Gravity at the Horizon:

from the cosmic dawn to ultra-large scales

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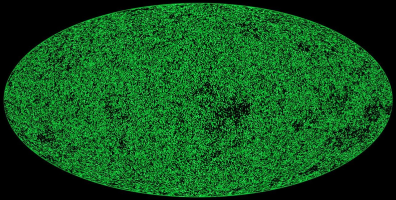
Gravity at the Largest Scales - Oct 2015

with L. Amendola, E. Bellini, J. Lesgourgues, V. Pettorino, J. Renk, I. Sawicki

(other work with D. Bettoni, F. Könnig and M. Martinelli)

Horndeski in the Cosmic Linear Anisotropy Solving System



hi_class

WINTER 2016

1. Scalar-tensor theories
2. Early modified gravity*
3. Non-linear BAO evolution
4. Ultra-large scales*

*at the horizon / beyond quasi-static

developed with Emilio Bellini, Julien Lesgourgues, Iggy Sawicki

Scalar-Tensor gravity

- ⋆ Old-School: $f(\phi)R + K(X,\phi)$ $\quad X \equiv -(\partial\phi)^2/2$
  - $\supset$ quintessence, $f(R)$, Brans-Dicke (Jordan '59, Brans & Dicke '61)

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⋆ Horndenski's Theory (1974)

$g_{\mu\nu}$ + $\boxed{\phi}$ + Local + 4-D + Lorentz theory with $\boxed{2^{nd} \text{ order Eqs.}}$

$$G_2(X,\phi) - G_3(X,\phi)\Box\phi + G_4(\phi,X)R + G_{4,X}\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right]$$
$$+ G_5 G_{\mu\nu}\phi^{;\mu\nu} - \frac{G_{5,X}}{6}\left[(\Box\phi)^3 - 3(\Box\phi)\phi_{;\mu\nu}\phi^{;\mu\nu} + 2\phi_{;\mu}{}^{;\nu}\phi_{;\nu}{}^{;\lambda}\phi_{;\lambda}{}^{;\mu}\right]$$

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⋆ Beyond Horndeski (MZ & Garcia-Bellido '13)

$\supset$ General disformal coupling (Bekenstein '92)

$\supset$ "Covariantized" galileons (Gleyzes *et al.* '14)

Unifying approaches to DE:

Post Friedman	15-22 $\times f_i(t)$	Baker *et al.* '12
EFT for DE	7-9 $\times f_i(t)$	Gubitosi *et al.*, Bloomfield *et al.* '12
		Gleyzes et al. '13 & '14, $\cdots$
EFT for $\mathcal{L}_H$	$\boxed{5 \times f_i(t)}$	Bellini & Sawicki '14

Parameterizations vs Lagrangian:

- Background $\longrightarrow$ often very constraining
- Non-linear effects
- Other regimes: Solar System, Lab., BH,...

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Horndeski in four words (Bellini & Sawicki JCAP '14)

Background expansion: $\longrightarrow H(t)$ (or $\Omega_{\rm de}$, or w...)

$$G_2 - G_3 \Box\phi + G_4 R + G_{4,X} \left[\nabla\nabla\phi\right]^2 + G_5 G_{\mu\nu}\phi^{;\mu\nu} - \frac{G_{5,X}}{6}\left[\nabla\nabla\phi\right]^3$$

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Standard kinetic term $\rightarrow c_S^2$

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- α_M, $\alpha_T \Rightarrow$ Mod. tensor eqs. (Saltas, Sawicki, Amendola, Kunz '14)
- α_K, $\alpha_B \Rightarrow$ Kinetic terms

Theory specific relations:

- Quintessence: $\alpha_K \propto \Omega_{\rm DE}$,
- JBD: α_K, $\alpha_B = -\alpha_M$, Galileon-like: $\alpha_B + \alpha_M$, α_T

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BS is no BS

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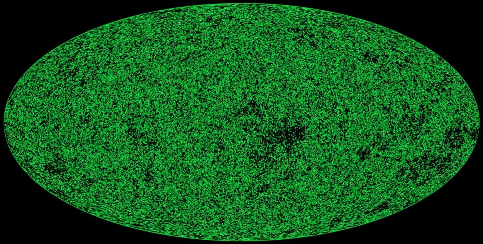
hi_class: How to use it...

Linear cosmology

$$\left.\begin{matrix} G_2,\, G_3,\, G_4,\, G_5 \\ \phi(t_0),\, \dot\phi(t_0) \end{matrix}\right\} \longrightarrow \left\{\begin{matrix} \text{Kineticity } \alpha_K \\ \text{Braiding } \alpha_B \\ M_p \text{ running } \alpha_M \\ \text{Tensor excess } \alpha_T \end{matrix}\right\} \longrightarrow \left\{\begin{matrix} D_A(z) \\ C_\ell \\ P(k) \\ \dots \end{matrix}\right.$$

1. Start with concrete model G's + IC
   - ⋆ covariant Galileons $G_2, G_3 \propto X$, $G_4, G_5 \propto X^2$
   - ...
2. Start with parameterization α's + H
   - ⋆ $\alpha_i =$ constant
   - ⋆ $\alpha_i \propto \Omega_{de}$
   - ...

Early Modified Gravity



with Luca, Julien and Valeria

151x.xxxxx

Early Dark Energy

- Models that address coincidence problem

  $\Rightarrow \Omega_{de} \neq 0$ at early times (e.g. growing ν quintessence)

- CMB $\Rightarrow \Omega_{de}(z_*) \lesssim 1\%$ (Pettorino, Amendola & Wetterich '13)

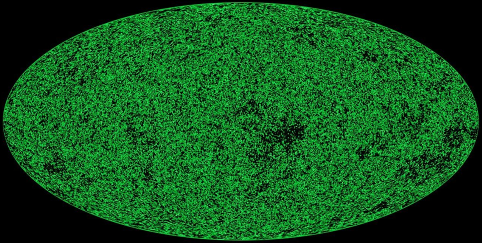
Early Modified Gravity

Soon in your favourite arxiv server...

How much early MG is allowed?

- Tensors $\Rightarrow \alpha_{M/T} \sim \mathcal{O}(1)$ (Amendola, Ballesteros & Pettorino '14)
- Scalars $\Rightarrow$ BS + `hi_class` (see also Brax, Bruck, Clesse *et al.*)

Non-linear Effects



with Emilio Bellini

PRD 92 (2015) 6, 063522

Non-linear evolution of the BAO scale

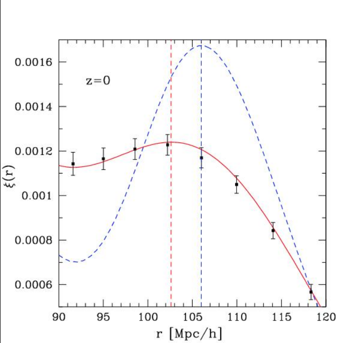
BAO scale in the galaxy distribution $\rightarrow$ comoving standard ruler

$$r_{\rm phys} = a(t) \cdot r_{\rm coord}$$

Non-linear BAO evolution $(z{=}0)$

- Shift $\sim 0.3\%$ smaller
- Broadening ~ 8 Mpc$/h$

(Prada *et al.* 1410.4684)



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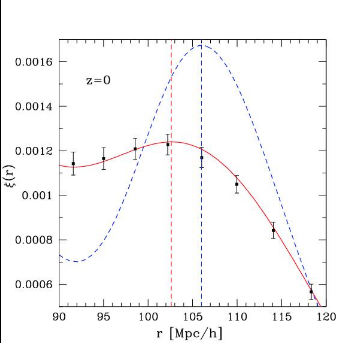


(from Crocce & Scoccimarro - PRD '08)

In 2012:

"(My work will) deal with the dynamical evolution of the BAO scale in (MG), which will be measured with growing precision by current and forthcoming surveys."

in 2013:

E. Bellini $\rightarrow$ Galileon bispectrum

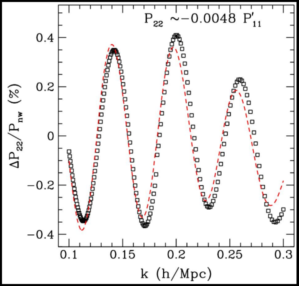
Eulerian perturbation theory

Adjust to a template (Padmanabhan & White '08):

$$P(k) = P_{11}(k/\alpha) \approx P_{11}(k) - \boxed{(\alpha-1)kP'_{11}(k)}$$

$$P(k) = \underbrace{\underbrace{P_{11}(k)}_{\text{linear}} + \underbrace{\sum_n P_{1n}(k)}_{\text{propagator}}}_{\propto P_{11}(k)} + \underbrace{\sum_{n,m>1} P_{nm}(k)}_{\text{mode coupling}} \qquad (P_{nm} \sim \langle \delta_n \delta_m \rangle)$$

- $P_{1n} \propto P_{11}$
- Mode coupling: $\supset (\cdots) kP'_{11} \propto P_{22}$



(from Padmanabhan & White - PRD'09)

Peak-background split (Sherwin & Zaldarriaga '12)

$$\alpha - 1 \approx \frac{47}{105}\sigma^2_{r_{BAO}} \quad \text{(standard GR)}$$

Mode coupling & BAO shift in modified gravity

Non-linear gravitational interactions $\Psi = \mathcal{I}_1 \delta\rho + \mathcal{I}_2 \delta\rho^2 + \cdots$

Modified mode coupling:

$$F_2(p,q,\mu) = C_0(t) + C_1(t)\mu\left(\frac{p}{q} + \frac{q}{p}\right) + C_2(t)\left[\mu^2 - \frac{1}{3}\right]$$

Kernel restrictions: $C_0 + \frac{2}{3}C_2 = 2C_1\,, \quad C_1 = \frac{1}{2}$

(Takushima *et al.* '14, Bellini *et al.* '15)

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Generalized shift formula (Bellini MZ '15)

$$\alpha_k - 1 = \frac{2}{5} \left(2C_0(t) - \frac{1}{2} \right) \langle \delta_L^2 \rangle \Rightarrow \begin{cases} \text{Linear growth: } \langle \delta_L^2 \rangle \approx \sigma^2_{r_{BAO}} \\ \text{Non-linear gravity: } C_0 \neq \frac{17}{21} \end{cases}$$

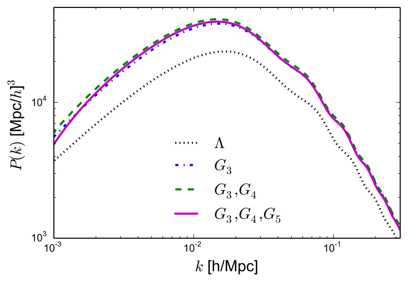
BAO Shift for Galileons: linear growth

$$\alpha_k - 1 \approx \frac{2}{5}\left(2C_0(t) - \frac{1}{2}\right)\sigma^2_{r_{BAO}} \Rightarrow \begin{cases} \text{Linear: } \sigma^2_{r_{BAO}} \\ \text{Non-linear: } C_0 \end{cases}$$

- Implement Covariant Galileon in `hi_class` ✓
- Obtain $\delta_1(z)$, $P_{11}(k)$, & $\sigma_{r_{BAO}}$

$$\begin{aligned} G_2 &= -X \\ G_3 &= c_3 X/M^3 \\ G_4 &= \frac{M_p^2}{2} + c_4 X^2/M^6 \\ G_5 &= c_5 X^2/M^9 \end{aligned}$$

Best fit models (Barreira *et al.* '14)



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- Expand $\mathcal{L}_H$ over FRW:

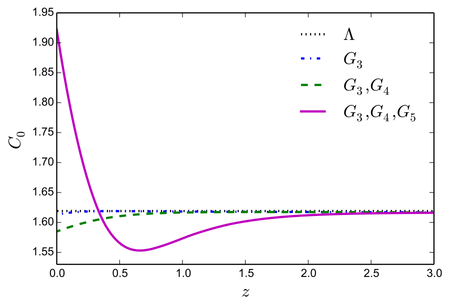
  scalar perturbations $\rightarrow \mathcal{O}(\delta^3)$

- Quasi-static + sub-horizon approx.
- Identify inhomogeneous sources:

$$\ddot{\delta}_2 + \cdots = S_2\left[\delta_1(p), \delta_1(q)\right]$$

- Integrate monopole component

$$S_2 \longrightarrow C_0(t)$$



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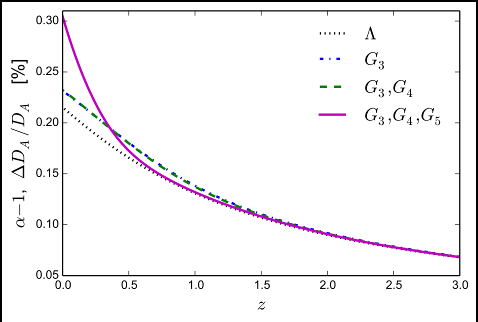
- Can have significant enhancement at $z \sim 0$:)

In 2012:

"Further research will focus on the possibility of measuring such effects on LSS surveys."



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- Can have significant enhancement at $z \sim 0$:)
- Forecast $\Rightarrow$ Utterly irrelevant... (Weinberg *et al.* '12)

In 2012:

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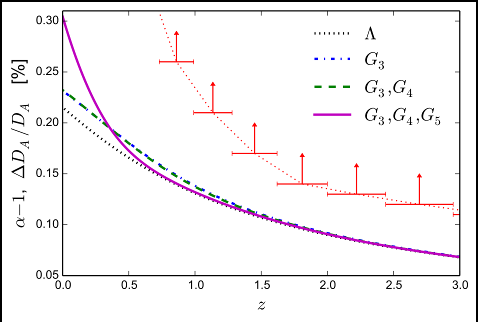
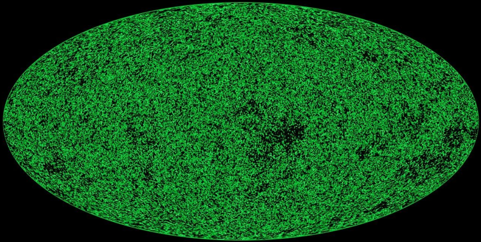
In 2015:

Nope...

but ask me again in 2016 ;)



Ultra-large Scales



Janina Renk's Master Thesis

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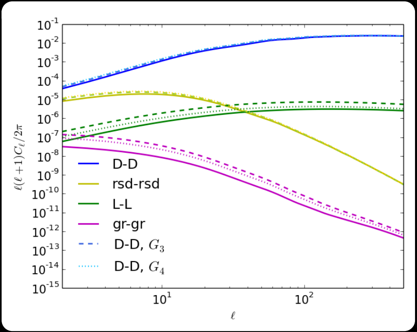
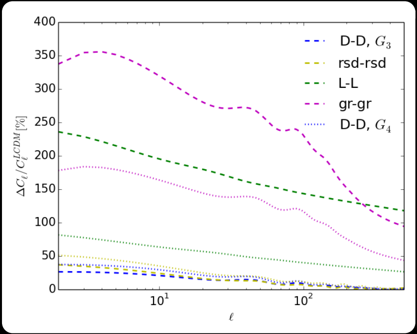
Relativistic effects in $\mathcal{L}_H$ (J. Renk's Master thesis, cf. Ruth's talk)



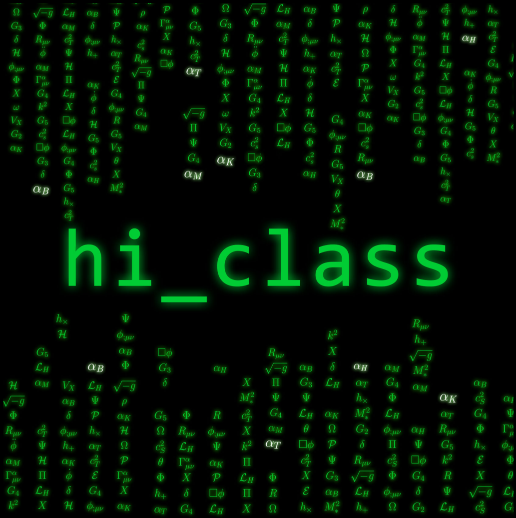


- Galileon $\Rightarrow$ modified $\Phi, \Psi \Rightarrow \uparrow$ Lens. & GR effects
- $\uparrow$ correction for $\downarrow$ dominant effects :(
  ΔGR $>$ Δ lens $>$ ΔRSD $>$ Δ density
- (maybe) detectable using multiple tracers (Alonso & Ferreira '15)

Conclusions

- Contemporary scalar-tensor cosmology well understood
- Early MG strongly constrained:
  - $\star$ Stability priors
  - $\star$ effects on the CMB
- BAO: great standard ruler
  - $\star$ even for extreme gravity in future surveys
- Interesting Non-linear effects in MG (more to come...)
- Ultra-large scales
  - $\star$ rel. effects enhanced but hard to measure
- Early MG + Ultra-large $\Rightarrow$ Horizon / beyond QS approx

Vielen Dank



und auf Wiedersehen Heidelberg!