Revisiting the LISA science case

Neil J. Cornish
Montana State University

eXtreme Gravity Institute
The Weiss Report: 1975

MANAGEMENT AND OPERATIONS
WORKING GROUP FOR SHUTTLE ASTRONOMY

REPORT OF THE SUB-PANEL ON RELATIVITY AND GRAVITATION

Weiss  Bender  Pound  Misner
LISA
Laser Interferometer Space Antenna for the detection and observation of gravitational waves
An international project in the field of Fundamental Physics in Space

Pre-Phase A Report
Second Edition
July 1998

NASA/ESA joint study 1996, Yellow Book 1998
Classic LISA Science Case

- Massive \((10^5 - 10^7 \text{ M}_\odot)\) Black Hole mergers to high \(z\) as tracers of BH-galaxy co-evolution
- Extreme Mass Ratio Inspirals (EMRIs) for tests of GR and as probes of galactic cusps
- Galactic binaries for stellar evolution and galactic structure
- Stochastic backgrounds from early Universe
Astrophysics in the 2034

- Assembly and growth of first galaxies observed by JWST
- Expansion history & distance scale to better than 1% from WFIRST
- High SNR (100+) gravitational wave signals detected by LIGO
- EM counterparts of LIGO sources detected
- Athena will have detected many IMBHs
- Supermassive Black Holes observed to high redshift ($z \sim 8$) by Athena
- Gravitational waves from supermassive black hole binaries discovered by IPTA
LISA - charting the BH merger history
Astrophysics in the 2034

Post EELT

• EELT will observe first stars in Universe and early black holes

Post GAIA

• Census of IMBH masses from stellar velocities in clusters from EELT

Post LSST

• GAIA catalog will include several hundred short period eclipsing WD binaries

Post GRAVITY

• SKA will have discovered pulsars at the galactic center giving insight into EMRI rates

Post SKA

• LSST will detect 100’s of SMBH stellar tidal disruption events per year and give insight into EMRI populations

• GRAVITY and its successors will have found stars with < year orbits around Sgr A* yielding insight into EMRI rates
Evolved LISA Science Case

- Classic LISA science case +
- Prompt and pre-cursor EM counterparts
- Intermediate mass black holes ($10^2 - 10^4 M_\odot$)
- Stellar remnant BHs (GW150914-like)
- IMRIs (mass ratios 100-1000)
- EMRI resonances
- WD resonances, detonations
- Unmodeled Bursts
Electromagnetic Counterparts

Old picture likely wrong - there will be significant pre and post merger EM counterparts to SMBHBs

(Farris et al. 2015 a,b)
Electromagnetic Counterparts

Tidally heated white dwarfs in binaries

(Fuller & Lai 2014)

(Burkart et al. 2013)

Guaranteed Sources: Galactic Binaries

![Graph showing linear PSD of strain h/(V/Hz) vs. log (f/Hz)]
New, loud verification binaries

SDSS J0651+2844  (Brown et al. 2011)
12 minute eclipsing WD-WD binary

\[ f_{GW} = 2.78 \text{ mHz} \]

WD0931+444  (Kilic et al. 2014)
20 minute detached WD-WD binary

\[ m_1 = 0.32M_\odot, \quad m_2 \geq 0.14M_\odot \quad 660 \text{ pc} \]

\[ f_{GW} = 1.68 \text{ mHz} \]

\[ h \sim 10^{-22} \rightarrow 10^{-21} \]
WD orbital resonances

Intermediate Mass Black Holes making news

NGC 2276, $5 \times 10^4 \, M_\odot$
Mezcua 2015

“Rare 'Missing Link' Black Hole Apparently Found”
Space.com 2015

M82 X-1, $428 \pm 105 \, M_\odot$
Pasham 2014

“It's Confirmed! Black Holes Do Come in Medium Sizes”
Space.com 2014

Milky Way, $10^5 \, M_\odot$
Oka 2016

“Signs of second largest black hole in the Milky Way”,
astronomy.com 2016

SDSS J1126+2944, $10^2 \rightarrow 10^6 \, M_\odot$
Comerford 2016

“'Stripped' black hole could be a rarely seen phenomenon, study says”
LaTimes 2016
Rescaling of M-sigma relation?

Selection bias in galaxies with measured BH masses. Typical galaxies have BHs 3 times smaller.

Suggest more IMBHs. Also no need for massive seeds (inferred large masses at high z not so large after all).
Multi-Band Observations

(Amaro-Seoane & Santamaria 2010)

(Sesana 2016)
Multi-Band Observations

(Amaro-Seoane & Santamaria 2010)

\[ \sqrt{S_n(f)} \text{ and } 2 |h|^2 \sqrt{1/N} \]

(Amaro-Seoane & Santamaria 2010)

(Sesana 2016)

(aLIGO/aVirgo Horizon)

\[ d_L \text{ for } \text{SNR}=12 \text{ (Gpc)} \]

\[ M_{\text{obs}} \text{ (M}_\odot) \]

\[ \text{Redshift}, z \]

(1.2 Gpc)
Multi-Band Observations

(Amaro-Seoane & Santamaria 2010)

\[ \sqrt{S_n(f)} \text{ and } 2\tilde{h}(f) \sqrt{1/N} \]

- LISA
- ET base
- Adv LIGO base
- (439.2 + 439.2) \( M_\odot \) @ 1Gpc

0.2 yrs

\[ f (\text{Hz}) \]

\[ 10^{-4} - 1000 \]

\[ 10^{-15} - 10^{-12} \]

\[ q=1 \]

\[ q=4 \]

\[ M_{\text{obs}} = 500 \ M_\odot \]

(Sesana 2016)

characteristic amplitude

\[ f (\text{Hz}) \]

0.001 - 1000

10^{-19} - 10^{-21}

10 year

1 year

1 week

1 day

1 hour

aLIGO

eLISA

aLIGO/aVirgo Horizon

\[ d_l \text{ for SNR} = 12 \ Gpc \]

\[ z = \text{Redshift} \]

\[ M_{\text{obs}} (M_\odot) \]

0 - 1600

1 - 10

2 - 6

3 - 4

4 - 5

5 - 6

Gpc

0.1 - 10

0 - 1

0.2 - 0.67

0.37 - 0.52

0.52 - 0.67

eLISA Horizon

\[ M_{\text{obs}} = 500 \ M_\odot \]
EMRI orbital resonances

- Each EMRI in LISA band passes through several resonances
- Jump in the frequency and phasing a challenge for detection algorithms
- Potential to improve parameter estimation and provide ultra-stringent GR tests

[Brink, Geyer, Hinderer 13]  [Ruangsrri, Hughes 13]
“It would be unprecedented in the history of astronomy if the gravitational radiation window being opened up by LISA does not reveal new, enigmatic sources”
Exotic Sources

**Imagined**

- Topological defects
- Pre-heating/Re-heating
- Warped extra dimensions
- Phase transitions- bubble nucleation, cavitation, collisions
- Braneworlds

**Un-Imagined**

- Burst sources?
Detecting the Unmodeled and Unexpected
Is this a signal or an instrumental artifact?
Detecting the Unmodeled and Unexpected

Is this a signal or an instrumental artifact?

a.k.a. Guano or Gold?
Three arms are better than two
Three arms are better than two
Three arms are better than two

\[
S_+ = \frac{\sqrt{3}}{2} X \\
S_\times = \frac{1}{2} (X + 2Y) \\
S_\odot = \frac{1}{3} (X + Y + Z)
\]

\[
\{
\text{Instantaneous measurement of both polarization states and increased signal-to-noise}
\}
\]

\[
\{
\text{Null channel to monitor average low frequency instrument noise}
\}
\]
Triangulation- Source Localization
Triangulation- Source Localization
Separating Burst Signals from Noise

Noise delays

\[ \Delta t = n \frac{L}{c} \]

Signal delays

\[ \Delta t = n \frac{L}{c} + \frac{\hat{k} \cdot \vec{L}}{c} \]
Detecting a Stochastic Background: (e)LISA

(Adams & Cornish 14)
LISA Sensitivity

Noise ASD

Response

Sensitivity
LISA Sensitivity

\[ h(f) = \left( \frac{4S_{\alpha}}{S_p} \right)^{1/4} \]

\[ f_1 = \frac{1}{2\pi} \left( \frac{4S_{\alpha}}{S_p} \right)^{1/4} \]

\[ f_2 = \frac{c}{2\pi L} \]
If just shot noise

\[ S_p \sim \frac{L^2}{\epsilon P_{\text{laser}} D^4} \]

\[ f_1 \sim \frac{1}{L^{1/2}} \]

\[ f_2 \sim \frac{1}{L} \]
LISA Sensitivity

Fixed position noise

\[ f_1 \sim L^0 \]

\[ f_2 \sim \frac{1}{L} \]
Orbit Selection

\[ \alpha_\oplus = \frac{2GM_\oplus L}{(\alpha \text{ AU})^3} \]
LISA Design Trades

- Low frequency sensitivity - Bigger better
- High frequency sensitivity - Shorter not always better
- Lifetime - Shorter arms = longer life
- Orbit - Further away better
- Articulation vs Infield Guiding - Shorter better
- Number of links should never be on the table

See talks by G. Mueller and J. Livas in this session
To learn more....

http://brownbag.lisascience.org/

https://www.elisascience.org/whitepaper/

http://www.cosmos.esa.int/web/GOAT