Advanced Detector Era Overview

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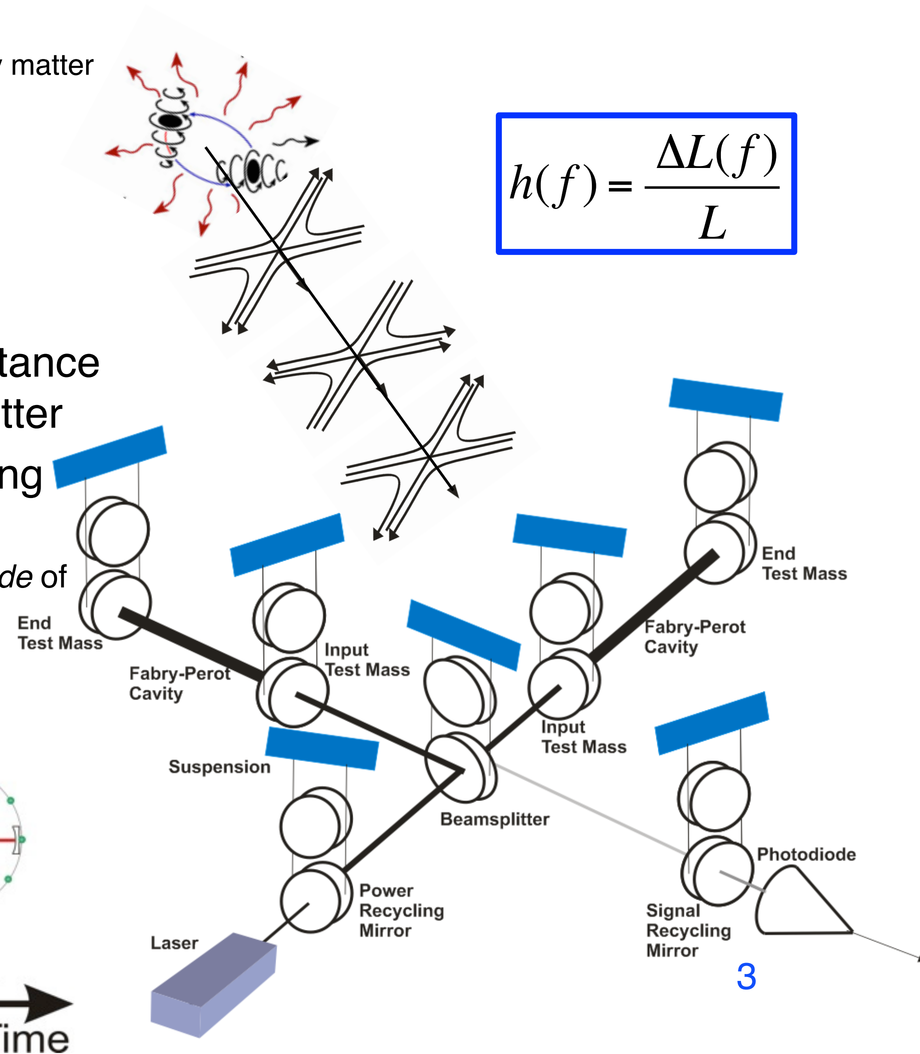
Topics

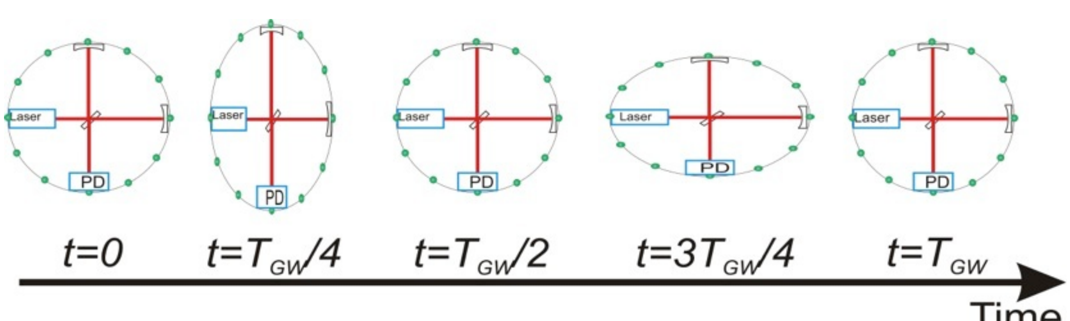
- Primer on Gravitational Waves Interferometry
- Status/timelines of Second Generation Gravitational-wave Detectors
  - Advanced LIGO
  - Advanced Virgo
- Blind Injections

Primer on Gravitational-wave Interferometry

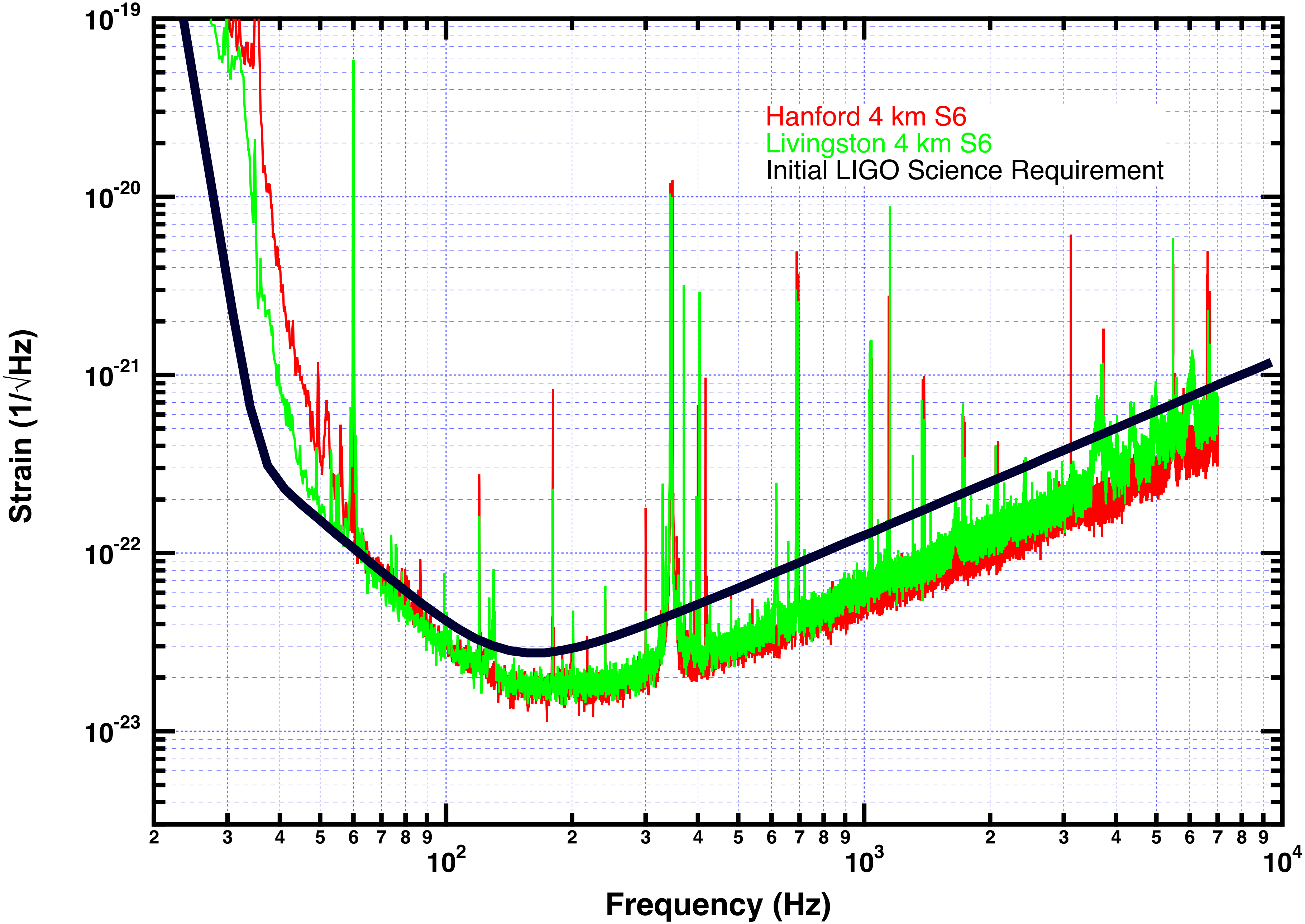
- Gravitational waves are propagating dynamic fluctuations in the curvature of space-time
  - Physically manifested as strains
  - Emitted from accelerating mass distributions, unimpeded by matter
  - If GR is right, they travel at the speed of light
  - Possess two polarizations, h_+ and h_x
- GW interferometers use enhanced Michelson interferometry
  - With suspended ('freely falling') mirrors
- Passing GWs 'stretch' and 'compress' the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent
  - A coherent detector → signal is proportional to *amplitude* of GW

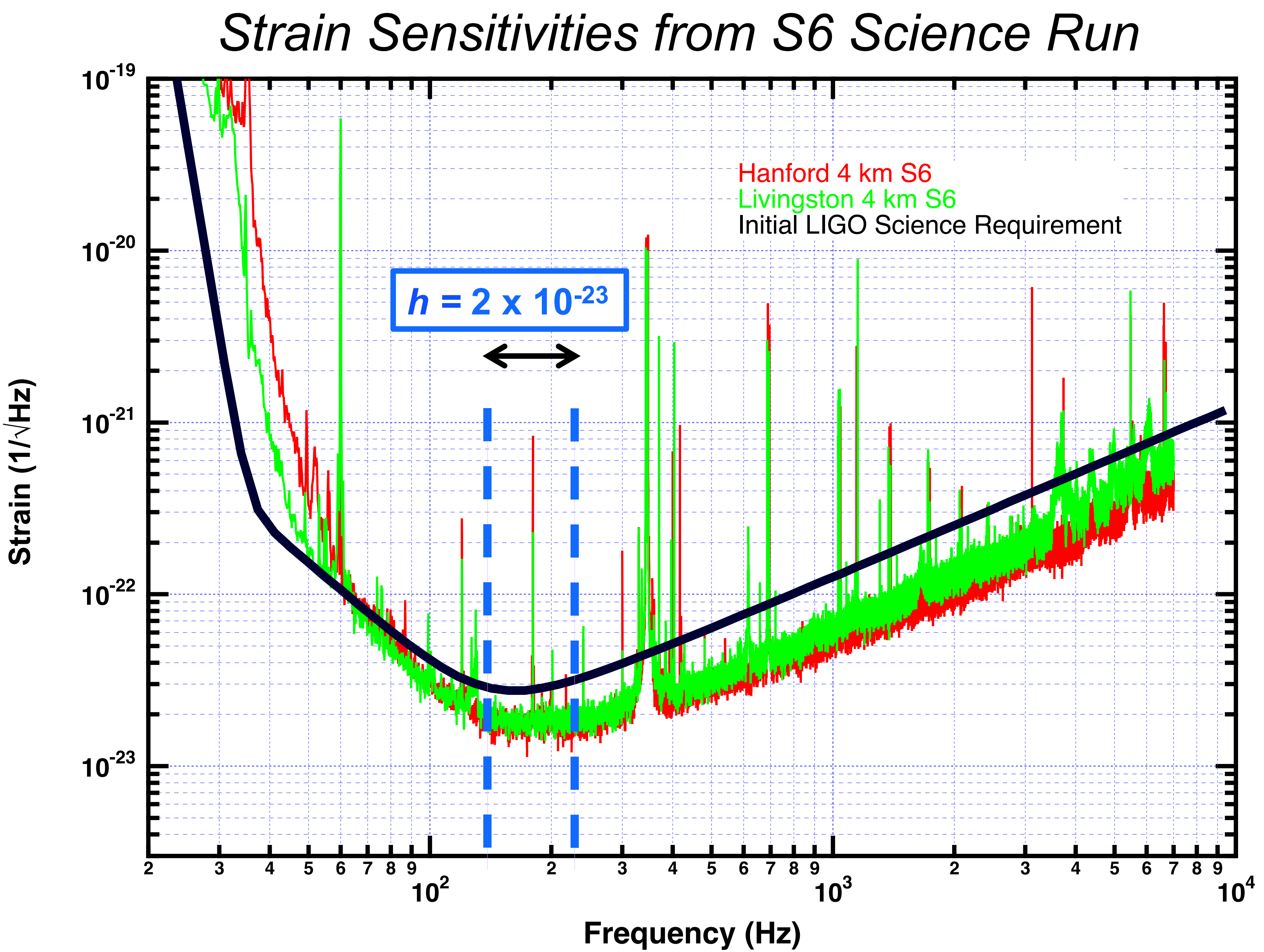
$$h(f) = \frac{\Delta L(f)}{L}$$





Strain Sensitivities from LIGO's S6 Science Run (2009-2010)

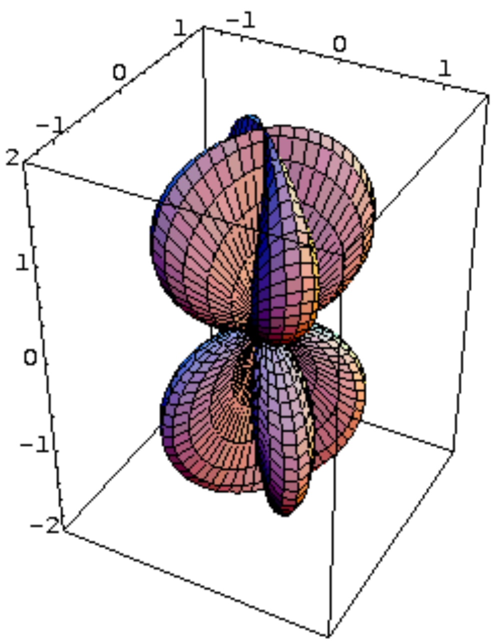



Strain Sensitivities from S6 Science Run
Hanford 4 km S6
Livingston 4 km S6
Initial LIGO Science Requirement
h = 2 x 10^-23
Strain (1/√Hz)
Frequency (Hz)
10^-19
10^-20
10^-21
10^-22
10^-23
10^2
10^3
10^4

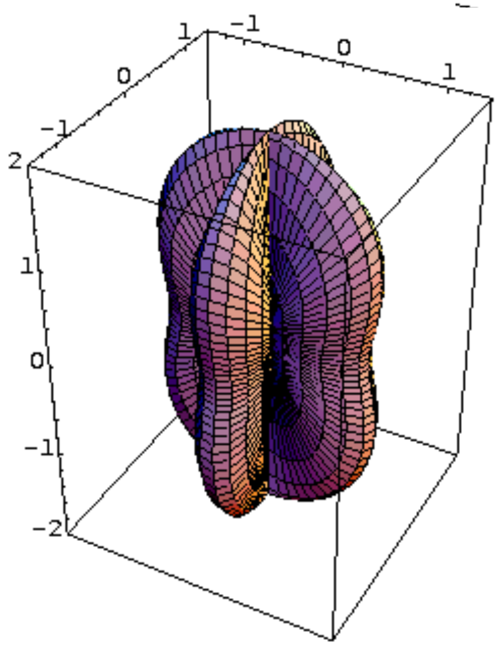
An individual GW interferometer has omnidirectional sensitivity

- Sensitivity depends both on propagation direction and polarization

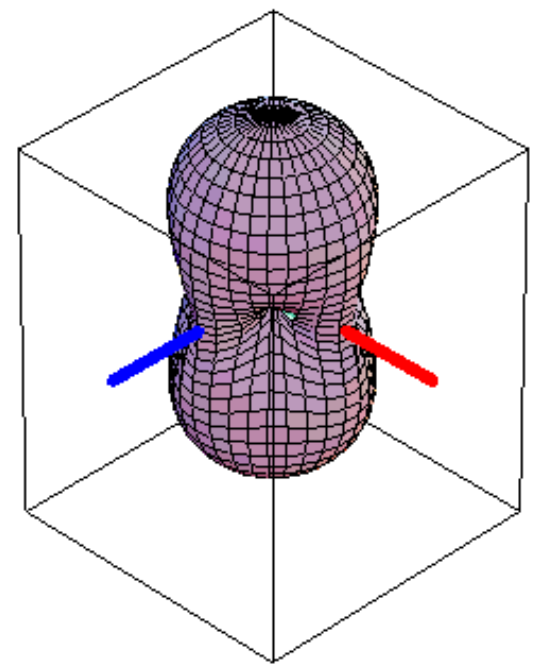
"×" polarization



"+" polarization

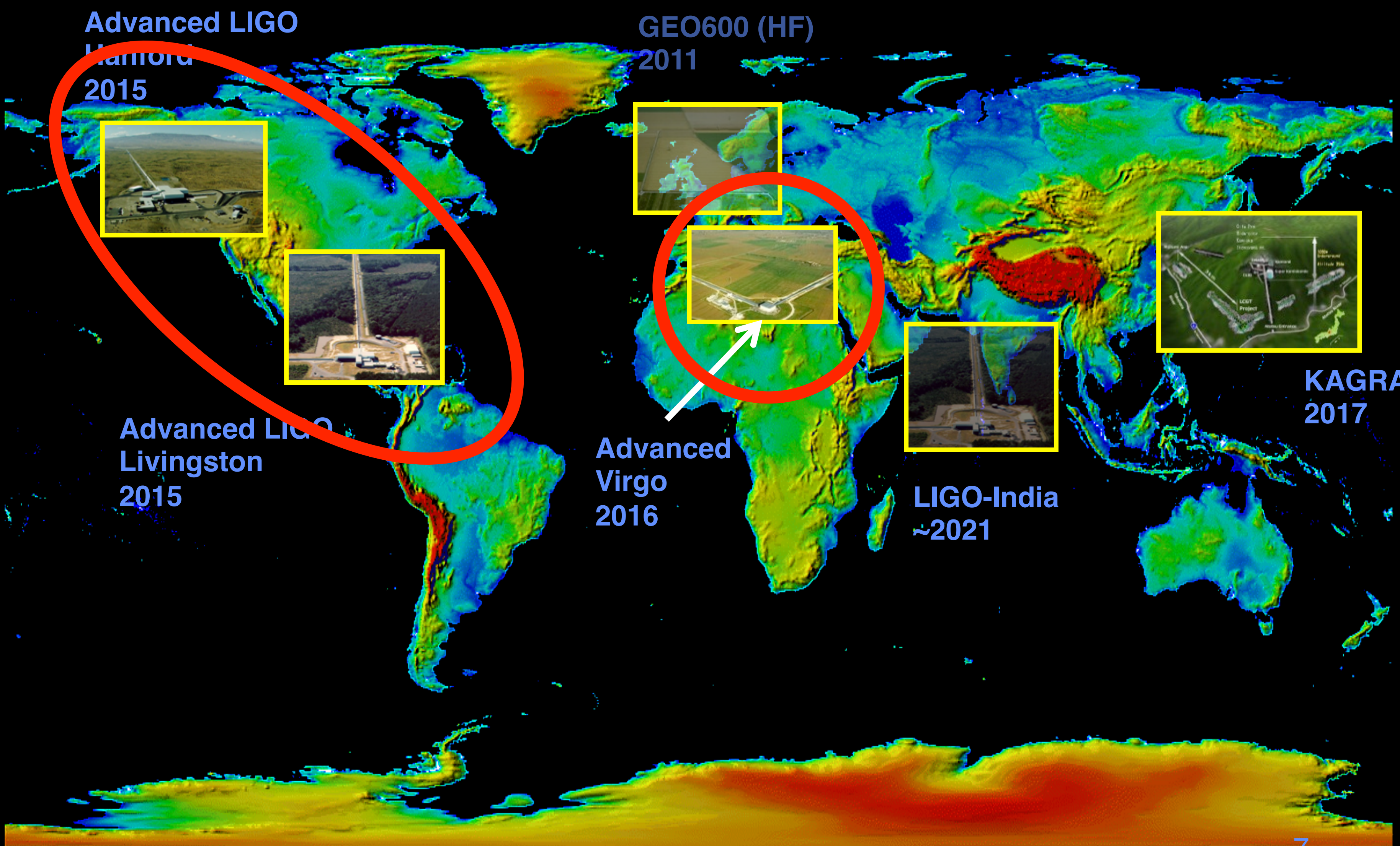


RMS sensitivity



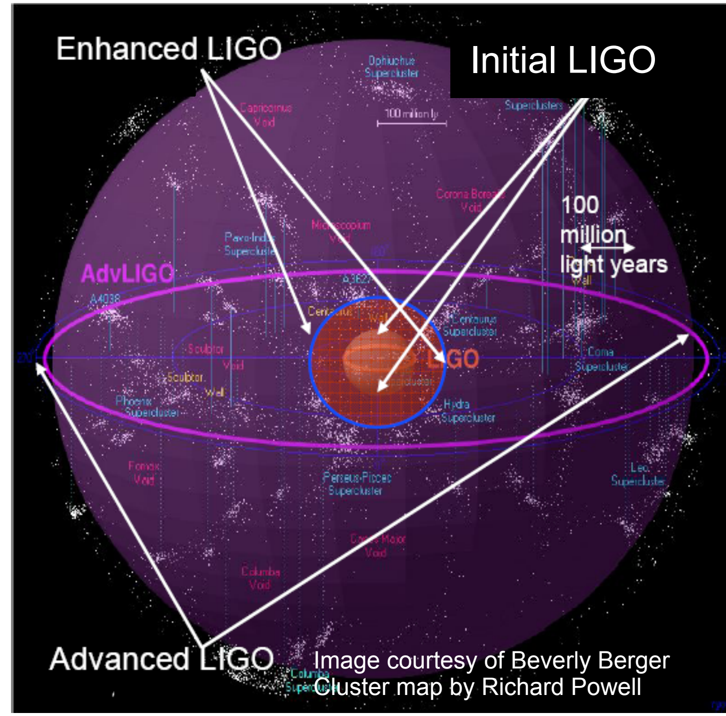
→ ***Global network needed to localize signals***

The Advanced GW Detector Network



Advanced LIGO

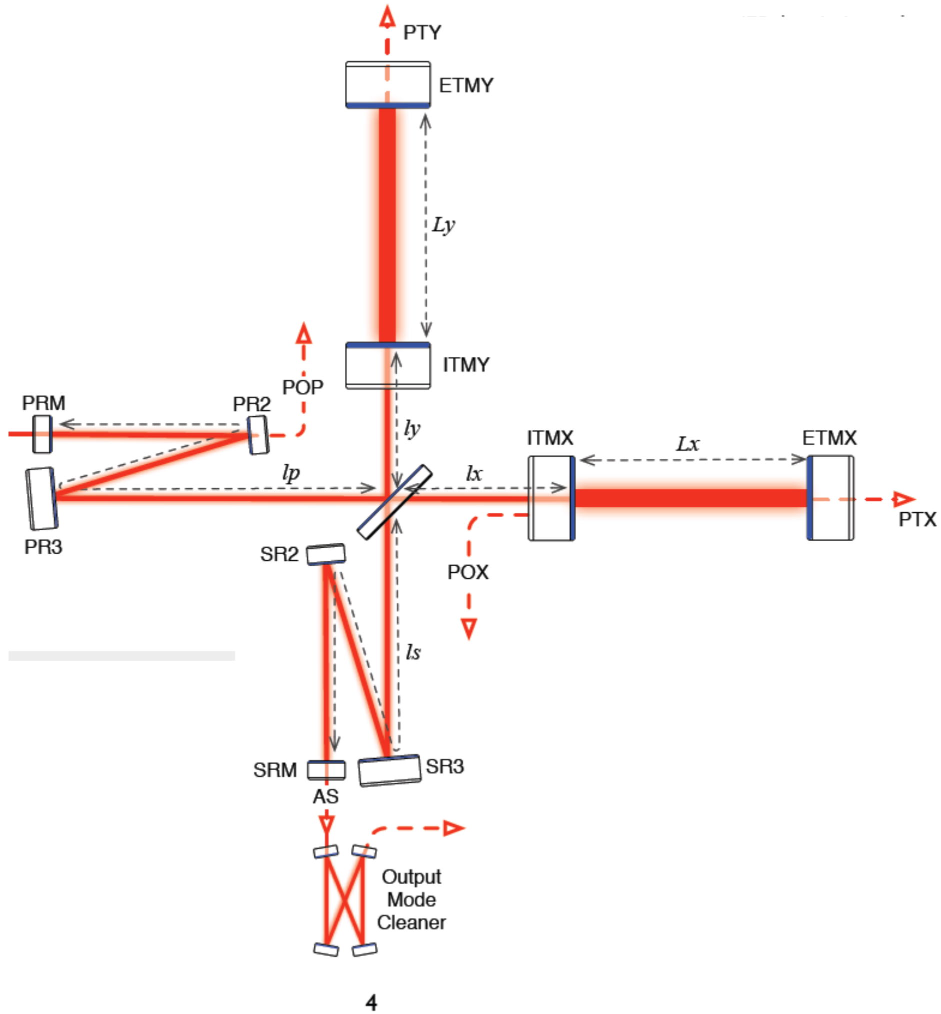
- A complete redesign and rebuild of the LIGO interferometers
  - » 10x more sensitive →1000x more volume probed
- Advanced LIGO funded by NSF in April 2008
  - » 7 year construction project, planned end in March 2015
- $205.1M in funding from NSF
- Capital contributions from international partners
  - » Science and Technology Facilities Council, UK ($14M), Max Planck Society, Germany ($14M), Australian Research Council ($1.7M)
- Three interferometer upgrade: Original plan to place 2 interferometers @ Hanford and 1 @ Livingston has been modified to place 1 each @ Hanford and Livingston and store third interferometer for construction in India late this decade
- Construction by LIGO Laboratory with participation by member groups of the LIGO Scientific Collaboration
- Project-wise, ~ 87% complete
  - » Through most of the subsystem assembly, testing, and installation
  - » Through some of the more complex integrated testing phase
- ***On time and on budget for completion in March 2015***



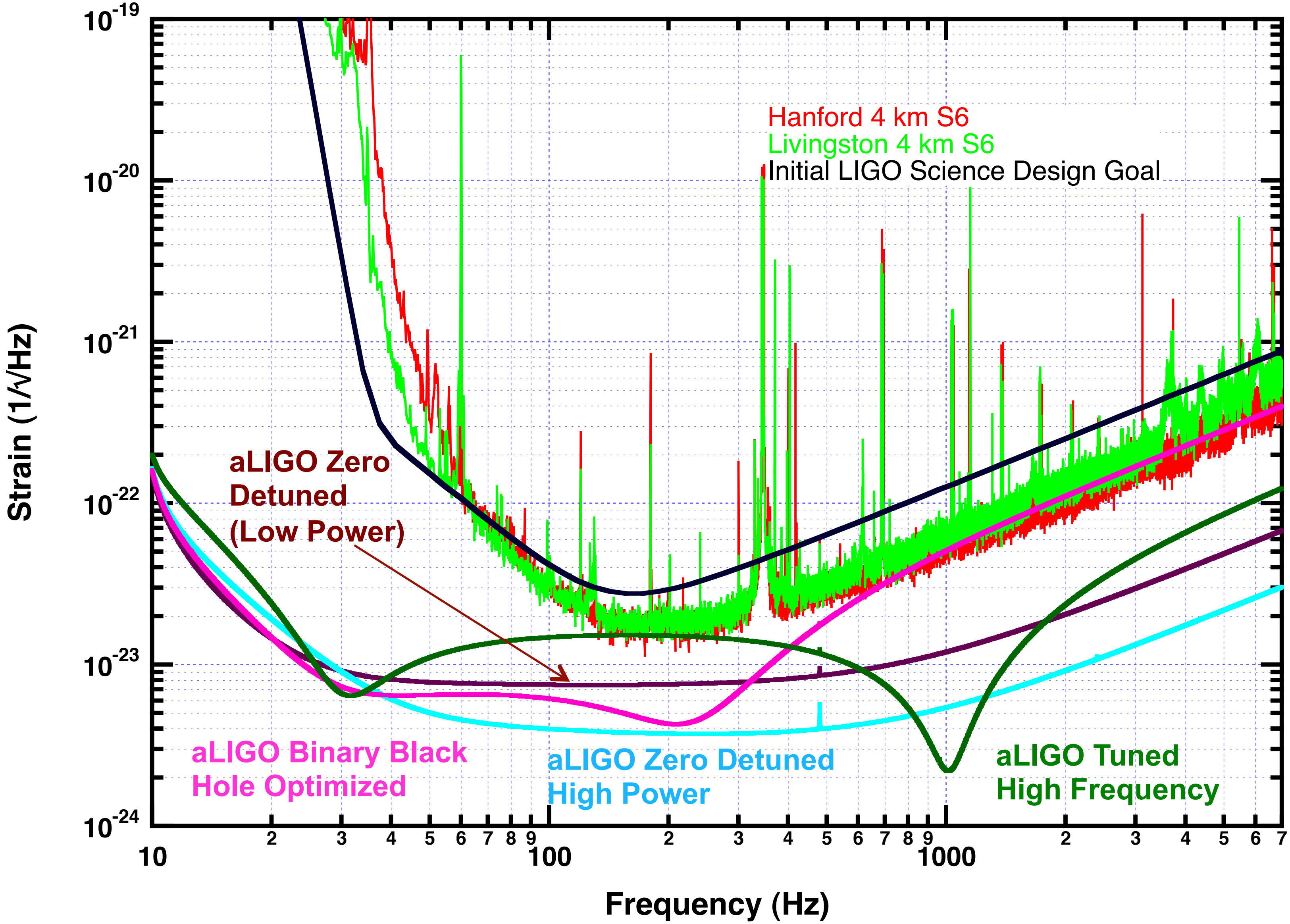
Advanced LIGO Overview

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 RC)
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3×10^{-23} / rHz	Tunable, better than 5×10^{-24} / rHz in broadband
Seismic Isolation Performance	$f_{low} \sim 50$ Hz	$f_{low} \sim 12$ Hz
Mirror Suspensions	Single Pendulum	Quadruple pendulum



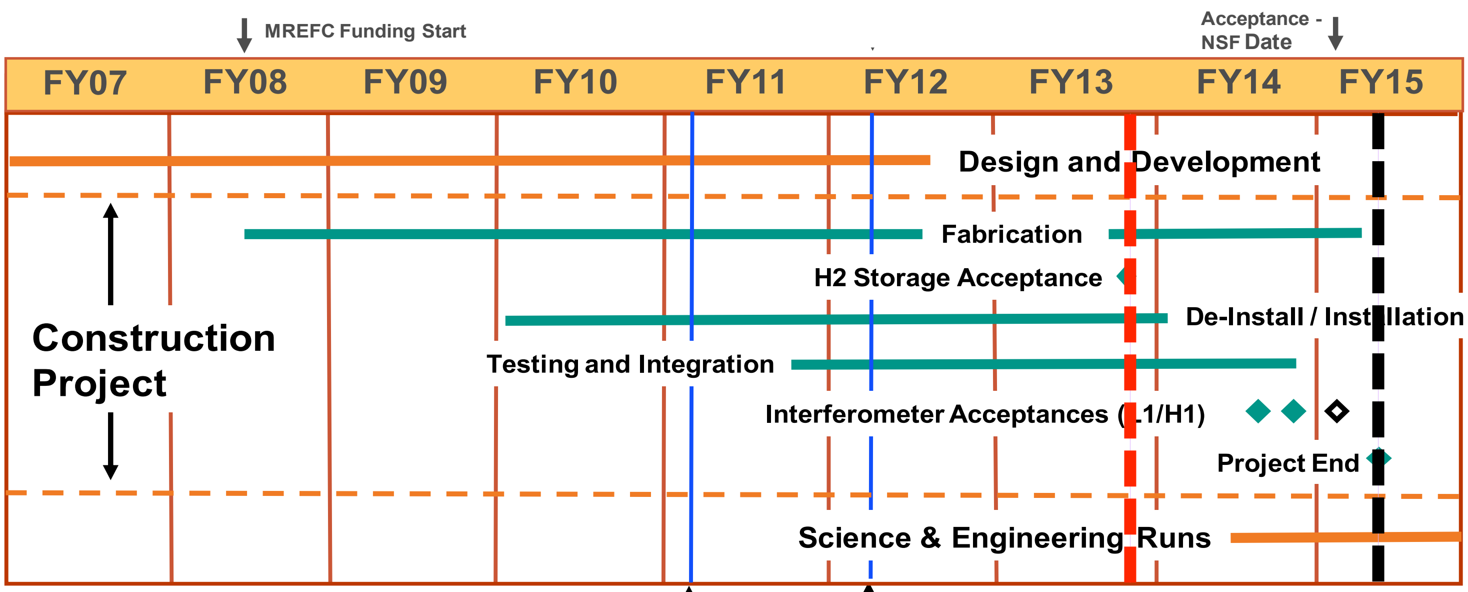
Advanced LIGO Sensitivity



LIGO

Timeline From Now to Advanced LIGO Science Operations

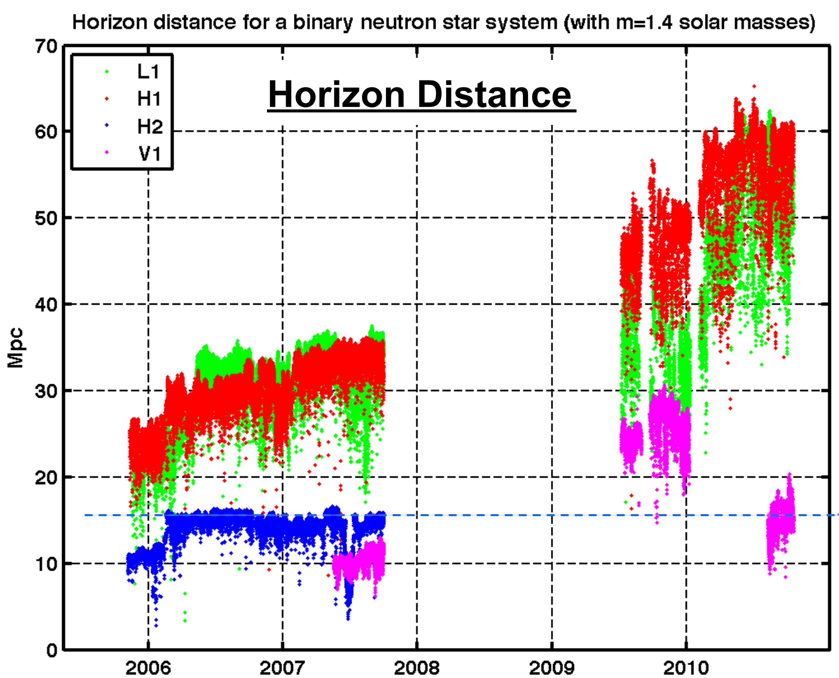
- Formal hand-off of the interferometers to observatory operations requires each to interferometer lock for 2 hours
- We expect both Hanford and Livingston interferometers to be turned over to observatory operations in late 2014
  - ***Very important point: hand-off does not imply astrophysically interesting sensitivity***
- Advanced LIGO Project formally ends March 2015 after installation of storage and analysis computers
- **The inaugural Advanced LIGO science run will take place after interferometers have been tuned to reach 'good sensitivity' → likely the latter half of 2015**

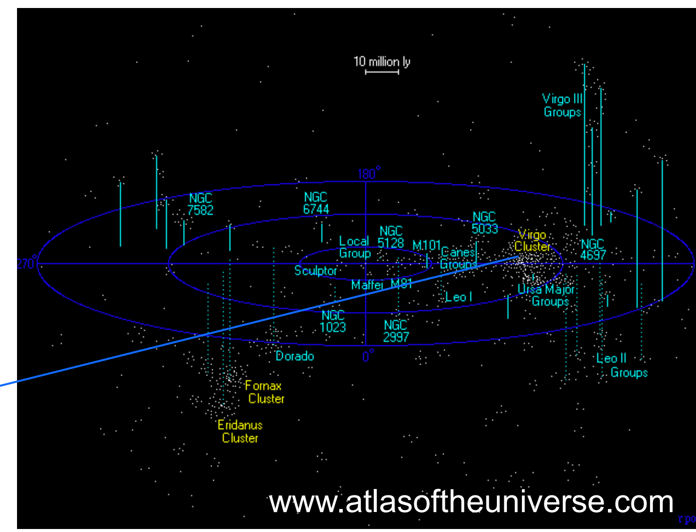


Distance reach to coalescing binary neutron star systems

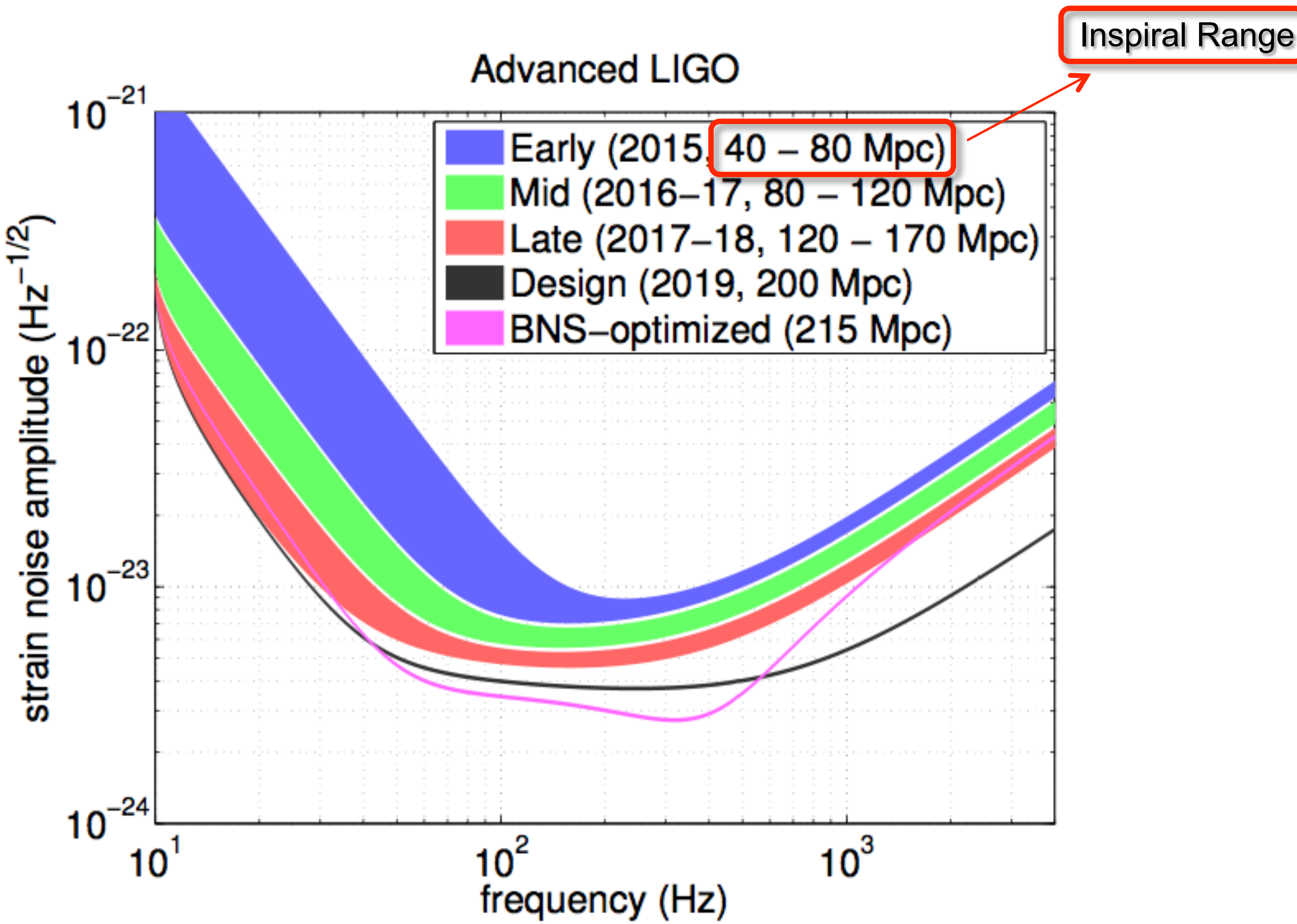
- We quote the reach of our detectors to binary neutron star (BNS) mergers range in two ways:
  - ***Horizon distance*** – the distance to which an interferometer can detect an optimally oriented and located 1.4-1.4 $M_{\odot}$ BNS merger with an SNR of 8
  - ***Inspiral range*** – the 'average' distance to which an interferometer can detect a 1.4-1.4 $M_{\odot}$ BNS merger with an SNR of 8 (averaged over all sky positions and orbital inclinations)

Conversion: ***Inspiral range ≅ Horizon distance/2.25***





Advanced LIGO Projected Sensitivity Evolution



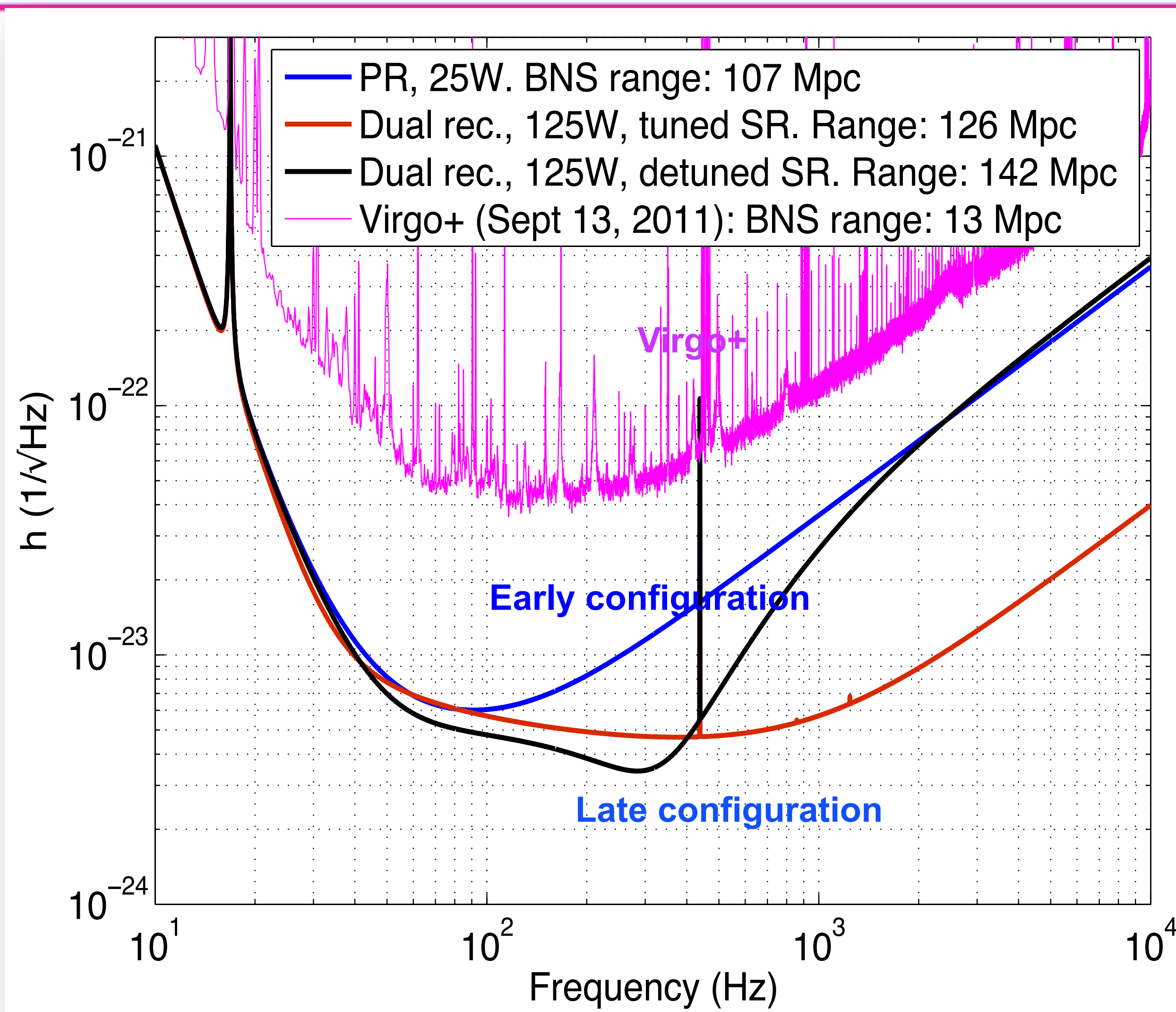
ADVANCED VIRGO

- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector of gravitational waves
- Participation by scientists from Italy and France (former founders of Virgo), The Netherlands, Poland and Hungary
- Funding approved in Dec 2009
- Construction in progress. End of installation planned for Fall 2015
- First science data planned in 2016

5 European countries
19 labs, ~200 authors

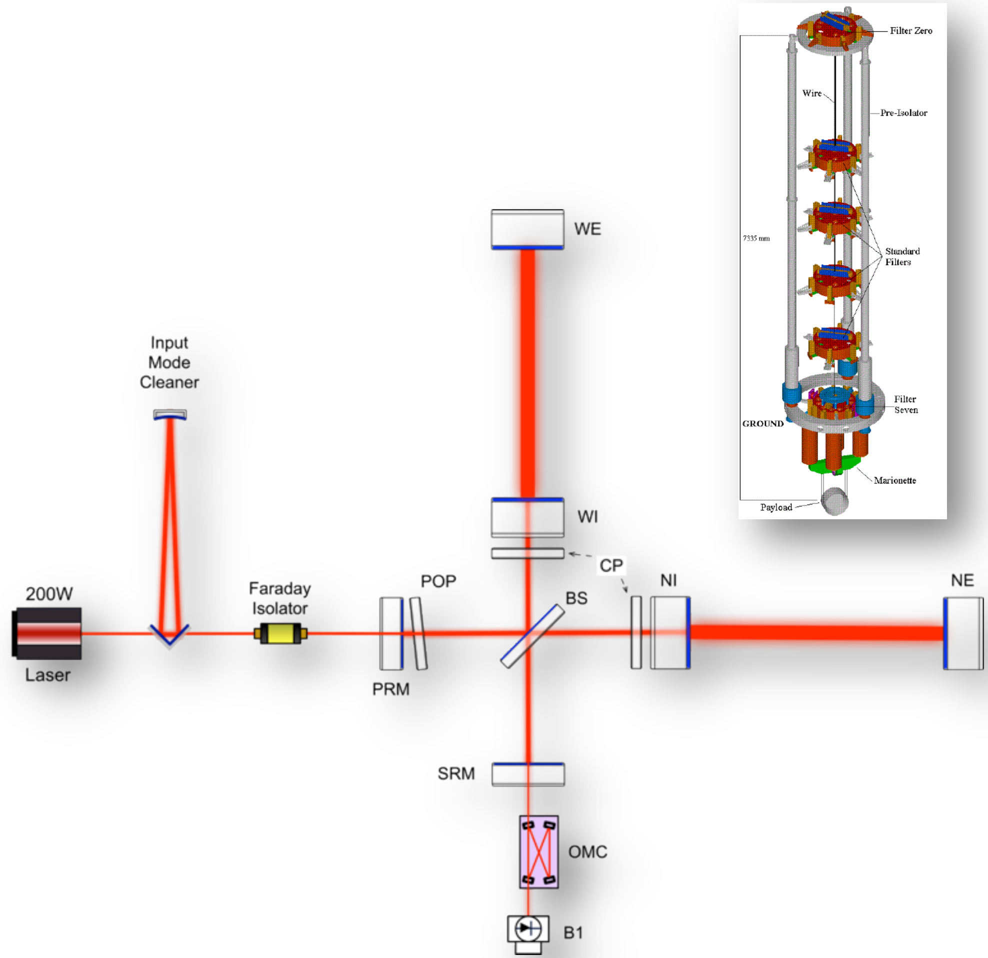
APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest

Projected Advanced Virgo Sensitivity



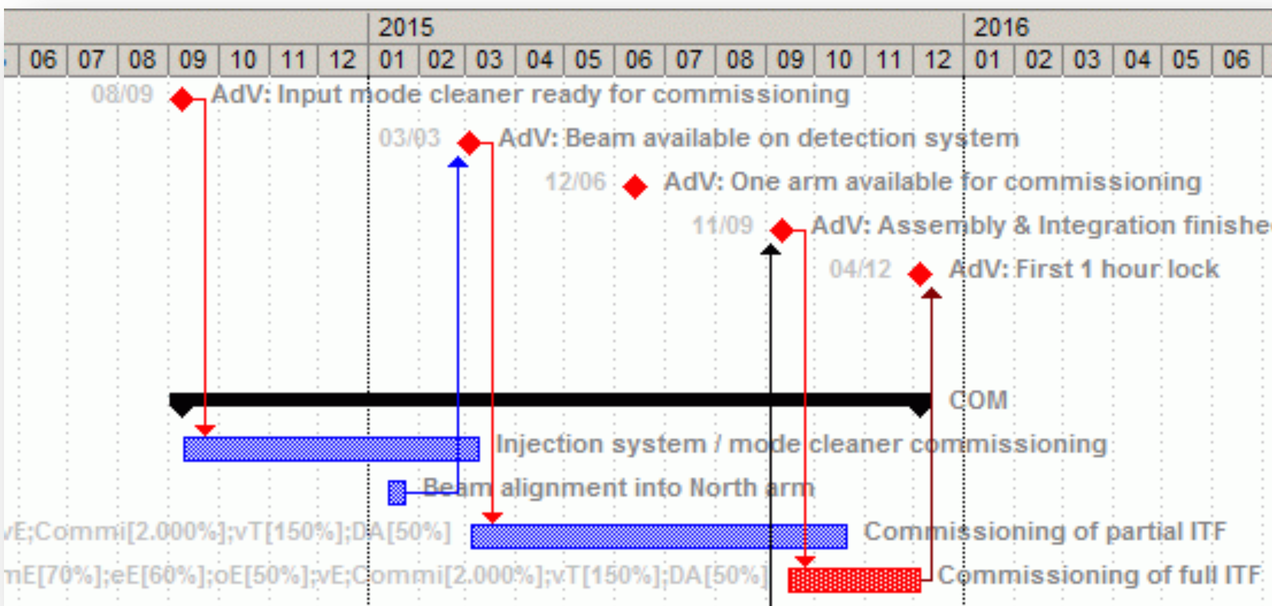
Advanced Virgo Design

- Main improvements w.r.t. Virgo
  - larger optical beams
  - More massive mirrors
  - higher quality optics
  - Better thermal control of aberrations
  - 200W fiber laser
  - signal recycling
- Already proven: vibration isolation by Virgo superattenuators
  - performance demonstrated
  - large experience gained with commissioning at low frequency



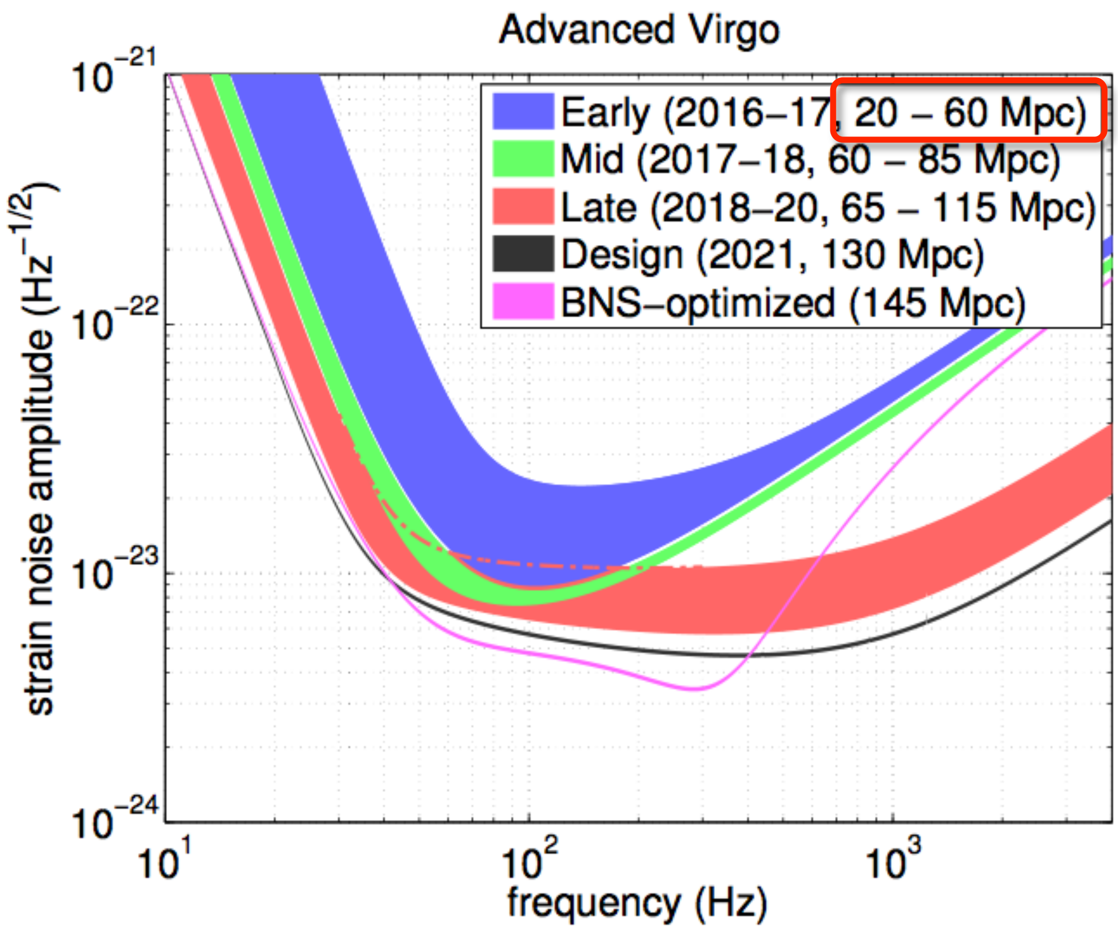
Advanced Virgo Status

- ~40% of budget committed thus far
- Infrastructure works planned for completion in Oct ‘13: equipment installation starts soon after
- Early commissioning to start next year (input mode cleaner)
- End of installation/integration: fall 2015



Advanced Virgo Projected Sensitivity Evolution

Inspiral Range

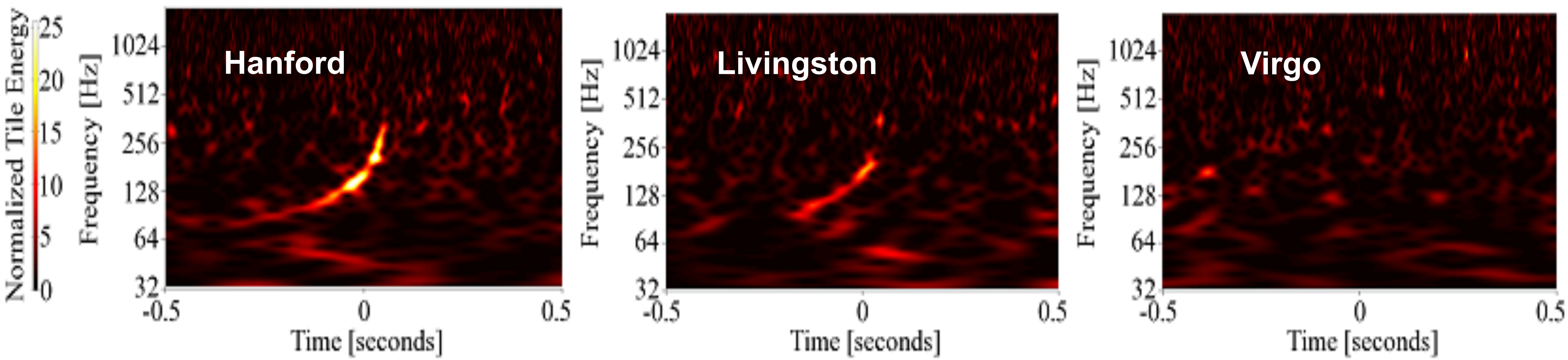


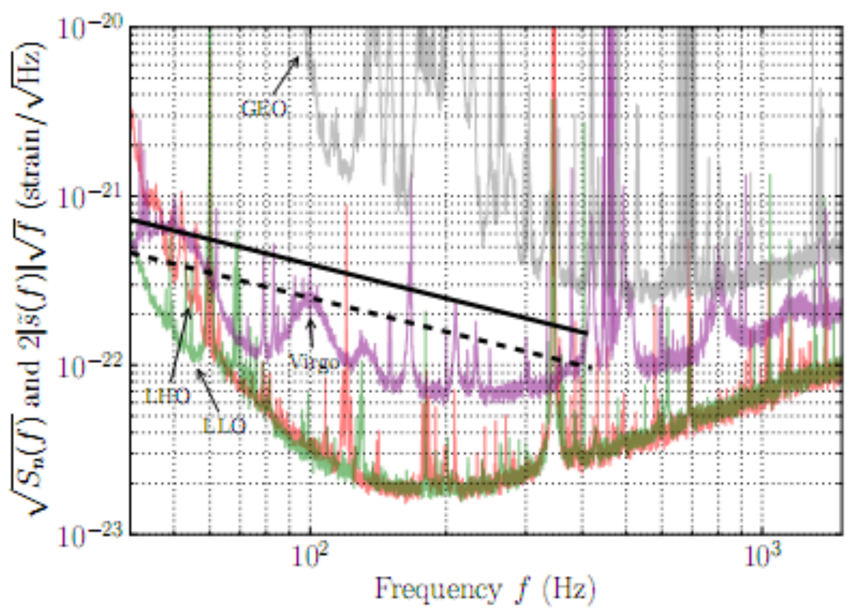
Blind Injections in Advanced Detector Era

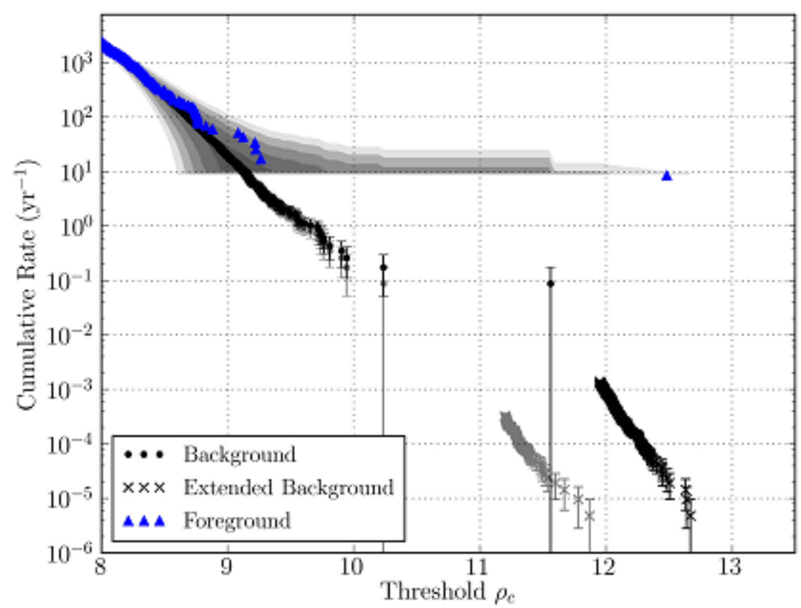
- In order to ability of analysis pipelines to detect GWs, LIGO and Virgo perform hardware injections
- Simulated GW signals are coherently injected into the LV interferometers
  - » End test masses are 'wiggled' with the characteristic gravitational waveform corresponding to specific source type, event time, sky location, and distance
- All hardware injections are logged as such in the data stream, with one important exception → **Blind injections**
  - » Secretly injected by a very small select group within LIGO-Virgo; information kept confidential from the LIGO-Virgo Collaboration
- *Rationale for blind injections – a system test of the Collaborations' ability to take a GW event candidate all the way to detection*
- Blind injections were performed in S5/VSR1 and S6/VSR2,3 science runs.
  - Injection rate during a science run was Poissonian with an expected value of 1

‘Event’ GW100916 – A Blind Injection

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







Blind Injections in Advanced Detector Era

- Blind injections are not revealed as such until the LSC and Virgo have fully vetted potential candidates and declared them as detection (or not)
- Although we will strive to assess detection candidates quickly, in the past it has taken a while (eg, GW100916 took 6 months)

- Blind injections have proven to be very valuable to the LSC and Virgo in the past, so we have made the decision to continue them into the next science runs (at least through the first detection)
  - » valuable lessons on detection confidence, importance of parameter estimation
- Although the blind injection rate hasn't been formally decided, it will very likely be quite low
  - » 0, 1, or possibly 2 during a science run in the early going, commensurate with expected rates for binary coalescences
- It would be very difficult to selectively unblind the injections before passing them to EM follow up partners

Blind Injections in Advanced Detector Era

- It is possible that during a science run, you will receive an alert that isn't real.

- Are you willing to 'chase a ghost'?
- What rate would be considered tolerable for you?

LIGO

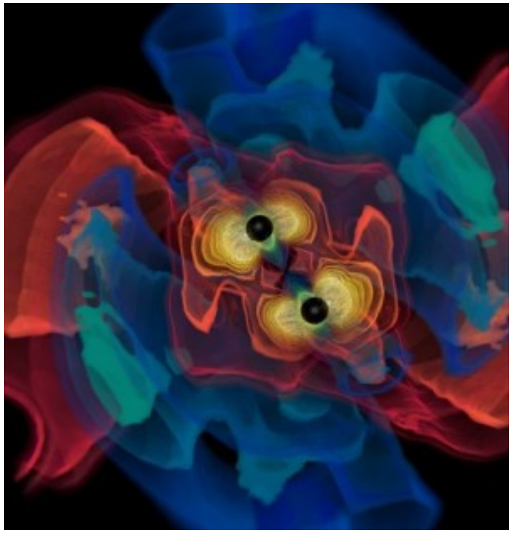
Summary

- Second generation interferometers to begin science operations in 2015
  - » Advanced LIGO (two interferometers) – 2015
  - » Advanced Virgo (one interferometer) – 2016
- Based on present knowledge, we are planning on the following approximate run schedule:
  - » Advanced LIGO: ~ 3 month run in 2015, ~ 6 month run in 2016-17, ~ 9 month run in 2017-18
  - » Advanced Virgo: ~ 6 month run in 2016-17, ~ 9 month run in 2017-18
  - » Modification of run schedules is likely as we learn more about the instruments

Extra Slides

LIGO

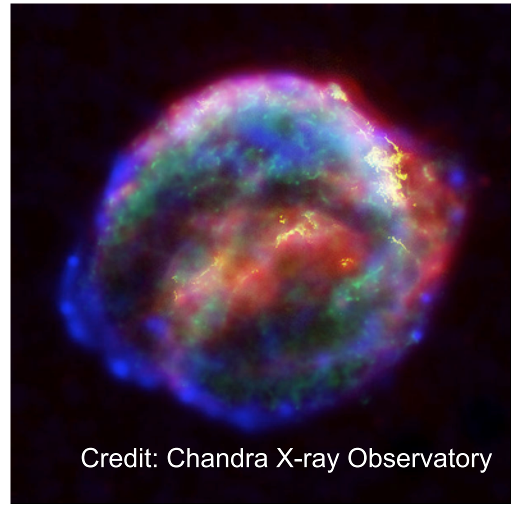
Gravitational-wave Sources


Credit: AEI, CCT, LSU

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

- Strong emitters, well-modeled,

- (effectively) transient

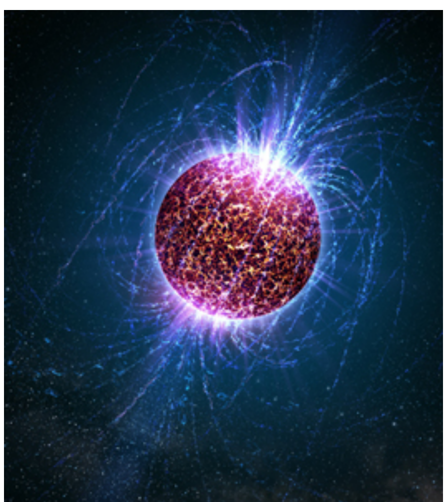

Credit: Chandra X-ray Observatory

Asymmetric Core Collapse Supernovae

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

- transient

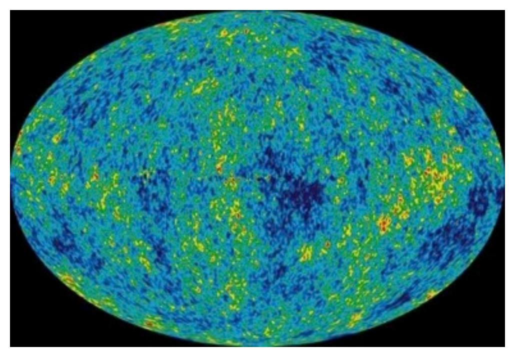
- Cosmic strings, soft gamma repeaters, pulsar glitches also in 'burst' class


Casey Reed, Penn State

Spinning neutron stars

- (effectively) monotonic waveform

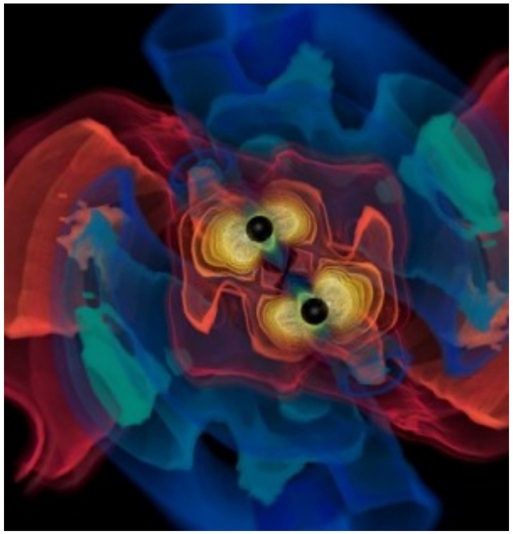
- Long duration


NASA/WMAP Science Team

Cosmic Gravitational-wave Background

- Residue of the Big Bang, or incoherent ensemble of point emitters
- Long duration

Gravitational-wave Sources



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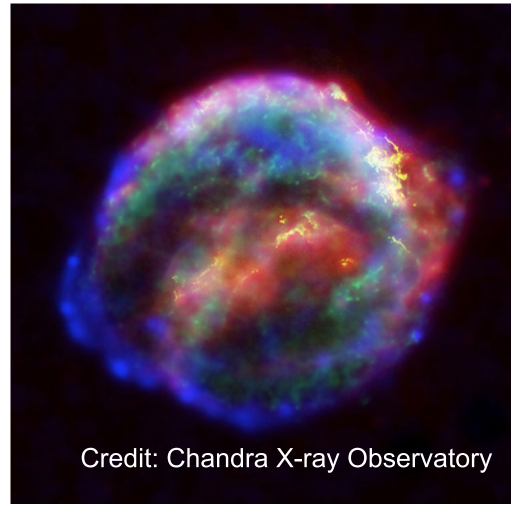

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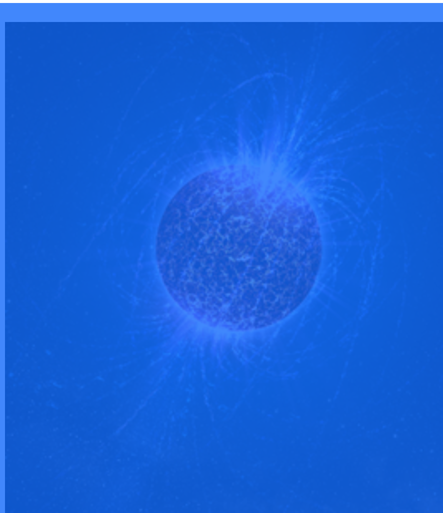

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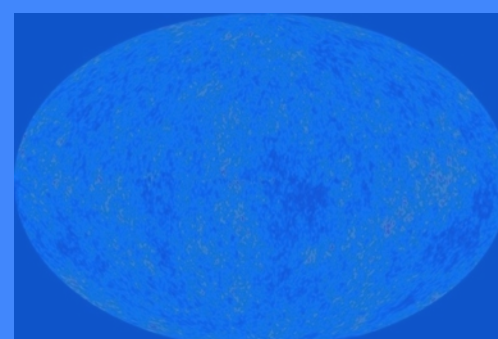

NASA/WMAP Science Team

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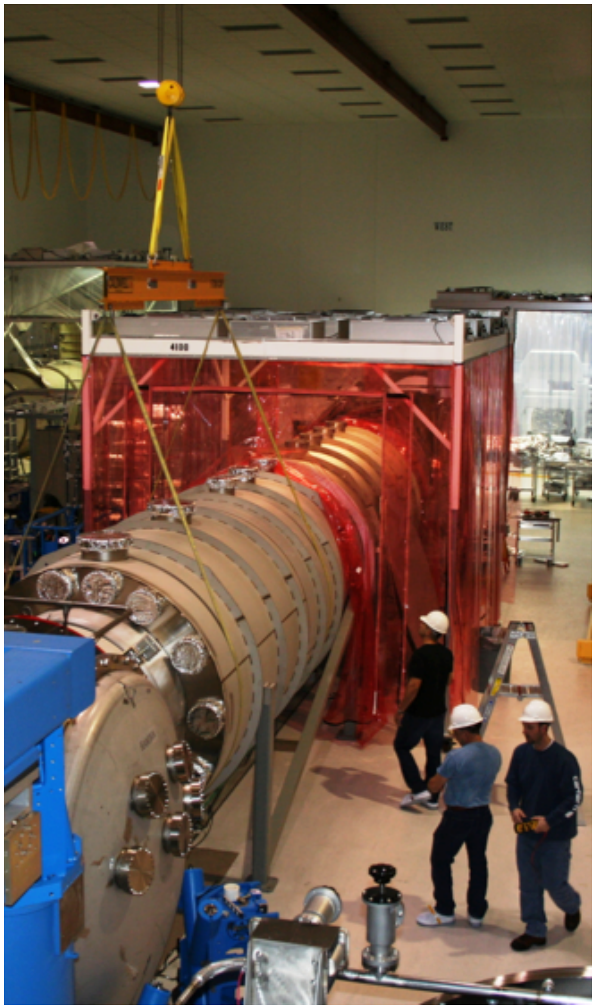
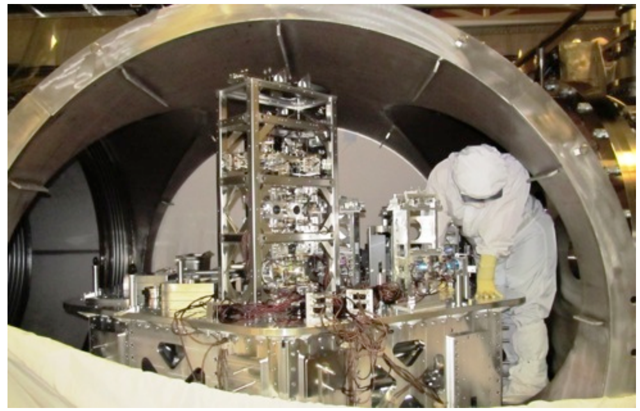
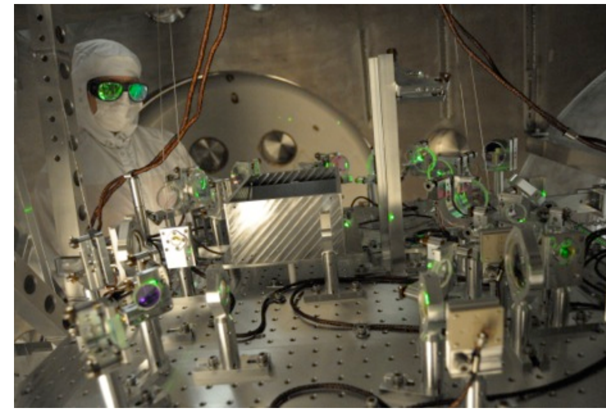
Advanced LIGO in Pictures



Placing Input/Output Vacuum Tubes

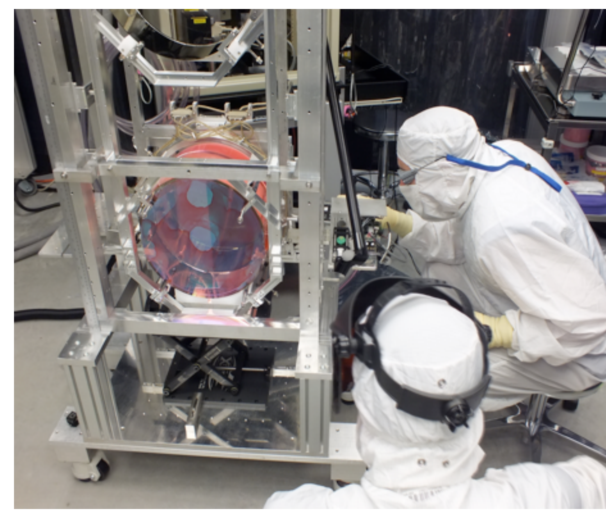


LIGO Livingston HAM2 Vacuum Chamber Installation Nears Completion



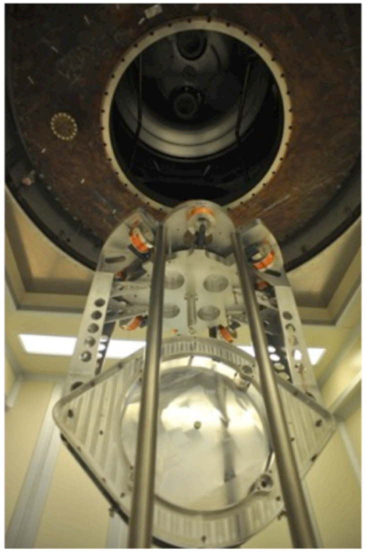
Transmission Monitor and Arm Length Stabilization System

LIGO Hanford Pre-Stabilized Laser in Clean Room Enclosure



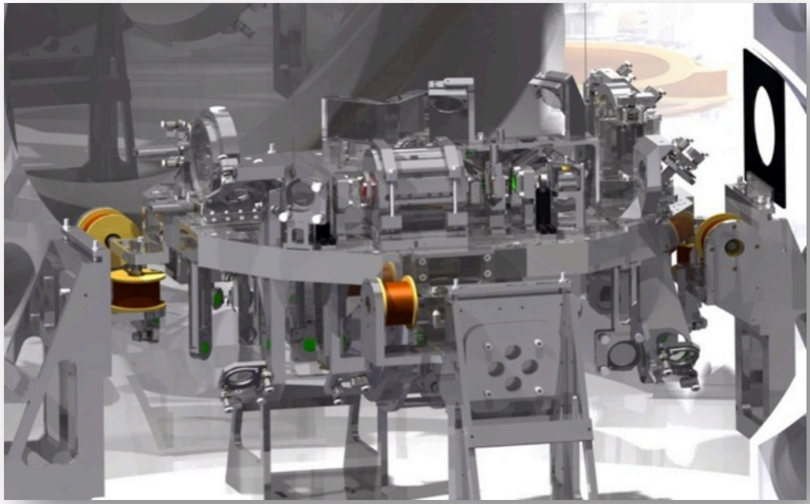
Welding the LIGO Livingston X-arm Input Test Mass to Fused Silica Fibers

Advanced Virgo in Pictures

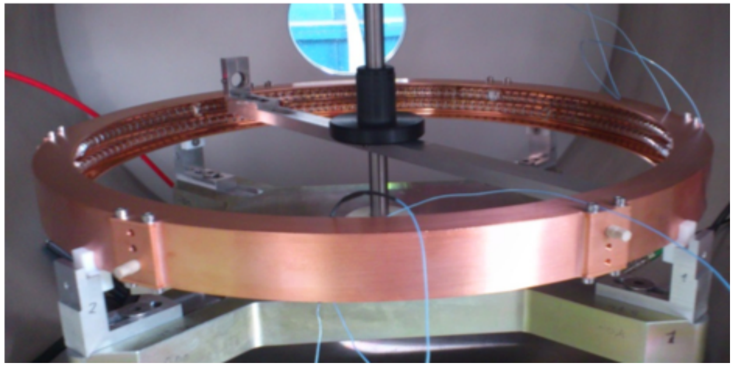


AdV beamsplitter payload

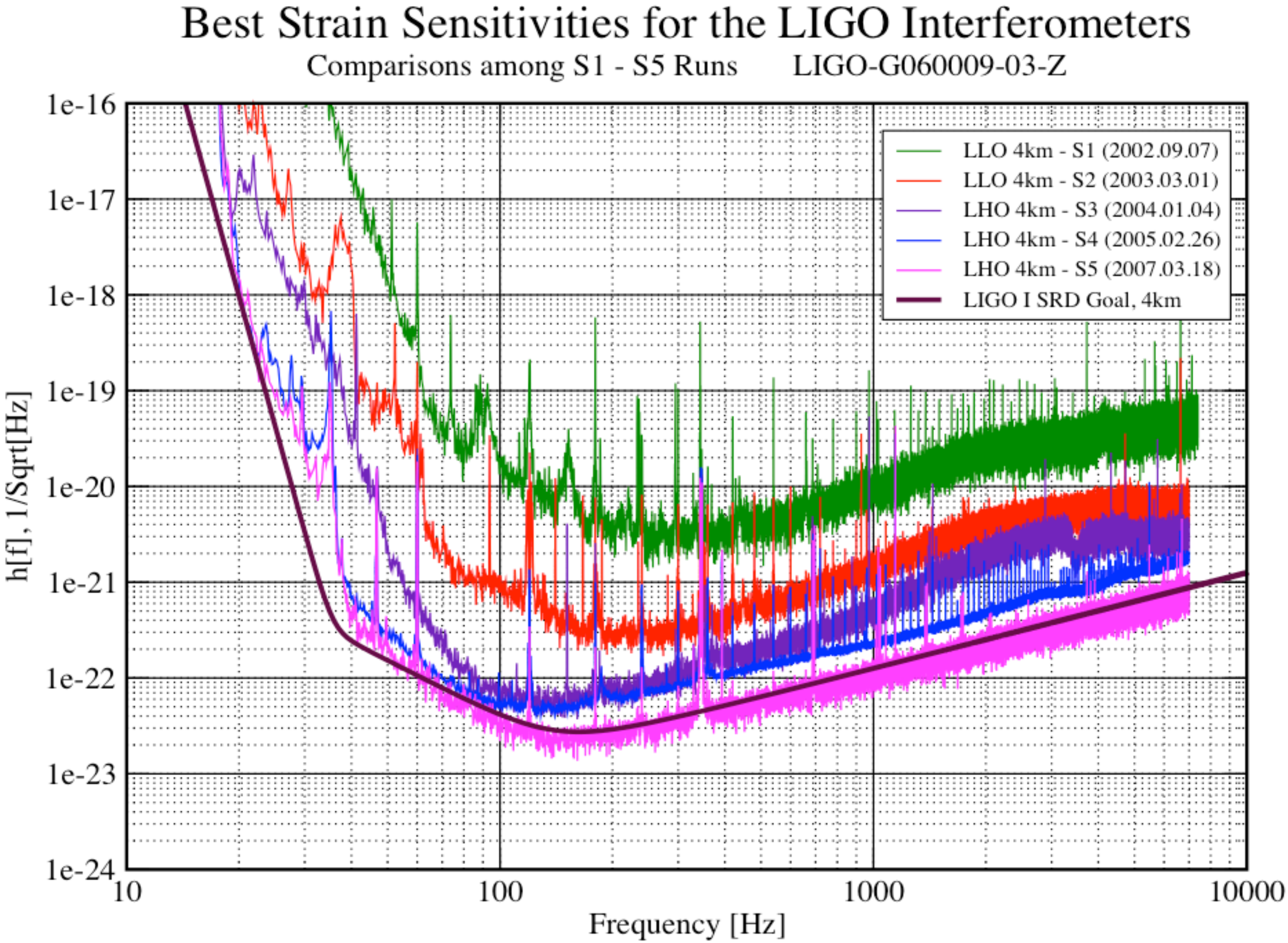
AdV test mass substrate



AdV input optics suspended bench

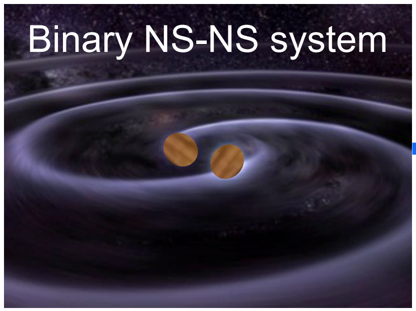


Test mass ring heater

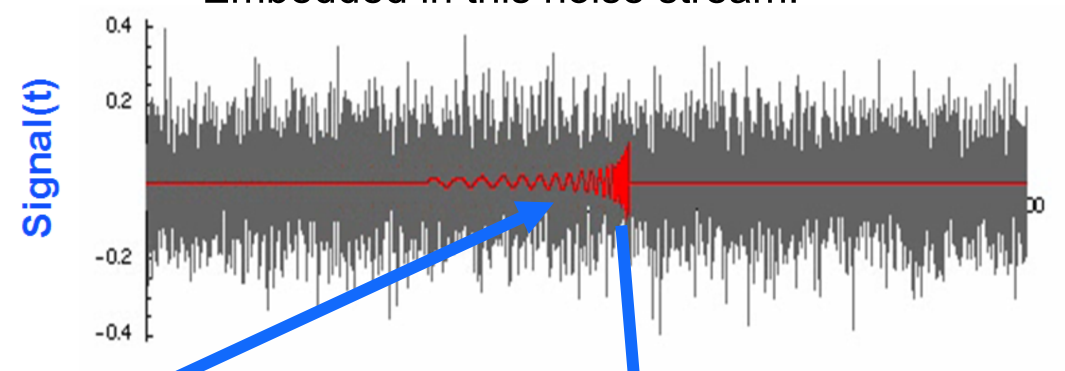

Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1 - S5 Runs LIGO-G060009-03-Z
LLO 4km - S1 (2002.09.07)
LLO 4km - S2 (2003.03.01)
LHO 4km - S3 (2004.01.04)
LHO 4km - S4 (2005.02.26)
LHO 4km - S5 (2007.03.18)
LIGO I SRD Goal, 4km
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]

What might the first GW detection look like?

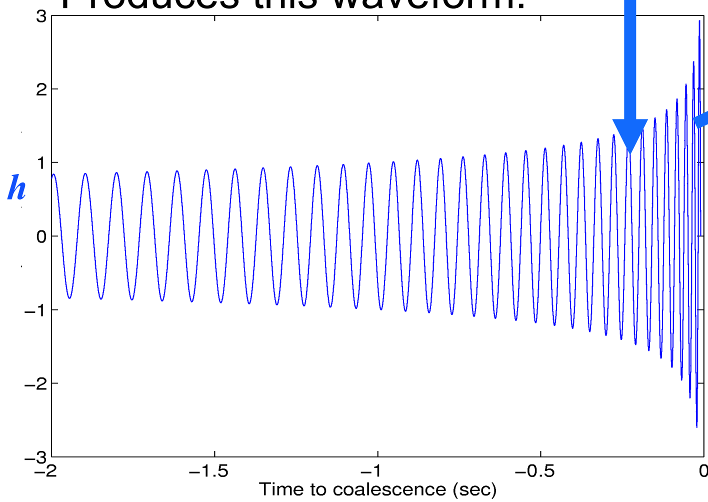
This source:



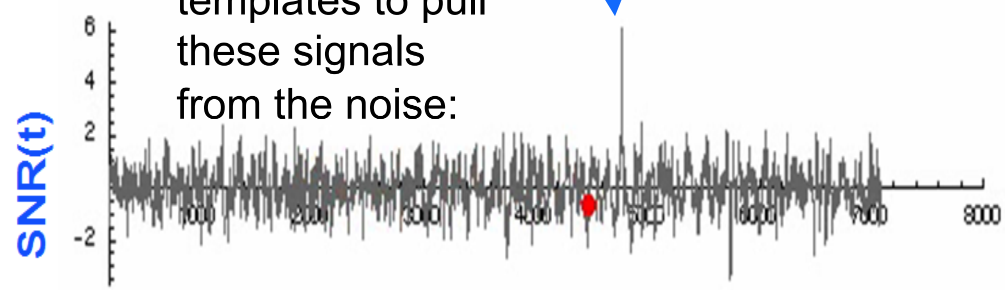
Embedded in this noise stream:



Produces this waveform:

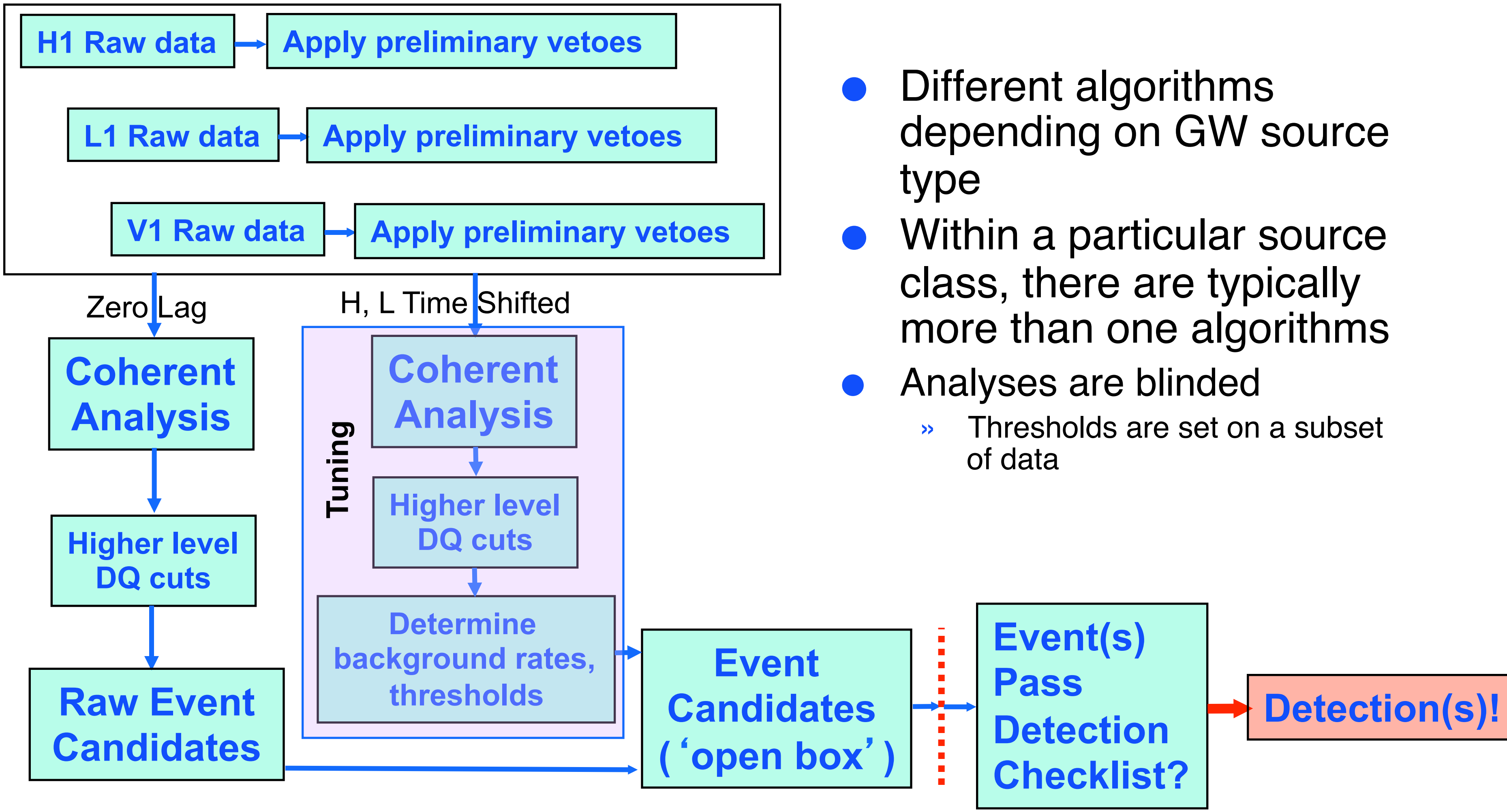


We use optimal Weiner filtering using matched templates to pull these signals from the noise:



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

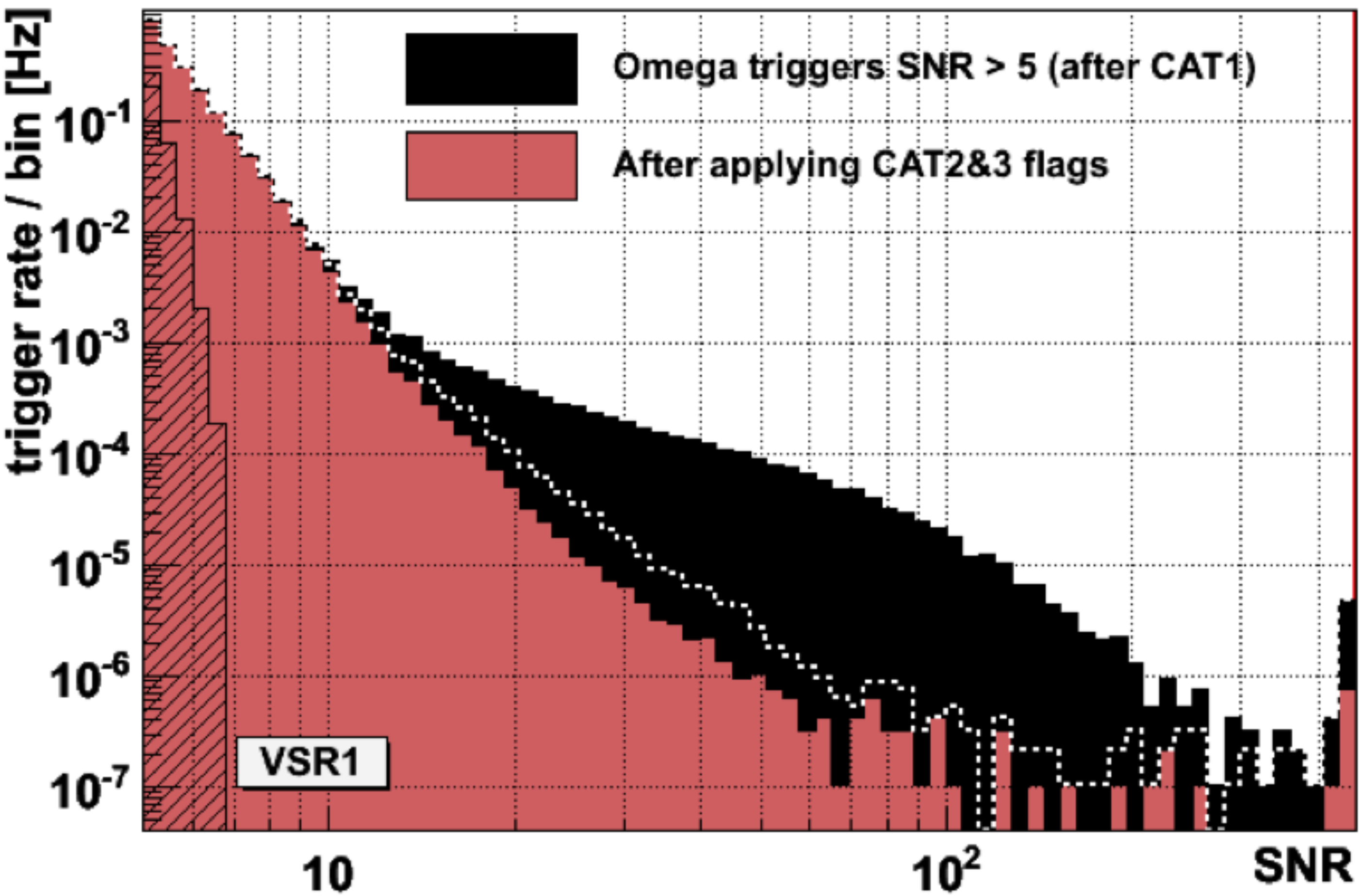
A typical pipeline



- Different algorithms depending on GW source type
- Within a particular source class, there are typically more than one algorithms
- Analyses are blinded
  - Thresholds are set on a subset of data

The challenge posed by data quality

- There are a large number of background triggers in the data



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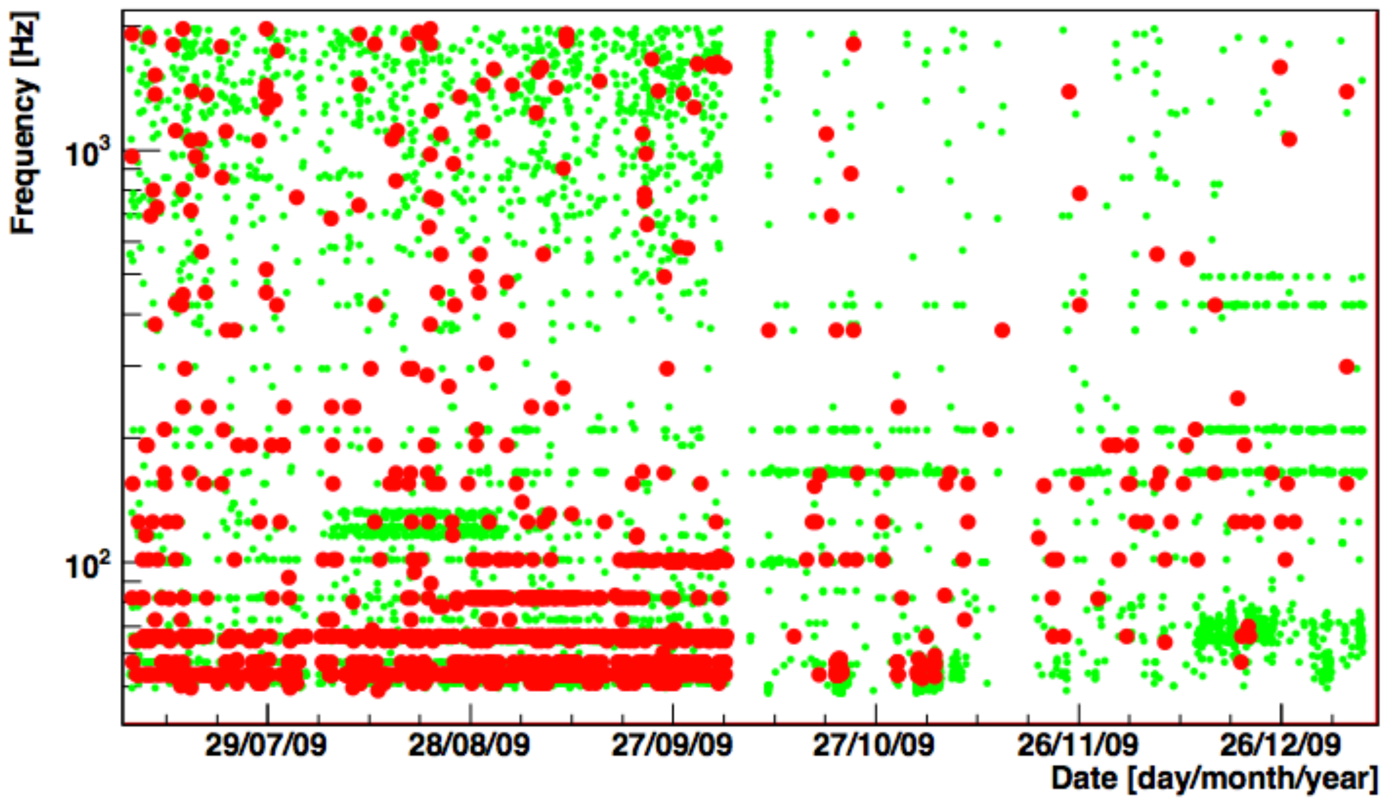

Figure 10. Time-frequency distribution of the remaining VSR2 Omega triggers (from 48 Hz to 2048 Hz) with SNR>10 after having applied the CAT2&3 DQ flags (green dots). Triggers with SNR>20 are represented with a red full circle.

Projecting Advanced LIGO Sensitivity Progression 2015-2018