Searching for gravitational waves from compact binary coalescences with Advanced LIGO

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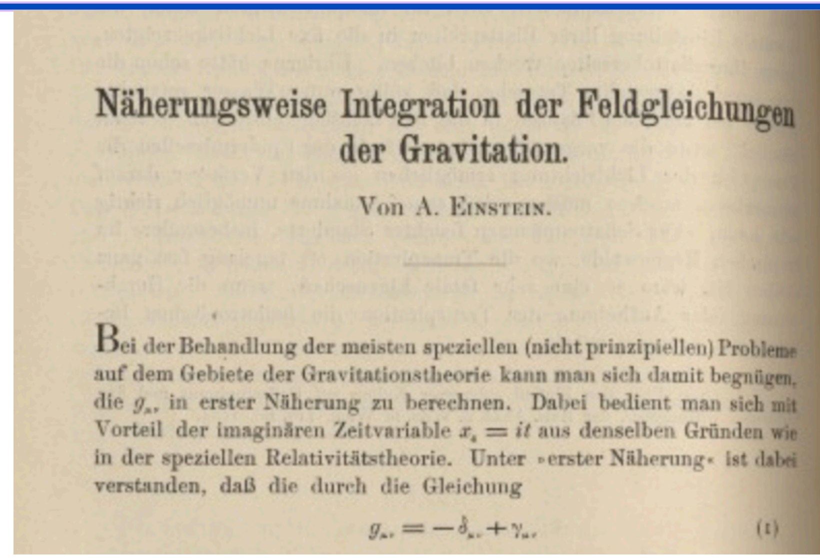
credit: NASA/AEI/ZIB/M. Koppitz and M. Rezzola

General Relativity turns 100

- GR published in 1915, turns 100 this year
- Gravitational waves first predicted in 1916; centennial next year
- No direct observations yet
- Chance for first direct detection by ground-based interferometers in that time frame



Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

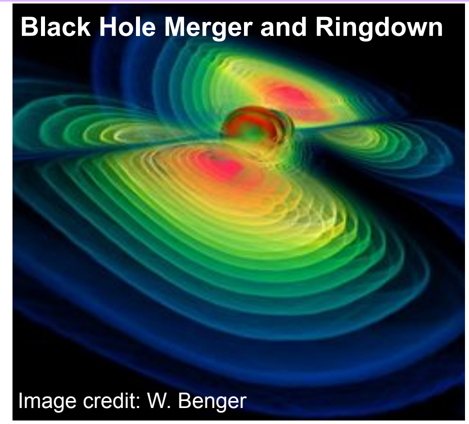
Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

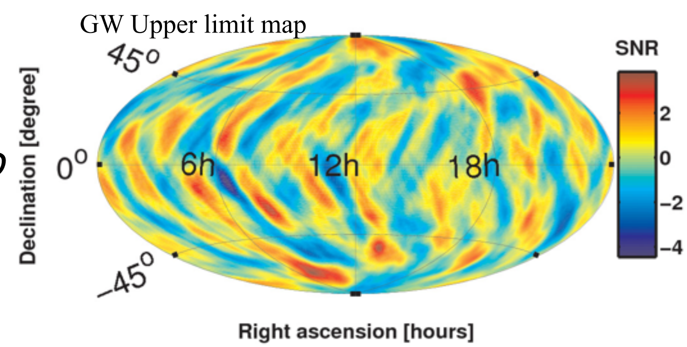
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

Albert Einstein, *Näherungsweise Integration der Feldgleichungen der Gravitation*, 22.6.Berlin 1916

Questions GWs may be able to answer

- **Fundamental Physics**
  - *Is General Relativity the correct theory of gravity?*
  - *How does matter behave under extreme gravity?*
  - *What equation of state describes a neutron star?*
- **Astrophysics, Astronomy, Cosmology**
  - *Do compact binary mergers cause short GRBs?*
  - *What is the supernova mechanism in core-collapse of massive stars?*
  - *How many low mass black holes are there in the universe?*
  - *Do intermediate mass black holes exist?*
  - *How bumpy are neutron stars?*
  - *Is there a primordial gravitational-wave residue?*
  - *Can we observe populations of weak gravitational wave sources?*
  - *Can binary inspirals be used as "standard candles" to measure the local Hubble parameter?*



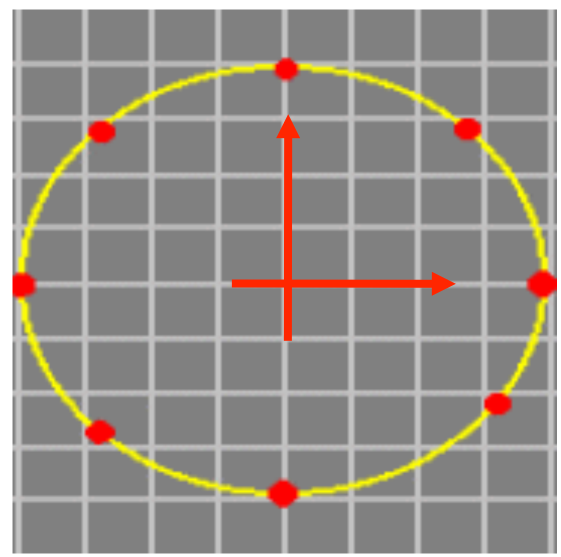


Gravitational waves

- Predicted by Einstein's theory of gravity, General Relativity, in 1916
- Generated by changing quadrupole moments such as in co-orbiting objects, spinning asymmetric objects
- Interact weakly with matter - even densest systems transparent to gravitational waves
- An entirely new phenomenon with which to explore the universe

Physically, gravitational waves are *strains*:

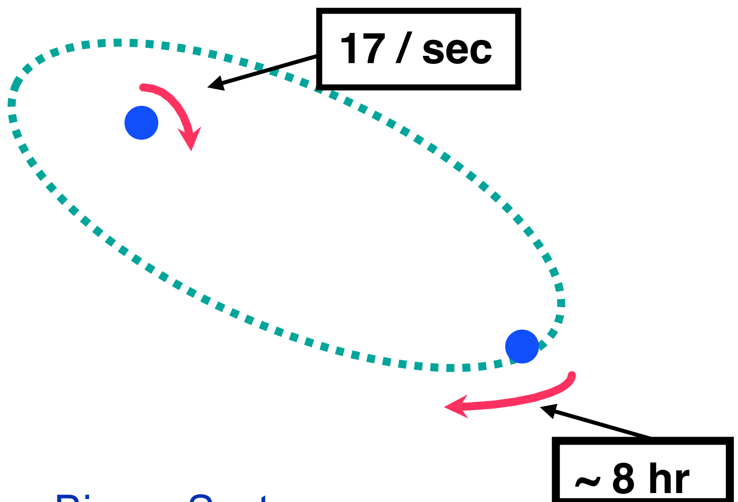
$$h = \frac{\Delta L(f)}{L}$$



Binary Pulsar data confirms energy carried away by GWs

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



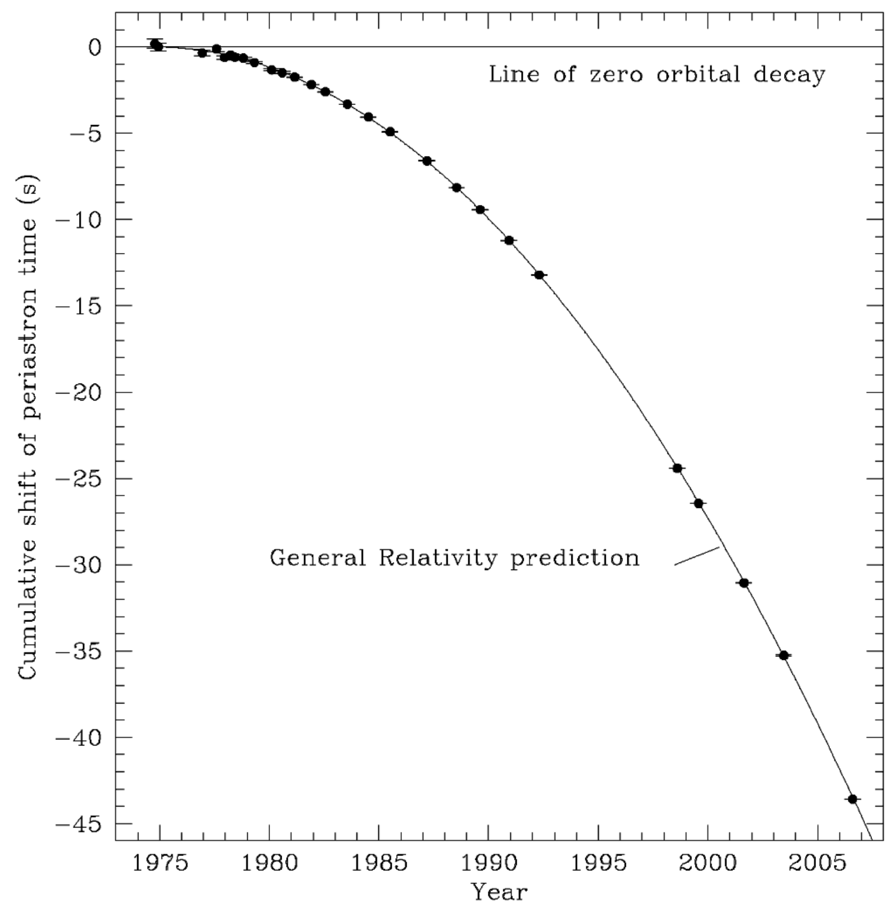
Neutron Binary System

- separated by 10^6 miles
- $m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$

Prediction from general relativity

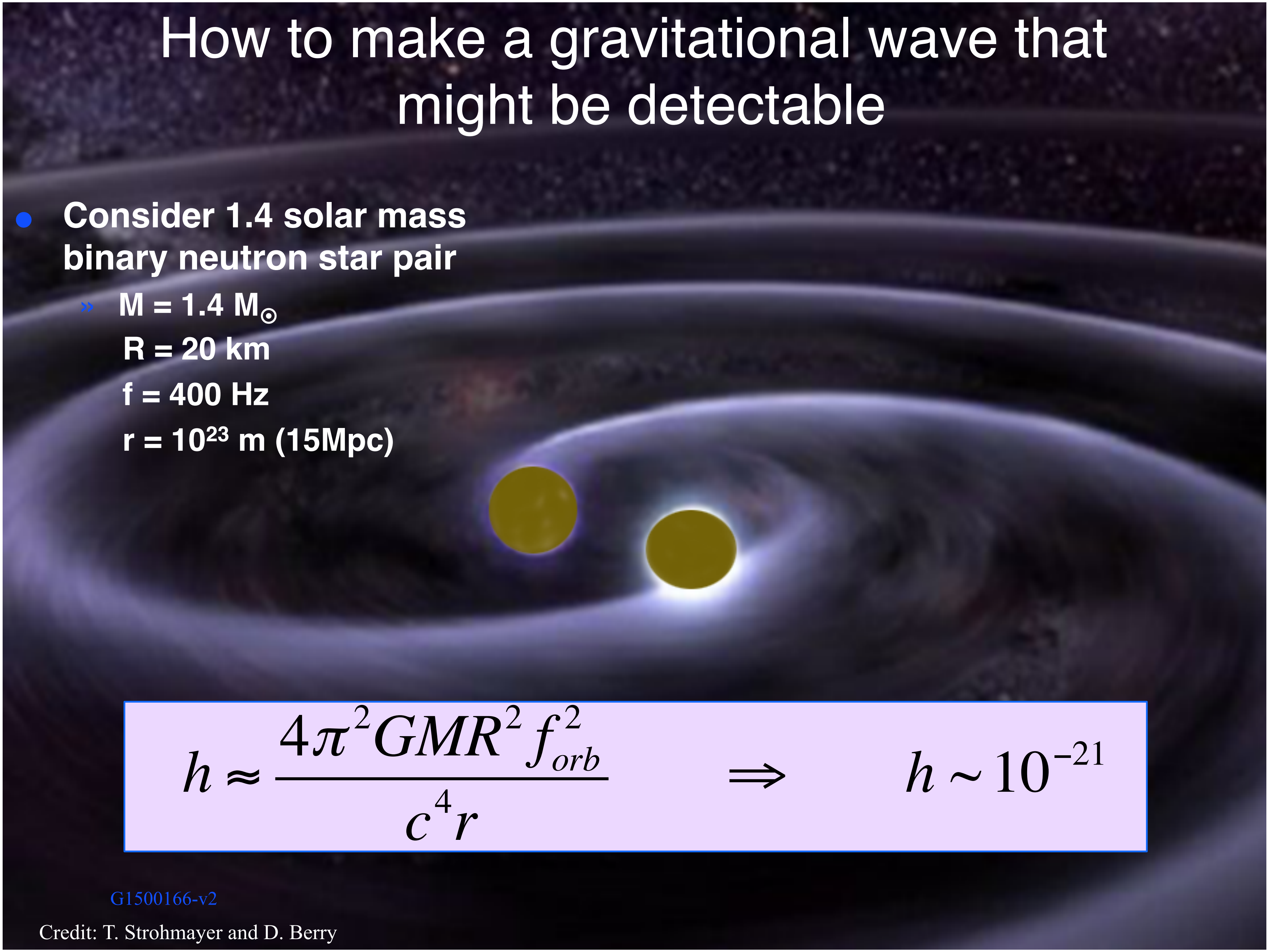
- spiral in by 3 mm/orbit
- rate of change orbital period

Emission of gravitational waves



How to make a gravitational wave that might be detectable

- **Consider 1.4 solar mass binary neutron star pair**
  - **$M = 1.4\ M_\odot$**
    $R = 20$ km
    $f = 400$ Hz
    $r = 10^{23}$ m (15Mpc)

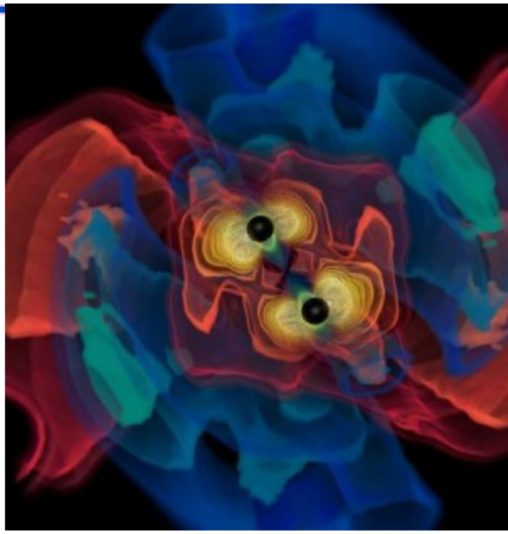


$$h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r} \quad \Rightarrow \quad h \sim 10^{-21}$$

G1500166-v2

Credit: T. Strohmayer and D. Berry

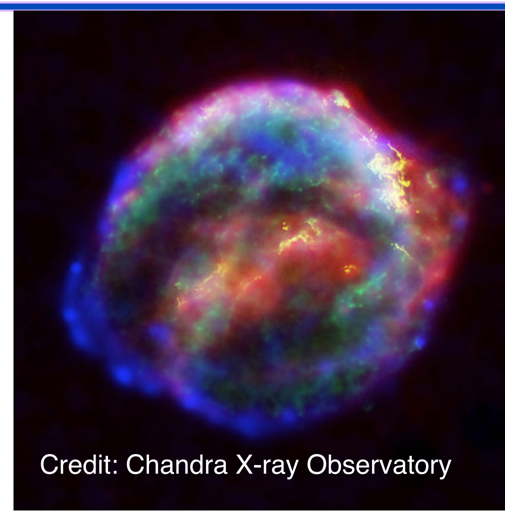
Astrophysical sources of gravitational waves



Credit: AEI, CCT, LSU

<u>Coalescing Compact Binary Systems</u>: Neutron Star-NS, Black Hole-NS, BH-BH

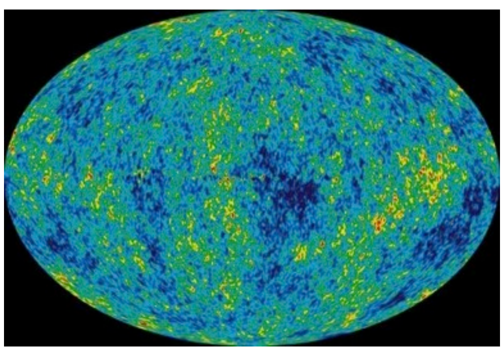
- Strong emitters, well-modeled,
- (effectively) transient



Credit: Chandra X-ray Observatory

<u>Asymmetric Core Collapse Supernovae</u>

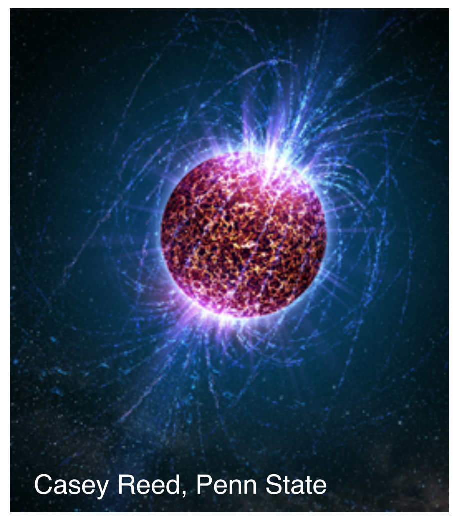
- Weak emitters, not well-modeled ('bursts'), transient
- Also: cosmic strings, SGRs, pulsar glitches



NASA/WMAP Science Team

<u>Cosmic Gravitational-wave Background</u>

- Residue of the Big Bang
- Long duration, stochastic background



Casey Reed, Penn State

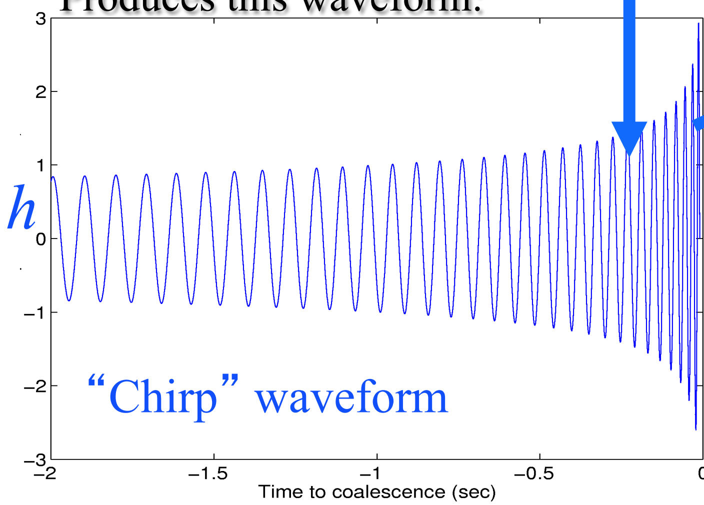
<u>Spinning neutron stars</u>

- (nearly) monotonic waveform
- Long duration

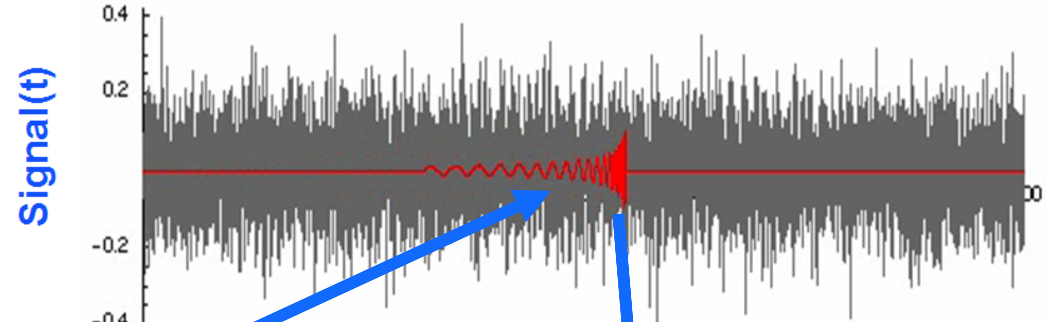
Searching for compact binary coalescences

This source:

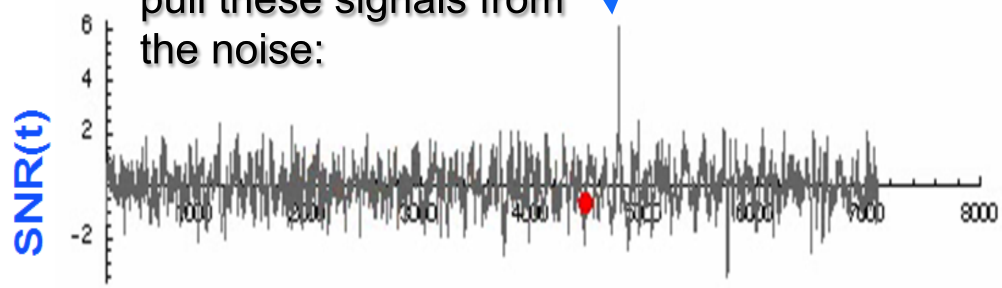
Produces this waveform:



Buried in this noise stream:

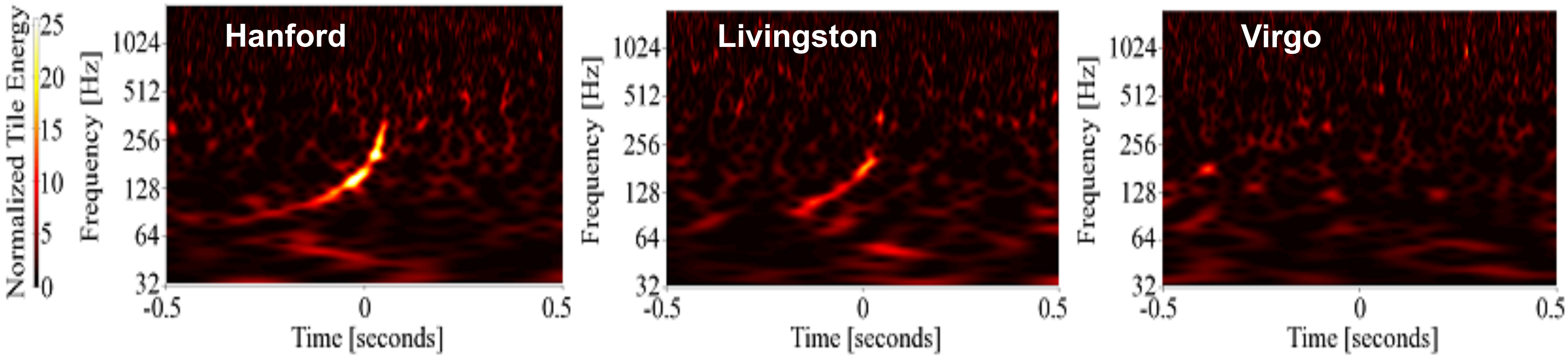


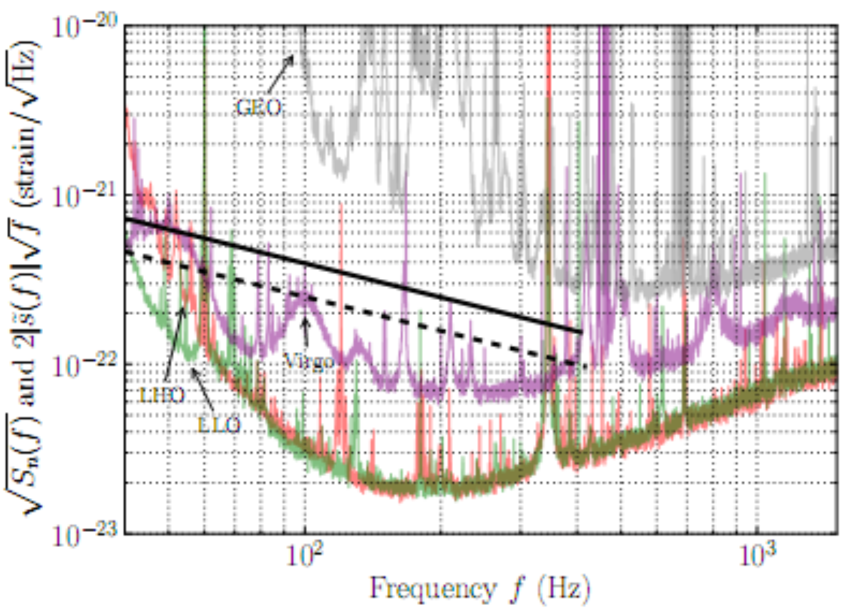
We use different methods (in this case matched templating) to pull these signals from the noise:

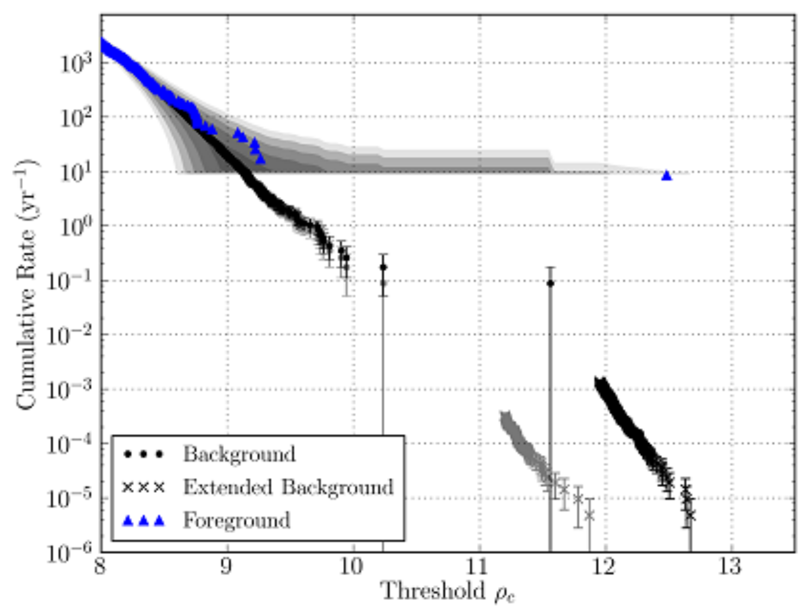


Event GW100916: a test injection

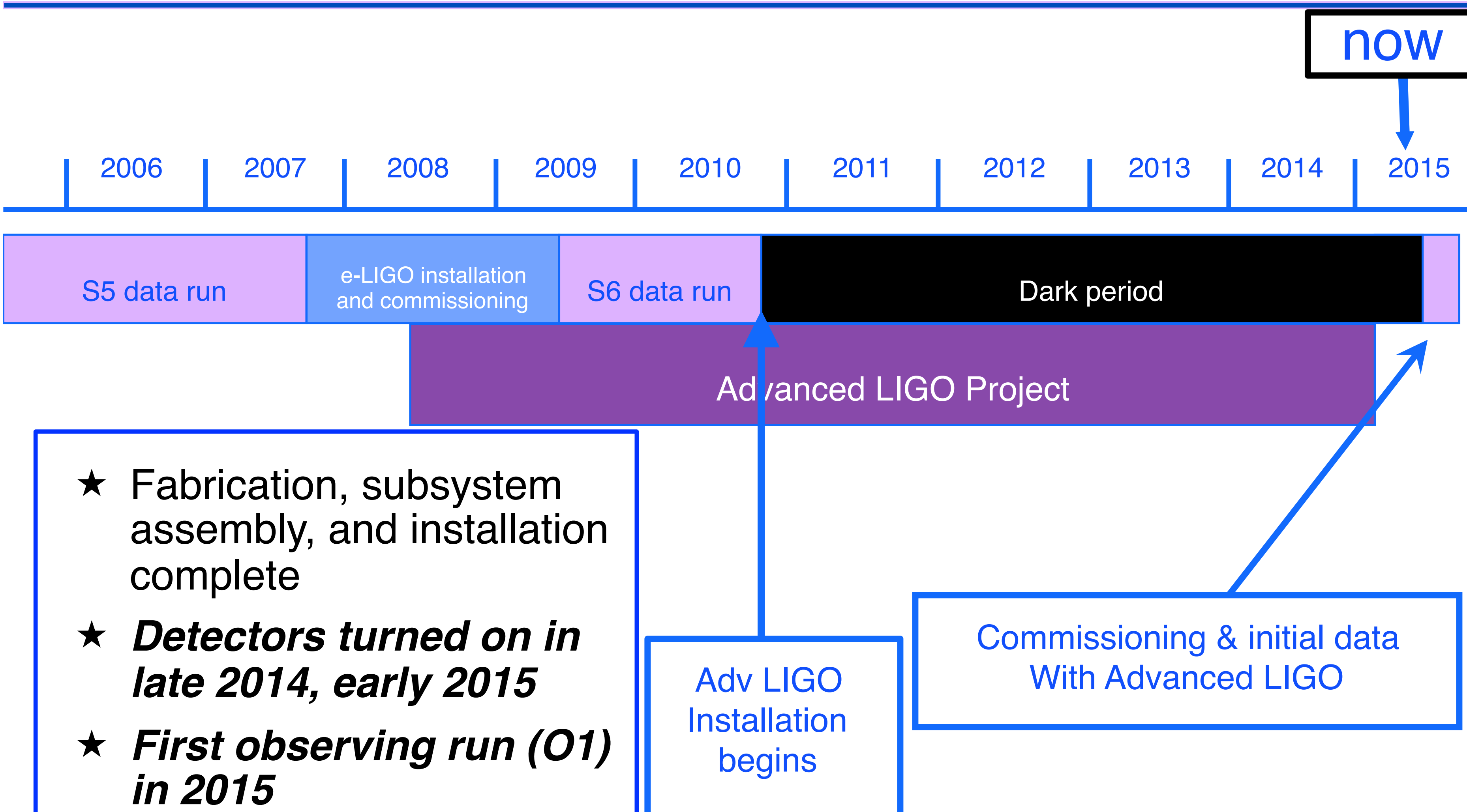
http://www.ligo.org/science/GW100916/





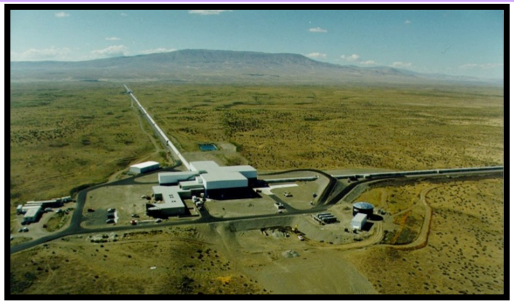


LIGO time line

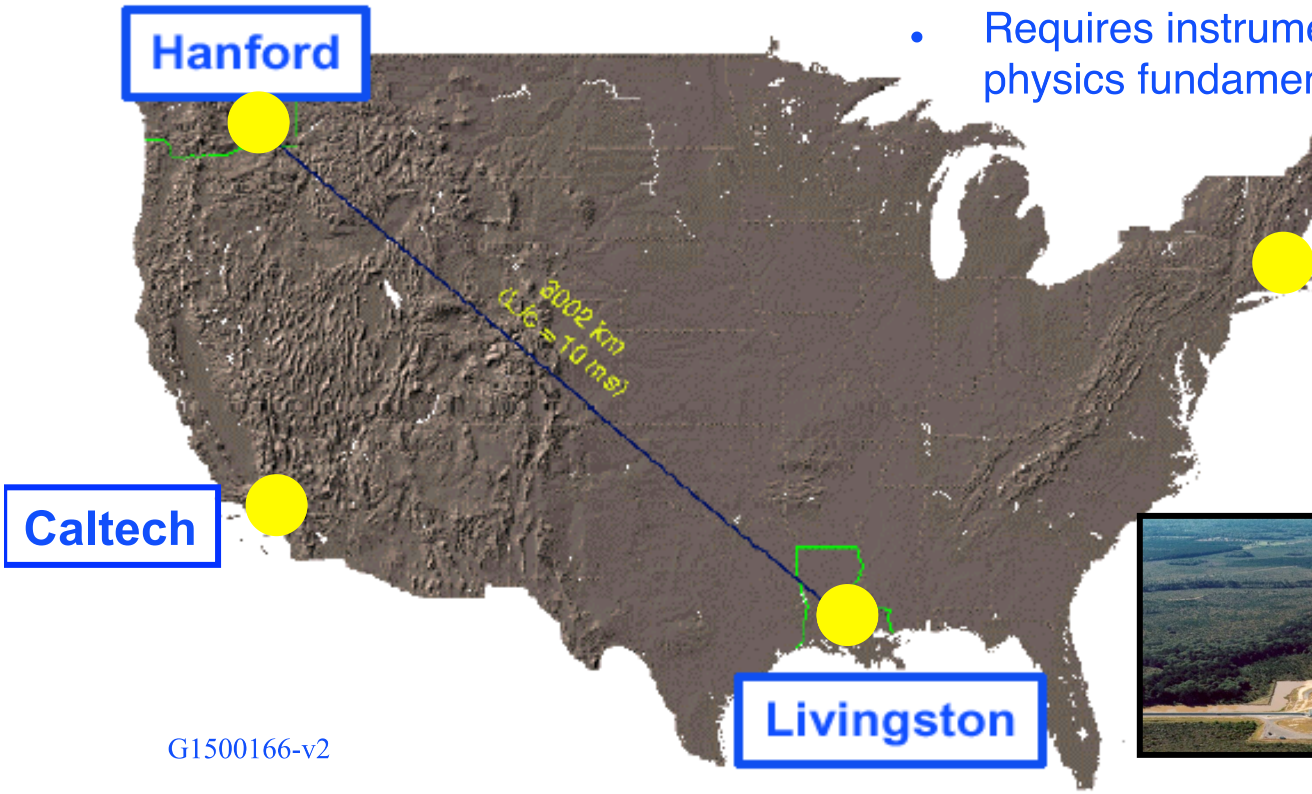


- ★ Fabrication, subsystem assembly, and installation complete
- ★ ***Detectors turned on in late 2014, early 2015***
- ★ ***First observing run (O1) in 2015***

LIGO Laboratory: two observatories, Caltech and MIT campuses



- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; responsible for operating LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits



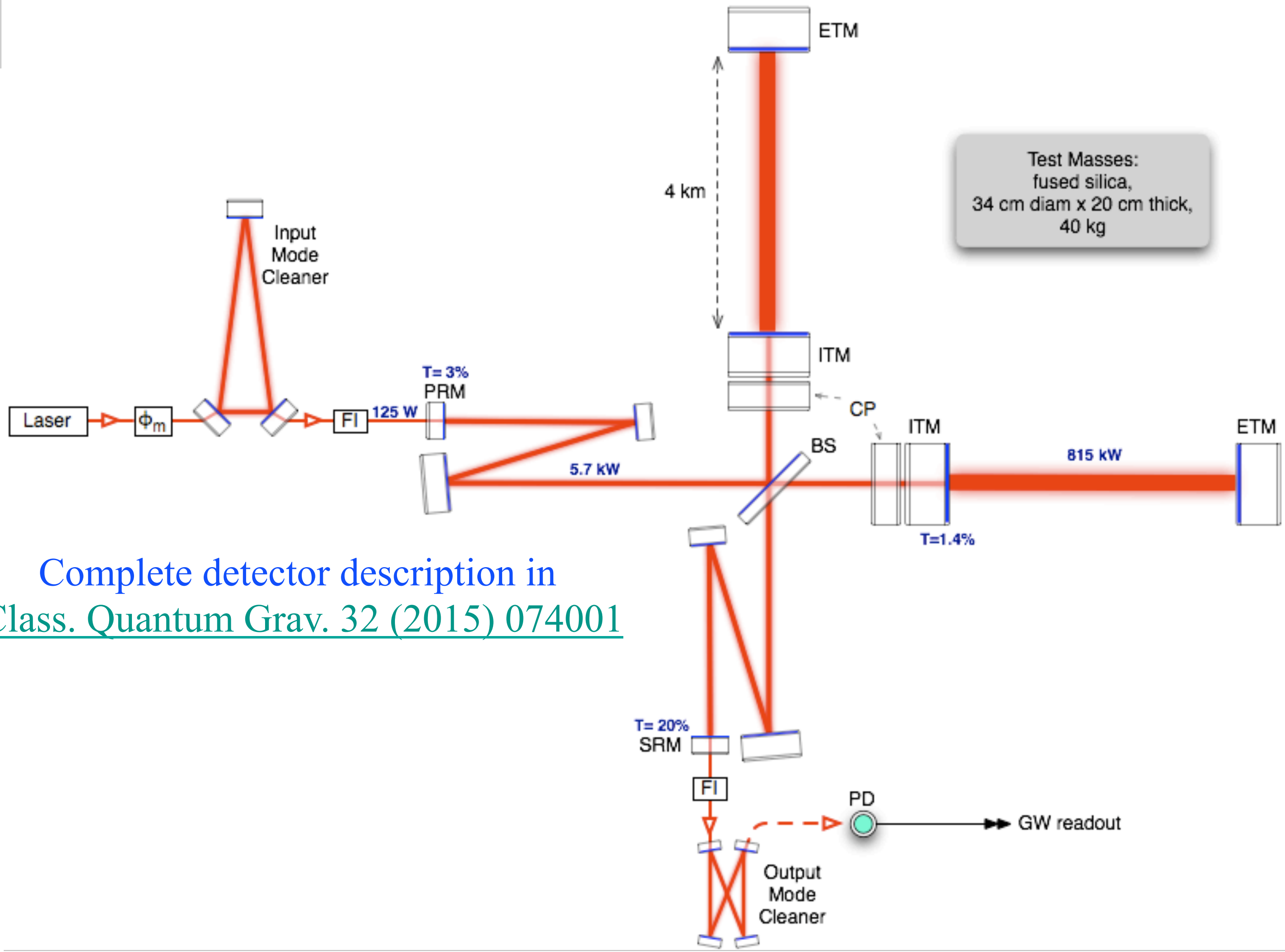
LIGO Scientific Collaboration

LIGO

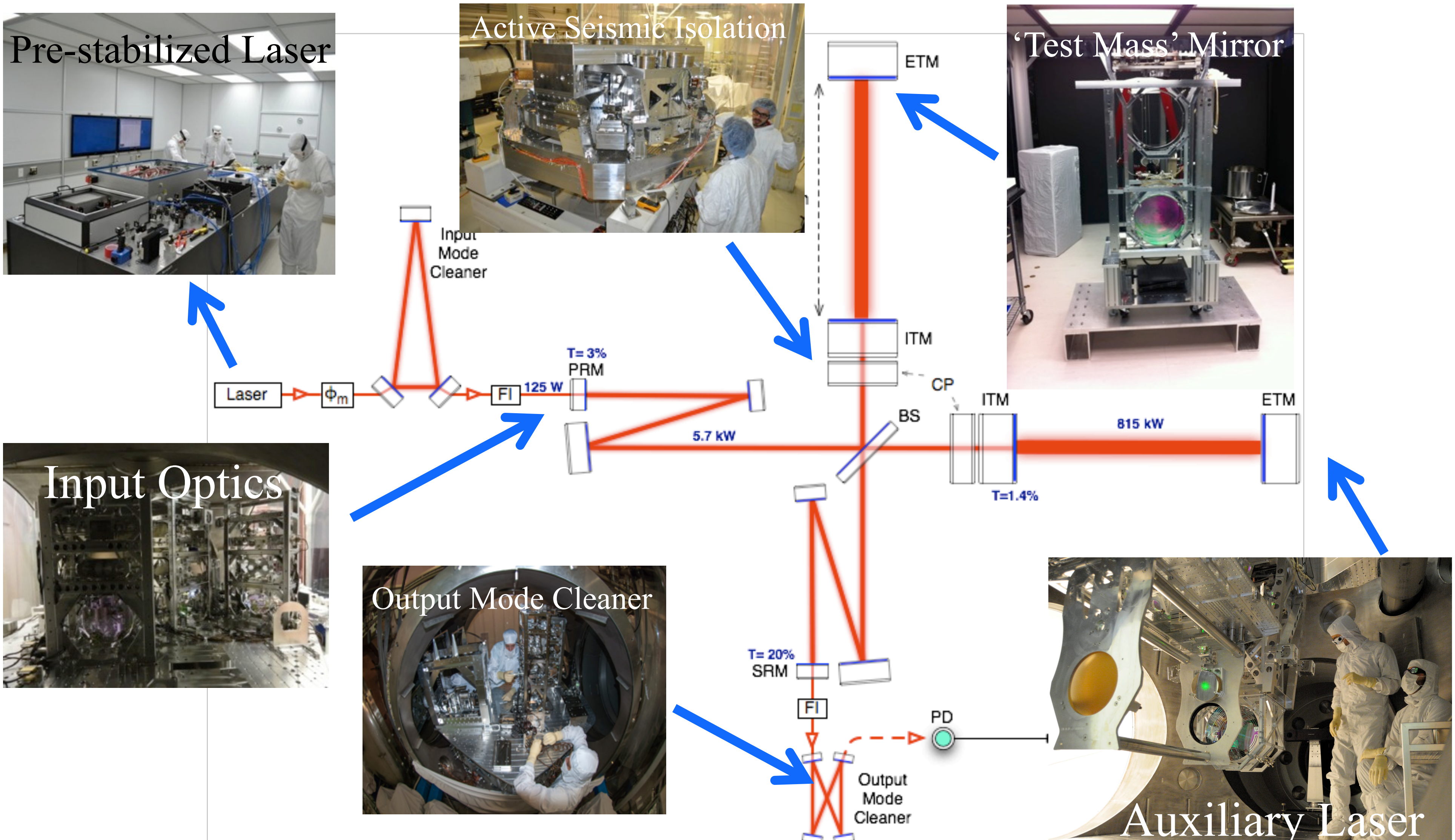
LSC

Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
indigo
The Australian National University (ANU)
Seal of Texas Tech University
R·I·T
ICTP SAIFR
Montana State University
American University, Washington, DC
Sonoma State University
University of the West of Scotland (UWS)
Montclair State University
清華大學 Tsinghua University
University of Strathclyde
Michigan
CITA–ICAT
University of Glasgow
NASA Goddard Space Flight Center
Whitman College
LSU
PAH
ACU
UTB TSC
University of Cambridge
Massachusetts Institute of Technology
Southern University Agricultural & Mechanical College
The University of Western Australia
Universitas Scientiarum Szegediensis
California Institute of Technology
University of Minnesota
The University of Mississippi
The University of Adelaide Australia
The University of Melbourne
Embry-Riddle Aeronautical University
Universitas Budapestinensis de Rolando Eötvös Nominata
University of Washington
Northwestern University
GEO 600
Universitat de les Illes Balears
Carleton College
Georgia Tech
Syracuse University
Cardiff University
UF University of Florida
Charles Sturt University
Tsing Hua University
Universität Hamburg
UW Milwaukee, University of Wisconsin
Korean Gravitational-Wave Group
ACIGA
University of Southampton
Penn State
University of Rochester
Leibniz Universität Hannover
Hobart and William Smith Colleges
Science & Technology Facilities Council Rutherford Appleton Laboratory

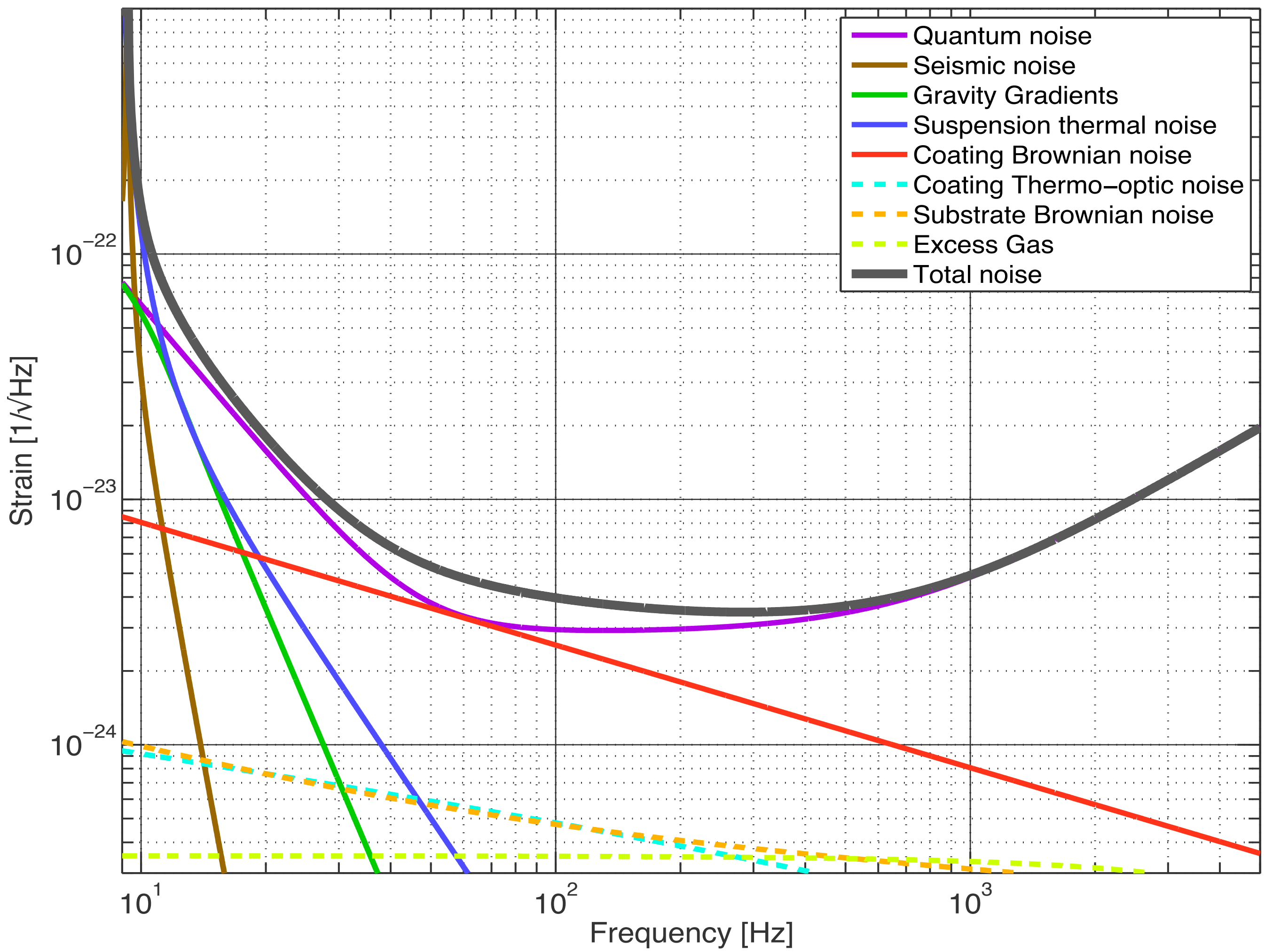
Optical configuration



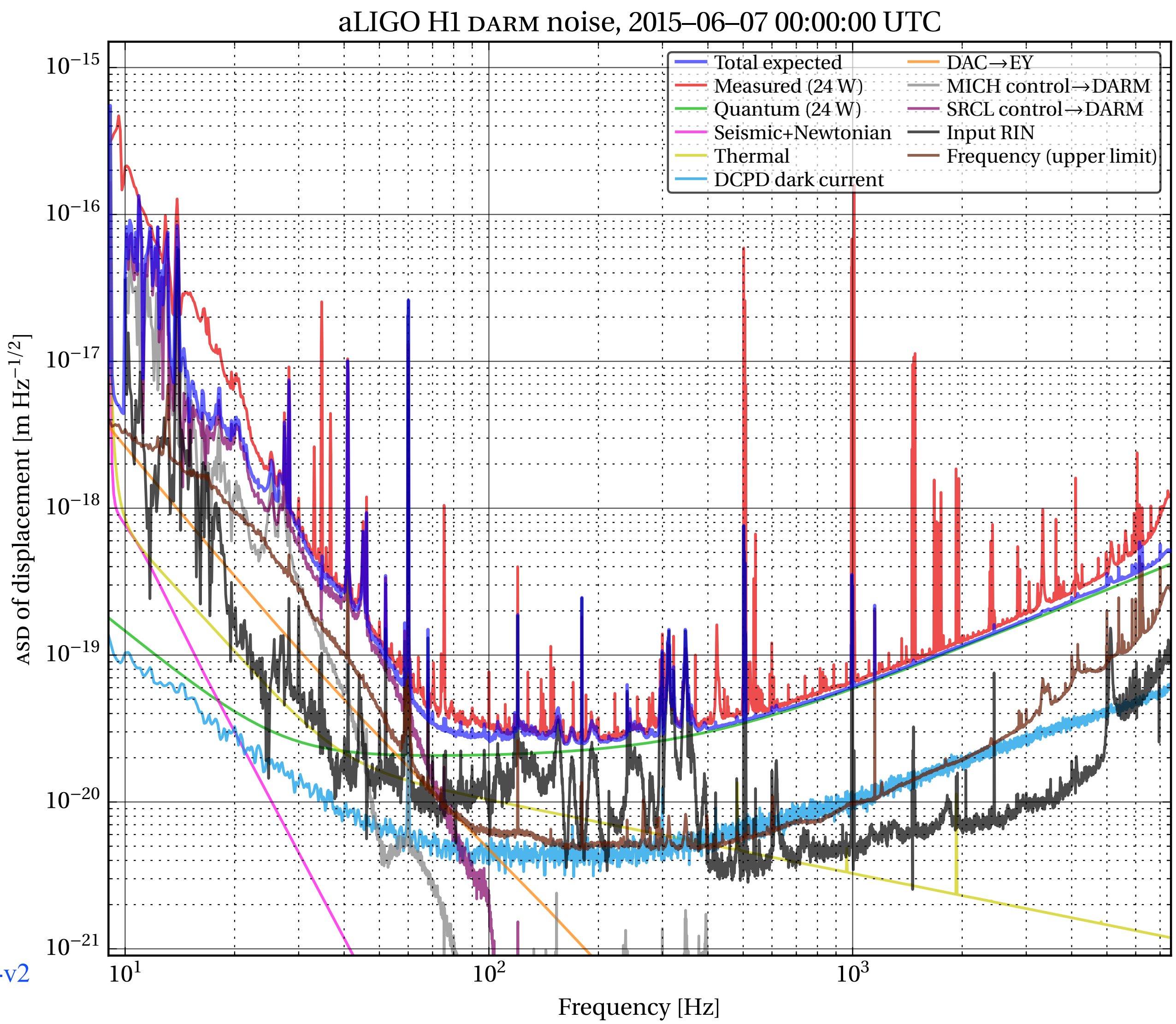
Complete detector description in
Class. Quantum Grav. 32 (2015) 074001


Pre-stabilized Laser
Active Seismic Isolation
'Test Mass' Mirror
Input Optics
Output Mode Cleaner
Auxiliary Laser
ETM
ITM
CP
BS
ITM
ETM
815 kW
T=1.4%
Input
Mode
Cleaner
T= 3%
PRM
Laser
Φ_m
FI
125 W
5.7 kW
T= 20%
SRM
FI
PD
Output
Mode
Cleaner

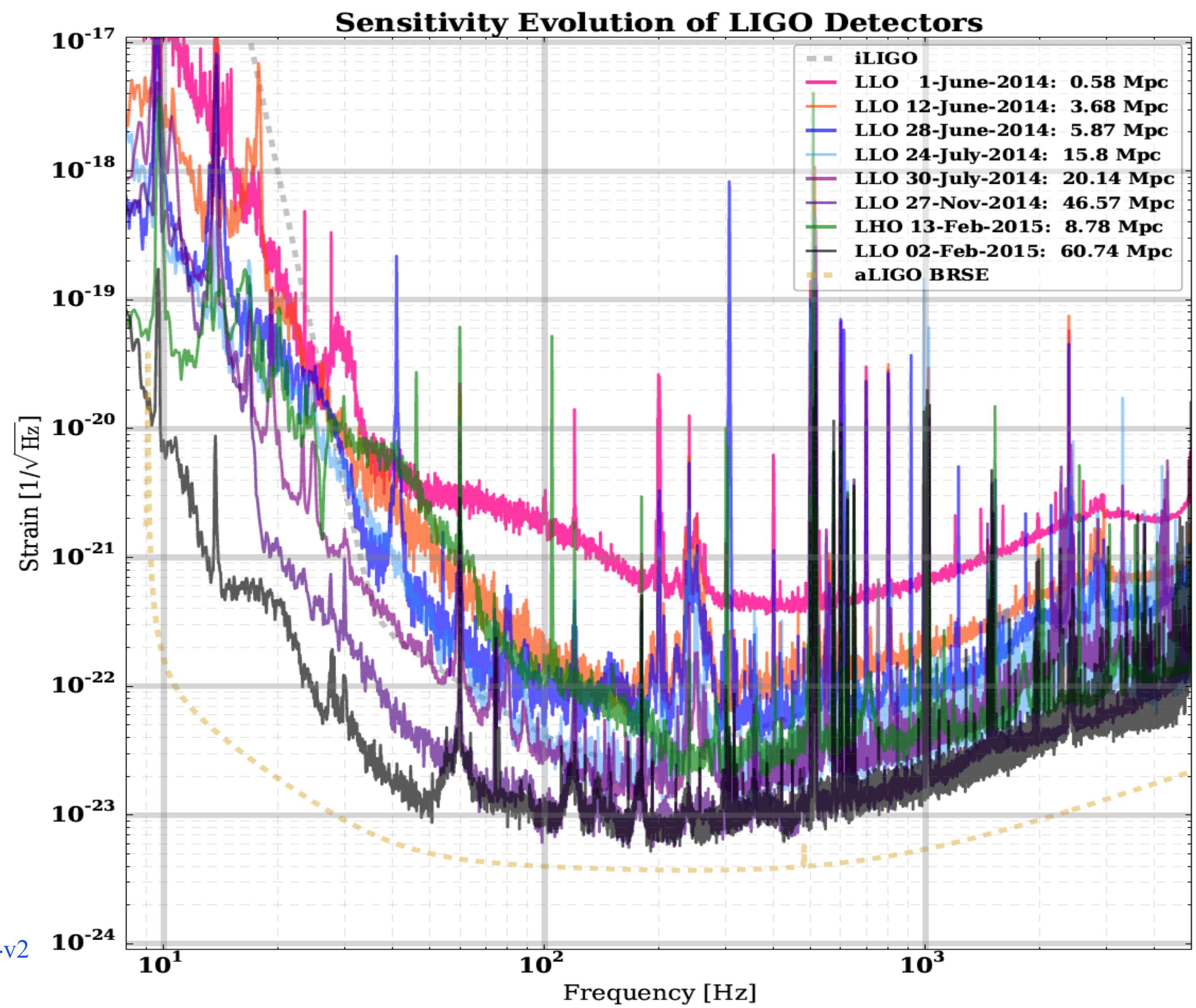
Principal noise terms



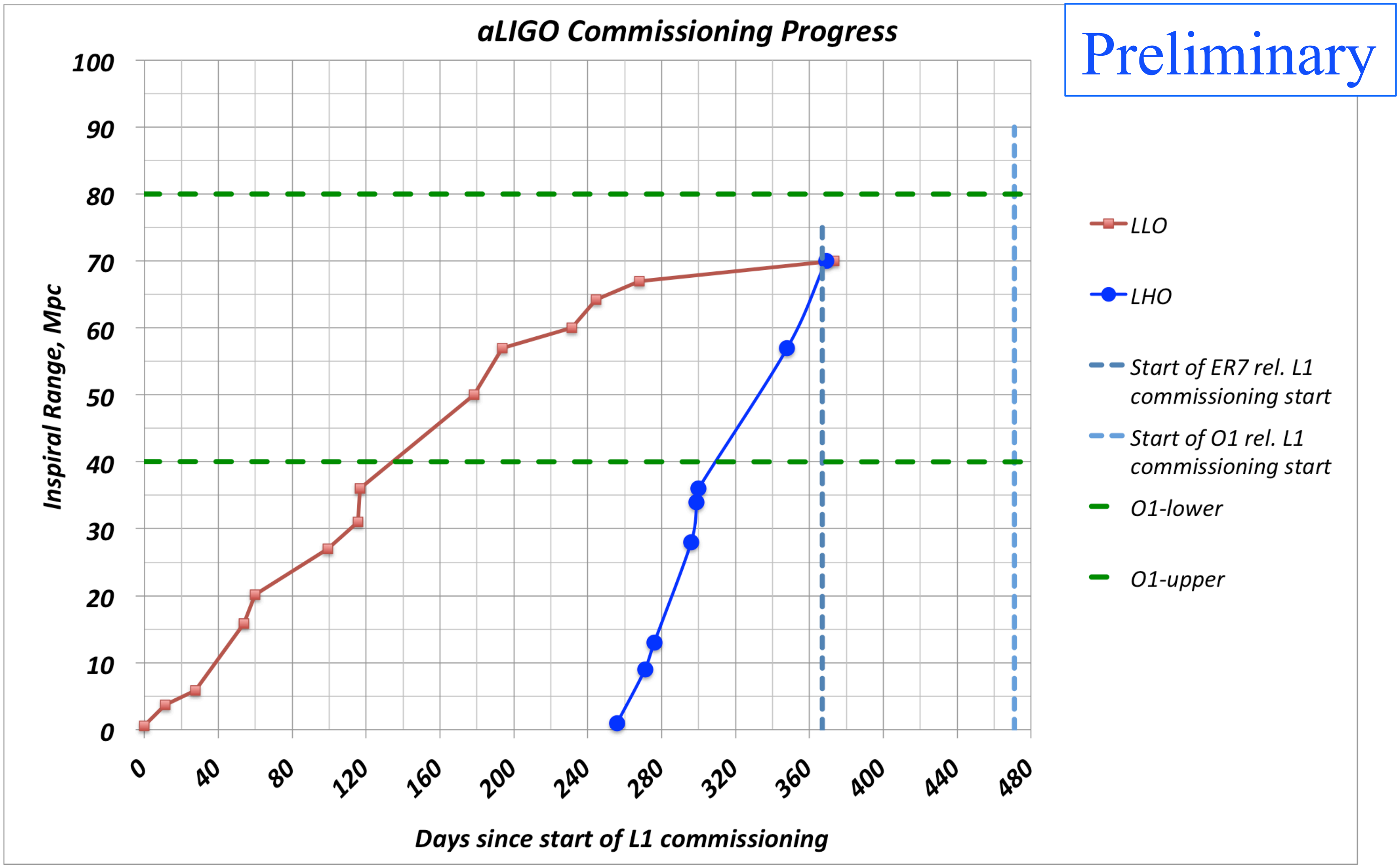
H1 noise budget



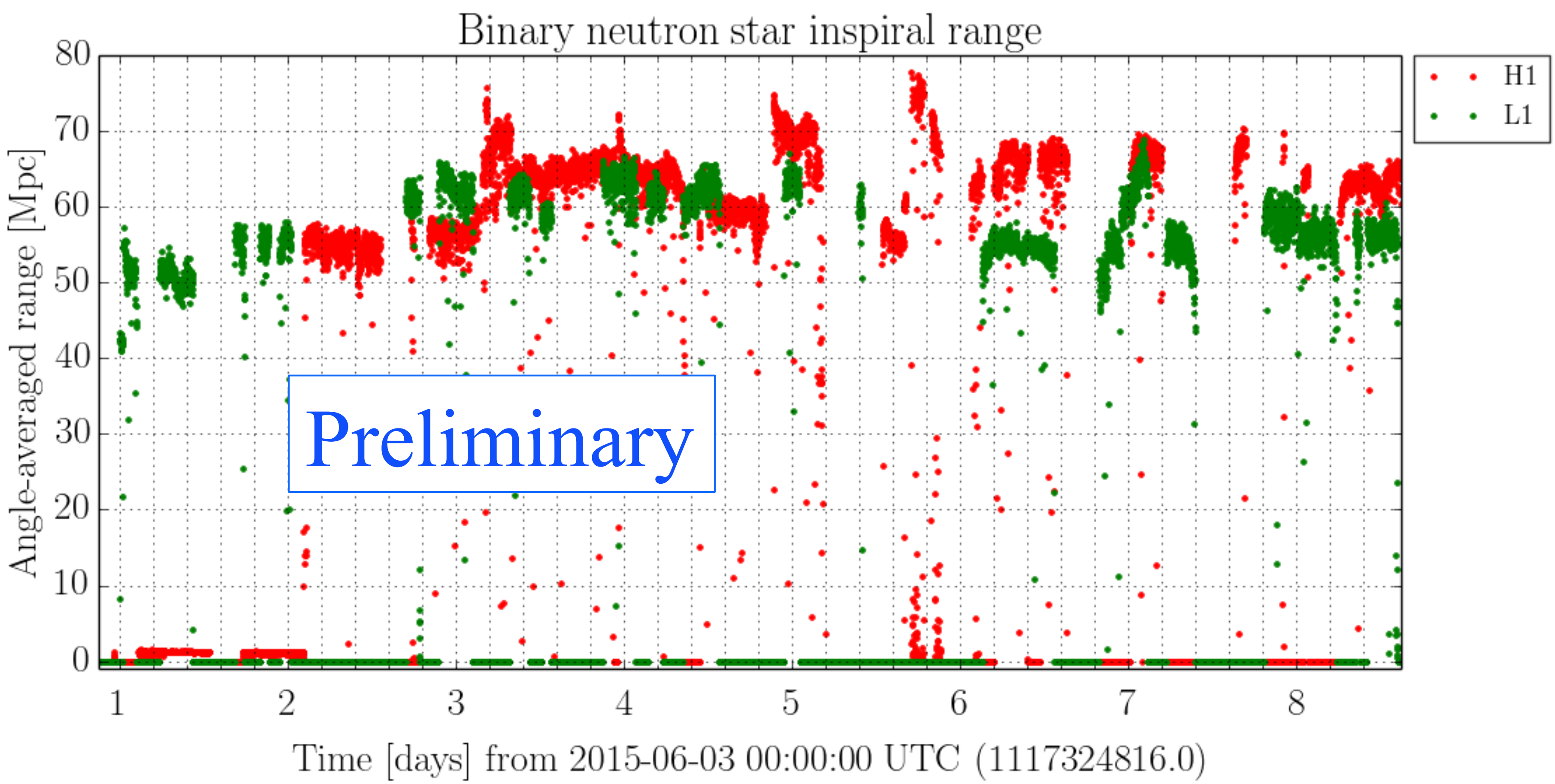
LIGO Sensitivity Progression



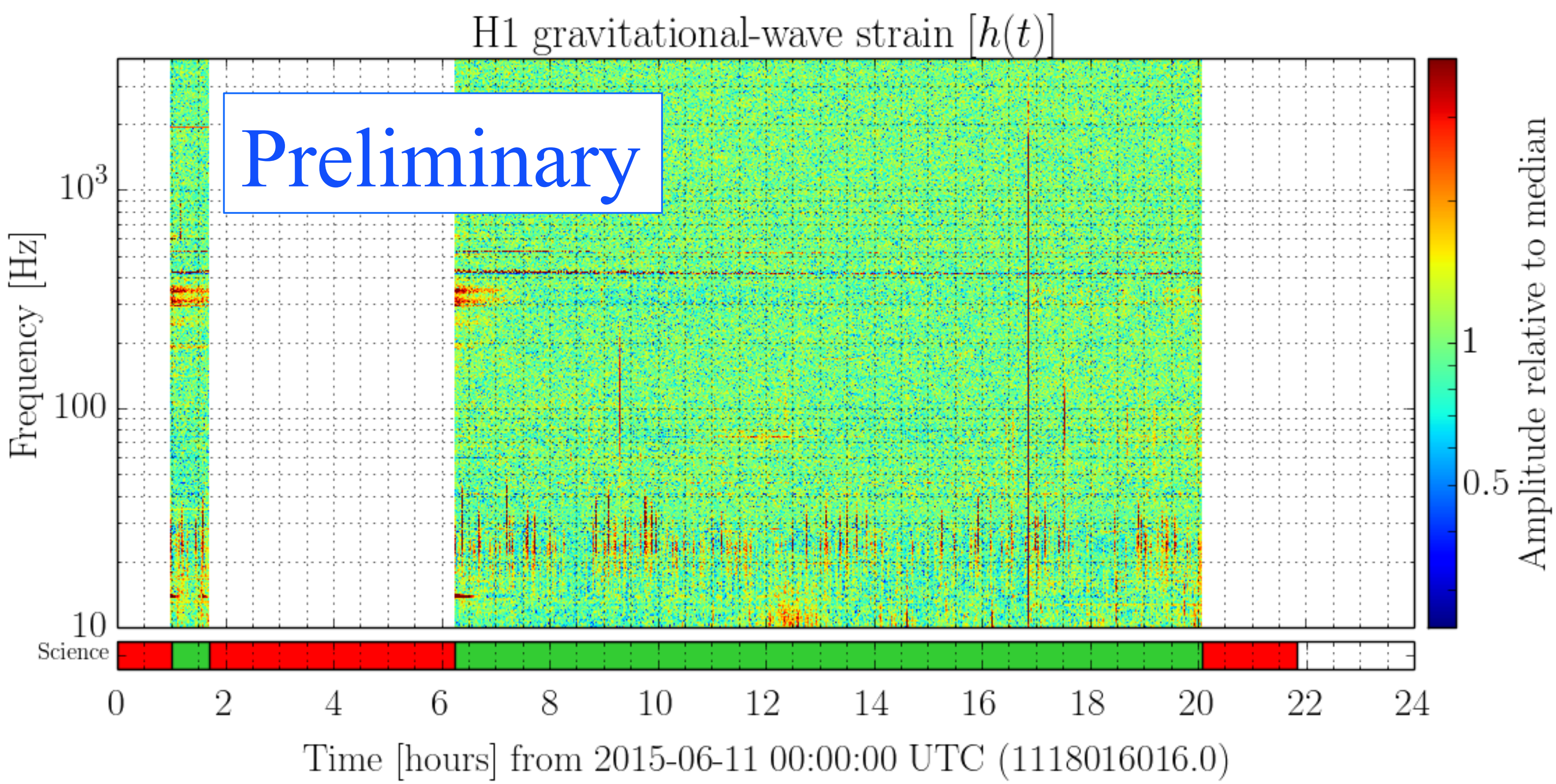
Rapid improvement in reach



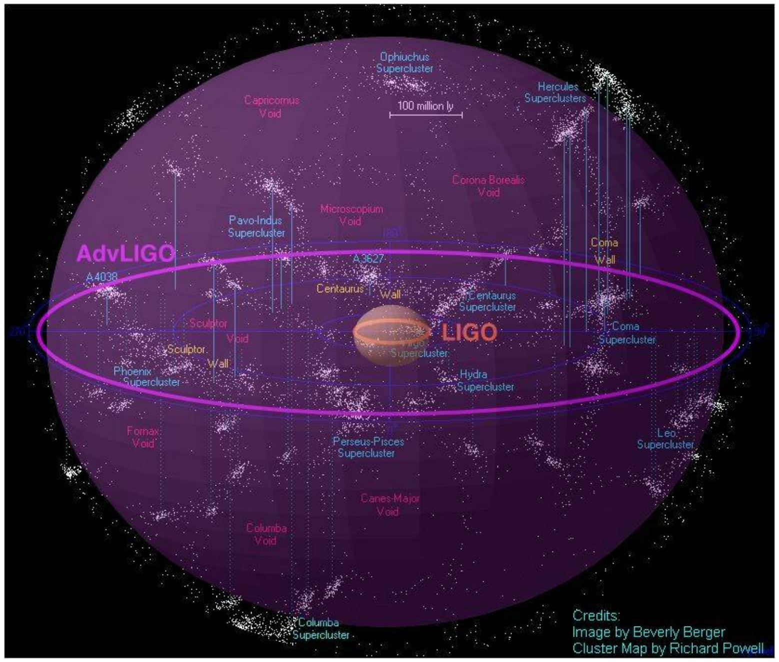
First joint engineering run



Tracking transients



Expected event rates



Binary neutron stars

- Initial LIGO reach: 15Mpc; rate ~ 1/50yrs
- Advanced LIGO ~ 200Mpc
- ‘Realistic’ rate ~ 40 events/yr

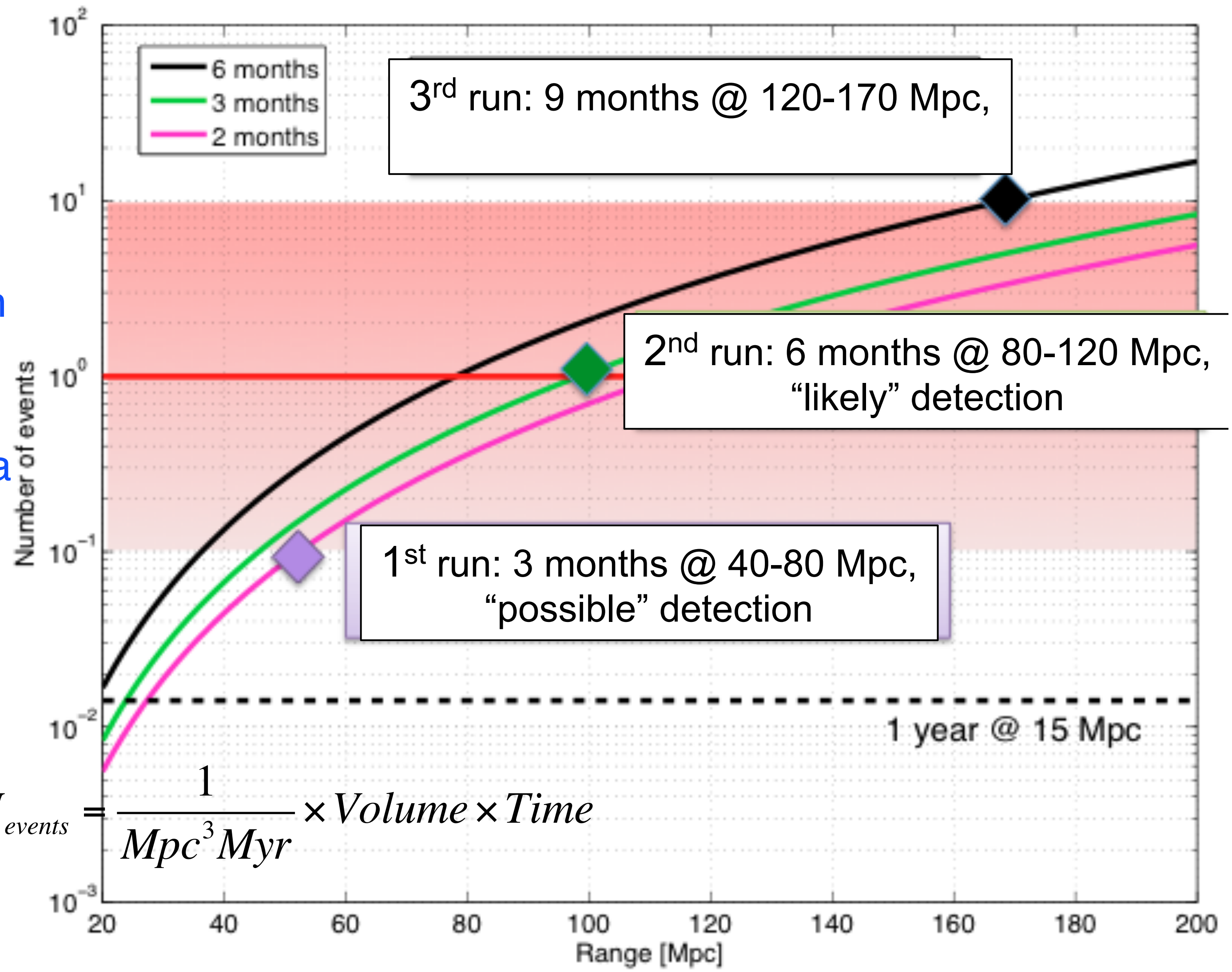
Rates paper: Class. Quant. Grav, 27 (2010) 173001

Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
Initial	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
Advanced	BH–BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

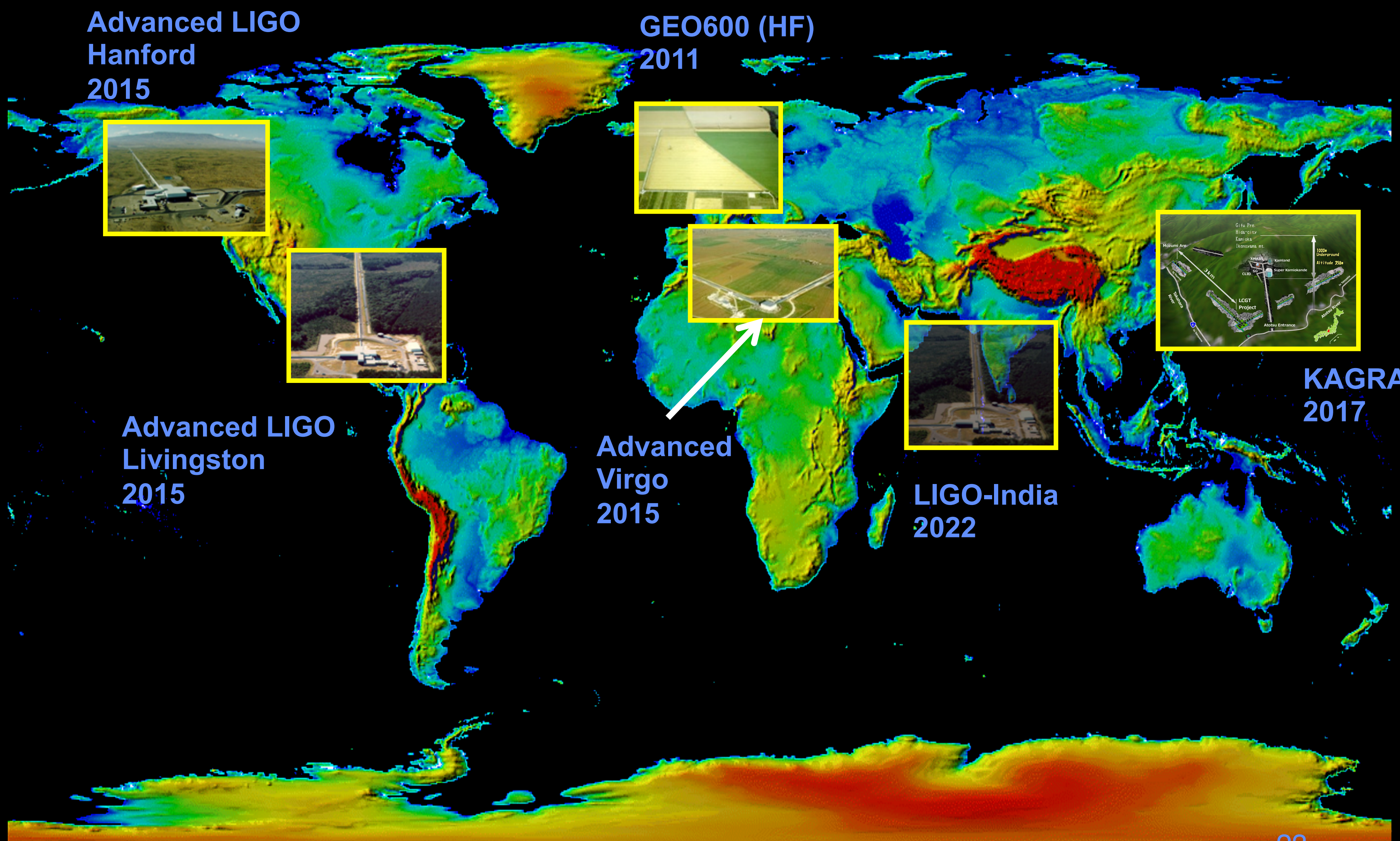
Current guess for sensitivity evolution, observation

- Vertical scale is the number of binary inspirals detected
- Rates based on population synthesis, realistic but uncertain
- LIGO Scientific Collaboration (LSC) preparing for the data analysis challenge
- Close collaboration with Virgo
- Early detection looks feasible
- arXiv:1304.0670, arXiv:1003.2480



$$N_{events} = \frac{1}{Mpc^3 Myr} \times Volume \times Time$$

The advanced GW detector network: 2015-2025



- The Advanced LIGO detector has completed a comprehensive 7 year upgrade
- LIGO will resume the search for gravitational waves in the Fall of 2015
- The next few years should be very interesting ones for the field of gravitational-wave science!