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Testing DDE and Constraining high-z reionization with Cosmological Data

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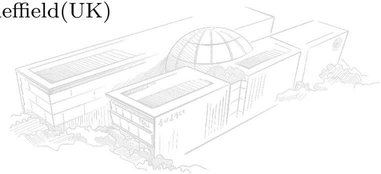
University of Sheffield



Content

1. **Constraining Pressure-Based Dynamical Dark Energy(DDE) Models with Latest Cosmological Data**
2. **Constraining exotic high-z reionization histories with Gaussian processes and the cosmic microwave background**

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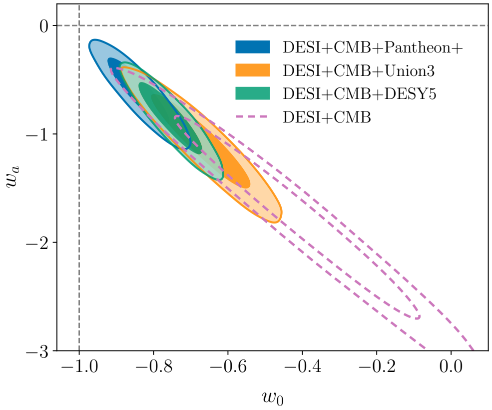
CPL Parametrization:

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

- 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)

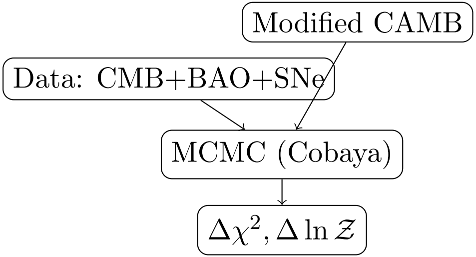
Our Approach: Pressure Parametrization

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



Statistical Methods:

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

$$p(a) = -p_0 + \sum_{n=1}^{\infty} \frac{(1-a)^n}{n!} p_n \,, \tag{1.1}$$

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

$$\dot{\rho} + 3H\,(p + \rho) = 0 \,. \tag{1.2}$$

First-Order Expansion Model

Using the first-order term in (1.1), the DE energy density evolves as:

$$\rho(a) = \rho_{\mathrm{DE},0} - \tfrac{3}{4}(1-a)\, p_1\,, \tag{1.3}$$

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

$$\Omega_{\mathrm{DE},0} \equiv \frac{\rho_{\mathrm{DE},0}}{\rho_{\mathrm{crit}}}\,, \quad \Omega_1 \equiv \frac{3}{4}\frac{p_1}{\rho_{\mathrm{crit}}}\,, \quad \rho_{\mathrm{crit}} = \frac{3H_0^2}{8\pi G}, \tag{1.4}$$

we can rewrite (1.3) as

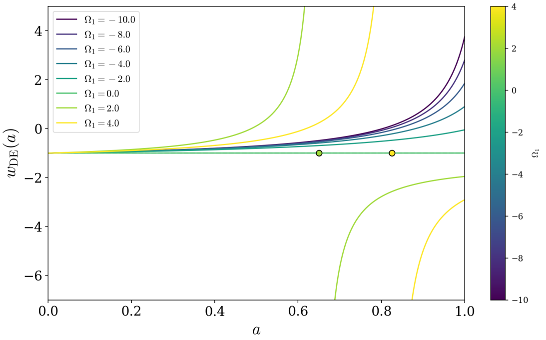
$$\rho(a) = \rho_{\mathrm{DE},0}\left[1 + (a-1)\,\frac{\Omega_1}{\Omega_{\mathrm{DE},0}}\right]. \tag{1.5}$$

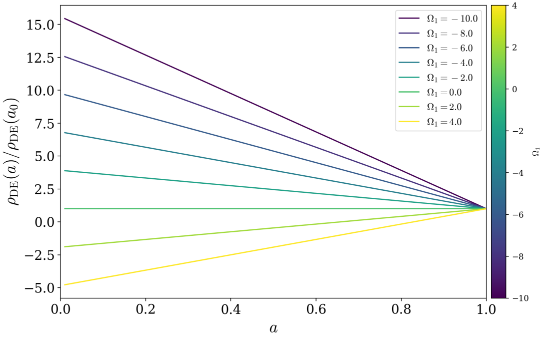
The corresponding equation-of-state parameter is

$$w_{\mathrm{DE}}(a) = -1 + \frac{1}{3}\,\frac{\Omega_1\, a}{\Omega_1\,(1-a) - \Omega_{\mathrm{DE},0}}\,. \tag{1.6}$$

A singularity appears in $w_{\mathrm{DE}}(a)$ when the denominator of (1.6) vanishes, at the scale factor

$$a_{\mathrm{pole}} = 1 - \frac{\Omega_{\mathrm{DE},0}}{\Omega_1}\,. \tag{1.7}$$





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Second-Order Expansion Model

Including terms up to second order in (1.1), and defining

$$\Omega_2 \equiv \frac{3}{4}\frac{p_2}{\rho_{\rm crit}}\,, \tag{1.8}$$

the DE density becomes:

$$\rho(a) = \rho_{\rm DE,0}\left[1 + (a-1)\left(\frac{\Omega_1+\Omega_2}{\Omega_{\rm DE,0}}\right) + \tfrac{2}{5}(1-a^2)\frac{\Omega_2}{\Omega_{\rm DE,0}}\right]. \tag{1.9}$$

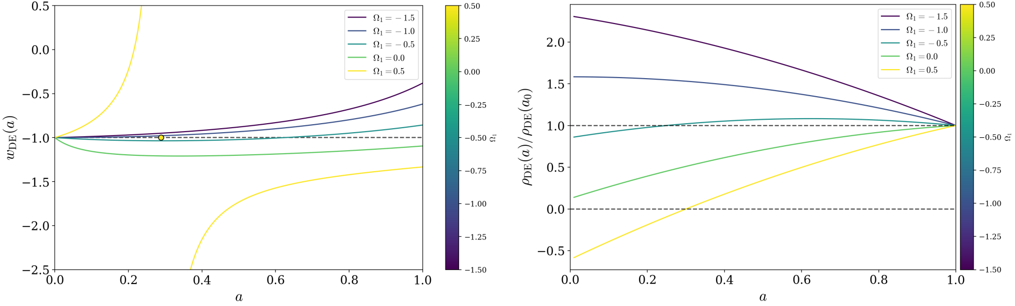
The equation-of-state parameter is then:

$$w_{\rm DE}(a) = -1 + \frac{1}{3}\frac{\left(\Omega_1 + (1-\tfrac{4}{5}a)\,\Omega_2\right)a}{\left[\Omega_1 + \tfrac{3}{5}(1-\tfrac{2}{3}a)\,\Omega_2\right](1-a) - \Omega_{\rm DE,0}}\,. \tag{1.10}$$

This expression can exhibit poles when the denominator vanishes.

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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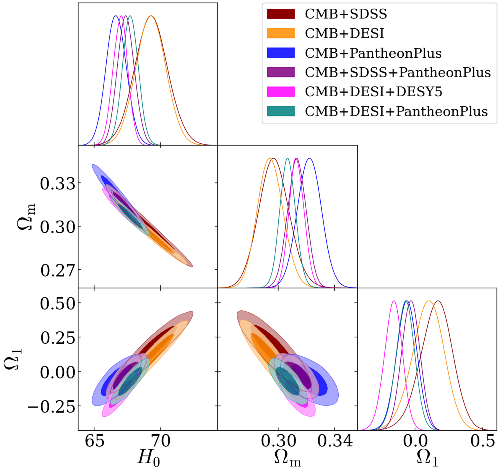
First-Order Expansion Results

Dataset	Ω_1	H_0	Ω_m	$\Delta\chi^2_{\Lambda\mathrm{CDM}}$
CMB only	$0.89^{+0.62}_{-0.14}$	83^{+10}_{-7}	$0.217^{+0.019}_{-0.074}$	-4.13
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 trend in the right direction to alleviate H_0 and S_8 tensions
- CMB+DESI+DESY5 shows $> 2\sigma$ deviation from ΛCDM
- Other cosmological parameters remain close to Planck ΛCDM values



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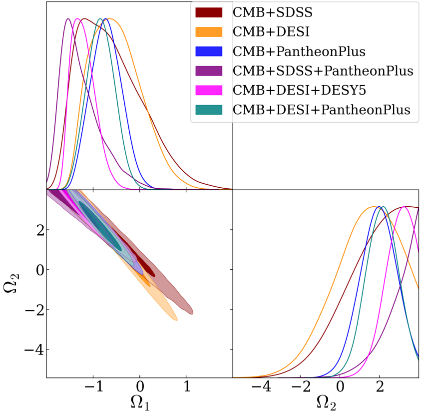
- CMB+DESI:
  $H_0 = 69.3 \pm 1.1$ km/s/Mpc
  $\Omega_m = 0.2946 \pm 0.0090$;
  CMB+PP:
  $H_0 = 66.68 \pm 0.76$ km/s/Mpc
  $\Omega_m = 0.3221 \pm 0.0084$
- Adding SNe data pulls H_0 and Ω_m toward Planck values

Second-Order Expansion Results

Dataset	Ω_1	Ω_2	$\Delta\chi^2_{\Lambda\mathrm{CDM}}$
CMB	$0.42^{+1.1}_{-0.83}$	> -0.0245	-5.34
CMB+SDSS	$-0.64^{+0.41}_{-0.86}$	> 1.23	-1.81
CMB+DESI	$-1.25^{+0.21}_{-0.53}$	> 2.69	-6.46
CMB+PP	$-0.52^{+0.39}_{-0.65}$	$1.4^{+2.0}_{-1.1}$	-0.93
CMB+SDSS+PP	-0.72 ± 0.33	1.96 ± 0.92	-3.92
CMB+DESI+DESY5	$-1.21^{+0.19}_{-0.31}$	$2.94^{+1.0}_{-0.31}$	-19.24
CMB+DESI+PP	-0.84 ± 0.29	2.15 ± 0.80	-6.36



Strongest Evidence

CMB+DESI+DESY5:

- 4σ preference over ΛCDM
- Bayesian factor $\Delta \ln \mathcal{Z} = 3.67$

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Key Features

- Strong negative correlation between Ω_1 and Ω_2.

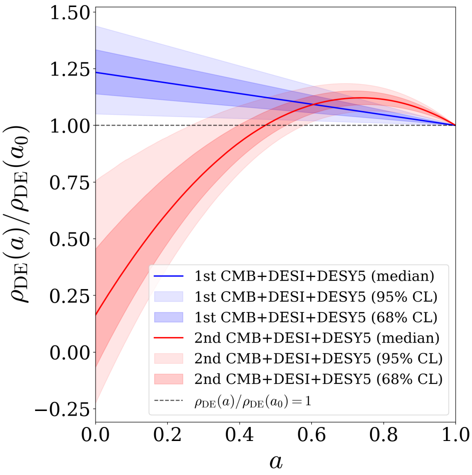
Evolution of Dark Energy Density

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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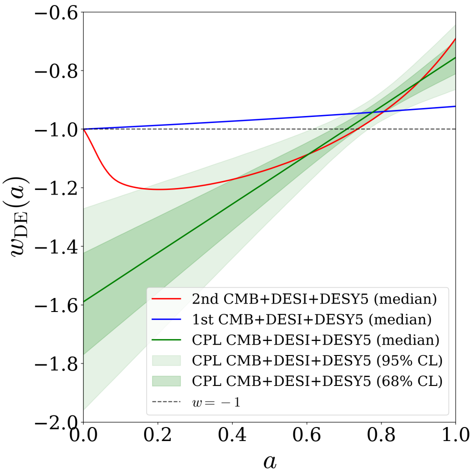
Equation of State Evolution

Key Features:

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



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w_0-w_a Parameter Space

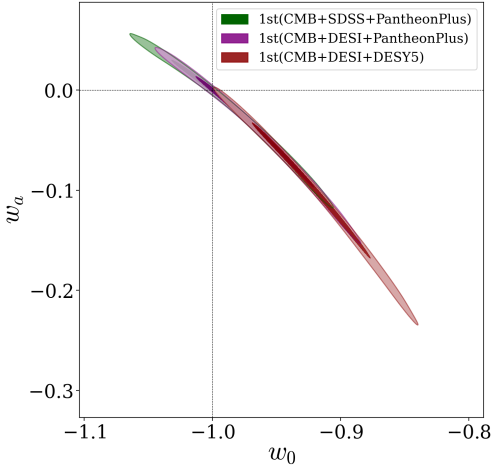
Present-day EoS:

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

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

First-Order:

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



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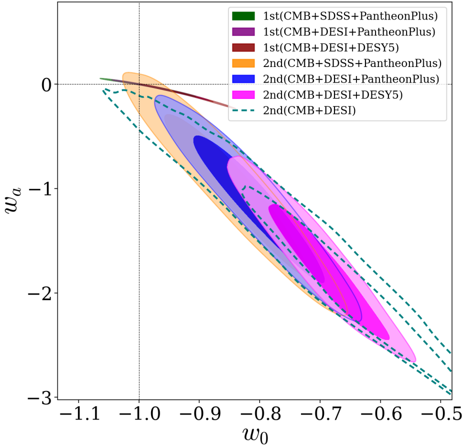
Second-Order:

- $w_0 > -1$ (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

Second Order Model

Dataset	$\Delta\chi^2_{\mathrm{min,CPL}}$	$\Delta \ln \mathcal{Z}_{\mathrm{CPL}}$
CMB	−0.25	−0.26
CMB+SDSS	0.64	0.53
CMB+PP	0.57	1.02
CMB+SDSS+PP	0.26	0.78
CMB+DESI	1.09	−0.89
CMB+DESI+DESY5	0.21	0.96
CMB+DESI+PP	1.18	0.6

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

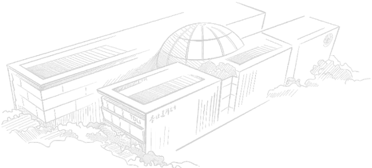
Summary (Part 1)

1. **First-Order Model:**
   - Generally consistent with ΛCDM
   - CMB+SDSS, CMB+DESI alleviate H_0 and S_8 tensions

2. **Second-Order Model:**
   - Distinctive non-monotonic behavior in both energy density and $w_{\rm DE}(a)$ evolution
   - Late time $w_{\rm DE}(a)$ shows strong agreement with the CPL parameterization across datasets (Phantom crossing behavior and Dark energy is weakening)

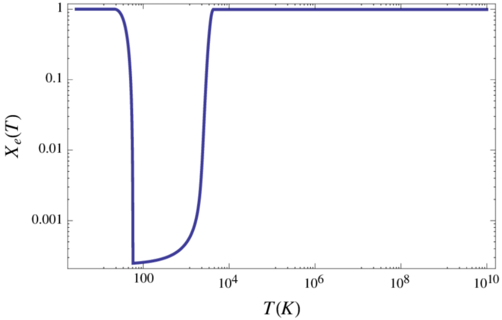
3. CMB+DESI+DESY5 always give much stronger preference for DDE compared to other datasets combination.

Content



Reionization: Imprint on the CMB

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



CMB Signatures

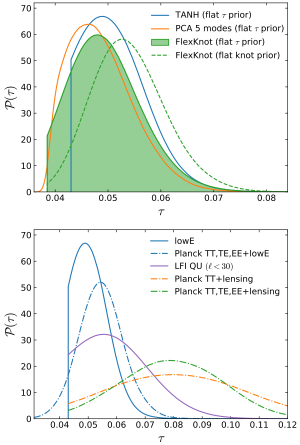
1. Temperature Anisotropies
2. Polarization
3. kSZ (kinetic Sunyaev-Zel'dovich) effect

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**

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 τ_{highz}, offers tighter constraints on new physics sources compared to the low-redshift optical depth τ_{lowz}.
- **Public Code:** `https://github.com/Cheng-Hanyu/CLASS_reio_gpr`
- **Dataset:** Analysis with Planck 2018 low-ℓ EE likelihood

Gaussian Process Method

RBF Kernel:

$$k(z_1, z_2) = \sigma_f^2 \exp\left[-\frac{(z_1 - z_2)^2}{2l^2}\right] \tag{2.1}$$

GP Prediction:

$$X_e^{\mathrm{GP}}(z) = \bar{m}(z) + \mathbf{k}_*^T \mathbf{K}^{-1}[\mathbf{X}_{\mathrm{train}} - \bar{m}(\mathbf{z}_{\mathrm{train}})] \tag{2.2}$$

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:

$$X_e(z) = X_e^{\mathrm{GP}}(z_i) + \frac{1}{2}\left[1 + \tanh\left(\frac{z - z_{\mathrm{jump}}}{\Delta z}\right)\right] \times \left[X_e^{\mathrm{GP}}(z_{i+1}) - X_e^{\mathrm{GP}}(z_i)\right] \tag{2.3}$$

Boundary Conditions:

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

Workflow

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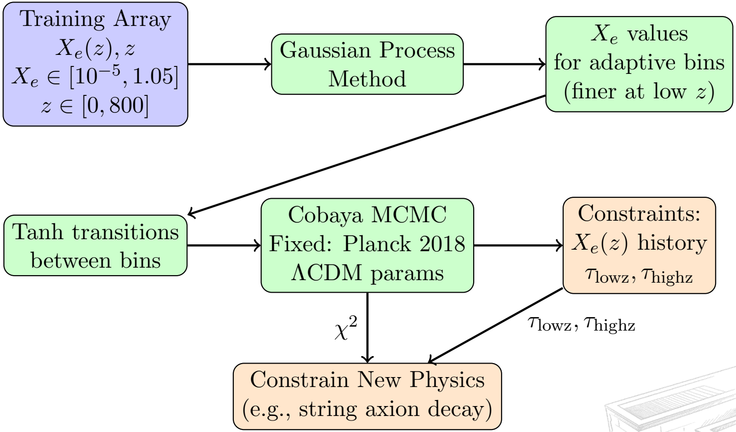

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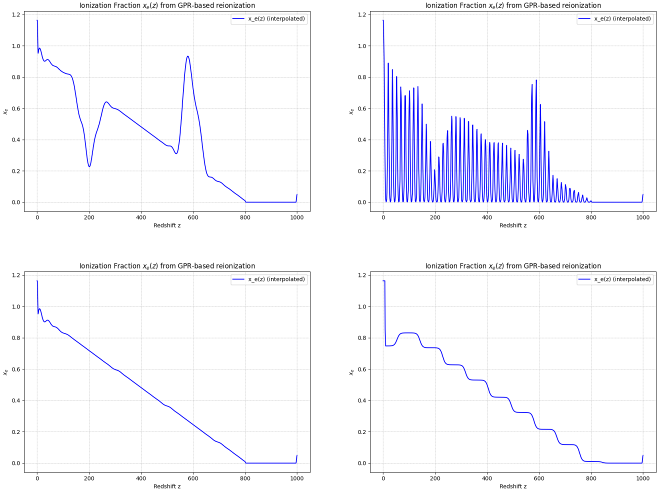
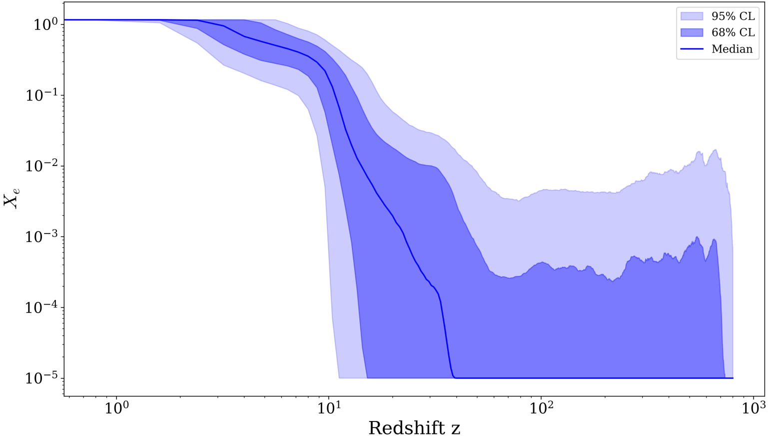
Demonstrate the flexibility of our method to explore the X_e-z parameter space.



Reconstruction history of $X_e(z)$



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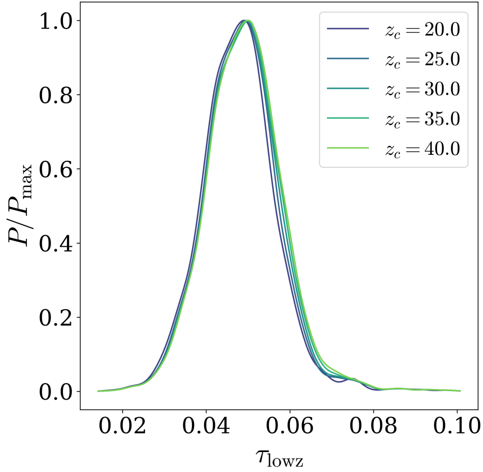
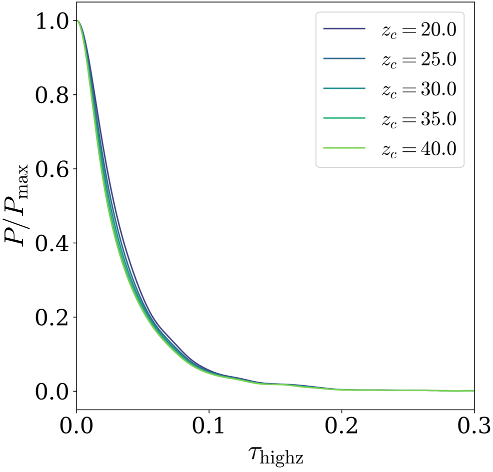
Parameter Definitions

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

z_c	68% CL		95% CL	
	τ_{lowz}	τ_{highz}	τ_{lowz}	τ_{highz}
20.0	$0.0474^{+0.0079}_{-0.0080}$	< 0.036	$0.047^{+0.018}_{-0.017}$	< 0.109
25.0	$0.0480^{+0.0080}_{-0.0080}$	< 0.035	$0.048^{+0.018}_{-0.017}$	< 0.108
30.0	$0.0483^{+0.0083}_{-0.0080}$	< 0.035	$0.048^{+0.018}_{-0.017}$	< 0.108
35.0	$0.0486^{+0.0086}_{-0.0081}$	< 0.035	$0.049^{+0.018}_{-0.017}$	< 0.107
40.0	$0.0488^{+0.0088}_{-0.0082}$	< 0.035	$0.049^{+0.019}_{-0.017}$	< 0.107

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





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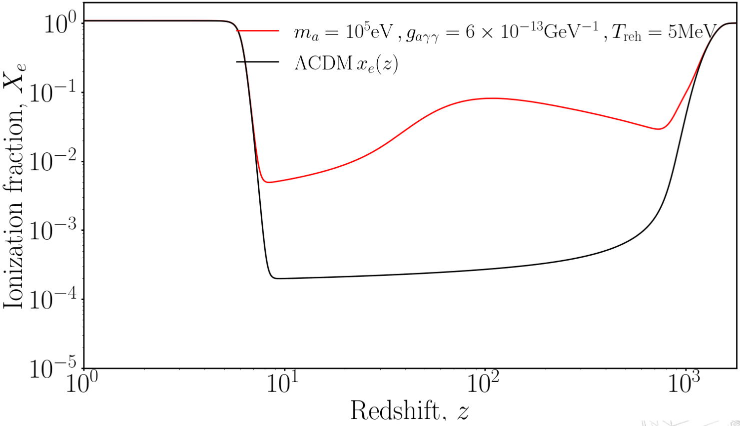

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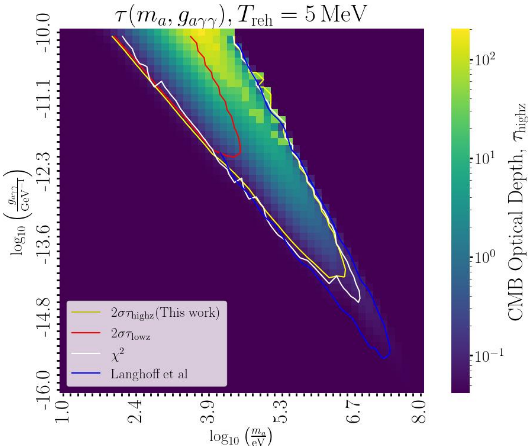

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95% CL upper limits:

- $\chi^2 < 403.2$
- $\tau_{\rm highz} < 0.111$

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,
- $\tau_{\rm highz}$ providing conservative constraints compared to χ^2 analyses using Planck low-ℓ EE-only likelihood. (reliable)

Conclusions

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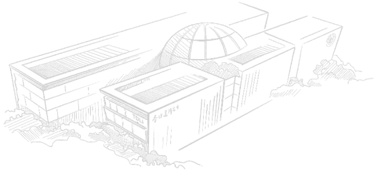
- **Model-independent approach:** Used GP method to sample random reionization histories $X_e(z)$
  - MCMC analysis with $\mathcal{O}(20)$ GP parameters
  - Planck low-ℓ EE-only SimAll likelihood
- **New derived parameter:** $\tau_{\rm highz}$ - high-z contribution to CMB optical depth
  - Extended existing 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 Ziwen Yin's poster)
- **Importance:** Offer a clean and general way to constrain new physics using $\tau_{\rm highz}$ posterior.
- **Public Code**: https://github.com/Cheng-Hanyu/CLASS_reio_gpr https://github.com/ZiwenYin/Reionization-with-multi-axions-decay

Thanks

Thanks



Question

Questions?

DE Decomposition

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

$$\rho = \rho_{\mathrm{DE},0}\left[\left(1 - \frac{\Omega_1}{\Omega_{\mathrm{DE},0}}\right) + \frac{\Omega_1}{\Omega_{\mathrm{DE},0}} a\right] \tag{4.1}$$

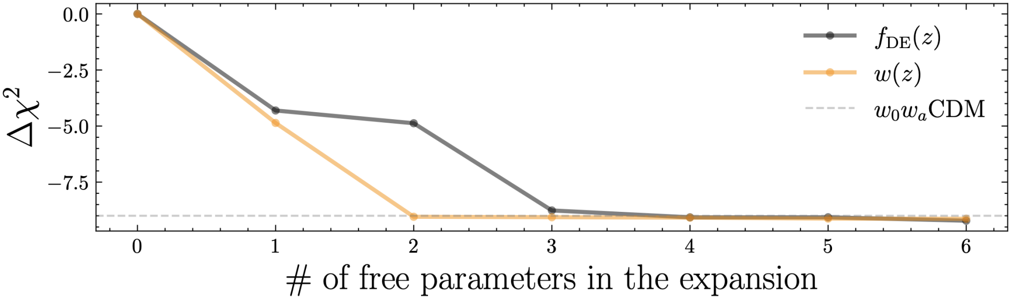
Second Order: Dark energy = cosmological constant + two fluids ($w = -4/3$ and $w = -5/3$)

$$\rho = \rho_{\mathrm{DE},0}\left[\left(1 - \frac{\Omega_1}{\Omega_{\mathrm{DE},0}} - \frac{3}{5}\frac{\Omega_2}{\Omega_{\mathrm{DE},0}}\right) + \left(\frac{\Omega_1}{\Omega_{\mathrm{DE},0}} + \frac{\Omega_2}{\Omega_{\mathrm{DE},0}}\right) a - \frac{2}{5}\frac{\Omega_2}{\Omega_{\mathrm{DE},0}} a^2\right] \tag{4.2}$$

	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

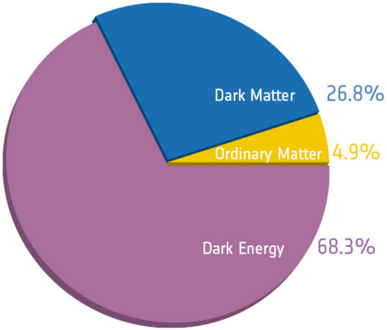
χ^2-Paramter number



Planck 2018 results (arxiv:1807.06209)

Dark Energy: The Cosmic Mystery

- 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



Cosmic Microwave Background (CMB)

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"

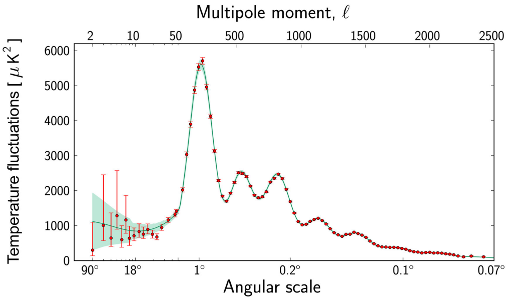


Figure 3: This graph shows the temperature fluctuations in the CMB detected by Planck at different angular scales on the sky from ESA and the Planck Collaboration.

Baryon Acoustic Oscillations (BAO)

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: $0.1 < z < 4$

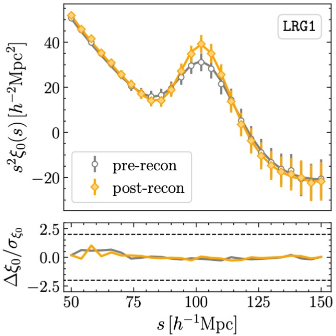


Figure 4: Two point correlation function of the average of 25 Abacus galaxy mock catalogs (data points) compared to the model prediction (lines) pre- (grey) and post-reconstruction (yellow) from DESI Collaboration.

Type Ia Supernovae

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
  - $0.1 < z < 1.13$

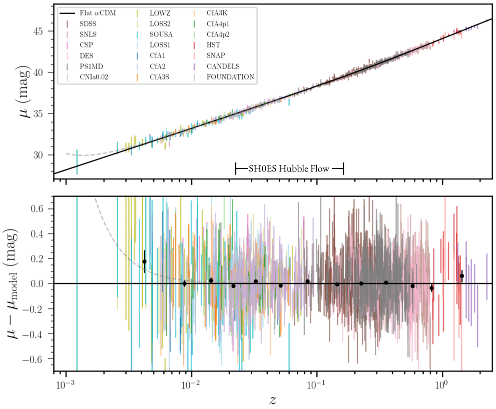


Figure 5: distance modulus vs redshift from The Pantheon+ Analysis paper (https://arxiv.org/abs/2202.04077)