Title: Approaches to tests of gravity on cosmological scales

Date: Mar 31, 2015 11:00 AM

URL: http://pirsa.org/15030103

Abstract: <p>More than a decade after its discovery, cosmic acceleration still
poses a puzzle for modern cosmology and a plethora of models of dark energy
or modified gravity, able to reproduce the observed expansion history, have
been proposed as alternatives to the cosmological standard model. In recent
years it has become increasingly evident that probes of the expansion his-
tory are not sufficient to distinguish among the candidate models, and that
it is necessary to combine those with observations that probe the dynamics
of inhomogeneities. Future cosmological surveys will map the evolution of
inhomogeneities to high accuracy, allowing us to test the relationships be-
tween matter overdensities, local curvature, and the Newtonian potential on
cosmological scales.</p>

<p>I will discuss theoretical issues involved in finding an optimal framework to
study deviations from General Relativity on cosmological scales, giving an
overview of recent progress, with a focus on model-independent, parametrized
approaches. I will summarize where we stand and what are the next steps
we should take.</p>

Cosmological Tests of Gravity: why & what?

It is now an exceptional time for modern cosmology, when we can observe the universe with high precision and connect cosmological measurements with theory.

eBOSS

Ongoing and upcoming wide field imaging and spectroscopic redshift surveys are in line to map more than a 100 cubic-billion-light-year of the Universe: exquisite measurements of expansion rate, reconstruction of lensing potentials and cosmic structure growth rate reconstructed to 1% in $0<z<2$, over the last 3/4 of the age of the Universe !

WFIRST

Cosmological Tests of Gravity: why & what?

... yes, right! We do face some major challenges ... in the theory camp, we still lack theoretically compelling models for what is making up ~95% of the current energy budget of the universe, i.e. the nature of what we call **dark matter** (and is responsible for the structure we observe around us) and **dark energy** (which is sourcing cosmic acceleration).

As well as a deeper understanding of the mechanism that set up primordial conditions, and these puzzles have deep roots in particle theory and gravity.

One of the challenges in front of us

That the expansion rate of the Universe is accelerating is now a firmly established aspect of cosmology and a testament to the breathtaking convergence of techniques that has emerged in observational cosmology. In turn, cosmic acceleration has introduced new wrinkles into almost every part of theoretical cosmology: *what is sourcing it ??*

Stockholm, Dec. 2011

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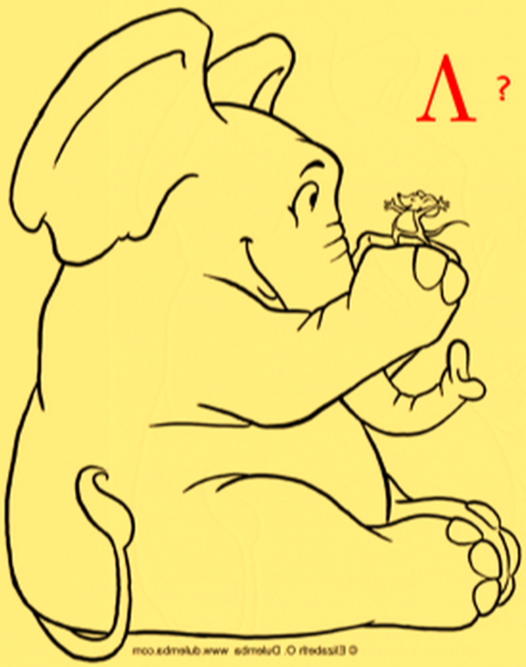
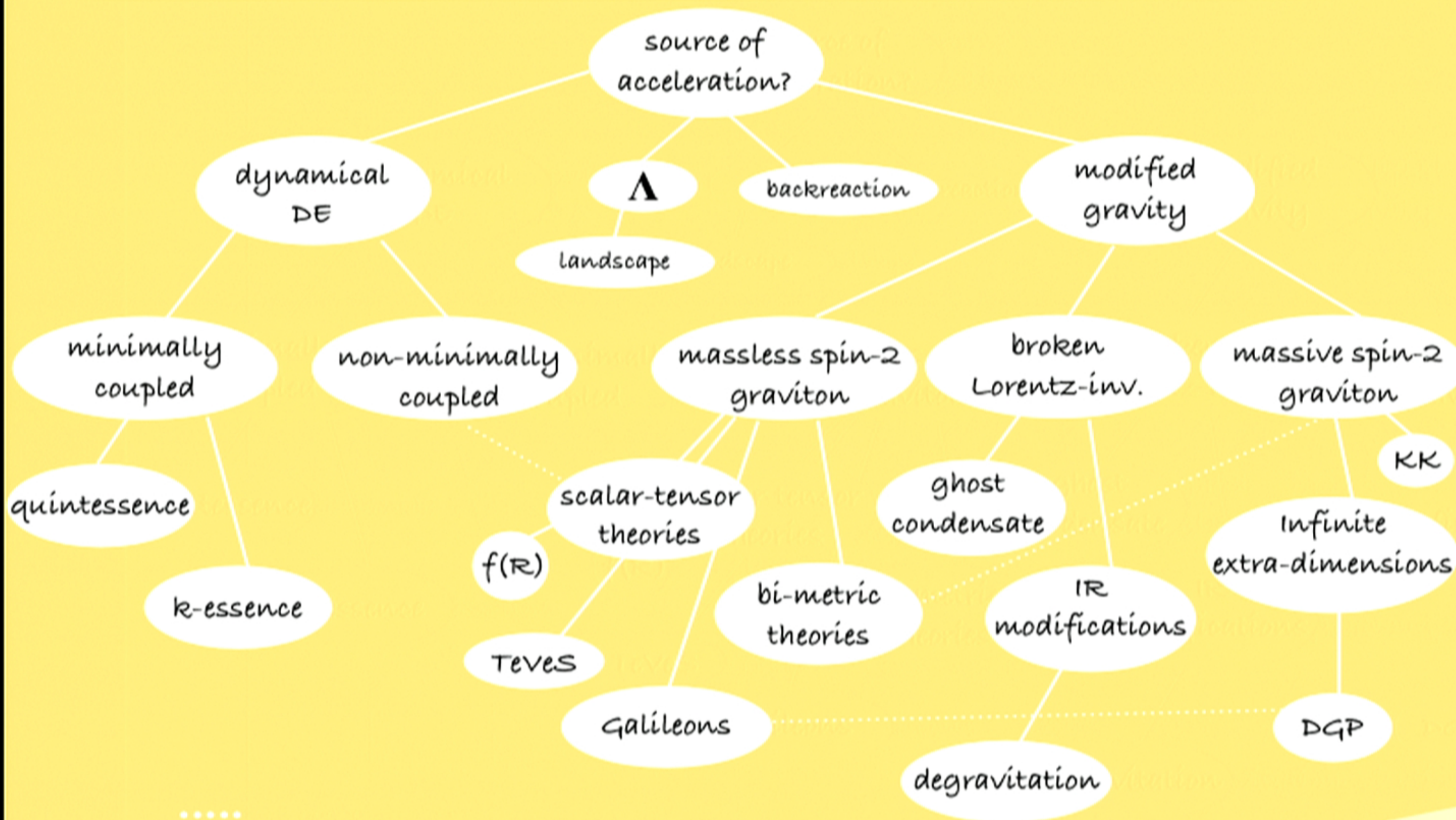


Λ ?

Modified Gravity ?

Dark Energy?

One of the challenges in front of us



A.S., M.Trodden, Rept.Prog.Phys. 72 (2009). Clifton, Ferreira, Padilla,Skordis, Phys.Rep. 513 (2012), Hinterbichler, Rev.Mod.Phys. 84 (2012)

Cosmological Tests of Gravity: why & what?

So until we have a compelling theoretical model,
let's keep an open mind and use that to:

1. test the consistency with LCDM (GR)

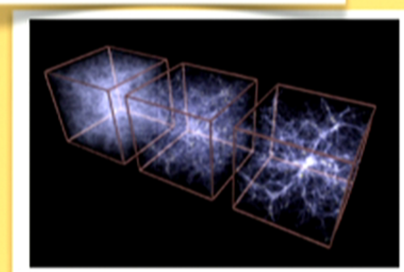
2. explore the parameter space allowed to alternative models

Cosmic functions of interest

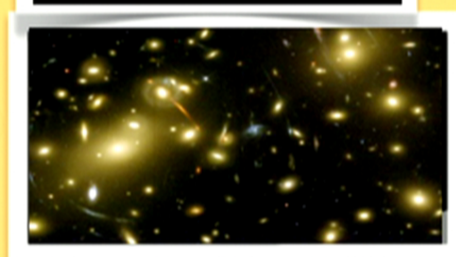
$$ds^2 = -a^2(\tau)\left[(1+2\Psi(\tau,\vec{x}))\,d\tau^2 - (1-2\Phi(\tau,\vec{x}))\,d\vec{x}^2\right]$$

Expansion history: $a(\tau)$

Non-relativistic dynamics
(growth of structure, pec. vel.): $\Psi(\tau,\vec{x})$



Relativistic dynamics
(weak lensing, ISW): $(\Phi+\Psi)\,(\tau,\vec{x})$



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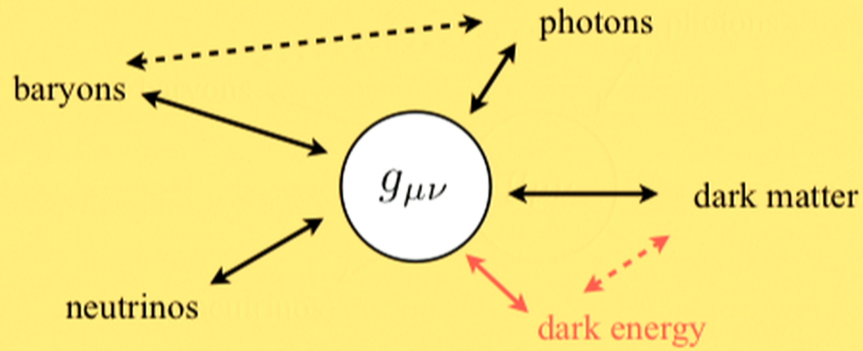
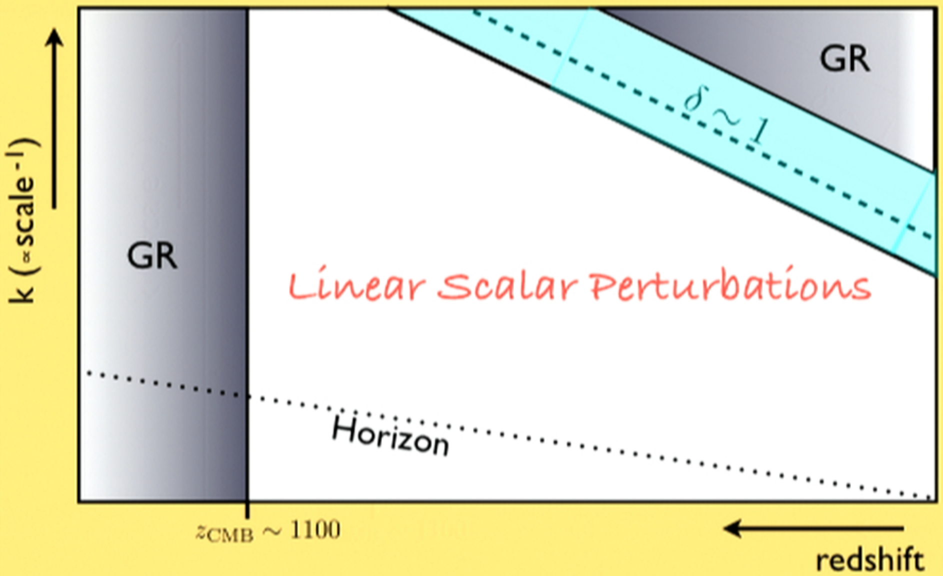


Boltzmann eqs.: $\frac{df}{dt} = C[f]$ where f is the phase-space distribution function of a given species

Einstein eqs.: $G_{\mu\nu} \leftrightarrow T_{\mu\nu}$

Cosmic functions of interest



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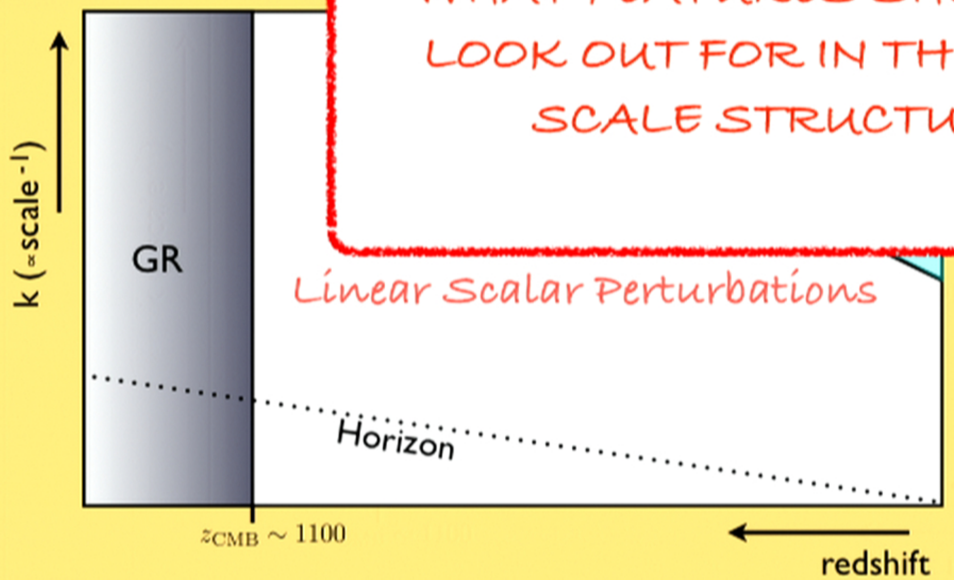

WHAT FEATURES SHOULD WE LOOK OUT FOR IN THE LARGE SCALE STRUCTURE ?

Signatures on LSS: the LCDM lore

... it is based on GR : $G_{\mu\nu} = \dfrac{T_{\mu\nu}}{M_P^2}$

$$T_0^0 = -\left(\rho + \delta\rho\right)$$

$$T_j^0 = \left(\rho + p\right) v_j$$

$$T_j^i = \left(p + \delta p\right) \delta_j^i + \frac{1}{2} \left(\rho + p\right) \left(\nabla^i \nabla_j - \frac{1}{3} \delta_j^i \Delta\right) \pi$$

... the energy-momentum tensor is characterized by $\Delta\pi \ll \delta p \ll \delta\rho$

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LCDM: $w = -1 \qquad \Phi = \Psi \qquad \Psi = -\frac{a^2}{k^2}\frac{\rho\Delta}{2M_P^2}$

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LCDM

- relativistic and non-relativistic probes respond to the same metric potential
- the growth of structure is scale-independent
- the growth rate is easily inferred from the expansion rate

Signatures on LSS: Modified Gravity

When the theory is modified, and typically is of higher order, involving an extra scalar d.o.f., we find that while there is enough freedom to reproduce any expansion history at the background level, still the dynamics of perturbations can be quite different.

Overall we observe a scale-dependent pattern of growth and a non-negligible anisotropic stress. The dynamics of perturbations is richer, and different observables are described by different functions, not by a single growth factor.

Hence the growth of structure offers a way of testing gravity that is complementary to distance measurements

Pogosian & A.S., Phys. Rev. D77, 023503 (2008)

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MG: $w_{\rm eff} \approx -1 \qquad \Phi \neq \Psi \qquad \Psi \neq -\frac{a^2}{k^2}\frac{\rho\Delta}{2M_P^2}$

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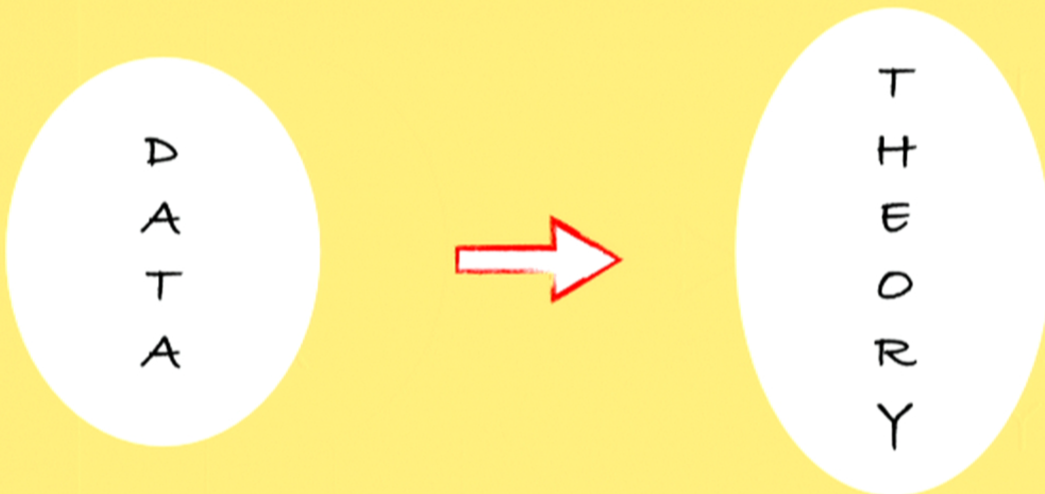
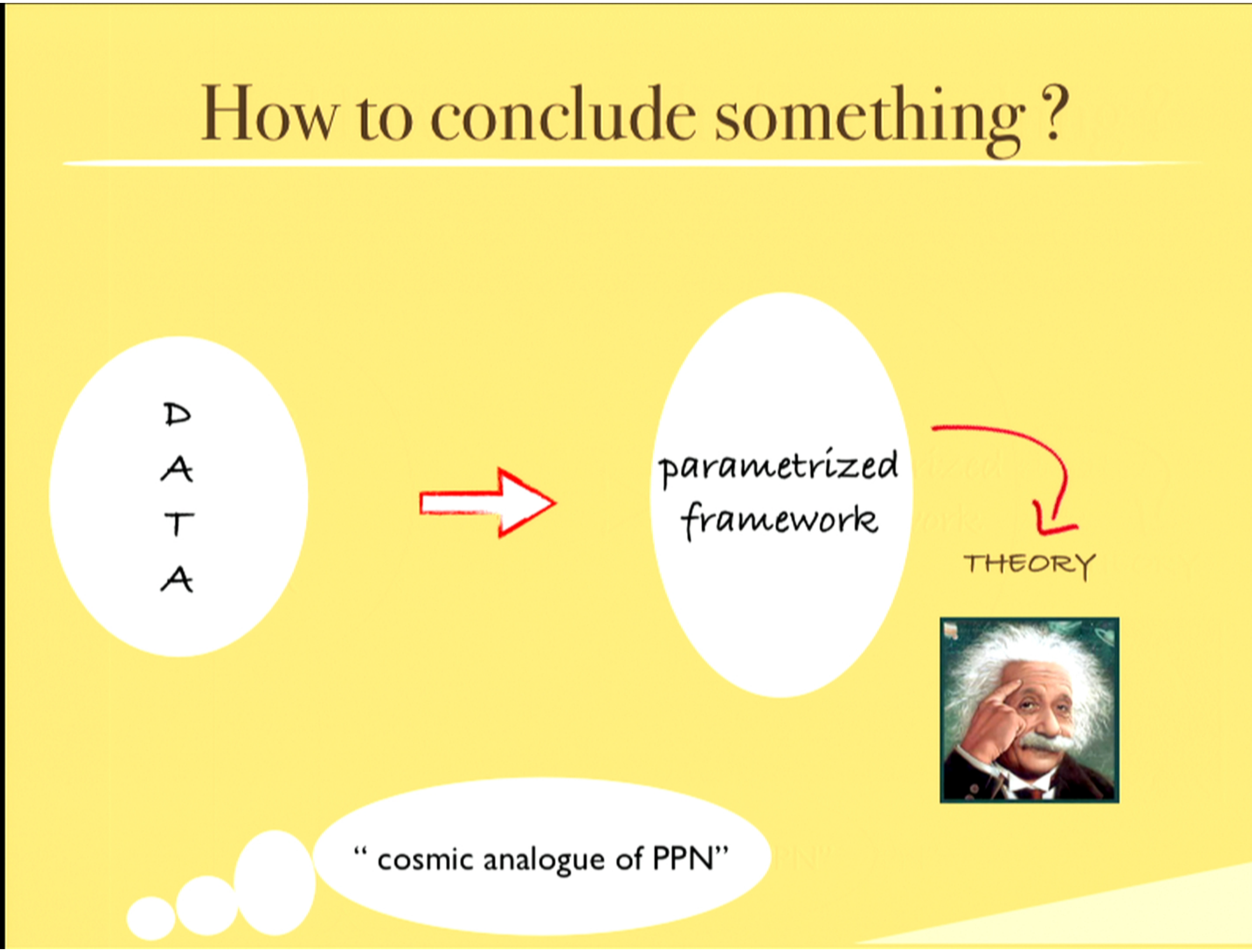
MG:
- relativistic and non-relativistic probes DO NOT respond to the same metric potential
- the growth of structure is scale-dependent
- the consistency btw expansion and growth rate is broken

How to conclude something ?




How to conclude something ?
D
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T
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parametrized
framework
THEORY
" cosmic analogue of PPN"

On parametrizing

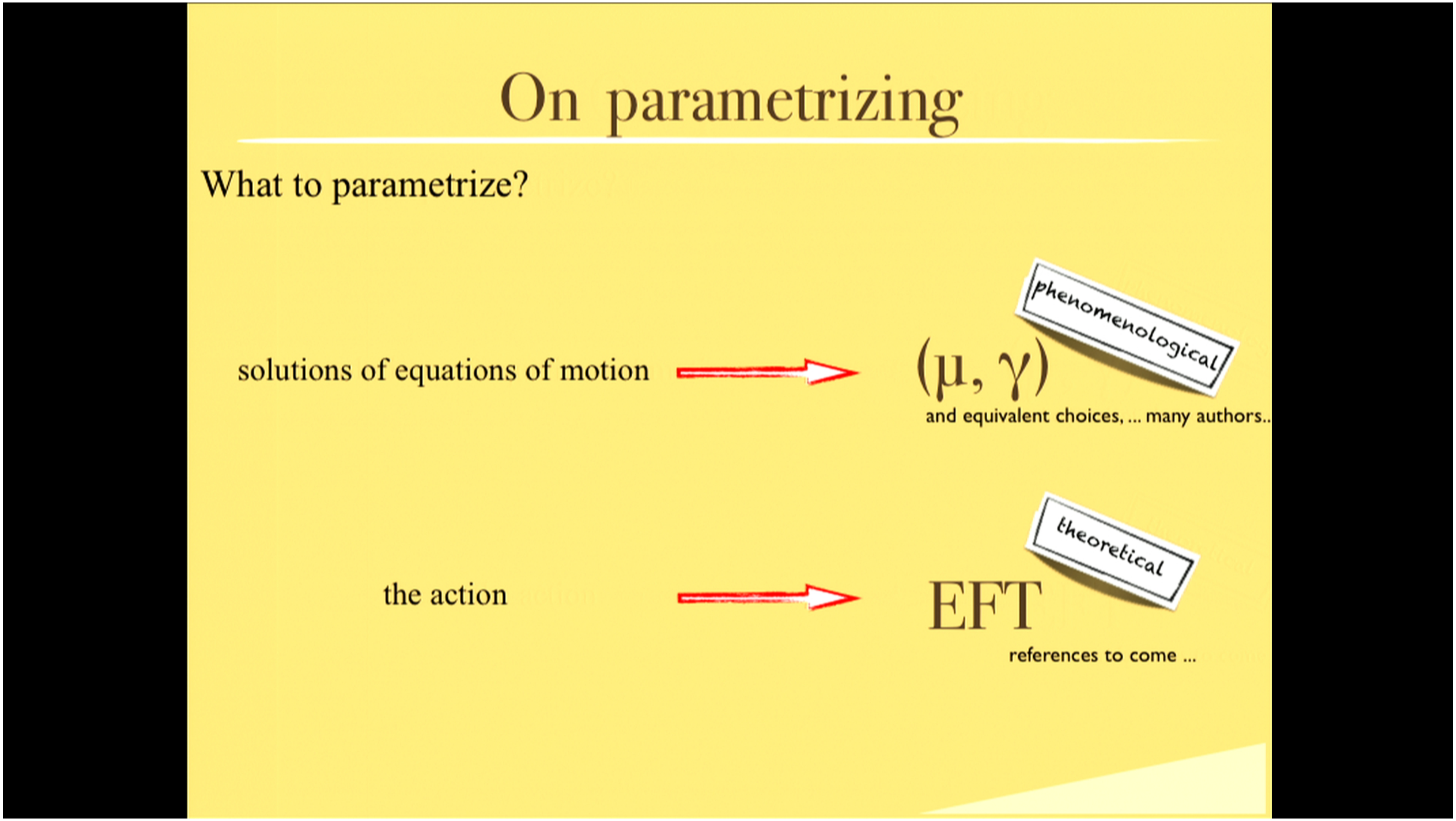
What to parametrize?

solutions of equations of motion → (μ, γ)

and equivalent choices, ... many authors..

the action → EFT

references to come ...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(μ, γ)

and

MGCAMB

(μ,γ)

Energy-momentum conservation eqs.

$$\nabla_\mu T^{\mu\nu} = 0$$

$$\delta' + \frac{k}{aH}v - 3\Phi' = 0$$

$$v' + v - \frac{k}{aH}\Psi = 0$$

Einstein eqs.

Poisson: $$k^2\Psi = -\mu(a,k)\frac{a^2}{2M_P^2}\rho\Delta$$

anisotropy: $$\frac{\Phi}{\Psi} = \gamma(a,k)$$

Pogosian, A.S., Koyama, Zhao, Phys. Rev. D 81 (2010), 104023

(μ,γ)

This is a consistent set of equations for the evolution of perturbations that can be incorporated into std Boltzmann codes, like CAMB

Solutions of linear cosmological perturbations in any particular theory can be expressed in terms of μ and γ; moreover, on sub-horizon scales they can have particularly simple forms

Everything that observations can tell us about the growth of structure can be stored as a measurement of μ and γ (and projected onto solutions of specific models if needed)

They allow us to perform consistency tests of GR *as well as* exploring allowed parameter space of alternative models

$$\delta' + \frac{k}{aH}v - 3\Phi' = 0$$

$$v' + v - \frac{k}{aH}\Psi = 0$$

$$k^2\Psi = -\mu(a,k)\frac{a^2}{2M_P^2}\rho\Delta$$

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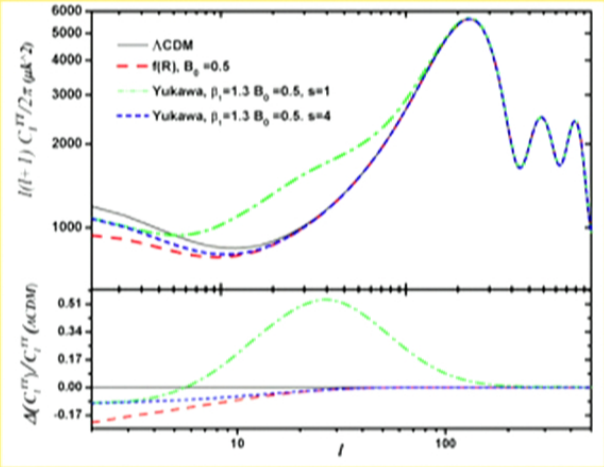
MGCAMB

http://www.sfu.ca/~aha25/MGCAMB.html

Introduced in 2008 as a patch to the publicly available Boltzmann-Einstein solver CAMB to evolve linear scalar perturbations in a consistent parametrized framework and perform cosmological tests of gravity



'Searching for modified growth patterns with tomographic surveys'
Phys. Rev. D 79, 083513 (2009)
Zhao, Pogosian, A.S., Zylberberg

'Testing gravity with CAMB and CosmoMC'
JCAP 1108:005 (2011)
Hojjati, Pogosian, Zhao

$$k^2\Psi = -\mu(a,k)\frac{a^2}{2M_P^2}\left\{\rho\Delta + 3\left(\rho+P\right)\sigma\right\}$$
$$k^2\left[\Phi - \gamma(a,k)\Psi\right] = \mu(a,k)\frac{3a^2}{2M_P^2}\left(\rho+P\right)\sigma$$

Hojjati, Pogosian, Zhao, JCAP 1108:005 (2011)

choices for (μ,γ)

What to do with μ and γ themselves?

- pick a specific functional form

$$\mu = \mu_0 \frac{\Omega_\Lambda(a)}{\Omega_\Lambda}$$

CFHTLenS:F. Simpson et al., arXiv: 1212.3339

$$\mu = \mu_0 + \frac{1-\mu_0}{2}\left(1 + \tanh\frac{z - z_s}{\Delta z}\right)$$

Zhao et al., Phys. Rev. D 81, 103510 (2010)

- QSA:

$$\mu = \frac{1 + \beta_1 \lambda_1^2 k^2 a^s}{1 + \lambda_1^2 k^2 a^s}$$

Bertschinger & Zukin, Phys. Rev. D 78, 024015(2008)

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$$\mu = \frac{1 + \beta_1 \lambda_1^2 k^2 a^s}{1 + \lambda_1^2 k^2 a^s} \xrightarrow{f(R)} \mu = \frac{1}{1-(1/6)B_0 a^3}\frac{1+(2/3)B_0 k^2 a^4}{1+(1/2)B_0 k^2 a^4}$$

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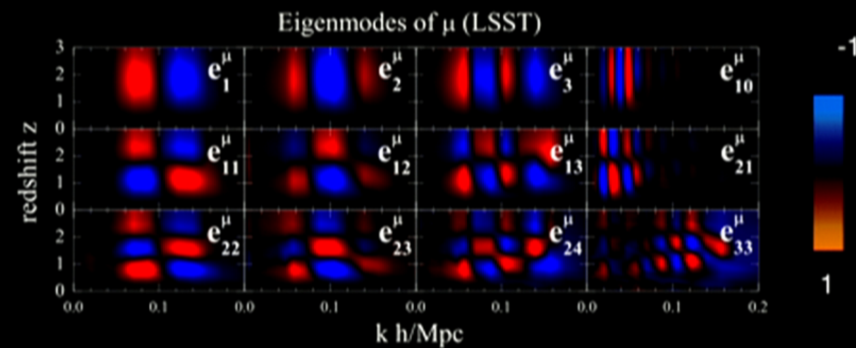
- bin them in time and space and constrain directly the resulting parameters or perform a 2D PCA (which is a very useful forecast tool)

- QSA: fix their scale-dependence, according to general arguments of locality and then perform a 1D PCA on the time-dependence

‘Cosmological tests of GR: a PC analysis’, Phys. Rev. D85, 043508 (2012)

Hojjati, Zhao, Pogosian, A.S., Crittenden, Koyama



PCA is a very useful forecasting tool. It tells us:

- which observables are more likely to be sensitive to the modified growth functions;

- or, inversely, given a survey which features of modified growth will be better constrained, at which scales/times, (sweet spots)

etc.

All this while taking into account degeneracies among the functions used to describe modified growth and cosmological parameters.

What to d

- pick a
  - Q
- bin th
  - Q

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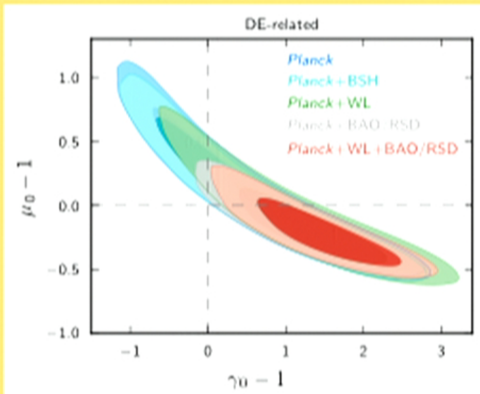
What Planck just said….

$$\mu(a) - 1 = (\mu_0 - 1)\Omega_{\rm DE}(a)$$



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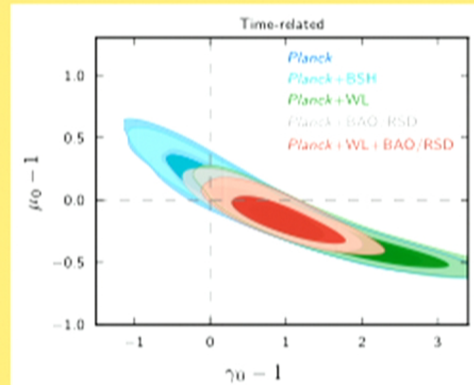

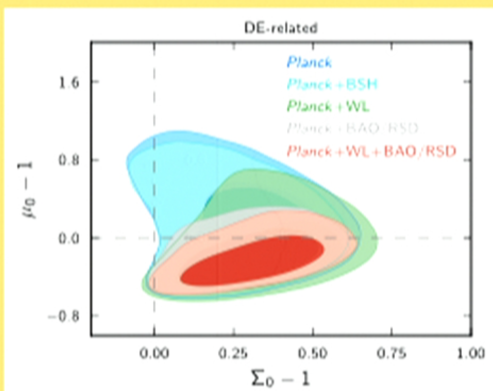

$$k^2\left(\Phi + \Psi\right) = -\Sigma(a,k)\frac{a^2}{2M_P^2}\rho\Delta$$

'Planck 2015 results. XIV. Dark energy and modified gravity'
arXiv:1502.01590, Planck Collaboration

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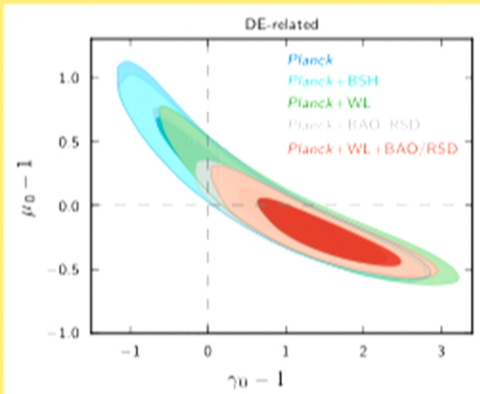

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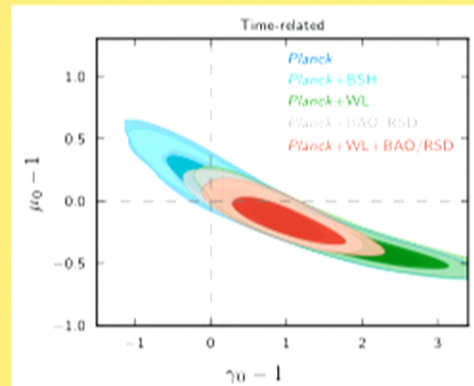

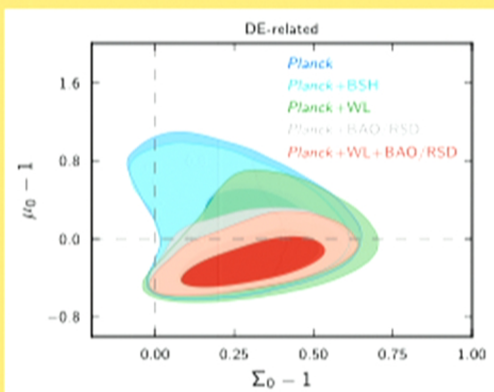

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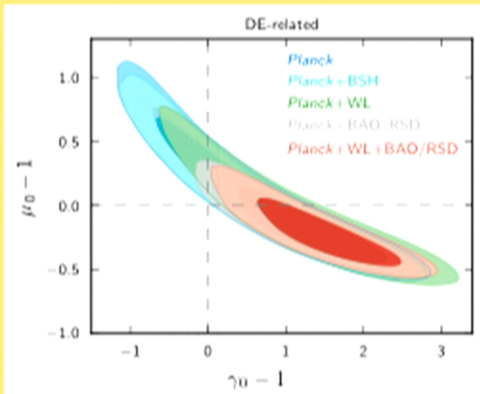

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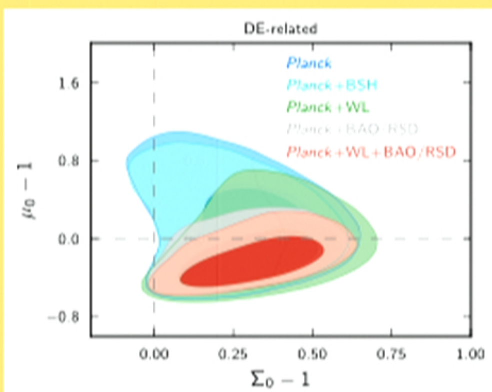
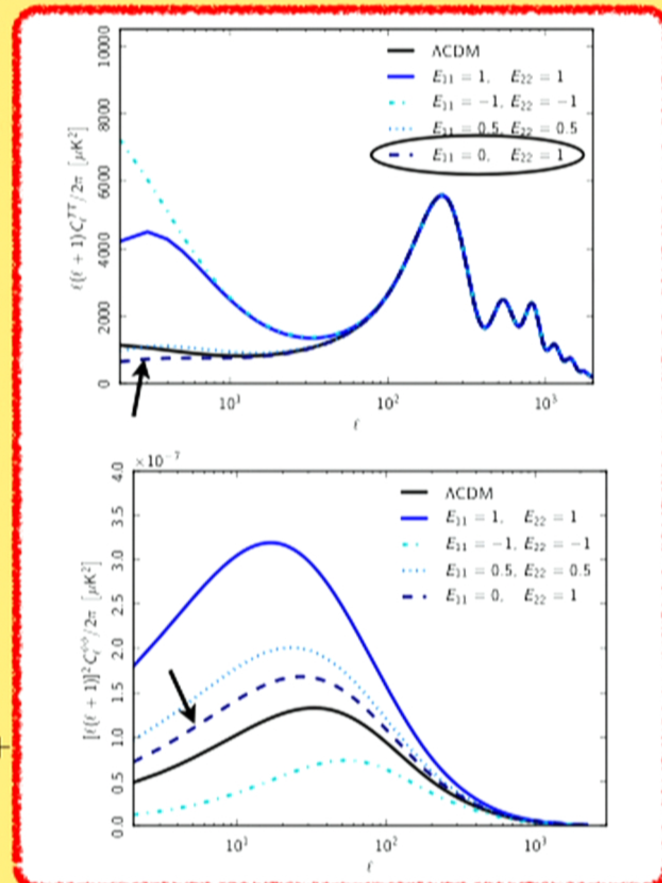


$k^2\ (\Phi +$



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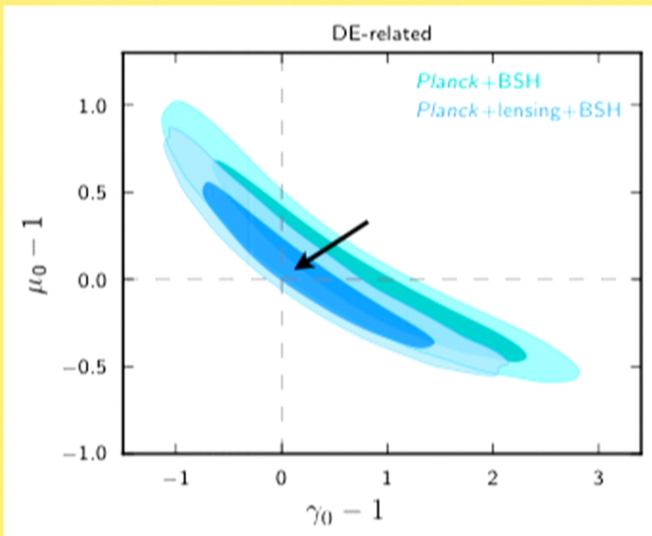
arXiv:1502.01590, Planck Collaboration

Tensions...?!

Adding CMB lensing into the game:

$$\mu(a) - 1 = (\mu_0 - 1)\Omega_{\rm DE}(a)$$



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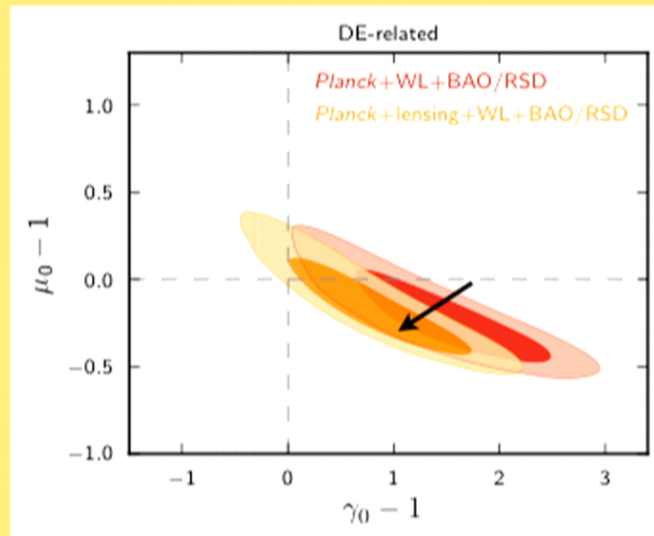

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arXiv:1502.01590, Planck Collaboration

k-dependence

A.S., Pogosian, Buniy, Phys. Rev. D87 (2013) 10, 104015

The k-dependence of these functions should not be completely arbitrary if we wish to consider local covariant theories with equations of motion derived from a variational principle. Restricting to the Quasi-Static regime, it can be shown that generally μ and γ will be *ratio of polynomials in k* (with the denominator of γ equal to the numerator of μ)

For models with one scalar obeying 2nd order eoms, (this includes non-minimal coupling and theories with functions of Lovelock invariants), μ and γ reduce to:

f(R), f(R,G), quintessence, k-essence, coupled quintessence, covariant galilelon, scalar-tensor, ...

Horndeski Theories

$$\gamma = \frac{p_1(t) + p_2(t)k^2}{1 + p_3(t)k^2}$$

$$\mu = \frac{1 + p_3(t)k^2}{p_4(t) + p_5(t)k^2}$$

$$\{p_1(t), p_2(t), p_3(t), p_4(t), p_5(t)\}$$

De Felice, Kobayashi, Tsujikawa, Phys.Lett.B 706 (2011)

EFT of Dark Energy

and

EFTCAMB

EFT of Dark Energy

Jordan frame, unitary gauge action

$$S = \int d^4x\,\sqrt{-g}\left\{\frac{m_0^2}{2}\left[1+\Omega(\tau)\right]R+\Lambda(\tau)-a^2c(\tau)\delta g^{00}\right.$$
$$+\frac{M_2^4(\tau)}{2}(a^2\delta g^{00})^2-\frac{\bar{M}_1^3(\tau)}{2}a^2\delta g^{00}\delta K_\mu^\mu-\frac{\bar{M}_2^2(\tau)}{2}(\delta K_\mu^\mu)^2-\frac{\bar{M}_3^2(\tau)}{2}\delta K_\nu^\mu\delta K_\mu^\nu$$
$$\left.+\frac{a^2\hat{M}^2(\tau)}{2}\delta g^{00}\delta R^{(3)}+m_2^2(\tau)(g^{\mu\nu}+n^\mu n^\nu)\partial_\mu(a^2g^{00})\partial_\nu(a^2g^{00})\right\}+S_m[g_{\mu\nu}]$$

Stückelberg trick
$\tau \to \tau + \pi(x^\mu)$

Gubitosi, Piazza, Vernizzi, JCAP 1302 (2013) 032
Piazza, Vernizzi, Class.Quant.Grav. 30 (2013) 214007
Bloomfield, Flanagan, Park, Watson JCAP 1308 (2013) 010

Jordan frame, Stuckelberg field action

$$S = \int d^4x\sqrt{-g}\left\{\frac{m_0^2}{2}\left[1+\Omega(\tau+\pi)\right]R+\Lambda(\tau+\pi)-c(\tau+\pi)a^2\left[\delta g^{00}-2\frac{\dot{\pi}}{a^2}+2\mathcal{H}\pi\left(\delta g^{00}-\frac{1}{a^2}-2\frac{\dot{\pi}}{a^2}\right)\right.\right.$$
$$\left.\left.+2\dot{\pi}\delta g^{00}+2g^{0i}\partial_i\pi-\frac{\dot{\pi}^2}{a^2}+g^{ij}\partial_i\pi\partial_j\pi-\left(2\mathcal{H}^2+\dot{\mathcal{H}}\right)\frac{\pi^2}{a^2}\right]+\dots\right\}+S_m[g_{\mu\nu}]$$

EFT of Dark Energy

it is an interesting framework that offers both a model-independent parametrization of alternatives to LCDM and a unifying language to analyze specific DE/MG models.

pure EFT:

$$\{\Omega(\tau), c(\tau), \Lambda(\tau), M_2(\tau), \bar{M}_1(\tau), \bar{M}_2(\tau), \bar{M}_3(\tau), \hat{M}(\tau), m_2(\tau)\}$$

mapping EFT:

f(R) $\quad \Omega = f_R; \quad \Lambda = \frac{m_0^2}{2}\left[f - Rf_R\right]; \quad c = 0$

minimally coupled quintessence $\quad \Omega = 0; \quad c - \Lambda = V(\phi); \quad c = \frac{\dot{\phi}^2}{2}$

Gubitosi, Piazza, Vernizzi, JCAP 1302 (2013) 032

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unifying language

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Gubitosi, Piazza, Vernizzi, JCAP 1302 (2013) 032

EFT of Dark Energy

... that offers both a model-independent
... to LCDM and a unifying language to
... ific DE/MG models.

all single-field scalar DE/MG models
for which there exists a well defined
Jordan frame

f(R)

f(R,G)

quintessence
(minimally and non-minimally coupled)

k-essence

kinetic braiding

galileon

Horndeski

Hořava-Lifshitz

model-independent

$\bar{M}_1(\tau), \bar{M}_2(\tau), \bar{M}_3(\tau), \hat{M}(\tau), m_2(\tau)\}$

unifying language

$- Rf_R]; \quad c = 0$

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Gubitosi, Piazza, Vernizzi, JCAP 1302 (2013) 032

EFT of Dark Energy

Let's put this framework to work!

energy-momentum equations: standard ones since we are in the Jordan frame

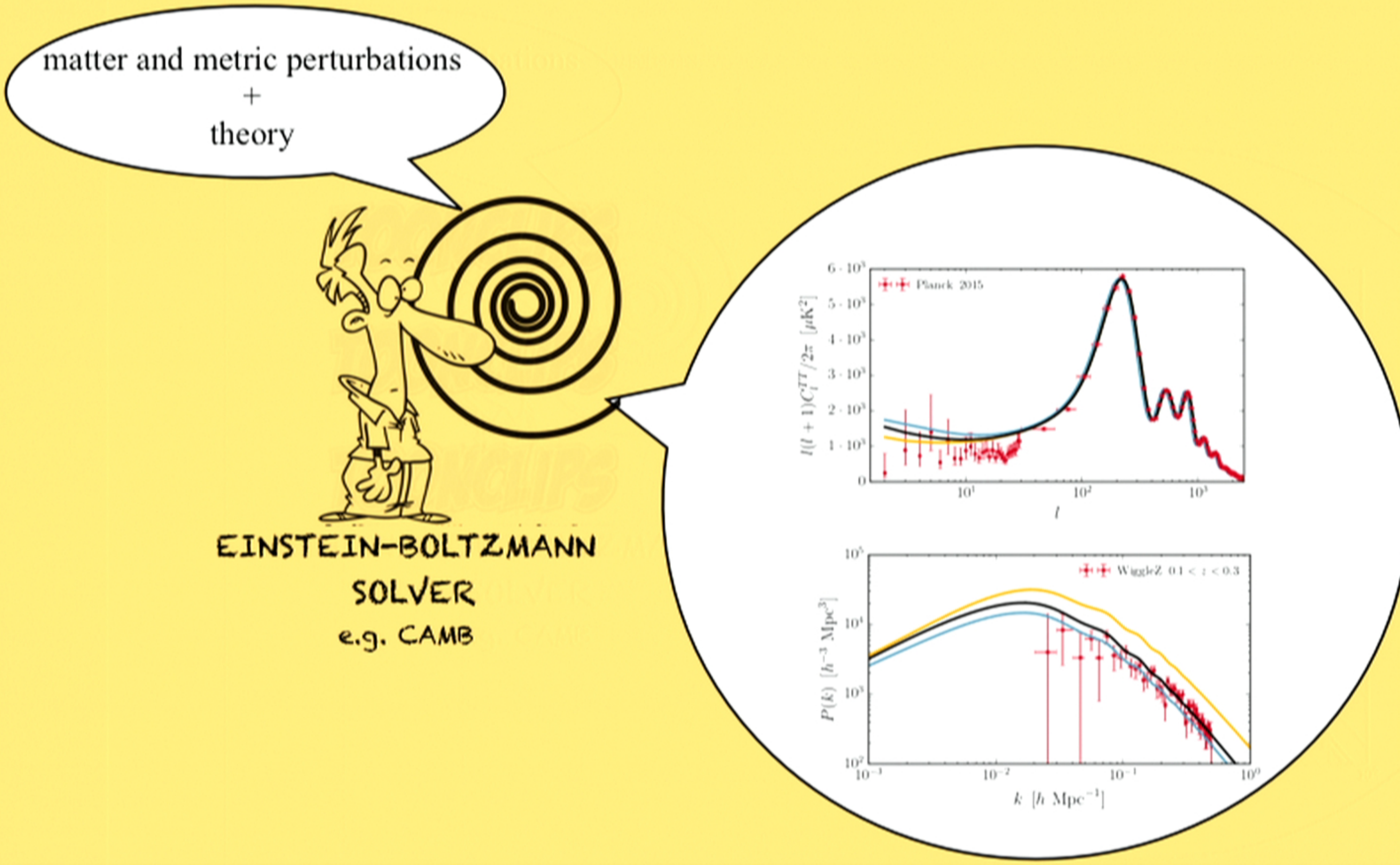
Einstein equations: messy equations involving contributions from 'all' EFT functions

π field equation:

$$A\ddot{\pi} + B\dot{\pi} + \left(C + k^2 D\right)\pi + E = 0$$

$$A = A[c, \Lambda, \Omega, \ldots](\tau, k)$$

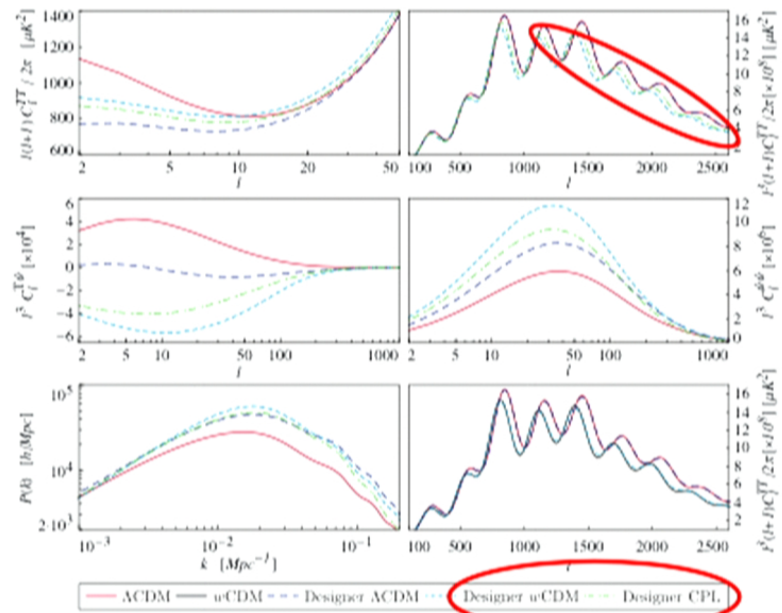
EFT of Dark Energy



Effective Field Theory with CAMB

http://www.lorentz.leidenuniv.nl/~hu/codes/

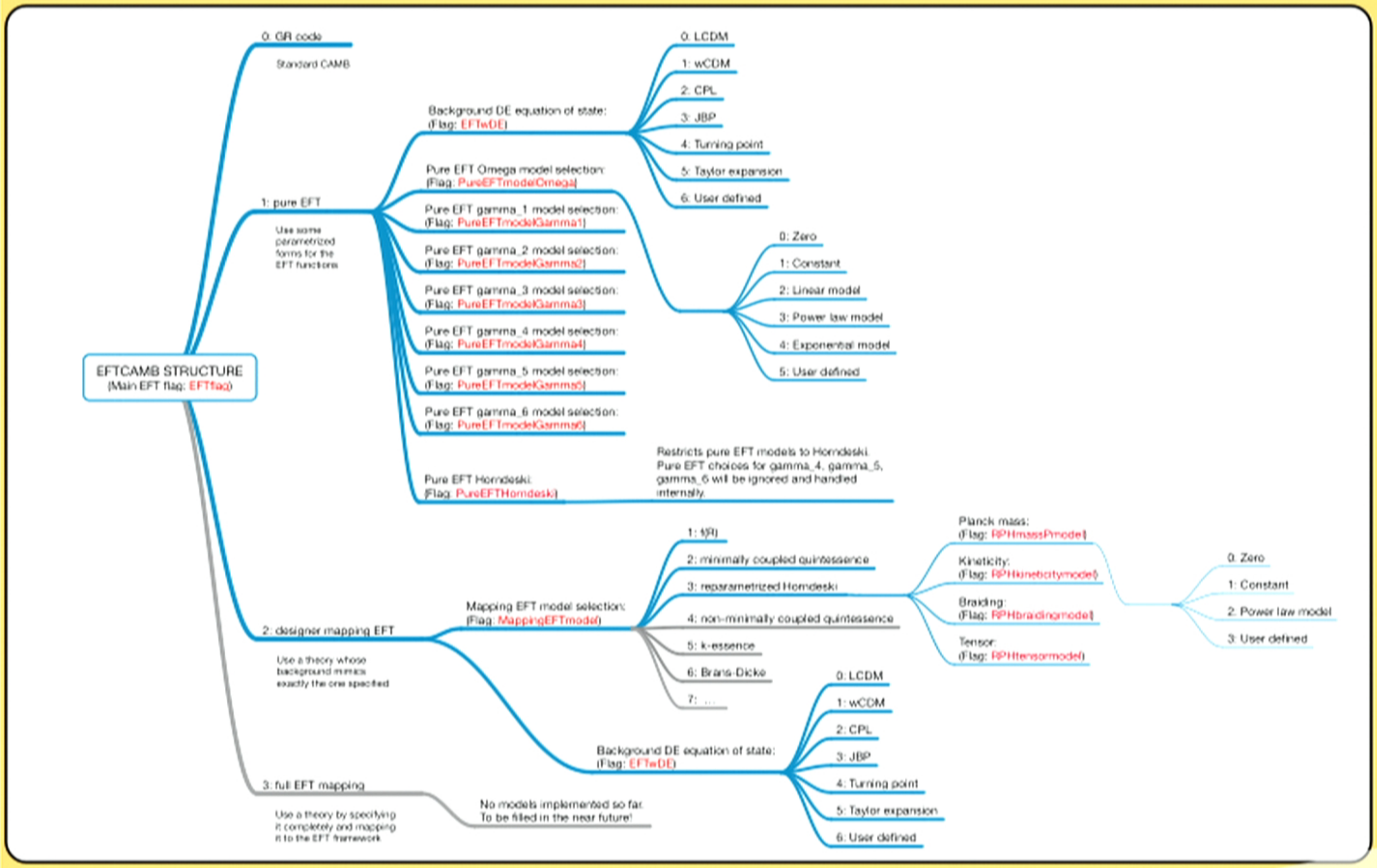
f(R)



'Effective Field Theory of DE: an implementation in CAMB'
Phys. Rev. D 89, 103530 (2014)
by Hu, Raveri, Frusciante, A.S.

We do not implement any QS approx. (still we can treat any specific single field model) and we can easily cross the phantom divide while controlling stability and viability of the theory with a built-in check.

The outcome is a versatile powerful Boltzmann code to evolve the full dynamics of linear scalar perturbations both in the model-independent EFT framework and for any specific single field DE/MG model (for which there exists a well defined Jordan frame).



no QS approximation and exact implementation of background !

On Quasi-Static Approximation

Often employed on sub-horizon scales. It significantly simplifies the work because it reduces the Einstein equations, and any equation for additional scalar d.o.f., to algebraic relations in Fourier space. What does it effectively correspond to?
Is it always a good approximation?

in LCDM

- sub-horizon scales: $k \gg aH$

↓

- time derivatives of metric potentials negligible w.r.t. space derivatives

in DE/MG

- sub-horizon scales: $k \gg aH$

and

- time derivatives negligible w.r.t. space derivatives for both metric potentials and additional scalars, i.e.

$$\delta\ddot{\phi} \ll c_s^2 k^2 \delta\phi$$

On Quasi-Static Approximation

Often employed on sub-horizon scales. It significantly simplifies the work because it reduces the Einstein equations, and any equation for additional scalar d.o.f., to algebraic relations in Fourier space. What does it effectively correspond to?
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in LCDM

- sub-horizon scales: $k \gg aH$
- time derivatives of metric pot
negligible w.r.t. space derivatives

how restrictive/realistic is the QS approximation?

EFTCAMB can help exploring this!

in DE/MG

- b-horizon scales: $k \gg aH$

and

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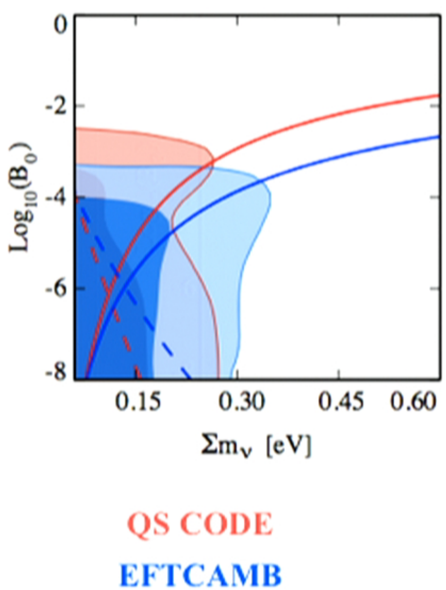
$$\delta\ddot{\phi} \ll c_s^2 k^2 \delta\phi$$

Massive neutrinos and f(R)

w.r.t. previous analyses, EFTCAMB implements exactly f(R), properly including massive neutrinos in designer reconstruction of f(R) and evolving the full dynamics of perturbations.



data set: Planck, BAO, Wiggle Z

	Varying m_ν	Varying m_ν	Fixed m_ν
	$\log_{10} B_0$ (95%CL)	$\sum m_\nu$ (95%CL)	$\log_{10} B_0$ (95%CL)
EFTCAMB	<-3.8	<0.30	<-3.9
QS CODE	<-3.2	<0.24	<-3.7

EFTCAMB V1.1

'Exploring massive neutrinos in dark cosmologies with EFTCAMB/EFTCosmoMC'
Phys. Rev. D 91 (2015) 6, 063524 by Hu, Raveri, Frusciante, A.S.

Massive neutrinos and f(R)

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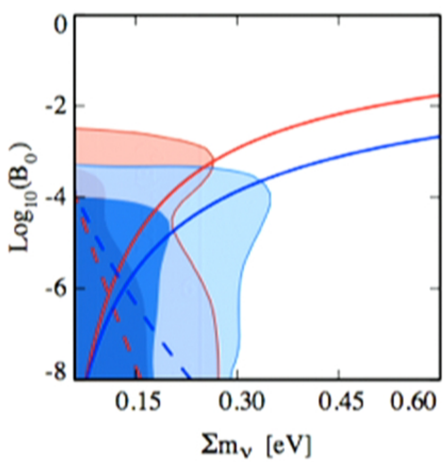
perturbatio

d

Also very important in order to provide N-body simulations with precise initial conditions !



QS CODE
EFTCAMB

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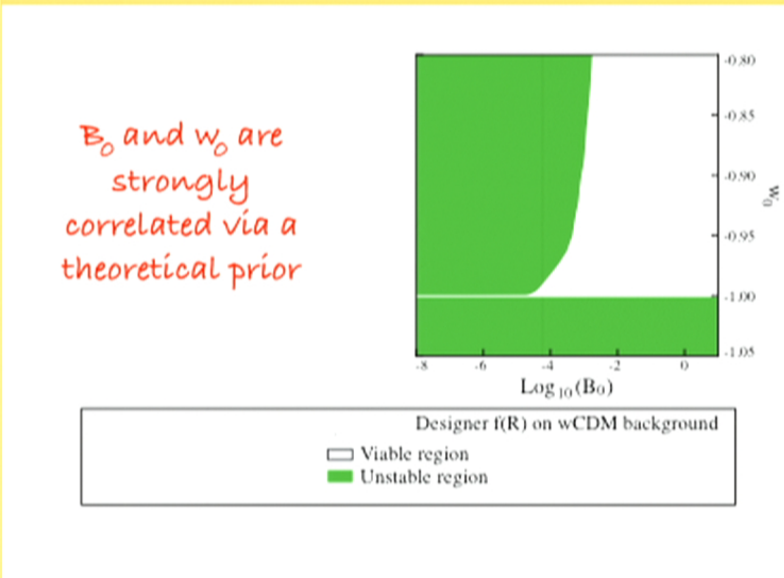
EFT meets CosmoMC: viability priors

Through the equation for the π field we can introduce viability conditions that are well motivated theoretically (e.g. no ghosts) *and* often ensure also numerical stability; when exploring the parameter space we impose them in the form of <u>*viability priors*</u>. In some cases they dominate over the constraining power of data.



designer f(R) on wCDM background:

$$w_0 \in (-1, -0.9997) \;\; (95\%\mathrm{C.L.})$$

with Planck, lensing, WP, BAO data

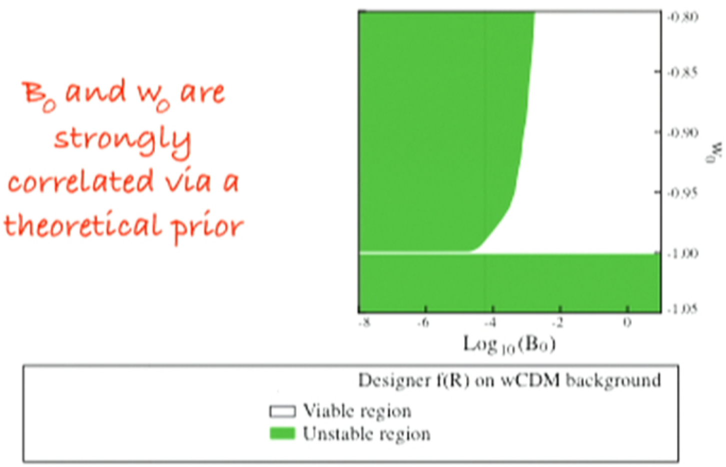
'Effective Field Theory of Cosmic Acceleration: constraining dark energy with CMB data'
Phys. Rev. D 90, 043513 (2014) by Raveri, Hu, Frusciante, A.S.

EFT meets CosmoMC: viability priors

Through the equation for the π field we can introd[...] theoretically (e.g. no ghosts) *and* often ensure also n[...] space we impose them in the form of *viability p*[...] constraining po[...]

Viability priors make EFTCAMB/ EFTCosmoMC a powerful and safe tool for the advocated open-minded approach to cosmological tests of GR. They provide *theoretically motivated yet model-independent* conditions to impose in order to ensure the investigation of physically viable models.

B_0 and w_0 are strongly correlated via a theoretical prior



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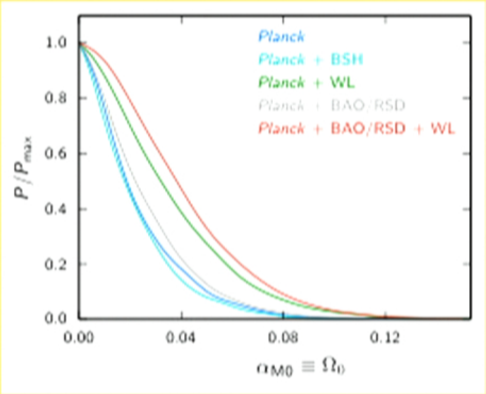
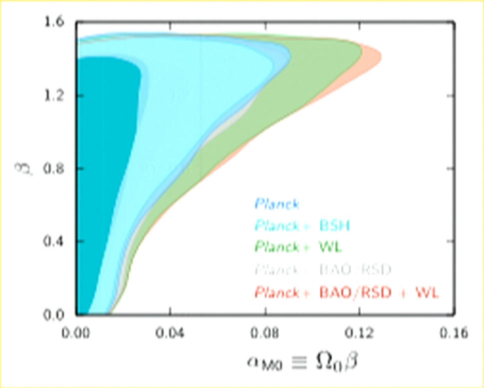
What Planck just said….

LCDM backgrounds

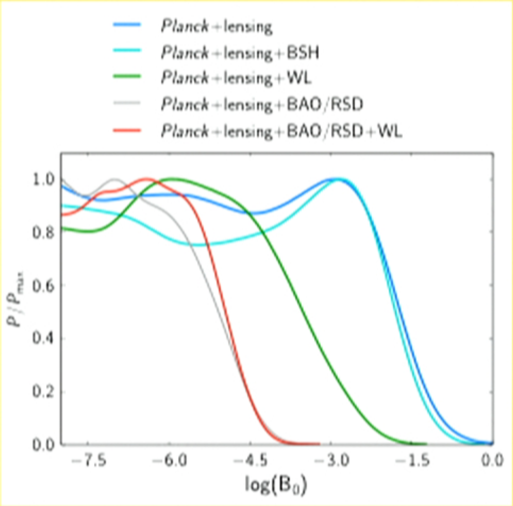
$\Omega(a) = \Omega_0 \cdot a$



$\Omega(a) = e^{\Omega_0 a^\beta} - 1$



f(R)



'Planck 2015 results. XIV. Dark energy and modified gravity'
arXiv:1502.01590, Planck Collaboration

What Planck just said….

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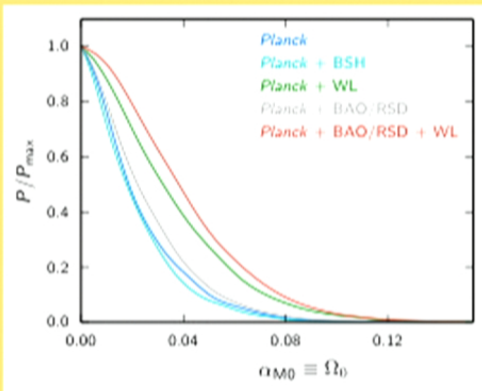
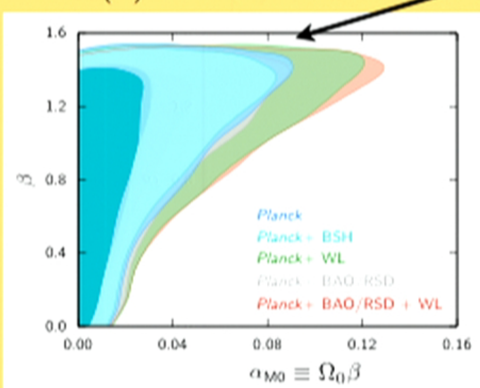


$\Omega(a) = e^{\Omega_0 a^\beta} - 1$

viabi



LCDM backgrounds

Conditions of theoretical consistency/stability

$$A(\tau,k)\ddot{\pi} + B(\tau,k)\dot{\pi} + C(\tau)\pi + k^2 D(\tau,k)\pi + E(\tau,k) = 0$$

- $A > 0$ no ghost
- $1 + \Omega > 0$ positive effective Newton constant
- $D > 0$ no gradient instability
- $C > 0$ positive squared mass
- $c_s^2 = D/A \leq 1$ no superluminal perturbations

Outlook

This was a brief tale of the ongoing quest to test gravity on cosmological scales.

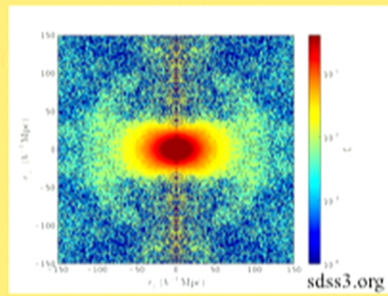
While we have big challenges in front of us, this is an exciting prospect that will be enabled by upcoming surveys.
A wealth of high-precision information will be soon available and we should get ready to make the best out of it!

I focused on the challenges, approaches and prospects on the theory side.

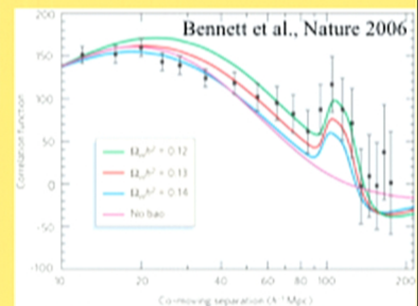
Outlook

Future missions (DESI, Euclid, LSST, ...) will provide high precision measurements of:

* Cosmic Microwave Background



* GALAXY CLUSTERING with spectroscopic redshift



* WEAK LENSING

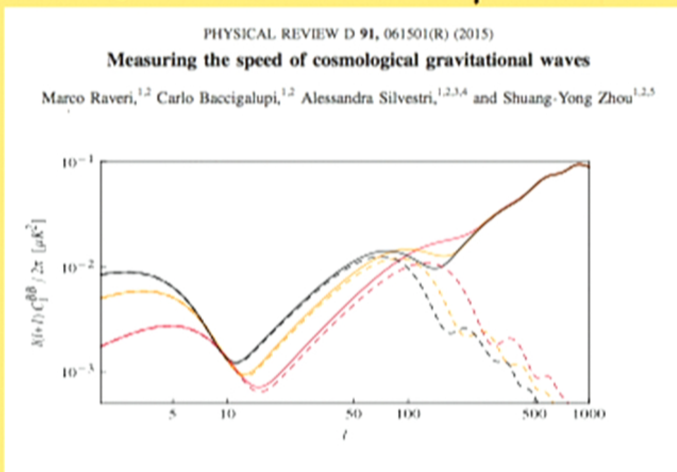
The combination of these probes will be key to test gravity on large scales.

With a big effort we are making progress in terms of theoretical frameworks to interpret these data ... bare with us!

Outlook

Things to keep in mind:

* CMB lensing and B modes of polarization !



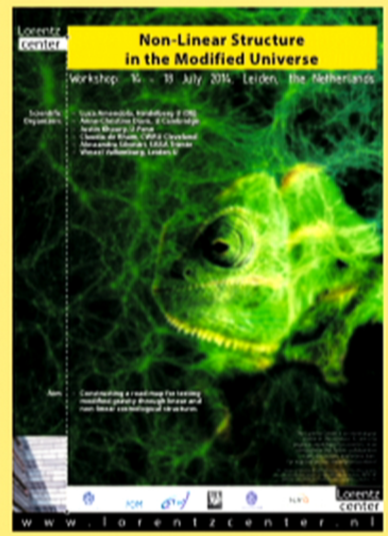
PHYSICAL REVIEW D **91**, 061501(R) (2015)

Measuring the speed of cosmological gravitational waves

Marco Raveri,[1,2] Carlo Baccigalupi,[1,2] Alessandra Silvestri,[1,2,3,4] and Shuang-Yong Zhou[1,2,5]

* all possible cross-correlations: great to bit systematics and learn about bias

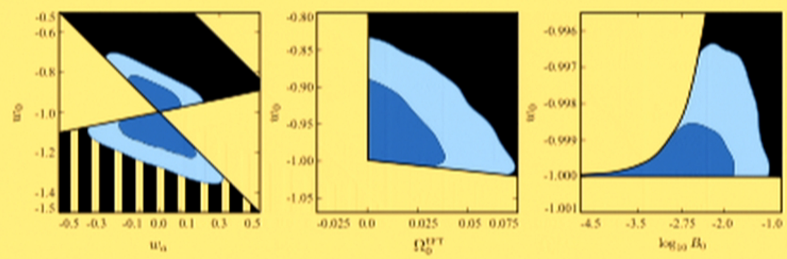
* non-linear scales and screening mechanisms



Outlook

Within the EFT approach

- Further investigation of viability priors



- Further investigation of Quasi-Static Approximation
- Modeling of Weak Lensing systematics in generalized theories of gravity
- Principal Component Analysis of EFT functions
- Optimization (HPC) and maintenance of a publicly available, broad and efficient Einstein-Boltzmann code (EFTCAMB)