Constraining Dark Energy and Modified Gravity with Euclid

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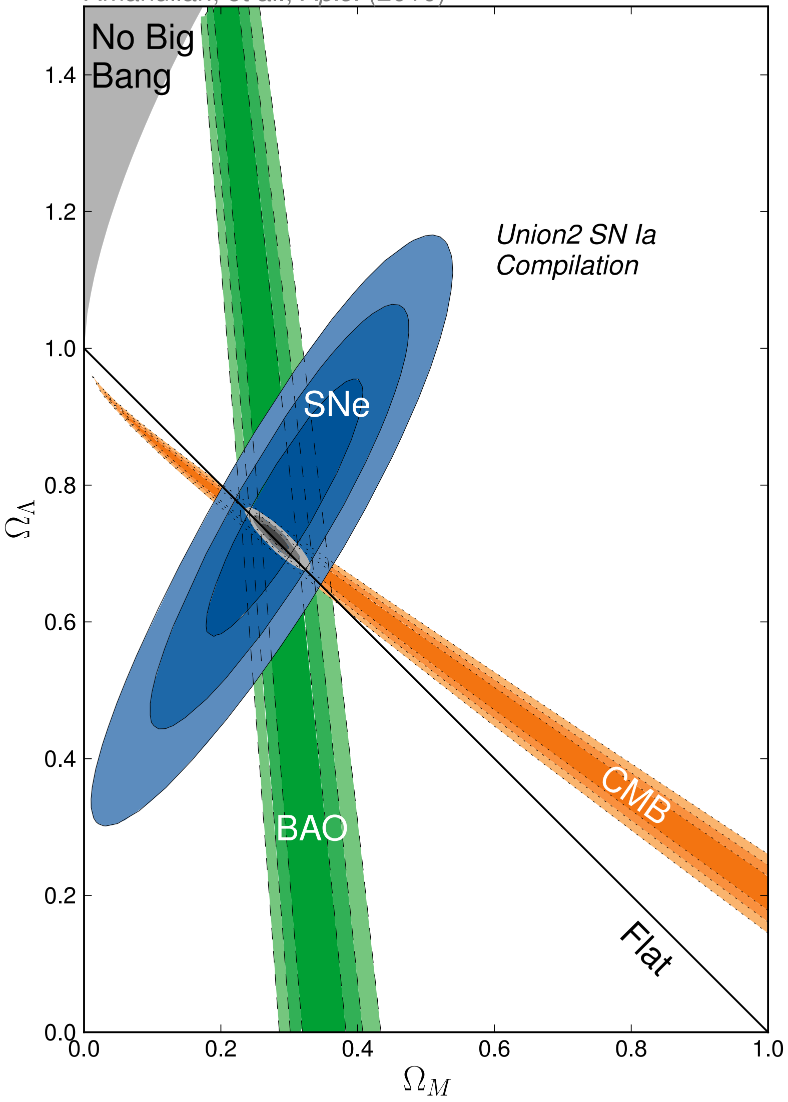
for the Euclid Consortium

Outline

- Why study Dark Energy?
- How to model Dark Energy for observations?
- Current and future (Euclid) constraints on ‘Dark Energy’

The cosmological constant

Supernova Cosmology Project
Amanullah, et al., *Ap.J.* (2010)



Physics Nobel prize 2011:

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

- Λ: w = -1 < -1/3 → expansion accelerates
- Λ is unique natural extension (Lovelock)
- Data is consistent with Λ

why look elsewhere?

- Test **all** assumptions (goes beyond Λ!)
- Λ has problems (coincidence, naturalness)
- Early universe seems to have dynamical DE period
- And of course …

… we promised ESA!

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.

How to model Dark Energy?

fundamental (action-based) models

effective field theories (action-based)

equivalent fluid description

phenomenological metric parameters

cosmological observations

more physical

more general

constrain physics

not independent

test for deviations

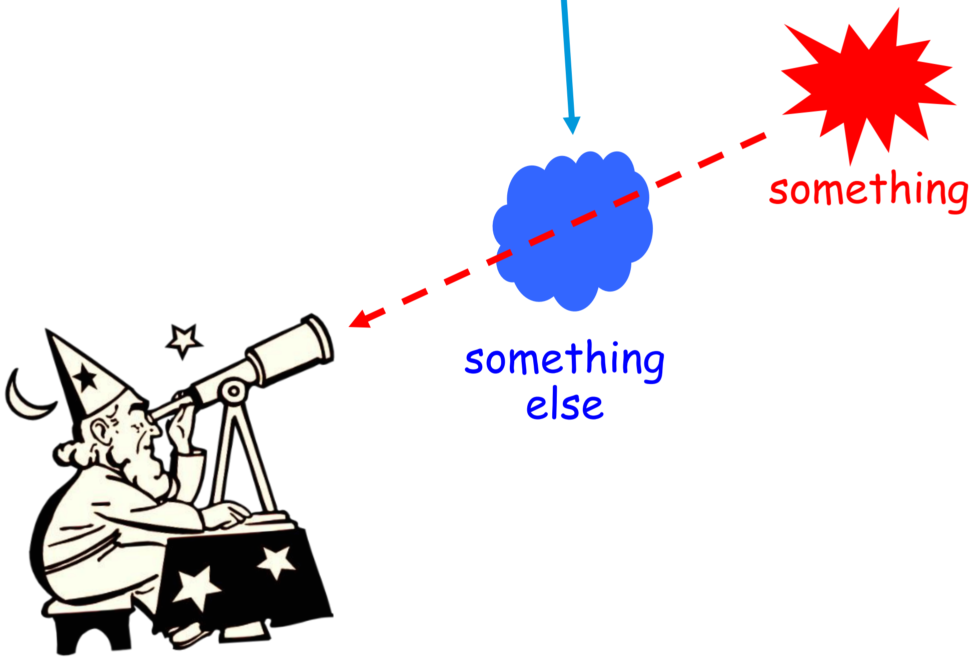
Phenomenology of the Dark Side

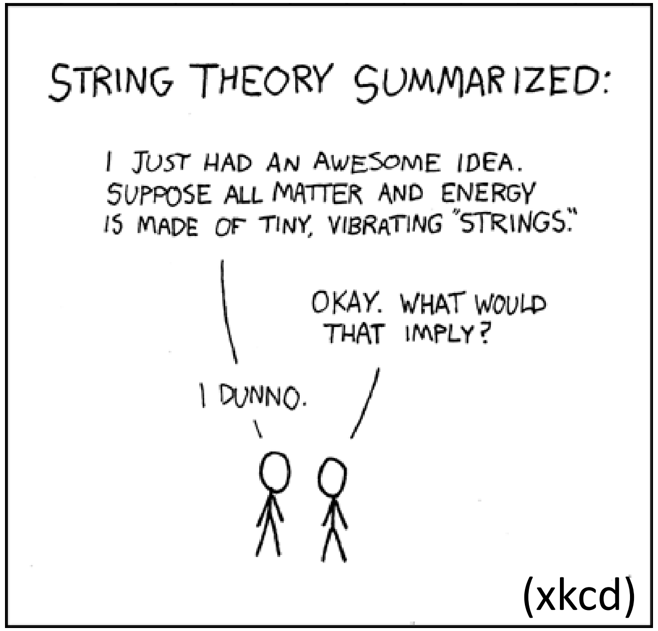
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

(determined by the metric) → geometry

stuff (what is it?)

your favourite theory





(xkcd)

Phenomenology of the Dark Side

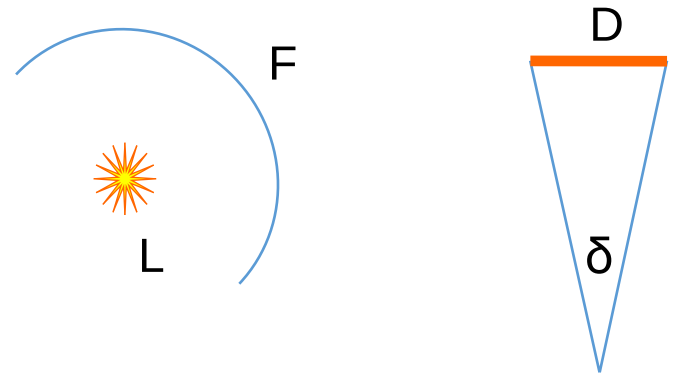
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

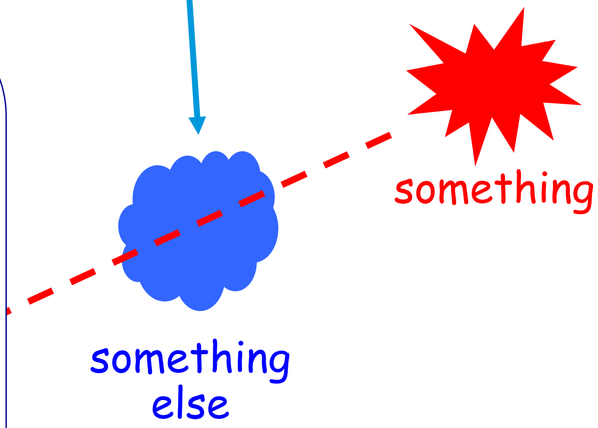
(determined by the metric) geometry

stuff (what is it?)

(your favourite theory)

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





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

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

p = w ρ

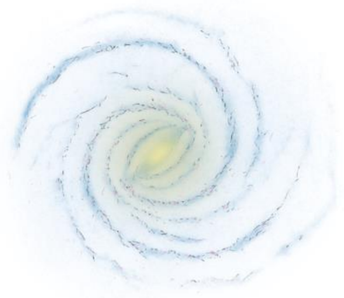
Metric phenomenological parameters

(e.g. Amendola et al, arXiv:0704.2421)

$$ds^2 = -(1+2\Psi)\,c^2\,dt^2 + a^2(t)\,(1-2\Phi)\,\delta_{ij}\,dx^i\,dx^j$$

→ characterize deviation of metric from reference (like PPN but in a cosmological context)

→ Geometry instead of fluid properties



Light deflection (lensing) : $\nabla_\perp(\Phi+\Psi)$

Acceleration : $\nabla\Psi$ (RSD)

(of course there are many other observations)

$$-k^2\Psi = \frac{4\pi G_N}{c^2}\,a^2\boxed{\mu(a,k)}\left[\bar\rho\Delta + 3\left(\bar\rho + \bar p/c^2\right)\sigma\right],$$

$$-k^2(\Phi+\Psi) = \frac{8\pi G_N}{c^2}\,a^2\left\{\boxed{\Sigma(a,k)}\left[\bar\rho\Delta + 3\left(\bar\rho + \bar p/c^2\right)\sigma\right] - \frac{3}{2}\mu(a,k)\left(\bar\rho + \bar p/c^2\right)\sigma\right\},$$

Alternatively replace one by slip, an observable and 'MG' diagnostic : $\eta = \Phi/\Psi$.

$$\Sigma = \frac{1}{2}\mu(1+\eta)$$

Action-based models

There is a huge number of possible models (theorists are very inventive), e.g.

- Quintessence (“Dark energy”) [Wetterich, 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: more general clustering (cs2≠1) [Armendariz-Picon et al. 2000]

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

- f(R): “modified gravity” [Weyl ca 1918?] – scale-dependent clustering, gravitational slip

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

- Jordan-Brans-Dicke [Brans, Dicke 1961]

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

- Many more (Horndeski & EFT, DGP & other extra dimensions, bigravity & massive gravity, vectors, …)

Phenomenology of DE/MG : f(R)

$df/dR = f_R$ satisfies a field equation and can be considered as a 'scalaron'

$$\Box f_R = \frac{1}{3}(R + 2f - R f_R) - \frac{\kappa^2}{3}(\rho - 3P) \equiv \frac{\partial V_{\rm eff}}{\partial f_R}$$

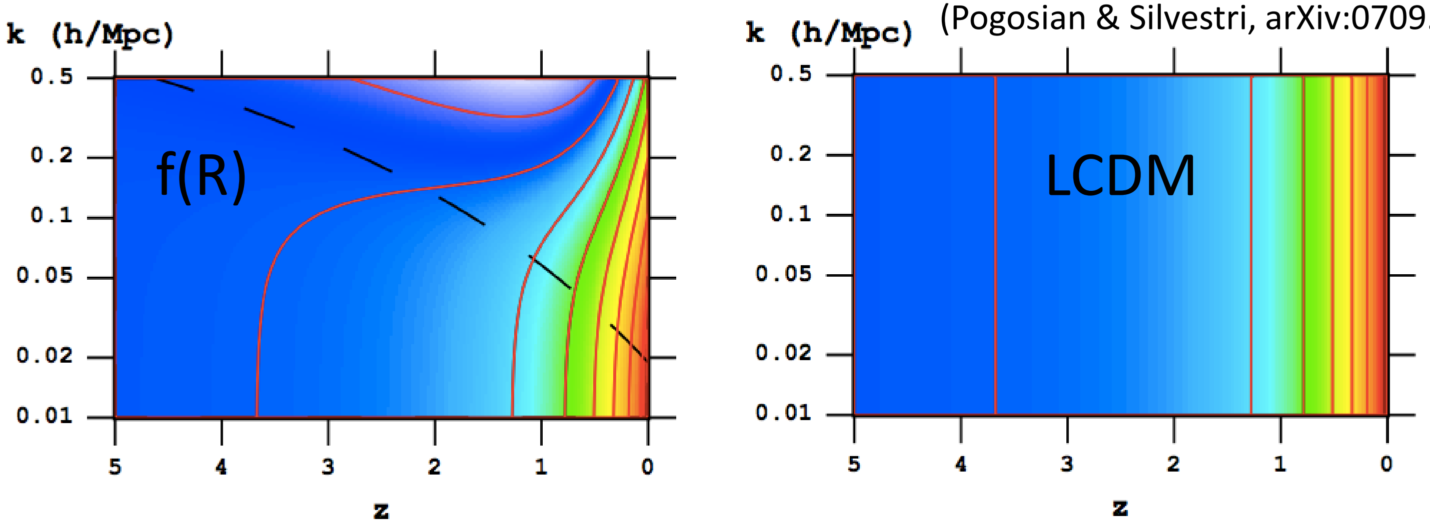
$$m_{f_R}^2 \equiv \frac{\partial^2 V_{\rm eff}}{\partial f_R^2} = \frac{1}{3}\left[\frac{1+f_R}{f_{RR}} - R\right]$$

the massive scalaron mediates a 5th force at short distances (Yukawa-type potential)

→ scale dependence:
$\lambda \gg \lambda_C$: $G_{\rm eff} \approx G/F$, $\Phi \approx \Psi$; $F = 1+f_R$
$\lambda \ll \lambda_C$: $G_{\rm eff} \cong 4/3\, G/F$, $\Phi \approx \Psi/2$
and non-vanishing slip on small scales

→ Needs screening on very small scales (Chameleon mechanism)

(Pogosian & Silvestri, arXiv:0709.0296)



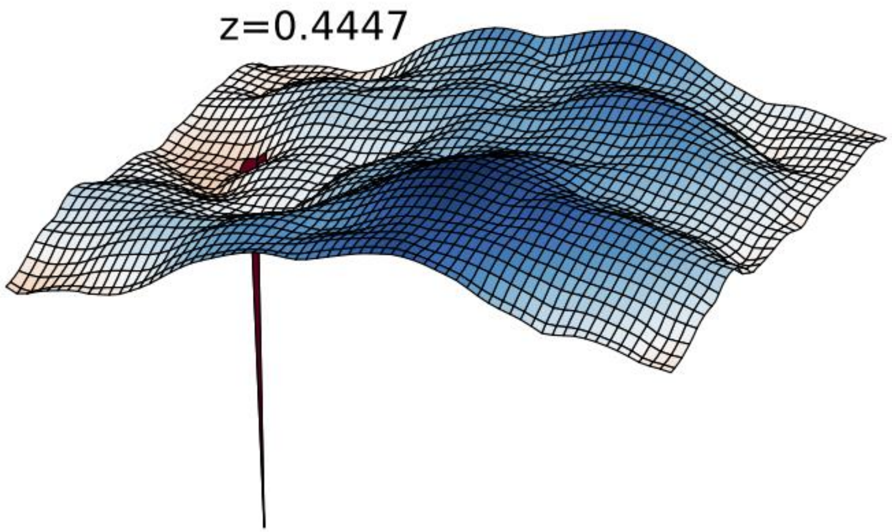
Scale-dependent growth is typical for non-Λ (sound horizon, massive scalaron, screening) and **non-vanishing slip** is typical for modified gravity models (as well as modified GW propagation).

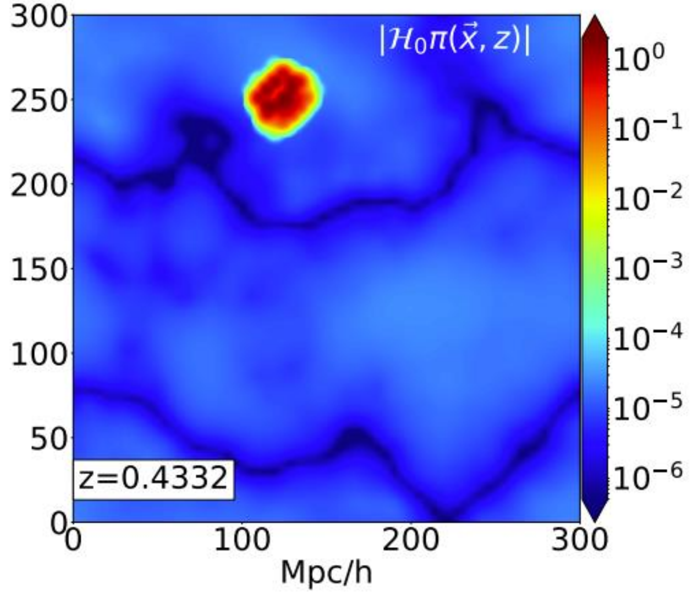
Non-linear scales are a key challenge

- Boltzmann solvers (for scalar-field & phenomenological models) are now reliable.
- But we need reliable model predictions at <1% accuracy also on small, non-linear scales – this is already a challenge for LCDM!
- There are *many* DE/MG models, and each one is more complicated to simulate than LCDM.
- Typically, we have to resort to ‘small’ N-body simulations or approximate approaches.
- MG models also include features like screening and instabilities that may be absent in linear calculations or simplified treatments.

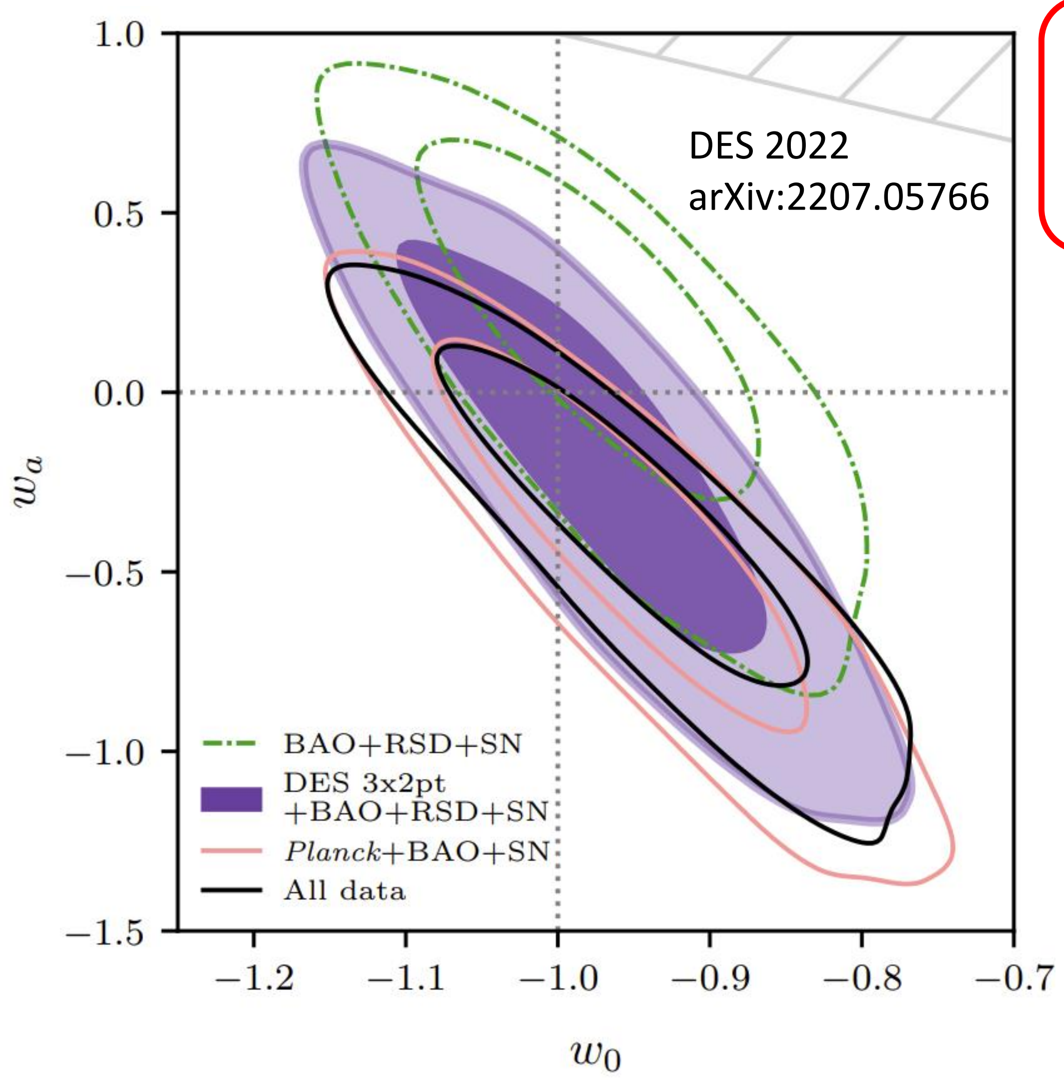
Example: k-essence with low speed of sound in EFT framework is unstable at non-linear level, but non-linear contributions are important for those models.

(Hassani et al. arXiv:2204.13098)

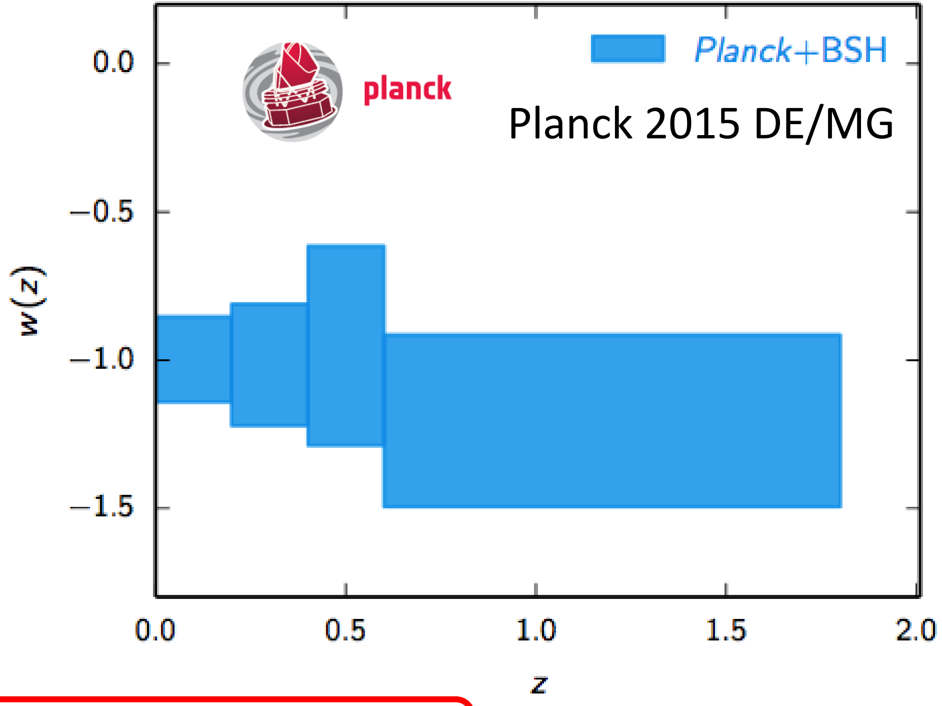




Constraints on “Dark Energy”



effective quintessence
$w(z) = w_0 + (1-a)w_a$
$c_s^2=1$, $\sigma=0$,
→ $\eta=1$, $\mu(k > 1/H) = 1$



no deviation from w=-1

Euclid Figure of Merit

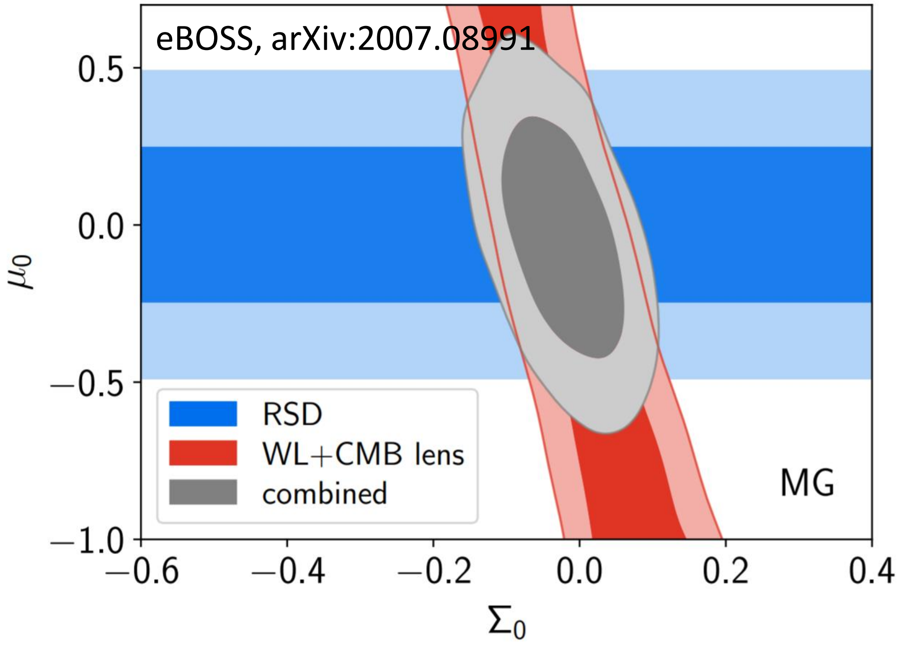
w_0, w_a FoM	Flat	Non-flat
Linear setting		
GC_s	40	19
Pessimistic setting		
GC_s	14	10
WL	23	5
GC_s+WL	99	40
GC_{ph}+WL	64	14
GC_s+WL+GC_{ph}	123	49
WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	367	59
GC_s+WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	377	128
Optimistic setting		
GC_s	55	19
WL	44	12
GC_s+WL	157	87
GC_{ph}+WL	235	129
GC_s+WL+GC_{ph}	398	218
WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	1033	326
GC_s+WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	1257	500

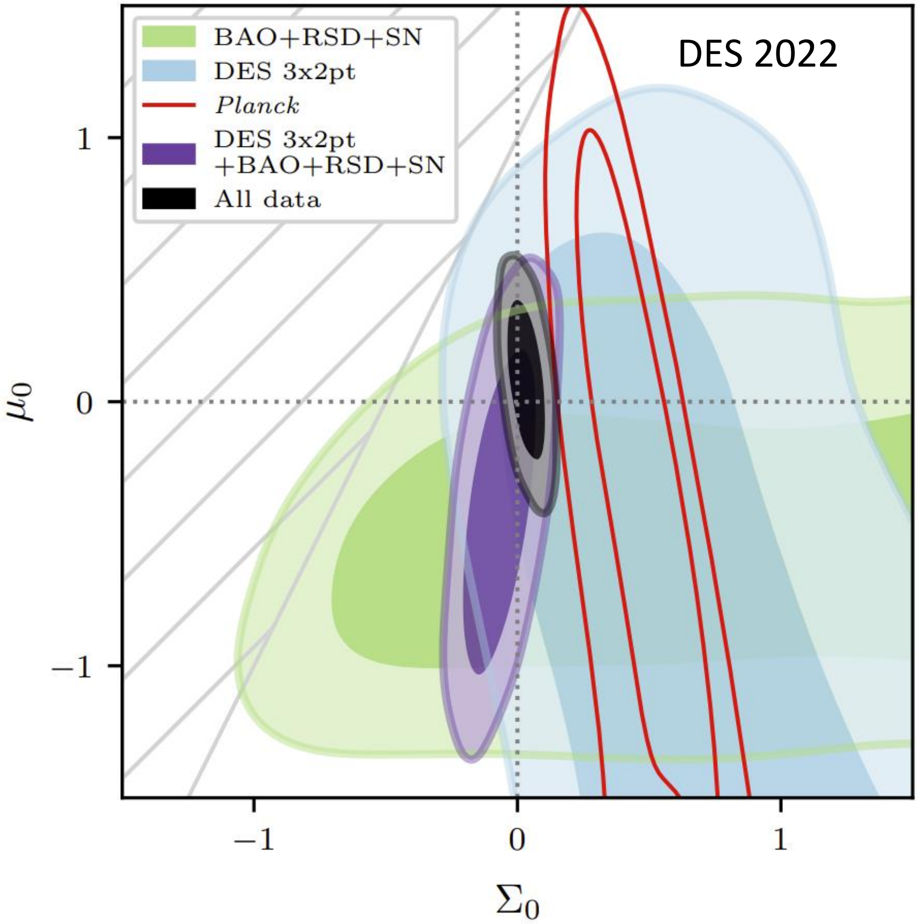
Euclid prep VII: Forecast validation
Blanchard et al, arXiv:1910.09273

Comments:

- FoM ~ inverse of w0/wa error ellipse.
- ESA expects a FoM of 400 for Euclid alone.
- Errors on w0/wa:
  - Planck + BAO/SN-Ia : 0.080 / 0.3
  - Planck + BAO/RSD WL : 0.2 / 0.6
  - Euclid 3x2pt pessimistic: 0.042 / 0.17
  - Euclid 3x2pt optimistic : 0.027 / 0.10
- Adding CMB can improve errors by ca 50% cf Ilic et al, arXiv:2106.08346

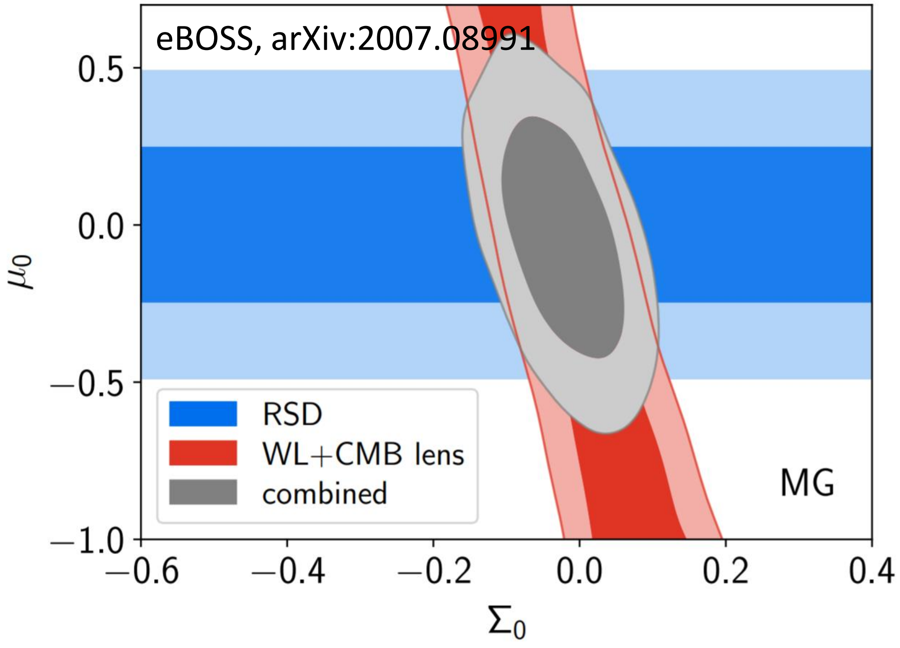
Constraints on “Modified Gravity”





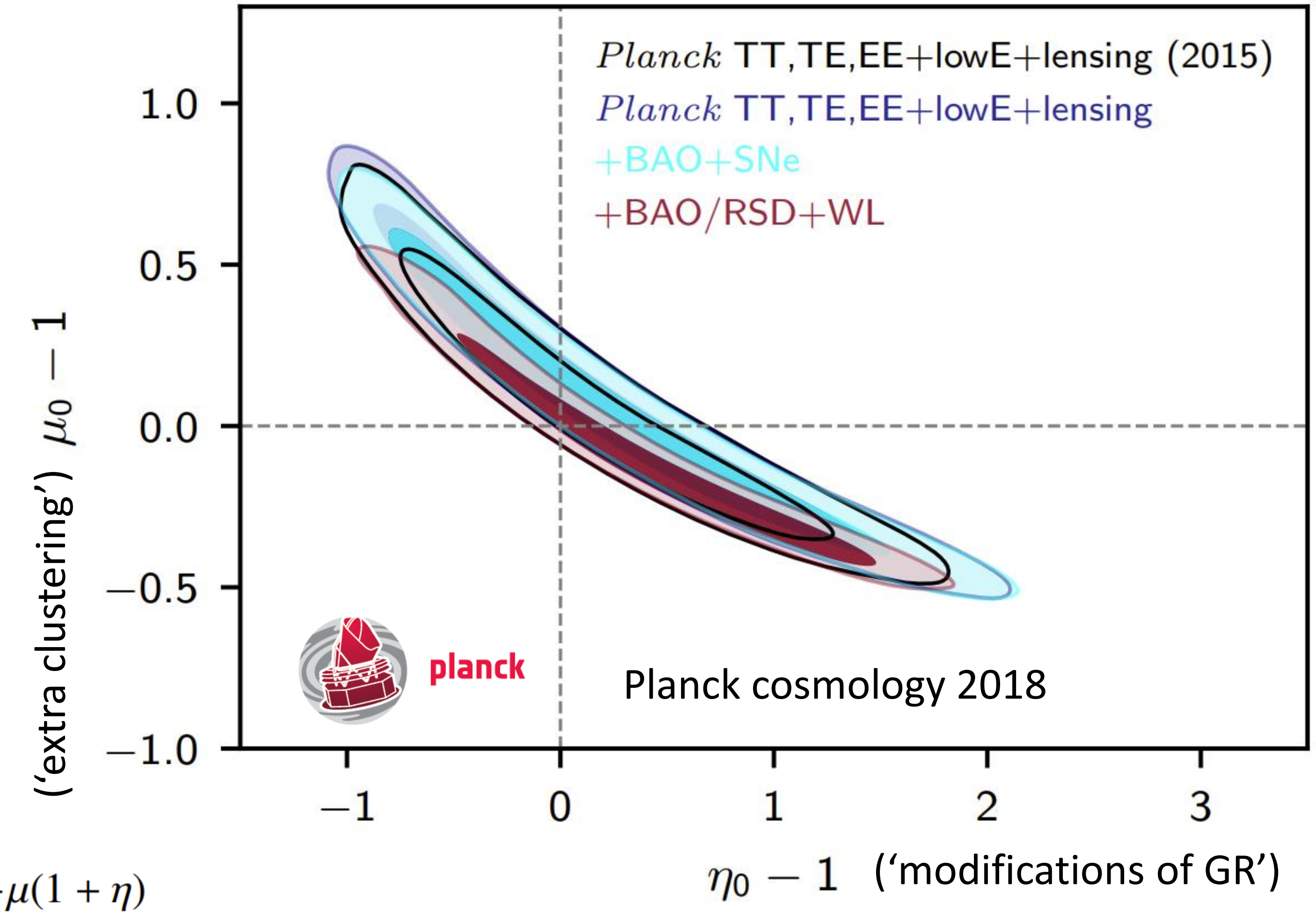
- Σ: (Φ+Ψ) → lensing
  Limit: ~ 0.05
- μ: Ψ → acceleration of massive particles
  Limit: ~ 0.25

Constraints on “Modified Gravity”



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

$$\Sigma = \frac{1}{2}\mu(1+\eta)$$



Euclid on "Modified Gravity"

(Casas et al arXiv:1703.01271 – not official Euclid forecast)

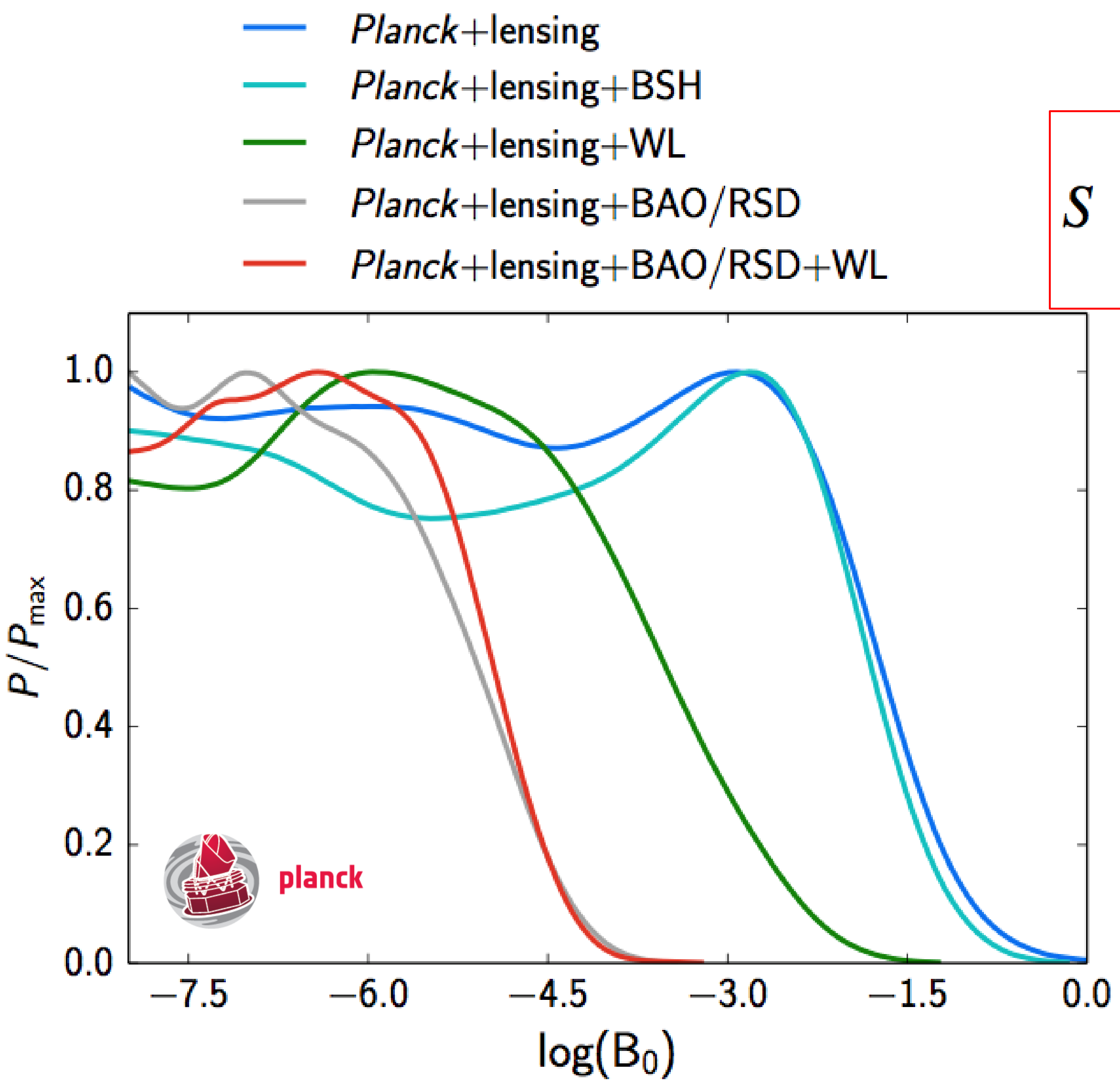
Parametrisation μ , Σ ~ $\Omega_{DE}(a)$, Red Book specifications for Euclid, fairly ad-hoc non-linear modeling

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

- WL best for Σ, GC for μ (no surprise)
- non-linear scales important
- ~percent uncertainties on μ, Σ (probably a bit optimistic)

Constraints on f(R)

Planck 2015 DE/MG



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

universal but non-minimal coupling

LCDM background used to reconstruct f(R)

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

(~inverse mass scale)

$$\mu(a,k) = \frac{1}{1 + f_R(a)}\frac{1 + 4k^2a^{-2}m_{f_R}^{-2}(a)}{1 + 3k^2a^{-2}m_{f_R}^{-2}(a)}$$

$$\Sigma(a) = \frac{1}{1 + f_R(a)}$$

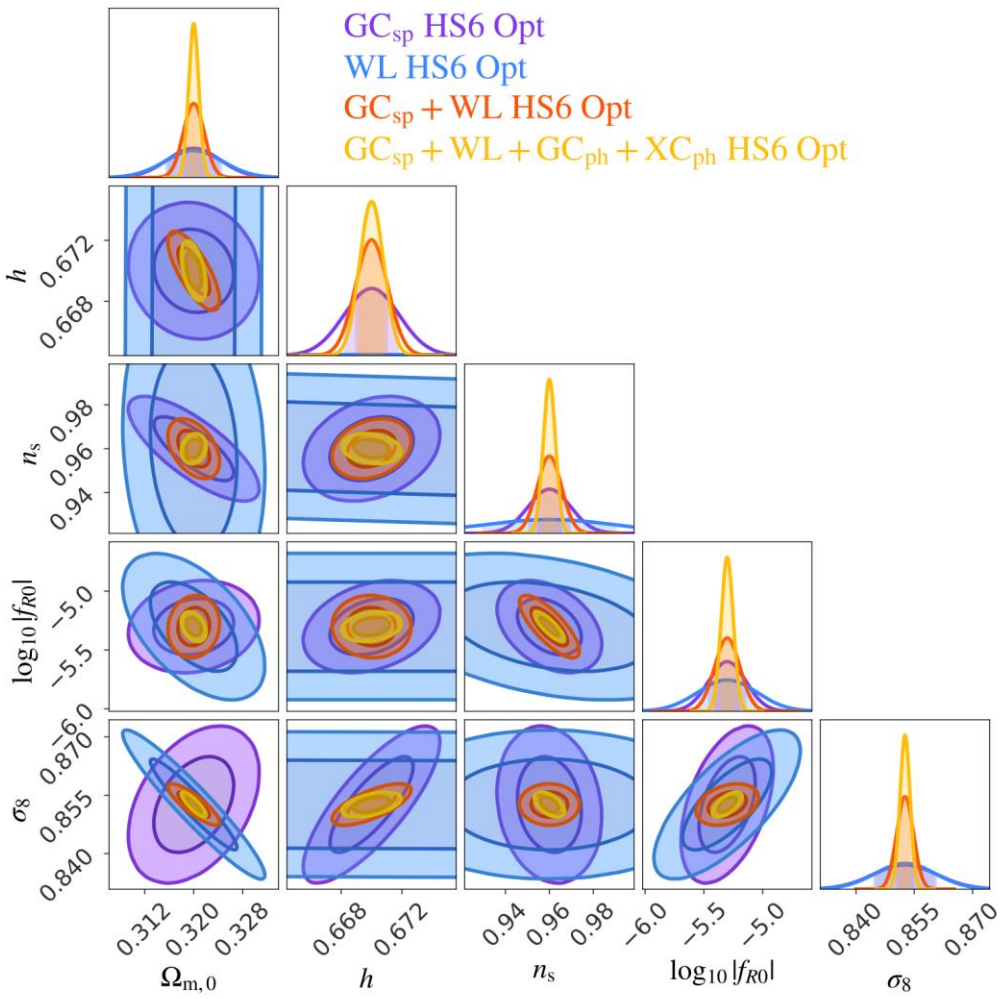
in quasistatic limit

4 orders of magnitude improvement from RSD!

best limit:
TT+lowP+lensing+WL
+BAO/RSD
$B_0 < 0.8 \times 10^{-4}$ (95% CL)

Euclid and f(R)

(Casas et al, arXiv:2306.11053, not yet published)



Hu & Sawicki type model: $\boxed{f(R) = -6\Omega_{DE,0}\frac{H_0^2}{c^2} + |f_{R0}|\frac{\bar{R}_0^2}{R}}$

Background close to LCDM as f_{R0} (< 0) small.

Non-linear scales: fitting formula calibrated with N-body sims

- $|f_{R0}| = (5.0^{+2.2}_{-1.5} \times 10^{-6})$ with spectroscopic GC_{sp} alone;
- $|f_{R0}| = (5.0^{+3.9}_{-2.2} \times 10^{-6})$ with WL alone;
- $|f_{R0}| = (5.0^{+0.91}_{-0.77} \times 10^{-6})$ combining WL, GC_{ph}, and XC_{ph}
- $|f_{R0}| = (5.0^{+0.62}_{-0.55} \times 10^{-6})$
  with the combination GC_{sp}+WL+GC_{ph}+XC_{ph}.

Significant impact of pessimistic cuts on photometric probes.

Euclid and Jordan-Brans-Dicke

(Frusciante et al, arXiv:2306.12368, not yet published)

$$S_{\rm BD} = \int {\rm d}^4x \sqrt{-g}\left[\frac{c^4}{16\pi}\left(\phi R - \frac{\omega_{\rm BD}}{\phi} g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - 2\Lambda\right) + \mathcal{L}_{\rm m}\right]$$

$$\Sigma = \frac{1}{G_{\rm N}\phi}\,, \quad \mu = \frac{4+2\omega_{\rm BD}}{3+2\omega_{\rm BD}}\Sigma\,, \quad \eta \equiv \frac{\Phi}{\Psi} = \frac{1+\omega_{\rm BD}}{2+\omega_{\rm BD}}$$

(quasistatic limit)

current constraints:
small scales: ω_{BD} > 10^5 → absence of screening is a problem
cosmology : ω_{BD} >~ 10^3 [prior dependence]

Euclid: 2 scenarios: fiducial ω_{BD} = 800 and 2500 (using $\log_{10} \omega_{BD}$)
NL spectra from HMCODE calibrated to N-body sims

Optimistic:
JBD1: 3x2pt : 27% ; adding GCsp : 25%
JBD2: 3x2pt : 48%; adding GCsp : 40%

Pessimistic:
JBD1 can be detected,
JBD2 not with high significance.

Euclid and DGP (Dvali et al, 2000)

(Frusciante et al, arXiv:2306.12368, not yet published)

$$\boxed{S = \frac{c^4}{16\pi G_5}\int_{\mathcal{M}} d^5x\,\sqrt{-\gamma}R_5 + \int_{\partial\mathcal{M}} d^4x\,\sqrt{-g}\left[\frac{c^4}{16\pi G_N}R + \mathcal{L}_m\right]}$$

"normal" branch, additional DE to impose LCDM background (DGP has Vainshtein screening)

$$H^2 = \pm c\frac{H}{r_c} + \frac{8\pi G}{3}\bar{\rho}$$

$$r_c = G_5/(2G_N)$$

$$\Sigma = 1 \qquad \mu(a) = 1 + \frac{1}{3\beta},$$

(quasistatic limit)

$$\beta(a) \equiv 1 + \frac{H}{H_0}\frac{1}{\sqrt{\Omega_{rc}}}\left(1 + \frac{\dot{H}}{3H^2}\right)$$

$$\boxed{\Omega_{rc} \equiv c^2/(4r_c^2 H_0^2)}$$

Current constraints: Ω_{rc} <~ 0.2 – 0.3

Euclid: 2 scenarios: fiducial $\log_{10}\Omega_{rc}$ = -0.6 (Ω_{rc} = 0.25) and $\log_{10}\Omega_{rc}$ = -6

NL spectra from halo-model reaction approach based on MG change to linear clustering

Optimistic: nDGP1: 3x2pt 32%, adding GCsp 26%

nDGP2: only upper limit Ω_{rc} < 0.072 (~ consistent with nDGP1 results)

Summary

- We can model DE/MG at different levels, closer to theory or closer to observations.
- Euclid will allow to significantly tighten DE/MG constraints, relative to today.
  - But of course we really want to see a deviation from Lambda – Euclid will allow us to distinguish between models that are still compatible with Lambda.
- Much information comes from non-linear scales, this is a critical challenge for theorists / simulators.
- We also want to include CMB data (ongoing).
- And remember that we should check ***everything*** (not only Lambda), including the cosmological principle!

Thank you!

BACKUP SLIDES

Euclid consortium

Fluids at perturbation level

metric (gauge fixed, scalar dof)

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

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

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

conservation eq's

metric perturbations

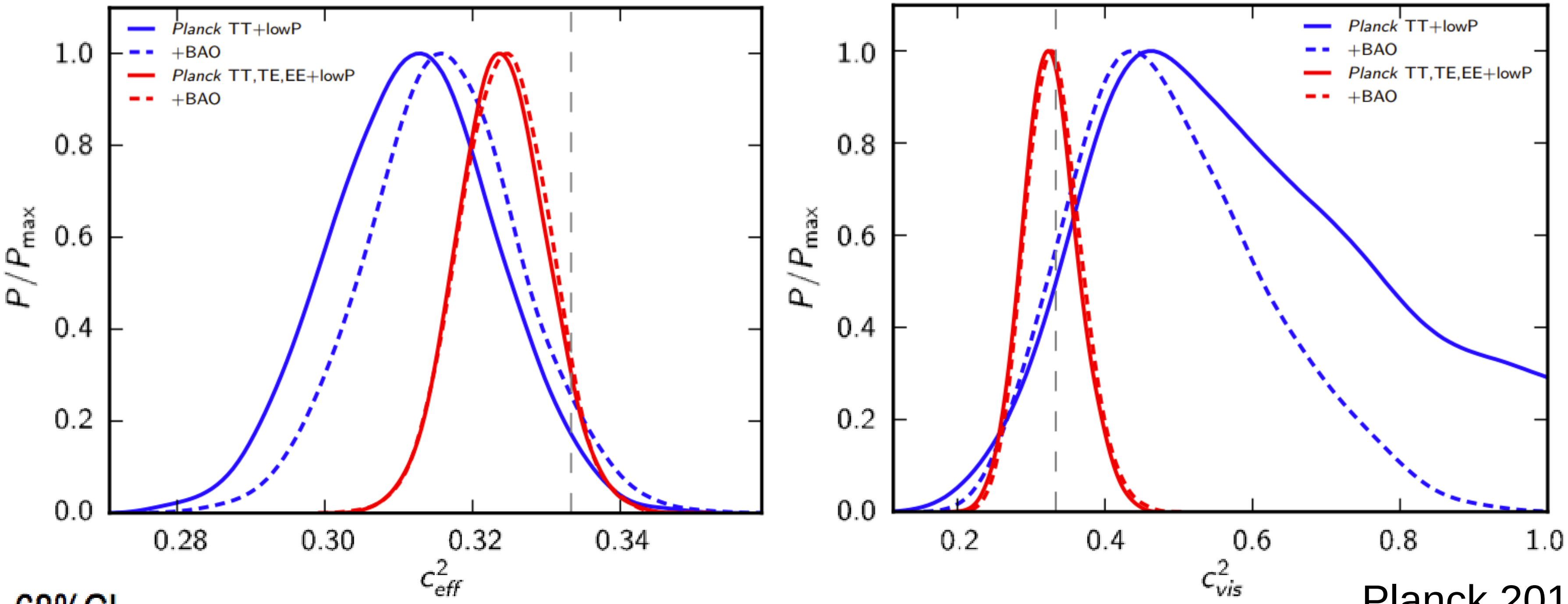
fluid properties

fluid evolution

Einstein eq's

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

Constraining the neutrino fluid



Planck 2015

- significant detection of additional radiation fluid in the CMB : "neutrino anisotropies"
- compatible with expected values

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

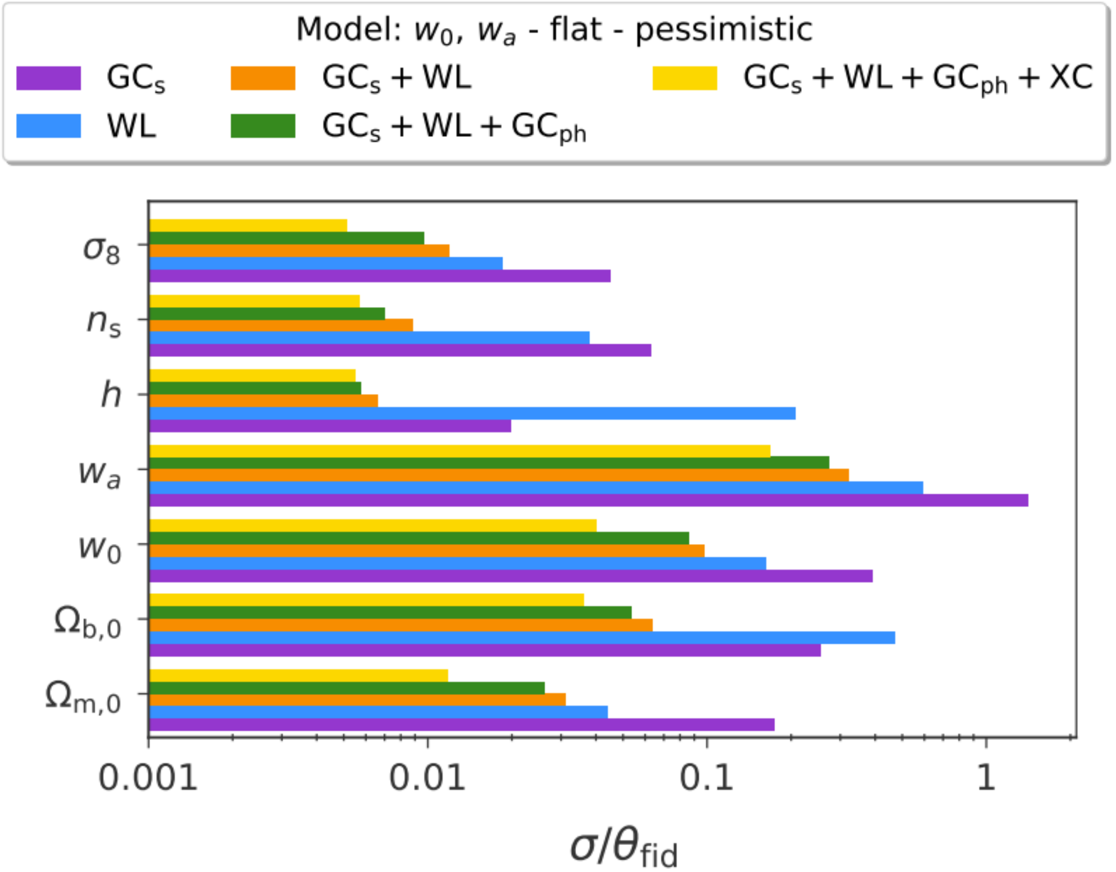
Forecast specifications

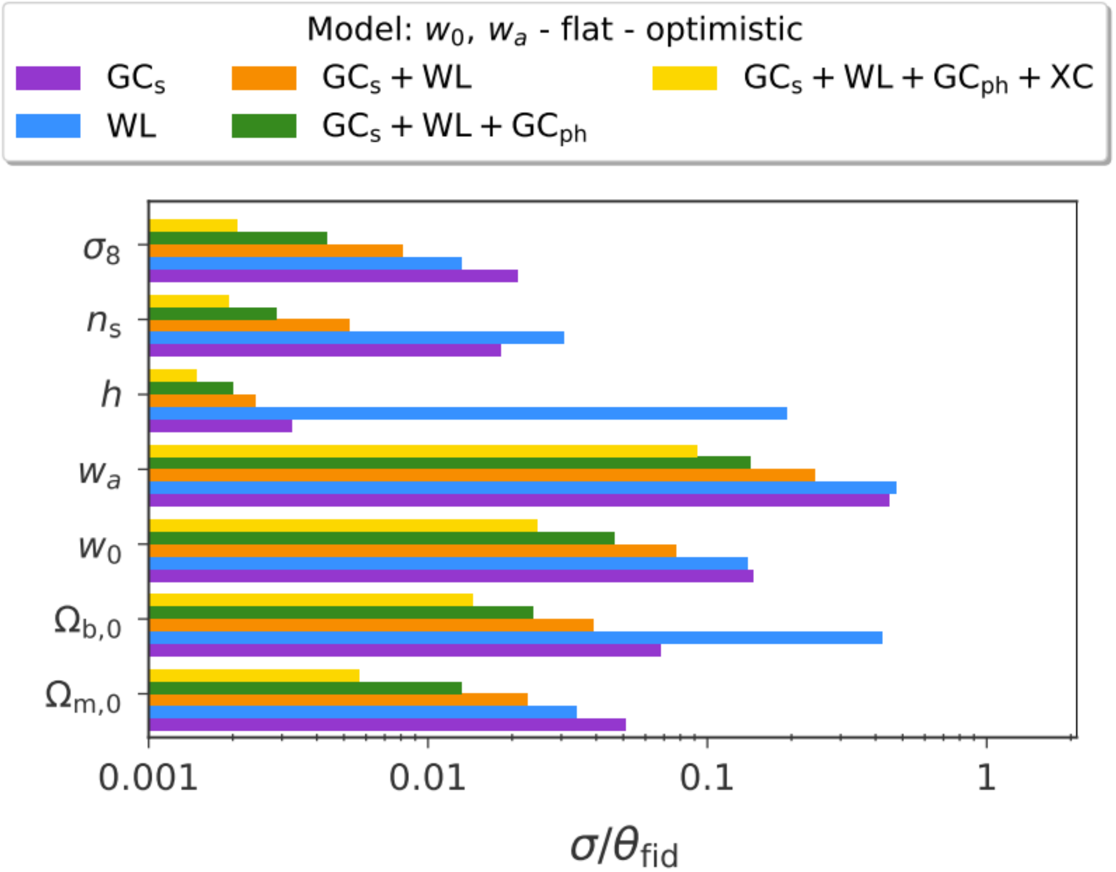
$$
\begin{aligned}
\textit{pessimistic settings:} & k_{\max}(\mathrm{GC_s}) = 0.25\,h\,\mathrm{Mpc}^{-1} \;, \\
& \ell_{\max}(\mathrm{WL}) = 1500 \;, \\
& \ell_{\max}(\mathrm{GC_{ph}}) = \ell_{\max}(\mathrm{XC}^{(\mathrm{GC_{ph}},\mathrm{WL})}) = 750 \;, \\
& \mathrm{GC_{ph}} \text{ for } z < 0.9 \text{ when combined with } \mathrm{GC_s} \;; \\
\textit{optimistic settings:} & k_{\max}(\mathrm{GC_s}) = 0.3\,h\,\mathrm{Mpc}^{-1}, \text{with fixed } \sigma_{\mathrm{p}} \text{ and } \sigma_{\mathrm{v}} \;, \\
& \ell_{\max}(\mathrm{WL}) = 5000 \;, \\
& \ell_{\max}(\mathrm{GC_{ph}}) = \ell_{\max}(\mathrm{XC}^{(\mathrm{GC_{ph}},\mathrm{WL})}) = 3000 \;.
\end{aligned}
$$

- No cross-correlation (XC) between GCs and WL/GCph included (but no redshift overlap in pessimistic scenario).
- Changing neutrino mass sum to 0.15 eV does not change the forecasted errors significantly (<~ 1% on errors).

Euclid and Dark Energy

Euclid prep VII: Forecast validation
arXiv:1910.09273





Adding CMB to Euclid can give another ca 50% improvement on w_0 and on w_a, cf arXiv:2106.08346