Constraining Dark Energy and Modified Gravity with Euclid

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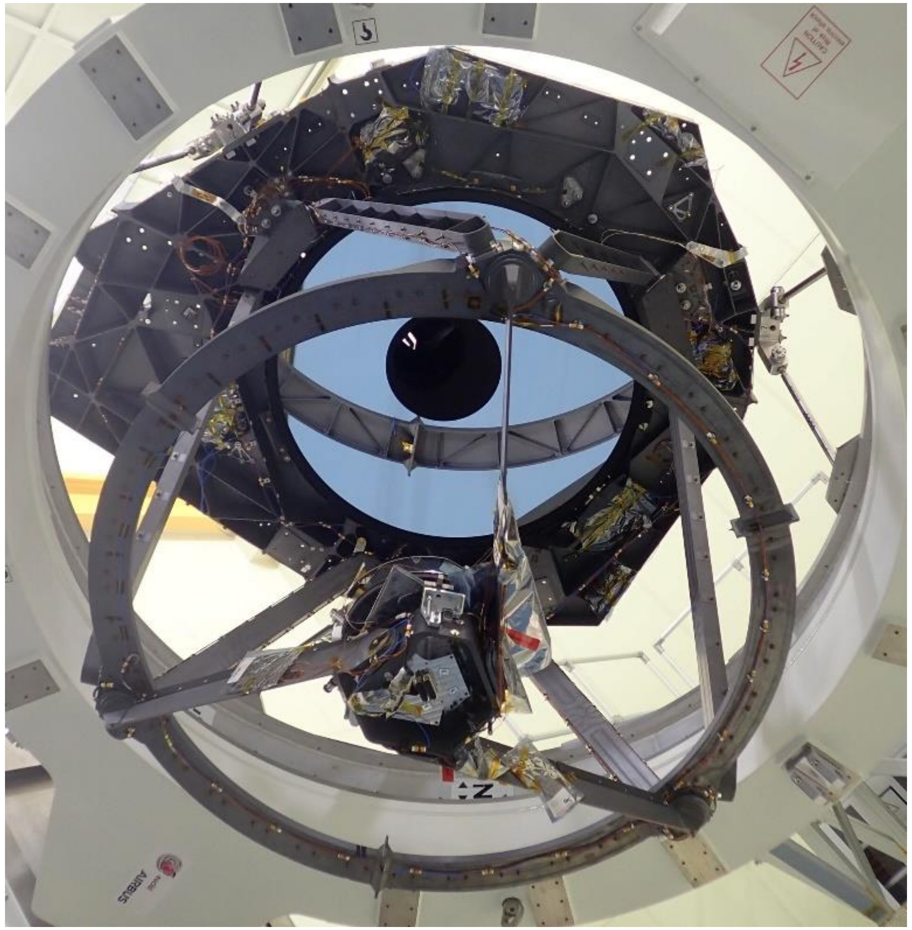
for the Euclid Consortium

Outline

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

Euclid

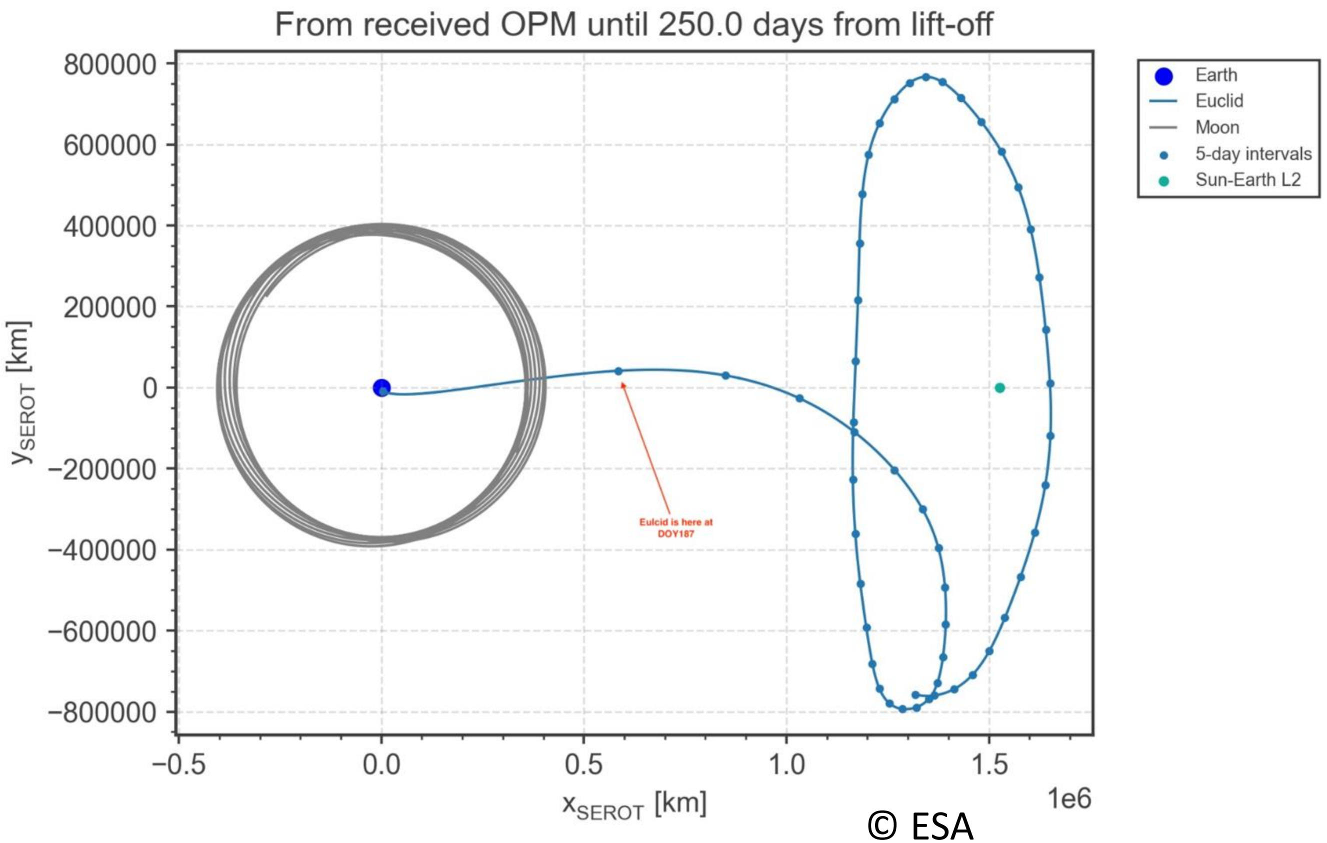
- Ca 4.7m tall, 3.7m wide
- 1988kg launch mass
- 1.2m primary mirror
- Near-infrared & optical instruments.
- Launch: July 1st, 2023 on SpaceX Falcon 9
- Daily data rate of ca 100GB compressed data
- Nominal mission duration of 6 years, extension possible.

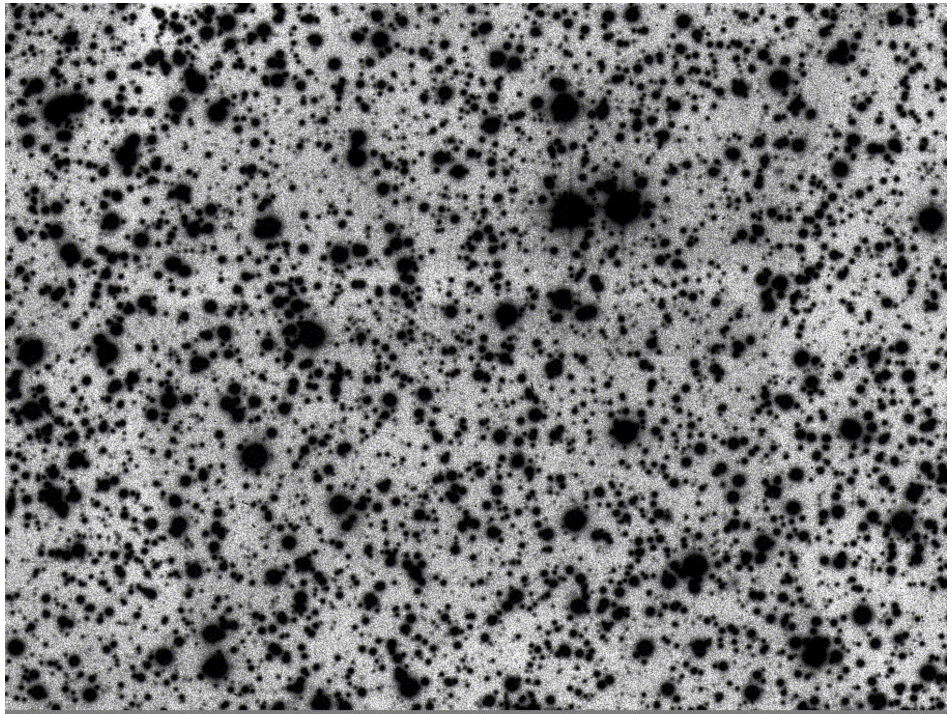


'eye of Euclid' ©Airbus

euclid
esa
STRONGBACK RETRACT
STARTUP
LIFTOFF
MAX-Q
MECO
FAIRING
T - 00:00:15
EUCLID
STARTUP
THE FALCON 9 FLIGHT COMPUTERS HAVE TAKEN CONTROL OF THE COUNTDOWN

Euclid transfer



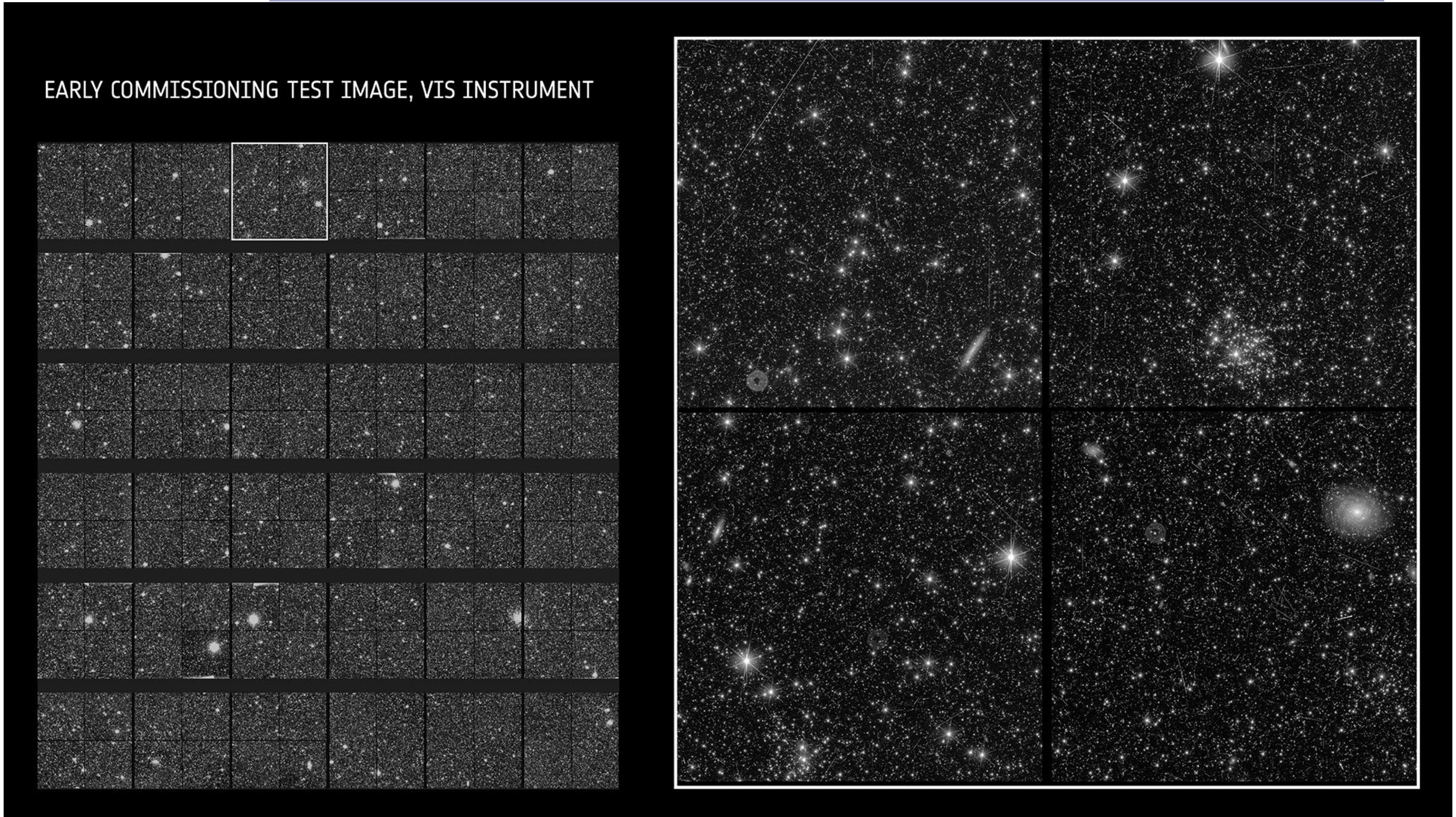


Euclid moving to L2 by CFHT-MegaCam / 12-07-2023

VIS commissioning

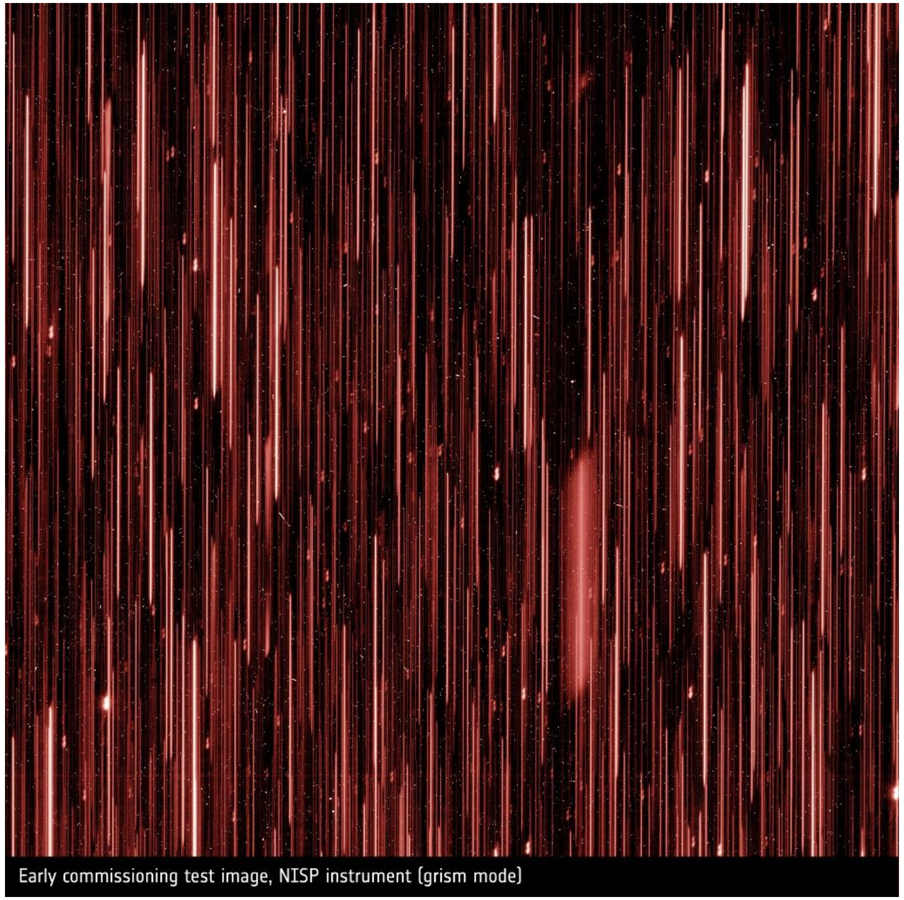
FOV 42’x44’

VIS:
36 Si CCD’s
4096x4132
0.1”/pixel
530-920 nm

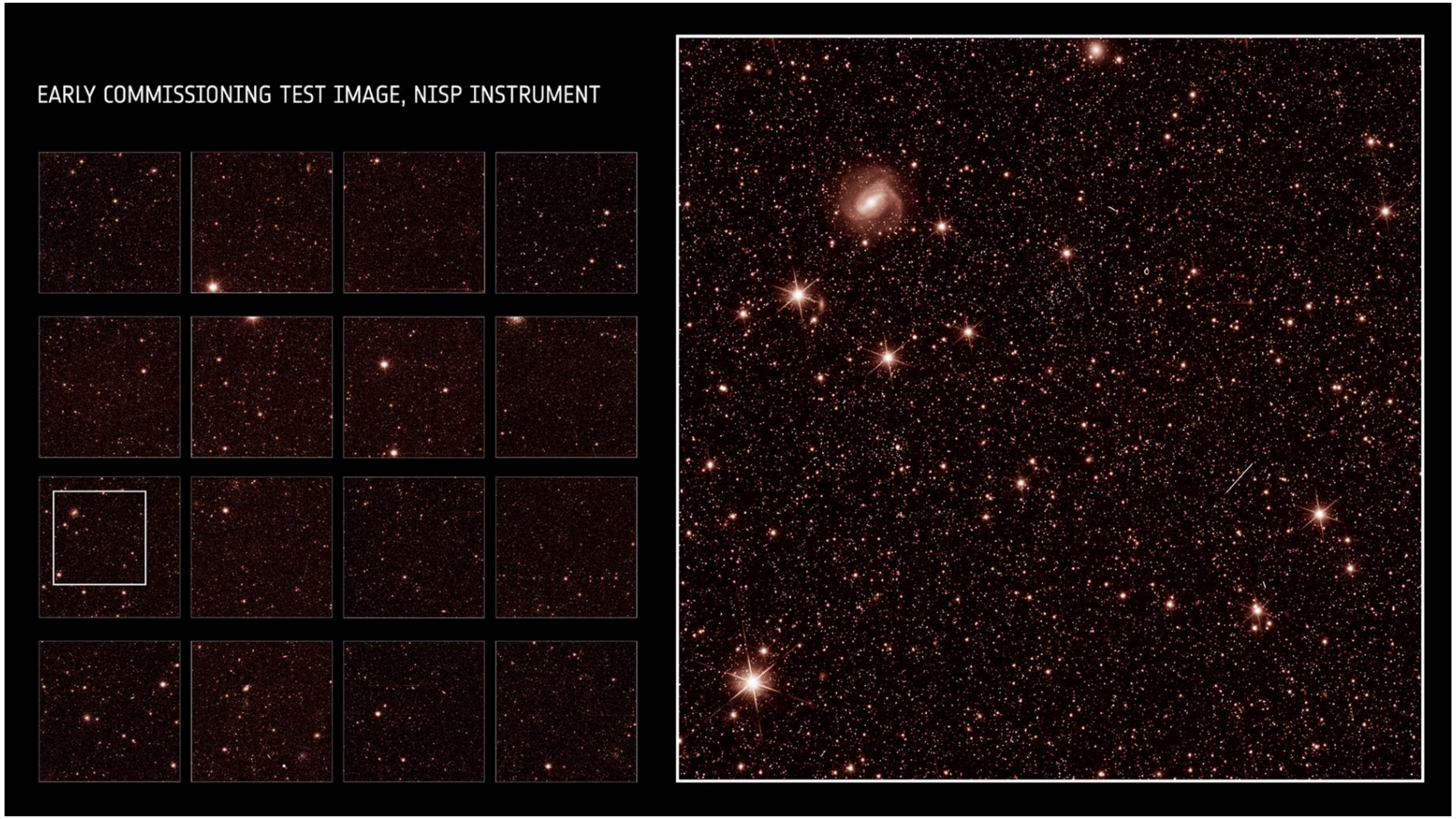


NISP commissioning

FOV 42'x44' **NISP**: 16 HgCdTe arrays 2048x2048 0.3"/pixel Y/J/H-band imaging & R>400 slitless spectr.

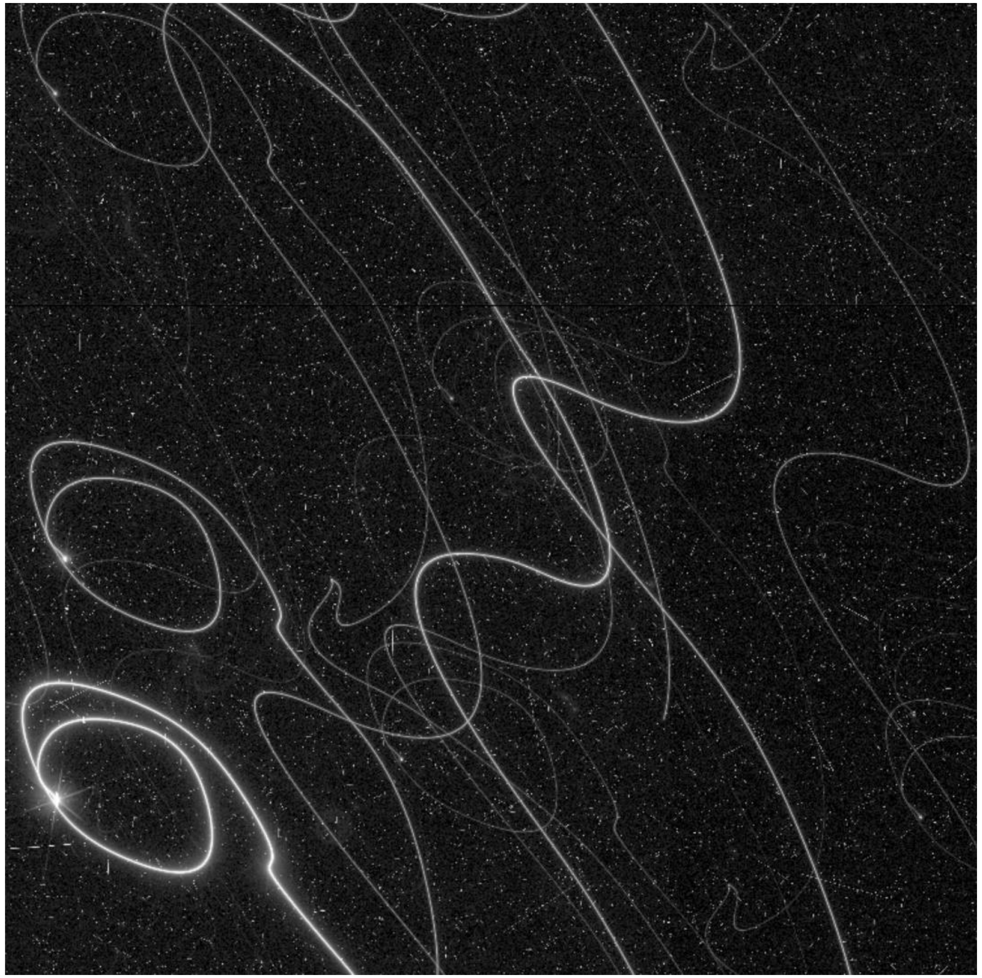


Early commissioning test image, NISP instrument (grism mode)

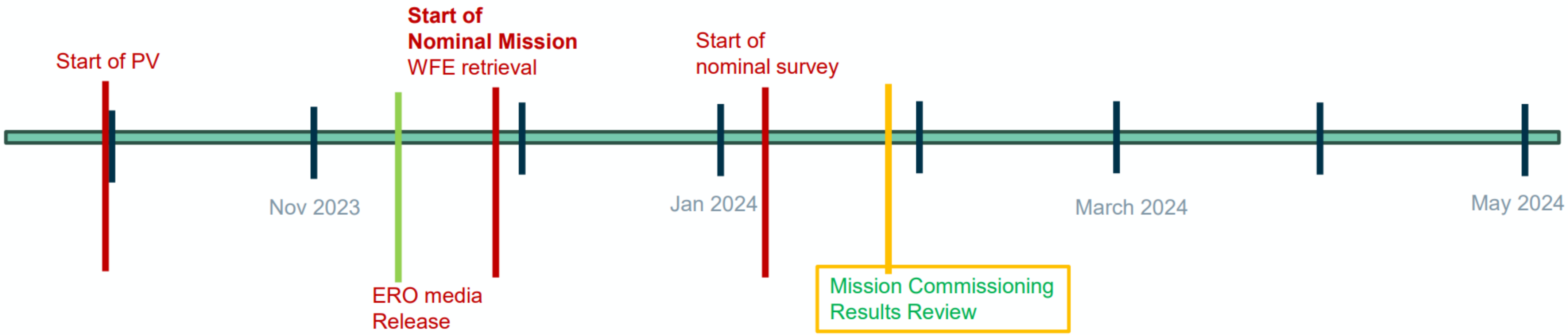


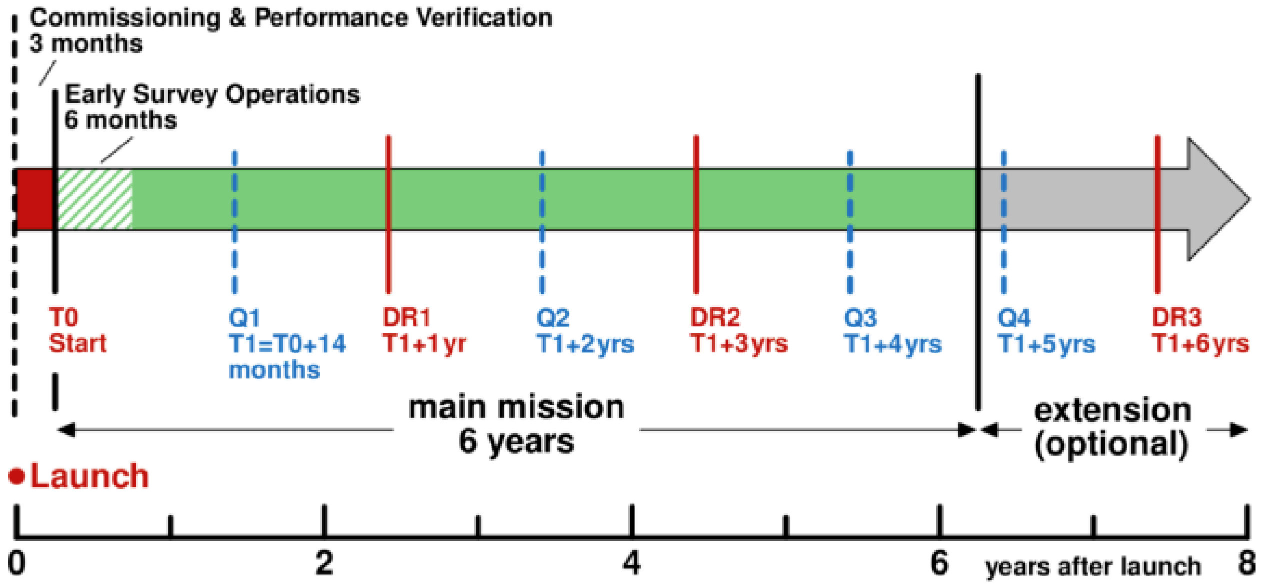
Problems & solutions

- Cosmic rays: A fact of life at L2 …
- Straylight: A thruster nozzle scatters light past the sun shield through the thermal insulation and via a VIS shutter mounting leg to the VIS focal plane. Requires turning the satellite so that the nozzle is in the sun shield shadow.
- X-rays from solar flares: X-rays can penetrate the sun shield in the gaps between the solar panels and deposit energy in some of the VIS detectors. No damage to CCD’s but will have to be mitigated.
- Fine Guidance Sensor: Uses CCD’s at the edge of the focal plane. Cosmic rays were mistaken as guide stars, leading to a loss of tracking. A software patch has restored nominal performance.



Euclid timeline





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

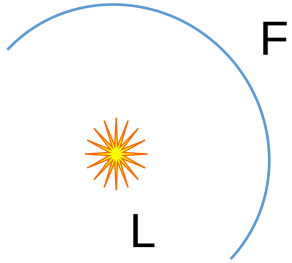
← constrain physics

↕ not independent

← test for deviations

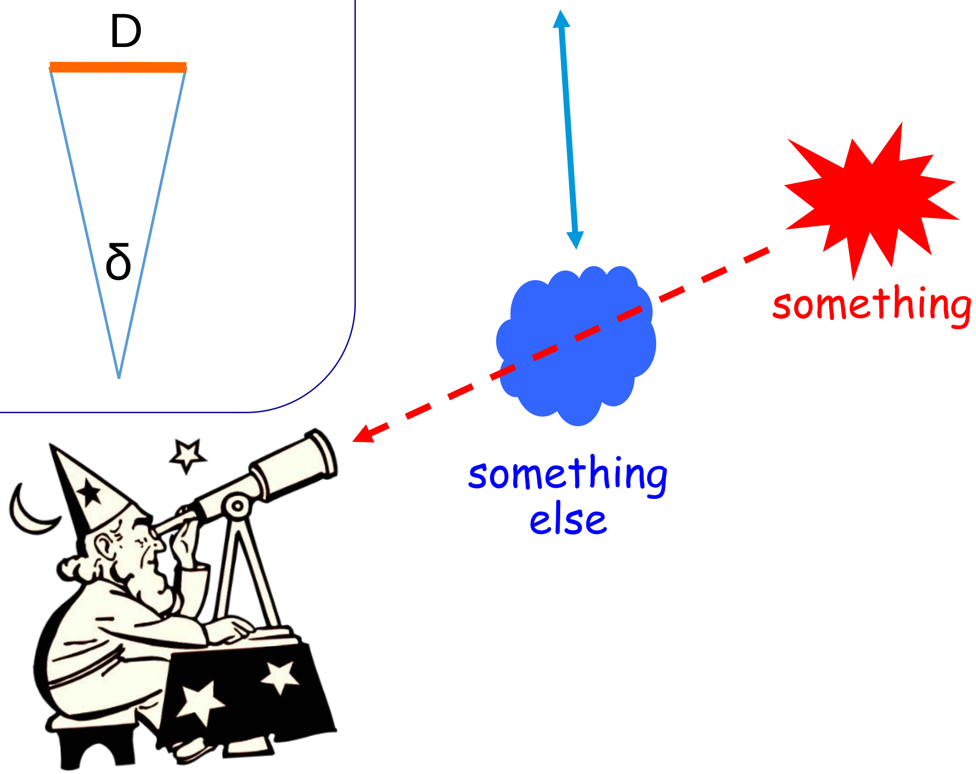
Phenomenology of the Dark Side

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



(metric) → geometry → $G_{\mu\nu} = 8\pi G T_{\mu\nu}$ ← stuff (what is it?)

(your favourite theory)



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

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

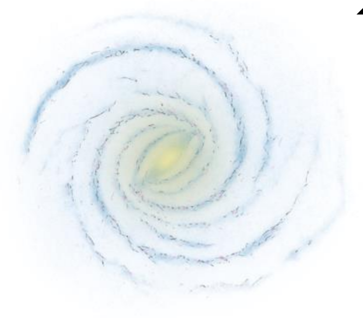
p = w ρ

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)

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

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

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

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

Phenomenology of DE/MG : f(R)

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

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

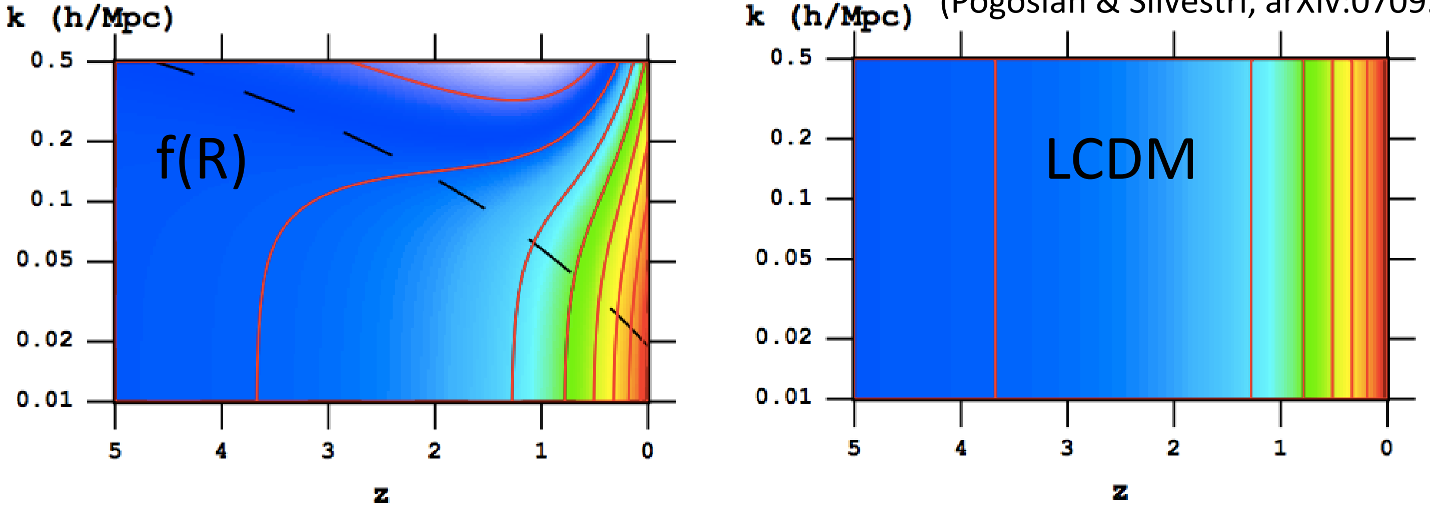
$$m_{f_R}^2 \equiv \frac{\partial^2 V_{\rm eff}}{\partial f_R^2} = \frac{1}{3}\left[\frac{1+f_R}{f_{RR}} - R\right]$$

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

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

→ Needs screening on very small scales (Chameleon mechanism)

(Pogosian & Silvestri, arXiv:0709.0296)

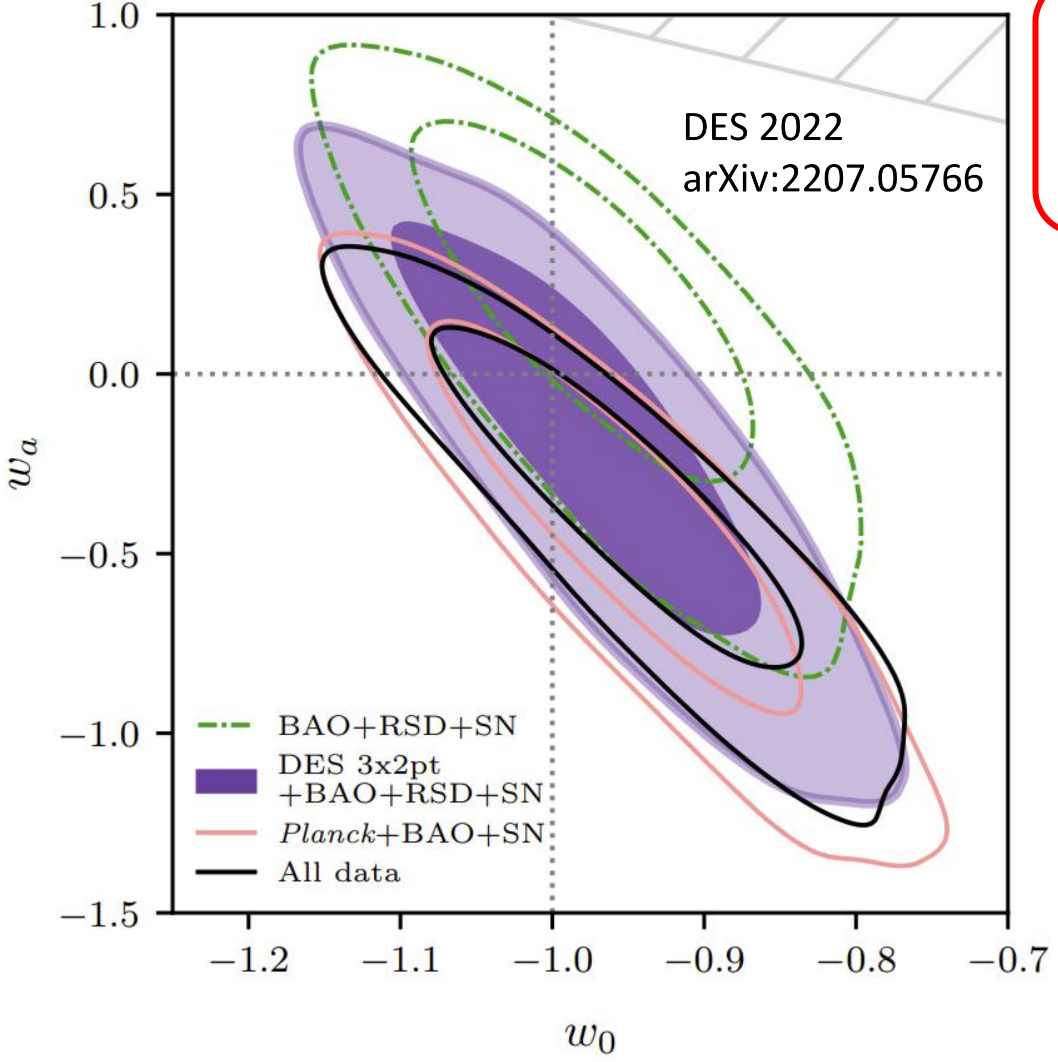


Scale-dependent growth is typical for non-Λ (sound horizon, massive scalaron, screening) and **non-vanishing slip** is typical for modified gravity models (as well as modified GW propagation).

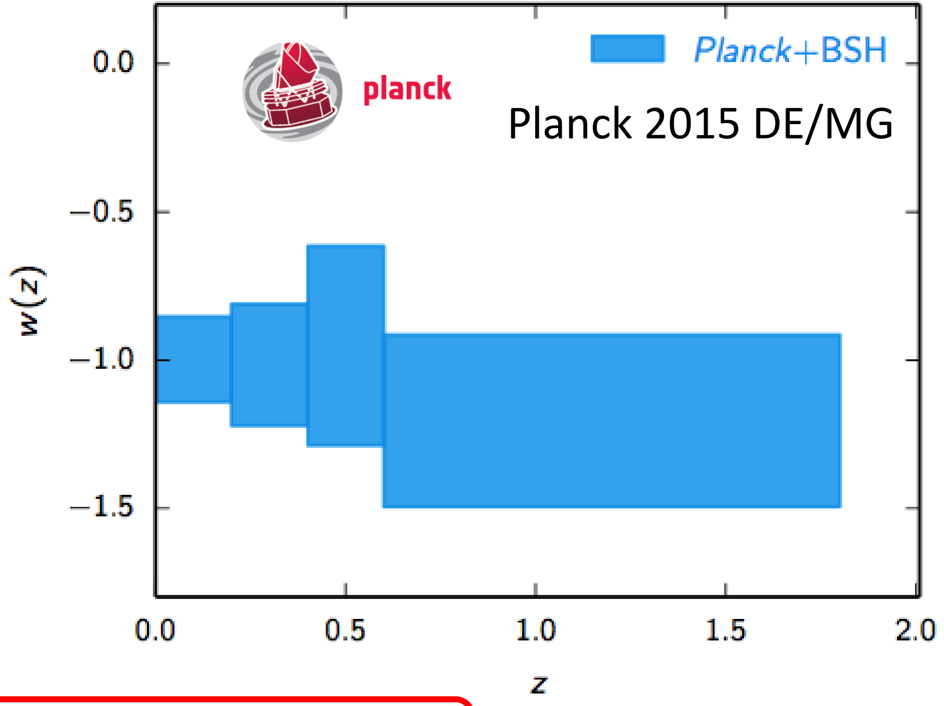
Surveys and what they tell us about DE

- CMB
  - Anisotropies – last scattering & ISW (& lensing!) – distance to last scattering
  - Lensing (φ+ψ)
- Supernovae
  - Luminosity distance (normalized or not) (w) [with enough SN-Ia can do clustering too!]
- Galaxy surveys – imaging, multi-band, spectroscopic
  - BAO, transverse & radial : Angular diameter distance, expansion rate (w)
  - Galaxy spectrum, multipoles : RSD / velocities, dipole : acceleration / 'time distortion' (ψ)
  - Cosmic shear : gravitational lensing (φ+ψ)
- Radio surveys
  - As above, but potentially higher redshift, larger volumes with intensity mapping
- Gravitational waves
  - Dark sirens, GW propagation (speed, friction)
  - Strong-field tests / PPN
- Other – FRB, GRB / gamma-rays, X-ray, neutrinos, …
- Cross-correlations of all the above … 20x2pt … who offers more? ☺

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

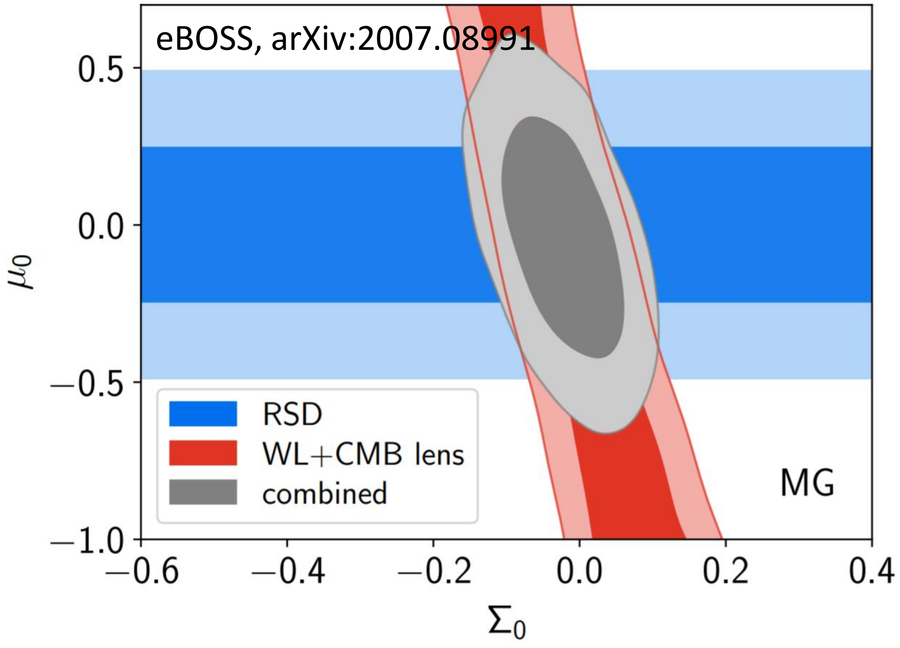
w_0, w_a FoM	Flat	Non-flat
Linear setting		
GC_s	40	19
Pessimistic setting		
GC_s	14	10
WL	23	5
GC_s+WL	99	40
GC_{ph}+WL	64	14
GC_s+WL+GC_{ph}	123	49
WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	367	59
GC_s+WL+GC_{ph}+$XC^{(GC_{ph},WL)}$	377	128
Optimistic setting		
GC_s	55	19
WL	44	12
GC_s+WL	157	87
GC_{ph}+WL	235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

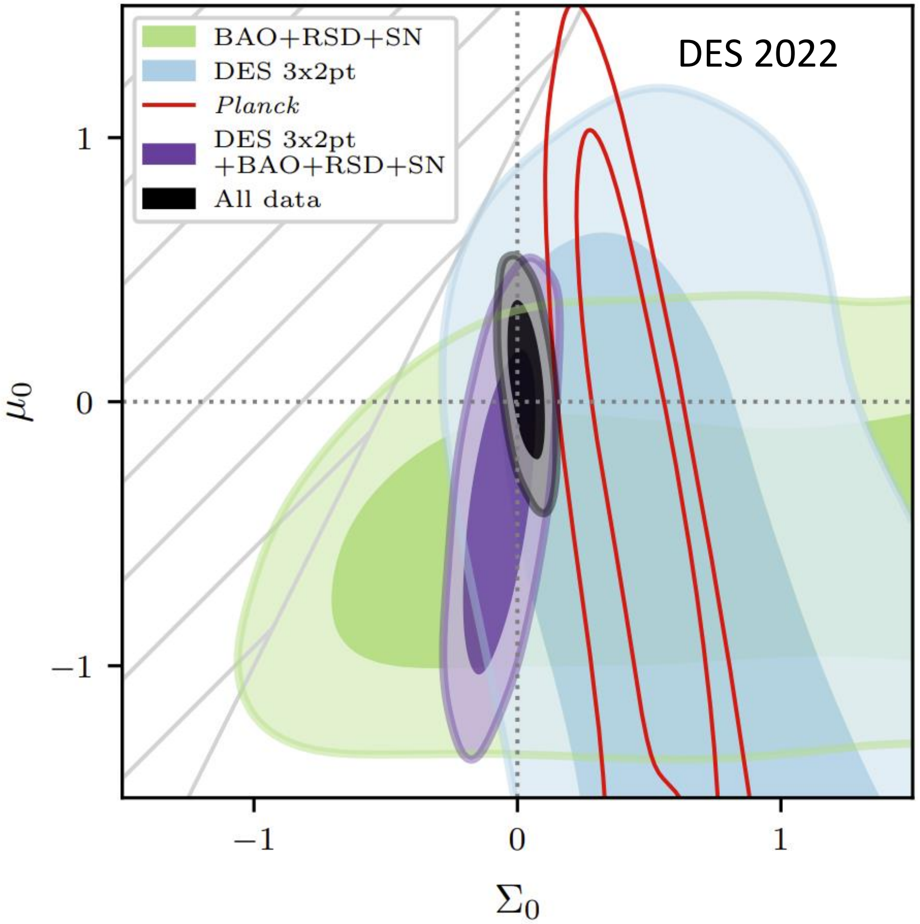
Euclid prep VII: Forecast validation
Blanchard et al, arXiv:1910.09273

Comments:

- FoM ~ inverse of w_0/w_a error ellipse.
- ESA expects a FoM of 400 for Euclid alone.
- Errors on w_0/w_a :
    - 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
- There are other probes (eg clusters, strong lensing) and combinations (6x2pt, external).

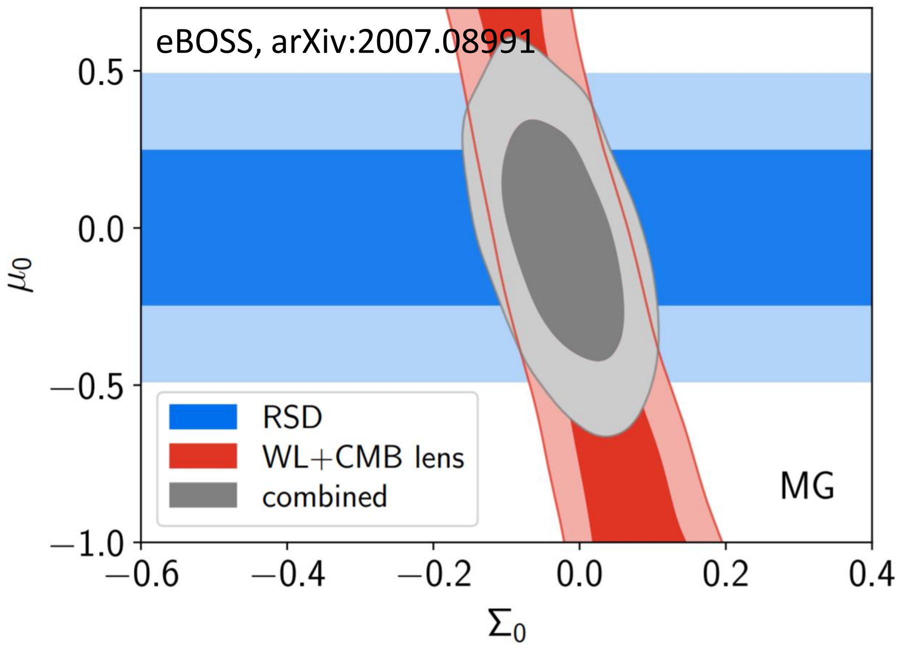
Constraints on "Modified Gravity"

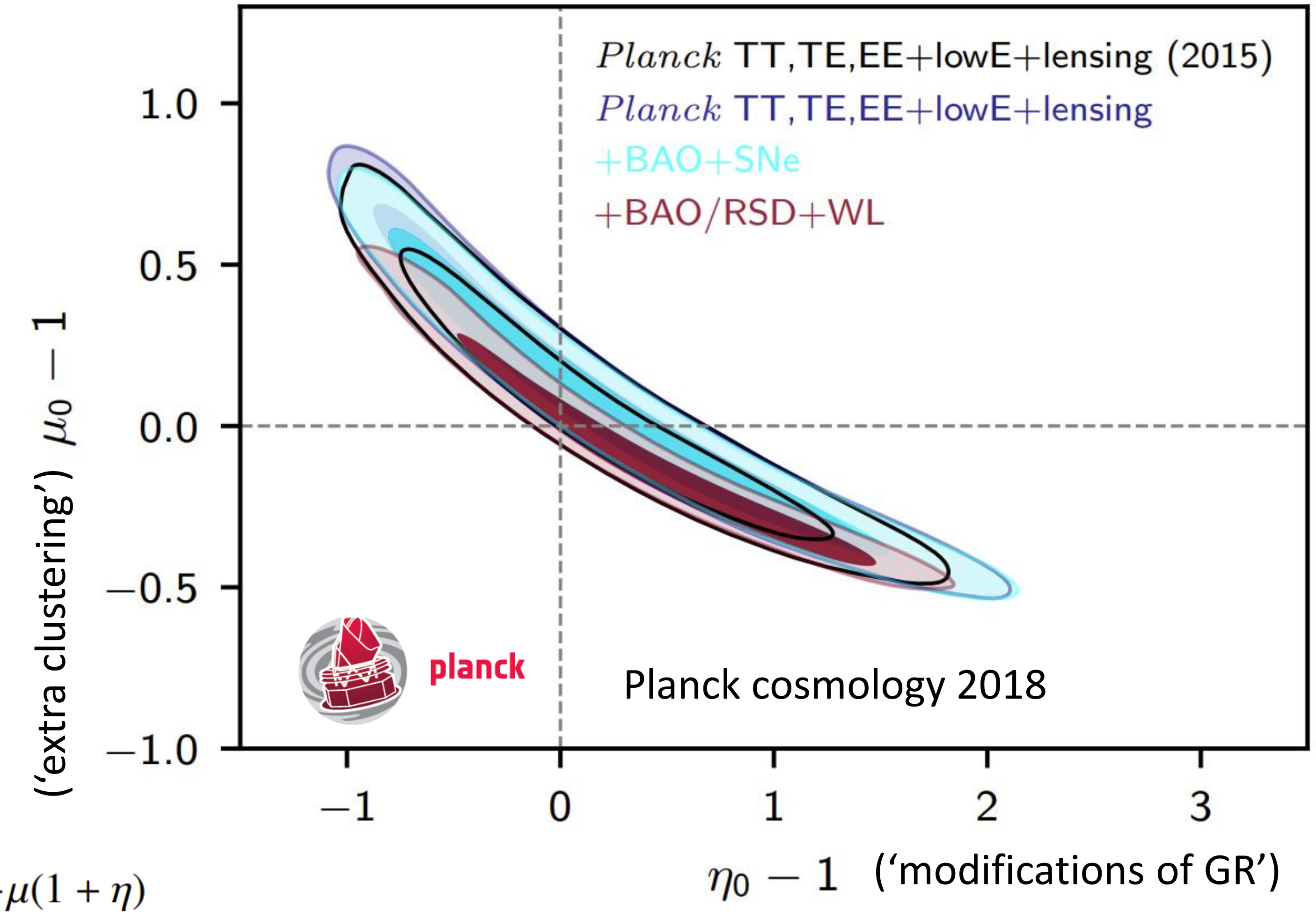




- Σ: (Φ+Ψ) → lensing
  Limit: ~ 0.05
- μ: Ψ → acceleration of massive particles
  Limit: ~ 0.25

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”

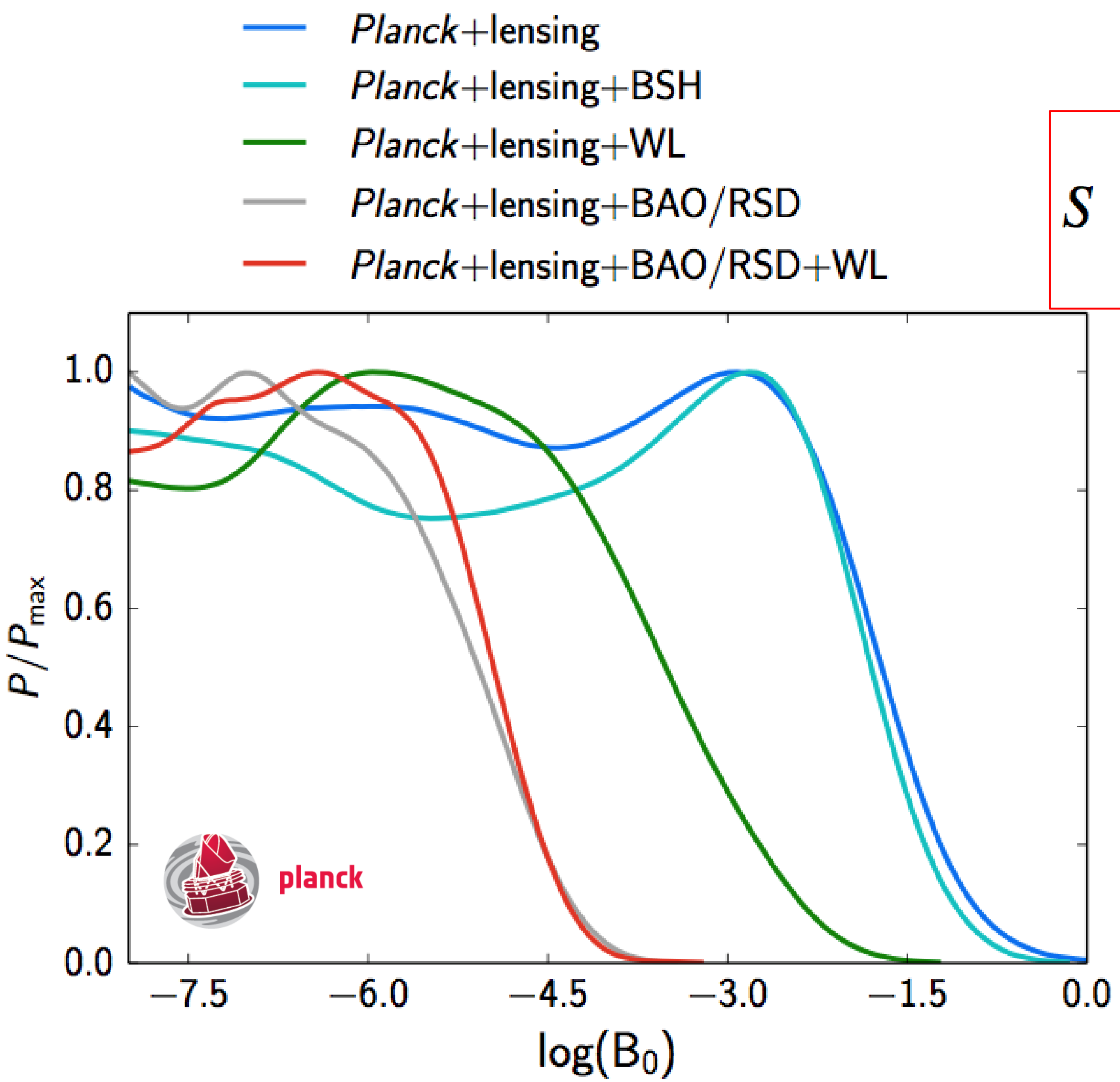
(Casas et al arXiv:1703.01271 – not official Euclid forecast)

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

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

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)

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

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

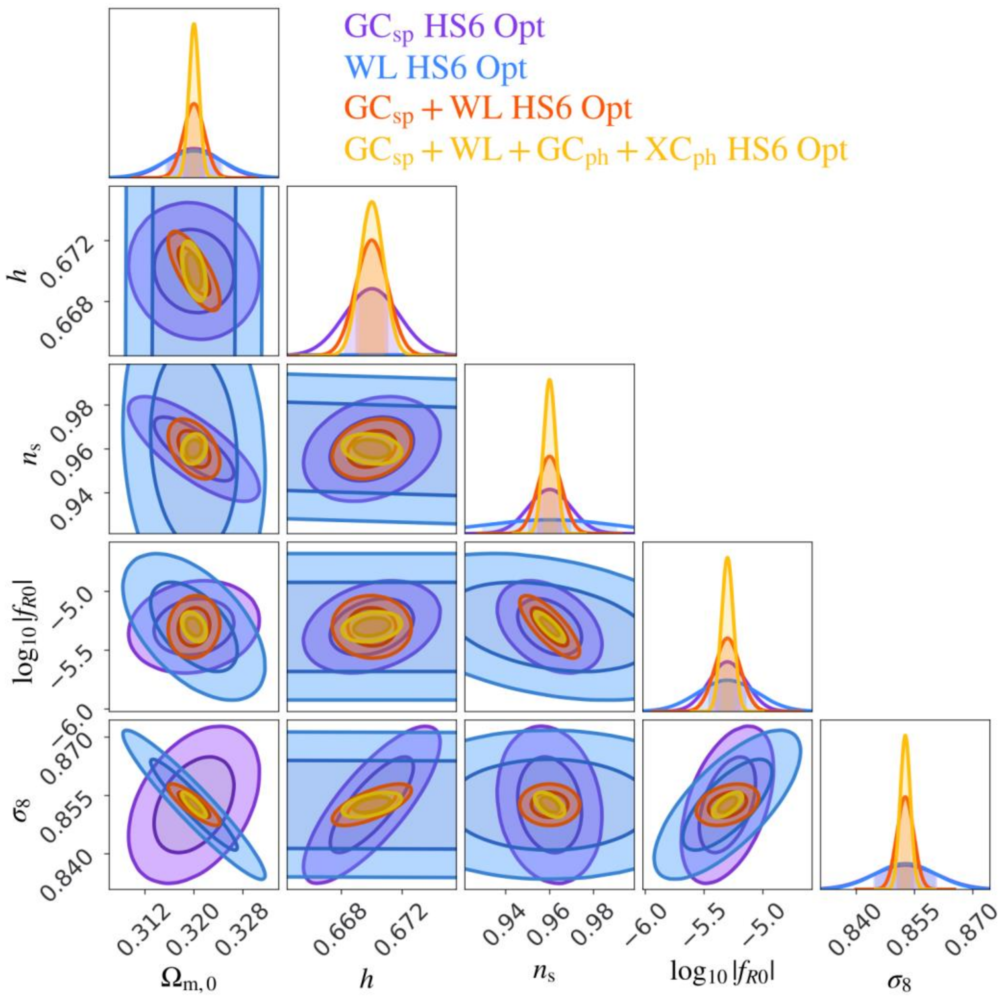
in quasistatic limit

4 orders of magnitude improvement from RSD!

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

Euclid and f(R)

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



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

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)

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

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

(quasistatic limit)

current constraints:
small scales: $\omega_{BD} > 10^5$ → absence of screening is a problem
cosmology : $\omega_{BD} \gtrsim 10^3$ [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 relative uncertainty on ω_{BD}:	Pessimistic:
JBD1: 3x2pt : 27% ; adding GCsp : 25%	JBD1 can be detected,
JBD2: 3x2pt : 48%; adding GCsp : 40%	JBD2 not with high significance.

Euclid and DGP (Dvali et al, 2000)

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

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

"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)

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

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

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

- Euclid was successfully launched and is operating nominally now.
- Euclid & other surveys will significantly tighten DE/MG constraints.
  - 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 challenge for theorists / simulators to keep systematics below statistics.
- Other observables exist too! Both to measure the same things in different ways (eg magnification) or to observe other things (GW).
- And remember that we need to check ***everything*** (not only Lambda), including the cosmological principle!


Thank you!