Astrophysics and Cosmology with LISA Sources

Nicola Tamanini

Max-Planck-Institut
für Gravitationsphysik
(Albert-Einstein-Institut)

LISA

Outline

Astrophysics with LISA: peculiar acceleration measurements

- Applications to stellar-mass BBHs: AGN disks/GCs formation
- Applications to white dwarf binaries: triple systems and circumbinary exoplanets

Cosmology with LISA: standard sirens

- Low redshift: stellar-mass BBHs and EMRIs
- High redshift: massive BBHs and beyond ΛCDM tests

Outline

Astrophysics with LISA: <u>peculiar acceleration measurements</u>

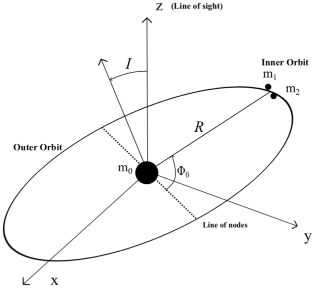
- Applications to stellar-mass BBHs: AGN disks/GCs formation
- Applications to white dwarf binaries: triple systems and circumbinary exoplanets

Cosmology with LISA: <u>standard sirens</u>

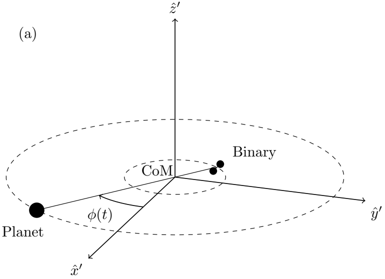
- Low redshift: stellar-mass BBHs and EMRIs
- High redshift: massive BBHs and beyond ΛCDM tests

Peculiar acceleration measurements

Long-lasting binaries (stellar-mass BBHs or WD binaries) perturbed by a third object will be on a wide Keplerian orbit



[Wong *et al*, arXiv:1902.01402]



[Tamanini & Danielski, arXiv:1812.04330]

Peculiar acceleration measurements

In first approximation (assuming $d_{12} \ll d_3$) the GW frequency of the binary will be modulated through the Doppler effect

$$f_{\rm obs}(t) = \left(1 + \frac{v_{\rm com}(t)}{c}\right) f_{\rm gw}(t) \quad \Rightarrow \quad \Psi_{\rm obs}(t) = 2\pi \int_0^t f_{\rm obs}(t')dt'$$

From the modulation of the GW waveform one can recover the following parameters of the perturbing object:

- Line-of-sight velocity: $K = \left(\frac{2\pi G}{P_3}\right)^{1/3} \frac{M_3 \sin i}{(M_{12}+M_3)^{2/3}}$ (for circ. orb.)
- Period: P_3
- Initial phase: ϕ_3
- Eccentricity: e_3

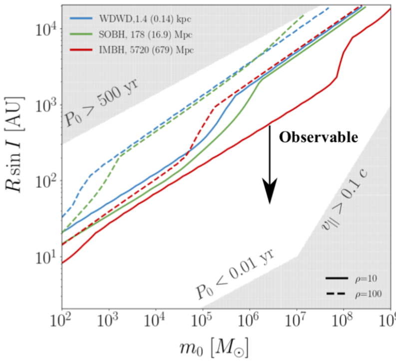
GW equivalent of **radial velocity** measurements!

Peculiar acceleration measurements: applications

The peculiar acceleration might be detected by LISA for the following systems:

- **BBHs in globular clusters**:
  - Interaction with a third stellar-mass BBHs or IMBBHs
  - P_3 comparable to or longer than LISA observational time
- **BBHs in AGN disks or close to galactic center**:
  - Interaction with the central SMBBHs
  - P_3 longer than LISA observational time
  - $\Rightarrow$ peculiar acceleration is constant $a_{\rm com} \simeq$ const
- **DWDs in the Milky Way**:
  - Interaction with circumbinary star or planet
  - P_3 comparable to LISA observational time

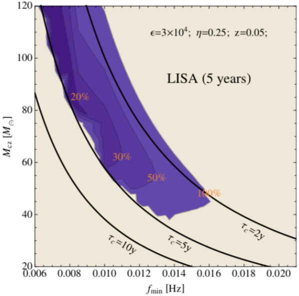
Applications to BBHs

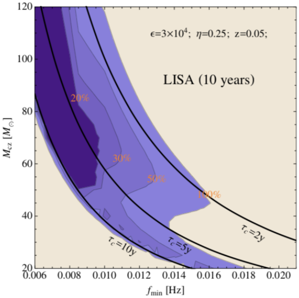


- The presence of a third companion can be detected if it is close/massive enough

[Wong, Baibhav, Berti, 1902.01402]

Applications to BBHs





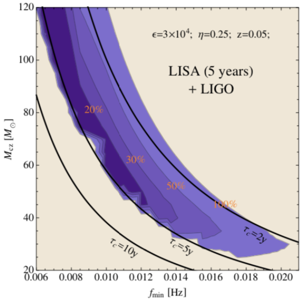
- The presence of a third companion can be detected if it is close/massive enough

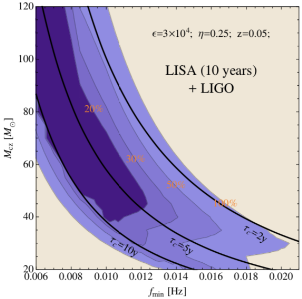
[Wong, Baibhav, Berti, 1902.01402]

- The peculiar acceleration is better measured for BBHs close to coalescence

[Inayoshi, NT, Caprini, Haiman, 1702.06529]

Applications to BBHs





- The presence of a third companion can be detected if it is close/massive enough

  [Wong, Baibhav, Berti, 1902.01402]

- The peculiar acceleration is better measured for BBHs close to coalescence

  [Inayoshi, NT, Caprini, Haiman, 1702.06529]

- Easier to detect for multi-band BBHs and for longer LISA observational time

  [Bonvin, Caprini, Sturani, NT, 1609.08093]

Implications for BBHs

- Using peculiar acceleration measurements LISA will probe the environment of BBHs and provide information on BBH formation

[Inayoshi, NT, Caprini, Haiman, 1702.06529]
[Randall & Xianyu, 1805.05335]

- Significant measurements are obtained only for long observational times and/or multi-band detections

[NT, Klein, Bonvin, Barausse, Caprini, *in prep*] → preliminary

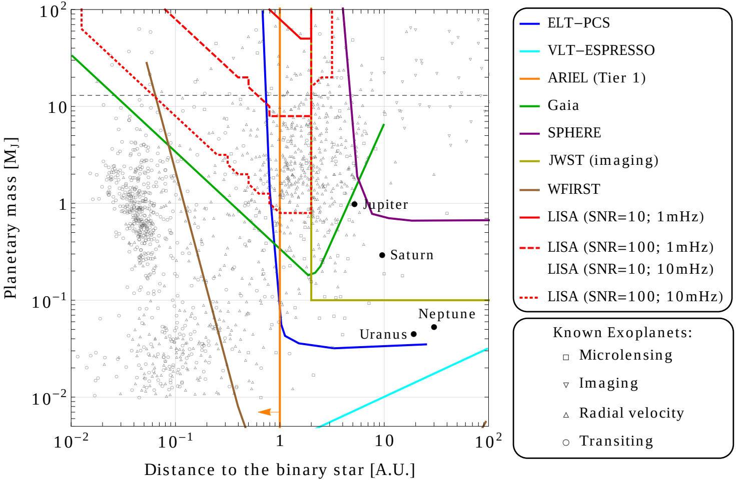
LISA mission duration	LISA only					LISA+Earth ($t_c < 10$y)				
	Total	100%	50%	30%	10%	Total	100%	50%	30%	10%
4 years	51.5	1	0	0	0	138	3	0	0	0
10 years	213	39.5	20.5	9.5	0	243	103.5	67	38.5	7.5

- Many events can be biased if peculiar acceleration is neglected

[Bonvin, Caprini, Sturani, NT, 1609.08093]
[NT, Klein, Bonvin, Barausse, Caprini, *in prep*] → preliminary

	4 years LISA					10 years LISA				
$\log_{10}(a_{\rm com}[m/s^2])$	-10	-9	-8	-7	-6	-10	-9	-8	-7	-6
Fraction of biased events	0.1	3.4	16.8	38.2	76.9	3.9	14.5	42.6	77.8	96.9

Applications to DWDs



[Tamanini & Danielski, 1812.04330]

Implications for DWDs

- LISA can detect circumbinary stellar companions with periods up to $\sim$ 100 years

[Robson, Cornish, NT, Toonen, 1806.00500]

- LISA can detect circumbinary exoplanets down to Jupiter masses and periods comparable to the mission lifetime

[Tamanini & Danielski, 1812.04330]

- LISA will have the potential to detect circumbinary exoplanets everywhere in the Milky Way and even in nearby galaxies overcoming the observational bias of EM searches which are limited to measurements in the solar neighborhood

[Tamanini & Danielski, 1812.04330]

- LISA observations might provide useful information to constrain formation and evolution of giant exoplanets

[Tamanini & Danielski, 1812.04330]

Outline

Astrophysics with LISA: peculiar acceleration measurements

- Applications to stellar-mass BBHs: AGN disks/GCs formation
- Applications to white dwarf binaries: triple systems and circumbinary exoplanets

Cosmology with LISA: standard sirens

- Low redshift: stellar-mass BBHs and EMRIs
- High redshift: massive BBHs and beyond ΛCDM tests

Standard sirens for LISA

Possible standard sirens sources for LISA:

- Massive BHBs ($10^4 - 10^7\, M_\odot$)
- Stellar mass BHBs ($10 - 100\, M_\odot$)
- EMRIs

Standard sirens for LISA

Possible standard sirens sources for LISA:

- Massive BHBs ($10^4 - 10^7\ M_\odot$)
- Stellar mass BHBs ($10 - 100\ M_\odot$)
- EMRIs

Characteristics of Massive BHB mergers:

- High SNR
- High redshifts (up to ∼10-15)
- Merger within LISA band ↴
- Gas rich environment → *EM counterparts expected!*

Standard sirens for LISA

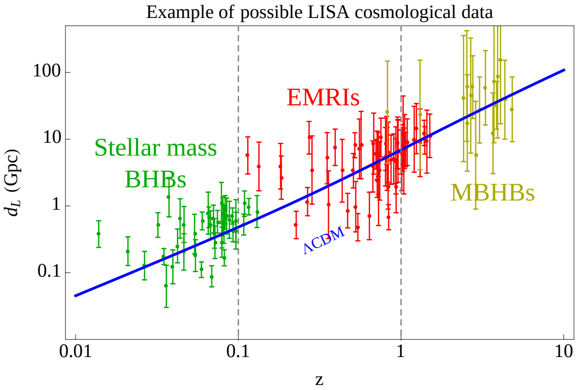
Possible standard sirens sources for LISA:

- Massive BHBs ($10^4 - 10^7\ M_\odot$)
- Stellar mass BHBs ($10 - 100\ M_\odot$)
- EMRIs

Characteristics of StMBHBs and EMRIs:

- Low redshifts ($\lesssim 0.1$ for StBHBs and $\lesssim 1$ for EMRIs)
- Merger outside the LISA band (StMBHBs)$\lnot$
- Gas poor environment $\rightarrow$ *No EM counterparts expected!*

Standard sirens for LISA

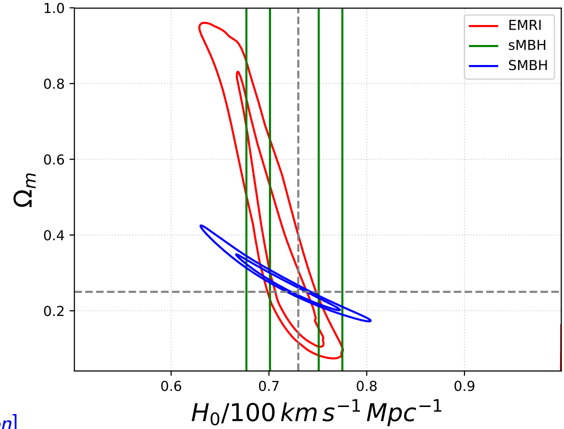


- StMBHBs: [Del Pozzo *et al*, 1703.01300; Kyutoku & Seto, 1609.07142]
- EMRIs: [MacLeod & Hogan, 0712.0618]
- MBHBs: [Tamanini *et al*, 1601.07112; Petiteau *et al*, 1102.0769]

Combined cosmological analysis with all LISA sources

We are currently completing the cosmological forecasts combining together all standard siren sources: smBHBs, EMRIs and MBHBs.

Preliminary results: **Realistic case** for ΛCDM



[Tamanini, Del Pozzo, Sesana et al. *in preparation*]

MBHBs: data simulation approach

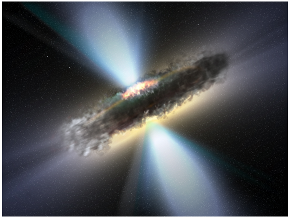
To obtain cosmological forecasts, we have adopted the following **realistic strategy**:

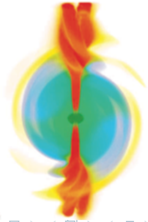
[Tamanini, Caprini, Barausse, Sesana, Klein, Petiteau, arXiv:1601.07112]

- Start from simulating MBHBs merger events using **3 different astrophysical models** [Klein+ 1511.05581]
  - Light seeds formation (popIII)
  - Heavy seeds formation (with delay)
  - Heavy seeds formation (without delay)
- Compute for how many of these a GW signal will be **detected by LISA** (SNR>8)
- Among these select the ones with a **good sky location accuracy** ($\Delta\Omega < 10\,\mathrm{deg}^2$)
- Focus on **5 years** LISA mission (the longer the better for cosmology)

MBHBs: data simulation approach

- **To model the counterpart** we generally consider two mechanisms of EM emission at merger: (based on [Palenzuela+ 1005.1067])
  - A quasar-like luminosity **flare** (optical)
  - Magnetic field induced **flare** and **jet** (radio)
- Magnitude of EM emission computed using data from simulations of MBHBs and galactic evolution
- EM transients expected long after the merger (up to weeks/months)

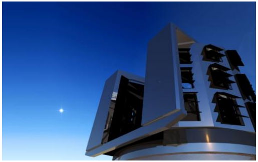
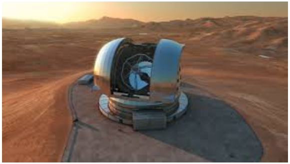




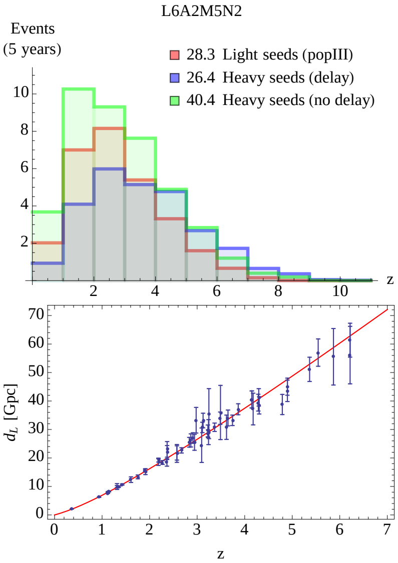
MBHBs: data simulation approach

Finally **to detect the EM counterpart** of an LISA event sufficiently localized in the sky we use the following two methods:

- **LSST**: direct detection of optical counterpart
- **SKA + E-ELT**: first use SKA to detect a radio emission from the BHs and pinpoint the hosting galaxy in the sky, then aim E-ELT in that direction to measure the redshift from a possible optical counterpart either
  - Spectroscopically or Photometrically


Standard sirens for LISA: massive BHBs



- *Redshift range*: $1 \lesssim z \lesssim 8$
- *Average LISA errors*:
  - $\Delta d_L/d_L \lesssim$ few % (lensing dom.)
  - $\Delta\Omega < 10\,\mathrm{deg}^2$
- *Useful standard sirens*:
  $\sim 5/\mathrm{yr}$ (with counterpart)
- *Results*: H_0 to $\sim$ few %
- Bad for dark energy (low-z)
- Good for testing beyond-ΛCDM models at high-z

[Tamanini+ 1601.07112]

[LISA CosmoWG 1906.01593]

Constraining modified gravity with LISA standard sirens

If one modifies the GW propagation equation, the amplitude no longer scales as $1/d_L$:

$$h'' + 2\mathcal{H}[1 - \delta(\eta)]h' + k^2 h = 0 \quad \Rightarrow \quad h \propto 1/d_L^{GW}(z)$$

$$d_L^{GW}(z) = d_L^{EM}(z) \exp\left\{ - \int_0^z \frac{dz'}{1+z'} \delta(z') \right\}$$

A simple and quite general parametrization for $\delta(z)$ is the following: [Belgacem+ 1805.08731]

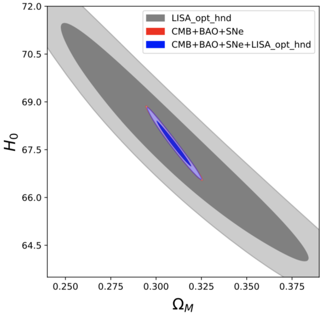
$$\frac{d_L^{GW}}{d_L^{EM}} = \Xi_0 + \frac{1 - \Xi_0}{(1 + z^n)}$$

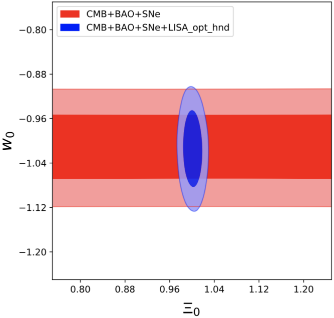
It well approximates several modified gravity models of dark energy: Scalar-Tensor theories, Hordenski theories, Non-local gravity, ...
[LISA CosmoWG 1906.01593]

Constraining modified gravity with LISA standard sirens

LISA MBHBs (with EM counterpart) at high redshift will be extremely useful to constrain modified GW propagation:

[LISA CosmoWG 1906.01593]





Ξ_0 constrained at the $\sim$2% level

Improving LISA cosmology with MBHBs

How can we improve the MBHB cosmological analysis?

- Use up-to-date simulations of MBHB mergers
- Improve PE for MBHBs (better Δd_L and $\Delta\Omega$)
- Consider all possible EM signatures
  - Radio (jet/flare), optical, X-rays, periodic modulations?, ...
- What future EM facilities can we use/do we need?
- Understand how redshift can be measured
  - How many transients in localization region?
  - Can we (always) identify the hosting galaxy?
  - What methods can we use? (spectro, photo, 21cm, ...)
- Understand possible systematics (lensing/delensing?)

Summary

Astrophysics with LISA: peculiar acceleration measurements

- Sufficiently close/massive objects orbiting compact binaries can be detected by LISA through the Doppler modulation of the GW waveform phase
- Can be used to probe the environment and formation mechanism of BBHs (AGN disks, GCs, ...)
- Can be used to detect triples stellar systems and circumbinary exoplanets (beyond the solar neighborhood)

Cosmology with LISA: standard sirens

- Three possible sources:
  SOBHBs (no EM cp), EMRIs (no EM cp), MBHBs (EM cp)
- Probing the cosmic expansion from $z \sim 0.01$ to $z \sim 10$
- Tests of alternative cosmological models and modified gravity