Complete Reionization Constraints from Planck 2015 Polarization

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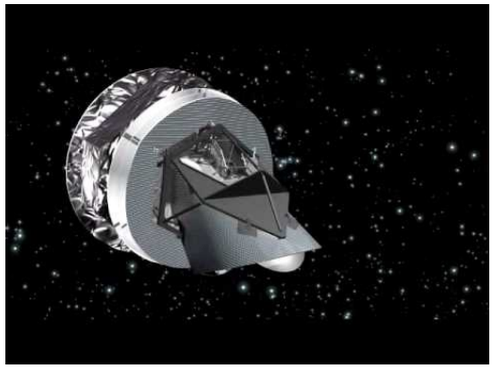
University of Chicago

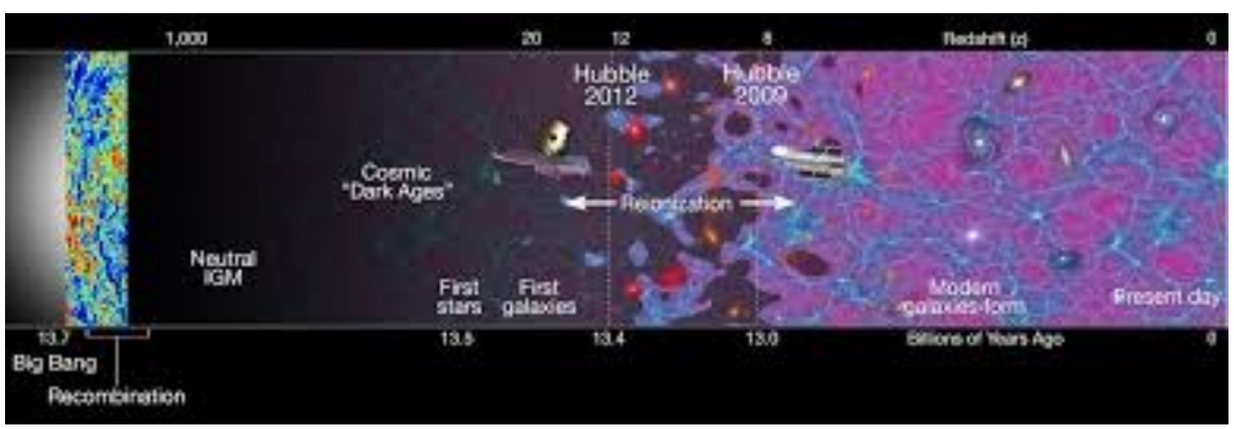
Oct. 2016
UC Berkeley - Cosmology Seminar

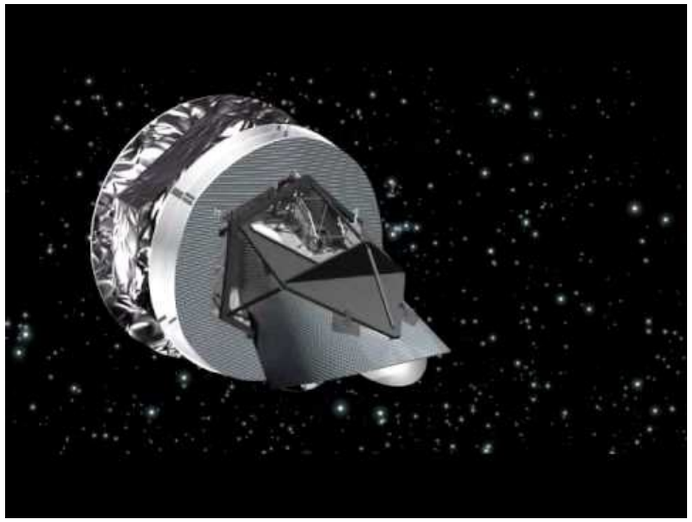


Heinrich, Miranda & Hu
arXiv:1609.04788

Outline

- Intro: Probing reionization with CMB polarization
- Advantages of principal components (PCs)
- Probing high-z ionization with Planck 2015
- Fast model testing with our effective likelihood code





z ~1000

z ~10

z = 0

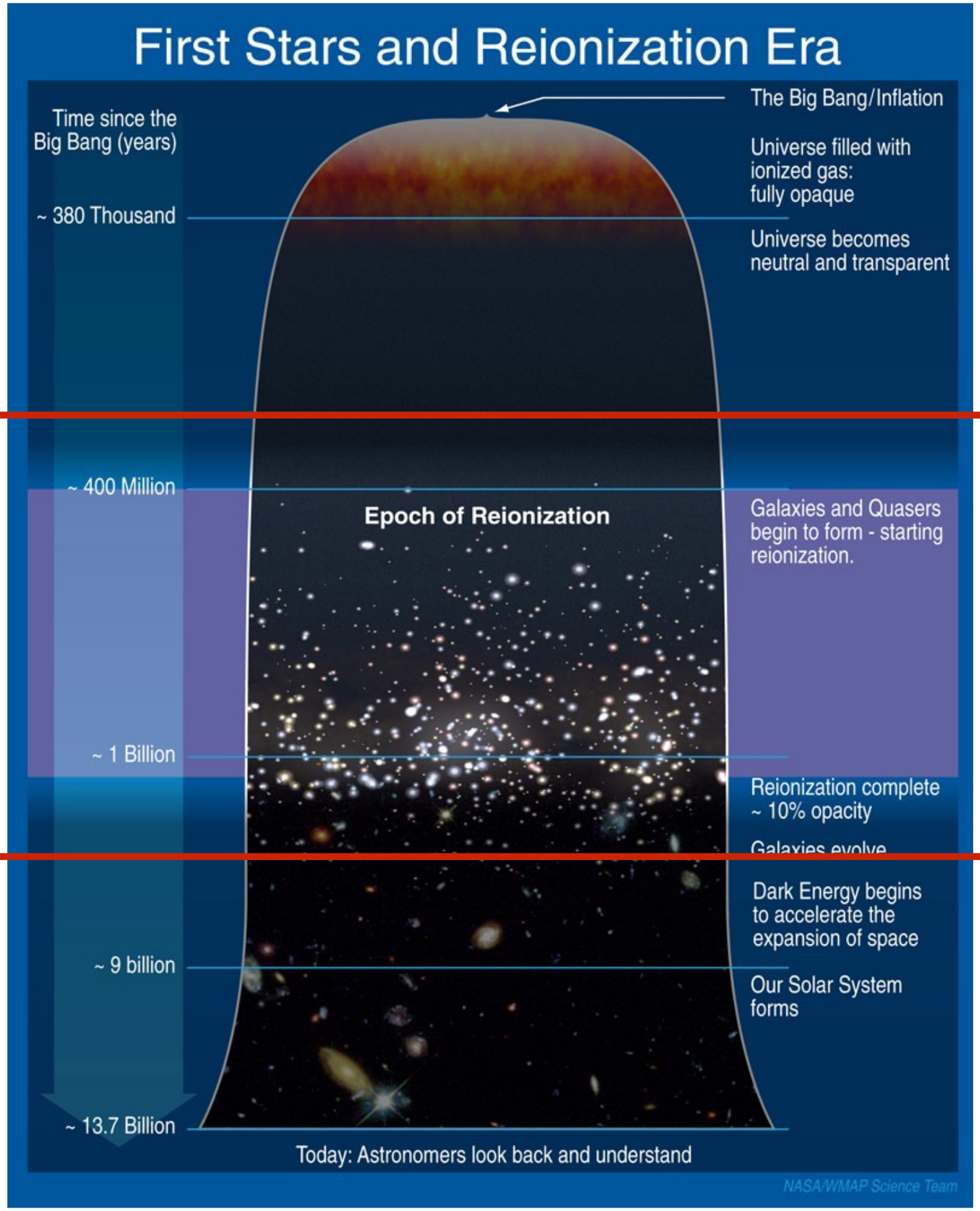
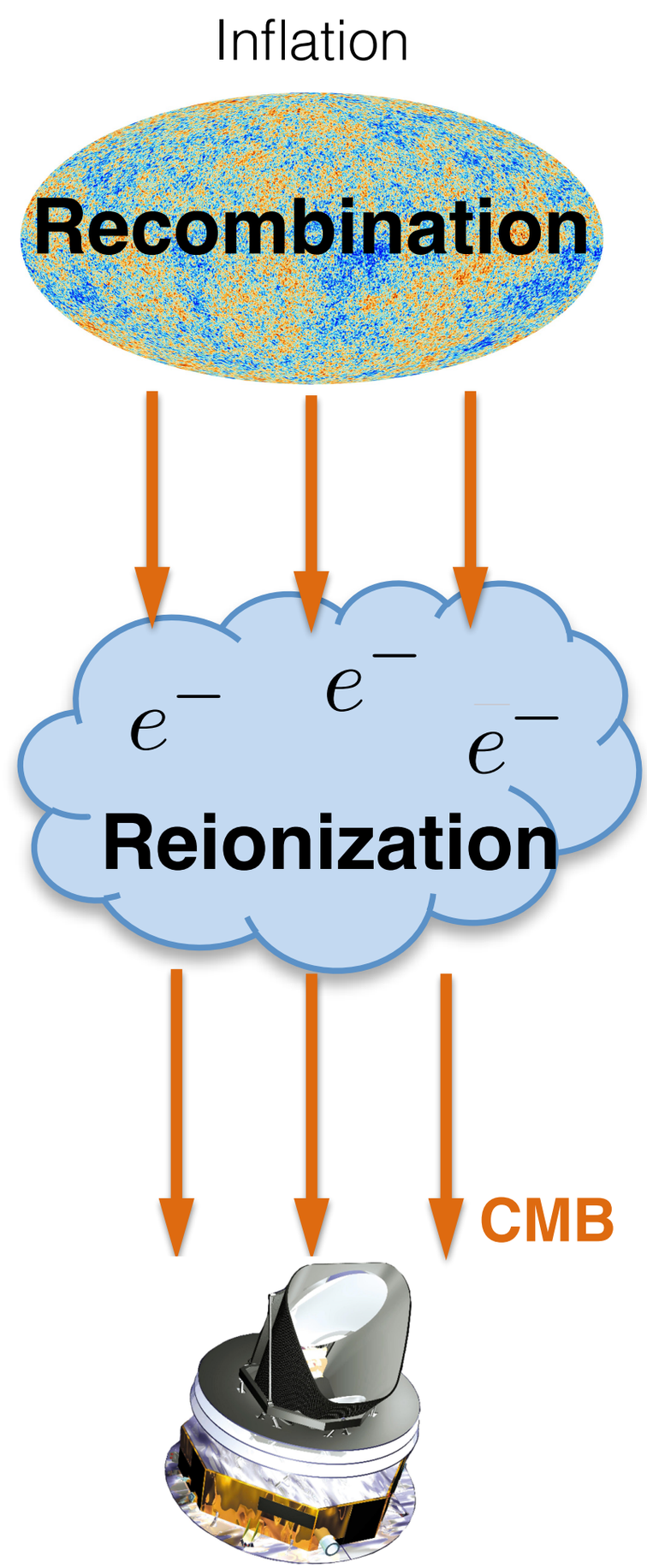
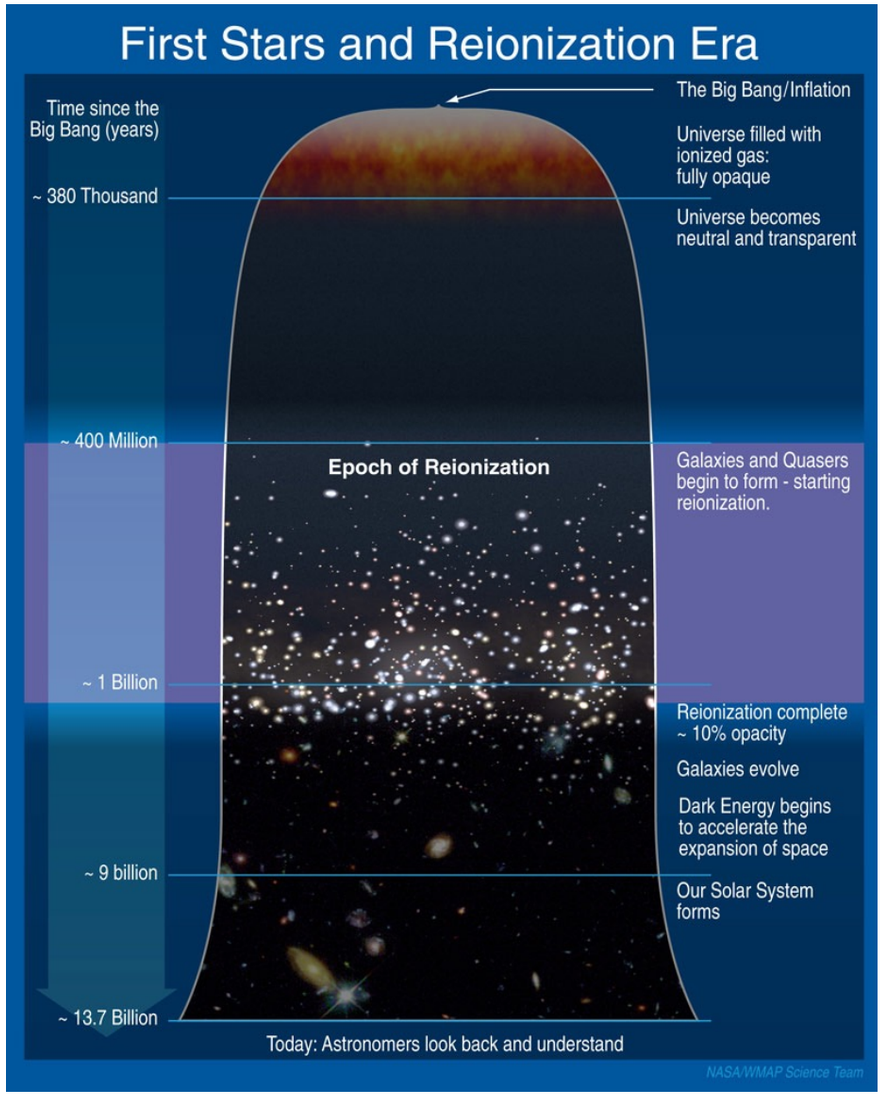


Image credit: https://en.wikipedia.org/wiki/Reionization



Reionization

- Astrophysical interest
- Cosmology: τ (optical depth) error propagates to other cosmological parameters
  - leading source of error for neutrino mass from gravitational lensing
  - growth of structure and cosmic acceleration [Hu & Jain 04]



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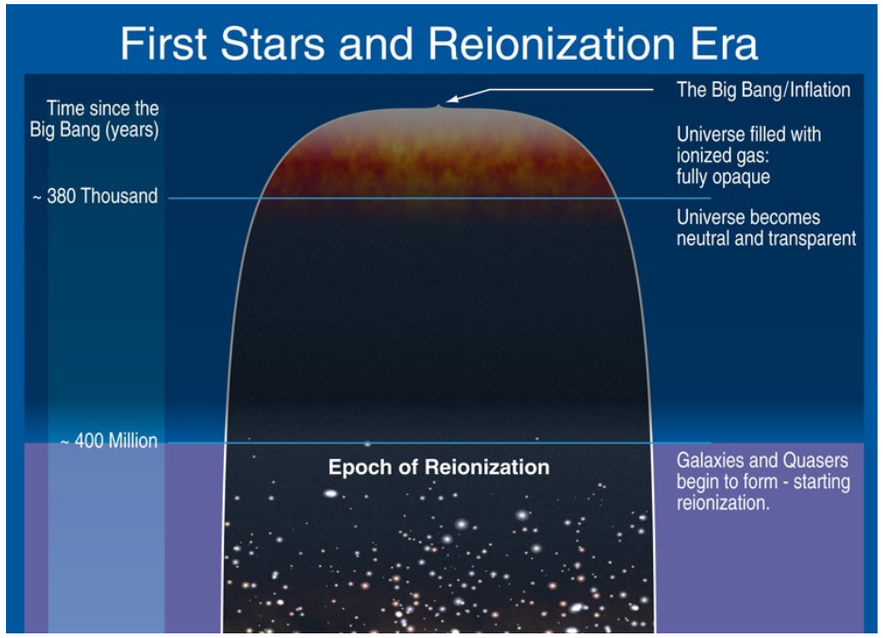


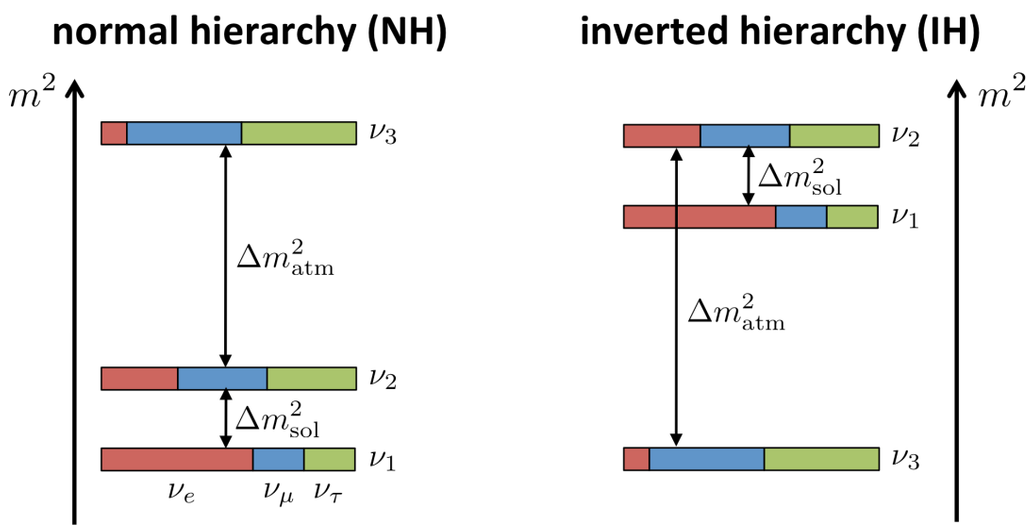


Image Credit: http://www.staff.uni-mainz.de/wurmm/wurm-home/mass-hierarchy.png

Probes of reionization

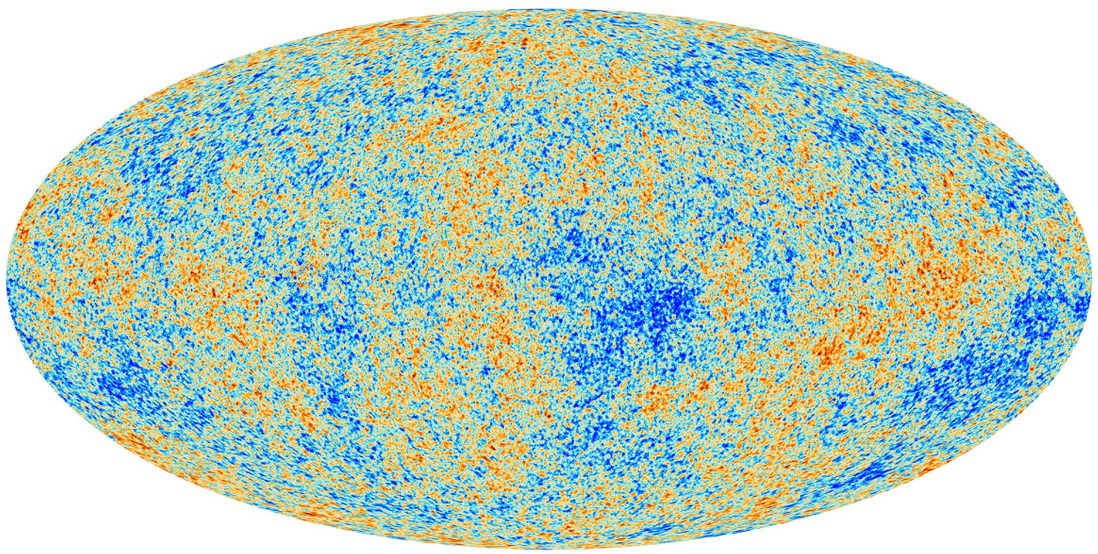
- **Gunn-Peterson effect** (in quasar spectra): conclude that Universe is fully ionized by z=6.

- **CMB anisotropies**: signatures on the temperature and polarization power spectra.

- **Galaxy luminosity function**: well measured for $z < 8$, ~10s of galaxies at $z > 9$.

- **21cm experiments** (underway): map the distribution of neutral hydrogen with redshift. (PAPER, LOFAR, MWA, MITEoR, HERA, SKA …)

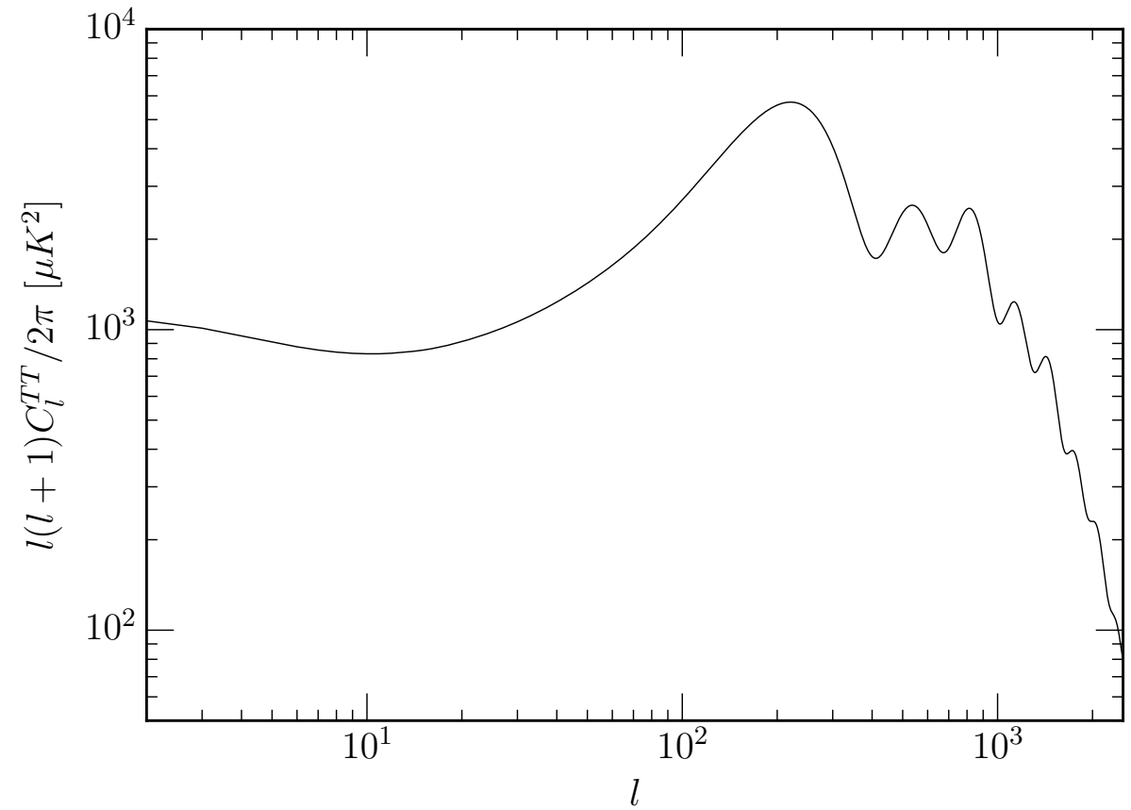
Cosmic microwave background (CMB)



temperature anisotropies

(mean = 2.7K)

Temperature power spectrum



angular wavenumber

Fourier Transform

Image Credit: http://www.esa.int/spaceinimages/Images/2013/03/Planck_CMB

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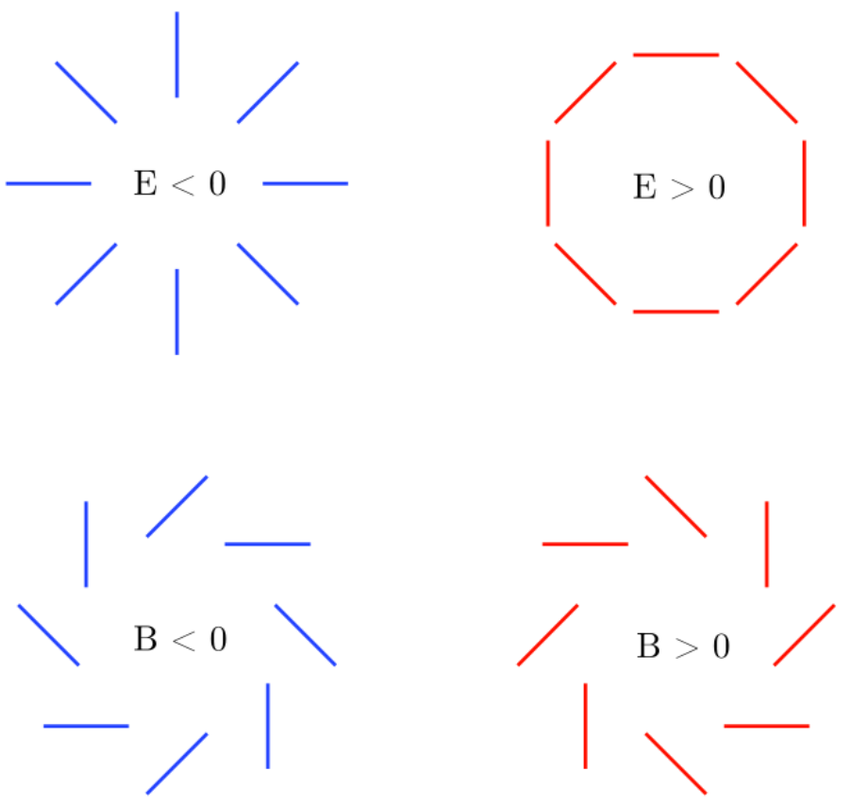
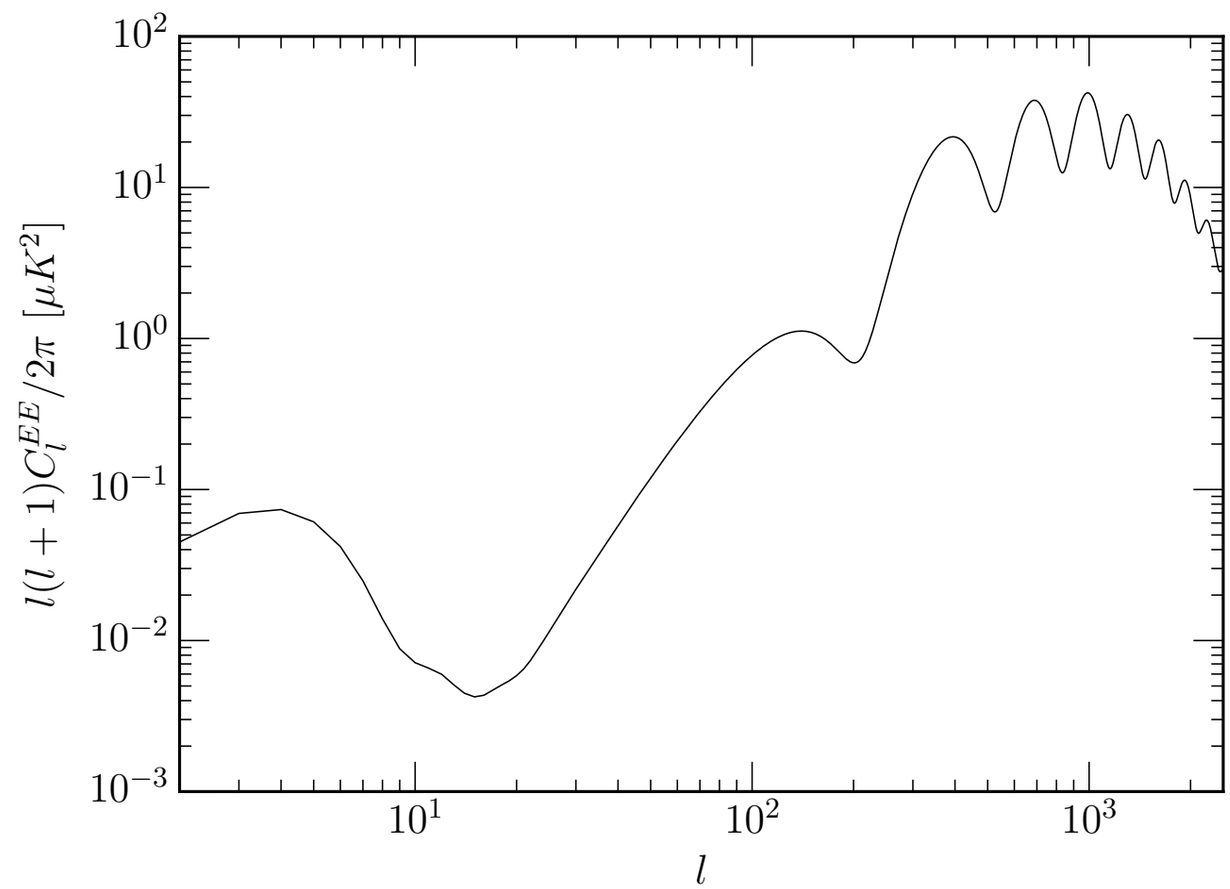


E-mode polarization

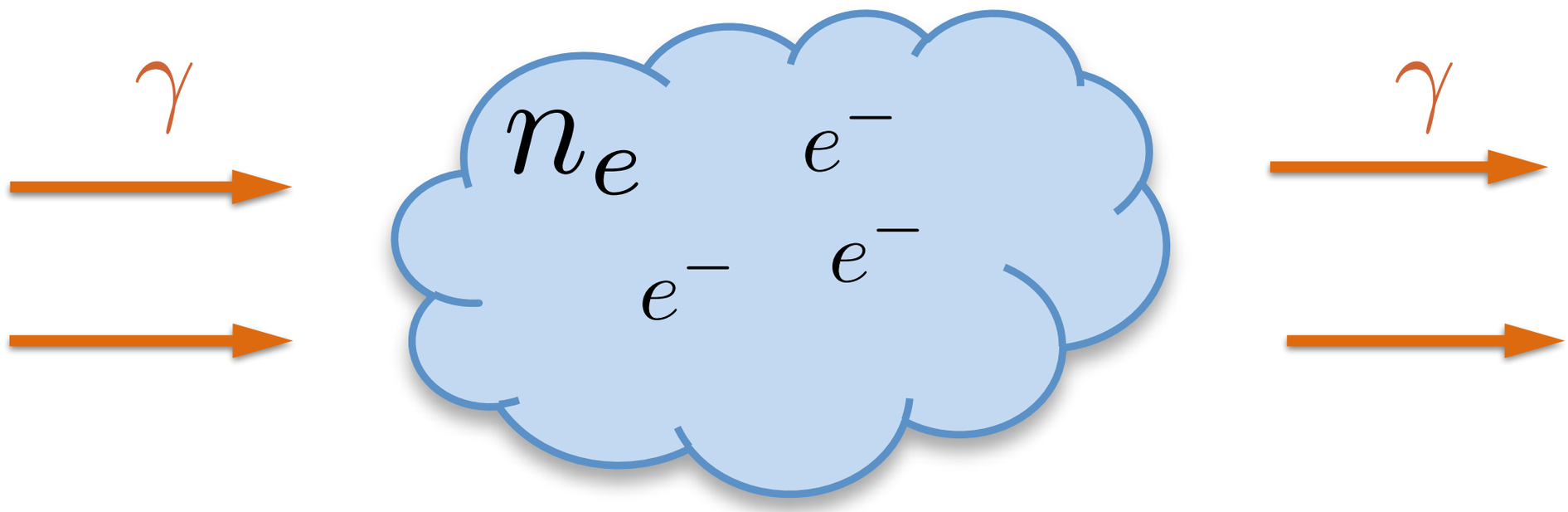
power spectrum



angular wavenumber

Image Credit: http://www.esa.int/spaceinimages/Images/2013/03/Planck_CMB

CMB photons Thomson scatter with free electrons



σ_T $\quad e^- + \gamma \to e^- + \gamma$

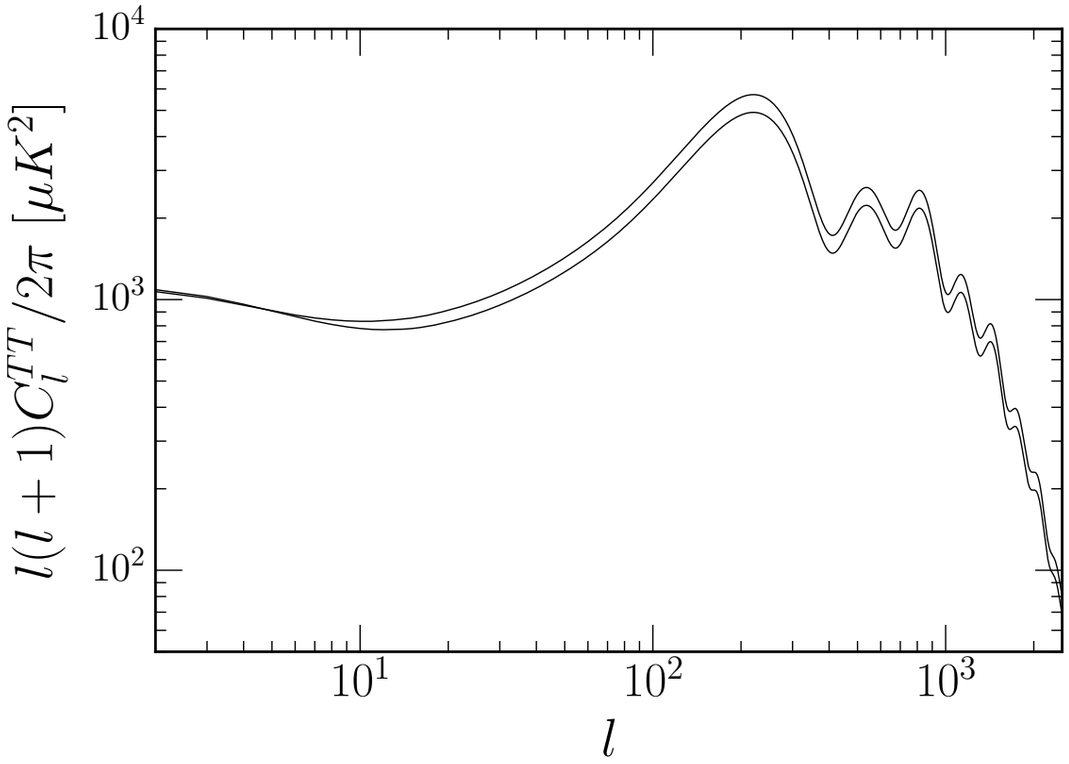
Optical depth: $\tau = \int_0^\eta d\eta' \sigma_T n_e a$

Effects of reionization on the CMB

1. **Suppress anisotropies** (both temp. and pol.)

Power spectrum suppressed as $e^{-2\tau}$, $\tau = \int_0^\eta d\eta' \sigma_T n_e a$

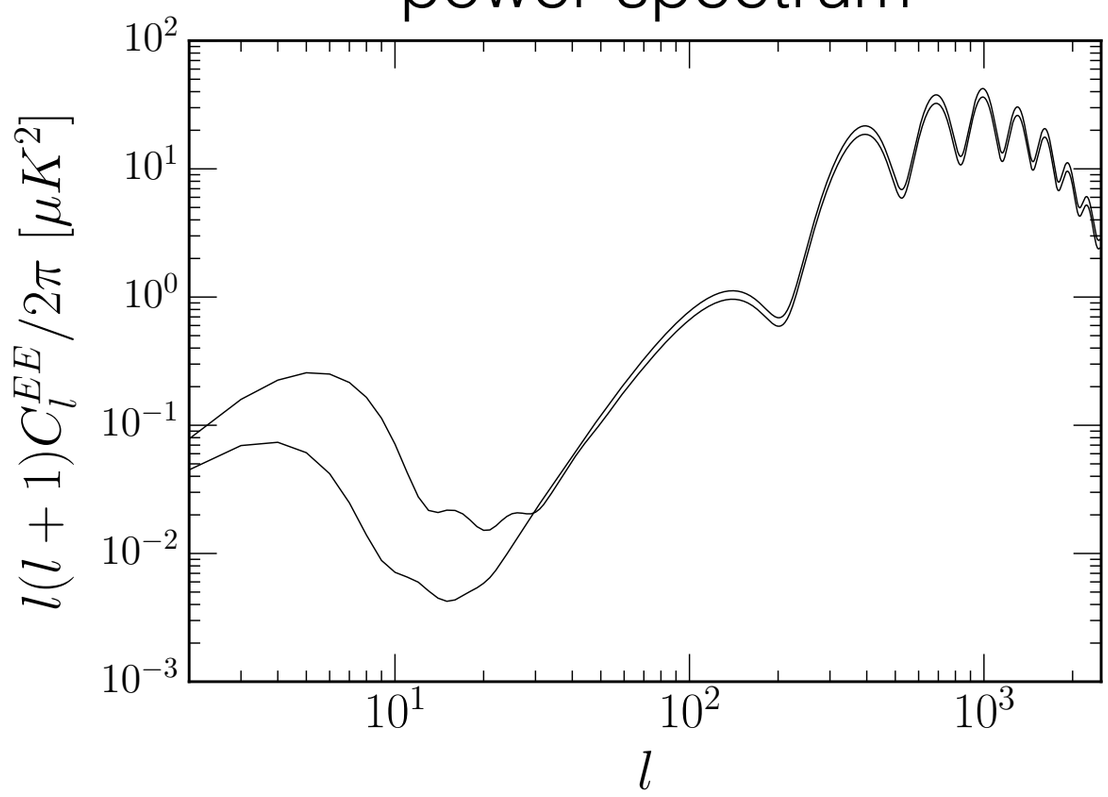
temperature power spectrum



angular wavenumber

τ

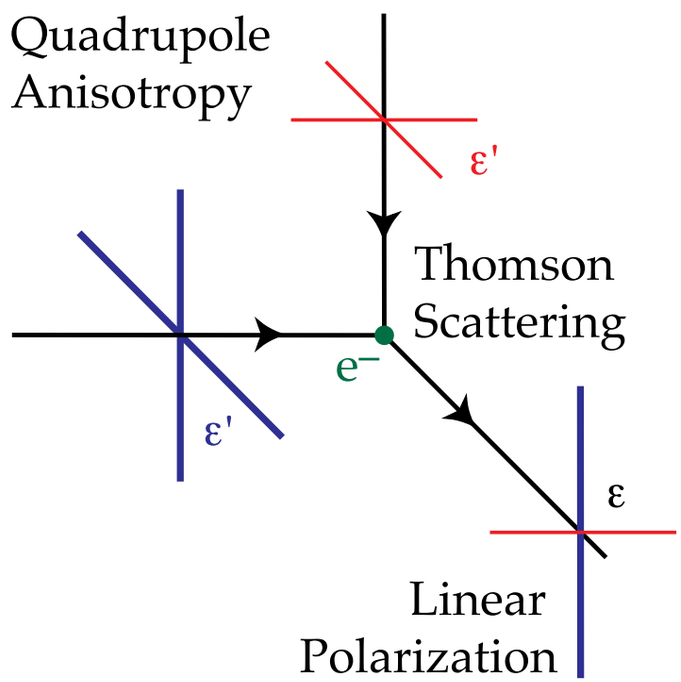
E-mode polarization power spectrum



angular wavenumber

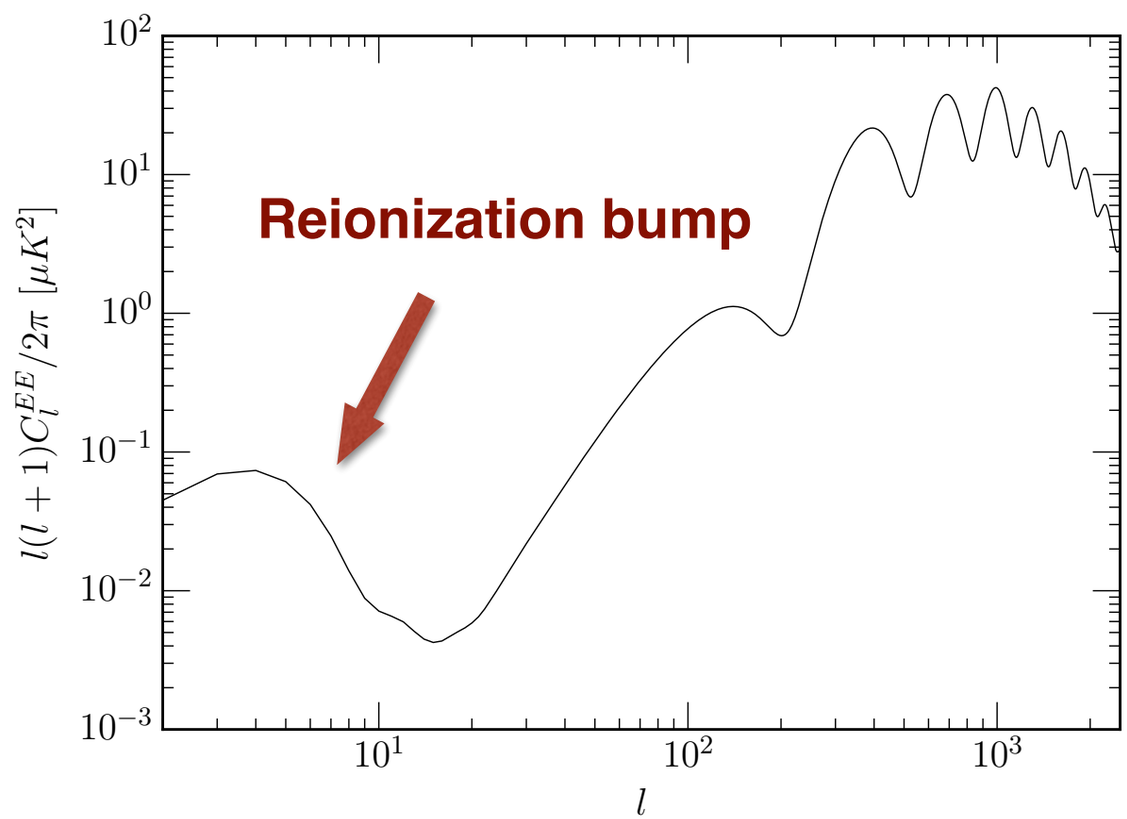
Effects of reionization on the CMB

2. **Create polarization anisotropies** on large scales



Temperature quadrupole
—> polarization

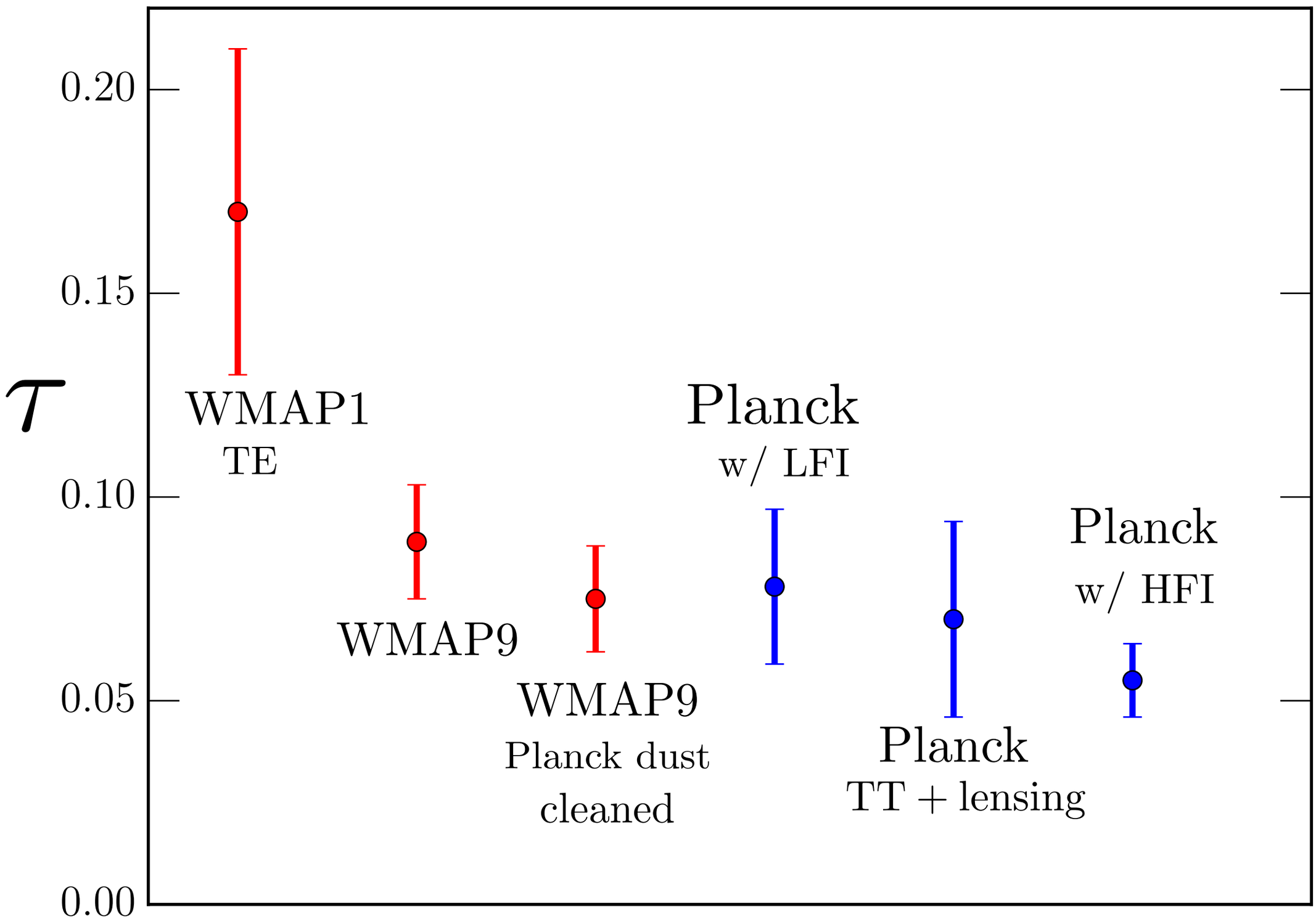
E-mode polarization
power spectrum



angular wavenumber

Image Credit: Wayne Hu's Tutorials

CMB measurements of τ



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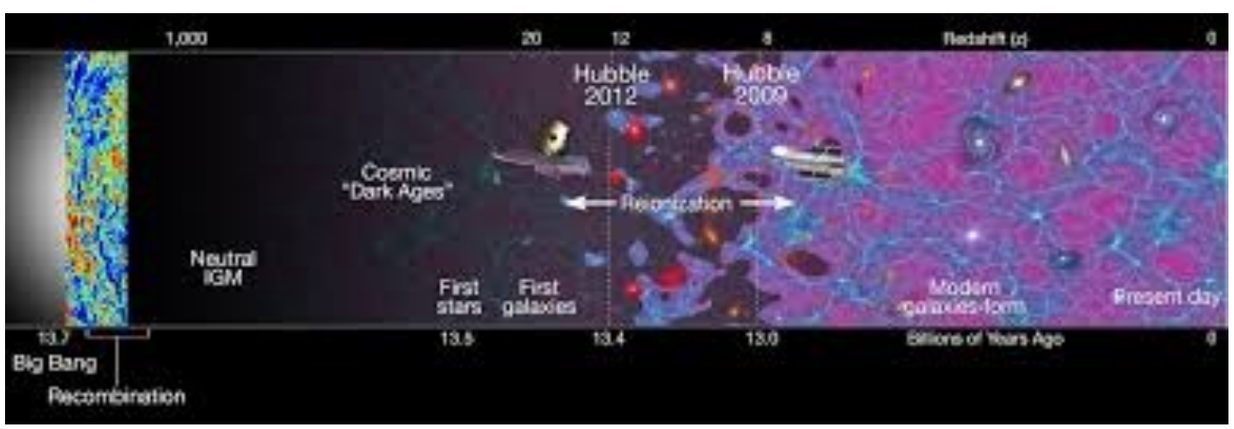
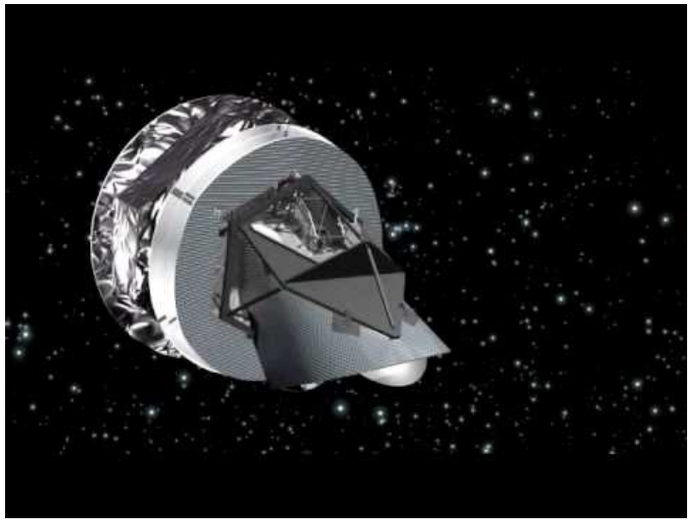


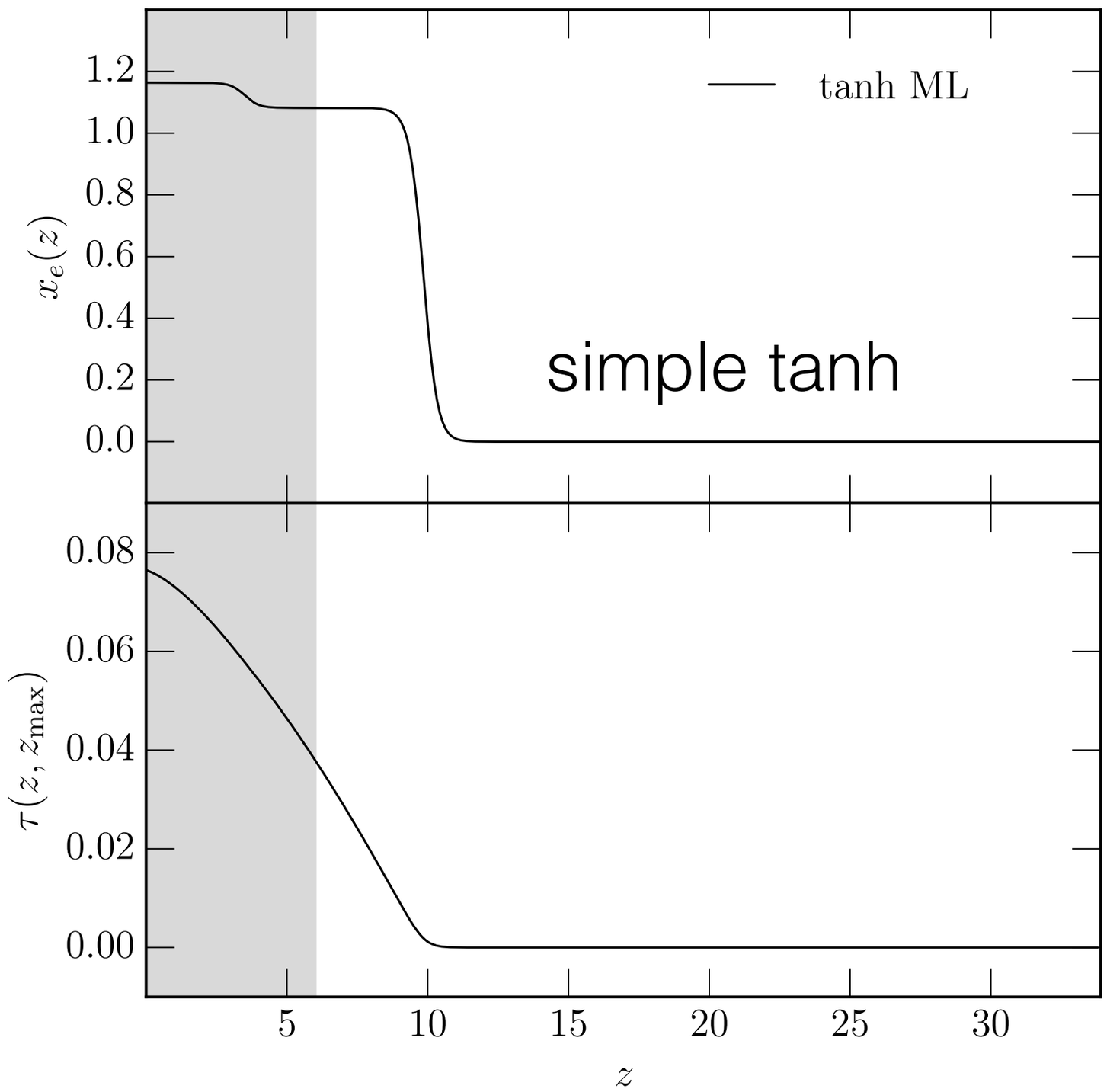


Standard approach: tanh

ionization fraction

$$x_e(z) = \frac{n_e}{n_H}$$

optical depth



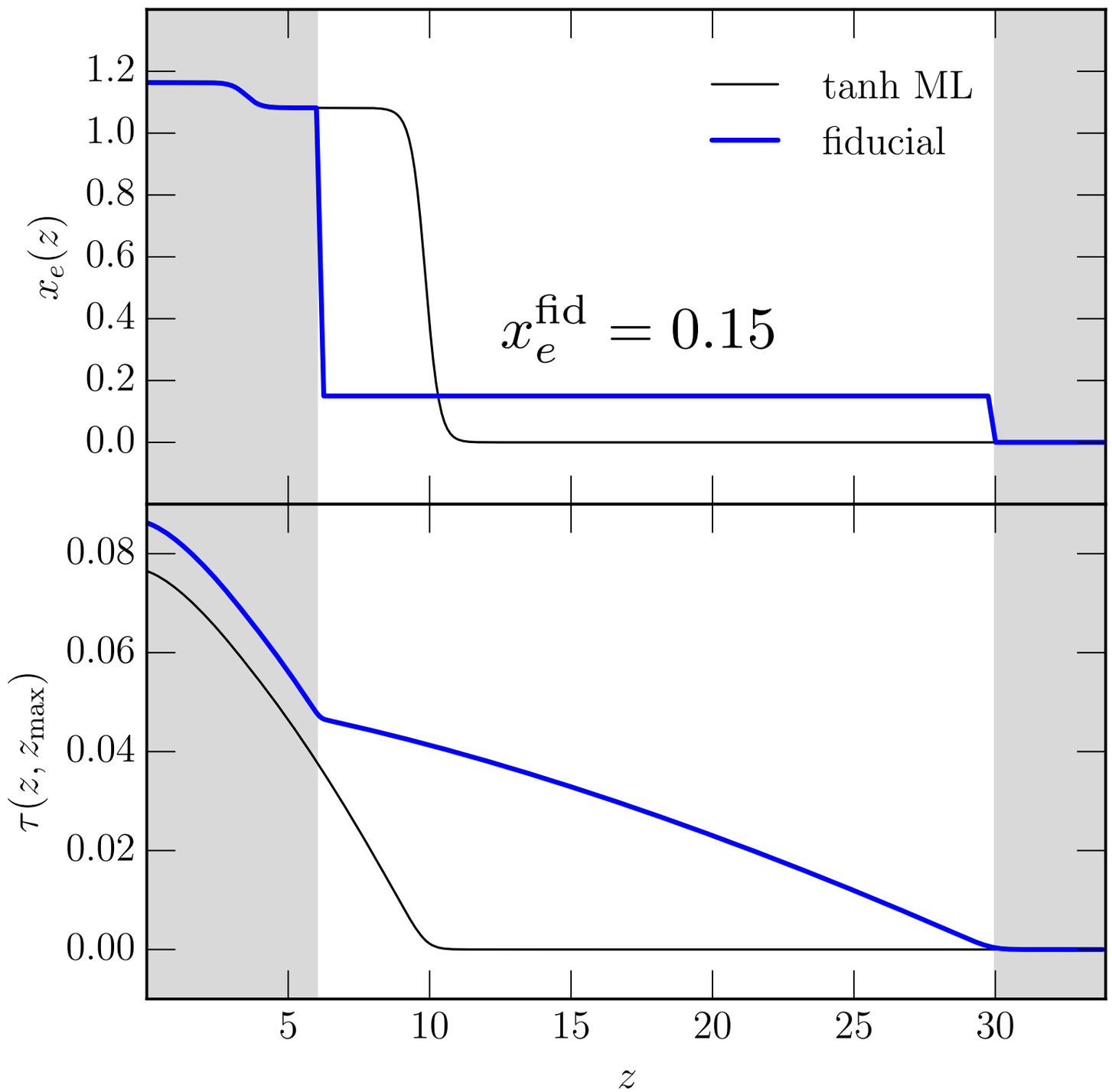
Our model independent approach:

$$x_e(z) = x_e^{\rm fid} + \sum_a m_a S_a(z)$$

(Hu & Holder 03)

ionization fraction

optical depth

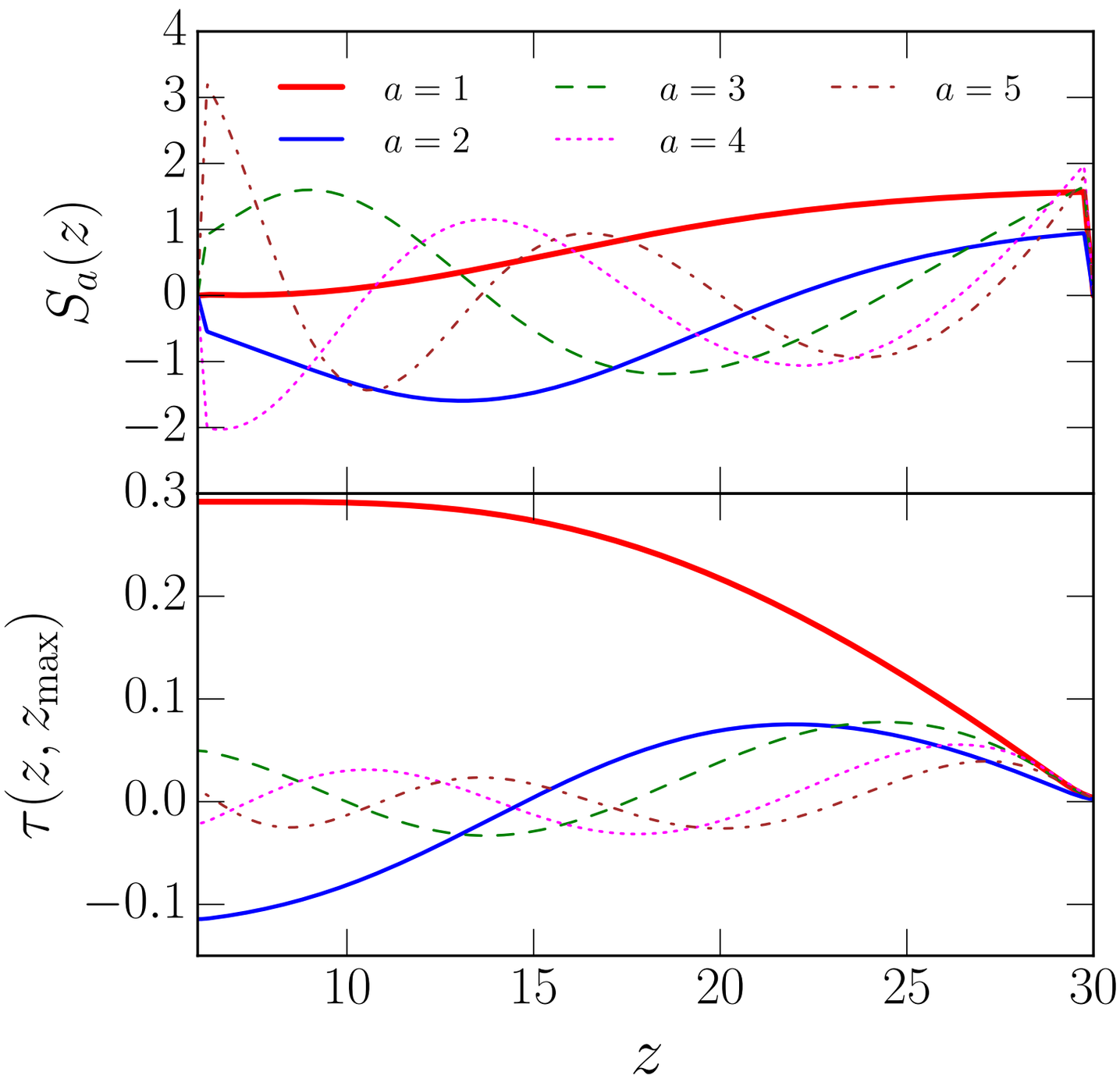


Eigenfunctions ranked by contribution to observables

ionization fraction

optical depth

Contribution to τ from each eigenfunction



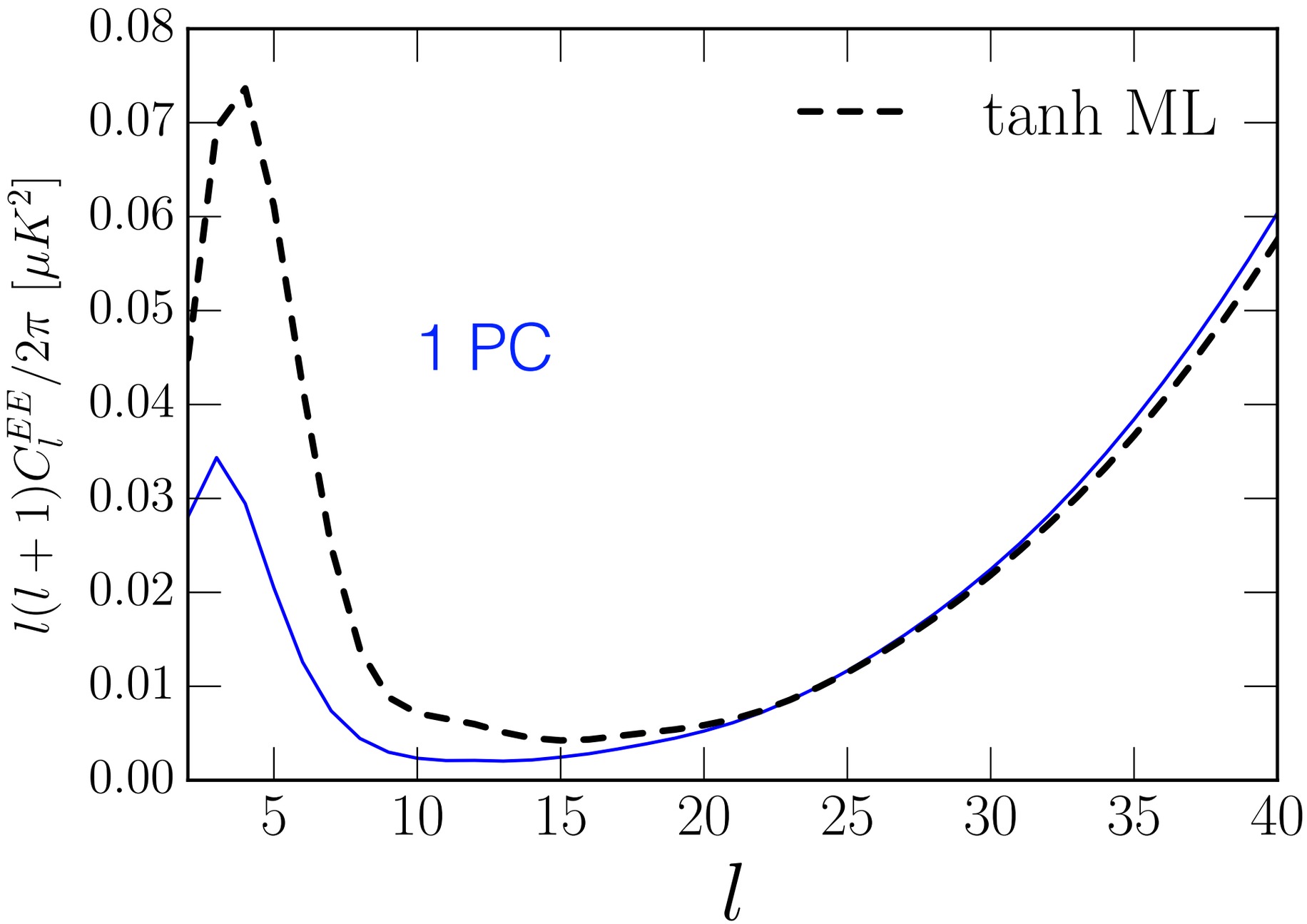
a = 1

~ weighted τ

a = 2

~ high vs low z

5 PCs completely describe E-mode power spectrum



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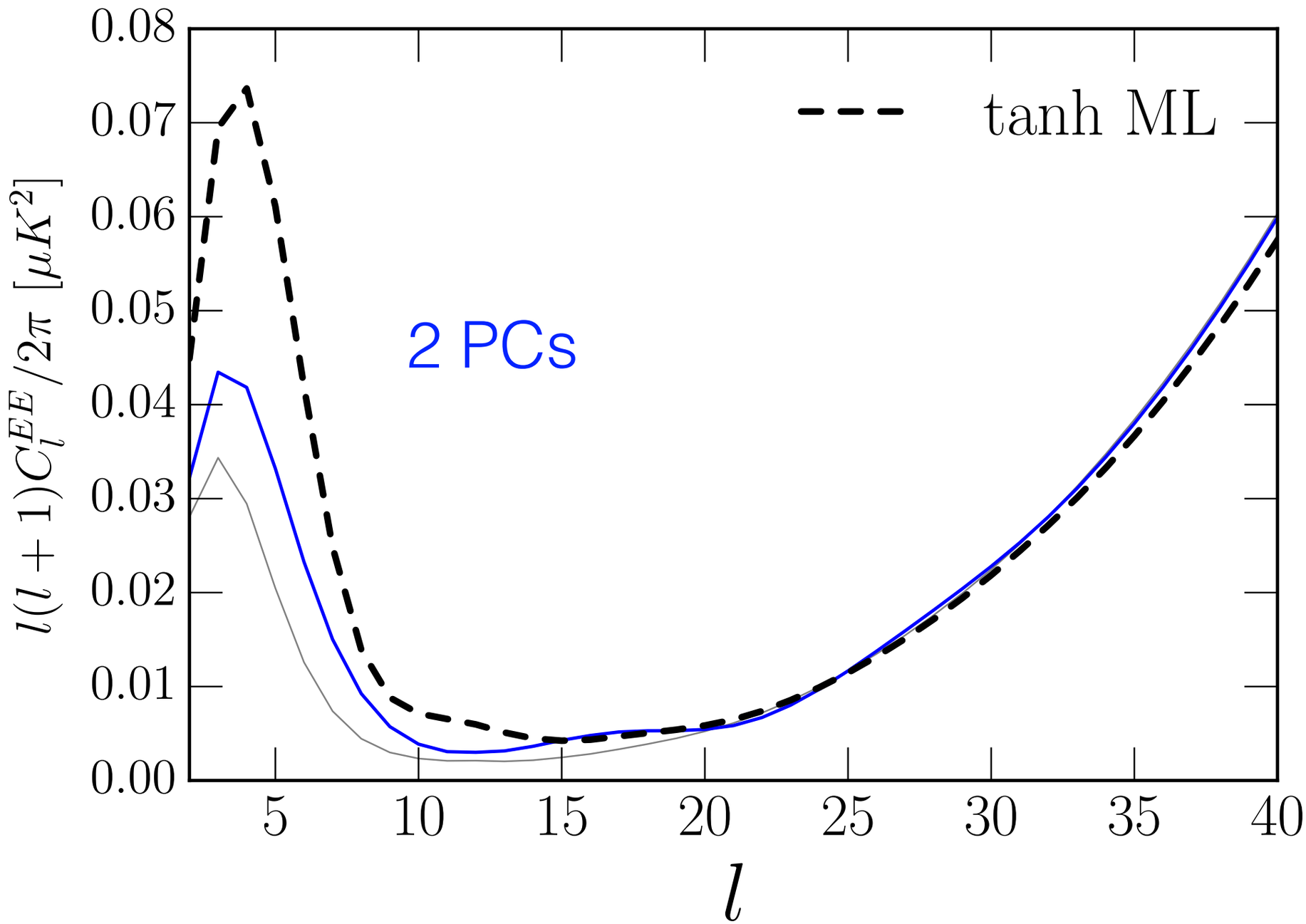

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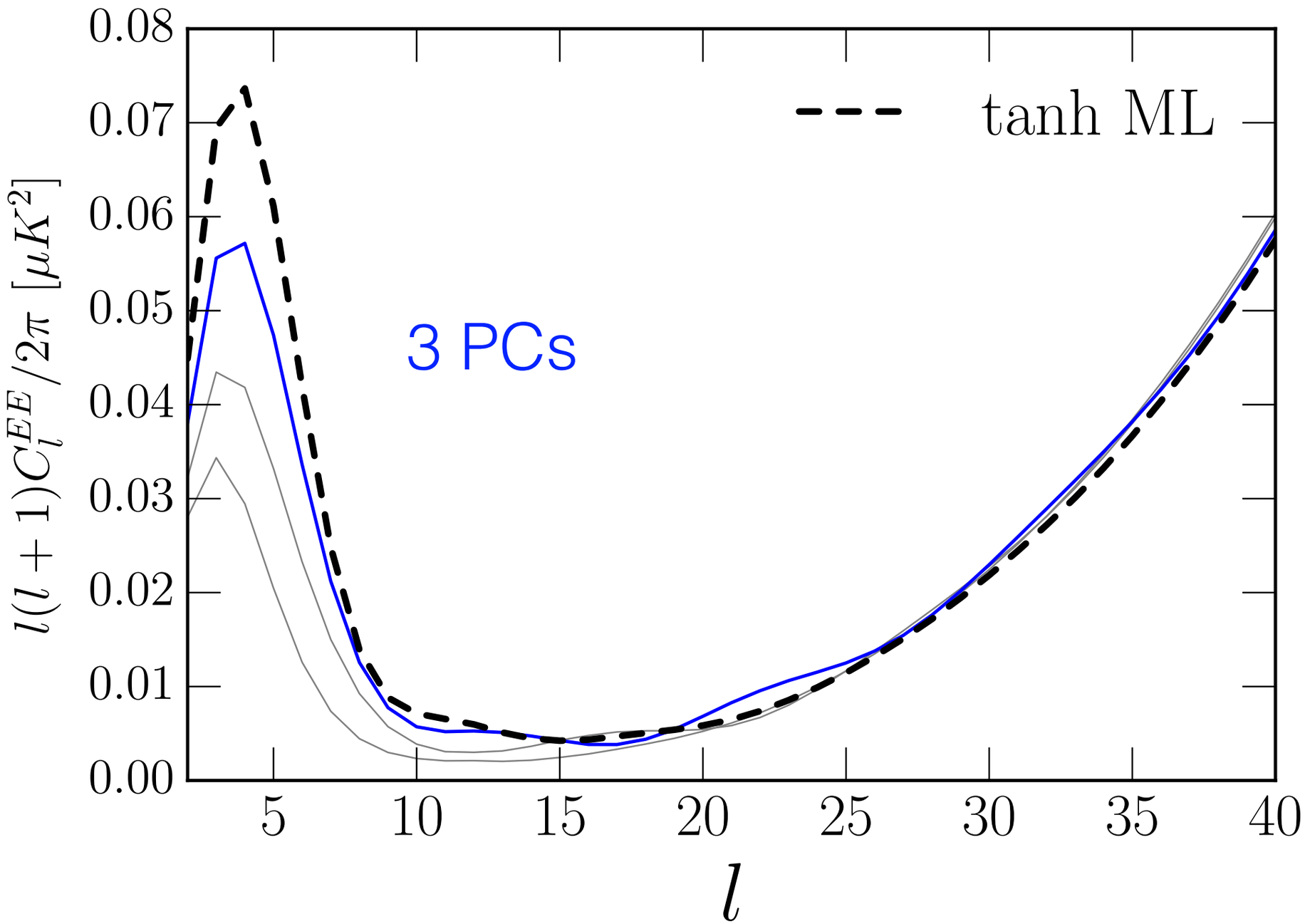

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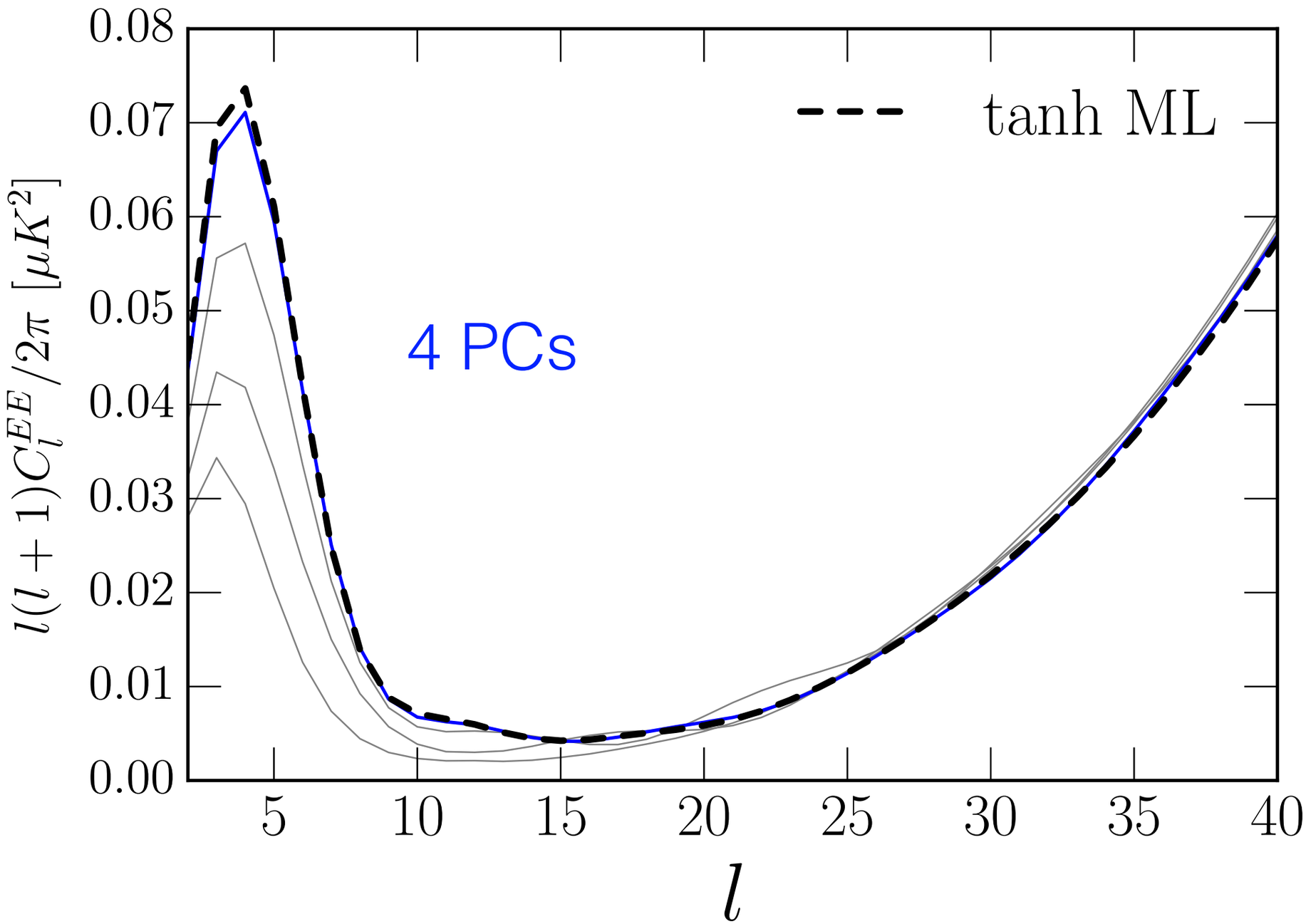

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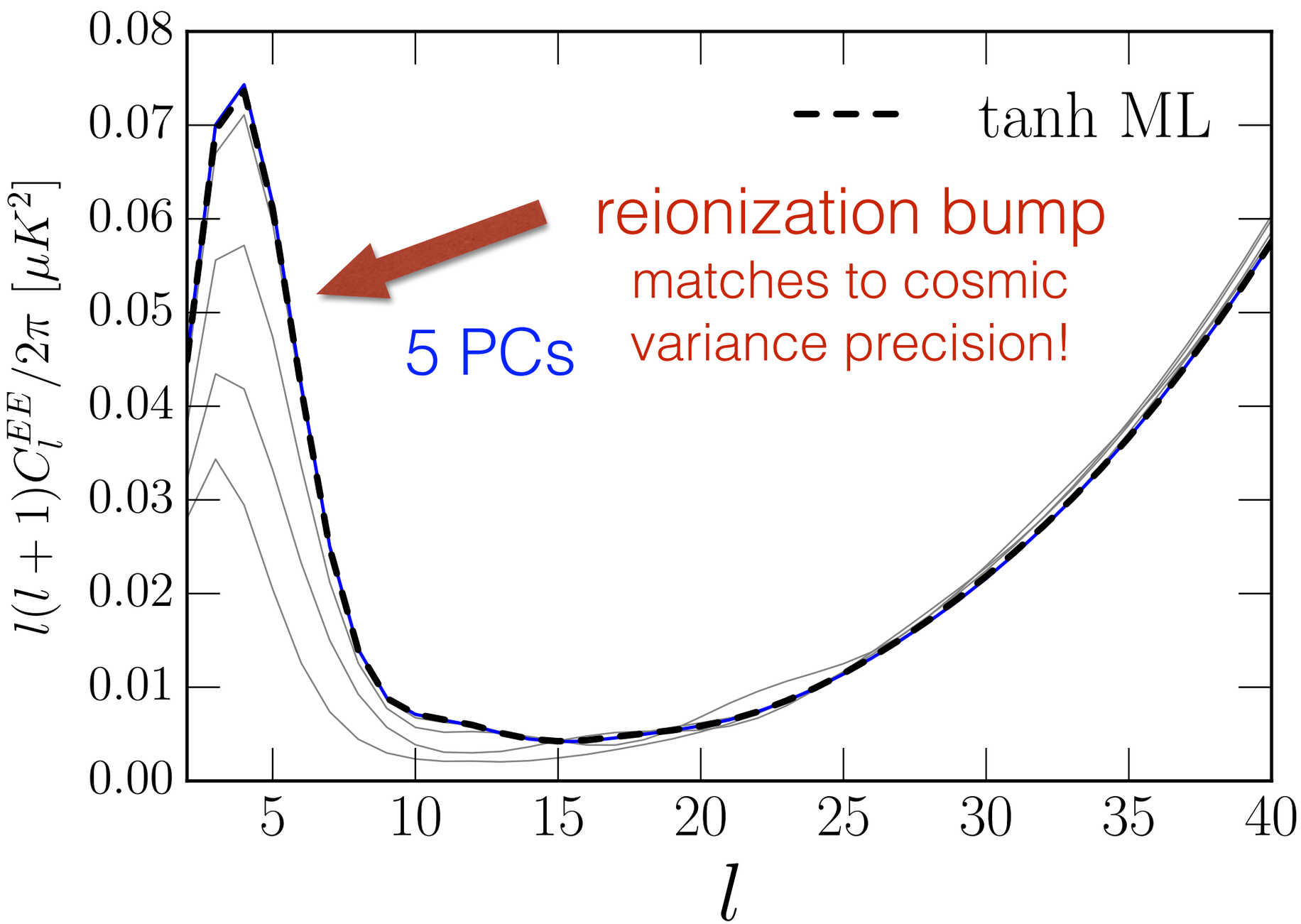


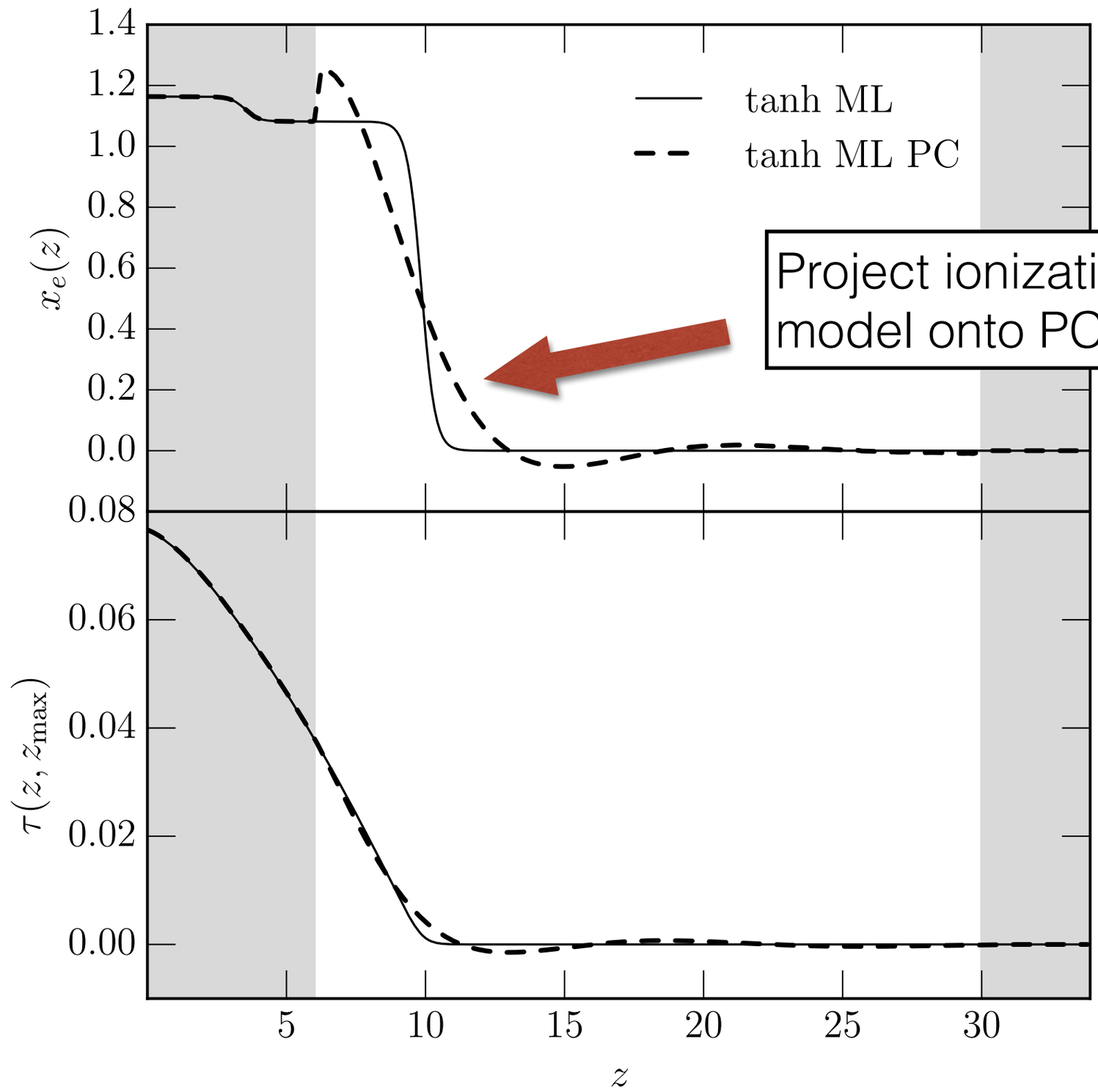
5PCs designed for observables, not model reconstruction (remove fiducial)

ionization fraction

not well constrained by data

optical depth

data reflects better this integrated quantity



Project ionization fraction model onto PCs

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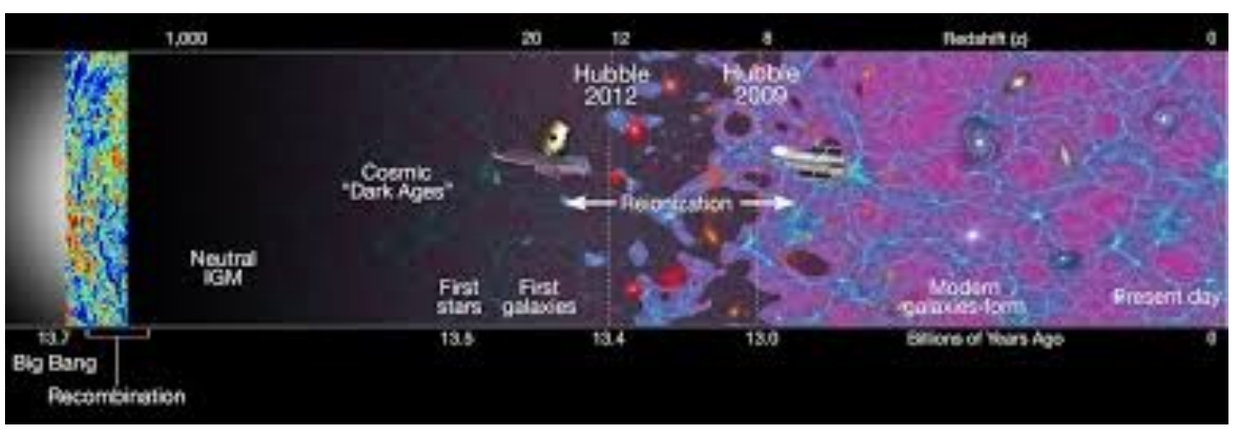
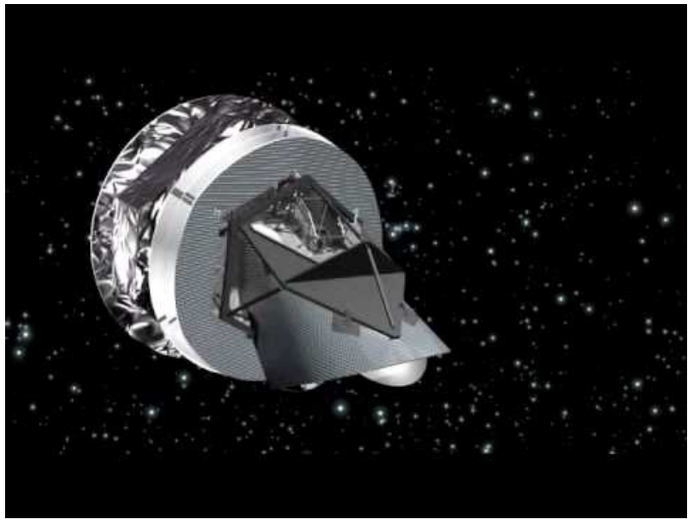
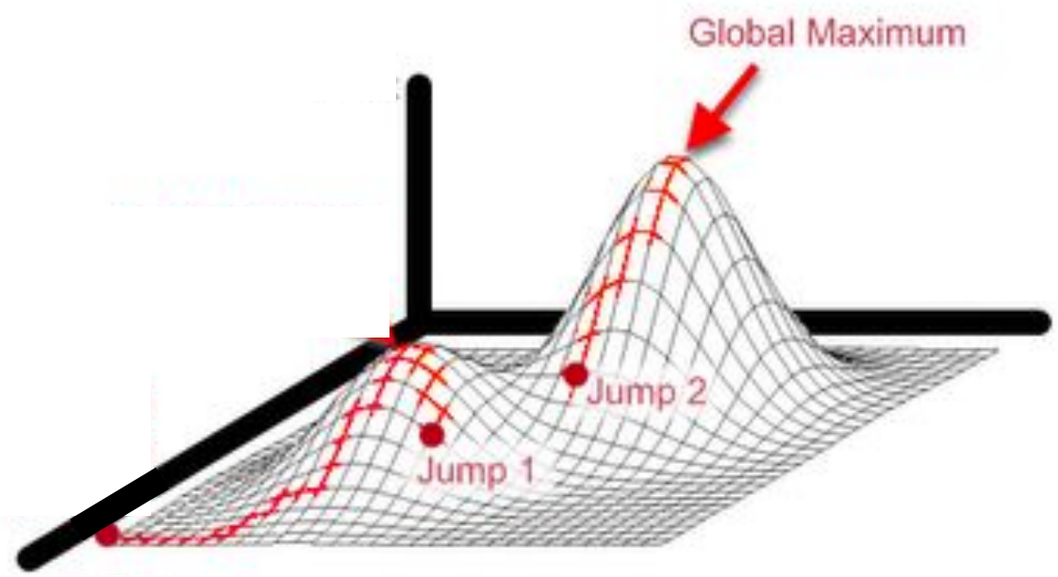




Method: Apply MCMC to Planck 2015

10 parameters



sampled with COSMOMC

LCDM

$$\Omega_b h^2, \Omega_c h^2, \theta_{\mathrm{MCMC}}, A_s, n_s \; +$$

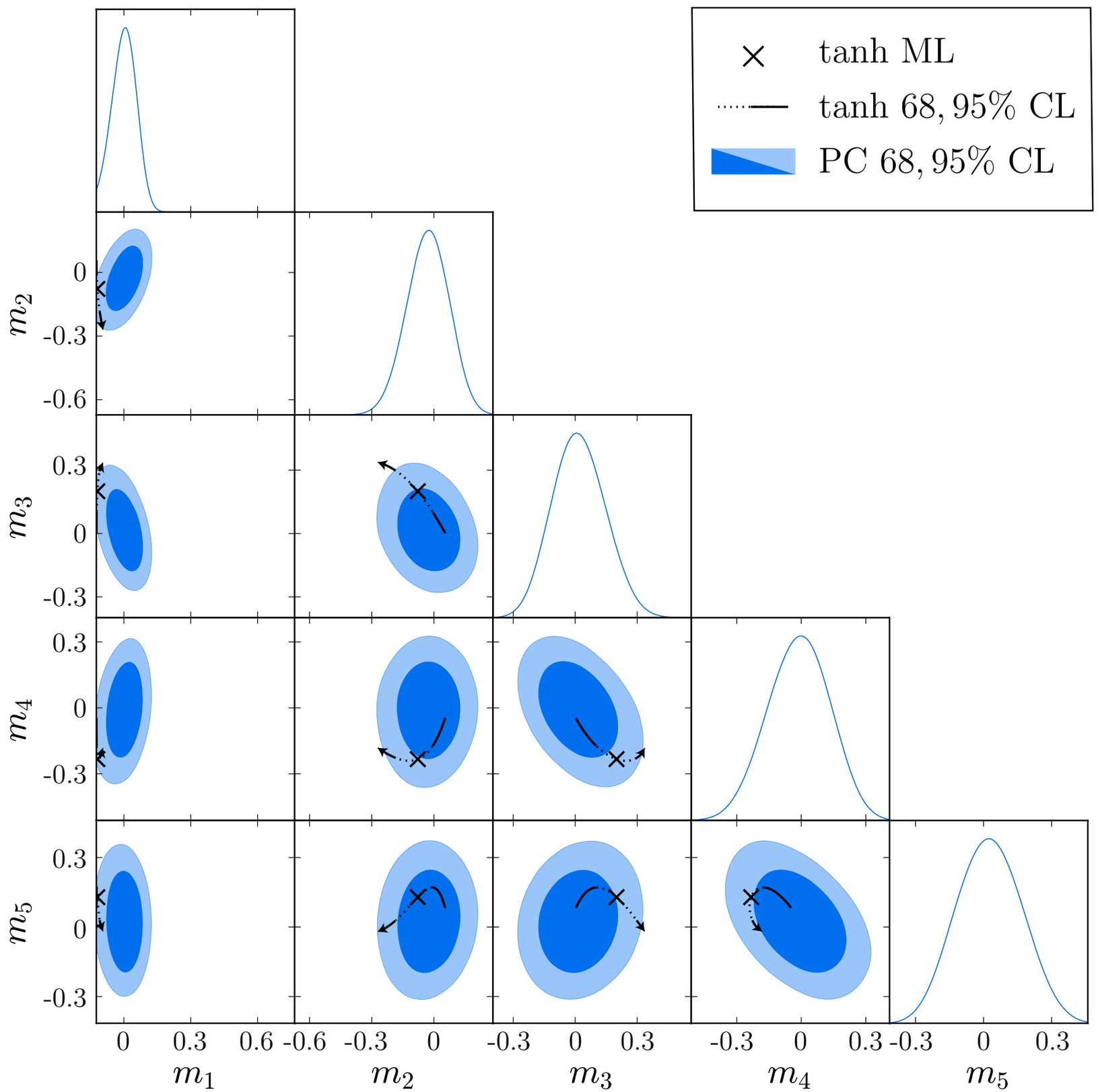
PCs

$m_1, \ldots, m_5$ (modify CAMB)

τ (corresponds to step time)

tanh

$$x_e(z) = x_e^{\rm fid} + \sum_a m_a S_a(z)$$



Constraints on 5PC parameters

- Constraints on the PC amplitude in the space of physical models (edge of box)

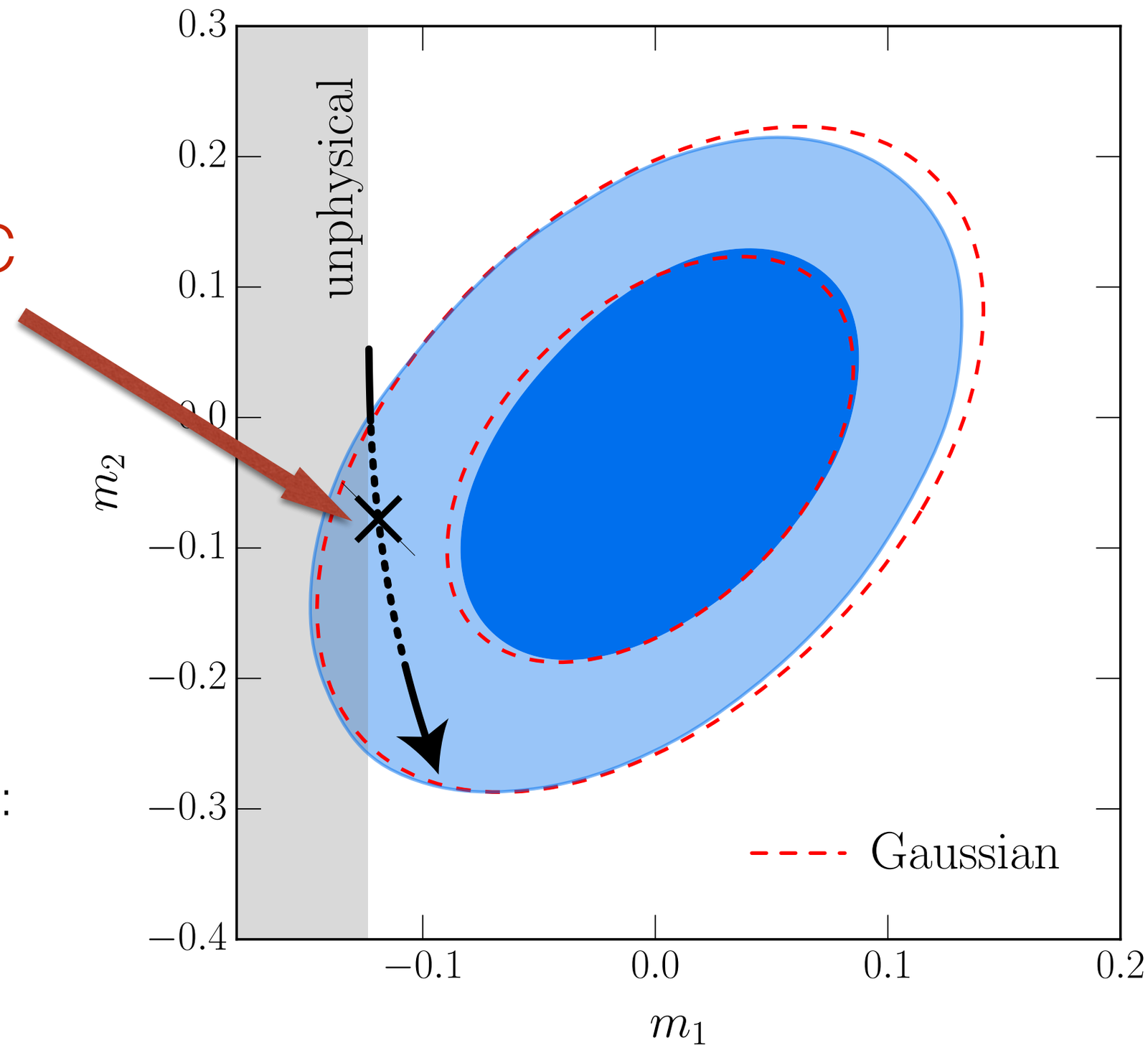
$$0 < x_e < 1 + f_{\rm He}$$

- First two PCs best constrained, third to fifth still constrained!
- tanh trajectory not favored by data

CH, Miranda, Hu 2016

Tanh less favoured in PC space

- tanh ML ~2σ away from PC mean



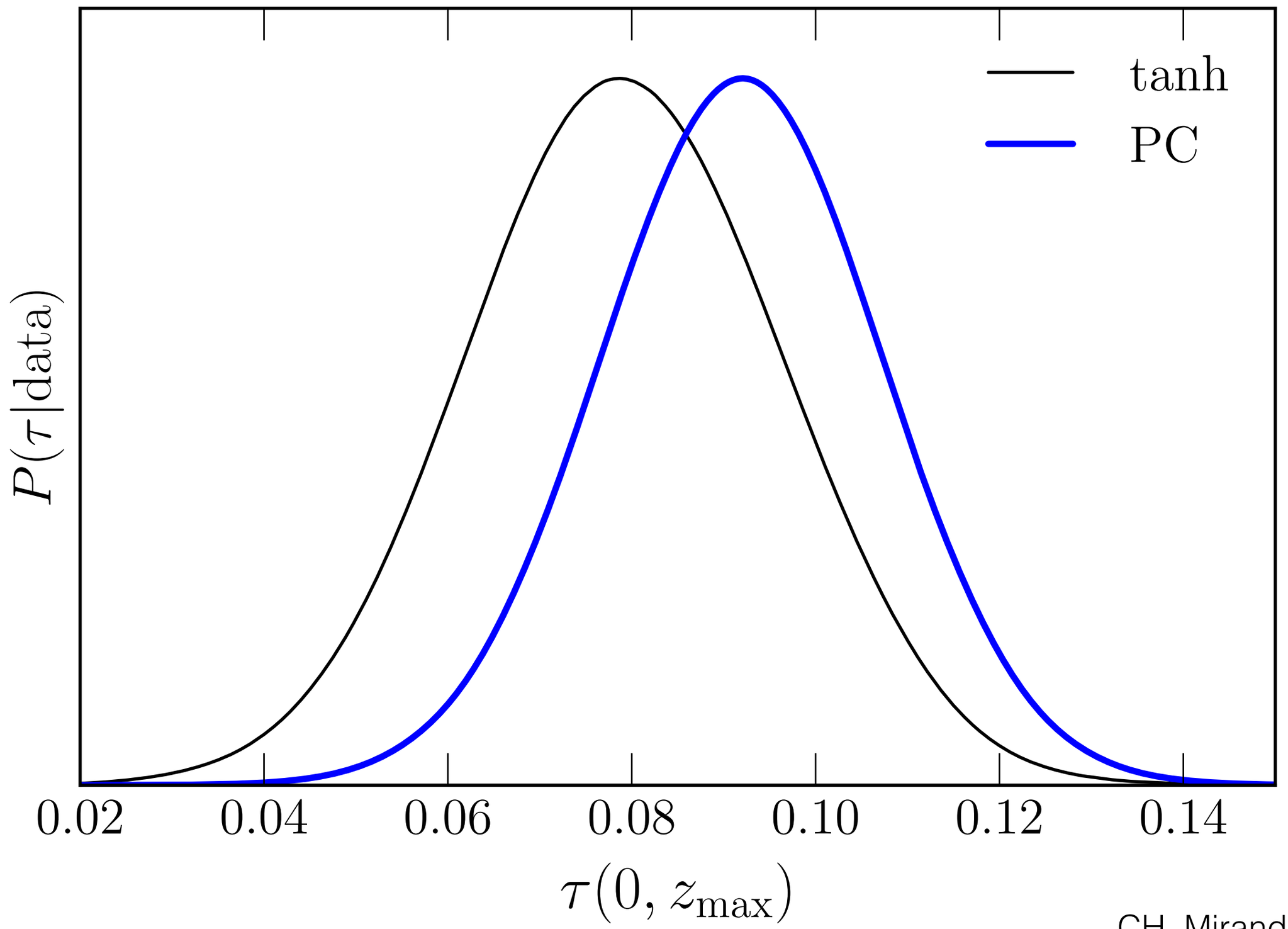
* PC ML vs tanh ML:

$$2\Delta\log\ \mathrm{Like} = 5.3$$

CH, Miranda, Hu 2016

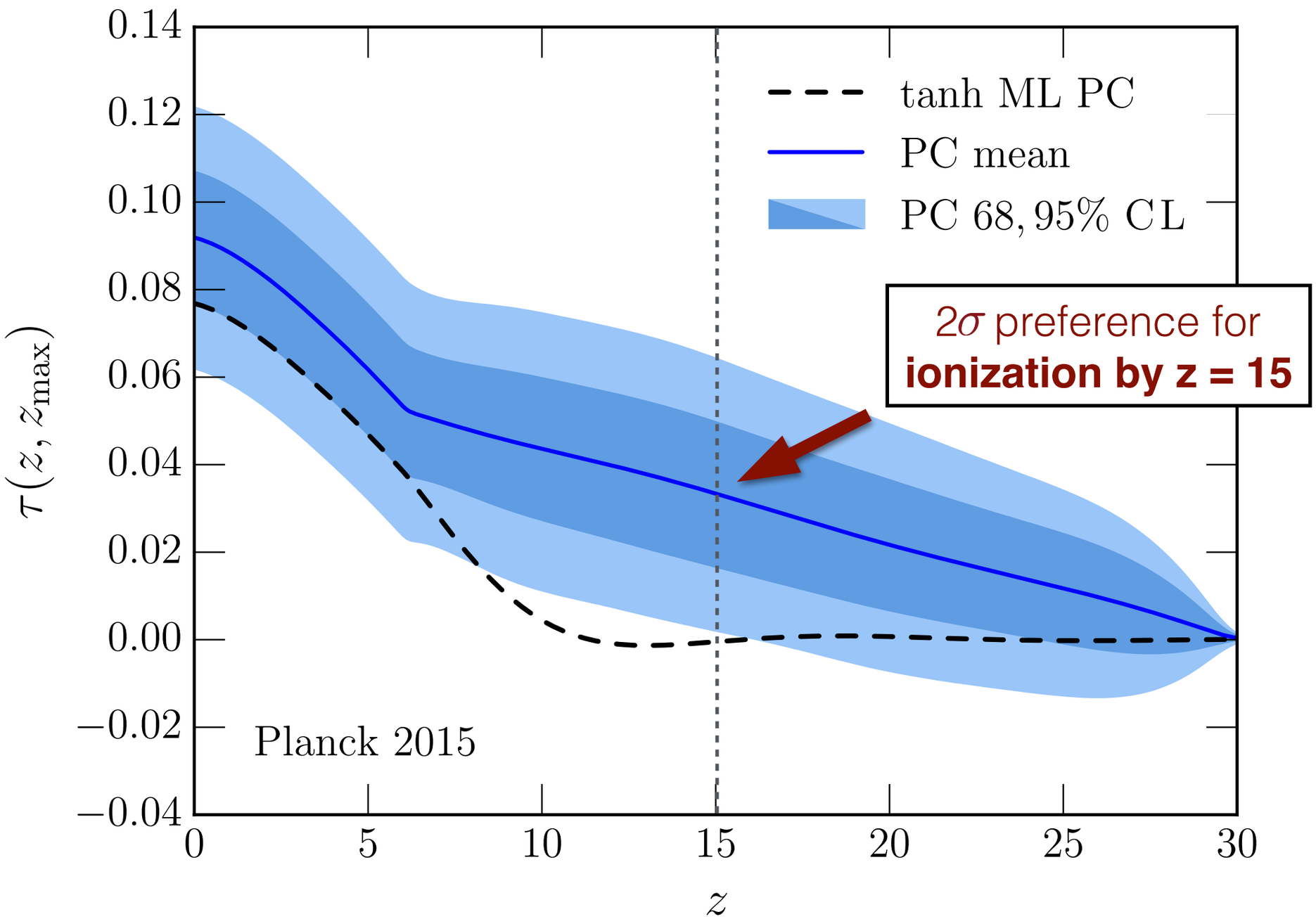
τ shifts by 1 σ

Model	$\tau(0, z_{\max})$
PC	0.092 ± 0.015
tanh	0.079 ± 0.017



CH, Miranda, Hu 2016

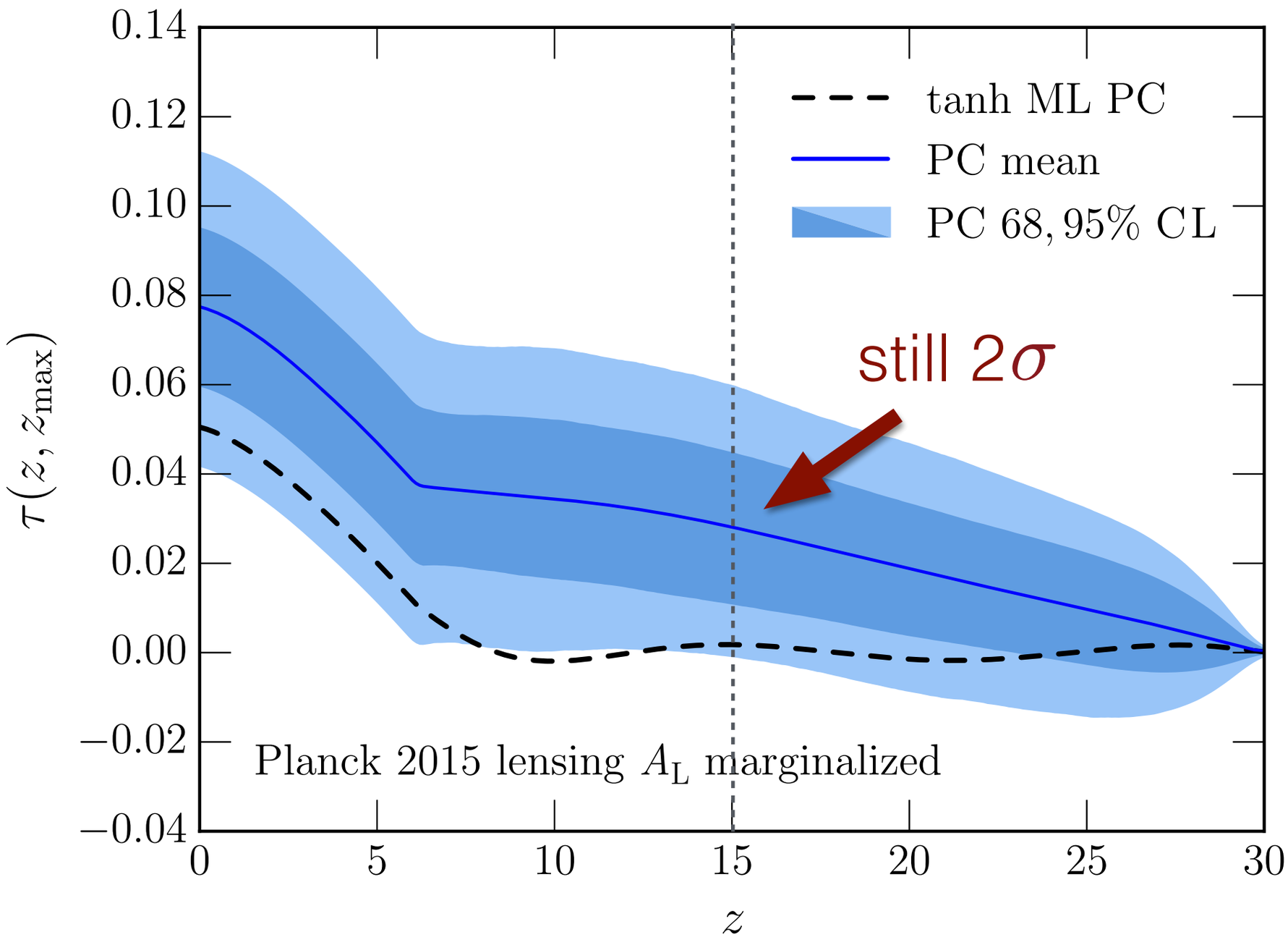
High redshift ionization shifts tau



- **Standard tanh misses** this by assumption of form

CH, Miranda, Hu 2016

Removing effects of lensing



Marginalize over A_L

A_L ↑

More smoothing

A_s ↓

Less initial power

$A_s e^{-2\tau}$

Fixed

τ ↓

goes down

High redshift ionization is **not due to lensing** effects

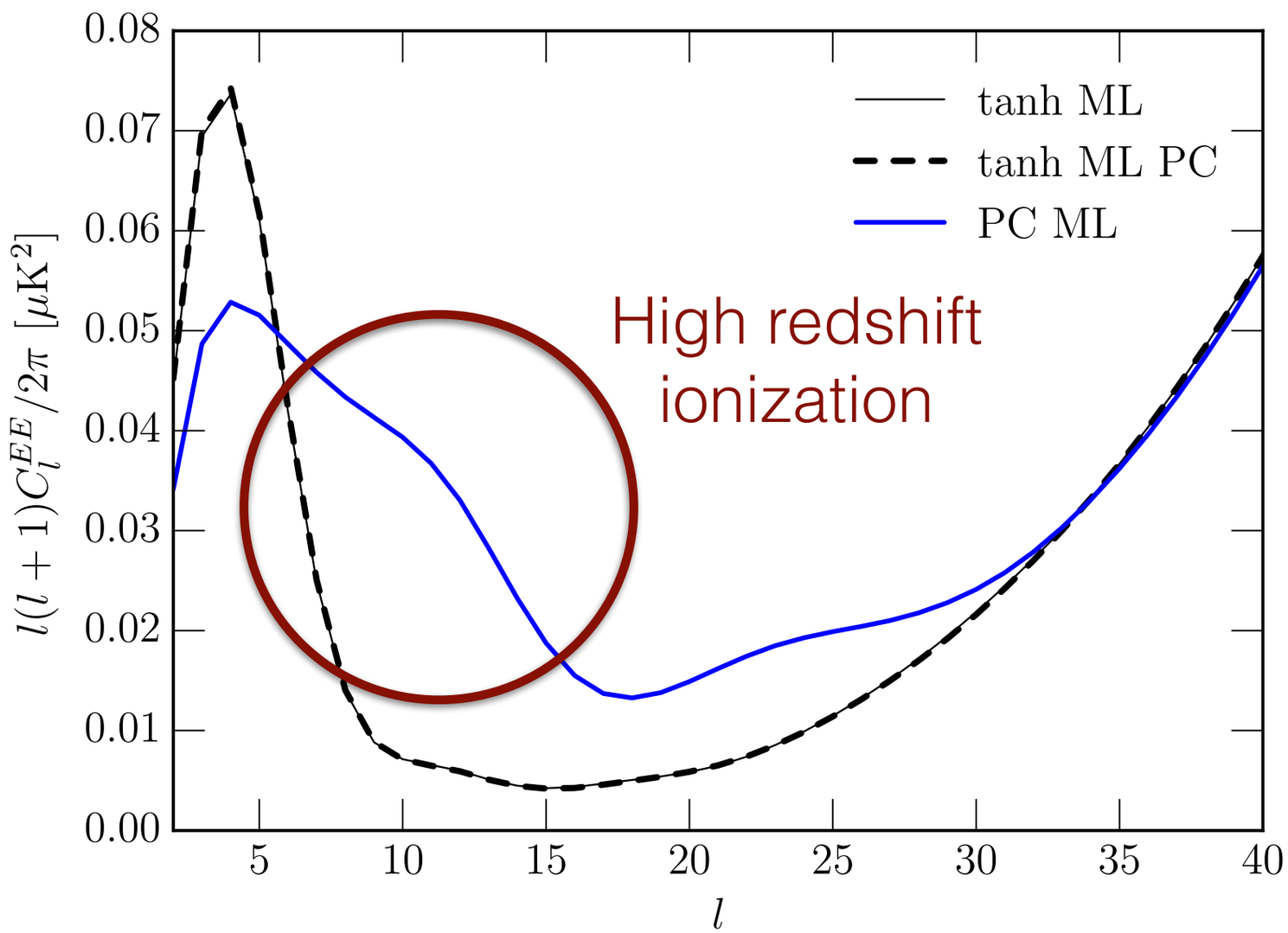
CH, Miranda, Hu 2016

High z ionization only found in Planck

Data	$\tau(15, z_{\max})$
P15	0.033 ± 0.016
P13 +WMAP(P)	0.022 ± 0.018

- Planck pol —> WMAP pol: **preference dropped** to 1σ
- High redshift ionization: **origin is Planck polarization** (LFI)

Extended ionization broadens bump



- PC ML: **broader bump** —> extended ionization to higher z.
- E-mode polarization 8 < l < 20. **Tanh fails to pick this out.**

CH, Miranda, Hu 2016

Sources

- Foregrounds or systematics (Planck 2017 will clarify)
- Possible high redshift reionization sources:
  - DM annihilation
  - POP II + POP III stars (metal-poor stars), etc …
- Running MCMC vs PC effective likelihood

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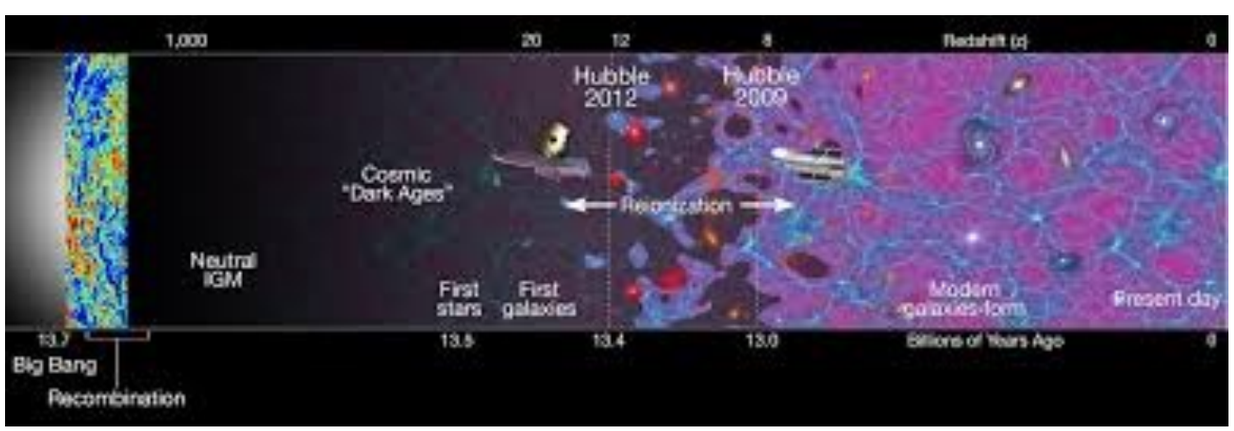
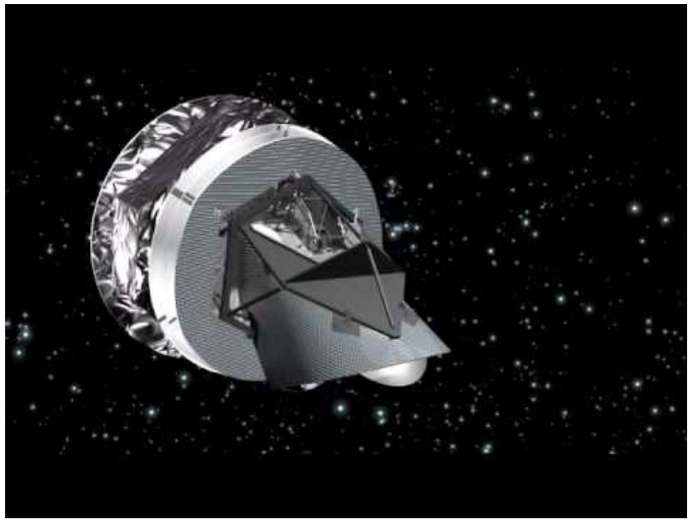




Effective Likelihood Code

- Easily tests **any models of ionization model** xe(z) between 6 < z < 30.
  - Projection unto PCs: $\mathbf{p} \to x_e(z) \to \mathbf{m}$
  - Kernel density estimate: $\mathcal{L}_{\rm PC}(\text{data}|\mathbf{m}) = \sum_{i=1}^{N} w_i K_f(\mathbf{m} - \mathbf{m}_i)$

Gaussian kernel (zero mean, covariance a fraction *f* of the chain covariance)

$$P(\tau|\text{data}) \propto \mathcal{L}_{\rm PC}[\text{data}|\mathbf{m}(\tau)]\, P(\tau)$$

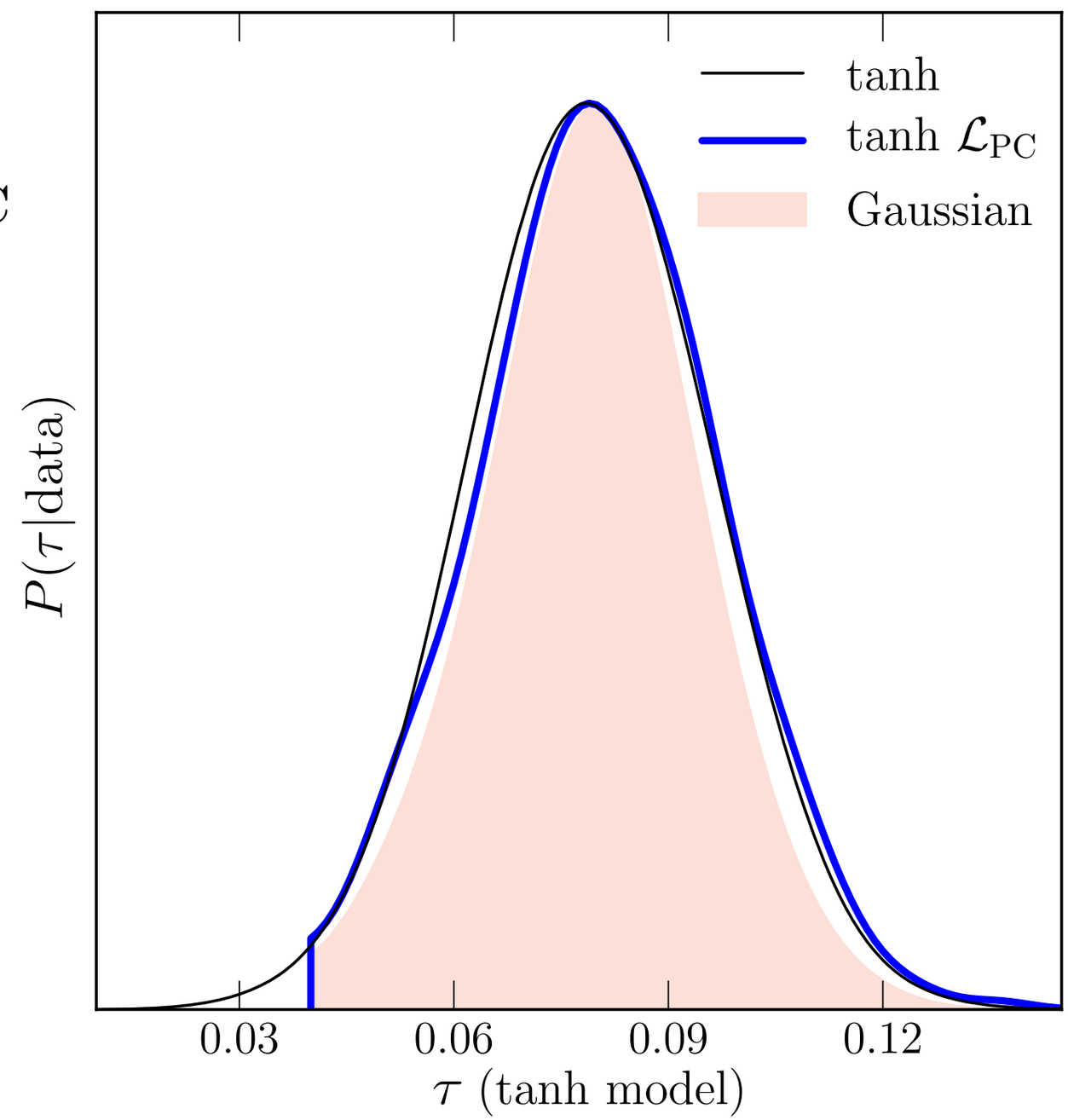
Example: tanh

5min vs 24 hours!

$$\tau \to x_e(z) \to \{m_a\} \to \mathcal{L}_{\rm PC}$$

- Cutoff due to full ionization by z = 6
- f = 0.14 smoothing suffices for tanh (should work better for models favoured by data)

$$P(\tau|\text{data}) \propto \mathcal{L}_{\rm PC}[\text{data}|\mathbf{m}(\tau)]\, P(\tau)$$



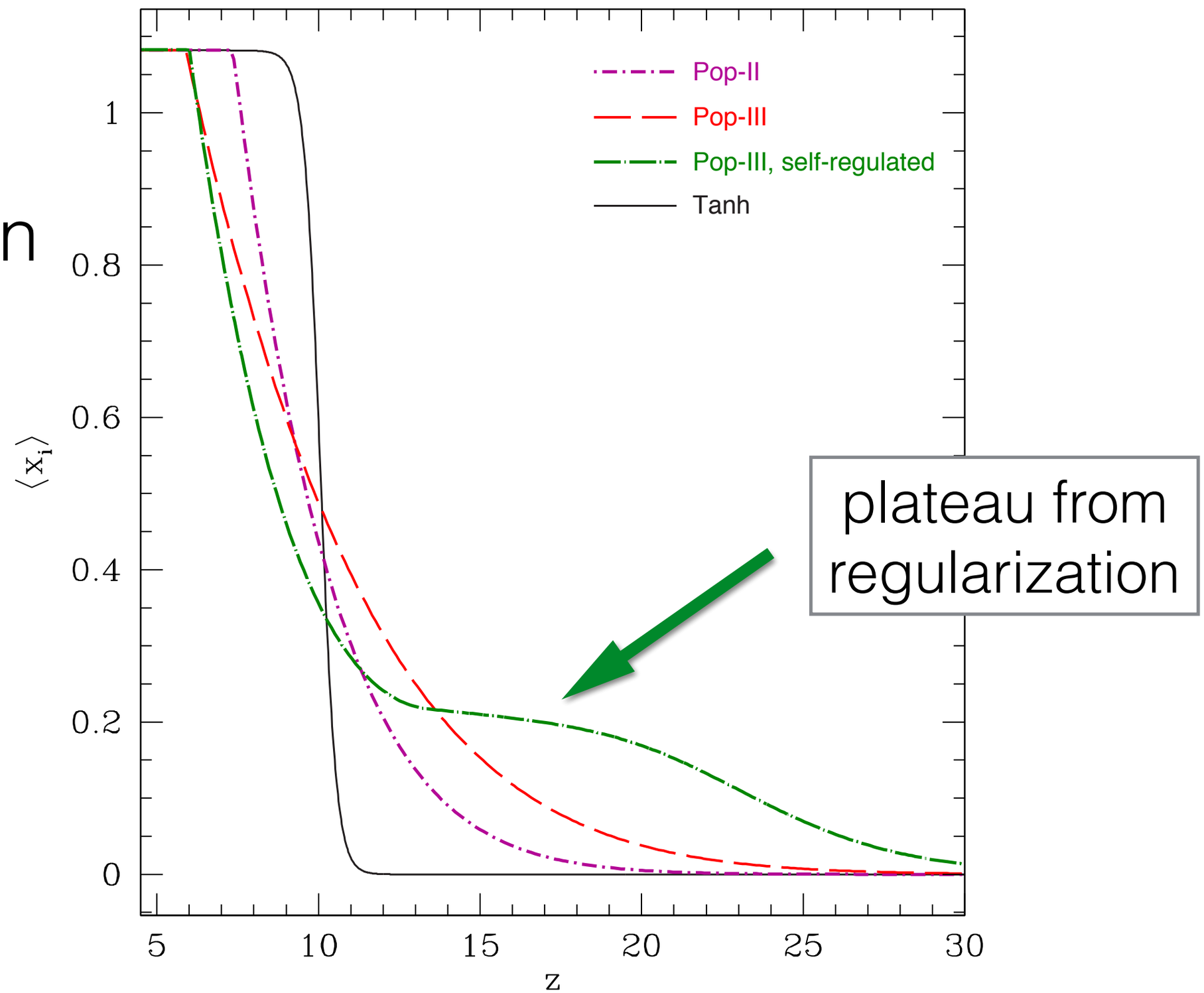
CH+16, submitted to PRD

High z ionization: Pop-III stars?

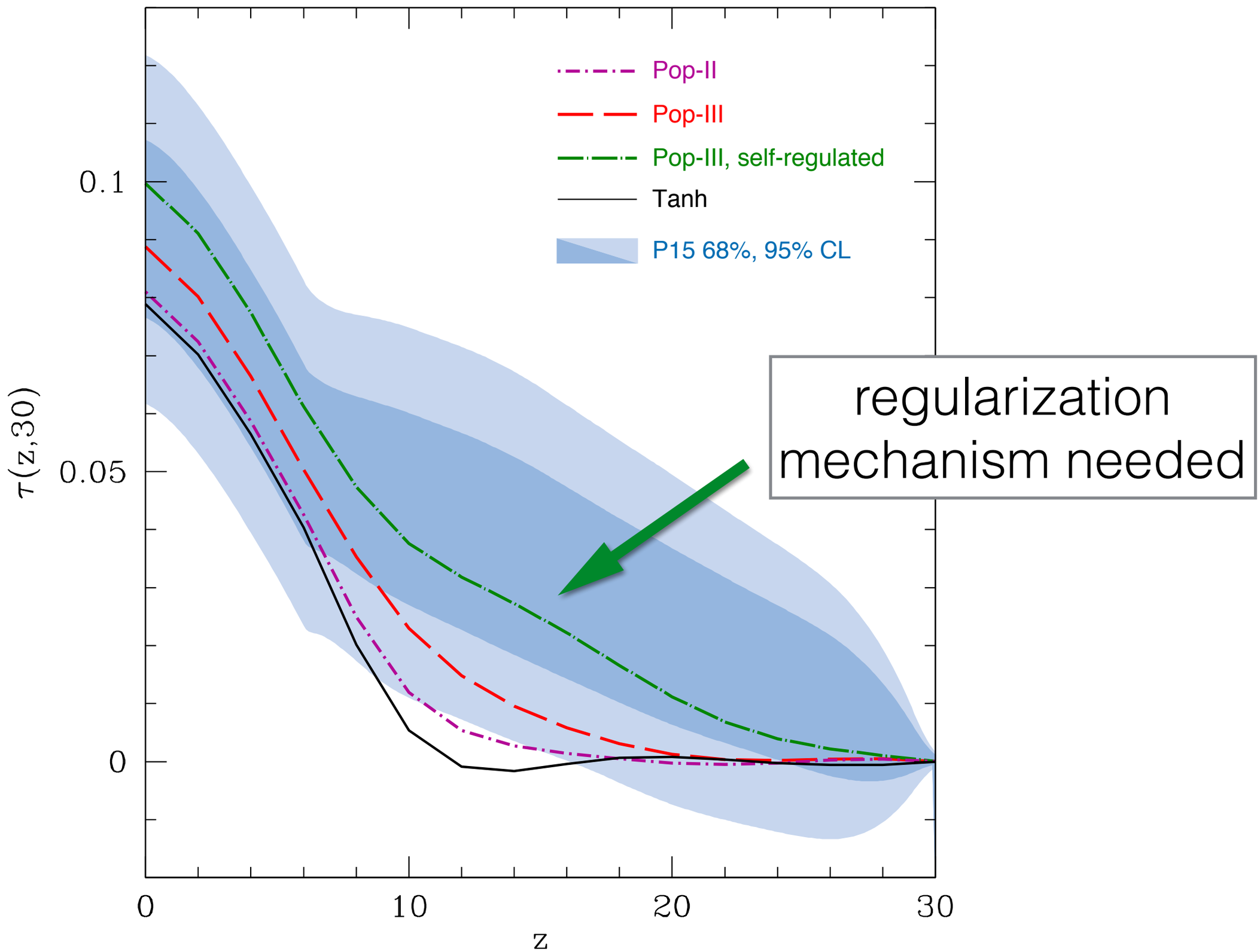
Type of star	Metal Content	Cooling	Host halos
Pop-III	Metal-free	Molecular hydrogen	Minihalos $10^5 - 10^6 M_\odot$
Pop-II	Metal-poor	Atomic line emission	More massive halos

Regularization mechanism needed

Ionization fraction



Miranda, Lidz, CH, Hu 2016



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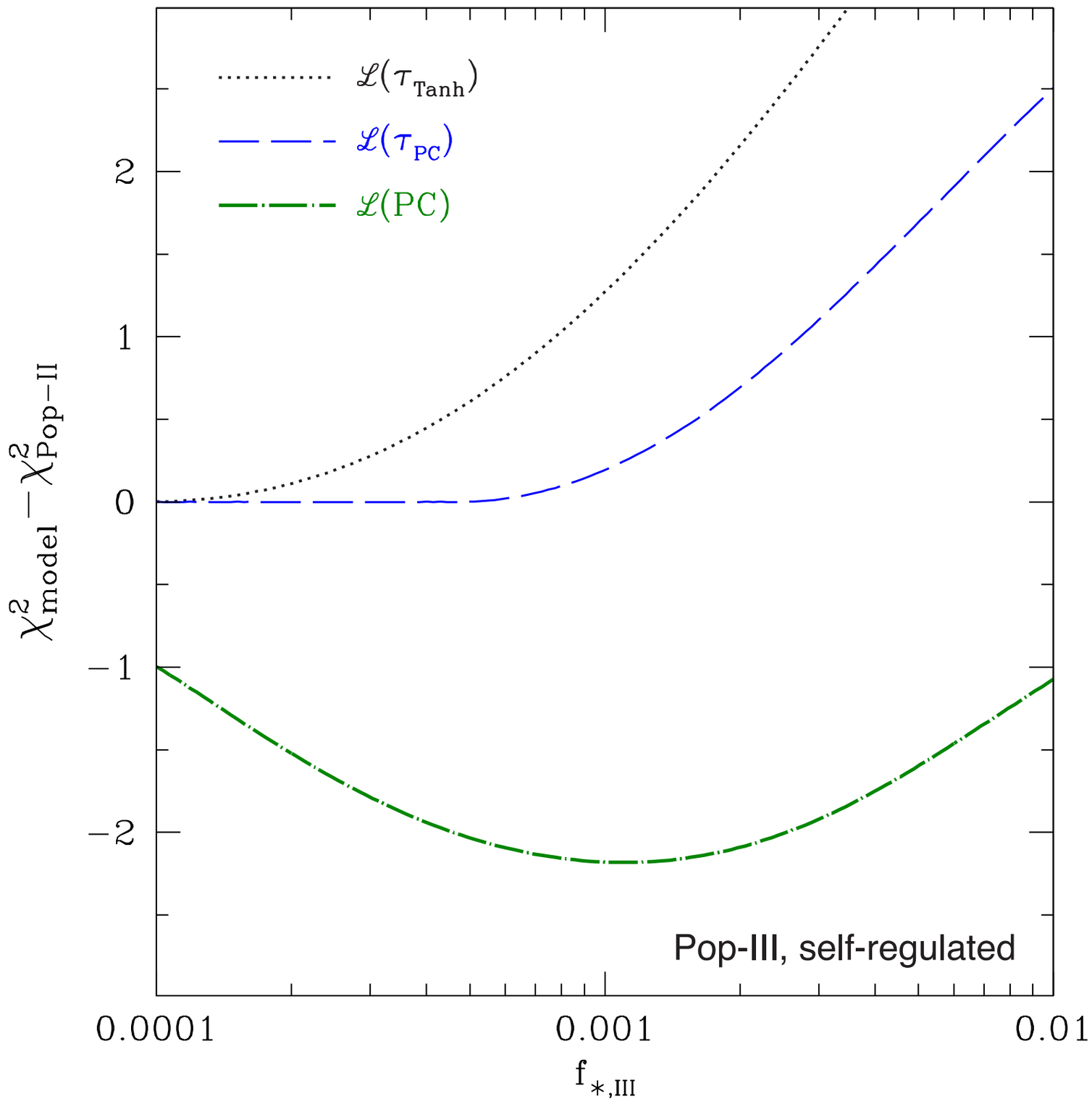


Miranda, Lidz, CH, Hu 2016

Conclusion

- We probed **reionization** using CMB polarization data
- With the **principal component** analysis, we can extract all information available in the observable
- **Planck 2015 polarization data** allows us to constrain an additional mode: **high redshift polarization.**
  - Optical depth shifts by 1σ (compared to tanh)
  - z >15 optical depth preferred at ~ 2σ
  - **Use PC analysis!**

Effective Likelihood Code

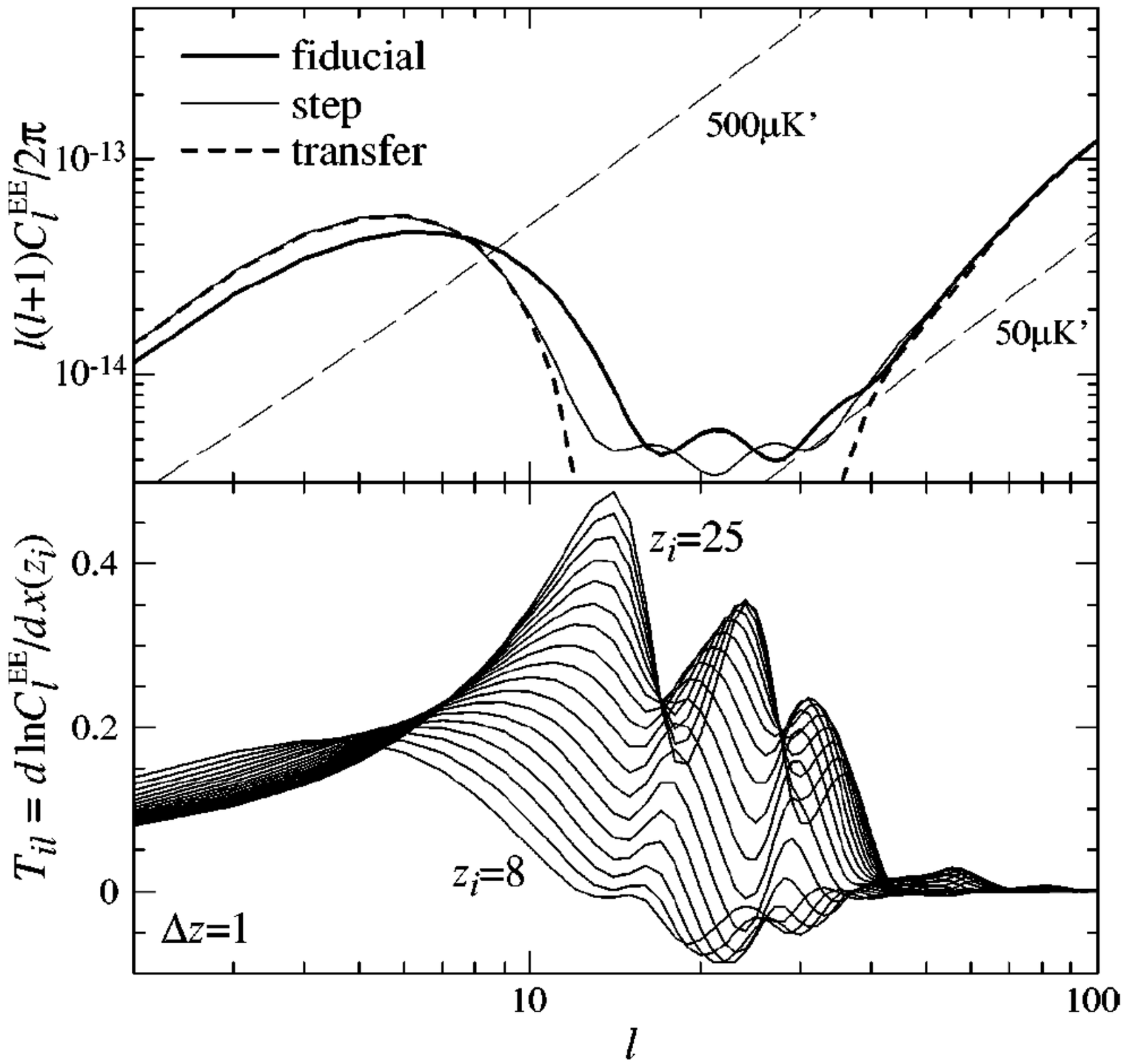
- Use our **effective likelihood code** for efficient and unbiased testing of ***any*** **ionization history models**.
  (tanh: 5min vs 24 hours MCMC).

- When applied on **Planck 2017 polarization data** — better constraints on high redshift ionization component.

(Code available on request)

Thank you!

Back-up slides


fiducial
step
transfer
500μK'
50μK'
10^{-13}
10^{-14}
$l(l+1)C_l^{EE}/2\pi$
z_i=25
z_i=8
Δz=1
0.4
0.2
0
$T_{il} = d\ln C_l^{EE}/dx(z_i)$
10
100
l

CMB measurements of τ

$$\tau = 0.17 \pm 0.04 \ (\mathrm{WMAP1}, TE)$$

$$\tau = 0.089 \pm 0.014 \ (\mathrm{WMAP9})$$

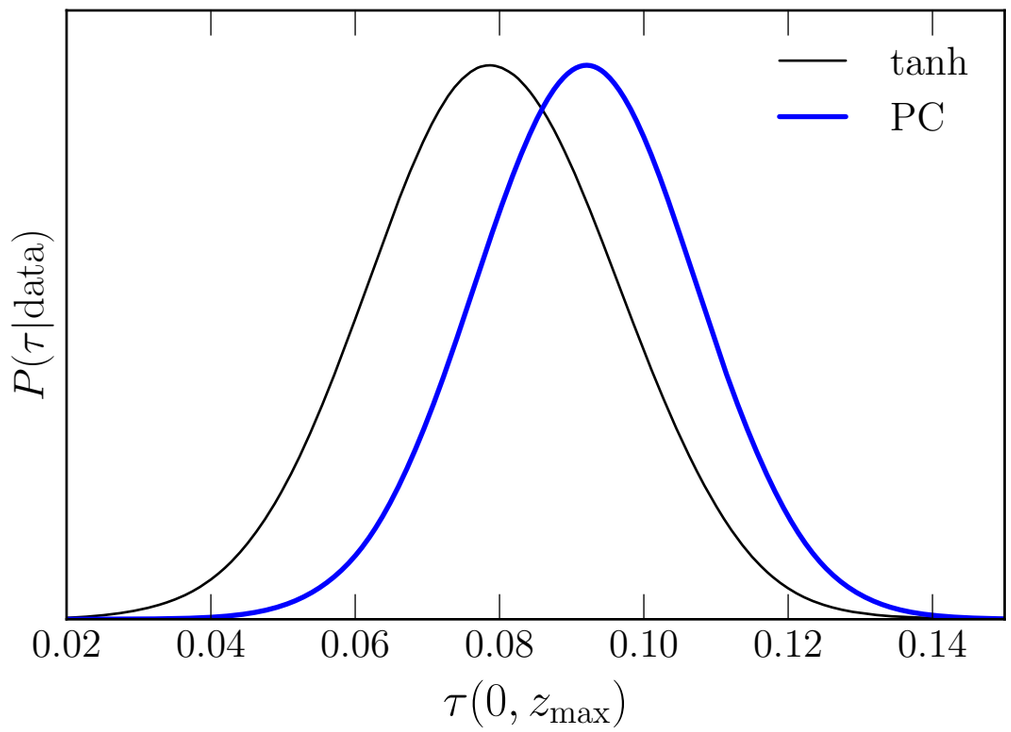
$$\tau = 0.075 \pm 0.013 \ (\mathrm{WMAP9\ dust\ cleaned\ with\ Planck\ 353})$$

$$\tau = 0.078 \pm 0.019 \ (\mathrm{Planck\ LFI\ low}\ l + \mathrm{high}\ l\ TT)$$

$$\tau = 0.070 \pm 0.024 \ (\mathrm{Planck}\ TT + \mathrm{lensing})$$

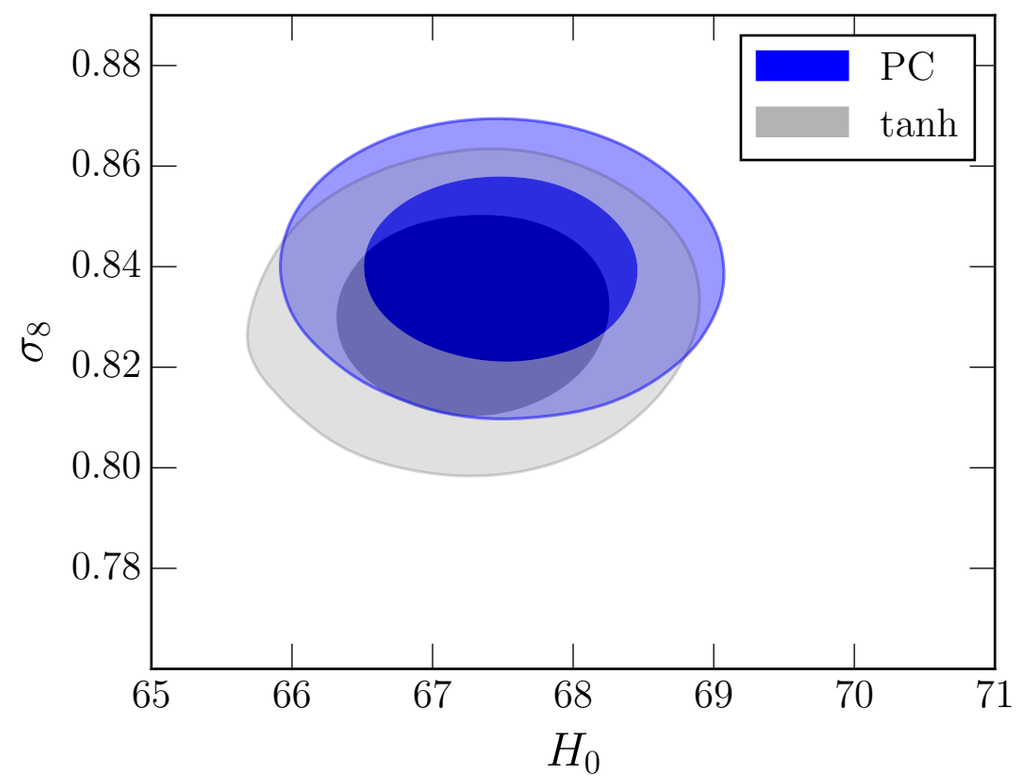
$$\tau = 0.055 \pm 0.009 \ (\mathrm{Planck\ HFI\ low}\ l)$$

Parameter shifts



Model	$\tau(0, z_{\max})$
PC	0.092 ± 0.015
tanh	0.079 ± 0.017

- τ shifts up by 1σ
- consequence on other cosmo parameters



End of Back-up slides