Gravity has a story to tell: LISA and the search for low frequency gravitational waves

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Storyline

- Probing the Gravitational Wave Spectrum
- The LISA Mission

- Short Astrophysics Vignettes
  - Extreme mass ratio inspirals
  - Galactic Binary Stars

- The Future
The Cosmos as we know it

- **Light** has been our messenger from the Universe
Photon eyes

- A myriad of instruments exist to detect photons, but photons are limited by the fact that they interact readily with matter.
Don’t look with light, look with **gravity**.

Detect ripples in the fabric of spacetime generated by the **dynamic motion** of matter and energy in the Cosmos.

Gravitational waves travel unimpeded from source to observer.
Gravitational wave Spectrum

Extremely Low Frequency: $10^{-16}$ Hz

Very Low Frequency: $10^{-8}$ Hz

Low Frequency: 1 Hz

High Frequency: $10^{+8}$ Hz

CMB Polarization

Pulsar Timing

Space

Ground
Gravitational wave Spectrum

- **Extremely Low Frequency**
  - $10^{-16}$ Hz

- **Very Low Frequency**
  - $10^{-8}$ Hz

- **Low Frequency**
  - 1 Hz

- **High Frequency**
  - $10^{+8}$ Hz

**Big Bang waves; inflationary epoch**

**Early Universe exotic physics**
- phase transitions, cosmic strings, domain walls...

**Massive BH**
- ~300 to 30 million solar masses
- Binary stars
- Galactic structure

**“Small” BH**
- ~2 to 100 solar masses
- Neutron stars
- Supernovae

**Singularities? Exotic stars?**

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Pulsar timing search for G-waves rules out supermassive black hole binary in quasar 3C66b

LIGO limits on Crab pulsar
Abbott et al. (ApJL 683, 2005)

LIGO limits on Cosmic GW Background

LIGO limits on 78 Radio Pulsars
Abbott et al. (PRD 76, 2007)

Singularities? Exotic stars?

? ? ?
Joint NASA/ESA mission, expected to launch in the mid-2010s

- Baseline 5 million kilometer armlength
- Sensitive to waves in the low frequency band, between $\sim 10^{-5}$ Hz and 1 Hz
LISA Orbit

- LISA is in an Earth-trailing or Earth-leading orbit, 20° away from the Earth, inclined to the ecliptic by 60°
- The constellation motion modulates signals, giving pointing capability
LISA Discovery Space

http://www.srl.caltech.edu/~shane/sensitivity/

Larson, Hiscock & Hellings (2000)
LISA Discovery Space

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Larson, Hiscock & Hellings (2000)
**Extreme Mass Ratio Inspirals**

- **EMRIs**: little stars & big black holes, \((m^*/m\bullet) \sim 10^{-5} \text{ to } 10^{-8}\)

- **CAPTURE CONTENT**: what are the constituents of nuclear star clusters? What is the growth history of galactic black holes?

- **HOLIODESEY**: the mapping of black hole spacetimes
Zoom whirl orbits

Gair, Kennefick & Larson (PRD, 2005)
Zoom whirl orbits
Why do the orbits whirl?

- The extreme whirling behaviour is perihelion precession gone wild
- Happens when particle probes effective potential near the inner peak, near the black hole!
Songs of the black holes

- The waveforms encode information about the black hole system, which I can demonstrate by converting into sound.
- Consider black hole + black hole with $\sim 10^{-5}$ mass ratio
  - **Sound 1**: Non-spinning big black hole, circular orbits
  - **Sound 2**: Spinning big black hole, circular orbits
  - **Sound 3**: Spinning big black hole, eccentric orbits

Sounds by Scott Hughes, MIT
The Close Binaries

- There are so many binaries, their signals overlap, and it is difficult to tell them apart.

- This is called the "confusion limit", and is analogous to a party.

- You can hear people nearby.

- You can hear loud people.

- All else is a dull noise.
- There are 30 million close galactic binaries in the Milky Way. As probes of the galaxy, they can all be seen by LISA.
- These binaries encode the physical structure of the Milky Way...
Songs of the Binaries

- LISA’s motion also complicates the received signals
- LISA is omnidirectional, so it points everywhere!
- Motion of LISA modulates signals!
LISA's motion also complicates the received signals. LISA is omnidirectional, so it points everywhere! Motion of LISA modulates signals! 

Monochromatic lat = $\frac{\pi}{4}$

long = $\frac{\pi}{16}$

lat = $\frac{\pi}{16}$

long = $\frac{\pi}{2}$

**Songs of the Binaries**

[Diagram of celestial bodies and connections, showing 60° angle]
LISA's motion also complicates the received signals. LISA is omnidirectional, so it points everywhere! Motion of LISA modulates signals!

Monochromatic lat = $\pi/4$

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Songs of the Binaries
LISA's motion also complicates the received signals. LISA is omnidirectional, so it points everywhere! Motion of LISA modulates signals!

\[ \text{Monochromatic lat} = \frac{\pi}{4} \]
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\[ \text{long} = \frac{\pi}{2} \]

_Songs of the Binaries_
The Low Frequency Galaxy

- ~10,000 binaries will be separable from the confusion
- You can still recover the structure of the galaxy!

Larson, Benacquista & Taylor (in prep)
The Future of Gravitational Wave Astronomy

- **LIGO**
  - Currently upgrading to **Enhanced LIGO**, with science runs beginning next year, expanding reach in volume by 8x
  - Upgrades to **Advanced LIGO** have been funded, and slated for operation in 2014, expanding reach in volume by 1000x

- **LISA**
  - 2007 National Academy BEPAC Report gave LISA it’s highest scientific ranking: “**LISA, in the committee’s view, should be the flagship mission of a long-term program addressing Beyond Einstein goals.**”
  - Decadal Survey in Astronomy & Astrophysics is beginning
  - **LISA Pathfinder** in 2011
LISA Pathfinder

- The LISA Technology Development Mission
- Launch in late 2011
- Core instrument is the LISA Technology Package
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LISA Pathfinder

- LTP is the basic LISA sensing instruments on the scale of 35cm, not 5 million km!
- Coupled to the Disturbance Reduction System
- Micro-Newton thrusters control the spacecraft position to a millionth of a millimeter
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The Future of Gravitational Wave Astronomy

- Gravitational wave astronomy, like most of modern astronomy, is highly **interdisciplinary**. There are several main thrusts:

  - **Technology**
  - **Science Analysis**
  - **Astrophysics & Gravitational Science**
Summary

- The Gravitational Wave Enterprise is progressing rapidly, with LISA as a major component.
- LISA will be a new tool for probing the Cosmos that complements other astronomical tools and enhances our science capabilities.
- Because of the nature of the enterprise, broadly trained people able to communicate across discipline boundaries are highly valued.

- Come visit us at the *American Astronomical Society Meeting* in Long Beach this January (mission booth, posters, evening splinter session, special invited session on gravitational waves).