Disentangling Inflation, Reionization and Cosmic Acceleration with the CMB

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Dark Energy Survey member

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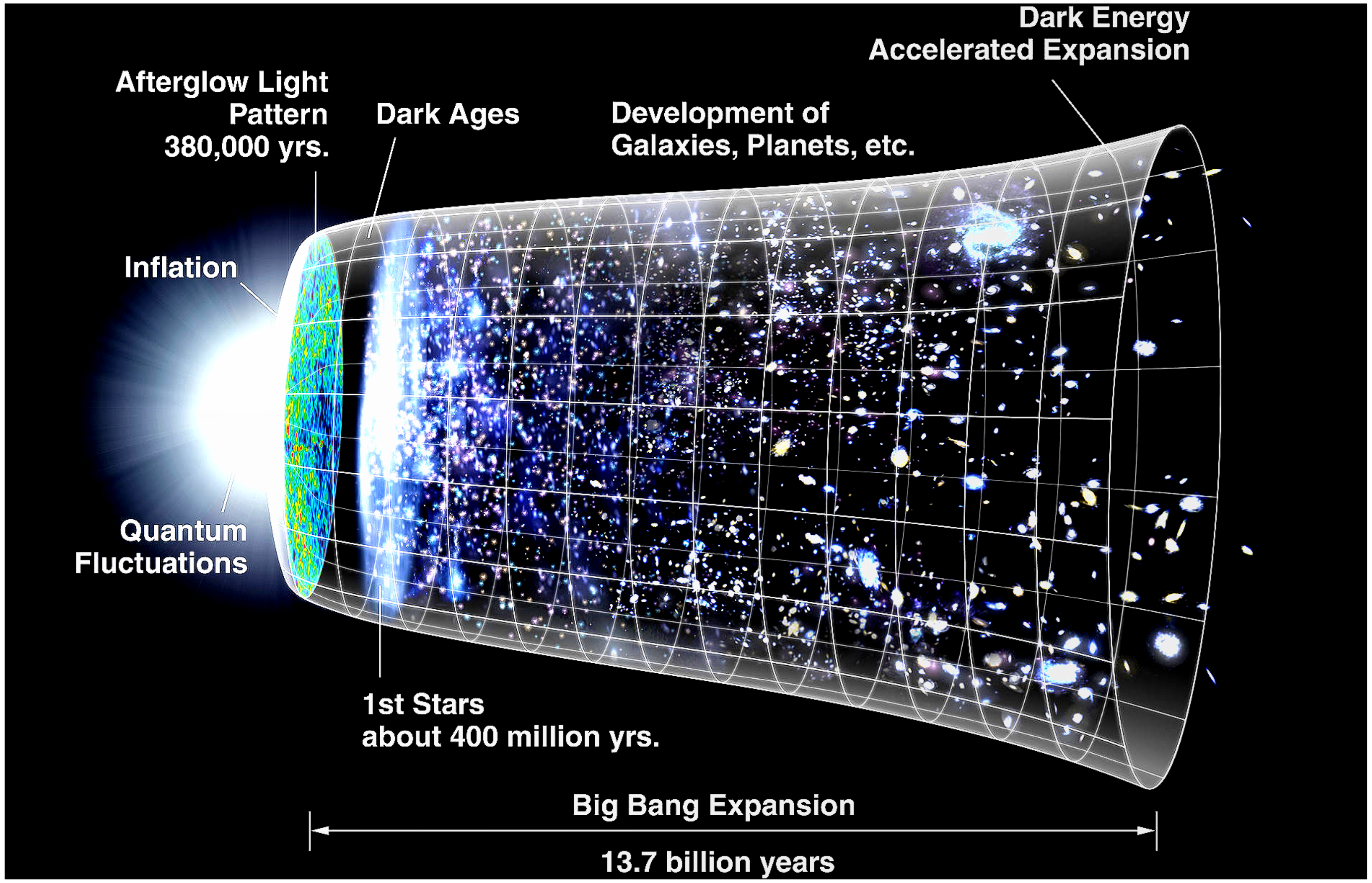
Inflation, Reionization and Cosmic Acceleration

They are the backbones of the standard model of cosmology.

Underlying physics is not well understood.

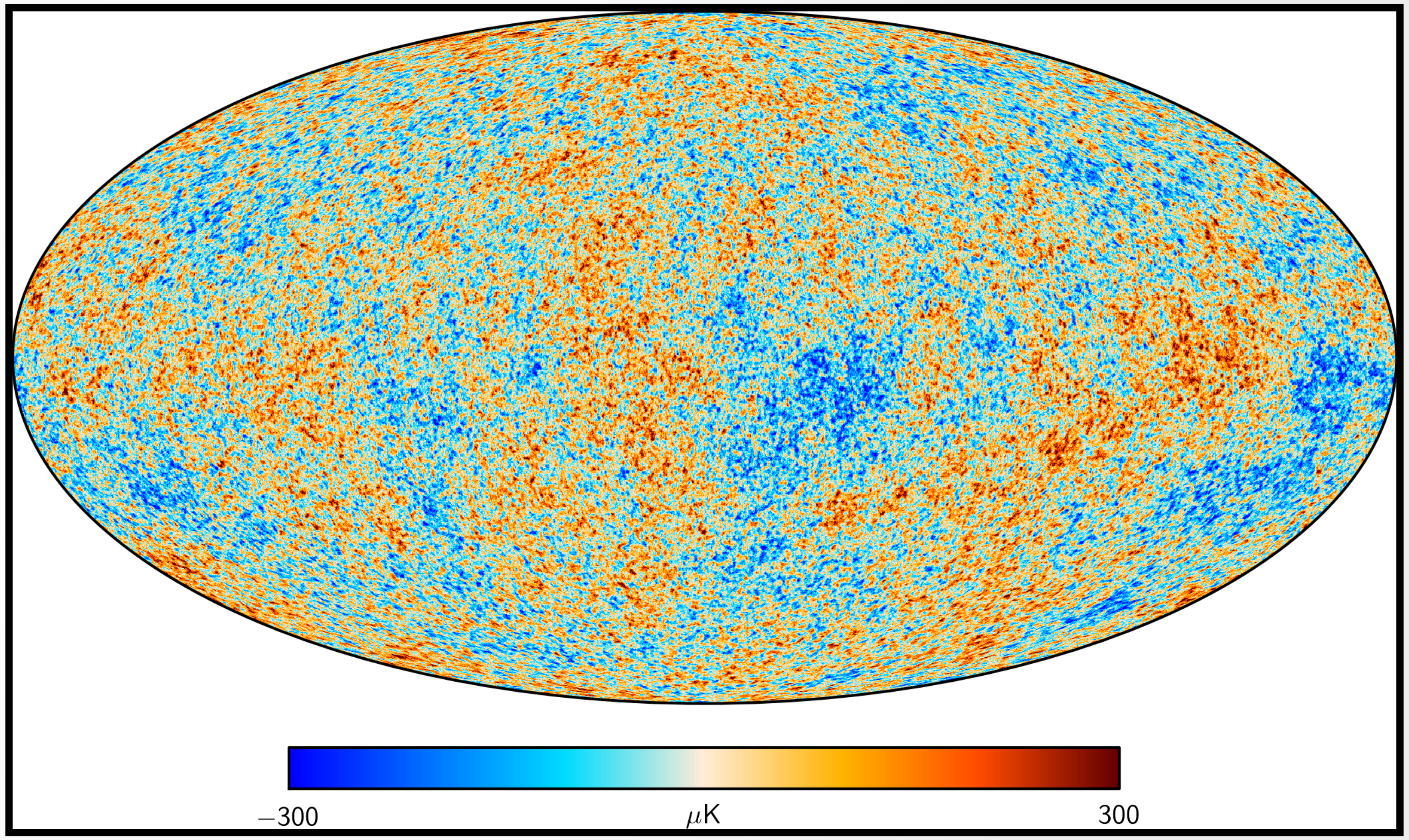
There is an abundant amount of data that can constrain each epoch.



Inflation, Reionization and Cosmic Acceleration

Most inferences rely on the CMB to some degree

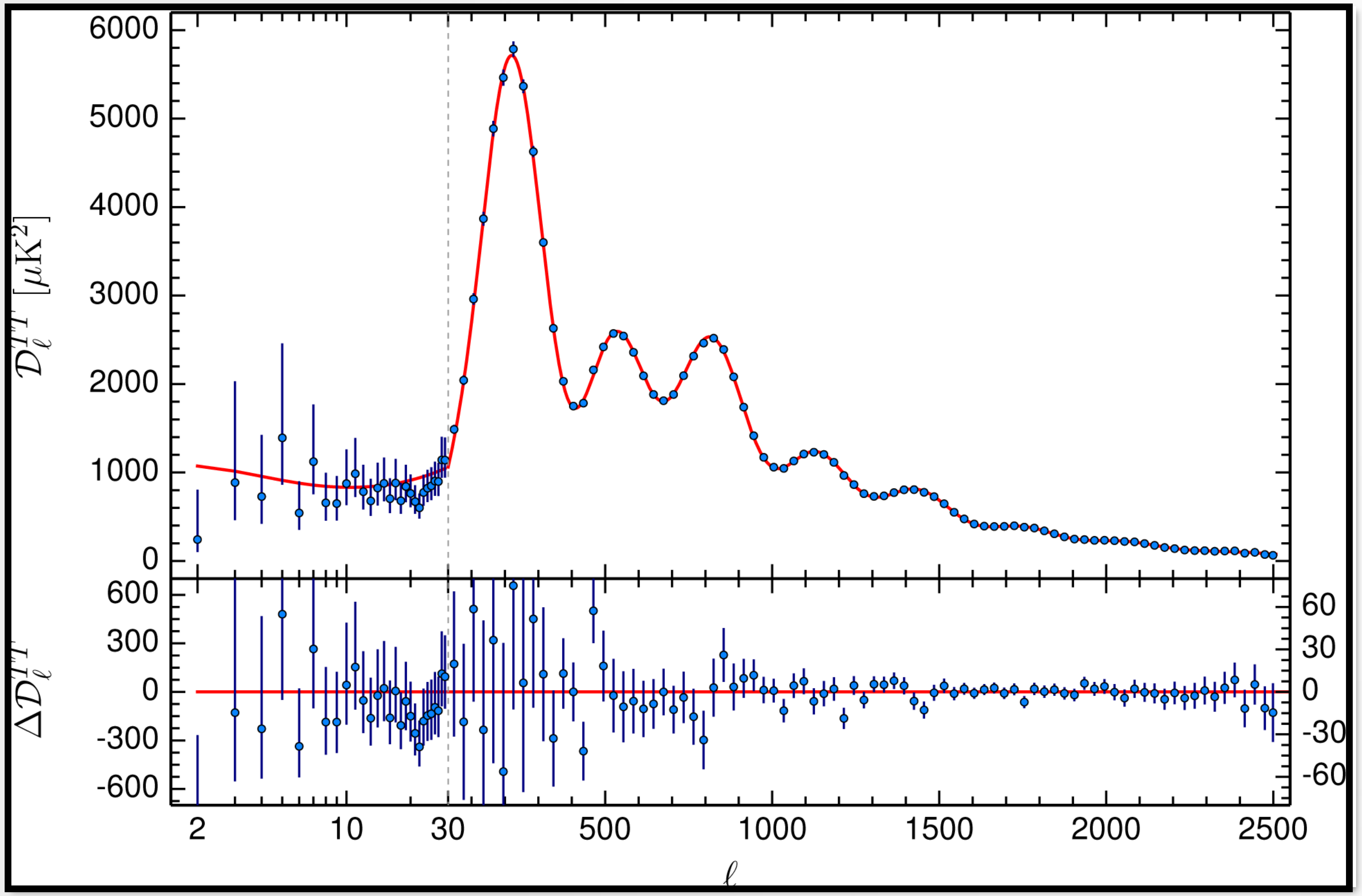
CMB: disentangling Inflation, Reionization and Cosmic Acceleration is not trivial



Observed maps = primordial + lensing + reionization + ISW + foregrounds + SZ effect + …

Part I: Inflation vs Cosmic Acceleration

Basic cookbook of inflation: slow-roll approximation



Inflation: power law

$$\Delta^2_{\mathcal{R}} = A_s \left(\frac{k}{k_0} \right)^{n_s - 1}$$

$$D_\ell^{TT} \propto \int d \ln k \text{ Inflation} \times \text{Transfer}$$

Transfer: physics of baryon-photon coupling

How can we compute observables in such models?

The Generalized Slow-Roll Approximation

$$\ln \Delta^2_{\mathcal{R}} = I_0(k) + \ln[1 + I_1^2(k)]$$

Cora Dvorkin

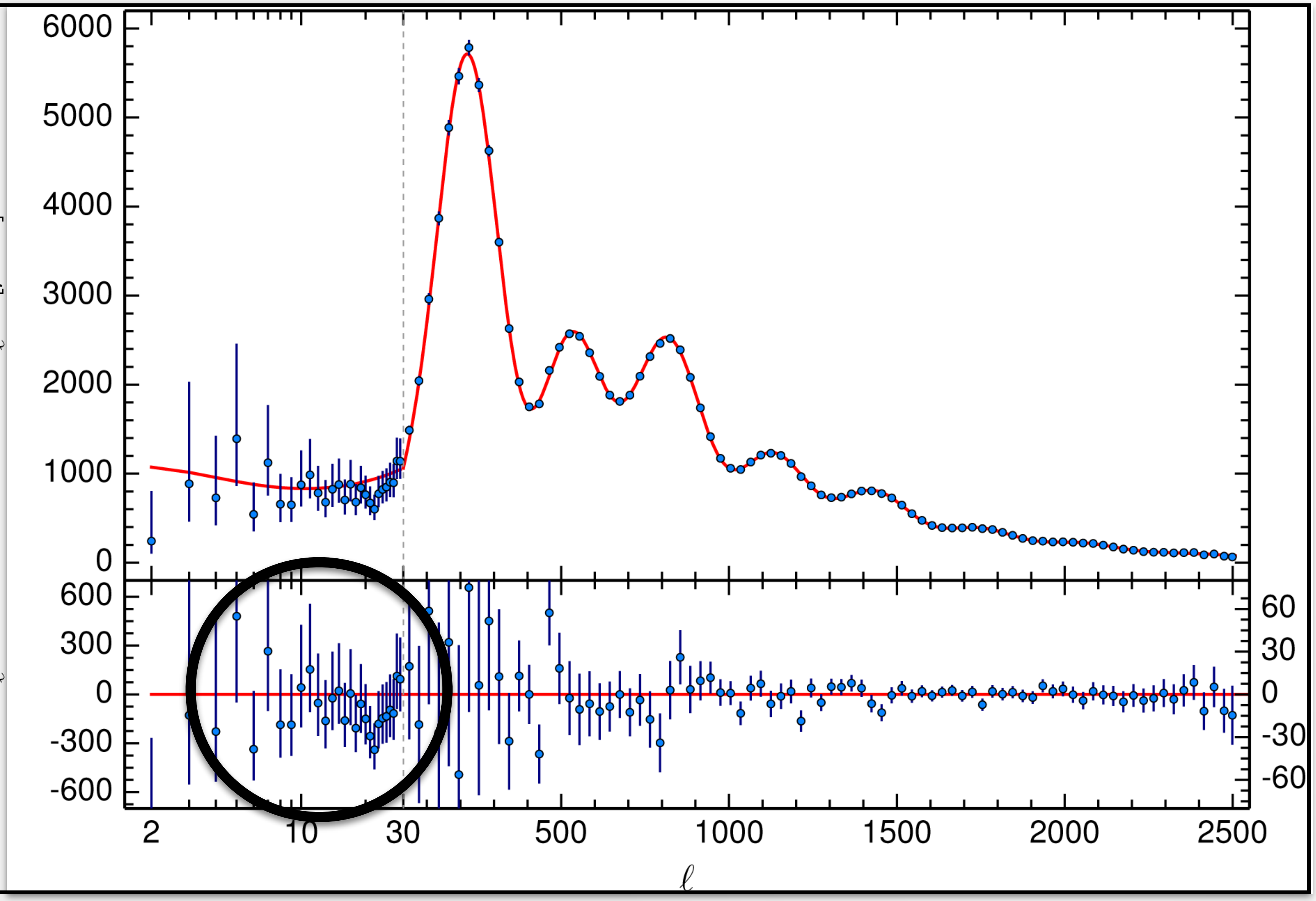
Wayne Hu

$$I_j(k) \propto \int d\ln s \, W_j(ks) G'(\ln s)$$

Single kernel encompasses power spectrum observables

arXiv:0910.2237, arXiv:1102.3435, arXiv:1110.3050

Model Independent Search For features



The well known:

l~20 feature

If the feature comes from early universe physics, what it does tell us about inflation?

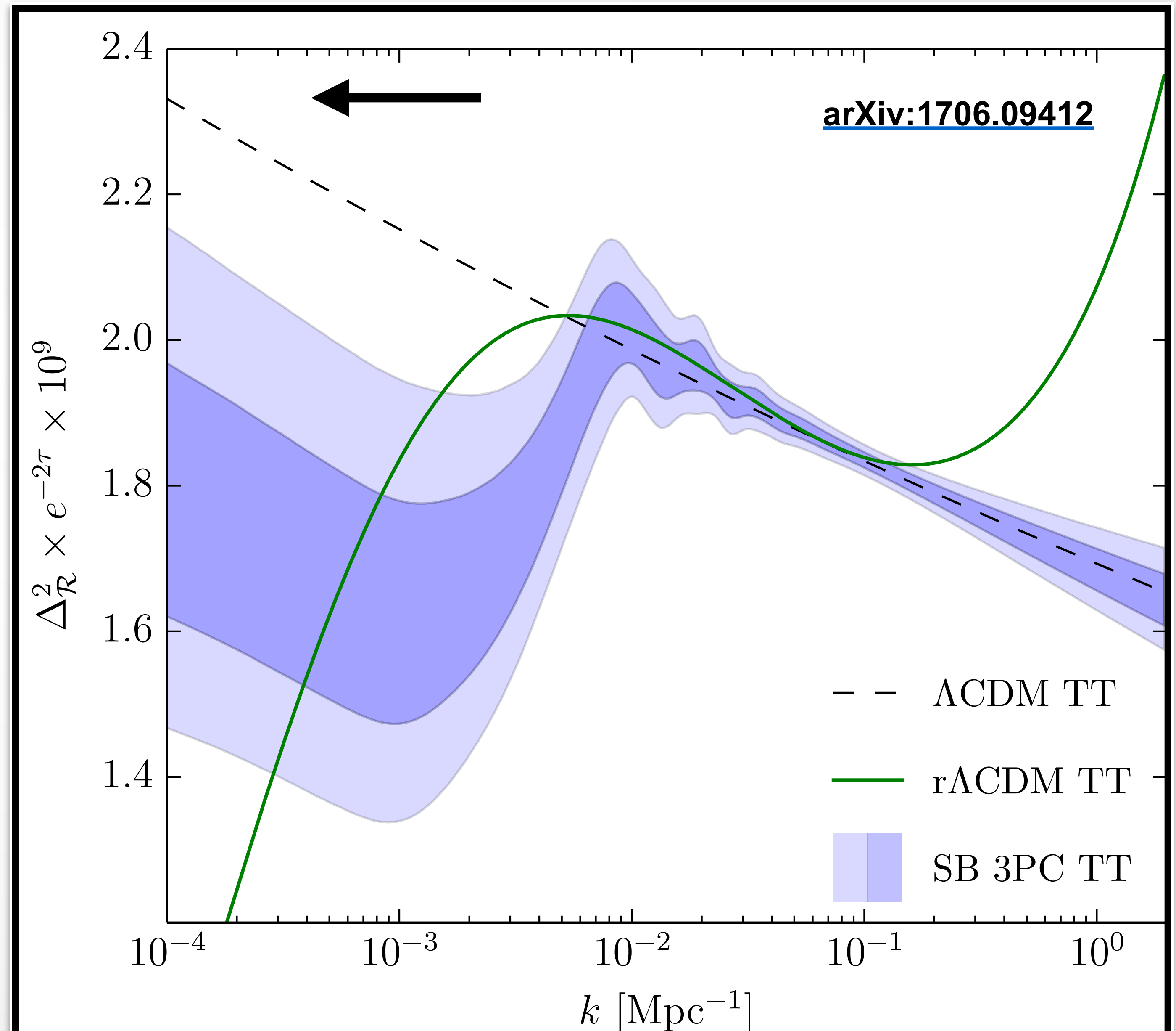
Are these models viable?

The well known: l~20 feature

Key question: how this feature impact inferences on cosmic acceleration?

Georges Obied

Chen He



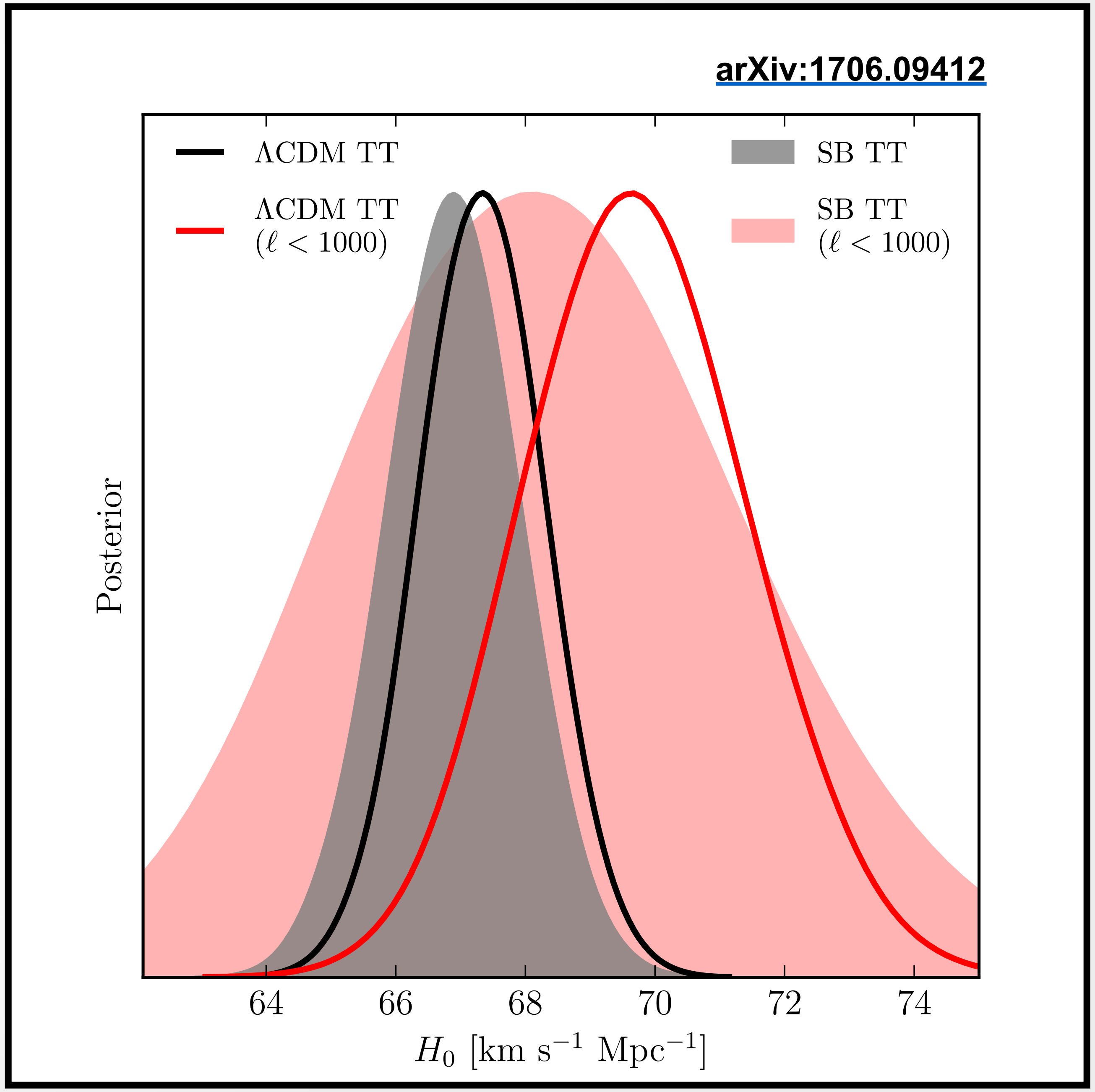
CMB mixes inferences on inflation vs dark energy

H0 problem: stringent test to LCDM

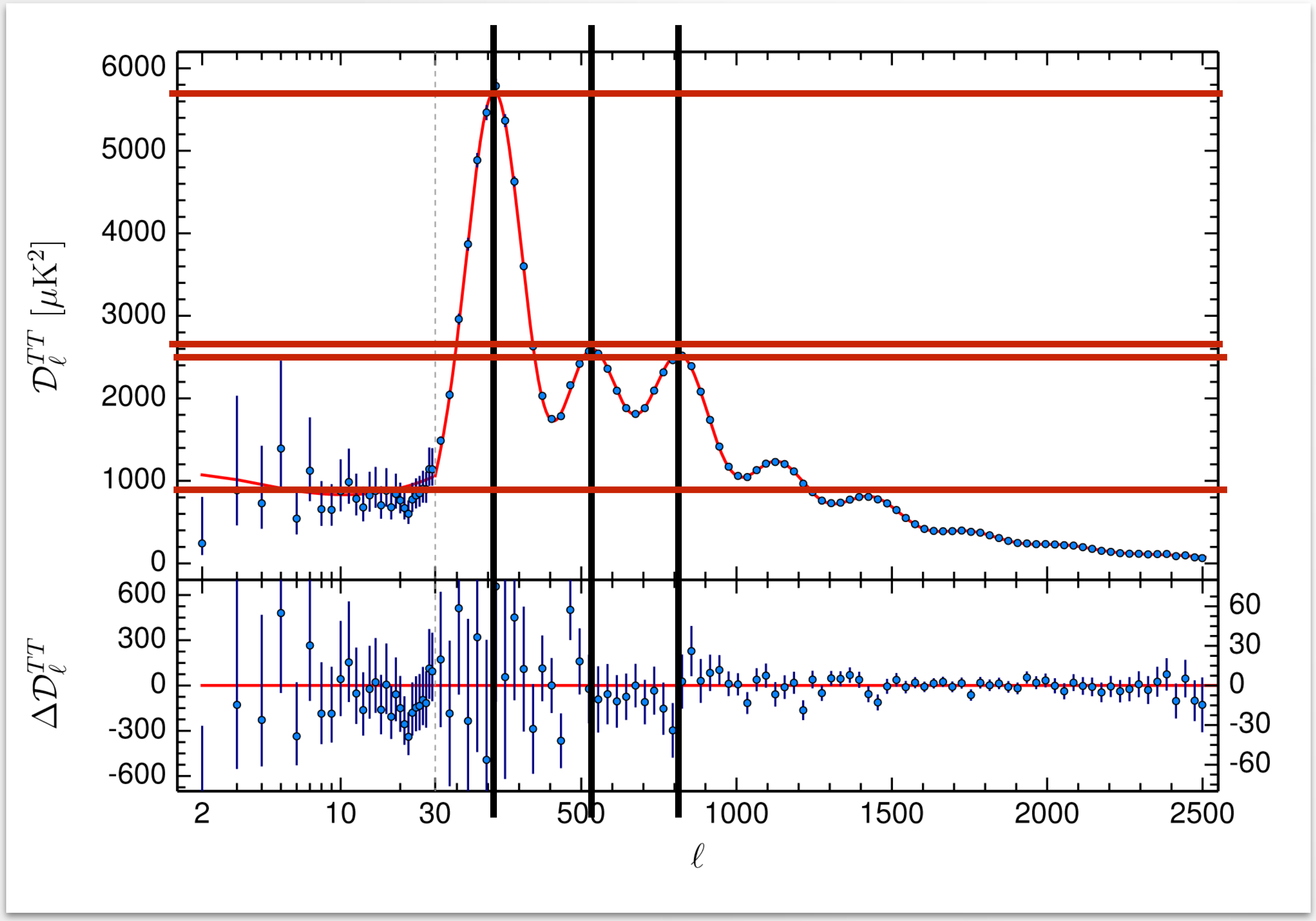
CMB vs local measurements

WMAP vs Planck

Hypothesis on inflation impact CMB constraints on Dark Energy!



How CMB mixes inferences about inflation x dark energy



Peak Positions
(assuming DE model)

$$\Omega_m h^3$$

+ Peak amplitudes

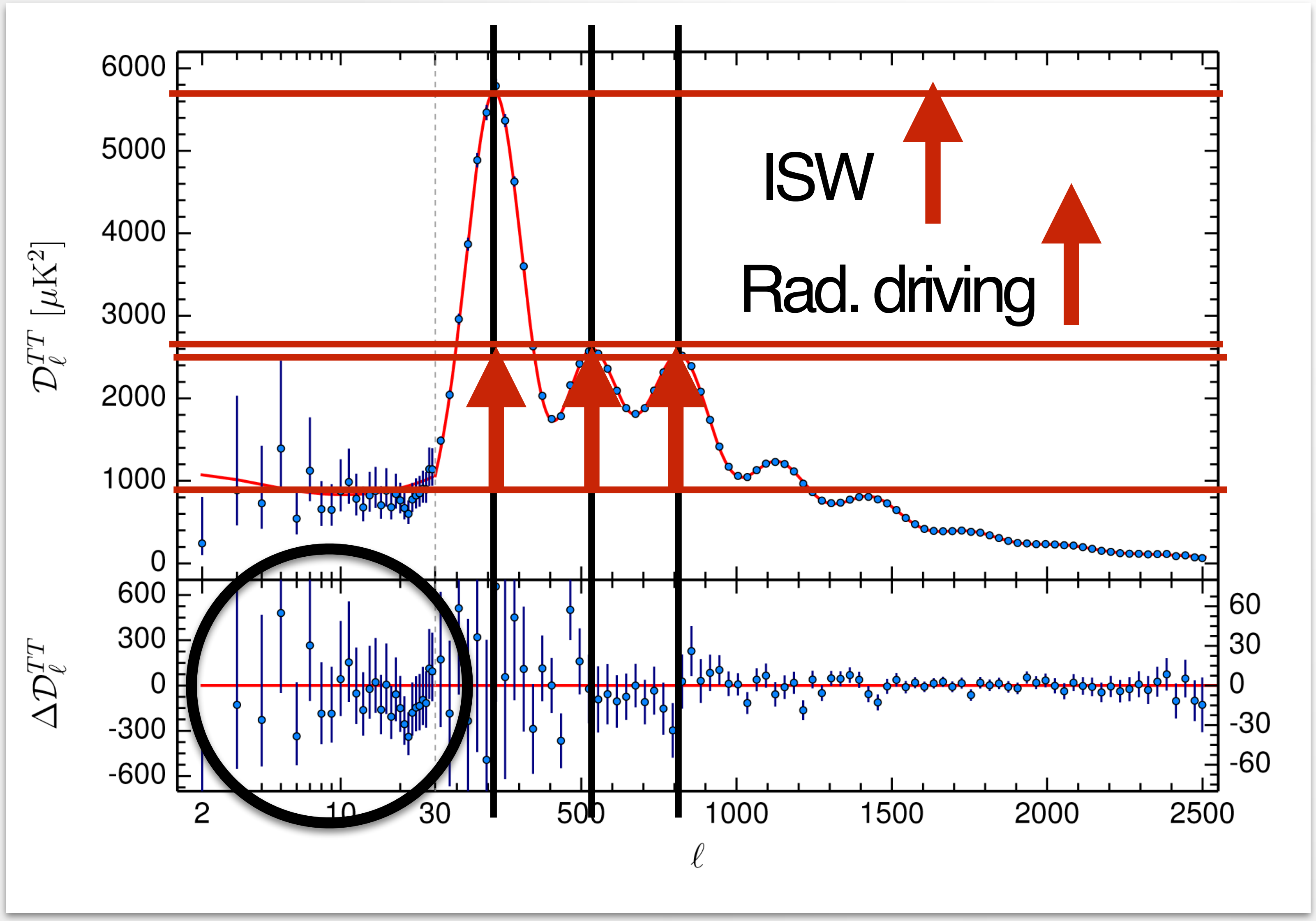
$$\Omega_m h^2$$

= Prediction on

$$h = H_0 / 100$$

Effect of low-l anomaly - part I

requires more power at first peaks in comparison to low-l



Peak Positions (assuming DE model)

$$\Omega_m h^3$$

+ Peak amplitudes

$$\Omega_m h^2$$

= Prediction on

$$h = H_0 / 100$$

How CMB mixes inferences about inflation x dark energy Part II - ISW

CMB VS BAO

CMB VS Local

Cosmology could be correct up to very low redshift then something abrupt happens

Something is missing on Cosmic Acceleration/Dark Matter

Something is missing on early universe

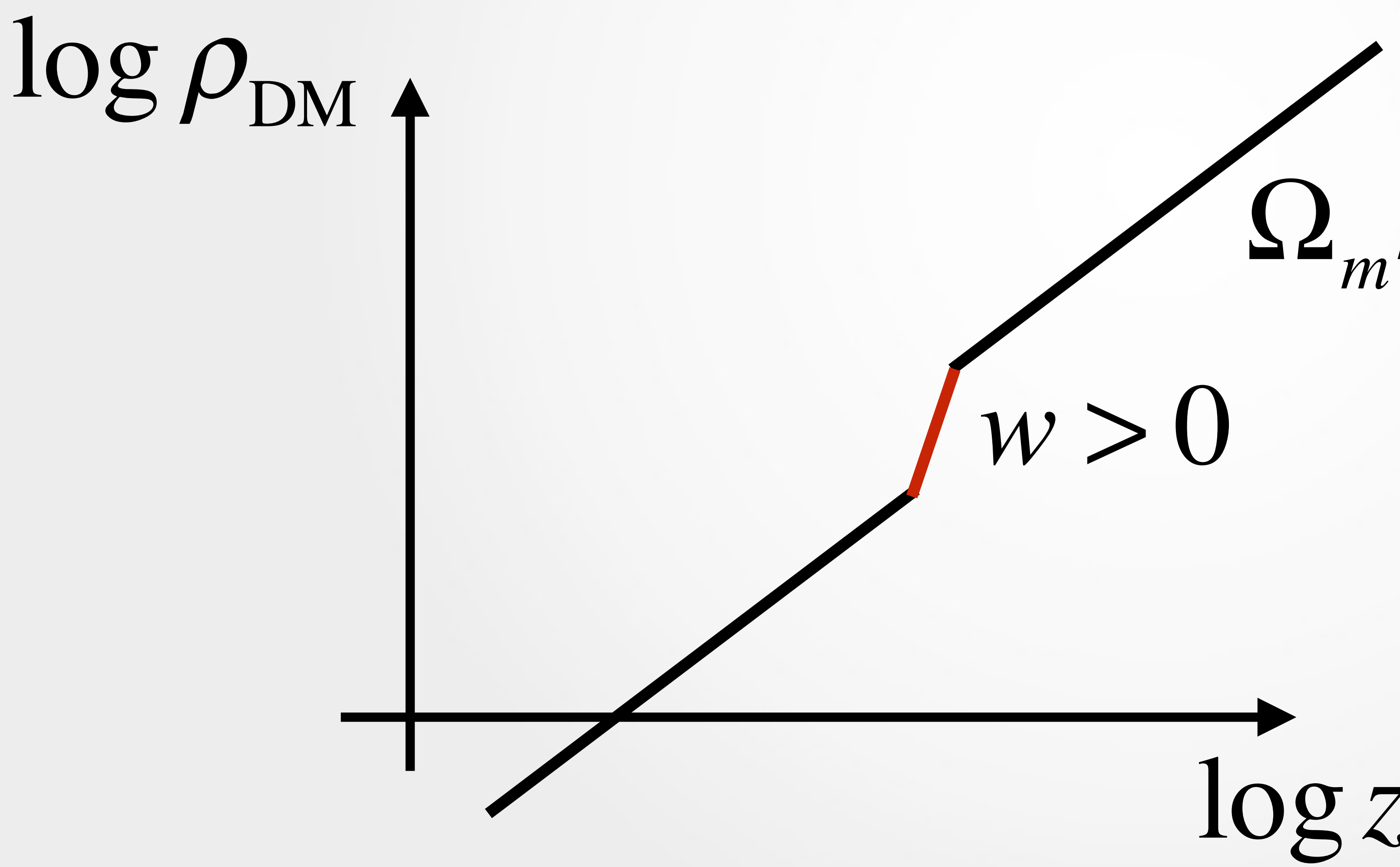
Something is missing on Cosmic Acceleration/Dark Matter

$$\frac{\overset{\text{CMB}}{\Delta\left[\int_0^{1000}\frac{dz}{E(z)}\right]}}{\int_0^{1000}\frac{dz}{E(z)}} = \frac{\overset{\text{BAO}}{\Delta\left[\int_0^{0.5}\frac{dz}{E(z)}\right]}}{\int_0^{0.5}\frac{dz}{E(z)}}$$

Dark Energy/Dark Matter importance on both integrals are different

Something may be missing on Dark Matter

Example: Dark Matter decay (you would get wrong OMh^2 today)



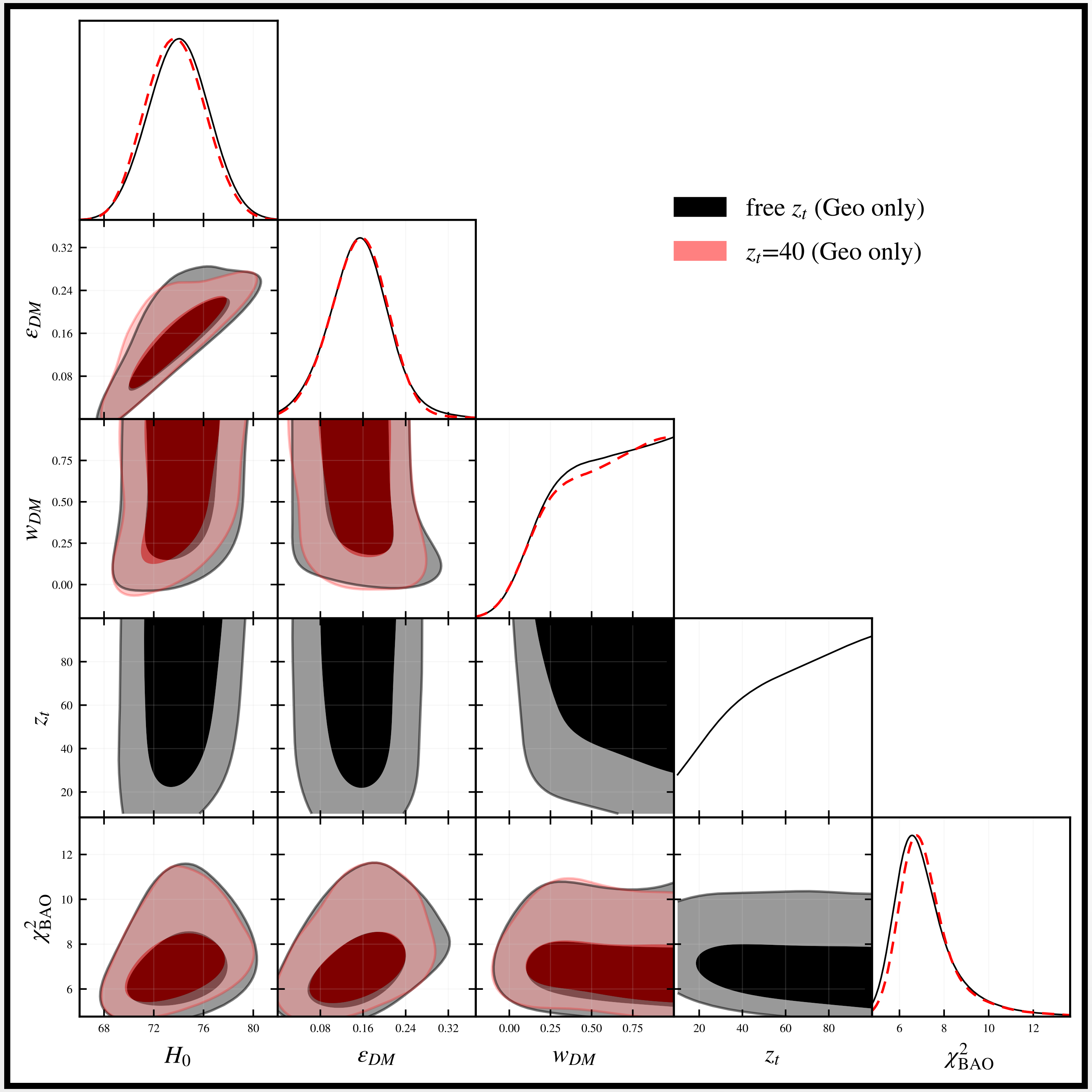
Fixed CMB
DM density

$$\Omega_m h^2 (z = 1000)$$

$$\frac{\Delta H_0}{H_0} \propto \epsilon$$

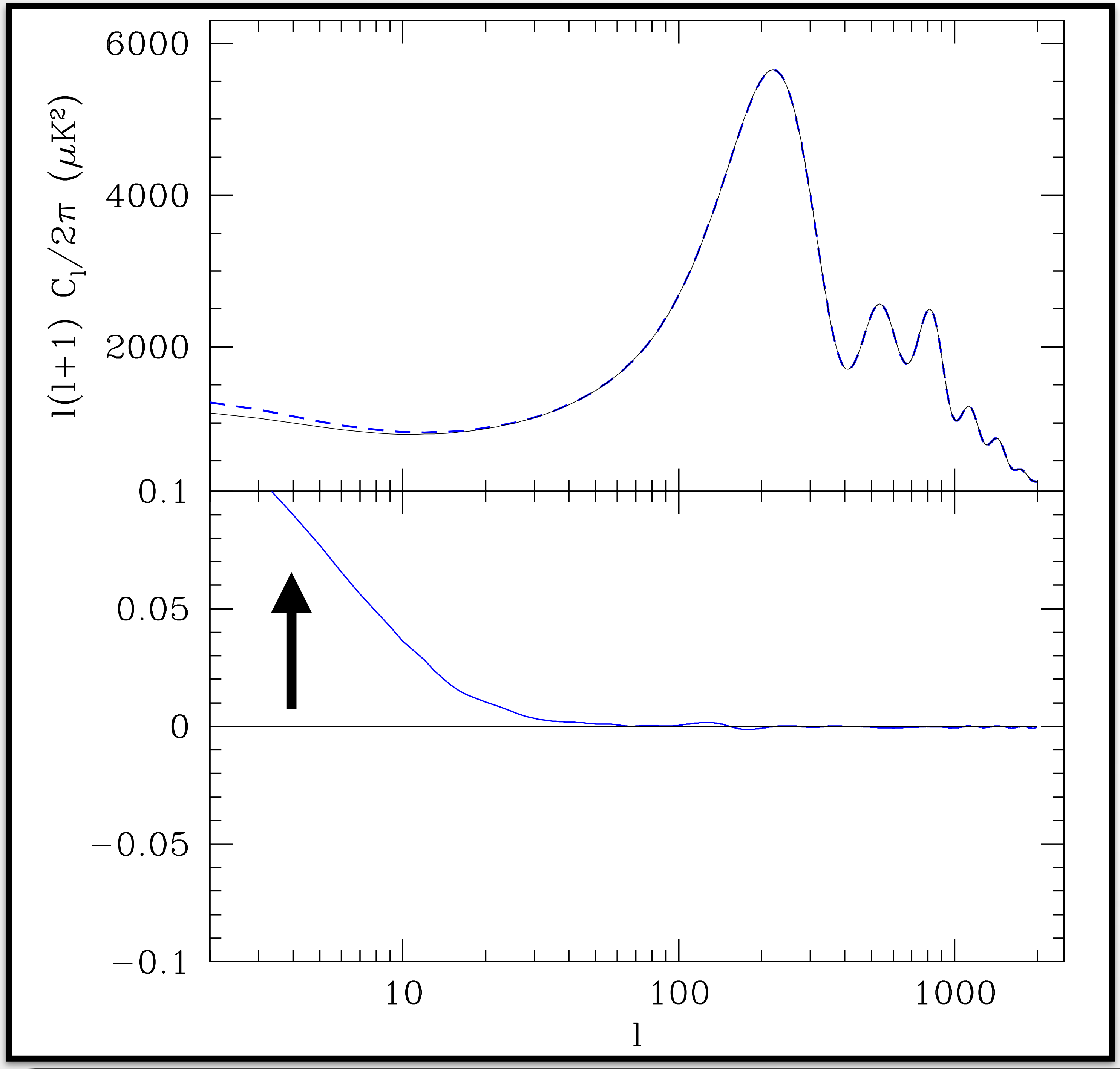
That explains why massive neutrinos don't work! (rad -> CDM at z~200)

Something may be missing on Dark Matter



Example: Dark Matter decay

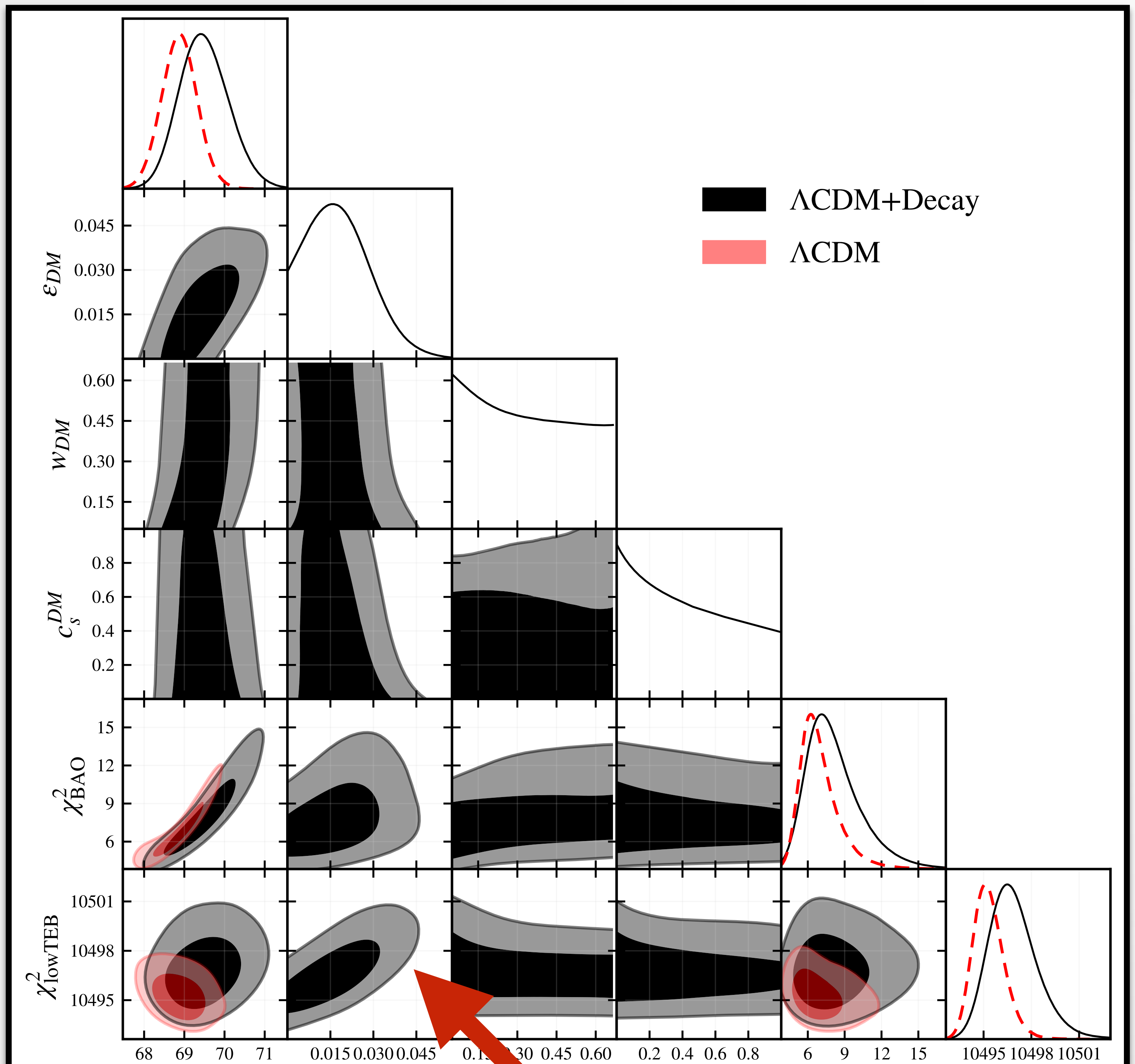
Something may be missing on Dark Matter



Problem - ISW

results can change if inflation surpasses low-l power

Something may be missing on Dark Matter



Problem - ISW

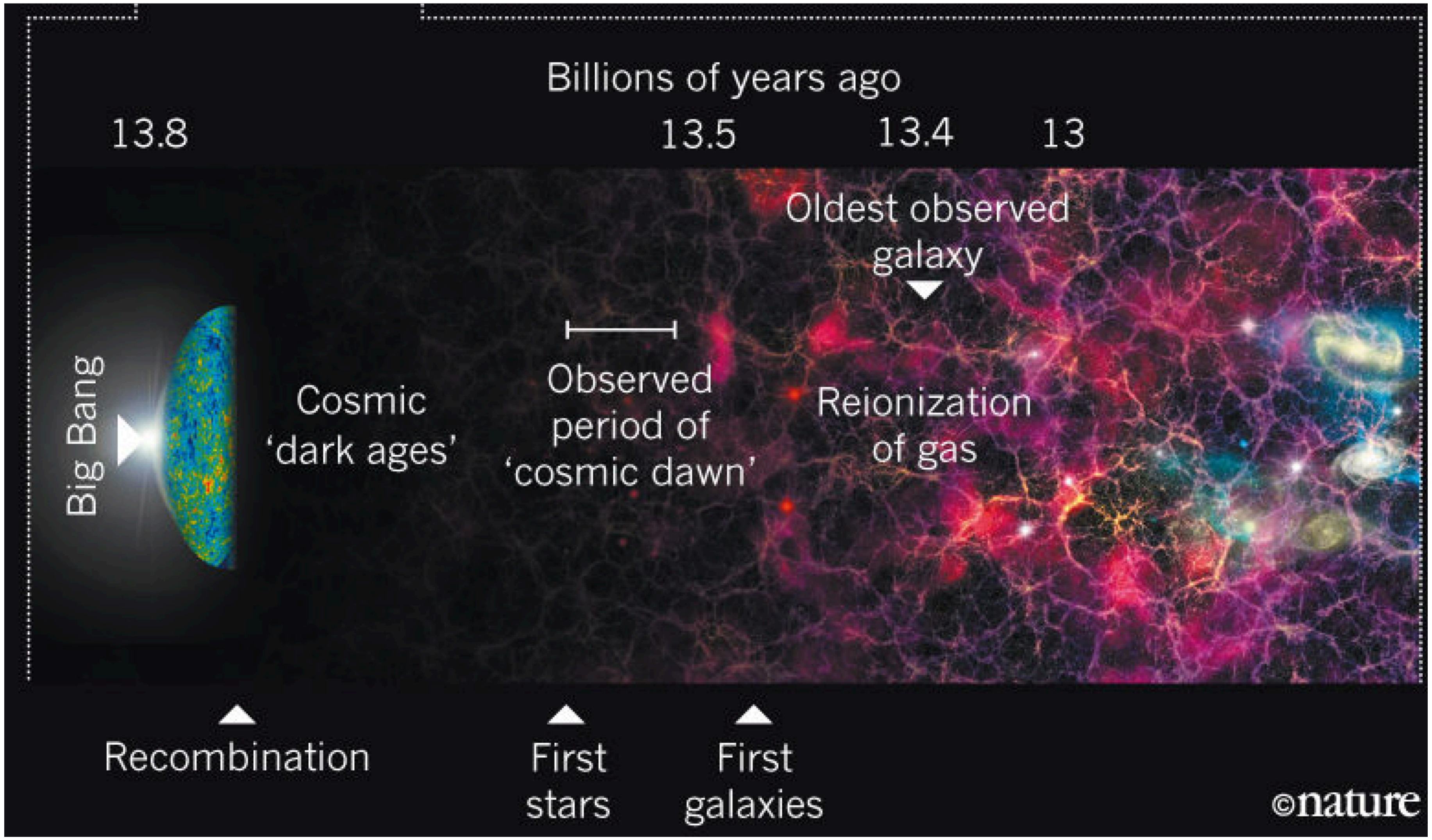
summary of research in one emoticon

Inflation vs Reionization

The Epoch of Reionization

First stars produces ionizing radiation (hydrogen atoms)

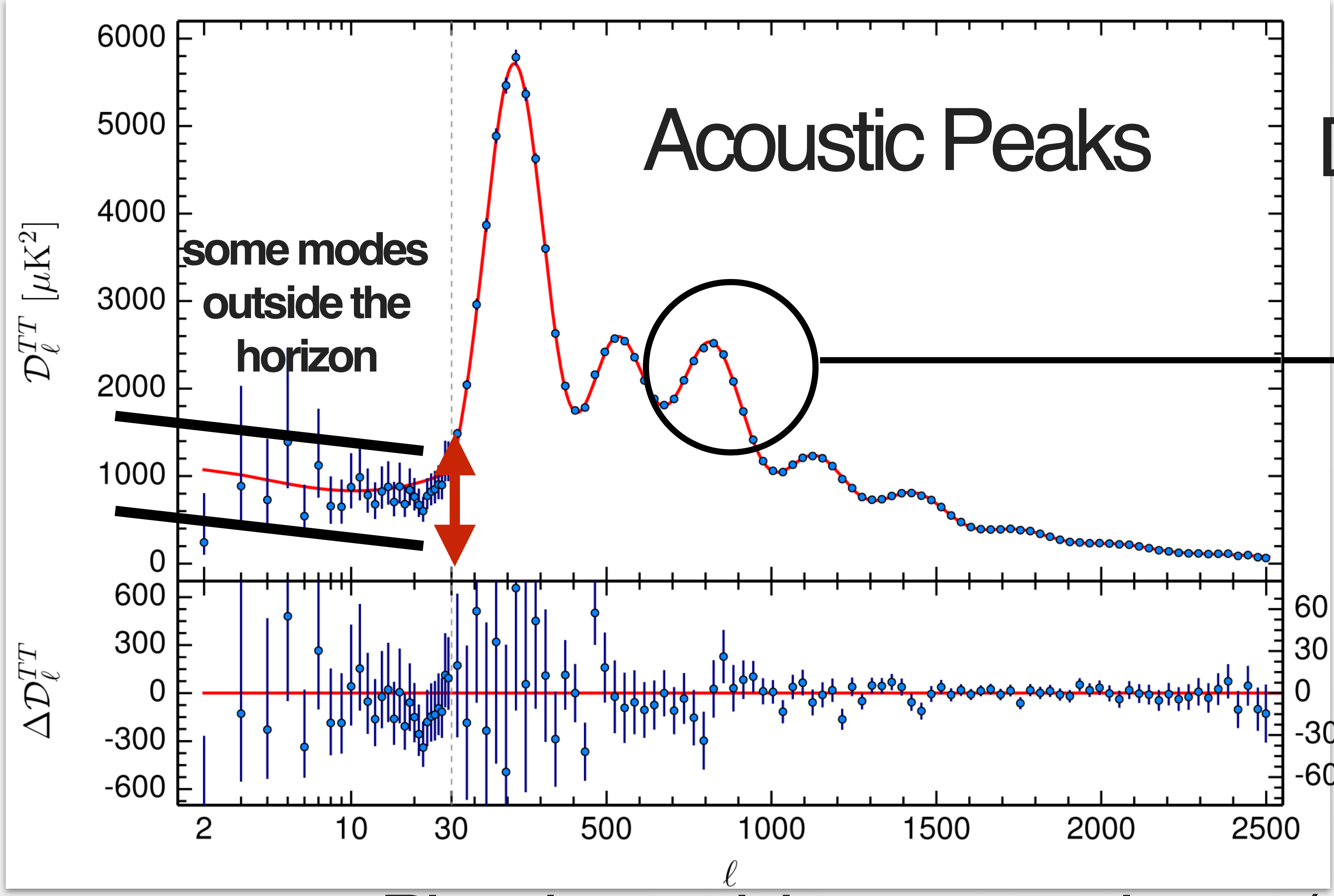
Universe becomes slightly opaque



Difficult to model: requires *radiative transfer* + n-body simulations on cosmological scales to model *non-linear gravitational collapse*

How can we probe the Epoch of Reionization?

CMB temperature spectrum - opaqueness damps the CMB signal



Degenerate w/ inflation?

$$A_S e^{-2\tau}$$

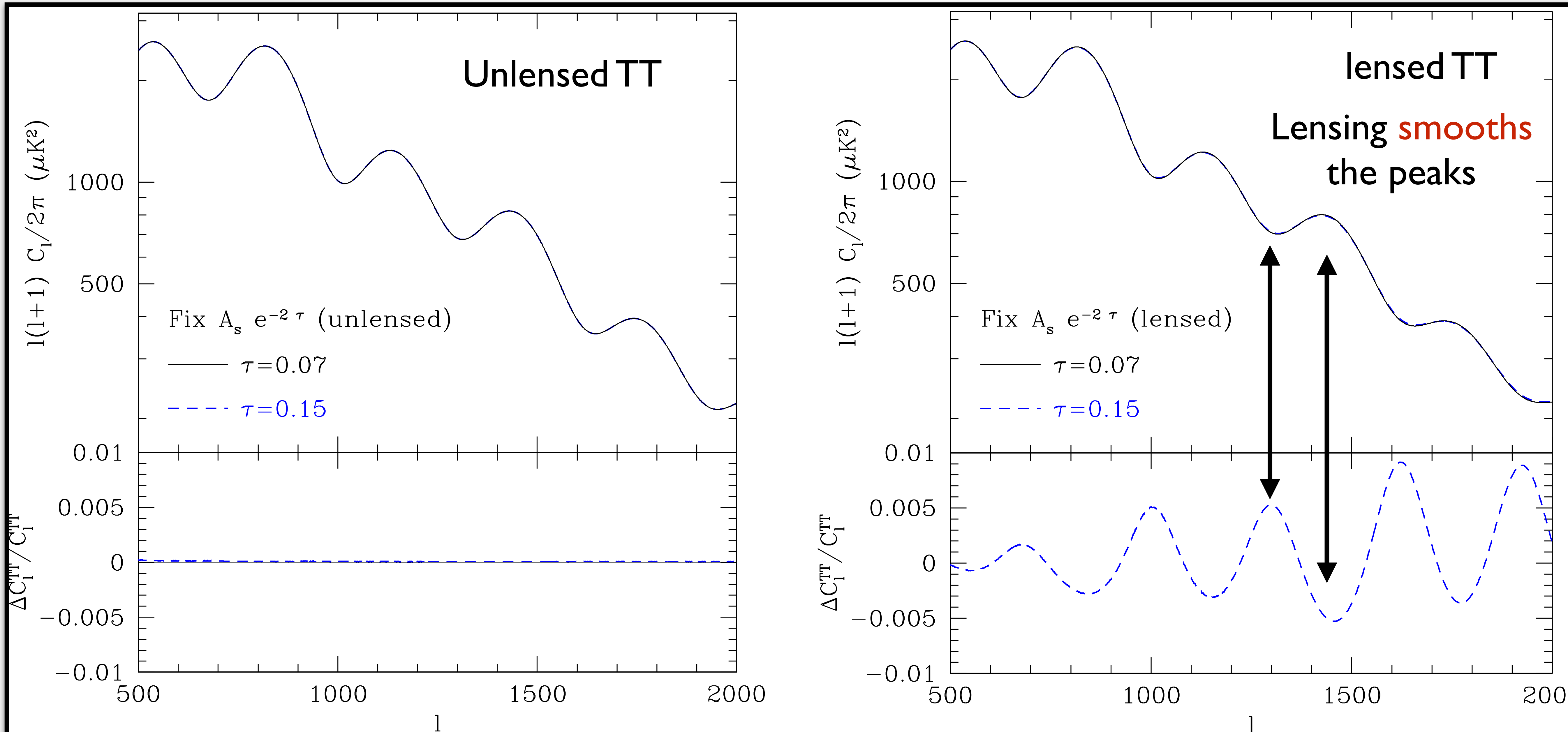
Initial seeds

optical depth

Planck: precision < 1% at l~900 (when binned)

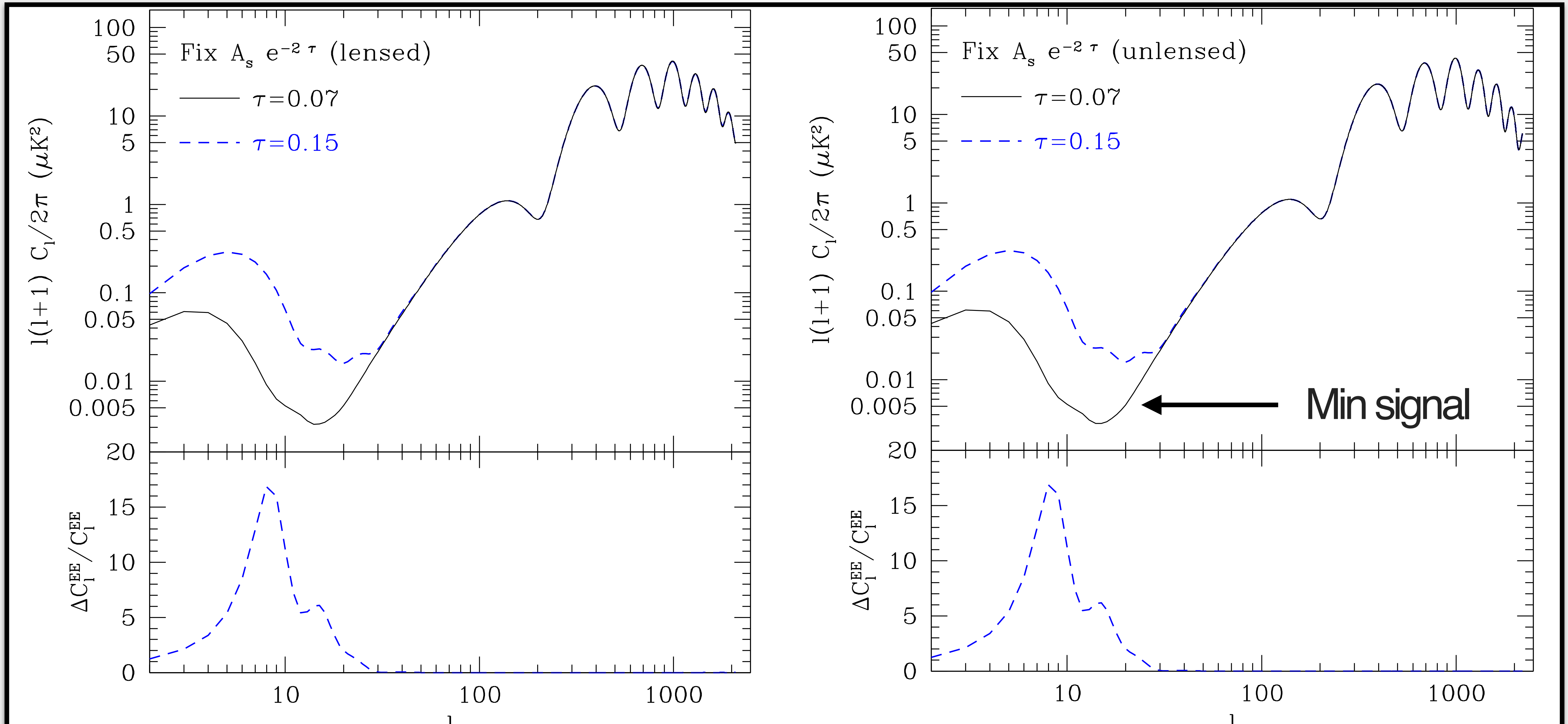
How can we probe the Epoch of Reionization?

Not quite: gravitational lensing partially breaks this degeneracy



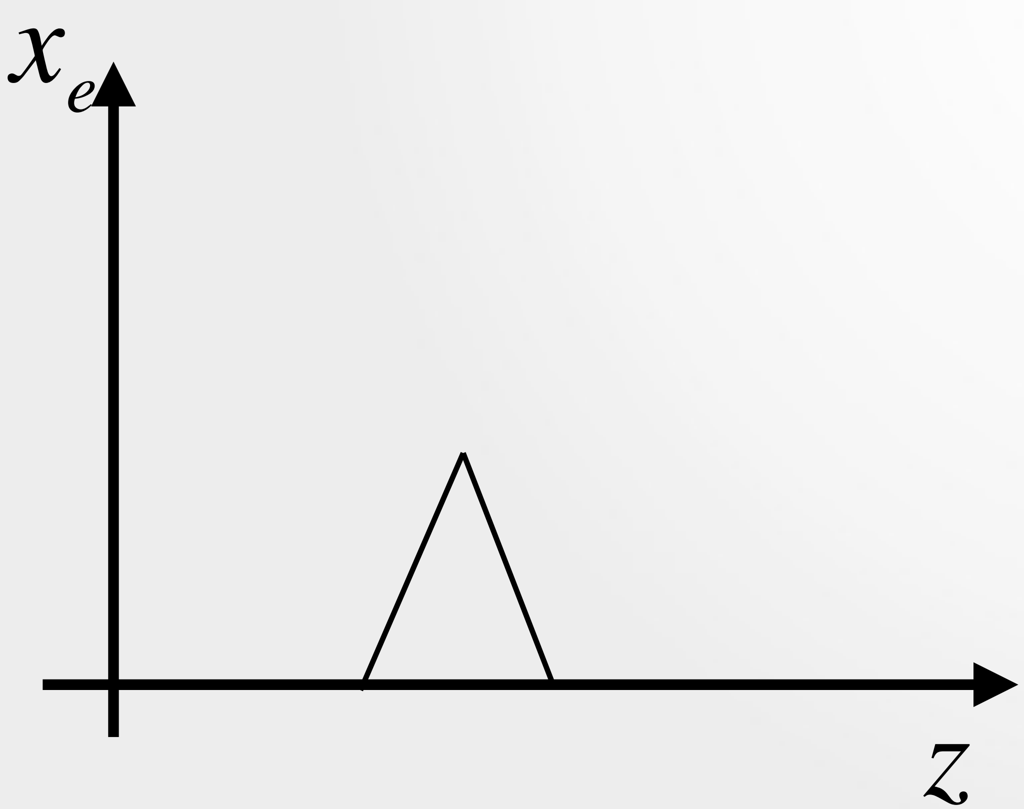
How can we probe the Epoch of Reionization?

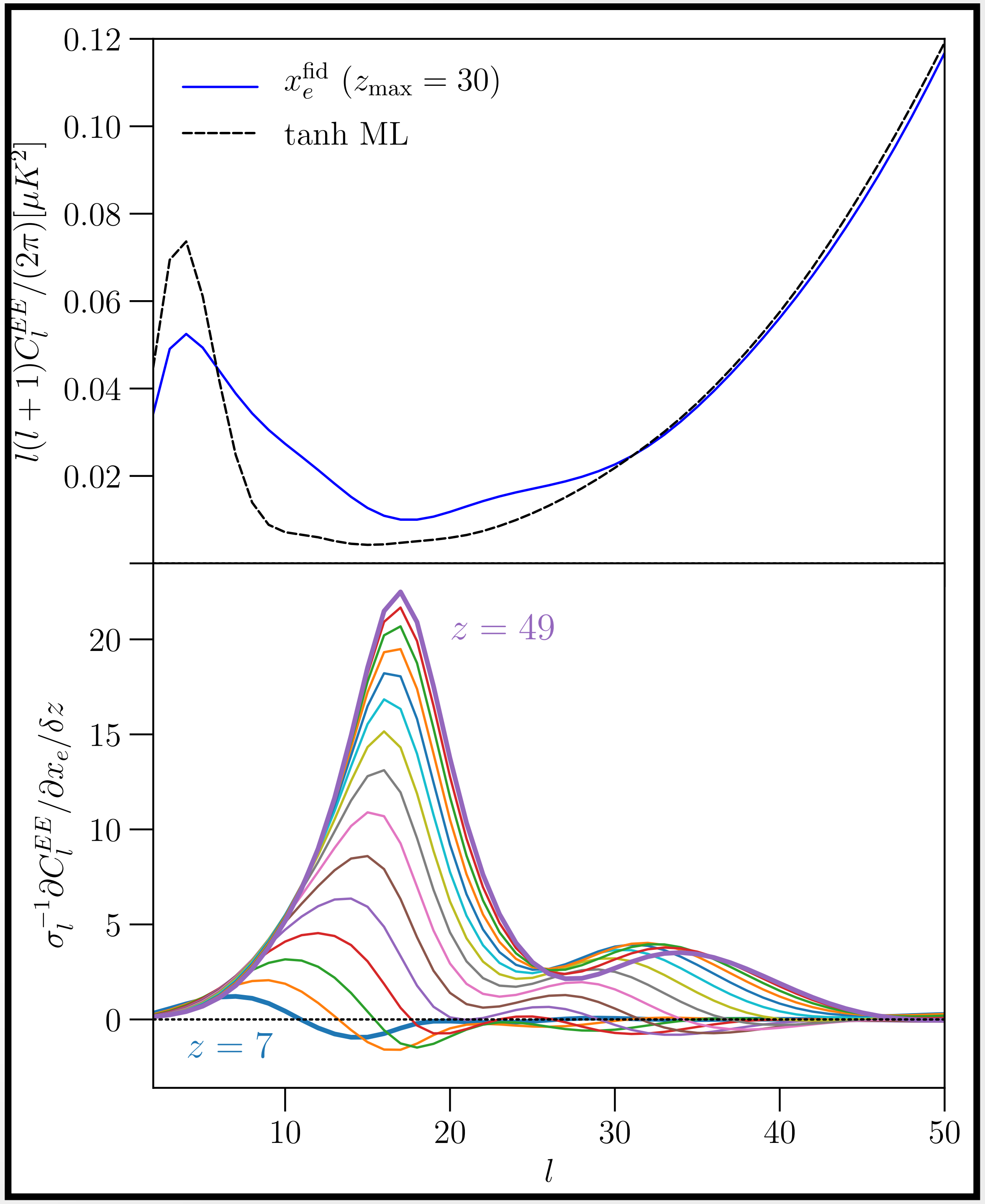
CMB Polarization: reionization generates polarization anisotropy



How can we probe the Epoch of Reionization?

CMB Polarization: can measure more than just the total optical depth



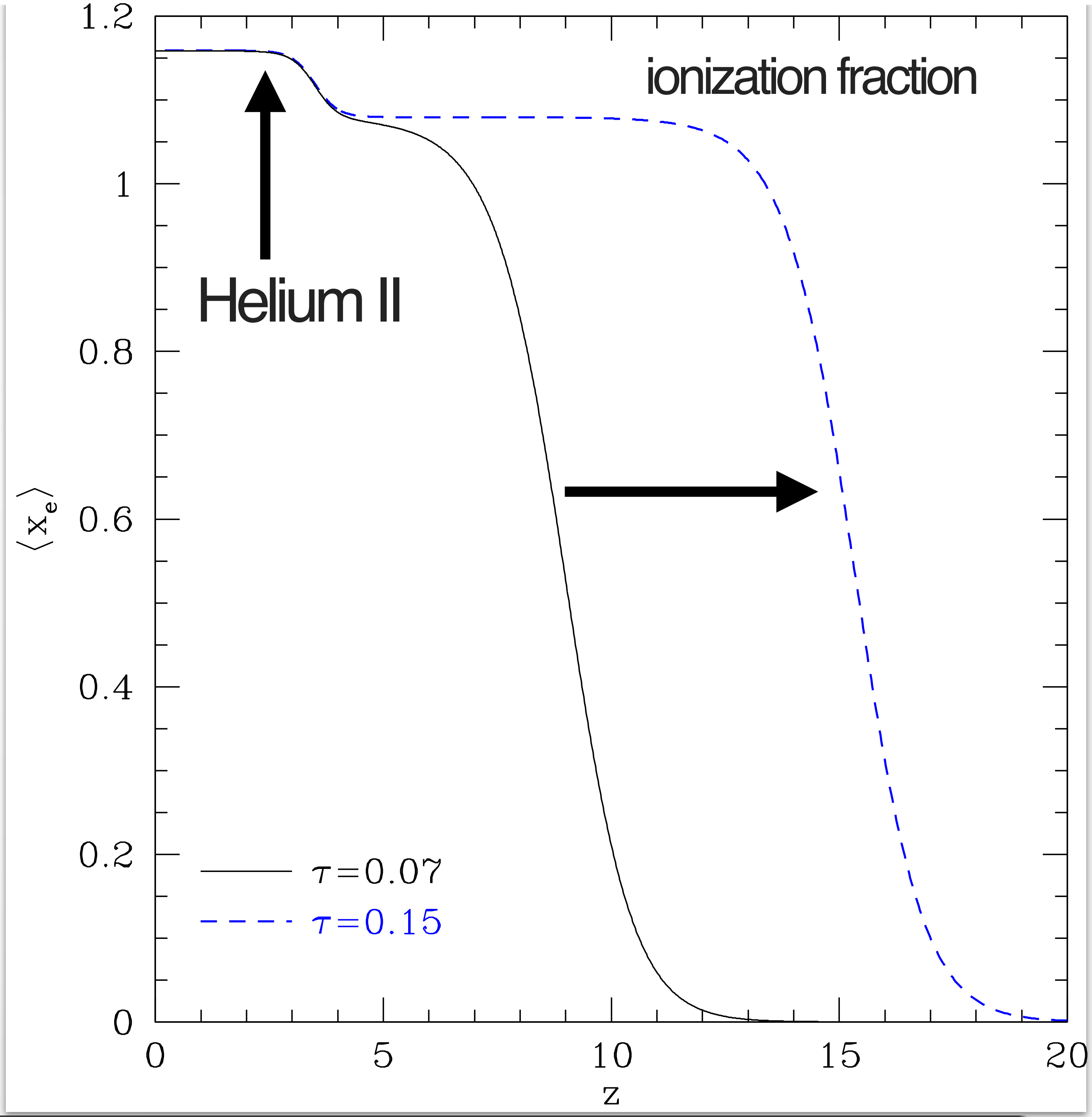


The Instantaneous Reionization model

Pop-II stars on IGM drive the reionization

Higher optical depth implies transition at higher redshift

The only free parameter (given tau) is the width of the transition



Test that Pop-II stars are the **only** source of radiation?

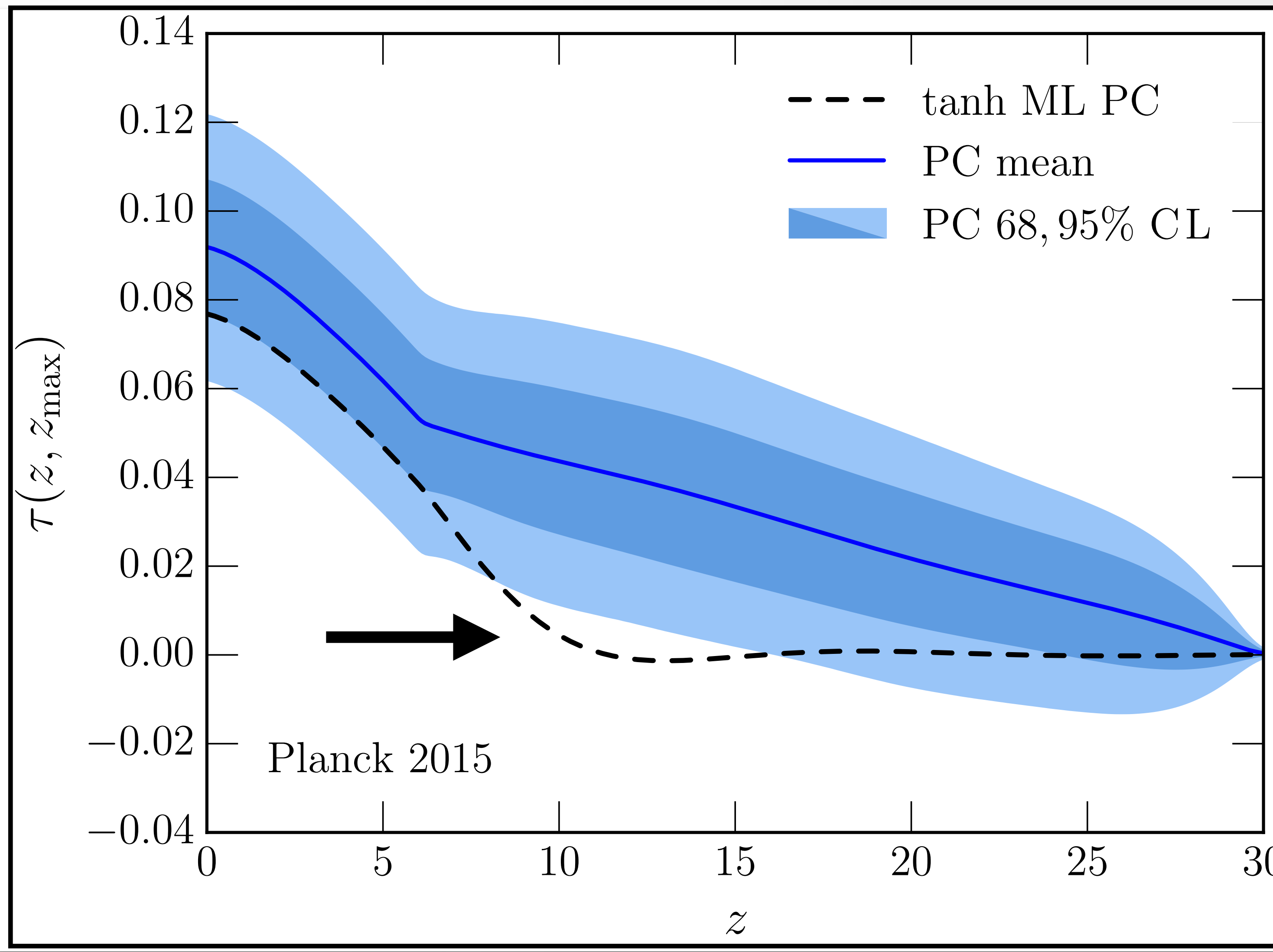
Complete reionization constraints from Planck 2015 polarization

Chen He Heinrich*,[1,2] Vinicius Miranda,[3] and Wayne Hu[4,5]
[1] *Kavli Institute for Cosmological Physics, Enrico Fermi Institute, University of Chicago, Illinois 60637*
[2] *Department of Physics, University of Chicago, Illinois 60637, USA**
[3] *Center for Particle Cosmology, Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
[4] *Kavli Institute for Cosmological Physics, Enrico Fermi Institute, University of Chicago, Chicago Illinois 60637, USA*
[5] *Department of Astronomy & Astrophysics, University of Chicago, Illinois 60637, USA*
(Dated: April 10, 2017)

Our analysis showed hints of high redshift signal in the LFI

$$\tau(15 < z < 30) = 0.033$$

HFI data seems much more constraining



How degenerate is this signal with inflation (LFI data)?

Inflationary vs. Reionization Features from *Planck* 2015 Data

Georges Obied,[1] Cora Dvorkin,[1] Chen Heinrich,[2,3] Wayne Hu,[4] and Vinicius Miranda[5]
[1] *Harvard University, Department of Physics, Cambridge, MA 02138, USA*
[2] *California Institute of Technology, Pasadena California 91125*
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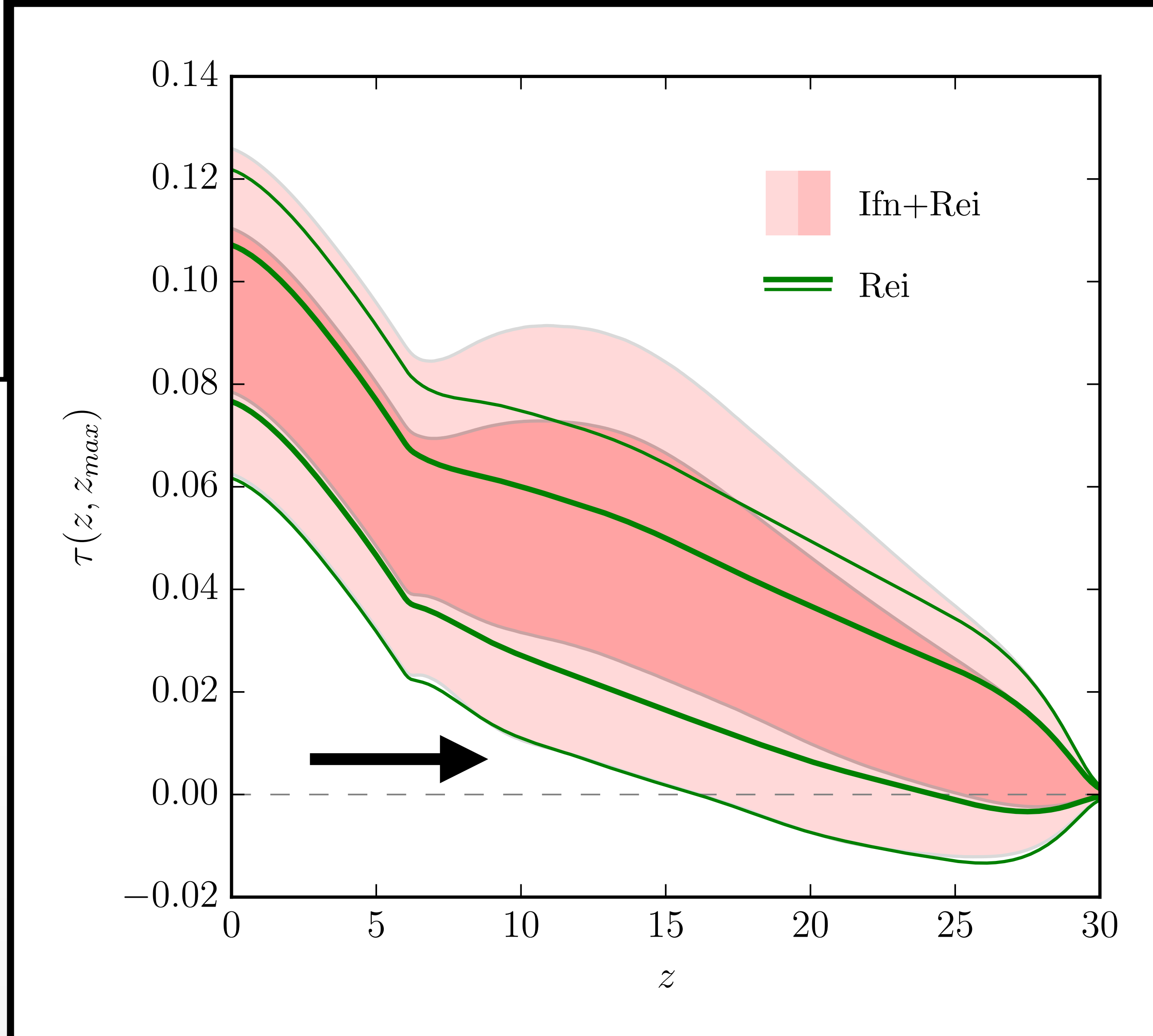
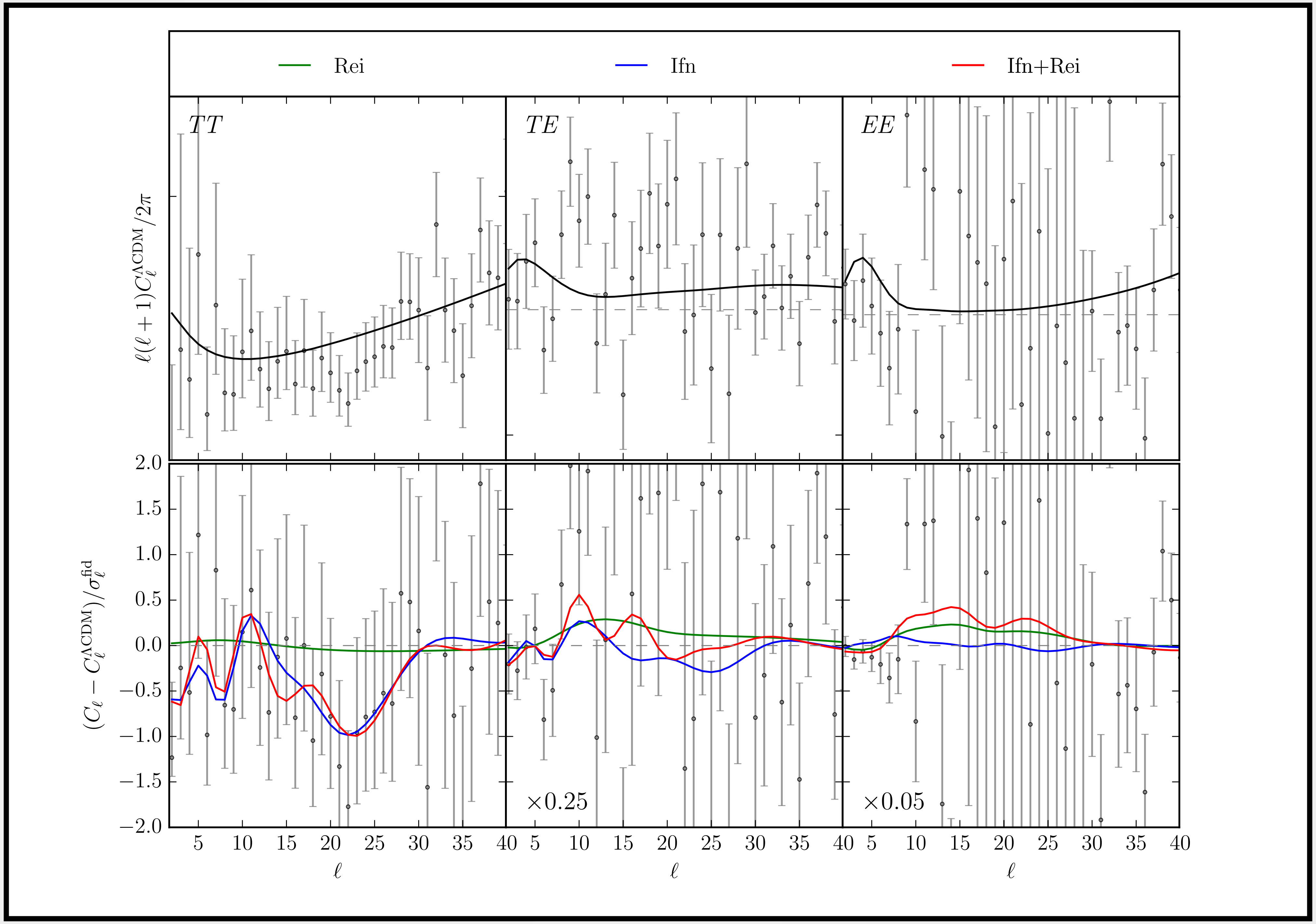
[4] *Kavli Institute for Cosmological Physics, Department of Astronomy & Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, IL 60637*
[5] *Center for Particle Cosmology, Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*

Signal robust even when marginalized over general single-field inflation!

Non-trivial result given that inflation affects low-l polarization



How **degenerate** is this signal with inflation (LFI data)?



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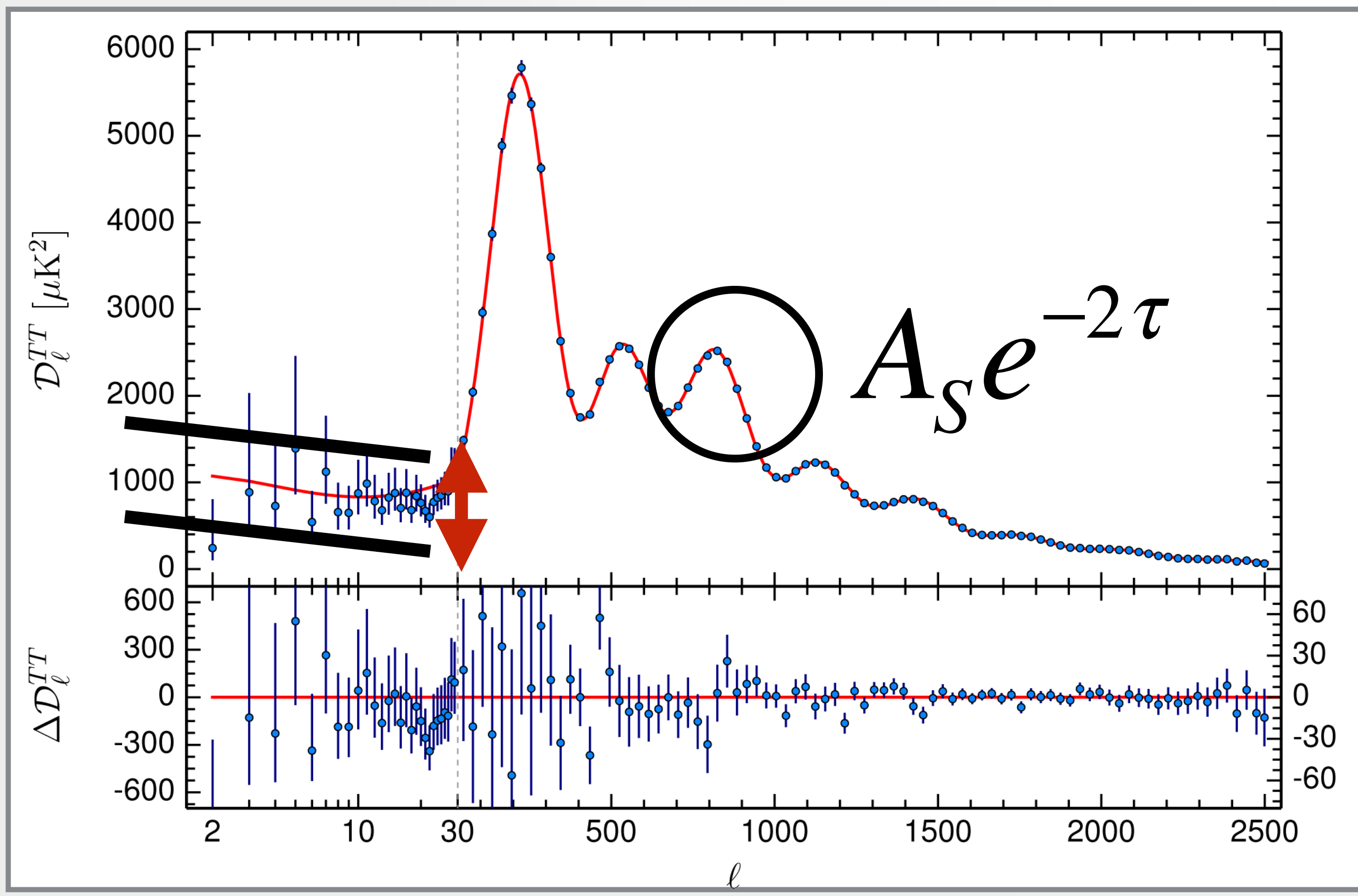
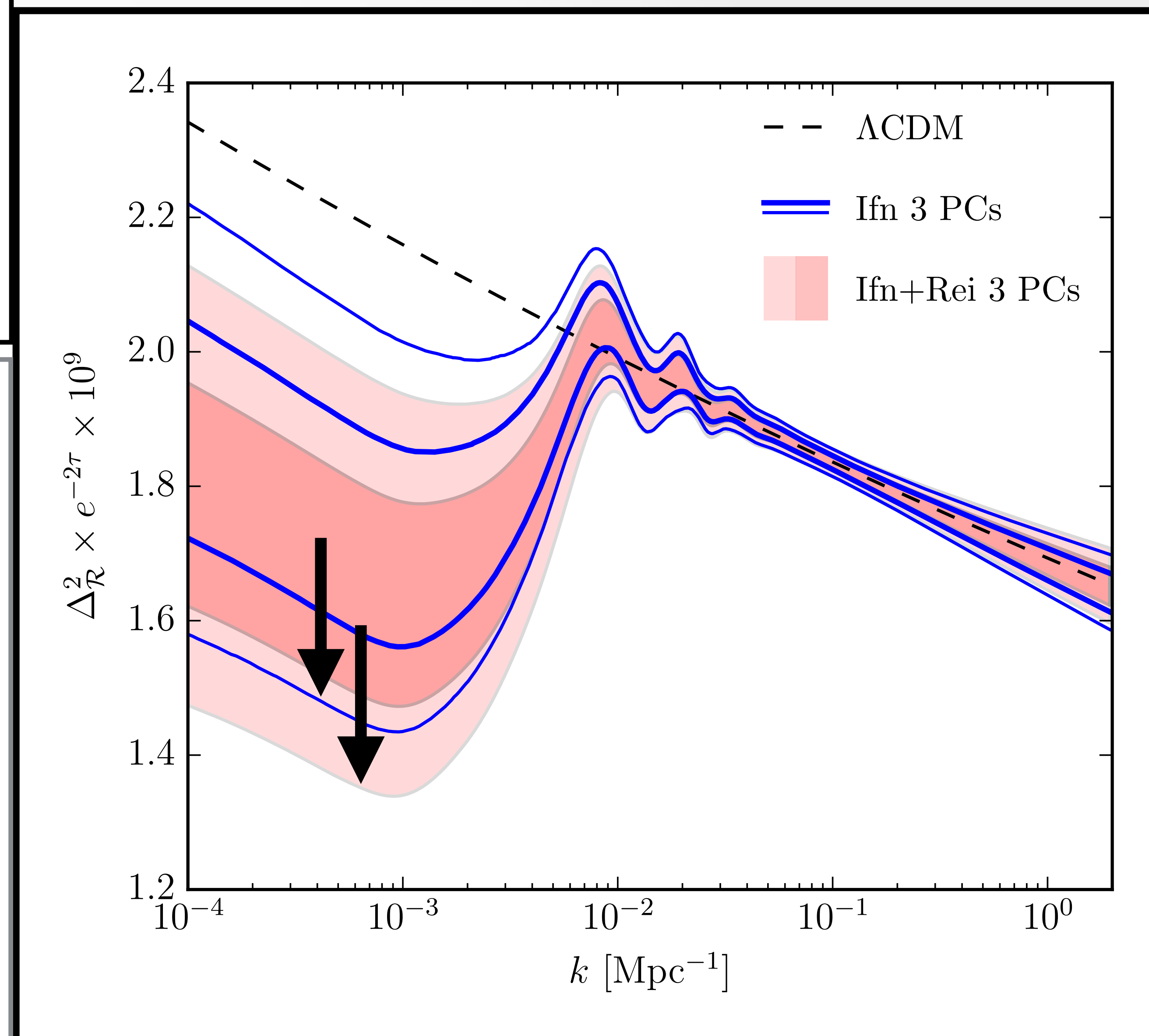
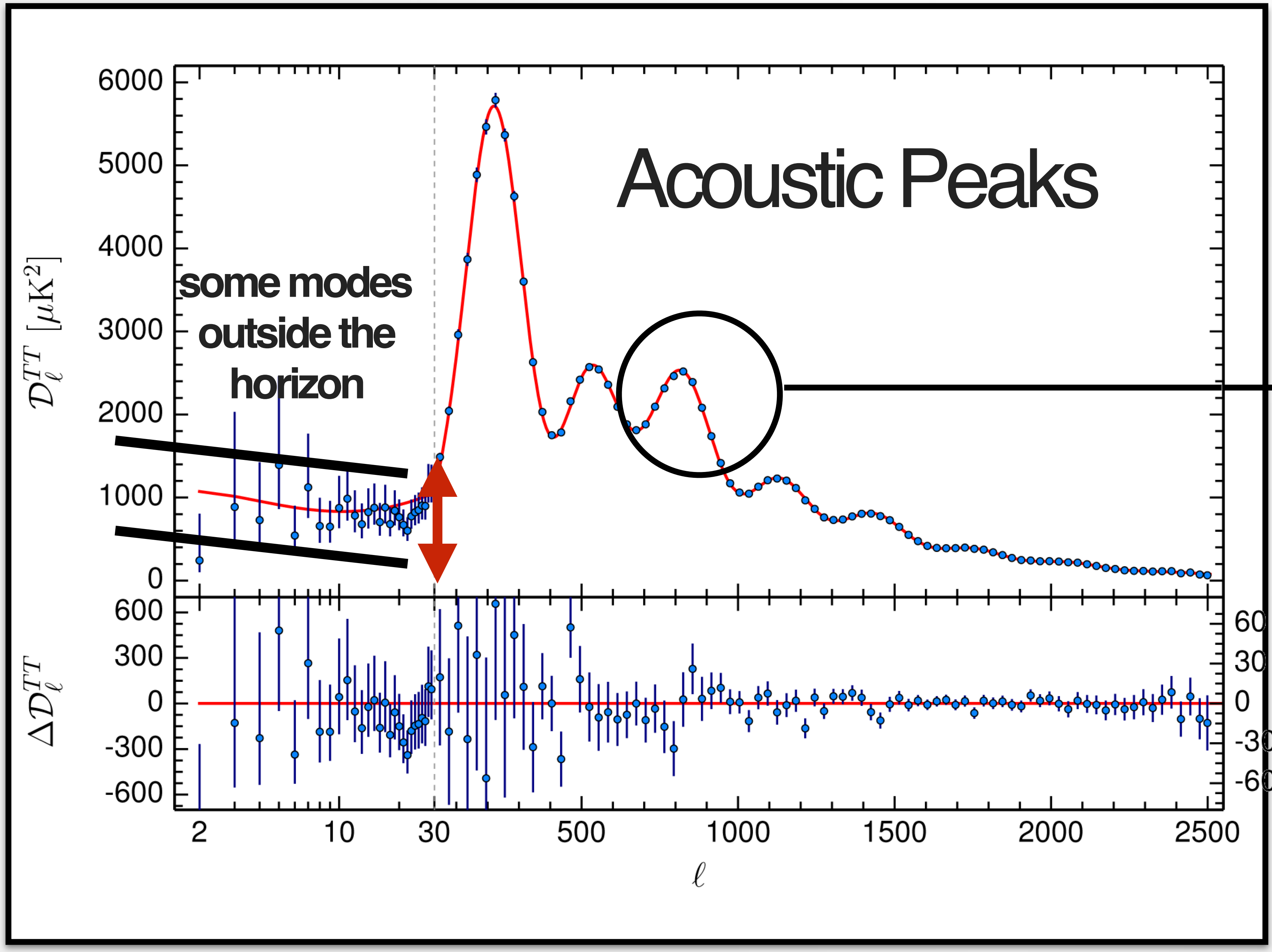




Reionization vs Massive Neutrinos

Reionization affects lensing!



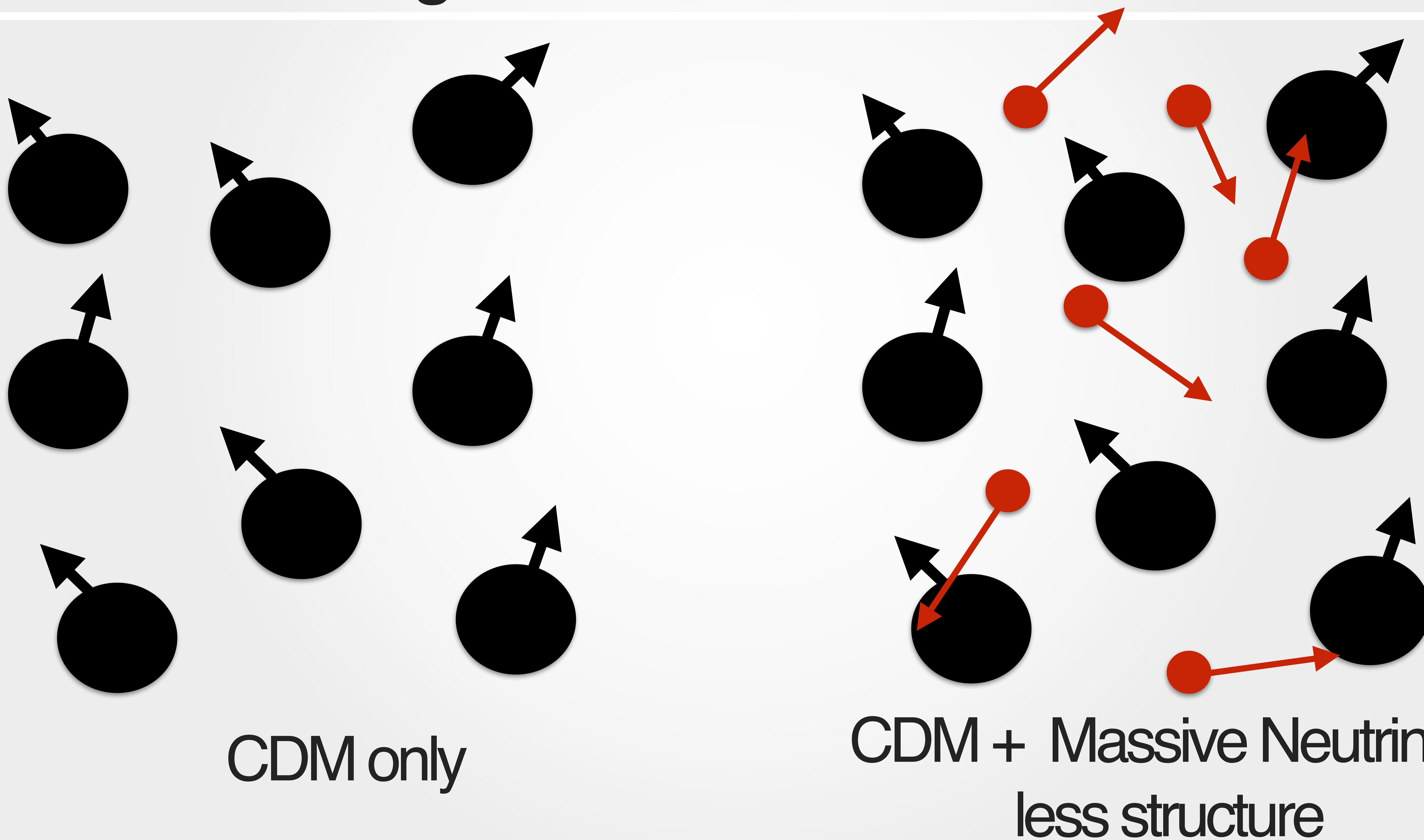
Degenerate w/ inflation?

$$A_S e^{-2\tau}$$

Lensing only cares about As

optical depth

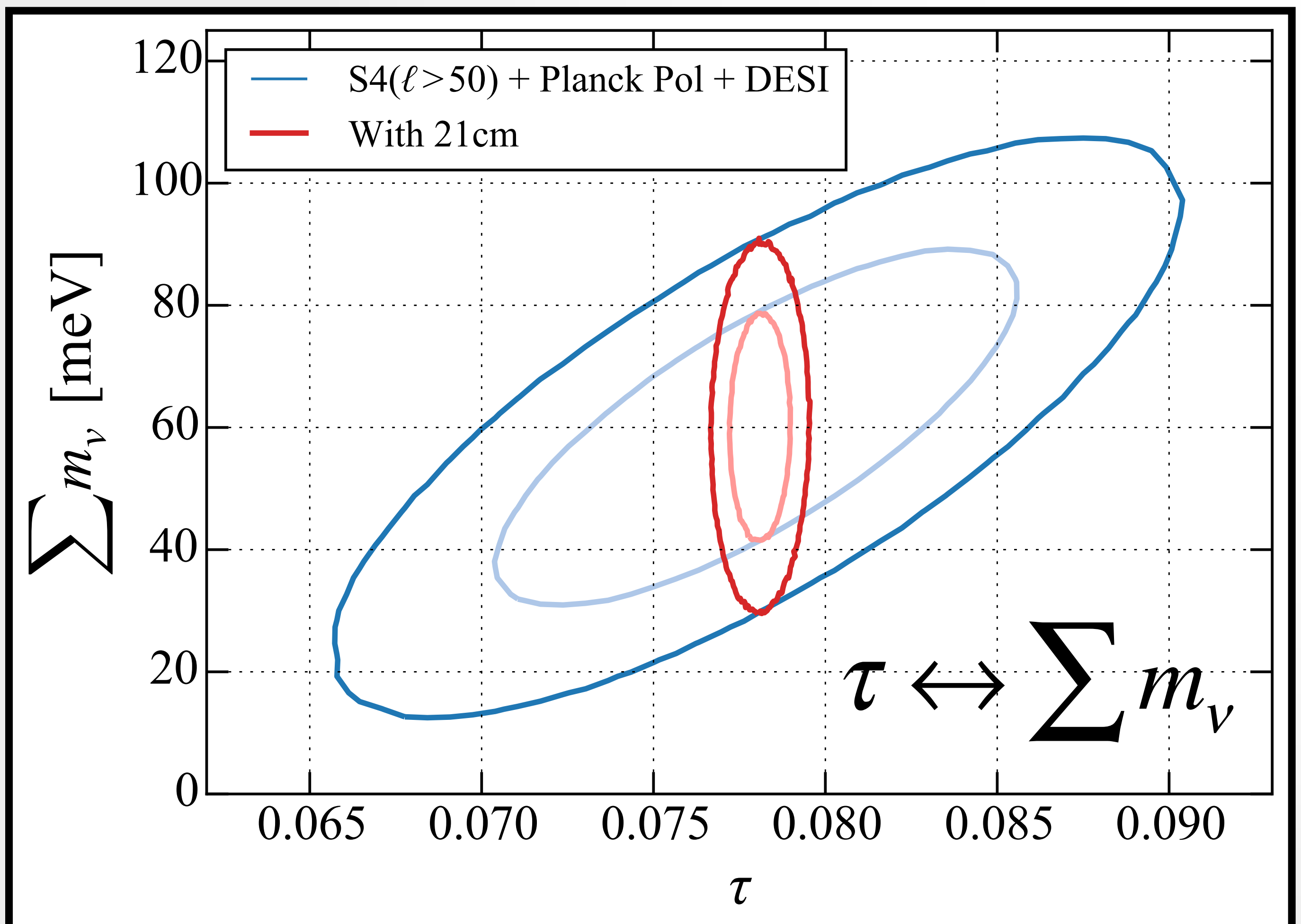
If it affects lensing - then it makes the search for Mnu hard



If it affects lensing - then it makes the search for Mnu hard

$$\tau_{\rm PC}^{\rm LFI}(15 < z < 30) = 0.033(> 0 \text{ at } 2\sigma)$$

$$\tau_{\rm PC}^{\rm HFI}(15 < z < 30) < 0.028(!)$$



(!) Different prior that may over penalize high redshift reionization

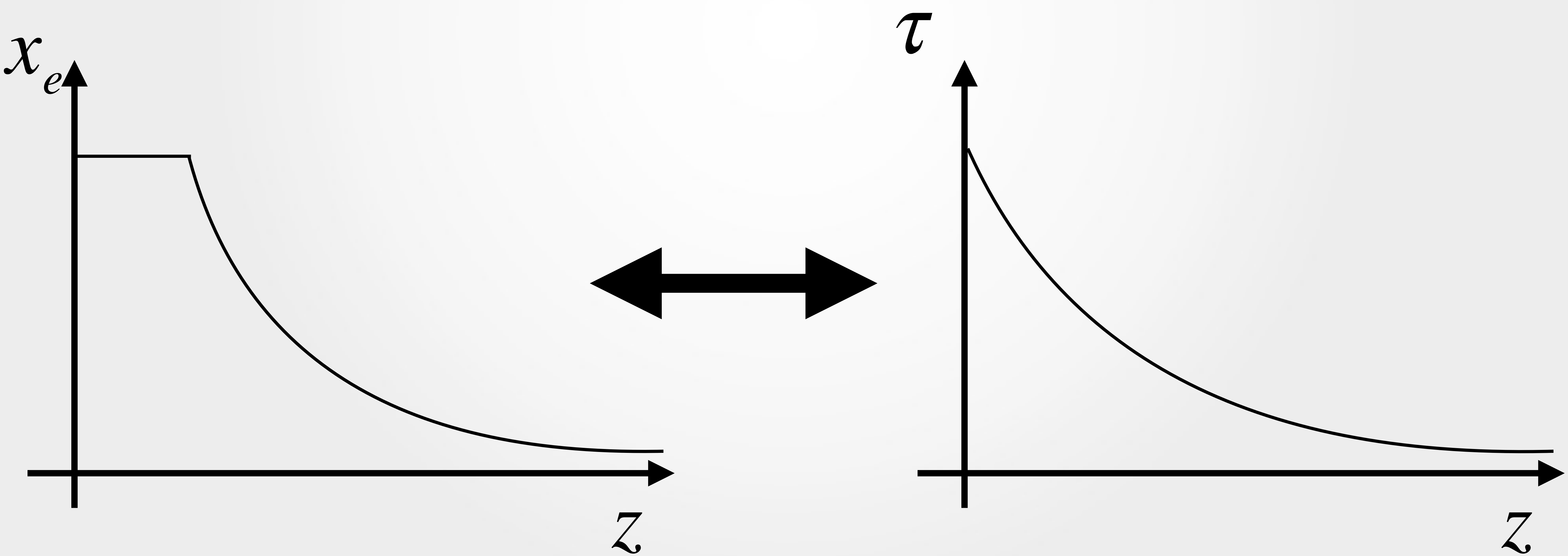
21-cm claims it can measure tau better than cosmic variance

Improvement on neutrinos/DE with lensing measurements

in fact - it is even worse!

$$\tau_{\mathrm{PC}}^{\mathrm{HFI}}(15 < z < 30) < 0.028(!)$$

This number is somewhat prior dependent

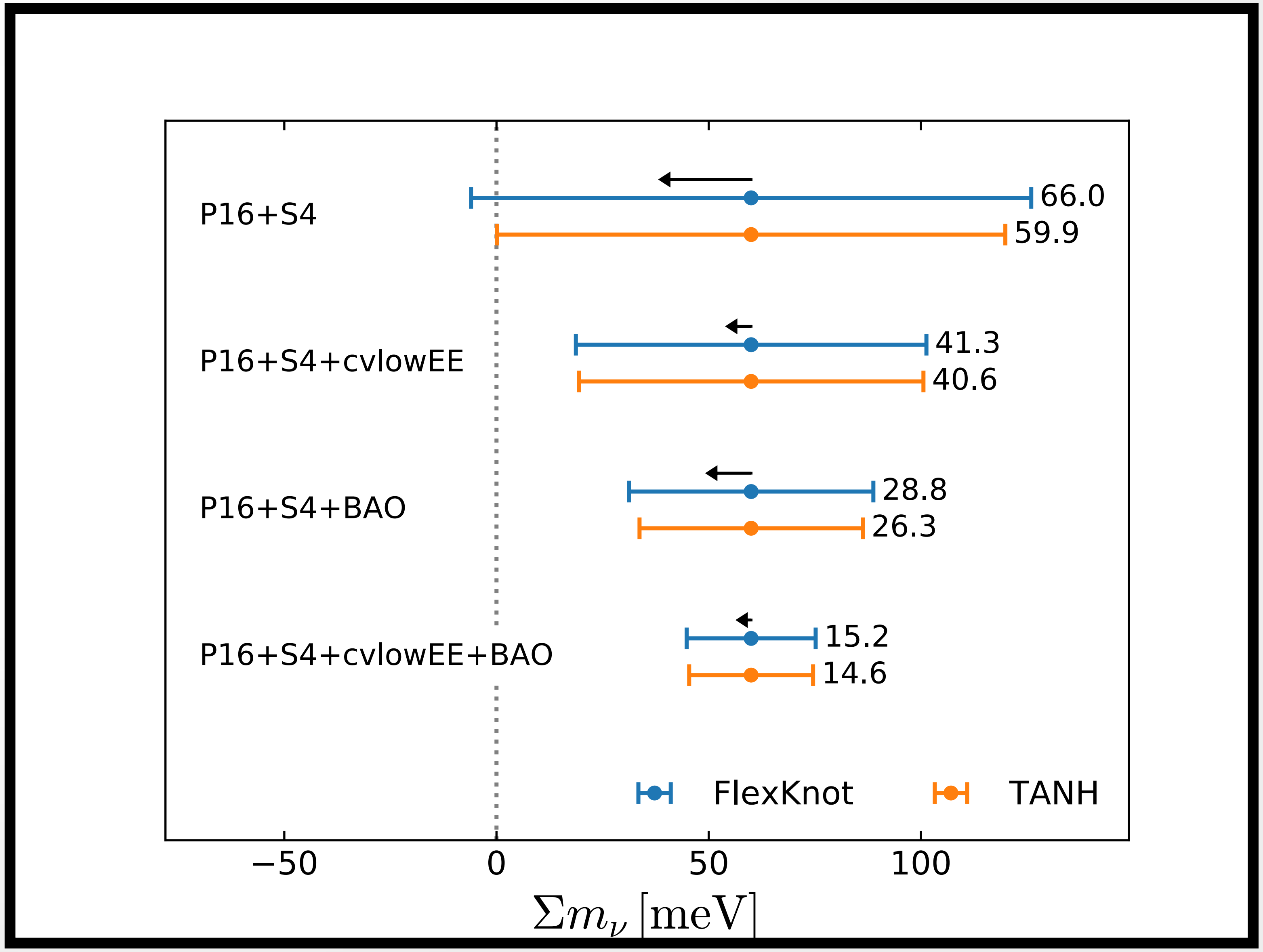


conclusion: reionization makes our life miserable!

Cosmic Microwave Background Constraints in Light of Priors Over Reionization Histories

Marius Millea[1,2,3] and François Bouchet[2]

Flat prior on ionization history vs optical depth



Conclusion

- Cosmology is not just a game of sigma -> we need better first principle physics! (we never fitted the CMB using free functions)
- Be careful with our assumptions about intermediate and high redshift even if you only care about $z<1$
- Smoothness will never be enough of solid argument! Ex: GMR effect and solid state drives!

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Thank you!