Chapter I:
Overview of LISA sources

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OUTLINE

>LISA privileged place in the GW landscape

>massive black hole binaries (MBHBs) detection, parameter estimation and scientific potential

>Extreme mass ratio inspirals (EMRIs) unique probes of spacetime metric

>An eye on the Galaxy: white dwarf (WD) binaries

...and more...
Binaries in the gravitational wave landscape

- $10^6 M_\odot @ 10\text{Gpc}$, $h \sim 10^{-17}$, $f < 10^{-2}$
- $10^9 M_\odot @ 1\text{Gpc}$, $h \sim 10^{-14}$, $f < 10^{-6}$
- $10^3 M_\odot @ 100\text{Mpc}$, $h \sim 10^{-21}$, $f < 10^3$

MBHB confusion noise

- EMRI @ $z = 1$ ($M = 3 \times 10^8 + 10 M_\odot$)
- Resolved BHB + unresolved BHB

characteristic amplitude vs. frequency [Hz]
Possible other sources (not shown): cosmic strings (kink, cusps), cosmological backgrounds (non-standard inflation, phase transitions)
Observational facts

1- In all the cases where the inner core of a galaxy has been resolved (i.e. in nearby galaxies), a massive compact object (which I'll call Massive Black Hole, MBH for convenience) has been found in the centre.

2- MBHs must be the central engines of Quasars: the only viable model to explain this cosmological objects is by means of gas accretion onto a MBH.

3- Quasars have been discovered at z~7, their inferred masses are ~$10^9$ solar masses!

THERE WERE $10^9$ SOLAR MASS BHs WHEN THE UNIVERSE WAS <1Gyr OLD!!!

**MBH formation and evolution have profound consequences for GW astronomy**
Core of Galaxy NGC 4261

Hubble Space Telescope
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk

380 Arc Seconds
88,000 LIGHTYEARS

17 Arc Seconds
400 LIGHTYEARS

Quasar 3C175
YLA 6cm image (c) NRAO 1996
Structure formation in a nutshell

(From de Lucia et al. 2006)

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

(Menou et al 2001, Volonteri et al. 2003)
Structure formation in a nutshell

*Where and when do the first MBH seeds form?
*How do they grow along the cosmic history?
*What is their role in galaxy evolution?
*What is their merger rate?
*How do they pair together and dynamically evolve?

(From de Lucia et al. 2006)

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

Binaries inevitably form

(Menou et al 2001, Volonteri et al. 2003)
Structure formation in a nutshell

*Where and when do the first MBH seeds form?*
*How do they grow along the cosmic history?*
*What is their role in galaxy evolution?*
*What is their merger rate?*
*How do they pair together and dynamically evolve?*

(From de Lucia et al. 2006)

(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

- When did the first black holes form in pre-galactic halos, and what is their initial mass and spin?
- What is the mechanism of black hole formation in galactic nuclei, and how do black holes evolve over cosmic time due to accretion and mergers?
- What is the role of black hole mergers in galaxy formation?

(Menou et al 2001, Volonteri et al. 2003)
Masses have the largest impact on the phase modulation.

Eccentricity impacts the waveform and the phase modulation.

Spins impact the waveform and the phase modulation (but weaker effect).

Depend on the number of cycles and SNR, can be easily measured with high precision.

Sky location impacts the waveform modulation over time through antenna beam pattern.

Distance impacts the waveform amplitude (degenerate with masses, and sky location, inclination).

Depend on the time in band, polarization disentanglement, SNR. Measurement is more difficult.

For MBH binaries, strong impact of having: 1) longer baseline 2) 6 laser links.
Assuming 5 years of operation and 6 links:

~100+ detections

~100+ systems with sky localization to 10 deg2

~100+ systems with individual masses determined to 1%

~50 systems with primary spin determined to 0.01

~50 systems with secondary spin determined to 0.1

~50 systems with spin direction determined within 10deg

~30 events with final spin determined to 0.1
**MBH astrophysics with GW observations**

**Astrophysical unknowns in MBH formation scenarios**

1. MBH seeding mechanism *(heavy vs light seeds)*
2. Metallicity feedback *(metal free vs all metallicities)*
3. Accretion efficiency *(Eddington?)*
4. Accretion geometry *(coherent vs. chaotic)*

**CRUCIAL QUESTION:**
Given a set of LISA observation of coalescing MBH binaries, what astrophysical information about the underlying population can we recover?

Create catalogues of observed binaries including errors from eLISA observations and compare observations with theoretical models

*AS et al. 2011, see also Plowman et al 2011*
Different GW sources will allow an independent assessment of the geometry of the Universe at all redshifts.
Cosmography with MBHBs

(Tamanini et al. 2016)
Measuring $w$ without counterparts

Electromagnetic counterpart difficult to identify: cannot measure $z$!
Play the same game as before: need to consider all galaxy distribution in the measurement errorbox.

One can then write the posterior for $w$ considering all distributions in the error boxes of several events:

$$P(w) = \frac{p_0(w) \prod_{j=1}^{N_{\text{ev}}} P_j(s \mid w)}{\int p_0(w) \prod_{j=1}^{N_{\text{ev}}} P_j(s \mid w) dw}$$

Petiteau Babak AS 2011
LIGO will not enable BH spectroscopy on individual BHB mergers

Voyager/ET type detectors are needed

eLISA will enable precise BH spectroscopy on few to 100 events/yr also at very high redshifts

Resolving ringdown modes: BH spectroscopy (Berti et al. 2016)
Extreme mass ratio inspirals (EMRIs)

- What is the mass distribution of stellar remnants at the galactic centres and what is the role of mass segregation and relaxation in determining the nature of the stellar populations around the nuclear black holes in galaxies?
- Are massive black holes as light as $\sim 10^5 M_\odot$ inhabiting the cores of low mass galaxies? Are they seed black hole relics? What are their properties?

- Does gravity travel at the speed of light?
- Does the graviton have mass?
- How does gravitational information propagate: Are there more than two transverse modes of propagation?
- Does gravity couple to other dynamical fields, such as, massless or massive scalars?
- What is the structure of spacetime just outside astrophysical black holes? Do their spacetimes have horizons?
- Are astrophysical black holes fully described by the Kerr metric, as predicted by General Relativity?
Astrophysical uncertainties are huge:

- MBH mass function unknown below $10^6$ solar masses
- Distribution of compact objects (CO) around MBH (Preto & Amaro-Seoane 2010)?
- Are CO inspiralling (thus producing EMRIs) or plunging (Merritt 2015)?

Using astrophysically motivated prescriptions we generated 12 models:

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass function</th>
<th>MBH spin</th>
<th>Cusp erosion</th>
<th>$M-\sigma$ relation</th>
<th>$N_p$</th>
<th>CO mass [$M_\odot$]</th>
<th>Total</th>
<th>EMRI rate [yr$^{-1}$]</th>
<th>Detected (AKK)</th>
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Selected results: LISA reach and parameter estimation
(Babak et al, almost submitted...finally!)
Summary of EMRI parameter estimation

~1-1000 detections/yr
~typical sky localization better than 10 deg2
~distance to better than 10%
~MBH mass to better than 0.01%
~CO mass to better than 0.01%
~MBH spin to better than 0.001
~plunge eccentricity to better than 0.0001
~deviation from Kerr quadrupole moment to <0.001

New tool for astrophysics (Gair et al 2010) cosmology (McLeod & Hogan 2008), and fundamental physics (Gair et al 2013) ... to be further explored
Galactic binaries

- How many ultra-compact binaries exist in the Milky Way?
- What is the merger rate of white dwarfs, neutron stars and stellar mass black holes in the Milky Way (thus better constraining the rate of the explosive events associated with these sources)?
- What does that imply for, or how does that compare to, their merger rates in the Universe?
- What happens at the moment a white dwarf starts mass exchange with another white dwarf or neutron star, and what does it tell us about the explosion mechanism of type Ia supernovae?
- What is the spatial distribution of ultra-compact binaries, and what can we learn about the structure of the Milky Way as a whole?
Galactic binaries

- How many ultra-compact binaries exist in the Milky Way?
- What is the merger rate of white dwarfs, neutron stars and stellar mass black holes and what does that tell us (in terms constraining the rate of Type Ia supernovae)?
- What happens at the moment of a neutron star exchange with another white dwarf, what does it tell us about type Ia supernovae?
- What is the spatial distribution of binaries, and what can we learn about the Milky Way as a whole?
Galactic binaries

- How many ultra-compact binaries exist in the Milky Way?
- What is the merger rate of white dwarfs, neutron stars and stellar mass black holes in the Milky Way (subsequently constraining the rate of type Ia supernovae)?
- What does that imply for, and help constrain, their merger rates in the Universe?
- What happens at the moment of merging? What kind of exchange with another white dwarf, for example, does it tell us about type Ia supernovae?
- What is the spatial distribution of these binaries, and what does that tell us about the Milky Way?

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Teaser of Chapter II: LIGO BHs in the LISA band

(AS 2016, PRL 116, 1102)
Summary:

>LISA will potentially detect hundreds of MBH binaries per year throughout the Universe

>MBHB GW observations will enable new studies in astrophysics, cosmology, fundamental physics

>between 1 and 1000 EMRI/yr will be detected, and will come with a RIDICULOUS estimate of the source parameters

>LISA will detect ~10000 WD-WD binaries in the Galaxy, shedding light on the evolution of compact binaries