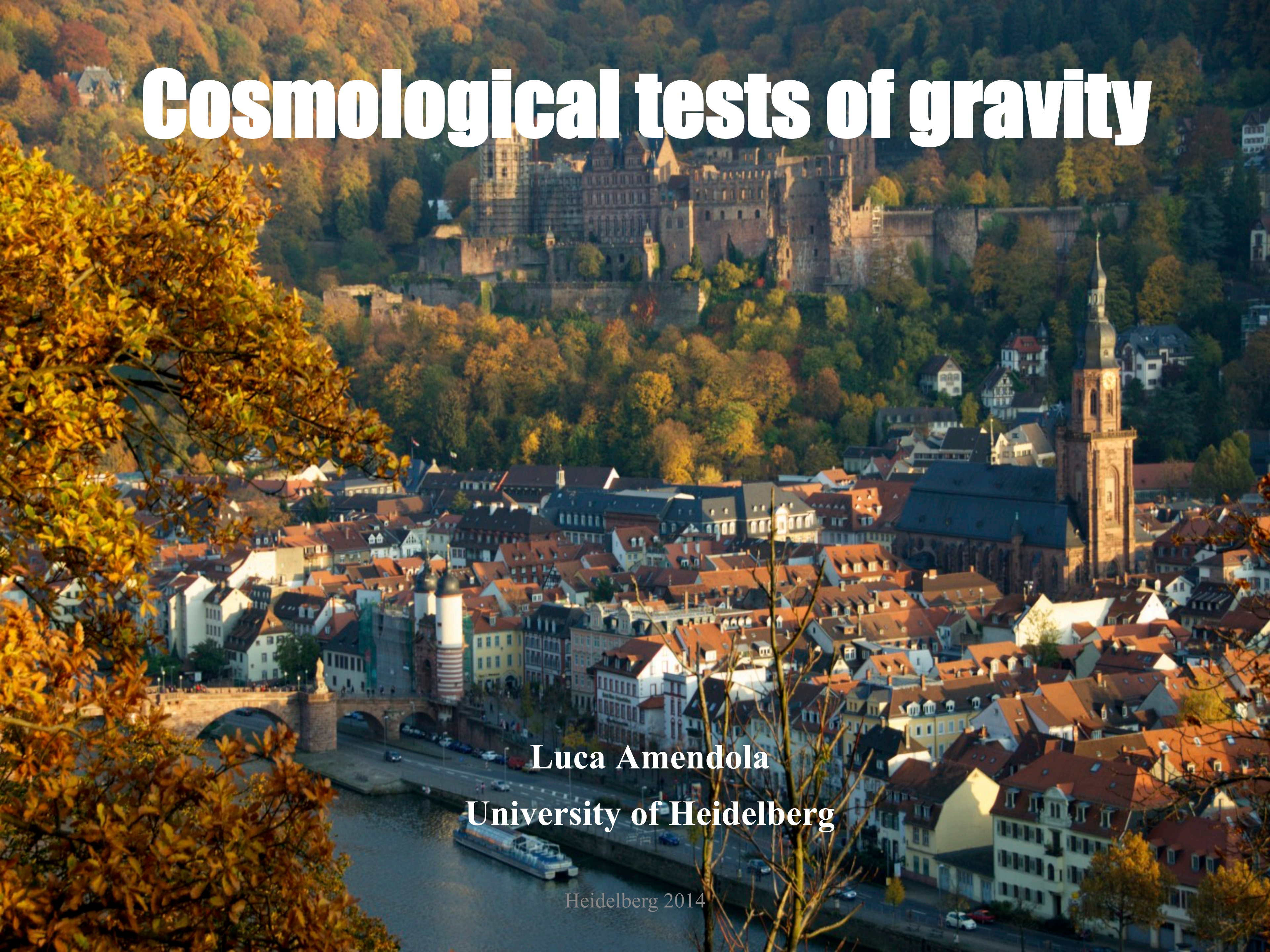


Cosmological tests of gravity

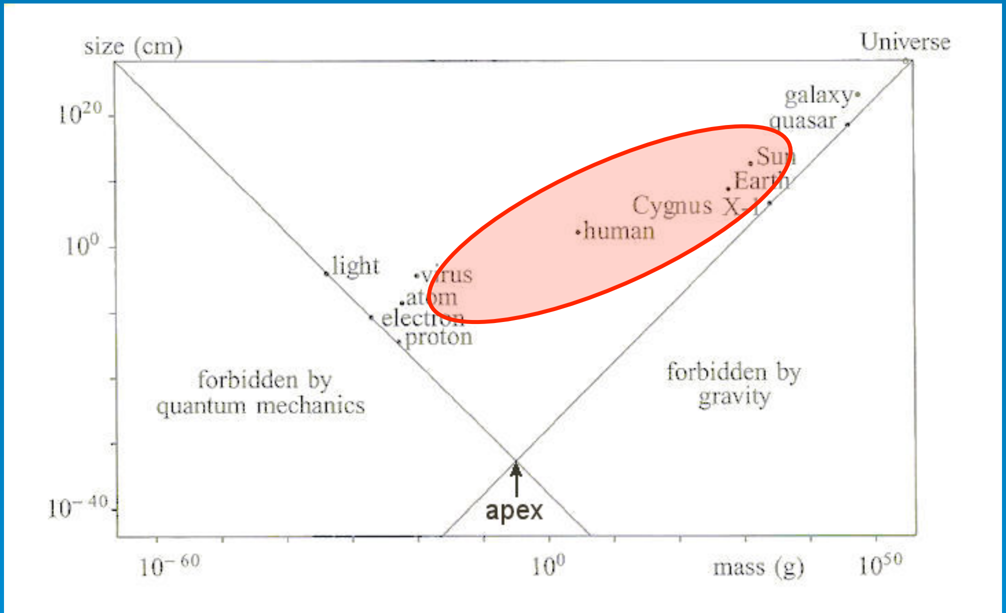
Luca Amendola

University of Heidelberg

Heidelberg 2014

Why testing gravity?

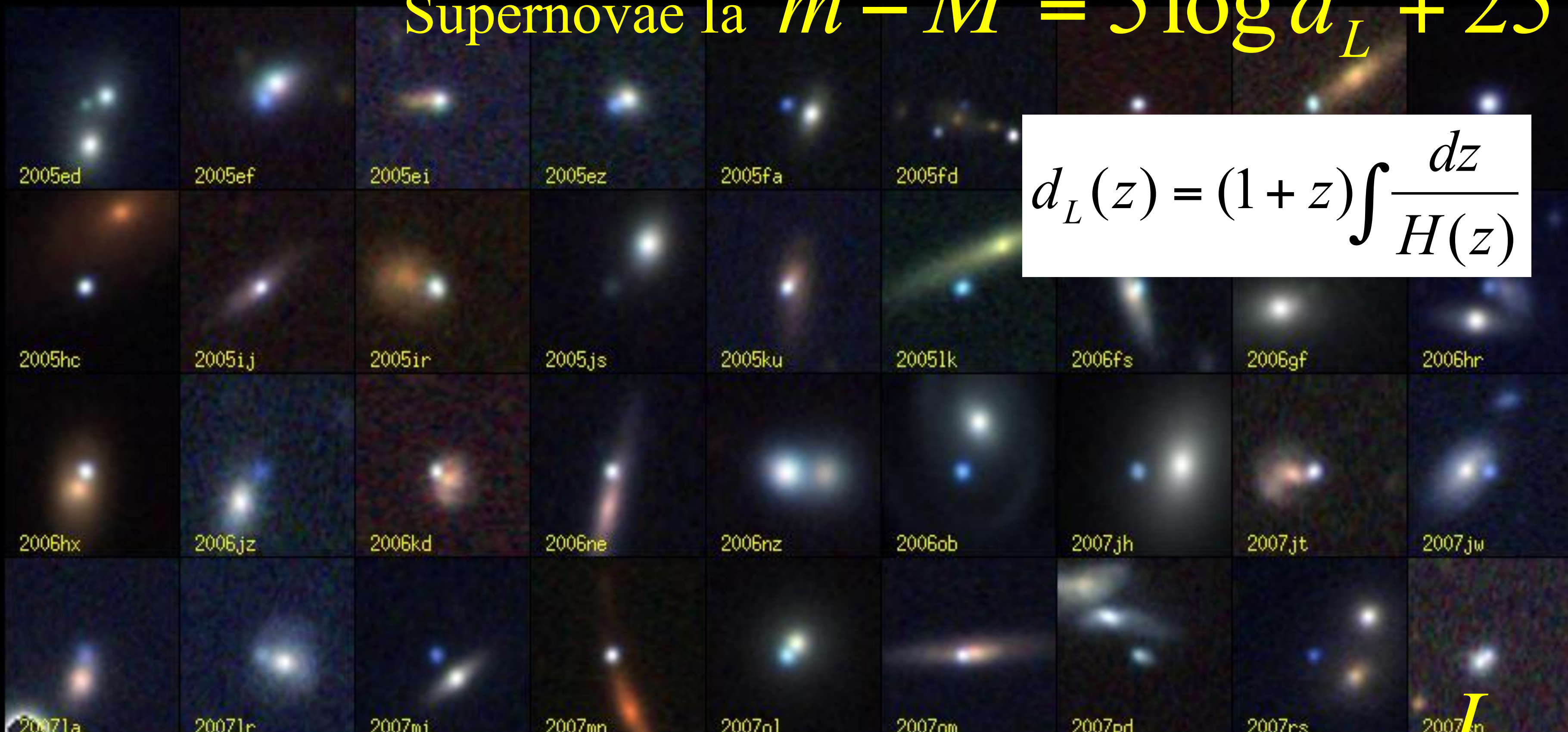
we only directly test gravity within the solar system, at the present time, and with “baryons”



On Space and Time, Edited by Shahn Majid

Lighthouses in the dark

Supernovae Ia $m - M = 5\log d_L + 25$



$$d_L(z) = (1+z)\int \frac{dz}{H(z)}$$

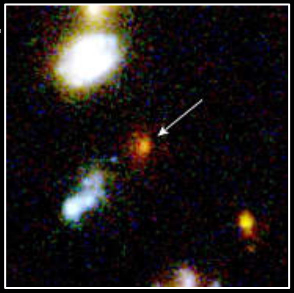
$$d^2 = \frac{L}{4\pi f}$$

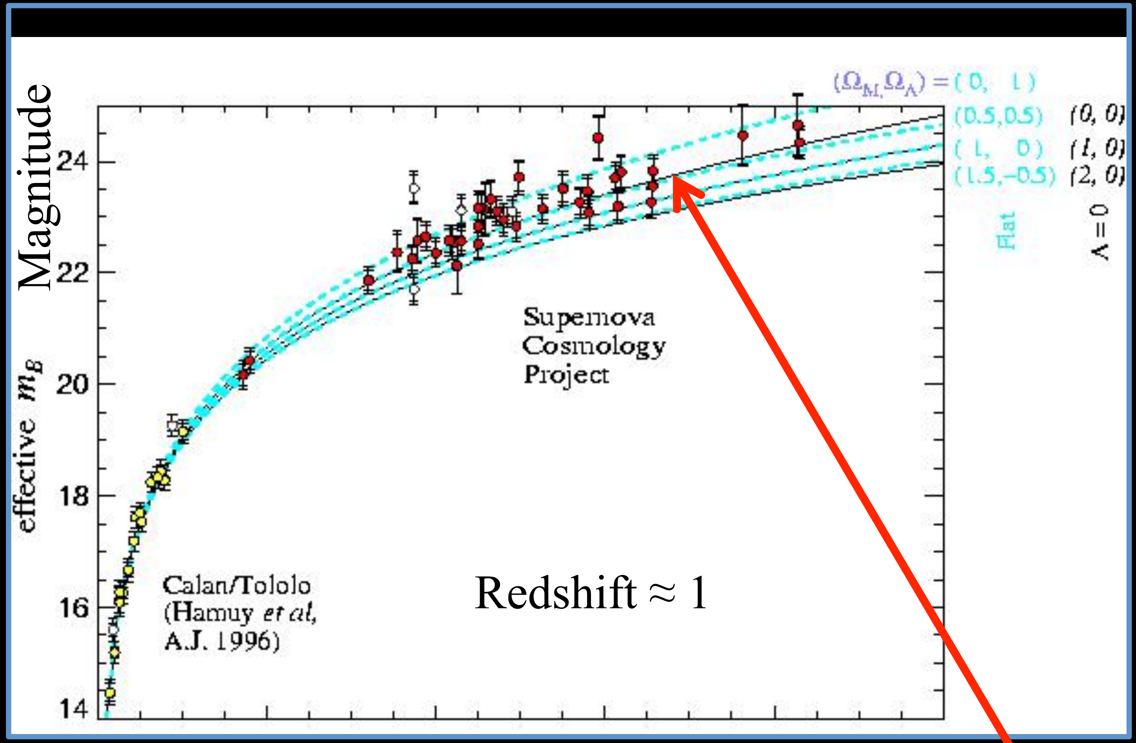
Bug or feature?

Conclusion: SNIa are dimmer than expected in a matter universe !

BUT:

- Dependence on progenitors?
- Contamination?
- Environment?
- Host galaxy?
- Dust?
- Lensing?
-





Ordinary matter

$$d_L(z) = (1+z)\int \frac{dz}{H(z)}$$

Cosmological explanation

There is however a simple cosmological solution

Local Hubble law

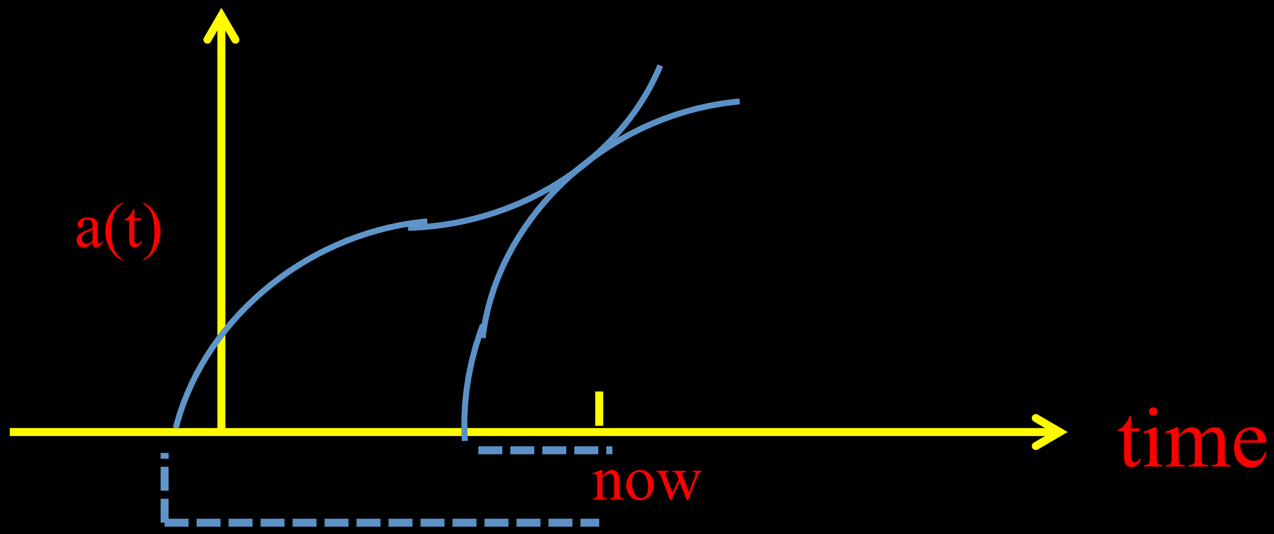
$$r(z) = \frac{z}{H_0}$$

$\longrightarrow$

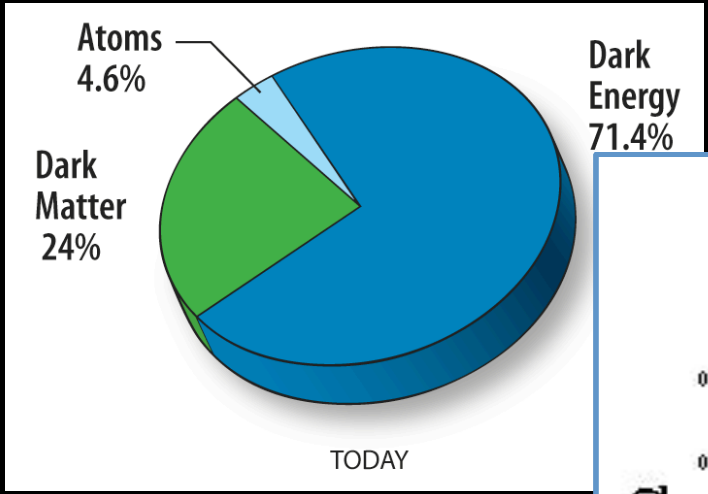
$$r(z) = \int \frac{dz}{H(z)}$$

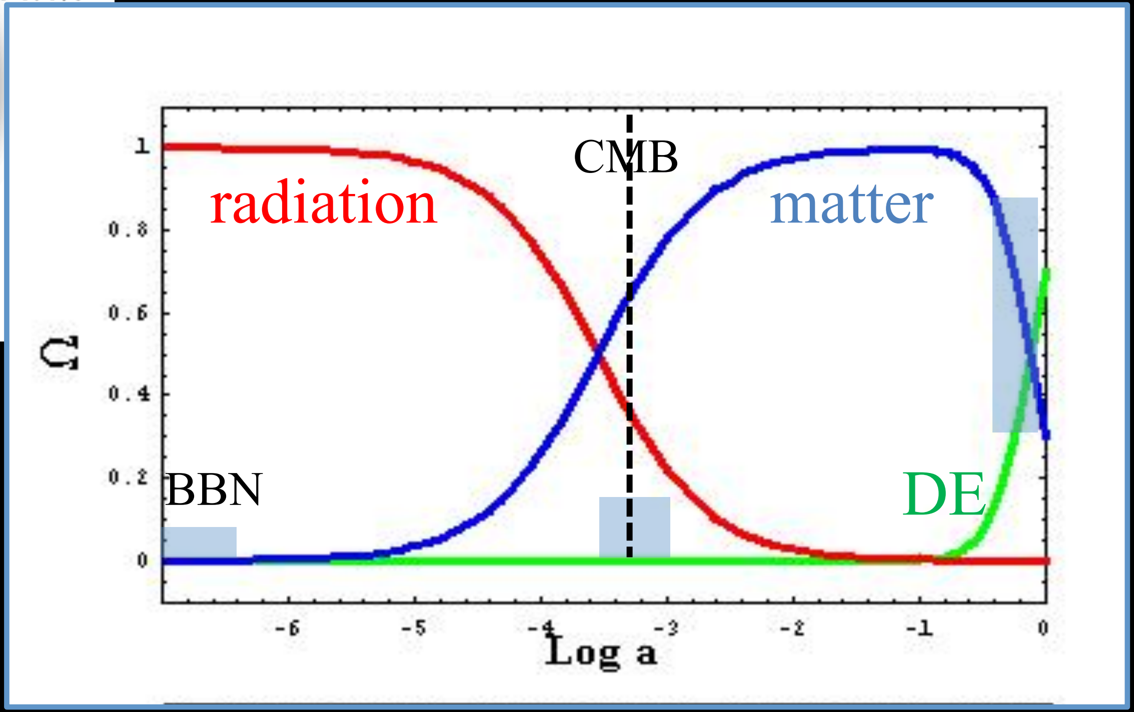
Global Hubble law

If H(z) in the past is smaller (i.e. acceleration), then r(z) is larger: larger distances (for a fixed redshift) make dimmer supernovae



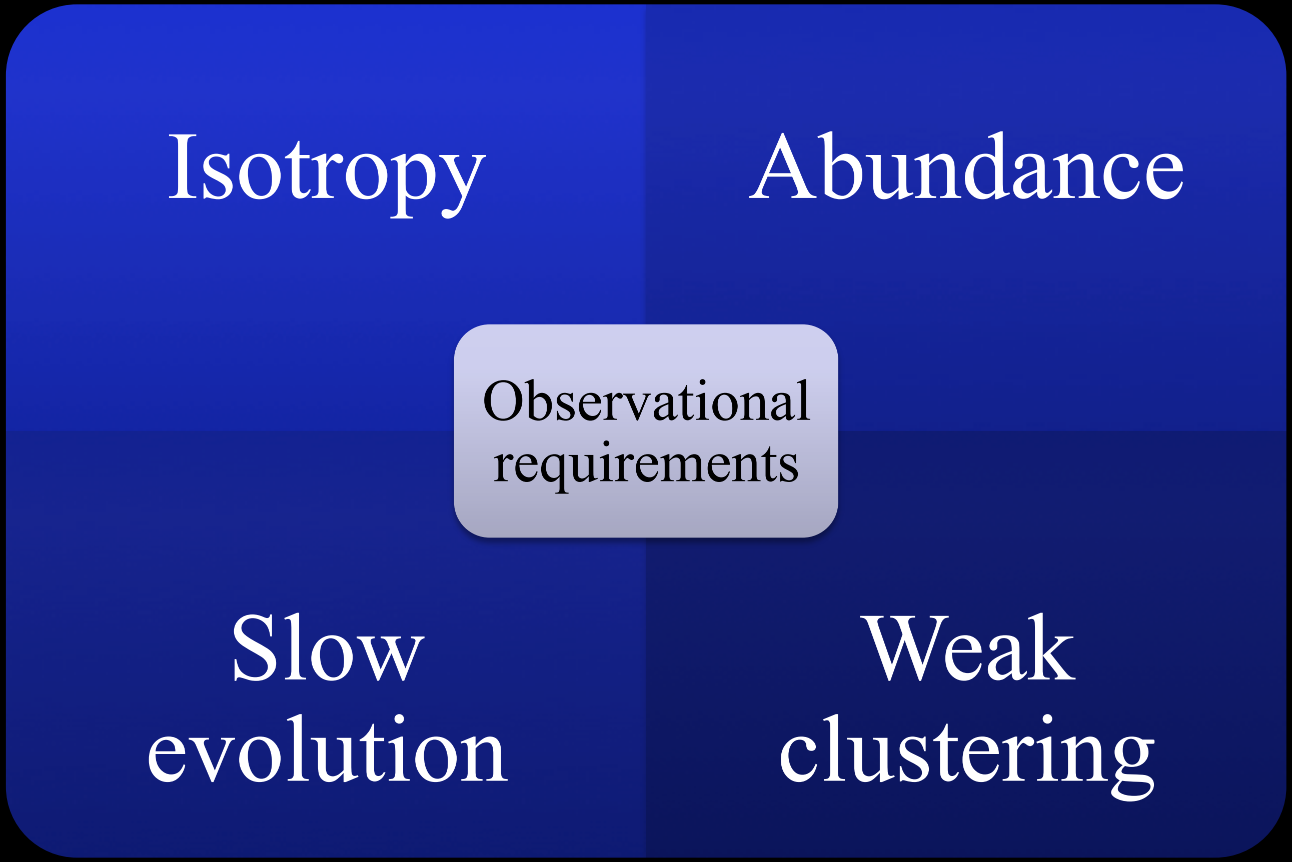
Time view


Atoms
4.6%
Dark
Energy
71.4%
Dark
Matter
24%
TODAY


radiation
matter
CMB
BBN
DE
Ω
Log a
1
0.8
0.6
0.4
0.2
0
-6
-5
-4
-3
-2
-1
0

Prolegomena zu einer jeden künftigen Dark Energy physik

©Kant



Classifying the unknown

1. Cosmological constant
2. Dark energy w=const
3. Dark energy w=w(z)
4. quintessence
5. scalar-tensor models
6. coupled quintessence
7. mass varying neutrinos
8. k-essence
9. Chaplygin gas
10. Cardassian
11. quartessence
12. quiessence
13. phantoms
14. f(R)
15. Gauss-Bonnet
16. anisotropic dark energy
17. brane dark energy
18. backreaction
19. degravitation
20. TeVeS
21. oops....did I forget *your* model?

The past ten years of dark energy models

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

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

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

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

The Horndeski Lagrangian

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

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

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

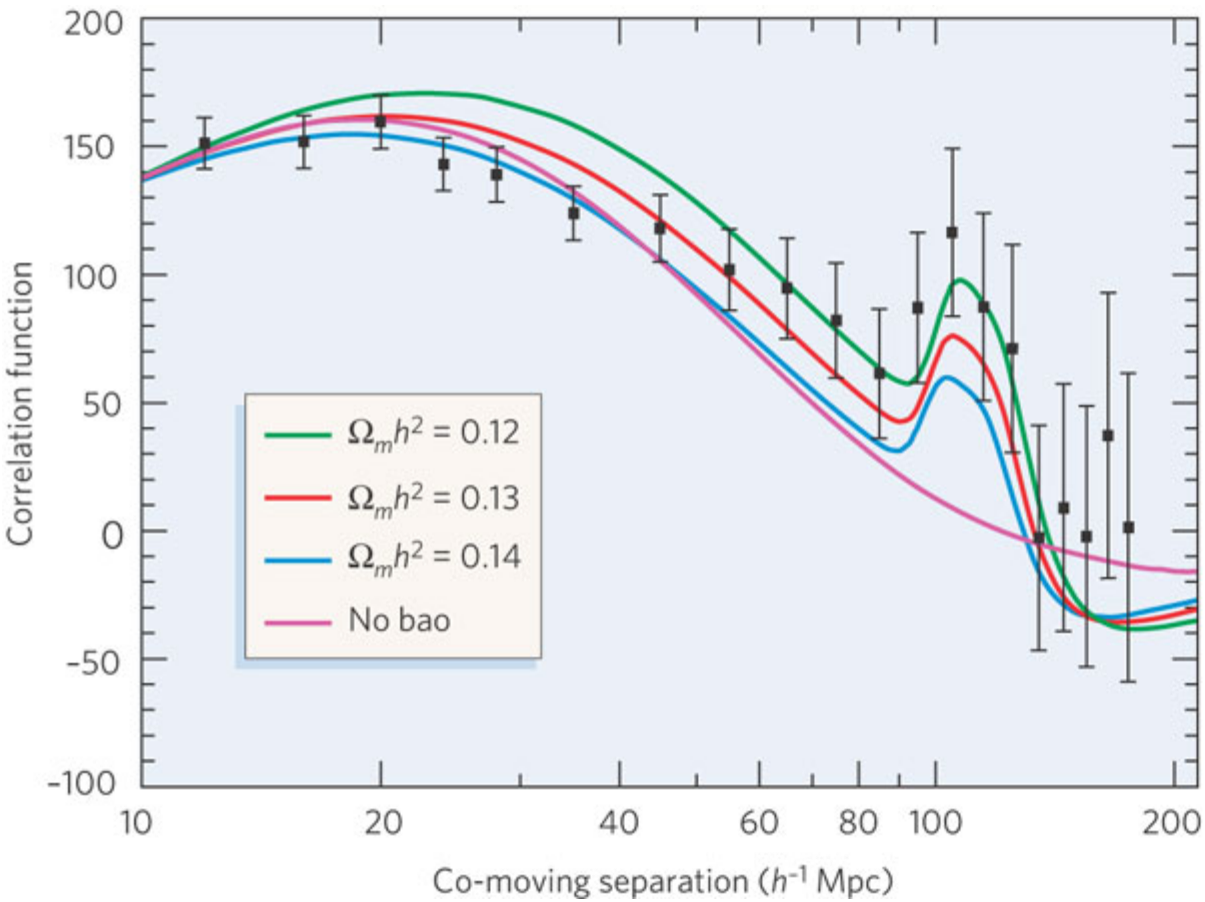
- ✓ First found by Horndeski in 1975
- ✓ rediscovered by Deffayet et al. in 2011
- ✓ no ghosts, no classical instabilities
- ✓ it modifies gravity!
- ✓ it includes f(R), Brans-Dicke, k-essence, Galileons, etc etc etc

The next ten years of DE research

Combine observations of background, linear and non-linear perturbations to reconstruct as much as possible the Horndeski/bimetric model

… or rule it out!

BAO ruler

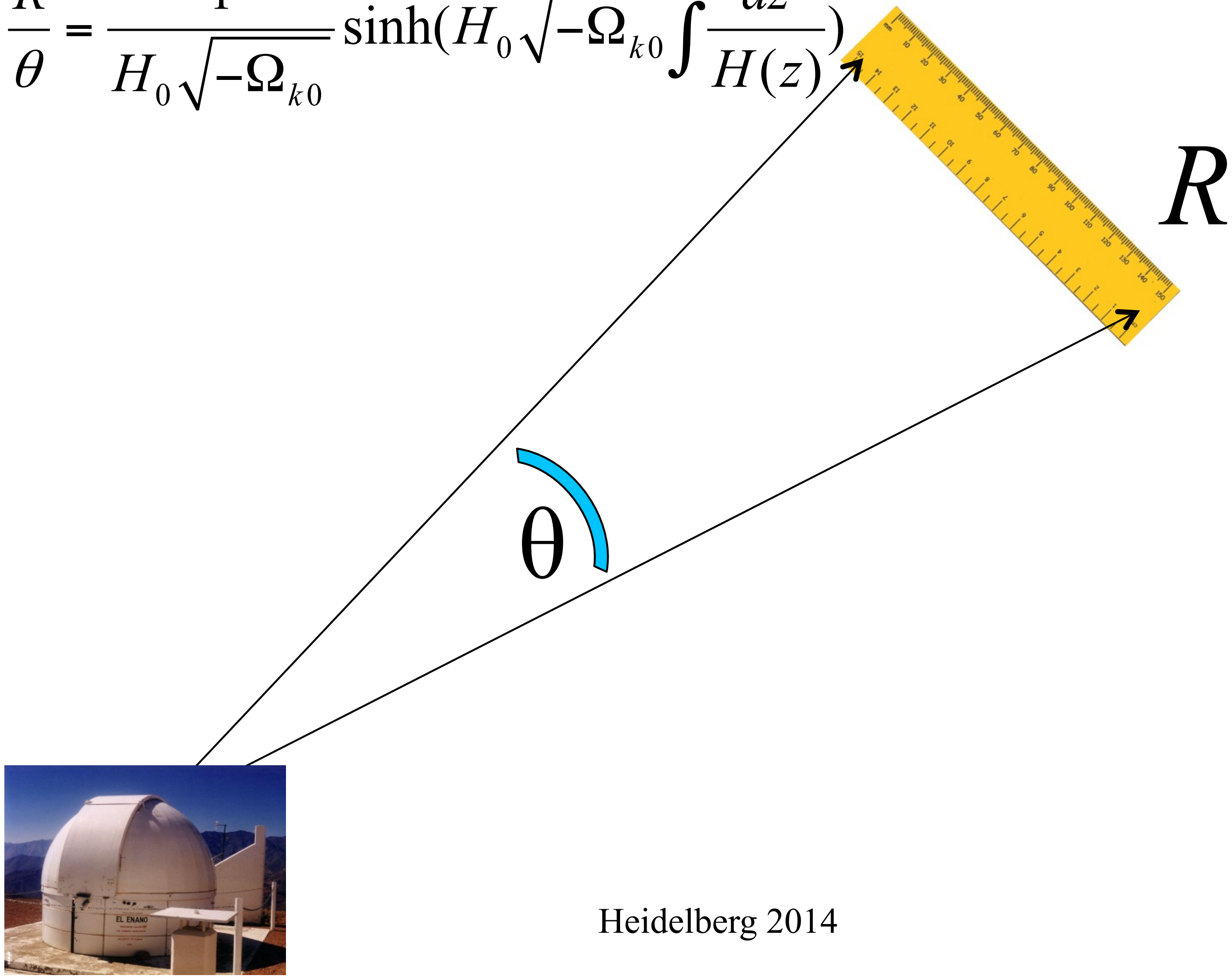


Charles L. Bennett

Nature 440, 1126-1131(27 April 2006)

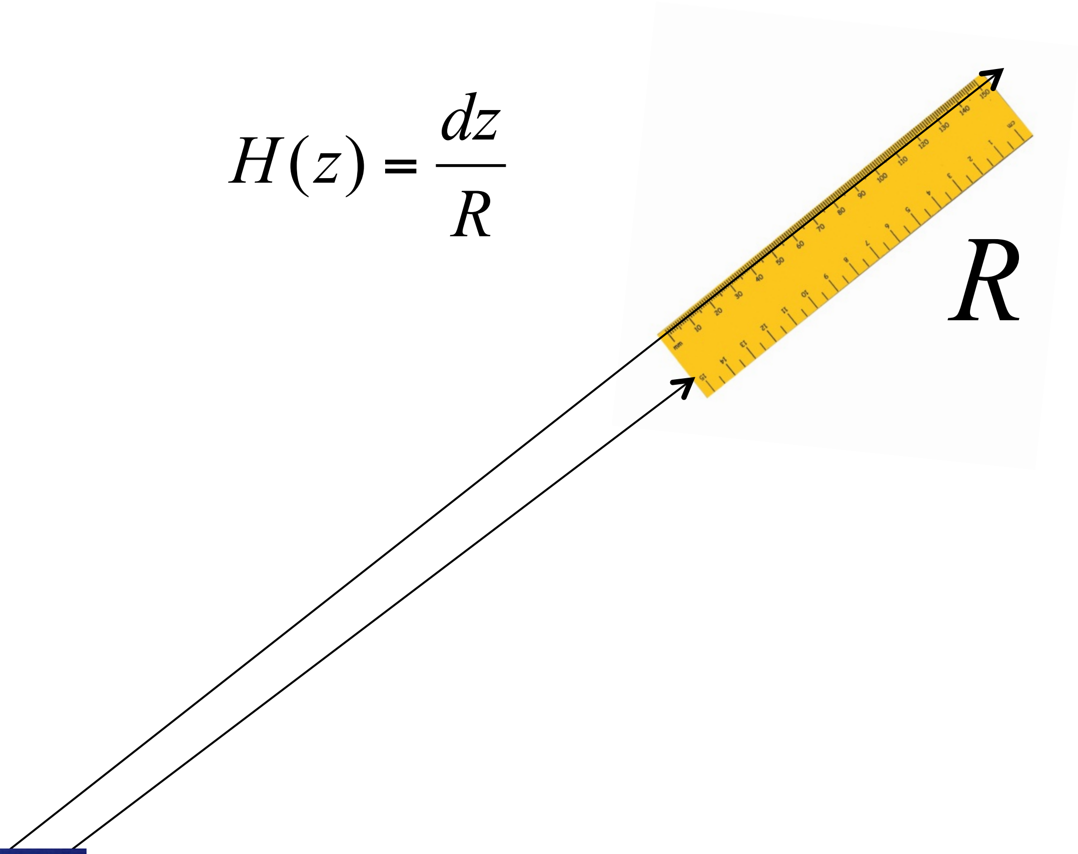
Standard rulers

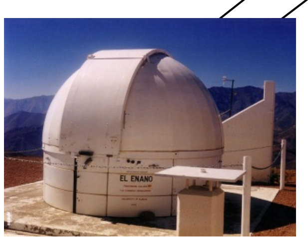
$$D(z) = \frac{R}{\theta} = \frac{1}{H_0\sqrt{-\Omega_{k0}}}\sinh\left(H_0\sqrt{-\Omega_{k0}}\int\frac{dz}{H(z)}\right)$$



Standard rulers

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





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

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

Two free functions

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

At linear order we can write:

- Poisson equation

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

- zero anisotropic stress

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

Two free functions

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

At linear order we can write:

- modified Poisson equation

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

- non-zero anisotropic stress

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

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. Koennig and L. A. 2014

Modified Gravity at the linear level

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

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

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

k = wavenumber

h_i = time-dependent functions

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

Modified Gravity at the linear level

$$h_1 \equiv \frac{w_4}{w_1^2} = \frac{c_T^2}{w_1}, \qquad h_2 \equiv \frac{w_1}{w_4} = c_T^{-2},$$

$$h_3 \equiv \frac{H^2}{2XM^2}\frac{2w_1^2 w_2 H - w_2^2 w_4 + 4w_1 w_2 \dot{w}_1 - 2w_1^2(\dot{w}_2 + \rho_m)}{2w_1^2},$$

$$h_4 \equiv \frac{H^2}{2XM^2}\frac{2w_1^2 H^2 - w_2 w_4 H + 2w_1 \dot{w}_1 H + w_2 \dot{w}_1 - w_1(\dot{w}_2 + \rho_m)}{w_1},$$

$$h_5 \equiv \frac{H^2}{2XM^2}\frac{2w_1^2 H^2 - w_2 w_4 H + 4w_1 \dot{w}_1 H + 2\dot{w}_1{}^2 - w_4(\dot{w}_2 + \rho_m)}{w_4},$$

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

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

The Yukawa correction

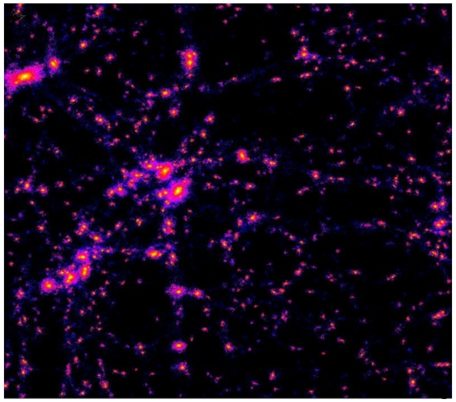
Every Horndeski model induces at linear level, on sub-Hubble scales, a Newton-Yukawa potential

$$\Psi(r) = -\frac{G_{eff} M}{r}\left(1+\beta e^{-r/\lambda}\right)$$

where G_{eff}, β and λ depend on space and time

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

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

All you can ever observe in linear Cosmology

Expansion rate
Amplitude of the power spectrum
Redshift distortion of the power spectrum
Weak lensing

as function of redshift and scale!

How to combine observations to test the theory?

Four model-independent observational quantities

Redshift distortion/Amplitude

$$P_1 = \frac{\text{redshift distortion}}{\text{amplitude}}$$

Lensing/Redshift distortion

$$P_2 = \frac{\text{lensing}}{\text{redshift distortion}}$$

Redshift distortion rate

$$P_3 = \text{rate of redshift distortion}$$

Expansion rate

$$E = \text{expansion rate}$$

Testing the entire Horndeski Lagrangian

A unique combination of model independent observables

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

Observables

Theory

L.A. et al. 1210.0439

Combine lensing and galaxy clustering !

Euclid in a nutshell

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

15,000 square degrees

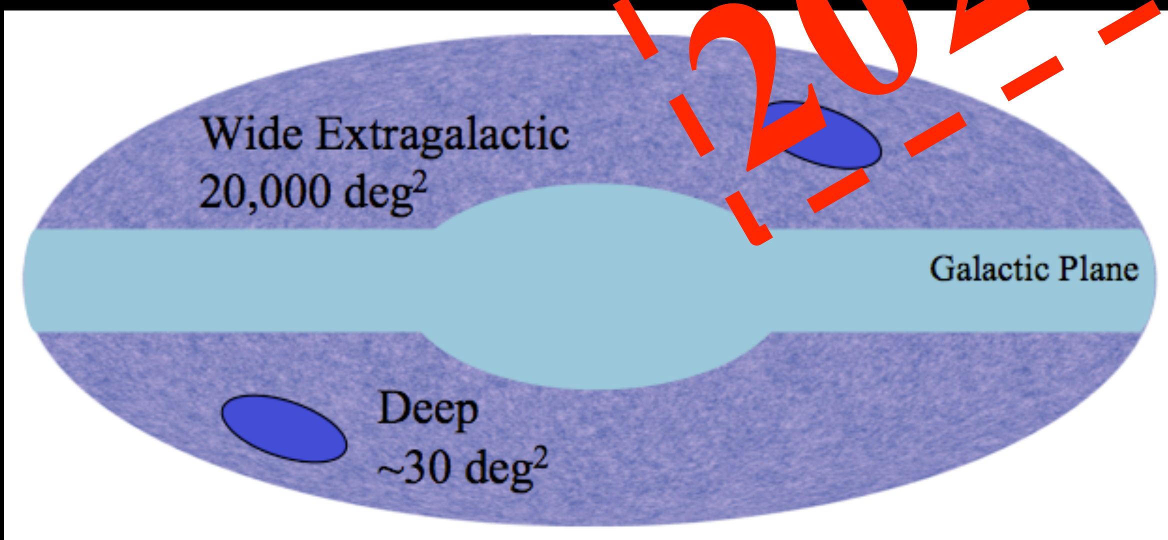
70 million redshifts, 2 billion images

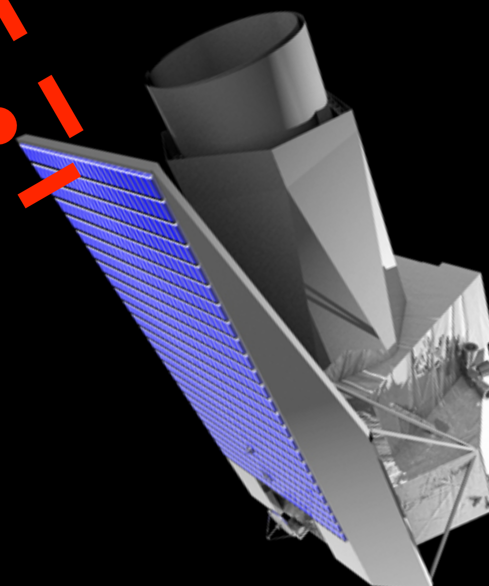
Median redshift z = 1

PSF FWHM ~0.18’’

>1000 peoples, >10 countries

2020!

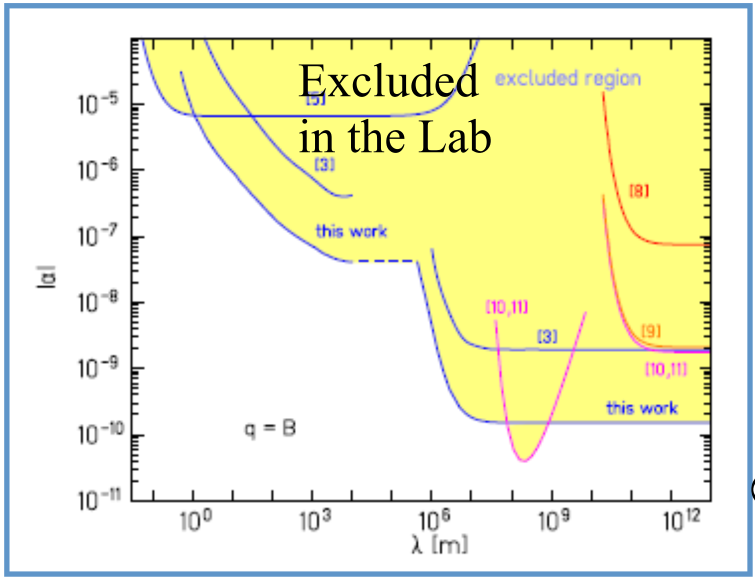


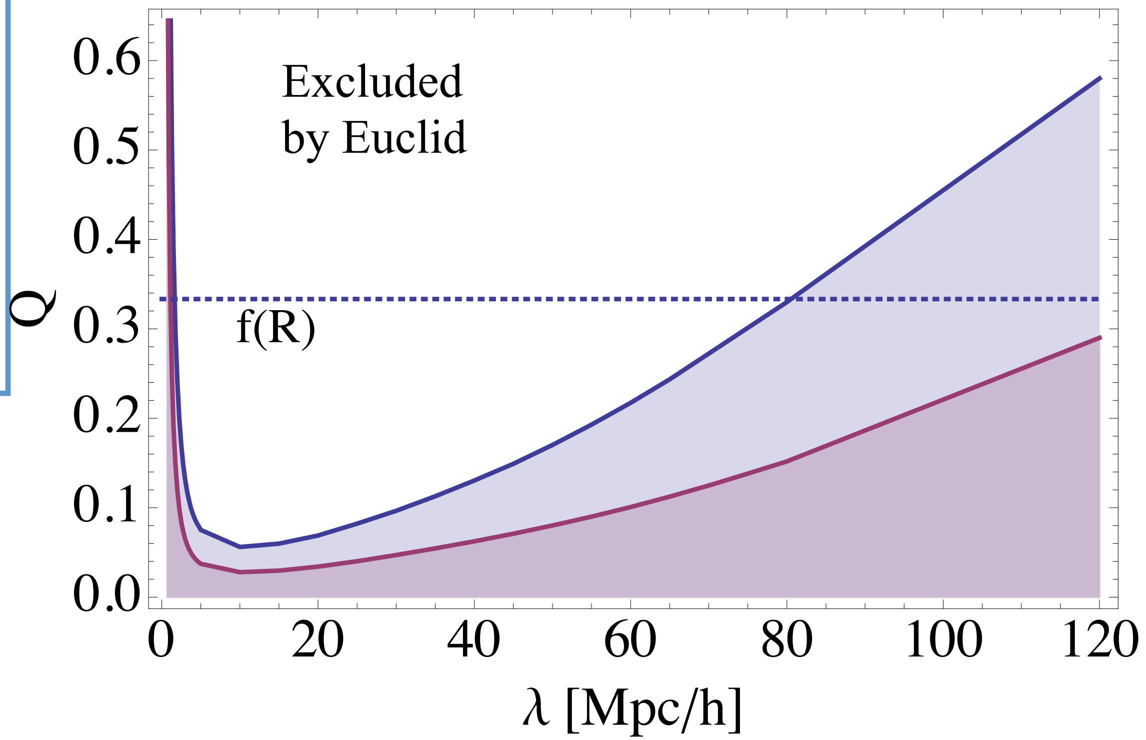


Euclid satellite

arXiv Red Book 1110.3193

Cosmological exclusion plot





$$\Psi(r) = -\frac{GM}{r}(1 + Qe^{-r/\lambda})$$

L. Taddei, L.A., 2014

Three Messages

1

If DE is not a Horndeski field or massive gravity, then…

2

k-binned data are crucial for model-indep tests!
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

Caveats, caveats

1

Universal coupling?

2

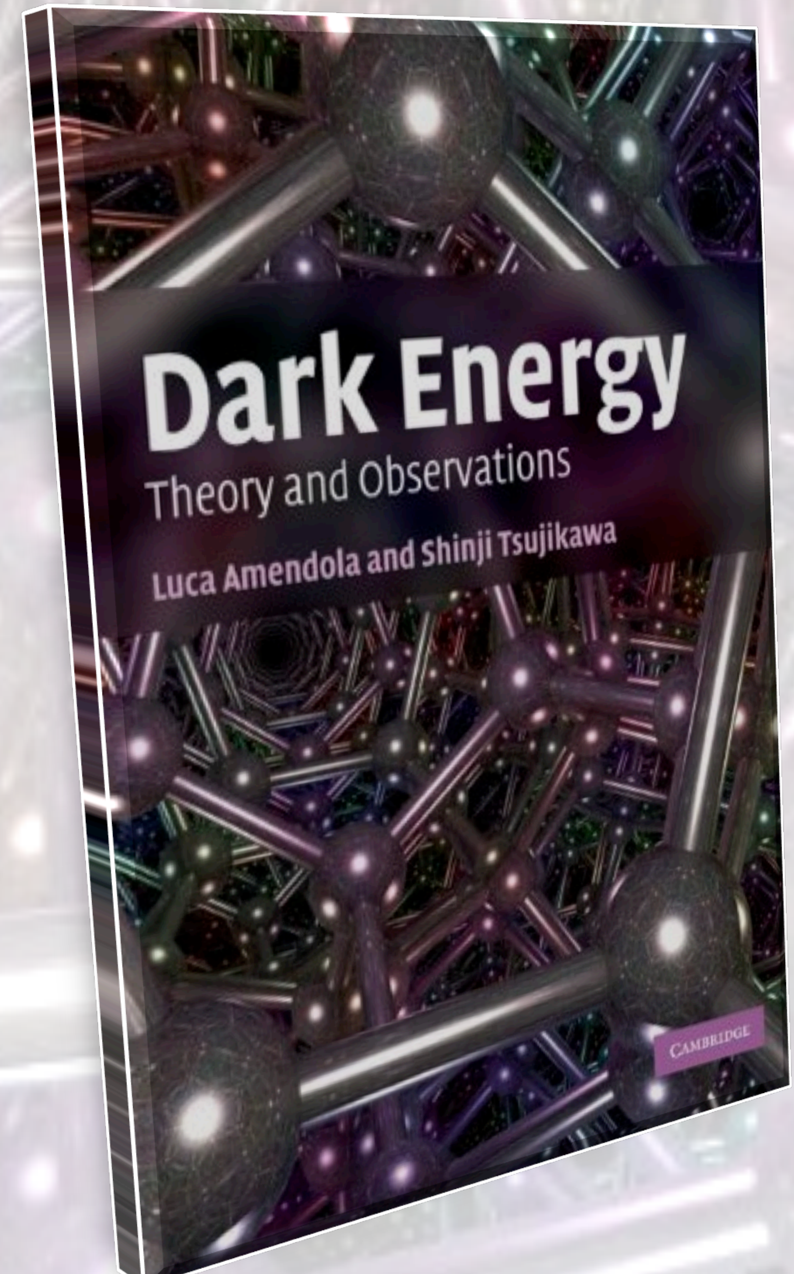
unknown matter properties (sound speed)?

3

window between sound-horizon and non-linearity?

4

quasi static limit?



Cambridge University Press