Constraints on the speed of gravitational waves at high z

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Outline

1. Introduction and Motivation
2. Theoretical framework
    2.1. Gravitational waves in modified gravity
    2.2. Methodology and results
3. Summary and conclusions

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Introduction and Motivation

1. **Astronomical information from gravitational wave (GW) observations will open a new and wide spectrum of possibilities to investigate fundamental physics, which might shed light to clarify open questions in modern cosmology, especially regarding the dark sector of the Universe.**

2. **At present, one Binary Neutron Star (BNS) merger event has been detected, the GW170817 event, accompanied by its electromagnetic counterpart, the GRB 170817A event, located at 40 Mpc ($z \approx 0.01$).**

3. **This event was also the first standard siren (SS) observation, the GWs analog of astronomical standard candles, and opened the window for the multi-messenger GW astronomy.**

4. **Although the GW170817 event is located at very low z, preliminary cosmological information and consequences of this observation are important to the understanding of our Universe locally.**

5. **A very important consequence of this BNS signals was the strong bound placed on the GW speed, $|c_T /c - 1| \leq 10^{-16}$, where c_T and c are the propagation speed of the GWs and light, respectively.**

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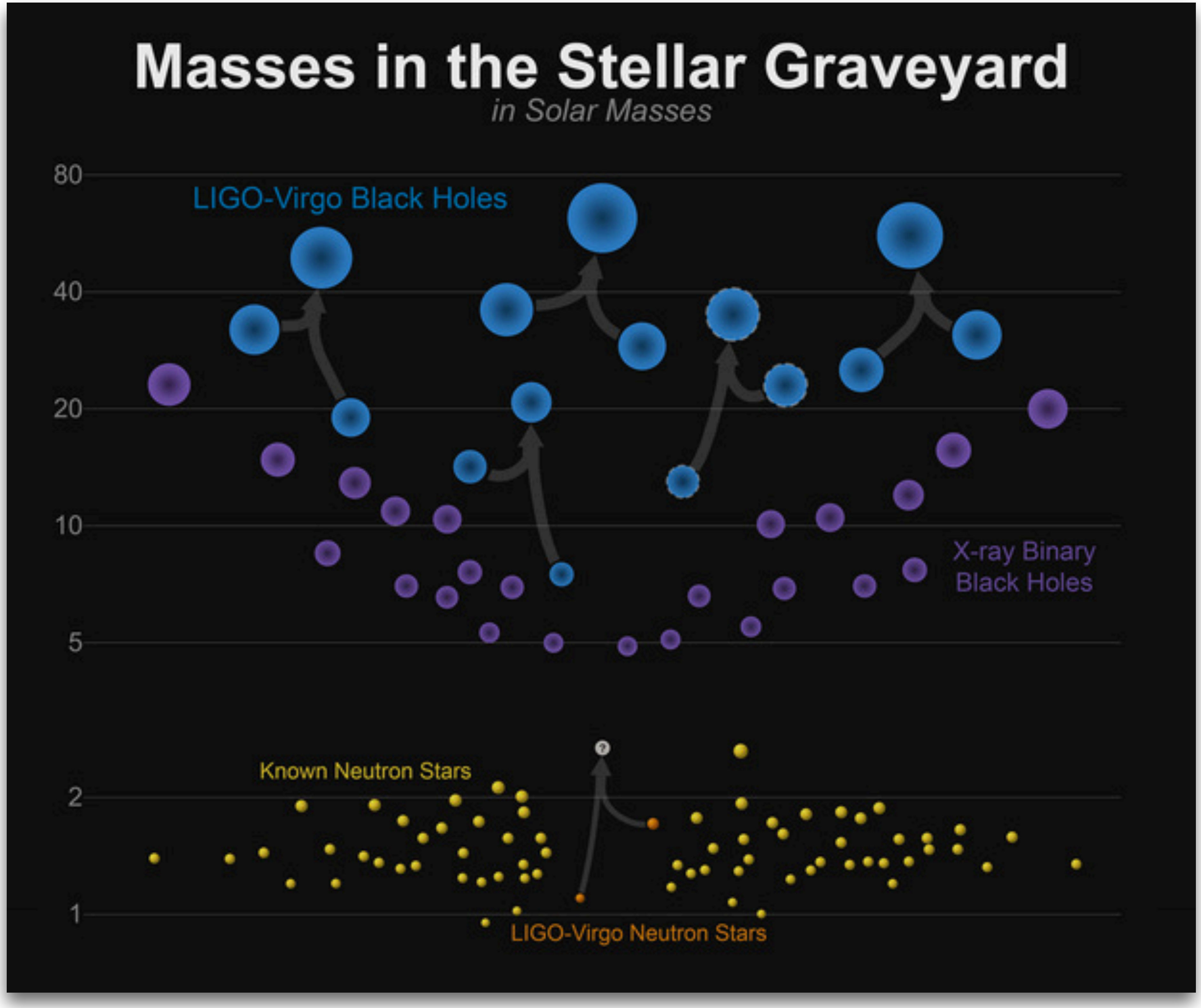
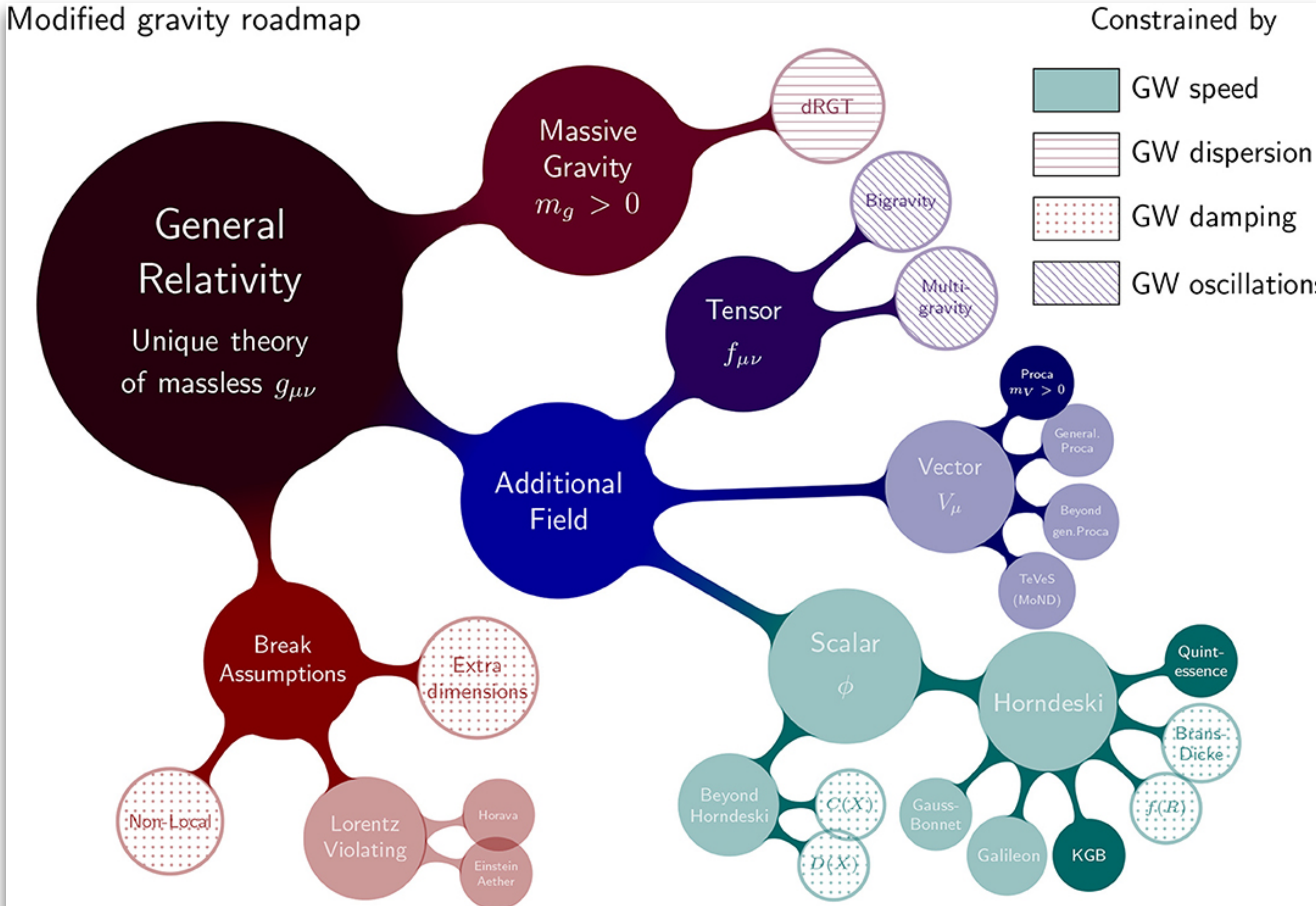
GravWaves in modified gravity



GravWaves in modified gravity



GravWaves in modified gravity

Horndeski action reads

$$S = \int d^4x\sqrt{-g}\left[\sum_{i=2}^{5} M_P^2\mathcal{L}_i + \mathcal{L}_m\right], \tag{1}$$

where g is the determinant of the metric tensor, and

$$\mathcal{L}_2 = G_2(\phi, X), \tag{2}$$
$$\mathcal{L}_3 = -G_3(\phi, X)\Box\phi, \tag{3}$$
$$\mathcal{L}_4 = -G_4(\phi, X)R + G_{4,X}[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}], \tag{4}$$
$$\mathcal{L}_5 = -G_5(\phi, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5,X}[(\Box\phi)^3 \tag{5}$$
$$+ 2\phi_{;\mu\nu}\phi^{;\mu\sigma}\phi^{;\nu}_{;\sigma} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi]. \tag{6}$$

Here, G_i (i runs over 2, 3, 4, 5) are functions of a scalar field ϕ and the kinetic term $X \equiv -1/2\nabla^\nu\phi\nabla_\nu\phi$, and $G_{i,X} \equiv \partial G_i/\partial X$. For $G_2 = \Lambda$, $G_4 = M_P^2/2$ and $G_3 = G_5 = 0$, we recover GR with a cosmological constant. For

$$M_*^2 = 2(G_4 - 2XG_{4X} + XG_{5\phi} - \dot{\phi}HXG_{5X})$$

Effective Planck mass

GravWaves in modified gravity

The most general tensor metric perturbation evolution, under the FRW metric, can be written as [39]

$$h''_A + (2+\nu)\mathcal{H}h'_A + (c_T^2 k^2 + \mu^2)h_A = \Pi_A \ , \qquad (1)$$

where h_A is the metric tensor perturbation, being $A = \{+, \times\}$ the label of the two polarization states, and $\mathcal{H}$ is the Hubble rate in conformal time. The quantities ν, c_T and μ represent the running of the effective Planck mass, the GW propagation speed and the effective graviton mass, respectively. The function Π_A denotes extra sources generating GWs, which we assume to be null.

$$\nu = \alpha_M$$

GravWaves in modified gravity

luminosity distance for non-trivial function ν and c_T satisfies the equation[1]

$$d_L^{GW}(z) = \sqrt{\frac{c_T(z)}{c_T(0)}} \exp\left[\frac{1}{2}\int_0^z \frac{dz'}{1+z'}\nu(z')\right] \times (1+z)\int_0^z \frac{c_T(z')dz'}{H(z')}, \tag{2}$$

where, for $\nu = 0$ and $c_T = 1$, we recover the general relativity case (ΛCDM cosmology), that is, $d_L^{GW}(z) = d_L^{EM}(z)$, where d_L^{EM} is the standard luminosity distance for an electromagnetic signal. Generalizations and inter-

GravWaves in modified gravity

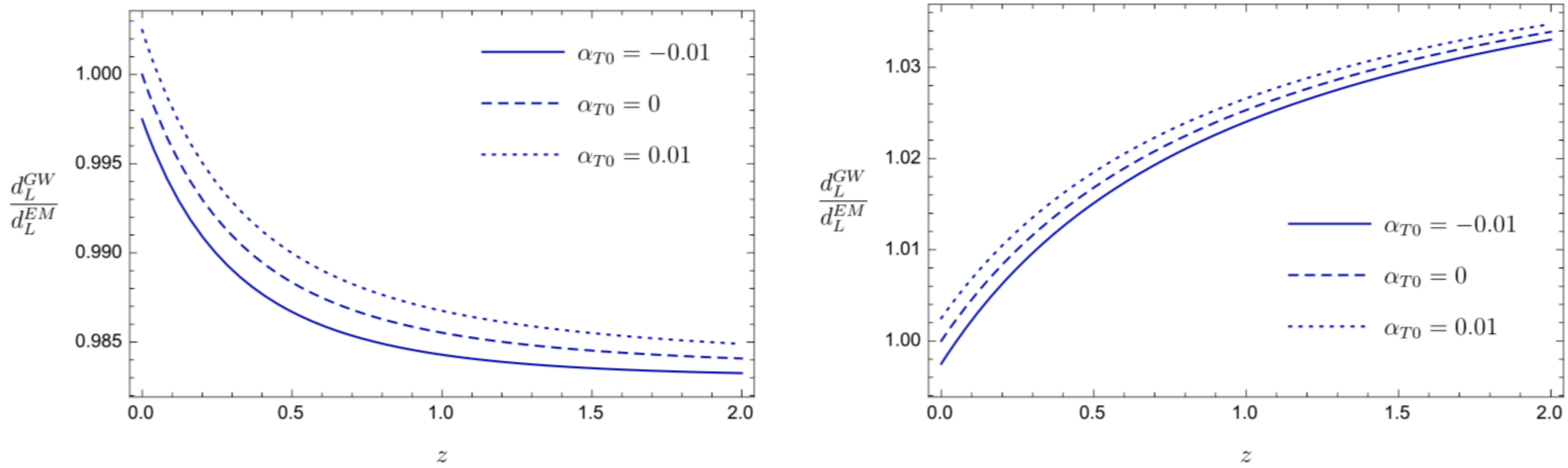


FIG. 1. Corrections on the effective GW luminosity distance (cf. Eq. (2)) as a function of the redshift for different values of the tensor speed excess α_{T0} with fixed values of α_{M0}. Left panel: $\alpha_{M0} = -0.1$, $n_1 = 3$, $n_2 = 1$. Right panel: $\alpha_{M0} = 0.1$, $n_1 = 1$, $n_2 = 1$. The limit $d_L^{EM}(z)/d_L^{EM} = 1$ represents general relativity.

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Introduction and Motivation

LIGO Laser Interferometer Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech and MIT

ET EINSTEIN TELESCOPE

DECIGO Space Gravitational Wave Antenna

$$c_T/c = 1 \text{ for } z < 0.1$$

Gravitational Wave Speed

$$c_T^2(z) = 1 + \alpha_T(z).$$

α_T (tensor speed excess)

$$\alpha_T = \alpha_{T0} a^{n_2}$$

Running of the Planck mass

$$\alpha_M = \frac{1}{HM_*^2}\frac{dM_*^2}{dt},$$

M∗ is the effective Planck mass

$$\alpha_M = \alpha_{M0} a^{n_1}$$

Methodology and results

GW strain signal

GW strain signal $h(t) = A(t)\cos[\Phi(t)]$,

Fourier transform

$$\tilde{h}(f) = Q\mathcal{A}f^{-7/6}e^{i\Phi(f)},$$

GW inspiral amplitude

$$\mathcal{A} = \sqrt{\frac{5}{96}}\frac{\mathcal{M}_c^{5/6}}{\pi^{2/3}d_L^{GW}}\left(\sum_{i=0}^{6}A_i(\pi f)^{i/3}\right)$$

$$Q^2 = F_+^2(1+cos^2(\iota))^2 + 2F_\times^2 cos^2(\iota)$$

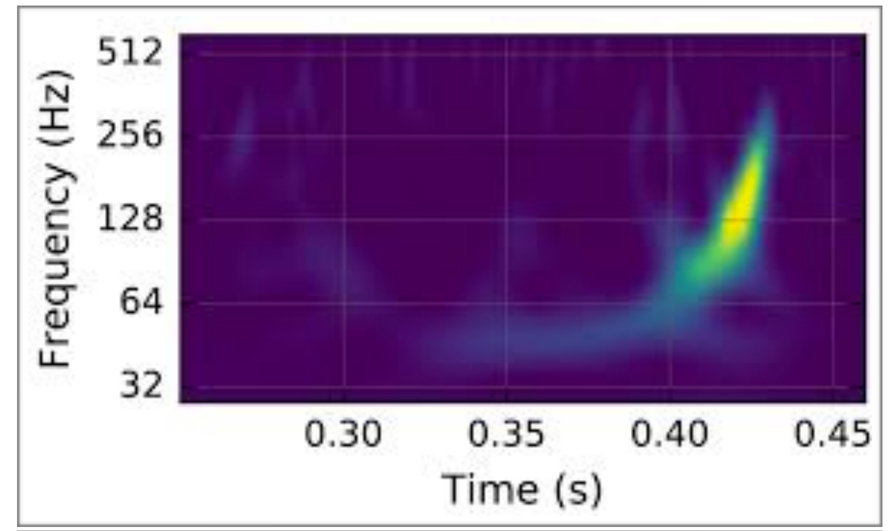
ι is the inclination angle of the binary orbital angular momentum with respect to the line of sight

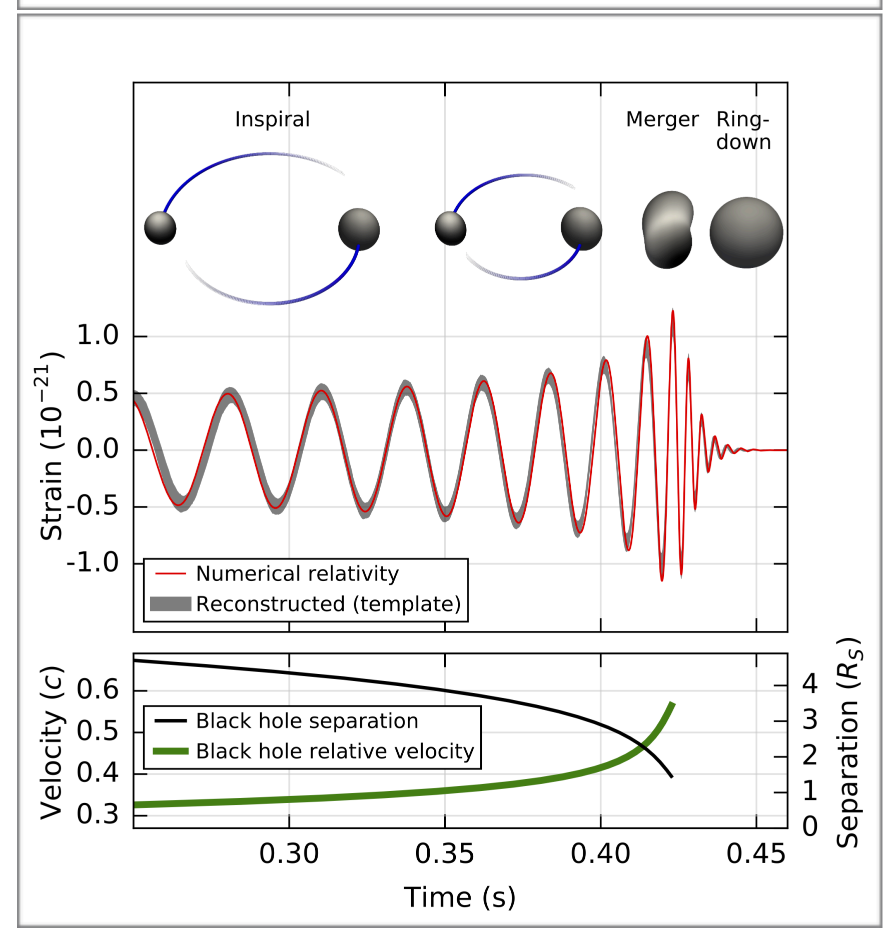
F_+^2 , $F_\times^2$ are the two antenna pattern functions

$$\Phi(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128\eta v^5}\left[1 + \sum_{i=2}^{7}\alpha_i v^i\right]$$

inspiral phase of the binary system

Waveform emitted by the binary system





Methodology and results

GW strain signal

Simulation: 1000 data points

$$\text{GW strain signal } h(t) = A(t)\cos[\Phi(t)],$$

Fourier transform **GW inspiral amplitude**

$$\tilde{h}(f) = Q\mathcal{A} f^{-7/6} e^{i\Phi(f)}, \quad \mathcal{A} = \sqrt{\frac{5}{96}} \frac{\mathcal{M}_c^{5/6}}{\pi^{2/3} d_L^{GW}} \left(\sum_{i=0}^{6} A_i (\pi f)^{i/3} \right)$$

$$Q^2 = F_+^2 (1 + cos^2(\iota))^2 + 2F_\times^2 cos^2(\iota)$$

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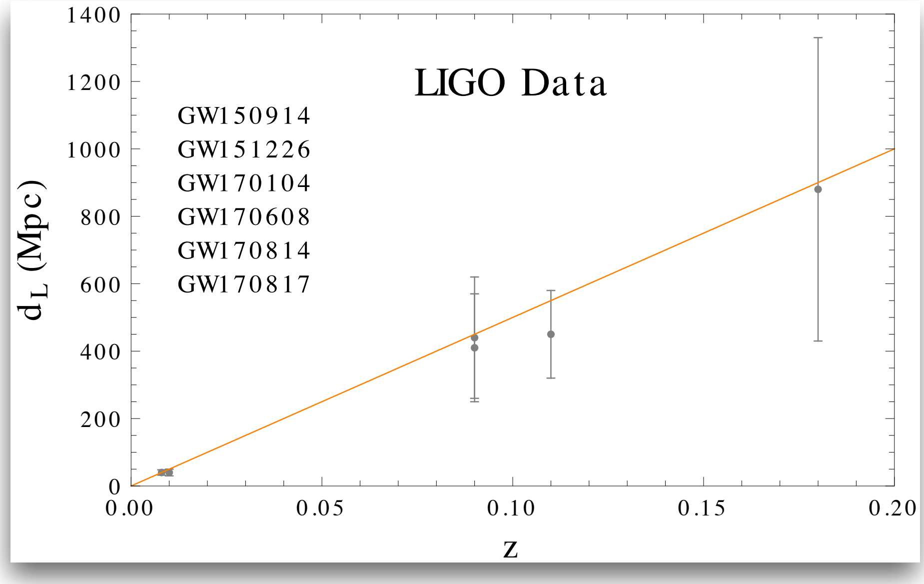
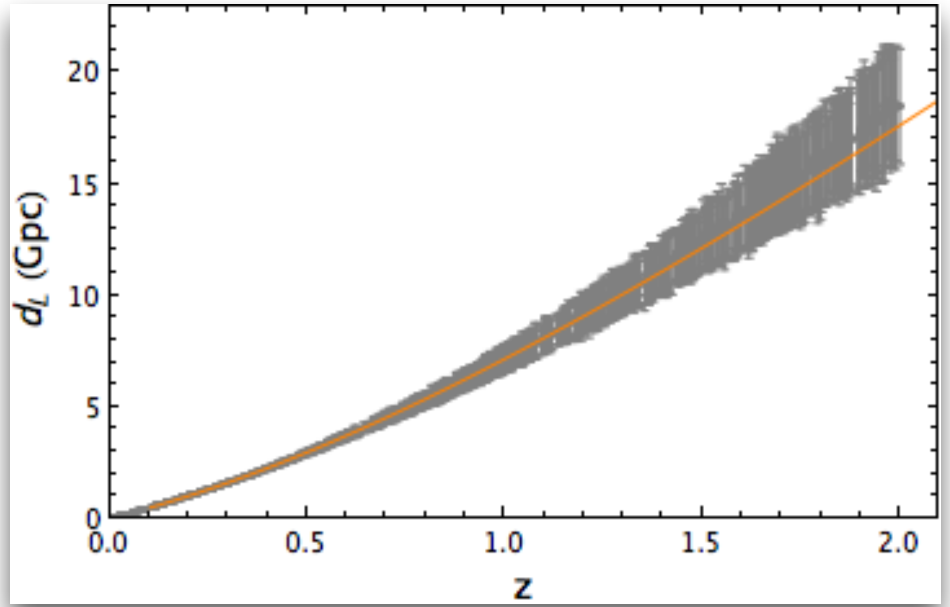
inspiral phase of the binary system





Methodology and results

$$F_{ij} = \sum_n \frac{1}{\sigma_{\rm ins}^2 + \sigma_{\rm lens}^2(z_n) + \sigma_v^2(z_n)} \frac{\partial d_L(z_n)}{\partial \theta_i} \frac{\partial d_L(z_n)}{\partial \theta_j} \, , \tag{6}$$

where the sum n runs over all standard sirens mock events. The derivatives are performed with respect to the cosmological parameters $\theta_i = \{H_0,\ \Omega_{m0},\ \alpha_{M0},\ \alpha_{T0},\ n_1,\ n_2\}$ evaluated at their fiducial input values. In our analysis, we used $\theta_i = \{67.4,\ 0.30,\ 0.0,\ 0.0,\ 3.0\ (1.0),\ 1.0\}$ as fiducial

Methodology and results

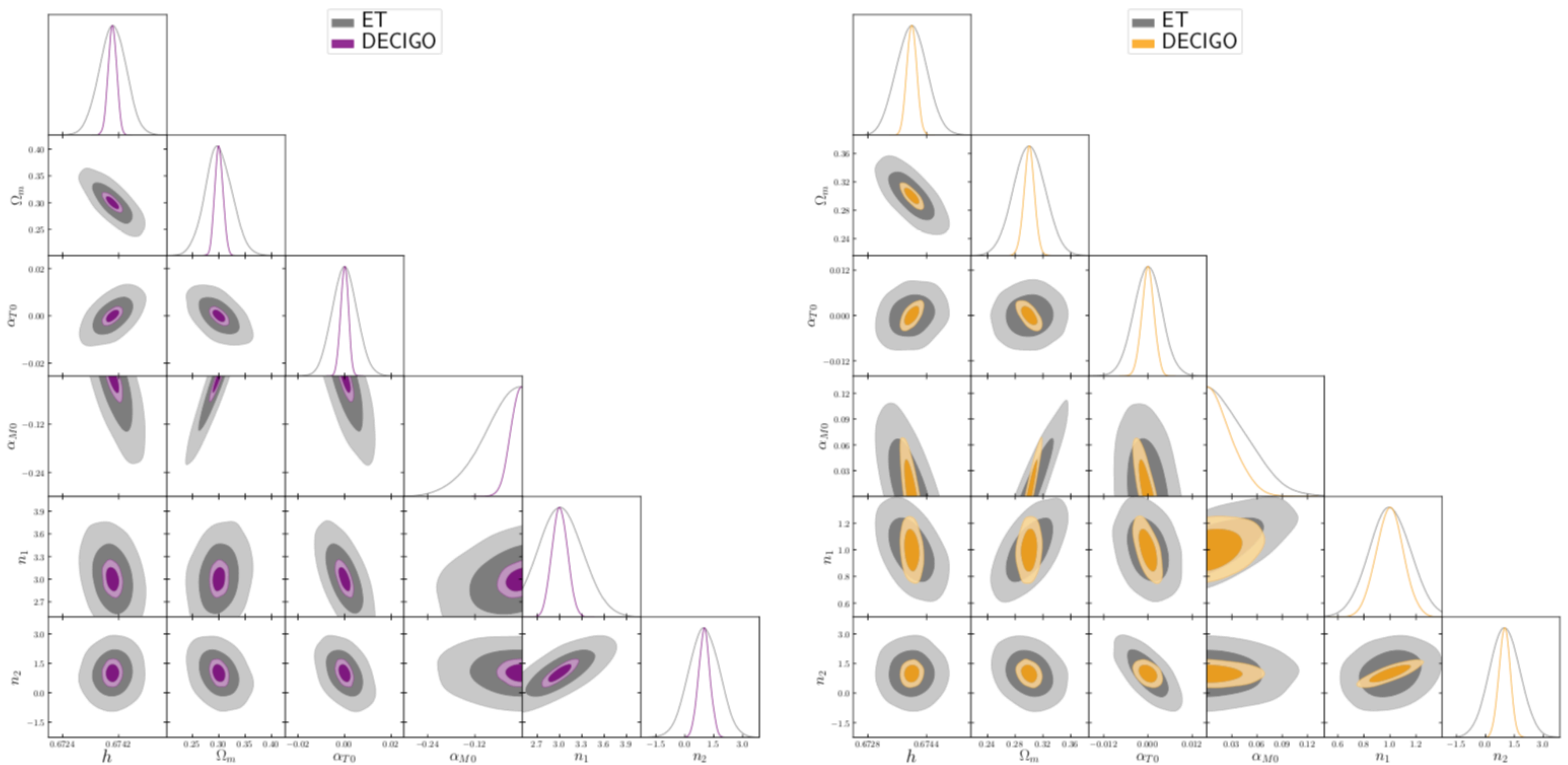


FIG. 3. One-dimensional marginalized distribution, and 68% and 95% C.L. regions for the parameters of the theoretical models under study, from the ET and DECIGO experiments. On the left panel and right panel, the stability conditions $\alpha_{M0} < 0$ and $\alpha_{M0} > 0$ are considered, respectively.

Methodology and results

IMPLICATIONS ON MODIFIED GRAVITY PHENOMENOLOGY

Parameter	σ(ET)	σ(DECIGO)
α_{T0}	0.0099	0.0033
α_{M0}	> -0.17	> -0.055
n_1	0.60	0.22
n_2	1.50	0.59

TABLE I. Forecast constraints from the ET and DECIGO experiments, under the stability condition $\alpha_{M0} < 0$. The notations σ(ET) and σ(DECIGO) represent the 95% C.L. estimation on the fiducial input values from ET and DECIGO, respectively.

Parameter	σ(ET)	σ(DECIGO)
α_{T0}	0.0077	0.0032
α_{M0}	< 0.091	< 0.052
n_1	0.31	0.21
n_2	1.50	0.59

TABLE II. Forecast constraints from the ET and DECIGO experiments, under the stability condition $\alpha_{M0} > 0$. The notation is the same as in Table I.

Within the Horndeski theories of gravity

$$M_*^2 \alpha_T = 2X(2G_{4X} - 2G_{5\phi} - (\ddot{\phi} - \dot{\phi})G_{5X})$$

scalar field couples to the Einstein tensor

$$\xi \phi G_{\mu\nu} \nabla^\mu \nabla^\nu \phi$$

The parameter ξ represents the coupling constant of the theory and quantifies possible **anomalies** on the GWs speed propagation.

$$M_*^2 \alpha_T = 2\xi \dot{\phi}^2.$$

$$G_4 = M_{pl}^2/2 \text{ and } G_5 = \xi\phi.$$

$$c_T^2 = 1 + \frac{2\dot{\phi}^2}{M_*^2}\xi \ .$$

At intermediate z, it is reasonable to assume $\dot{\phi}/M_* \simeq 1$, so that we estimate $-0.005 < \xi < 0.006$ ($-0.002 < \xi < 0.002$) at the 95% C.L. from ET (DECIGO), in the case $\alpha_{M0} < 0$.

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Summary and conclusions

1. **Due to extra degrees of freedom of gravitational origin, modified gravity models predict physical properties beyond the standard features of general relativity.**

2. **Motivated by this aspect, we thus performed a forecast analysis using 1000 standard siren events from BNS mergers, within the sensitivity predicted for ET and DECIGO up to z = 2 (~ 15539 Mpc).**

3. **We found |cT/c – 1| ≤ 10^-2 (10^-3) from ET (DECIGO), which leaves room for small possible corrections predicted by alternative theories, compared to the only information from GW170817 event at very low z.**

4. **Nevertheless, the main findings of this work represent the first observational constraints obtained by using information from SS mock data from future detector design.**

5. **In this respect, our results open a new window for possible tests on $c_T(z)$ in the future.**

Bibliography

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Constraints on the speed of gravitational waves at high z

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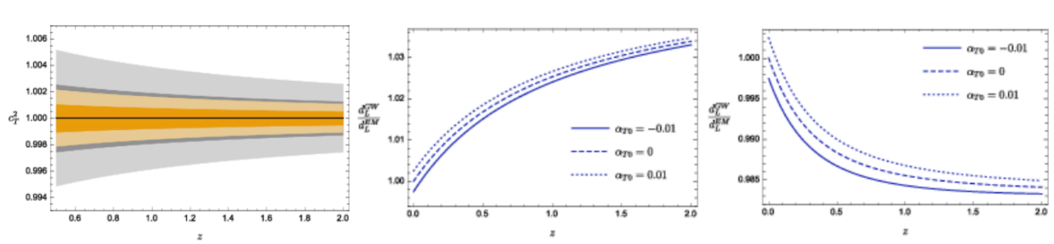
Oct 12, 2019 - 8 pages

e-Print: arXiv:1910.05631 [gr-qc] | PDF

Abstract (arXiv)
The observation of GW170817 binary neutron star (BNS) merger event has imposed strong bonds on the speed of gravitational waves (GWs) locally, inferring that the speed of GWs propagation is equal to the speed of light. Current GW detectors in operation will not be able to observe BNS merger to long cosmological distance, where possible cosmological corrections on the cosmic expansion history are expected to play an important role, specially for investigating possible deviations from general relativity. Future GW detectors designer projects will be able to detect many coalescences of BNS at high z, such as the third generation of the ground GW detector called Einstein Telescope (ET) and the space-based detector deci-hertz interferometer gravitational wave observatory (DECIGO). In this paper, we relax the condition $c_T/c = 1$ to investigate modified GW propagation where the speed of GWs propagation is not necessarily equal to the speed of light. Also, we consider the possibility for the running of the Planck mass corrections on modified GW propagation. We parametrize both corrections in terms of an effective GW luminosity distance and we perform a forecast analysis using standard siren events from BNS mergers, within the sensitivity predicted for the ET and DECIGO. We find very strong constraints on the running of the Planck mass, namely $\mathcal{O}(10^{-1})$ and $\mathcal{O}(10^{-2})$ from ET and DECIGO, respectively. Possible anomalies on GW propagation are bound to $|c_T/c - 1| \leq 10^{-2}$ (10^{-3}) from ET (DECIGO). We finally discuss the consequences of our results on modified gravity phenomenology.

Note: 8 pages, 7 figures
Keyword(s): INSPIRE: * Automatic Keywords * | scale: Planck | photon: velocity | mass: correction | neutron star: binary | gravitation: model | family: 3 | propagation | gravitational radiation | Einstein Telescope | general relativity | interferometer | observatory | sensitivity | coalescence | anomaly | history



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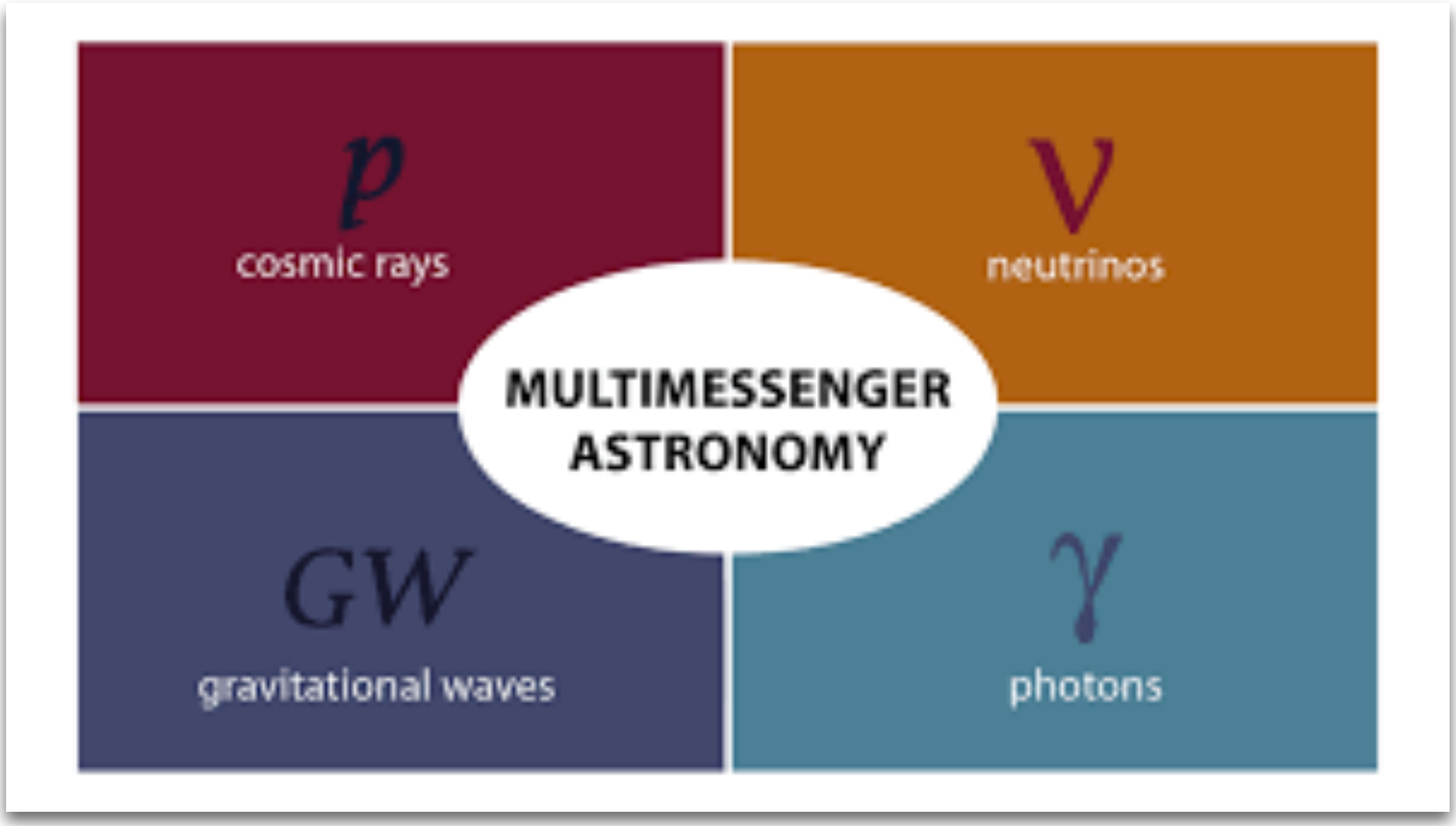
Introduction and Motivation



Introduction and Motivation

The Effective Planck Mass and the Scale of Inflation

$$\alpha_M = \frac{1}{HM_*^2}\frac{dM_*^2}{dt},$$

Running of the Planck mass

$$V_*^{1/4} = M_*\left(\frac{3\pi^2 \mathcal{A} r_*}{2\cdot 10^{10}}\right)^{1/4}$$

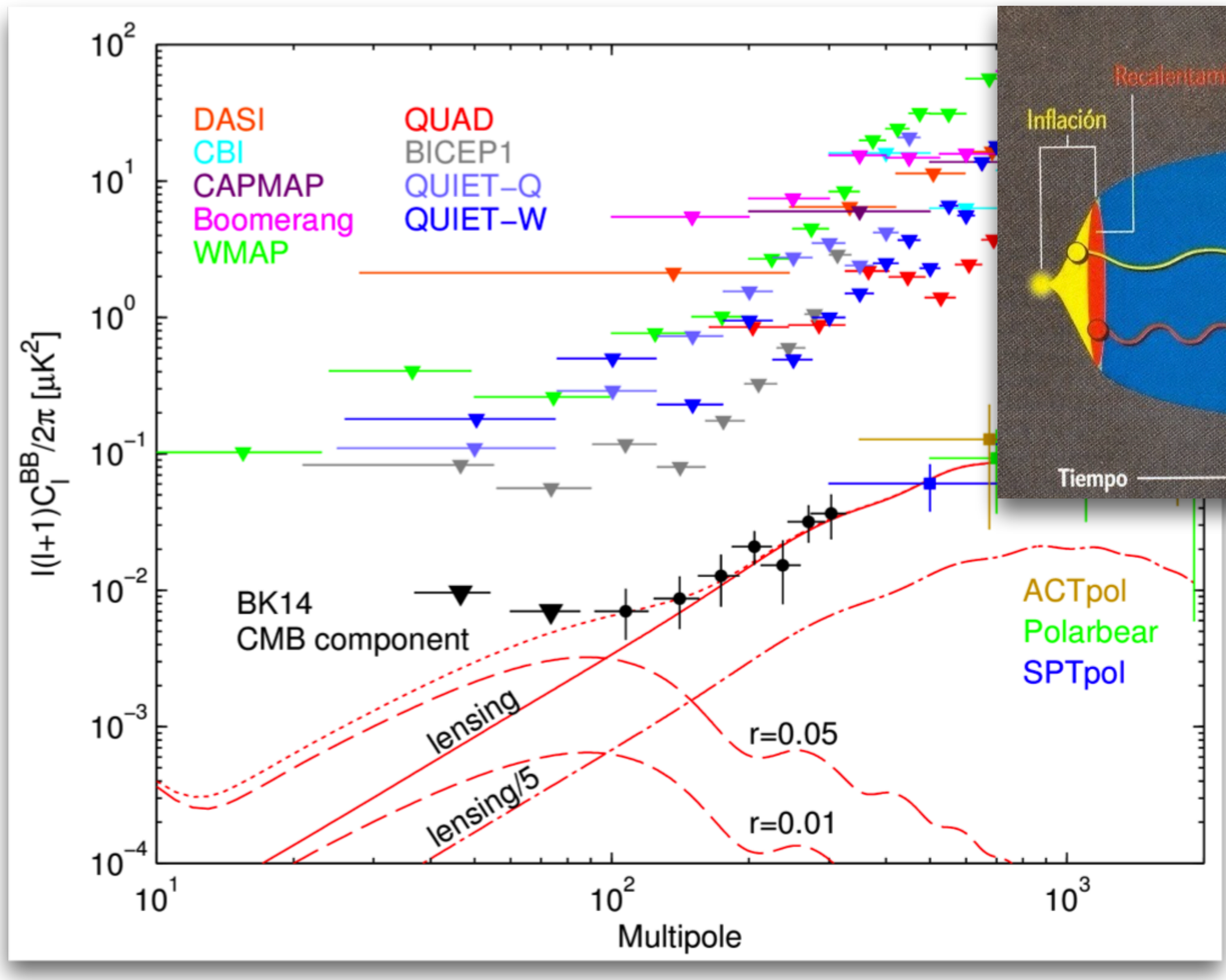
$$M_* \sim \frac{M_{\rm pl}}{\sqrt{N}}$$

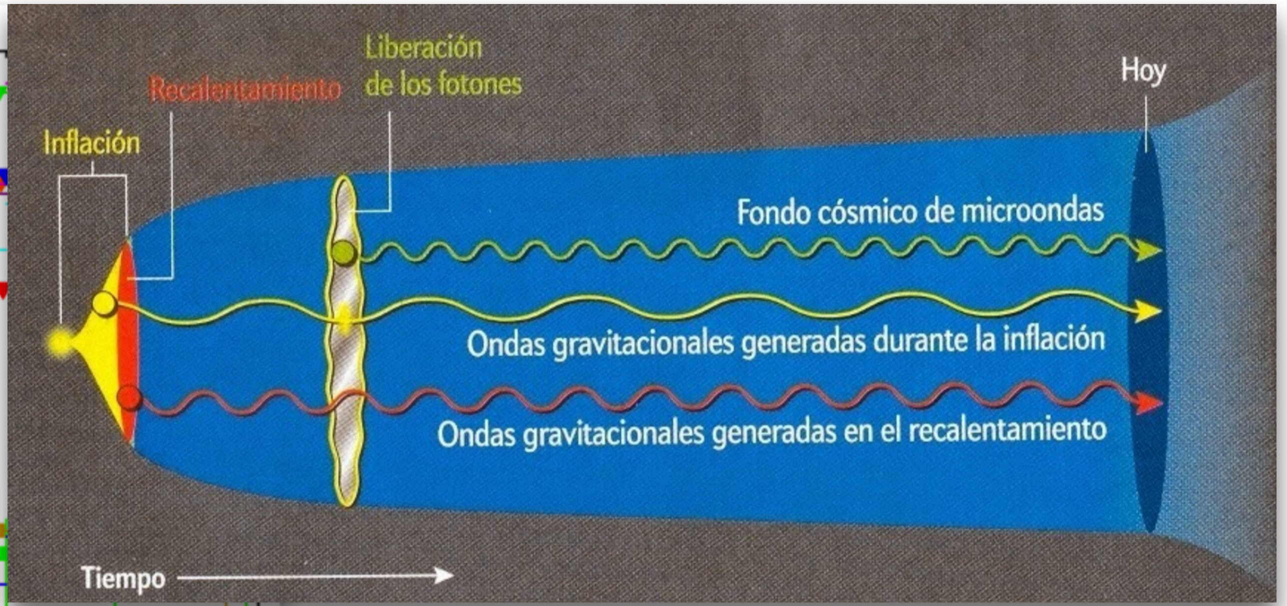
$$r_* := \frac{\mathcal{P}_\gamma}{\mathcal{P}_\mathcal{R}} = 16\epsilon_*.$$

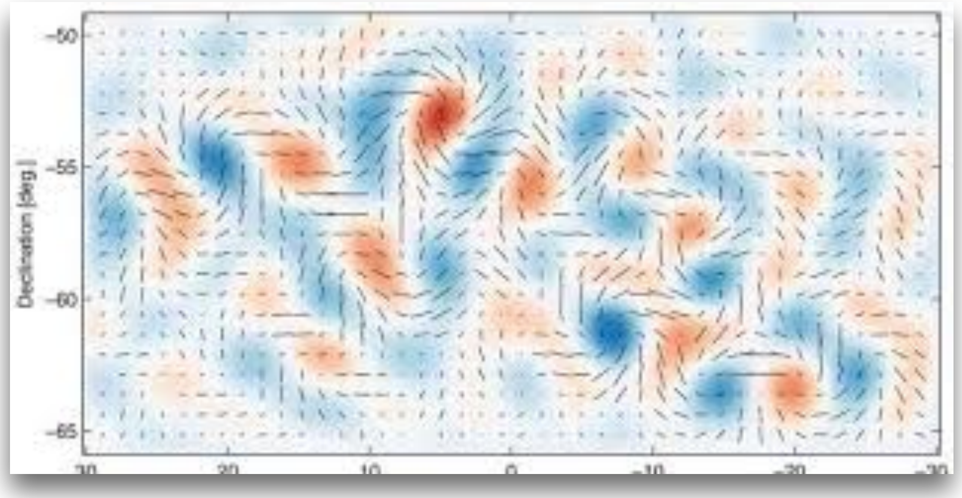
$$\epsilon_* := -\dot{H}_*/H_*^2$$

- N central charge ($N\phi$ scalars, $N\psi$ Dirac fermions and NV vector bosons).
- $M_{pl} = 2.435\times10^{18}$ GeV reduced Planck mass.
- $M*$ is the effective Planck mass.
- $H*$ being the Hubble factor during inflation.
- $r*$ tensor to scalar ratio.
- A ~ 22.15 relates to the amplitude of the late time CMB anisotropies.

Introduction and Motivation







Any collaboration will be welcome...!