Einstein, Black Holes and the Cosmic Tango

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General Relativity (GR)

- **Gravity**
  - Newton:  Force \( F = G \frac{m_1 m_2}{r^2} \)
  - Einstein: Geometric property of spacetime

- **Einstein’s theory of general relativity (1916)**
  “Spacetime tells matter how to move; matter tells spacetime how to curve.”
  
  John Archibald Wheeler
Predictions of General Relativity

- Orbit of Mercury explained
- Mass bends light
  - Gravitational lensing (confirmed in 1919)
- Existence of black holes
- Existence of gravitational waves
GR Prediction: Black Holes

• Black hole: A region in space so dense that not even light can escape it (a “singularity”)

• Event horizon: the point of no return
  Sun: 3 km  Earth: 9 mm
GR Prediction: Gravitational Waves

• Gravitational waves
  – Created by massive cosmic bodies
    BH/neutron star mergers, explosions...
  – Ripples in spacetime, propagate at speed of light
  – Unimpeded propagation through spacetime
  – Extremely difficult to detect

Need an extremely precise instrument and a bit of luck
Laser Interferometer Gravitational Wave Observatory (LIGO)

- Two locations
  - Hanford, WA and Livingston, LA
- Construction began in 1994
- Upgrades completed 2015
- Total Cost: $620 million
  - Largest project ever by NSF
  - Thank you, taxpayers!
- Collaboration: 900 scientists
- Accuracy: 1 part in $10^{21}$
  - Breadth of a human hair over 1 light year
- Most accurate instrument ever built!
LIGO Interferometer
LIGO: Why Two?

1. Cross-check the ambient noise

2. Localization of the source
   – Similar to stereo sound
   – For full triangulation, need 3

• 3 other instruments around the world will help
  – Advanced Virgo (Italy)
  – KAGRA (Japan)
  – LIGO India (in planning stages)
The Event: GW150914

• Lucky!
  – New, more sensitive runs began on Sept. 12, 2015
  – Event recorded on Sept. 14, 2015 (only 2 days later!)
  – Other facilities not observing or being upgraded

• Merger of two black holes (BH)
  – 1.3 billion light years away
  – Right before they merged:
    • Separated by 210 km (130 miles)
    • Last 0.2 seconds: sped up from 35 Hz to 150 Hz
  – \(36 \, M_\odot \, BH + 29 \, M_\odot \, BH = 62 \, M_\odot \, BH + 3 \, M_\odot \, GW\)
    \(M_\odot =\) Mass of the Sun

• Powerful! \((3.6 \times 10^{49} \, W)\)
  More power than the rest of the observable universe
The Great Cosmic Song

- If these gravitational waves were sound waves, here is what they would sound like
Next

Laser Interferometer Space Antenna (LISA)
Why Should You Care?

1. Basic Science: Pursuit of the Truth

2. Technology Transfer
   Optics, laser systems, material science, geodesy, geology, computing, ...

3. Unforeseen Future Benefits
Backup Slides
LIGO Results: The Event
LIGO Results: The Event Recorded

Hanford, Washington (H1)

Livingston, Louisiana (L1)

Strain ($10^{-21}$)

Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)

Residual

Frequency (Hz)

Normalized amplitude

Time (s)
LIGO Results: Layout
The Event

Binary Black Hole Evolution:
Caltech/Cornell Computer Simulation

Top: 3D view of Black Holes and Orbital Trajectory

Middle: Spacetime curvature:
Depth: Curvature of space
Colors: Rate of flow of time
Arrows: Velocity of flow of space

Bottom: Waveform
(red line shows current time)
The Life Cycle of a Star
Indirect Evidence for GW

- Binary neutron stars (pulsars): PSR B1913+16
- Cosmic “slow dance” timidly getting closer
  
  *Merge in 300 million years*

- Orbital time decreasing
  → pulsars getting closer
  → losing gravit. energy
  → radiation through GW

- Important evidence for GW, but indirect
The Main Sequence Stars
General Relativity (GR)

• Gravity
  – Newton: Force \( F = Gm_1 m_2 / r^2 \)
  – Einstein: Geometric property of spacetime
    \[
    R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8 \pi G}{c^4} T_{\mu\nu}
    \]

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