Testing DDE and Constraining high-z reionization with Cosmological Data

arXiv: 2505.02932, 2506.19096, 2507.03535, 2512.09866, 2602.06794

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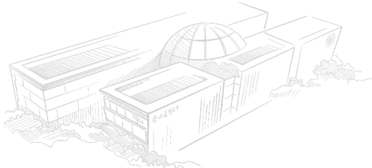
Content

1. **Constraining Pressure-Based and Four-Parameter Dynamical Dark Energy(DDE) Models with Latest Cosmological Data**

2. **Constraining exotic high-z reionization histories with Gaussian processes and the cosmic microwave background**



Key Features:

- Snapshot at $z \sim 1100$
- Temperature anisotropies $\Delta T/T \sim 10^{-5}$
- Acoustic peaks encode cosmology

Datasets Used:

- **Planck 2018**:
  - high-ℓ Plik TT, TE, EE likelihoods
  - low-ℓ TT-only Commander likelihood
  - low-ℓ EE-only SimAll
- **ACT DR6**: Lensing (`actplanck baseline`)
- Combined as "CMB"

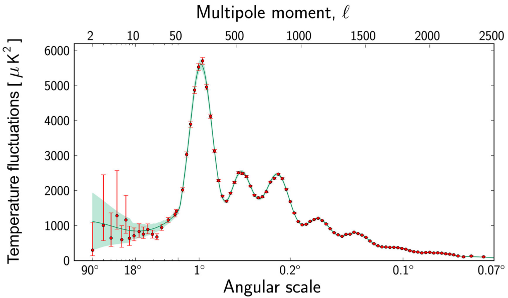


Figure 1: This graph shows the temperature fluctuations in the CMB detected by Planck at different angular scales on the sky from ESA and the Planck Collaboration.

Standard Ruler:

- Sound waves in early universe
- Frozen at recombination
- Characteristic scale ~ 150 Mpc
- Geometric Probe: Measures $D_A(z)$ and $H(z)$ directly through angular and radial BAO scales

Datasets:

- **SDSS**: the completed SDSS-IV eBOSS survey
- **DESI DR2**: 3-year data
- Redshift range: $0.1 < z < 4$

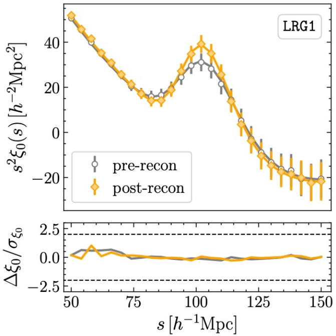


Figure 2: Two point correlation function of the average of 25 Abacus galaxy mock catalogs (data points) compared to the model prediction (lines) pre- (grey) and post-reconstruction (yellow) from DESI Collaboration.

Standard Candles:

- Uniform peak luminosity
- Distance ladder calibration
- Direct evidence for acceleration
- Late-time Probe: Directly measures luminosity distance $D_L(z)$ and expansion history

Datasets:

- **PantheonPlus**: 1550 SNe
  - $0.001 < z < 2.26$
- **DES Y5**: 1635 SNe
  - $0.1 < z < 1.13$
- **Union3**: 2087 SNe

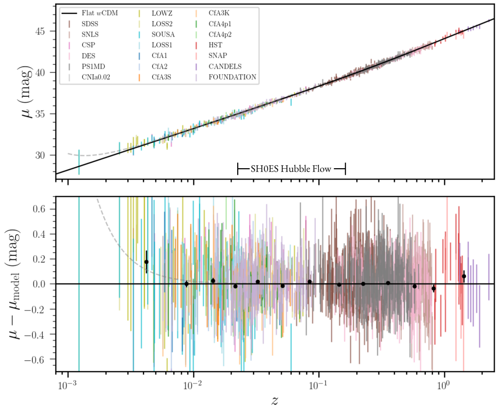


Figure 3: distance modulus vs redshift from The Pantheon+ Analysis paper (https://arxiv.org/abs/2202.04077)

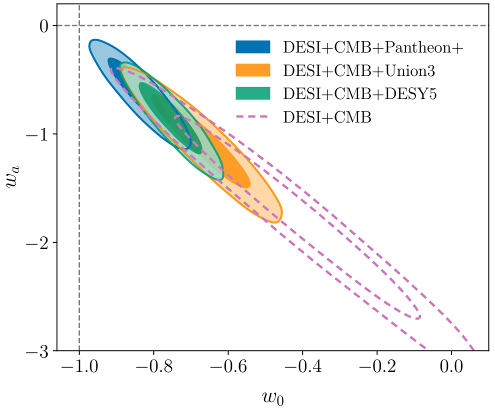
CPL Parametrization:

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

- Taylor expansion of EoS w
- w_0: present-day value
- w_a: time evolution
- ΛCDM: $w_0 = -1, w_a = 0$

DESI Finding:

- Deviation from ΛCDM at $> 2\sigma$
- Hints at dynamical DE
- CMB+DESI+DESY5 shows 4.2σ preference over ΛCDM



$w_0 - w_a$ plot from The DESI DR2 paper (arxiv:2503.14738)

Why Pressure Parameterization

- **Why Fundamental Equation:** Cosmic dynamics driven by total pressure

$$2\dot{H}(t) + 3H^2(t) = -8\pi G p_{\text{total}} \tag{1.1}$$

- **Late-time Universe:** $p_{\text{matter}} = 0$, $p_{\text{rad}} \approx 0 \Rightarrow$ Evolution dominated by p_{DE}
- **Key Insight:** Both $H(t)$ and $\dot{H}(t)$ directly relate to observables:
  - Angular diameter distance: $d_A(z)$
  - Luminosity distance: $d_L(z)$
- **Main Advantage:** Reconstruct $p_{\text{DE}}(z)$ without knowing Ω_{m0}!
  - $p_{\text{DE}} = \text{const} \Rightarrow \Lambda\text{CDM}$ confirmed
  - $p_{\text{DE}}(z)$ varies $\Rightarrow$ Dynamical dark energy
- **Why pressure over $w(a)$?**
  - Avoids implicit biases from assuming $w_{\text{DE}}(a)$ as the most fundamental quantity to model and specific functional forms

Our Approach: Pressure Parametrization

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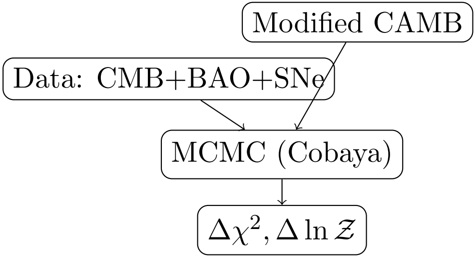
Alternative to CPL:

- Taylor expansion for **pressure** p, not EoS w

$$p = -p_0 + (1-a)p_1 + (1-a)^2 p_2 + \ldots$$

- Free Parameters: $\Omega_{1,2} \equiv \frac{3}{4}\frac{p_{1,2}}{\rho_{\mathrm{crit}}}$
- $\Omega_{\mathrm{DE},0} = f(p_0, p_1, p_2) = 1 - \Omega_{\mathrm{m}} - \Omega_{\mathrm{k}} - \Omega_{\mathrm{r}}$
- Independent consistency check



Statistical Methods:

1. **$\Delta\chi^2$ test**:
   - $\Delta\chi^2 = \chi^2_{\mathrm{DDE}} - \chi^2_{\Lambda\mathrm{CDM}}$
   - Convert to $N\sigma$ significance
2. **Bayesian Evidence**:
   - $\Delta \ln \mathcal{Z} = \ln \mathcal{Z}_{\mathrm{DDE}} - \ln \mathcal{Z}_{\Lambda\mathrm{CDM}}$
   - Jeffreys' scale interpretation

Tools: CAMB, Cobaya, getdist, `MCEvidence`[a]

[a] https://github.com/williamgiare/wgcosmo

DDE Pressure Parametrization

The dark energy (DE) pressure can be expanded in a Taylor series around the present epoch (A. A. Sen, arXiv:0708.1072):

$$p(a) = -p_0 + \sum_{n=1}^{\infty} \frac{(1-a)^n}{n!} p_n \,, \tag{1.2}$$

where $-p_0$ is the current DE pressure and p_n are the higher-order coefficients. The DE density then satisfies the continuity equation:

$$\dot{\rho} + 3H\,(p+\rho) = 0\,. \tag{1.3}$$

First-Order Expansion Model

Using the first-order term in (1.2), the DE energy density evolves as:

$$\rho(a) = \rho_{\mathrm{DE},0} - \tfrac{3}{4}(1-a)\, p_1 \,, \tag{1.4}$$

where $\rho_{\mathrm{DE},0}$ is the present DE density and p_1 is the first-order pressure coefficient. Defining the dimensionless parameters

$$\Omega_{\mathrm{DE},0} \equiv \frac{\rho_{\mathrm{DE},0}}{\rho_{\mathrm{crit}}} \,, \quad \Omega_1 \equiv \frac{3}{4}\frac{p_1}{\rho_{\mathrm{crit}}} \,, \quad \rho_{\mathrm{crit}} = \frac{3H_0^2}{8\pi G}, \tag{1.5}$$

we can rewrite (1.4) as

$$\rho(a) = \rho_{\mathrm{DE},0}\left[1 + (a-1)\,\frac{\Omega_1}{\Omega_{\mathrm{DE},0}}\right] . \tag{1.6}$$

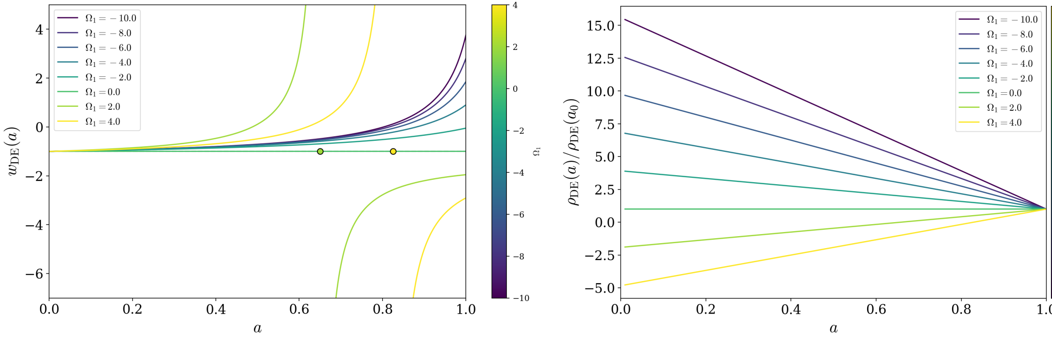
The corresponding equation-of-state parameter is

$$w_{\mathrm{DE}}(a) = -1 + \frac{1}{3}\frac{\Omega_1\, a}{\Omega_1\,(1-a) - \Omega_{\mathrm{DE},0}} . \tag{1.7}$$

Pole in the Equation of State

A singularity appears in $w_{\rm DE}(a)$ when the denominator of (1.7) vanishes, at the scale factor

$$a_{\rm pole} = 1 - \frac{\Omega_{\rm DE,0}}{\Omega_1}\,. \tag{1.8}$$



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Second-Order Expansion Model

Including terms up to second order in (1.2), and defining

$$\Omega_2 \equiv \frac{3}{4}\frac{p_2}{\rho_{\text{crit}}}\,, \tag{1.9}$$

the DE density becomes:

$$\rho(a) = \rho_{\text{DE},0}\left[1 + (a-1)\left(\frac{\Omega_1+\Omega_2}{\Omega_{\text{DE},0}}\right) + \tfrac{2}{5}(1-a^2)\frac{\Omega_2}{\Omega_{\text{DE},0}}\right]. \tag{1.10}$$

The equation-of-state parameter is then:

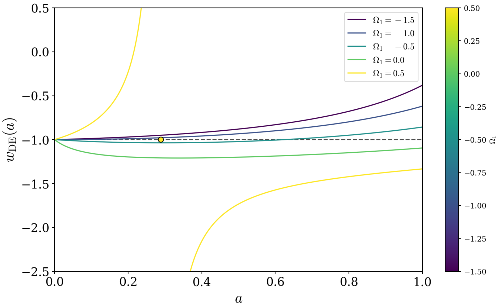
$$w_{\text{DE}}(a) = -1 + \frac{1}{3}\frac{\left(\Omega_1 + (1-\tfrac{4}{5}a)\,\Omega_2\right)a}{\left[\Omega_1 + \tfrac{3}{5}(1-\tfrac{2}{3}a)\,\Omega_2\right](1-a) - \Omega_{\text{DE},0}}\,. \tag{1.11}$$

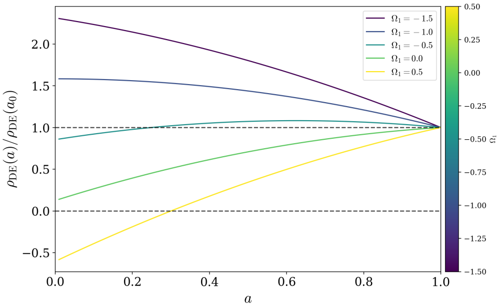
This expression can exhibit poles when the denominator vanishes.

Comprehensiveness of the Second-Order Model

Fixing $\Omega_2 = 1$ and $\Omega_{\mathrm{DE},0} = 0.7$ while varying Ω_1, the model can reproduce:

- Quintessence behavior ($-1 < w_{\mathrm{DE}} < -\frac{1}{3}$),
- Phantom DE ($w_{\mathrm{DE}} < -1$),
- Phantom crossing (w_{DE} crosses -1), and
- Poles in w_{DE} where ρ_{DE} changes sign.





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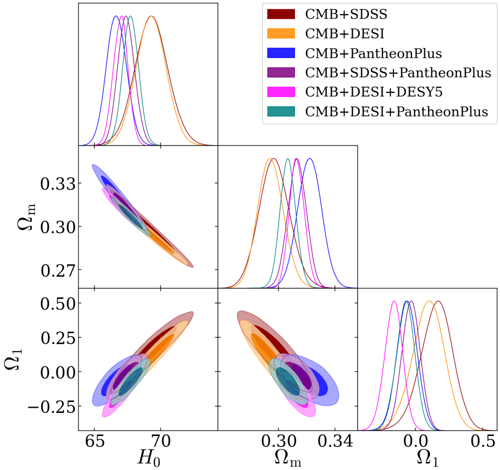
First-Order Expansion Results

Dataset	Ω_1	H_0	Ω_m	$\Delta\chi^2_{\Lambda\mathrm{CDM}}$
CMB+SDSS	$0.16^{+0.12}_{-0.11}$	69.3 ± 1.3	0.297 ± 0.011	0.23
CMB+DESI	$0.095^{+0.12}_{-0.11}$	69.3 ± 1.1	0.2946 ± 0.0090	0.7
CMB+PP	-0.062 ± 0.075	66.68 ± 0.76	0.3221 ± 0.0084	0.34
CMB+SDSS+PP	-0.032 ± 0.068	67.40 ± 0.64	0.3132 ± 0.0065	0.28
CMB+DESI+DESY5	-0.162 ± 0.067	66.98 ± 0.56	0.3131 ± 0.0053	-7.35
CMB+DESI+PP	-0.072 ± 0.068	67.74 ± 0.61	0.3068 ± 0.0056	-0.33

Key Findings

- CMB+SDSS, CMB+DESI: mild trend in the H_0/S_8 direction
- CMB+DESI+DESY5 shows $> 2\sigma$ deviation from ΛCDM
- **1st-order:** $w_0 = -1 - \Omega_1/(3\Omega_{\mathrm{DE},0})$; $\Omega_1 > 0 \Rightarrow w_0 < -1$. CMB+DESI only: $\Omega_1 = +0.095 \Rightarrow$ phantom, $H_0 = 69.3$; +SNe flips $\Omega_1 < 0$, $w_0 > -1$, H_0 down.



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- CMB+DESI:
  $H_0 = 69.3 \pm 1.1$ km/s/Mpc
  $\Omega_m = 0.2946 \pm 0.0090$;
  CMB+PP:
  $H_0 = 66.68 \pm 0.76$ km/s/Mpc
  $\Omega_m = 0.3221 \pm 0.0084$
- Adding SNe data pulls H_0 and Ω_m toward Planck values

Second-Order Expansion Results

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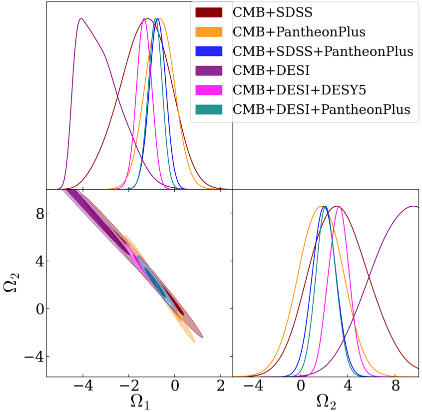
Dataset	Ω_1	Ω_2	$\Delta\chi^2_{\Lambda\mathrm{CDM}}$
CMB	$-0.6^{+1.7}_{-2.6}$	> 1.30	-6.31
CMB+SDSS	$-1.3^{+1.2}_{-1.0}$	$3.3^{+2.3}_{-2.6}$	-2.72
CMB+DESI	$-3.24^{+0.54}_{-1.2}$	> 6.44	-8.97
CMB+PP	-0.64 ± 0.63	1.7 ± 1.9	-1.49
CMB+SDSS+PP	-0.74 ± 0.36	2.01 ± 0.99	-3.35
CMB+DESI+DESY5	-1.33 ± 0.33	3.25 ± 0.88	-18.41
CMB+DESI+PP	-0.85 ± 0.31	2.17 ± 0.85	-6.53

Strongest Hint

- CMB+DESI+DESY5: 4σ preference over ΛCDM
  Bayesian factor $\Delta \ln \mathcal{Z}_{\Lambda\mathrm{CDM}} = 1.84$ (weak Evidence)
- $\Delta \ln \mathcal{Z}_{\Lambda\mathrm{CDM}} < 0$ for all other dataset combinations. (Be careful, also for CPL)

Geometry degeneracy

CMB+BAO: Ω_2 dominated: $w_0 > -1$, but H_0 shifts lower.



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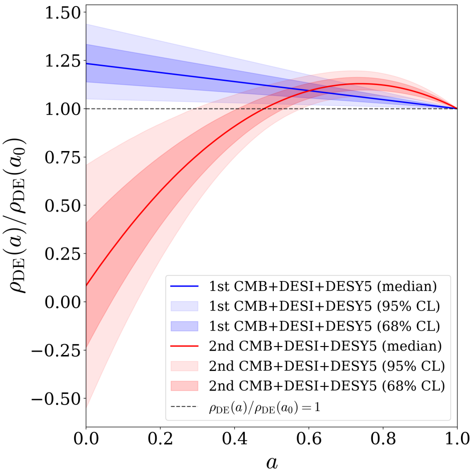
Evolution of Dark Energy Density

First-Order Model:

- Mild evolution
- $\rho_{DE}(a)/\rho_{DE,0}$ stays near unity
- Narrow confidence intervals

Second-Order Model:

- Deviate ΛCDM CC (Largest CMB+DESI+DESY5 more than 2 σ)
- Non-monotonic behavior
- Peak at $a \approx 0.7 - 0.8$ ($z \approx 0.3 - 0.4$)



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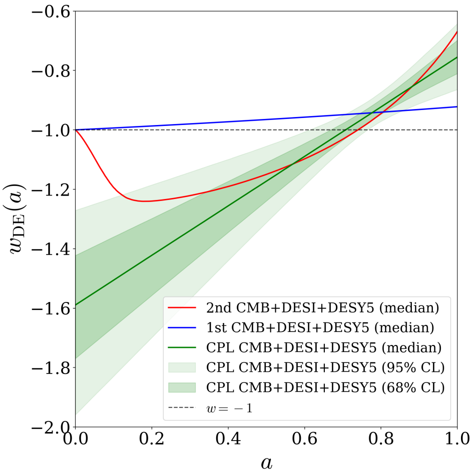
Key Features:

- First-order: Stays in quintessence regime
- Second-order: Crosses phantom divide ($w_{\rm DE} = -1$) at $a \approx 0.7 - 0.8$ ($z \approx 0.3 - 0.4$)
- Agreement with CPL at late times



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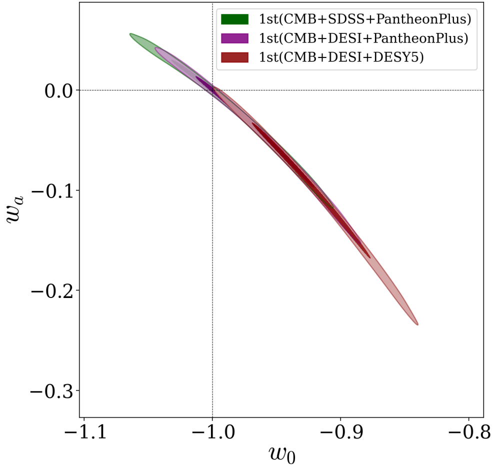
Present-day EoS:

$$w_0 \equiv w_{DE}(a=1)$$

$$w_a \equiv -\frac{dw_{DE}}{da}\bigg|_{a=1}$$

First-Order:

- Tight constraints
- Near ΛCDM point
- Strong w_0-w_a degeneracy



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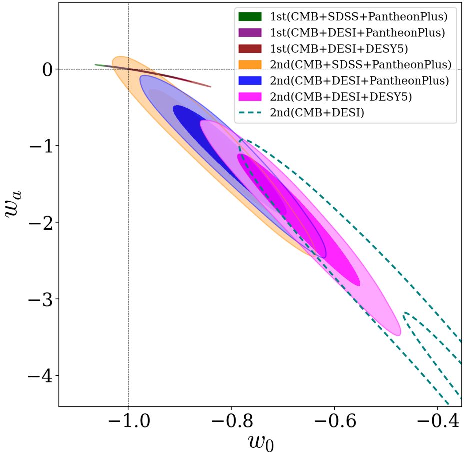
Second-Order:

- $w_0 > -1$ (quintessence today)
- $w_a < 0$ (evolution toward phantom)
- CMB+DESI+DESY5: $> 2\sigma$ from ΛCDM

Dataset Comparison

- DESI $\rightarrow$ stronger DDE preference than SDSS
- DESY5 $\rightarrow$ stronger DDE preference than PP



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Model Compared to CPL

First Order Model

Dataset	$\Delta\chi^2_{\mathrm{min,CPL}}$	$\Delta \ln \mathcal{Z}_{\mathrm{CPL}}$
CMB	0.96	0.55
CMB+SDSS	2.68	1.21
CMB+PP	1.85	2.05
CMB+SDSS+PP	4.45	0.93
CMB+DESI	8.25	−1.94
CMB+DESI+DESY5	12.1	−2.71
CMB+DESI+PP	7.2	−0.1

- All $\Delta\chi^2$ values are worse than CPL
- Datasets without DESI show positive $\Delta \ln \mathcal{Z}$ (better than CPL due to 1 less parameter)

Second Order Model

Dataset	$\Delta\chi^2_{\mathrm{min,CPL}}$	$\Delta \ln \mathcal{Z}_{\mathrm{CPL}}$
CMB	−1.23	−0.38
CMB+SDSS	−0.27	−0.88
CMB+PP	0.01	−0.85
CMB+SDSS+PP	0.83	−1.28
CMB+DESI	−1.42	−0.44
CMB+DESI+DESY5	1.04	−0.87
CMB+DESI+PP	1.01	−0.94

- All $|\Delta\chi^2|$ and $|\Delta \ln \mathcal{Z}|$ values < 1
- Differences between models are minor in both likelihood and Bayesian terms

Four-Parameter DDE Parametrization

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DESI-era question

Can the data constrain more than two DE degrees of freedom?

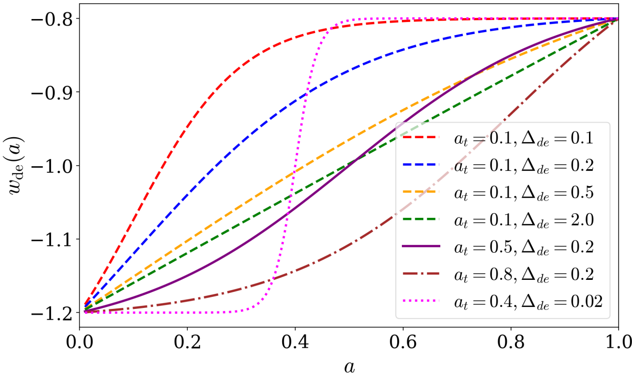
4PDE EoS

$$w_{\rm de}(a) = w_0 + (w_m - w_0)\mathcal{G}(a)$$

$$\mathcal{G}(a) = \frac{1-\exp[-(a-1)/\Delta_{\rm de}]}{1-\exp(1/\Delta_{\rm de})}\,\frac{1+\exp(a_t/\Delta_{\rm de})}{1+\exp[-(a-a_t)/\Delta_{\rm de}]}$$

Parameters

w_0	today	w_m	early
a_t	epoch	$\Delta_{\rm de}$	width/sharpness



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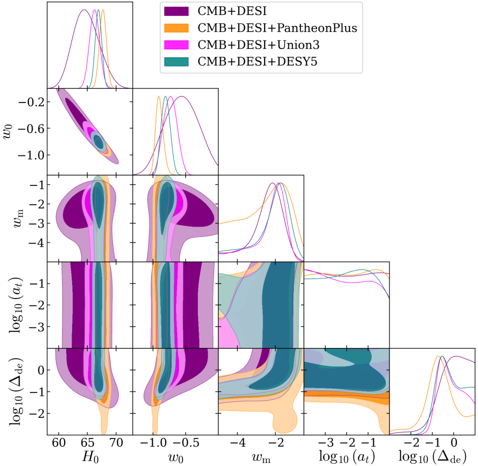


H. Cheng et al. arXiv:2512.09866

Constraints

- robust: w_0
- unconstrained: a_t
- **CMB+DESI+DESY5:** $w_0 = -0.804 \pm 0.066$ ($\sim 3\sigma$ from -1); $\log_{10}\Delta_{\rm de} > -0.896$ (95% CL); smooth > sharp

H_0 caution

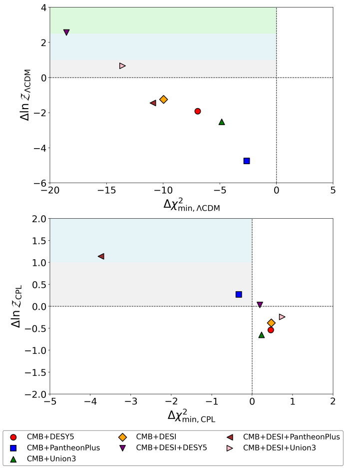
CMB+DESI: $w_0 = -0.57 \pm 0.24$, $H_0 \simeq 64.8$. Geometry: quintessence $\leftrightarrow$ lower H_0; worsens H_0 tension.

vs ΛCDM:

- $\Delta\chi^2 < 0$ all combos
- evidence: Occam penalty
- DESY5: $(-18.54, +2.57)$ moderate
- Union3: $\Delta \ln \mathcal{Z} = +0.67$ inconclusive

vs CPL:

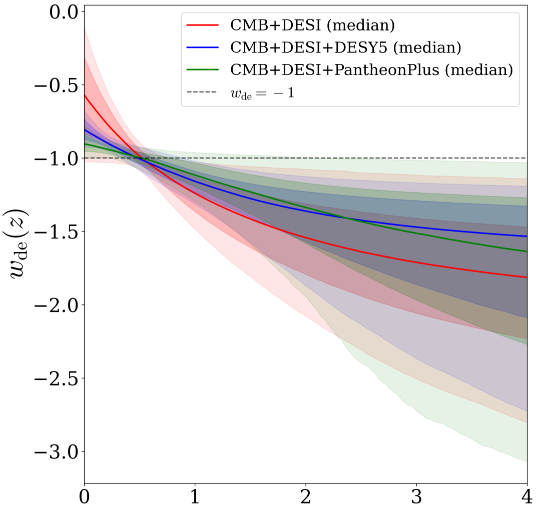
- usually: $|\Delta\chi^2|, |\Delta \ln \mathcal{Z}| < 1$
- PantheonPlus: $\Delta \ln \mathcal{Z}_{\mathrm{CPL}} = +1.14$ weak
- reason: tighter Δ_{de}



Statistical lesson

Extra freedom helps only when data compress Δ_{de}.

Reconstructed $w_{\mathrm{de}}(z)$



- today: quintessence
- past: phantom
- crossing: $z \sim 0.4$
- constrained window: $z \lesssim 0.5$
- high-z fan-out: data-blind w_m
- open: a_t degeneracy

Take-home

phantom→quintessence, like CPL.
Need future data to break a_t/Δ_{de}.

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Pressure + 4PDE + CPL: same today, different past.

1. **Built-in:** $w(a=1) = w_0$ for all.
2. **Data window:** $z \lesssim 0.5$; DE dominates near $z_{\rm eq}^{\text{m-de}} \approx 0.3$.
3. **Shared signal:** $w_0 > -1$, recent phantom, crossing $z \sim 0.3$–0.4.

$$\text{High-}z\text{ asymptotics:} \quad \underbrace{w \to -1}_{\text{Pressure}} \;\Big|\; \underbrace{w \to w_m}_{\text{4PDE}} \;\Big|\; \underbrace{w \to w_0 + w_a}_{\text{CPL}}$$

High-z: different histories, data-blind.

Real DDE preference

$w_0 > -1$ + phantom crossing; form-independent, not early-time DE.

Be careful

Bayes vs ΛCDM (CMB+DESI+DESY5): Pressure +1.84 (weak), 4PDE +2.57 (moderate).
Most combos still favor ΛCDM.

Content

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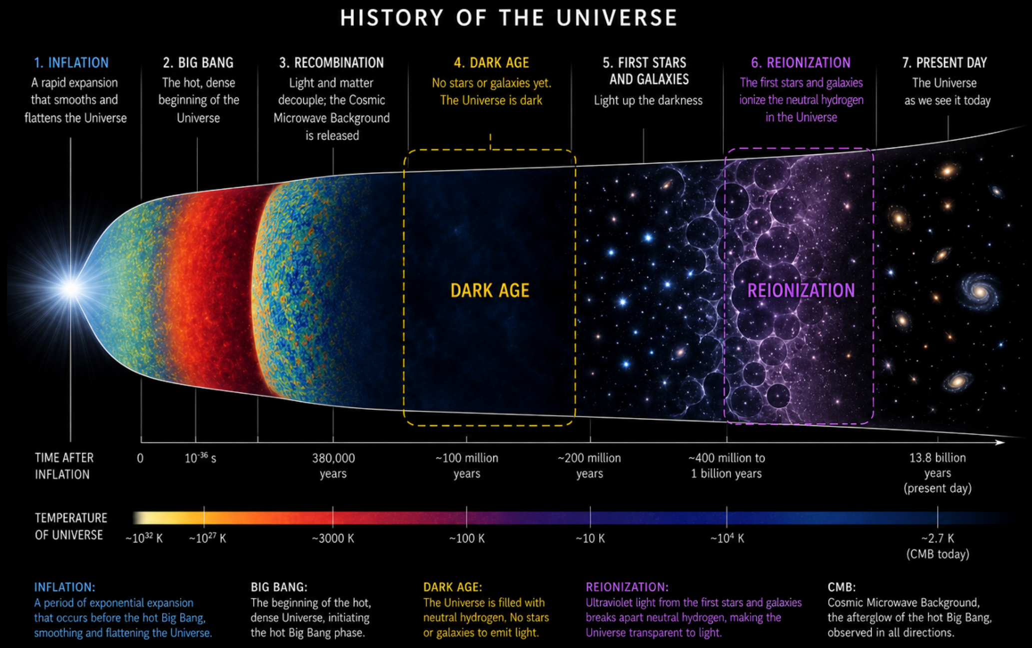
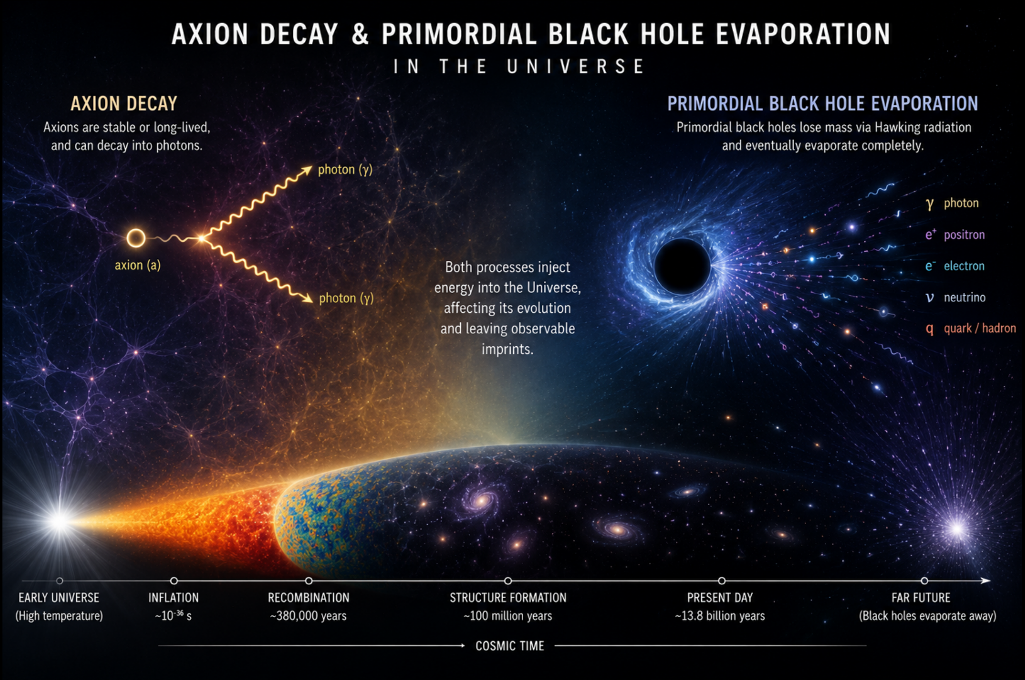
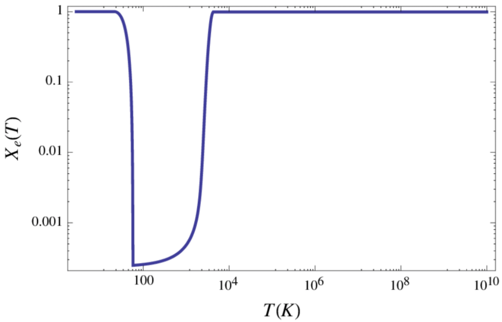
2. **Constraining exotic high-z reionization histories with Gaussian processes and the cosmic microwave background**


HISTORY OF THE UNIVERSE
1. INFLATION
A rapid expansion that smooths and flattens the Universe
2. BIG BANG
The hot, dense beginning of the Universe
3. RECOMBINATION
Light and matter decouple; the Cosmic Microwave Background is released
4. DARK AGE
No stars or galaxies yet. The Universe is dark
5. FIRST STARS AND GALAXIES
Light up the darkness
6. REIONIZATION
The first stars and galaxies ionize the neutral hydrogen in the Universe
7. PRESENT DAY
The Universe as we see it today
DARK AGE
REIONIZATION
TIME AFTER INFLATION
0
10^{-36} s
380,000 years
~100 million years
~200 million years
~400 million to 1 billion years
13.8 billion years (present day)
TEMPERATURE OF UNIVERSE
~10^{32} K
~10^{27} K
~3000 K
~100 K
~10 K
~10^{4} K
~2.7 K (CMB today)
INFLATION:
A period of exponential expansion that occurs before the hot Big Bang, smoothing and flattening the Universe.
BIG BANG:
The beginning of the hot, dense Universe, initiating the hot Big Bang phase.
DARK AGE:
The Universe is filled with neutral hydrogen. No stars or galaxies to emit light.
REIONIZATION:
Ultraviolet light from the first stars and galaxies breaks apart neutral hydrogen, making the Universe transparent to light.
CMB:
Cosmic Microwave Background, the afterglow of the hot Big Bang, observed in all directions.


AXION DECAY & PRIMORDIAL BLACK HOLE EVAPORATION
IN THE UNIVERSE
AXION DECAY
Axions are stable or long-lived, and can decay into photons.
photon (γ)
axion (a)
photon (γ)
Both processes inject energy into the Universe, affecting its evolution and leaving observable imprints.
PRIMORDIAL BLACK HOLE EVAPORATION
Primordial black holes lose mass via Hawking radiation and eventually evaporate completely.
γ photon
e+ positron
e− electron
ν neutrino
q quark / hadron
EARLY UNIVERSE
(High temperature)
INFLATION
~10^-36 s
RECOMBINATION
~380,000 years
STRUCTURE FORMATION
~100 million years
PRESENT DAY
~13.8 billion years
FAR FUTURE
(Black holes evaporate away)
COSMIC TIME

- Intergalactic gas transitioned from cold and neutral to hot and ionized
- Complex mechanisms: structure formation, thermodynamics, astrophysical sources



CMB Signatures

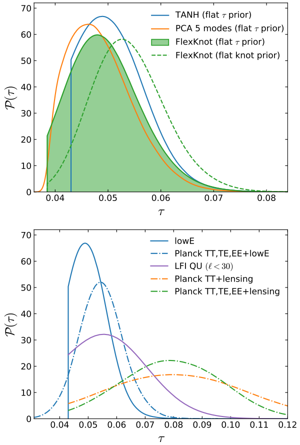
1. Temperature Anisotropies
2. Polarization
3. kSZ (kinetic Sunyaev-Zel'dovich) effect

Key quantity: electron Thomson scattering optical depth

$$\tau(z) = \int_{t(z)}^{t_0} n_e \sigma_T c\, dt'$$

New Physics Sources: Dark matter decay, primordial black holes, exotic energy injection

Constraints on Reionization Optical Depth



Planck 2018 results (arxiv:1807.06209)

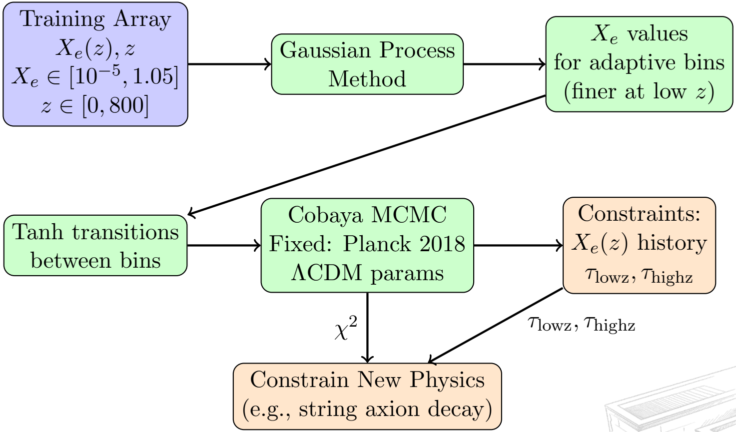
Planck 2018 Results:

- $\tau = 0.0519^{+0.0030}_{-0.0079}$ (lowE; flat prior; TANH)

Key Points:

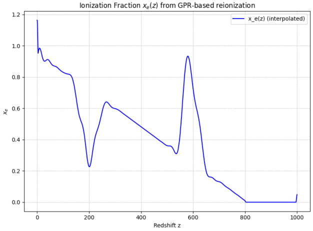
- Large-scale polarization tightens constraints
- **Planck low-ℓ EE-only SimAll likelihood provides strongest constraints on reionization history**

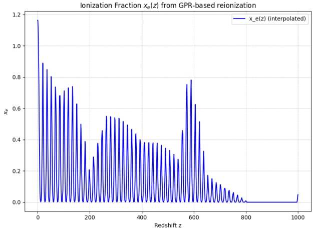
Workflow

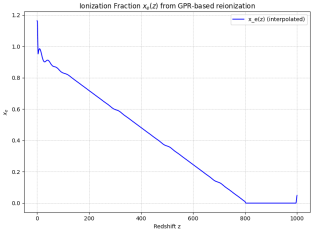

Training Array
$X_e(z), z$
$X_e \in [10^{-5}, 1.05]$
$z \in [0, 800]$
Gaussian Process Method
X_e values for adaptive bins (finer at low z)
Tanh transitions between bins
Cobaya MCMC Fixed: Planck 2018 ΛCDM params
Constraints: $X_e(z)$ history $\tau_{\rm lowz}, \tau_{\rm highz}$
χ^2
$\tau_{\rm lowz}, \tau_{\rm highz}$
Constrain New Physics (e.g., string axion decay)

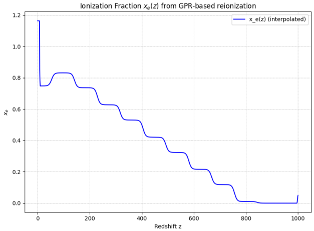
Some Examples for $X_e(z)$

Demonstrate the flexibility of our method to explore the X_e-z parameter space.









Reconstruction history of $X_e(z)$

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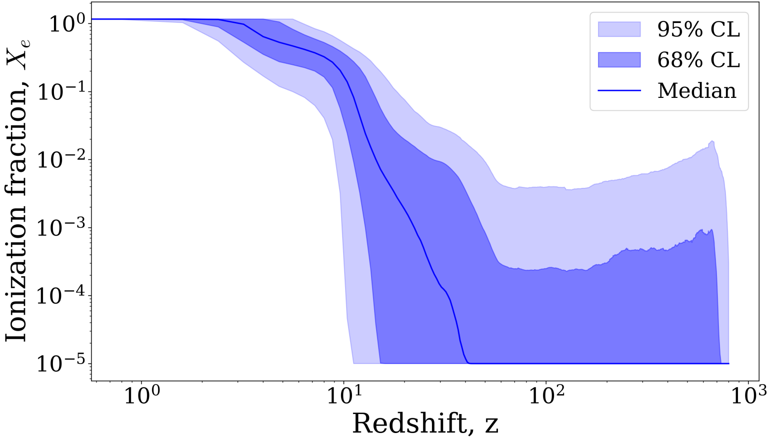


H. Cheng et al. arXiv:2506.19096

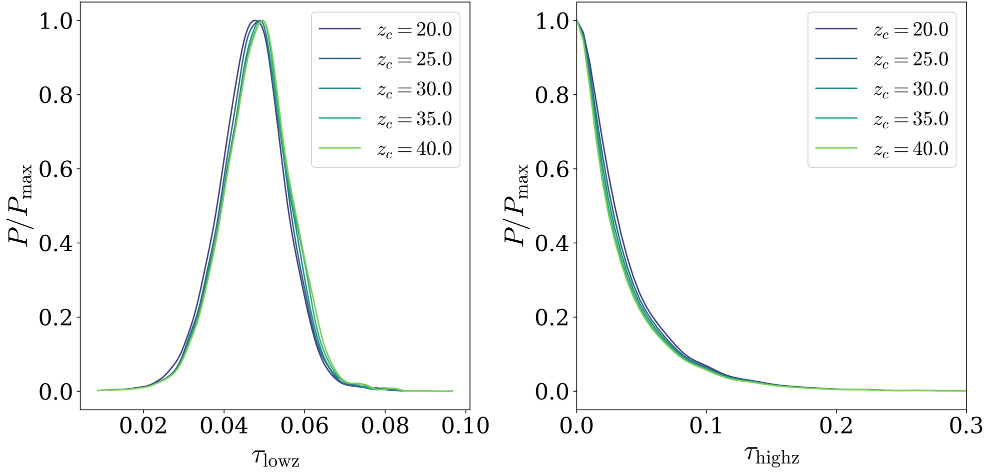
Optical Depth Constraints

Parameter Definitions

- z_c: Critical redshift separating low and high redshift regimes
- $\tau_{\rm lowz}$: Optical depth integration for $z \in [0, z_c]$
- $\tau_{\rm highz}$: Optical depth integration for $z \in [z_c, z_{\rm max}]$ ($z_{\rm max} = 800$ set by hand)

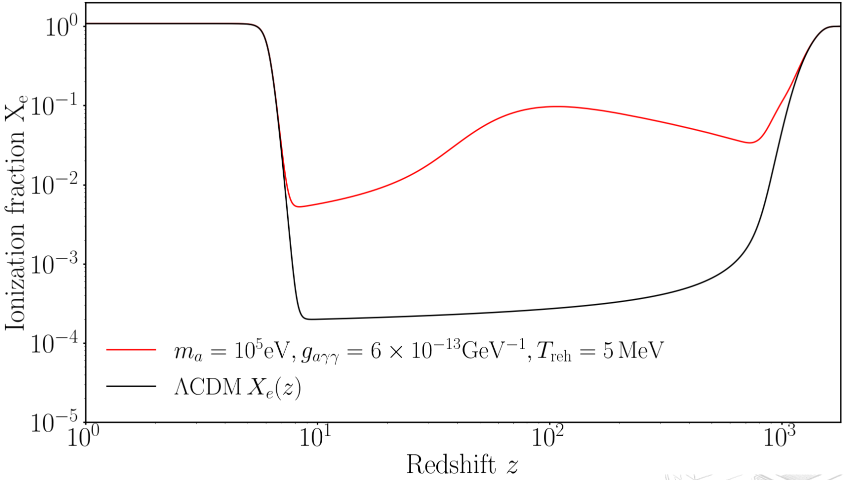
z_c	68% CL		95% CL	
	$\tau_{\rm lowz}$	$\tau_{\rm highz}$	$\tau_{\rm lowz}$	$\tau_{\rm highz}$
20.0	$0.0471^{+0.0076}_{-0.0082}$	< 0.038	$0.047^{+0.016}_{-0.017}$	< 0.112
25.0	$0.0477^{+0.0076}_{-0.0082}$	< 0.038	$0.048^{+0.016}_{-0.017}$	< 0.112
30.0	$0.0480^{+0.0078}_{-0.0082}$	< 0.037	$0.048^{+0.016}_{-0.017}$	< 0.111
35.0	$0.0483^{+0.0079}_{-0.0083}$	< 0.037	$0.048^{+0.016}_{-0.017}$	< 0.111
40.0	$0.0486^{+0.0080}_{-0.0084}$	< 0.037	$0.049^{+0.016}_{-0.018}$	< 0.111

$P/P_{\max}$ for τ_{lowz} and τ_{highz}

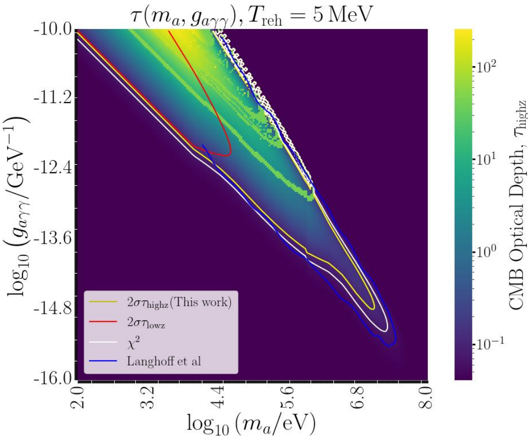


H. Cheng et al. arXiv:2506.19096

Example for "irreducible" axion decay



H. Cheng et al. arXiv:2506.19096



H. Cheng et al. arXiv:2506.19096

$$\Gamma_{a\to\gamma\gamma} \propto g_{a\gamma\gamma}^2 m_a^3$$

95% CL upper limits:

- $\chi^2 < 403.3$
- $\tau_{\rm highz} < 0.111$

Key Finding:

- $\tau_{\rm highz}$ statistics provide constraints comparable to those from Langhoff et al. (arXiv:2209.06216), who derived constraints from freeze-in abundance.
- $\tau_{\rm highz}$ statistics and χ^2 analyses agree well,
- $\tau_{\rm highz}$ gives conservative constraints compared to χ^2 analyses using Planck low-ℓ EE-only likelihood.

Alleviating lowlEE vs. highl Tension

Case	Likelihood	Integration Method	$\tau_{\rm reio}$ (68% CL)	Tension
1. Our work	lowlEE	Integrate to $z_{\max} = 800$	$0.070^{+0.041}_{-0.018}$	0.2σ
2. Our work	lowlEE	Standard $\tau_{\rm reio}$	$0.064^{+0.004}_{-0.027}$	1.3σ
3. Giarè+23[1]	highl+ACT lensing +SDSS+PantheonPlus	Standard $\tau_{\rm reio}$	0.080 ± 0.012	(reference)
4. Planck 2018	lowlEE	Standard $\tau_{\rm reio}$	$0.0531^{+0.0027}_{-0.0099}$	2.2σ

Standard $\tau_{\rm reio}$ Definition

Optical depth integrated from $z = 0$ to the redshift of the global minimum of $X_e(z)$.

Key Result

Our model-independent $X_e(z)$ reconstruction **alleviates the lowlEE vs. highl tension** from $\sim 2.2\sigma$ to $\sim \mathbf{1.3}\sigma$ using the the same integration method, with

$$\tau_{\rm reio} = 0.064^{+0.004}_{-0.027} \quad (68\%\ \text{CL})\,, \quad \tau_{\rm reio} = 0.064^{+0.063}_{-0.038} \quad (95\%\ \text{CL})$$

[1] From William Giarè et al. arXiv:2312.06482

Summary (Part 2)

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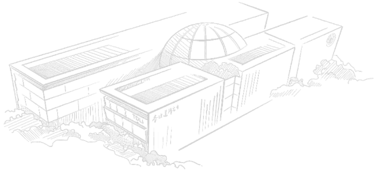
- **Model-independent approach:** Used GP method to sample random reionization histories $X_e(z)$
  - MCMC analysis with $\mathcal{O}(50)$ GP parameters
  - Planck low-ℓ EE-only SimAll likelihood
- **New derived parameter:** $\tau_{\rm highz}$ - high-z contribution to CMB optical depth
  - Extended existing Planck analyses to high-z
  - Verified via χ^2 analysis to be reliable
  - Model-independent posterior for testing any energy injection model
- **Applications:**
  - Decaying "irreducible" axion DM constraints
  - String axion constraints (See Z. Yin et al. arXiv:2507.03535)
  - PBH constraints (See Z. Yin et al. arXiv:2602.06794)
- **Importance:**
  - Offer a clean and general way to constrain new physics using $\tau_{\rm highz}$ posterior
  - alleviates tension between τ measured from low-ℓ EE and from high-ℓ data.
- **Public Code**: https://github.com/Cheng-Hanyu/CLASS_reio_gpr

Thanks

Thanks



Questions?

Overview of our work

- **Innovation:**
  - Implement a new, flexible **Gaussian Process (GP)-based reionization scheme**, called `reio_gpr_tanh`, in the CLASS code.
  - Constrain **high-redshift reionization** histories using GP-based reionization scheme and CMB data.
  - First propose use **high-redshift optical depth, $\tau_{\mathbf{highz}}$ posterior** to constrain energy ejection in reionization history.
- **Advantages:**
  - Model-independent reconstruction of $X_e(z)$
  - The $\tau_{\rm highz}$, offers tighter constraints on new physics sources compared to the low-redshift optical depth $\tau_{\rm lowz}$.
- **Public Code:** `https://github.com/Cheng-Hanyu/CLASS_reio_gpr`
- **Dataset:** Analysis with Planck 2018 low-ℓ EE likelihood

RBF Kernel:

$$k(z_1, z_2) = \sigma_f^2 \exp\left[-\frac{(z_1 - z_2)^2}{2l^2}\right] \tag{4.1}$$

GP Prediction:

$$X_e^{\mathrm{GP}}(z) = \bar{m}(z) + \mathbf{k}_*^T \mathbf{K}^{-1}[\mathbf{X}_{\mathrm{train}} - \bar{m}(\mathbf{z}_{\mathrm{train}})] \tag{4.2}$$

Key Parameters:

- σ_f: Overall variance scale
- l: Correlation length in redshift space
- Training points: $\{(z_i, X_e^{\mathrm{IN}}(z_i))\}$
- $\mathbf{k}_*$ is the vector of covariances between the new point z and each training redshift z_{i} (i.e. $\mathbf{k}_{*,\mathrm{i}} = k(z, z_{\mathrm{i}})$)
- $\mathbf{K}^{-1}$ is the inverse matrix of the kernel function $\mathbf{K}$ ($\mathbf{K}_{\mathrm{ij}} = k(z_{\mathrm{i}}, z_{\mathrm{j}})$)
- $\bar{m}(z) = 0$: mean function (Set $= 0$ in our case.)

Tanh Transitions Between Adaptive Bins

Adaptive binning: Smaller intervals at low-z, larger at high-z

Tanh Transition Formula:

$$X_e(z) = X_e^{\mathrm{GP}}(z_i) + \frac{1}{2}\left[1 + \tanh\left(\frac{z - z_{\mathrm{jump}}}{\Delta z}\right)\right] \times \left[X_e^{\mathrm{GP}}(z_{i+1}) - X_e^{\mathrm{GP}}(z_i)\right] \tag{4.3}$$

Boundary Conditions:

- Low-z (post-reionization): $X_e \approx 1 + \frac{Y_{\mathrm{He}}}{4(1-Y_{\mathrm{He}})}$
- High-z (pre-reionization): $X_e \approx 10^{-5}$

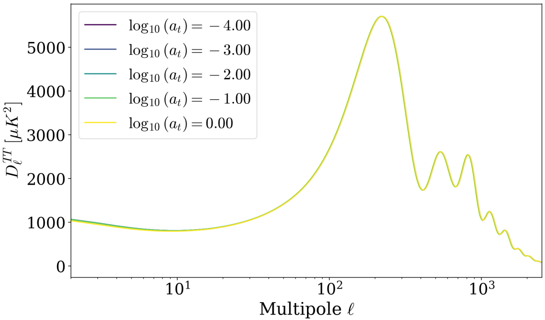
Comparison: τ Reconstruction Methods

Aspect	Traditional	Our Method
Primary parameter	τ (with prior)	$X_e(z)$ (direct)
Reconstruction	Parameterized (reio_camb)	Model-independent
τ treatment	Input parameter	Derived quantity
Physical link	Indirect via model	Direct to data
Model assumptions	Specific reionization shape	None
$z_{\max}$ coverage	Limited ($\sim$50 in CLASS)	Extended ($\sim$800)

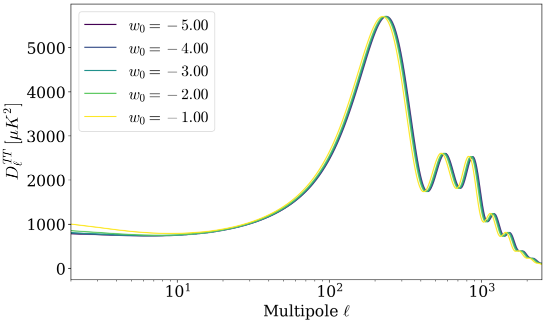
Traditional: τ (prior) $\rightarrow$ model $\rightarrow X_e(z) \rightarrow$ CMB Data $\rightarrow \tau$ (posterior)

Ours: CMB Data $\rightarrow X_e(z) \rightarrow \tau$ (derived posterior)

4PDE CMB Phenomenology



Varying a_t: TT curves nearly overlap.



Varying w_0: low-ℓ late-ISW plateau changes.

Why a_t is hard to constrain

a_t mainly shifts the timing of the late DE transition, while CMB sensitivity is mostly through late-ISW; w_0 directly changes the late-time potential evolution.

Dark Energy: The Cosmic Mystery

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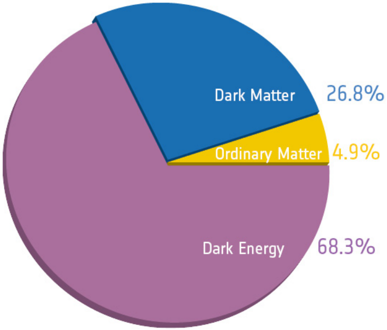
- Universe's expansion is **accelerating**
- First evidence: Type Ia Supernovae (1998)
- **2011 Nobel Prize**: Saul Perlmutter, Brian Schmidt, Adam Riess
- Dark Energy (DE) $\approx 70\%$ of universe
- Standard model: ΛCDM
  - Λ = cosmological constant
  - CDM = Cold Dark Matter
- Recent challenges from DESI & DES



DE Decomposition

First Order ($\Omega_2 = 0$): Dark energy = cosmological constant + fluid with $w = -4/3$ (phantom)

$$\rho = \rho_{\mathrm{DE},0}\left[\left(1 - \frac{\Omega_1}{\Omega_{\mathrm{DE},0}}\right) + \frac{\Omega_1}{\Omega_{\mathrm{DE},0}}a\right] \tag{4.4}$$

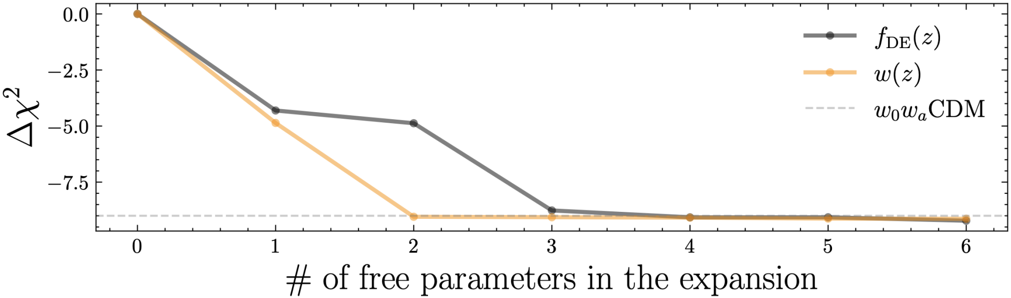
Second Order: Dark energy = cosmological constant + two fluids ($w = -4/3$ and $w = -5/3$)

$$\rho = \rho_{\mathrm{DE},0}\left[\left(1 - \frac{\Omega_1}{\Omega_{\mathrm{DE},0}} - \frac{3}{5}\frac{\Omega_2}{\Omega_{\mathrm{DE},0}}\right) + \left(\frac{\Omega_1}{\Omega_{\mathrm{DE},0}} + \frac{\Omega_2}{\Omega_{\mathrm{DE},0}}\right)a - \frac{2}{5}\frac{\Omega_2}{\Omega_{\mathrm{DE},0}}a^2\right] \tag{4.5}$$

	Pressure Parameterization	**CPL Parameterization**
$a = 0$	$w = -1$	$w = w_0 + w_a$
$a = \infty$	$w = -4/3$ (1st order), $w = -5/3$ (2nd order)	$w = \infty$
Parameters	1 parameter Ω_1 (1st order) 2 parameters Ω_1 and Ω_2 (2nd order)	2 parameters w_0 and w_a (1st order)

Not nested with CPL

χ^2-Paramter number



DESI DR1 results (arxiv:2405.04216)

Field-Theoretic Foundation

- **Lagrangian realization:** Multi-field k-essence model

$$\mathcal{L} = -\Lambda - \sum_{i=1}^{n} c_i X_i^{i/2(3+i)} \tag{4.6}$$

  where $X_i = g^{\mu\nu}\phi^i_{,\mu}\phi^i_{,\nu}$ is the kinetic term for field ϕ^i
- **Key insight:** Each Taylor term $\leftrightarrow$ distinct k-essence component
  - n-th order expansion requires n fields
  - Similar to assisted inflation mechanism
  - Provides consistent field-theoretic embedding