



## Exploring the New Frontier of Gravitational-Wave Astronomy

Fred Raab, for the LIGO Scientific Collaboration and the Virgo Collaboration 9 Jan 2017

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Two Black Holes 1.3 Billion Years Ago (Give or Take)

Black Hole #1 36X more massive than the Sun 210 km in diameter

Black Hole #2 29X more massive than the Sun 170 km in diameter

> Raab - Exploring the New Frontier of GW Astronomy Andy Bohn, François Hébert, and William Throwe, SXS



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





## LIGO

### Then on 14 September 2015 at the LIGO sites ...









#### Basic idea is simple



# Gravitational waves: hard to ((())) (RG) find because space-time is stiff!



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

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

#### ⇒ Wave can carry huge energy with miniscule amplitude!

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#### Expected strength

#### Sense of scale: strain from a binary neutron star pair

- » M = 1.4 M☉,
- » *r* = 10<sup>23</sup> m (15 Mpc, Virgo),
- » R = 20 km
- »  $f_{orb} = 400 \text{ Hz}$

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



B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)



# **LIGO's** 1<sup>st</sup> Observations





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#### Advanced LIGO's First Observations





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11

### **LIGO** Known Stellar-Mass Black Holes – June 2016







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#### 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?

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- 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!

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#### Astrophysical Sources of Gravitational Waves





Credit: AEI, CCT, LSU



NASA/WMAP Science Team

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

- Strong emitters, well-modeled,

Cosmic Gravitational-

wave Background

- Residue of the Big

stochastic background

- Long duration,

- (effectively) transient

Bang



Credit: Chandra X-ray Observatory



Asymmetric Core Collapse Supernovae

<u>-</u>Weak emitters, not well-modeled ('bursts'), transient

#### <u>Spinning neutron</u> <u>stars</u>

- (nearly) monotonic waveform

- Long duration

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#### time **Ringdowns Broadband Background** frequency Bursts **CW** (quasi-periodic) .... Chirps **Earth's rotation** Earth's orbit requency equenc $\frac{\delta f}{f} \approx 2.6 \times 10^{-4}$ 8.4×10<sup>6</sup> 8.6×10 $\approx 4 \times 10^{-6}$ 1×10<sup>7</sup> 5×10 2.5×10<sup>7</sup> time time



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17





The rate of future discovery in gravitationalwave astronomy will be determined by the number and sensitivity of gravitational-wave detectors and the number and skill of GW experimentalists.

## **LIGO** 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)

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#### 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

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







Fairhurst 2011

LIGO+Virgo only

With LIGO-India



### Improved Localization: LIGO→Virgo→LIGO-India





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24



Sensitivity of Detectors is Determined by Noise and Background



- The key to improving detectors is sensitivity which is 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).



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## Noise and background cartoon













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







#### 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

# LIGO 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

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• A single example: working around the classical and quantum nature of light



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



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#### Quantum Noise is Fundamental, Caused by Vacuum Fluctuations







## Vacuum squeezing: a partial work-around





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33



#### A better work-around: frequencydependent 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

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aboration



#### 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





#### The Gravitational Wave Spectrum



Credit: NASA





#### Summary

- 1<sup>st</sup> observing run of LIGO's 2<sup>nd</sup>-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

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#### Principal noise terms



40