Explain DESI Dynamical DE and S8 Tension with Dark Axion and Dark Baryons Interactions

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(with Justin Khoury, Mark Trodden)

arXiv > astro-ph > arXiv:2503.16415

Astrophysics > Cosmology and Nongalactic Astrophysics

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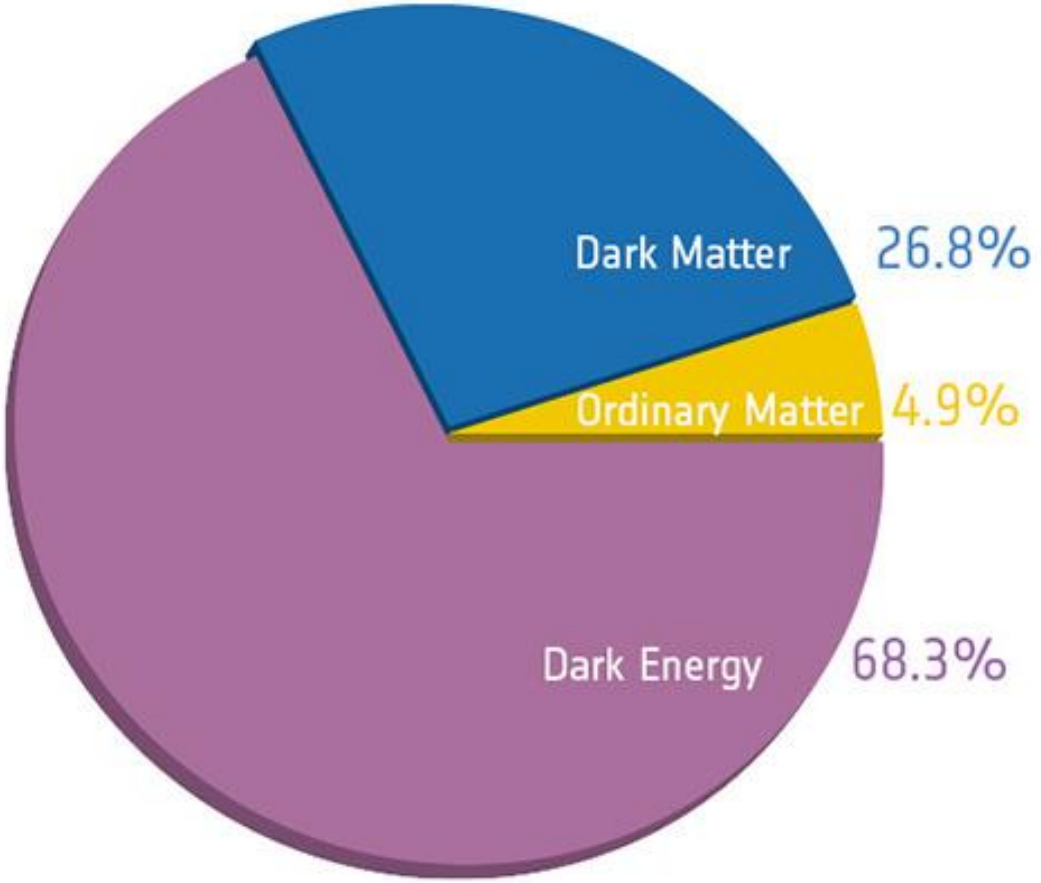
Apparent $w < -1$ and a Lower S_8 from Dark Axion and Dark Baryons Interactions

Justin Khoury, Meng-Xiang Lin, Mark Trodden

Two Fundamental Mysteries

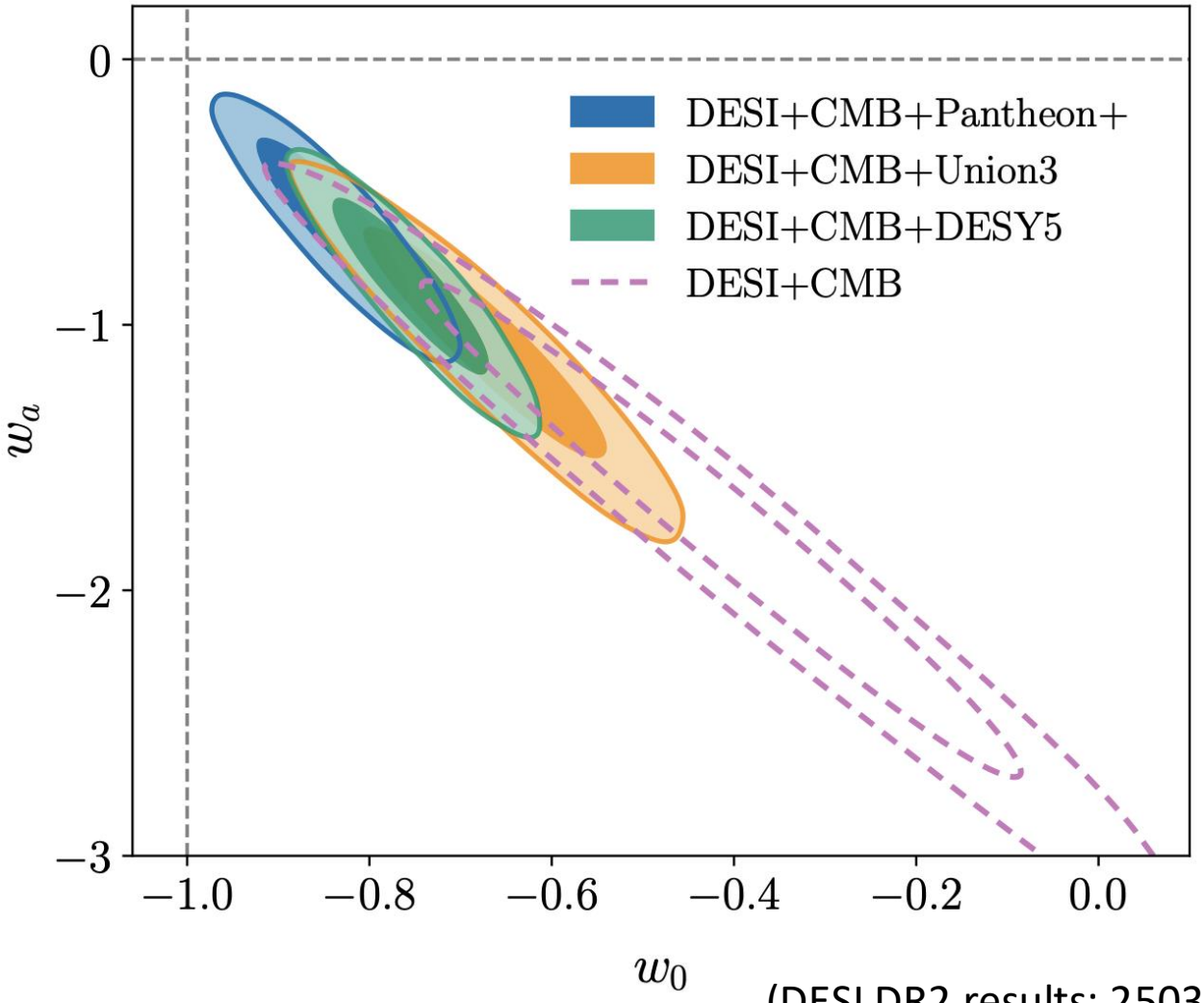


What are the the natures of Dark Matter and Dark Energy?

Observational Hints

- Dynamical Dark Energy: Phantom crossing?
- S8 tension?
- Hubble tension?
- Cosmic Birefringence?

Evidence for dynamical DE



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

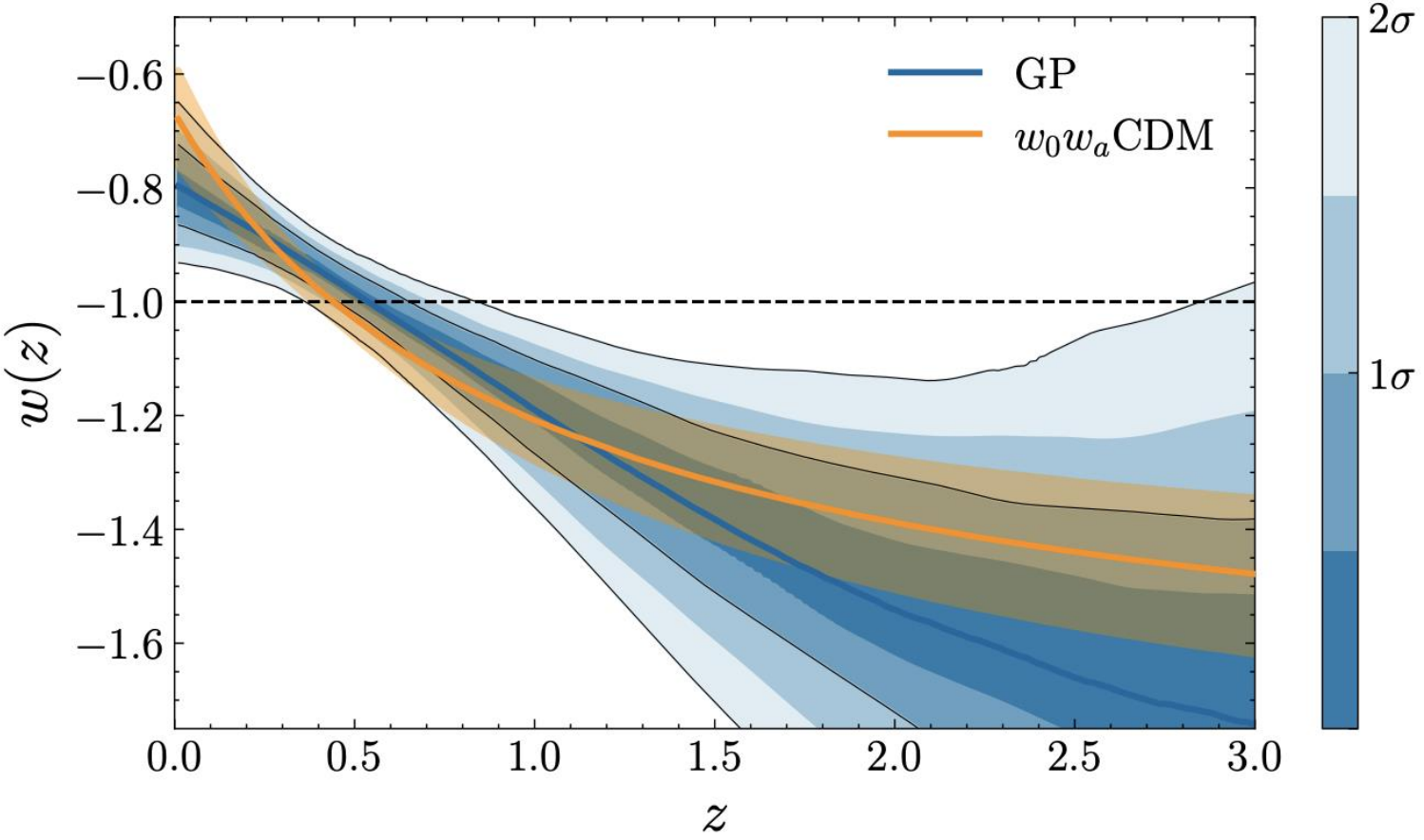
w<-1 at early time
w>-1 today

Compared to DESI DR1:
Much more robust!
4.2 σ DESI+CMB+DESY5
3.1 σ without SN

(DESI DR2 results: 2503.14738)

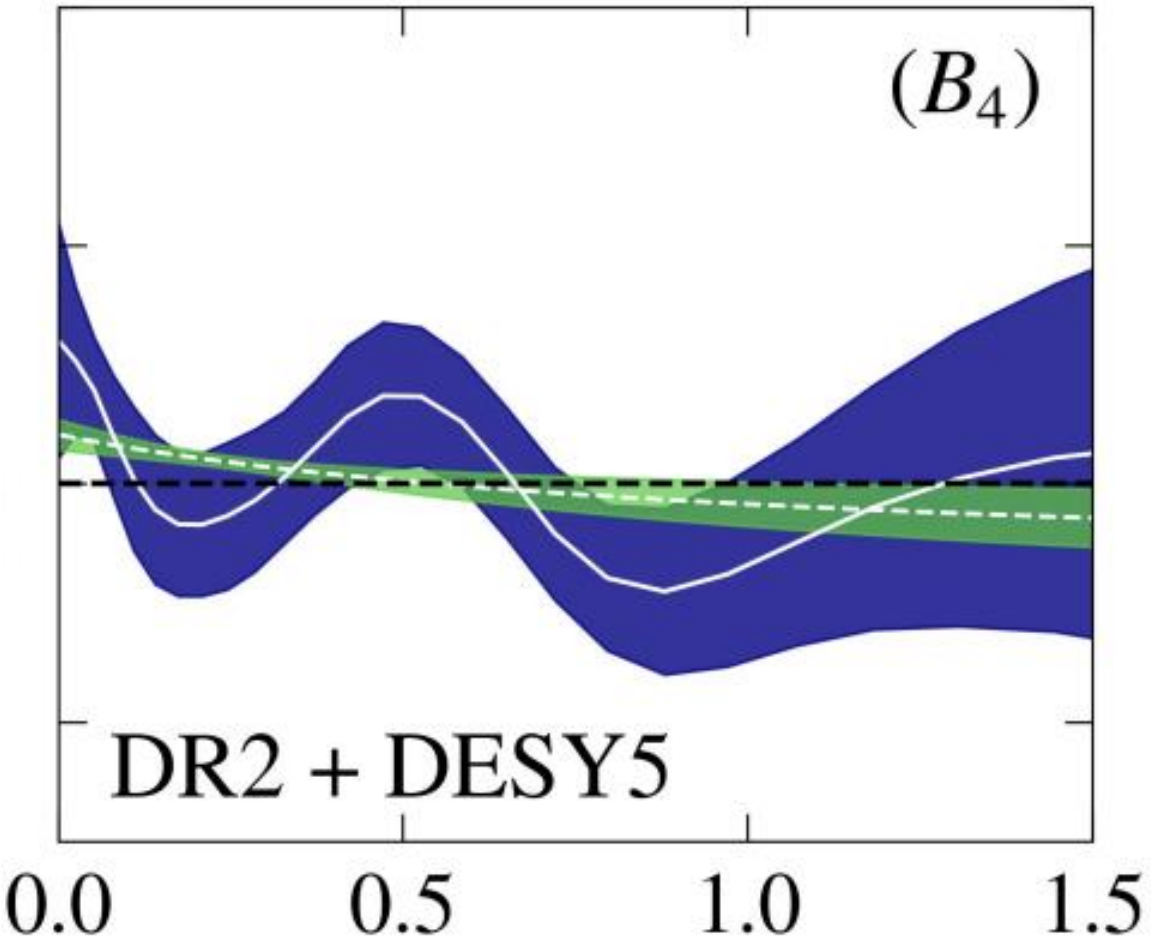
Evidence for dynamical DE

Gaussian Process Regression: Cross -1 at $z \sim 0.5$



(DESI DR2 results: 2503.14743)

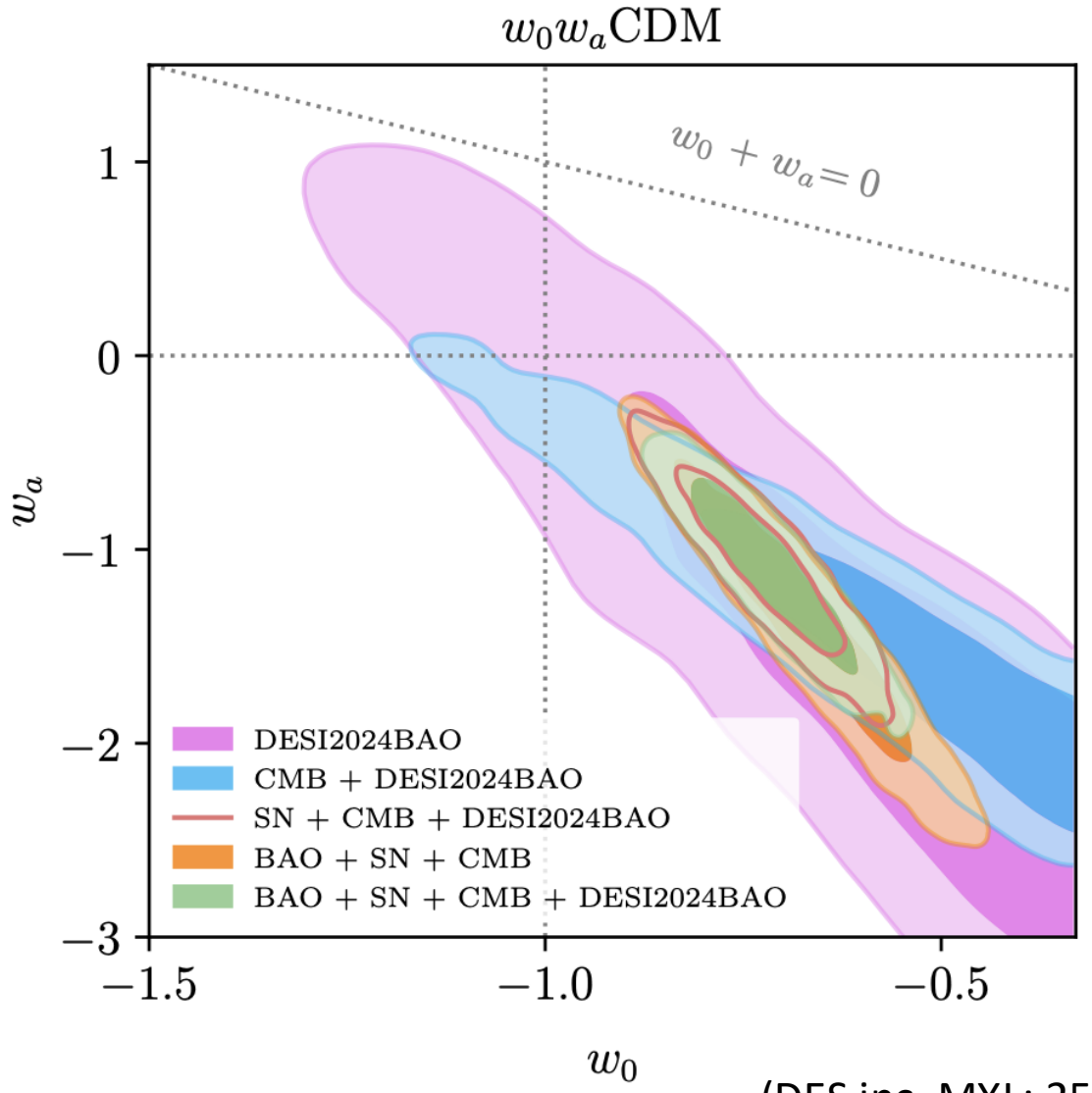
Evidence for dynamical DE



Reconstruction: still show Phantom Cross behavior, consistent with previous results

(Gu+ 2025: 2504.06118)

Evidence for dynamical DE



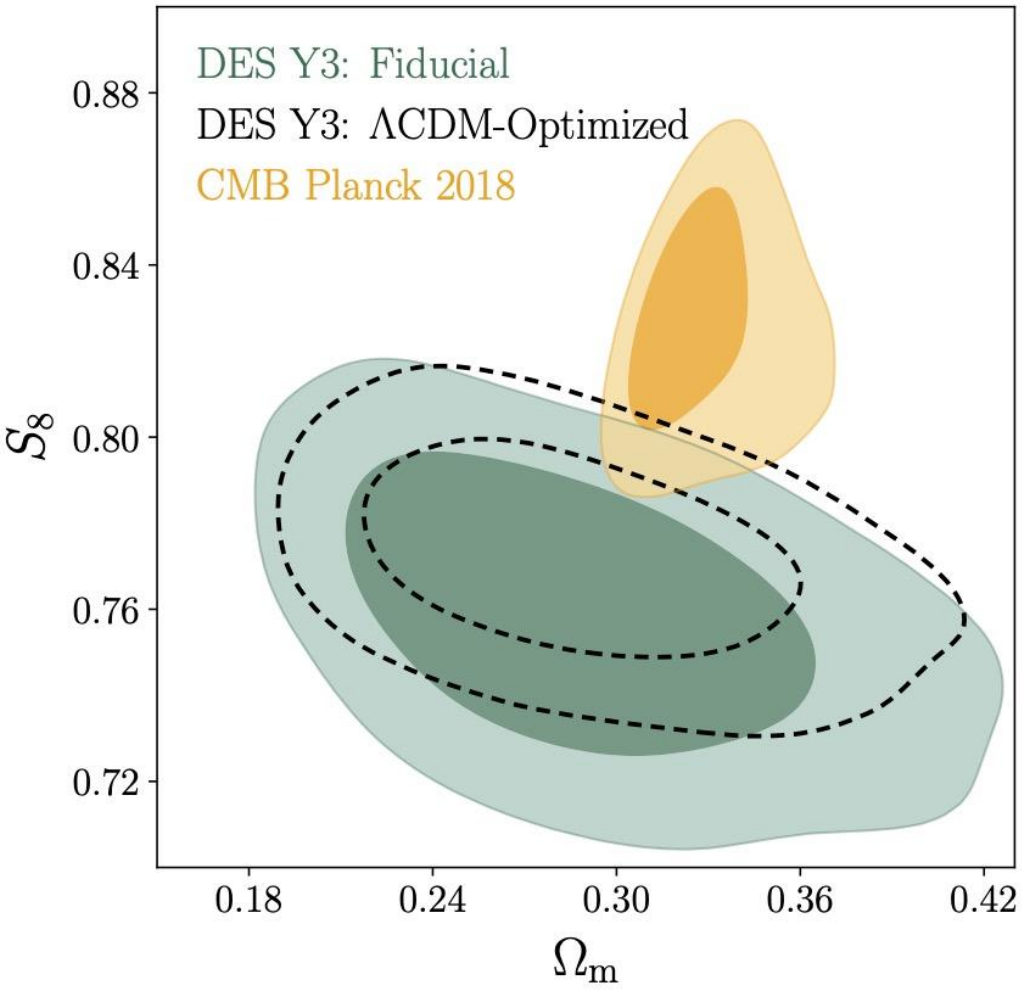
DES results: independent evidence without DESI

(DES inc. MXL: 2503.06712)

Theoretical Interpretation

- Phantom crossing?
  - w>-1: quintessence; w<-1: phantom
  - Two field model (Quintom) to cross -1 (e.g. Feng+ 2005; Guo+ 2005; Hu 2005; Cai+ 2025 for review)
- Theoretical Challenges: phantom field is dynamically unstable (Carroll+2003; Cline+2004; Dubovsky+2006; Nicolis+2010; Creminelli+2010; Creminelli+2013)
  - Violation of the Null Energy Condition $\rho + P \geq 0$
  - Almost invariably imply ghost/gradient instabilities and/or superluminal propagation
- Some possibilities of stable solutions (apparent phantom DE):
  - Modified gravity (e.g. Carroll+ 2005; Ye+ 2025; Wolf+ 2025;)
  - DM-DE interactions (e.g. Huey & Wandelt 2006; Das+ 2006)

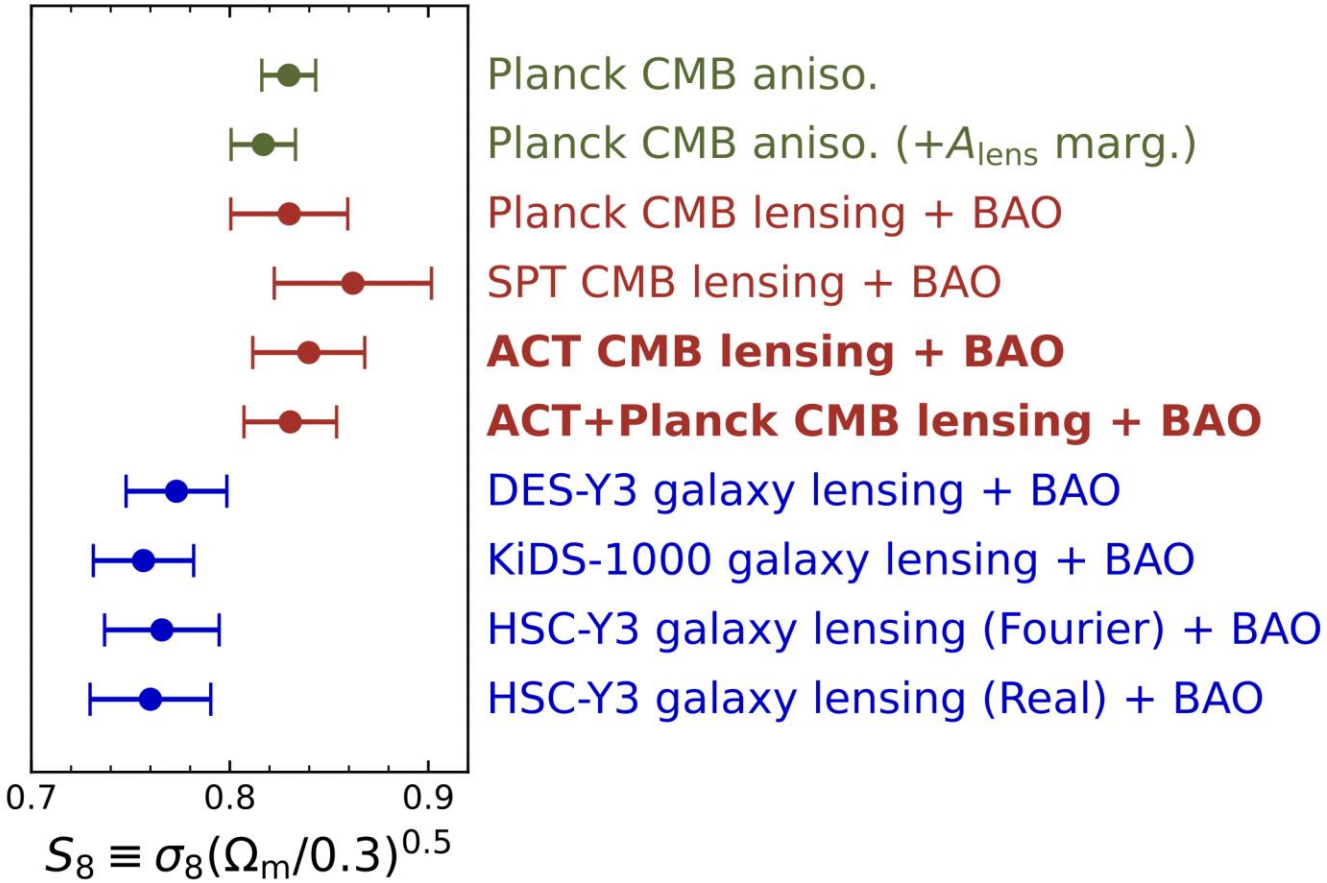
S8 tension



(DES-Y3 results)

- CMB anisotropy vs galaxy survey
- $S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}$: the clustering amplitude
- $\sim 2-3\,\sigma$ tension between CMB primary and galaxy survey within LCDM

S8 tension

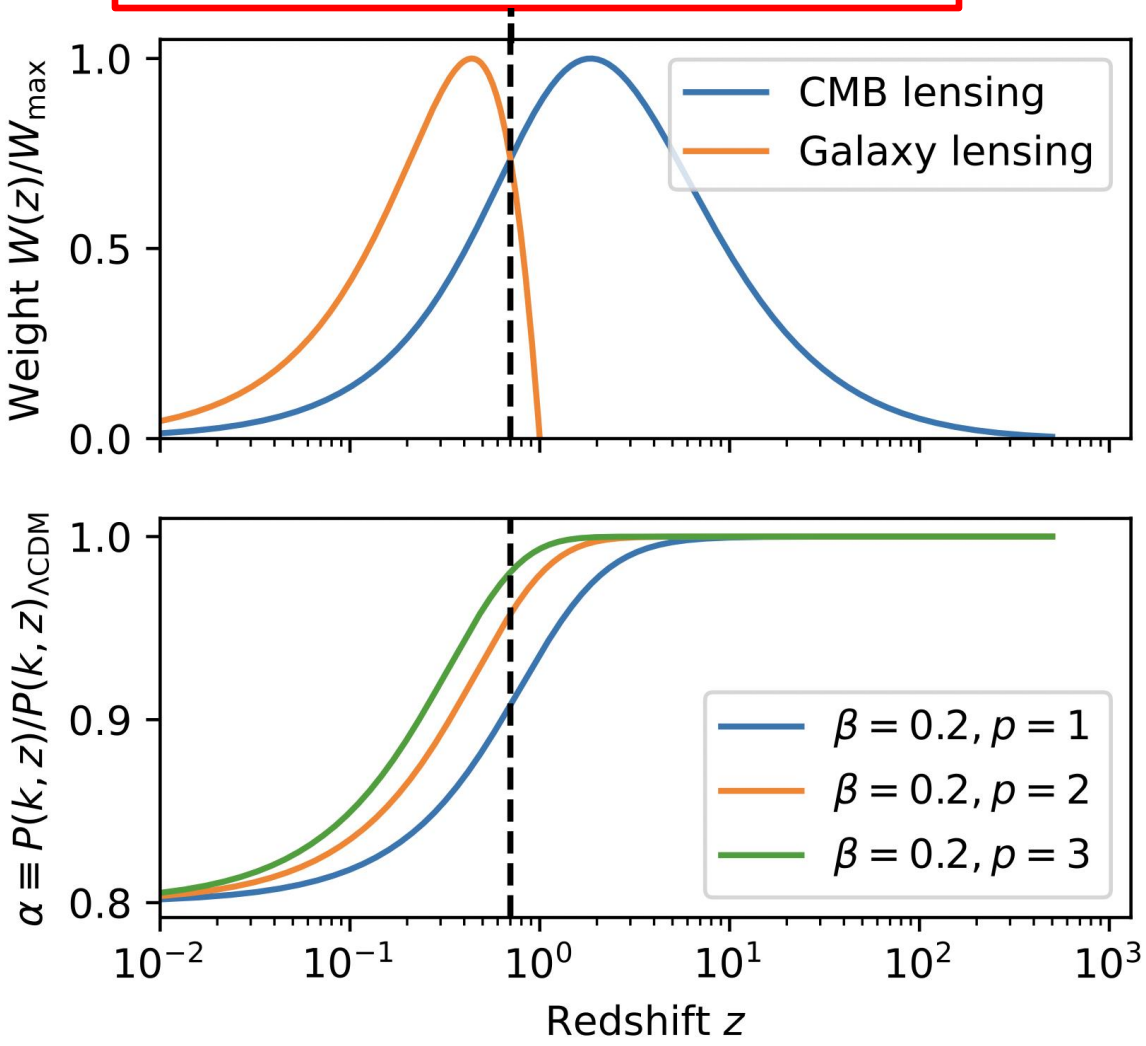


(ACT DR6: 2304.05203)

- CMB lensing is consistent with CMB aniso.
- 2-3 σ tension between CMB aniso/lensing and galaxy lensing

Dark Energy Tracking Growth

Coincidence with DM-DE equality



A simple modification to the late time growth can resolve S8 tension

Hint for DM-DE interaction?

(MXL+ 2308.16183)

Outline

- Theoretical Mysteries: natures of DM and DE
- Observational hints
  - Phantom crossing dark energy?
  - S8 tension?
- DM-DE Interaction: a generic frame
- A Particle Physics Realization: Dark Baryons + Dark Axion
- Future

DM-DE interaction

Yukawa-like coupling: $\mathcal{L}_{\rm int} = m_0 A(\phi)\bar{\psi}\psi$

DE: scalar field ϕ with potential $V(\phi)$

DM: varying mass $m(\phi) \equiv m_0 A(\phi)$

DM density: $\rho_{\rm DM}(\phi) = \frac{A(\phi)}{A(\phi_0)} \frac{\rho^0_{\rm DM}}{a^3}$

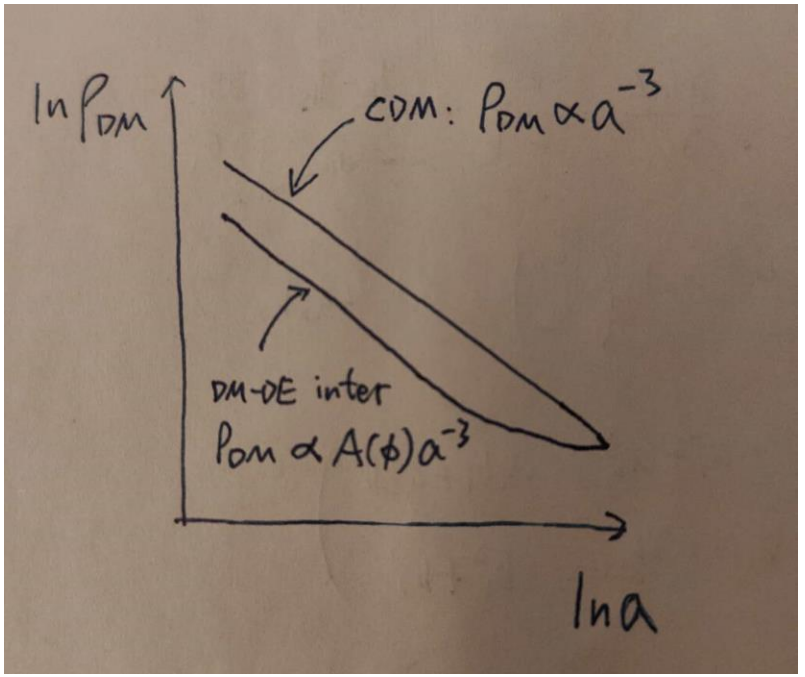
DM-DE interaction

$$\rho_{\rm DM}(\phi) = \frac{A(\phi)}{A(\phi_0)} \frac{\rho^0_{\rm DM}}{a^3}$$

If we fit the data assuming constant-mass CDM, we would ascribe the DM time evolution to DE density:

$$\rho^{\rm eff}_{\rm DE} = \rho_\phi + \left[\frac{A(\phi)}{A(\phi_0)} - 1\right] \frac{\rho^0_{\rm DM}}{a^3}$$

<0



$w_{eff} < -1$

(Das+ 2006: astro-ph/0510628)

Apparent phantom crossing

Effective DE EoS: $$w_{\rm eff} = \frac{w_\phi}{1 + \left[\frac{A(\phi)}{A(\phi_0)} - 1\right] \frac{\rho^0_{\rm DM}}{a^3 \rho_\phi}}$$

If DM mass increasing -> apparent phantom crossing

$$\frac{A(\phi)}{A(\phi_0)} < 1$$

No real phantom field, the apparent phantom crossing comes from assuming standard non-interacting DM

Apparent phantom crossing

Another possibility: decreasing DM mass

(motivated from Swampland conjecture in String Theory)

(Agrawal, Obied, Vafa 2021 1906.08261; Bedroya+2025 2507.03090)

Linear Density Growth

- Shift matter-radiation equality to a later time

  (see also McDonough, **MXL**, Hill, Hu 2112.09128)

  - Density inhomogeneities $\delta_c \equiv \delta\rho/\rho$ grows logarithmically in radiation-dominated, and linearly in matter-dominated epoch
  - Delay the density growth: $$\left.\frac{\delta_{\rm c}}{\delta_{\rm c}^{\Lambda{\rm CDM}}}\right|_{a=1} \simeq \frac{a_{\rm eq}^{\Lambda{\rm CDM}}}{a_{\rm eq}} \simeq \frac{A(\phi_{\rm eq})}{A(\phi_0)}$$
- Different Expansion history in DE-dominated epoch
  - Increasing $w_{\rm eff} \rightarrow$ growth suppression

In the same direction for DESI and S8!

Linear Density Growth

- Shift matter-radiation equality to a later time
  - Density inhomogeneities $\delta_c \equiv \delta\rho/\rho$ grow logarithmically in radiation-dominated, and linearly in matter-dominated epoch
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- Different Expansion history in DE-dominated epoch
  - Increasing $w_{\rm eff} \rightarrow$ growth suppression
- Fifth-force between DM
  - Attractive force
  - Subdominant $\left(\frac{d\ln A(\phi)}{d\phi}\right)^2$

Naturalness of DM-DE interaction

- A long history study
  - (Amendola 2000; Copeland+2006; Bolotin+2014; Wang+2016;)
- The coupling usually gives a large radiative correction to DE mass, but it needs to be small for slow-roll
- Axion: an exception due to discrete shift symmetry (but usually couple to matter only derivatively)
- Following: Axion depends on matter density in the exactly right way!

Particle Physics Model

- DM: dark baryons
  - A natural candidate for self-interacting DM
- DE: associated dark QCD axion

  (Di Vecchia&Veneziano 1980; di Cortona+ 1511.02867)

$$V(\phi) = \Lambda^4 \left[1 - \sqrt{1 - \xi \sin^2 \left(\frac{\phi}{2f} \right)} \right]$$

- $\xi = \dfrac{4 m_{\mathrm{u}} m_{\mathrm{d}}}{(m_{\mathrm{u}} + m_{\mathrm{d}})^2}$ quark mass $m_{\mathrm{u}} = m_d$ $\rightarrow$ cos potential
- Energy scale: $\Lambda \sim \mathrm{meV}$ to serve as DE proportional to pion mass

$$\Lambda^4 = \epsilon m_\pi^2 f_\pi^2$$

$$\epsilon \ll 1$$

(Hook & Huang 1708.08464)

Particle Physics Model

- DM-DE interaction comes from the correction the quark condensate in finite baryon density

  (Cohen, Furnstahl, Griegel 1992; Balkin+ 2003.04903)

  - Gell-Mann-Oakes-Renner relation:

$$\langle \bar{q}q \rangle_{\rm vac} = -\frac{m_\pi^2 f_\pi^2}{m_{\rm u} + m_{\rm d}}$$

  - Quark condensate correction:

$$\frac{\langle \bar{q}q \rangle_n}{\langle \bar{q}q \rangle_{\rm vac}} \simeq 1 + \frac{n\sigma_{\rm N}}{m_q \langle \bar{q}q \rangle_{\rm vac}} \simeq 1 - \frac{2n\sigma_{\rm N}}{m_\pi^2 f_\pi^2} \qquad \sigma_N \equiv \frac{\partial m}{\partial \ln \bar{m}_q}$$

(~59MeV in SM)

  - Potential correction (Hook & Huang 1708.08464):

$$U(\phi) \simeq 2\sigma_{\rm N} n \sqrt{1 - \xi \sin^2\left(\frac{\phi}{2f}\right)} + \mathcal{O}\left(\frac{n^2\sigma_{\rm N}^2}{m_\pi^4 f_\pi^4}\right)$$

Particle Physics Model

- Potential correction

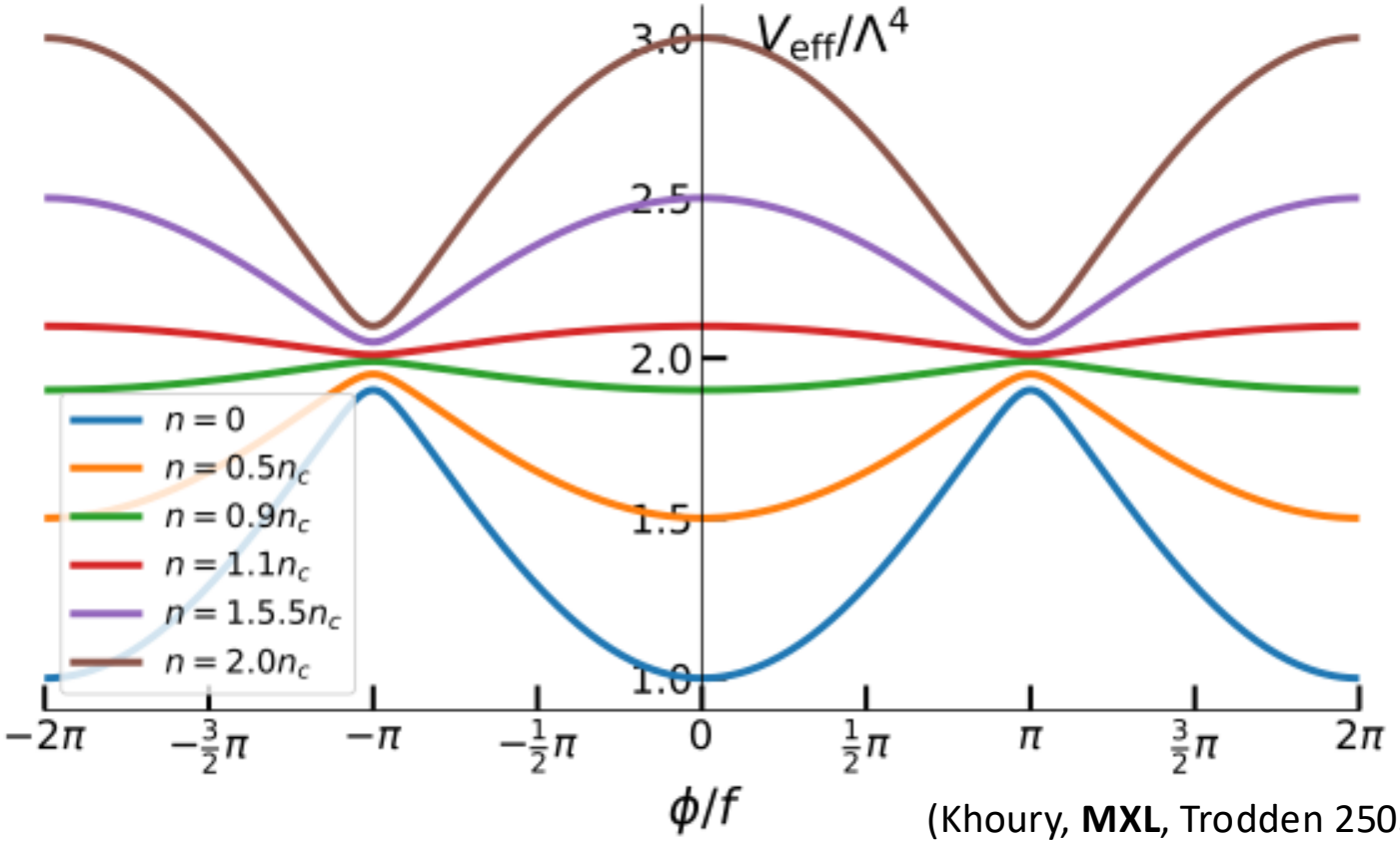
$$U(\phi) \simeq 2\sigma_{\rm N} n \sqrt{1 - \xi \sin^2\left(\frac{\phi}{2f}\right)} + \mathcal{O}\left(\frac{n^2\sigma_{\rm N}^2}{m_\pi^4 f_\pi^4}\right)$$

- DM mass

$$A(\phi) \simeq 1 + 2\frac{\sigma_{\rm N}}{m_0}\sqrt{1 - \xi \sin^2\left(\frac{\phi}{2f}\right)}$$

- $\sigma_N \equiv \dfrac{\partial m}{\partial \ln \bar{m}_q}$ is positive
  - DM mass increases as we want
  - Potential flip

Effective potential

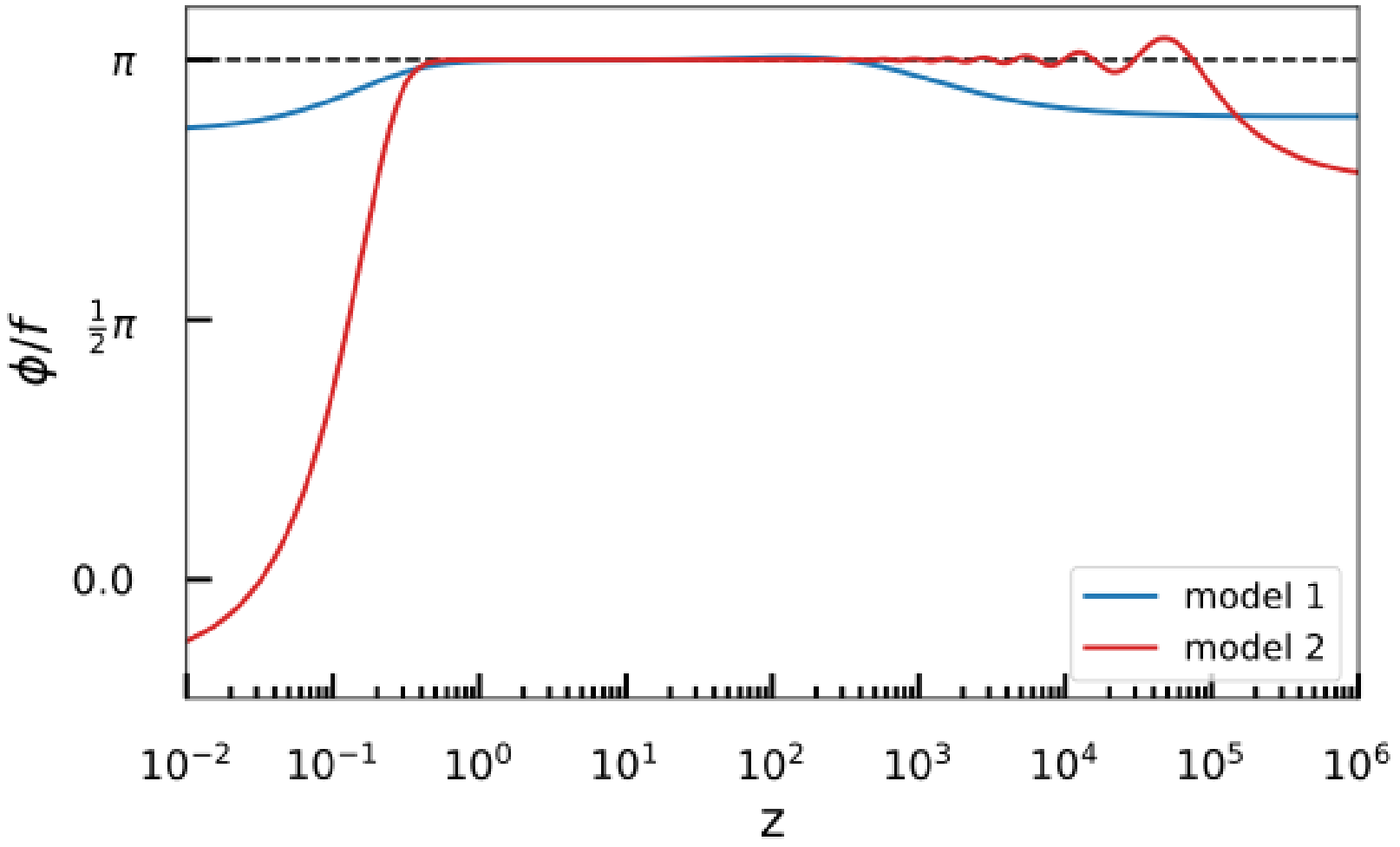


(Khoury, **MXL**, Trodden 2503.16415)

$$V_{\rm eff}(\phi) = \Lambda^4 \left\{ 1 - \left(1 - \frac{2\sigma_{\rm N} n}{\Lambda^4} \right) \sqrt{1 - \xi \sin^2 \left(\frac{\phi}{2f} \right)} \right\}$$

Critical density for potential flip: $n_{\rm c} = \dfrac{\Lambda^4}{2\sigma_{\rm N}} = \dfrac{\epsilon m_\pi^2 f_\pi^2}{2\sigma_{\rm N}}$

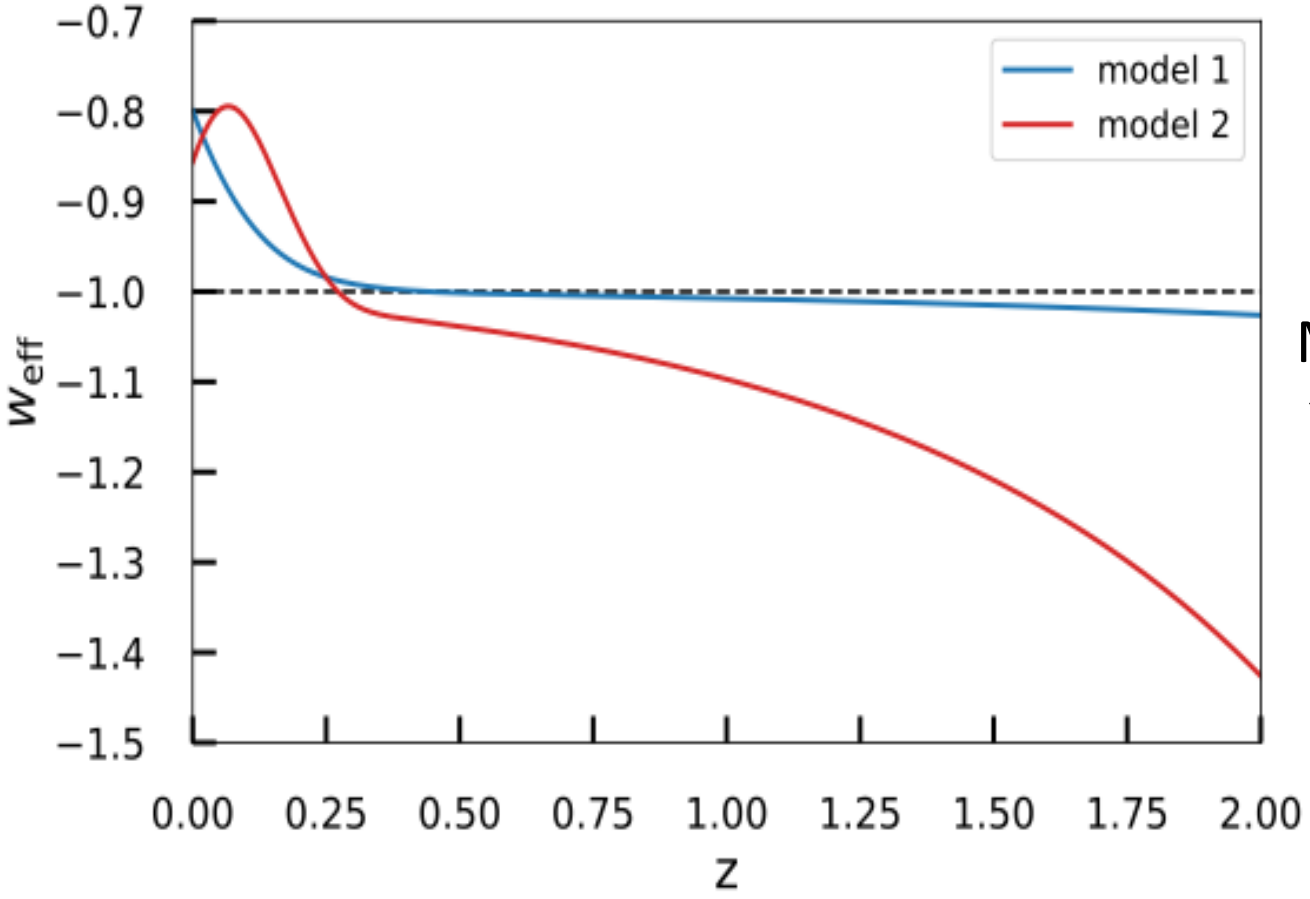
Working Examples



Naturalness

- Any field initial position: no fine-tuning
- Give the initial condition for axion potential to serve as DE
- DM-DE equality as a special timing
- No radiative correction
- Stable in perturbations

Effective w of DE



Cross -1 at $z \sim 0.5$

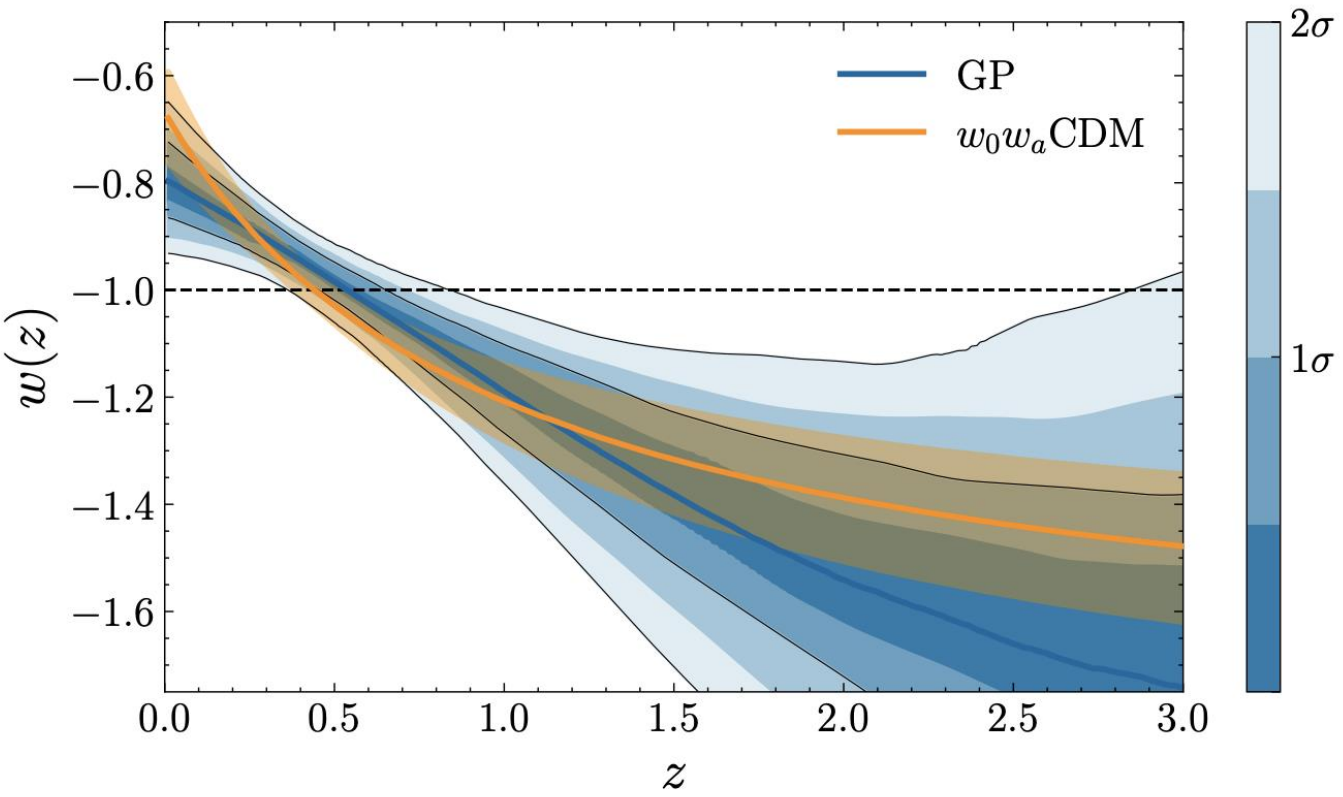
$w \sim -0.8$ today

Mapping to

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

$w_0 > -1, w_a < 0$

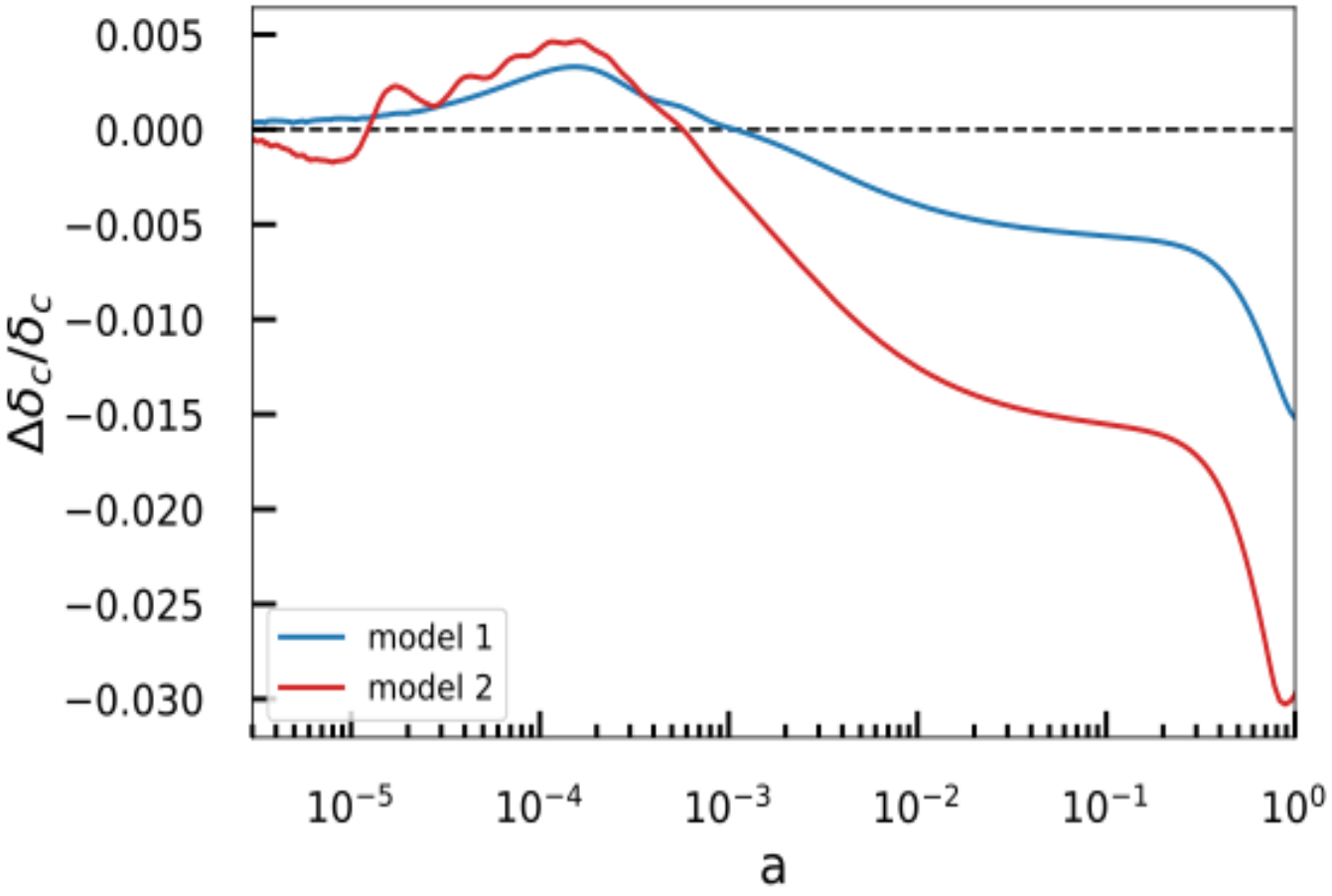
Evidence for dynamical DE



Cross -1 at $z\sim0.5$

(DESI DR2 results: 2503.14743)

Density Growth compared to LCDM



$$\frac{\Delta\delta_c}{\delta_c} = \frac{\delta_c - \delta_c^{\mathrm{LCDM}}}{\delta_c^{\mathrm{LCDM}}}$$

Suppress the late-time growth compared to LCDM

Reduce S8 value

Remarks on Parameter choice

- Initial field position: any, no fine-tuning
- Quark mass ratio: $\frac{m_u}{m_d} = 0.8$, close to 1
- Decay constant: $f \lesssim M_{pl}$
- Coupling param σ_N/m_0:
  - definition of pion-nucleon sigma term $\sigma_N \equiv \frac{\partial m}{\partial \ln \bar{m}_q}$ (~59MeV in SM)
  - 0.06 in standard QCD
  - Our "data-preferred" value: 0.01-0.02, same order of magnitude

Future

- Full likelihood analysis (CLASS code is ready)
- Hubble tension? (we are working on this)
- Cosmic Birefringence?
- Environment dependent DE fluctuation?

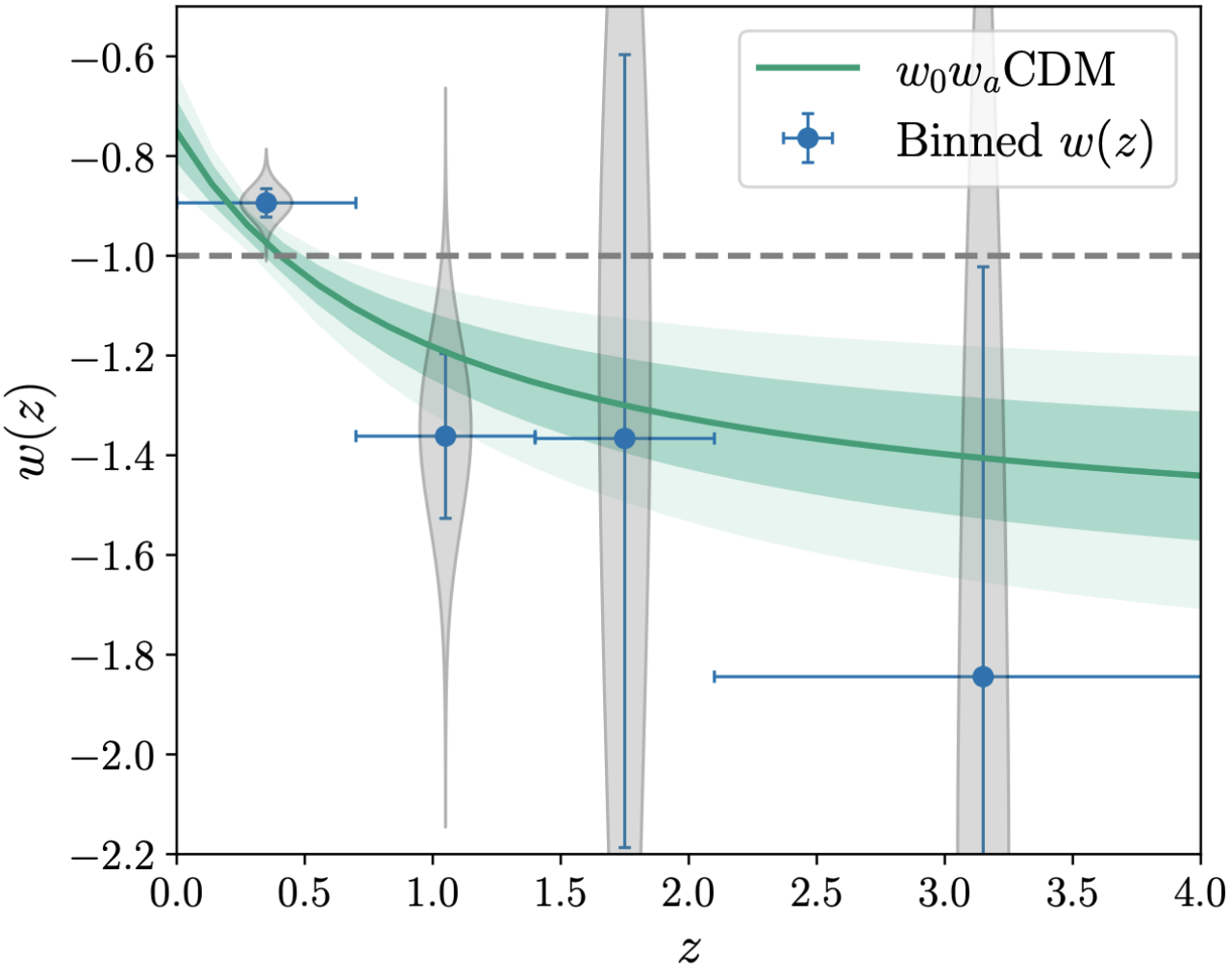
- Higher redshift observations: DESI, PFS, MUST

Summary

- DM-DE interaction can simultaneously explain the apparent phantom crossing behavior in DESI and the S8 tension
- We provide a stable and technically natural particle physics realization: Dark baryons + Dark axion
- Interaction comes from the correction to the quark condensate in a finite baryon density
- No initial fine-tuning, natural parameter choice

BACKUP

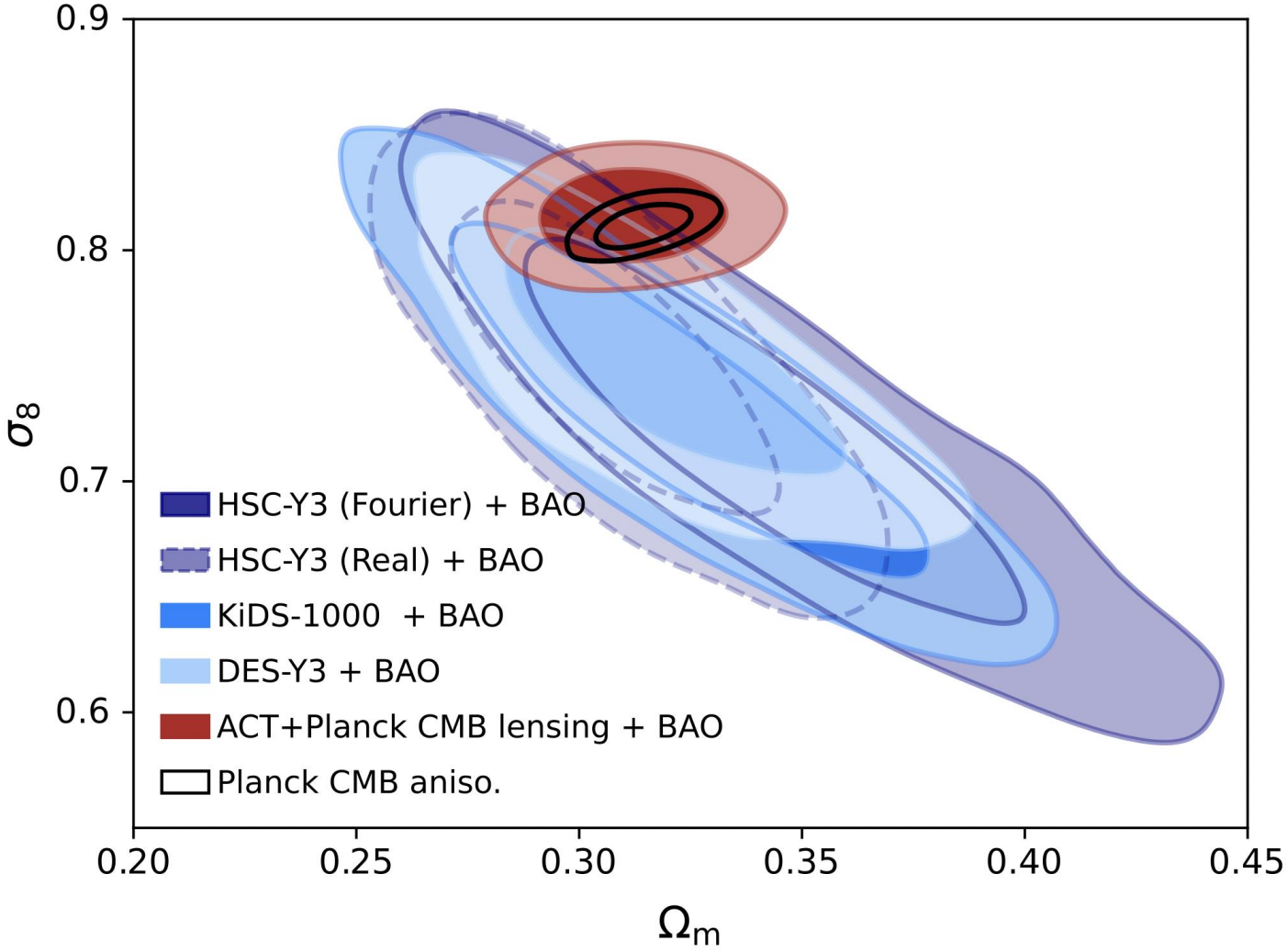
Evidence for dynamical DE



A clear w<-1 point at $z\sim1$

(DESI DR2 results: 2503.14738)

CMB lensing vs galaxy lensing



(ACT DR6: 2304.05203)

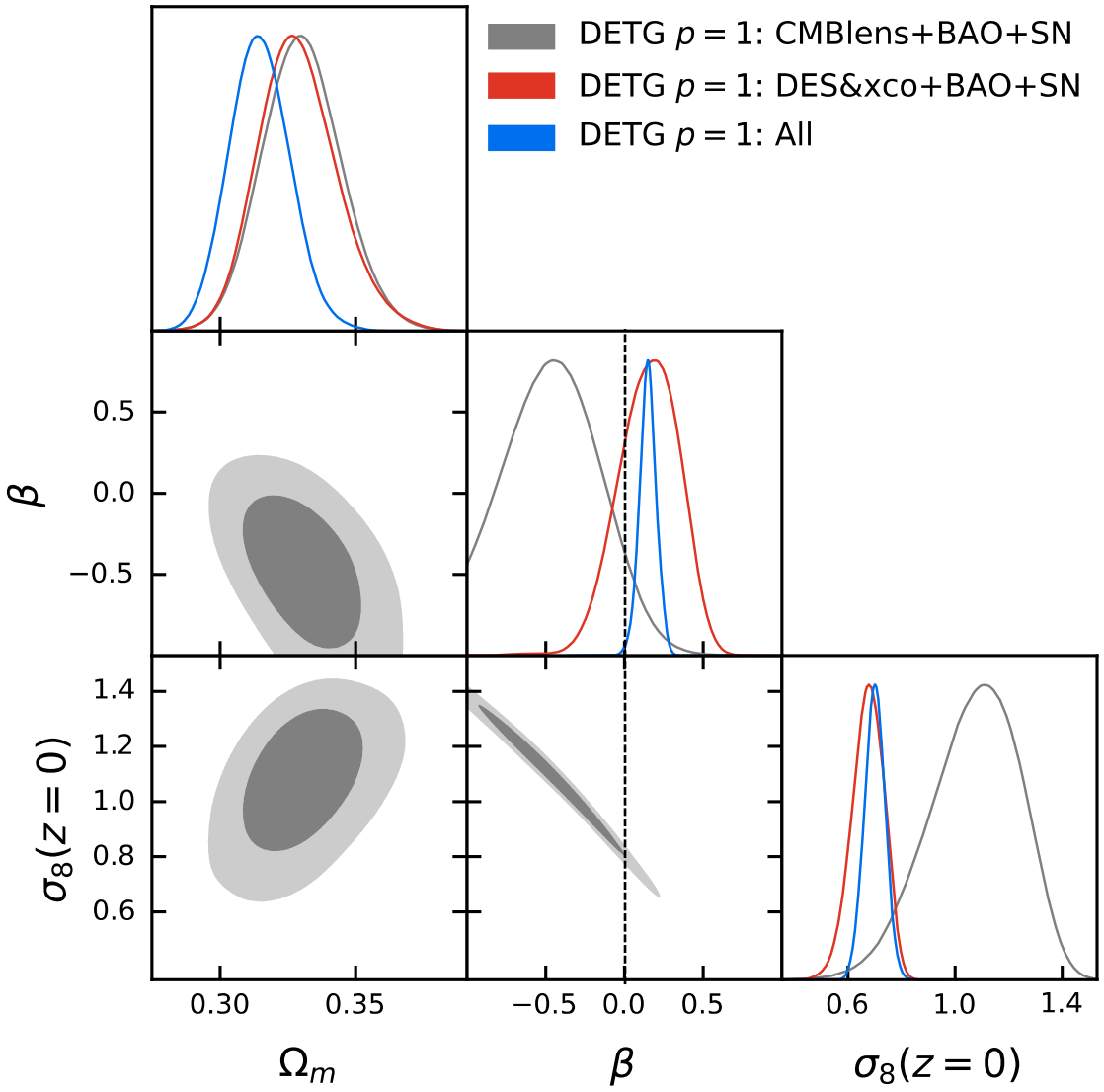
Dark Energy Tracking Growth

$$\alpha(z) \equiv \frac{P(k,z)}{P(k,z)_{\Lambda\mathrm{CDM}}} = 1 - \beta \left(\frac{\Omega_{\mathrm{DE}}(z)}{\Omega^0_{\mathrm{DE}}} \right)^p$$

- $P(k,z)$ is the linear matter power spectrum
- $\Omega_{DE}(z)$ is the fractional dark energy density
- The background is still LCDM
- Use Halofit to compute the non-linear power spectrum
- Only one free parameter β (when p is fixed)

(Lin+ 2308.16183)

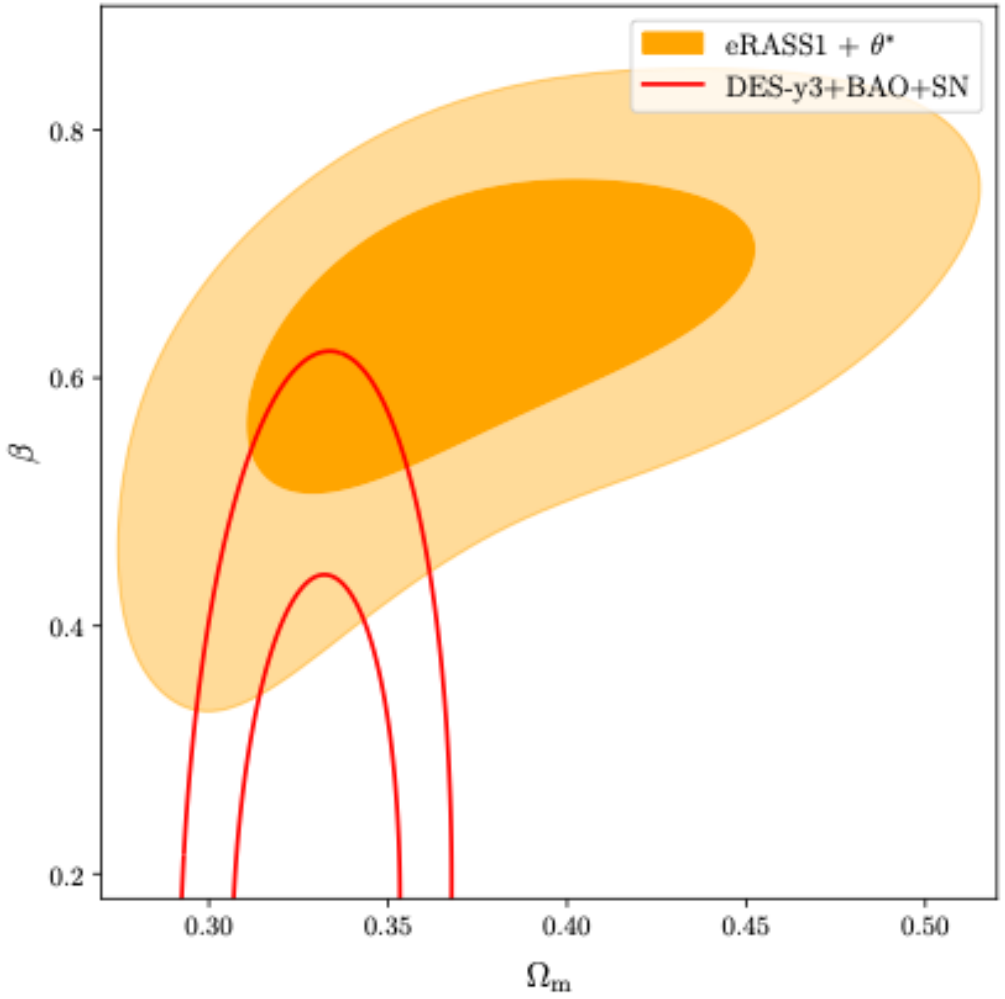
DETG results: the simplest model



- All = CMBlens +DES&xco+BAO+SN: positive β, LCDM is excluded at $2.9\,\sigma$
- All p=1 best fit : $\Delta\chi^2 = -7.2$

(MXL+ 2308.16183)

DETG: Other independent chekcs

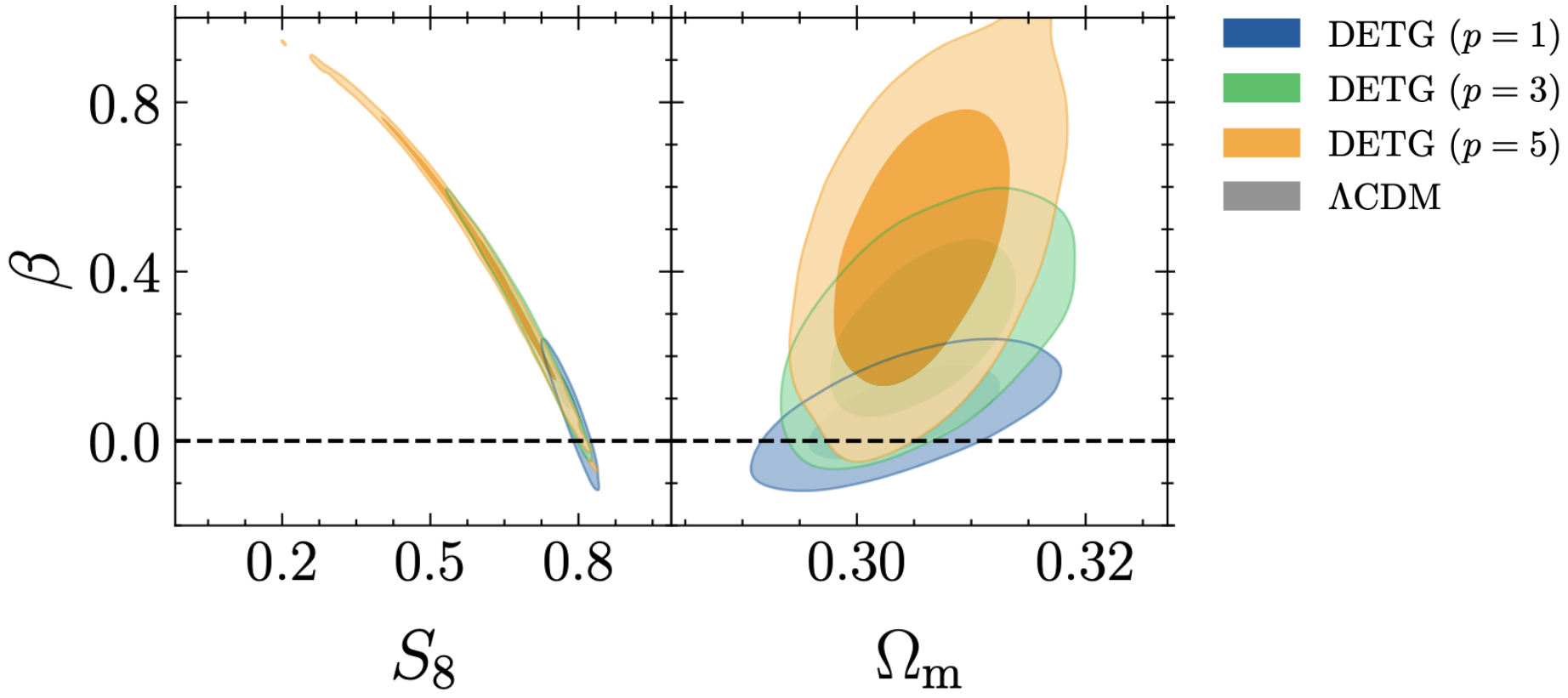


SRG/eROSITA Results:
4.4 σ

(eROSITA team 2024: 2410.09499)

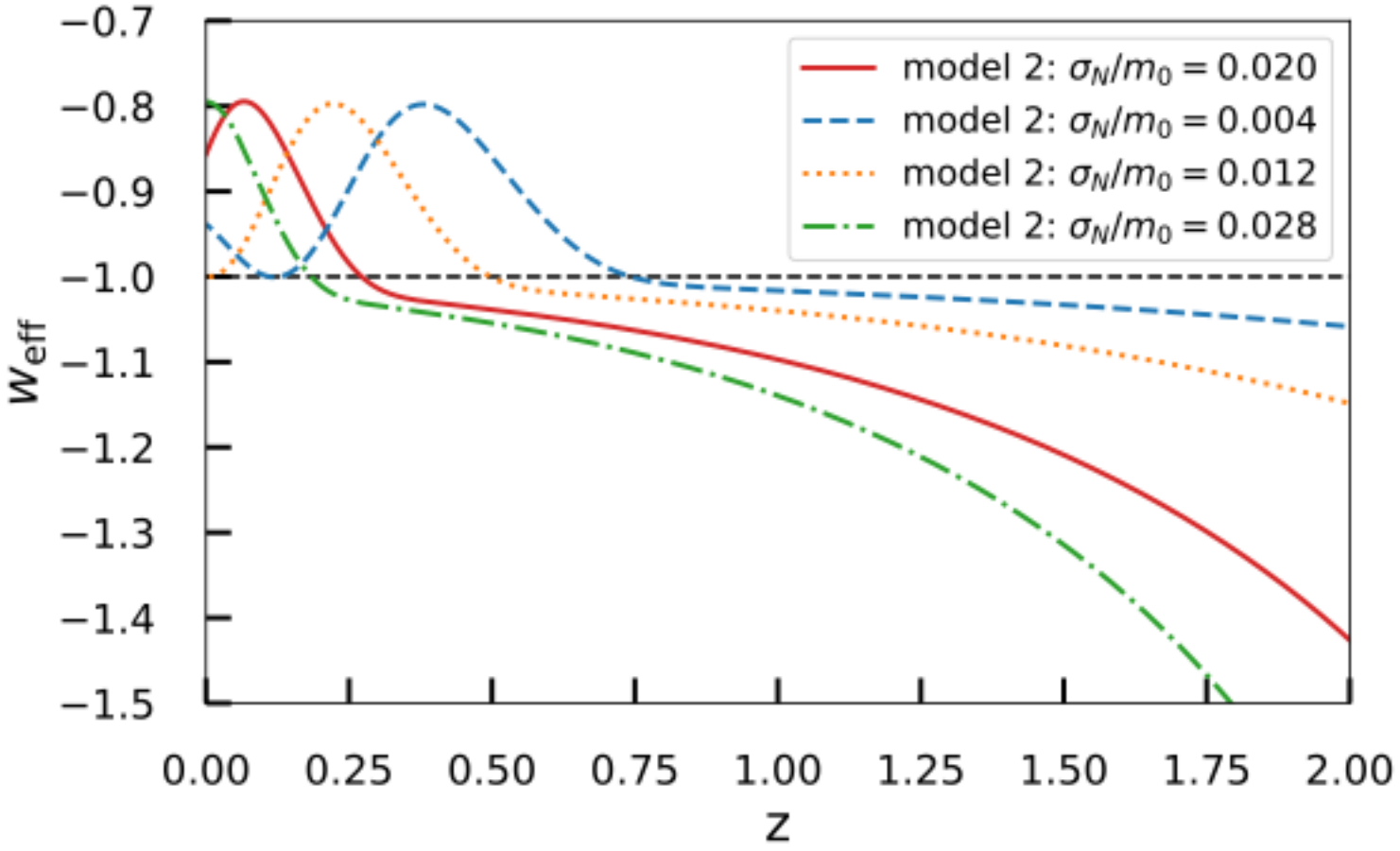
DETG: Other independent checks

Subaru HSC Results: $\sim 2\,\sigma$

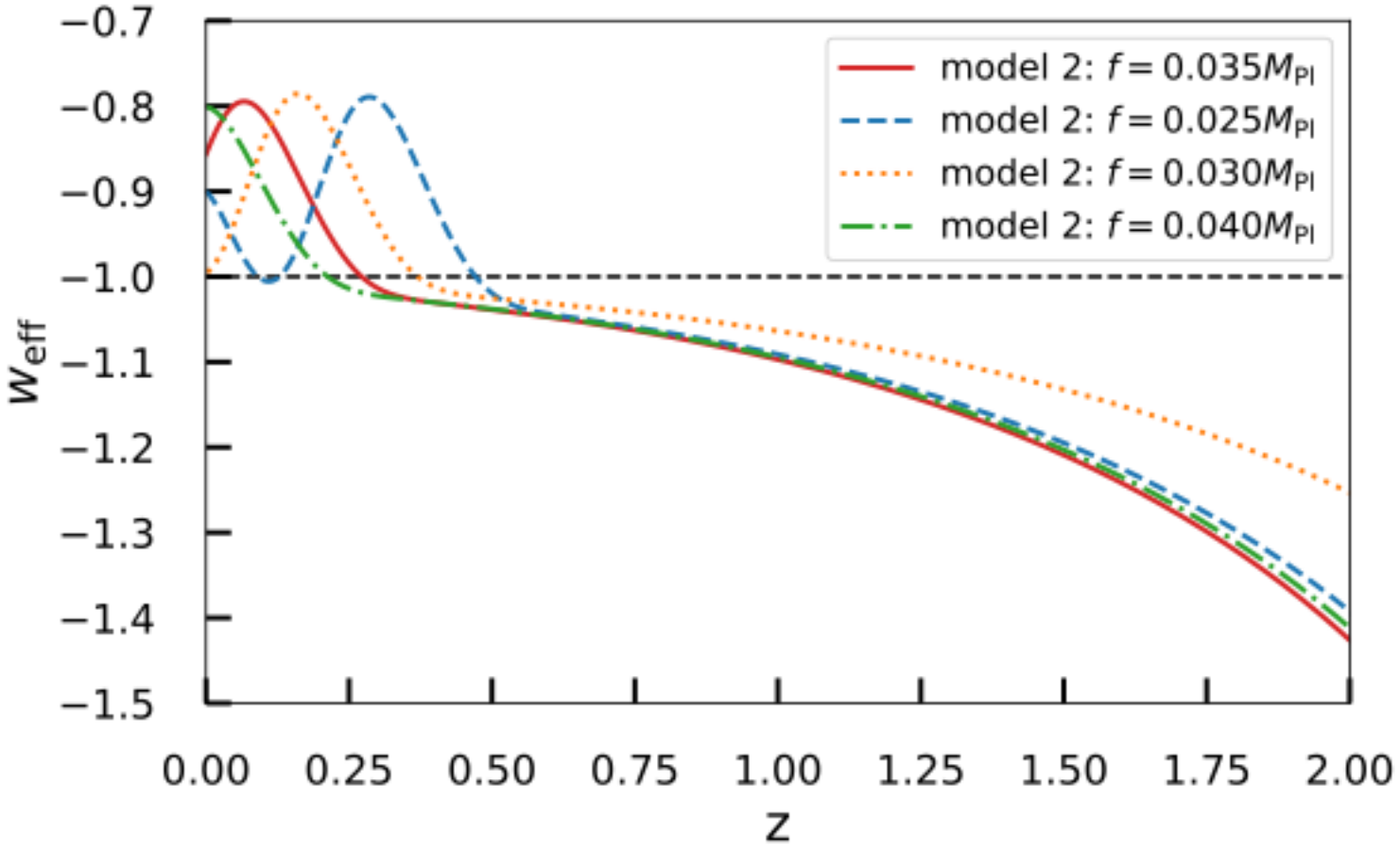


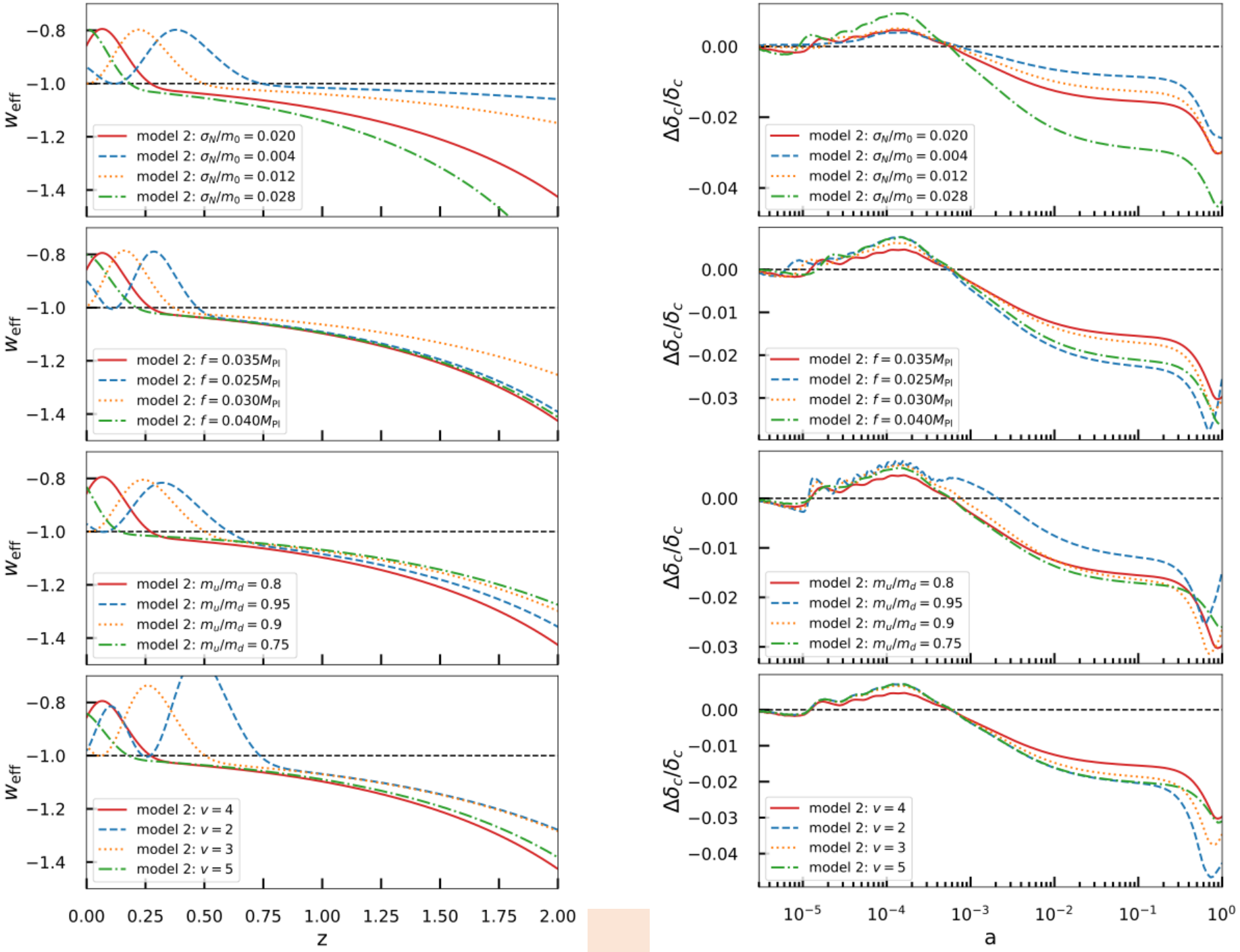
(Terasawa+ 2505.09176)

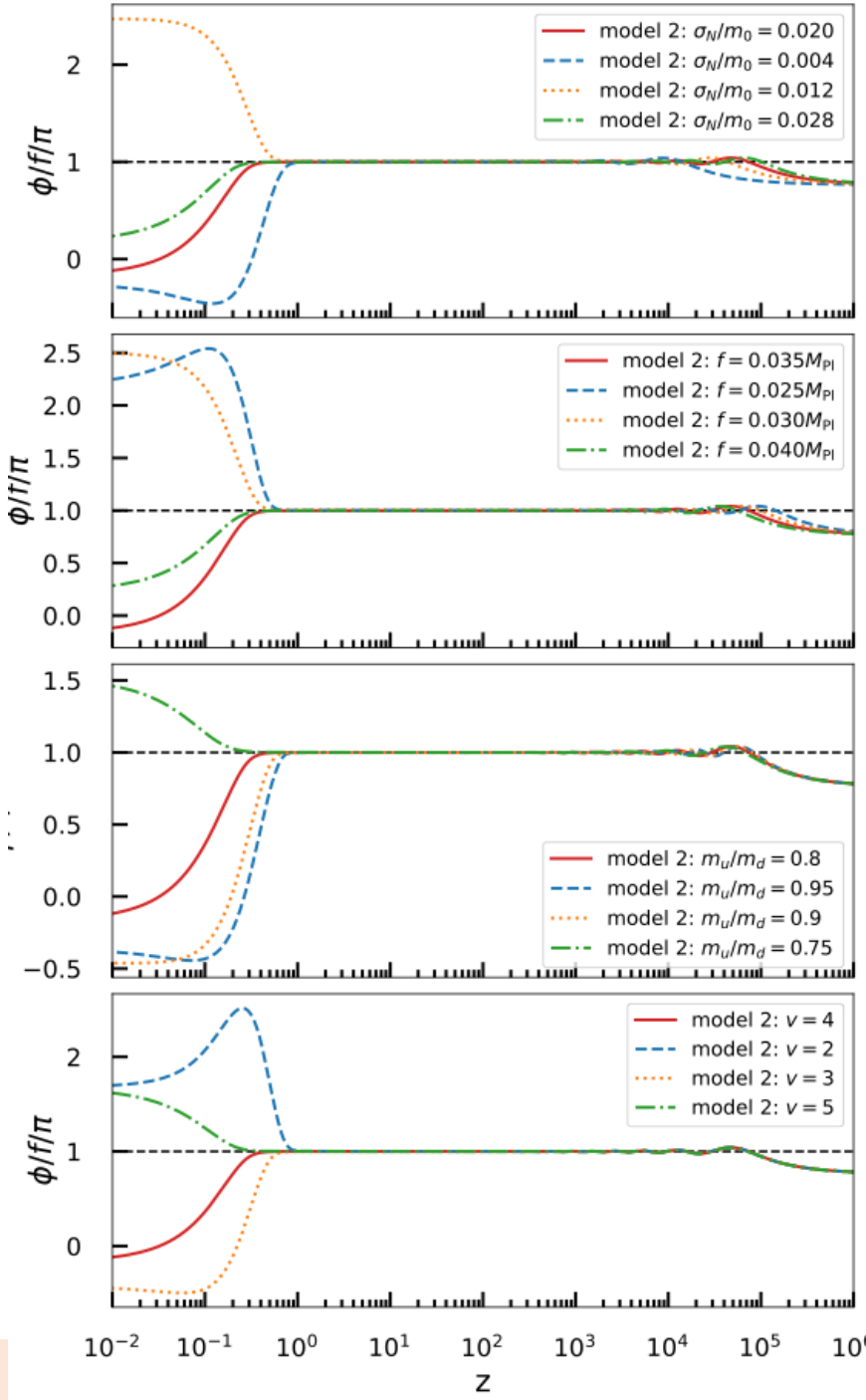
Varying coupling



Varying decay constant




$w_{\rm eff}$
model 2: $\sigma_N/m_0 = 0.020$
model 2: $\sigma_N/m_0 = 0.004$
model 2: $\sigma_N/m_0 = 0.012$
model 2: $\sigma_N/m_0 = 0.028$
model 2: $f = 0.035 M_{\rm Pl}$
model 2: $f = 0.025 M_{\rm Pl}$
model 2: $f = 0.030 M_{\rm Pl}$
model 2: $f = 0.040 M_{\rm Pl}$
model 2: $m_u/m_d = 0.8$
model 2: $m_u/m_d = 0.95$
model 2: $m_u/m_d = 0.9$
model 2: $m_u/m_d = 0.75$
model 2: $\nu = 4$
model 2: $\nu = 2$
model 2: $\nu = 3$
model 2: $\nu = 5$
z
$\Delta\delta_c/\delta_c$
a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model 2: $\sigma_N/m_0 = 0.028$
$\phi/f/\pi$
model 2: $f = 0.035M_{Pl}$
model 2: $f = 0.025M_{Pl}$
model 2: $f = 0.030M_{Pl}$
model 2: $f = 0.040M_{Pl}$
$\phi/f/\pi$
model 2: $m_u/m_d = 0.8$
model 2: $m_u/m_d = 0.95$
model 2: $m_u/m_d = 0.9$
model 2: $m_u/m_d = 0.75$
model 2: $v = 4$
model 2: $v = 2$
model 2: $v = 3$
model 2: $v = 5$
$\phi/f/\pi$
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
z