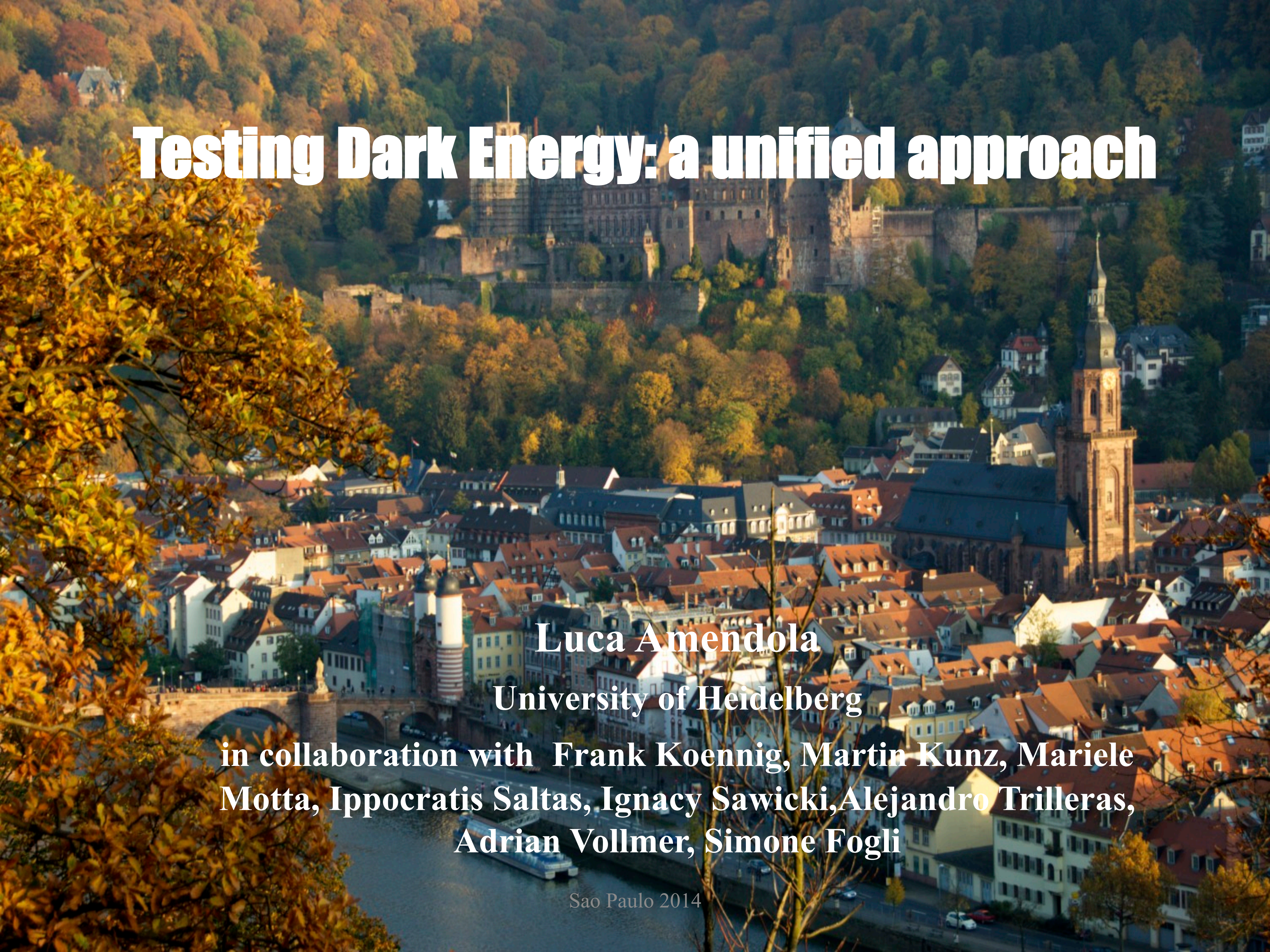

Testing Dark Energy: a unified approach

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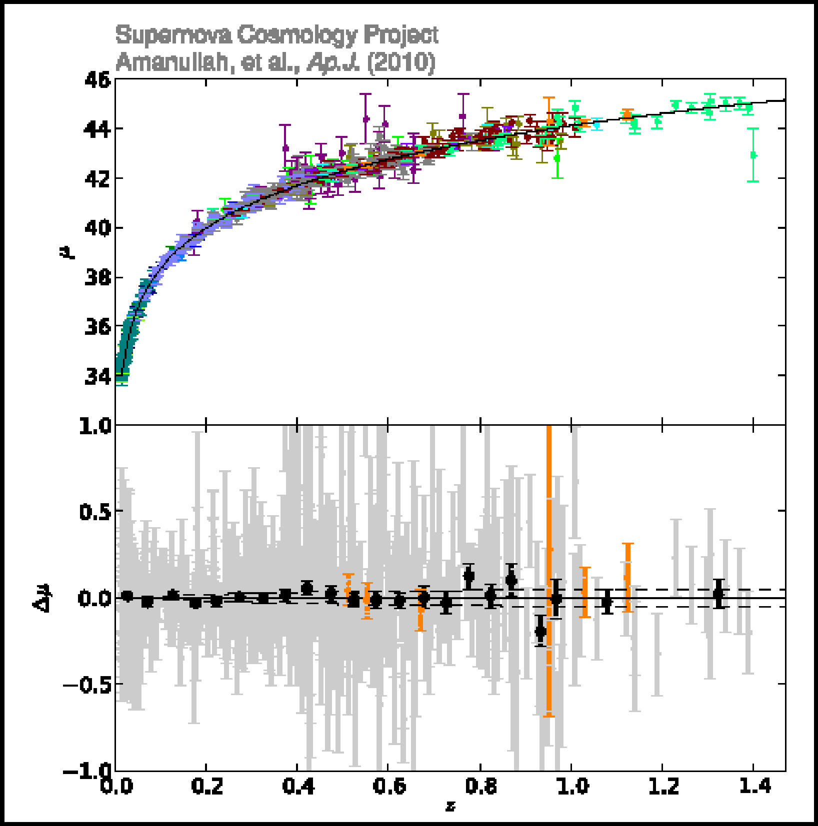
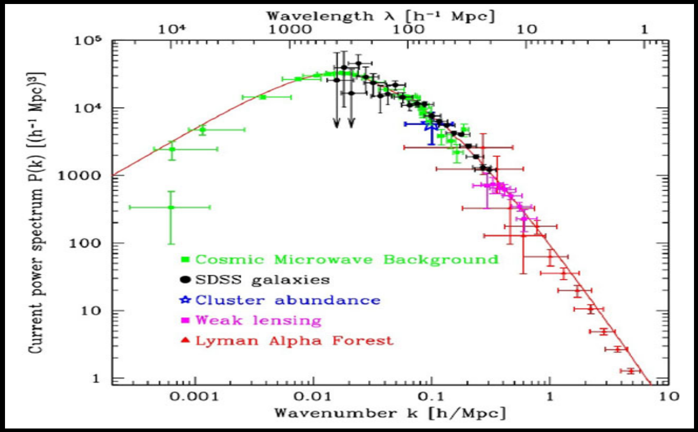
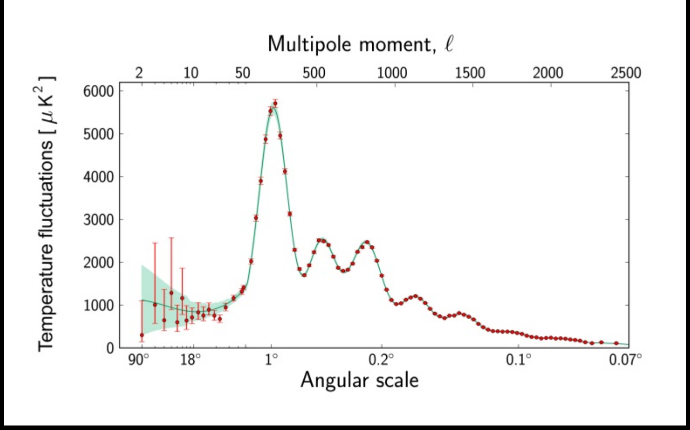
Sao Paulo 2014

Testing dark energy



expansion



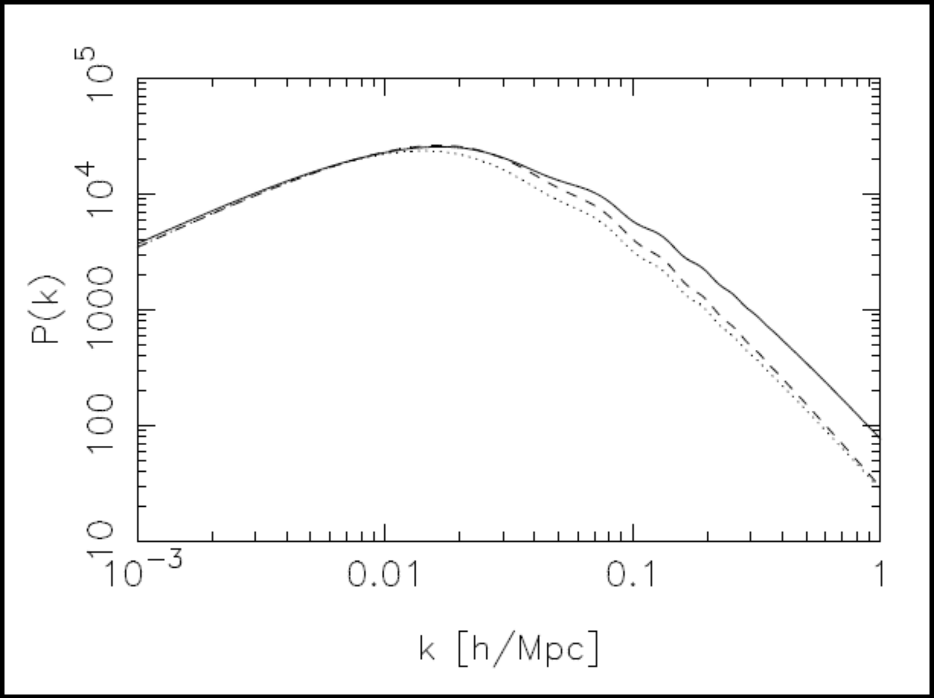


perturbations

The two main problems of testing dark energy

1) Problem of initial conditions

For instance, how do we know if the shape of the power spectrum we observe is due to dark energy or to initial conditions?



The two main problems of testing dark energy

1) Problem of initial conditions

e.g, how do we know if the shape of the power spectrum we observe is due to dark energy or to initial conditions?

2) Problem of design

If our model parameter space is sufficiently large, we can design a model to fit any observation

Cosmological constant, Dark energy w=const. Dark energy w=w(z), Quintessence. scalar-tensor models, coupled quintessence, mass varying neutrinos, k-essence, Chaplygin gas, Cardassian, quartessence, quiessence, phantoms, f(R), Gauss-Bonnet, anisotropic dark energy, brane dark energy, backreaction, degravitation, TeVeS, Galileons, KGB, multiple dark matter,…

Prolegomena zu einer jeden künftigen Dark Energy physik

©Kant

Observations:

- Isotropy
- Large abundance
- Slow evolution
- Weak clustering

Theory:

- Scalar field?
- $\Omega_{DE} \approx \Omega_m$
- $w_{eff} \approx -1$
- $c_s \approx 1$

The past ten years of DE research

$$\int dx^4 \sqrt{-g}\left[R+\frac{1}{2}\phi_{,\mu}\phi^{,\mu}+V(\phi)+L_{matter}\right]$$

$$\int dx^4 \sqrt{-g}\left[f(\phi)R+\frac{1}{2}\phi_{,\mu}\phi^{,\mu}+V(\phi)+L_{matter}\right]$$

$$\int dx^4 \sqrt{-g}\left[f(\phi)R+K(\frac{1}{2}\phi_{,\mu}\phi^{,\mu})+V(\phi)+L_{matter}\right]$$

$$\int dx^4 \sqrt{-g}\left[f(\phi,\frac{1}{2}\phi_{,\mu}\phi^{,\mu})R+G_{\mu\nu}\phi^{,\nu}\phi^{,\mu}+K(\frac{1}{2}\phi_{,\mu}\phi^{,\mu})+V(\phi)+L_{matter}\right]$$

Cosmological constant, Dark energy w=const, Dark energy w=w(z),quintessence, scalar-tensor model, coupled quintessence, k-essence, f(R), Gauss-Bonnet, Galileons, KGB,

The Horndeski Lagrangian

The most general 4D scalar field theory with second order equation of motion

$$\int dx^4 \sqrt{-g}\left[\sum_i L_i + L_{matter}\right]$$

$$\begin{aligned}
\mathcal{L}_2 &= \underline{K(\phi, X)}, \\
\mathcal{L}_3 &= \underline{-G_3(\phi, X)}\Box\phi, \\
\mathcal{L}_4 &= \underline{G_4(\phi, X)}\, R + G_{4,X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)\,(\nabla^\mu\nabla^\nu\phi)\right], \\
\mathcal{L}_5 &= \underline{G_5(\phi, X)}\, G_{\mu\nu}\,(\nabla^\mu\nabla^\nu\phi) - \frac{1}{6}G_{5,X}\left[(\Box\phi)^3 - 3(\Box\phi)\,(\nabla_\mu\nabla_\nu\phi)\,(\nabla^\mu\nabla^\nu\phi) + 2(\nabla^\mu\nabla_\alpha\phi)\,(\nabla^\alpha\nabla_\beta\phi)\,(\nabla^\beta\nabla_\mu\phi)\right].
\end{aligned}$$

- First found by Horndeski in 1975
- rediscovered by Deffayet et al. in 2011
- no ghosts, no classical instabilities
- it modifies gravity!
- it includes f(R), Brans-Dicke, k-essence, Galileons, clustering DE etc etc
- Invariant under conformal and disformal transformations

Massive gravity

Pauli-Fierz (1939) action: the only ghost-free quadratic action for a massive spin two field

$$\int d^4x\sqrt{g}R_g + m^2\int d^4x h_{\mu\nu}h_{\alpha\beta}\left(\eta^{\mu\alpha}\eta^{\nu\beta} - \eta^{\mu\nu}\eta^{\alpha\beta}\right)$$

The three capital sins of Pauli-Fierz theory:

- It does not reduce to massless gravity for $m \to 0$ (vDVZ disc.)
- It is linear
- It contains a ghost when extended to non-linear level (Boulware-Deser ghost)

Massive gravity versus bigravity

- The first problem was partially solved by Vainshtein (1972): there exists a radius below which the linear theory cannot be applied;
- For the Sun, this radius is larger than the solar system!

- The second and third problems have been reconsidered very recently:

$$S = -\frac{M_g^2}{2}\int d^4x\sqrt{-\det g}R(g) - \frac{M_f^2}{2}\int d^4x\sqrt{-\det f}R(f) + m^2 M_g^2\int d^4x\sqrt{-\det g}\sum_{n=0}^{4}\beta_n e_n\left(\sqrt{g^{\alpha\beta}f_{\beta\gamma}}\right) + \int d^4x\sqrt{-\det g}L_m(g,\Phi)$$

The only ghost-free local non-linear
massive gravity theory is a second order theory!

deRham, Gabadadze, and coll., 2010
Hassan & Rosen, 2011

The next ten years of DE research

Combine observations of background, linear and non-linear perturbations to reconstruct as much as possible the Horndeski & Massive Gravity model

… or to rule them out!

The Great Horndeski Hunt

Let us assume we have only

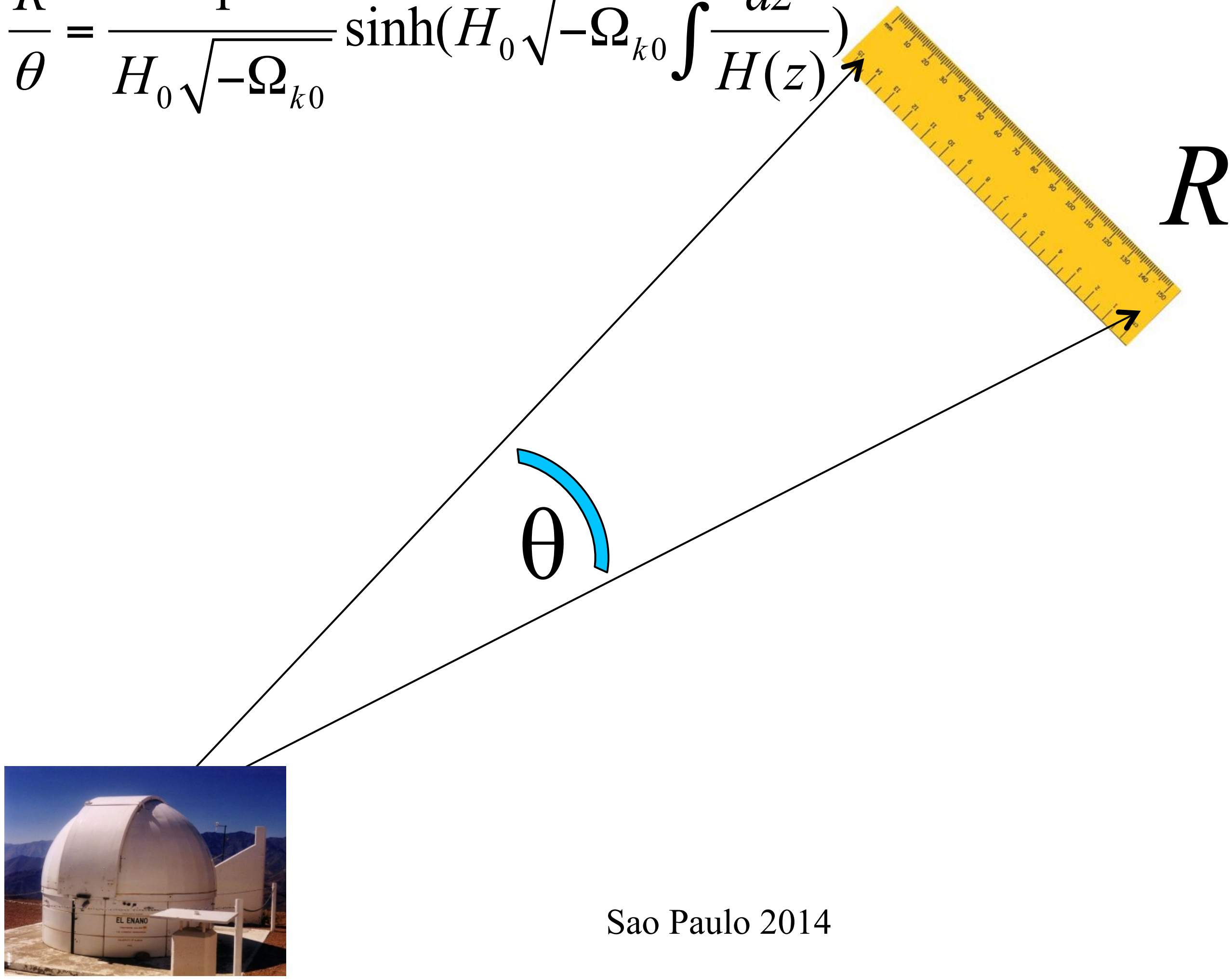
1) a perturbed FRW metric

2) pressureless matter

3) the Horndeski field

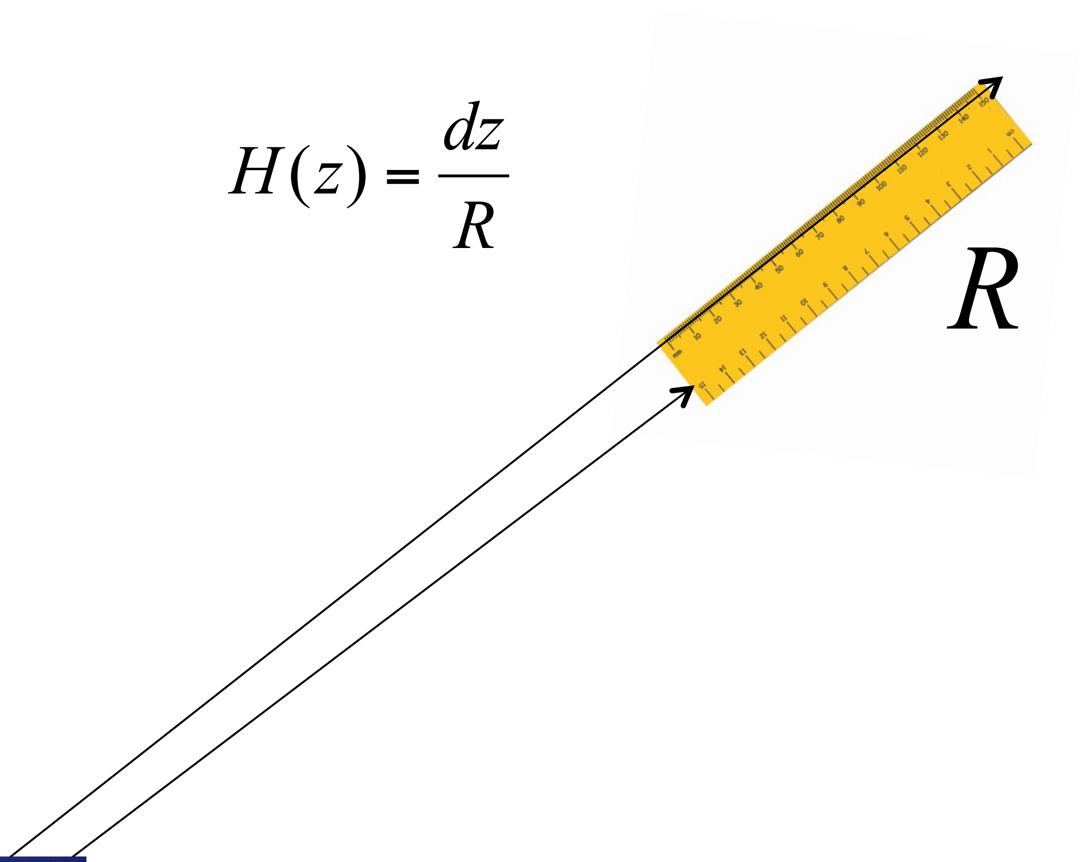
Standard rulers

$$D(z) = \frac{R}{\theta} = \frac{1}{H_0\sqrt{-\Omega_{k0}}}\sinh\left(H_0\sqrt{-\Omega_{k0}}\int\frac{dz}{H(z)}\right)$$

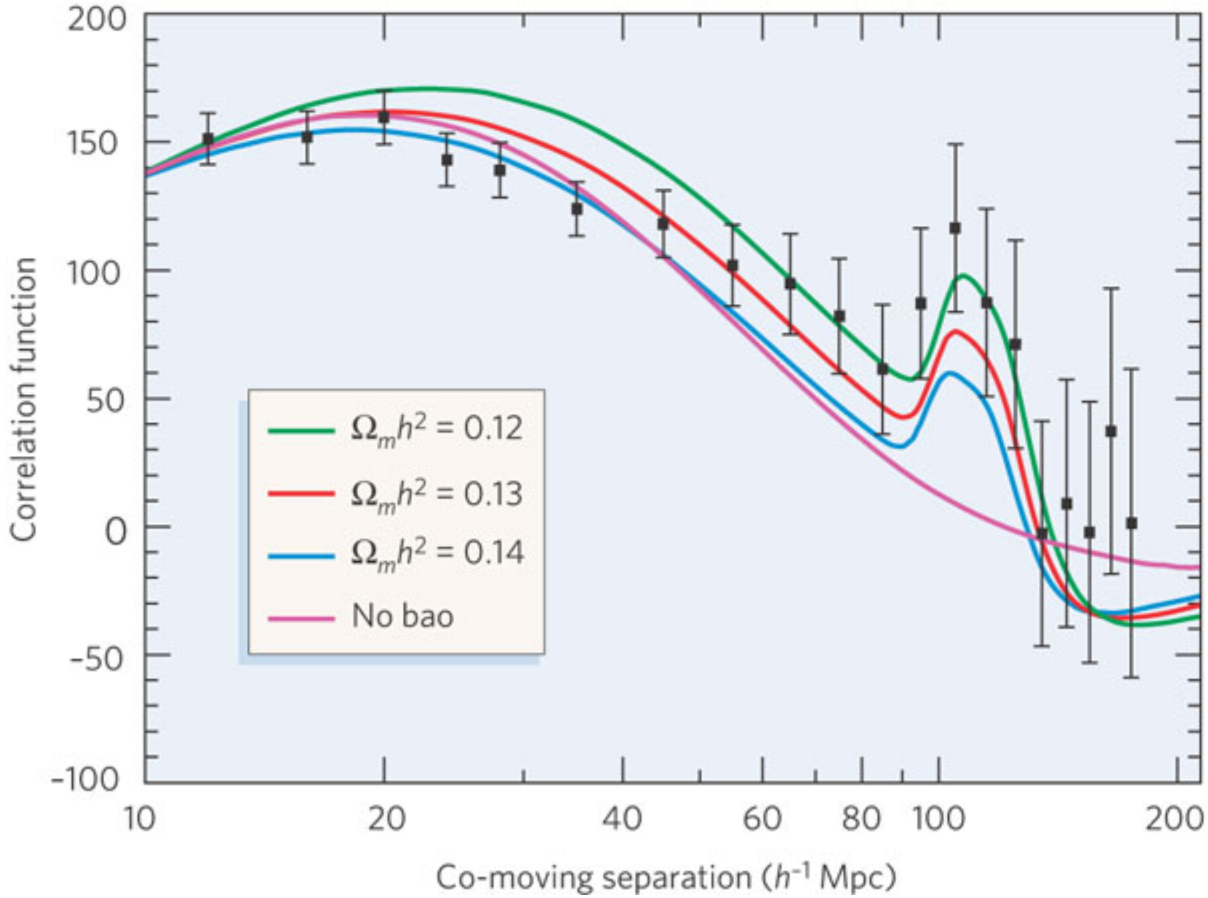


Standard rulers

$$H(z) = \frac{dz}{R}$$



BAO ruler



Charles L. Bennett

Nature 440, 1126-1131(27 April 2006)

Background: SNIa, BAO, …

Then we can measure H(z) and

$$D(z) = \frac{1}{H_0\sqrt{-\Omega_{k0}}}\sinh(H_0\sqrt{-\Omega_{k0}}\int\frac{dz}{H(z)})$$

and therefore we can reconstruct the full FRW metric

$$ds^2 = dt^2 - \frac{a(t)^2}{\left(1-\frac{\Omega_{k0}}{4}r^2\right)^2}(dx^2+dy^2+dz^2)]$$

Two free functions

The most general linear, scalar metric

$$ds^2 = a^2[(1+2\Psi)dt^2 - (1+2\Phi)(dx^2 + dy^2 + dz^2)]$$

- Poisson's equation

$$\nabla^2\Psi = 4\pi G\rho_m\delta_m$$

- anisotropic stress

$$1 = -\frac{\Psi}{\Phi}$$

Two free functions

The most general linear, scalar metric

$$ds^2 = a^2[(1+2\Psi)dt^2 - (1+2\Phi)(dx^2 + dy^2 + dz^2)]$$

- Poisson's equation $\qquad \nabla^2\Psi = 4\pi G\, Y(k,a)\rho_m \delta_m$

- anisotropic stress $\qquad \eta(k,a) = -\dfrac{\Phi}{\Psi}$

Modified Gravity at the linear level

- standard gravity

$$Y(k,a)=1$$
$$\eta(k,a)=1$$

- scalar-tensor models

$$Y(a)=\frac{G^*}{FG_{cav,0}}\frac{2(F+F'^2)}{2F+3F'^2}$$
$$\eta(a)=1+\frac{F'^2}{F+F'^2}$$

Boisseau et al. 2000
Acquaviva et al. 2004
Schimd et al. 2004
L.A., Kunz &Sapone 2007

- f(R)

$$Y(a)=\frac{G^*}{FG_{cav,0}}\frac{1+4m\frac{k^2}{a^2R}}{1+3m\frac{k^2}{a^2R}},\quad \eta(a)=1+\frac{m\frac{k^2}{a^2R}}{1+2m\frac{k^2}{a^2R}}$$

Bean et al. 2006
Hu et al. 2006
Tsujikawa 2007

- DGP

$$Y(a)=1-\frac{1}{3\beta};\quad \beta=1+2Hr_c w_{DE}$$
$$\eta(a)=1+\frac{2}{3\beta-1}$$

Lue et al. 2004;
Koyama et al. 2006

- massive bi-gravity

$$Y(a)=....$$
$$\eta(a)=....$$

see F. Koenig and L. A. 2014

Modified Gravity at the linear level

In the quasi-static limit, every Horndeski model is characterized at linear scales by the two functions

$$\eta(k,a) = h_2\left(\frac{1+k^2h_4}{1+k^2h_5}\right)$$

$$Y(k,a) = h_1\left(\frac{1+k^2h_5}{1+k^2h_3}\right)$$

k = wavenumber

$\boldsymbol{h_i}$ **= time-dependent functions**

De Felice et al. 2011; L.A. et al.PRD, arXiv:1210.0439, 2012

Modified Gravity at the linear level

$$
\begin{aligned}
h_1 &\equiv \frac{w_4}{w_1^2} = \frac{c_T^2}{w_1}, \qquad h_2 \equiv \frac{w_1}{w_4} = c_T^{-2}, \\
h_3 &\equiv \frac{H^2}{2XM^2}\frac{2w_1^2 w_2 H - w_2^2 w_4 + 4w_1 w_2 \dot{w}_1 - 2w_1^2(\dot{w}_2 + \rho_m)}{2w_1^2}, \\
h_4 &\equiv \frac{H^2}{2XM^2}\frac{2w_1^2 H^2 - w_2 w_4 H + 2w_1 \dot{w}_1 H + w_2 \dot{w}_1 - w_1(\dot{w}_2 + \rho_m)}{w_1}, \\
h_5 &\equiv \frac{H^2}{2XM^2}\frac{2w_1^2 H^2 - w_2 w_4 H + 4w_1 \dot{w}_1 H + 2\dot{w}_1{}^2 - w_4(\dot{w}_2 + \rho_m)}{w_4},
\end{aligned}
$$

$$
\begin{aligned}
w_1 \equiv& 1 + 2\left(G_4 - 2XG_{4,X} + XG_{5,\phi} - \dot{\phi}XHG_{5,X}\right), \\
w_2 \equiv& -2\dot{\phi}\left(XG_{3,X} - G_{4,\phi} - 2XG_{4,\phi X}\right) + \\
&+ 2H\left(w_1 - 4X\left(G_{4,X} + 2XG_{4,XX} - G_{5,\phi} - XG_{5,\phi X}\right)\right) - \\
&- 2\dot{\phi}XH^2\left(3G_{5,X} + 2XG_{5,XX}\right), \\
w_3 \equiv& 3X\left(K_{,X} + 2XK_{,XX} - 2G_{3,\phi} - 2XG_{3,\phi X}\right) + 18\dot{\phi}XH\left(2G_{3,X} + XG_{3,XX}\right) - \\
&- 18\dot{\phi}H\left(G_{4,\phi} + 5XG_{4,\phi X} + 2X^2 G_{4,\phi XX}\right) - \\
&- 18H^2\left(1 + G_4 - 7XG_{4,X} - 16X^2 G_{4,XX} - 4X^3 G_{4,XXX}\right) - \\
&- 18XH^2\left(6G_{5,\phi} + 9XG_{5,\phi X} + 2X^2 G_{5,\phi XX}\right) + \\
&+ 6\dot{\phi}XH^3\left(15G_{5,X} + 13XG_{5,XX} + 2X^2 G_{5,XXX}\right), \\
w_4 \equiv& 1 + 2\left(G_4 - XG_{5,\phi} - XG_{5,X}\ddot{\phi}\right).
\end{aligned}
$$

De Felice et al. 2011; L.A. et al.,PRD, arXiv:1210.0439, 2012

Yukawa Potential

$$\eta(k,a) = h_2\left(\frac{1+k^2h_4}{1+k^2h_5}\right)$$

$$Y(k,a) = h_1\left(\frac{1+k^2h_5}{1+k^2h_3}\right)$$

Momentum space

$$\nabla^2\Psi = 4\pi G\, Y(k,a)\rho_m\delta_m$$

$$\Psi = -\frac{GM}{r}h_2\left(1+\frac{h_4-h_5}{h_5}e^{-r/\sqrt{h_5}}\right) = -\frac{\bar{G}M}{r}\left(1+Qe^{-mr}\right)$$

Real space

De Felice et al. 2011; L.A. et al.PRD, arXiv:1210.0439, 2012

Quasi-static approximation

$$c_s^2 k^2 \gg a^2 H^2$$

From a wave equation:

$$\begin{aligned} E_{\delta\phi} \equiv\ & D_1\ddot{\Phi} + D_2\ddot{\delta\phi} + D_3\dot{\Phi} + D_4\dot{\delta\phi} + D_5\dot{\Psi} + D_6\frac{k^2}{a^2}\dot{\chi} \\ & + \left(D_7\frac{k^2}{a^2} + D_8\right)\Phi + \left(D_9\frac{k^2}{a^2} - M^2\right)\delta\phi + \left(D_{10}\frac{k^2}{a^2} + D_{11}\right)\Psi + D_{12}\frac{k^2}{a^2}\chi = 0\,, \end{aligned}$$

To a "Poisson" equation:

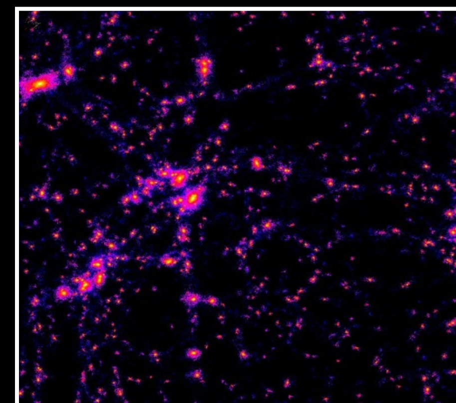
$$B_7\frac{k^2}{a^2}\Phi + \left(D_9\frac{k^2}{a^2} - M^2\right)\delta\phi + A_6\frac{k^2}{a^2}\Psi \simeq 0\,,$$

Reconstruction of the metric

$$ds^2 = a^2[(1+2\Psi)dt^2 - (1+2\Phi)(dx^2 + dy^2 + dz^2)]$$

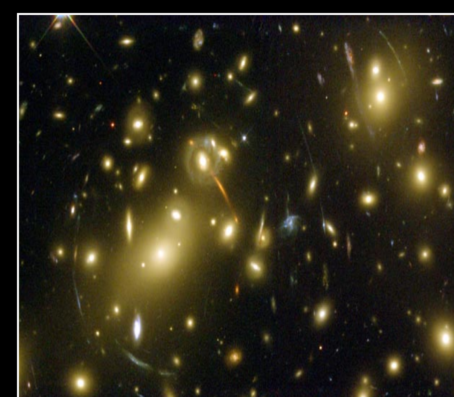
Non-relativistic particles respond to Ψ

$$\delta_m'' + (1 + \frac{\mathcal{H}'}{\mathcal{H}})\delta_m' = -k^2\Psi$$



Relativistic particles respond to Φ-Ψ

$$\alpha = \int \nabla_{perp}(\Psi - \Phi)dz$$



Deconstructing the galaxy power spectrum

Redshift distortion

Galaxy clustering

Line of sight angle

$$\delta_{gal}(k,z,\mu) = Gb\sigma_8\left(1+\frac{f}{b}\mu^2\right)\delta_{t,0}(k)$$

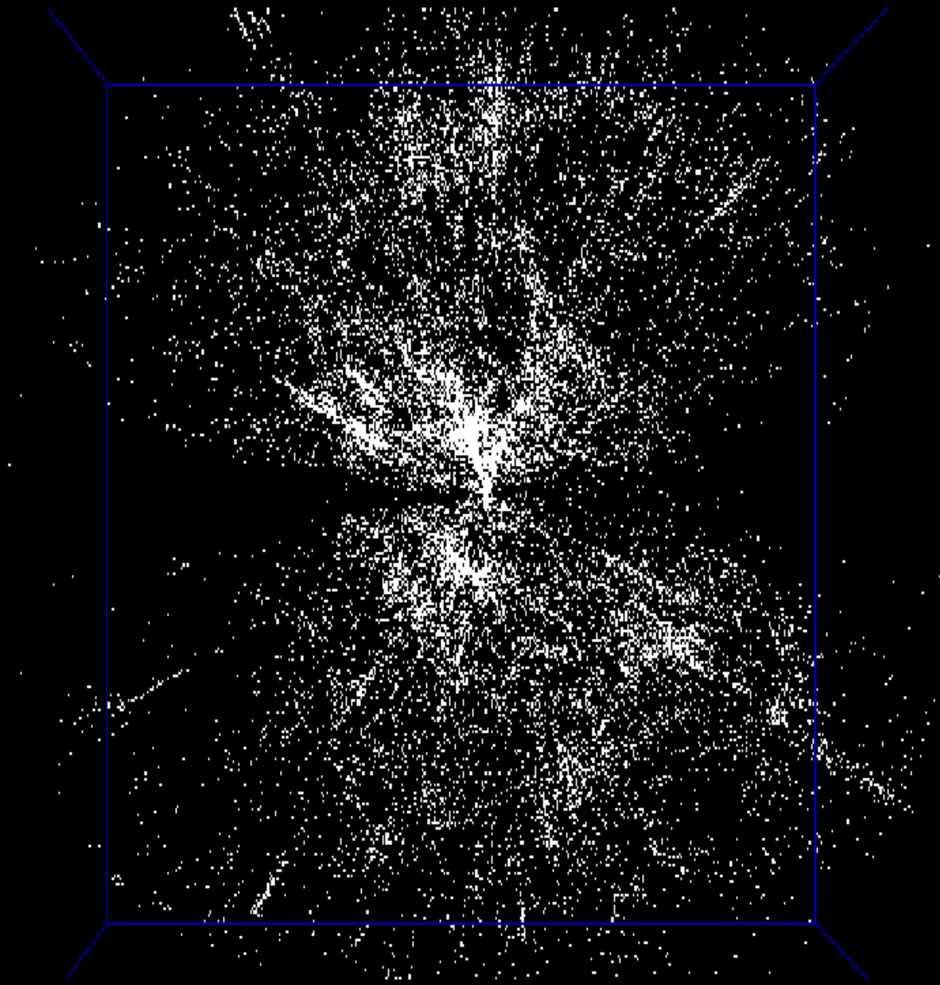
$$\left(f = \frac{\delta'}{\delta}\right)$$

Growth function

Galaxy bias

Present mass power spectrum

normalization



Sao Paulo 2014

Three linear observables: A, R, L

clustering

μ=0
Amplitude
A

$$\delta_{gal}(k,z,0) = Gb\sigma_8\delta_{m,0}(k) \equiv A$$

μ=1
Redshift distortion
R

$$\delta_{gal}(k,z,1) = G\sigma_8 f\,\delta_{m,0}(k) \equiv R$$

lensing

Lensing
L

$$k^2\Phi_{lens} = k^2(\Psi - \Phi) = -\frac{3}{2}\Sigma G\Omega_m\sigma_8\delta_{m,0}(k) \equiv L$$

$$\Sigma = Y(1+\eta)$$

The only model-independent ratios

Redshift distortion/Amplitude

$$P_1 = \frac{R}{A} = \frac{f}{b}$$

Lensing/Redshift distortion

$$P_2 = \frac{L}{R} = \frac{\Omega_{m0} Y(1+\eta)}{f}$$

Redshift distortion rate

$$P_3 = \frac{R'}{R} = \frac{f'}{f} + f$$

Expansion rate

$$E = \frac{H}{H_0}$$

How to combine them to test the theory?

Summarizing….

Matter conservation equation independent of gravity theory

$$\delta''_m + (1 + \frac{\mathcal{H}'}{\mathcal{H}})\delta'_m = -k^2\Psi \ :$$

Observables

$$P_2 = \frac{L}{R} = \frac{\Omega_{m0} Y(1+\eta)}{f} \qquad P_3 = \frac{R'}{R} = \frac{f'}{f} + f \qquad E = \frac{H}{H_0}$$

The anisotropic stress is directly observable

A unique combination of model independent observables

$$\frac{3P_2(1+z)^3}{2E^2(P_3+2+\frac{E'}{E})}-1=\eta$$

Observables

Theory

Testing the entire Horndeski Lagrangian

A unique combination of model independent observables

$$\frac{3P_2(1+z)^3}{2E^2(P_3+2+\frac{E'}{E})}-1=\eta=h_2\left(\frac{1+k^2h_4}{1+k^2h_5}\right)$$

Observables

Theory

L.A., M. Motta, I. Sawicki,
M. Kunz, I. Saltas, 1210.0439
1305.0008

Horndeski Lagrangian: not too big to fail

$$g(z,k) \equiv \frac{(REa^2)'}{LEa^2}$$

$$2g_{,k}g_{,kkk} - 3(g_{,kk})^2 = 0$$

If this relation is falsified, the Horndeski theory is rejected*

L.A., M. Motta, I. Sawicki,
M. Kunz, I. Saltas, 1210.0439

Beyond the quasi-static condition

General consistency relation

$$\eta\Gamma' + \eta'' + \Gamma\left(\eta\Gamma + 2\eta' + \bar{\alpha}_1\eta - \bar{\alpha}_2\right) + \\ + \bar{\alpha}_1\eta' + \bar{\alpha}_3\eta - \bar{\alpha}_5 + k^2\left(\bar{\alpha}_4\eta - \bar{\alpha}_6\right) = \bar{\alpha}_7\varpi\,.$$

$$\Gamma \equiv \frac{\Psi'}{\Psi} = \frac{L'}{L} - \frac{\eta'}{1+\eta} - 1\,,$$

$$\varpi = \frac{1+\eta}{P_2}$$

M. Motta, L.A, I. Sawicki,
M. Kunz, I. Saltas, 1305.0008
2013

Massive gravity versus bigravity

The only ghost-free local non-linear massive gravity theory

$$S = -\frac{M_g^2}{2}\int d^4x\sqrt{-\det g}R(g) - \frac{M_f^2}{2}\int d^4x\sqrt{-\det f}R(f)$$

$$+ \; m^2M_g^2\int d^4x\sqrt{-\det g}\sum_{n=0}^{4}\beta_n e_n(\sqrt{g^{\alpha\beta}f_{\beta\gamma}}) + \int d^4x\sqrt{-\det g}L_m(g,\Phi)$$

Two dynamical metrics!

Only one is coupled

$$g_{\mu\nu}, \quad f_{\mu\nu}$$

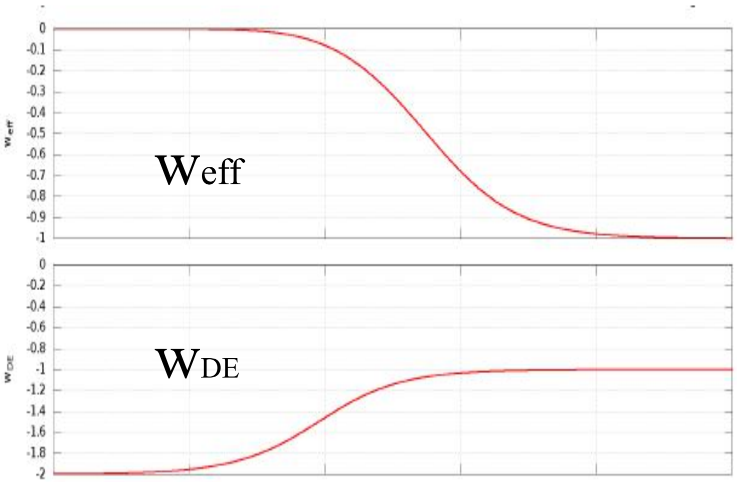
Bigravity at the background level

Let us drastically simplify the problem:
We assume two spatially flat FRW-like metrics,
with two scale factors a(t), b(t)

At the background level, one finds that the problem is one-dimensional

$$r' = \frac{3r\Omega_m(\beta_1 + 3\beta_2 r + 3\beta_3 r^2 + \beta_4 r^3)}{\beta_1 - 3\beta_3 r^2 + 2\beta_4 r^3 + 3(\beta_1 + 2\beta_2 r + \beta_3 r^2) r^2}, \quad r \equiv \frac{b}{a}$$

Final state always de Sitter
No problem in recovering an approximate LCDM behavior, fitting SN etc.



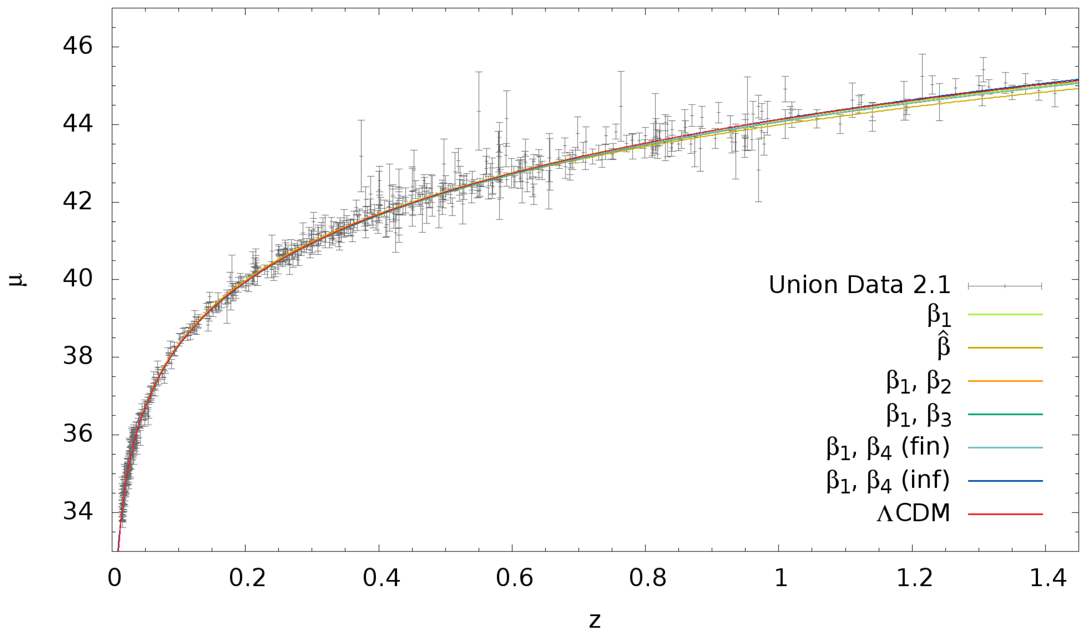
F. Koennig, L.A. (1312.3208, 1402.1988)

Minimal Bimetric Model

$$\beta_{0,2,3,4} = 0,$$
$$\beta_1 \neq 0$$

$$r' = \frac{3r(1-3r^2)}{1+3r^2}, \quad r \equiv \frac{b}{a}$$

$$w_{MBM} = \frac{2}{\Omega_m - 2},$$



One parameter, analytical background behavior, as simple as LCDM, but fully distinguishable

$$\beta_1 = 1.38 \pm 0.03 \qquad w_{MBM} \sim -1.22 - 0.64 \frac{z}{1+z}$$

Bigravity at the linear level

The linear perturbations are much more complicated.
6 d.o.f., instead of 2 in standard gravity, for scalar perturbations.

$$\Phi = -\frac{B_2 a^2 r}{2k^2 + 3B_2 a^2 r} k^2 \Delta E + \frac{3B_2 a^2 r}{2k^2 + 3B_2 a^2 r} \Phi_f + \frac{a^2 \rho_m}{2k^2 + 3B_2 a^2 r} \delta_m$$

$$\Psi = -\Phi - A_2 a^2 r \Delta E$$

$$\Phi_f = \frac{B_2 a^2}{3B_2 a^2 + 2k^2 r} k^2 \Delta E + \frac{B_2 a^2}{3B_2 a^2 + 2k^2 r} \Phi$$

Sub-horizon approximation

$$\Psi_f = \frac{2A_2 a^2}{3B_2 a^2 + 2k^2 (r + r')} k^2 \Delta E + \frac{6A_2 a^2}{3B_2 a^2 + 2k^2 (r + r')} \Phi + \frac{3B_2 a^2}{3B_2 a^2 + 2k^2 (r + r')} \Psi + \frac{6A_1 a^2 r - 2k^2 (r + r')}{3B_2 a^2 + 2k^2 (r + r')} \Phi_f$$

$$\Psi_f = -\Phi_f + \frac{A_2 a^2}{r + r'} \Delta E$$

F. Koennig, M.Motta, L.A., in preparation

Bigravity at the linear level

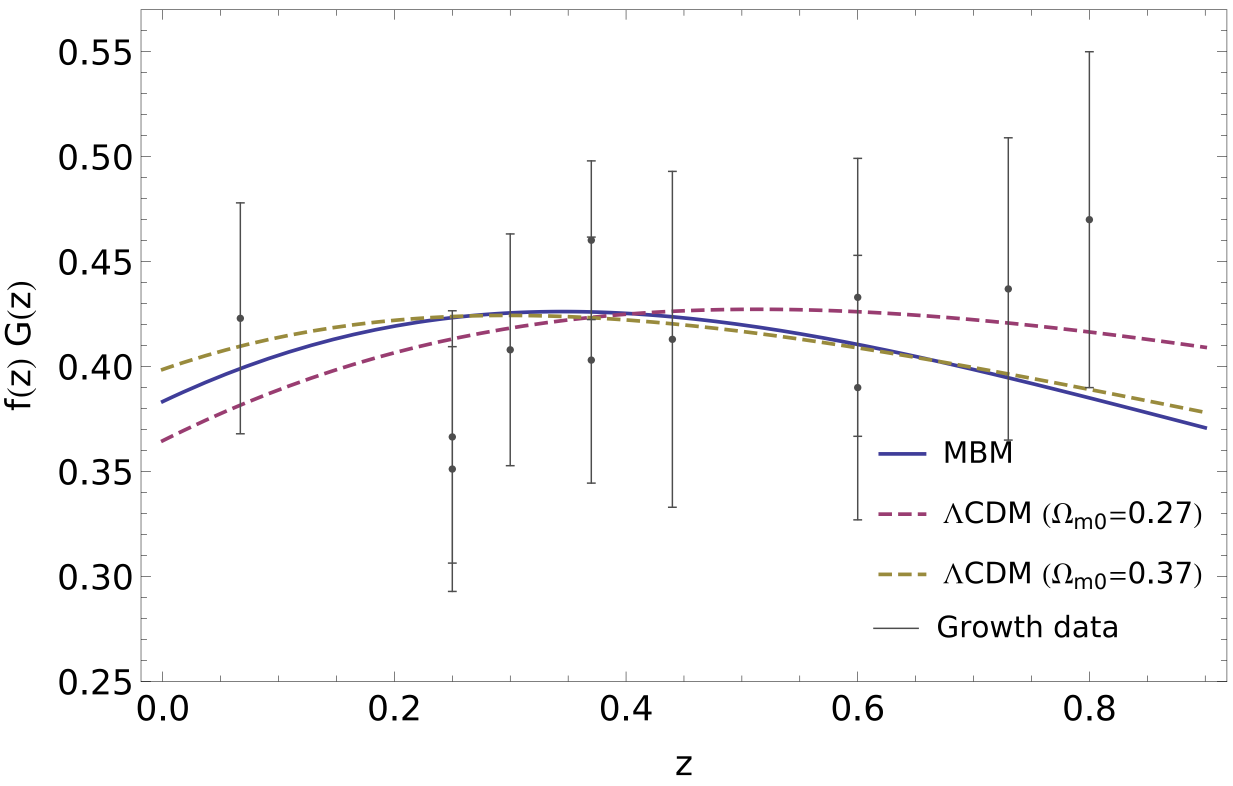
In the quasi-static limit we obtain again the Horndeski form!

$$\eta(k,a) = H_2\left(\frac{1+k^2H_4}{1+k^2H_5}\right)$$

$$Y(k,a) = H_1\left(\frac{1+k^2H_5}{1+k^2H_3}\right)$$

F. Koennig, L.A. 1402.1988

Bigravity at the linear level



Euclid in a nutshell

Simultaneous (i) visible imaging (ii) NIR photometry (iii) NIR spectroscopy

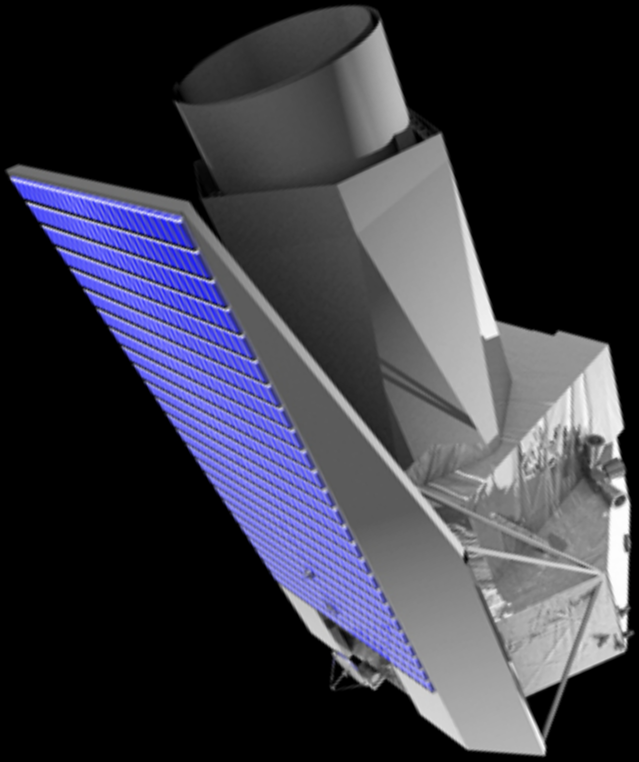
15,000 square degrees

70 million redshifts, 2 billion images

Median redshift z = 1

PSF FWHM ~0.18’’

>1000 peoples, >10 countries



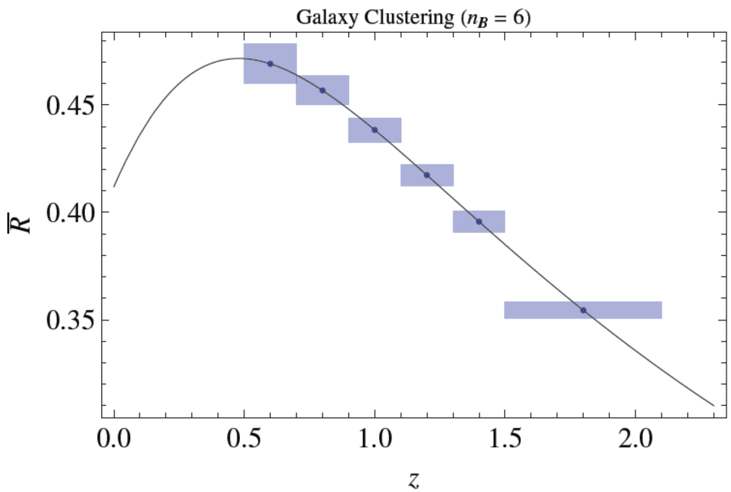
Euclid satellite

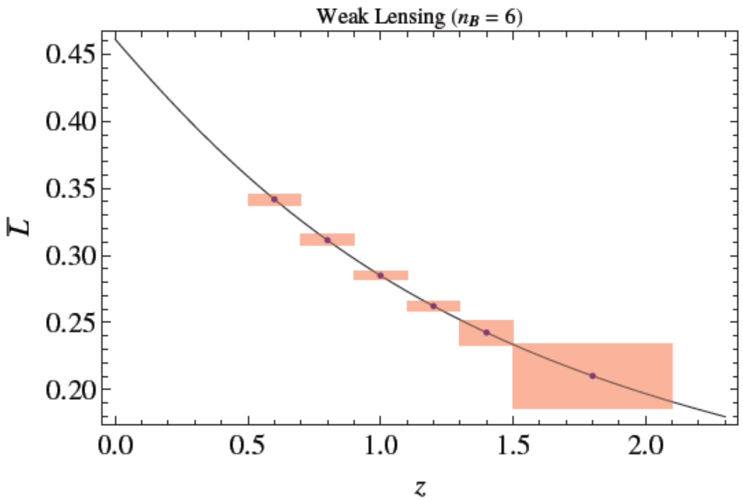
arXiv Red Book 1110.3193

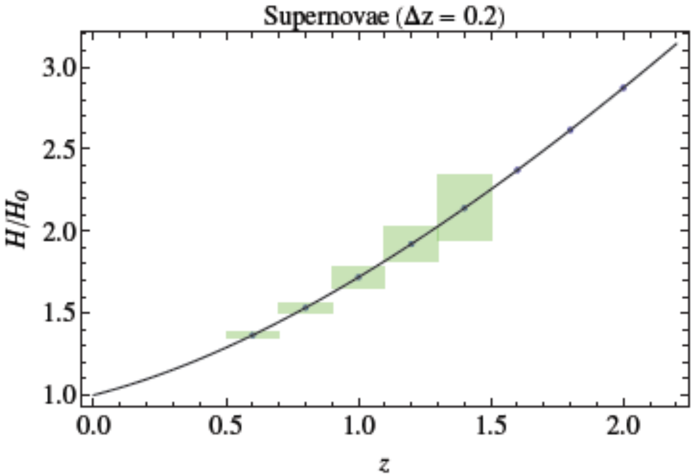
arXiv Theory Review 1206.1225

Euclid forecasts...

Combining galaxy clustering, weak lensing and SN....







100k SN (LSST)

$$G\sigma_8 f\delta_{m,0}(k) \equiv R$$

$$-\frac{3}{2}\Sigma G\Omega_m\sigma_8\delta_{m,0}(k) \equiv L$$

Results..

$$\eta(k,a) = H_2\left(\frac{1+k^2H_4}{1+k^2H_5}\right)$$

Model 1: η constant for all z, k
Error on η around 1%

Model 2: η varies in z
Error on η

$\bar{z}$	$P_1(\bar{z})$	ΔP_1	$\Delta P_1(\%)$	$P_2(\bar{z})$	ΔP_2	$\Delta P_2(\%)$	$P_3(\bar{z})$	ΔP_3	$\Delta P_3(\%)$	$(E'/E)(\bar{z})$	$\Delta E'/E$	$\Delta E'/E(\%)$	$\bar{\eta}$	$\Delta\bar{\eta}$	$\Delta\bar{\eta}(\%)$
0.6	0.766	0.012	1.6	0.729	0.011	1.6	0.134	0.13	99.	-0.92	0.018	1.9	1	0.11	11.
0.8	0.819	0.01	1.2	0.682	0.0088	1.3	0.317	0.12	38.	-1.04	0.038	3.7	1	0.091	9.1
1.	0.859	0.0093	1.1	0.65	0.0086	1.3	0.46	0.12	26.	-1.13	0.085	7.5	1	0.089	8.9
1.2	0.888	0.0092	1.	0.628	0.014	2.3	0.569	0.13	23.	-1.21	0.11	9.5	1	0.097	9.7
1.4	0.911	0.01	1.1	0.613	0.019	3.2	0.654	0.05	7.7	-1.26	0.052	4.1	1	0.034	3.4

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Results..

Model 3: η varies in z and k
Error on η

$\bar{z}$	i	P_1	ΔP_1	$\Delta P_1(\%)$	P_2	ΔP_2	$\Delta P_2(\%)$	P_3	ΔP_3	$\Delta P_3(\%)$	$\bar{\eta}$	$\Delta\bar{\eta}$	$\Delta\bar{\eta}(\%)$
0.6	1	0.766	0.14	18	0.729	0.12	17	0.134	1.4	1100	1	1.1	120
	2		0.032	4.1		0.030	4.1		0.33	240		0.26	26
	3		0.013	1.7		0.015	2.0		0.15	110		0.12	12
0.8	1	0.819	0.11	13	0.682	0.092	13	0.317	1.2	380	1	0.93	93
	2		0.024	2.9		0.021	3.1		0.26	83		0.2	20
	3		0.011	1.4		0.013	1.9		0.14	43		0.1	10
1.0	1	0.859	0.093	11	0.65	0.076	12	0.46	1.1	240	1	0.82	82
	2		0.020	2.3		0.019	2.9		0.23	51		0.17	17
	3		0.011	1.2		0.012	1.8		0.14	31		0.1	11
1.2	1	0.888	0.084	9.4	0.628	0.074	12	0.569	1.1	190	1	0.78	78
	2		0.017	2.0		0.021	3.3		0.23	40		0.16	16
	3		0.011	1.2		0.017	2.7		0.17	29		0.12	12
1.4	1	0.911	0.079	8.7	0.613	0.084	14	0.654	0.79	120	1	0.55	55
	2		0.017	1.9		0.027	4.4		0.17	26		0.12	12
	3		0.013	1.4		0.023	3.8		0.14	21		0.094	9.4

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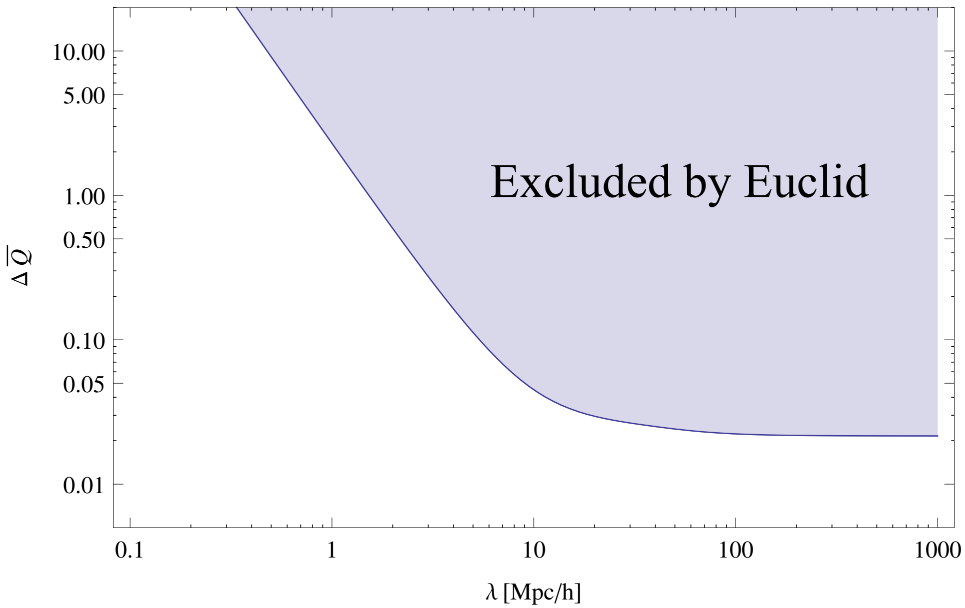
A cosmological exclusion plot

Model 4: η has the Horndeski form
Error on h2, (h4-h5) in h/Mpc

$$\eta = h_2 \left(\frac{1 + k^2 h_4}{1 + k^2 h_5} \right)$$

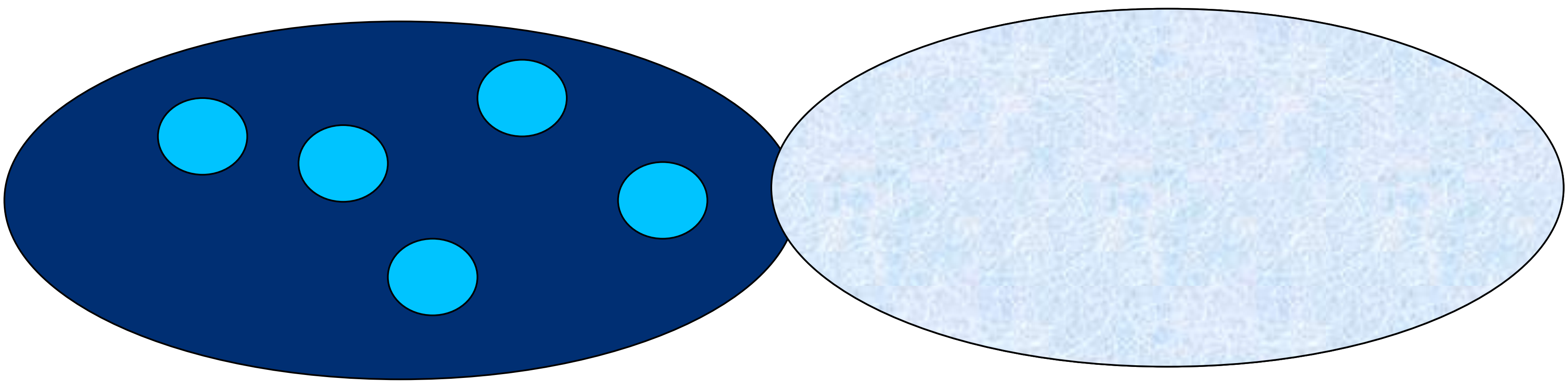
$$\eta = -\frac{\bar{G}\mu}{r}(1 + Qe^{-r/\lambda})$$



Under the carpet..

Problem of non-linearity:
screening effects mix linear and non-linear scales

same density contrast



different physics

Three Messages

1

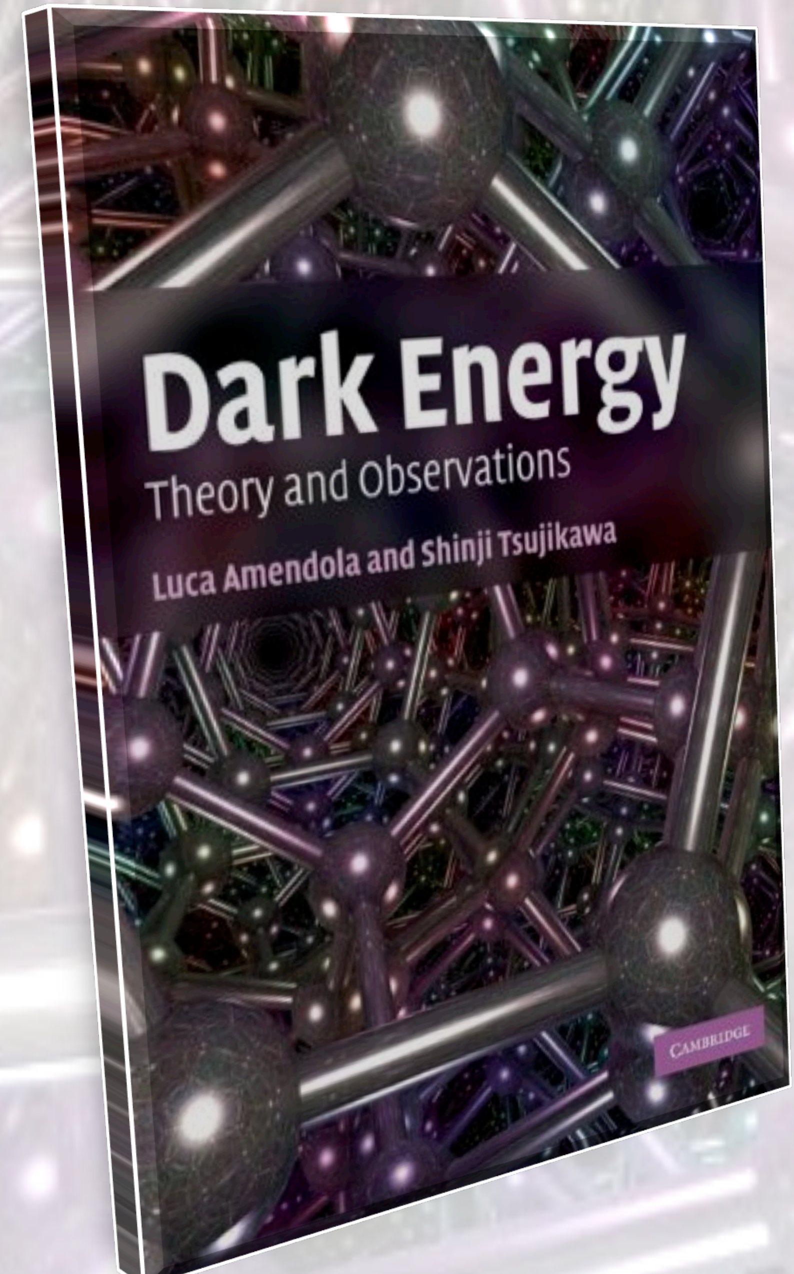
If DE is not a Horndeski field or massive gravity, then
I don't know what could be

2

k-binned data are crucial!
e.g. growth factor, redshift distortion parameter

3

Only by combining galaxy clustering and lensing
can DE be constrained (or ruled out!) in a model-independent way



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