Next Generation Event Horizon Telescope

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We will observe gravitational waves in space

Forecasts on the speed of gravitational waves at high z

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XIV Latin American Symposium
on High Energy Physics
Ecuador, November 14 -18, 2022
Universidad San Francisco de Quito

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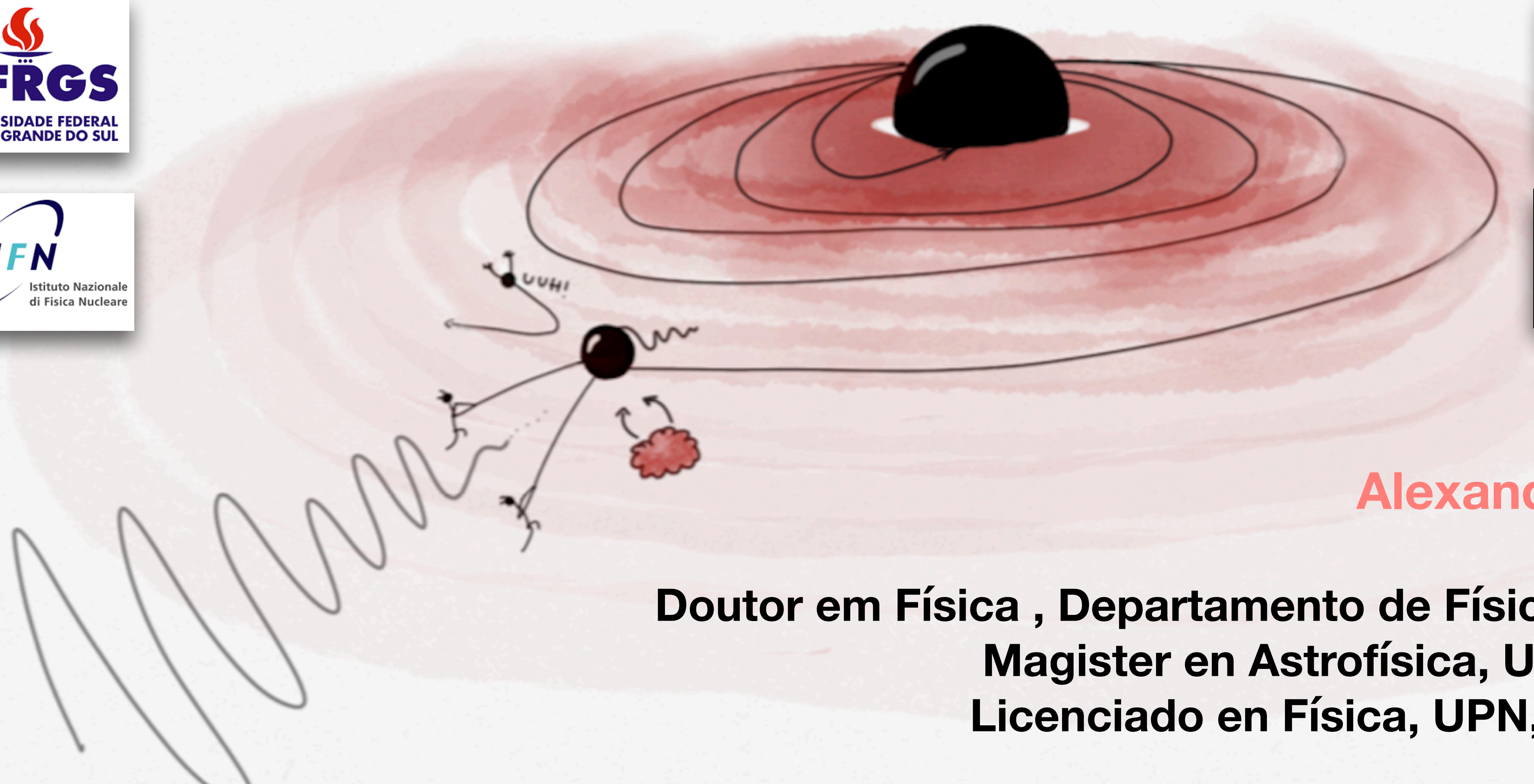
FRANCISCO JOSÉ DE CALDAS
Acreditación Institucional de Alta Calidad



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Cosmology /Astrophysics & Fundamental Physics, PI-UN-UD/ Laser Interferometer Space Antena (LISA Cosnsortium)

Galaxies /Cosmology & Fundamental Physics SWG's / next generation Event Horizon Telescope (ngEHT)

Based on: arXiv 1910.05631, in collaboration with: Rafael Nunes (UFRGS-Bra), Rocco D'Agostino (U Napoles-Ita)

Outline

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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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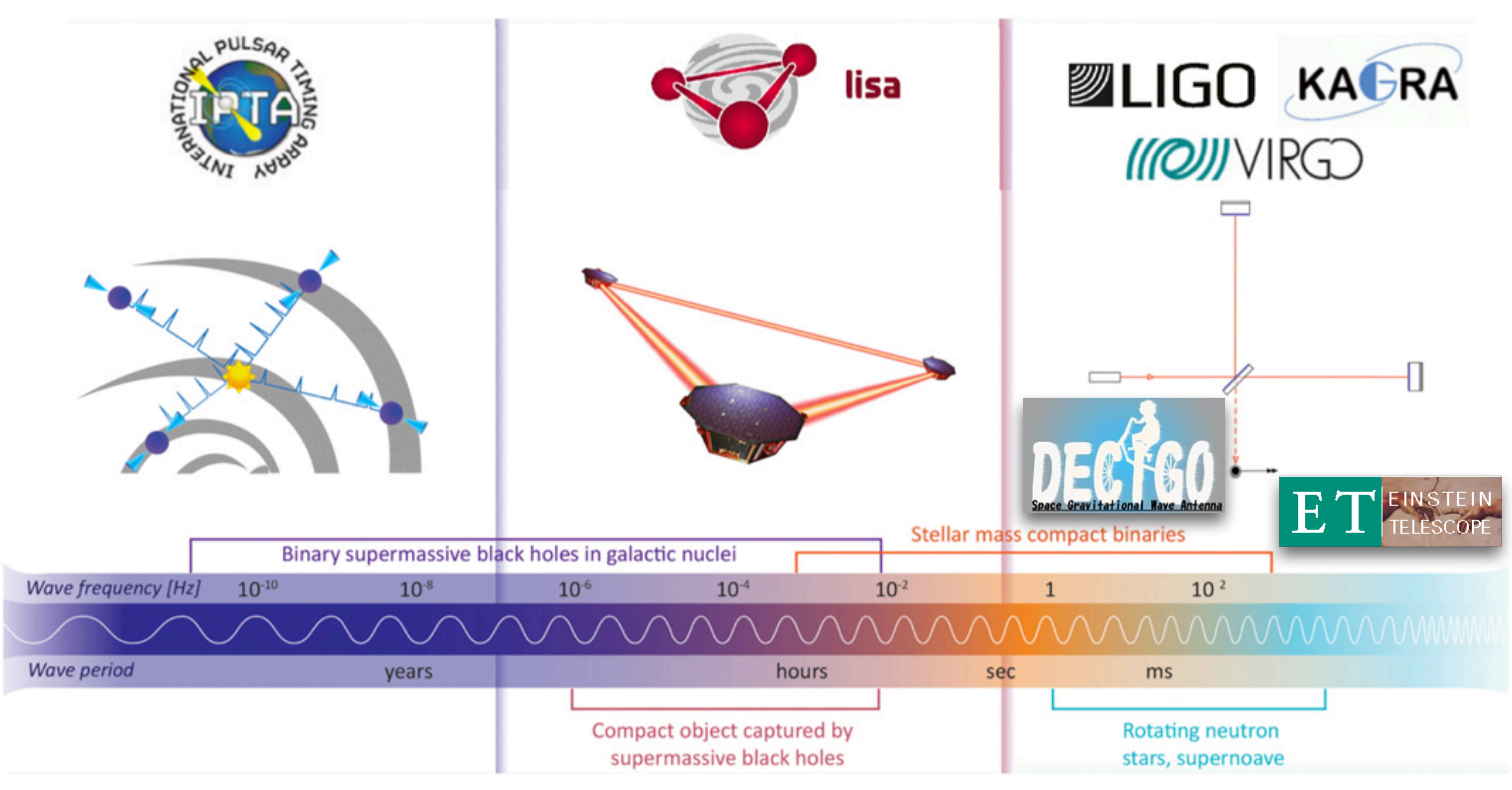

INTERNATIONAL PULSAR TIMING ARRAY
IPTA
lisa
LIGO
KAGRA
VIRGO
DECIGO
Space Gravitational Wave Antenna
ET EINSTEIN TELESCOPE
Binary supermassive black holes in galactic nuclei
Stellar mass compact binaries
Wave frequency [Hz]
10^-10
10^-8
10^-6
10^-4
10^-2
1
10^2
Wave period
years
hours
sec
ms
Compact object captured by supermassive black holes
Rotating neutron stars, supernoave

Introduction and Motivation

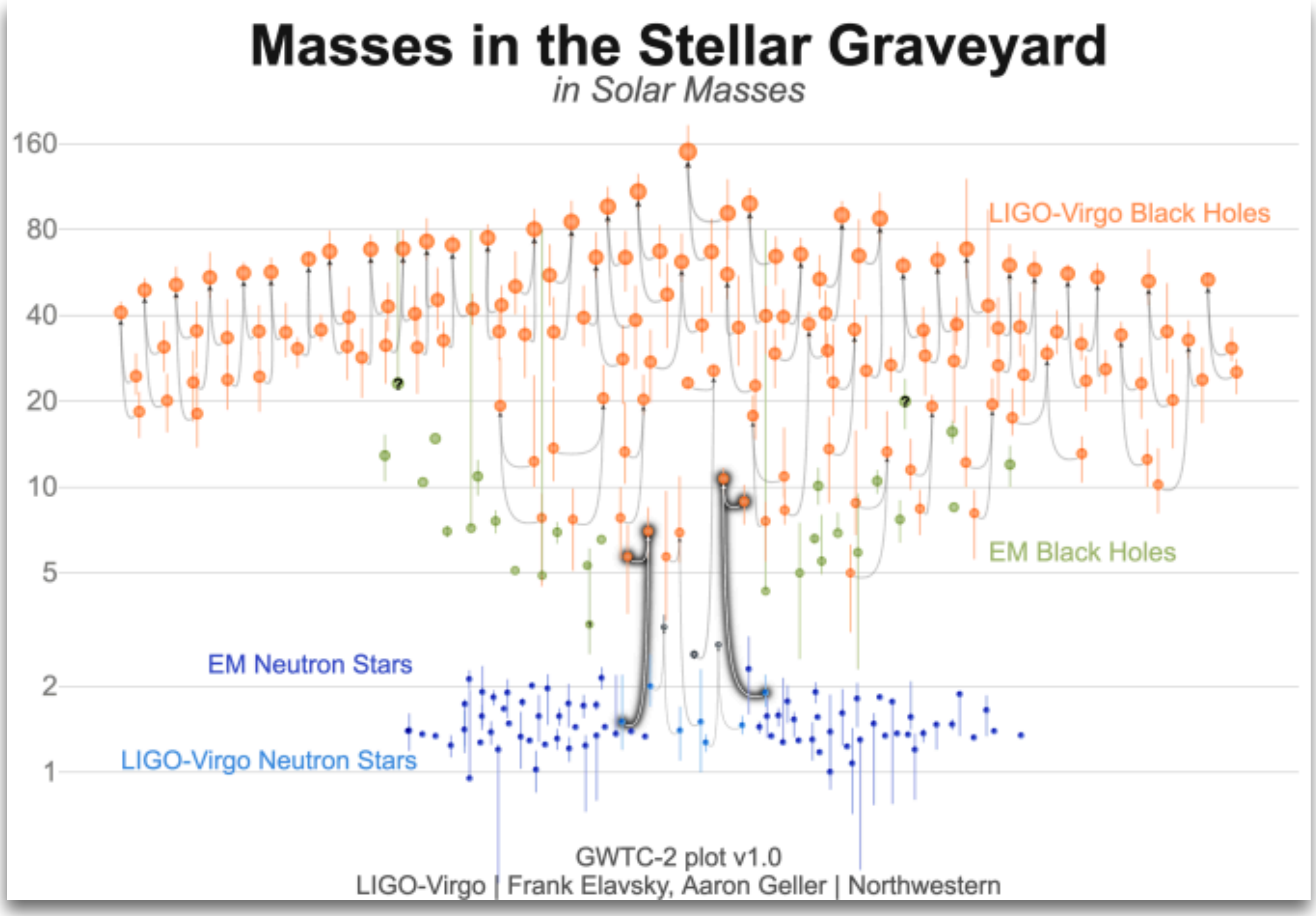
1. The observation of GW170817 binary neutron star (BNS) merger event has imposed strong bounds on the speed of gravitational waves (GWs) locally, inferring that the speed of GWs propagation is equal to the speed of light $c_T/c = 1 \left(|c_T/c - 1| \leq 10^{-16} \right)$, where c_T and c are the propagation speed of the GWs and electromagnético radiation, respectively.

2. 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

3. 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).

4. In this work, 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.

Introduction and Motivation



Introduction and Motivation

Some theoretical problems with the standard model of cosmology…!

1. COSMIC COINCIDENCE PROBLEM: ¿Why the density of matter and dark energy today are of the same order of magnitude?.
2. Fine-Tuning PROBLEM: ¿Why is the cosmological constant so small?
3. QUANTUM VACUUM ENERGY DENSITY: ¿Why the calculated value of the cosmological constant from quantum field theory is 120 orders of magnitude larger than the observed?

Introduction and Motivation

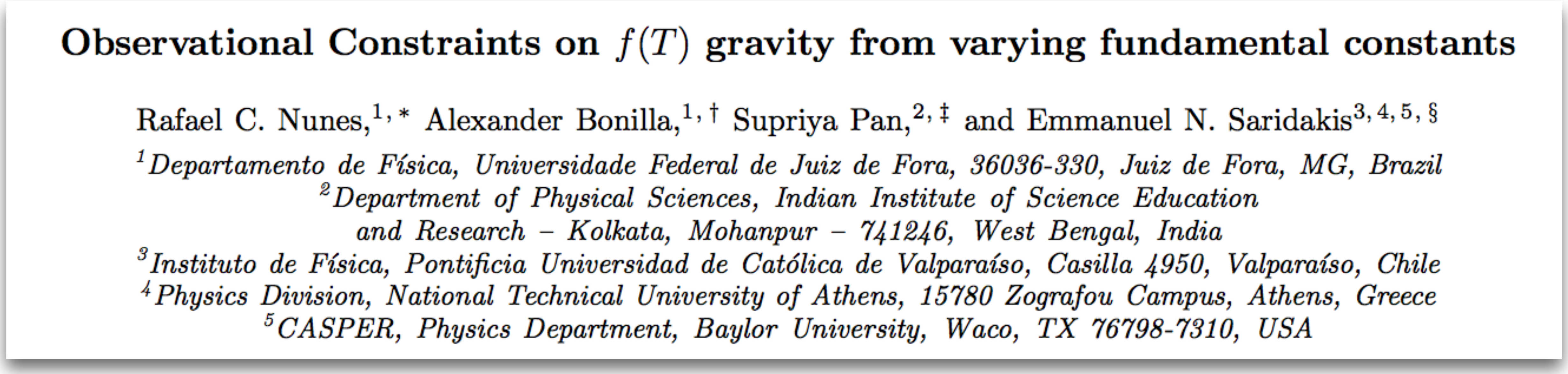
$$G_{\mu\nu} + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

1. Alternative models of dark Energy: wCDM ($w \neq -1$), Chevalier-Polarski-Linder (CPL), Interacting Dark Energy (IDE), Generalized Chapliygin Gas (GCG)..etc.

2. Modified Gravity: f(R), f(T), Massive Gravity, Tensor, Vector, Scalar (Horndeski).

3. Holographic Dark Energy: Tsallis' entropy, Kaniadakis statistics, Fluid/Gravity Duality .

Introduction and Motivation



Observational Constraints on $f(T)$ gravity from varying fundamental constants

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$$\frac{\Delta\alpha}{\alpha}(z) \approx \frac{\left[1 - b\left(\frac{1-\Omega_{m0}}{2b-1}\right)\right]}{\left\{1 - b\left(\frac{1-\Omega_{m0}}{2b-1}\right)\left[\frac{H^2(z)}{H_0^2}\right]^{(b-1)}\right\}} - 1,$$

$$G_{eff}(z) = \frac{G_N}{1 - b\left(\frac{1-\Omega_{m0}}{2b-1}\right)\left[\frac{H^2(z)}{H_0^2}\right]^{(b-1)}},$$

Cosmological variation of the fine structure constant and the universal constant of gravitation

Introduction and Motivation

Important equations of Universe evolution

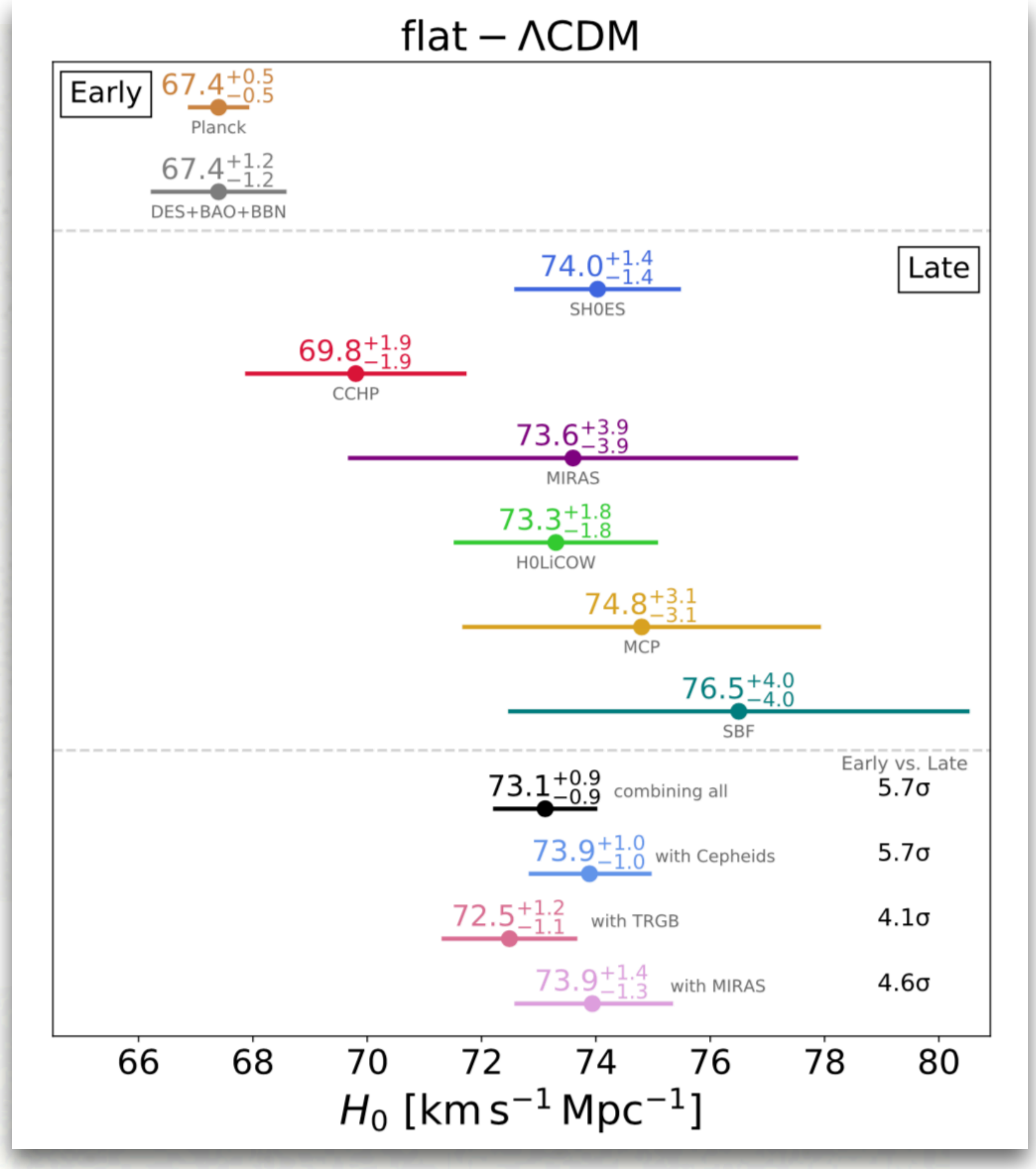
Same equation, new nomenclature:

$$\begin{aligned} H &= \dot{a}/a \\ H_0 &= \dot{a}/a)_{\rm today} \\ \rho_{cr} &= 3H_0^2/8\pi G \\ \Omega_i &= \rho_i/\rho_{cr} \end{aligned}$$

and some numbers:

$$H_0 = 67.3 \pm 1.2\,{\rm km/s/Mpc}$$

Hubble tensión



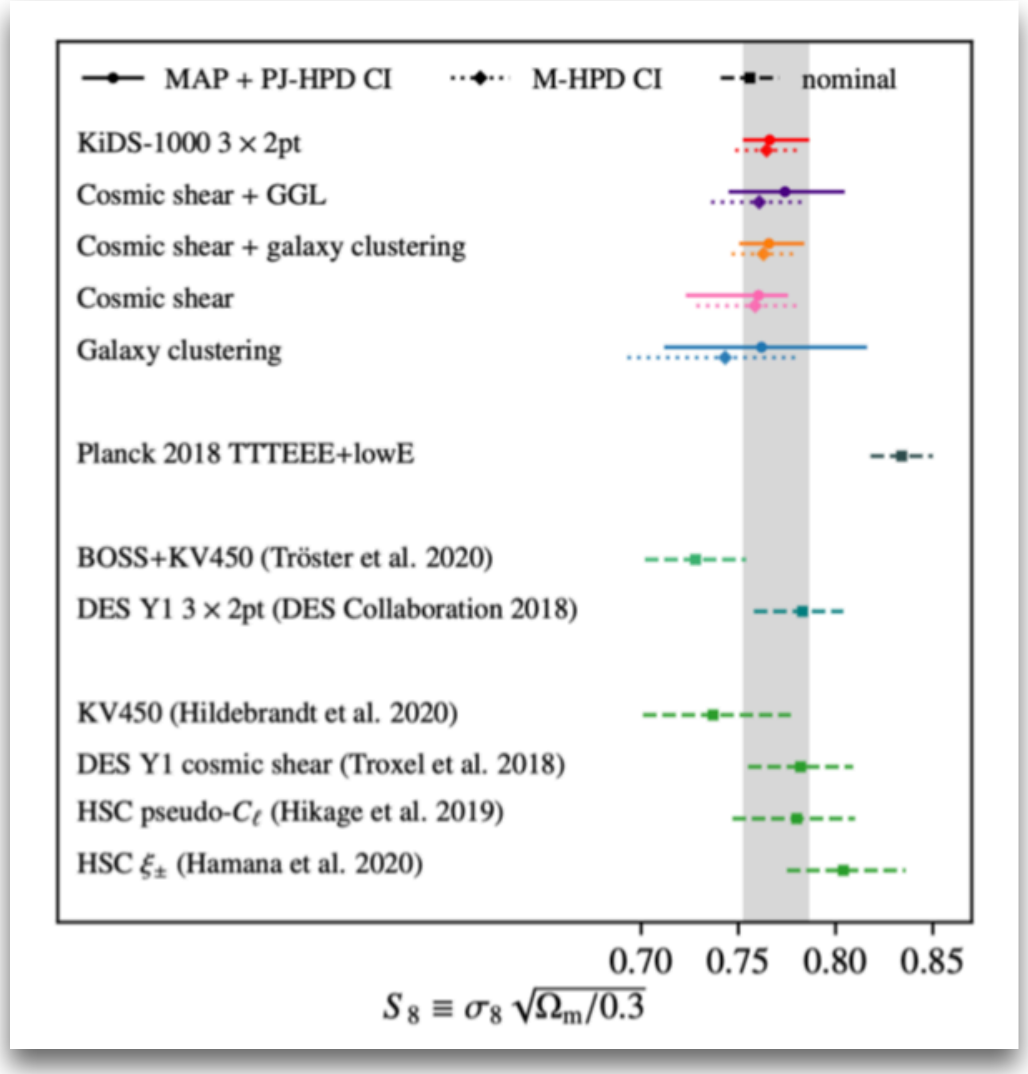
Introduction and Motivation

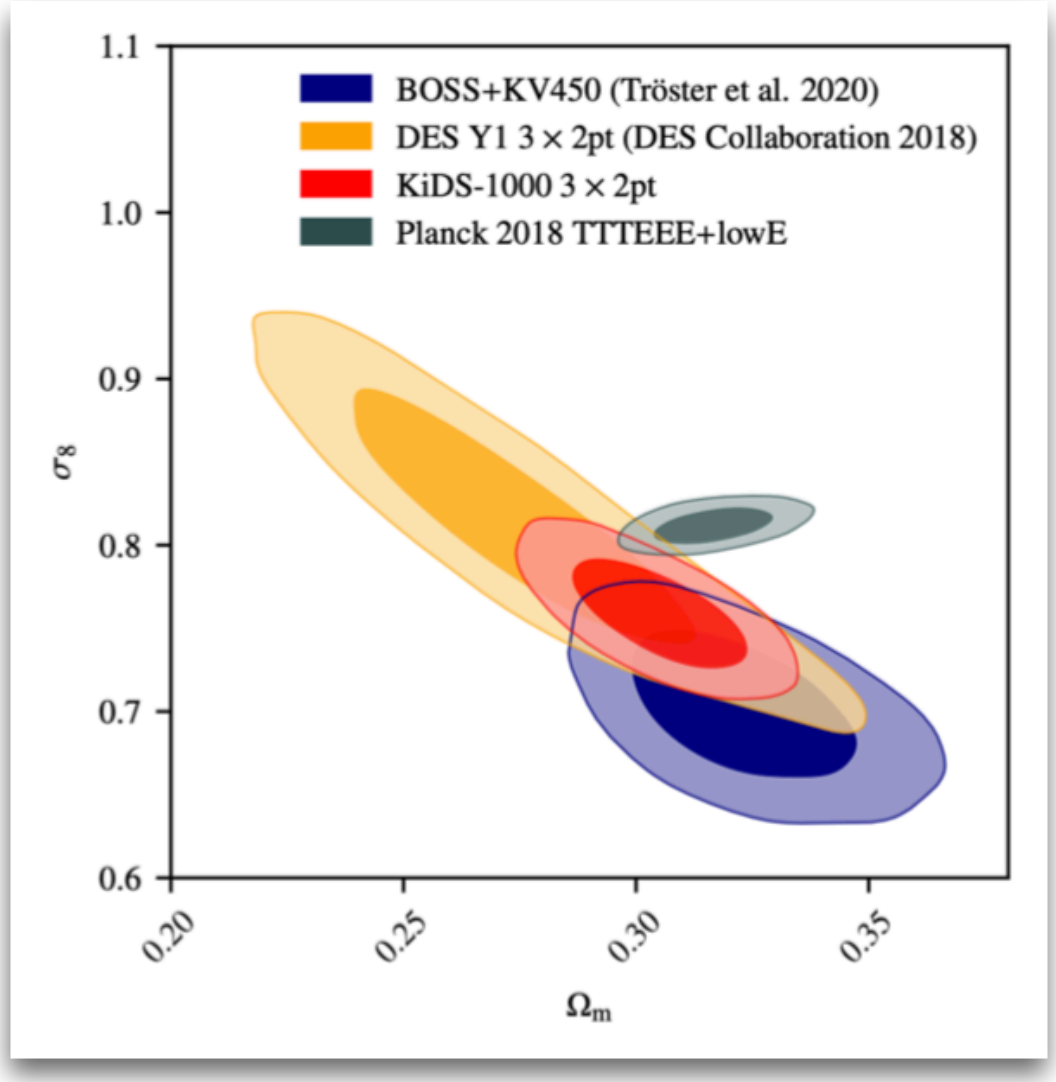
$$\frac{k^3}{2\pi^2}P(k,z) = \delta_H^2 \left(\frac{ck}{H_0}\right)^{3+n} T^2(k,z)\,D_1^2(z)/D_1^2(0).$$

Power spectrum of matter

$$\sigma_R = \left[\int_0^\infty \frac{dk}{k}\,\frac{k^3}{2\pi^2}P(k)\left|\tilde{W}_R(k)\right|^2\right]^{1/2},$$

Mass fluctuación R= 8 Mpc





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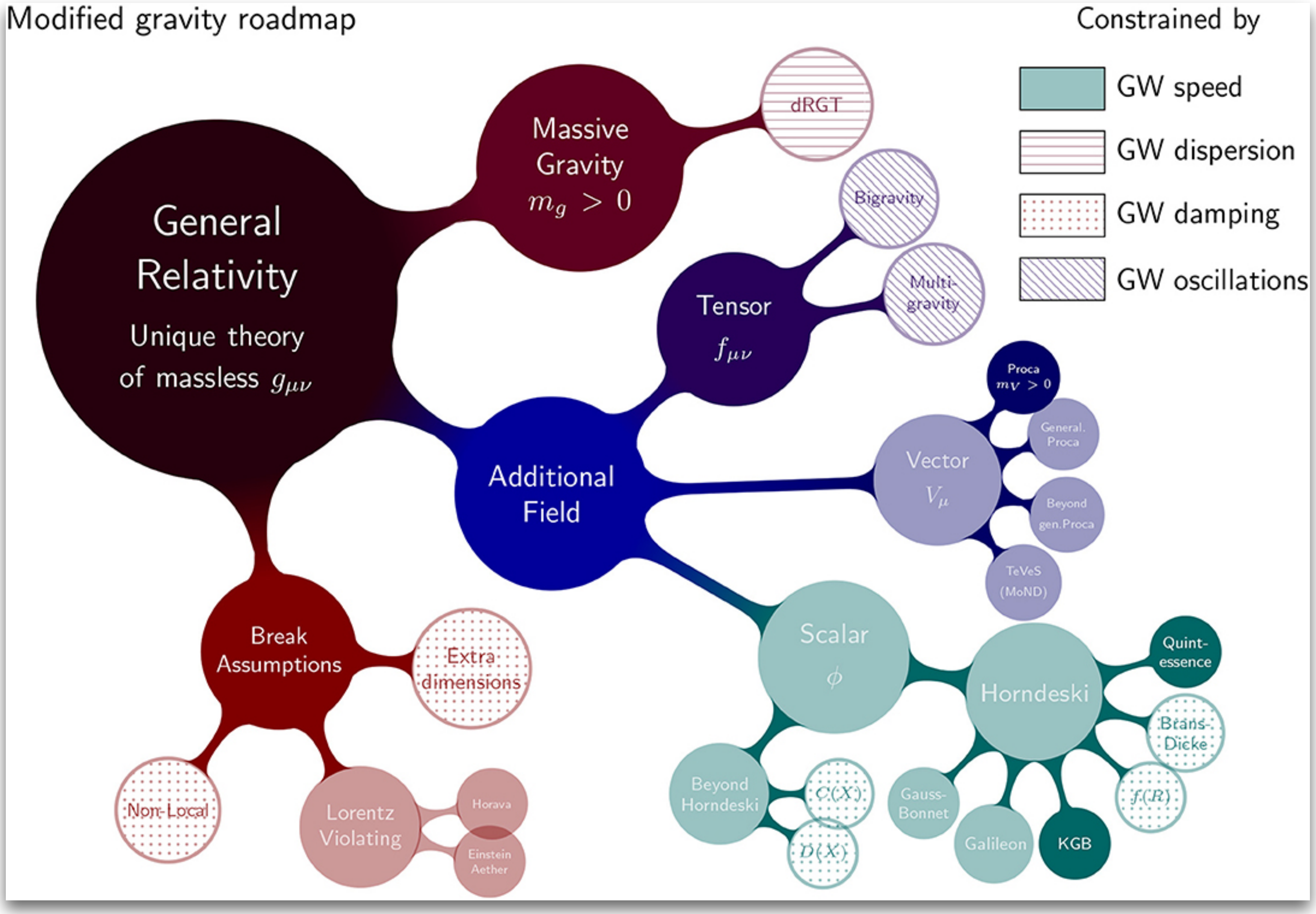
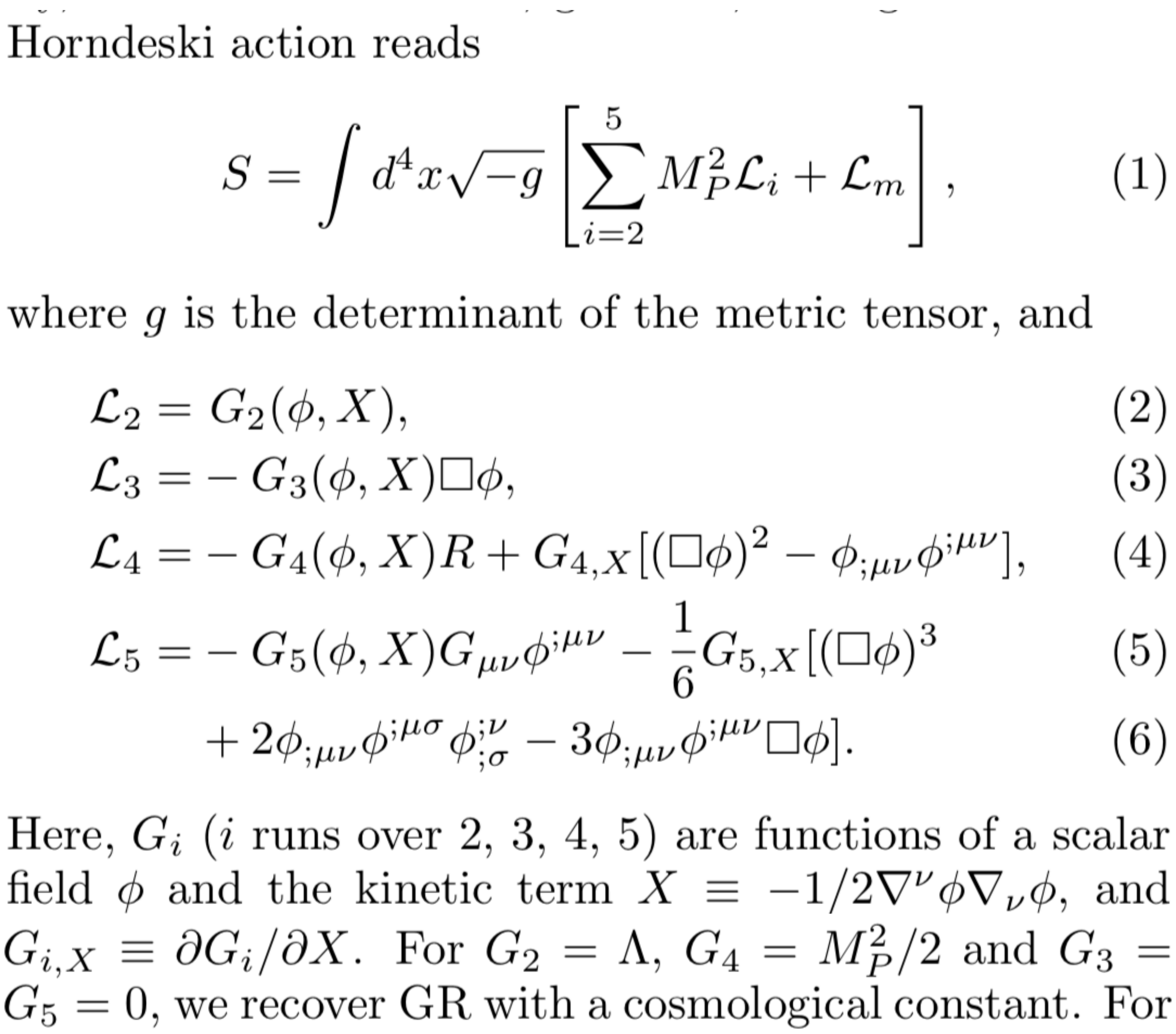
GravWaves in modified gravity



GravWaves in modified gravity



Horndeski action reads

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

where g is the determinant of the metric tensor, and

$$\mathcal{L}_2 = G_2(\phi, X), \qquad (2)$$

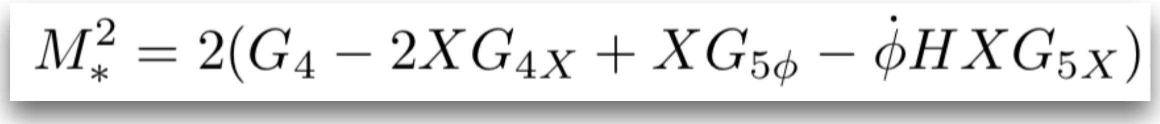
$$\mathcal{L}_3 = -G_3(\phi, X)\Box\phi, \qquad (3)$$

$$\mathcal{L}_4 = -G_4(\phi, X)R + G_{4,X}[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}], \qquad (4)$$

$$\mathcal{L}_5 = -G_5(\phi, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5,X}[(\Box\phi)^3 \qquad (5)$$

$$+ 2\phi_{;\mu\nu}\phi^{;\mu\sigma}\phi^{;\nu}_{;\sigma} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi]. \qquad (6)$$

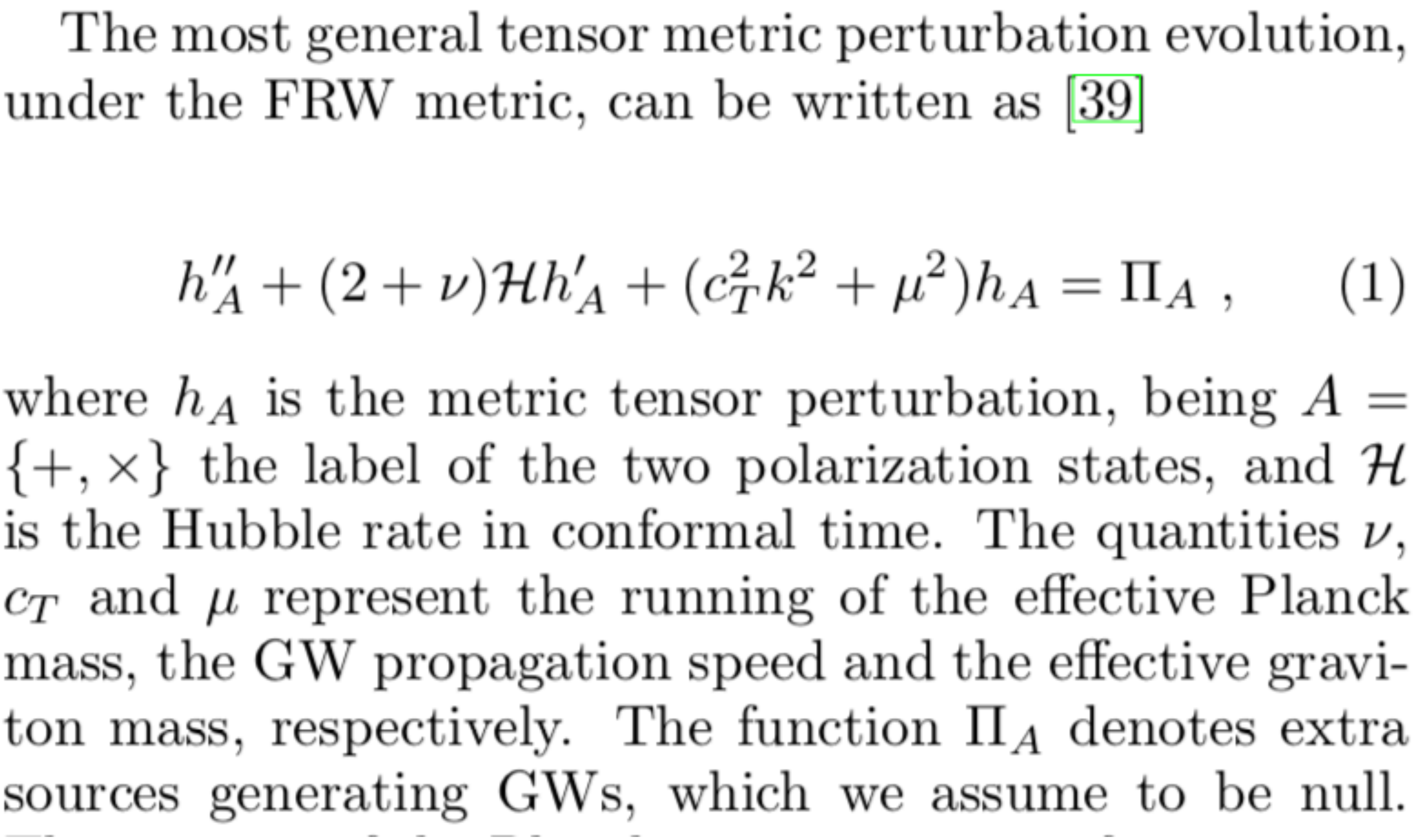
Here, G_i (i runs over 2, 3, 4, 5) are functions of a scalar field ϕ and the kinetic term $X \equiv -1/2\nabla^\nu\phi\nabla_\nu\phi$, and $G_{i,X} \equiv \partial G_i/\partial X$. For $G_2 = \Lambda$, $G_4 = M_P^2/2$ and $G_3 = G_5 = 0$, we recover GR with a cosmological constant. For



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

Effective Planck mass

GravWaves in modified gravity



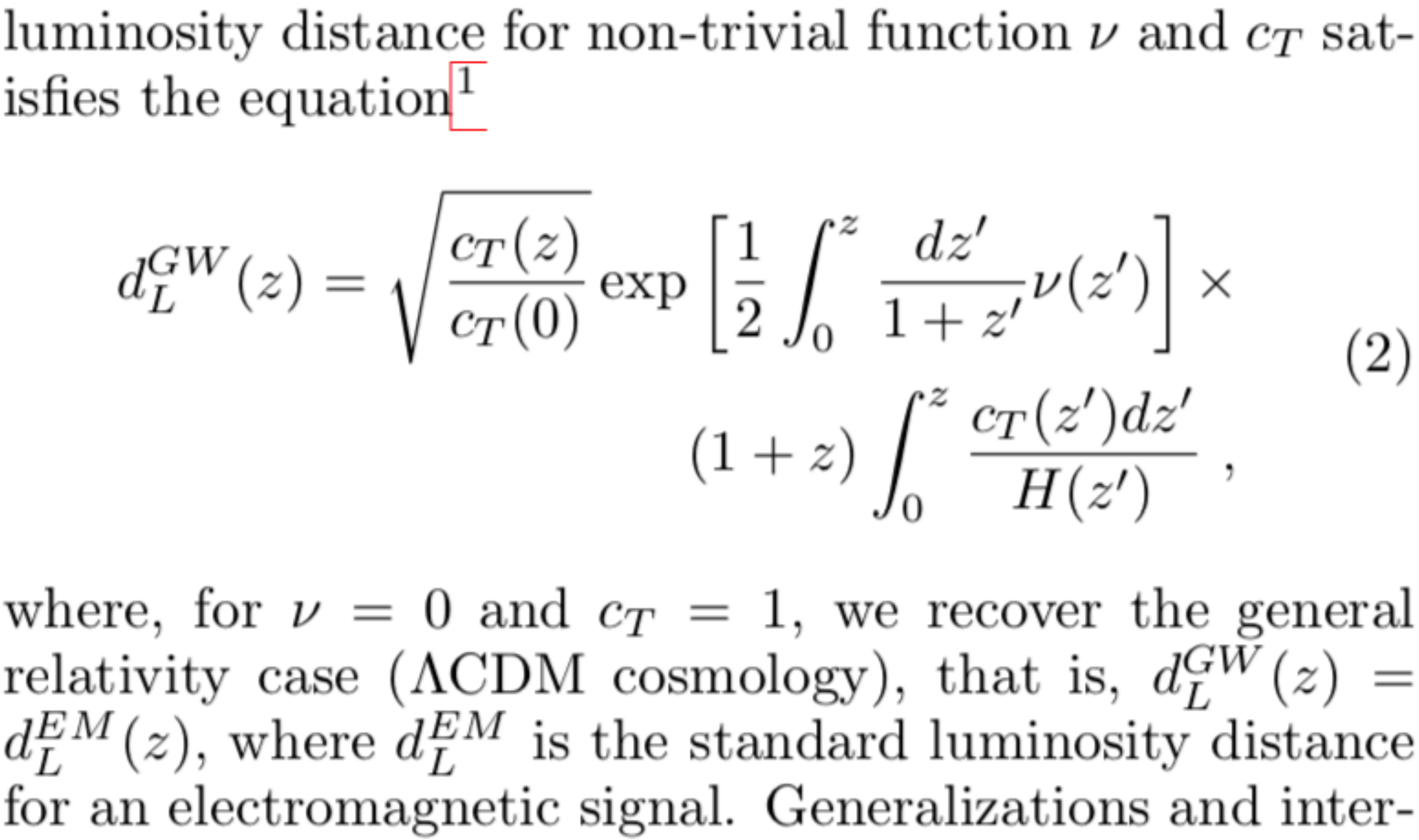
The most general tensor metric perturbation evolution, under the FRW metric, can be written as [39]

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

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.

$$\boxed{\nu = \alpha_M}$$

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-

Introduction and Motivation

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

Gravitational Wave Speed

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

$$\alpha_T \ (\text{tensor speed excess})$$

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

Running of the Planck mass

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

M∗ is the effective Planck mass

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

GravWaves in modified gravity

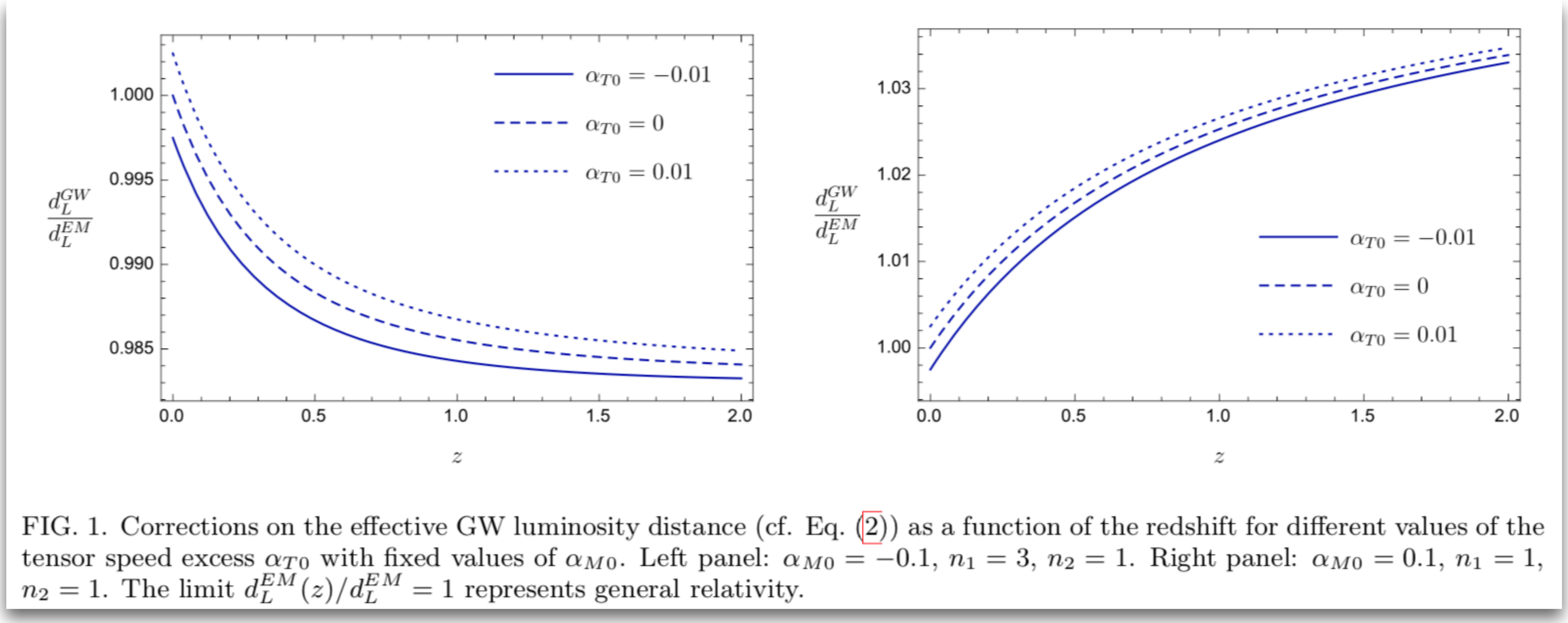


FIG. 1. Corrections on the effective GW luminosity distance (cf. Eq. (2)) as a function of the redshift for different values of the tensor speed excess α_{T0} with fixed values of α_{M0}. Left panel: $\alpha_{M0} = -0.1$, $n_1 = 3$, $n_2 = 1$. Right panel: $\alpha_{M0} = 0.1$, $n_1 = 1$, $n_2 = 1$. The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

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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

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

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

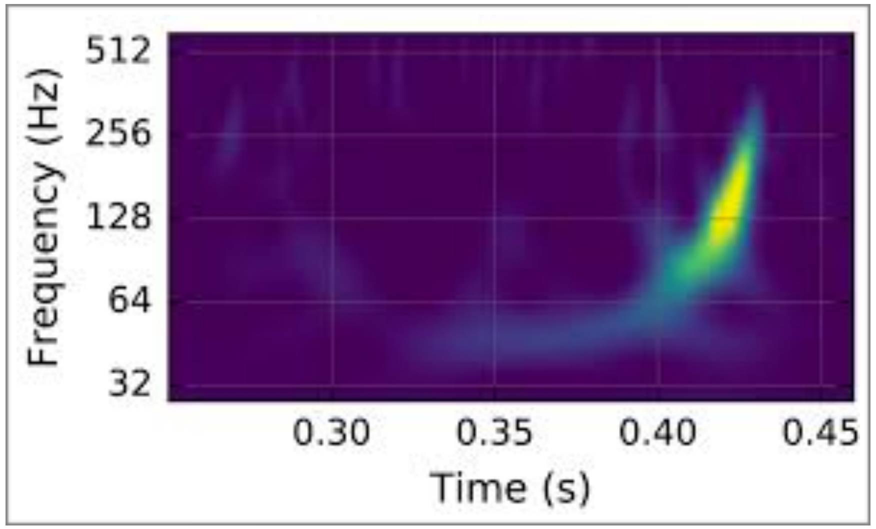
ι is the inclination angle of the binary orbital angular momentum with respect to the line of sight

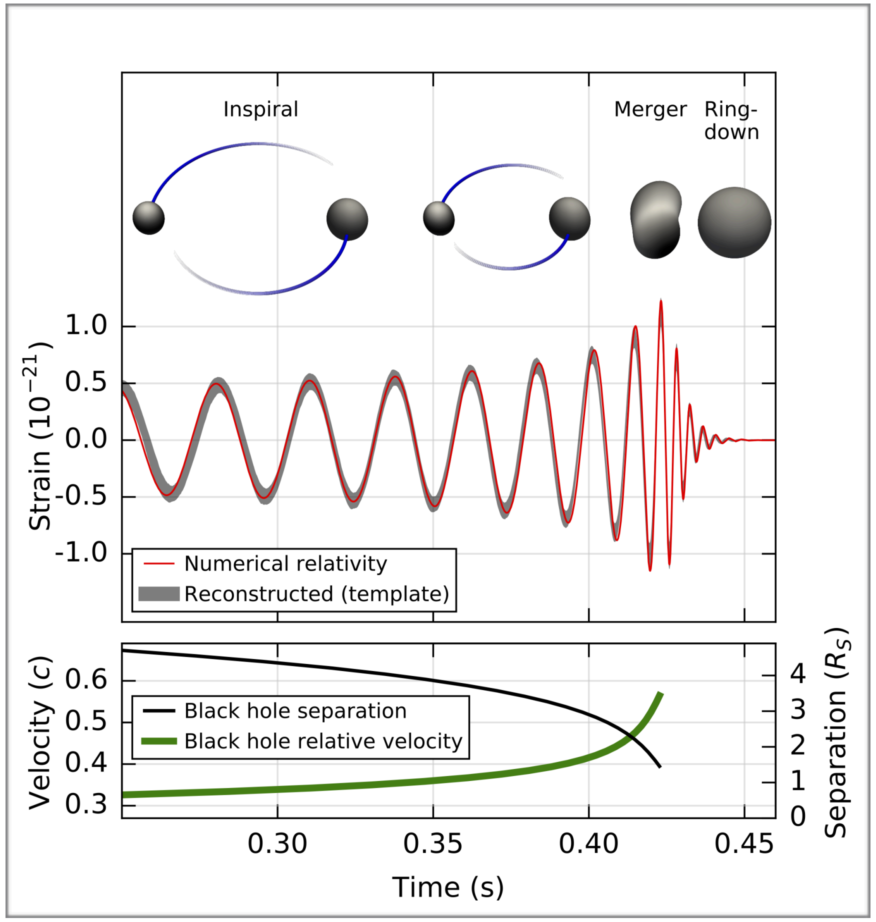
F_+^2 , $F_\times^2$ are the two antenna pattern functions

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

inspiral phase of the binary system

Waveform emitted by the binary system





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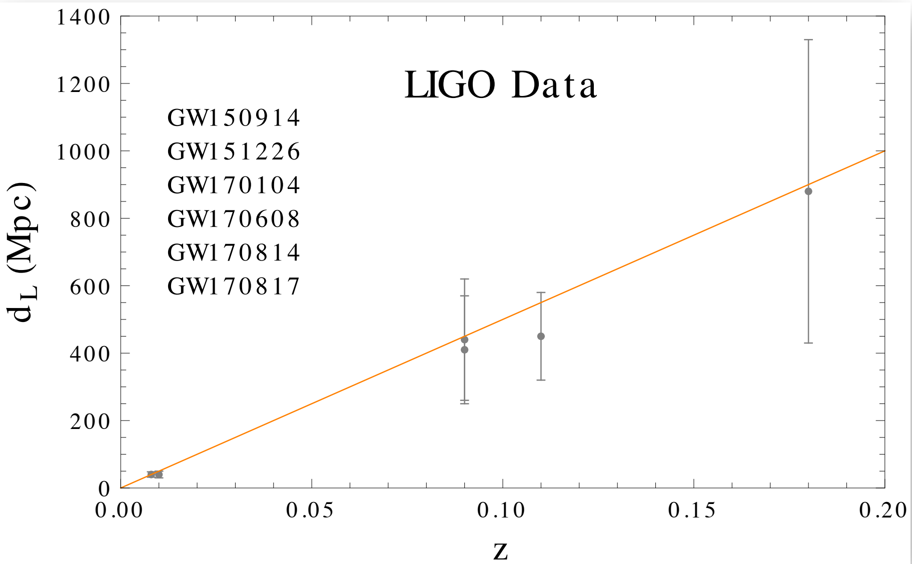
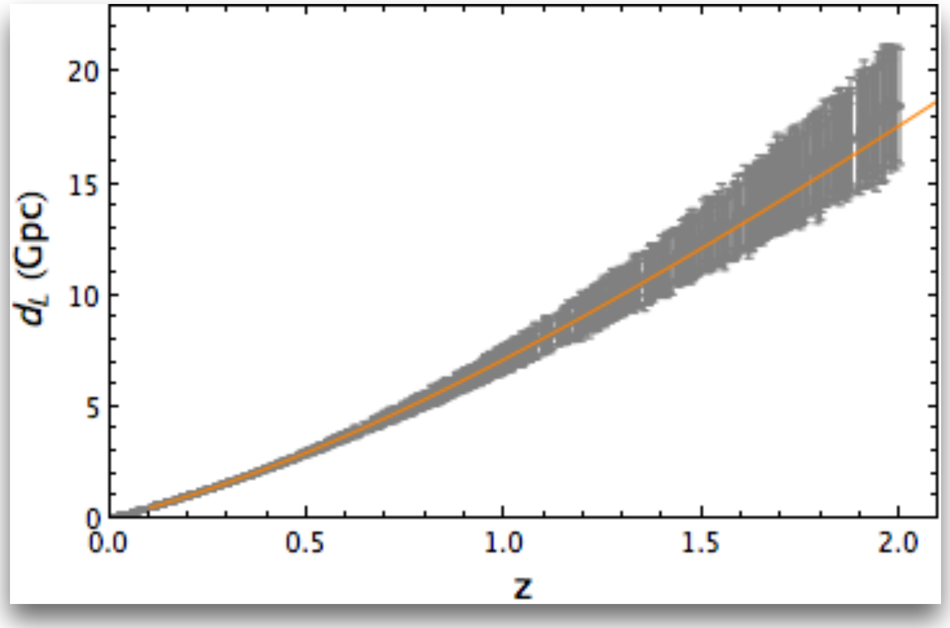
inspiral phase of the binary system

Simulation: 1000 data points





Methodology and results

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

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

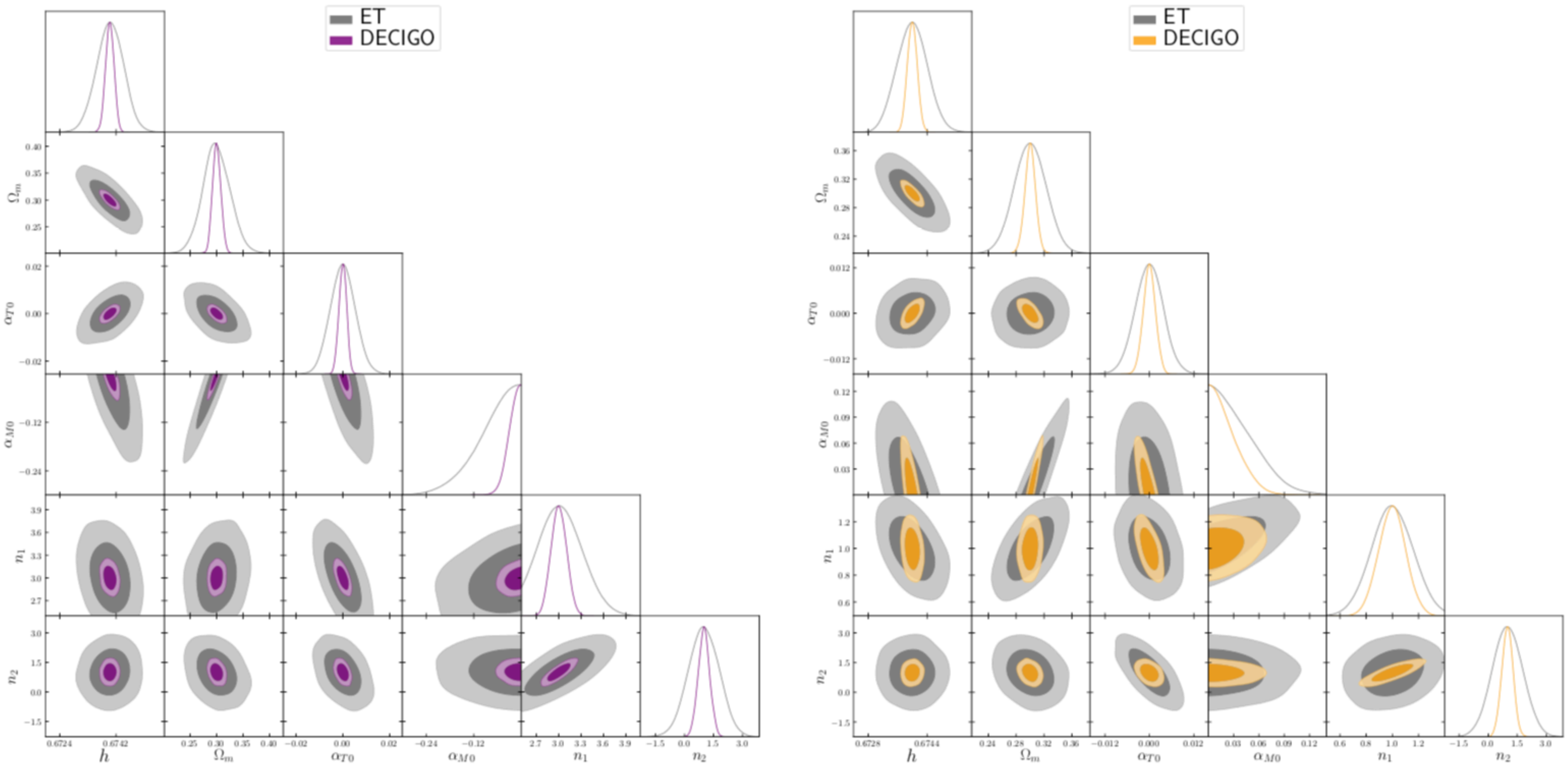
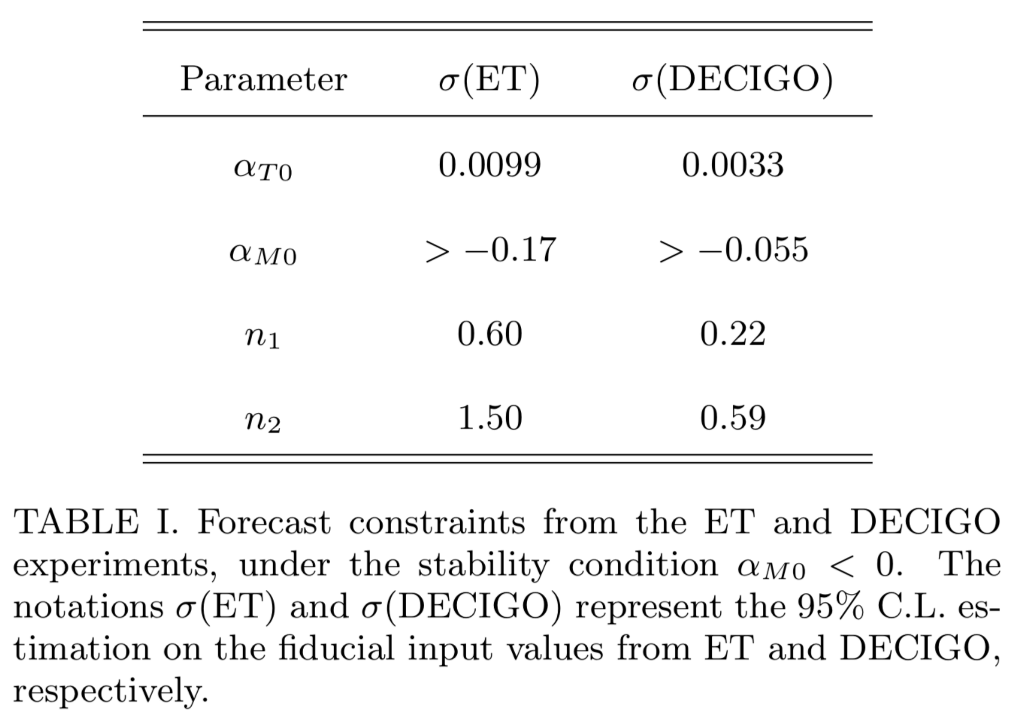


FIG. 3. One-dimensional marginalized distribution, and 68% and 95% C.L. regions for the parameters of the theoretical models under study, from the ET and DECIGO experiments. On the left panel and right panel, the stability conditions $\alpha_{M0} < 0$ and $\alpha_{M0} > 0$ are considered, respectively.

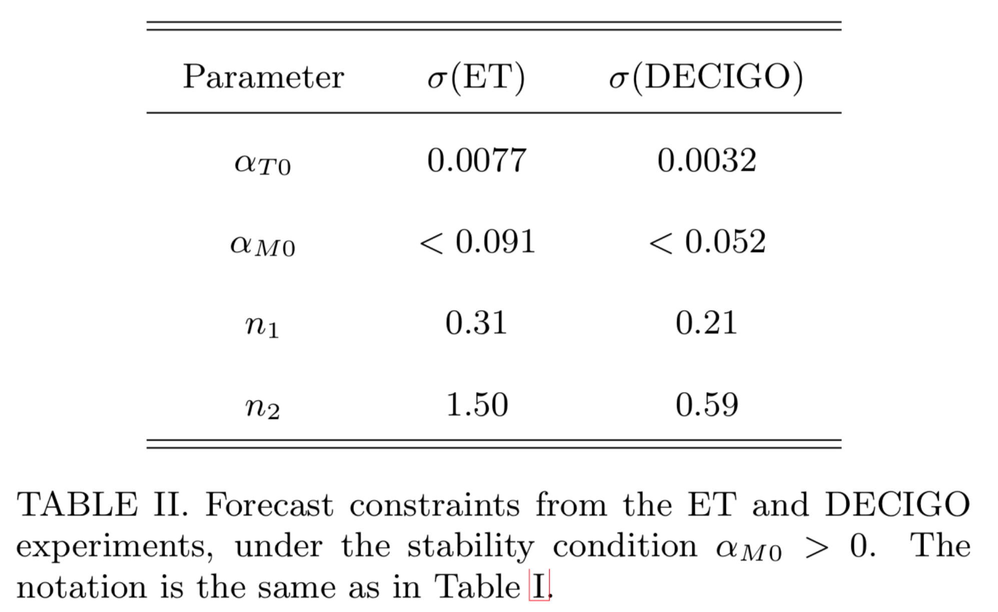
Methodology and results

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

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

we consider the “derivative coupling theory” in which thescalar 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 ($\xi = 0$ in GR), so

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

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

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

At intermediate z, it is reasonable to assume $\dot{\phi}/M_* \simeq 1$, so that we estimate $-0.005 < \xi < 0.005$ $(-0.0018 < \xi < 0.0018)$ 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.

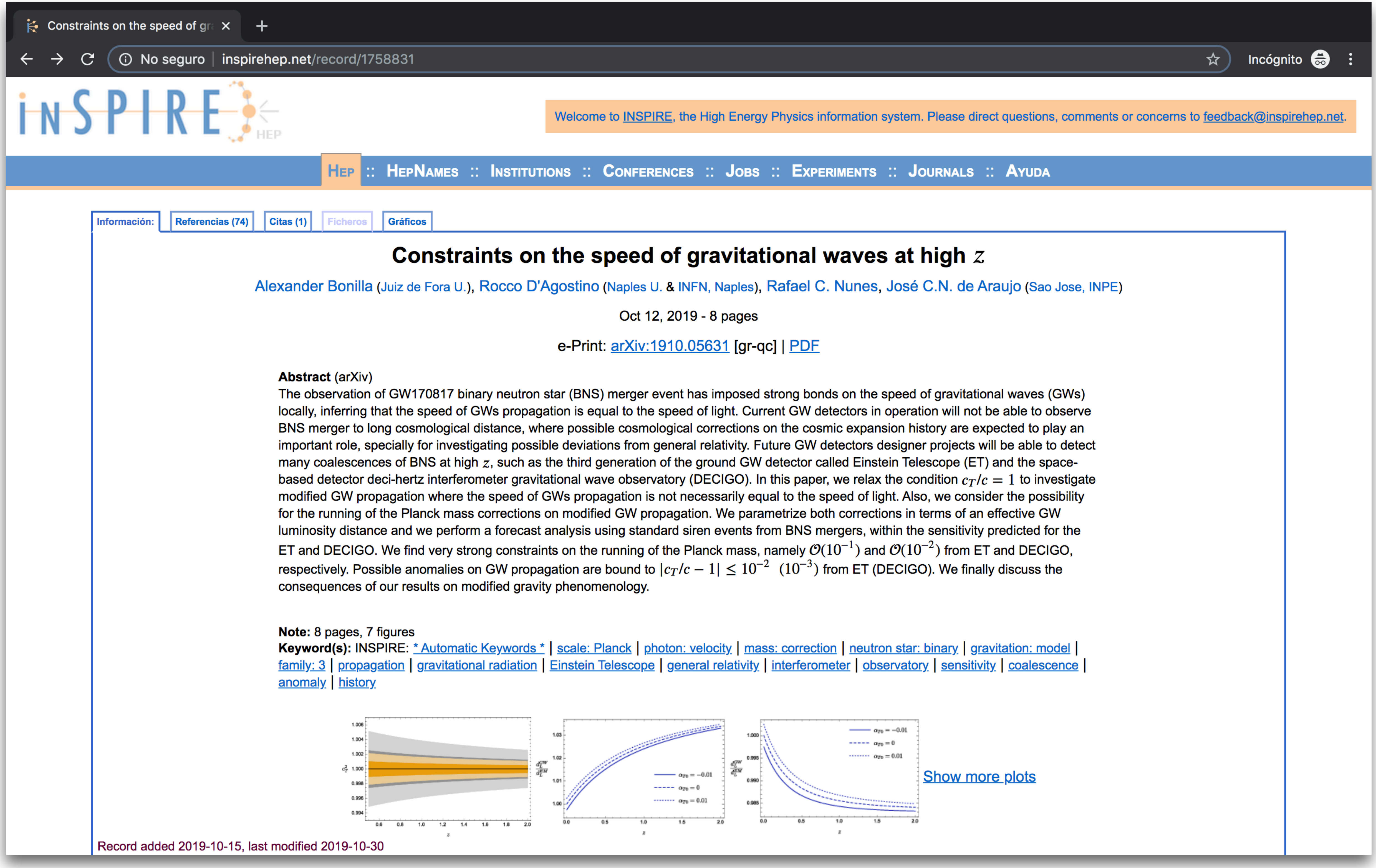
2. Motivated by this aspect, we thus performed a forecast analysis using 1000 standard siren events from BNS mergers, within the sensitivity predicted for ET and DECIGO up to $z = 2$ ($\simeq 15539Mpc$).

3. We found $| c_T/c - 1 | \leq 10^{-2}\,(10^{-3})$ 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

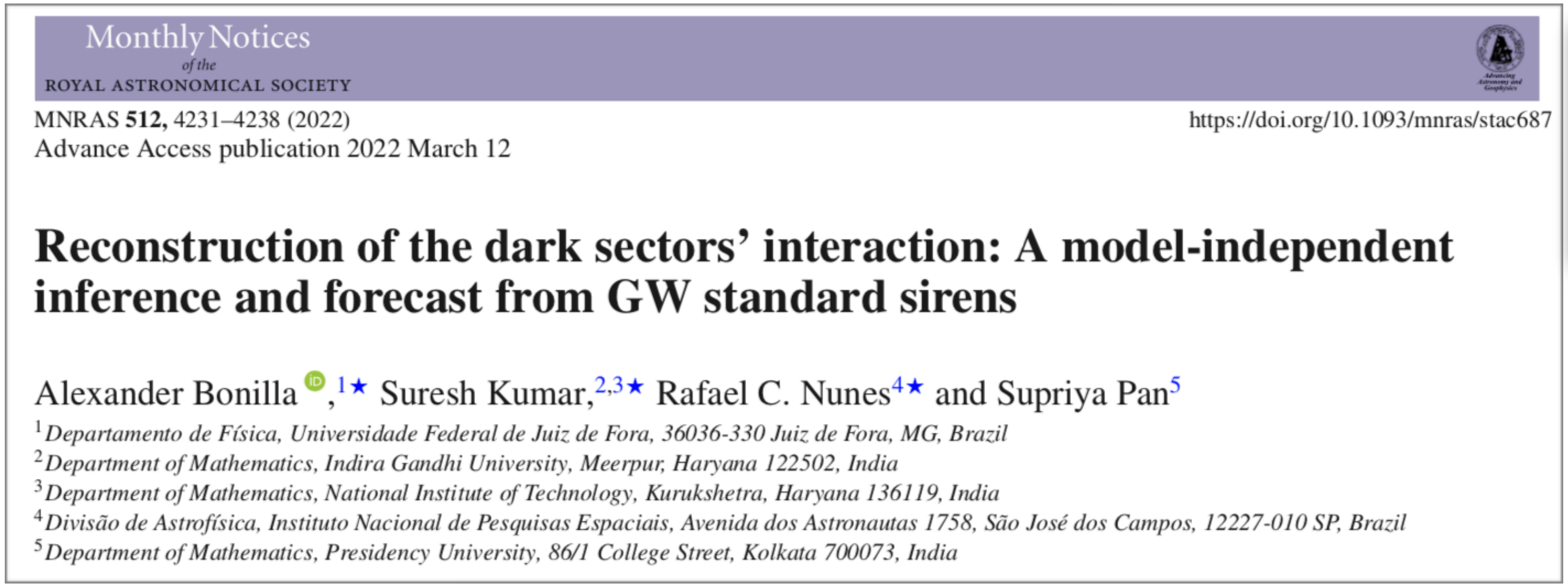
e-Print: arXiv:1910.05631 [gr-qc] | PDF

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

Record added 2019-10-15, last modified 2019-10-30

Machine Learning (Gaussian Processes)



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MNRAS **512,** 4231–4238 (2022) https://doi.org/10.1093/mnras/stac687
Advance Access publication 2022 March 12

Reconstruction of the dark sectors' interaction: A model-independent inference and forecast from GW standard sirens

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$$\dot{\rho}_{\rm DM} + 3H\rho_{\rm DM} = -Q(t)\,,$$

$$\dot{\rho}_{\rm DE} + 3H\rho_{\rm DE}(1+w) = Q(t)\,,$$

$$q = Q(t)/H_0^3 \qquad E(z) = H(z)/H_0$$

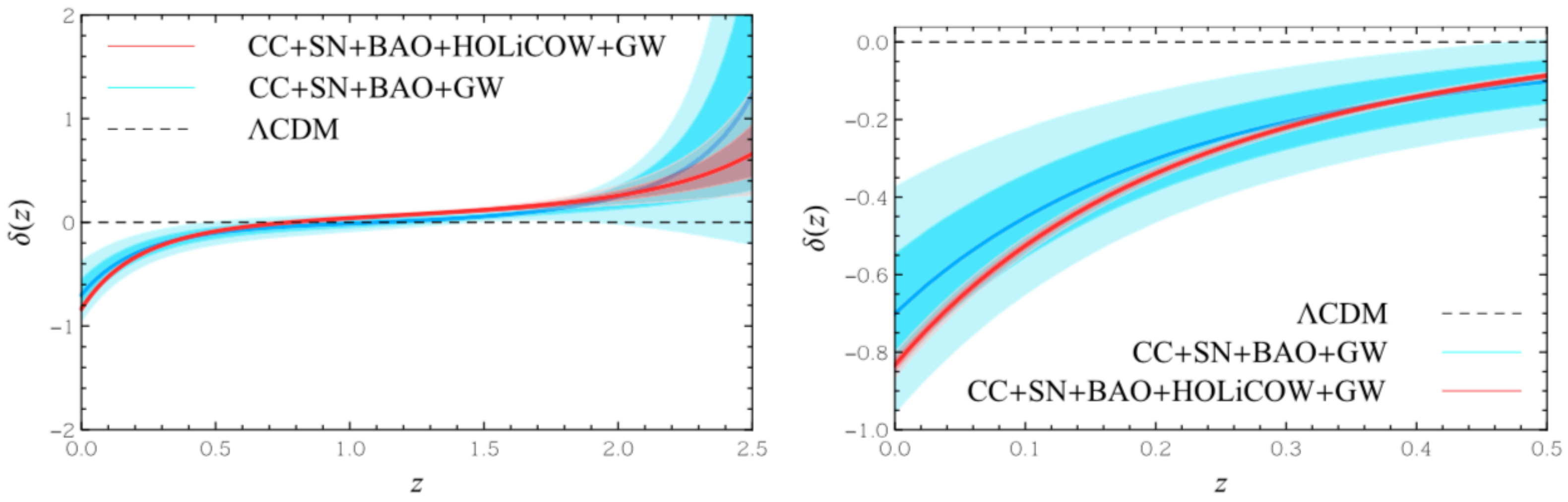

Figure 3. Left-hand panel: Reconstructed coupling function $\delta(z)$ at 1σ and 2σ CL from CC+SN+BAO+GW (Blue) and CC+SN+BAO+H0LiCOW+GW (Red) data, in the interacting vacuum energy scenario. Right-hand panel: The same as in left-hand panel, but restricted to the range $z \in [0, 0.5]$. The dashed black curve corresponds to the canonical ΛCDM prediction and the solid curves are for the GP mean.

$$-wq = 2\left(EE'^2 + E^2E'' - \frac{w'}{w}E^2E'\right)(1+z)^2 - \left[2(5+3w)E^2E' - 3\frac{w'}{w}E^3\right](1+z) + 9(1+w)E^3,$$

Big announcement between Dec 2022 and Jun 2023. Stay tuned.

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NANOGrav
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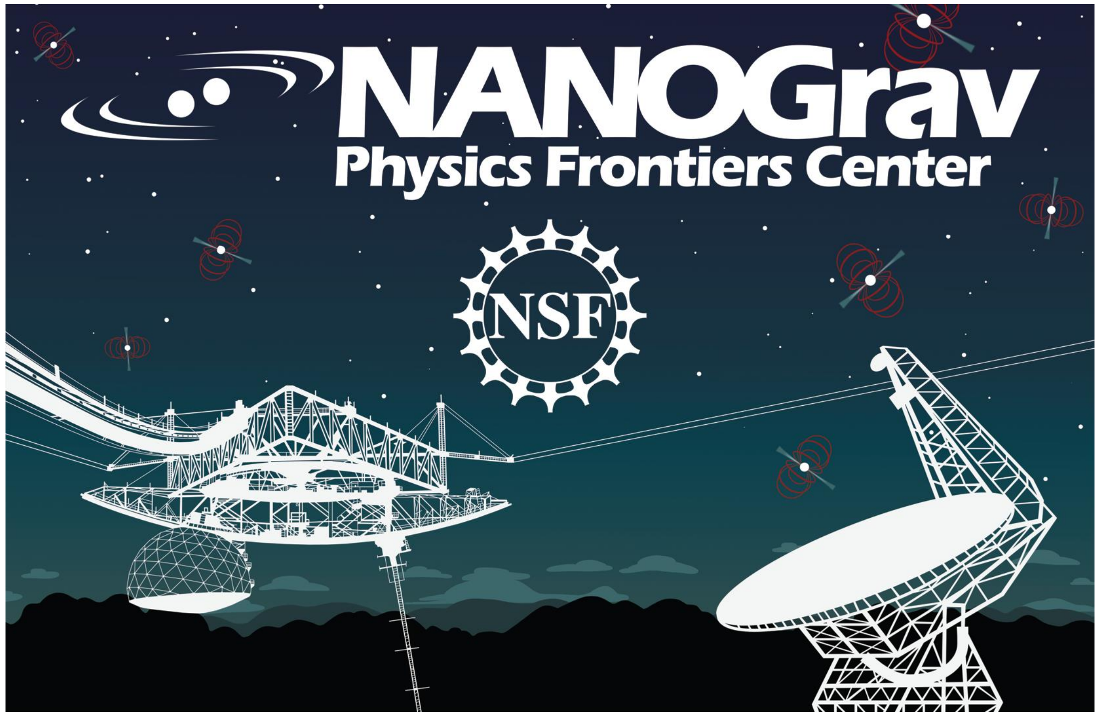

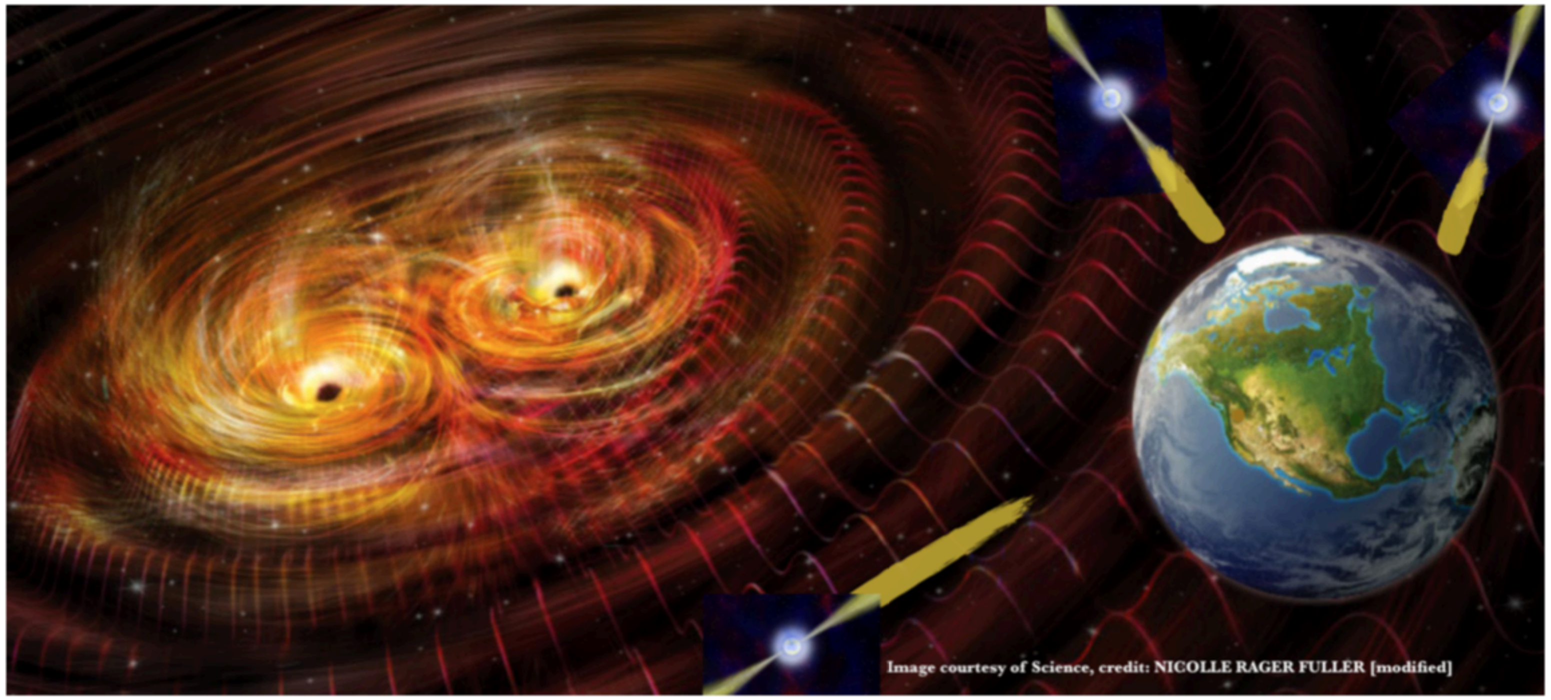
Image courtesy of Science, credit: NICOLLE RAGER FULLER [modified]

End

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