Finding the Voice of the Universe

Fred Raab, for the LIGO Scientific Collaboration and
the Virgo Collaboration

The stage for this story is space and time.

The Origins of Relativity

- Relativity describes how things move through space and time
- Galileo (1564-1642) first realized that uniform (constant velocity) motion was relative
  - » Consider two canoes on a placid lake, moving ***relative*** to each other. How do we establish which canoe is moving? We can only describe an object as moving if we can relate that motion to some frame (Shoreline? Water surface? Canoeist?)
  - » Motion of either canoe is ***relative*** to a reference frame, implying there is no such thing as **absolute** motion
- Isaac Newton (1643-1727), the master of motion, codified Galilean relativity into his laws of mechanics
  - » space and motion were defined ***relative*** to a reference frame
  - » time was an **absolute** quantity ⇒ all clocks ticked at the same rate
  - » law of *universal* gravitation ⇒ “action at a distance”

Fast Forward 200 Years

- About 100 years ago, Albert Einstein (1879-1955) began to explore anew the concepts of space and time
  - » Only two forces were known at that time: electromagnetism & gravity
  - » Theory of electromagnetism had correctly described motors, generators, radio and light transmission
  - » Newton's mechanics had correctly described motion of neutral matter, including an accurate description of how gravity acts, but not how it arises
  - » But the two theories were incompatible in the description of rapidly moving electrical charges
- Einstein eventually discovered that the incompatibility was caused by the presence of "absolute" time
  - » Two travelers in relative motion, not only cannot define who is moving, if they move fast enough they also disagree on the time between events

Special Relativity

- Einstein's *Special* Theory of Relativity (1905) described motion of matter *in the absence of gravity*
  - » Everything is relative, except the speed of light, which is absolute, in agreement with electromagnetism
  - » Speed of light is a property of space
  - » There is a special symmetry between space and time, mass and energy
  - » All observers in relative motion observe the same laws of physics but they disagree on the definitions of time and space used to describe those laws
- Predictions:
  - » Moving rulers contract
  - » Moving clocks tick slower
  - » Matter is just a "frozen" form of energy (e.g., nuclear power industry)

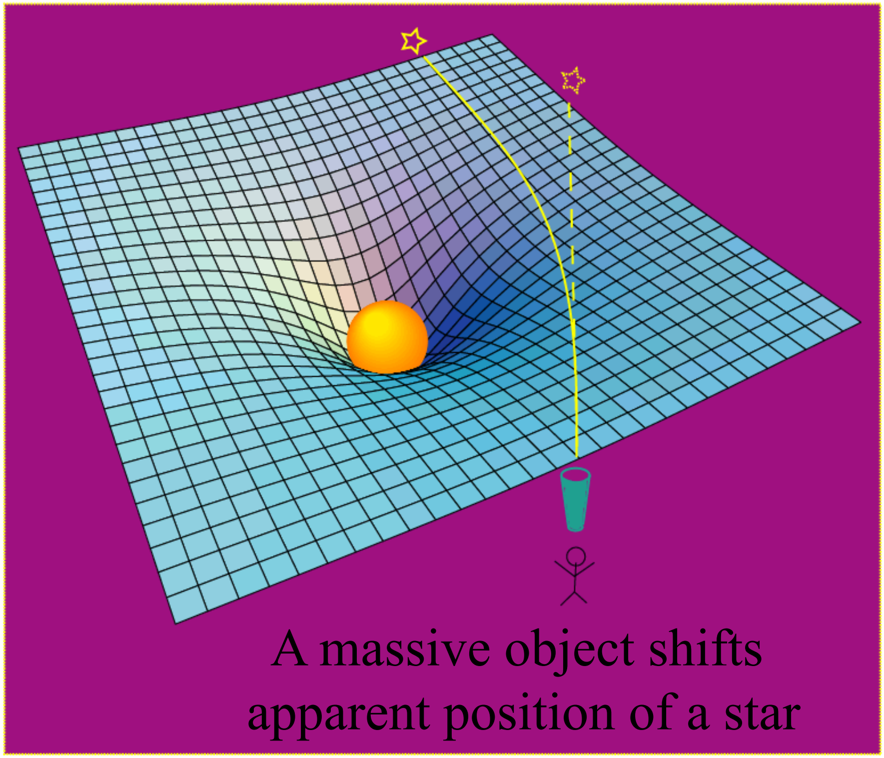
Basics of General Relativity and Gravitational Waves

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

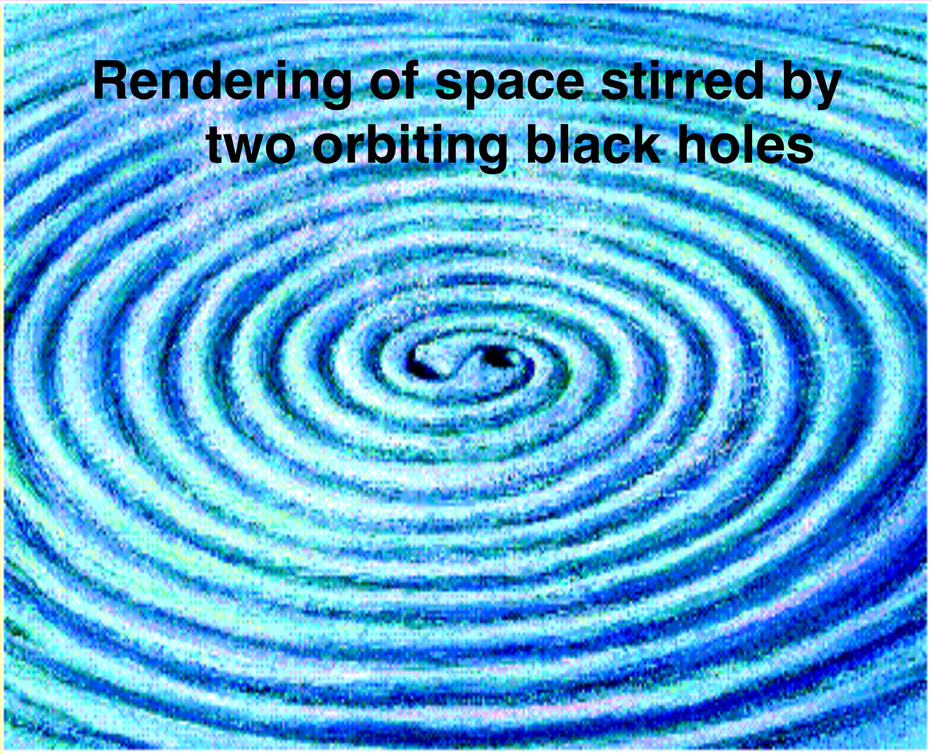
Special Relativity and the Case of the Missing Sun

Free fall is weightless

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



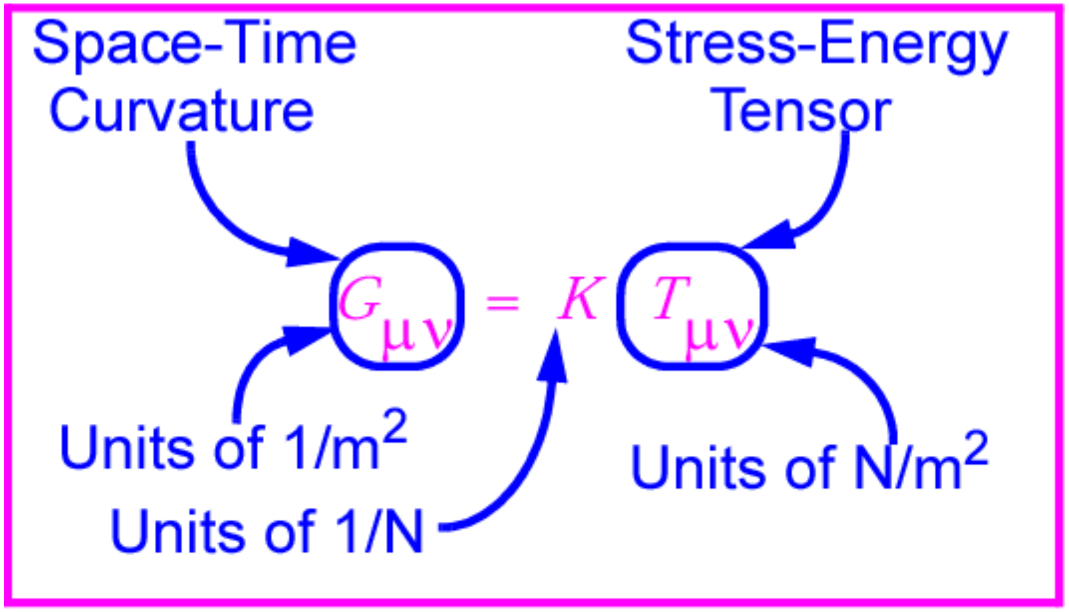
A massive object shifts apparent position of a star



Rendering of space stirred by two orbiting black holes

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!



Space-Time Curvature

Stress-Energy Tensor

$$G_{\mu\nu} = K\, T_{\mu\nu}$$

Units of $1/m^2$

Units of $1/N$

Units of N/m^2

Following I.R. Kenyon, *General Relativity*

$K \sim [G/c^4]$ is combination of G and c with units of $1/N$

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

⇒ Wave can carry huge energy with miniscule amplitude!

Expected strength

- Sense of scale: strain from a binary neutron star pair
  - » $M = 1.4\ M_\odot$,
  - » $r = 10^{23}$ m (15 Mpc, Virgo),
  - » $R = 20$ km
  - » $f_{orb} = 400$ Hz

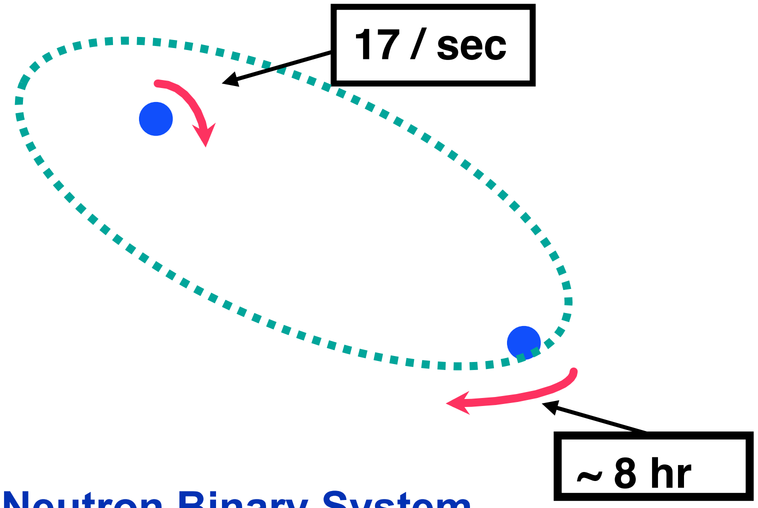
$$h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r} \qquad \Rightarrow \qquad \boxed{h \sim 10^{-21}}$$

Gravitational Waves

a well-understood transmitter

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



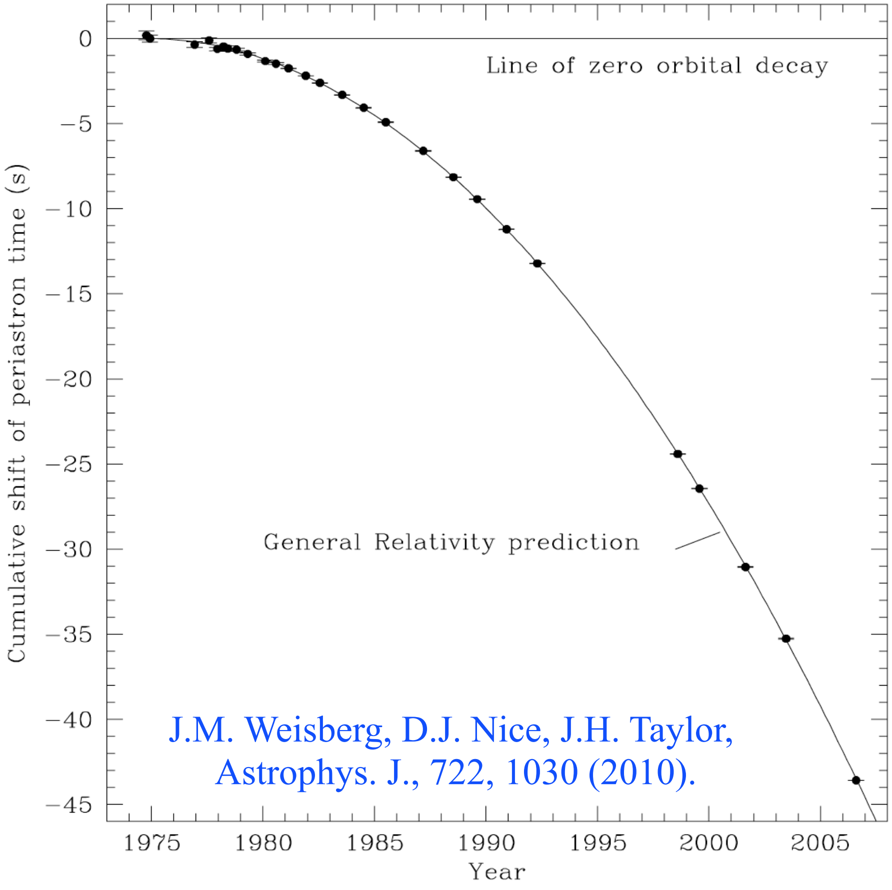
Neutron Binary System

- **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**

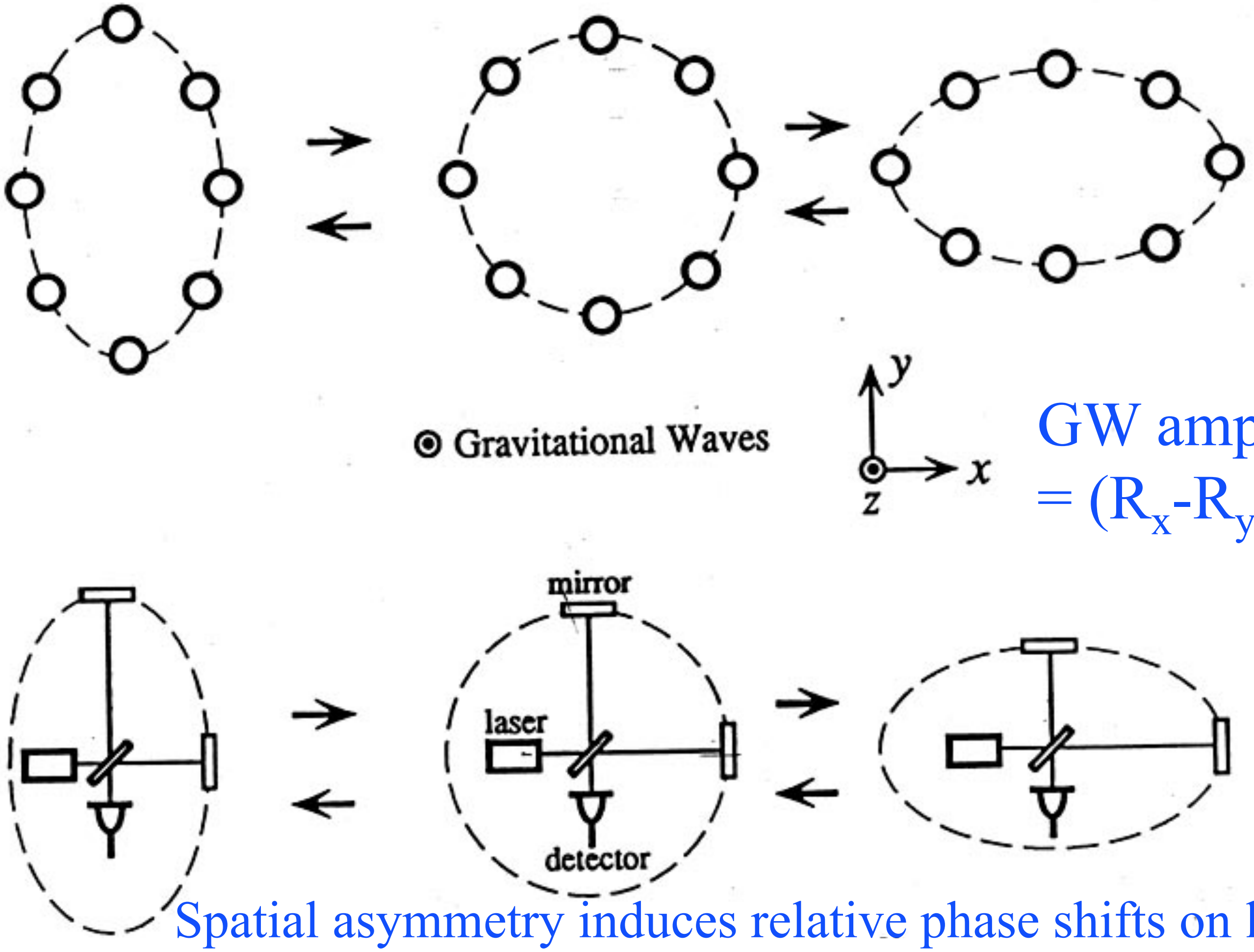
Emission of gravitational waves



J.M. Weisberg, D.J. Nice, J.H. Taylor, Astrophys. J., 722, 1030 (2010).

the Universe

Basic idea for detection is simple



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

Spatial asymmetry induces relative phase shifts on light in arms

The Laser Interferometer Gravitational-Wave Observatory

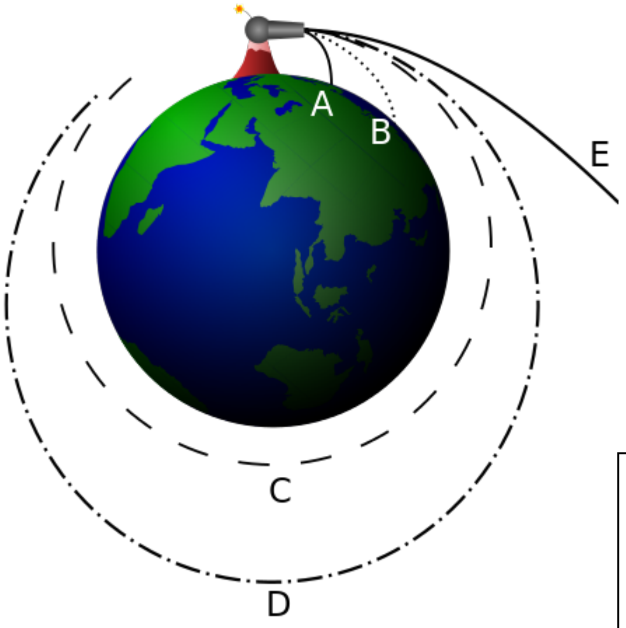
LIGO (Washington)

LIGO (Louisiana)

Brought to you by the National Science Foundation; operated by Caltech and MIT; the research focus for more than 1000 LIGO Scientific Collaboration members worldwide.

The actors are monster objects called “black holes” which became locked in a death spiral and died in an event of unimaginable violence.

Schwarzschild Black Hole



Newton's Cannonball
Credit: Brian Brondel

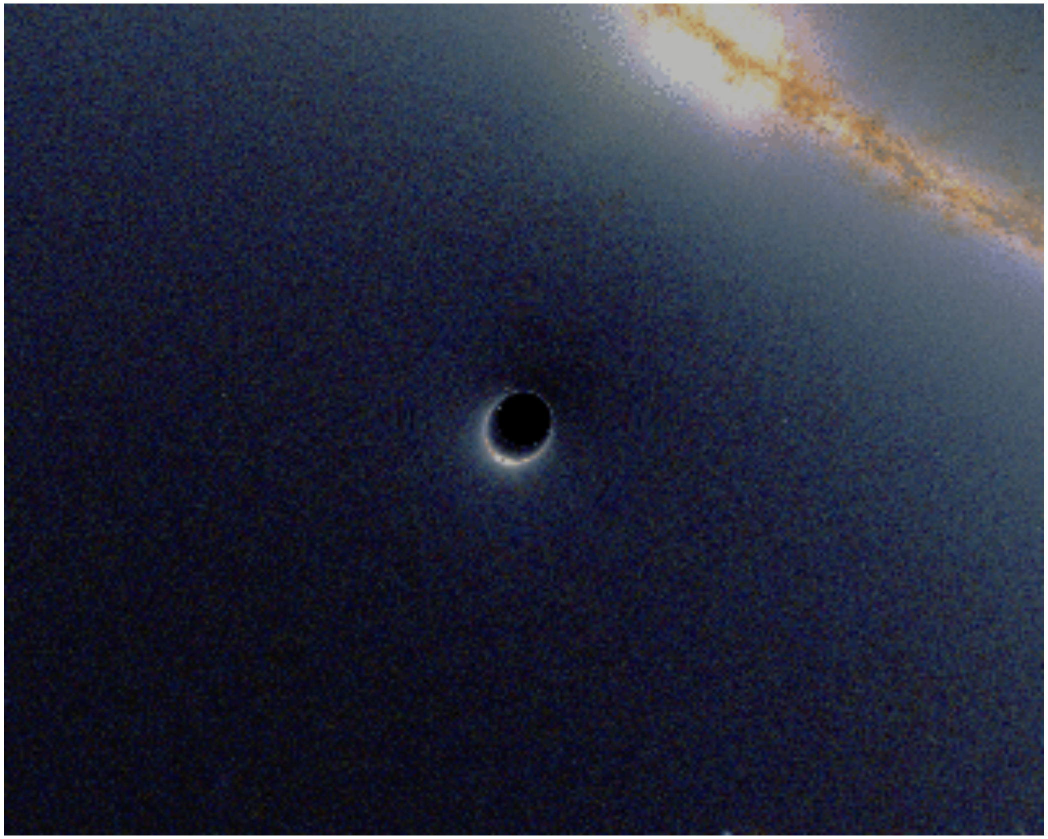
Escape Velocity $$v_{esc} = \sqrt{\frac{2GM}{r}}$$

Schwarzschild Radius $$R_s = \frac{2GM}{c^2}$$

Object	Schwarzschild Radius
Earth	1 cm (size of marble)
Sun	3 km (2 miles)

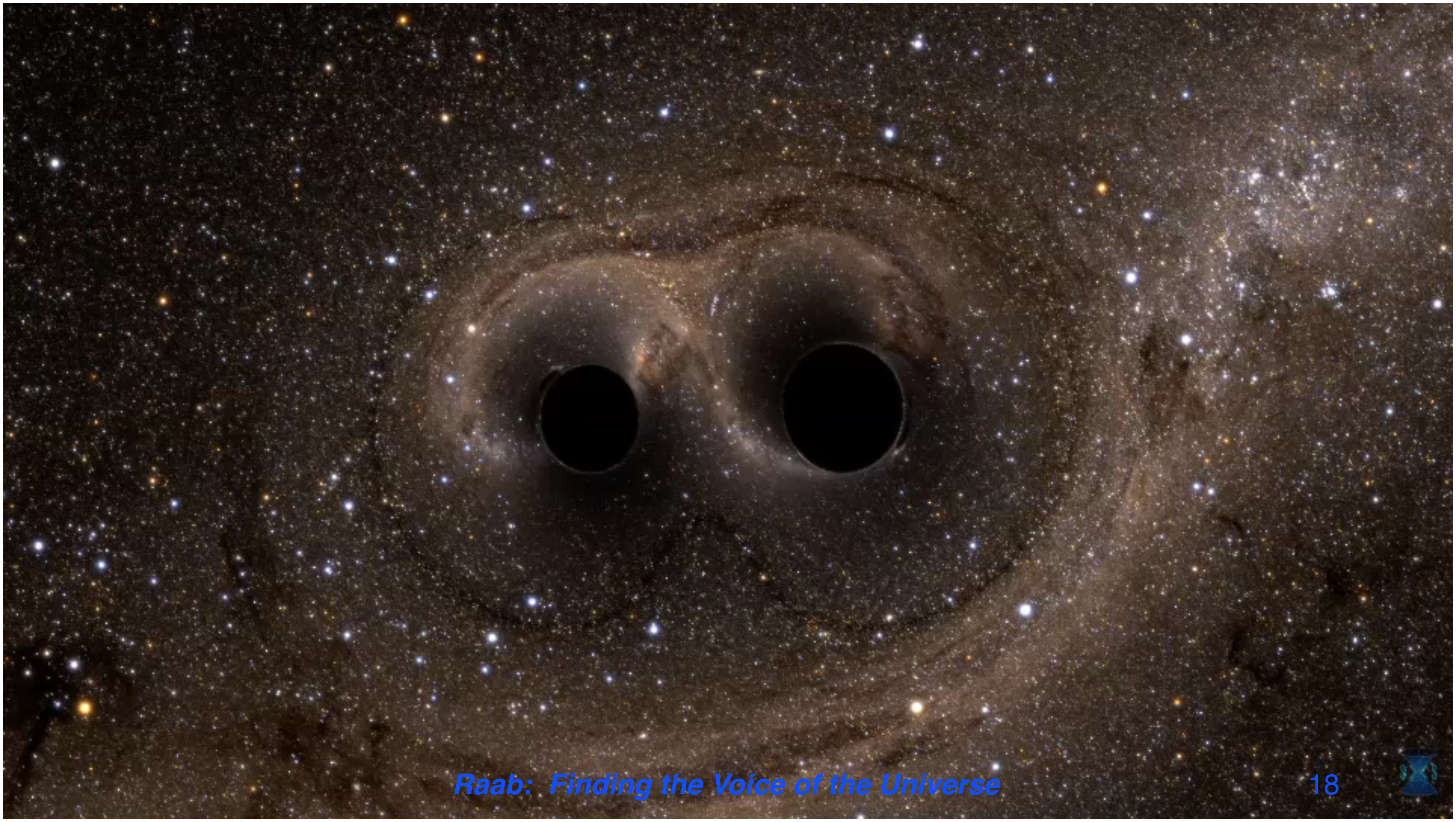
Karl Schwarzschild

Illustration of How a Black Hole Distorts Background Light

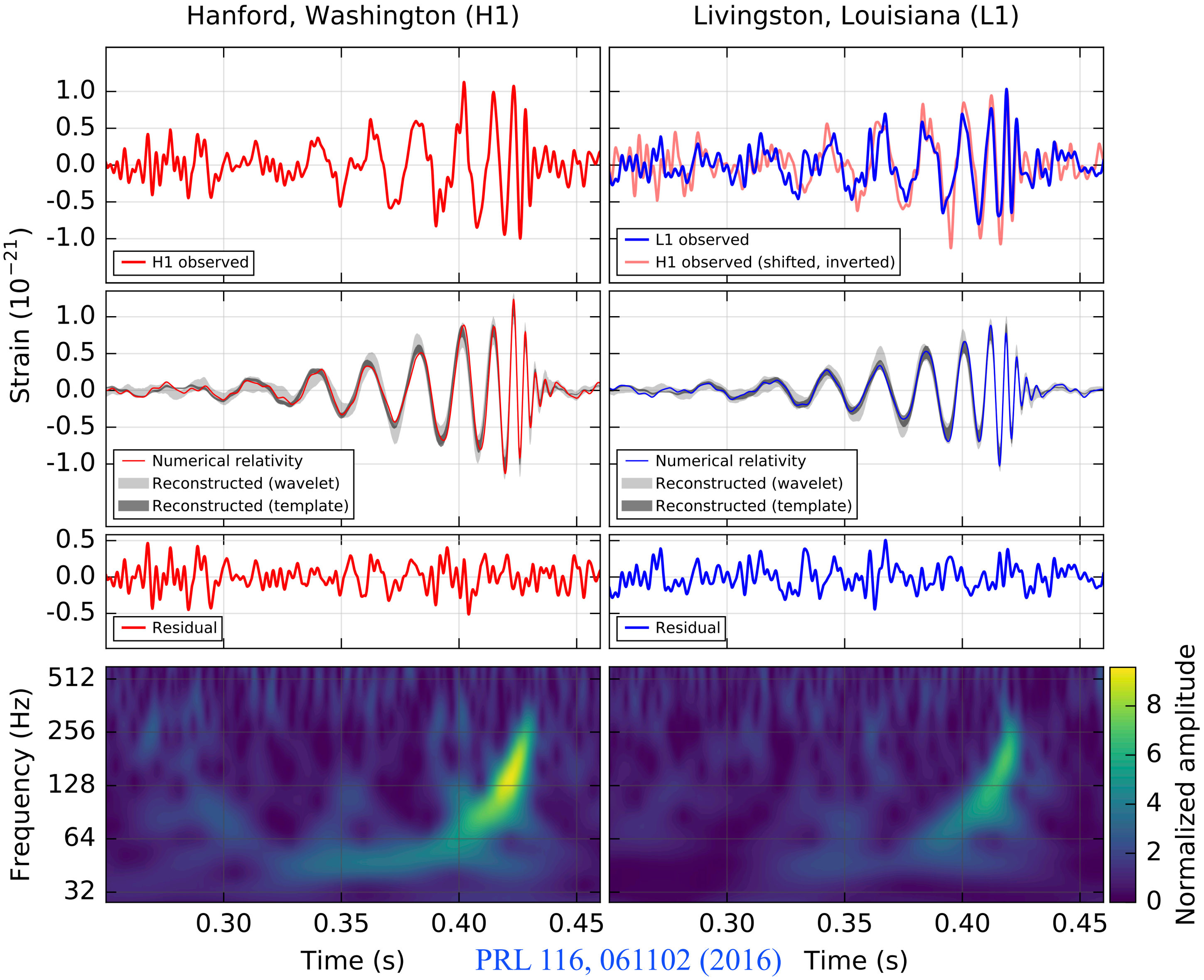


https://en.wikipedia.org/wiki/File:BlackHole_Lensing.gif

The story starts a long time ago in a part of our universe far, far away…

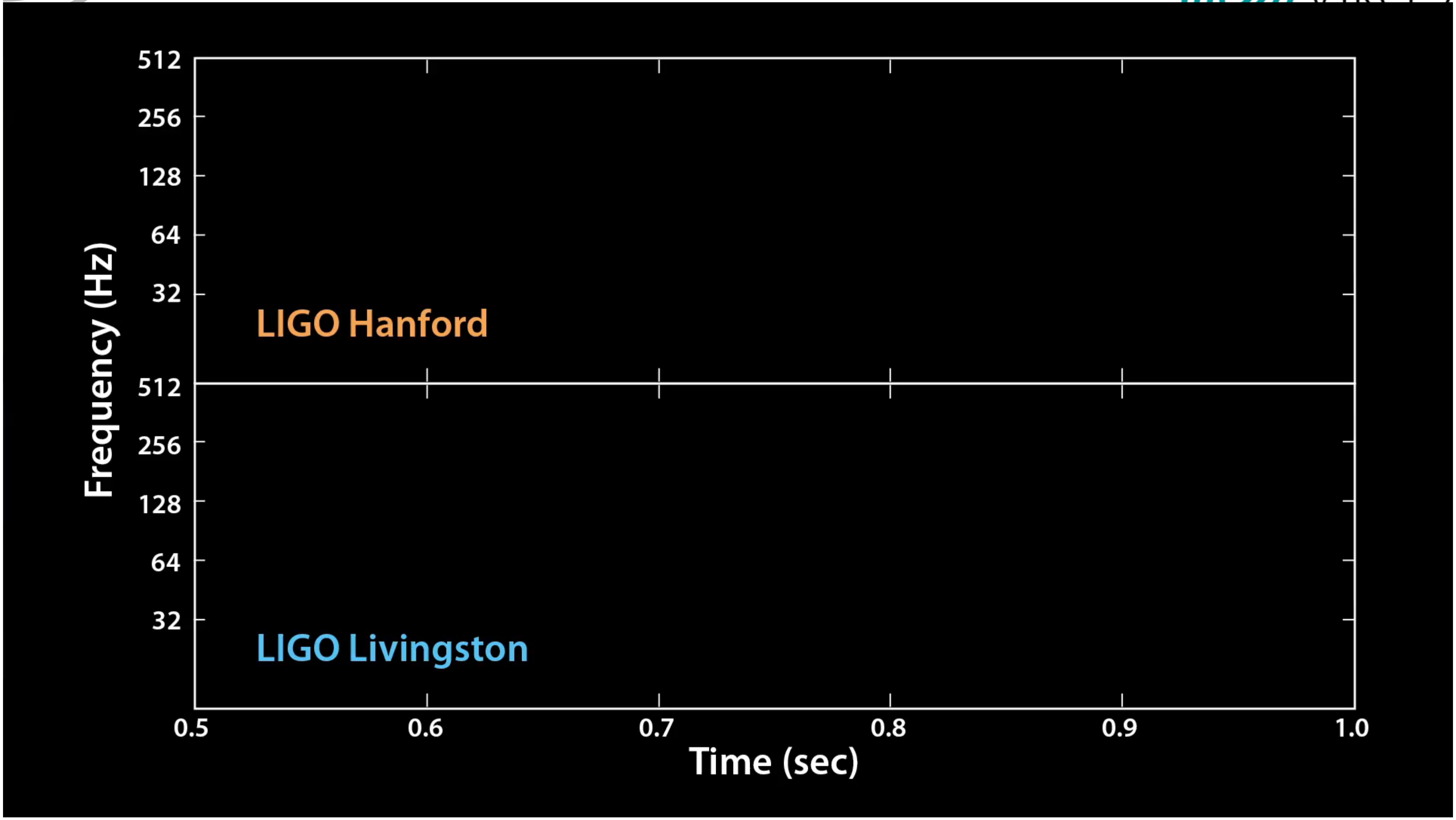


LIGO Observed on Sep 14, 2015



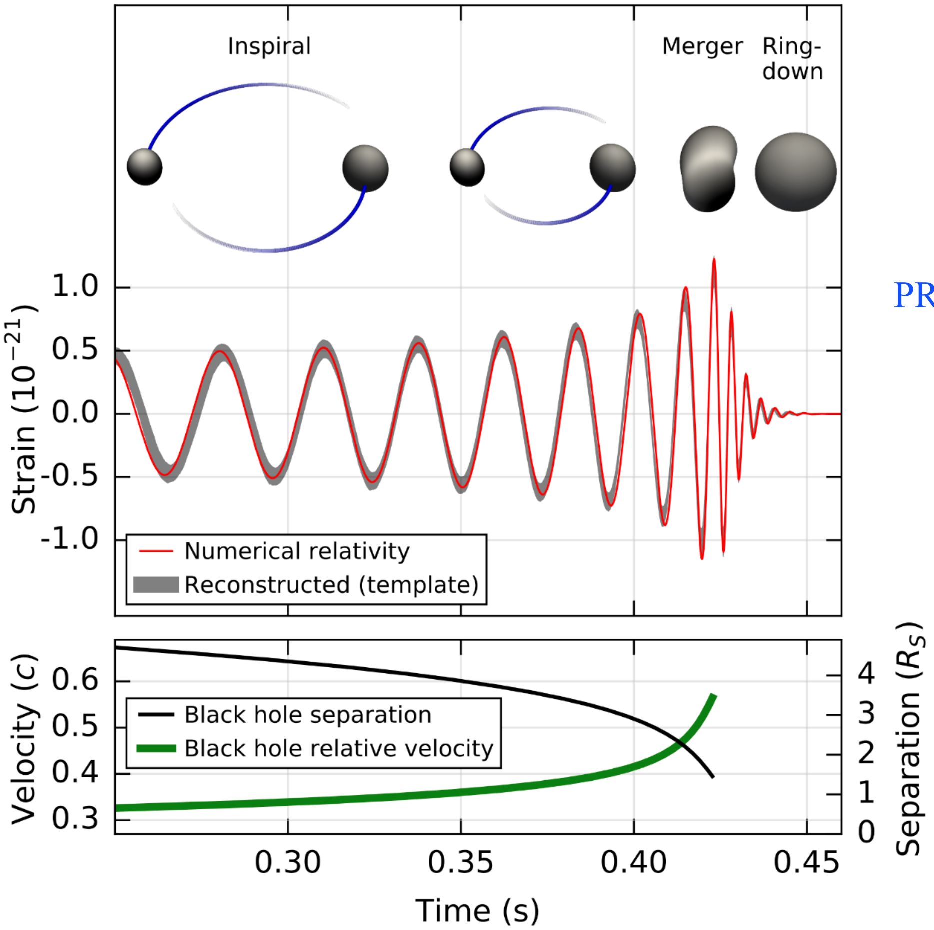
PRL 116, 061102 (2016)

LI



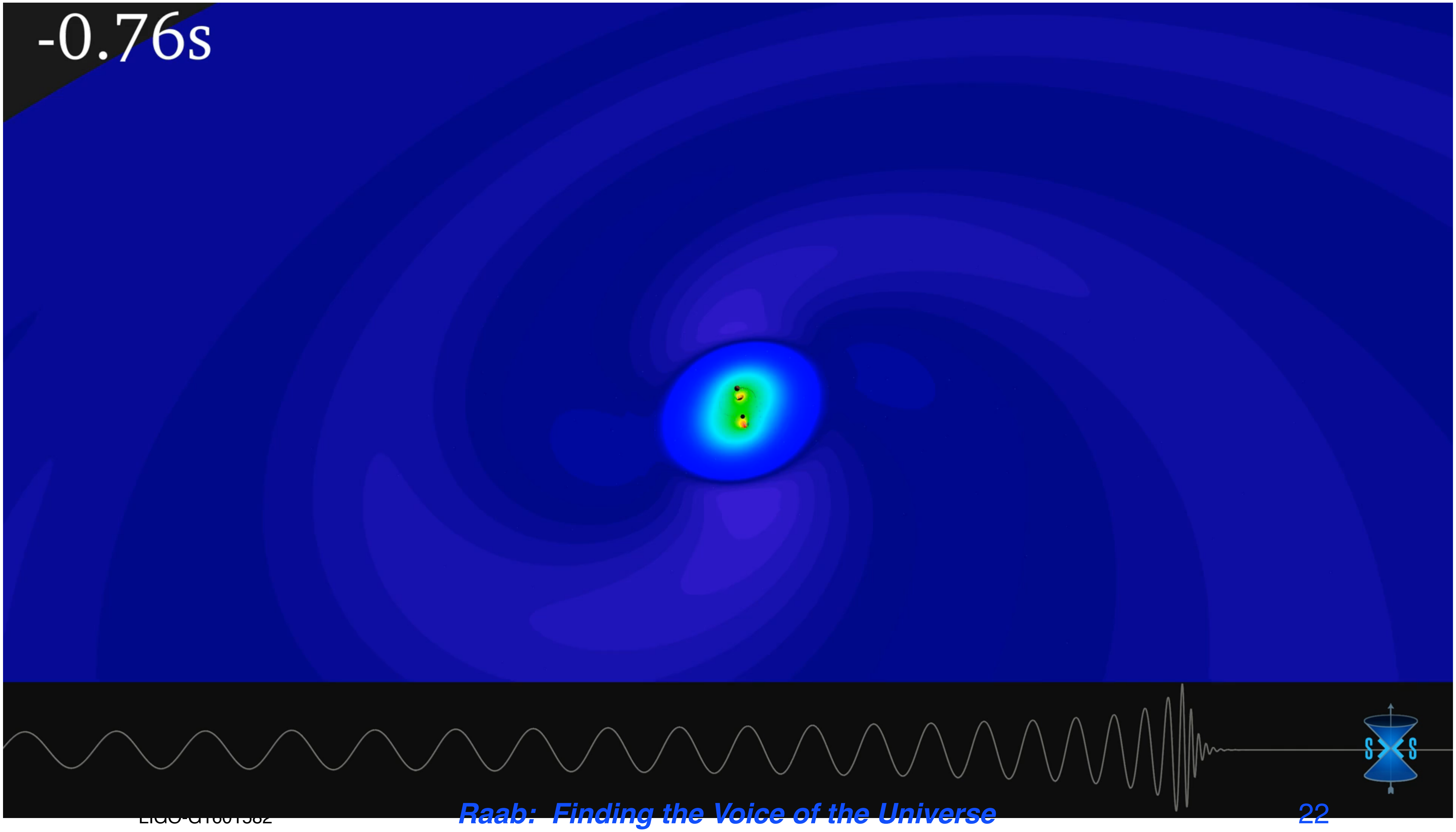
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

LIGO A signal from a binary black hole merger



PRL 116, 061102 (2016)

A signal from a binary black hole merger



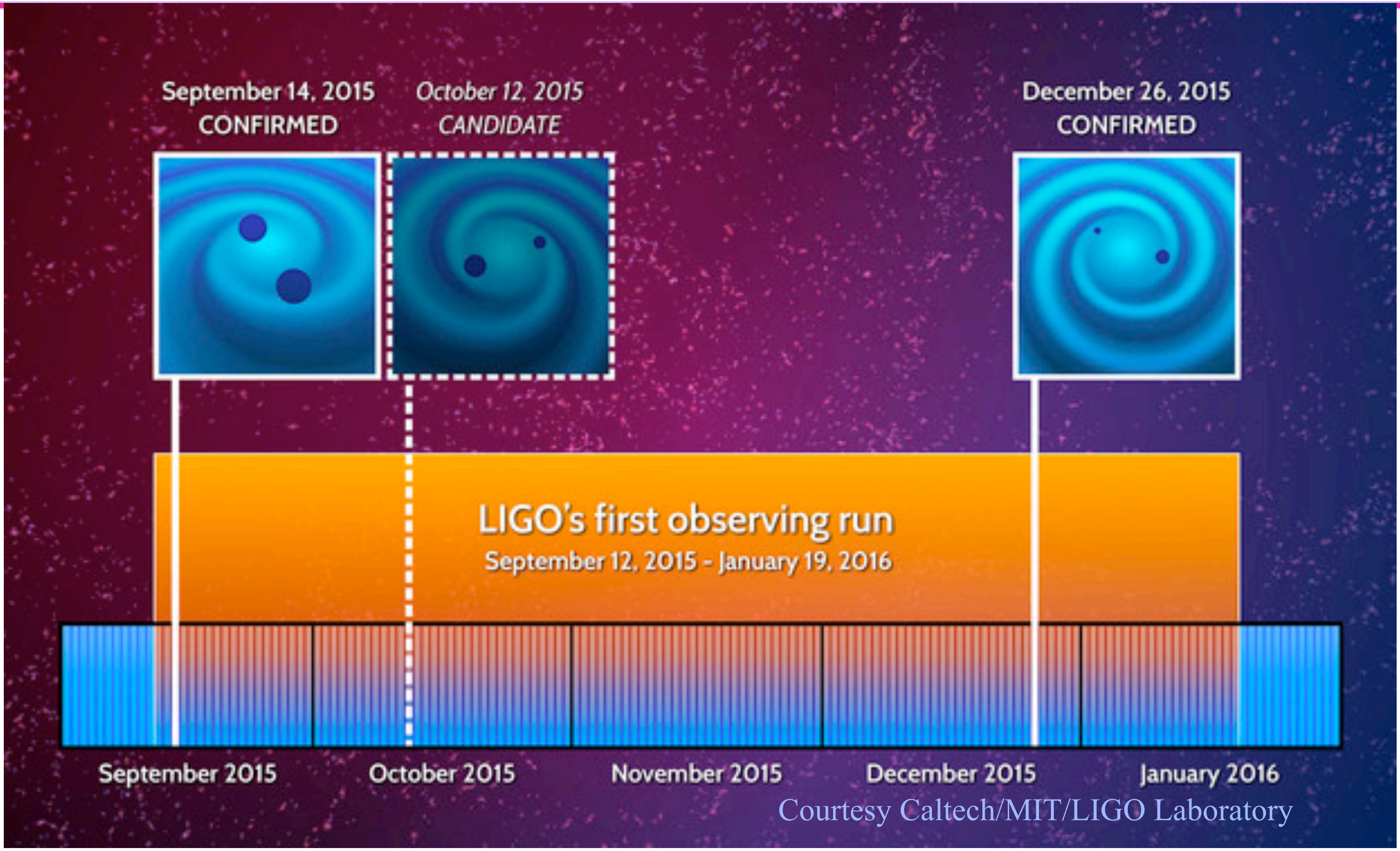
Long, long ago?
Far, far away?

- GW150914 occurred more than a billion years ago.
- At that time, life on Earth consisted of only single-cell creatures.
- We can express vast distances using light, which travels at a speed of 30 cm per nanosecond:
  - Moon is 1.3 light-sec away
  - Sun is 8.3 light-minutes away
  - Jupiter is 35-52 light-minutes away
  - Globular cluster M13 is 21,000 light years away
  - M31, the Andromeda Galaxy, is 2.3 million light years away
- M31 is our closest large galaxy. In the volume that we can see systems like GW150914, there are more than 5 million galaxies.

GW150914

- This first gravitational wave discovery was named GW150914:
  - » Event type = gravitational wave
  - » Detection year = 2015
  - » Detection month = 09 = September
  - » Detection day = 14
- This was the most energetic event ever detected by humans, converting a mass equivalent to a million Earths into gravitational-wave energy.
- For a few tenths of a second the power in this gravitational wave was 50 times greater than the total power output of all the stars in the universe.
- But there were more discoveries to come…

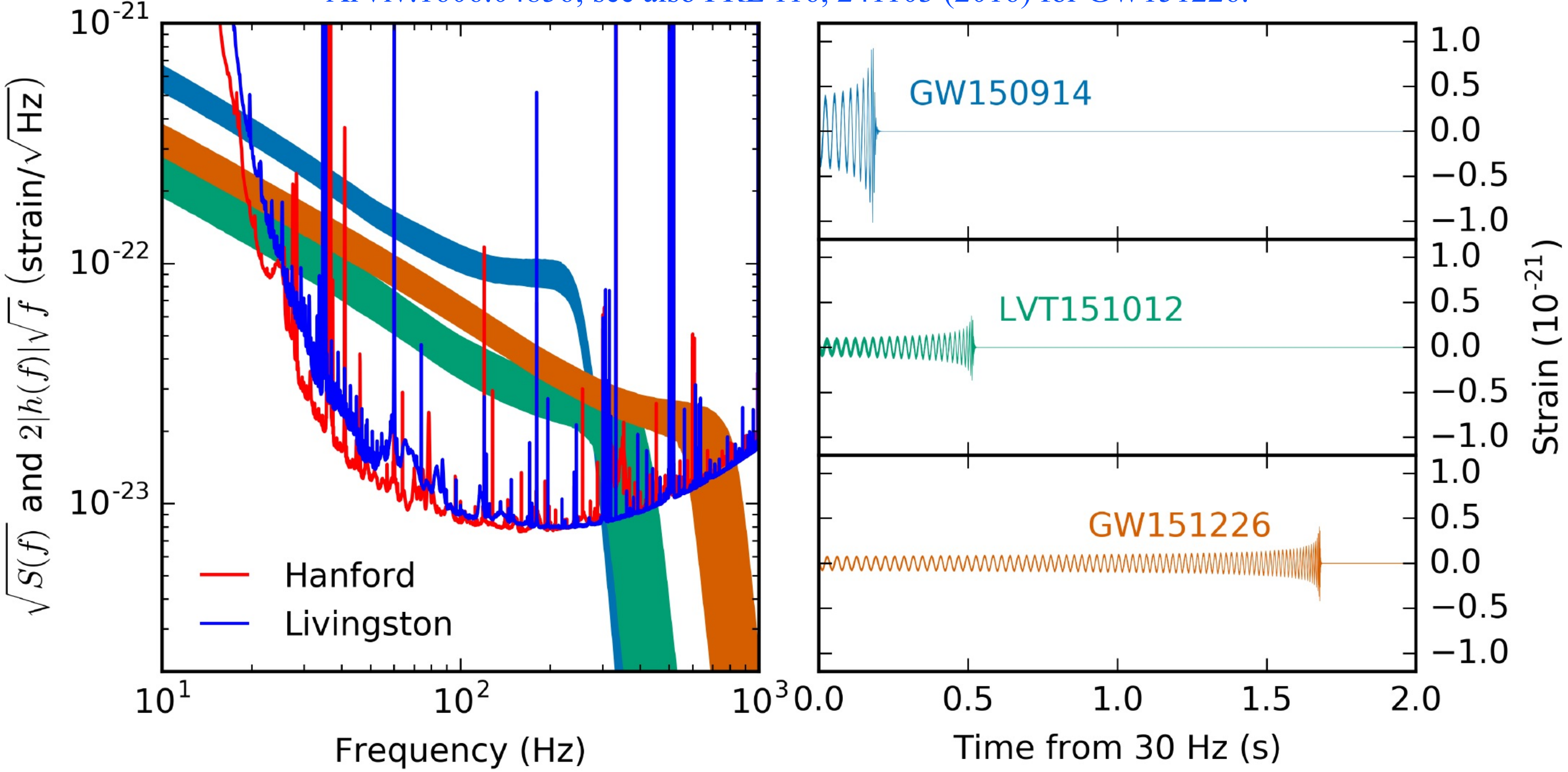
Discovery Timeline – Advanced LIGO's 1st Observations



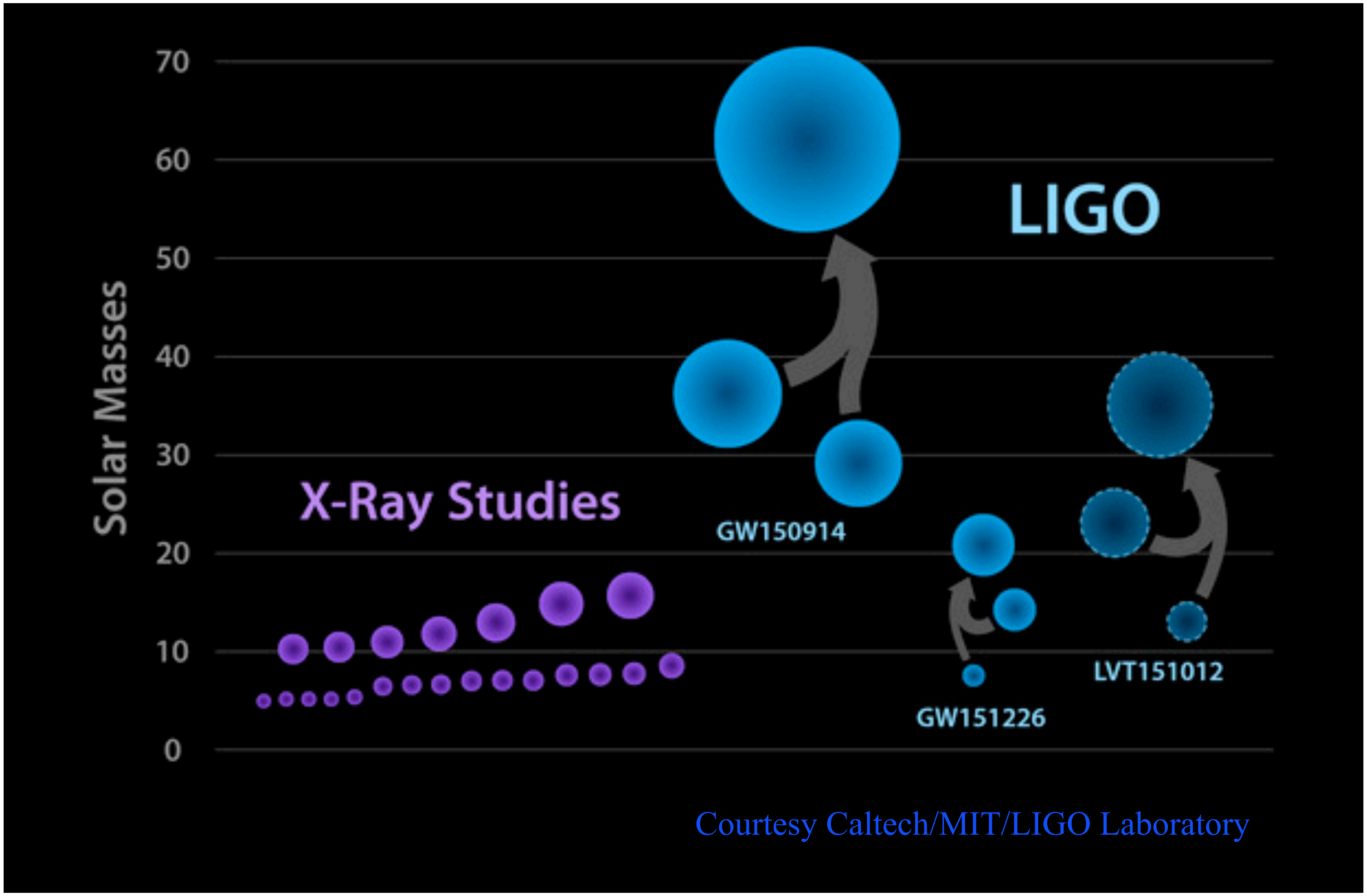
Courtesy Caltech/MIT/LIGO Laboratory

Advanced LIGO's First Observations

ArViv:1606.04856; see also PRL 116, 241103 (2016) for GW151226.



Known Stellar-Mass Black Holes – June 2016



Courtesy Caltech/MIT/LIGO Laboratory

Unfortunately, Sky Localization Is Poor With Only Two Detectors

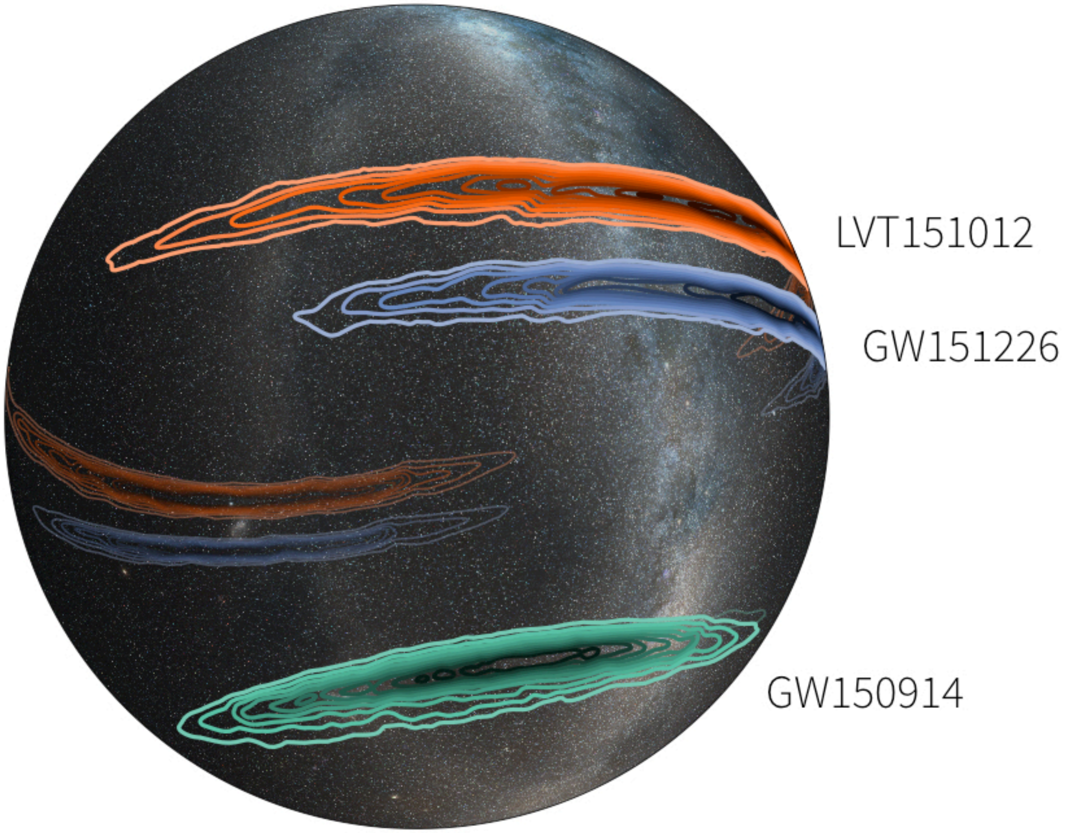
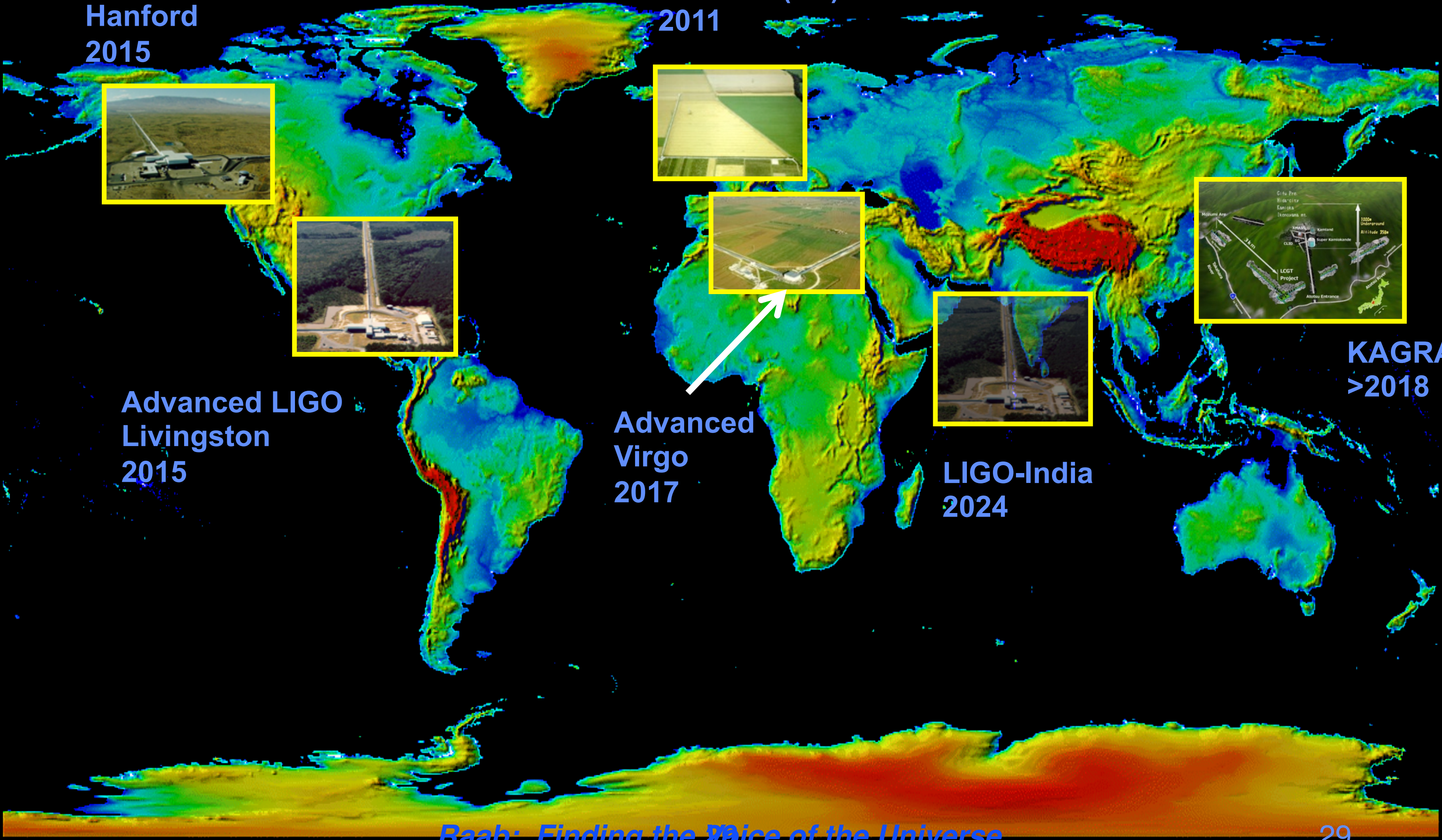


Image credit: LIGO (Leo Singer) /Milky Way image (Axel Mellinger)

The advanced GW detector network: 2015-2025



Advanced LIGO Hanford 2015

GEO600 (HF) 2011

KAGRA >2018

Advanced LIGO Livingston 2015

Advanced Virgo 2017

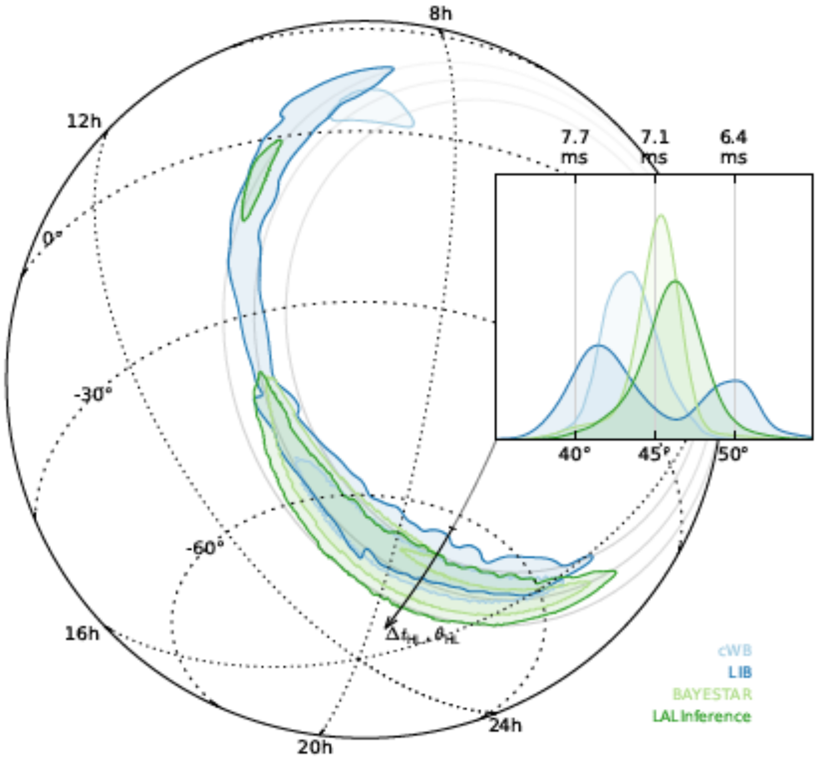
LIGO-India 2024

LIGO-India Concept

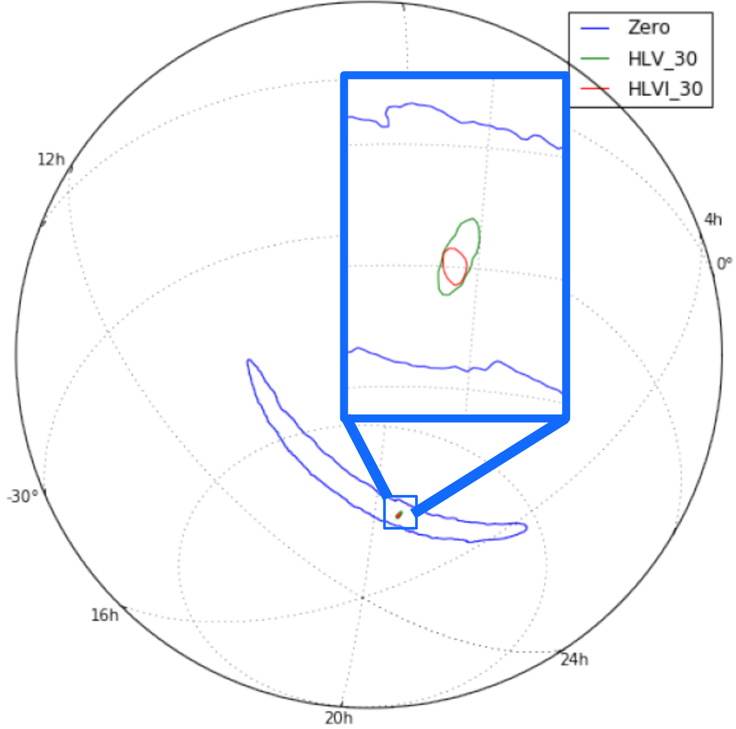
- Started as a partnership between LIGO Laboratory and IndIGO collaboration to build an Indian interferometer
  - » LIGO Lab (with its UK, German and Australian partners) provides components for one Advanced LIGO interferometer (H2) from the Advanced LIGO project
  - » LIGO Lab provides designs and design assistance for facilities and vacuum system and training for Indian detector team
  - » India provides the infrastructure (site, roads, building, vacuum system), staff for installation & commissioning, operating costs
- LIGO-India would be operated as part of LIGO network to maximize scientific impact
- Major enhancement to the global network and to the capabilities for GW astrophysics and Multi-messenger Astronomy

Improved Localization: LIGO→Virgo→LIGO-India

GW150914: LIGO only



GW150914: LIGO →LV →LVI (Preliminary)



375° → 9.3° → 7.8°
(99% confidence level)

What did it take to make these discoveries?

- This was a high-risk, high-reward endeavor that took decades to produce discoveries. It required:
  - Vision and persistence by proposers and funders of the R&D and construction to overcome the technical challenges;
  - Humility
    - Don't overpromise
  - Transparency
    - Be honest about progress and challenges
  - Openness
    - Need a village of experts, not a guru
  - Optimism
    - Failure is the tuition we pay for learning

Issues to address in 1989 proposal to build a gravitational wave detector

- Signal has never been detected directly
- Understanding of either source strengths or source populations ranges from "not well" to "poorly" known
- Simple arguments based on available information indicate the need to cover a space-time volume from billions to a trillion times larger than previous detector searches
- Need to scale up size 100-fold from largest existing device
- Need to push frontier of measurement science, but no law of physics prevents it
- Any feasible detector using current or close-to-hand technology may not be sufficiently sensitive to make detections
- Very expensive: failure is not an option
- Strategy: build initial km-scale facilities and a pathfinder detector (iLIGO) and conduct searches, while pushing R&D toward an advanced detector (aLIGO) capable of routine detections

Original detection strategy

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

Rochus E. Vogt
Principal Investigator and Project Director
California Institute of Technology

Ronald W. P. Drever
Co-Investigator
California Institute of Technology

Kip S. Thorne
Co-Investigator
California Institute of Technology

Frederick J. Raab
Co-Investigator
California Institute of Technology

Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology

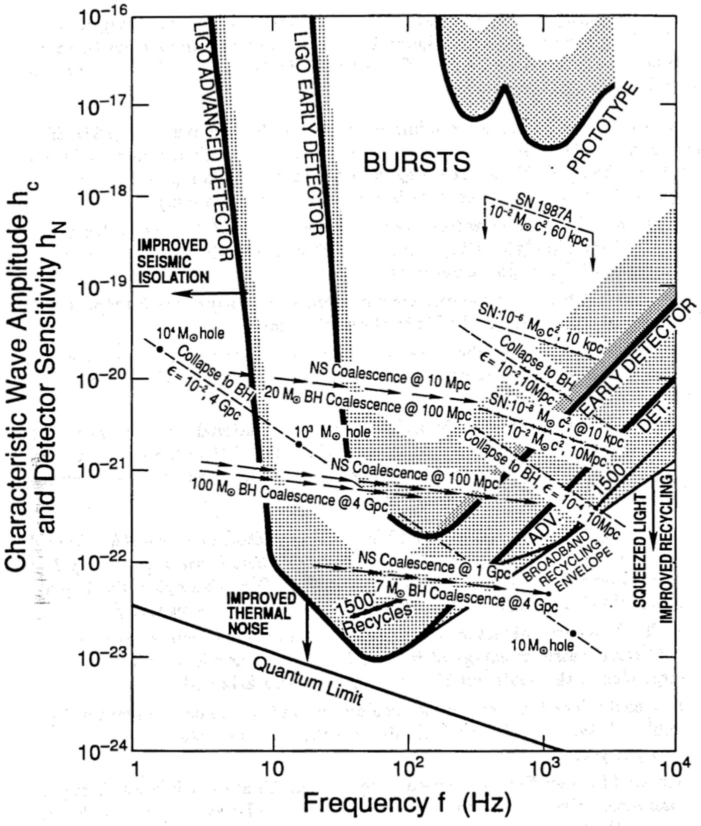


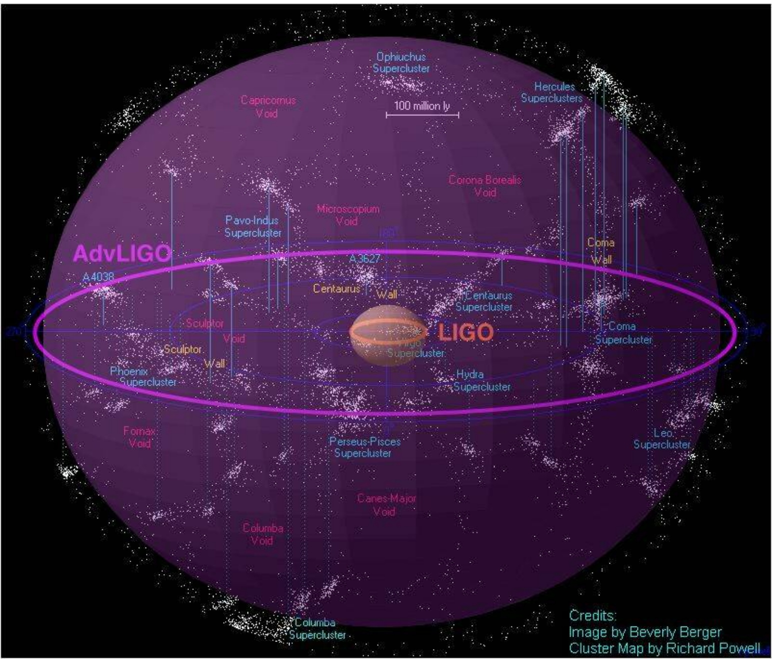
Figure II–2 A comparison of the strengths of gravitational waves (characteristic amplitude h_c and frequency f) for burst signals from various sources (dashed lines and arrows), and benchmark sensitivities h_N (solid curves and stippled strips atop them) for interferometric detectors today (*prototype*) 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.

Some of the technical challenges for design and commissioning

- ✓ Typical Strains < 10^{-21} at Earth ~ 1 hair's width at 4 light years
- ✓ Understand displacement fluctuations of 4-km arms at the millifermi level (1/1000th of a proton diameter)
- ✓ Control km-scale arm lengths to 10^{-13} meters RMS
- ✓ Detect optical phase changes of ~ 10^{-10} radians
- ✓ Hold mirror alignments to 10^{-8} radians
- ✓ Engineer structures to mitigate recoil from atomic vibrations in suspended mirrors
- Do all of the above 7x24x365

✓ S5 science run 14Nov05 to 30Sep07

Expected event rates



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

Binary neutron stars

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

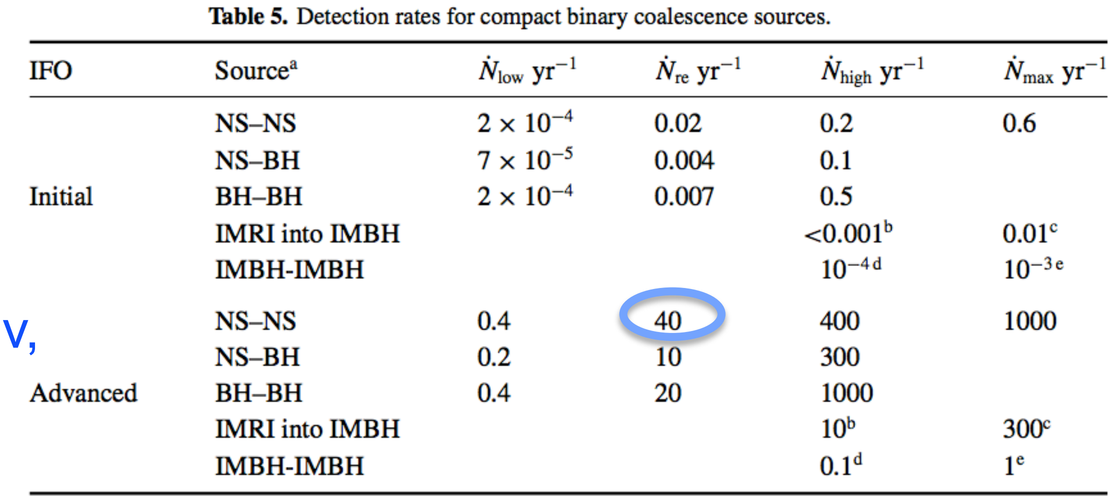


Table 5. Detection rates for compact binary coalescence sources.

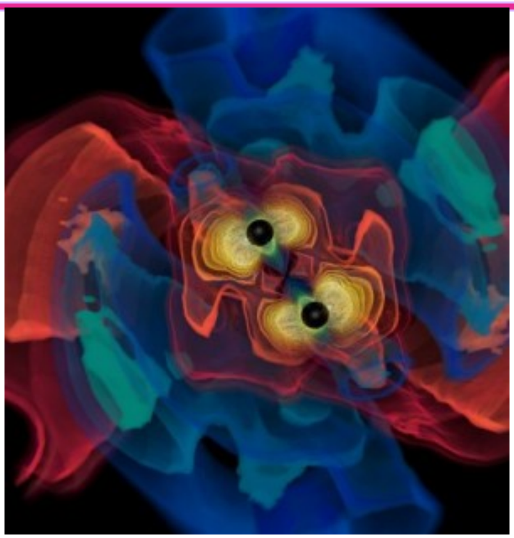
IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
Initial	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
	NS–NS	0.4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

Now what?

- These first observations open up access to a vast new frontier for exploration
- How and where have these objects been formed?
- Initial observations indicate that stellar-mass or “heavy” black hole binaries merge hourly somewhere in the universe
- What can these mergers teach us?
- Where is the matter?
    - No “known” form of matter can explain LIGO’s early discoveries, and they behave like black holes.
    - Can we prove that these objects are black holes?
    - Where are the neutron stars and how do they behave?

Astrophysical Sources of Gravitational Waves

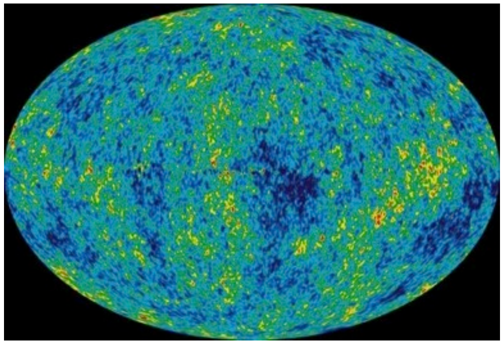


Credit: AEI, CCT, LSU

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

- Strong emitters, well-modeled,

- (effectively) transient

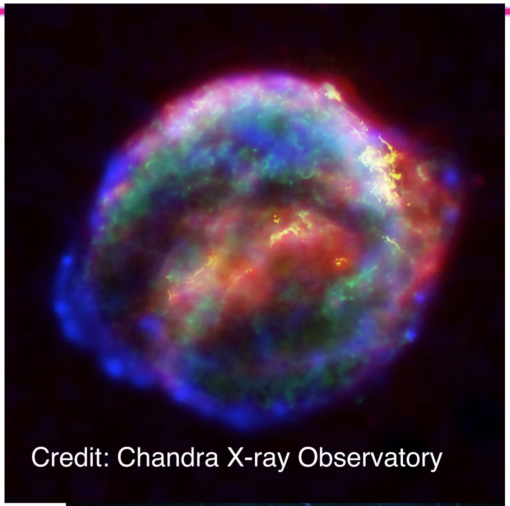


NASA/WMAP Science Team

Cosmic Gravitational-wave Background

- Residue of the Big Bang

- Long duration, stochastic background

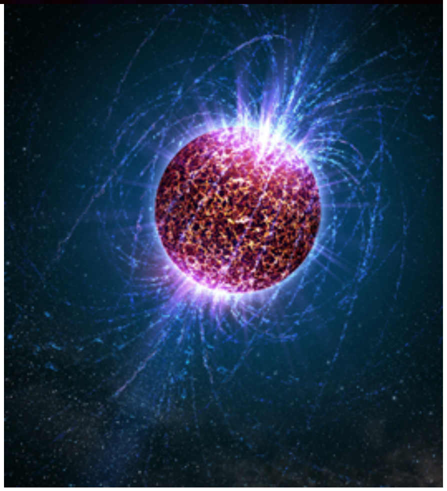


Credit: Chandra X-ray Observatory

Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled

('bursts'), transient



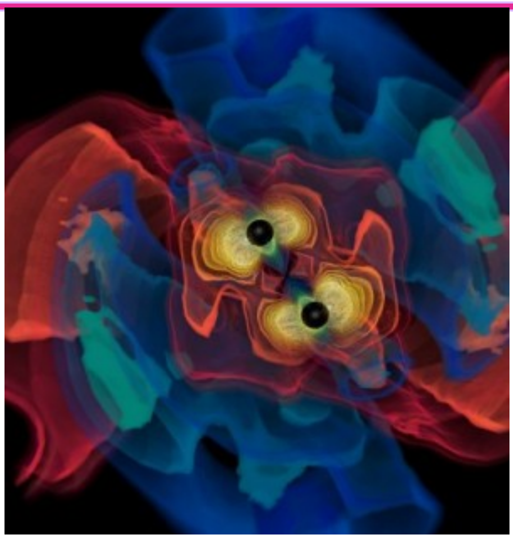
Casey Reed, Penn State

Spinning neutron stars

- (nearly) monotonic waveform

- Long duration

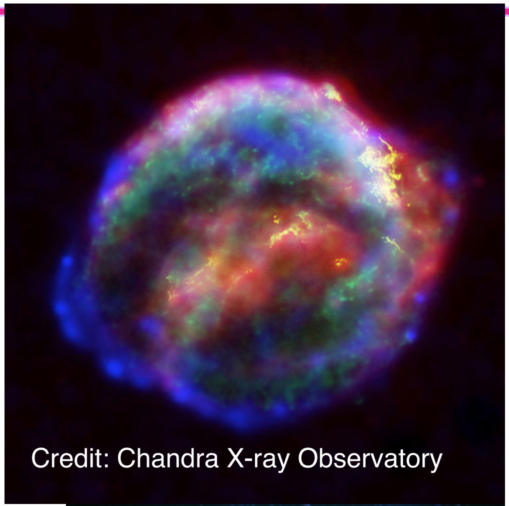
Astrophysical Sources of Gravitational Waves


Credit: AEI, CCT, LSU

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

- Strong emitters, well-modeled,

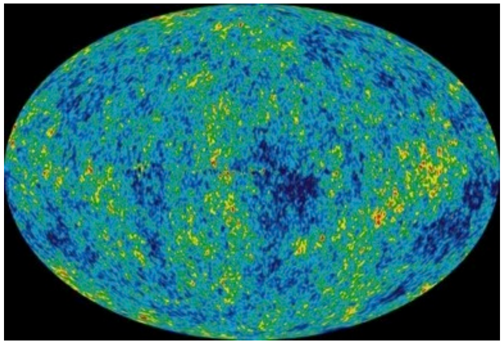
- (effectively) transient


Credit: Chandra X-ray Observatory

<u>Asymmetric Core Collapse Supernovae</u>

- Weak emitters, not well-modeled

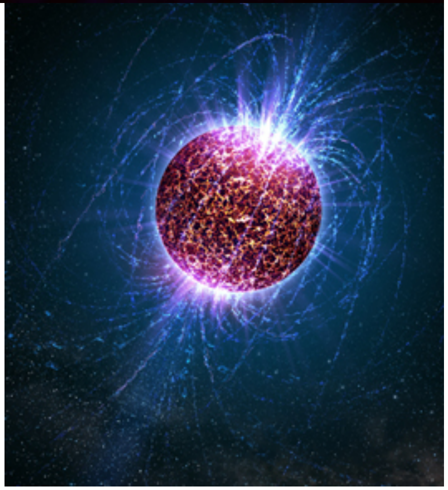
('bursts'), transient


NASA/WMAP Science Team

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

- Residue of the Big Bang

- Long duration, stochastic background

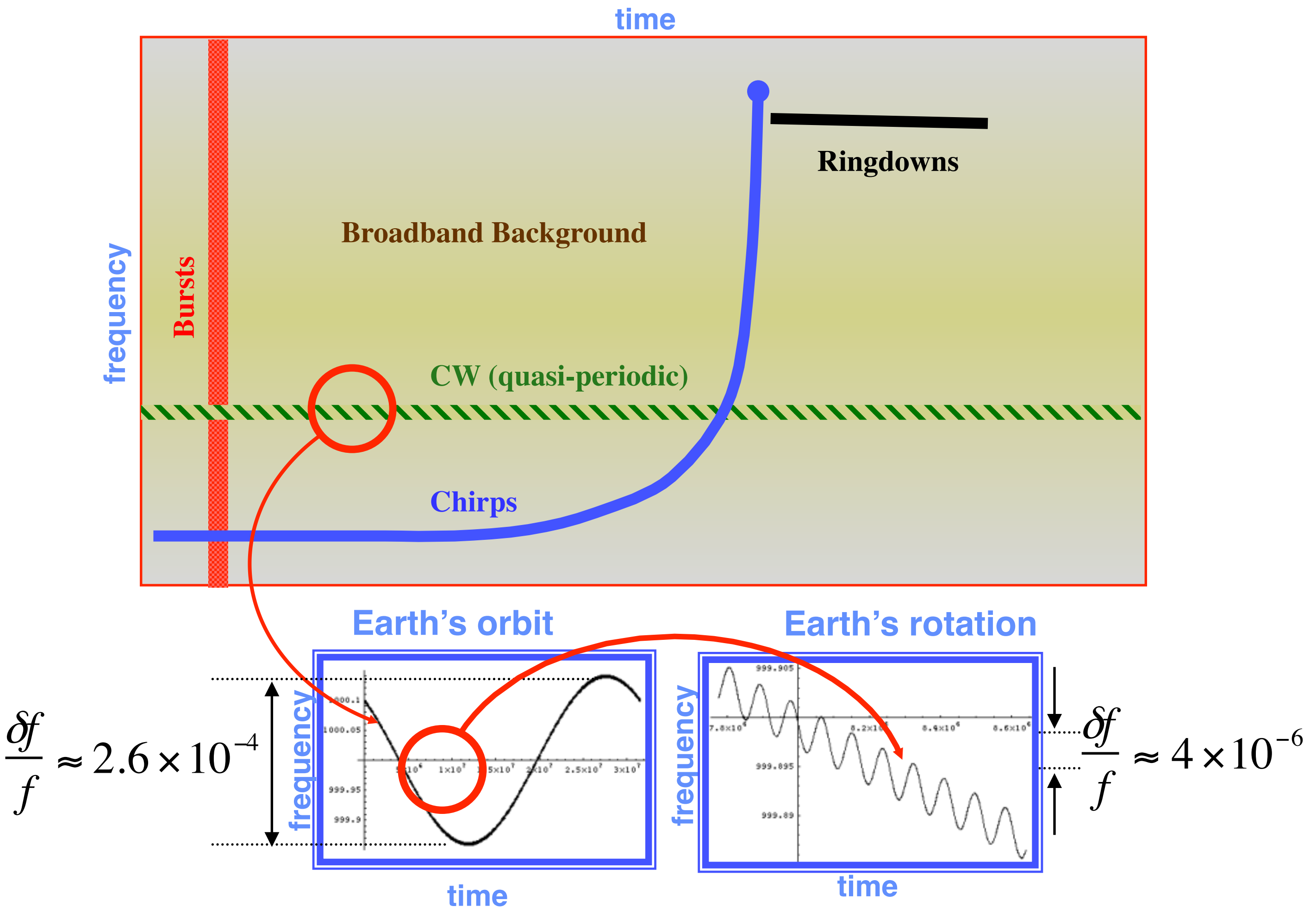

Casey Reed, Penn State

<u>Spinning neutron stars</u>

- (nearly) monotonic waveform

- Long duration

Frequency-Time Characteristics of GW Sources



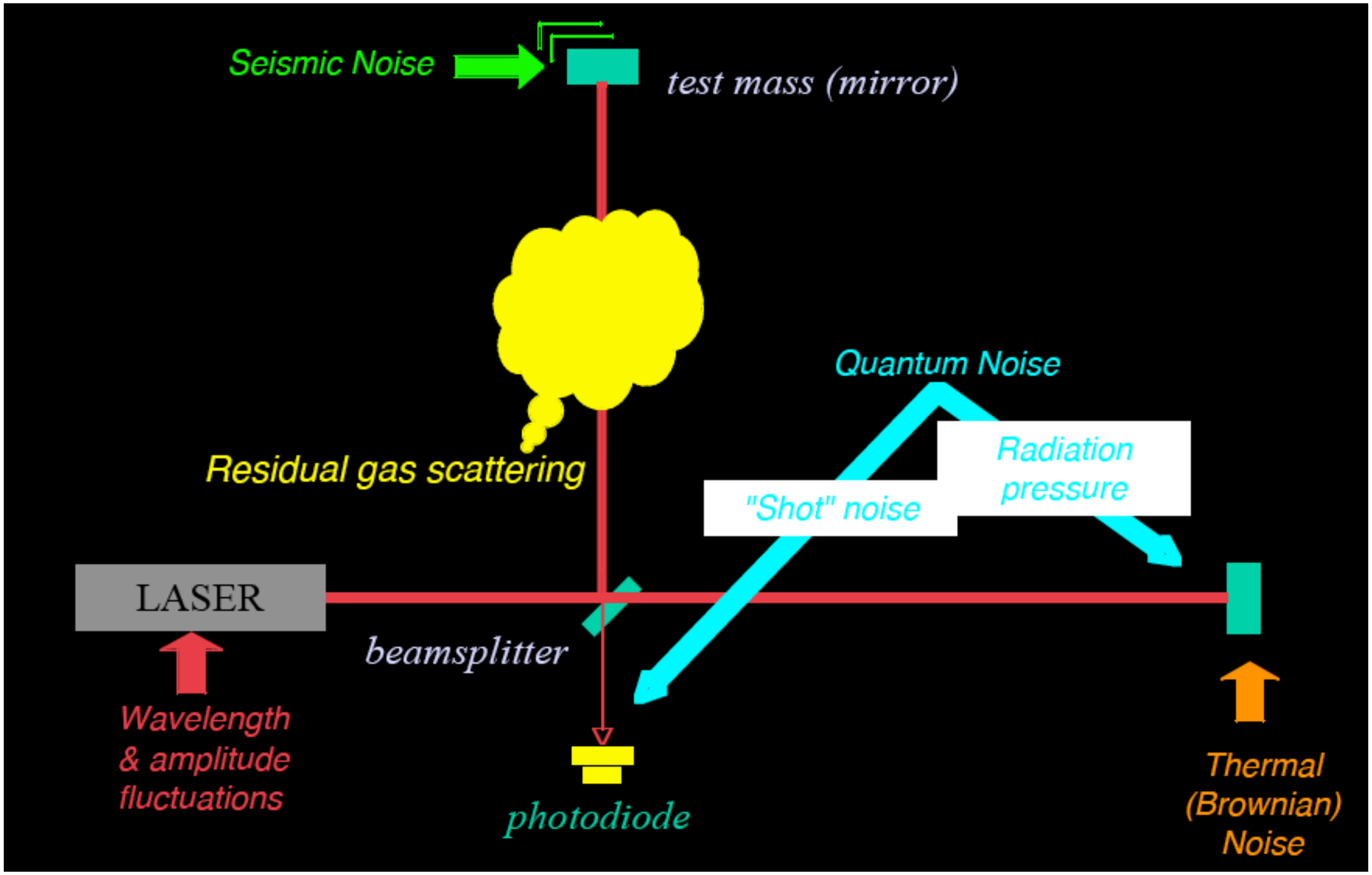
$$\frac{\delta f}{f} \approx 2.6 \times 10^{-4}$$

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

Sensitivity and Noise

- The keys to improving detectors are sensitivity and noise. The lower the noise the higher the sensitivity.
- Range is proportional to sensitivity. Range is the average distance at which a source can be detected with confidence.
- Event rate is proportional to volume, which is proportional to Range cubed.
- Thus a factor of 2 in sensitivity gives a factor of 8 in event rate (nearly an order of magnitude).

Noise cartoon



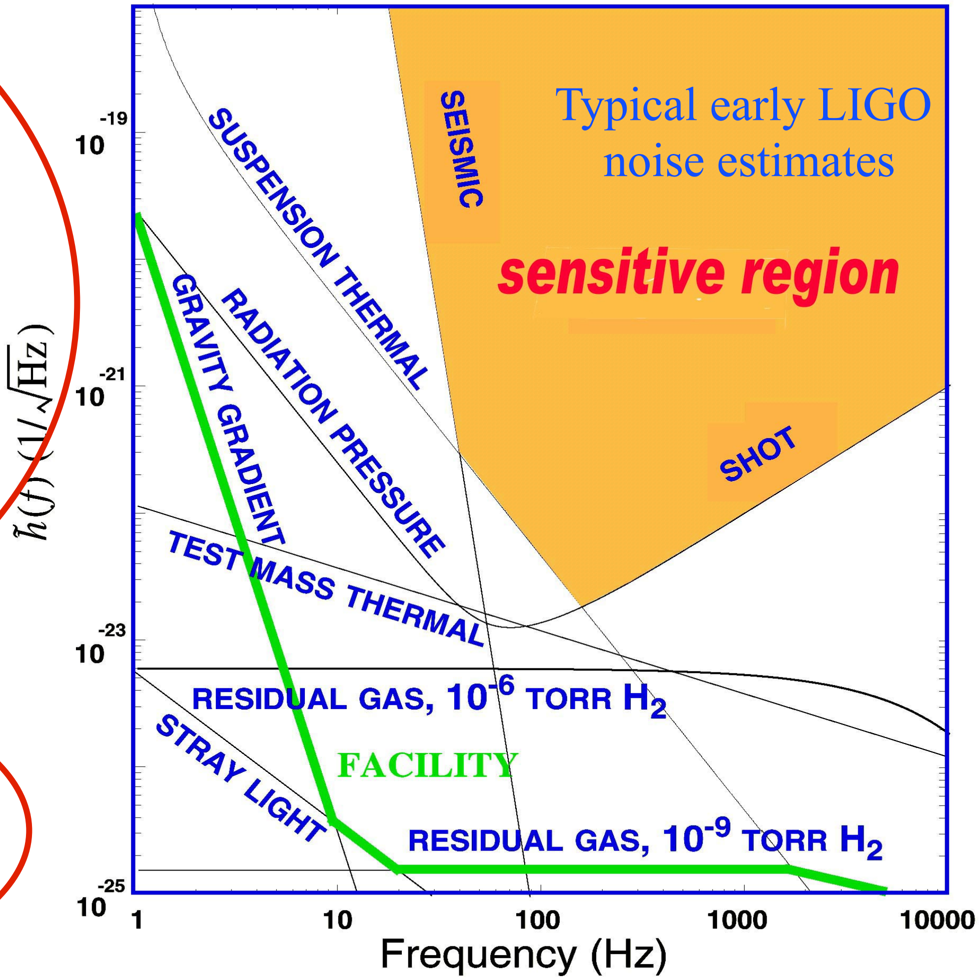
R. Adhikari

What Limits Sensitivity of Interferometers?

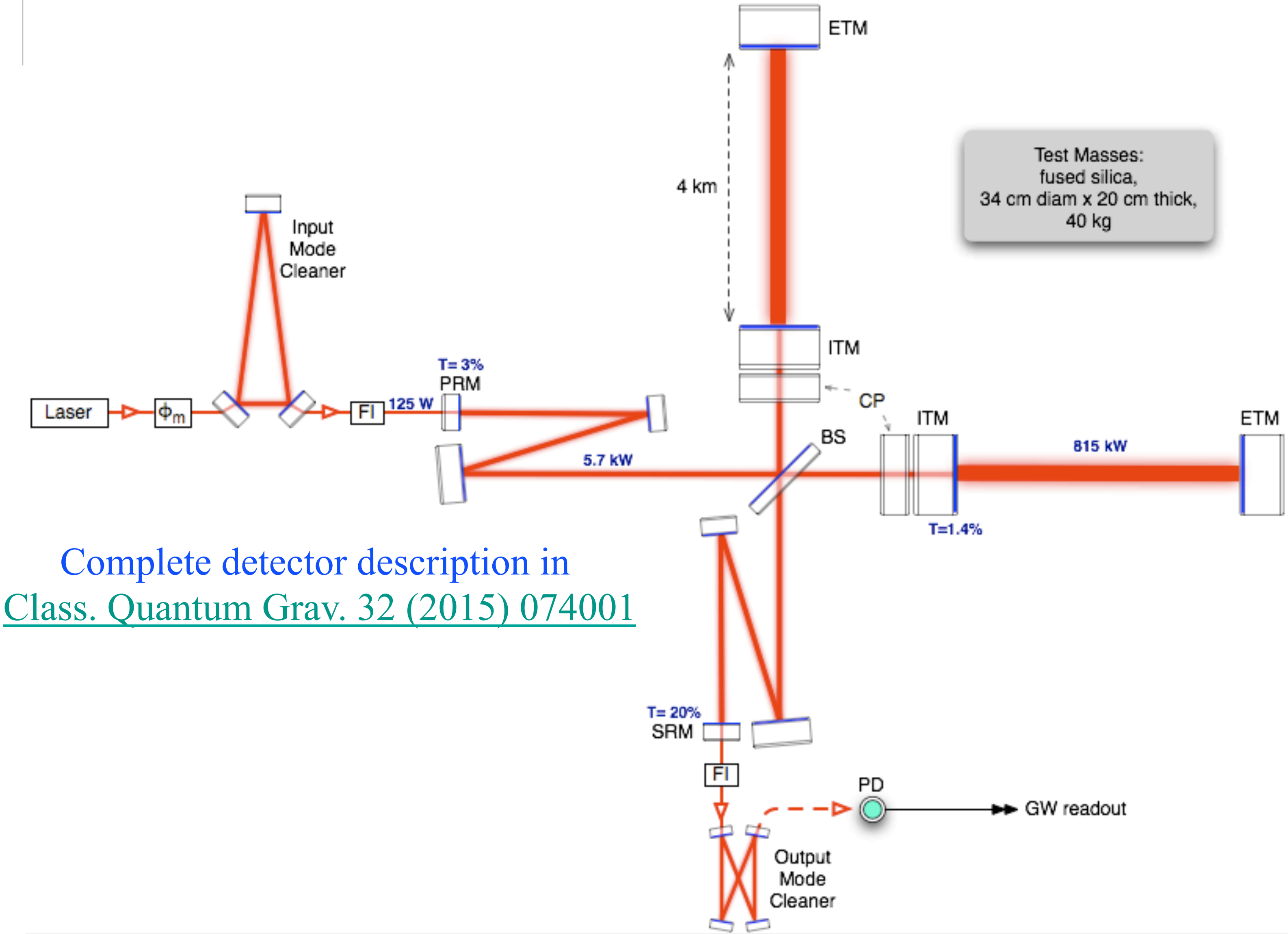
DESIGN

- 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

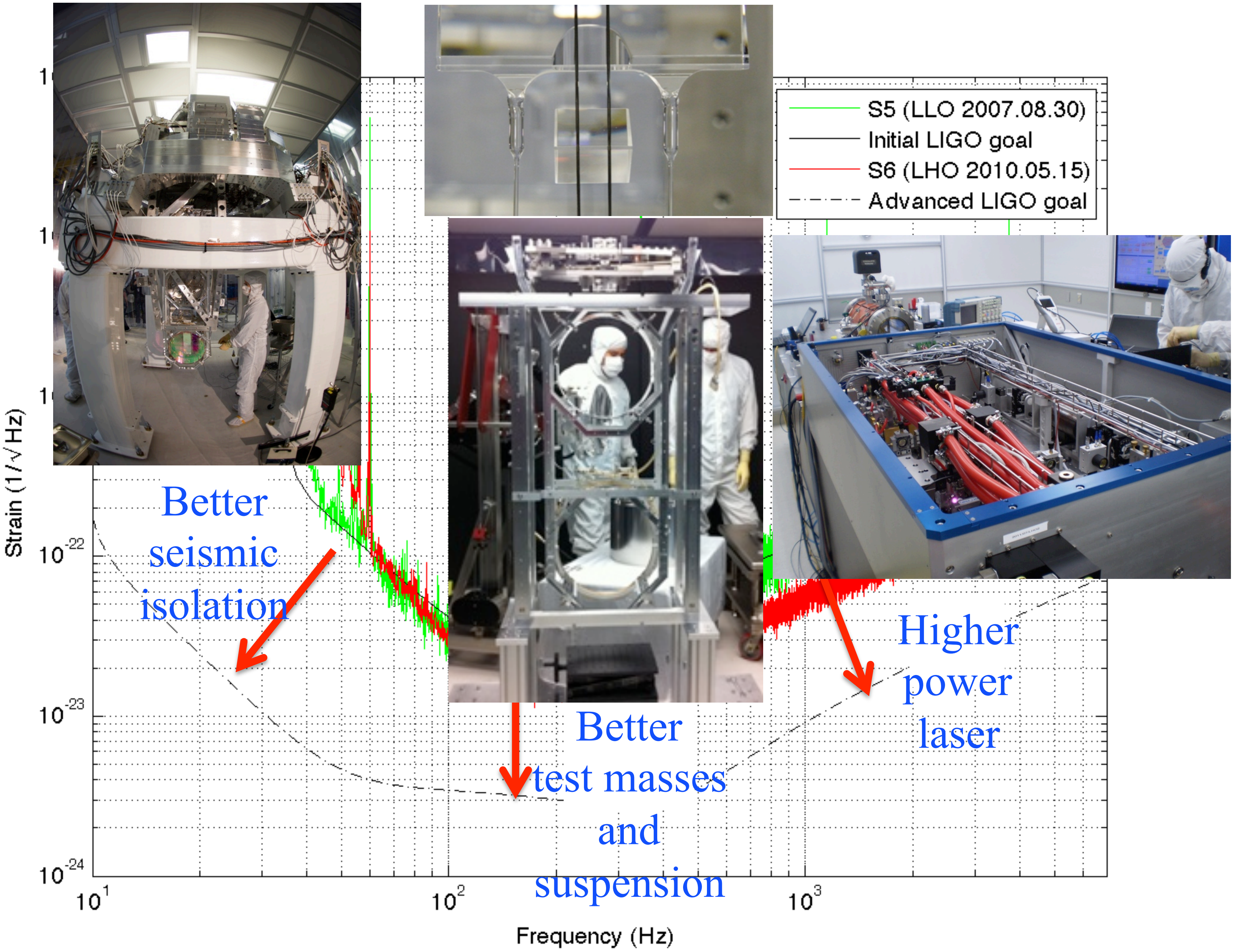


Optical configuration



Test Masses:
fused silica,
34 cm diam x 20 cm thick,
40 kg

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



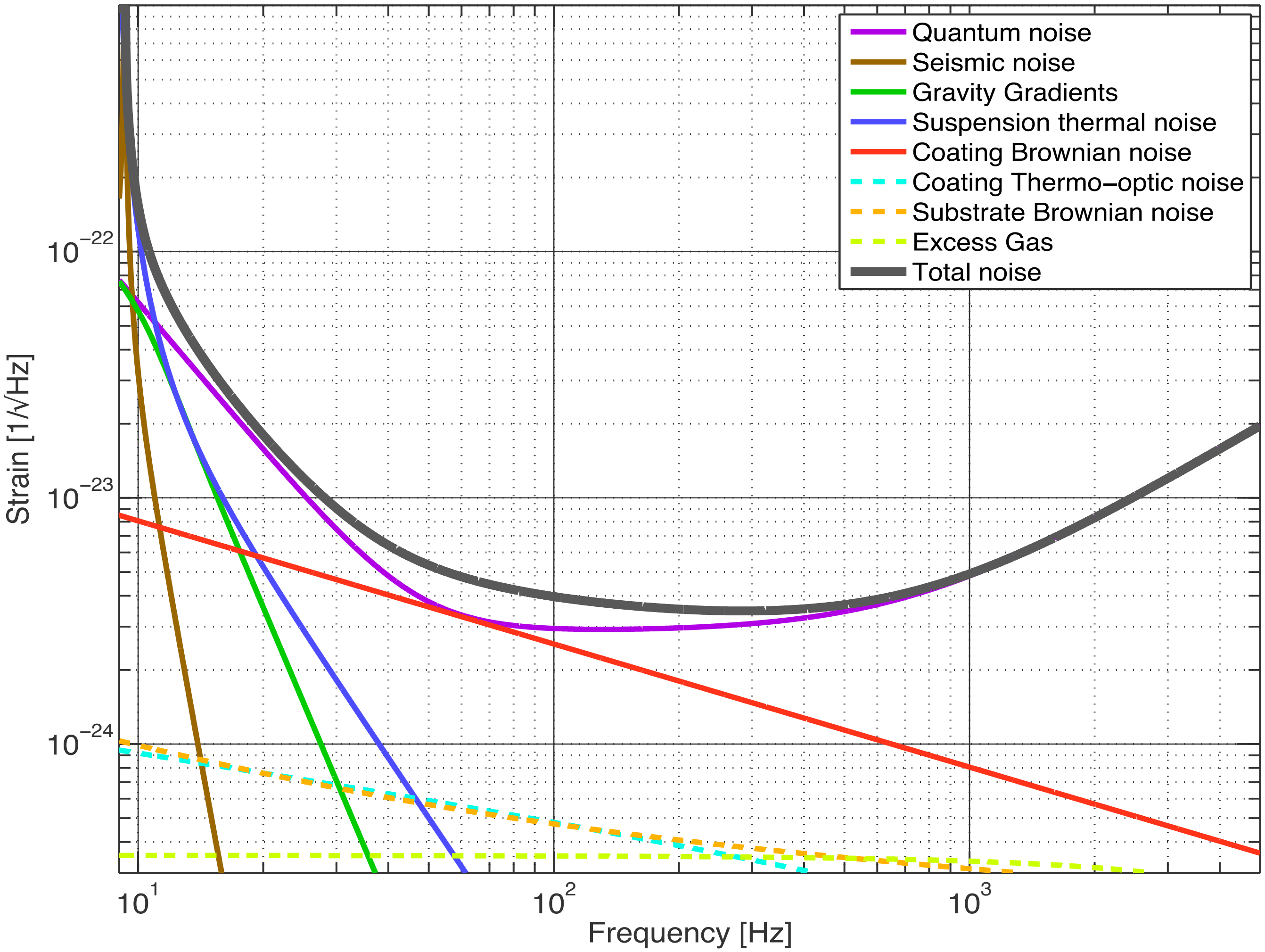
Better seismic isolation

Better test masses and suspension

Higher power laser

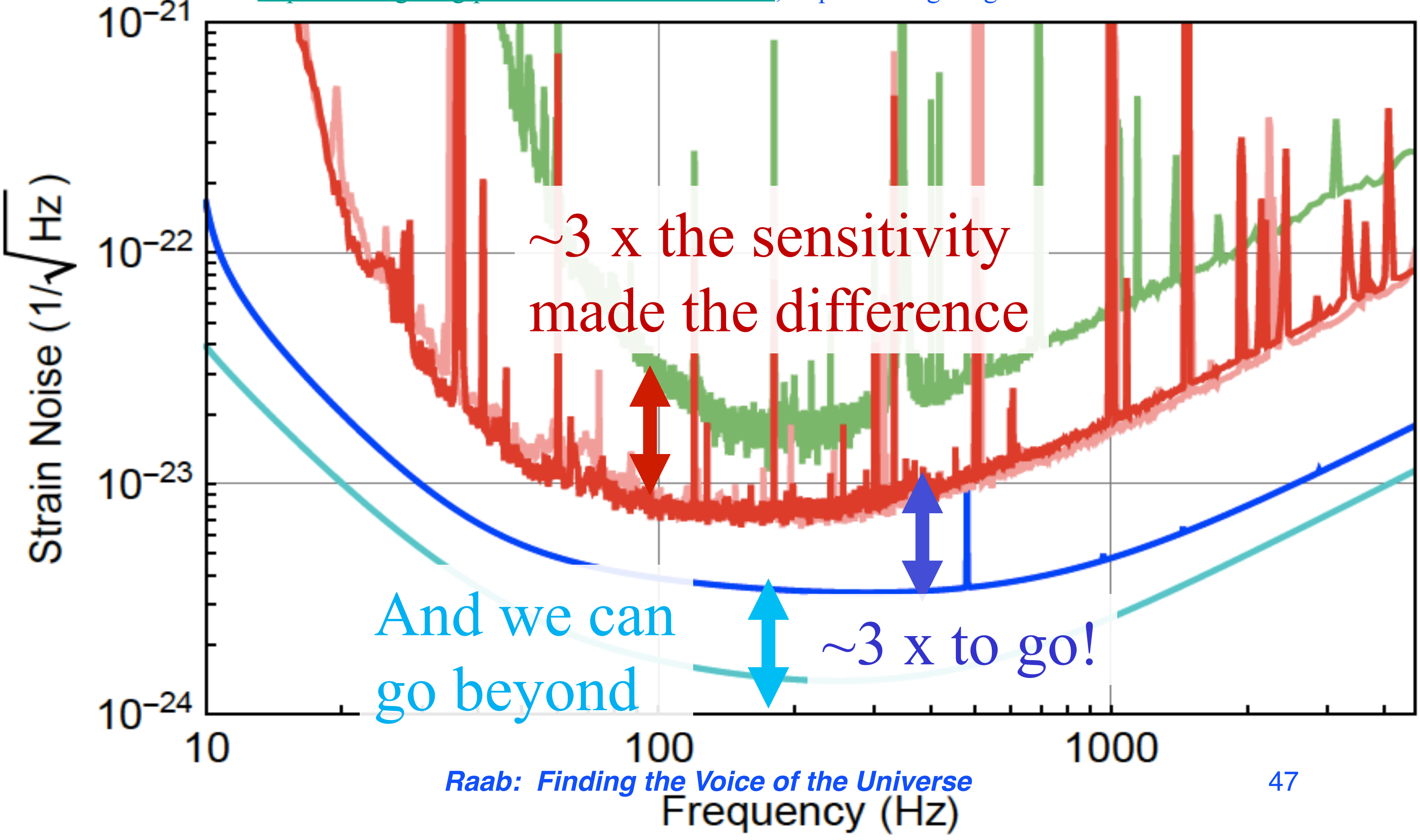
Principal noise terms

https://dcc.ligo.org/public/0113/T1400316/004



Initial S6 / Advanced O1
Design / A+ Upgrade

https://dcc.ligo.org/public/0113/T1400316/004; https://dcc.ligo.org/LIGO-G1500623



~3 x the sensitivity made the difference

And we can go beyond

~3 x to go!

Raab: Finding the Voice of the Universe

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

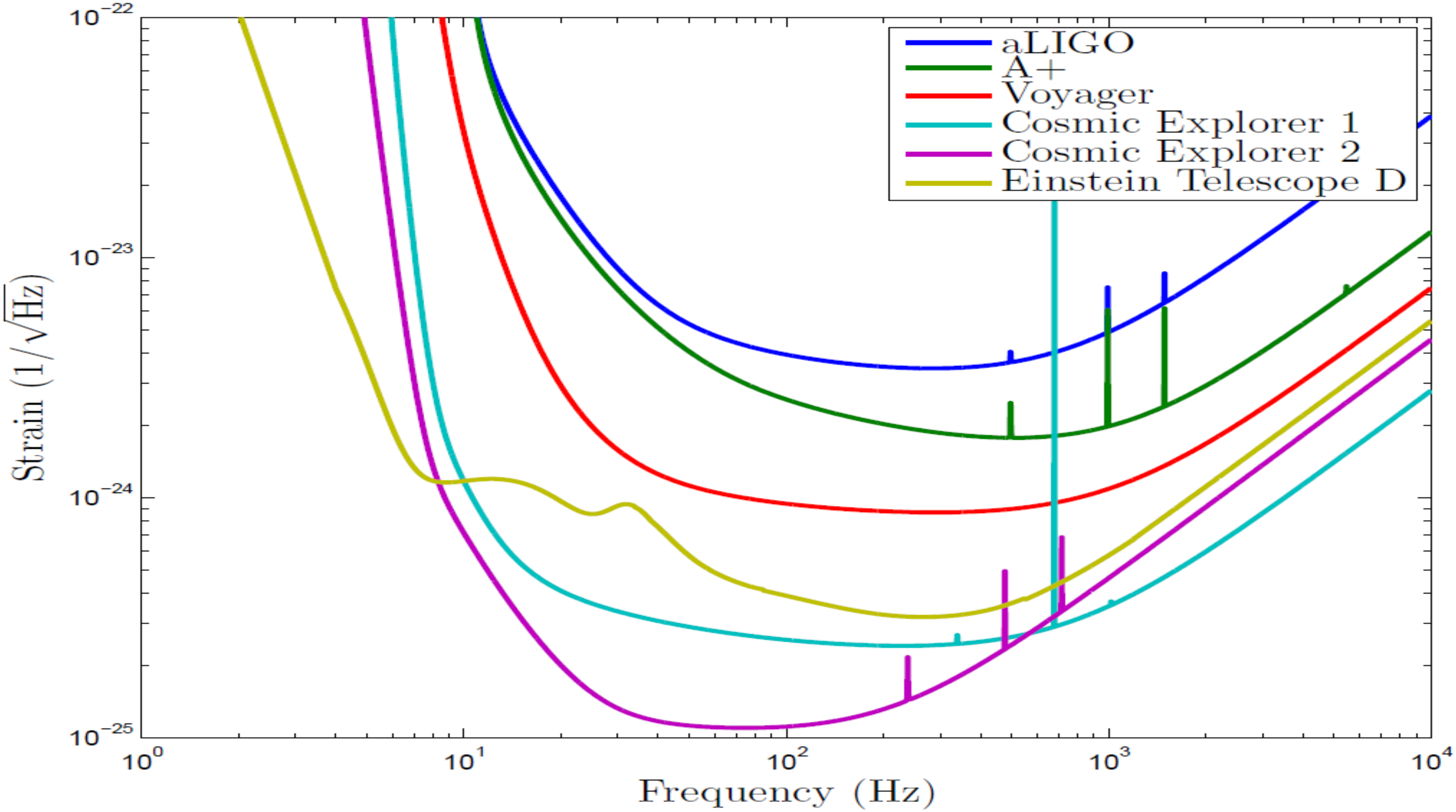
Advanced LIGO upgrade path

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

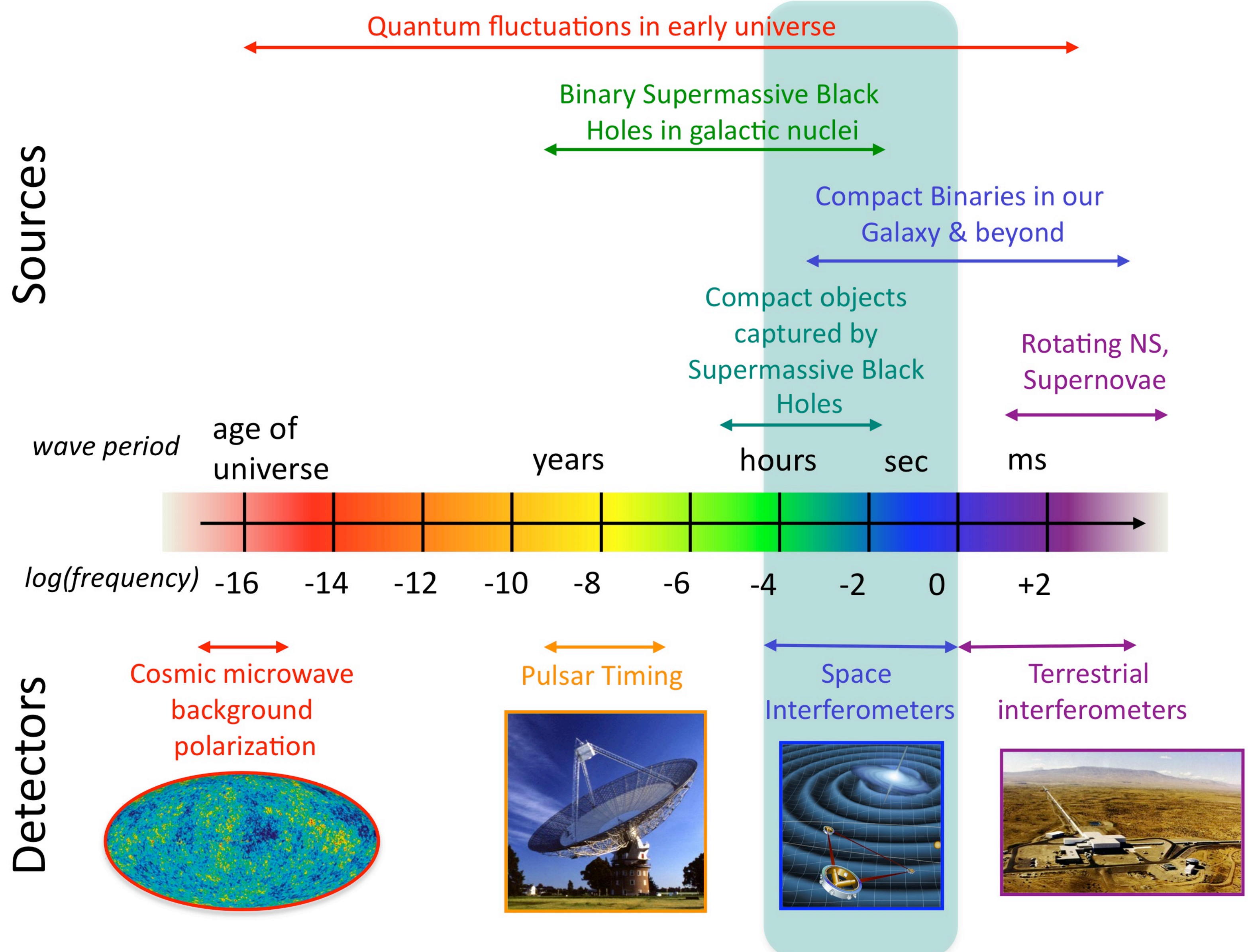
- Squeezed vacuum to reduce quantum noise
- Options for thermal noise:
  - » Better coatings
  - » Cryogenic operation
  - » Longer arms (new facility)

Upgrade possibilities

https://dcc.ligo.org/public/0113/T1400316/004; www.et-gw.eu



The Gravitational Wave Spectrum



Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

Rotating NS, Supernovae

wave period age of universe years hours sec ms

log(frequency) -16 -14 -12 -10 -8 -6 -4 -2 0 +2

Detectors

Cosmic microwave background polarization

Pulsar Timing

Space Interferometers

Terrestrial interferometers

Credit: NASA

Gravitational-Wave Astronomy as of today.

- The 1st observing run of LIGO's 2nd-generation detectors has initiated Gravitational-Wave Astronomy, opening a new frontier for exploration.
- We have seen the annihilations and the births of black holes for the first time.
- General Relativity provides a powerful framework from Earth-bound physics to mergers of stellar mass black holes at velocities near the speed of light.
- Black Hole Binaries exist and merge hourly somewhere in the universe
- An emerging international network of detectors soon will provide more accurate positions of sources to enable EM follow-ups of GW events.
- It is possible to develop more powerful generations of detectors and there is much physics still to be harvested from their observations.

What will be the legacy of LIGO discoveries?

- Attempts in the 19th century to explain why the sky is blue, sunsets red and clouds white led to the 20th century economy:
  - Atomic and nuclear physics and modern materials
  - Modern chemical and pharmaceutical industries
  - Modern electronics and computer industries
  - Unraveling the structure of DNA and other bio-molecules, leading to modern biochemistry and gene therapy
  - Development of almost all medical diagnostic machines
  - Also a new phrase, “Blue-sky research”
- LIGO discoveries likely will revolutionize our understanding of space, time, matter and energy, as well as redefine what people can imagine and build.

It’s never as easy as it looks…