Cosmology and Gravity in the New Era of Gravitational Waves Observations

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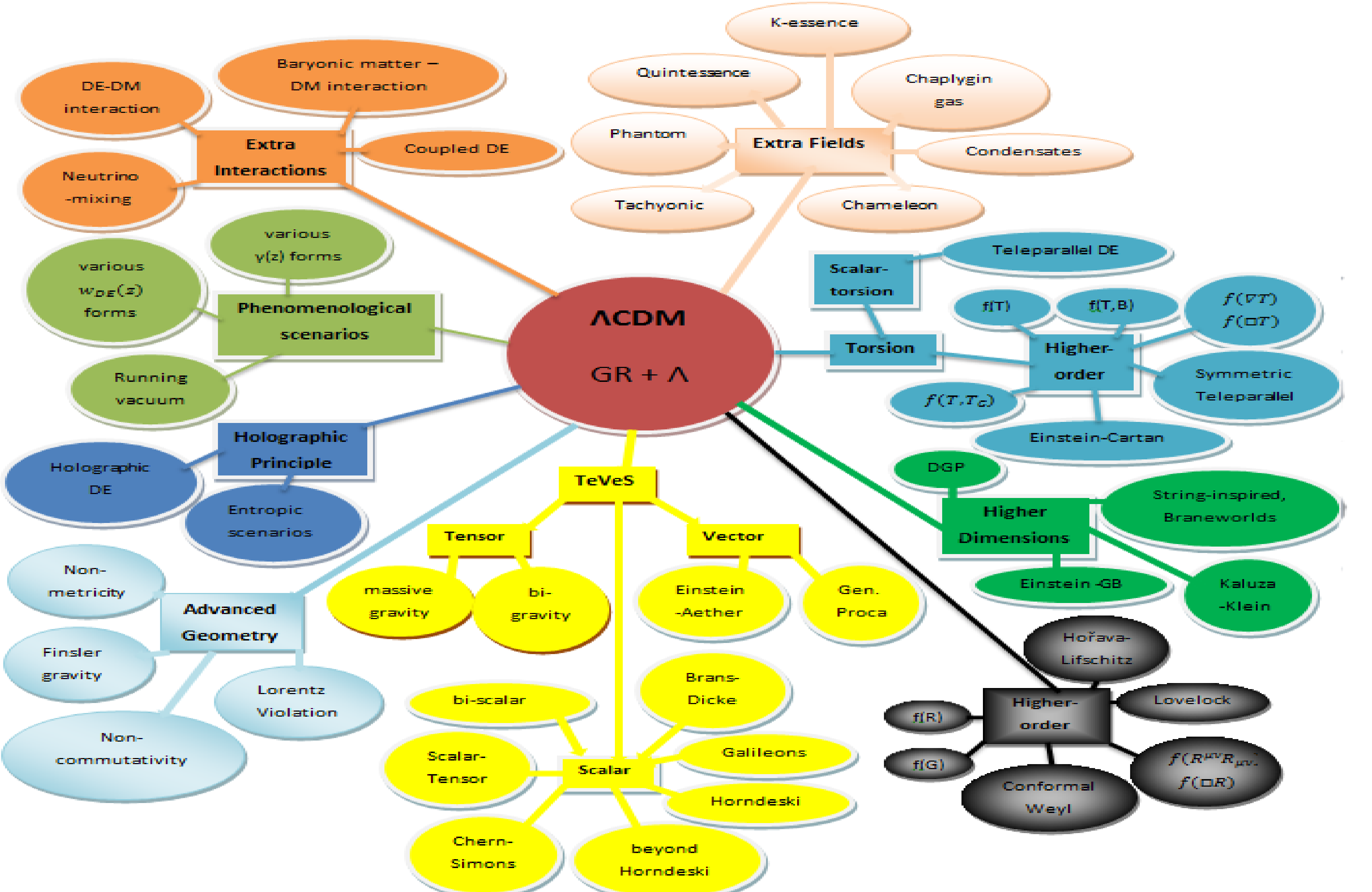
Standard Model of Cosmology

- ΛCDM concordance model is almost perfect!
- Issues of ΛCDM cosmology

1) General Relativity is non-renormalizable. It cannot get quantized.
2) The cosmological-constant problem. Calculation of Λ gives a number 120 orders of magnitude larger than observed.
   Worst error in the ~~history of physics~~, ~~history of science~~, history
3) How to describe primordial universe (inflation)
4) Tensions with some data sets, e.g. H0, fσ8, AL data
5) Missing galaxy satellites, curspy-core problems.

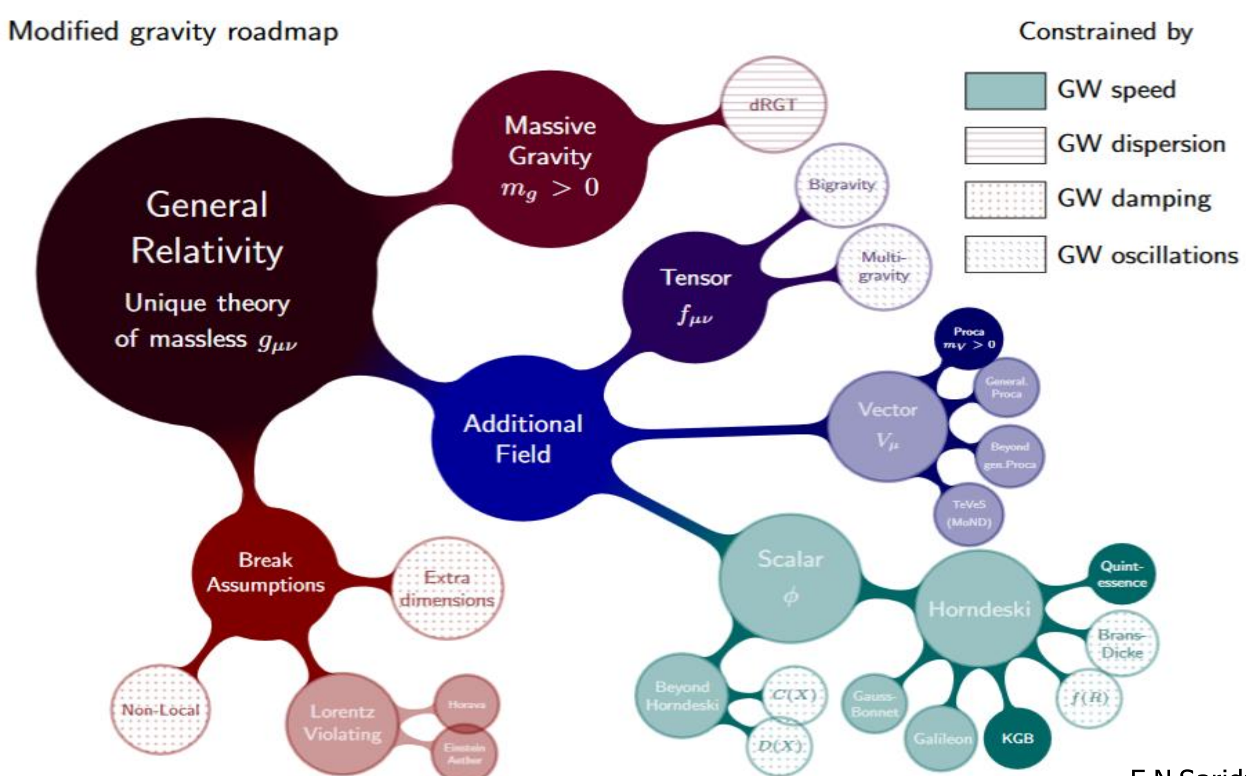
Modified Gravity



E.N.Saridakis – LISA in Greece, Feb 2022

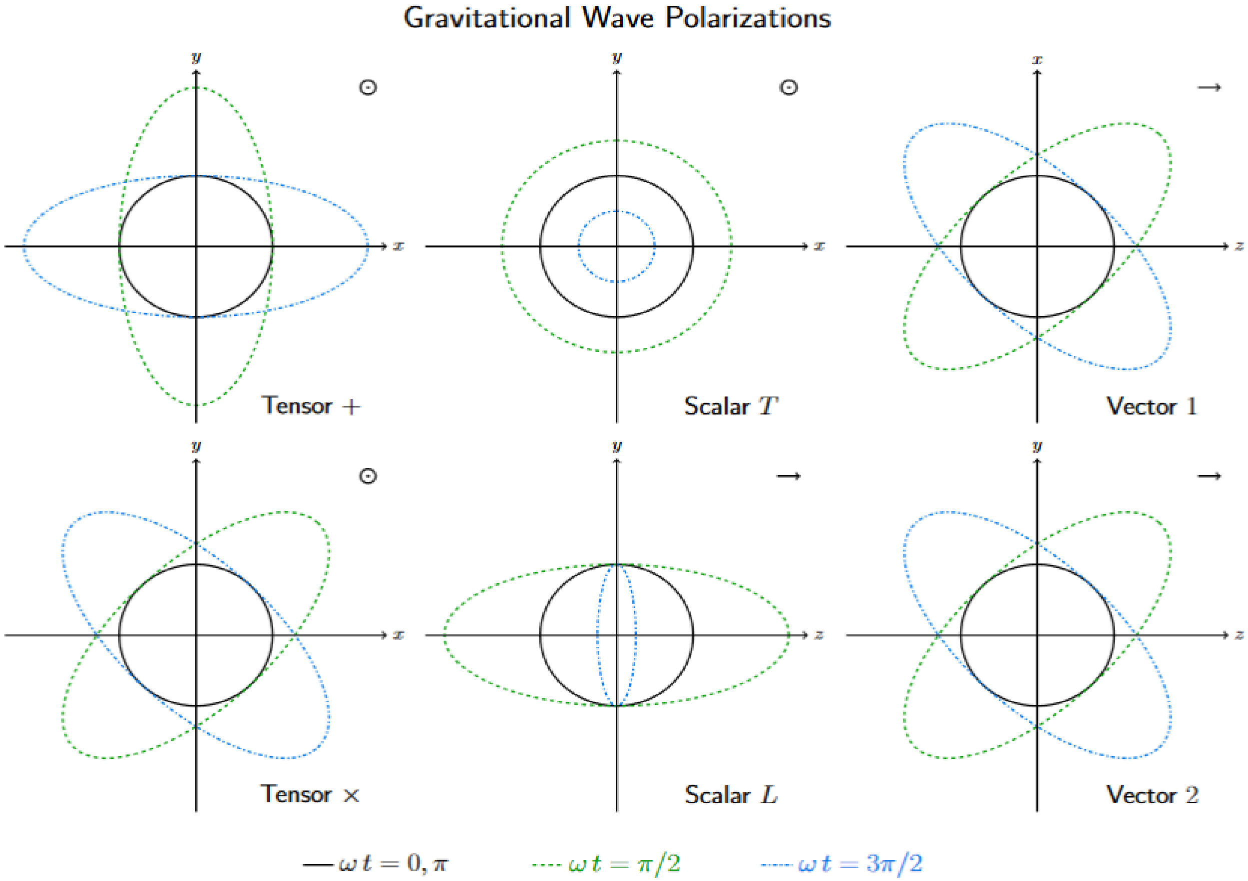
The New Tool: Gravitational Waves Observations

- Modified gravity changes both the signal and the propagation of GWs.
- Hence, GWs observations can act as an independent tool of testing General Relativity and constrain its possible modifications.



Smoking Gun of Modified Gravity

- Extra Polarizations:



Multi-messenger Astronomy

- In case of GWs from black hole mergers we know their properties at the moment of detection, and their direction (in case of three detectors). Assuming GR and ΛCDM we can extract their speed, distance, and properties at the moment of emission.

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- In case of GWs from neutron star mergers, and their E/M counterpart, we know their properties at the moment of detection and their direction, but using the implied physics from the E/M information we can extract their speed, distance and properties at the moment of emission, independently of the underlying gravitational theory and cosmological scenario.

- Great tool for testing General Relativity and cosmological scenarios!

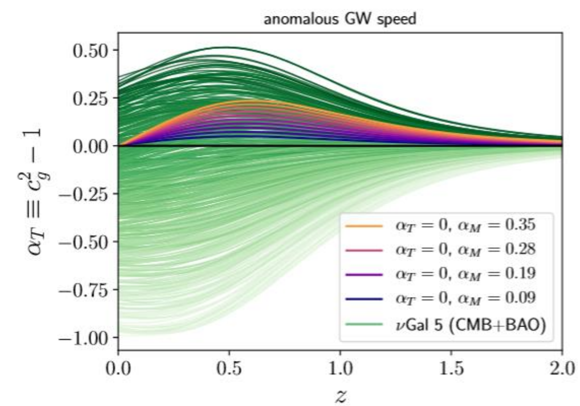
The power of GW observations

- An immediate result: The speed of GWs is equal to the speed of light!

GW170817 time delay $1.74 \pm 0.05\mathrm{s}$ constrains: $-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 7 \cdot 10^{-16}$

- Excludes a large number of theories that were consistent with other data (SnIa, CMB, BAO, H(z), LSS etc) !

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [46] Brans-Dicke/$f(R)$ [47, 48] Kinetic Gravity Braiding [50]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [49] $G_{\mu\nu}\phi^\mu\phi^\nu$ [51], $f(\phi)$·Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817



[Ezquiaga, Zumalacarregui PRL 119]

Gravitational waves in Modified Gravity

- For tensor perturbations: $g_{00} = -1\,, \quad g_{0i} = 0\,,$
  $g_{ij} = a^2(\delta_{ij} + h_{ij} + \frac{1}{2}h_{ik}h_{kj})$

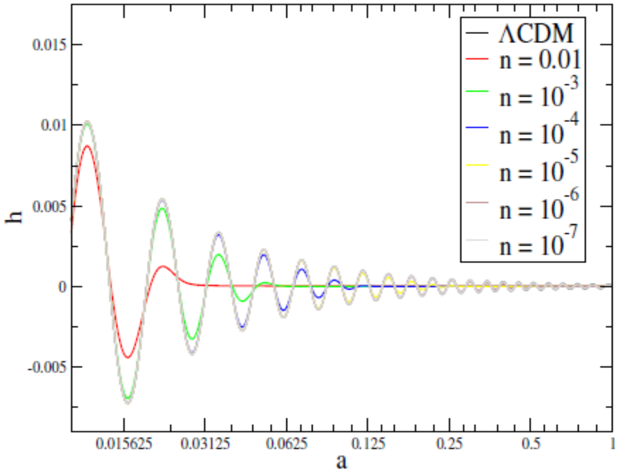
$$\ddot{h}_{ij} + (3 + \alpha_M)\dot{h}_{ij} + (1 + \alpha_T)\frac{k^2}{a^2}h_{ij} = 0$$

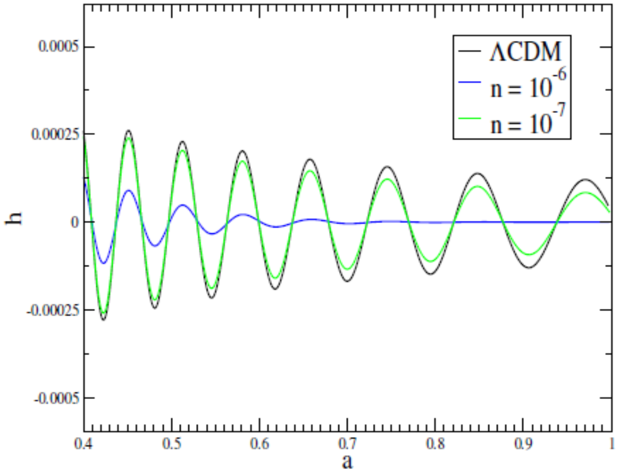
$$\alpha_M = \frac{d\log(M_*^2)}{d\log a} \qquad c_g^2 = (1 + \alpha_T)$$

- $$h_{\rm GW} \sim h_{\rm GR} \underbrace{e^{-\frac{1}{2}\int \nu \mathcal{H} d\eta}}_{\text{Affects amplitude}} \underbrace{e^{ik\int (\alpha_T + a^2 m^2/k^2)^{1/2} d\eta}}_{\text{Affects phase}}$$

Cosmology Group of NOA

- In the cosmology group of NOA we extract the properties of GWs in various modified theories of gravity.
- We use the GW data to test General Relativity and impose constrains.
- We perform analytical calculations and numerical elaboration (needs numerical gravity not only numerical relativity).



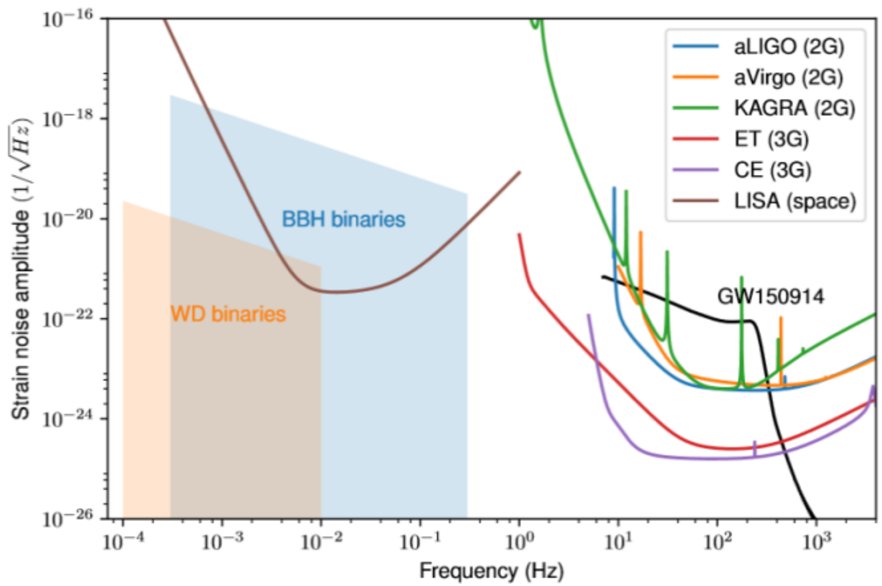


$$h^{(1)}_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 2\gamma_1^{(1)1} & {B_1}^2 \exp(ip_\mu x^\mu) & 0 \\ 0 & {B_1}^2 \exp(ip_\mu x^\mu) & -2\gamma_1^{(1)1} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

[Basilakos, Plionis, Saridakis, Papanikolaou, Anagnostopoulos, Lymperis, Assimakis, Papagiannopoulos, Tsiapi, Petronikolou, Tzerefos, Drepanou, Stasinou, Tsilioukas, Telali]

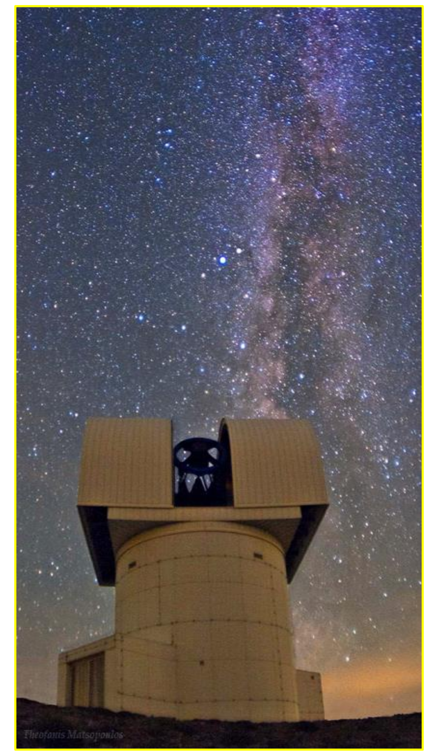
NOA <--> LISA

- i) LISA data will be crucial. Very interesting frequency range.



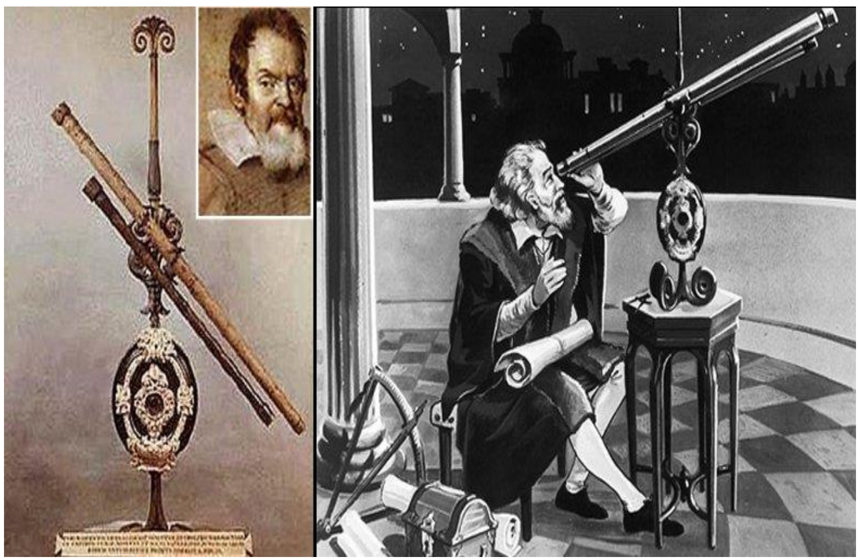
- ii) We can provide various possible deviations and signatures to test General Relativity.

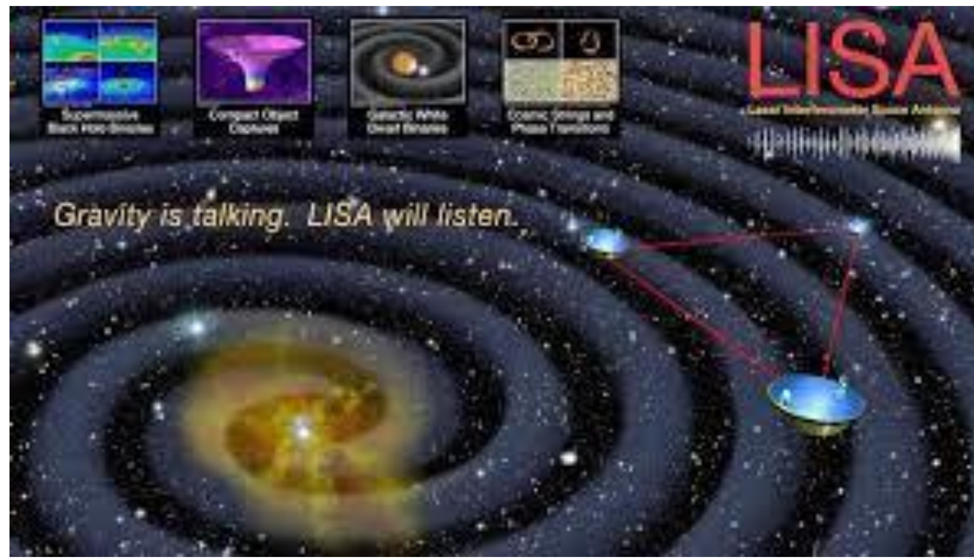
Aristarchos Telescope
Helmos Observatory



- It can be used to probe the EM counterparts of GWs form neutron star mergers.

A New Window in the Universe





EM observations: 400 years

GW observations: 6 years

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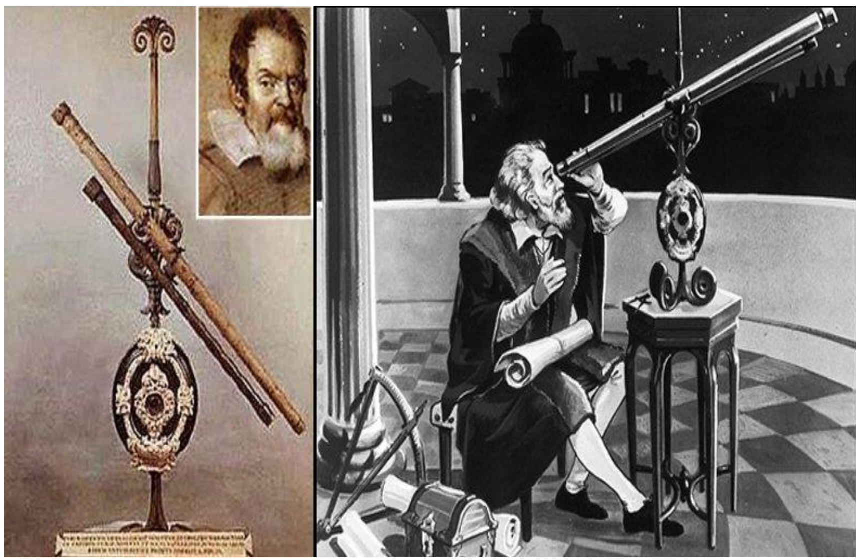

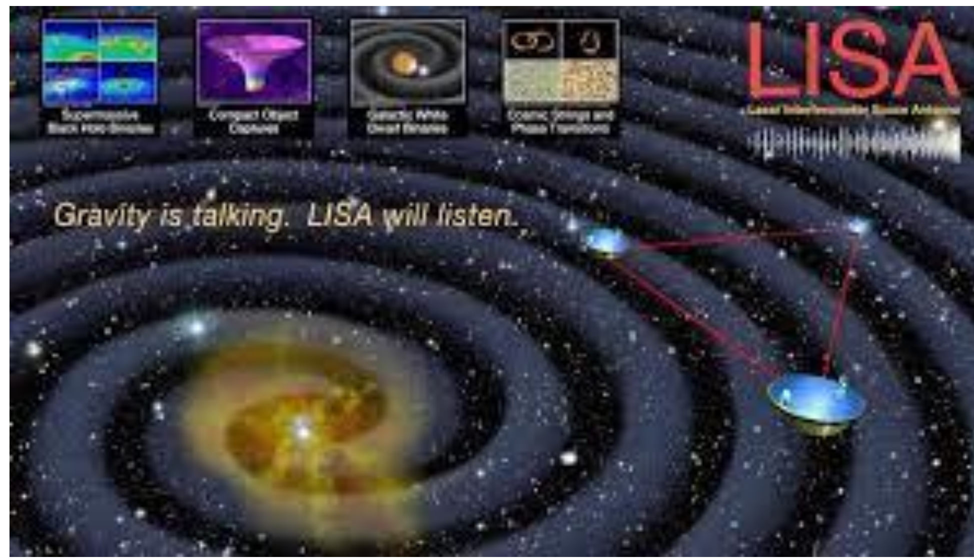

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THANK YOU!