Constrains on modified theories of gravity with LISA

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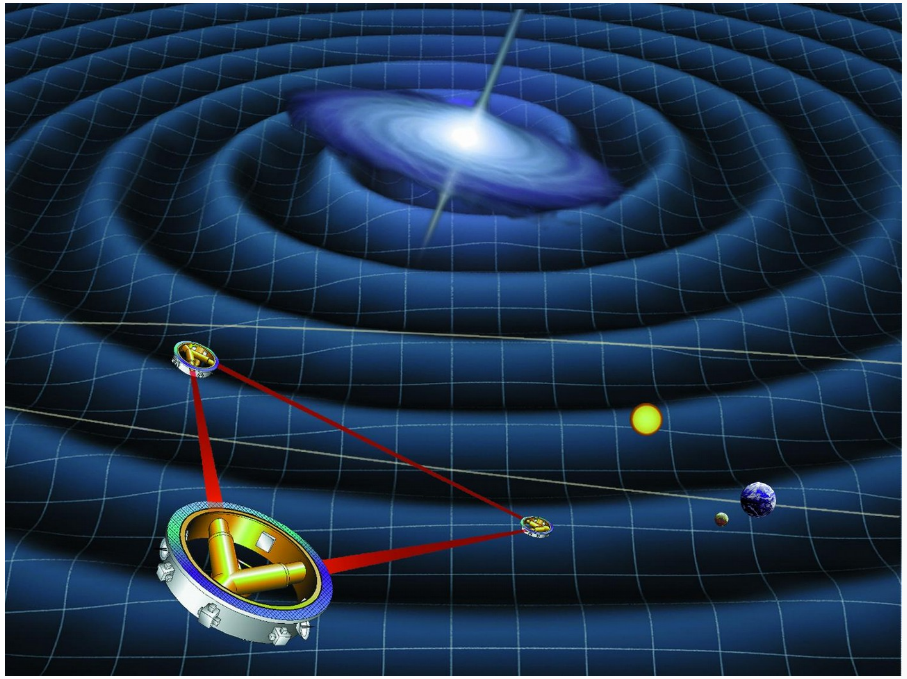
Context

- Recent ability to directly detect Gravitational Waves with earth-based interferometers:
  - LIGO/VIRGO
  - KAGRA (soon)
- Next generation of detectors is already being planned:
  - Earth based: Einstein Telescope, Cosmic Explorer
  - Space based: LISA (2034)

Gravitational Waves detectors

	Earth based	Space based
Detector	VIRGO/ LIGO	LISA(2034)
Arm length	3 / 4 km	2.5 x 10^6 km
Frequency range	10 - 10^3 Hz	10^{-5} - 1 Hz
Detectable objects	Stellar Origin Black Holes, Neutron star binaries …	Massive Black Holes, Stellar Origin Black Holes ...



Modifications to GR

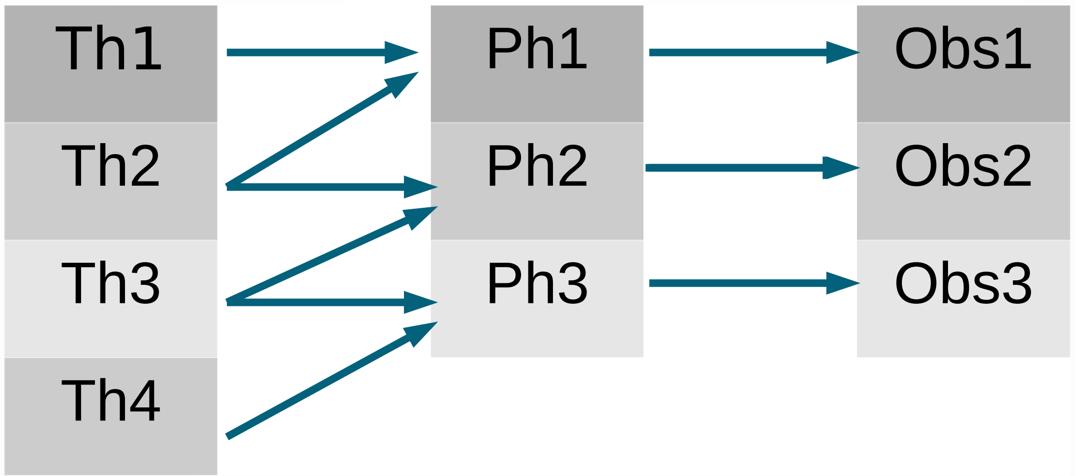
- Why?
  - Dark Matter and Dark Energy
  - Black Hole singularities
  - General Relativity is not renormalizable, need for a quantum gravity theory

Many (many) theories and Gravitational Waves computation are very difficult

→ Parametrized tests of General Relativity

Phenomenological Modifications

Map theories into phenomenological effects and compute their consequences on observables



Parametrized Post Einsteinian framework

- Phenomenological modifications, which can affect either the generation or the propagation of Gravitational Waves, induce a change in the waveform:

$$\tilde{h} = A_{GR}\, e^{i\psi_{GR}}\, (1 + \alpha f^{a}) e^{i\beta f^{b}}$$

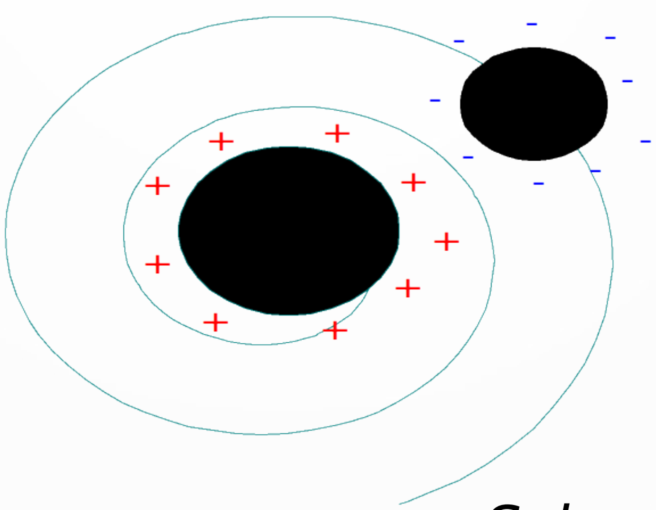
$$\alpha \ll 1 \qquad \beta \ll 1$$

- Neglect the change in the amplitude: $\alpha = 0$

- Phase: $\psi_{GR} = \phi_0 f^{-5/3}(1 + \phi_1 f^{1/3} + \phi_2 f^{2/3} + ...)$

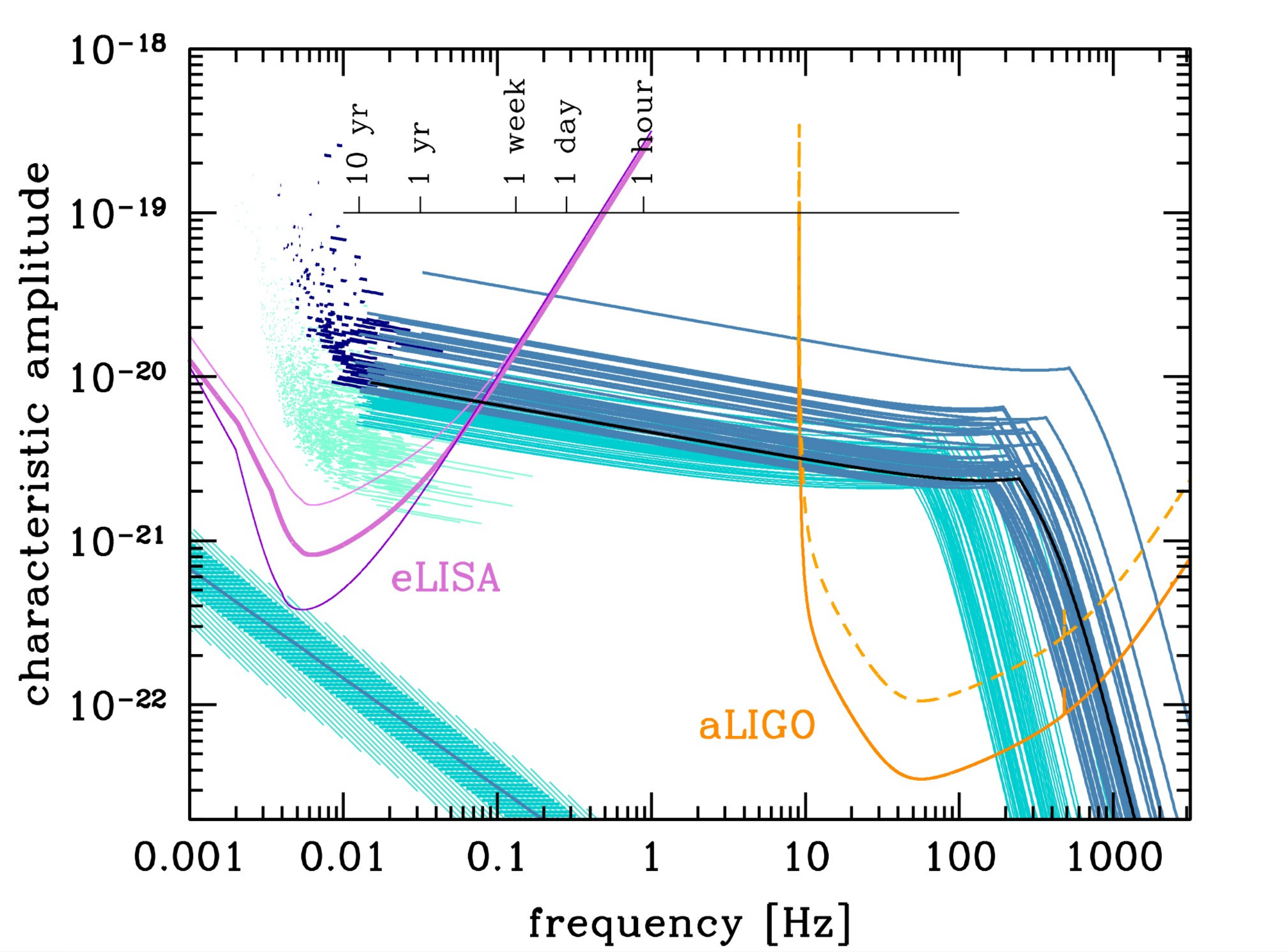
Generation: dipolar radiation

- Additional energy emission: $\dot{E} = \dot{E}_{GR}(1 + Bv^{-2})$
- PPE: $\beta \propto B$ $\quad b = -7/3$
- $B \propto (s_1 - s_2)^2$, s_i is the charge of the body i. For a scalar charge: $s_i = \left.\frac{\partial m_i}{\partial \phi}\right|_{\phi_0}$



Scheme of charged BH binary

Multiband astronomy



Multiband GW astronomy with Stellar Origin Black Holes (A.Sesana, PRL 2016)

Astrophysical systems

Adapted from simulated catalog by Alberto Sesana

	System 1	System 2	System 3
Masses (solar masses)	(40, 30)	(50, 45)	(60, 45)
Spins	(0.05, 0.02)	(-0.10, -0.33)	(0.78, 0.22)
Distance (Mpc)	250	767	550
Time to coalescence (years)	8.3	6.1	2.9
Observation time (years)	5.3	5.3	2.8
SNR	18	9.8	8.5

LISA signal generated using phenomenological waveform (PhenomD) and simulating LISA response

Bayesian Analysis

- Bayes theorem: $$p(\theta|d,\mathcal{H}) = \frac{p(d|\theta,\mathcal{H})p(\theta|\mathcal{H})}{p(d|\mathcal{H})}$$
- Sample the posterior using Markov Chain Monte Carlo
- Home made code designed to explore efficiently this very high dimensional problem (11-13 dimensions)

Parameter estimation

Run bayesian analysis only with GR parameters on GR signal

	System 1	System 2	System 3
Δm1/m1	1.5	1.2	1.2
$\Delta m_2/m_2$	0.56	0.49	0.51
$\Delta M_c/M_c$	$7.6\ 10^{-5}$	$5.8\ 10^{-5}$	$9.5\ 10^{-5}$
Δa_1	0.88	0.74	0.77
Δa_2	1.67	1.60	1.60
Δa_{eff}	0.55	0.2	0.44
$\Delta D_L/D_L$	0.44	0.62	0.99
ΔΩ (deg²)	0.62	0.95	0.98

$$M_c = \left(\frac{m_1^3 m_2^3}{m_1 + m_2}\right)^{1/5}$$

$$a_{eff} = \frac{m_1 a_1 + m_2 a_2}{m_1 + m_2}$$

Amplitude of the 90% confidence intervals

Constrains on dipolar radiation

Run bayesian analysis considering the possibility of having phenomenological modifications to GR on GR signal

	B
Current constrains	Binary pulsars: $<2 \times 10^{-9}$ Low Mass X-ray binary: $<4 \times 10^{-2}$
System 1	$< 5\ 10^{-11}$
System 2	$< 7\ 10^{-11}$
System 3	$< 3\ 10^{-10}$

Summary and perspectives

We have analyzed how well could LISA perform in the detection of Stellar Origin Binary Black Holes

Results:

- Poor determination of the individual masses and spins
- Good measurement of chirp mass, reasonably good measurement of the effective spin and good localization of the source
- We should be able to improve current constrains on dipolar radiation

Perspectives:

- Consider modifications to propagation of gravitational waves
- Combine with simulated observations by ground based detectors