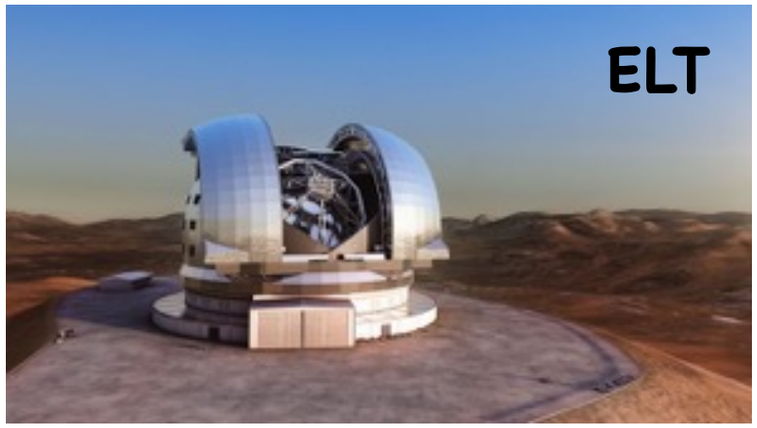
Lighting up Einstein's Dark Universe

Alessandra Silvestri
Instituut Lorentz, Leiden U.

An impressive line-up of surveys …

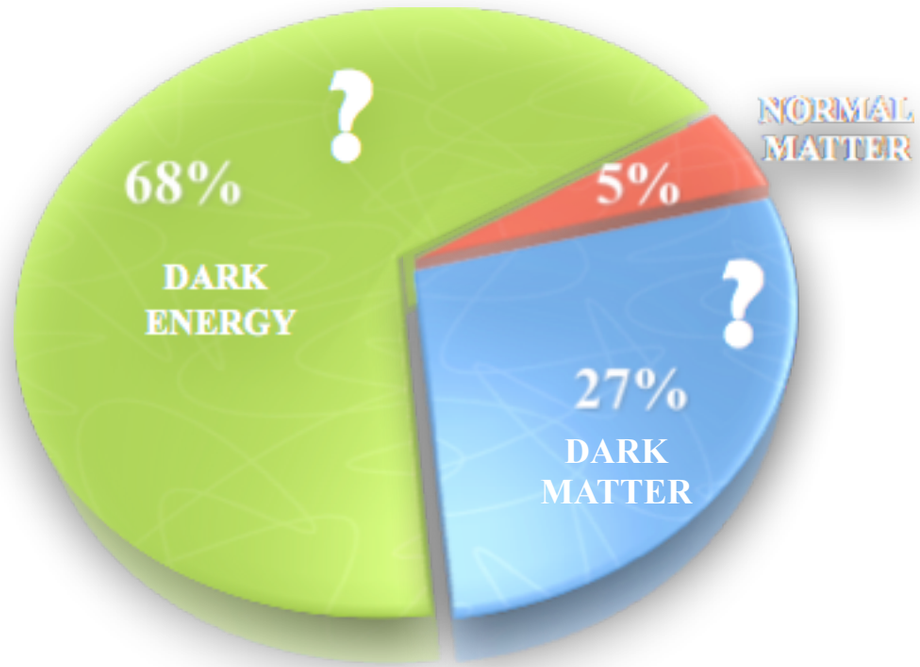


eBOSS

Ongoing and upcoming <u>wide field imaging</u> and <u>spectroscopic redshift surveys</u> 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** to ~ O(1)% over wider redshift range.

DARK ENERGY SURVEY

… and a quite dark Universe !



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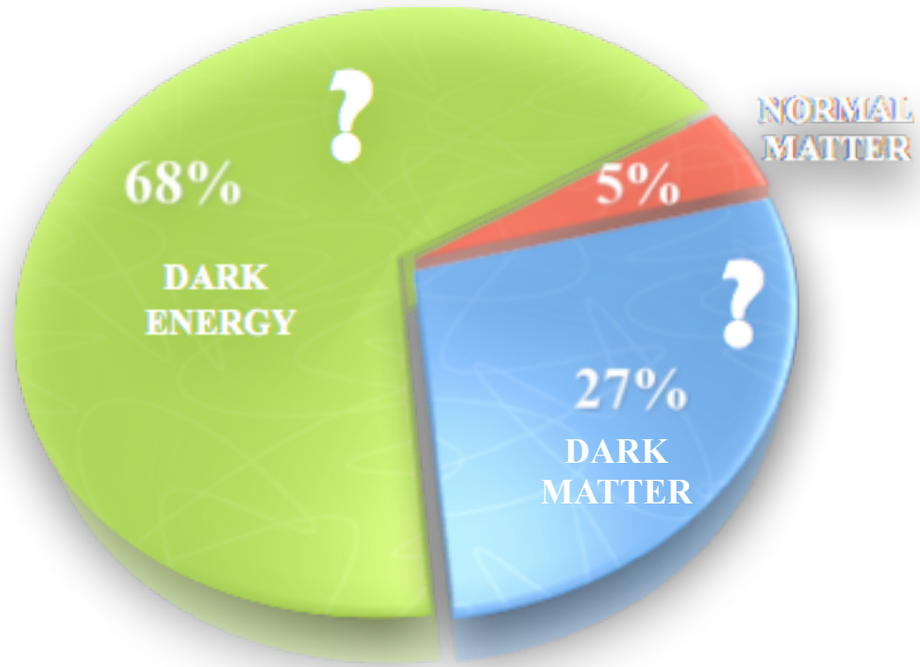

While GR has so far passed all experimental tests, it has yet to be accurately tested on scales beyond our solar system.

1. test the consistency with LCDM (GR)

2. explore the parameter space allowed to alternative models

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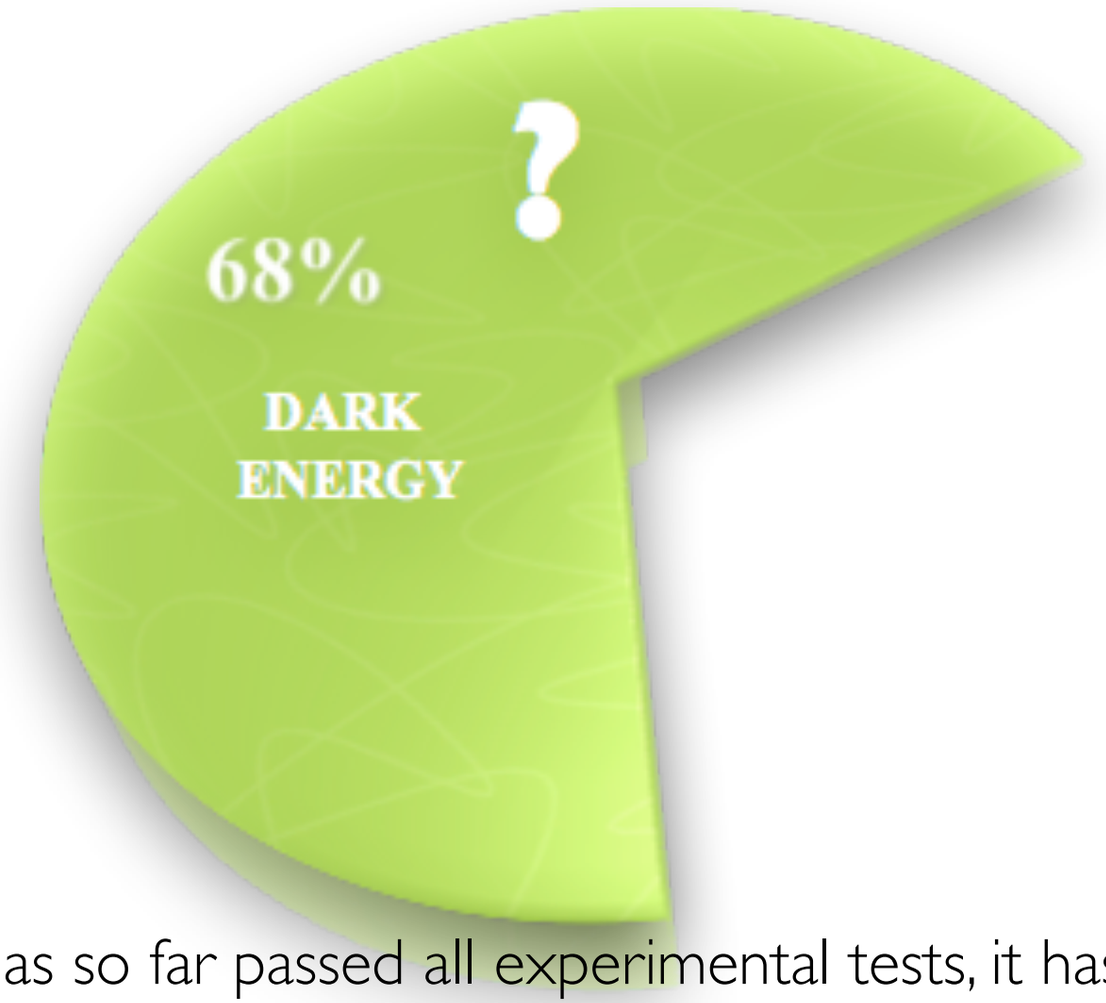

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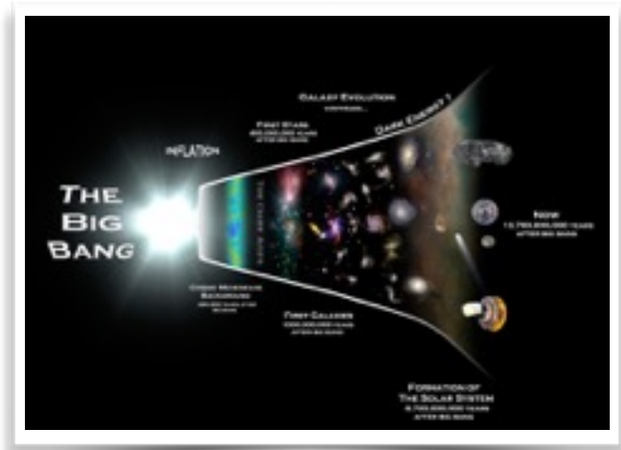
2. explore the parameter space allowed to alternative models

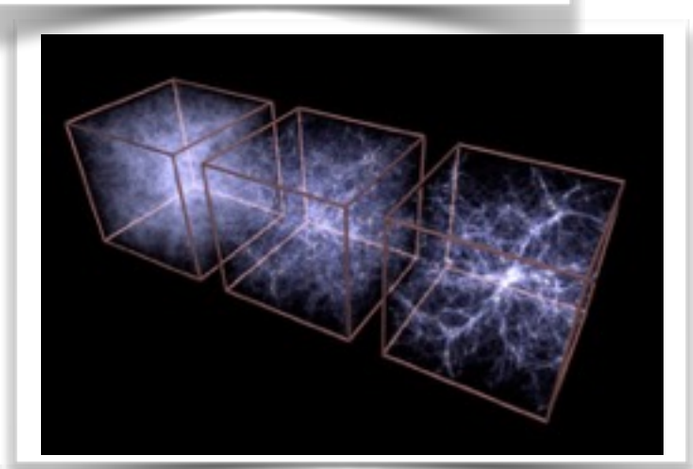
Cosmic functions of interest

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

Expansion history: $a(\tau)$



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



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

The Standard Model of Cosmology

The standard model is based on GR : $G_{\mu\nu} = \frac{T_{\mu\nu}}{M_P^2}$

Cosmic acceleration is sourced by the cosmological constant.

The energy-momentum tensor
is characterized by: $\Delta\pi \ll \delta p \ll \delta\rho$

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The growing mode goes like: $D_1(a) = \frac{5\Omega_m}{2}\frac{H(a)}{H_0}\int_0^a \frac{da'}{\left[a'\frac{H(a')}{H_0}\right]^3}$

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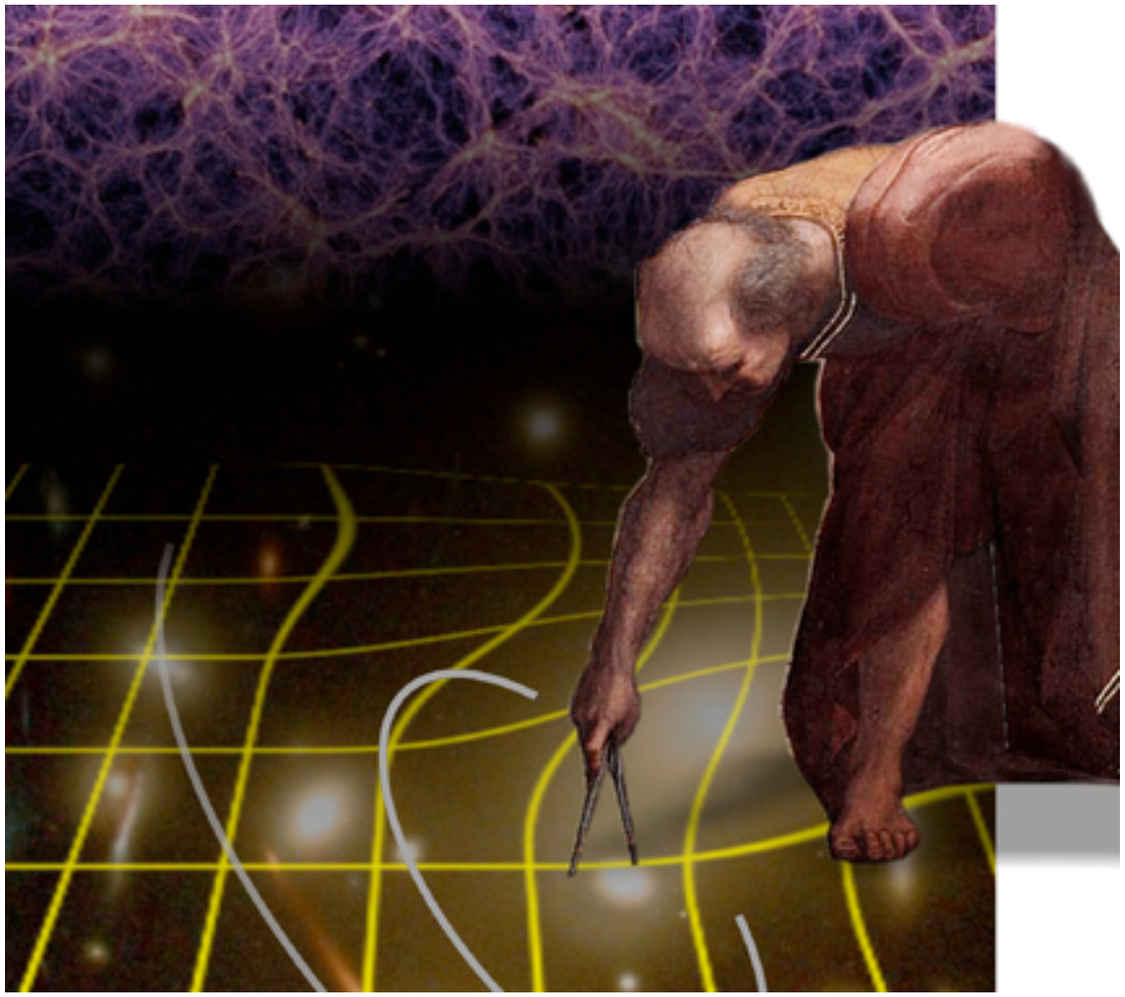
- relativistic and non-relativistic probes respond to the same metric potential
- the growth of structure is scale-independent
- there is a consistency relation btw expansion history and growth of structure.

EUCLID: Mapping the geometry of the Universe



to be launched in 2021 ...

1. 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

Beyond LCDM

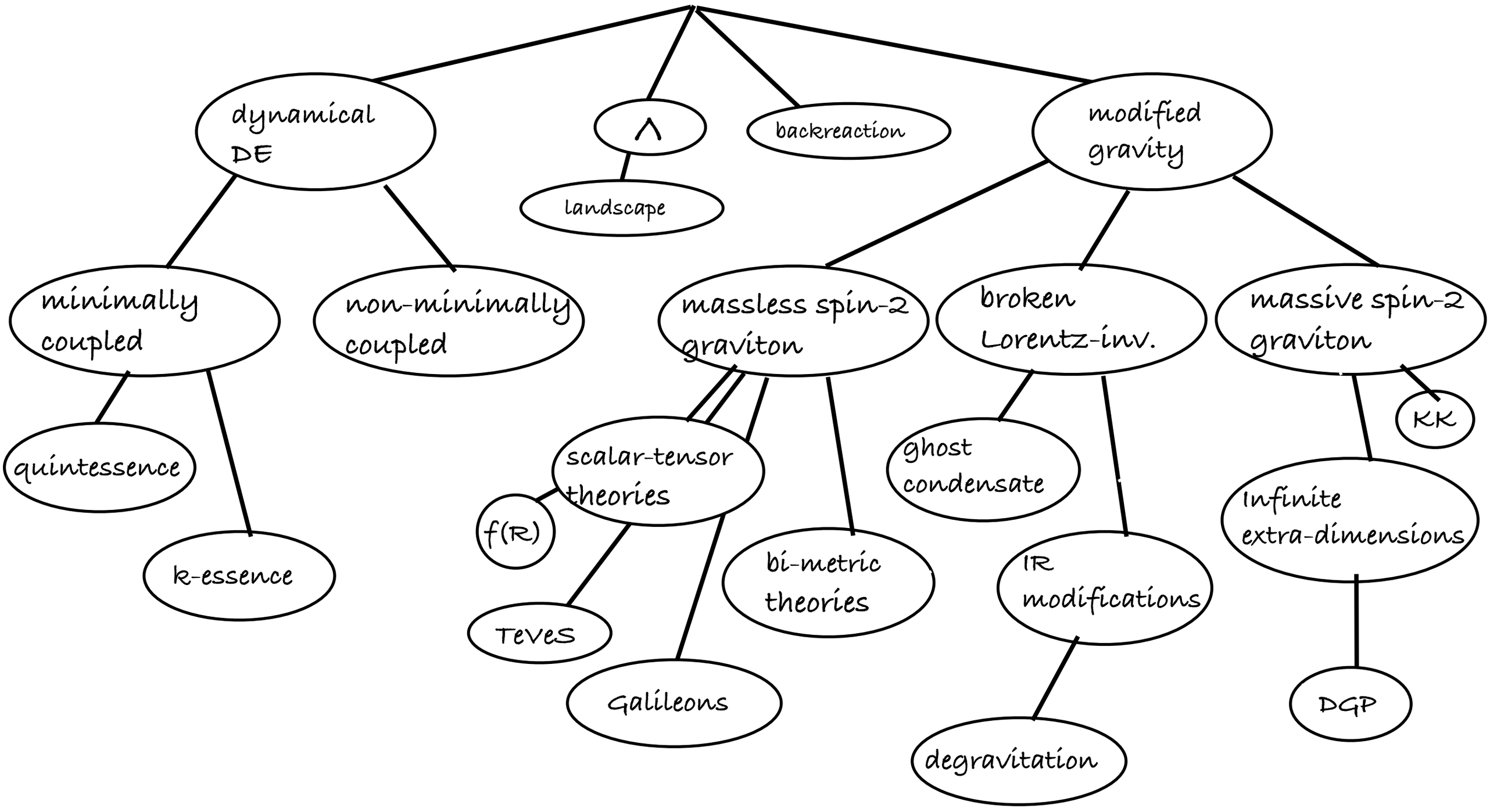
Where do we stand on the theory side?

Beyond LCDM

Where do we stand on the theory side?

How can we optimally explore departures from the LCDM scenario?

The theoretical gravitational landscape



The theoretical gravitational landscape

PARAMETRIZED
FRAMEWORKS

EFT of Dark Energy

A unified action

Jordan frame

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

IN UNITARY GAUGE

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

J. Gleyzes et al., Phys.Rev.Lett. 114 (2015) J. B. Achour et al., JHEP 1612 (2016) 100 R. Kase, S. Tsujikawa, Int.J.Mod.Phys

A unified action

matter follows geodesic of the metric

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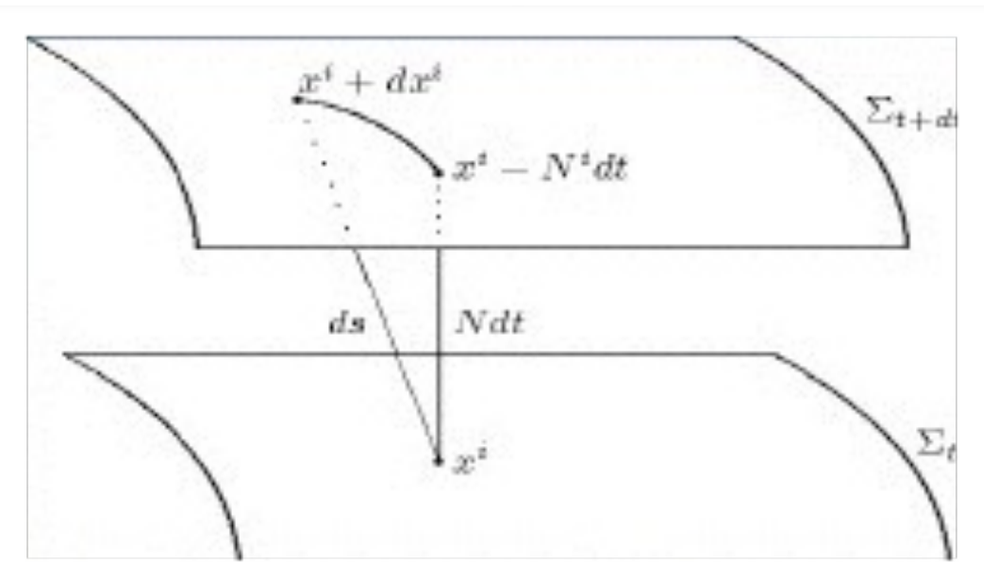
A unified action

The presence of an extra dynamical scalar d.o.f. wrt the standard model of cosmology naturally singles out a preferred foliation of space-time.

It is natural to employ the ADM (Arnowitt-Deser-Misner) decomposition of spacetime:



$$ds^2 = -N^2 dt^2 + h_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$$

lapse function — 3D metric — shift vector

If we define: $n_\mu \equiv N t_{;\mu}$ $\quad h_{\mu\nu} = g_{\mu\nu} + n_\mu n_\nu$

intrinsic curvature: $R^{(3)}_{\mu\nu}$

extrinsic curvature: $K_{\mu\nu} = h^\lambda_\mu n_{\nu;\mu}$ $\quad K_{ij} = \frac{1}{2N}\left(\partial_t h_{ij} - \nabla_i N_j - \nabla_j N_i\right)$

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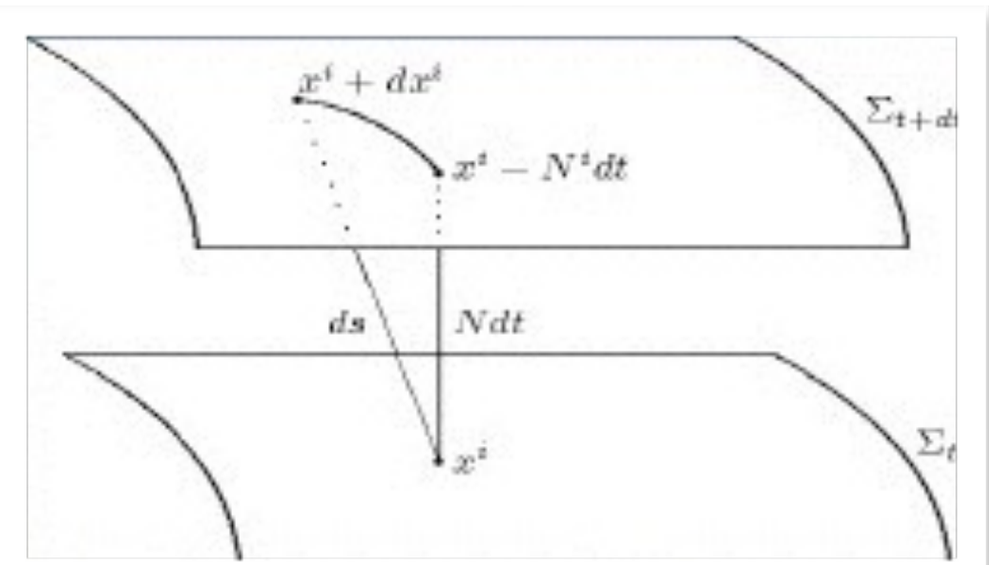

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UNITARY GAUGE $\longrightarrow$ $n_\mu \equiv \frac{\partial_\mu \phi}{\sqrt{(\partial_\mu \phi)^2}}$

And the action is built out of all geometrical quantities that are invariant under the time-dependent 3D spatial diffeomorphisms.

A unified action

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:

$$\left\{\Omega(\tau), \Lambda(\tau), M_2^4(\tau), \bar{M}_1^3(\tau)\bar{M}_2^2(\tau)\right\}$$

mapping EFT:

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

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

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

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

A unified action

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

A unified action

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Quintessence	1/✓	✓	✓	-	-	-	-	-	-
$F(R)$	✓	✓	0	-	-	-	-	-	-
k-essence	1/✓	✓	✓	✓	-	-	-	-	-
Galileon [39] Kinetic Braiding [40]	1/✓	✓	✓	✓	✓	-	-	-	-
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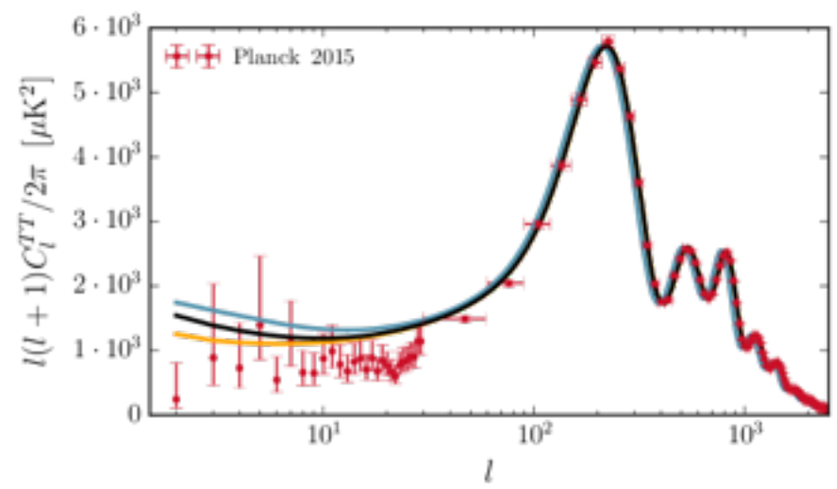
Horndeski [26]	✓	✓	✓	✓	✓	✓†	✓†	✓†	-

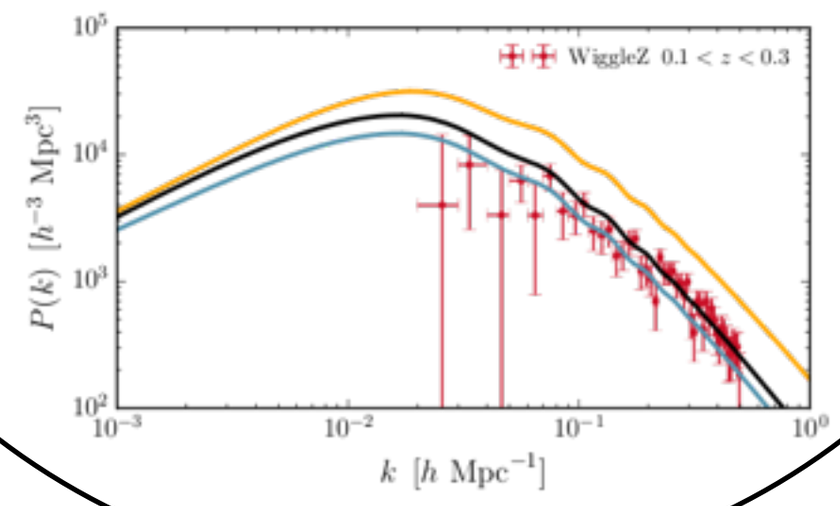
Bloomfield, Flanagan, Park, Watson JCAP 1308 (2013) 010

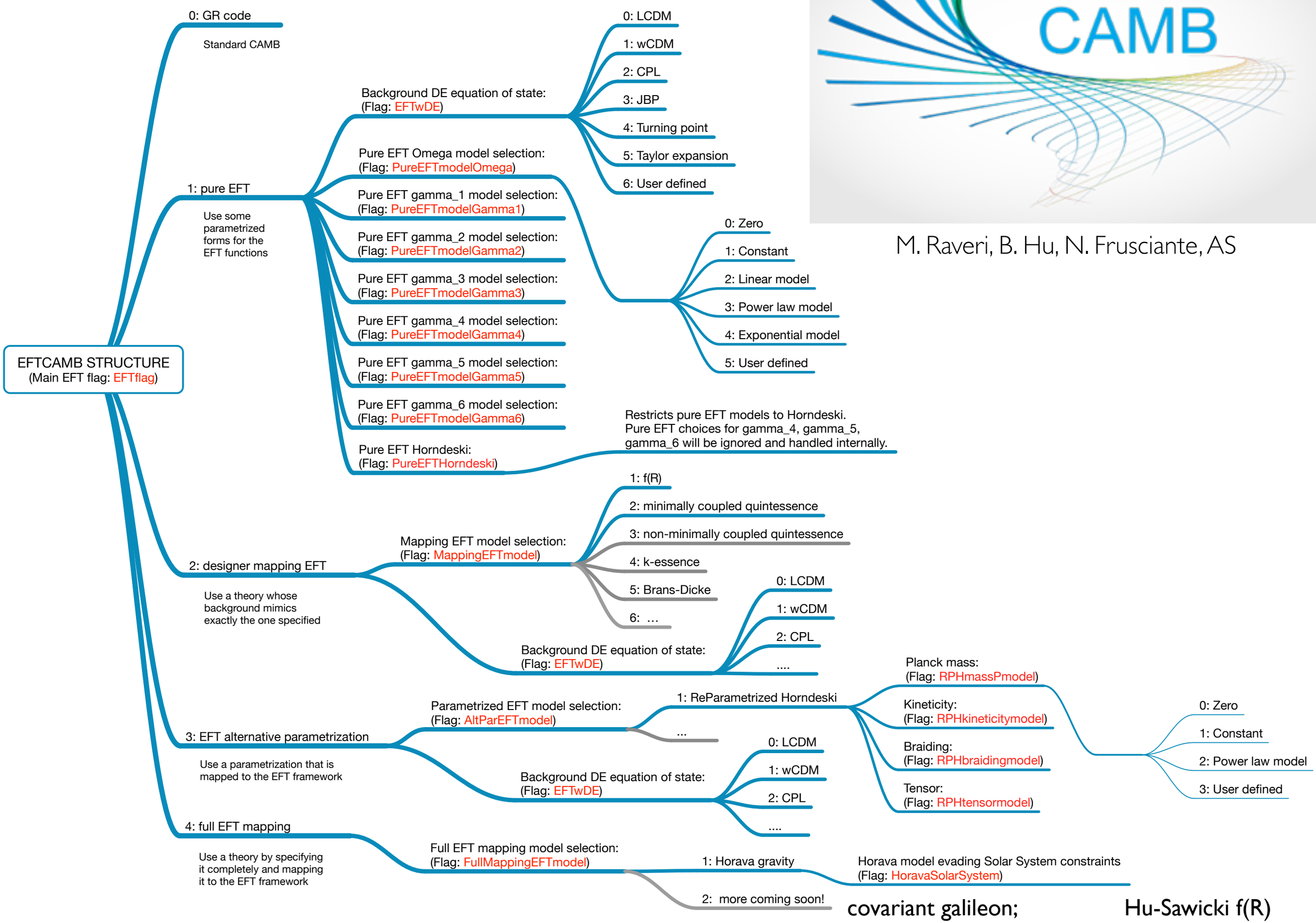
From Theory to Observables

matter and metric perturbations
+
theory

EINSTEIN-BOLTZMANN
SOLVER
e.g. CAMB



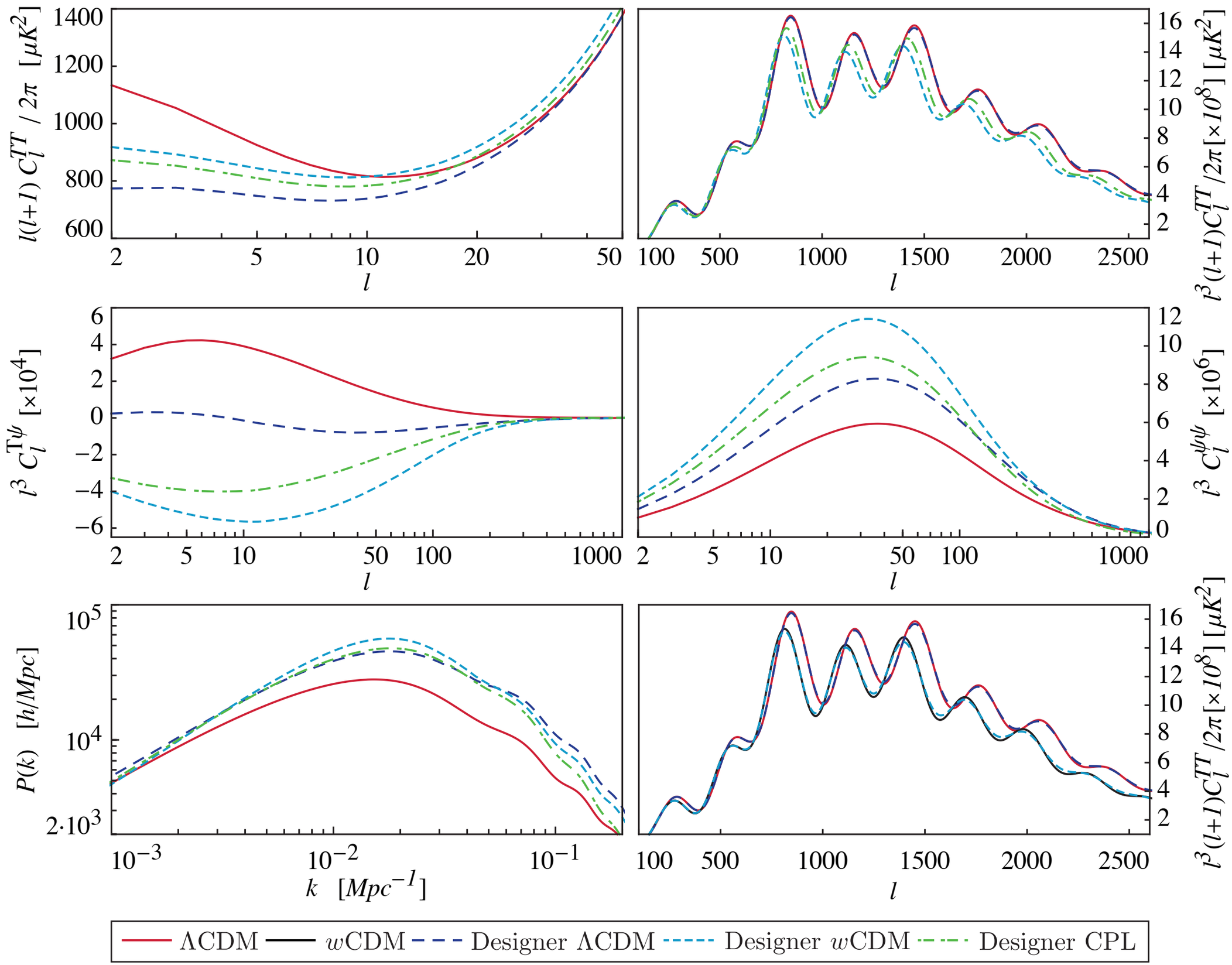


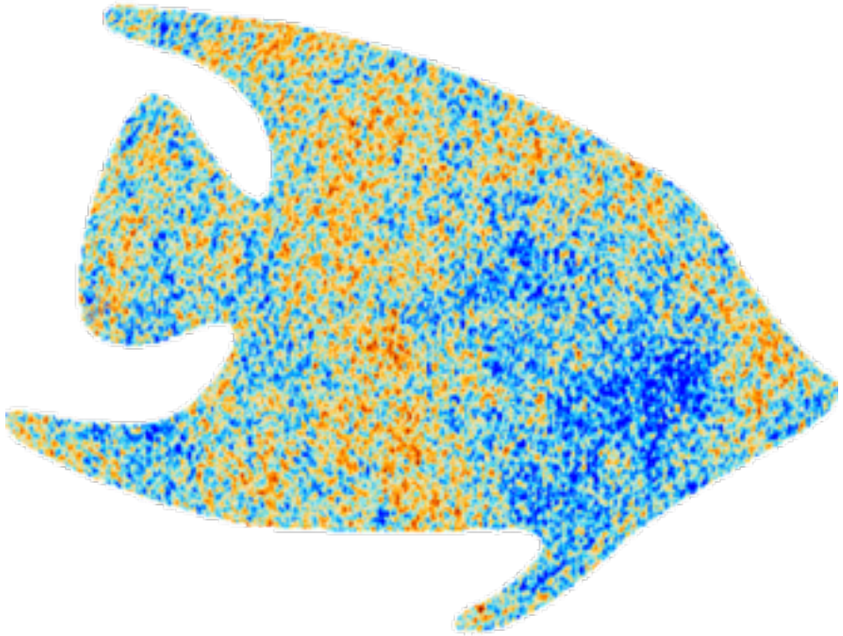


M. Raveri, B. Hu, N. Frusciante, AS

covariant galileon;

Hu-Sawicki f(R)


$l(l+1)\,C_l^{TT}\,/\,2\pi\ \ [\mu K^2]$
l
$l^3(l+1)C_l^{TT}/2\pi[\times 10^8]\ [\mu K^2]$
$l^3\,C_l^{T\psi}\ [\times 10^4]$
$l^3\,C_l^{\psi\psi}\ [\times 10^6]$
$P(k)\ \ [h/Mpc]$
$k\ \ [Mpc^{-1}]$
ΛCDM
wCDM
Designer ΛCDM
Designer wCDM
Designer CPL



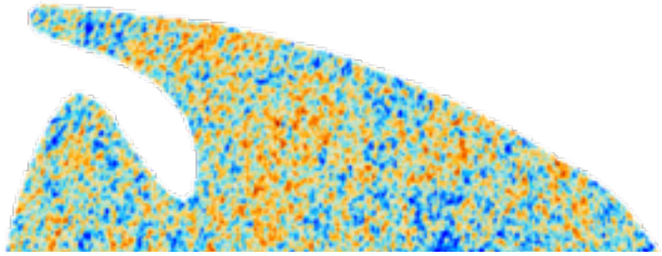
CosmicFish

https://cosmicfish.github.io/

models:
CAMB
MGCAMB
EFTCAMB

observables:
Cosmic Microwave Background
Weak Lensing tomography
Galaxy Clustering
Supernovae
Redshift drift
…

Raveri, Martinelli, Zhao, Wang, arXiv:1606.06273



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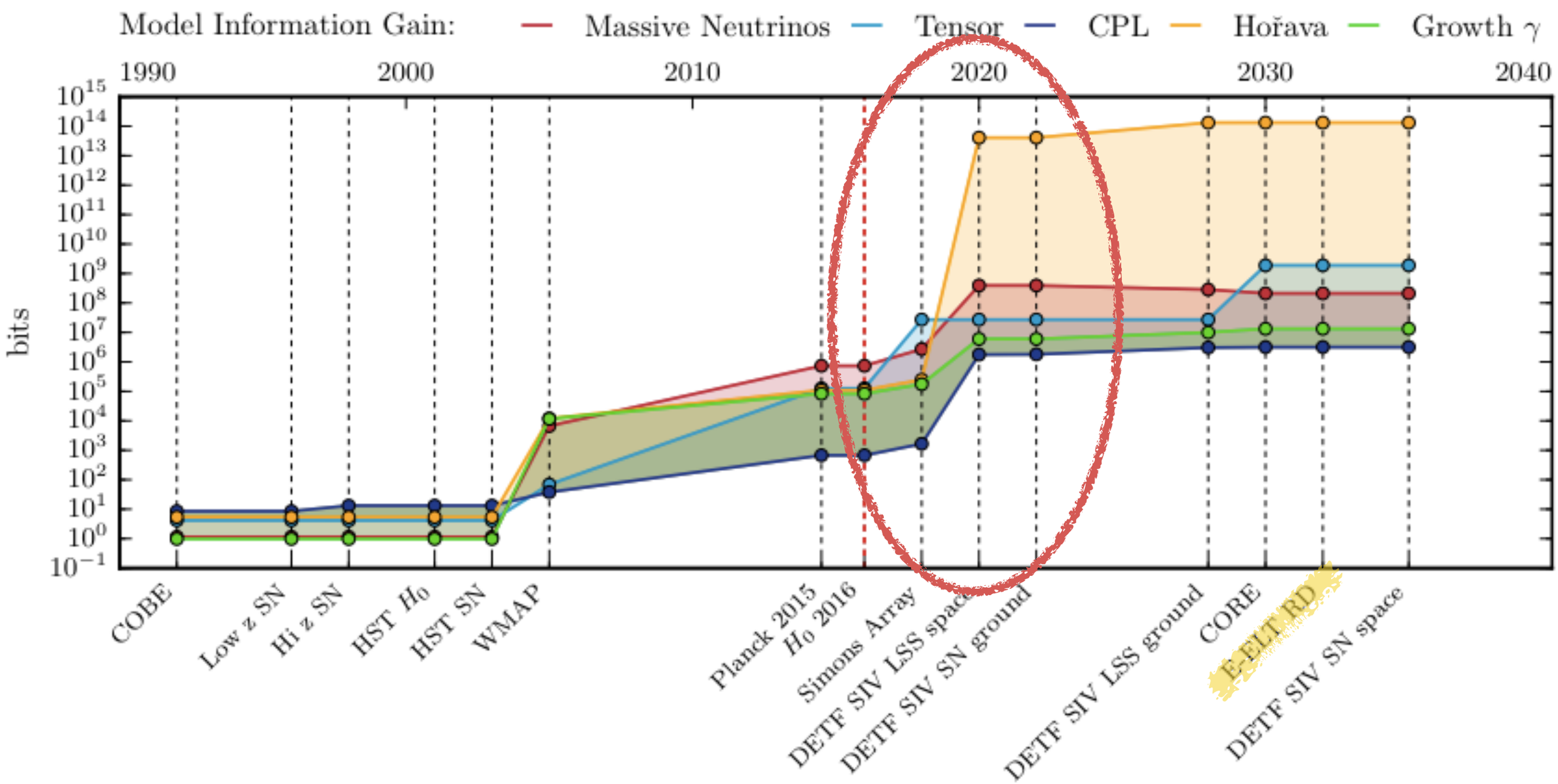


Model cumulative Information Gain

Raveri, Martinelli, Zhao, Wang, arXiv:1606.06273

Redshift drift to access the DE redshift desert

Looking at how the redshift of a source changes over an observed time interval Δt_0:

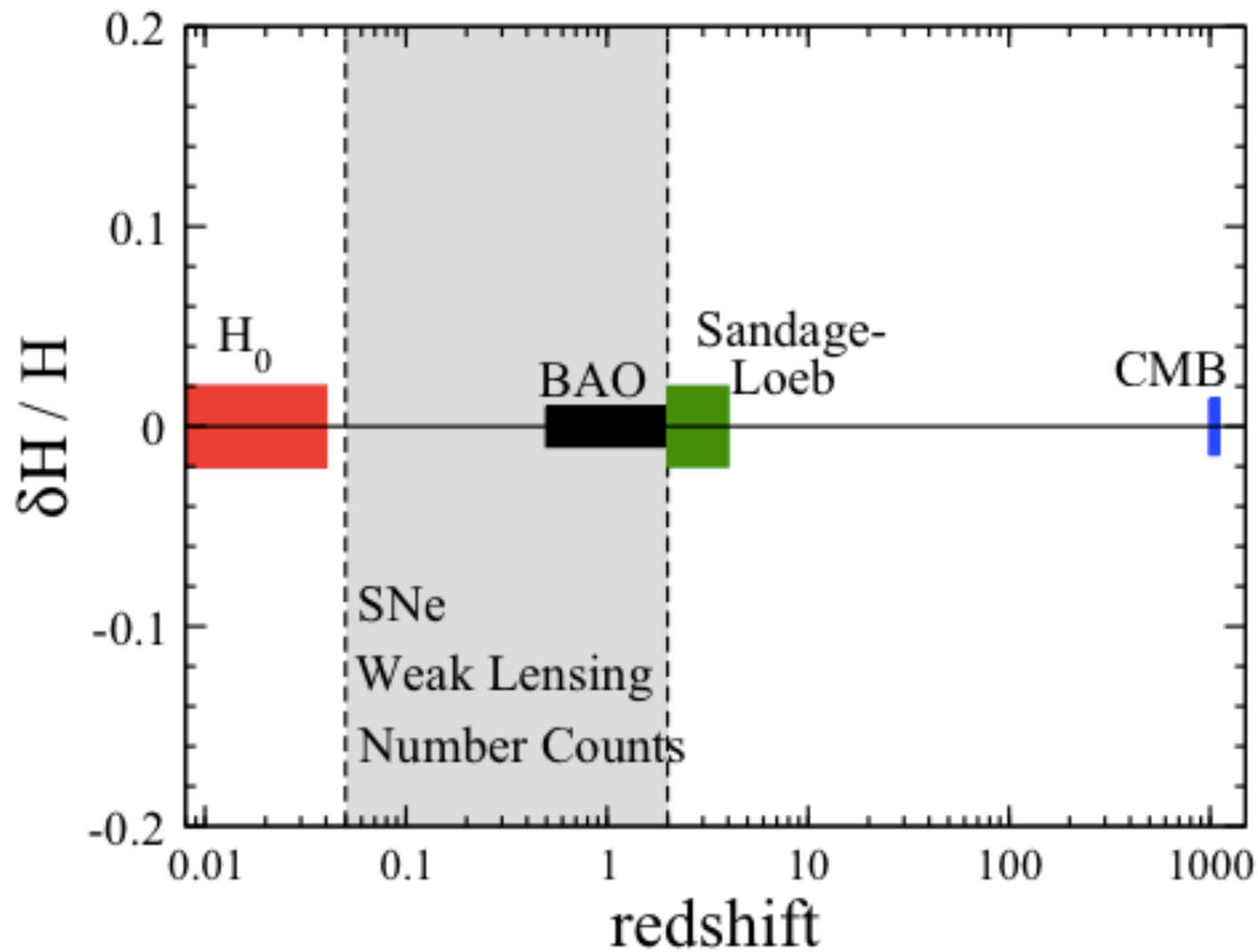
$$\Delta z_s \approx \frac{\dot{a}(t_0) - \dot{a}(t_s)}{a(t_s)} \Delta t_0.$$

This translates into a spectroscopic velocity shift:

$$\Delta v = \frac{c \Delta z_s}{1 + z_s}$$

that can be used to probe H(z):

$$\frac{\Delta v}{c} = H_0 \Delta t \left[1 - \frac{E(z_s)}{1 + z_s} \right]$$

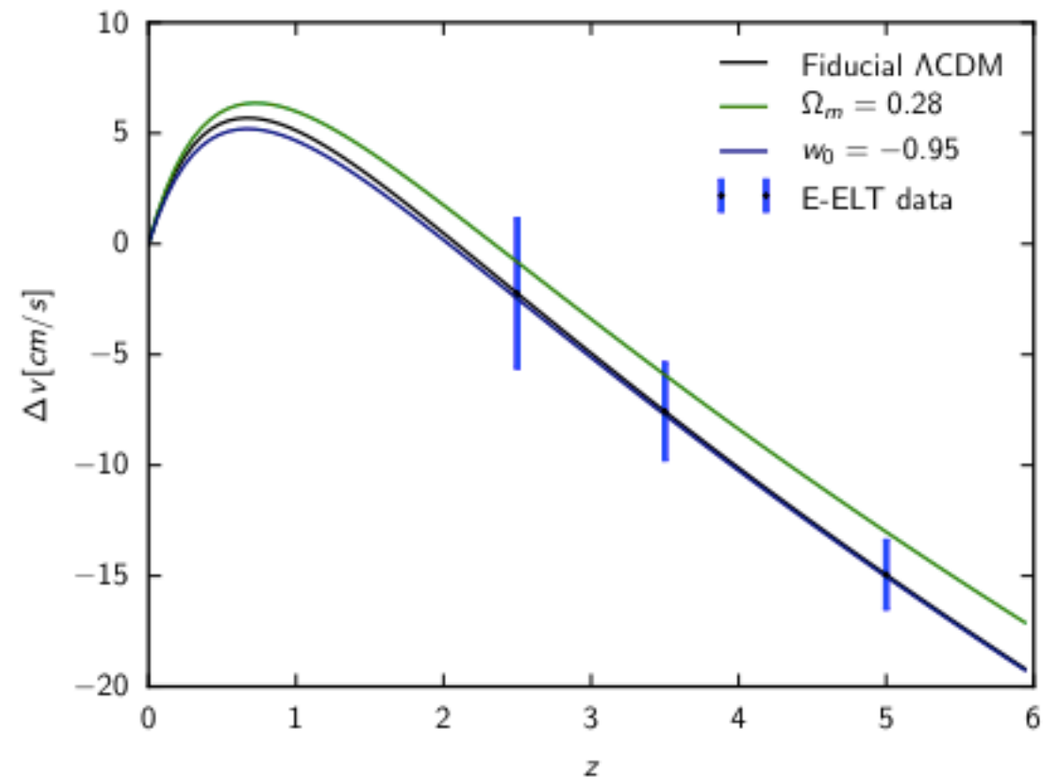


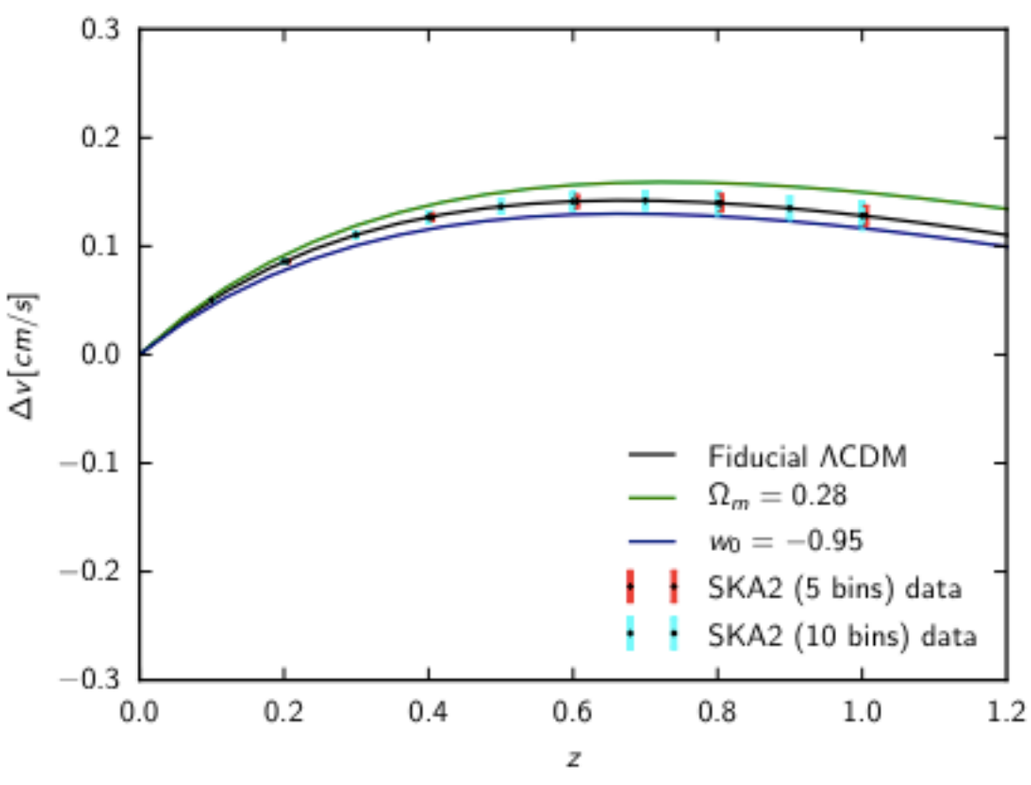
Corasaniti, Huterer, Melchiorri, PRD 2007

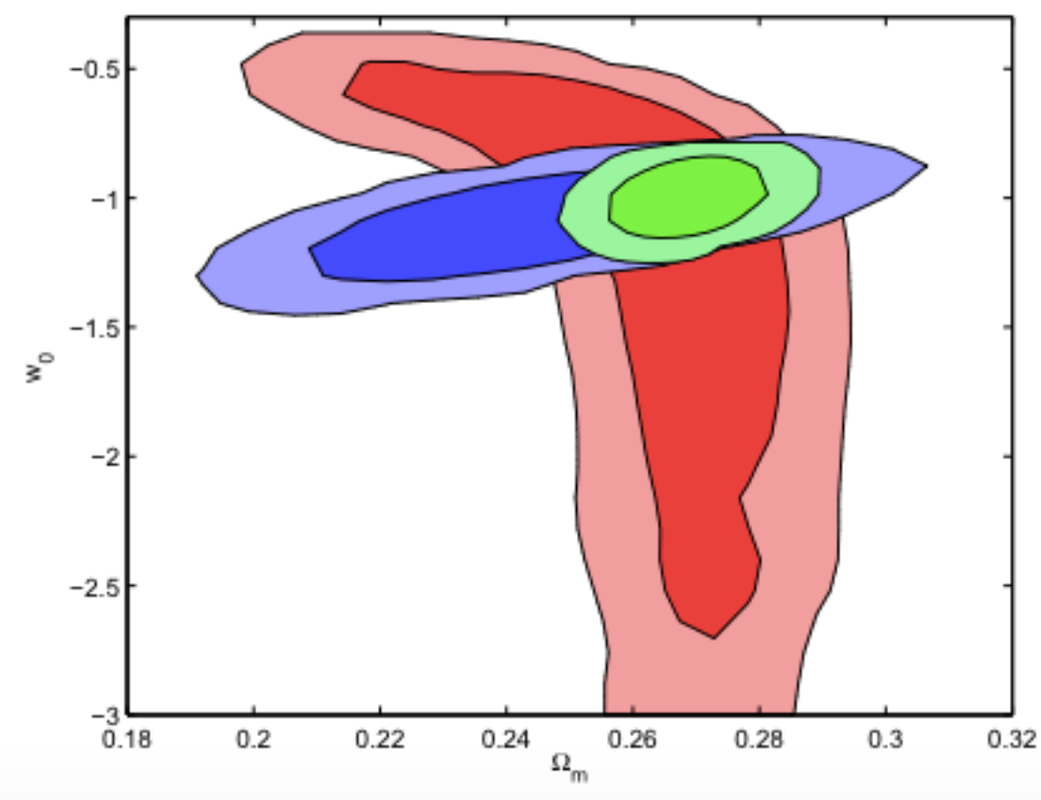
It is becoming real! Some forecasts

Upcoming experiments such as the E-ELT and SKA will achieve, through different means, high enough spectroscopic sensitivity to measure this velocity shift.

The E-ELT's high-resolution optical spectrograph will be able to measure the shift in the spectroscopic velocity, observing the Lyman α absorption lines of distant quasar systems, in a redshift range 2 < z < 5.







Martinelli et al., PRD86 (2012), Martins et al., PRD94 (2016)

Theoretical priors

Since we start from an action, we can identify general, model-independent viability conditions that are well motivated theoretically and ensure also numerical stability.

This can significantly restrict the parameter space, and represents a powerful tool for the advocated open-minded approach to cosmological tests of GR.

The world is beautiful outside only if it is stable inside.

Theoretical priors

Expanding the given action up to second order in the perturbations, and removing spurious DOFs, we can inspect the dynamics of perturbations; in this case one scalar field, i.e. ξ, and the tensor:

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

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

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

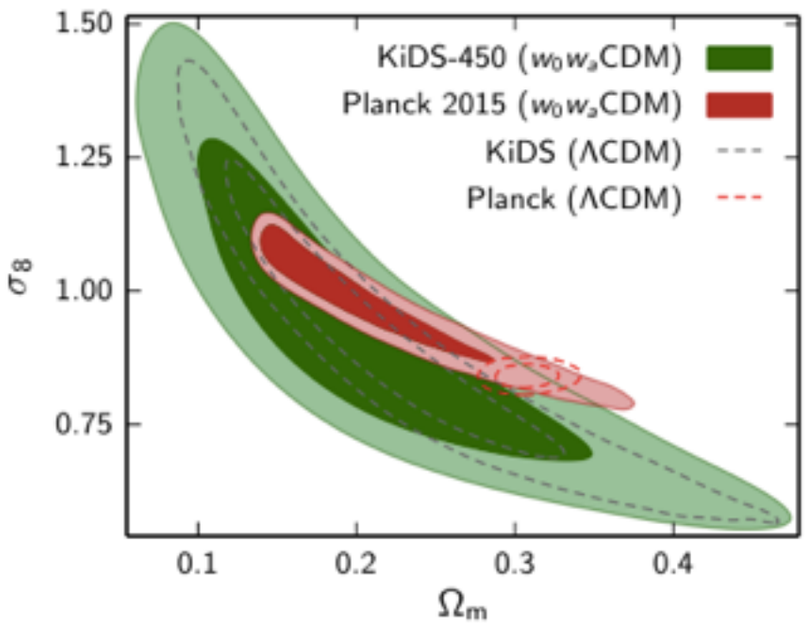
$\Rightarrow$ very general conditions in terms of the EFT functions, that constitute a stability check to be run at the very beginning!

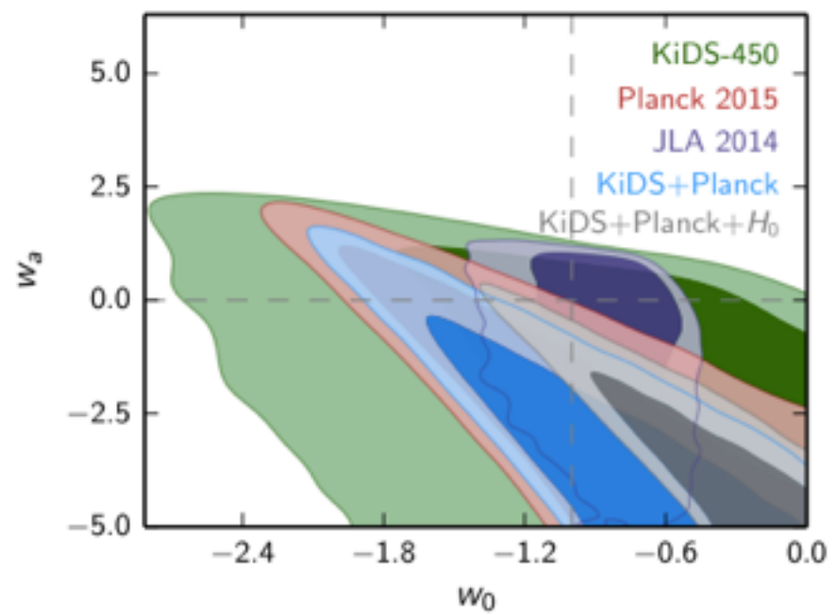
Frusciante, Papadomanolakis, AS JCAP 1607 (2016).

De Felice et al., JCAP 1703 (2017); J. Gleyzes et al., Int.J.Mod.Phys. D23 (2015); R. Kase, S. Tsujikawa, Int.J.Mod.Phys. D23 (2015)

Theoretical priors & Observational Constraints

CPL DE: $w = w_0 + w_a(1-a)$





Joudaki et al., arXiv:1610.04606

Theoretical priors & Observational Constraints

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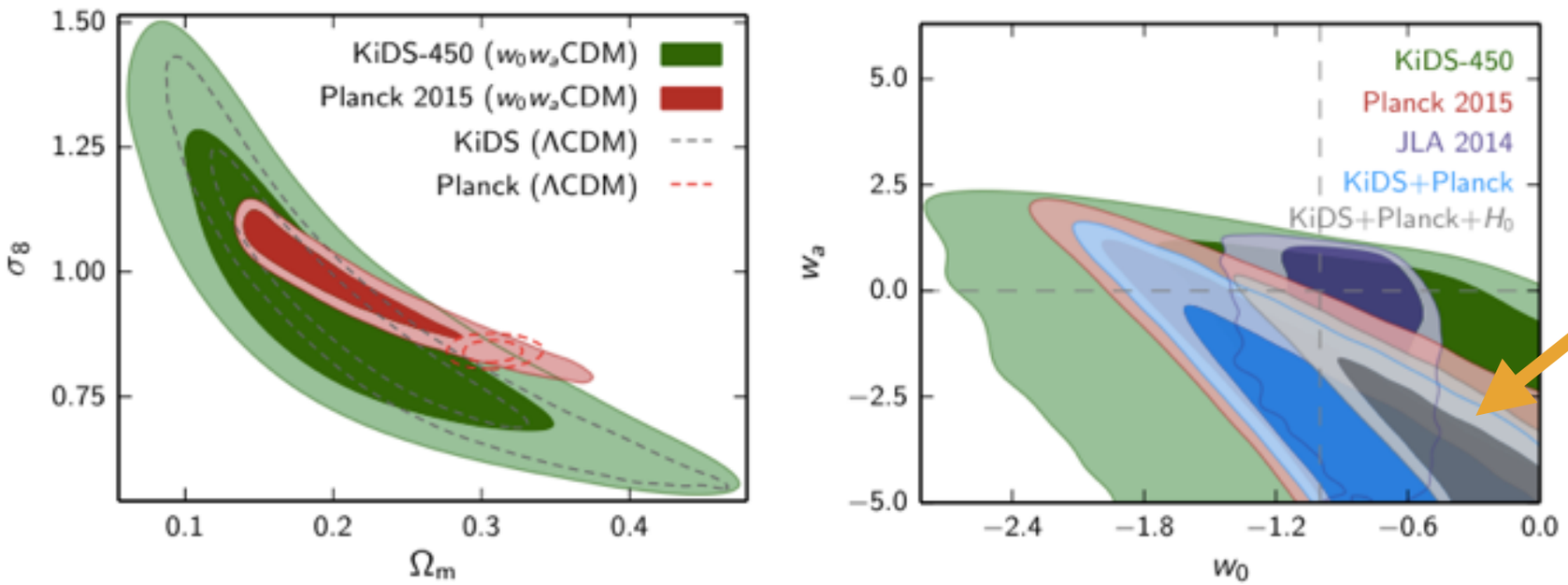
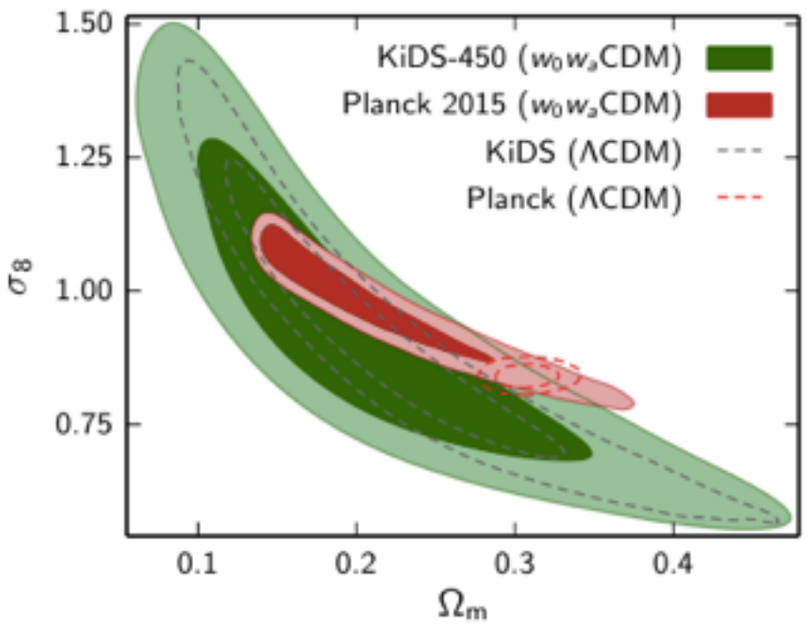


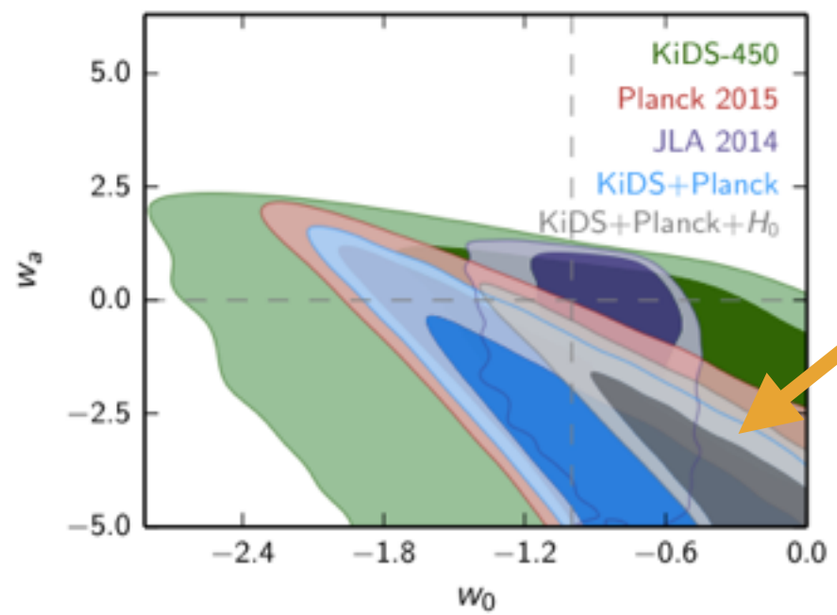
WHICH DE IS IT?

Joudaki et al., arXiv:1610.04606

Theoretical priors & Observational Constraints

CPL DE: $w = w_0 + w_a(1-a)$



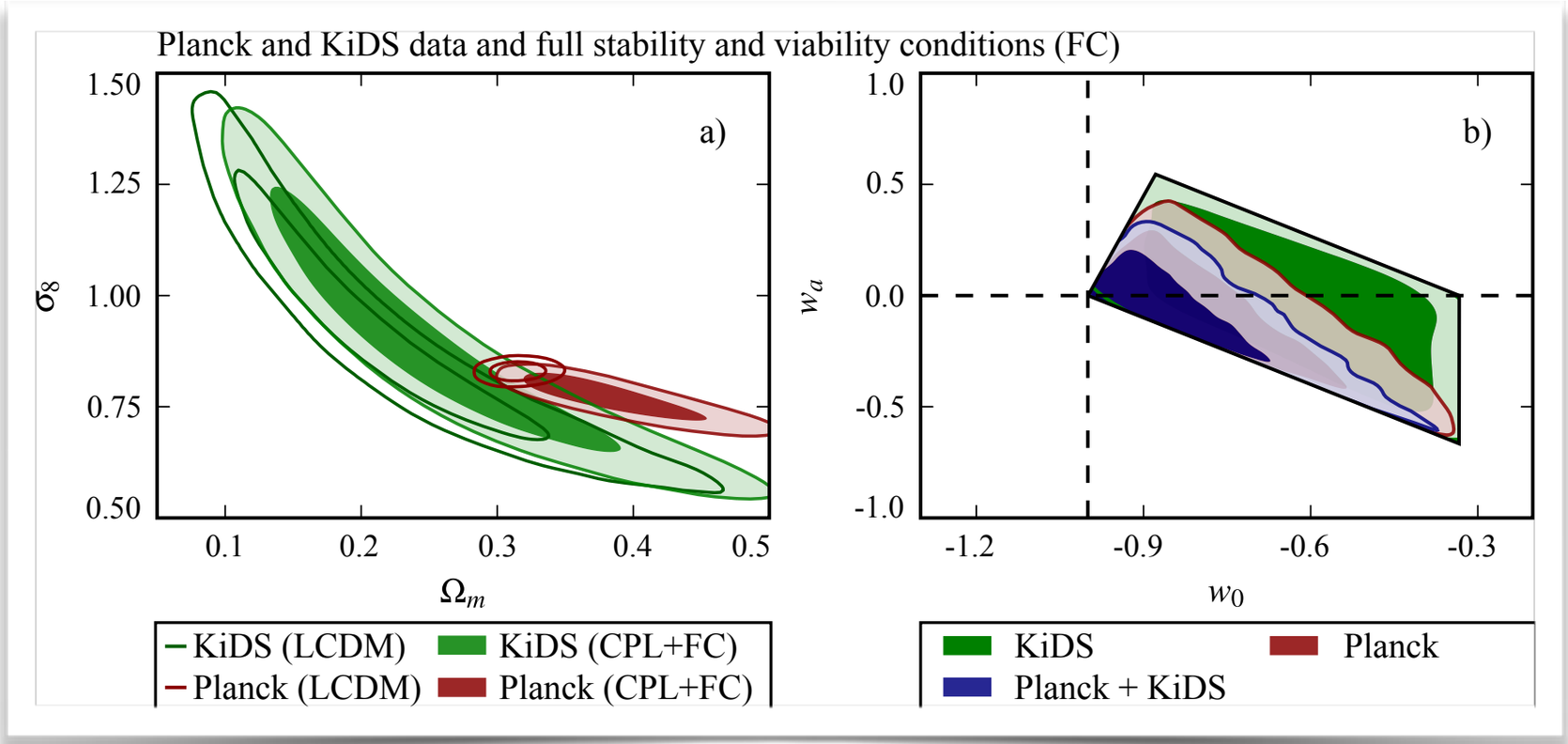


WHICH DE IS IT?

Joudaki et al., arXiv:1610.04606

A stable Horndeski model will not give you that expansion!

Multifield scenarios shall be invoked…



Peirone et al., PRD (2017)

Horndeski theoretical priors …

HORNDESKI gravity → $\{\Omega(a), \Lambda(a), M_2^4(a), \bar{M}_1^3(a), \bar{M}_2^2(a)\}$

$$f(a) = \sum_{n=0}^{N} \frac{\alpha_n}{n!}(a - a_0)^n$$

$$f(a) = \sum_{n=0}^{N} \alpha_n (a - a_0)^n$$

$$f(a) = \frac{\sum_{n=0}^{N} \alpha_n (a - a_0)^n}{1 + \sum_{m=1}^{M} \beta_m (a - a_0)^m}$$

$a_0 = 0, 1$

$\alpha_n, \beta_m \, \epsilon [-1, 1]$

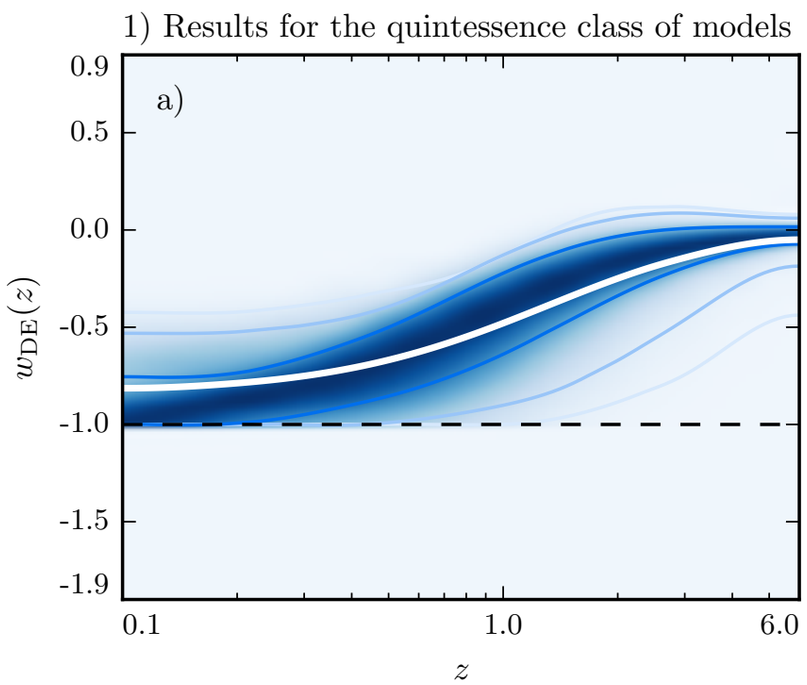
$M, N = 9$

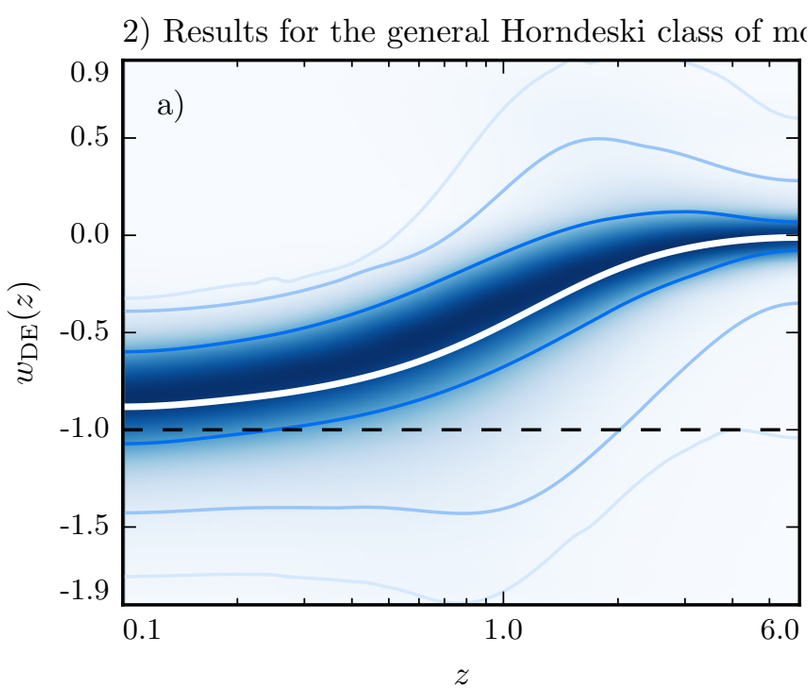
$O(10^8)$ **models!**

Raveri, Bull, AS, Pogosian, PRD 2017

… on DE equation of state

$$\mathcal{H}(a) \to w(a) = \frac{\rho_{\rm DE}}{p_{\rm DE}}$$





Raveri, Bull, AS, Pogosian, PRD 2017

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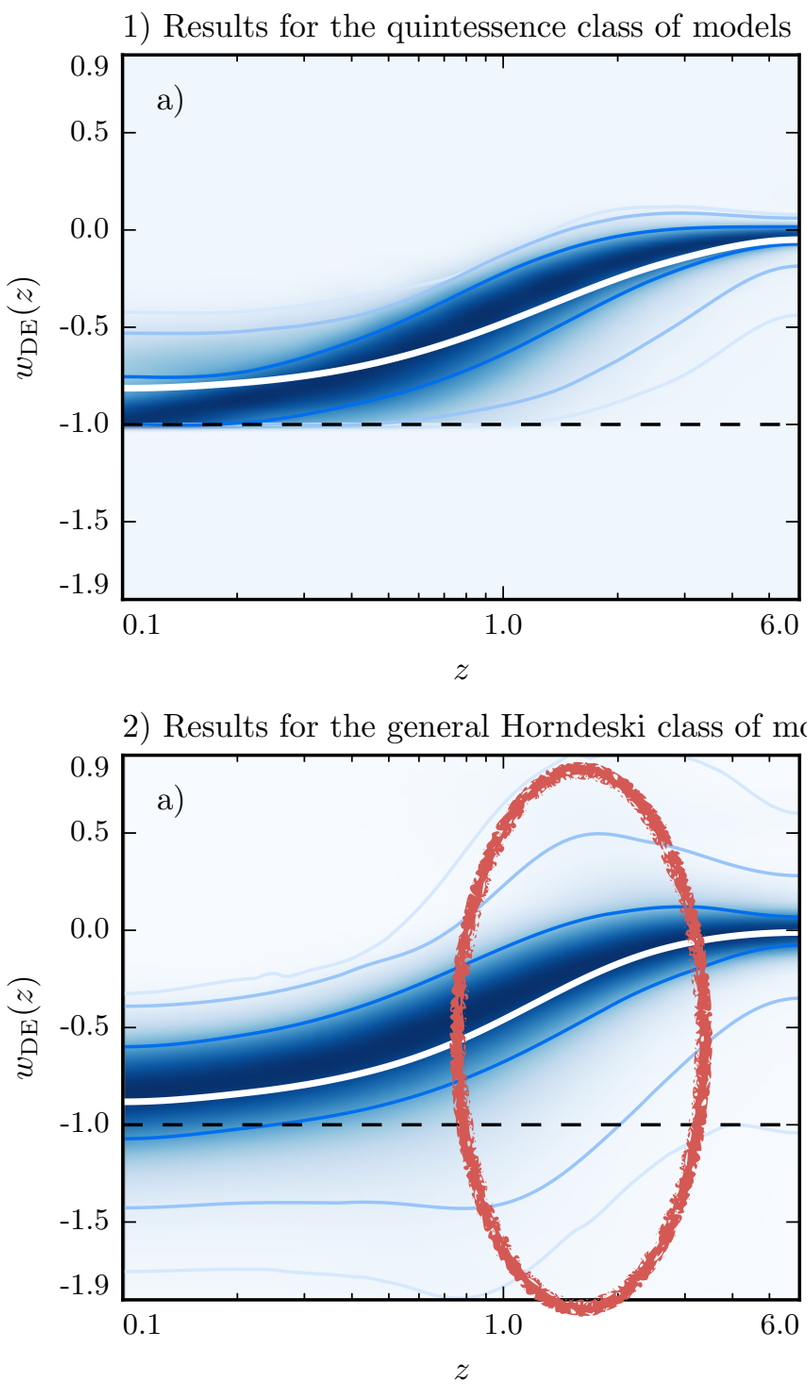
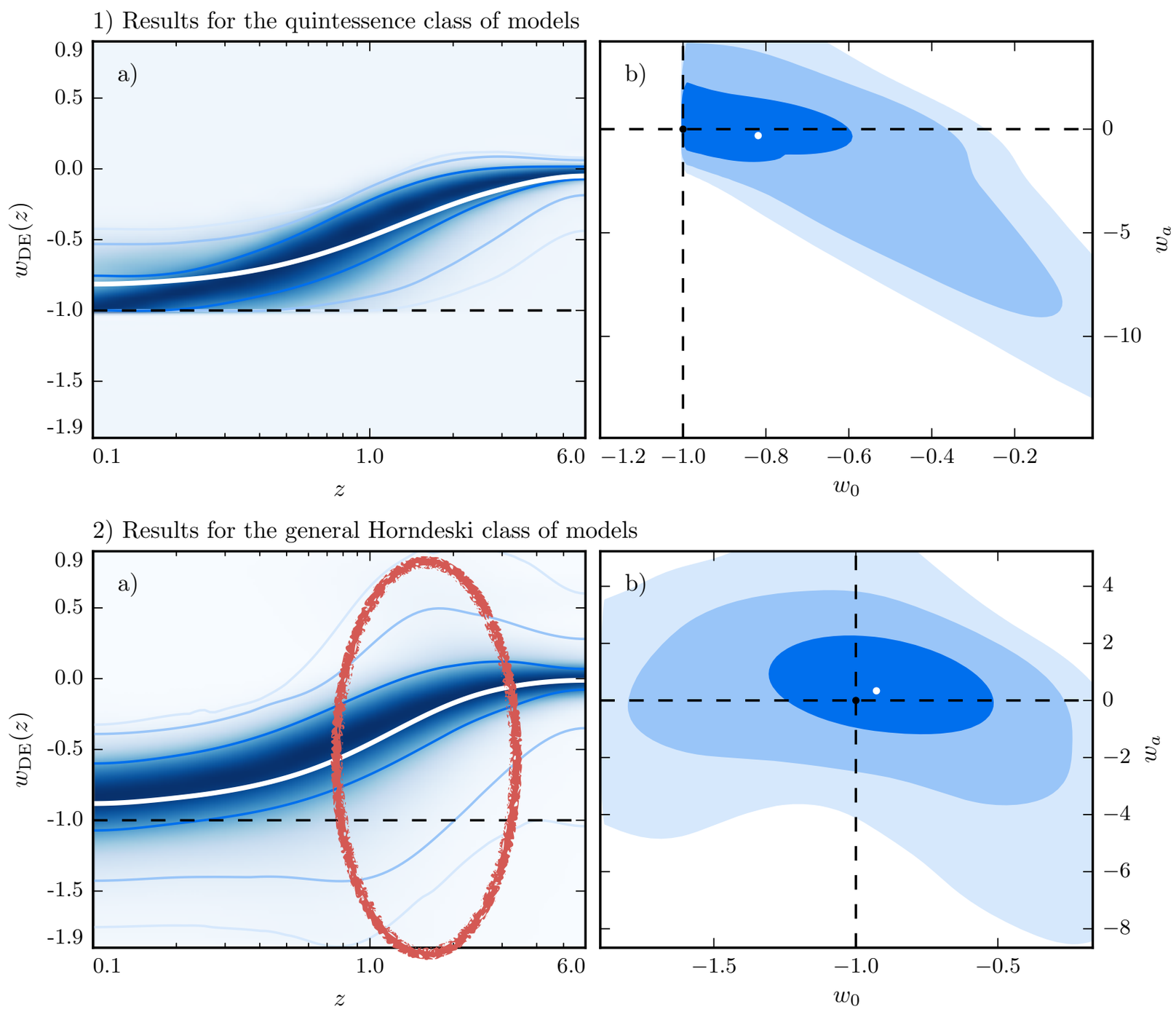


Raveri, Bull, AS, Pogosian, PRD 2017

… on DE equation of state

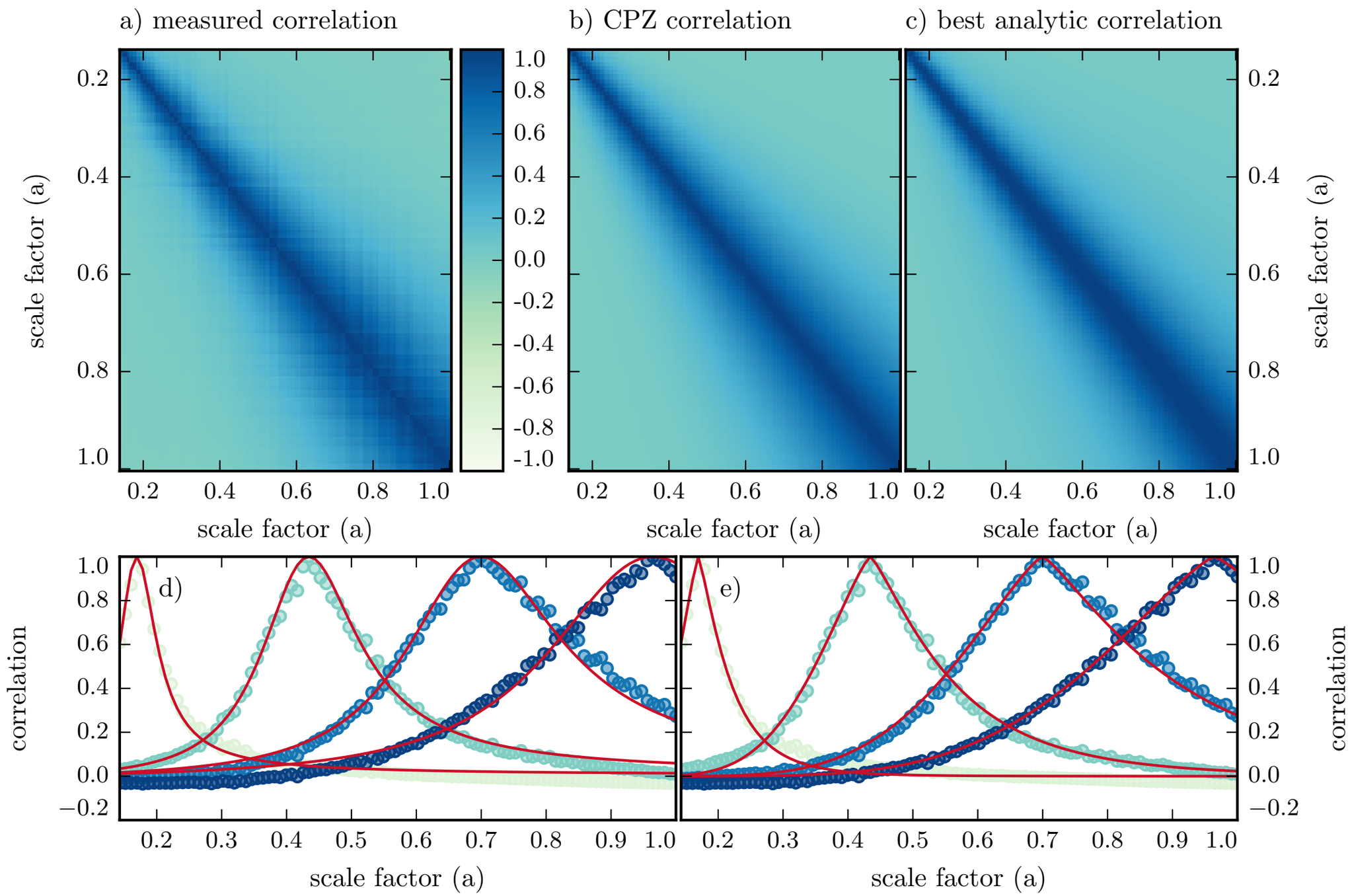
$$\mathcal{H}(a) \to w(a) = \frac{\rho_{\rm DE}}{p_{\rm DE}} \qquad w(a) = w_0 + w_a(1-a)$$



Raveri, Bull, AS, Pogosian, PRD 2017

Towards correlation priors for non-parametric reconstructions

Horndeski gravity

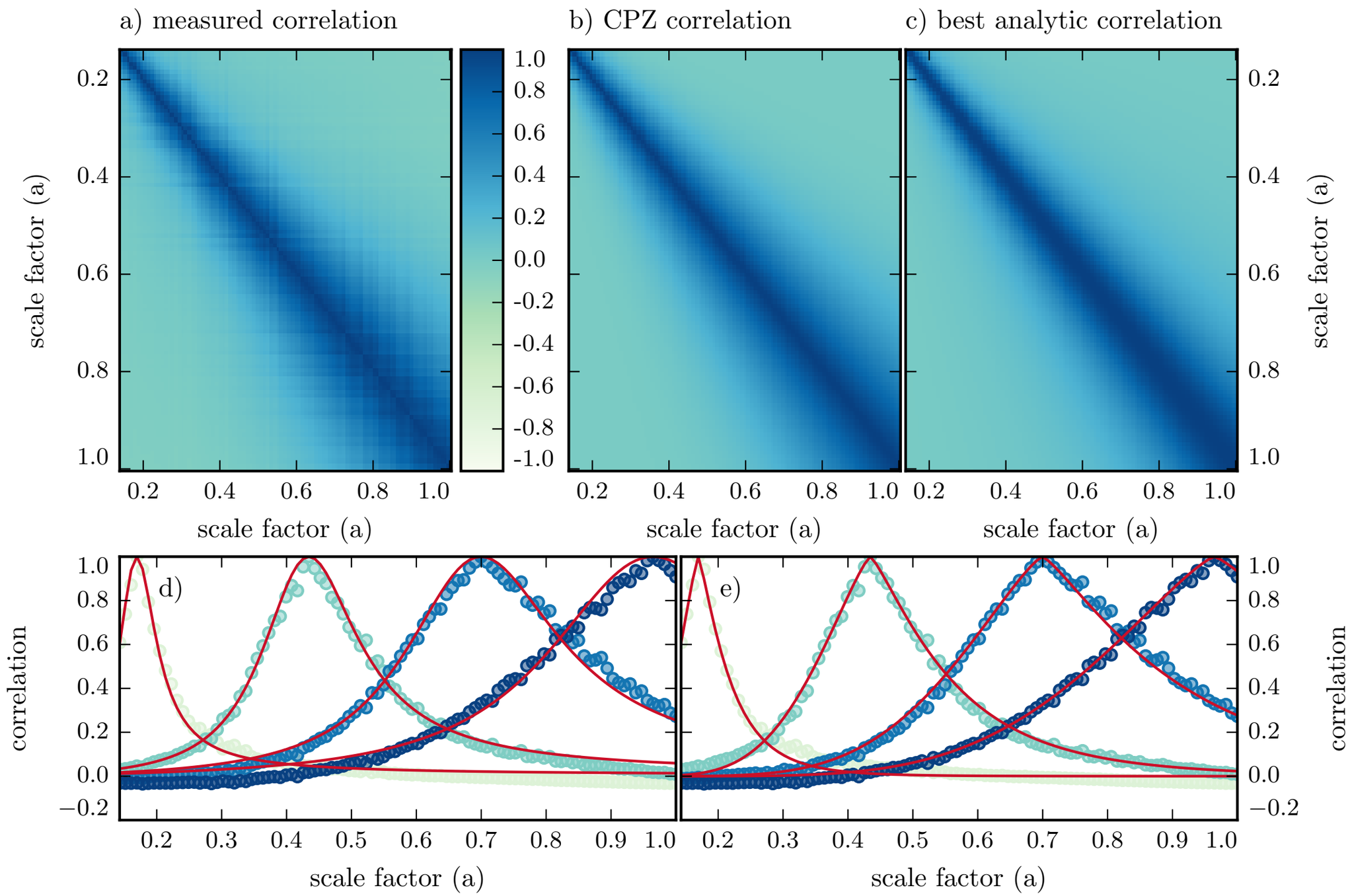


correlation of w at a single scale factor against all other scale factors

Raveri, Bull, AS, Pogosian, PRD 2017

Towards correlation priors for non-parametric reconstructions

Horndeski gravity

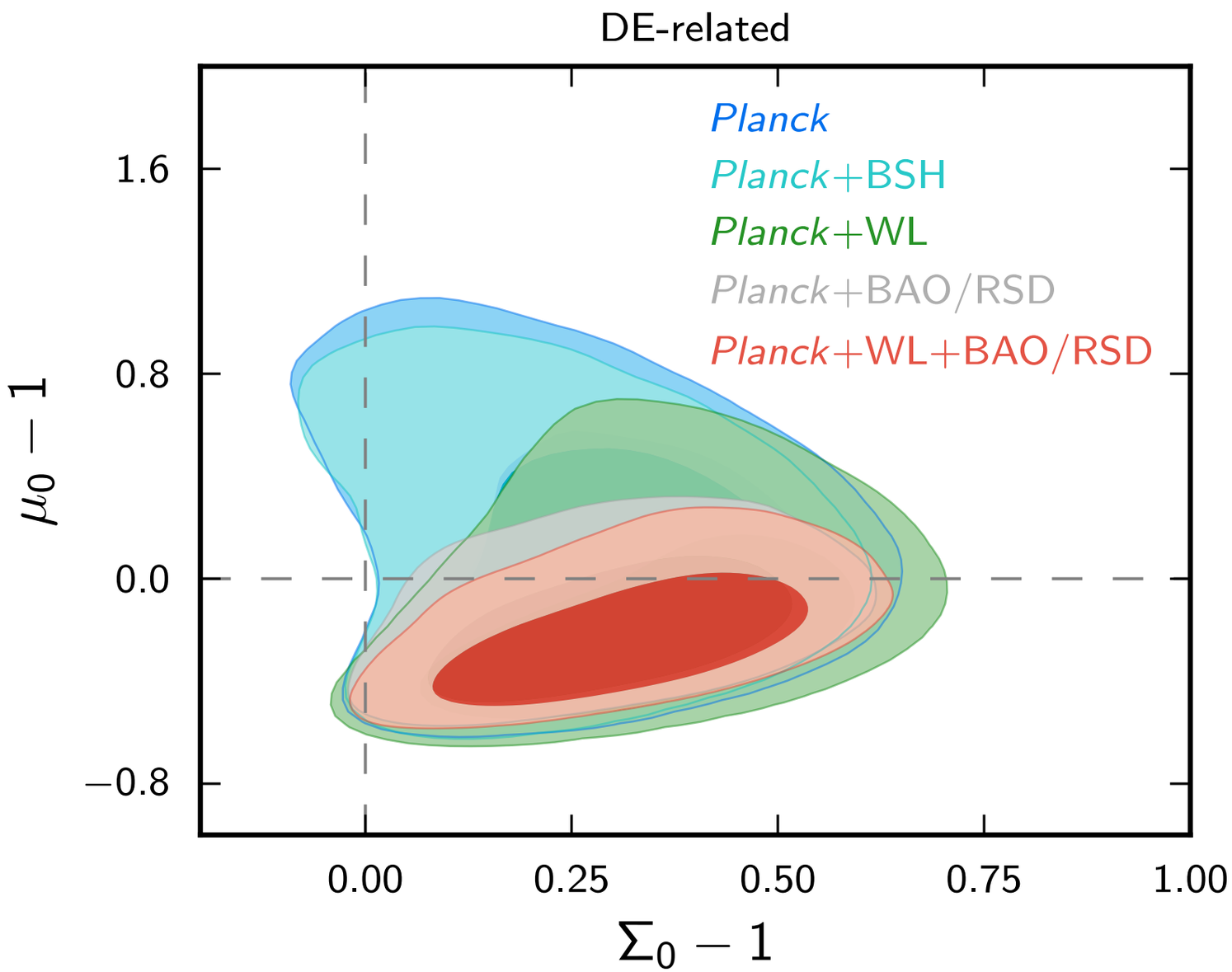


correlation of w at a single scale factor against all other scale factors

Raveri, Bull, AS, Pogosian, PRD 2017

… and on Large Scale Structure

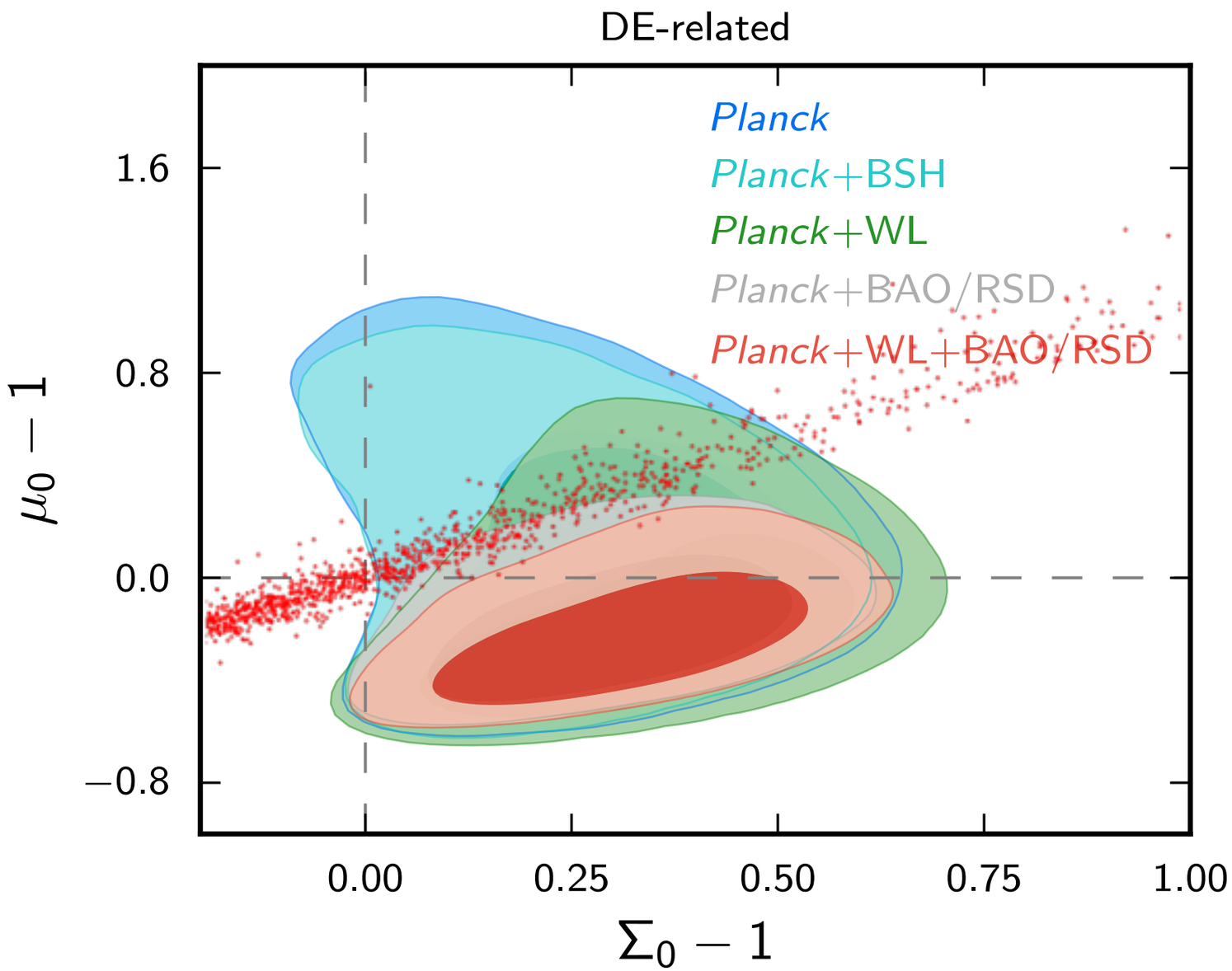
Constraining Horndeski gravity with Σ and μ



Planck 2015 Results. XIV. DE/MG, Astron. Astrophys. 594 (2016)

… and on Large Scale Structure

Constraining Horndeski gravity with Σ and μ



Planck 2015 Results. XIV. DE/MG, Astron. Astrophys. 594 (2016)

… and on Large Scale Structure

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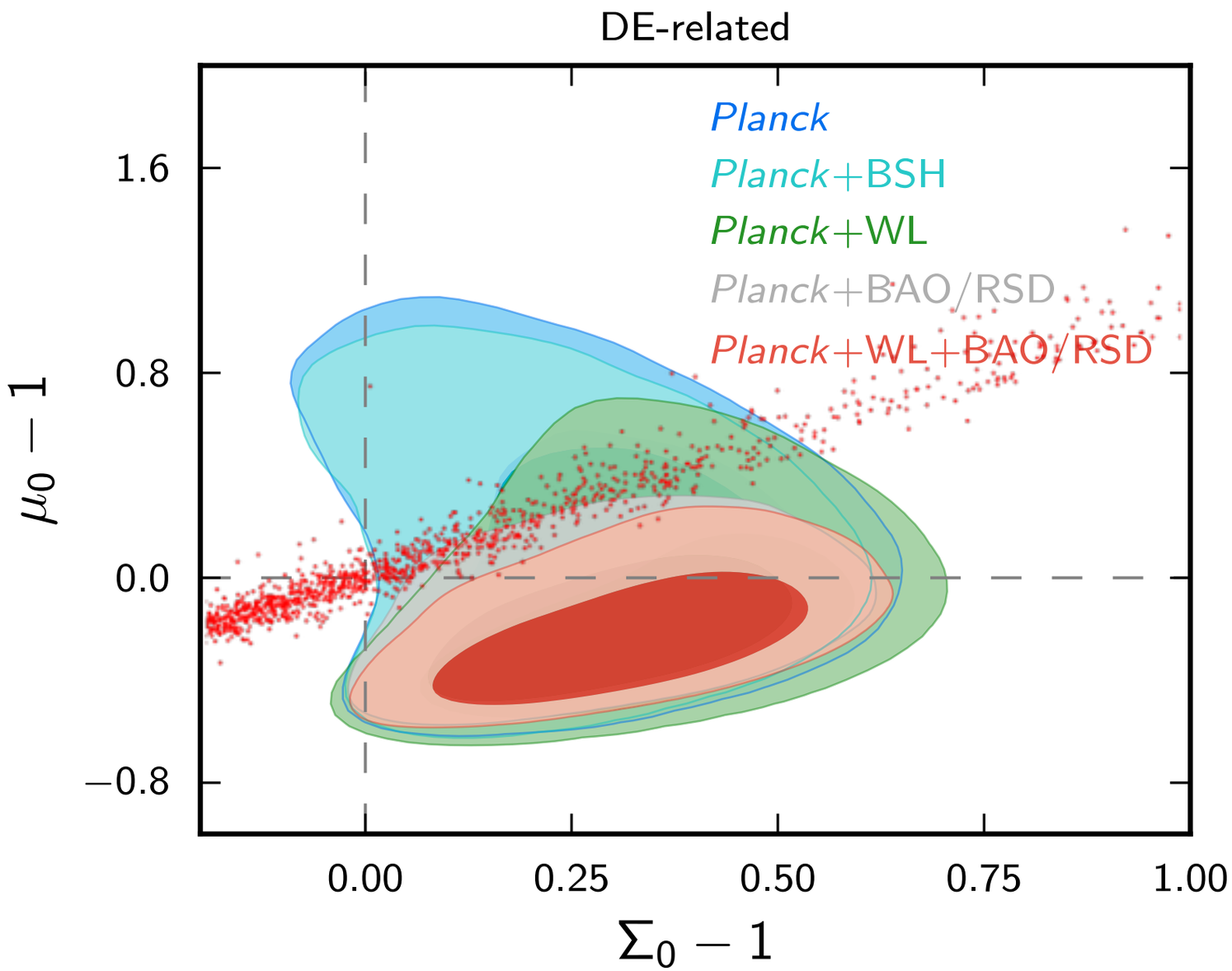
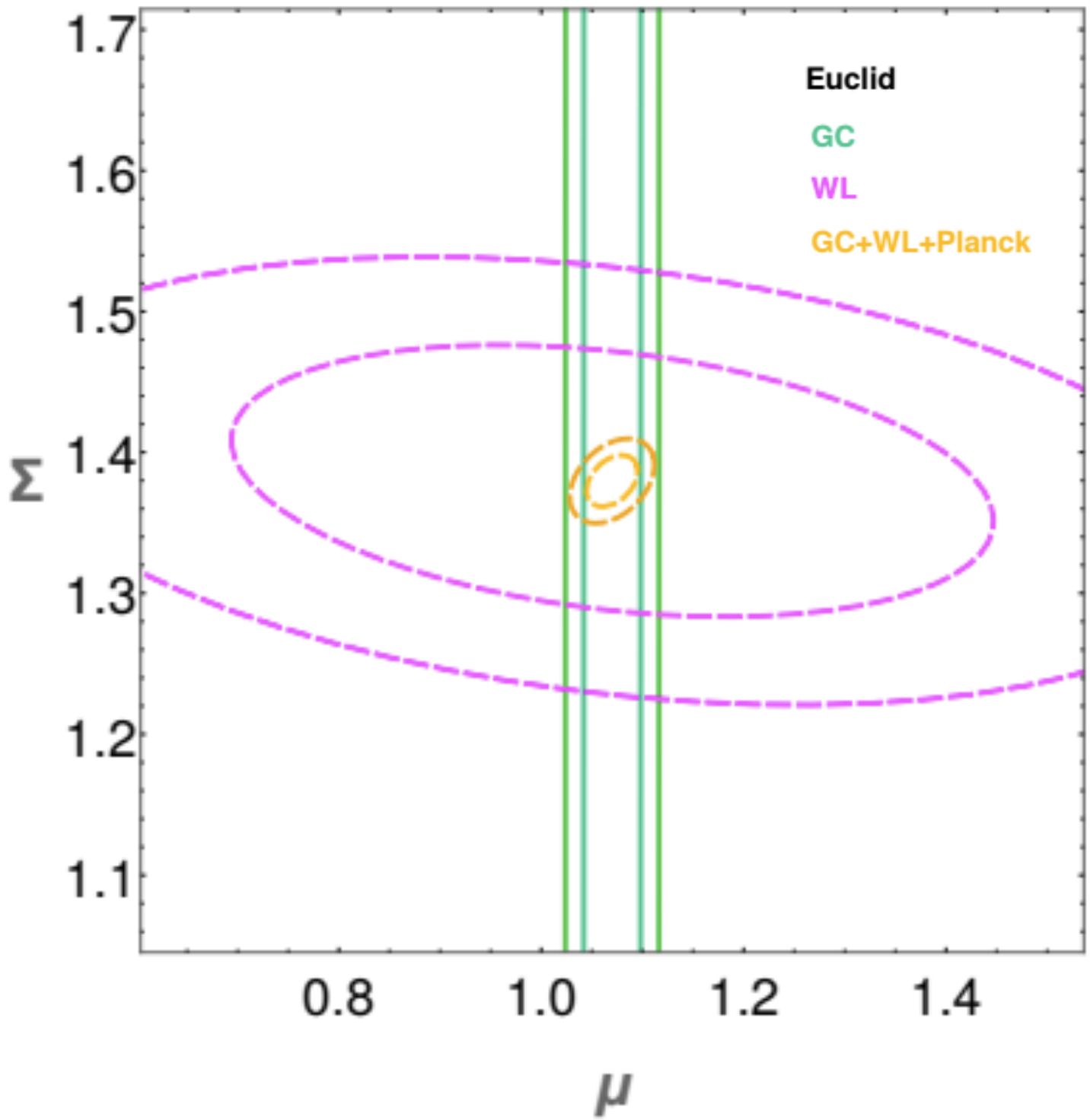


Planck 2015 Results. XIV. DE/MG, Astron. Astrophys. 594 (2016)

FOM will increase by 2-3 orders of magnitude!

… and on Large Scale Structure

Constraining Horndeski gravity with Σ and μ



Santiago et al., Phys. Dark Univ. 2017

The framework: (μ,Σ)

Let us focus on linear scalar perturbations, described in Newtonian gauge by:

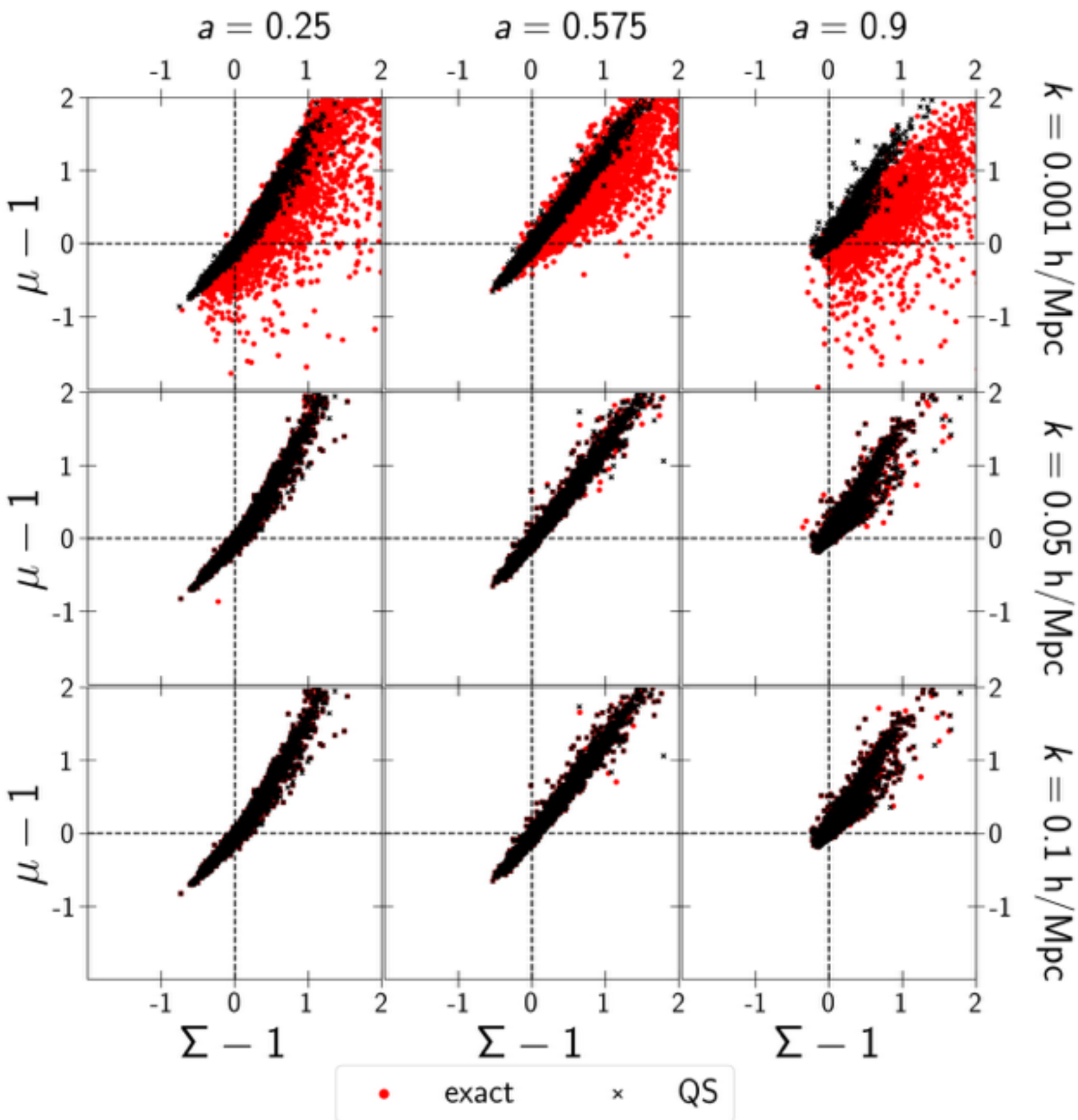
$$\boxed{ds^2 = -a^2(\tau)\left[(1+2\Psi(\tau,\vec{x}))\,d\tau^2 - (1-2\Phi(\tau,\vec{x}))\,d\vec{x}^2\right]}$$

In a quite general manner, we can describe any deviation from LCDM in terms of two functions of time and scale:

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

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

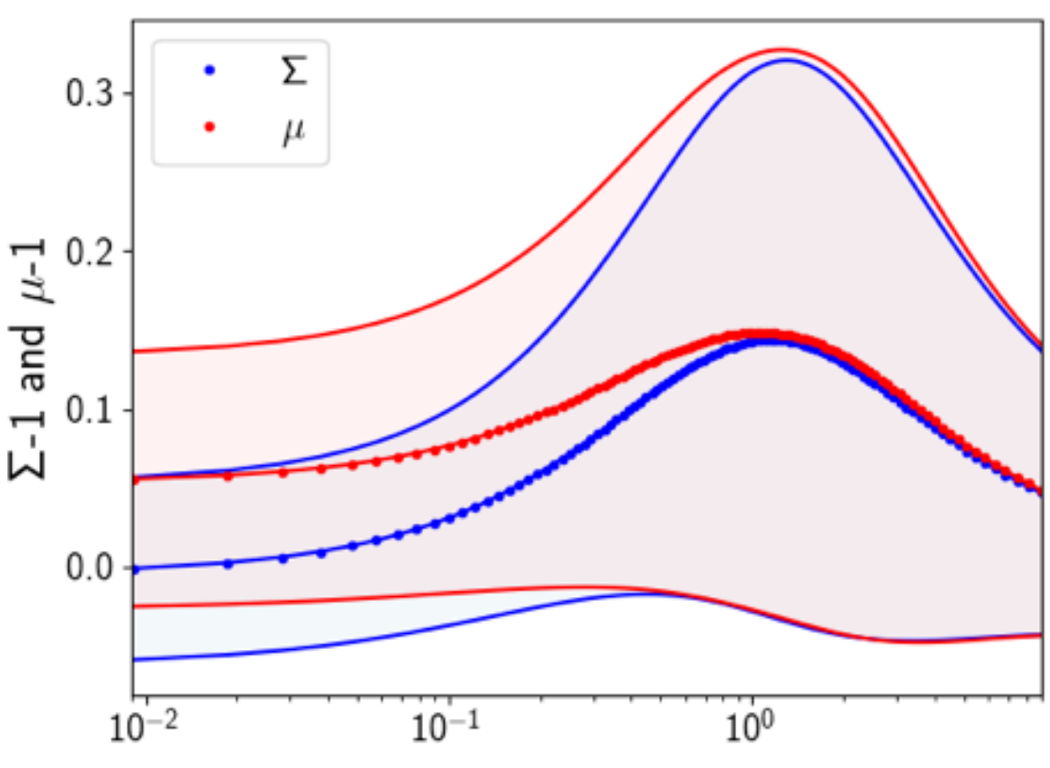
(μ,Σ) in Horndeski



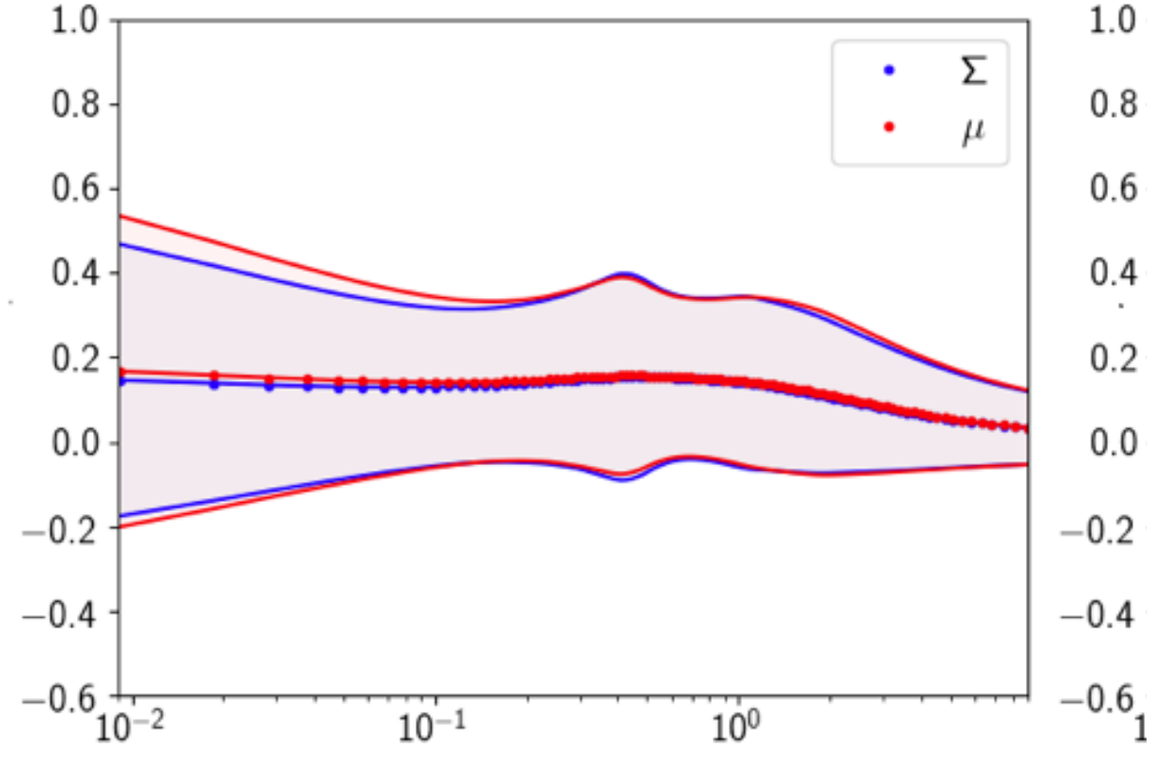
Peirone, Raveri, Pogosian, AS, Koyama, PRD 2018

(μ,Σ) theoretical distribution functions

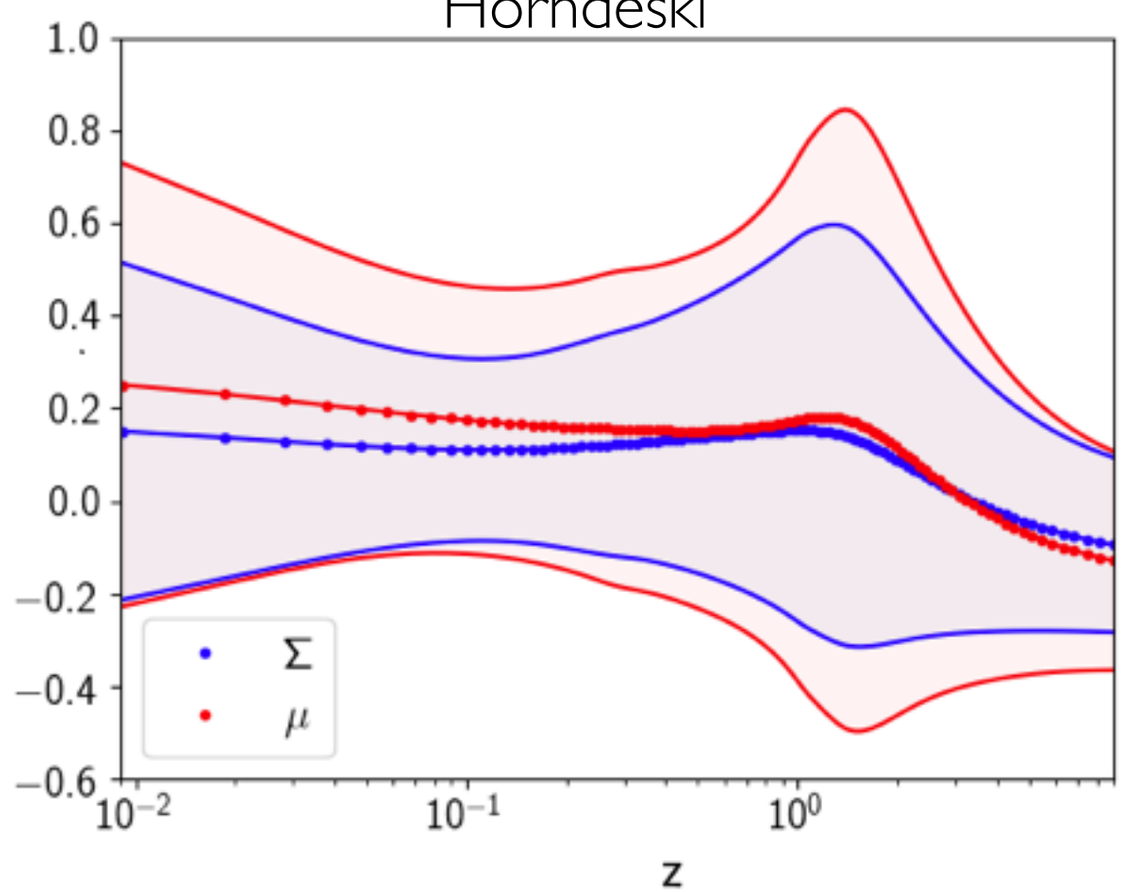
GBD



Horndeski + GWs



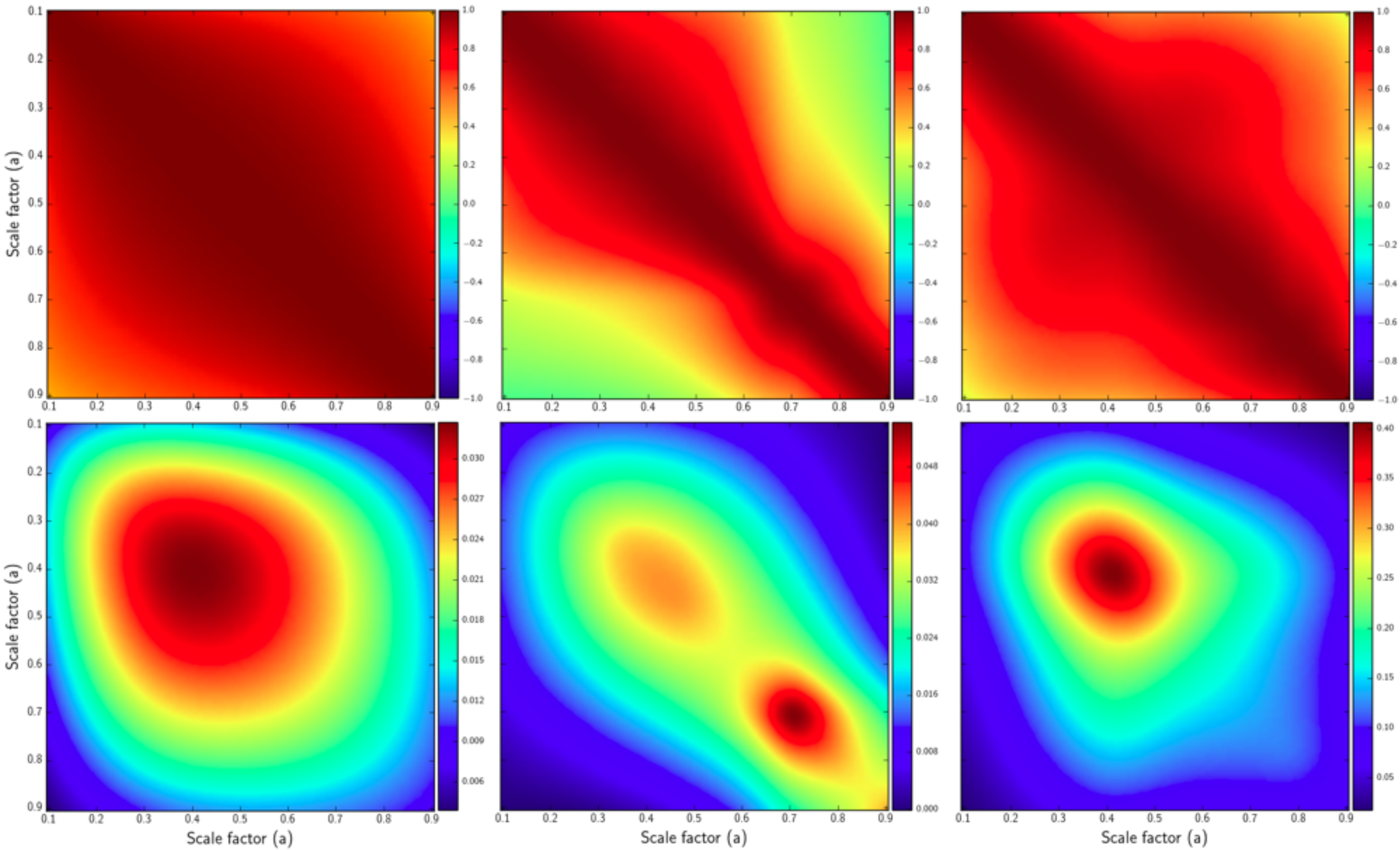
Horndeski



Espejo et al., in preparation

Correlation and Covariance prior matrices

GBD | Horndeski + GWs | Horndeski

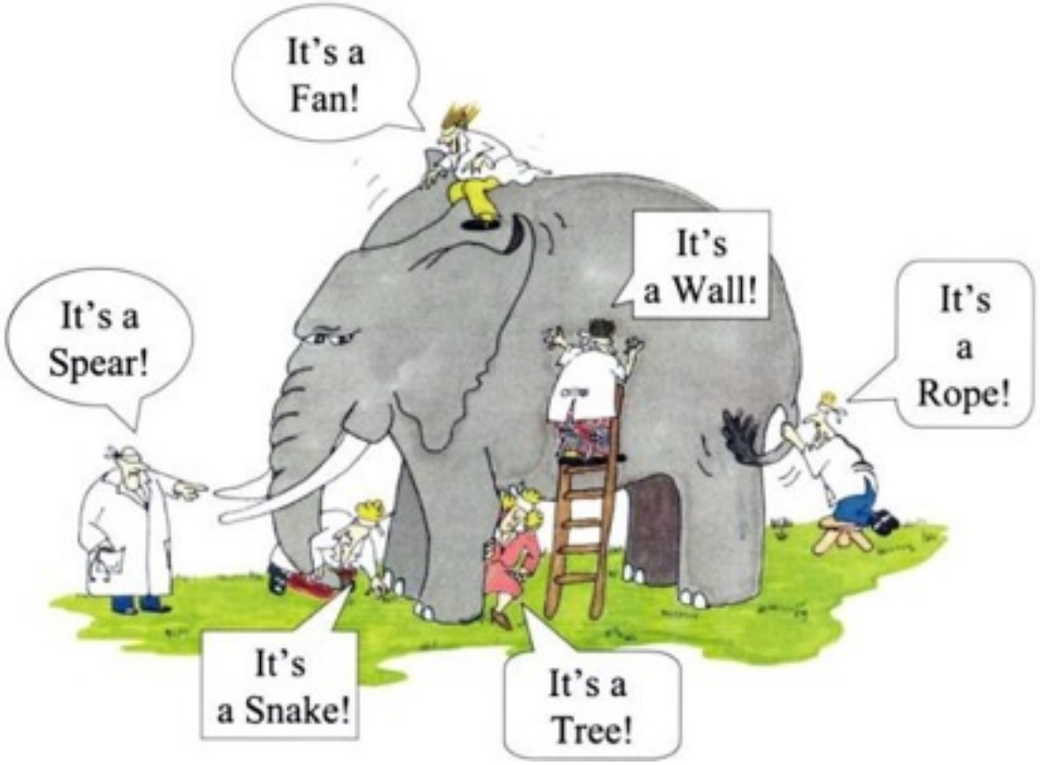


Espejo et al., in preparation

Wrapping up!

This was a brief tale of the ongoing quest to test gravity on cosmological scales, eventually unveiling dark energy.

This is an exciting prospect that will be enabled by the SYNERGY of 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 <u>theoretical frameworks to interpret the data</u> ... bare with us, next years will be exciting!

THANK YOU !