Dark Energy
theory and observational constraints

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outline (for both slots)

1. what is the problem?
2. dark energy theory
   - action based models
   - more on scalar field DE
   - phenomenological approach
3. observational constraints
   - simple principles
   - current constraints from Planck+
   - outlook

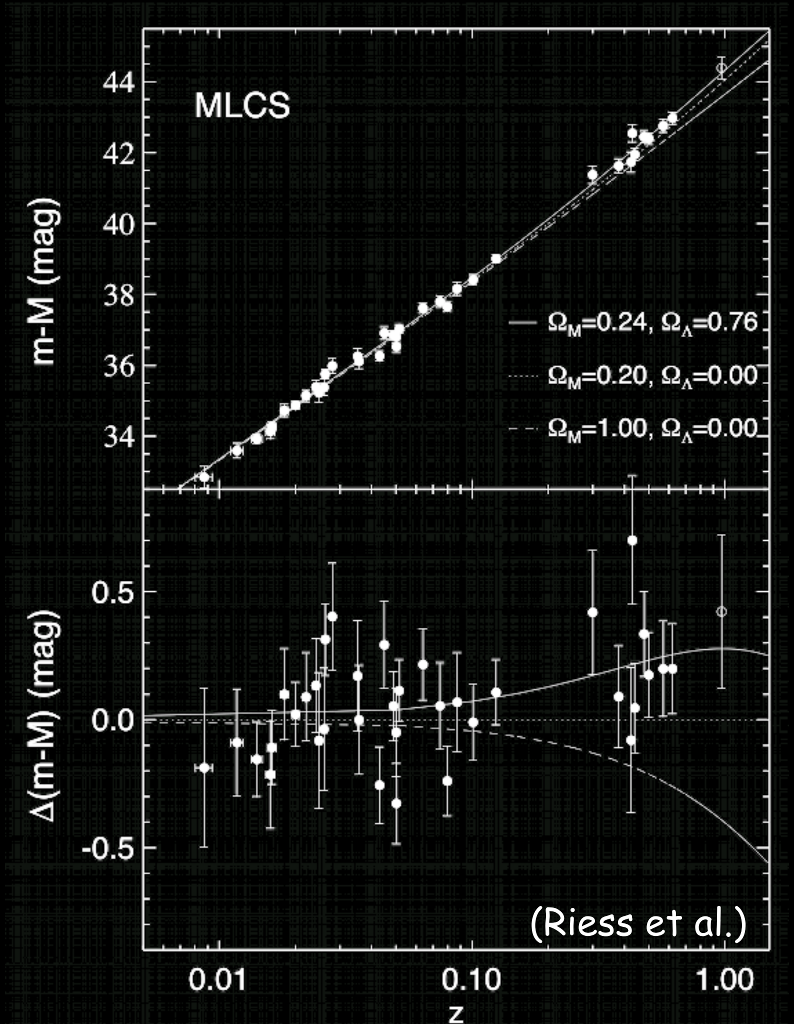
The Nobel Prize 2011

"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!

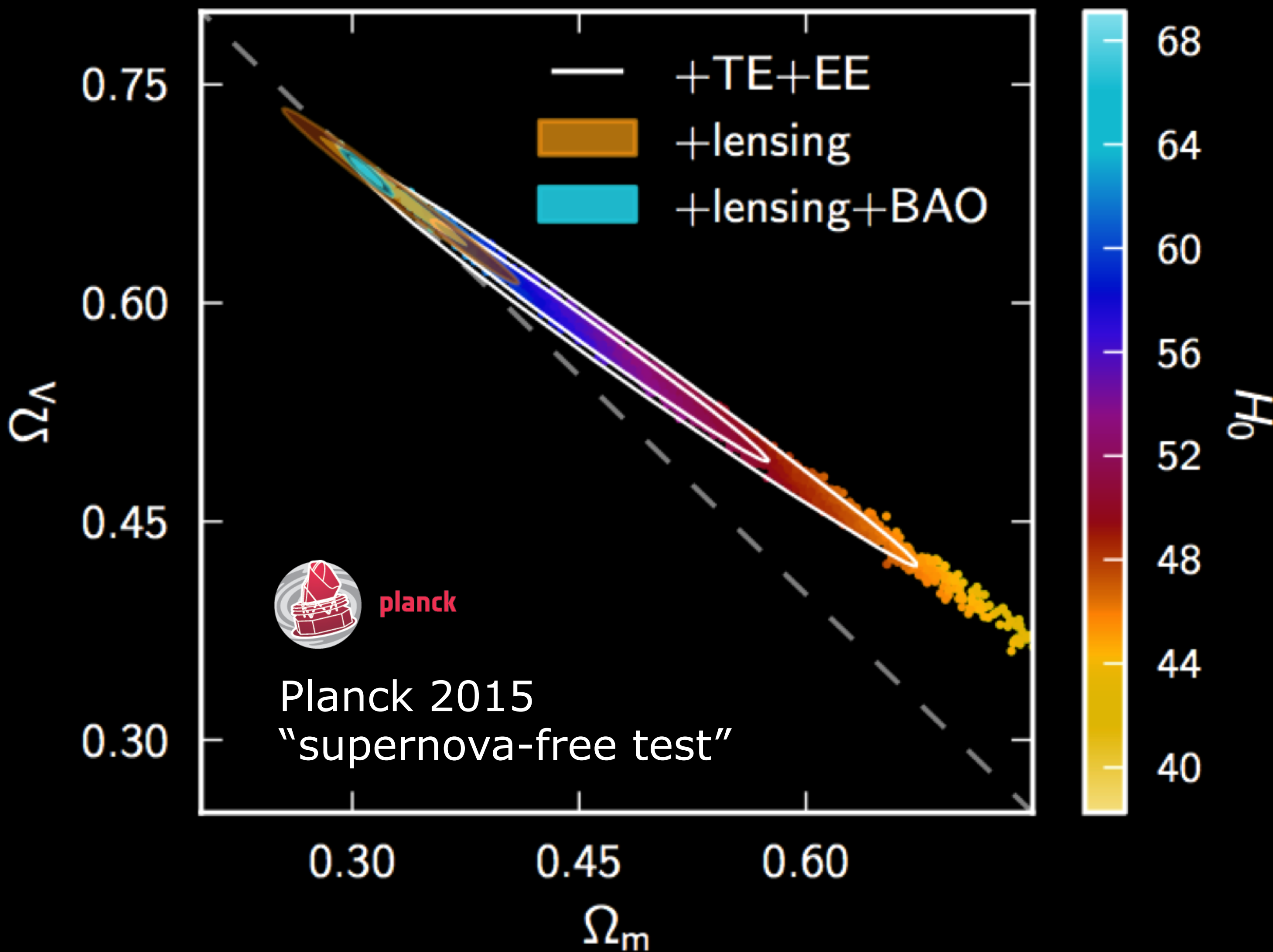
One well-motivated model:

the cosmological constant



(Riess et al.)

can the data be wrong?

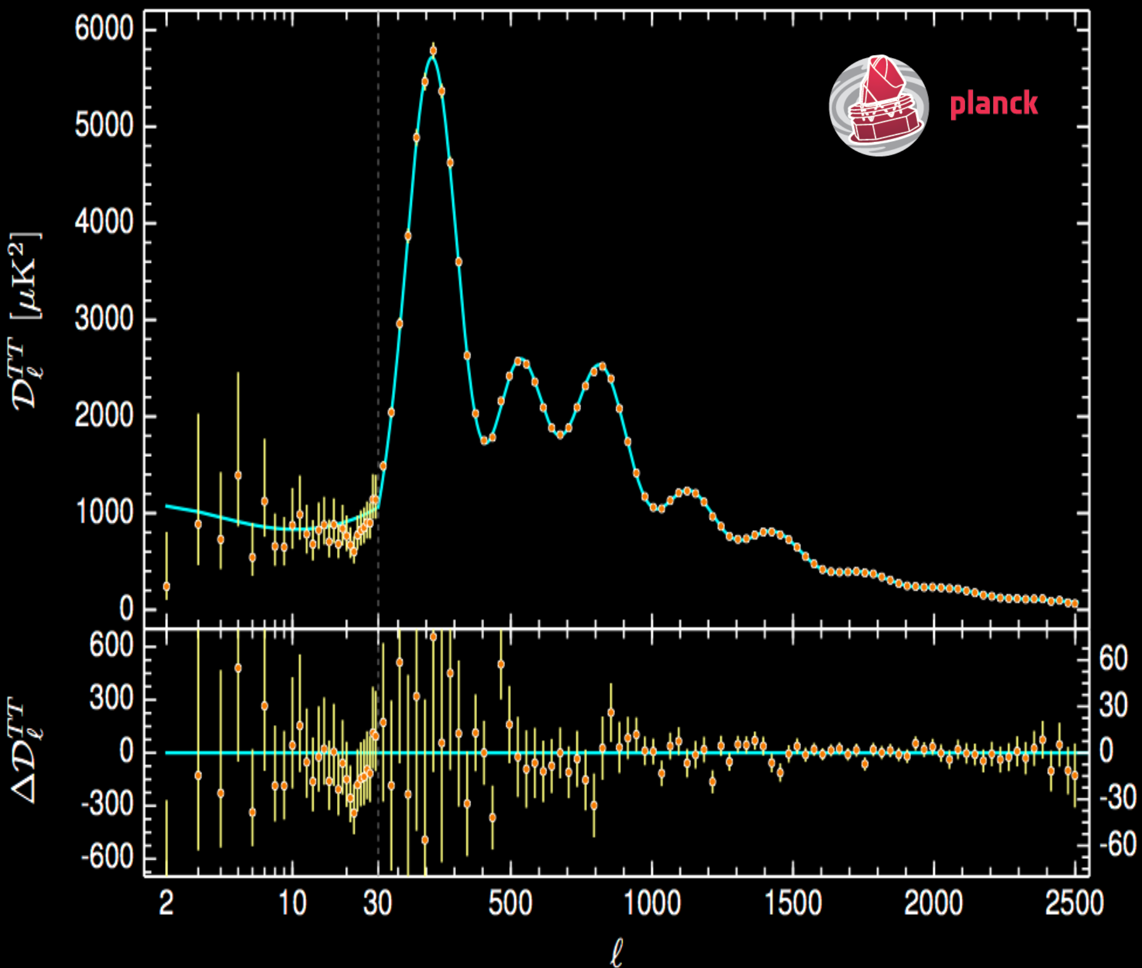


CMB alone rules out no accelerated expansion at high significance

…

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

Planck vs ΛCDM



cyan curve:
best fit 6-parameter flat ΛCDM model

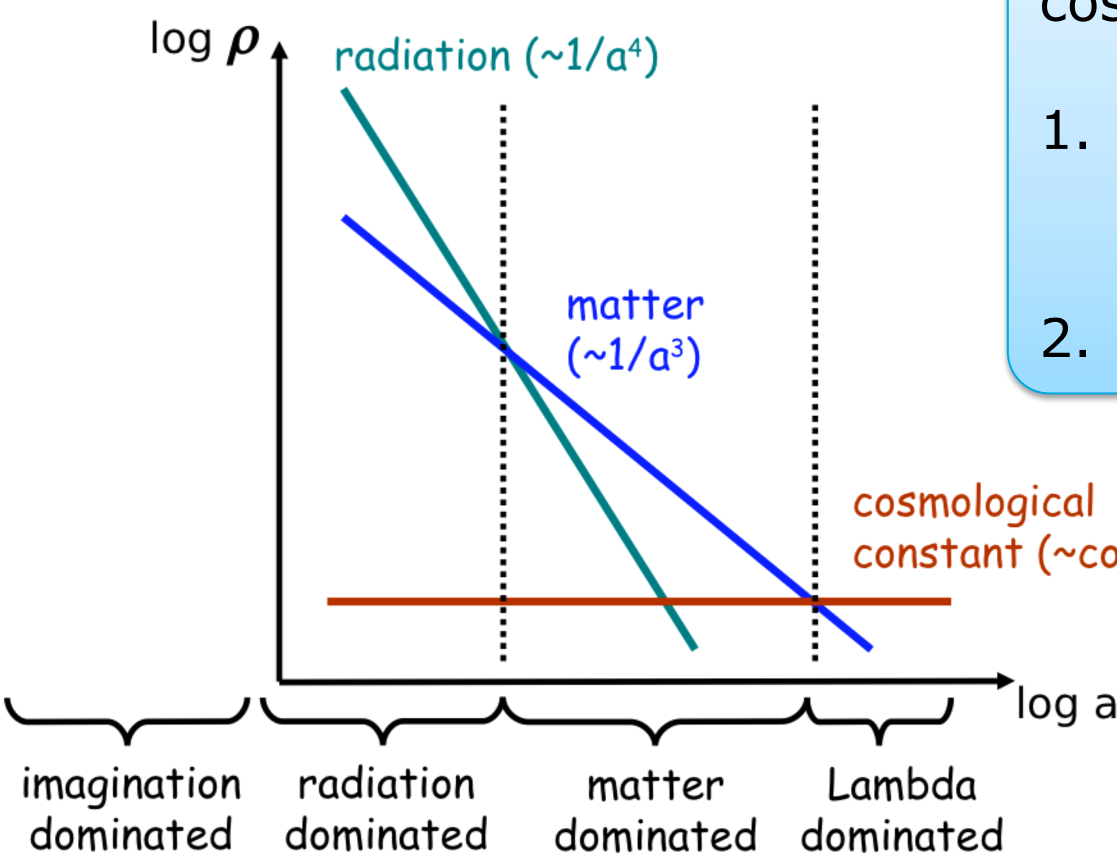
fits millions of CMB pixels (or thousands of C_l)

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:

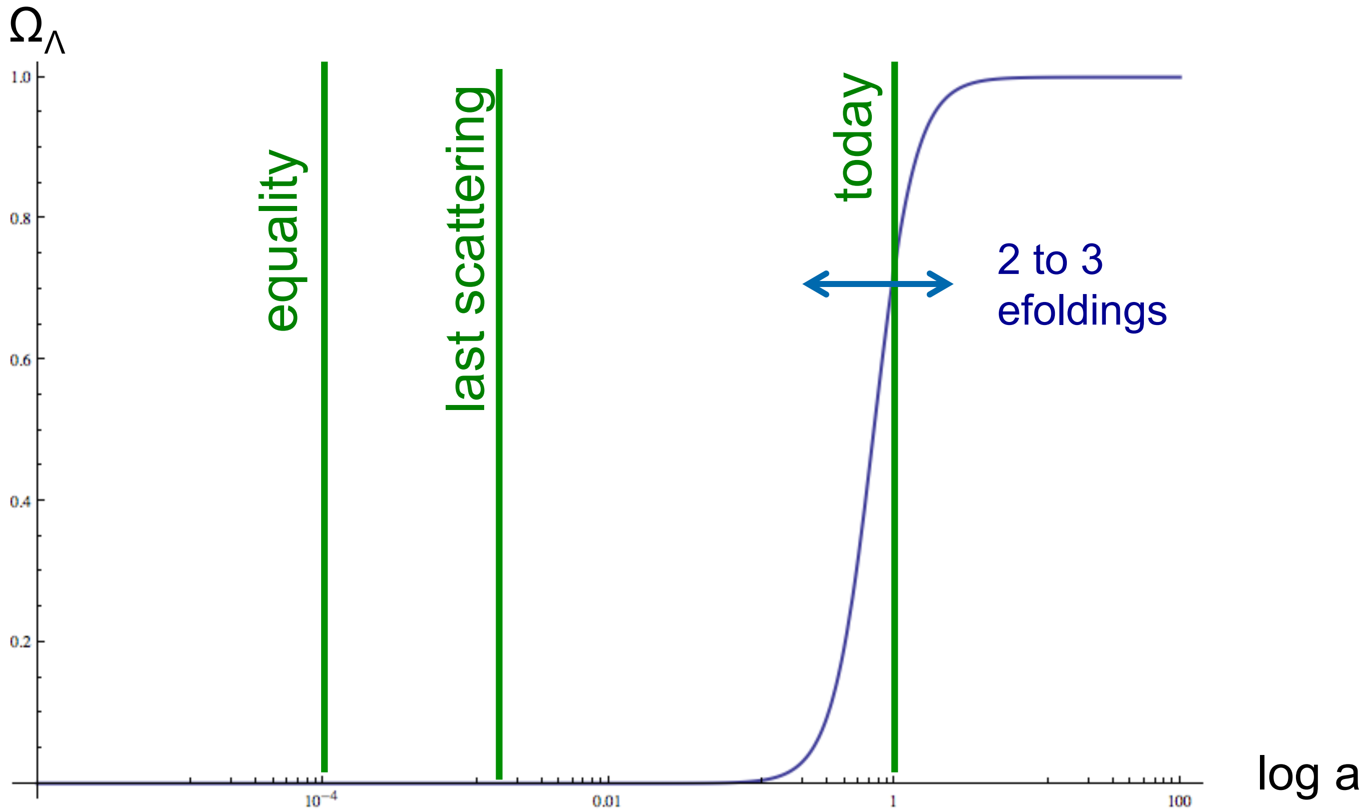


Classical problems of the cosmological constant:

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 ~ 2x10^{-3} eV

zero point fluctuations of a heavier particle of mass m:

cutoff scale

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

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

w during inflation

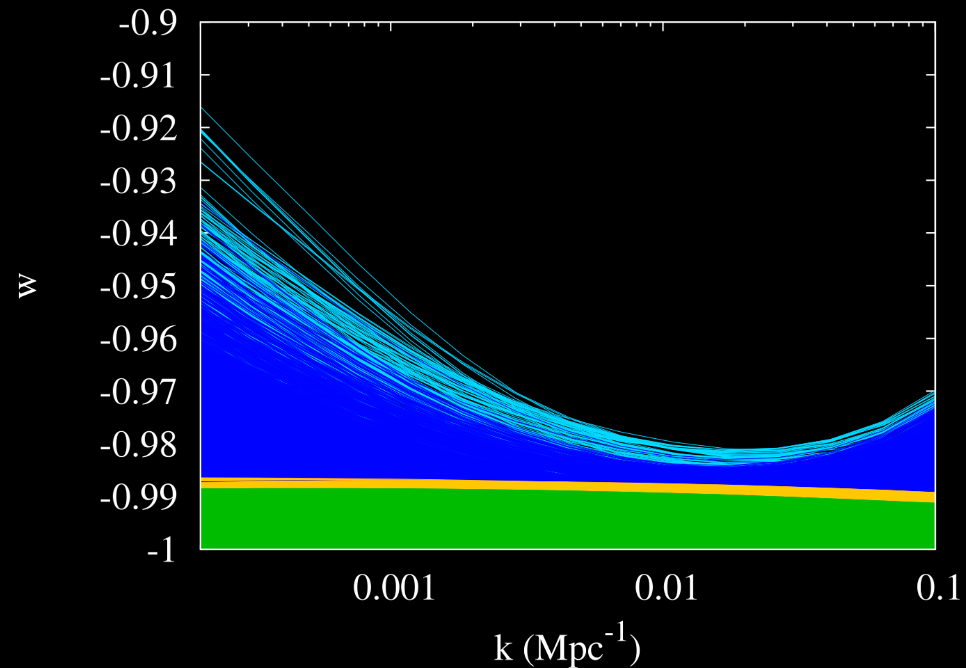
(Ilic, MK, Liddle & Frieman, 2010)

- 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 ≠ -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

(left for discussion over drinks tonight!)

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’)

LTB and Backreaction

Two large classes of models:

- Inhomogeneous cosmology: Copernican Principle is wrong, Universe is not homogeneous (and we live in a special place).

- Backreaction: GR is a nonlinear theory, so averaging is non-trivial. The evolution of the 'averaged' FLRW case may not be the same as the average of the true Universe.

testing the Copernican principle

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 in future redshift drift or supernova dipole).

Lemaitre-Tolman-Bondi

We live in the center of the world!

LTB metric: generalisation of FLRW to spherical symmetry, with new degrees of freedom

-> can choose a radial density profile, e.g. a huge void, to match one chosen quantity

☺ can mimic distance data (need to go out very far)

☺ demonstrates large effect from inhomogeneities

☹ unclear if all data can be fitted (D, H, ISW, kSZ)

☹ mechanism to create such huge voids?

☹ fine-tuning to live in centre, ca $1:(1000)^3$ iirc

→ **probably not (but needs testing!)**

Backreaction

normal approach: separation into “background” and “perturbations”

$$g_{\mu\nu}(t,x) = \bar{g}_{\mu\nu}(t) + h_{\mu\nu}(t,x)$$
$$\rho(t,x) = \bar{\rho}(t) + \delta\rho(t,x)$$

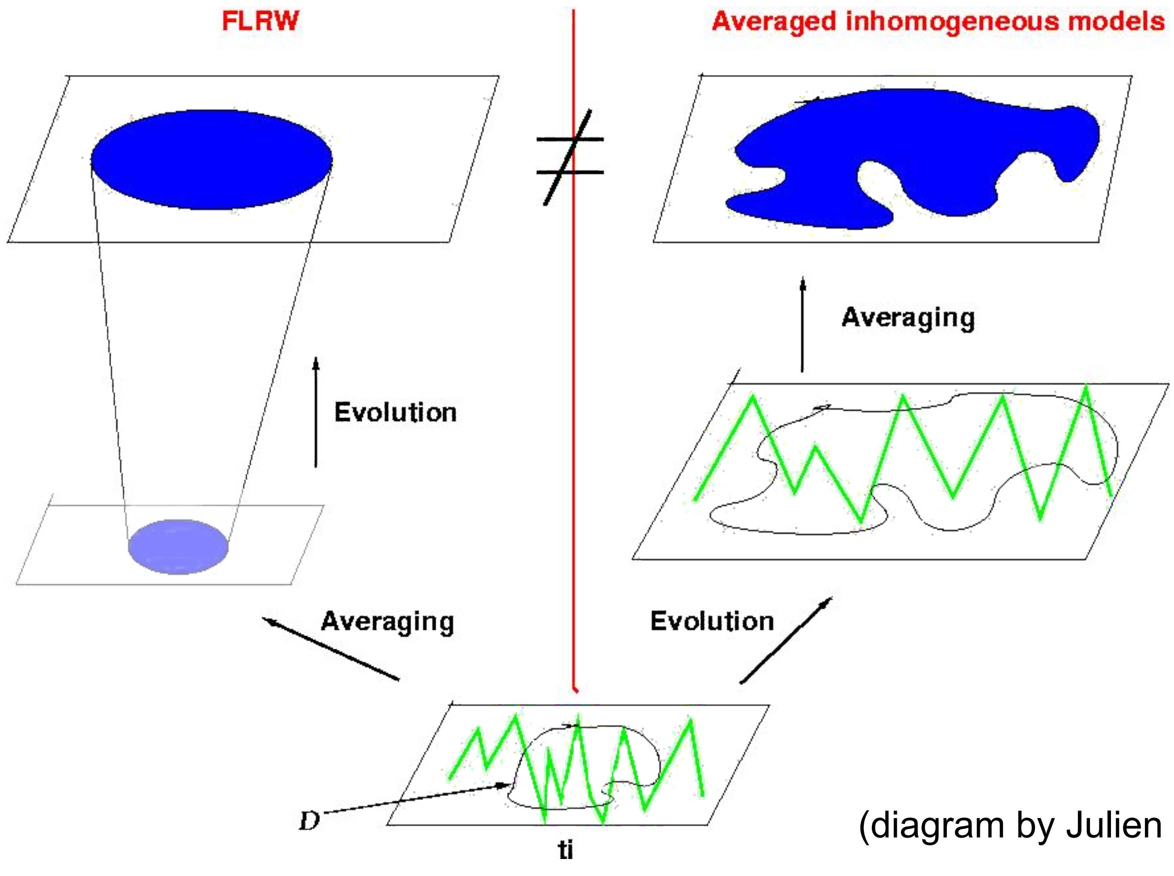
but which is the “correct” background, and why should it evolve as if it was a solution of Einsteins equations? The averaging required for the background does not commute with derivatives or quadratic expressions,

$$\partial_t \langle \phi \rangle \neq \langle \partial_t \phi \rangle \qquad \langle \theta^2 \rangle \neq \langle \theta \rangle^2$$

-> can derive set of averaged equations, taking into account that some operations not not commute: “Buchert equations”

average and evolution

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



(diagram by Julien Larena)

Buchert equations

- Einstein eqs, irrotational dust, 3+1 split (as defined by freely-falling observers)
- averaging over spatial domain D
- $a_D \sim V_D^{1/3}$ [<-> enforce isotropic & homogen. coord. sys.]
- set of effective, averaged, local eqs.:

$$\frac{\dot{a}_D}{a_D} = \frac{8\pi G}{3}\langle\rho\rangle_D - \frac{1}{6}\left(\mathscr{Q} + \langle\mathscr{R}\rangle_D\right) \quad 3\frac{\ddot{a}_D}{a_D} = -4\pi G\langle\rho\rangle_D + \mathscr{Q}$$

if this is positive then
it looks like dark energy!

$$\mathscr{Q} = \frac{2}{3}\left\langle\left(\theta - \langle\theta\rangle_D\right)^2\right\rangle_D - \langle\sigma_{ij}\sigma^{ij}\rangle_D$$

(θ expansion rate, σ shear, from expansion tensor Θ)

- $<\rho> \sim a^{-3}$
- looks like Friedmann eqs., but with extra contribution!

Backreaction

- ☺ is certainly present at some level
- ☺ could possibly explain (apparent) acceleration without dark energy or modifications of gravity
- ☺ then also solves coincidence problem

- ☹ amplitude unknown (too small? [*])
- ☹ scaling unknown (shear vs variance of expansion)
- ☹ link with observations difficult

[*] Poisson eq: $-\left(\frac{k}{Ha}\right)^2 \phi = \frac{3}{2}\delta$ (k = aH : horizon size)

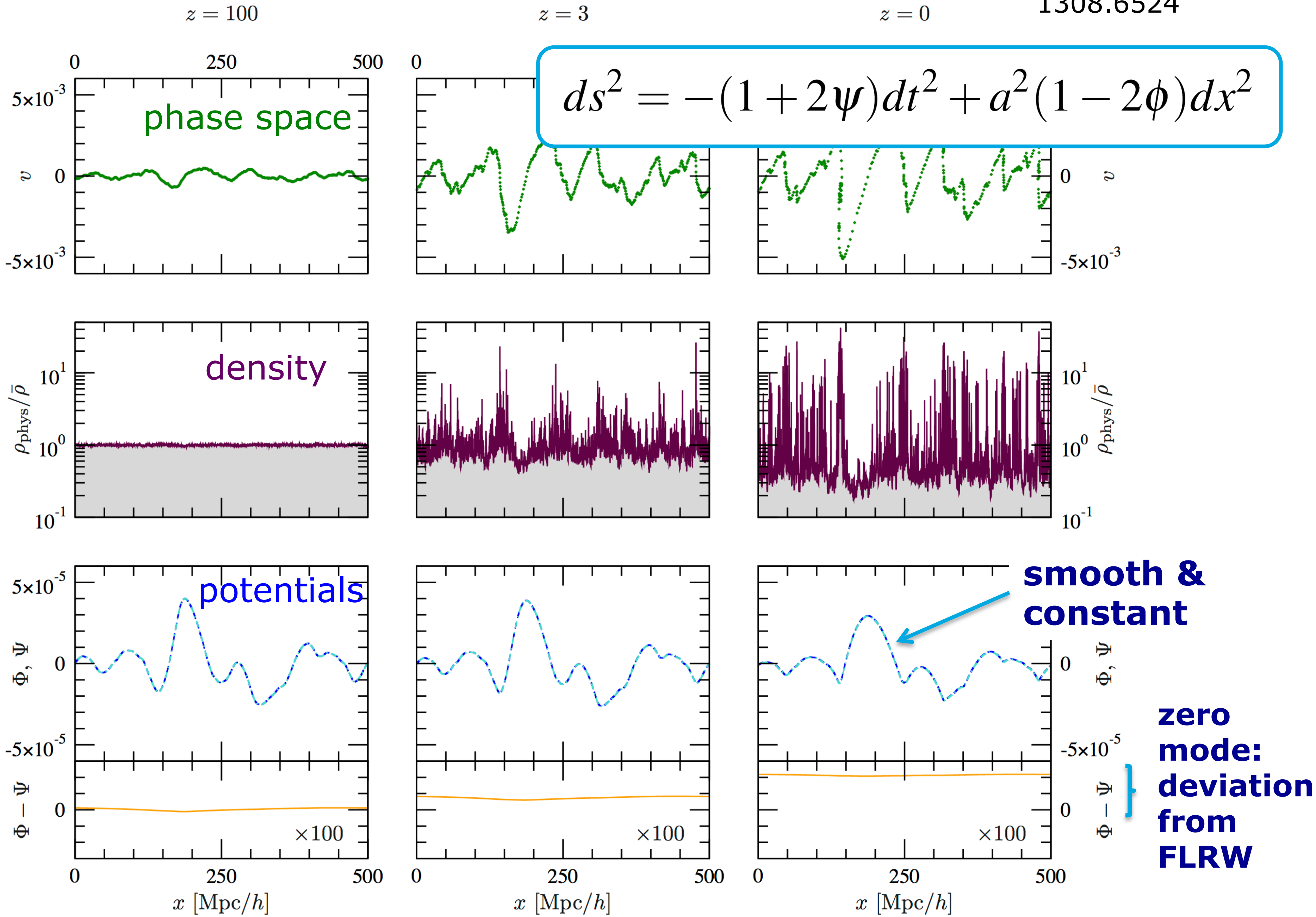
=> Φ never becomes large, only δ ! (but this is not a sufficient argument)

→ look at 'weak-field' fully relativistic N-body code that works as long as Φ << 1

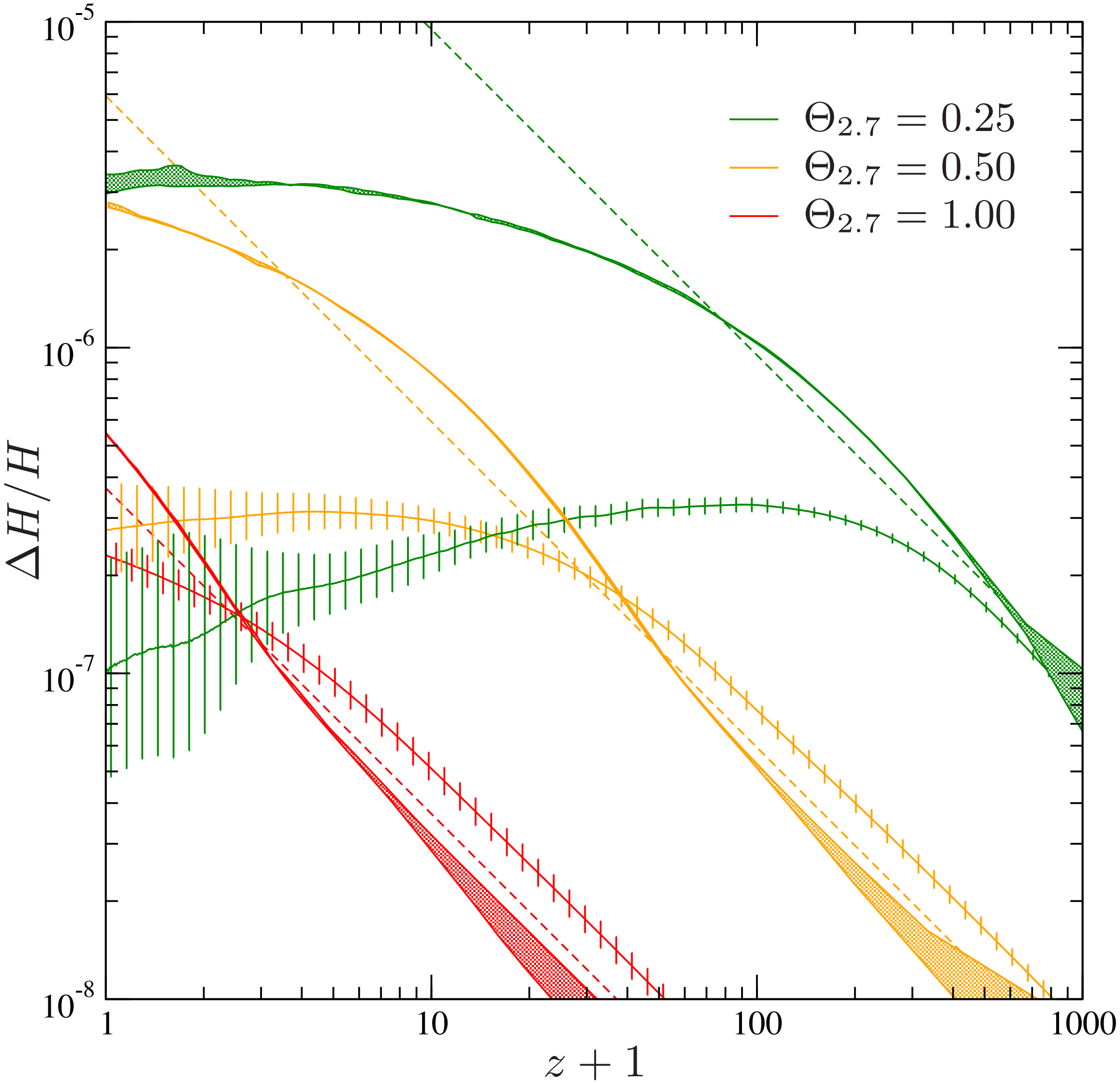
the 1D universe

Adamek, Daverio, Durrer, MK arXiv: 1308.6524

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



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 running right now … but also need observables!

Adamek, Clarkson, Durrer, MK arXiv: 1408.2741

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5. GR is wrong and needs to be modified (‘modified gravity’) ← Philippe Brax

dark energy models

1. action-based approach
   - explicit models … but too many?
   - Horndeski action (“most general”)
   - effective field theory
   - beyond scalars – massive gravity et al
2. scalar field dark energy
   - dynamical systems approach
   - equivalence to fluid variables
   - DE perturbations, sound horizon
3. phenomenological DE and MG modeling

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 (e.g. screening, solar-system tests), 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

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

- **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 2nd order e.o.m.
  (higher than 2nd order is in general unstable, cf Ostrogradski)

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

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, Tolley 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

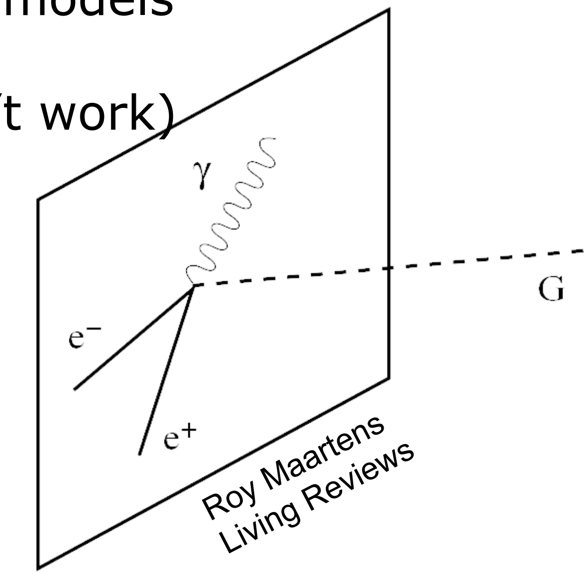
$$S_{\rm NL} = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,[R - \frac{1}{6}m^2 R\frac{1}{\Box_g^2}R]$$

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

non-cosmological probes

- fifth force (weak, long-range) from couplings of standard model to new fields → **Philippe Brax**

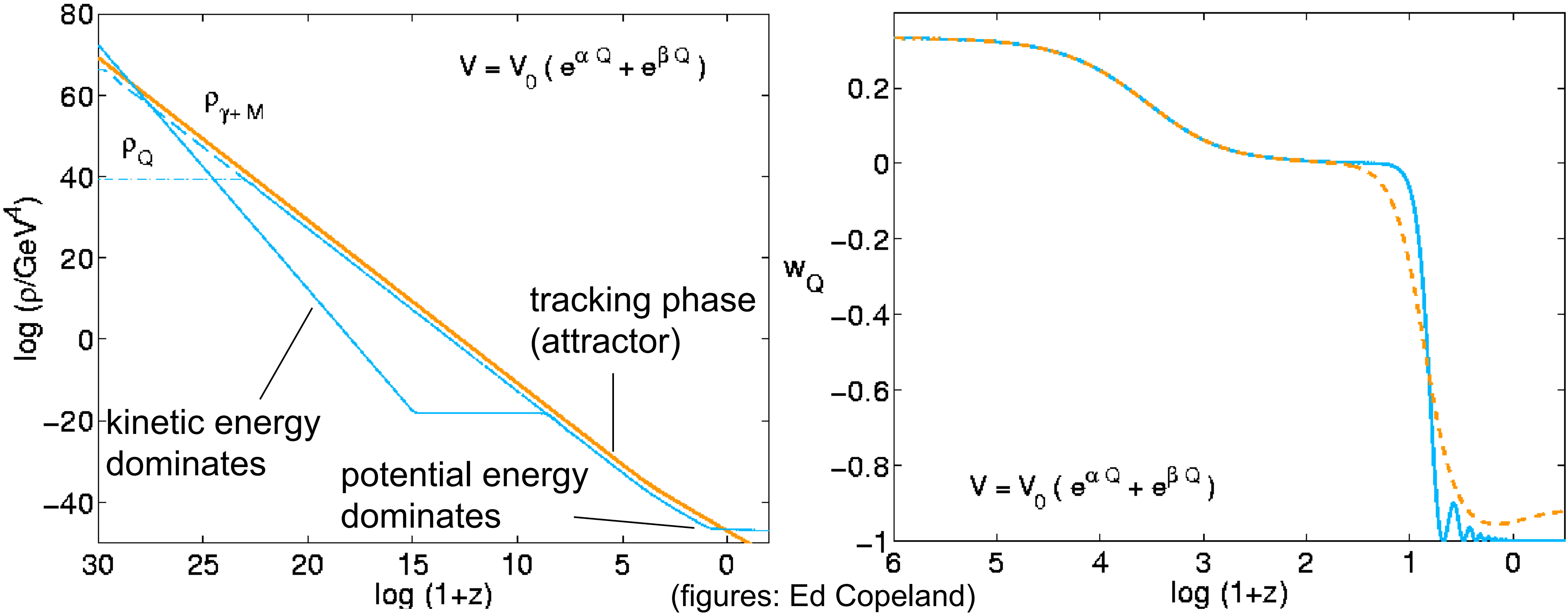
-> screening mechanisms (Chameleon, Vainshtein, …)

- new particles with strange couplings and/or mass hierarchies (KK)
- varying "fundamental constants" and other violations of the equivalence principle
- perihelion shifts / solar system constraints (including double pulsar timings, etc)
- modifications to stellar structure models
- short-distance gravity modified (now well below 0.1mm)

back to 'simple scalars'

$$\ddot{\phi} + 3H\dot{\phi} + dV(\phi)/d\phi = 0 \qquad \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi) \qquad w = p/\rho$$

- If w=p/ρ can change, then initial dark energy density can be much higher -> solves one problem of Λ
- extra bonus: tracking behaviour



(figures: Ed Copeland)

$$\ddot{\phi} + 3H\dot{\phi} + dV(\phi)/d\phi = 0 \qquad \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

w = p/ρ

Can write scalar field + ‘matter’ fluid as dynamical system

-> example for $V(\phi) \propto \exp(-\kappa\lambda\phi)$ $\quad (\kappa^2 = 8\pi G)$

use new variables & write Friedmann and field equations as

$$x = \frac{\kappa\dot{\phi}}{\sqrt{6}H} \quad y = \frac{\kappa\sqrt{V}}{\sqrt{3}H} \quad N = \ln a \qquad x^2 + y^2 + \frac{\kappa^2\rho_m}{3H^2} = 1$$

$$\frac{dx}{dN} = -3x + \frac{\sqrt{6}}{2}\lambda y^2 + \frac{3}{2}x\left[(1-w_m)x^2 + (1+w_m)(1-y^2)\right]$$

$$\frac{dy}{dN} = -\frac{\sqrt{6}}{2}\lambda xy + \frac{3}{2}y\left[(1-w_m)x^2 + (1+w_m)(1-y^2)\right]$$

fixed points (for details see e.g. hep-th/0603057)

1.{x=0,y=0} -> Ω_ϕ=0 (fluid dominated phase)

2.{x=+/-1,y=0} -> Ω_ϕ=1, w_ϕ=1 (kinetic phase)

3.{x=1/sqrt(6),y=$[1-\lambda^2/6]^{1/2}$} -> Ω_ϕ=1, $1+w_\phi = \lambda^2/3$ (dark energy phase)

4.{…} -> $\Omega_\phi = 3(1+w_m)/\lambda^2$, $w_\phi = w_m$ (tracking phase)

Quintessential problems

- no solution to coincidence problem (need to e.g. put a bump into the potential at the right place)
- Still need to get somehow $\Lambda = 0$
- potential needs to be very flat
- need to avoid corrections to potential
- need to avoid couplings to baryons
- no obvious candidates for scalar field
- but nonetheless quintessence is the 'standard evolving dark energy model'

(***there are many other scalar field models*** – e.g. 'k-essence' and 'growing neutrino' models offer potential solutions to coincidence problem.)

“effective” scalar field fluids

at ‘background’ level we do not need to use an actual scalar field, we can always* find a potential trajectory that gives us the desired H(z) or w(z)

exercise: show this equivalence:

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

$$\Updownarrow$$

$$\dot{\rho} = -3H(\rho + p)$$

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

*small print: see phantom crossing slides

"effective" scalar field fluids

How about perturbations? **It works too!**

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

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

Newtonian gauge perturbation equations

$$-\delta T_0^0 = \delta\rho = \frac{1}{a^2}\dot\phi\dot{\delta\phi} - \frac{1}{a^2}\dot\phi^2\Psi + \frac{dV}{d\phi}\delta\phi$$

$$\delta T_i^i = \delta p = \frac{1}{a^2}\dot\phi\dot{\delta\phi} - \frac{1}{a^2}\dot\phi^2\Psi - \frac{dV}{d\phi}\delta\phi$$

$$-ik\delta T_0^i = ik\delta T_i^0 = \frac{k^2}{a^2}\dot\phi\delta\phi = \bar\rho V$$

"dictionary" from

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

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

$$\ddot{\delta\phi} + 2aH\dot{\delta\phi} + a^2\left(\frac{d^2V}{d\phi^2} + \frac{k^2}{a^2}\right)\delta\phi = 4\dot\phi\dot\Psi - 2a^2\Psi\frac{dV}{d\phi}$$

perturbation e.o.m. from $\dfrac{\delta S[g_{\mu\nu},\phi]}{\delta\phi} = 0$

“effective” scalar field fluids

What is the equivalent model?

- Introduce rest-frame sound speed

  $\delta p = c_s^2\, \delta\rho$

- gauge transformation to Newtonian gauge

$$\delta p = \hat{c}_s^2 \delta\rho + \frac{3aH}{k^2}\left(\hat{c}_s^2 - c_a^2\right)\bar{\rho}V$$

- magic correspondence: evolution of linear scalar field perturbations correspond to fluid with

  $c_s^2=1, \sigma=0$

- K-essence is generalization to arbitrary $c_s^2 = K_{,X}/(K_{,X}+2XK_{,XX})$ (and KGB to more complicated δp)

behaviour of scalar field δ

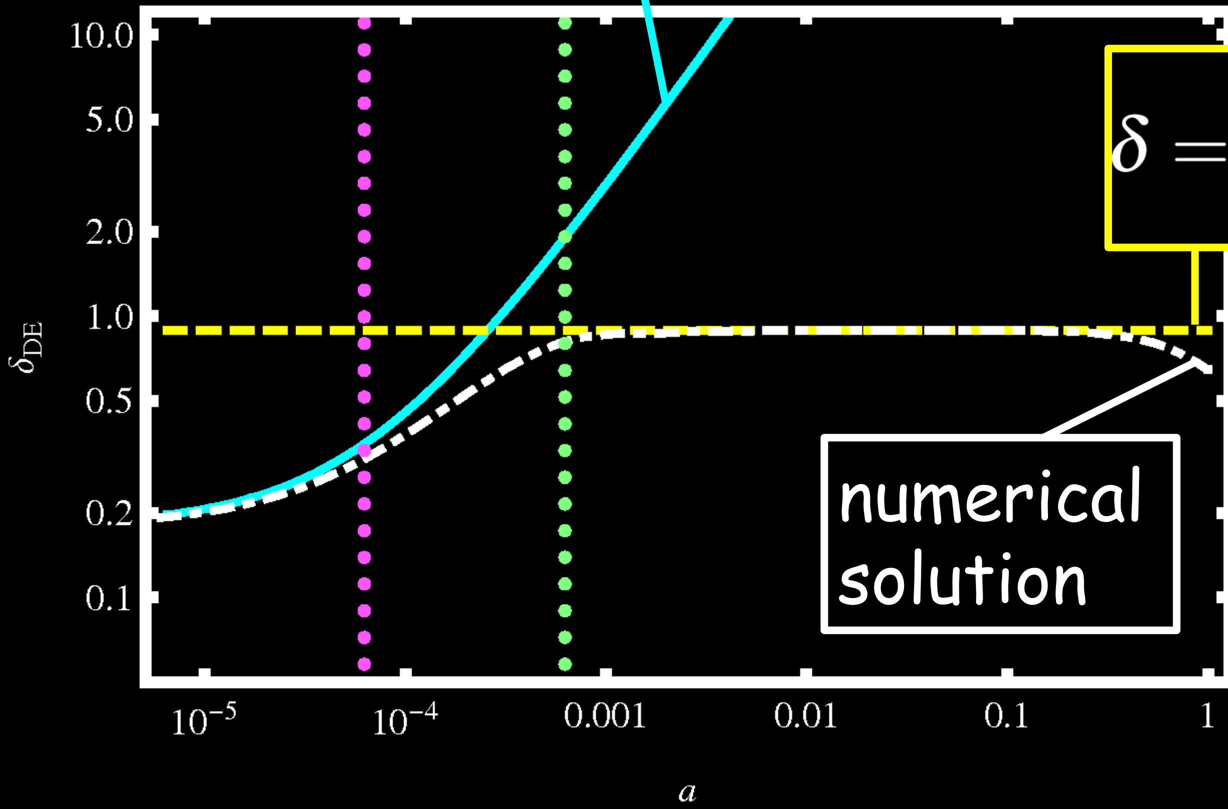
(e.g. Sapone & MK 09)

model $\{w, c_s, \sigma=0\}$; matter dom.: Φ = constant, $\delta_m \sim a$

$$\delta = \delta_0 (1+w) \left(\frac{a}{1-3w} + \frac{3H_0^2 \Omega_m}{k^2} \right)$$

$\rightarrow$ $\delta(w=-0.8) \lesssim 1/20\ \delta(w=0)$ on subhorizon scales

$$\delta = \delta_0 \frac{3}{2} (1+w) \frac{H_0^2 \Omega_m}{c_s^2 k^2}$$



- $w = -0.8$
- $c_s = 0.1$
- $k = 200\ H_0$

only Λ has no perturbations

immediate consequences:

- dark energy is never completely smooth if $w \neq -1$ (and not even then if $\sigma \neq 0$!)
- for nearly all data sets we MUST give perturbation description, not just w
- sound horizons (and other things) lead to scale-dependent clustering

phantom crossing

(e.g. MK & Sapone 2006)

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

A minimally coupled scalar does not cross w=-1:

$$\rho + p = \dot{\phi}^2 \geq 0$$

but in 'fluid formulation' we don't care?

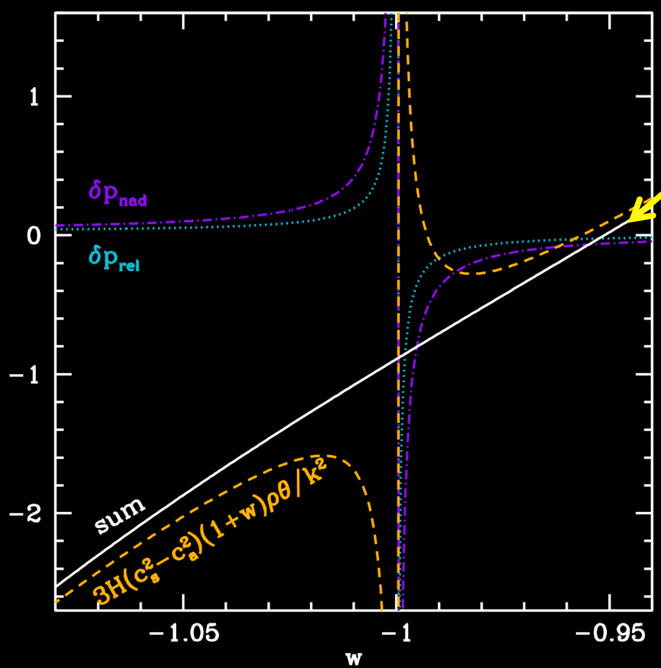
serious issue: we want to set $\delta p = c_s^2\, \delta\rho$ in fluid rest frame
-> gauge transformation to other frame:

$$\delta p = c_s^2 \delta\rho + 3\mathcal{H}(c_s^2 - c_a^2)\rho \frac{V}{k^2} \qquad c_a^2 = \frac{\dot{p}}{\dot{\rho}} = w - \frac{\dot{w}}{3\mathcal{H}(1+w)}$$

this transformation blows up (there is no DE rest frame for w=-1), except if V -> 0 fast enough <-> $w'=0$ or $c_s^2=0$ at crossing or δp has different form (→ KGB models)

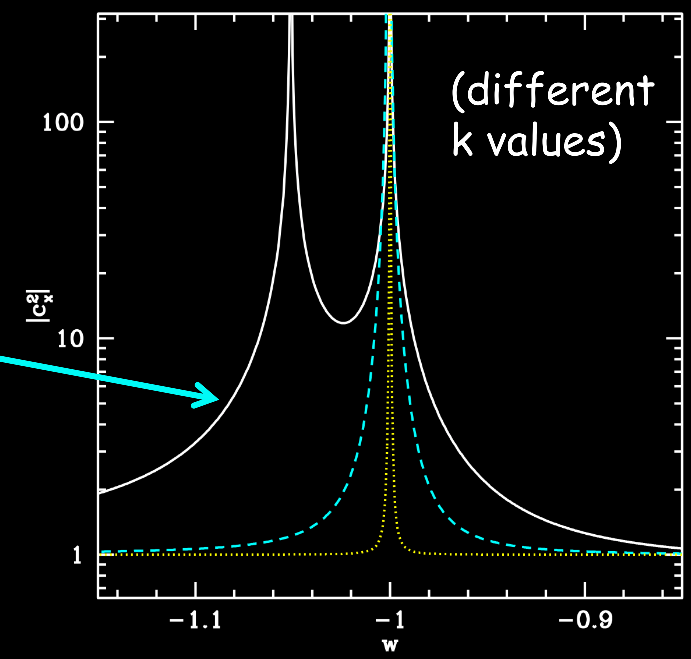
quintom crossing

Simple example of crossing the phantom barrier:
quintom: 2 fluids/fields with $w_1 > -1$ and $w_2 < -1$ (and $c_s=1$)



total δp is finite

eff. c_s^2 is not!



- In practice one usually pretends to have a K-essence model with simple c_s^2 and freezes perturbations near crossing
- EFT-type models may improve situation (but different!)

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 fluid degrees of freedom
- catches all possible deviations from LCDM predictions
- both EFT and fluid cases need mapping back to fundamental theory

Now a few more things:

1. more on “phenomenological” fluid approach
2. how does it work for modified gravity models?
3. link anisotropic stress <-> modified gravity models

Then we go to observations

phenomenological DE

action based models

↕

equivalent fluid description

↕

phenomenological parameters

↕

cosmological observations

the background case

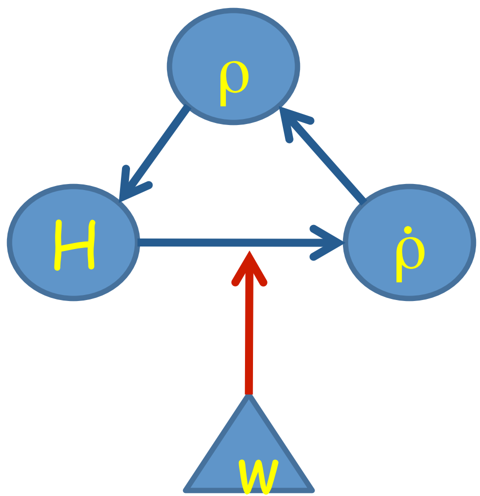
$$ds^2 = -dt^2 + a(t)^2 dx^2$$ metric "template"

Einstein eq'n $$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_1 + \rho_2 + \ldots + \rho_n)$$

conservation $$\dot{\rho}_i = -3H(\rho_i + p_i) = -3H(1 + w_i)\rho_i \qquad i = 1, \ldots, n$$

- w_i describe the fluids
- normally all but one known

- H|a describe observables (distances, ages, etc)



the background case

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

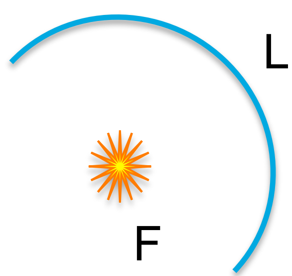
(determined by the metric)

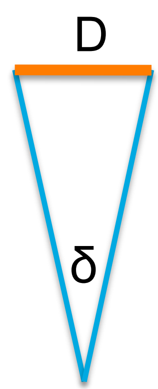
geometry

stuff (what is it?)

your favourite theory

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



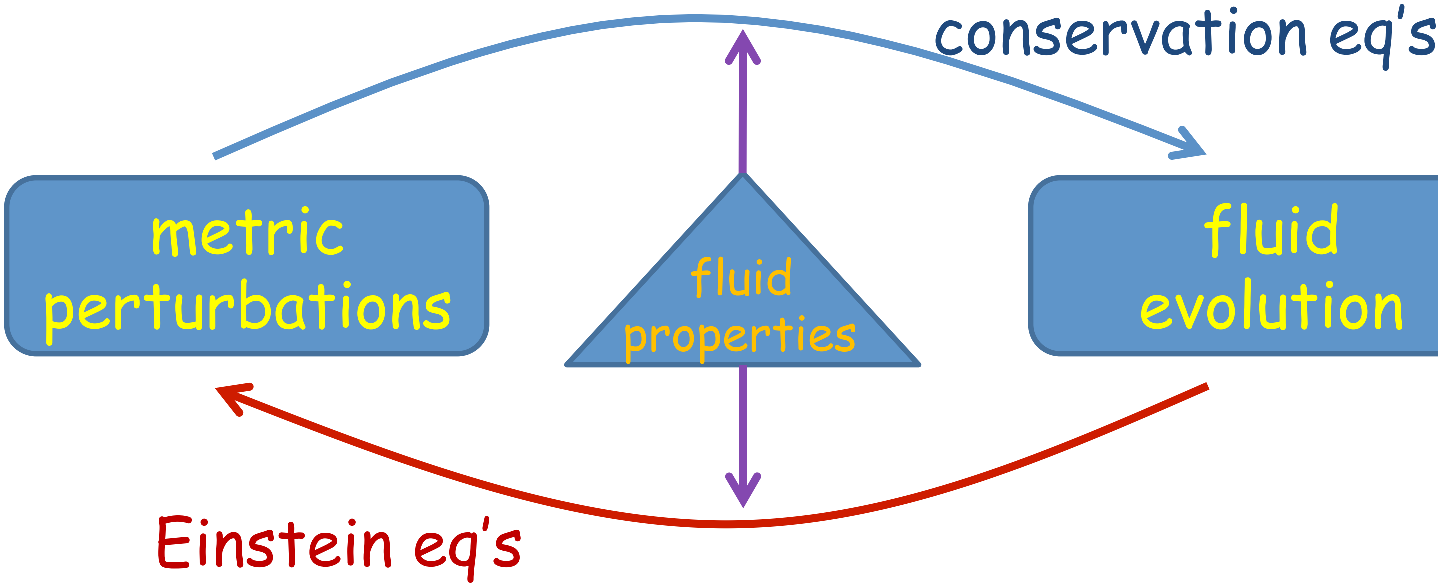


$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

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

perturbations

$$ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)dx^2$$ metric (gauge fixed, scalar dof)



$$k^2\phi = -4\pi G a^2 \sum_i \rho_i \left(\delta_i + 3Ha\frac{V_i}{k^2}\right), k^2(\phi-\psi) = 12\pi G a^2 \sum_i (1+w_i)\rho_i\sigma_i$$

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

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

the geometric EMT

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

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

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

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

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

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

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

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

how about modified gravity?

- our world is 3-dimensional, GR works well
- cosmology is governed by an effective 3+1 D metric: still same two function ϕ and ψ
- assume DM exists, behaves as 3D matter (i.e. conserved)
- but Einstein equations are now different

- *explicit DGP example of reconstructing a fitting DE model*
- *general argument why it is possible*

DGP example

$$\cancel{k^2\phi = -4\pi G a^2 \sum_i \rho_i \Delta_i}$$

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

changed! (eg Koyama & Maartens)

$$k^2\phi = -4\pi G a^2 (1+\zeta)\rho_m\Delta_m$$

$$k^2\psi = -4\pi G a^2 (1-\zeta)\rho_m\Delta_m$$

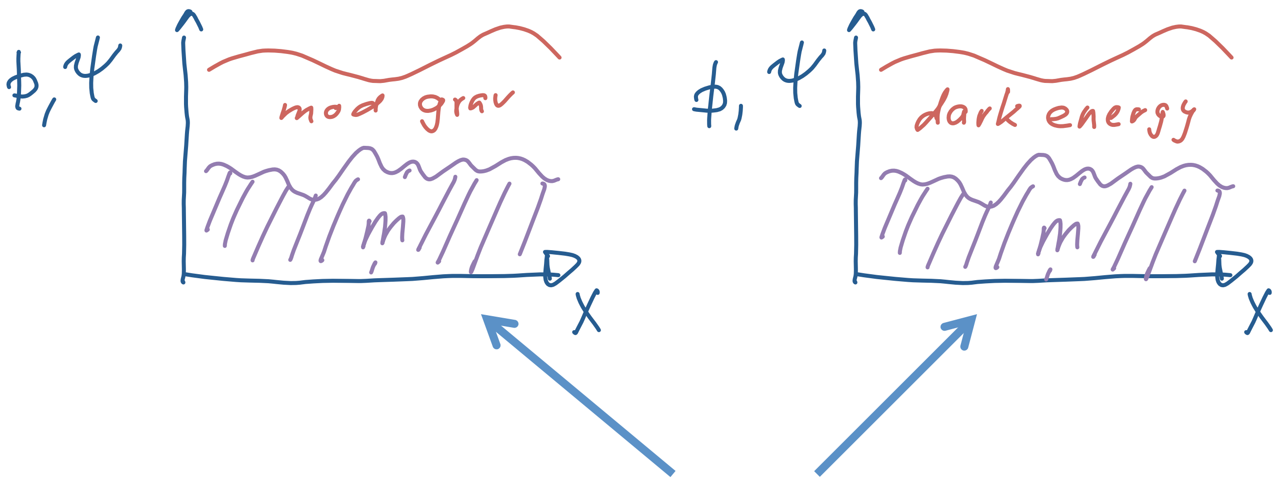
$$\delta_i' = 3(1+w_i)\phi' - \frac{V_i}{Ha^2} - \frac{3}{a}\left(\frac{\delta p_i}{\rho_i} - w_i\delta_i\right)$$

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

still valid, but we only have matter, i=m: $\delta p_m = w_m = \sigma_m = 0$

The matter (dark or baryonic) responds to ϕ and ψ. It does neither care nor "know" if there are other fluids or a modification of gravity for given ϕ and ψ!

DGP example



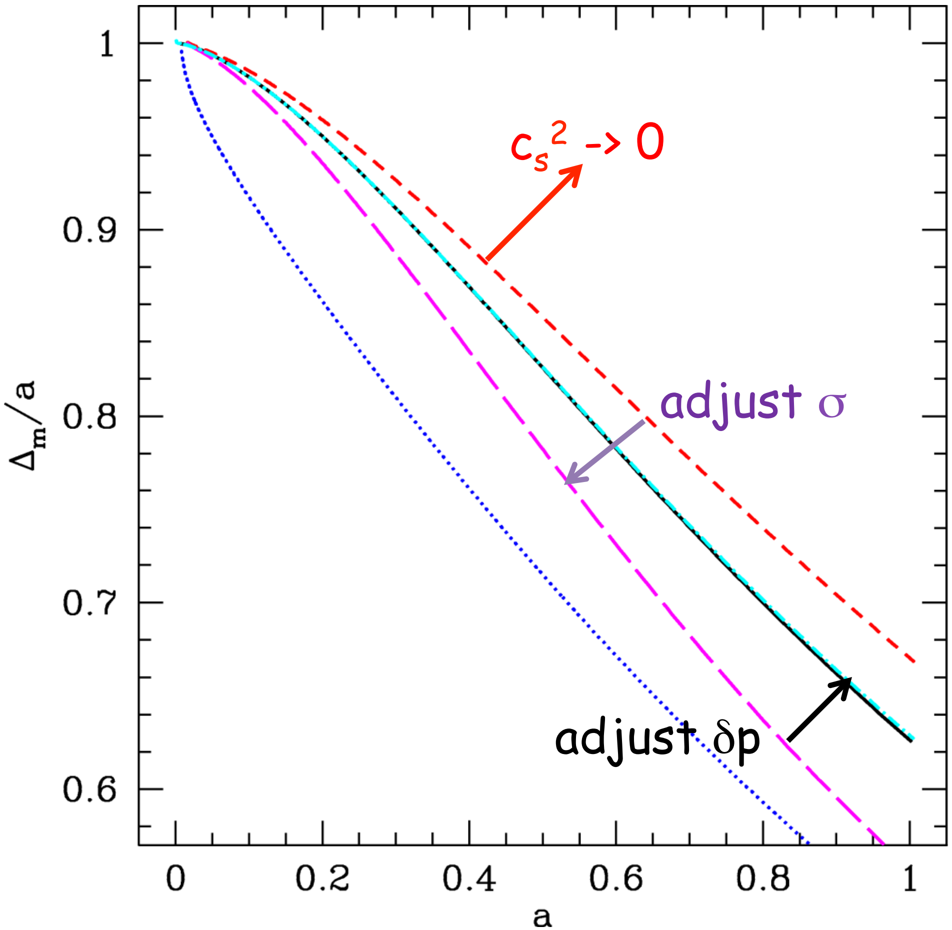
observationally indistinguishable!

-> can we create a “fake” dark energy fluid that leads to the same gravitational potentials as DGP by tuning the dark energy properties?

(question of principle, never mind the horrible fine-tuning)

-> 3 more equations, 3 more parameters

DGP example



1) adjust w to give same H(z)

scalar field: more DM perturbations than in **DGP** model

2) try decreasing sound speed: oops, DM perturbations go up!

3) choose $\sigma \sim (\phi - \psi)$ as required by DGP -> too much suppression

4) cancel direct effect of σ on V in DE rest-frame with $\delta p = (1+w)\,\rho\,\sigma$

-> matches both ϕ and ψ

- σ can be specified w/o recourse to the DM perturbations
- the DE perturbations are large, comparable to those in the DM

General Argument

modified "Einstein" eq:
(projection to 3+1D)

$$X_{\mu\nu} = -8\pi G T_{\mu\nu}$$

$$\boxed{G_{\mu\nu} = -8\pi G T_{\mu\nu} - Y_{\mu\nu} \quad Y_{\mu\nu} \equiv X_{\mu\nu} - G_{\mu\nu}}$$

$Y_{\mu\nu}$ can be seen as an effective DE energy-momentum tensor.

Is it conserved?

Yes, since $T_{\mu\nu}$ is conserved, and since $G_{\mu\nu}$ obeys the Bianchi identities!

There is also no place "to hide", since $T_{\mu\nu}$ is also derived from a general symmetric tensor.

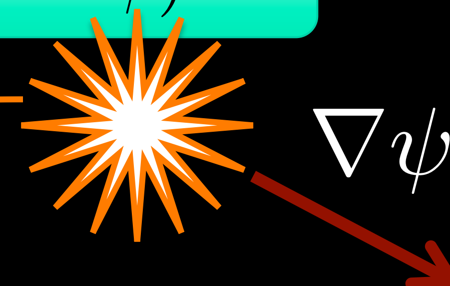
DE phenomenology

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

a(t)

$\nabla_\perp(\phi+\psi)$

(lensing)



$\nabla\psi$

(velocity field)

observations probe space-time geometry
→ characterize geometry instead of fluid

deviations from "standard clustering":

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

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

- extra clustering
- G_{eff}/G
- something else

We expect
Q = 1
η = 0
at low z

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

parametrisations

- could parametrise (effective) dark energy with anisotropic stress σ and sound speed c_s^2
- or directly deviations in metric potentials, e.g.

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

- in both cases two new functions of space and time -> much worse than w(z)!
- can either restrict form (e.g. just sub- and super-horizon behaviour) or course binning and PCA
- BUT: at least in principle we know what to look for! (And results can then be compared with theoretical predictions)

some model predictions

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: $c_s^2 = 1$, $\sigma = 0$

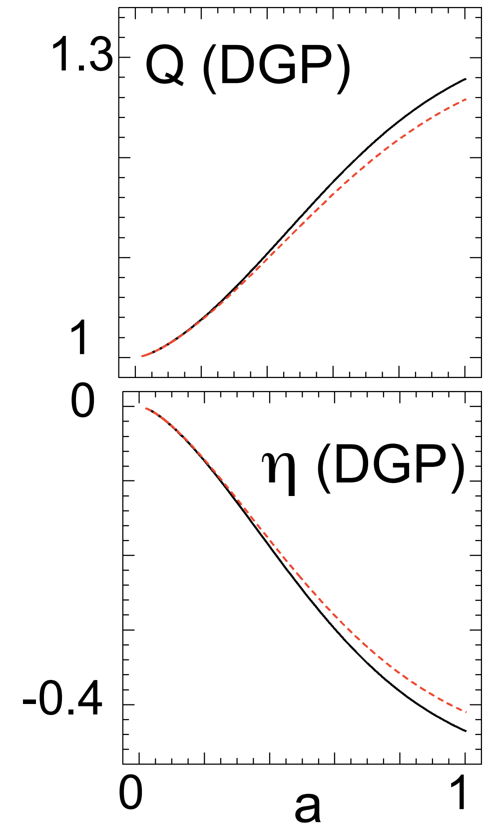
-> $\eta = 0$, $Q(k \gg H_0) = 1$, $Q(k \sim H_0) \sim 1.1$

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

Lue, Starkmann 04
Koyama, Maartens 06

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

implies large DE perturb.



Scalar-Tensor:

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

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

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

f(R): $S_g = \int d^4x \sqrt{-g} f(R)$ similar to scalar-tensor

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): [$Y=Q/(1+\eta)$]

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

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

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, KGB, 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:

$$h''_{ij} + (2+\nu)Hh'_{ij} + c_{\mathrm{T}}^2 k^2 h_{ij} + a^2\mu^2 h_{ij} = a^2\Gamma\gamma_{ij}\,,$$

$$\nu = \alpha_{\mathrm{M}}\,, \qquad c_{\mathrm{T}}^2 = 1 + \alpha_{\mathrm{T}}\,,$$

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

Saltas, Sawicki, Amendola, MK 2014

$$\Phi - \Psi = \sigma(t)\Pi + \pi_{\mathrm{m}}$$

$$\sigma = \alpha_{\mathrm{M}} - \alpha_{\mathrm{T}}$$

$$\Pi = H\delta\phi/\dot{\phi} + \alpha_{\mathrm{T}}/(\alpha_{\mathrm{M}} - \alpha_{\mathrm{T}})\Phi$$

can test grav. wave propagation with model-independent cosmological observation of anisotropic stress!

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)

Outlook to future observations

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

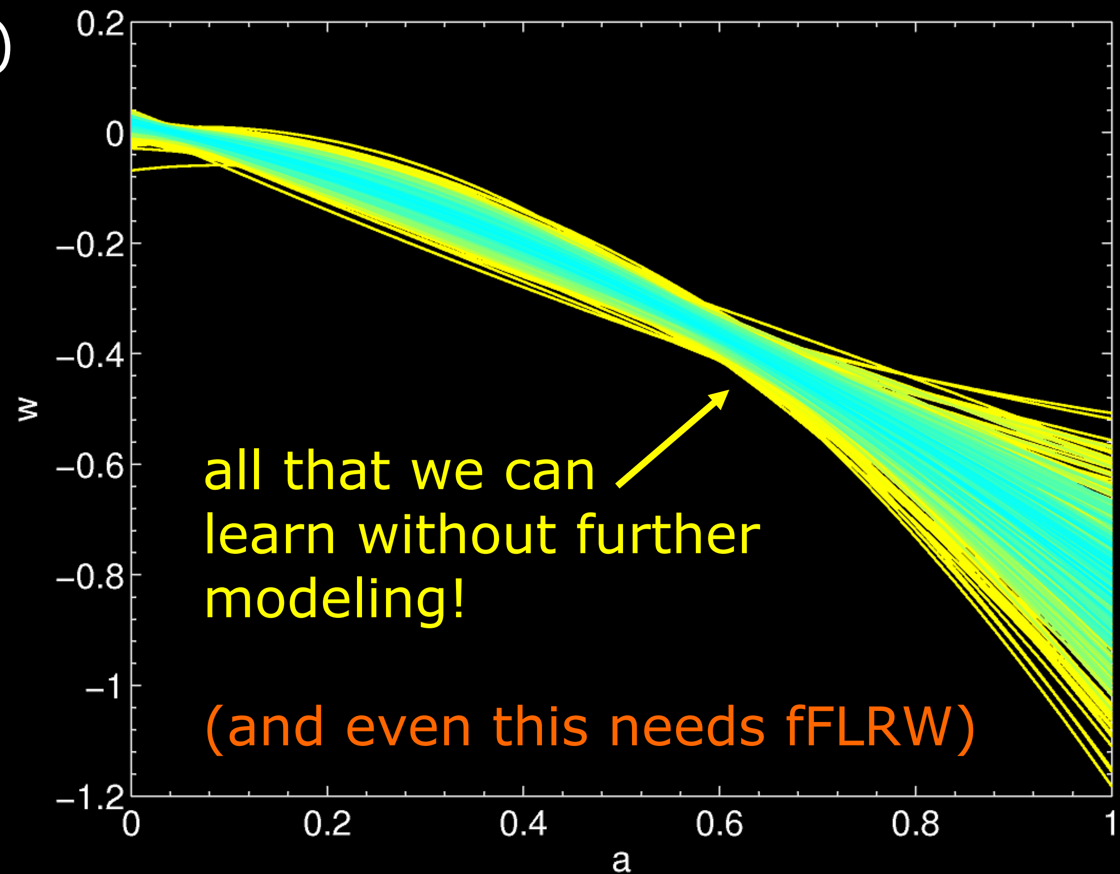
(-> Euclid ☺)

model independent w?

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

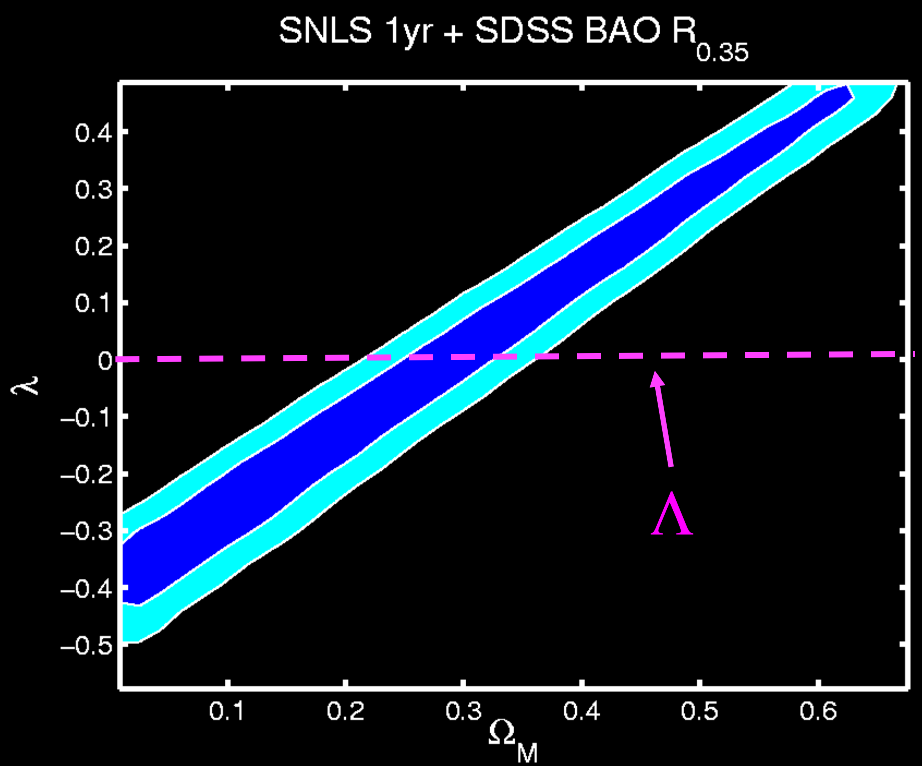
- quadratic expansion of w(a)
- fit to Union SNe, BAO and CMB peak location
  → just distances, no perturbations

so what is w_{DE}?
what is Ω_m?

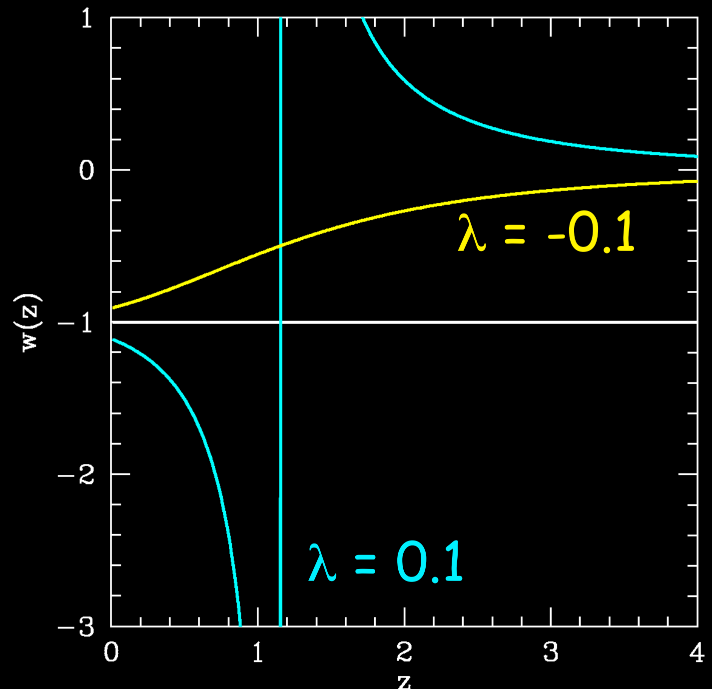


MK, A. Liddle, D. Parkinson & C. Gao, PRD 80, 083533 (2009)

what are w and Ω_m?



$$w(z) = \frac{H(z)^2 - \frac{2}{3}H(z)H'(z)(1+z)}{\Omega_m H_0^2(1+z)^3 - H(z)^2}$$



$$w(z) = \frac{-1}{1-\lambda(1+z)^3}$$

- all models have the same expansion history for different Ω_m
- this extends to linear perturbation theory when c_s is unknown

galaxy clustering

total perturbation: $\delta_t = \Omega_m \delta_m + \Omega_x \delta_x$

galaxies: we assume they move with the same velocity field as dark matter -> $\theta_{gal} = \theta_m = -\delta_m' = -f \delta_m = -(f/b) \delta_{gal}$ for f = G'/G matter growth rate (growth function G(k,z) is in general changed by dark energy!)

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

From the power spectrum in transverse (μ=0) and radial (μ=1) directions we can extract two quantities:

$$A = Gb\sigma_8\delta_{t,0} \qquad R = Gf\sigma_8\delta_{t,0}$$

A and R are therefore directly observable from the galaxy distribution, but e.g. $\delta_{t,0}$ is not directly observable.

weak lensing

weak lensing is driven by the lensing potential $\Phi+\psi$ (entering the geodesic equation of photons) which is affected both by changes in clustering and the effective anisotropic stress, with

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

$$k^2\Phi_{\text{lens}} = k^2(\phi+\psi) = -\frac{3}{2}\Sigma G\Omega_{m,0}\sigma_8\delta_{t,0}$$

The observable ellipticity correlation function is a convolution of the lensing potential potential with a survey window function. At least in principle (knowing the background evolution and the galaxy distribution) we can recover Φ_{lens} as an observable and thus determine

$$L = \Sigma G\Omega_{m,0}\sigma_8\delta_{t,0}$$

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 $\delta_{t,0}$!

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

P_1 ← usually called β, but we don't know b

P_2 ← introduced as E_G in Zhang et al 2007

P_3 ← "growth" observable

η is directly observable:
(but Q, f, Σ, Ω_m, … not!)

$$\boxed{1 + \eta = \frac{3P_2H_0^2(1+z)^3}{2H^2(P_3 + 2 + H'/H)} - 1}$$

testing Horndeski

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

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

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, ...)

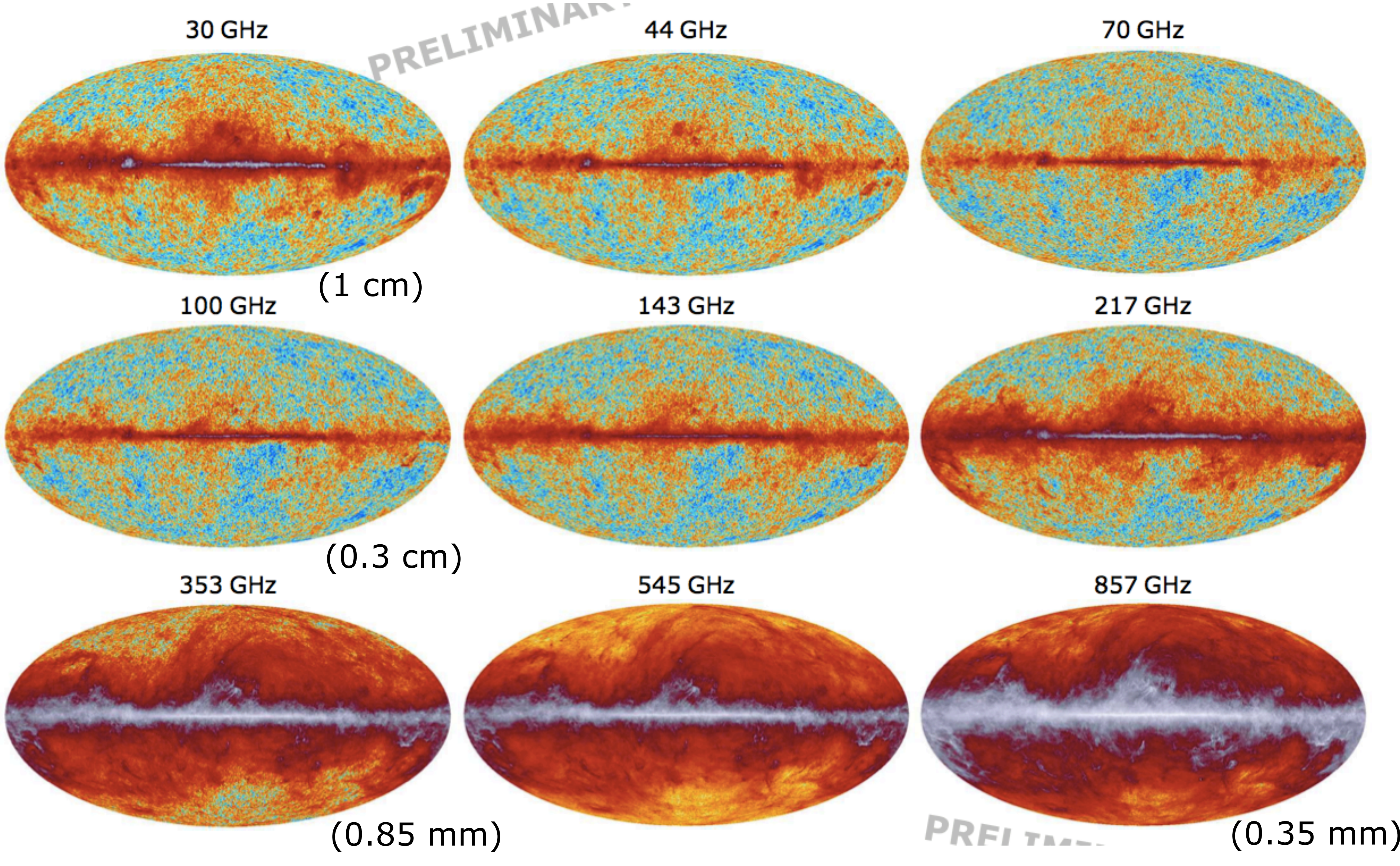
Planck DE/MG results

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

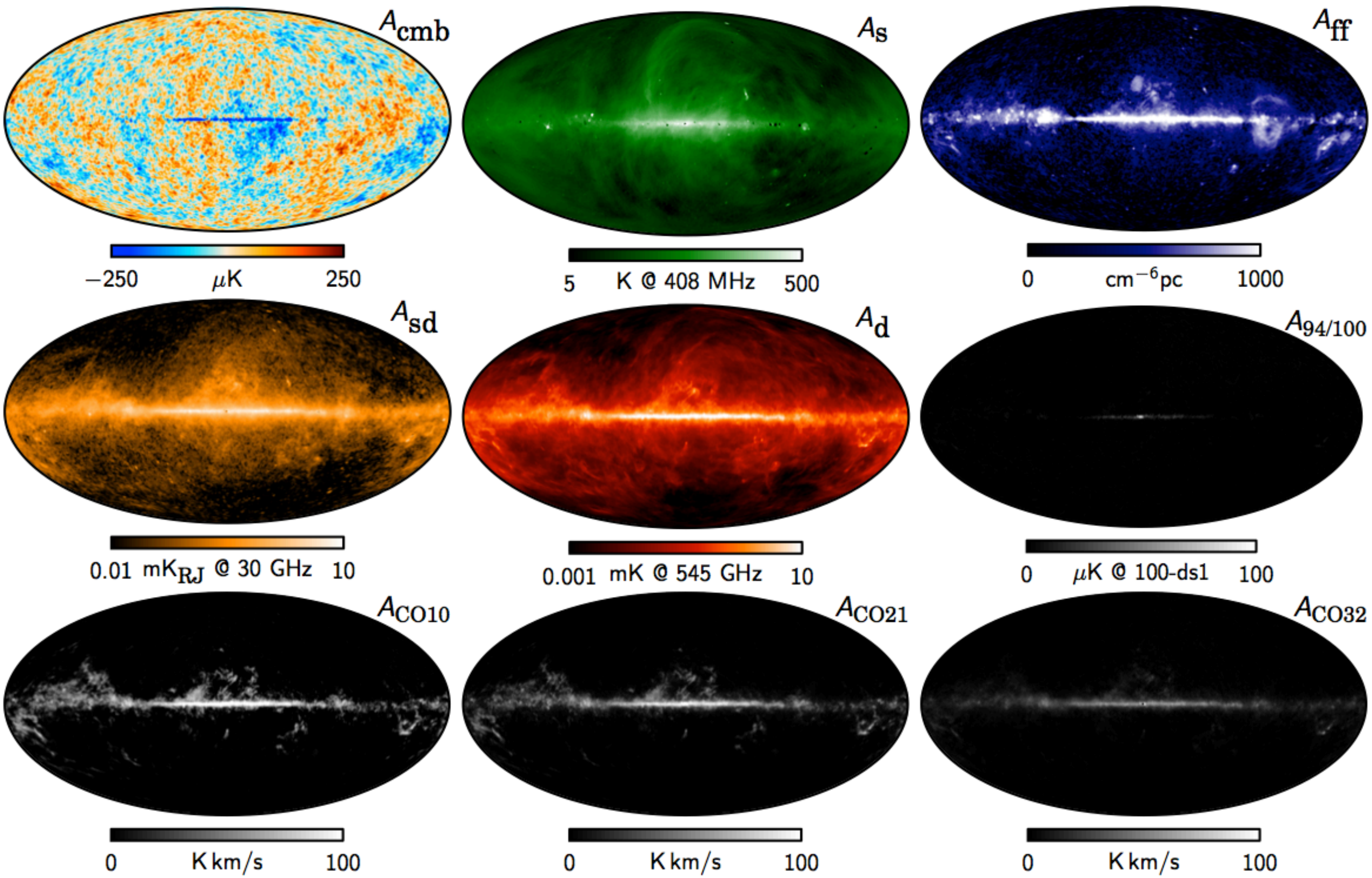
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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)

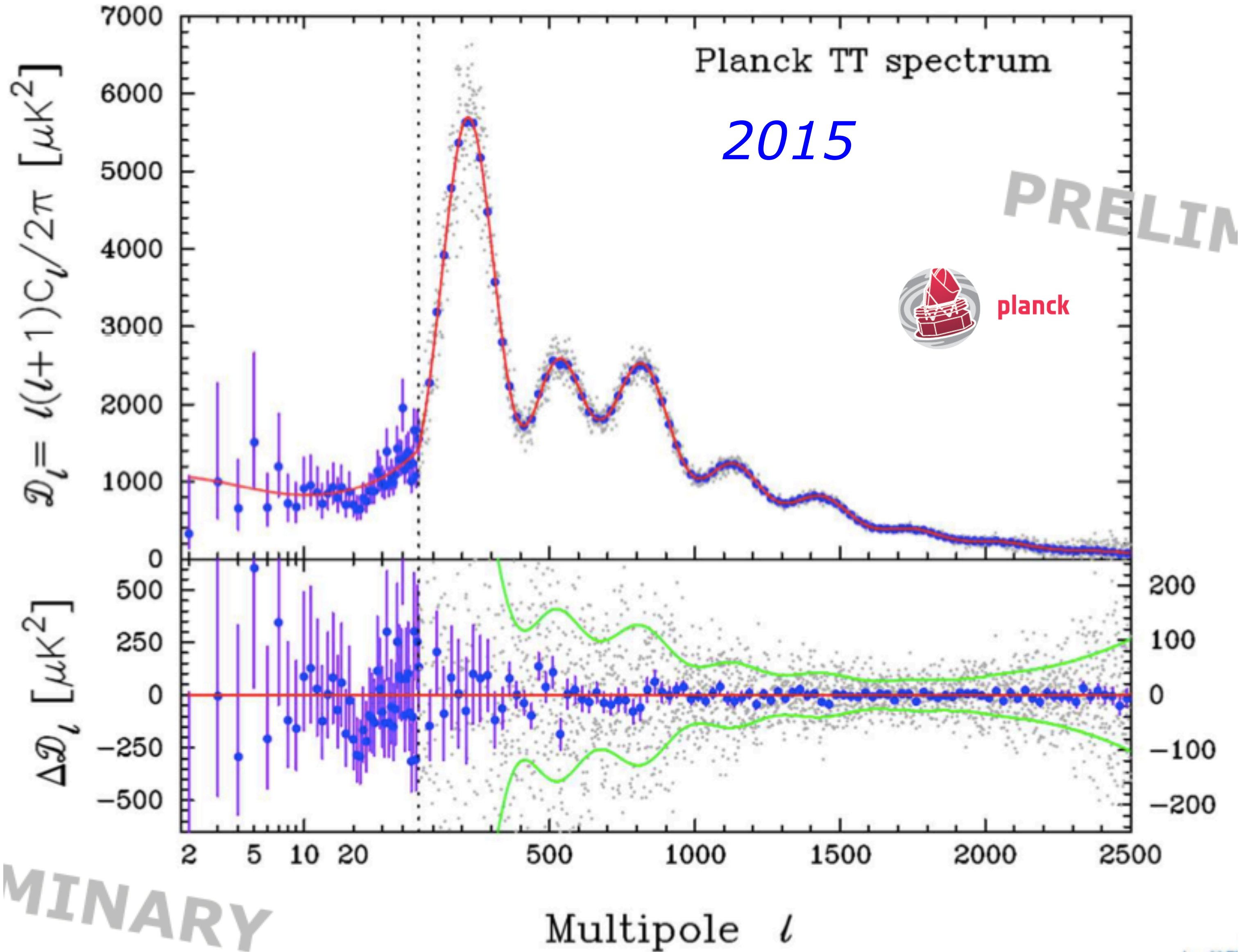


Planck 2015 component maps



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

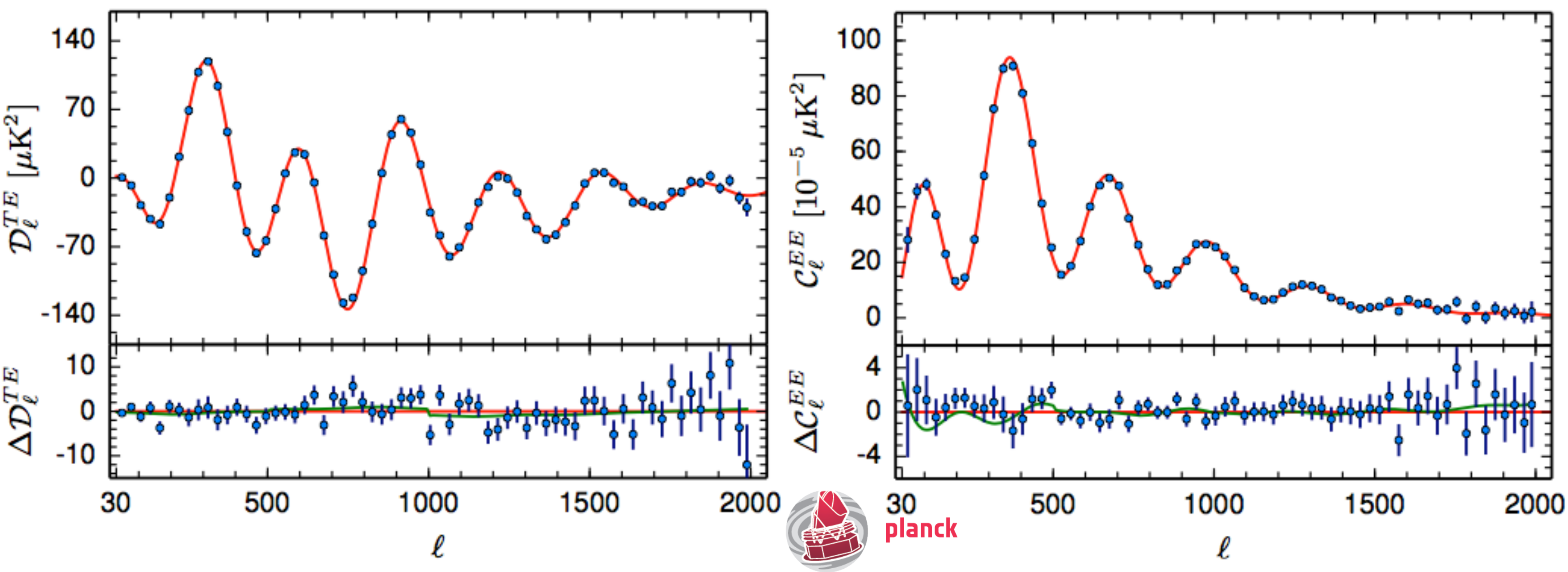
2015 TT power spectrum



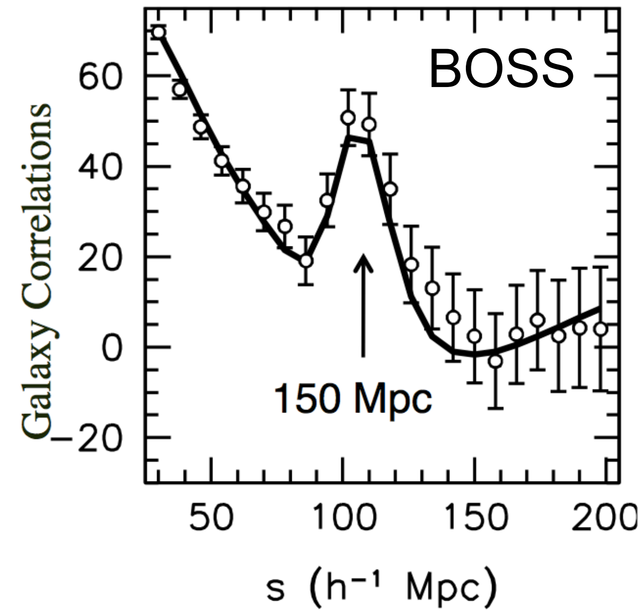
2015 polar power spectrum

- 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

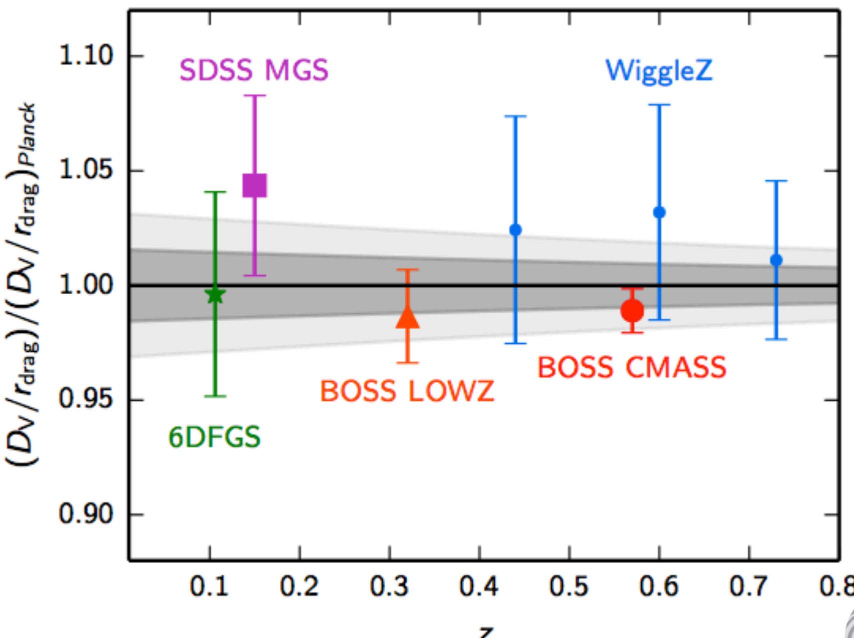


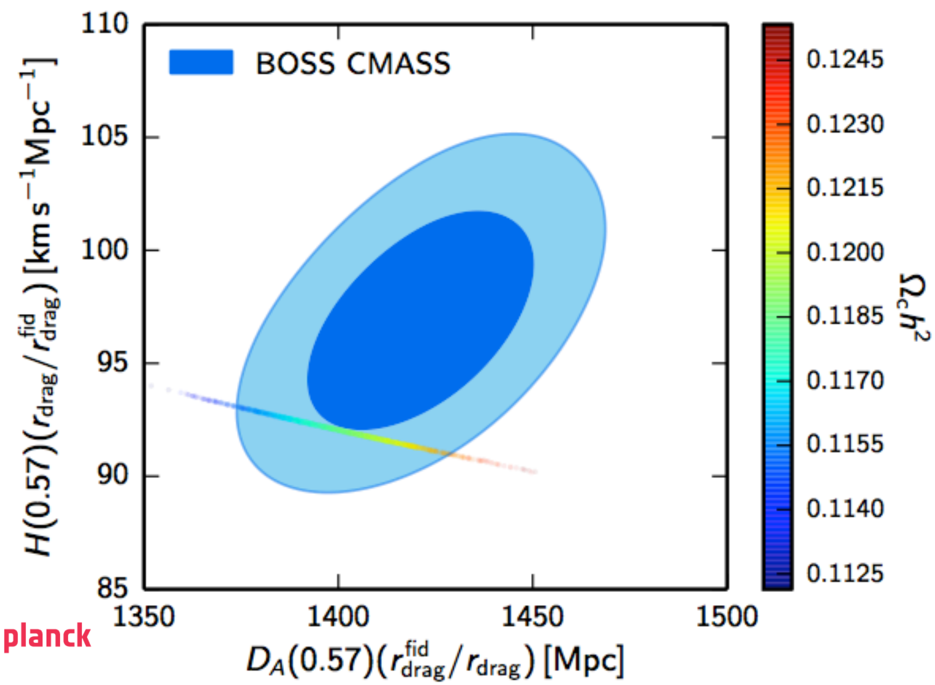
BAO distances



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

Planck 2015



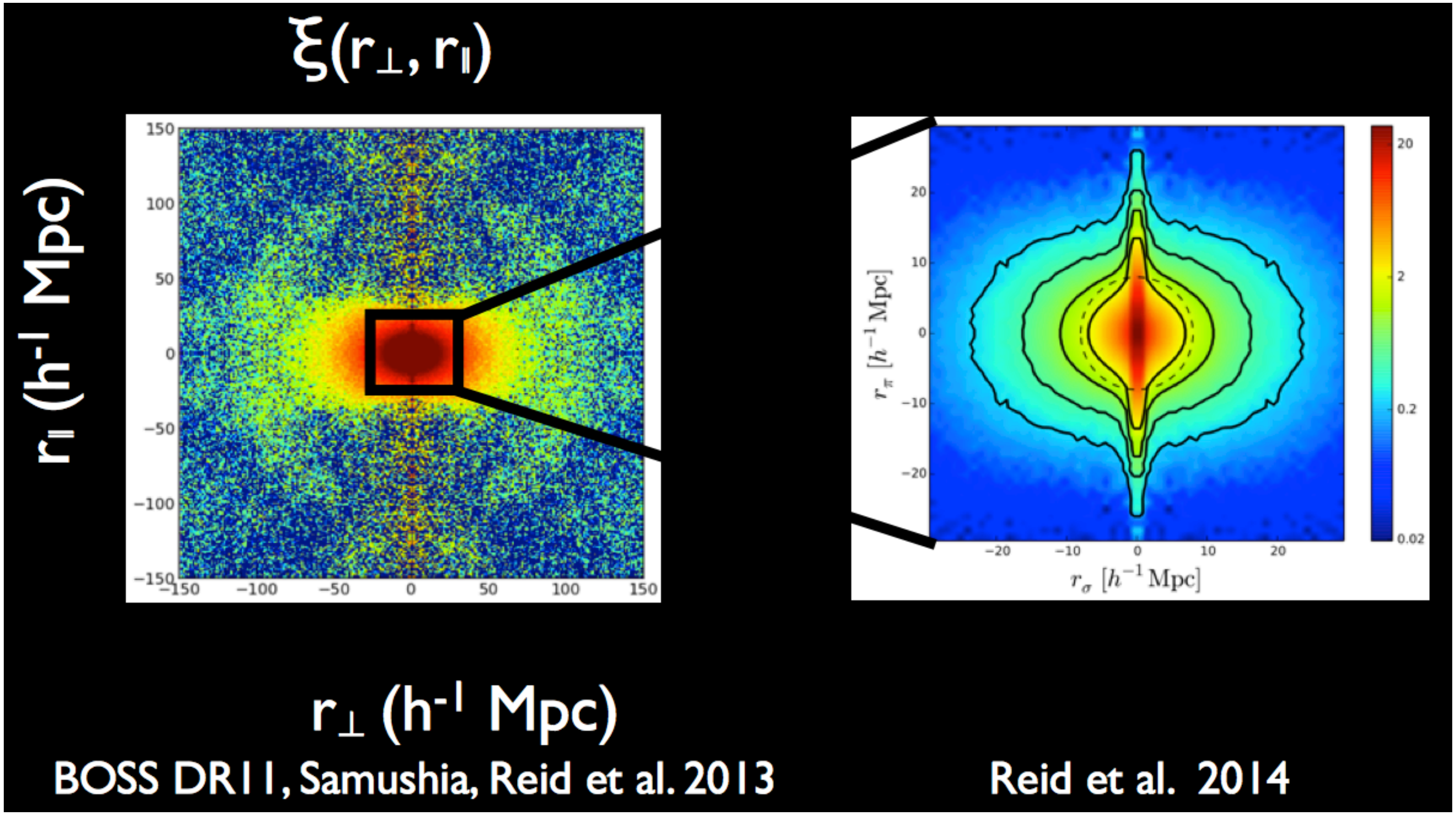


planck

redshift space distortions

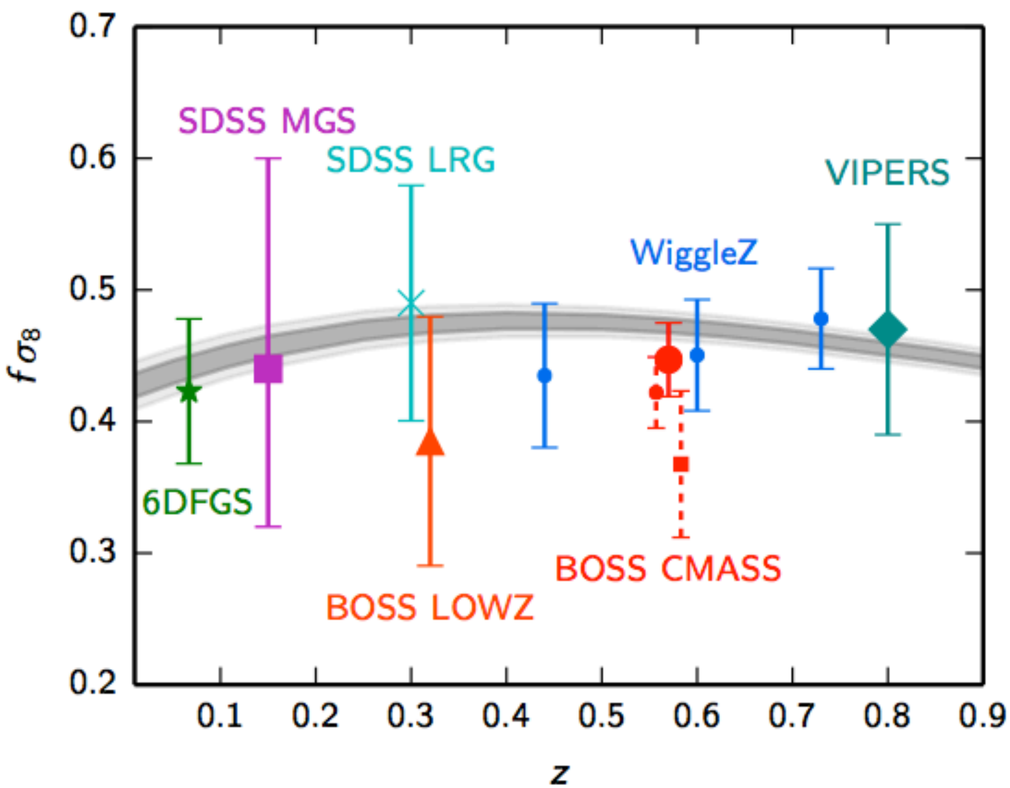
We observe galaxies in redshift space, not real space

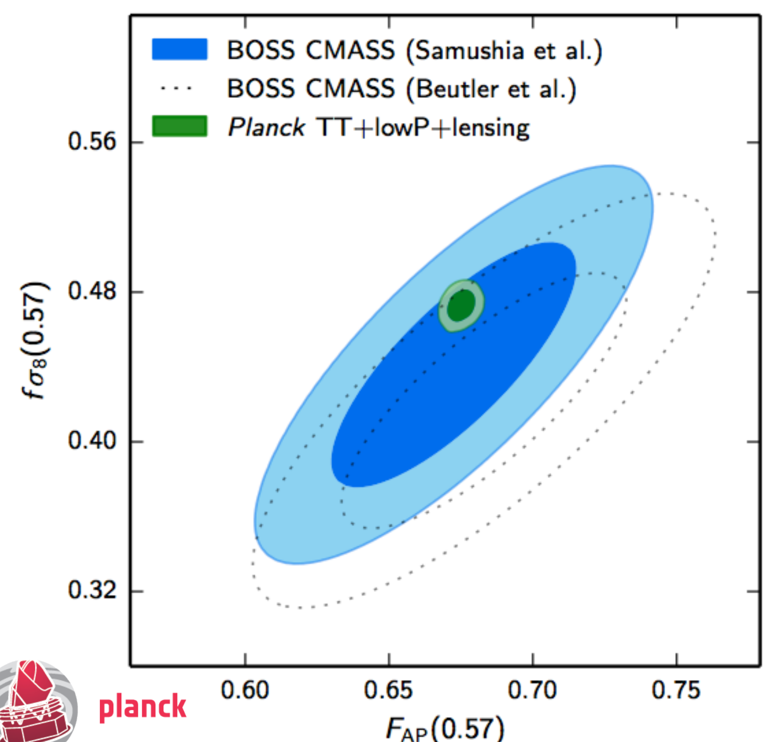
- large scales: coherent infall → squashing
- small scales random motion → elongation (`finger of god')



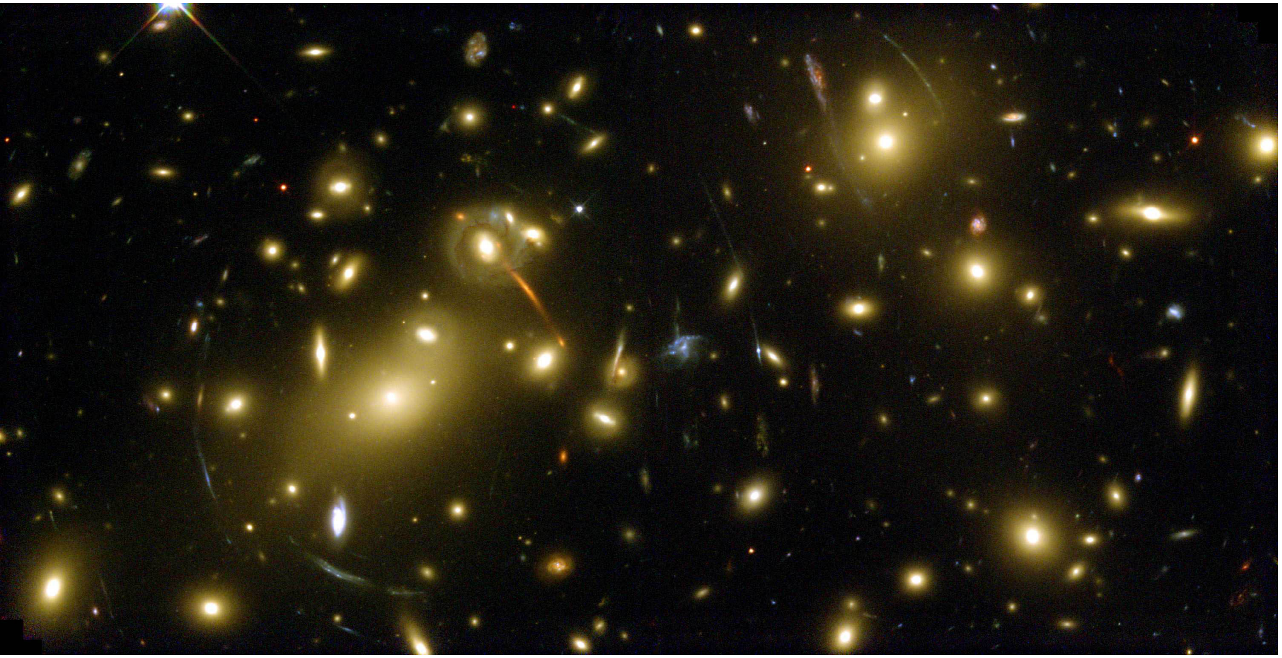
redshift space distortions

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



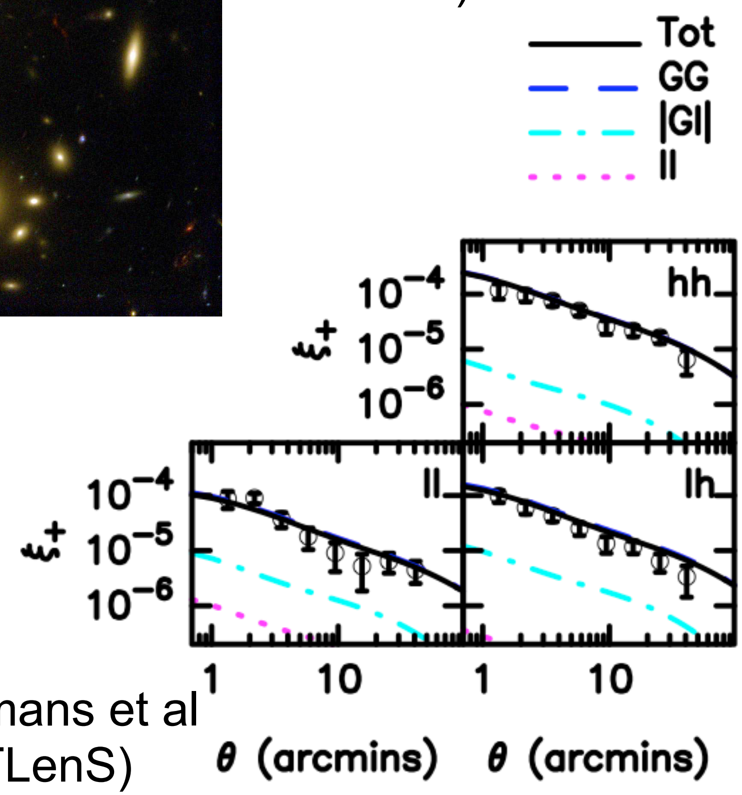


gravitational lensing



mass deflects light
this distorts galaxy
shapes a tiny bit

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

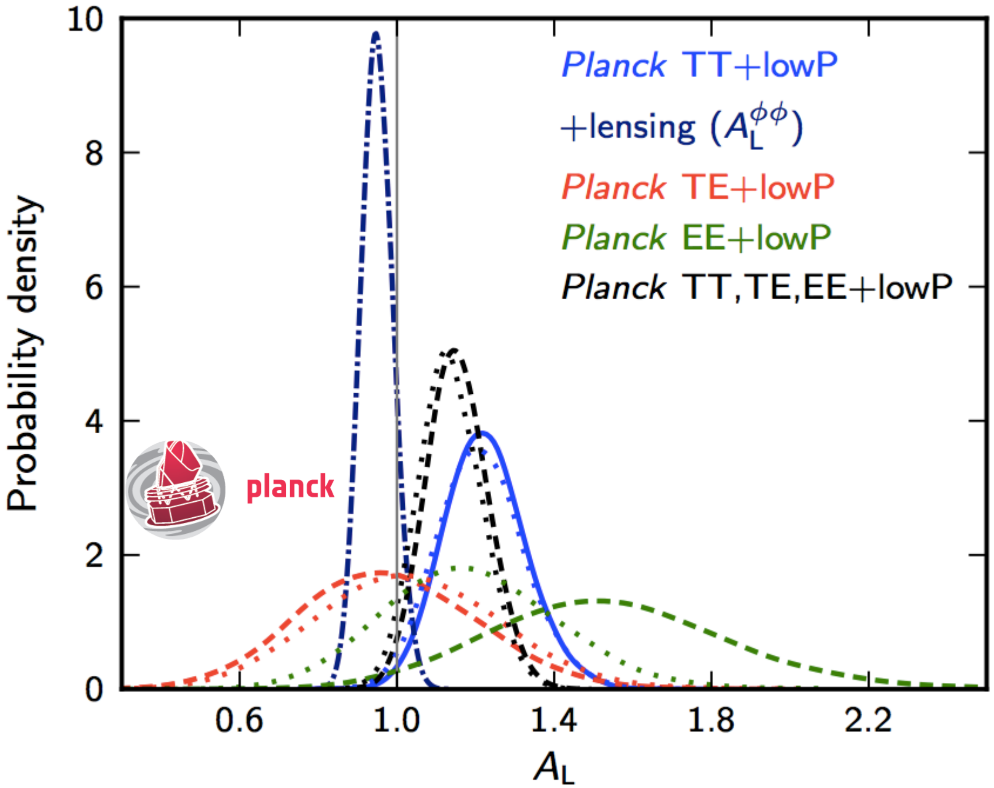


(Heymans et al
CFHTLenS)

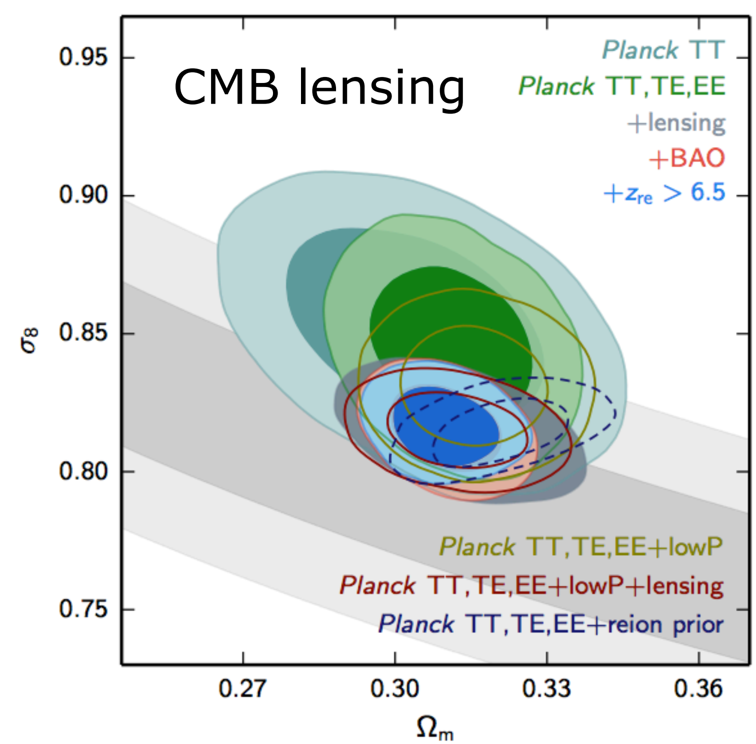
seen as a future key probe,
but difficult:

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

comparison with lensing data

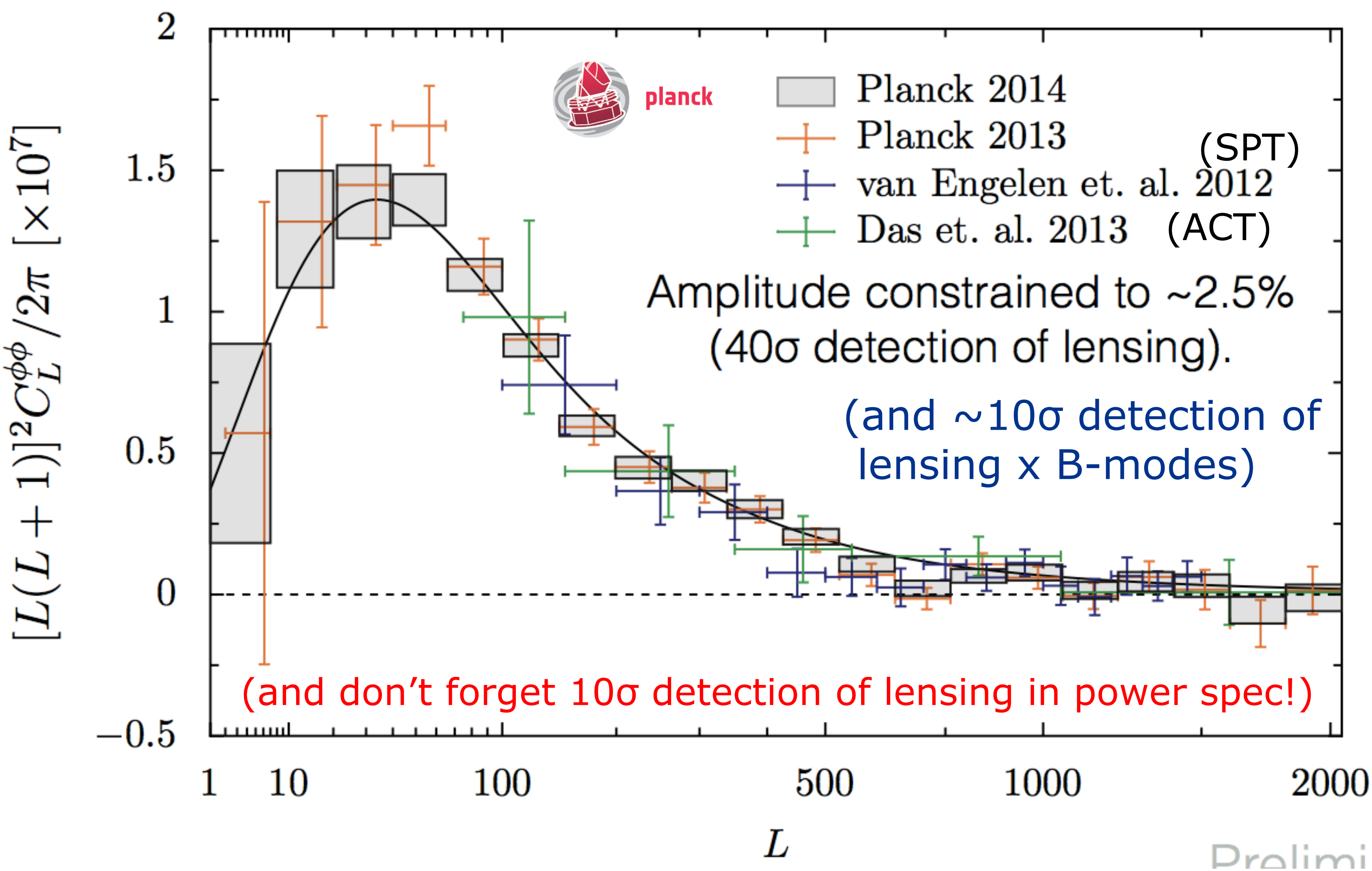


- WL still young technique
- CFHTLenS analyses marginally compatible with each other
- region ~Planck needs high H0
- we use 'ultraconservative' cut



- 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)
(and don't forget 10σ detection of lensing in power spec!)
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi\ [\times 10^7]$
L
Prelimi

how to constrain parameters

likelihood

posterior

prior

Bayes theorem: $$P(\theta|D,H) = \frac{P(D|\theta,H)P(\theta|H)}{P(D|H)}$$

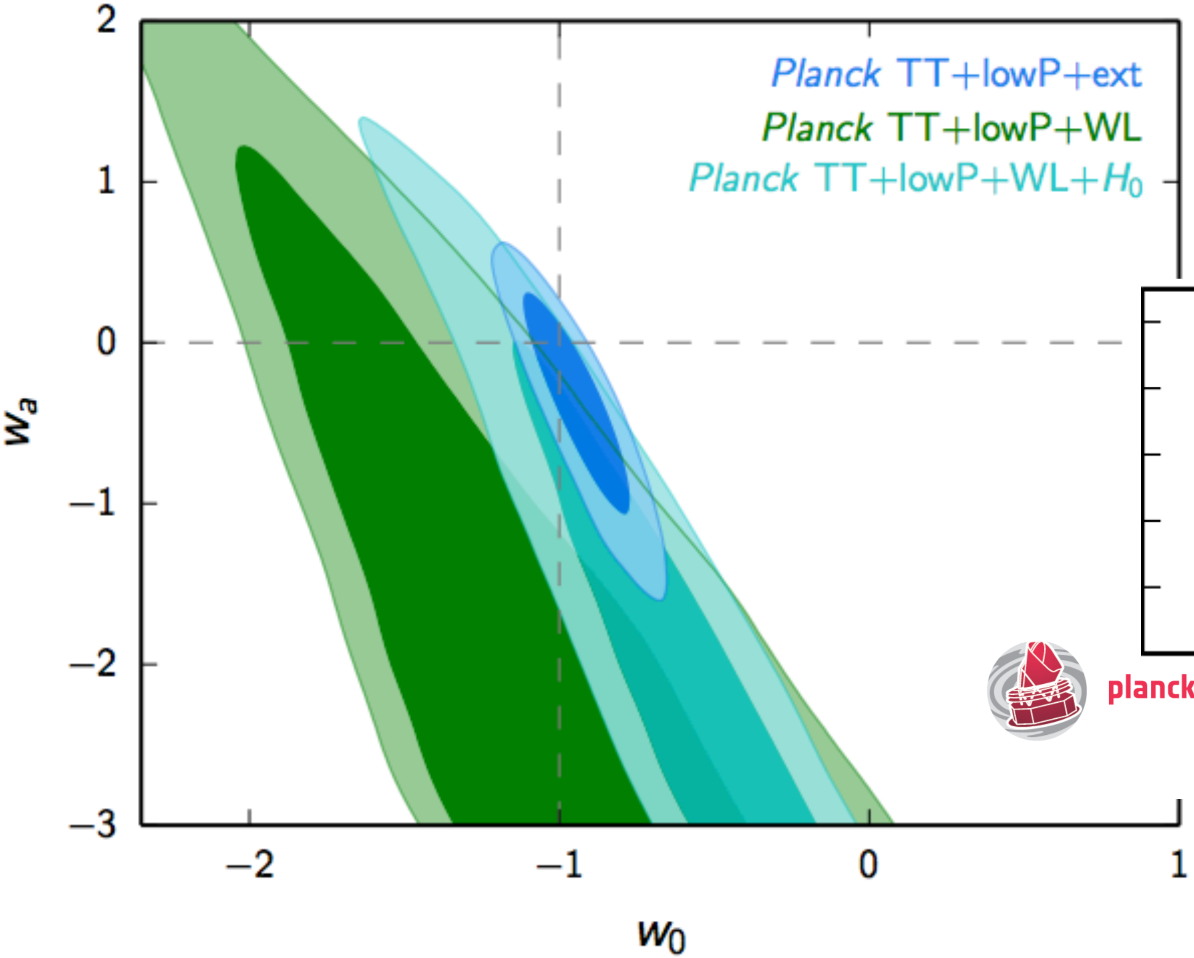
data

parameters

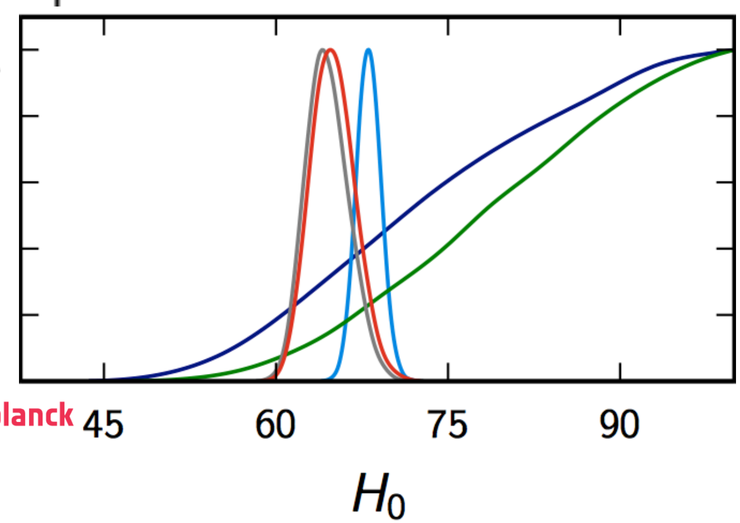
hypothesis
(e.g. model)

- pick a model H with parameters θ, decide on a prior
- get code to compute ‘observables’ (camb or CLASS for us)
- get likelihood (encapsulates data)
- explore posterior with MCMC (e.g. cosmomc)
- obtain credible intervals, model probabilities, etc.

dark energy

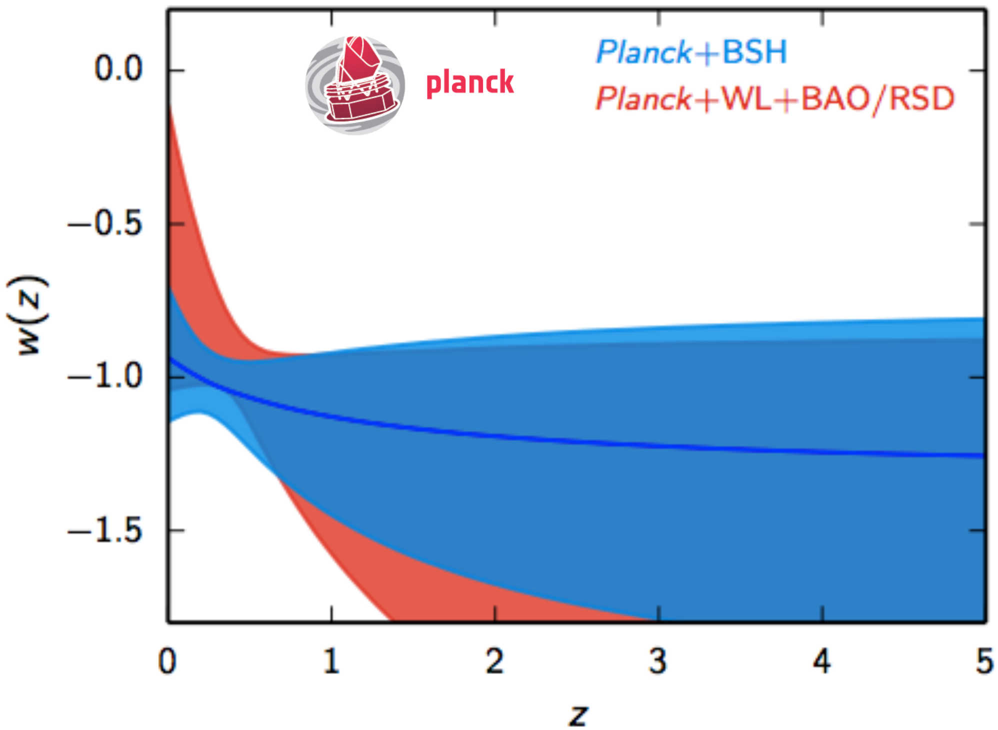


effective quintessence
$w(z) = w_0 + (1\text{-}a)w_a$

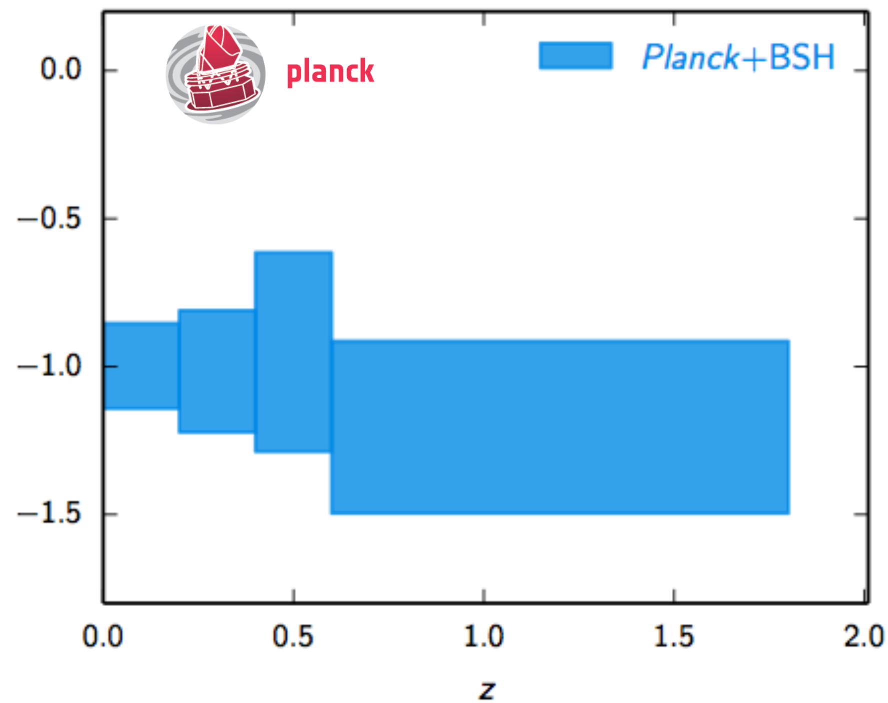


- Planck and WL prefer high H_0 and the 'phantom domain'
- no deviation from LCDM when adding BAO+JLA+H0
- **const w: w=-1.02±0.04** (TT,TE,EE+lowP+lensing+ext)

w(z) reconstruction



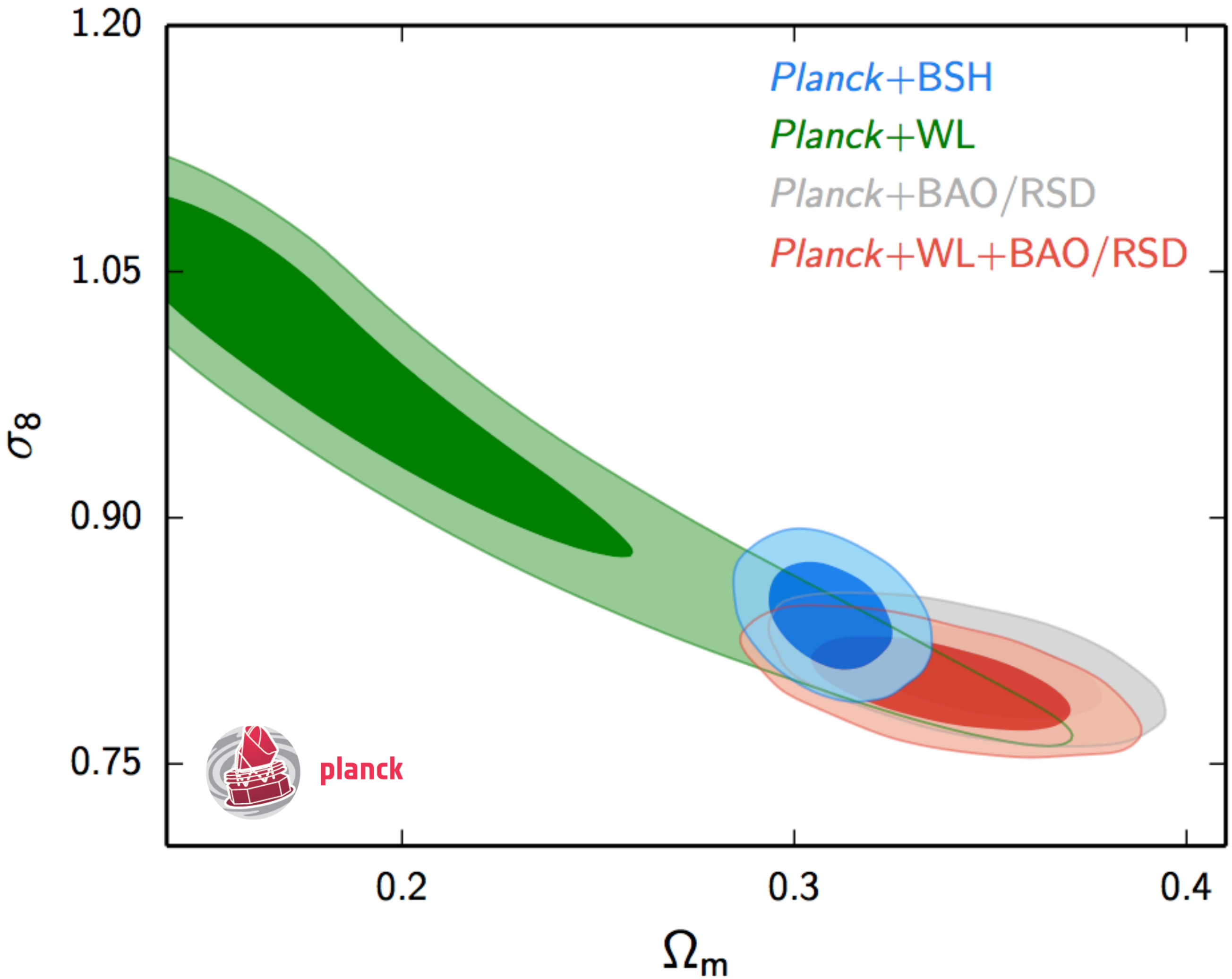
from ensemble of
$w_0+(1-a)w_a$ curves
(we also tried cubic in a)



PCA
(we also tried more bins)

no deviation from w=-1

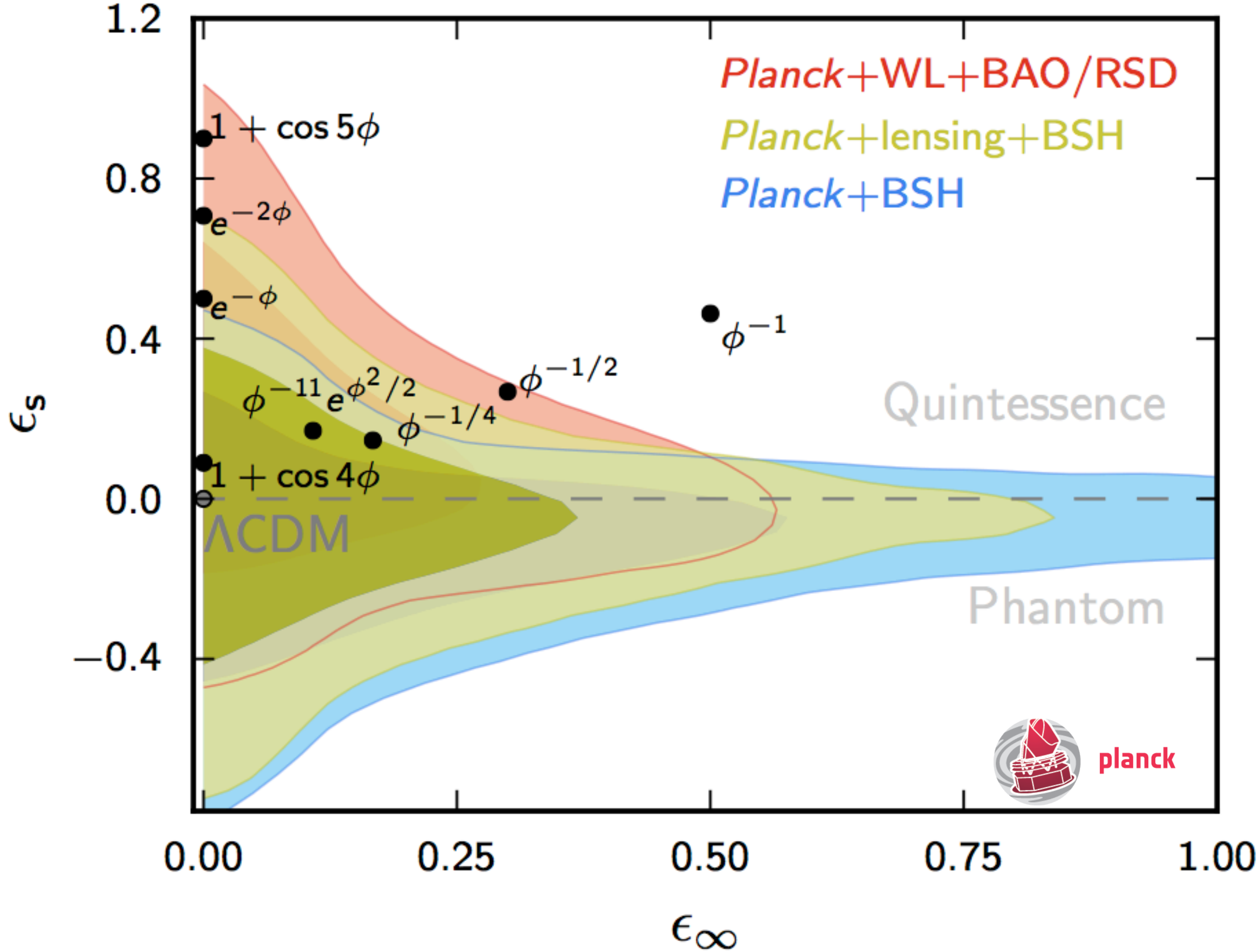
quintessence and growth



Quintessence can affect growth significantly

But Planck+WL would push into ‘wrong’ direction

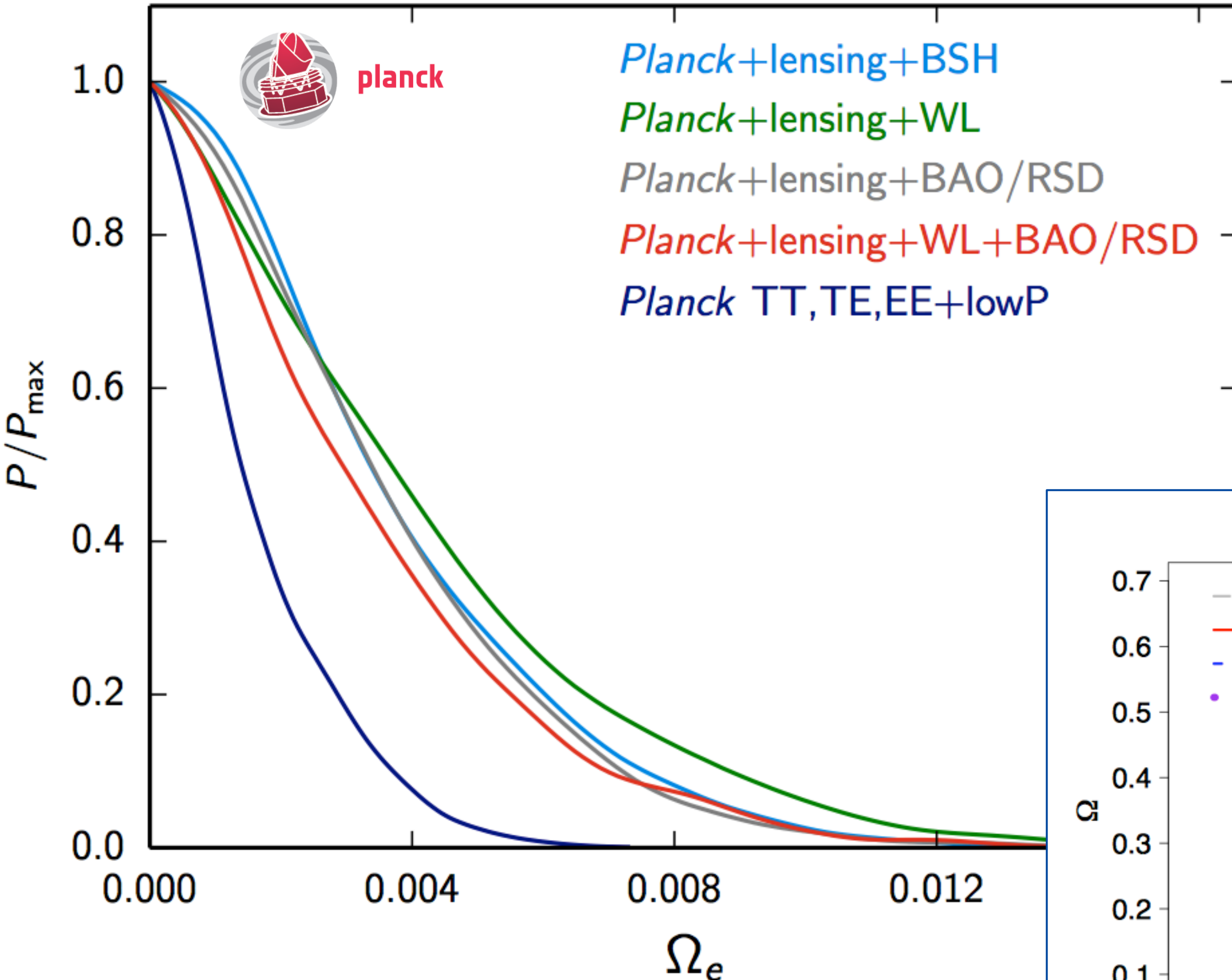
quintessence landscape



similar to scalar field inflation

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

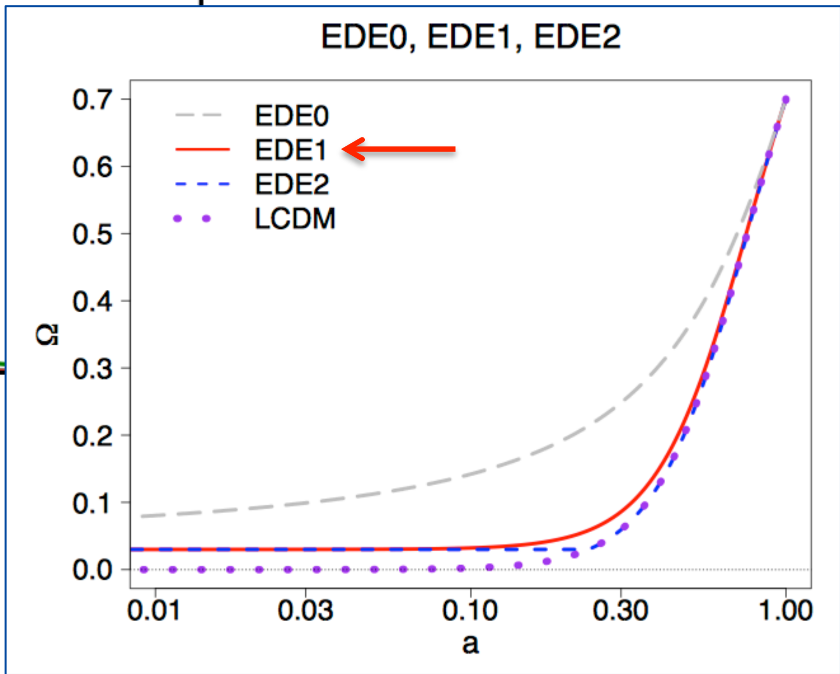
early dark energy



TT,TE,EE+lowP+BSH:

$\Omega_e < 0.0036$ @95%

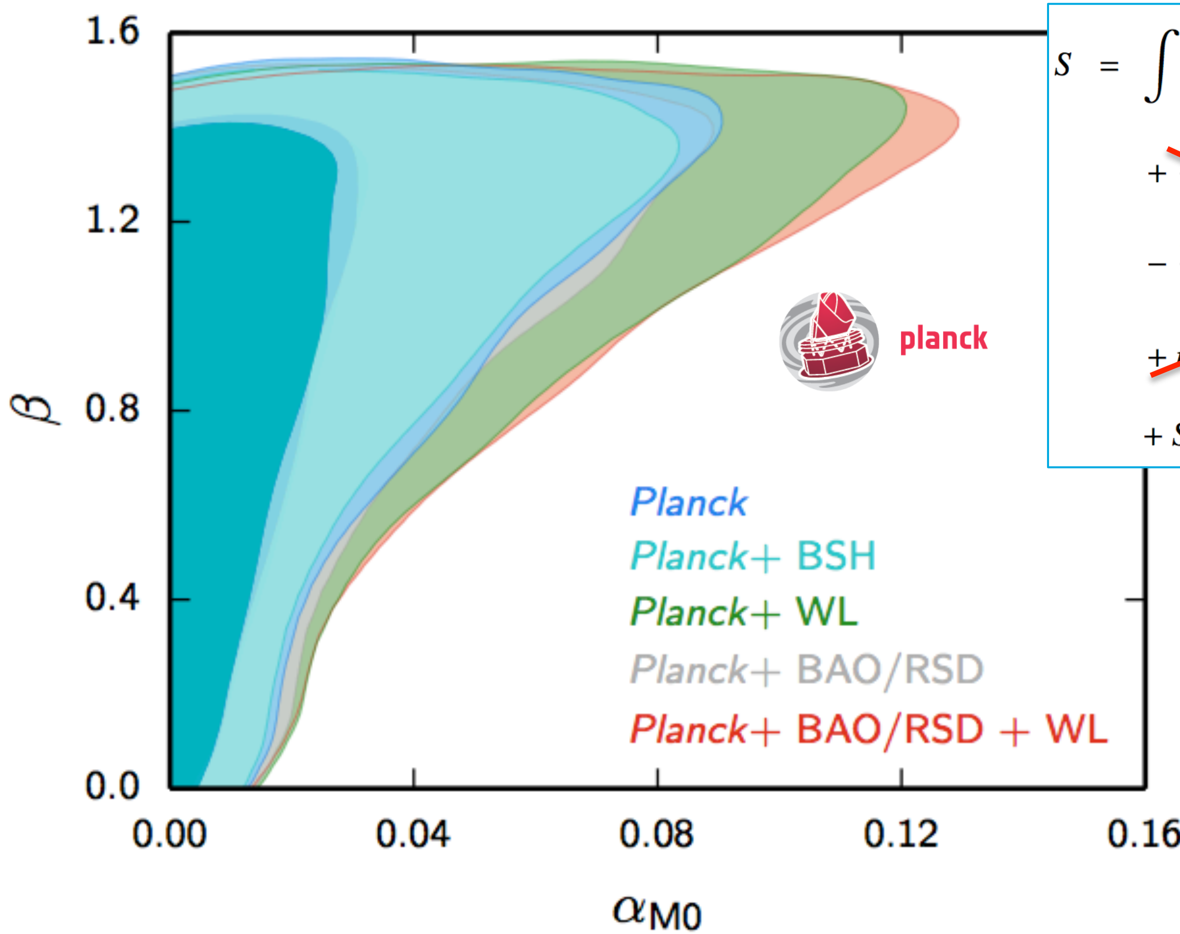
$w_0 < -0.94$ @95%



[if DE important for $z \leq 50$ 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



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

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

→ non-minimally coupled K-essence model

phenomenological approach

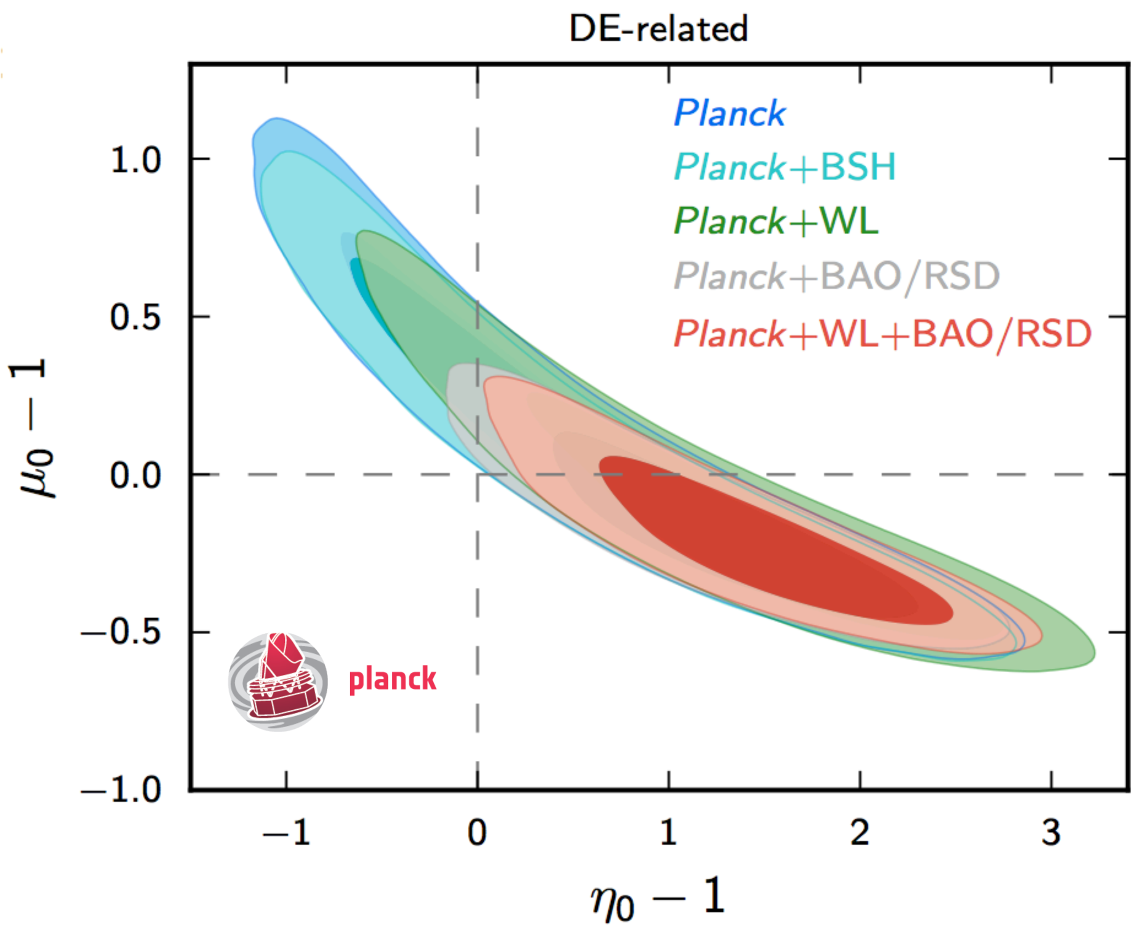
parameterisation of
late-time perturbations:

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

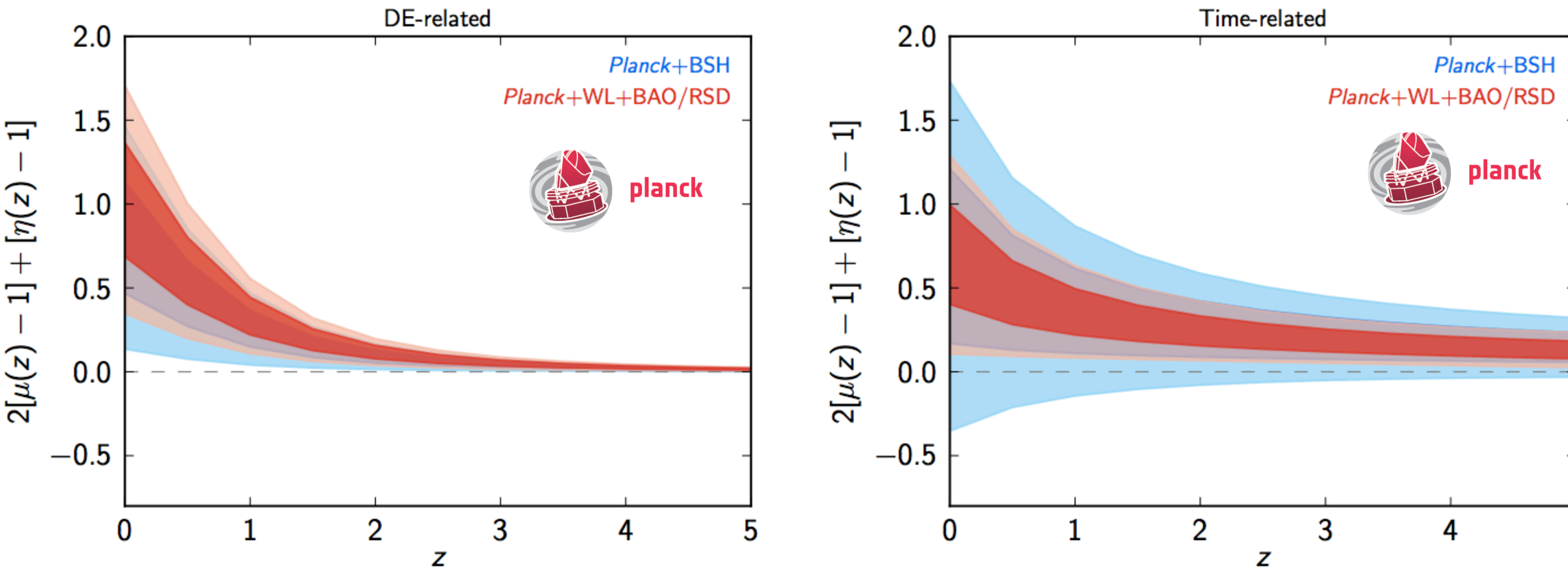
$$\eta(a,\boldsymbol{k}) \equiv \Phi/\Psi$$

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

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



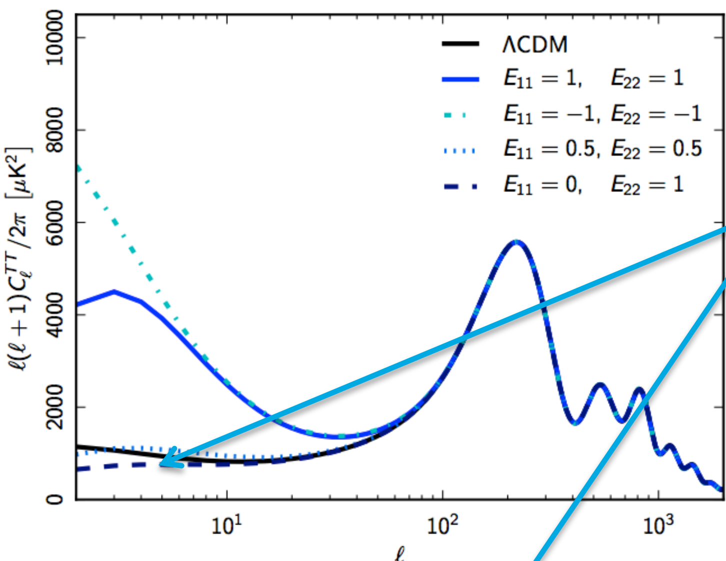
evolution of deviation

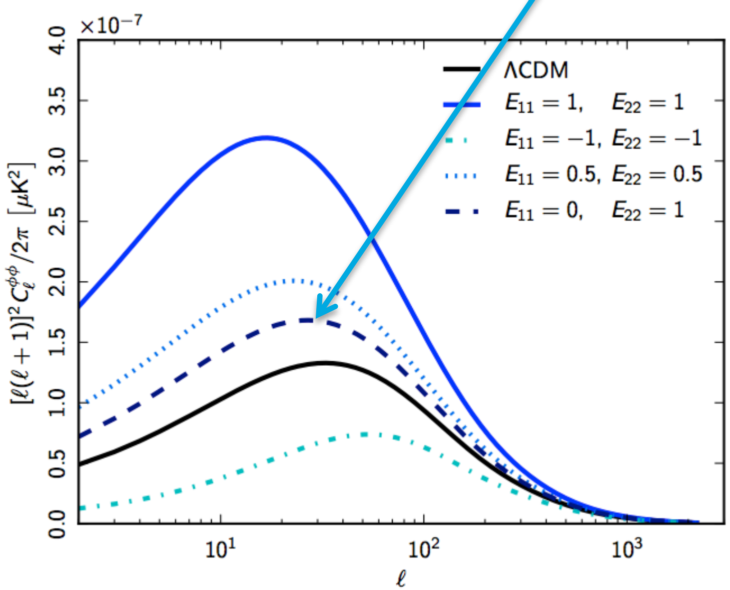


DE related parameterization:

- 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



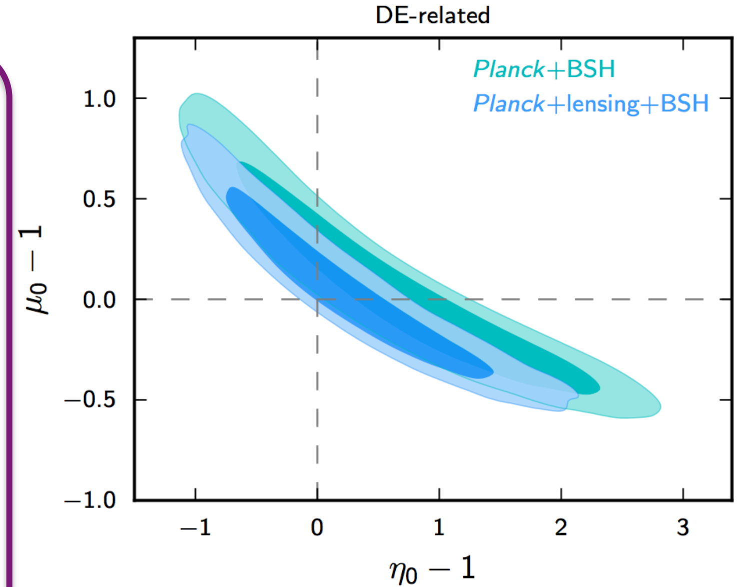


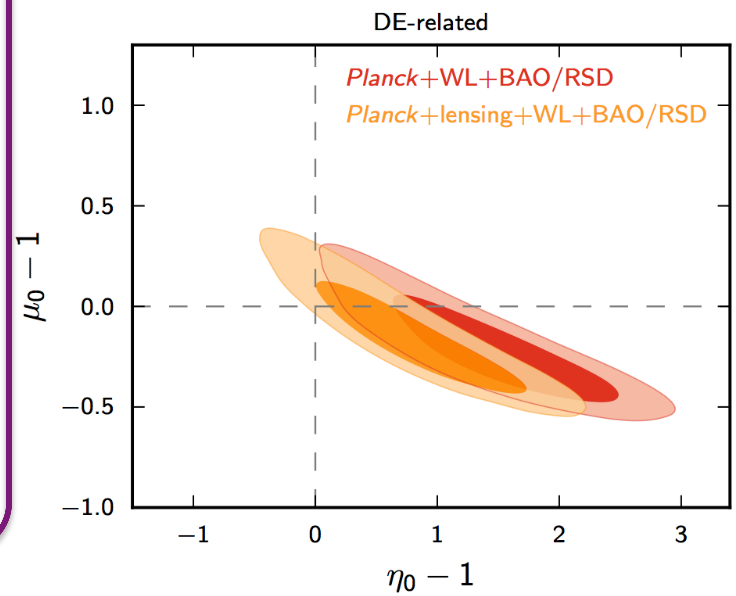
best-fit model is similar to -- model

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

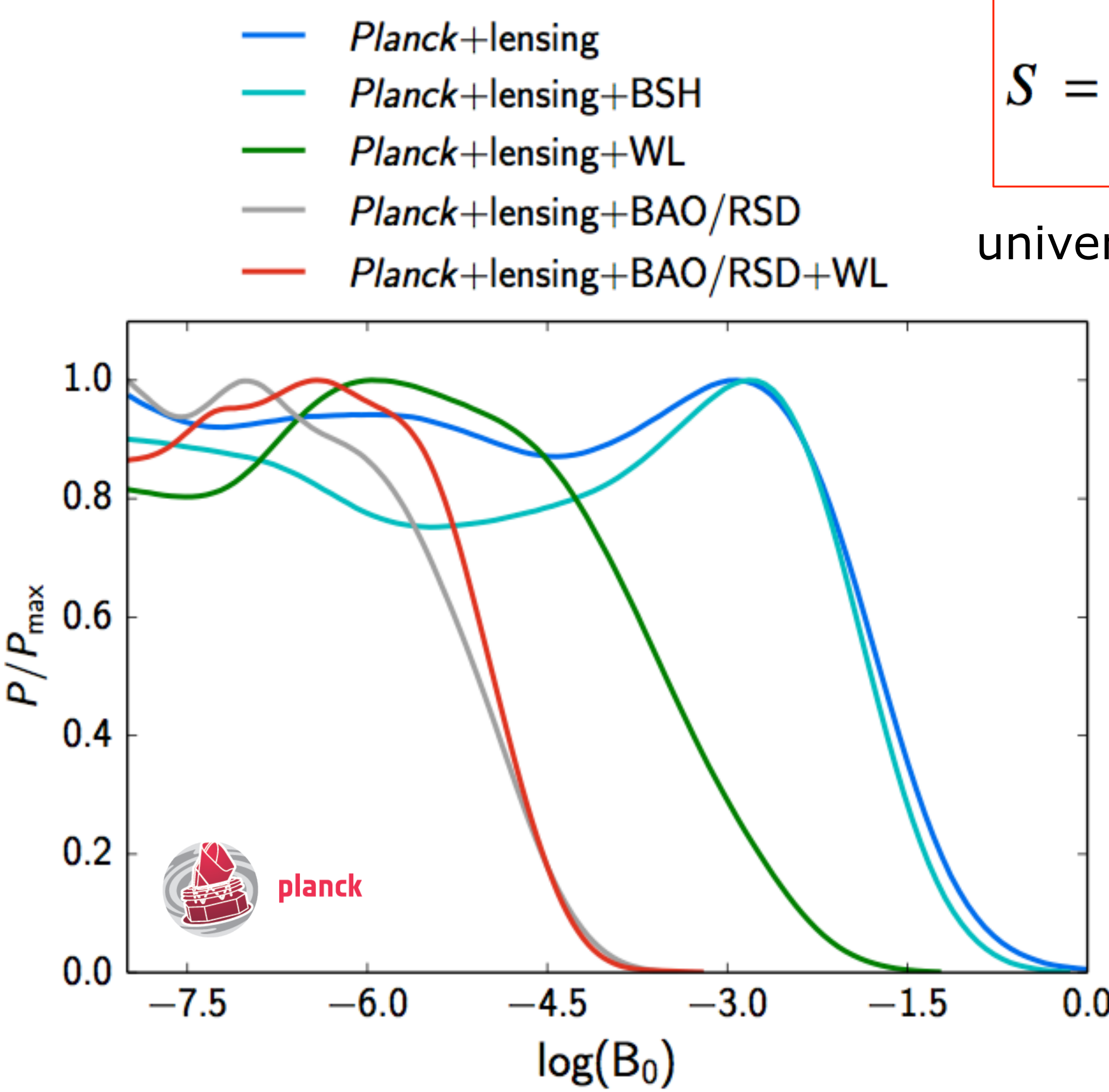
BUT NOT in the 4-point lensing → CMB lensing prefers LCDM!

→ 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!

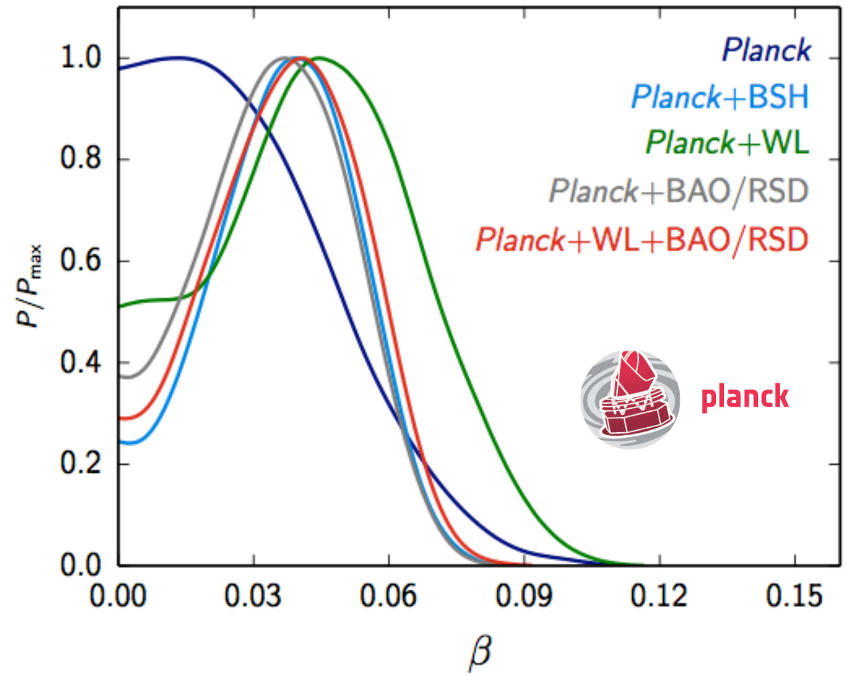
best limit:
TT+lowP+lensing+WL
+BAO/RSD
$B_0 < 0.8\times10^{-4}$ (95% CL)

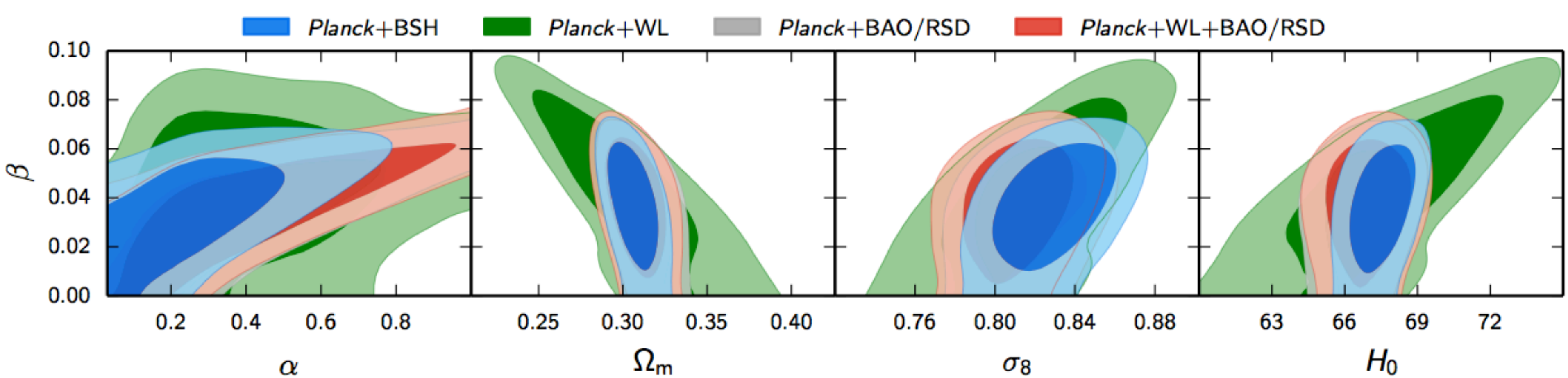
coupled quintessence

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?





ISW cross-corr.

(there is a funny issue when stacking CMB anisotropies at locations of known structures)

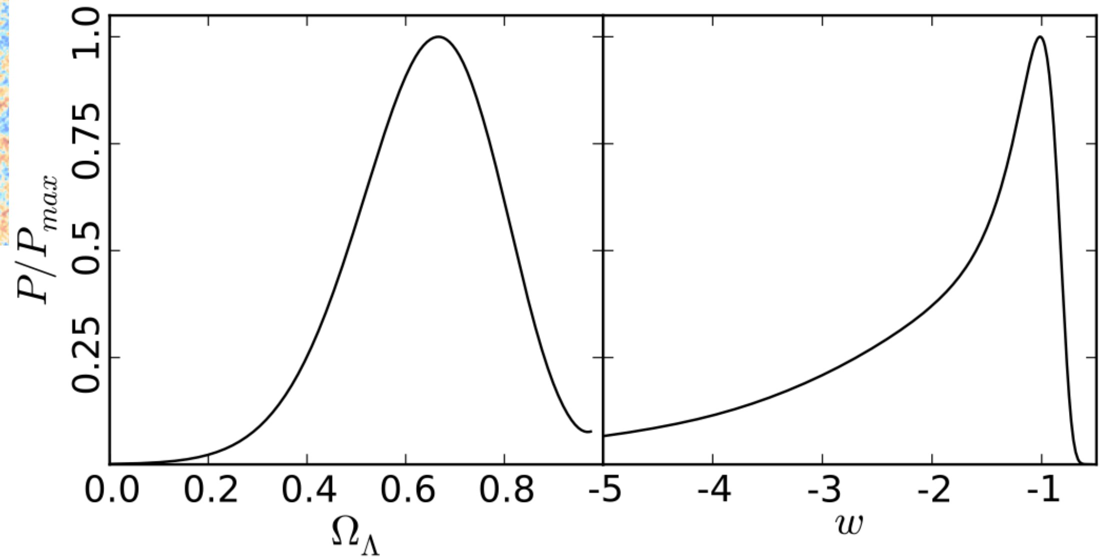
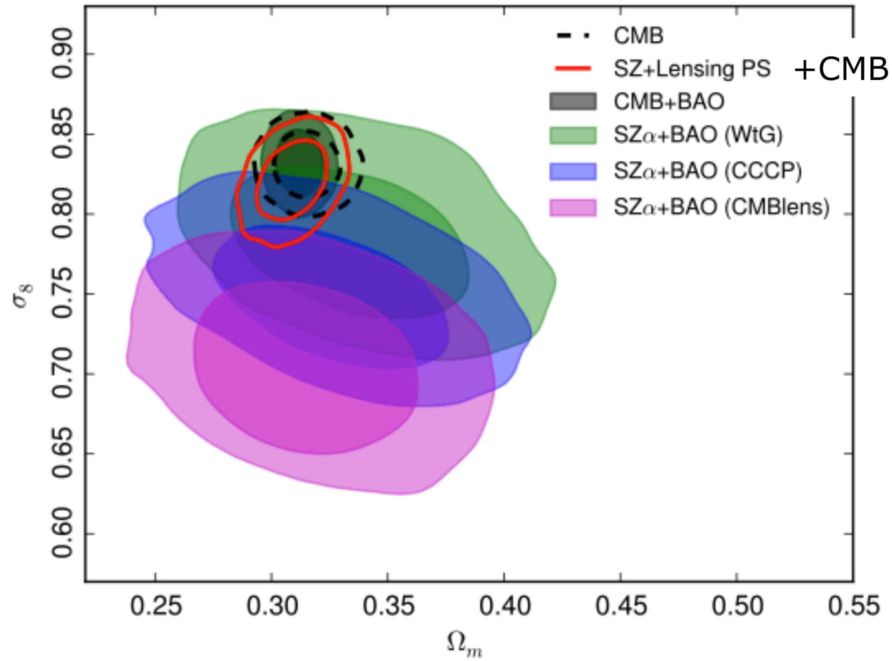


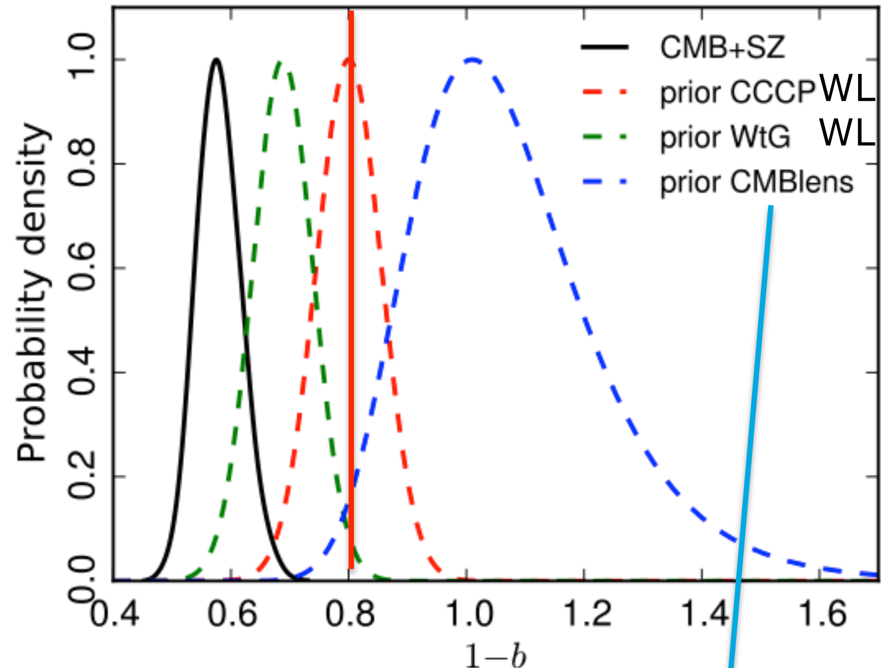
Table 2. ISW amplitudes A, errors σ_A, and significance levels S/N = A/σ_A of the CMB-LSS cross-correlation (survey-by-survey and for different combinations). These values are reported for the four *Planck* CMB maps: COMMANDER, NILC, SEVEM, and SMICA. The last column stands for the expected S/N within the fiducial ΛCDM model.

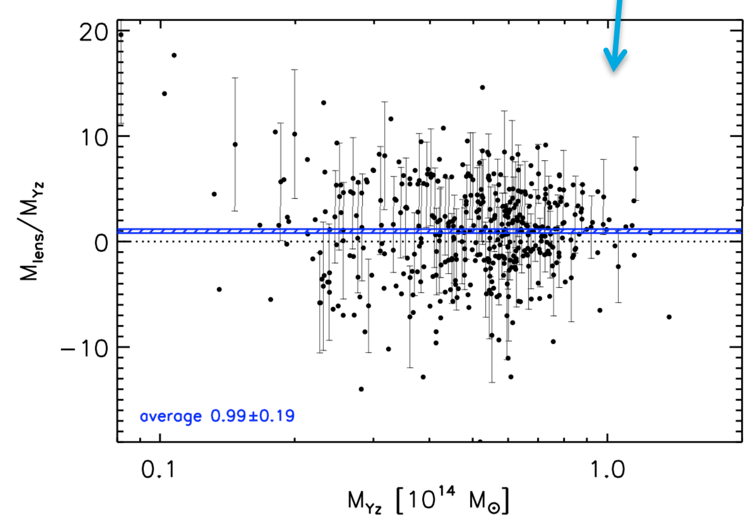
LSS data	COMMANDER		NILC		SEVEM		SMICA		Expected
	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	S/N
NVSS	0.95 ± 0.36	2.61	0.94 ± 0.36	2.59	0.95 ± 0.36	2.62	0.95 ± 0.36	2.61	2.78
WISE-AGN ($\ell_{min} \geq 9$)	0.95 ± 0.60	1.58	0.96 ± 0.60	1.59	0.95 ± 0.60	1.58	1.00 ± 0.60	1.66	1.67
WISE-GAL ($\ell_{min} \geq 9$)	0.73 ± 0.53	1.37	0.72 ± 0.53	1.35	0.74 ± 0.53	1.38	0.77 ± 0.53	1.44	1.89
SDSS-CMASS/LOWZ	1.37 ± 0.56	2.42	1.36 ± 0.56	2.40	1.37 ± 0.56	2.43	1.37 ± 0.56	2.44	1.79
SDSS-MphG	1.60 ± 0.68	2.34	1.59 ± 0.68	2.34	1.61 ± 0.68	2.36	1.62 ± 0.68	2.38	1.47
Kappa ($\ell_{min} \geq 8$)	1.04 ± 0.33	3.15	1.04 ± 0.33	3.16	1.05 ± 0.33	3.17	1.06 ± 0.33	3.20	3.03
NVSS and Kappa	1.04 ± 0.28	3.79	1.04 ± 0.28	3.78	1.05 ± 0.28	3.81	1.05 ± 0.28	3.81	3.57
WISE	0.84 ± 0.45	1.88	0.84 ± 0.45	1.88	0.84 ± 0.45	1.88	0.88 ± 0.45	1.97	2.22
SDSS	1.49 ± 0.55	2.73	1.48 ± 0.55	2.70	1.50 ± 0.55	2.74	1.50 ± 0.55	2.74	1.82
NVSS and WISE and SDSS	0.89 ± 0.31	2.87	0.89 ± 0.31	2.87	0.89 ± 0.31	2.87	0.90 ± 0.31	2.90	3.22
All	1.00 ± 0.25	4.00	0.99 ± 0.25	3.96	1.00 ± 0.25	4.00	1.00 ± 0.25	4.00	4.00

SZ clusters

planck







- cosmological constraints fully degenerate with mass bias
- widely varying results from different lensing approaches
- use spread as indication of systematics? if so then no disagreement with Planck CMB

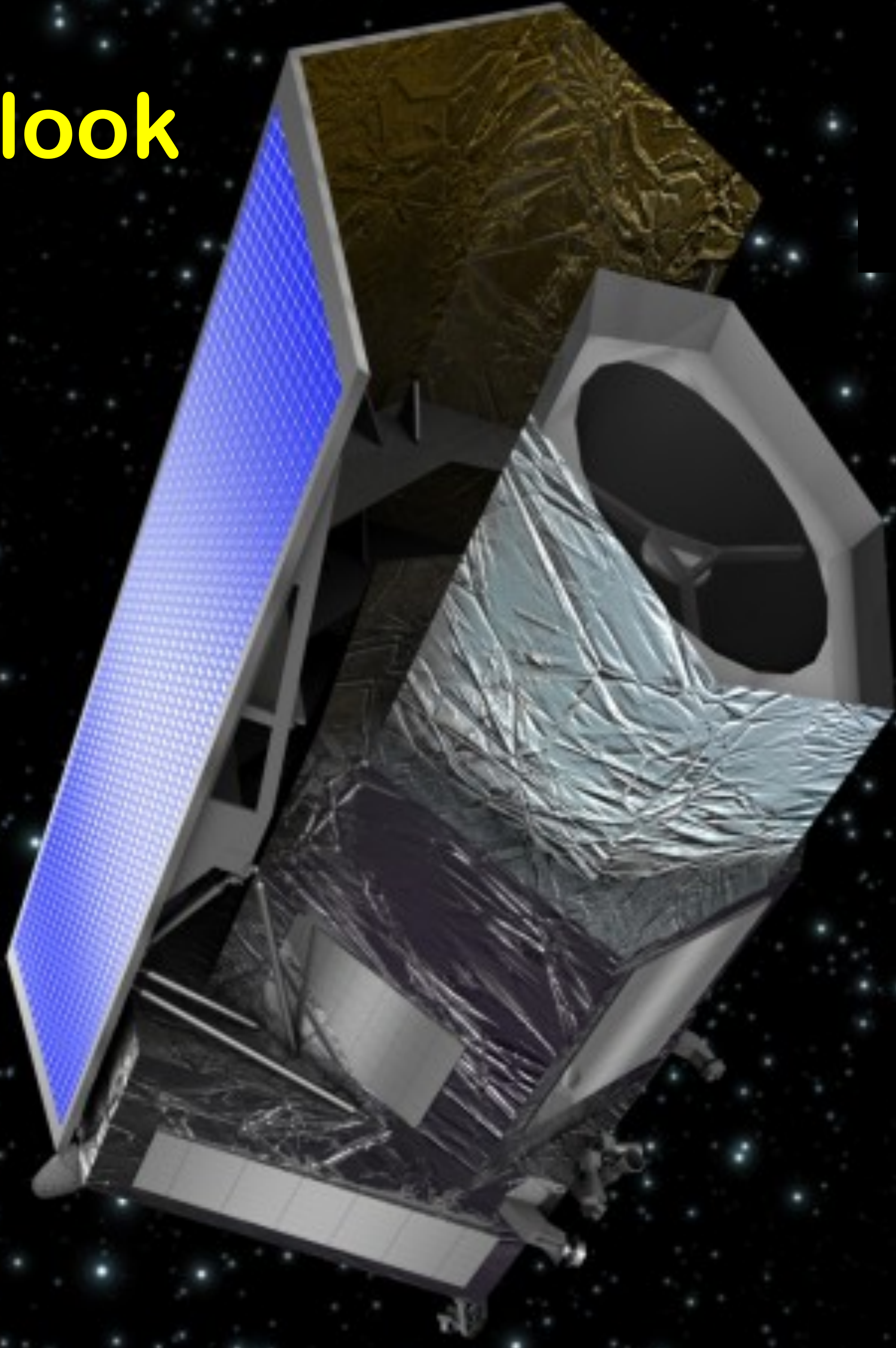
conclusions

- 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: $w(z) \leftarrow$ distances
  - perturbations: 2 functions ← e.g. RSD + WL
- Where will we stand in 15 to 20 years?

outlook

Euclid

ca 2020



Euclid

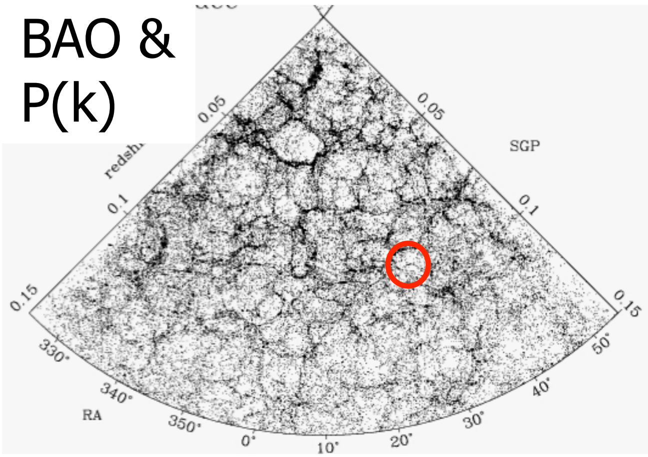
the consortium

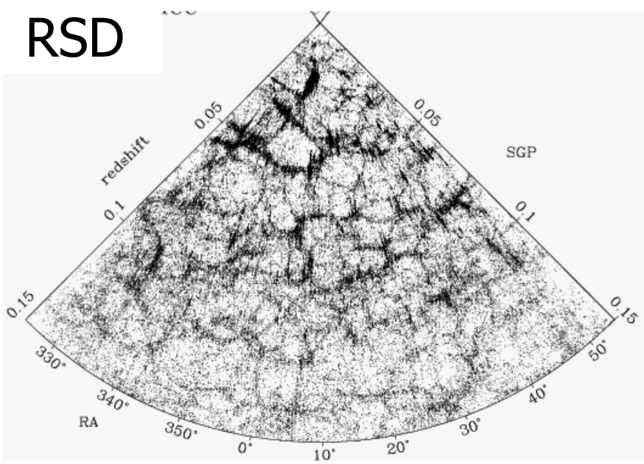
- 1150 members
- 120 Labs
- 13 European countries: Austria, Denmark, France, Finland, Germany, Italy, The Netherlands, Norway, Portugal, Romania, Spain, Switzerland, UK + US/NASA and Berkeley labs

Euclid primary probes:

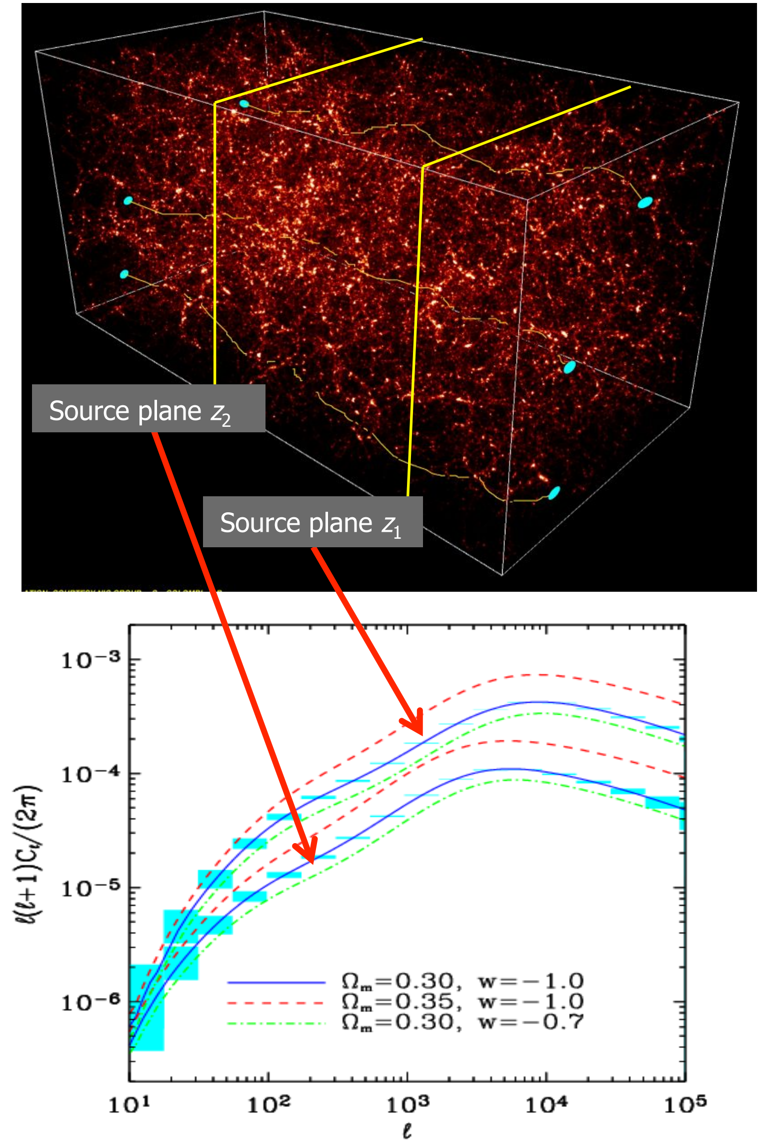
Euclid Consortium

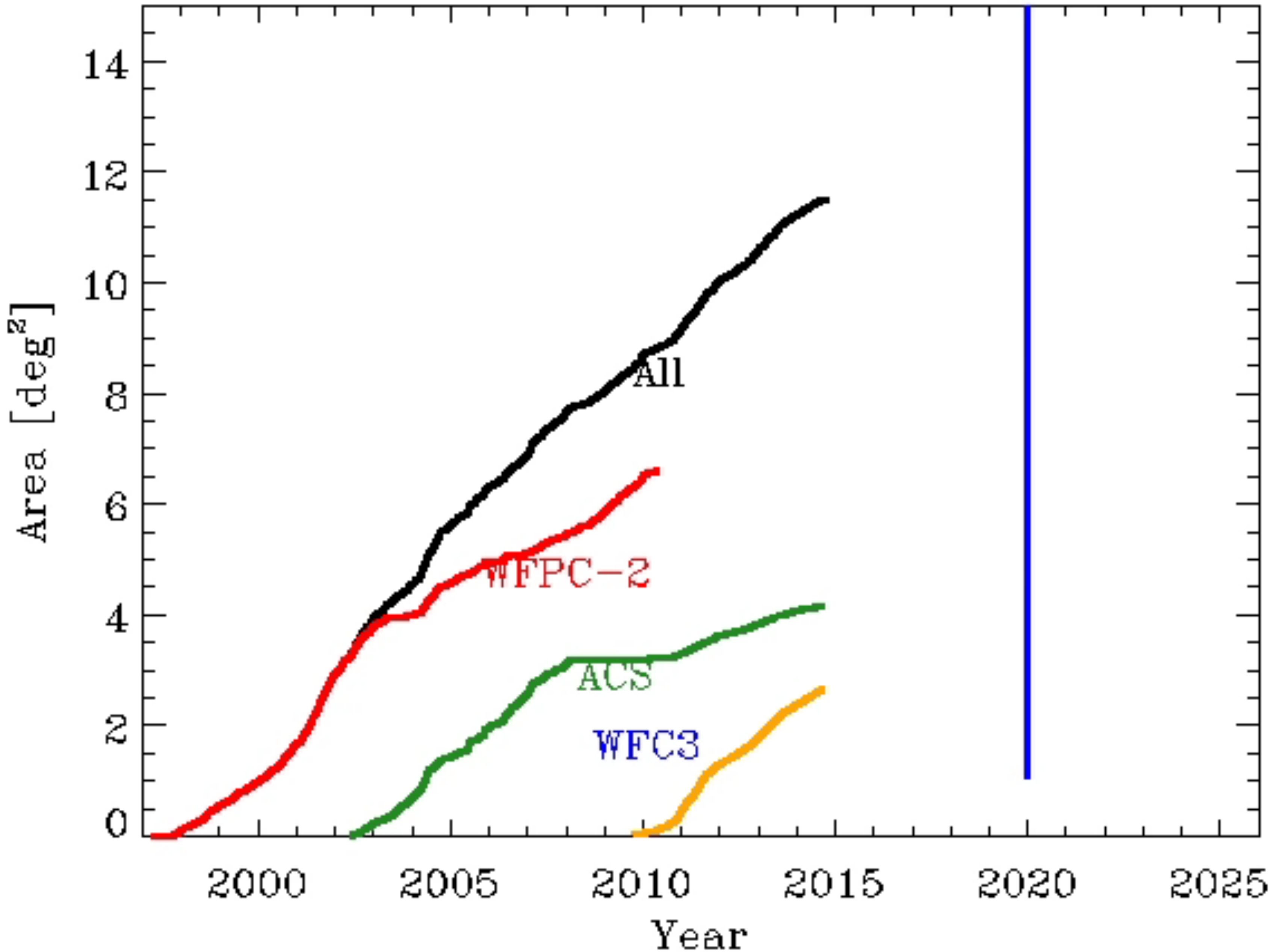
50 million galaxies with redshifts





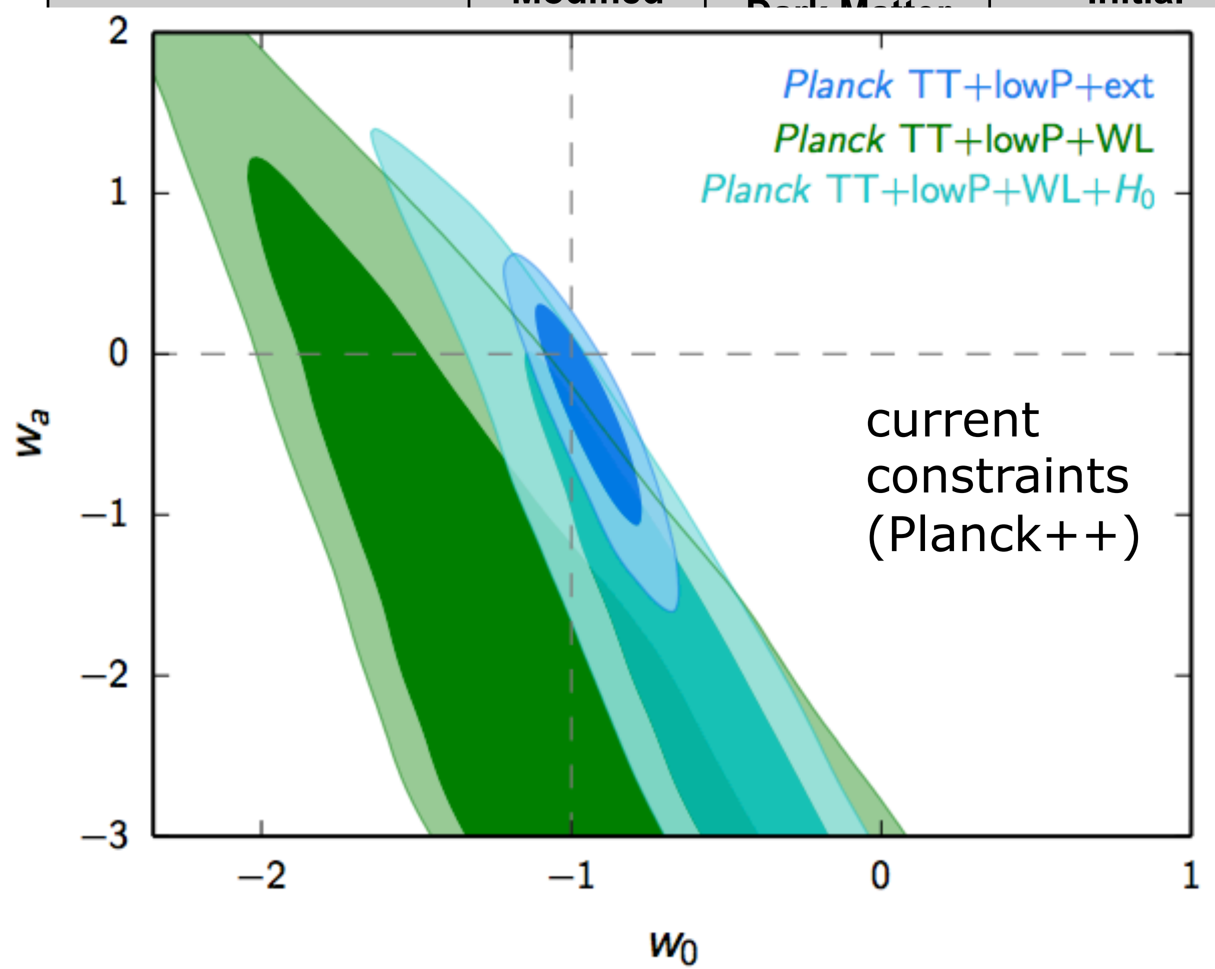
1.5 billion sources with shapes, 10 slices





Movie from J. Brinchmann

	Modified	Dark Matter	Initial	Dark Energy		
				w_p	w_a	**FoM**
				0.015	0.150	430
				0.013	0.048	1540
				0.007	0.035	4020
				0.100	1.500	~10
				>10	**>40**	**>400**



rule out even models that

).

ossible ~ 0.05 eV!

- These numbers have a meaning only if we can control the systematic errors.

Ref: Euclid RB arXiv:1110.3193 – currently updating constraints

But Euclid goes far beyond DE!

- A unique NIR facility:
  - Wide:15,000 deg^{2}, YJH_{AB}=24
  - Deep: 40 deg^{2} , YJH_{AB}=26
  - with VISTA: Euclid-Wide in 600 yrs and Euclid-Deep in 70 yrs.
- Billions of stars and galaxies
  - 1.5 10^9 galaxies @ S/N >10 ; 12 10^9 galaxies S/N>3
  - Statistics:
    - Euclid = SDSS @ 1<z<3
    - Rare objects
    - High Res. imaging of extragalactic sky,
    - NIR: cool, obscured and high-*z* sources
- Synergy: LSST, SKA, GAIA, e-ROSITA, Planck
- Targets for JWST, E-ELT, TMT, GMT, ALMA, MOS for VLTs (MOONS, 4 MOST, PFS)
- e-Euclid: exo-planets, SNs, Galaxy (?)

Euclid Legacy and other surveys

Target	Euclid	Before Euclid
Galaxies at 1<z<3 with good mass estimates	~ 2×10^8	~ 5×10^6
Massive galaxies (1<z<3) w/ spectra	~ few x 10^3	~ few tens
Hα emitters/metal abundance in z~2-3	~ 4×10^7 / 1×10^4	~ 10^4/ ~10^2?
Galaxies in massive clusters at z>1	~ 2×10^4	~ 10^3?
Type 2 AGN (0.7<z<2)	~ 10^4	<10^3
Dwarf galaxies	~ 10^5	
T_{eff} ~400K Y dwarfs	~ few 10^2	<10
Strongly lensed galaxy-scale lenses	~ 300,000 (5000 arcs in clusters)	~ 10-100
z > 8 QSOs	~ 30	None

Ref: Euclid RB arXiv:1110.3193

Radio Astronomy in the era of the SKA

SKA Phase 1 (SKA1)
Cost: €650M, construction start 2017

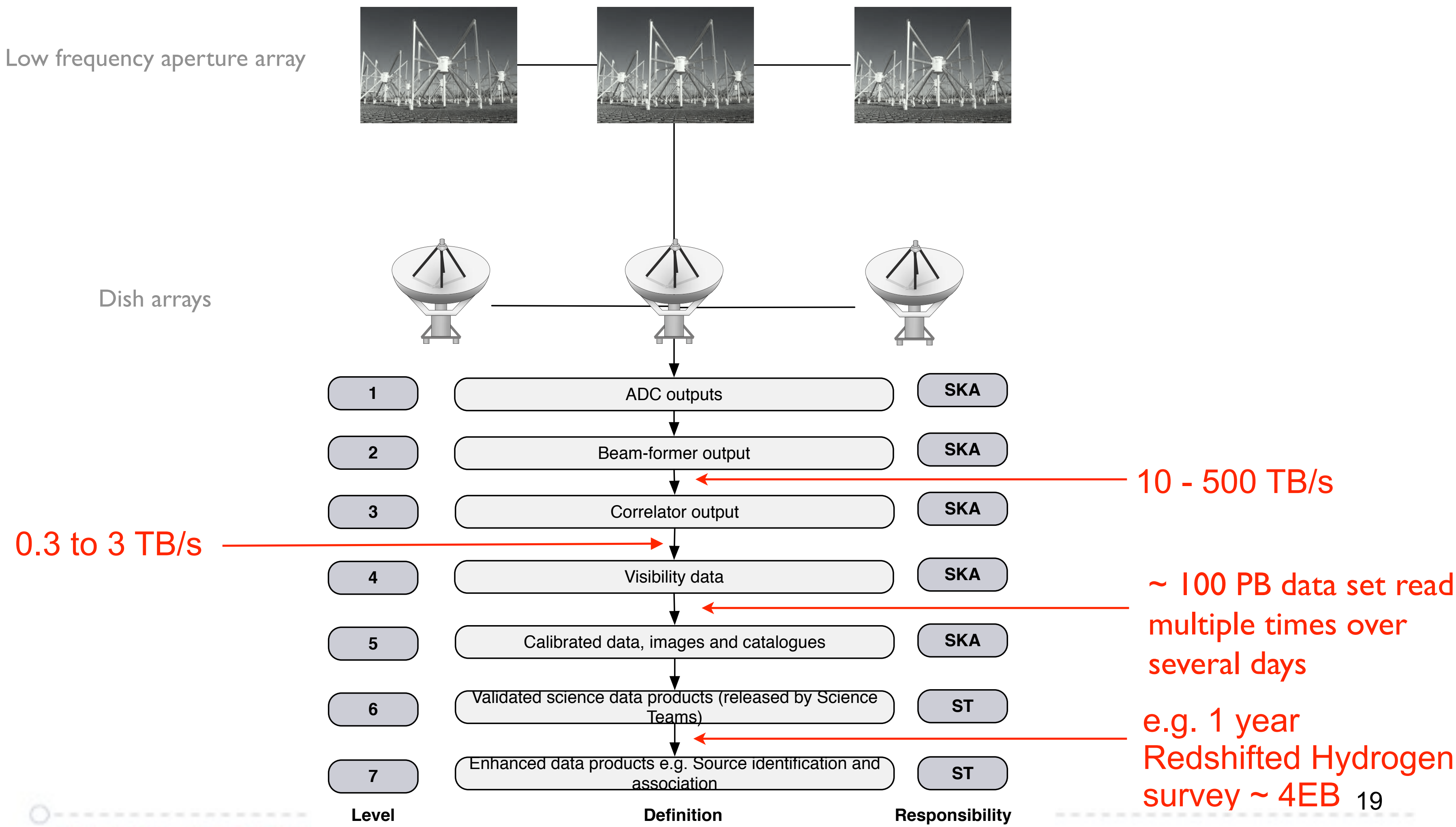
Southern Africa

SKA1_MID
254 Dishes including:
64 x MeerKAT dishes
190 x SKA dishes

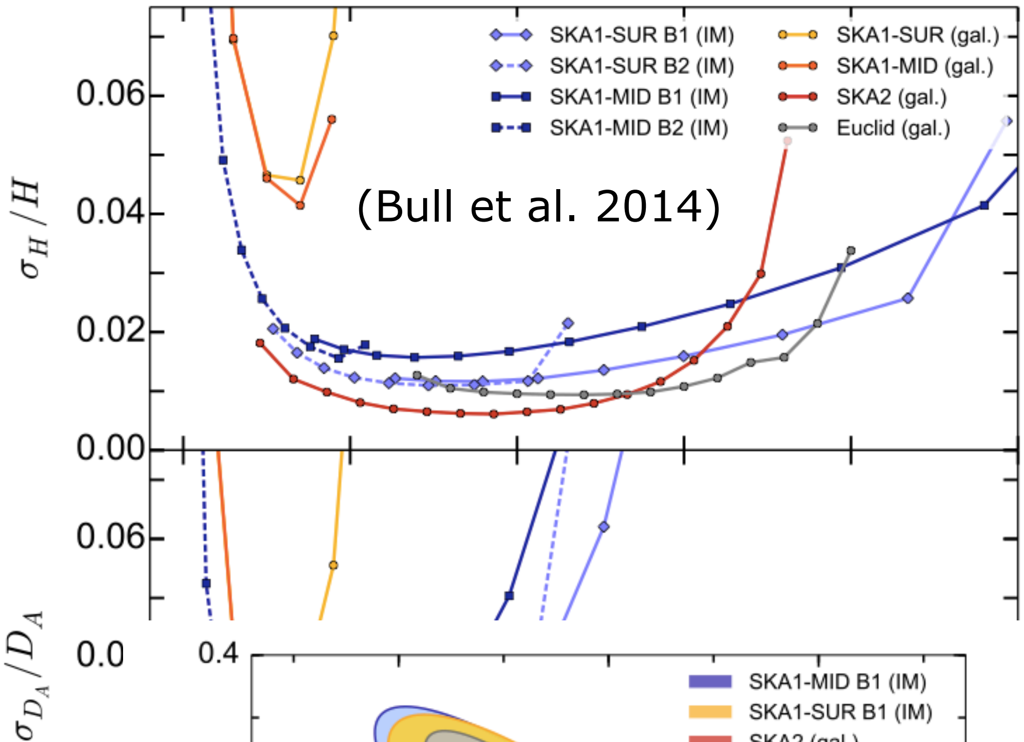
Australia

SKA1_LOW
Low Frequency Aperture Array Stations

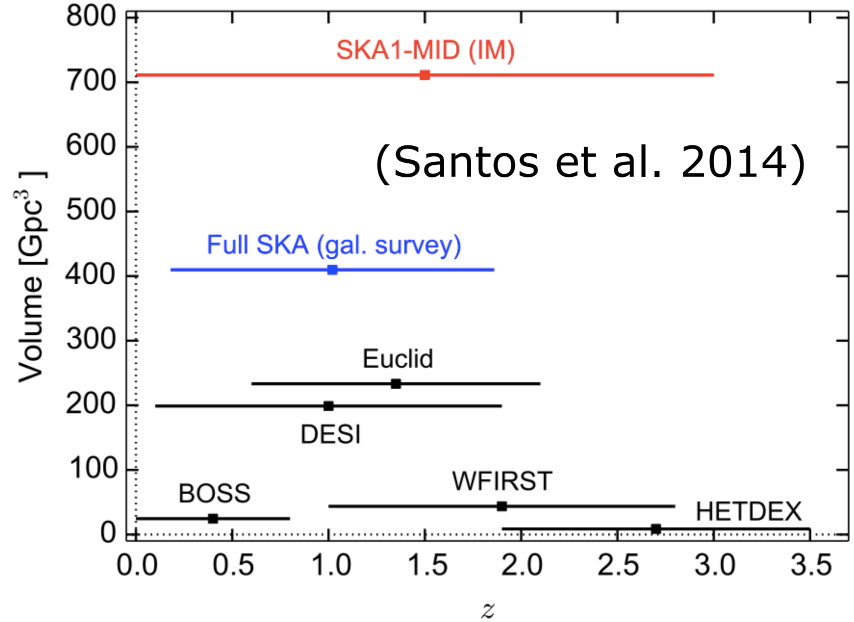
SKA1 data product sizes



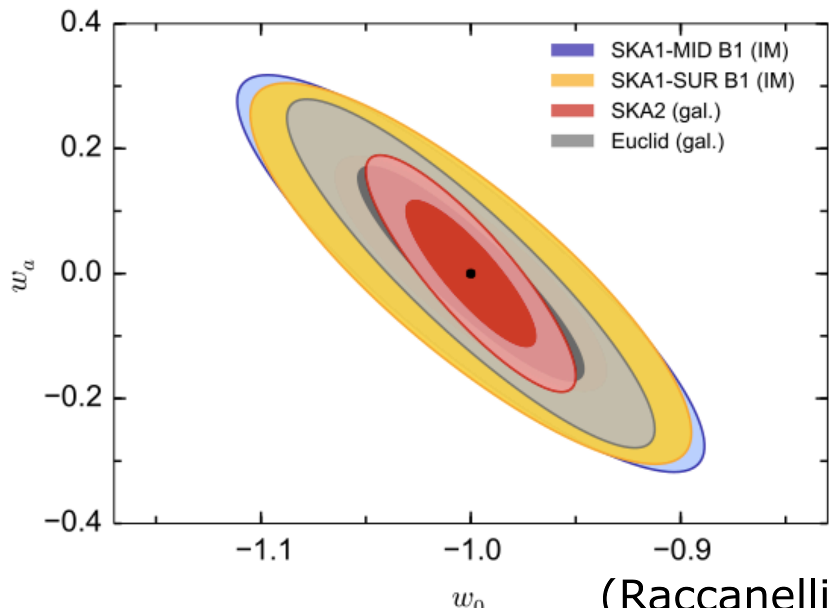
outlook to SKA constraints

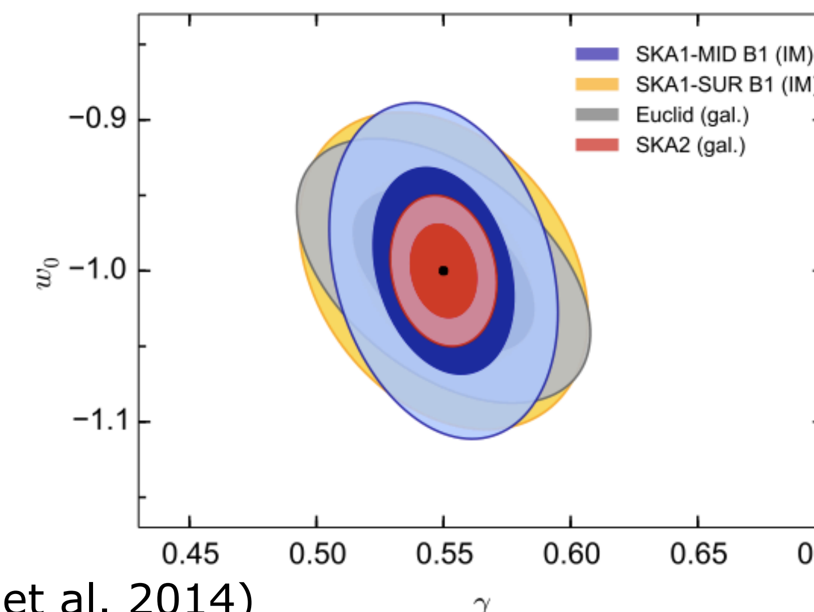


(Bull et al. 2014)



(Santos et al. 2014)





(Raccanelli et al. 2014)


Thank you