PARAMETRIZED APPROACHES TO COSMOLOGICAL TESTS

Alessandra Silvestri
Instituut Lorentz, Leiden U.

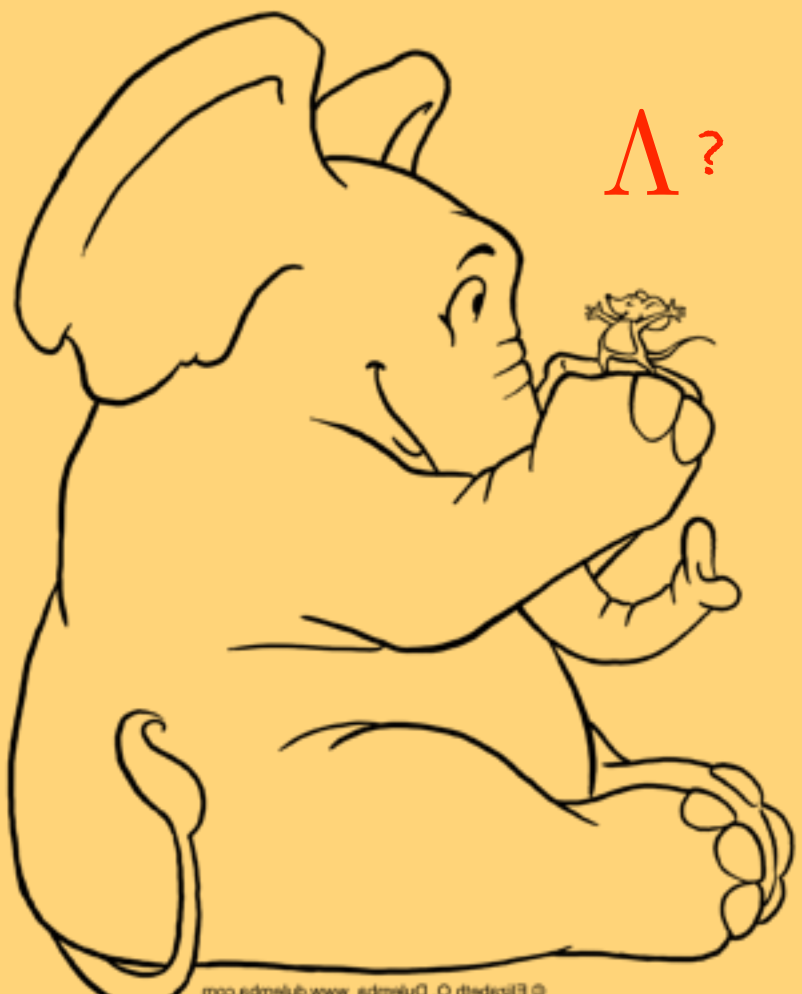
Talking about gravity, by G. Horndeski

benefiting from collaborations with:
L. Pogosian, N.Frusciante, A.Hojjati, B. Hu, M.Raveri,G.Zhao

Testing Gravity 2015
SFU Harbour Center
15-17 January 2015

Cosmological tests of GR

Ongoing and upcoming wide field imaging and spectroscopic redshift surveys are in line to provide exquisite measurements of the expansion rate, reconstruction of lensing potentials and reconstruct the cosmic structure growth rate to 1% in 0<z<2, over the last 3/4 of the age of the Universe ! The excitement about the advances of observational cosmology is accompanied by the awareness that we face some *major challenges* ...... *cosmic acceleration* is the one on which I will focus for this talk. A plethora of candidate models.....



Λ ?

Modified Gravity ?

Dark Energy?

Until we have a compelling theoretical model, let us keep an open mind and use the wealth of data to:

1. test the consistency with LCDM (GR)

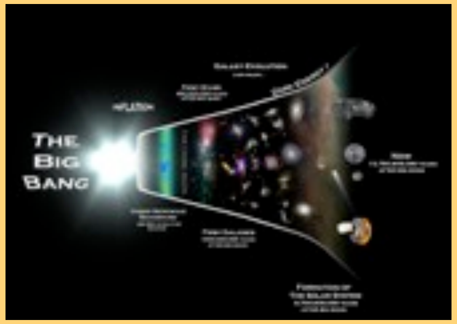
2. explore the parameter space allowed to alternative models

Cosmic functions of interest

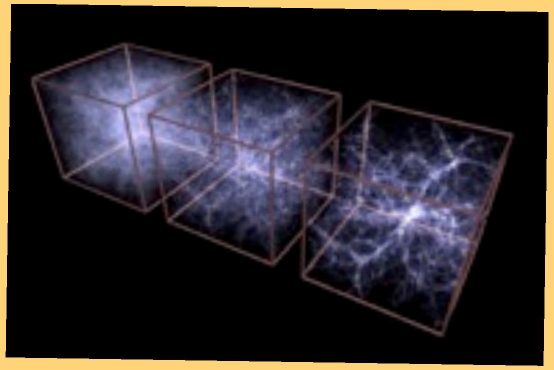
Linear Scalar Perturbations

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

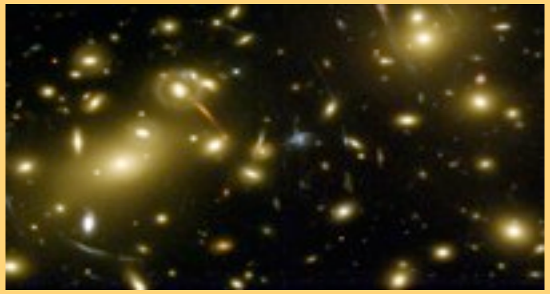
expansion history: $a(\tau)$



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

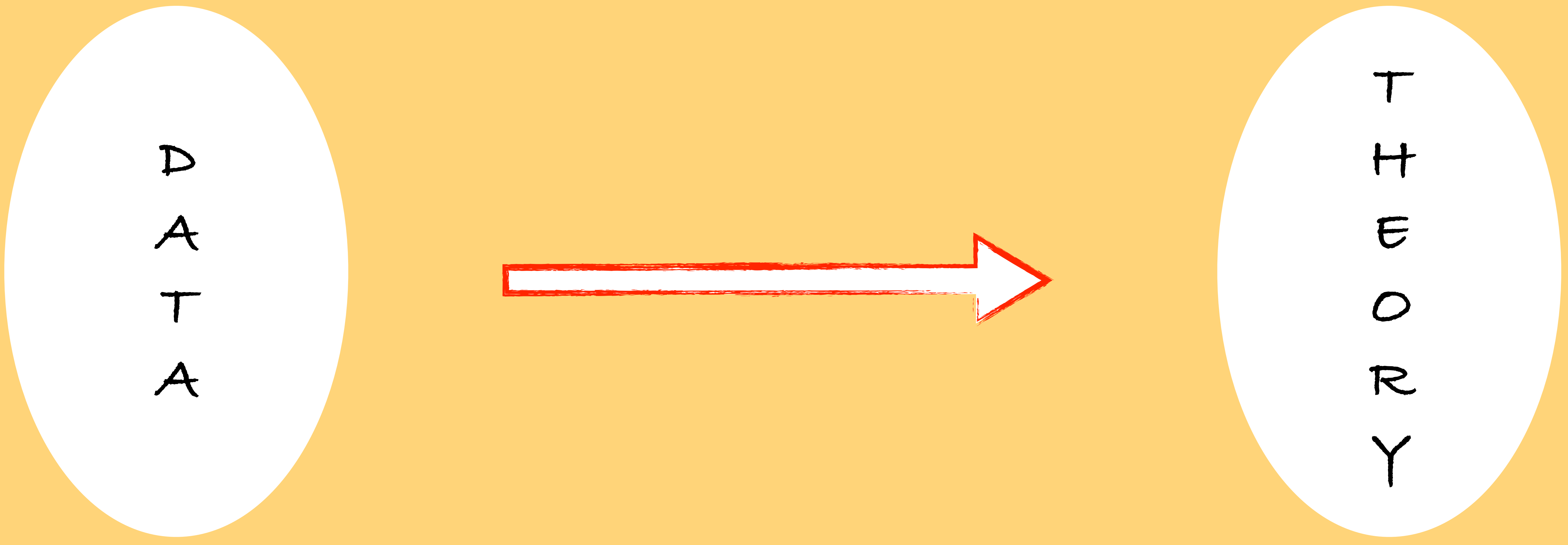


relativistic dynamics
(weak lensing, ISW): $(\Phi+\Psi)\,(\tau,\vec{x})$



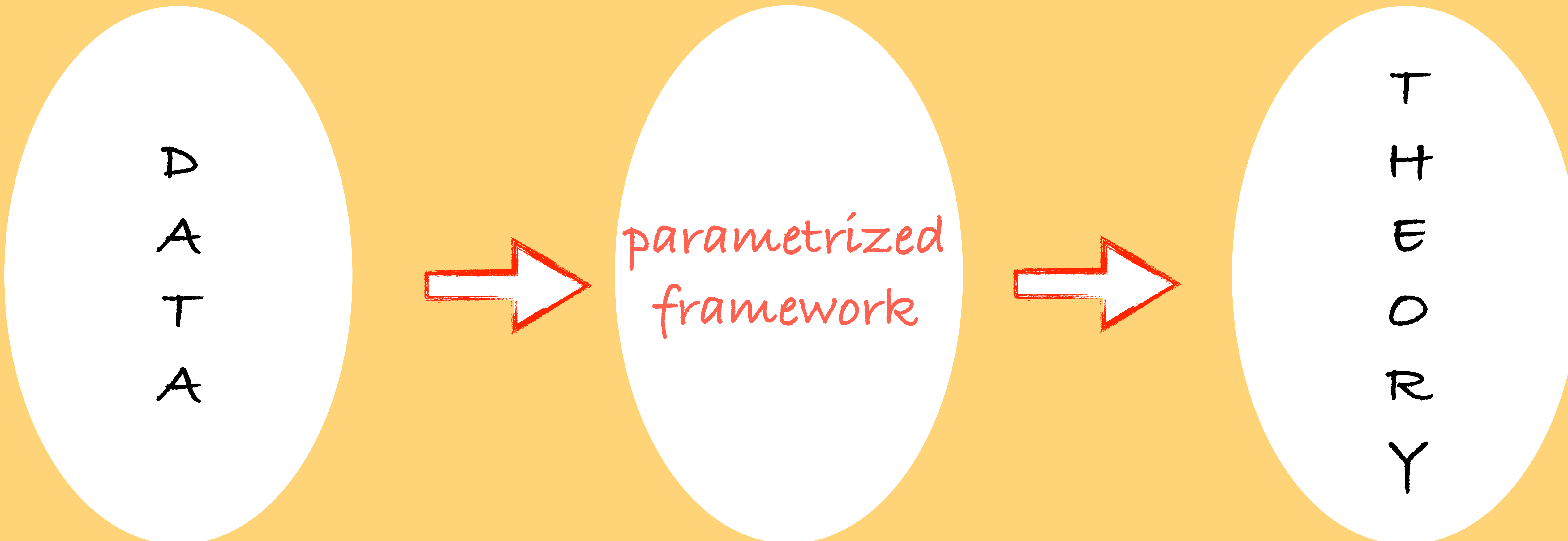
+ matter perturbations which obey continuity and Euler equations

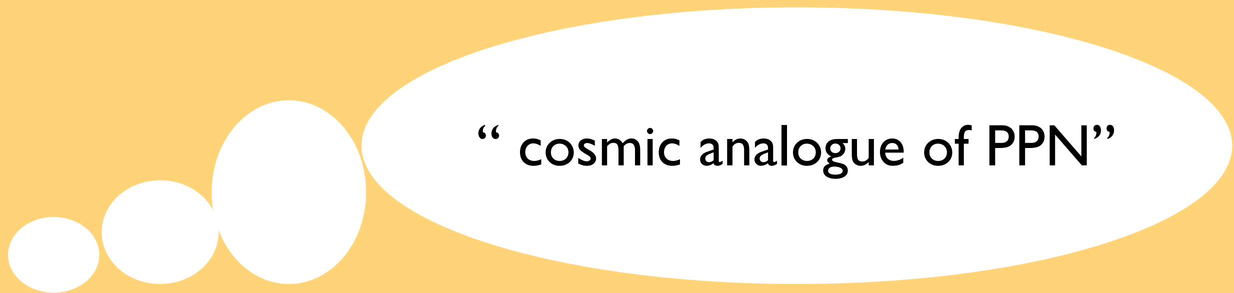
Efficient way of proceeding



Efficient way of proceeding

Given the absence of a theoretically compelling model of cosmic acceleration, we strive to keep and open-minded approach, *concentrating on very general theoretical arguments and on observables more than on specific models*





On parametrizing

What to parametrize?

solutions of equations of motion → (μ, γ)

references to follow

the action → EFT

references to follow

equations of motion → PPF and equations of state for perturbations

Baker, Ferreira, Skordis (2012)
Battye & Pearson (2013)

On parametrizing

What to parametrize?

solutions of equations of motion → (μ, γ) *phenomenological*

references to follow

the action → EFT *theoretical*

references to follow

equations of motion → PPF and equations of state for perturbations

Baker, Ferreira, Skordis (2012)
Battye & Pearson (2013)

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

(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

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

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

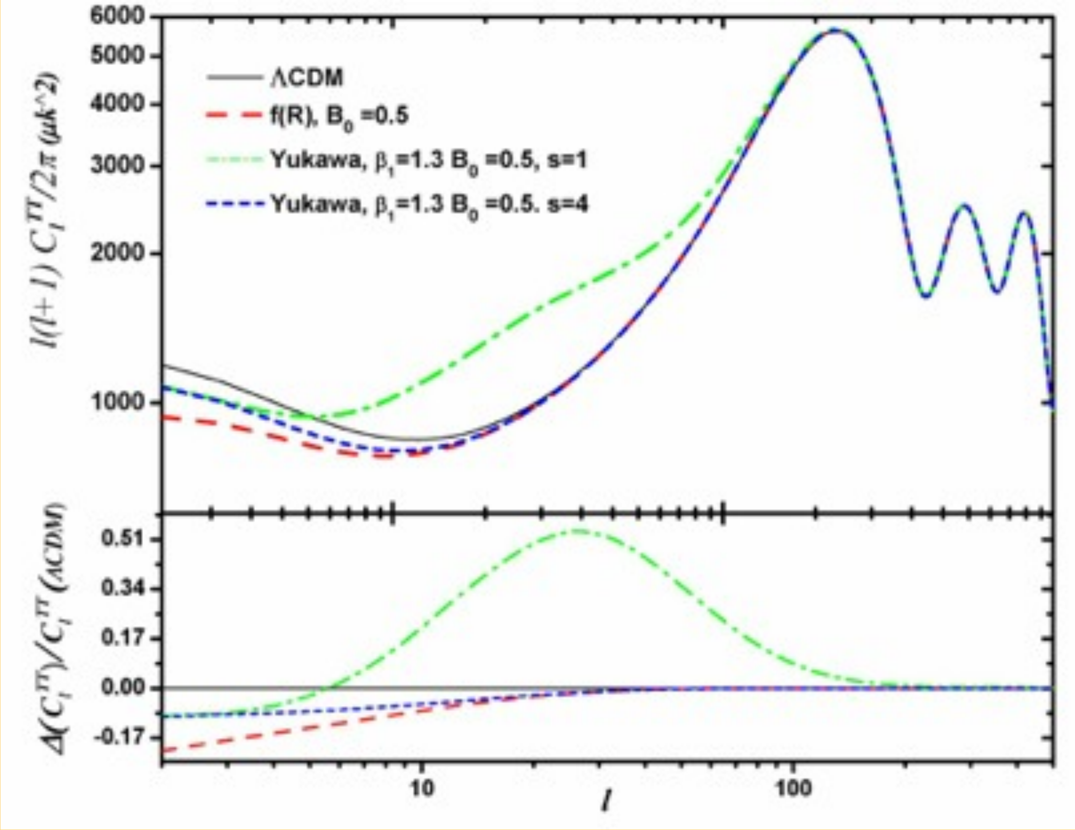
$$k^2\Psi = -\mu(a,k)\frac{a^2}{2M_P^2}\rho\Delta$$

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

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, Silvestri, 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
and more recently Planck 2014

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

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)

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
and more recently Planck 2014

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

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. ... D 78, 024015(2008)

$$\Phi_{\rm Yuk} \sim \frac{1}{r}\left[1 + (\beta_1 - 1)\, e^{-r/\lambda_1}\right]$$

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
and more recently Planck 2014

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

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

- QSA:

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

Bertschinger & Zukin, Phy[illegible] D 78, 024015(2008)

$$\Phi_{\rm Yuk} \sim \frac{1}{r}\left[1 + (\beta_1 - 1)\, e^{-r/\lambda_1}\right]$$

this is good for f(R) models
reproducing LCDM background

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
and more recently Planck 2014

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

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

- QSA:

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

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

$$\Phi_{\rm Yuk} \sim \frac{1}{r}\left[1 + (\beta_1 - 1)\, e^{-r/\lambda_1}\right]$$

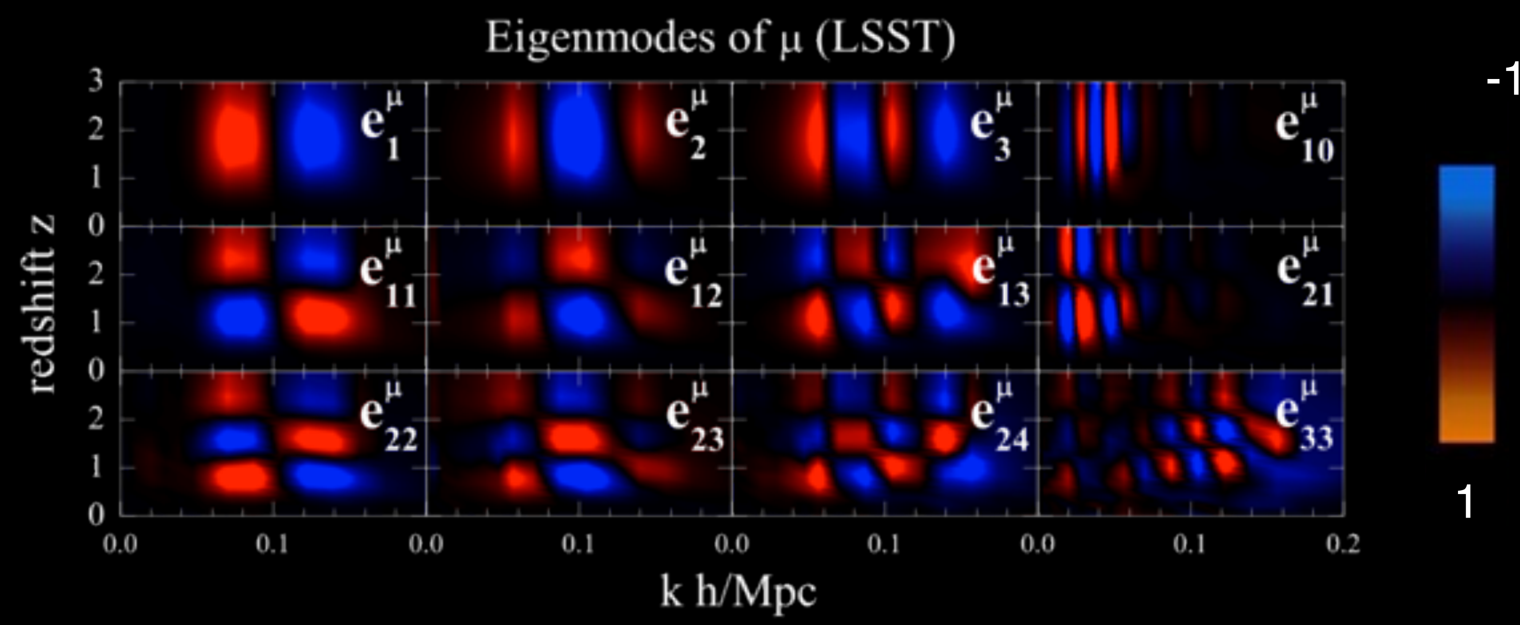
this is good for f(R) models reproducing LCDM background

- 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

Be

- bin th
  - Q

fix their scale-dependence, acco g to general arguments of locality and then perform a 1D A on the time-dependence

EFT of Dark Energy

and

EFTCAMB

EFT of Dark Energy

Jordan frame, unitary gauge action

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

Gubitosi, Piazza, Vernizzi, JCAP 1302 (2013) 032
Piazza, Vernizzi, Class.Quant.Grav. 30 (2013) 214007
Gleyzes, Langlois, Piazza, Vernizzi, JCAP 1308 (2013) 025
Bloomfield, Flanagan, Park, Watson JCAP 1308 (2013) 010

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

Jordan frame, Stuckelberg field action

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

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)

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

minimally coupled quintessence

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

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

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.

model-independent

pure EFT:

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

unifying language

mapping EFT:

f(R)

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

minimally coupled quintessence

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

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

EFT of Dark Energy

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

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

model-independent

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

unifying language

$- Rf_R] ; \quad c = 0$

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

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

EFT of Dark Energy

Let's put this framework to work! i.e. let's implement it in CAMB.

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:

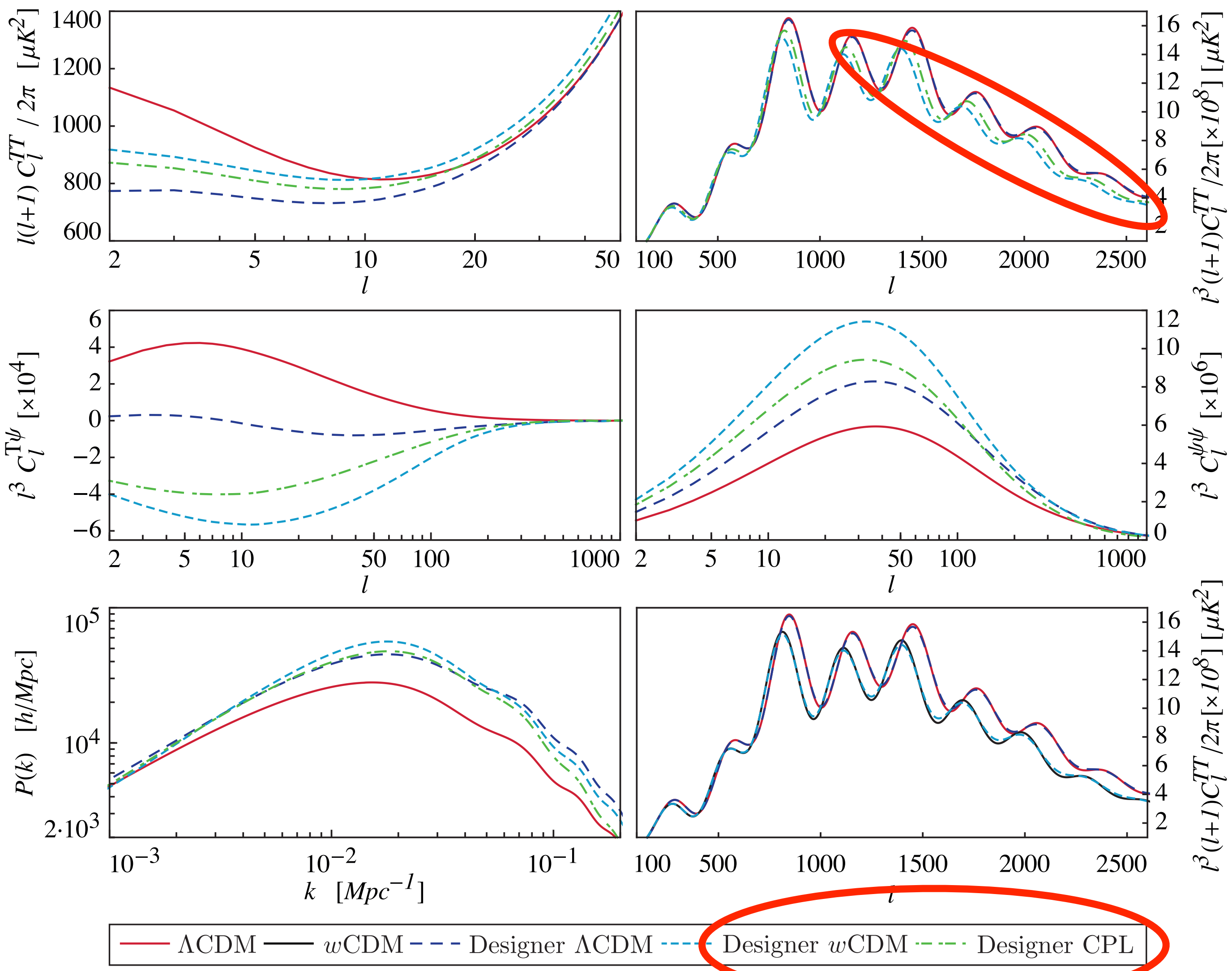
$$A\ddot{\pi} + B\dot{\pi} + \left(C + k^2 D\right)\pi + E = 0$$

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

EFTCAMB

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

f(R)



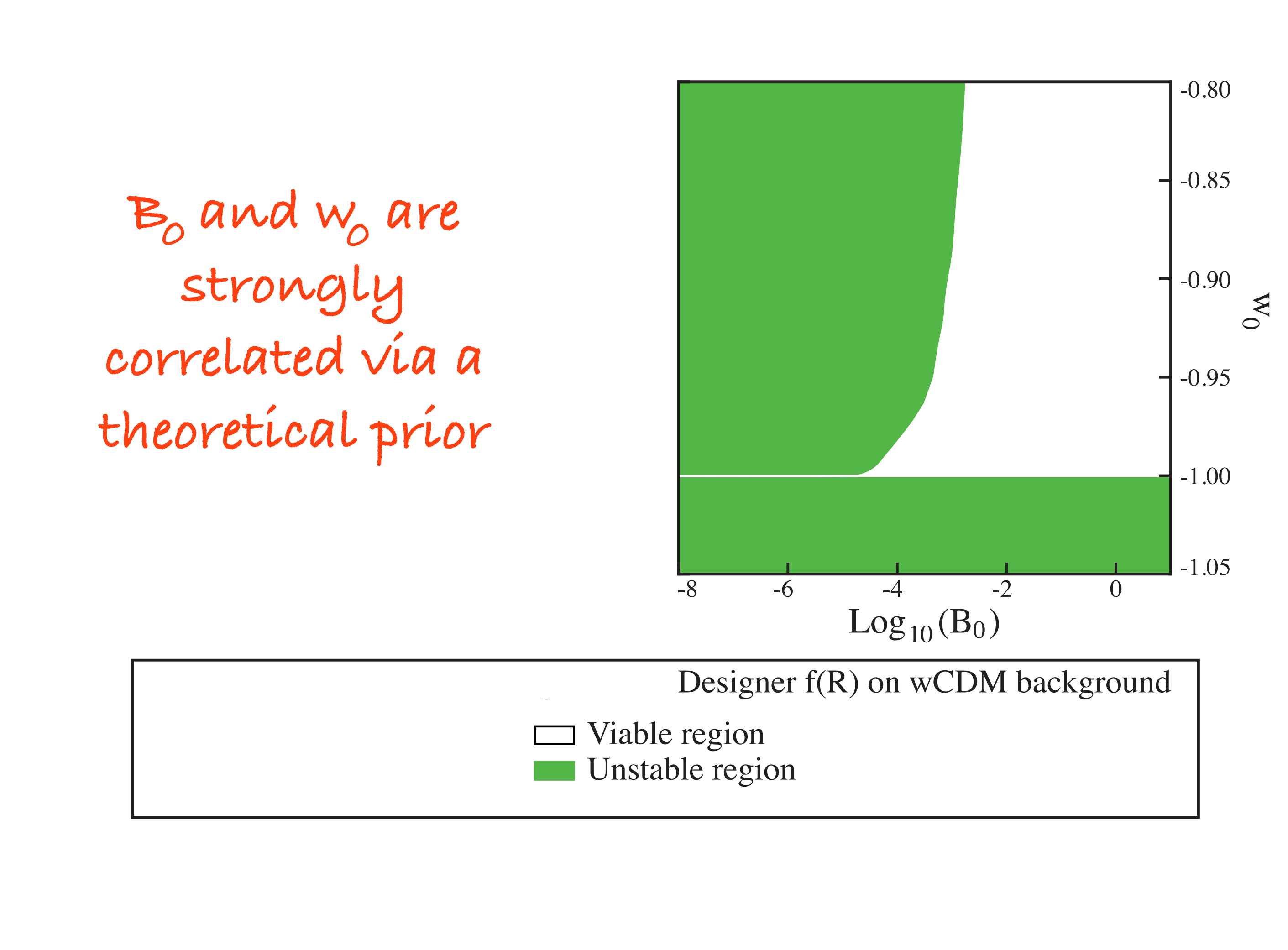
'Effective Field Theory of DE: an implementation in CAMB'
Phys. Rev. D 89, 103530 (2014)
by Hu, Raveri, Frusciante, A.S.

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).

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 *viability priors*. In some cases they dominate over the constraining power of data.



designer f(R) on wCDM background:

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

with Planck, lensing, WP, BAO data

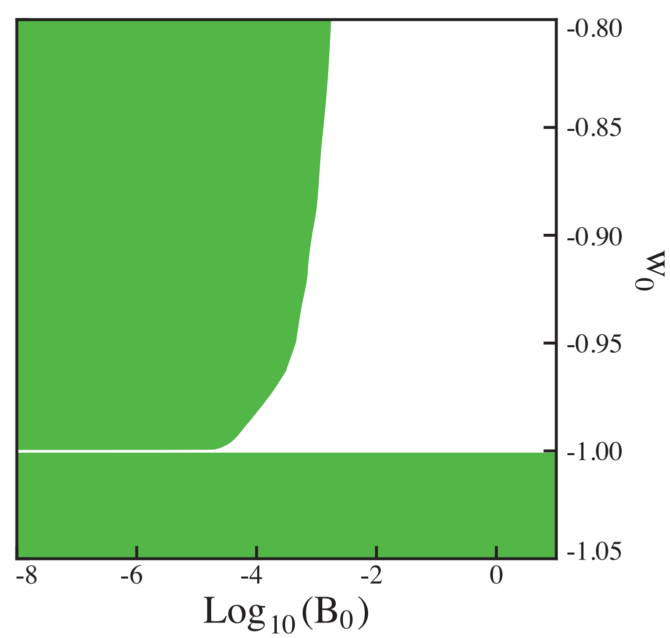
'Effective Field Theory of Cosmic Acceleration: constraining dark energy with CMB data'
Phys. Rev. D 90, 043513 (2014)
by Raveri, Hu, Frusciante, A.S.

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



Designer f(R) on wCDM background

Viable region

Unstable region

designer f(R) on wCDM background:

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

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.

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?
Is it always a good approximation?

in LCDM

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

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

how restrictive/realistic is the QS approximation?

EFTCAMB can help exploring this!

in DE/MG

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

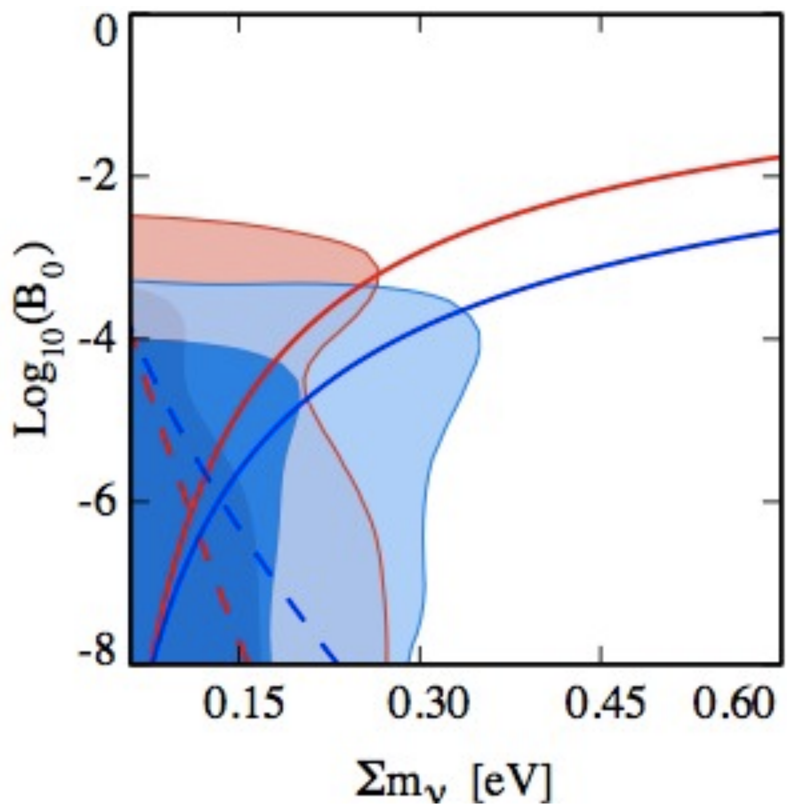
and

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

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

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.



QS CODE

EFTCAMB

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

under further investigation ...

Summary

We have big challenges in front of us, yet testing GR on cosmological scales 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!

* future missions (Euclid, LSST, ...) will combine WL, GC and expansion history measurements...key mix for tests of GR. With a big effort we are making progress in terms of theoretical frameworks...bare with us!

* CMB lensing and B modes of polarization !

* coming soon EFTCAMBv1.2: tensors, sources code (for number counts, galaxy lensing, etc..), impl. Horndeski, ...

* TO DO: further investigation of viability priors, PCA of EFT functions, QS version of EFTCAMB, ...

THANK YOU !