Title: Complete Reionization Constraints with Planck 2015 Polarization

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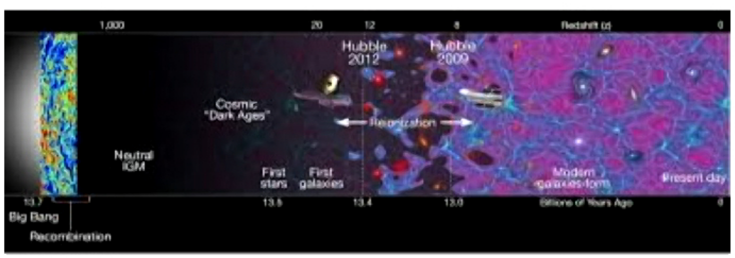
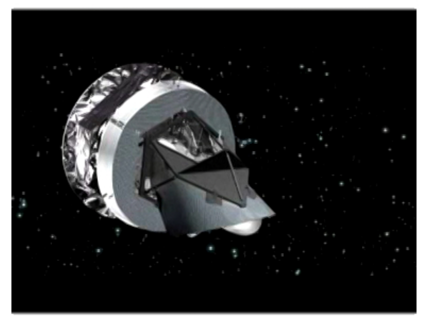
Abstract: I will present a recent analysis of the Planck 2015 data that is complete in the reionization observables from large angle CMB polarization measurements using principal components (PC). By allowing for an arbitrary ionization history, this technique tests the robustness of total optical depth inferences from the usual instantaneous reionization assumption. A reliable measurement of the total optical depth is important for the interpretation of many other cosmological parameters such as the dark energy and neutrino mass. We found that Planck 2015 data not only allow a high redshift z>15 component to the optical depth but prefer it at the 2Ïƒ level. This high redshift component contributes to a higher total optical depth than in the instantaneous reionization analysis, illustrating the need for a complete treatment of reionization in CMB data. I will further demonstrate the power of the PC method at efficiently constraining models with ionization history predictions, by applying our fast and effective likelihood code.

Outline

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





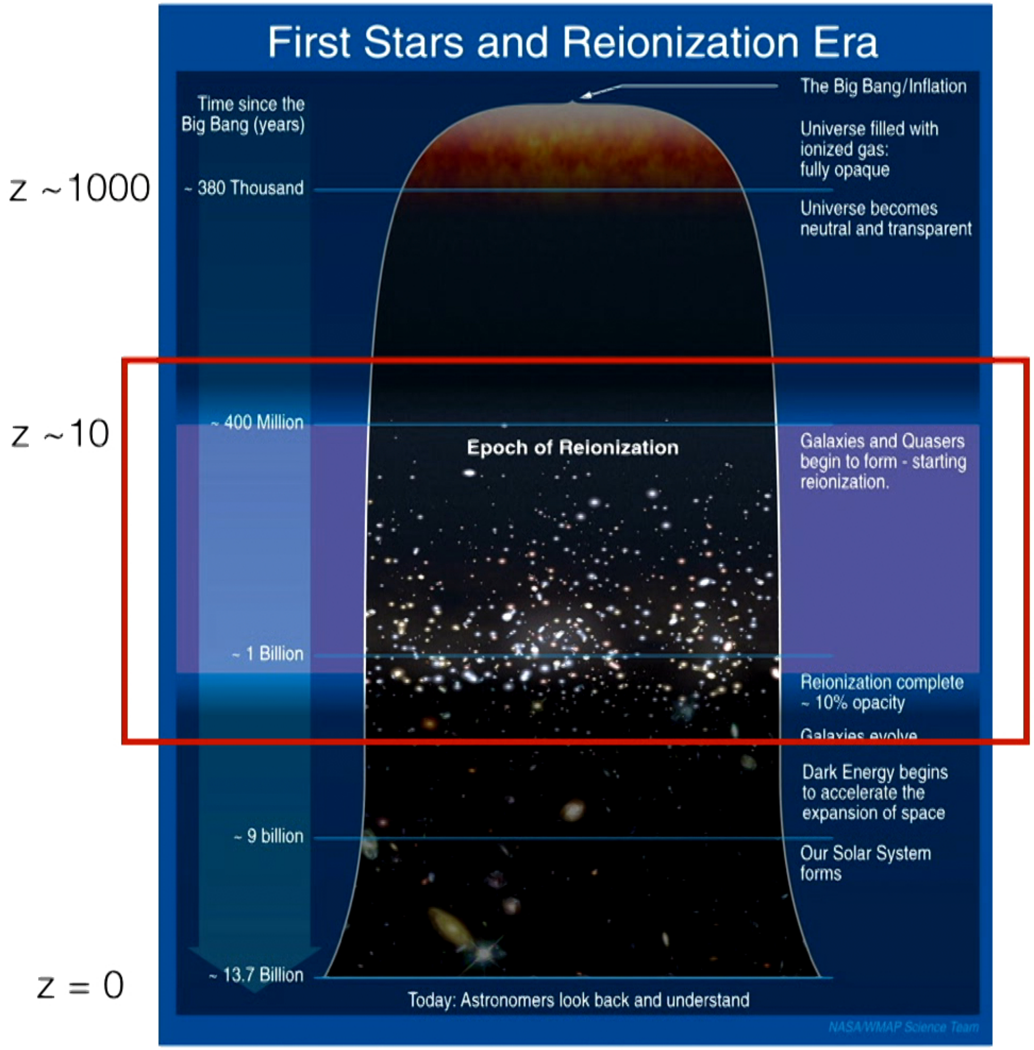
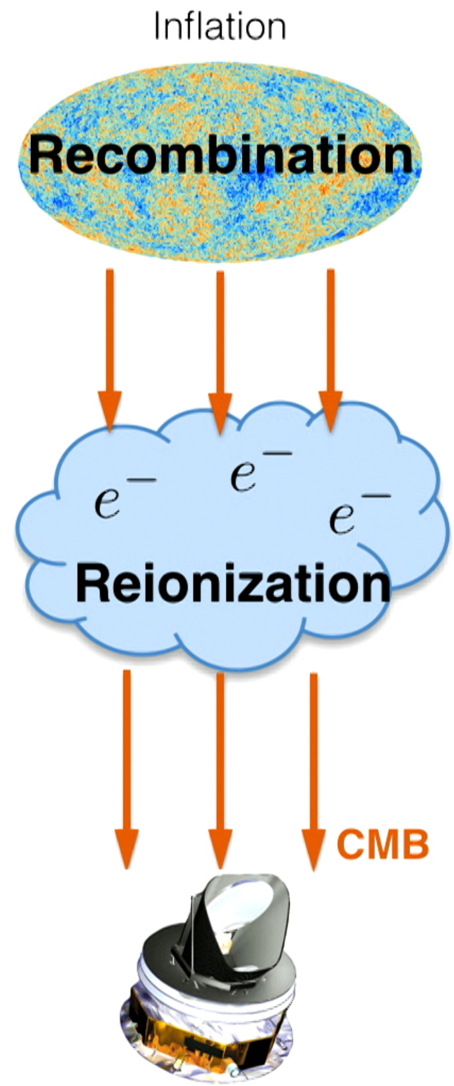
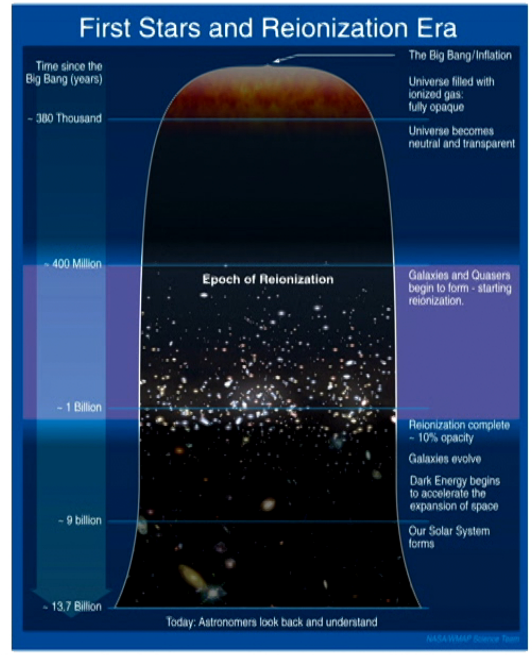


Image credit: https://en.wikipedia.org/wiki/Reionization



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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Probes of reionization

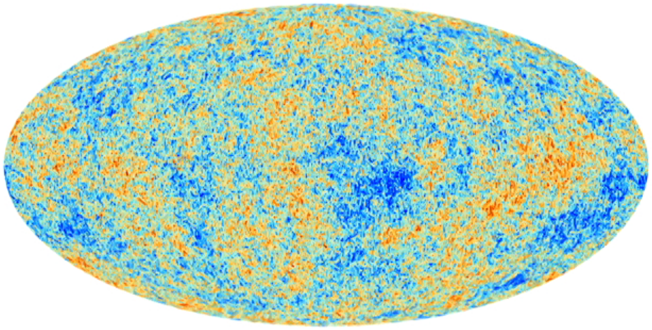
- **Gunn-Peterson effect** (in quasar spectra): conclude that Universe is fully ionized by z=6.

- **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 …)

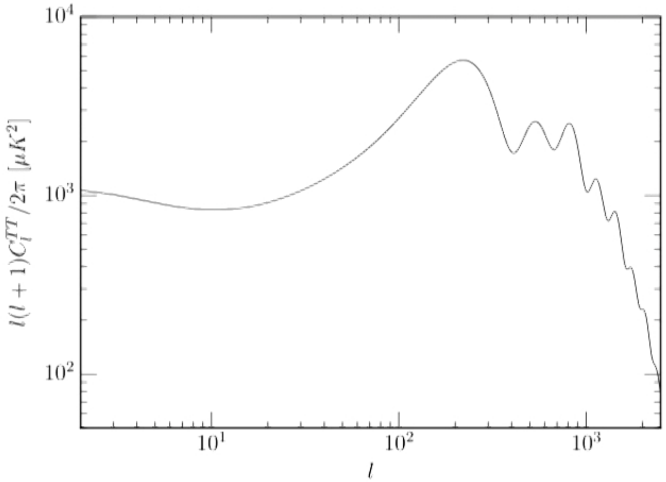
Cosmic microwave background (CMB)



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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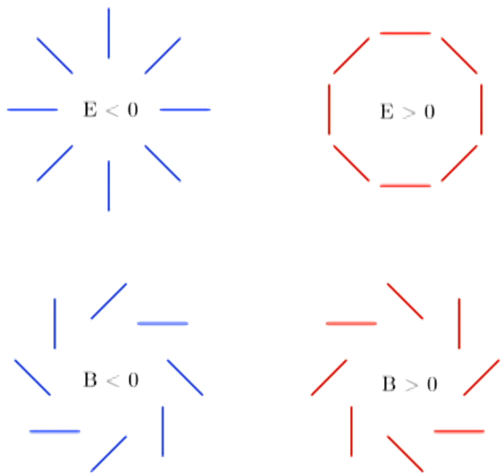
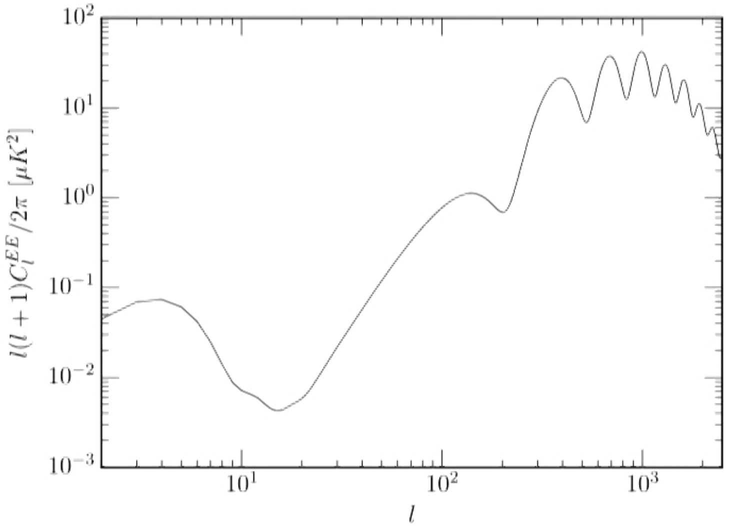


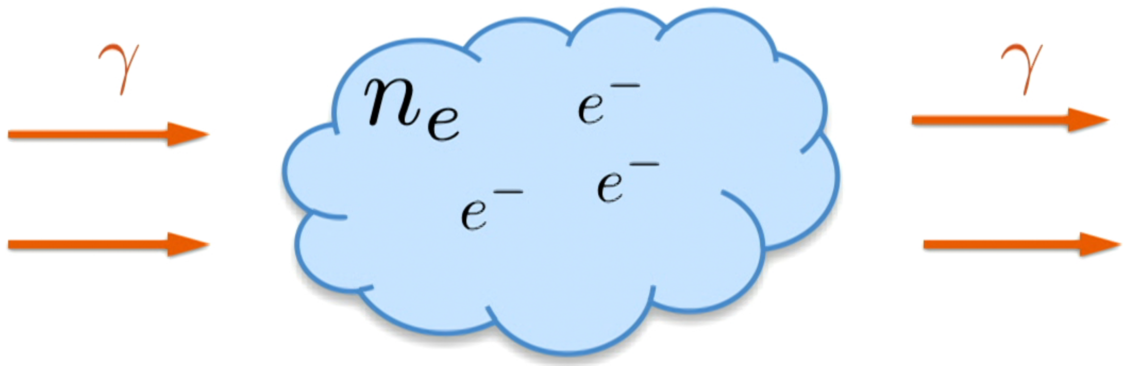
E-mode polarization
power spectrum



angular wavenumber

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

CMB photons Thomson scatter with free electrons



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

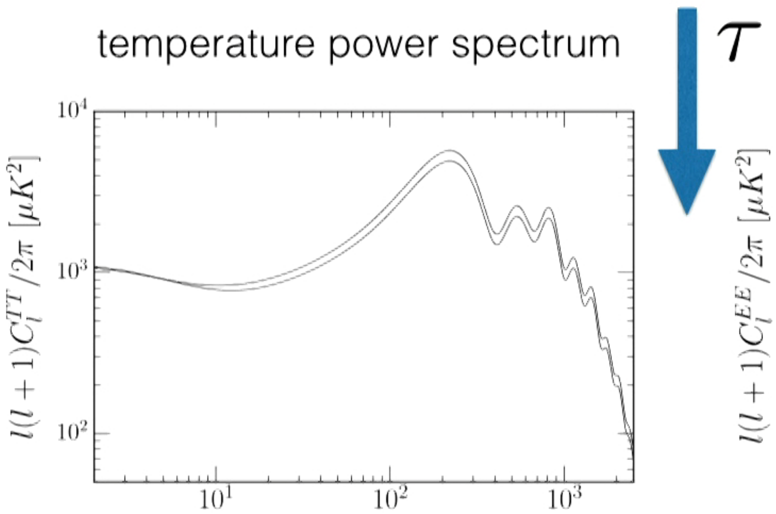
Optical depth: $\tau = \int_0^{\eta} d\eta' \sigma_T n_e a$

Effects of reionization on the CMB

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

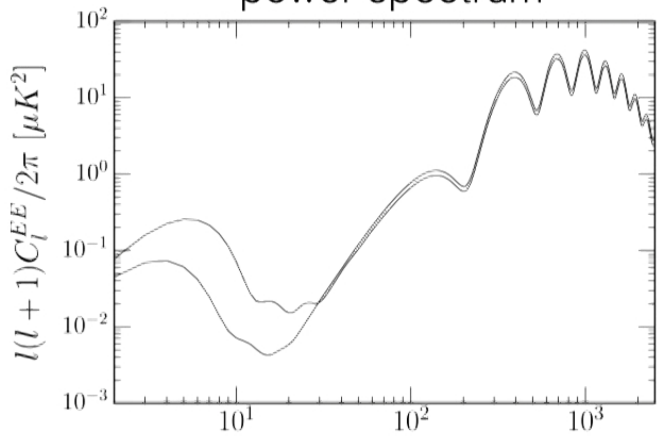
Power spectrum suppressed as $e^{-2\tau}$, $\tau = \int_0^{\eta} d\eta' \sigma_T n_e a$

temperature power spectrum



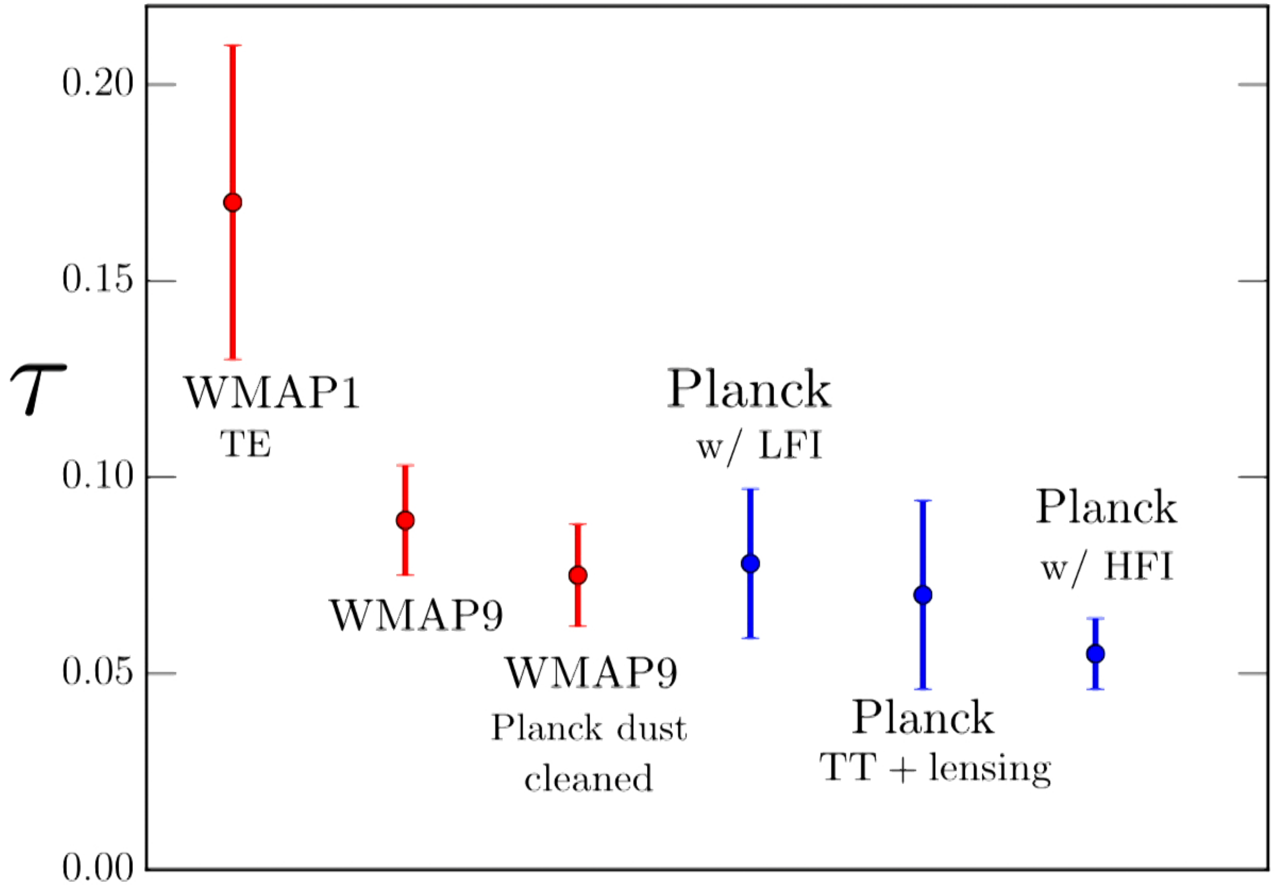
angular wavenumber

E-mode polarization power spectrum



angular wavenumber

CMB measurements of τ

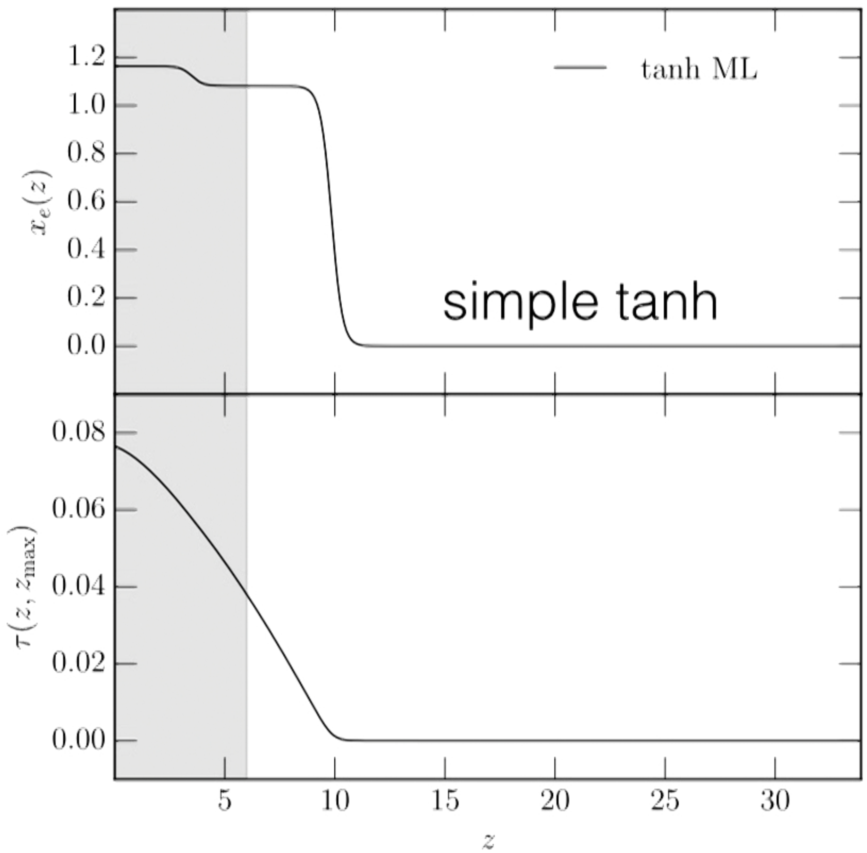


Standard approach: tanh

ionization fraction

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

optical depth

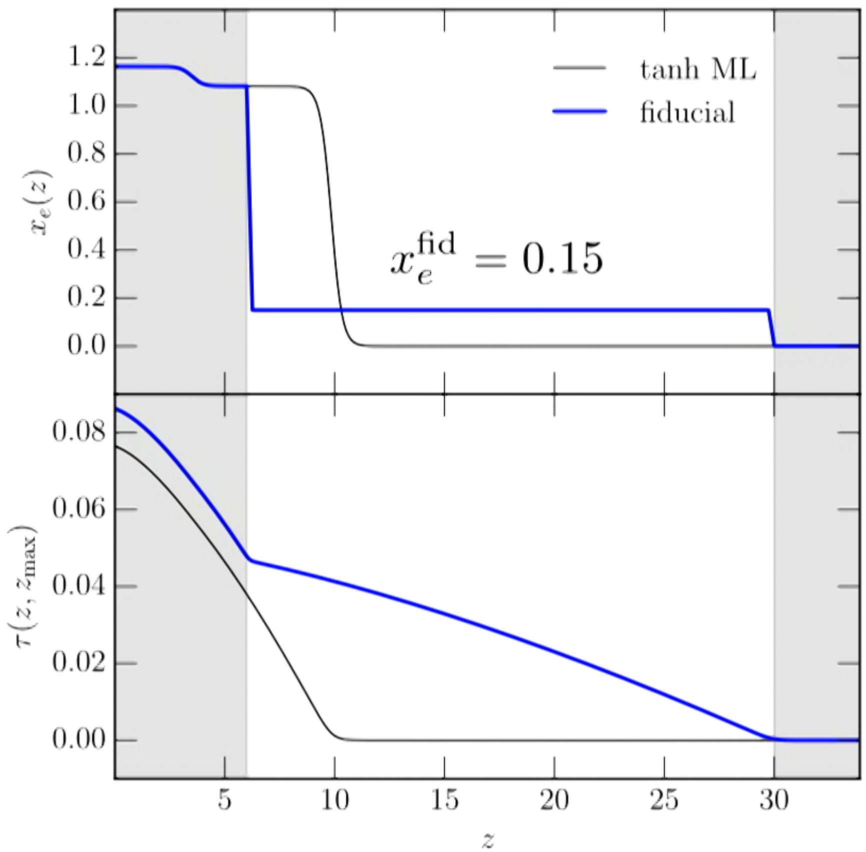


Our PC approach: $x_e(z) = x_e^{\rm fid} + \sum_a m_a S_a(z)$

(Hu & Holder 03)

ionization fraction

optical depth



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(Hu & Holder 03)

Fisher matrix

parameter: xe(zi); observable: ClEE

$$F_{ij} = \sum_l (l + 1/2) T_{li} T_{lj}$$

$$T_{li} \equiv \frac{\partial \ln C_l^{EE}}{\partial x(z_i)}$$

$$\langle \delta x(z_i) \delta x(z_j) \rangle \approx (F^{-1})_{ij}$$

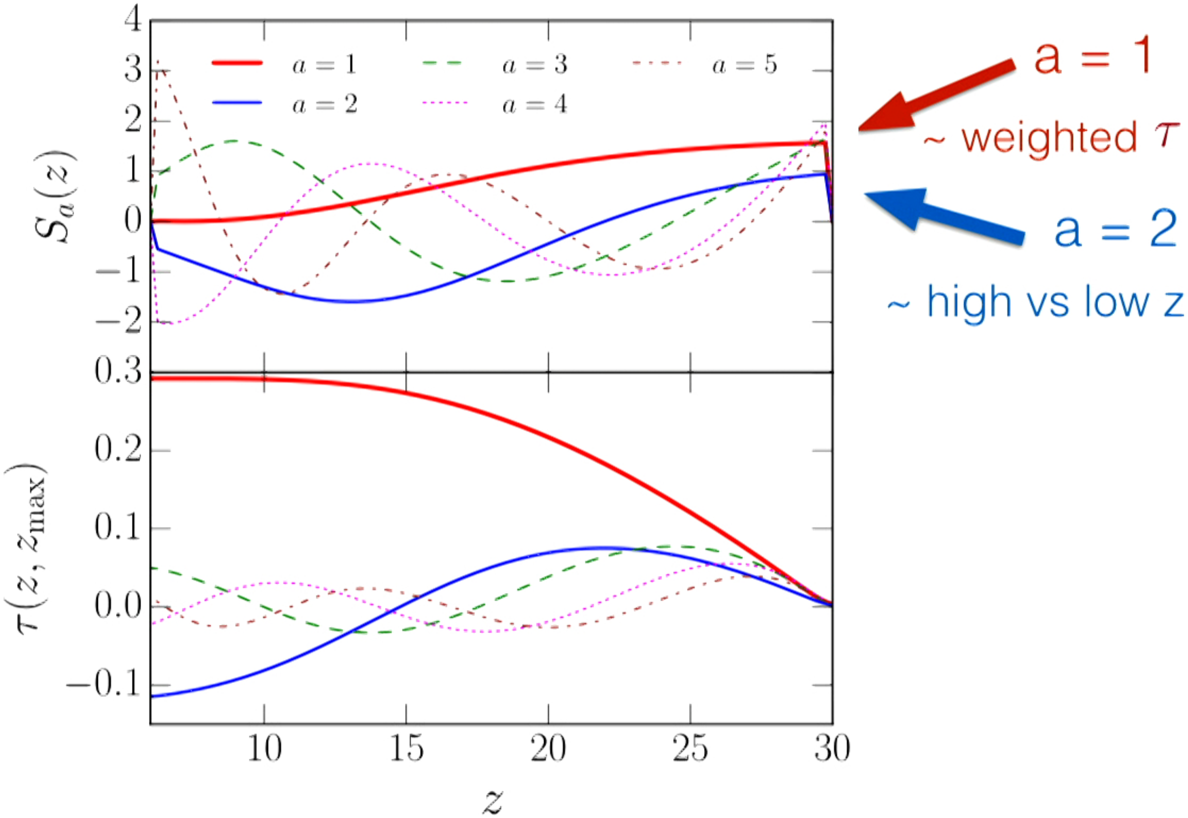
Eigenfunctions of Fisher matrix

Eigenfunctions ranked by contribution to observables

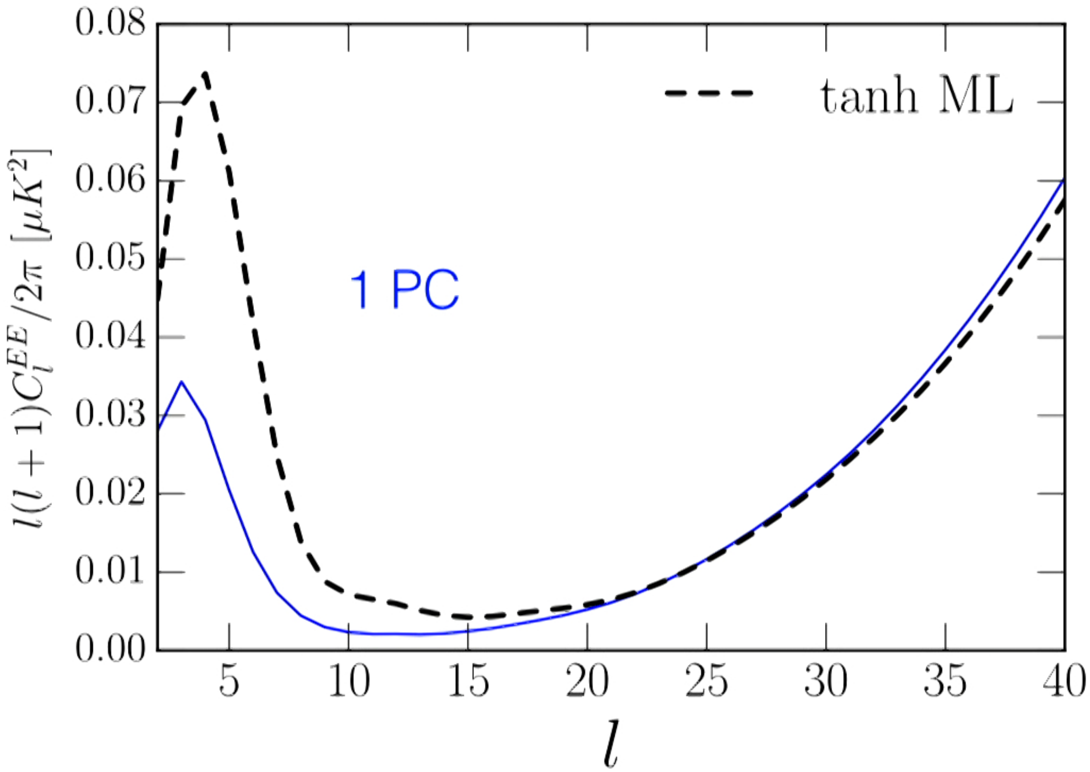
ionization fraction

optical depth

Contribution to τ from each eigenfunction



5 PCs completely describe E-mode power spectrum



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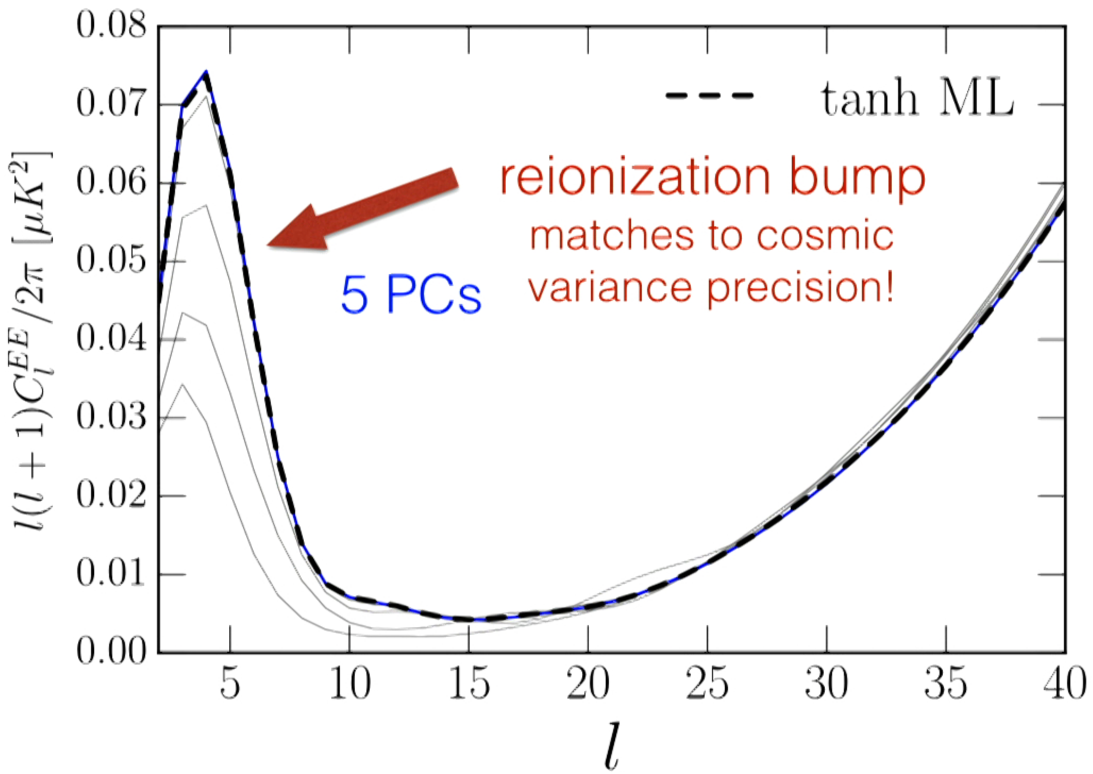


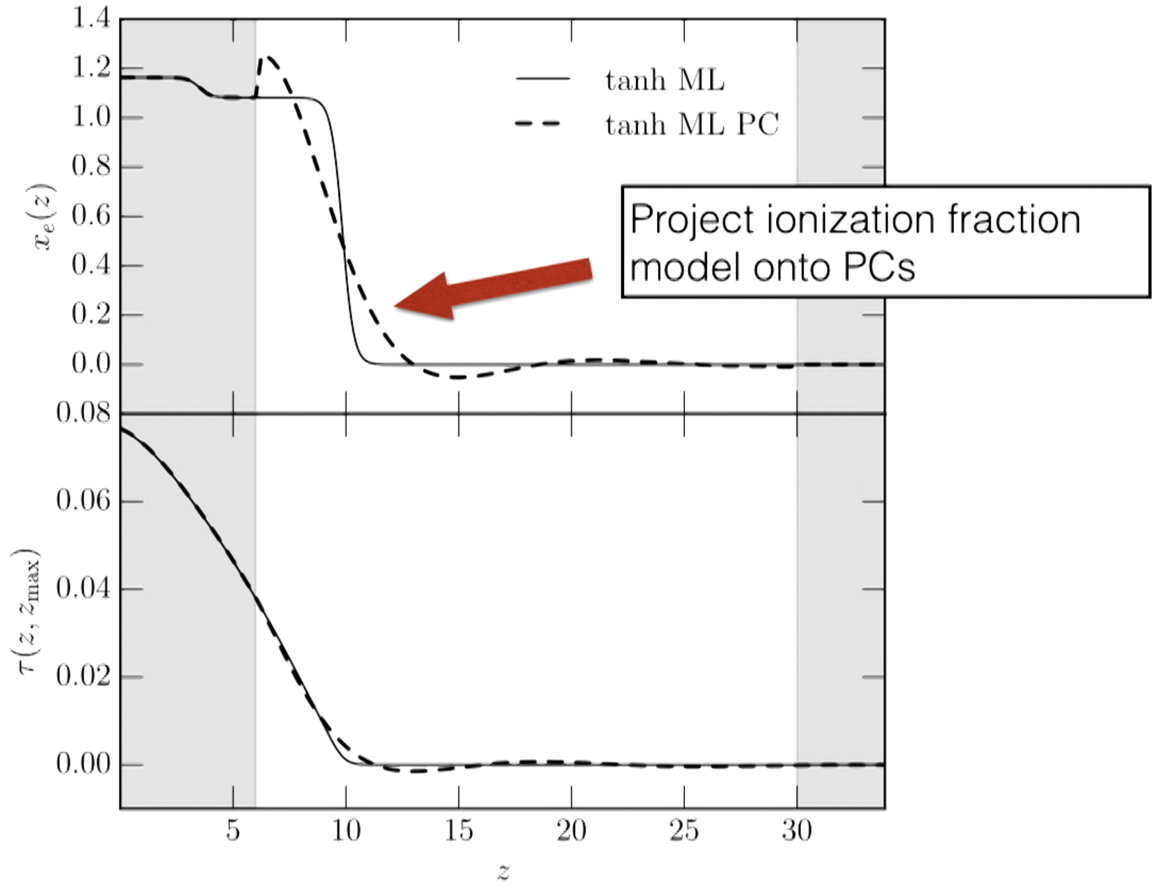
5PCs designed for observables, not model reconstruction

ionization fraction

not well constrained by data

optical depth

data reflects better this integrated quantity



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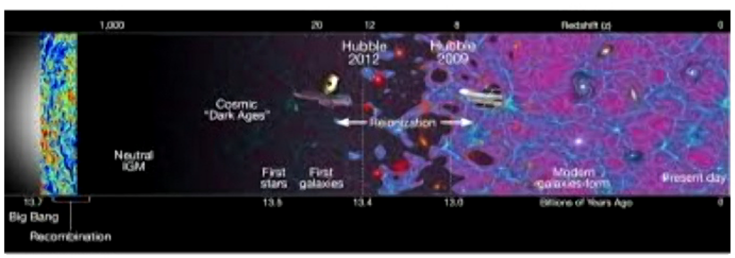
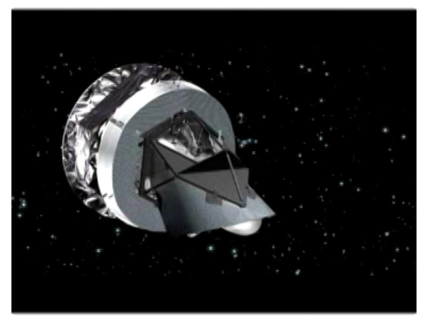
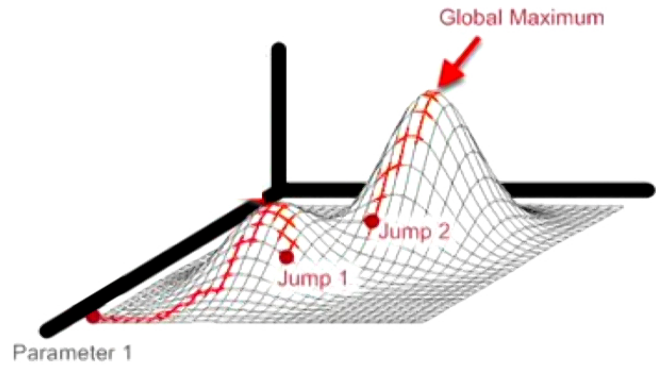




Method: Apply MCMC to Planck 2015

10 parameters



sampled with COSMOMC

LCDM

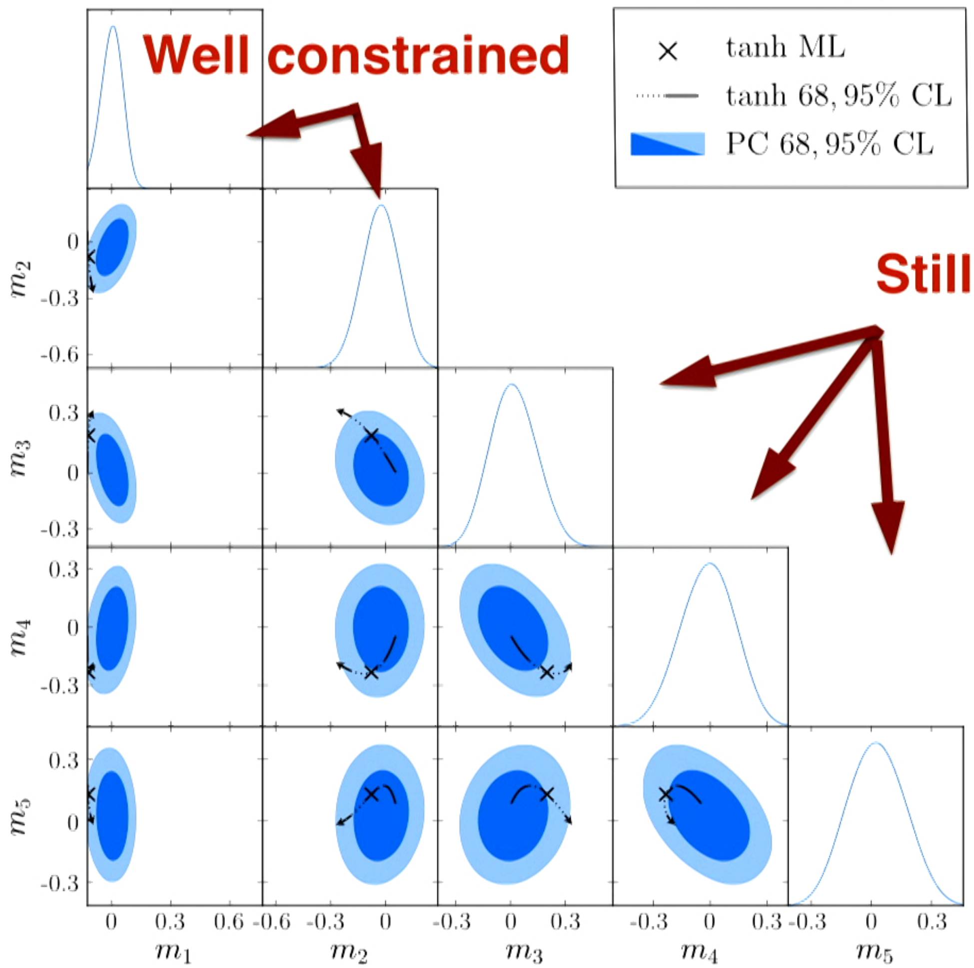
$\Omega_b h^2, \Omega_c h^2, \theta_{\rm MCMC}, A_s, n_s$ +

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

tanh: τ (corresponds to step time)

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

Constraints on 5 PCs



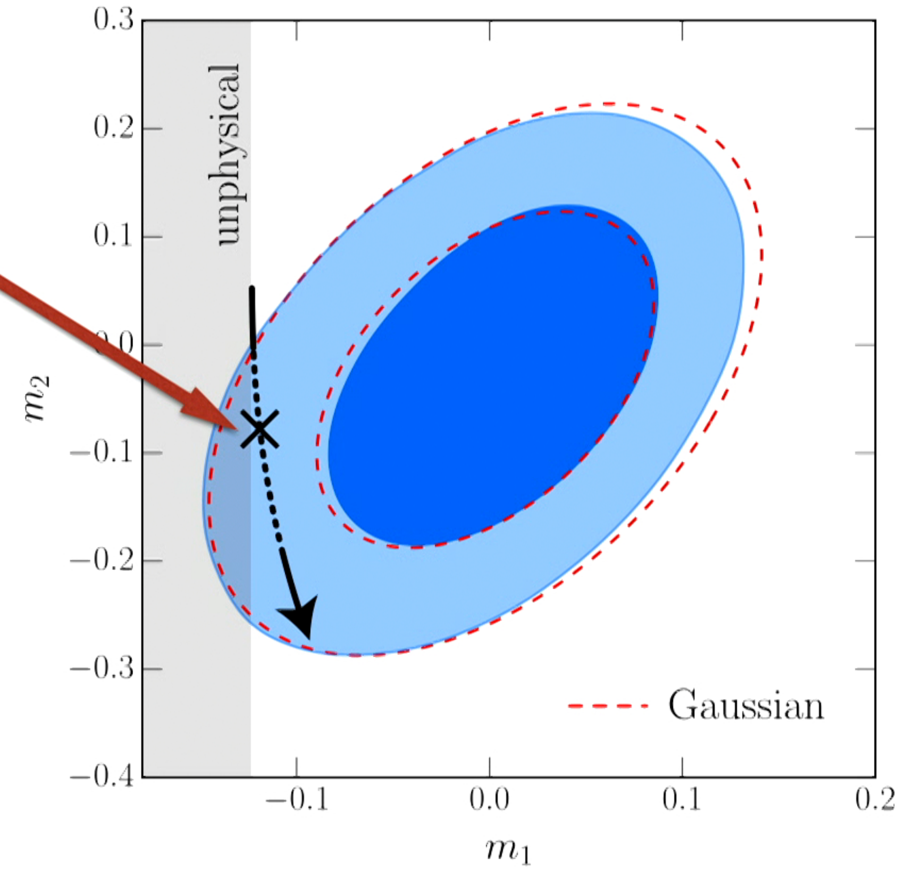
Box edges:

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

CH, Miranda, Hu 2016

Tanh less favoured in PC space

- tanh ML ~2σ away from PC mean



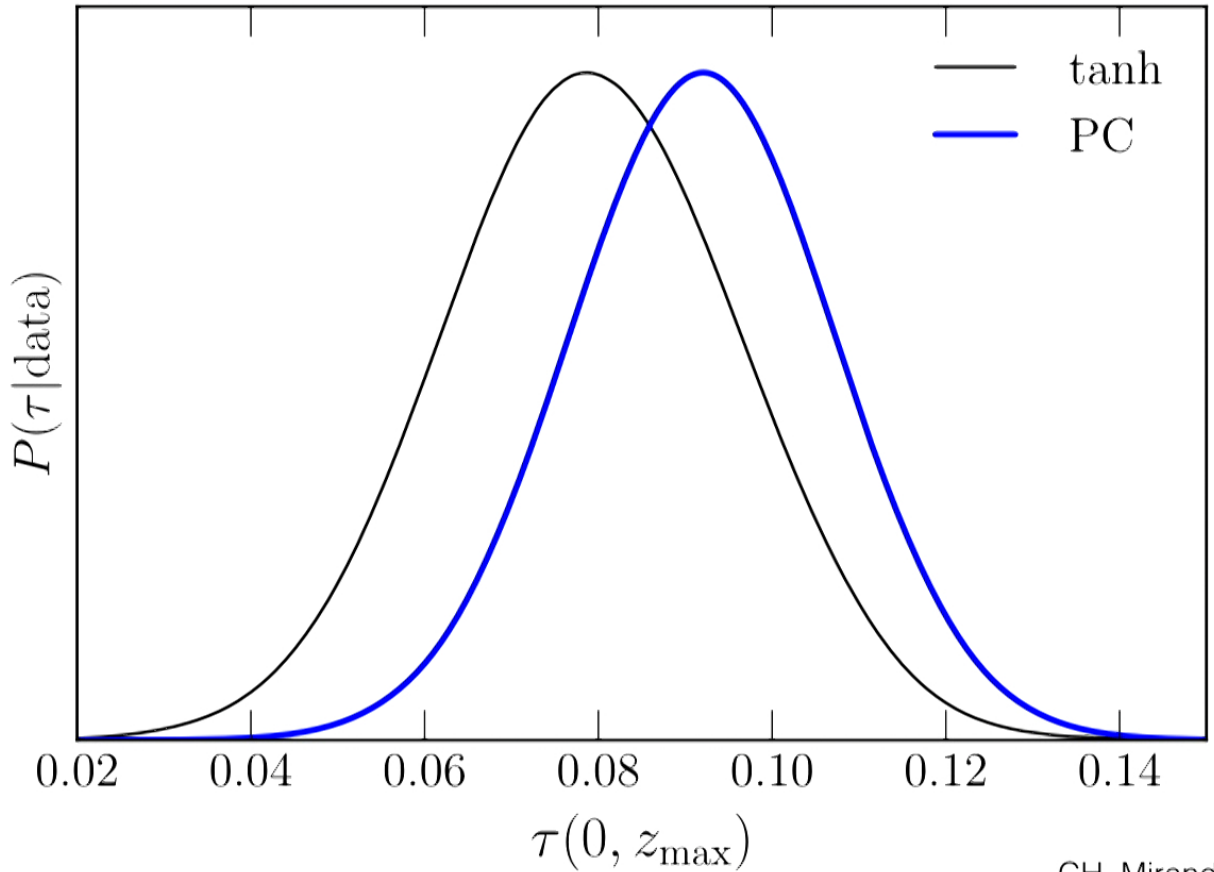
* PC ML vs tanh ML:

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

CH, Miranda, Hu 2016

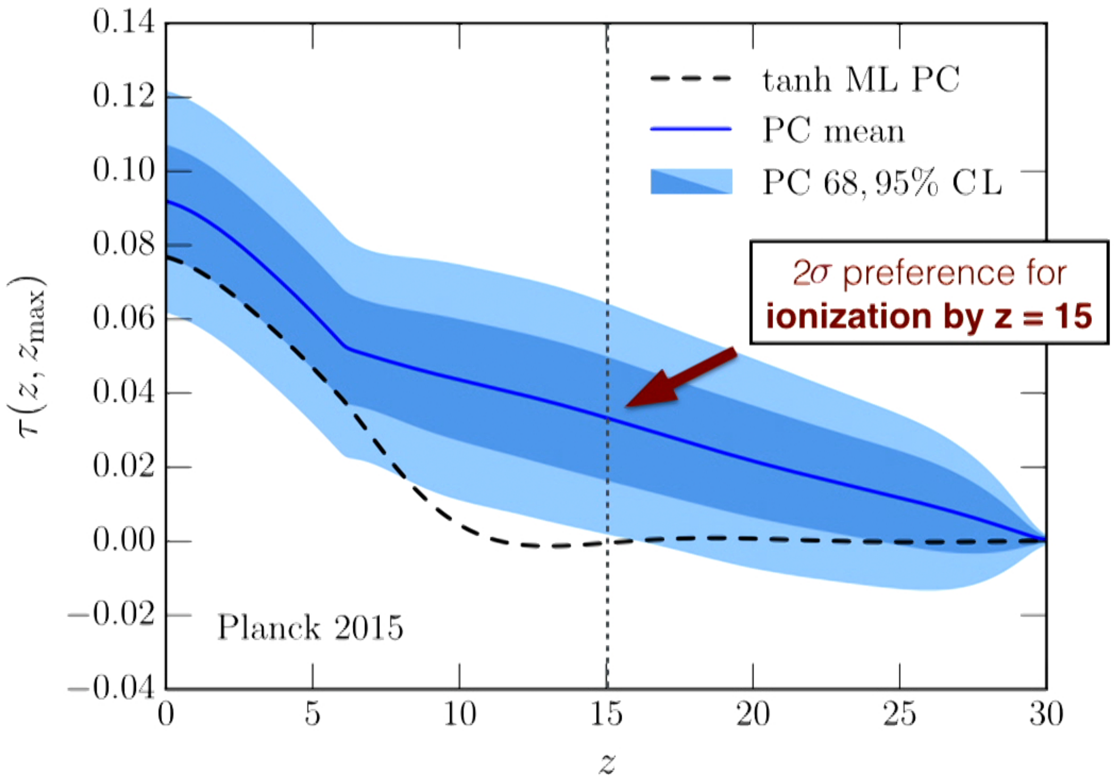
τ shifts by 1 σ

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



CH, Miranda, Hu 2016

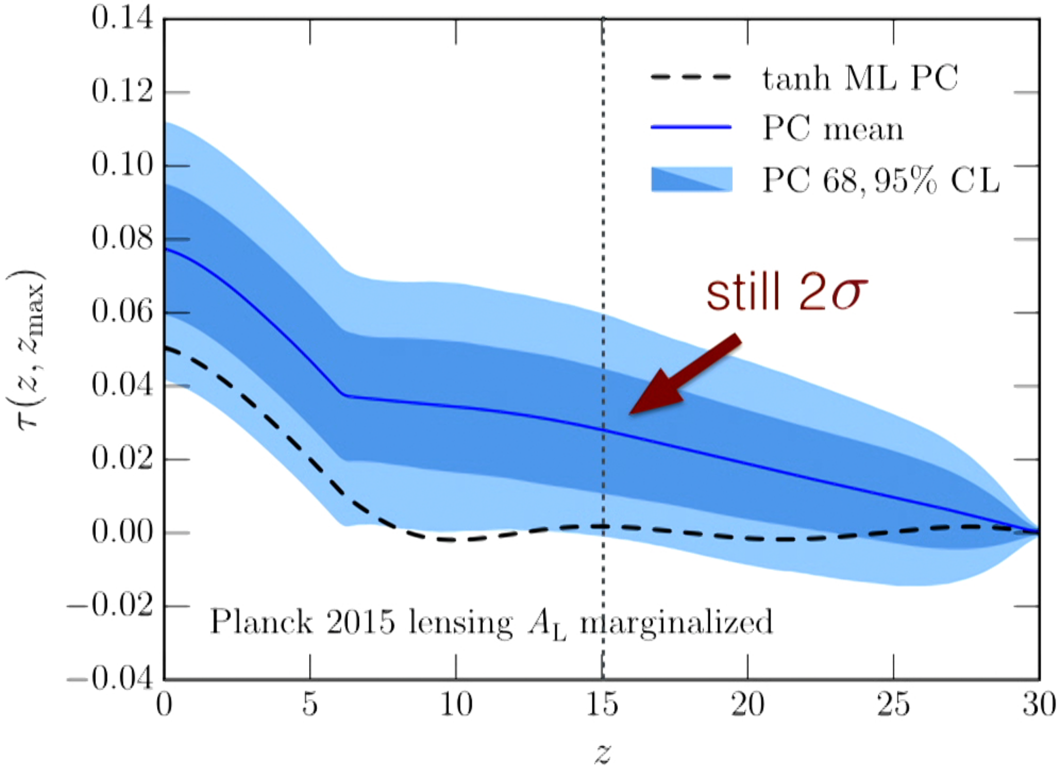
High redshift ionization shifts τ



- **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

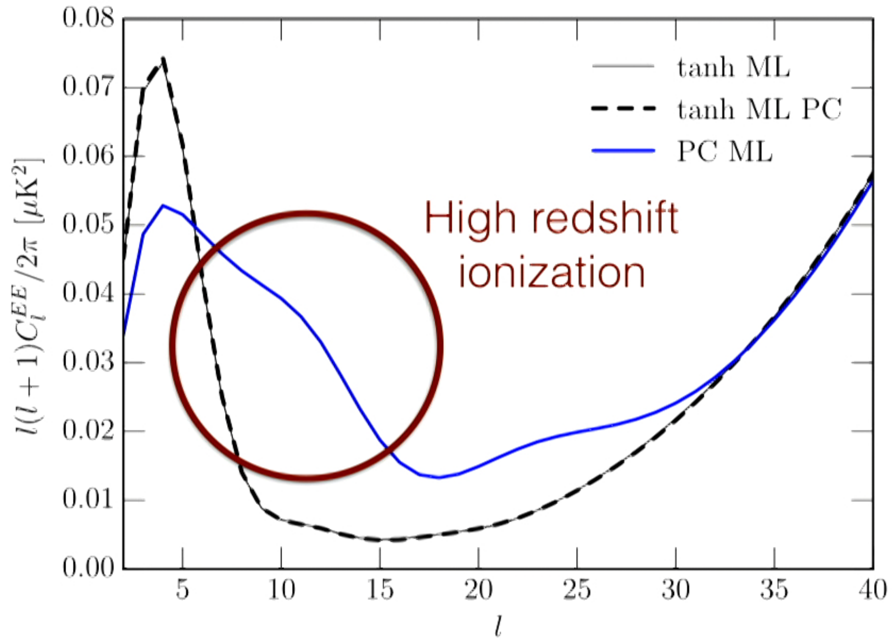
CH, Miranda, Hu 2016

High z ionization only found in Planck

Data	$\tau(15, z_{\rm max})$
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:
  - POP II + POP III stars (metal-poor stars), etc …
  - DM annihilation
- Model testing with ReLike: reionization likelihood code based on PCs.

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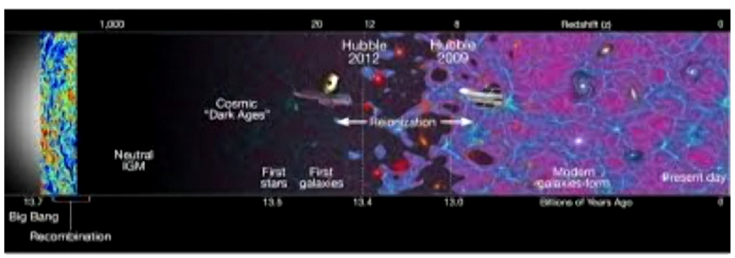
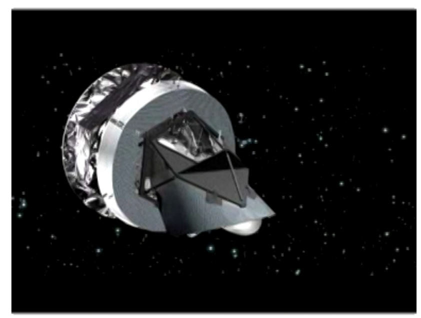




Effective Likelihood Code

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

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

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

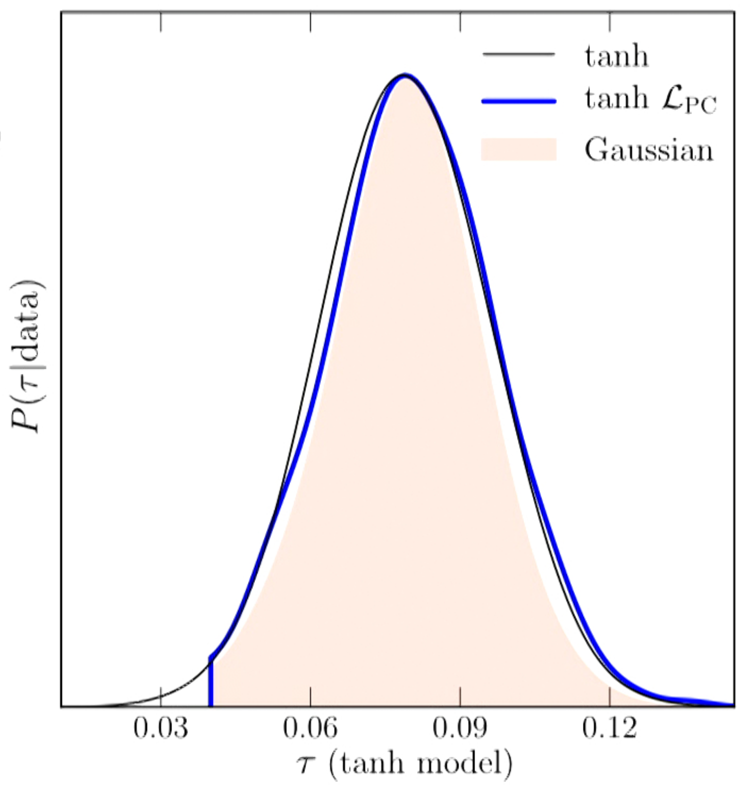
Example: tanh

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)

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



CH+16, submitted to PRD

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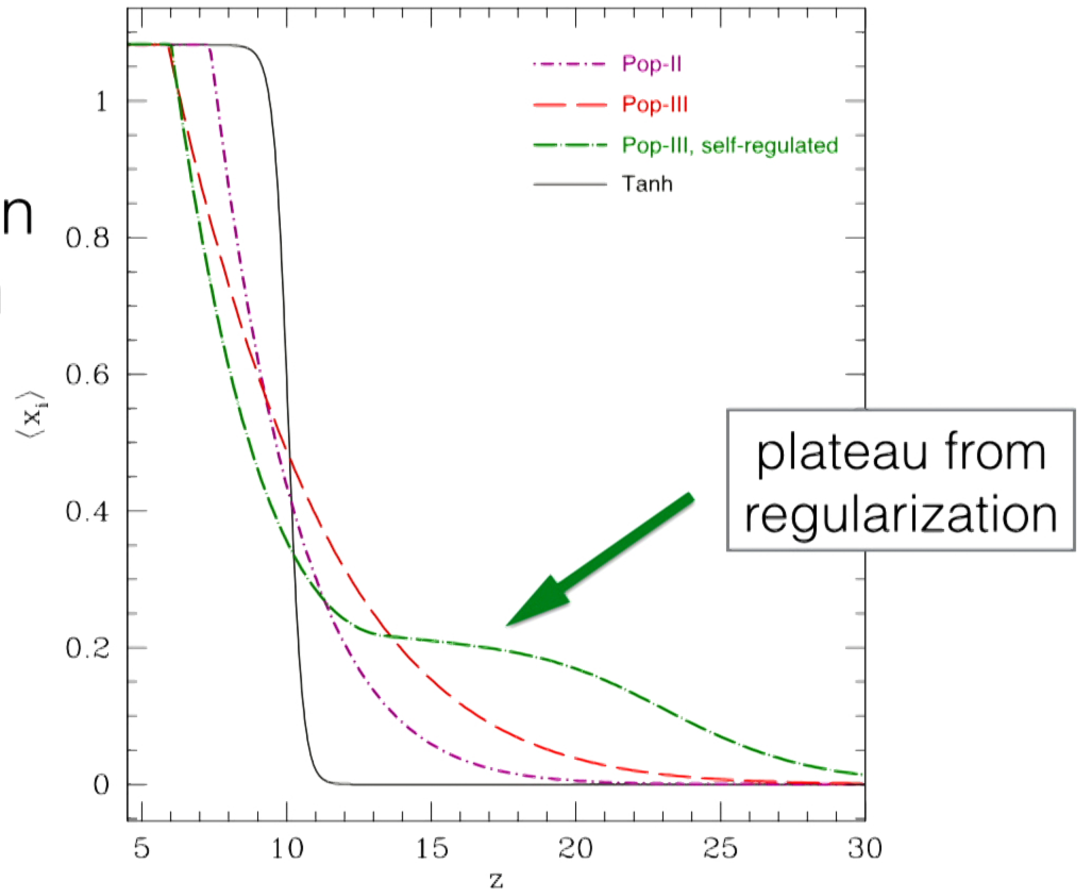
High z ionization: Pop-III stars?

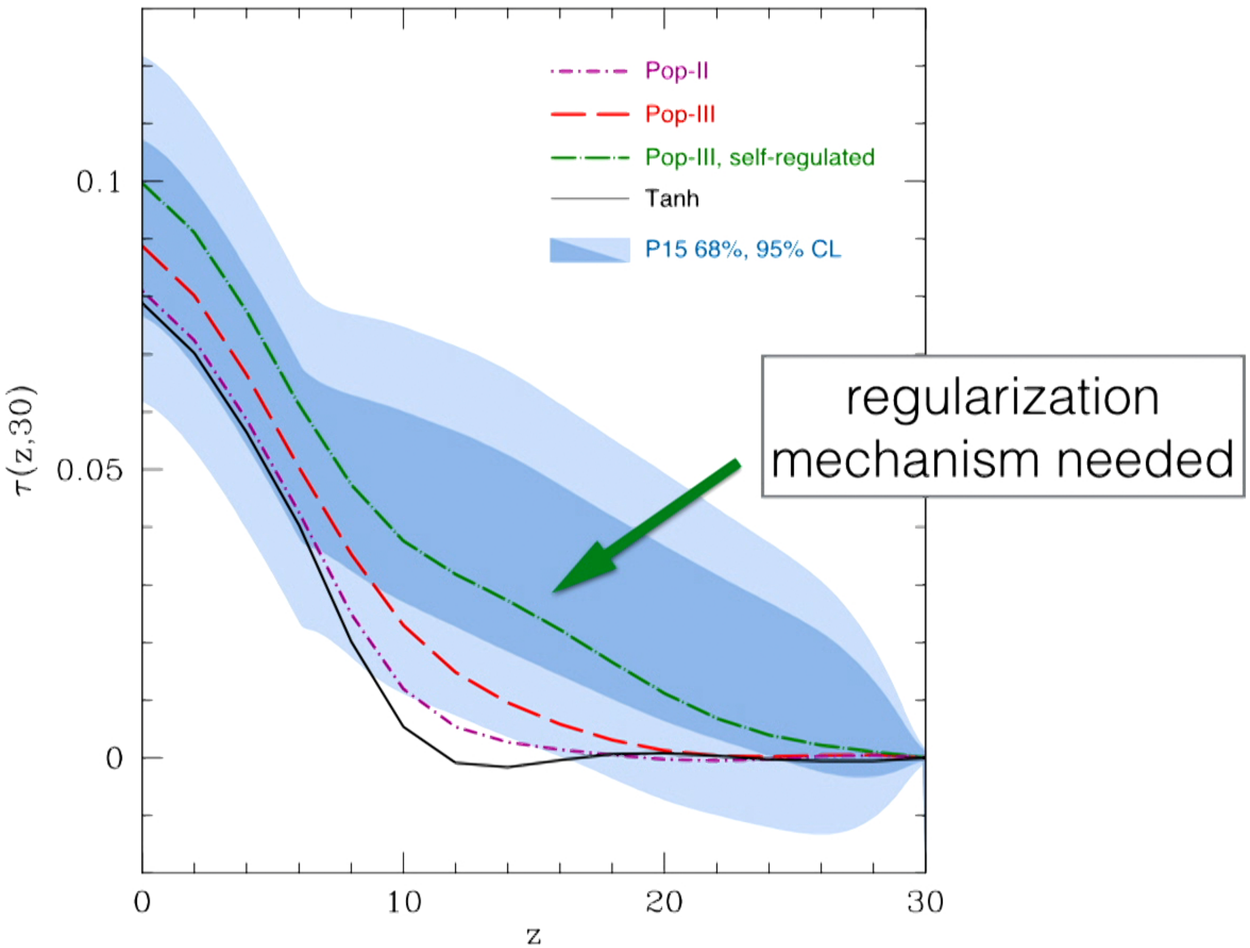
Type of star	Metal Content	Cooling	Host halos
Pop-III	Metal-free	Molecular hydrogen	Minihalos $10^5 - 10^6 M_\odot$
Pop-II	Metal-poor	Atomic line emission	More massive halos

Regularization mechanism needed

Ionization fraction



Miranda, Lidz, CH, Hu 2016



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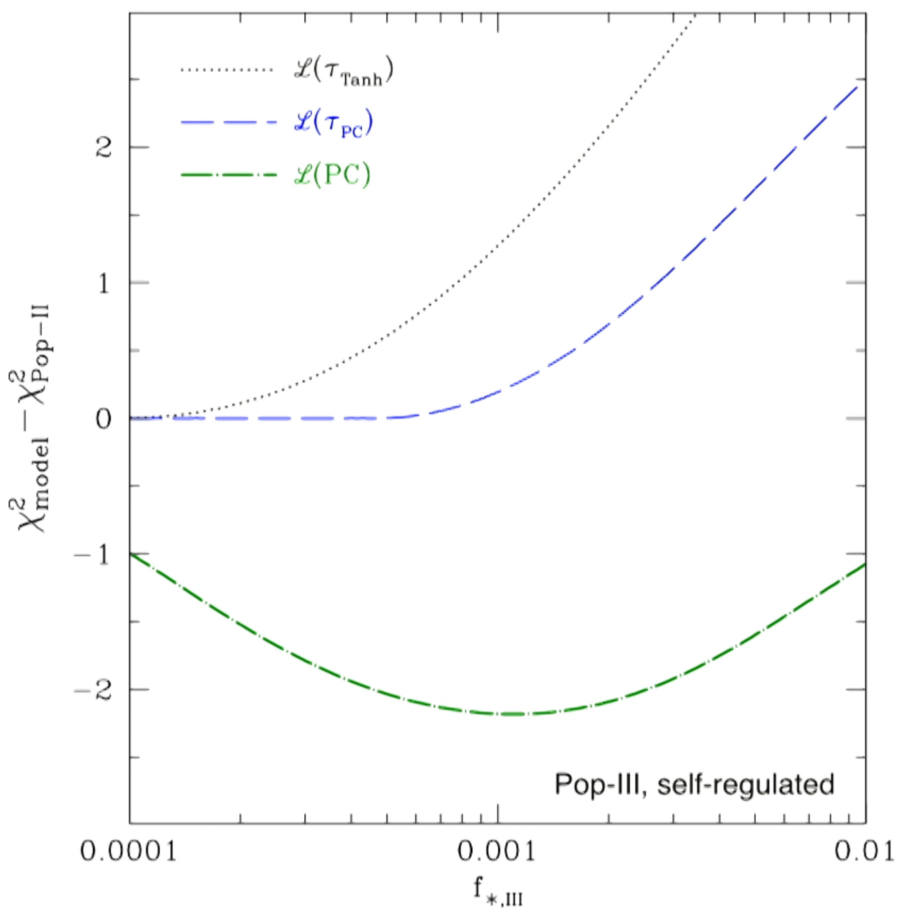

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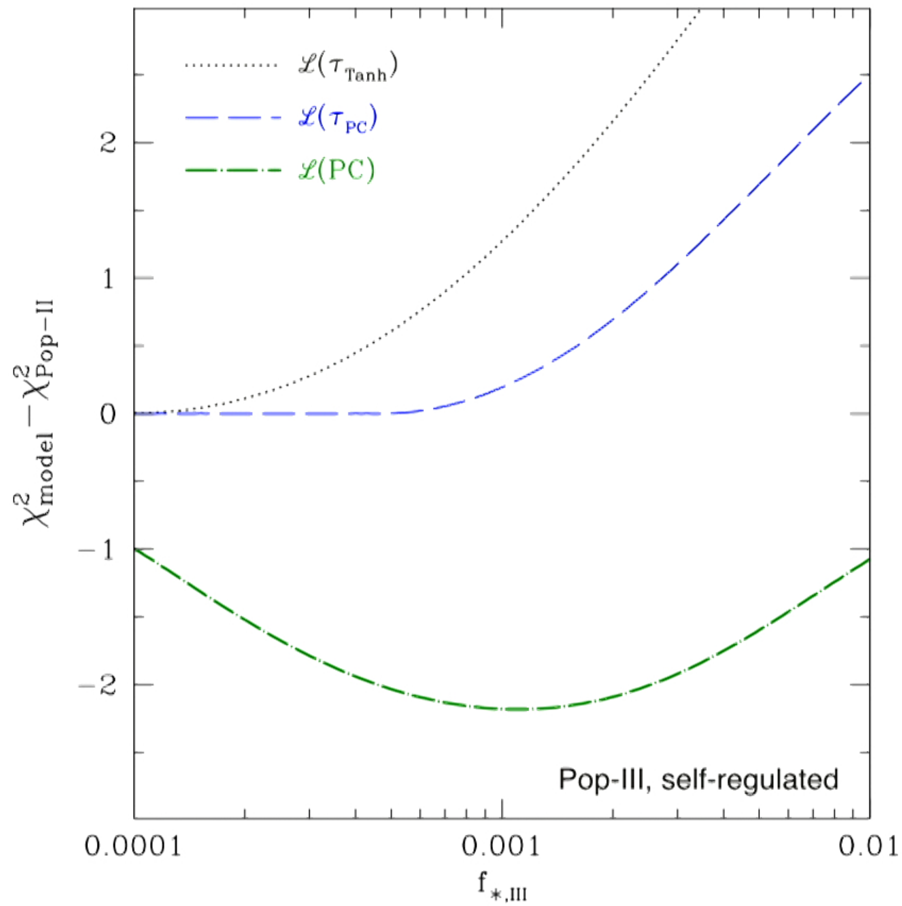

Miranda, Lidz, CH, Hu 2016

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 ReLike** 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.