The effect of reionization on small-scale structure in the intergalactic medium

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IGM-Galaxy Workshop at IFPU
June 8, 2025

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Reionization: critical juncture in IGM evolution

- IGM conditions changed radically during reionization
- Example: IGM temperature evolution

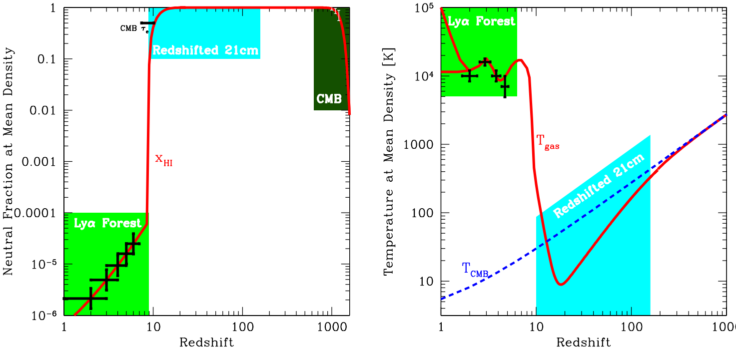


Figure: McQuinn 2016

Goals of this talk

1. **Understand how reionization changes the small-scale structure of the IGM**

2. **Look for physics that we might have missed**

3. **Answer the question "Do we know how to** ***resolve the IGM*** **during reionization?"**

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, dramatically changing IGM conditions

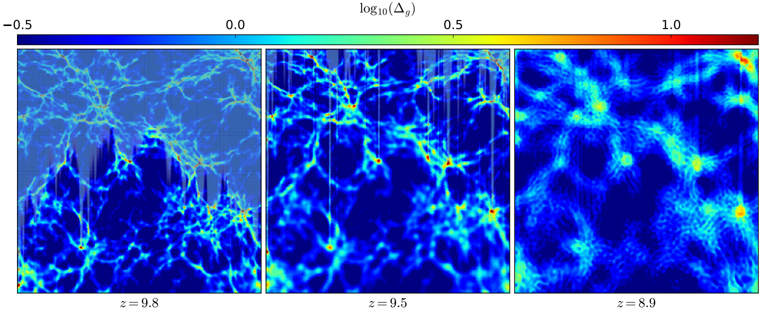


Figure: D'Aloisio,...,**CC**+20

Effects of "IGM relaxation" on small scales

- Photo-evaporation of mini-halos with masses $\lesssim 10^8\ M_\odot$ (Shapiro+04, Iliev+05, Chan+23)
- Pressure smoothing "Lyman-limit" HI absorption systems that set the IGM mean free path (Gnedin 2000, Park+16, D'Aloisio,..,**CC**+20, **CC**+20/21/22a)
- Back-reaction on the reionization photon budget and morphology (McQuinn+06, Davies+21, **CC**+21/22b)
- **Alters the IGM thermal structure (Hirata+18, CC+24)**
- **Drives turbulence in the IGM (CC+25)**

Thermal Structure of the IGM

- Evolution of the mean IGM temperature and its fluctuations during and after reionization

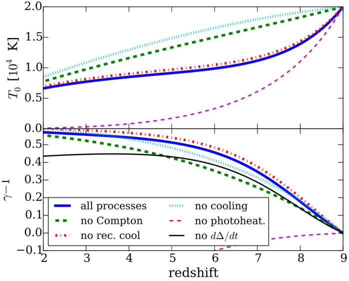
- A key ingredient in forward-modeling the Lyα forest

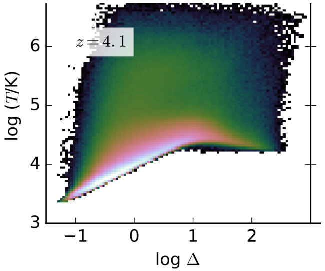
- Important for: reionization timeline, measurements of $\Gamma_{\rm HI}$, constraints on dark matter models, etc.

The IGM Temperature-Density Relation

- The low-density IGM is believed to follow a tight power law temperature-density relation (TDR)

$$T(\Delta) = T_0 \Delta^{\gamma - 1}$$





Figures: McQuinn+15, Keating+17

Is the TDR a tight power law on small scales?

Is the TDR a tight power law on small scales?

No!

Resolution convergence of the TDR

- $L_{\rm box} = 2\ h^{-1}$cMpc with 8 h^{-1}ckpc spatial resolution - on the high-end for standard Lyα forest simulations

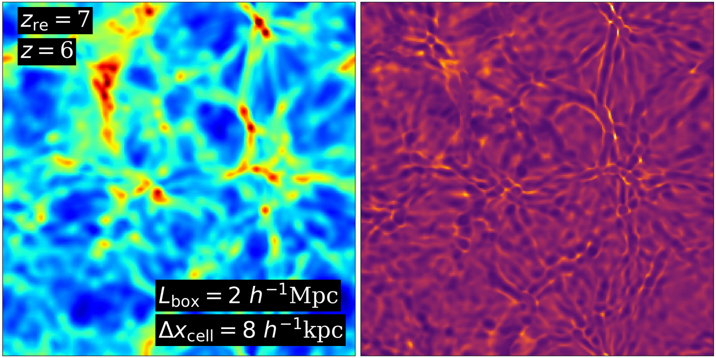


Figure: **CC**+24

Resolution convergence of the TDR

- Increasing resolution to 2 h^{-1}ckpc (by a factor of $4^3\times$) makes a significant difference for small-scale thermal structure!

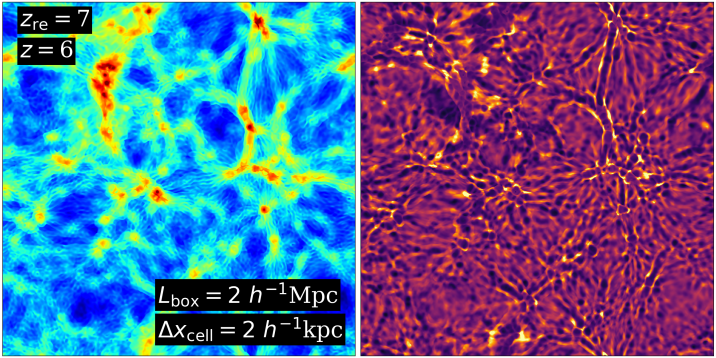
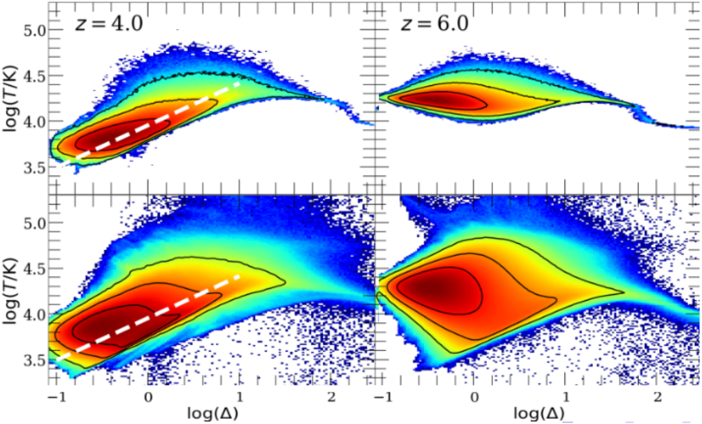


Figure: **CC**+24

Resolution convergence of the TDR

The TDR is nowhere near converged at 8 h^{-1}ckpc resolution, even at $z = 4$ (assuming $z_{\mathrm{reion}} = 7$)



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?

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Yes!

Magnetic field growth via the Turbulent Dynamo

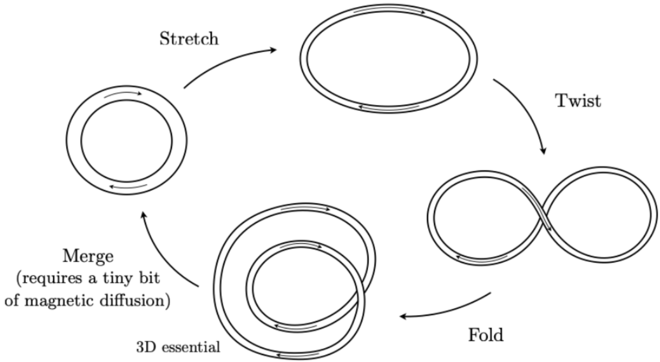
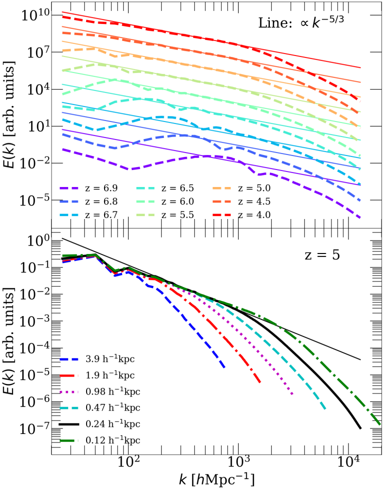


FIGURE 9. The famous stretch-twist-fold dynamo cartoon, adapted from Vainshtein & Zel'dovich (1972) and many others. (from Rincon 2019)

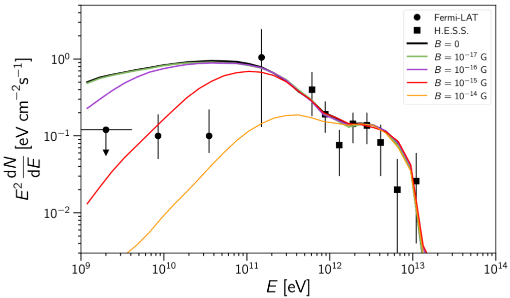
Do we see a Kolmogorov energy spectrum?

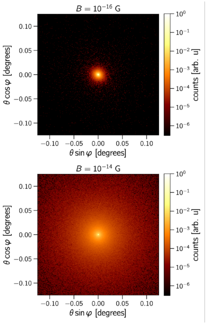
- Yes!
- Characteristic $\propto k^{-5/3}$ scaling emerges $\Delta t \approx 100$ Myr after ionization
- $300 < k/[h\mathrm{Mpc}^{-1}] < 1000$ in our highest-resolution simulation
- Diffuse hydrogen has $\mathrm{Re} \sim 10^5$, turbulence could extend to $10^{-4}\times$ driving scale (~ 1 pc!)



Could turbulence explain limits from TeV Blazars?

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

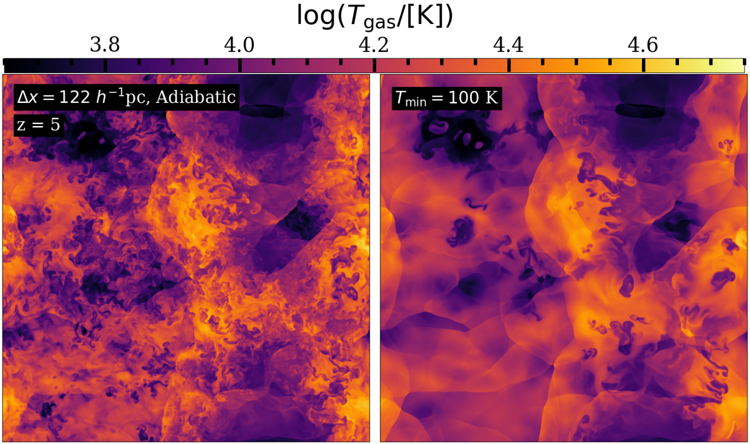




Figures: Batista & Saveliev 2021

Sensitivity to IGM pre-heating

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



Conclusions

- Reionization drives considerable pressure-smoothing of the IGM, dramatically altering its structure on small scales
- The IGM has a complex temperature-density structure *and* turbulent behavior on kpc scales and smaller, which is missed in low-resolution simulations (https://arxiv.org/abs/2405.02397, `https://arxiv.org/abs/2504.21082`)
- The physics of the IGM is still not completely converged at **100** h^{-1}**pc** resolution! This presents a major challenge for future simulations