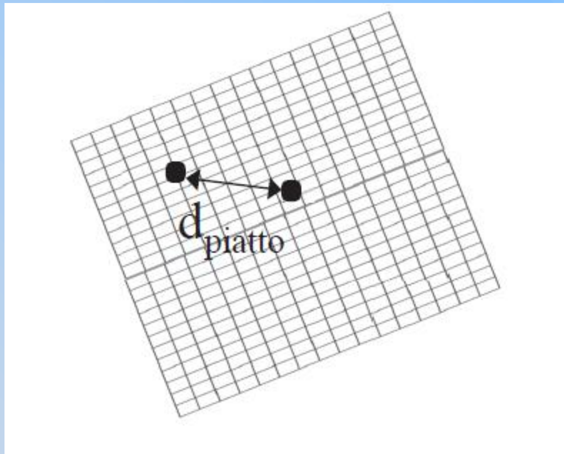
Status and developments of Advanced LIGO and Advanced Virgo gravitational wave detectors

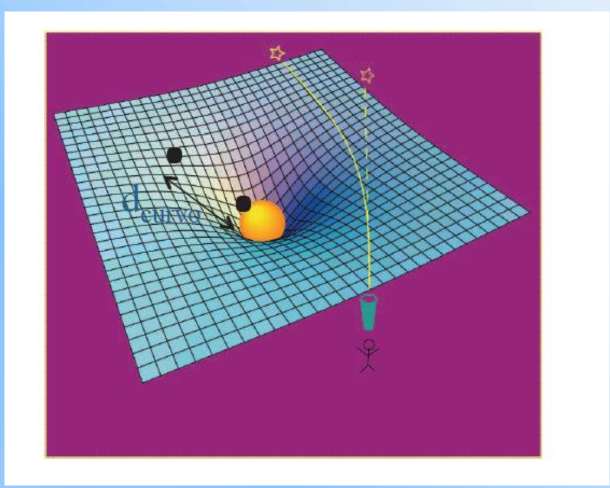
E. Calloni for the LIGO Scientific Collaboration and the Virgo Collaboration

LIGO G1200545-v1

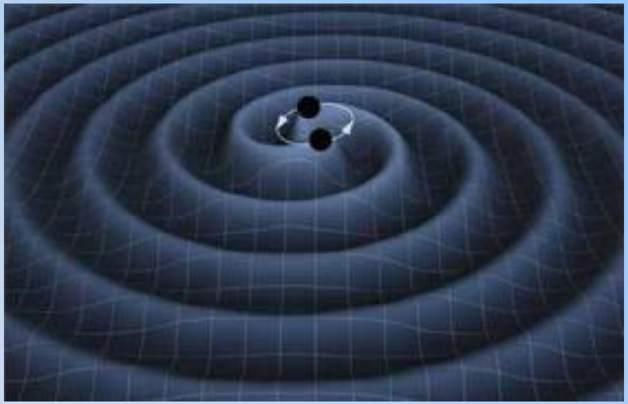
Masses curve the space-time



Distance of two points
In flat space



When the space is curved the
distance of the two points varies



When masses move, explode, interact, the distance among points changes: gravitational waves are ripples in space time generated by motion of mass-energy, propagating at the speed of light

Gravitational waves amplitude

$$h = \left[\frac{2G}{c^4}\right] \times \left[\frac{1}{r}\right] \times \left[\frac{d^2}{dt^2}(Q(t))\right]$$

Q(t) is the quadrupolar moment of the source
r is the distance from the source

h is the amplitude of the gravitational wave (the amplitude of the pertubation of the metric tensor)

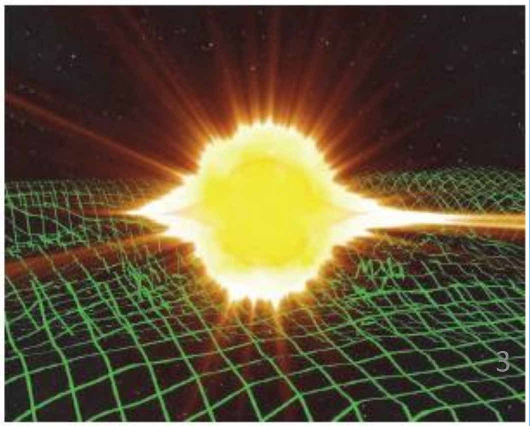
- The amplitude is very low

$$\left[\frac{2G}{c^4}\right] = 8 \times 10^{-45} s^2 / kg \cdot m$$

- Gravitational waves are generated by sources with a certain degree of asymmetry

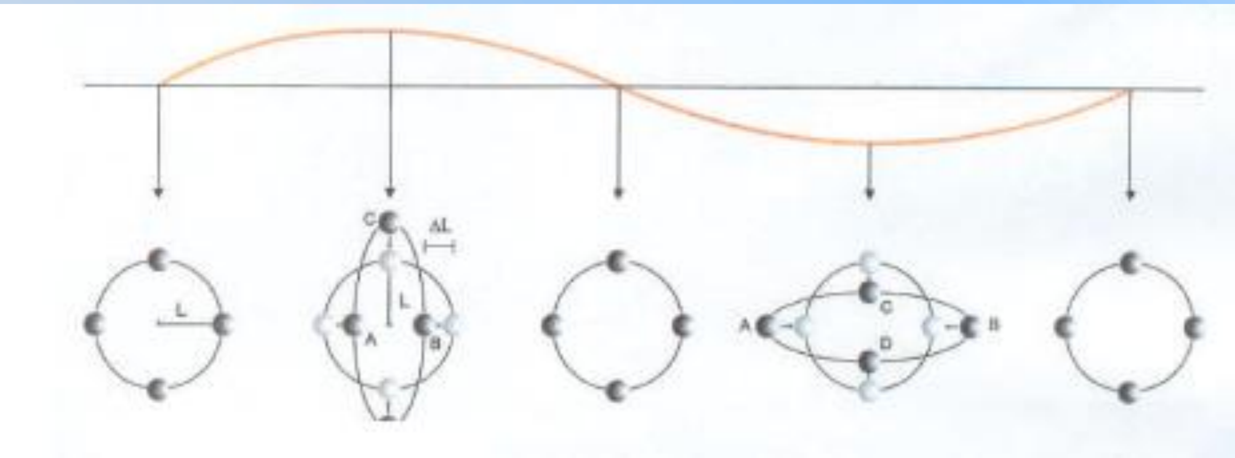
A spherical gravitational collapse does not generate gravitational waves

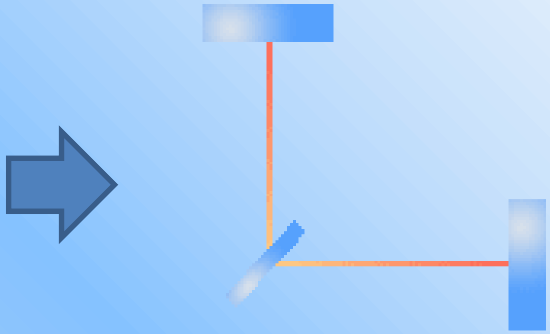
Non -spherical gravitational collapses, coalescing black holes or neutron stars, non axisymmetric rotating stars do generate gravitational waves – they are the target sources of GW search



Effects of a GW

- Consider a ring a free falling masses and a GW impinging normal to the plane of the ring





$$\Delta L = \tfrac{1}{2} h L$$

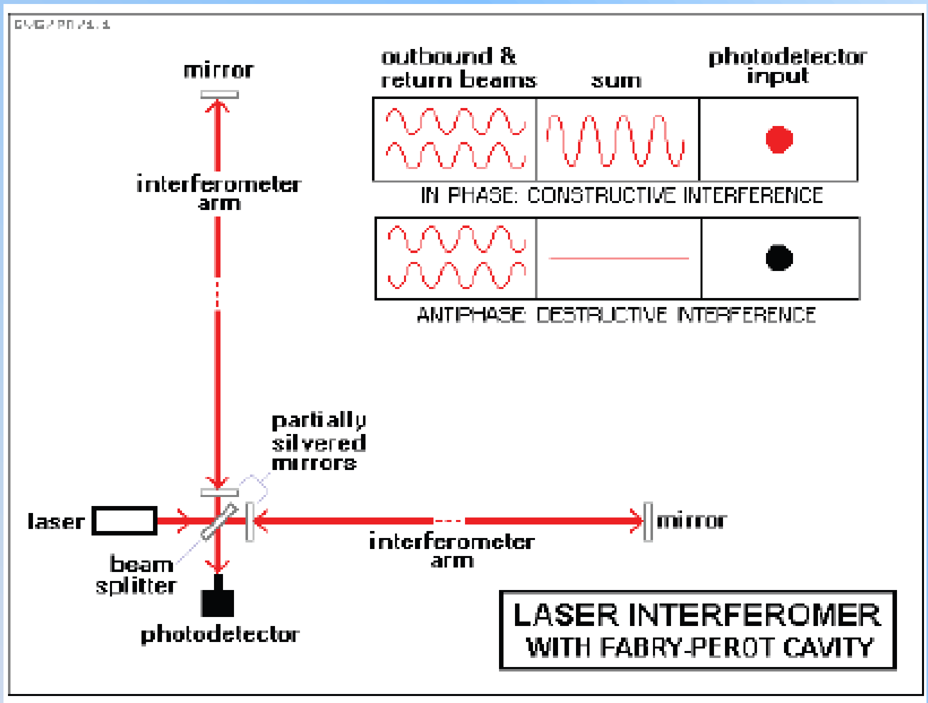
A Supernova explosion in our galaxi $h \approx 10^{-18}$

$L = 1$ km : $\Delta L = h L/2 \approx 10^{-18}\ 10^{3} = 10^{-15}$ m

GW is transverse → produces deformation only in the plane normal to the propagation
2 polarization – the effect is rotated by 45°

Interferometric detectors

- The interferometers are a natural way to detect quadrupolar deformations



When a GW impinges on the plane of the interferometer the lenght of the arms is varied in opposite way → the beams recombining at the beam splitter acquire a differential phase changing the interference condition → variation of the light impinging on the photodiode

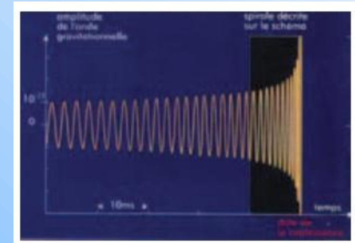
Main targets sources

- Coalescing binaries

$$\nu_{GW}^{ISCO} = \frac{c^3}{\pi G \sqrt{6^3}} \frac{1}{M_{tot}}$$

$$h \approx 10^{-23}$$

r = 10 Mpc



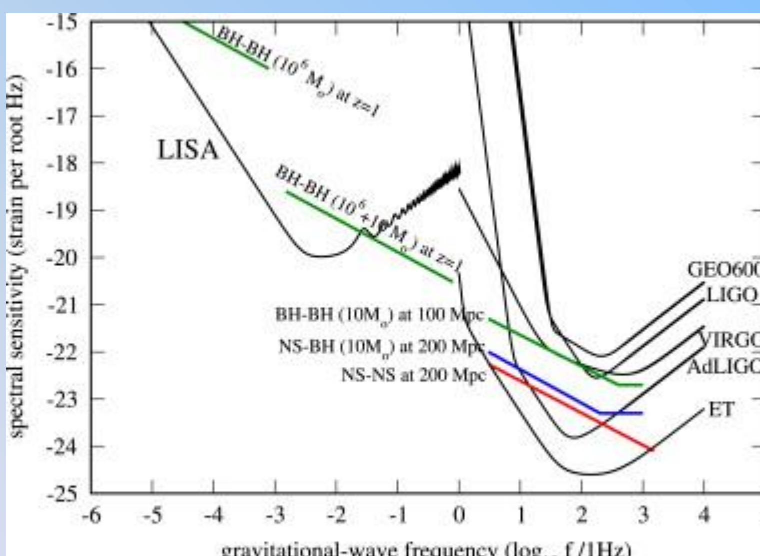
CHIRP

- Rotating neutron stars

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} \nu_{gw}^2}{d} \epsilon$$

$$\varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

- Supernova explosions, Stochastic background.....



Order of Km detectors: a legacy of the past decade for the ADV generation

GEO600 (British-German)
Hannover, Germany

600m

LIGO- I (USA)
Hanford, WA

4 Km

LIGO-II (USA)
Livingston, LA

KAGRA-LCGT (Japan)
Kamioka

In construction

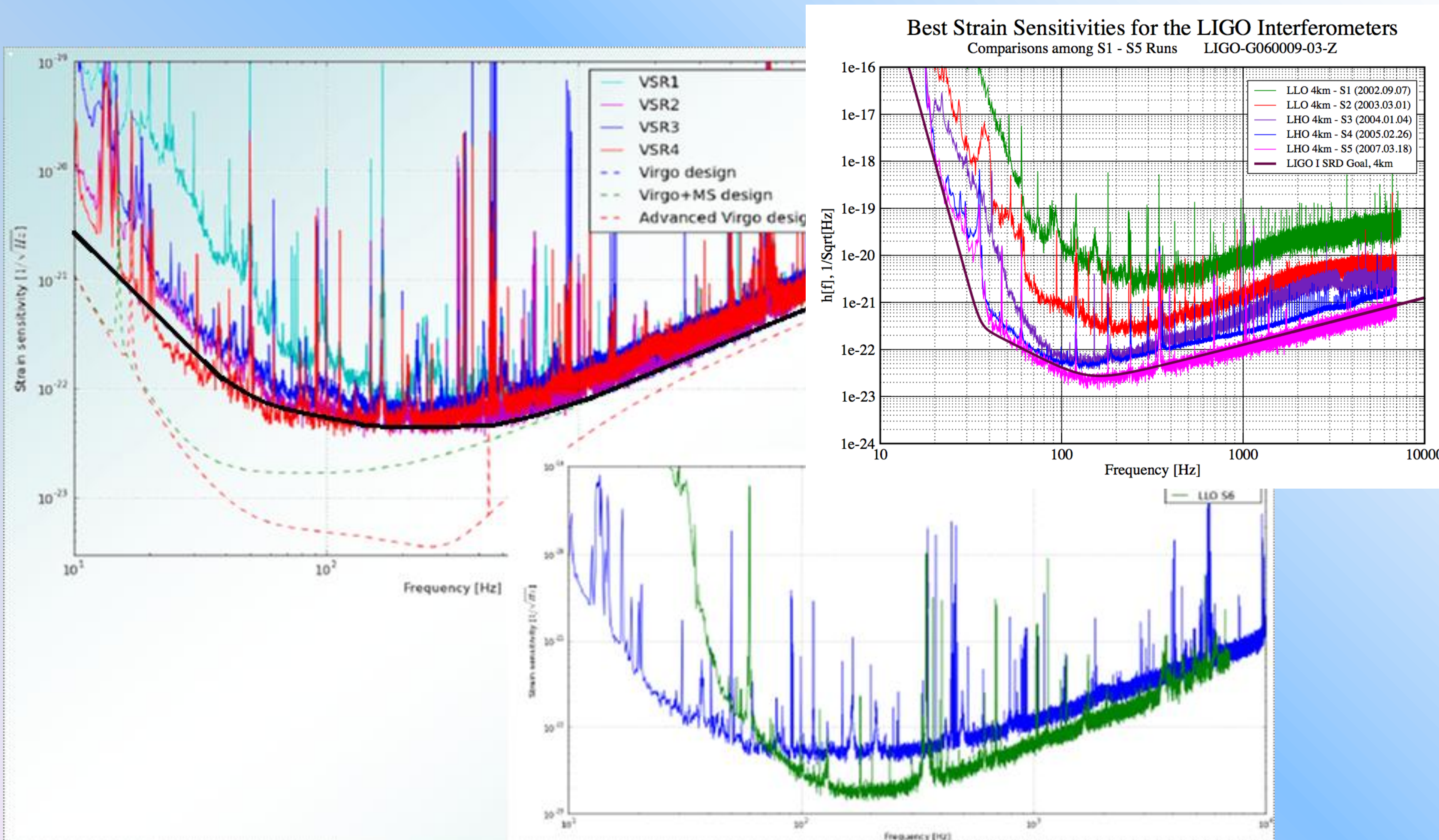
INDIGO (India),
Project for the LIGO-III 4km Interferometer

Proposal

VIRGO (French-Italian)
Cascina, Italy

3 Km

NOISE AND SENSITIVITY

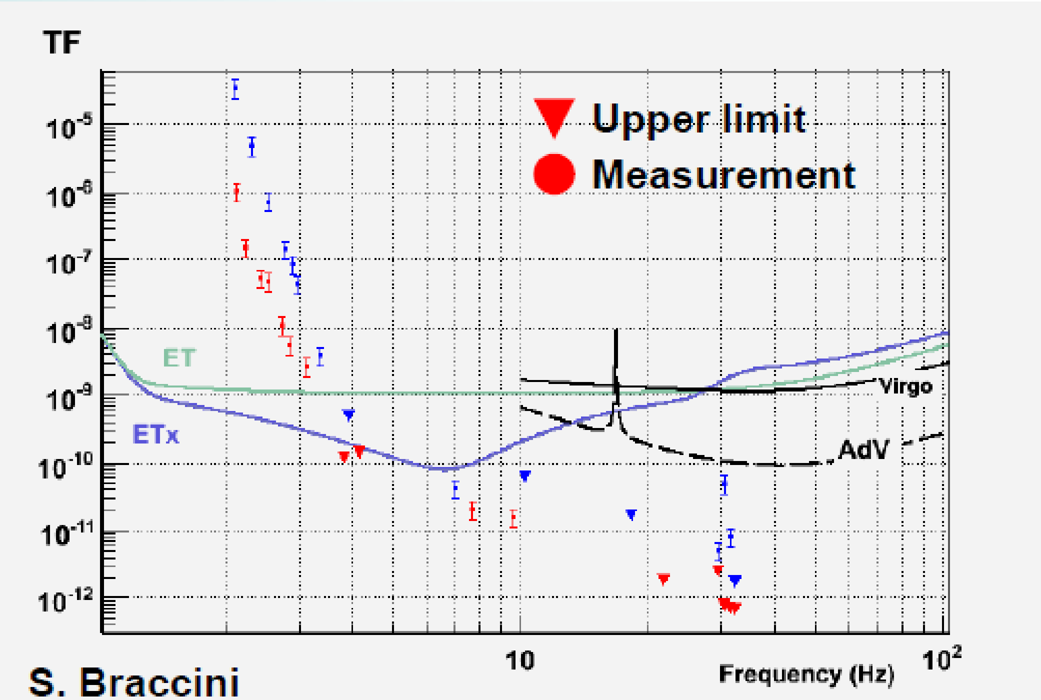


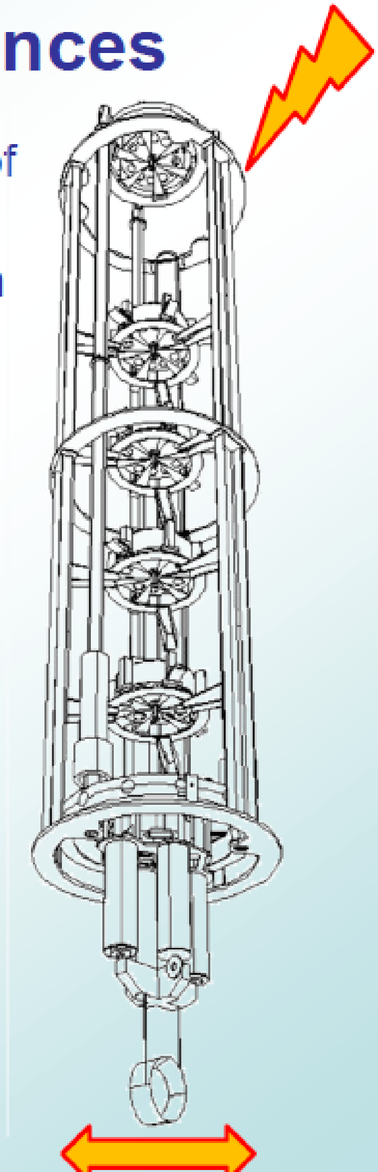
The 1st generation design sensitivities have been approached closely (and somewhere exceeded upon detector upgrades)

Some paricularities: Virgo Low frequency behaviour

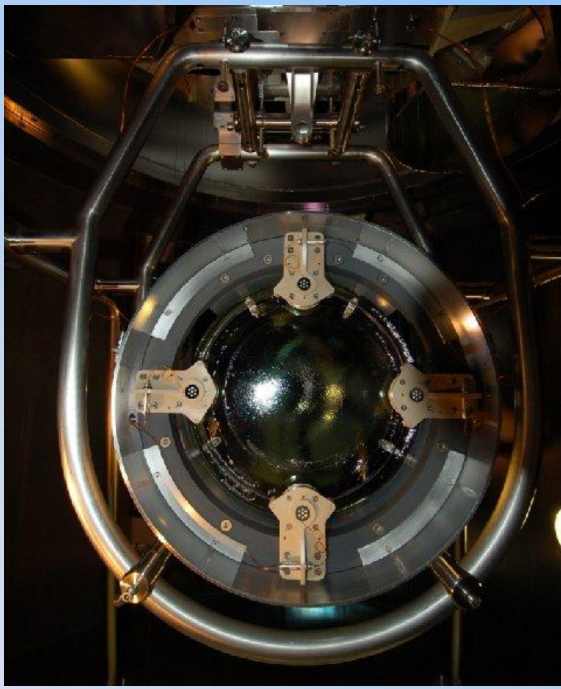
Super attenuator performances

- Direct measurements (or upper limits) of the coupling of excitations at top stage to mirror motion
- Does not include additional effect of inverted pendulum pre-isolation stage (resonance about 40 mHz)

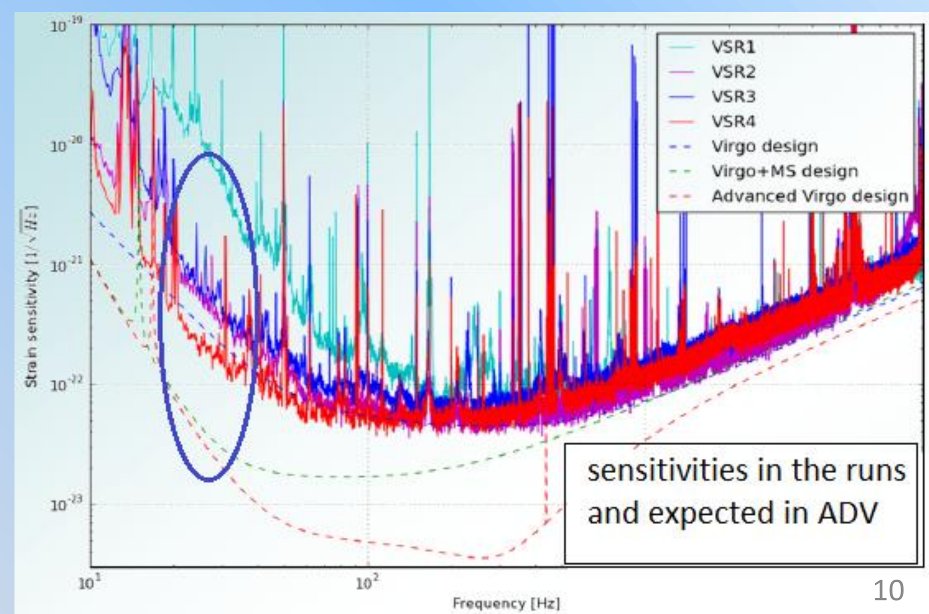




Monolithic suspensions and thermal noise

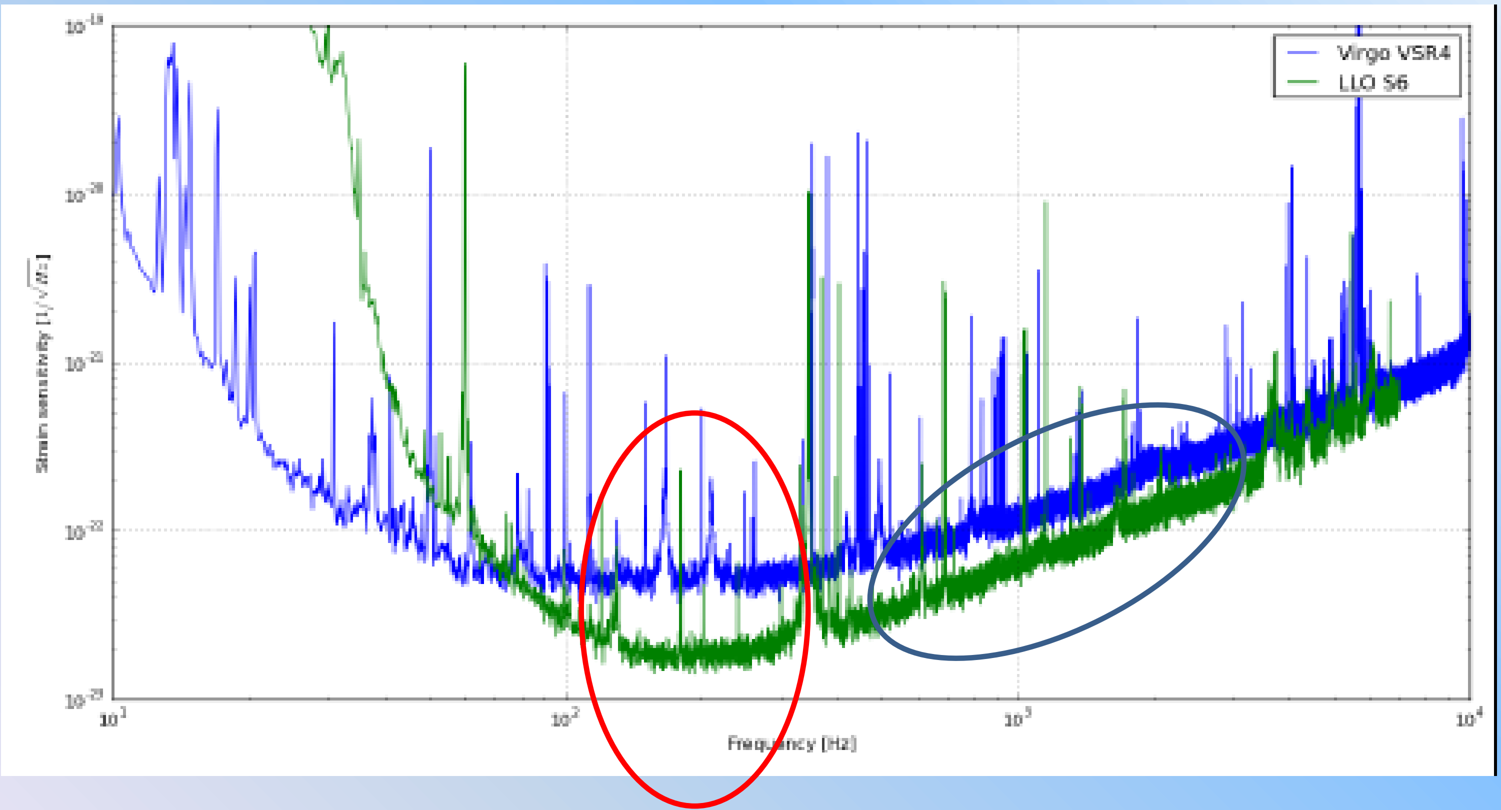


- Super-attenuator performances critical
  - Not only for passive in-band attenuation
  - Also very important reduction of low frequency mirror motion that relaxes control requirements, allowing better control noise performances
  - Already complaint with Advanced Detector requirements



- After the installation of monolithic suspensions the measured sensitivity is below the expected steel wire thermal noise
  - Good hint that we were before limited by steel wires thermal noise

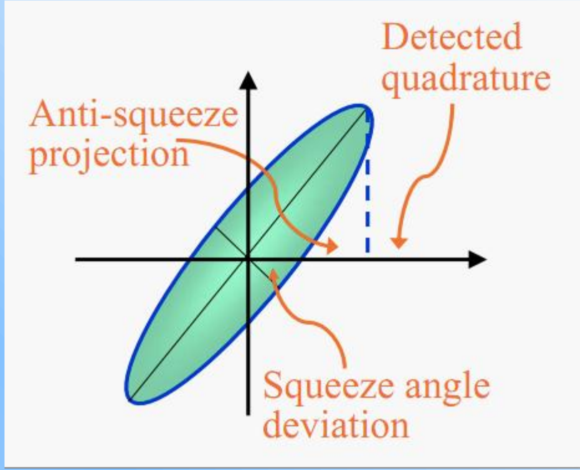
Remarks on LIGO intermediate and high frequencies

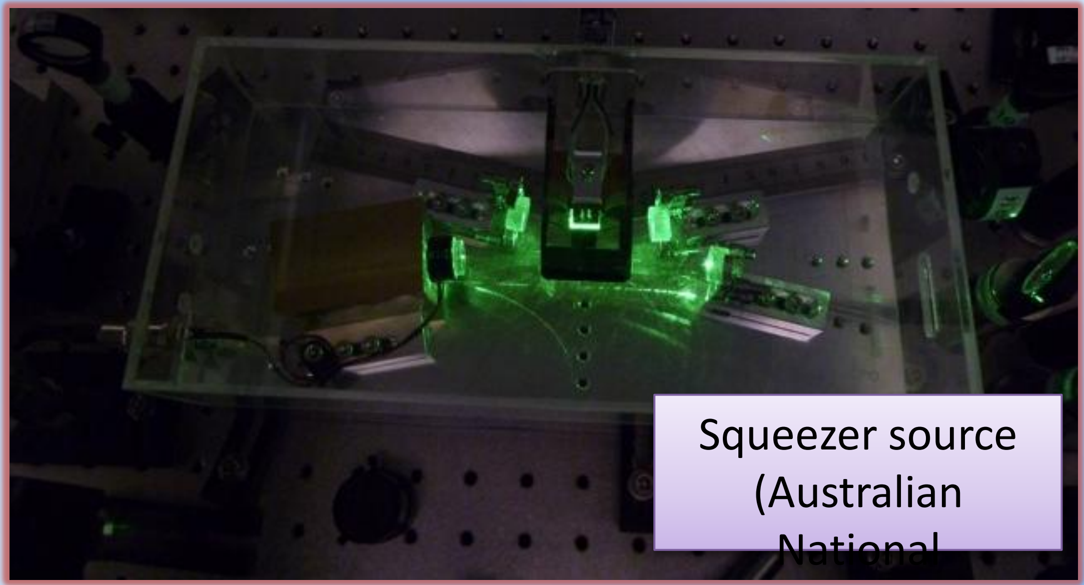


LIGO

Squeezing: something for (almost) nothing

- One can reduce quantum noise by injecting squeezed light into Advanced LIGO
  - 3 dB injected squeezed light = 2x reduction in power
- Recently demonstrated on GEO600 (Run S6b in common with Virgo VSR4)
- On LIGO, the goal was to understand noise couplings, locking techniques, losses
- Successfully injected squeezed light into Hanford H1 interferometer and demonstrated > 2 dB reduction in shot noise

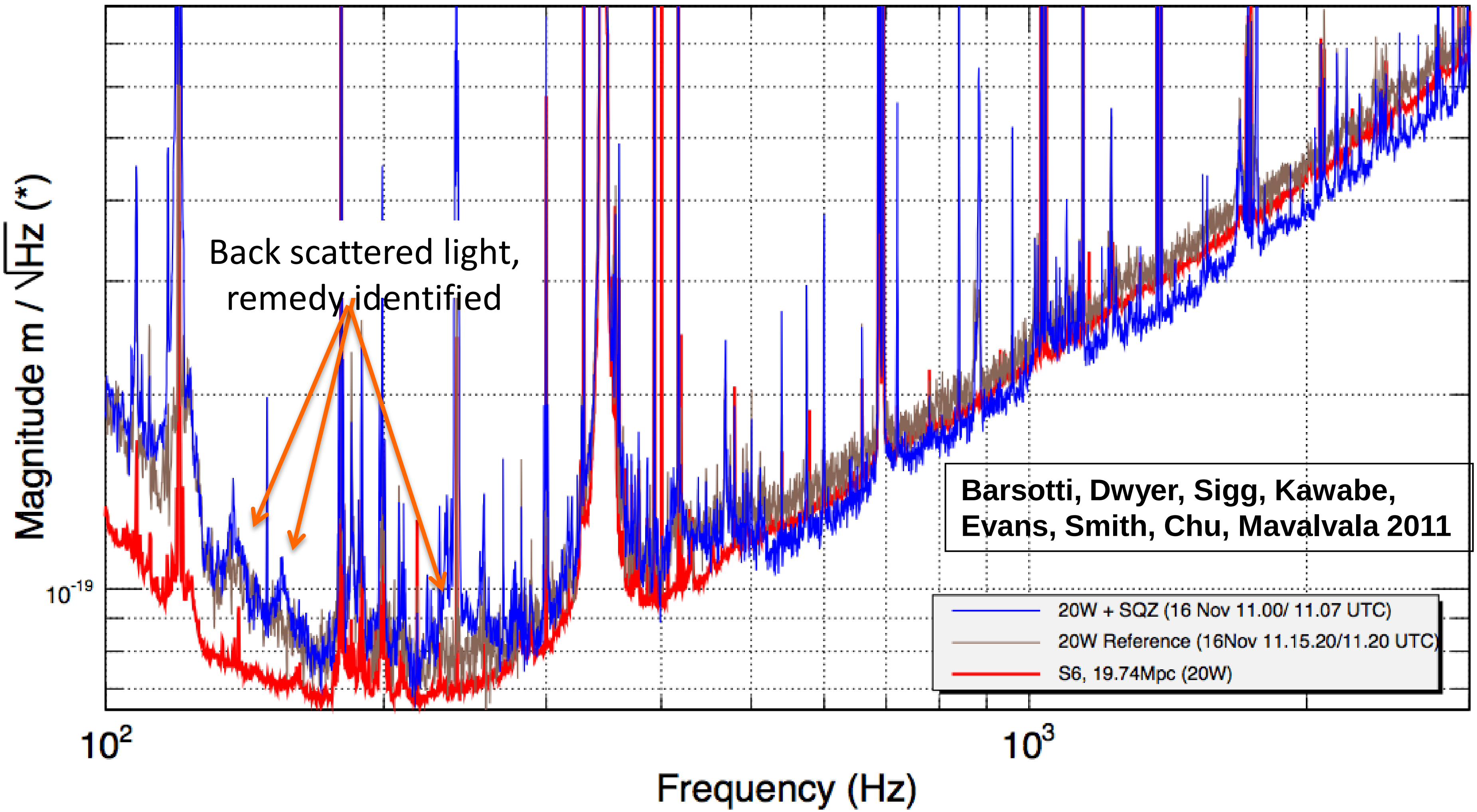




Squeezer source (Australian National University design)

LIGO

Squeezing the LIGO Interferometer!



Common RUNs - interesting results – upper limits - ....!

THE ASTROPHYSICAL JOURNAL, 715:1438–1452, 2010 June 1 doi:10.1088/0004-637X/715/2/1438
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SEARCH FOR GRAVITATIONAL-WAVE BURSTS ASSOCIATED WITH GAMMA-RAY BURSTS USING DATA FROM LIGO SCIENCE RUN 5 AND VIRGO SCIENCE RUN 1

PHYSICAL REVIEW D **82,** 102001 (2010)

Search for gravitational waves from compact binary coalescence in LIGO and Virgo data from S5 and VSR1

PHYSICAL REVIEW D **81,** 102001 (2010)

All-sky search for gravitational-wave bursts in the first joint LIGO-GEO-Virgo run

THE ASTROPHYSICAL JOURNAL, 715:1453–1461, 2010 June 1 doi:10.1088/0004-637X/715/2/1453
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SEARCH FOR GRAVITATIONAL-WAVE INSPIRAL SIGNALS ASSOCIATED WITH SHORT GAMMA-RAY BURSTS DURING LIGO'S FIFTH AND VIRGO'S FIRST SCIENCE RUN

nature

LETTERS

Beating the spin-down limit on gravitational wave emission from the Vela pulsar

arXiv:1104.2712v2 [astro-ph.HE] 15 Apr 2011

An upper limit on the stochastic gravitational-wave background of cosmological origin

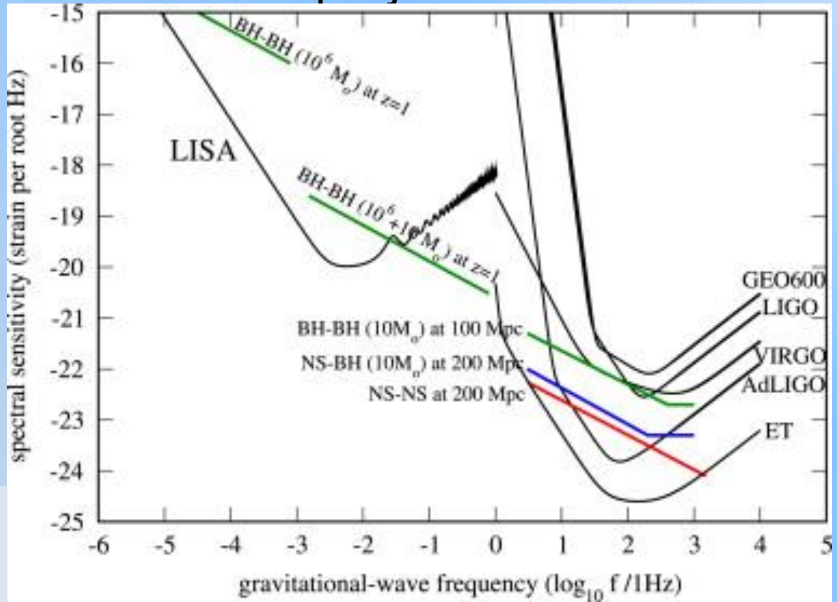
The LIGO Scientific Collaboration* & The Virgo Collaboration*

See **Brennan HUGHEY** Talk

THE LEGACY OF THE PAST DECADE

- 1st generation detectors were a success:
  - established the infrastructures
  - basically reached the design sensitivities
  - realized robust and reliable instruments
  - developed the paradigm for data analysis
  - established a network
  - started the multi-messenger approach
  - did real astrophysics
  - tested some technologies for 2nd generation (and beyond)
  - a large (O(1000)) community grew around these projects and is now solidly established

- We still need a factor 10!



Early Advanced LIGO history

CALTECH/MIT PROJECT

FOR A

LASER INTERFEROMETER

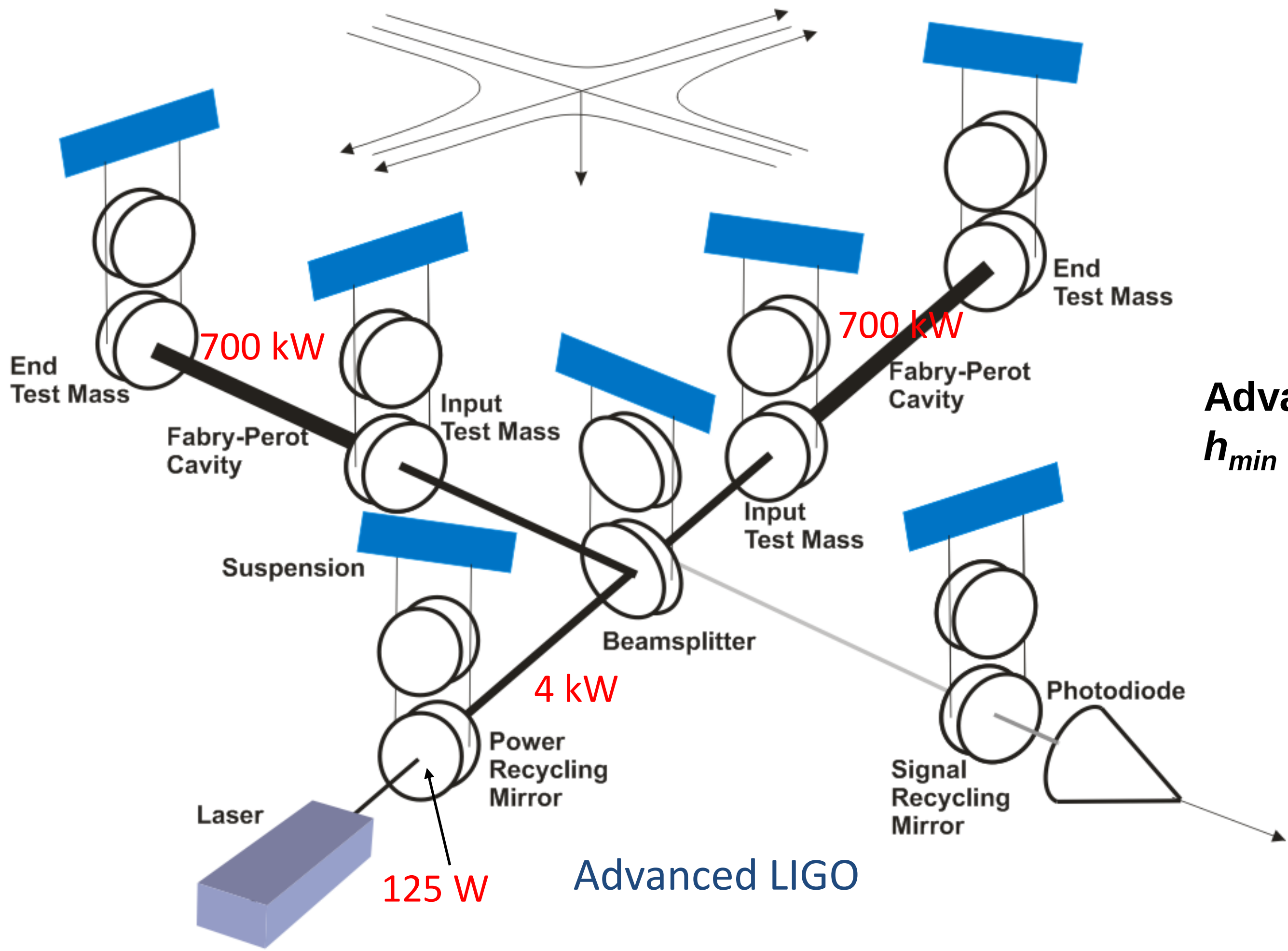
GRAVITATIONAL WAVE OBSERVATORY

December 1987

LIGO-M870001-00-M

By comparing the source strengths and benchmark sensitivities in Figure II-2 and in the periodic and stochastic figures A-4b,c (Appendix A), one sees that *(i) There are nonnegligible possibilities for wave detection with the first detector in the LIGO. (ii) Detection is probable at the sensitivity level of the advanced detector. (iii) The first detection is most likely to occur, not in the initial detector in the LIGO but rather in a subsequent one, as the sensitivity and frequency are being pushed downward from the middle curve toward the bottom curve of Figure II-2.*

Advanced LIGO/Virgo

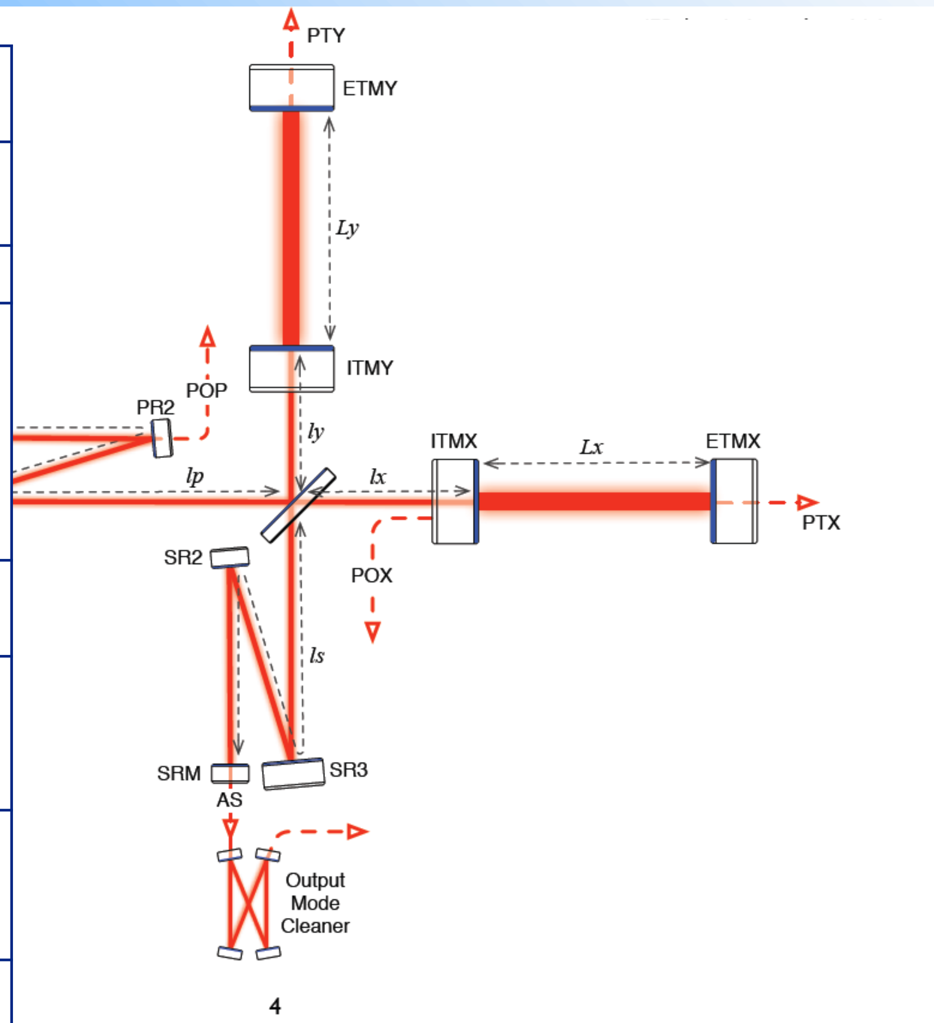


Advanced LIGO
$h_{min} \sim 3 \times 10^{-23}$ √Hz

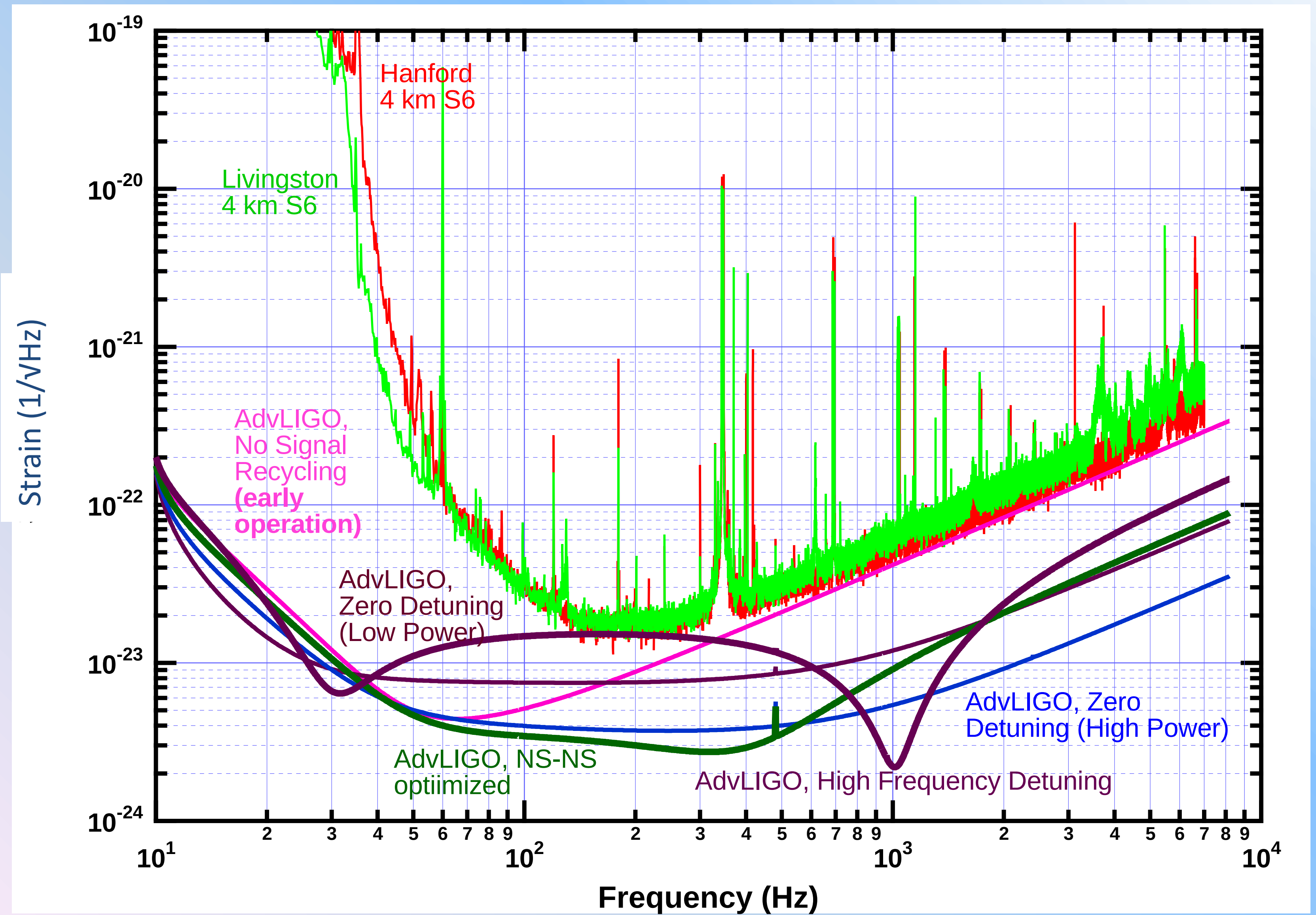
Advanced LIGO/virgo overview

What is Advanced?

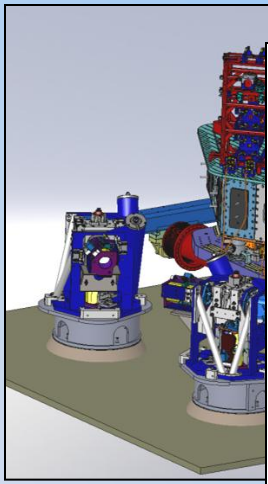
Parameter	Initial LIGO/Virgo	Advanced LIGO/Virgo
Input Laser Power	10 W (10 kW arm)	180 W (>700 kW arm)
Mirror Mass	10 kg/20kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson (LIGO stable recycling cavities)
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3 x 10-23 / rHz 6 x 10-23 / rHz	Tunable, better than 5 x 10-24 / rHz in broadband
Seismic Isolation Performance	flow ~ 50 Hz flow ~ 10 Hz	flow ~ 12 Hz flow ~ 10 Hz
Mirror Suspensions	Single Pendulum/ Hepta Pendulum	Quadruple Pendulum/ Hepta Pendulum



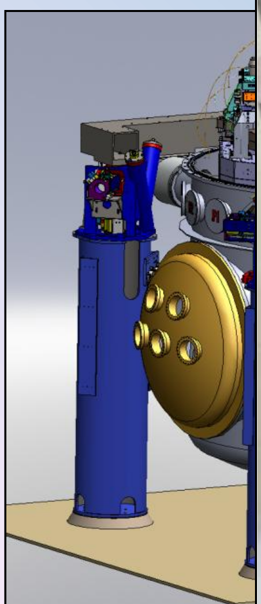
The expected sensitivity



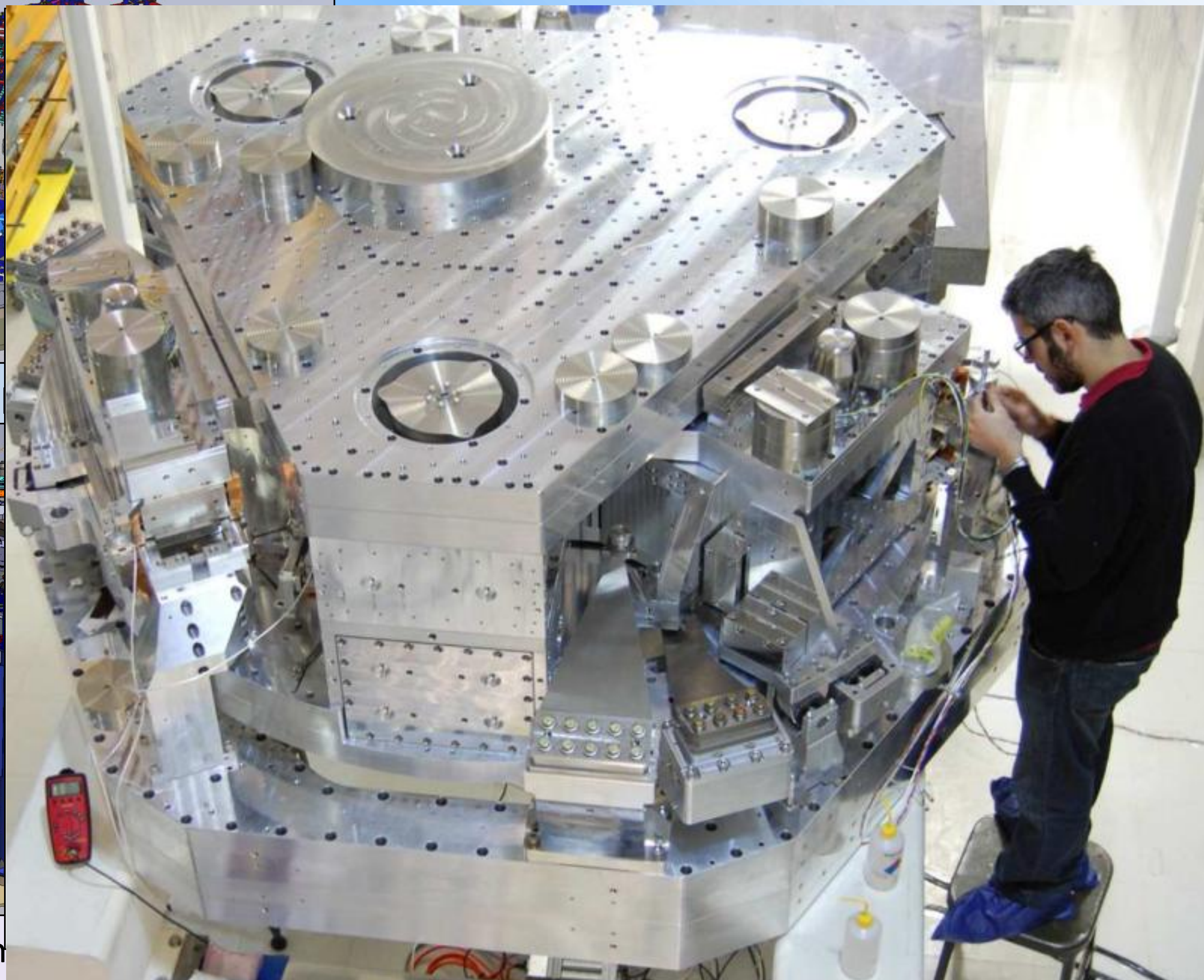
Advanced LIGO Seismic Isolation

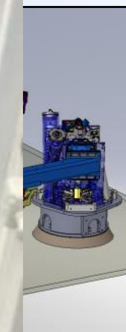


HAM Ch



BSC Ch





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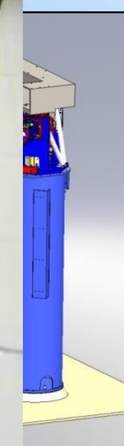
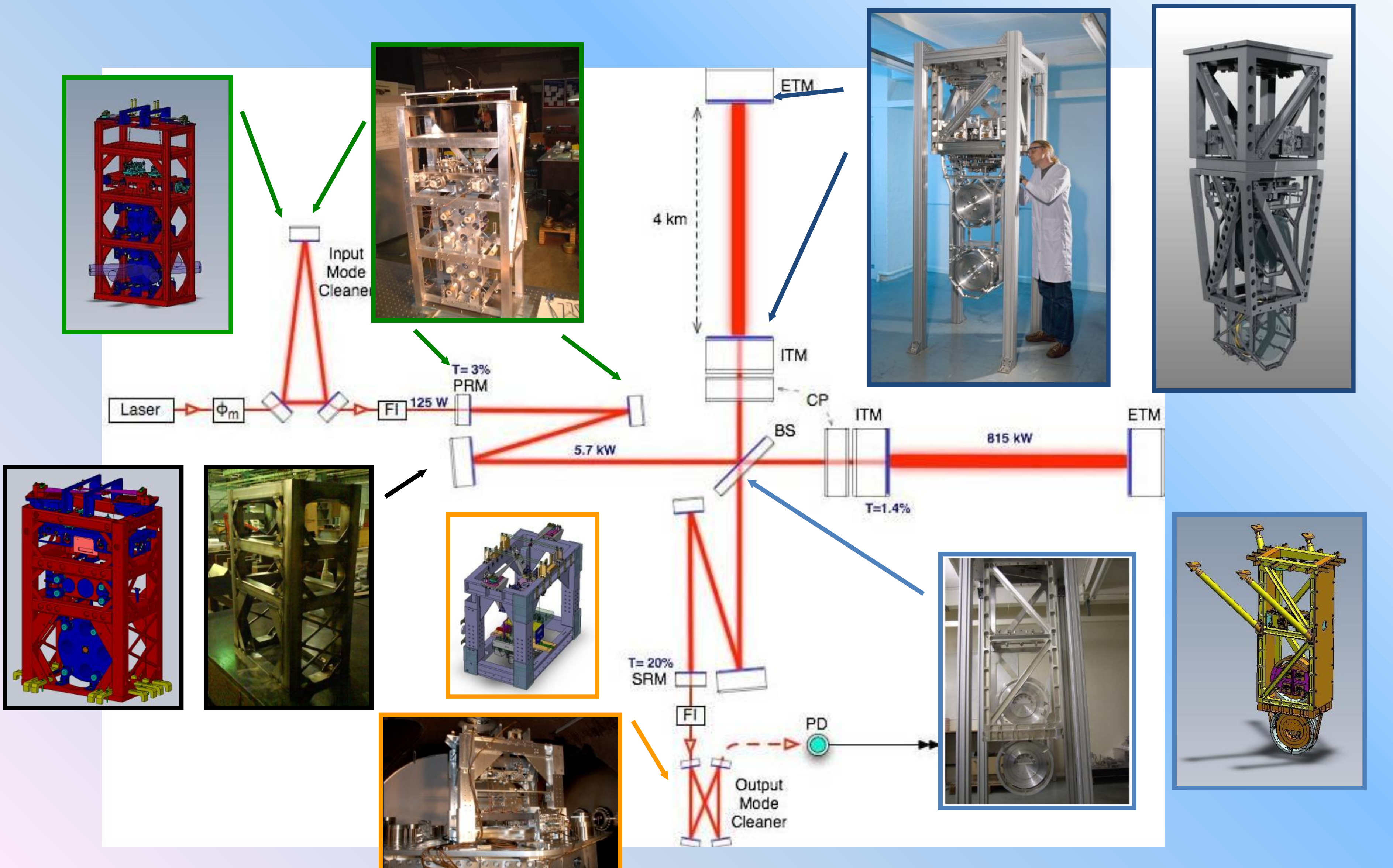


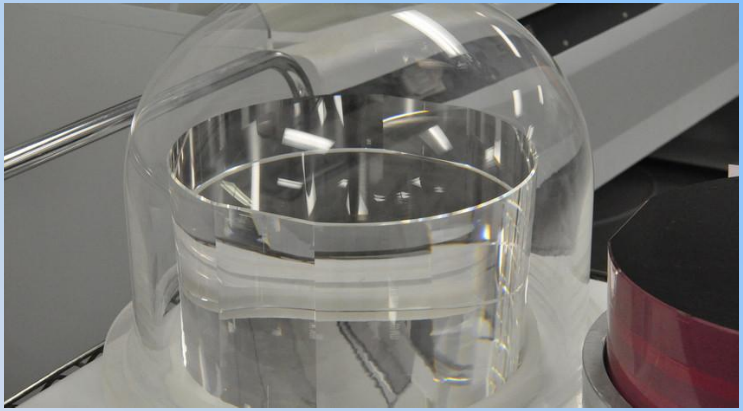
ernal

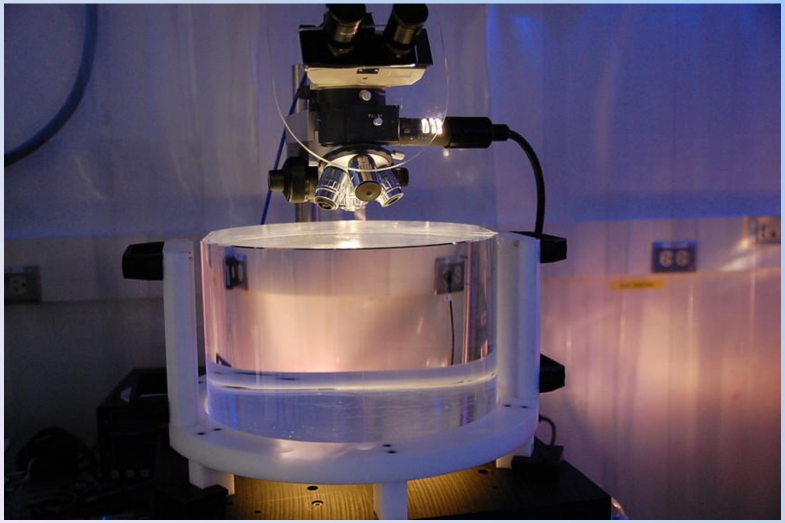
Advanced LIGO Suspensions

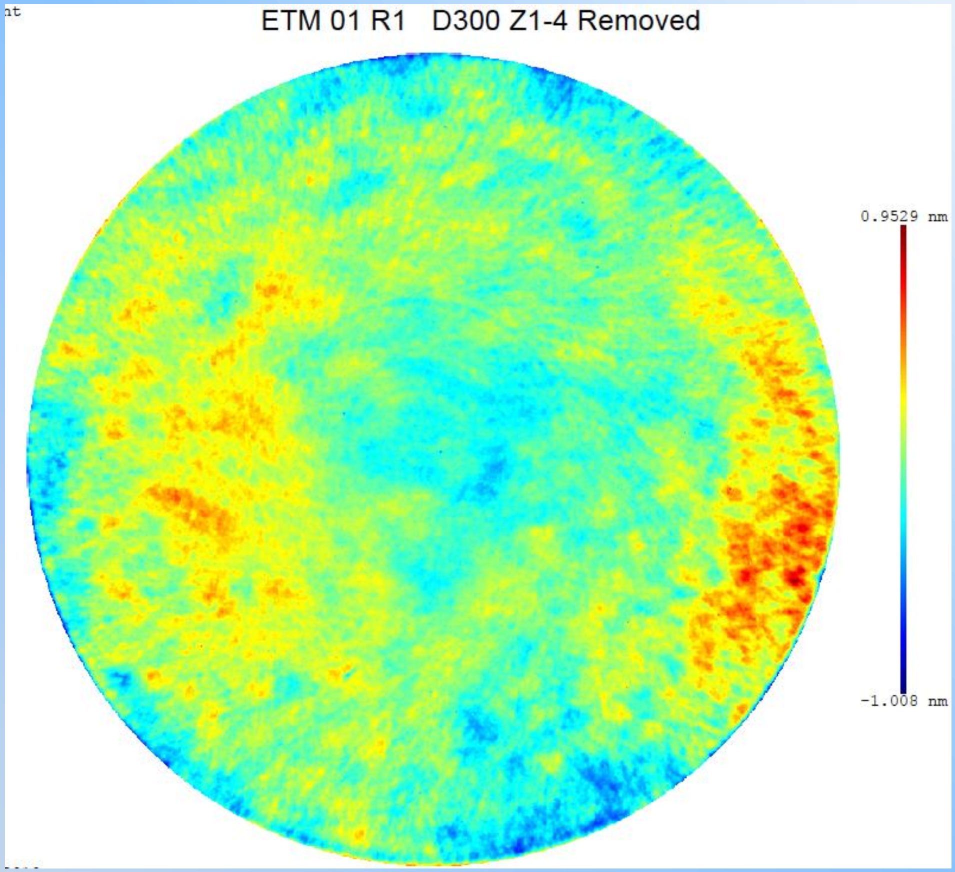


Advanced LIGO/Virgo Core Optics

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







Expected detection rates for binary mergers

Abadie, et al. "Predictions for the Rates of Compact Binary Coalescences Observable by Ground-based Gravitational-wave Detectors" CQG 27 173001 (2010), arXiv:1003.2480

- Binary coalescences rates
  - neutron star (NS) = 1.4 $M_{\odot}$, Black Hole (BH) = 10 $M_{\odot}$

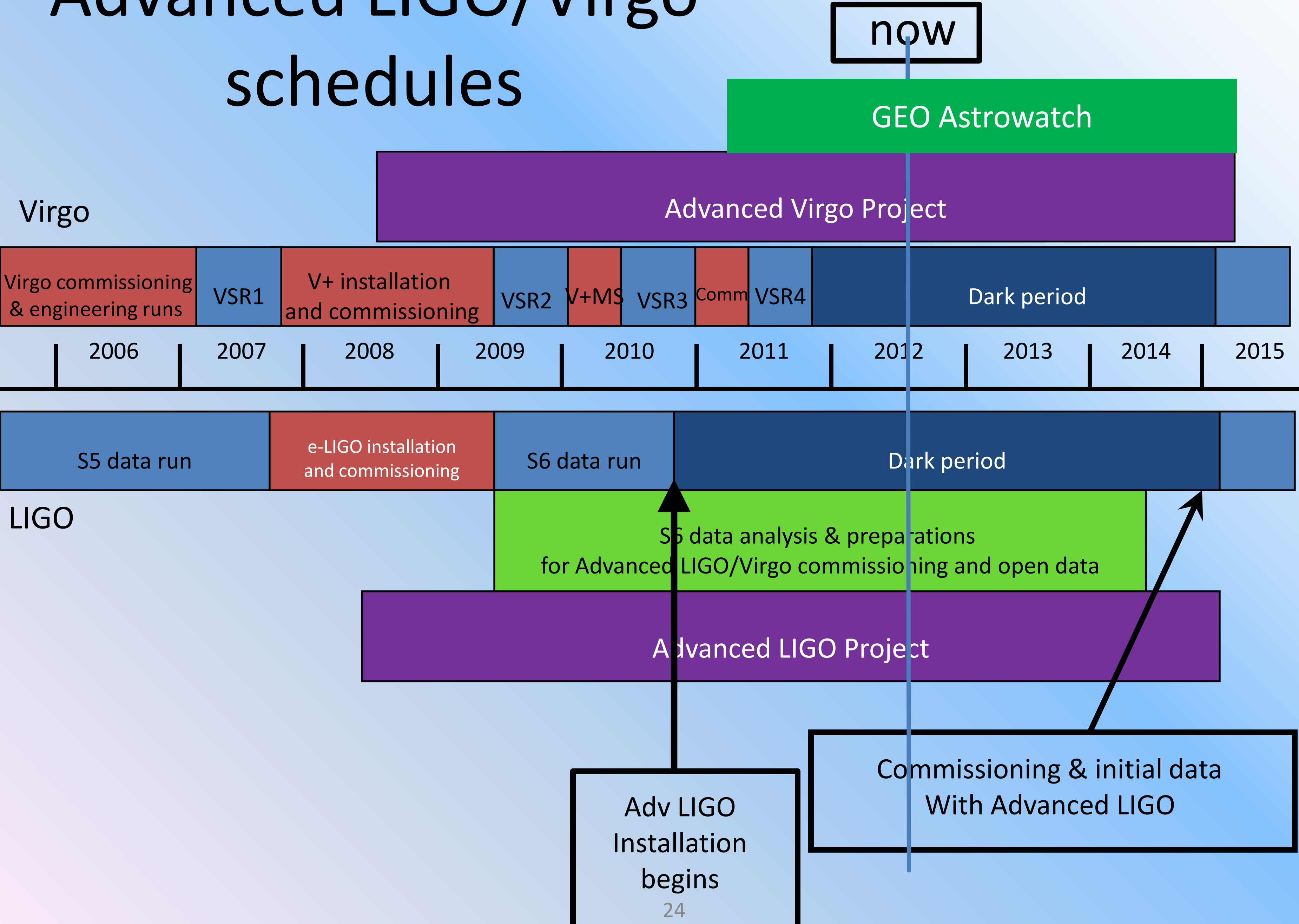
TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm pl}$ yr^{-1}	$\dot{N}_{\rm up}$ yr^{-1}
Initial LIGO/Virgo	NS-NS	2×10^{-4}	0.02	0.2	0.6
	IS-BH	7×10^{-5}	0.004	0.1	
	H-BH	2×10^{-4}	0.007	0.5	
	into IMBH			$< 0.001^b$	0.01^c
	IMBH-IMBH			$10^{-4\,d}$	$10^{-3\,e}$
Advanced LIGO/Virgo	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^b	300^c
	IMBH-IMBH			0.1^d	1^e

- ***<u>The error bar is large and important!</u>***

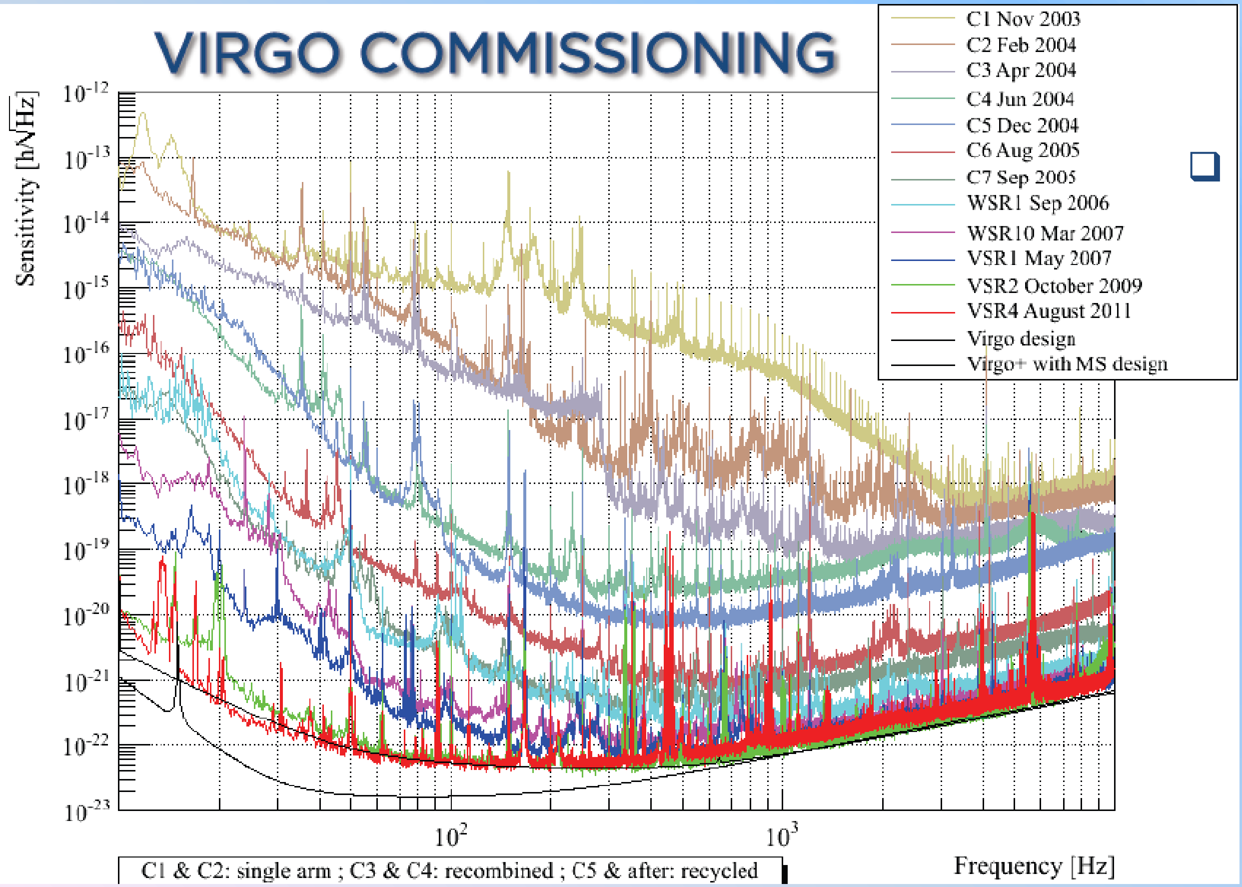
From a "chance" to a GW astronomy

Advanced LIGO/Virgo schedules



The commissioning struggles

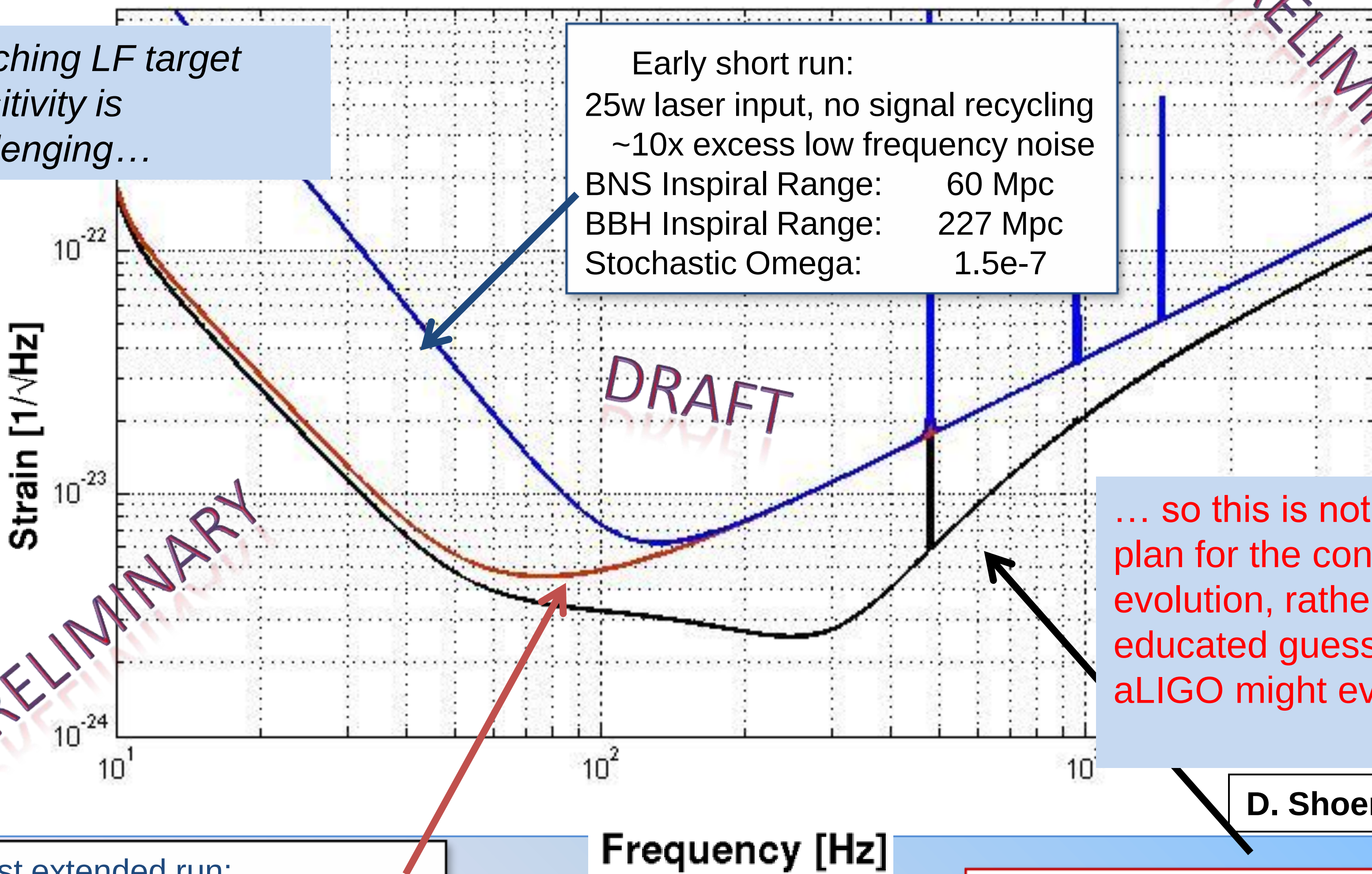
- All detectors went through a long commissioning/learning phase
  - Asymptotic process. It slows down when approaching the design curve
- Many common troubles: great benefits from reciprocal exchanges (to be continued in the advanced detectors era)



- Lessons we had to learn:
  - operating controls
  - coping with increasing complexity of the optical configuration
  - coping with thermal effects
  - coping with scattered light
  - identifying unknown noise
  - fix detector bugs
  - …and many others

Sketch of ***possible*** progression for Advanced **LIGO** sensitivity

Reaching LF target sensitivity is challenging…



Early short run:
25w laser input, no signal recycling
~10x excess low frequency noise
BNS Inspiral Range: 60 Mpc
BBH Inspiral Range: 227 Mpc
Stochastic Omega: 1.5e-7

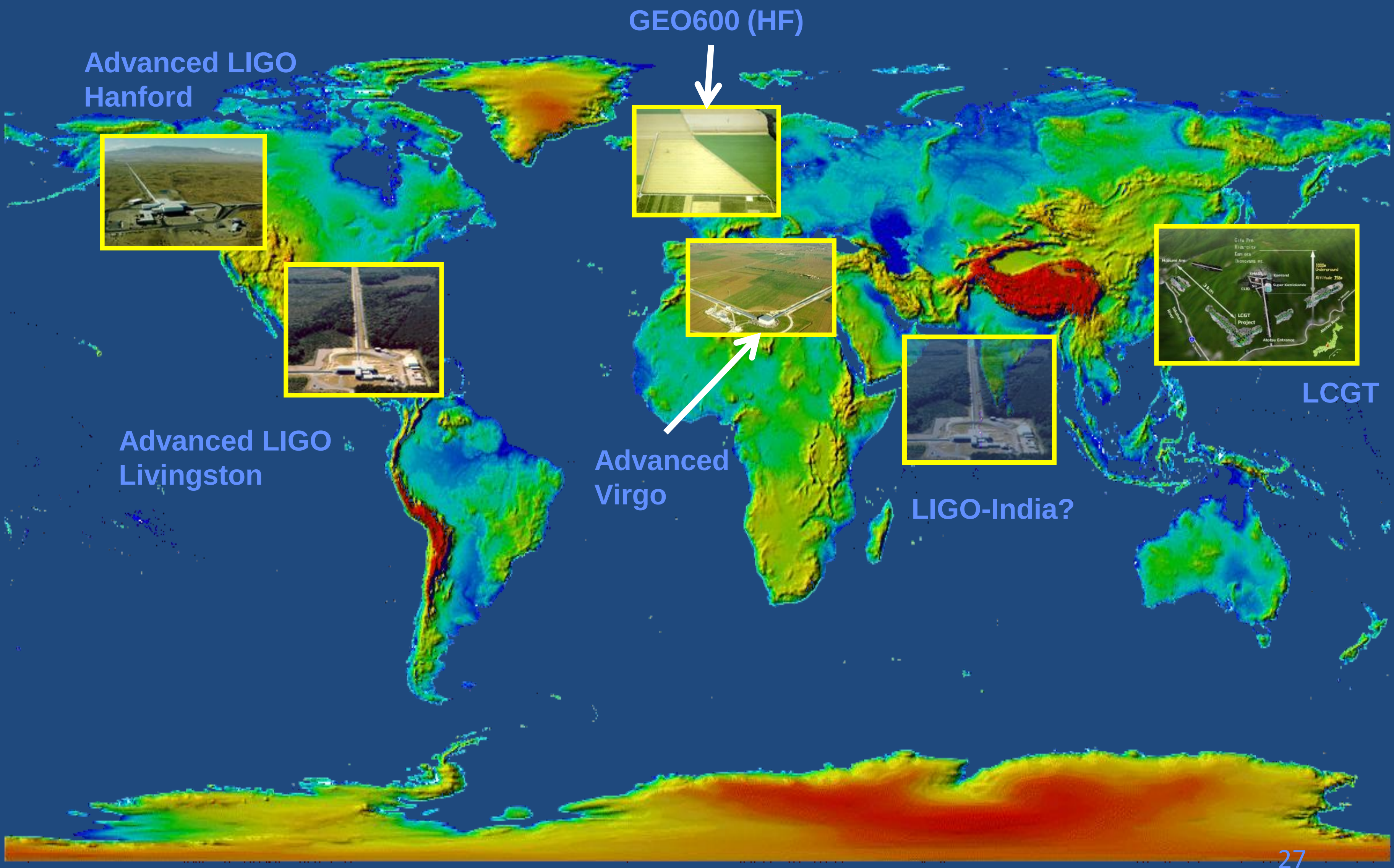
… so this is not an official plan for the configuration evolution, rather, an educated guess at how aLIGO might evolve

D. Shoemaker, 2011

First extended run:
25w laser input, no signalrecycling
BNS: 142 Mpc
BBH: 1400 Mpc
Stochastic Omega: 3e-9

125w laser input, signal recycling
BNS Inspiral Range: 200 Mpc
BBH Inspiral Range: 1640 Mpc
Stochastic Omega: 2.25e-9

The Advanced GW Detector Network



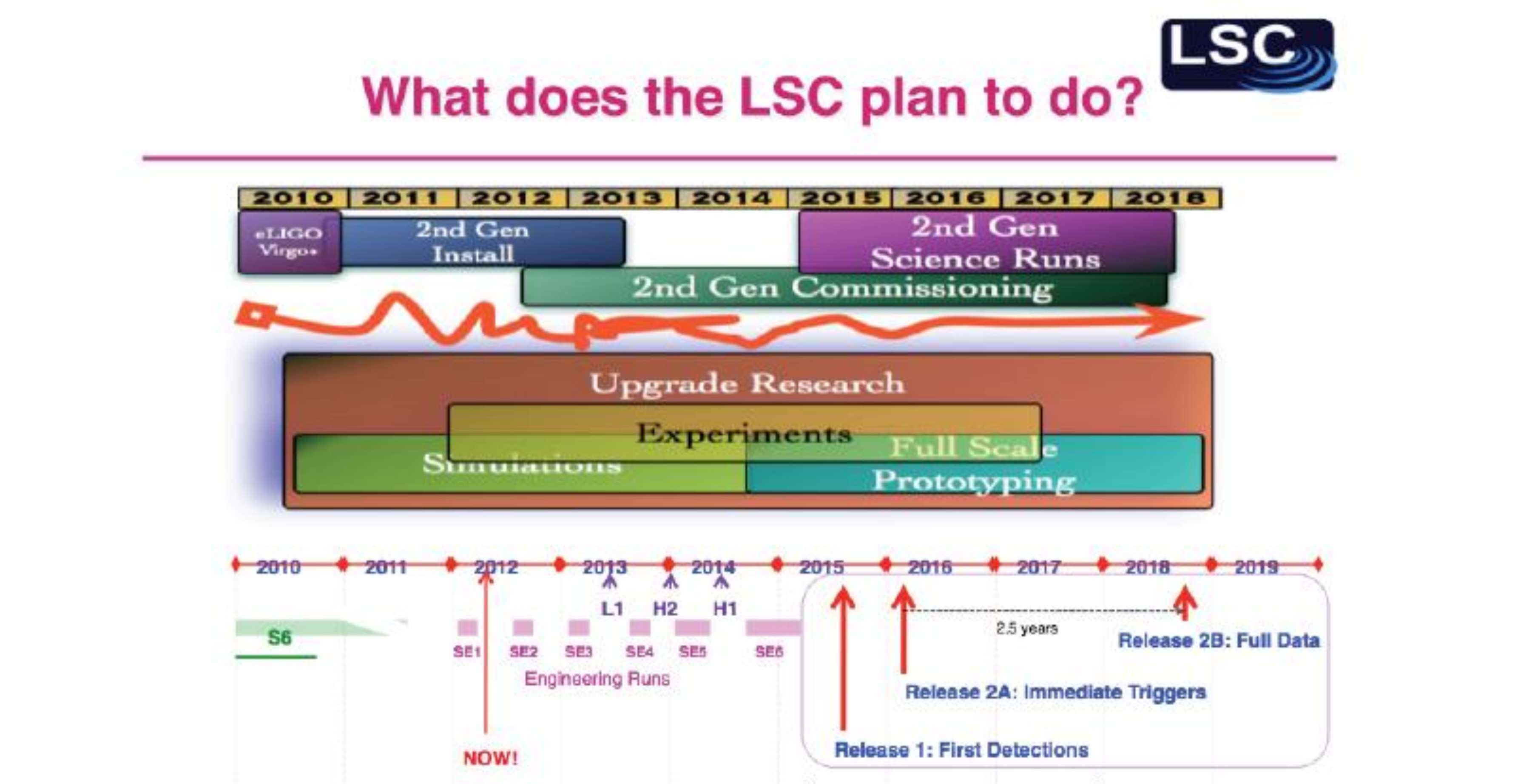
Extending the collaboration to the other astronomical, neutrinos, gamma rays..,observatories

"LSC AND VIRGO POLICY ON RELEASING GRAVITATIONAL WAVE TRIGGERS TO THE PUBLIC IN THE ADVANCED DETECTORS ERA

….They are open to all requests from interested astronomers or astronomy projects which want to become partners through signing an MoU. They encourage colleagues to help set up and organize this effort in an efficient way to guarantee the best science can be done with gravitational wave triggers.
After the published discovery of gravitational waves with data from LSC and/or Virgo detectors, both the LSC and Virgo will begin releasing especially significant triggers promptly to the entire scientific community to enable a wider range of follow-up observations. This will take effect after the Collaborations have published papers (or a paper) about 4 GW events, at which time a detection rate can be reasonably estimated.
….Throughout the Advanced Detectors era, the LSC and Virgo will release appropriate segments of data from operating detectors corresponding to detected gravitational waves presented in LSC/Virgo authored publications, at the time of the publication, including the first claimed detection of gravitational waves."

Text approved by LSC and EGO council

Conclusion



(not earlier than...)