Gravity at the Horizon:

from the cosmic dawn to ultra-large scales

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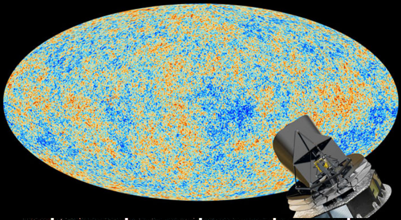
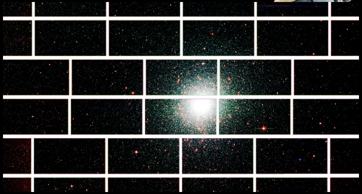
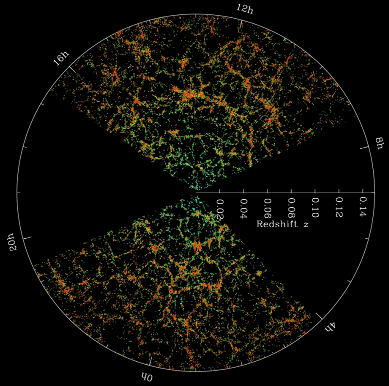
A Golden Era for Cosmology

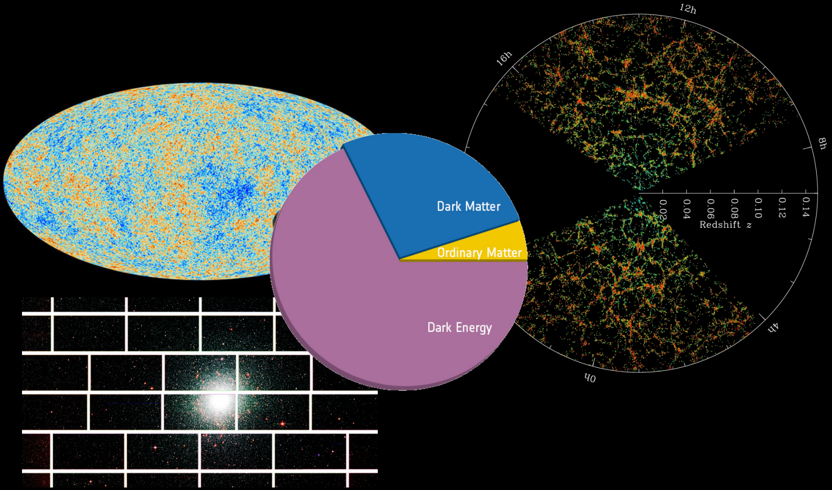






images from Planck , SDSS, Dark Energy Survey

A Golden Era for Cosmology



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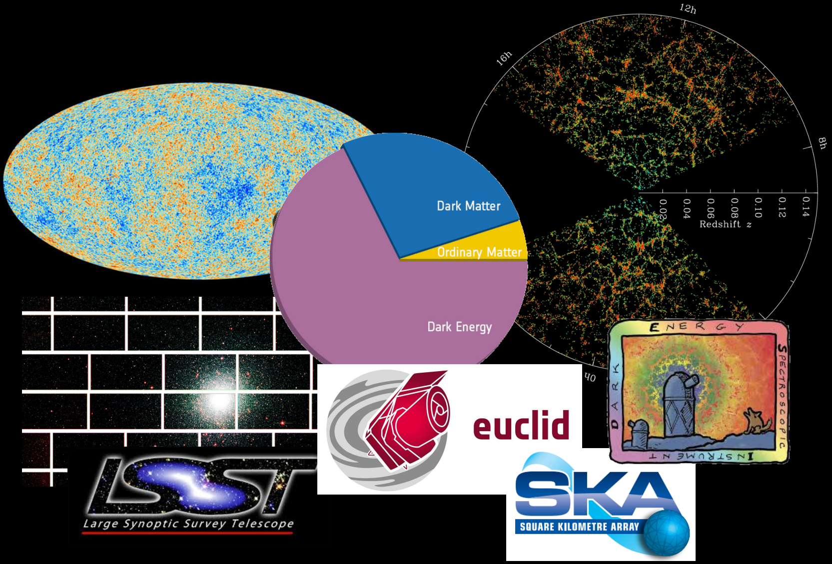

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Why alternative gravities?

- Alternatives to Λ?

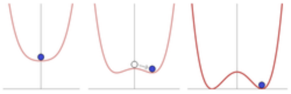
  Inflation again? $n_s \neq 1$

- Interesting field-theoretical questions

  proxy for inflation/quantum gravity?

  viable massive spin-2 particles?

  cosmological constant problems?



- Test gravity on cosmological scales

  effects on cosmological scales?

  model independence of tests?

How to modify gravity

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Diet + Exercise → already very hard!

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Lorentz + QM ⇒ restrictions on massless graviton interactions!

(Weinberg '64)

Einstein gravity: only covariant metric theory with 2^{nd} order eqs.

(Lovelock '71)

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Diet + Exercise $\rightarrow$ already very hard!

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Einstein gravity: only covariant metric theory with 2nd order eqs.

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Need to give up some of the assumptions:

- Add degrees of freedom:
  - Massive gravity: $\rightarrow$ 5 d.o.f. $\rightarrow$ very tough!
  - Scalar-tensor: $\rightarrow$ 2+1 d.o.f.
  - vector-tensor, tensor-vector-scalar (TeVeS), $\cdots$
- Lorentz violation, Non-local interactions, $\cdots$

Scalar-Tensor gravity

$\star$ Old-School: $f(\phi)R + K(X,\phi)$ $\qquad X \equiv -(\partial\phi)^2/2$

$\supset$ quintessence, $f(R)$, Brans-Dicke (Jordan '59, Brans & Dicke '61)

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⋆ Horndeski's Theory (1974)

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

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

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

$\supset$ all Old-school,

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$\supset$ all Old-school, kin. grav. braiding, covariant Galileons

$\supset$ proxy th. for massive gravity (de Rham & Heisenberg '11)

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

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

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

Cosmology: 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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Kineticity: α_K

Standard kinetic term $\rightarrow c_S^2$

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Variation rate of effective M_p

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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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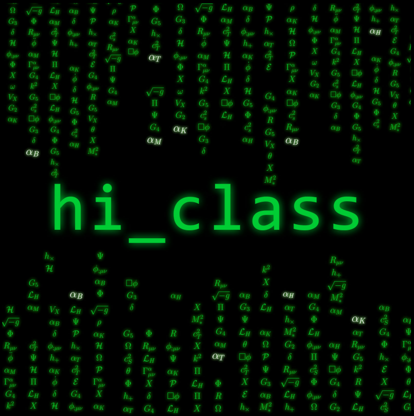
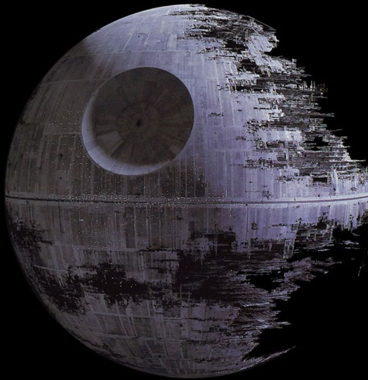
Horndeski in the Cosmic Linear Anisotropy Solving System

hi_class

developed with Emilio Bellini, Julien Lesgourgues, Iggy Sawicki

Horndeski in the Cosmic Linear Anisotropy Solving System





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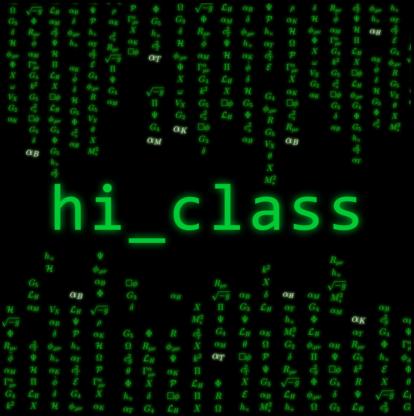


1. Early modified gravity*
2. Non-linear effects:
   BAO and Bispectrum
3. Ultra-large scales*

*at the horizon / beyond quasi-static

developed with Emilio Bellini, Julien Lesgourgues, Iggy Sawicki

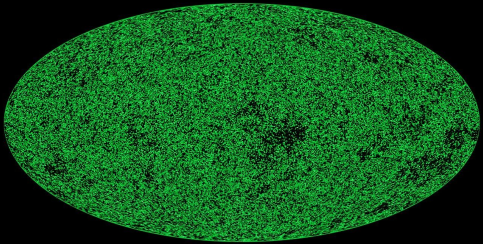
hi_class: How to use it...

Linear cosmology

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

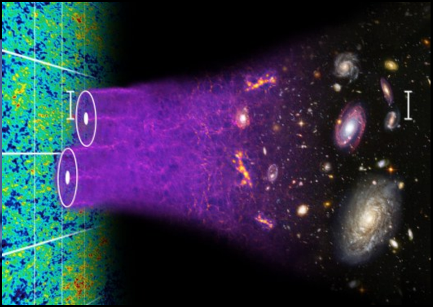
1. Start with concrete model G's + IC
   - ⋆ covariant Galileons $G_2, G_3 \propto X$, $G_4, G_5 \propto X^2$
   - ...
2. Start with parameterization α's + H
   - ⋆ $\alpha_i =$ constant
   - ⋆ $\alpha_i \propto \Omega_{de}$
   - ...

Non-linear Effects



PRD 92 (2015) 6, 063522 with E. Bellini

Baryon Acoustic Oscillations



images from `WiggleZ`, `www.sdss3.org` , Aubourg *et al.*'14

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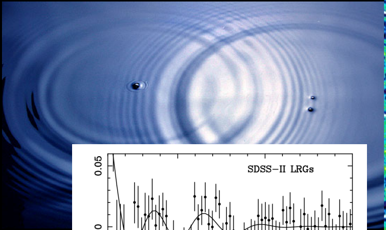

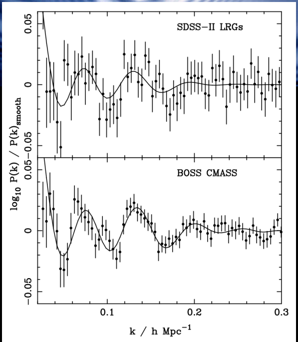

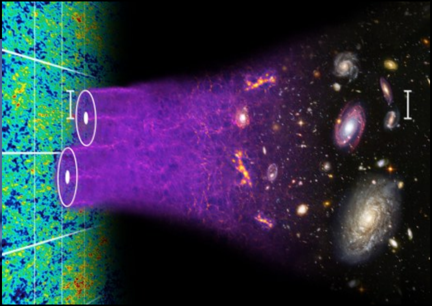

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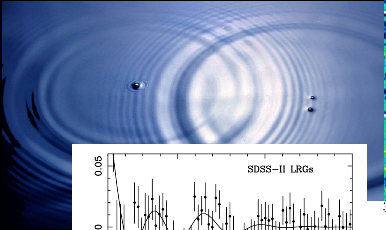
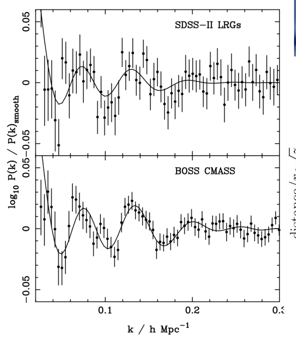
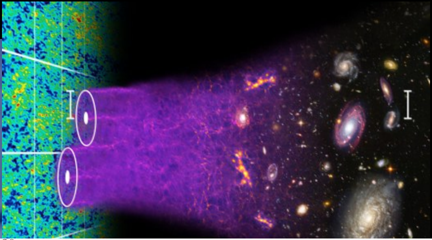
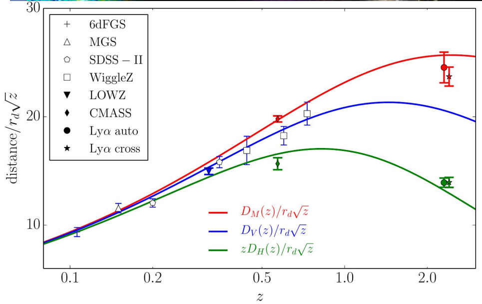




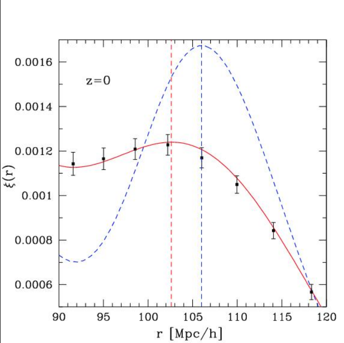




Non-linear evolution of the BAO scale

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

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



(from Crocce & Scoccimarro - PRD '08)

⋆ BAO shift beyond Einstein gravity?

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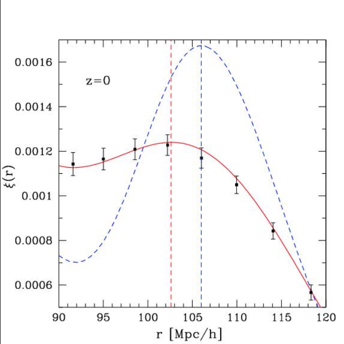
$$r_{\rm phys} = a(t) \cdot r_{\rm coord} + \mathcal{O}(\delta^2)$$



(from Crocce & Scoccimarro - PRD '08)

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

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

(Prada *et al.* 1410.4684)

$\star$ BAO shift beyond Einstein gravity?

Eulerian perturbation theory

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

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

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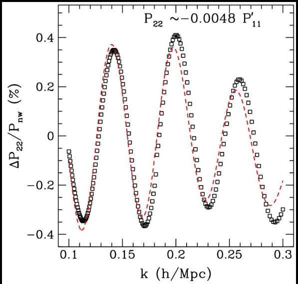

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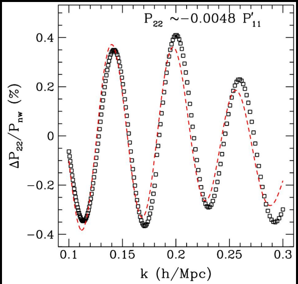
Peak-background split (Sherwin & Zaldarriaga '12)

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



(from Padmanabhan & White - PRD'09)

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)

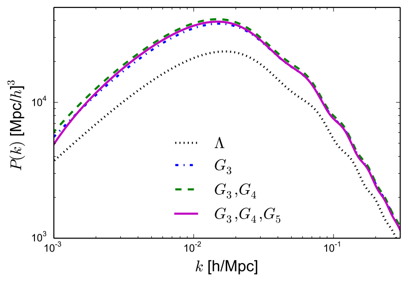
$$\alpha_k - 1 = \frac{2}{5}\left(2C_0(t) - \frac{1}{2}\right)\sigma^2_{r_{BAO}} \Rightarrow \begin{cases} \text{Linear growth} \\ \text{Non-linear gravity: } C_0 \neq \frac{17}{21} \end{cases}$$

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)

BAO Shift for Galileons: mode coupling

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

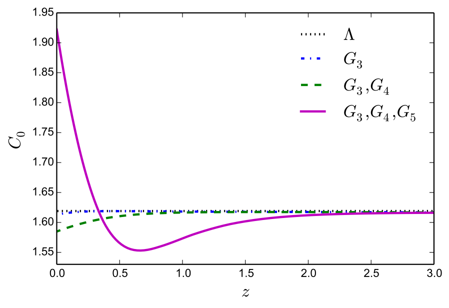
- Expand $\mathcal{L}_H$ over FRW:

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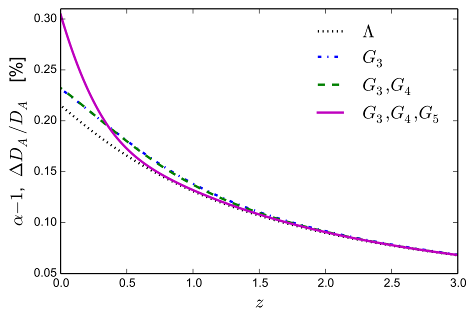

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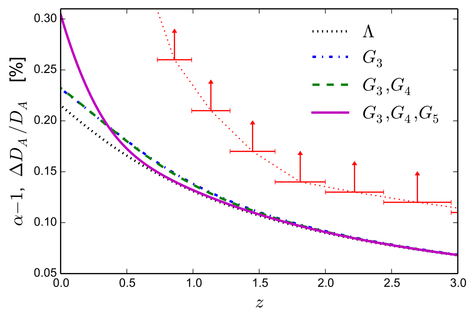
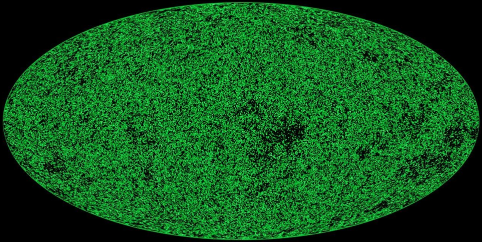
- Can have significant enhancement at $z \sim 0$
- Forecast $\Rightarrow$ irrelevant...

  (Weinberg *et al.* '12)
- But interesting NL effects...



Ultra-large Scales



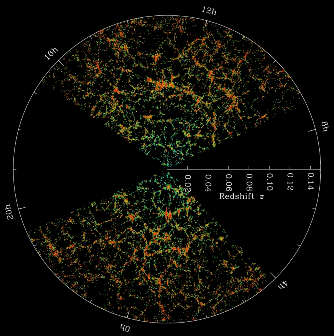
Janina Renk's Master Thesis
with L. Amendola and F. Montanari

160x.xxxxx

Counting Galaxies

Galaxy catalogues:

- observe angles and redshift: $(\hat{n}, z)$



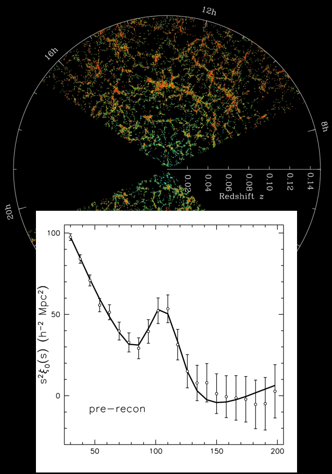
SDSS collaboration

Counting Galaxies

Galaxy catalogues:

- observe angles and redshift: $(\hat{n}, z)$
- project $(\hat{n}, z) \rightarrow \vec{x} \rightarrow \boxed{\xi(r)}$

  $\rightarrow$ assumes $H(z)$!



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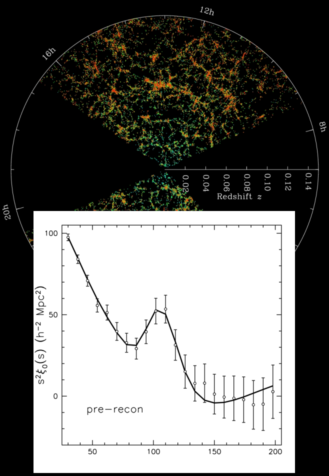


SDSS collaboration

Galaxy Number Counts

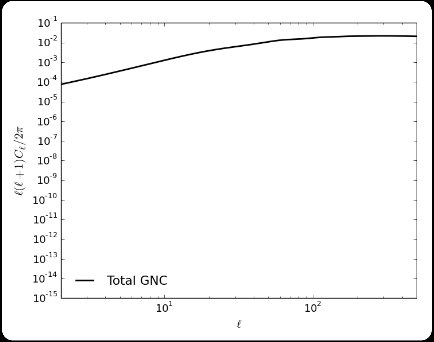
$$\Delta(\hat{n}, z) = \frac{n_{\rm g}(\hat{n}, z) - \langle n_{\rm g}\rangle(z)}{\langle n_{\rm g}\rangle(z)}$$

- Observable $\Rightarrow$ Gauge invariant
- Consistent with any model
- Well defined on all scales

Relativistic effects (Yoo et al. '09, Bonvin & Durrer '11, Challinor & Lewis '11)

$$\Delta(\hat{n}, z) = \underbrace{\Delta_\delta + \Delta_{\rm rsd}}_{\xi(r,\mu)} + \underbrace{\Delta_\kappa + \Delta_{\rm v} + \Delta_{\rm pot}}_{\text{relativistic effects}}$$

Correlations: $\langle \Delta(\hat{n}, z)\Delta(\hat{n}', z')\rangle = \sum_l \frac{2l+1}{4\pi} C_l(z, z') P_l(\cos(\theta))$



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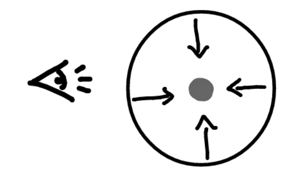
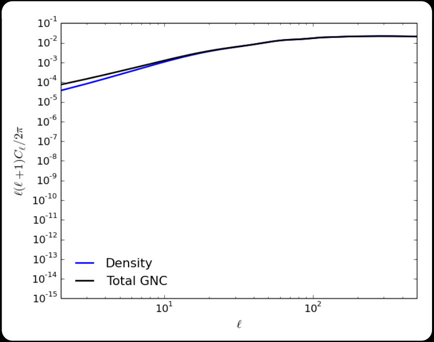


Newtonian Clustering



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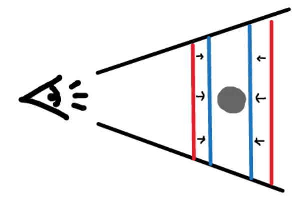
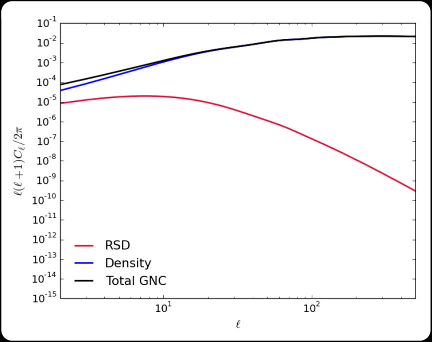


Redshift-Space Distortions



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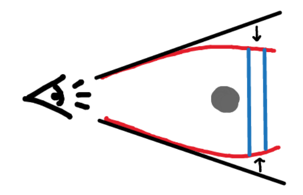
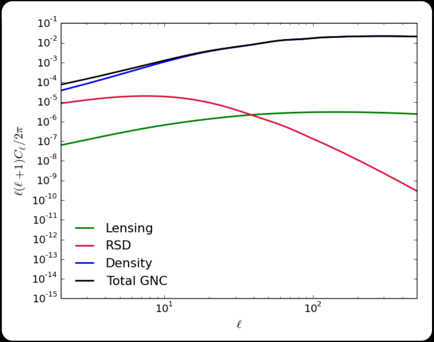


Lensing Magnification



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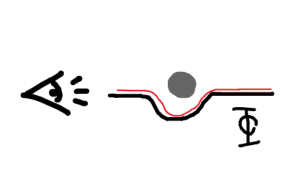
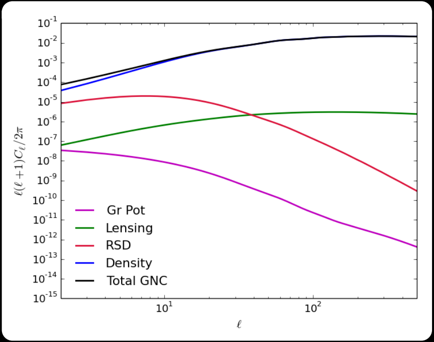


GR effects: time delay, ISW, SW...

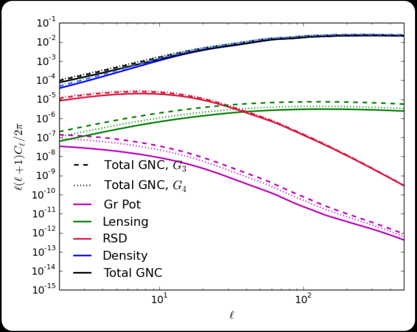


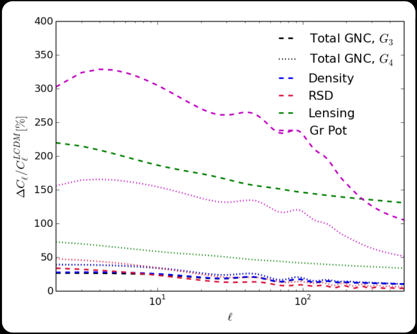
Relativistic effects in Horndeski Gravity

- hi_class + class_Gal (Di Dio, Montanari et al. '13)

Relativistic effects in Horndeski Gravity

- `hi_class` + `class_Gal` (Di Dio, Montanari et al. '13)



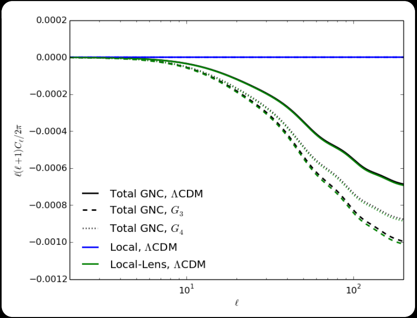


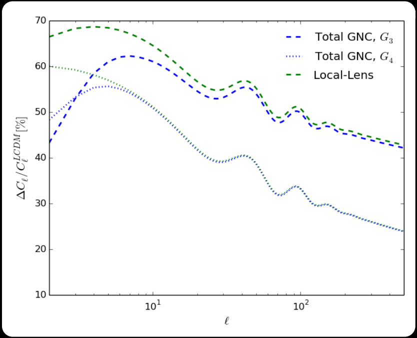
- Galileon $\Rightarrow$ modified $\Phi, \Psi \Rightarrow \uparrow$ Lens. & GR effects
- $\boxed{z = z' = 0.3} \Rightarrow \uparrow$ correction for $\downarrow$ dominant effect

$$\Delta\text{GR} > \Delta \text{ lens} > \Delta\text{RSD} > \Delta \text{ density}$$

Relativistic effects in Horndeski Gravity

- Cross-correlated different redshifts (Montanari & Durrer '15)





- $z = 0.3,\ z' = 1$ ⇒ Correction from lensing magnification
- Departures hard to measure

Conclusions

- Contemporary scalar-tensor cosmology well understood
- Early MG strongly constrained: $\alpha_M \lesssim 10^{-3}$, $\alpha_T \lesssim 10^{-2}$

  Stability priors + effects on the CMB
- BAO: great standard ruler

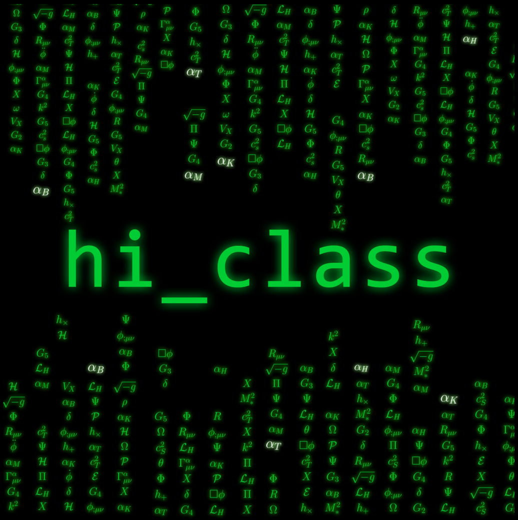
  (even for extreme gravity in future surveys)
- Ultra-large scales:

  rel. effects enhanced but hard to measure
- Lots to learn about gravity in new regimes

  ⋆ non-linear

  ⋆ at the Horizon

Kiitos paljon



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