Exploring the New Frontier of Gravitational-Wave Astronomy

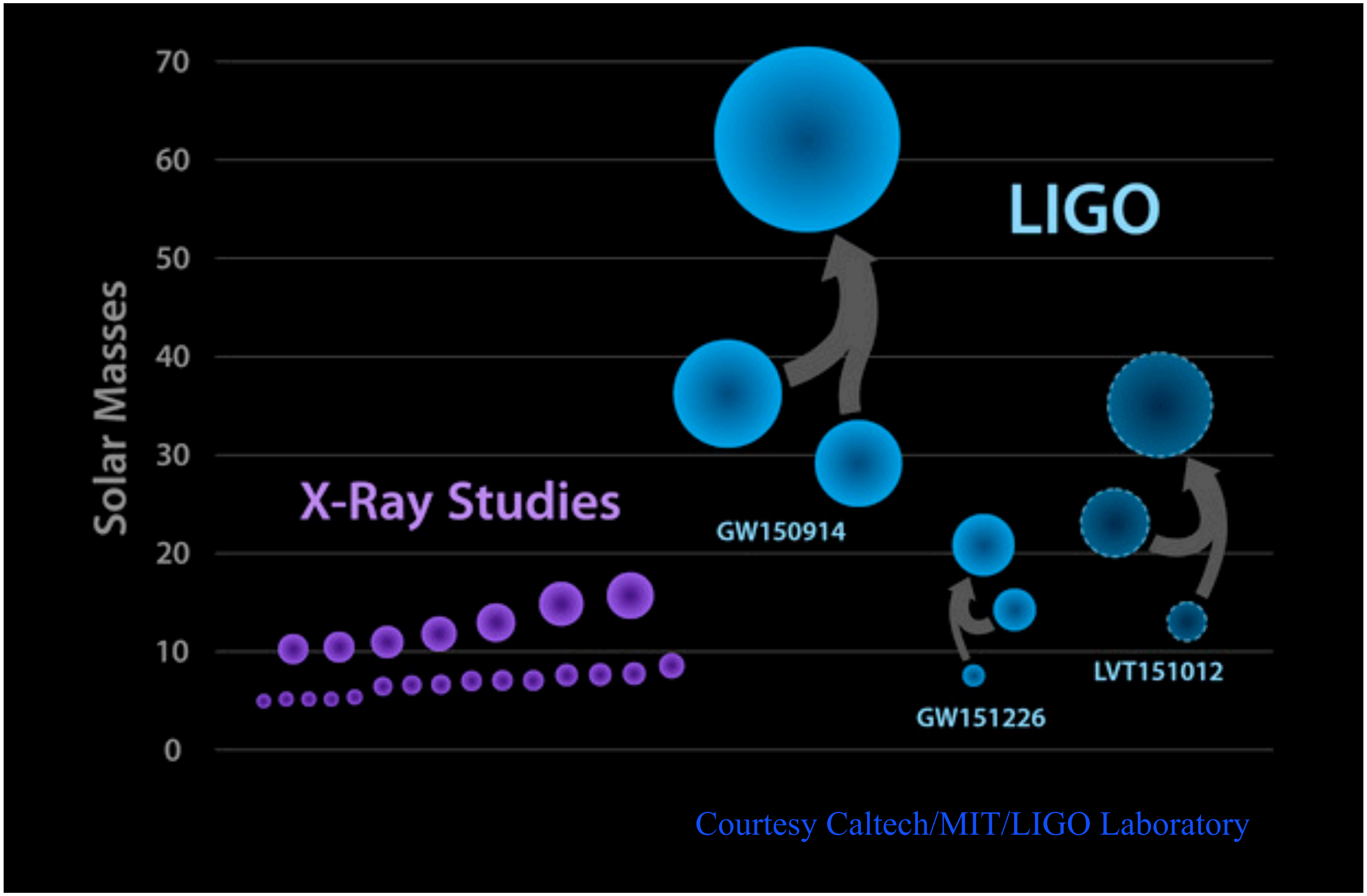
Fred Raab, for the LIGO Scientific Collaboration and the Virgo Collaboration

TWAS2016

16 Nov 2016

LIGO-G1602006

Known Stellar-Mass Black Holes – June 2016



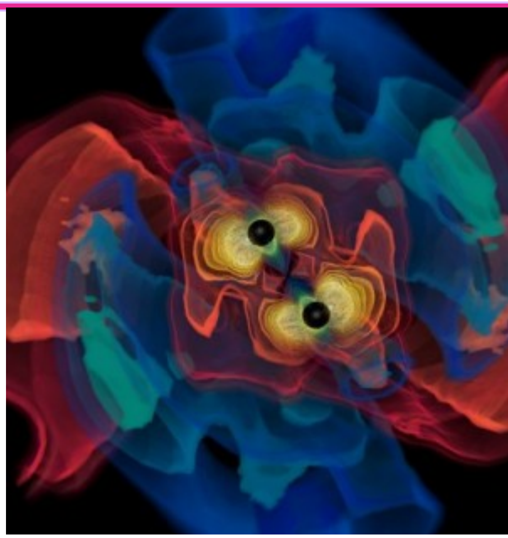
Now what?

- These first observations open up access to a vast new frontier for exploration
- Initial observations indicate that stellar-mass or "heavy" black hole binaries merge hourly somewhere in the universe
- What can these mergers teach us?
- How and where have these objects been formed?
- 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?

Multi-Messenger Astronomy

- These first observations of dynamic extreme spacetimes show us that GR is reasonably accurate in this regime and can be used as a tool for examining and interpreting extreme states of matter.
- There are a rich collection of sources still to be examined!

Astrophysical Sources of Gravitational Waves

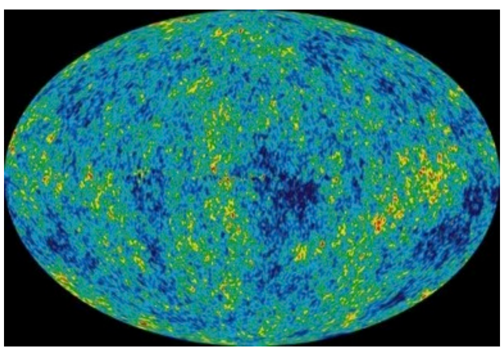


Credit: AEI, CCT, LSU

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

- Strong emitters, well-modeled,

- (effectively) transient

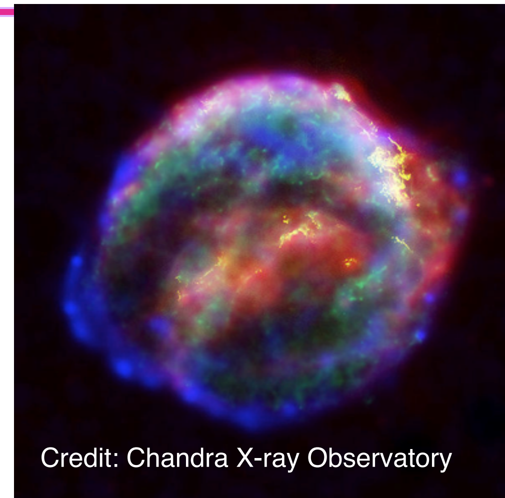


NASA/WMAP Science Team

Cosmic Gravitational-wave Background

- Residue of the Big Bang

- Long duration, stochastic background

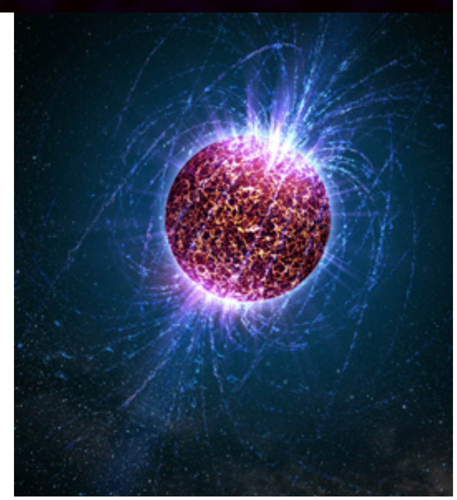


Credit: Chandra X-ray Observatory

Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled

('bursts'), transient



Casey Reed, Penn State

Spinning neutron stars

- (nearly) monotonic waveform

- Long duration

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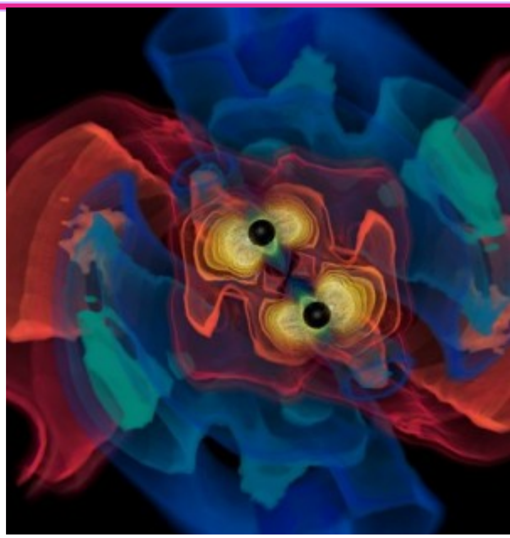

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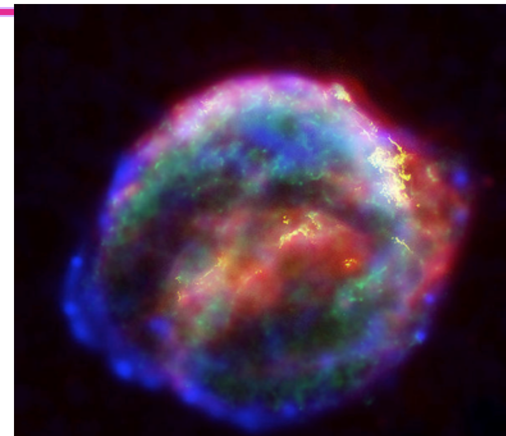

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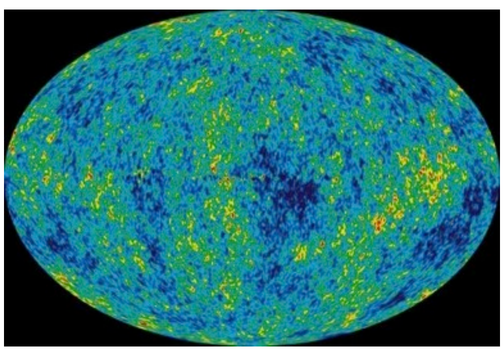

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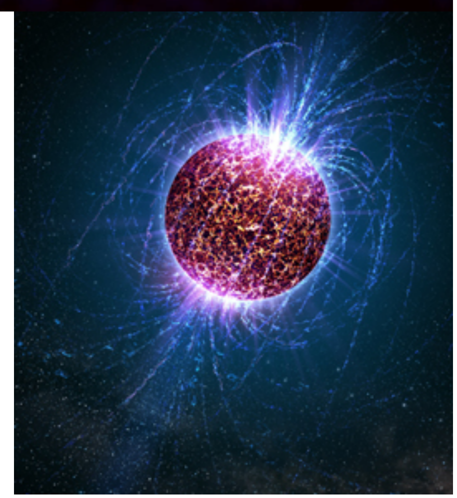

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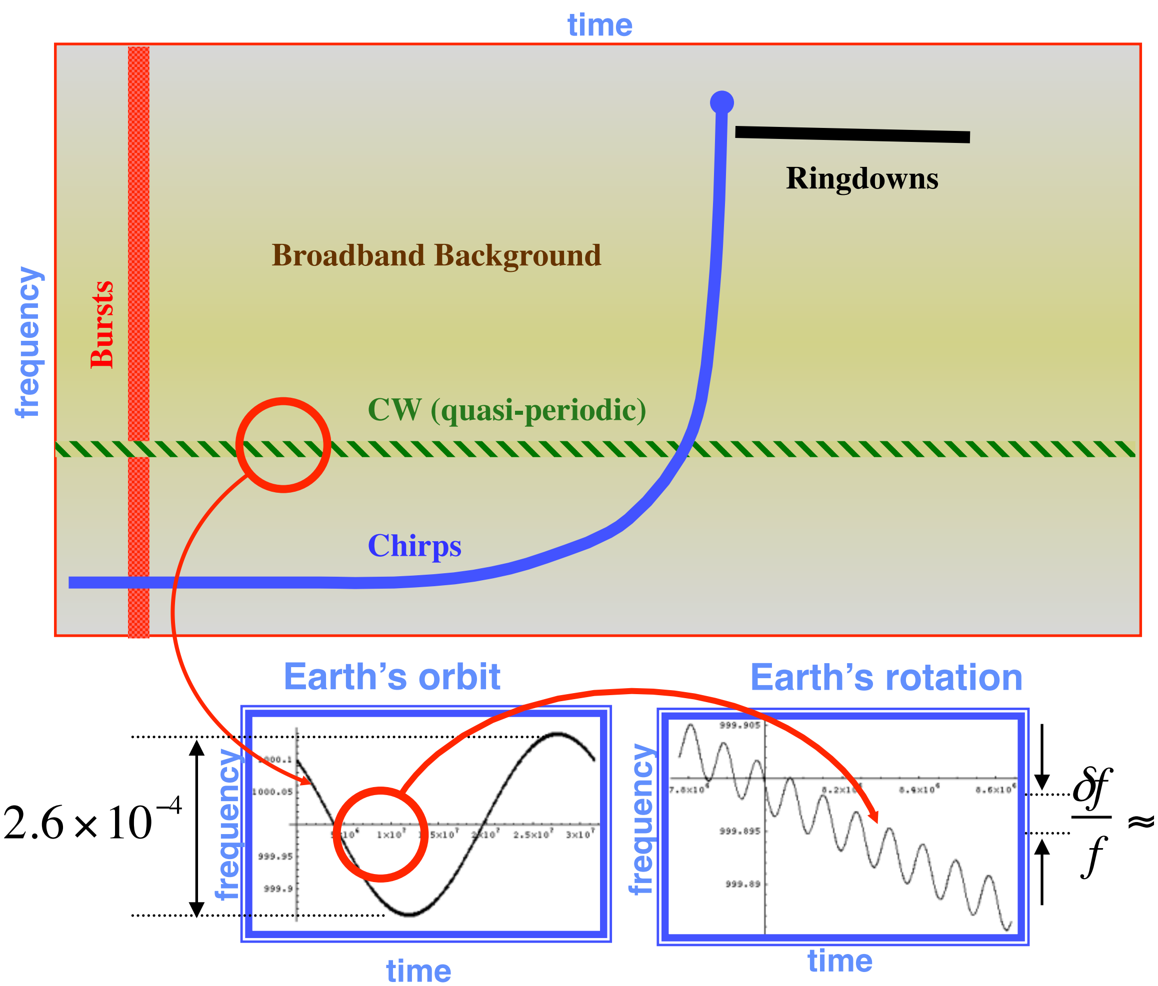
Frequency-Time Characteristics of GW Sources



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

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

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.

Building Out the Terrestrial Gravitational-Wave Network

- A greater number of detector facilities around the world improves:
  - Sky localization
  - Polarization information
  - CBC orbital inclination
  - CBC Distance information
  - CBC precession information
  - Network robustness

Sky Localization Is Poor With Only Two Detectors

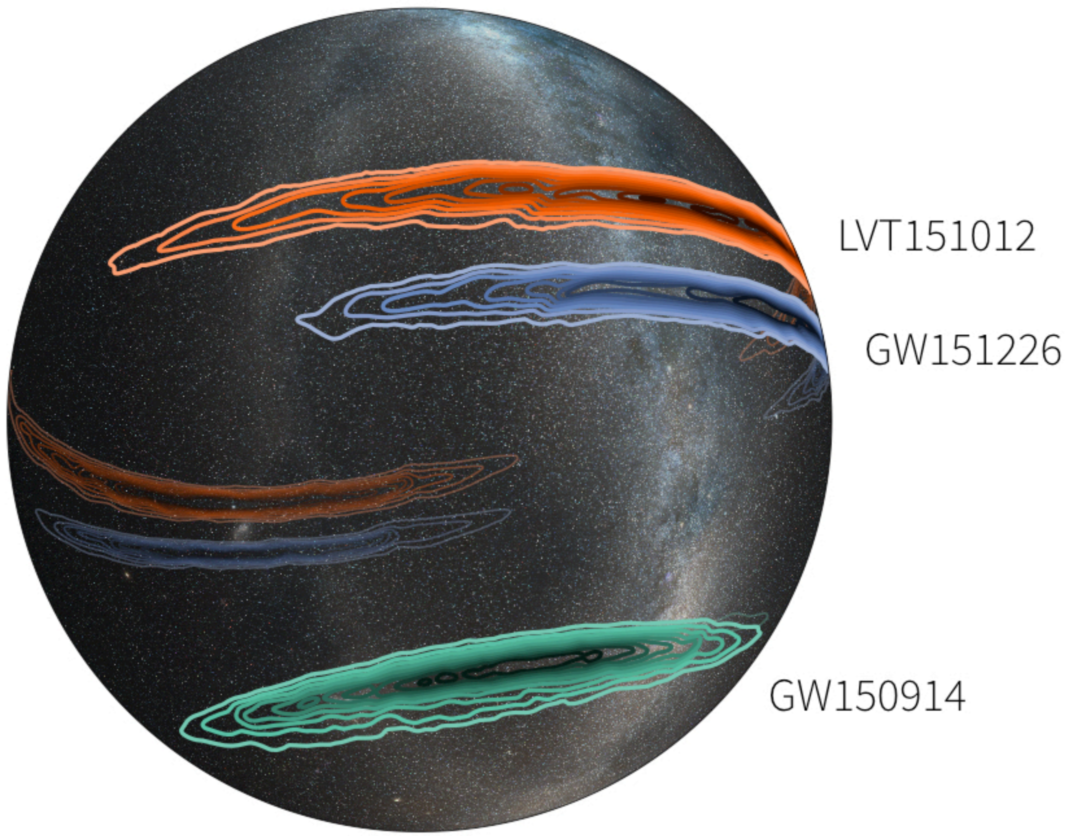
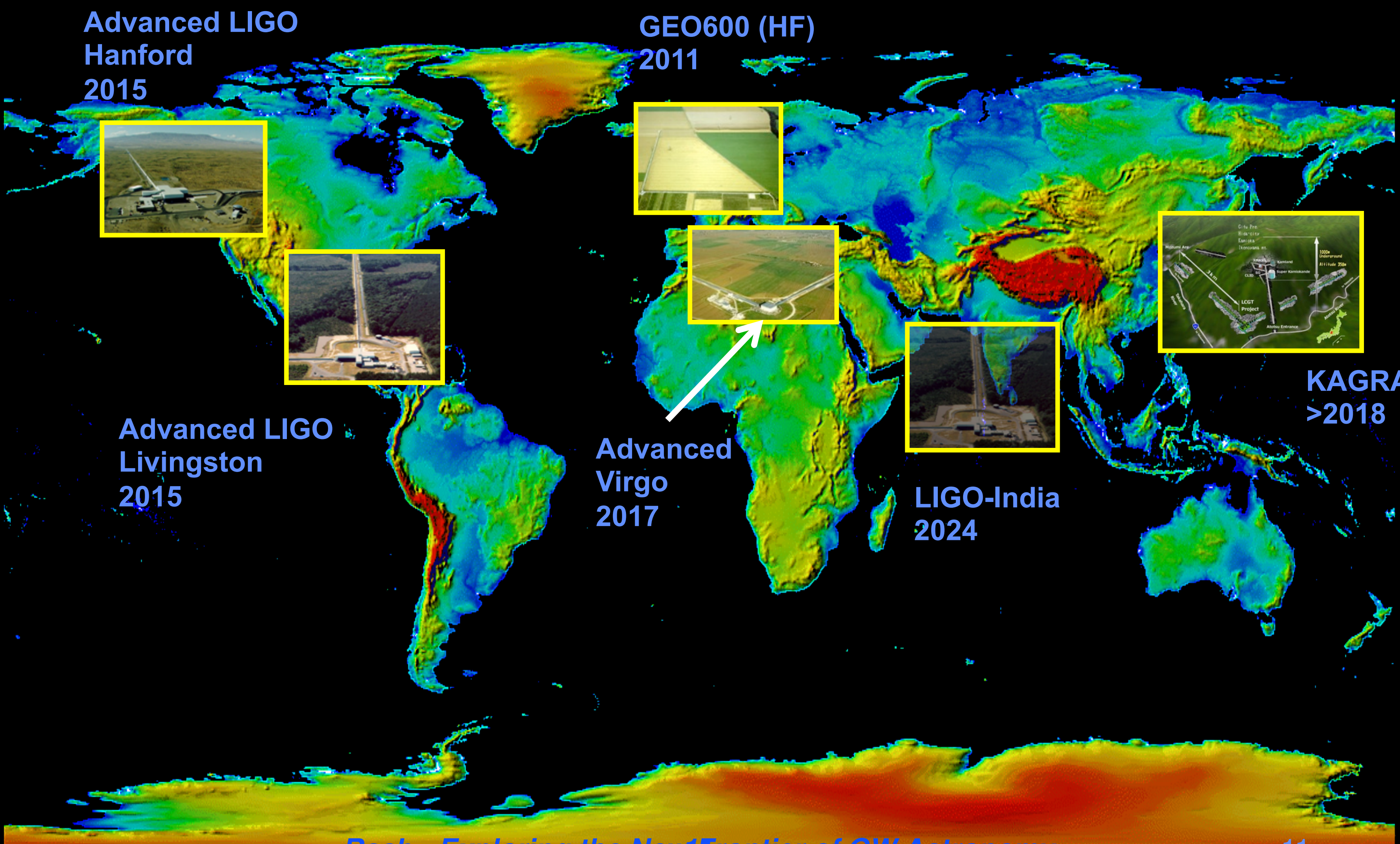


Image credit: LIGO (Leo Singer) /Milky Way image (Axel Mellinger)

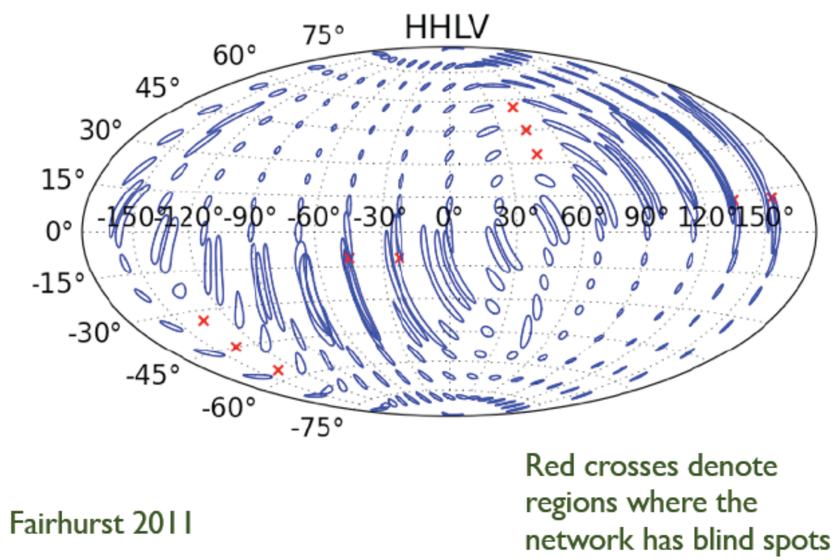
The advanced GW detector network: 2015-2025



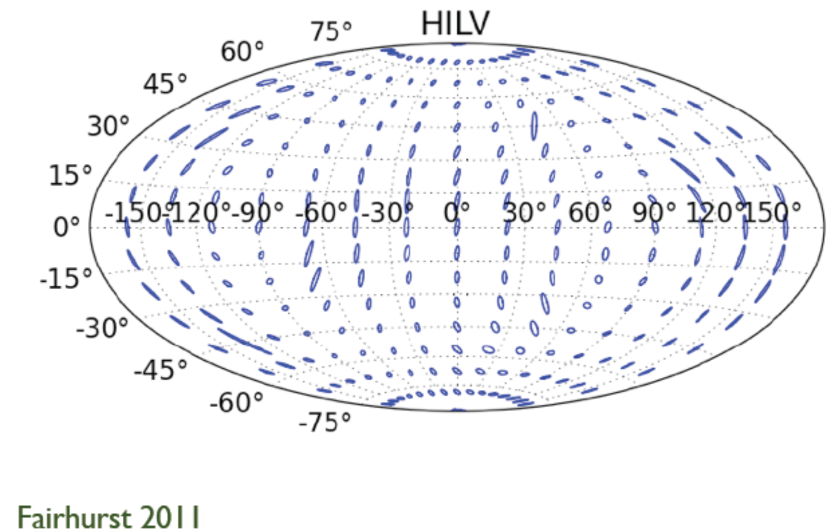
LIGO-India Concept

- 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 Global Network to maximize scientific impact
- Major enhancement to the global network and to the capabilities for GW astrophysics and Multi-messenger Astronomy

Effect of Adding LIGO-India to the LIGO+Virgo Network



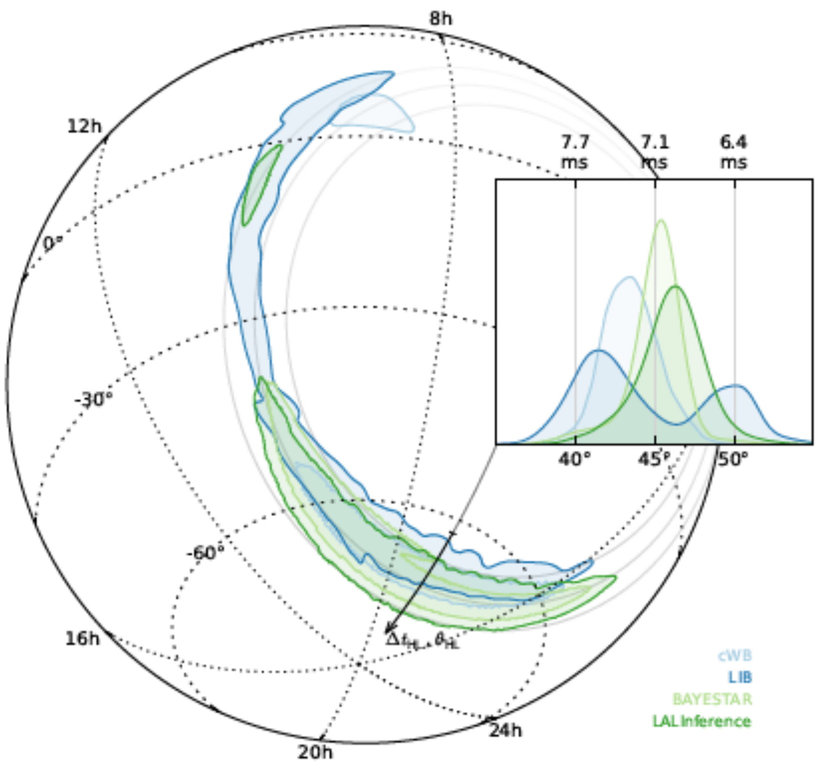
LIGO+Virgo only



With LIGO-India

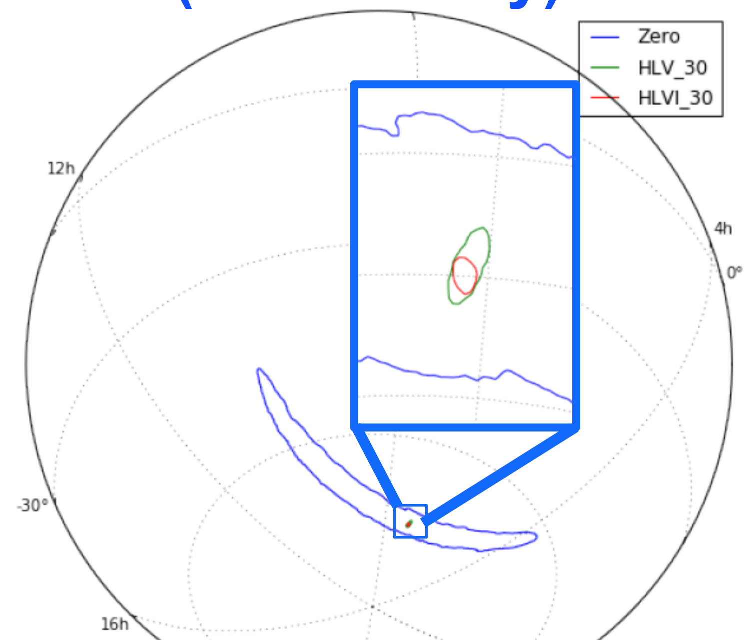
Improved Localization: LIGO→Virgo→LIGO-India

GW150914: LIGO only



LSC/Virgo et al. 2016, ApJL
arXiv:1602.08492

GW150914: LIGO →LV →LVI (Preliminary)



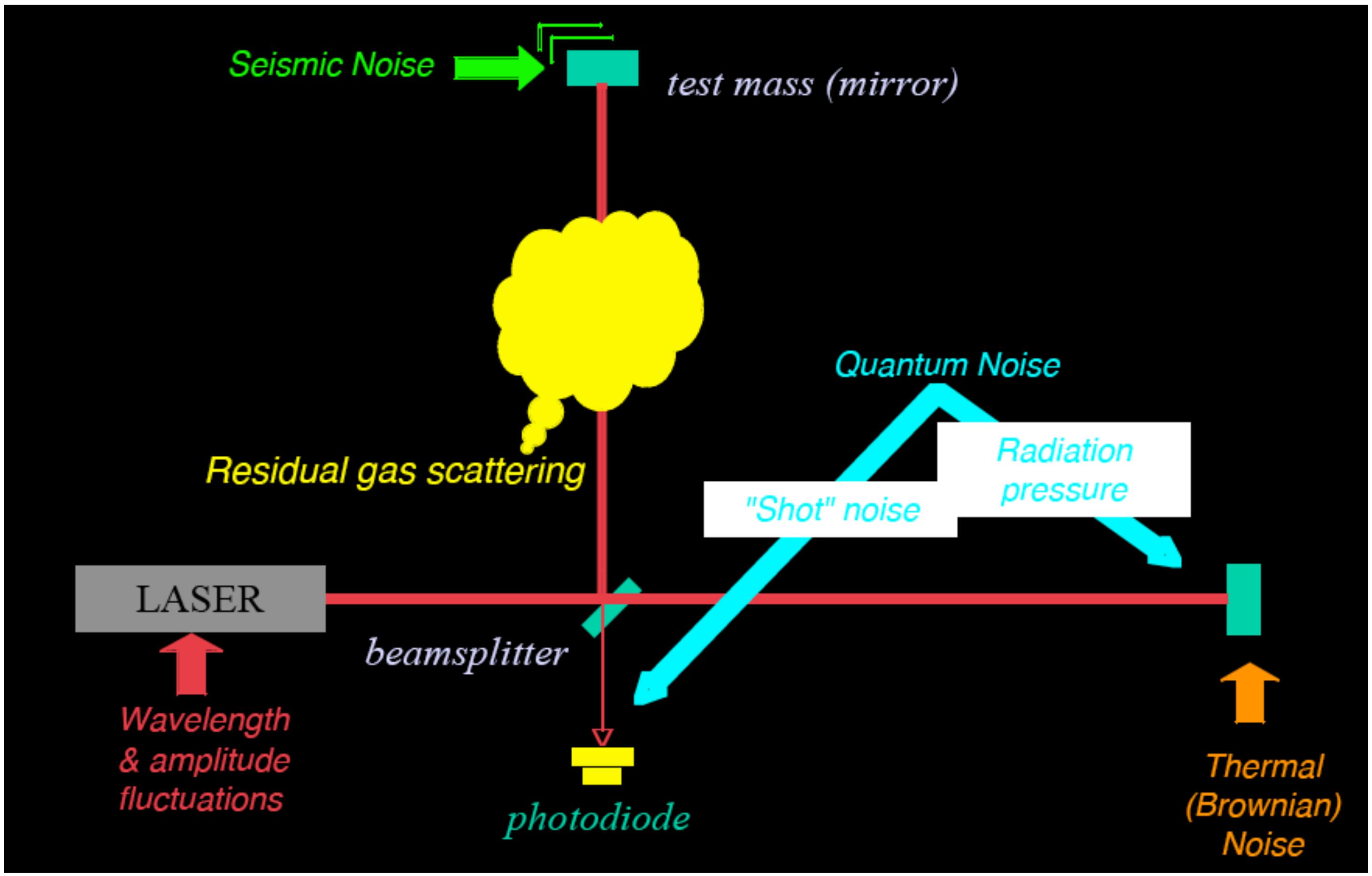
375° → 9.3° → 7.8°
(99% confidence level)

LSC/Virgo, L. Singer, S. Gaebel

Sensitivity of Detectors is Determined by Noise and Background

- The key to improving detectors is sensitivity which improved by reducing noise and background.
- 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 and background cartoon



R. Adhikari

LVC Observing Scenario (arXiv:1304.0670)

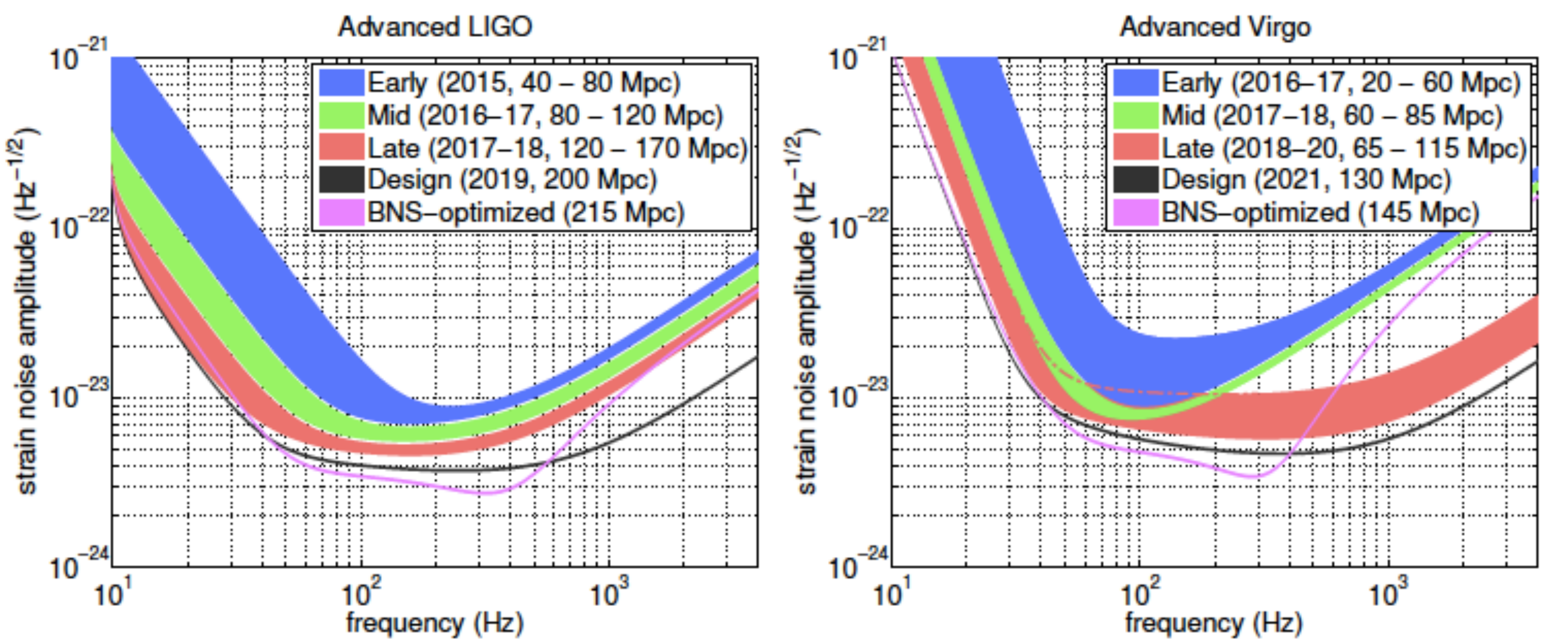
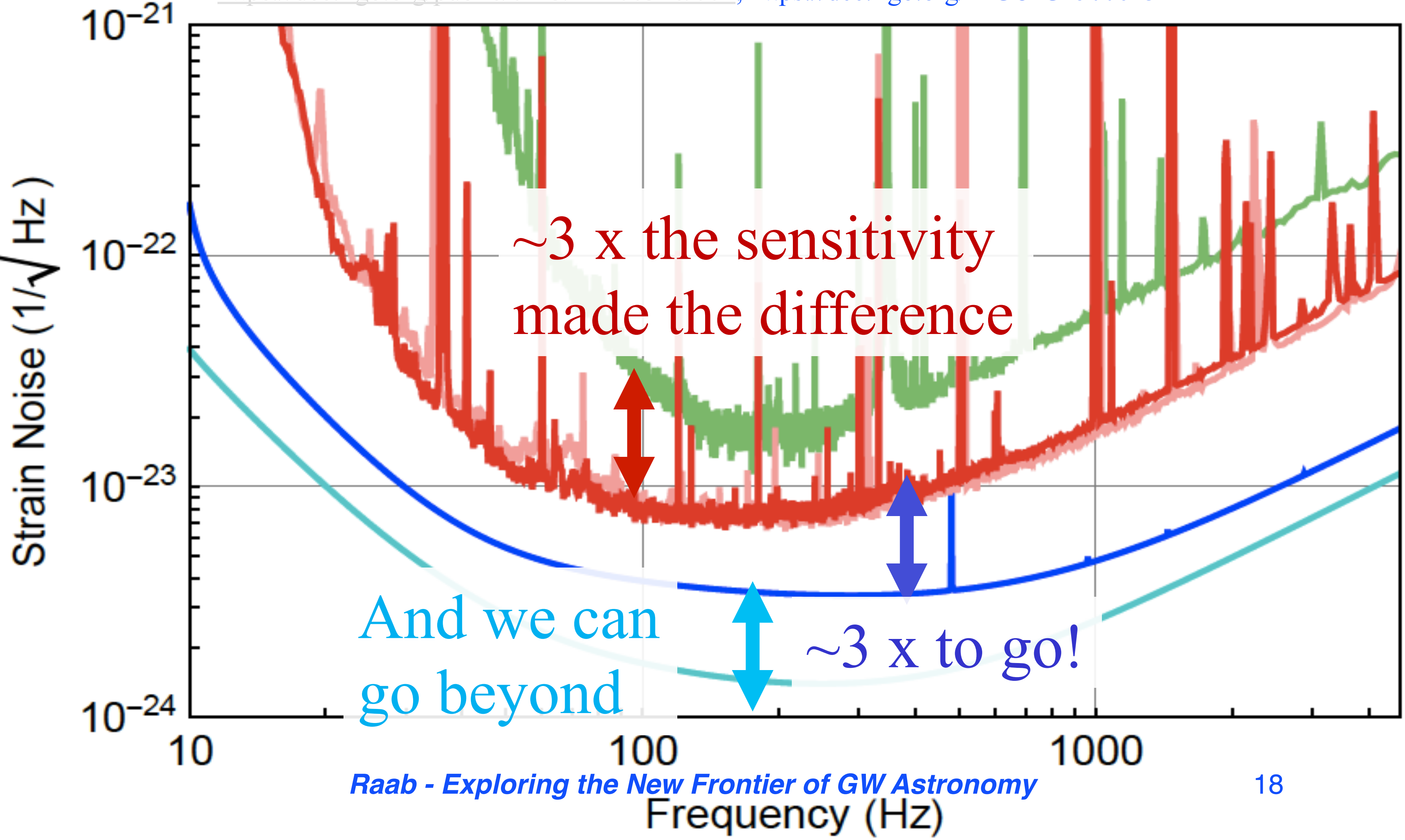


Figure 1: aLIGO (left) and AdV (right) target strain sensitivity as a function of frequency. The average distance to which binary neutron star (BNS) signals could be seen is given in Mpc. Current notions of the progression of sensitivity are given for early, middle, and late commissioning phases, as 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.

Initial S6 / Advanced O1 Design / A+ Upgrade

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



Science drives Requirements

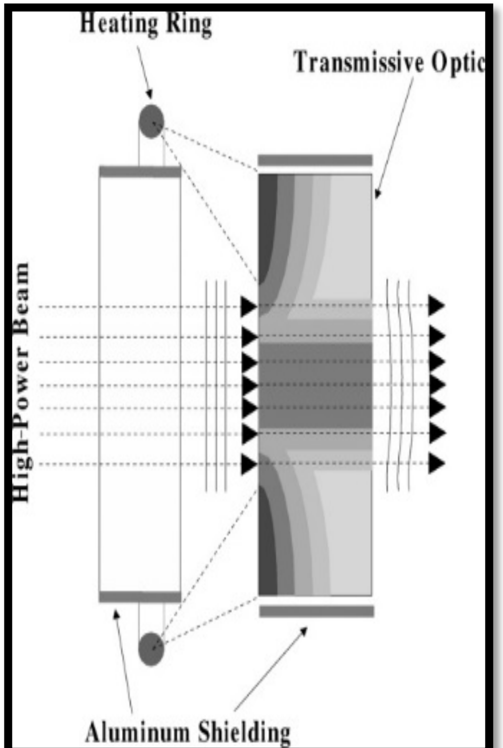
- **Stellar Evolution at High Red-Shift: Black Holes from the first stars (Population III)**
  - » Reach $z > \sim 10$
  - » At least moderate GW luminosity distance precision
- **Independent Cosmology and the Dark Energy Equation of State**
  - » Needs precision GW luminosity distance and localization 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

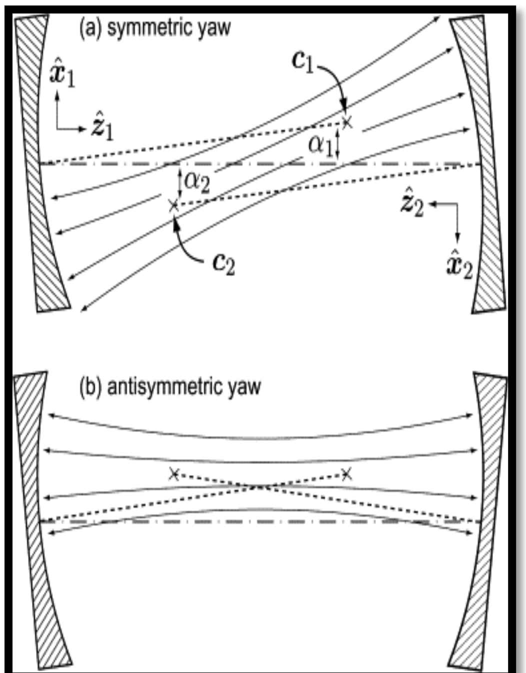
Nothing Is Easy: Classical Challenges to High-Power Operation

Thermal lensing and compensation



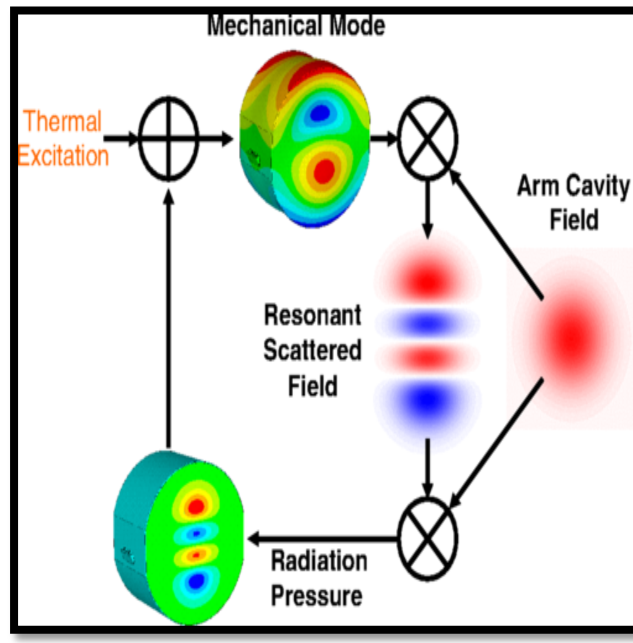
R Lawrence *et al* (2004) Opt Lett **29**(22)2635-2637

Angular radiation pressure instabilities



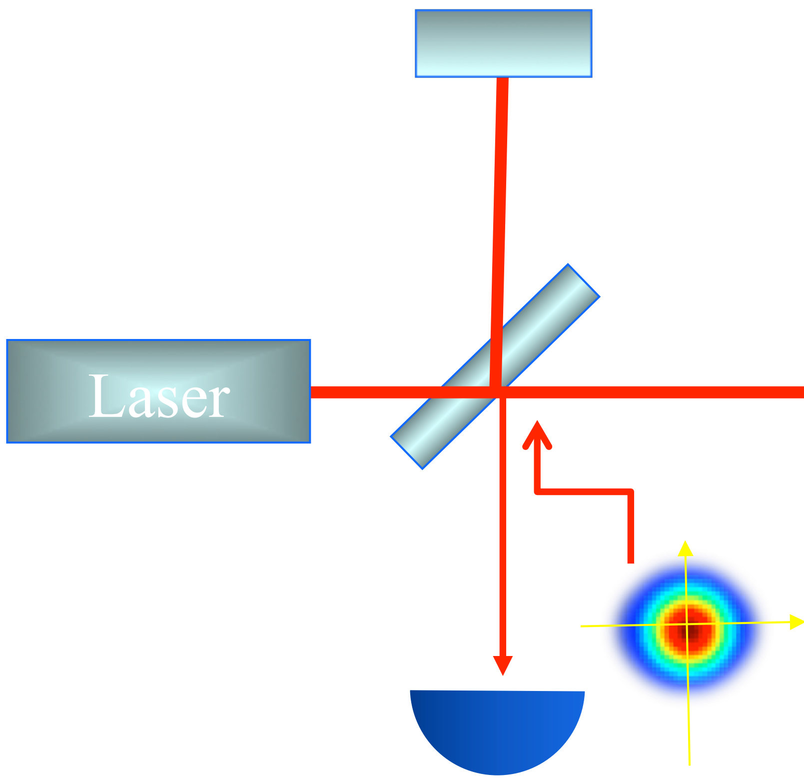
J Sidles, D Sigg, Phys. Lett. A. 354, 167-172 (2006)

Parametric instabilities



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

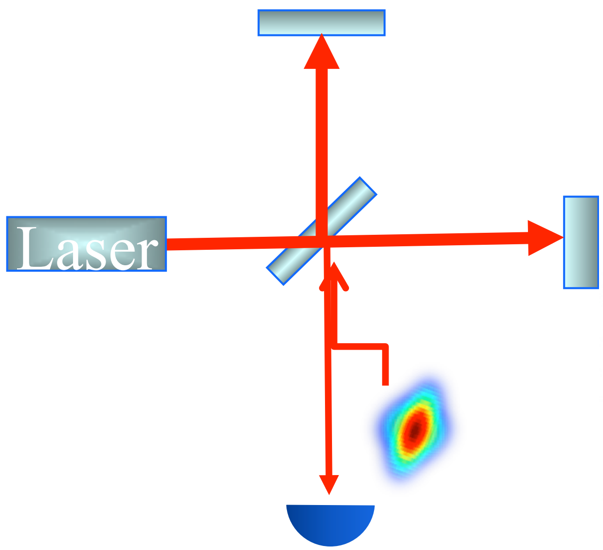
Quantum Noise is Fundamental, Caused by Vacuum Fluctuations



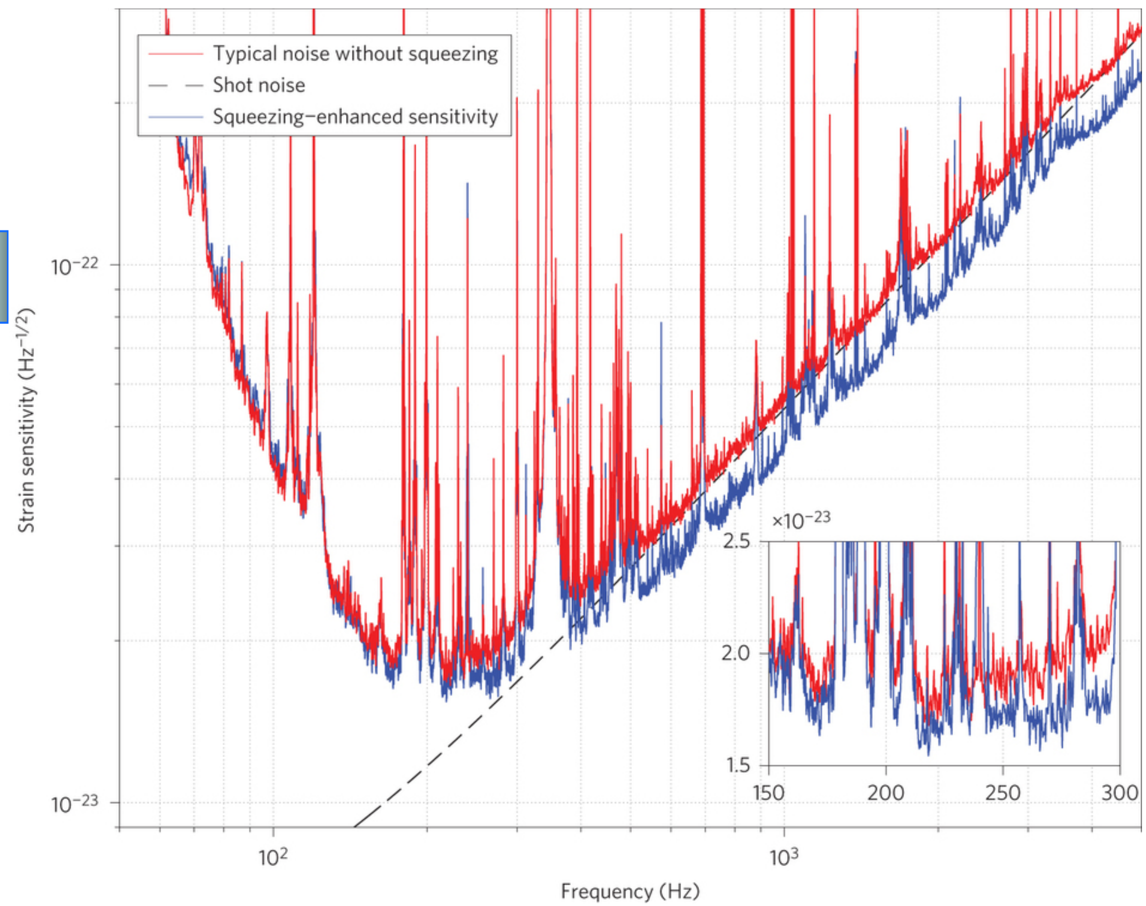
EM Vacuum Fluctuations
Cause Shot Noise and
Radiation Pressure Noise

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

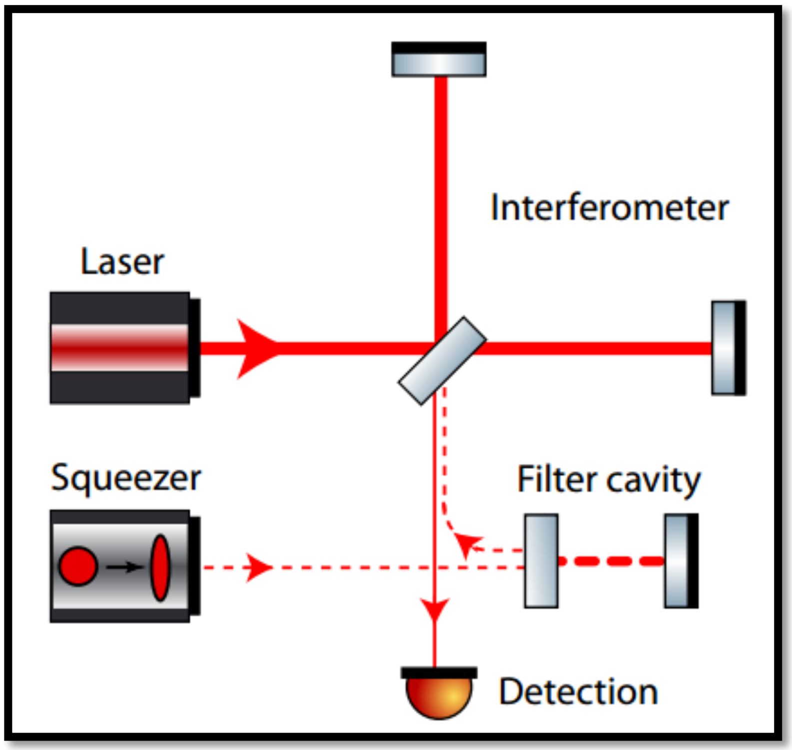
Vacuum squeezing: a partial work-around



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

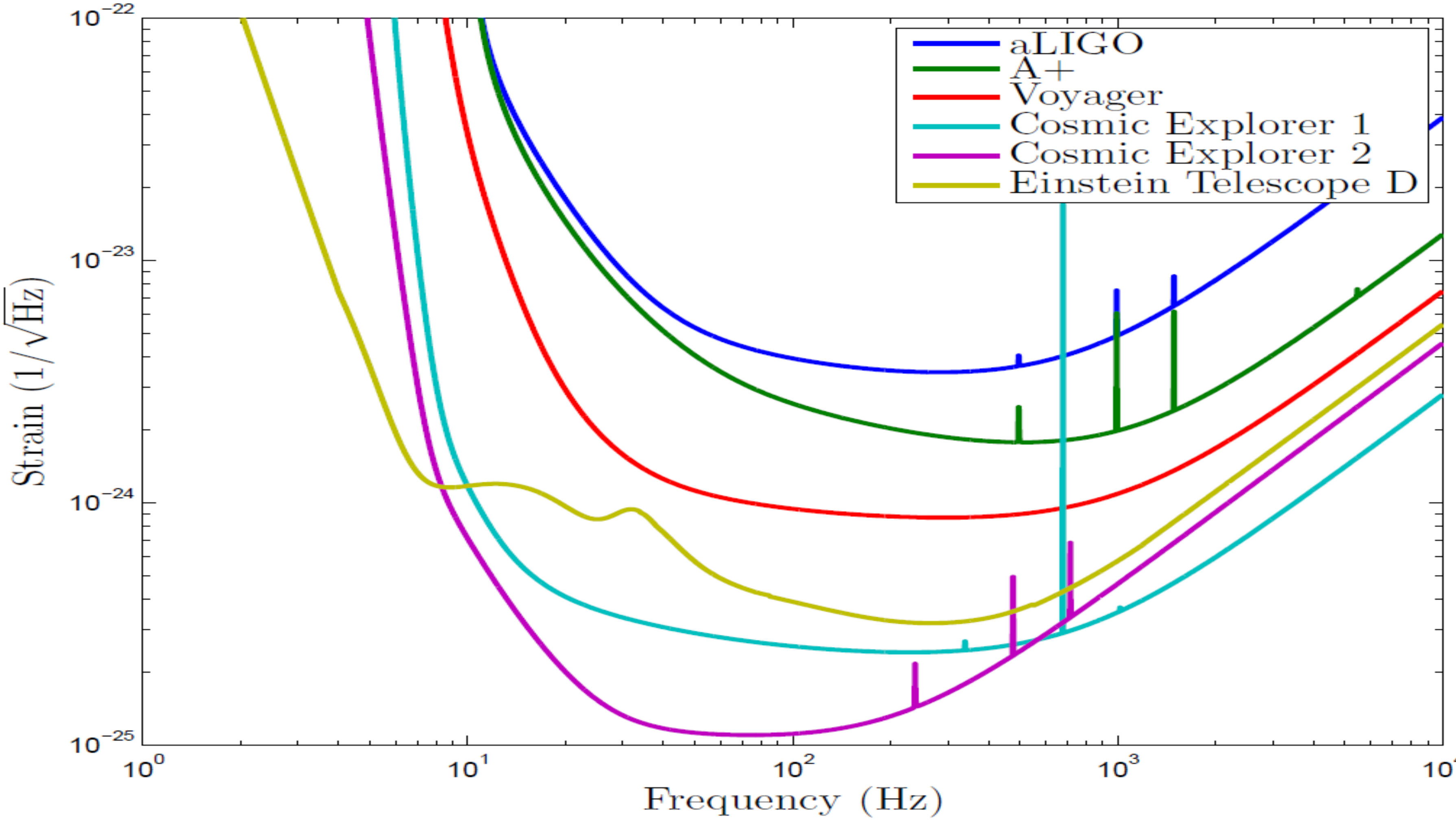
Advanced LIGO upgrade path

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

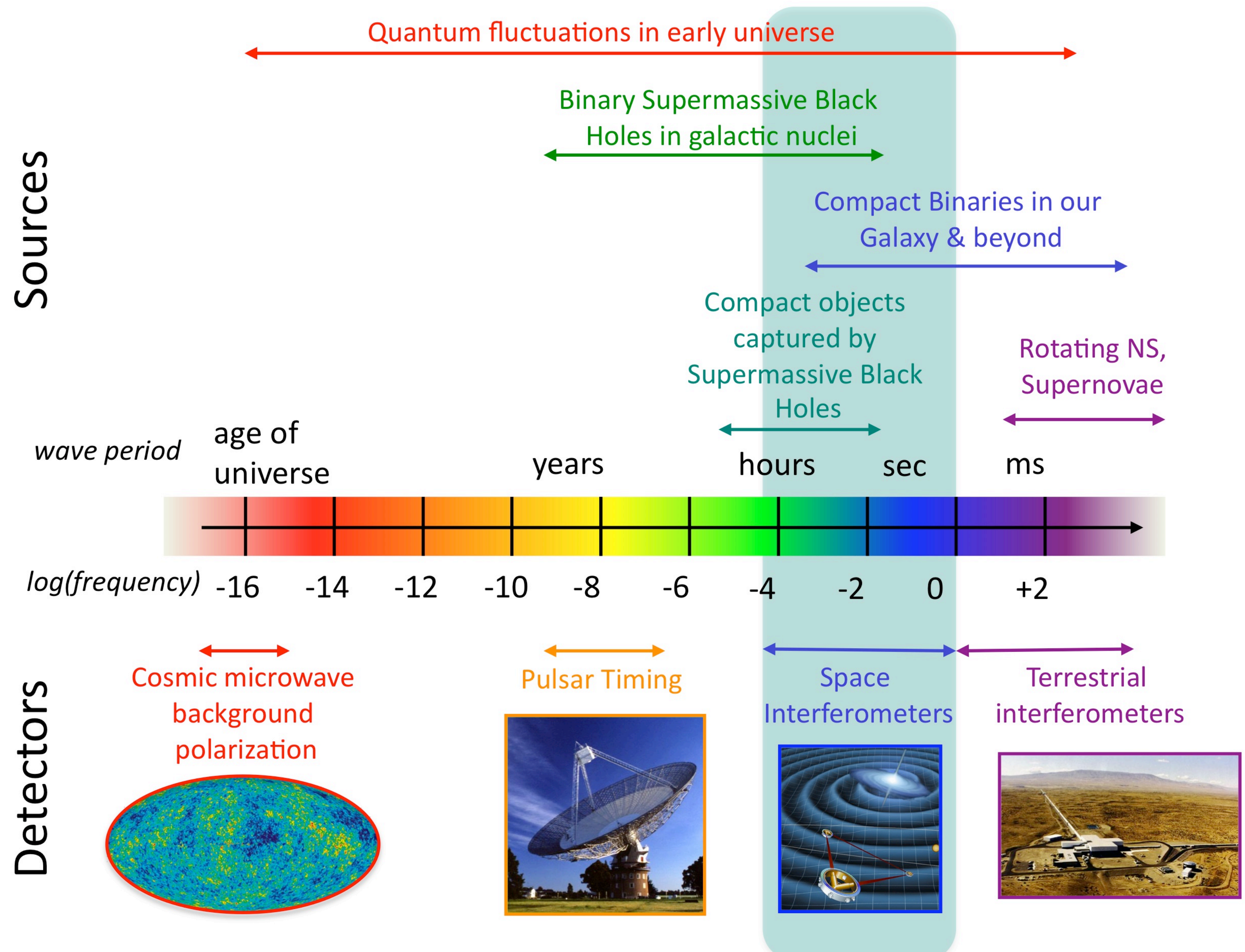
- Squeezed vacuum to reduce quantum noise
- Options for thermal noise:
  - » Better coatings
  - » Cryogenic operation
  - » Longer arms (new facility)

Upgrade possibilities

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



The Gravitational Wave Spectrum



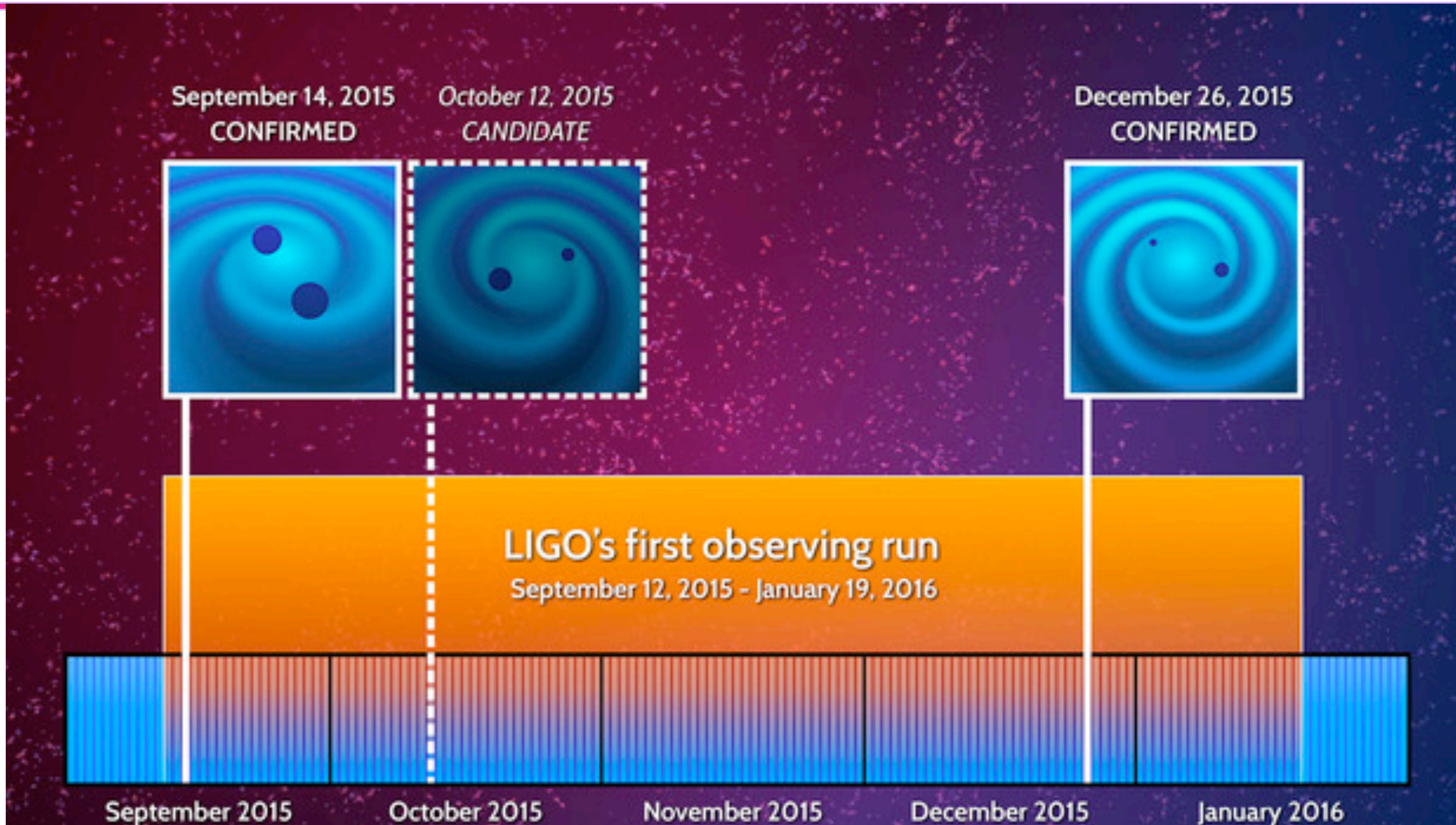
Credit: NASA

Summary

- 1st observing run of LIGO's 2nd-generation detectors have initiated Gravitational-Wave Astronomy, opening a vast 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.

Extra slides

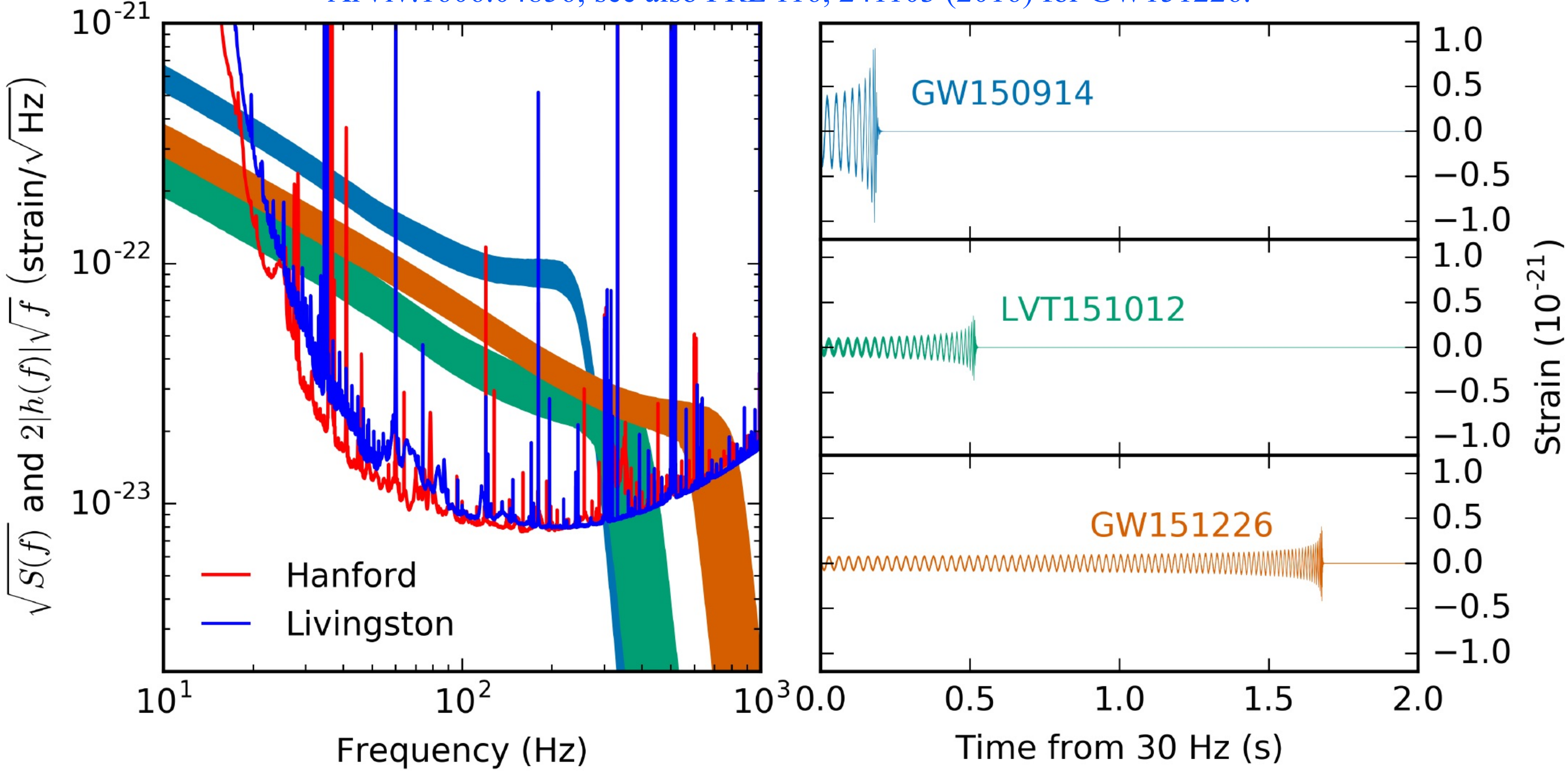
Discovery Timeline – Advanced LIGO's 1st Observations



Courtesy Caltech/MIT/LIGO Laboratory

Advanced LIGO's First Observations

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



Principal noise terms