Dark Energy
(a classical, black and white view)

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VI CHALLENGES OF
NEW PHYSICS IN SPACE

outline

1. what is the problem?
2. dark energy theory
    - action based models
    - phenomenological approach
    - some more things
3. observations
    - simple principles
    - current constraints from Planck+

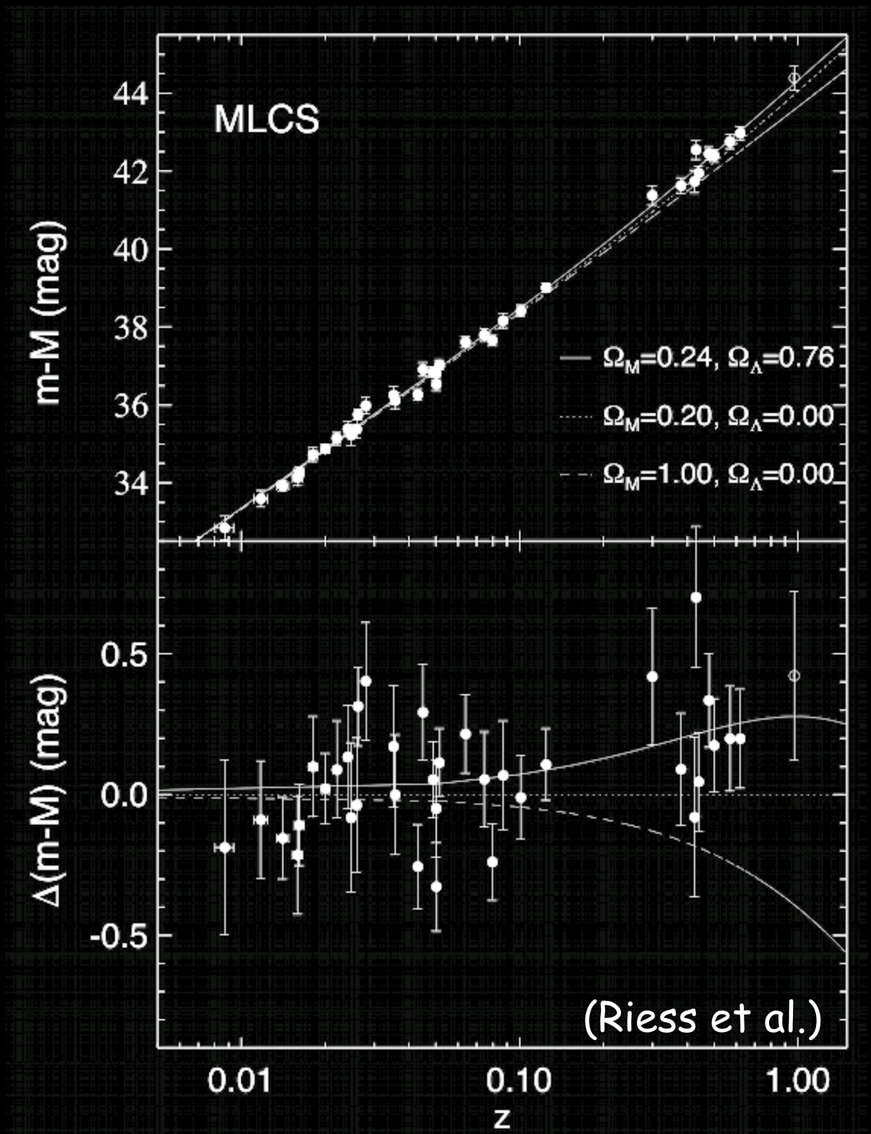
The Nobel Prize 2011

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

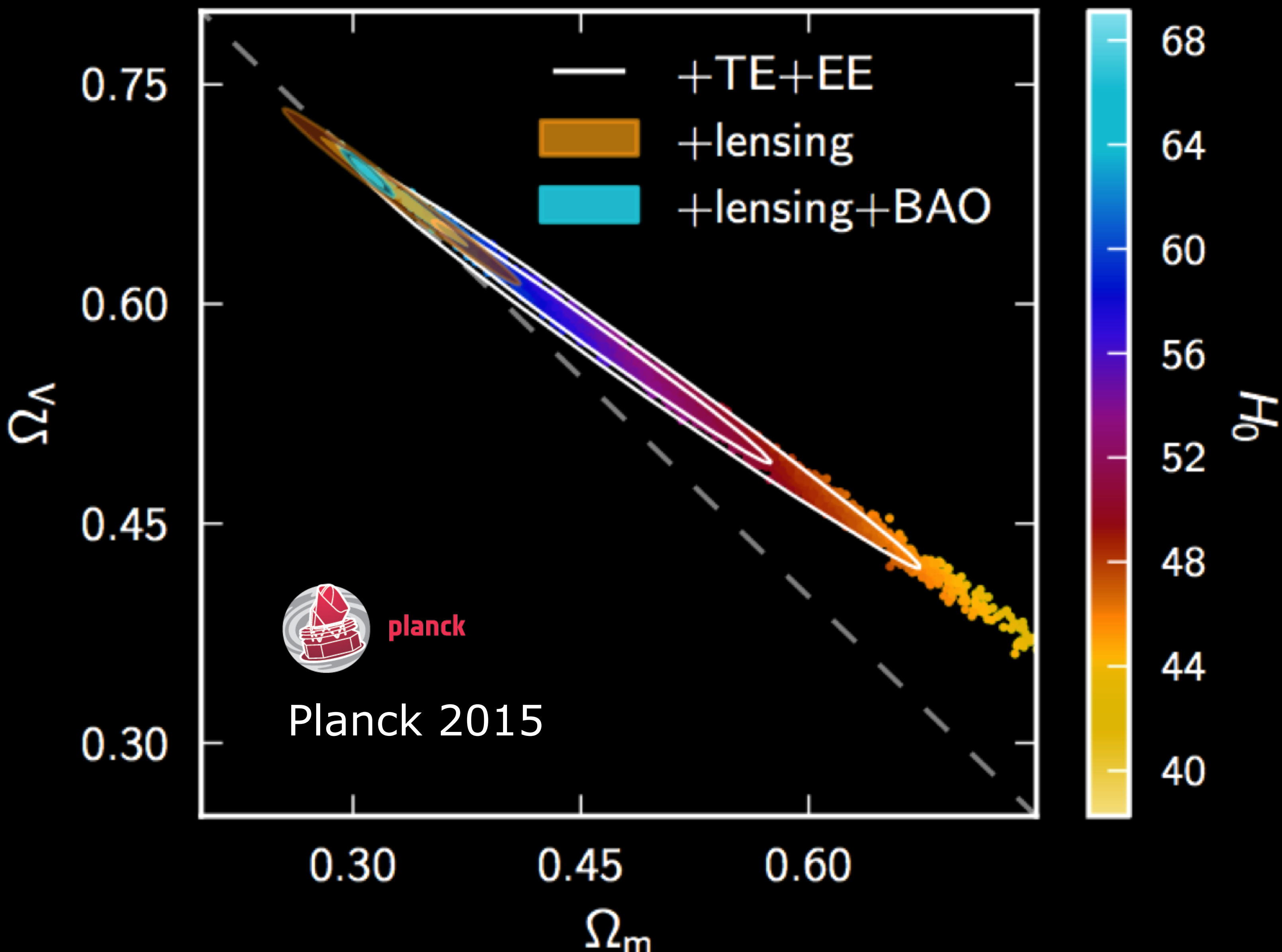
The Universe is now officially accelerating, thanks to the prize given to Saul Perlmutter, Brian P. Schmidt and Adam G. Riess, and we need to understand the reason!

One well-motivated model:

the cosmological constant



can the data be wrong?

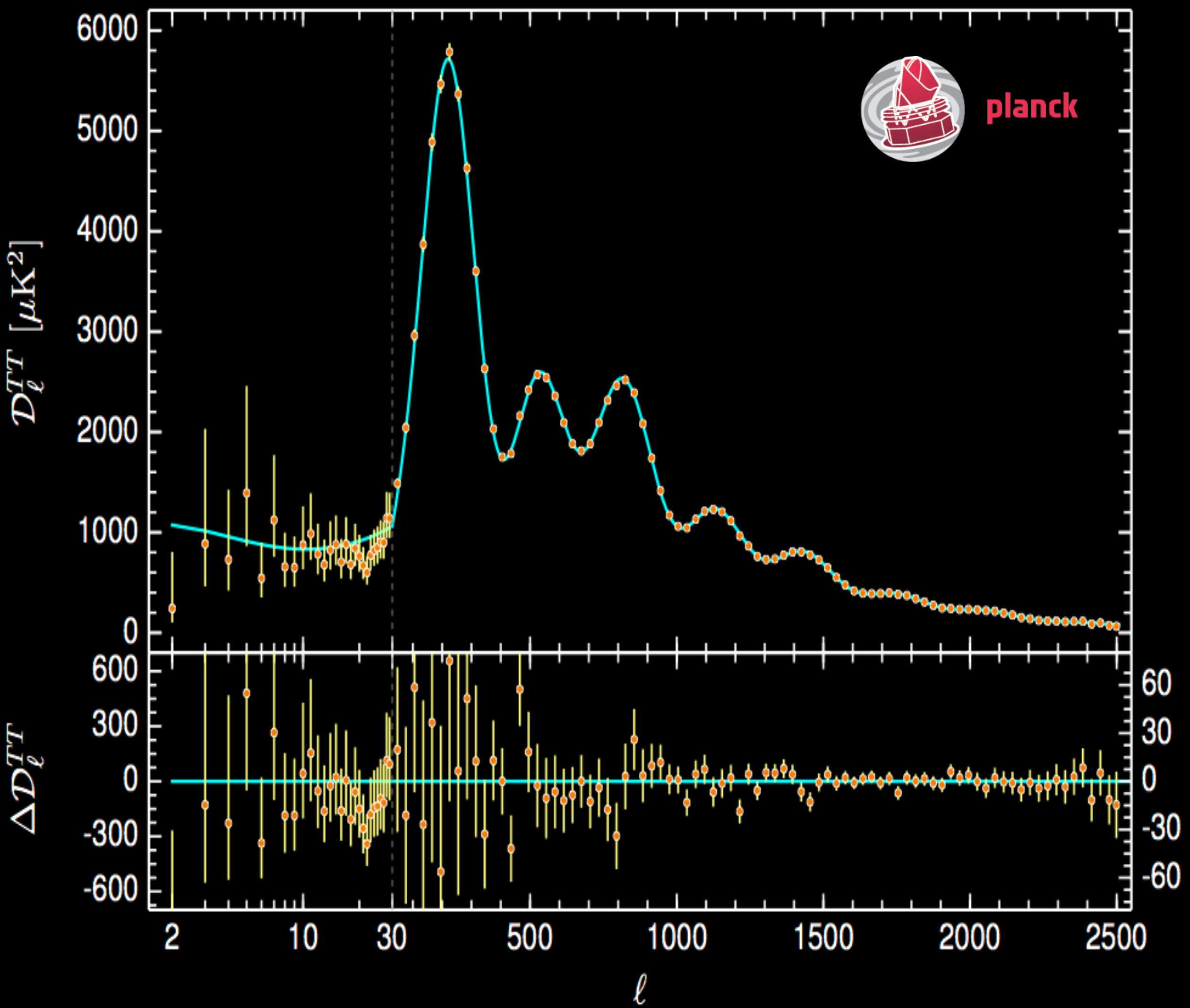


CMB alone rules out no accelerated expansion at high significance

…

cosmic concordance would require quite a conspiracy for data to fail consistently?

Planck vs ΛCDM



cyan curve:
best fit 6-parameter flat ΛCDM model

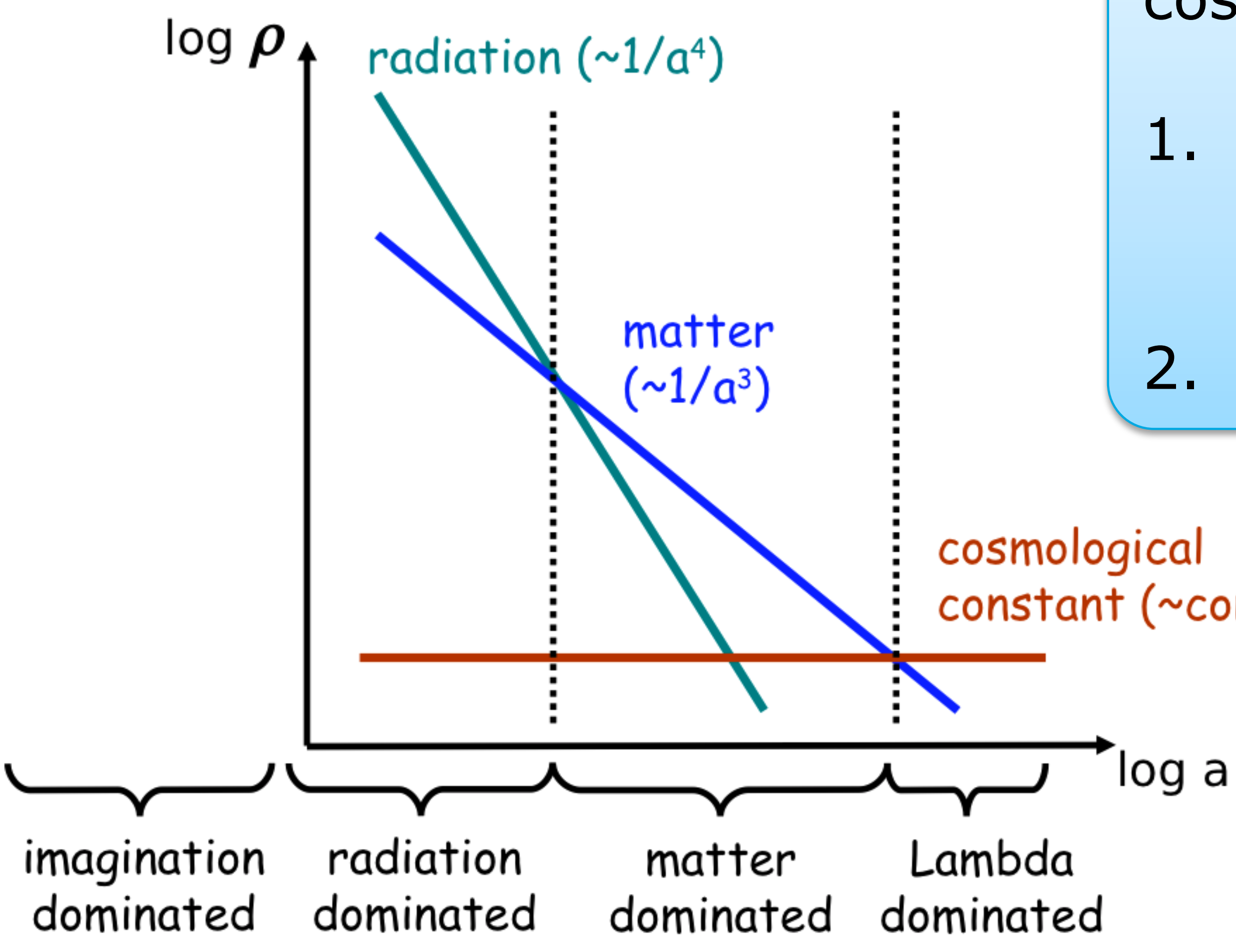
fits millions of CMB pixels (or thousands of C_l)

Planck 2015 TT combined
ell range 30 – 2508
X^2 = 2546.67
N_{dof} = 2479
PTE 16.8%

reasonable fit except maybe at lowest ell's

What's the problem with Λ ?

Evolution of the Universe:

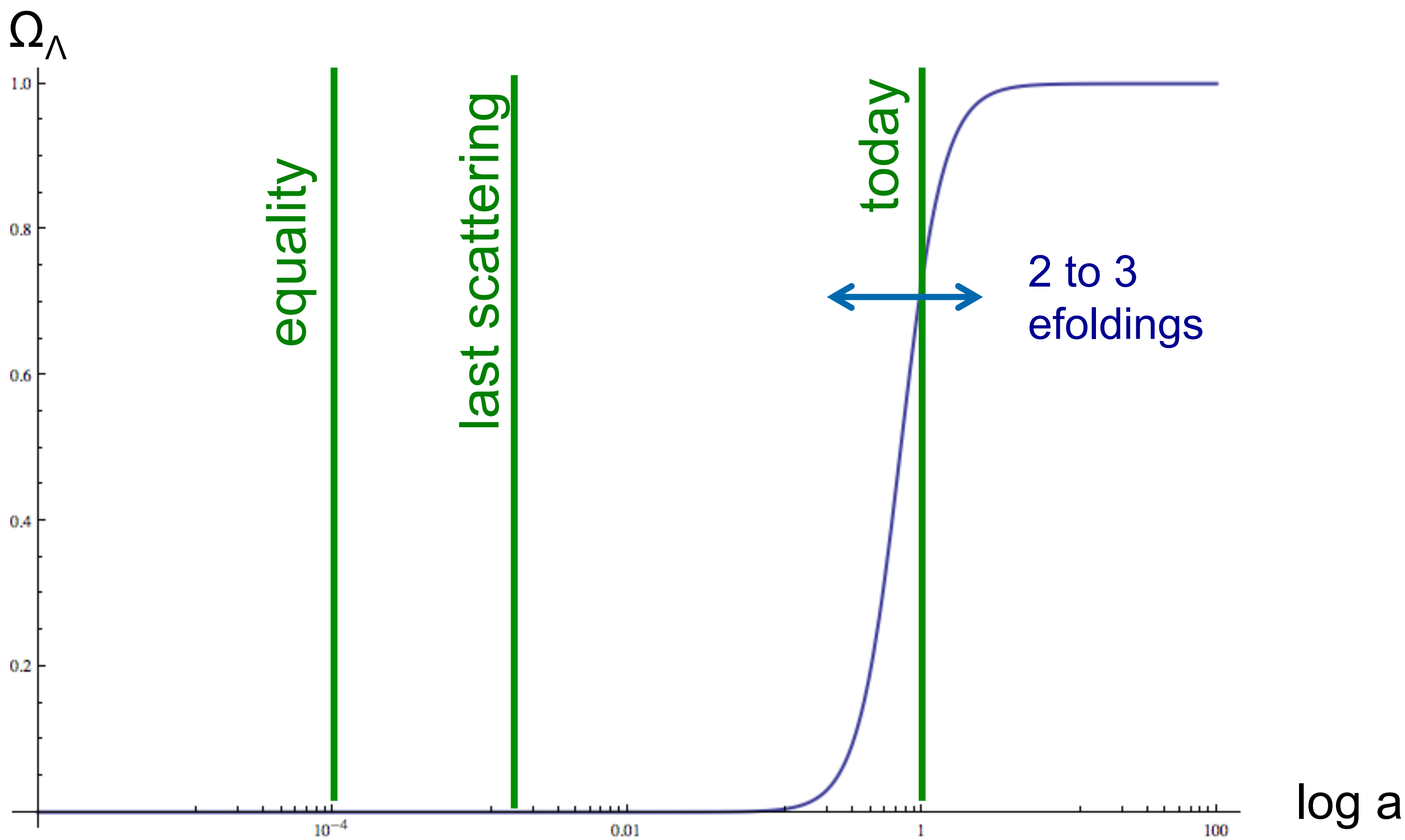


Classical problems of the cosmological constant:

1. Value: why so small?
   Natural?
   (but is 0 more natural?)
2. Coincidence: Why now?

the coincidence problem

- why are we just now observing $\Omega_\Lambda \approx \Omega_m$?
- past: $\Omega_m \approx 1$, future: $\Omega_\Lambda \approx 1$



the naturalness problem

energy scale of observed Λ is ~ 2×10^{-3} eV
zero point fluctuations of a heavier particle of mass m:

$$\int_0^{\overset{\text{cutoff scale}}{\Lambda}} \frac{1}{2} \frac{d^3p}{(2\pi)^3} \sqrt{p^2 + m^2} \simeq \frac{1}{16\pi^2} \Big[\underbrace{\Lambda^4 + m^2\Lambda^2}_{\text{can in principle be absorbed into renormalization of observables}} \underbrace{- \frac{1}{4} m^4 \log\left(\frac{\Lambda^2}{m^2}\right)}_{\text{“running” term: this term is measureable for masses and couplings! Why not for cosmological constant?!}} \Big]$$

already the electron should contribute at m_e >> eV
(and the muon, and all other known particles!)

w during inflation

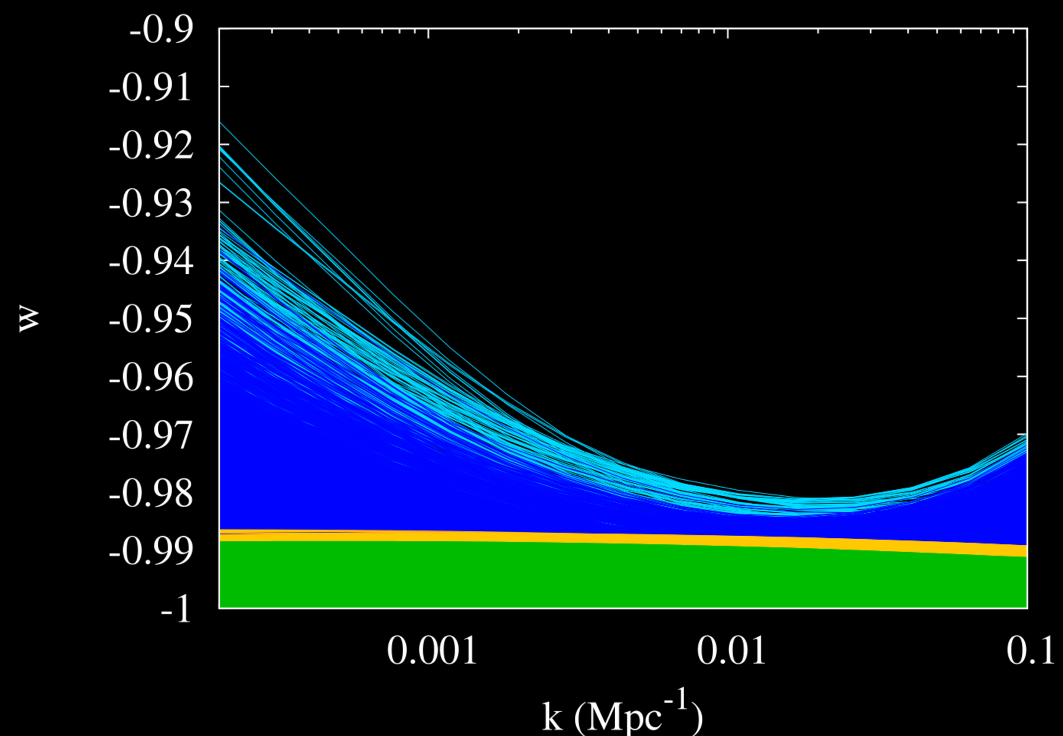
(Ilic, MK, Liddle & Frieman, 2010)

- Scalar field inflaton: $1 + w = -\frac{2}{3}\frac{\dot{H}}{H^2} = \frac{2}{3}\epsilon_H$ and r = T/S ~ 24 (1+w)
- Link to dw/da: $\frac{d\ln(1+w)}{dN} = 2(\eta_H - \epsilon_H)$ $\quad 2\eta_H = (n_s - 1) + 4\epsilon_H$

$n_s \neq 1 \Rightarrow \varepsilon \neq 0$ or $\eta \neq 0$
=> $w \neq -1$ and/or w not constant
=> not a cosmological constant!

WMAP 5yr constraints on w:
- (1+w) < 0.02
- No deviation from w=-1 visible

(but of course not clear if applicable to dark energy)



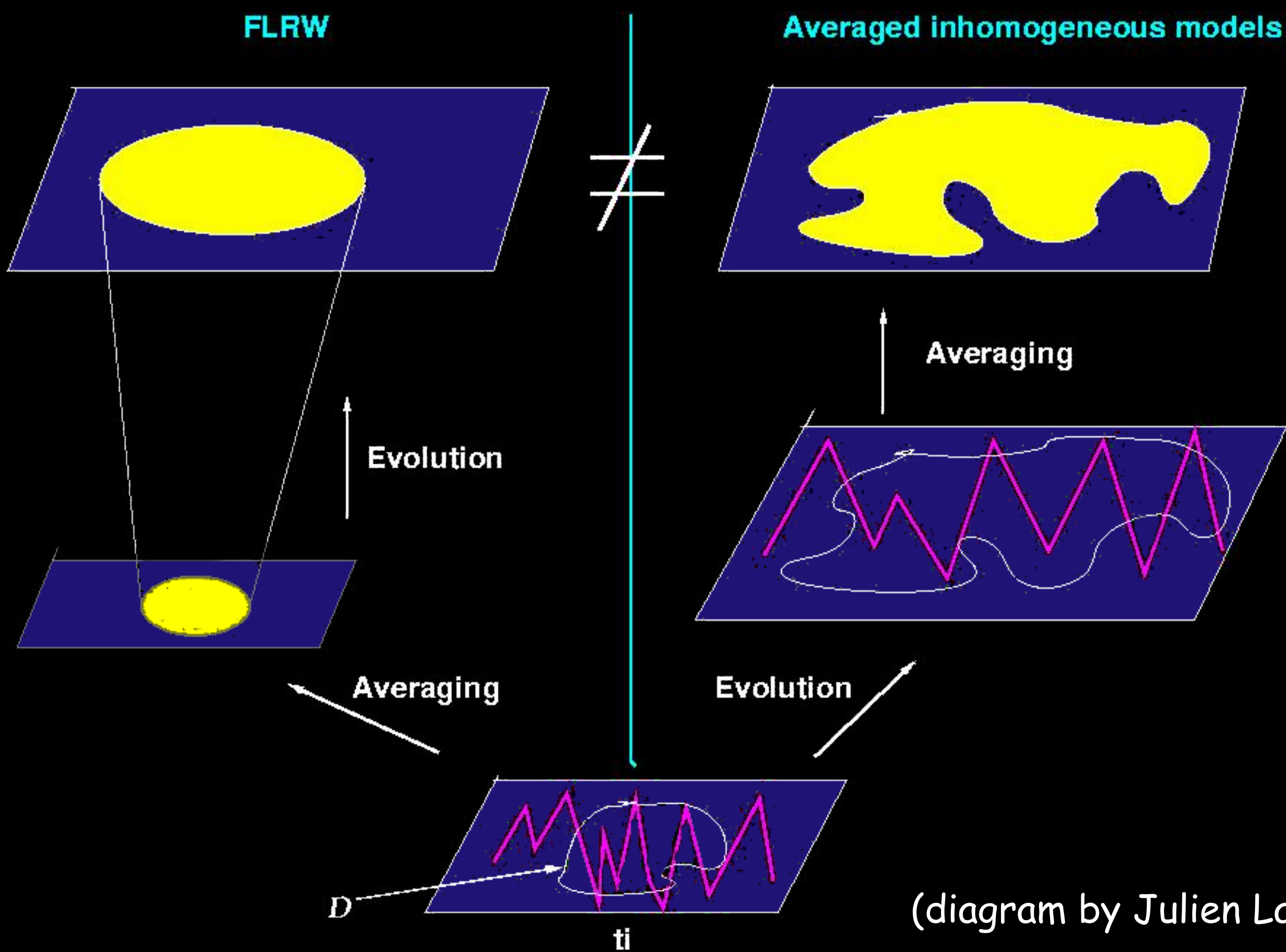
→ **inflation was not an (even effective) cosmological constant!**
→ inflation is one measurement ahead of dark energy research!

Possible explanations

1. It is a cosmological constant, and there is no problem (‘anthropic principle’ , ‘string landscape’)
2. ~~The (supernova) data is wrong~~
3. We are making a mistake with GR (aka ‘backreaction’) or the Copernican principle is violated (‘LTB’)
4. It is something evolving, e.g. a scalar field (‘dark energy’)
5. GR is wrong and needs to be modified (‘modified gravity’)

average and evolution

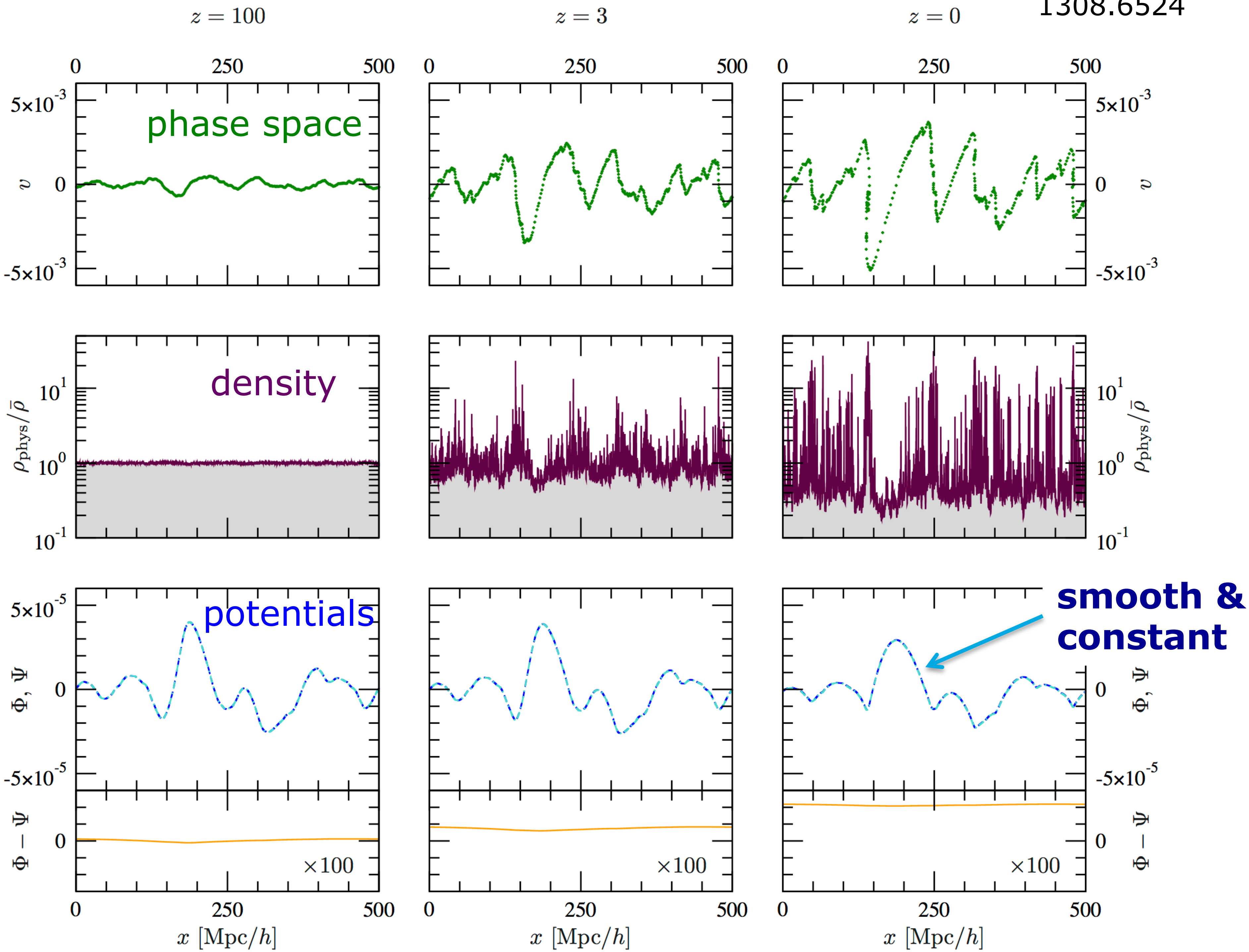
the average of the evolved universe is in general not the evolution of the averaged universe!



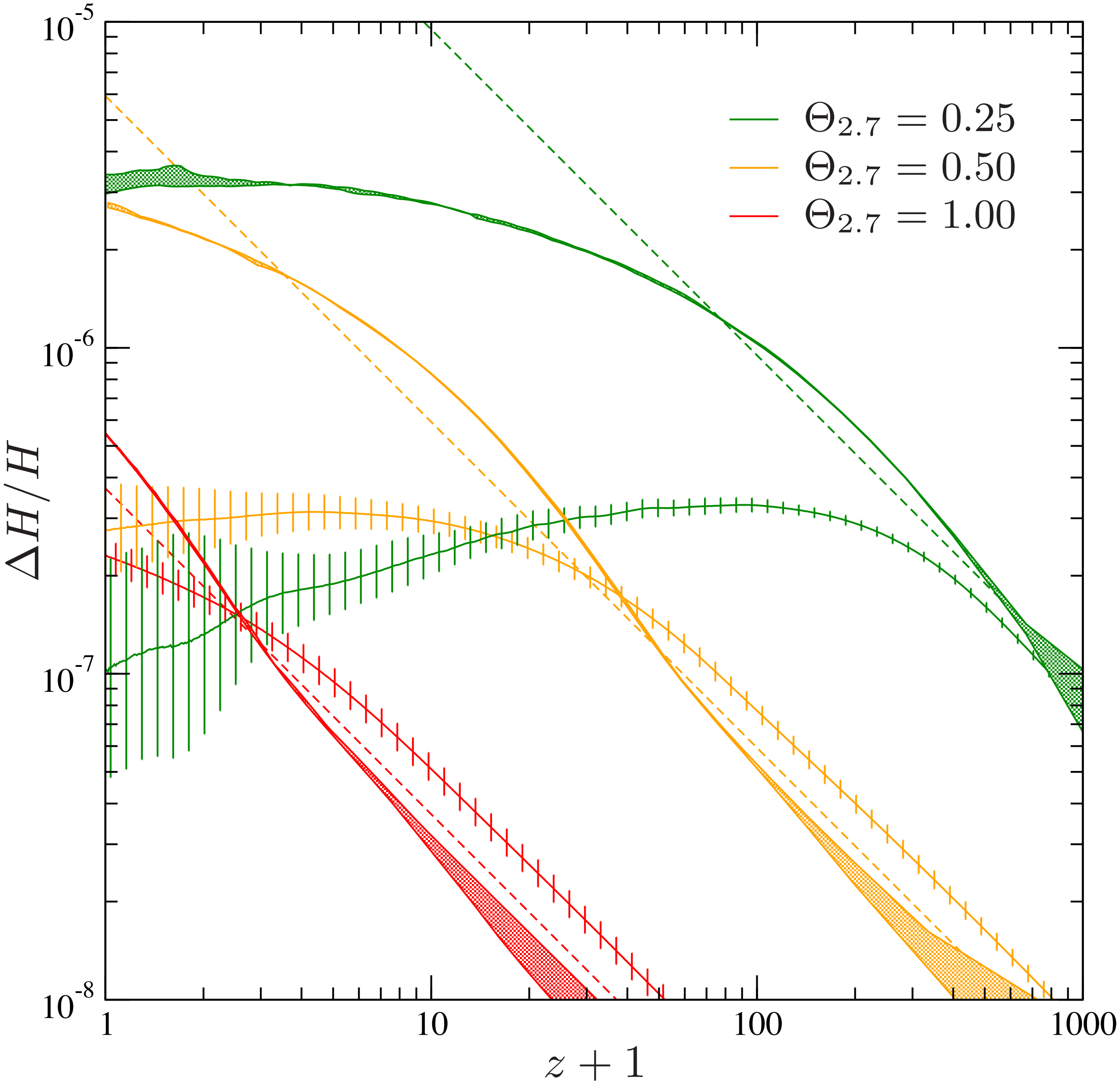
(diagram by Julien Larena)

the 1D universe

Adamek, Daverio, Durrer, MK arXiv: 1308.6524



does backreaction stop?



backreaction seems to stop rather than accelerate when structures go non-linear …

conjecture: virialization leads to freeze-out of the backreaction?

3D fully relativistic sims very soon

Adamek, Clarkson, Durrer, MK arXiv: 1408.2741

and how about inhomogeneity?

1. Is it possible to test the geometry (Copernican principle) directly?
2. Yes! Clarkson et al, PRL (2008) -> in FLRW (integrate along ds=0):

$$H_0 D(z) = \frac{1}{\sqrt{-\Omega_k}} \sin\left(\sqrt{-\Omega_k}\int_0^z \frac{H_0}{H(u)}du\right)$$

$$\Rightarrow H_0 D'(z) = \frac{H_0}{H(z)} \cos\left(\sqrt{-\Omega_k}\int_0^z \frac{H_0}{H(u)}du\right)$$

$$\rightarrow \left(HD'\right)^2 - 1 = \sin^2(\cdots) = -\Omega_k \left(H_0 D\right)^2$$

It is possible to reconstruct the curvature by comparing a distance measurement (which depends on the geometry) with a radial measurement of H(z) without dependence on the geometry.

Baryon Acoustic Oscillations may be able to do that
(or supernova dipole Bonvin, Durrer, MK, PRL 96, 191302, 2006).

Possible explanations

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modeling dark energy

1. action-based approach
   - explicit models … but too many?
   - Horndeski action ("most general")
   - effective field theory
   - beyond scalars – massive gravity et al
2. phenomenological approach
   - modeling observations
   - fluid variables vs geometric variables
   - links to action-based models
3. beyond linear perturbations
   - screening

action-based approach

GR + scalar field:

$$S = S_g + S_\phi = \int d^4x\sqrt{-g}\left(\frac{R}{16\pi G} + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + V(\phi)\right)$$

gravity e.o.m. (Einstein eq.):

$$\boxed{\frac{\delta S[g_{\mu\nu},\phi]}{\delta g^{\mu\nu}} = 0} \qquad G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

scalar field e.o.m. :

$$\boxed{\frac{\delta S[g_{\mu\nu},\phi]}{\delta\phi} = 0} \qquad \ddot{\phi} + 3H\dot{\phi} + dV(\phi)/d\phi = 0$$

Actions specify the model fully

→ but not all properties may be immediately obvious

→ examples: tracking, behaviour in non-linear regime, stability and ghost issues

some examples I

(from the Euclid parameter definitions document –
warning: sketchy citations ahead! Please see reviews)

- **quintessence:** minimally coupled canonical scalar field
  - can track background evolution, but cannot avoid fine-tuning
  - could add couplings to gravity and matter

Wetterich 1988
Ratra & Peebles 1988

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}R - \int d^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi + V\right] + S_{\mathrm{matter}}[g]$$

- **K-essence:** generalized kinetic term
  - different clustering (see later), more general tracking

$$\mathcal{L}_\phi = \sqrt{-g}K(\phi, X) \qquad X = \frac{1}{2}(\nabla\phi)^2$$

Armendariz-Picon et al. 2000

some examples II

- **f(R) models:** simplest model with higher derivatives Weyl 1918?
  - many popular choices for function f

$$\mathcal{L} = \sqrt{-g} f(R)$$

Brans, Dicke 1961

- f(R) is just a **scalar-tensor theory** (universal but non-minimal coupling) after a Legendre transformation Φ~f'
  - Jordan frame and Einstein frame (conformal transf.)
  - S/T theories need to be 'hidden' in the solar system

$$\mathcal{L} = \frac{1}{16\pi}\sqrt{-g}\left[\phi R - \frac{\omega(\phi)}{\phi}\nabla_\mu\phi\nabla^\mu\phi - 2\Lambda(\phi)\right] + \mathcal{L}_m(\Psi, g_{\mu\nu})$$

- **scalar-vector-tensor**, etc

some examples III

- **Horndeski:** most general theory with 2[nd] order e.o.m.

$$\mathcal{L} = \sum_{i=2}^{5} \mathcal{L}_i$$

Horndeski 1974

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

- popular sub-classes of Horndeski

  Deffayet, Pujolas, Sawicki, Vikman 2010

  - **Kinetic gravity braiding:** most general 'dark energy'
  - **Galileons**

  Nicolis, Rattazzi, Trincherini 2009

- **Effective field theory:** write all operators that are compatible with symmetries (isotropy, homogeneity), single extra scalar – similar to Horndeski, some extra terms?

Creminelli et al 2008
Cheung et al 2008

some examples IV

Hassan, Rosen 2012

de Rham, Gabadadze 2010

- **bigravity** and **massive gravity** models
  - very interesting – massive gravity solved 40 year old problem (non-linear completion of Fierz-Pauli)
  - viability and self-consistency still unclear
  - interesting links to other models (e.g. Horneski, Galileons)

$$S = -\frac{M_g^2}{2}\int d^4x\sqrt{-\det g}R(g) - \frac{M_f^2}{2}\int d^4x\sqrt{-\det f}R(f)$$
$$+ m^2 M_g^2 \int d^4x\sqrt{-\det g}\sum_{n=0}^{4}\beta_n e_n\left(\sqrt{g^{-1}f}\right)$$
$$+ \int d^4x\sqrt{-\det g}\mathcal{L}_m\left(g,\Phi\right),$$

- **non-local massive gravity**: viable cosmology w/o direct LCDM limit

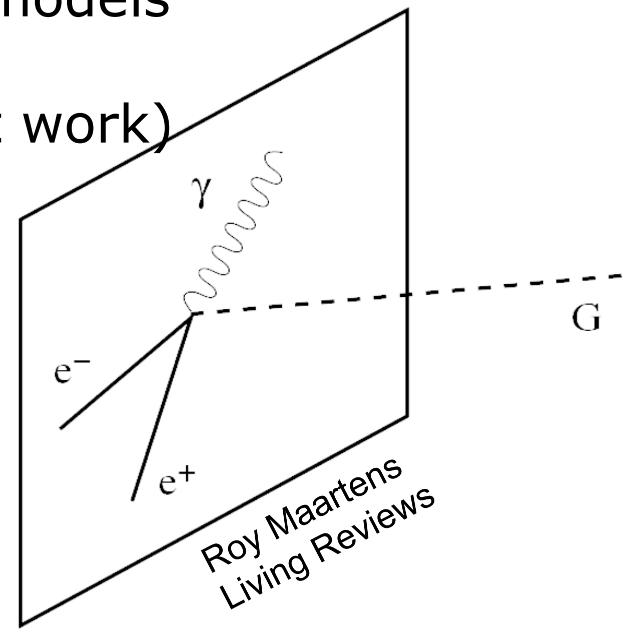
$$S_{\rm NL} = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,[R - \frac{1}{6}m^2 R\frac{1}{\Box_g^2}R]$$

Jaccard, Maggiore, Mitsou 2013

some examples MCXIII…?!

e.g. Dvali, Gabadadze, Porrati 2000

- **higher dimensional theories** – typically brane models
  - gravity weakened by leaking into bulk
  - DGP: sum of 4 and 5 dim EH action (doesn't work)
  - 6+ dimensions (may work?)
  - rewrite as 4D effective model
    → EFT / Horndeski



- we could go on a for a while …

Many more examples (apologies if I did not mention your favourite theory ; ☹ read a review for details! ☺) … some approaches (Horndeski/EFT) are very general, but are they general enough? Can we do something else to look for deviations from LCDM?

→ phenomenological approach based on evolution of the geometry and/or properties of the effective dark energy fluid

action-based approach

GR + scalar field:

$$S = S_g + S_\phi = \int d^4x\sqrt{-g}\left(\frac{R}{16\pi G} + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \boxed{V(\phi)}\right)$$

gravity e.o.m. (Einstein eq.):

$$\boxed{\frac{\delta S[g_{\mu\nu},\phi]}{\delta g^{\mu\nu}} = 0}$$

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$\boxed{w = p/\rho}$$

scalar field e.o.m. :

$$\boxed{\frac{\delta S[g_{\mu\nu},\phi]}{\delta \phi} = 0}$$

$$\ddot{\phi} + 3H\dot{\phi} + dV(\phi)/d\phi = 0$$

- The equation of motion of Φ corresponds to a fluid with certain parameters
- The free function V(Φ) corresponds to a choice of w(z) or H(z)
- Can we bypass the field-based model and look at w or H directly?

phenomenology of the dark side

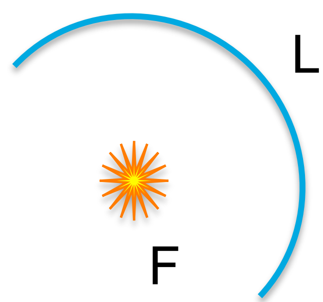
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

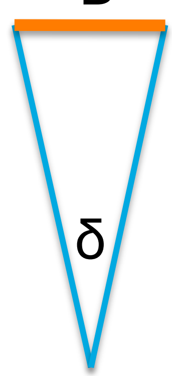
(determined by the metric) → geometry

stuff (what is it?)

your favourite theory

distances $d \sim \int_0^z \frac{dz}{H(z)}$



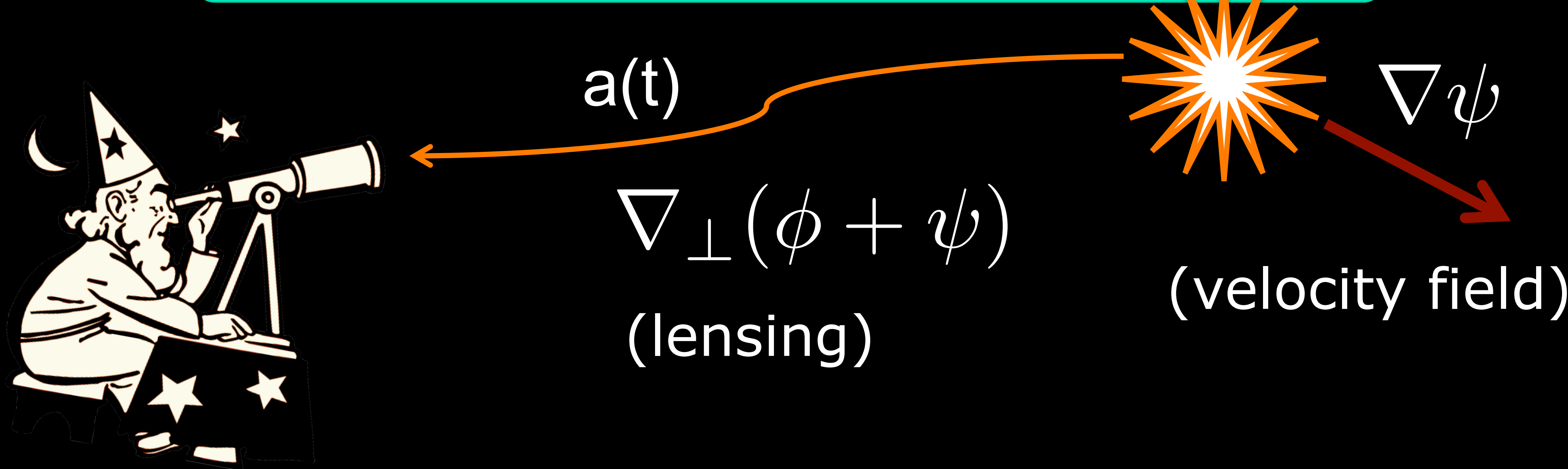


$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$\dot{\rho} = -3\frac{\dot{a}}{a}(1+w)\rho$$

beyond the background

$$ds^2 = -(1+2\psi)dt^2 + a(t)^2(1-2\phi)dx^2$$



deviations from “standard clustering”:

$$k^2\phi = -4\pi G a^2 Q \rho_m \Delta_m$$

$$\psi = (1+\eta)\phi$$

We expect
Q = 1
η = 0
at low z

(many equivalent parametrisations cf e.g. MK 2012)

model predictions

$$\boxed{k^2\phi = -4\pi G a^2 Q \rho_m \Delta_m \qquad \psi = (1+\eta)\phi}$$

scalar field: $$S = \int d^4x\sqrt{-g}\left(\frac{1}{2}\partial_\mu\phi\partial^\mu\phi + V(\phi)\right)$$

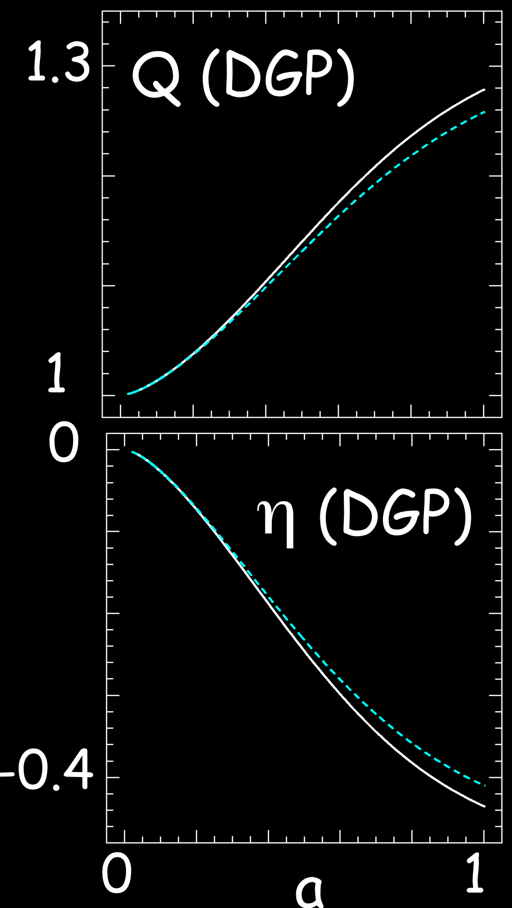
One degree of freedom: $V(\phi)$ <-> $w(z)$
therefore other variables fixed: $c_s^2 = 1$, $\pi = 0$
-> $\eta = 0$, $Q(k \gg H_0) = 1$, $Q(k \sim H_0) \sim 1.1$ [$w \neq -1$]

(naïve) DGP: compute in 5D, project result to 4D

Lue, Starkmann 04
Koyama, Maartens 06
Hu, Sawicki 07

$$\eta = \frac{2}{3\beta - 1} \qquad Q = 1 - \frac{1}{3\beta}$$

implies large DE perturb.



Scalar-Tensor: Boisseau, Esposito-Farese, Polarski, Starobinski 2000, Acquaviva, Baccigalupi, Perrotta 04

$$\mathcal{L} = F(\varphi)R - \partial_\mu\varphi\partial^\mu\varphi - 2V(\phi) + 16\pi G^* \mathcal{L}_{\rm matter}$$

$$\eta = \frac{F'^2}{F + F'^2} \qquad Q = \frac{G^*}{F G_0}\frac{2(F + F'^2)}{2F + 3F'^2}$$

how about Horndeski?

Horndeski (1974): most general action for single scalar field that leads to second-order equations of motion.

$$S = \int d^4x \sqrt{-g} \left(R + \sum_i \mathcal{L}_i + \mathcal{L}_m \right)$$

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

coupling to gravity: h_4,h_5

in quasistatic limit (de Felice & Tsujikawa 2011): [$Y=Q/(1+\eta)$]

$$1+\eta = h_2 \left(\frac{1+k^2 h_4}{1+k^2 h_5} \right) \qquad Y = h_1 \left(\frac{1+k^2 h_5}{1+k^2 h_3} \right)$$

h_i are functions of time -> scale dependence can be tested … in principle

intermediate summary

- action-based approach straightforward (well…)
- many different possible actions
- Horndeski/EFT general cases that can be fitted to data
- can take a shortcut and directly model observational degrees of freedom, “phenomenological approach”
- catches all possible deviations from LCDM predictions
- both EFT and phenomenological cases need mapping back to fundamental theory

Now a few more things:

1. anisotropic stress as a diagnostic for modified gravity
2. link of phenomenological approach to fluid variables
3. screening on small scales

Then we go to observations

the importance of η / π

(MK, Sapone 2007; Amendola, MK, Sapone 2008; Saltas & MK 2011)

non-minimal coupling f(φ)R in action : $\pi \sim \dfrac{f'}{1+f}\delta\phi$

-> unique link π <-> MG

quintessence, K-essence, etc: π = 0

DGP, S/T, f(R), f(G), etc: π ≠ 0
(except in GR limit)
-> extra scalar d.o.f. very directly linked to π

→ η or π can rule out whole classes of models!

actually it is a diagnostic for 'modifications of GR'!

aniso stress & grav. waves

gravitational waves are the dynamical d.o.f. of GR
→ modification of their propagation is really 'modified gravity'

Horndeski, bimetric massive gravity and other theories show a direct link between anisotropic stress and gravitational wave propagation, e.g. in Horndeski:

$$h''_{ij} + (2+\nu)\mathcal{H}h'_{ij} + c_T^2 k^2 h_{ij} + a^2\mu^2 h_{ij} = a^2\Gamma\gamma_{ij}\,,$$

$$\nu = \alpha_M\,, \qquad c_T^2 = 1 + \alpha_T\,,$$

$$\mu^2 = 0\,, \qquad \Gamma = 0\,.$$

Saltas, Sawicki, Amendola, MK 2014

$$\Phi - \Psi = \sigma(t)\Pi + \pi_m$$

$$\sigma = \alpha_M - \alpha_T$$

$$\Pi = H\delta\phi/\dot{\phi} + \alpha_T/(\alpha_M - \alpha_T)\Phi$$

could e.g. be tested by CMB B-modes

link to dark energy fluid

Einstein eq. (possibly effective - defines $T_{\mu\nu}^{(dark)}$):

$$G_{\mu\nu} - 8\pi G T_{\mu\nu}^{(bright)} = 8\pi G T_{\mu\nu}^{(dark)}$$

directly measured

given by metric:
- $H(z)$
- $\Phi(z,k)$, $\Psi(z,k)$

- inferred from lhs
- obeys conservation laws
- can be characterised by
  - $p = w(z)\,\rho$
  - $\delta p = c_s^2(z,k)\,\delta\rho$, $\pi(z,k)$

linear perturbation equations

metric: $$ds^2 = -(1+2\psi)dt^2 + a(t)^2(1-2\phi)dx^2$$

(Bardeen 1980)

conservation equations (in principle for full dark sector)

$$\delta_i' = 3(1+w_i)\phi' - \frac{V_i}{Ha^2} - \frac{3}{a}\left(\frac{\delta p_i}{\rho_i} - w_i\delta_i\right) \qquad \delta p = c_s^2\delta\rho + 3Ha(c_s^2 - c_a^2)\rho\frac{V}{k^2}$$

$$V_i' = -(1-3w_i)\frac{V_i}{a} + \frac{k^2}{Ha}\left(\frac{\delta p_i}{\rho_i} + (1+w_i)(\psi - \sigma_i)\right)$$

(vars: $\delta=\delta\rho/\rho$, V ~ divergence of velocity field, δp , σ anisotropic stress)

Einstein equations (common, may be modified if not GR)

$$k^2\phi = -4\pi G a^2 \sum_i \rho_i \left(\delta_i + 3Ha\frac{V_i}{k^2}\right)$$

Q: additional clustering

$$k^2(\phi - \psi) = 12\pi G a^2 \sum_i (1+w_i)\rho_i\sigma_i$$

η: additional anisotropic stress

the geometric EMT

(G. Ballesteros, L. Hollenstein, R. Jain & MK)

$$1 + w_G = -\frac{2}{3}\frac{\dot{H}}{H^2}$$

$$\delta\rho_G = -2M_P^2\left[3H\left(\dot{\phi} + H\psi\right) - a^{-2}\nabla^2\phi\right]$$

$$\delta p_G = 2M_P^2\left[\ddot{\phi} + H\left(3\dot{\phi} + \dot{\psi}\right) - 3w_G H^2\psi - \frac{1}{3}a^{-2}\nabla^2\Pi\right]$$

$$\delta q_{\mu\,G} = -2M_P^2\,\delta^i_\mu\left[\partial_i\left(\dot{\phi} + H\psi\right)\right]$$

$$\delta\pi_{\mu\nu\,G} = M_P^2\,\delta^i_\mu\delta^j_\nu\left[\left(\partial_i\partial_j - \frac{1}{3}\delta_{ij}\nabla^2\right)\Pi\right]$$

$$\Pi = \phi - \psi$$

We can always reconstruct an effective fluid EMT that gives the observed metric!

DE models and fluid properties

- **quintessence:**
    - only d.o.f. is potential $V[\Phi(z)]$
    - linked to equation of state parameter $w(z)$
    - $\pi=0$, $c_s^2=1$ (→ 'smooth DE')
- **k-essence:**
    - now $c_s^2 = K_{,X}/(K_{,X}+2XK_{,XX})$, still $\pi=0$
- **kinetic gravity braiding:**
    - most general theory with $\pi=0$
    - δp more complicated, possible scale dependence
- anisotropic stress <-> modified gravity models
- can use effective fluid properties to constrain model space if perturbations different from LCDM

screening

e.g. Khoury
arXiv:1011.5909

- universally coupled scalar d.o.f. → 5th force
- needs to be hidden in the solar system, or model ruled out
- interestingly, many have generic mechanisms to do just do that

schematic Lagrangian in Einstein frame:

$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, \partial\phi, \partial^2\phi)\partial_\mu\phi\partial_\nu\phi - V(\phi) + \beta(\phi)T^\mu_\mu$$

- matter EMT can give dependence on local density

1. **chameleon mechanism**: large mass in high-density region, Yukawa force leads to short-range effects only
2. **symmetron/dilaton** mechanism: small coupling in high-density region
3. **k-mouflage/Vainshtein** mechanism: large kinetic function Z (large derivatives) in high-density region to suppress effective coupling to matter

- needs numerical simulations → not easy for future surveys like Euclid
- baryons look atm like a much worse problem on small scales…

theory summary

- cosmological constant is a bit unsatisfactory
- but data requires some kind of dark energy, alternative explanations not working well
- modifications of (GR + matter) action can explain observations in principle, but
  - nothing really natural either
  - often suffer from ghosts, instabilities, etc
  - need screening on small scales to survive solar system constraints
  - why so close to LCDM?
- phenomenological approach to constrain fluid properties and check if data agrees with LCDM as an alternative

“observation” overview

‘Theoretical’ observations:

- high-level approach
- model independent observables

  also in data analysis, eg P(k) vs $C_l(z,z')$

- testing models / consistency relations

Actual observations:

- current constraints (Planck DE paper)

simplified observations

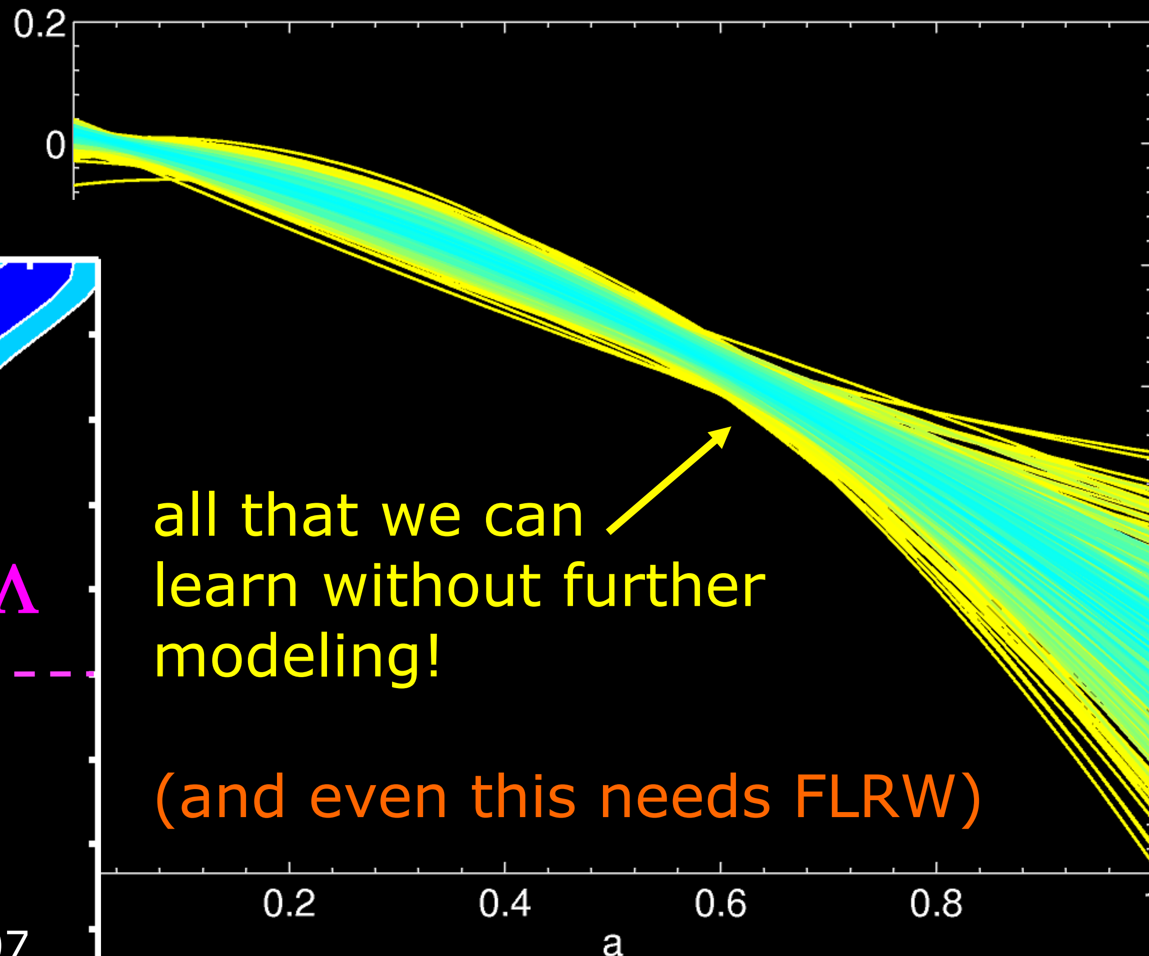
- Curvature from radial & transverse BAO
- w(z) from SN-Ia, BAO directly (and contained in most other probes)
- In addition 5 quantities, e.g. ϕ, ψ, bias, δ_m, V_m
- Need 3 probes (since 2 cons eq for DM)
- e.g. 3 power spectra: lensing, galaxy, velocity
- Lensing probes $\phi + \psi$
- Velocity probes ψ (z-space distortions?)
- And galaxy P(k) then gives bias

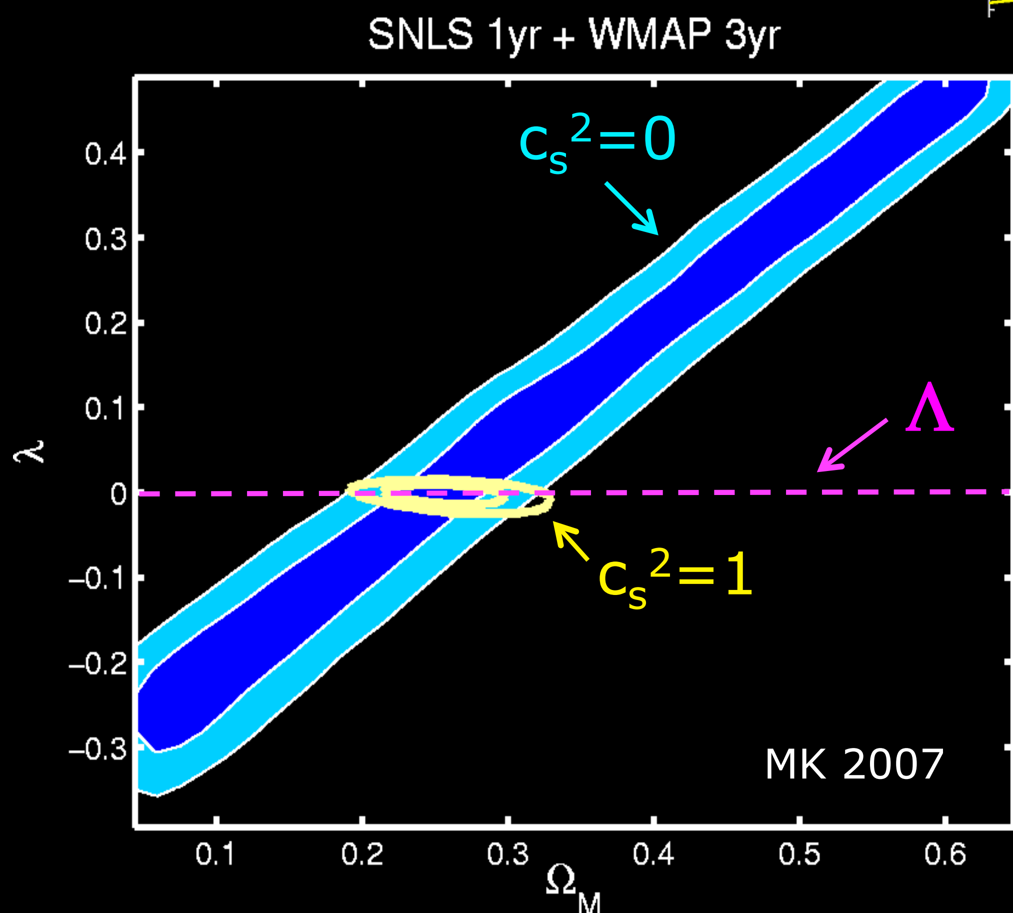
(-> Euclid ☺)

model independent w?

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho \quad \dot{\rho} = -3\frac{\dot{a}}{a}(\rho + p)$$ → rewrite p = w ρ

- quadratic expansion of w(a)
- fit to Union SNe, BAO and





le, D. Parkinson & C. Gao, PRD 80, 083533 (2009)

linear cosmological observables

Amendola, MK, Motta, Saltas, Sawicki 2013

We can observe these quantities, but we want b, f and Σ …

$$\underbrace{A = Gb\sigma_8\delta_{t,0} \qquad R = Gf\sigma_8\delta_{t,0}}_{\text{transverse \& radial } P(k)} \qquad \underbrace{L = \Sigma G\Omega_{m,0}\sigma_8\delta_{t,0}}_{\text{weak lensing}}$$

weak lensing
$\Sigma = Y(2+\eta) = Q(2+\eta)/(1+\eta)$

We need to build combinations that do not contain $\delta_{t,0}$!

$$\boxed{\begin{aligned} P_1 &= R/A = f/b \\ P_2 &= L/R = \Omega_{m,0}\Sigma/f \\ P_3 &= R'/R = f + f'/f \end{aligned}}$$

usually called β, but we don't know b

introduced as E_G in Zhang et al 2007

"growth" observable

That's all – other combinations can be expressed in terms of P_1 – P_3 and their derivatives. (However, a peculiar velocity observable V would be great, as we could then get $L/V = 1+\eta$ directly.)

testing Horndeski

In the quasistic regime, the Horndeski model makes a very specifc prediction for the scale dependence of the anistropic stress:

$$\frac{3P_2 H_0^2(1+z)^3}{2H^2(P_3+2+H'/H)} - 1 = h_2\left(\frac{1+k^2h_4}{1+k^2h_5}\right) = 1+\eta$$

h_2, h_4 and h_5 are only functions of time, i.e. constants at a given redshift. Measurements on (at least) 4 scales could therefore test the relation and support or rule out all Horndeski-type models.

Horndeski is not too big to fail!

(but too big for full, unique reconstruction: many choices of coupling functions can match a given compatible set of linear observations)

Amendola, MK, Motta, Saltas, Sawicki 2013

consistency relations

A related approach where observational quantities need to verify a relation, based on conditions like the one in the previous slide, e.g.

$$g(z,k) \equiv \frac{(RHa^2)'}{LHa^2}$$

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

If this is not true at all scales and redshifts then either DE is not of Horndeski type or we are not in the quasistatic limit.

This can be generalized to avoid the quasistatic condition (see arXiv:1305.0008) and to many other situations (other models, testing FLRW metric, ...)

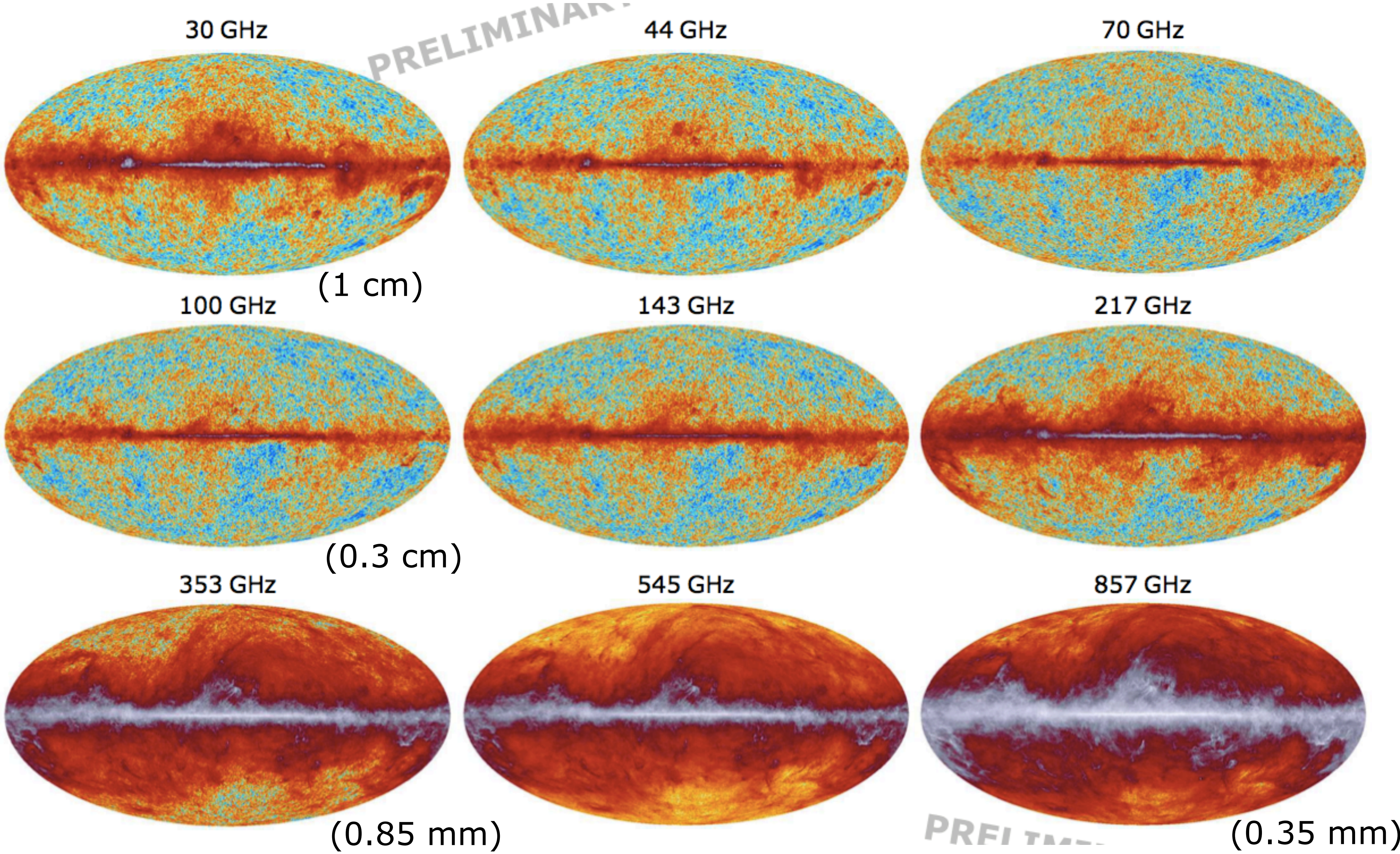
Planck DE/MG results

1. **Overview of data sets**
2. **'Dark Energy'**: effective quintessence model, determined by w(z)
    a. Taylor expansions / PCA
    b. mapping on quintessence potentials
    c. early dark energy
3. **'Modified Gravity'**
    a. Effective Field Theory (EFT)
    b. DE phenomenology
4. **Specific examples**
    a. f(R) – universal, non-minimal coupling
    b. coupled quintessence: non-universal coupling

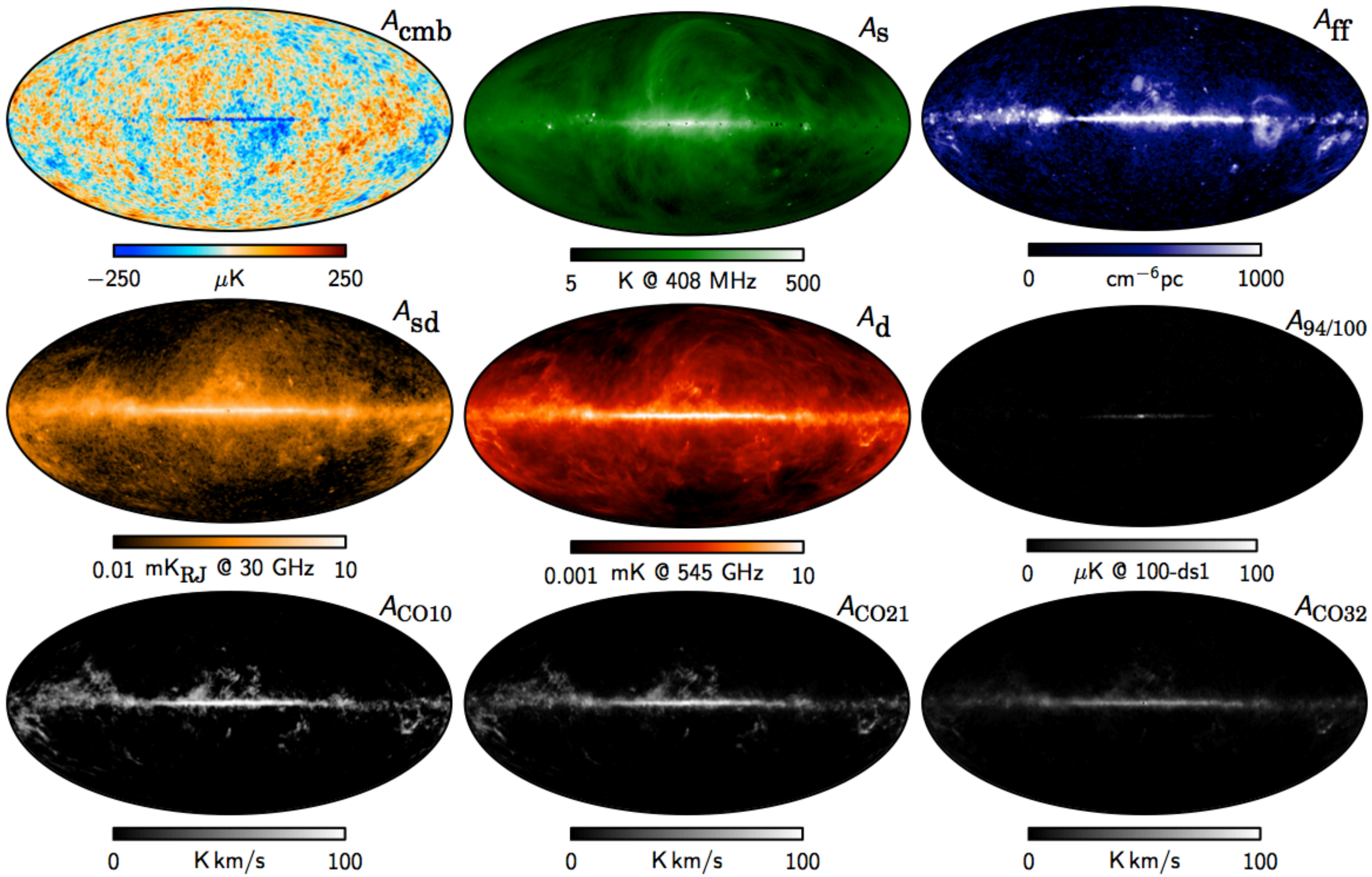
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

Planck 2015 maps (temperature)

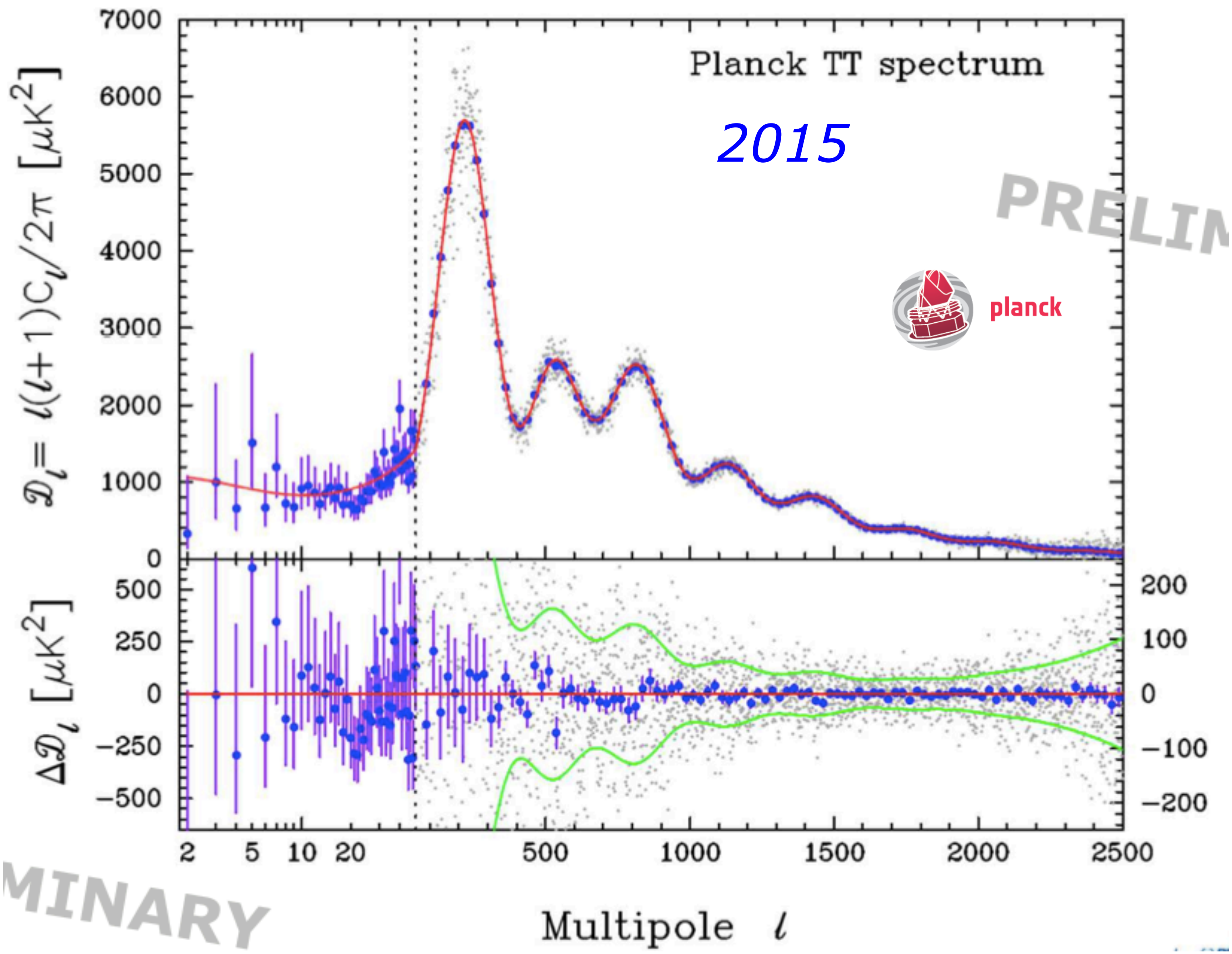


Planck 2015 component maps



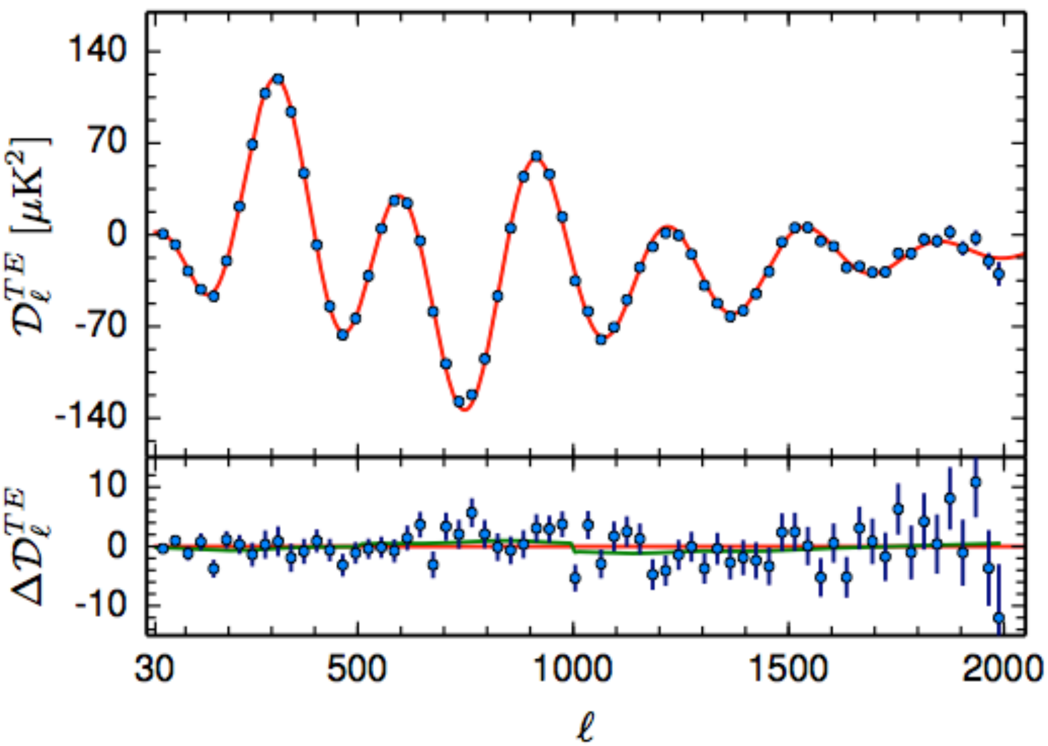
Maximum posterior intensity maps derived from the joint analysis of Planck, WMAP, and 408MHz observations

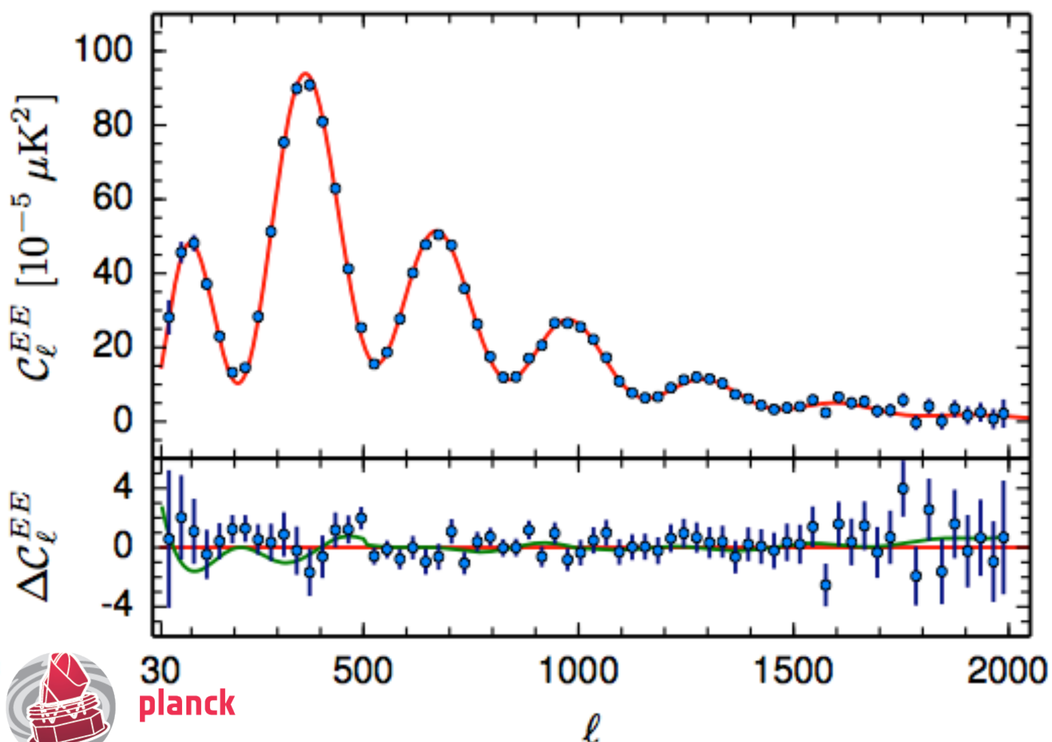
2015 TT power spectrum



2015 polar power spectrum

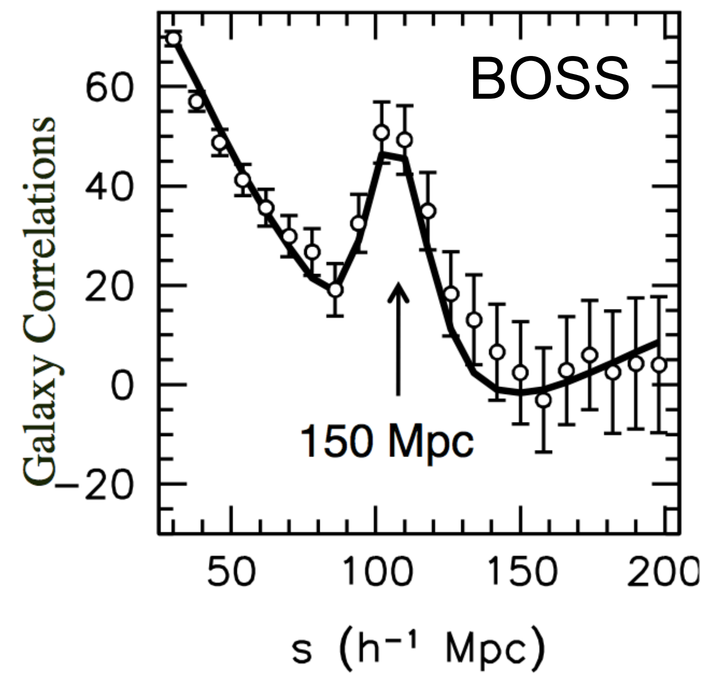
- scattering of photons off electrons depends on polarisation
- polarisation decomposed into
  - E: gradient type
  - B: vector / rotation type
- for density / scalar perturbations alone, TT predicts TE and EE (and no B-type polarisation)
- CMB lensing, other constituents (e.g. grav. waves) and foregrounds create B-type polarisation





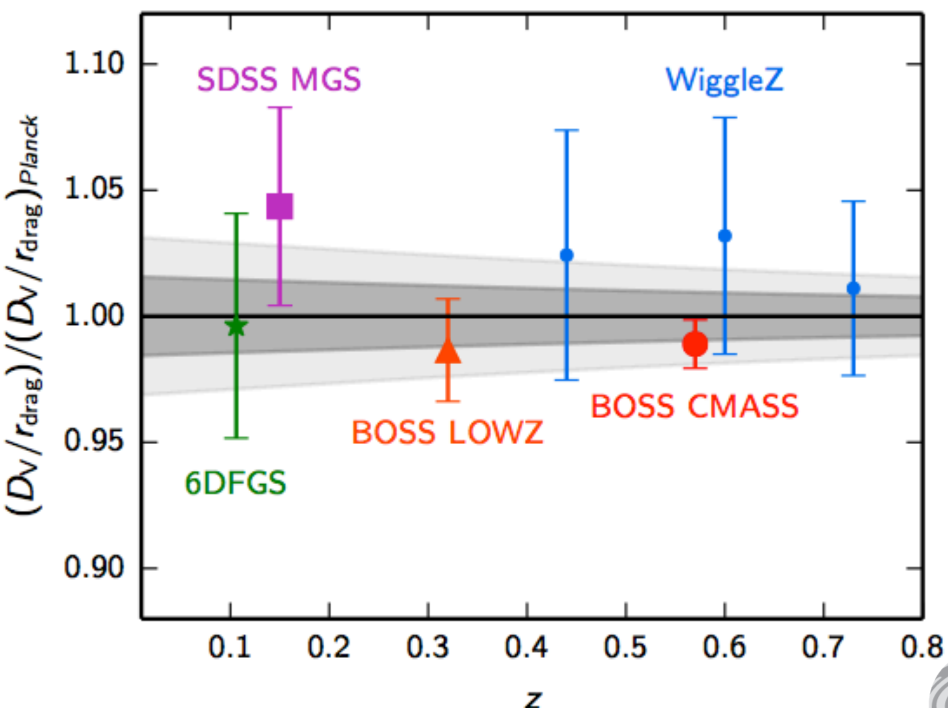
planck

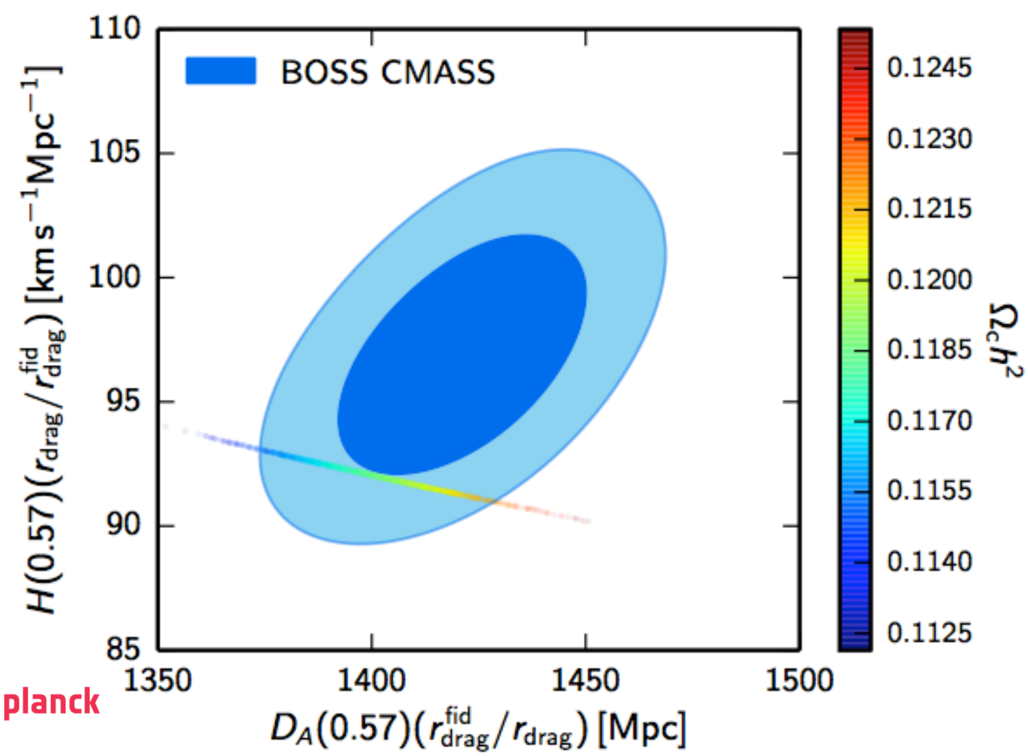
BAO distances



a standard ruler of ~150 comoving Mpc gives us an angular diameter distance (linked to same scale as CMB peak position!)

Planck 2015



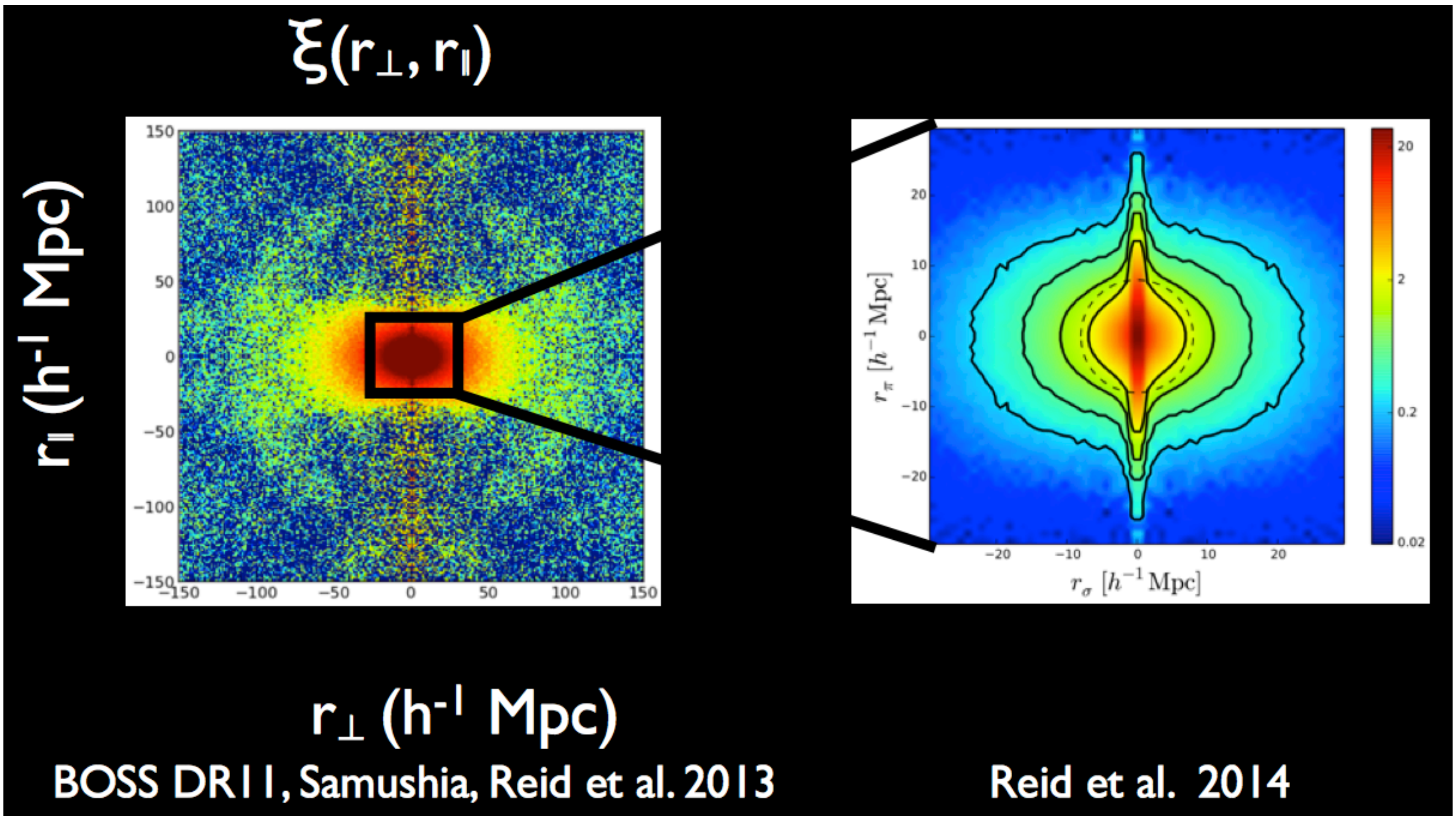


planck

redshift space distortions

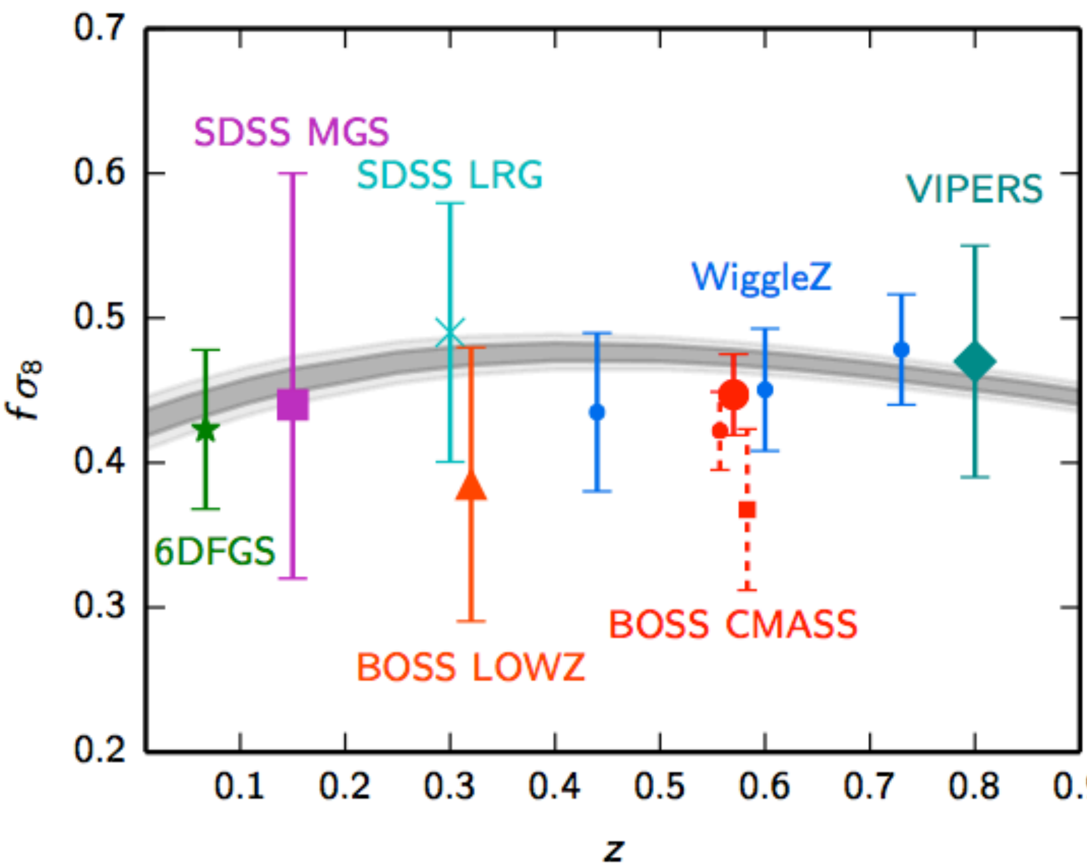
We observe galaxies in redshift space, not real space

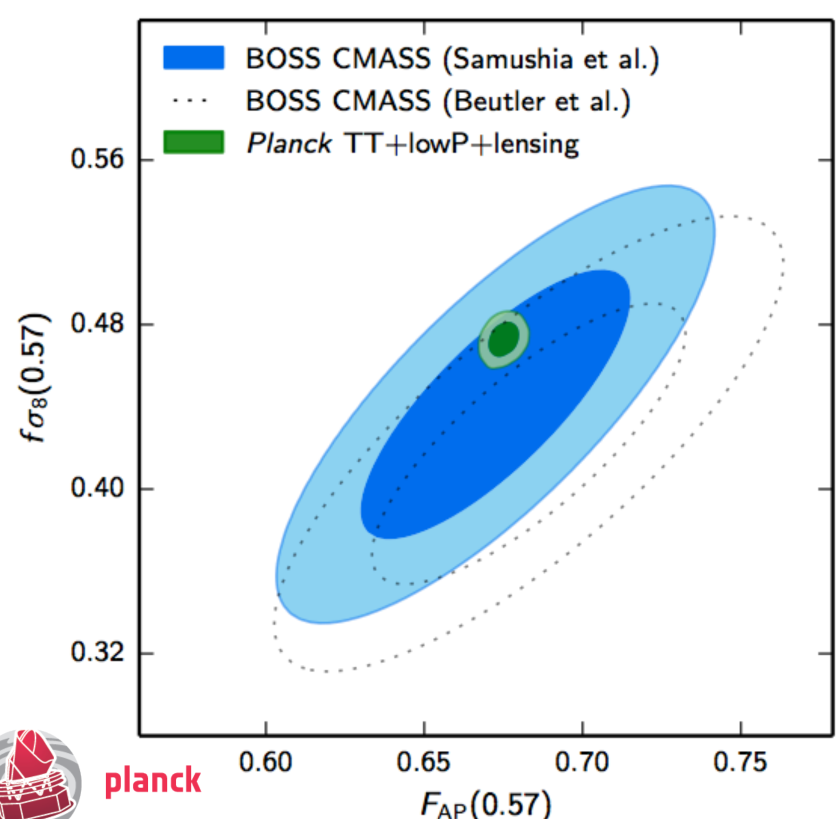
- large scales: coherent infall → squashing
- small scales random motion → elongation (`finger of god')



redshift space distortions

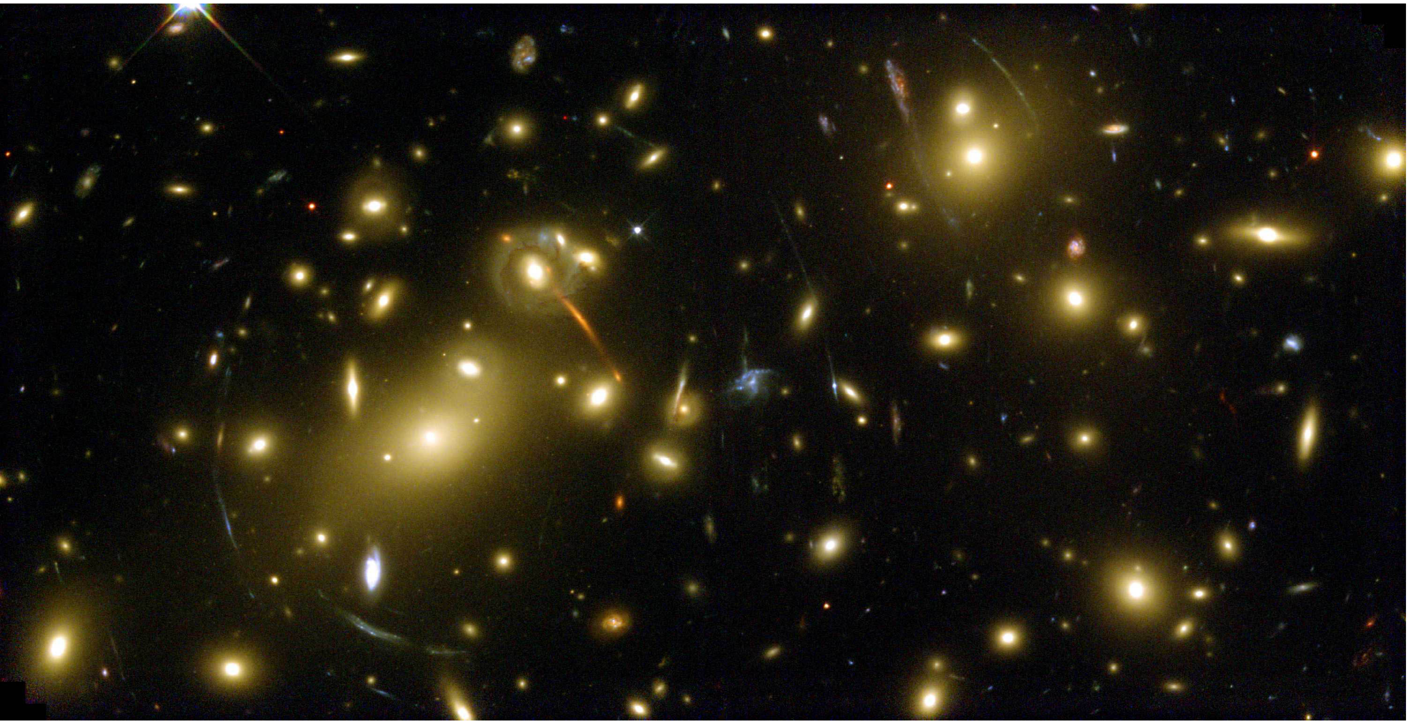
- particle conservation: velocities → growth
  → RSD measure combination $f\sigma_8$, $f = d\ln D/d\ln a$
- particle acceleration ~ grad Ψ





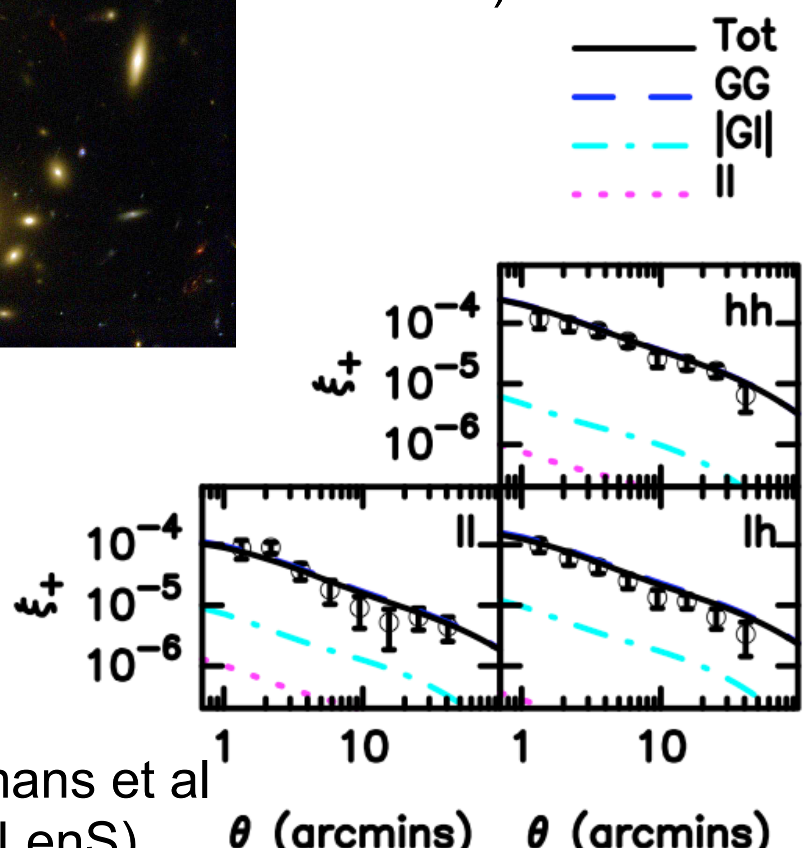
planck

gravitational lensing



mass deflects light
this distorts galaxy shapes a tiny bit

(lensing potential ~ $\Phi+\Psi$)

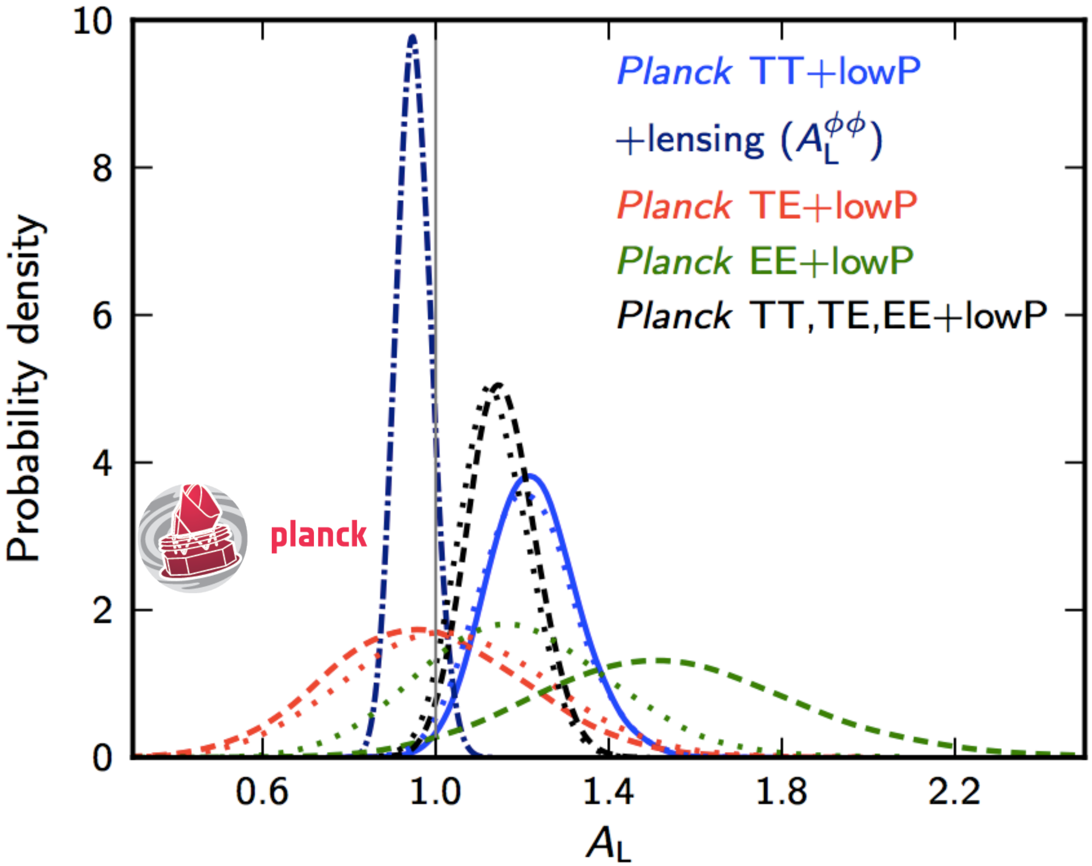


(Heymans et al CFHTLenS)

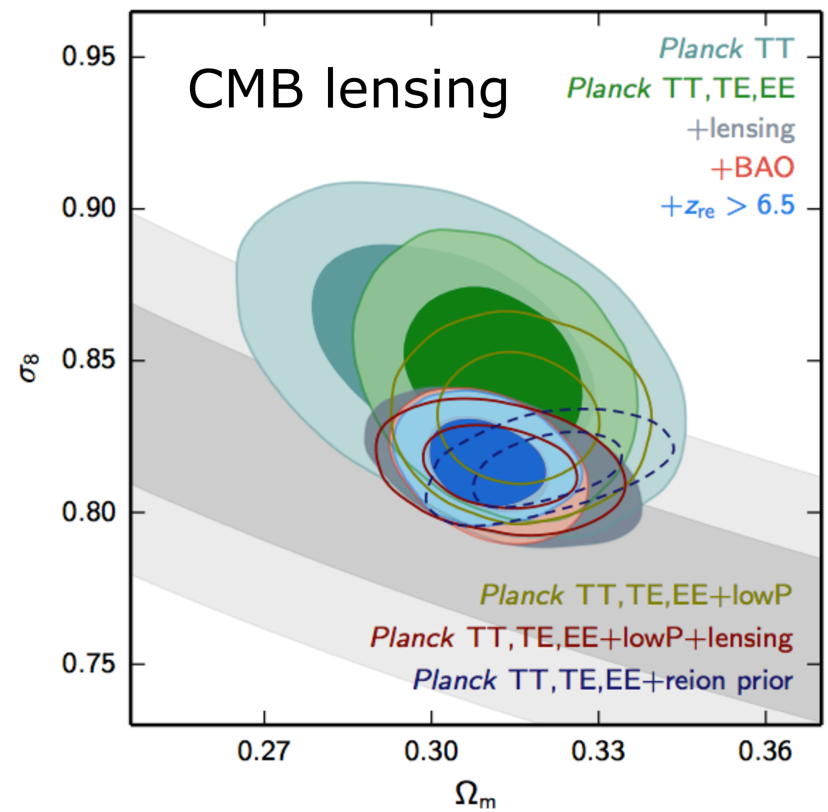
seen as a future key probe, but difficult:

- **non-linear scales**
- **baryons**
- **intrinsic alignments**

comparison with lensing data

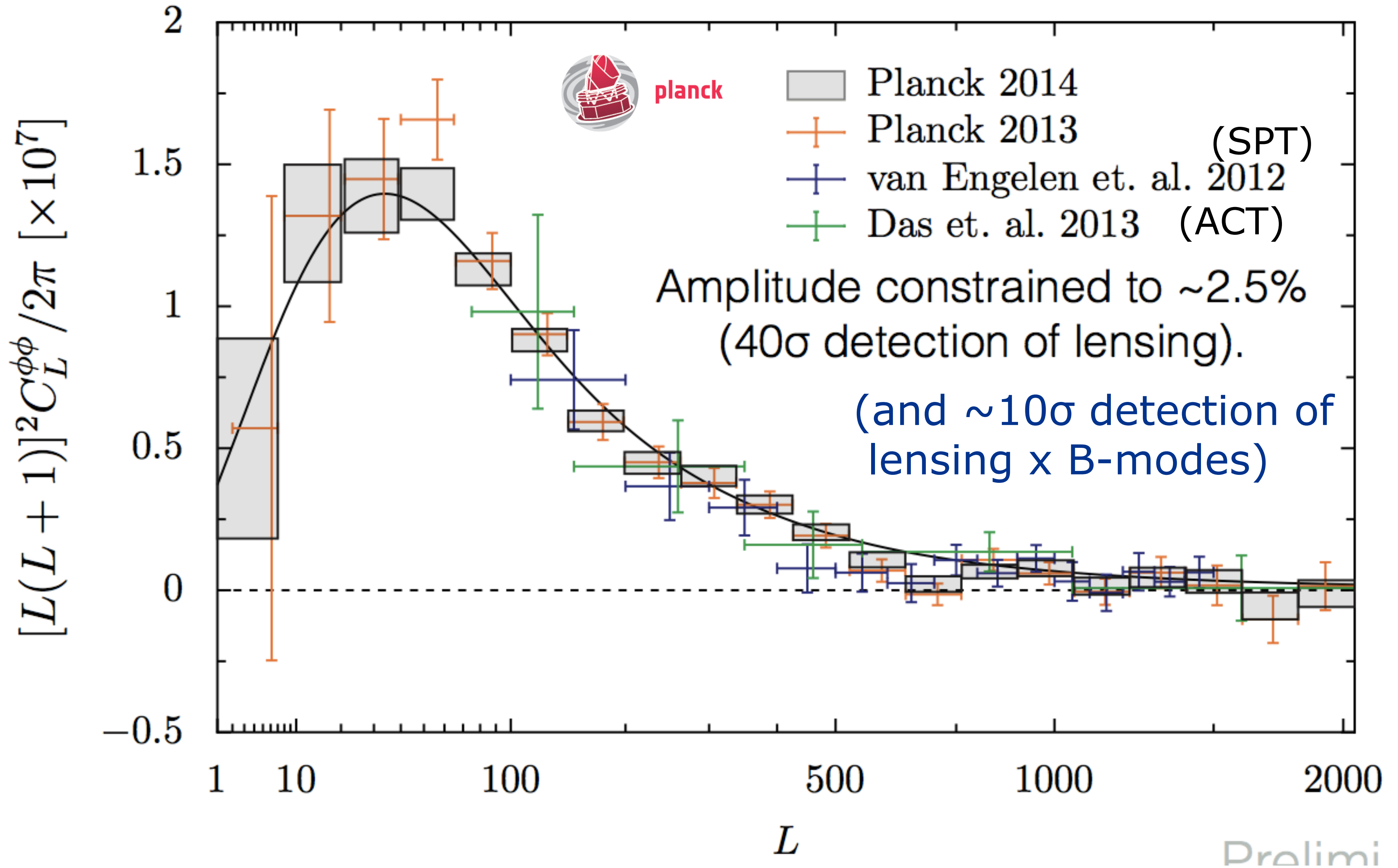


- WL still young technique
- CFHTLenS analyses marginally compatible with each other
- region ~Planck needs high H0
- we use 'ultraconservative' cut

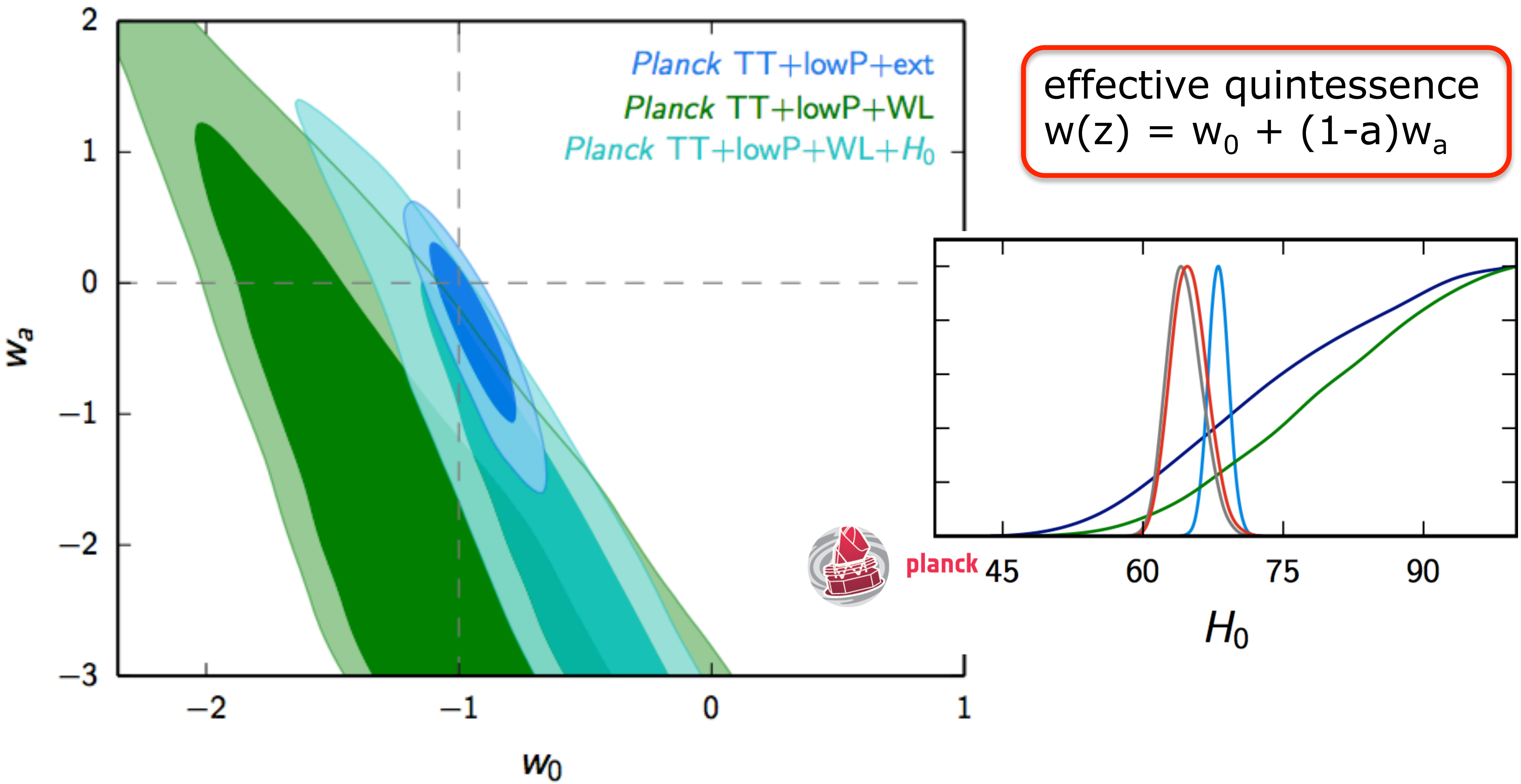


- CMB lensing now quite mature
- relatively good agreement with primary CMB
- (still a slight 'lensing excess' in power spectrum)

CMB lensing


planck
Planck 2014
Planck 2013
van Engelen et. al. 2012
Das et. al. 2013
(SPT)
(ACT)
Amplitude constrained to ~2.5%
(40σ detection of lensing).
(and ~10σ detection of
lensing x B-modes)
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi\ [\times 10^7]$
L
2
1.5
1
0.5
0
−0.5
1
10
100
500
1000
2000
Prelimi

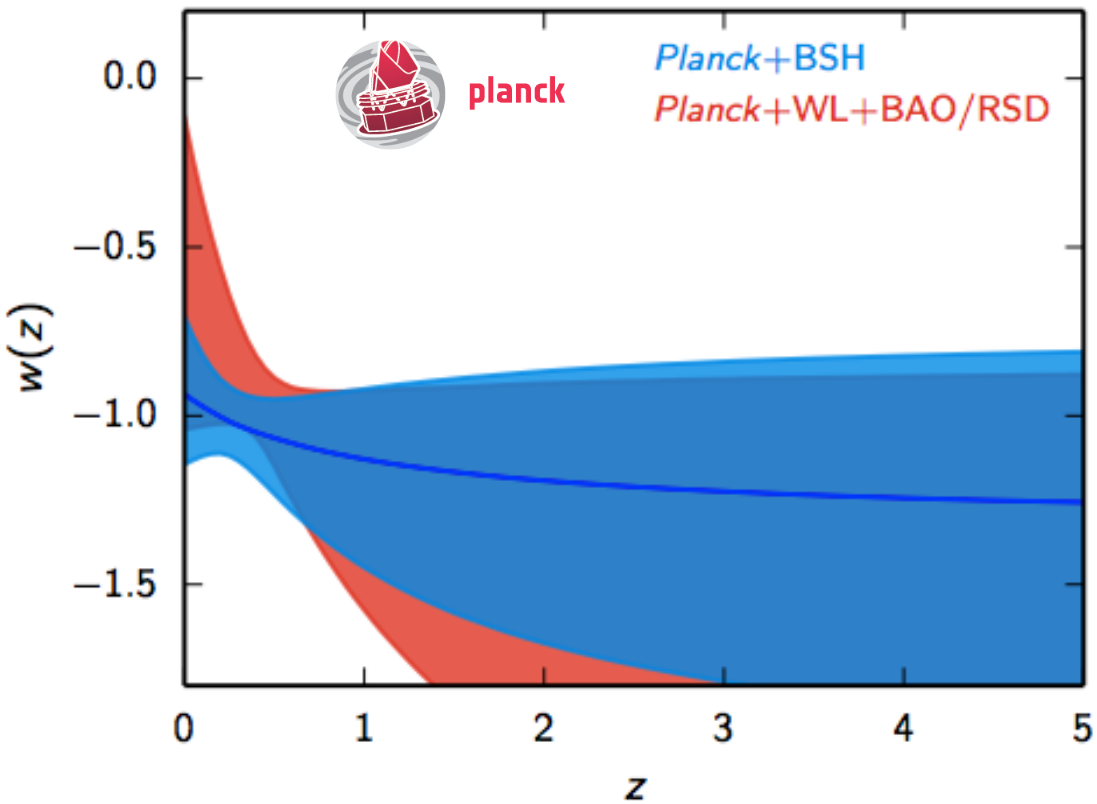
dark energy



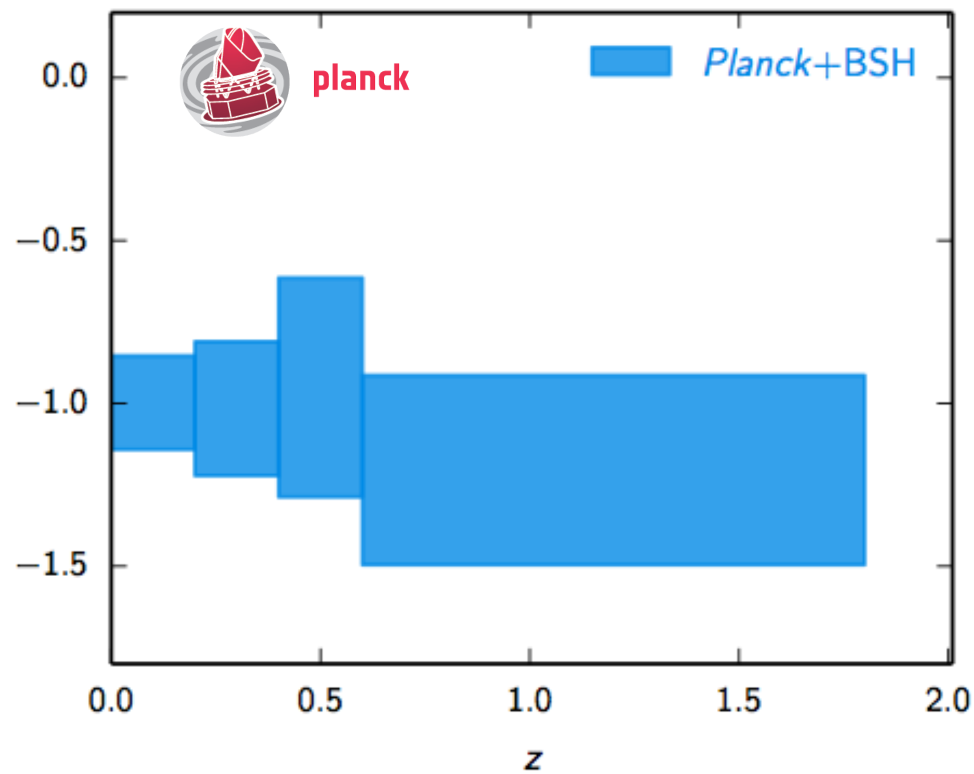
effective quintessence
$w(z) = w_0 + (1\text{-}a)w_a$

- Planck and WL prefer high H_0 and the 'phantom domain'
- no deviation from LCDM when adding BAO+JLA+H0
- **const w: w=-1.02±0.04** (TT,TE,EE+lowP+lensing+ext)

w(z) reconstruction



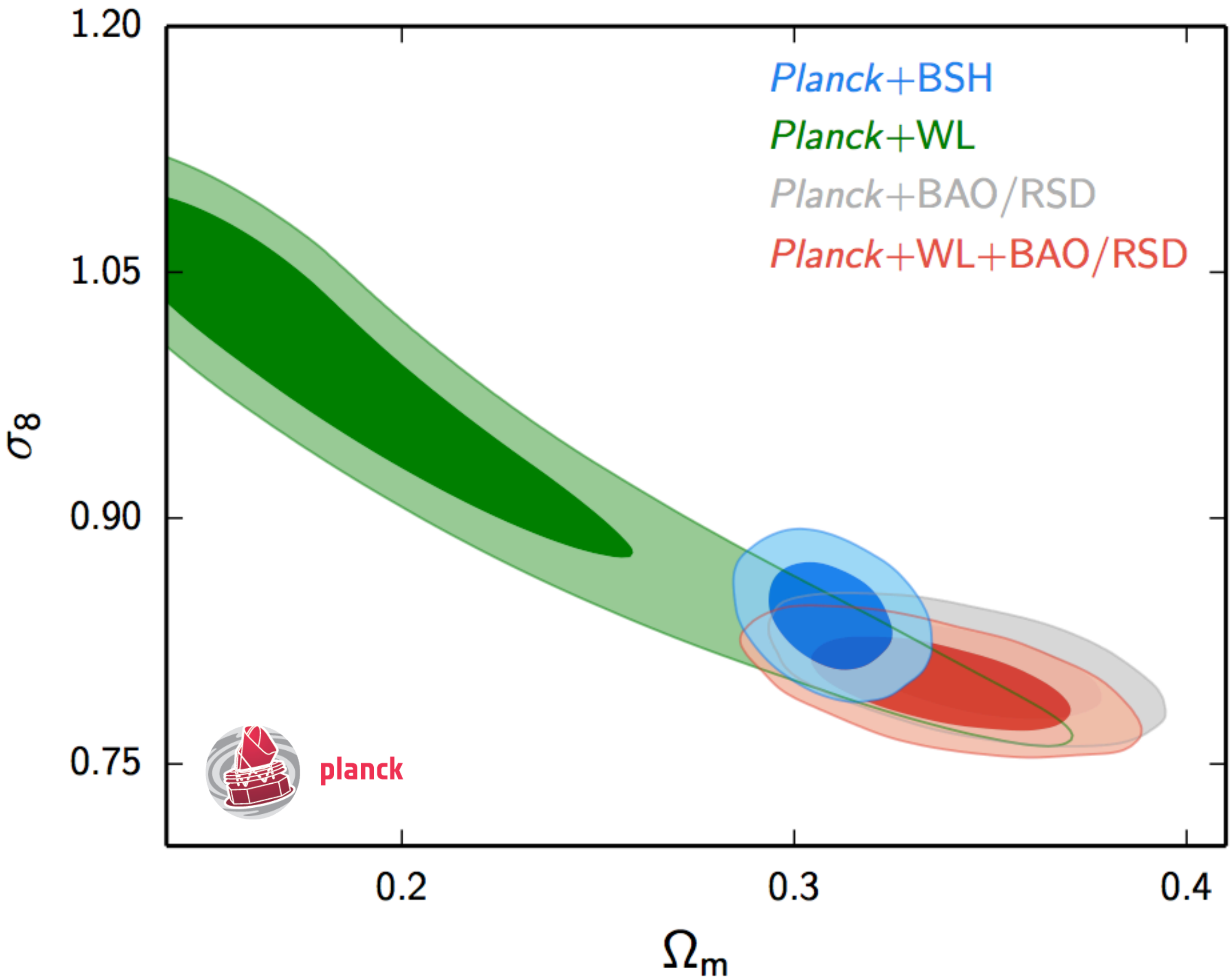
from ensemble of
$w_0+(1\text{-}a)w_a$ curves
(we also tried cubic in a)



PCA
(we also tried more bins)

no deviation from w=-1

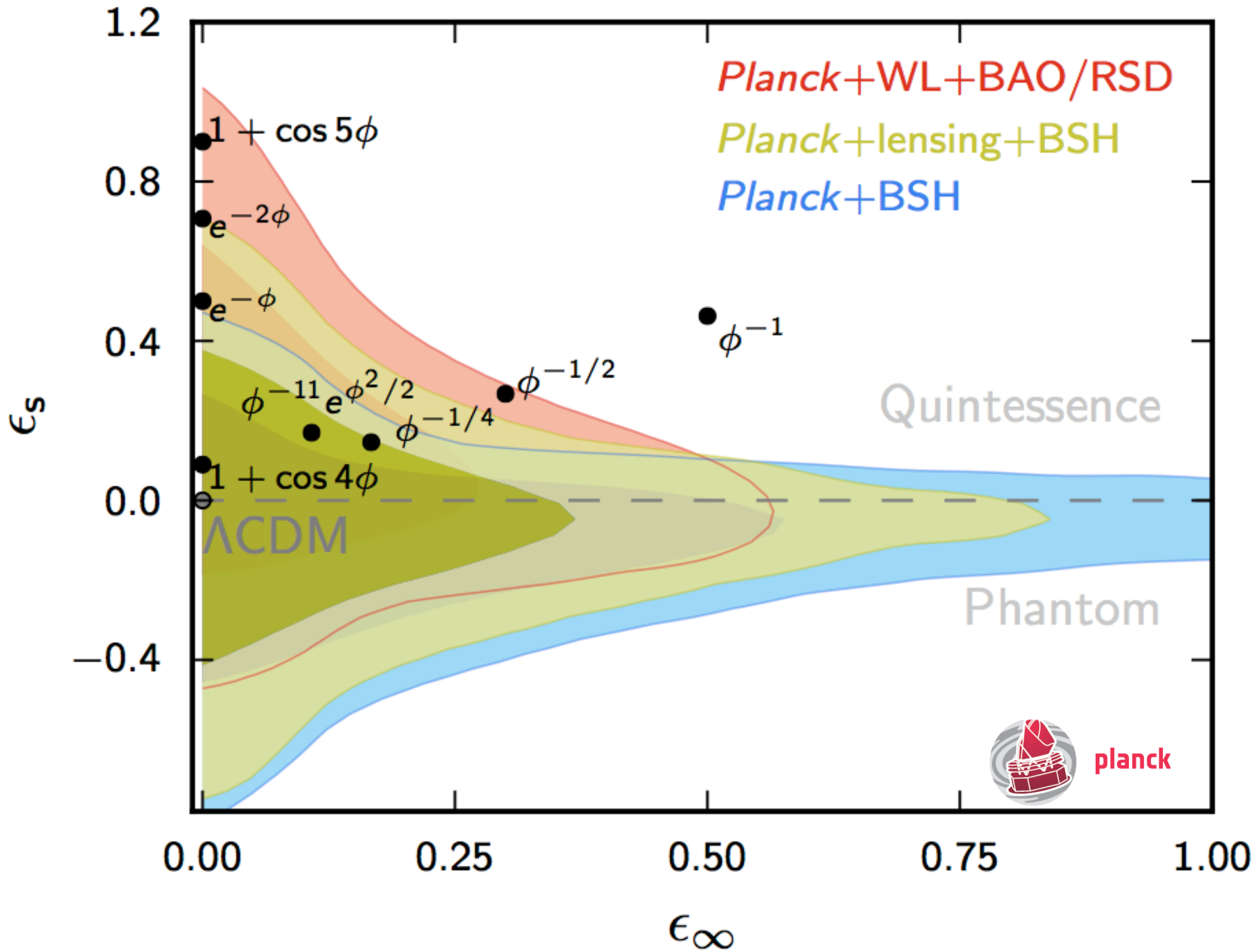
quintessence and growth



Quintessence can affect growth significantly

But Planck+WL would push into 'wrong' direction

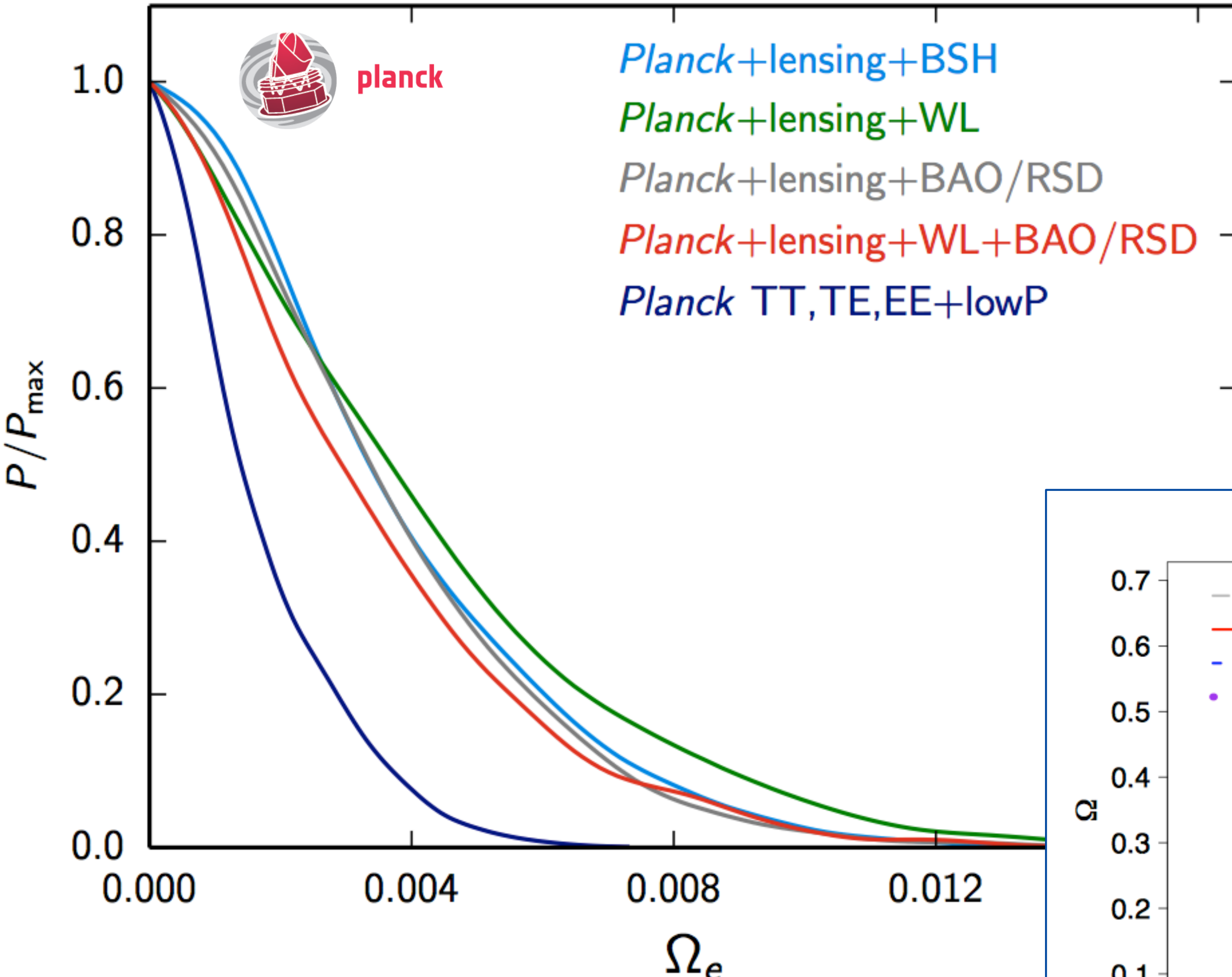
quintessence landscape



similar to scalar field inflation

$\varepsilon_s \approx 3/2(1+w)$
ε_∞ early time

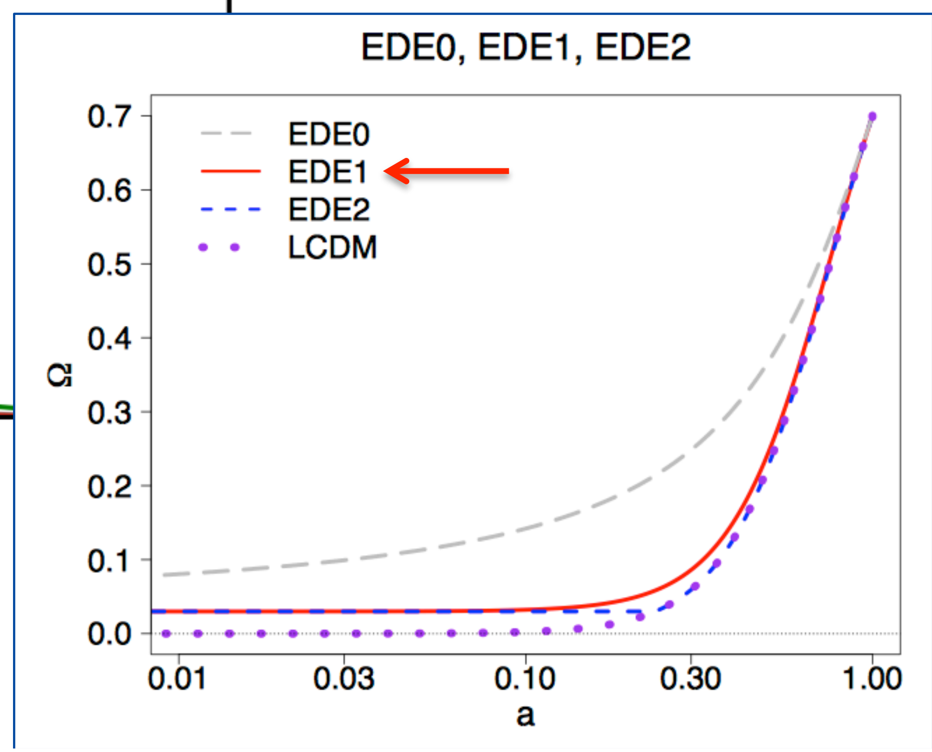
early dark energy



TT,TE,EE+lowP+BSH:

$\Omega_e < 0.0036$ @95%

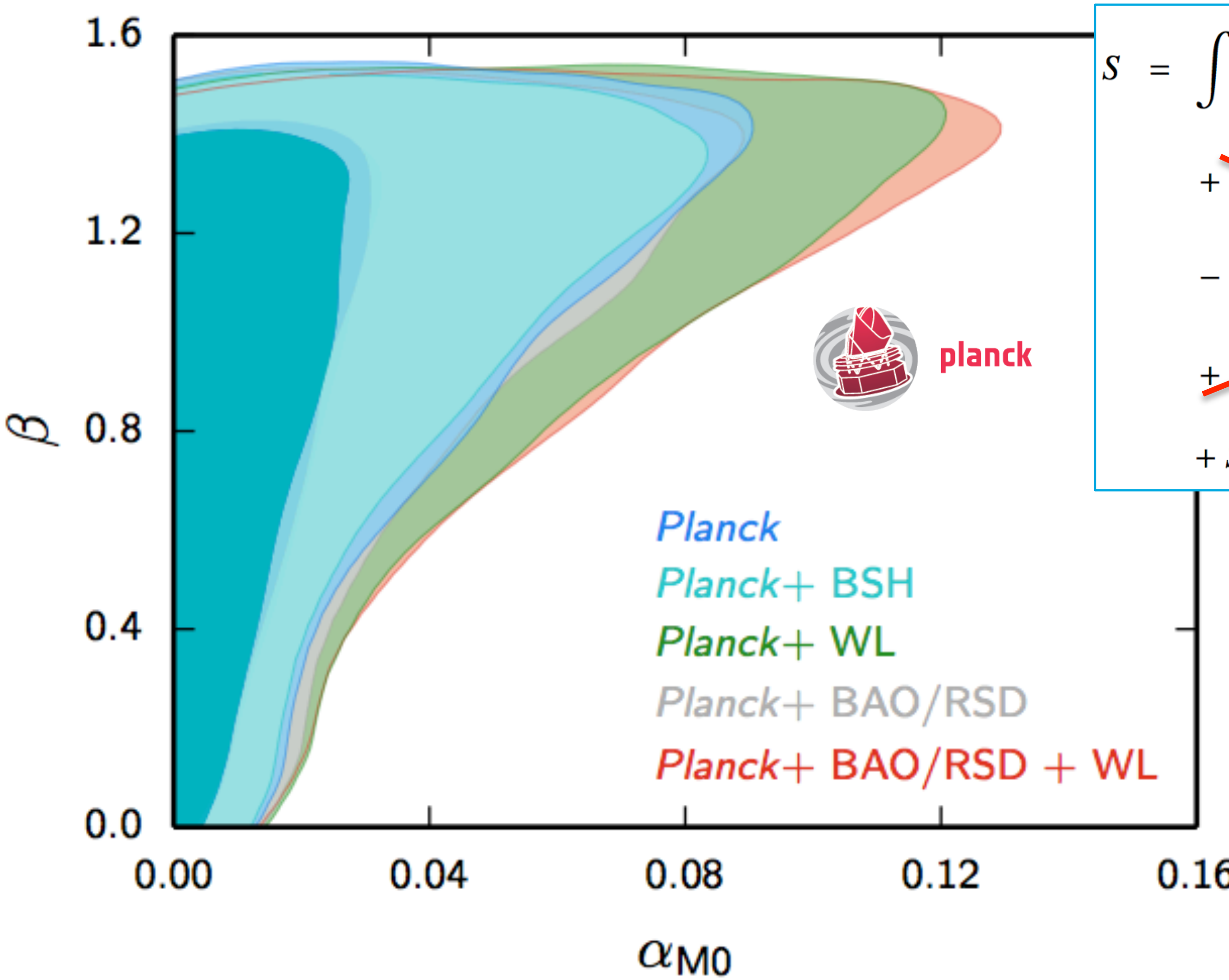
$w_0 < -0.94$ @95%



[if DE important for z ≤ 50 only then $\Omega_e \leq 2\%$ (95%CL)]

effective field theory of DE

→ generalize action (consider it as EFT action)
→ e.g. universally coupled theories of one extra scalar d.o.f. with 2nd order equations of motion respecting isotropy and homogeneity



$$\begin{aligned} S = & \int d^4x \sqrt{-g}\left\{\frac{m_0^2}{2}\left[1+\Omega(\tau)\right]R + \Lambda(\tau) - a^2 c(\tau)\delta g^{00} \right. \\ & + \frac{M_2^4(\tau)}{2}\left(a^2\delta g^{00}\right)^2 - \bar{M}_1^3(\tau) 2a^2\delta g^{00}\delta K^\mu_\mu \\ & - \frac{\bar{M}_2^2(\tau)}{2}\left(\delta K^\mu_\mu\right)^2 - \frac{\bar{M}_3^2(\tau)}{2}\delta K^\mu_\nu \delta K^\nu_\mu + \frac{a^2\hat{M}^2(\tau)}{2}\delta g^{00}\delta R^{(3)} \\ & \left. + m_2^2(\tau)\left(g^{\mu\nu}+n^\mu n^\nu\right)\partial_\mu\left(a^2 g^{00}\right)\partial_\nu\left(a^2 g^{00}\right)\right\} \\ & + S_{\mathrm{m}}[\chi_i, g_{\mu\nu}]. \end{aligned}$$

$$\Omega(a) = \exp\left\{\frac{\alpha_{M0}}{\beta}a^\beta\right\} - 1$$

→ non-minimally coupled K-essence model

phenomenological approach

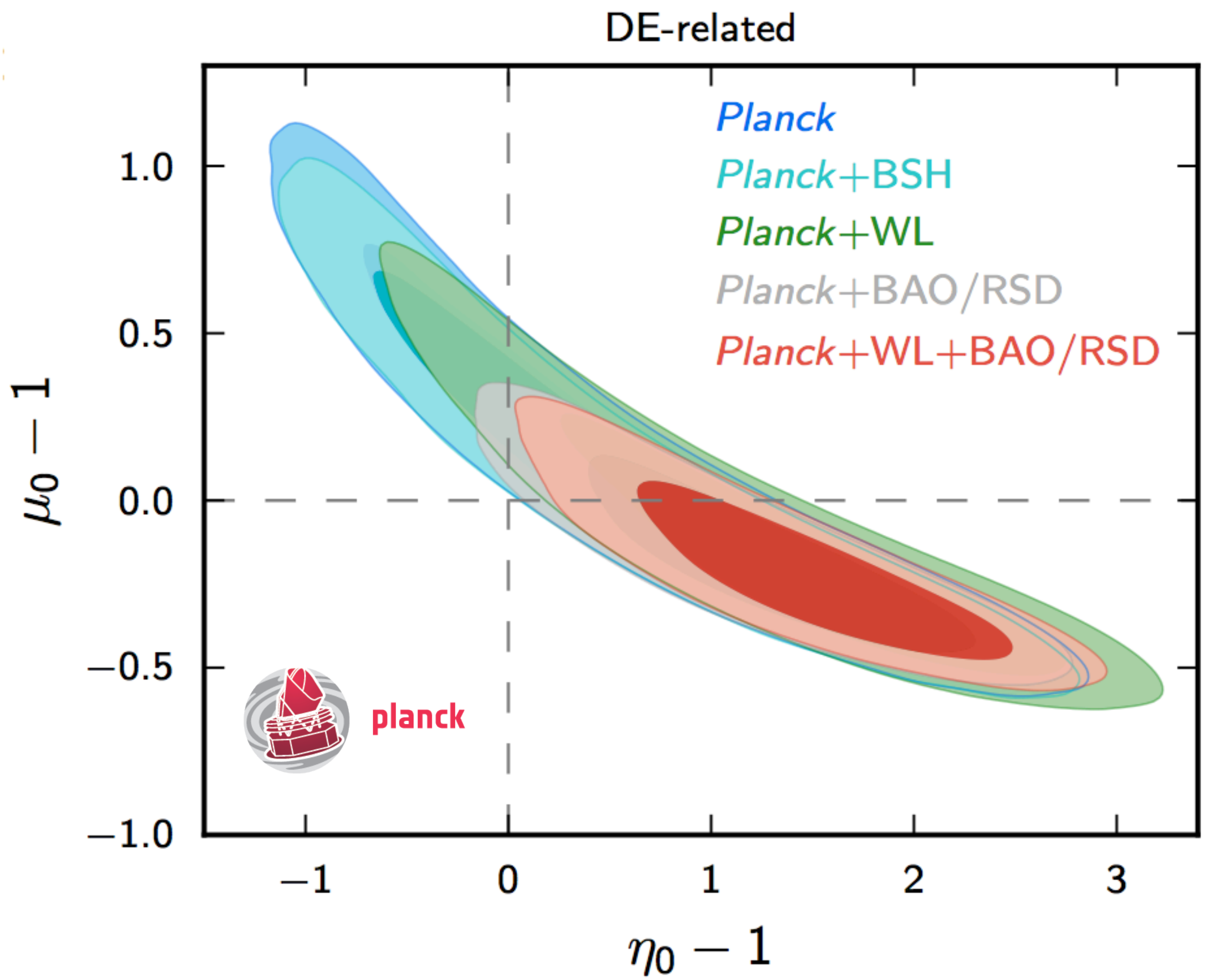
parameterisation of
late-time perturbations:

$$-k^2\Psi \equiv 4\pi G a^2 \mu(a, \boldsymbol{k})\rho\Delta$$

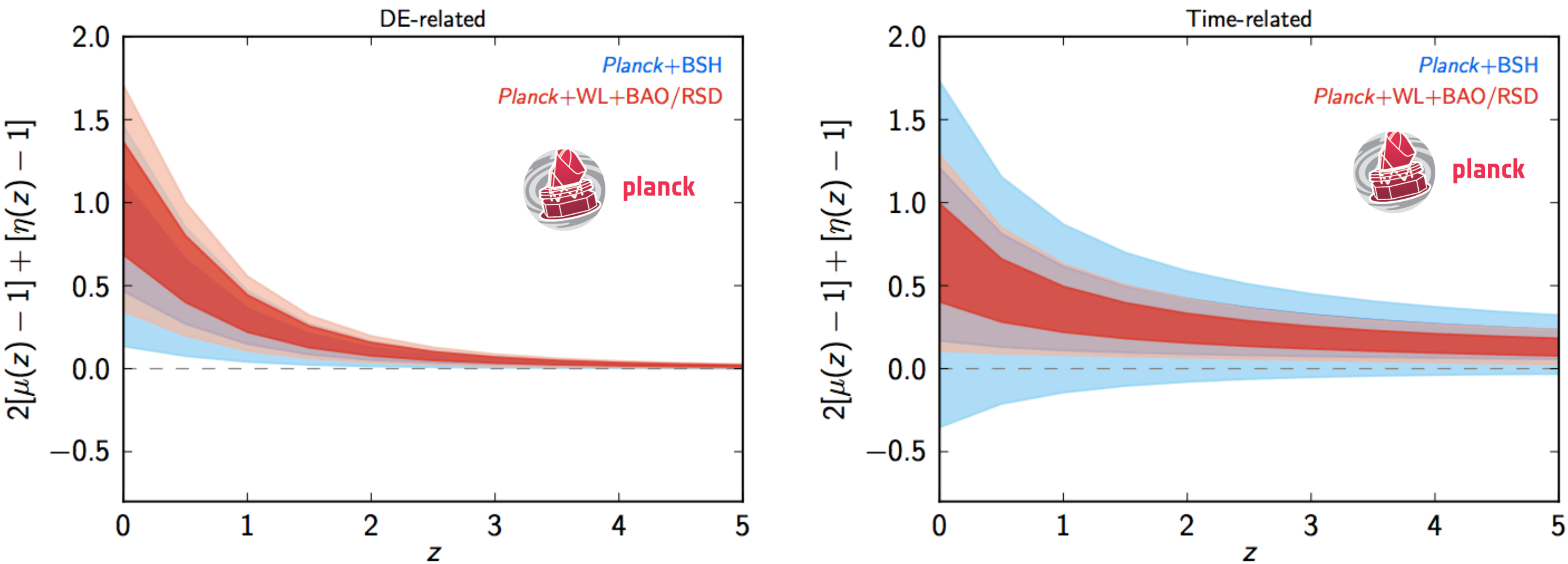
$$\eta(a, \boldsymbol{k}) \equiv \Phi/\Psi$$

functions ~ $\Omega_{DE}(a)$
ΛCDM background

- no scale dependence detected
- deviation driven by CMB and WL



evolution of deviation

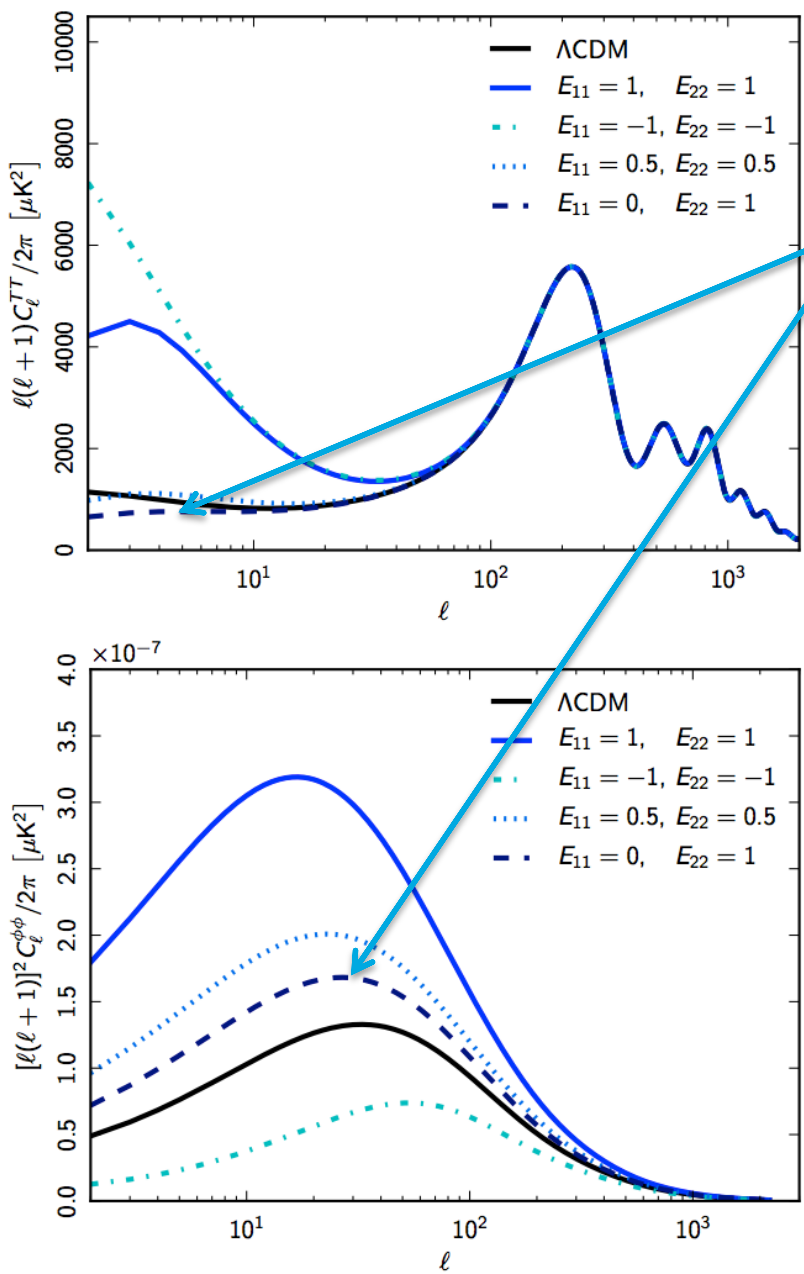


DE related parameterization:

- ΔX^2 = -6.3 (Planck TT+lowP)
- ΔX^2 = -10.6 (Planck TT+lowP+WL)
- ΔX^2 = -10.8 (Planck TT+lowP+WL+BAO/RSD)
- roughly 3σ when projected on single combination

MG impact on observables

planck

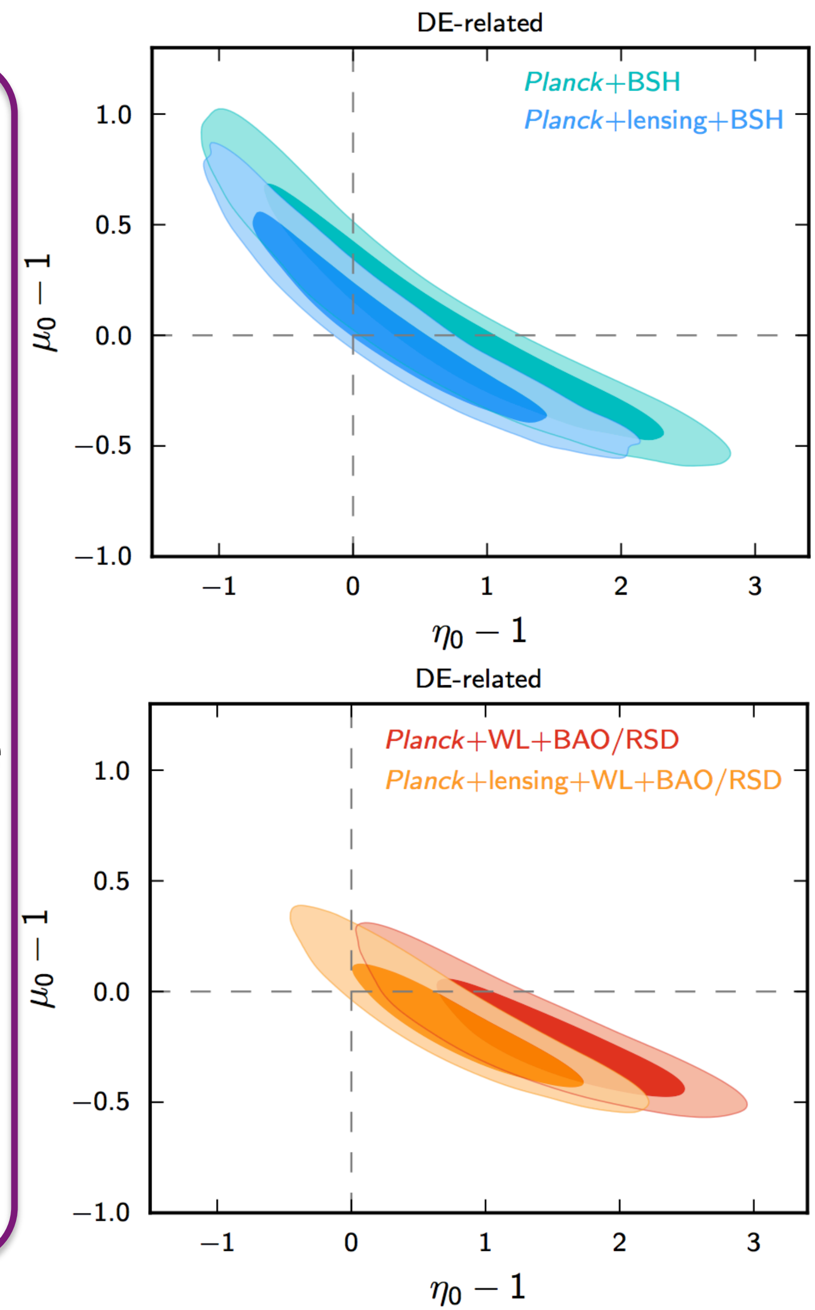


best-fit model is similar to -- model

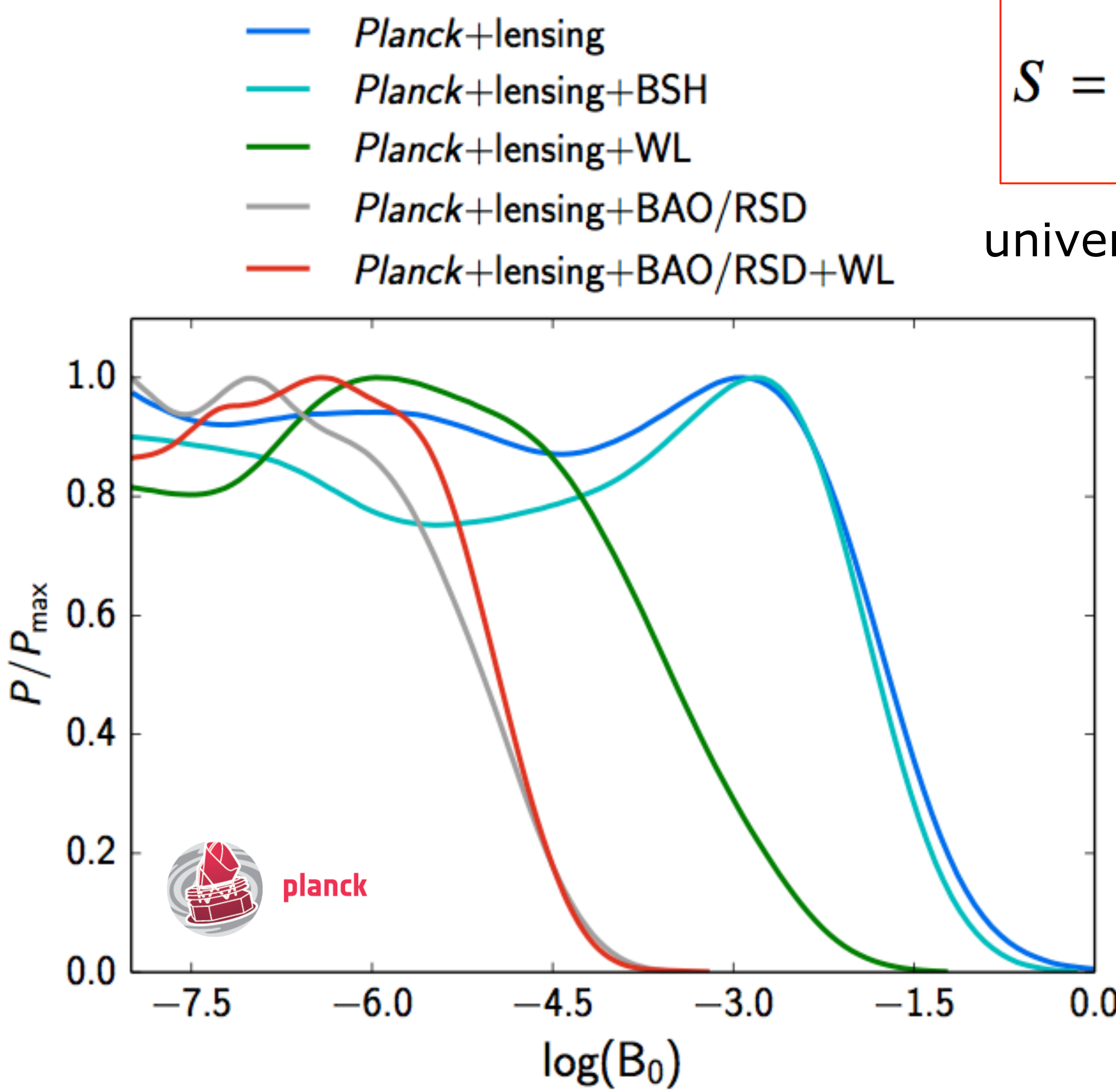
CMB data prefers lower low-l value and higher lensing in TT

BUT NOT in the 4-point lensing → CMB lensing prefers LCDM!

→ doesn't look very significant after all ☺



f(R) models



$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}(R + f(R))$$

universal but non-minimal coupling

LCDM background

$$B(z) = \frac{f_{RR}}{1+f_R}\frac{H\dot{R}}{\dot{H}-H^2}$$

4 orders of magnitude
improvement from RSD!

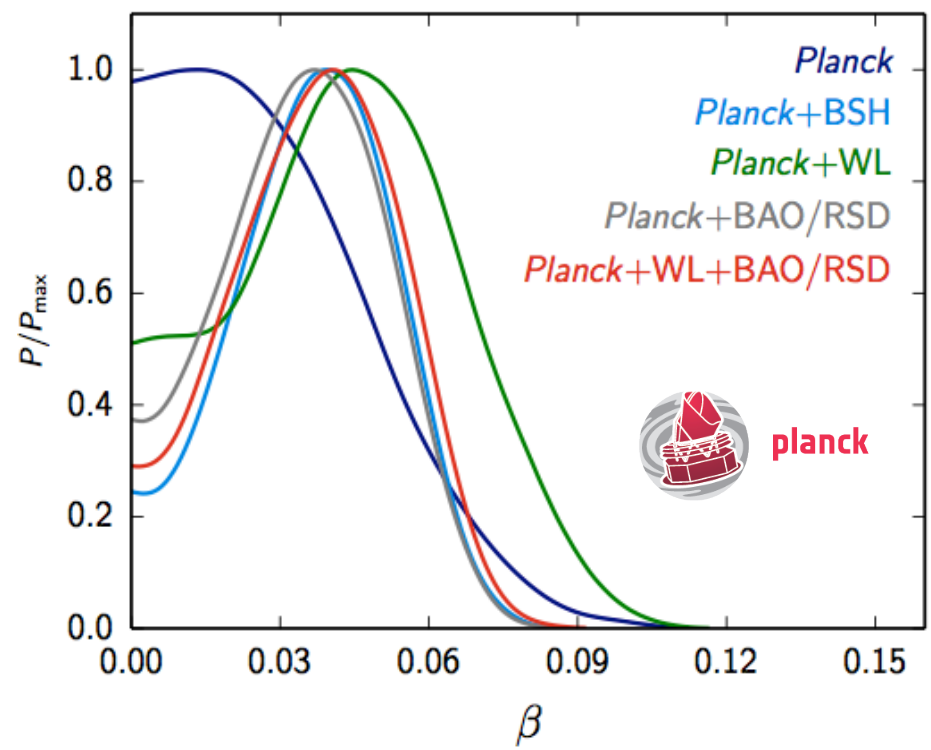
best limit:
TT+lowP+lensing+WL
+BAO/RSD
$B_0 < 0.8\times10^{-4}$ (95% CL)

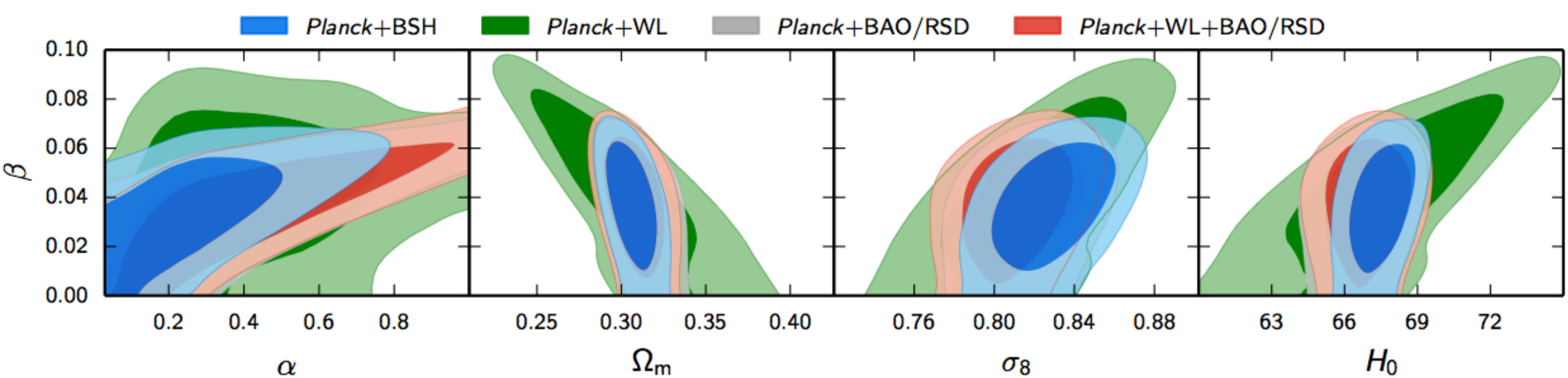
coupled quintessence

coupling strength β only to CDM
→ no screening mechanism
→ non-universal coupling

Planck+BSH give 2.5σ tension
with LCDM

but no improvement in X^2!
→ volume effect from marginalisation?





conclusions

- Flat ΛCDM is a good fit to current data in spite of many tests, no compelling evidence for deviations from this simple 6-parameter model
- We don't like the cosmological constant … but while there are many alternative models, none are compelling
- Characterize the dark sector phenomenologically
    - background: w(z) ← distances
    - perturbations: 2 functions ← e.g. RSD + WL
- Where will we stand in 15 to 20 years?