LIGO: the Dawn of Gravitational Wave Astronomy

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Albert Einstein was a smart guy
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Why?
(partially) because of...
General Relativity: gravity is curved spacetime

“Mass tells spacetime how to curve, spacetime tells mass how to move.”
- J. Wheeler

\[ G_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu} \]

Curvature of spacetime = ~10^{-43}

Mass-energy content
GR predicts *gravitational waves*: ripples in spacetime
GW produced by accelerating asymmetric mass distributions

1993 Nobel Prize in Physics: pulsar in binary system

Russell Hulse and Joseph Taylor
(decay measurement with J. Weisberg)
Weber built the first ever gravitational wave detectors in the 1960s.

**resonant mass detector**

Designed to ring like a bell when struck by a gravitational wave.

He thought he detected something (but probably didn’t).
In 1970s a new detection paradigm was conceived

Rainer Weiss
(MIT)

Kipp Thorne, Ronald Drever, Rochus Voigt (Caltech)
Examine effect GW have on spacetime

Gravitational waves cause a peculiar motion of spacetime as they pass:

**differential strain**

\[ h = \frac{\Delta L}{L} \]

\(x\) stretches while \(y\) contracts, and vice versa.

Test masses placed on the ring will move with the spacetime.
Use **light** to measure the strain:
Michelson interferometer
Michelson interferometer gives direct measure of strain

If the Michelson end mirrors rest on ring they *directly measure* the strain of the passing gravitational wave.
Prototype interferometric detectors were built

MIT 1.5m prototype

Caltech 40m prototype
After much research, simple Michelson concept...
...evolved into something much more sensitive
Laser Interferometer Gravitational-wave Observatory

Hanford, WA (LHO)  Livingston, LA (LLO)
Laser Interferometer Gravitational-wave Observatory

NSF funded, jointly run by Caltech and MIT

Two identical facilities operated as astrophysical observatories for gravitational waves.

International scientific collaboration
60 institutions
1000 individuals

S = 3002 km
S/c = 10 ms
Very large ultra-high vacuum enclosure
Seven stages of active seismic isolation
Seismic isolation platform
Large test masses and monolithic suspensions

- Vertical Isolation: 3 Stages of Maraging Steel Blade Springs
- Fused Silica Penultimate Mass [40 kg]
- Ring Heater
- Fused Silica Input Test Mass (ITM) [40 kg]
- Compensation Plate (CP)
- Electrostatic Actuator
- Metal “Catcher” Structure
- Steel suspension wires leading to upper metal suspension stages
- Silica fibers between the ears
- Welds
- Ear
Large test masses and monolithic suspensions
High power pre-stabilized laser source
Readout optics and electronics
End test mass chamber assembly
LIGO employs a hierarchical control structure for the full detector.

Feedback loops control all degrees of freedom (DOF) at the microscopic level with a custom built, modular, distributed, real-time digital control system (RTS) (using off the shelf PCs and a small linux kernel patch).
Fully digital controls

Hundreds of feedback loops:

**suspensions** active damping of 3-24 DOF per suspension ($\times 18$)

**seismic isolation** active damping and isolation of 18 DOF per seismic platform ($\times 9$)

**global control** 5 length and 10 angular global DOF
Supervisory control (automation) handled by a hierarchical, modular, distributed, state machine platform called Guardian.
LIGO measurement as a function of frequency

LIGO Strain Amplitude Spectral Density

- iLIGO “S6” measured (~20Mpc)
- aLIGO “O1” measured (~70Mpc)
- aLIGO design (~200 Mpc)
- seismic noise
- thermal noise
- quantum noise
Performance: displacement sensitivity

LIGO Strain Amplitude Spectral Density

- Displacement sensitivity: $\sim 3 \times 10^{-20}$ meters/$\sqrt{\text{Hz}}$

![Graph showing LIGO Strain Amplitude Spectral Density with a peak at $\sim 3 \times 10^{-20}$ meters/$\sqrt{\text{Hz}}$.](image-url)
How small *is* that?!
Ultimately limited by fundamental noise sources

LIGO Strain Amplitude Spectral Density

- Seismic noise
- Quantum radiation pressure noise
- Thermal noise
- Quantum shot noise
What does it sound like? Noise!

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Strain [1/√Hz]

Displacement [m/√Hz]

Frequency [Hz]
Meanwhile...

1.3 billion years ago,

in a galaxy far, far away...
A pair of orbiting black holes inspiral and merge...
...and emit a lot of gravitational waves
Back on Earth, September 14, 2015...
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of $1.0 \times 10^{-21}$. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole.

https://papers.ligo.org/
GW150914 - Observed strain

Hanford, Washington (H1)  Livingston, Louisiana (L1)

H1 observed  L1 observed  H1 observed (shifted, inverted)

Numerical relativity  Reconstructed (wavelet)  Reconstructed (template)

Hanford, Washington (H1)  Livingston, Louisiana (L1)

Resolved

Time (s)

Frequency (Hz)

Normalized amplitude

0.30 0.35 0.40 0.45

0
2
4
6
8

0.30 0.35 0.40 0.45

0
2
4
6
8
And then again on Christmas Day 2015

replay of collision
All events from the first observing run (O1)
GW150914 by the numbers

collision was 1.3 billion light years away

1/10th distance to edge of observable Universe

\[ BH_1 + BH_2 \Rightarrow BH_f \]

\[ 36.2 \, M_\odot + 29.1 \, M_\odot \Rightarrow 62.3 \, M_\odot \] ???

3 suns worth of energy released as gravitational waves

peak luminosity: \( 3.6 \times 10^{56} \) ergs/s

solar luminosity: \( 3.8 \times 10^{33} \) ergs/s

universe luminosity: \( \sim 10^{55} \) ergs/s

30\( \times \) brighter than the entire Universe
All known black holes
Where in the sky did they come from it?
Where in the sky did they come from it?

Why do we care?
This is what a binary black hole merger actually *looks* like
But a binary neutron star merger...
Or a core-collapse supernova...
World-wide network needed for better sky localization
The future of LIGO

LIGO currently down for improvements, prepping for late 2016 observing run start (hoping for $\sim 20\%$ sensitivity improvement).

At design sensitivity:

expect multiple events per week

More big discoveries soon?

- binary neutron star collisions?
- electromagnetic counterparts?
- ???
Future of gravitational wave detection

New and improved detectors needed

- **quantum noise**
  - more laser power
  - *squeezed* vacuum

- **thermal noise**
  - better mirror coatings
  - cryogenics

- **seismic noise**
  - longer suspensions, more stages
  - seismic feed-forward cancellation

- **everything else**
  - longer arms

4th generation detectors can potentially have *cosmological* reach
GW should exist across a large spectrum
Thank you