Introduction to Gravitational-Wave Astronomy

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27-Apr-16

LIG

Outline

- My talk today
  - » Basics of General Relativity and Gravitational Waves
  - » Sources of Gravitational Waves
  - » Detectors of Gravitational Waves
  - » Some history
  - » International Network of Terrestrial GW Detectors
  - » Future detectors
- Mike Landry's talk next week
  - » Advanced LIGO Detector
  - » First Direct Detection of Gravitational Waves

Basics of General Relativity and Gravitational Waves

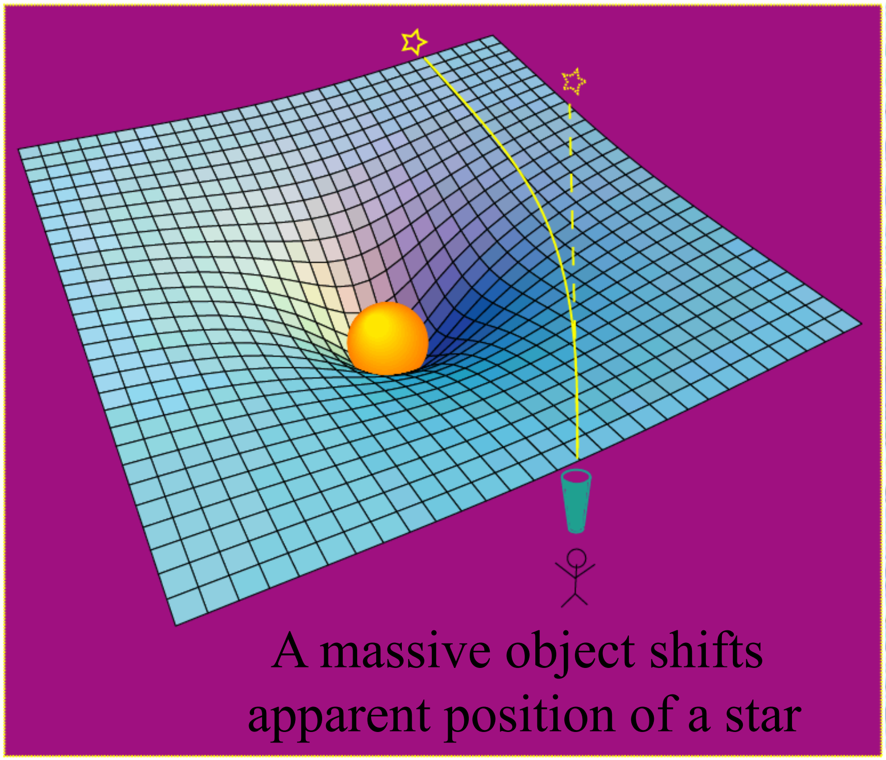
Wherein it is realized that space and time are things whose properties are manifested by phenomena that we collectively refer to as "gravity".

LIGO-G1600932

Special Relativity and the Case of the Missing Sun

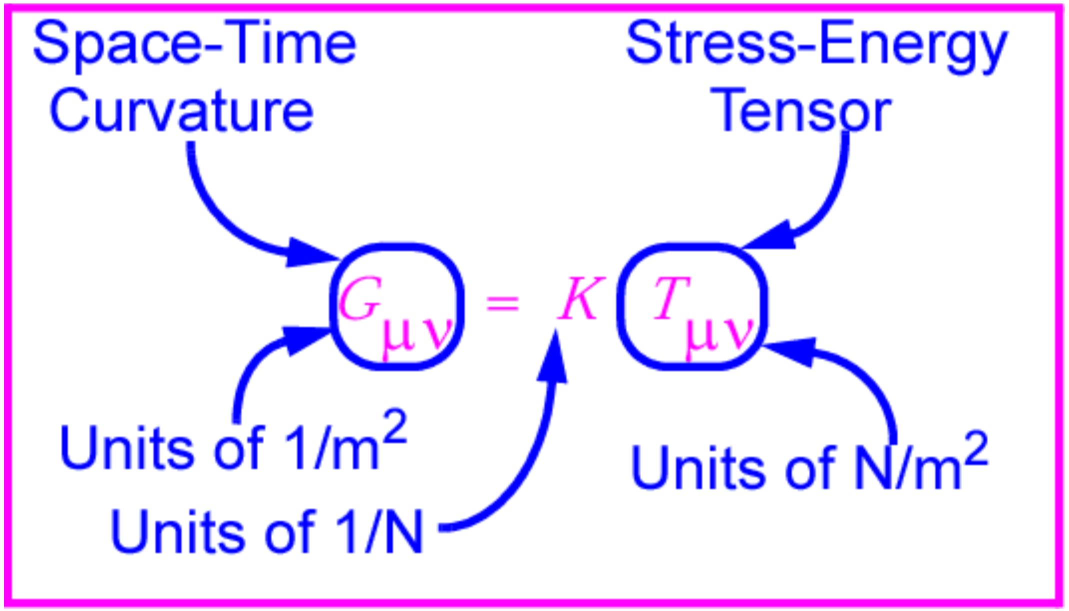
Free fall is weightless

Einstein’s General Relativity re-wrote the rules of space and time



Empty space and time are things, with real physical properties. Space has a shape, a stiffness and a maximum speed for information transfer.

Gravitational waves: hard to find because space-time is stiff!



- K~[G/c^4] is lowest order combination of G, c with units of 1/N

$$K \sim 10^{-44}\ N^{-1}$$

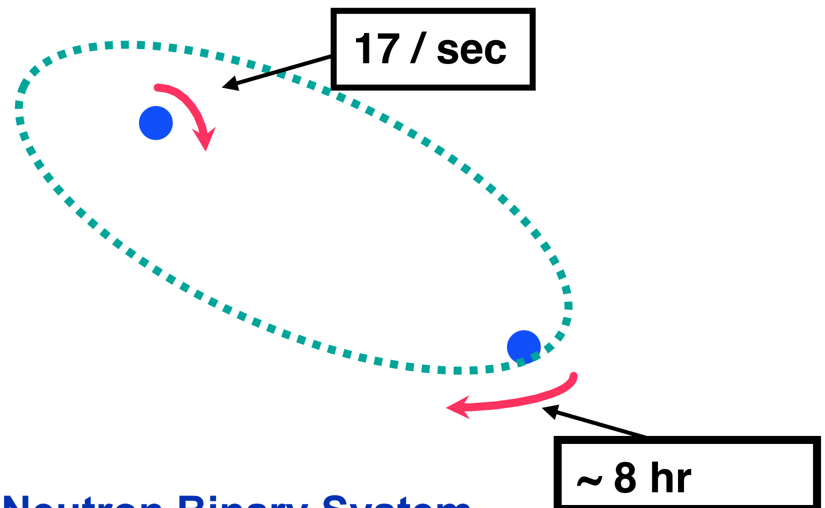
⇒ Wave can carry huge energy with miniscule amplitude!

Gravitational Waves

hard to find, but known to exist

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



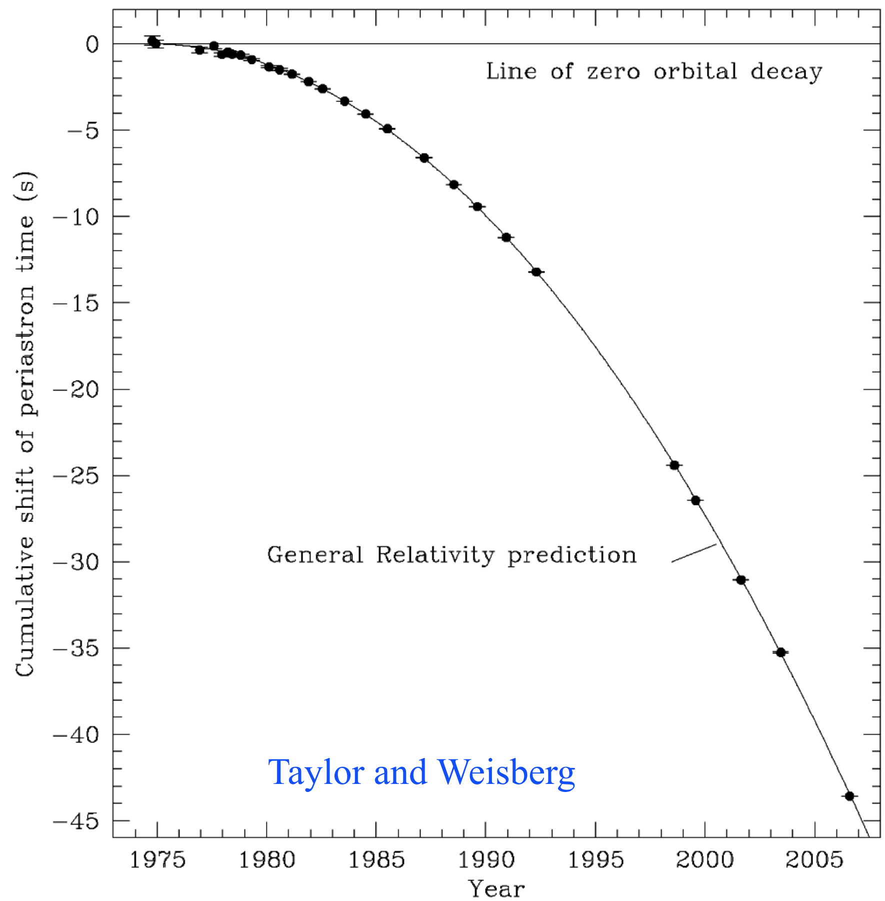
Neutron Binary System

- **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



Sources of Gravitational Waves

Accelerating Quadrupole Mass Moments

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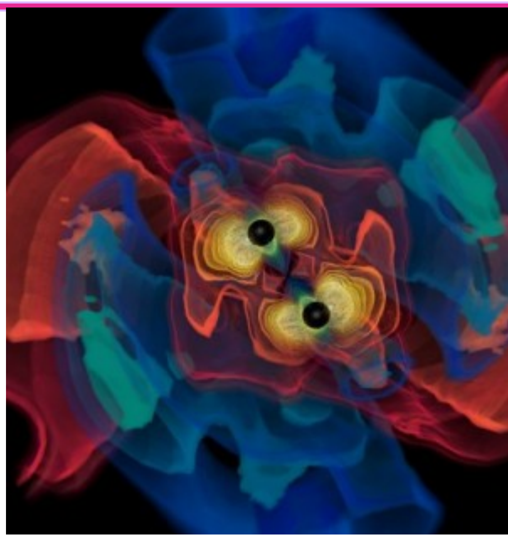
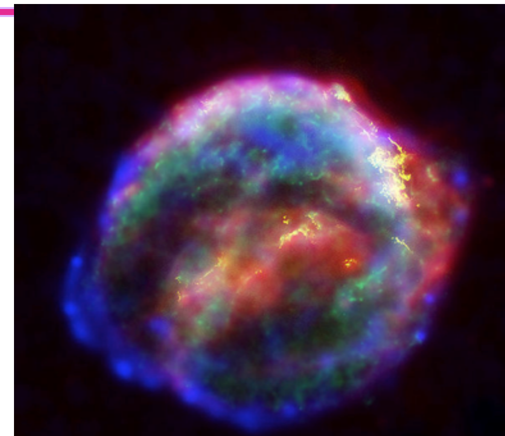
Astrophysical Sources of Gravitational Waves



Credit: AEI, CCT, LSU

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

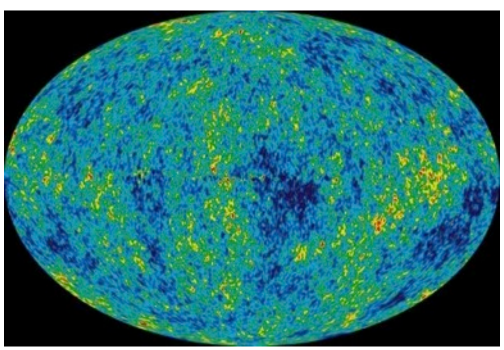
- Strong emitters, well-modeled,
- (effectively) transient



Credit: Chandra X-ray Observatory

Asymmetric Core Collapse Supernovae

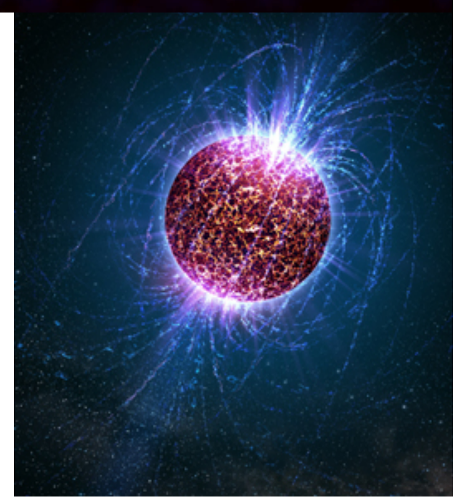
- Weak emitters, not well-modeled ('bursts'), transient



NASA/WMAP Science Team

Cosmic Gravitational-wave Background

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

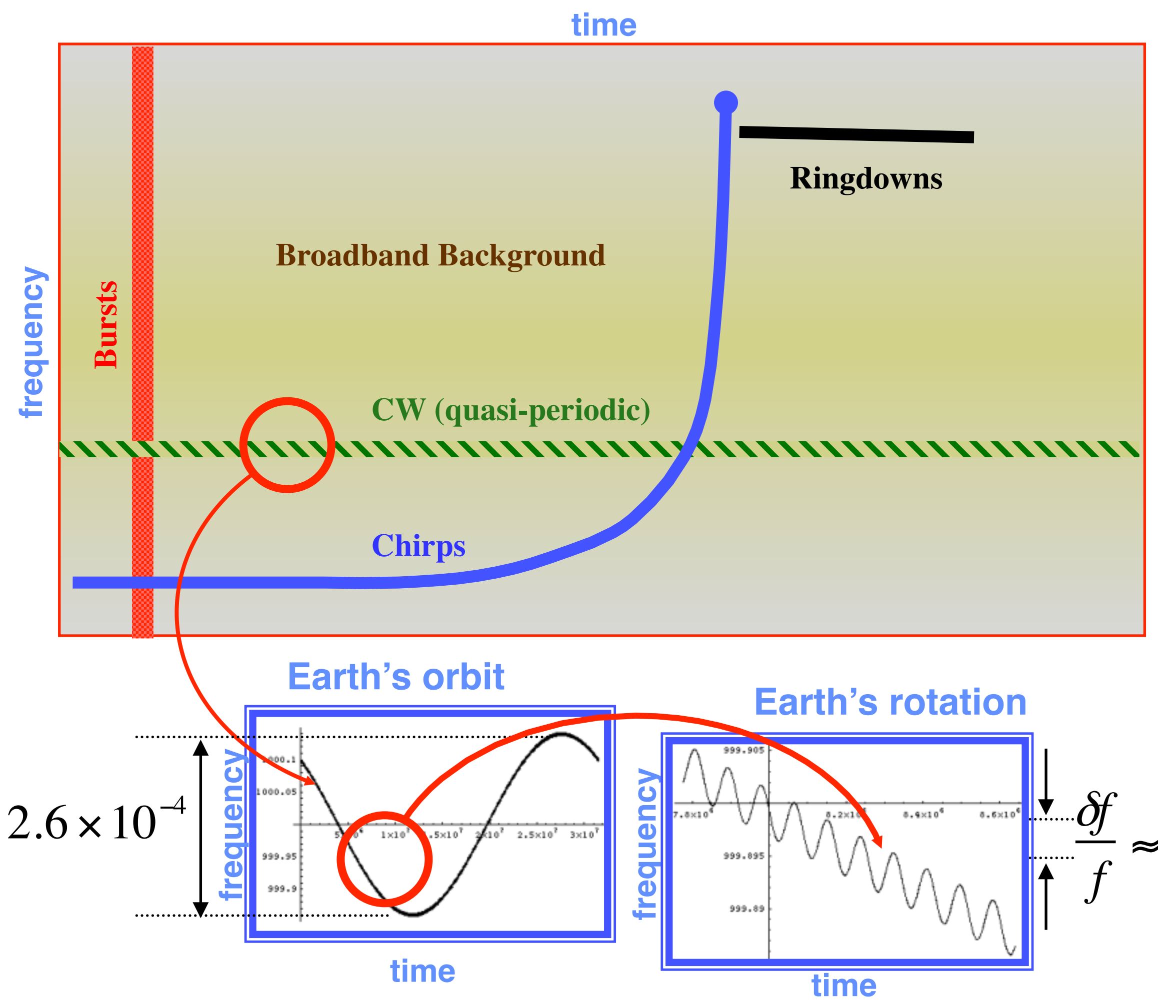


Casey Reed, Penn State

Spinning neutron stars

- (nearly) monotonic waveform
- Long duration

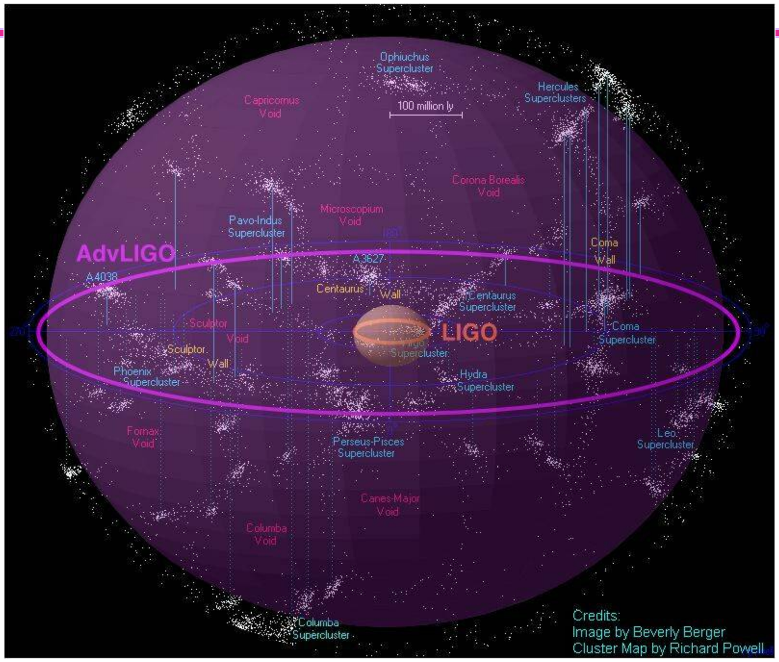
Frequency-Time Characteristics of GW Sources



$$\frac{\delta f}{f} \approx 2.6 \times 10^{-4}$$

$$\frac{\delta f}{f} \approx 4 \times 10^{-6}$$

Expected event rates



Binary neutron stars

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

Table 5. Detection rates for compact binary coalescence sources.

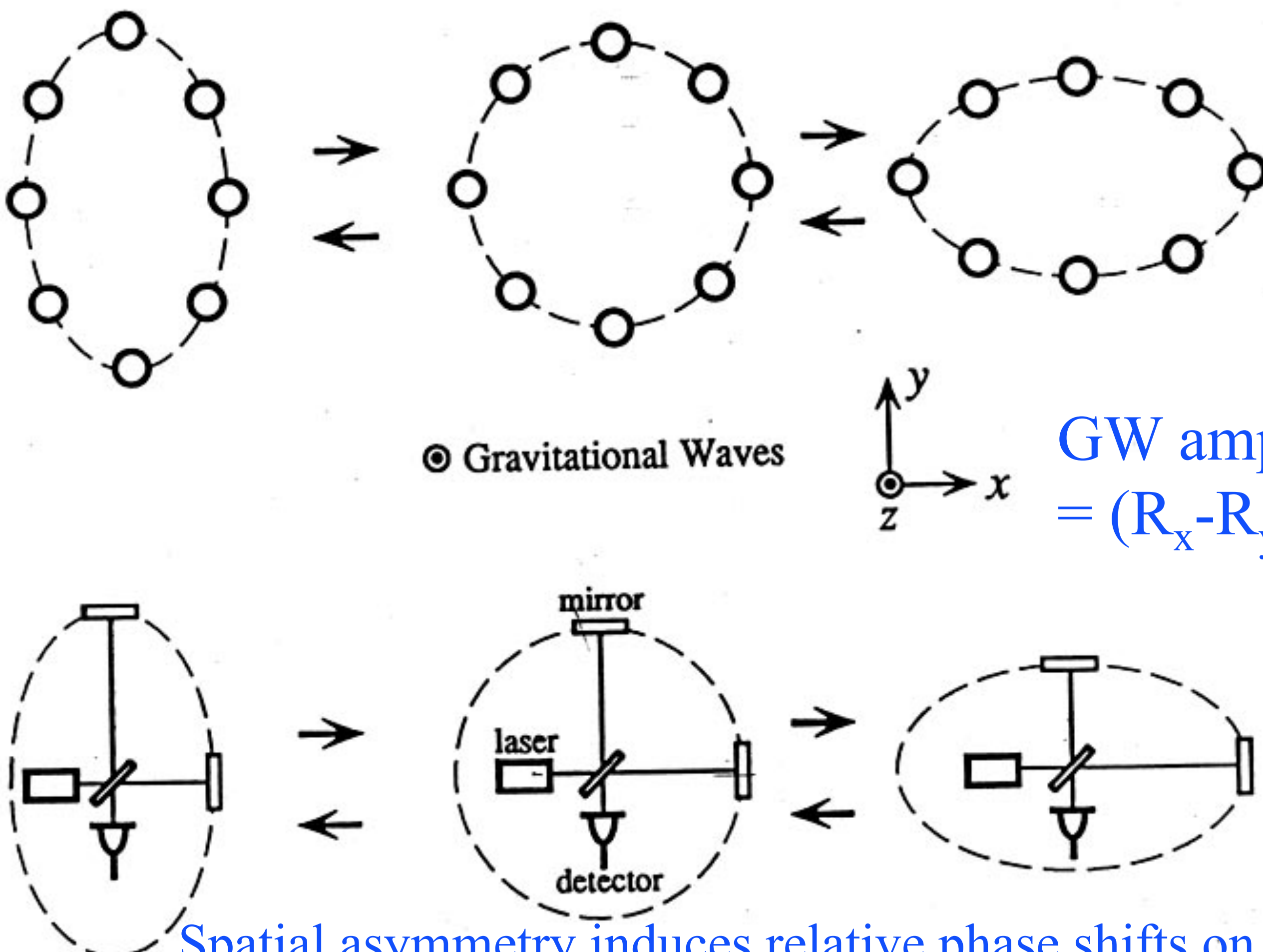
IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
Initial	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
	NS–NS	0.4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

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

Detectors of Gravitational Waves

No Law of Physics Forbids Them

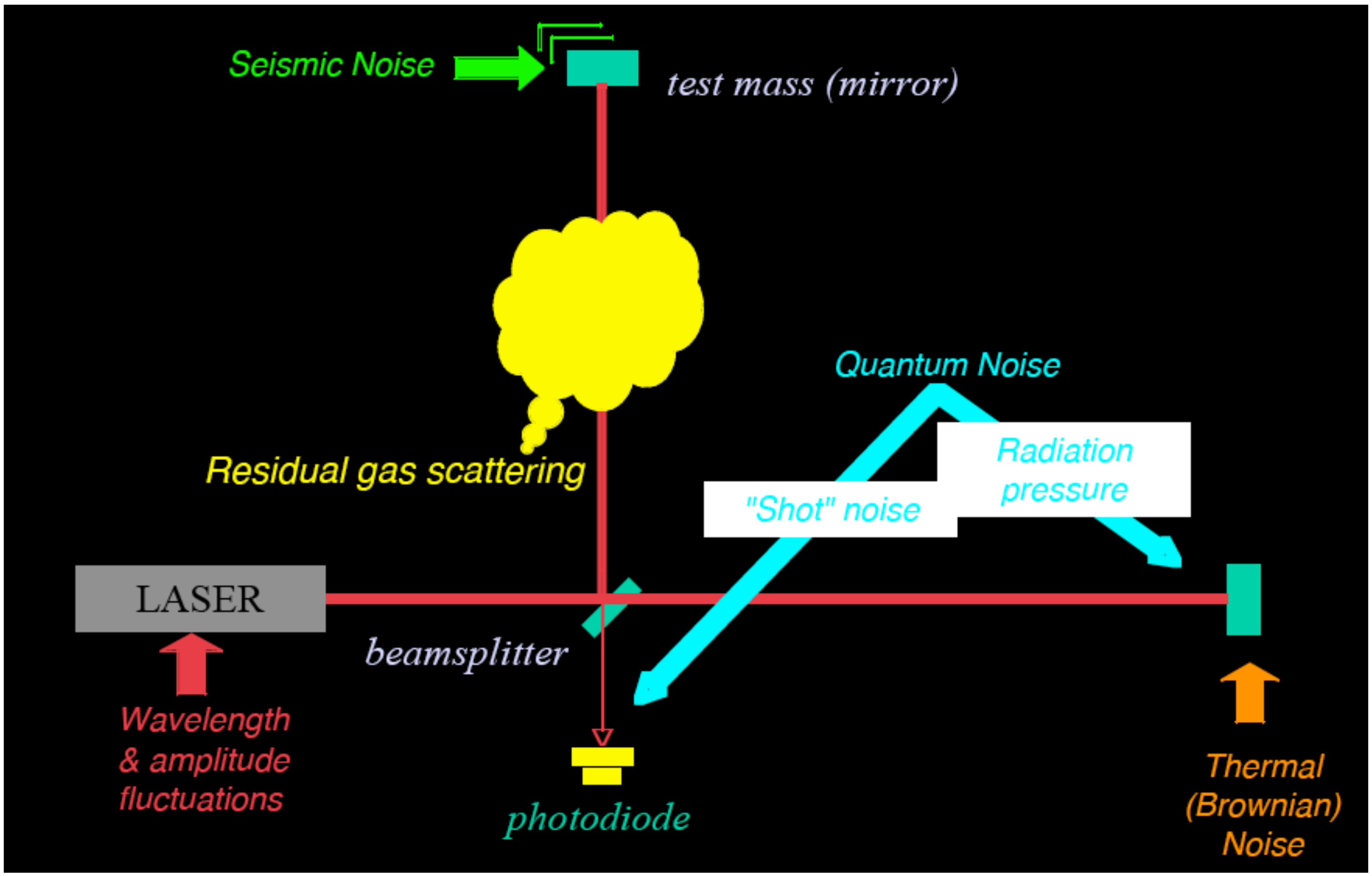
Basic idea is simple



GW amplitude h
= $(R_x - R_y)/R$

Spatial asymmetry induces relative phase shifts on light in arms

Noise cartoon



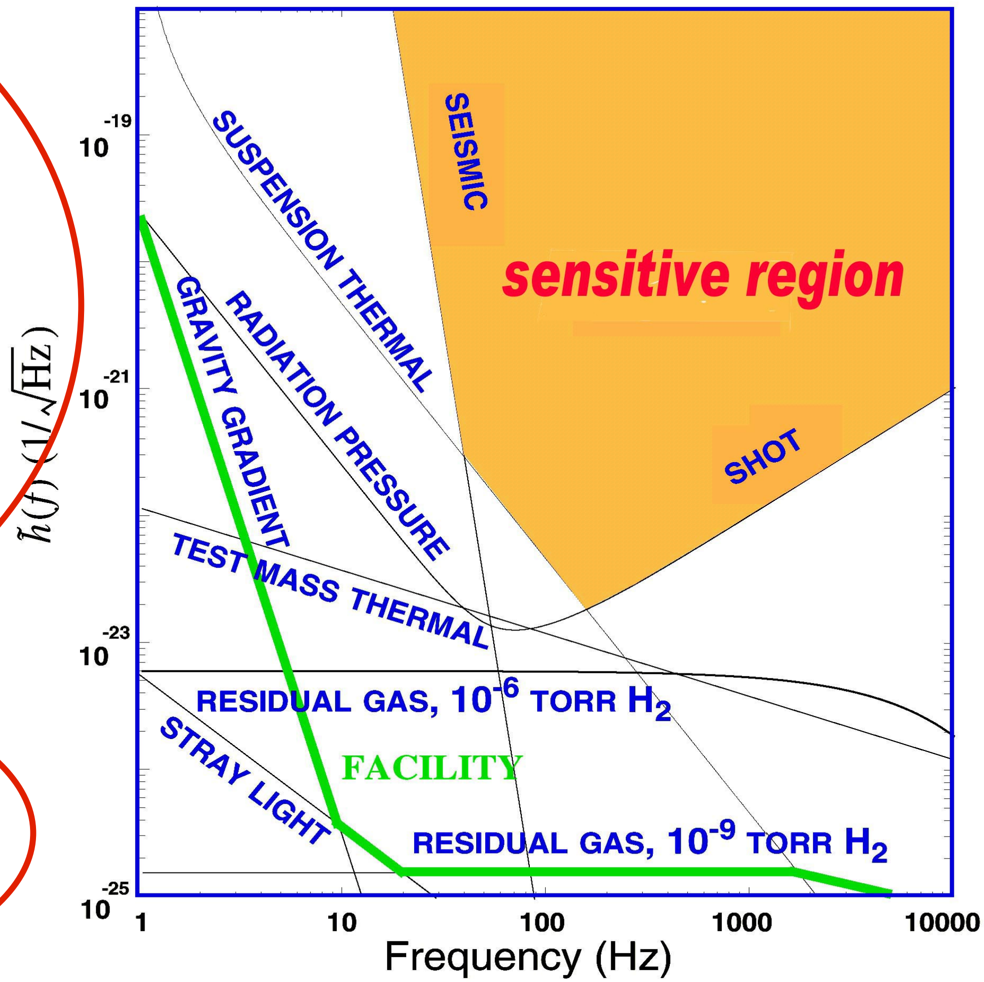
R. Adhikari

What Limits Sensitivity of Interferometers?

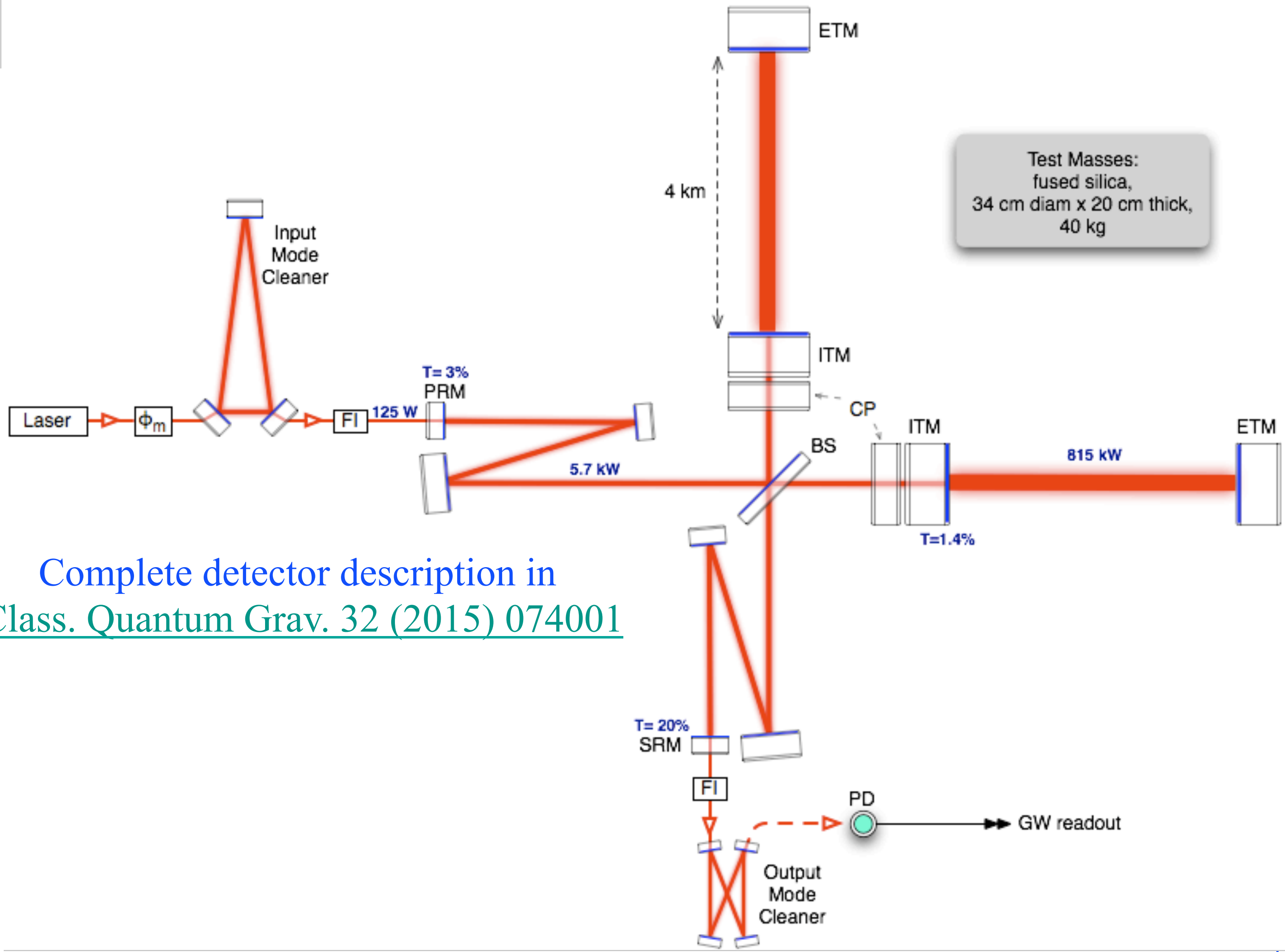
DESIGN

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels

COMMISSIONING

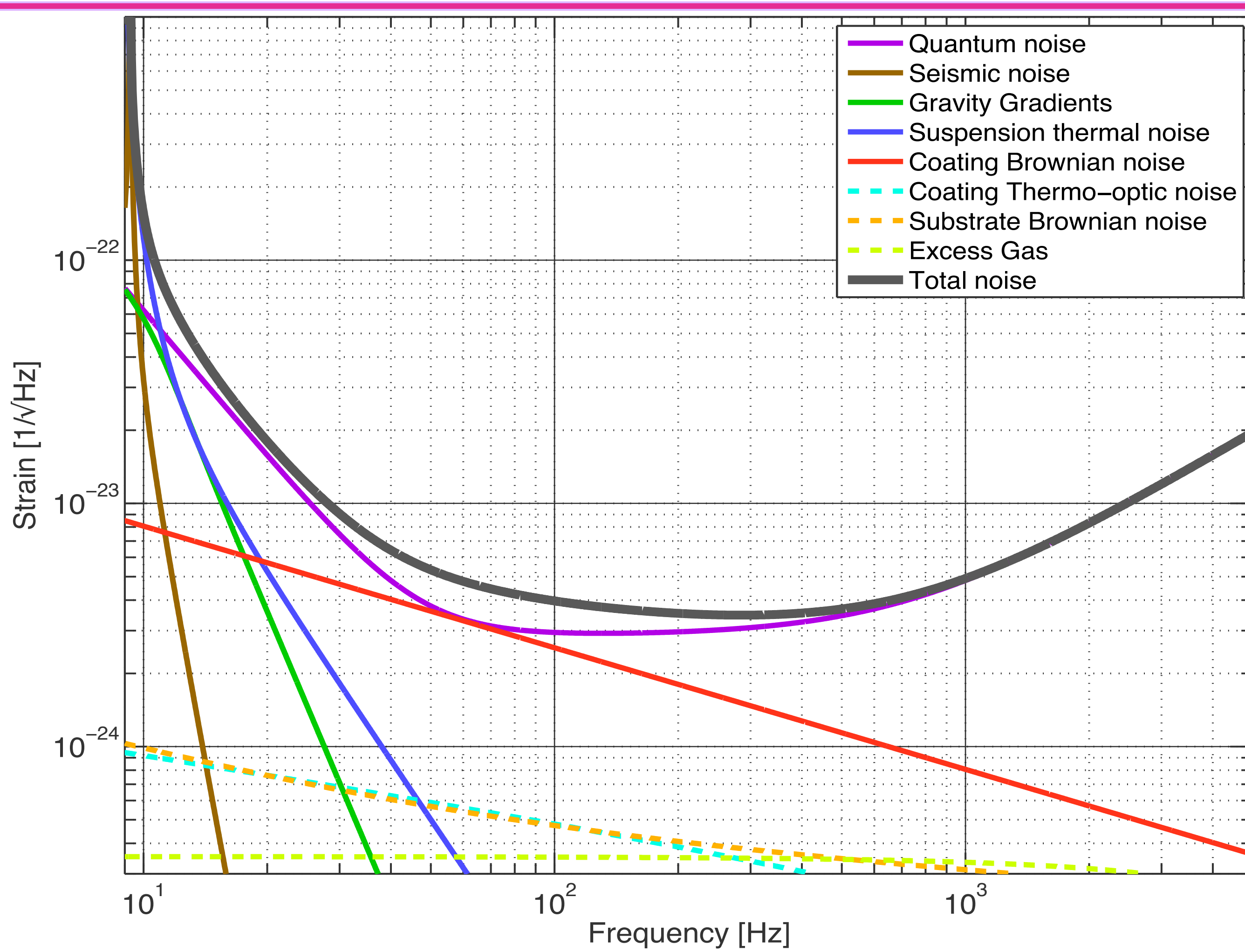


Optical configuration



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

Principal noise terms



Some History

Strategy: Build a Facility That Can House Evolving Generations of More Powerful Detectors

Proposal to the National Science Foundation

THE CONSTRUCTION, OPERATION, AND SUPPORTING RESEARCH AND DEVELOPMENT OF A

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY
Copyright © 1989

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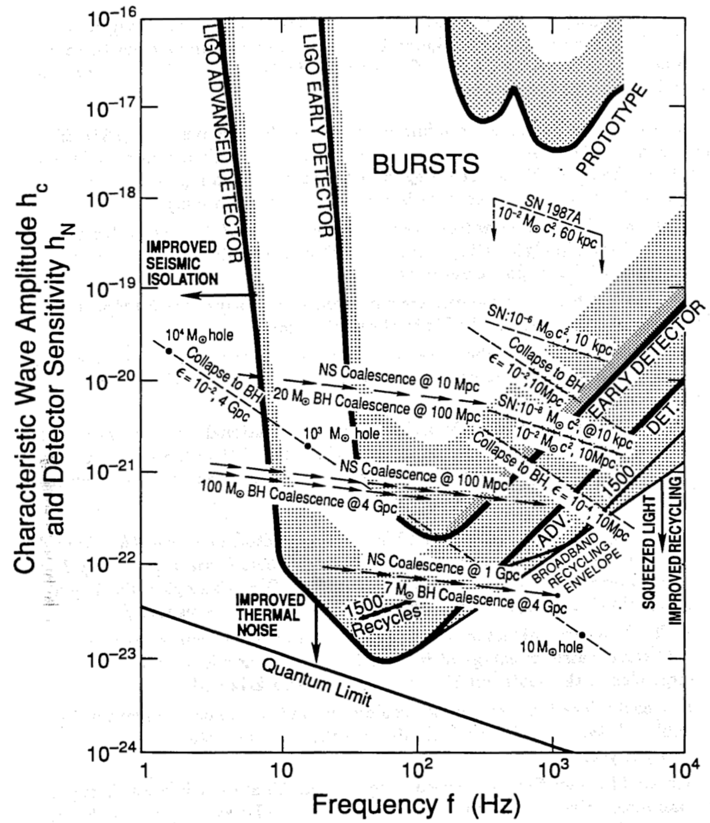


Figure II–2 A comparison of the strengths of gravitational waves (characteristic amplitude h_c and frequency f) for burst signals from various sources (dashed lines and arrows), and benchmark sensitivities h_N (solid curves and stippled strips atop them) for interferometric detectors today (*prototype*) and in the proposed LIGO (*early detector*, *advanced detector*). See the caption of Figure A-4a (a duplicate of this figure) and the associated discussion in Appendix A for more details.

The Laser Interferometer Gravitational-wave Observatory

- LIGO Observatories constructed from 1994-2000
- LSC created 1997
- Initial LIGO operated from 2002-2010
- Advanced LIGO 2015

Advanced LIGO detectors:

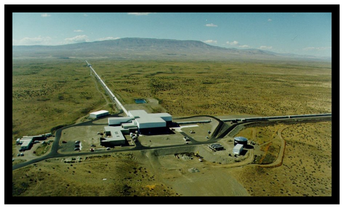
MAX-PLANCK-GESELLSCHAFT

Science & Technology Facilities Council

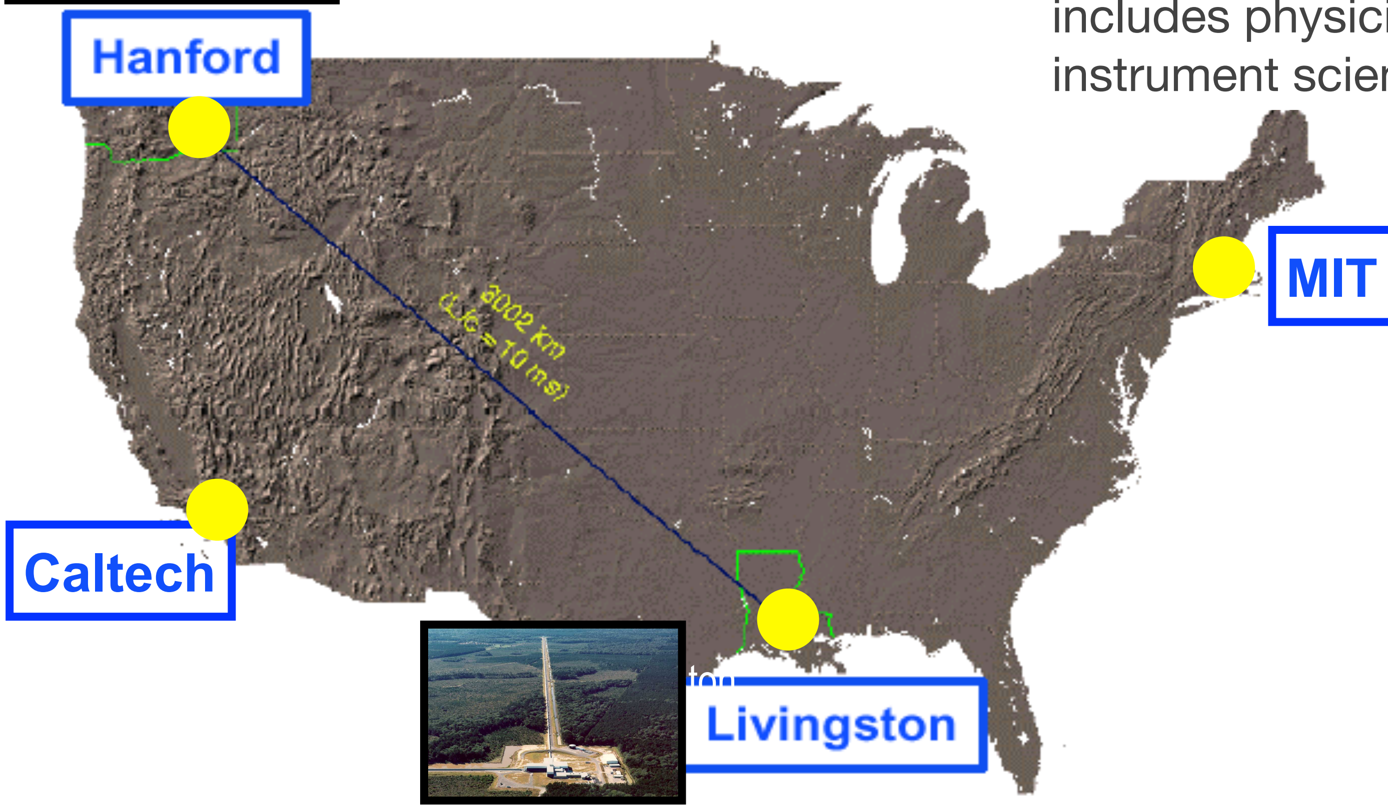
Australian Government
Australian Research Council

LIGO Laboratory

Mission: Observe gravitational wave sources; operate the LIGO facilities; instrument science and technology; scientific education and public outreach.



~200 scientists, engineers and staff; includes physicists working on instrument science and data analysis.



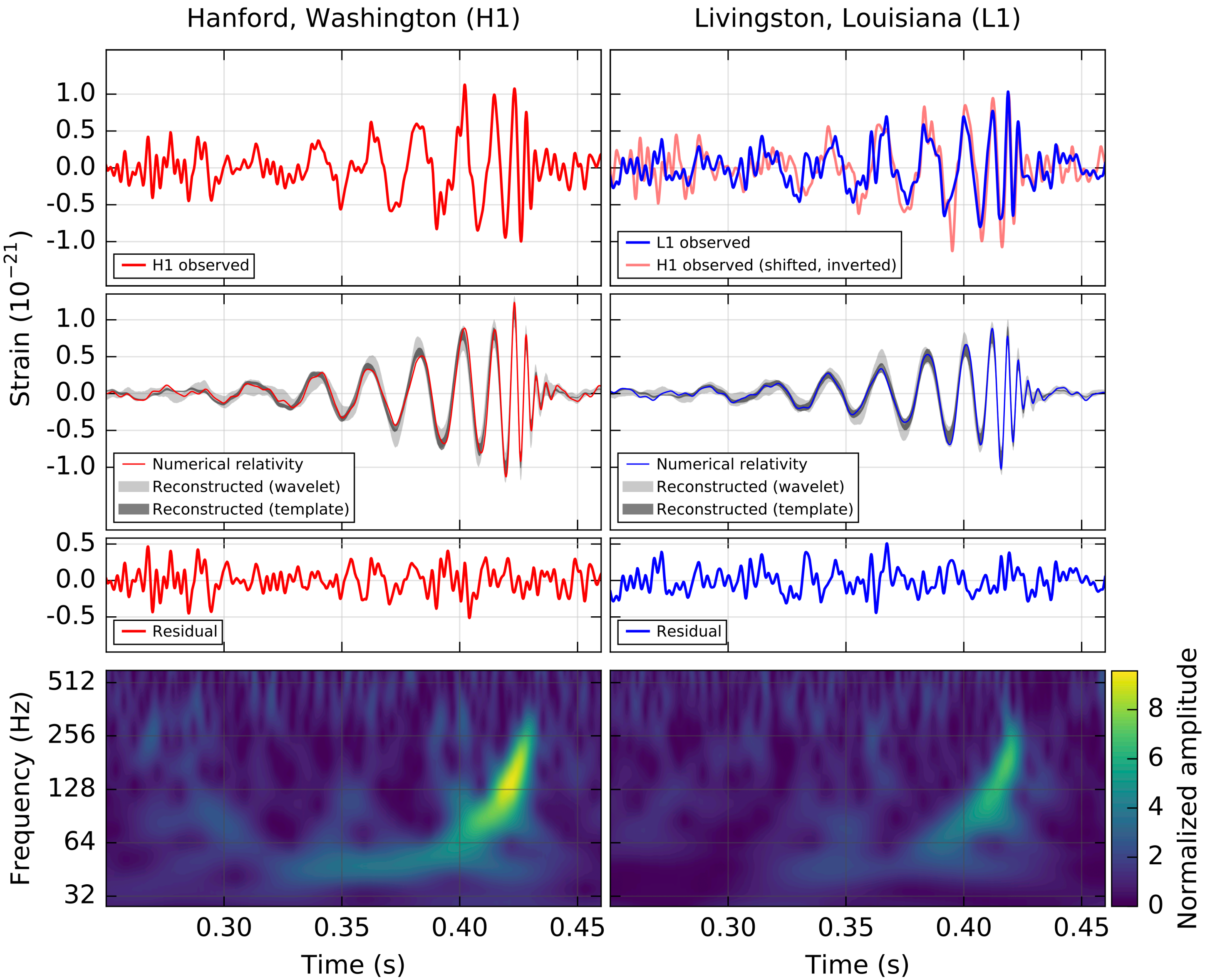
First Direct Detection of Gravitational Waves

Opening a New Window on the Universe

LIGO-G1600932

GW150914: What was observed?

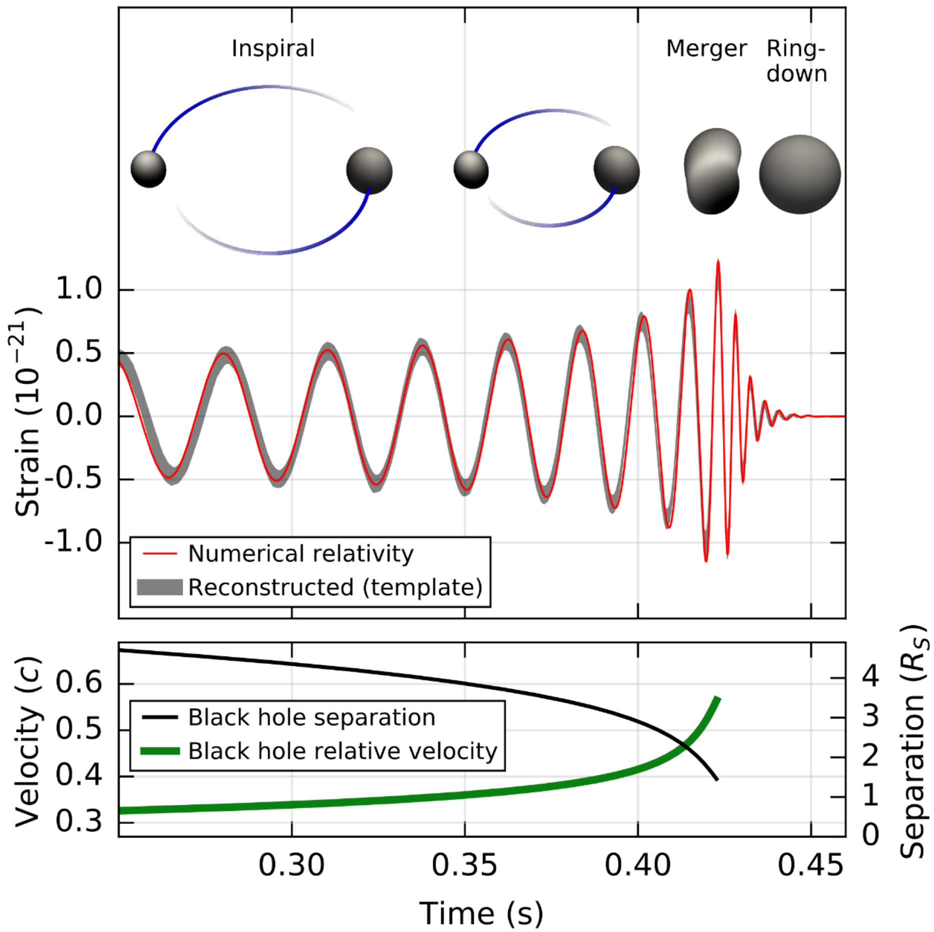
B. P. Abbott *et al.*, Phys. Rev. Lett. 116, 061102



LI

A signal from a binary black hole merger

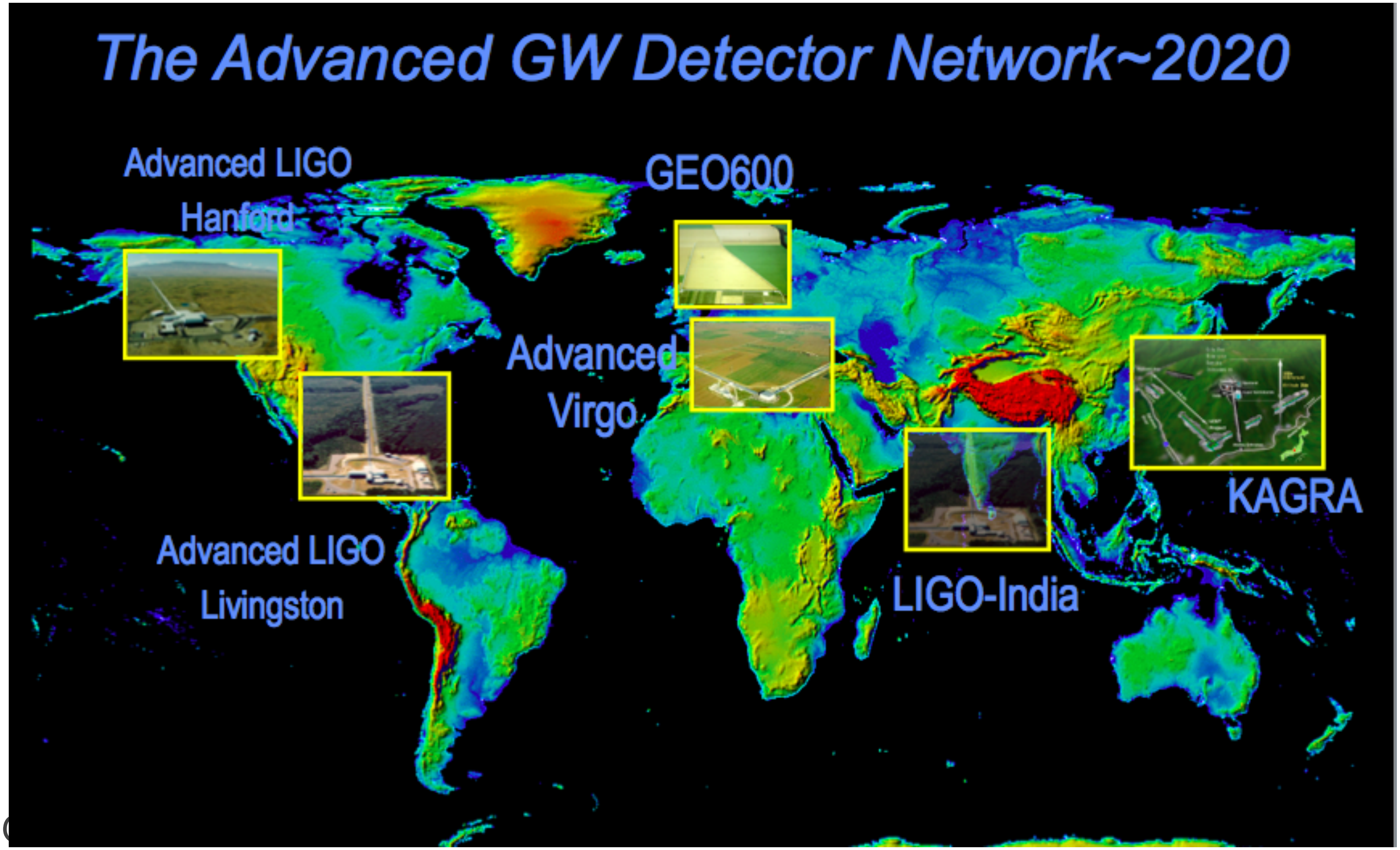
B. P. Abbott *et al.*, Phys. Rev. Lett. 116, 061102



But what have you done for us lately?

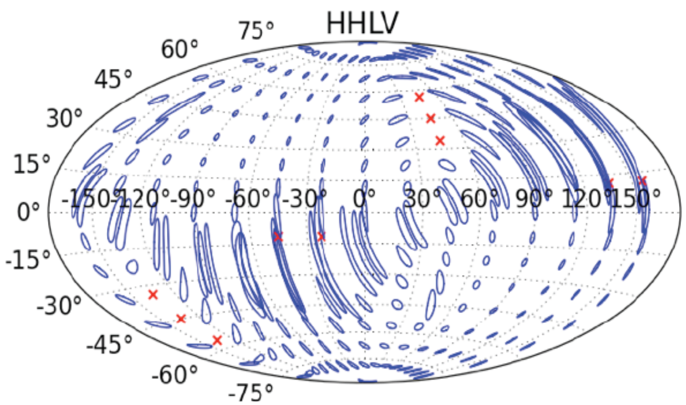
- Emphasis on the O in LIGO:
  - More BBHs
  - Better location information
  - New sources like BS-NS and NS-NS
  - Better throughput, from online triggers to released skymaps to submitted papers
- Our collaboration is focusing on the phase transition brought on by first detection.
- The quality and number of available detectors is key
  - More detectors to form a global array are needed for many science objectives
  - Current facilities can be upgraded
  - New facilities can achieve factor of x10 and more beyond ALIGO design

LIGO leads but it's not alone: The global gravitational wave array

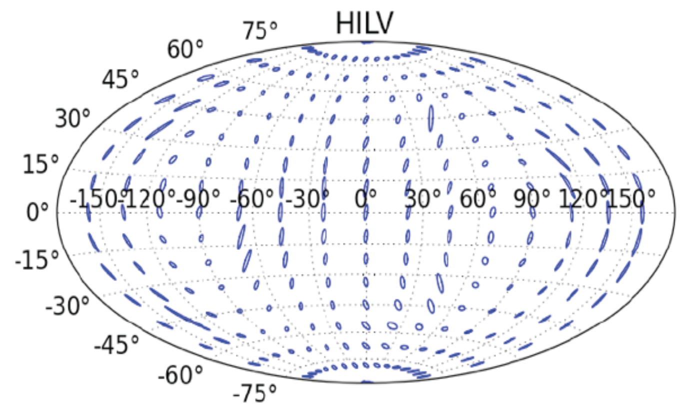


Location, location, location…

- EM follow-ups are greatly facilitated by improving GW source location
- This requires a worldwide network of GW detectors operating at comparable sensitivities



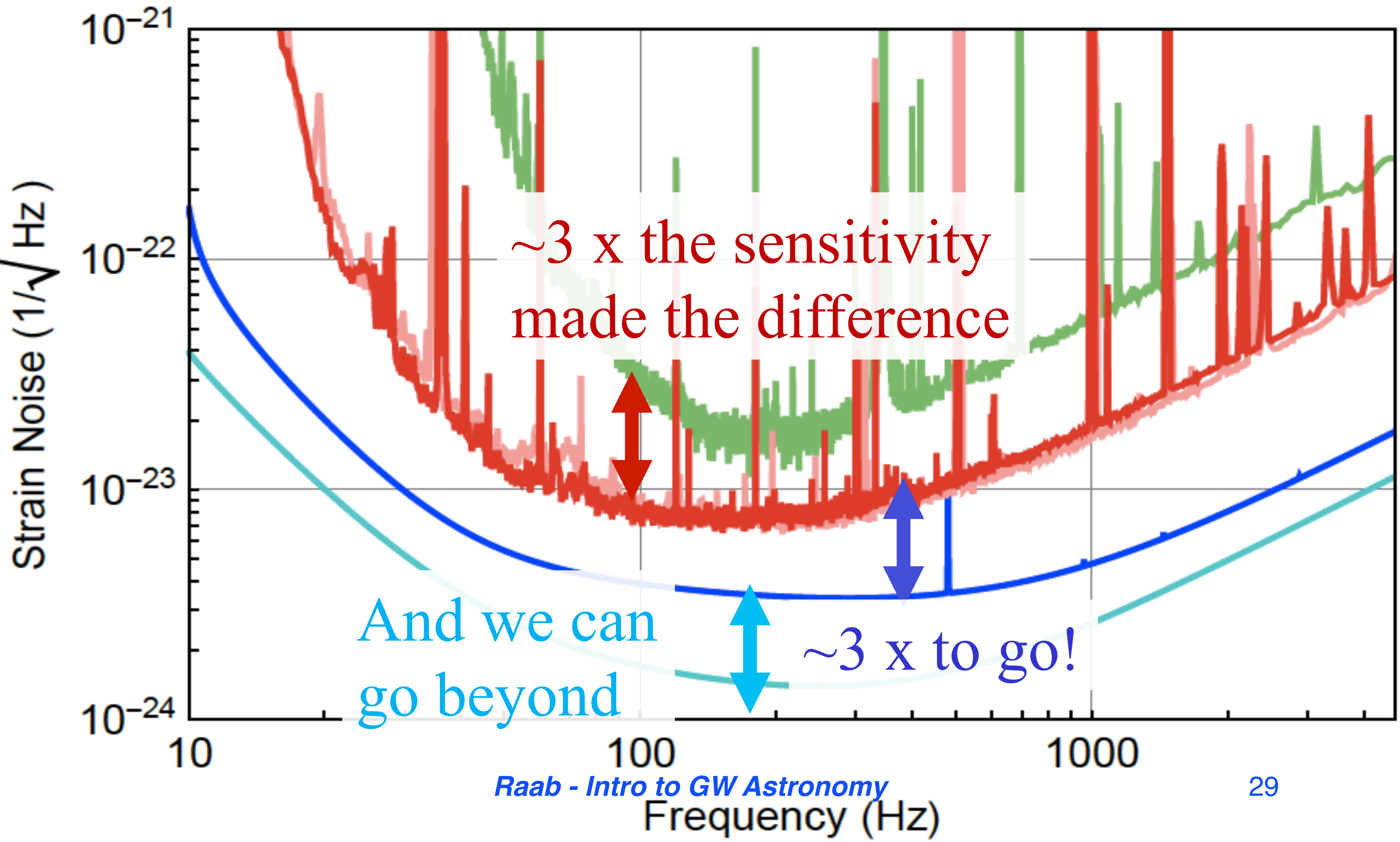
Error ellipses with 2 US sites + Virgo



Error ellipses with 2 US sites + Virgo + India

B.P. Abbott, et al., Living Rev. Relativity, 19, (2016), 1

Initial S6 / Advanced O1 Design / A+ Upgrade



Science drives Requirements

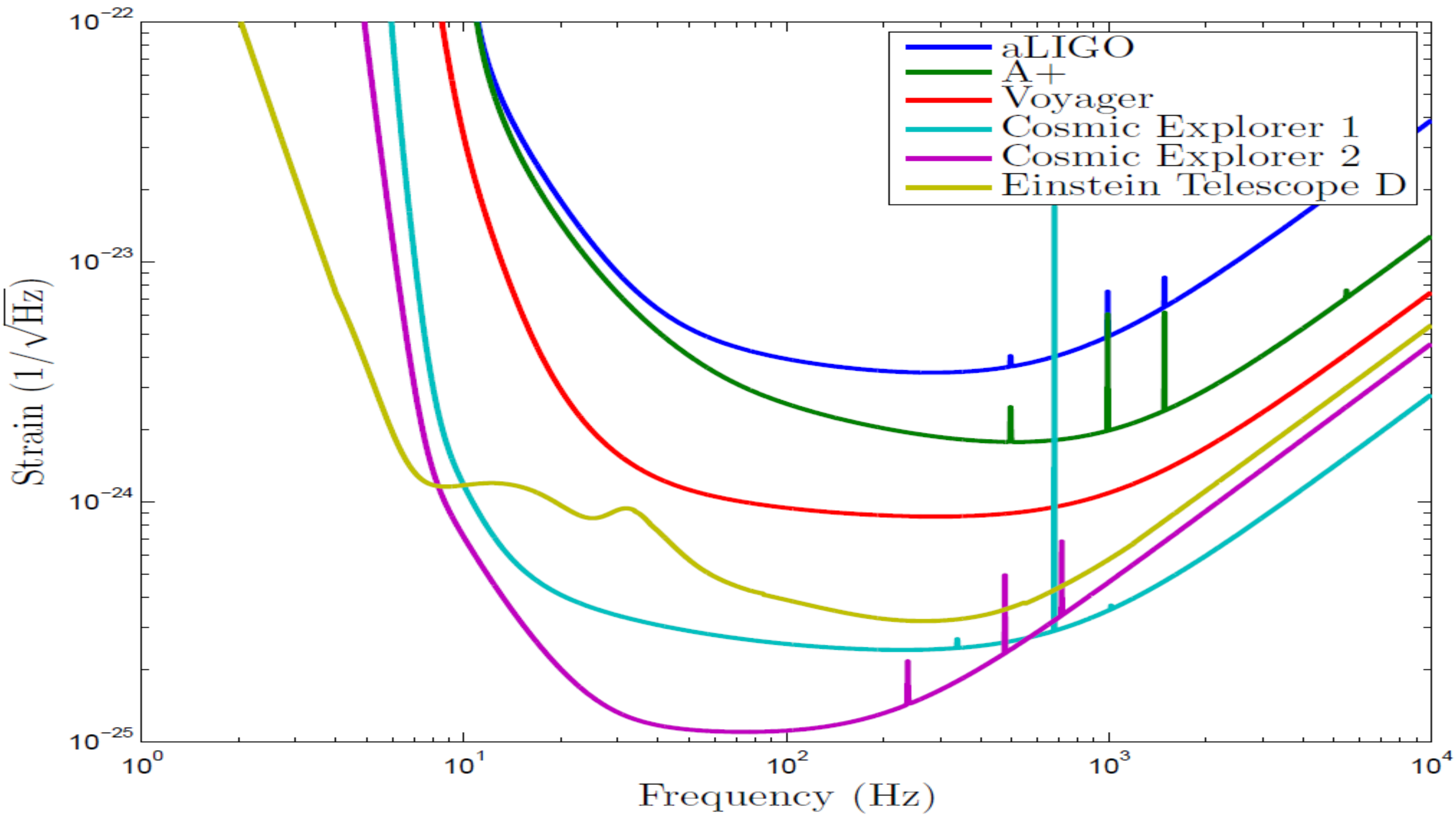
- **Stellar Evolution at High Red-Shift: Black Holes from the first stars (Population III)**
  - » Reach z>~10
  - » At least moderate GW luminosity distance precision
- **Independent Cosmology and the Dark Energy Equation of State**
  - » Needs precision GW luminosity distance and localization for EM follow-ups (for redshift)
- **Checking GR in extreme regime**
  - » High SNR needed
  - » GW luminosity distance and localization not essential

Advanced LIGO upgrade path

- Advanced LIGO is limited by quantum noise & coating thermal noise

- Squeezed vacuum to reduce quantum noise
- Options for thermal noise:
  - » Better coatings
  - » Cryogenic operation
  - » Longer arms (new facility)

Upgrade possibilities



Summary

- GW150914 initiates Gravitational-Wave Astronomy.
- General Relativity provides an powerful framework from Earth-bound physics to mergers of stellar mass black holes at velocities near the speed of light.
- An emerging international network of detectors will provide more accurate positions of sources to enable EM follow-ups of GW events.
- There is still room within the laws of physics to develop more powerful generations of detectors.

Advanced LIGO timeline