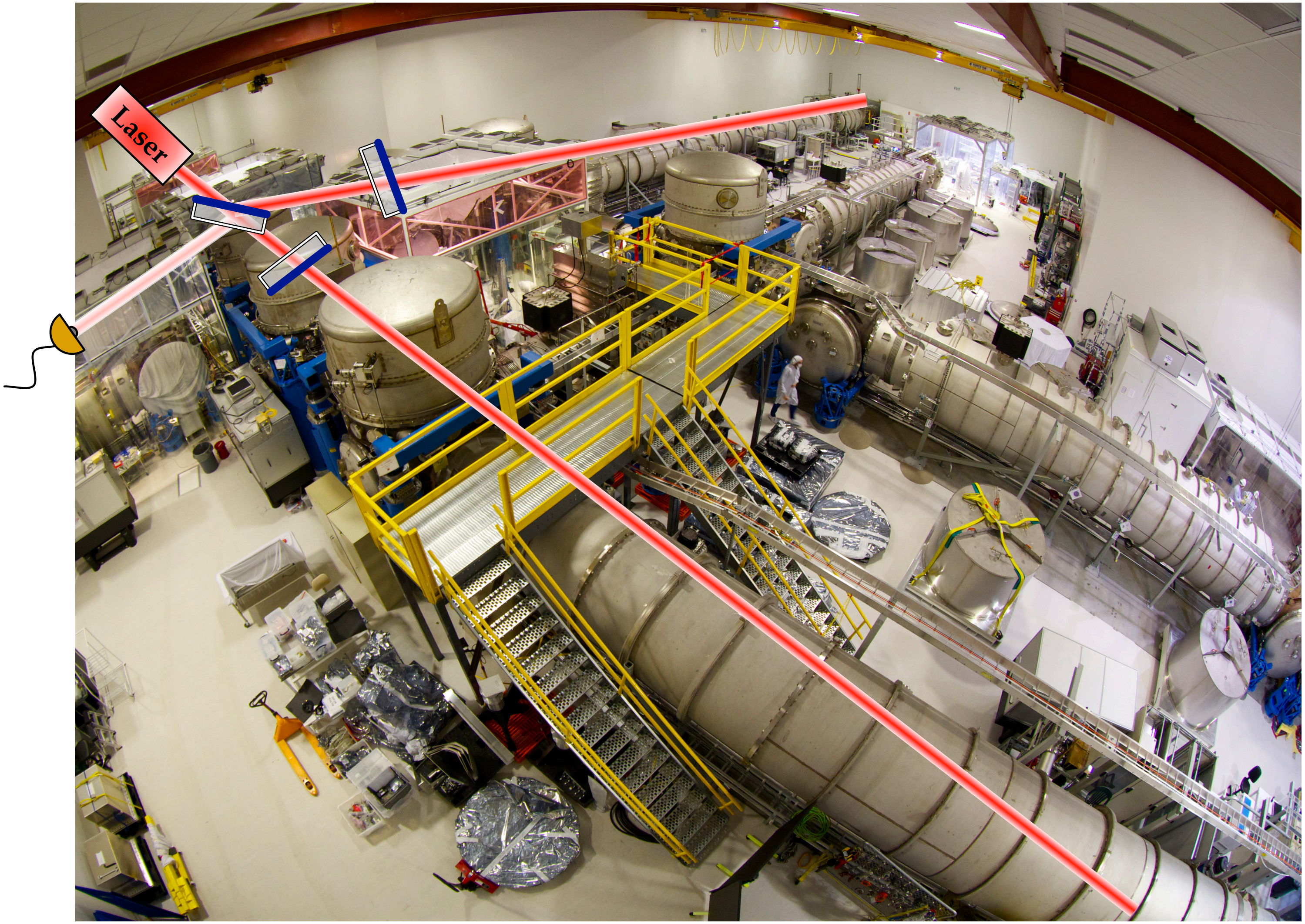
Figure 1 – (Left) A simple Michelson interferometer, showing the proof of concept of Advanced LIGO.[5] (Right) The Advanced LIGO optical layout.[6]

M. Pitkin and et. al. LIGO-P110004-v3, 2011.
G. M. Harry, CQG 27(084006), 2010.

Instrument Hall

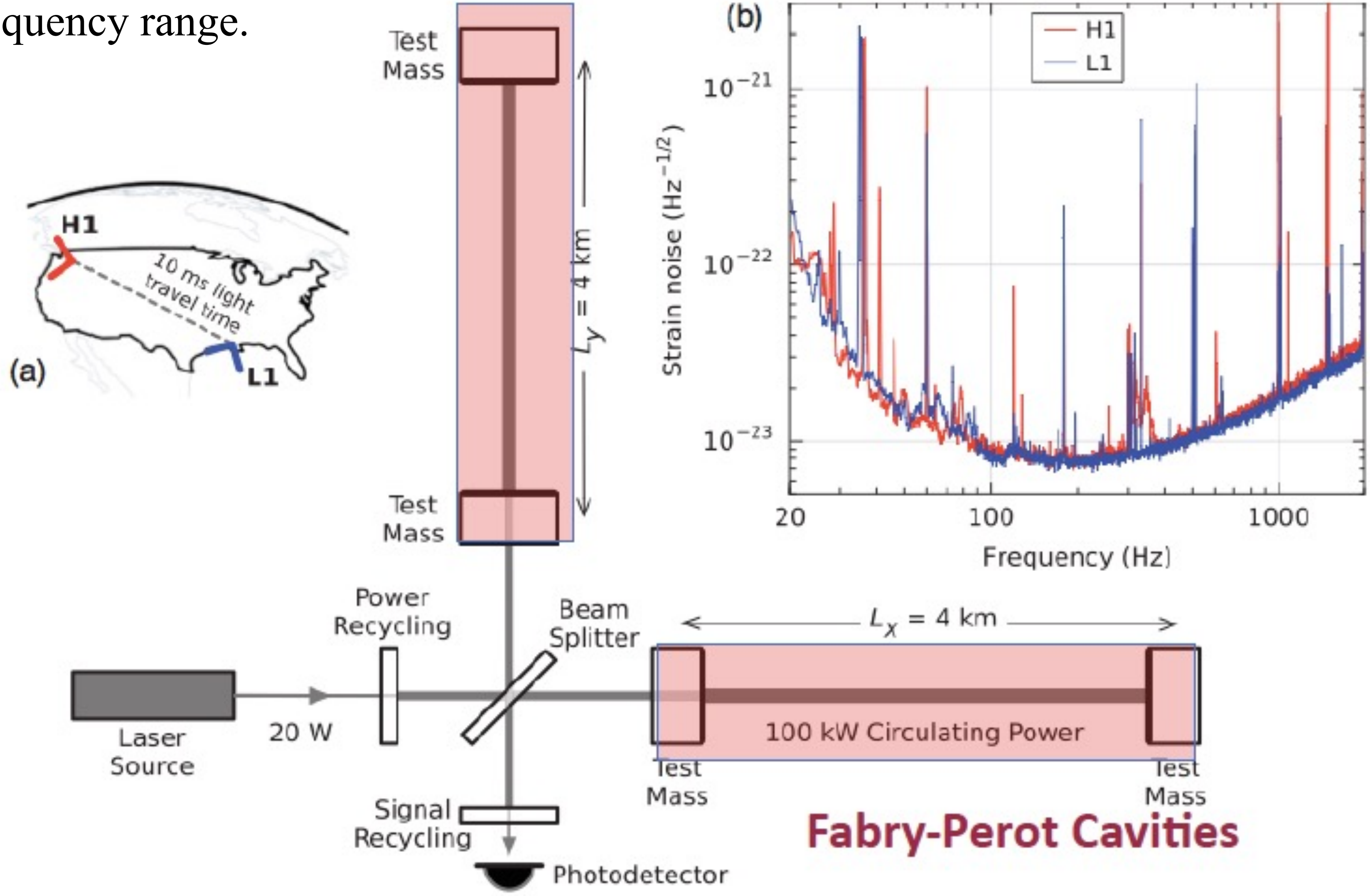


Instrument Hall



LIGO Interferometer sketch

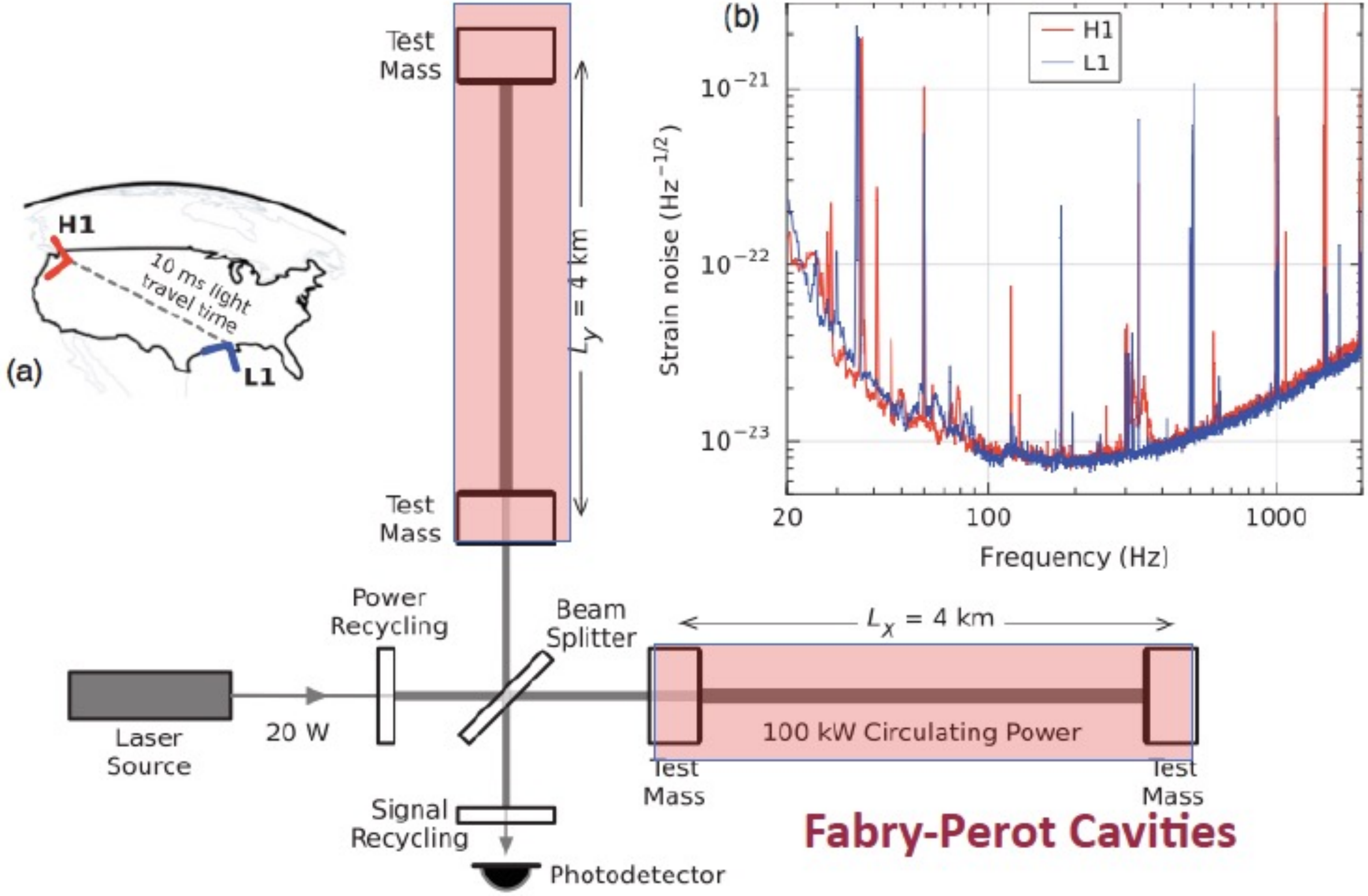
- *Power recycling mirror* at the input increases the laser intensity circulating in the arms.
- *Signal recycling mirror* at the output enhances the sensitivity at a particular frequency range.



Fabry-Perot Cavities

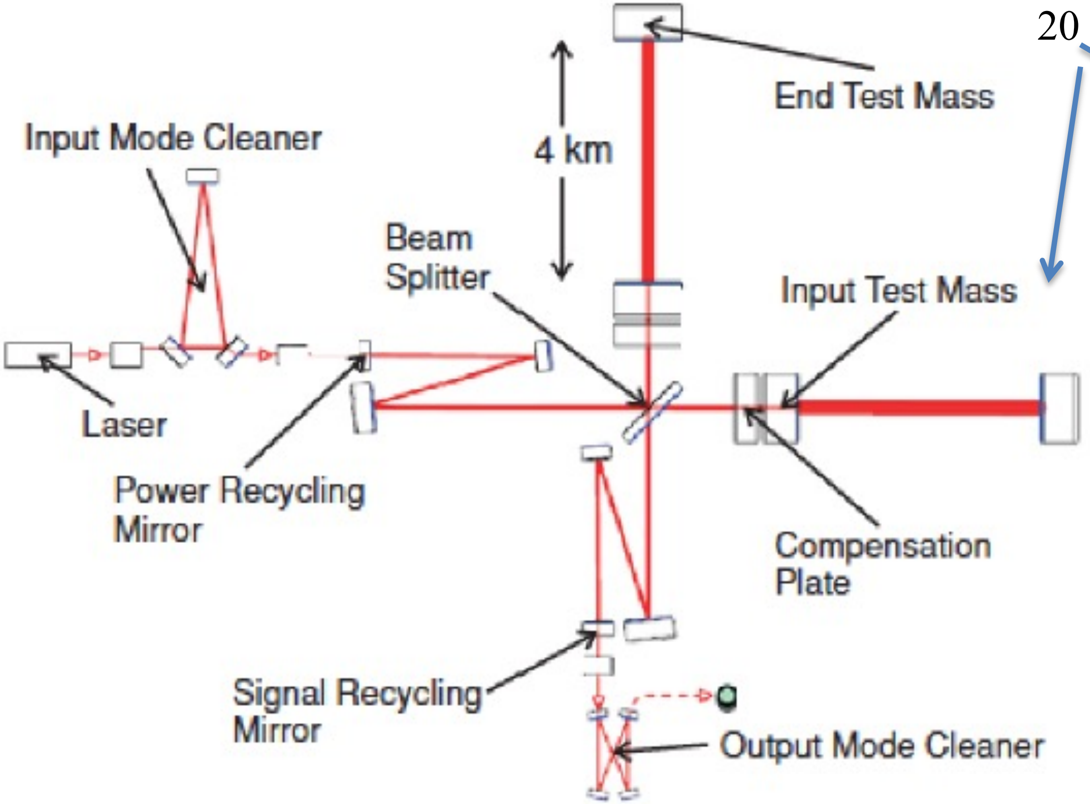
LIGO Interferometer sketch

- A Fabry–Pérot (FP) cavity is a linear optical resonator which consists of two highly reflecting mirrors, where the light bounces between the two reflecting surfaces, and is transmitted only for well-defined wavelengths.

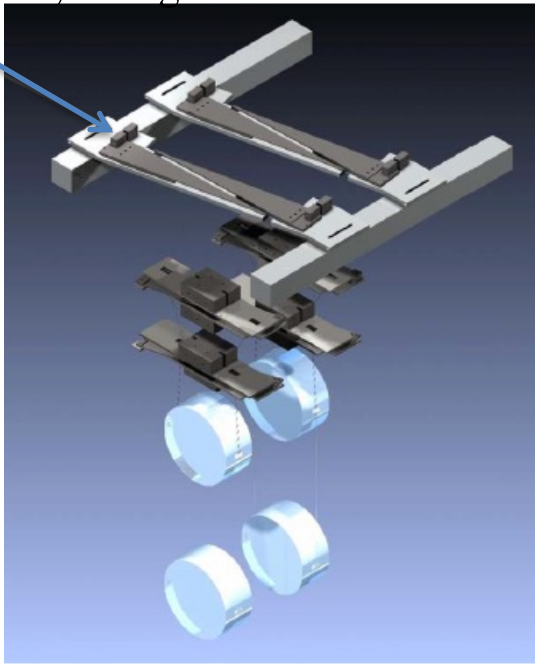


Fabry-Perot Cavities

Advanced LIGO Detectors: optical layout

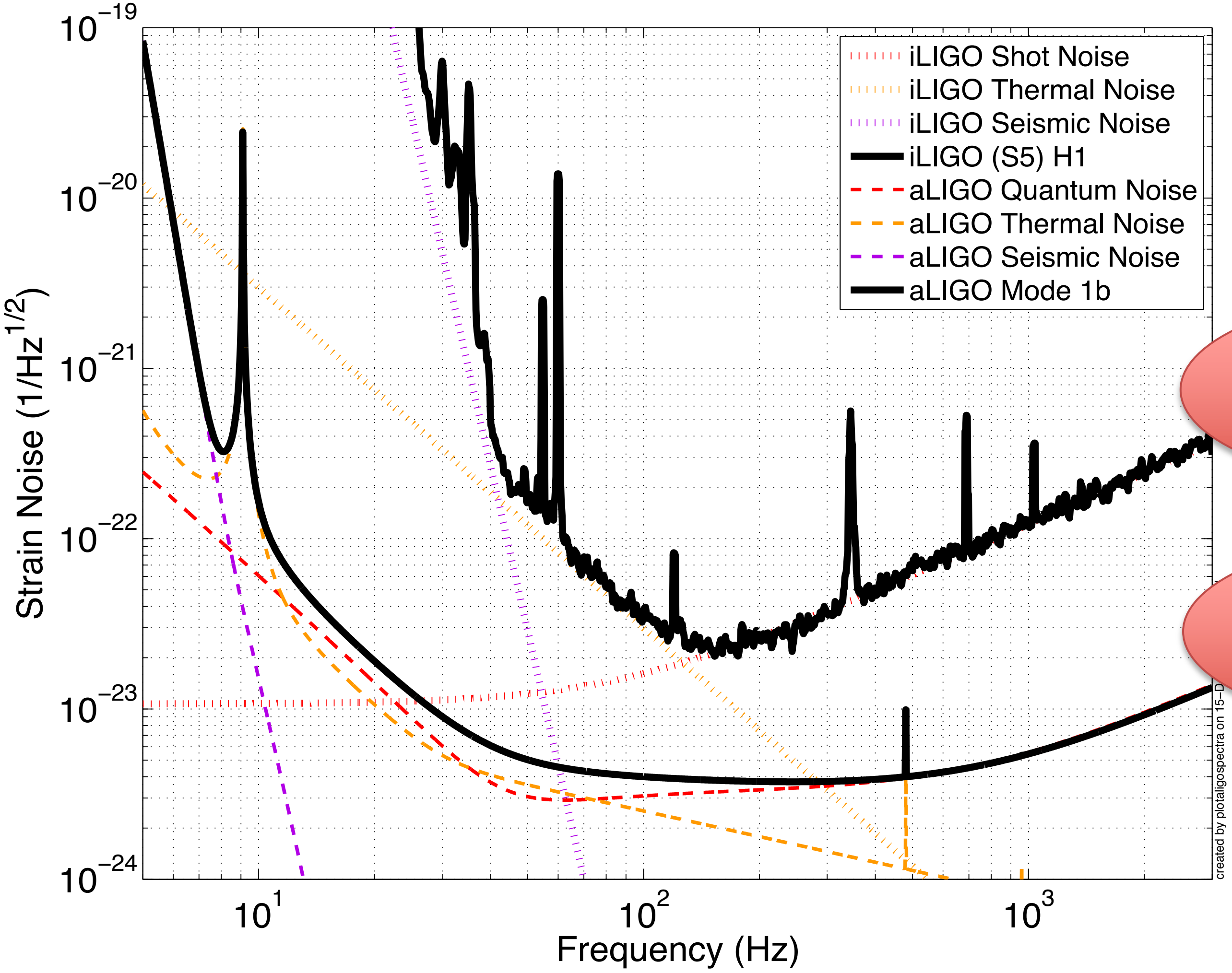


Test Masses: fused silica, 34 cm diam x 20 cm thick, 40 Kg



G. M. Harry, CQG 27(084006), 2010.

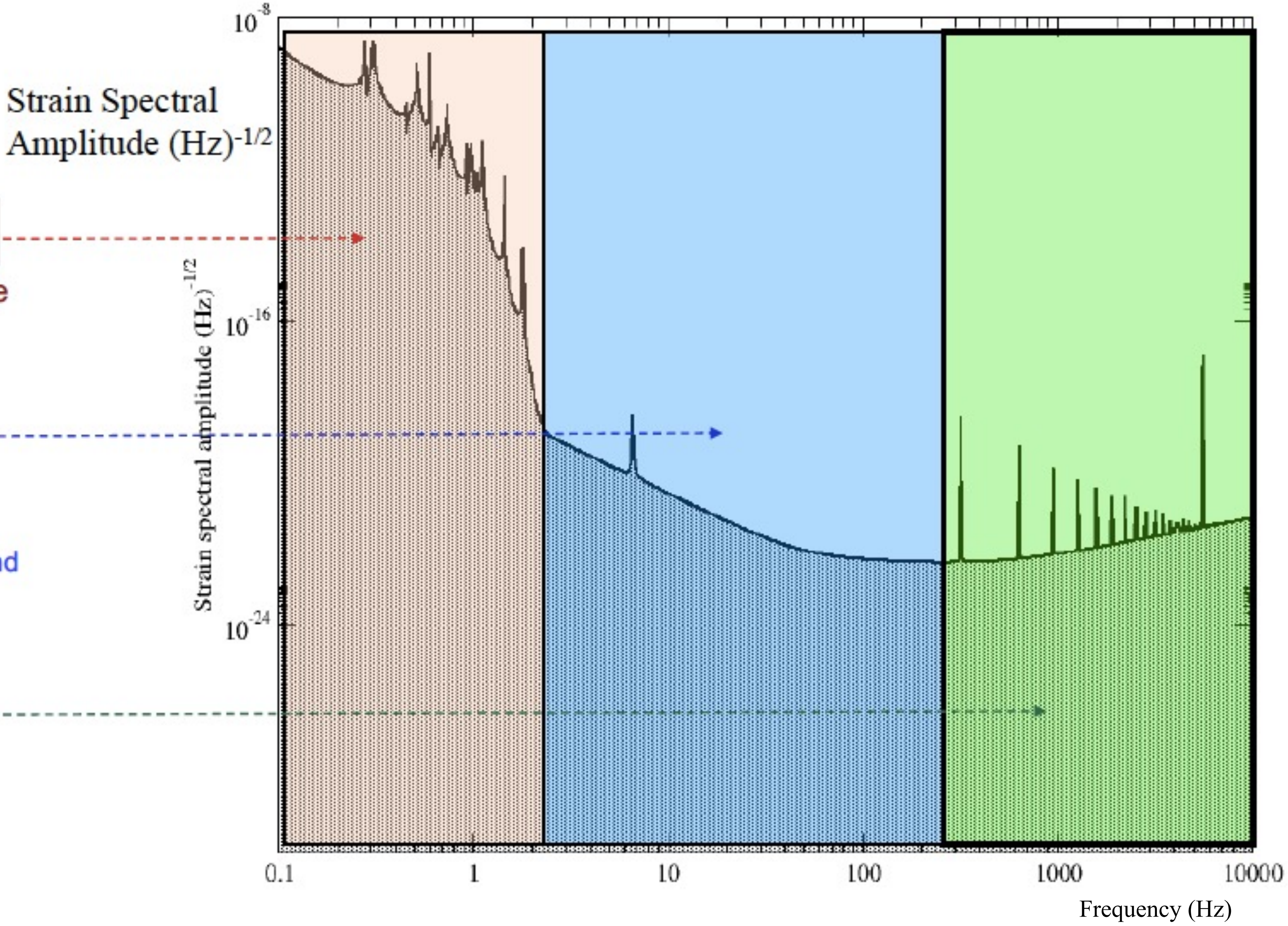
Advanced LIGO vs. Initial LIGO



15-20 Mpc BNS inspiral range

~200 Mpc BNS inspiral range

Interferometer Instrinsic Noise Spectrum



Seismic

Passive and Active Attenuators

Thermal

Low dissipation materials for coatings, mirrors and suspensions

Shot

High Laser Power, Signal Recycling Techniques

Credit: P. Leaci

Interferometer Instrinsic Noise Spectrum

- Below 10Hz the sensitivity is limited by **seismic noise**: ground motion drives the structure holding the apparatus, thus coupling a displacement noise to the mirror. The solution is to suspend each mirror to a chain of several stages in series, each composed of a pendulum, and connected by vertical springs.

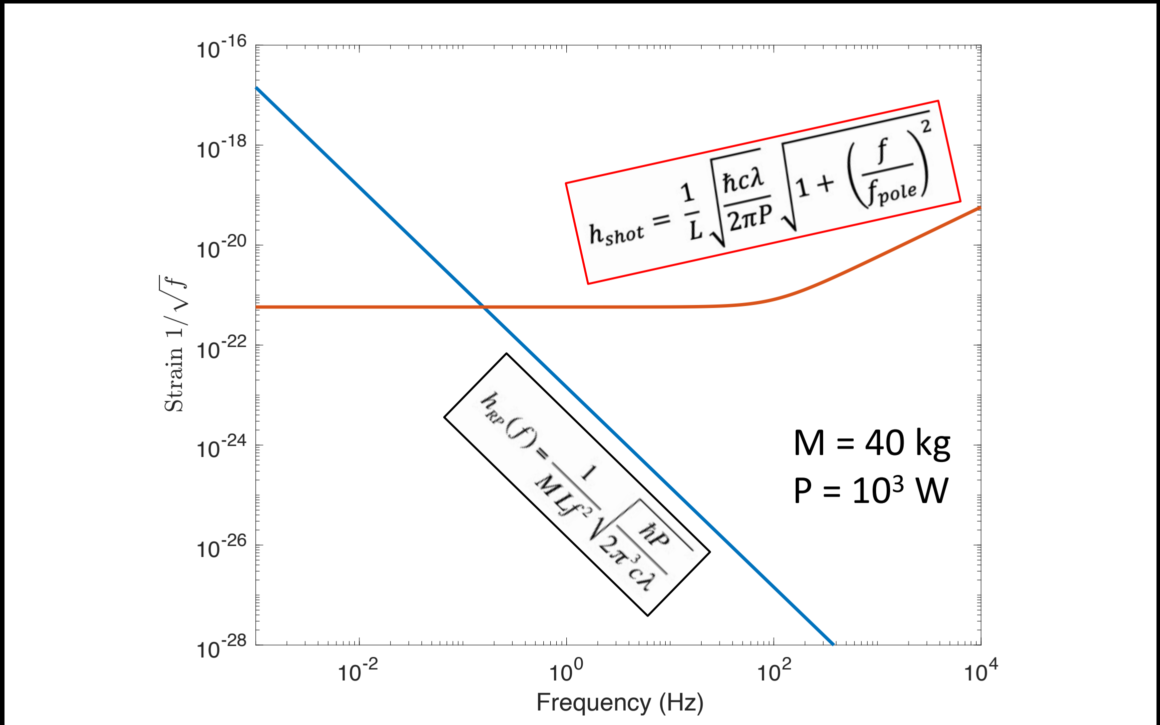
$$S_f = 4k_B T \Re[Z(\omega)]$$

- The **Thermal noise** is due to both the normal modes of the mirror and vibration modes of the suspension fibres. Each mode has an associated fluctuation energy equal to $k_B T$, where T is the equilibrium temperatur of the mirror

$$S_h^{(shot)}(\nu) = \frac{1}{L^2}\frac{\hbar c\lambda}{2\pi\eta P_{in}}$$

- The **Shot noise** of a laser light is derived by the fluctuactions in the number of detected photons. The sensitivity increases with the arm length L, and with the input power P_{in}.

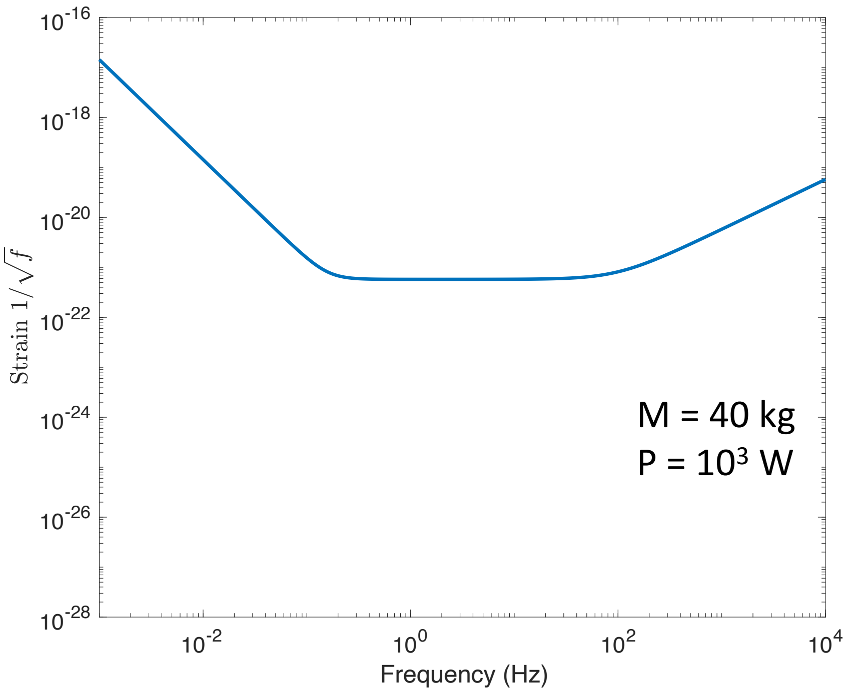
Coupled Quantum “Optical Readout” Noise



Credit: D. Reitze

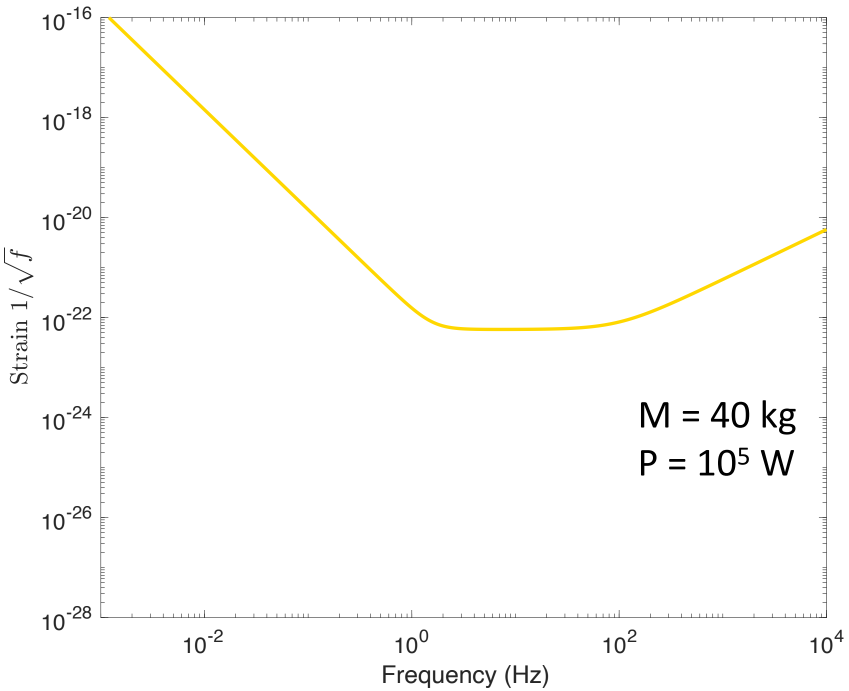
Radiation Pressure Noise. The quantum fluctuations of light result in fluctuations in the radiation pressure of the light beam and in the impulse transferred to the mirror.

Coupled Quantum "Optical Readout" Noise



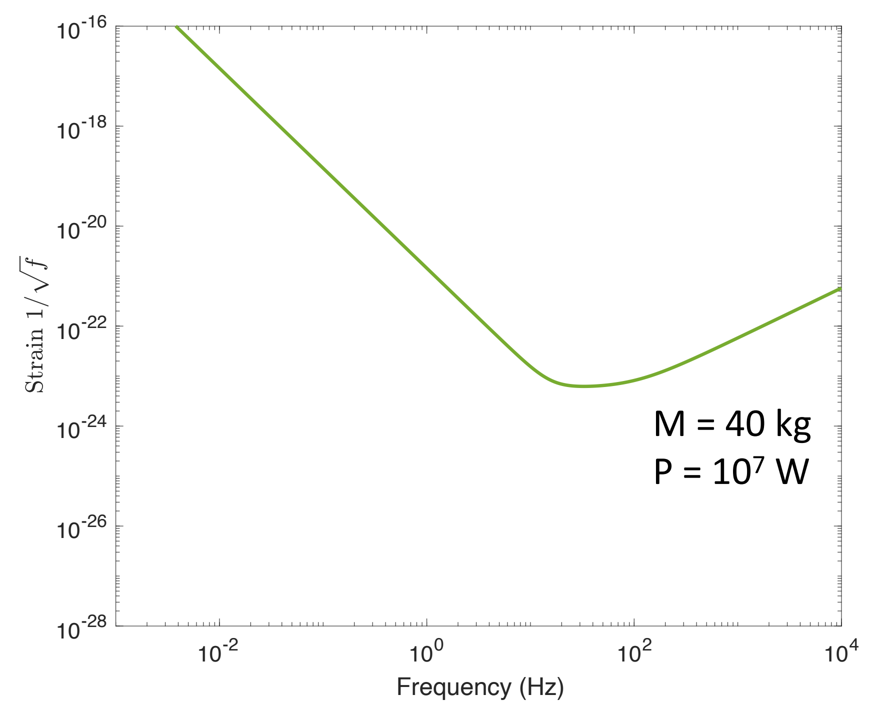
Credit: D. Reitze

Coupled Quantum “Optical Readout” Noise



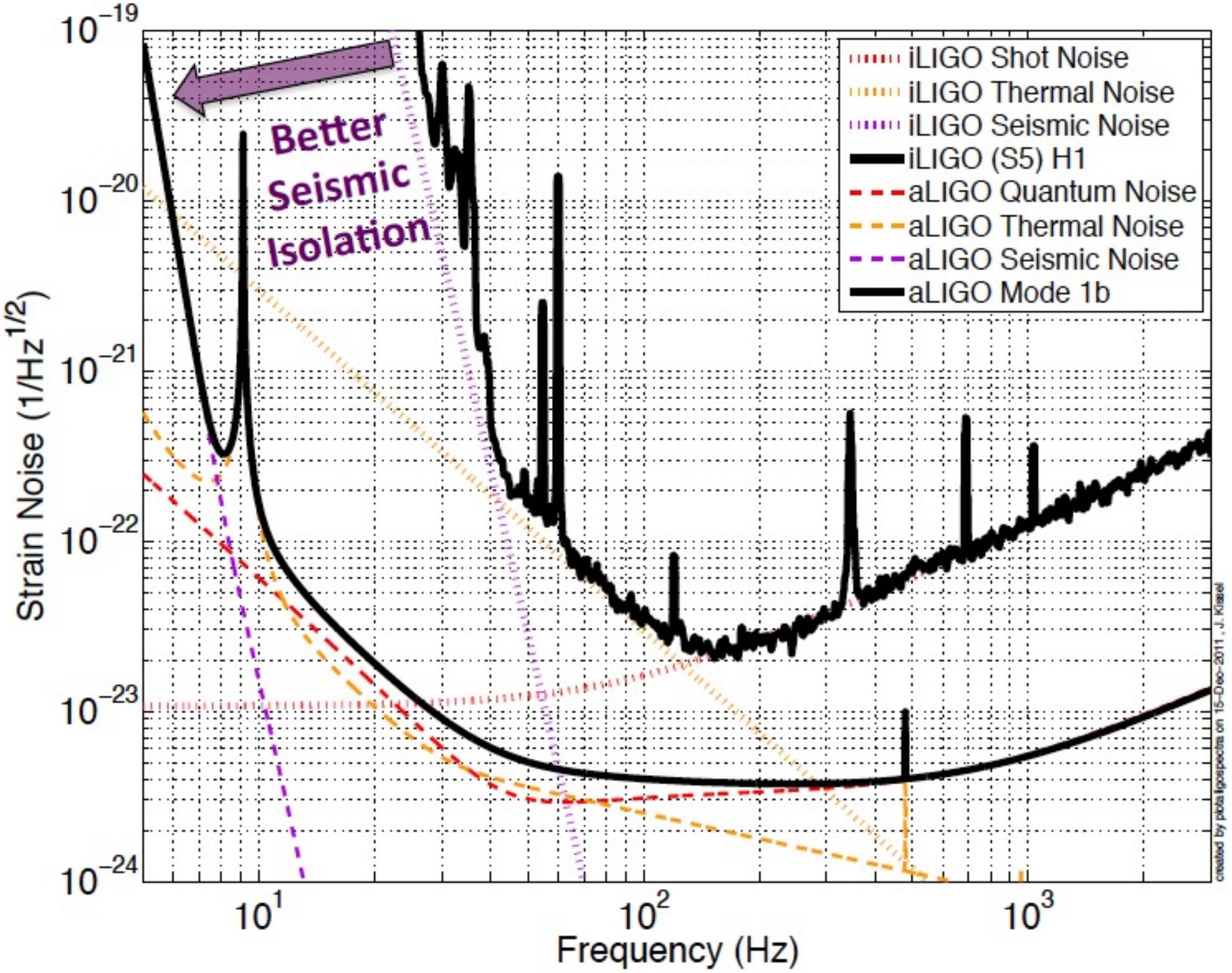
Credit: D. Reitze

Coupled Quantum "Optical Readout" Noise



Credit: D. Reitze

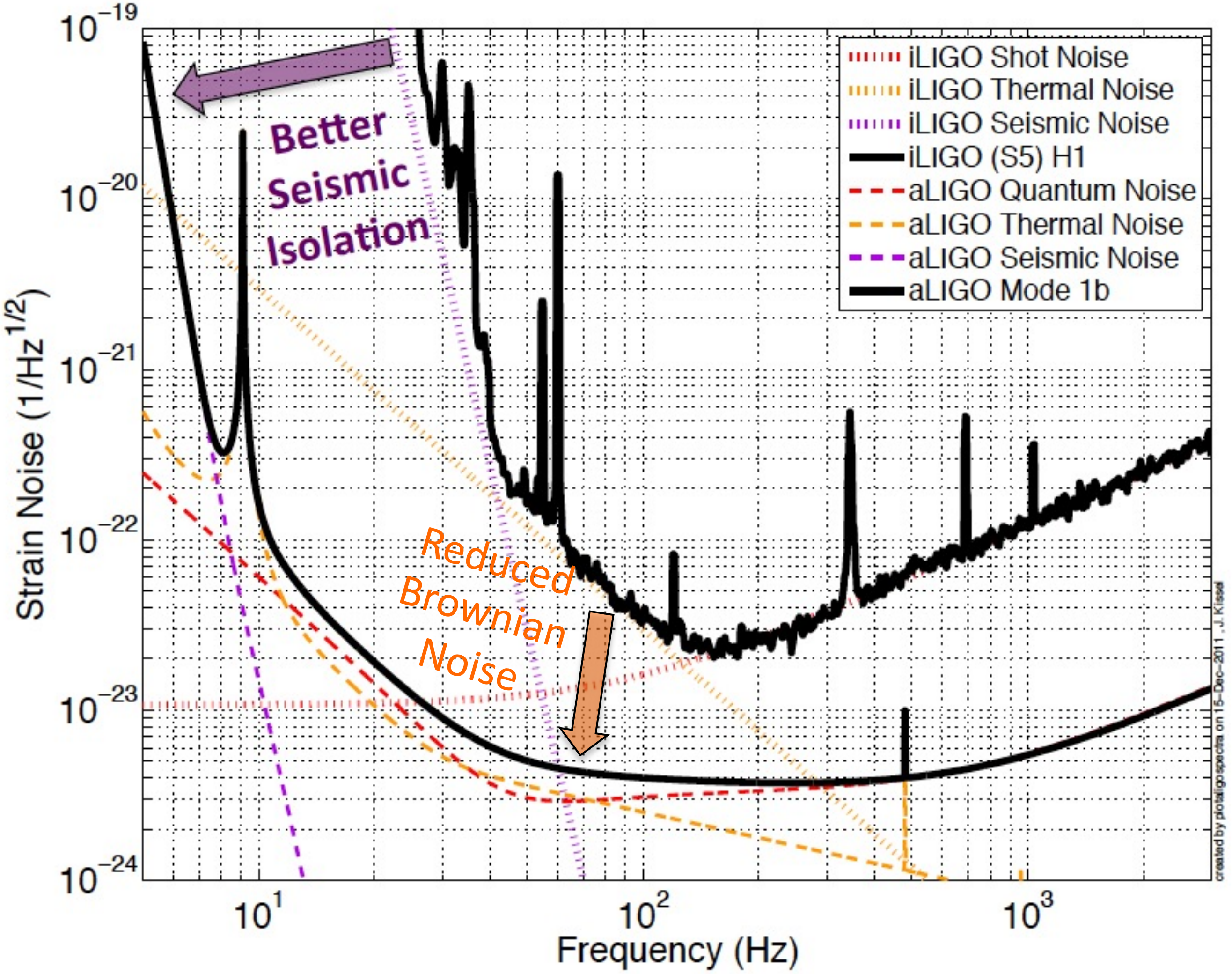
Advanced LIGO vs. Initial LIGO



- **Seismic Noise:**

Test masses are suspended from seven stages of passive and active isolation systems.

Advanced LIGO vs. Initial LIGO



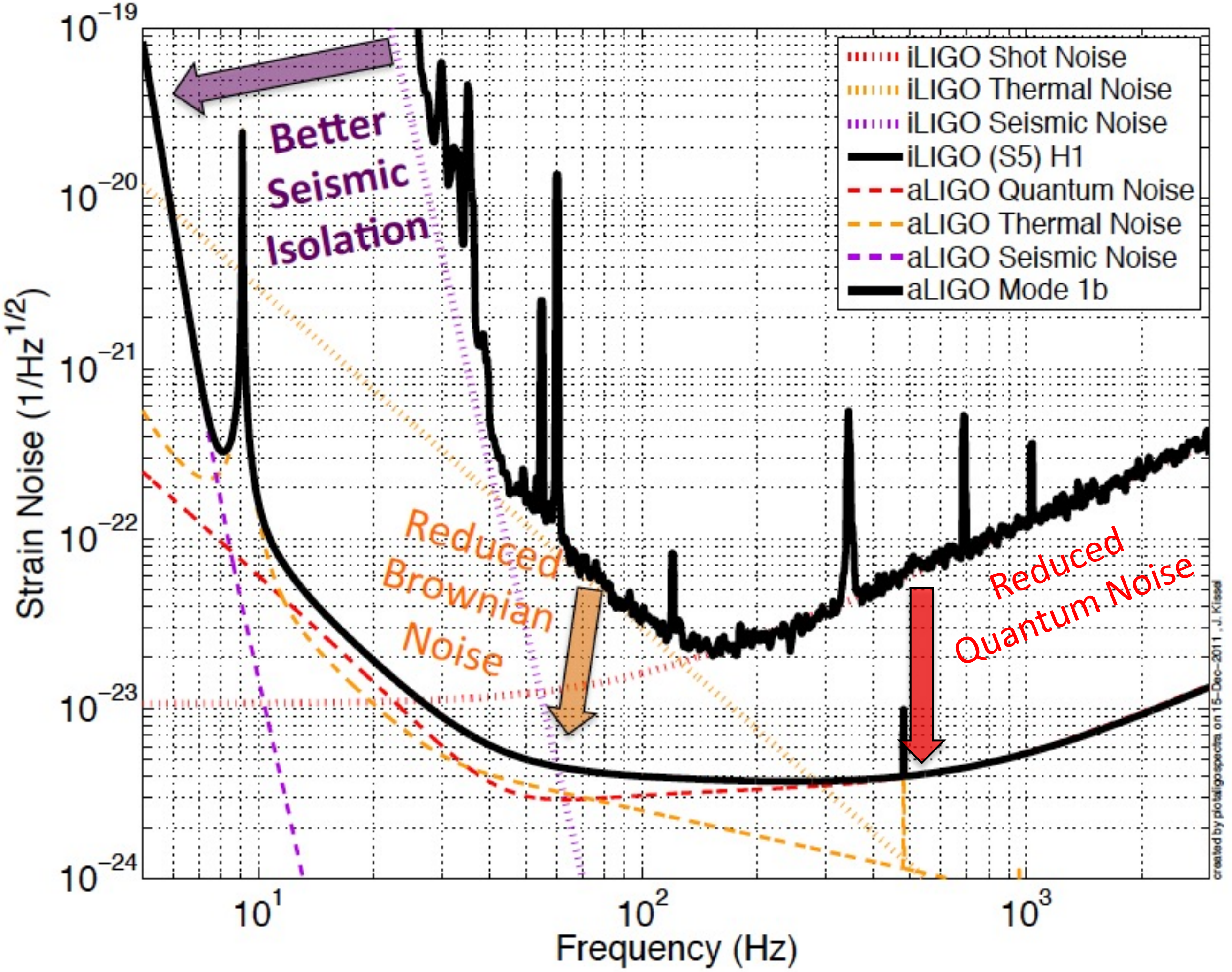
- **Seismic Noise:**

Test masses are suspended from seven stages of passive and active isolation systems.

- **Brownian Noise:**

Last two suspension stages are monolithic to improve thermal noise.

Advanced LIGO vs. Initial LIGO



– **Seismic Noise:**

Test masses are suspended from seven stages of passive and active isolation systems.

– **Brownian Noise:**

Last two suspension stages are monolithic to improve thermal noise.

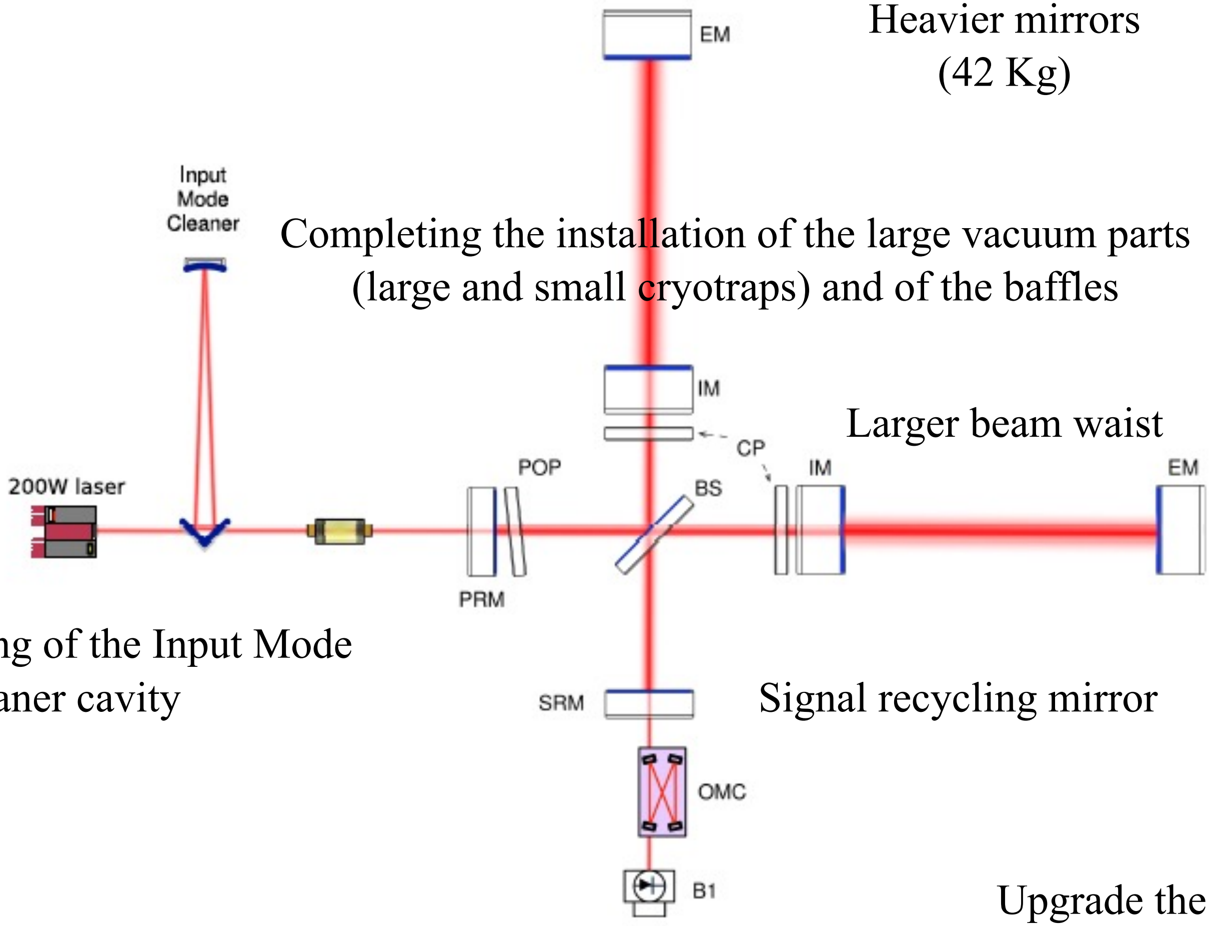
– **Quantum Noise:**

180W Laser

40 kg test masses

Signal Extraction Cavity

Advanced Virgo Detector: optical layout



Heavier mirrors
(42 Kg)

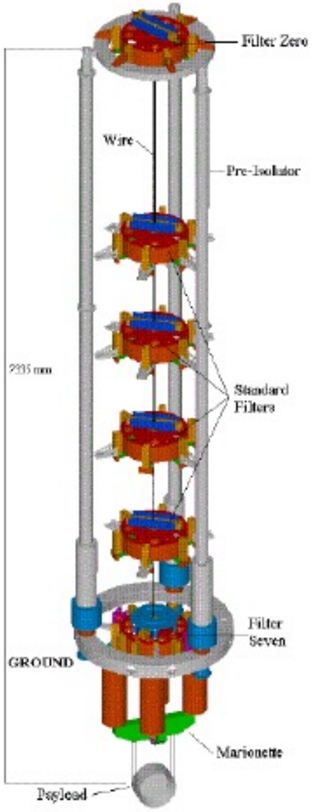
Completing the installation of the large vacuum parts
(large and small cryotraps) and of the baffles

Larger beam waist

Commissioning of the Input Mode
Cleaner cavity

Signal recycling mirror

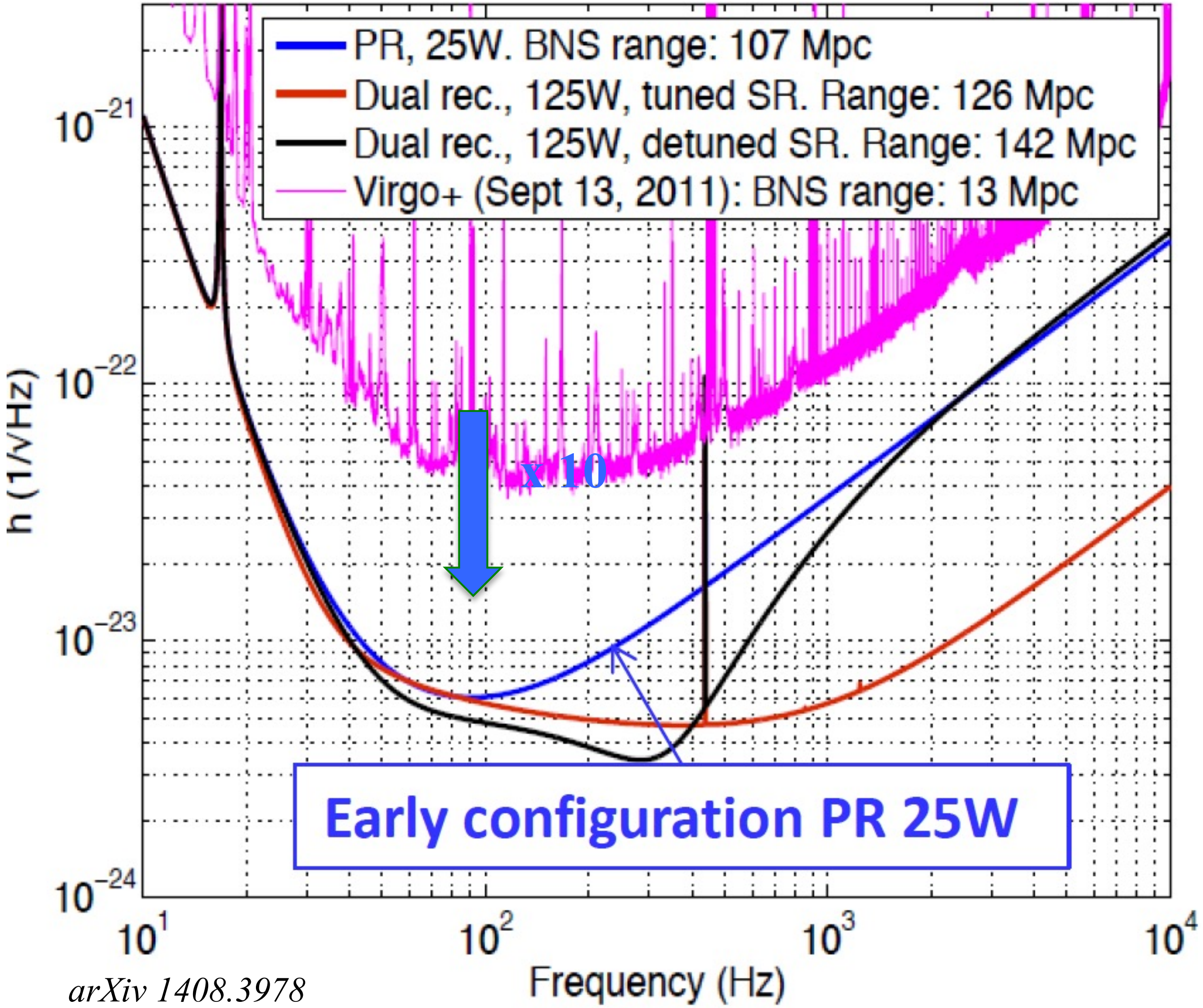
Preparation/installation of the
suspended detection benches



Upgrade the superattenuator:
new payload, fused silica suspensions

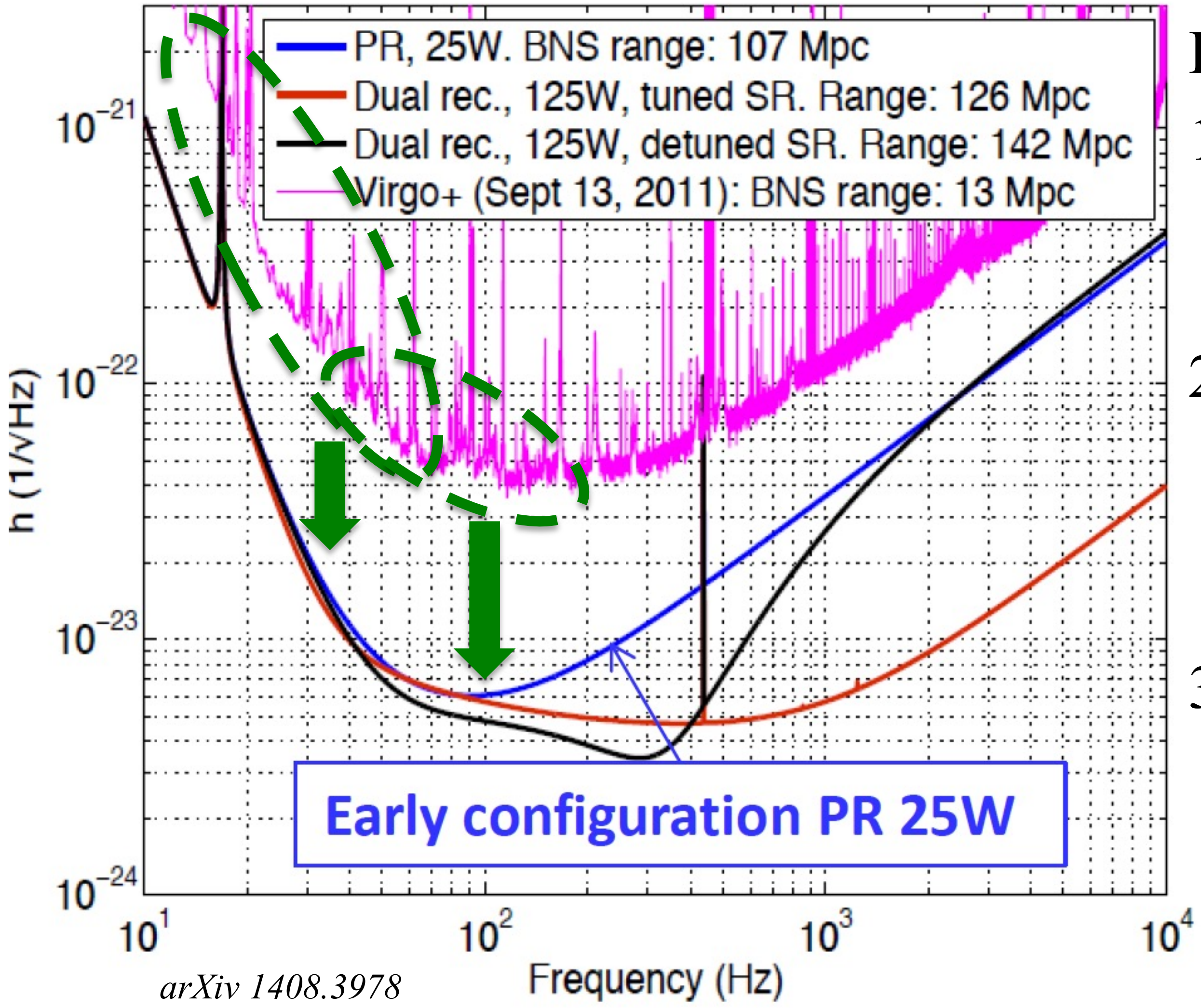
arXiv 1408.3978

Advanced Virgo vs. Virgo+



arXiv 1408.3978

Advanced Virgo vs. Virgo+



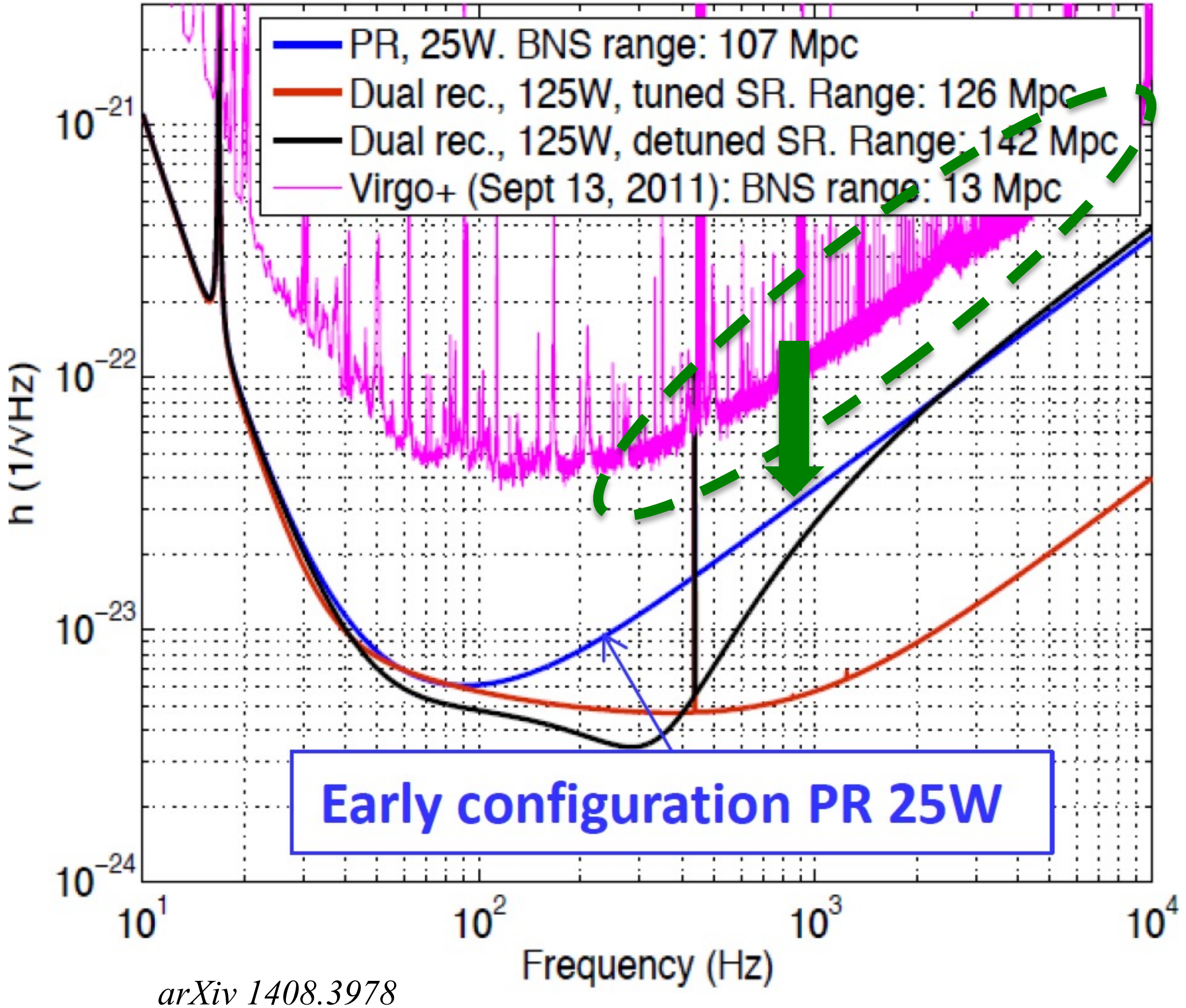
arXiv 1408.3978

- **Thermal noise:**

Improved with

1. Optical configuration: larger beam spot
2. Test masses suspended by fused silica fibers (low mechanical losses)
3. Mirror coatings engineered for low losses

Advanced Virgo vs. Virgo+



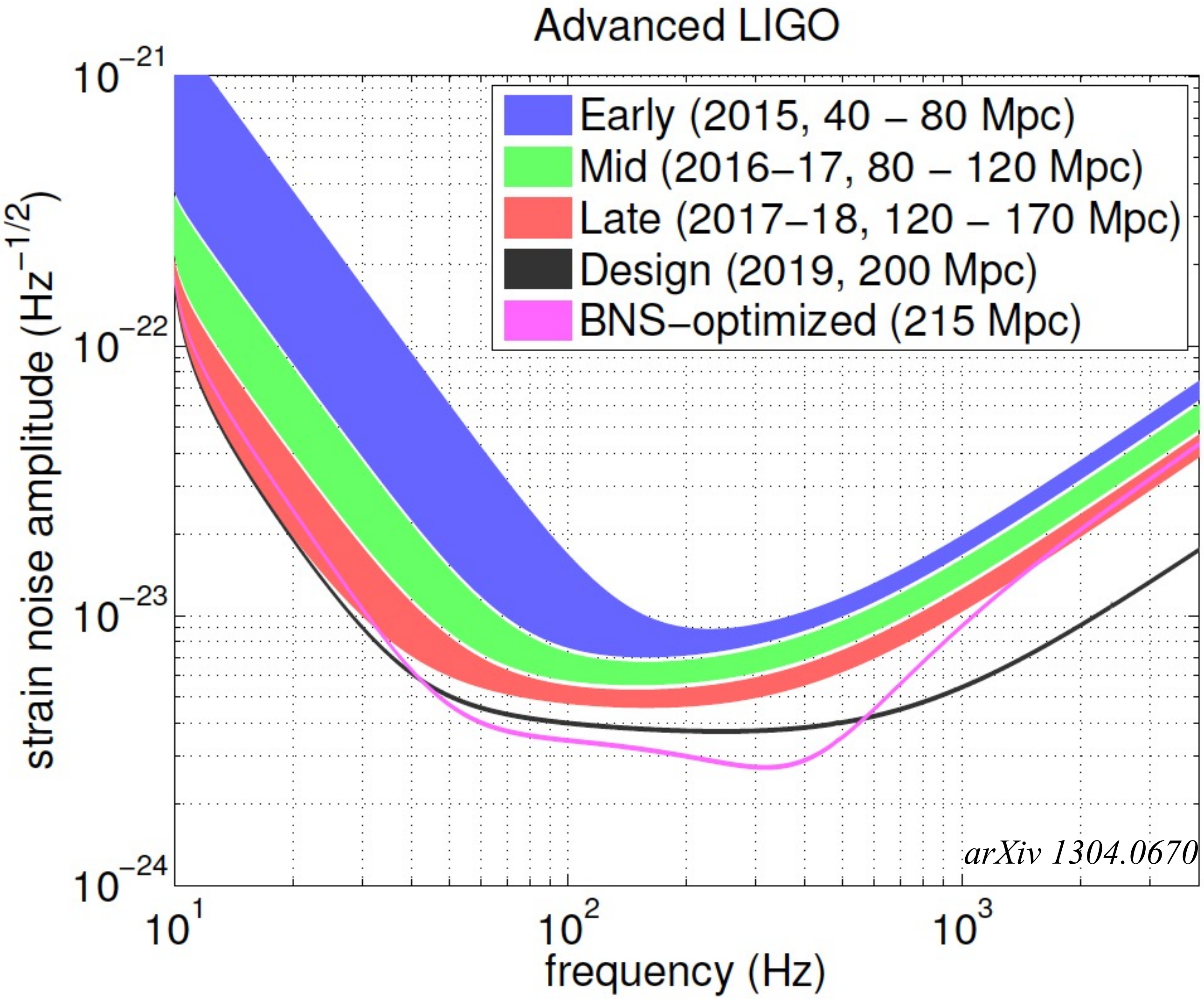
arXiv 1408.3978

- **Laser shot noise:**

Improved with

1. Higher laser power: 125 W injected
2. Higher finesse of the arm cavities
3. Optical configuration: signal recycling

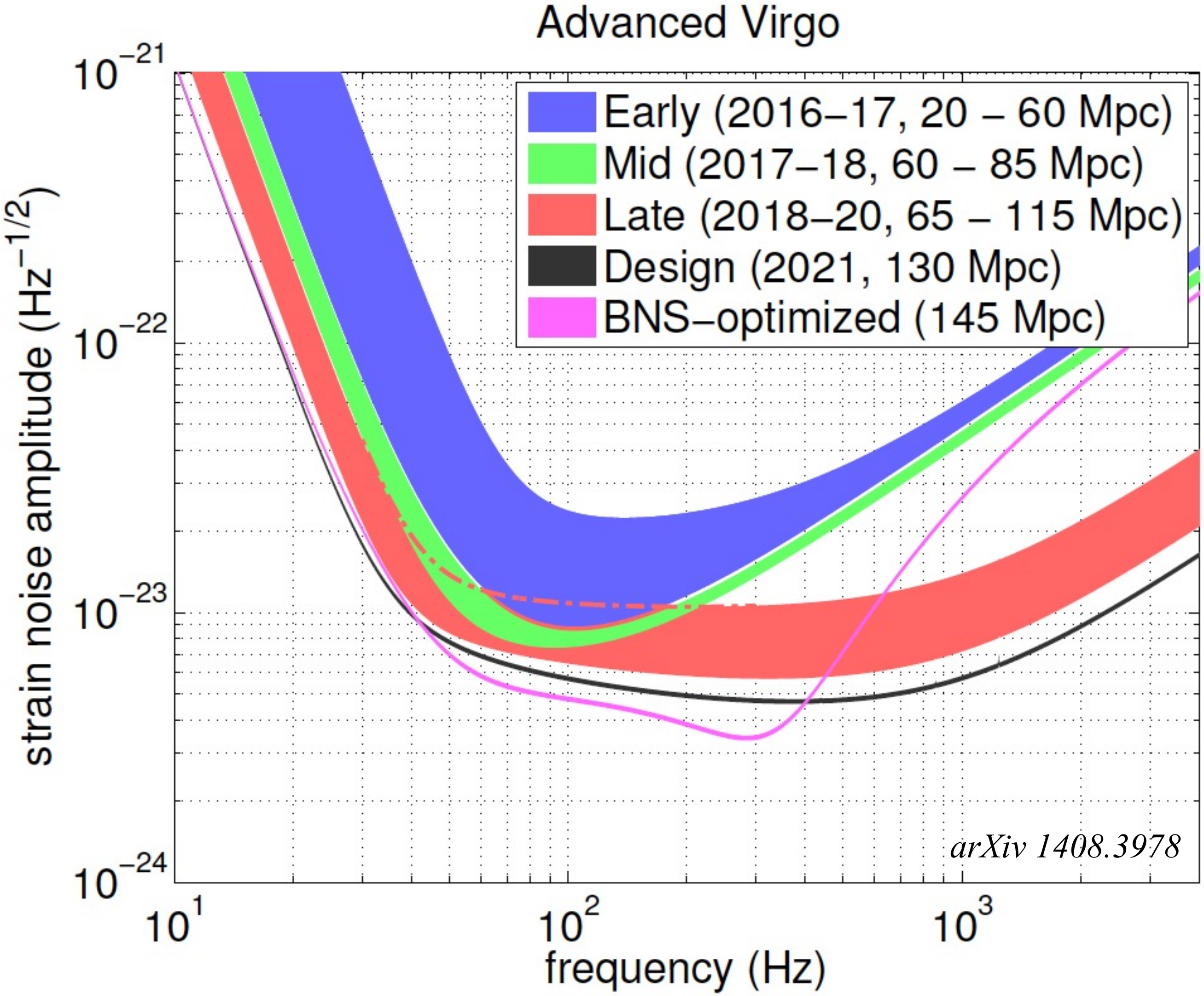
Advanced LIGO Evolution



arXiv 1304.0670

- A standard figure of merit for the sensitivity of an interferometer is the binary neutron star range: the volume and the orientation average distance at which a compact binary coalescence, consisting of two 1.4 M_{sun} neutron stars, gives a matched filter signal-to-noise-ratio of 8 in a single detector.
- Current notions of the progression of sensitivity are given for early, middle, and late commissioning phases, as well as the final design sensitivity target and the BNS-optimized sensitivity.

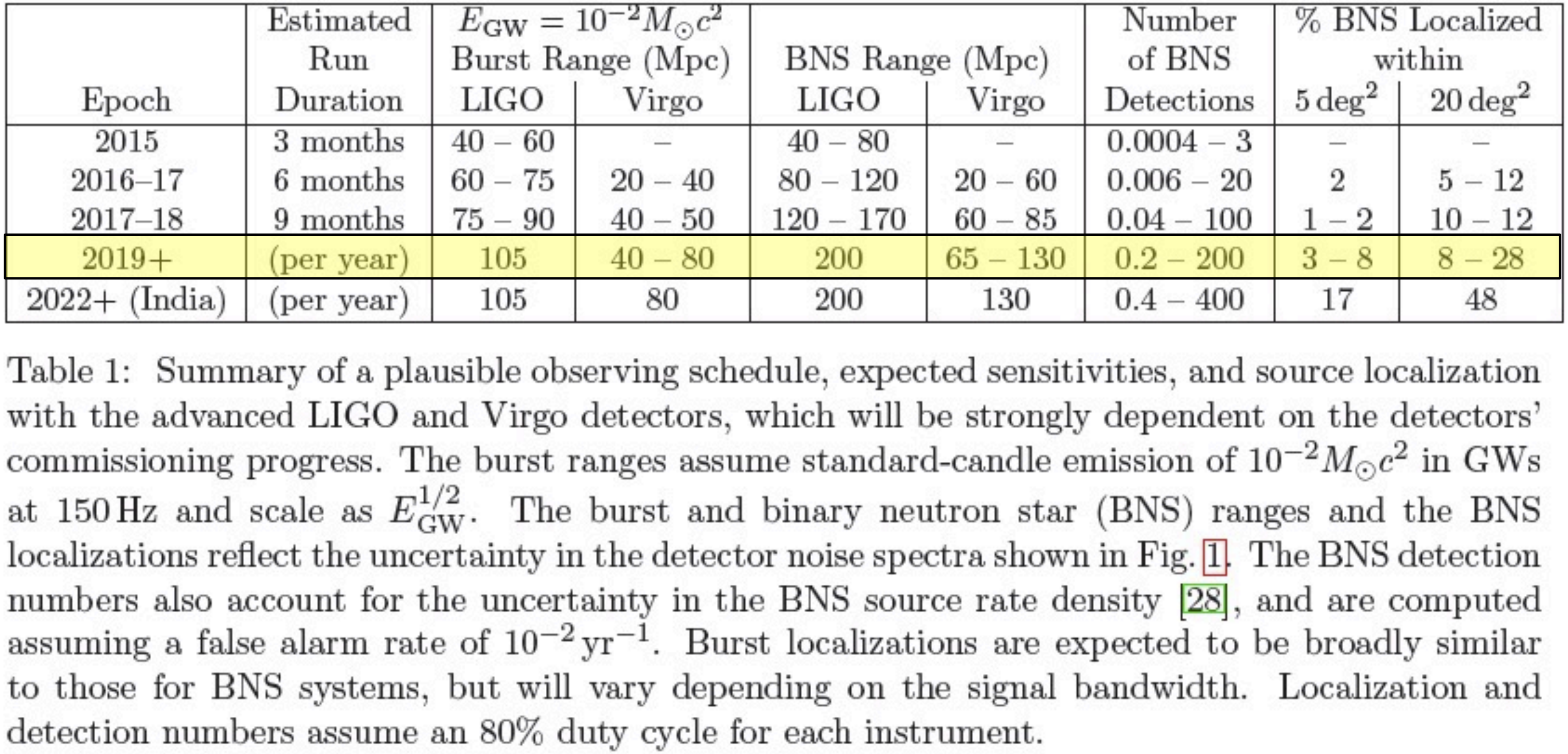
Advanced Virgo Evolution



arXiv 1408.3978

- The average distance to which binary neutron star (BNS) signals could be seen is given in Mpc.
- Current notions of the progression of sensitivity are given for early, middle, and late commissioning phases, as well as the final design sensitivity target and the BNS-optimized sensitivity.

Estimated observing scenario

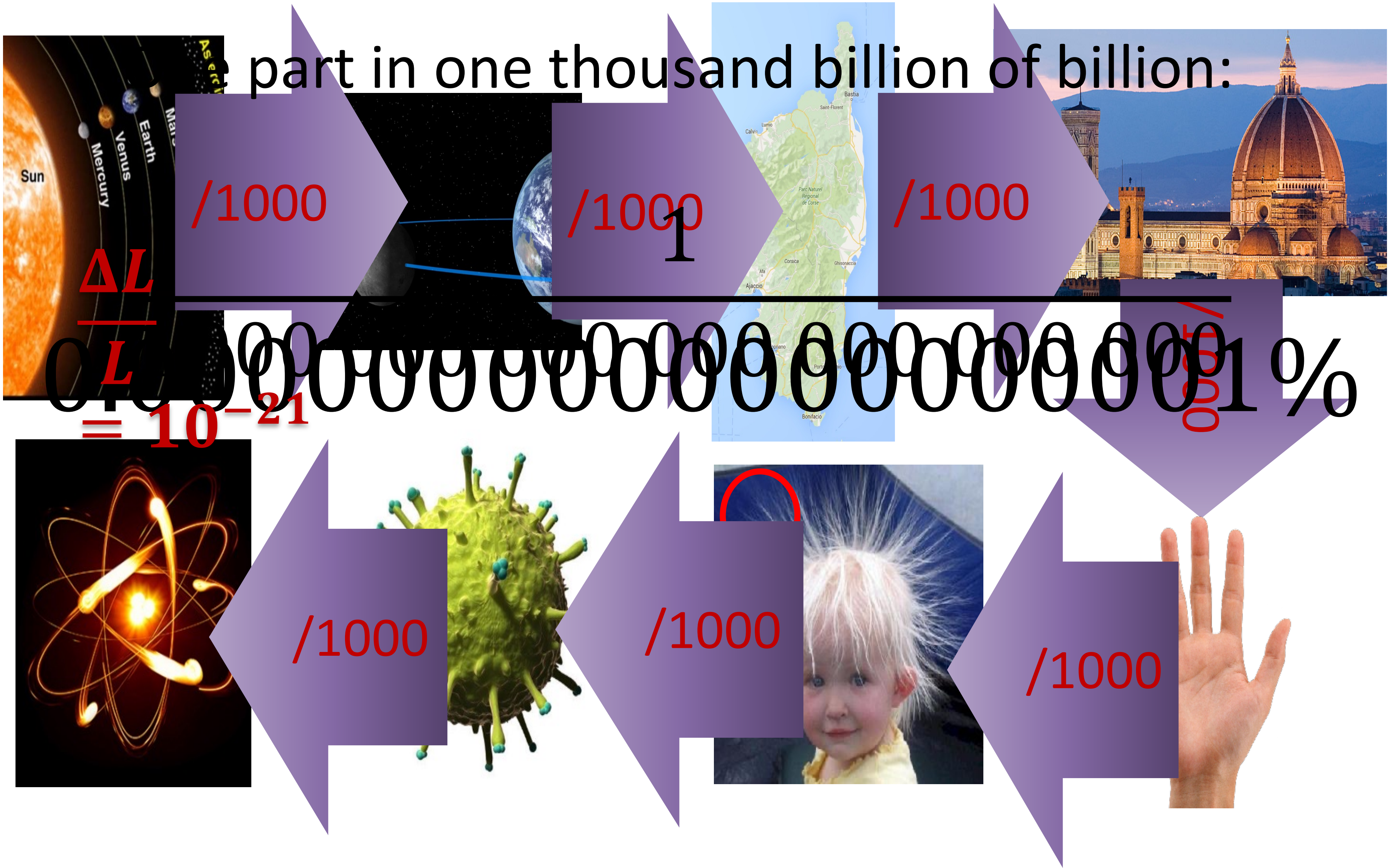


Epoch	Estimated Run Duration	$E_{\mathrm{GW}} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		$5\,\mathrm{deg}^2$	$20\,\mathrm{deg}^2$
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 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 $E_{\mathrm{GW}}^{1/2}$. The burst and binary neutron star (BNS) ranges and the BNS localizations reflect the uncertainty in the detector noise spectra shown in Fig. 1. The BNS detection numbers also account for the uncertainty in the BNS source rate density [28], and are computed assuming a false alarm rate of $10^{-2}\,\mathrm{yr}^{-1}$. Burst localizations are expected to be broadly similar to those for BNS systems, but will vary depending on the signal bandwidth. Localization and detection numbers assume an 80% duty cycle for each instrument.

arXiv 1304.0670

Tiny ripples



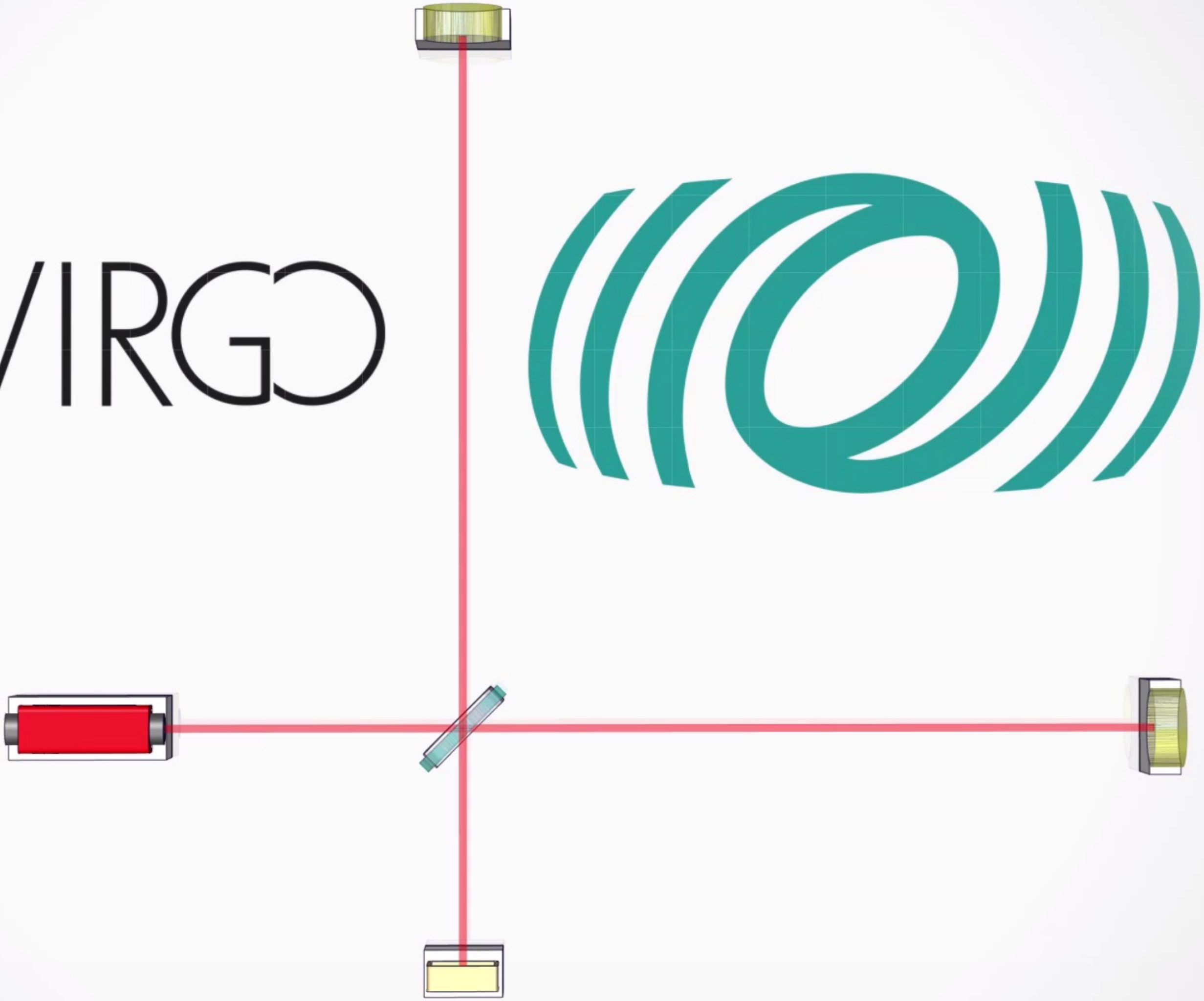
e part in one thousand billion of billion:

$$\frac{1}{000\,000\,000\,000\,000\,000\,000}$$

0.000000000000000000001%

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

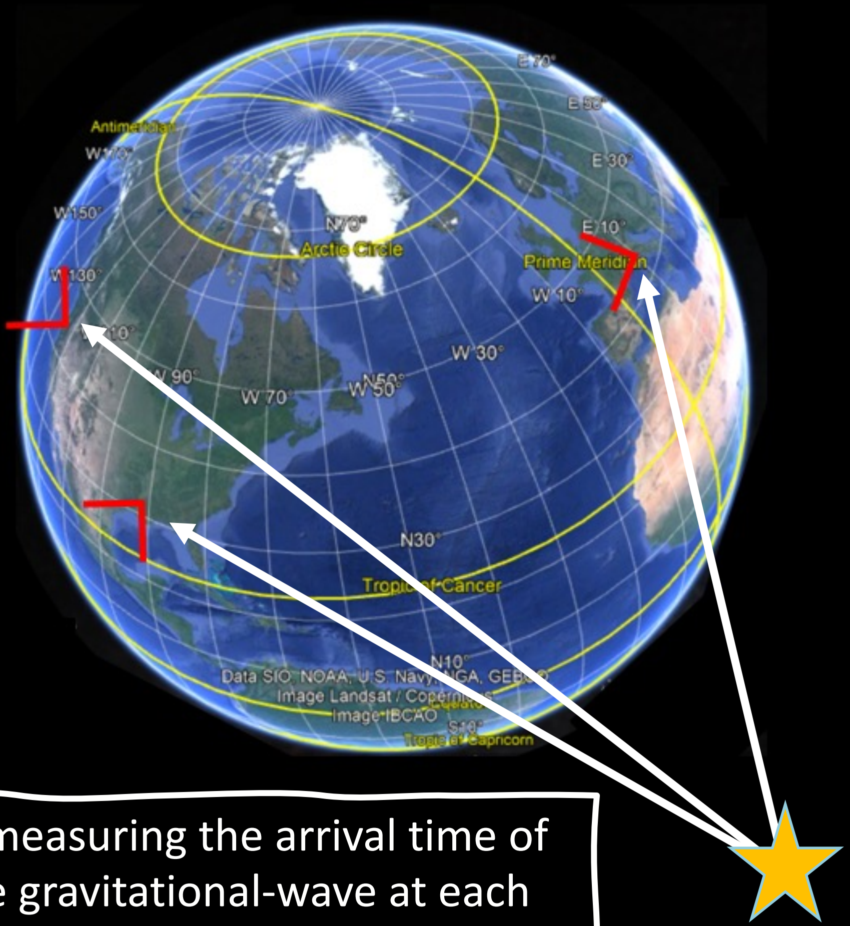
VIRGO




Virgo, Cascina, Italy


LIGO, Livingston, LA


LIGO, Hanford, WA

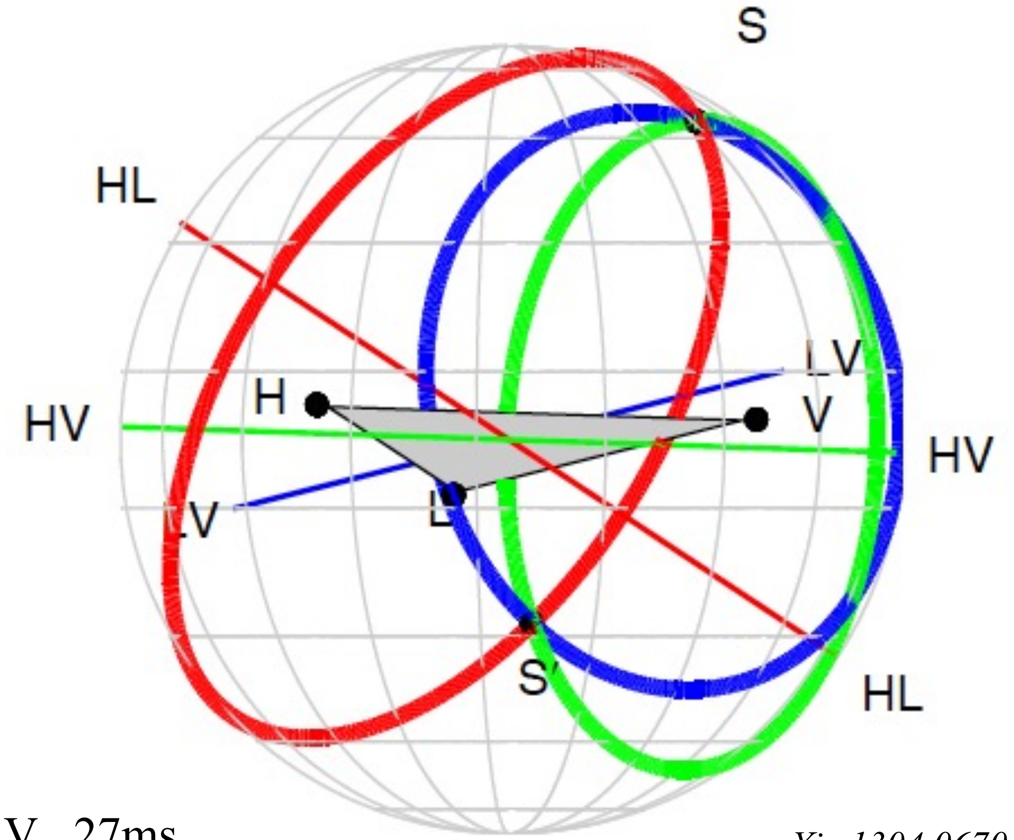


By measuring the arrival time of the gravitational-wave at each observatory, it's possible to identify its location on the sky

A single GW observatory is mostly insensitive to the sky location; we want two and preferably three or more observatories

Sky localization: triangulation

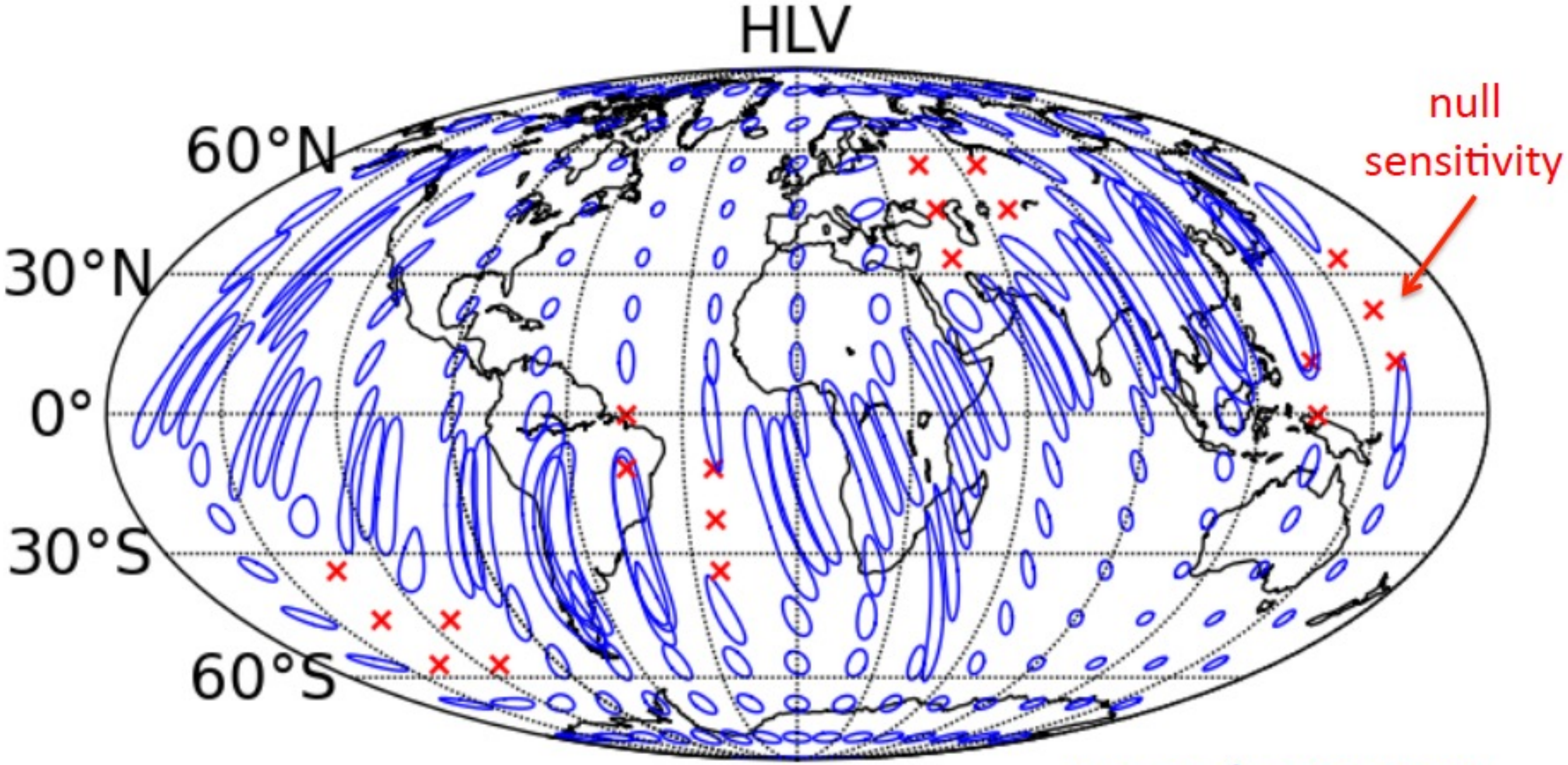
- A pair of detectors localizes to a ring on the sky.
- Width of rings depends upon timing accuracy and distance between detectors.
- More widely spaced detectors improves localization



LH ←→ V 27ms
LH ←→ LL 10ms

arXiv 1304.0670

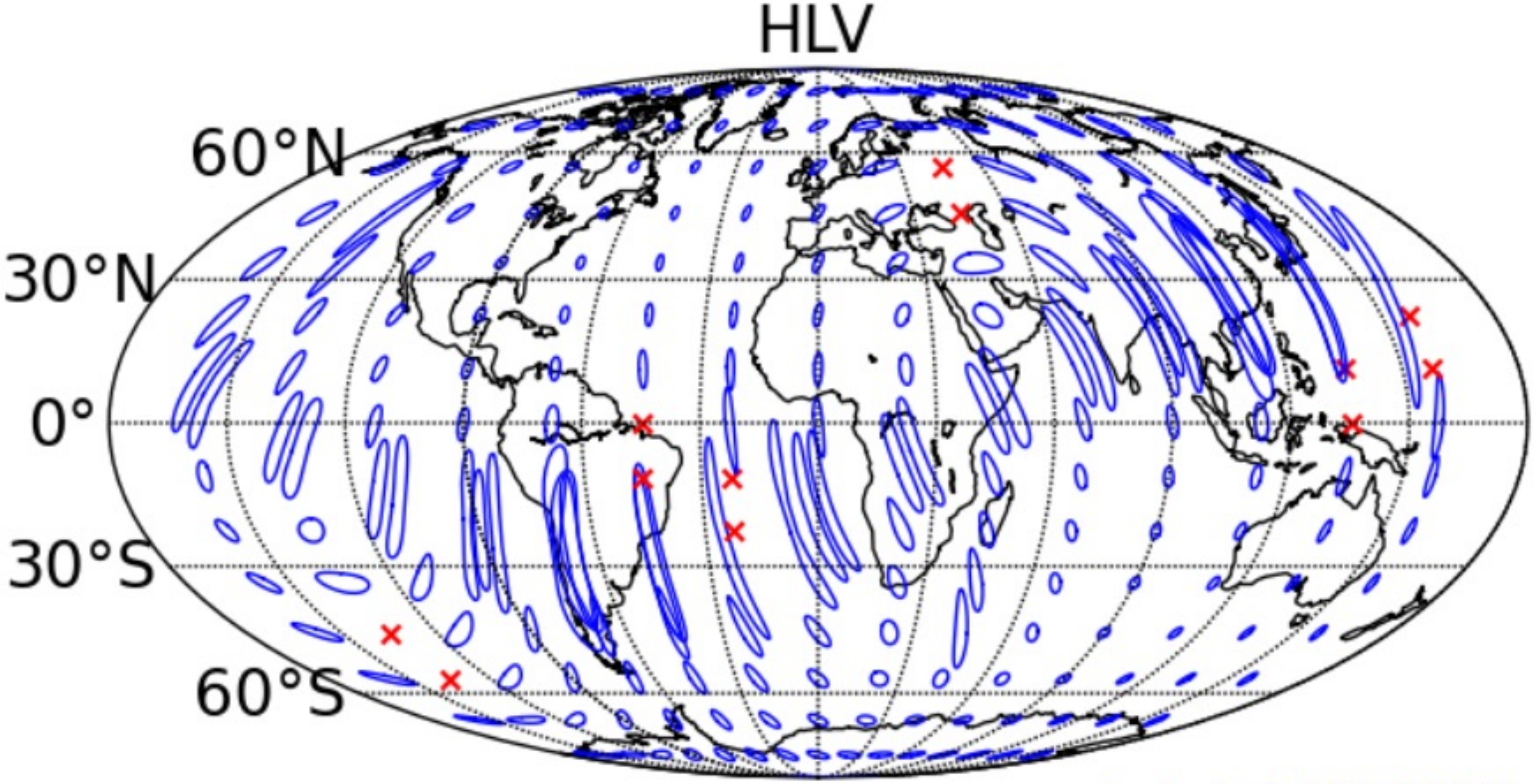
Sky localization – 2015



Aasi et al. 1304.0670

Localization expected for a BNS system at 80 Mpc by the HLV network. The ellipses show 90% confidence localization areas and the red crosses regions of the sky where the signal would not be confidently detected.

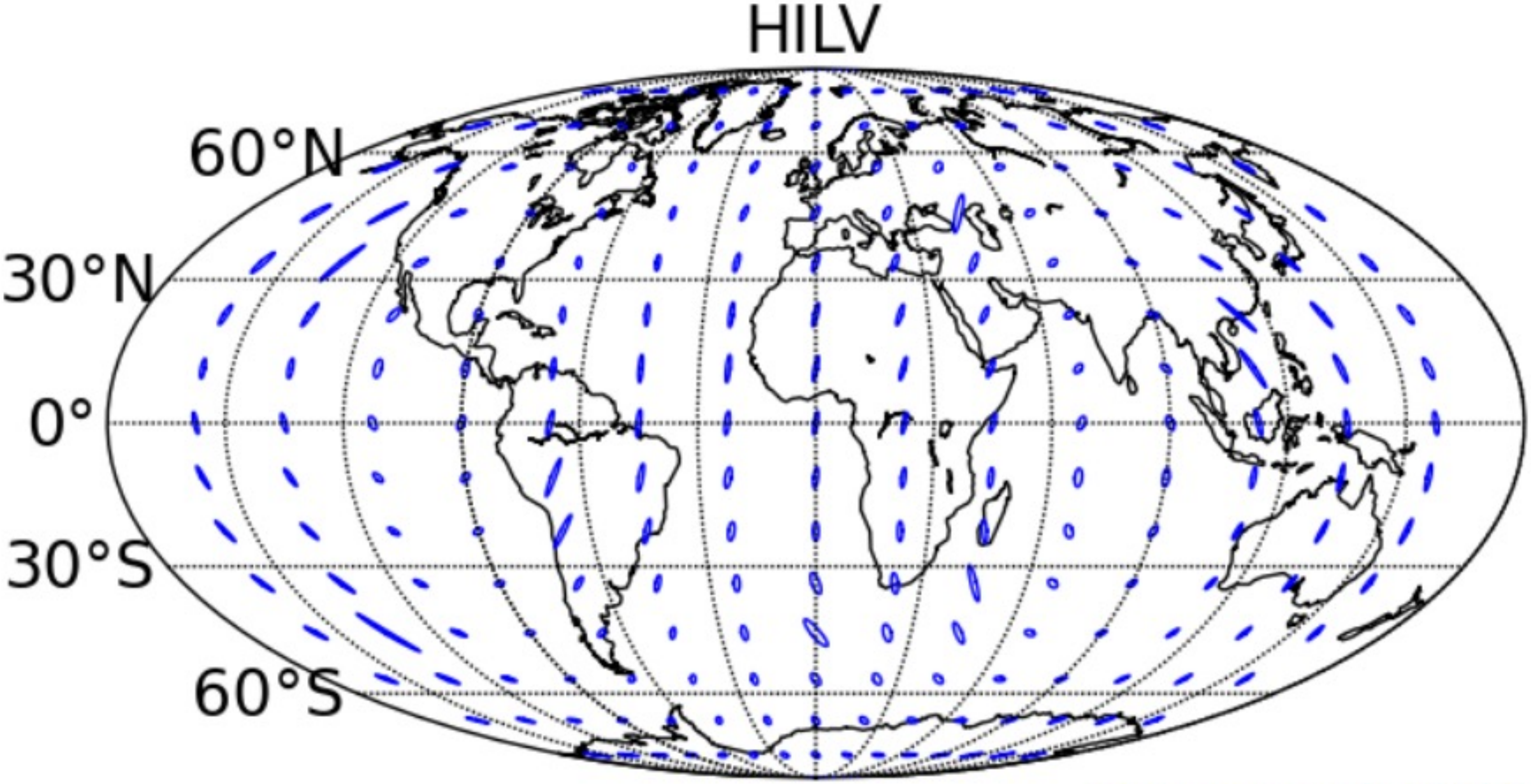
Sky localization – 2019+ (design)



Aasi et al. 1304.0670

Localization expected for a BNS system at 160 Mpc by the HLV network. The ellipses show 90% confidence localization areas and the red crosses regions of the sky where the signal would not be confidently detected.

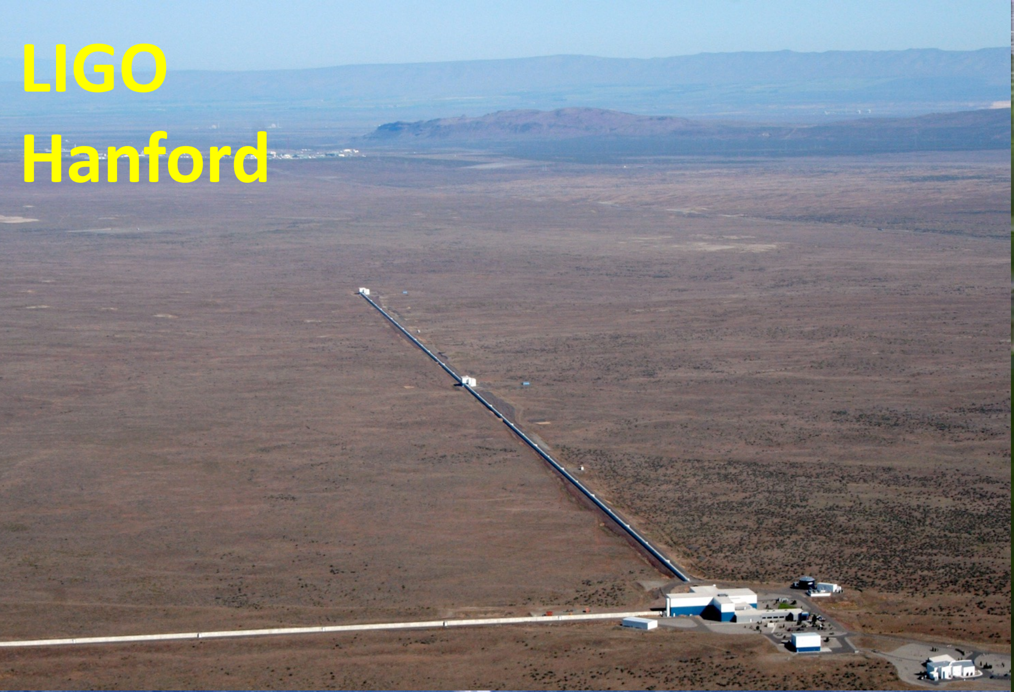
Sky localization – 2022+ (LIGO-India)



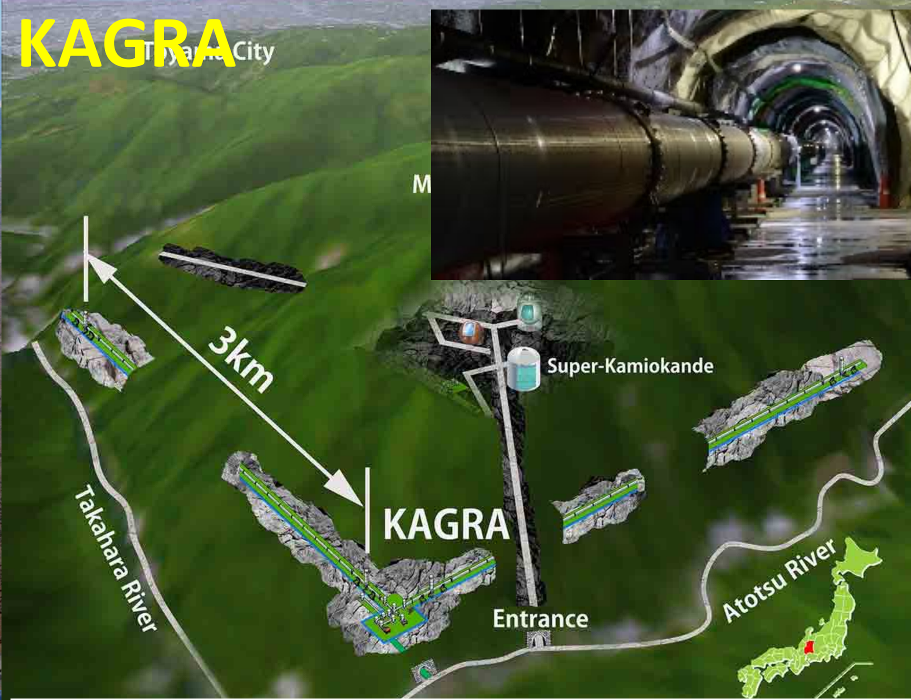
Aasi et al. 1304.0670

Localization expected for a BNS system at 160 Mpc by all detectors at final design sensitivity. The inclusion of a fourth site in India provides good localization over the whole sky.

LIGO-KAGRA network qualitatively similar. (Fairhurst 2011)



LIGO Hanford



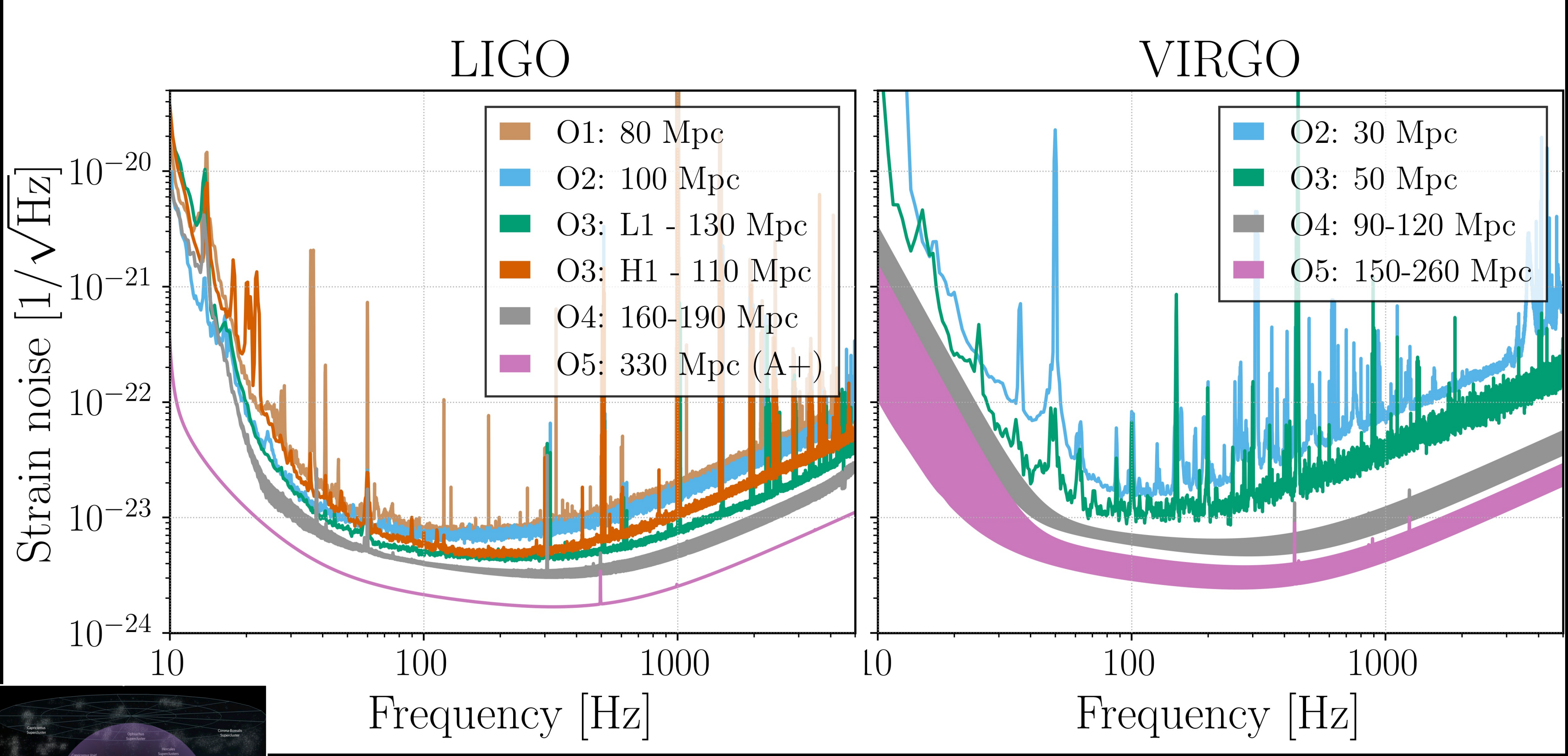
KAGRA

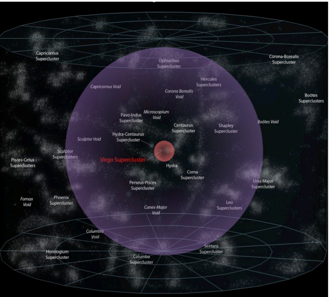
LIGO Livingston

Virgo

Upgrades do Advanced LIGO and Advanced Virgo and LIGO

Detector noise expressed as equivalent GW strain

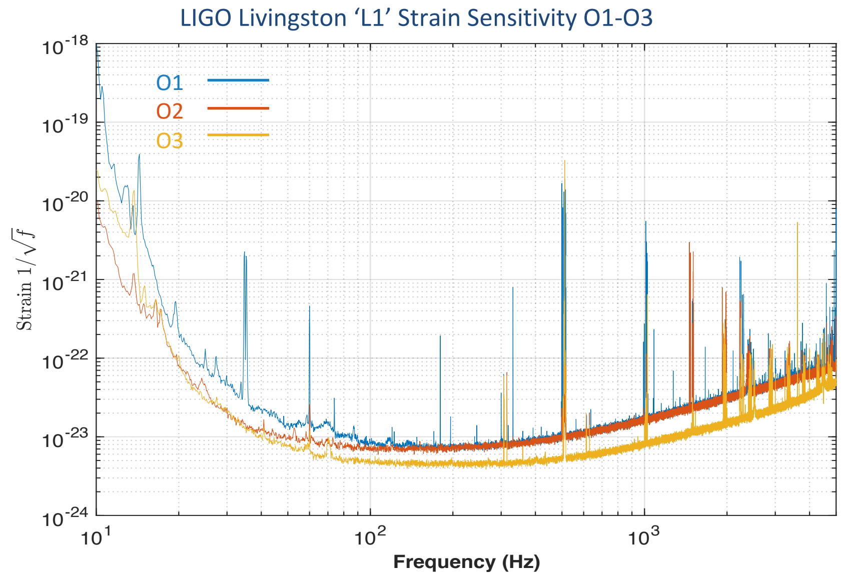


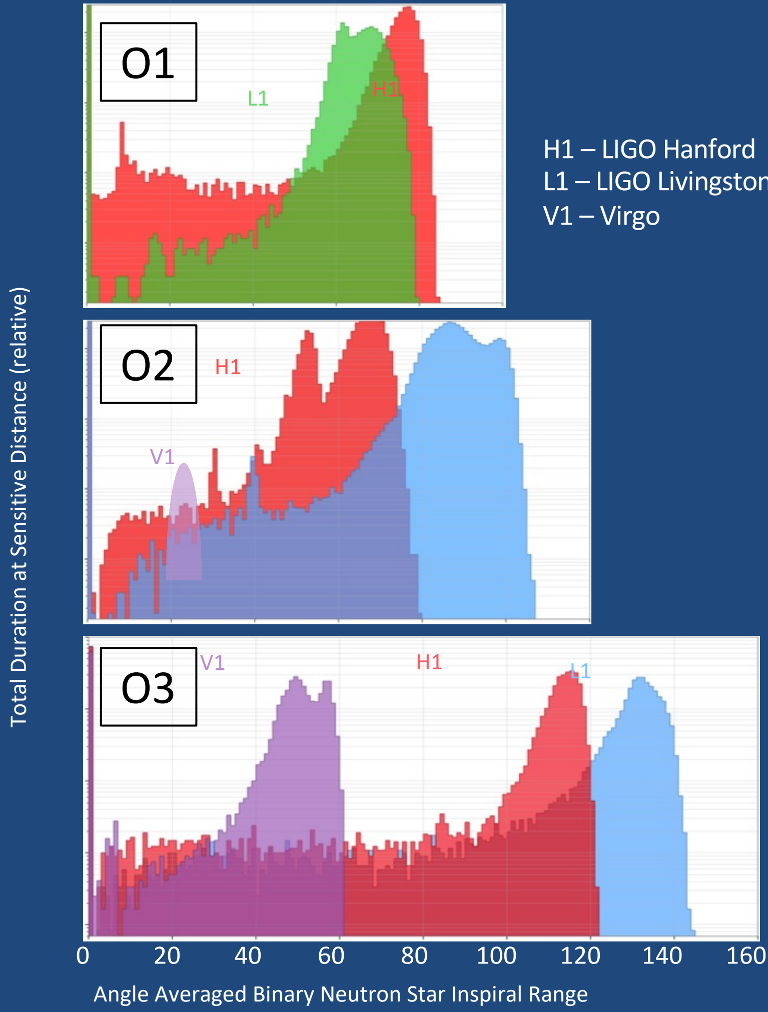


Upcoming update of the LIGO-VIRGO-KAGRA observing scenario document

Ground-based Detector Performance O1-O3

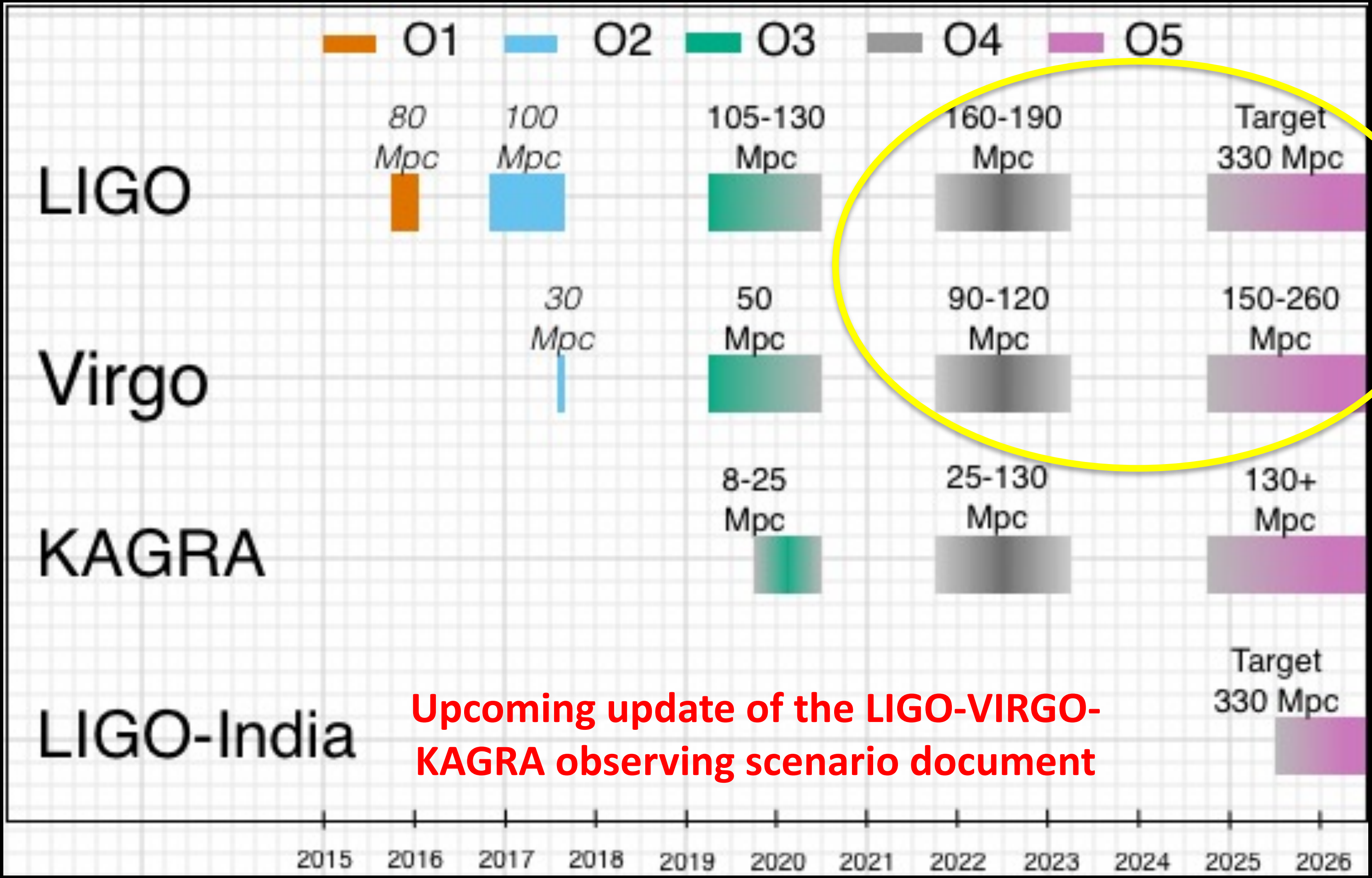
- Advanced detector network began operations in Sept 2015
- O1 Observing Run: Sept 12, 2015 – Jan 19, 2016
  - Two detector run: LIGO H1,L1
- O2 Observing Run: Nov 20, 2016 – Aug 25, 2017
  - Three detector run: LIGO H1, L1; Virgo V1 (Aug 1 - Aug 25, 2017)
- O3 Observing Run: April 1, 2019 – Mar 27, 2020
  - Three detector run: LIGO H1, L1; Virgo V1
  - April 2020: O3GK run with KAGRA and GEO600


LIGO Livingston 'L1' Strain Sensitivity O1-O3



H1 – LIGO Hanford
L1 – LIGO Livingston
V1 – Virgo

Observing Run Timeline



Upcoming update of the LIGO-VIRGO-KAGRA observing scenario document

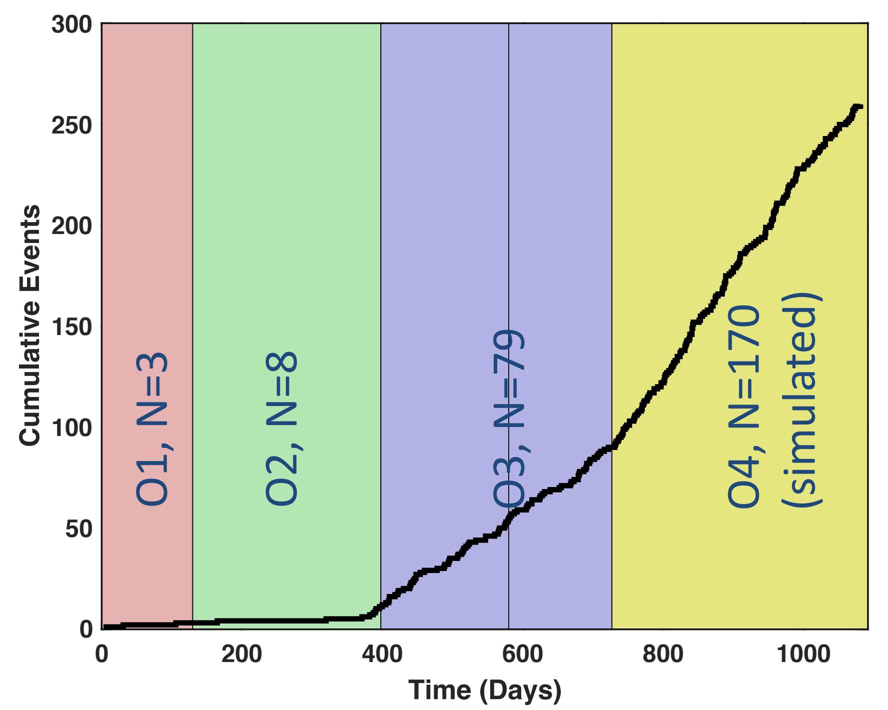
O4 Will be Better Than O3!

- There is a compelling scientific rationale for carrying out detector upgrades.

- SNR scales with sensitivity - Improved sensitivity produces higher SNR events
  - Critical for probing BBH ringdown, BNS postmerger dynamics, improved tests of GR, …

Simulated O4 event stream, assuming
- 190 Mpc BNS range for H1, L1
- 90 Mpc BNS range for Virgo

Simulated Event Stream for a one year duration O4 run



Path to better detectors

- **More of the same, but even better:** more power, more squeezing, bigger/heavier masses, lower loss mirror coatings, better suspensions, …
- **New technologies**: alternative wavelengths + cryogenics, alternative optical configurations, ..

- **Make it longer:** take advantage of scaling of noises with arm length
- **Go Underground:** access low frequencies
- **New concepts:** triangular shape, xylophone, ..

ONLY FOR NEW FACILITIES

Looking Further in the Future

After O4, another break will be taken to complete upgrades and to continue improving KAGRA 's sensitivity

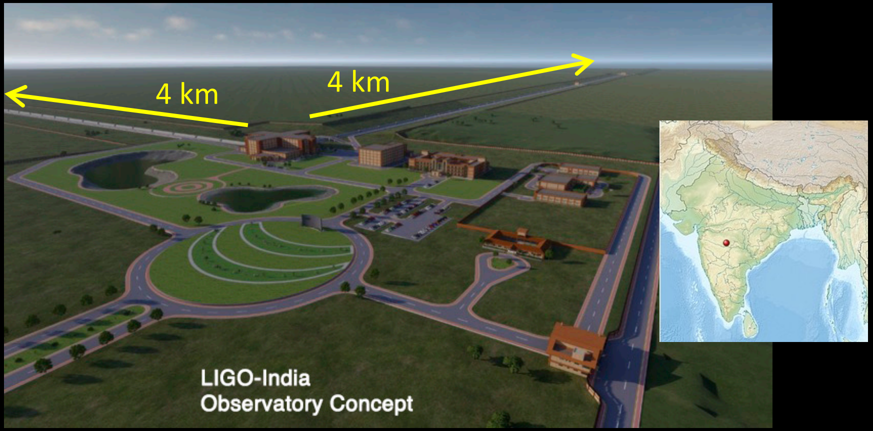
- Start and end states are to be determined

Following these upgrades, the O5 run is planned in the middle of the decade

- Start date paced by O4 duration and follow on break

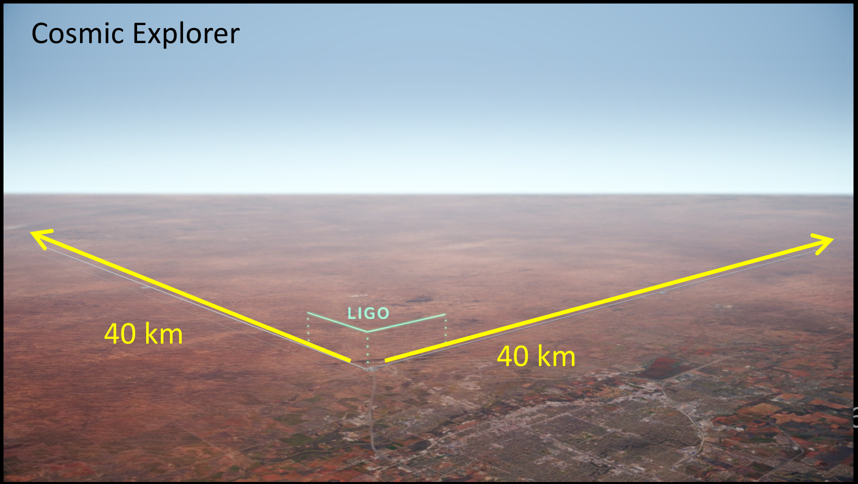
Later this decade: LIGO-India

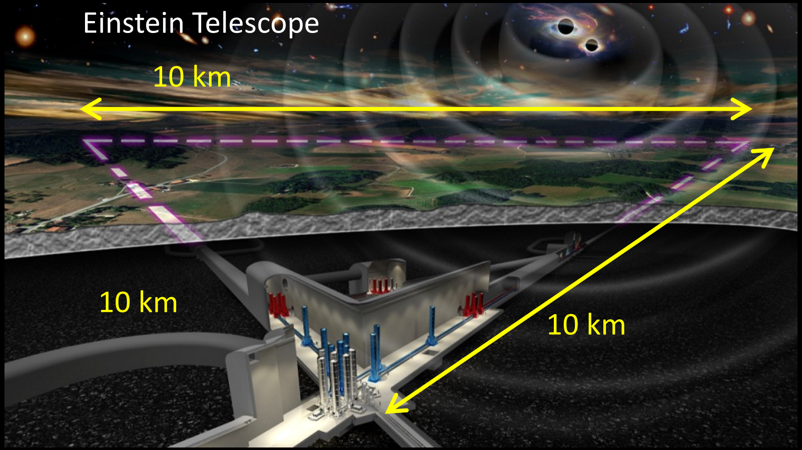
- A third LIGO Observatory identical to two US LIGO Observatories located in Maharashtra, India
- Detector components supplied by the USA; observatory construction and operation carried out by India
- Project approved by India in 2016, now awaiting construction funding



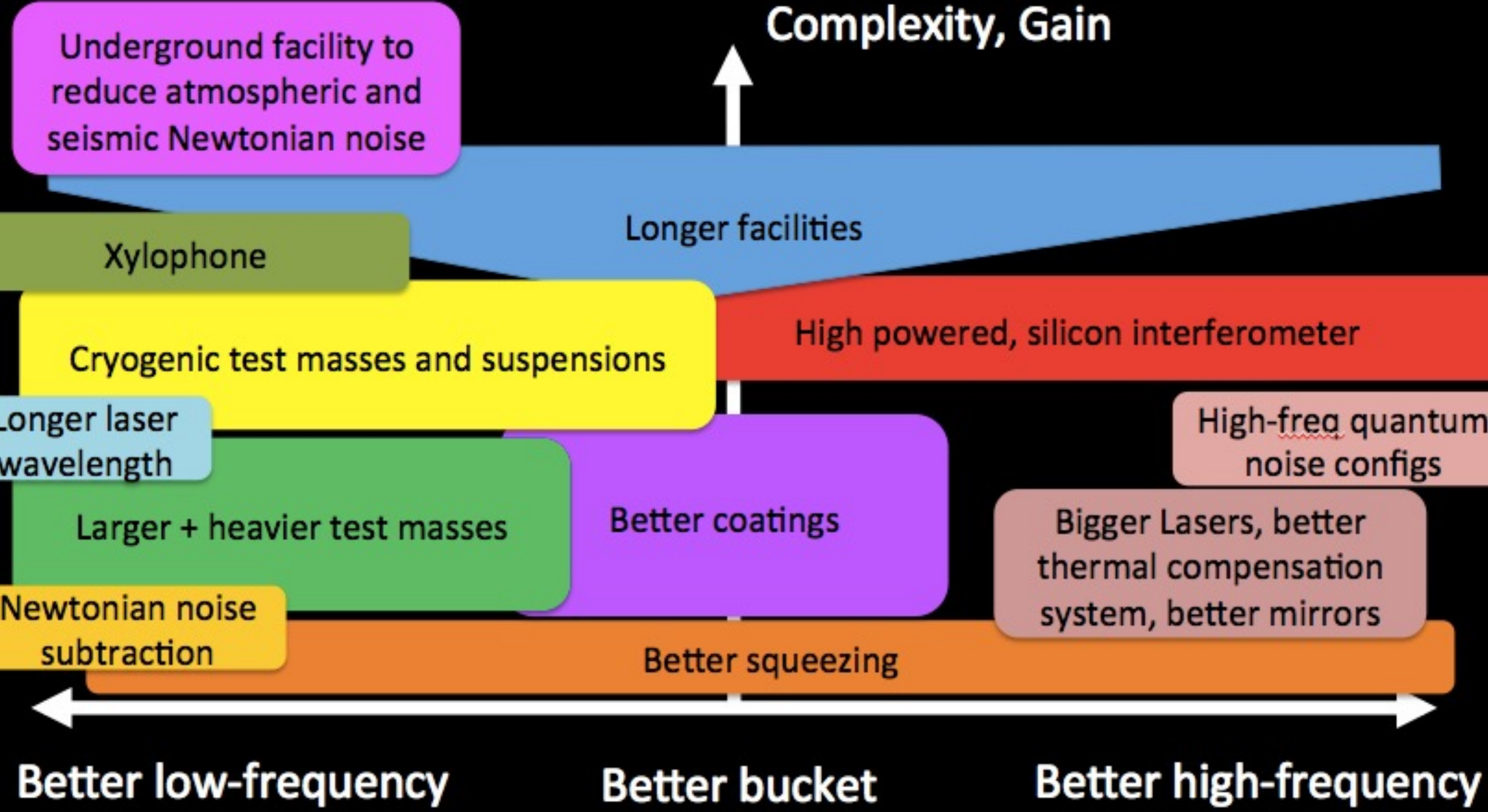
2030s: Construction of a new generation of GW observatories targeting a 10X increase in sensitivity over the current GW observatory network

- Europe: Einstein Telescope
- USA: Cosmic Explorer





3G Instrumentation Roadmap



Complexity, Gain

Underground facility to reduce atmospheric and seismic Newtonian noise

Longer facilities

Xylophone

Cryogenic test masses and suspensions

High powered, silicon interferometer

Longer laser wavelength

High-freq quantum noise configs

Larger + heavier test masses

Better coatings

Bigger Lasers, better thermal compensation system, better mirrors

Newtonian noise subtraction

Better squeezing

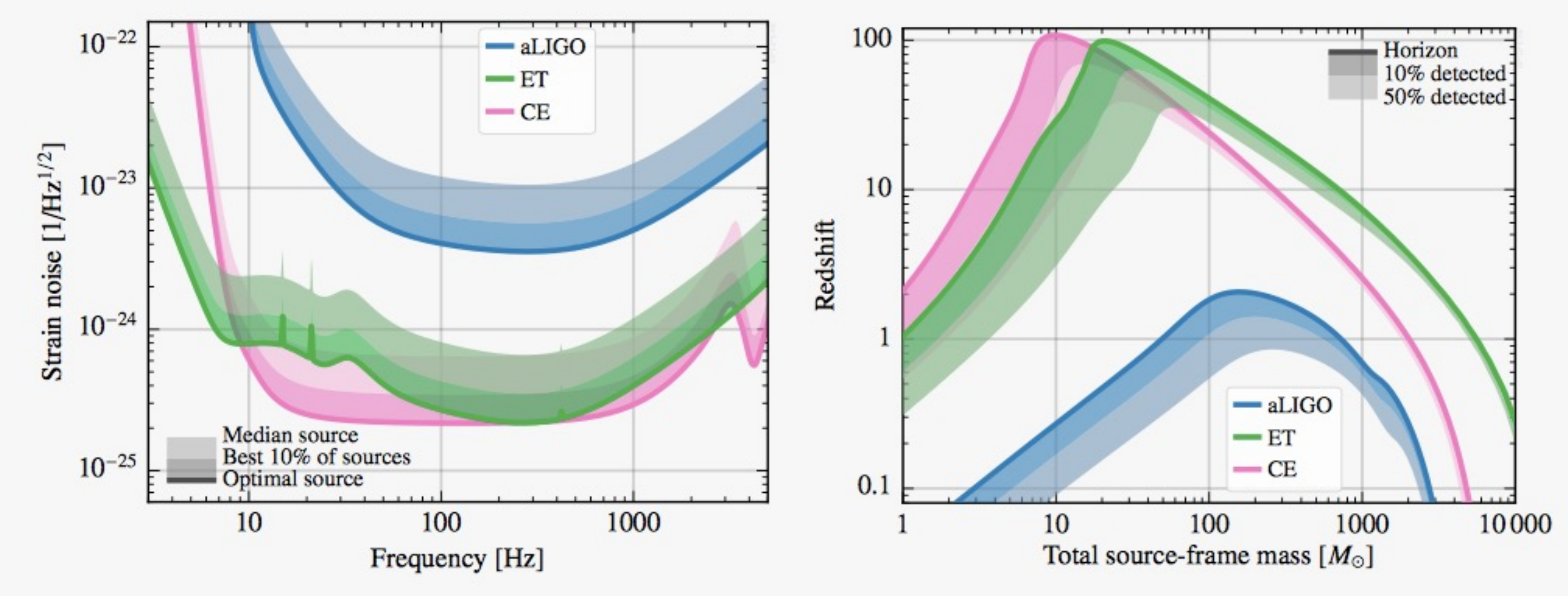
Better low-frequency

Better bucket

Better high-frequency

Credit: S. Hild

3rd Generation Ground-based Gravitational-wave Observatory => 3G



- *explore* new physics in gravity and in the fundamental properties of compact objects,
- *determine* the properties of the hottest and densest matter in the Universe,
- *reveal* the merging black hole population throughout the Universe and search for massive black hole seeds,
- *understand* the physical processes and mechanisms that underlie the most powerful astrophysical phenomena,
- *investigate* the particle physics of the primeval Universe and probe its dark sectors.

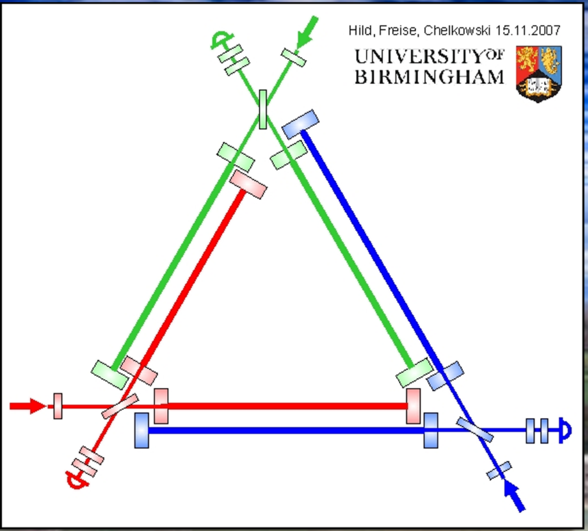
https://gwic.ligo.org/3Gsubcomm/documents/3G-observatory-science-case.pdf

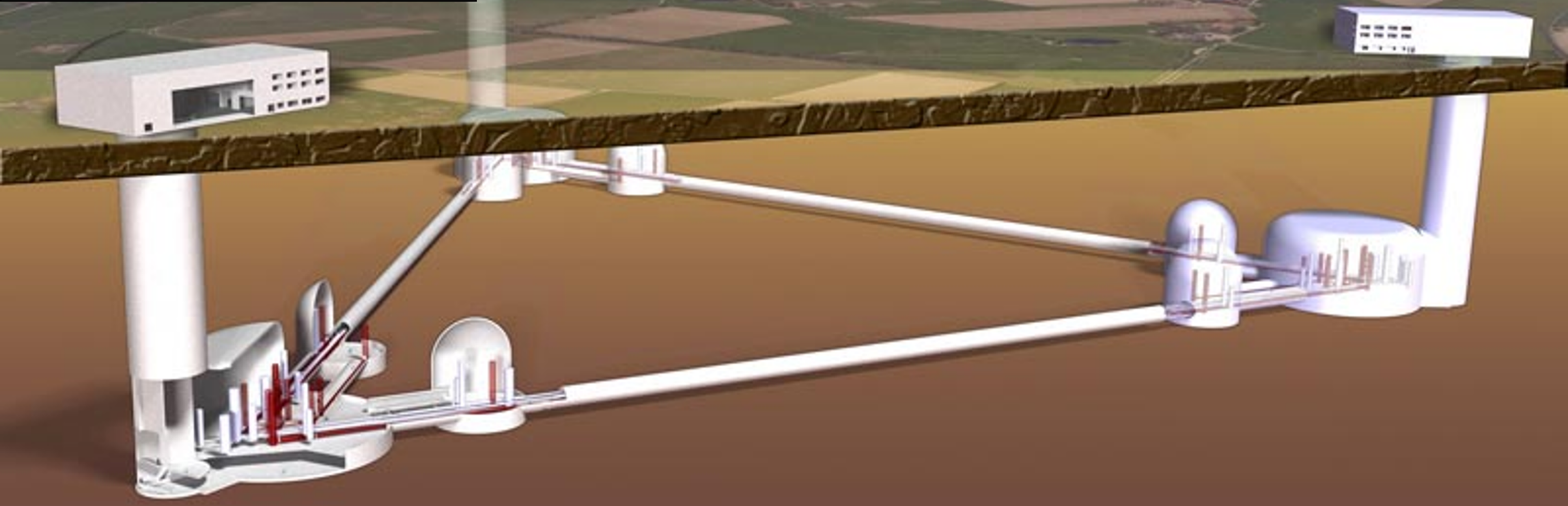
LIGO VIRGO KAGRA

ET EINSTEIN TELESCOPE

et-gw.eu

The ET Collaboration





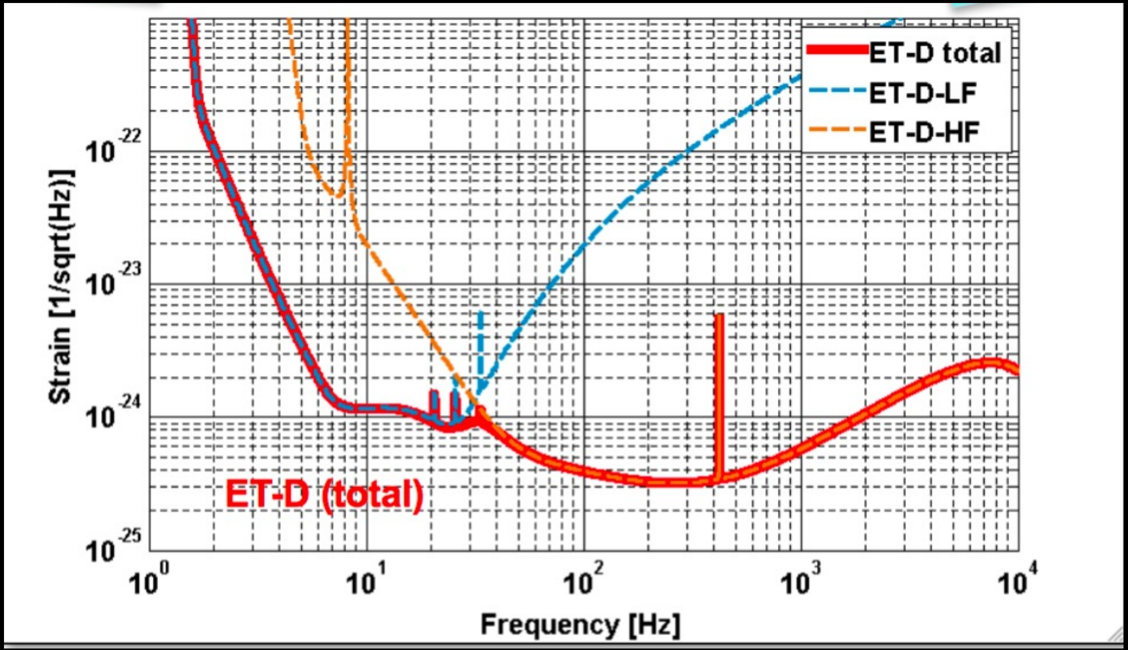
Underground, triangular, 10km on a side, up to 6 interferometers

Einstein Telescope design

(see http://www.et-gw.eu/index.php/etdsdocument)

- **Triangle**
- **Underground** to fit a 10 km triangle and mitigate environmental/Newtonian noise
- **Xylophone**

Cryogenic detector for low-freq



High power detector for high-freq

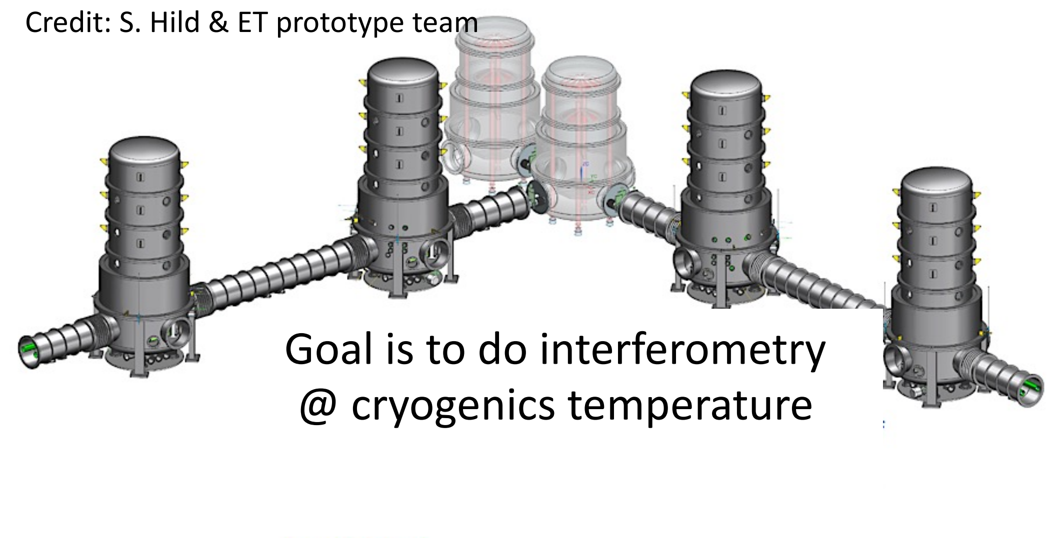
ET has two site candidates!!

@ Limburg, a cross-border region in the **Netherlands, Belgium, Germany**

@ Sos Enattos in **Sardinia, Italy**

ET news

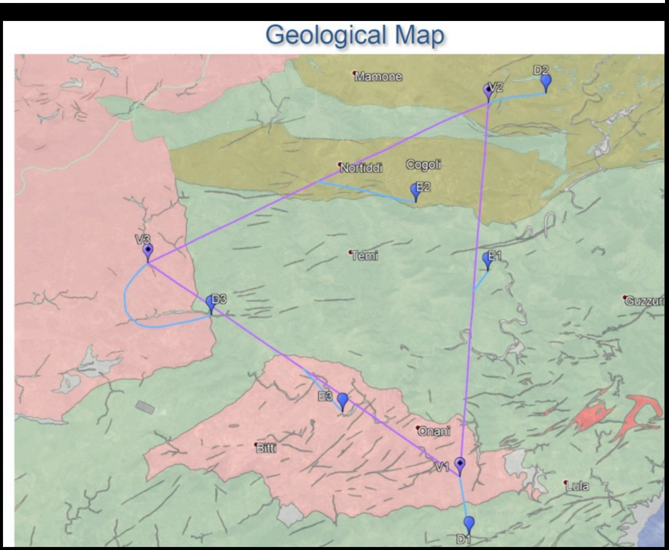
- **ET prototype funded,**
  to be built in Maastricht


Credit: S. Hild & ET prototype team

Goal is to do interferometry
@ cryogenics temperature

- Seismic studies in
  Limburg underway

- Preliminary qualification of the Sardegna site (Sos Enattos) completed; underground lab funded for final seismic studies



Cosmic Explorer News

Concept for a single 40km detector per site, on the surface

- Fundamental noises scale with length
- Free-Spectral-Range for a 40km detector is 3.75kHz, going beyond 40km would reduce the interferometer bandwidth and compromise its scientific potential (like neutron-star merger and supernovae)

Cosmic Explorer News

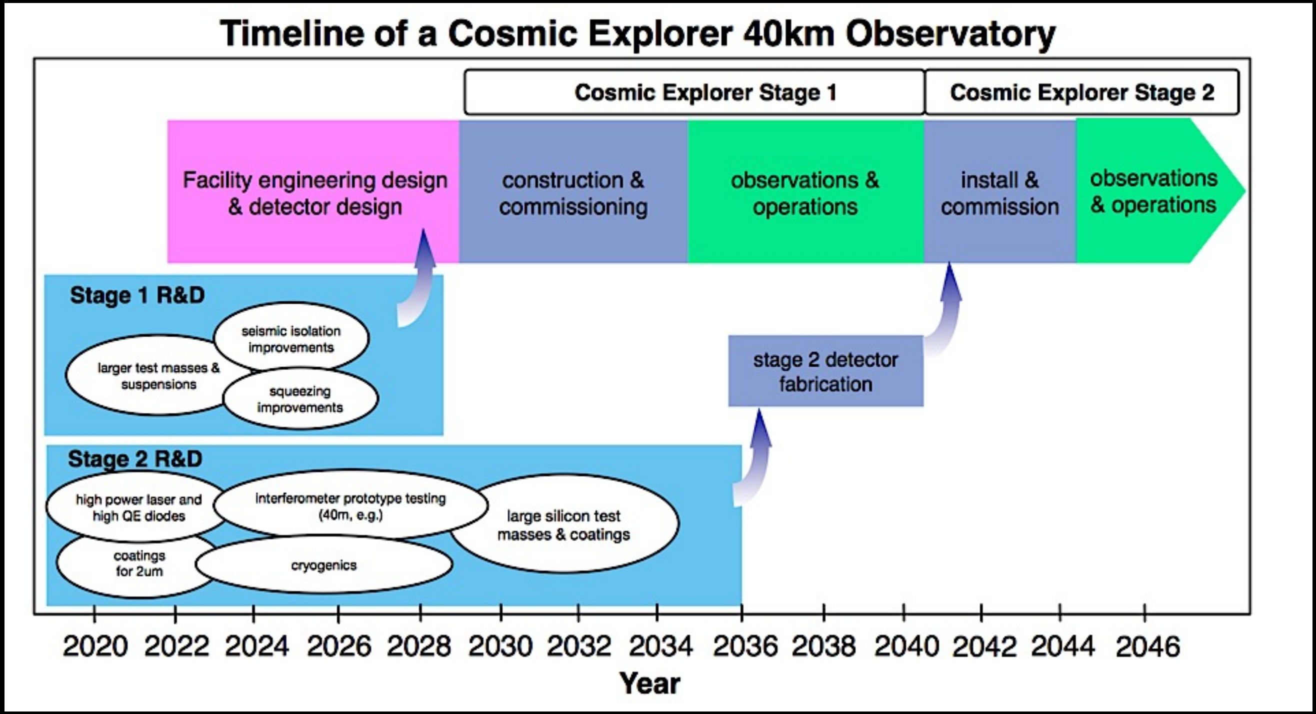
- NSF grant awarded to develop Cosmic Explorer white paper (2018-21)
- NSF **Workshop on Large Ultrahigh-Vacuum Systems** (Jan 2019)
- **Technology Development** White Paper for Astro2020
  - **Cosmic explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO**

Astro 2020

Board on Physics and Astronomy
Space Studies Board

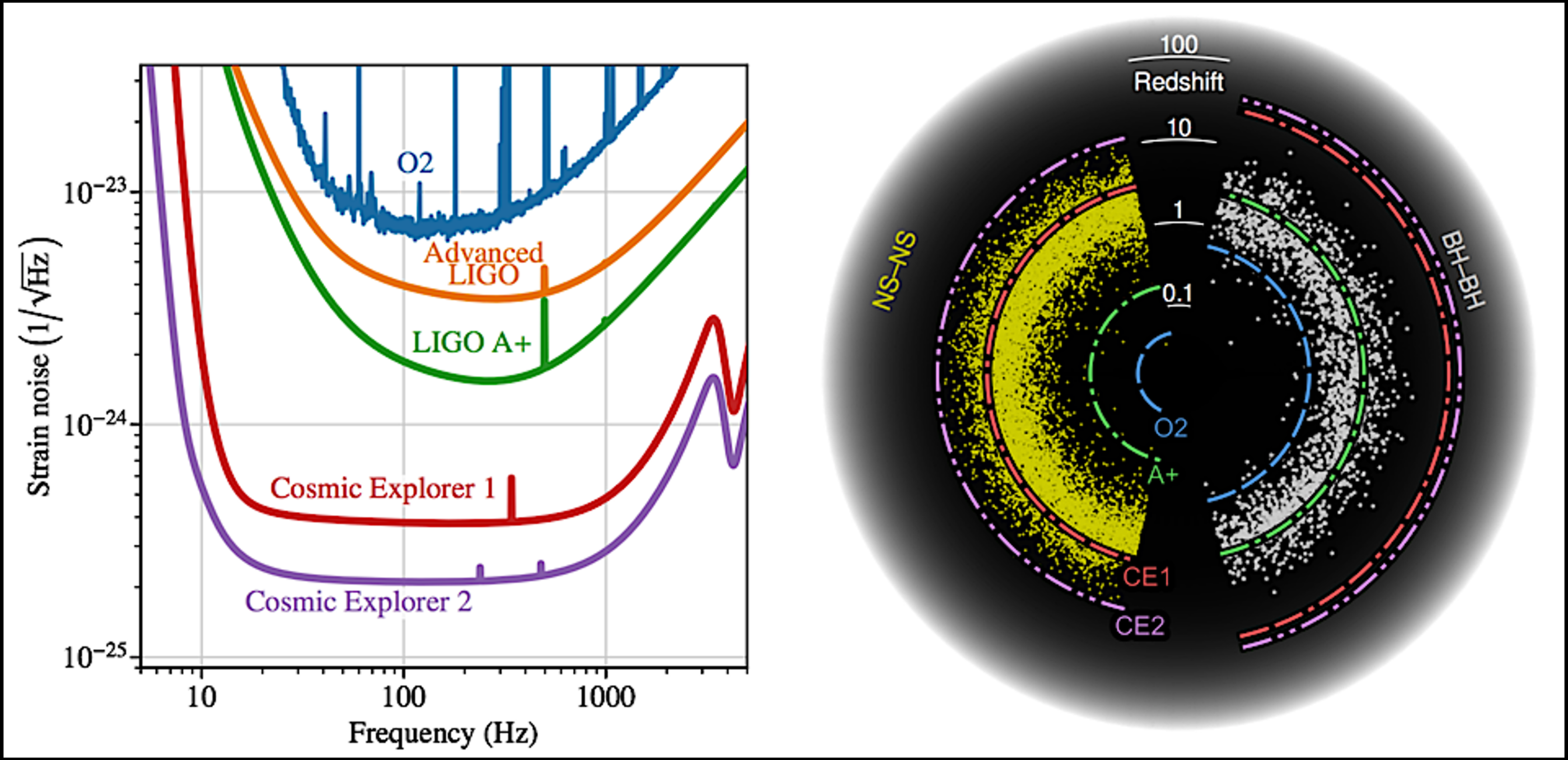
Stage 1:
Room temperature
detector

Stage 2:
Cryogenic Detector
Silicon, 2um, 123K
(Voyager technology)



arxiv.org/abs/1903.04615

CE will give us access to all of the stellar-mass binaries mergers in the Universe



Credit: Hall/Vitale

Concept for a high frequency detector in Australia

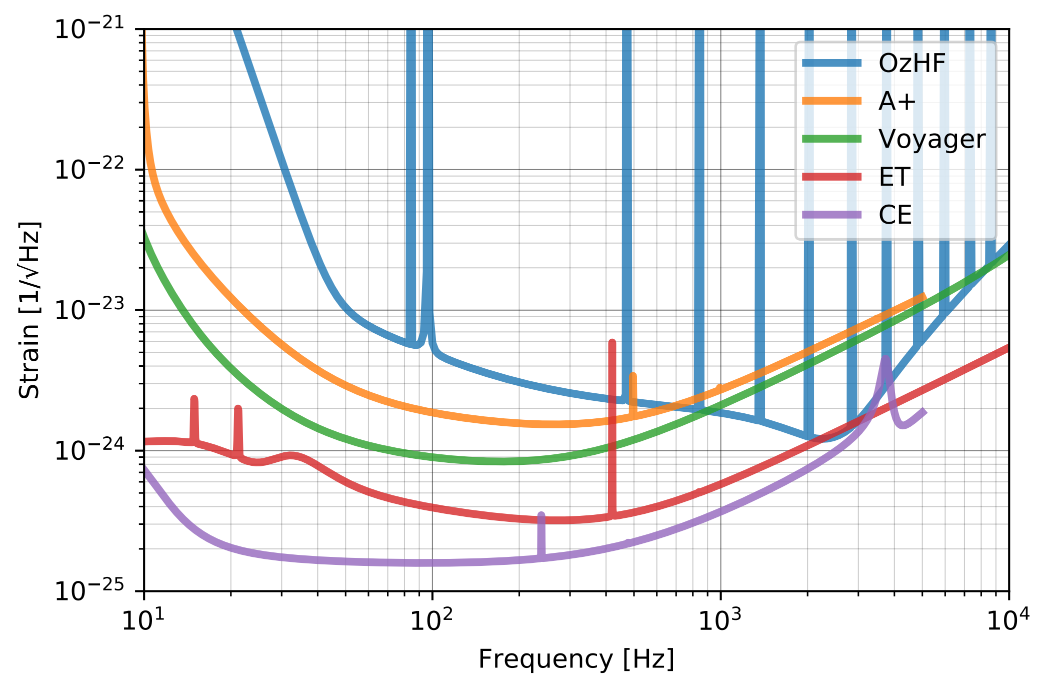
- Target sensitivity better than 10^{-24} $\mathrm{Hz}^{-1/2}$ between 1-4kHz
- Complementary to a network of 3G detectors..
- ..but could also find a site for a second Cosmic Explorer!

OzGrav

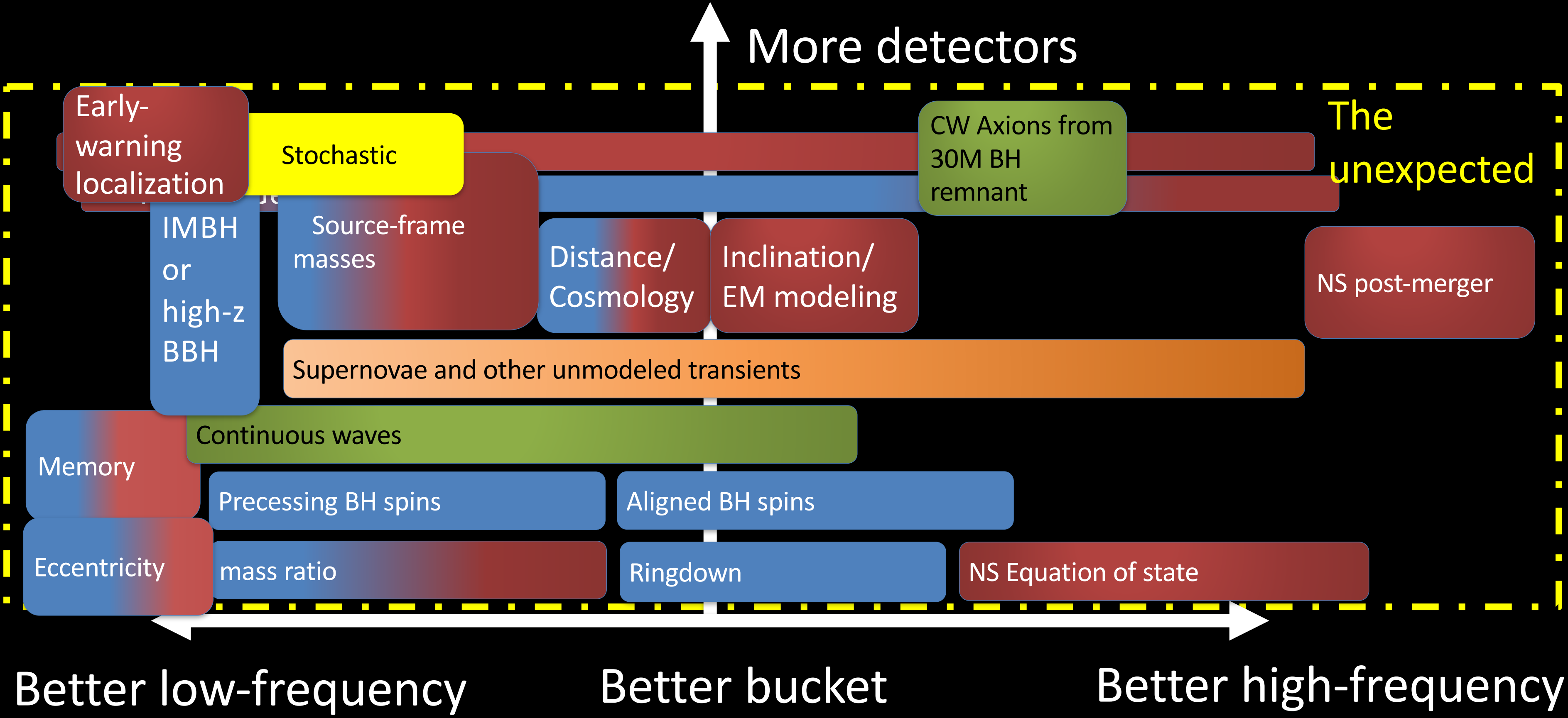
ARC Centre of Excellence for Gravitational Wave Discovery

Parameter	OZHF (long SRC)	aLIGO
Wavelength	2 um	1064 nm
Mirror Mass	94.4 kg	40 kg
Arm Gain	364	270
Arm length	2 km	4 km
Power recycling gain	54	50
Signal recycling transmissivity	0.048	0.32
Signal recycling length	500 m	56 m
Arm cavity bandwidth	66 Hz	45 Hz
Input power	500 W	125 W
Power on beamsplitter	27 kW	6.2 kW
Arm cavity power	5.0 MW	0.8 MW
Squeezing level	10 dB	3 dB

Courtesy of B. Slagmolen



What can a 3G network do?



More detectors

Early-warning localization

Stochastic

CW Axions from 30M BH remnant

The unexpected

IMBH or high-z BBH

Source-frame masses

Distance/ Cosmology

Inclination/ EM modeling

NS post-merger

Supernovae and other unmodeled transients

Continuous waves

Memory

Precessing BH spins

Aligned BH spins

Eccentricity

mass ratio

Ringdown

NS Equation of state

Better low-frequency

Better bucket

Better high-frequency

Credit: S. Vitale

https://dcc.ligo.org/G1900660

“GWIC 3G” Science Case

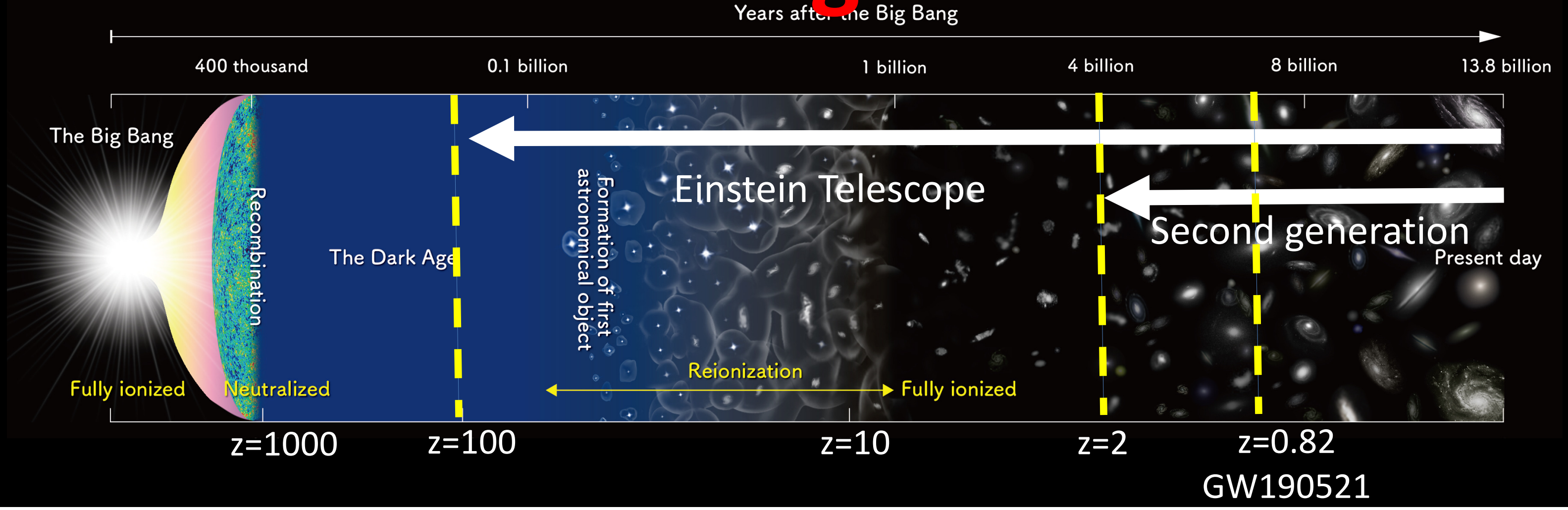
https://gwic.ligo.org/3Gsubcomm/documents/3G-observatory-science-case.pdf

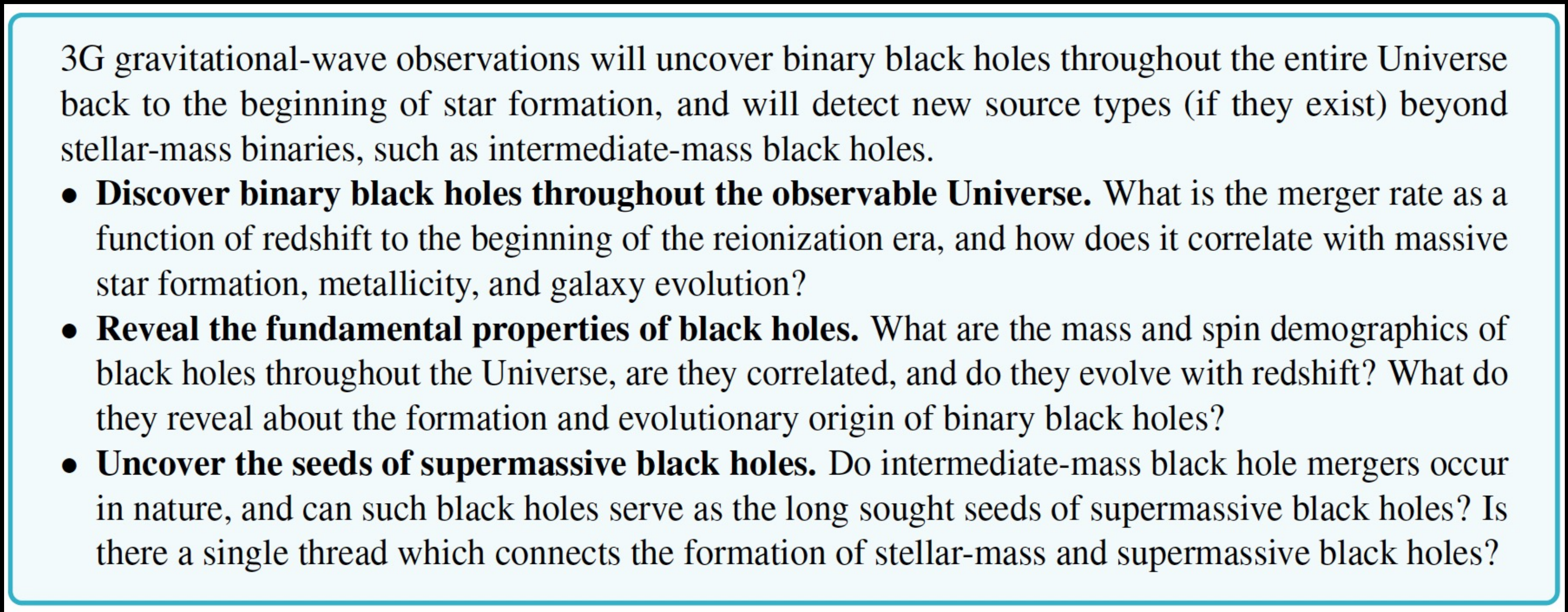
5 main science targets

studied by assuming one ET observatory in Europe, and 2 CE (one in US and one in Australia):

- Extreme gravity and fundamental physics
- Extreme Matter, Extreme Environs
- Observing Stellar-mass Black Holes throughout the Universe
- Sources at the Frontier of Observations
- Cosmology and Early History of the Universe

3G Science Highlight: black holes throughout cosmic history





3G gravitational-wave observations will uncover binary black holes throughout the entire Universe back to the beginning of star formation, and will detect new source types (if they exist) beyond stellar-mass binaries, such as intermediate-mass black holes.

- **Discover binary black holes throughout the observable Universe.** What is the merger rate as a function of redshift to the beginning of the reionization era, and how does it correlate with massive star formation, metallicity, and galaxy evolution?
- **Reveal the fundamental properties of black holes.** What are the mass and spin demographics of black holes throughout the Universe, are they correlated, and do they evolve with redshift? What do they reveal about the formation and evolutionary origin of binary black holes?
- **Uncover the seeds of supermassive black holes.** Do intermediate-mass black hole mergers occur in nature, and can such black holes serve as the long sought seeds of supermassive black holes? Is there a single thread which connects the formation of stellar-mass and supermassive black holes?

Global Timeline

Einstein Telescope

- 2010 ET conceptual design
- 2018-2019 **ET collaboration**
- 2019-2021 ESFRI roadmap
- 2021-2022 Site Selection
- 2023 **Full Technical Design**
- 2025 Infrastructure realization start (excavation, ….)
- 2032+: installation / commissioning / operation

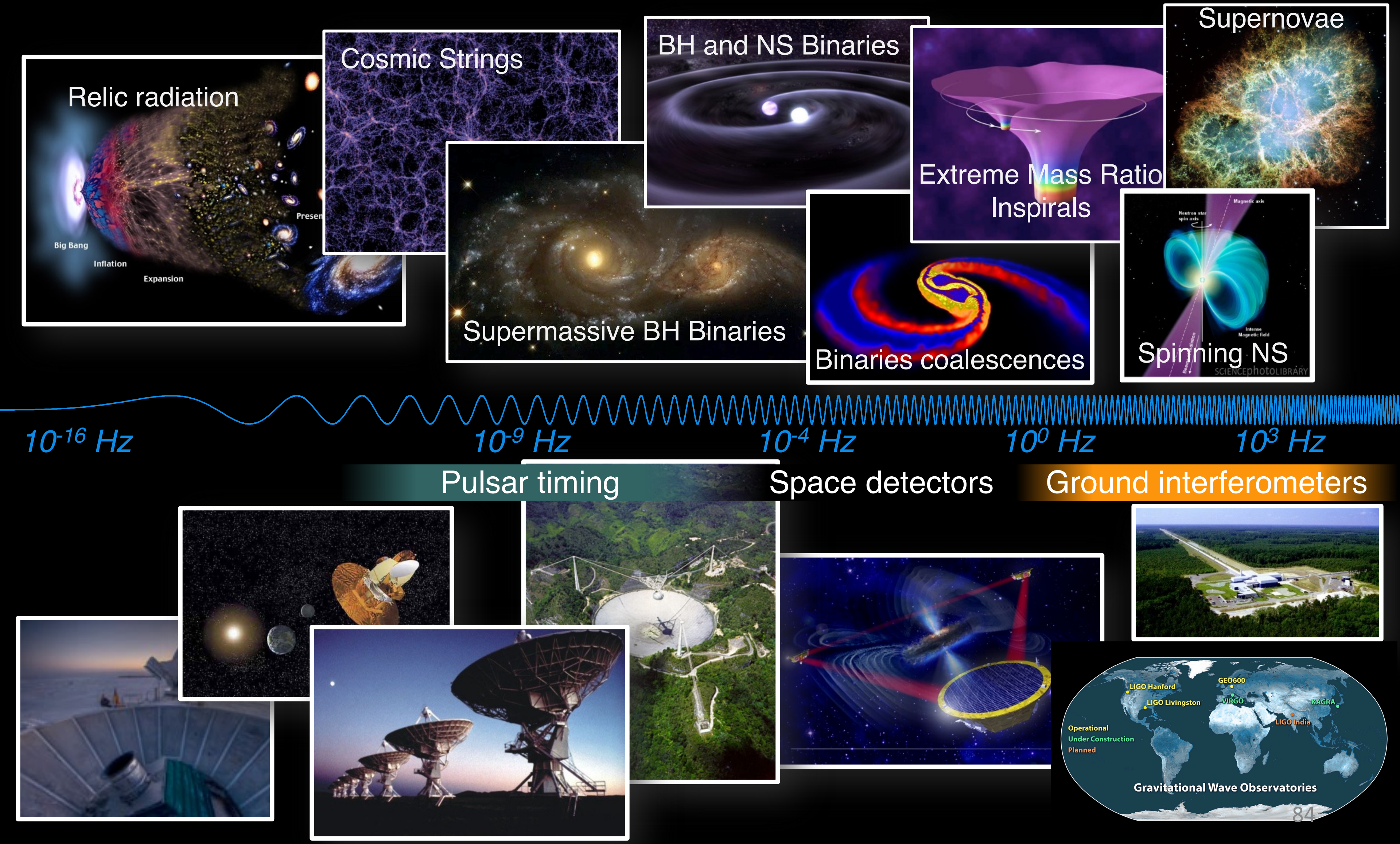
Credit: A. Freise

Cosmic Explorer

- 2015 first CE paper
- 2018 NSF grant for US3G study
- 2020-2021 CE white paper
- 2022-2026 Initial Design Phases
- 2027-2029 Final Design
- 2030+ US Congress appropriates funds

Credit: M. Evans

The Gravitational Wave Spectrum



Relic radiation

Cosmic Strings

BH and NS Binaries

Extreme Mass Ratio Inspirals

Supernovae

Supermassive BH Binaries

Binaries coalescences

Spinning NS

10^{-16} Hz

10^{-9} Hz

10^{-4} Hz

10^{0} Hz

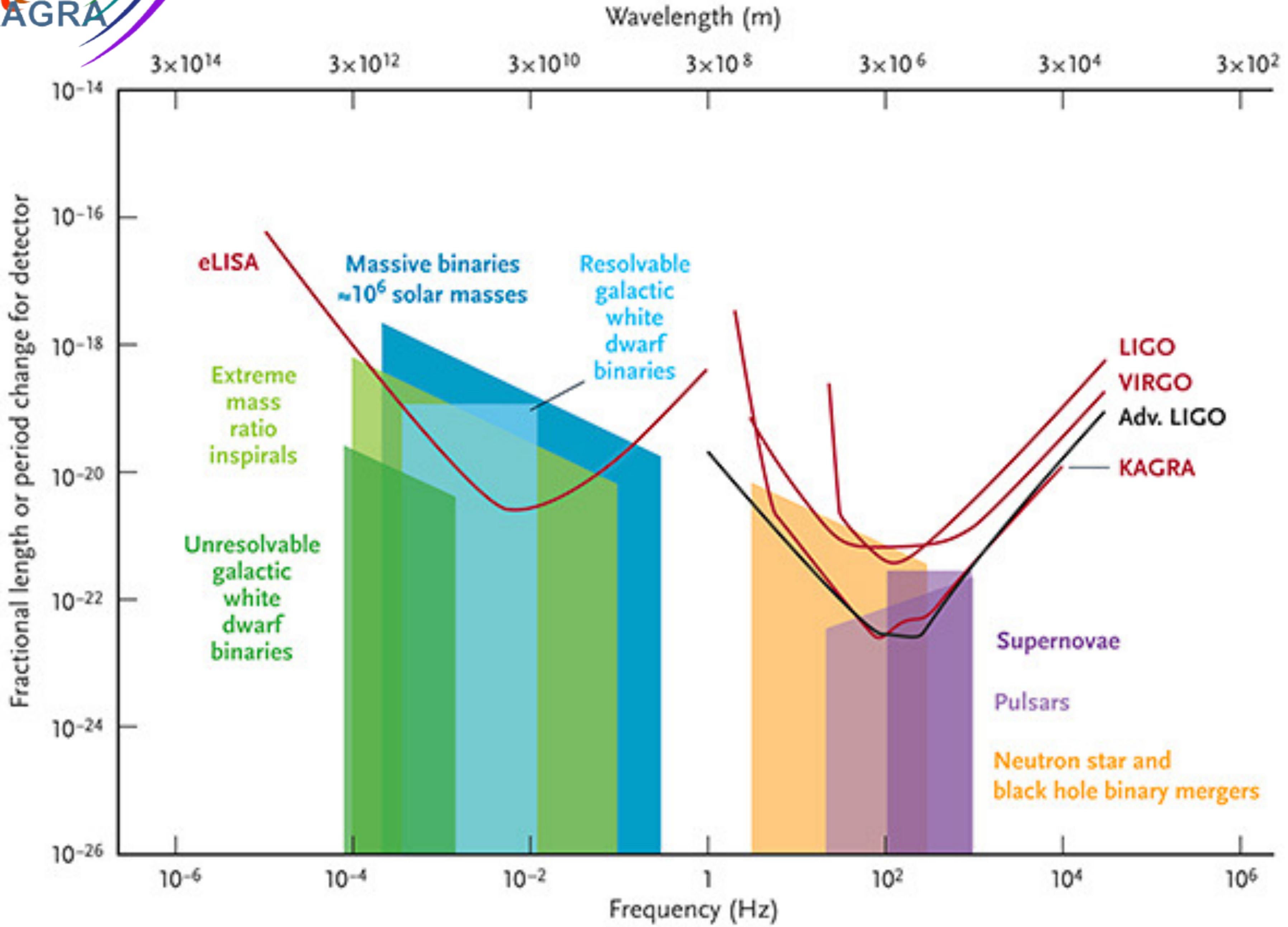
10^{3} Hz

Pulsar timing

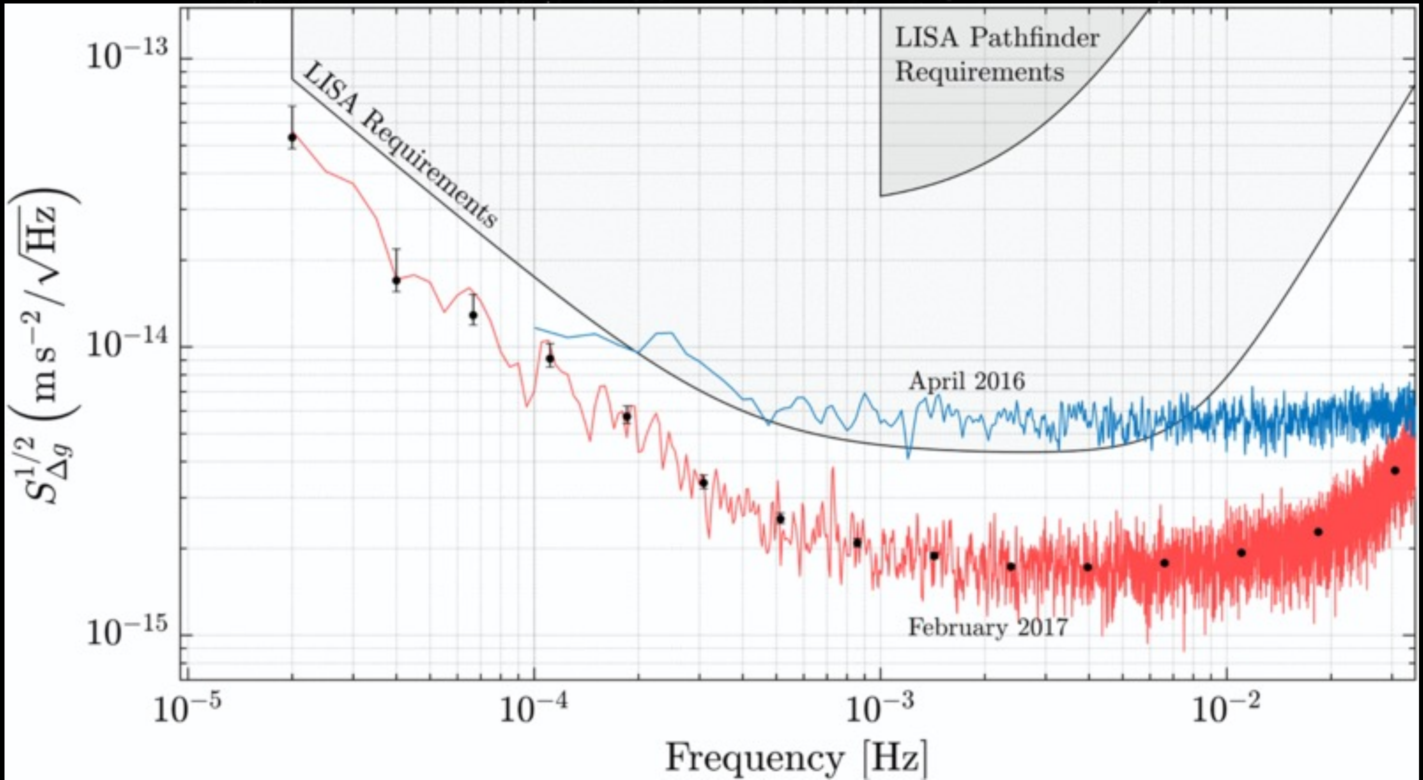
Space detectors

Ground interferometers

The Gravitational Wave Spectrum

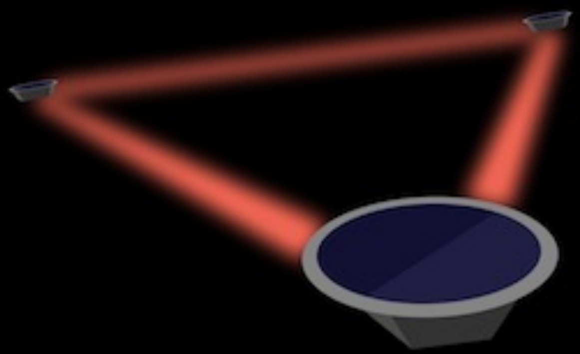


LISA PATHFINDER



LISA

Laser Interferometer Space Antenna



Gravitational waves

The first gravitational wave observatory in space

50 million km from Earth

Following Earth in its orbit around the Sun

3 spacecraft separated by **2.5 million km** in triangular formation

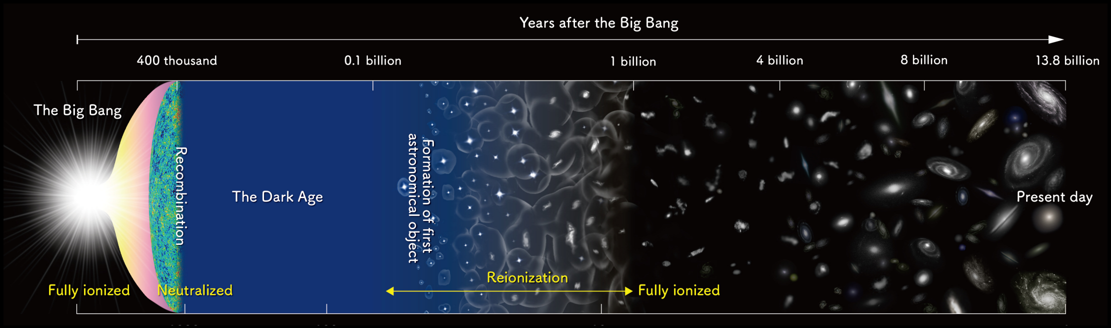
2034 Planned launch date

Predecessors: LISA Pathfinder (technology demonstration)

Core science goals

- **Mergers of supermassive black holes at the centre of galaxies**
- **White dwarf binaries in the Milky Way**
- **Stellar-origin black holes falling into supermassive black holes**

The Message



Current generation of gravitational wave instruments are detecting only the tip of the iceberg

The world-wide GW community is getting organized to build a 3G network to observe gravitational waves throughout cosmic history