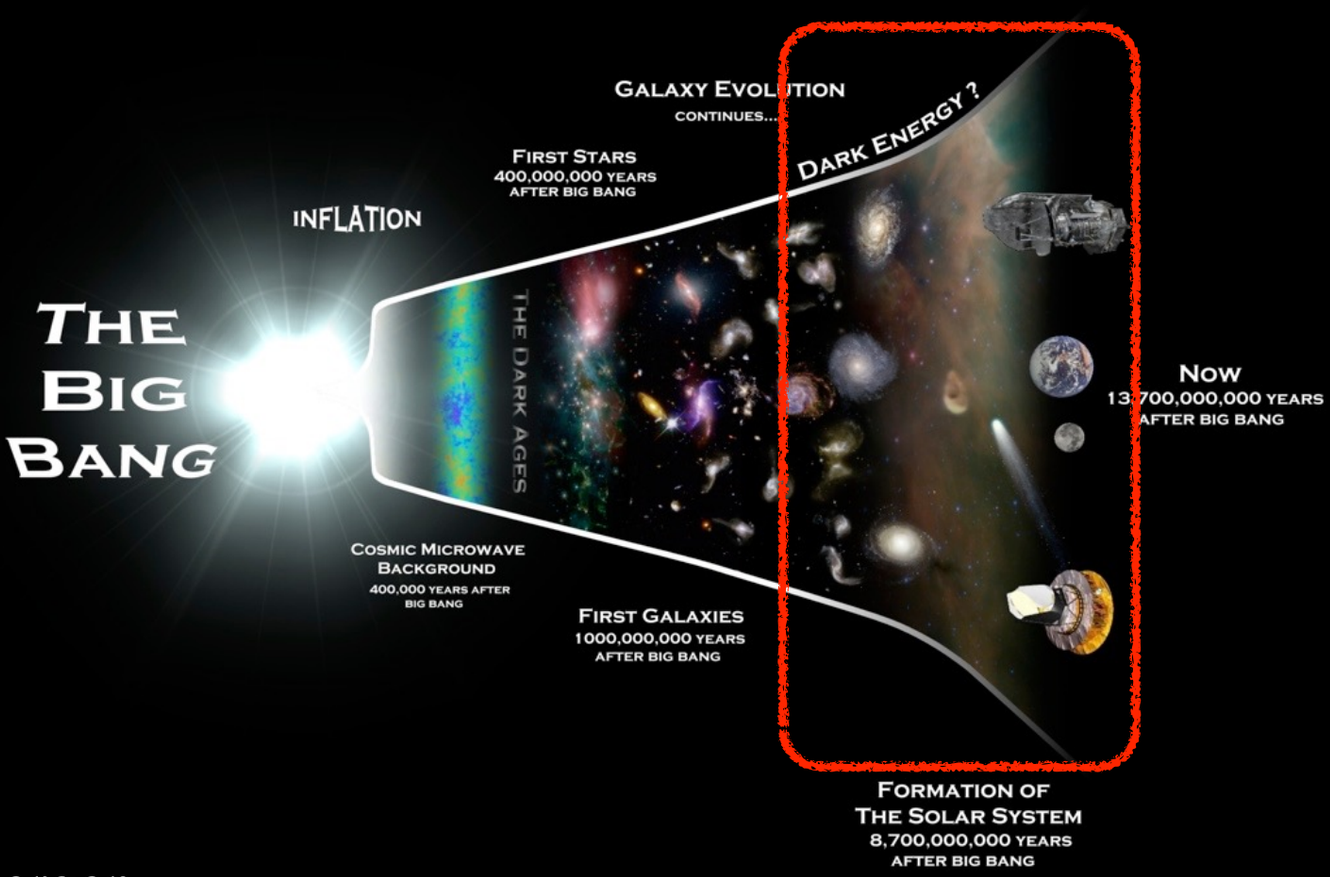
Unveiling Dark Energy with Large Scale Structure:

the theoretical side of the challenge.

Alessandra Silvestri

Instituut Lorentz (Leiden U.)

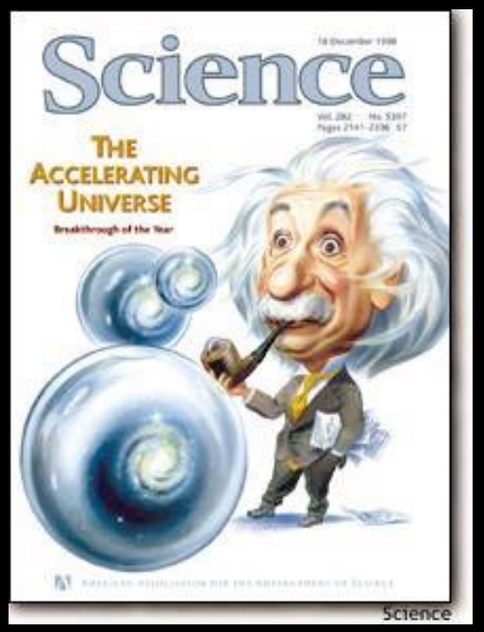


XII DSU

July 25-29 2016 Bergen

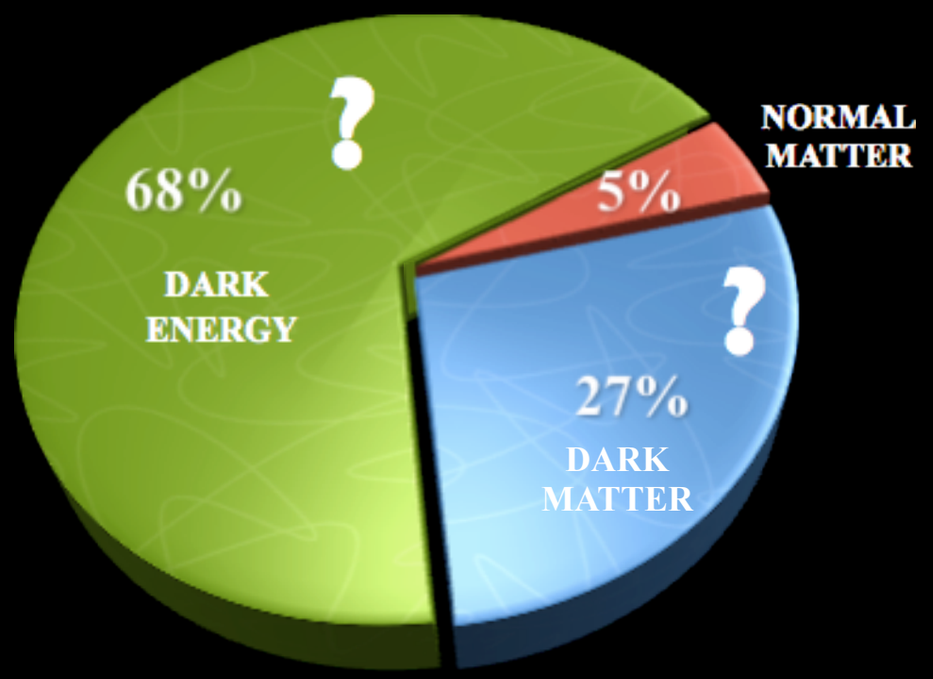
INSTITUUT LORENTZ

A Challenge for Modern Cosmology



The expansion is speeding up!

What is sourcing this acceleration?



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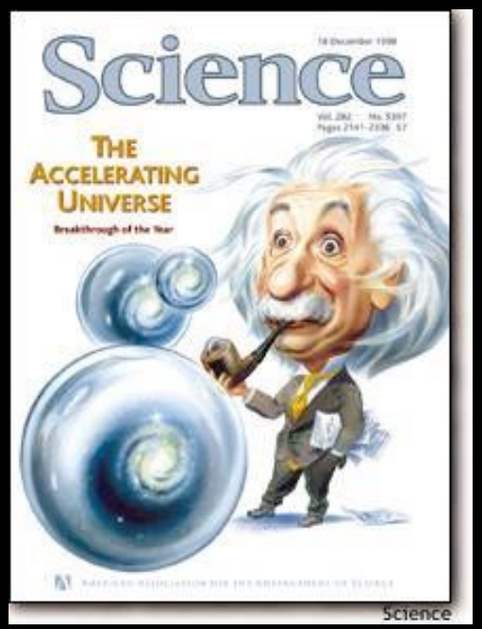

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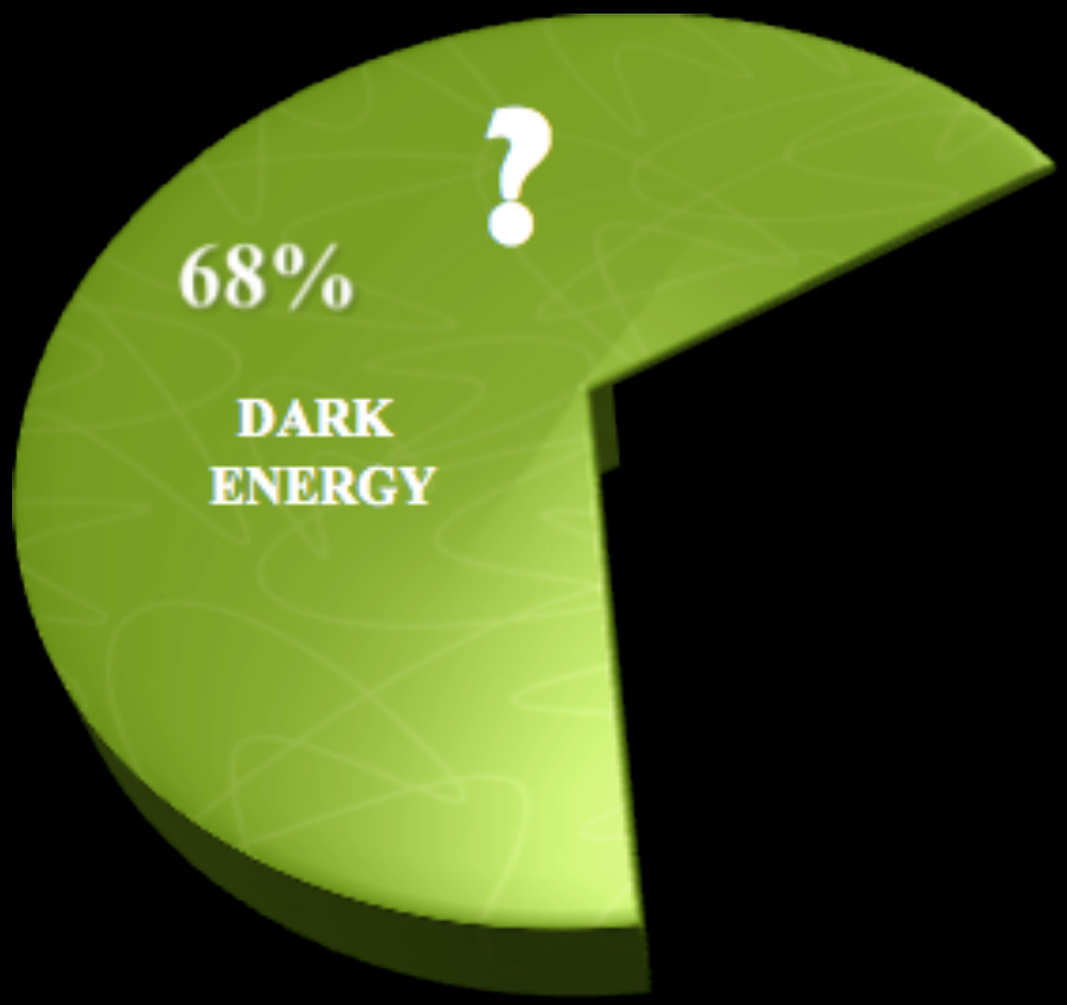
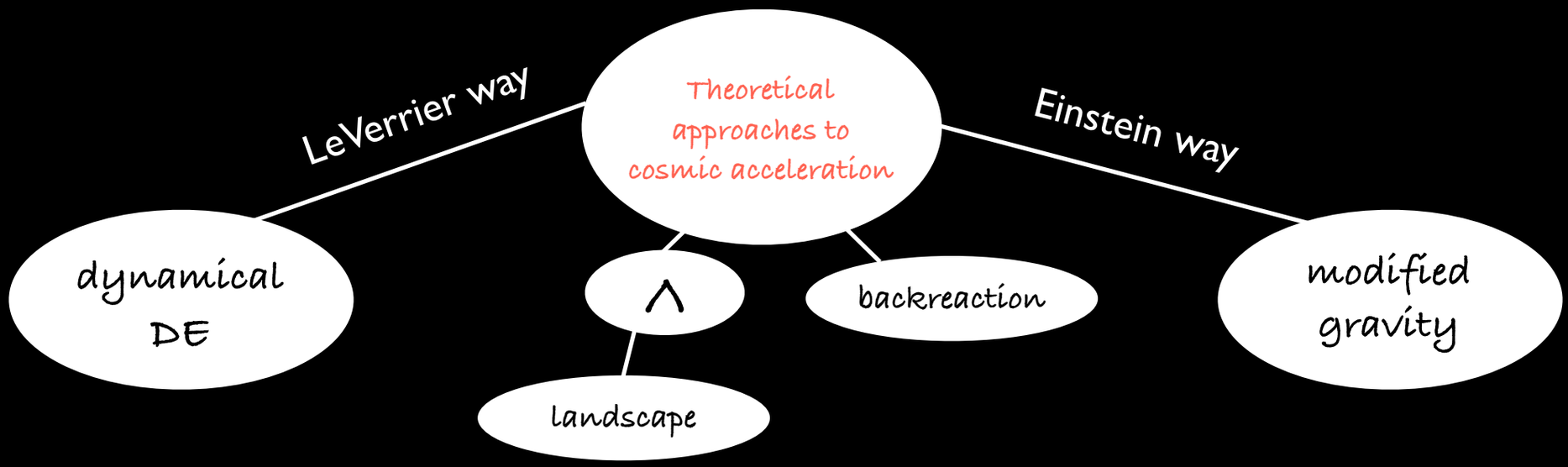


Theoretical approaches to cosmic acceleration


Theoretical approaches to cosmic acceleration
LeVerrier way
Einstein way
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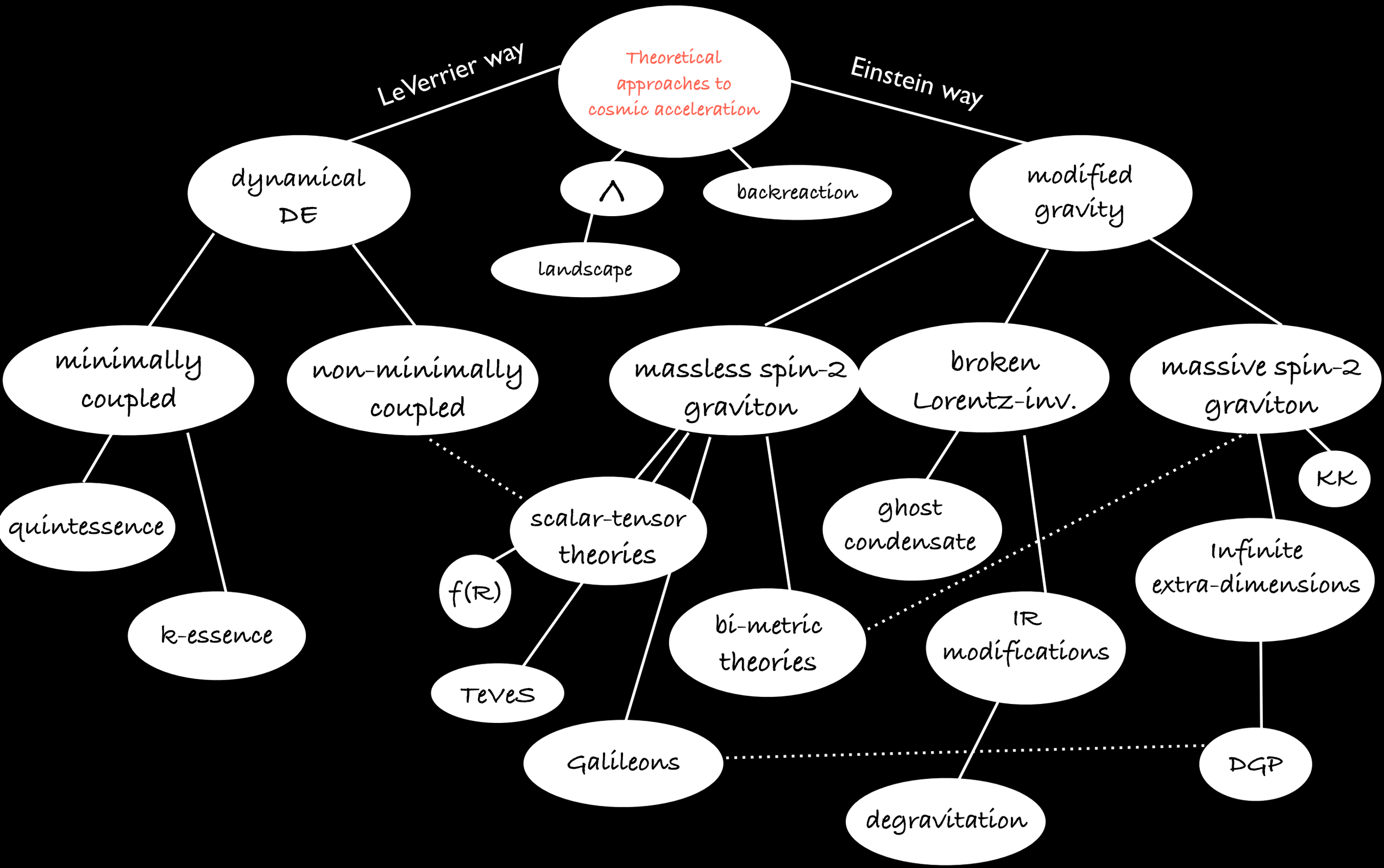
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k-essence
scalar-tensor theories
f(R)
TeVeS
Galileons
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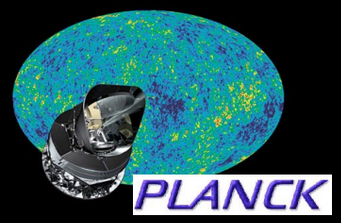
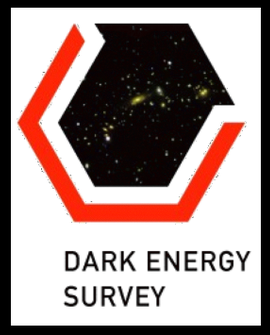
ghost condensate
IR modifications
degravitation
KK
Infinite extra-dimensions
DGP

An impressive line-up of surveys



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



WFIRST

Surveys

EUCLID: Mapping the geometry of the Universe

Together, dark matter and dark energy pose some of the most important questions in fundamental physics today.

....

Euclid is a high-precision survey mission optimised for two independent cosmological probes:

1. Weak Gravitational Lensing
   from a high-resolution imaging survey

.....

2. Galaxy Clustering
   measured via a massive spectroscopic redshift survey

To be launched in December 2020 ...

INSTITUUT LORENTZ

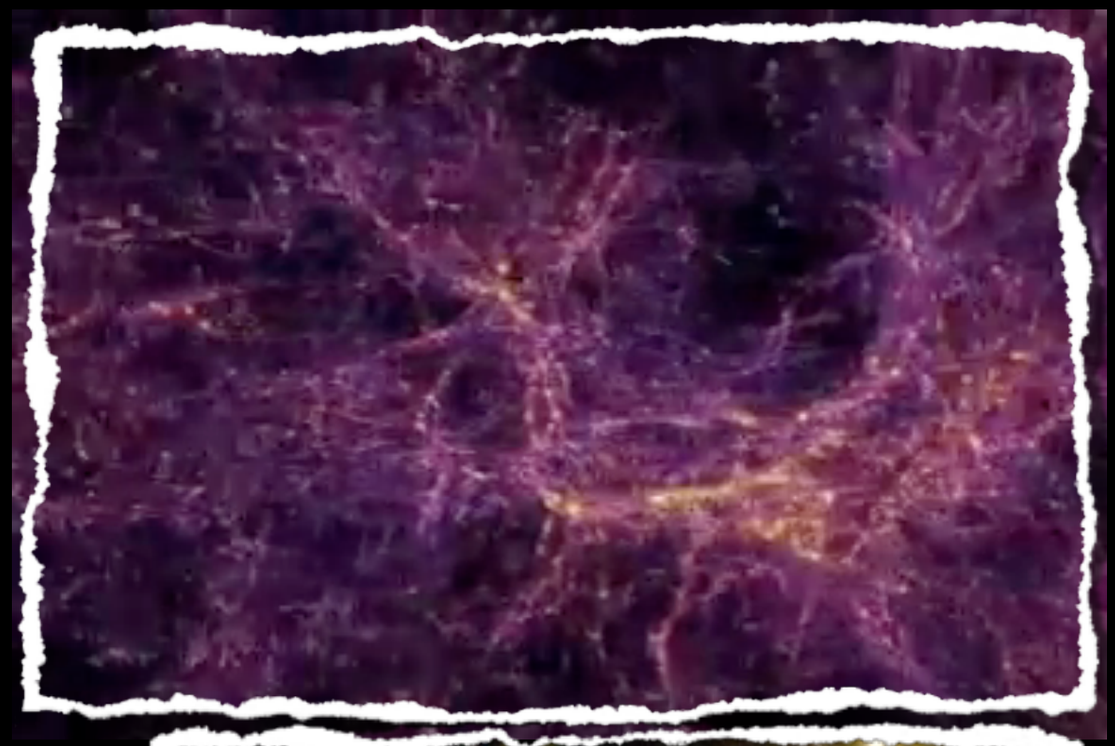
What can we measure cosmologically ?

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

$a(\tau)$: expansion history

Ψ : non-relativistic tracers
(growth of structure and peculiar velocities)

$\Phi + \Psi$: relativistic particles
(Weak lensing, Integrated Sachs-Wolfe)



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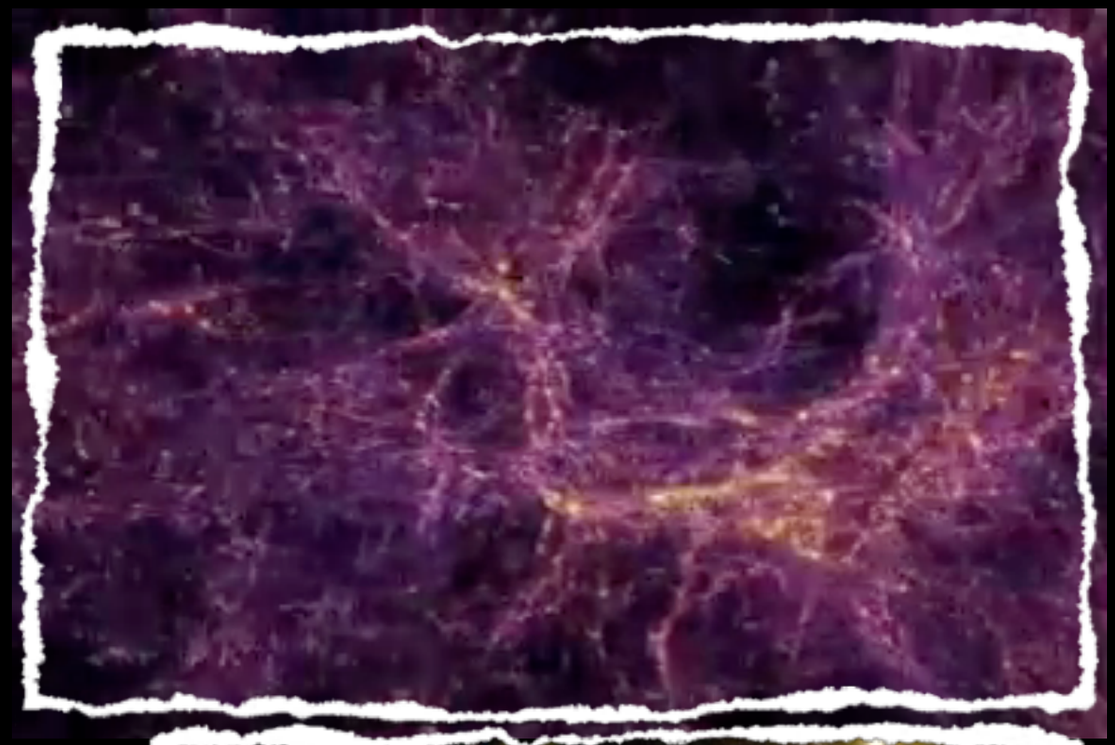
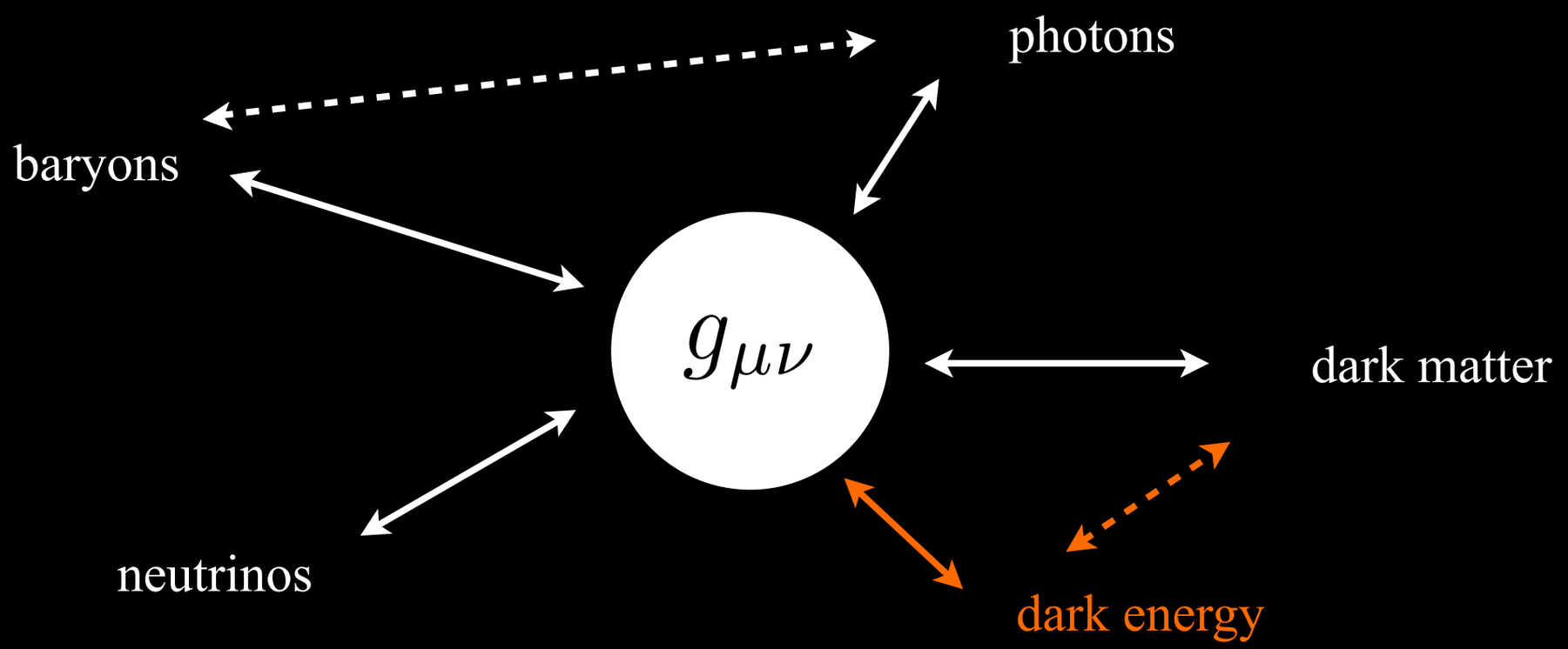


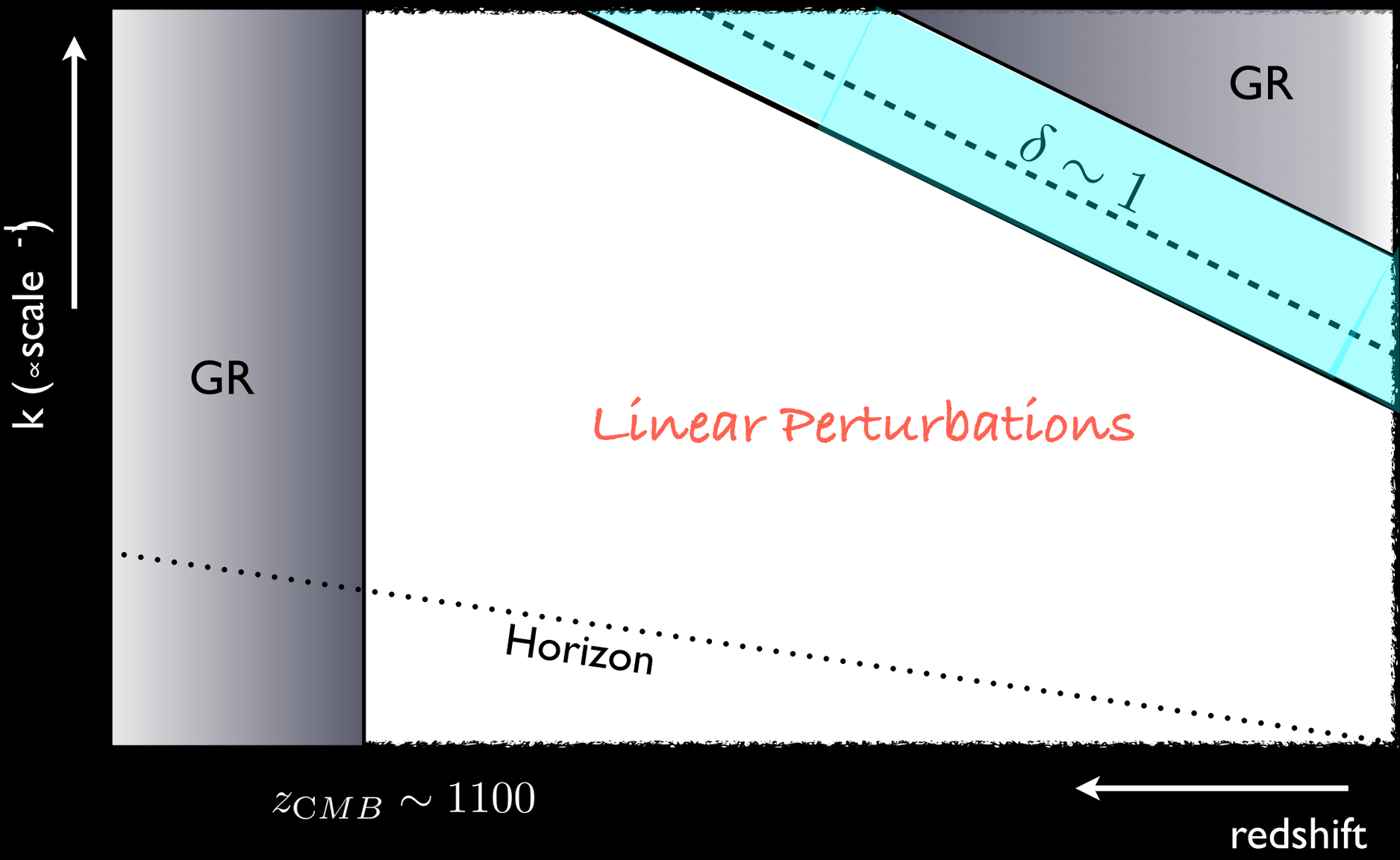
The cosmic play



THEORETICAL MODELING of DARK ENERGY.

How to optimally parametrize our ignorance?

Our cosmic players



What to parametrize ?

solutions of equations of motion → (μ, γ)

and equivalent choices, ... many authors...

the action → EFT

references to come ...

general th. of lin. cosm. pert.

Lagos, Baker, Ferreira, Noller (2016)

equations of motion → α- parametrization

Bellini, Sawicki (2014)

PPF, equations of state

Baker, Ferreira, Skordis (2012)
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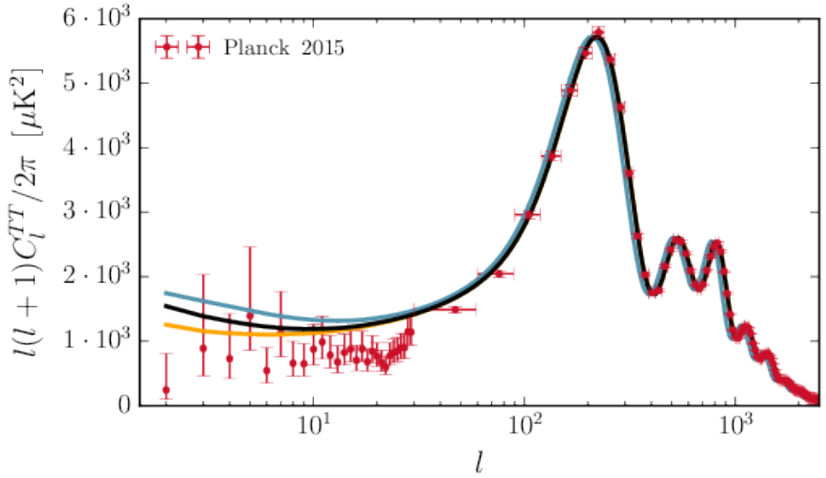
Linking the observables to the theoretical framework is not a direct inversion process !

Codes

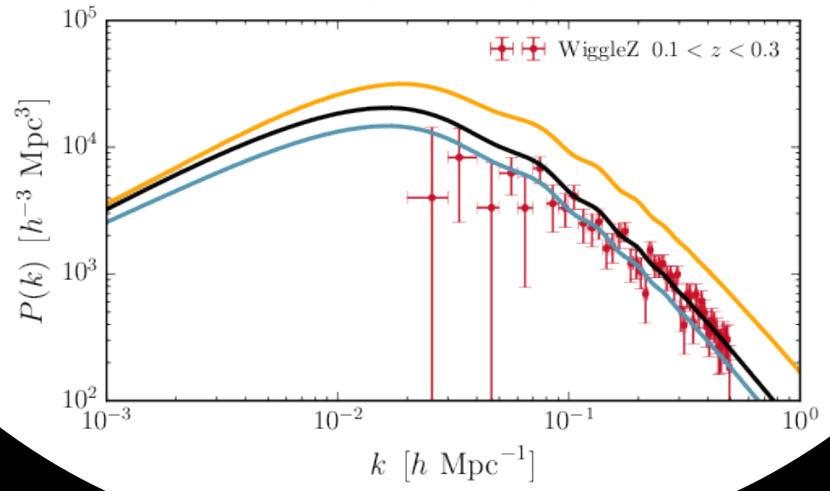
ICs for matter and metric perturbations
+
theory

EINSTEIN-BOLTZMANN SOLVER

CMB power spectrum



matter power spectrum



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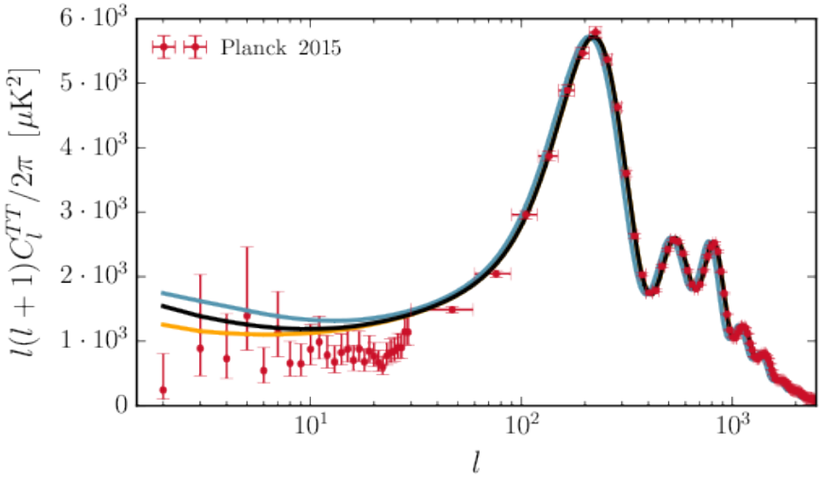
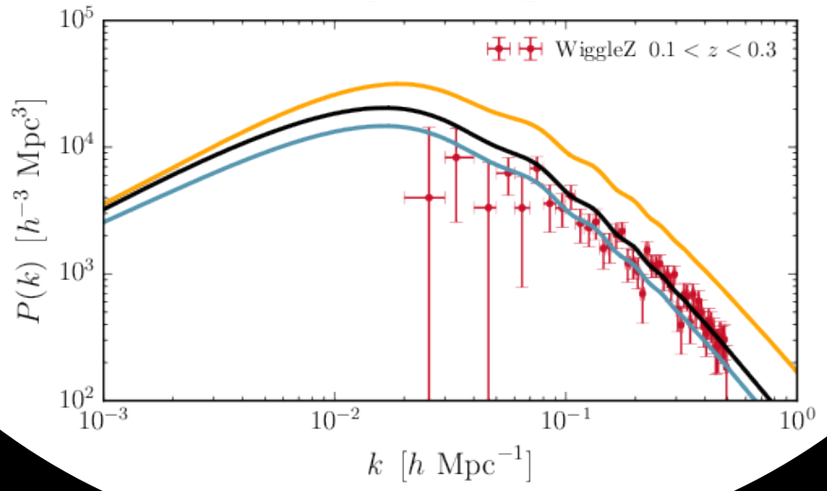
EINSTEIN-BOLTZMANN SOLVER

CAMB, A. Lewis & A. Challinor

CMB power spectrum



matter power spectrum



Einstein-Boltzmann Solvers

(μ, γ) → MGCAMB

http://aliojjati.github.io/MGCAMB/home.html

EFT → EFTCAMB

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α- parametrization → hi_class

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What can be treated

(μ, γ)

scalar perturbations

very general modifications of gravity

specific models under QS approximation

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to come…specific models exactly

μ and γ

For the observables in LSS the relevant quantities are the scalar perturbations to the metric,(Φ , Ψ), and the matter density contrast and velocity field, (δ , v)

Energy-momentum conservation eqs.

$$\nabla_\mu T^\mu_\nu = 0$$

$$\begin{aligned} \delta' + \frac{k}{aH} v - 3\Phi' &= 0 \\ v' + v - \frac{k}{aH}\Psi &= 0 \end{aligned}$$

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.D81 (2010) 104023

μ and γ

For the observables in LSS the relevant quantities are the scalar perturbations to the metric,(Φ , Ψ), and the matter density contrast and velocity field, (δ , v)

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)

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Alternative functions and letters

lensing: $k^2(\Phi+\Psi) = -\Sigma(a,k)\frac{a^2}{M_P^2}\rho\Delta$ $\qquad (\mu,\gamma) \to (\mu,\Sigma)$

$$\mu \leftrightarrow G_{\rm matter}$$

$$\Sigma \leftrightarrow G_{\rm light}$$

$$\gamma \leftrightarrow \varpi = \frac{1}{\gamma} - 1$$

$$\gamma \leftrightarrow \eta$$

many references ...

EFT of DE

Effective Field Theory of Dark Energy: 1 action 4 all

$$S = \int d^4x \sqrt{-g} \frac{m_0^2}{2} R \; + \; S_m[g_{\mu\nu}]$$

Creminelli *et al.*, JCAP 0902 (2009) 018 ; Gubitosi *et al.*, JCAP 1302 (2013) 032 ; Bloomfield *et al.*, JCAP 1308 (2013) 010

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$$S = \int d^4x \sqrt{-g} \left\{ \frac{m_0^2}{2} \left[1 + \Omega(\tau)\right] R + \Lambda(\tau) - a^2 c(\tau) \delta g^{00} \right\} + S_m[g_{\mu\nu}]$$

Creminelli *et al.*, JCAP 0902 (2009) 018 ; Gubitosi *et al.*, JCAP 1302 (2013) 032 ; Bloomfield *et al.*, JCAP 1308 (2013) 010

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$$\left. - \frac{\bar{M}_3^2(\tau)}{2} \delta K^\mu_\nu \delta K^\nu_\mu + \frac{a^2 \hat{M}^2(\tau)}{2} \delta g^{00} \delta R^{(3)} + \dots \right\} + S_m[g_{\mu\nu}]$$

IN UNITARY GAUGE

Creminelli *et al.*, JCAP 0902 (2009) 018 ; Gubitosi *et al.*, JCAP 1302 (2013) 032 ; Bloomfield *et al.*, JCAP 1308 (2013) 010

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Effective Field Theory of Dark Energy: 1 action 4 all

scalar & tensor perturbations !

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EFT of DE

It offers a model-independent parametrization of alternatives to LCDM
and a unifying language to analyze specific DE/MG models.

pure EFT:

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

mapping EFT:

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

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

Gubitosi *et al.*, JCAP 1302 (2013) 032 ;

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EFT of DE

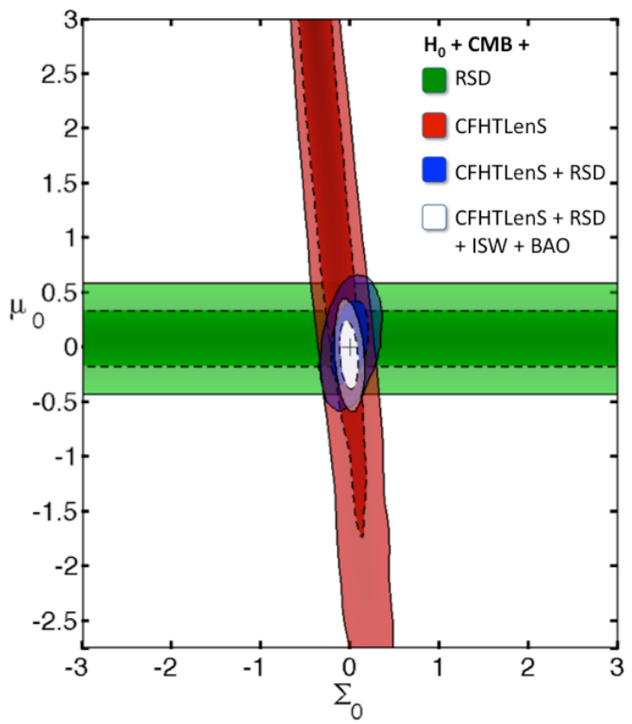
Operator	Ω	Λ	c	M_2^4	$\bar{M}_1^3$	$\bar{M}_2^2$	$\bar{M}_3^2$	$\hat{M}^2$	m_2^2
Model	R		δg^{00}	$(\delta g^{00})^2$	$\delta g^{00}\delta K^\mu{}_\mu$	$(\delta K^\mu{}_\mu)^2$	$\delta K^\mu{}_\nu K^\nu{}_\mu$	$\delta g^{00}\delta R^{(3)}$	$\frac{\tilde{g}^{ij}}{a^2}\partial_i g^{00}\partial_j g^{00}$
ΛCDM	1	✓	0	-	-	-	-	-	-
Quintessence	1/✓	✓	✓	-	-	-	-	-	-
$F(R)$	✓	✓	0	-	-	-	-	-	-
k-essence	1/✓	✓	✓	✓	-	-	-	-	-
Galileon [39] Kinetic Braiding [40]	1/✓	✓	✓	✓	✓	-	-	-	-
DGP [41]	✓	✓†	✓†	✓†	✓	-	-	-	-
Ghost Condensate [42]	1/✓	✓	0	-	-	✓	✓	-	-
Horndeski [26]	✓	✓	✓	✓	✓	✓†	✓†	✓†	-

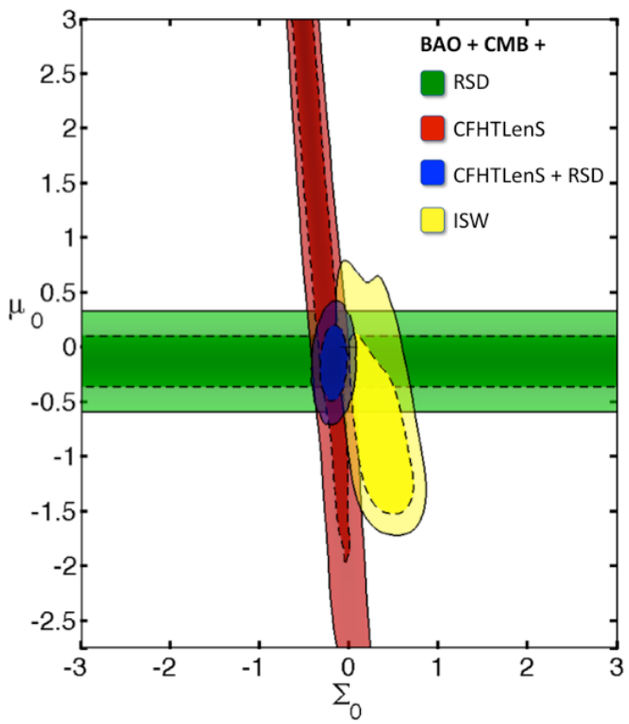
Bloomfield, Flanagan, Park, Watson JCAP 1308 (2013) 010

FACING DATA!

Exploring constraints with (μ, γ) - MGCAMB

$$\Sigma(a) = \Sigma_0 \frac{\Omega_\Lambda(a)}{\Omega_\Lambda}$$





CFHTLenS: Testing the Laws of Gravity with Tomographic Weak Lensing and Redshift Space Distortions'
MNRAS 429 3 (2013)
F. Simpson et al.

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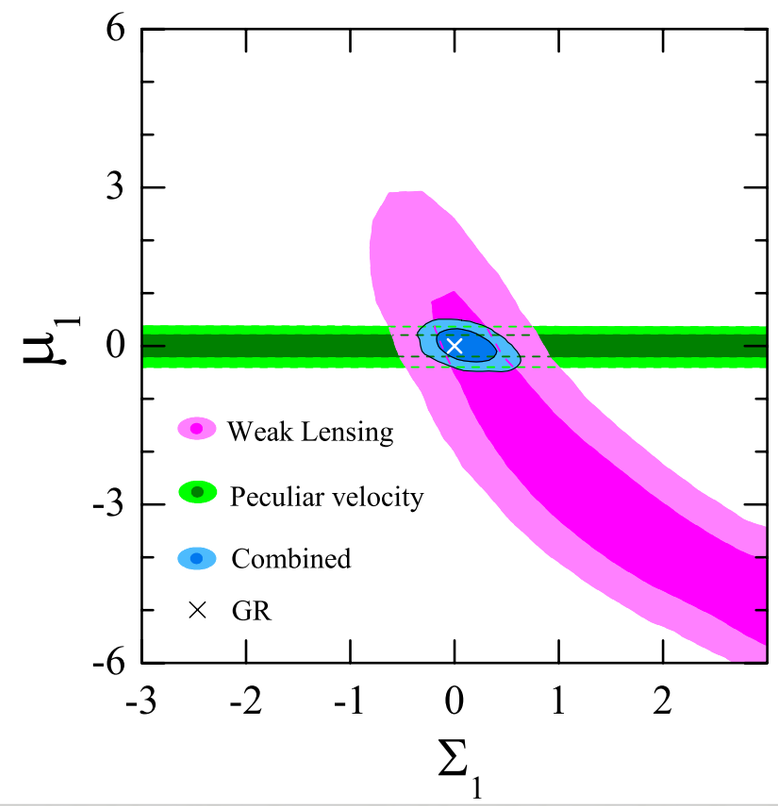

'Complementarity of WL and PV Measurements in Testing GR'
Phys. Rev. D84, 083523 (2011)
Y.-S. Song et al.

Exploring constraints with (μ, γ) - MGCAMB

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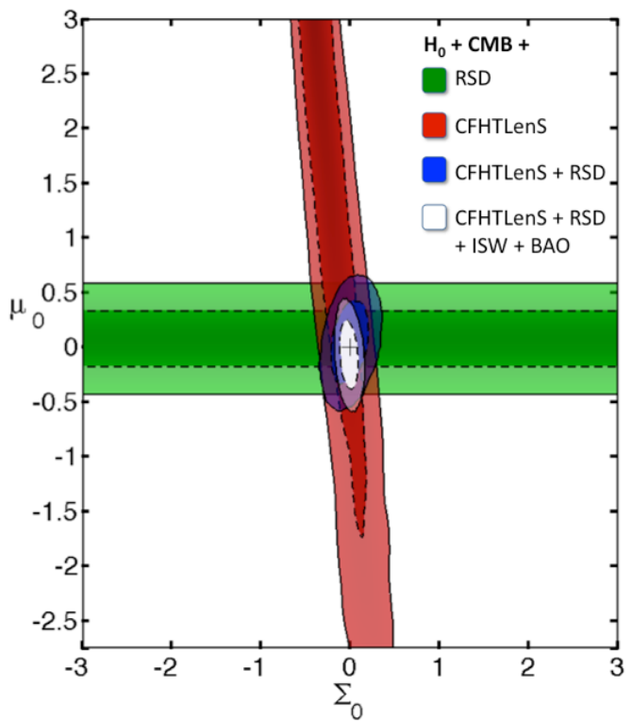

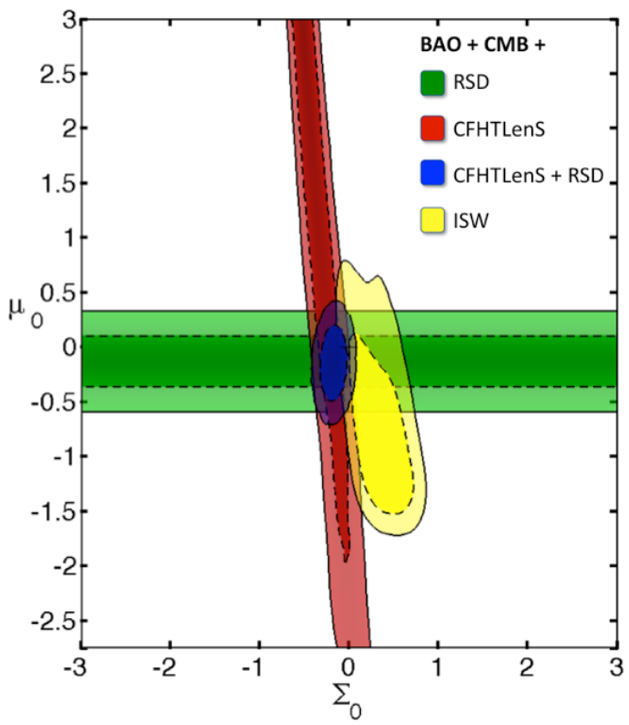

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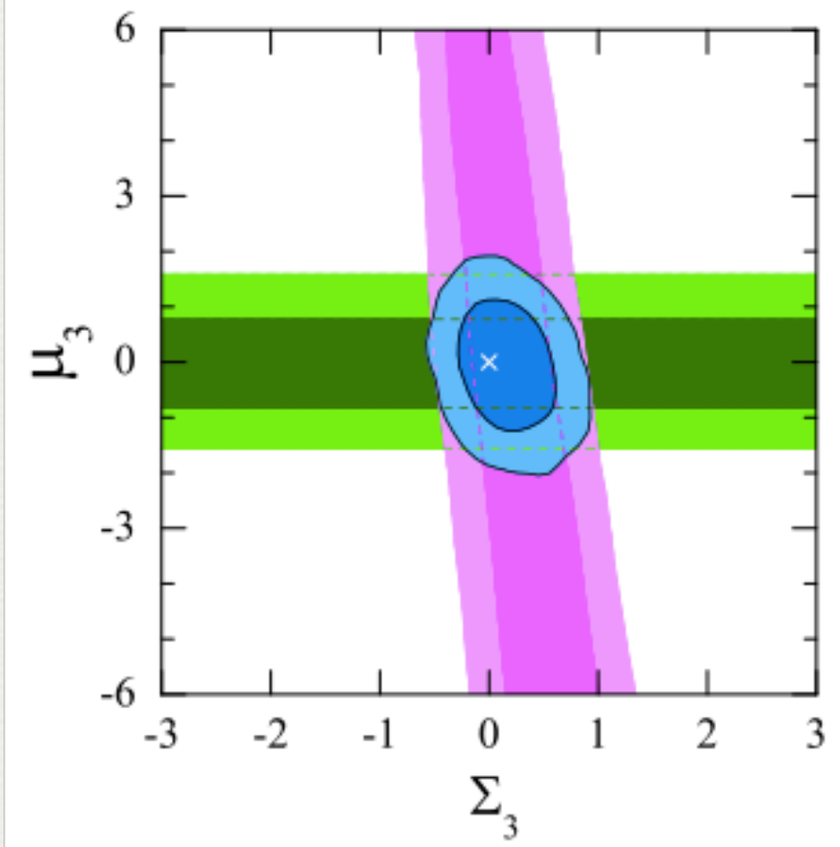

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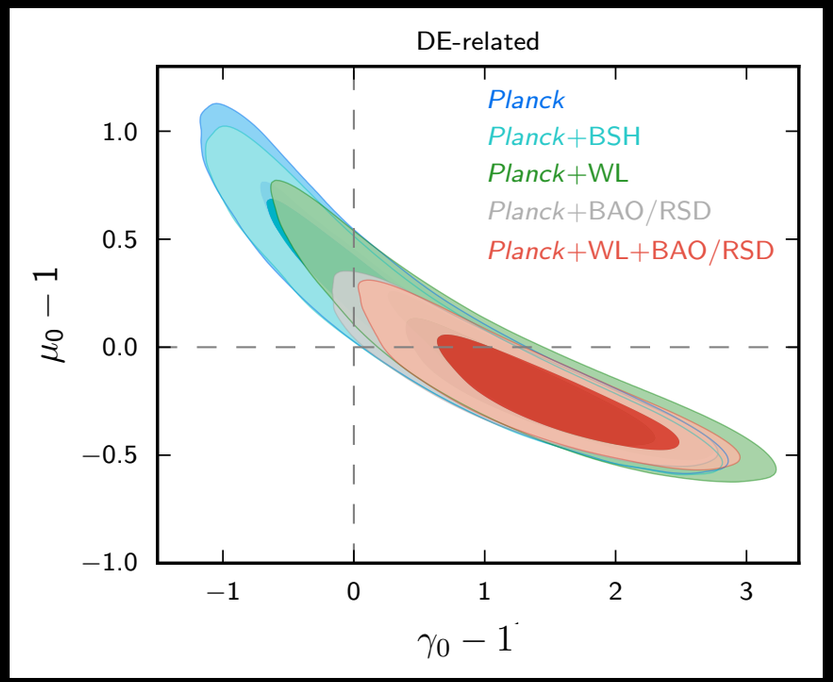
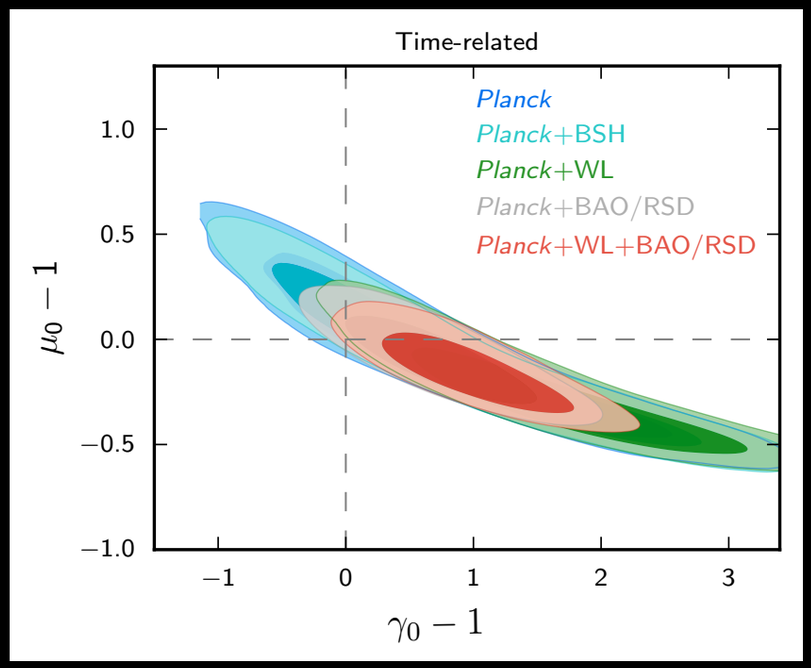
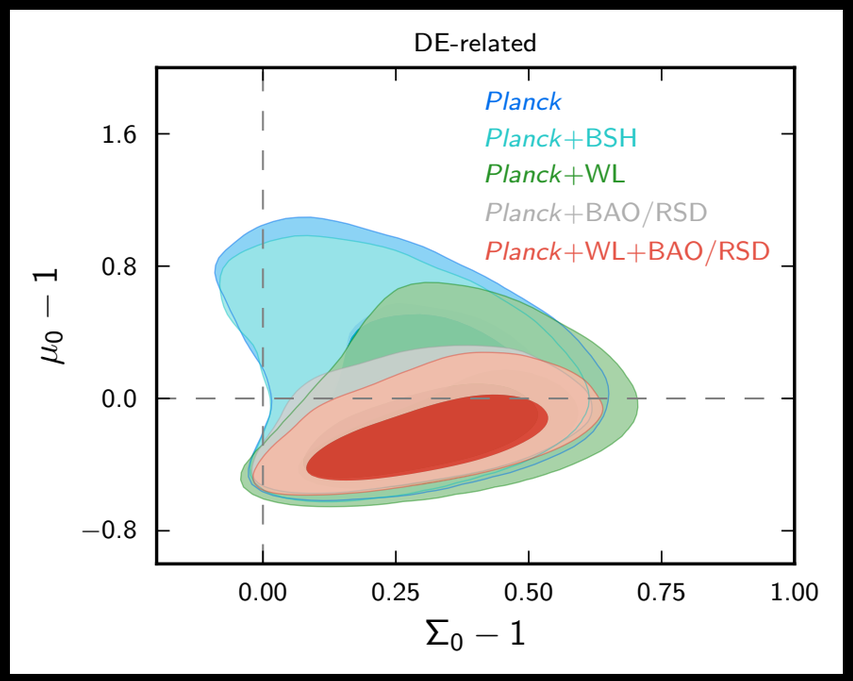
$\mu(a) - 1 = (\mu_0 - 1)\Omega_{\rm DE}(a)$

LCDM backgrounds

$\mu(a) - 1 = \mu_0 + \mu_1(1 - a)$







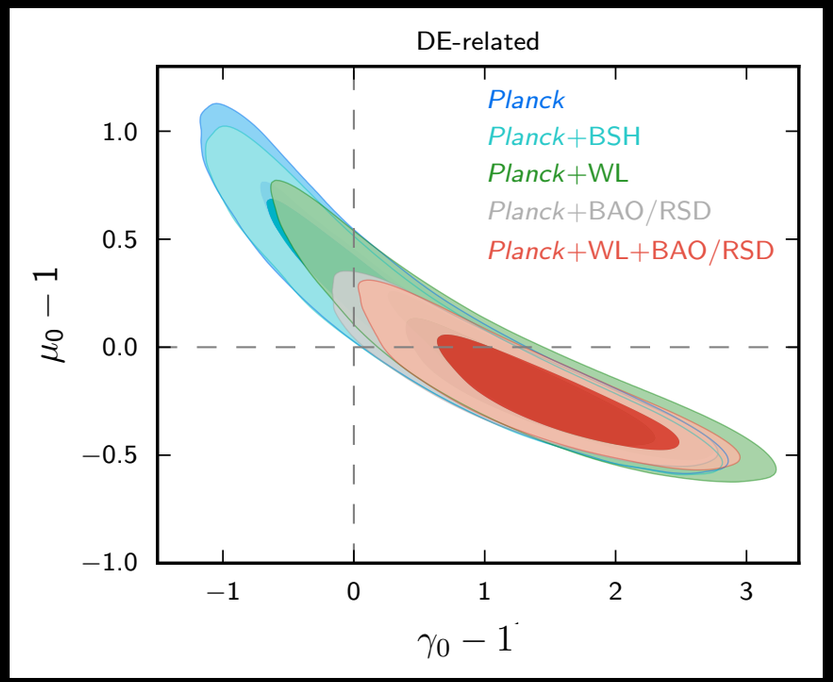
‘Planck 2015 results. XIV. Dark energy and modified gravity’

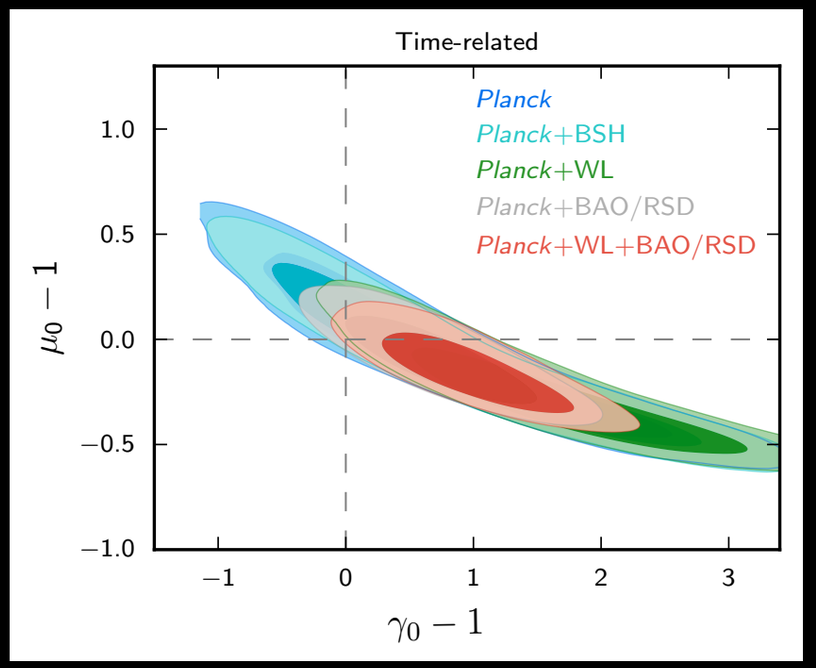
Exploring constraints with (μ, γ) - MGCAMB

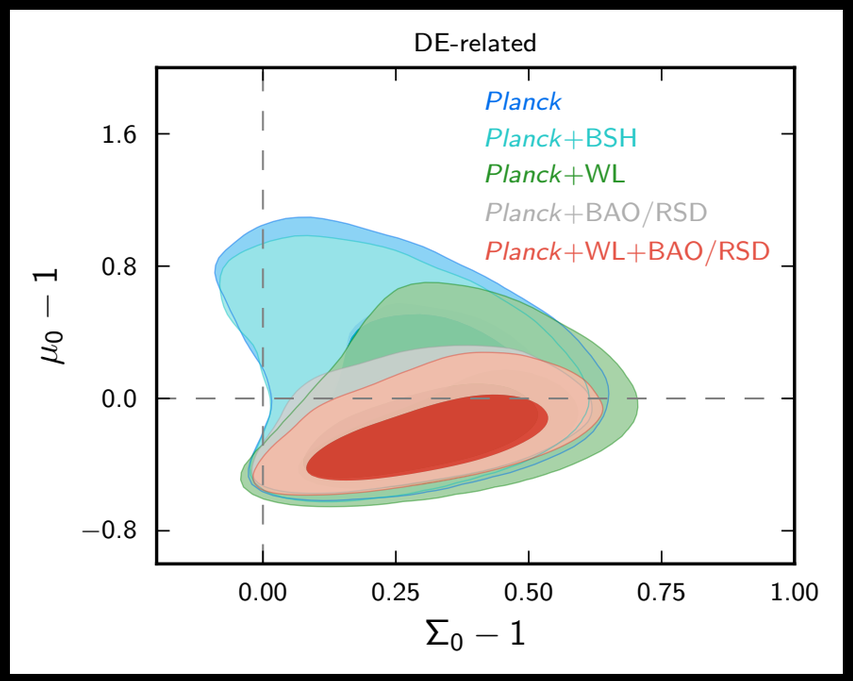
$\mu(a) - 1 = (\mu_0 - 1)\Omega_{\rm DE}(a)$

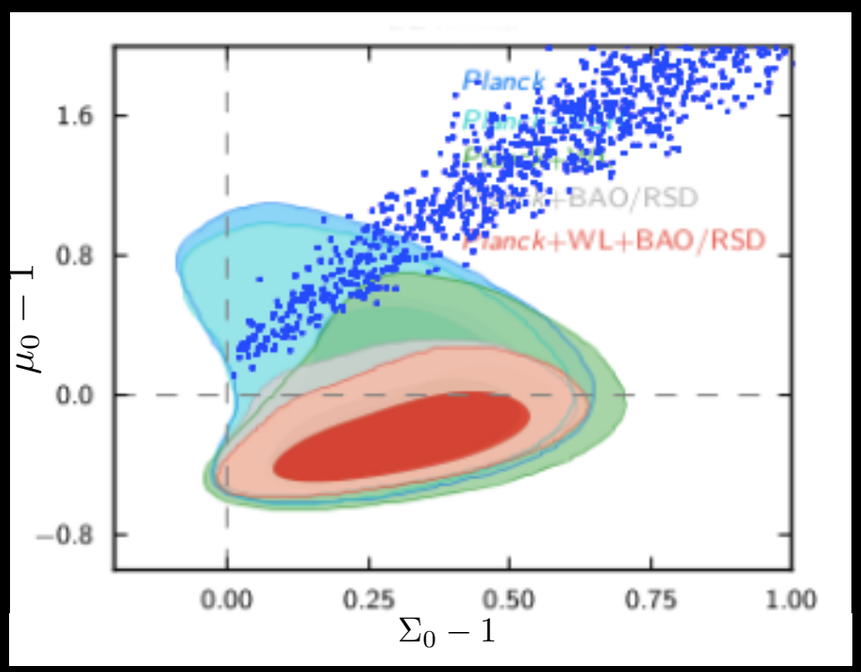
LCDM backgrounds

$\mu(a) - 1 = \mu_0 + \mu_1(1 - a)$









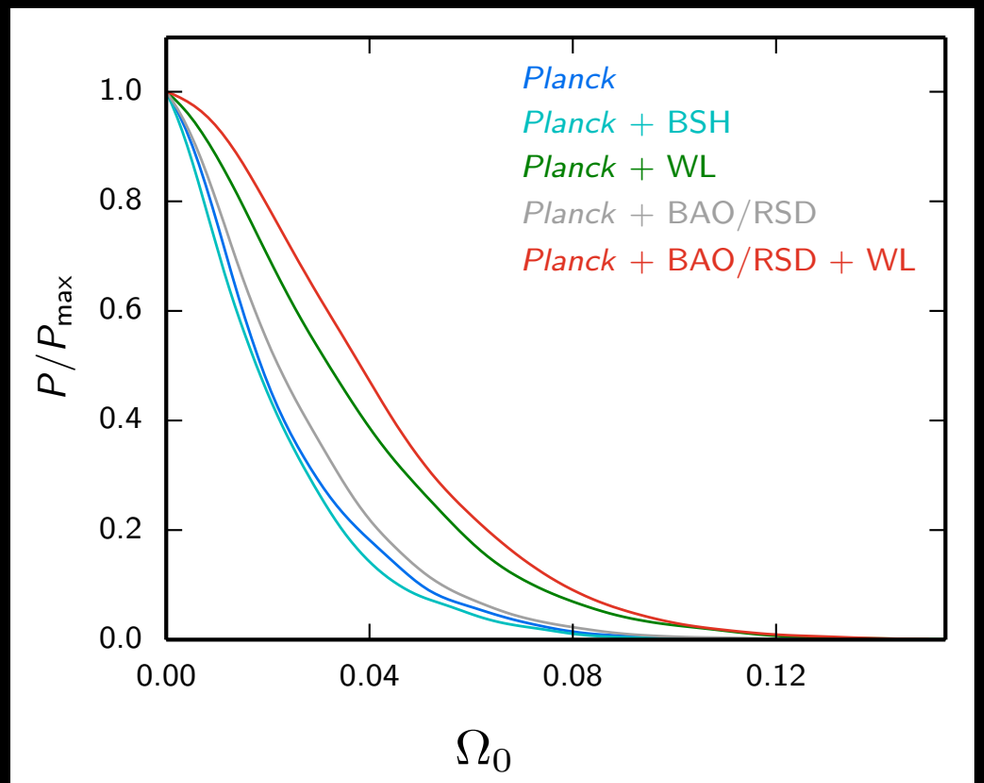
'Planck 2015 results. XIV. Dark energy and modified gravity'

Perenon, Piazza, Marinoni, Hui (2015)

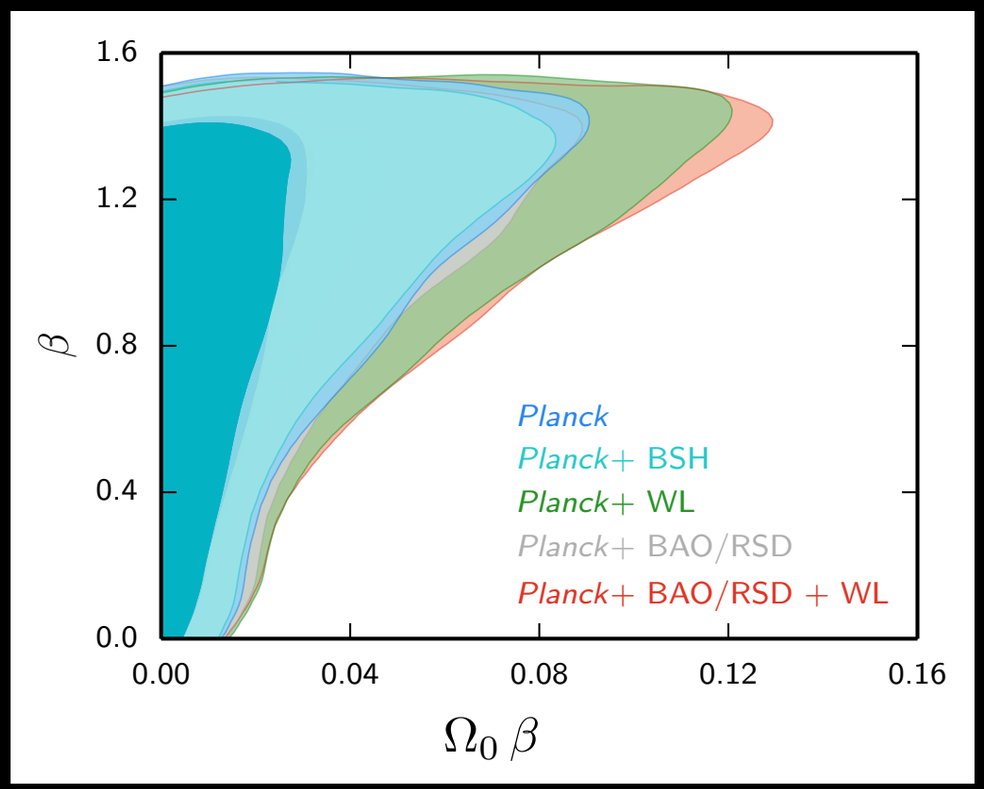
Exploring constraints on MG - EFTCAMB

LCDM backgrounds

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



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



'Planck 2015 results. XIV. Dark energy and modified gravity'

Exploring constraints on MG - EFTCAMB

LCDM backgrounds

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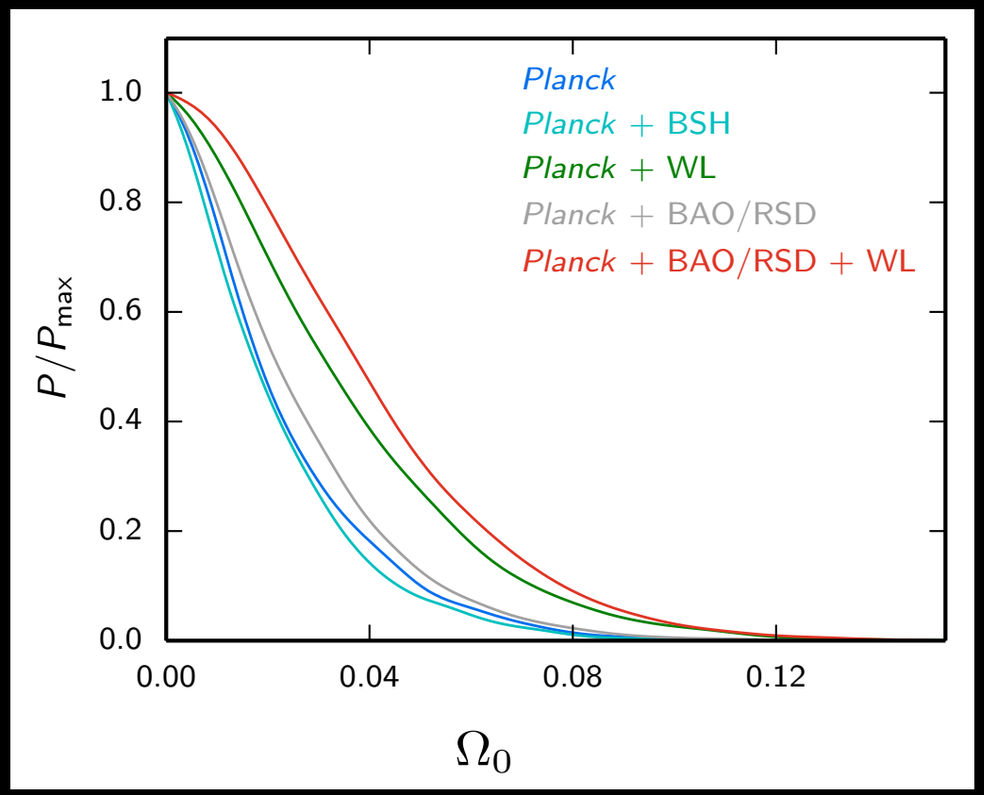
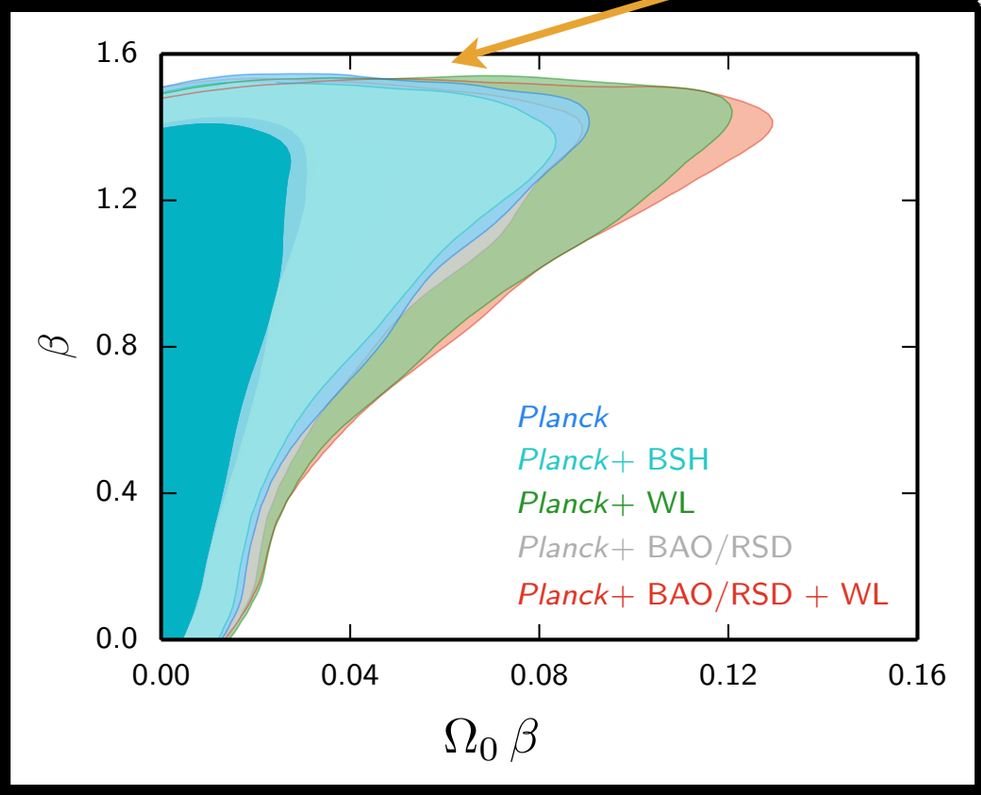


$\Omega(a) = e^{\Omega_0 \cdot a^\beta} - 1$

viability cut



'Planck 2015 results. XIV. Dark energy and modified gravity'

Exploring constraints under *stability conditions* - EFTCAMB

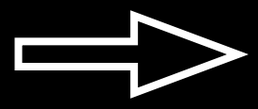
In the EFT approach, we can expand the action up to second order in the perturbations:

$$S^{(2)}_{\xi,h^T} = \frac{1}{(2\pi)^3}\int d^3k\, dt\, a^3 \left\{\left[\mathcal{L}_{\dot\xi\dot\xi}\dot\xi^2 - k^2 G\xi^2\right] + \frac{A_T}{8}\left[\left(\dot h^T_{ij}\right)^2 - \frac{c_T^2}{a^2}\left(h^T_{ij}\right)^2\right]\right\}$$

we can inspect the dynamics of perturbations in a general way !

E.g., avoidance of ghost and gradient instabilities translate into the following set of conditions:

$$\begin{aligned}\mathcal{L}_{\dot\xi\dot\xi} &> 0\\ c_s^2 \equiv \frac{G}{\mathcal{L}_{\dot\xi\dot\xi}} &> 0\\ A_T &> 0\\ c_T^2 &> 0\end{aligned}$$



very general conditions in terms of the EFT functions, that constitute a stability check to be run at the very beginning!

*including the matter sector these will change

In terms of EFT functions:

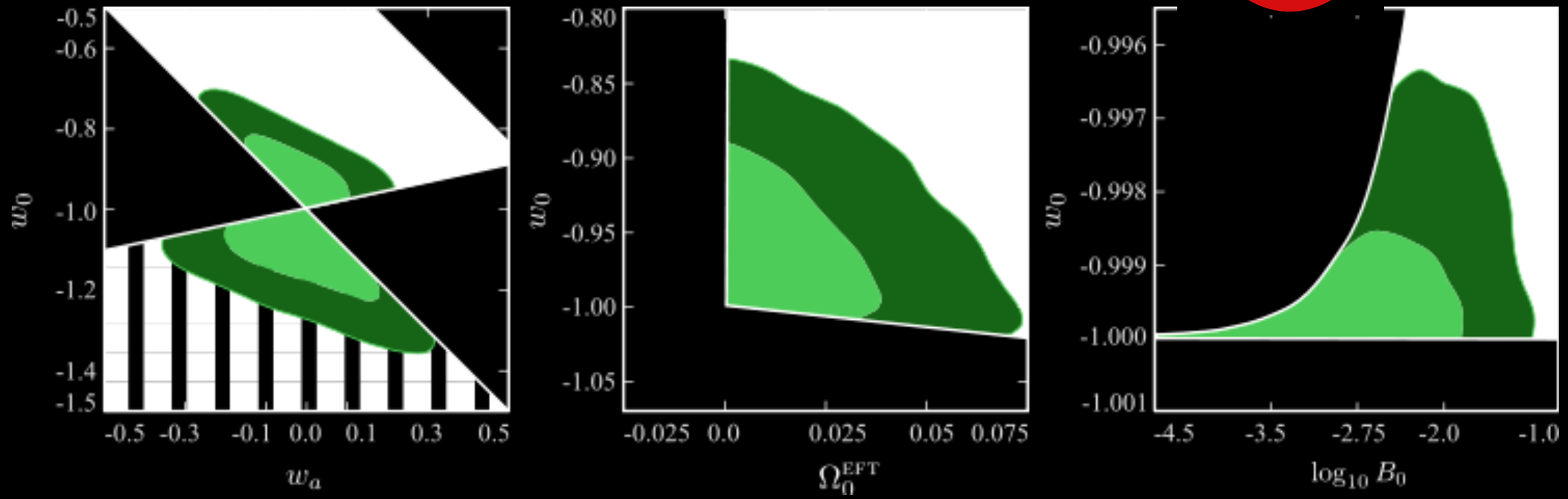
$$A_T(t) = m_0^2\,(1+\Omega) - \bar M_3^2$$

$$c_T^2(t) = \frac{m_0^2\,(1+\Omega)}{m_0^2\,(1+\Omega) - \bar M_3^2}$$

Frusciante, Papadomanolakis, Silvestri, JCAP (2016); De Felice, Frusciante, Papadomanolakis *in progress*.

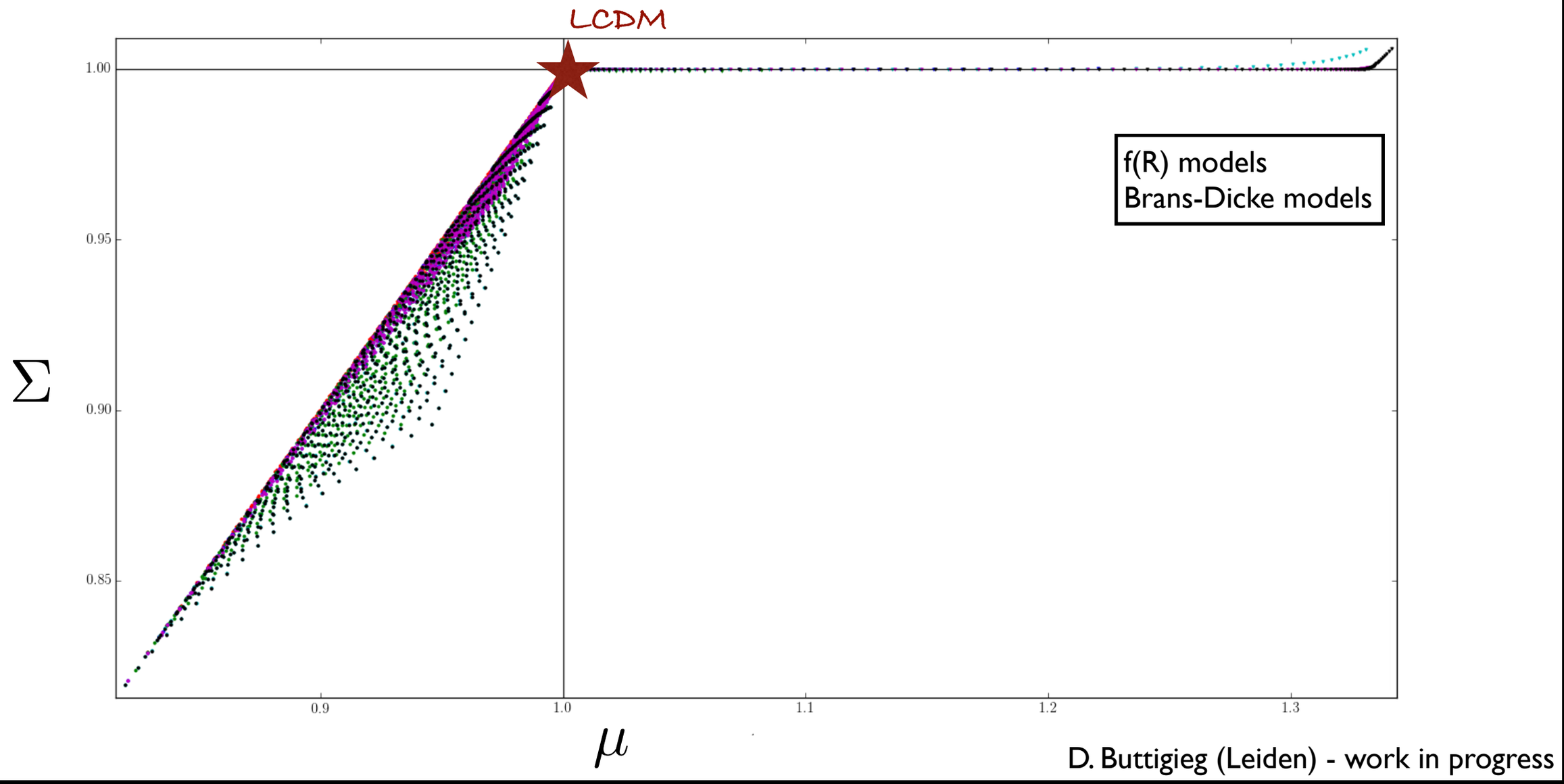
Exploring constraints under *stability conditions* - EFTCAMB

Physics remains the guiding principle in the agnostic exploration of dark energy!



Marginalized joint likelihoods for parameters of interest in three different dark energy models: quintessence, non-minimally coupled quintessence and f(R) gravity.

Exploring constraints with (μ, Σ) - EFTCAMB



D. Buttigieg (Leiden) - work in progress

physically viable models.

Exploring constraints for *specific models*

EXACT vs. QUASI-STATIC IMPLEMENTATION ?

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 » aH

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

in DE/MG

sub-horizon scales: k » aH

and

for both metric potentials and additional scalars, i.e.

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

Exploring constraints for *specific models*

EXACT vs. QUASI-STATIC IMPLEMENTATION ?

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 » aH

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

how restrictive/realistic is the QS approximation?

EFTCAMB can help with this!

in DE/MG

zon scales: k » aH

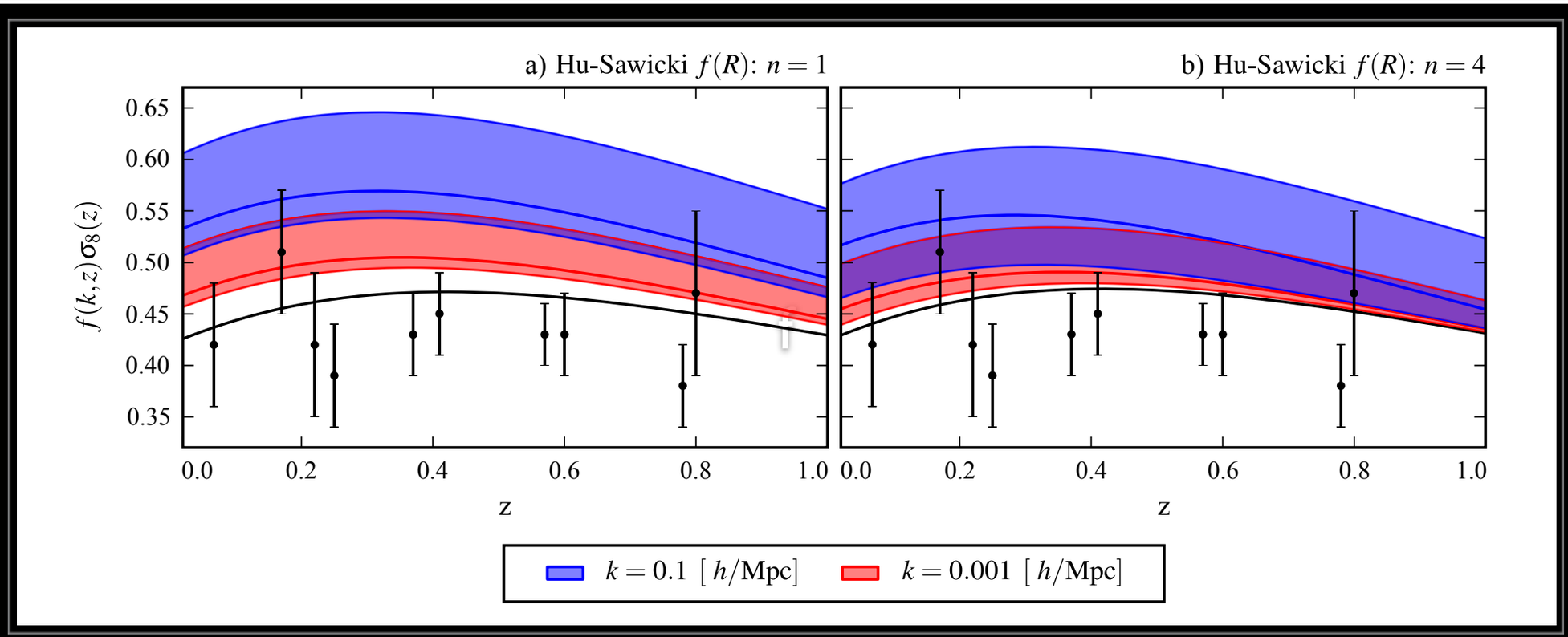
and

for both metric potentials and additional scalars, i.e.

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

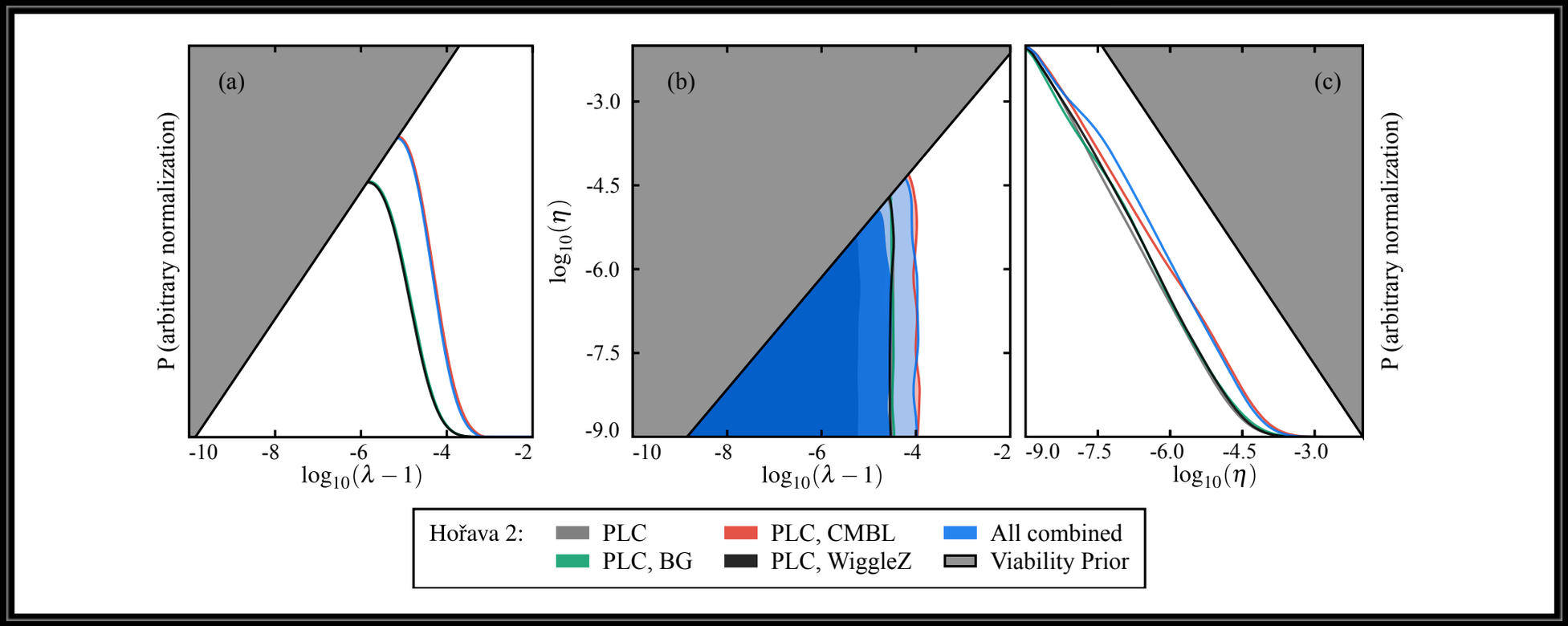
Exploring constraints for *specific models* - EFTCAMB

f(R)



Hu, Raveri, Rizzato, A.S., PRD (2014);

Horava gravity



Frusciante, Raveri, Vernieri, Hu, A.S., Phys. Dark Univ. (2016)

Complementary approaches

(μ,γ)

* very general, captures basically *any* deviation from LCDM

* needs QSA to treat specific models

* quite distant from theoretical details. Might end up exploring physically unviable options…?! or simply keeping a very open mind …

EFT

* ~ single scalar field models allowing a well defined Jordan frame

* NO QSA when specializing to models

* closer link to theory (EFT in particular); allows implementation of theoretical *viability priors* to make exploration much more efficient…too strong?!

Consistency conditions

Assuming the QS approximation is valid, one can 'easily' derive analytical expressions for the MG functions (μ, Σ). Quite generally, they will be ratio of polynomials even in k and at mot quadratic if we have only a single scalar-field with 2nd order EOMs

A.S., L.Pogosian, R. Buniy, PRD (2013)

We can do it generally in terms of the EFT functions.
For the broad Horndeski class of models, we have:

$$\mu = \frac{m_0^2}{M_*^2} \frac{1 + M^2\ a^2/k^2}{f_3/2f_1M_*^2 + M^2(1+\alpha_T)^{-1}a^2/k^2}$$

$$\Sigma = \frac{m_0^2}{2M_*^2} \frac{1 + f_5/f_1 + M^2[1+(1+\alpha_T)^{-1}]a^2/k^2}{f_3/2f_1M_*^2 + M^2(1+\alpha_T)^{-1}a^2/k^2}$$

It is then possible to derive some consistency conditions on and btw these functions that can help ruling out classes of models with data.

L.Pogosian & A.S., arXiv:1606.05339

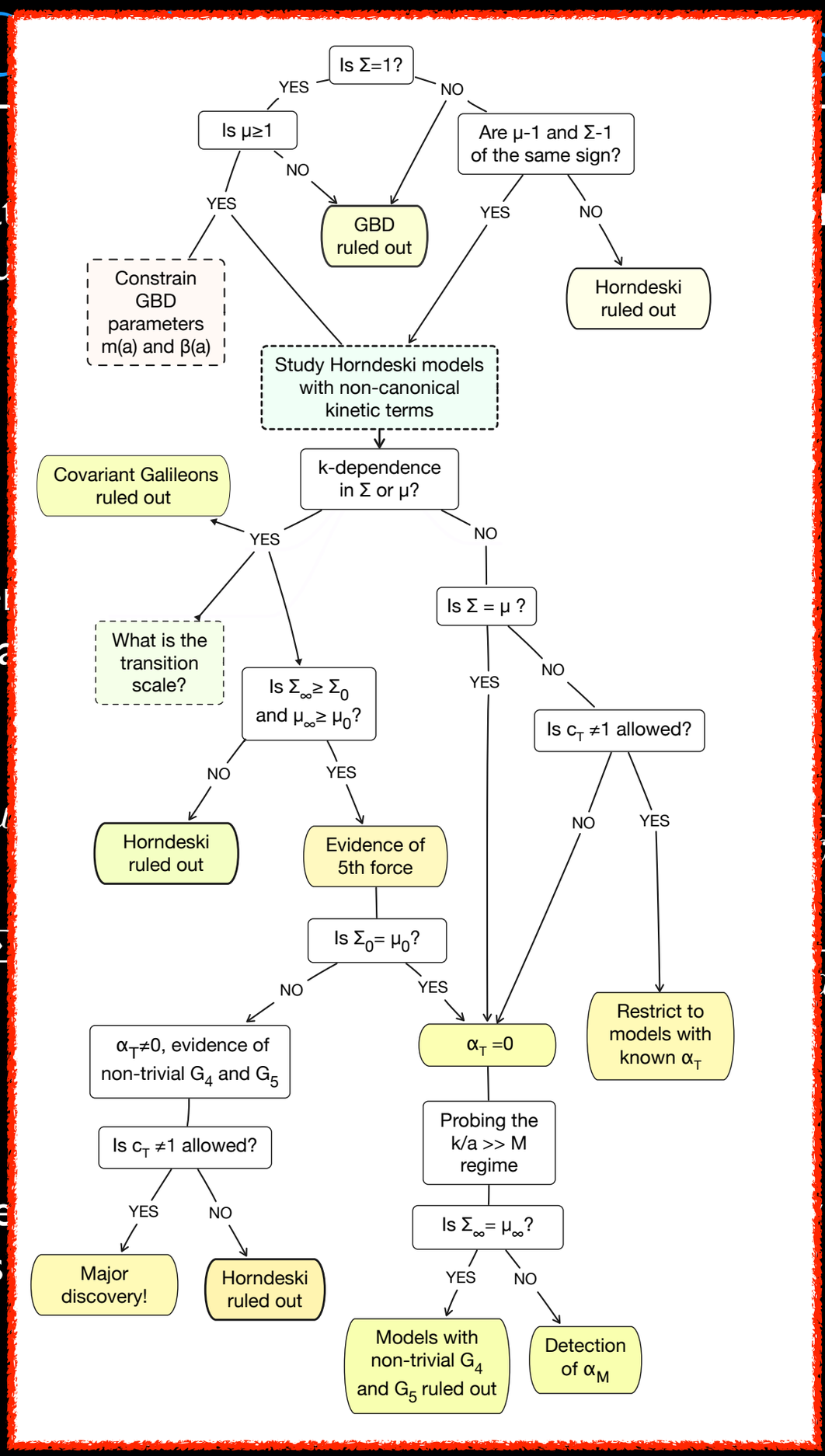
Assuming the QS approximat… l expressions for the MG functions (μ, Σ). Qu… polynomials even in k and at … r-field with 2nd order EOMs

A.S., L.Pogosian, R. Buniy, PRD (2013)

We can do it generally in te…
For the broad Horndeski cla…

$$\mu$$

$$\Sigma$$



It is then possible to derive… these functions that can help ruling out classes of models…

L.Pogosian & A.S., arXiv:1606.05339

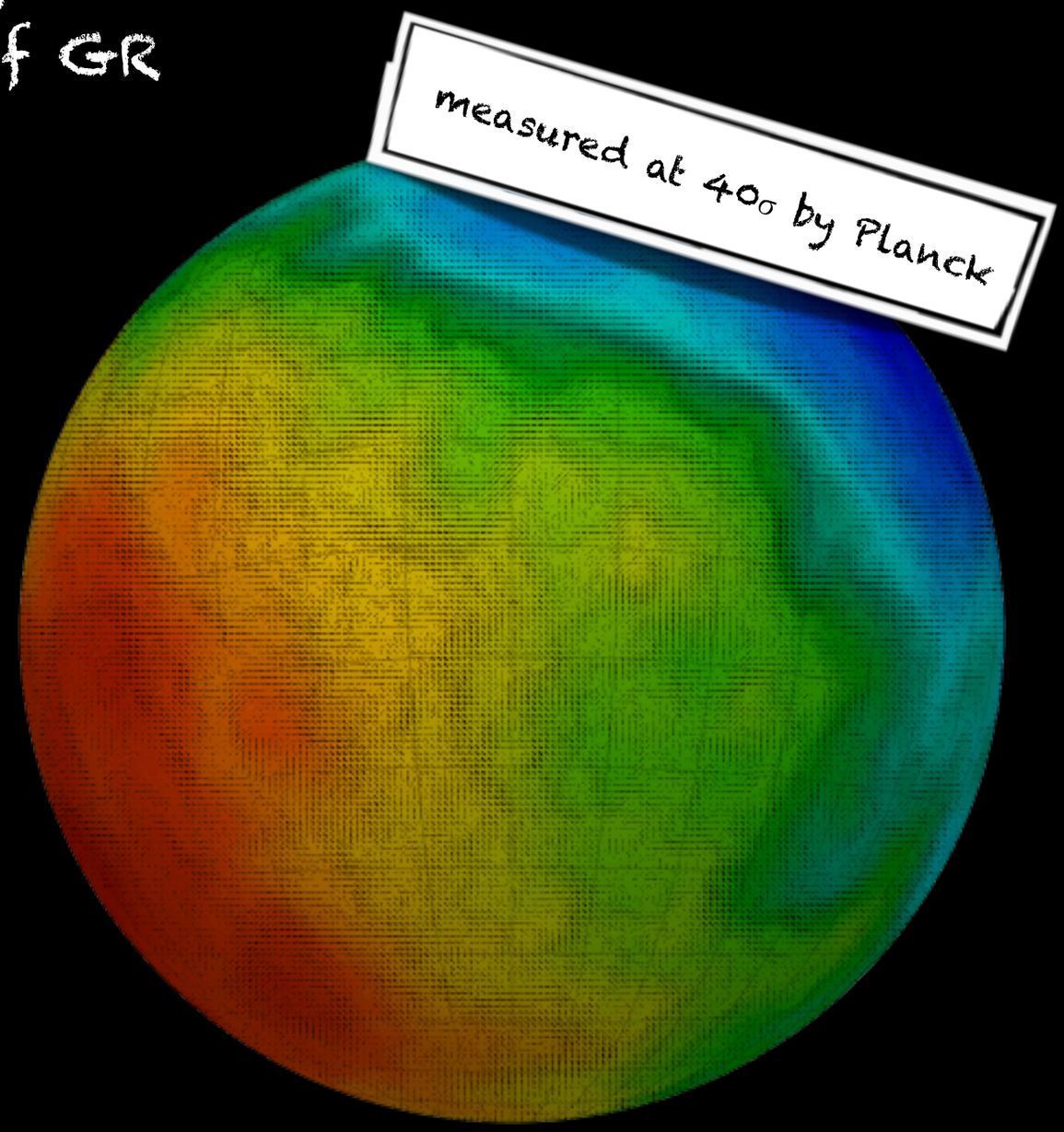
This was a brief tale of the ongoing quest to test gravity on cosmological scales.

This is an exciting prospect that will be enabled by upcoming surveys.

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

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

Future missions (Euclid, LSST, ...) will combine WL, GC and expansion history measurements...key mix for tests of GR



CMB lensing and B modes of polarization !

Non-linear scales: screening mechanisms, N-body simulations and EFT of LSS.

image credits: M. Calabrese & F. Bianchini

THANK YOU !

z = 0