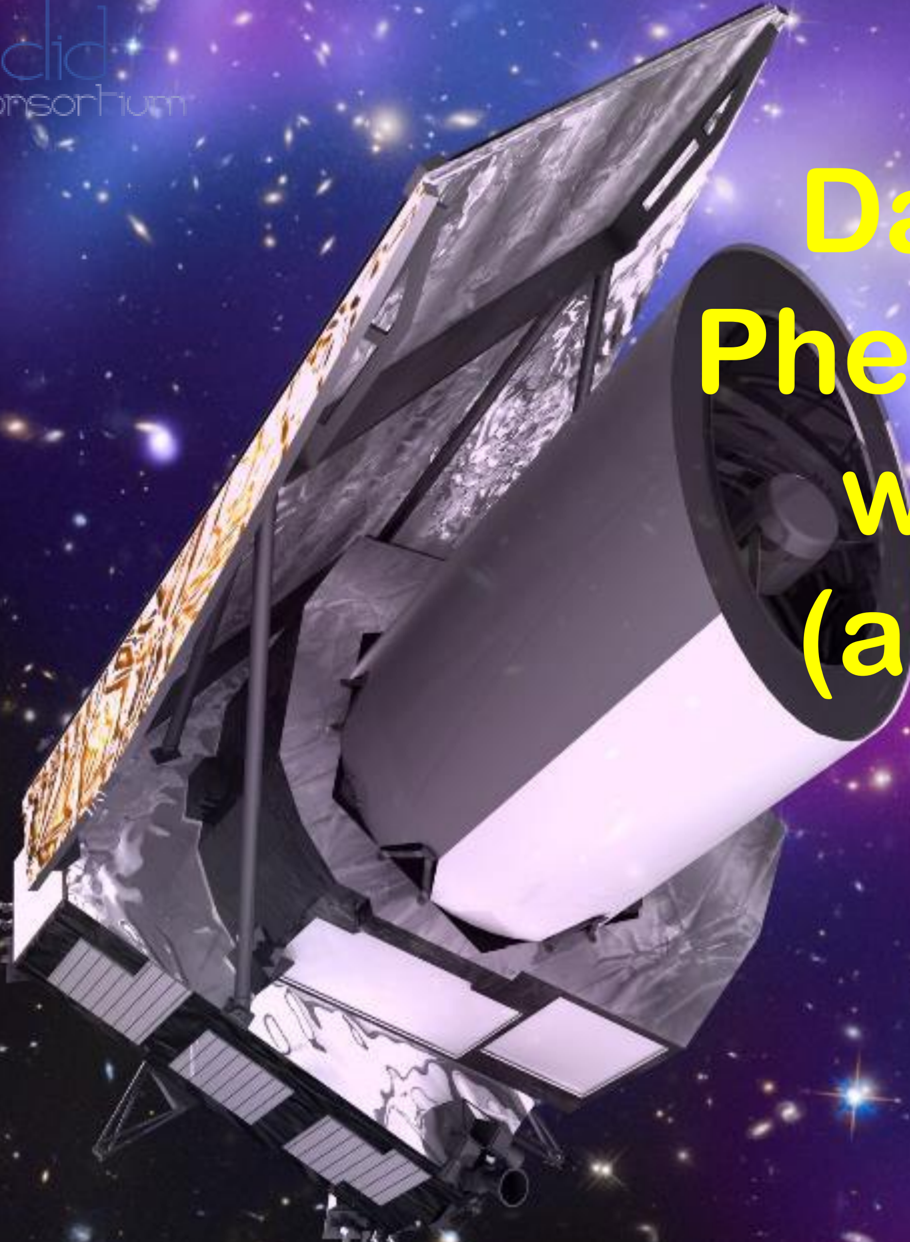
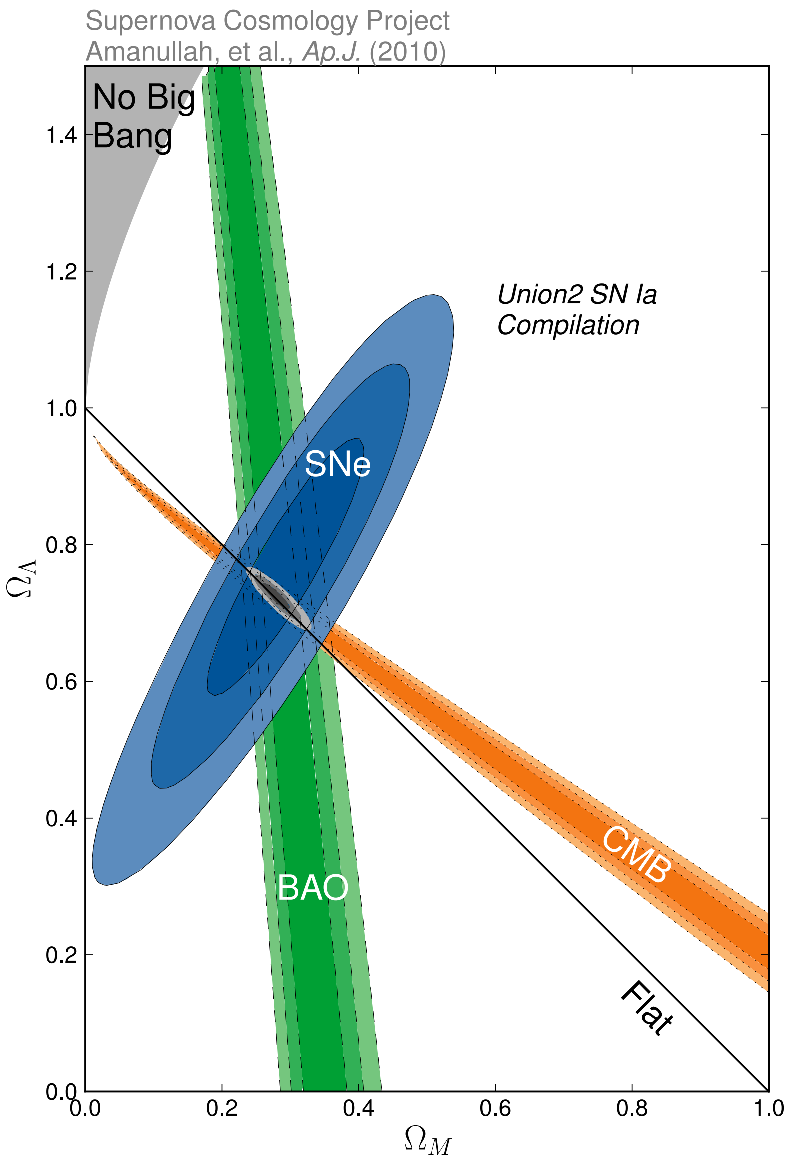


Dark Energy Phenomenology with Euclid (and Planck)

Martin Kunz
University of Geneva

Dark Energy



Physics Nobel prize 2011:

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

accelerating expansion: w < -1/3

- we know that for Λ: w = -1
- data is consistent with Λ
- Λ is unique natural extension (Lovelock) – should be there

why look elsewhere?

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')

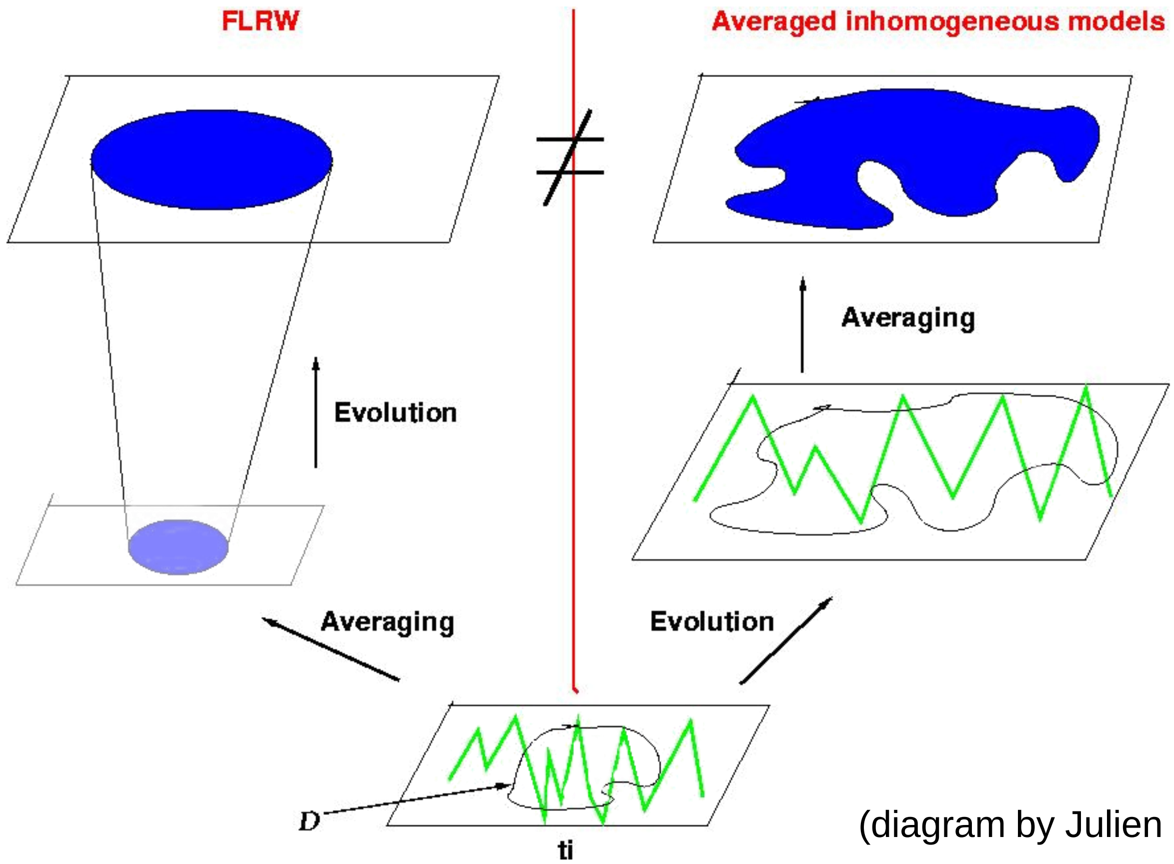
LTB and Backreaction

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.

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.:

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

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

if this is positive then
it looks like dark energy!

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

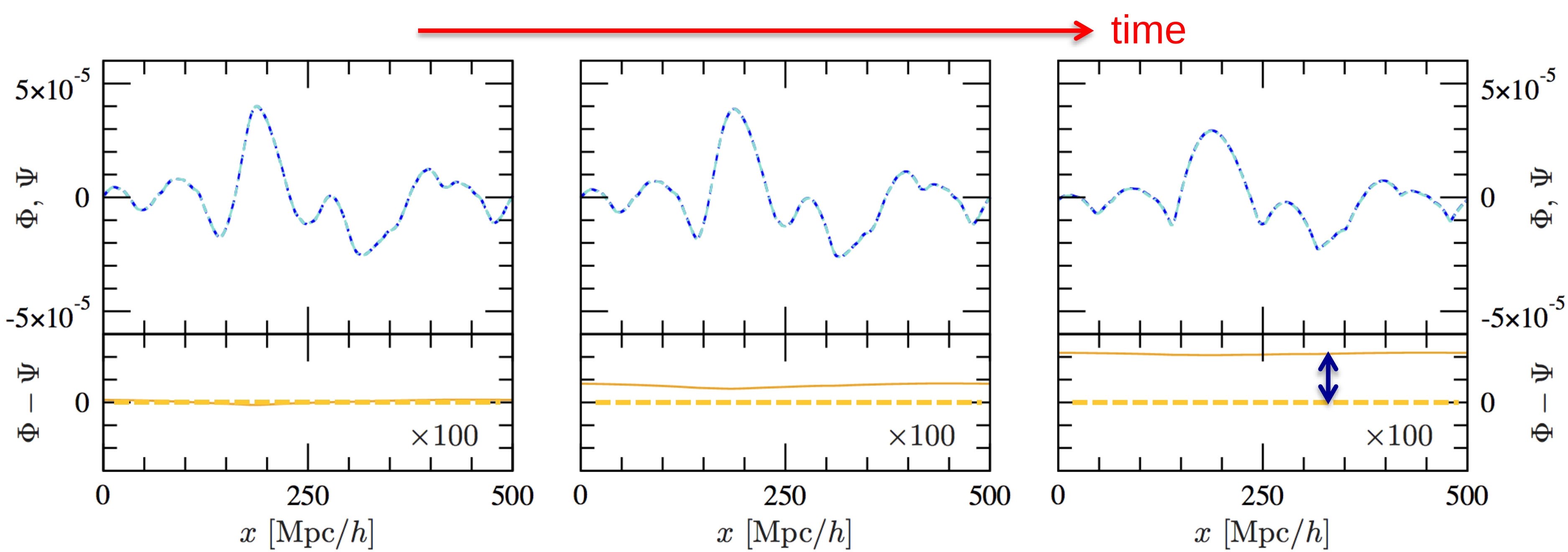
- $<\rho> \sim a^{-3}$
- looks like Friedmann eqs., but with extra contribution!

deviation from FLRW background in *gevolution*

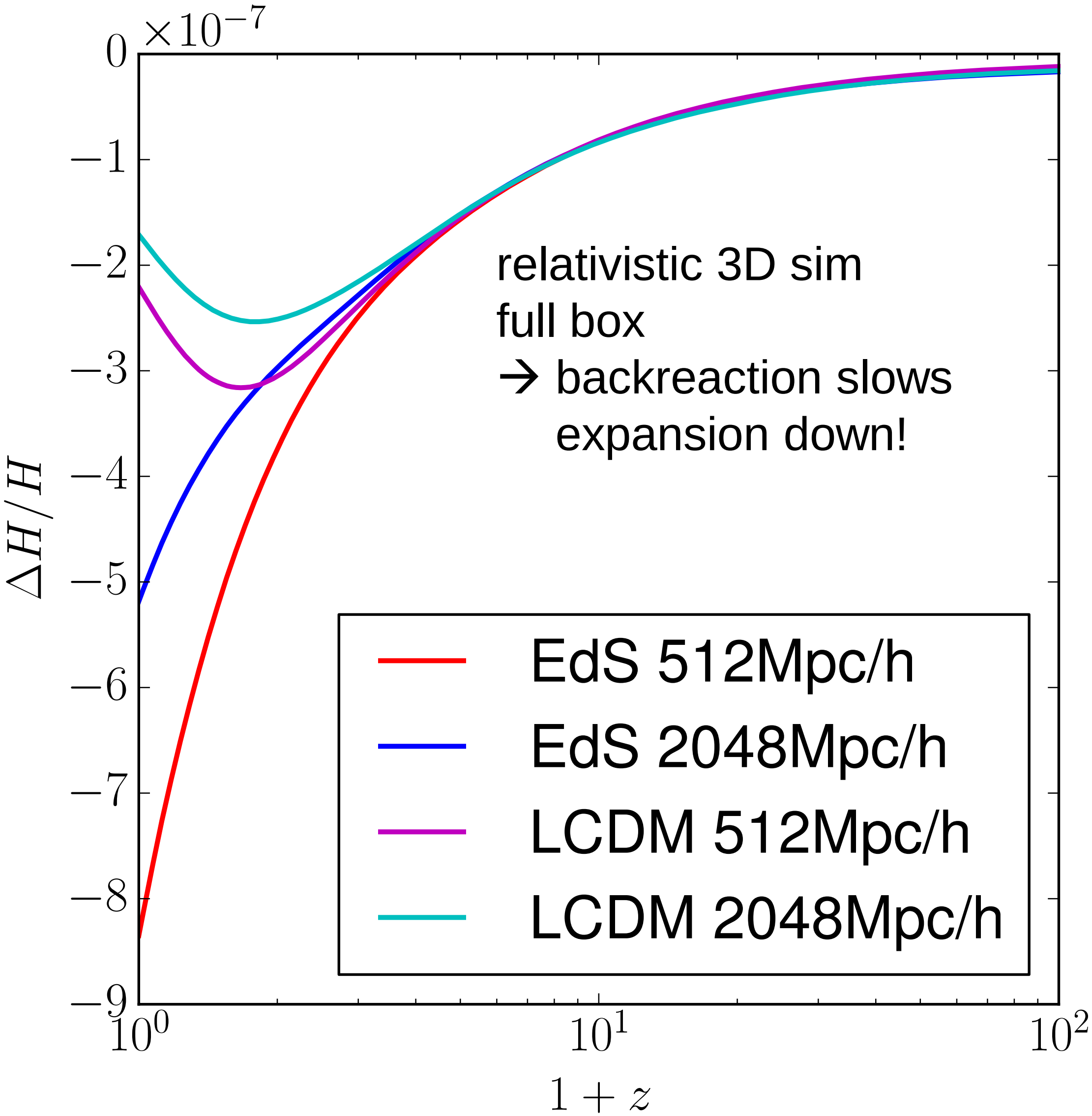
$$\boxed{ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)dx^2}$$

arXiv:1408.2741
arXiv:1604.06065
arXiv:1812.04336

- absorb Ψ zero mode into time redefinition
- interpret Φ zero mode as correction to chosen background evolution a(t)
- can check if background evolves differently than in FLRW → not possible in Newtonian simulations!



'geometric' backreaction



Earlier k_{eq} should increase effect (→ Clarkson & Umeh arXiv:1105.1886)

True at early times, but correction stops increasing when density perturbations go non-linear!

(Perturbation theory diverges there, can't predict what happens)

Is backreaction self-limiting? Can we understand this?

Layzer-Irvine equation & virialization

correction to expansion rate from zero mode: $\mathcal{H} \to \mathcal{H} - \Phi_0' = n^{\mu}_{;\mu}/3$

equation for evolution of zero mode:

$$\boxed{2\Phi_0' + 3\mathcal{H}\Omega_m\Phi_0 = -\mathcal{H}\Omega_m \frac{T+U}{M}}$$

(In a 'Newtonian interpretation', using $2T = \Sigma m_i v_i^2$ and $2U = \Sigma m_i \psi(x_i)$)

Newtonian gravity:

Layzer-Irvine equation $T' + U' + \mathcal{H}\left(2T + U\right) = 0$

virialization: 2T = -U

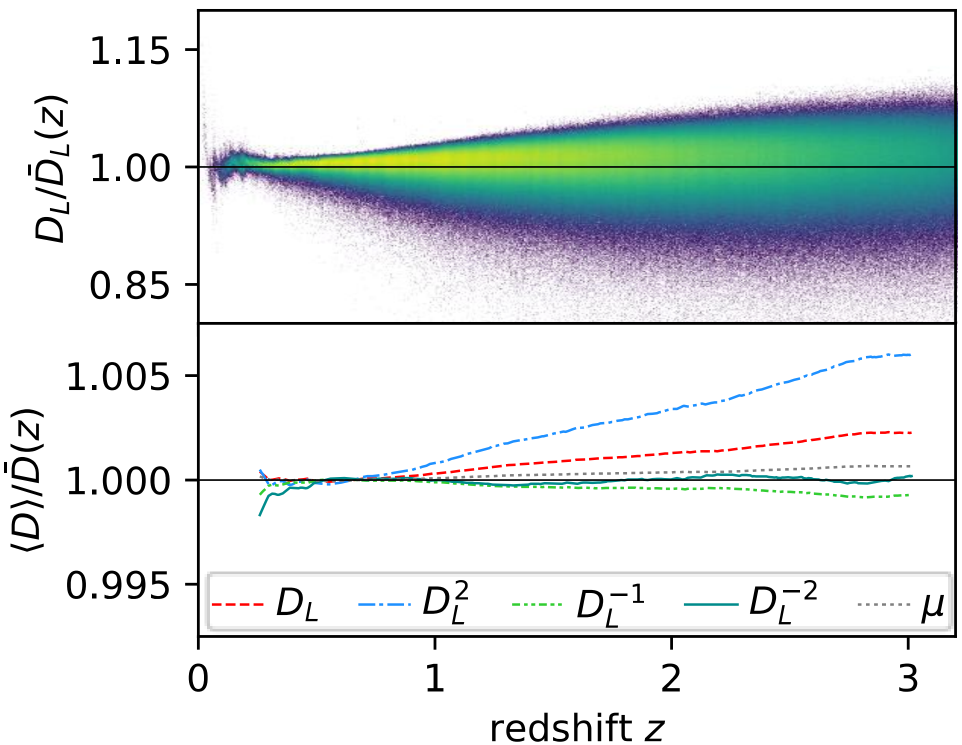
→ zero mode approaches a constant value $\boxed{\Phi_0 \;\to\; -(T+U)/(3M)}$

→ correction to expansion rate goes to zero in the virial limit! $\Delta\mathcal{H} \;=\; -\Phi_0'$

Nice… but is this relevant? In the end, need to consider ***observations***!

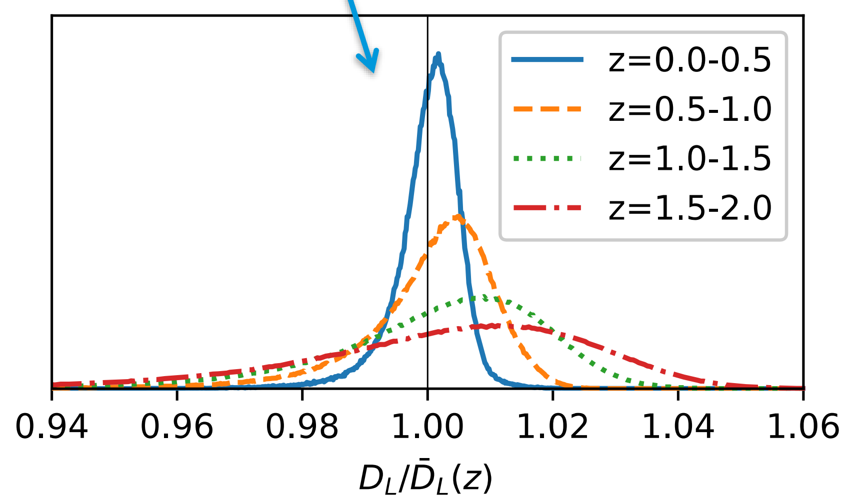
gevolution light-cone simulations

- relativistic N-body simulation from gevolution
- $4.5\text{x}10^{11}$ ‘particles’ in volume of $(2.4 \text{ Gpc/h})^3$, $2.6\text{x}10^9$ $M_{\odot}$/h per particle
- metric sampled on Cartesian 7680^3 grid [resolution 312.5 kpc/h]
- light-cone saved for circular 450 deg^2 beam to distance 4.5 Gpc/h
- ray-traced with exact GR Sachs equations for scalar sector (and leading order for vector sector, GW neglected)



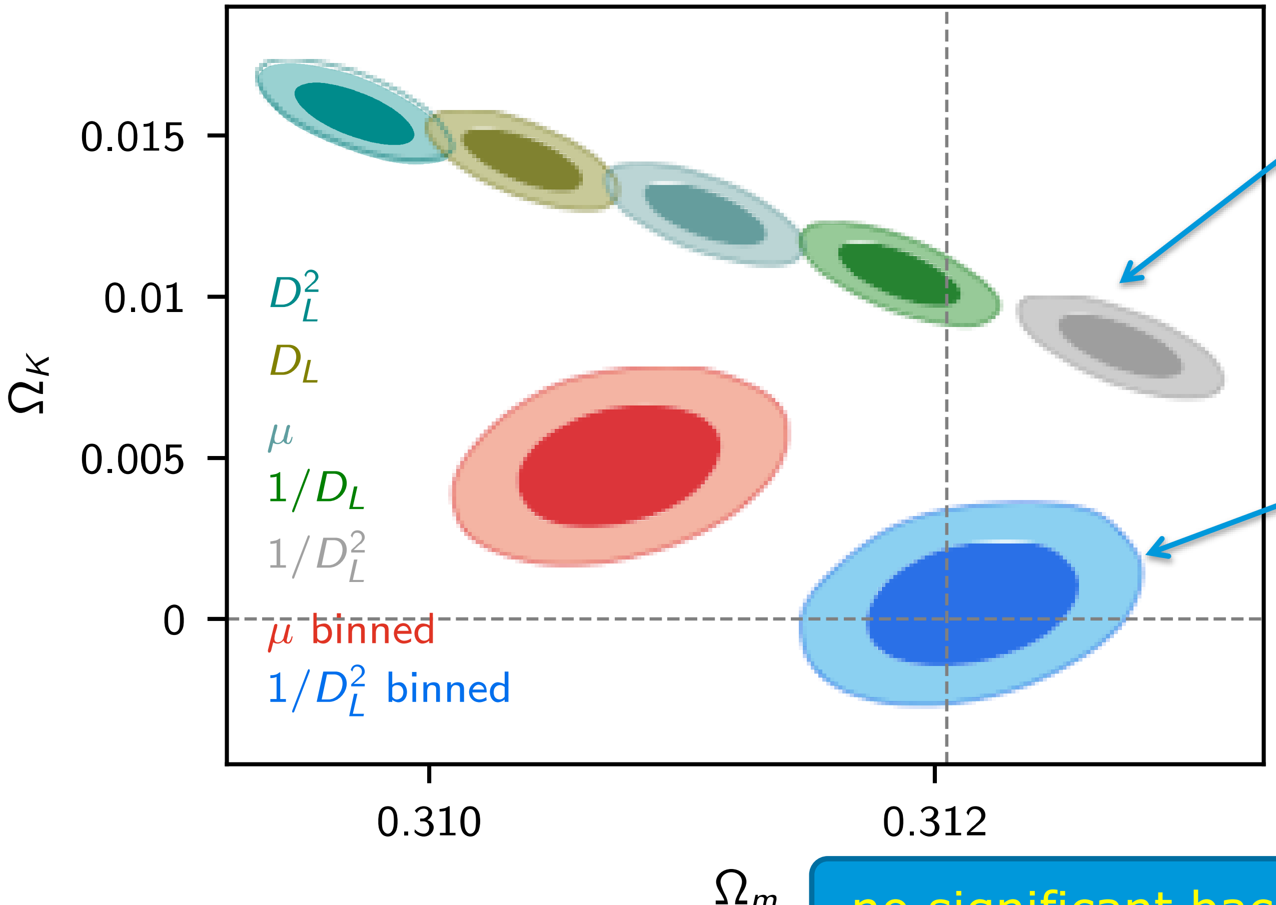
distances for 11M halos

pdf (mostly lensing)



how important is ‘generalized backreaction’ for supernovae?

analysing a ‘super-supernova’ sample with ~500k standard candles assuming standard Gaussian likelihood:



small shifts, mostly due to pdf not being Gaussian

shifts can be reduced/ removed by

- binning in redshift (gaussianizing pdf)
- using $1/D_L^2$

(of course better to use full info!)

no significant backreaction on distances

Possible explanations

1. It is a cosmological constant, and there is no problem (‘anthropic principle’, ‘string landscape’) – unsatisfactory but agrees with data

2. The (supernova) data is wrong – unlikely [?]

3. We are making a mistake with GR (aka ‘backreaction’) or the Copernican principle is violated (‘LTB’) – unlikely [?]

4. It is something evolving, e.g. a scalar field (‘dark energy’)

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

why bother?

- we should test assumptions
- problems of Λ
- we saw a kind of DE before

Euclid science requirements doc

Table 1: Euclid Primary Science Objectives – see RD10 for a full description.

Sector	Euclid Targets
Dark Energy	• Measure the cosmic expansion history to better than 10% for several redshift bins from $z = 0.7$ to $z = 2$. • Look for deviations from $w = -1$, indicating a dynamical dark energy. • Euclid *alone* to give $FoM_{DE} \geq 400$ (roughly corresponding to 1-sigma errors on w_p, & w_a of 0.02 and 0.1 respectively)
Test of Gravity	• Measure the growth index, γ, to a precision better than 0.02 • Measure the growth rate to better than 0.05 for several redshift bins between $z = 0.5$ and $z = 2$ • Separately constrain the two relativistic potentials φ and ψ • Test the cosmological principle
Dark Matter	• Detect dark matter halos on a mass scale between 10^8 and $>10^{15}$ M_{Sun} • Measure the dark matter mass profiles on cluster and galactic scales. • Measure the sum of neutrino masses, the number of neutrino species and the neutrino hierarchy with an accuracy of a few hundredths of an eV
Initial Conditions	• Measure the matter power spectrum on a large range of scales in order to extract values for the parameters σ_8 and n_s to 0.01. • For extended models, improve constraints on n_s and α with respect to Planck alone by a factor 2. • Measure the non-Gaussianity parameter f_{NL} for local-type models with an error better than $\pm$ 2.

a hierarchy of DE modelling

more physical

fundamental action based models

effective field theories (action based)

equivalent fluid description

phenomenological metric parameters

cosmological observations

more general

phenomenology of the dark side

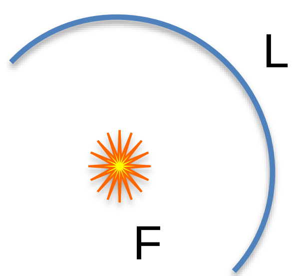
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

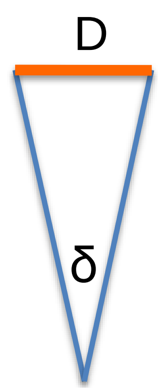
(determined by the metric) → geometry

stuff (what is it?)

your favourite theory

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





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

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

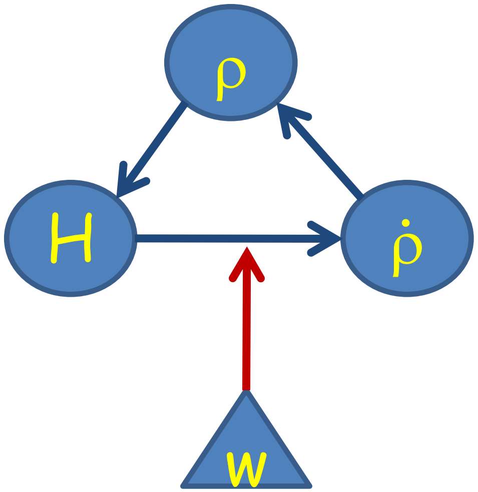
the background case

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

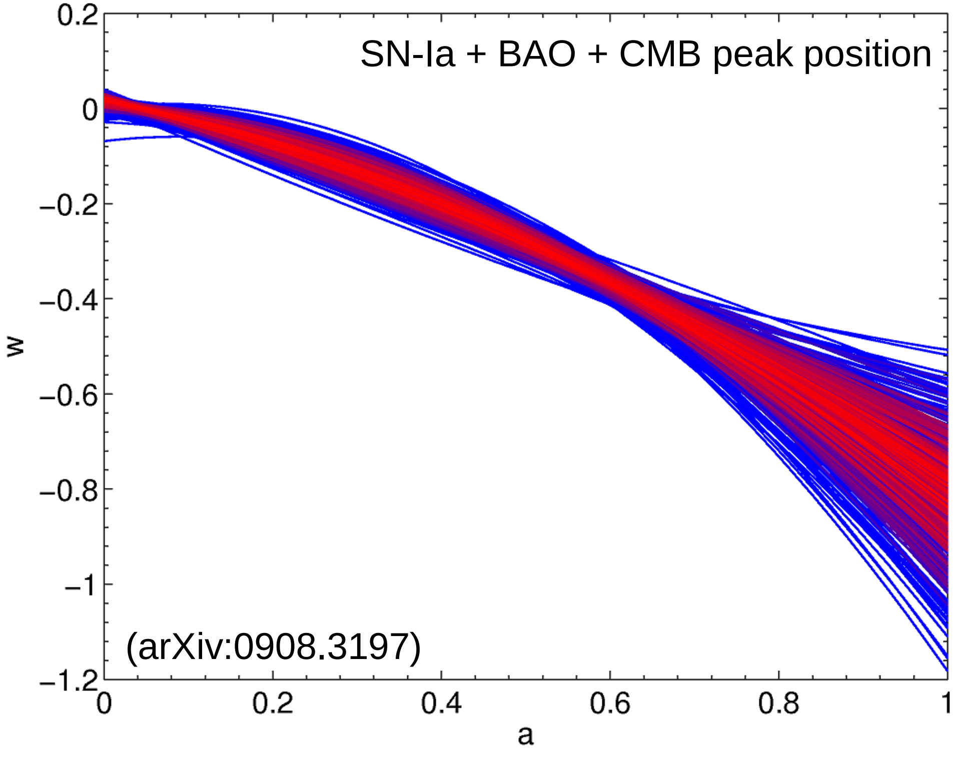


link w(z) ←→ d_L(z)

flat universe: $H^2 = \frac{8\pi G}{3}\rho \quad \dot\rho + 3H(\rho + p) = 0 \quad\quad p = w\rho$

$$\int \frac{d\rho}{\rho} = 3\int (1+w)\frac{da}{a}$$

$$H^2 = H_0^2 \exp\left\{\int_0^z \frac{3(1+w)}{(1+z')}dz'\right\} \quad\quad d_L = (1+z)\int_0^z \frac{du}{H(u)}$$



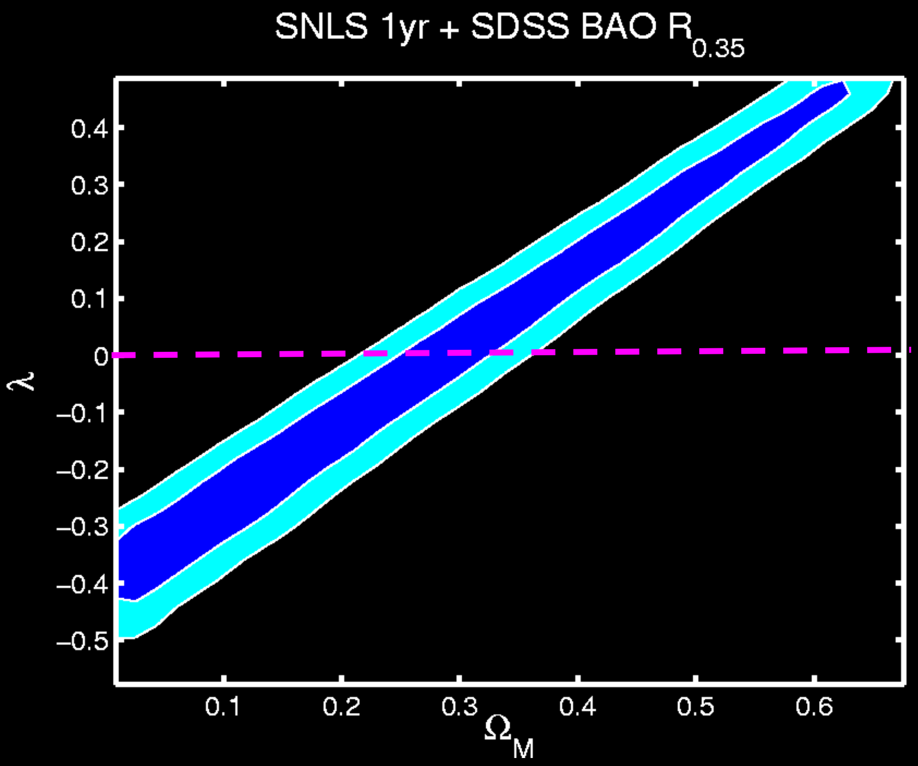
- double integral: strong smoothing
- here for total 'fluid' but can of course include multiple constituents (→ degeneracies)

example:
$w(a) = w_0 + w_1\, a + w_2\, a^2$

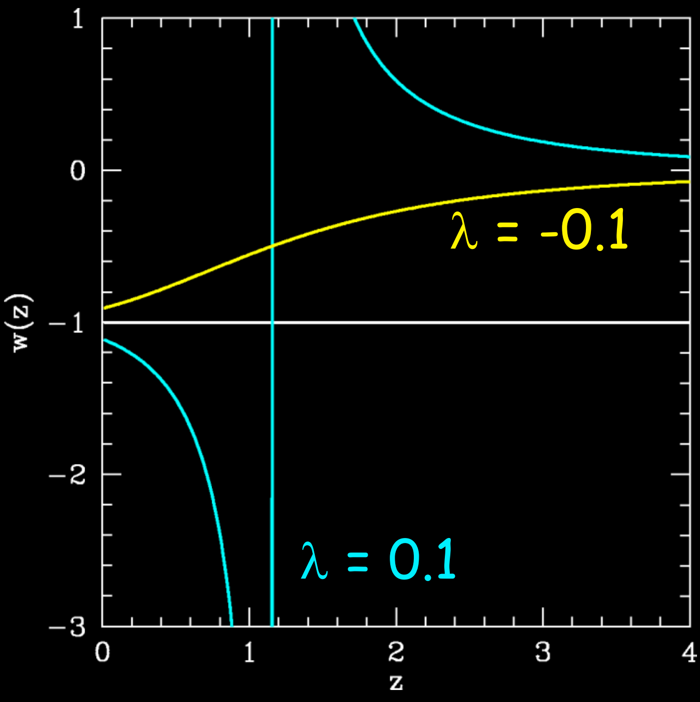
how should one parameterize w(a)?

what are w and Ω_m ?

astro-ph/0702615



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



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

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

reminder: perturbation theory

basic method:

- set $g_{\mu\nu} = \bar{g}_{\mu\nu} + a^2 h_{\mu\nu}$ $\quad T^{\nu}_{\mu} = \bar{T}^{\nu}_{\mu} + \delta T^{\nu}_{\mu}$
- stick into Einstein and conservation equations
- linearize resulting equation (order 0 : “background evol.”)

$\Rightarrow$ two 4x4 symmetric matrices -> 20 quantities

$\Rightarrow$ we have 4 extra reparametrization d.o.f. -> can eliminate some quantities (“gauge freedom”)

$\Rightarrow$ at linear level, perturbations split into “scalars”, “vectors” and “tensors”, we will mostly consider scalar d.o.f.

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

$\Rightarrow$ do it yourself as an exercise ☺

scalar perturbation equations

Einstein equations:
r.h.s. summed over "stuff" in universe

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

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

δ = δρ/ρ density contrast
V divergence of velocity field

conservation equations:
one set for each type (matter, radiation, DE, …)

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

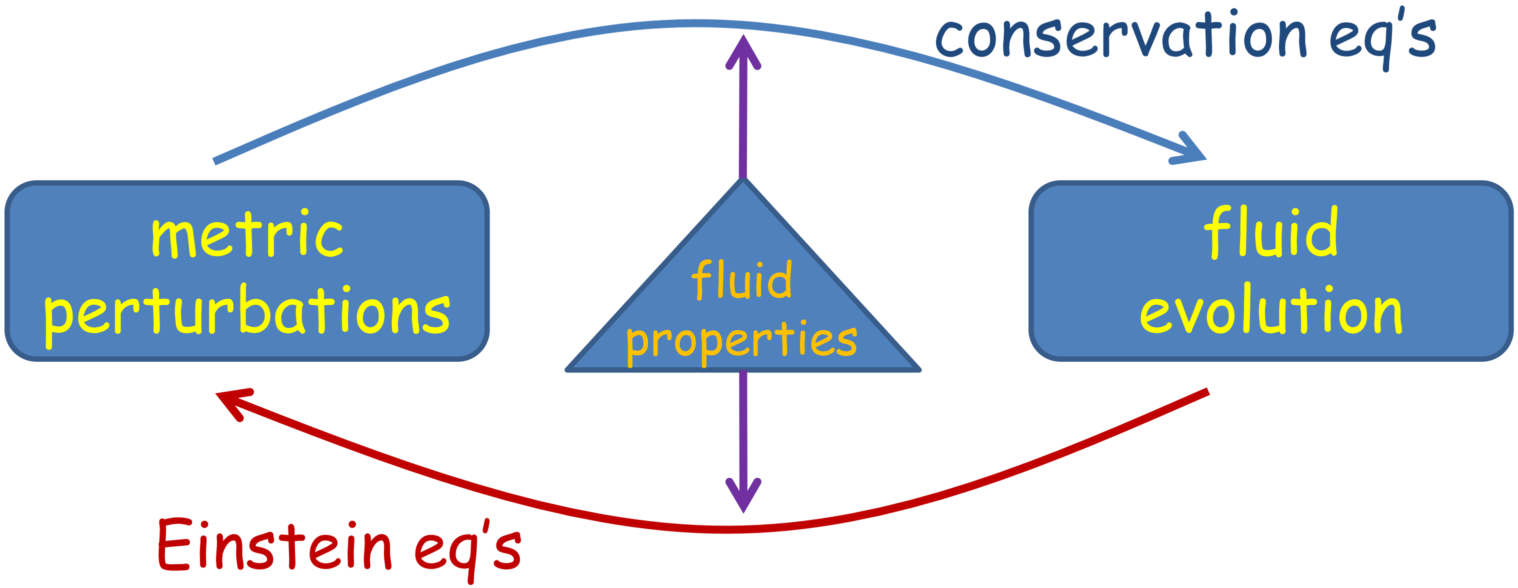
$$V_i' = -(1-3w_i)\frac{V_i}{a} + \frac{k^2}{Ha}\left(\frac{\delta p_i}{\rho_i} + (1+w_i)(\psi - \sigma_i)\right)$$

w, δp, σ: determines physical nature, e.g. cold dark matter: w=δp=σ=0

$$\delta_m' = 3\phi' - \frac{V_m}{Ha^2} \quad V_m' = -\frac{V_m}{a} + \frac{k^2}{Ha}\psi$$

perturbations

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

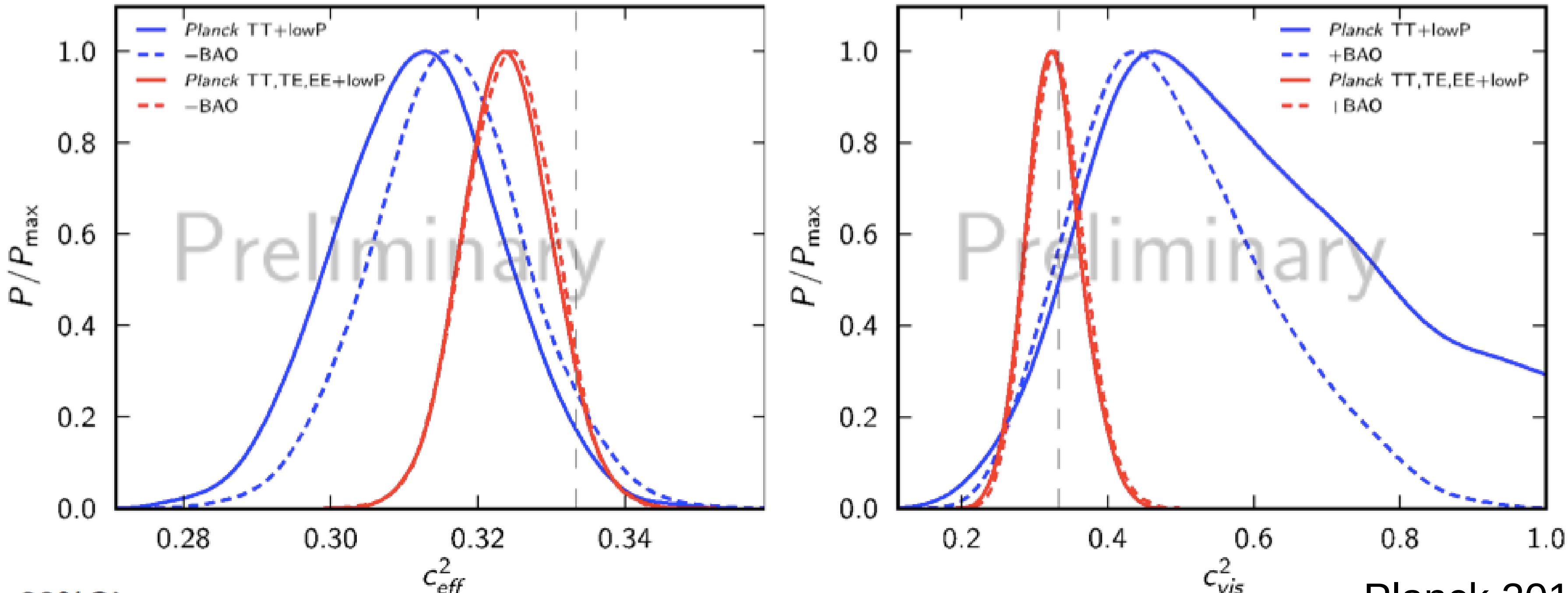


$$k^2\phi = -4\pi G a^2 \sum_i \rho_i \left(\delta_i + 3Ha\frac{V_i}{k^2}\right), k^2(\phi-\psi) = 12\pi G a^2 \sum_i (1+w_i)\rho_i\sigma_i$$

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

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

neutrino properties



Planck 2015

68%CL

Parameter	TT+lowP	TT+lowP+BAO	TT,TE,EE+lowP	TT,TE,EE+lowP+BAO
σ : $c^2_{\rm vis}$	$0.47^{+0.26}_{-0.12}$	$0.44^{+0.15}_{-0.10}$	0.327 ± 0.037	0.331 ± 0.037
δp : $c^2_{\rm eff}$	0.312 ± 0.011	0.316 ± 0.010	0.3240 ± 0.0060	0.3242 ± 0.0059

- significant detection of “neutrino anisotropies”
- compatible with expected values

general dark phenomenology

Does this make sense for 'modified gravity models'?!

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!

Cosmology can measure total effective dark EMT

a hierarchy of DE modelling

more physical

fundamental action based models

effective field theories (action based)

equivalent fluid description

phenomenological metric parameters

cosmological observations

more general

phenomenological parameters

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

a(t)

$\nabla\psi$

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

(velocity field)

(lensing)

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

deviations from "standard clustering":

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

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

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

We expect
μ = 1
η = 1
at low z

Slide from Filippo Vernizzi
AES 2020

Compare to PPN

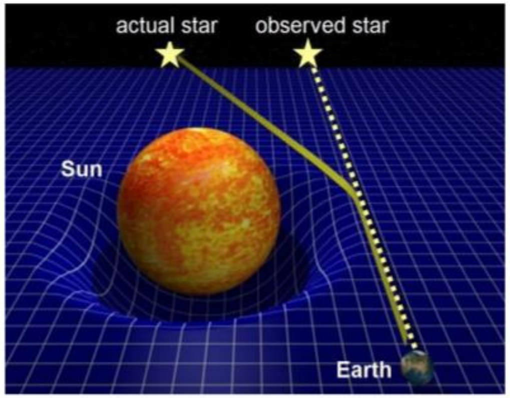
Post-Newtonian Parametrization (PPN): $g_{00} = -(1 + 2\Phi)\,, \qquad g_{ij} = \delta_{ij}\,(1 - 2\Psi)$

slip parameter $\gamma = \Psi/\Phi$ $\qquad \gamma = 1$ is the GR value, $\gamma = 0$ is the Newtonian value

- **Light bending**

$$\theta = 2(1+\gamma)\frac{GM_\odot}{r} = \frac{1+\gamma}{2}\theta_{\rm GR}$$

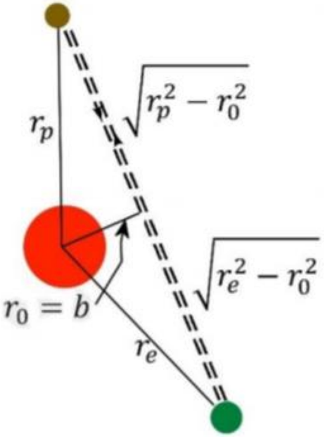
$$\gamma - 1 = (-1.7 \pm 4.5) \times 10^{-4}$$

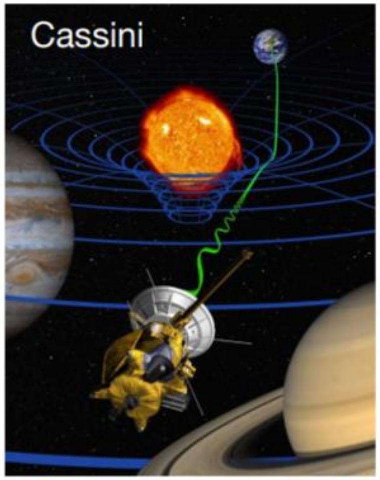


- **Shapiro time-delay**

$$\Delta t = 2(1+\gamma)GM_\odot\left[\ln\left(4\frac{r_p r_e}{r_0}\right) + 1\right]$$

$$\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$$





WARNING -- many conventions:

1. $Q(a, \boldsymbol{k})$, which modifies the relativistic Poisson equation through extra DE clustering according to

$$-k^2\Phi \equiv 4\pi G a^2 Q(a, \boldsymbol{k})\rho\Delta, \tag{3}$$

where Δ is the comoving density perturbation;

2. $\mu(a, \boldsymbol{k})$ (sometimes also called $Y(a, \boldsymbol{k})$), which modifies the equivalent equation for Ψ rather than Φ:

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

3. $\Sigma(a, \boldsymbol{k})$, which modifies lensing (with the lensing/Weyl potential being $\Phi + \Psi$), such that

$$-k^2(\Phi + \Psi) \equiv 8\pi G a^2 \Sigma(a, \boldsymbol{k})\rho\Delta; \tag{5}$$

4. $\eta(a, \boldsymbol{k})$, which reflects the presence of a non-zero anisotropic stress, the difference between Φ and Ψ being equivalently written as a deviation of the ratio[2]

$$\eta(a, \boldsymbol{k}) \equiv \Phi/\Psi. \tag{6}$$

you can pick any two as independent

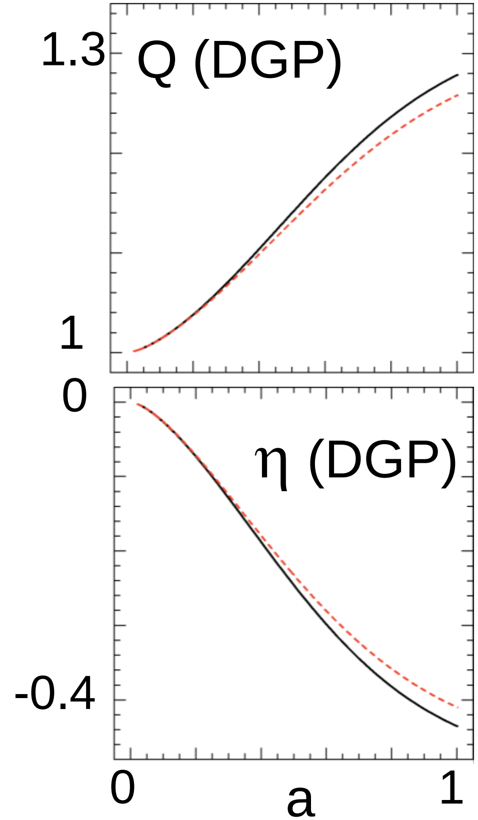
model predictions for pheno

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

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

$$-k^2\Phi = 4\pi G a^2 Q\rho\Delta$$



(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

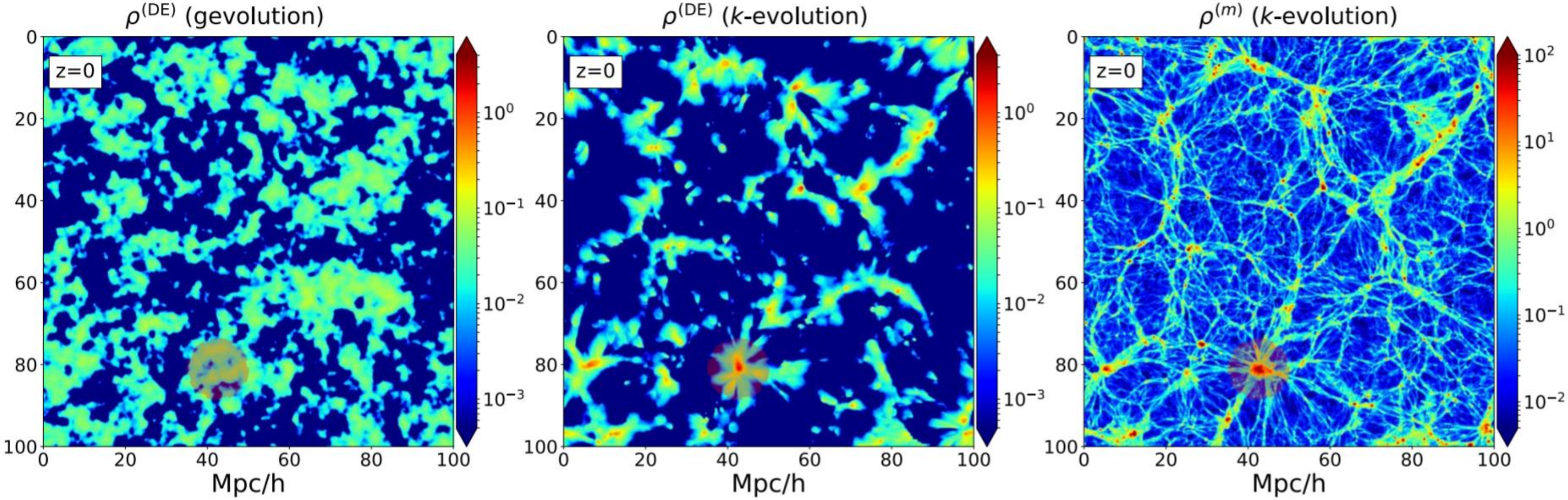
$$\mathcal{L} = F(\varphi)R - \partial_\mu\varphi\partial^\mu\varphi - 2V(\phi) + 16\pi G^*\mathcal{L}_{\text{matter}}$$

$$\eta = \frac{F'^2}{F + F'^2} \qquad Q = \frac{G^*}{FG_0}\frac{2(F + F'^2)}{2F + 3F'^2}$$

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

precision predictions

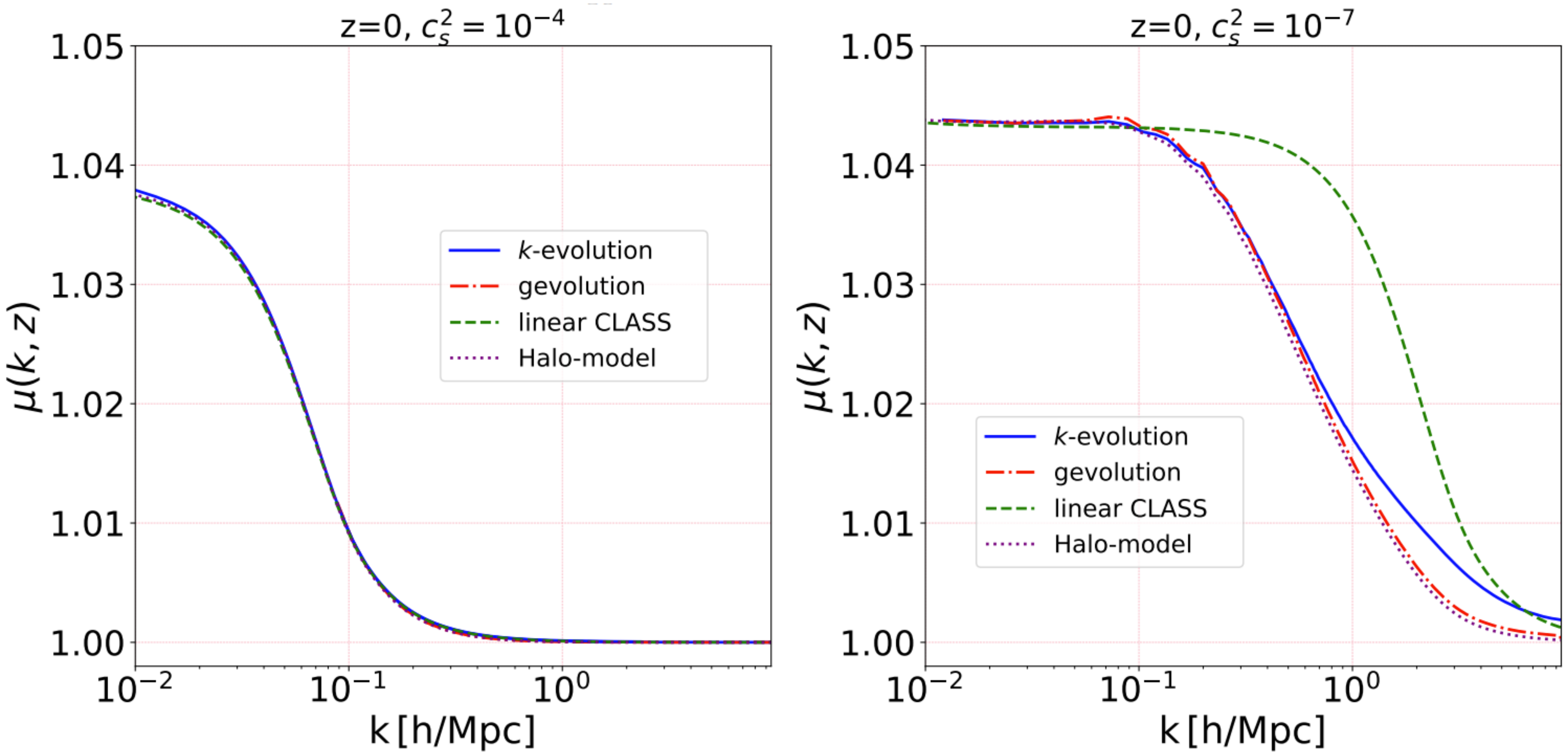
- Analysis of DE/MG models with Euclid will require precise predictions, also on non-linear scales! (Linear Boltzmann code is only starting point)
- But MG models have often a complicated behaviour (scale dependence, screening, …)
- Easiest example: k-essence [here from Hassani et al, arXiv:1910.01104 and arXiv:1910.01105]
    - Dark matter clustering is highly non-linear on small scales
    - Dark energy follows DM outside of its sound horizon
    - Small sound speed: DE clustering can become non-linear too



Non-linear DE clustering

It turns out that in GR the Poisson equation is a good approximation on *all* scales relevant for cosmology, down to milli-parsec!

$$-k^2\Phi = 4\pi G_N a^2 \mu(k,z) \sum \bar{\rho}_X \Delta_X \qquad \Delta_X = \delta_X - 3\mathcal{H}(1+w_X)\nabla^{-2}\theta_{\mathrm{tot}}$$



(Possibly even more exciting: in higher-order EFT calculations an instability is hiding for low sound speeds…)

general idea

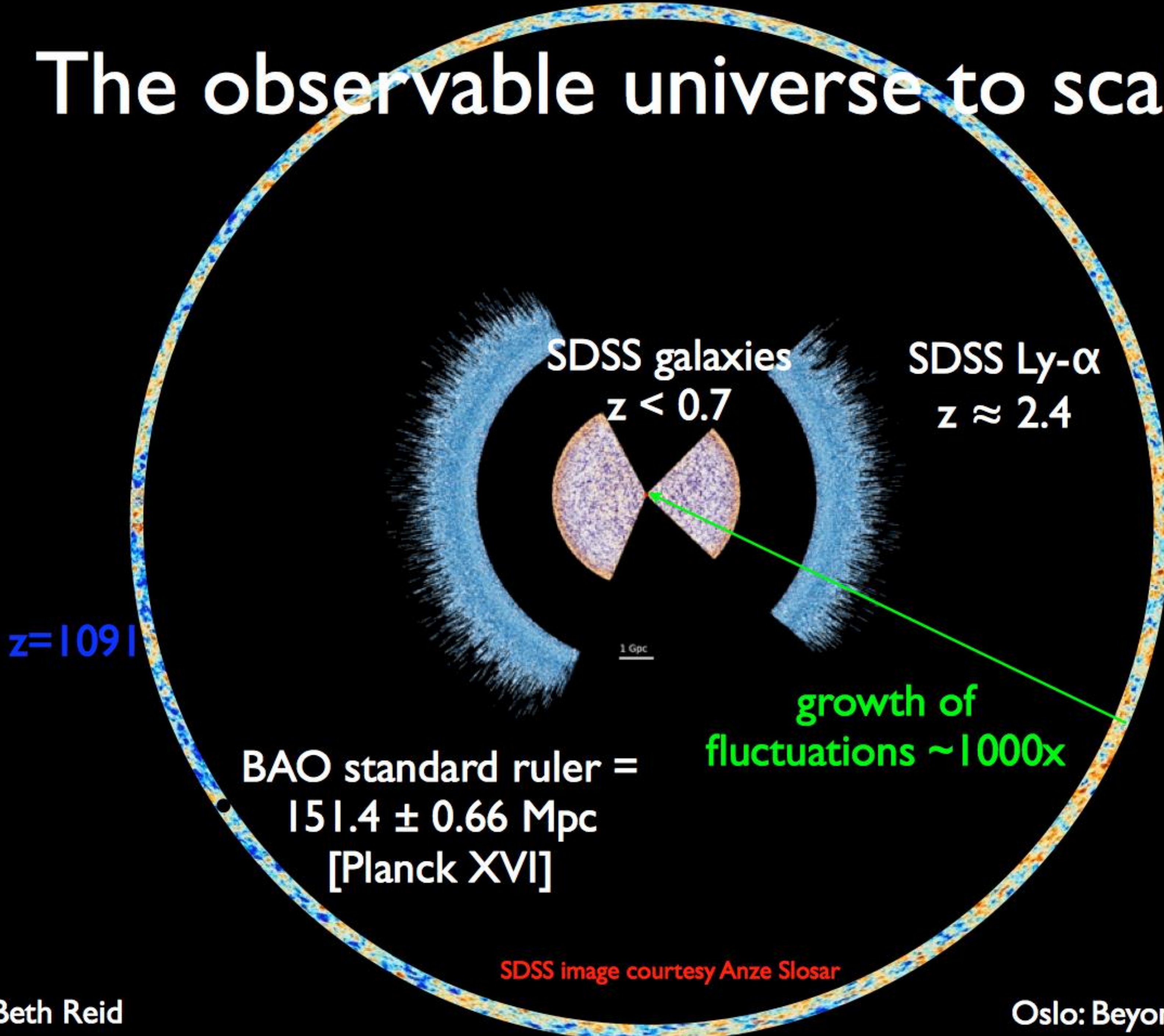
- We want to probe expansion rate and clustering properties (2 grav. potentials ϕ, ψ)
- H(z) : BAO directly (and most other probes)
- Lensing probes $\phi + \psi$
- Velocity / RSD probe ψ
- The Euclid primary probes provide all of these, but there also others (eg. clusters, SL)
- 30 million spectra (RSD, BAO) and 1.5 billion photo-z/shapes (weak lensing, BAO)

DE/MG constraints w/ current data

(Planck 2015 paper XIV, 2018 paper VI)

- **Planck CMB data** (temperature + polarization)
- **'background'** (BSH): constrain **$H(z) \leftrightarrow w(z)$**
  - supernovae: JLA (2015) / Pantheon (2018)
  - Baryon acoustic oscillations (BAO) 2018: BOSS DR12 consensus, SDSS-MGS, 6dFGS
  - H_0: not used in 2018
- **redshift space distortions** (BAO/RSD)
  - sensitive to velocities from gravitational infall
  - acceleration of test-particles (galaxies) come from **grad $\psi \sim \mu$**
  - usually given as limit on $f\sigma_8$ (continuity eq.)
  - 2018: we use BOSS DR12 consensus
- **gravitational lensing** (WL and CMB lensing)
  - deflection of light governed by **$\varphi+\psi \sim \Sigma$**
  - galaxy weak lensing: CFHTLenS (2015) / DES (2018)
  - CMB lensing: lensing of Planck CMB map
    - extracted from map trispectrum
    - power spectrum is also lensed!

The observable universe to scale*



effective field theory of DE

→ lots of parameters: $\alpha_M(t)$, $\alpha_T(t)$, $\alpha_K(t)$, $\alpha_B(t)$, $\alpha_H(t)$ and $H(t)$

→ action also predicts equation for gravitational waves

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

→ joint GW / counterpart observation: $c_T = c$! → $\alpha_T = 0$ [at least today]

→ further `naturalness' constraints: $\alpha_M = -\alpha_B$ or `non-MG dark energy'

→ `beyond-Horndeski' constrained by astrophysical tests → $\alpha_H = 0$

→ sound speed not strongly constrained, pick convenient α_K

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

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

H(t) : LCDM background

$\alpha_T = \alpha_H = 0$, α_M, α_B, $\alpha_K = f(\Omega)$

→ **non-minimally coupled *k*-essence model**

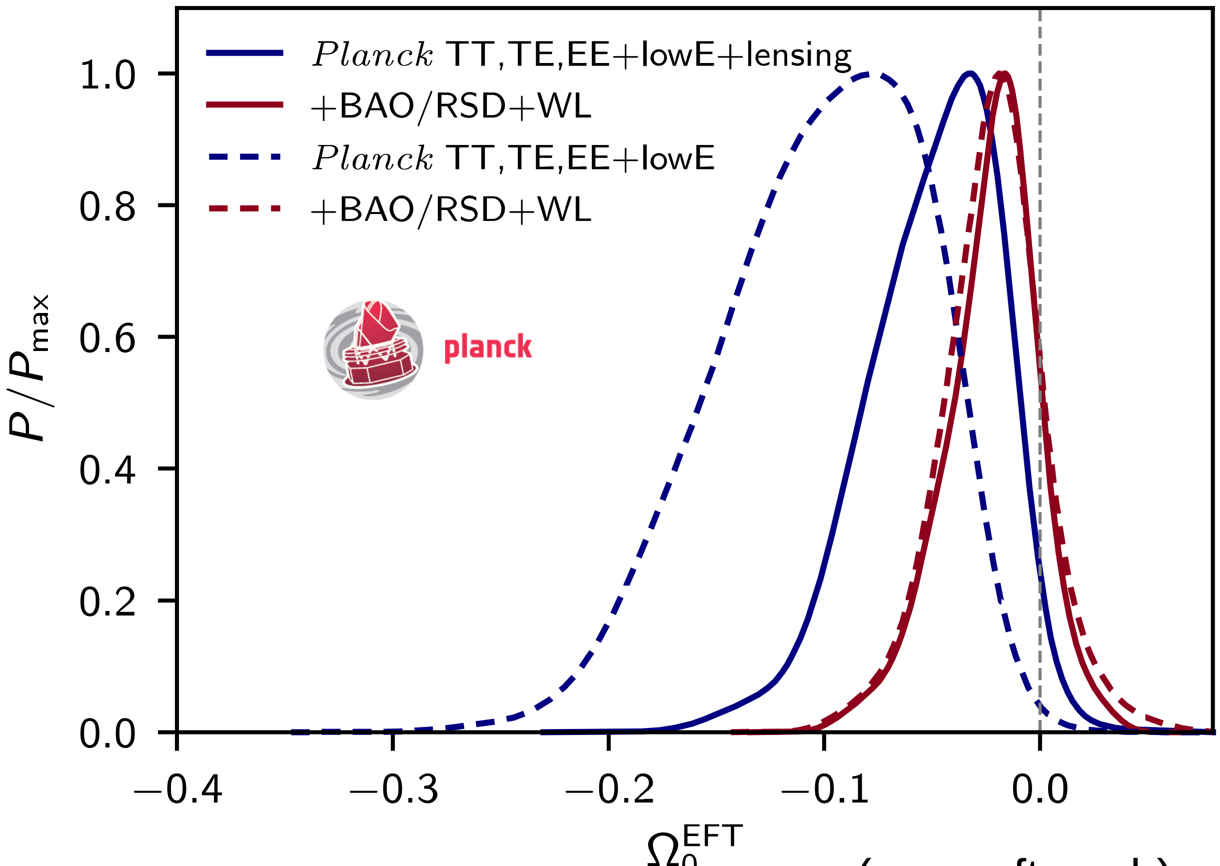
(same as 2015)

EFT of DE (2018)

→ non-minimally coupled *k*-essence model

$$\Omega^{\mathrm{EFT}}(a) = \exp\left\{\frac{\alpha_{M0}}{\beta}a^{\beta}\right\} - 1 = \exp\left\{\Omega_0^{\mathrm{EFT}}a^{\beta}\right\} - 1$$

- marginalized over $\beta > 0$
- we allow $\Omega_0 < 0$
- Planck alone: $\Delta\chi^2 \sim 10$
- lensing (CMB or WL) pushes posterior back to ΛCDM ($\Omega_0 = 0$), $\Delta\chi^2 \sim 2$ - 3
- preference for $\Omega_0 < 0$ degenerate with A_L>1



(uses eftcamb)

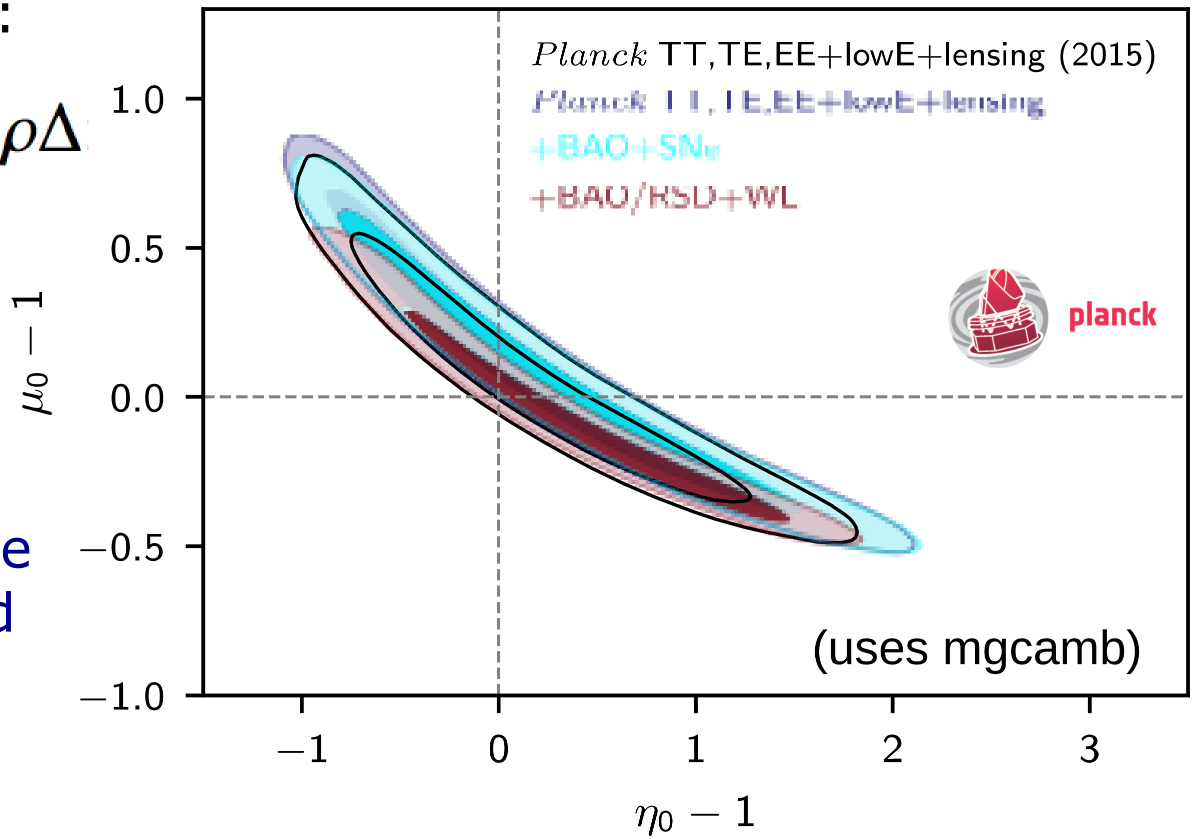
phenomenological approach (2018)

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

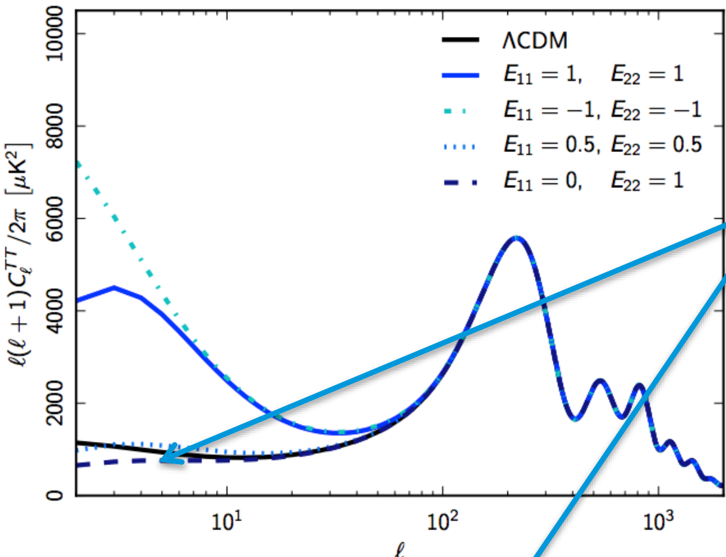


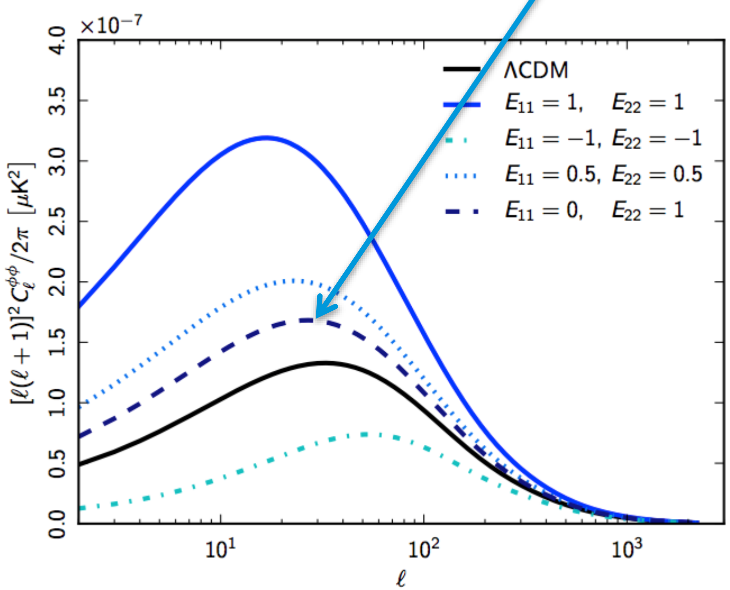
- no scale dependence used (data not good enough)
- deviation driven by CMB, deg. w/ A_L

$\Delta\chi^2$ = -11: Planck + BAO/SNe – similar to EFT

$\Delta\chi^2$ ~ -1: Planck + (lensing) + BAO/RSD + WL

MG impact on observables (2015)



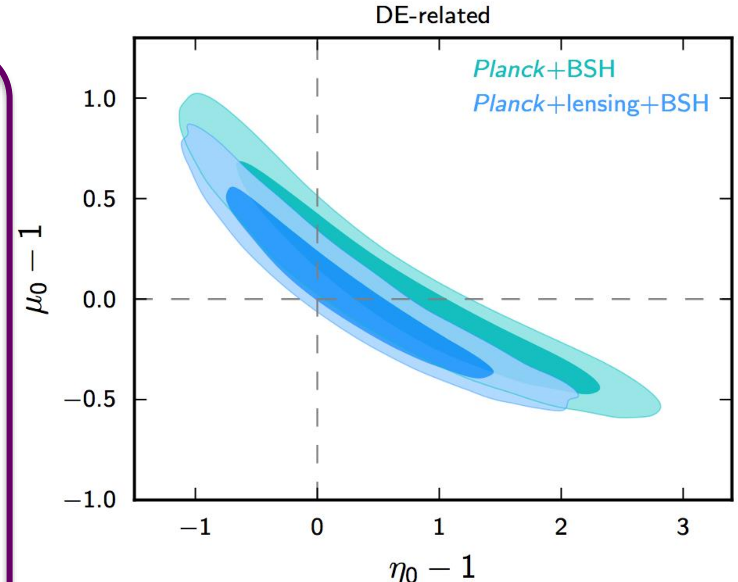


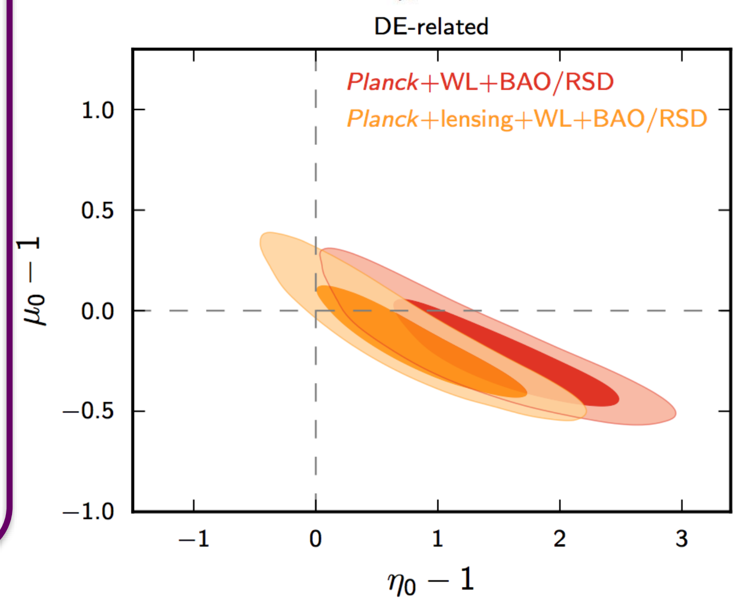
best-fit model is similar to -- model

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

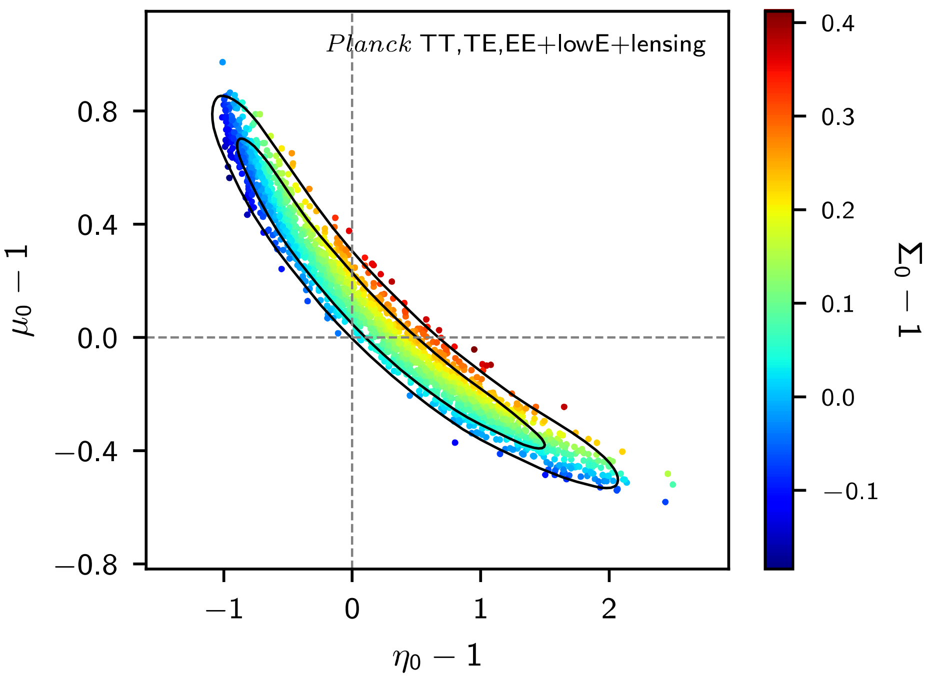
BUT NOT in the 4-point lensing → CMB lensing prefers LCDM!

→ doesn't look very significant after all?



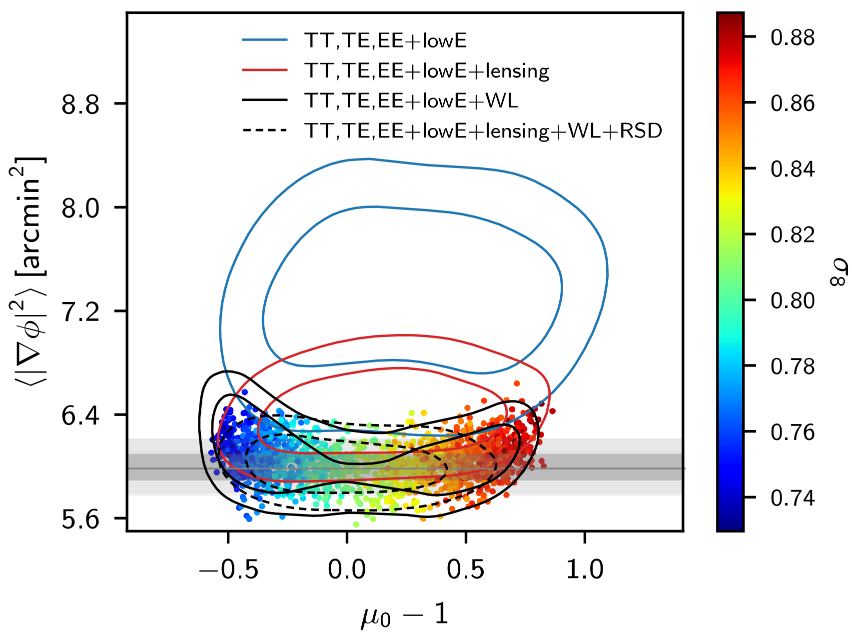


lensing and MG



We see that 'lensing modification' Σ varies in direction orthogonal to banana
→ `tension' is lensing related?

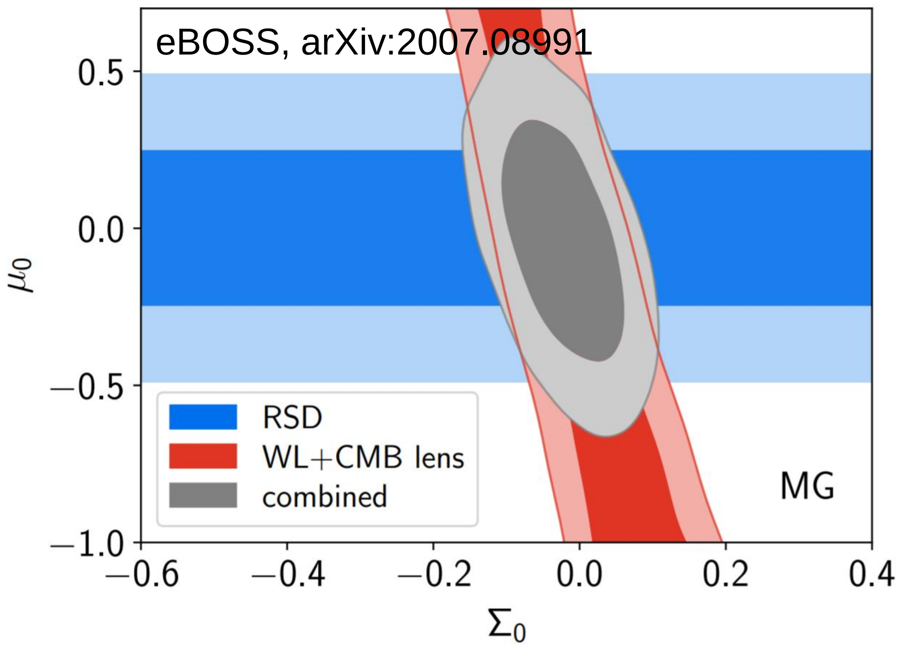
(plots by Antony Lewis and Matteo Martinelli)



Similar conclusions:

- Planck likes higher lensing
- WL and CMB lensing pull it down
- BAO/RSD shrink μ uncertainty a bit

Cosmology vs PPN



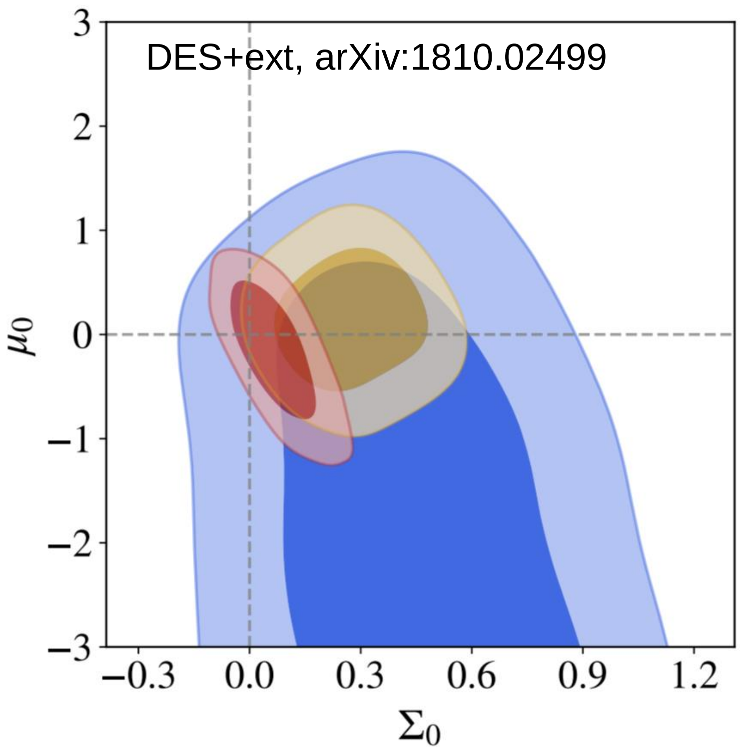


Table 4: Current limits on the PPN parameters.

Parameter	Effect	Limit	Remarks
$\gamma - 1$	time delay	2.3×10^{-5}	Cassini tracking
	light deflection	2×10^{-4}	VLBI
$\beta - 1$	perihelion shift	8×10^{-5}	$J_{2\odot} = (2.2 \pm 0.1) \times 10^{-7}$
	Nordtvedt effect	2.3×10^{-4}	$\eta_N = 4\beta - \gamma - 3$ assumed
ξ	spin precession	4×10^{-9}	millisecond pulsars
α_1	orbital polarization	10^{-4}	Lunar laser ranging
		7×10^{-5}	PSR J1738+0333
α_2	spin precession	2×10^{-9}	millisecond pulsars
α_3	pulsar acceleration	4×10^{-20}	pulsar $\dot{P}$ statistics
ζ_1	—	2×10^{-2}	combined PPN bounds
ζ_2	binary acceleration	4×10^{-5}	$\ddot{P}_p$ for PSR 1913+16
ζ_3	Newton's 3rd law	10^{-8}	lunar acceleration
ζ_4	—	—	not independent (see Eq. (71))

- Σ: (Φ+Ψ) → lensing
  Limit: ~ 0.05
- μ: Ψ → acceleration of massive particles
  Limit: ~ 0.25

Clifford Will, LRR, arXiv:1403.7377

Euclid MG forecasts
(Casas et al, 2017)

- forecasts for Euclid (Redbook) WL and GC
- phenomenological DE model

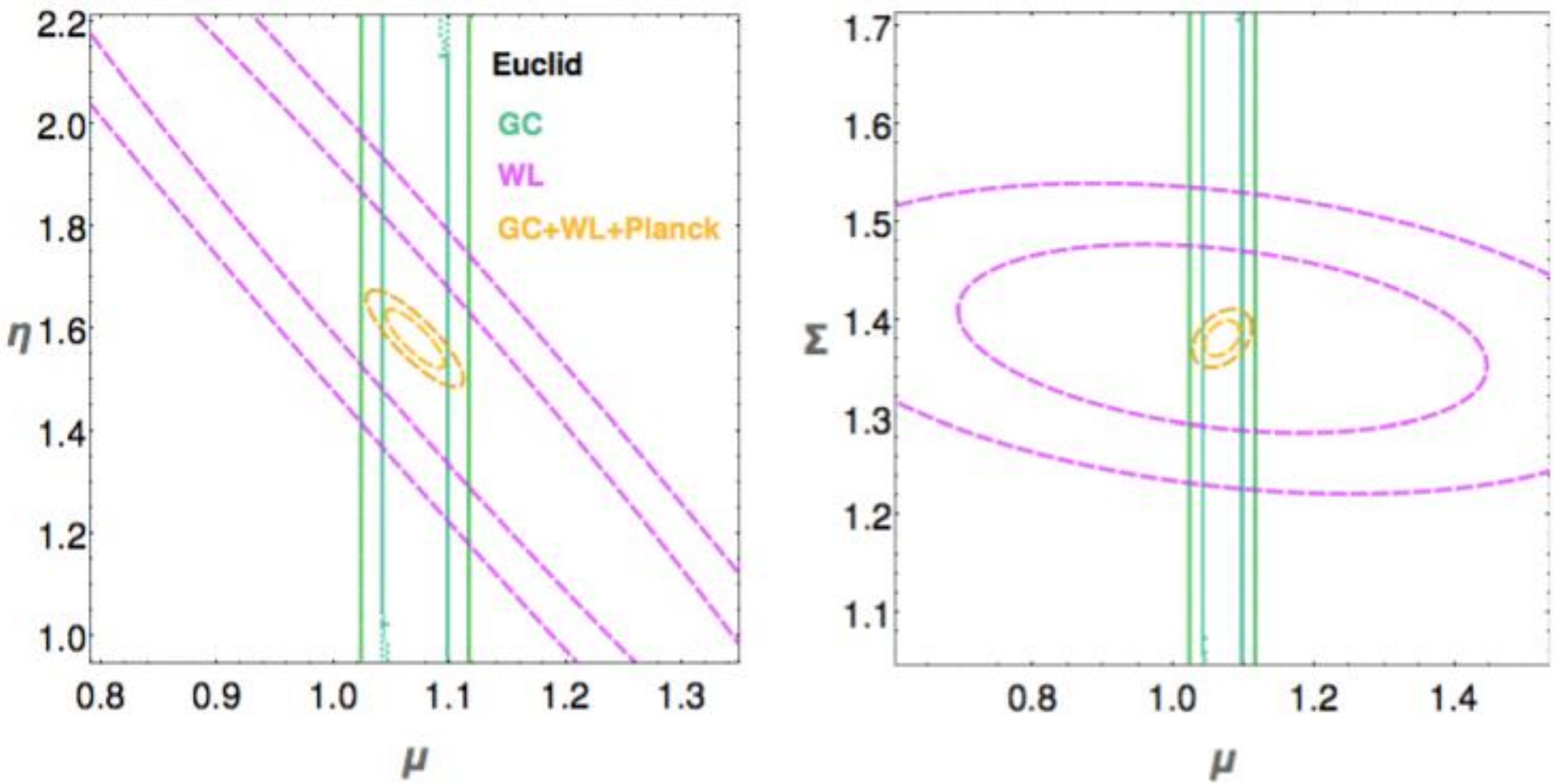
$$-k^2\Psi(a,k) \equiv 4\pi G a^2 \mu(a,k)\rho(a)\Delta(a,k)$$
$$\eta(a,k) \equiv \Phi(a,k)/\Psi(a,k) \quad .$$

- functions in bins (w/ PCA) or proportional to $\Omega_{DE}(a)$
- background is ΛCDM
- nonlinear treatment: interpolate between 'MG' and ΛCDM (both with halofit applied) based on $k^3P(k)$, to mimic screening
- we also included a Planck 'prior'

Euclid (Redbook)	Ω_c	Ω_b	n_s	$\ell\mathcal{A}_s$	h	μ	η	Σ	MG FoM
Fiducial	0.254	0.048	0.969	3.060	0.682	1.042	1.719	1.416	relative
GC(lin)	1.9%	6.4%	3%	2.8%	4.5%	17.1%	1030%	641%	0
GC(nl-HS)	0.9%	2.5%	1.3%	0.8%	1.7%	1.7%	475%	291%	2.9
GC(nl-HS)+*Planck*	0.7%	0.6%	0.3%	0.2%	0.3%	1.7%	16.8%	10.3%	6.3
WL(lin)	7.8%	25.7%	9.9%	10.3%	19.1%	58.2%	106%	9.3%	3.2
WL(nl-HS)	6.3%	20.7%	4.6%	5.8%	13.8%	23.3%	40.9%	4.6%	4.5
WL(nl-HS)+*Planck*	2.1%	1.1%	0.4%	0.7%	0.7%	11.8%	21.8%	2.8%	5.7
GC+WL(lin)	1.8%	5.9%	2.8%	2.3%	4.2%	7.1%	10.6%	2%	6.6
GC+WL(lin)+*Planck*	1.0%	0.7%	0.4%	0.4%	0.4%	6.2%	9.8%	1.5%	7.0
GC+WL(nl-HS)	0.8%	2.2%	0.8%	0.7%	1.5%	1.6%	2.4%	1.0%	8.8
GC+WL(nl-HS)+*Planck*	0.7%	0.6%	0.2%	0.2%	0.3%	1.6%	2.4%	0.9%	8.9
GC+WL(nl-Halofit)+*Planck*	0.6%	0.5%	0.2%	0.2%	0.2%	0.8%	1.7%	0.8%	9.6

Parametrisation ~ $\Omega_{DE}(a)$

- WL best for Σ, GC for μ (no surprise)
- non-linear scales important
- Planck strongly helps GC and WL, but less important in GC+WL
- WL here as powerful or more than GC, in binned case GC more powerful
- combined constraints O(1%)



Parametrisation ~ $\Omega_{DE}(a)$, using mildly non-linear scales

- shows degeneracies in WL and GC
- adding all breaks also degeneracies in parameters that aren’t shown

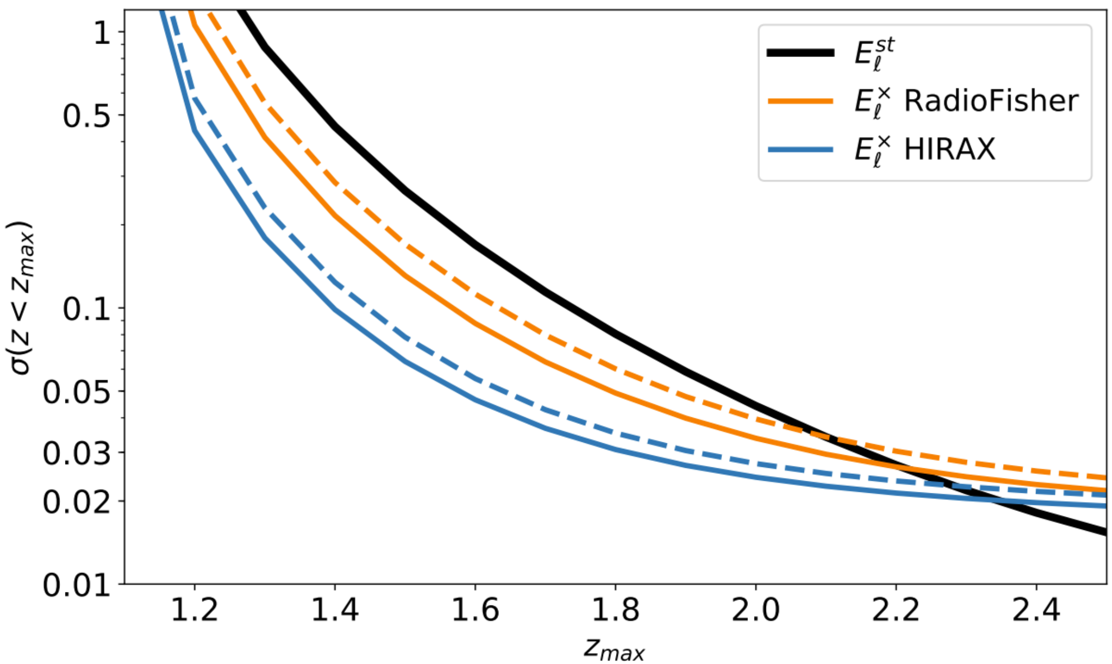
synergy Euclid - HIRAX

Just one example, from arXiv:1907.00071:
Galaxy number counts have a lensing contribution ('magnification'):

$$\Delta_g(\mathbf{n}, z) = b_g(z)\,\delta(\mathbf{n}, z) + (2 - 5s(z))\;\phi(\mathbf{n}, z)$$

Φ: lensing potential, s: slope of luminosity function
BUT: radio intensity mapping (like CMB) has no first-order lensing contribution (photon conservation) → we can use this to isolate Φ → reduce variance and systematics:

$$\mathrm{IM}(z_f) \times \mathrm{galaxy}(z_b) - \mathrm{galaxy}(z_f) \times \mathrm{IM}(z_b)$$



summary

- The standard ΛCDM model is composed of
  - an homogeneous & isotropic background metric, FLRW
  - dark matter & cosmological constant
  - other ingredients (perturbations, radiation, neutrinos, …)
- We want to test all assumptions
- We want to understand the physical nature / origin of the dark components, especially of the cosmological constant
- The space of possible models is very large
  - effective field theory of dark energy
  - phenomenological models (fluid / metric)
- Observations currently indicate no clear deviation from ΛCDM (but keep eye on σ_8, $\mathbf{H_0}$, large-scale anomalies, …)
- Euclid combines probes to test a wide range of models, e.g. phenomenological metric parameters to percent-level.

Thank you