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Testing gravity at cosmological scales

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General Fellini Meeting - Ferrara

We have General Relativity, why Modified Gravity?

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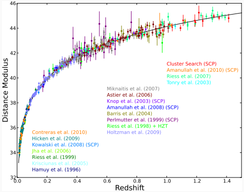

Suzuki et al. (2012)

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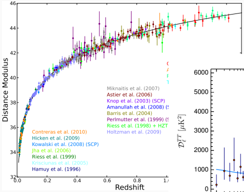
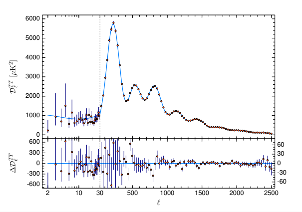


Suzuki et al. (20



Planck Collaboration (2018)

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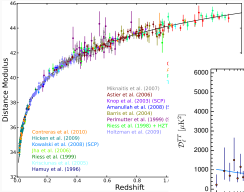

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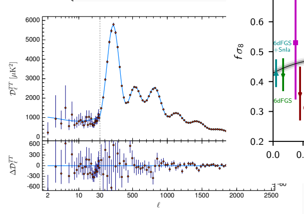

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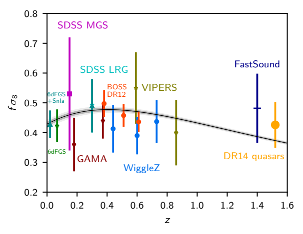

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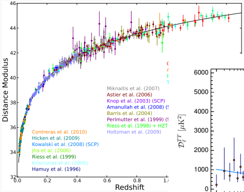

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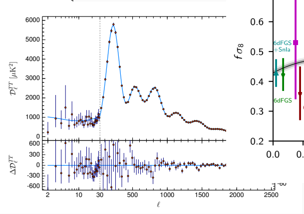

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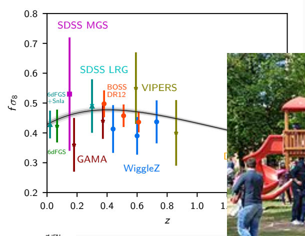

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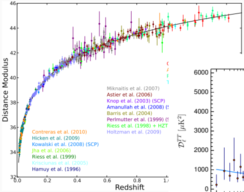

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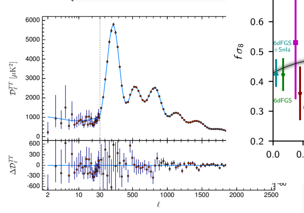

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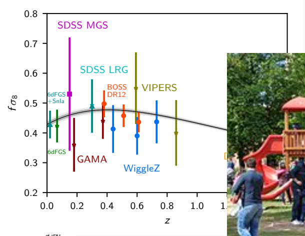

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We are curious, but most importantly...

In Physics we have Heroes, not Prophets - S. Weinberg

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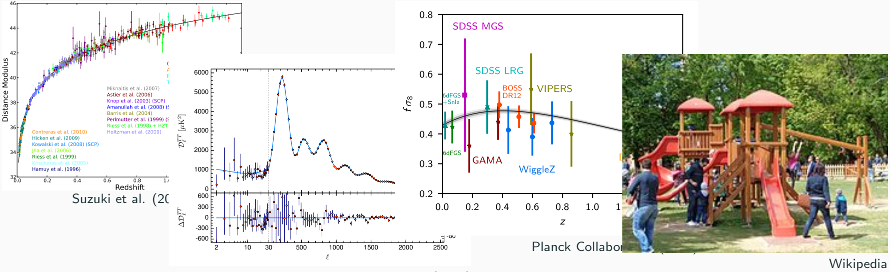

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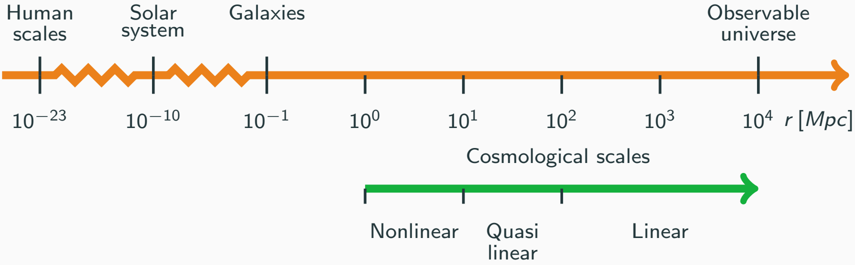
Go beyond GR if you:

- Have a favourite/competitive model
- Want to test the robustness of GR

The observable universe



Goal: determine the content, structure and dynamics of the universe

- Describe: model gravity and the ingredients of our cosmos
- Phenomenology: estimate observables for better understanding
- Build the tools: codes for precision/accuracy cosmology
- Theory vs observations: explore the content of the universe

The modified gravity lagrangian

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\sum_{i=2}^{5} \frac{1}{8\pi G_{\mathrm{N}}} \mathcal{L}_i(g_{\mu\nu}, \phi) + \mathcal{L}_{\mathrm{m}}(g_{\mu\nu}, \psi_M) \right]$$

$$\begin{aligned}
\mathcal{L}_2 &= G_2(\phi,\, X) \\
\mathcal{L}_3 &= -\, G_3(\phi,\, X)\Box\phi \\
\mathcal{L}_4 &= G_4(\phi,\, X)R + G_{4X}(\phi,\, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right] + F_4(\phi,\, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'} \\
\mathcal{L}_5 &= G_5(\phi,\, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5X}(\phi,\, X)\left[(\Box\phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\right] \\
&\quad + F_5(\phi,\, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}\phi_{;\sigma\sigma'}
\end{aligned}$$

Will we ever be able to constrain the functional form of G_2, G_3, G_4, G_5, F_4 and F_5 with observations?

The modified gravity lagrangian

Covariant Theory | Effective Description (linear) | Predictions

$S[g_{\mu\nu}, \phi]$ +initial cond.

$G_i(X,\phi)\big|_{i=2,3,4,5}$

$\phi'(\tau_0)$, $\phi(\tau_0)$

$\longrightarrow$

- Expansion $w(\tau)$
- Kineticity $\alpha_K(\tau)$
- Braiding $\alpha_B(\tau)$
- M_p running $\alpha_M(\tau)$
- Tensor speed $\alpha_T(\tau)$

$\longrightarrow$

- $H(z)$
- C_ℓ^{ij}
- $P(k,z)$
- $\dots$

Effective theory approach $\longrightarrow$

Covariant theory approach $\longrightarrow$

Effective theory: test deviations from a well established model (ΛCDM)!

Universally adopted as the standard description for alternative theories of gravity!

The linear universe: `hi_class` (`www.hiclass-code.net`)

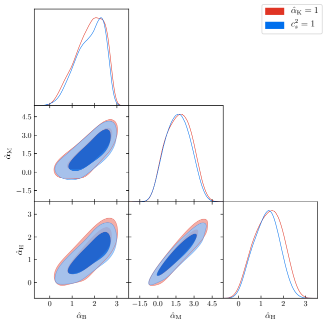
Einstein-Boltzmann solvers

Simulate the evolution of the (linear) universe to compute CMB and large scale structure observables.

Philosophy

- level of detail and control available to standard cosmology
- better an (controlled) error than a wrong solution

Parameter estimation with cosmology



Robustness of GR+Λ

- still $\mathcal{O}(1)$ constraints on gravity
- $\mathcal{O}(0.1)$ with next generation of surveys
- No significant evidence of MG ($\sim 2\sigma$, mostly low-l in the CMB)
- typical DE parameters remain largely unconstrained

Why should we continue doing that?

- explore degeneracies among different species (help from non-linear)
- avoid blind extrapolation of GR over 15 orders of magnitude in length scale
- avoid biasing all measurements

Interplay Cosmology - GW propagation

Two signals one event

- Light (GRB170817A)
- Gravity (GW170817)

- $\Delta t \simeq 1.7$ s, $z \simeq 0.01$
- $d_s/c \simeq 40\mathrm{Mpc}/c \simeq 4 \times 10^{15} s$

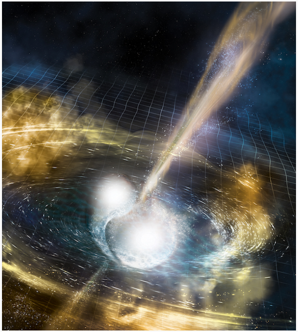
$$\Downarrow$$

What happens to MG?

$$\left|\alpha_T^0\right| \simeq |2c\Delta t/d_s| \lesssim 10^{-15} \qquad \text{(GW)}$$

vs

$$\left|\alpha_T^0\right| \lesssim \mathcal{O}(1) \qquad \text{(cosmology)}$$

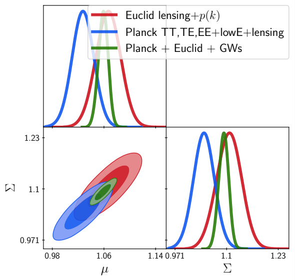


NSF/LIGO/Sonoma State University/A. Simonnet

Drastically constrain the parameter space of gravity
Combine different regimes to improve our knowledge

Interplay Cosmology - GW propagation

- CMB: Planck (Past)
- LSS: Euclid (Present/Future)
- GW: Einstein Telescope (Future)



PRELIMINARY

Interplay between scalar and tensor sectors improves constraints on cosmological parameters!

Summary

Linear PT

- well understood and easy enough
- we have codes for accurate predictions
- easier to detect modified gravity

Non-linear PT

- difficult to model and understand (semi-analytical methods vs N-body simulations)
- we don't have yet robust and general machinery for accurate predictions (part of my Fellini project)
- helps to remove degeneracies (e.g. bias parameters)

Interplay cosmology - GW

- already great success
- crucial to improve our knowledge on gravity