# The Coming Global Gravitational-wave Detector Network with an Emphasis on Advanced LIGO

LSC VIRGO

LIGO-G1201199


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**LIGO Laboratory**
**California Institute of Technology**

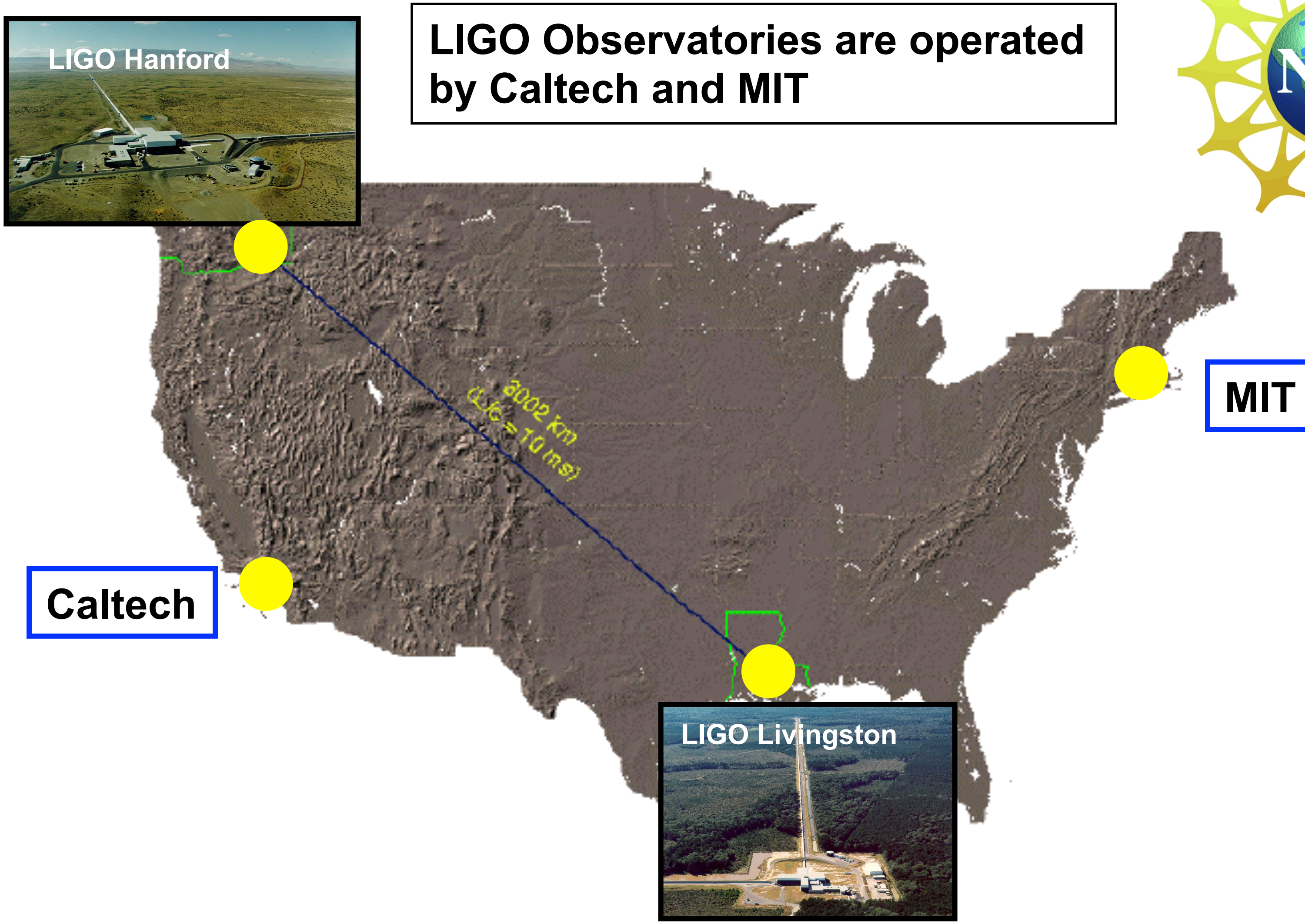
# *Topics*

- Initial LIGO
- Selected Science Results from LIGO's S5 and S6 Science Runs
- Advanced LIGO – Status and Progress
- LIGO-India: Status and Prospects

LIGO

# *LIGO Laboratory*

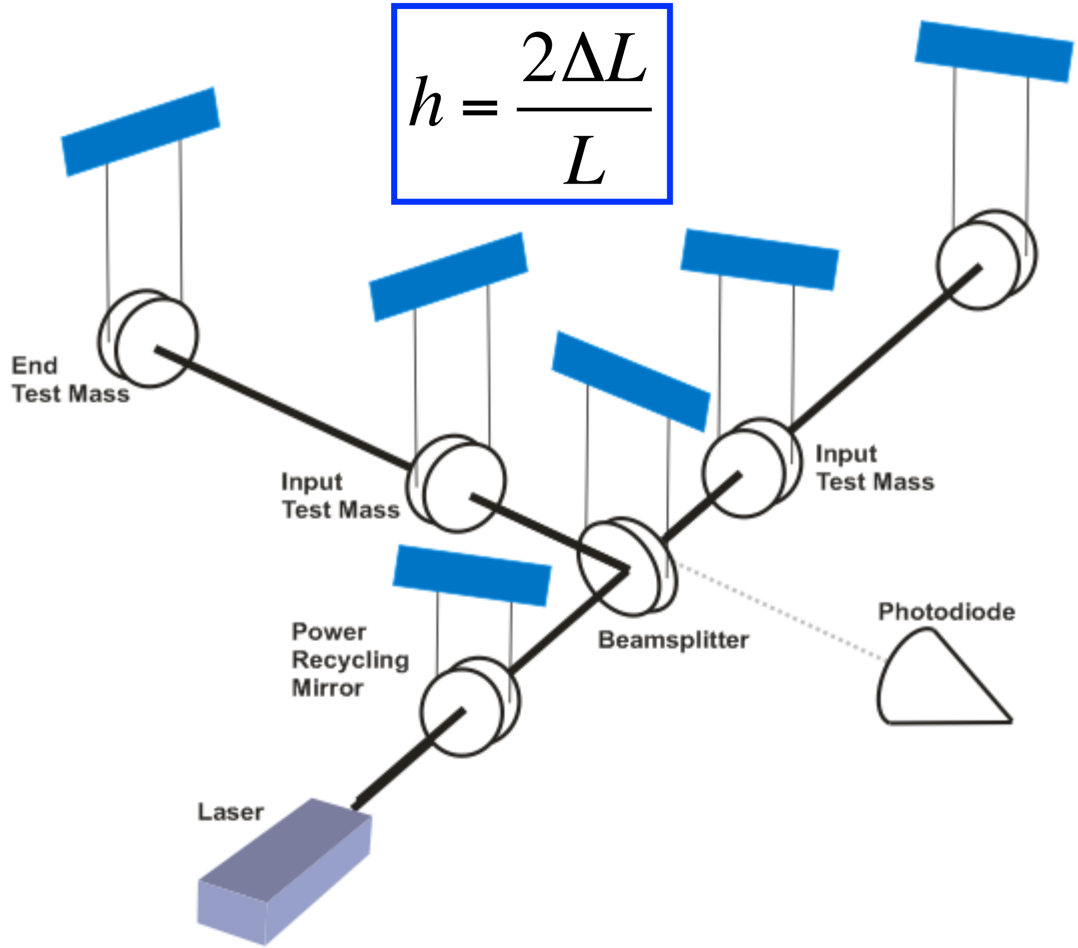
**LIGO Observatories are operated by Caltech and MIT**



# Initial LIGO Concept

- Power-recycled Michelson interferometer
- 4 km long Fabry-Perot arm cavites
- Passive seismic isolation
- 10 kg mirrors figured to $\lambda/1000$
- 10 W → 30 W pre-stabilized laser operating at 1064 nm

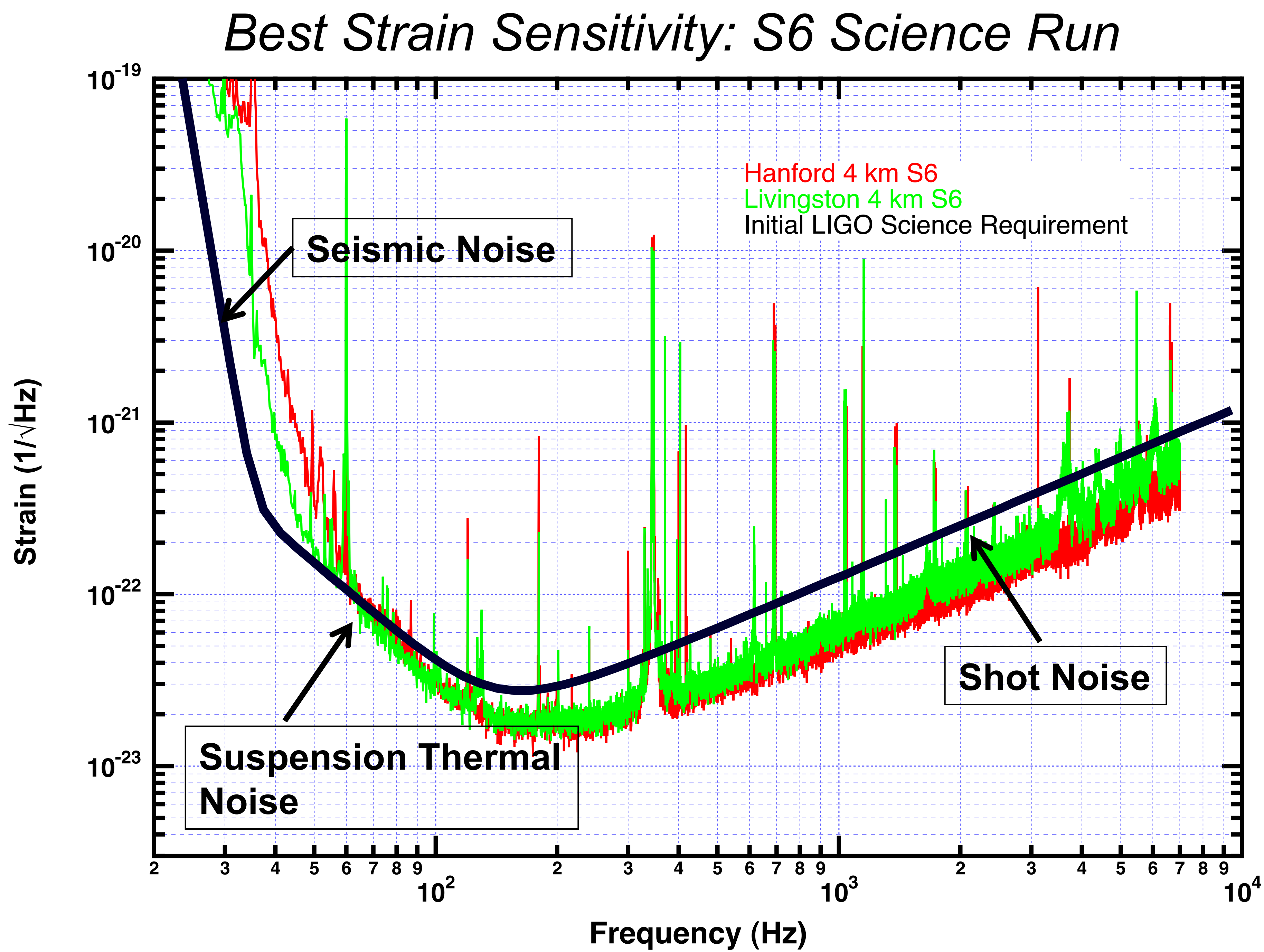
$$h = \frac{2\Delta L}{L}$$




- Passing GWs modulate the time-of-flight of light between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent
  - » A coherent detector

# LIGO History

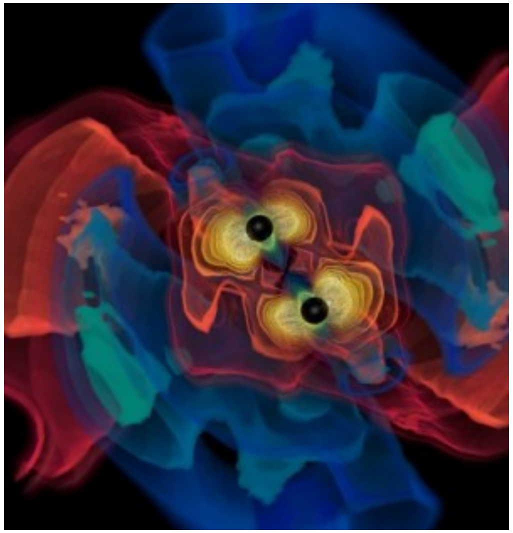
- **1989: LIGO Project proposed to NSF**
- 1992: LIGO Project funded by NSF
- 1995 – 1999: LIGO facilities construction at Hanford and Livingston
- 1998 – 2002: Installation/integration of initial LIGO interferometers
- 2002 - 2005: Interferometer commissioning interleaved with science runs (S1-S4)
- **Nov 4, 2005 – Sept 31, 2007: S5 science run**
  - Design sensitivity reached; 15 Mpc range; > 1 year of triple coincidence data
- 2007 – 2009: Enhanced LIGO instrument upgrade
  - Low cost upgrade, tests key Advanced LIGO technologies
- **April 2008: Advanced LIGO Construction begins**
- **July 7, 2009 – Oct 20, 2010: S6 science run**
  - 18 Mpc range to merging binary neutron stars


Best Strain Sensitivity: S6 Science Run
Hanford 4 km S6
Livingston 4 km S6
Initial LIGO Science Requirement
Seismic Noise
Suspension Thermal Noise
Shot Noise
Strain (1/√Hz)
Frequency (Hz)
10^-19
10^-20
10^-21
10^-22
10^-23
10^2
10^3
10^4

# *Recent LIGO/Virgo/GEO science results*

**All LSC/Virgo Observational Papers:**
**https://www.lsc-group.phys.uwm.edu/ppcomm/Papers.html**

# Astrophysical Sources of Gravitational Waves

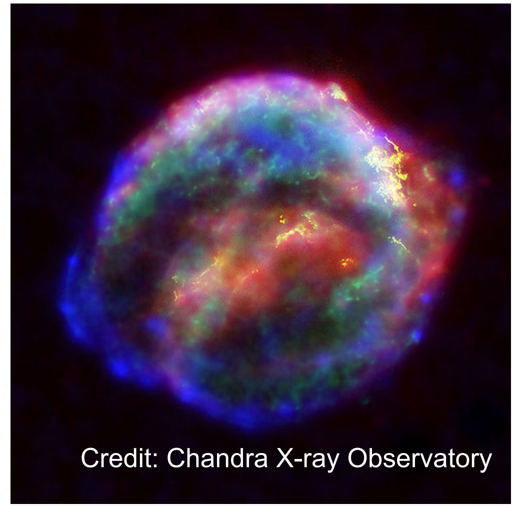


Credit: AEI, CCT, LSU

*Coalescing Compact Binary Systems:* *Neutron Star-NS, Black Hole-NS, BH-BH*

- Strong emitters, well-modeled,

- (effectively) transient

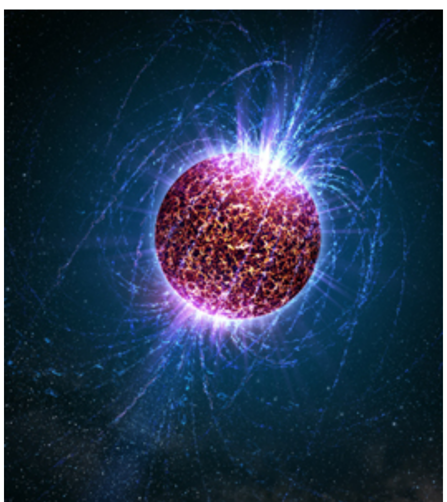


Credit: Chandra X-ray Observatory

*Asymmetric Core Collapse Supernovae*

- Weak emitters, not well-modeled ('bursts'), transient

- Cosmic strings, soft gamma repeaters, pulsar glitches also in 'burst' class

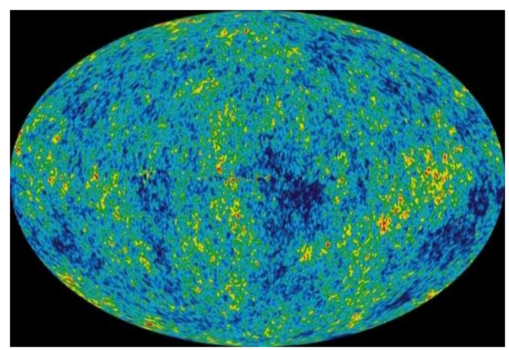


Casey Reed, Penn State

*Spinning neutron stars*

- (effectively) monotonic waveform

- Long duration



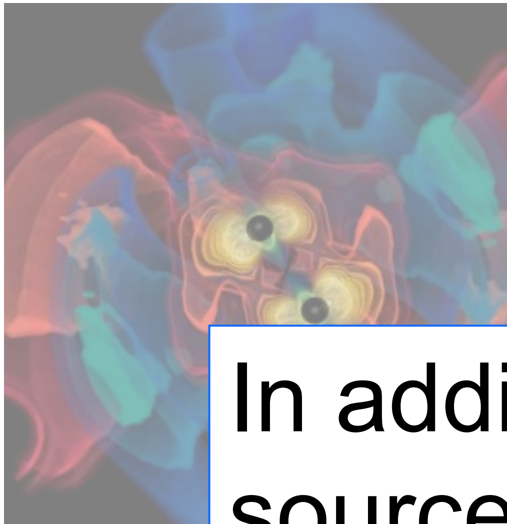
NASA/WMAP Science Team

*Cosmic Gravitational-wave Background*

- Residue of the Big Bang, long duration

- Long duration, stochastic background

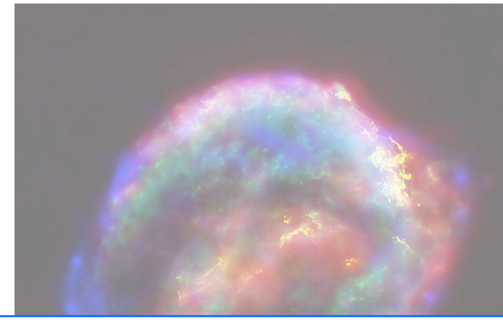
# Astrophysical Sources of Gravitational Waves



Credit: AEI, CCT

Coalescing Compact Binary Systems: Neutron Star-NS, Black Hole-NS, BH-BH

- Strong emitters



Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled ('bursts'), transient

...ngs, soft ...eaters, ...es also in

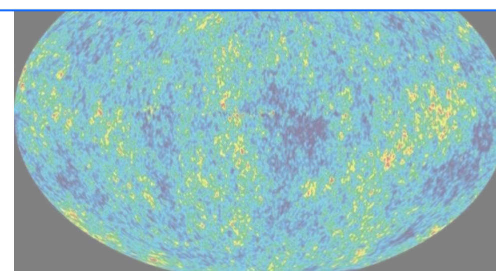
**In addition to these known sources, there may be surprising sources of gravitational waves.**

Casey Reed, Penn State

Spinning neutron stars

- (effectively) monotonic waveform

- Long duration



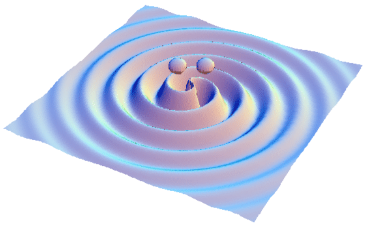
NASA/WMAP Science Team

...vitational-wave Background

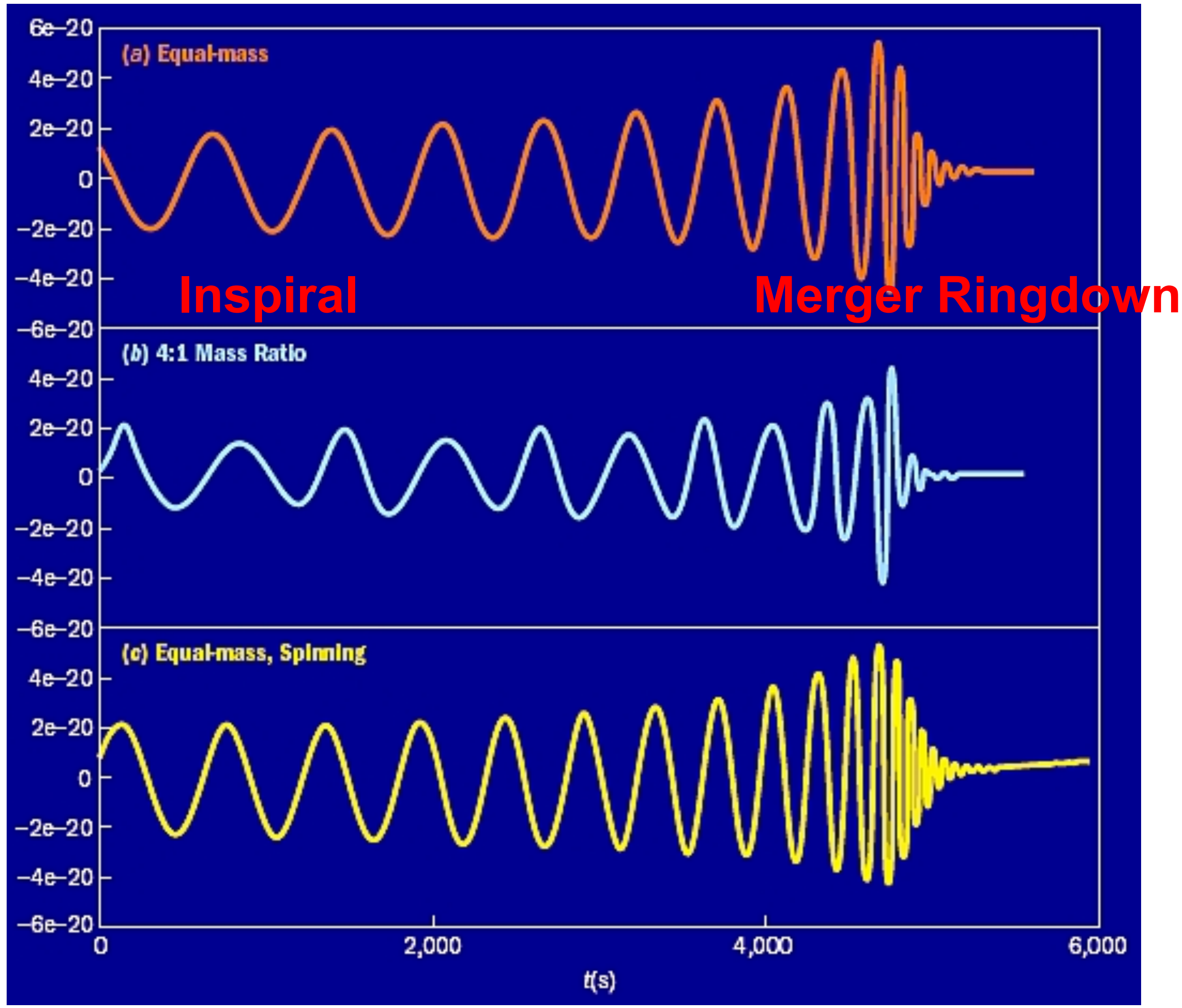
- Residue of the Big Bang, long duration

- Long duration, stochastic background

# Compact binary inspiral, merger, ringdown



- There's a lot of physics and astrophysics in the waveforms!
- Waveform reconstruction (often buried in detector noise).

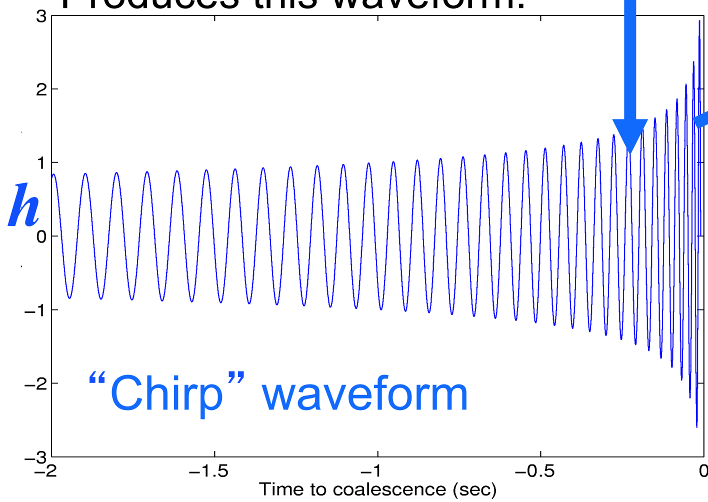


LIGO

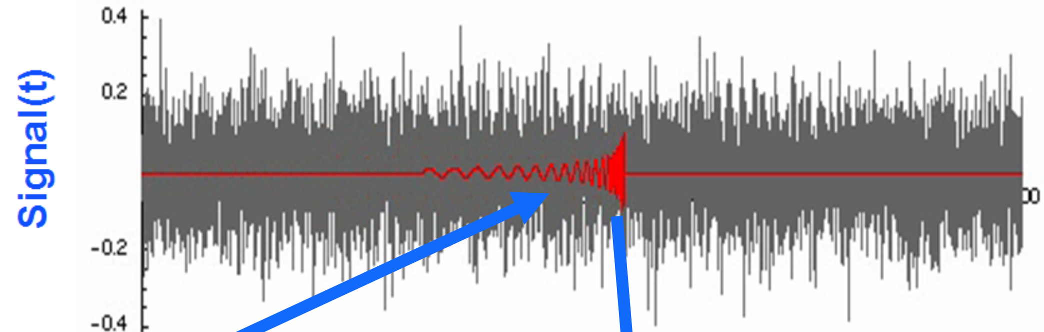
# *Searches for Binary Mergers*

This source:

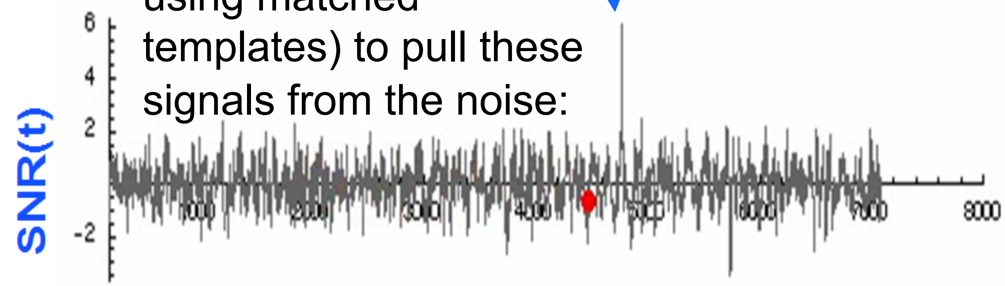

Produces this waveform:




Buried in this noise stream:

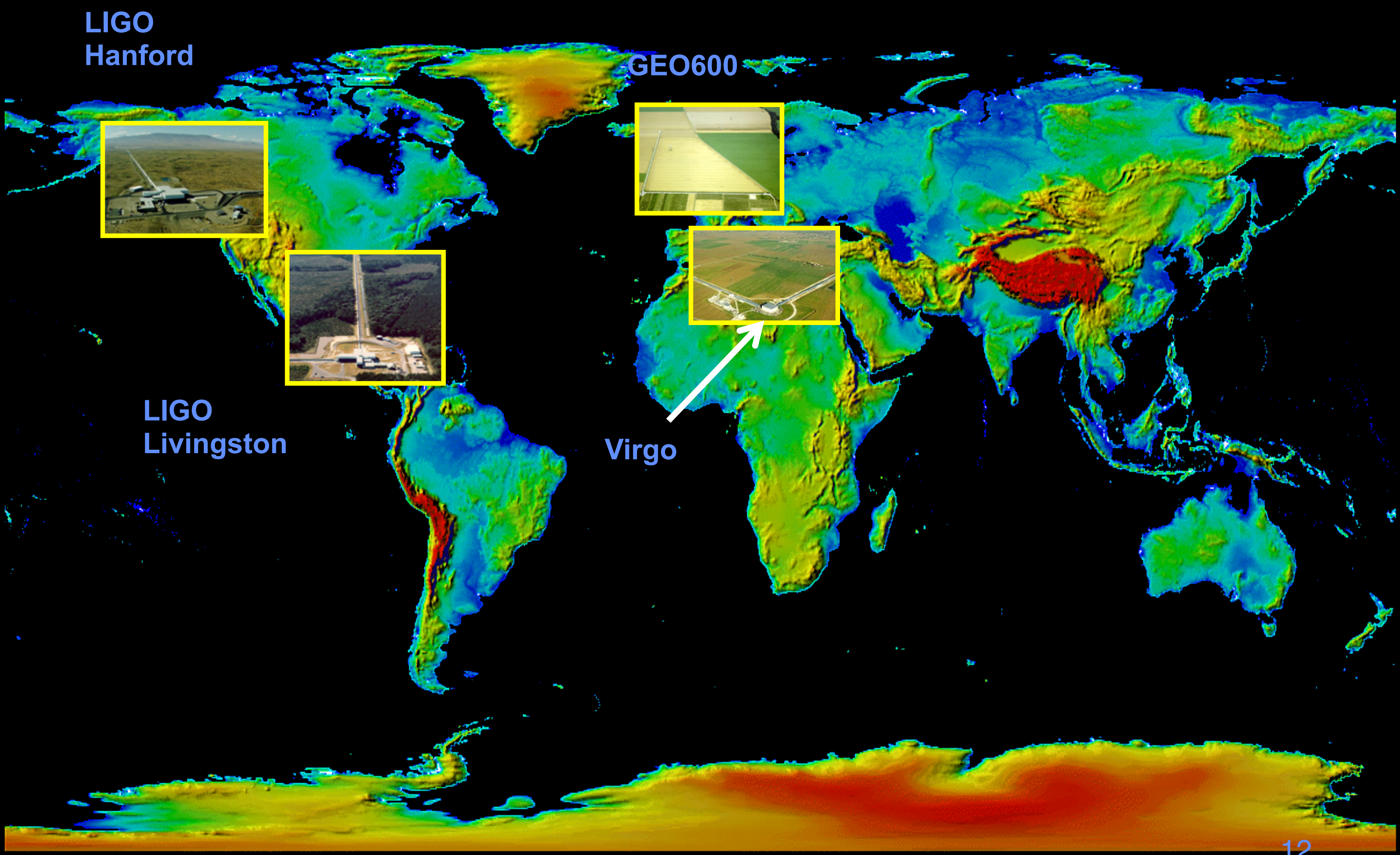



We use different methods (in this case optimal Wiener filtering using matched templates) to pull these signals from the noise:




**The problem is that non-astrophysical sources also produces signals (false positives)**

# The Current GW Detector Network



# Expected detection rates for compact binary mergers

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

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

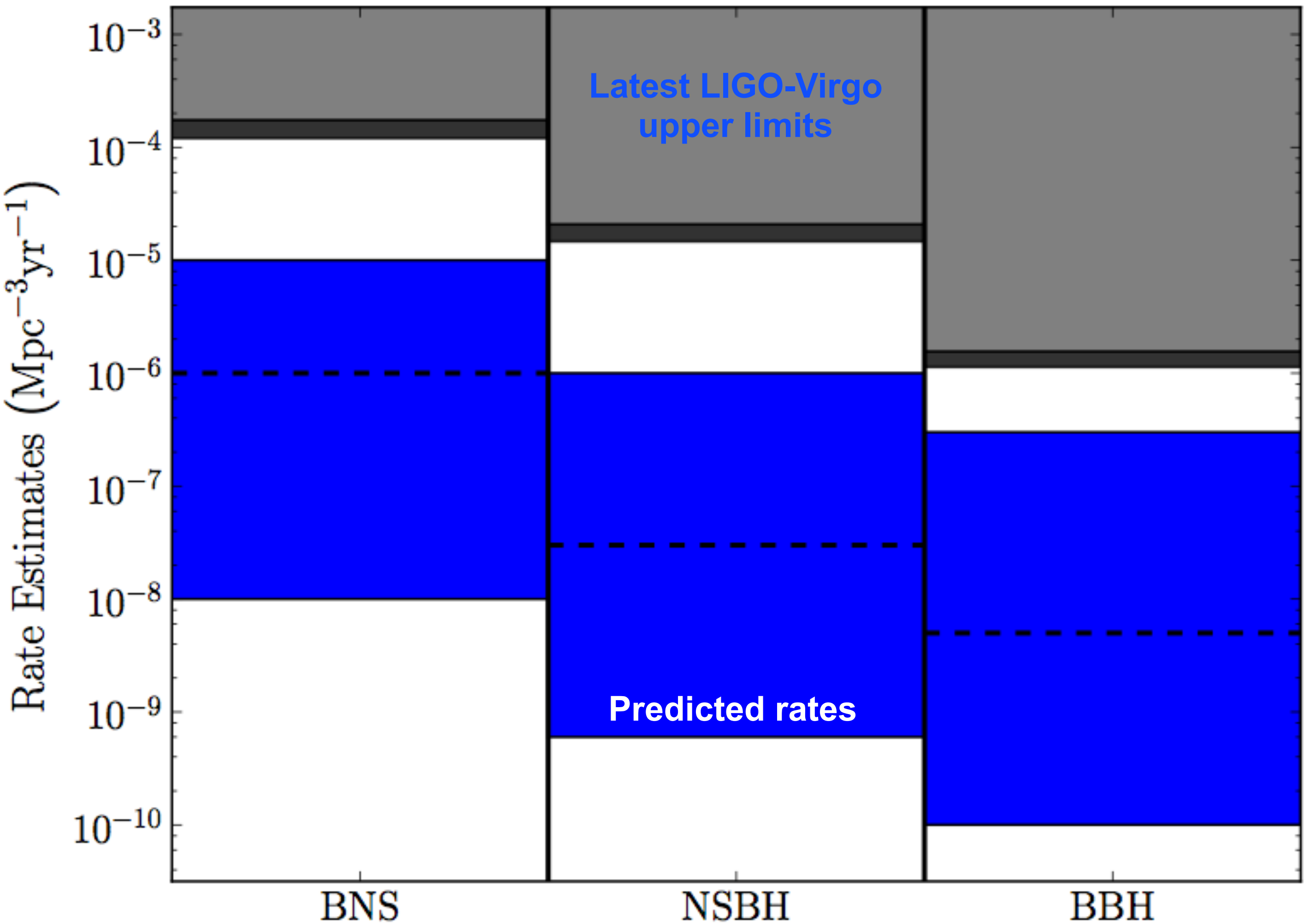
TABLE V: Detection rates for compact binary coalescence sources.

| 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 | NS-NS | $2 \times 10^{-4}$ | 0.02 | 0.2 | 0.6 |
| | NS-BH | $7 \times 10^{-5}$ | 0.004 | 0.1 | |
| | BH-BH | $2 \times 10^{-4}$ | 0.007 | 0.5 | |
| | IMRI into IMBH | | | $< 0.001^b$ | $0.01^c$ |
| | IMBH-IMBH | | | $10^{-4\,d}$ | $10^{-3\,e}$ |
| [redacted] | | | | | |

- **The error bar is large and important!**

# Searching for Low Mass Compact Binary Coalescences

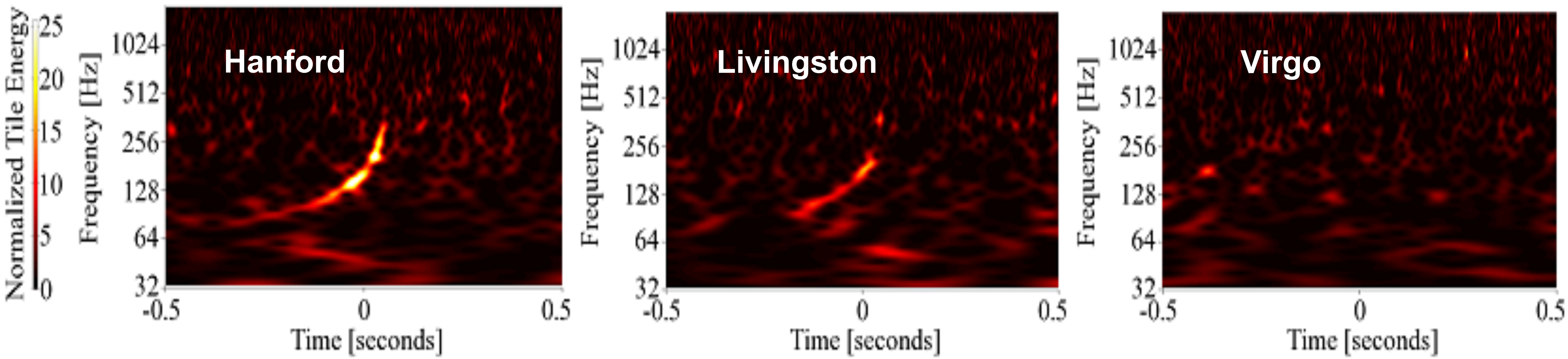
LIGO Scientific and Virgo Collaborations, "Search for Gravitational Waves from Low Mass Compact Binary Coalescence in LIGO's Sixth Science Run and Virgo's Science Runs 2 and 3", [Phys. Rev D**85** (2012) 082002]

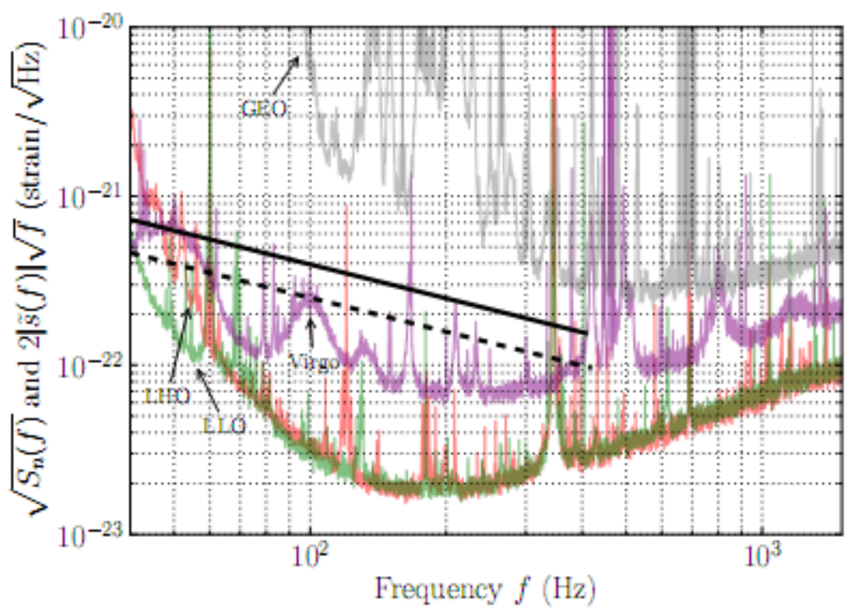


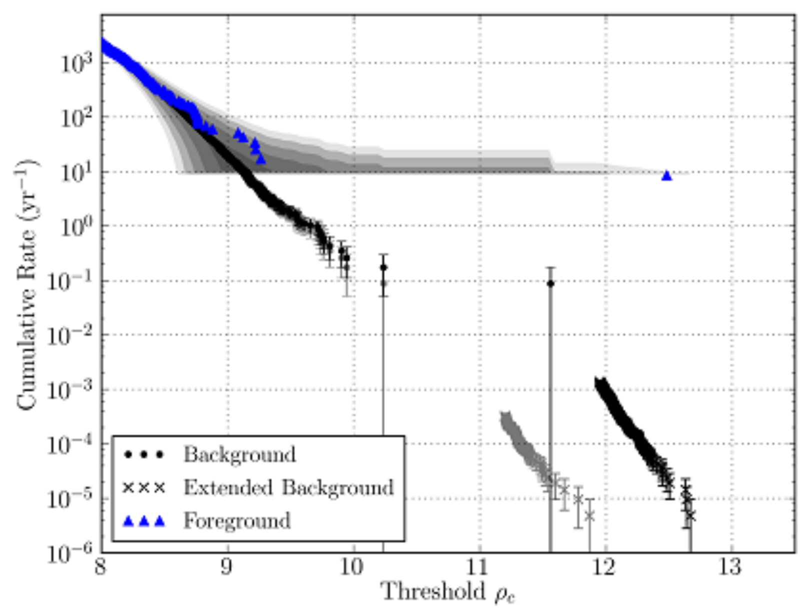
LIGO

# ‘Event’ GW100916 – A Blind Injection

http://www.ligo.org/science/GW100916/

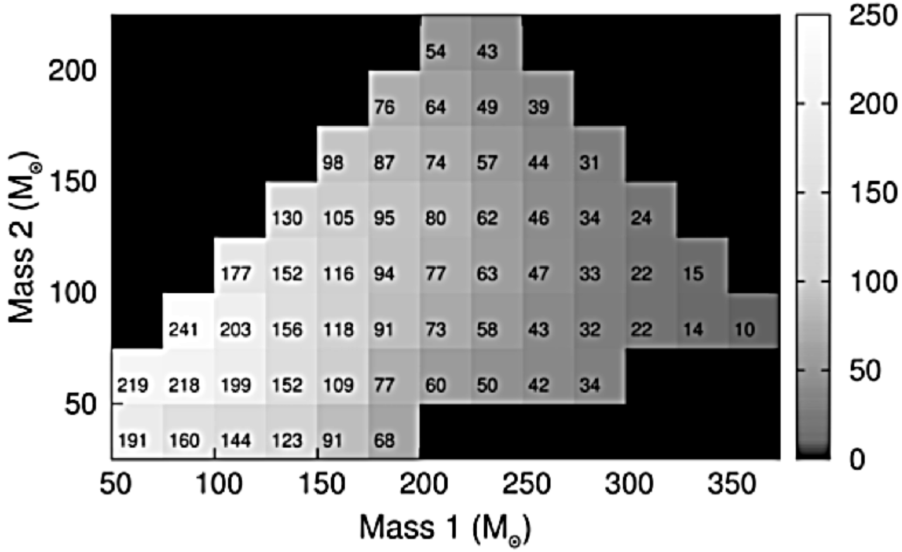


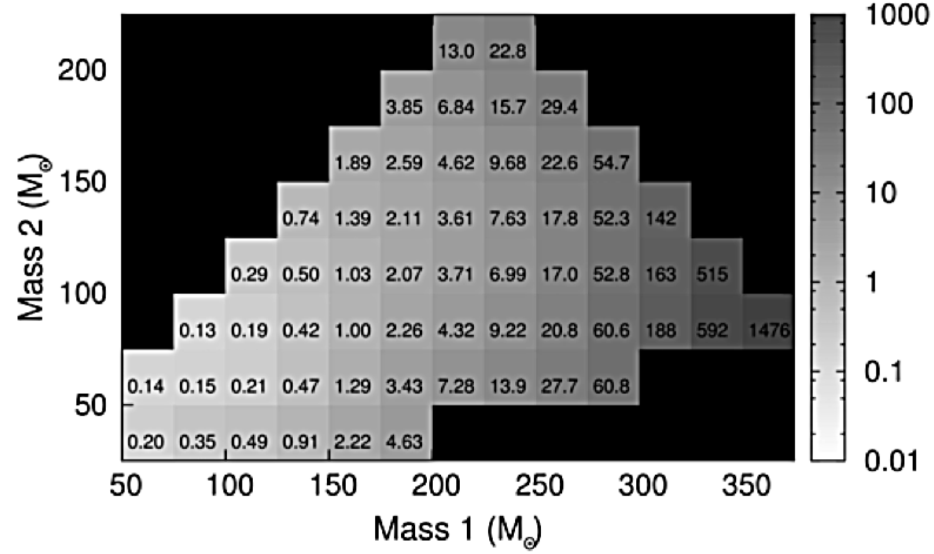



# Searching for High Mass Compact Binary Coalescences

- IMBH formation proposed to complete BH mass hierarchy…
  - Via stellar collision in globular clusters, stalled supernovae of early pop III stars, progressive accumulation into higher mass
- …but their existence is uncertain
  - Stellar winds suppression of runaway accumulation, merger recoil ejection of BH from GC
- Candidates exist: ultraluminous x-ray sources M82 X-1, NGC 1313 X-2
- S5/VSR1 search using constrained unmodelled waveform (Coherent WaveBurst algorithm)

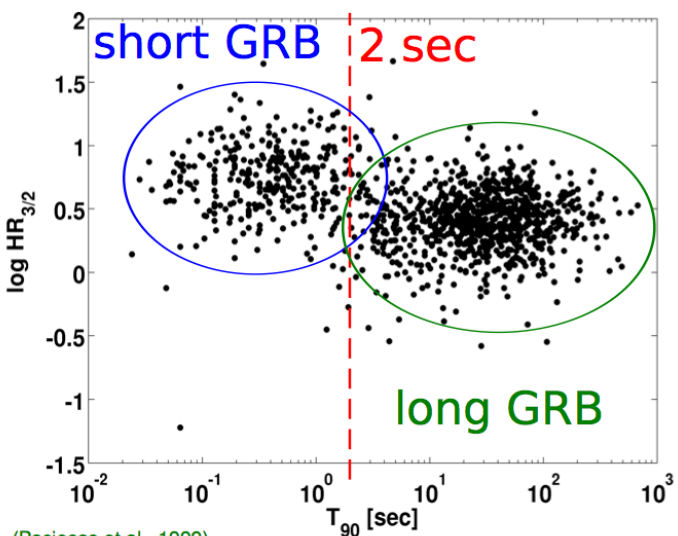


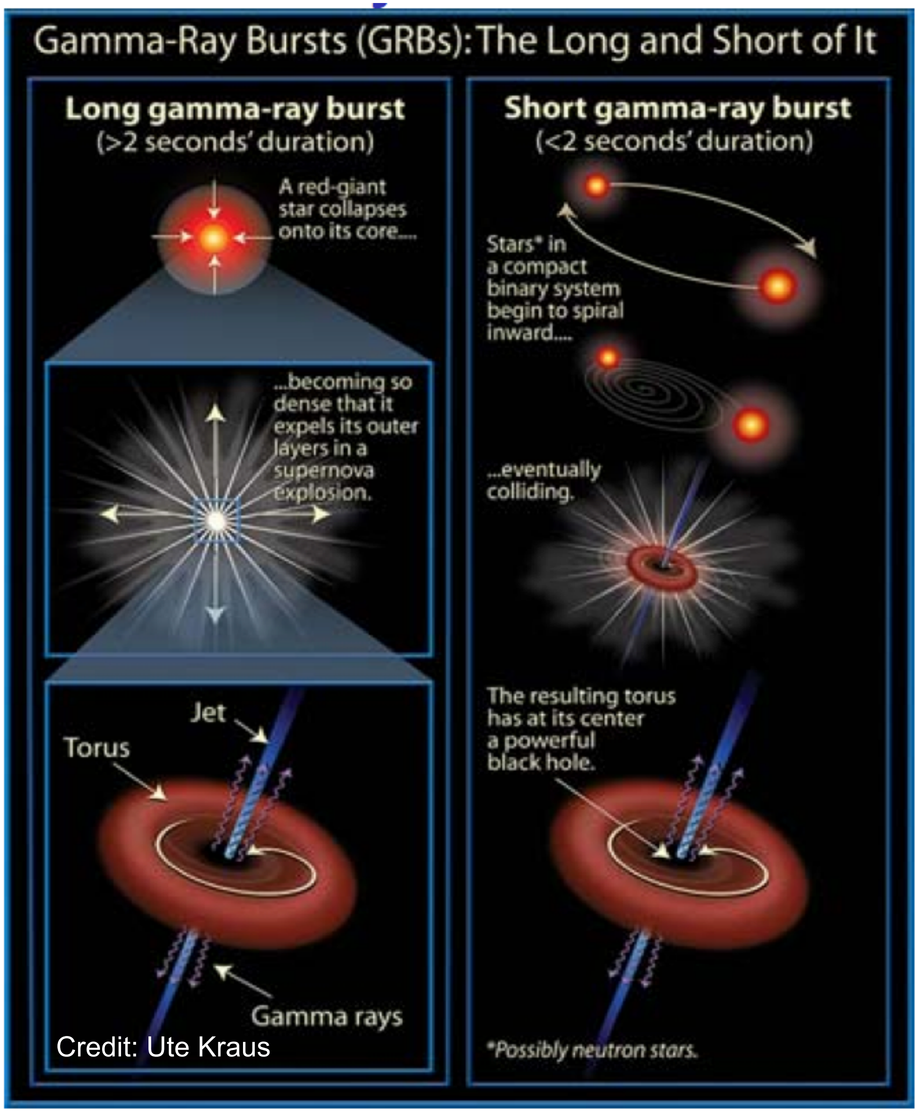

LIGO Scientific and Virgo Collaborations, "*Search for gravitational waves from intermediate mass binary black holes*", Phys. Rev. D**85**, 102004 (2012)

# Triggered searches for gamma-ray bursts

- GRBs are good candidates for GW emission
- GRB progenitor models
  - » Long GRB → Core collapse SN of a massively spinning star
  - » Short GRB → coalescence of a neutron star and a compact object
    - – ≤ 15% from neutron star quakes
- Compact, relativistic, asymmetric!
  - » But measured red shifts → 10 Gpc



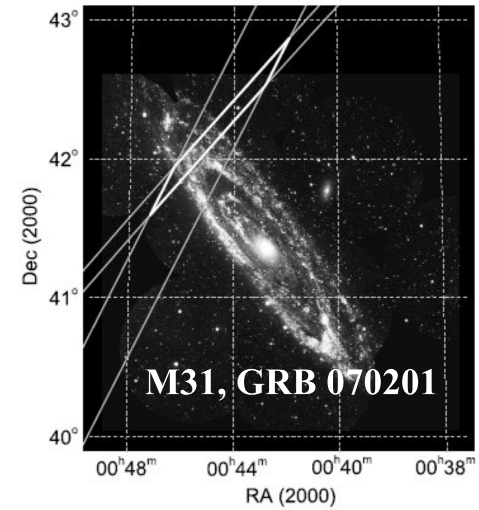

(Paciesas et al., 1999)

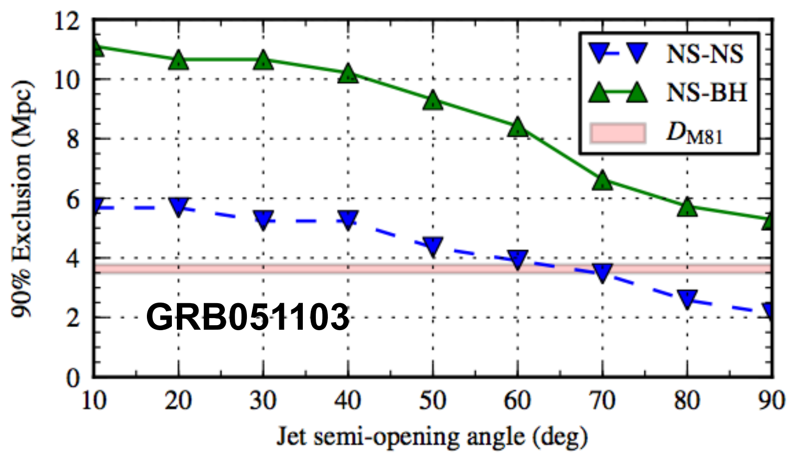


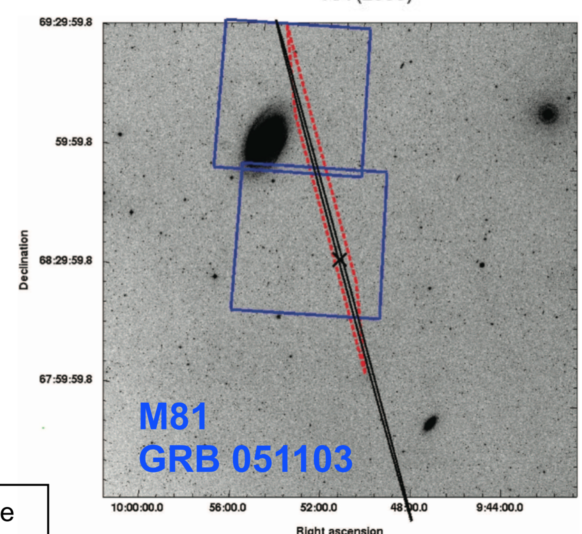

Credit: Ute Kraus

# Searches for GWs from nearby GRB sources

- GRB050311, GRB070201: short GRBs with sky localizations that overlap nearby galaxies
  - » GRB050311 overlap with M81 (3.6 Mpc)
  - » GRB070201 overlap with M31 (770 kpc)
- Binary coalescence in M31 excluded at >99% confidence level
- BNS coalescence in M81 excluded at 98% confidence level



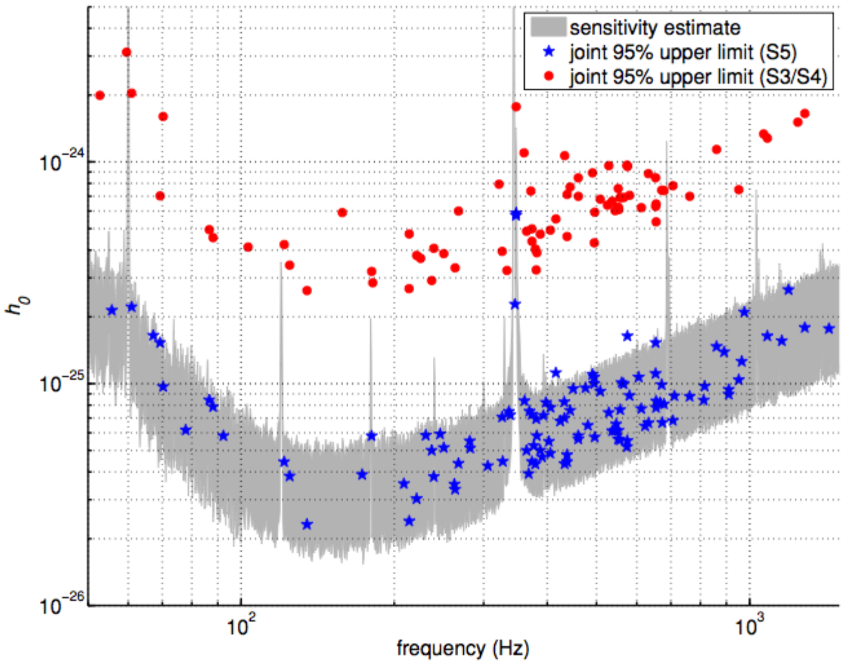




LIGO Scientific Collaboration, K. Hurley, "Implications for the Origin of GRB 070201 from LIGO Observations", [Astrophys. J. **681** (2008) 1419]

LIGO Scientific Collaboration, "Implications for the Origin of GRB 051103 from LIGO Observations", [arXiv:1201.4413]

# Searches for GWs from known pulsars

- Continuous gravitational-wave emission due to asymmetry rotation axis
  - » elastic deformations of the solid crust or core
  - » Distortion an extremely strong misaligned magnetic field
  - » Weak emitters
- Spin-down limit: $h_{sd} = \left(\frac{5}{2}\frac{GI_{zz}|\dot{\nu}|}{c^3 r^2 \nu}\right)^{1/2}$
- Crab pulsar (using LIGO data):
  - » $h_0 < h_{sd}/7$, $E_{GW} < 0.02E_{total}$
- Vela pulsar (using Virgo data):
  - » $h_0 < 0.66h_{sd}$, $E_{GW} < 0.45E_{total}$
- S5 search of 116 pulsars
  - Lowest upper-limit $h_0$: 2.3 x $10^{-26}$ (PSR J1603-7202)
  - Lowest upper-limit ellipticity: 7 x $10^{-8}$ (PSR J2124-3358)





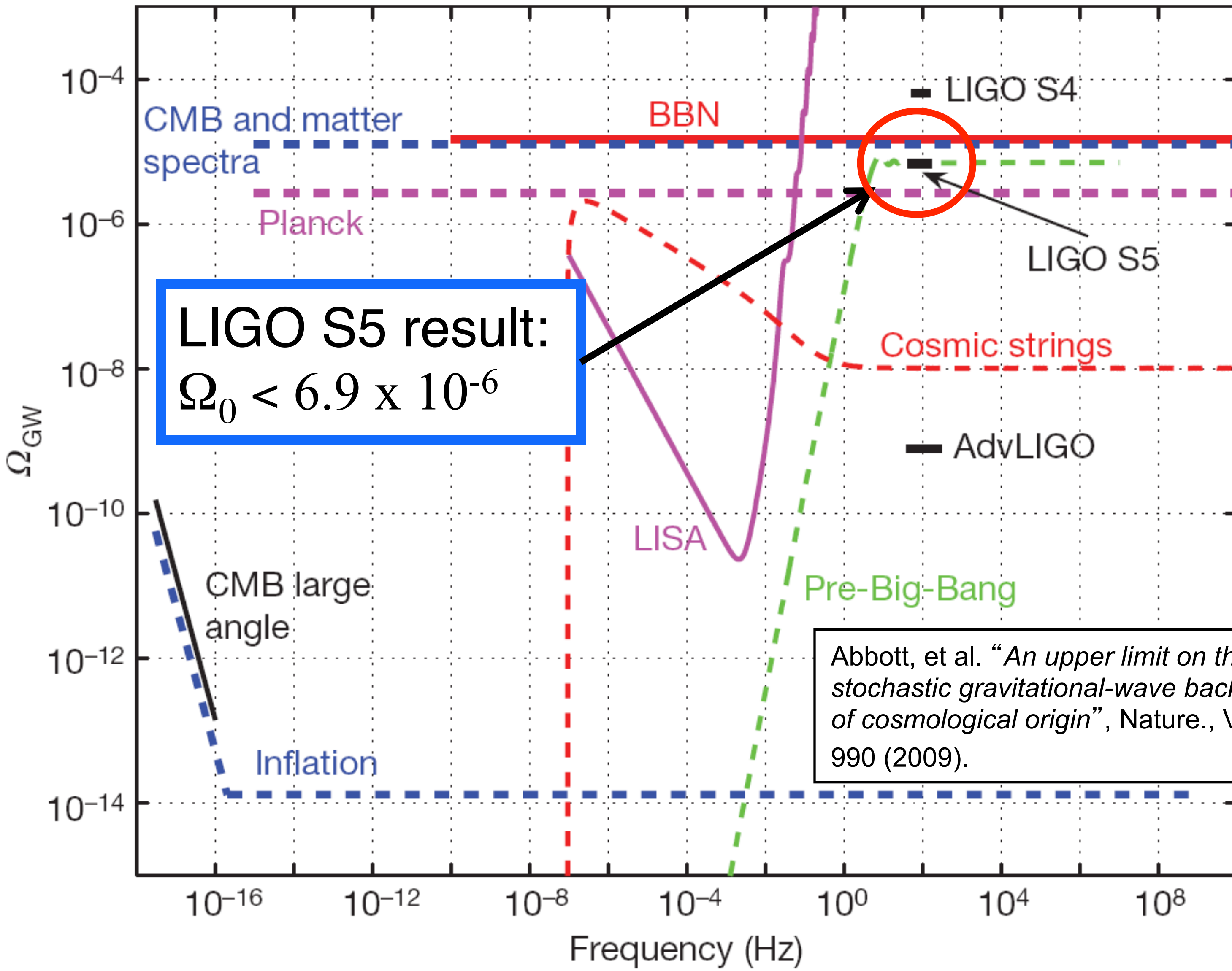
LIGO Scientific and Virgo Collaborations, "*Beating the spin-down limit on gravitational wave emission from the Crab pulsar*", Astrophys. J. Lett. **683** (2008) 45

LIGO Scientific and Virgo Collaborations, "*First search for gravitational waves from the youngest known neutron star*", Astrophys. J. **722** (2010) 1504

LIGO Scientific and Virgo Collaborations, "*Beating the spin-down limit on gravitational wave emission from the Vela pulsar,*" Astrophys. J. **737** (2011) 93

LIGO Scientific and Virgo Collaborations, "*Searches For Gravitational Waves From Known Pulsars With Science Run 5 LIGO Data*", Astrophys. J. **713** (2010) 671

# Upper limit on the Stochastic GW Background




Abbott, et al. "*An upper limit on the stochastic gravitational-wave background of cosmological origin*", Nature., V460: 990 (2009).

# *Advanced LIGO*

# Advanced LIGO

- Advanced LIGO – a complete upgrade of the LIGO interferometers
- Advanced LIGO is designed to increase the distance probed (‘reach’) by ~ 10X
  - » Leads to 1000X increase in volume → 1000X increase in event rate
- *<u>Expect 10s of detections per year at design sensitivity</u>*
  - » 1 aLIGO observational day = a few years of iLIGO

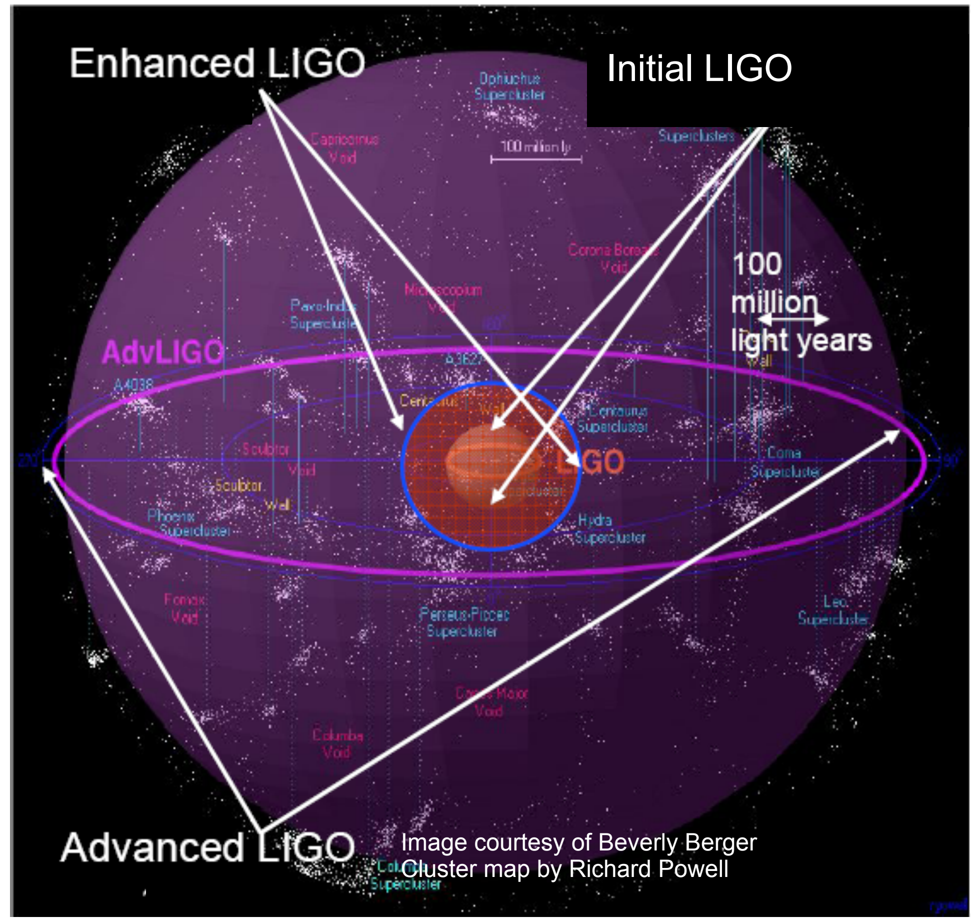


Image courtesy of Beverly Berger
Cluster map by Richard Powell

# CALTECH/MIT PROJECT

# FOR A

# LASER INTERFEROMETER

# GRAVITATIONAL WAVE OBSERVATORY

**December 1987**

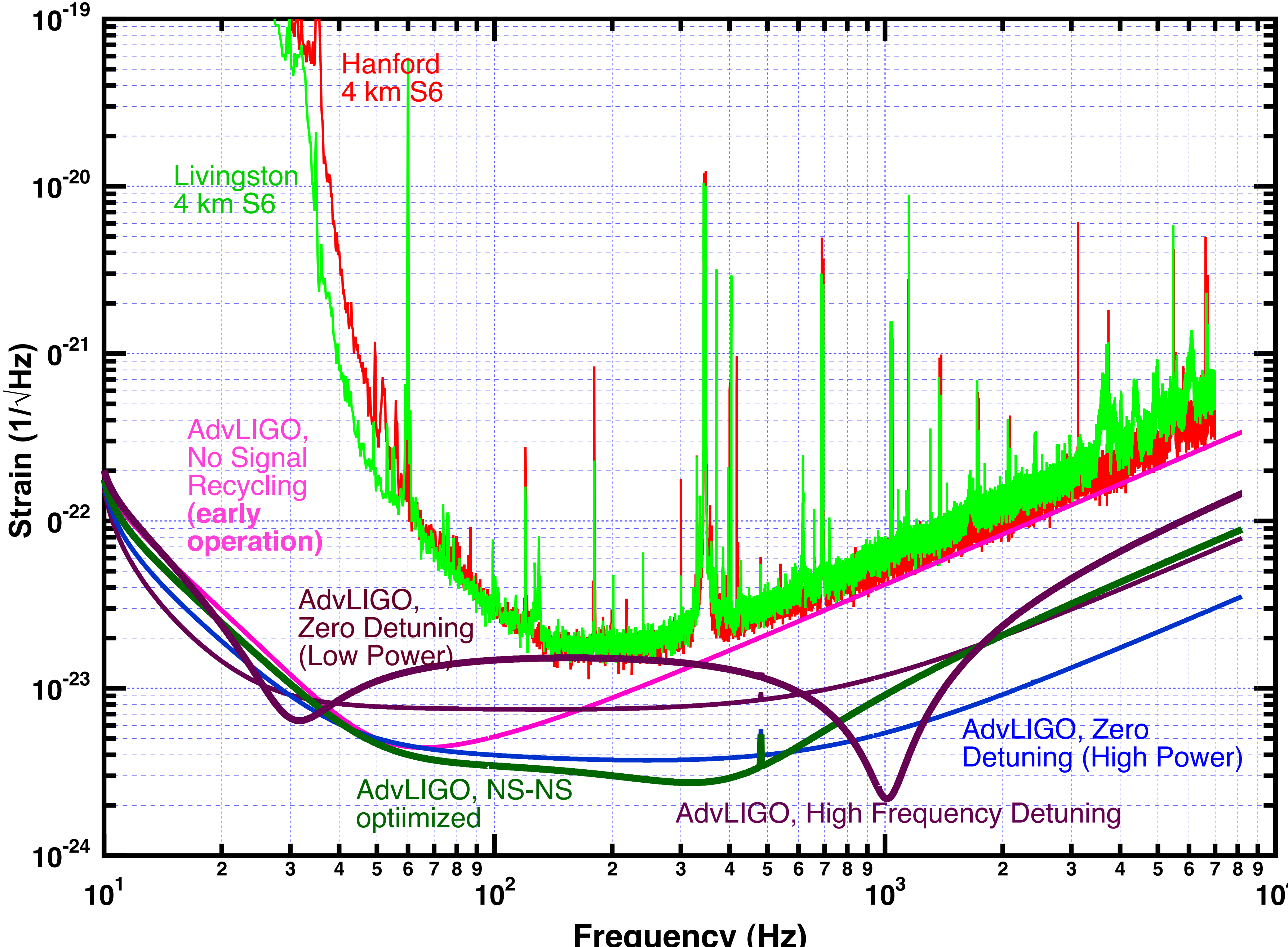
LIGO-M870001-00-M

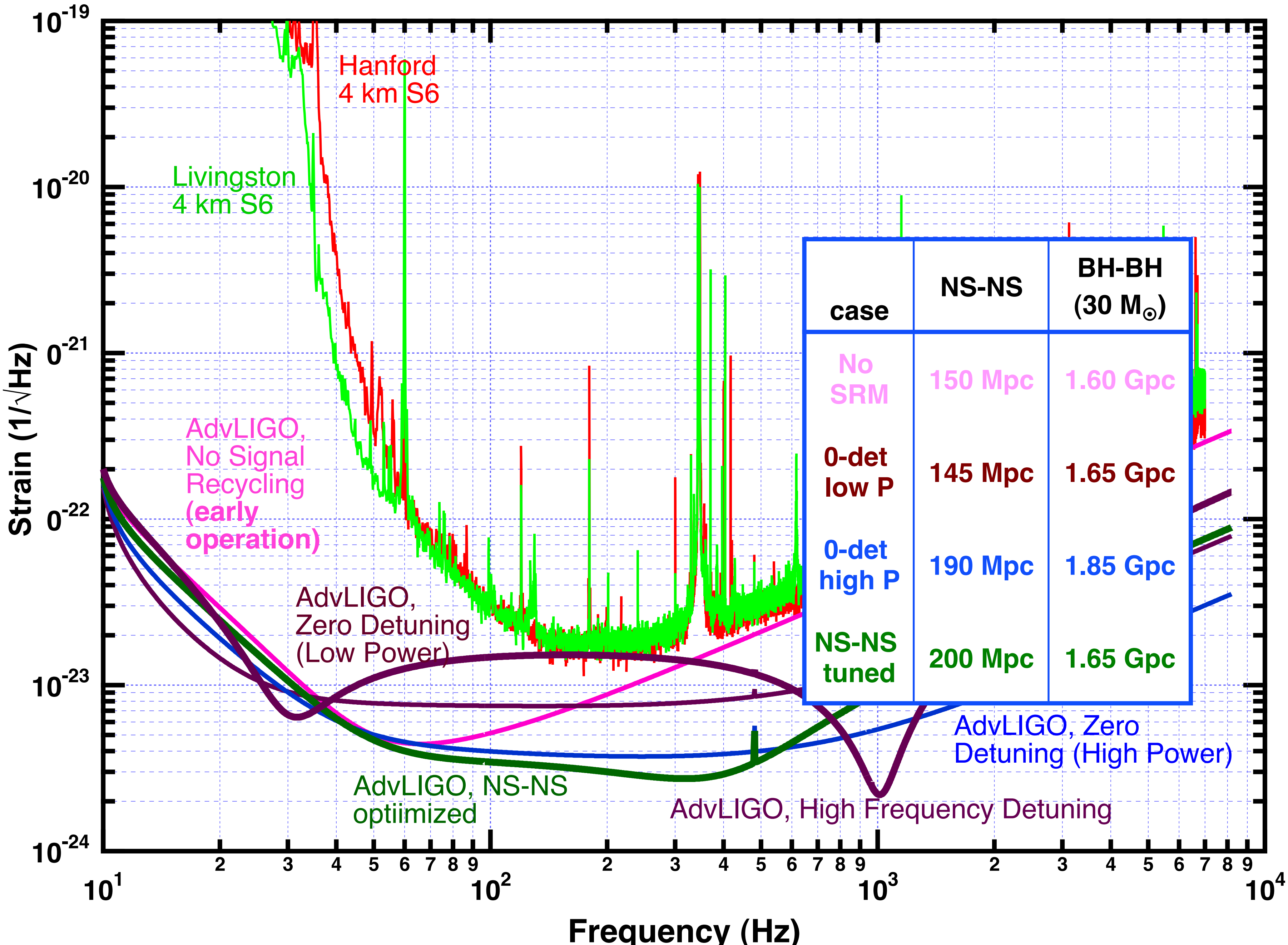
By comparing the source strengths and benchmark sensitivities in Figure II-2 and in the periodic and stochastic figures A-4b,c (Appendix A), one sees that *(i) There are nonnegligible possibilities for wave detection with the first detector in the LIGO. (ii) Detection is probable at the sensitivity level 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.*

**Rochus Vogt, Ron Drever, Kip Thorne, Rai Weiss 1987**

# Advanced LIGO MREFC construction project

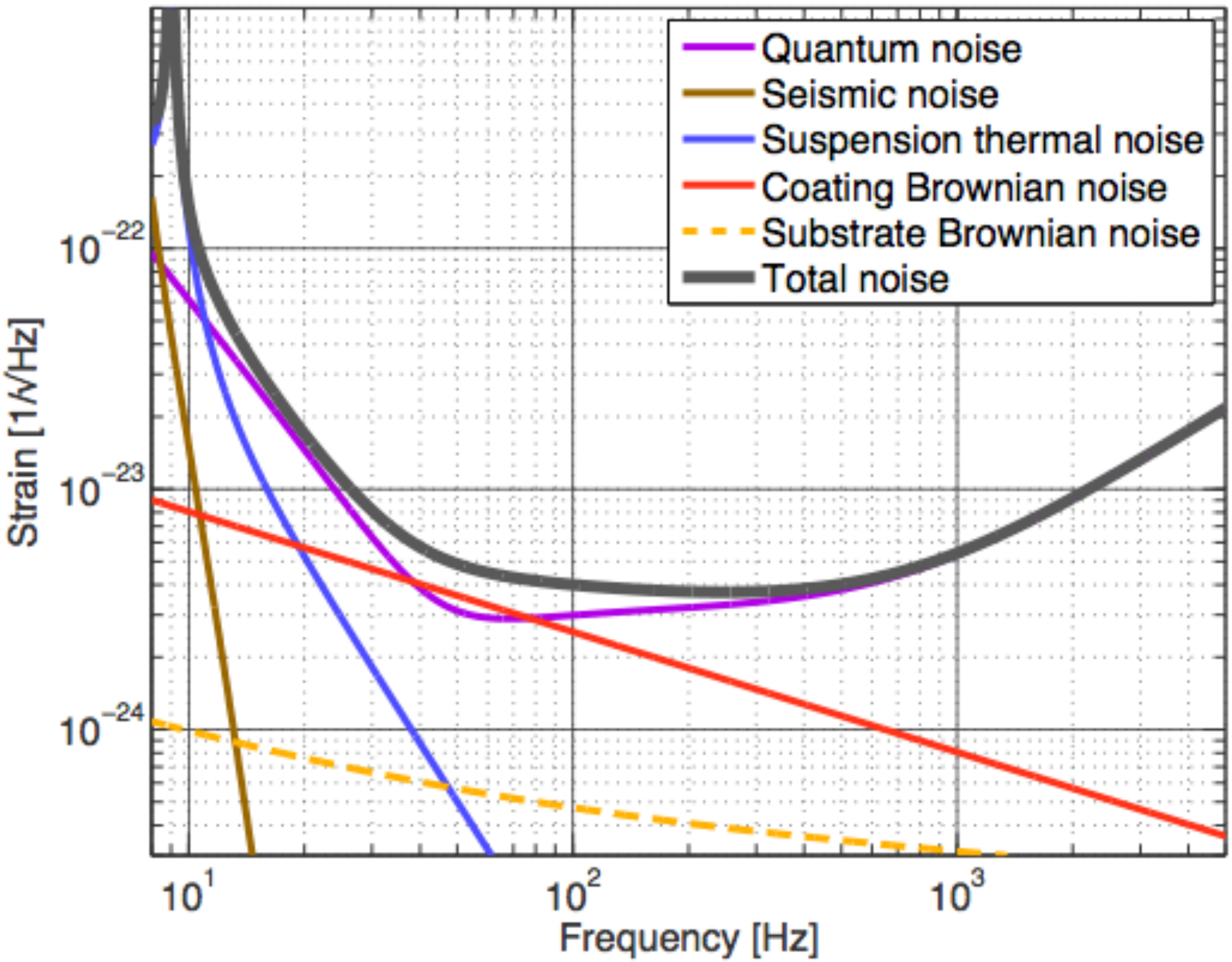
- Advanced LIGO funded April 2008
  - 7 year construction project
- $205.1M in funding from NSF
- Plus capital contributions from international partners
  - $14M from the Science and Technology Facilities Council (UK) – quadruple test mass suspensions
  - $14M from the Max Planck Institute (Germany) – 200 W front-end stabilized laser
  - $1.7M from the Australian Research Council – interferometer sensing and control components
- Complete upgrade to 2 Hanford and 1 Livingston 4 km interferometers
  - Advanced LIGO baseline plan (more later)
- Construction by LIGO Laboratory with participation by member groups of the LIGO Scientific Collaboration
- On schedule (and on budget) to complete in March 2015


Hanford
4 km S6
Livingston
4 km S6
AdvLIGO,
No Signal
Recycling
(early
operation)
AdvLIGO,
Zero Detuning
(Low Power)
AdvLIGO, Zero
Detuning (High Power)
AdvLIGO, NS-NS
optiimized
AdvLIGO, High Frequency Detuning
Strain (1/√Hz)
Frequency (Hz)



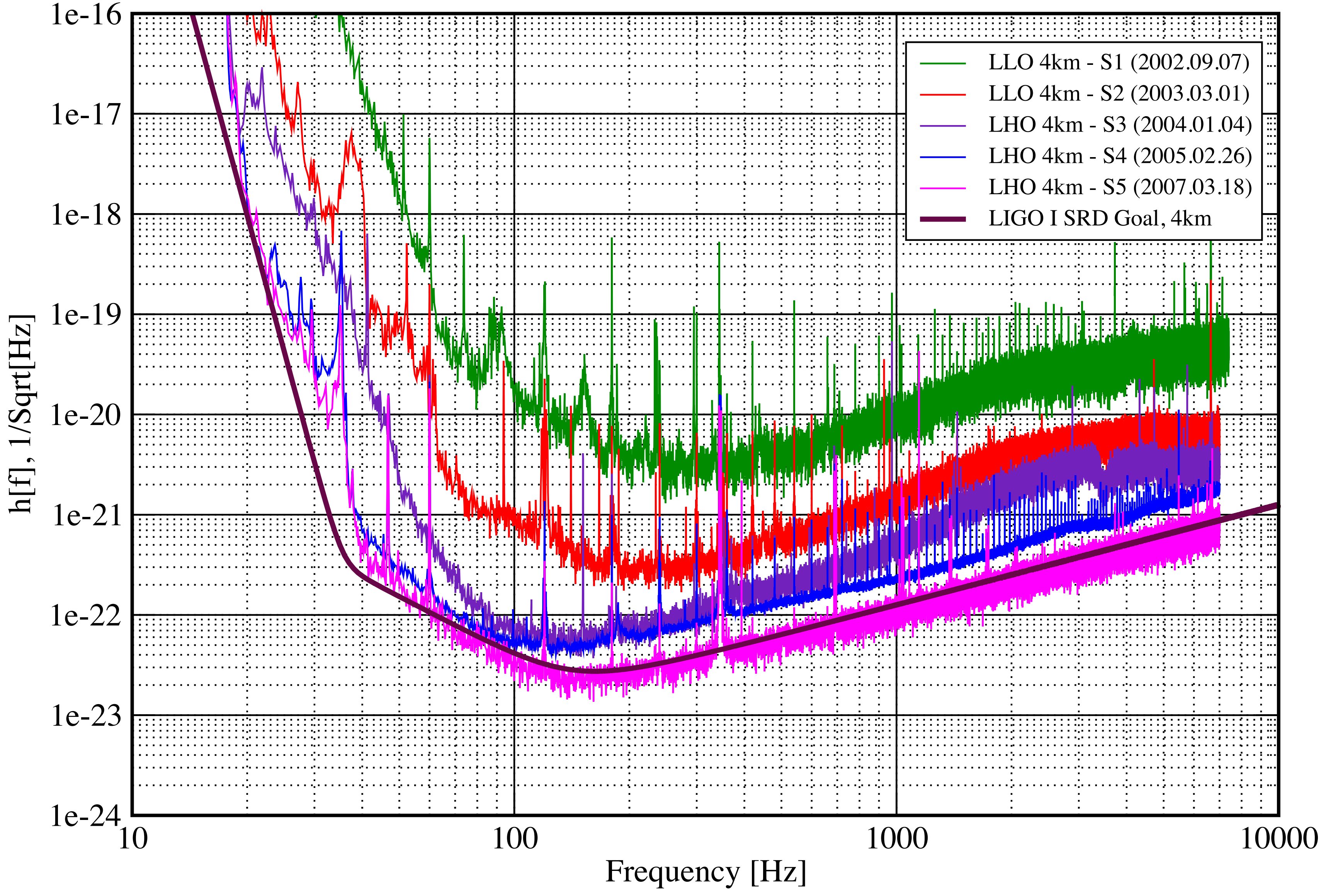

| case | NS-NS | BH-BH (30 $M_\odot$) |
|---|---|---|
| No SRM | 150 Mpc | 1.60 Gpc |
| 0-det low P | 145 Mpc | 1.65 Gpc |
| 0-det high P | 190 Mpc | 1.85 Gpc |
| NS-NS tuned | 200 Mpc | 1.65 Gpc |

# Fundamental Noise Budget



# Best Strain Sensitivities for the LIGO Interferometers

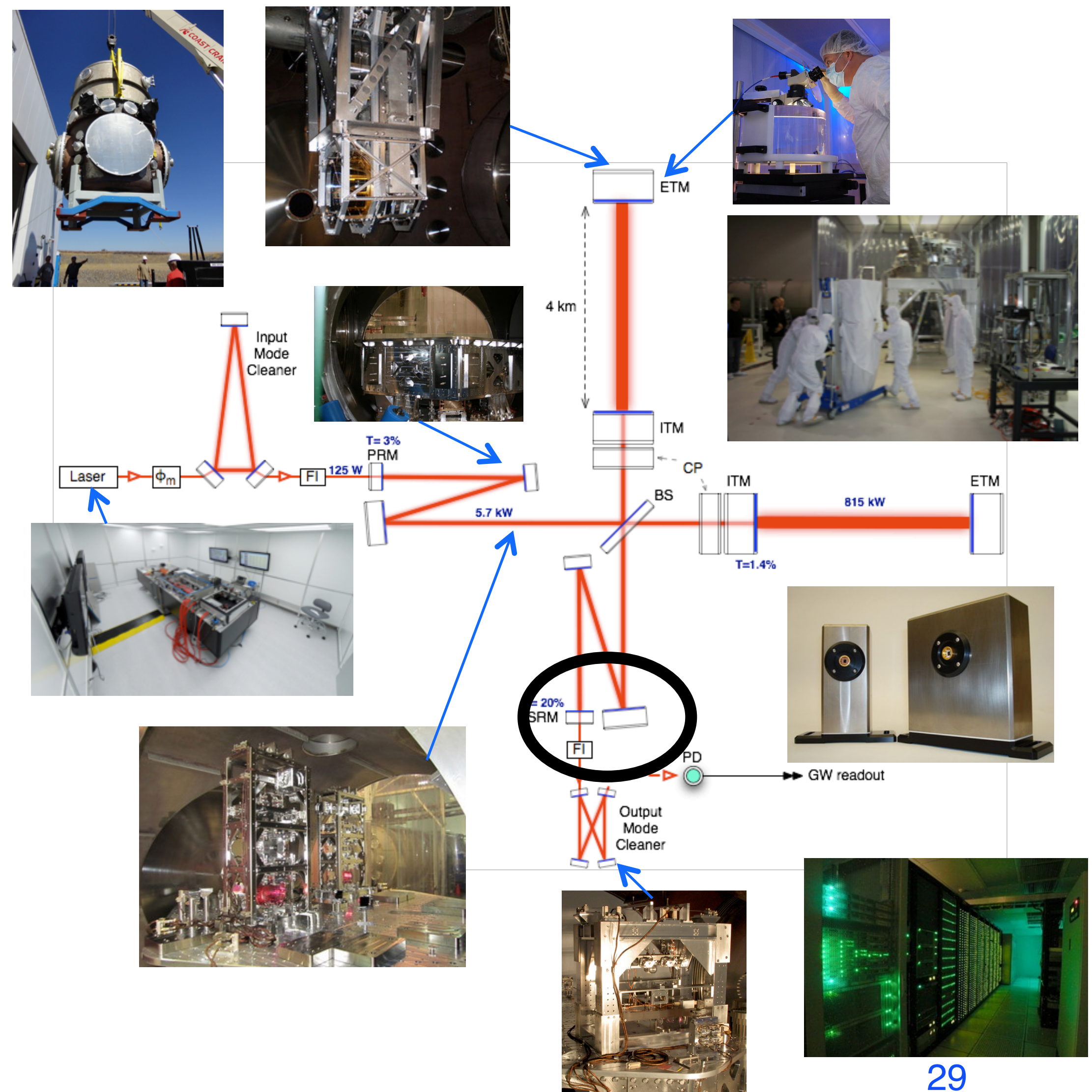
Comparisons among S1 - S5 Runs      LIGO-G060009-03-Z



# Advanced LIGO overview

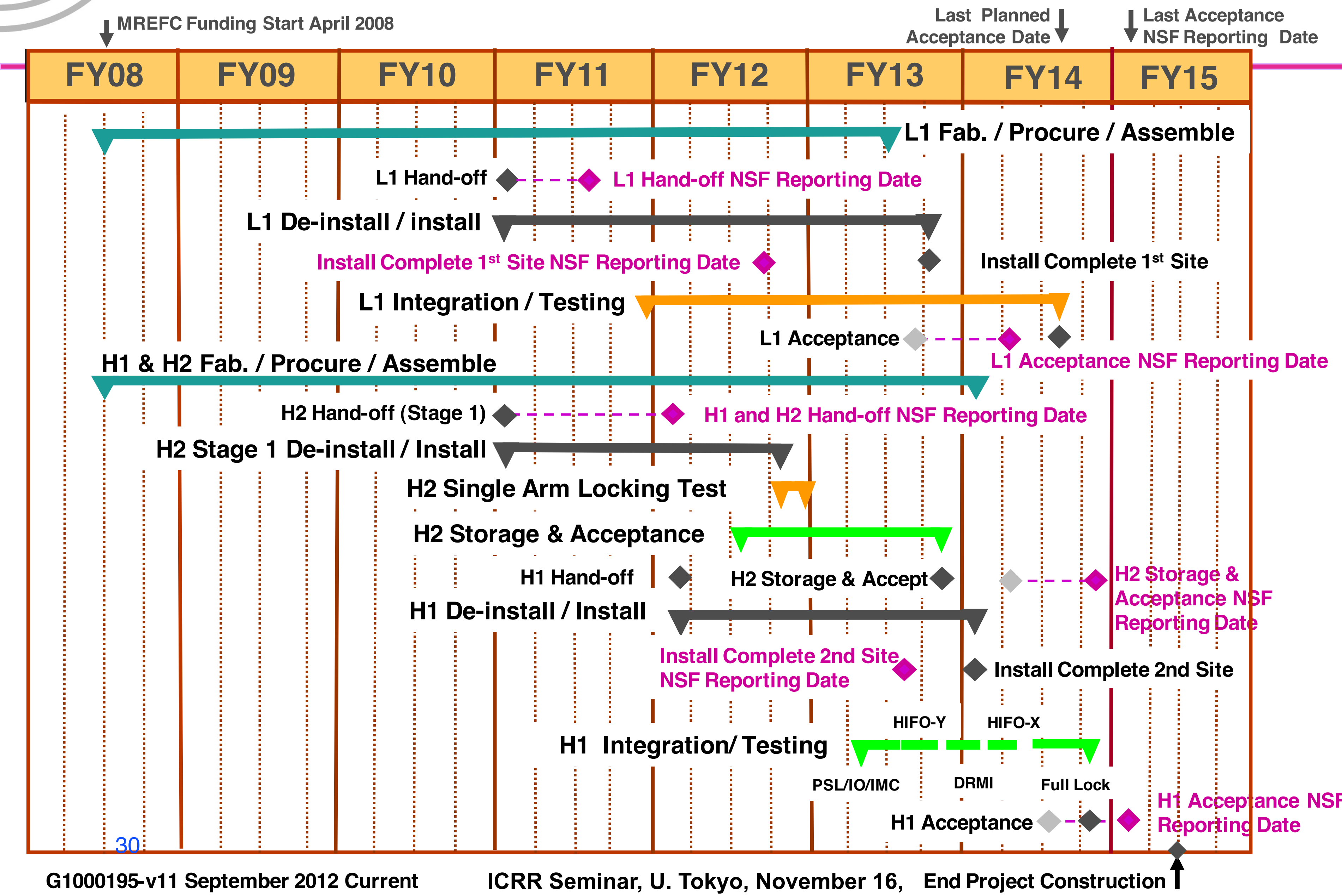
## What is Advanced?

| *Parameter* | *Initial LIGO* | *Advanced LIGO* |
|---|---|---|
| Input Laser Power | 10 W (10 kW arm) | 180 W (>700 kW arm) |
| Mirror Mass | 10 kg | 40 kg |
| Interferometer Topology | Power-recycled Fabry-Perot arm cavity Michelson | Dual-recycled Fabry-Perot arm cavity Michelson (stable recycling cavities) |
| GW Readout Method | RF heterodyne | DC homodyne |
| Optimal Strain Sensitivity | $3 \times 10^{-23}$ / rHz | Tunable, better than $5 \times 10^{-24}$ / rHz in broadband |
| Seismic Isolation Performance | $f_{low} \sim 50$ Hz | $f_{low} \sim 13$ Hz |
| Mirror Suspensions | Single Pendulum | Quadruple pendulum |



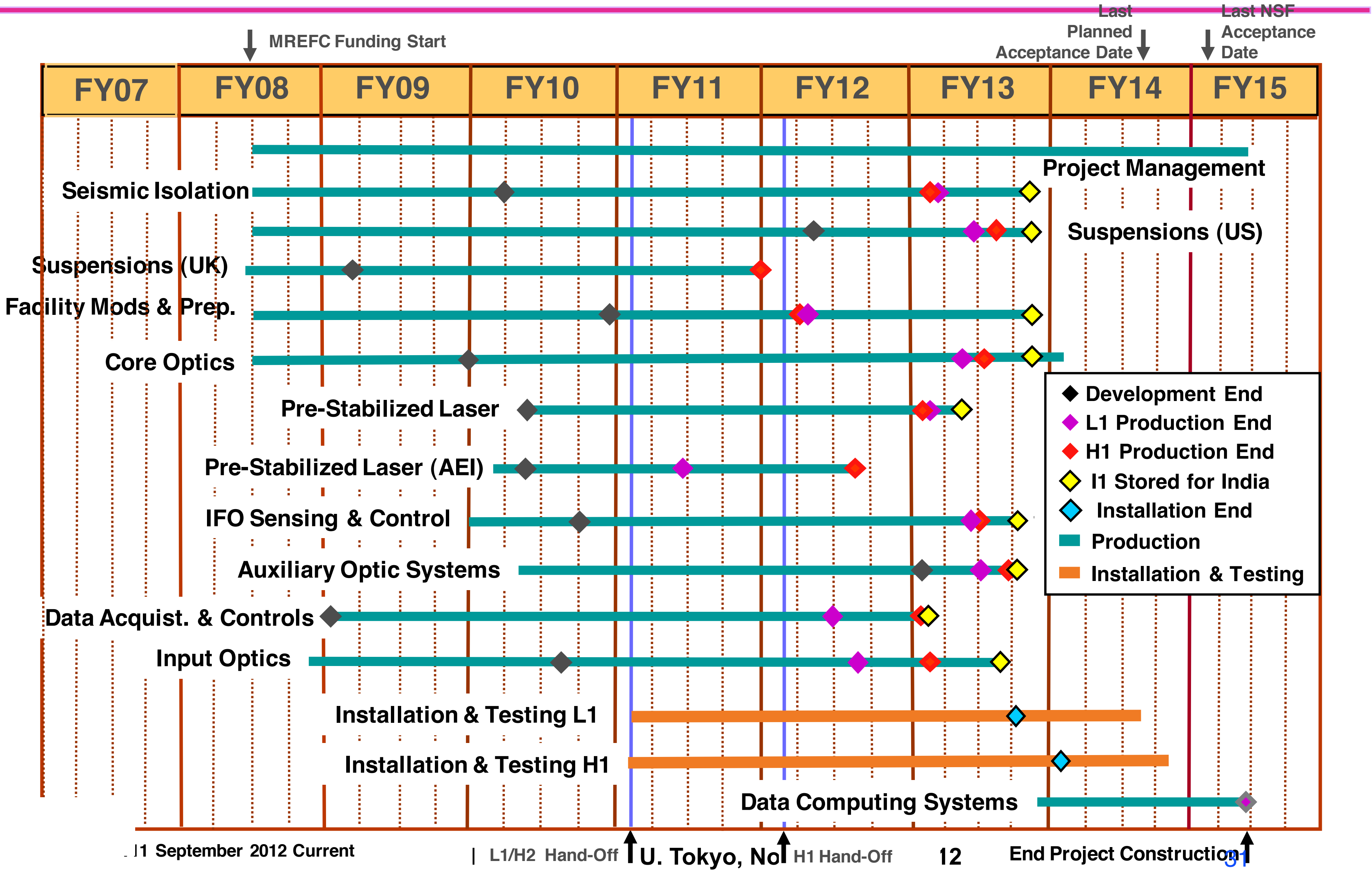
# Advanced LIGO Schedule Summary - Sept. '12

(Including selected control milestones showing project contingency)

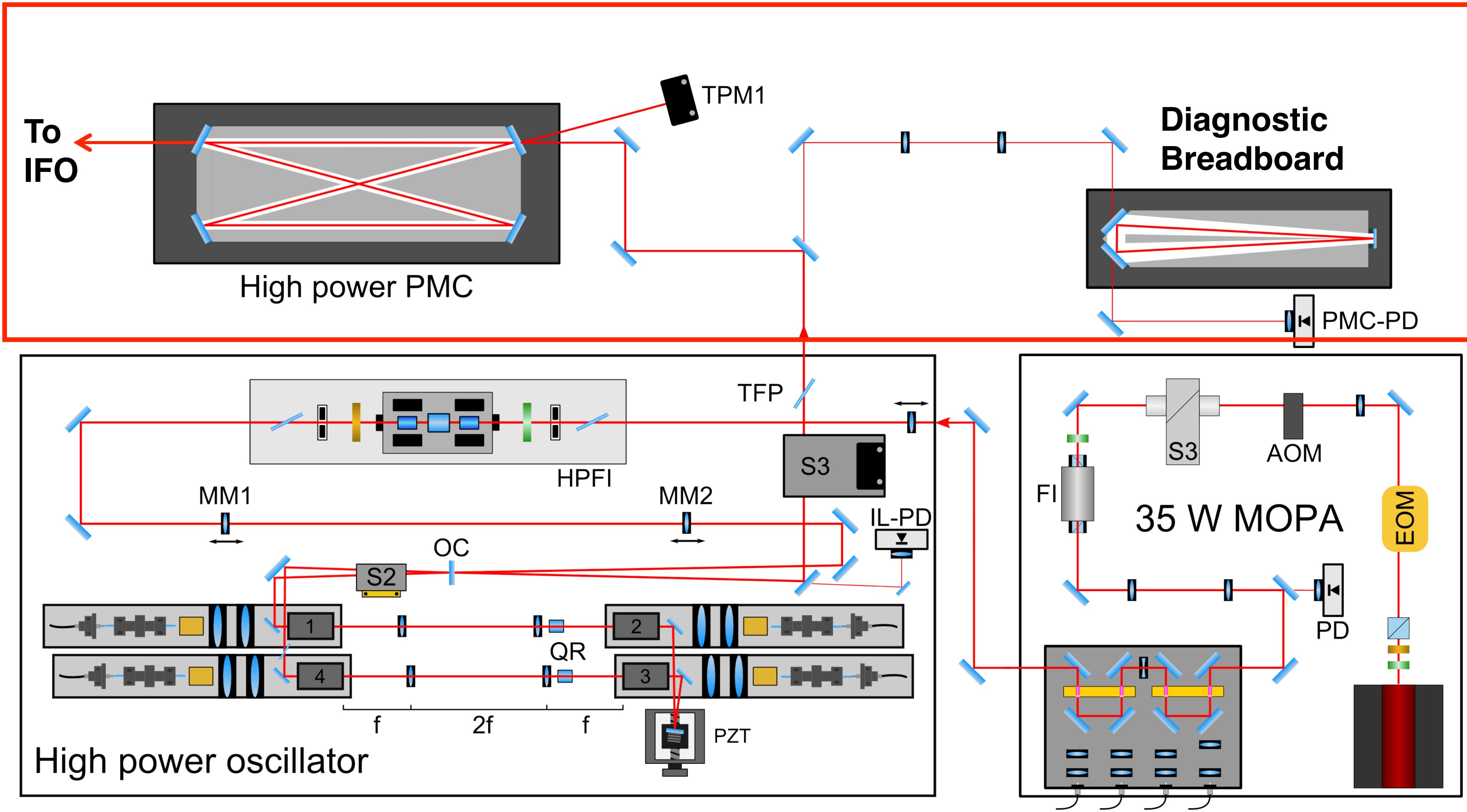


# Advanced LIGO Subsystem Summary – Sept '12

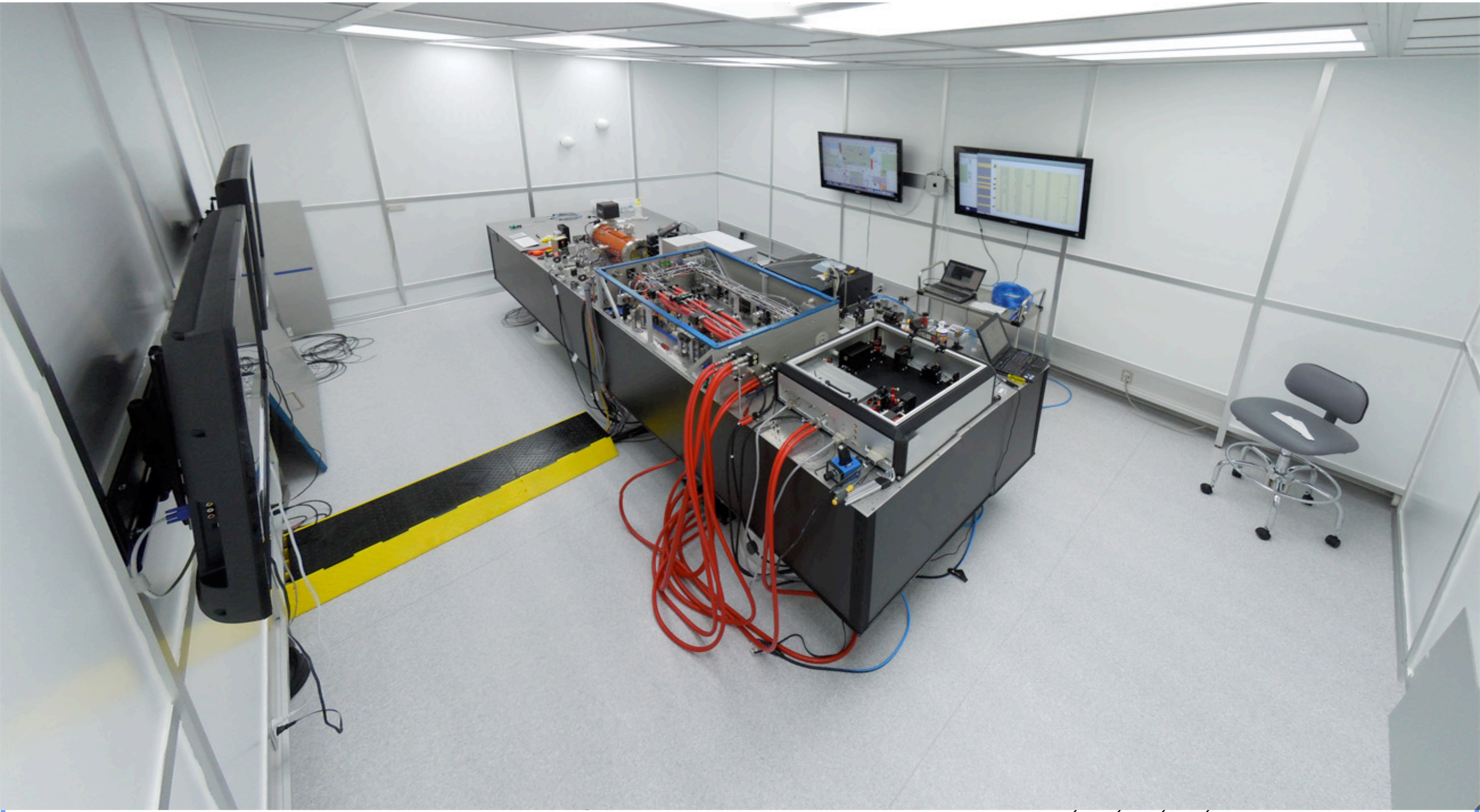
(Showing Development and Project Production Early Milestones)



# Pre-stabilized Laser

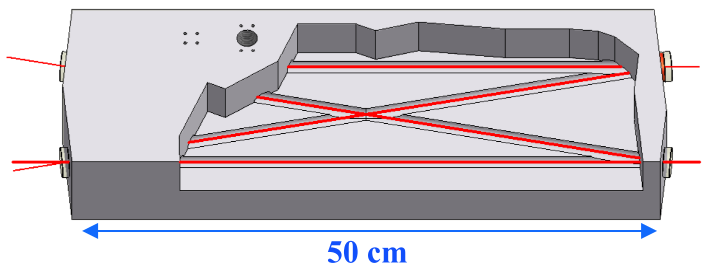


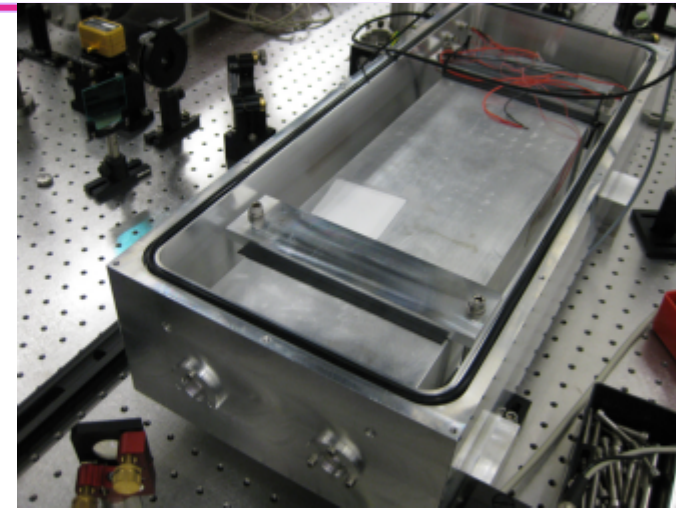
# Advanced LIGO Pre-stabilized Laser

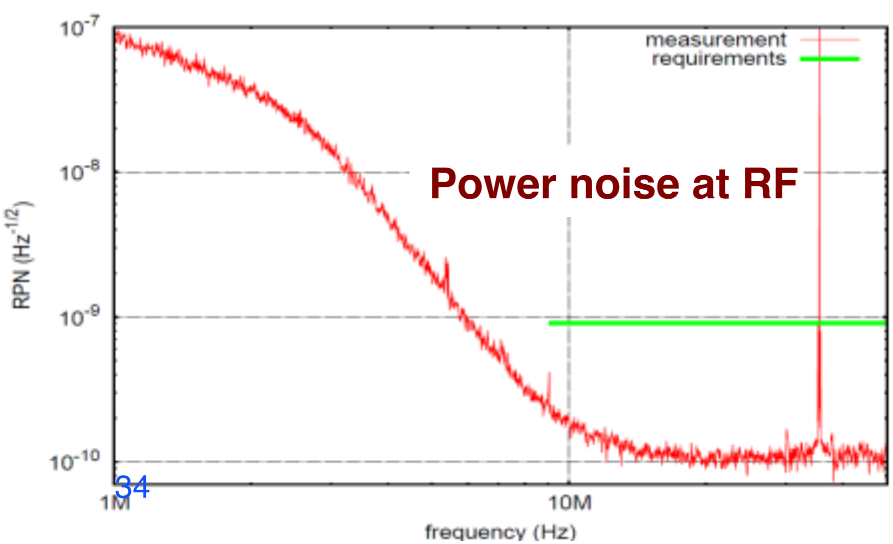


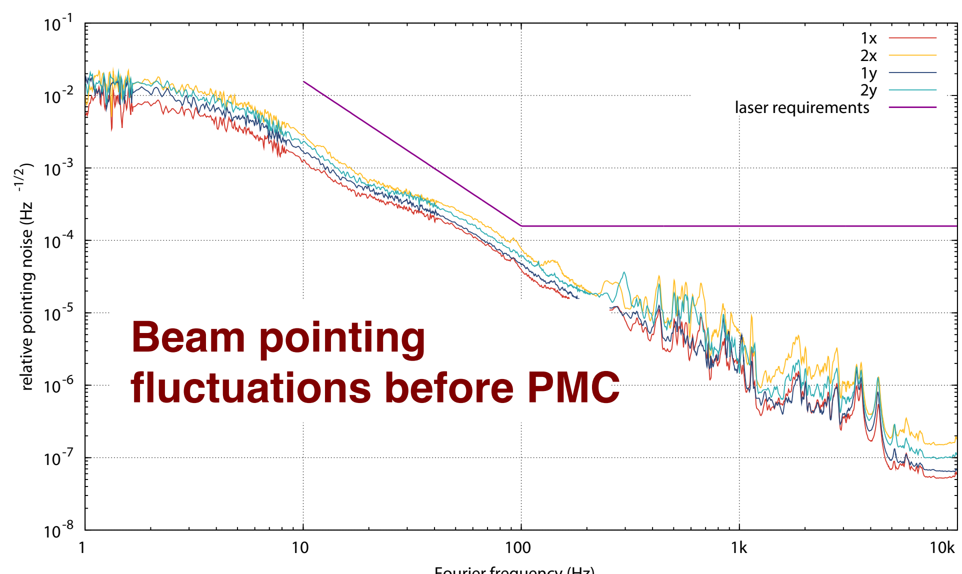
# *Pre-mode cleaner: spatial & temporal filtering*

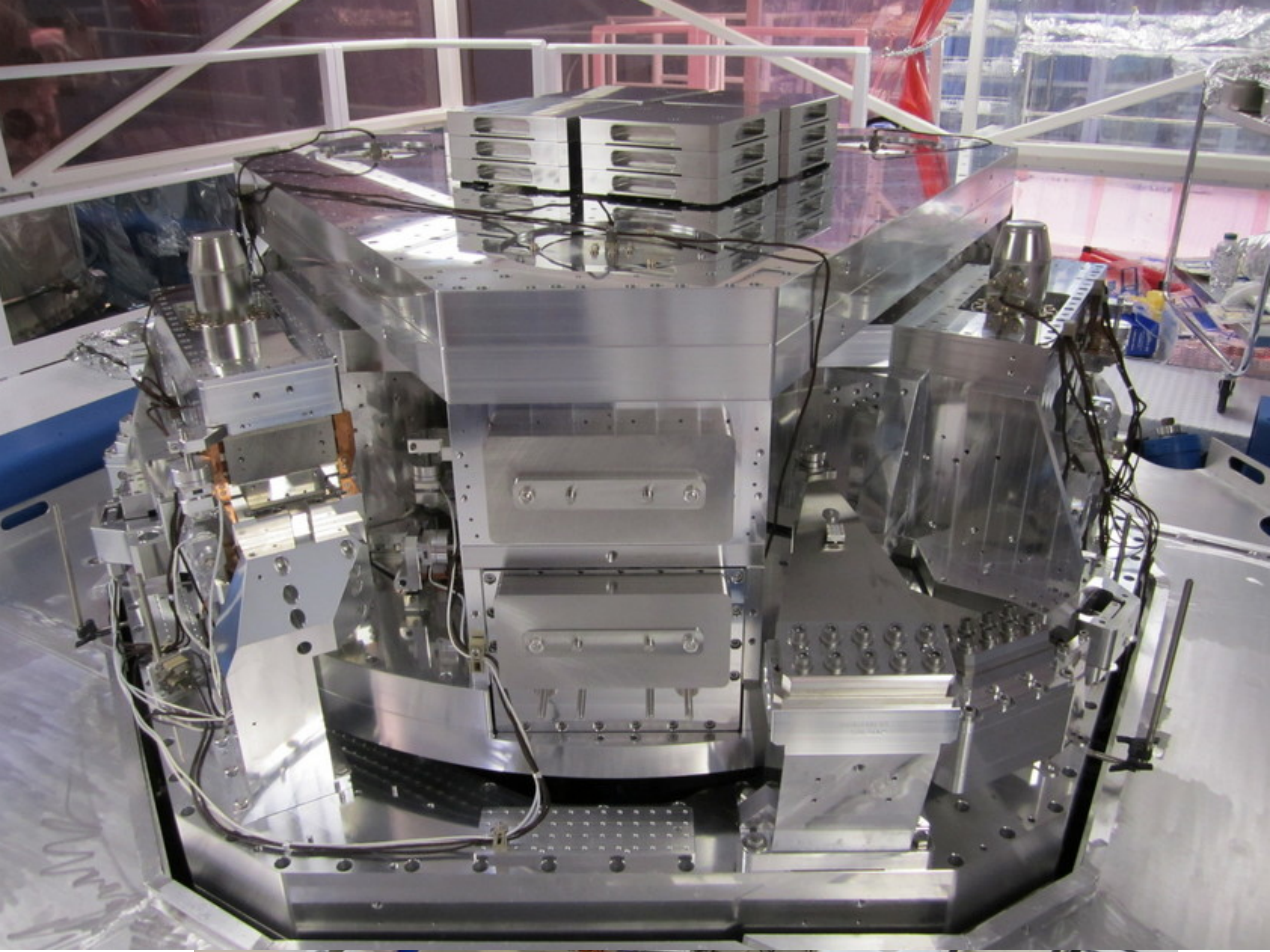
- bow tie configuration, round-trip length of 2m
- Finesse of 124, circulating power 9kW (200W input)
- Linewidth: 575 kHz (HWHM)
- Length control with automatic lock acquisition
- PZT actuator / thermal actuator to off-load PZT



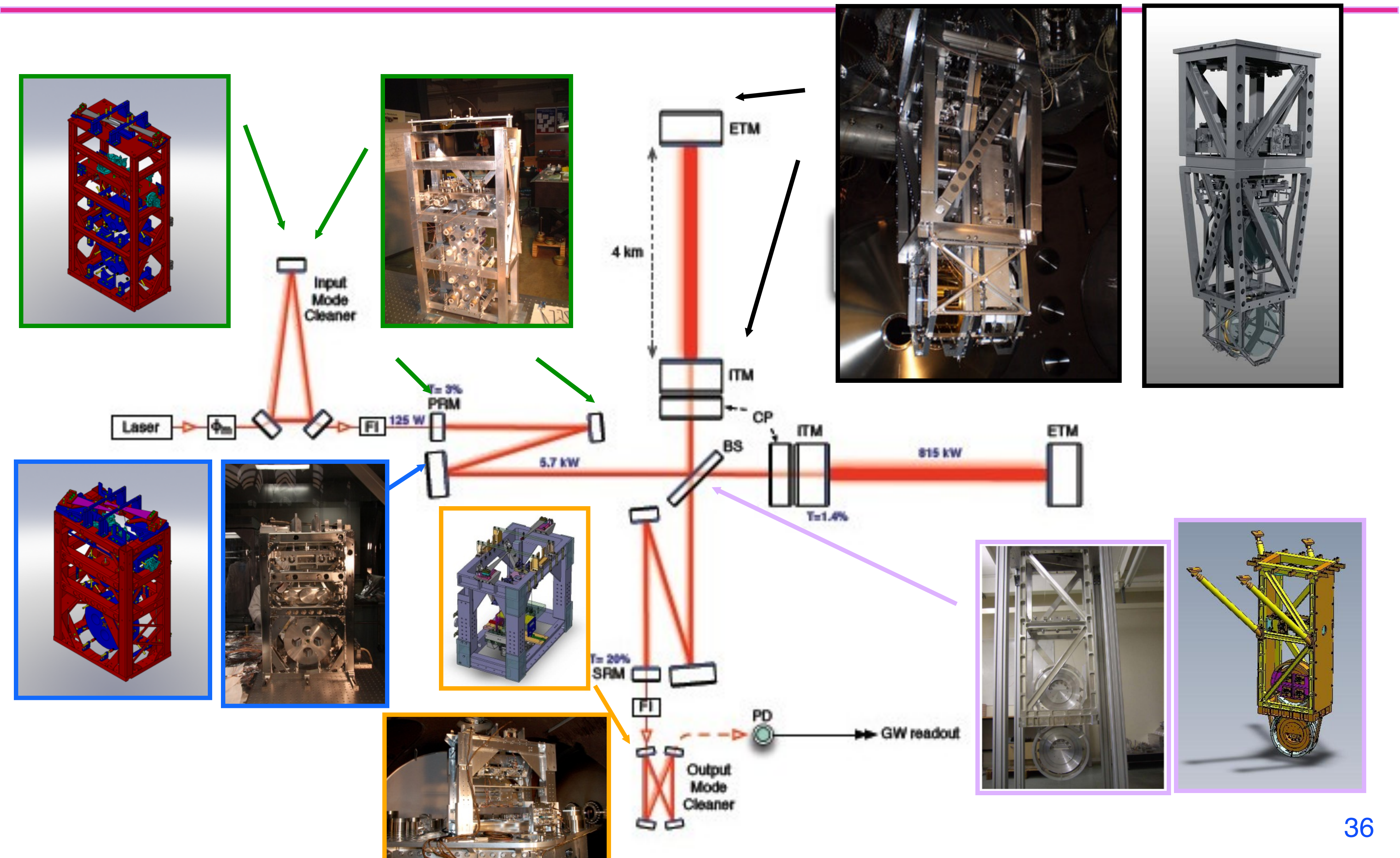


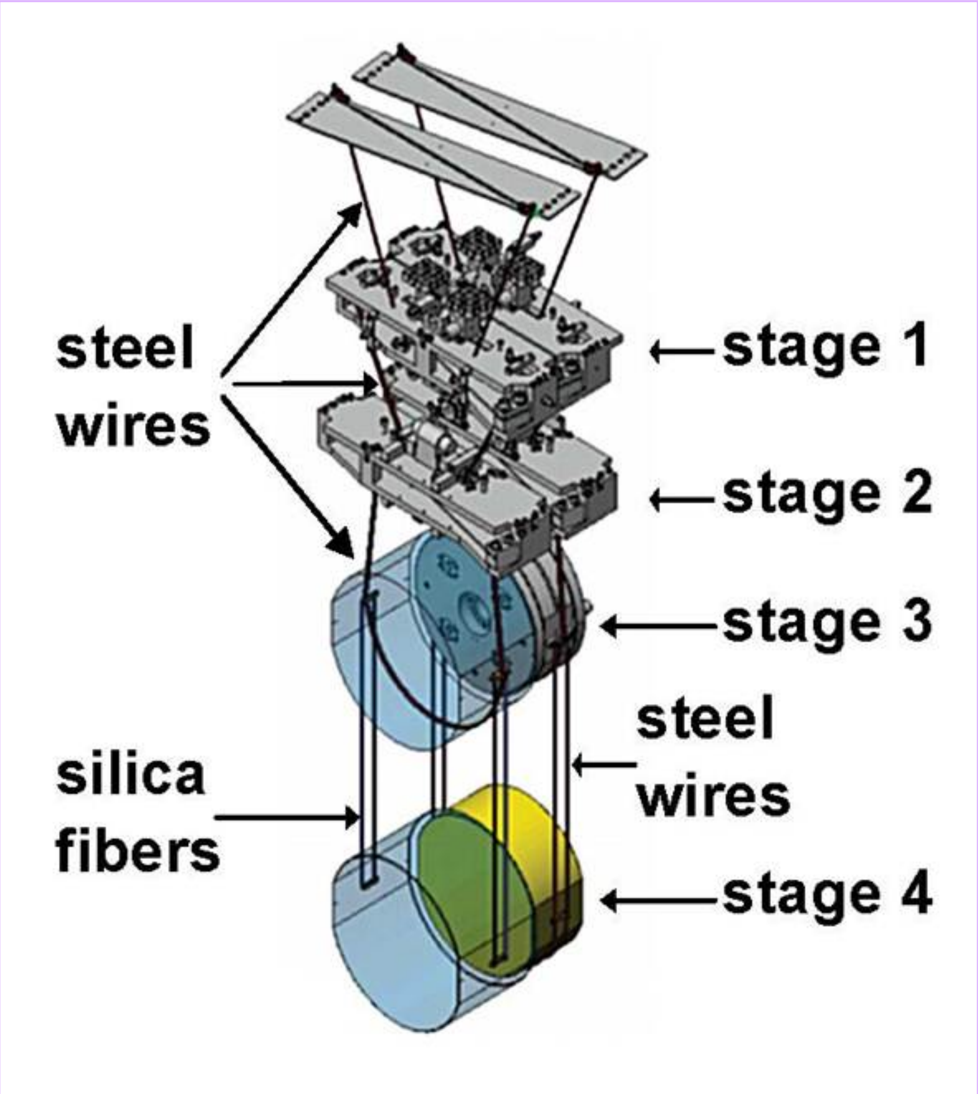


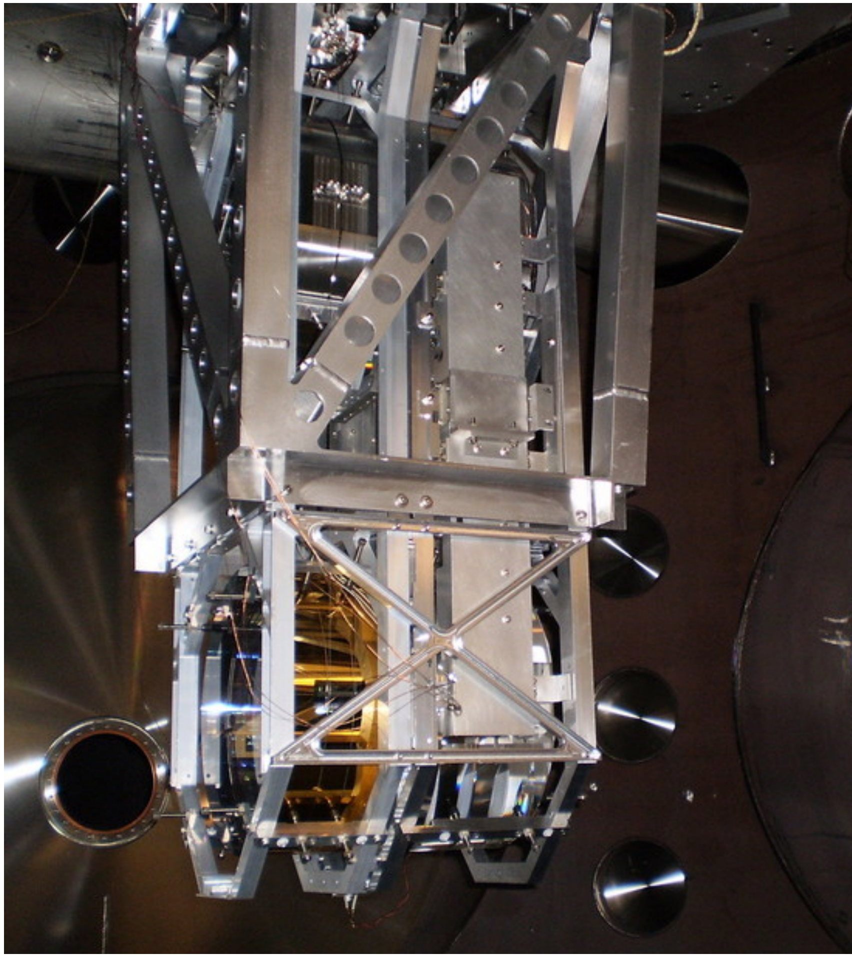
LIGO

# *Suspensions*



# Quadruple Suspensions

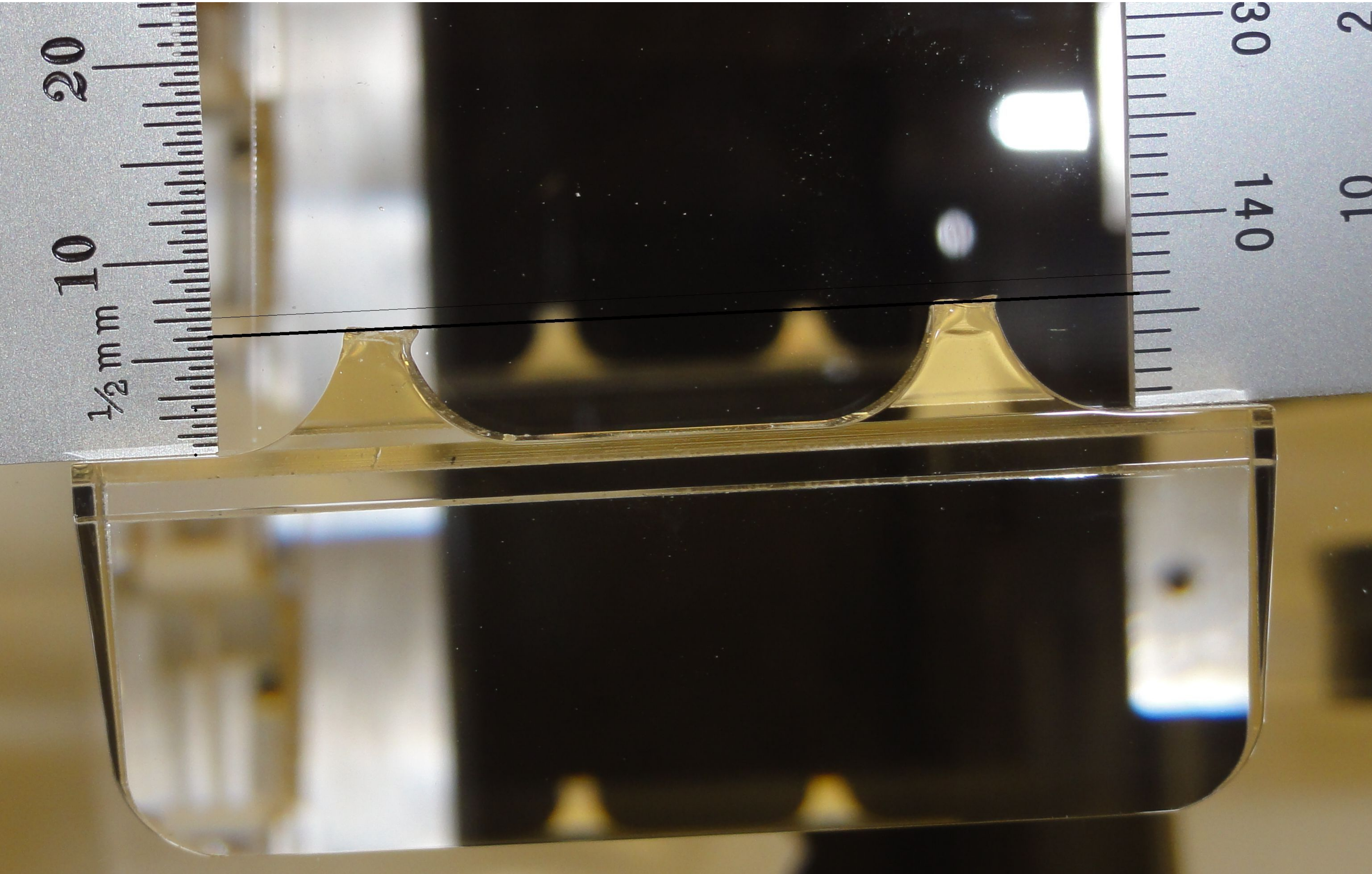


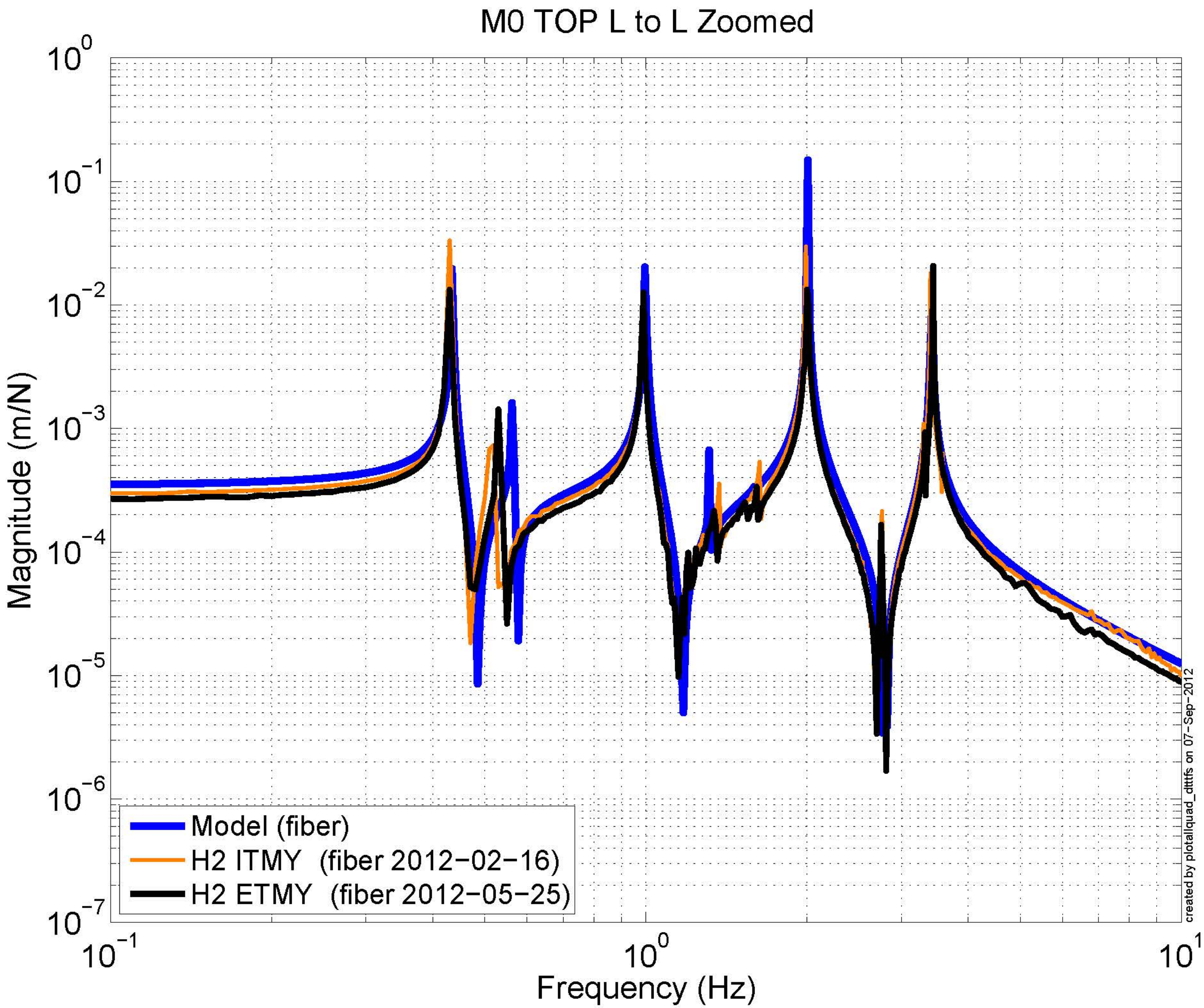
# Welding Suspension Fibers to a Test Mass

LIGO

# *Fibers Are Fragile….*

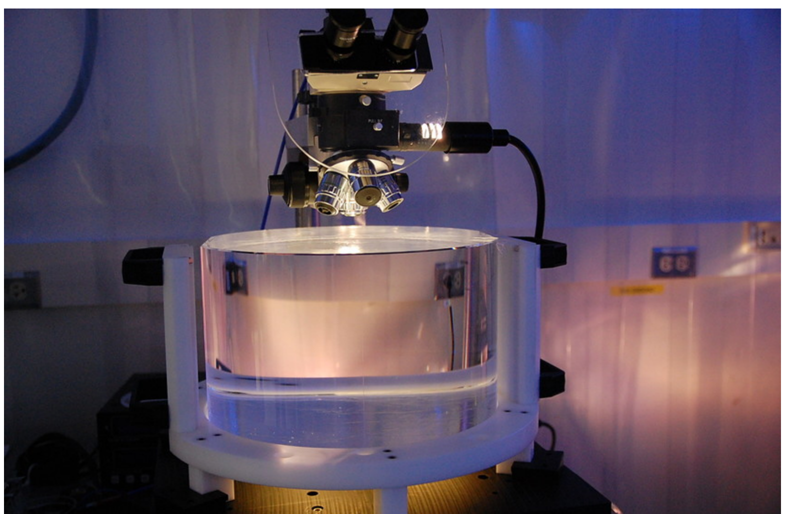


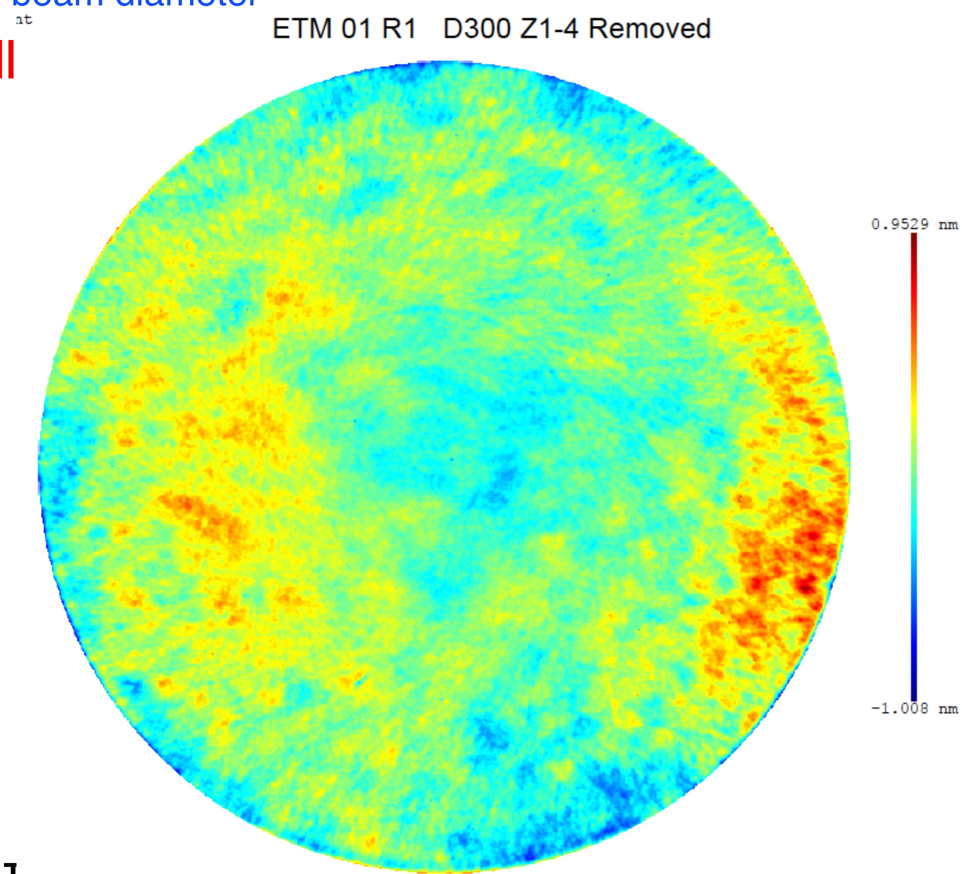
# *1 DOF of Top2Top TFs for All 2 Fiber/ Glass QUADs*



# *Advanced LIGO Core Optics*

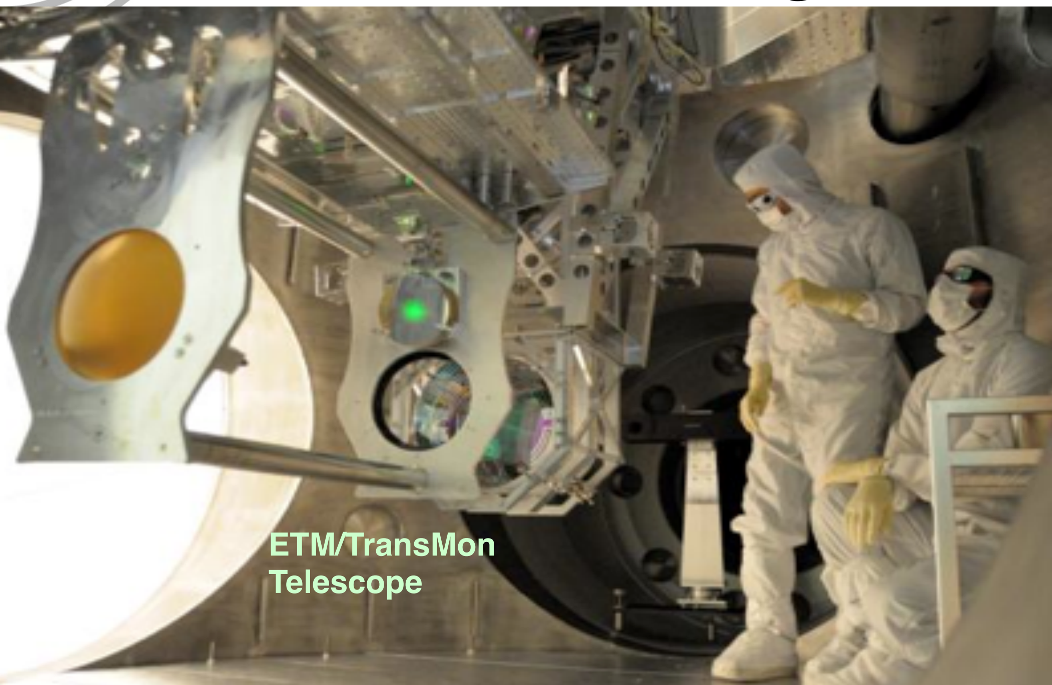
- 40 kg masses, 38 cm in diameter, and figured to 0.15 nm rms
- All substrates and polishing successfully executed
- Successful coatings demonstrated for all kinds of optics except for ETMs
  - challenge is $10^{-3}$ uniformity over the larger beam diameter
- The greatest single technical risk, still





LIGO

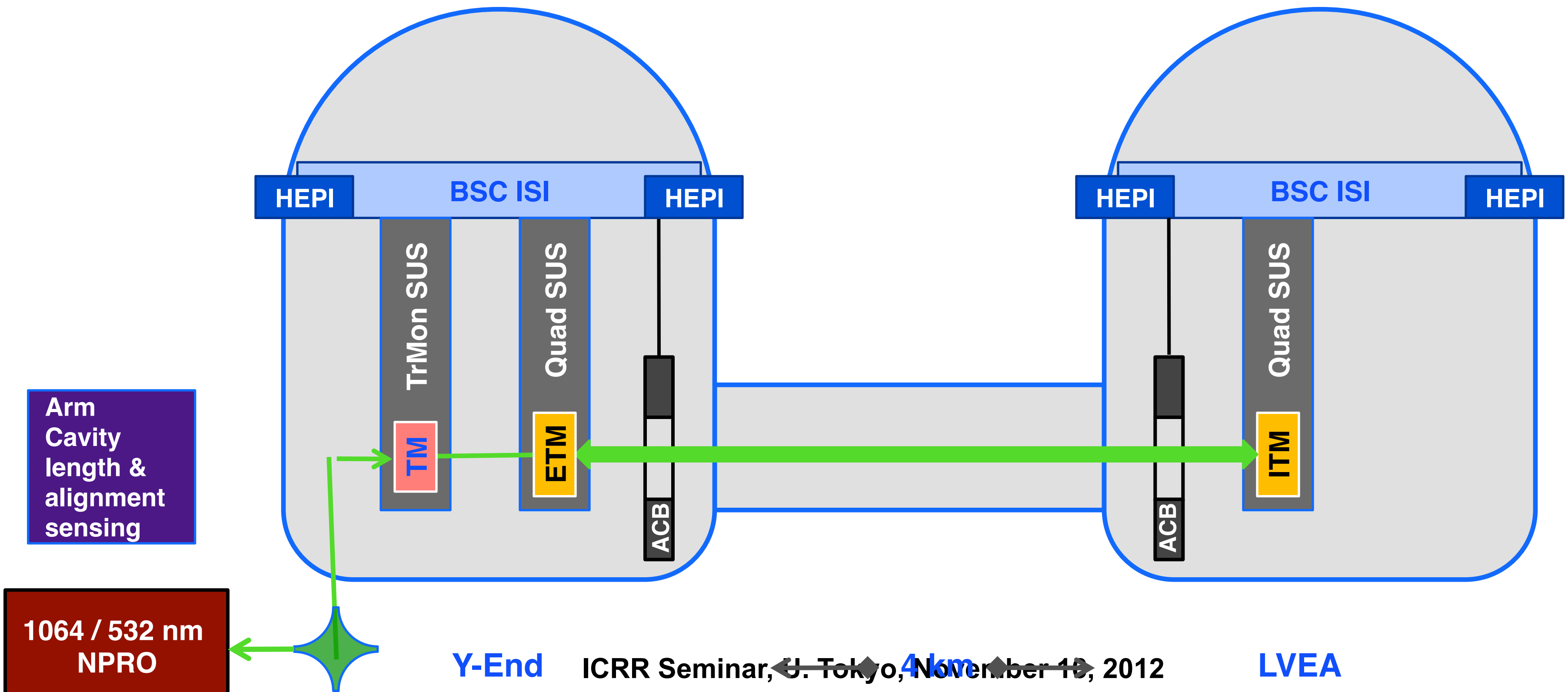
# *Putting it all together…*





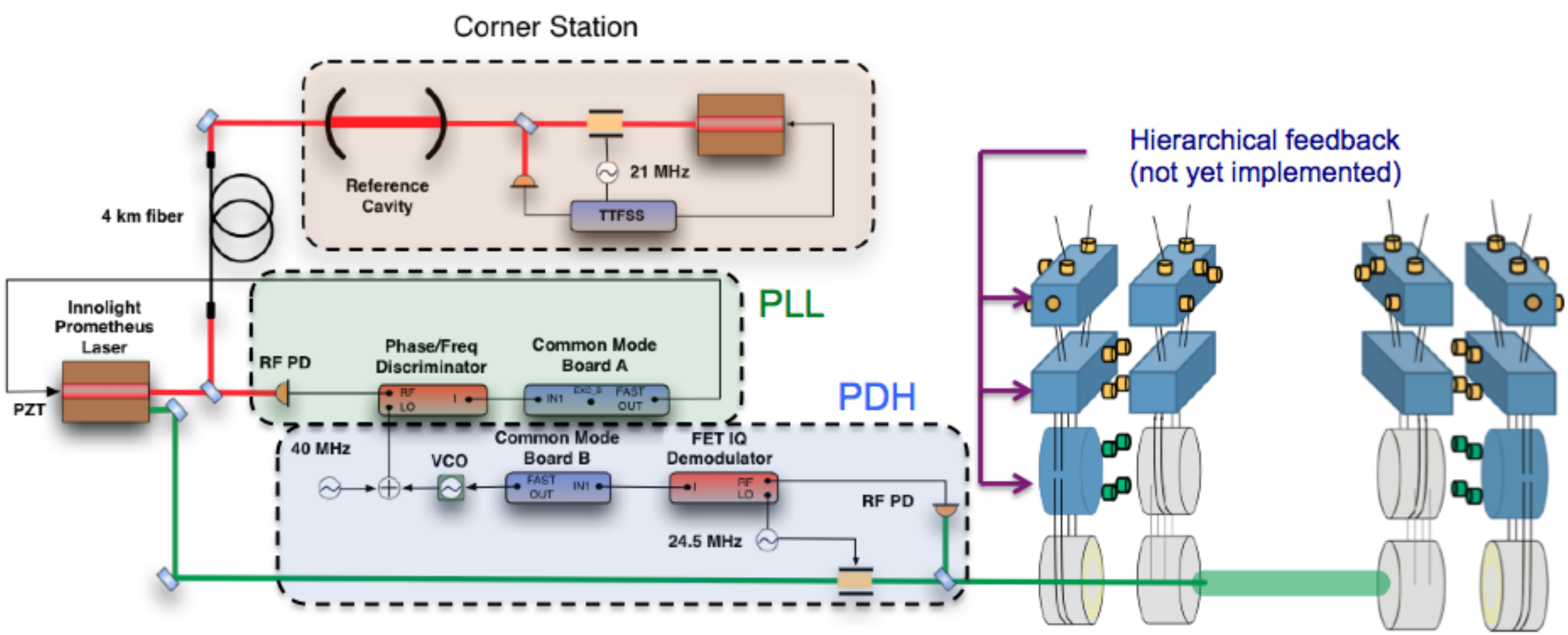
# One-Arm Test (OAT)

- A single, complete 4km arm at LHO, to perform integrated testing
- Arm-length stabilization system using phase-locked 532 nm light
  - Addresses biggest initial challenge – locking – seen in iLIGO
- Two complete chambers: Optics, suspensions, seismic isolation
  - One optics suspended with fused-silica fibers, one with wire suspension



LIGO

# OAT Set-up

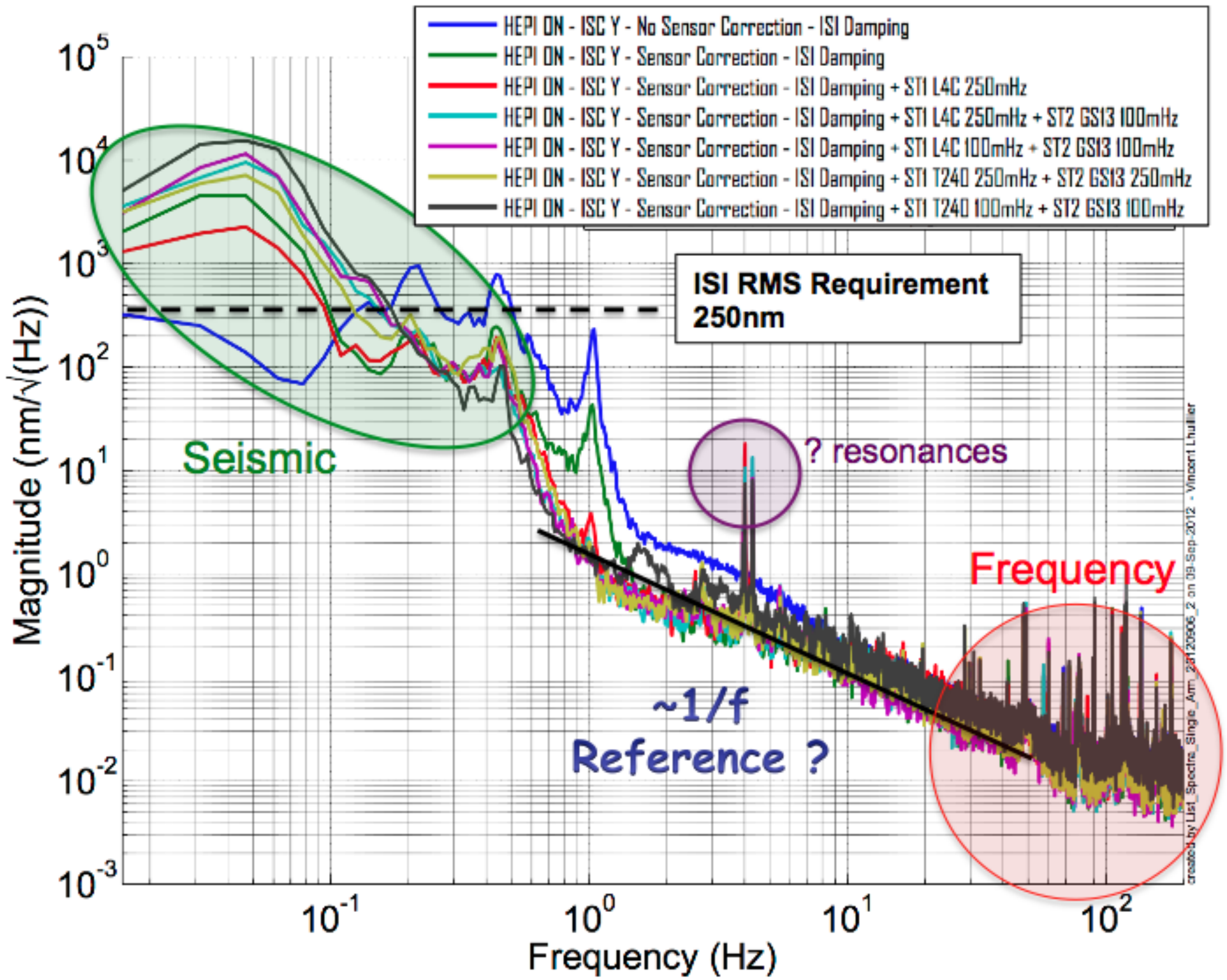



- PDH UGF = 8 kHz
- PLL UGF = 30 kHz
- FSS UGF = 250 kHz
- No Electrostatic Drive (ESD) in OAT
- No feedback to test masses
  - only damping of suspensions
- Length offload to HEPI at END-Y

(Quad illustration courtesy of *Brett Shapiro*)

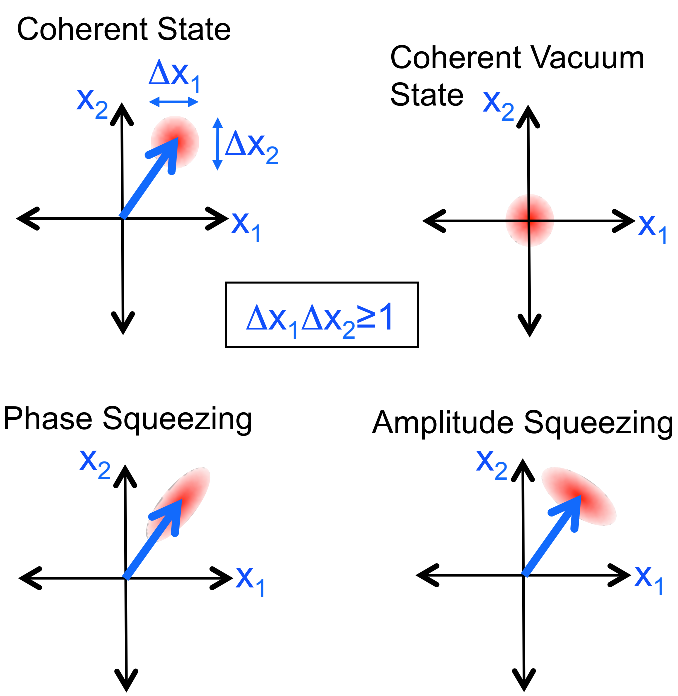
# One-Arm Test

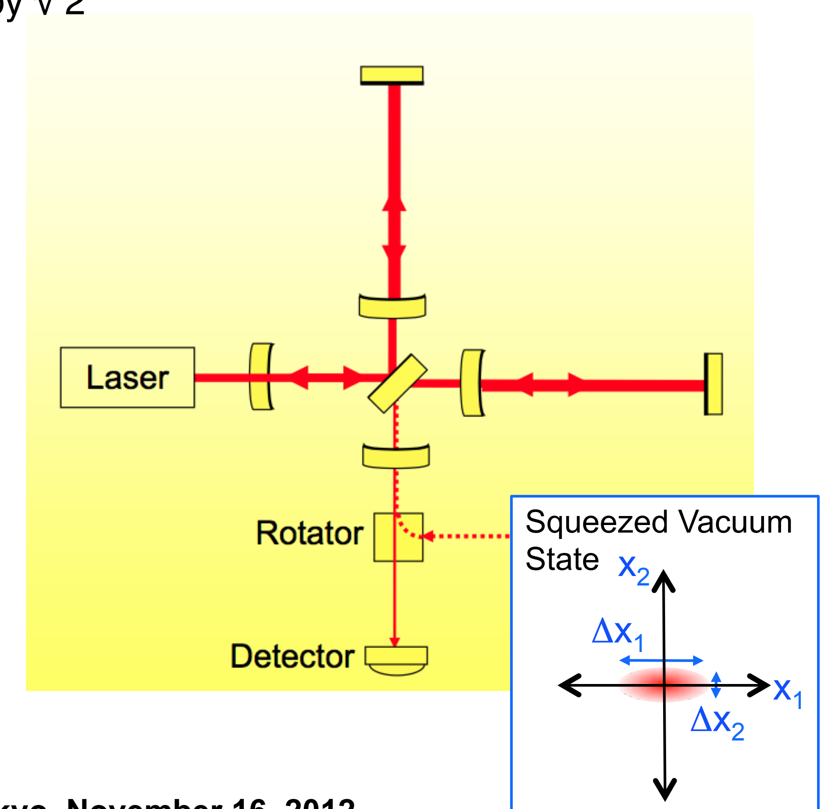
- Locking came very quickly (subsystem test paying off!), enabling real characterization of system
- Extremely useful for tuning seismic isolation system before full interferometer configuration realized



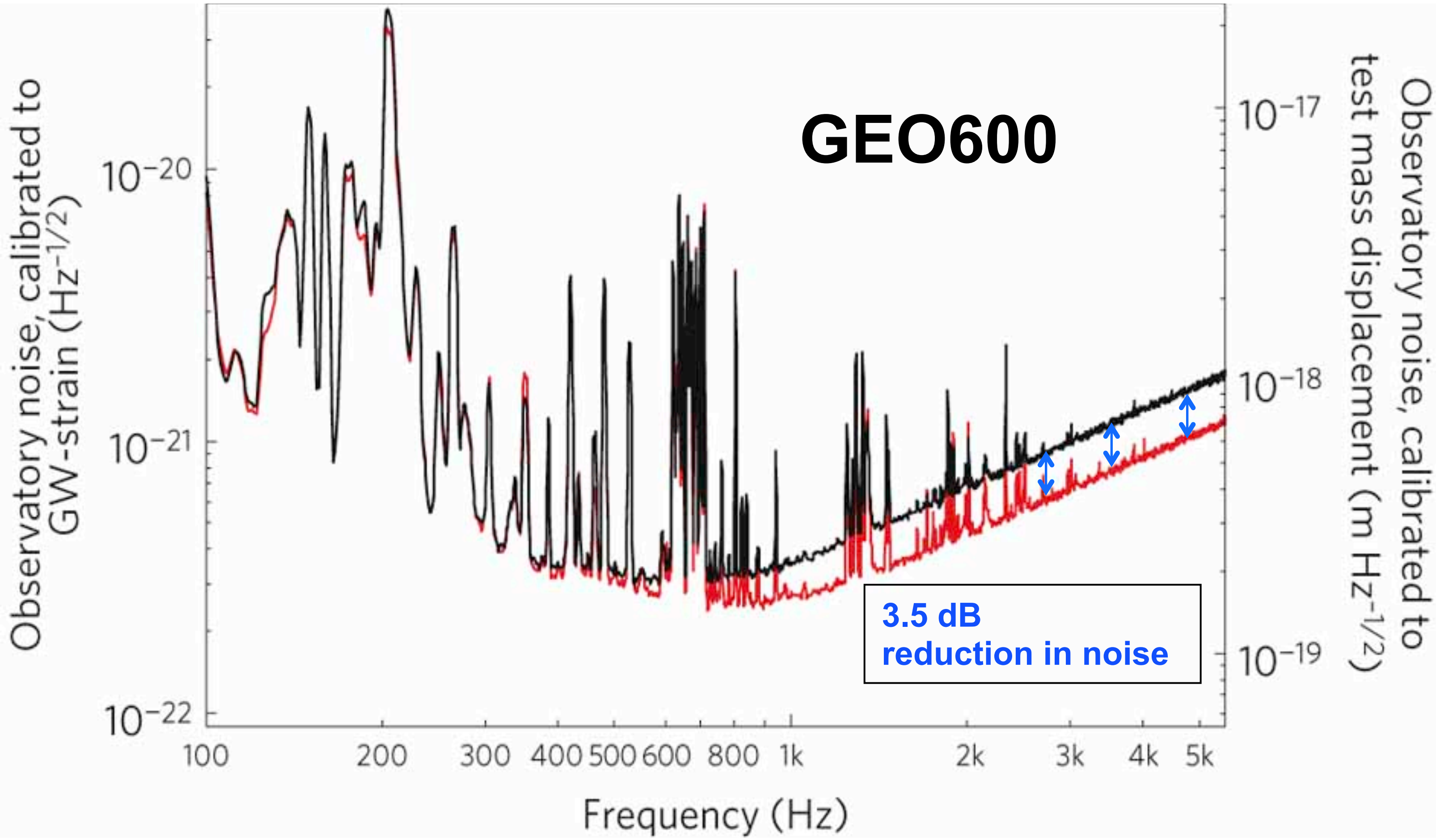
# *Squeezed Interferometry: A Possible Upgrade to Advanced LIGO*

- Shot noise and radiation pressure come from statistical fluctuations ultimately arising from the Heisenberg uncertainty principle
  - These fluctuations exist in the vacuum state. They enter the interferometer at the output port.
- A noise reduction in one quadrature can be achieved at the expense of the other quadrature → 'squeezed light'
  - 3 dB injected squeezed vacuum reduces noise by √ 2
  - Possible to achieve 10 dB



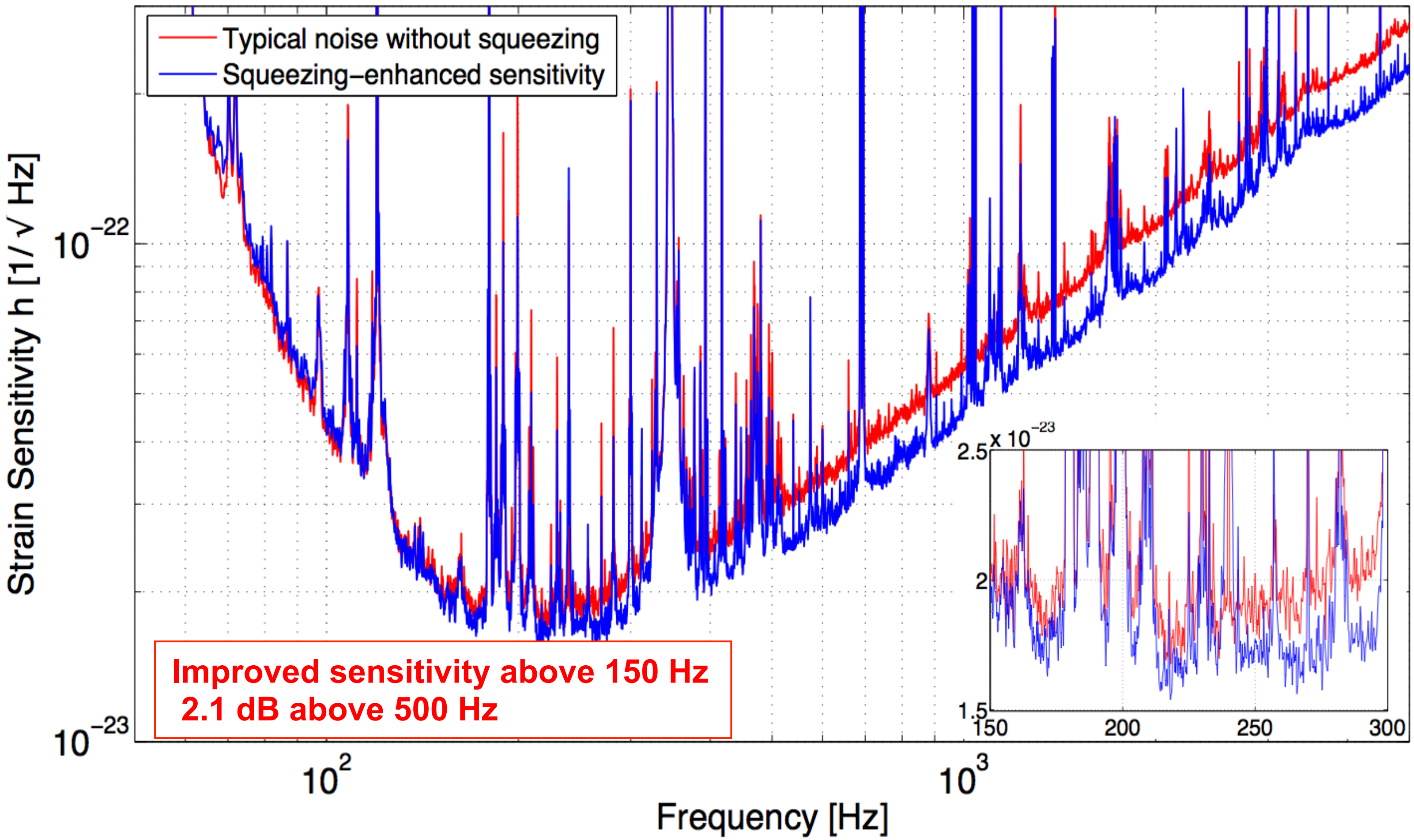
# *First Demonstration of Squeezed Interferometry in a Gravitational-wave Detector*




LIGO Scientific Collaboration, "*A gravitational wave observatory operating beyond the quantum shot-noise limit*", Nature Physics **7**, 962–965 (2011)

# *Using Squeezed Light to Improve LIGO Sensitivity*

LSC, "Enhancing the astrophysical reach of the LIGO gravitational wave detector by using squeezed states of light”, in preparation



# *LIGO-India*

# LIGO-India

- The idea in a nutshell–
- A direct partnership between LIGO Laboratory and India to build a LIGO interferometer on Indian soil

- Follows from earlier attempt to locate a LIGO detector in Australia

# *Enabling multi-messenger astronomy with gravitational waves*

- Many GWs sources are likely to radiate in the electromagnetic spectrum
- We want to see them via different observational methods simultaneously
- GW 'Aperture synthesis'
  - » Crude estimate of angular resolution

$$\theta_{GW} \sim \lambda_{GW} / d \sim \text{few degrees}$$

→ wide field telescopes
  + Image tiling
  + Galaxy weighting

→ Neutrino observatories

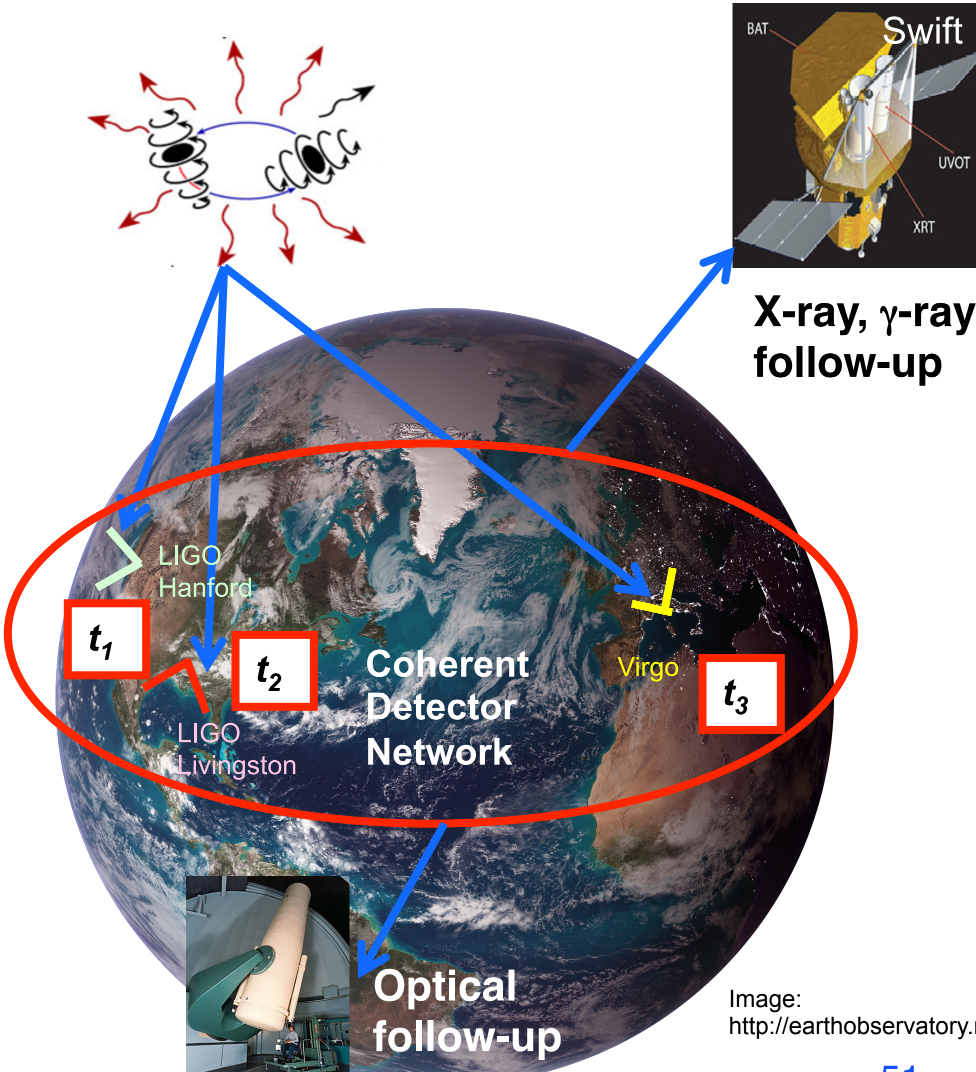
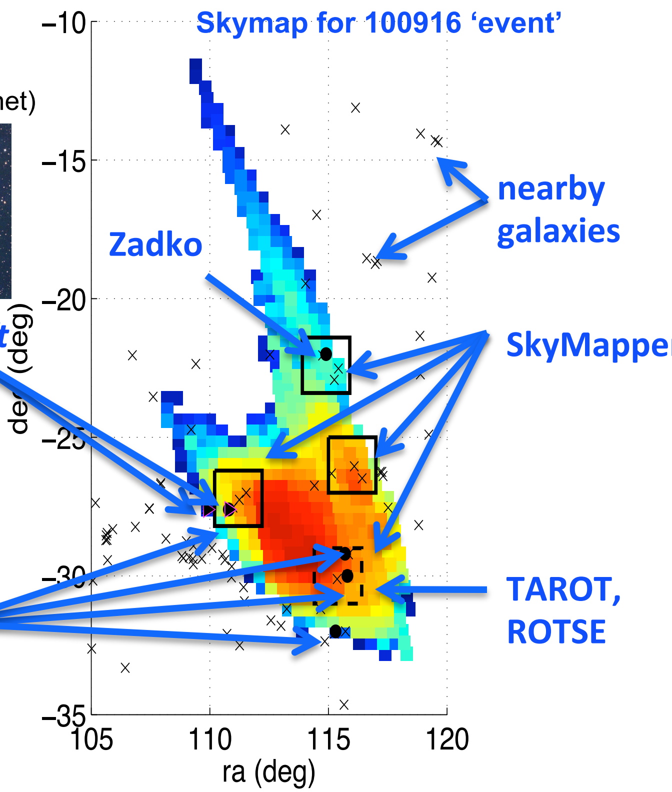


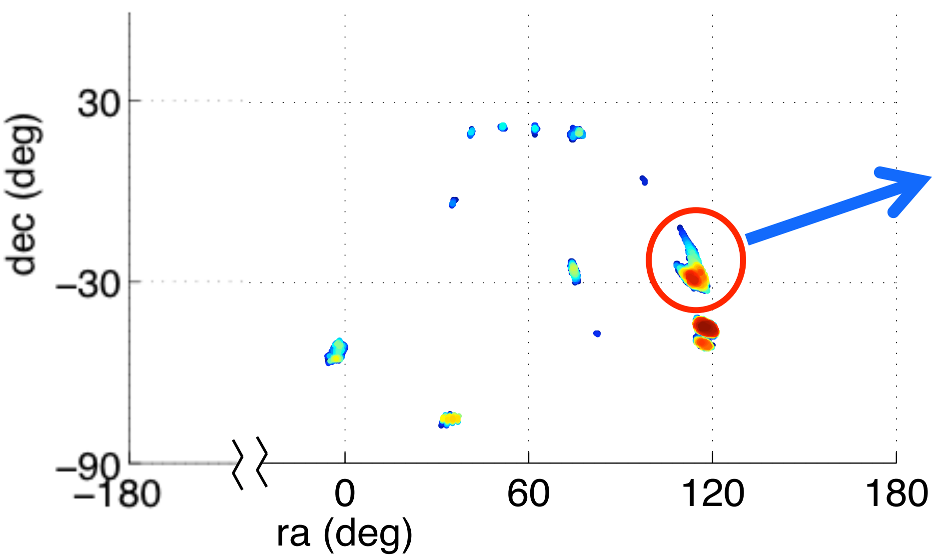

Image: http://earthobservatory.nasa.gov/

# Example: GW100916 Skymap

- LIGO-Virgo source localization ~ O(100 deg$^2$)
  - Disconnected regions
- Top probability pixels imaged by Swift and other ground-based optical telescopes
- Swift pixels maximized probability on NGC2380 and ESO492-010

NGC2380
(Credit: Las Cumbras Observatory www.lcogt.net)




LIGO Scientific and Virgo Collaborations, "*Swift Follow-Up Observations Of Candidate Gravitational-Wave Transient Events*" arXiv:1205.1124

# *LIGO-India*

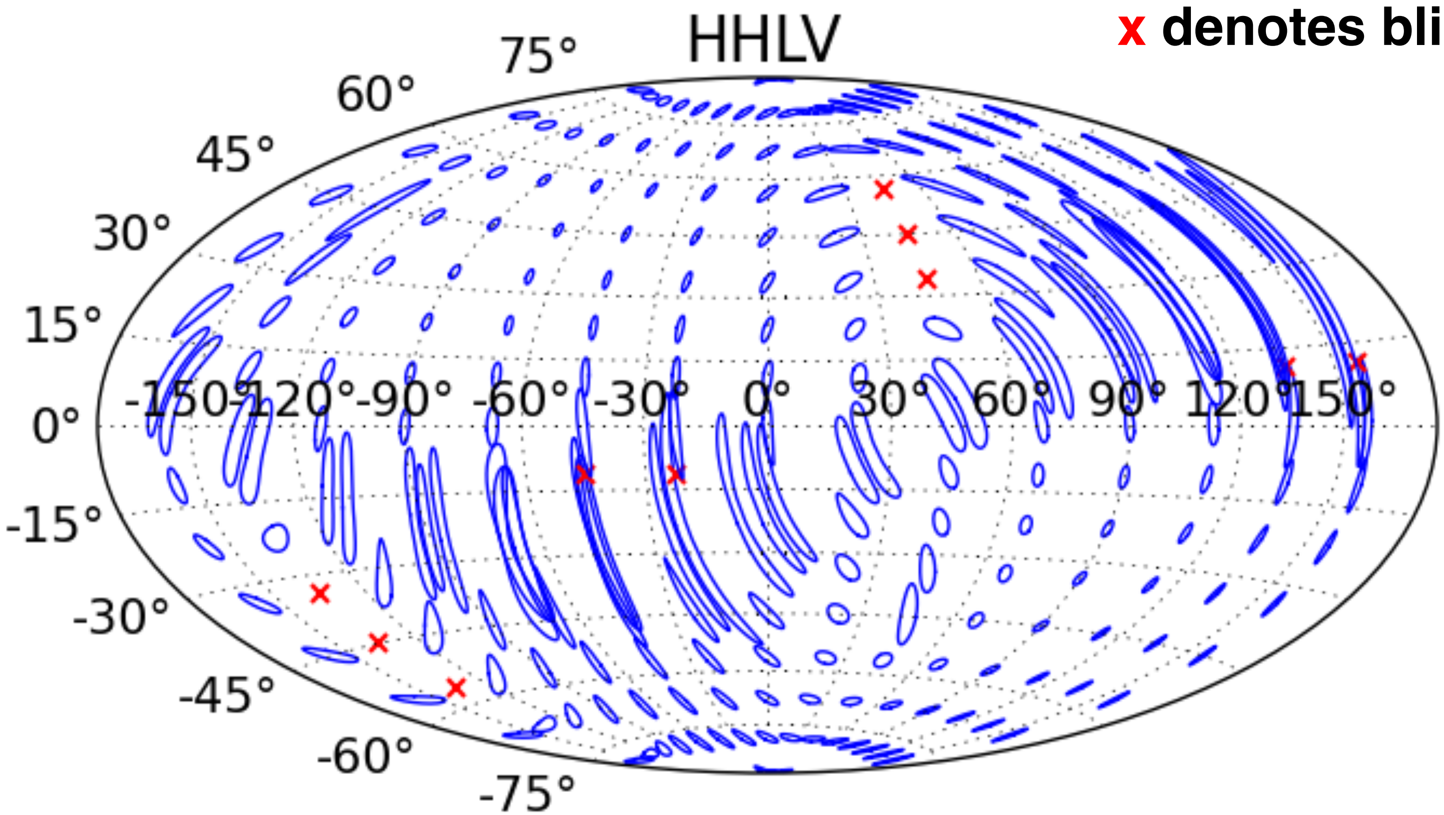
- LIGO Lab (with its UK, German and Australian partners) provides components for one Advanced LIGO interferometer (H2) from the Advanced LIGO project
- India provides the infrastructure (site, roads, building, vacuum system), "shipping & handling," staff for installation & commissioning, operating costs

- Indian Institutional Participants:
  - Inter-University Centre for Astronomy and Astrophysics (Astrophysics, Site Selection, Computing)
  - Raja Ramanna Centre for Advanced Technology (Detector Development)
  - Institute for Plasma Research (Facility and Vacuum construction, control systems)
  - + IndIGO Consortium (broader scientific community in India)

- Indian funding – LIGO-India is a Mega-science Project
  - Total request of ~ $230M to fund construction and operations
  - Funding status: approved by DAE/DST, referred to Cabinet of the Prime Minister of India for approval
- US funding – funding for aLIGO components through MREFC (no new costs)
  - Total contribution $140M (includes aLIGO components, designs, documentation)

# Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo

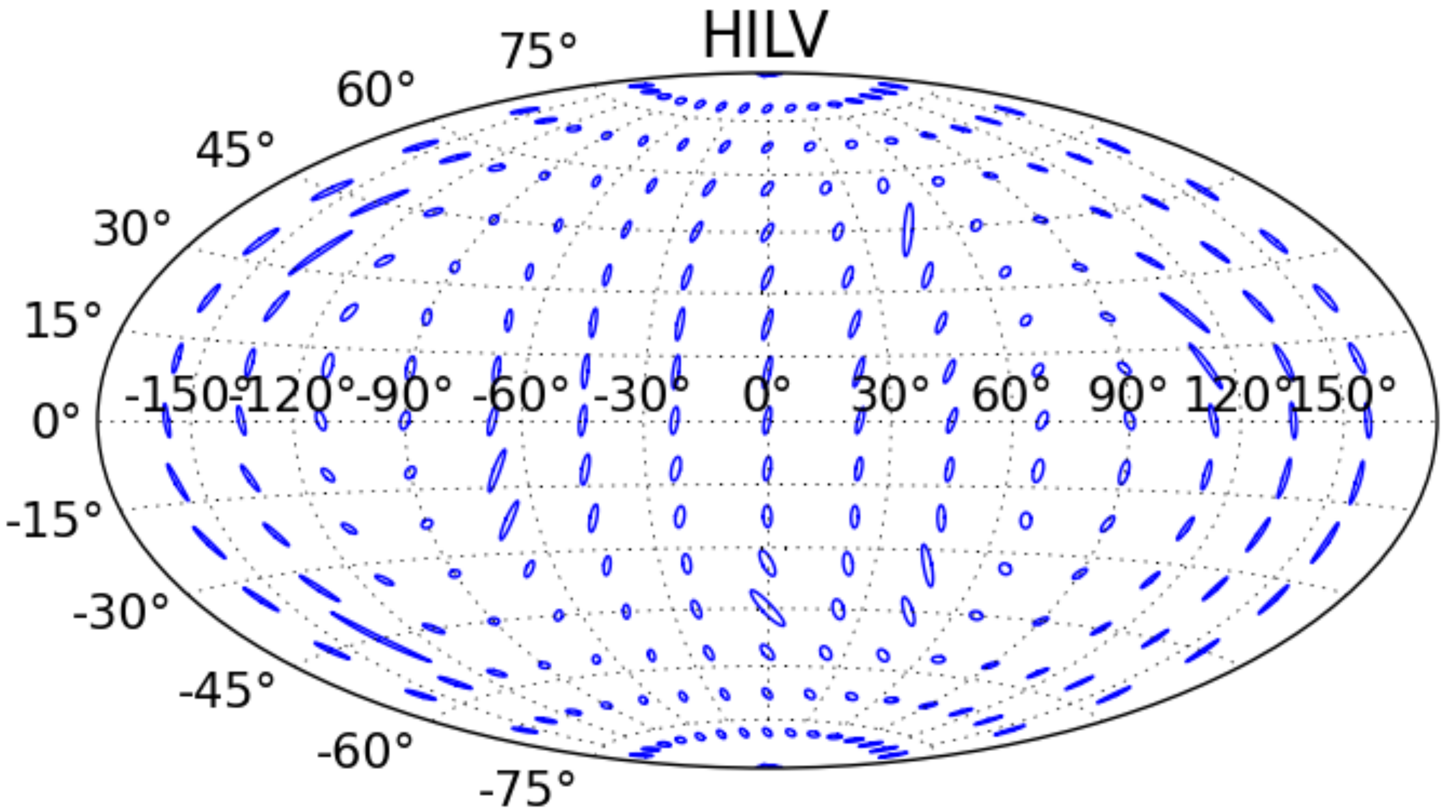
**3 site network**
**x denotes blind spots**




S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

# *Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo-India*

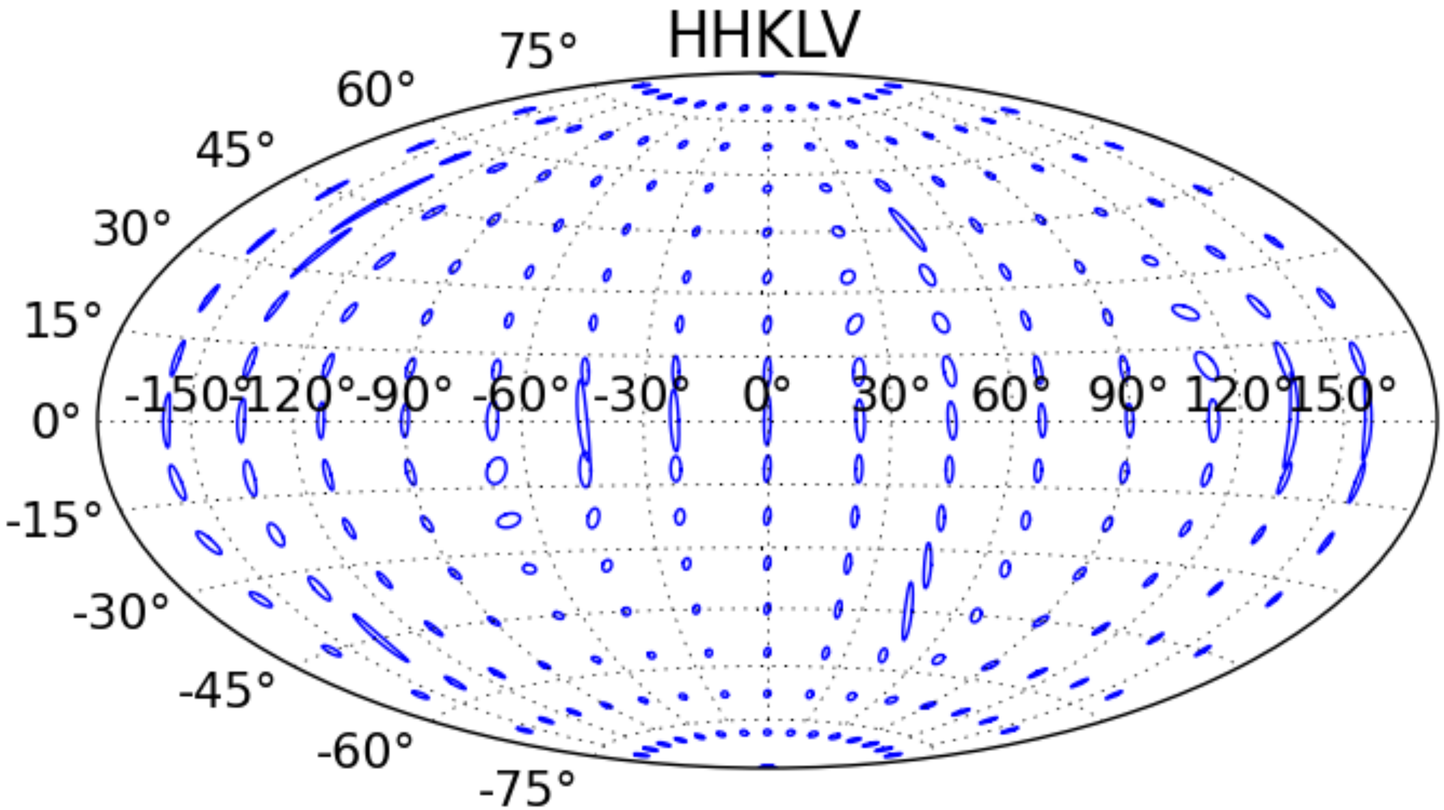
**4 site network**




S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

# *Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo-KAGRA*

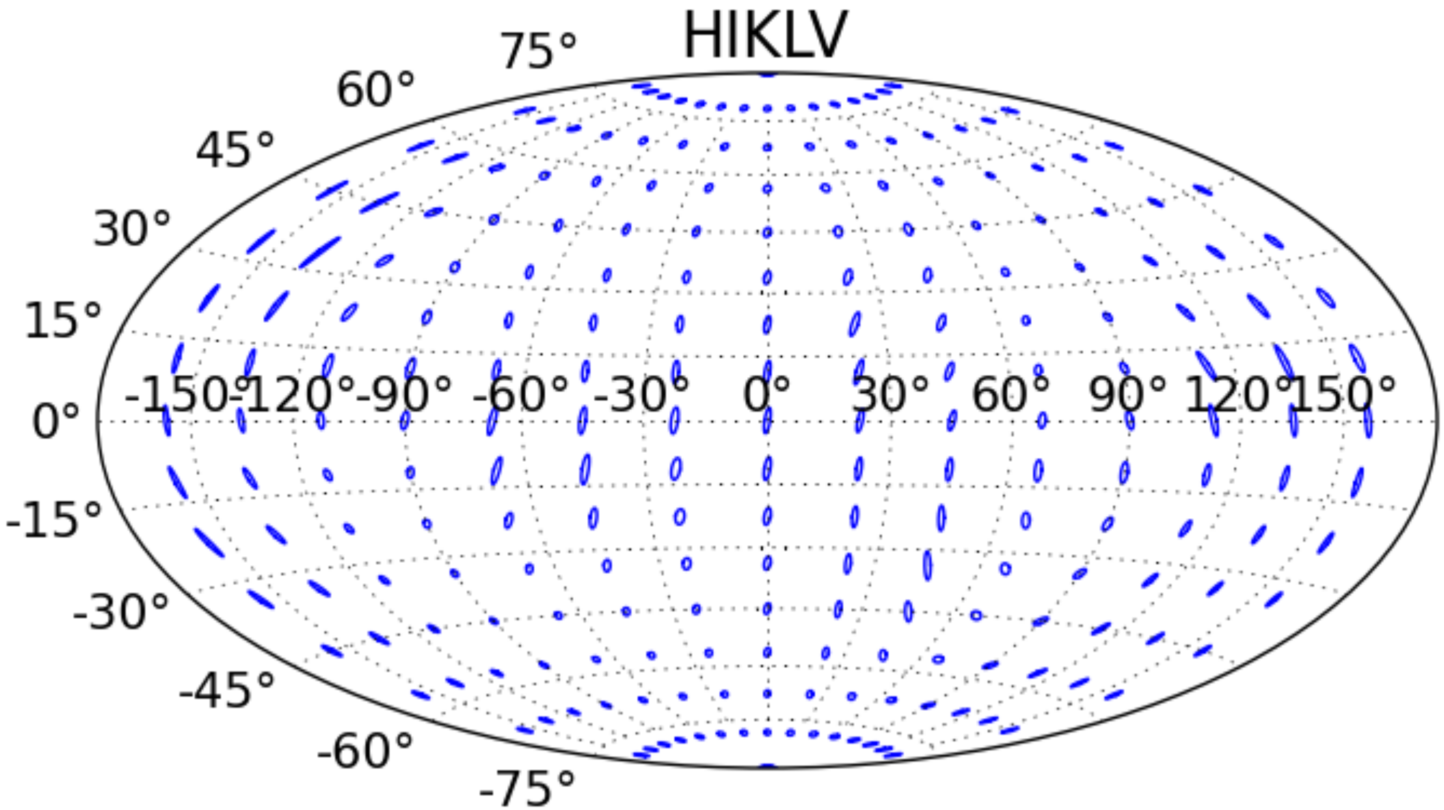
**4 site network**




S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

# Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo-India-KAGRA

**5 site network**




S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

# LIGO-India Status

- Status in the US: -- the National Science Board has given permission to NSF, at its discretion, "to approve the proposed aLIGO Project in scope, enabling plans for the relocation of an advanced detector to India"
- Status in India – awaiting Cabinet approval and beginning of seed funding for facility design work
- Major activities in India are now focused on site evaluation/selection as well as development of a Tier 2 computing center @ IUCAA

- ***Expect LIGO-India to begin operations in 2020 or 2021***

# *Summary*

- Observational papers from initial LIGO in partnership with Virgo producing interesting limits on astrophysical sources of gravitational waves
- Advanced LIGO progressing well; on target to begin operations by 2015
- LIGO-India is an exciting opportunity to expand the global gravitational wave network

- *We are excited by the prospects for KAGRA*
- *These are exciting times for gravitational wave physicists and astronomers!*

*どうもありがとう！*