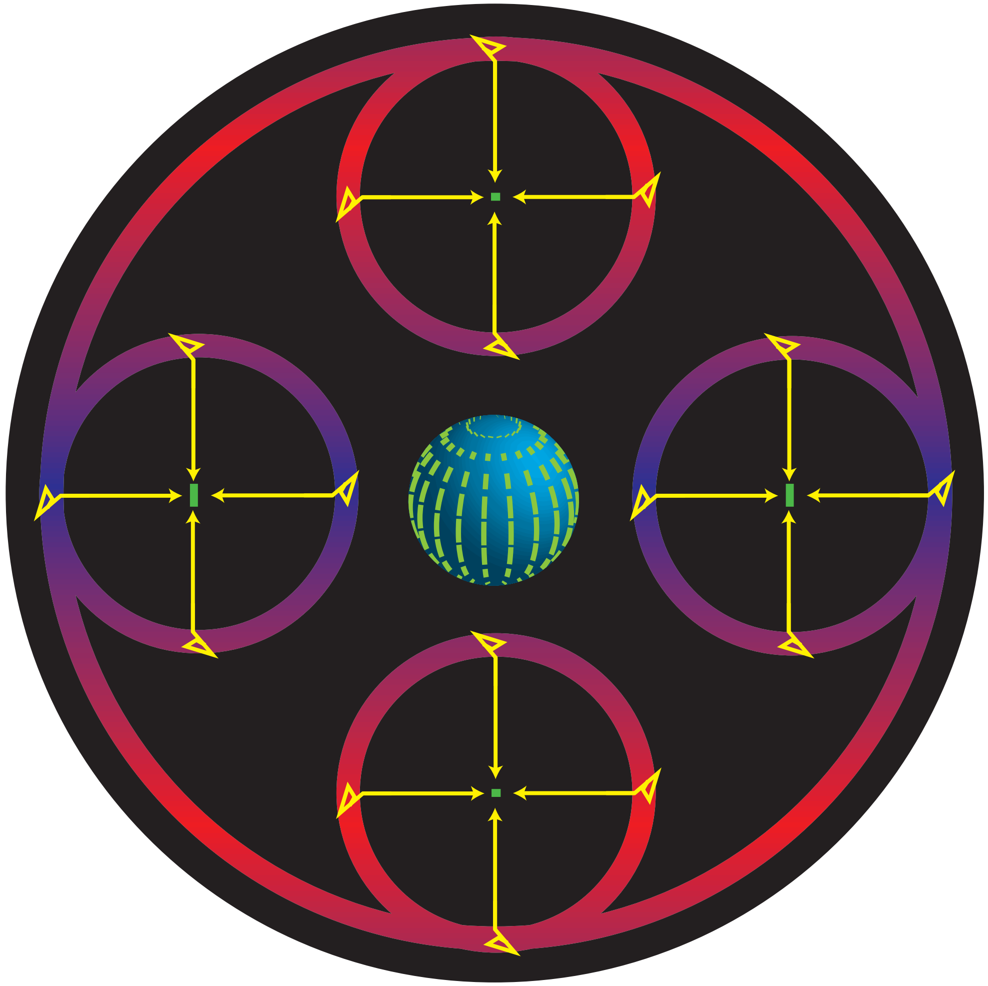
Complete (but not completed!)



CMB Constraints from Large-Angle Polarization

Wayne Hu

March 2019, Aspen

Complete Principal Components

with Chen Heinrich, Vivian Miranda, Georges Obied

- Large angle CMB polarization depends not just on total Thomson optical depth τ
- τ from a steplike ionization history can falsely rule out reionization scenarios and bias cosmological parameters, e.g. m_ν, σ_8

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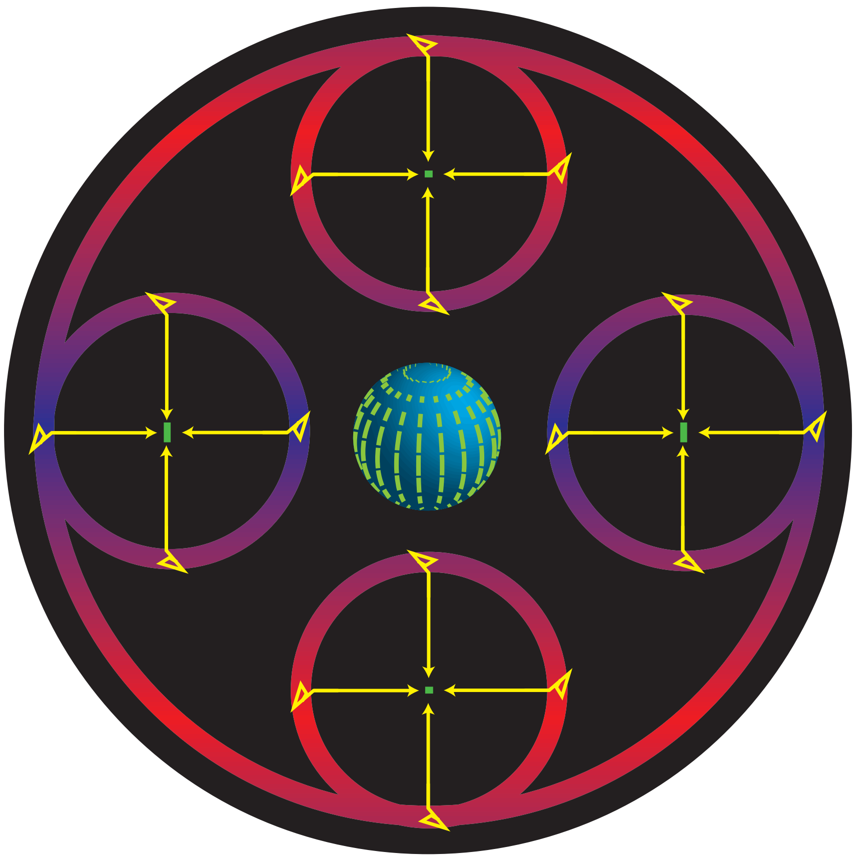
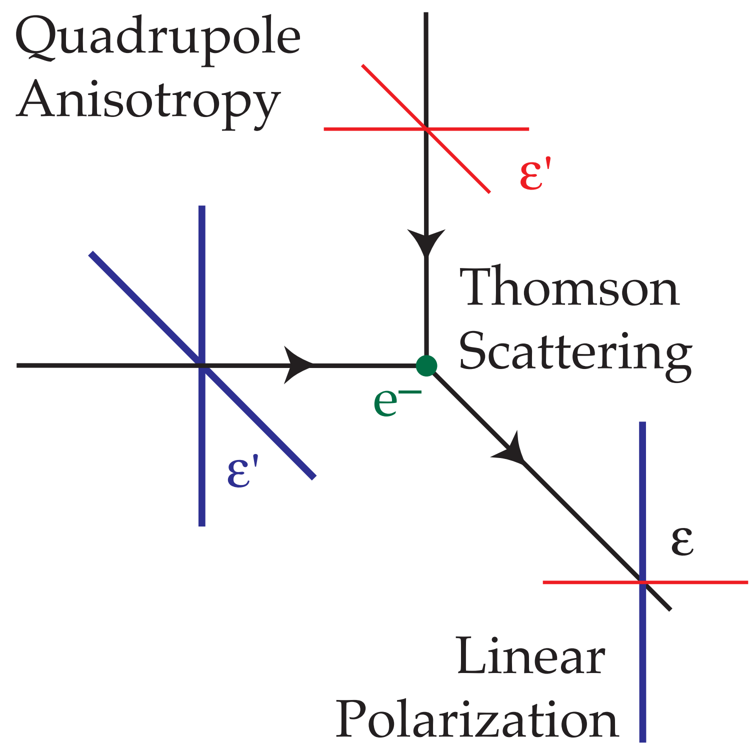
Handful of parameters completely describes observables:

- Any ionization history $x_e(z)$ to a given $z_{\rm max}$
- Single compact, complete, description for all models
- Effective likelihood, can be combined with other reionization data
- Priors appropriate for model parameters (unlike other model independent approaches)

Horizon Scale Features

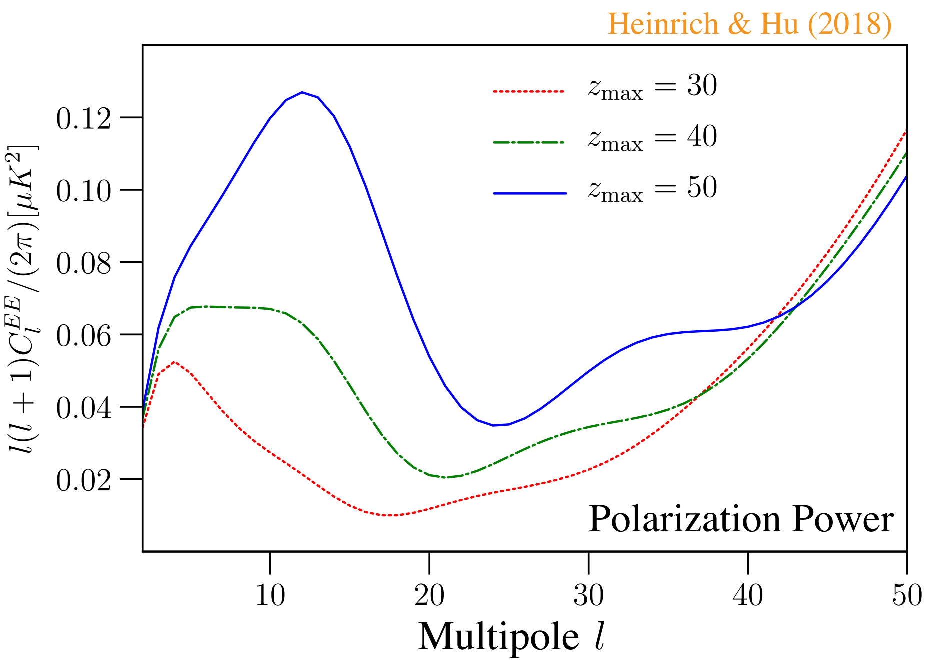
- Streaming photons from temperature inhomogeneities at recombination → temperature quadrupole
- Thomson scattering of quadrupole leads to linear polarization
- Quadrupole, polarization features on horizon scale of reionization





Polarization Power Transfer

- Polarization bump at horizon scale during scattering
- Higher redshift leads to higher multipoles



Horizon scale

$\longrightarrow$ Polarization feature

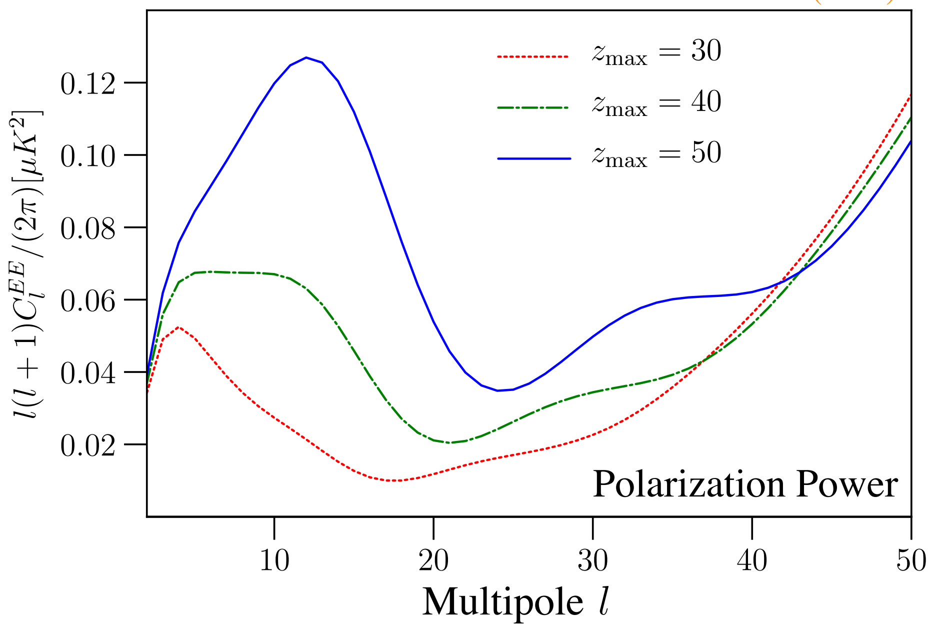
Higher multipole

$\longrightarrow$ Lower cosmic variance

Polarization Power Transfer

- Polarization bump at horizon scale during scattering
- Higher redshift leads to higher multipoles
- Transfer of power per unit ionization, redshift
- Cosmic variance errors imply rich information on high z ionization history

Heinrich & Hu (2018)



Horizon scale

$\longrightarrow$ Polarization feature

Higher multipole

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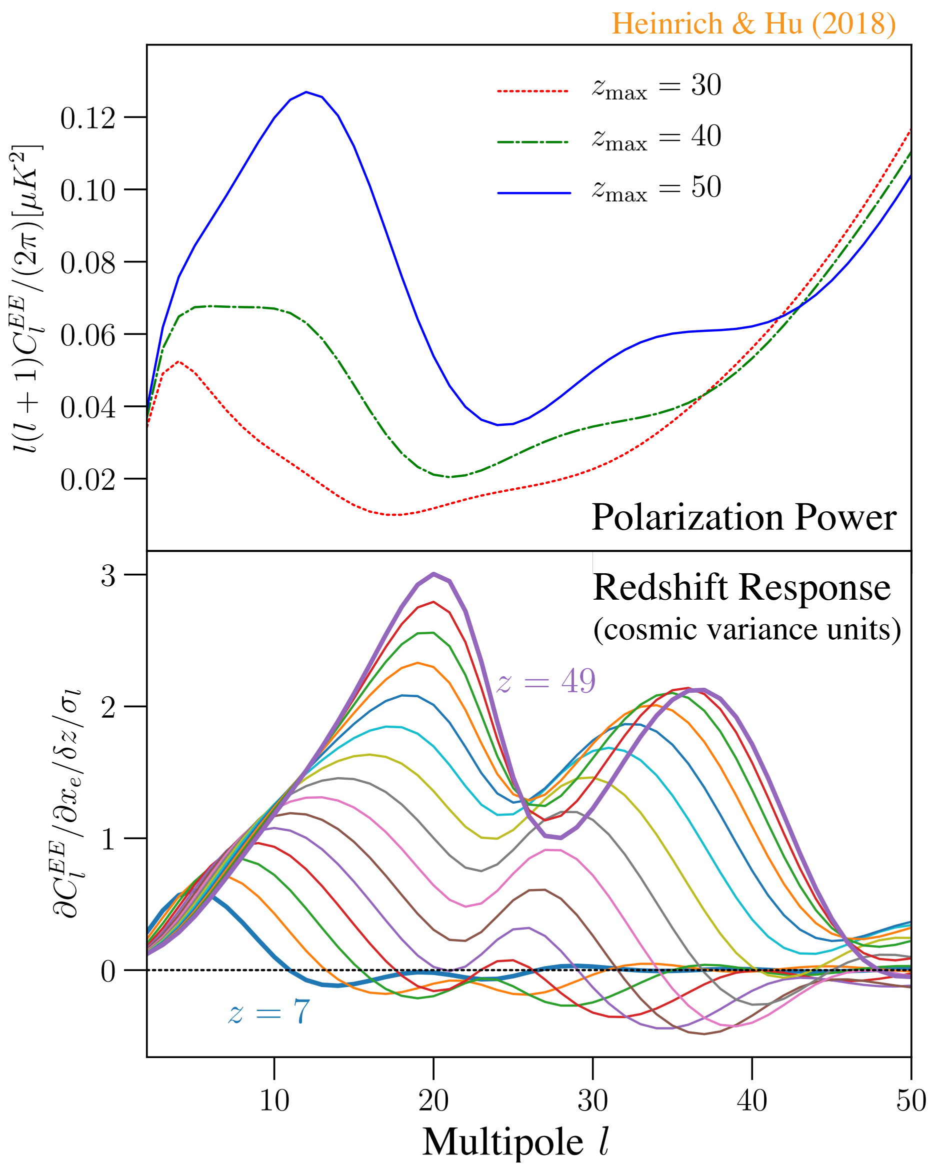
Polarization Power Transfer

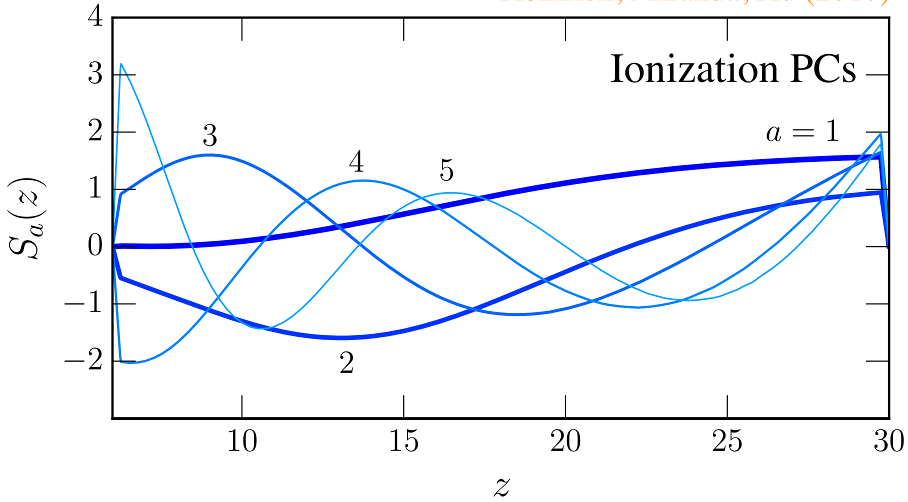
- Polarization bump at horizon scale during scattering
- Higher redshift leads to higher multipoles
- Transfer of power per unit ionization, redshift
- Cosmic variance errors imply rich information on high z ionization history
- Neighboring redshifts give degenerate response
- Requires optimized parameterization...



Principal Components

- Ionization principal components pre-determined from Fisher forecast Hu & Holder 2003; Mortonson & Hu 2007
- Basis functions, like Fourier basis, capture observable low frequency information
- Faithful representation of observables to cosmic variance limit

Heinrich, Miranda, Hu (2017)



Five components:

first two - high to low z

Principal Components

- Ionization principal components pre-determined from Fisher forecast Hu & Holder 2003; Mortonson & Hu 2007
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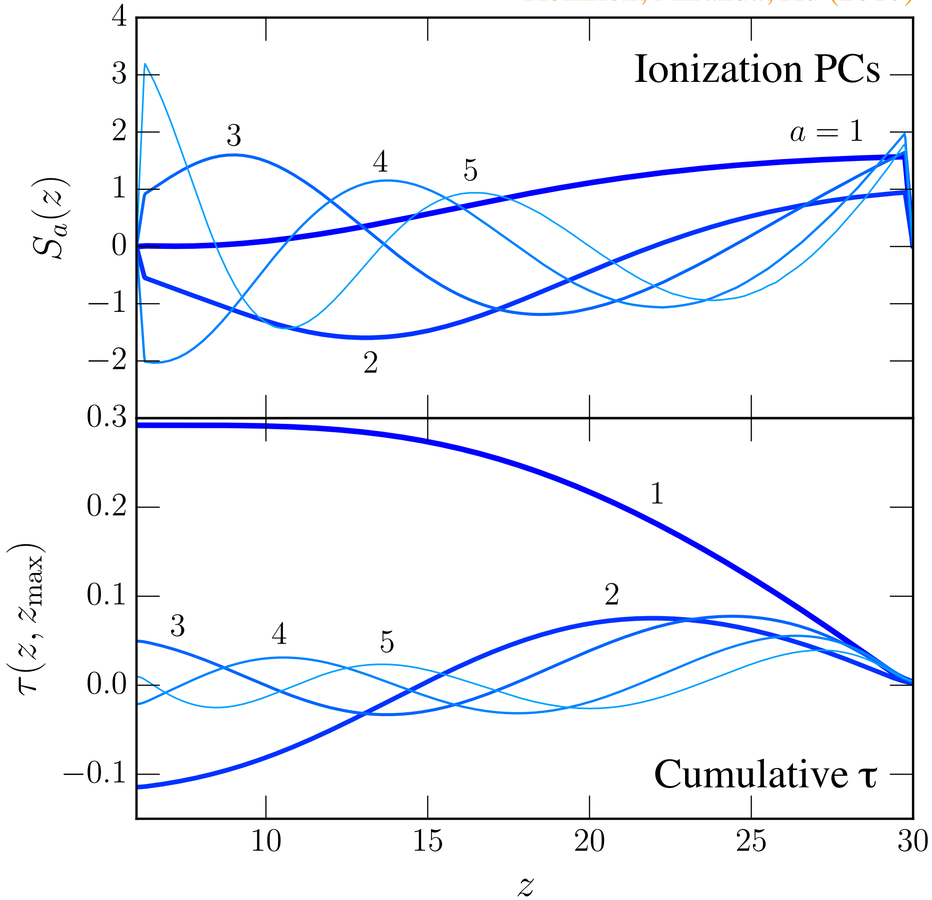


- Not a faithful reconstruction of ionization history
- Visualized best as cumulative high-z optical depth between $(z, z_{\rm max})$ — first two modes, low vs high z

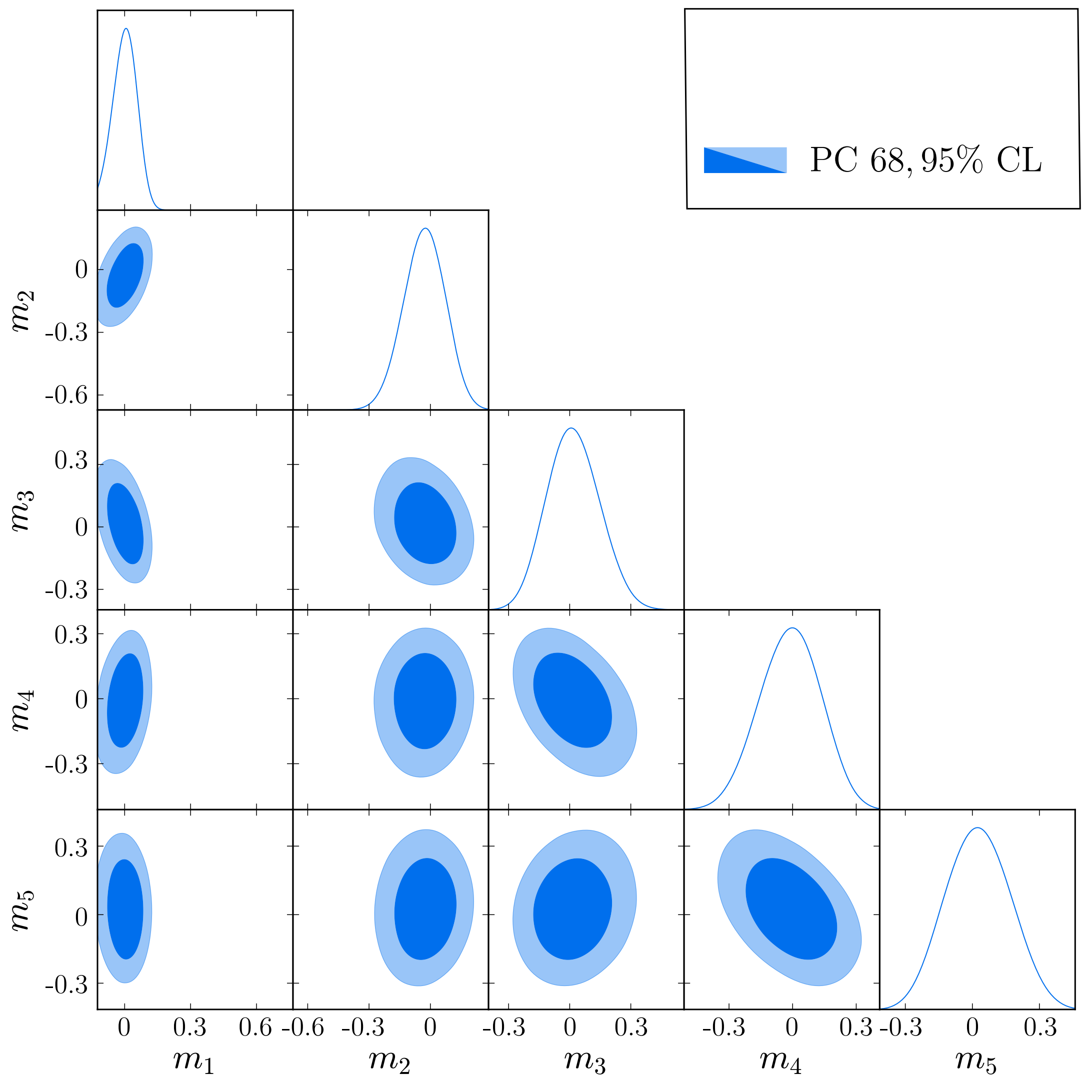
User's Guide

- Provide(d) an effective likelihood for the PC parameters
  (Heinrich, Miranda, Hu 2017)
- Extracts all reionization information to $z_{\rm max}$ from polarization
- For any such model of reionization, incorporate Planck constraints simply with effective likelihood - no need to reanalyze data
- Complete and allows any physically motivated Prior(parameters) to be applied to analysis unlike other approaches
- Unphysical $x_e < 0$, allowed by PCs, automatically eliminated
- Users guide for forward modeling using PCs:

Model		PCs		Parameters
x_e(param)	project →	m_a(param)	constrain →	P[param]
		$= I_a[x_e(\text{param})]$		$= \text{Like}[m_a(\text{param})]$
				x Prior[param]

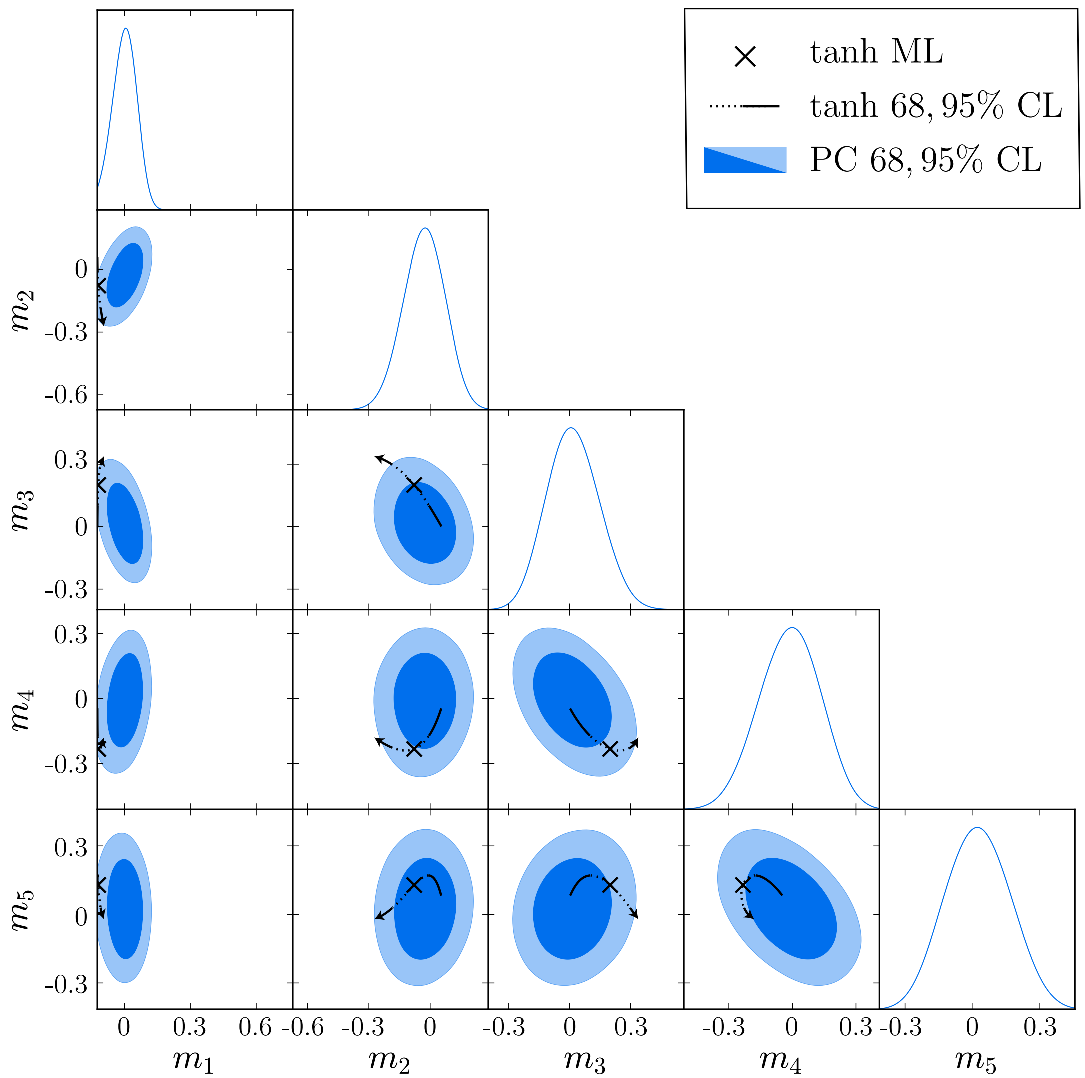
Planck 2015

- Tests on Planck 2015 data – (2018 VI data much improved stat & syst: $\tau_{\rm tanh} = 0.0544 \pm 0.0073$ - likelihood not yet public)



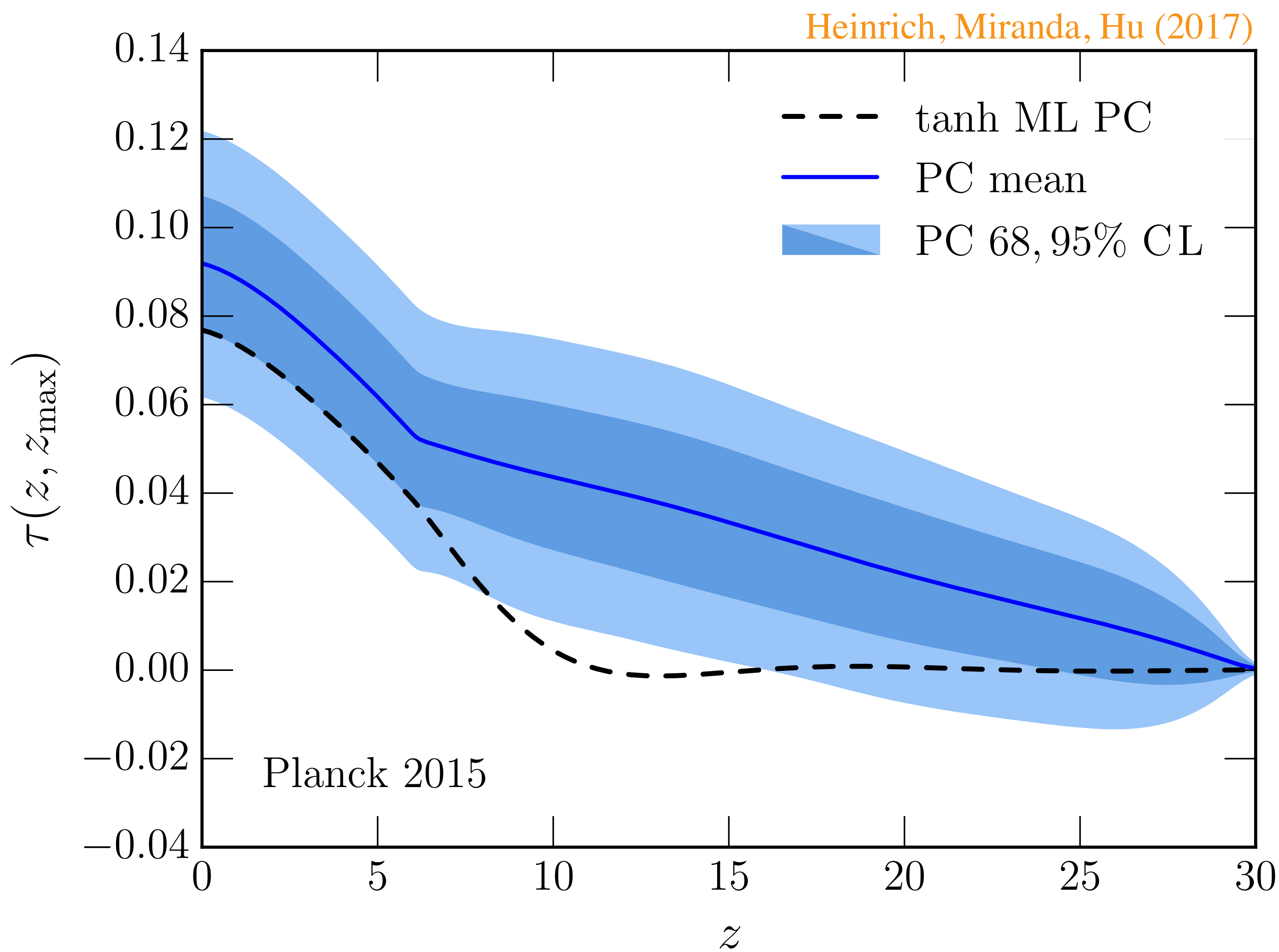
Planck 2015

- Standard step function (tanh) executes a 1D trajectory in space - much larger allowed space to high z ionization



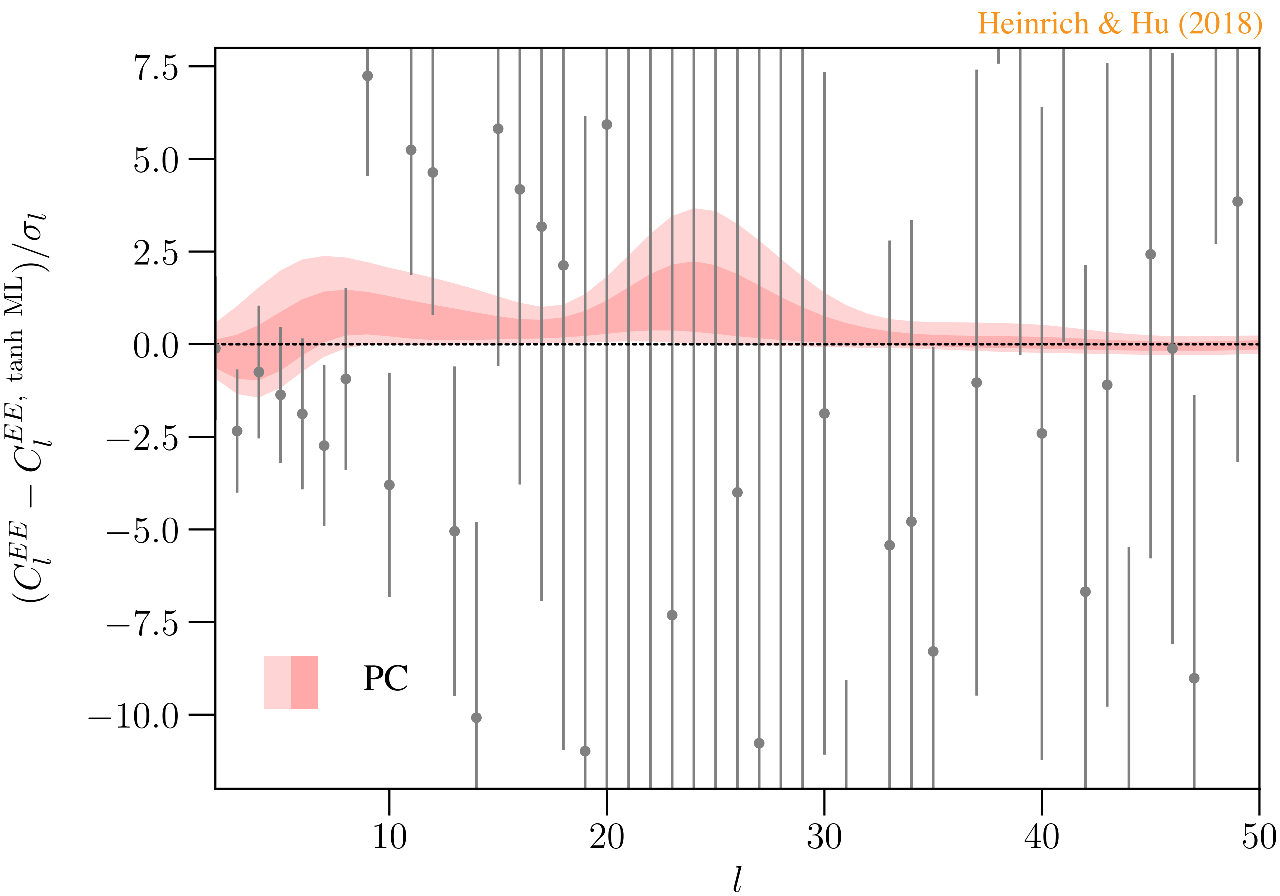
Planck 2015

- Allows much more ionization at high redshift than tanh τ analysis would imply (2σ, $z > 15$)



Planck 2015

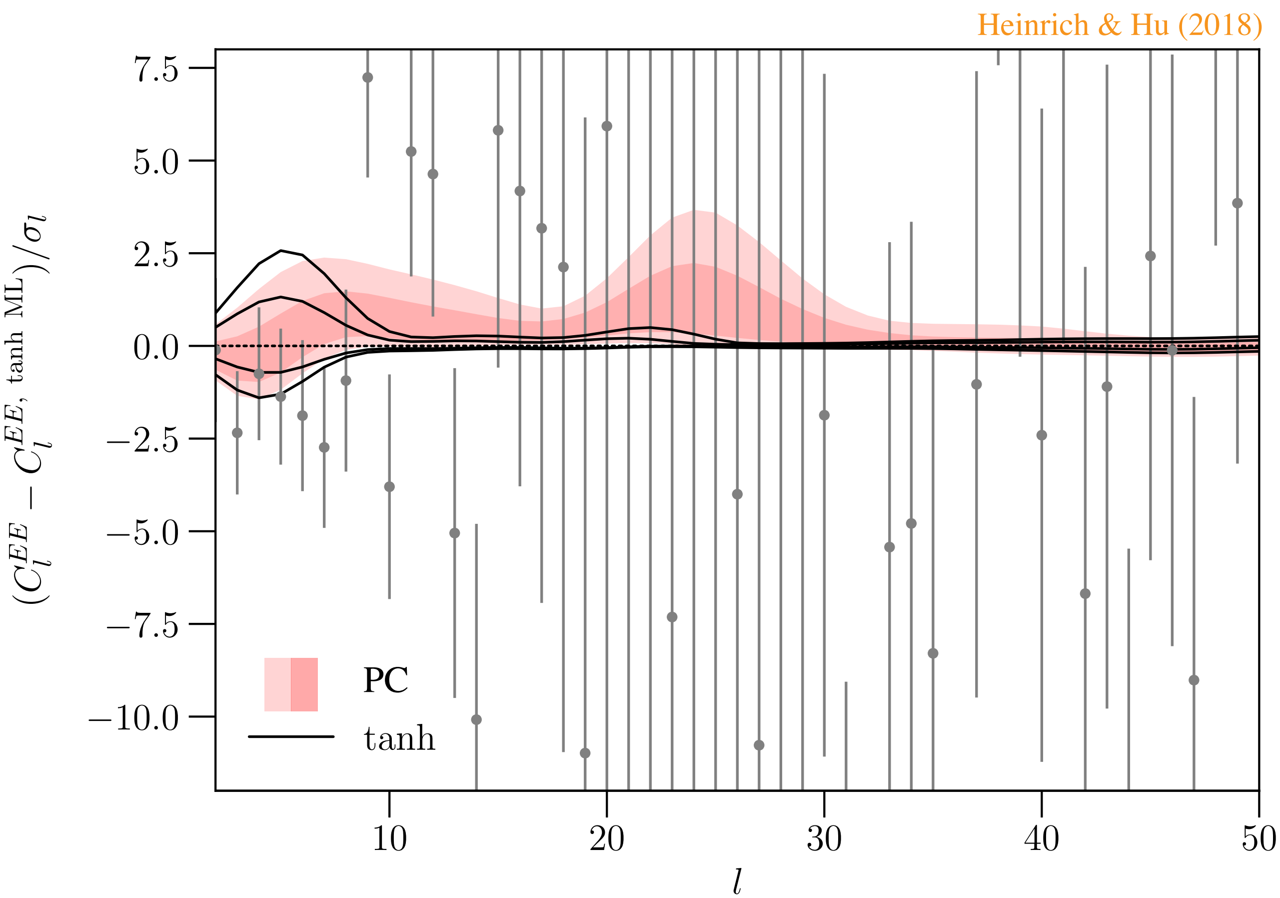
- Originate from tight constraints at lowest ℓ but glitchy/noisy data at higher ℓ



- Improved in Planck 2018 VI - high-z constraints $\tau(15,30) < 0.006$

Planck 2015

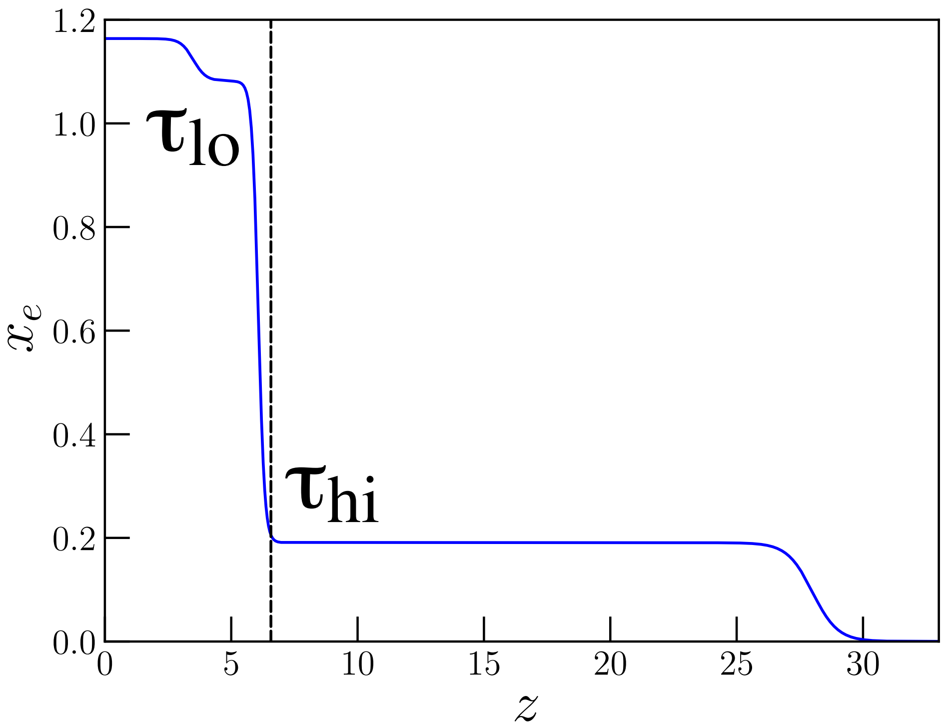
- If priored to tanh models lowest ℓ constraints forbid raising τ



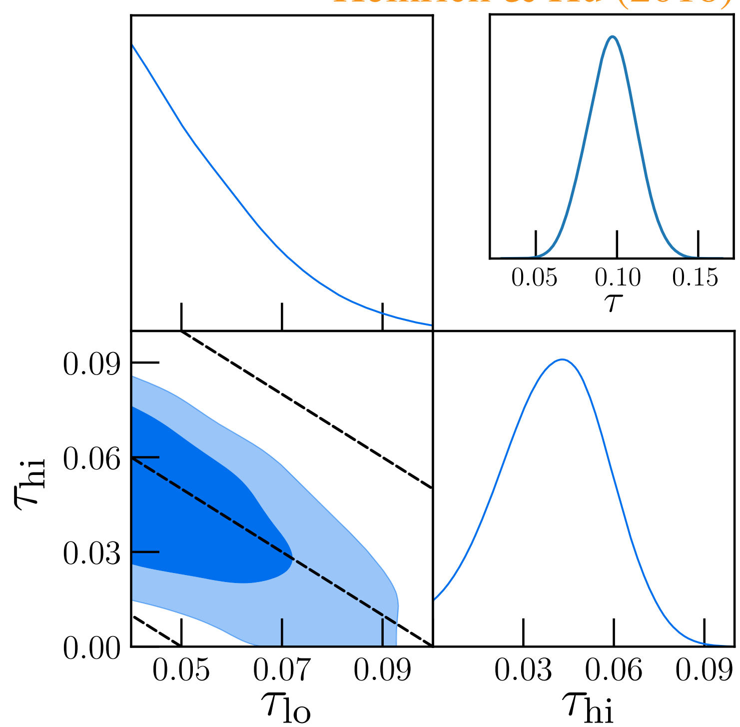
- Improved in Planck 2018 VI - high-z constraints $\tau(15, 30) < 0.006$

Model Parameter Counting

- Example usage: double step reionization analyzed by PCs or directly give same results
- Shows improved $\Delta\chi^2 \sim 5.3$ can be achieved by single extra parameter — τ at high $z \to \tau_{\rm hi}$
- Represented by 5 PCs for completeness



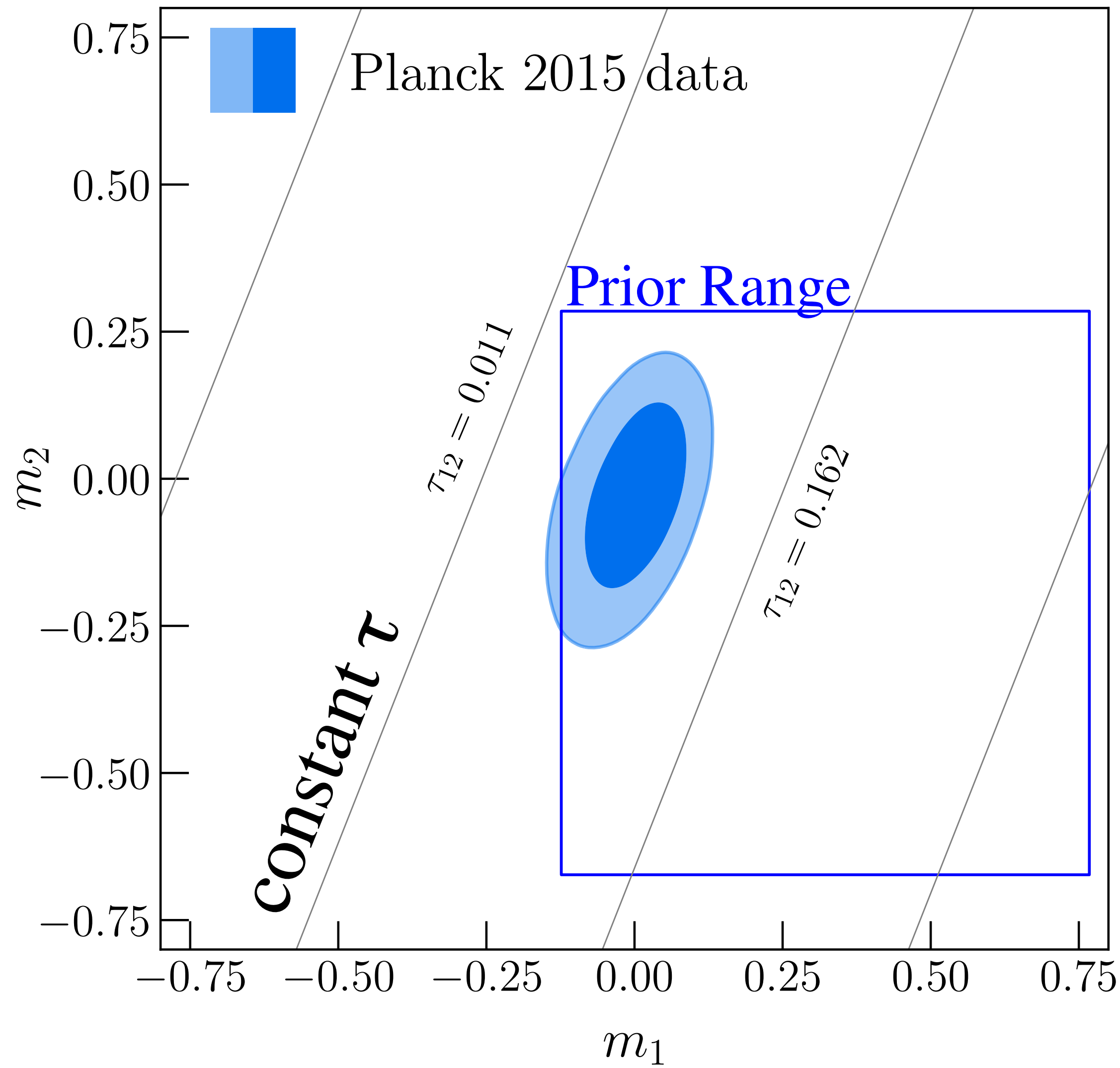
Heinrich & Hu (2018)



Bias: Millea & Bouchet

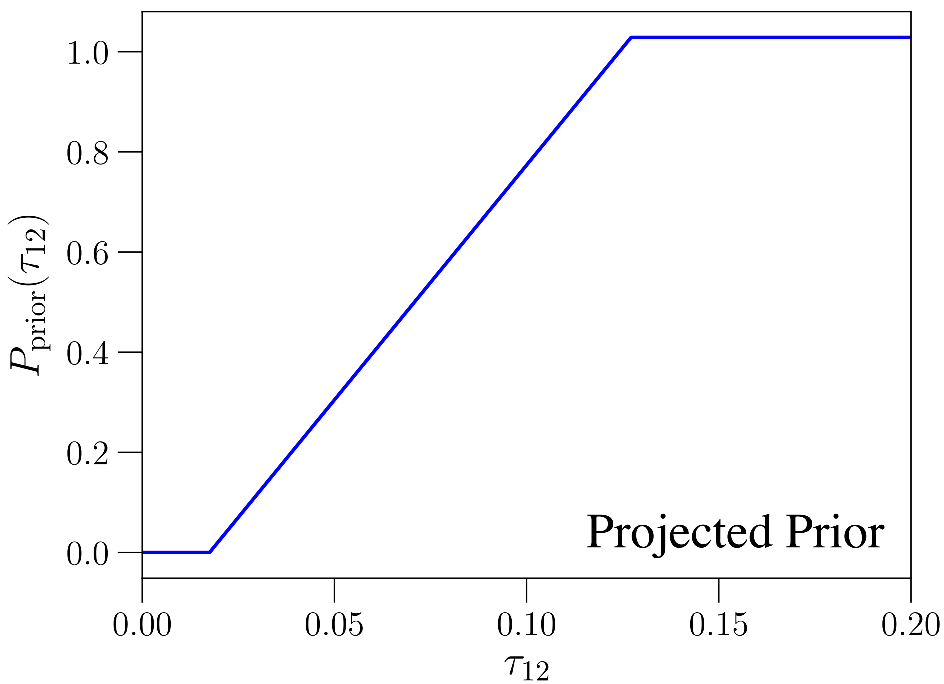
- Priors on model parameters can be accounted for leading to no bias
- Millea & Bouchet 1804.08476 claim technique is biased when considering total τ
- τ : linear combination of m_1, m_2 with flat priors from physical bound $0 \leq x_e \leq x_{\max}$

Heinrich & Hu (2018)



Bias: Millea & Bouchet

- When this prior is projected from 2D to the 1D τ dimension it has a global shape even though locally flat by linearity
- Millea & Bouchet (adopted by Planck 2018) advocate dividing by prior point by point in multidimensional space



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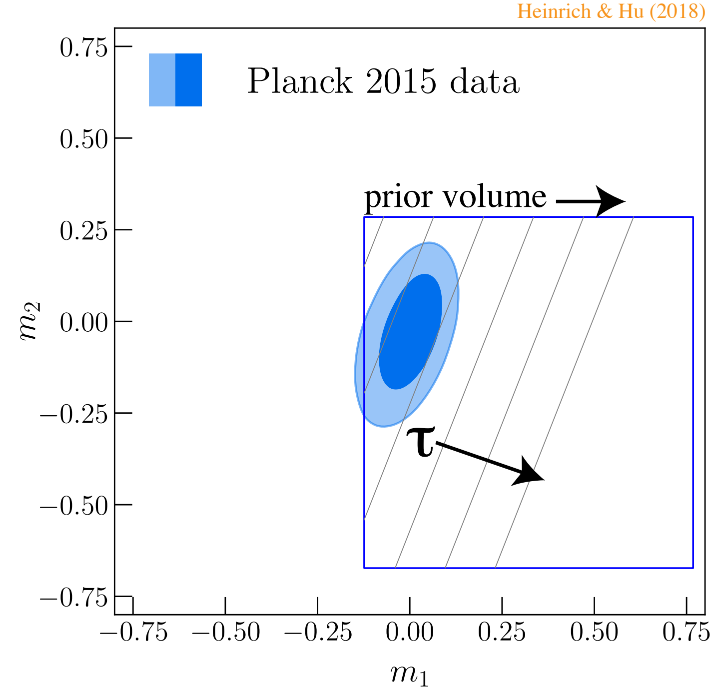
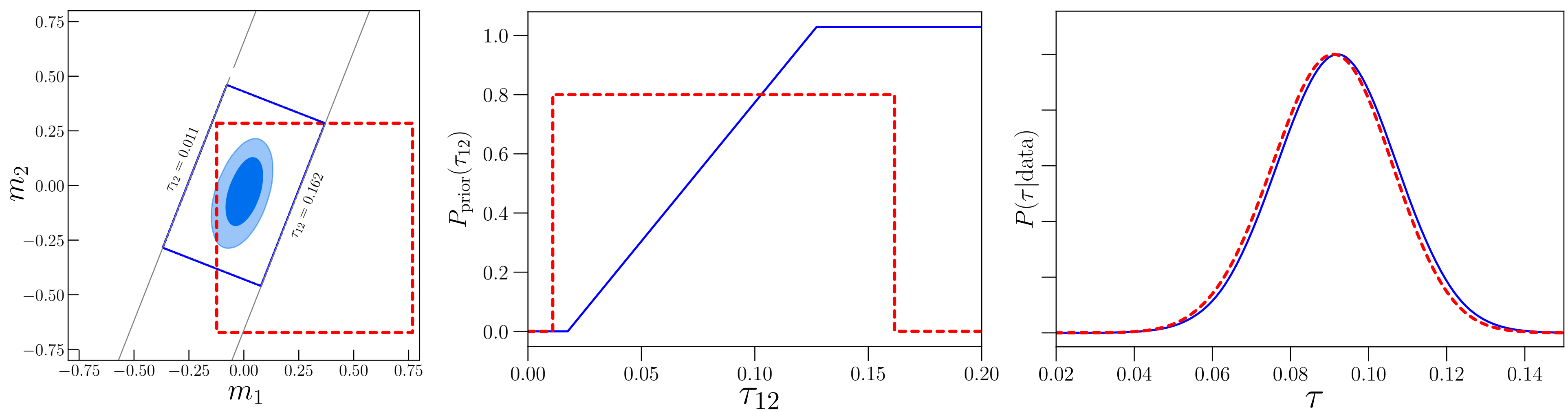


- Flaw: only valid if the data does not constrain the orthogonal dimension

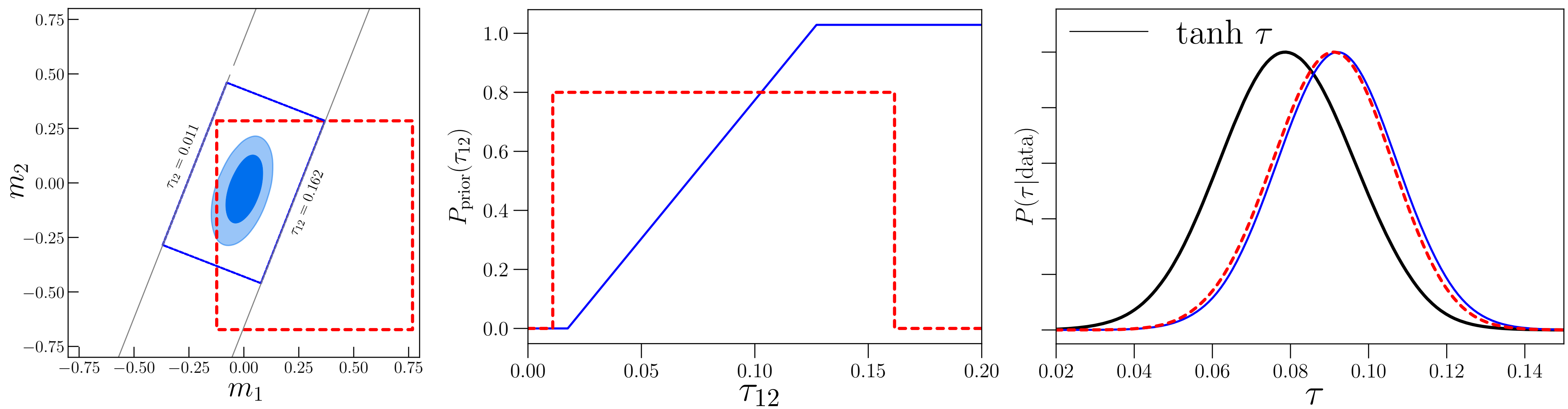
Bias: Millea & Bouchet

- Thought experiment: orthogonal dimension is precisely measured, prior irrelevant: correction for the non-existent bias, thereby introduces a bias
- Currently, orthogonal direction already constrained better than prior range
- Explicit test: change the prior range to be flat a priori rather than by inversion – nearly identical results



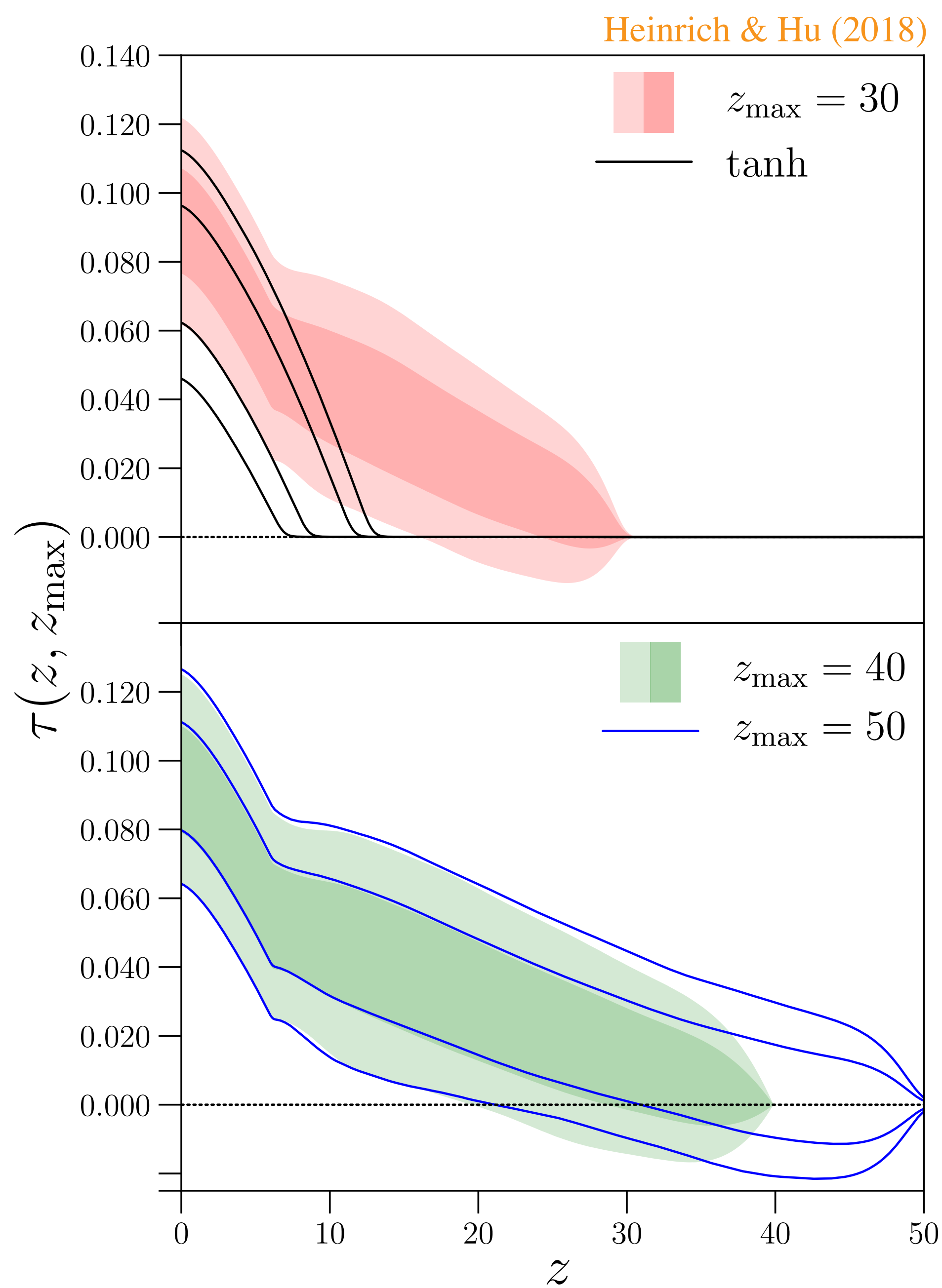
Bias: Millea & Bouchet

- Thought experiment: orthogonal dimension is precisely measured, prior irrelevant: correction for the non-existent bias, thereby introduces a bias
- Currently, orthogonal direction already constrained better than prior range
- Explicit test: compared with larger shift from tanh assumption



Fiducial Model and Range

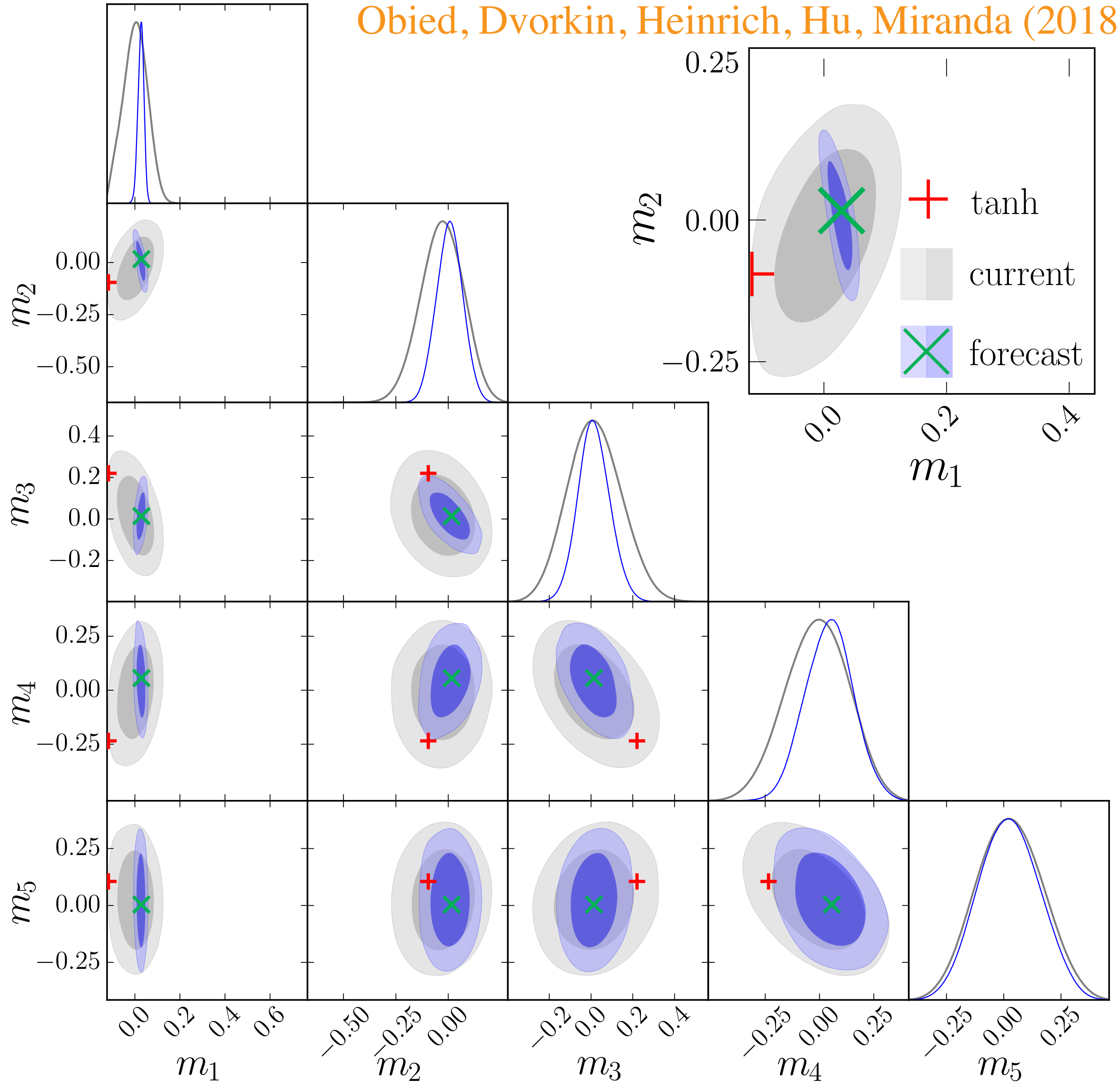
- Results robust to extending redshift range
- More parameters, up to 7 for $z_{\rm max} = 50$
- Changes in fiducial model around which PCs built
- Cumulative optical depth mostly unchanged
- Little current ability to distinguish high from ultra high
- Due to noisy measurements for $15 \lesssim \ell \lesssim 30$



Toward Cosmic Variance

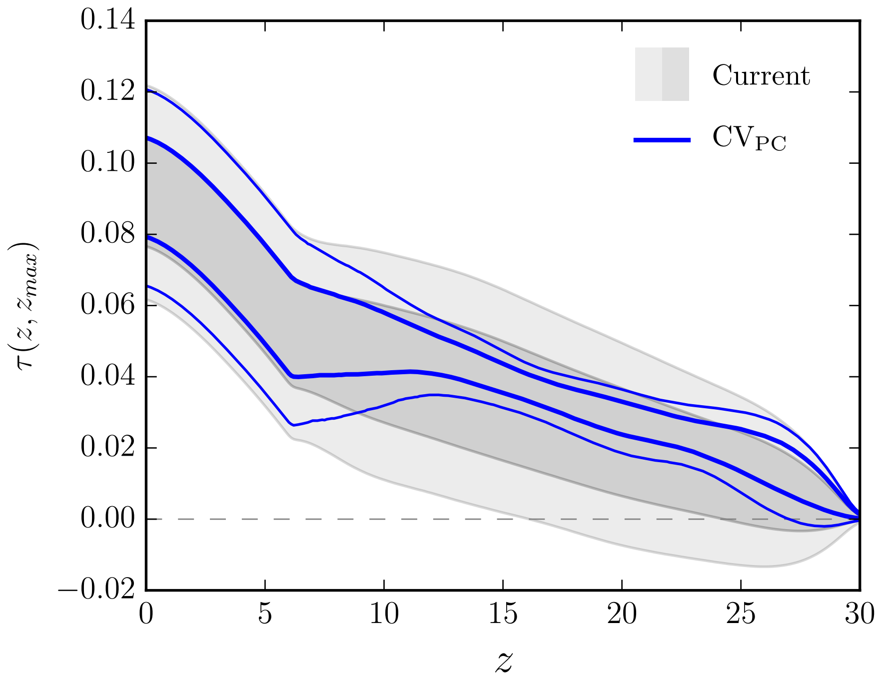
- Forecast $14 \leq \ell \leq 30$ polarization cosmic variance limit

Obied, Dvorkin, Heinrich, Hu, Miranda (2018)



Toward Cosmic Variance

- Cumulative τ forecast improved



- Post collaboration Planck systematics/maps improvement in arXiv:1901.11386 – cv-limited at $\ell < 8$, $\sigma_{\tau_{\rm tanh}} = 0.005$, no single multipole glitches
- Ground based CLASS experiment potentially can also reach near cv-limited arXiv:1801.01481

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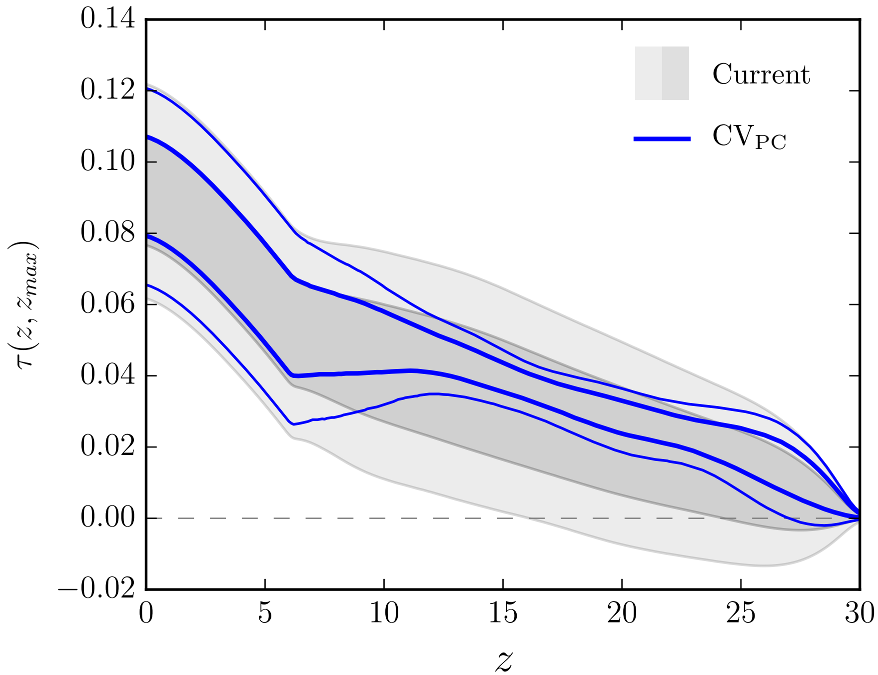
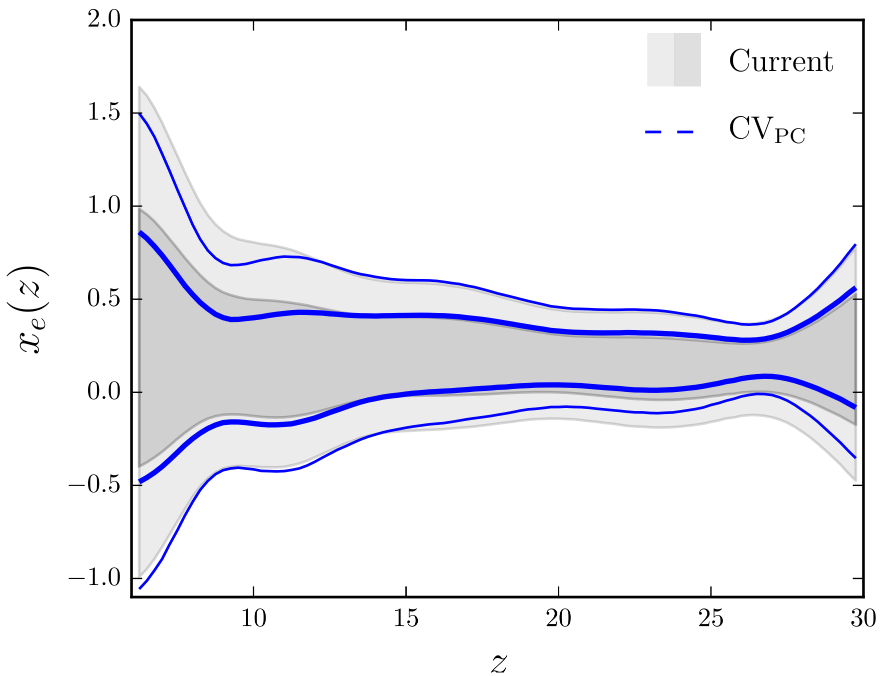
- Cumulative τ forecast improved





- Post collaboration Planck systematics/maps improvement in arXiv:1901.11386 – cosmic variance limited at $\ell < 8$, $\sigma_{\tau_{\rm tanh}} = 0.005$, no single multipole glitches
- Aside: ionization history reconstruction never improved: visualization always dominated by the worst constrained mode

Summary

- Planck will be the definitive source of large angle CMB polarization information on reionization for foreseeable future
- PC technique encapsulates all of the Planck polarization information on reionization out to $z_{\rm max}$
- Additional constraints on cumulative optical depth at high-z
- Effective likelihood tools for fast, lossless analysis of any such reionization model
- Priors can be chosen appropriate to model tested
- Questions:

  what software tools would help allow this technique to be used?

  what redshift ranges would be most useful?