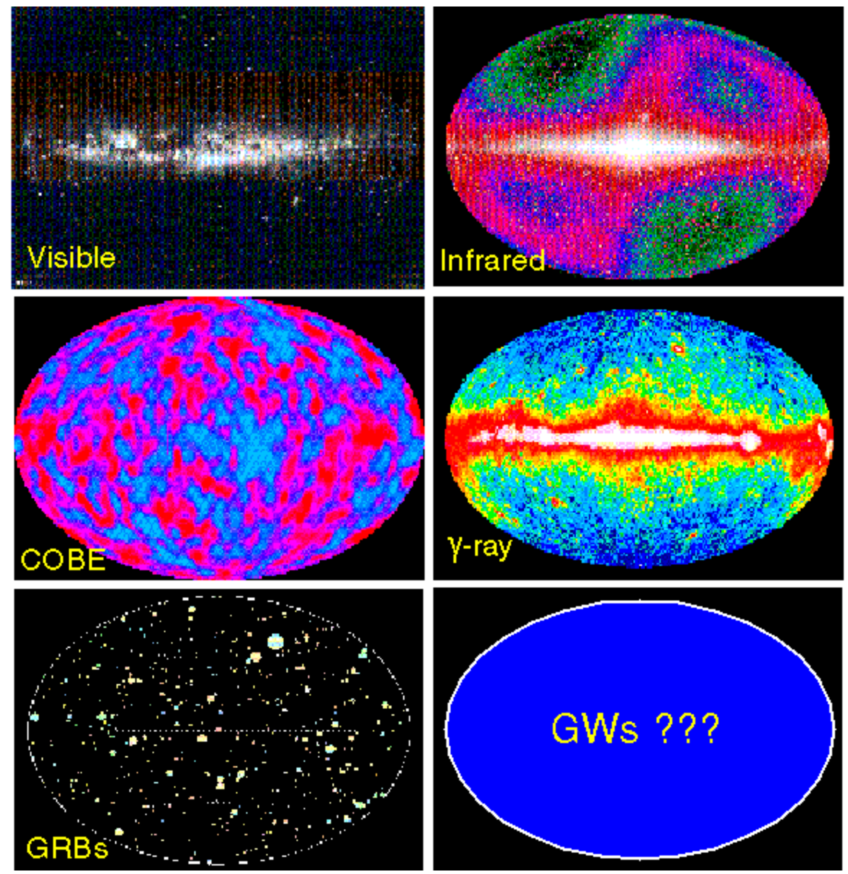
Advanced LIGO : Aiming for the detection of the gravitational wave signal, and beyond

Hiro Yamamoto LIGO lab/Caltech

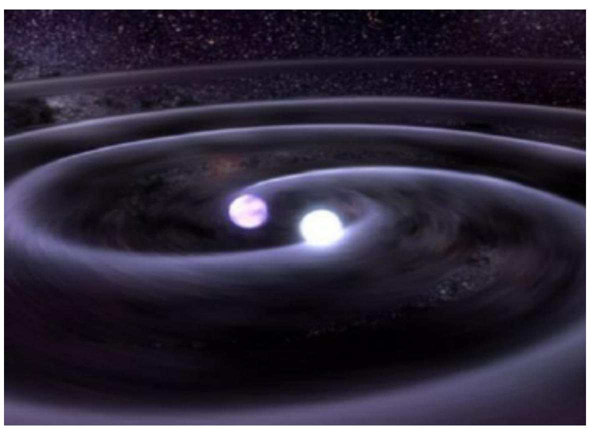
- New Astronomy by gravitational wave signal at the 100th memorial year of general relativity
  - » In the beginning…
- 2nd generation detector - advanced LIGO
- Targeting the first observation
- Aiming for the future

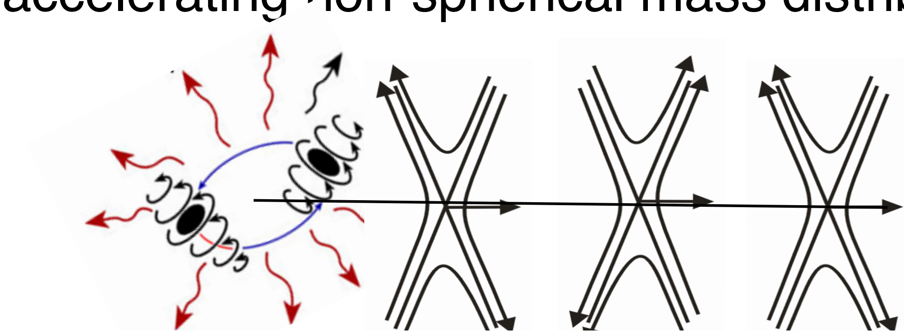


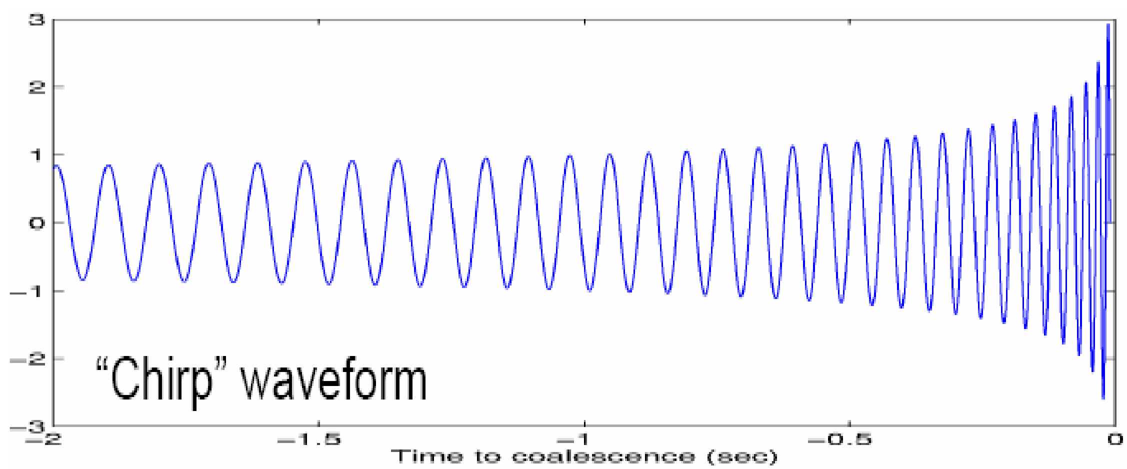
Some slides are copied from talks in 2015 March LVC meeting and from the talk by D. Reitze G1500139

Gravitational waves

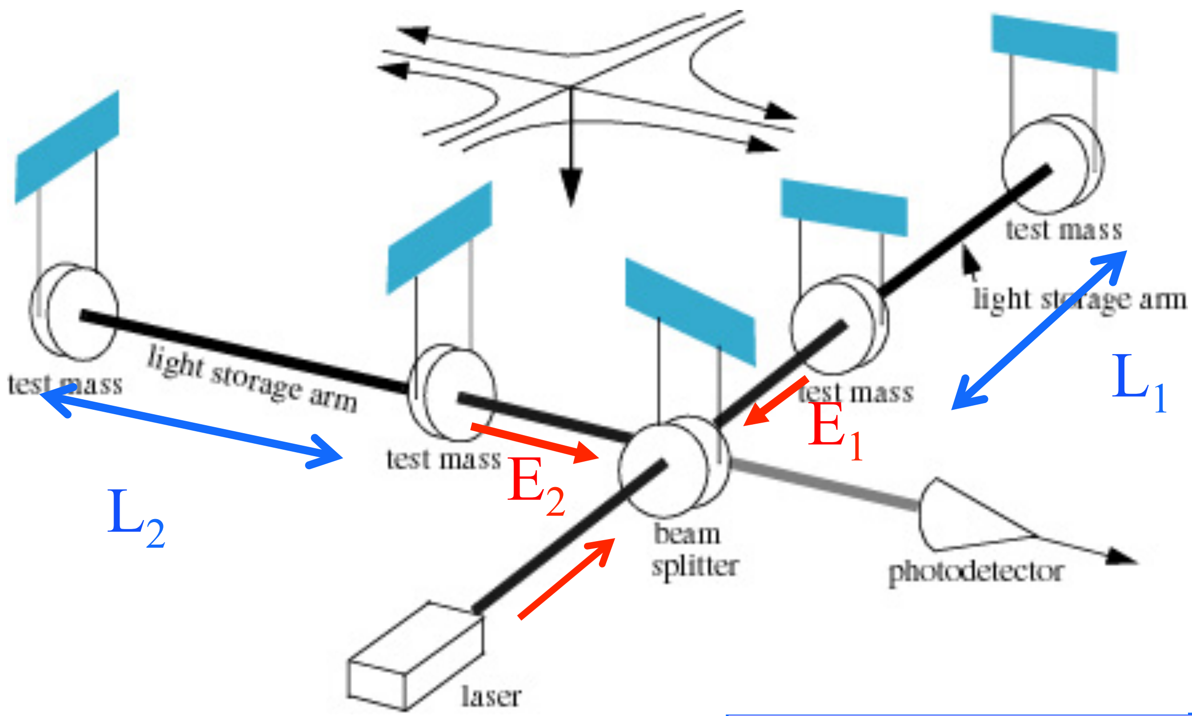
- Gravitational waves are propagating dynamic fluctuations in the curvature of space-time (‘ripples’ in space-time)
- Emissions from rapidly accelerating non-spherical mass distributions
  - » Quadrupolar radiation







Interferometer for Gravitational Wave detection



$E_1 - E_2 \propto L_1 - L_2$

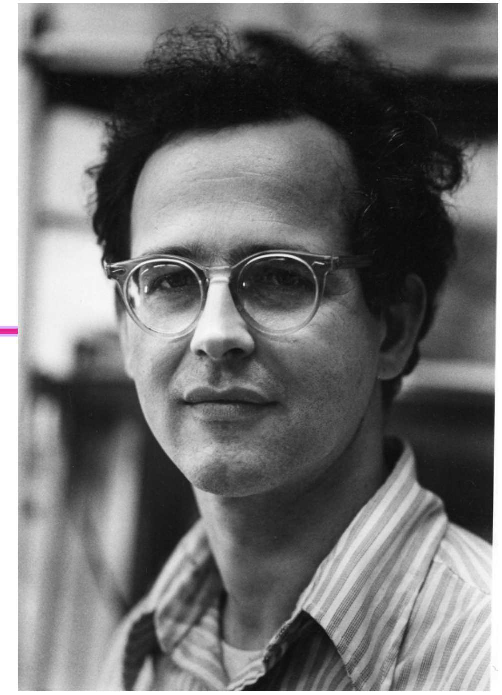
$$h = \frac{L_1 - L_2}{L_1 + L_2}$$

$h \sim 10^{-23}$

$L_1 - L_2 \sim 10^{-19}$ m

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

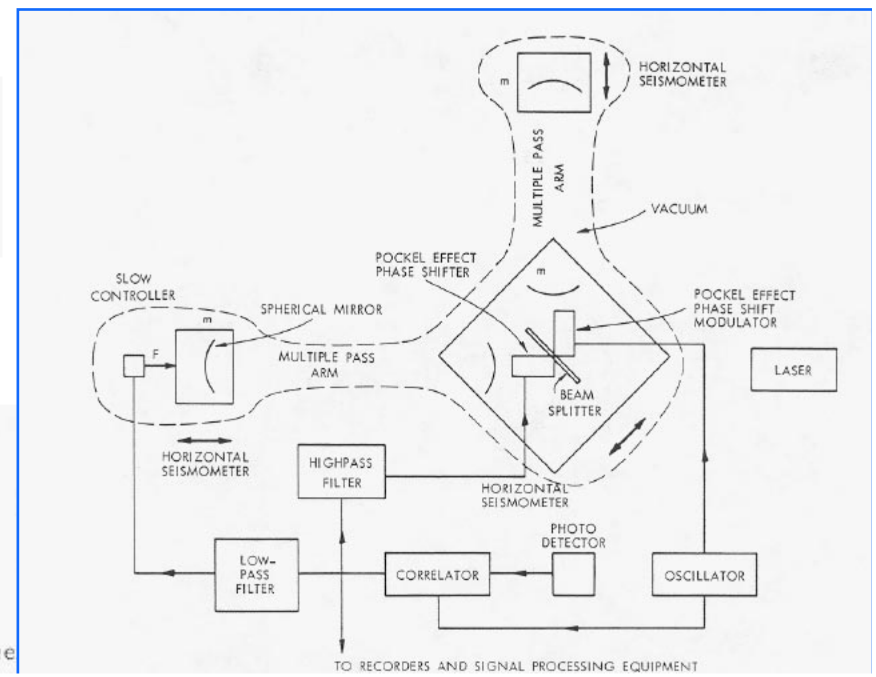
CAMBRIDGE, MASSACHUSETTS 02139

(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

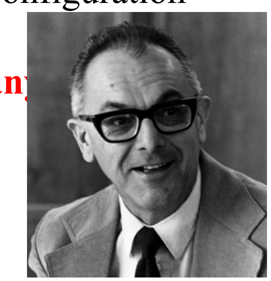
LIGO Chronology
idea to realization ~ 15 years


Weiss

Real size R&D for the real detection

Journey for the new astronomy

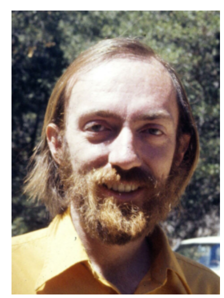
1970s		Feasibility studies and early work on laser interferometer gravitational-wave detectors
1979		National Science Foundation (NSF) funds Caltech and MIT for laser interferometer R&D
1984		Development of multiple pendulum Advanced LIGO Concept
1989	**December**	**Construction proposal for LIGO submitted 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

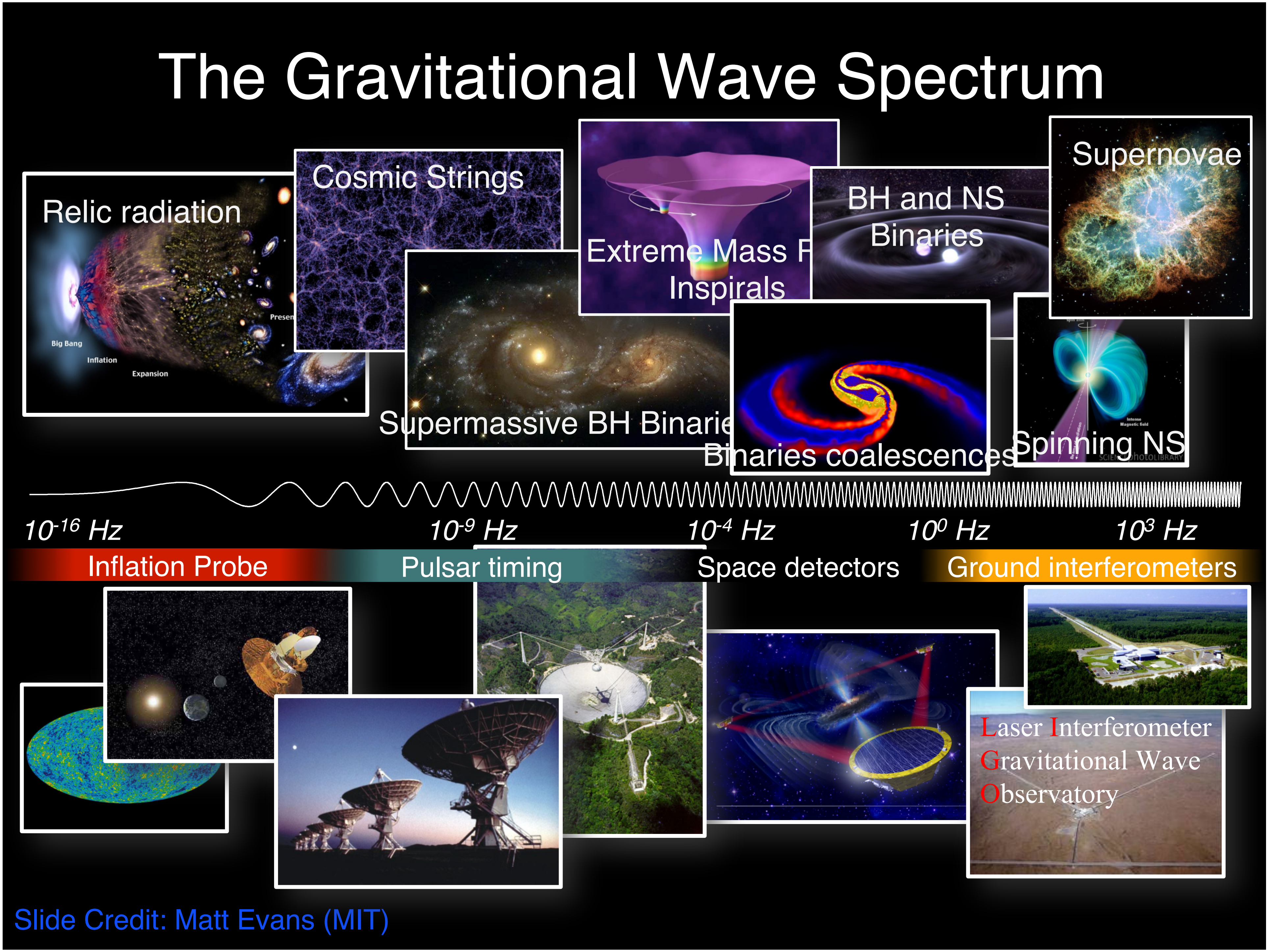
Initial LIGO events

Advanced LIGO events

R&D of aLIGO using iLIGO facility


Thorn

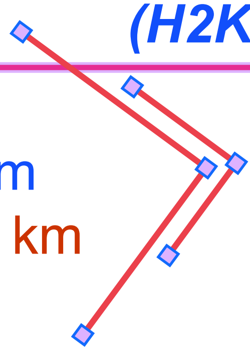
Executive producer & consultant of movie “Intersteller”



The Gravitational Wave Spectrum
Relic radiation
Big Bang
Inflation
Expansion
Cosmic Strings
Extreme Mass
Inspirals
BH and NS
Binaries
Supernovae
Supermassive BH Binarie
Binaries coalescences
Spinning NS
10^{-16} Hz
10^{-9} Hz
10^{-4} Hz
10^{0} Hz
10^{3} Hz
Inflation Probe
Pulsar timing
Space detectors
Ground interferometers
Laser Interferometer
Gravitational Wave
Observatory
Slide Credit: Matt Evans (MIT)

LIGO sites

Hanford Observatory (H2K and H4K)



Hanford, WA (LHO)

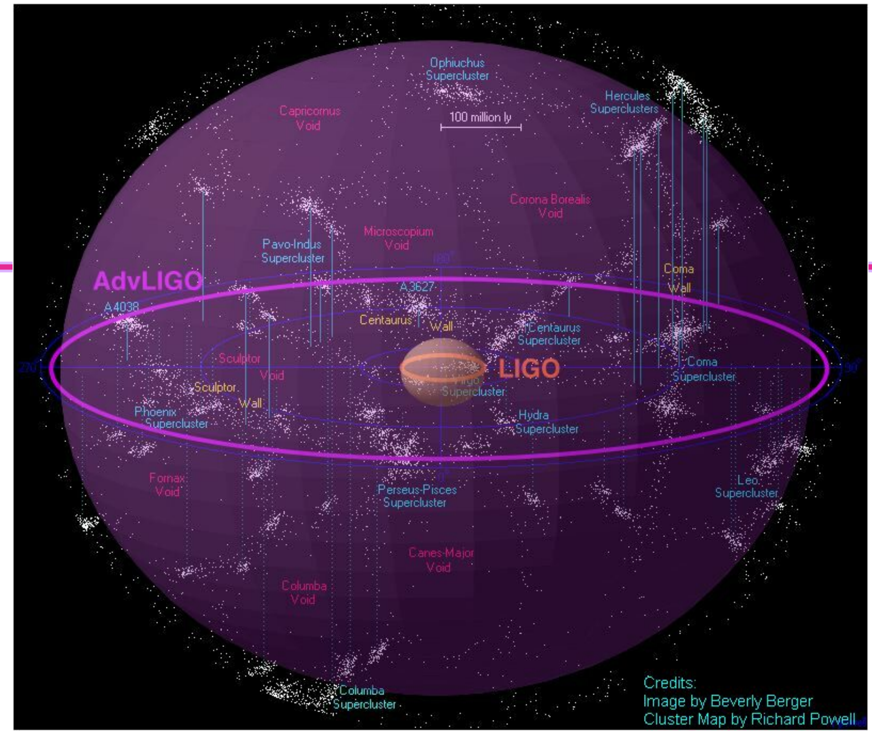
- located on DOE reservation
- treeless, semi-arid high desert
- 25 km from Richland, WA
- **iLIGO : H2K and H4K ⇒**
  aLIGO : 4k LHO + 4k LIGO-India

Livingston, LA (LLO)

- located in forested, rural area
- commercial logging, wet climate
- 50km from Baton Rouge, LA
- **One L4K IFO**

Livingston Observatory (L4K)

Advanced LIGO ~ event rates



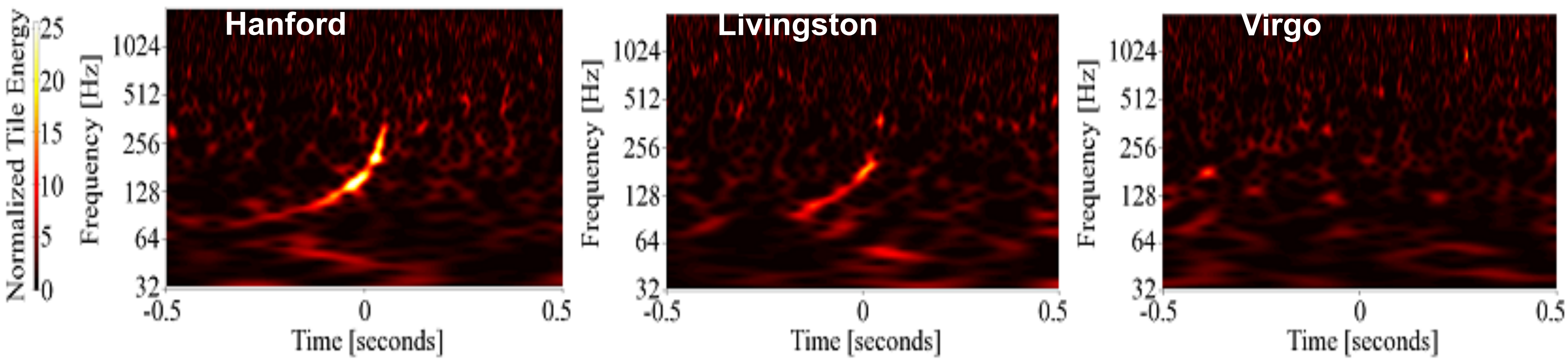
#events by advanced LIGO ~
1000 x #events by initial LIGO

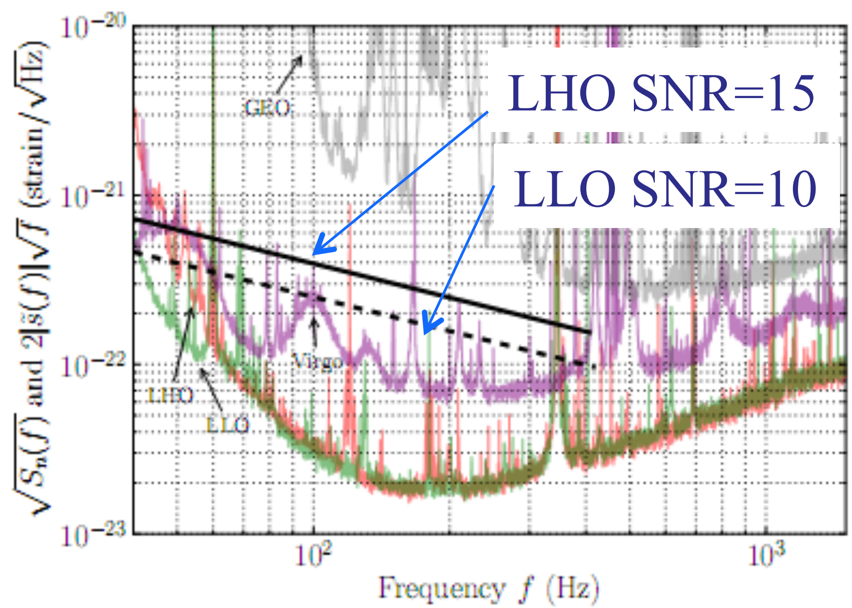
Assumes NS-NS rate between $10^{-8}\ Mpc^{-3}yr^{-1}$ and $10^{-5}\ Mpc^{-3}yr^{-1}$

Observation run	Epoch	Estimated Run Duration	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections
1	2015	3 months	40 – 80	–	0.0004 – 3
2	2016–17	6 months	80 – 120	20 – 60	0.006 – 20
3	2017–18	9 months	120 – 170	60 – 85	0.04 – 100
	2019+	(per year)	200	65 – 130	0.2 – 200
	2022+ (India)	(per year)	200	130	0.4 – 400

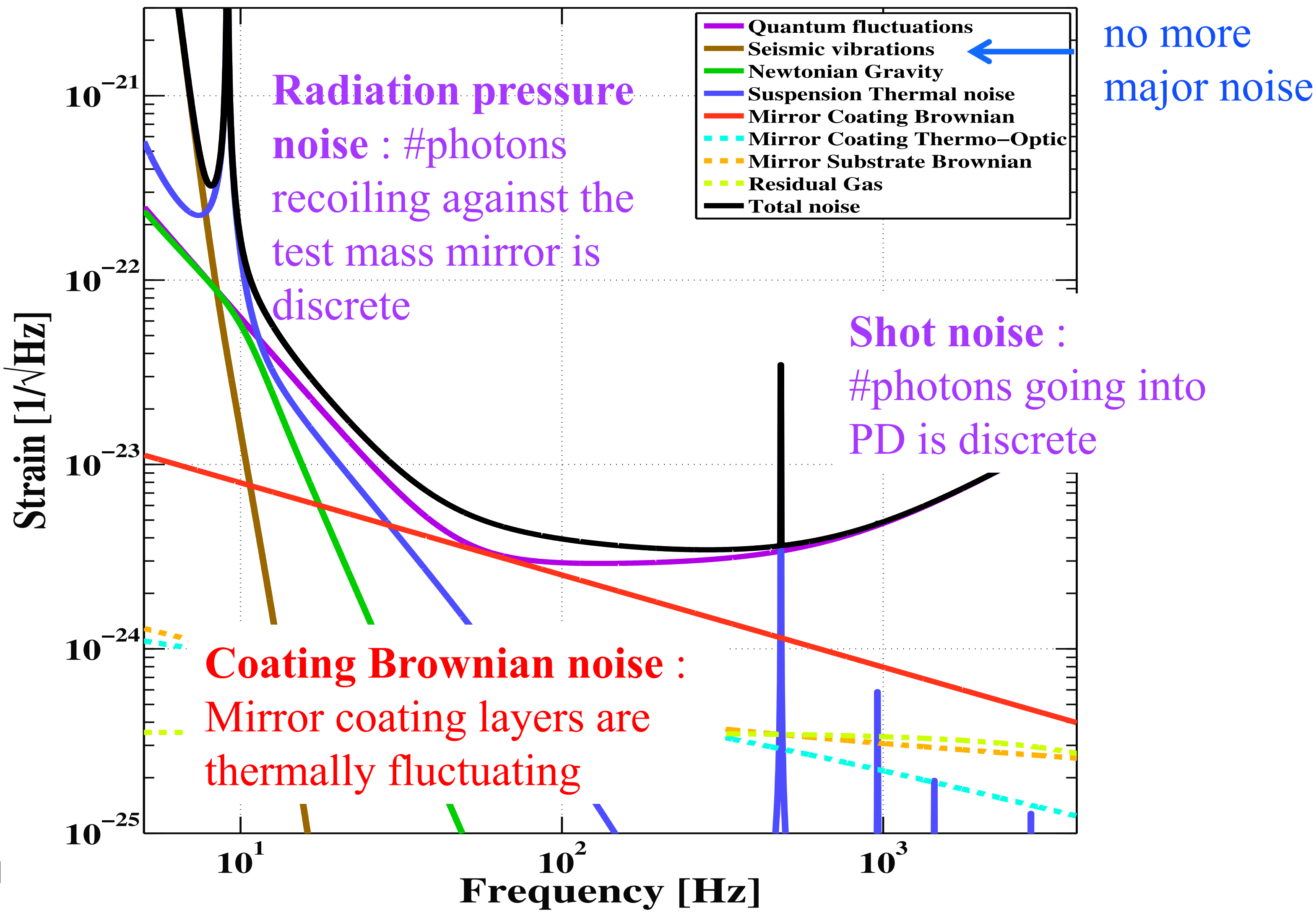
Event GW100916: blind injection

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



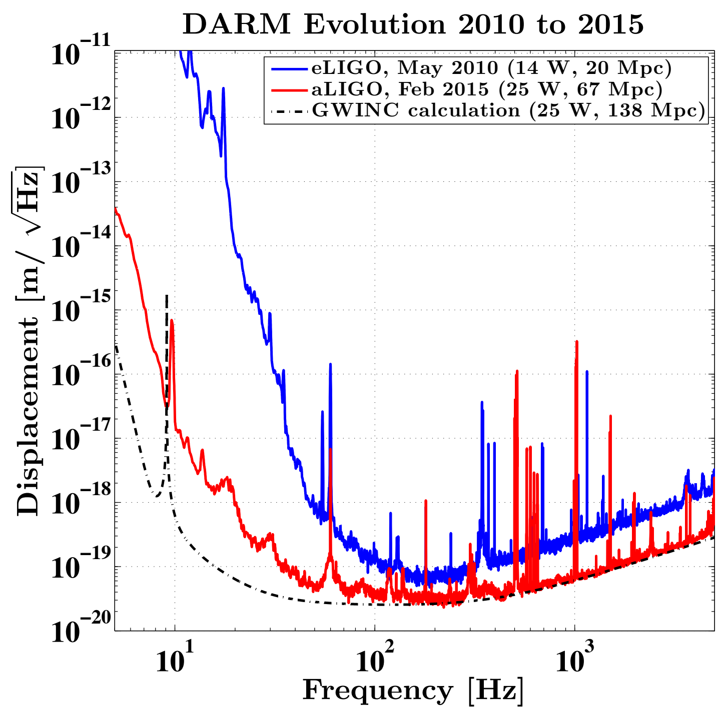


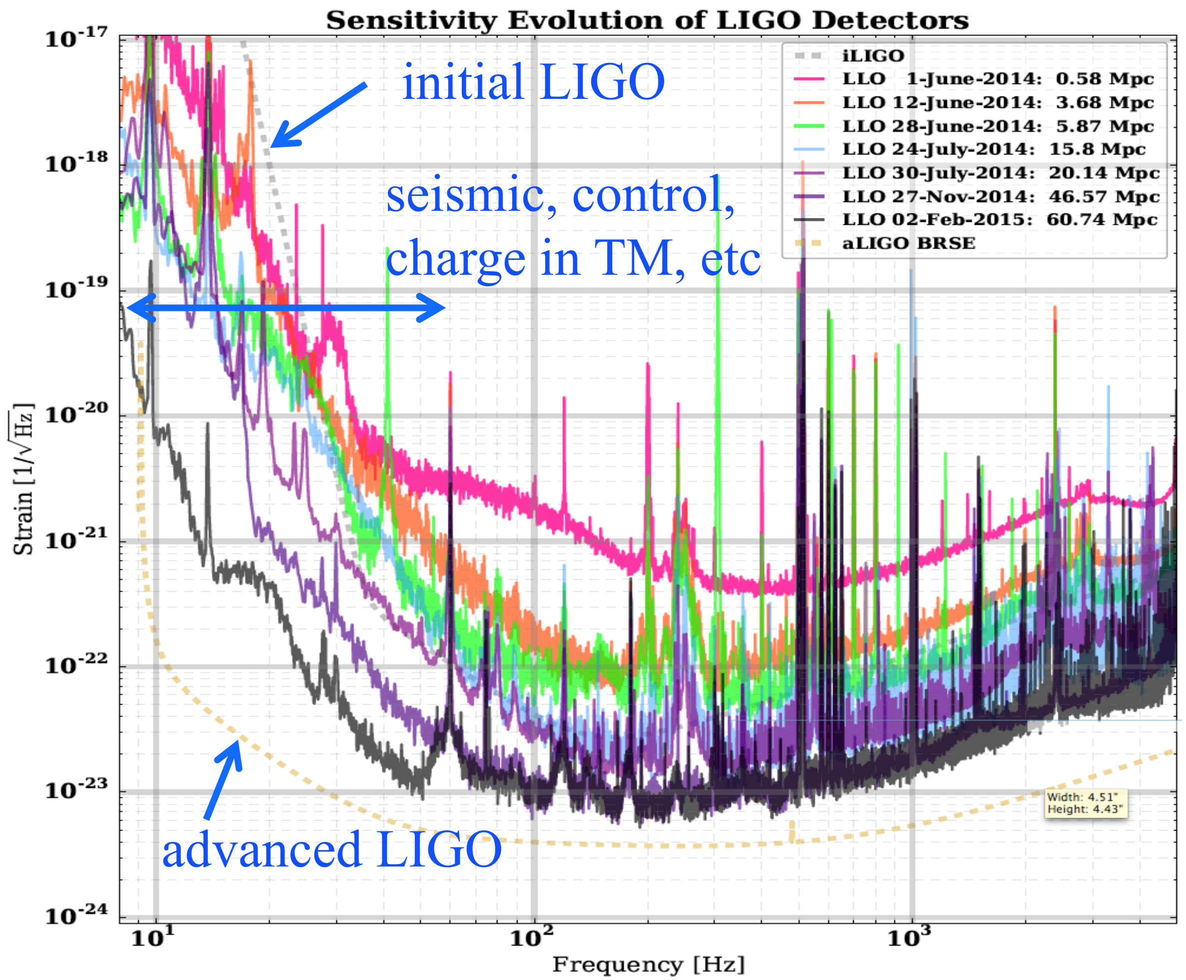
Fundamental Sensitivity Limits in Advanced LIGO



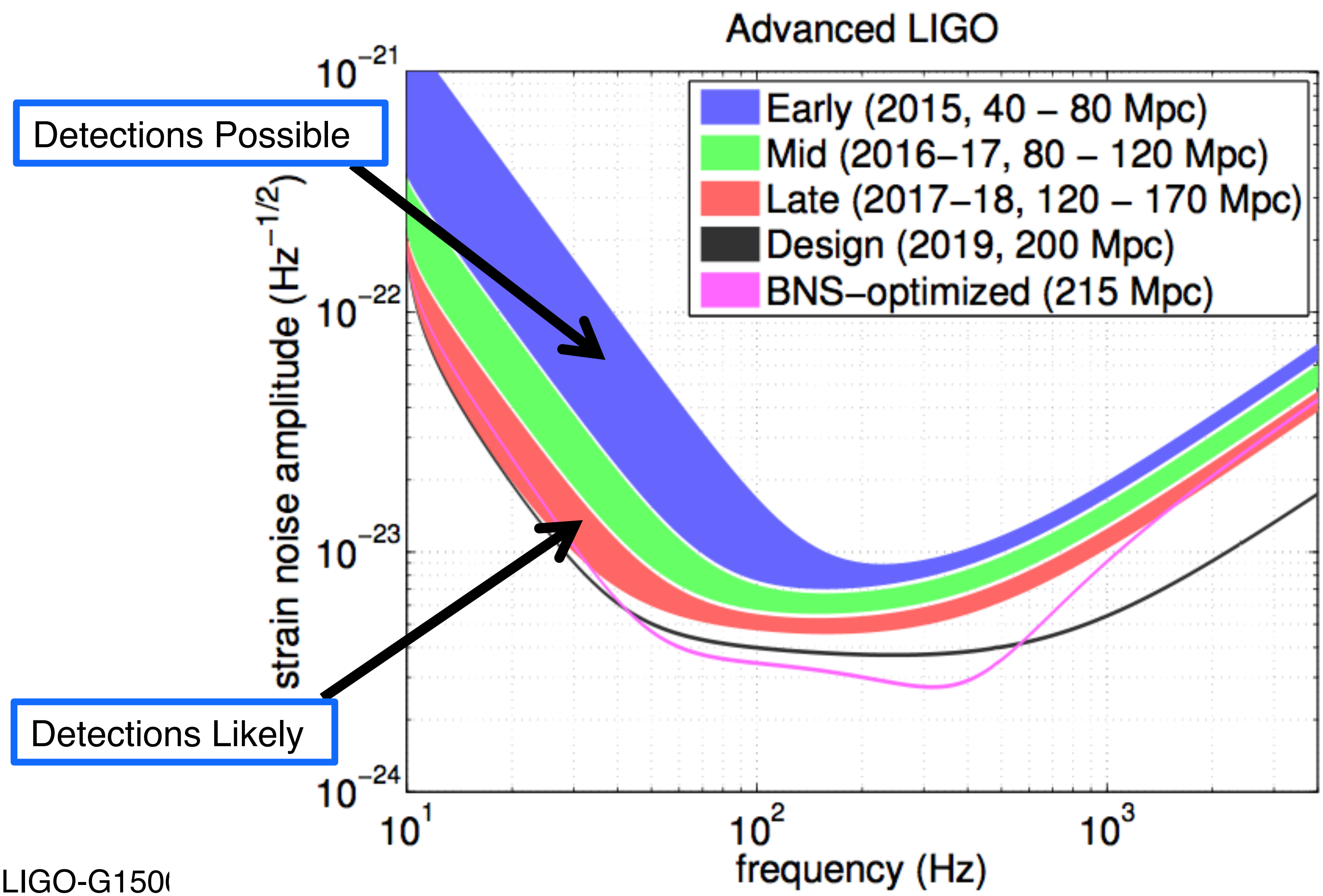
LIGO-G150041

LIGO Livingston Sensitivity Progression





Planning for Advanced LIGO Science



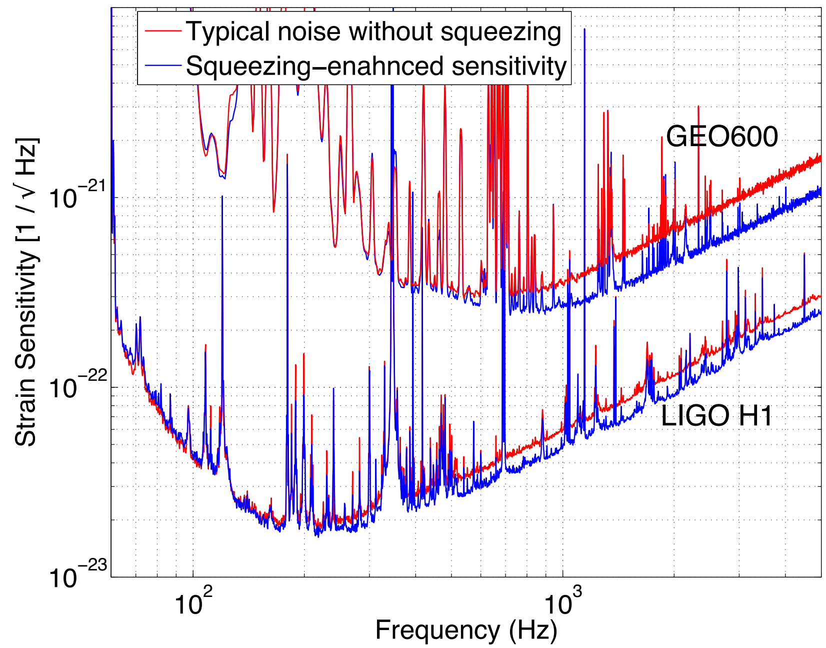
Squeezed Light in LIGO

suppressing quantum noise without increasing power

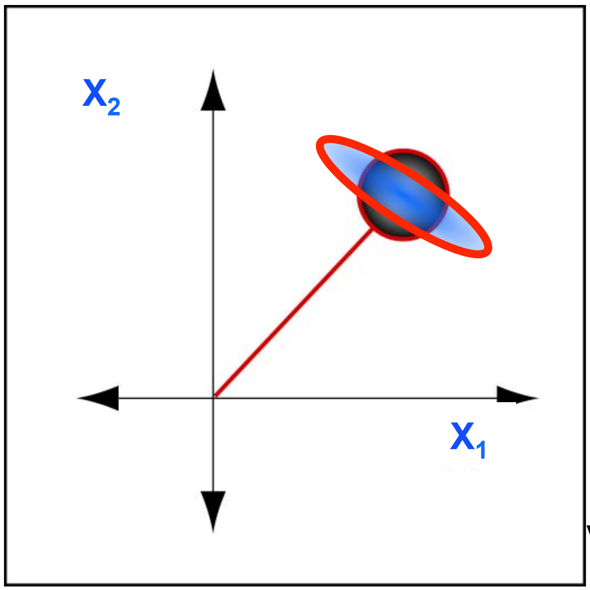
- Heisenberg Uncertainty Principle

$$\langle(\Delta\hat{X}_1)^2\rangle\,\langle(\Delta\hat{X}_2)^2\rangle \geq 1$$

- Squeezed state
  - Reduce noise in one quadrature at the expense of the other
  - Shot noise - phase, radiation pressure - amplitude

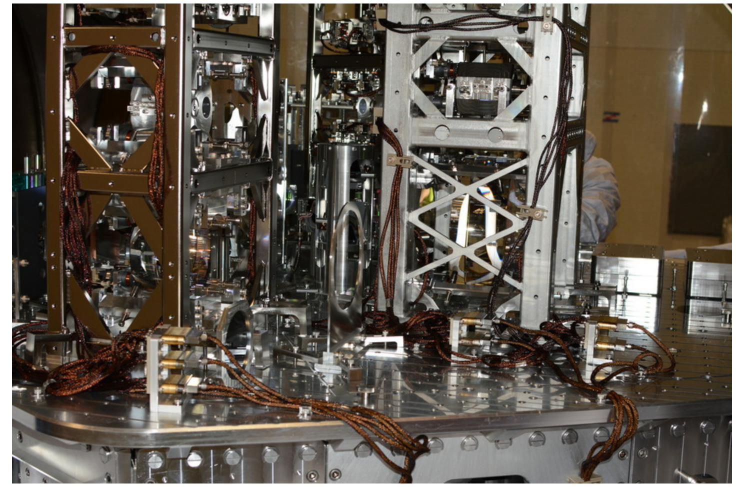


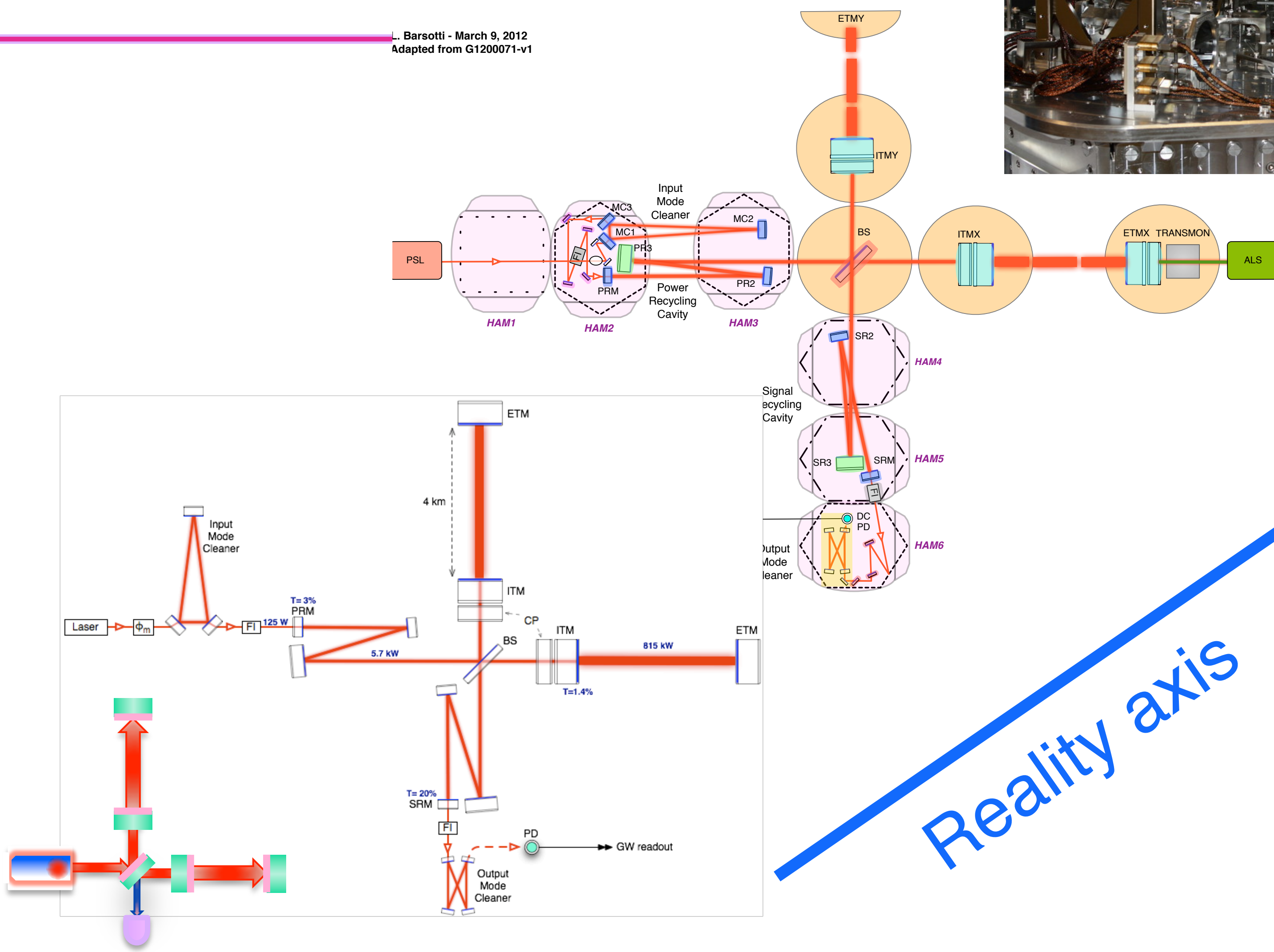
X_1 and X_2 associated with amplitude and phase



Aasi, et al., (LIGO Scientific Collaboration), Nature Physics, 7, 962 (2011); Nature Photonics 7 613 (2013).

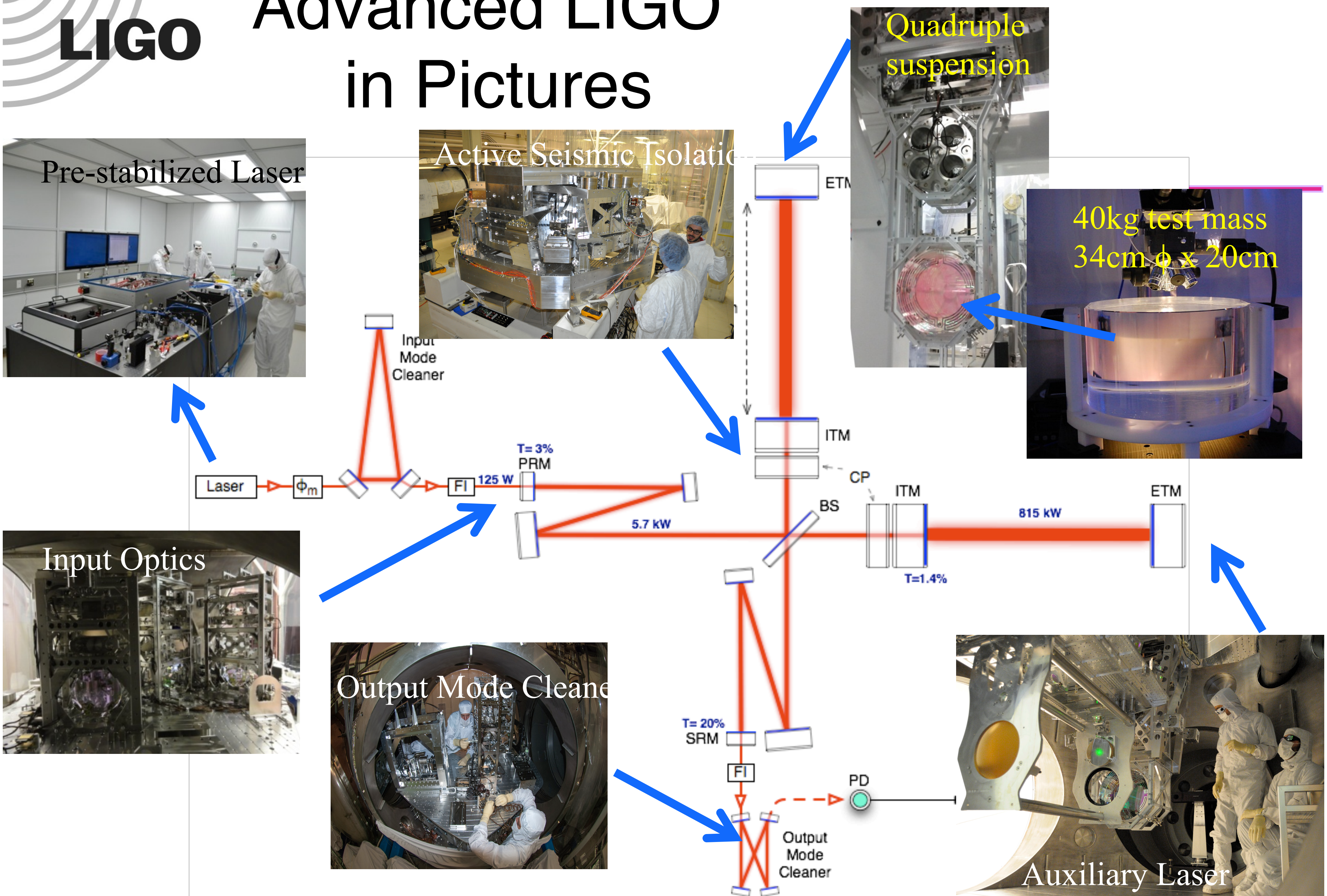
The real instrument is far more complex…





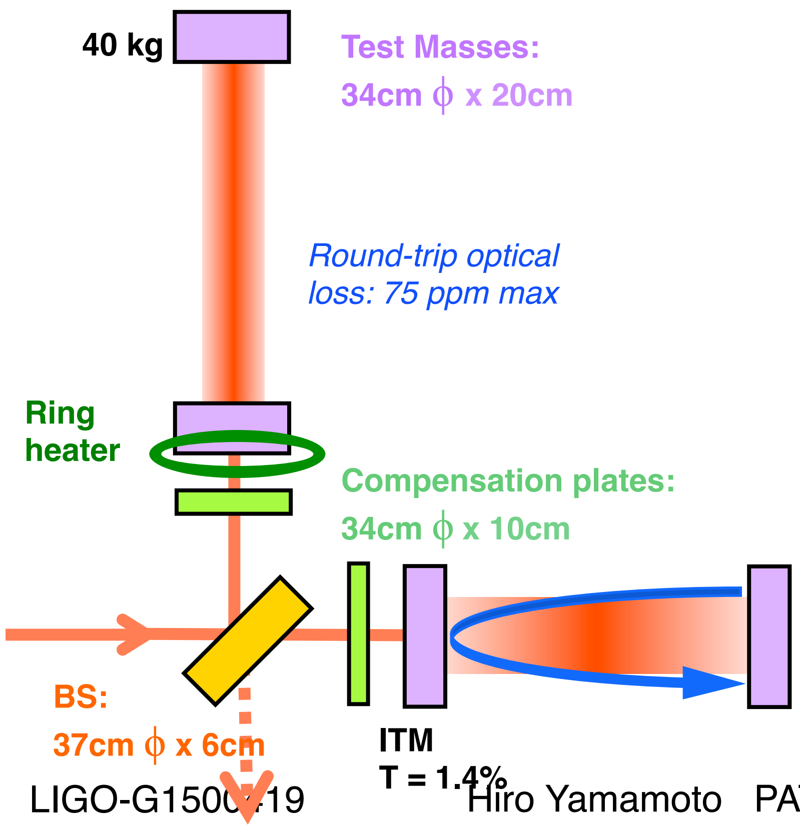
Reality axis

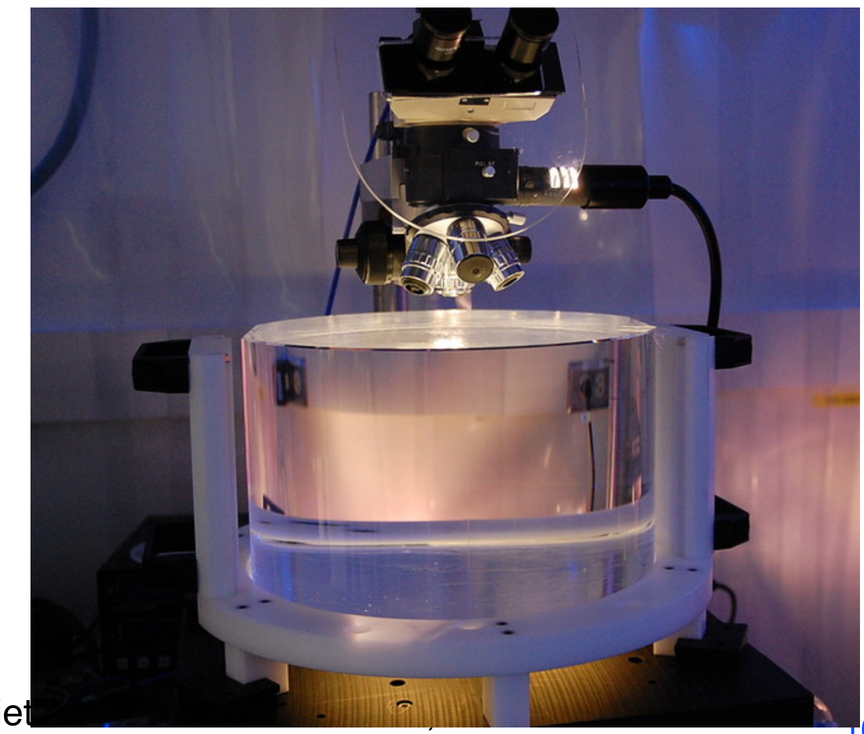
Advanced LIGO in Pictures



Test Masses with thermal compensation system

- Requires the state of the art in substrates, polishing and coating
  - » Fabri-Perot cavity is used to measure arm length or space distortion
- Half-nm flatness over 300mm diameter
- 0.2 ppm absorption at 1064nm
- Coating specs for 1064 and 532 nm
- Mechanical requirements: bulk and coating thermal noise, high resonant frequency





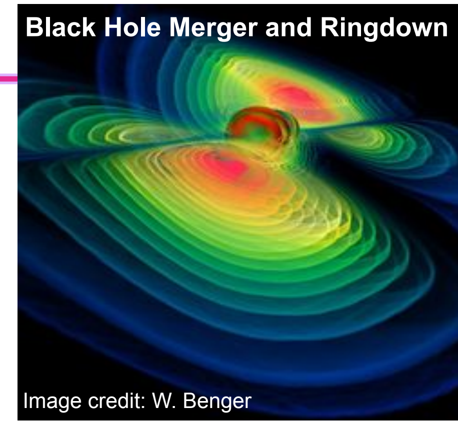
LIGO vacuums

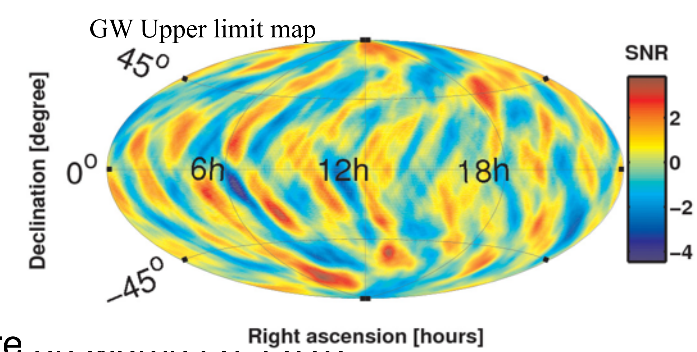
Beam light path must be high vacuum to minimize "phase noise". The 4km arm is the world's biggest UHV vacuum system, and is straighter than earth's curvature

All optical components must be in high vacuum, so mirrors are not "knocked around" by gas pressure

Some Questions Gravitational Waves May Be Able to Answer

- **Fundamental Physics**
  - *Is General Relativity the correct theory of gravity?*
  - *How does matter behave under extreme conditions?*
  - *What equation of state describes a neutron star?*
- **Astrophysics, Astronomy, Cosmology**
  - *Do compact binary mergers cause 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?*





Advanced LIGO Data analysis

- Burst
  - » All-sky search for generic GW transients, in low latency for EM follow up and deep, offline for 4σ detection confidence
- Compact Binary Coalescence
  - » Low latency, all-sky search for BNS and NS-BH systems
  - » Search for binary neutron-star and black-hole systems (BNS, BHNS, BBH)
- Continuous Wave
  - » All-sky deep/broad search for isolated starts
  - » Targeted search for high value, known pulsars
- Stochastic Gravitational Wave background
  - » Directional and isotropic search for stochastic gravitational wave background
  - » Constraints of a detected background of astrophysical origin with long transients

✓ Search for GW signals using alerts by other signals

✓ Parameter estimation for the astrophysical interpretation of detected events

LIGO = LIGO Lab (CIT,MIT,UFL) + LSC (LIGO Science Collaboration)

- 900+ members, 82 institutions, 16 countries, 52 MOUs.
- https://my.ligo.org/census.php
- https://roster.ligo.org/roster.php

LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the National Science Foundation of the United States.

Welcome! The LIGO Open Science Center (LOSC, https://losc.ligo.org) provides access to a variety of LIGO data products, as well as documentation, tutorials, and online tools for finding and viewing data.

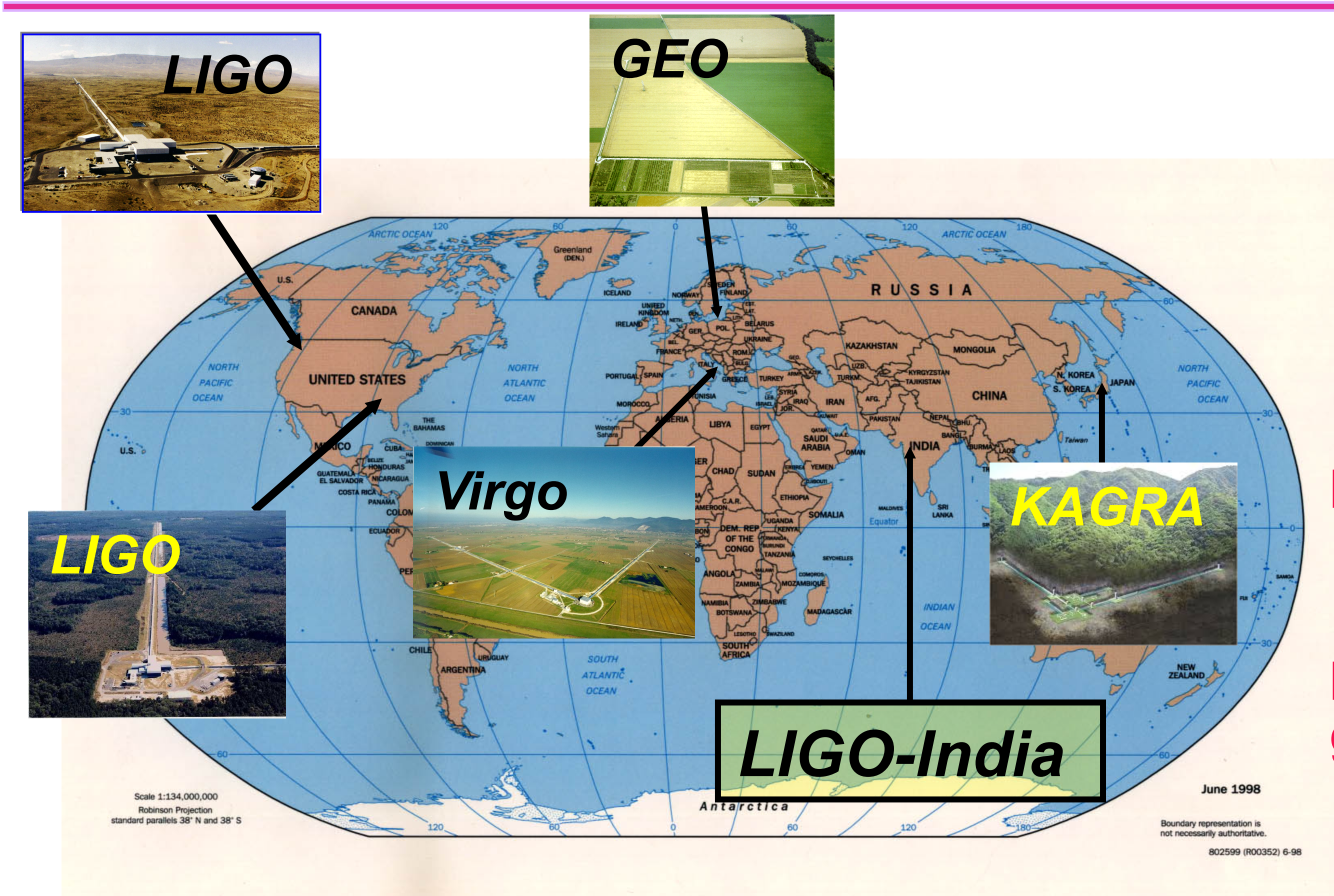
The S5 Data Release
S5 Time Range: Nov. 4, 2005 ~ Oct. 1, 2007
Detectors: H1, H2, and L1

The S6 Data Release
S6 Time Range: Jul.7, 2009 ~ Oct 20, 2010
Detectors: H1 and L1

All Science Mode Times for LIGO/Virgo/GEO Network
Time Range: 2004 ~2014
Detectors: H1, H2, L1, G1, V1

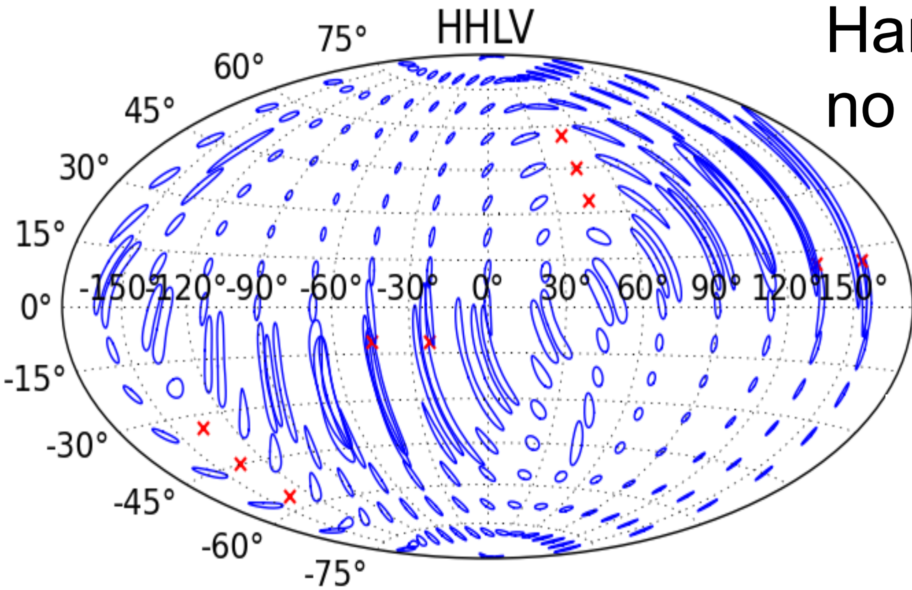
IP addresses who downloaded data

International network



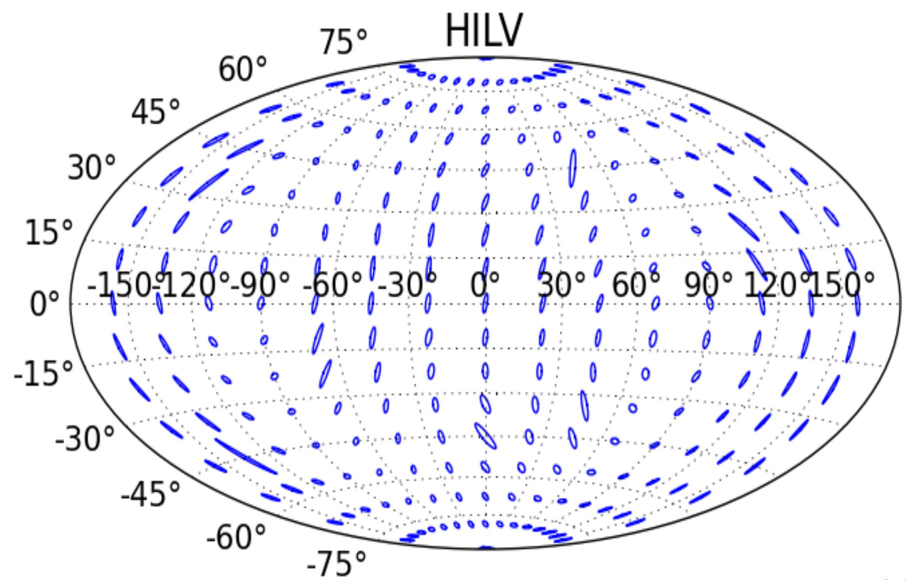
- detection confidence
- locate the sources
- verify light speed propagation
- decompose the polarization of gravitational waves
- **Open up a new field of astrophysics!**

Improvement of Binary Neutron Star Merger Localization by Adding LIGO-India



Hanford+Livingston+Virgo
no LIGO-India

Hanford+Livingston+Virgo
And LIGO-India

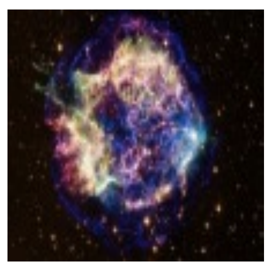
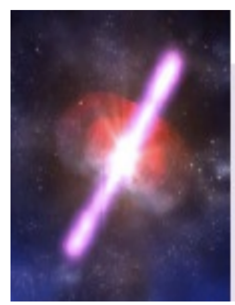


x denotes blind spots

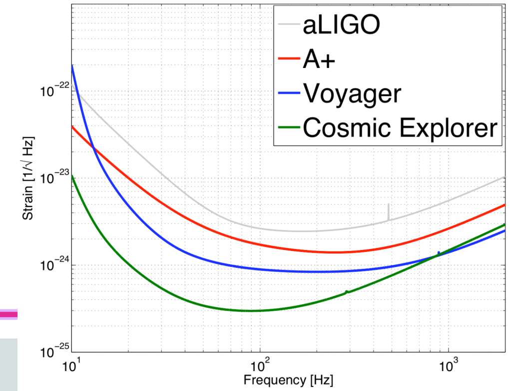
S. Fairhurst, "*Improved source localization with LIGO India*", *J. Phys.: Conf. Ser.* 484 012007

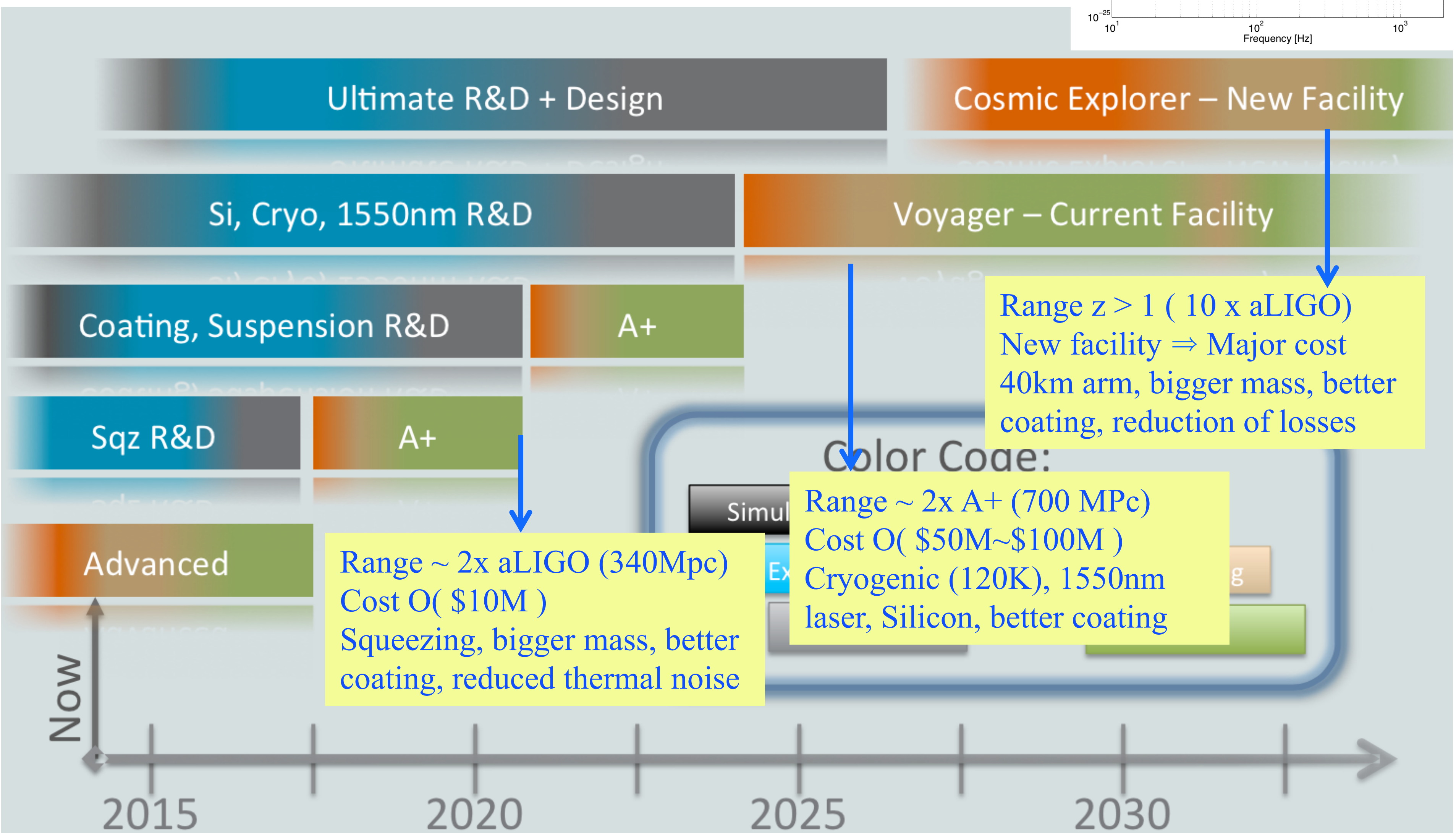
Multi-messenger astronomy
collaborations with Groups Detecting other signals

- Discussions going toward the new astrophysical era
- Complementary alert system
- Complementary and supplemental information about the source
- Many MOUs exchanged with EM partners, covering the whole EM spectrum.


Aiming for the future
beyond advanced LIGO





Range z > 1 (10 x aLIGO)
New facility ⇒ Major cost
40km arm, bigger mass, better coating, reduction of losses

Range ~ 2x A+ (700 MPc)
Cost O($50M~$100M)
Cryogenic (120K), 1550nm laser, Silicon, better coating

Range ~ 2x aLIGO (340Mpc)
Cost O($10M)
Squeezing, bigger mass, better coating, reduced thermal noise

Slide prepared for 2016 announcement