Tsung-Dao Lee Institute

Constraining high-z reionization with CMB

arXiv: 2506.19096, 2507.03535, 2602.06794

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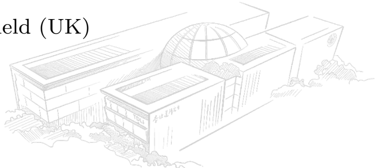
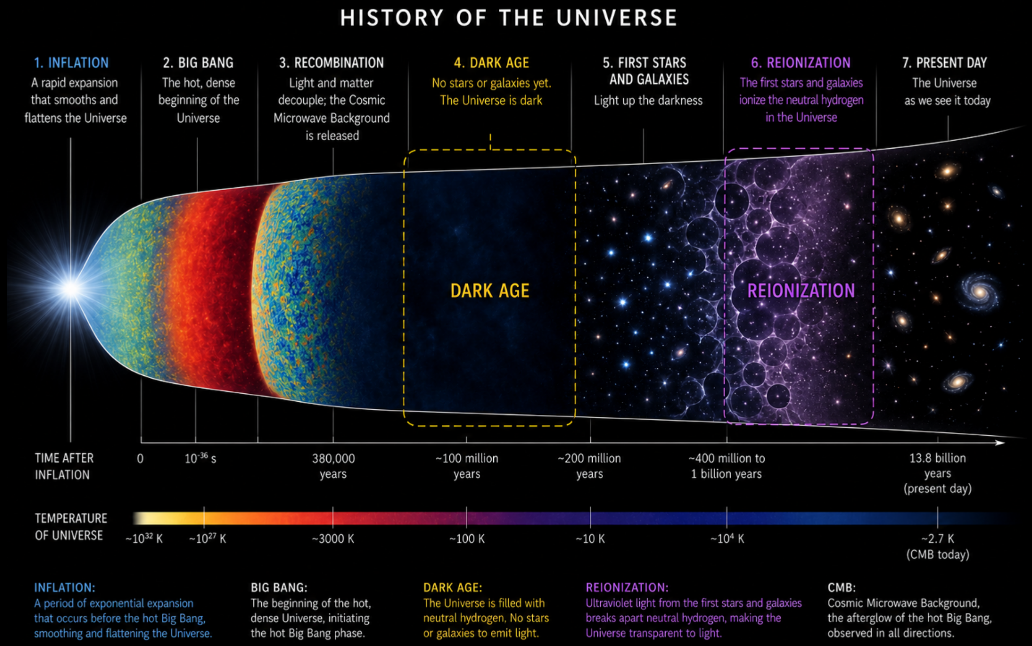
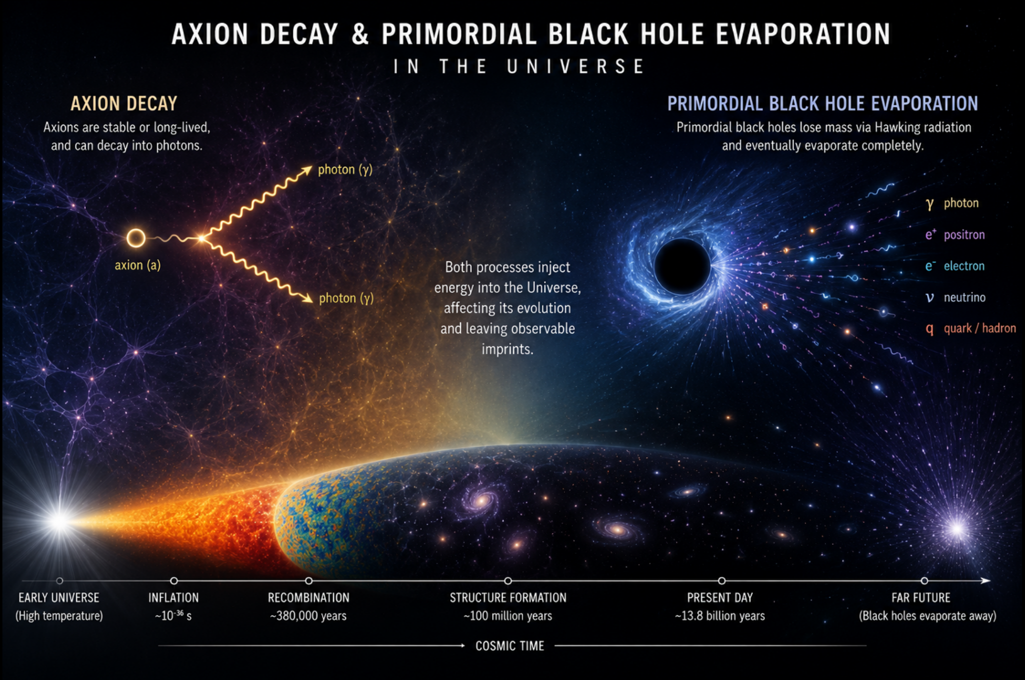
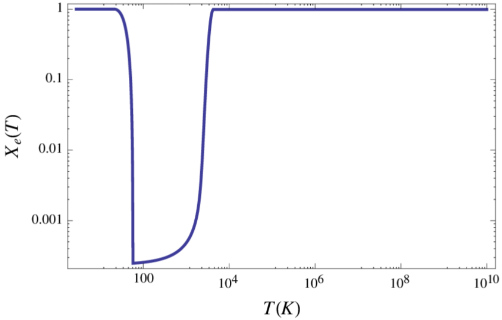



HISTORY OF THE UNIVERSE
1. INFLATION
A rapid expansion that smooths and flattens the Universe
2. BIG BANG
The hot, dense beginning of the Universe
3. RECOMBINATION
Light and matter decouple; the Cosmic Microwave Background is released
4. DARK AGE
No stars or galaxies yet. The Universe is dark
5. FIRST 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)
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
Both processes inject energy into the Universe, affecting its evolution and leaving observable imprints.
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



CMB Signatures

1. Temperature anisotropies
2. Polarization
3. kSZ (kinetic Sunyaev–Zel'dovich) effect

Key quantities:

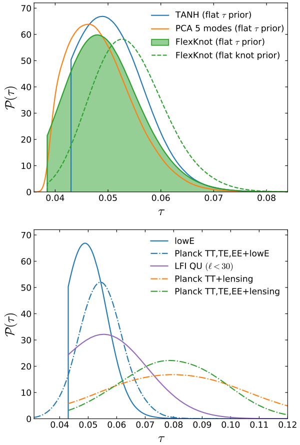
Free electron fraction: $X_e(z) \equiv \frac{n_e(z)}{n_{\mathrm{H}}(z)}$

Electron Thomson scattering optical depth:

$$\tau(z) = \int_0^z \frac{c\,\sigma_T\,n_{\mathrm{H}}(z')\,X_e(z')}{(1+z')H(z')}\,dz'$$

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**

Split optical depth into low-z and high-z

$$\frac{d\tau}{dz} = \frac{c\,\sigma_T n_e(z)}{(1+z)H(z)}, \qquad \tau_{\rm total} \equiv \tau(0, z_{\rm max}) = \tau_{\rm lowz} + \tau_{\rm highz}$$

Low redshift: $0 \leq z < z_c$

$$\tau_{\rm lowz} = \int_0^{z_c} dz \, \frac{c\,\sigma_T n_e(z)}{(1+z)H(z)}$$

Standard astrophysical reionization + low-z exotic injection.

$z_c = 30$ isolates the exotic-search window.

High redshift: $z_c \leq z \leq z_{\rm max}$

$$\tau_{\rm highz} = \int_{z_c}^{z_{\rm max}} dz \, \frac{c\,\sigma_T n_e(z)}{(1+z)H(z)}$$

Exotic high-z energy injection.

$z_{\rm max} = 800$ stays below recombination-era physics.

Source: H. Cheng et al., arXiv:2506.19096.

A nonparametric bridge from CMB polarization to high-redshift new physics

1. Flexible re-construction

`reio_gpr_tanh`

Gaussian-process module implemented in `CLASS`

Parameterization-independent reconstruction of $X_e(z)$

→

2. CMB inference

Planck 2018 low-ℓ EE

$\Downarrow$

High-redshift ionization histories

$\Downarrow$

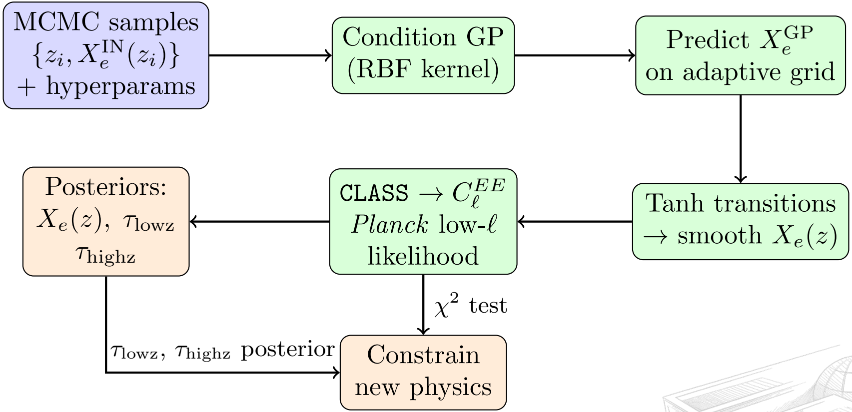
$p(\tau_{\rm highz} \mid \mathrm{CMB})$

→

3. New-physics constraints

Use the $\tau_{\rm highz}$ posterior to constrain exotic high-z energy injection

Workflow


MCMC samples $\{z_i, X_e^{\mathrm{IN}}(z_i)\}$ + hyperparams
Condition GP (RBF kernel)
Predict X_e^{GP} on adaptive grid
Tanh transitions $\rightarrow$ smooth $X_e(z)$
CLASS $\rightarrow C_\ell^{EE}$ *Planck* low-ℓ likelihood
Posteriors: $X_e(z)$, τ_{lowz} τ_{highz}
χ^2 test
τ_{lowz}, τ_{highz} posterior
Constrain new physics

Gaussian Process Method

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RBF Kernel:

$$k(z_1, z_2) = \sigma_f^2 \exp\left[-\frac{(z_1 - z_2)^2}{2l^2}\right] \tag{0.1}$$

GP Prediction:

$$X_e^{\mathrm{GP}}(z) = \bar{m}(z) + \mathbf{k}_*^T \mathbf{K}^{-1}[\mathbf{X}_{\mathrm{train}} - \bar{m}(\mathbf{z}_{\mathrm{train}})] \tag{0.2}$$

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

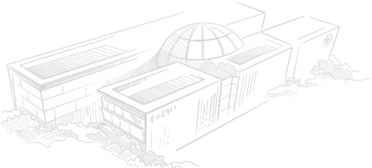
Adaptive binning: Smaller intervals at low-z, larger at high-z

Tanh Transition Formula:

$$X_e(z) = X_e^{\mathrm{GP}}(z_i) + \frac{1}{2}\left[1 + \tanh\left(\frac{z - z_{\mathrm{jump}}}{\Delta z}\right)\right] \times \left[X_e^{\mathrm{GP}}(z_{i+1}) - X_e^{\mathrm{GP}}(z_i)\right] \qquad (0.3)$$

Boundary Conditions:

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



Fixed-A_s robustness check

$$\mathcal{A}_{\rm reio} \equiv C_\ell^{EE,\rm reio} \propto A_s\left(1 - e^{-\tau}\right)^2 \simeq A_s\tau^2$$

Compare the two conditionings

$$\mathcal{A}_{\rm reio}\big|_{A_s} \propto A_s(1-e^{-\tau})^2,$$
$$\mathcal{A}_{\rm reio}\big|_{S} \propto S e^{2\tau}(1-e^{-\tau})^2, \quad S \equiv A_s e^{-2\tau}.$$

Fixed A_s is more conservative; fixed S is $\sim 13\%$ tighter.

Direct `SimAll` stress test

Sample: random 51 posterior histories; Planck $A_s \pm 3\sigma$.

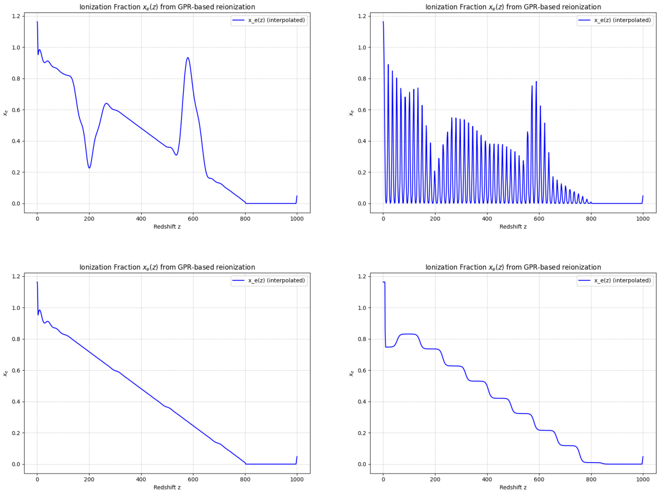
$$\max|\Delta\chi^2| = 0.72 < 1$$

Conclusion: fixed A_s is conservative, and the $\pm 3\sigma$ test leaves the $\tau_{\rm highz}$ bound unchanged.

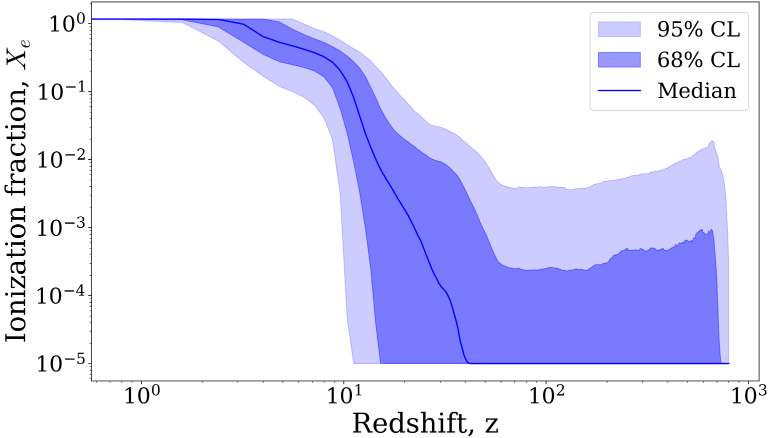
Source: H. Cheng et al., arXiv:2506.19096.

Some Examples for $X_e(z)$

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

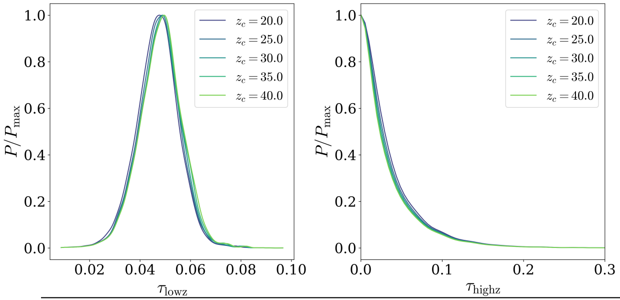


Reconstruction history of $X_e(z)$



H. Cheng et al. arXiv:2506.19096

Optical depth constraints



Parameter definitions

z_c: critical redshift separating the low- and high-z regimes.

$\tau_{\rm lowz}$: optical depth integrated over $0 \leq z \leq z_c$.

$\tau_{\rm highz}$: optical depth integrated over $z_c \leq z \leq z_{\rm max}$, with $z_{\rm max} = 800$ fixed.

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

Source: H. Cheng et al., arXiv:2506.19096.

Example for "irreducible" axion decay

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}\, g_{a\gamma\gamma}\, a F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

1. Freeze-in production

Primakoff $e^\pm + \gamma \to e^\pm + a$

$$\mathcal{F}_{\rm Prim} \propto T_{\rm reh}\, m_a\, g_{a\gamma\gamma}^2$$

Inverse decay $\gamma + \gamma \to a$

$$\mathcal{F}_{\rm id} \propto T_{\rm reh}^0\, m_a^2\, g_{a\gamma\gamma}^2$$

$T_{\rm reh} \gtrsim 2.5 m_a$

→

2. Axion decay

$$a \to \gamma + \gamma$$

$$\tau_a = \frac{64\pi}{g_{a\gamma\gamma}^2 m_a^3}$$

→

3. DarkHistory

Axion decay

$\Downarrow$

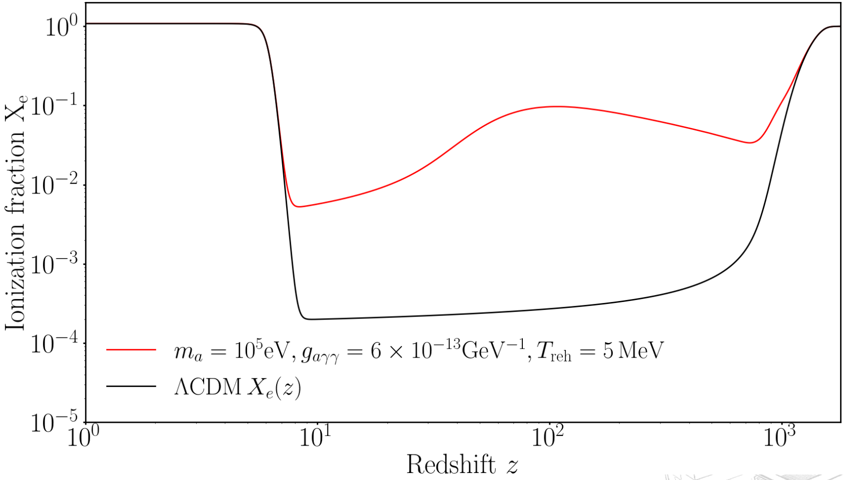
`DarkHistory`

$\Downarrow$

$X_e(z)$

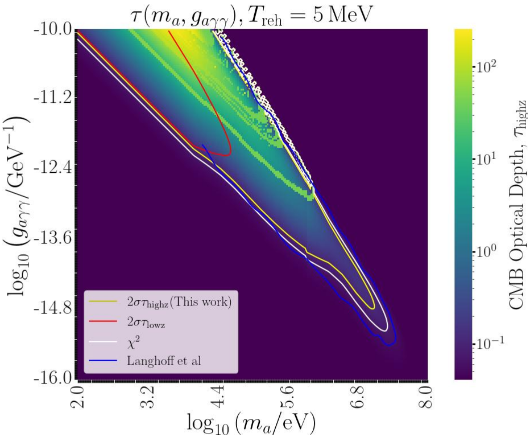
Sources: M. Jain et al., arXiv:2406.01678; H. Liu, G. W. Ridgway and T. R. Slatyer, arXiv:1904.09296.

Example for "irreducible" axion decay



H. Cheng et al. arXiv:2506.19096

Example for "irreducible" axion decay



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 likelihood ($\tau_{\rm highz}$ is compressed observable; fixed A_s).

From single-axion limits to string-axiverse constraints

A Calabi–Yau compactification yields many axions, each with distinct $\{m_i,\, g_{i\gamma\gamma},\, \mathcal{F}_i,\, \Gamma_i^{-1}\}$.

Traditional point-by-point route

each decay model $\to$ `DarkHistory` $\to$ $X_e(z)$ $\to$ `CLASS` $\to$ `Cobaya/Likelihood` $\to$ χ^2 $\to$ constraint

This work: compress Planck low-ℓ polarization information into the $\tau_{\rm highz}$ posterior

each decay model $\to$ `DarkHistory` $\to$ $X_e(z)$ $\to$ predicted $\tau_{\rm highz}$ vs. $\tau_{\rm highz}$ posterior $\to$ constraint

Source: Z. Yin et al., arXiv:2507.03535.

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1. More production

$T_{\rm reh}\uparrow \Rightarrow \mathcal{F}_{\rm Prim}\uparrow$

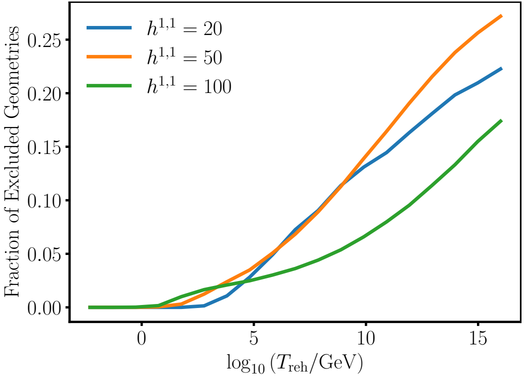
2. More ionization

$\sum_i$ axion decays $\Rightarrow X_e(z)\uparrow \Rightarrow \tau_{\rm highz}\uparrow$.

3. 95% CL exclusion

$\tau_{\rm highz} > 0.111$

$z_c = 30$, $z_{\rm max} = 800$; all relevant axions are included simultaneously.



Takeaway: for $h^{1,1} = 20, 50, 100$, about 15%, 15%, 10% of models prefer $T_{\rm reh} \lesssim 10^{10}$ GeV at 95% CL; at $T_{\rm reh} \simeq 10^{16}$ GeV, up to $\sim 25\%$ of the $h^{1,1} = 20, 50$ geometries are excluded.

Source: Z. Yin et al., arXiv:2507.03535.

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$$30 \le z \le 800, \qquad 3.2 \times 10^{13} \lesssim M_{\rm PBH}/{\rm g} \lesssim 5 \times 10^{14}$$

1. Initial abundance

$$\beta \equiv \left.\frac{\rho_{\rm PBH}}{\rho_{\rm tot}}\right|_{t_f}$$

$$\beta = \frac{8\pi G_N}{3H_f^2}\rho_{\rm PBH}(t_f)$$

monochromatic $M_{\rm PBH}$

→

2. Hawking evaporation

$$T_H = \frac{1}{8\pi G_N M_{\rm PBH}}$$

$$\frac{dM_{\rm PBH}}{dt} = -\sum_i \int dE\, E\, \frac{d^2N_i}{dE\,dt}$$

$$\tau_{\rm PBH} \propto M_{\rm PBH}^3$$

continuous emission

`BlackHawk` + `HAZMA`

→

3. Deposition and CMB

$$\left.\frac{dE}{dV\,dt}\right|_{\rm dep,c} = f_c(z) \times \left(\frac{dE}{dV\,dt}\right)_{\rm inj}$$

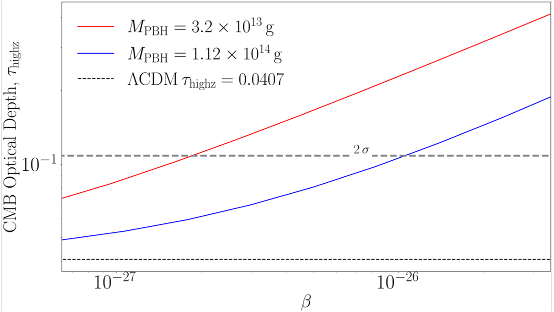
$$c = \{\text{ion}, \text{exc}, \text{heat}\}$$

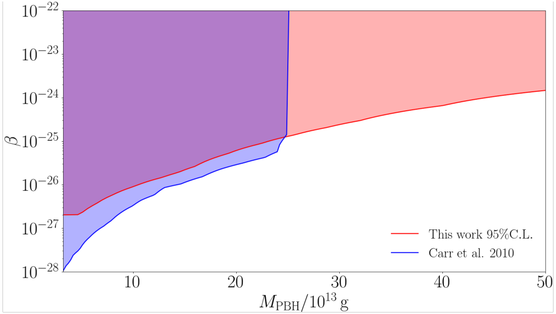
$$\texttt{DarkHistory} \Rightarrow X_e(z)$$

$$\tau_{\rm highz} = \int_{30}^{800} dz\, \frac{c\, n_e(z)\sigma_T}{(1+z)H(z)}$$

Source: Z. Yin, H. Cheng and L. Visinelli, arXiv:2602.06794

Example for PBH evaporation





Z. Yin et al. arXiv:2602.06794

$\tau_{\rm highz}$ posterior $\Longrightarrow \beta_{\max}(M_{\rm PBH})$

Mass window: $3.2 \times 10^{13} \lesssim M_{\rm PBH}/{\rm g} \lesssim 5 \times 10^{14}$.

Low-M plateau: $T_H \uparrow \Rightarrow q, g$, hadrons $\uparrow$, $P_{\nu,{\rm grav}} \uparrow$, ${\rm Br}_{\gamma,e^\pm} \downarrow$.

High-M reach: continuous pre-evaporation Hawking emission.

Alleviating lowlEE vs. highl Tension

Case	Likelihood	Integration Method	$\tau_{\rm reio}$ (68% CL)	Tension
1. Our work	lowlEE	Integrate to $z_{\rm max} = 800$	$0.070^{+0.041}_{-0.018}$	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

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

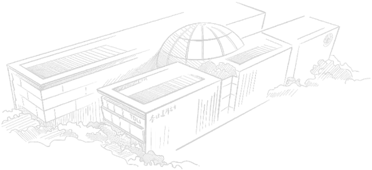
[1] From William Giarè et al. arXiv:2312.06482

Summary

- **Reionization Parameterization-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



Question

Questions?

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) $\to$ model $\to$ $X_e(z)$ $\to$ CMB Data $\to$ τ (posterior)

Ours: CMB Data $\to$ $X_e(z)$ $\to$ τ (derived posterior)