LISA
Unveiling a Hidden Universe

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(Animation: AEI/Milde Science Comm)
LISA: GW Observatory in Space

- LISA in ESA program since 1995; NASA joined soon after.
- Originally a Fundamental Physics mission, doing astronomy
- Today: an Astronomical Observatory with important work in Fundamental Physics
- Reasons for this change:

1. Astronomy’s focus is moving toward LISA’s capabilities:
   - Massive galactic black holes, key also to galaxy evolution
   - Transient astronomy: major ground-based facilities coming
   - The high-redshift universe: astronomy's next frontier

2. Astrophysics and Fundamental Physics are converging: cosmology

3. Large community of astronomers around LISA have been exploring LISA’s potential for many branches of astronomy.
LISA offers revolutionary science

- Direct proof that massive central objects in galaxies really are BHs
- Measurement of mass, spin of $10^6 \, M_\odot$ BHs at $z = 1$ to ±0.1%
- Observation of universe before re-ionisation: BH mergers at $z > 15$
- Revealing how massive BHs formed and evolved $z = 10-20$
- Tests of BH no-hair theorem, cosmic censorship
- Unaided: Hubble constant at $z = 0.5$ with 0.4% precision or better
- Unaided: dark-energy $w$ to $z = 3$ with 4% precision or better
- Mass function of central black holes of ordinary galaxies to $z = 0.2$
- Study of stellar black hole clusters around central black holes
- Catalogue $> 10^4$ new white-dwarf binary systems in the Galaxy
- Precise masses and distances for $> 100$ white dwarf binaries
- Determine the order of the electroweak phase transition
Why BHs? Co-evolution with galaxies

(De Lucia et al 2006)

(Gulketin et al. 2009)

(Volonteri Haardt & Madau 2003)
Gravitational Waves
LISA: Sensing Spacetime Vibrations

Gravitational Waves are an entirely new way to explore the Universe

- Caused by motions of mass and energy
- Waves penetrate:
  - any matter
  - black holes from the event horizon
  - early universe from singularity
- Waveforms record the motion of distant matter
- Frequencies probed by LISA (~0.1 to 100 mHz) are rich in gravitational activity
Gravitational waves

- **Newton**: tidal forces are the observable action of gravity in free fall.

- **Einstein**: tidal forces of gravity are the curvature of space-time.

- Gravitational waves are ripples in this curvature: tidal forces that move at speed of light.

- They cause changes in the travel time of light between free particles.

Anisotropic compression/expansion  

Bigger is better!  

(Kramer)
Understanding gravitational waves

- Strong analogies with EM radiation
  - Two transverse polarisations
  - Move at speed of light, follow geometrical optics
  - Same behaviour with gravitational lensing, cosmological redshift

- Like light, GW phase and polarisation follows source motions
  - NB: Measuring degree of circular polarisation gives *binary orbit inclination*.
- Signal phase encodes large-scale source dynamics.
But GWs are different …

- Coupling of GWs to matter is very different from EM.
- Very weak, $h << \frac{\phi}{c^2} = \frac{GM}{rc^2}$
  - This leads to $\delta L/L \sim h \sim 10^{-21}$ to $10^{-24}$.
  - $h \sim 1/r$
- Weakness negligible scatter, absorption: perfect messengers!
- Have huge energy flux; luminosity scale is $c^5/G \sim 3.6 \times 10^{59}$ erg/s.

Black hole mergers are more luminous than the rest of the universe put together!

(B Schutz LISA Science 03 February 2011)
Like *listening* to the universe

- GWs have many analogies to sound: waves of spacetime
- **Detectors are our “microphones”**
  - 1D response, not an image. Converts to sound: you can listen to GWs
  - Record the waves coherently, tracking phase and amplitude
  - Nearly omni-directional, but linearly polarised
- **LISA will add the audio dimension to our ability to monitor the dynamical universe.**
LISA Mission and Capabilities
The LISA Mission

B Schutz LISA Science 03 February 2011

(AEI/Milde Science Communications)
Technology of stillness

- LISA Pathfinder will fly the LISA isolation and interferometry systems for the first time.
  - Two proof masses in a single S/C.
  - Will test LISA hardware in a space environment.
  - Proof masses will be the **quietest places in the solar system**.
GW searches across the spectrum

Sources: quantum fluctuations in the very early Universe, binary supermassive black holes in galactic nuclei, phase transitions in the early universe, black holes, compact stars captured by supermassive holes in galactic nuclei, binary stars in the galaxy and beyond, merging binary neutron stars and stellar black holes in distant galaxies; fast pulsars with mountains.

Wave Period:
- CMB pol'n
- Pulsar Timing arrays, SKA
- LISA
- ALIA
- LIGO, GEO, VIRGO, LCGT

Frequency (Hz):
- 10^{-16}
- 10^{-14}
- 10^{-12}
- 10^{-10}
- 10^{-8}
- 10^{-6}
- 10^{-4}
- 10^{-2}
- 1
- 10^2
Ground-based detection

- Current LSC (LIGO, GEO) and VIRGO progress:
  - Initial LIGO reached promised sensitivity in 2005-7 observing run (S5).
  - Advanced LIGO, VIRGO expected to make regular observations 2016+
  - Large Japanese detector (LCGT) funded, maybe another in Australia

- Future
  - f>10 Hz, science is exclusively low-mass compact objects
  - SNR will never be high, probably < 30. Events rare, local (z< 0.1).

Ground-based interferometers currently measure displacements of $10^{-18}$ m.
LISA only needs to measure $10^{-11}$ m.
LISA Sensitivity Diagram

-19
-20
-21
-22
-23

Gravitational wave frequency (Hz)

\( \log_{10} (\text{strain sensitivity, h}) \)

- Massive binaries at \( z = 1 \)
- >10^4 Resolvable binaries 100 in the first week!
- Binary confusion
- Captures
- Shot noise
- Acceleration noise

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LISA measures absolute distances

- Almost all LISA sources are binary systems.
- A system that radiates GWs strongly will “chirp” up in $f$.
- **Standard sirens**: absolute luminosity distances to chirping binary systems can be derived *directly* from

$$\text{Distance} \approx \frac{1}{c^2 \cdot \frac{1}{\text{frequency}^2} \cdot \text{chirp rate} \cdot \text{amplitude}}$$

- Works for *any* chirping binary (mass ratio, eccentricity, spins)
- Distances $D_L$ given in light-seconds: no calibration needed.
- Clean systems: high accuracy, few systematic errors.
- Completely independent of other astronomical distance ladders
- If we assume a cosmology, $D_L \cdot z$ for each observed system.
- With a population, we can measure $H_0$, $w$ even without $z$’s.
Accuracy of $D_L$: weak lensing

Babak et al (2011)

Shapiro et al (2009)

LISA Science
What happens when MBHs merge?

- LISA should detect handful of $10^5$-$10^7 M_\odot$ BH-BH binary mergers at $z = 0.5$ to 2.

- What does galaxy look like? What are the effects of merger?
  - Notify other observatories (X-ray, optical, IR, radio) up to 3 months in advance, give 1° position 1 day in advance, 10' a few hours in advance. Luminosity distance accurate to ±30-300 Mpc.
Black hole science with SNR = $10^4$

- Masses to $\pm 0.1\%$
- Spin vectors to $\pm 3-5\%$
  - Alignment: wet or dry merger
- Distance to $\pm 1-4\%$ depending on $z$.
- Much work now on counterpart identification: what is the signature of a galaxy containing a merger?

- What happens at the edge of a black hole?
  - Test no-hair theorem
  - Look for violations of cosmic censorship

(Rossi, et al)
BH Geodesy: EMRLs

- Stellar BH in-spiral into a massive BH
- Map of near-horizon geometry: relativistic geodesy (GRACE/GOCE for black holes)
- Test the no-hair theorem to 1%

LISA observes $10^5$ cycles in a year
Studying central MBH environments

- Captures of stellar-mass black holes by single central massive black holes (~$10^6 M_\odot$) are called Extreme Mass-Ratio Inspirals (EMRIs)
- LISA will detect ~100 per year out to $z \sim 0.2$, SNR ~ 100, locations to $\sim 0.5^\circ$.

- Rich survey of local MBH population in normal galaxies (not AGNs)
  - Measure central mass, spin to 1%; captured mass to 1% and spin to 10%.
  - First survey of the stellar-origin BH population near central BHs in galaxies: important for our own Galactic central BH.
  - In our own GC, we see only 5% of the stars, no stellar BHs. Cusp?

- LISA will also detect any captures of larger BHs, up to $10^3 M_\odot$. 
Compact binaries

- LISA will make major contributions to the study of binary evolution and the endpoint of stellar evolution.
  
  1. LISA has guaranteed (known) sources: verification binaries

![Graph showing binary evolution and endpoint of stellar evolution.]

Nelemans et al, Decadal white paper arXiv:0902.2923v1
Compact binaries (2)

2. Hundreds of thousands of binaries in the LISA band.
3. LISA identifies tens of thousands of them, incl. all with P <30 m.

Unresolved double WD background

Above and at high f systems are resolved: ~10,000 of both double WD and AM CVns

At least several hundred will be observed optically

(Nelemans et al. 2004)

(Nelemans et al. 2009)
Compact binaries (3)

- Synergy with GAIA, upcoming large-area surveys, radio pulsar binary surveys
- LISA supplies unique new information:
  - Orbital inclination (helps determine masses)
  - Accurate distance (for known masses, or for chirping systems)
- These observations address key astrophysics issues, e.g.:
  - Binary evolution, common envelope evolution
  - Precursors of Type Ia supernovae in the Galaxy
  - Population studies of Galaxy, tracers of star formation
  - Interacting binaries, mass transfer, tides
  - Population studies of NS-NS, NS-BH, BH-BH binaries
Merging massive black holes are proxies for merging galaxies:
- Mass-ratio of BHs indicates mass ratio of merging proto-galaxies
- Spin orientations of BHs indicate “wet” or “dry” inspiral
**LISA’s wide spectrum of masses**

<table>
<thead>
<tr>
<th>Location</th>
<th>Masses</th>
</tr>
</thead>
<tbody>
<tr>
<td>At ( z = 15 )</td>
<td>( 2.5 \times 10^6 M_\odot )</td>
</tr>
<tr>
<td>At ( z = 2 )</td>
<td>( 1.3 \times 10^7 M_\odot )</td>
</tr>
<tr>
<td>LSO mass</td>
<td>( 4 \times 10^7 M_\odot )</td>
</tr>
</tbody>
</table>

\( 10^5 + 10^5 M_\odot \) at \( z=20! \)
How did SMBHs form and grow?

- LISA will detect enough mergers to $z = 15$ to discriminate among different seeds, accretion models, metallicities.

M. Volonteri: “Most if not all massive black holes are in the LISA band at some point in their cosmic evolution.”

(Sesana, et al, 2010)
Cosmology with standard sirens

- With luminosity distances, LISA can provide accurate and independent measurements of $H_0$ and $w$.

- Using EMRIs, without identifications, LISA can determine $H_0$ to $±0.4\% = ±0.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ after just 20 EMRI detections: ~3 months LISA data. (MacLeod & Hogan, PRD, 2008; SDSS) Today (WMAP) $±1.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Symmetry breaking after Big Bang

- BBN limit
- Phase transition: 490 GeV
- EW phase transition (Shellard)
- Strings, $10^{-11}$
- Strings, $10^{-15}$
- Hogan (2006)
- Randall & Servant (2007)
- Slow-roll inflation

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LISA’s solar-system science

1. Solar g-modes:
   - LISA responds to any time-dependent change in gravity.
   - Still big questions about solar model, opacity, rotation.
   - g-modes probe the interior where density is high

2. Solar p-modes:
   - LISA responds to any time-dependent fluctuations
   - Still big questions about solar model, opacity, rotation.
   - p-modes probe the surface where density is low

3. Asteroids (Close & Schutz 2011)
   - Disturbed by a body of size L, speed v, passing a distance d from one of its S/C, LISA will have a SNR
     \[
     \text{SNR} = 500 \left( \frac{L}{1 \text{ km}} \right)^3 \left( \frac{v}{25 \text{ km s}^{-1}} \right)^{-2} \left( \frac{d}{10^6 \text{ km}} \right)^{-3/2}
     \]
   - Detect 1-10 events/yr with L between 10 and 100 m.

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LISA data analysis

- Analysis is challenging because of confusion problem.
  - Heritage in well-understood ground-based data analysis problem: matched filtering based on well-understood waveform predictions.
- LISA signal data set small: 5 years would fit on an iPod.
- Data analysis for the mission will require closely integrated pipelines, but can be distributed geographically. LISA data will be released quickly. Catalogues updated periodically.
- Mission will have low-latency data service when major events are expected, such as a BH-BH coalescence at \( z = 1 \).
- MLDC – Mock LISA Data Challenge – creates test data sets containing simulated signals. Results of analysis by competing groups are published.
- Latest challenge identified 20,000 individual sources.

**MLDC a great success: the community has learned how to resolve the confusion problem.**
Mock LISA Data Challenge

MLDC4, training dataset

2 years of instrument noise, 60 million Galactic binaries, 4 MBH binaries, 9 EMRIs, 15 cosmic-string bursts, cosmological stochastic background

...plus the EMRIs...

...and the bursts...

(two-year time series filtered out > 33 mHz)

(M. Vallisneri, 11/2009)

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LISA addresses priority astronomy

- **US partners**: Decadal Review Astro2010 advised NASA that LISA is among the top 3 “large” mission priorities:
  - “… the recommendation and prioritization for LISA reflect its compelling science case and the relative level of technical readiness.”

- This echoed NASA’s Beyond Einstein Program Assessment Committee (BEPAC) in 2007:
  - “… the committee gave LISA its highest scientific ranking.”

- A large community of astrophysicists is developing a deeper and deeper understanding of LISA’s science potential
  - The literature contains ~1500 papers on LISA science (ADS)
  - The bi-annual LISA Symposium attracts hundreds of participants
  - New research started by the stimulus of LISA, eg EM counterparts of mergers

- LISA targets high-priority astronomy: massive black holes, stellar evolution, the high-redshift universe, cosmology.

- LISA’s astronomy is timely. **Now is the time for LISA!**