Research at the Cosmology group at the Instituto de Astrofísica e Ciências do Espaço

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instituto de astrofísica e ciências do espaço

The Institute

The Instituto de Astrofísica e Ciências do Espaço (IA) is a research infrastructure with a national dimension. It embodies a bold vision for the development of Astronomy, Astrophysics and Space Sciences in Portugal, taking full advantage and fully realizing the potential created by the national membership of the European Space Agency (ESA) and the European Southern Observatory (ESO).
Two Poles:

- **North Pole:** Centro de Astrofísica da Universidade do Porto – Porto
- **South Pole:** Faculdade de Ciências da Universidade de Lisboa & Observatório Astronómico de Lisboa

Thematic Lines

- Towards the detection and characterization of other Earths
- Towards a comprehensive study of stars
- The assembly history of galaxies resolved in space and time
- Unveiling the dynamics of the Universe
- Space and Ground Systems and Technologies

Missions Participation

Membership & Coordination:

- Euclid (**C. Martins**-Lead of WP in SWG, **A. da Silva & I. Tereno**-Euclid STAR prize 2020 for the Survey Group, **A. da Silva**-National coordinator, **I. Terreno**- National co-cordinator)
- Extremely Large telescope (**C. Martins**: Coordinator in ELT Line Calibrations Working Group & Fundamental Physics WG Deputy Lead in ELT-HIRES Core Science Team)
- LISA
- EXPRESSO
- Dark Energy Survey (**A. Liddle** - 3Year results– soon)

LISA participation

Membership: P. Avelino, T. Barreiro, F. Cabral, A. da Silva, N.Frusciante, F. Lobo, C. Martins, J. Mimoso, N. Nunes, L. Sousa, I. Tereno

LISA Science Group:

- Fundamental Physics Working Group:
  - Fundamental Physics White Paper
- Cosmology Working Group (CosWG):
  - LISA Cos-WG MG Project (work in progress, **N. Frusciante**),
  - LISA Cos-WG-cosmic strings

    [P. Auclair, J. J. Blanco-Pillado, D. G. Figueroa, A. C. Jenkins, Marek Lewicki, M. Sakellariadou, S. Sanidas, **L. Sousa**, D. A. Steer, J. M. Wachter, S. Kuroyanagi, JCAP 04 (2020) 034]
    (**see tomorrow talk by J.J. Blanco-Pillado**)
  - Cosmology White Paper

Main research Lines

- Cosmic defects(L. Sousa, P. Avelino, I. Rybak, C. Martins)
- General Relativity and extensions: phenomenology & constraints (N. Frusciante, F. Lobo, A. Liddle, C. Martins, N. Nunes, G. Fanizza, J. Mimoso, P. Avelino, T. Barreiro, C. Linares, M. Cortes)
- Dark couplings: phenomenology & constraints (N. Nunes, C. Martins, A. Rozas Fernandez, I. Tereno)
- Non-linear hydrodynamical evolution of galaxies and galaxy clusters (A. da Silva, C. Linares)

Ongoing projects for GWs exploration

- Spacetime ripples in the dark gravitational Universe (Dark Ripple) (FCT project) PI: F. Lobo):
  - Gravitational waves in modified gravity (Phenomenology & constraints)
- Probing cosmic stings and other topological defects with gravitational waves (Gwstrings) (FCT project), PI: L. Sousa:
  - GWs background from topological defects
  - development of semi-analytical models to describe the cosmological evolution of cosmic defect networks and their GW emission
  - Observational side: LIGO-VIRGO, IPTA, LEAP, LISA

Cosmic Defect

- spontaneous symmetry breaking in particle physics corresponds to a phase transition in the early universe
- cosmological phase transitions can give rise to defects of various kinds
- Depending on the symmetry groups involved, the defects can be in the form of surfaces, lines, or points. They are called domain walls, strings, and monopoles, respectively
- All three types of defects are stable (and is independent of the details of the models)
- The physical properties of defects can be very different depending on whether they are formed as a result of gauge or global symmetry breaking

Modelling of topological defect networks

- Development of accurate models to describe the cosmological evolution of topological defect networks of different types and in the extension of models to describe the evolution of non-standard defect networks.
- Development of a semi-analytical model to describe the dynamics of domain wall networks (the first derived analytically from first principles)

  [**P. Avelino, L. Sousa**, Phys.Rev.D83:043530,2011]
- Development of a unifying framework to describe topological defects of different dimensionality

  [**L. Sousa, P. Avelino**, Phys.Rev.D84:063502,2011]
- Revisiting semi-analytical model describing global and local monopoles that allow for a better description of the results of numerical simulations

  [**L. Sousa, P. Avelino**, Phys. Rev. D 96, 023521 (2017)]
- development of a GPU- accelerated cosmic string evolution code

  [**J. Correia, C. Martins**, arXiv:2005.14454 (2020)]

Observational Signatures of Topological defect networks

Stochastic GWs background generated by cosmic string networks

- development of a framework to compute this spectrum in the realistic cosmological background
- this allowed to determine the effect of the radiation-matter transition

  [**L. Sousa, P. Avelino**, Phys.Rev.D 88 (2013) 2, 023516

- determine the spectrum of cosmic string networks created during an inflationary era

  [**G.S.F. Guedes, P. Avelino, L. Sousa** , Phys.Rev.D 98 (2018) 12, 123505

- adopted as one of the models to be probed with LISA

  [LISA collaboration (among authors **L. Sousa**), JCAP 04 (2020) 034]

- adapted to describe the SGWB generated by cosmic superstring networks

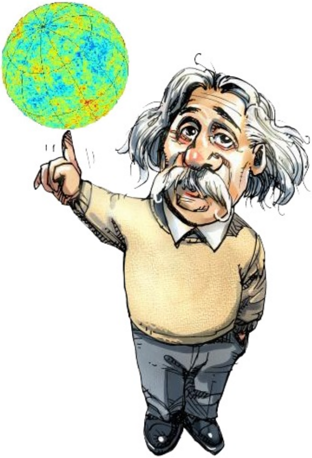
  [**L. Sousa, P. Avelino** , Phys.Rev.D 94 (2016) 6, 063529

MG/DE: Why do we need to go beyond ΛCDM?

- Theoretical issues with ΛCDM
- 4.4σ mismatch in H_0 between CMB probes (Planck) and local measurements (Chepheids)
- 2.3σ mismatch in σ_8 between CMB probes (Planck) and WL surveys (e.g. KiDS)
- more ....

How to modify GR:

- extra DoF(s): scalar, vector, tensor field(s);
- going beyond the 2nd order differential equations;
- diffeomorphism invariance breaking;
- higher than 4 dimensions;
- non-locality;
- non-dynamical field(s).



After GW170817 & GRB170817A

LIGO/Fermi: $-3 \times 10^{-15} \leq c_t - c \leq 7 \times 10^{-16}$

[Abbott, B.P. et al. Phys.Rev.Lett. 119 (2017) no.16, 161101
Goldstein, A. et al. Astrophys.J. 848 (2017) no.2, L14]

For theories with 1 extra scalar d.o.f in the EFT formulation (on FLRW background):

$$\ddot{h}_{ij}^T + H(3+\alpha_M(t))\dot{h}_{ij}^T + c_t^2(t)\frac{k^2}{a^2}h_{ij}^T = \delta T_{ij}^T$$

$$c_t^2(t) = 1 + \alpha_T(t) \quad \rightarrow \quad \alpha_T(t) \sim \mathcal{O}(10^{-15}) \qquad (c=1)$$

Who survives?

Class of models	$c_t^2 = 1$	$c_t^2 \neq 1$
Horndeski/Galileon	General Relativity Quintessence/K-essence Brans-Dicke/f(R) Cubic Galileon (G3& generalization, Galileon Ghost Condensate, Scaling Galileon) Non-minimal coupling with R K-mouflage	Quartic & quintic Horndeski (quartic & quintic covariant galileon, Fab4,de sitter Horndeski) Gauss Bonnet-term
Beyond	GLPV (Extended GGC) Quadratic DHOST (A1=0) Horava gravity	Quintic GLPV Quadratic DHOST (A1 not 0) Cubit DHOST

Galileon Ghost condensate

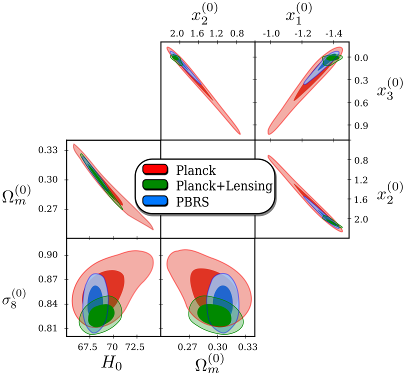
$$L = a_1 X + a_2 X^2 + 3a_3 X \Box\phi + \frac{m_0^2}{2} R$$

[Deffayet et al., JCAP 1010:026,2010]

$$x_1 = -\frac{a_1 \dot{\phi}^2}{3 m_0^2 H^2}\,,$$

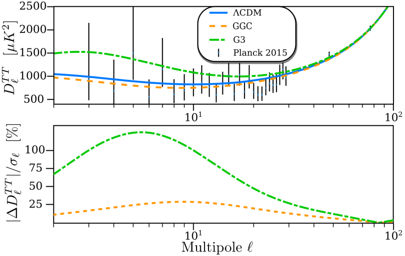
$$x_2 = \frac{a_2 \dot{\phi}^4}{m_0^2 H^2}\,,$$

$$x_3 = \frac{6 a_3 \dot{\phi}^3}{m_0^2 H}$$



[S. Peirone, G. Benevento, **NF**, S. Tsujikawa, Phys.Rev. D100 (2019) no.6, 063540]

Model selection



Model	Dataset	$\Delta\chi^2_{\rm eff}$	ΔDIC	$\Delta \log_{10} B$
GGC	Planck	-4.8	-2.5	4.4
GGC	PBRS	-2.8	-0.6	5.1
GGC	Planck+Lensing	-0.9	0.80	1.6

[S. Peirone, G. Benevento, **NF**, S. Tsujikawa, PRD100 (2019) no.6, 063509 & 063540]

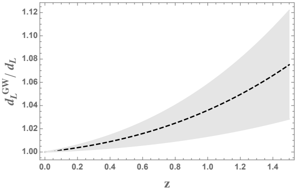
Running Planck mass: α_M

The GW luminosity distance is now related to the electromagnetic one by

$$d_{\rm L}^{\rm gw}(z) = d_{\rm L}^{\rm em}(z) \exp\left\{-\int_0^z \frac{dz'}{1+z'}\,\delta(z')\right\} \quad \text{with} \quad \alpha_M = -2\delta$$

The quartic gravity model considered:

$$S = -\frac{M_p^2}{2}\int d^4x\sqrt{-g}(R + c_2 R^2) + S_m$$



UNION2 data:

$$\delta(0) \simeq -0.015 \pm 0.009$$
$$c_2 = (1.128 \pm 0.670) \times 10^{-6} \mathrm{s}^2\mathrm{Mpc}^2/\mathrm{km}^2$$
$$H_0 = 69.84 \pm 0.30 \mathrm{km/s/Mpc}$$

[**G. Fanizza**, G. Franchini, M. Gasperini, L. Tedesco, arXiv:2010.06569]

Gravitational waves and electrodynamics

- explore the couplings between electromagnetic fields and gravity
- electric and magnetic oscillations are induced that propagate as EM waves and contain information about the GW which generates them
- Results: the presence of longitudinal modes and dynamical polarization patterns of EM radiation induced by GWs.
- Detect GWs by amplification of these effects using appropriate resonators (improvement in the S/N around a specific frequency)

[**F. Cabral, F. Lobo**, Eur. Phys. J. C 77 (2017) 237]

Gravitational waves in theories with a non-minimal curvature-matter coupling

- Detection of extra polarization modes is a signature of MG.
- Effects of a non-minimal coupling between matter and curvature on GWs
- $f(R)$ model and the non-minimal coupling between matter and a cosmological constant
- Results: At linear order, GWs propagate at velocities lower than c, and there are extra polarization modes
- Results: one scalar mode that propagates in the longitudinal way relatively to the GW has a mass that may be measured
- next: use combination of GWs detectors, such as Advanced-LIGO, Advanced-Virgo or Einstein GW Telescope

[O. Bertolami, C. Gomes and **F. Lobo**, Eur. Phys. J. C 78 (2018) no.4, 303]

Construction of GW catalogues

Ongoing project by **T. Barreiro, N. Nunes, J. Mimoso**

- GWs offer the possibility of an independent measurement of H_0
- valid for different cosmologies
- catalogues will be constructed considering LISA and ET-like sources

THANK YOU