Outline

- Introduction
  - What is LISA?
  - Gravitational waves
    - Characteristics
    - Detection (LISA design)

- Sources
  - Stochastic
  - Monochromatic
  - Chirping
What is LISA?

- Laser Interferometer Space Antenna (LISA)
  - Planned space-based gravitational wave detector
    - Why in space?
      - Dramatically reduced environmental noise compared to terrestrial detectors (i.e. LIGO, VIRGO, GEO600, TAMA3000)
      - Longer leg length (5,000,000 km vs. 4 km)
      - Better strain sensitivity
      - Sensitive at lower frequencies (0.05 mHz – 0.1 Hz)
      - New sources!
    - Complications
      - Solar winds
      - Radiation pressure
Gravitational Waves

- Plane wave solution in weak field limit
  - GR is extremely nonlinear near source
  - Far from source, we use a perturbation
    \[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \]
    - Solution to wave equation
      \[ h_{\mu\nu} = C_{\mu\nu} e^{ik_\sigma x^\sigma} \]
  - with
    \[ C_{\mu\nu} = \begin{pmatrix}
      0 & 0 & 0 & 0 \\
      0 & h_+ & h_\times & 0 \\
      0 & h_\times & -h_+ & 0 \\
      0 & 0 & 0 & 0
    \end{pmatrix} \]
    \[ k_\sigma = \{\omega, 0, 0, \omega\} \]
GW Characteristics

- Tends to “stretch” a distribution of matter in orthogonal directions, in an oscillating fashion

\[ h_{\mu\nu} \]
Polarizations

- Polarized
- Elliptically polarized
Three separate spacecraft with 2 incoming beams and 2 outgoing beams each. Define two independent Michelson interferometers (for redundancy).
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Sources

- Four classifications:
  - Stochastic
    - Backgrounds
  - Monochromatic
    - Galactic binaries
  - Chirping
    - Massive black hole binaries
    - EMRIs
Stochastic Sources
Inflationary Waves

- Arose from quantum fluctuations in early universe
- Amplified by cosmic inflation
Inflationary Waves

- Random, essentially “white” over wide range
  \[ 10^{-16} \text{ Hz} < f < 10^{10} \text{ Hz} \]

- Very interesting
  - Wave amplitudes determined by potential driving inflation
    - Direct probe of inflationary physics!

- TOUGH to detect
  - Drowned out by foreground sources
  - Current estimates suggest amplitudes \( \sim \) 4-5 orders of magnitude lower than LISA sensitivity.

- Side note:
  - GWs have a distinct effect on CMB photons, may be detected indirectly using this method
Phase Changes

- Additional backgrounds known to have been produced during universal phase changes
Example:

- At $T_{universe} = 10^{15} K$ electroweak force separates into electromagnetic and weak nuclear forces
- Not spatially homogenous
- Background!

Estimated that waves borne at this time will have frequencies $f \approx 10^{-2} Hz$, right in LISA band
- Good chance of detection
Monochromatic Sources

- Compact galactic binaries
  - Trillions of binary systems in our galaxy
  - Tens of millions compact (enough)
    - Radiate GWs in LISA band
  - GUARANTEED source

- Not truly monochromatic, but slllooooww

\[
\dot{f} = \frac{48}{5\pi} \mu M^{2/3} (2\pi f)^{11/3}
\]

\[
M_A = M_B = M_\odot \quad \rightarrow \quad \dot{f} = 9.2 \times 10^{-18} \text{Hz/sec}
\]
Monochromatic sources

- Over-guaranteed?
Chirping Sources
Chirping Sources

- Massive black hole binaries

\[ \dot{f} = \frac{48}{5\pi} \mu M^{2/3} (2\pi f)^{11/3} \]

- For appreciable frequency increase ('chirp'), need high mass

- For a system with

\[ M_{\text{system}} = 10^4 M_\odot - 10^7 M_\odot \]

\[ \frac{M_A}{M_B} = \frac{1}{20} \]

- GWs produced start in LISA band and sweep out in a period of between a few months and a few years
Chirping Sources

- Monte Carlo simulation showing mass and spin measurement errors for a set of 10,000 binaries randomly distributed on the sky.
  - Solid line: $m_1 = 10^6 M_\odot$
  - Dashed line: $m_2 = 3 \times 10^5 M_\odot$
Chirping Sources

Massive black hole binaries believed to be a side effect of galaxy merger. Depending on conditions, expectations are between a few and a few hundred events over LISA’s lifetime.
“Even a pessimist who assumes a rather long quasi-stellar object lifetime and only one binary coalescence per newly-formed halo should expect a couple of supermassive black hole binary coalescences during the lifetime of LISA while an optimist might expect to see up to several hundred of these exciting events.”

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Chirping Sources

- **Extreme Mass Ratio Inspirals (EMRI)**
  - **Formation:**
    - Compact object (~stellar mass) scattered onto highly eccentric orbit about supermassive galactic black hole
  - **Waveform:**
    - Strong-field effects
    - Complicated chirps
  - **Event Rates**
    - Estimates predict 1,000+ events over LISA’s lifetime
Chirping Sources

- **EMRI**
  - Infalling object executes 10,000 – 100,000 orbits before coalescence
  - Three periods (converge in Newtonian limit)
    - $T_\phi$ (axial)
    - $T_\theta$ (poloidal)
    - $T_r$ (radial)
  - Unique GW signature
    - Provides unprecedented description of spacetime near SMBH
    - IF orbit can be tracked throughout infall (difficult)
LISA will embody an unprecedented tool for the study of important and exotic processes of the universe. Together with the family of terrestrial detectors, such as LIGO, it represents an entirely new probe of the sky.
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References
- S. Carroll, *Spacetime and Geometry*

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