Cosmic Tensions and Interacting Dark Energy: Dynamics and Observations

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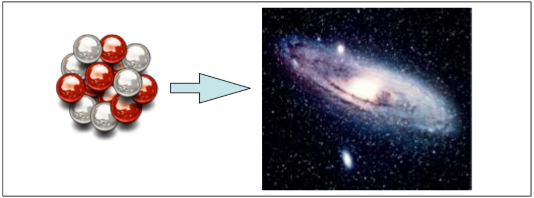
Cosmos and Physics: The Big Bang

The Big Bang Theory

- Universe undergone from an extremely hot and dense state (≈13.8 Gyr ago)
- Evolved to become **homogeneous and isotropic** – the Cosmological Principle
- leading to the formation of the universe as we know it
- Composition today: **68% Dark Energy, 27% Dark Matter, 5% Ordinary Matter**



Grew from the size of an atom to larger than the size of a grapefruit

Universe at Present

Our knowledge and understanding of the Universe have grown significantly. The late-time universe is dominated by two mysterious components:

Dark Matter (DM) — ∼27%

- Non-luminous - interacts only gravitationally
- Evidence: flat galactic rotation curves, gravitational lensing, cluster dynamics
- Drives formation of large-scale structures: galaxies, clusters, filaments
- CDM: non-relativistic at structure-formation epoch

Dark Energy (DE) — ∼68%

- Drives accelerated expansion (Riess et al. 1998)
- Standard model: Λ, equation of state $w_\Lambda = -1$
- Cosmic coincidence: why $\rho_{\mathrm{DE}} \approx \rho_{\mathrm{DM}}$ today?
- Dynamical alternatives: quintessence, k-essence, phantom field, . . .

Various theories about the beginning & end of the Universe.

Standard ΛCDM Model & Key Tensions

ΛCDM:
The standard model explaining CMB, BAO, and LSS. In the era of precision cosmology it encounters statistically significant **tensions** pointing to possible new physics beyond the standard model.

H_0 Tension

Hubble Constant Discrepancy

Planck: $H_0 = 67.37 \pm 0.54$
SH0ES: $H_0 = 73.04 \pm 1.01$

$\Rightarrow$ **4–5σ discrepancy**
Early vs. late Universe mismatch

S_8 Tension

Structure Growth Parameter

Planck: $S_8 = 0.830 \pm 0.013$
KiDS: $S_8 = 0.766^{+0.020}_{-0.014}$

$\Rightarrow$ **2–3σ discrepancy**
CMB vs. weak lensing mismatch

Coincidence Problem

Why $\rho_{\mathrm{DE}} \approx \rho_{\mathrm{DM}}$?

$\rho_{\mathrm{DE}} \approx$ const
$\rho_{\mathrm{DM}} \propto a^{-3}$

Fine-tuning problem
Motivates dynamical DE models

Motivation & Research Focus

Motivation -

- Address tensions in ΛCDM $\rightarrow$ explore beyond the standard model
- Formulate a theory based on the assumption of **Dark Matter–Dark Energy interaction** via a time-varying coupling (among various dynamical dark energy models)
- The theory of dark sector interaction well explain current observations.

Research Aims -

- Probe the dark sector and explain the accelerated expansion of the Universe
- Provide a solution to the **Cosmic Coincidence Problem**
- Alleviate the H_0 **Tension** – bridge local and CMB-derived values
- Resolve the S_8 **Tension** – reconcile CMB and weak lensing measurements

Coupled Scalar Field Model: Action & Setup

- **Assumption:** Universe geometry $\rightarrow$ flat, isotropic, homogeneous
- **Consideration:** canonical scalar field ϕ as dark energy; non-relativistic (cold) dark matter ($P_{\mathrm{dm}} = 0$) undergoing an interaction $\rightarrow$ **coupled quintessence DE model**

The action for dark sector coupling:

$$\boxed{S = \int d^4x \sqrt{-g} \left[\frac{R}{2} - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \, \partial_\nu \phi - V(\phi) + \sum_i \mathcal{L}_m^i(\chi_i, \phi) \right]} \tag{1}$$

- $\mathcal{L}_m^i$: matter Lagrangian; depends on ϕ through the coupling
- Radiation **uncoupled** due to conformal invariance
- Baryons **neglected**: since coupling to the baryons is strongly constrained by the local gravity measurements

Patil, Panda, Sharma & Ruchika, JCAP 05 (2024) 033

Coupled Field Model: Conservation Laws & Friedmann Equations

As dark species interact, they evolve together, and satisfy coupled conservation equations. $F(\phi)$ is the coupling strength function.

Energy-Momentum tensor conservation

$$-\nabla_\mu T^{(\phi)\mu}{}_\nu = Q_\nu = \nabla_\mu T^{(\mathrm{dm})\mu}{}_\nu \tag{2}$$

$$Q_\nu = F_{,\phi}\, \rho_{\mathsf{dm}}\, \nabla_\nu \phi, \quad F_{,\phi} \equiv \partial F / \partial \phi$$

Q_ν expresses the interaction between DM & DE.

Friedmann equations

$$3H^2 = \frac{\dot{\phi}^2}{2} + V(\phi) + F(\phi)\rho_{\mathsf{dm}} + \rho_r$$
$$3H^2 + 2\dot{H} = -\left[\frac{\dot{\phi}^2}{2} - V + F P_{\mathsf{dm}} + P_r\right] \tag{3}$$

Continuity equations

$$\dot{\rho_\phi} + 3H\rho_\phi(1+\omega_\phi) = Q \tag{4}$$
$$\dot{\rho_{\mathsf{dm}}} + 3H\rho_{\mathsf{dm}} = -Q$$
$$\dot{\rho}_r + 3H\rho_r(1+\omega_r) = 0$$

Dynamical System: Dimensionless Variables & Phase Space

Introduce dimensionless variables via - $3H^2 = \dot{\phi}^2/2 + V(\phi) + F(\phi)\rho_{\mathbf{dm}} + \rho_r$:

$$x = \frac{\phi'}{\sqrt{6}}, \quad y = \frac{\sqrt{V(\phi)}}{\sqrt{3}\,H}, \quad \Omega_{\mathrm{dm}} = \frac{F(\phi)\rho_{\mathrm{dm}}}{3H^2}, \quad \Omega_r = \frac{\rho_r}{3H^2} \tag{5}$$

along with:

$$\gamma = 1 + \omega_\phi = \frac{2x^2}{x^2+y^2}, \qquad \lambda = -\frac{V_{,\phi}}{V(\phi)}, \qquad m = \frac{F_{,\phi}}{F(\phi)}$$

For $V(\phi) \propto e^{-\lambda\phi}$ and $F(\phi) \propto e^{\beta\phi}$:

$$\Gamma_\lambda = \frac{V_{,\phi\phi}\,V}{V_{,\phi}^2} = 1, \qquad \Gamma_m = \frac{F_{,\phi\phi}\,F}{F_{,\phi}^2} = 1$$

Mathematical analysis: linear stability theory + centre manifold theory to analyze critical points. Calculations performed using `Mathematica`.

Coupled Equations & Matter Density Perturbations

The coupled autonomous system ($' = d/dN$, $N = \ln a$):

$$\begin{aligned}
\gamma' &= (2-\gamma)\sqrt{3\gamma\Omega_\phi}\Big(-\sqrt{3\gamma\Omega_\phi} + \lambda\Omega_\phi + m(1-\Omega_\phi-\Omega_r)\Big) \\
\Omega_\phi' &= 3(1-\gamma)\Omega_\phi(1-\Omega_\phi) + \Omega_\phi\Omega_r + m\sqrt{3\gamma\Omega_\phi}(1-\Omega_\phi-\Omega_r) \\
\Omega_r' &= \Omega_r(\Omega_r-1) + 3\Omega_r\Omega_\phi(\gamma-1) \\
\lambda' &= -\sqrt{3\gamma\Omega_\phi}\,(\Gamma_\lambda-1)\,\lambda^2 \\
m' &= \quad\sqrt{3\gamma\Omega_\phi}\,(\Gamma_m-1)\,m^2
\end{aligned} \tag{6}$$

Growth of matter perturbations (coupling modifies the clustering properties of galaxies):

$$\delta_c'' = -\Big[0.5 - 0.5\Omega_r - 1.5(\gamma-1)\Omega_\phi - m\sqrt{3\gamma\Omega_\phi}\Big]\,\delta_c' + \tfrac{3}{2}[1-\Omega_\phi(1+\gamma)-\Omega_r]\,(1+2m^2)\,\delta_c \tag{7}$$

Observational probes constraining the coupled quintessence model

1. Planck CMB
CMB distance priors; constrains early Universe

2. SH0ES (H_0)
Direct local measurements of H_0 via Cepheids + SN Ia ($H_0 = 73.04 \pm 1.01$ km/s/Mpc)

3. Pantheon+ (SNe Ia)
1701 SN Ia light curves, $z \in [0.01, 2.3]$

4. Cosmic Chronometers (CC)
$H(z)$ from differential ages of galaxies, $z \leq 2$

5. BAO Data
6dF, SDSS DR7/14/16 eBOSS; BOSS DR12 anisotropic

6. Megamasers (MCP)
Direct measurement H_0 by measuring angular-diameter distances, D_A to galaxies

7. Growth Rate $f\sigma_8(z)$
RSD data; constrains the clustering parameter S_8

8. H0LiCOW / SLTD
Strong Lensing Time Delays from 6 lensed quasar systems

MCMC Analysis: Sampled Parameters & Priors

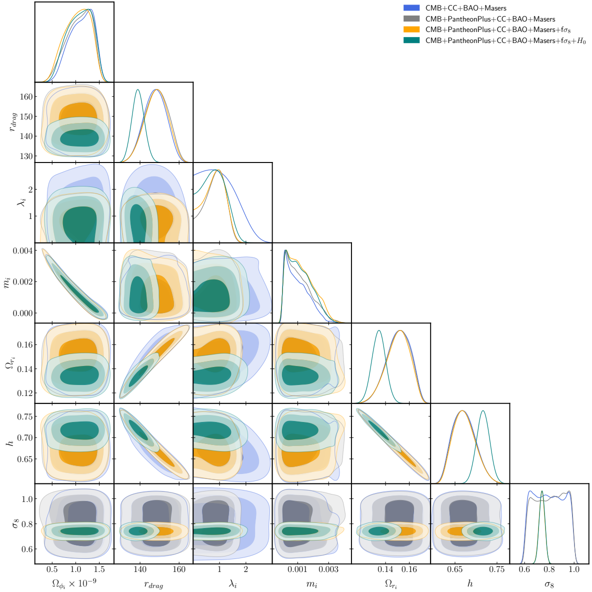
Sampled Parameters & Flat Priors

Parameter	Prior
$\Omega_{\phi_i} \times 10^{-9}$	$[0.05,\ 4.0]$
r_{drag} (Mpc)	$[130,\ 180]$
λ_i	$[10^{-4},\ 3.0]$
m_i	$[10^{-6},\ 10^{-2}]$
Ω_{r_i}	$[0.09,\ 0.17]$
h	$[0.5,\ 0.9]$
σ_8	$[0.6,\ 1.0]$
M_B	$[-21.0,\ -18.0]$

Statistical Methodology

- MCMC sampler: **emcee** — The MCMC Hammer (Foreman-Mackey et al.)
- Theoretical cosmology: Python tool **Scalpy**
- Mathematical analysis: **Mathematica**
- Dataset combinations: BASE $\rightarrow$ +PP $\rightarrow$ $+f\sigma_8$ $\rightarrow$ $+H_0$
- BASE: CMB+CC+BAO+Masers

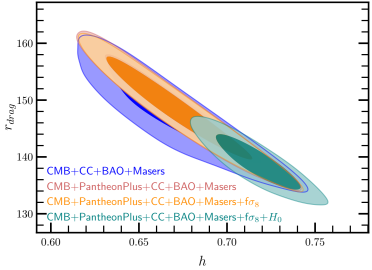
Parameter Correlations: MCMC Sampling Results



68% and 95% CL contour plots and 1D marginalized posteriors for Flat Coupled Quintessence model

Results: Flat Coupled Quintessence Model

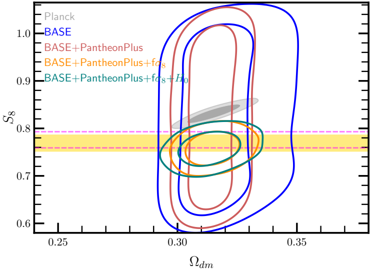
Constraints on H_0, r_{drag}, Ω_{dm} and S_8 from progressive dataset combinations



$H_0 = 67.37 \pm 0.54$ Km/s/Mpc (P18);
$H_0 = 73.04 \pm 1.01$ Km/s/Mpc (R21)

$H_0 = 67.1 \pm 2.8$ (BASE) $\rightarrow$ 0.3σ with Planck, 2σ with SH0ES

$H_0 = 71.7 \pm 1.54$ (ALL) $\rightarrow$ 2.5σ with Planck, $<1\sigma$ with SH0ES



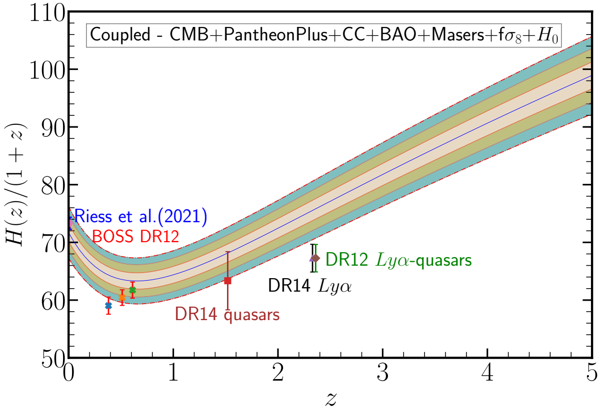
$S_8 = 0.830 \pm 0.013$(P18);
$S_8 = 0.766^{+0.020}_{-0.014}$(KiDS-1000-BOSS)

$S_8 = 0.758 \pm 0.023$ (BASE+PP+$f\sigma_8$) $\rightarrow$ 2σ-Planck, $\sim$0.3σ-KiDS

Results: Sound Horizon & Co-moving Hubble Parameter

$r_{drag} \sim 147\,\mathrm{Mpc}$ (P18), $r_{drag} \sim 137\,\mathrm{Mpc}$ (assuming SH0ES H_0)

r_{drag}: sound horizon at the end of the baryon drag epoch



Reconstruction of $H(z)/(1+z)$

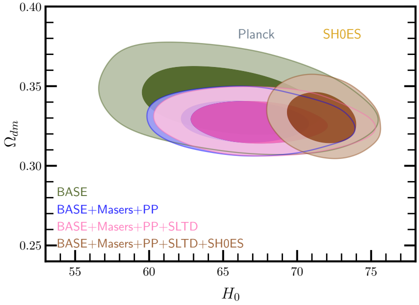
using CMB, SNe Ia, CC, BAO, Masers, H_0 and growth data.
Depicts the onset of acceleration just before $z \sim 0.6$.

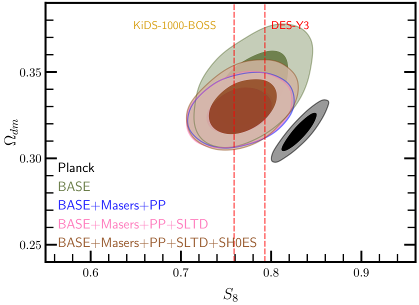
$r_{\mathrm{drag}} = 147.73^{+5.83}_{-5.86}$ Mpc (BASE)

$r_{\mathrm{drag}} = 139.03^{+3.16}_{-3.15}$ Mpc (ALL)

Modest discrepancy in r_{drag}; due to slight discrepancy in H_0 from SH0ES, consistent with h–r_{drag} relation constrained by BAO measurements.

IDE in a Curved Universe: H_0 & S_8 Constraints





A natural and important question: whether relaxing the assumption of spatial flatness changes these conclusions ?

BASE $\rightarrow$ BAO +CMB+CC+fσ_8

$H_0 = 65.5^{+3.8}_{-4.2}$ (BASE) $\rightarrow$ 0.4σ/Planck, 1.5σ/SH0ES

$H_0 = 71.7 \pm 1.5$ (ALL) $\rightarrow$ $<2.2\sigma$/Planck, $\sim 0.5\sigma$/SH0ES

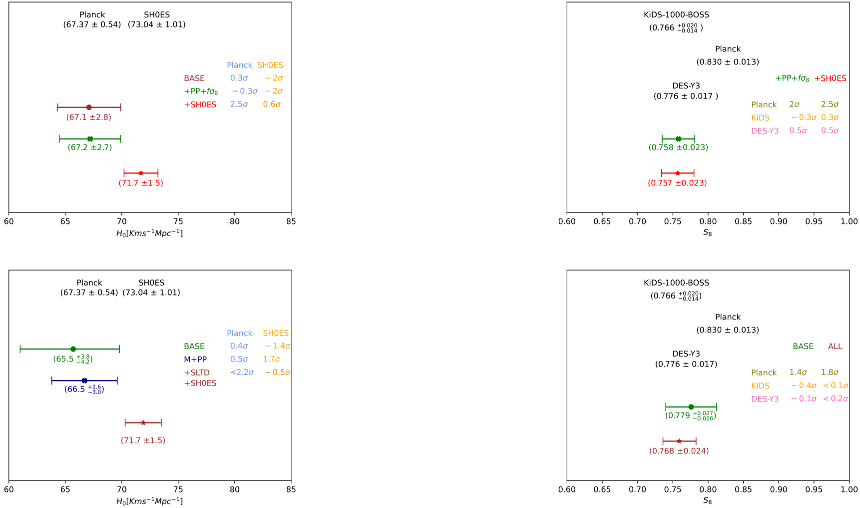
$S_8 = 0.779^{+0.027}_{-0.026}$ (BASE) $\rightarrow$ 1.4σ / Planck, $<0.5\sigma$/KiDS

$S_8 = 0.768 \pm 0.024$ (ALL) $\rightarrow$ $<2\sigma$ / Planck, $<0.1\sigma$/KiDS

Patil & Panda, EPJPlus 140 (2025) 1, 48

Results Summary: H_0 and S_8 — Flat vs. Non-flat Cases

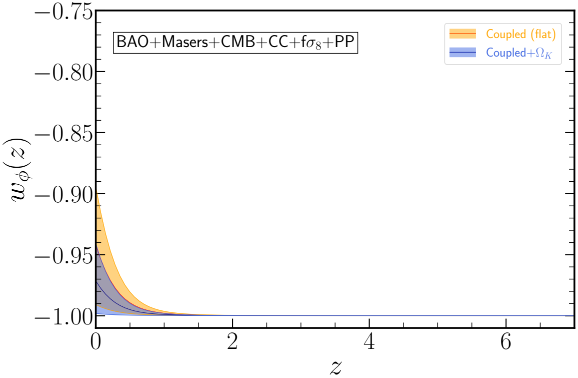
Whisker plots showing σ-level consistency with Planck, SH0ES, KiDS & DES-Y3



Coupled quintessence model. Top: flat case, Bottom: non-flat case.

Discussion: Spatial Curvature & the Dark Energy Equation of State

Beyond shifting the parameter constraints, allowing spatial curvature also changes the dark energy equation of state ω_ϕ



Key Insights

- ⋆ **Evidence for an open Universe:** $\Omega_K > 0$ favoured
- ⋆ **Non-flat scenario yields significantly lower values of** $\omega_\phi(z)$ than the flat interacting scenario
- ⋆ $\omega_\phi(z) < -0.85$ across all redshifts

Model Assessment: Goodness of Fit - AIC & BIC

Does the statistical evidence actually warrant the extra complexity of these model against the standard ΛCDM?

Flat + Coupled Quintessence Model

Model	χ^2_{min}	χ^2/n_{dof}	d	N	AIC	BIC
Coupled	1216.063	0.699	8	1748	1232.063	1275.792
Un-coupled	1345.614	0.773	7	1748	1359.614	1397.877
ΛCDM	1593.428	0.912	6	1748	1605.428	1638.225

Flat + Coupled:

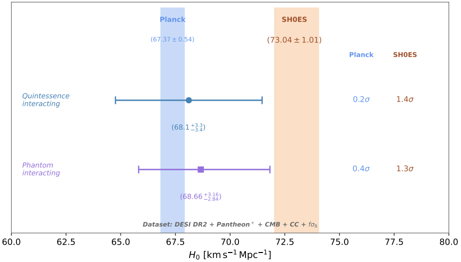
- Large reduction in χ^2, AIC, BIC $\rightarrow$ coupled model **preferred over ΛCDM**
- $\chi^2/n_{\text{dof}} < 1$ raises overfitting concern
- Indicates that ΛCDM model has the GoF to the data, hence a favored model

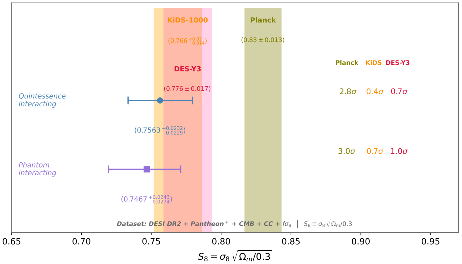
Curvature + Coupled:

- Predicts similar inconclusive results
- Insufficient to favor one model over another.

Overall: Coupled quintessence offers a compelling framework for addressing tensions, though definitive discrimination from ΛCDM requires next-generation surveys.

Comparison with Coupled Phantom Model using DESI DR2

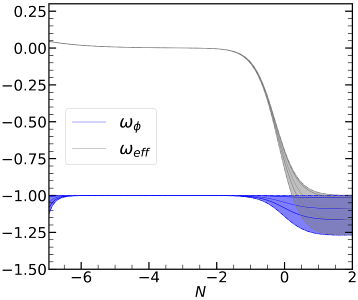




DESI DR2 BAO — Quintessence vs Phantom

- Same interacting dark energy framework, same dataset — two different coupling regimes: quintessence (exponential) and phantom ($m = \cot\phi - 1/\phi$: sinusoidal, field-dependent)
- H_0: both models consistent with Planck ($< 0.5\sigma$) — neither model resolves the Hubble tension with this dataset
- S_8: quintessence 2.8σ/Planck, phantom 3.0σ/Planck — both consistent with KiDS-1000 and DES-Y3 at $< 1\sigma$
- Tighter S_8 constraint places them more precisely in the low-S_8 regime preferred by weak lensing surveys
- Both interacting models show nearly identical central values ($H_0 \approx 68.1 – 68.7$, $S_8 \approx 0.747 – 0.756$) — converge to the similar observational signature today despite operating in different dark energy regimes and coupling mechanisms

Phantom Dark Energy: Equation of State Evolution and NEC Viability



DESI+PP+CMB

- Although $w_{\text{DE}} < -1$, interaction keeps $w_{\text{eff}} > -1$ at the present epoch $(N = 0)$.
  Caldwell1 & Linder 2025
- Extrapolate into the future $(N > 0)$, w_{eff} crosses -1 – implies future NEC violation
- Phantom model's NEC violation is a future prediction, not a current observational constraint. Current cosmology cannot yet observe this regime.

Present epoch $(N = 0)$

$w_{\text{DE}} < -1$ (phantom)
$w_{\text{eff}} > -1$ ✓
NEC satisfied
Interaction regulates dynamics

Future $(N > 0)$

w_{eff} crosses -1 - NEC violation
Potential Big Rip singularity
Model extrapolation only, beyond current data

Quintessence (prev. work)

$w_{\text{DE}} > -1$ always
$w_{\text{eff}} > -1$ always
NEC always satisfied
No Big Rip scenario

The models are physically distinct but phenomenologically/observationally degenerate at the present epoch. It is the future evolution and the NEC geometric test that can distinguish them.

Patil et al. (in prep.)

Null Energy condition - Geometric Test

A test of the expansion geometry of the universe – the shape of $H(z)$ relative to ΛCDM – derived from the precisely measured angle on the sky (The CMB acoustic scale θ).

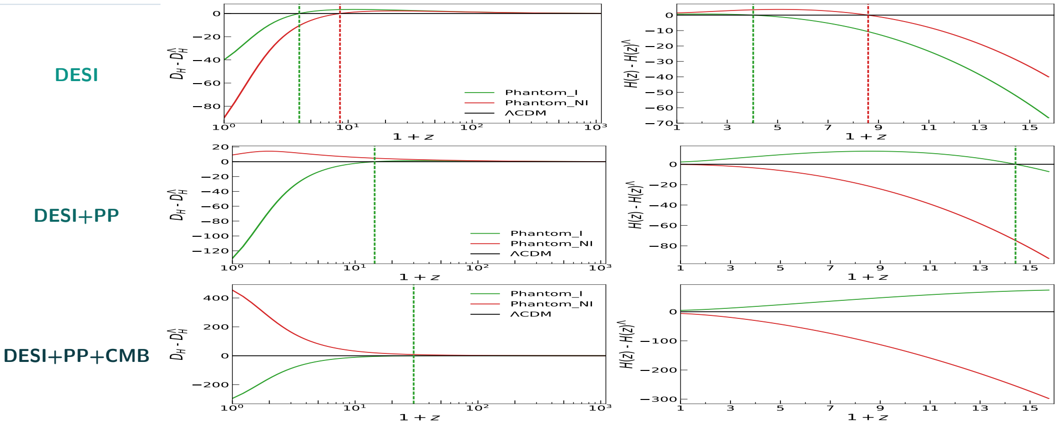
NEC viability criterion:

$D_H(z) \equiv c/H(z)$ *must* cross $D_H^\Lambda(z)$ at some z_c.
- geometrically mandatory to preserve the CMB acoustic scale θ_*. Lewis & Chamberlain 2025

- ⋆ Any dark energy model must cross the ΛCDM expansion rate at some redshift z_c – phantom DE crosses from below, quintessence from above, but both crossings are equally mandatory.
- ⋆ This is non-negotiable.
- ⋆ It is required by the precision measurement of the CMB acoustic scale θ, which fixes the integral of $1/H(z)$ all the way to recombination. Lemos & Lewis 2023
- ⋆ A phantom model that sits entirely on one side of ΛCDM cannot preserve this integral, and therefore cannot be NEC-consistent.

Historical Precursor: Sen & Scherrer (2008)

NEC: Phantom Dark Energy-Geometric Consistency & Interaction



- **DESI only:** both models NEC-consistent — $\text{Phantom}_{\text{I}}$ at $z_c \approx 4.2$, $\text{Phantom}_{\text{NI}}$ at $z_c \approx 8.7$
- **+Pantheon$^+$:** $\text{Phantom}_{\text{NI}}$ **fails** – no D_H crossover to $z = 1100$; $\text{Phantom}_{\text{I}}$ survives ($z_c \approx 15$)
- **+CMB:** $\text{Phantom}_{\text{NI}}$ still fails; $\text{Phantom}_{\text{I}}$ crossover shifts to $z_c \approx 30$
- **Dark sector coupling is observationally required:** preserves the geometrically mandatory $H(z)$ crossover - non-interacting phantom fails this test when SNe-Ia and CMB data are added; NEC-inconsistent.
- **Two-layer conclusion:** This result, combined with $w_{\text{eff}} > -1$ at present epoch – $\text{Phantom}_{\text{I}}$ is NEC-viable *locally* and *geometrically consistent with the CMB acoustic scale throughout cosmic history*

Ref: A. Lewis & E. Chamberlain, JCAP **05** (2025) 065 Patil et al. (in prep.)

Future Directions

⋆ Patil et al. (in prep.) — interacting phantom & NEC viability paper to appear shortly; include full quasar dataset, extended NEC analysis, and DESI DR2 constraints

Dark Energy Perturbations, Sound Speed, & Power Spectrum

- Extend the coupled quintessence framework to probe dark energy perturbations and structure formation
- Constrain the equation of state $w_{\mathrm{de}}(z)$ and speed of sound c_s^2, more effectively
- Assess the impact of DE Fluctuations on structure formation and growth
- Study DE perturbations signatures in CMB and matter power spectra
- Quantify suppression/enhancement vs. ΛCDM
- Assess detectability of DE perturbation signatures with Euclid weak lensing and DESI galaxy power spectrum

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Thank You!

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Questions & Discussion Welcome