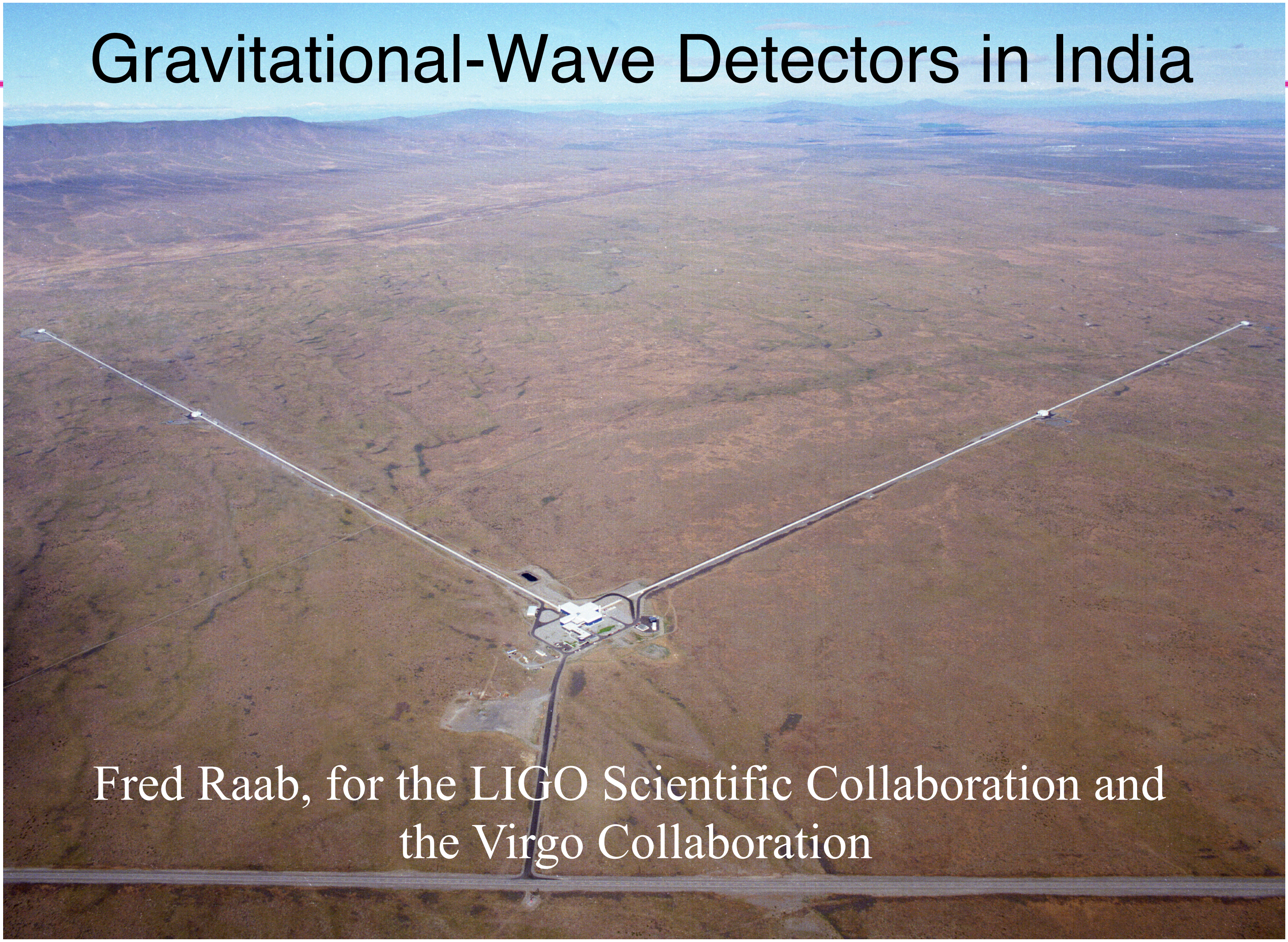
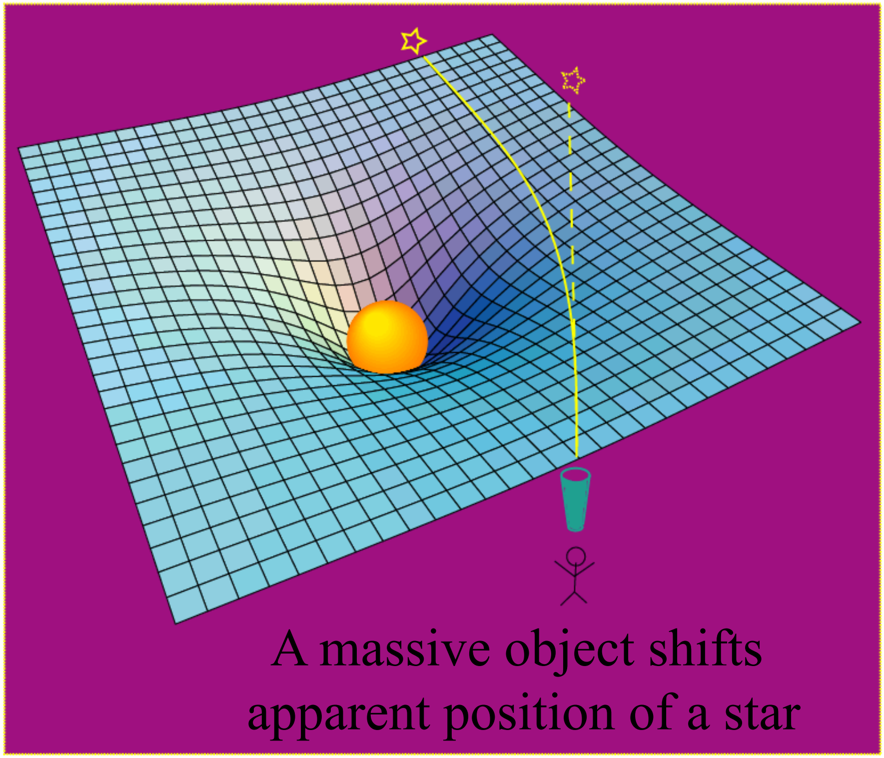
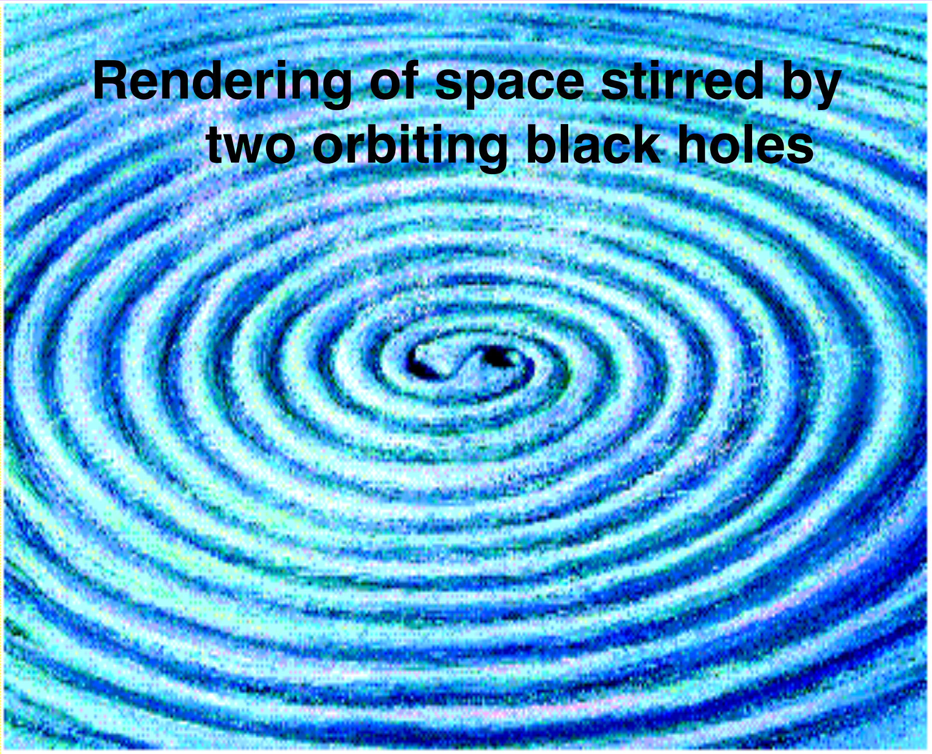
# Gravitational-Wave Detectors in India



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

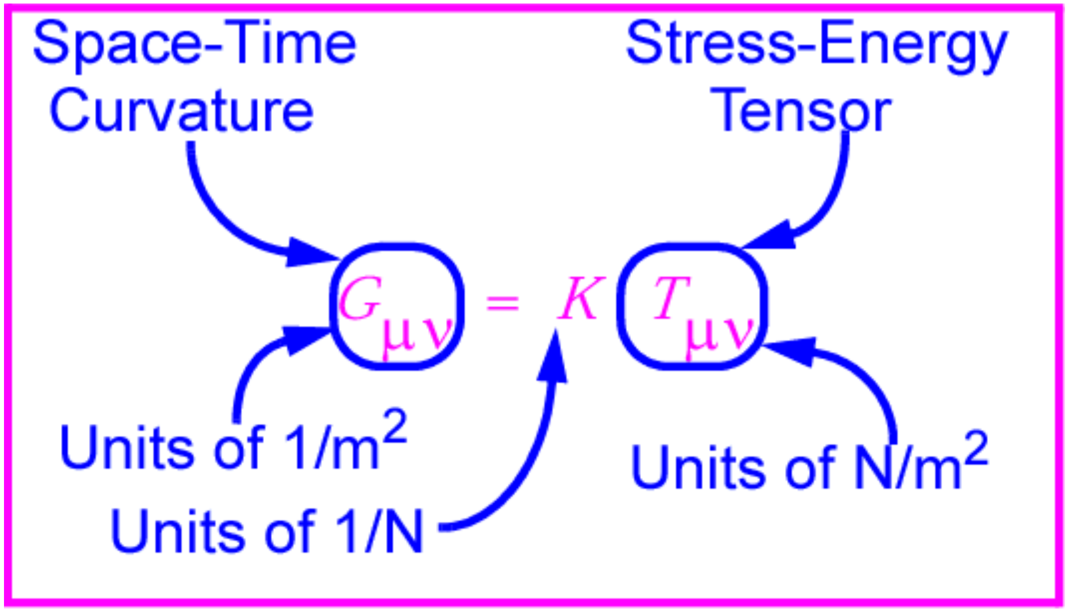
# Einstein's General Relativity re-wrote the rules of space and time


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

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

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 order-of-magnitude strength

- 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

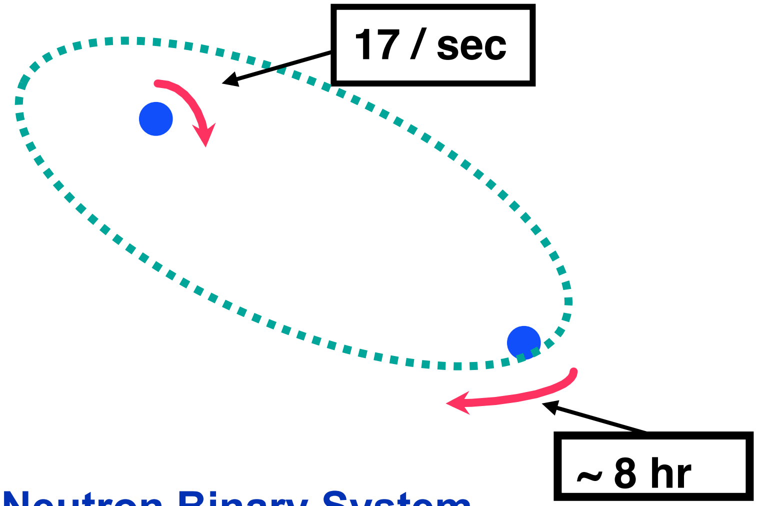
$$h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r} \quad \Rightarrow \quad \boxed{h \sim 10^{-21}}$$

Event rate is proportional to $h_{min}^{-3}$.

# Gravitational Waves;
# *a well-learned transmitter*

## Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



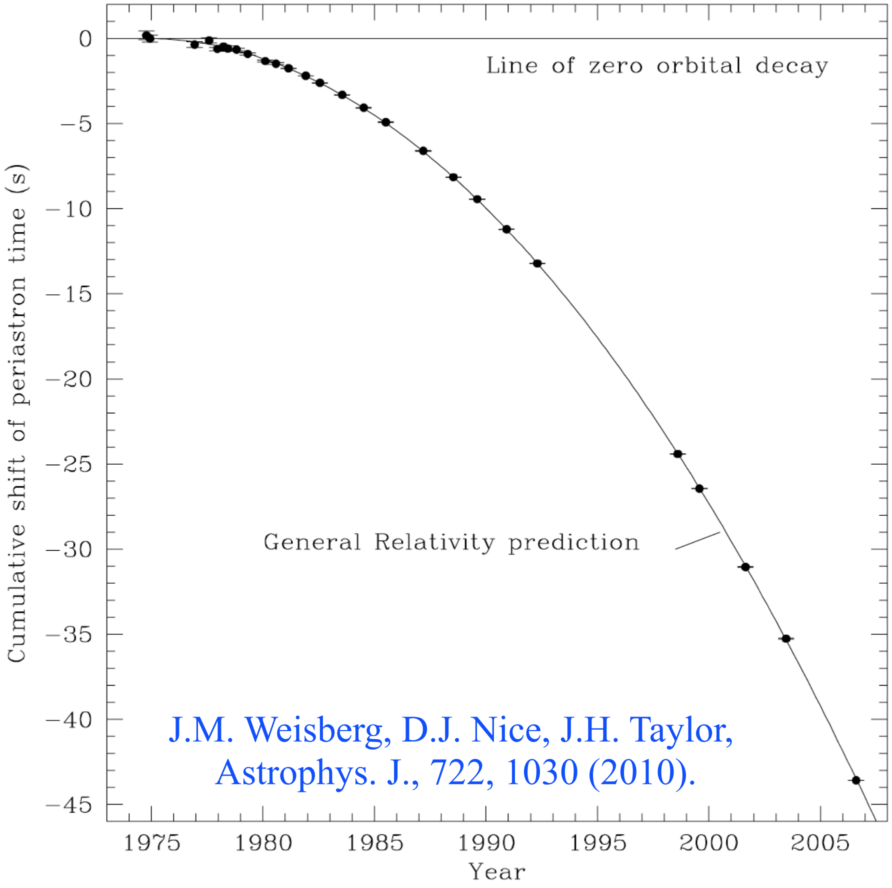
**Neutron Binary System**

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

**Prediction from general relativity**

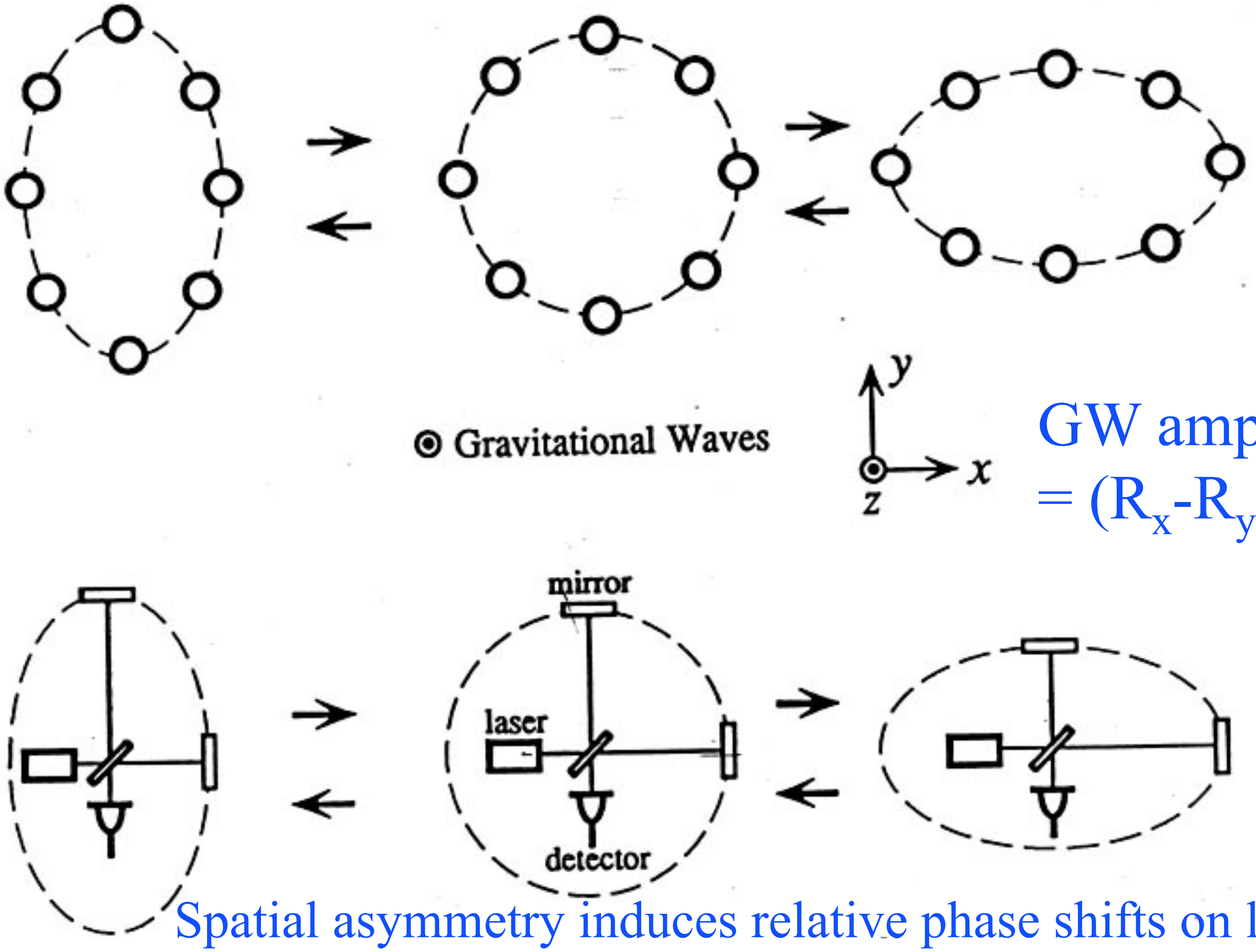
- **spiral in by 3 mm/orbit**
- **rate of change orbital period**

**Emission of gravitational waves**



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

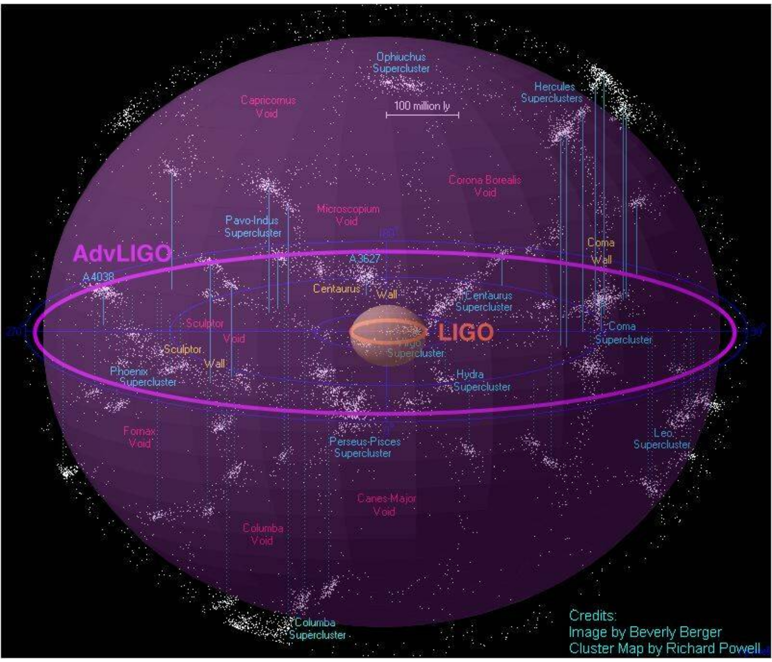
# Basic idea for detection is simple



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

Spatial asymmetry induces relative phase shifts on light in arms

# 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

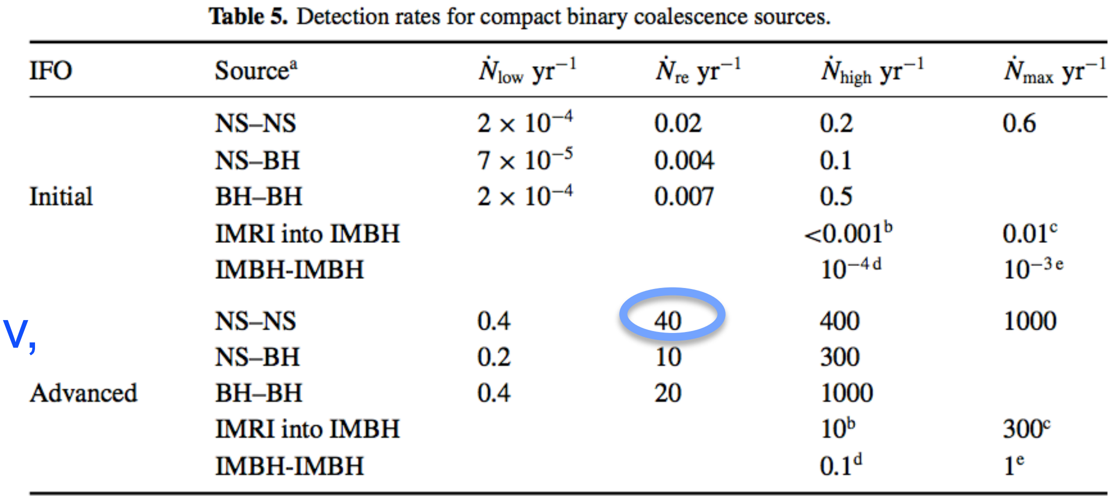


**Table 5.** Detection rates for compact binary coalescence sources.

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

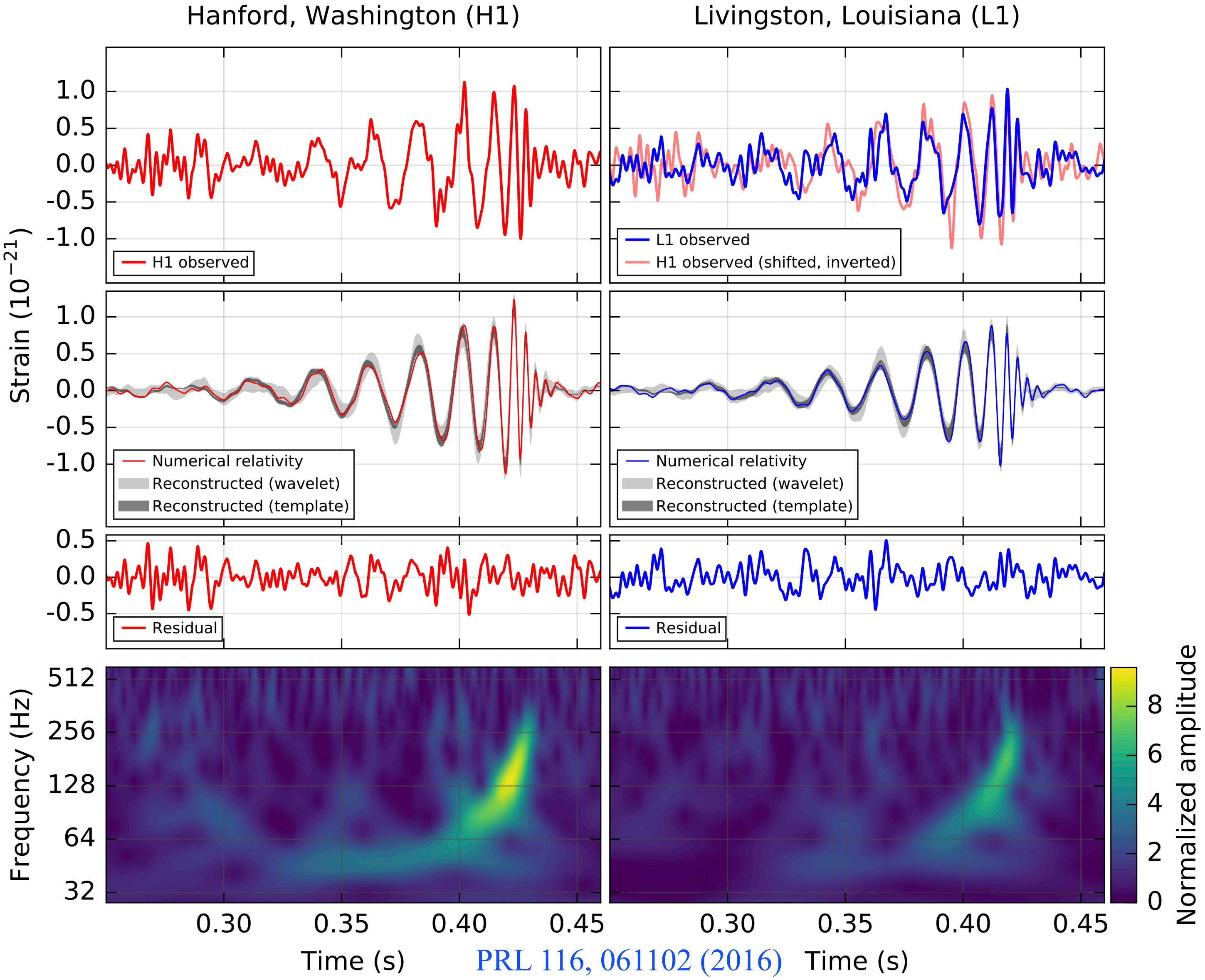
# The Laser Interferometer Gravitational-Wave Observatory

**LIGO (Washington)**

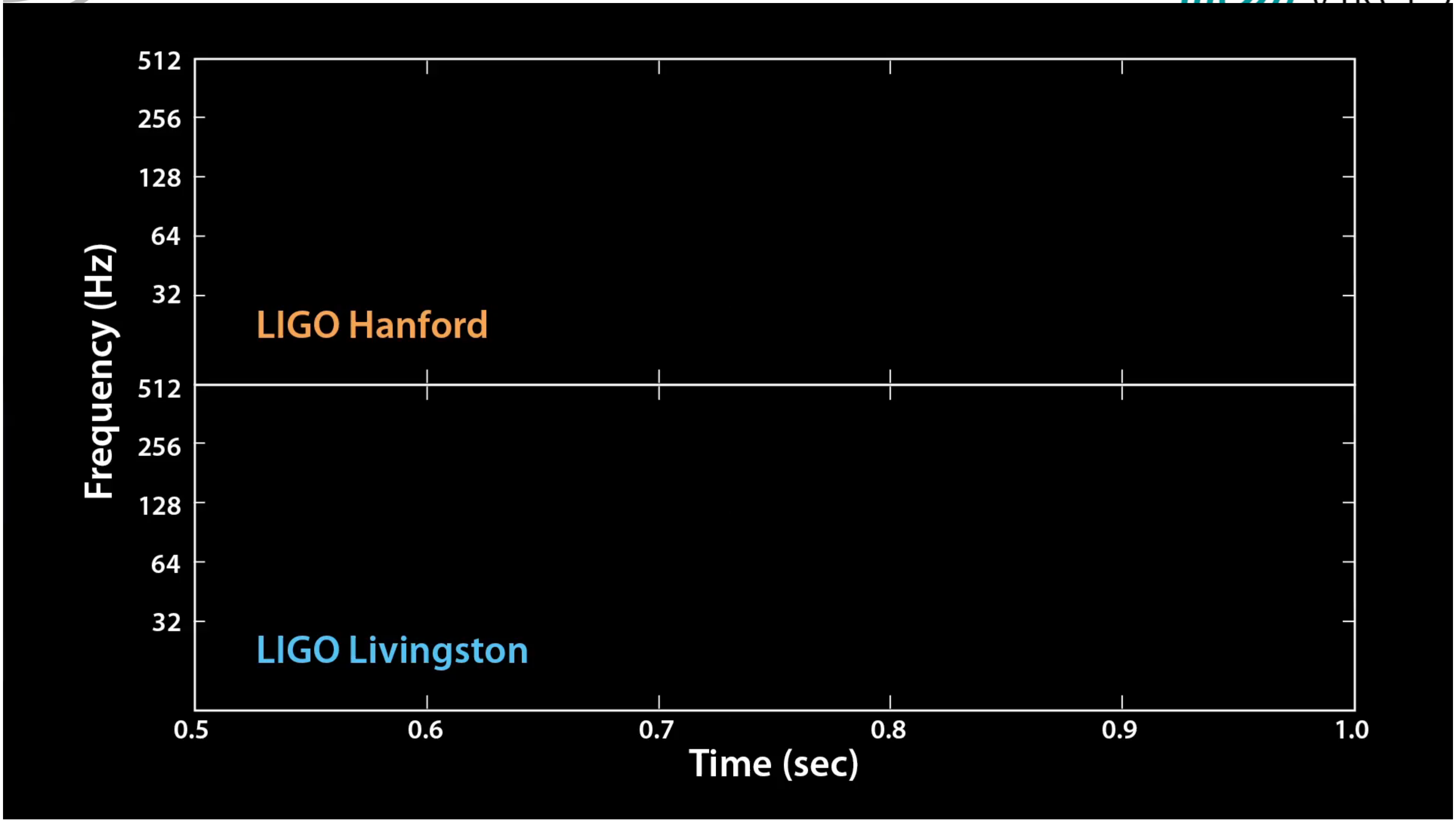
**LIGO (Louisiana)**

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.

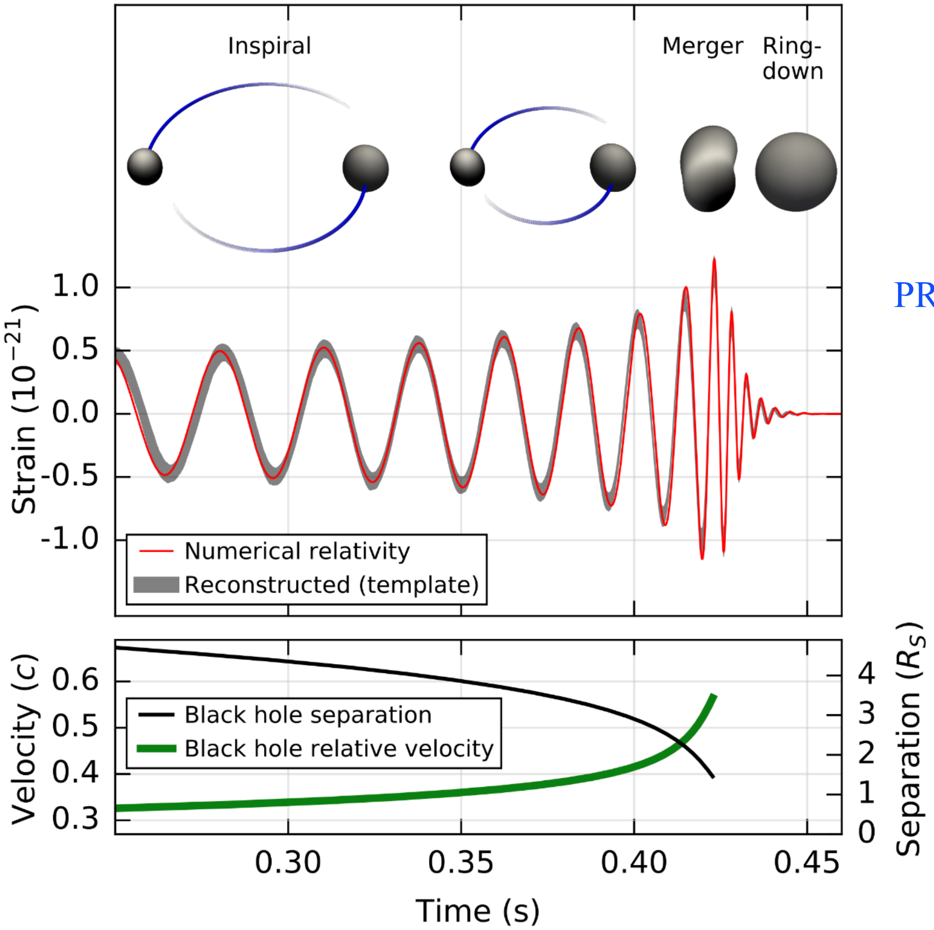
# Observed on Sep 14, 2015



PRL 116, 061102 (2016)

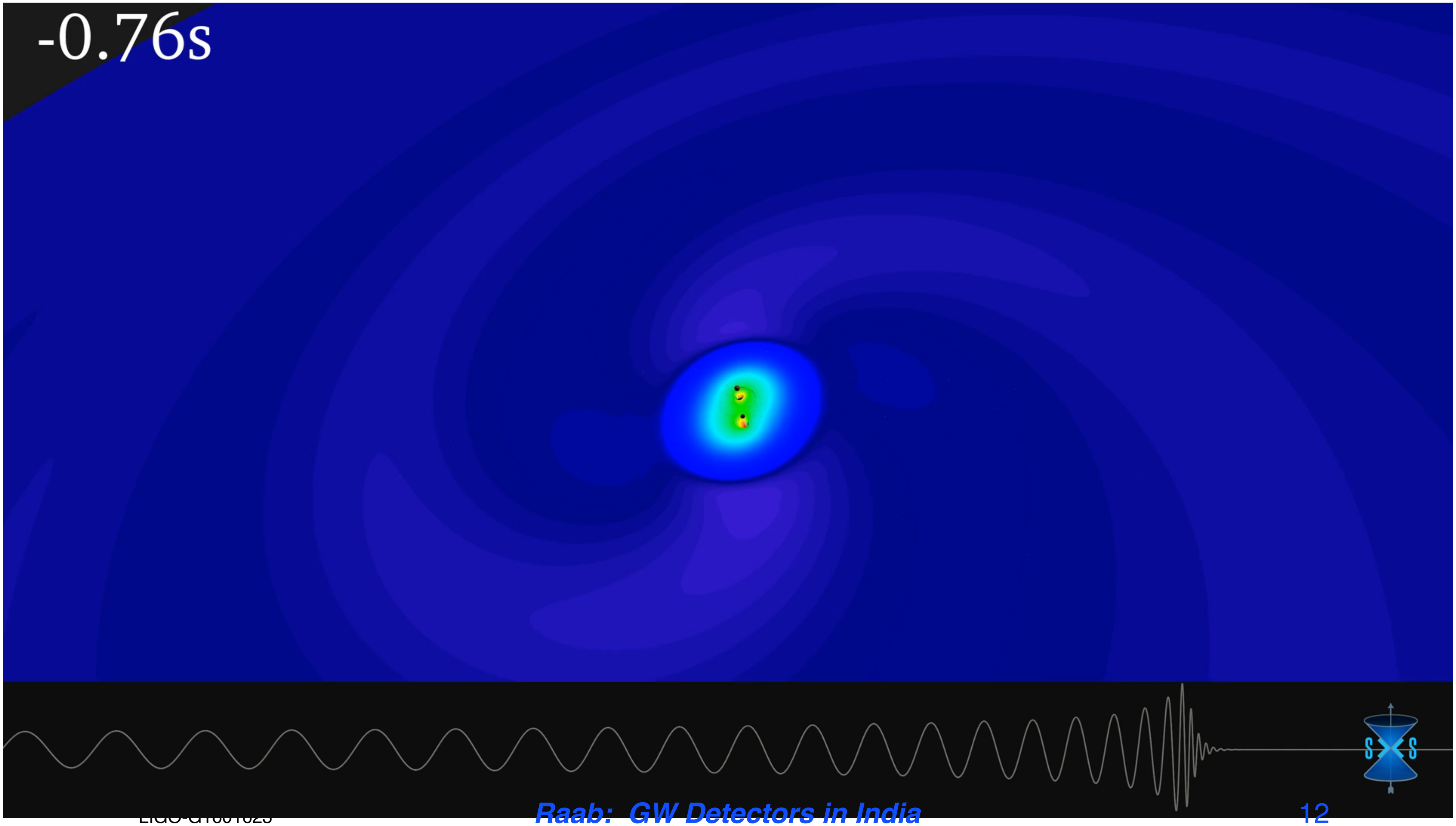

512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

# LIGO A signal from a binary black hole merger

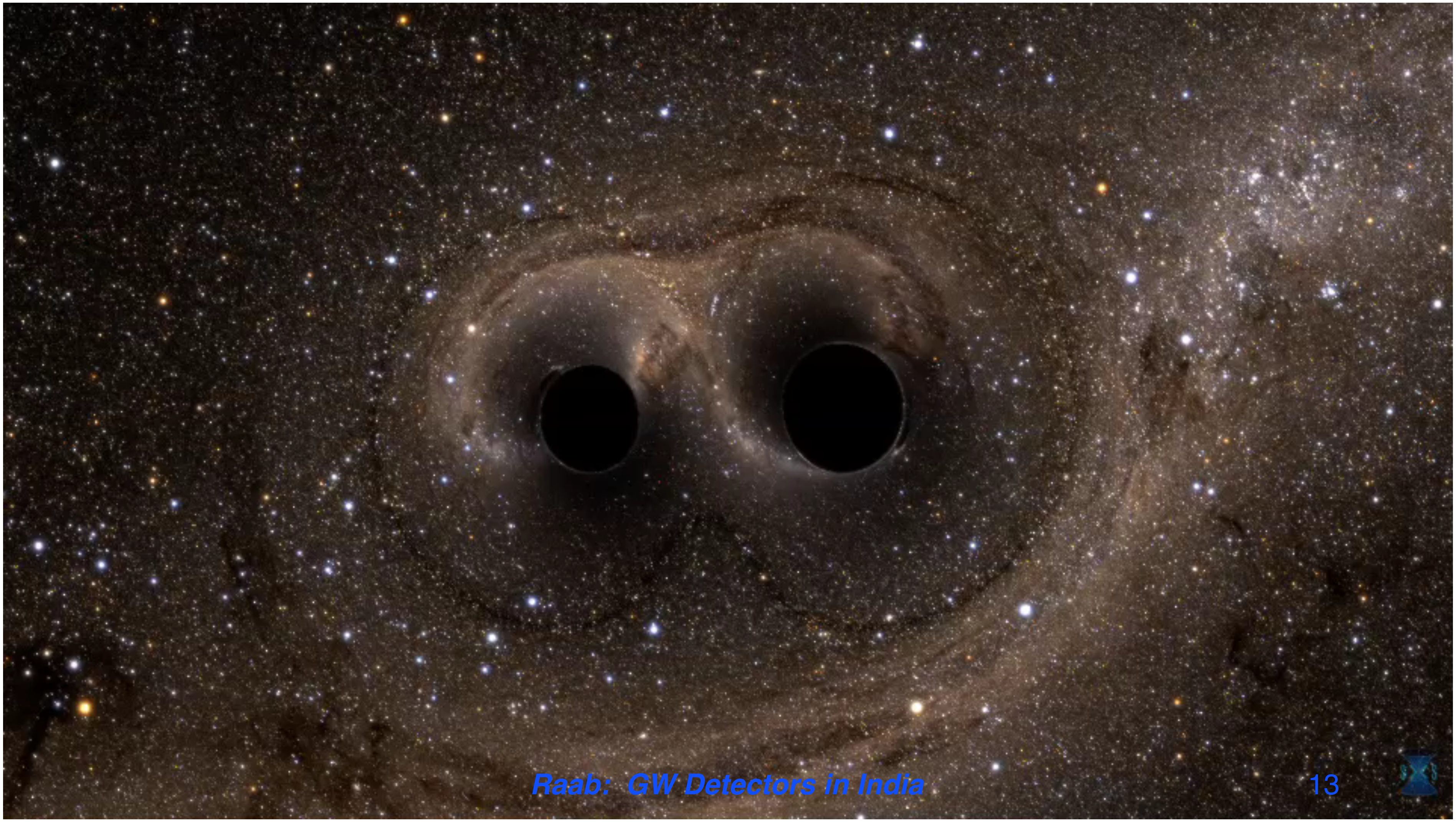


PRL 116, 061102 (2016)

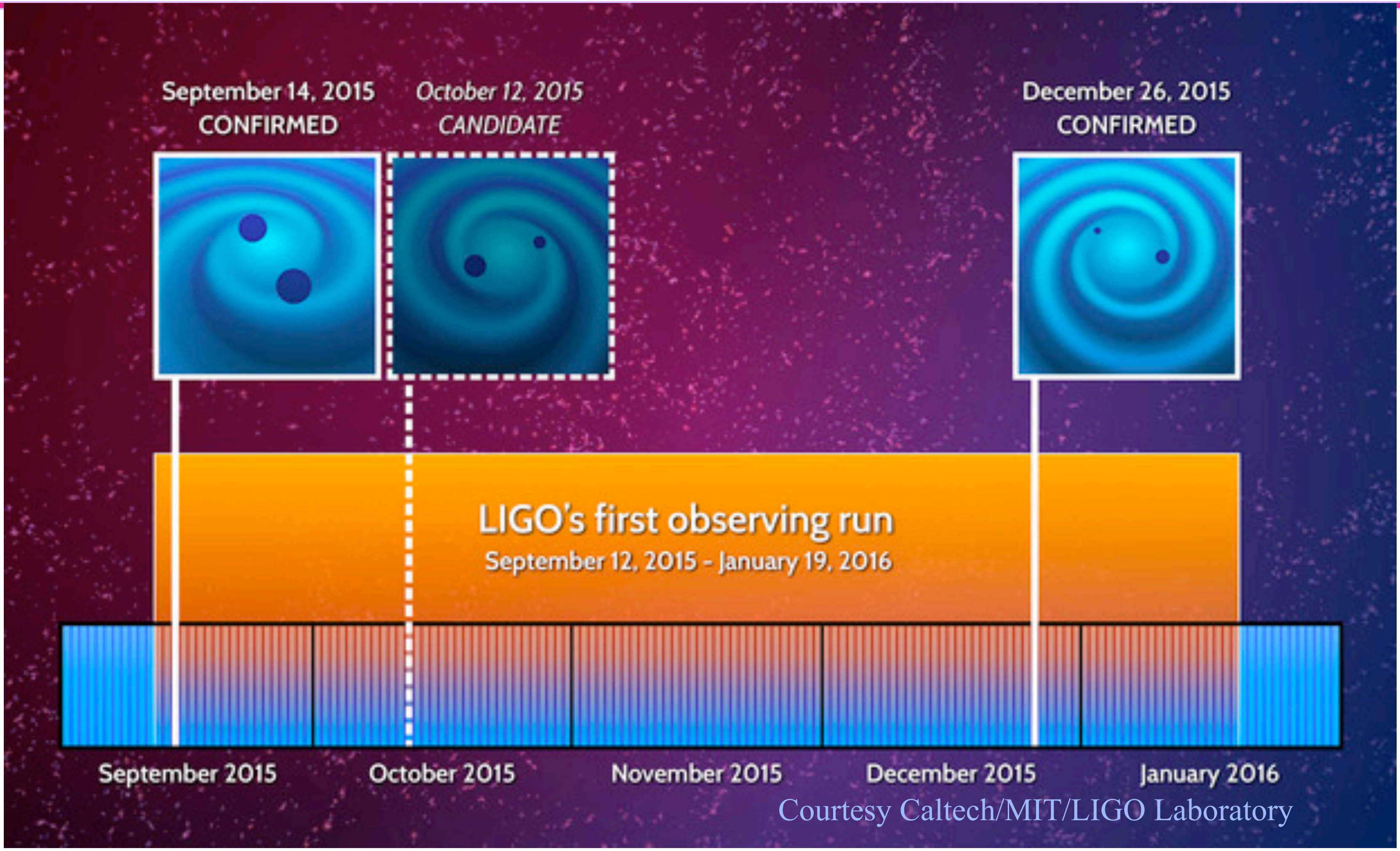
# GW150914: a signal from a binary black hole merger



# SXS Simulation of GW150914 aginst a field of stars



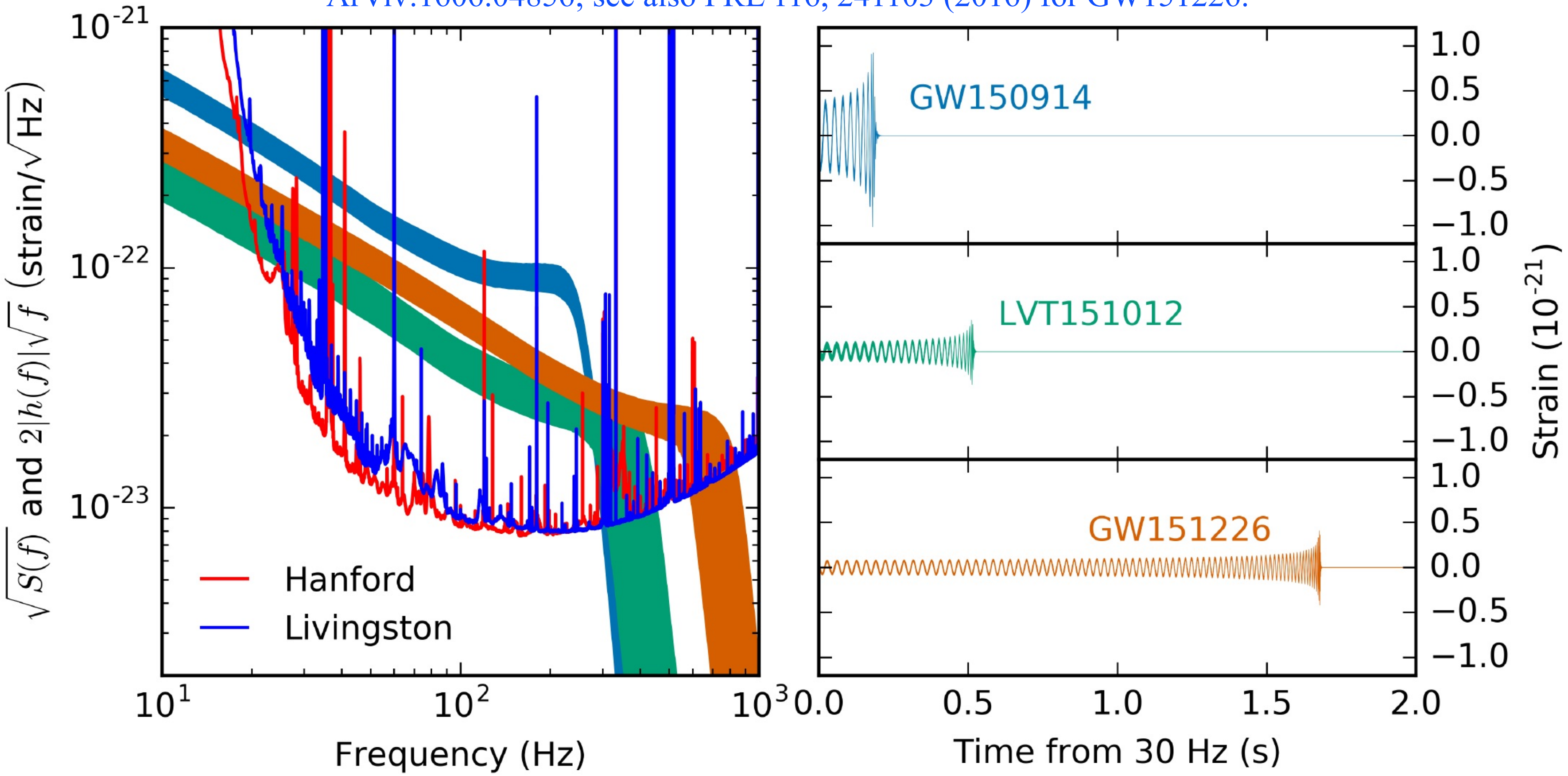
# Discovery Timeline – Advanced LIGO's 1$^{st}$ Observations



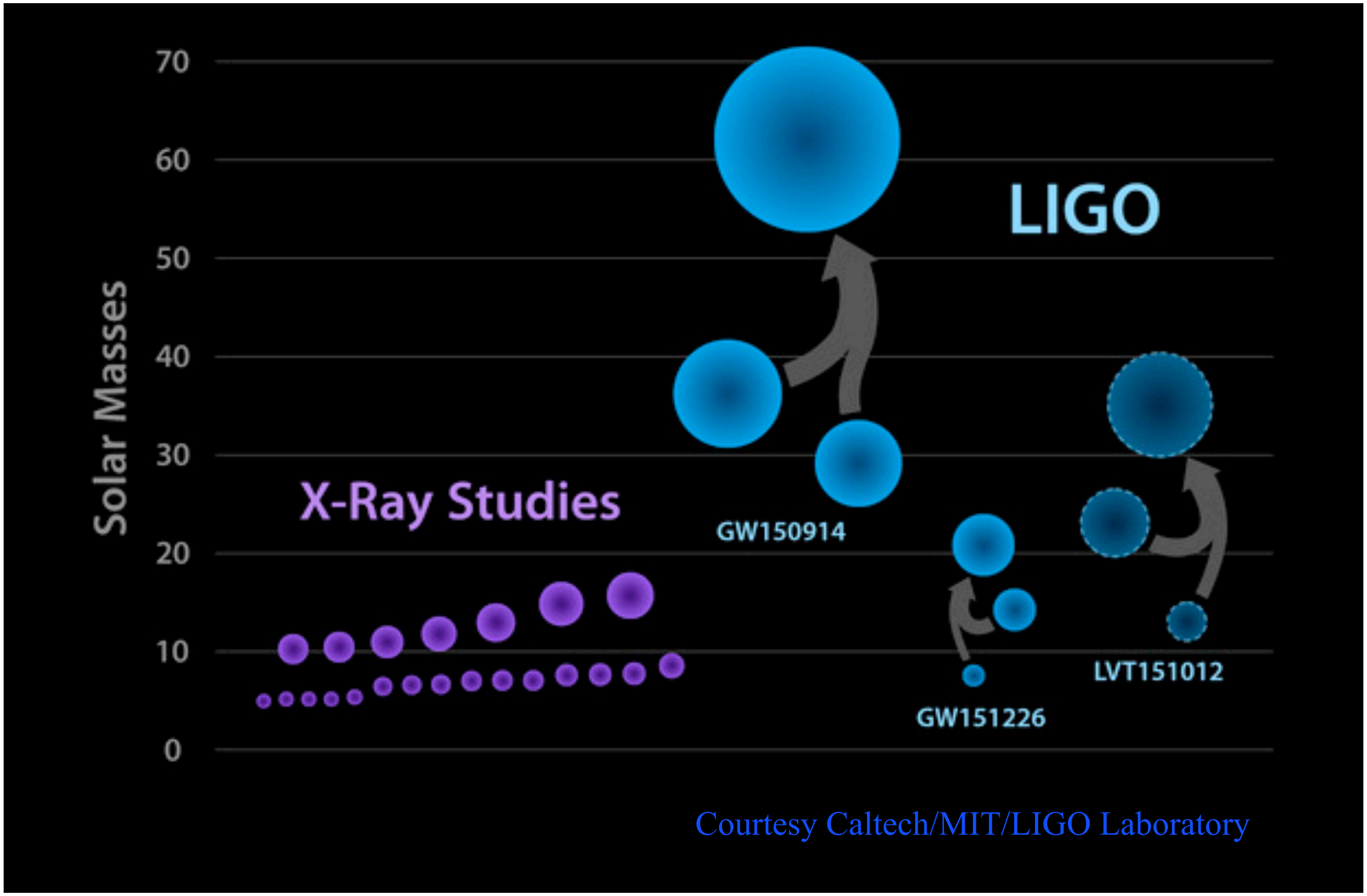
Courtesy Caltech/MIT/LIGO Laboratory

# 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

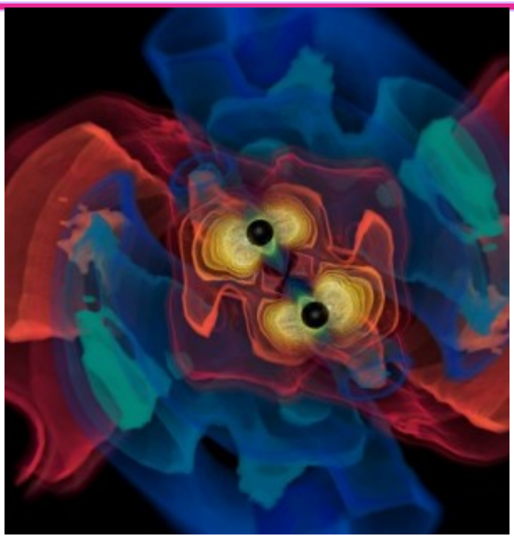
# Now what?

- 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?

# Sources of Gravitational Waves

## Accelerating Quadrupole Mass Moments

# Astrophysical Sources of Gravitational Waves

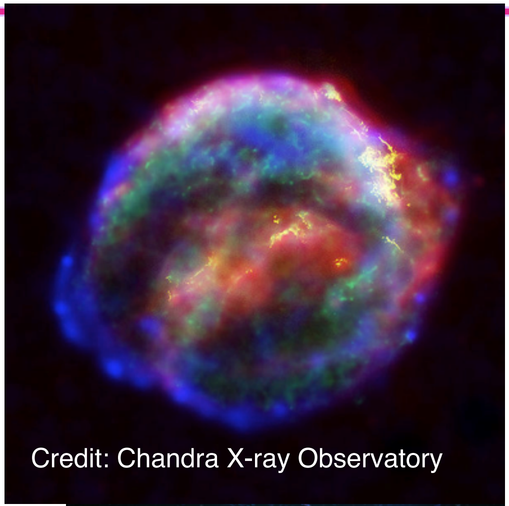


Credit: AEI, CCT, LSU

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

- Strong emitters, well-modeled,

- (effectively) transient

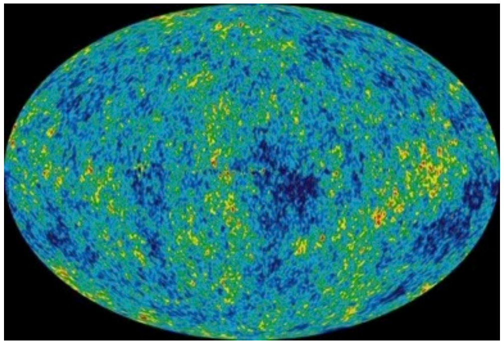


Credit: Chandra X-ray Observatory

*Asymmetric Core Collapse Supernovae*

- Weak emitters, not well-modeled

('bursts'), transient

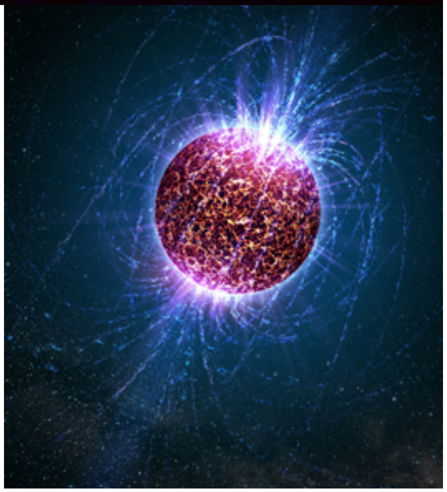


NASA/WMAP Science Team

*Cosmic Gravitational-wave Background*

- Residue of the Big Bang

- Long duration, stochastic background



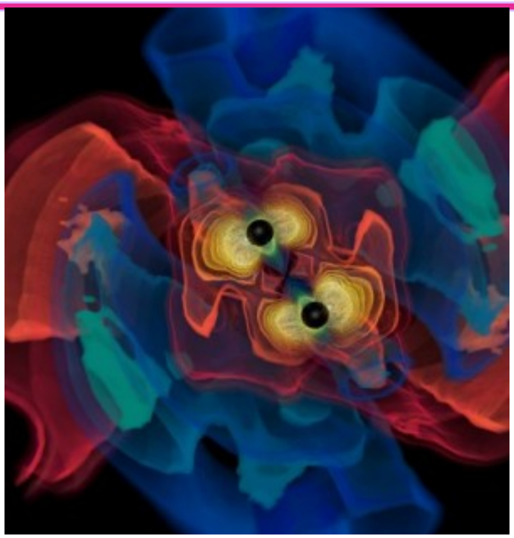
Casey Reed, Penn State

*Spinning neutron stars*

- (nearly) monotonic waveform

- Long duration

# Astrophysical Sources of Gravitational Waves



Credit: AEI, CCT, LSU

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

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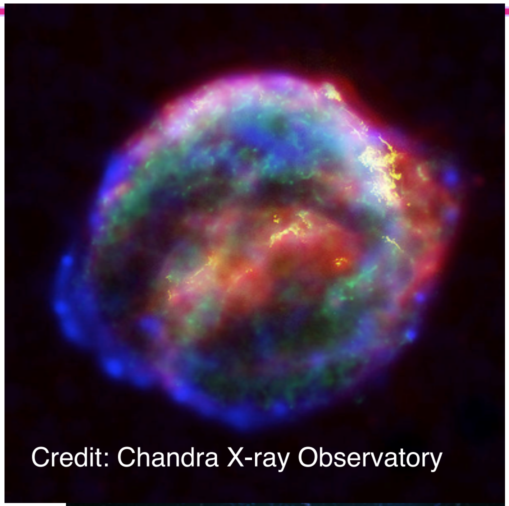

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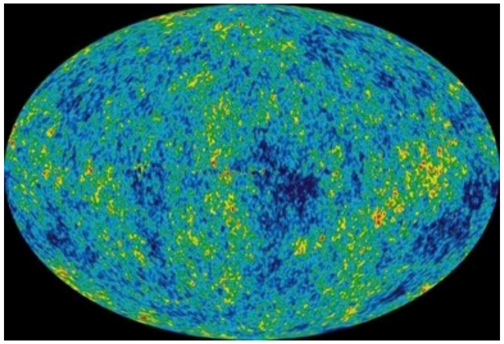

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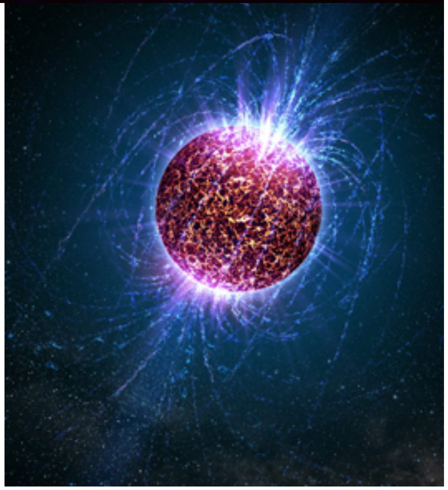

Casey Reed, Penn State

*Spinning neutron stars*

- (nearly) monotonic waveform

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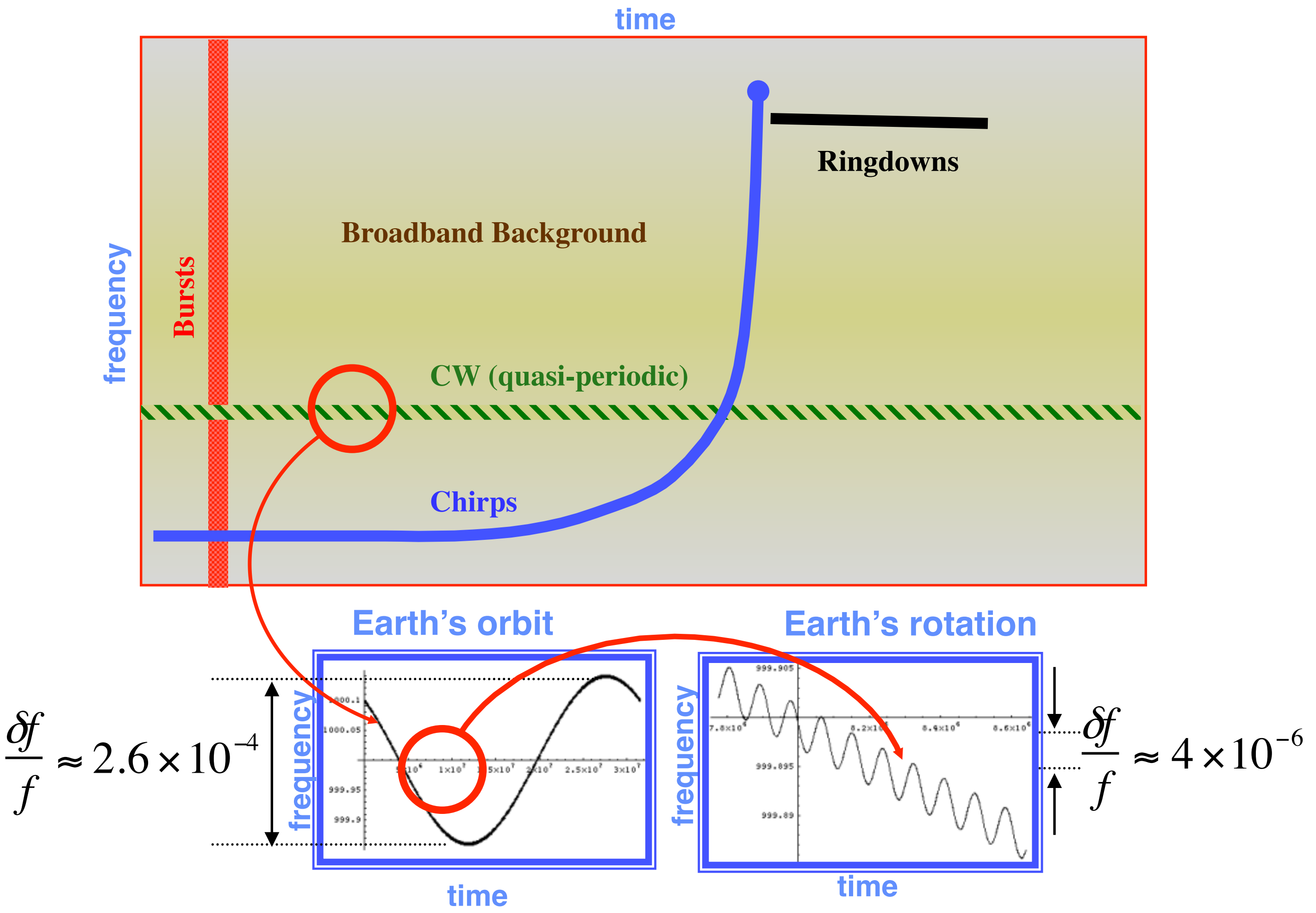
# Frequency-Time Characteristics of GW Sources



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

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

The rate of future discovery in gravitational-wave astronomy will be determined by the number and sensitivity of gravitational-wave detectors and the number and skill of GW experimentalists. For India to be successful in this field will require quickly growing a sufficiently large community of its own GW experimental experts.

# Sky Localization Is Poor With Only Two Detectors

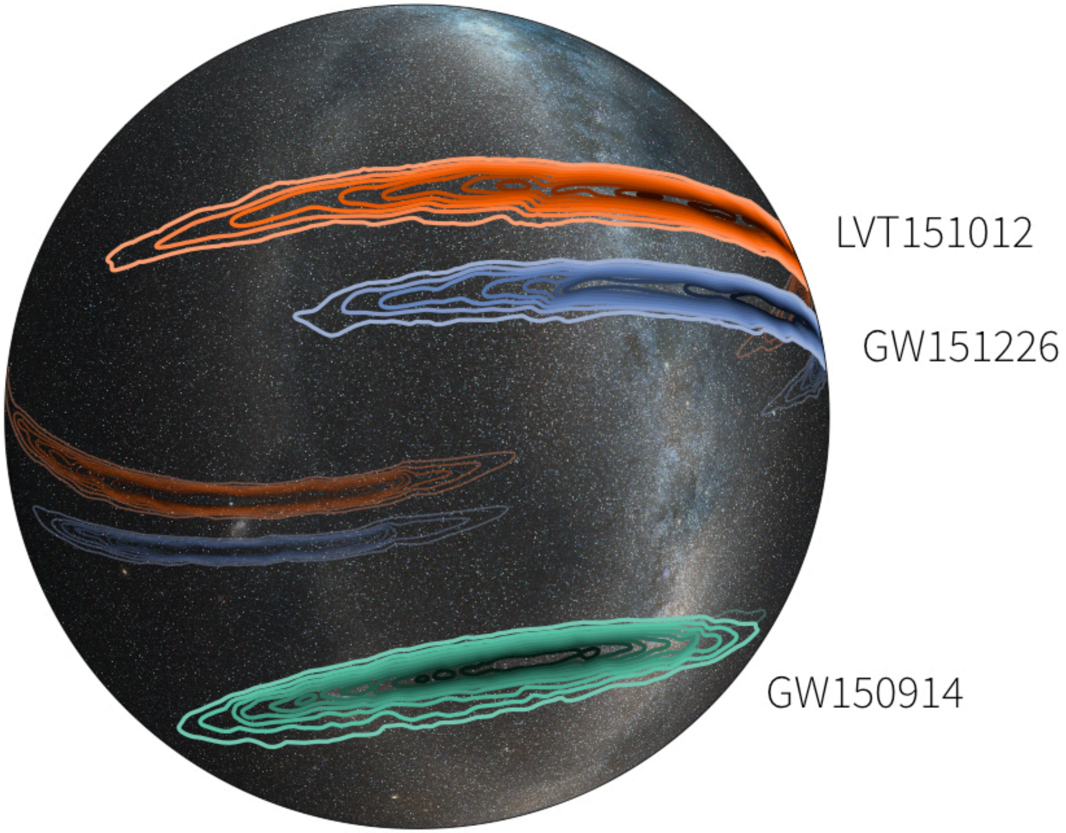
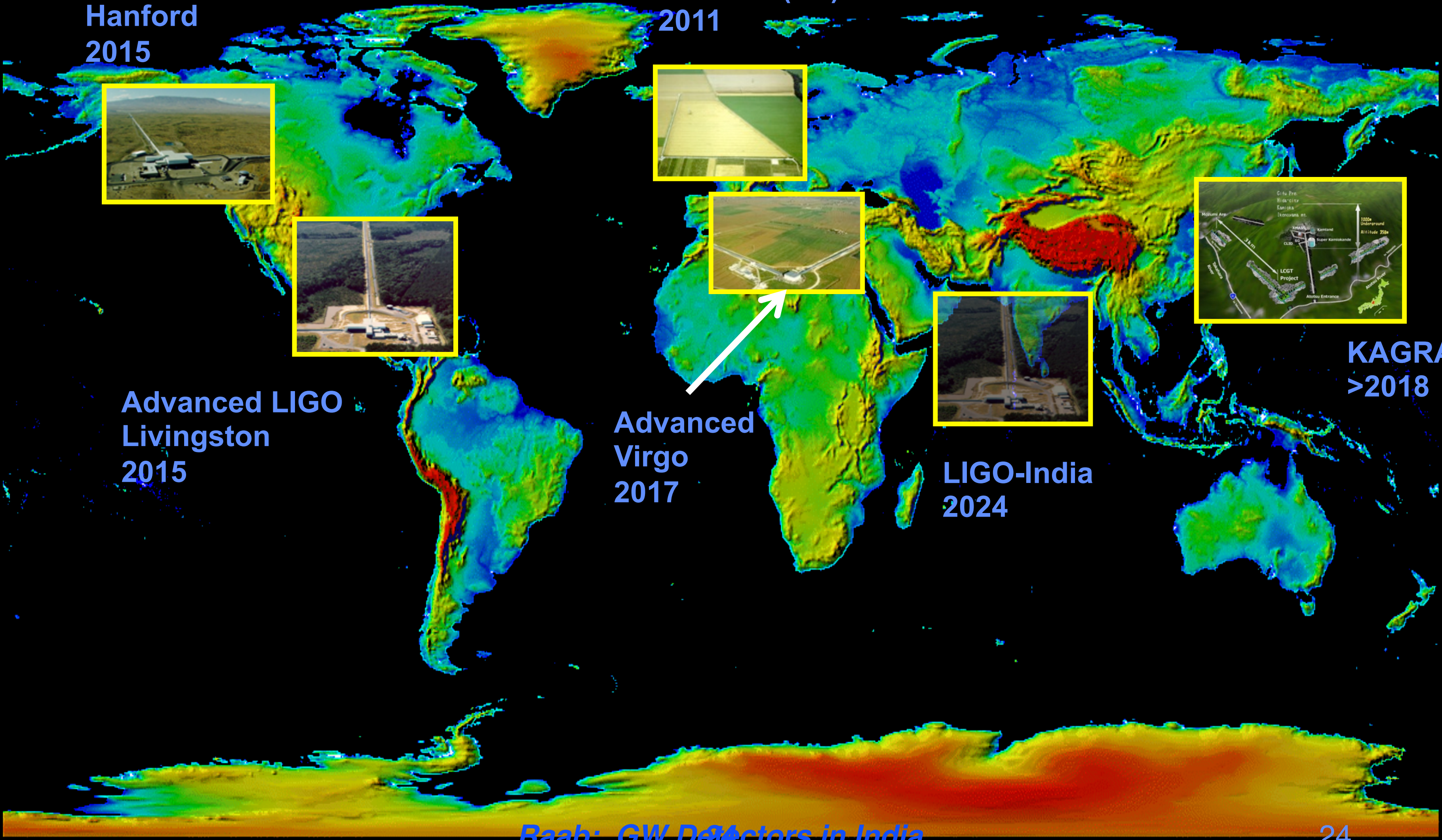


Image credit: LIGO (Leo Singer) /Milky Way image (Axel Mellinger)

# The advanced GW detector network: 2015-2025



**Advanced LIGO**
**Hanford**
**2015**

**GEO600 (HF)**
**2011**

**Advanced LIGO**
**Livingston**
**2015**

**Advanced**
**Virgo**
**2017**

**LIGO-India**
**2024**

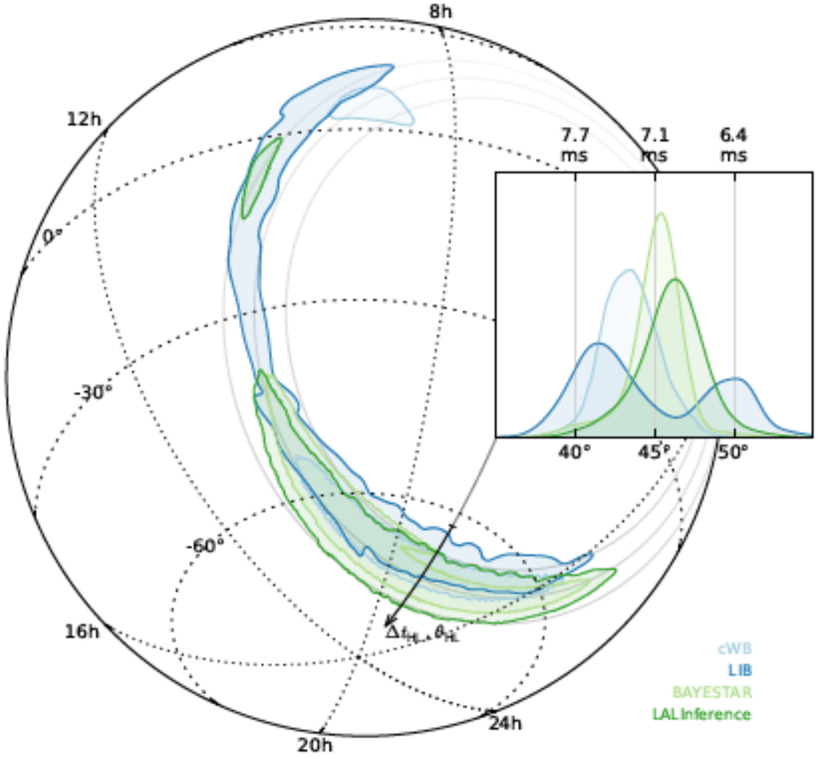
**KAGRA**
**>2018**

# LIGO-India Concept

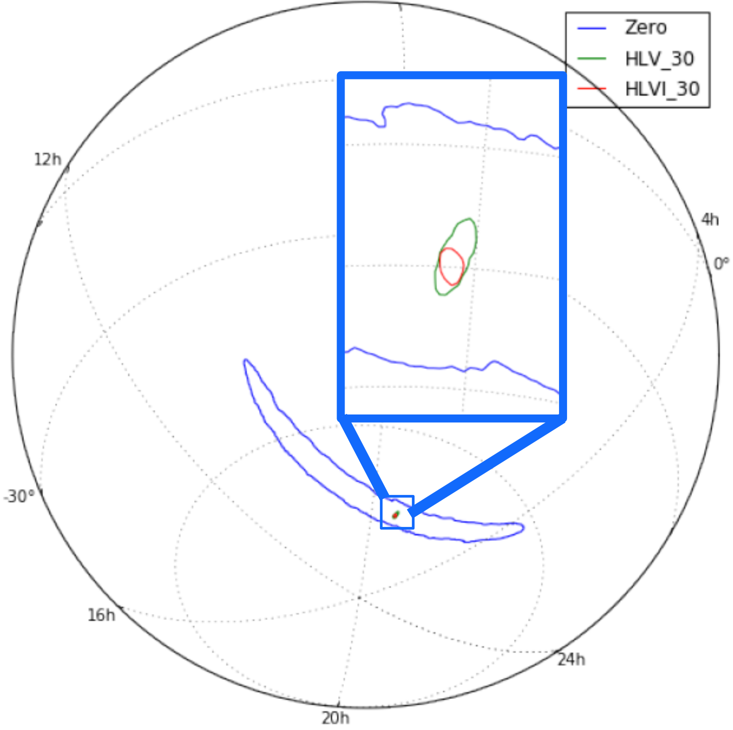
- Started as a partnership between LIGO Laboratory and IndIGO collaboration to build an Indian interferometer
  - » LIGO Lab (with its UK, German and Australian partners) provides components for one Advanced LIGO interferometer (H2) from the Advanced LIGO project
  - » LIGO Lab provides designs and design 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



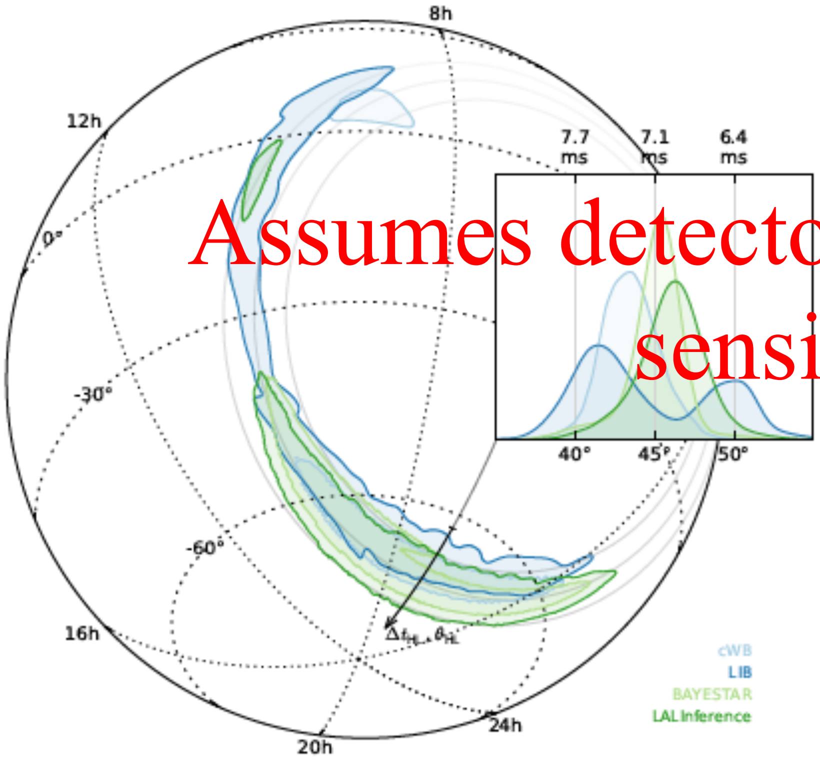
## GW150914: LIGO →LV →LVI (Preliminary)



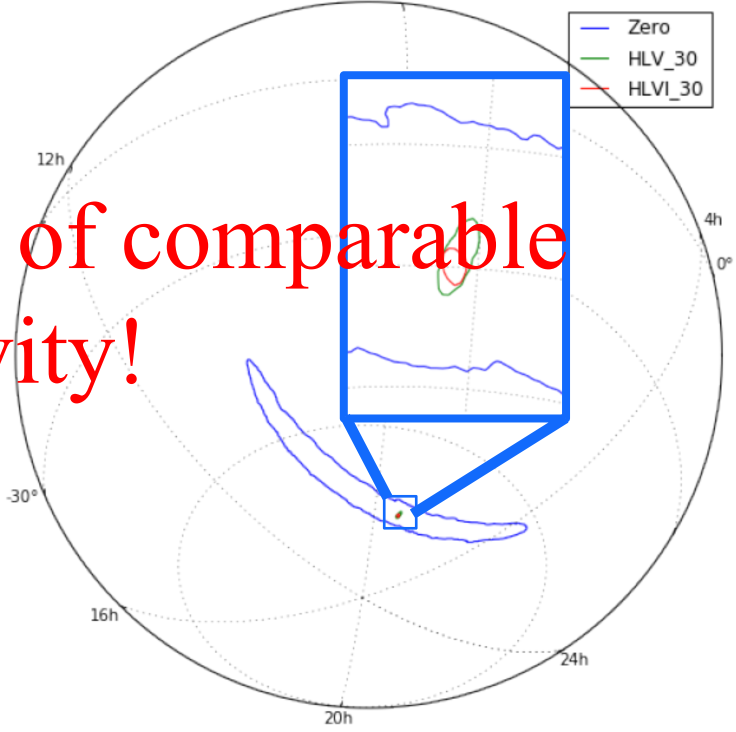
**375° → 9.3° → 7.8°**
**(99% confidence level)**

# Improved Localization: LIGO→Virgo→LIGO-India

## GW150914: LIGO only



## GW150914: LIGO →LV →LVI (Preliminary)



Assumes detectors of comparable sensitivity!

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

# The international GW network will not stay frozen in time.

- The detector now in storage for LIGO-India is 2015 technology.
- At best, LIGO-India will not be ready for joining observing runs until early 2024.
- At present, the LIGO H1 and L1 detectors are at 1/3 of design sensitivity.
- H1 and L1 should reach design sensitivity years before LIGO-India is ready for observing, probably by 2019.
- LIGO Laboratory will share knowledge gained getting to design sensitivity, but India's experimental community needs to implement them.

# LVC Observing Scenario (arXiv:1304.0670)

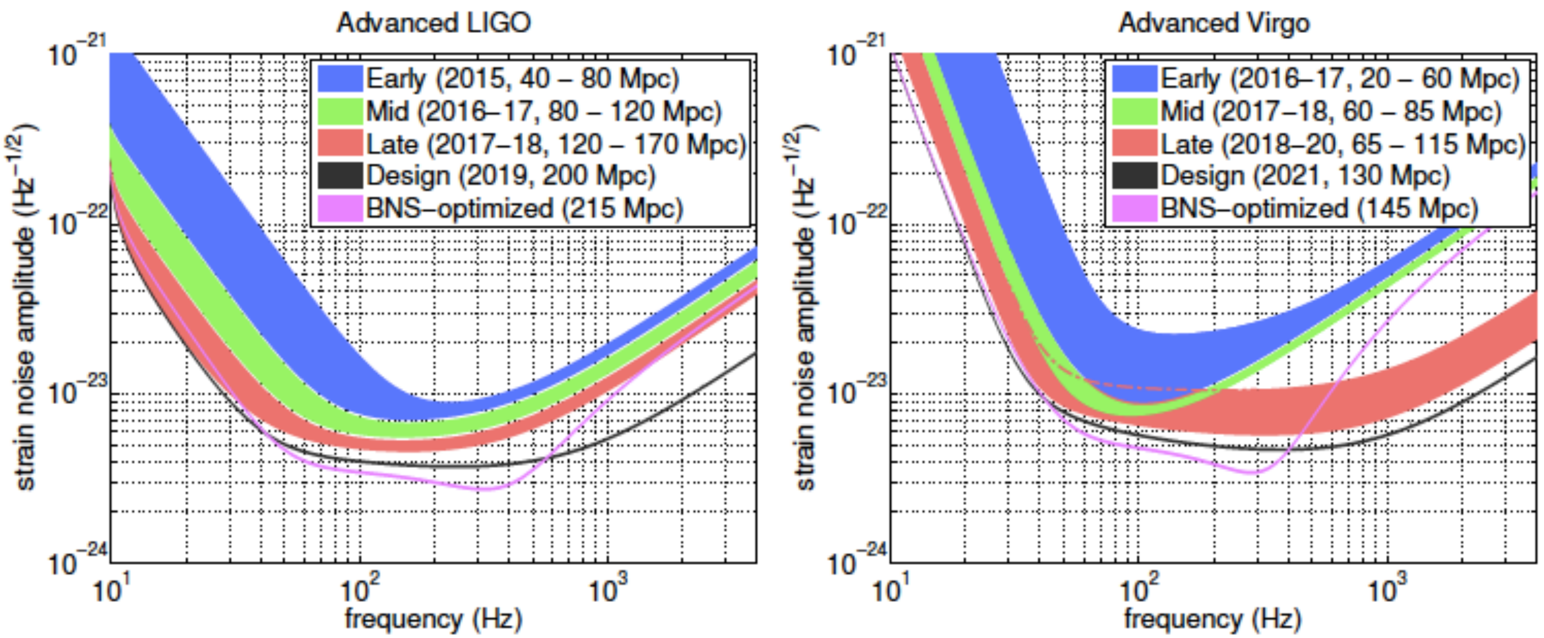
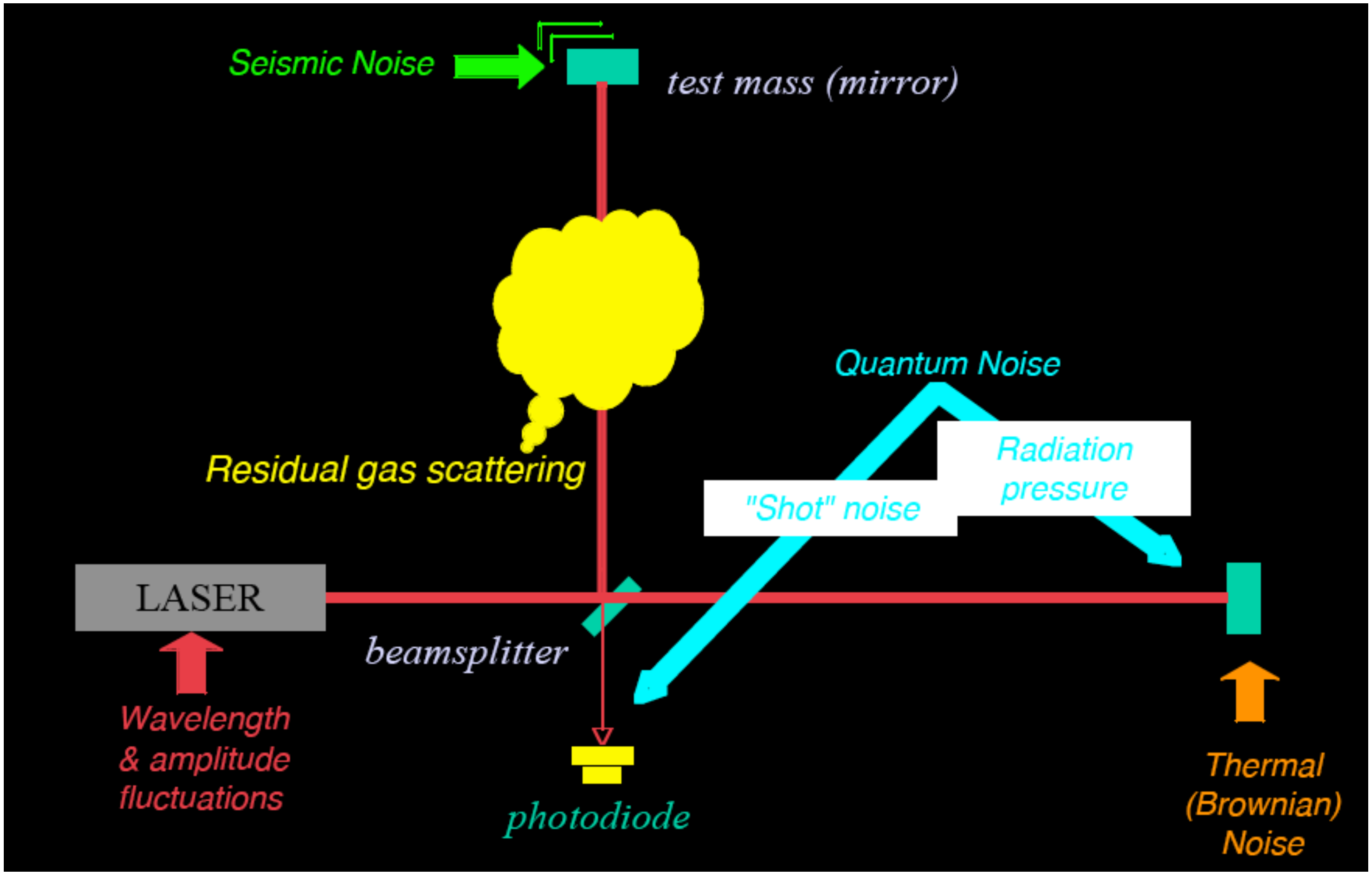


Figure 1: aLIGO (left) and AdV (right) target strain sensitivity as a function of frequency. The average distance to which binary neutron star (BNS) signals could be seen is given in Mpc. Current notions of the progression of sensitivity are given for early, middle, and late commissioning phases, as well as the final design sensitivity target and the BNS-optimized sensitivity. While both dates and sensitivity curves are subject to change, the overall progression represents our best current estimates.

# Sensitivity and Noise

- The keys to improving detectors are sensitivity and noise.
- Range is proportional to sensitivity.
- 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



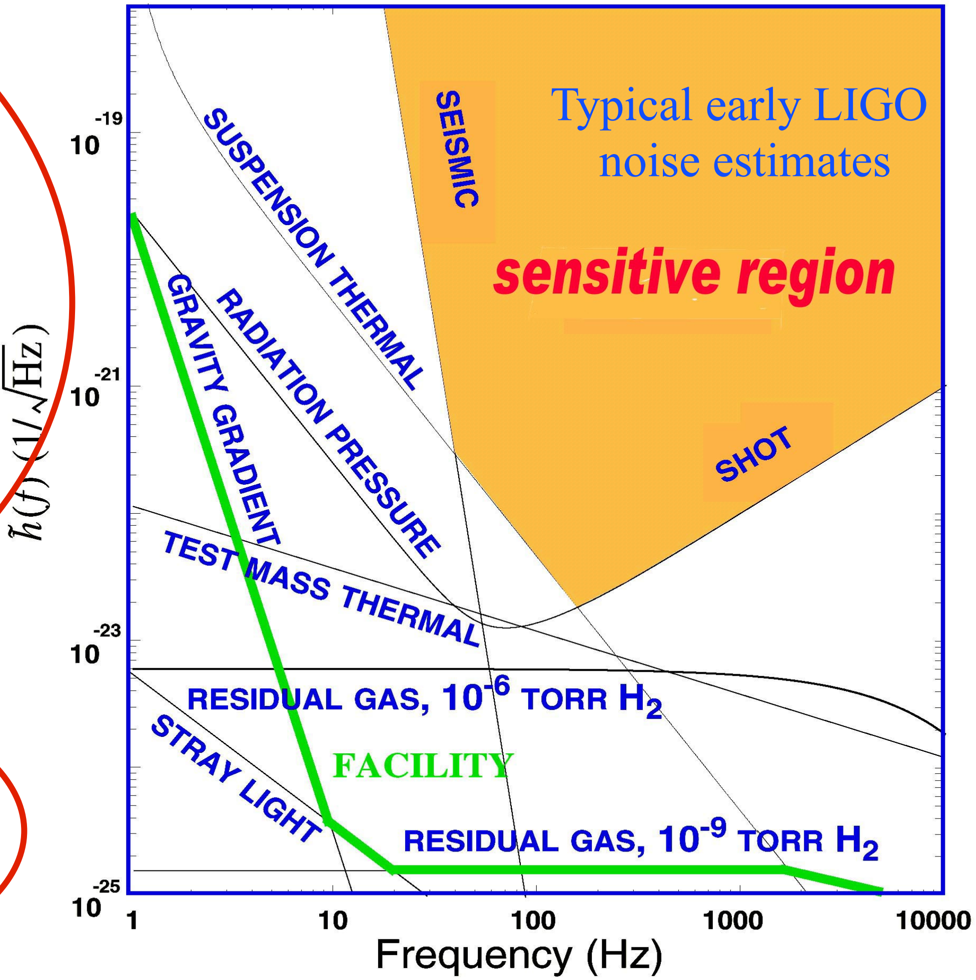
R. Adhikari

# What Limits Sensitivity of Interferometers?

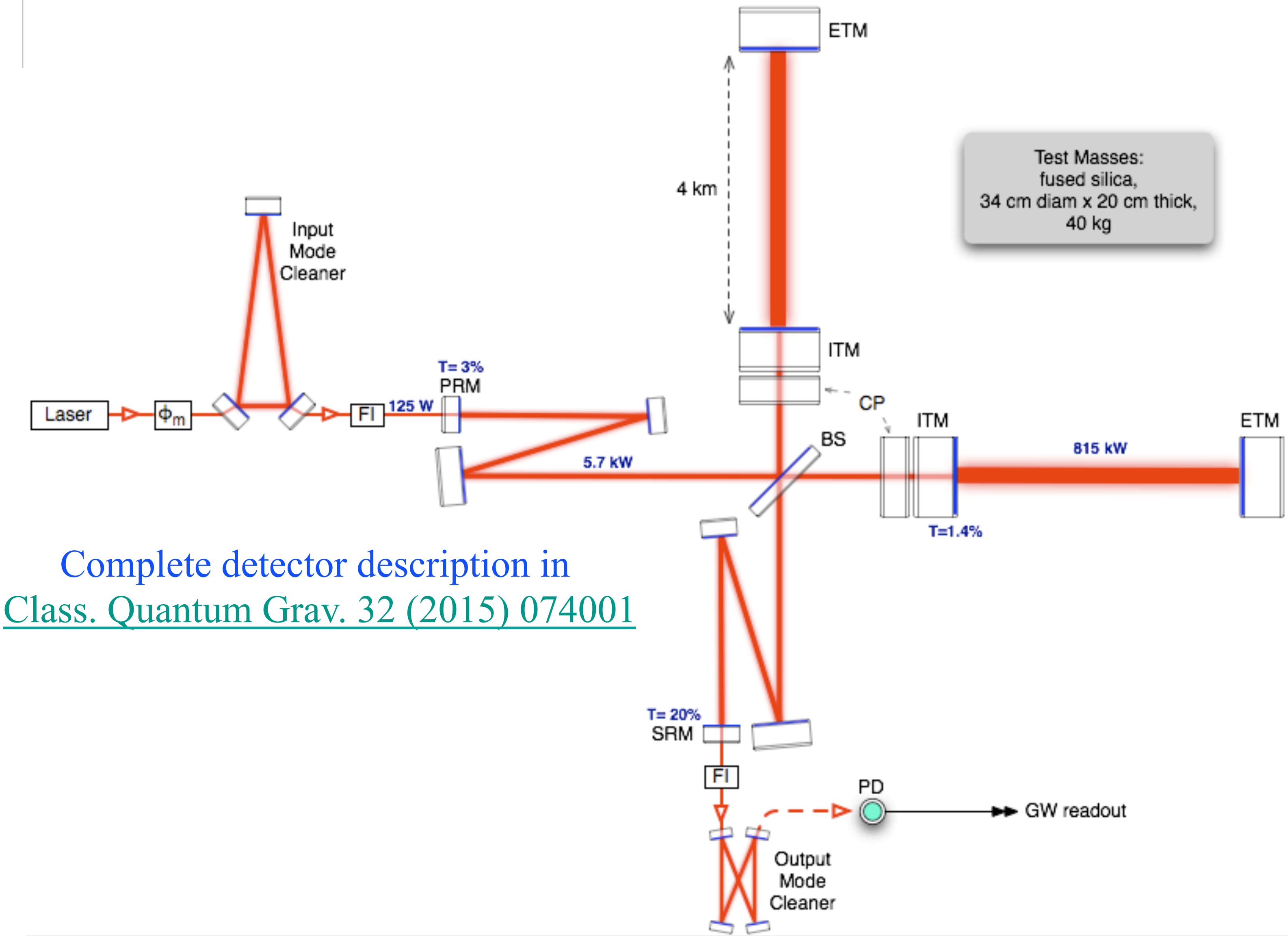
DESIGN

- 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

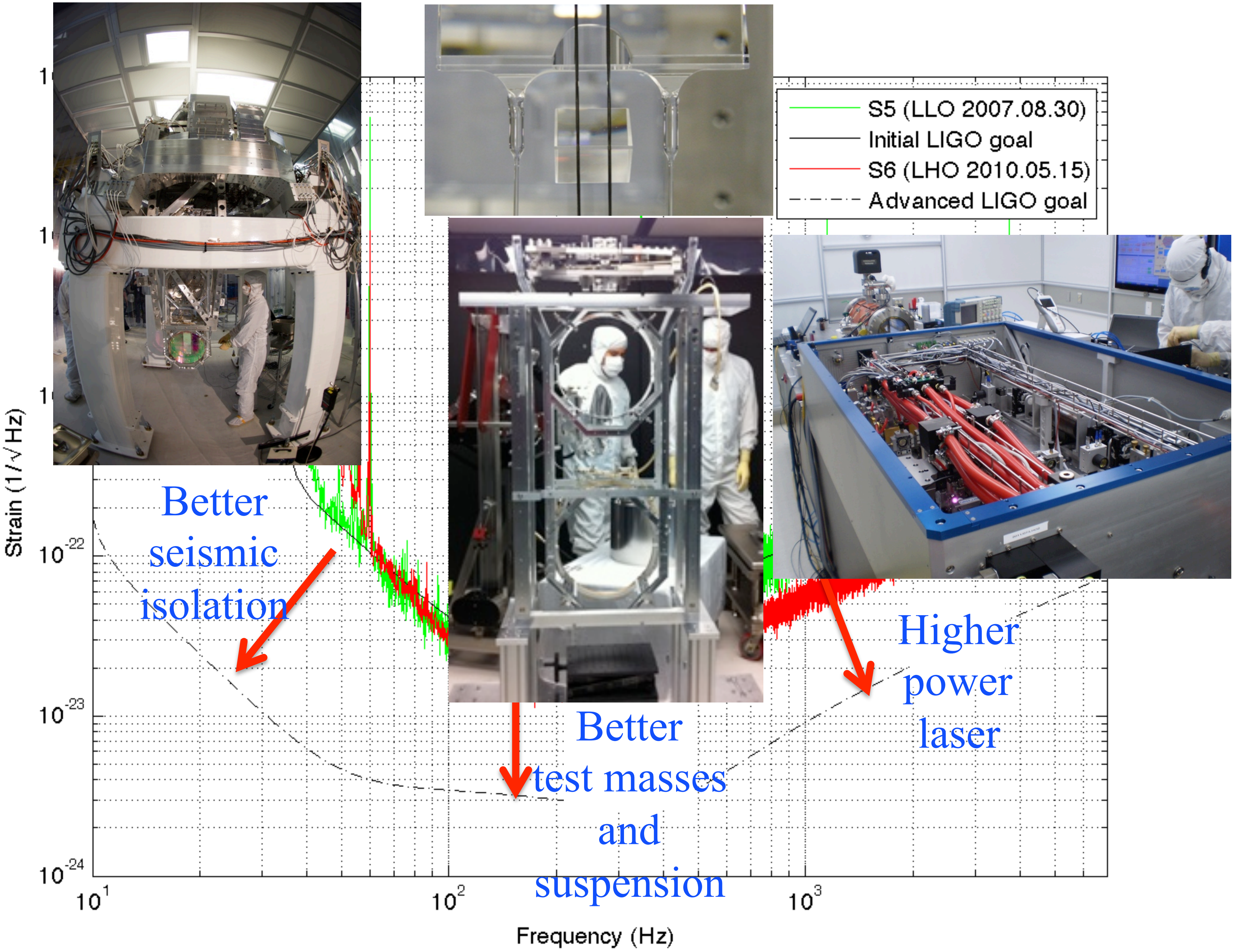
COMMISSIONING



# Optical configuration



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

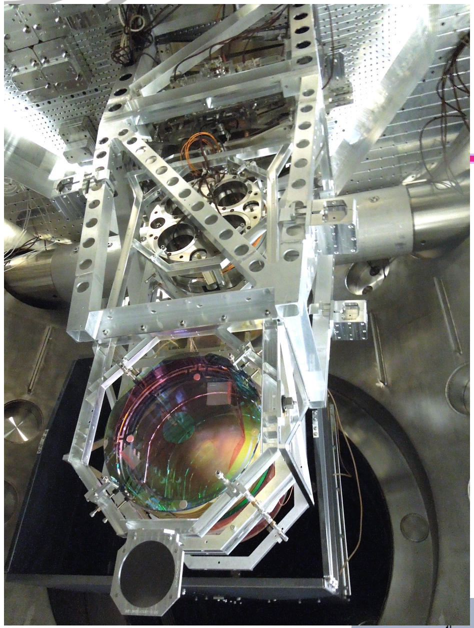


Better seismic isolation

Better test masses and suspension

Higher power laser

# Seismic Isolation

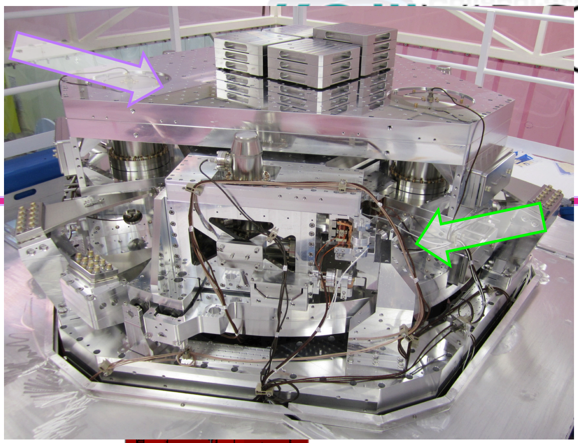


Ground Motion at 10 [Hz] ~ $10^{-9}$ [m/rtHz]

$$\Delta L = h\ L \sim 10^{-19}\ m / Hz^{1/2}$$

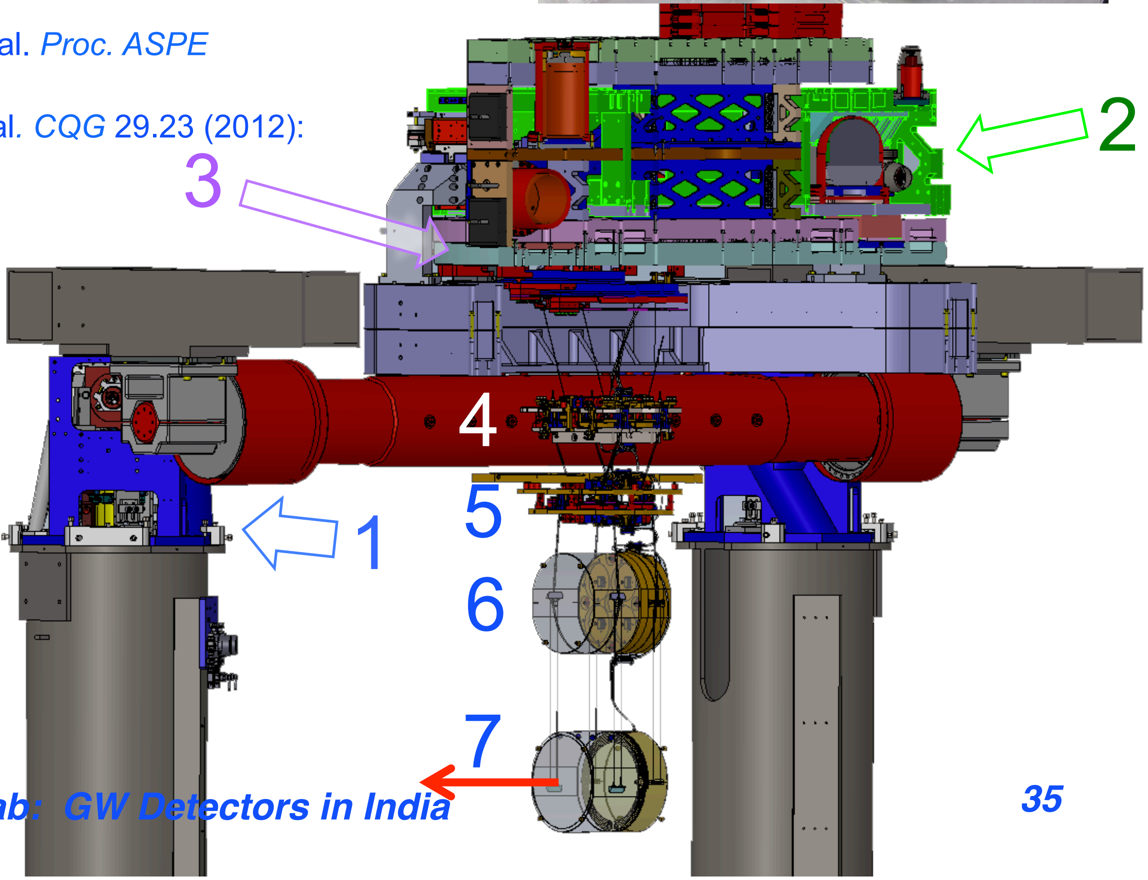
Need 10 orders of magnitude

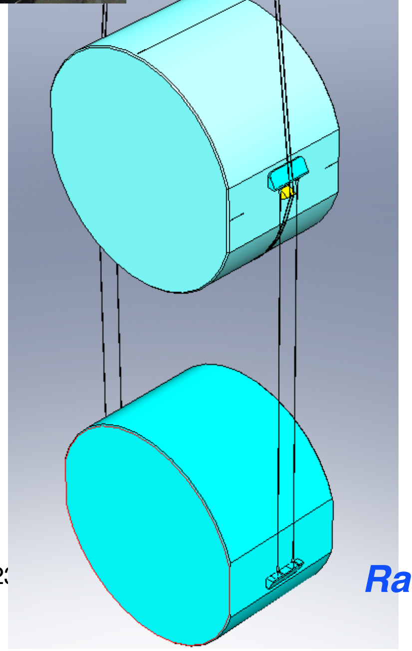
Test masses are suspended from 7 stages of active and passive vibration isolation



Matichard, F., et al. *Proc. ASPE* (2010)

Aston, S. M., et al. *CQG* 29.23 (2012): 235004.

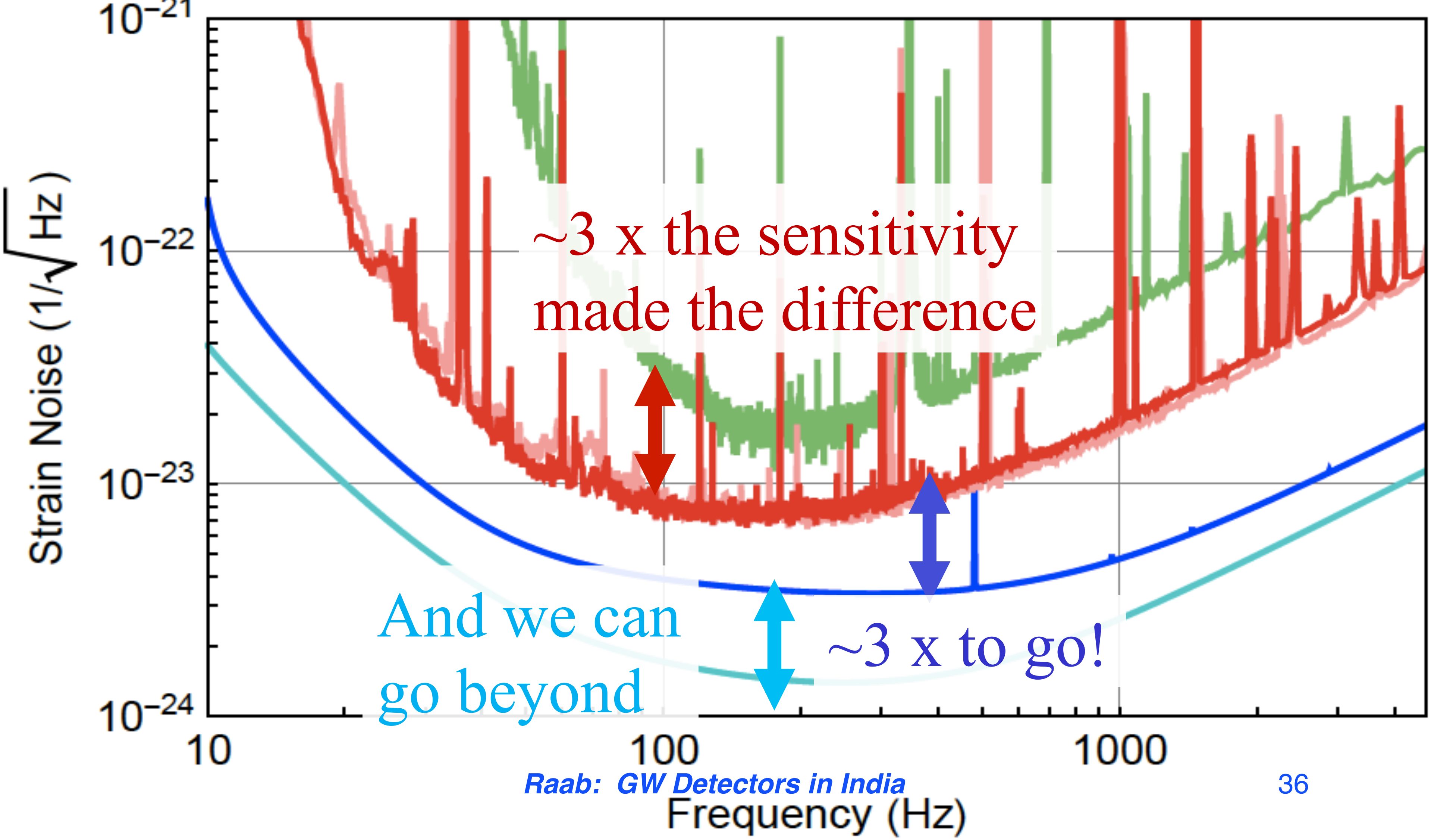




Last two stages are monolithic to improve Brownian noise

Cumming, A. V., et al. *CQG* 29.3 (2012): 035003.

# 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!

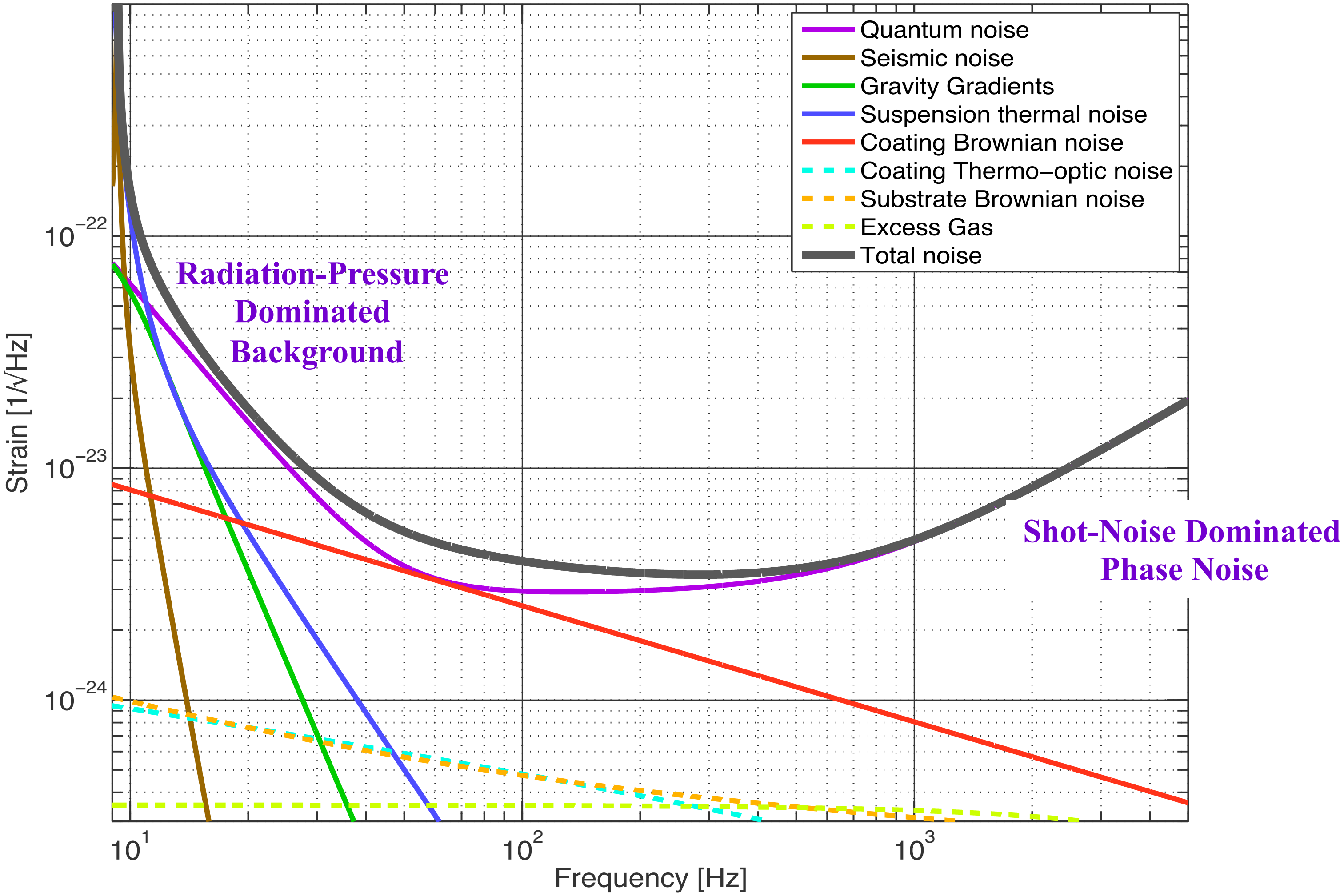
# Science drives Requirements

- **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

# What will it take to improve detectors?

- Clever experimental physicists and engineers, capable of solving multi-dimensional problems at the forefront of basic measurement science
- Advanced LIGO detectors are complex:
  - Approximately 350 high-performance servomechanisms
  - Many of these are multiple-input, multiple output
  - Sensors and actuators for these are operating at or beyond commercial limits
- Developing ways to work around fundamental limitations:
  - Quantum nature of light
  - Atomic nature of matter
- A single example: working around the classical and quantum nature of light

# Principal noise terms

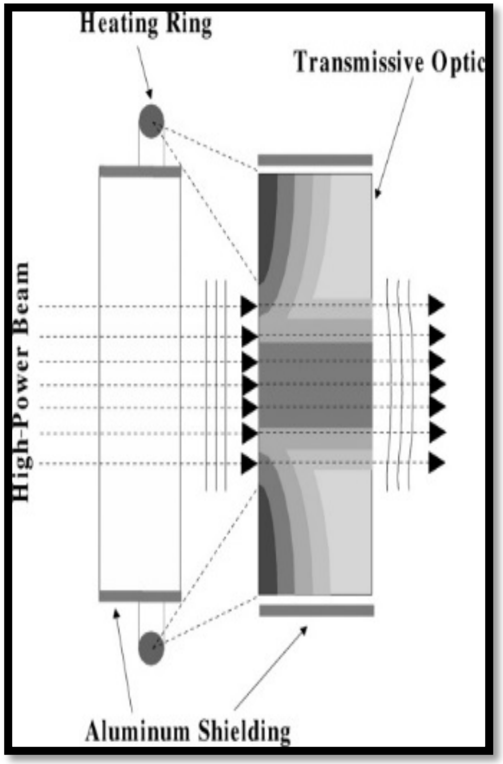


**Radiation-Pressure Dominated Background**

**Shot-Noise Dominated Phase Noise**

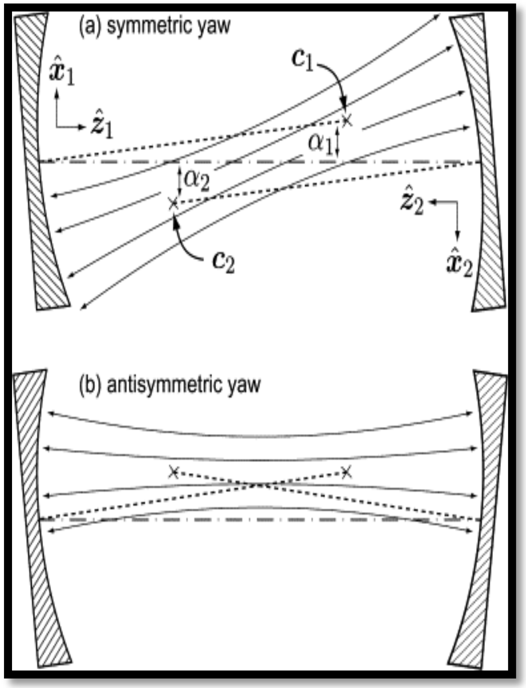
# Nothing Is Easy: Classical Challenges to High-Power Operation

Thermal lensing and compensation



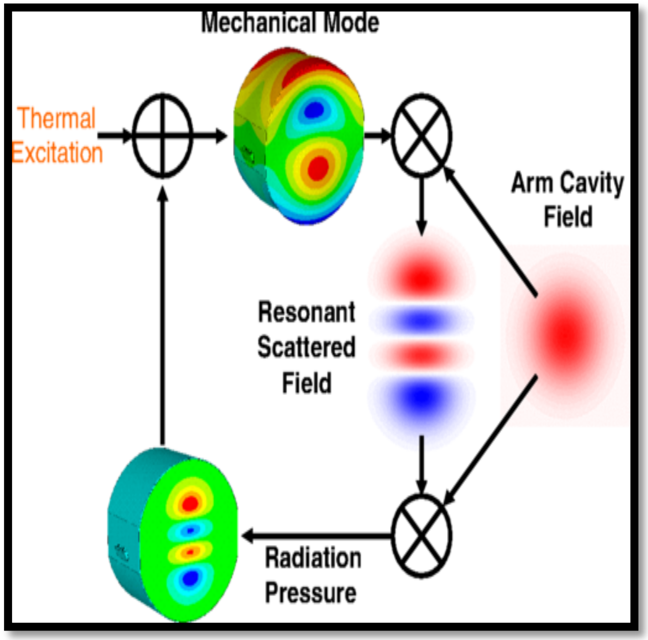
R Lawrence *et al* (2004)
Opt Lett **29**(22)2635-2637

Angular radiation pressure instabilities



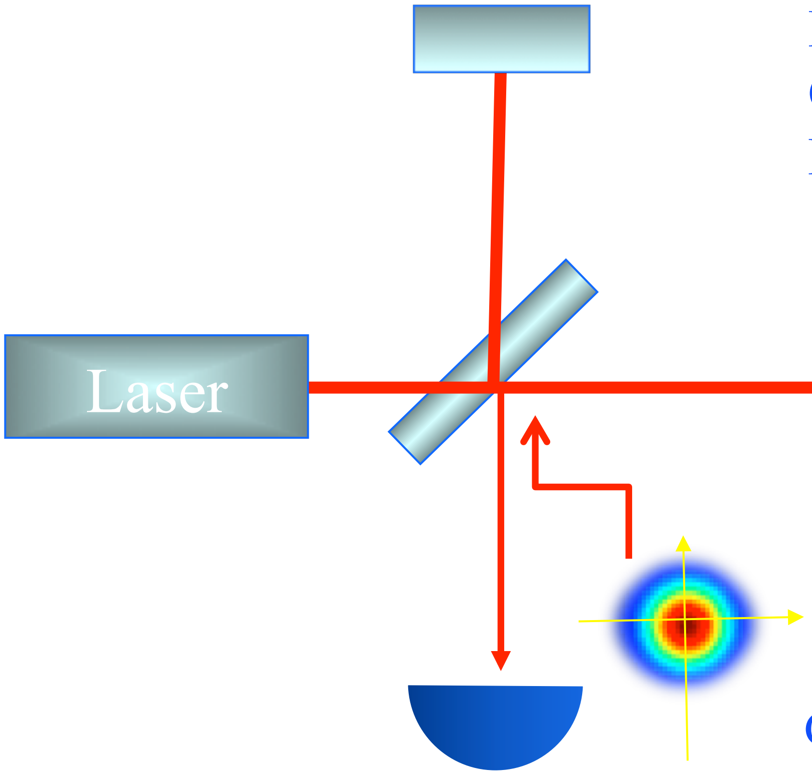
J Sidles, D Sigg, Phys. Lett. A. 354, 167-172 (2006)

Parametric instabilities



M Evans *et al* (2015) Phys. Rev. Lett. **114**, 161102

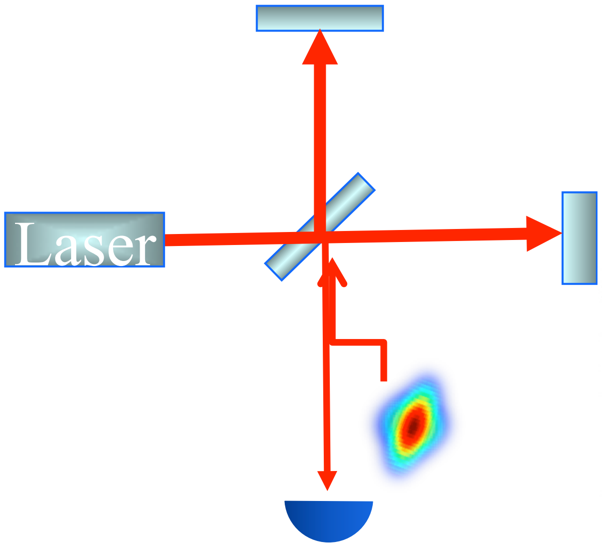
# Quantum Noise is Fundamental, Caused by Vacuum Fluctuations

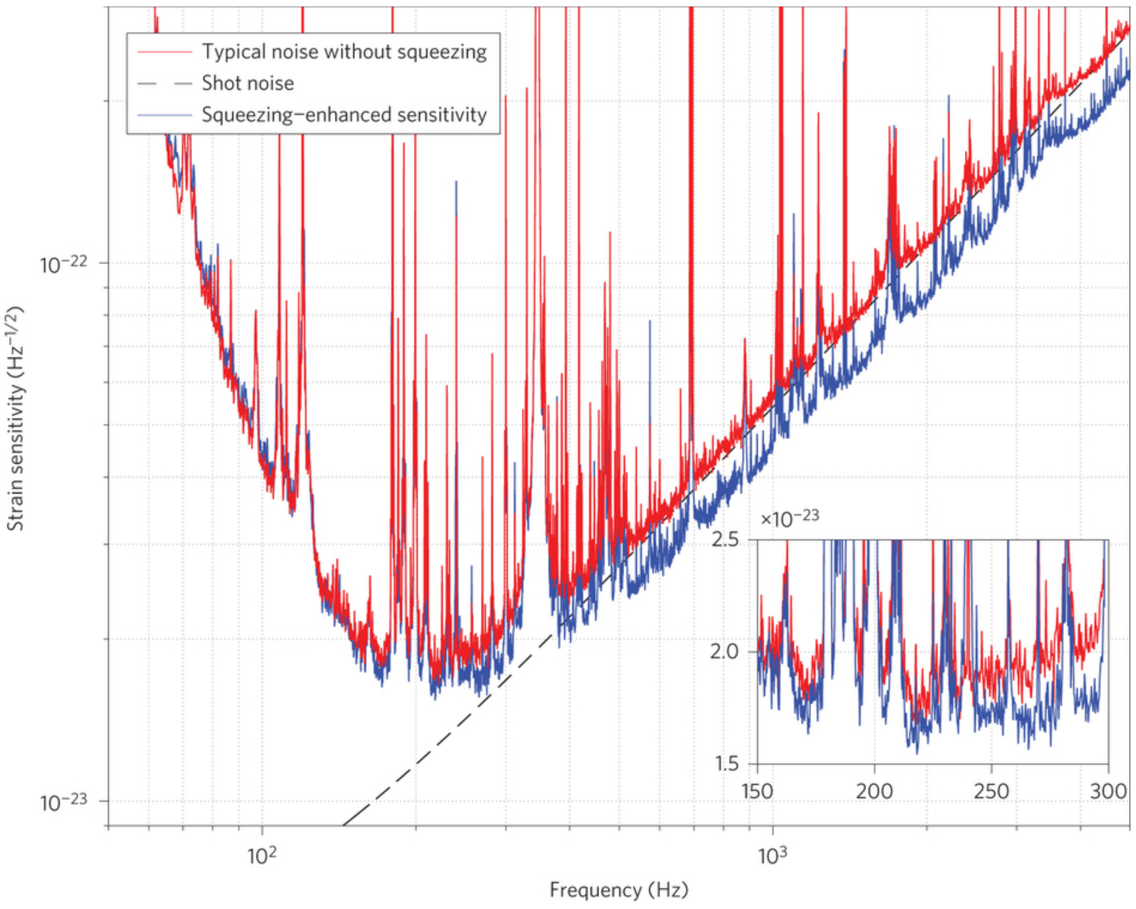


EM Vacuum Fluctuations
Cause Shot Noise and
Radiation Pressure Noise

C Caves (1981) Phys. Rev. D **23**, 1693

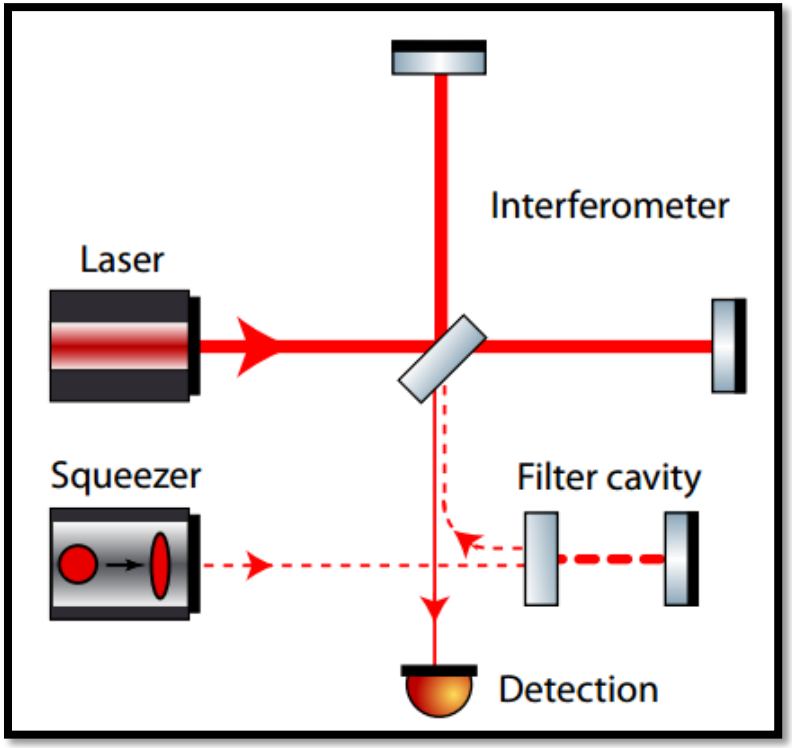
# Vacuum squeezing: a partial work-around





LIGO Scientific Collaboration, Nature Photonics 2013
doi:10.1038/nphoton.2013.177

# A better work-around: frequency-dependent squeezing



M Evans *et al*, (2013) PRD **88** 022002

- Original idea: J Kimble *et al* (2001) Phys. **Rev. D 65, 022002**
- Practical designs: T Corbitt *et al* (2004) **Phys. Rev. D 70, 022002**
- Demonstration in regime applicable to LIGO: E Oelker *et al* (2016) Phys. Rev. Lett. **116**, 041102

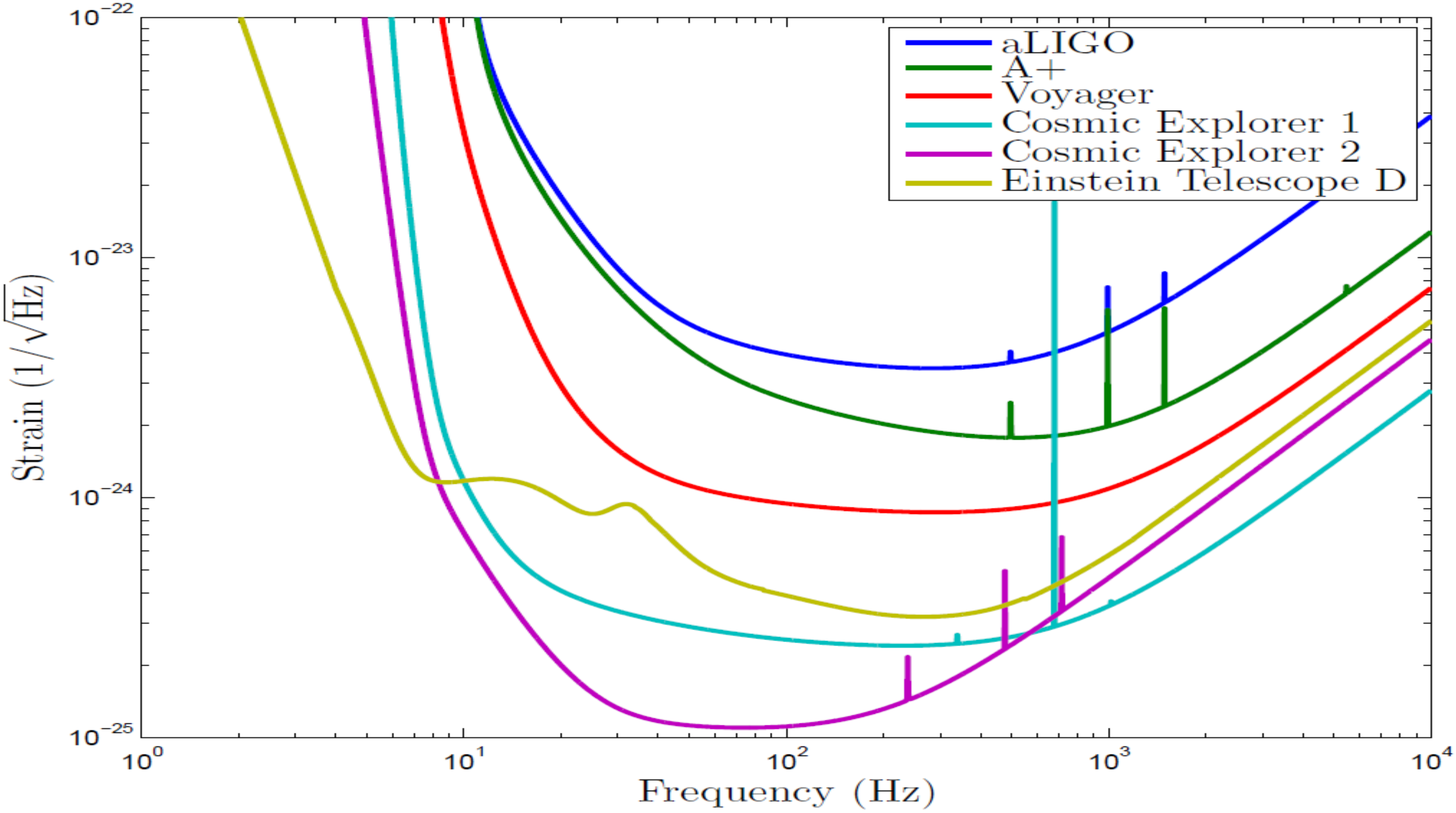
# Advanced LIGO upgrade path

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

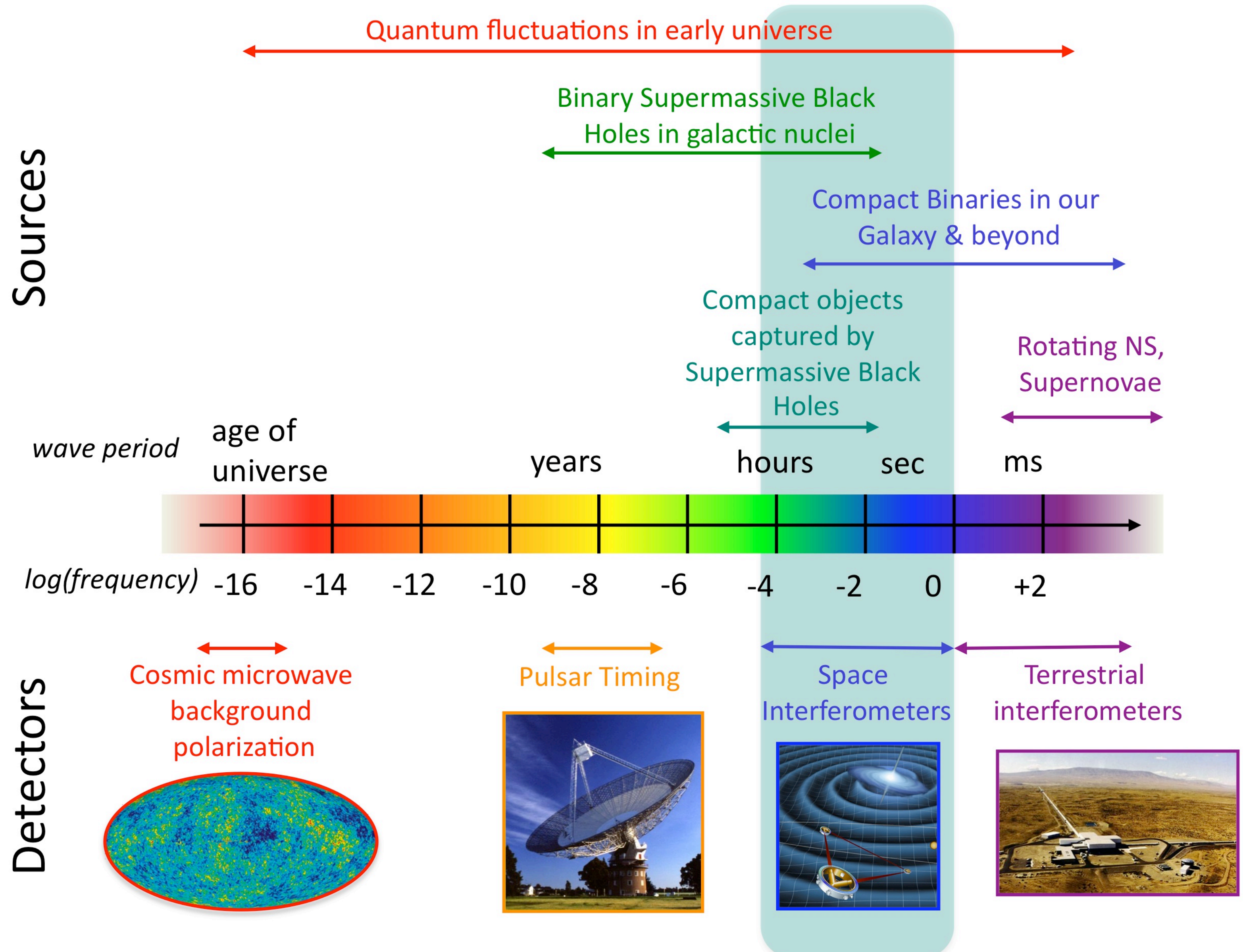
- Squeezed vacuum to reduce quantum noise
- Options for thermal noise:
  - Better coatings
  - Cryogenic operation
  - Longer arms (new facility)

# 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

# Summary

- 1st observing run of LIGO's 2nd-generation detectors have initiated Gravitational-Wave Astronomy, opening a new frontier for exploration.
- An emerging international network of detectors soon 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 and much physics still to be harvested from their observations.
- The role played by India in these developments will depend strongly on India's ability to supply quickly both GW observatory facilities and a team of brilliant experimentalists in India with expertise in the commissioning of state-of-the-art GW detectors.