

Tau and Turbulence: Understanding reionization at the largest and smallest scales

Christopher Cain

School of Earth & Space Exploration
Arizona State University

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Collaborators: Anson D'Aloisio (UCR), Matt McQuinn (UW), Alex Van Engelen (ASU), Evan Scannapieco (ASU), Kevin Croker (ASU), Hy Trac (CMU), Darby Kramer (ASU), Garrett Lopez (UCR)

Explaining the Title

This talk is about how reionization affects the intergalactic medium, and observations that probe it, at *every* spatial scale

Two parts:

- 1 The CMB optical depth & recent tensions in cosmology
<https://arxiv.org/abs/2505.15899>
- 2 The turbulent intergalactic medium
<https://arxiv.org/abs/2504.21082>

Part 1: The CMB optical depth & recent tensions in cosmology

What is reionization & why is it important?

- Ionization of the IGM by the first ionizing photon sources
- Took place at $z \sim 15 - 6(?)$
- Midpoint of $z \sim 7.5(?)$ (Planck)
- Driven by the first stars? Galaxies? AGN?

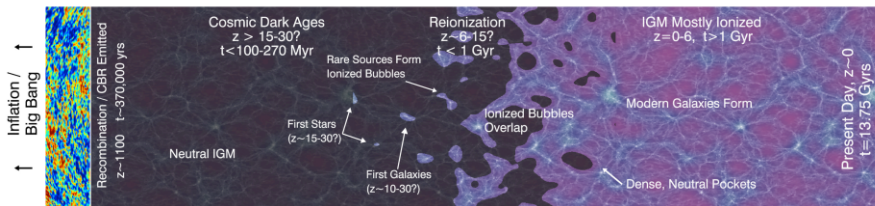
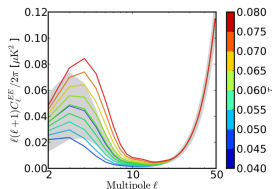
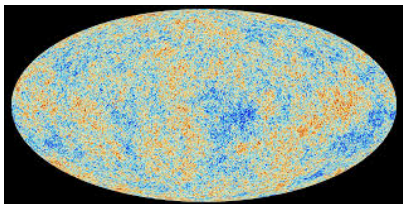


Figure: Robertson+10



The CMB Optical Depth

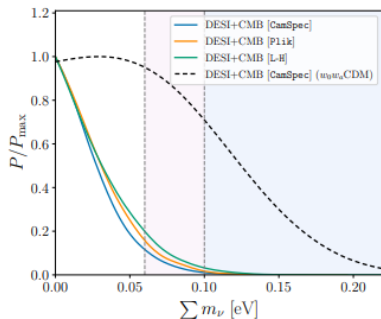
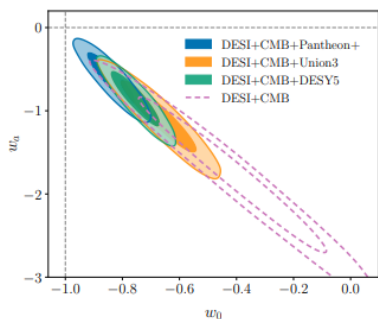
- Proportional to the integrated electron density to the CMB
- Tells us how early the universe re-ionized
- Measured by Planck to be $\tau_{\text{CMB}} = 0.058^{+0.006}_{-0.006} \rightarrow z_{\text{mid}} \approx 7.5$



The DESI-CMB Tension

DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints

M. Abdul Karim¹, J. Aguilar,² S. Ahlen,³ S. Alam,⁴ L. Allen,⁵ C. Allende Prieto^{6,7}, O. Alves,⁸ A. Anand^{9,2},
U. Andrade^{9,8}, E. Armengaud,¹ A. Aviles,^{10,11} S. Bailey², C. Baltay,¹² P. Bansal^{9,8}, A. Bault^{9,2},
T. Bekker,¹³ C. Bonvicini,¹⁴ D. Brinckhi,^{15,16} C. Blake,¹⁷ C. Brinkman,¹⁸ A. Brinkmann,² D. Bruna,¹⁹



A solution involving τ_{CMB} ?

Disputable: the high cost of a low optical depth

Noah Sailer^{*1,2} Gerrit S. Farren^{*‡,2,1} Simone Ferraro^{2,1} and Martin White^{1,2}

¹*Berkeley Center for Cosmological Physics, University of California, Berkeley, CA 94720, USA*

²*Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA*

Turning a negative neutrino mass into a positive optical depth

Tanisha Jhaveri,¹ Tanvi Karwal,¹ and Wayne Hu¹

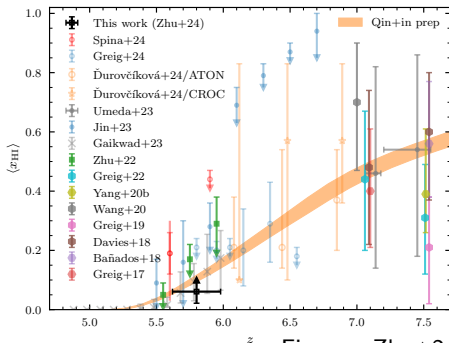
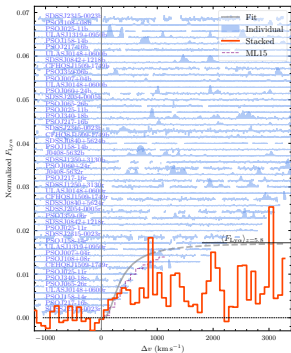
¹*Kavli Institute for Cosmological Physics, Enrico Fermi Institute,
and Department of Astronomy & Astrophysics, University of Chicago, Chicago IL 60637*

(Dated: May 1, 2025)

- $\tau_{\text{CMB}} \approx 0.09 \rightarrow$ lower $\Omega_m \rightarrow$ Higher $\Sigma m_\nu \rightarrow$ problem solved!
- This is a few σ too high for Planck - no problem??
- But does this break anything else?

What else do we know about reionization's timing?

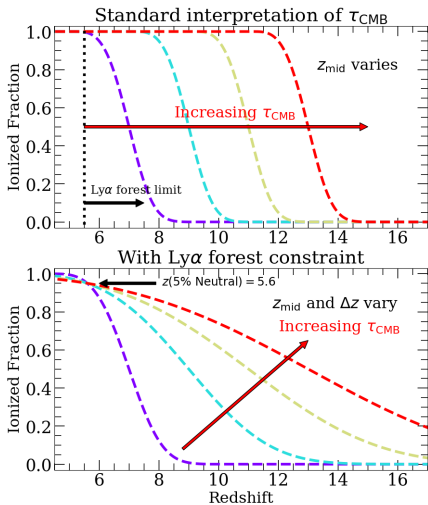
- The Ly α forest of high- z quasars at $5 < z < 6$!
- Stacked Ly α forest spectra reveal damping wing-like features
- Constrains the IGM to be at least 6% neutral at $z = 5.8$



Figures: Zhu+24

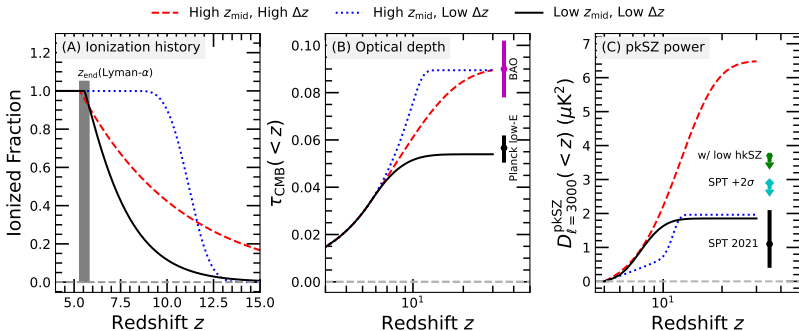
What is required for τ_{CMB} to be large?

- In the standard picture, τ_{CMB} is determined by reionization's midpoint
- Transmission in the Ly α forest of high- z quasars requires that reionization must end at $z \gtrsim 5.5$
- **NEWS FLASH!** - the forest requires reionization to end at $z \approx 5.5$
- This means an earlier midpoint requires a longer duration



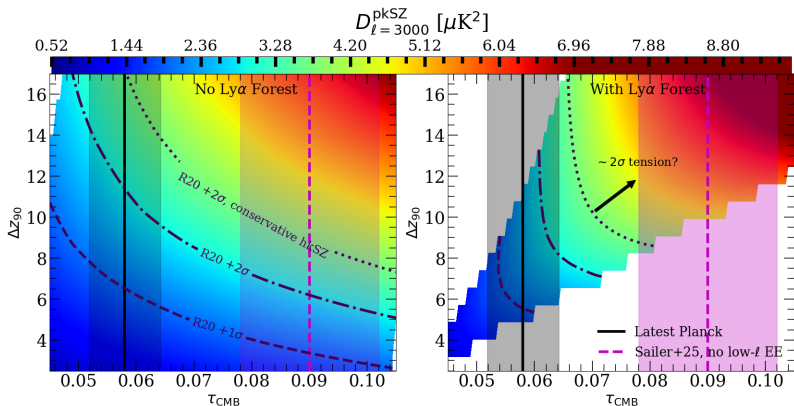
The Patchy Kinetic Sunyaev Zel'Dovich Effect

- Small-scale CMB anisotropy that constrains Δz_{reion}
- Conservative upper limit from SPT: $\lesssim 3.8 \mu\text{K}^2$ (2σ)
- You pick 2: $\tau_{\text{CMB}} \approx 0.09$, Ly α forest, pkSZ constraint



The Patchy Kinetic Sunyaev Zel'Dovich Effect

- $\tau_{\text{CMB}} = 0.09$ is in $\gtrsim 2\sigma$ tension with SPT limits when Ly α forest constraint is included!



Conclusions (Part 1)

- A large CMB optical depth is one of several ways to solve the DESI-CMB tension, including neutrino masses
- The Ly α forest now tells us when reionization ends - $z \approx 5.5$
- With the forest, early reionization = extended reionization
- Patchy kSZ constraints from SPT and ACT prefer a *short* duration of reionization
- **A high τ_{CMB} breaks the CMB twice**

Part 2: The turbulent intergalactic medium

Small-scale structure in the re-ionizing IGM

- Reionization impulsively heats the IGM by 2 – 3 OoM
- Reionization evaporates “mini-halos” and pressure-smooths filaments at 1 – 10 kpc scales

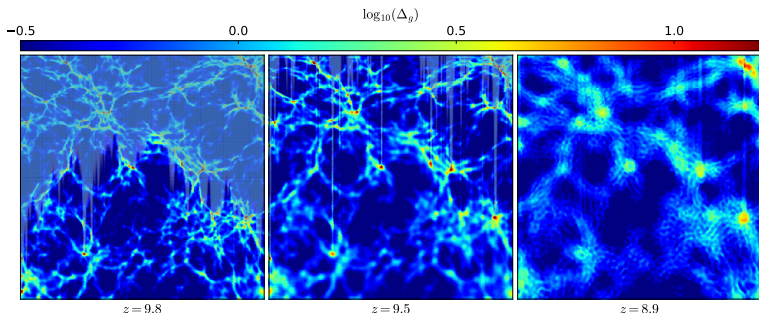


Figure: D'Aloisio+20



To even smaller scales: IGM turbulence??

Reasons to expect the \sim *sub-kpc scale* IGM to be turbulent:

- 1 Intergalactic hydrogen has near-zero viscosity
- 2 Impulsive heating by reionization produces large pressure imbalances \rightarrow driving force
- 3 Abundant small-scale structure throughout the IGM

Is the small-scale IGM turbulent?

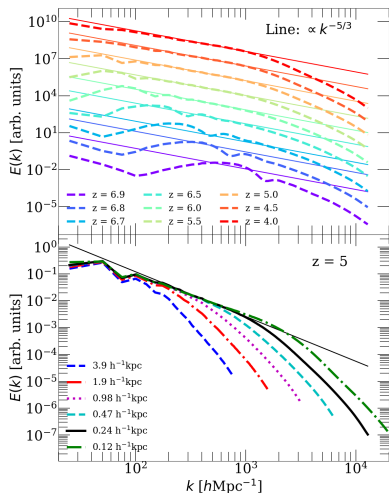
<https://www.youtube.com/watch?v=gmGBo0uBhA4&list=PLYp-rEuCYaWNrhud07MoJIH5uGydenQ5x&index=2>

Is the small-scale IGM turbulent?

Yes!

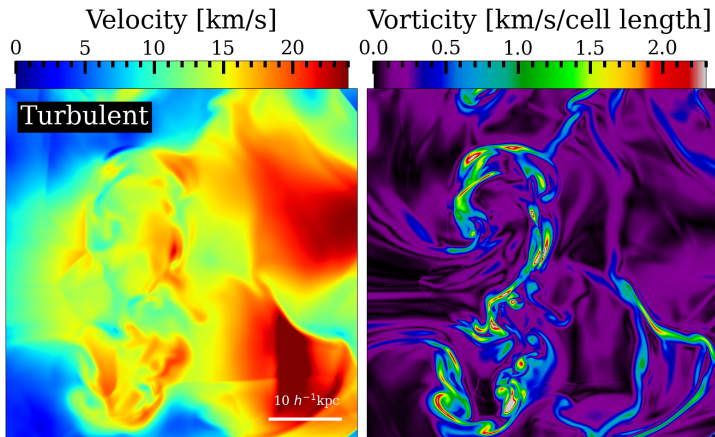
Kolmogorov energy spectrum?

- Yes!
- Characteristic $\propto k^{-5/3}$ scaling emerges $\Delta t \approx 100$ Myr after ionization
- $300 < k/[h\text{Mpc}^{-1}] < 1000$ in our highest-resolution simulation
- Diffuse hydrogen has $\text{Re} \sim 10^5$, turbulence could extend to $10^{-4} \times$ driving scale (~ 1 pc!)



Vorticity?

Turbulent regions display elevated vorticity (as they should)!



Magnetic field growth via the Turbulent Dynamo

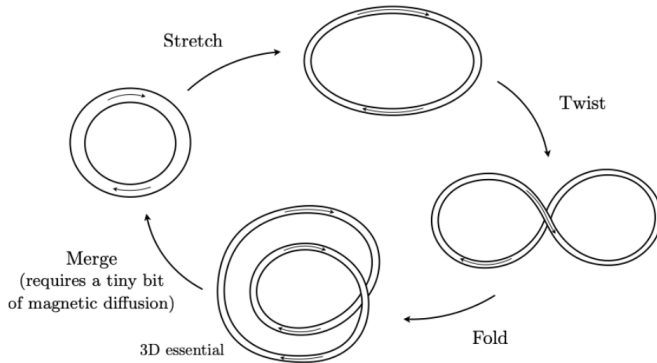
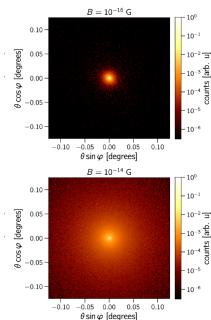
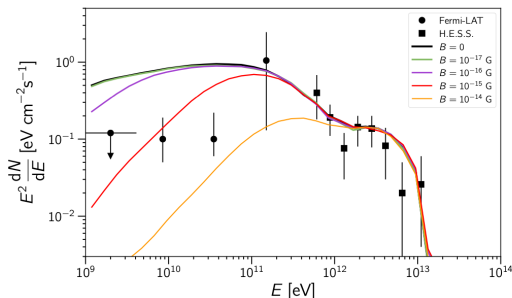


FIGURE 9. The famous stretch-twist-fold dynamo cartoon, adapted from [Vainshtein & Zel'dovich \(1972\)](#) and many others. (from Rincon 2019)

Could turbulence explain limits from TeV Blazars?

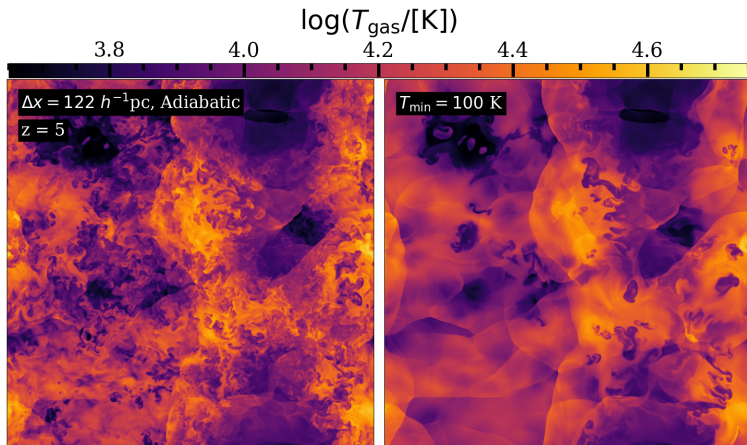
- Significant extended GeV emission missing from TeV blazars
- Preferred explanation is deflection by B-fields



Figures: Batista & Saveliev 2021

Caveat: sensitivity to IGM pre-heating

Highly uncertain! Depends on high-redshift X-ray sources!



Conclusions (Part 2)

- Reionization drives considerable pressure-smoothing of the IGM, which drives turbulent eddies at sub-kpc scales
- These eddies could be responsible for the growth of intergalactic magnetic fields, which could explain Blazar observations
- **The physics of the IGM is still not completely converged at ~ 100 pc resolution! This presents a major challenge for simulations!**

Takeaway Points

- **A high τ_{CMB} breaks the CMB twice**
(<https://arxiv.org/abs/2505.15899>)

- **The IGM is turbulent (and still not converged!) at sub-kpc scales** (<https://arxiv.org/abs/2504.21082>)