Bridging cosmology and astrophysics with gravitational waves

Ippocratis Saltas

Institute of Astrophysics and Space Sciences, U. Lisbon

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based on

I.D.S, I. Sawicki, L. Amendola, M. Kunz *PRL 113, 191101 (2014)*

M. Motta, I. Sawicki, I.D.S, L. Amendola, M. Kunz *PRD 88, 124035 (2013)*

L. Amendola, M. Kunz, I.D.S, I. Sawicki PRD 87, 023501 (2013)

and work soon to appear

instituto de astrofísica e ciências do espaço

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What is accelerating the universe?

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The dark sector is degenerate

Dark matter and dark energy density distributions are indistinguishable under pure gravity probes: Gravity probes the total energy-momentum tensor[1]

$$\boxed{G_{\mu\nu} = 8\pi G T_{\mu\nu}^{\text{total}}}$$

[1] **M. Kunz PRD 80 123001 (2009) — L. Amendola, M. Kunz, I.D.S, I. Sawicki, PRD 87, 023501 (2013)**

The universe perturbed

- The evolution of large scale structure of spacetime can be well described by small scalar fluctuations around a flat, Friedman–Lemaitre–Robertson–Walker spacetime

$$ds^2 = -\left(1 + 2\,\Psi(t, \mathbf{x}\,)\right) dt^2 + a(t)^2 \left(1 + 2\,\Phi(t, \mathbf{x}\,)\right) d\mathbf{x}^2$$

- The matter content is pressureless dark matter and baryons, with their density fractions $\delta_i \equiv \delta\rho_i/\rho_i$ related through the bias function $b(z, k)$:

$$\delta_b(z, k) = \; b(z, k)\; \delta_m(z, k)$$

- The relation between the potential Φ and the total matter density is described by

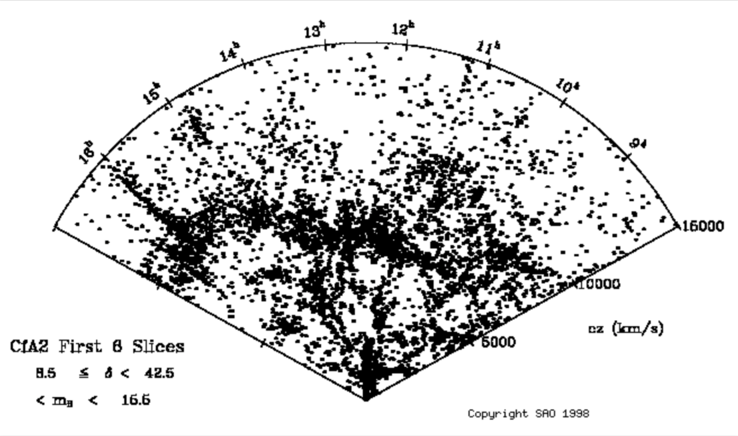
The Poisson equation: $k^2\;\Phi(t, k)\; = 4\pi a^2 G \times \delta\rho_{total} \equiv 4\pi a^2\; G_{\mathrm{eff}}\; \times \delta\rho_{\mathrm{m}}$

- The relation between the two gravitational potentials Φ and Ψ is described by

$$\Phi \;-\; \Psi \;= \sigma\left(\alpha_i(t)\right) \times \Pi(t, k)$$

Galaxy clustering

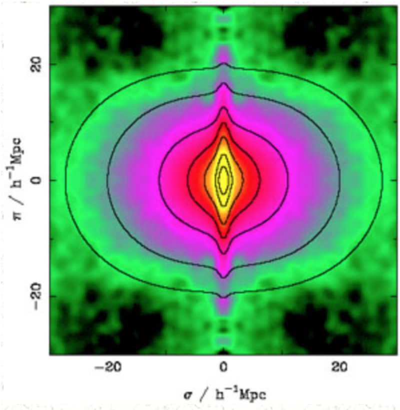
The clustering of galaxies provides very useful information for testing different cosmological models



From real to redshift space: The effect of redshift space distortions

Radial distances are always distorted due to the additional redshift caused by the galaxies' peculiar motion along the line of sight. [2]

$$s(\mathbf{r}) = \mathbf{r} + v(\mathbf{r}) \cdot \hat{\mathbf{r}}, \qquad v(r) \sim \nabla\Phi(r)$$



[2] **Picture from Peacock et al (2001), 2dF Galaxy redshift survey**

From real to redshift space: The effect of redshift space distortions

The linear galaxy clustering in real (δ_{gal}) and redshift (δ^z_{gal}) space differs by a correction term that accounts for the velocity gradient of the galaxies

$$\delta^z_{gal}(k,z,\mu) = \underbrace{\delta_{gal}(k,z)}_{observable} + cos^2\phi \underbrace{\frac{\theta_{gal}(k,z)}{H(z)}}_{observable} \qquad [\ \theta_{gal} \equiv \nabla \mathbf{u_{gal}}]$$

- Connecting observables with theory

$$\delta_{gal} = b \cdot \delta_m$$

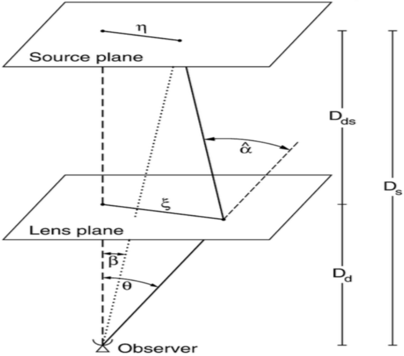
$$\frac{\theta_{gal}}{H(z)} = f_m \cdot \frac{\delta_b}{b}$$

$f_m \propto \frac{d\delta_m}{dlnz}$ is the "growth of structure" capturing how fast dark matter structures collapse at large scales

Weak gravitational lensing

Light reaching us from distant sources feels a force (or acceleration) produced produced by large inhomogeneities along its path[3]

$$\frac{d^2x^i}{dr^2} = \frac{\partial}{\partial x^i}\left(\Phi - \Psi\right) \equiv \frac{\partial}{\partial x^i}\Phi_{lens}$$



[3] **Picture credit: Bartelmann & Schneider, Phys. Rep. (2001)**

The gravitational slip η can be expressed only on observable quantities [4]

$$\eta(z,k) \equiv -\frac{\Phi(z,k)}{\Psi(z,k)} = \frac{3(1+z)^3}{2E^2\left(\mathcal{O}'_\theta/\mathcal{O}_\theta + E'/E + 2\right)}\frac{\Phi_{lens}}{\mathcal{O}_\theta} - 1$$

$[E(z) \equiv H(z)/H_0, \quad \mathcal{O}_\theta \equiv -\theta_{gal}/H]$

$\eta = 1$	$\eta \neq 1$
$\mathcal{L} \subset R - 2\Lambda,$	$\mathcal{L} \subset f(R)$
$\mathcal{L} \subset R + K(X,\phi),$	$\mathcal{L} \subset g(\phi)R + U(\phi)$
$\mathcal{L} \subset K(X,\phi) + G(X,\phi)\Box\phi$	$\mathcal{L} = \mathcal{L}_{Hordenski}$

$[X \equiv -\frac{1}{2}g^{\mu\nu}\nabla_\mu\nabla_\nu\phi]$

[4] L. Amendola, M. Kunz, I.D.S, I. Sawicki, PRD 87, 023501 (2013)
M. Motta, I. Sawicki, I.D.S, L. Amendola, M. Kunz, PRD 88, 124035 (2013)

The link between propagation of gravitational waves and gravitational slip

- In GR, the only propagating field is the massless graviton h_{ij}, travelling with the speed of light $c_T = 1$

- Modified gravity models in principle affect the propagation of tensors in a non–trivial way

$$h''_{ij} + (2 + \nu)Hh'_{ij} + c_T^2 k^2 h_{ij} + a^2 \mu^2 h_{ij} = a^2 \Gamma\gamma_{ij}$$

Parameter	**Modified in ......**
Planck mass rate: $\nu \equiv H(t)^{-1}\frac{d \ln M_p^2}{dt}$	Hordenski
Speed of tensors: c_T^2	Hordenski, Einstein–Aether
Graviton's mass: μ^2	Massive bi–metric gravity
Source term: $\Gamma\gamma_{ij}$	Massive bi–metric gravity

The link between propagation of tensors and anisotropic stress

- Given the anisotropy equation and tensor evolution at the linear level

$$\Phi(z,k) - \Psi(z,k) = \sigma(\nu, \mu^2, c_T, \Gamma)\Pi(z,k)$$
$$h_{ij}'' + (2 + \nu)\mathcal{H}h_{ij}' + c_T^2 k^2 h_{ij} + a^2 \mu^2 h_{ij} = a^2 \Gamma\gamma_{ij}$$

. . . and for the most popular large classes of modified gravity models in the literature[5],

- The most general second–order, scalar–tensor Hordenski theories (one extra scalar field ϕ),
- The massive bi–metric theories (one extra spin–two field),
- The Einstein–Aether theories (one extra vector field),

. . . *the coupling σ controlling the amplitude of the linear anisotropic stress at large scales, depends on exactly those theory parameters which modify the propagator of tensor waves.*

Conjecture

This underlying relation between scalar anisotropic stress and tensor propagation is a feature of all models on general configurations

[5]**I.D.S, I. Sawicki, L. Amendola, M. Kunz PRL 113, 191101 (2014)**

Summary

Using large-scale structure observations we can search for genuine modifications of the law of gravity at large scales in a model-independent way. In the near future, the EUCLID mission will be providing us with accurate enough observations making it potentially feasible to rule out large classes of gravity models for dark energy

A link between the possible modification of gravity at large scales and the propagation of tensors exists: The theory parameters modifying entering the gravitational slip, are exactly those which modify the propagation of tensor. A window to bridge cosmological with astrophysical observations