# Observational probes of dark energy/modified gravity

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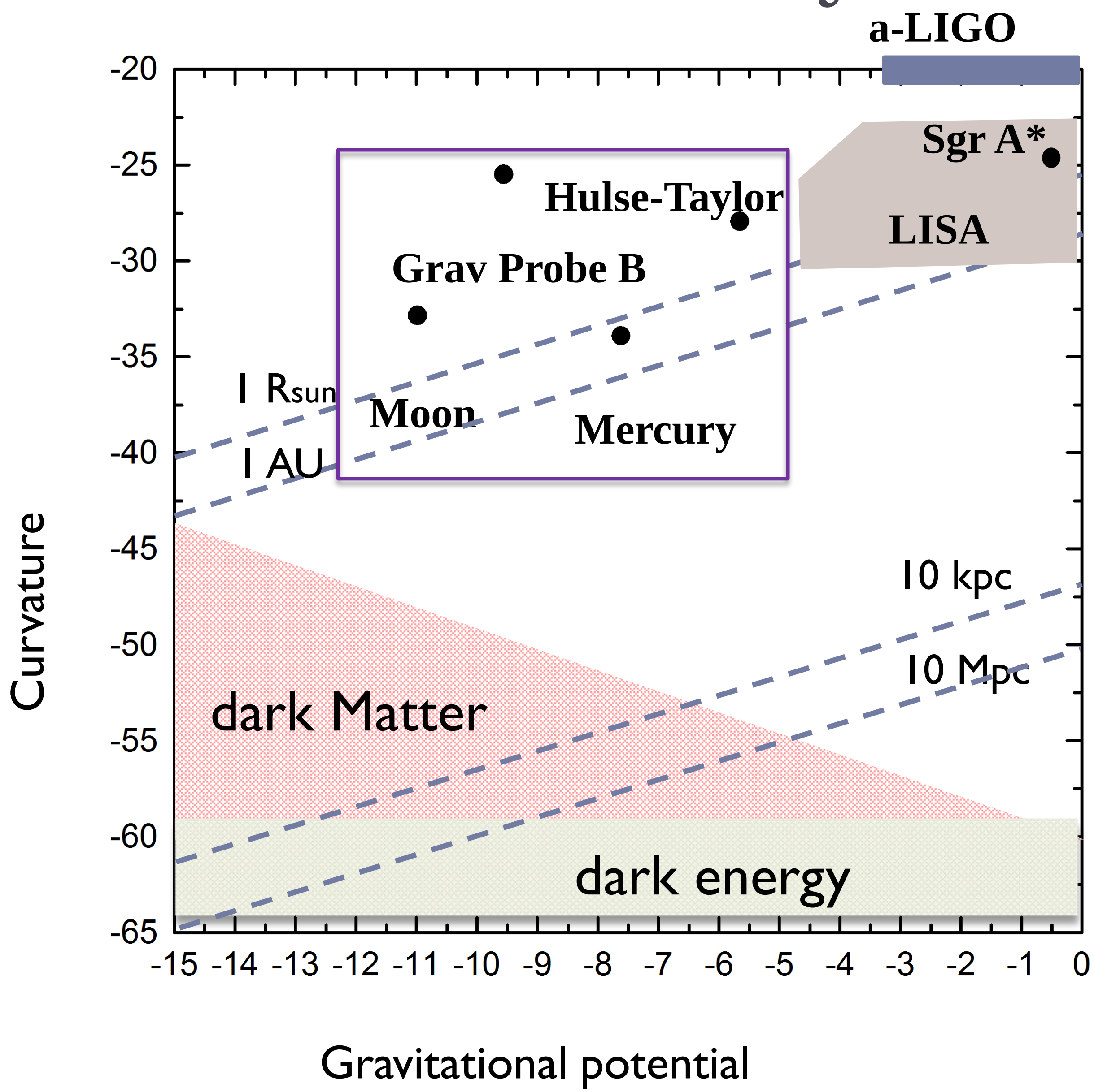
EuCAPT virtual colloquium 12 April

# Tests of General Relativity

Psaltis Living Rev. Relativity 11 (2008), 9
Baker et.al. 1412.3455




curvature

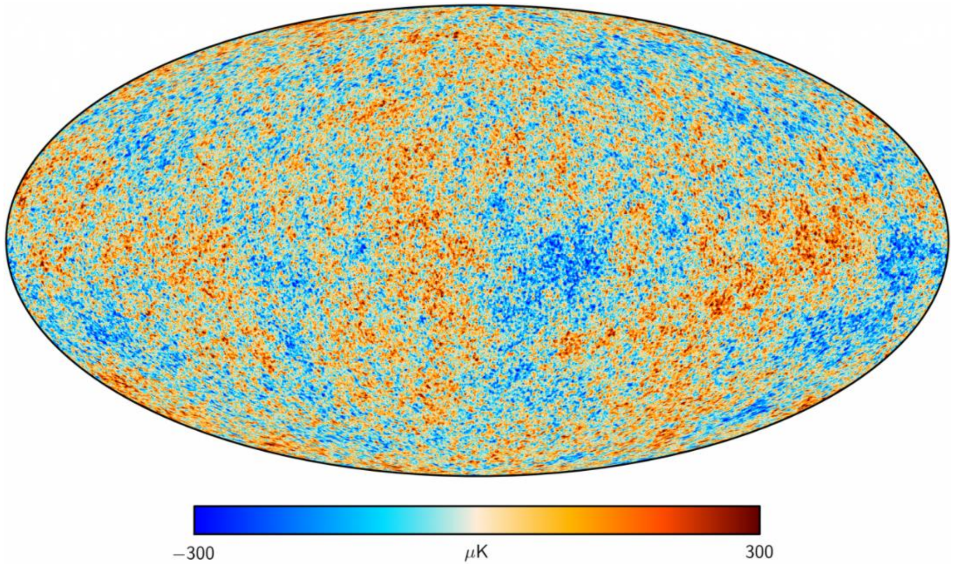
$$R = \frac{GM}{r^3}$$

potential

$$\Psi = \frac{GM}{r}$$

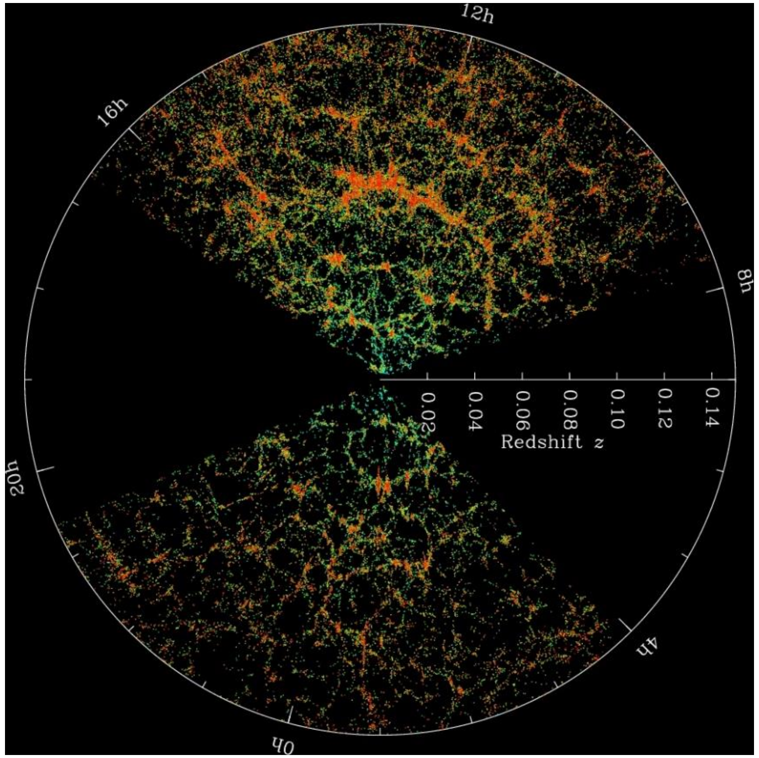
# Cosmological observations

## Cosmic microwave background (CMB)




https://www.cosmos.esa.int/web/planck

## Large scale structure




https://www.sdss.org/

# Standard model of cosmology

- Lambda (L) CDM model

Einstein equations and matter conservation

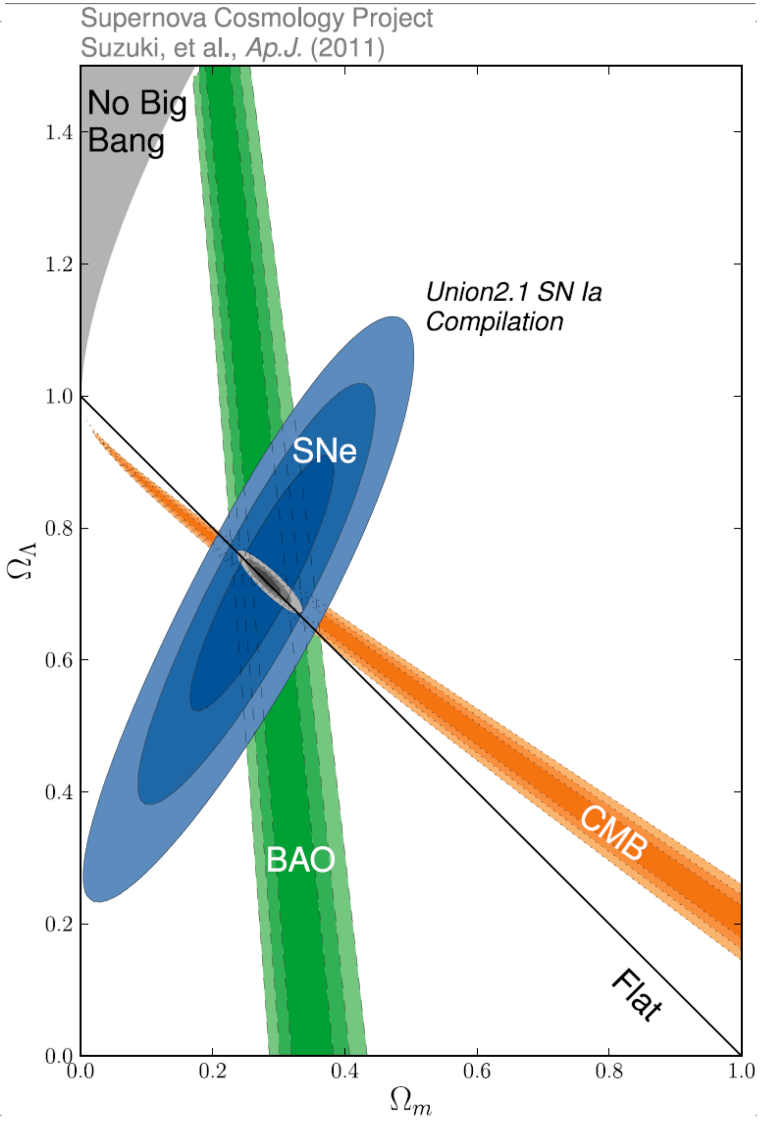
$$H(t)^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{K}{a^2}$$

$$\dot{\rho} + 3H(\rho + P) = 0, \quad \rho = \sum_i \rho_i$$

The background expansion history

$$E(z) = \frac{H(z)}{H_0} \qquad 1 + z = \frac{a_0}{a}$$

$$E(z)^2 = \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda$$



# Linear perturbations

- Geometry (FRW metric + perturbations)

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

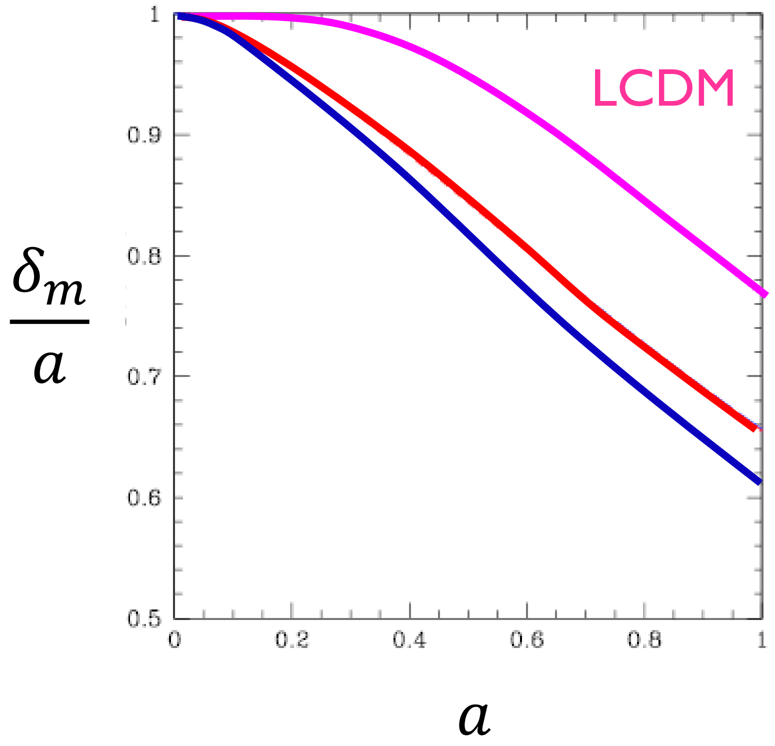
- Matter

$$T^0_0 = -\rho_m(1+\delta_m)$$
$$T^0_i = \rho_m v_{m_i}, \quad \partial^i v_{mi} = \theta_m$$

Energy-momentum conservation

$$\dot{\delta}_m - \frac{1}{a}\theta_m - 3\dot{\Phi} = 0$$
$$\dot{\theta}_m + H\theta_m - \frac{k^2}{a^2}\Psi = 0$$

$$\Rightarrow \quad \ddot{\delta}_m + 2H\dot{\delta}_m = \frac{k^2}{a^2}\Psi$$



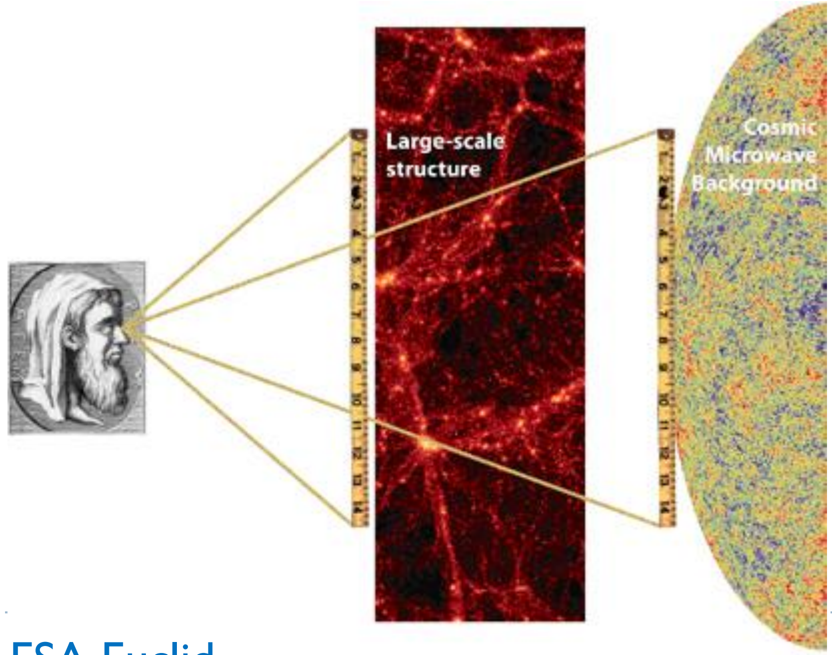

*modified gravity changes the growth of structure formation*

# Observations –background

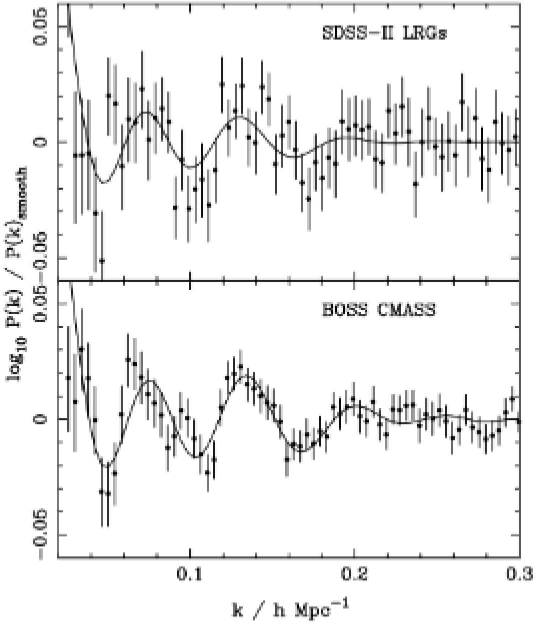
- Background $H(z)$ comoving distance $r(z) = H_0^{-1} \int_0^z \frac{1}{E(z')} dz'$

  Supernovae: luminosity distance

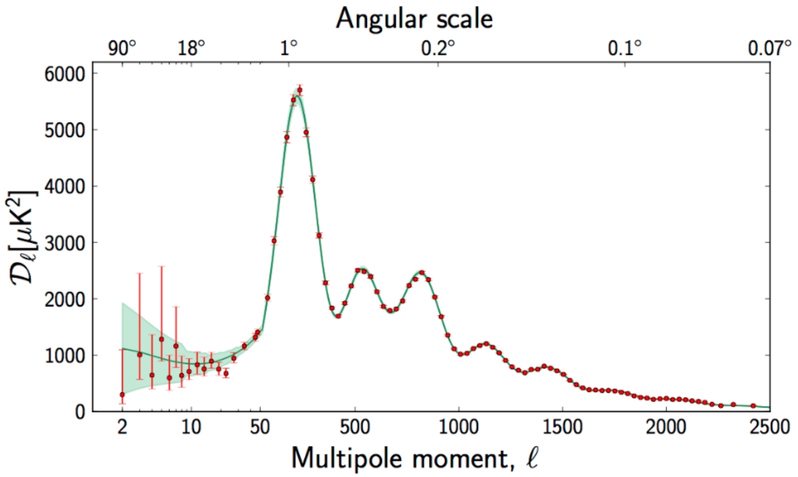
  CMB/Baryon Acoustic Oscillation (BAO): angular diameter distance




ESA Euclid




BOSS




ESA Planck

# Observations

- Weak lensing

Bartelmann & Schneider astro-ph/9912508

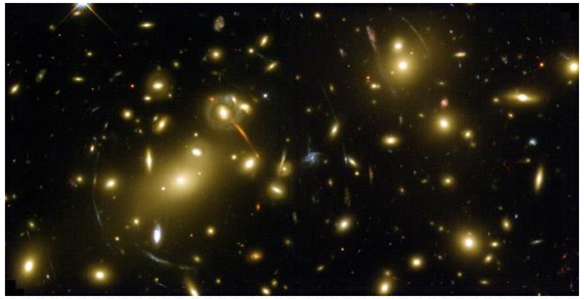
$$ds^2 = a^2\left[-(1+2\Psi)d\eta^2 + (1-2\Phi)\delta_{ij}dx^i dx^j\right]$$

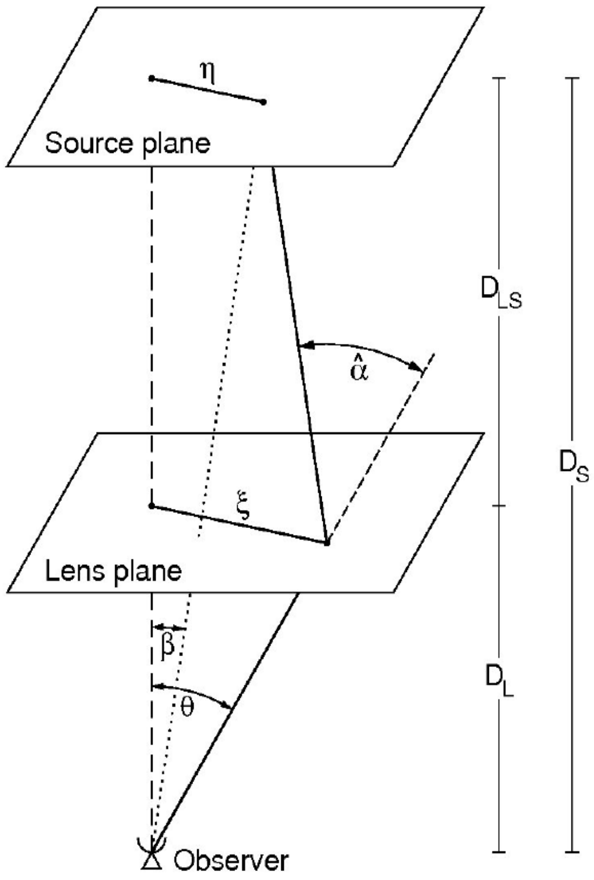
Convergence

$$\kappa(\vec{n}) = \int d\chi \boxed{\frac{D_{sL}D_L}{D_s}} \nabla_\perp{}^2 \phi_W(\eta_0 - \chi, \chi\vec{n}), \quad \phi_W = \frac{1}{2}(\Psi + \Phi)$$

geometry

Galaxy shape is determined by shear which can be computed from convergence





# Observations

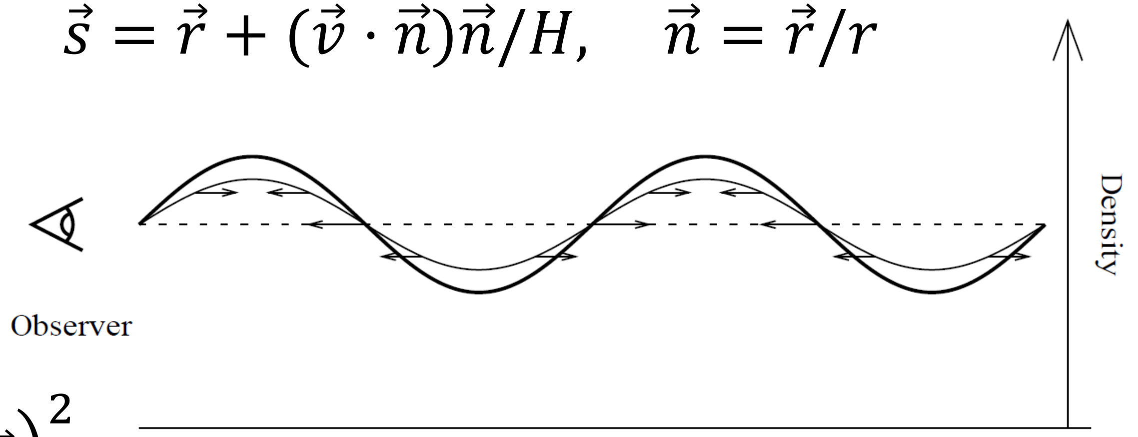
- Redshift distortions

  galaxies have peculiar velocities

  clustering of galaxies in redshift space

  is enhanced along the line of sight

$$\vec{s} = \vec{r} + (\vec{v}\cdot\vec{n})\vec{n}/H, \quad \vec{n} = \vec{r}/r$$




$$\delta^s(k,\mu) = \delta_m(k) - \mu^2\theta_m(k), \quad \mu^2 = \frac{\left(\vec{k}\cdot\vec{n}\right)^2}{k^2}$$

Hamilton astro-ph/9708102

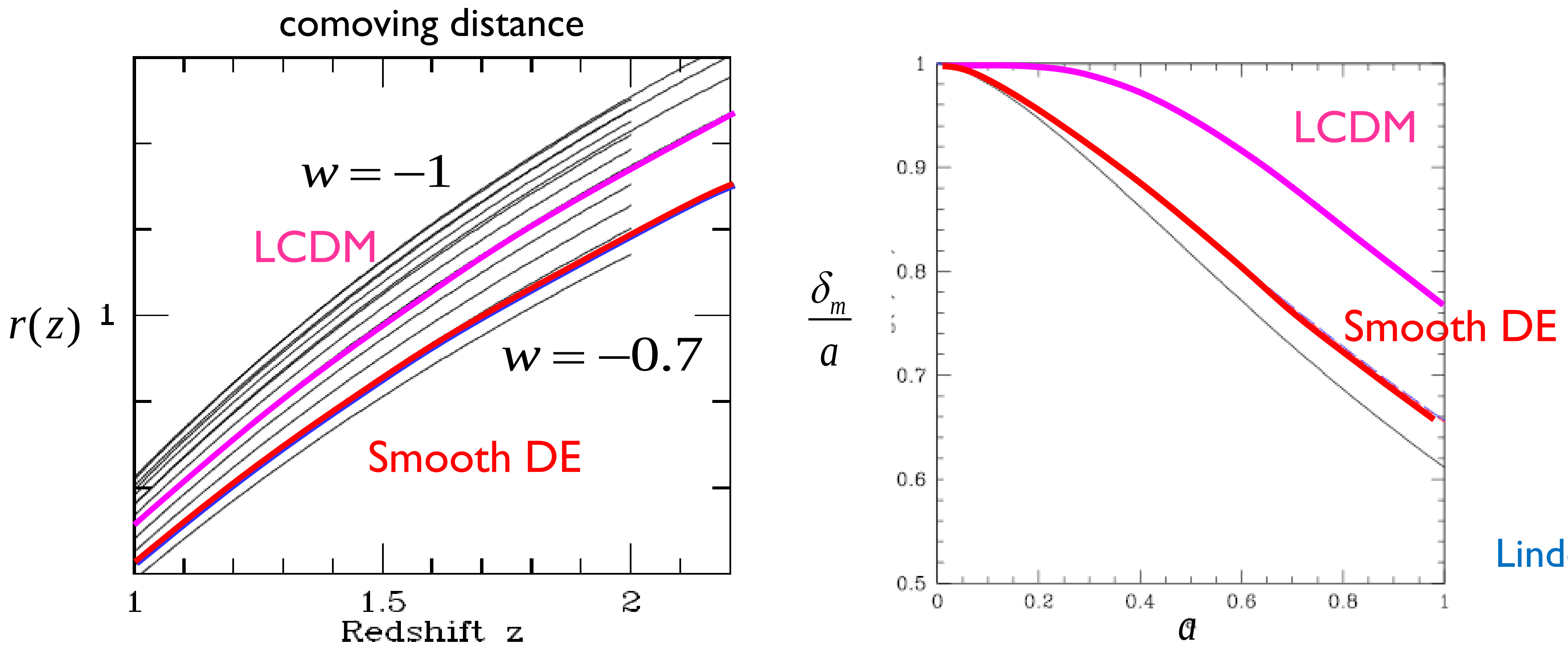
If the continuity equation holds, the velocity divergence is related to the growth rate

$$\delta^s(k,\mu) = \delta_m(k)\left(1 - \mu^2\frac{\theta_m(k)}{\delta_m(k)}\right) = \delta_m(k)\left(1+\mu^2 f\right) \qquad f = \frac{d\ln\delta_m}{d\ln a}$$

# Expansion history v structure growth

- LCDM/Smooth DE

There is a one-to-one correspondence between background expansion history and growth of structure




$$w(z) = \frac{P_{DE}}{\rho_{DE}}$$

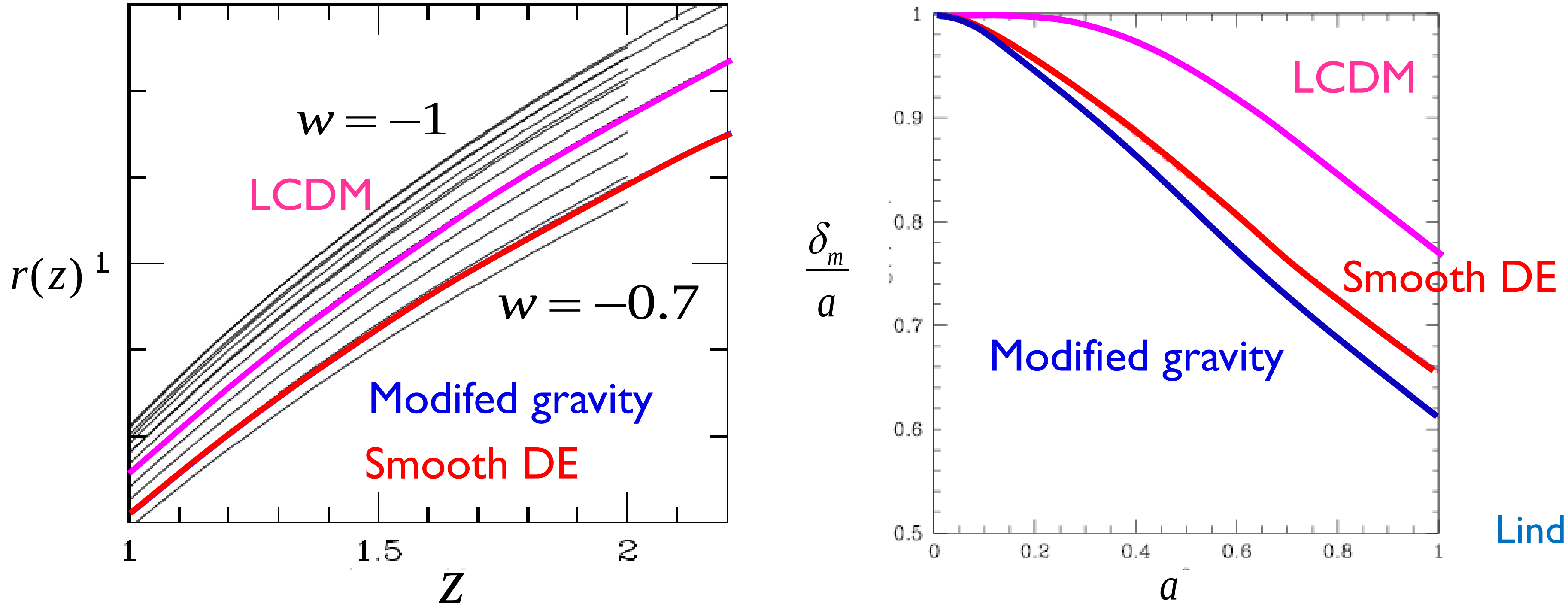
Linder astro-ph/0507263

# Expansion history v structure growth

- Modified gravity

Modified gravity changes the growth of structure formation

Even if it has the same expansion history as smooth DE, structure growth is different

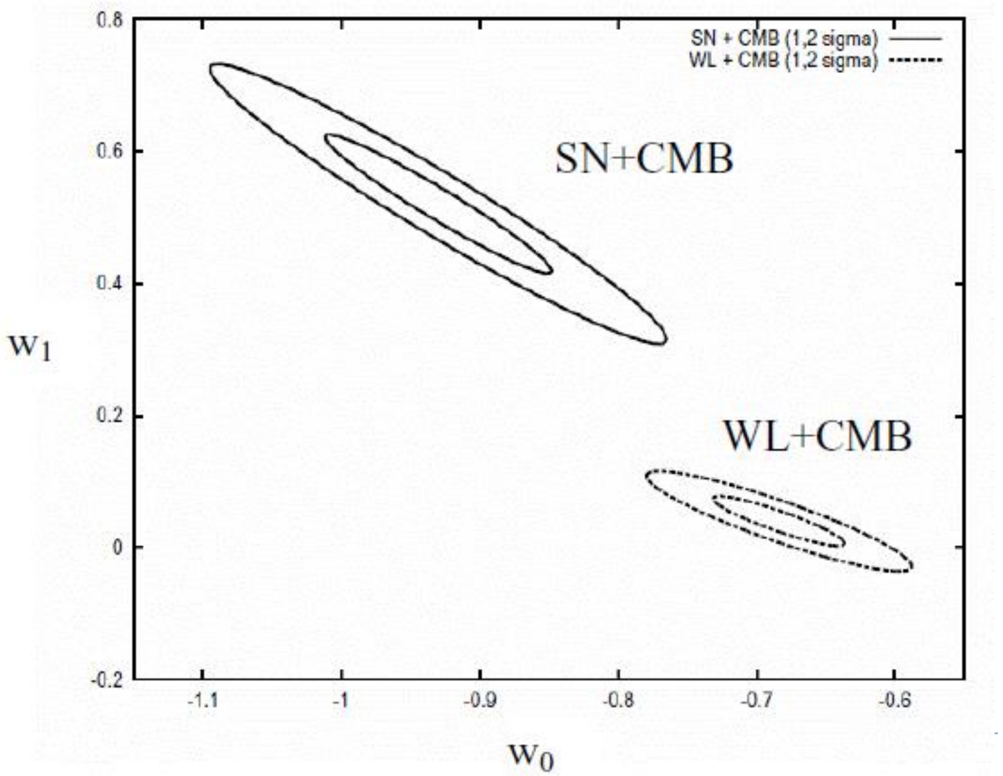



Linder astro-ph/0507263

# Consistency test

Assume that the Universe is described by a modified gravity model but we still try to fit the date using smooth DE

$$w(z) = w_0 + w_1 z,$$




SNe+CMB

SNe+weak lensing

$$w(z) = \frac{P_{DE}}{\rho_{DE}}$$

Inconsistent!

Ishak et.al. astro-ph/0507184

# Consistency relation

Zhang & Jain Phys. Rev. D78 (2008) 063503
Song & KK JCAP 0901(2009) 048

- In GR, gravitational equations are given by

$$H^2 = \frac{8\pi G}{3}\rho_T, \quad \rho_T = \sum_i \rho_i$$

$$\frac{k^2}{a^2}\Phi = 4\pi G a^2 \rho_T \delta_T, \quad \rho_T \delta_T = \sum_i \rho_i \delta_i$$

- Consistency relation

$$\alpha(k,t) = \frac{2k^2}{3a^2 H^2}\frac{(\Phi+\Psi)-\Psi}{\delta_T} = 1$$

background

Weak lensing

Redshift Space Distortion

$$k^2\Psi = \frac{d(a\theta_m)}{dt}$$

Galaxy distribution

$$\delta_g = b_T \delta_T$$

*We have just enough number of observations to check the relation*

# Parametrisation

Amendola et.al JCAP 0804 (2008) 013
Zhao et.al. Phys. Rev. Lett. 103 (2009) 241301

- Background

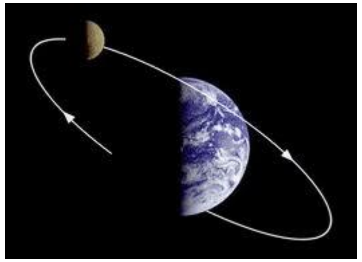
$$F(H^2) = \frac{8\pi G}{3}\rho_m \quad \Rightarrow \quad H^2 = \frac{8\pi G}{3}(\rho_m + \rho_{DE})$$

Equation of state $w_{DE}(z) = \frac{P_{DE}}{\rho_{DE}}$ can be ill-defined for modified gravity as $\rho_{DE}$ can vanish

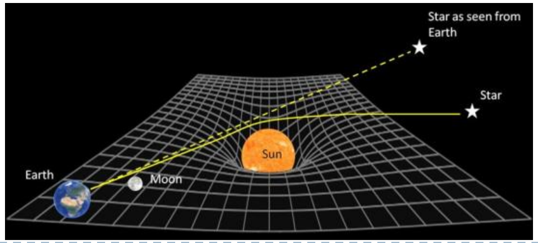
Instead, we can parametrise the effective dark energy density directly $\Omega_{DE}(z) = \frac{\rho_{DE(z)}}{\rho_{crit}}$

- Perturbations

$$k^2\Psi = -4\pi G a^2 \mu(z,k)\rho_m\delta_m$$ : Newton potential

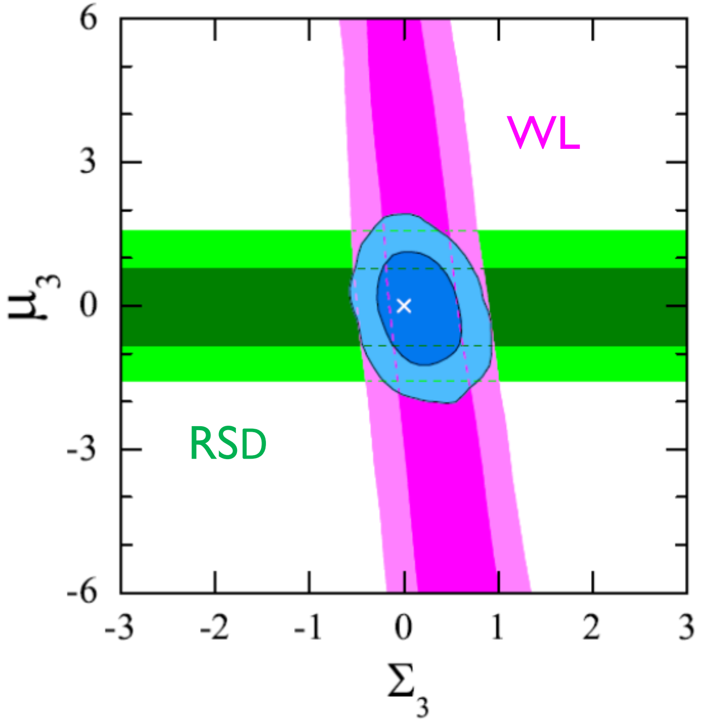


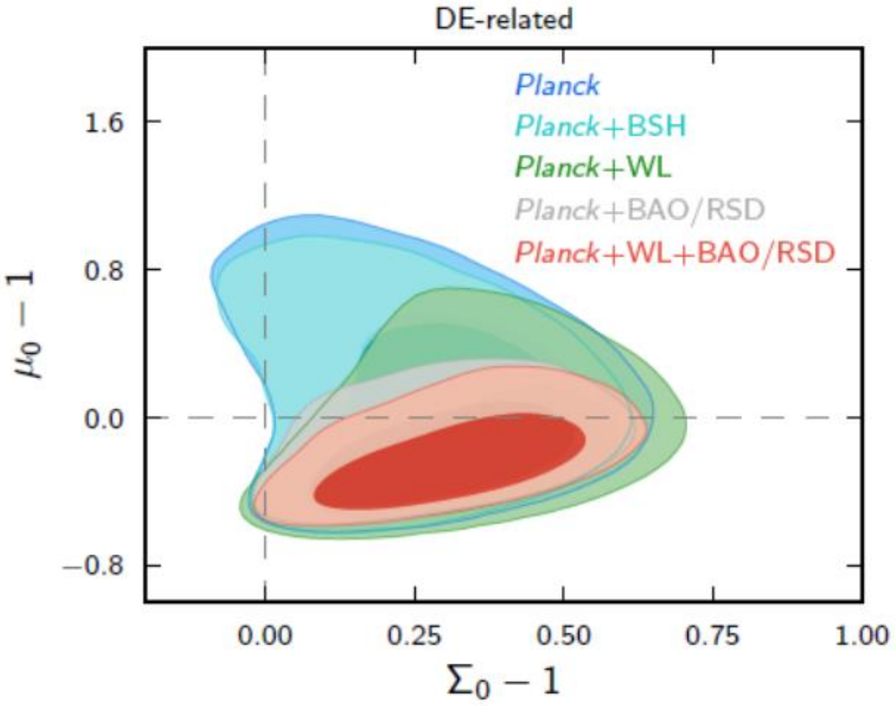
$$k^2(\Psi + \Phi) = -8\pi G a^2 \Sigma(z,k)\rho_m\delta_m$$ : lensing potential



# Current constraints

- Weak Lensing +Redshift distortion




$$\mu(a) = \mu_s(1 + a^s), \Sigma(a) = \Sigma_s(1 + a^s)$$

$$\mu(a, k) = \mu_0 \Omega_L(a), \quad \Sigma(a, k) = \Sigma_0 \Omega_L(a)$$

Song et.al. PRD84 (2011) 083523

Planck 2015 "Modified gravity and dark energy"

- RSD: Redshift space distortions WL: Weak lensing

# From theory to data

Peirone et.al. arXiv:1712.00444
Espejo et.al. arXiv:1809.01121

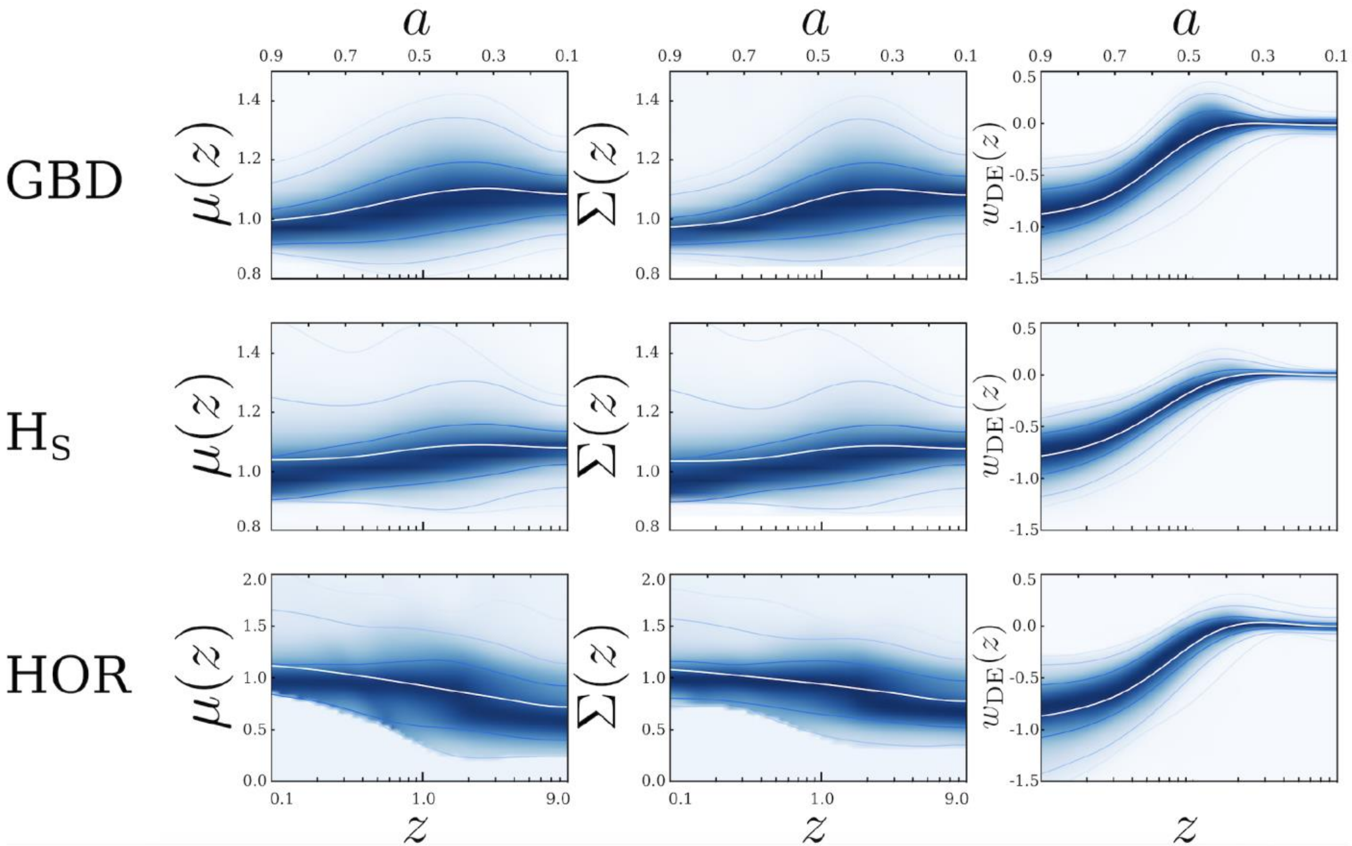
- Effective theory of dark energy Gubitosi et.al. arXiv:1210.0201

General description of the background and linear perturbations in a scalar-tensor theory

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

a random sample of these functions

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

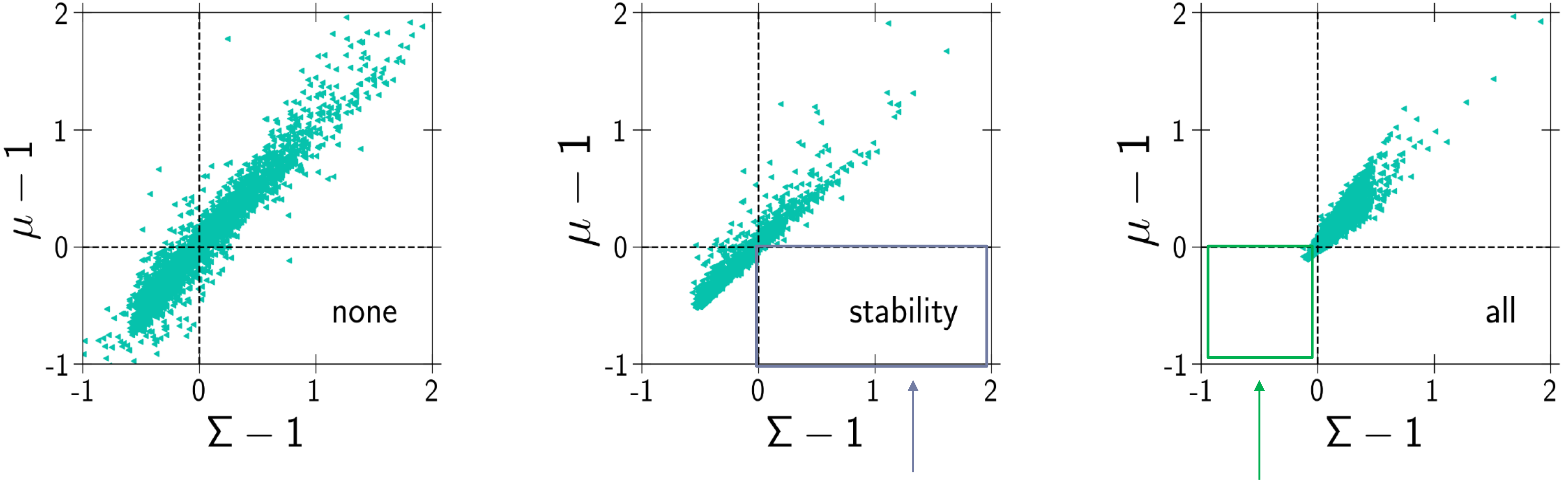


# The role of stability and observational prior

Peirone et.al. arXiv:1712.00444

- Horndeski theory (the most general scalar tensor theory with 2nd order e.o.m)

  gravitational wave constraints $-3 \times 10^{-15} < \frac{c_{\rm GW}}{c} - 1 < 7 \times 10^{-16}$




Stability condition removes this part

Observational prior removes this part

# "Tensions" with LCDM – Hubble constant

- Local measurement of Hubble constant

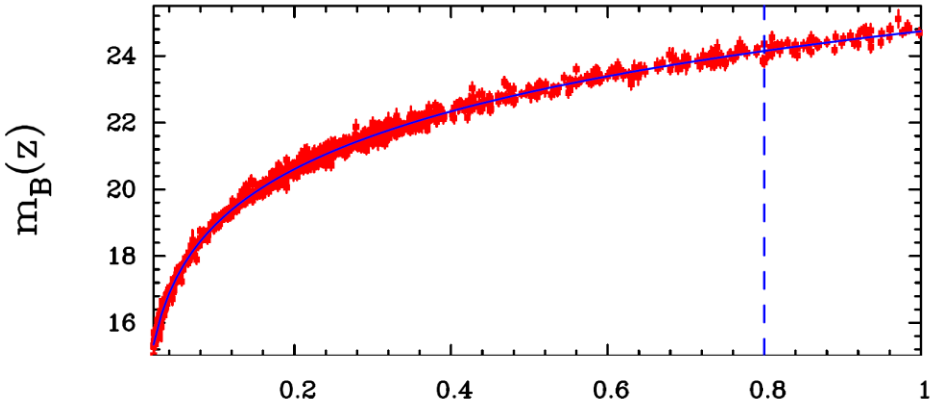
$$m = M + 25 + 5\log_{10} D_L(z),$$
$$= -5a + 5\log_{10} c\hat{d}_L(z)$$

$$5a = -(M + 25 - 5\log_{10} H_0)$$
$$\hat{d}_L(z) = H_0 D_L(z)/c$$

m: apparent magnitude, M: absolute magnitude

- Pantheon SNe   Efstathiou arXiv:2103.08723

$$a_B = 0.71273 \pm 0.00176$$




- Local distance ladder

$$M_B^0 = -19.253 \pm 0.027 \text{ mag}$$

SH0ES collaboration
Riess et.al. arXiv:2112.04510

⇒ $$\mathrm{H}_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

5 sigma tension with LCDM + Planck

$$\mathrm{H}_0 = 67.4 \pm 0.5 \text{ (Planck Collaboration et al. 2020)}$$

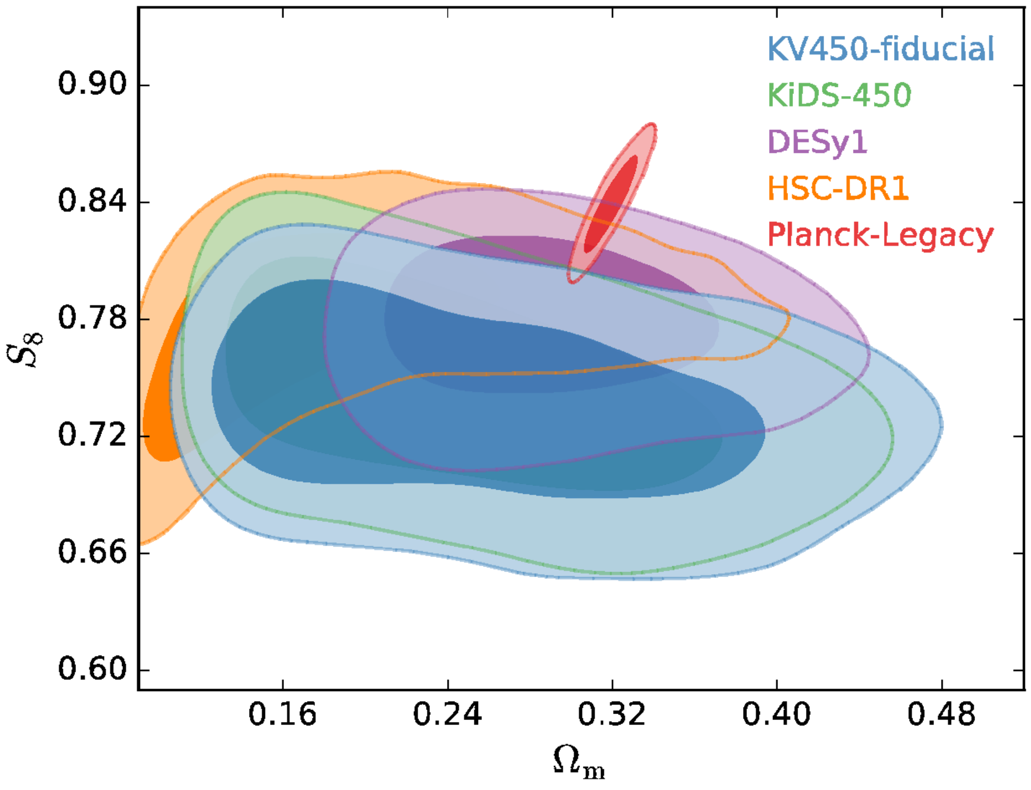
# “Tensions” with LCDM – weak lensing

- Weak lensing

The amplitude of weak lensing is determined by the S8 parameters

$$S_8 \equiv \sigma_8 \sqrt{\Omega_\mathrm{m}/0.3}$$

$\sigma_8$ : amplitude of fluctuations




The prediction from CMB is slightly larger than the values from WL surveys.
CMB constraint here assume LCDM

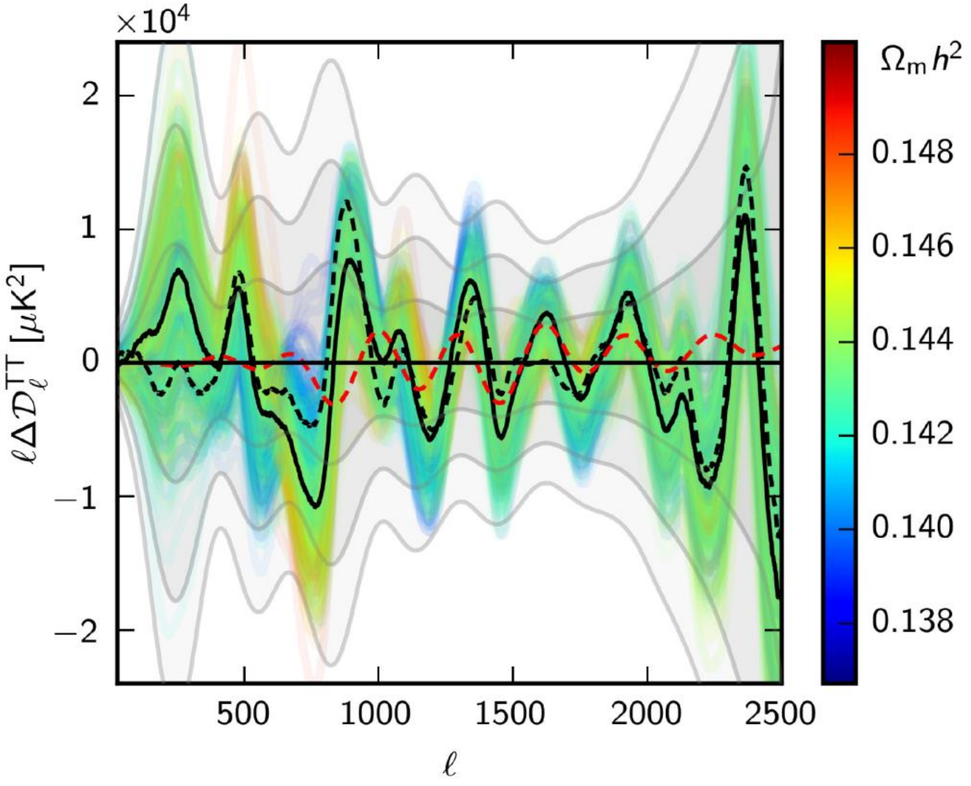
DES: https://www.darkenergysurvey.org/; HSC: https://www.naoj.org/Projects/HSC/;
KiDS: http://kids.strw.leidenuniv.nl/DR3/lensing.php

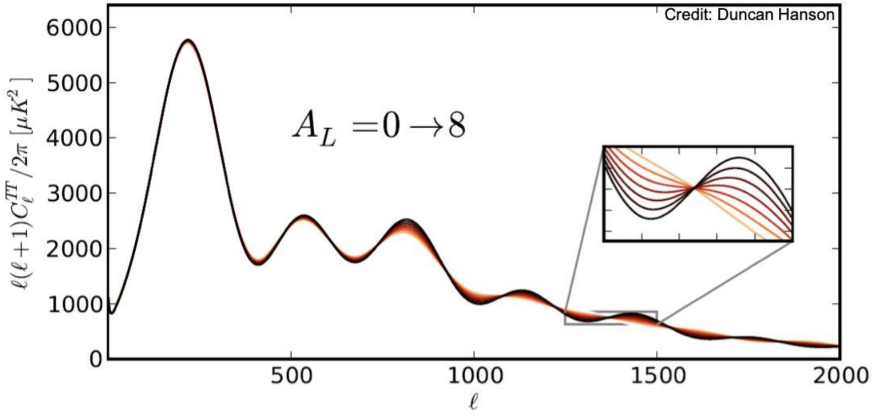
# “Tensions” with LCDM – CMB lensing

- CMB temperature power spectrum

The Planck CMB temperature power spectrum is well fitted by LCDM but at high ell, there are residual oscillations

CMB peaks are smeared out by CMB lensing. These residuals are well fitted if CMB lensing amplitude is larger than that in LCDM




$$\tilde{C}_\ell^{\phi\phi} = A_L C_\ell^{\phi\phi}$$

$$A_L = 1.243 \pm 0.096$$

Planck 2018 arXiv:1807.06209

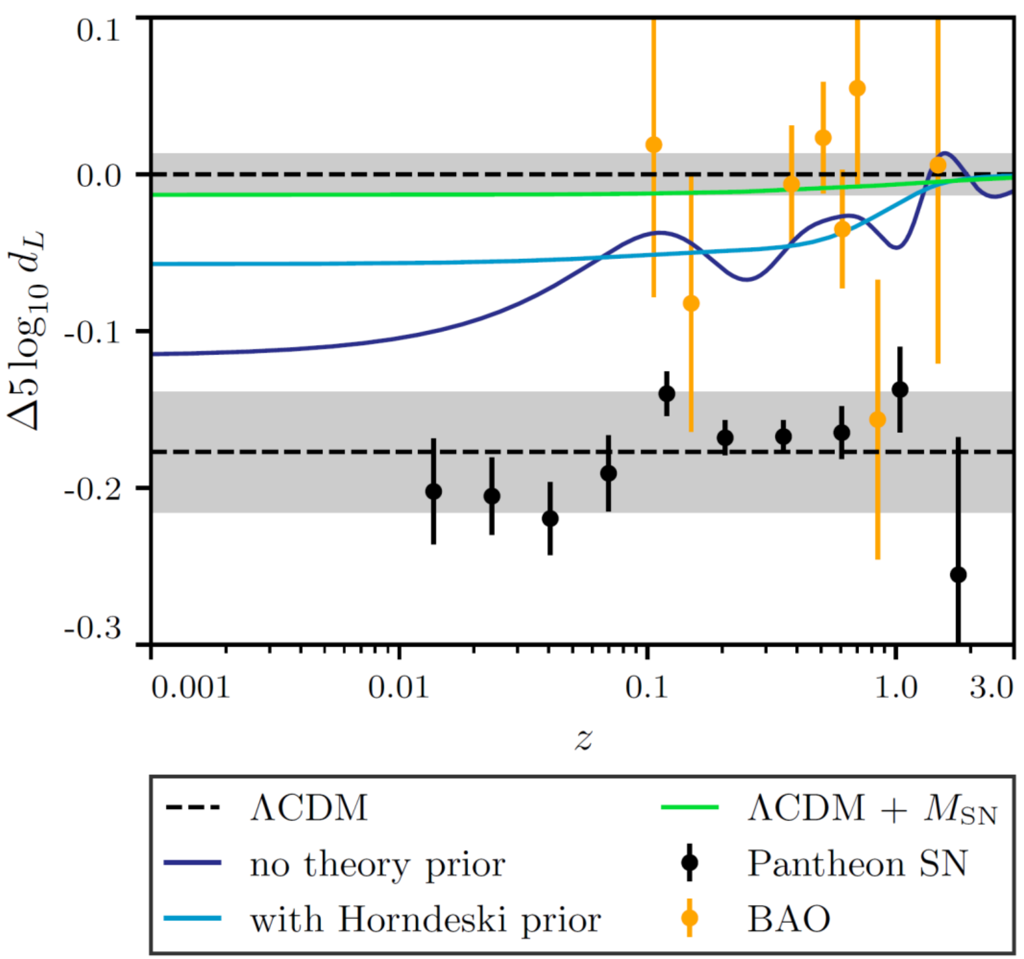
# Hubble constant tension in extended cosmologies

- Hubble constant tension

  The luminosity distance inferred from CMB and BAO does not agree with the one calibrated from SNe with the prior on the absolute magnitude from the local distance ladder

  This makes it hard for late time modifications to fully resolve the tension even though the fit can be improved from LCDM

  A prior on $H_0$ can lead to a inconsistent result
  The proper way is to put a prior on the absolute magnitude  Efstathiou arXiv:2103.08723




- Pogosian, Raveri, KK, Martinelli Silvestri, Zhao 2107.12990, 2107.12992

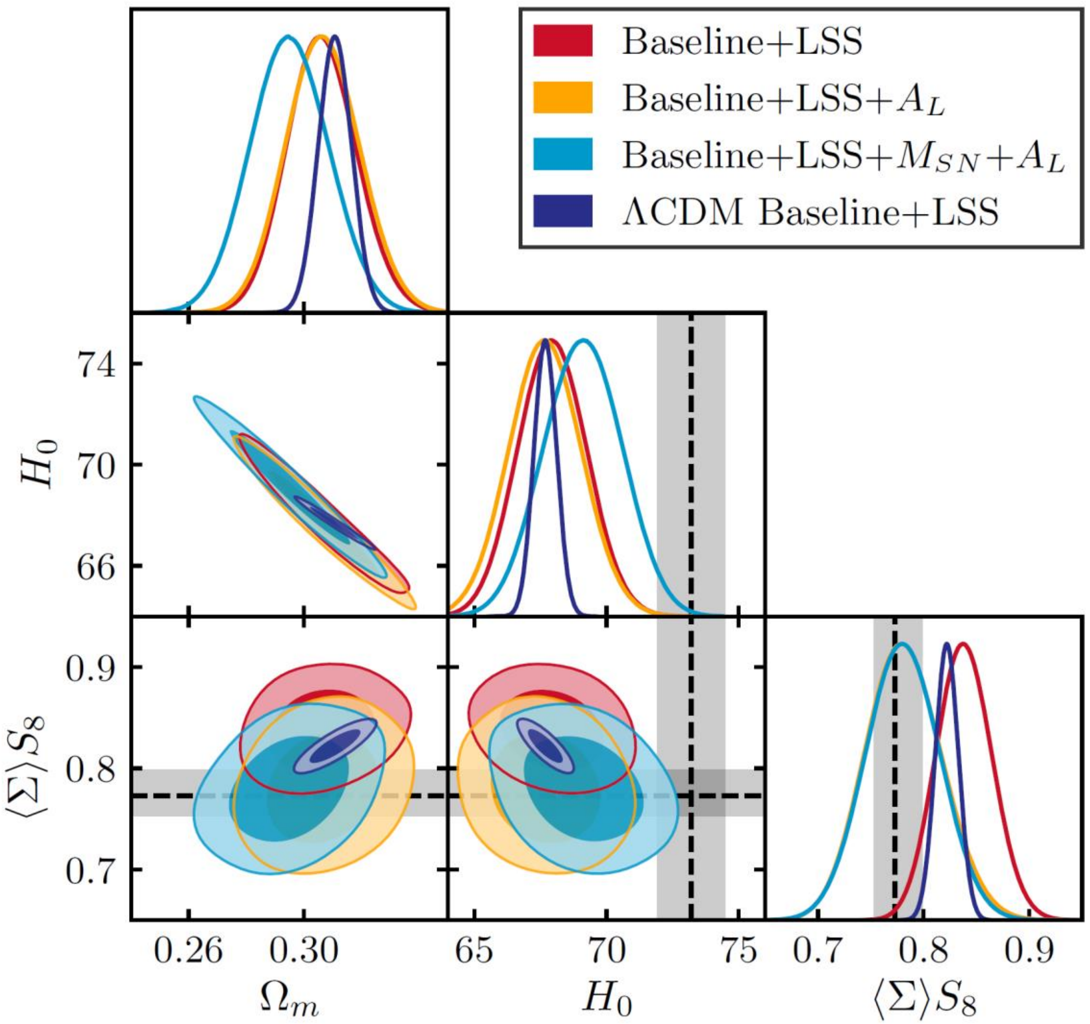
# Implications for tensions in extended cosmologies

- Extended cosmologies

  $\Omega_{DE}(z), \mu(z), \Sigma(z)$

- Hubble constant
  - It is not possible to resolve the tension fully due to the inconsistency with BAO

- Lensing anomalies
  - CMB lensing anomaly can be resolved either by $\Sigma > 1$ or $A_L > 1$.
  - Fit to DES cannot be improved even if $S_8$ is lower if $\Sigma > 1$ as $\Sigma \times S_8$ stays the same.
  - We need $A_L > 1$ to improve fit to DES




Pogosian, Raveri, KK, Martinelli Silvestri, Zhao 2107.12990, 2107.12992

# Going beyond linear scales

- Ample information on non-linear scales

  Parametrisation is valid only for linear perturbations

  Conservative cut-offs are required to remove data on non-linear scale, which significantly degrade the constraining power

- Extraction of linear information

  For redshift distortions, non-linear modelling is required to extract the linear growth rate, which is done normally within LCDM

- New information on non-linear scales

  On non-linear scales, ***screening mechanisms*** can be important leaving interesting signatures

# General picture

- Largest scales

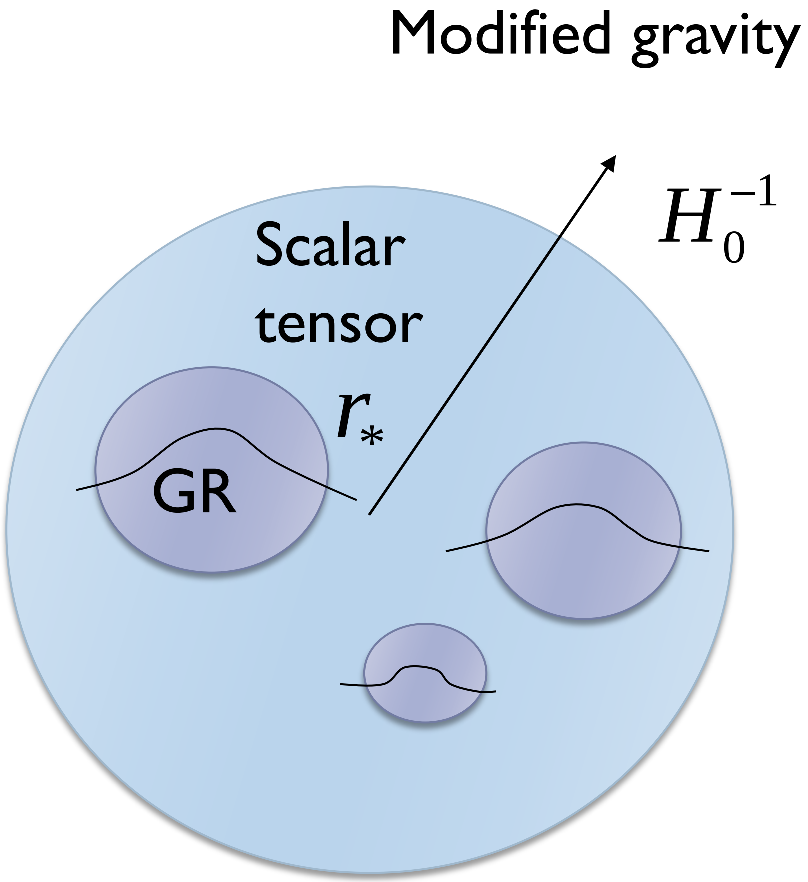
  gravity is modified so that the universe accelerates without dark energy

- Large scale structure scales

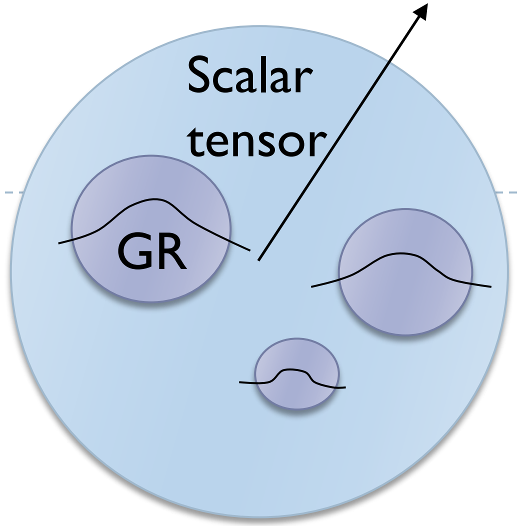
  gravity is still modified by a fifth force from scalar graviton

- Small scales (solar system)

  GR is recovered by "screening mechanism"



# Where to test GR




- GR is recovered in "high dense regions"

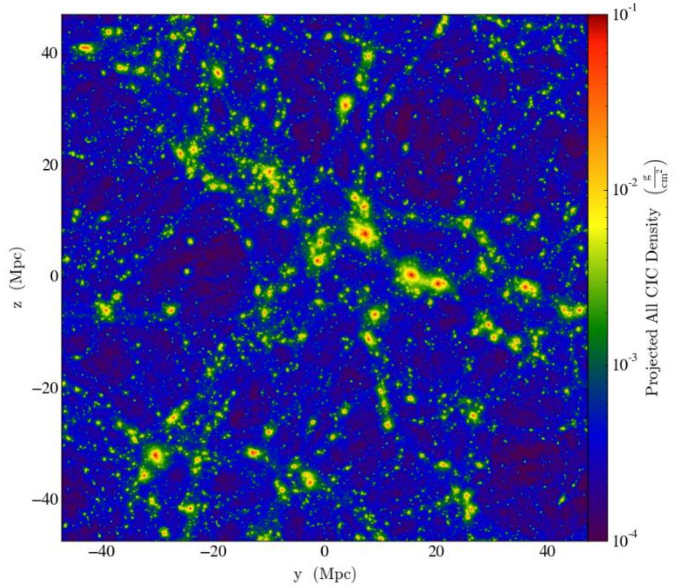
  Details depend on the screening mechanism

  Chameleon mechanism (environmental dependent mass)

  - Screening of dark matter halos depends on mass and environment
  - Strongest constraints come from objects with a shallow potential in low density environment

  Vainshtein mechanism (derivative interaction)

  - Screening of dark matter halos does not depend on mass and environment
  - Strongest constraints come from linear scales

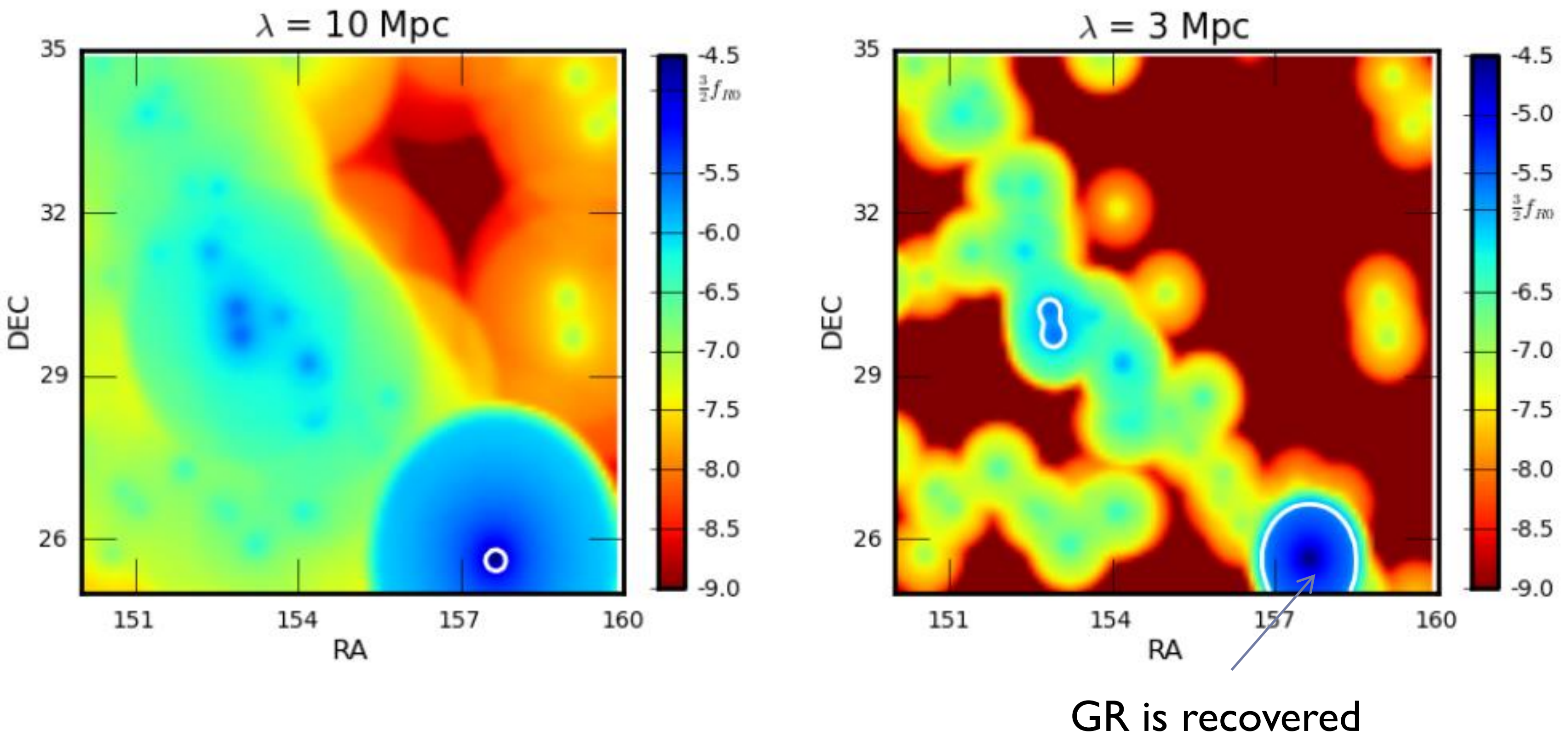



**Modified Gravity Simulations comparison**
**Winther et.al. arXiv: 1506.06384**

# Creating a screening map (chameleon mechanism)

- It is essential to find places where GR is not recovered
  - Small galaxies in underdense regions
  - SDSS galaxies within 200 Mpc

Cabre, Vikram, Zhao, Jain, KK JCAP 1207 (2012) 034



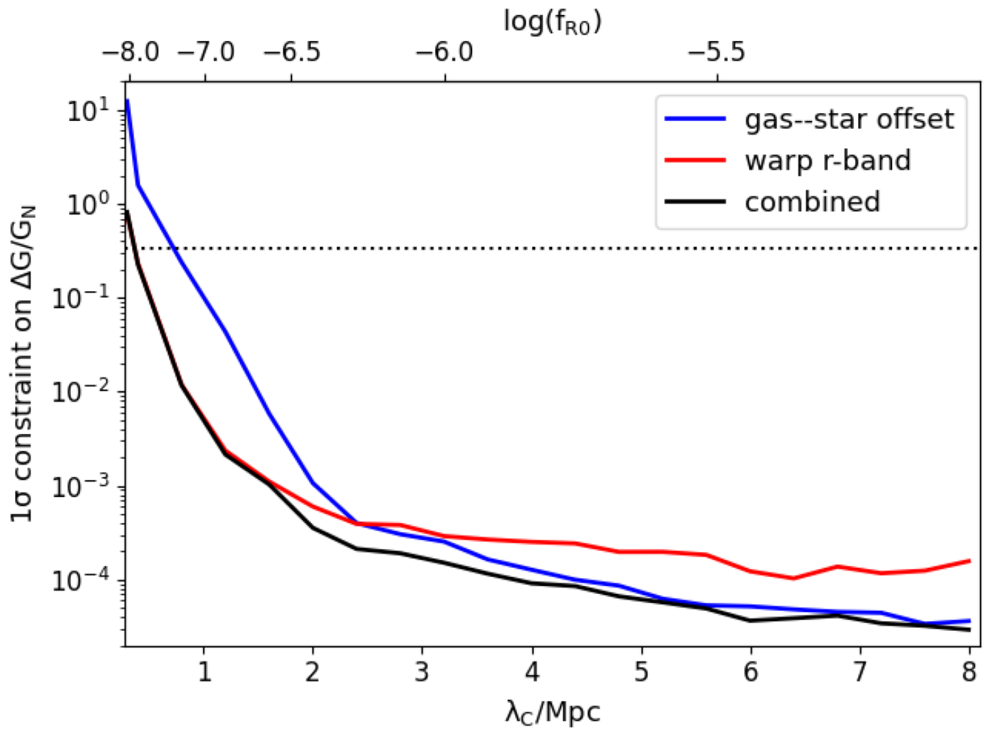
# Tests of chameleon gravity

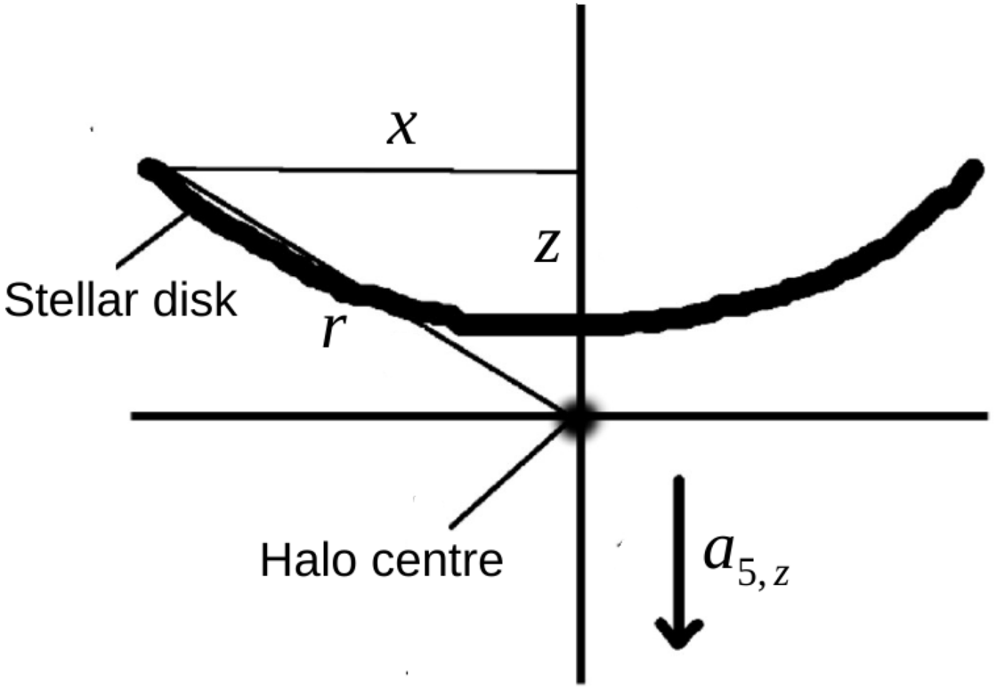
Hui, Nicolis & Stubbs Phys. Rev. D80 (2009) 104002

- dwarf galaxies in voids

  strong modified gravity effects on dark matter (but not on stars)

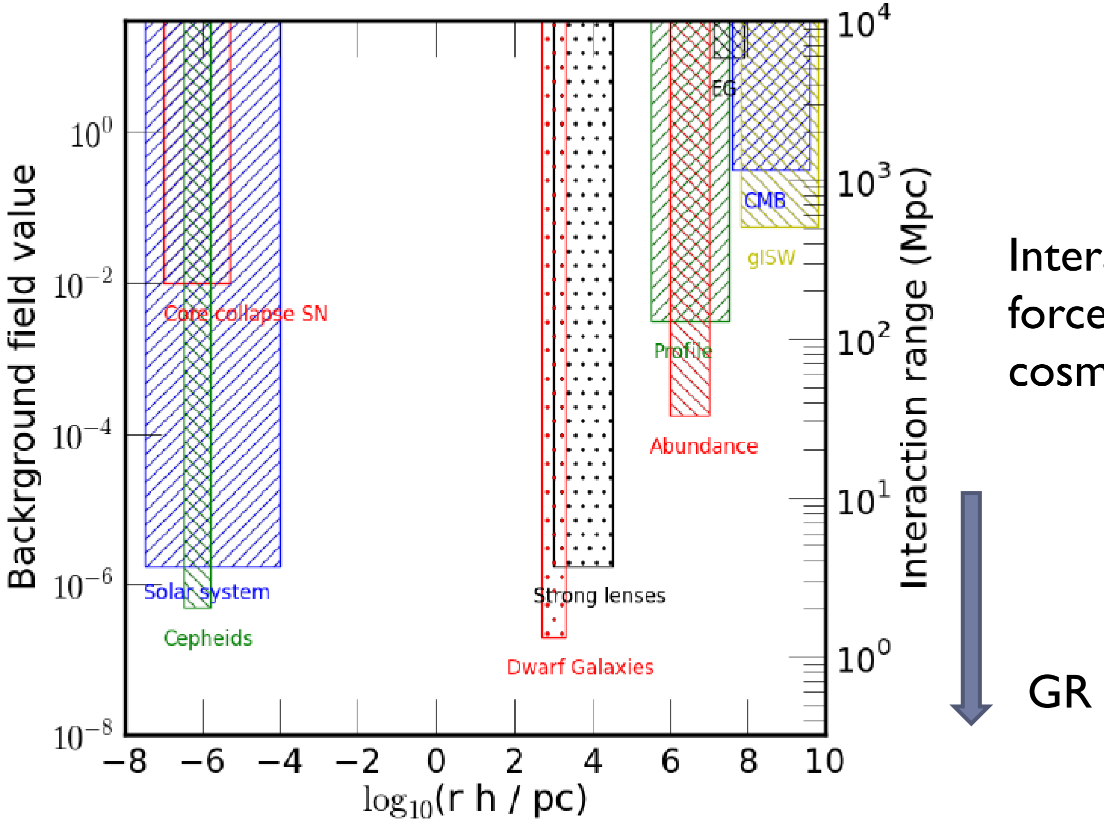
  - Warping of stellar disks
  - Gas-star offset




Desmond & Ferreira arXiv:2009.08743

# Constraints on chameleon gravity




Jain et.al. 1309.5389

Interaction range of the extra force that modifies GR in the cosmological background

- Non-linear regime is powerful for constraining chameleon gravity
- Astrophysical tests could give better constraints than the solar system tests

# Summary

- In the next decade, we will be able to test the nature of dark energy and may be able to detect the failure of GR on cosmological scales
  - Linear scales

    model independent tests of gravity

    SDSS III

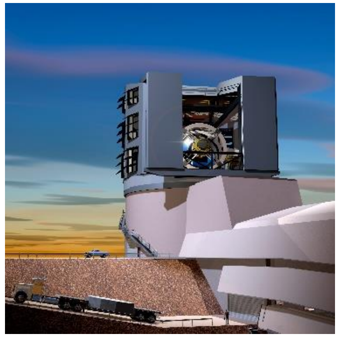
    DARK ENERGY SURVEY

    HSC

  - Non-linear scales

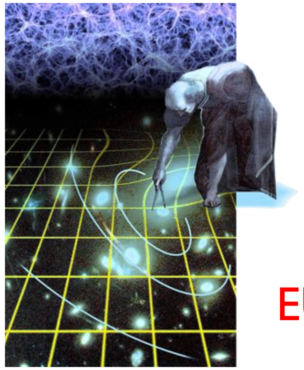
    novel astrophysical tests of gravity

    (in a model dependent way)



Vera C. Rubin Observatory

SKA SQUARE KILOMETRE ARRAY



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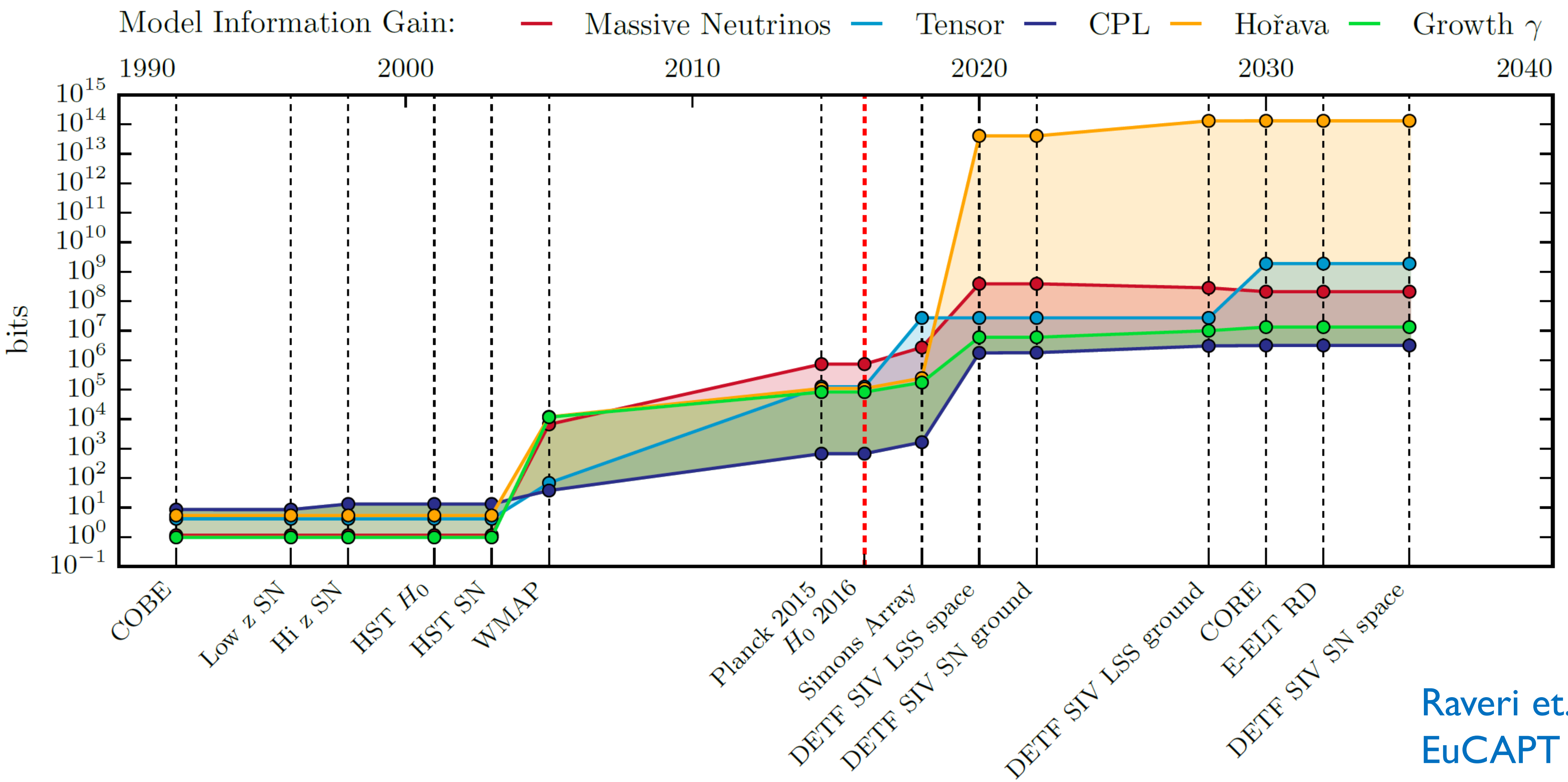


Raveri et. al. 1606.06273
EuCAPT white paper

- *It is required to develop more theoretical models as theoretical inputs are crucial for testing dark energy and modified gravity*