Models beyond LCDM

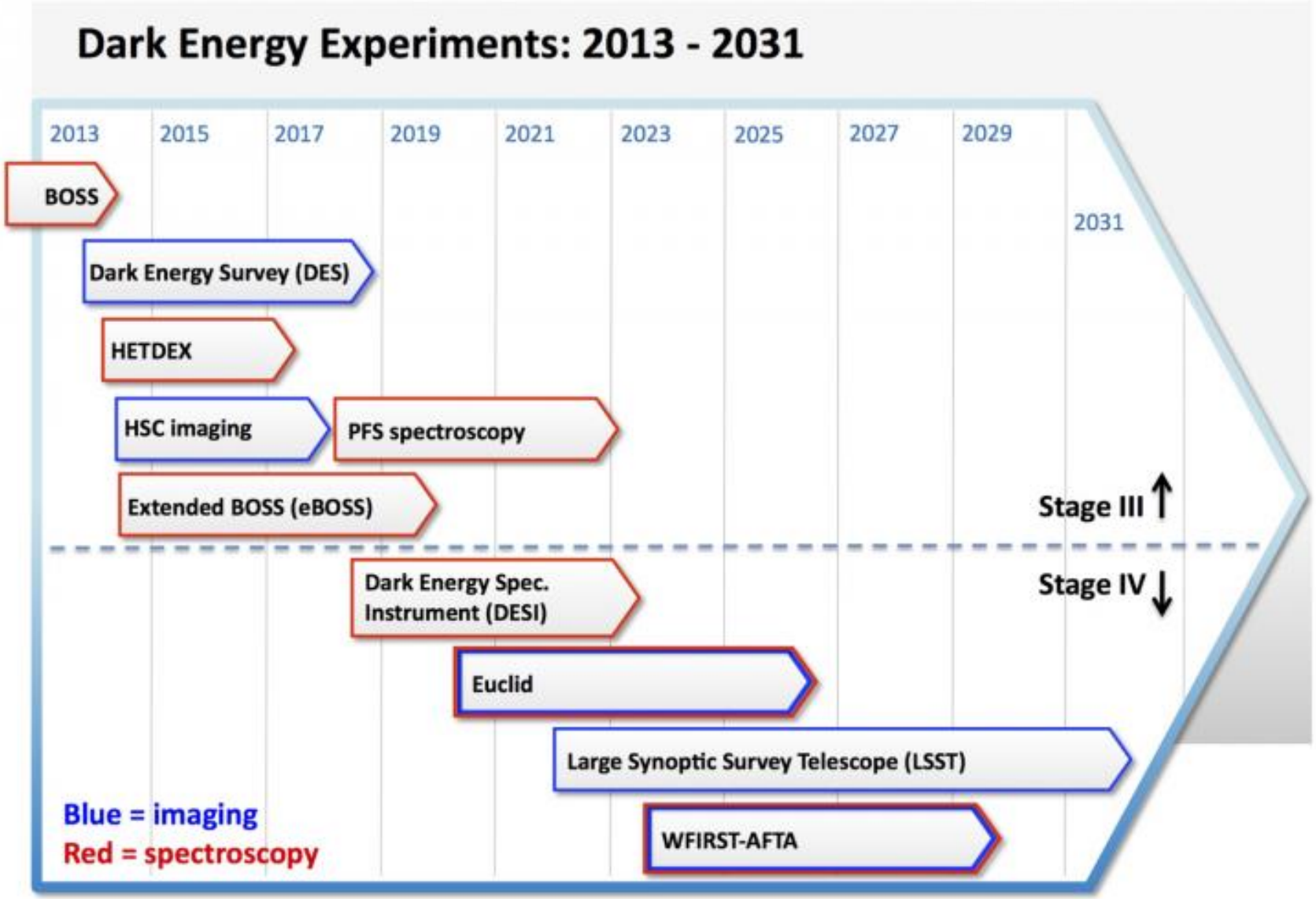
Kazuya Koyama

University of Portsmouth

Plan

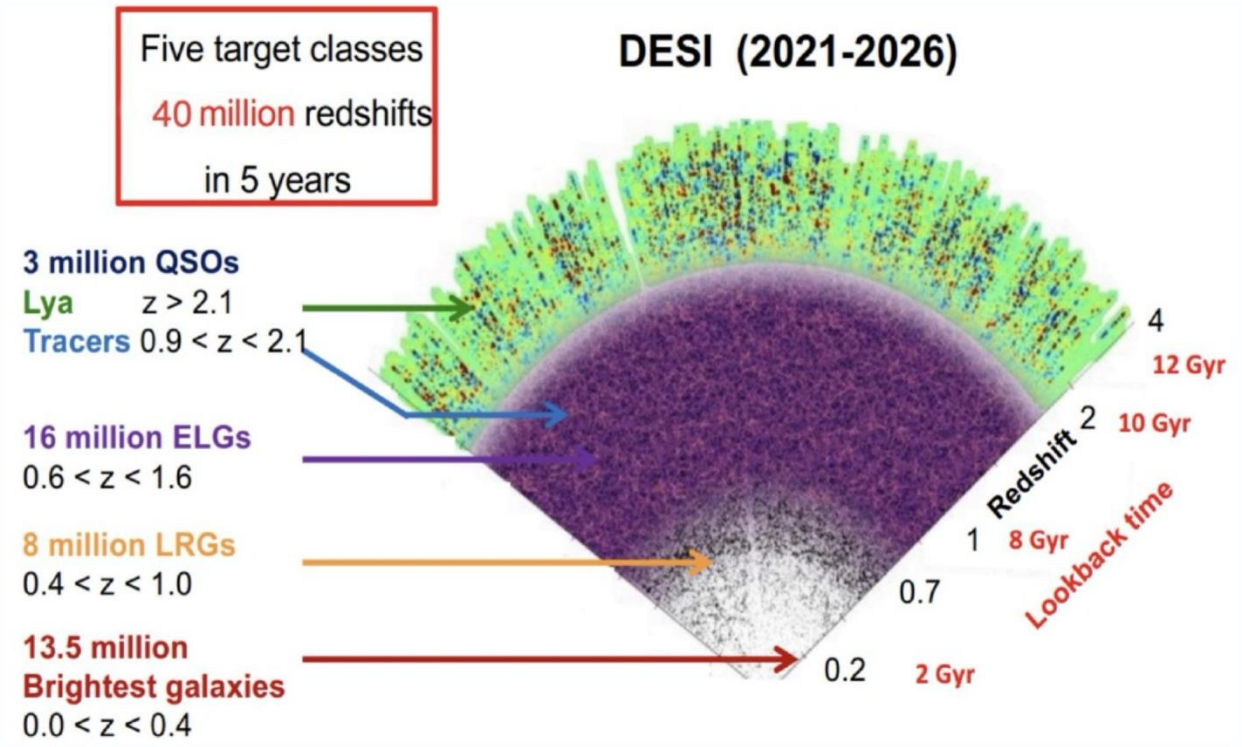
- Morning session: Kazuya Koyama
  kazuya.Koyama@port.ac.uk

- Afternoon session: Daniela Saadeh
  Daniela.Saadeh@port.ac.uk

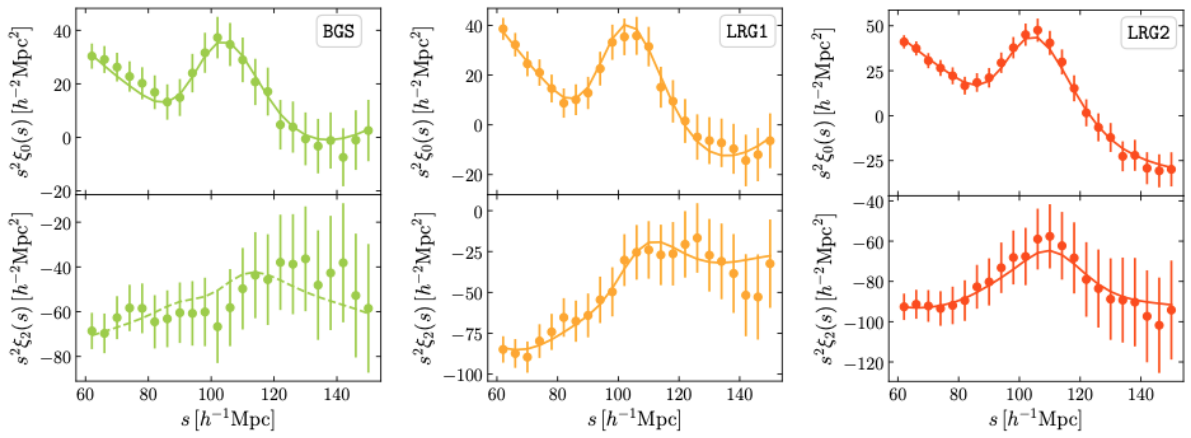

Dark Energy Experiments: 2013 - 2031
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
BOSS
Dark Energy Survey (DES)
HETDEX
HSC imaging
PFS spectroscopy
Extended BOSS (eBOSS)
Stage III
Stage IV
Dark Energy Spec. Instrument (DESI)
Euclid
Large Synoptic Survey Telescope (LSST)
WFIRST-AFTA
Blue = imaging
Red = spectroscopy

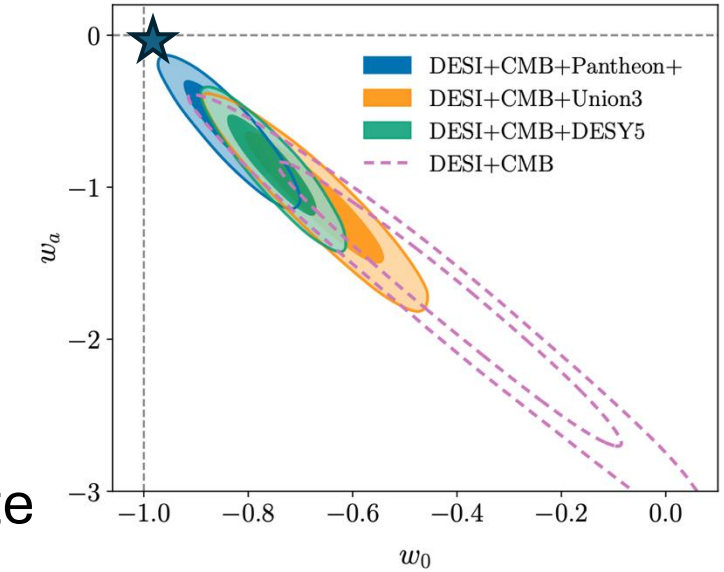
1401.6085

Dark Energy Spectroscopic Instrument (DESI)



Baryon Acoustic Oscillations



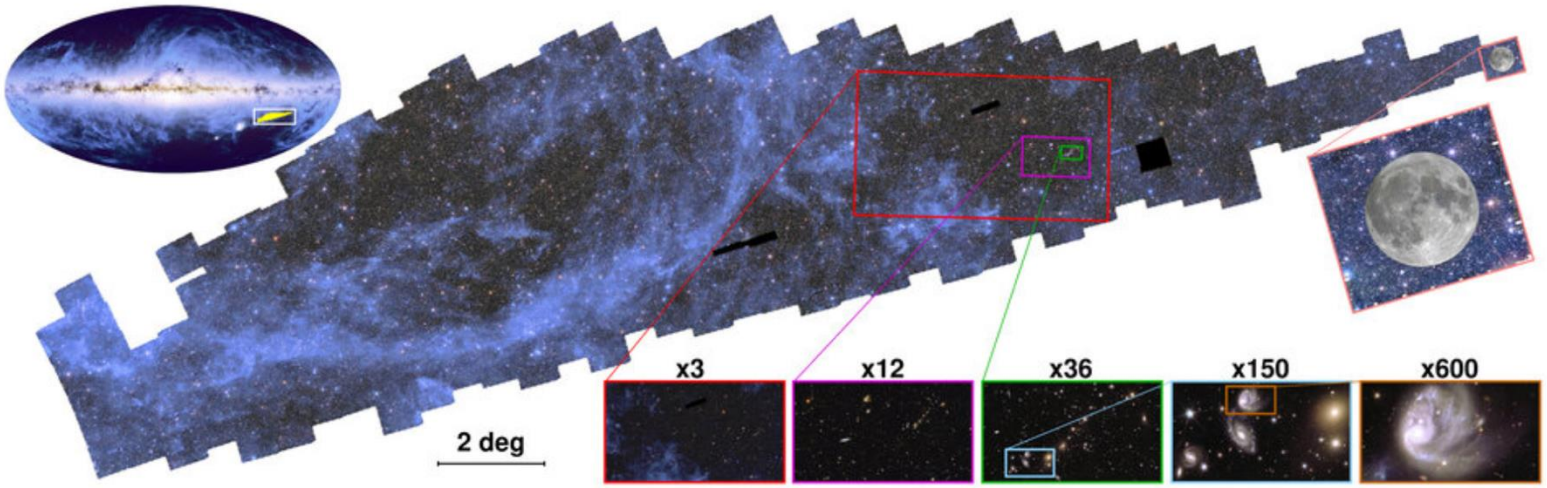


40 million spectroscopic redshifts
between 0 < z < 2.5
Y1 2024, Y3 2025, final data 2026

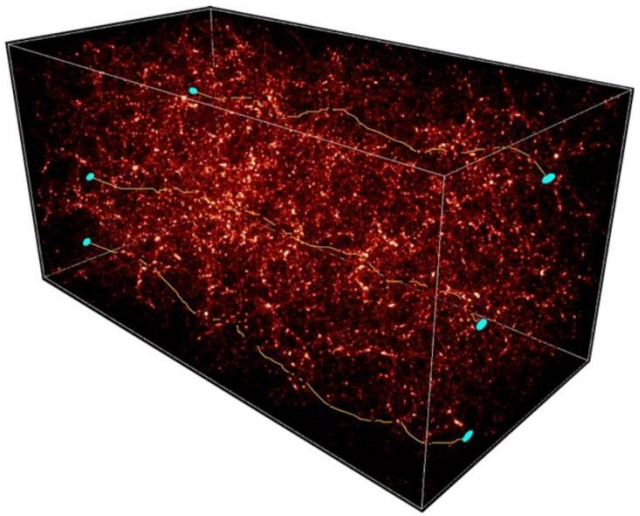
dark energy
equation of state

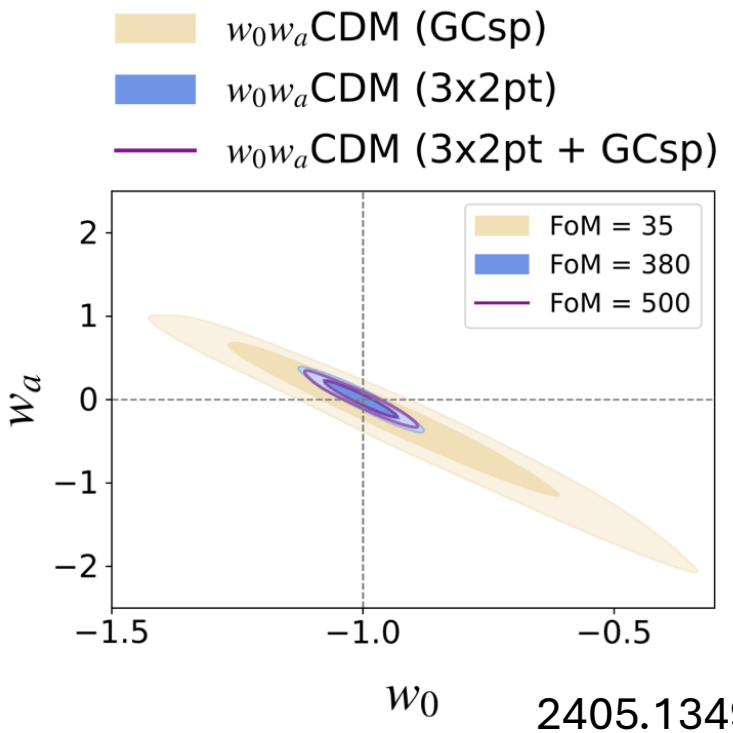
Euclid

Early Release Observations

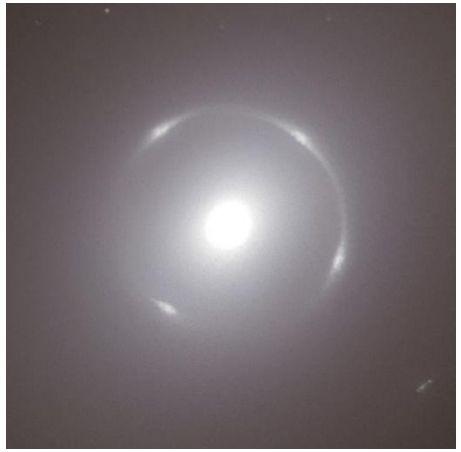


— Euclid's mosaic explained





Euclid Q1



Images of 1.5 billion galaxies
35 million spectroscopic redshifts
between 0.9 < z < 1.85

DR1 2026, 6-year mission

2405.13491

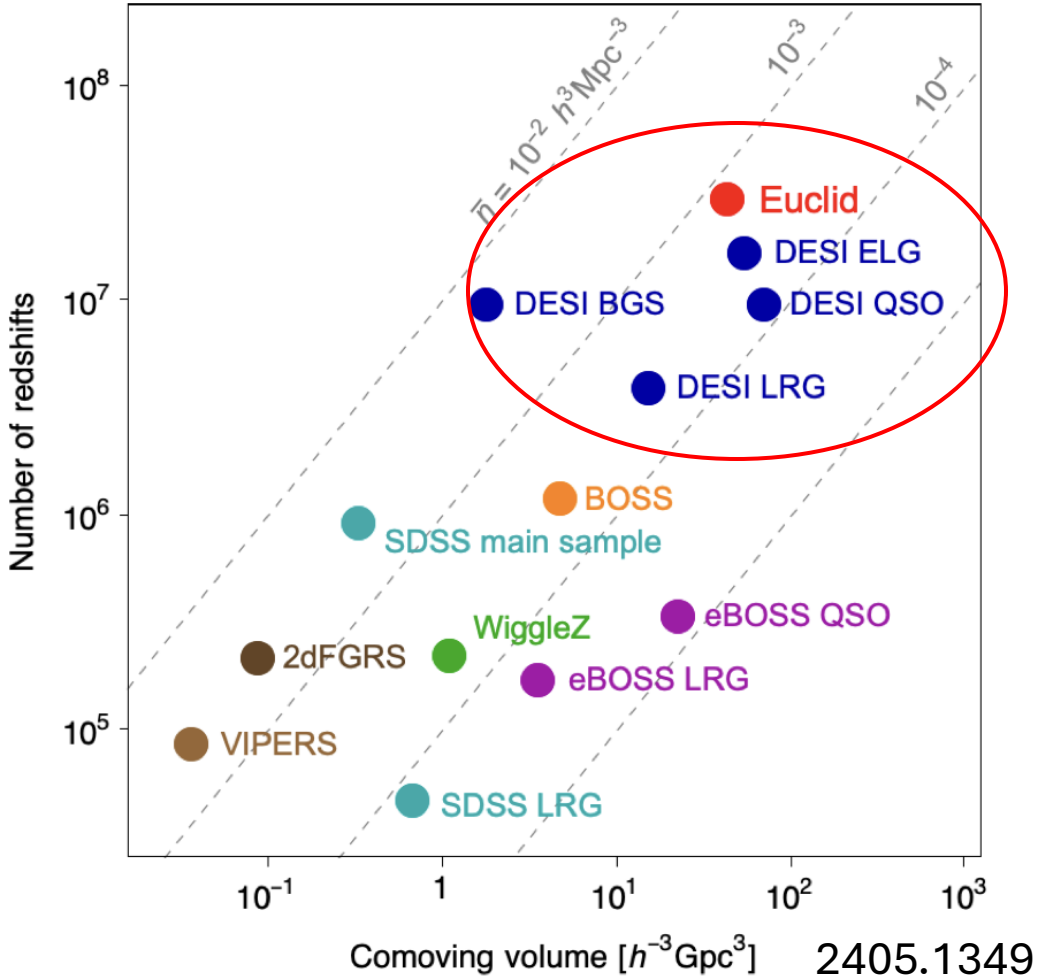
Rubin’s LSST (Legacy Survey of Space and Time)

Images of 20 billion galaxies
DR1 2026 10-year mission

First light images

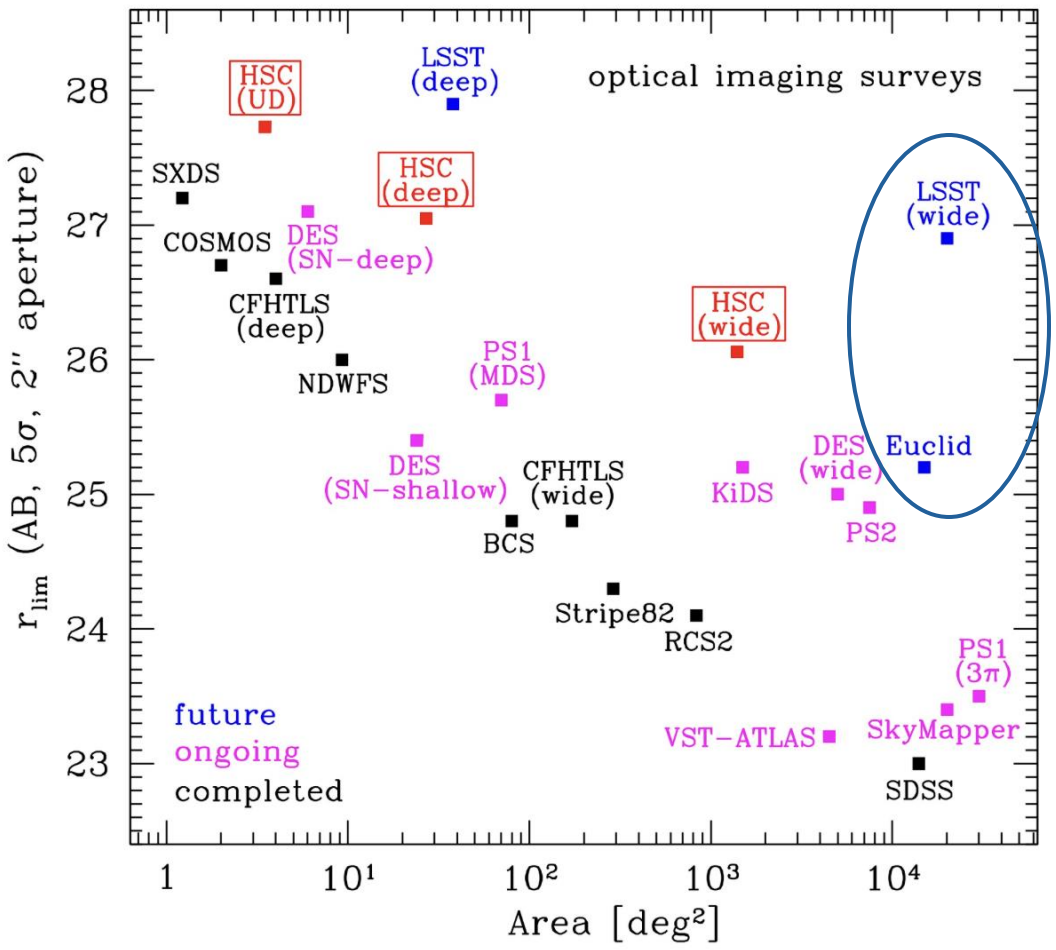
From stage III to stage IV

Spectroscopic surveys



2405.13491

Imaging surveys



https://hsc.mtk.nao.ac.jp/ssp/science/weak-lensing-cosmology/

Euclid Science Requirements Document

Date of Issue 2015-08-25

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.

Standard Cosmology

Basic assumptions (1)

Isotropy and homogeneity

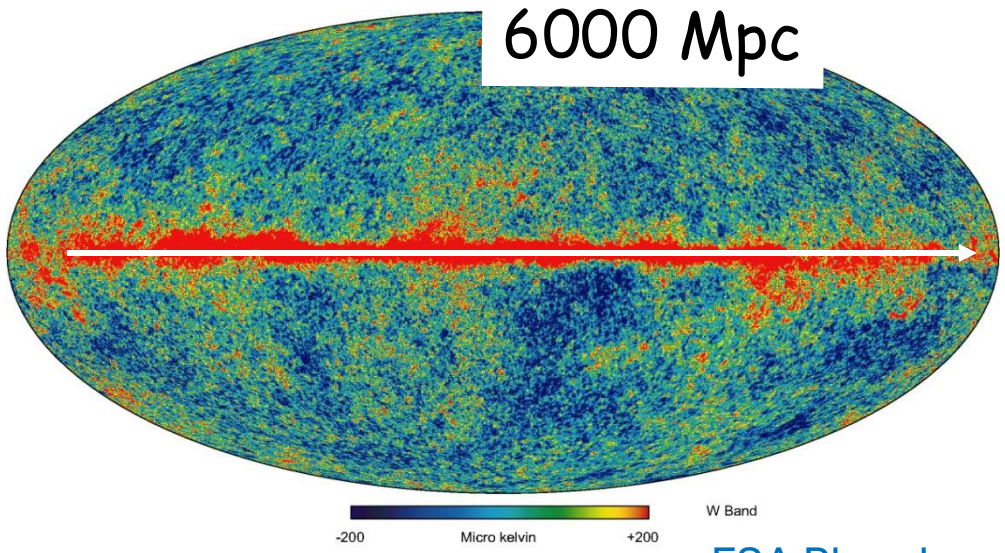
- Isotropy

  CMB fluctuations

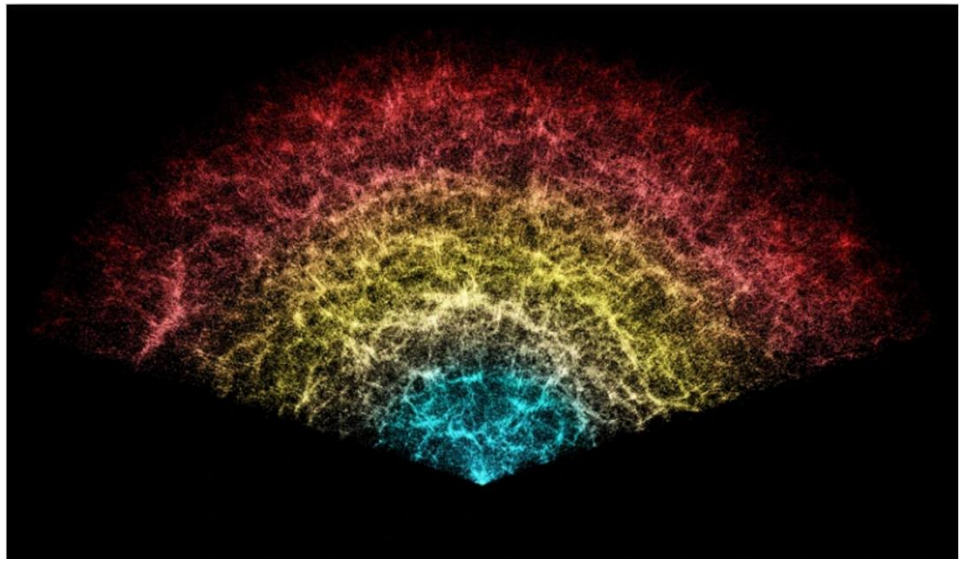
$$\frac{\Delta T}{T} \approx 10^{-5}$$

- Homogeneity

  galaxy distribution



ESA Planck



DESI

- Friedmann-Robertson-Walker (FRW) metric

$$ds^2 = -c^2 dt^2 + a(t)^2 \gamma_{ij} dx^i dx^j$$

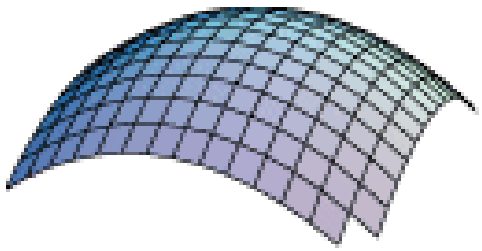
$$ds_3{}^2 = \gamma_{ij} dx^i dx^j = d\chi^2 + \begin{Bmatrix} \sin^2\chi \\ \chi^2 \\ \sinh^2\chi \end{Bmatrix} \left(d\theta^2 + \sin^2\theta d\phi^2 \right)$$

$${}^{(3)}R_{ijkl} = K(\gamma_{ik}\gamma_{jl} - \gamma_{il}\gamma_{jk}) : \text{ 3D curvature}$$

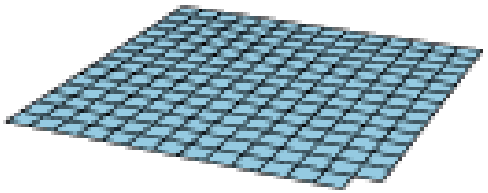
$S^3 : K = 1$

$E^3 : K = 0$

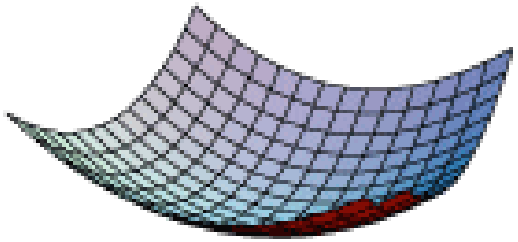
$H^3 : K = -1$



閉じた宇宙



平坦な宇宙



開いた宇宙

Basic assumption (2)

- General Relativity (GR)

$$\boxed{G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R} = \boxed{8\pi G T_{\mu\nu}}$$

geometry matter

- Matter

$$T^{\mu}{}_{\nu} = (\rho + p) u^{\mu} u_{\nu} + P \delta^{\mu}_{\nu} \qquad u^{\mu} = (-1, 0, 0, 0)$$

- Bianchi identity

$$\nabla^{\mu} G_{\mu\nu} = 0 \quad \Rightarrow \quad \nabla^{\mu} T_{\mu\nu} = 0$$

Friedman equation

- Einstein equations

$$H(t)^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

- Energy-momentum conservation

$$\dot{\rho} + 3H(\rho + p) = 0, \quad \rho = \sum_i \rho_i$$

- Two of these equations are independent

Three unknown quantities a, ρ, P

➡ we need to specify the equation of state $w = P/\rho$

Basic assumption (3)

- We introduce dark energy in addition to “known” matter such as baryons, cold dark matter and radiation and assume that they satisfy the conservation equation independently

$$\dot{\rho}_i + 3H(1+w_i)\rho_i = 0, \qquad w_i = \frac{P_i}{\rho_i} \qquad\qquad \rho_i \propto a^{-3(1+w_i)}$$

- equation of state

$$w_r = \frac{1}{3}, \quad w_m = 0, \quad w_{DE} = ?$$

- Density parameter

$$\Omega_i = \frac{8\pi G\rho_i}{3H^2}, \quad \Omega_K = -\frac{K}{(aH)^2} \qquad\qquad \sum_i \Omega_i = 1$$

What we measure

- Distance **assumption (1)**

$$ds_3^{\,2} = d\chi^2 + f_K(\chi)^2\left(d\theta^2 + \sin^2\theta d\phi^2\right), \quad f_K = \frac{1}{\sqrt{-K}}\sinh\left(\sqrt{-K}\,\chi\right)$$

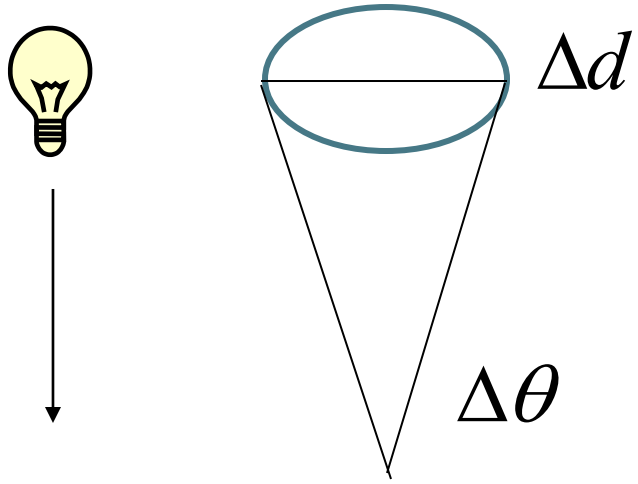
$$\chi = -\int_0^t \frac{c}{a(t')}dt' = \frac{c}{a_0 H_0}\int_0^z \frac{dz'}{E(z')}, \quad E(z) = \frac{H(z)}{H_0}$$

- Luminosity distance and angular diameter distance

$$d_L = f_K(\chi)(1+z)$$

redshift $1+z = \dfrac{a_0}{a}$

$$d_A = \frac{d_L}{(1+z)^2}$$



- Age of the universe

$$t = \int_0^{t_0} dt = H_0^{-1} \int_0^z \frac{dz'}{E(z)(1+z)}$$

- The present-day Hubble parameter

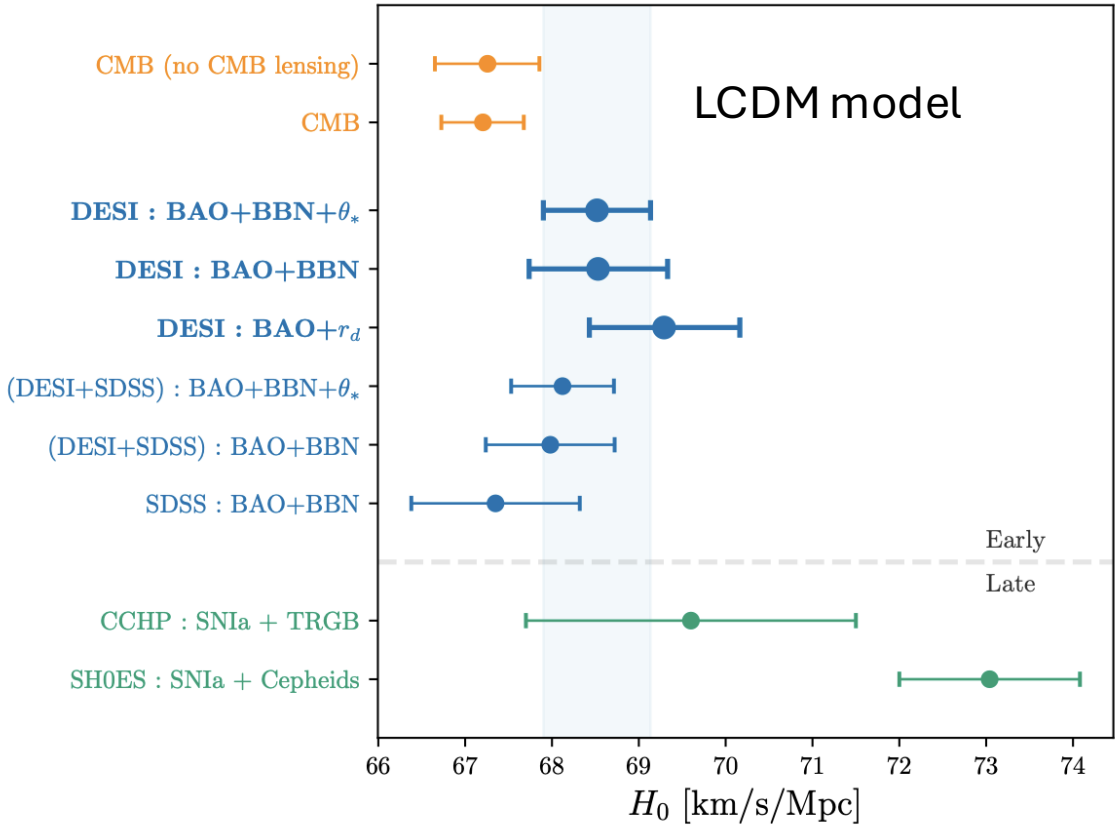
$$H_0^{-1} = 9.78 \times 10^9 \, h^{-1} \text{ years}$$

$$cH_0^{-1} = 2998 \, h^{-1} \text{ Mpc}$$

$$H_0 = 2.13 \times 10^{-42} \, h^{-1} \text{GeV}$$

- Distance at small redshifts

$$d_L \approx d_A \approx c H_0^{-1} z$$



DESI DR1 2404.03002

Theoretical predictions

- Now we use **assumption (2) and (3)**

$$E(z)^2 = \Omega_{m0}(1+z)^3 + \Omega_{r0}(1+z)^4 + \Omega_{K0}(1+z)^2 + \Omega_{DE}\exp\left[3\int_0^z dz'\frac{1+w_{DE}(z')}{1+z'}\right]$$

- LCDM model

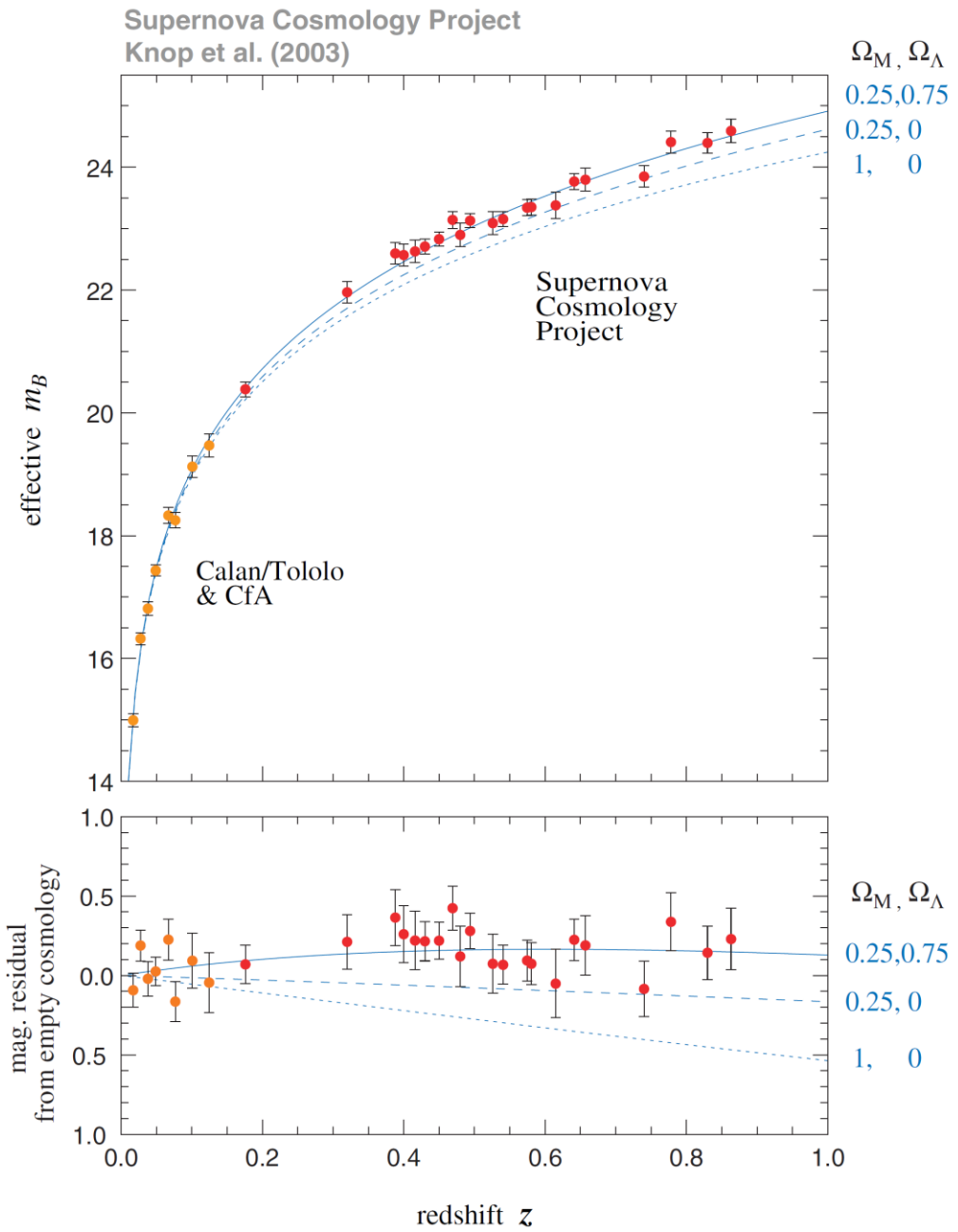
$$w_{DE} = -1, \quad \Omega_{DE0} = \Omega_\Lambda, \quad (\Omega_{r0} = 8\times10^{-5})$$

- Distance measurements

  Supernovae d_L

  Cosmic Microwave d_A

  Baryon Acoustic Oscillations d_A

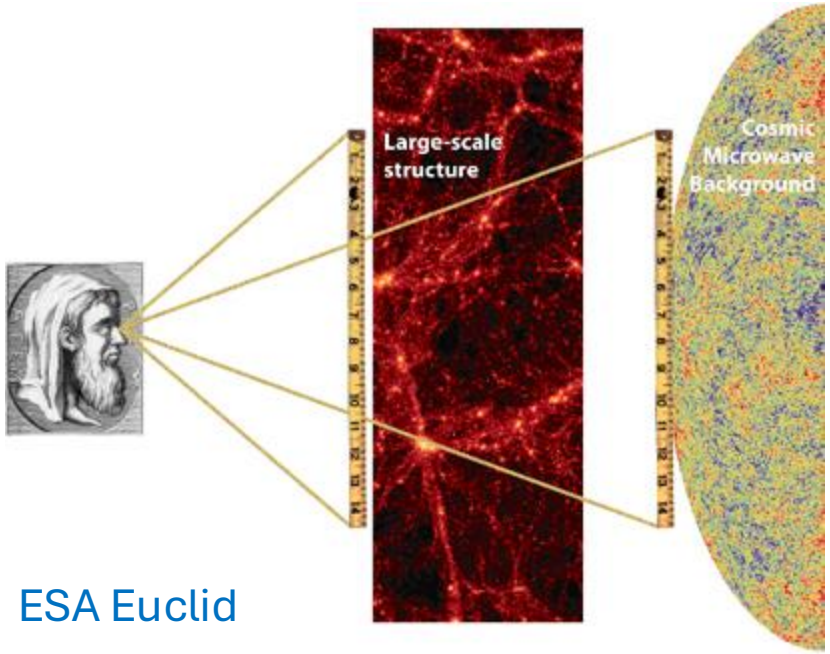


Observations – background

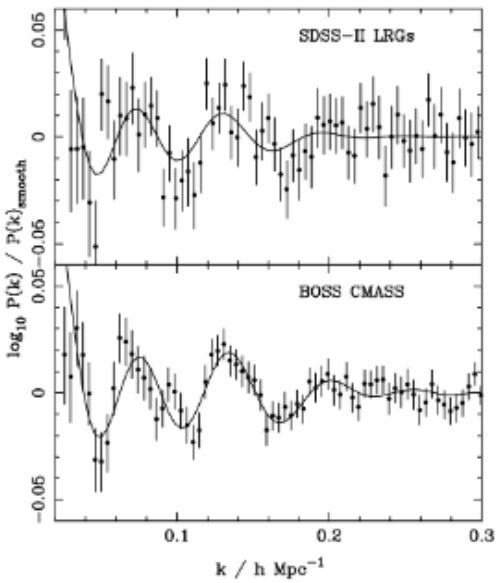
- Background $H(z)$

Supernovae: luminosity distance

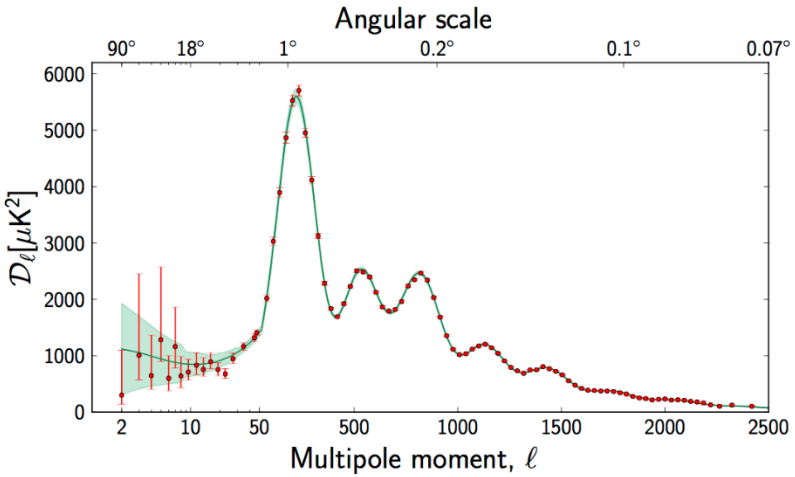
CMB/Baryon Acoustic Oscillations (BAO): angular diameter distance
(the sound horizon as a standard ruler)



ESA Euclid

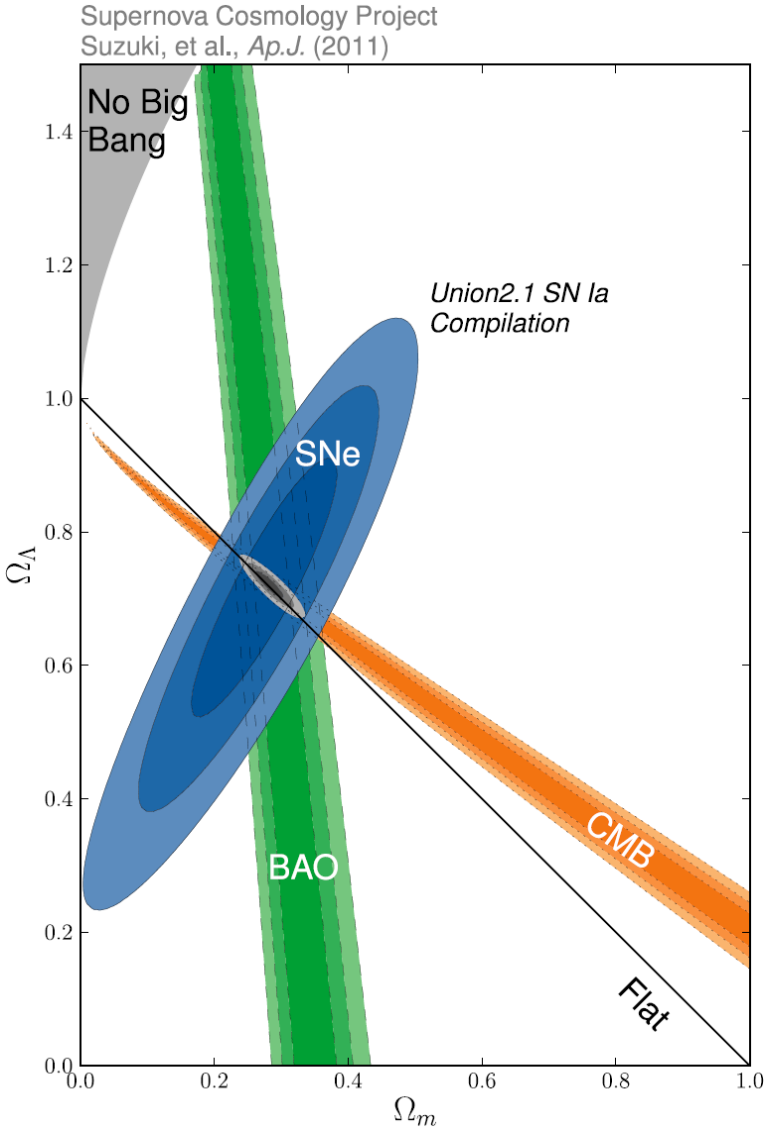


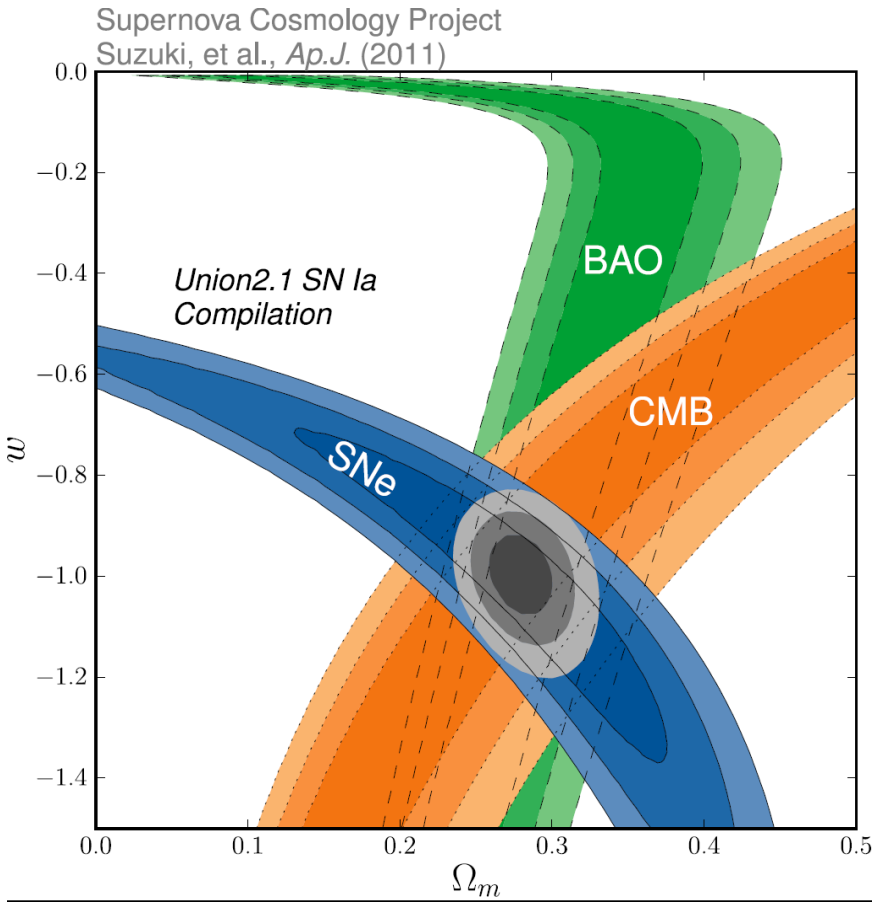
BOSS



ESA Planck

This is what we found



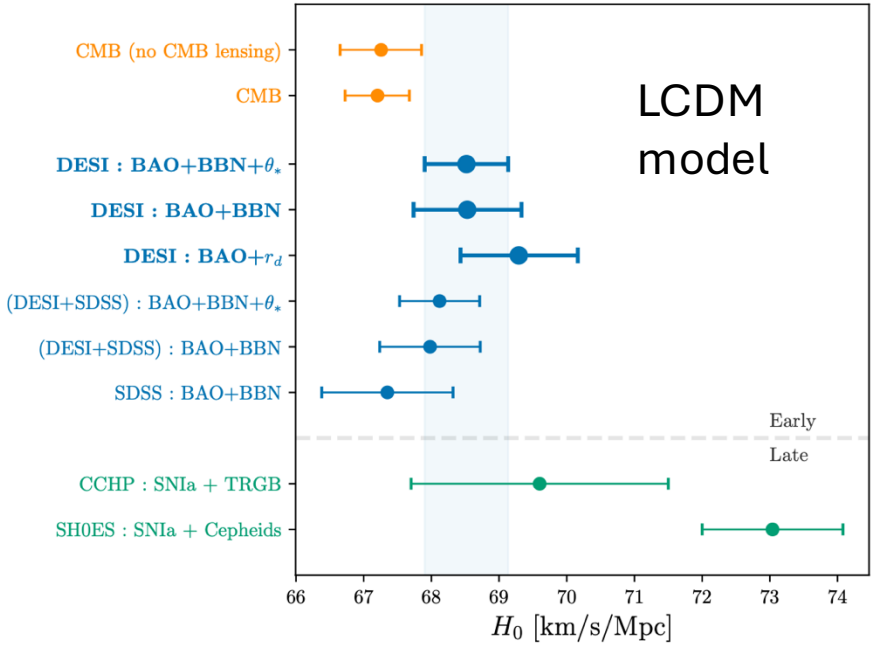


Tensions in LCDM

- Hubble constant

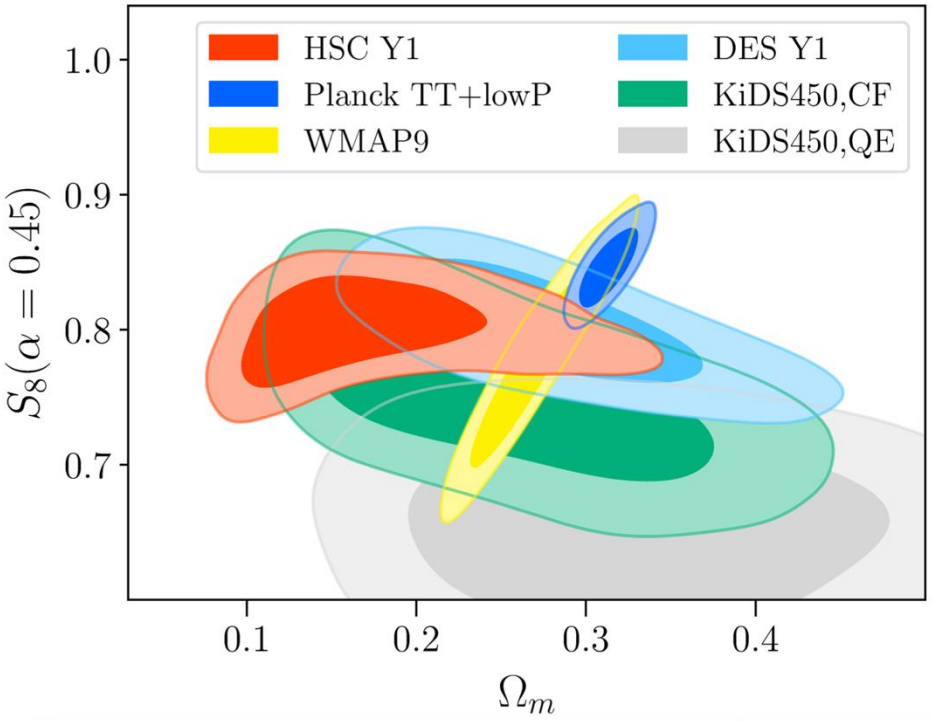
The H_0 Olympics 2107.10291

Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist	
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	X	0.00	0.00	X	X	
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	X	-6.10	-4.10	X	X	
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	X	-9.57	-7.57	✓	✓	3
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	X	-8.83	-4.83	X	X	
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	X	-8.92	-4.92	X	X	
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	X	-4.98	1.02	X	X	
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓	2
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	X	-11.42	-9.42	✓	✓	3
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓	1
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓	1
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓	2
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓	2
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓	2
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	X	-4.94	-0.94	X	X	
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	X	X	
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	X	-0.45	1.55	X	X	
DM $\to$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	X	-0.19	3.81	X	X	
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	X	-0.53	3.47	X	X	



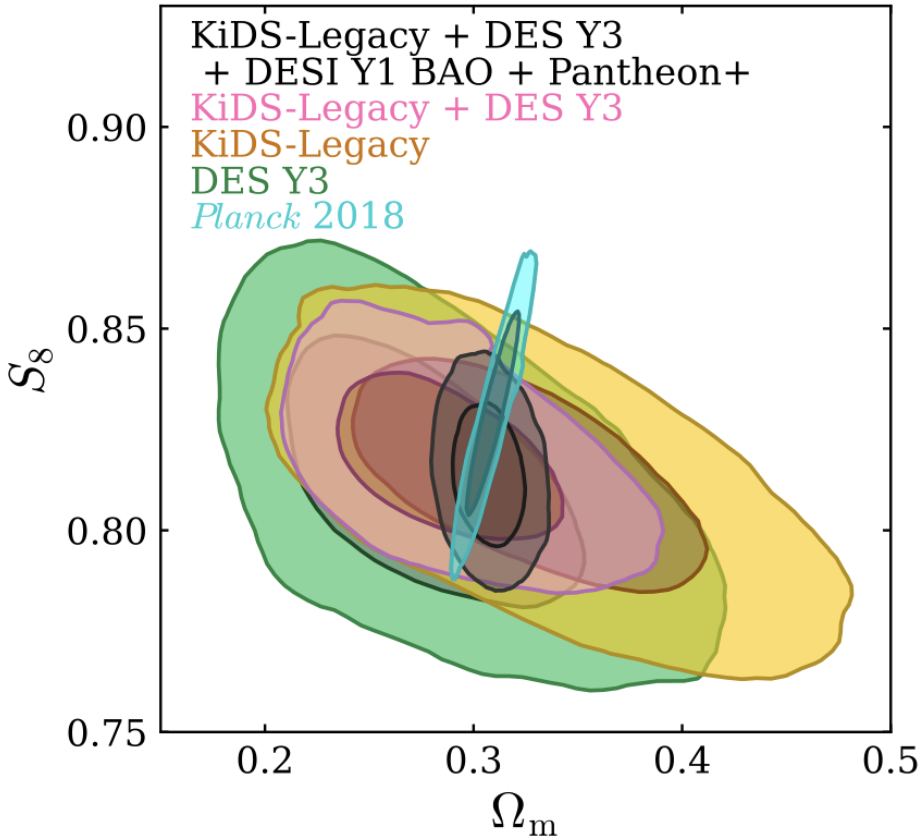
Tensions in LCDM

- S_8 tension



HSC Y1 1809.09148

$$S_8 = \sigma_8 (\Omega_m / 0.3)^{0.45}$$



KiDS-Legacy 2503.19442

$$S_8 \equiv \sigma_8 \sqrt{\Omega_m / 0.3}$$

Fundamental questions

Is dark energy the cosmological constant?

What is dark matter?

What is the origin of structure?

Is the fundamental assumption of the standard model robust? (General Relativity, homogeneity and isotropy)

Join at:

vevox.app

ID:

115-508-585

UNIVERSITY OF PORTSMOUTH

Dark Energy

Quintessence

- Scalar field

We now know a scale field exists (i.e. Higgs)

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}R + S_\phi$$

$$S_\phi = \int d^4x\left[-\frac{1}{2}g^{\mu\nu}\left(\partial_\mu\phi\right)\left(\partial_\nu\phi\right) - V(\phi)\right]$$

energy momentum tensor

$$T^\phi_{\mu\nu} = \left(\partial_\mu\phi\right)\left(\partial_\nu\phi\right) - g_{\mu\nu}\left[\frac{1}{2}g^{\alpha\beta}\left(\partial_\alpha\phi\right)\left(\partial_\beta\phi\right) + V(\phi)\right]$$

$$T^\phi_{\mu\nu} = -\frac{2}{\sqrt{-g}}\frac{\delta(\sqrt{-g}L_\phi)}{\delta g^{\mu\nu}}$$

scalar field equation

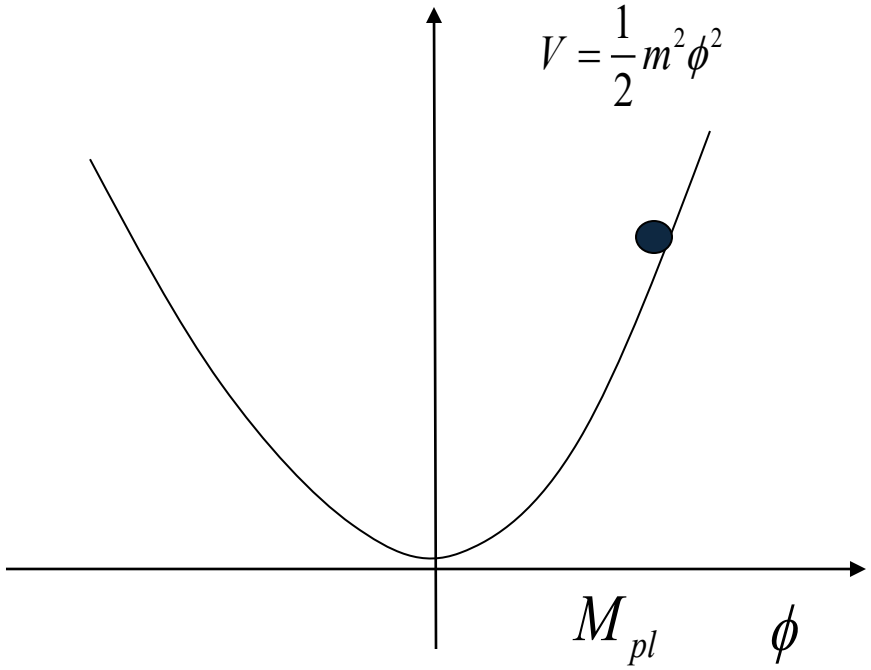
$$\frac{\delta S_\phi}{\delta\phi} = 0 \qquad \nabla^\mu\nabla_\mu\phi - V'(\phi) = 0 \quad \Longleftrightarrow \quad \nabla^\mu T^\phi_{\mu\nu} = 0$$

Background

- Energy density and pressure

$$\rho_\phi = -T_0^0 = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad \phi = \phi(t)$$

$$P_\phi = \frac{1}{3}T_i^i = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$



- Scalar field equation

$$\ddot{\phi} + \boxed{3H\dot{\phi}} + V'(\phi) = 0 \quad \Longleftrightarrow \quad \dot{\rho}_\phi + 3H(\rho_\phi + P_\phi) = 0$$

friction

to realise the acceleration, the scalar filed needs to slow-roll the potential

$$\dot{\phi}^2 << V(\phi) \qquad w_\phi = \frac{P_\phi}{\rho_\phi} \approx -1$$

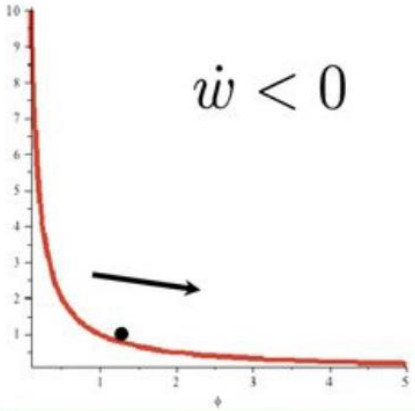
Equation of state

- The energy condition requires w > -1

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

(a) Freezing models

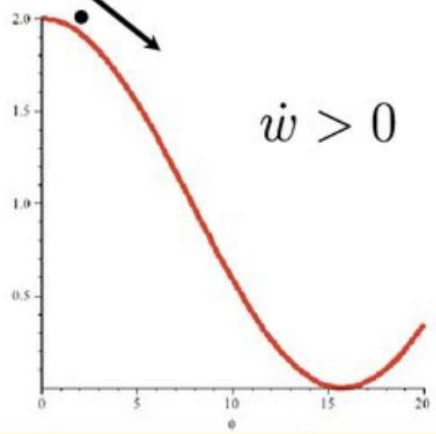
$V(\phi) = M^{4+n}\phi^{-n}, \quad (n > 0)$



w decreases toward -1

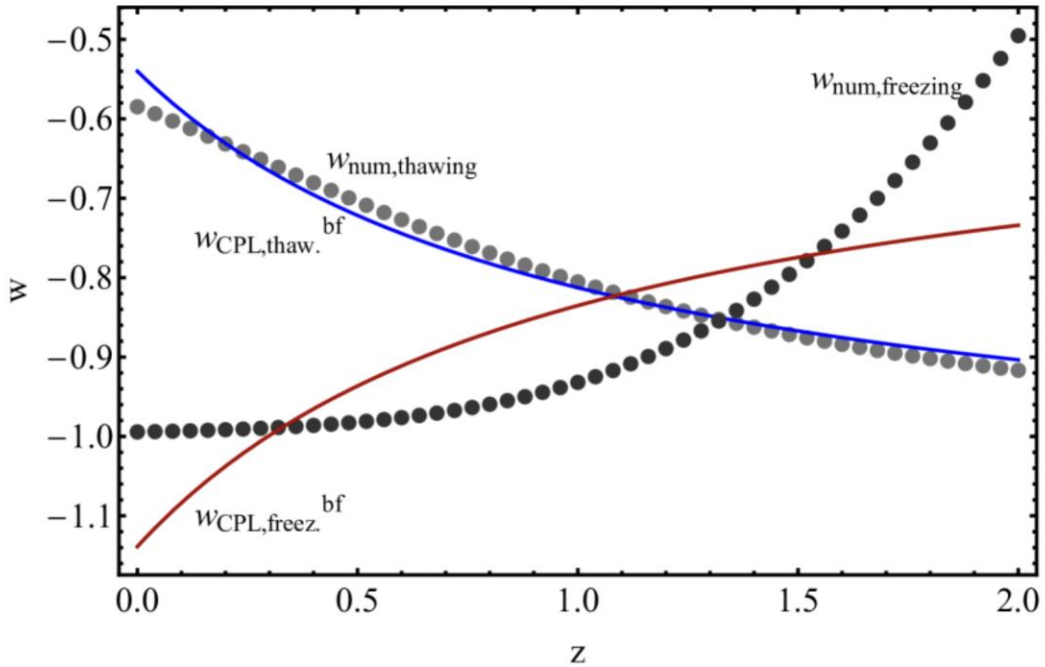
(b) Thawing models

$V(\phi) = \mu^4 [1 + \cos(\phi/f)]$



w increases from -1

e.g



Tsujikawa

1603.02164

Parametrisation

- Chevallier-Polarski-Linder (CPL)

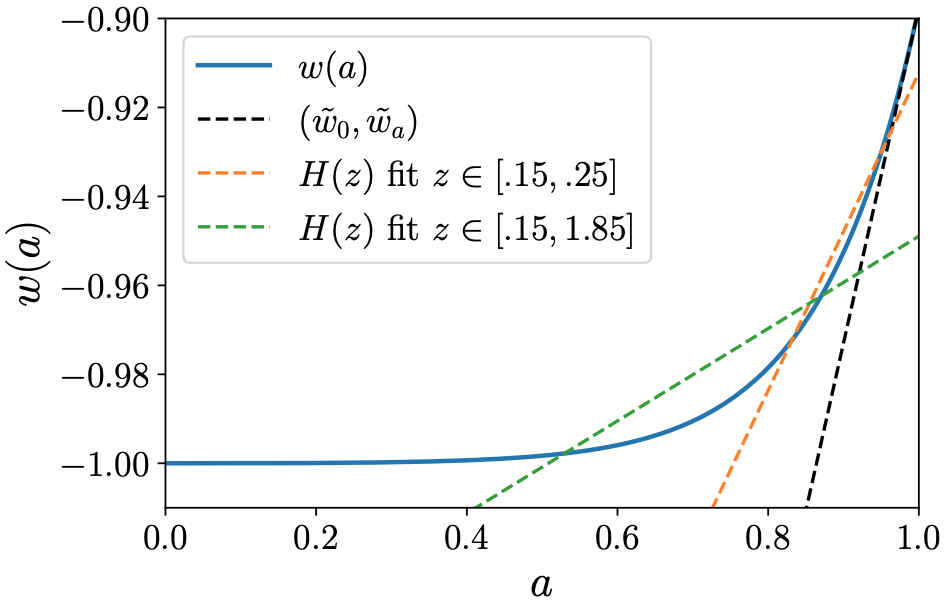
$$w(a) = w_0 + w_a(1-a)$$

- Fitting to quintessence

This parametrisation is not meant to fit w(z). Rather it needs to be fitted to the distance (or the Hubble function)

$$-2\ln\mathcal{L} \simeq \sum_i \frac{(H_{obs}(z_i) - H(z_i))^2}{\sigma_i^2},$$

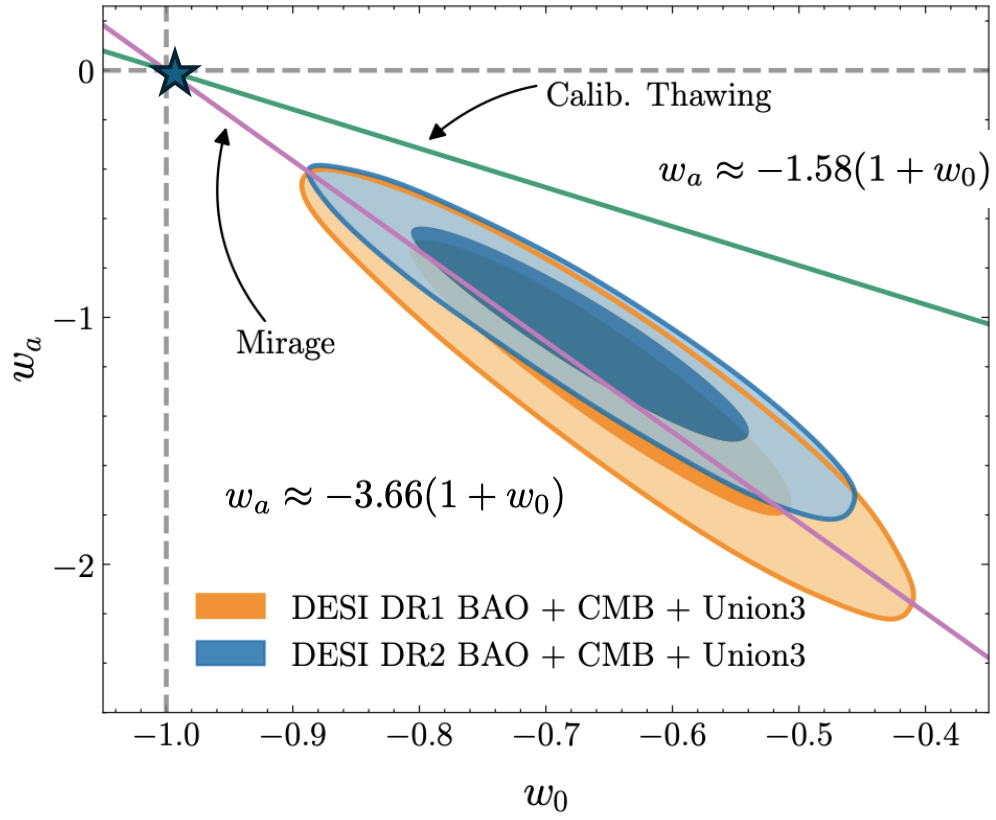
2310.07482

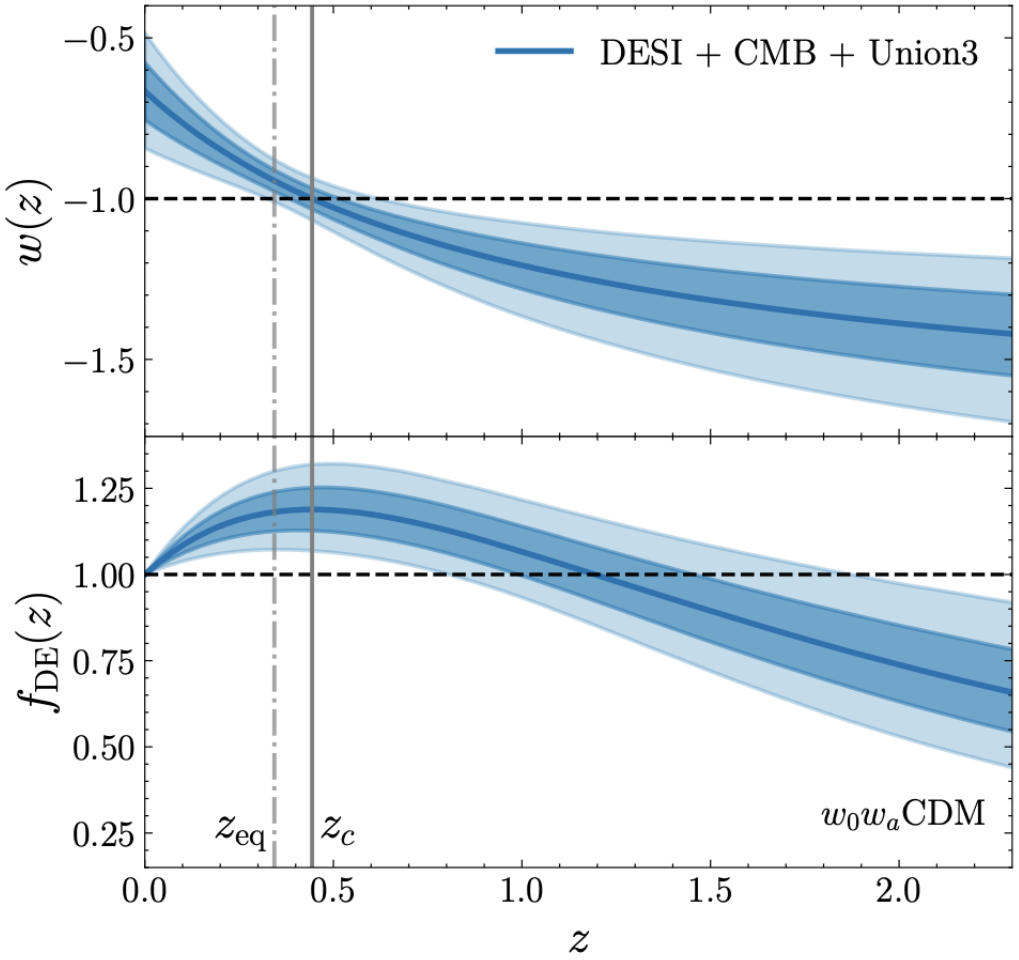


Observational constraints

2503.14743

BAO (DESI) + CMB + SNe





$$f_{\rm DE}(z) \equiv \frac{\rho_{\rm DE}(z)}{\rho_{\rm DE,0}} = \exp\left[3\int_0^z [1+w(z')]\frac{dz'}{1+z'}\right]$$

Mirage: $\langle w \rangle \sim -1$

DESI DR2

2503.14738

$w_0 w_a$CDM	w_0	w_a
CMB	$-1.23^{+0.44}_{-0.61}$	< -0.504
DESI	$-0.48^{+0.35}_{-0.17}$	< -1.34
DESI+Pantheon+	$-0.888^{+0.055}_{-0.064}$	-0.17 ± 0.46
DESI+Union3	-0.70 ± 0.11	-0.99 ± 0.57
DESI+DESY5	$-0.781^{+0.067}_{-0.076}$	-0.72 ± 0.47
DESI+$(\theta_*, \omega_b, \omega_{bc})_{CMB}$	-0.43 ± 0.22	-1.72 ± 0.64
DESI+CMB (no lensing)	-0.43 ± 0.21	-1.70 ± 0.60
DESI+CMB	-0.42 ± 0.21	-1.75 ± 0.58
DESI+CMB+Pantheon+	-0.838 ± 0.055	$-0.62^{+0.22}_{-0.19}$
DESI+CMB+Union3	-0.667 ± 0.088	$-1.09^{+0.31}_{-0.27}$
DESI+CMB+DESY5	-0.752 ± 0.057	$-0.86^{+0.23}_{-0.20}$
DESI+DESY3 (3×2pt)+Pantheon+	-0.870 ± 0.061	$-0.46^{+0.33}_{-0.29}$
DESI+DESY3 (3×2pt)+Union3	-0.68 ± 0.11	$-1.09^{+0.48}_{-0.39}$
DESI+DESY3 (3×2pt)+DESY5	-0.771 ± 0.068	$-0.82^{+0.38}_{-0.32}$

Datasets	$\Delta\chi^2_{MAP}$	Significance	Δ(DIC)
DESI	-4.7	1.7σ	-0.8
DESI+$(\theta_*, \omega_b, \omega_{bc})_{CMB}$	-8.0	2.4σ	-4.4
DESI+CMB (no lensing)	-9.7	2.7σ	-5.9
DESI+CMB	-12.5	3.1σ	-8.7
DESI+Pantheon+	-4.9	1.7σ	-0.7
DESI+Union3	-10.1	2.7σ	-6.0
DESI+DESY5	-13.6	3.3σ	-9.3
DESI+DESY3 (3×2pt)	-7.3	2.2σ	-2.8
DESI+DESY3 (3×2pt)+DESY5	-13.8	3.3σ	-9.1
DESI+CMB+Pantheon+	-10.7	2.8σ	-6.8
DESI+CMB+Union3	-17.4	3.8σ	-13.5
DESI+CMB+DESY5	-21.0	4.2σ	-17.2

Phantom or not Phantom

- CPL $w(a) = w_0 + w_a(1-a)$

At early times $w \to w_0 + w_a$

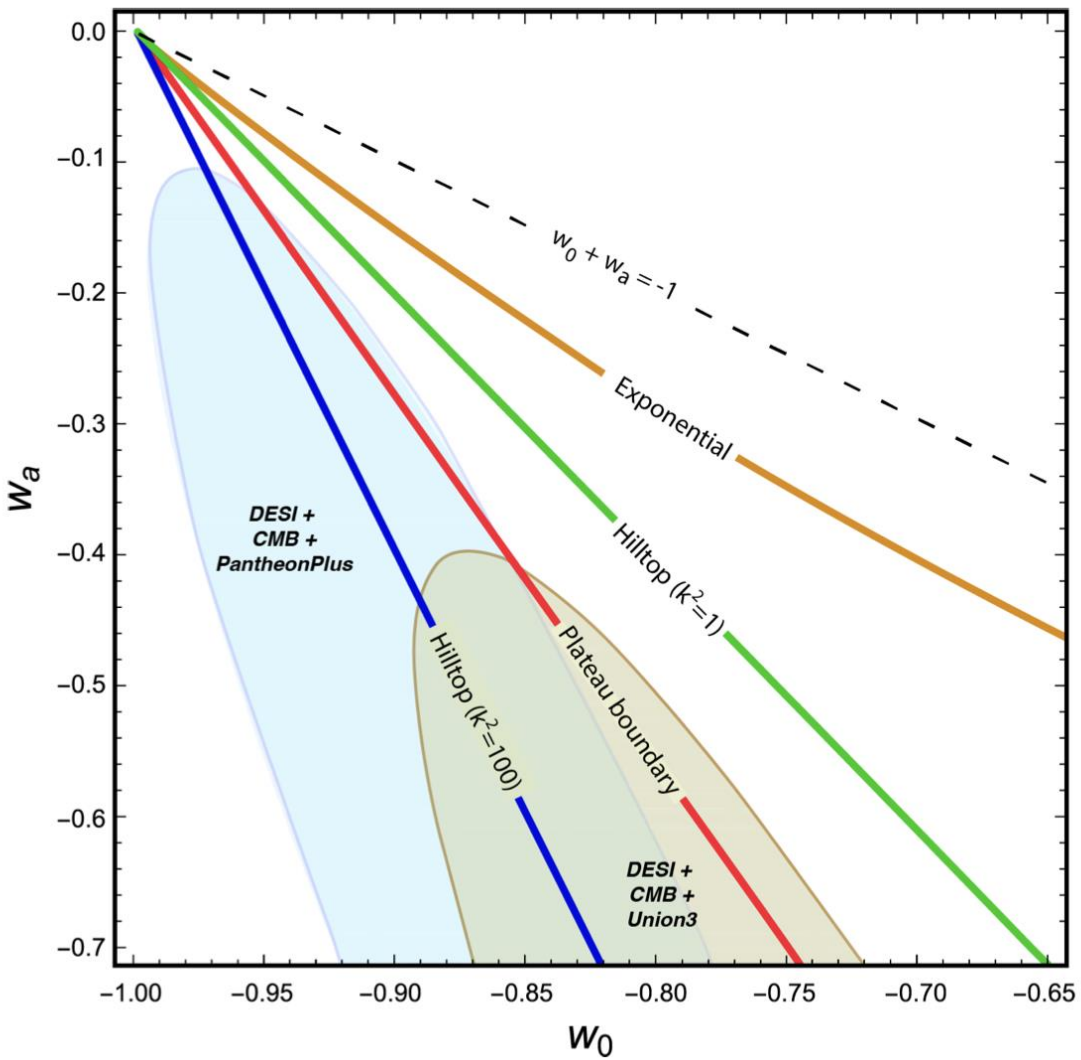
If $w_0 + w_a < -1,\ w < -1$ (phantom)

- Fitting to quintessence

$$E \equiv \max_{z<4} \left| \frac{H_{\rm fit}(z) - H_Q(z)}{H_Q(z)} \right|$$

Many models have $w_0 + w_a < 0$ despite that these models strictly obey $w \geq -1$

2405.03933



Distance to CMB

- Constant w 2404.03002

$$\left.\begin{aligned}\Omega_{\rm m} &= 0.3095 \pm 0.0069,\\ w &= -0.997 \pm 0.025,\end{aligned}\right\}\ \begin{array}{l}\text{DESI+CMB}\\ \text{+PantheonPlus.}\end{array}$$

consistent with w = -1

To achieve w=-1 on average up to CMB

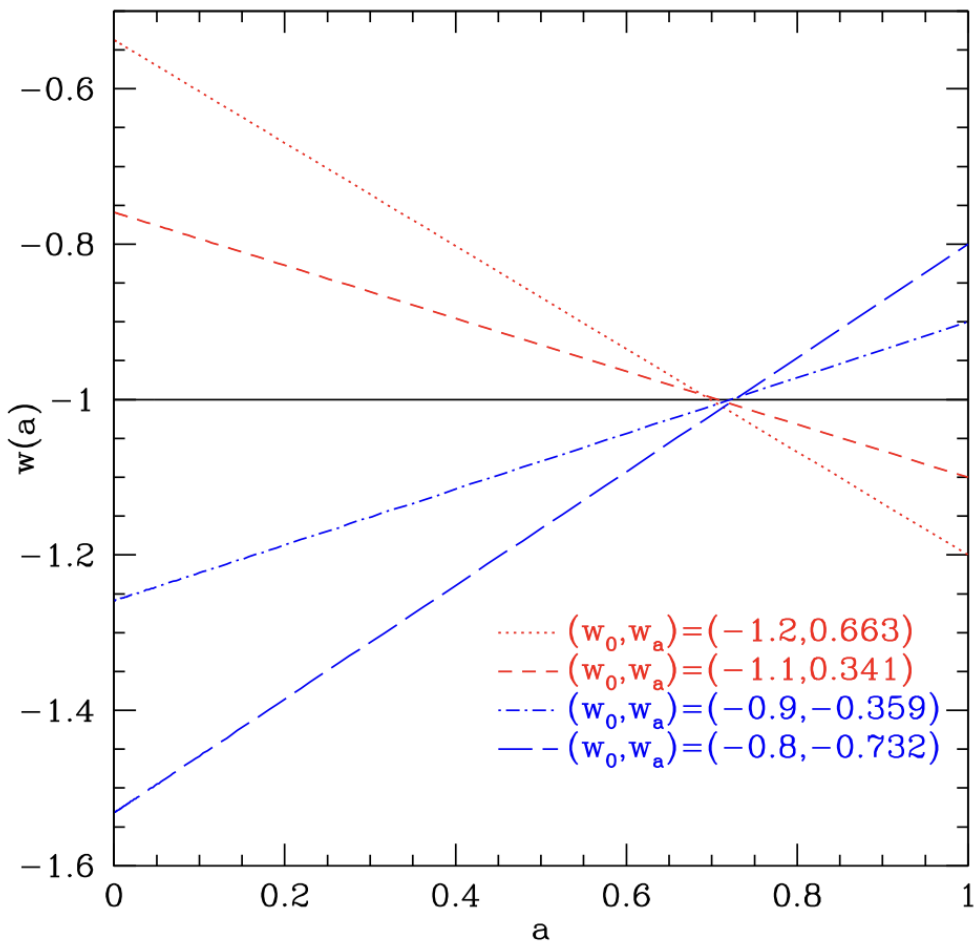
$$\langle w \rangle \sim -1 \qquad w_a \approx -3.66(1+w_0)$$

w(z) crosses -1 at a =0.7 (z=0.4)

DESI+CMB:	+PantheonPlus		+Union3		+DESY5	
DE classes			ΔDIC ($\Delta\chi^2$)			
Thaw. (Alg.)	−1.0	(−2.9)	−4.6	(−6.9)	−10.1	(−13.2)
$w_0 w_a$	−6.8	(−10.7)	−13.5	(−17.4)	−17.2	(−21.0)

2503.14743

0708.0024



$$1 + w(a) = (1+w_0)\, a^p \left(\frac{1+b}{1+ba^{-3}}\right)^{1-p/3} > 0$$

$$\Delta\chi^2_{\rm MAP} \equiv \chi^2_{\rm model} - \chi^2_{\Lambda\rm CDM}$$

Test of gravity

Phantom dark energy

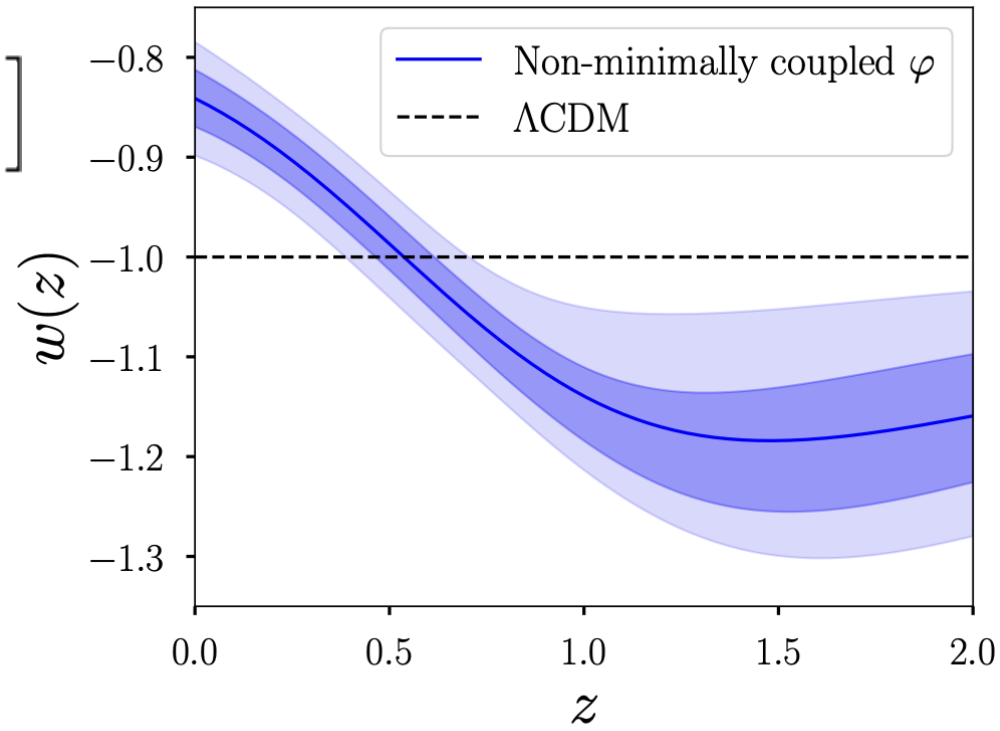
2504.07679

- Non-minimal coupling to gravity

$$S = \int d^4x\sqrt{-g}\Big[\frac{M_{\rm pl}^2}{2}F(\varphi)R - \frac{1}{2}(\partial\varphi)^2 - V(\varphi)\Big]$$

$$F(\varphi) \simeq 1 - \xi\frac{\varphi^2}{M_{\rm Pl}^2},$$

$$V(\varphi) \simeq V_0 + \beta\varphi + \frac{1}{2}m^2\varphi^2,$$



		Pantheon+	Union3	DESY5
$\log B$	Min. φ	-1.96	$+1.53$	$+3.46$
	w_0w_a	-1.57	$+4.02$	$+5.55$
	Non-min. φ	$+3.14$	$+6.45$	$+7.34$
$\Delta\chi^2$ (ΔDIC)	Min. φ	-2.9 (-0.32)	-7.4 (-3.41)	-14.1 (-9.96)
	w_0w_a	-8.0 (-4.89)	-14.0 (-12.2)	-18.2 (-16.4)
	Non-min. φ	-14.1 (-11.5)	-19.4 (-16.4)	-23.6 (-21.5)

← Minimal coupling (quintessence)

← Non-minimal coupling

Linear perturbations

- Geometry (FRW metric + perturbations)

$$ds^2 = a(\eta)^2[-(1+2\Psi)d\eta^2 + (1-2\Phi)d\vec{x}^2]$$

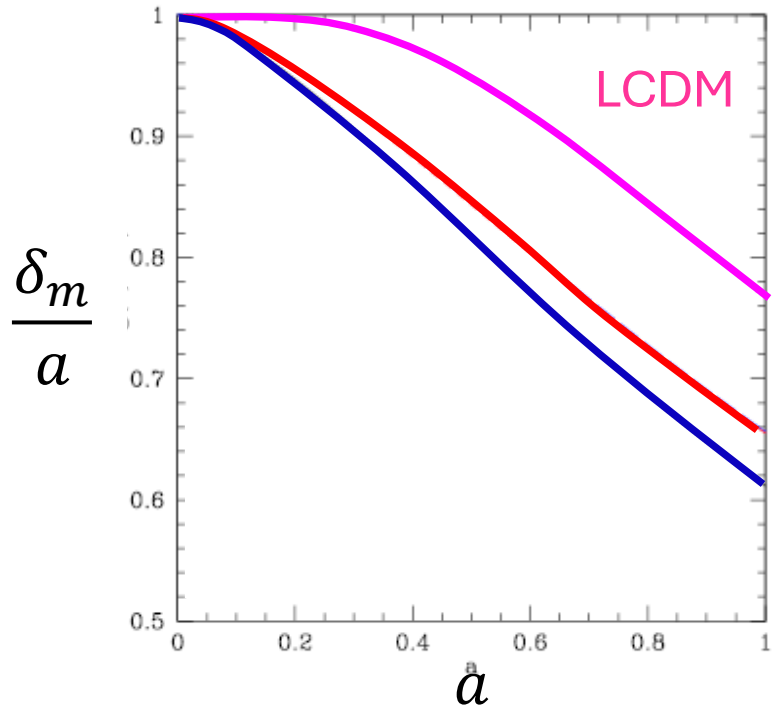
- Matter

$$T_0^0 = -\rho_m(1+\delta_m)$$
$$T_i^0 = \rho_m v_{m_i}, \quad \partial^i v_{mi} = \theta_m$$

Energy-momentum conservation (no interaction)

$$\dot{\delta}_m - \frac{1}{a}\theta_m - 3\dot{\Phi} = 0$$
$$\dot{\theta}_m + H\theta_m - \frac{k^2}{a^2}\Psi = 0$$

$$\Rightarrow \quad \ddot{\delta}_m + 2H\dot{\delta}_m = \frac{k^2}{a^2}\Psi$$



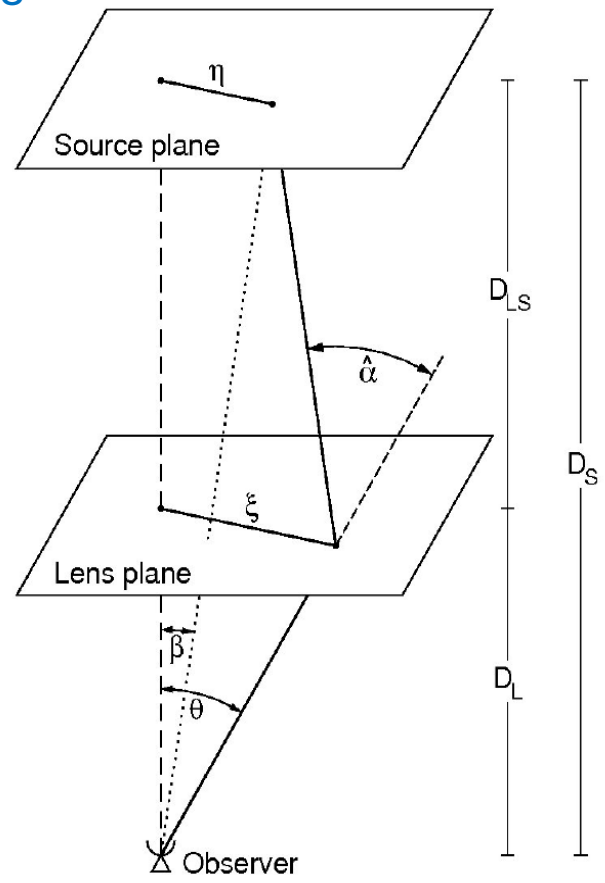
dark energy/modified gravity change the growth of structure formation

Observations

- Weak lensing

Bartelmann & Schneider astro-ph/9912508

$$ds^2 = a^2\left[-(1+2\Psi)d\eta^2 + (1-2\Phi)\delta_{ij}dx^i dx^j\right]$$

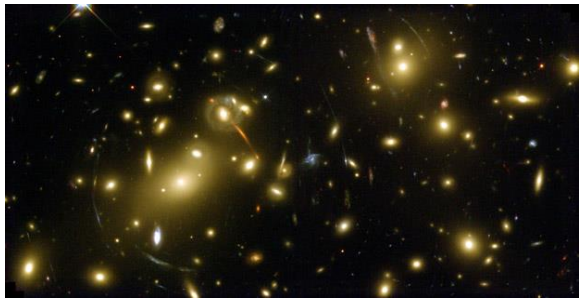


Convergence

$$\kappa(\vec{n}) = \int d\chi \boxed{\frac{D_{sL}D_L}{D_s}} \nabla_\perp{}^2 \phi_W(\eta_0 - \chi, \chi\vec{n}), \quad \phi_W = \frac{1}{2}(\Psi + \Phi)$$

geometry

Galaxy shape is determined by shear which can be computed from convergence



Observations

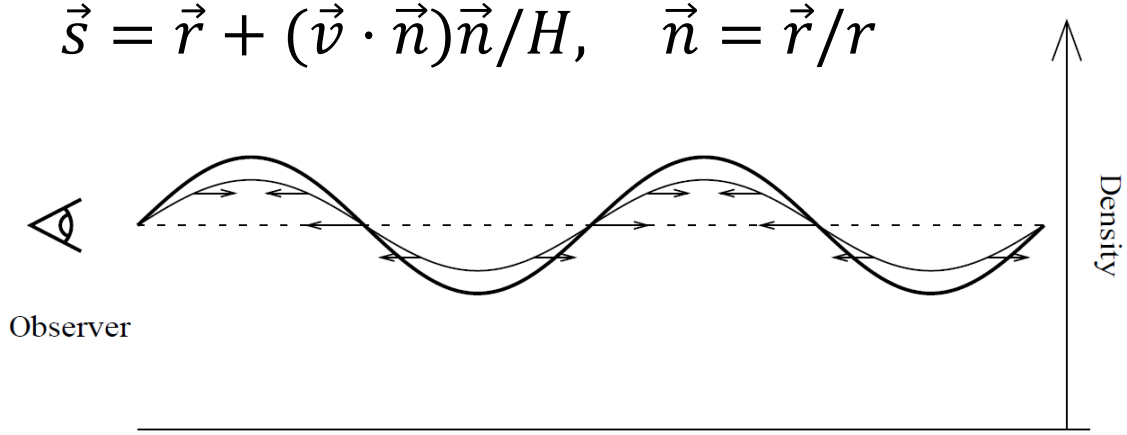
- Redshift distortions

galaxies have peculiar velocities

clustering of galaxies in redshift space

is enhanced along the line of sight

$$\vec{s} = \vec{r} + (\vec{v} \cdot \vec{n})\vec{n}/H, \quad \vec{n} = \vec{r}/r$$



Hamilton astro-ph/9708102

$$\delta^s(k,\mu) = \delta_m(k) - \mu^2\theta_m(k), \quad \mu^2 = \frac{\left(\vec{k}\cdot\vec{n}\right)^2}{k^2}$$

If the continuity equation holds, the velocity dispersion is related to the growth rate

$$\delta^s(k,\mu) = \delta_m(k)\left(1 - \mu^2\frac{\theta_m(k)}{\delta_m(k)}\right) = \delta_m(k)(1+\mu^2 f) \qquad f = \frac{d\ln\delta_m}{d\ln a}$$

Prametrisation - growth rate

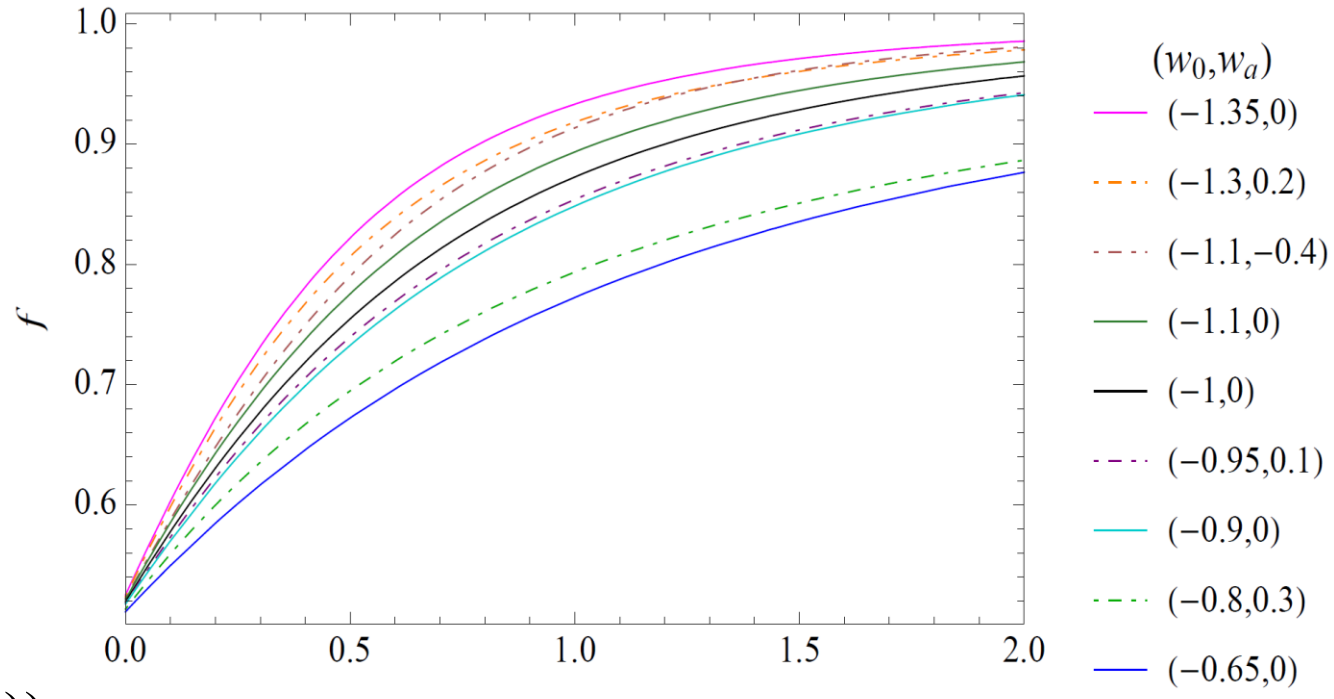
- Growth rate in GR

$$f = \frac{d\ln\Delta_m}{d\ln a} = \frac{a}{D_+}\frac{dD_+}{da}$$

$$\dot{f} + f^2 + \left[\frac{1}{2} - \frac{3}{2}w_{DE}(1-\Omega_m)\right]f = \frac{3}{2}\Omega_m$$

$$f = \Omega_m^{\gamma}, \quad \gamma = 0.545 + 0.05(1 + w_{DE}(z=1))$$

Linder 0507263



1311.0726

γ is insensitive to the equation of state w_{DE}
(but the growth rate depends on w_{DE} through Ω_m)

Changing gravity modifies γ

Consistency relation

Zhang & Jain Phys. Rev. D78 (2008) 063503
Song & KK JCAP 0901(2009) 048

- In GR, gravitational equations are given by

$$H^2 = \frac{8\pi G}{3}\rho_T, \quad \rho_T = \sum_i \rho_i$$

$$\frac{k^2}{a^2}\Phi = 4\pi G a^2 \rho_T \delta_T, \quad \rho_T \delta_T = \sum_i \rho_i \delta_i$$

- Consistency relation

$$\alpha(k,t) = \frac{2k^2}{3a^2 H^2} \frac{(\Phi + \Psi) - \Psi}{\delta_T} = 1$$

background

Weak lensing

Redshift Space Distortion

$$k^2\Psi = \frac{d(a\theta_m)}{dt}$$

Galaxy distribution

$$\delta_g = b_T \delta_T$$

We have just enough number of observations to check the relation

Parametrisation

Amendola et.al JCAP 0804 (2008) 013
Zhao et.al. Phys. Rev. Lett. 103 (2009) 241301

- Background

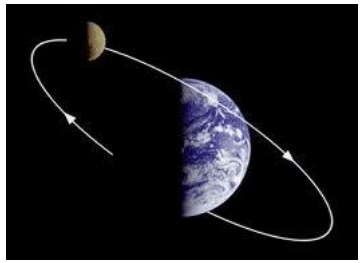
$$F(H^2) = \frac{8\pi G}{3}\rho_m \quad \Rightarrow \quad H^2 = \frac{8\pi G}{3}(\rho_m + \rho_{DE})$$

Equation of state $w_{DE}(z) = \frac{P_{DE}}{\rho_{DE}}$ can be ill-defined for modified gravity as ρ_{DE} can vanish

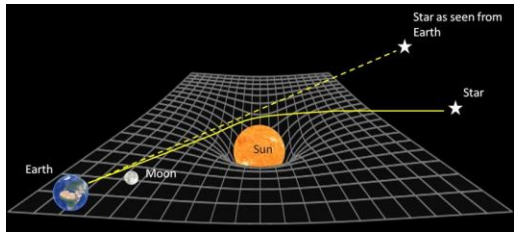
Instead, we can parametrise the effective dark energy density directly $\Omega_{DE}(z) = \frac{\rho_{DE(z)}}{\rho_{crit}}$

- Perturbations

$k^2\Psi = -4\pi G a^2 \mu(z,k)\rho_m \delta_m$: Newton potential

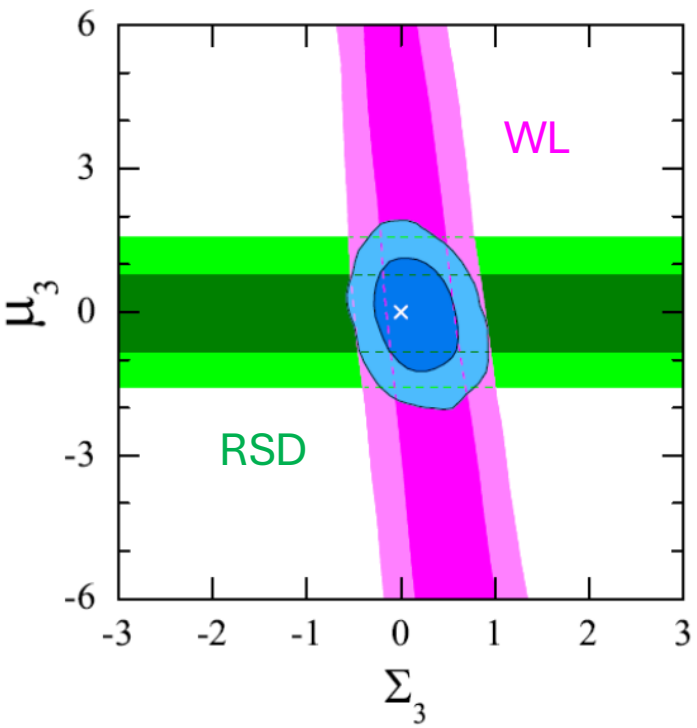


$k^2(\Psi + \Phi) = -8\pi G a^2 \Sigma(z,k)\rho_m \delta_m$: lensing potential



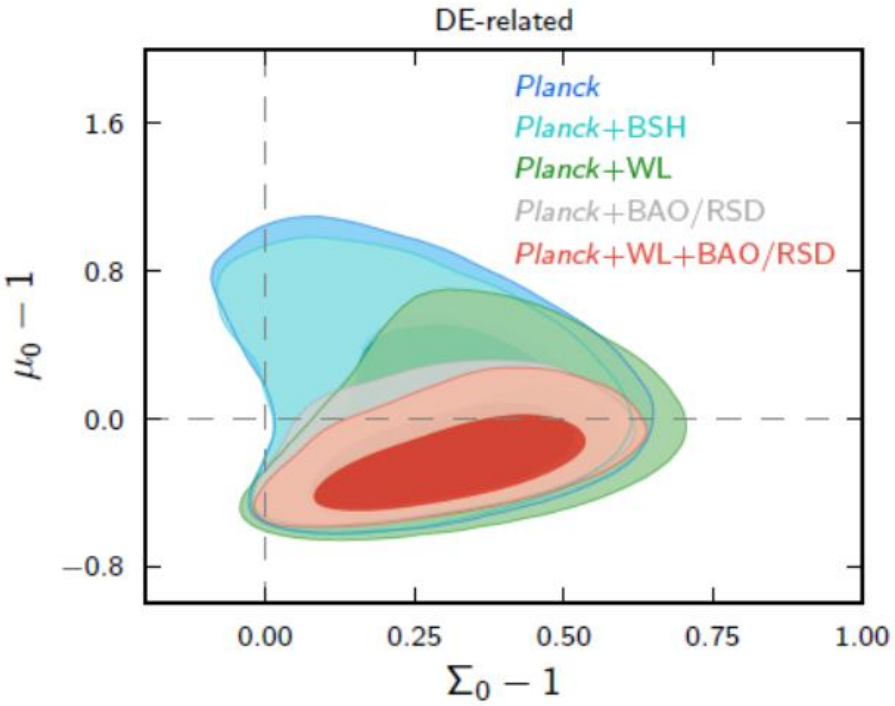
Current constraints

- Weak Lensing +Redshift space distortion



$$\Sigma = 1 + \Sigma_s a^s, \quad \mu = 1 + \mu_s a^s$$

Song et.al. PRD84 (2011) 083523



$$\mu(a,k) = \mu_0 \Omega_L(a), \quad \Sigma(a,k) = \Sigma_0 \Omega_L(a)$$

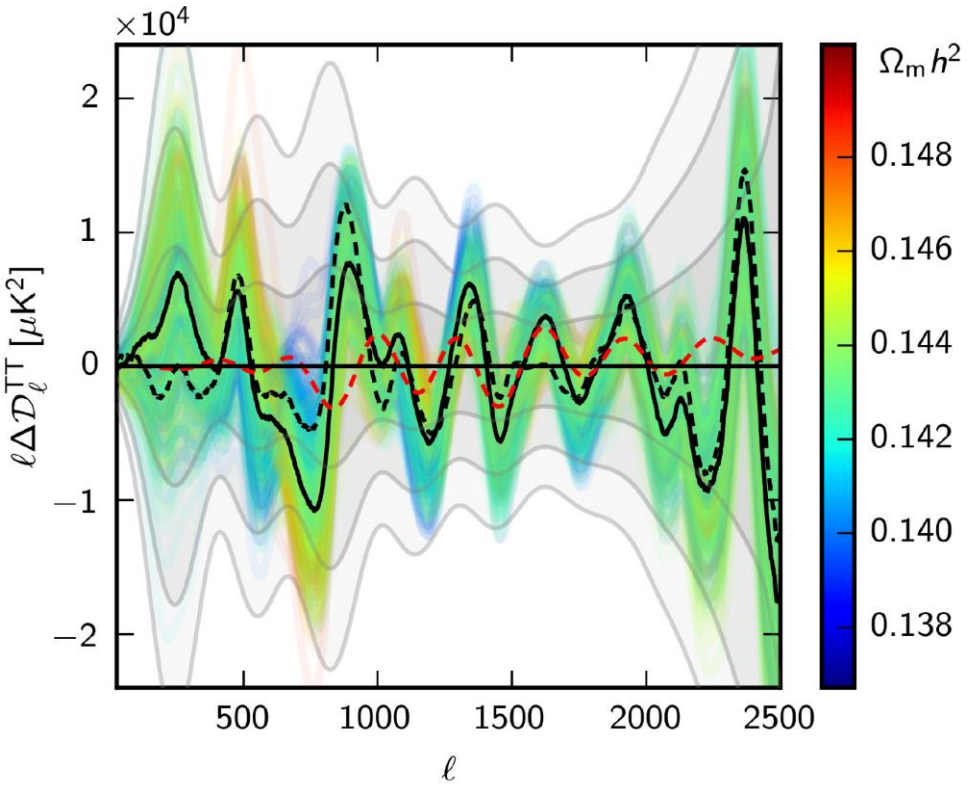
Planck 2015 “Modified gravity and dark energy”

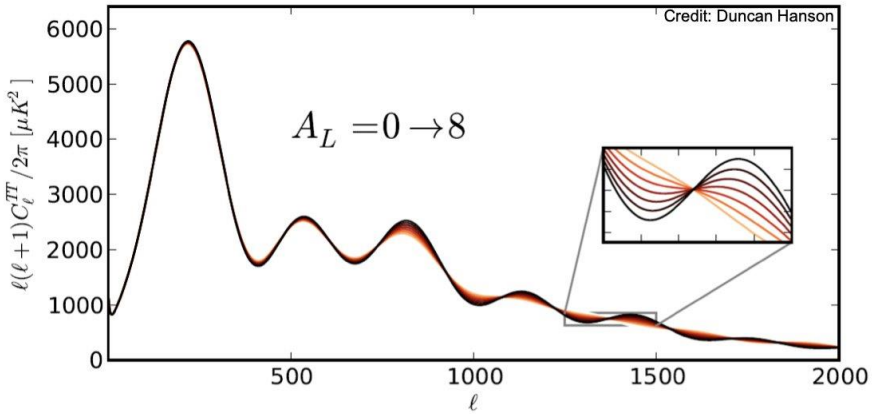
“Tensions” with LCDM – CMB lensing in TT

- CMB temperature power spectrum

  The Planck CMB temperature power spectrum is well fitted by LCDM but at high ell, there are residual oscillations

  CMB peaks are smeared out by CMB lensing. These residuals are well fitted if CMB lensing amplitude is larger than that in LCDM





$$\tilde{C}_\ell^{\phi\phi} = A_L C_\ell^{\phi\phi}$$

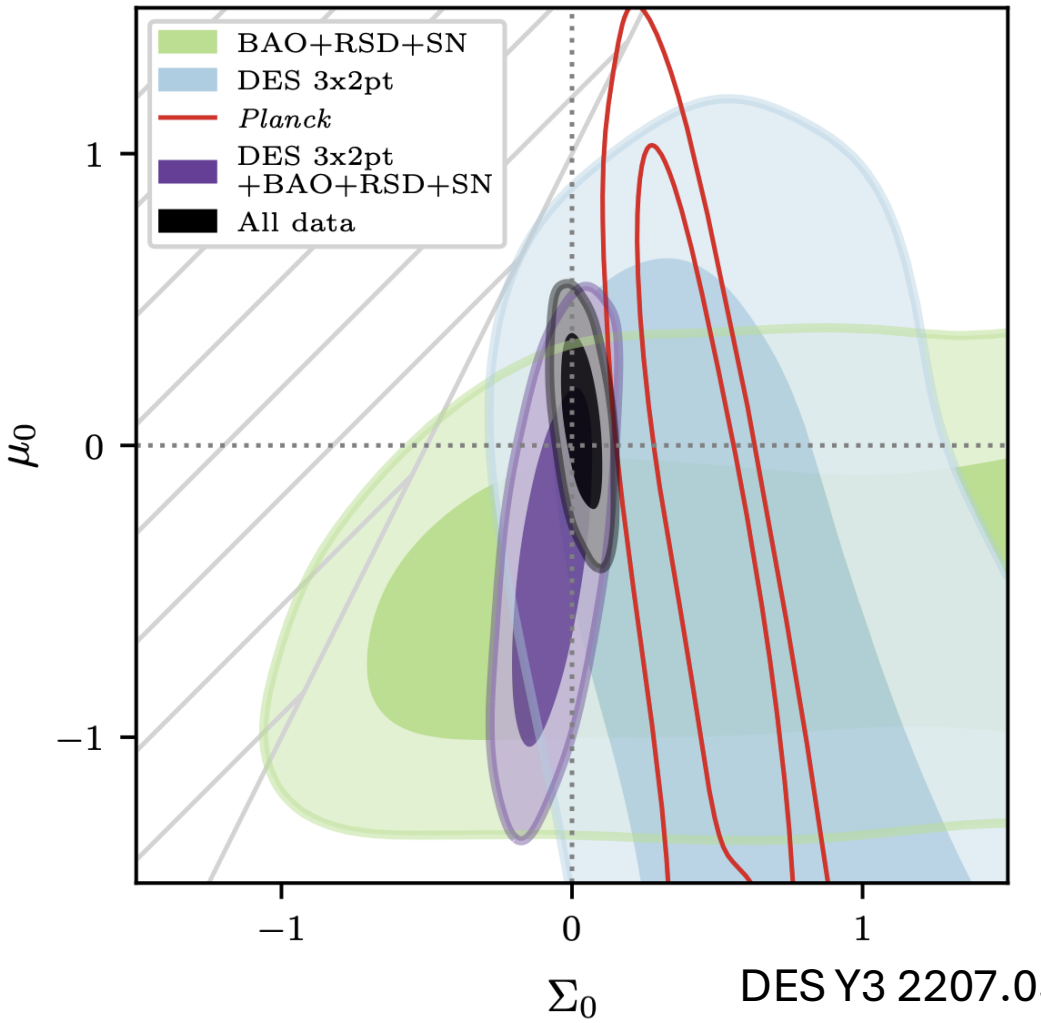
$$A_L = 1.243 \pm 0.096$$

Planck 2018 arXiv:1807.06209

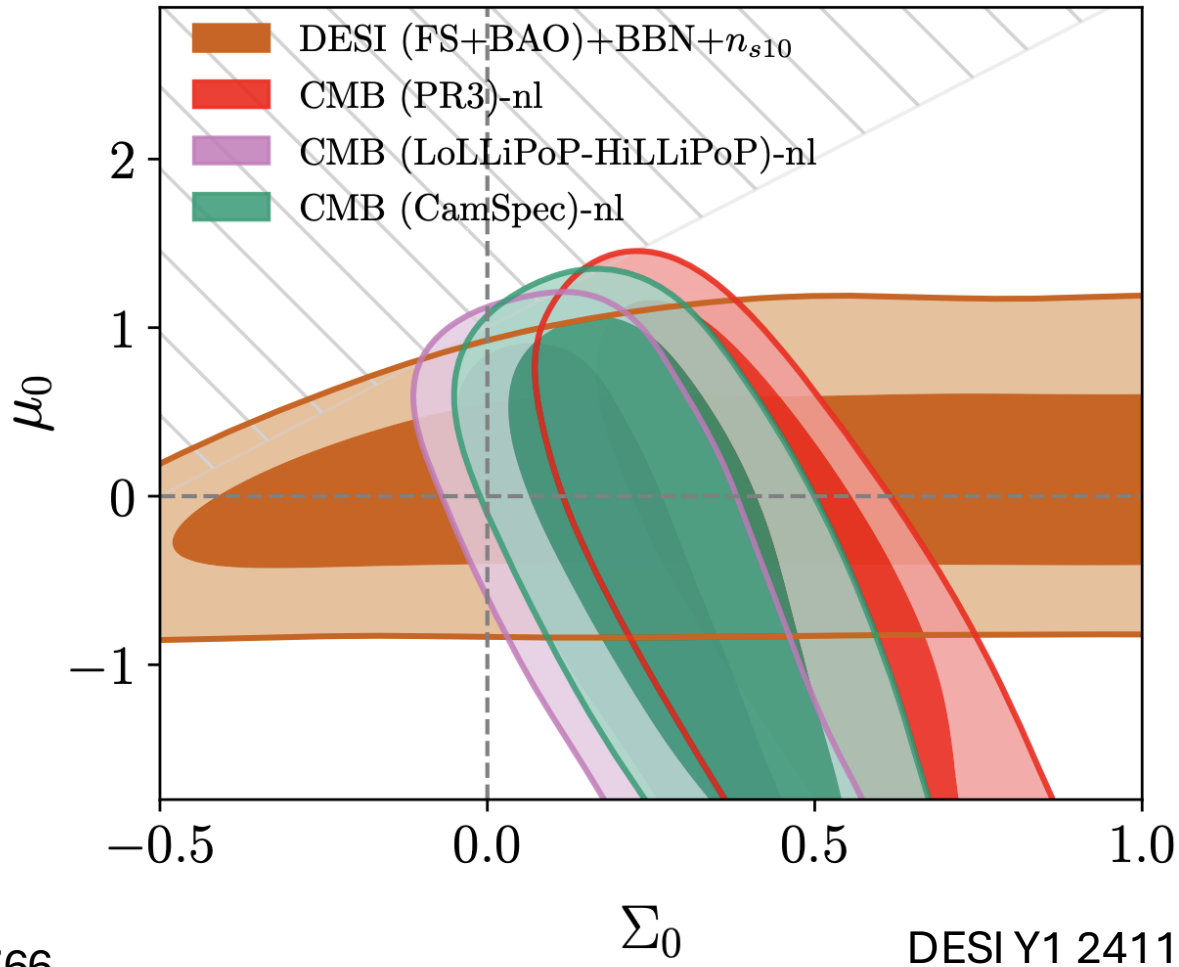
DES and DESI constraints

$$\Sigma(a,k) = \Sigma_0 \frac{\Omega_\Lambda(a)}{\Omega_{\Lambda,0}},$$

$$\mu(a,k) = \mu_0 \frac{\Omega_\Lambda(a)}{\Omega_{\Lambda,0}}.$$



DES Y3 2207.05766



DESI Y1 2411.12026

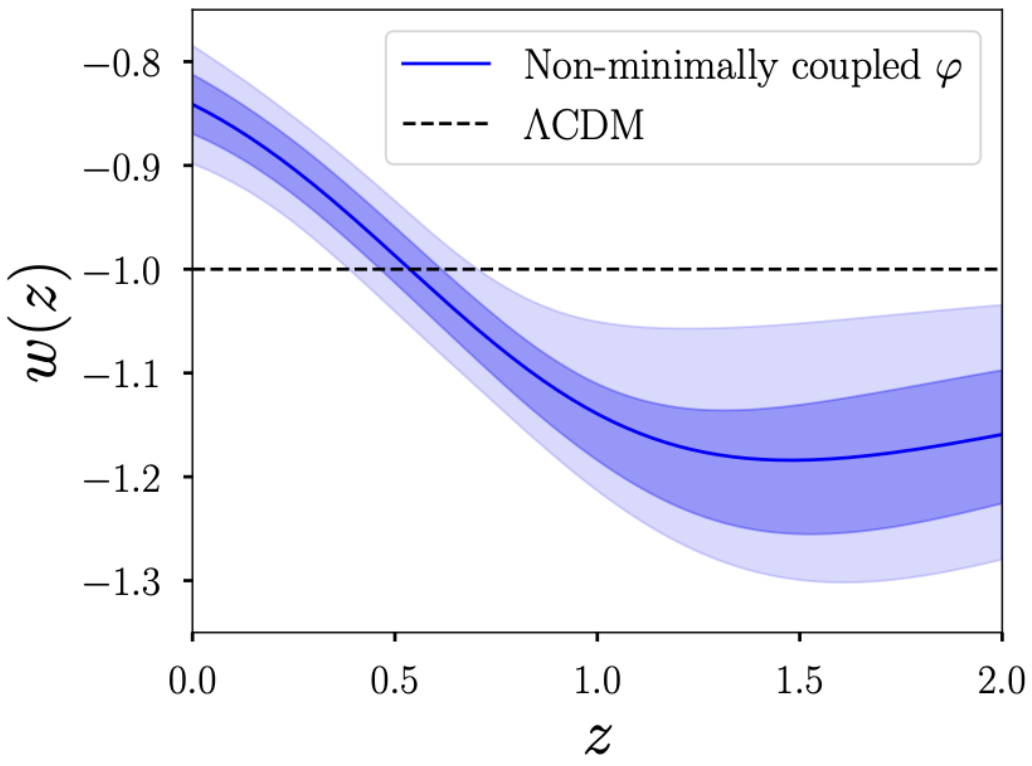
Non-minimal coupling

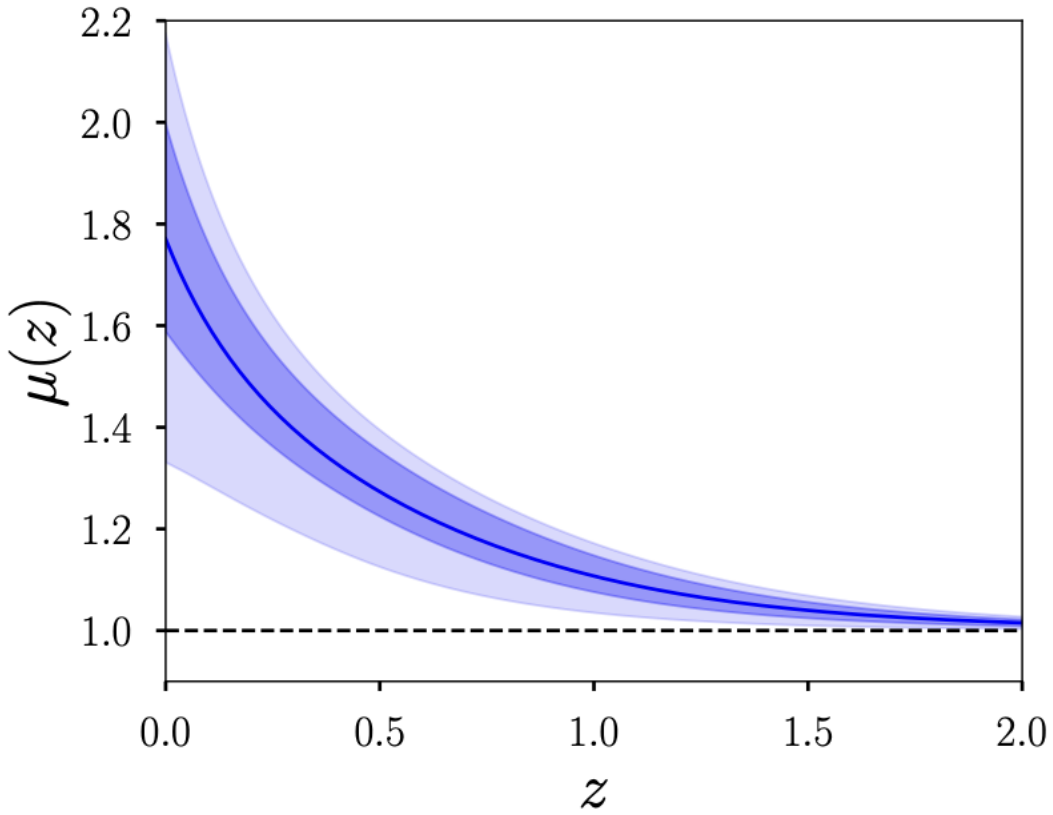
2504.07679

$$S = \int d^4x\sqrt{-g}\Big[\frac{M_{\rm pl}^2}{2}F(\varphi)R - \frac{1}{2}(\partial\varphi)^2 - V(\varphi)\Big]$$

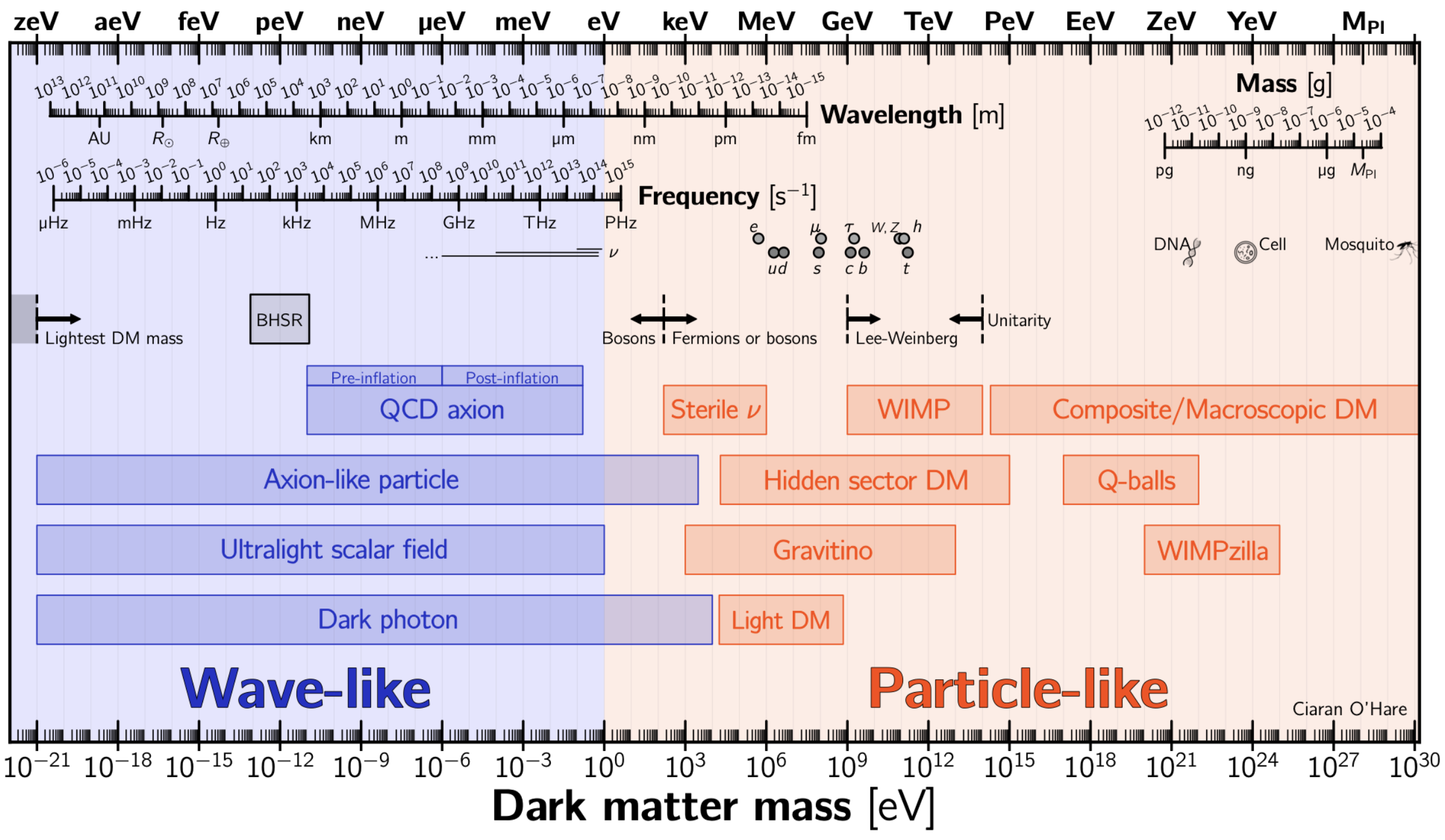
$$F(\varphi) \simeq 1 - \xi\frac{\varphi^2}{M_{\rm Pl}^2},$$

$$V(\varphi) \simeq V_0 + \beta\varphi + \frac{1}{2}m^2\varphi^2,$$





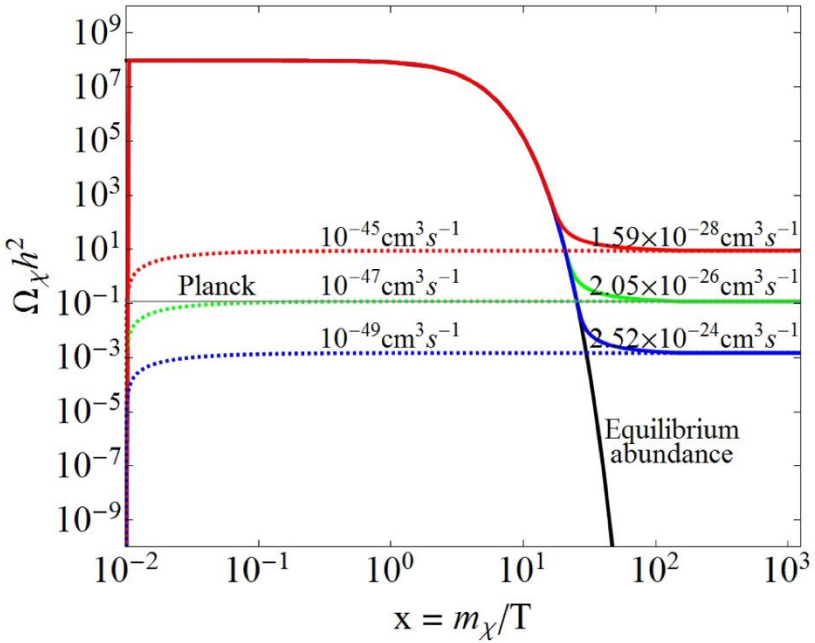
Dark matter


zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV EeV ZeV YeV M_{Pl}
Wavelength [m]
AU $R_\odot$ $R_\oplus$ km m mm μm nm pm fm
Frequency [s^{-1}]
μHz mHz Hz kHz MHz GHz THz PHz
Mass [g]
pg ng μg M_{Pl}
DNA Cell Mosquito
Lightest DM mass
BHSR
Bosons Fermions or bosons
Lee-Weinberg
Unitarity
Pre-inflation Post-inflation
QCD axion
Sterile ν
WIMP
Composite/Macroscopic DM
Axion-like particle
Hidden sector DM
Q-balls
Ultralight scalar field
Gravitino
WIMPzilla
Dark photon
Light DM
Wave-like
Particle-like
Ciaran O'Hare
10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18} 10^{21} 10^{24} 10^{27} 10^{30}
Dark matter mass [eV]

Weakly Interacting Massive Particle

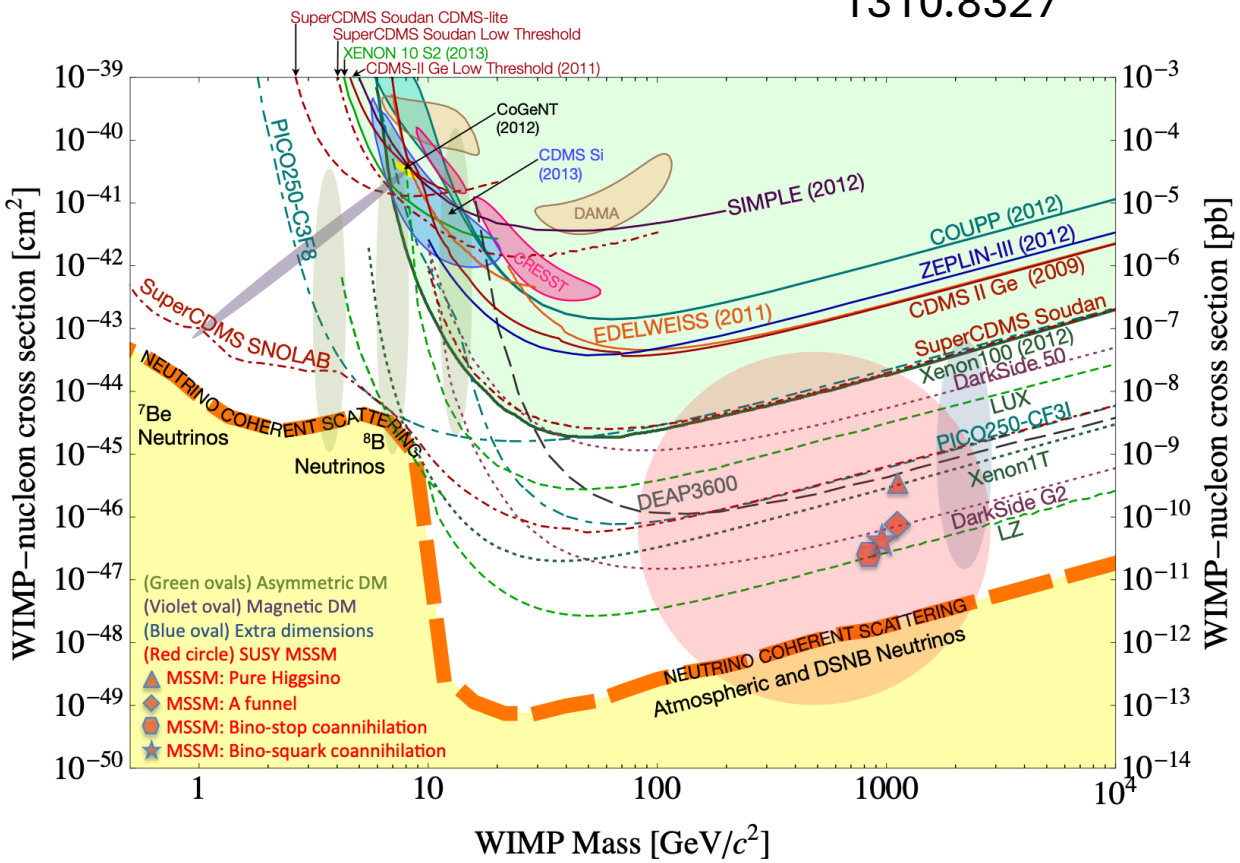
WIMP

If cross section is $\sigma v \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$ and mass is $100\mathrm{GeV}$, WIMP predicts the right amount of dark matter from thermal production (WIMP miracle)



1311.5297

1310.8327

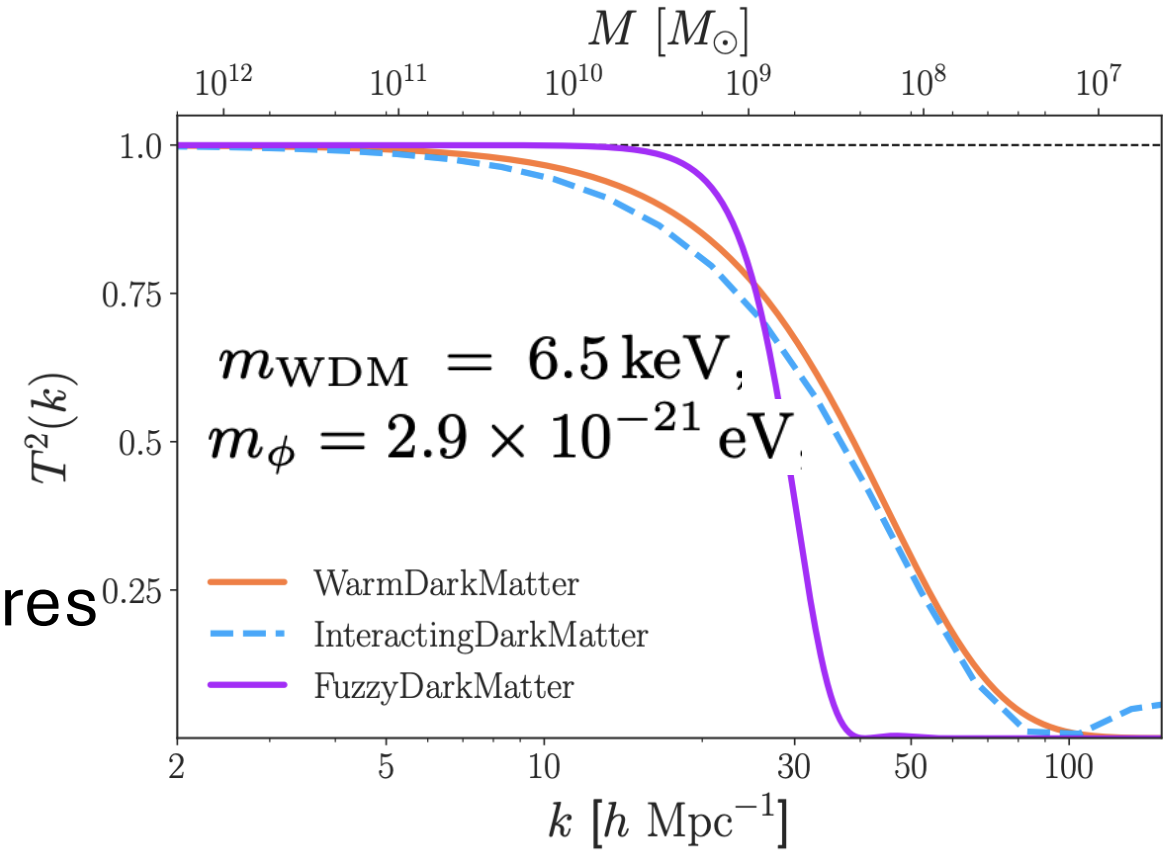


WIMP has not been detected

Warm/Fuzzy/Interacting dark matter

2008.00022

- Warm dark matter
  WDM is produced with a temperature of $O(1)\mathrm{keV}$
- Fuzzy dark matter
  Ultra light boson with a mass $O(10^{-22}\mathrm{eV})$



Suppression of small-scale structures compared with LCDM

$$T^2(k) \equiv \frac{P_{\mathrm{DM}}(k)}{P_{\mathrm{CDM}}(k)}$$

Massive neutrinos

- Neutrino oscillations measurements

$$\Delta m^2_{21} = \left(7.42^{+0.21}_{-0.20}\right) \times 10^{-5}\,\mathrm{eV}^2,$$

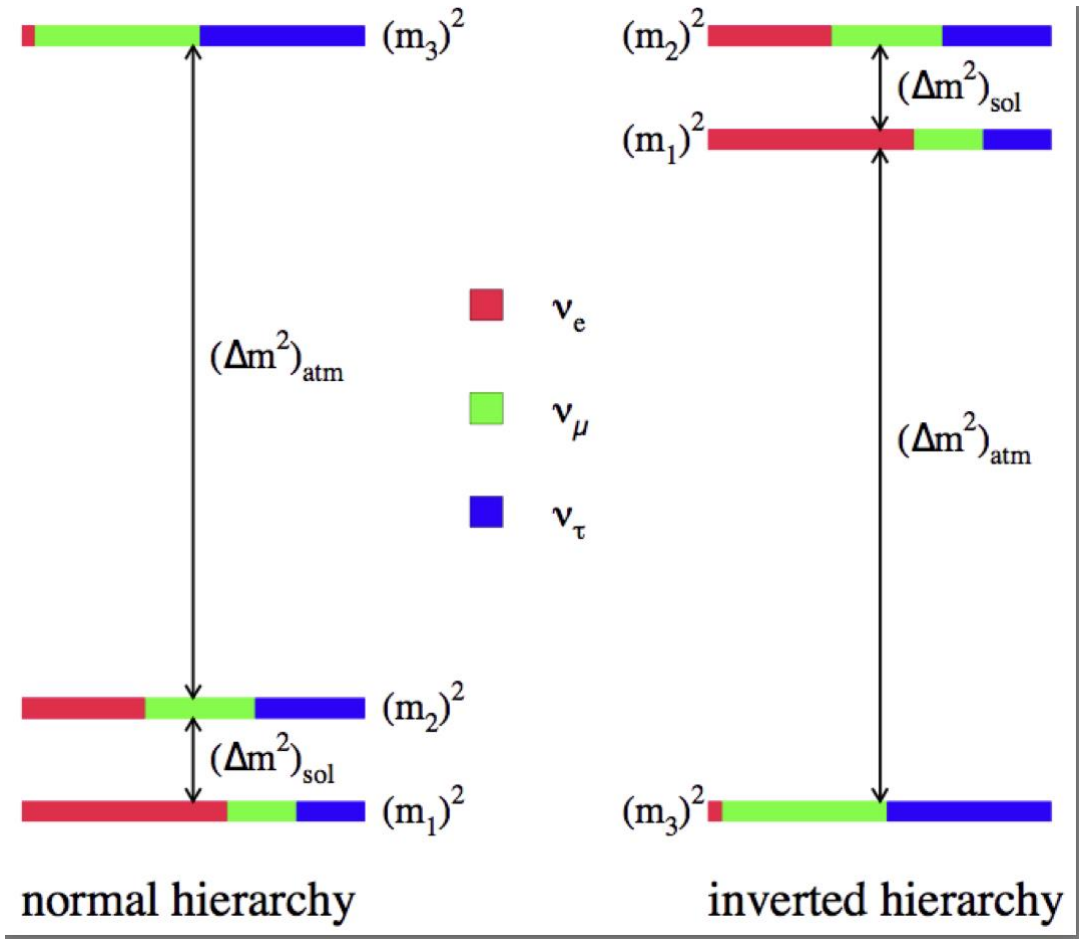
$$\Delta m^2_{3i} = \begin{cases} \left(2.517^{+0.026}_{-0.028}\right) \times 10^{-3}\,\mathrm{eV}^2 & \text{(NO)}, \\ \left(-2.498^{+0.028}_{-0.028}\right) \times 10^{-3}\,\mathrm{eV}^2 & \text{(IO)}, \end{cases}$$

- Minimum total mass

$$\sum m_\nu > \begin{cases} 0.05878 \pm 0.00023\,\mathrm{eV} & \text{(NO)}, \\ 0.09892 \pm 0.00041\,\mathrm{eV} & \text{(IO)}. \end{cases}$$

- KATRIN (beta-decay experiments)

$$m_\nu < 0.45\,\mathrm{eV}$$



Massive neutrinos in cosmology

2410.00090

- Massive neutrinos become non-relativistic at

$$z_{\nu_i} + 1 = \frac{m_{\nu_i}}{3.15 T_\nu(a_0)} = 113 \, \frac{m_{\nu_i}}{0.06 \text{ eV}}$$

- The present-day density $\Omega_{\nu,0} \, h^2$

$$\omega_{\nu_i} = \frac{3\zeta(3)}{2\pi^2} \frac{m_{\nu_i} T_\nu(a_0)^3}{3 H_{100}^2 M_{\rm pl}^2} = \frac{m_{\nu_i}}{93.1 \text{ eV}}$$

- Early time radiation density from neutrinos

$$\bar{\rho}_\nu(z \gg z_{\nu_i}) = \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} N_{\rm eff} \cdot \bar{\rho}_\gamma \qquad N_{\rm eff} = 3.044$$

2005.07047

Case	$z_{\rm fin}$	$N_{\rm eff}$
Instantaneous decoupling	1.40102	3.000
No mixing + No QED	1.39910	3.034
No mixing + QED up to $\mathcal{O}(e^2)$	1.39789	3.044
No mixing + QED up to $\mathcal{O}(e^3)$	1.39800	3.043
mixing + QED up to $\mathcal{O}(e^2)$	1.39786	3.045
mixing + QED up to $\mathcal{O}(e^3)$	1.39797	3.044

Observational effects

- Observational effects depend on the fraction (thus total mass)

$$f_\nu \equiv \frac{\omega_\nu}{\omega_m} = \frac{\omega_\nu}{\omega_b + \omega_c + \omega_\nu} \approx \frac{M_\nu}{13.2\ \mathrm{eV}} \left(\frac{\omega_b + \omega_c}{0.142} \right)^{-1}$$

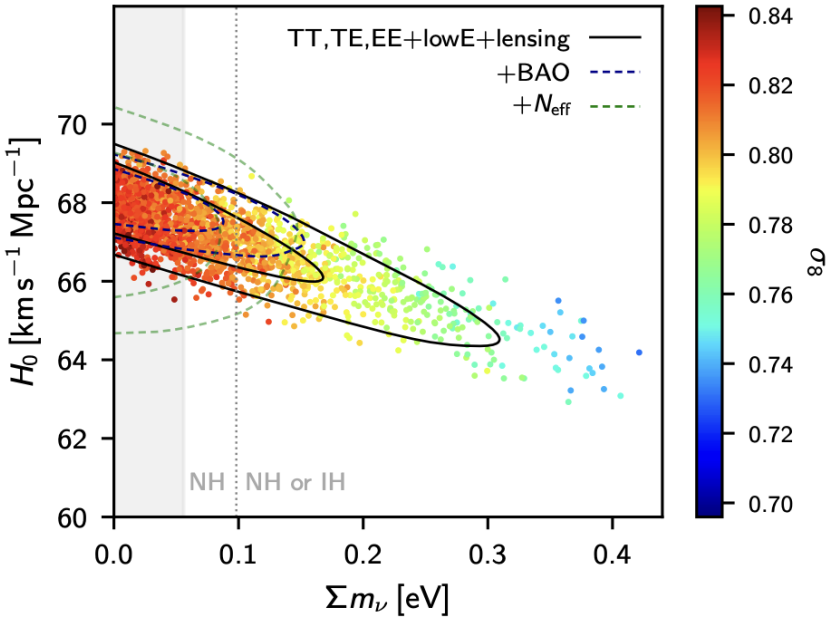
- Massive neutrinos become non-relativistic at z= O(100)

1807.06209

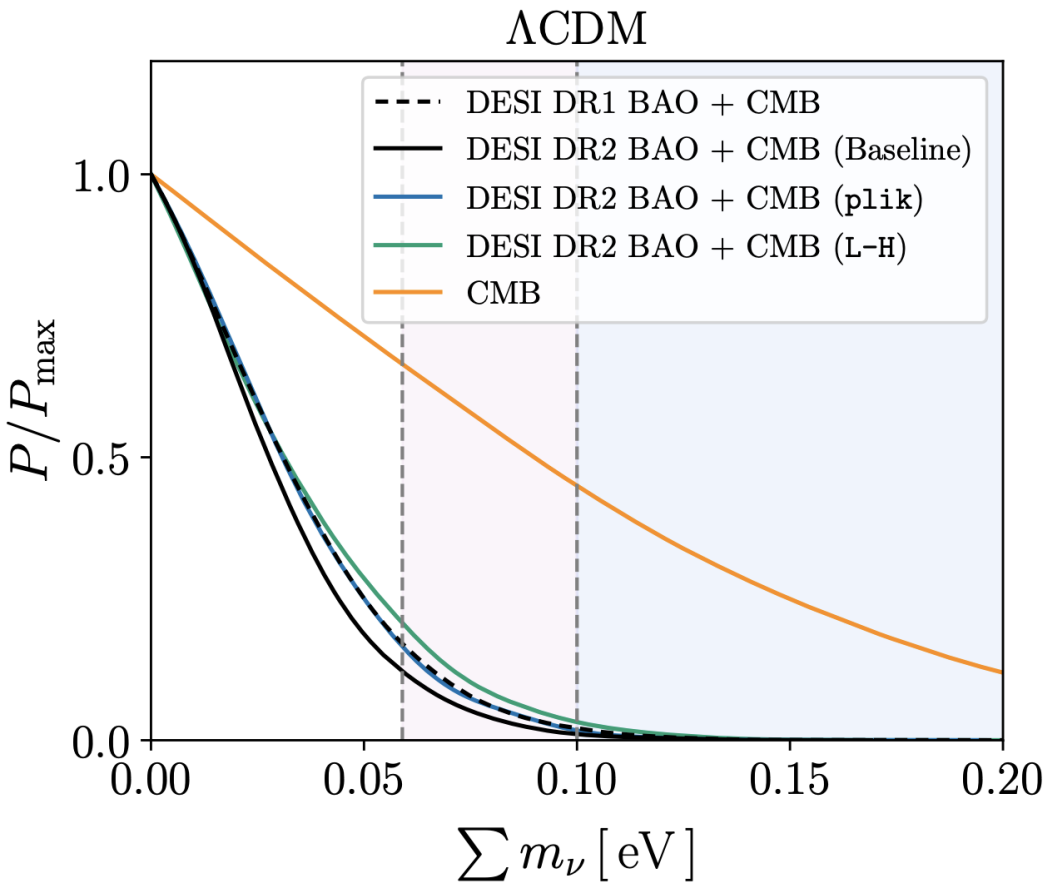
The distance to CMB last scattering is modified and the effect degenerates with h

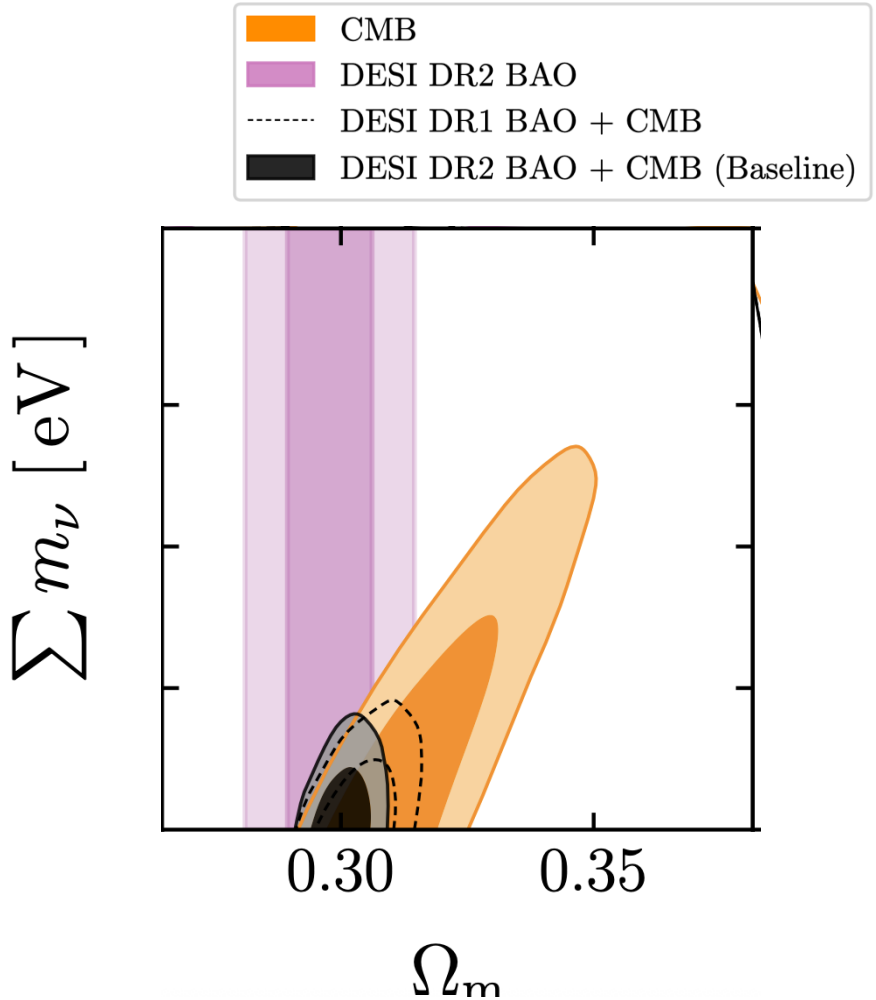
$$\sum m_\nu < 0.26\ \mathrm{eV} \quad (95\,\%,\ \textit{Planck}\ \mathrm{TT,TE,EE+lowE}).$$

late time BAO measurements are insensitive to massive neutrinos, but give tight constraints by breaking degeneracies



DESI constraint in LCDM



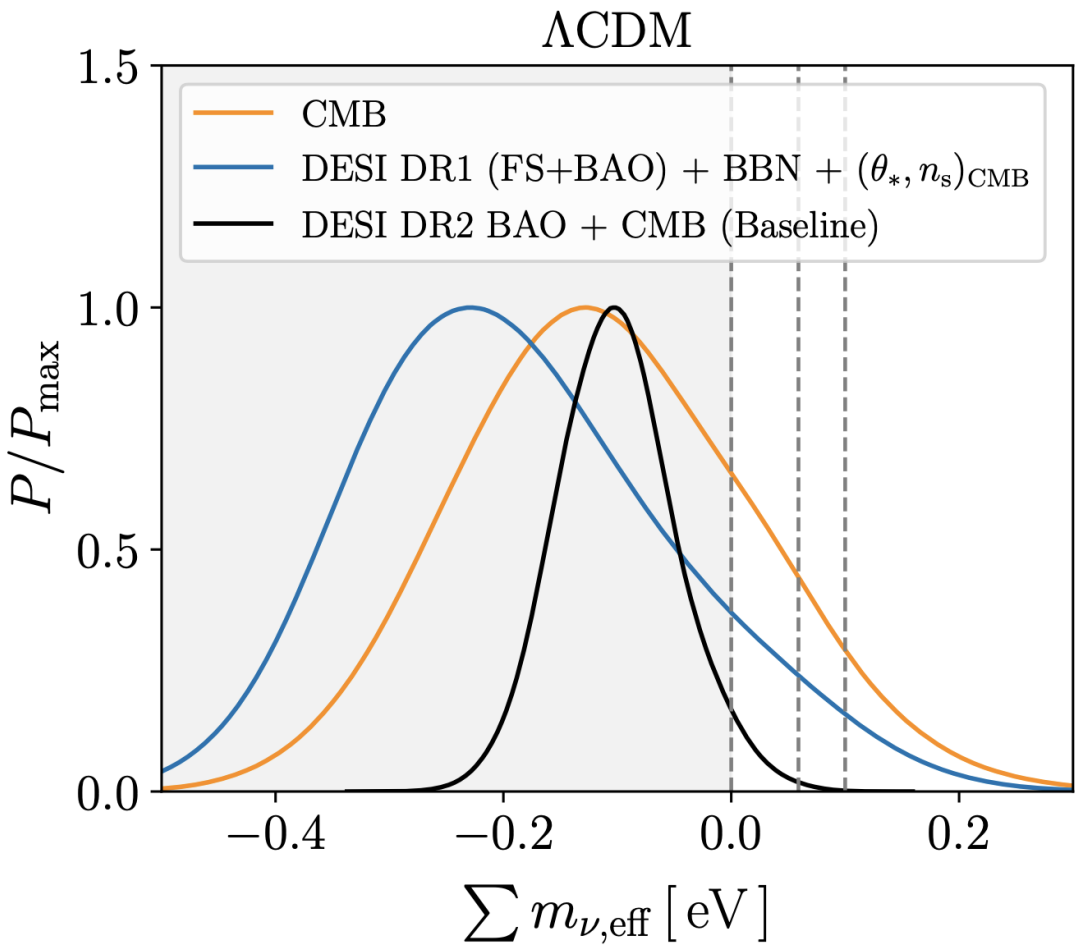


ΛCDM: DESI DR2 BAO + CMB:

$$\sum m_\nu < 0.053\,\mathrm{eV} \quad (95\%),$$

$$\sum m_\nu > \begin{cases} 0.05878 \pm 0.00023\,\mathrm{eV} & (\mathrm{NO}), \\ 0.09892 \pm 0.00041\,\mathrm{eV} & (\mathrm{IO}). \end{cases}$$

Negative “effective” mass



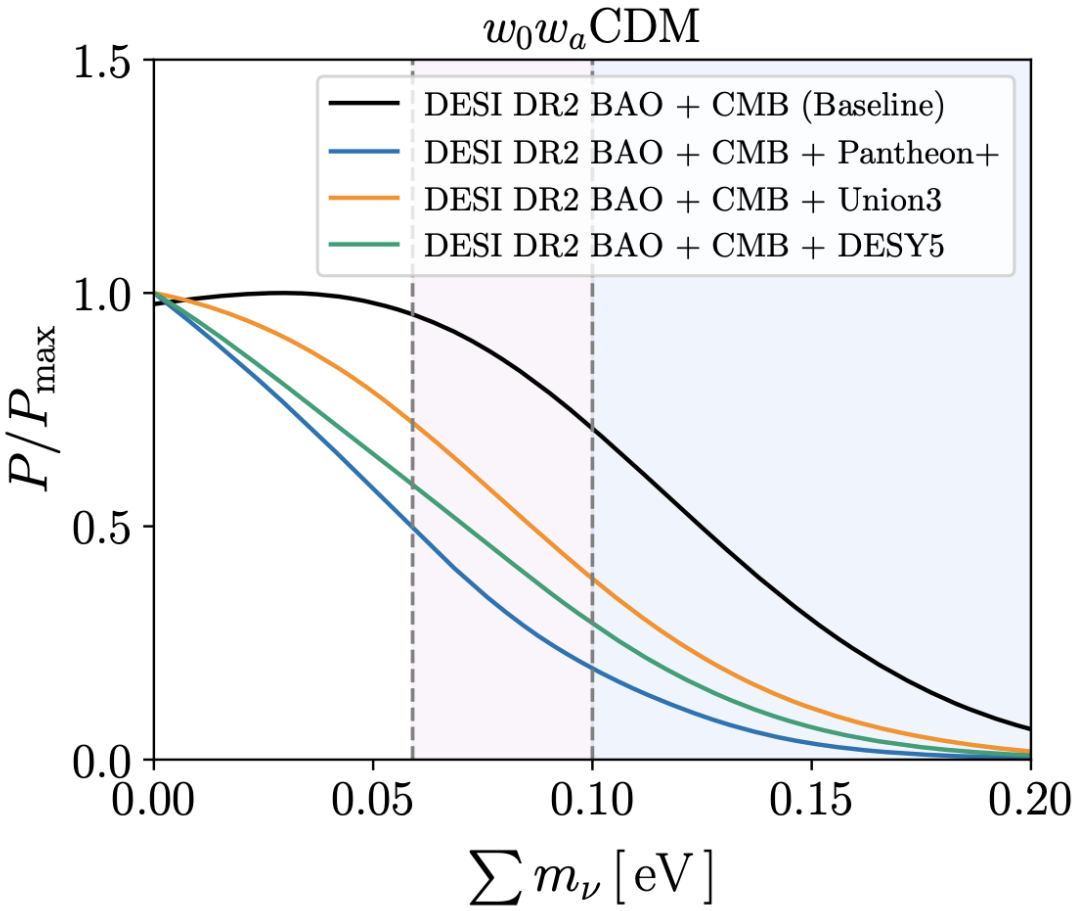
$$\rho_\nu(z) = \sum_{i=1}^{N_\nu} \frac{g_i(1+z)^4}{2\pi^2} \int_0^\infty \frac{p^2 \epsilon(p, m_i)}{1 + e^{p/T_{\nu,0}}} \mathrm{d}p,$$

$$\epsilon_{\rm eff} = \mathrm{sgn}(m_{\nu,\rm eff}) \sqrt{p^2 + a^2 m_{\nu,\rm eff}^2}$$

DESI DR2 BAO + CMB:

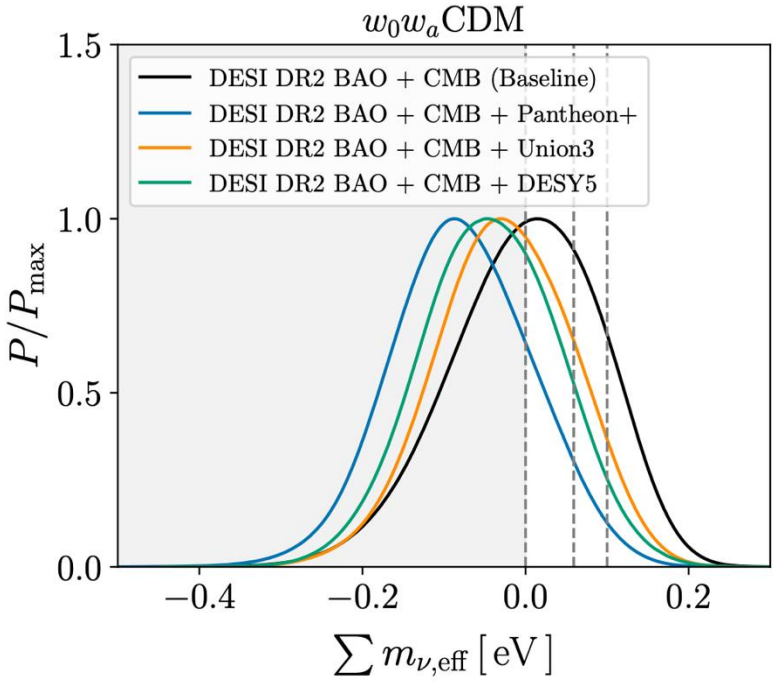
$$\sum m_{\nu,\rm eff} = -0.101^{+0.047}_{-0.056}\,\mathrm{eV} \quad (68\%).$$

w0-wa cosmology



$w_0 w_a$CDM: DESI DR2 BAO + CMB + DESY5:

$$\begin{cases} \sum m_\nu < 0.129\,\mathrm{eV} \\ w_0 = -0.76^{+0.12}_{-0.11} \\ w_a = -0.82^{+0.46}_{-0.48} \end{cases} \quad (95\%).$$



Effects on matter power spectrum

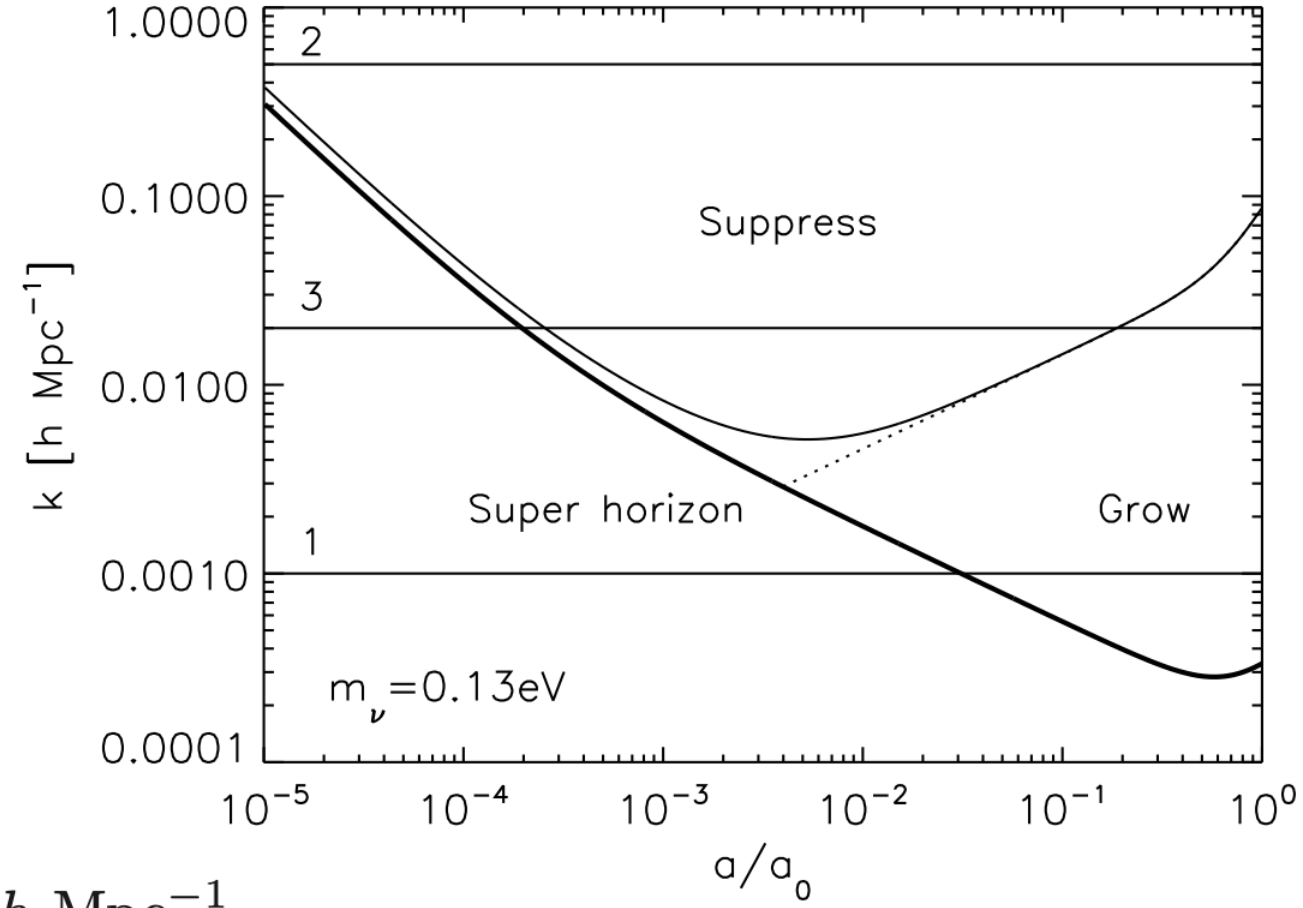
- Free streaming length

Neutrinos cannot cluster in regions smaller than their free streaming length

$$\lambda_{\rm FS} \;=\; 2\pi a/k_{\rm FS}$$

After they become non-relativistic

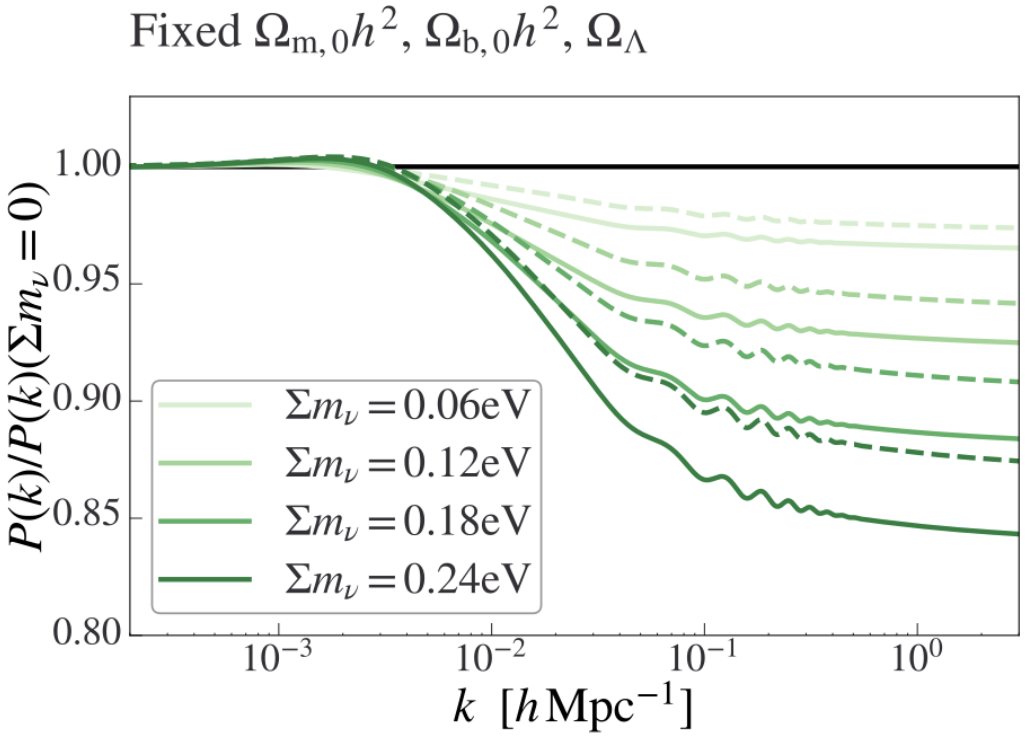
$$k_{\rm FS,i}(z) \simeq \frac{0.677}{(1+z)^2}\left(\frac{m_{\nu,\rm i}}{1\ \rm eV}\right)\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{\frac{1}{2}}\ h\ \rm Mpc^{-1}.$$



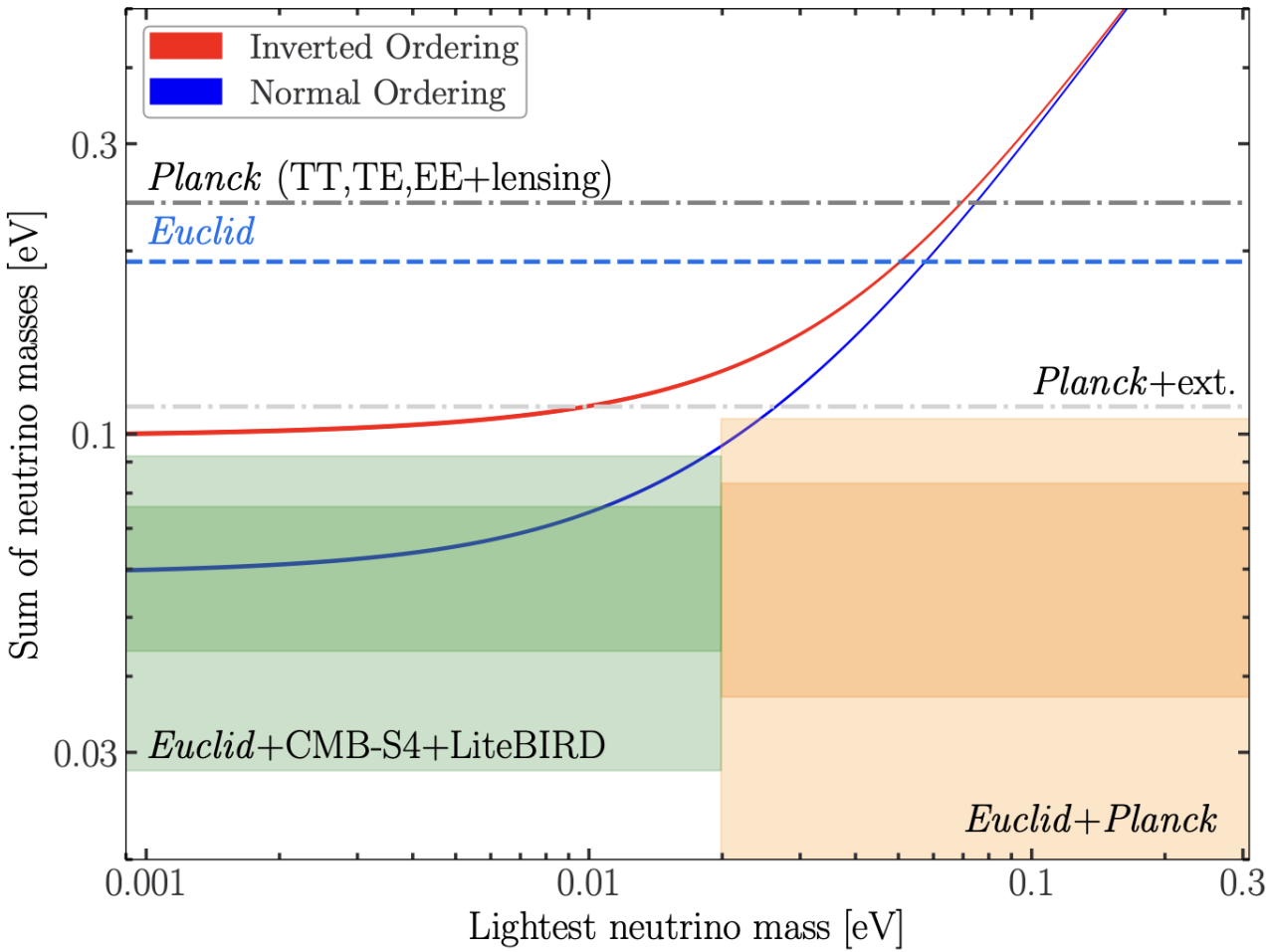
1003.0942

Euclid forecast

Euclid 2405.06047



$$\Delta P_{\rm mm}(k)/P_{\rm mm}(k) \simeq -8 f_\nu$$



Initial conditions

Predictions of inflation

- Primordial curvature perturbation

  Nearly scale invariant and Gaussian

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1} \quad k_* = 0.05\ \mathrm{Mpc}^{-1}$$

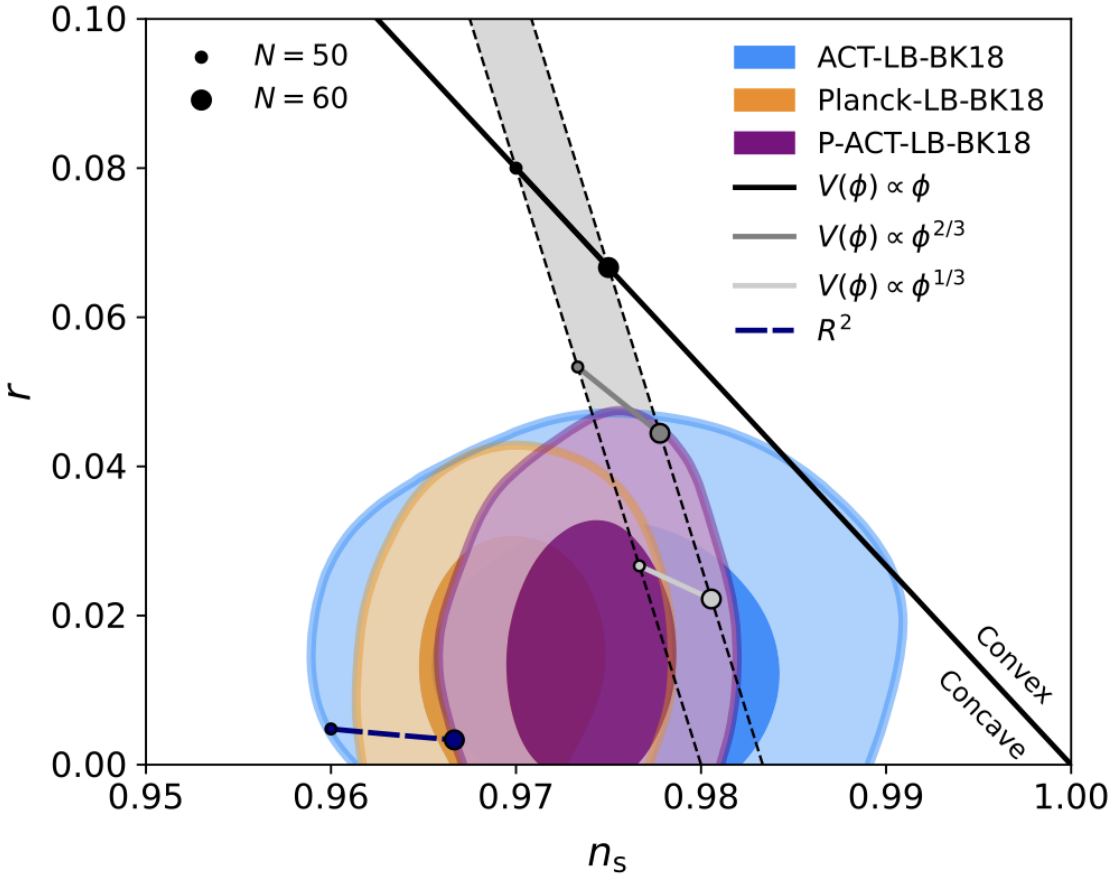
- Primordial gravitational waves

$$r = \mathcal{P}_t(k_*)/\mathcal{P}_{\mathcal{R}}(k_*)$$

- Primordial Non-Gaussianity

$$\Phi = \phi_G + f_{\mathrm{NL}}^{\mathrm{local}}(\phi_G^2 - \langle \phi_G^2 \rangle^2)$$

ACT DR6 2503.14454



Planck 2018 TT(TT,TE,EE)+lowE+lensing

$$n_s = 0.9587 \pm 0.0056\ (0.9625 \pm 0.0048)\,,$$

$$dn_s/d\ln k = 0.013 \pm 0.012\ (0.002 \pm 0.010)\,,$$

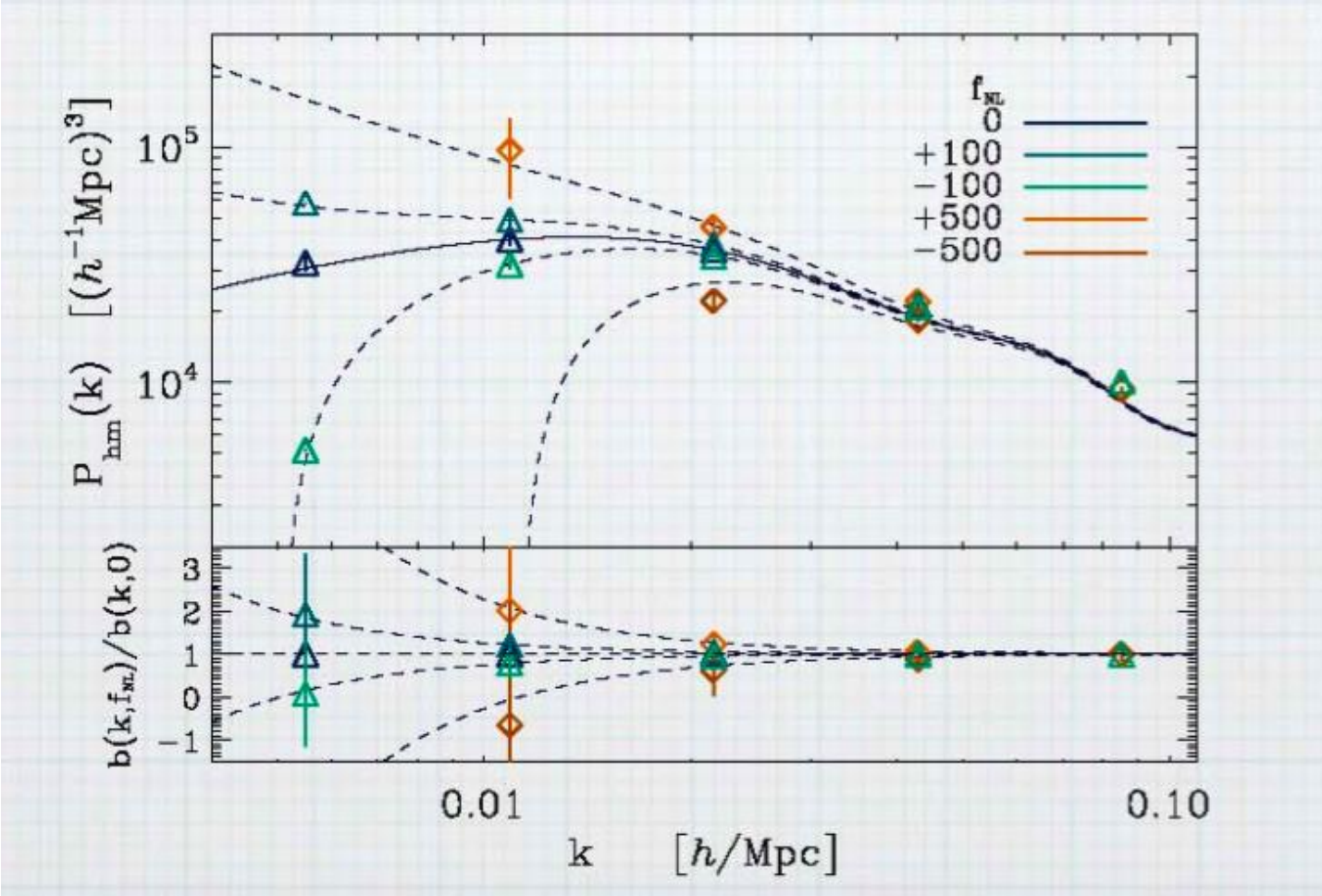
Scale dependent bias

0710.4560

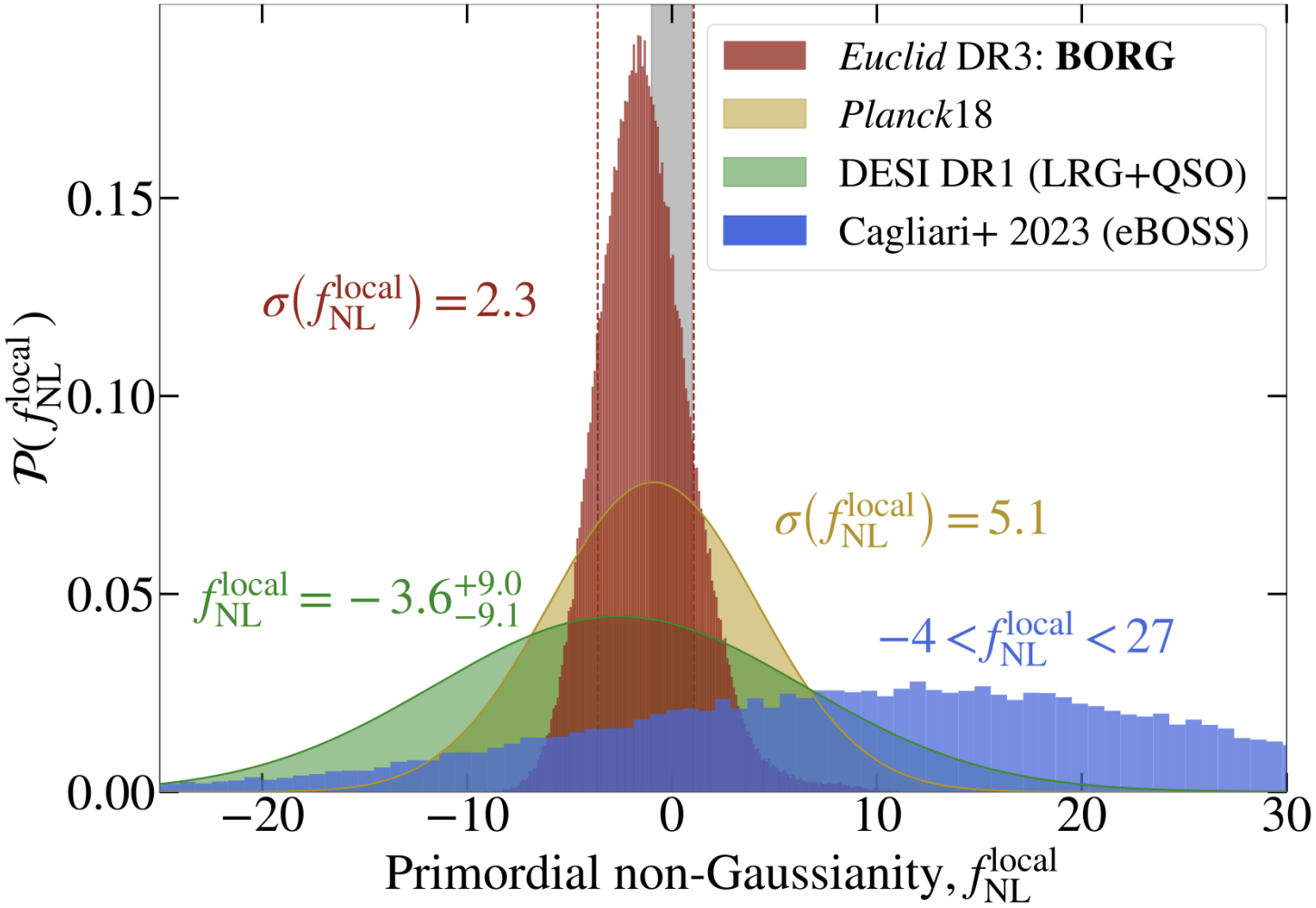
Local primordial Non-Gaussianity predicts a scale dependent bias which we can constrain by looking at the power spectrum on large scales.

$$P_h(k) = \left[b_G + \Delta b(k)\right]^2 P_m(k)$$

$$\Delta b = \frac{b_G f_{NL} \delta_c (8\pi G \bar{\rho}_m)}{k^2 T(k) D(z)}$$



Forecast for Euclid



2412.11945

$$\Phi = \phi_G + f_{\rm NL}^{\rm local}(\phi_G^2 - \langle \phi_G^2 \rangle^2)$$

Euclid Science Requirements Document

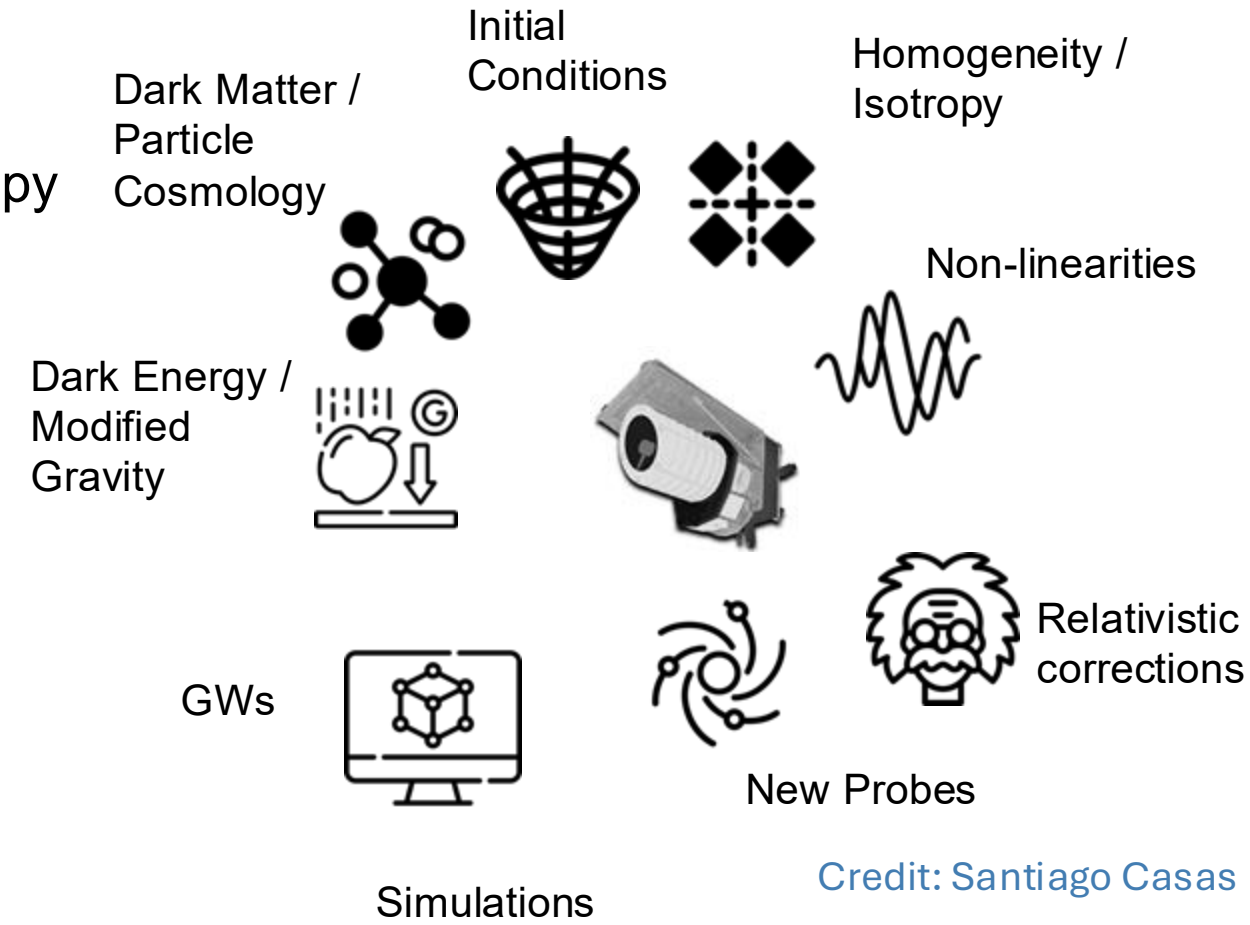
Date of Issue 2015-08-25

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.

Euclid Cosmological Theory Science Working Group

- WP1: Dark energy & Modified Gravity
- WP2: Dark Matter and Particle Cosmology
- WP3: Initial conditions
- WP4: Deviations from homogeneity and isotropy
- WP5: Analytical approaches to non-linearities
- WP6: Relativistic effects in observations
- WP7: New observational probes
- WP8: Joint WP Simulations - Theory
- WP9: Joint WP Gravitational Waves -Theory



Credit: Santiago Casas

Leads

Fabio Finelli

Kazuya Koyama

Noemi Frusciante (Deputy)