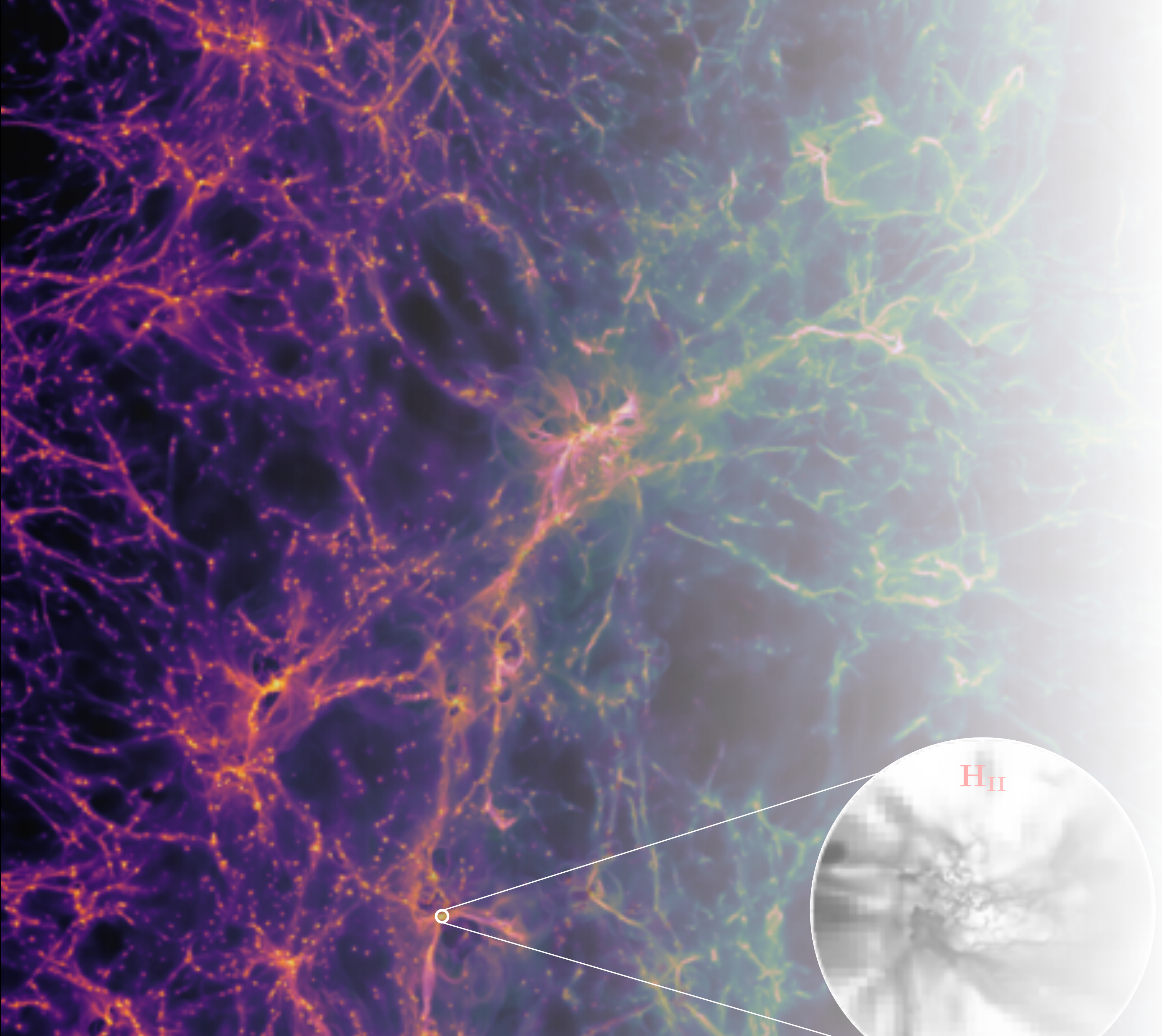
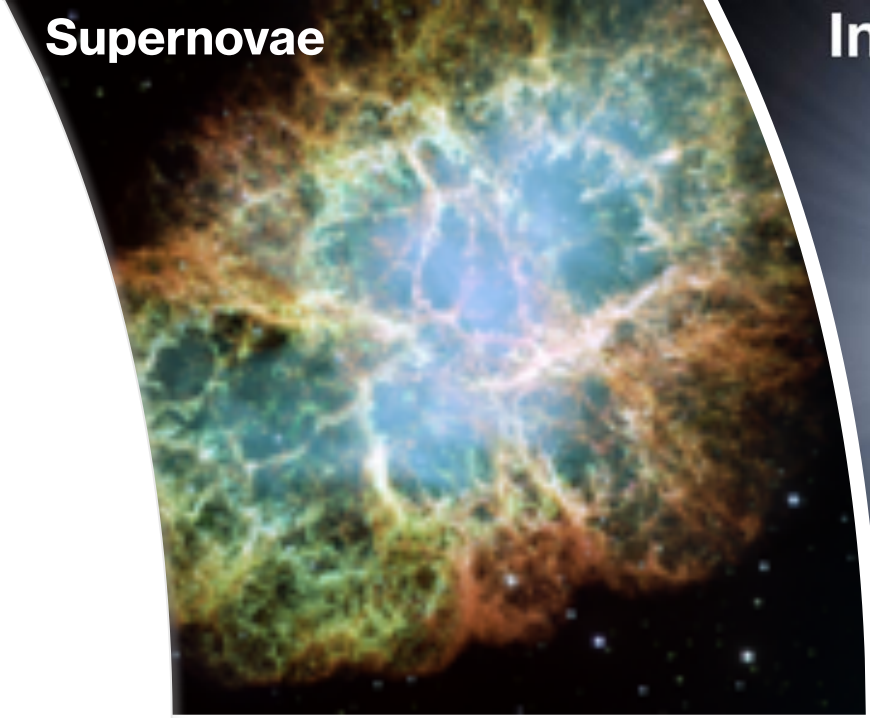


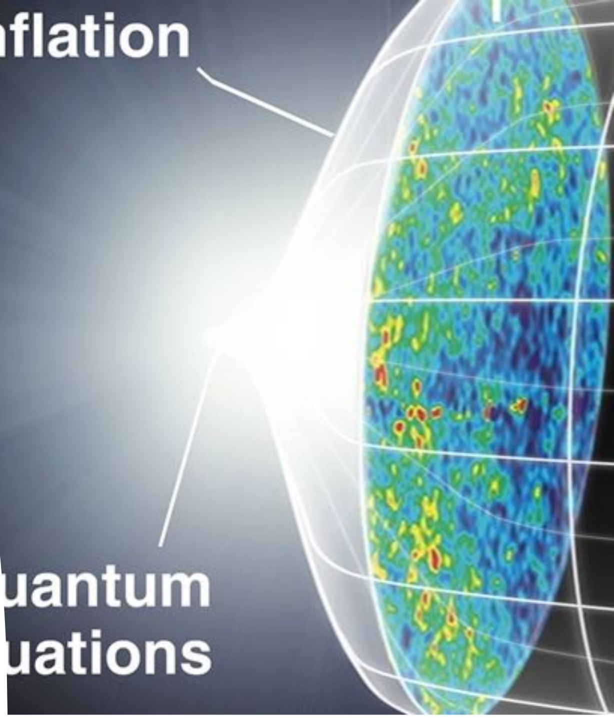
Introducing SPHINX-MHD

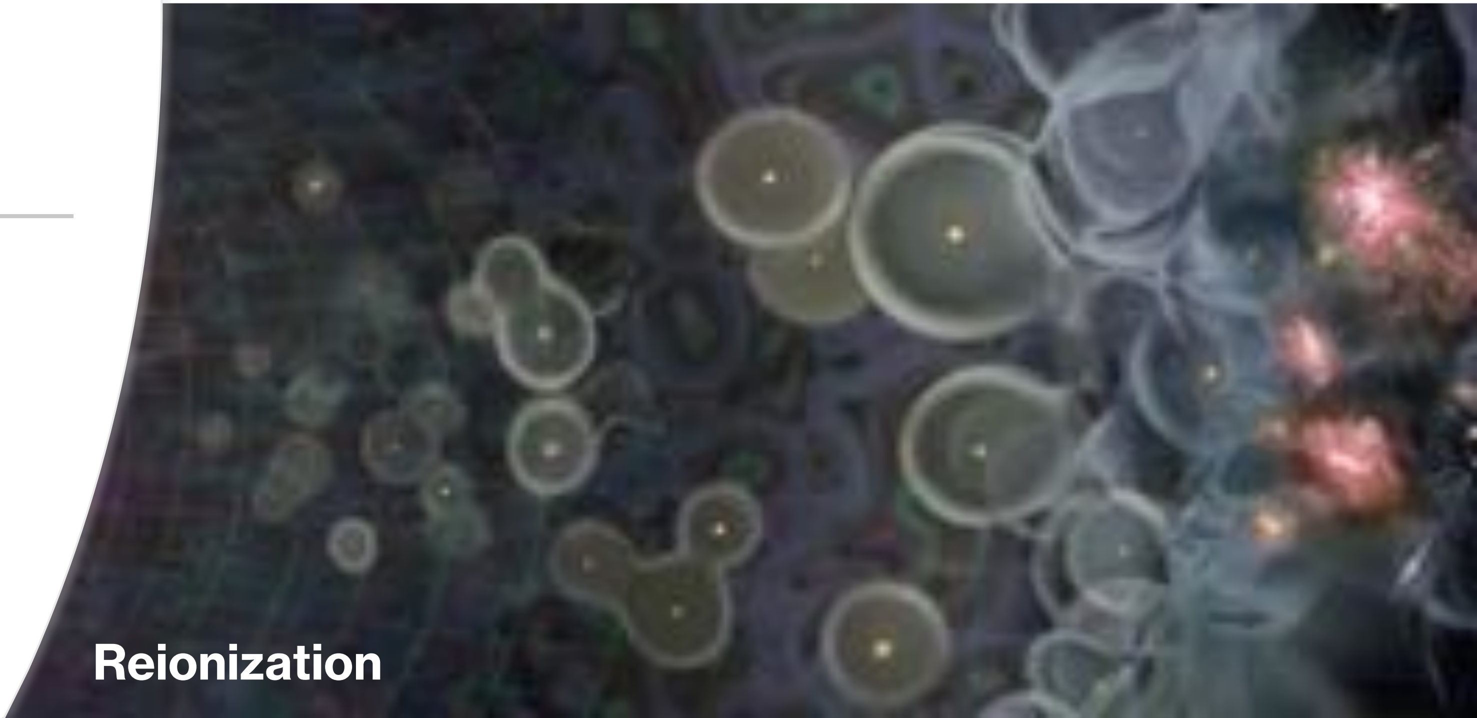
The impact of primordial magnetic fields on the first galaxies, reionization, and the global 21cm signal

Harley Katz | March 5, 2020 | arXiv 2101.11624

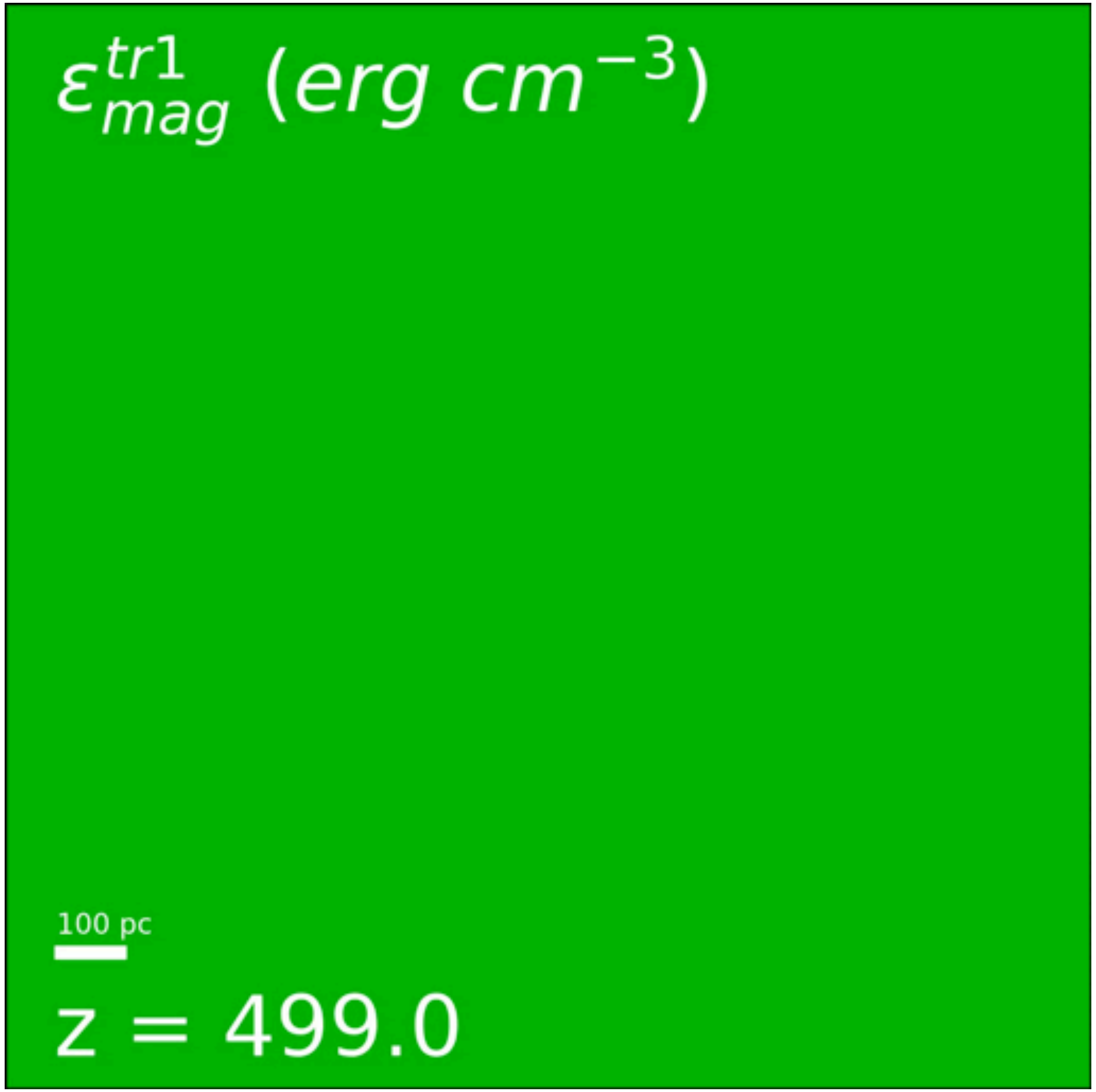
Magnetic fields are everywhere, but we don’t know what generated them


Supernovae


Inflation

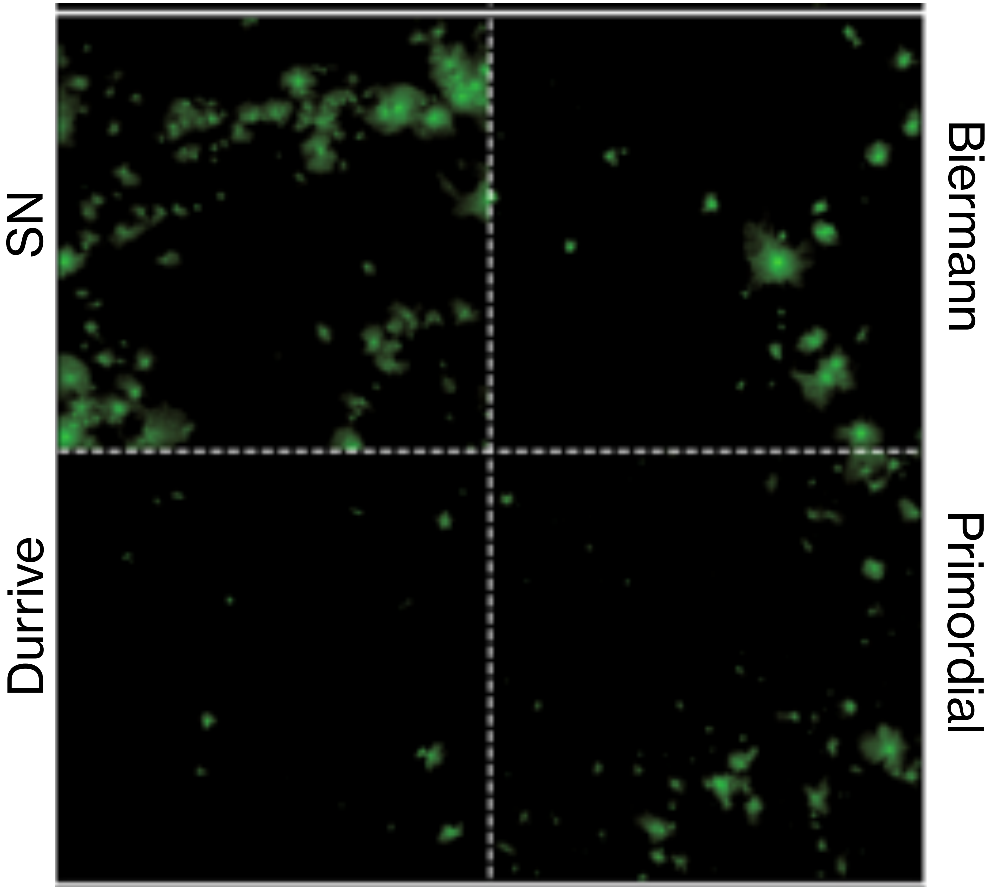

Reionization

Magnetogenesis in simulations

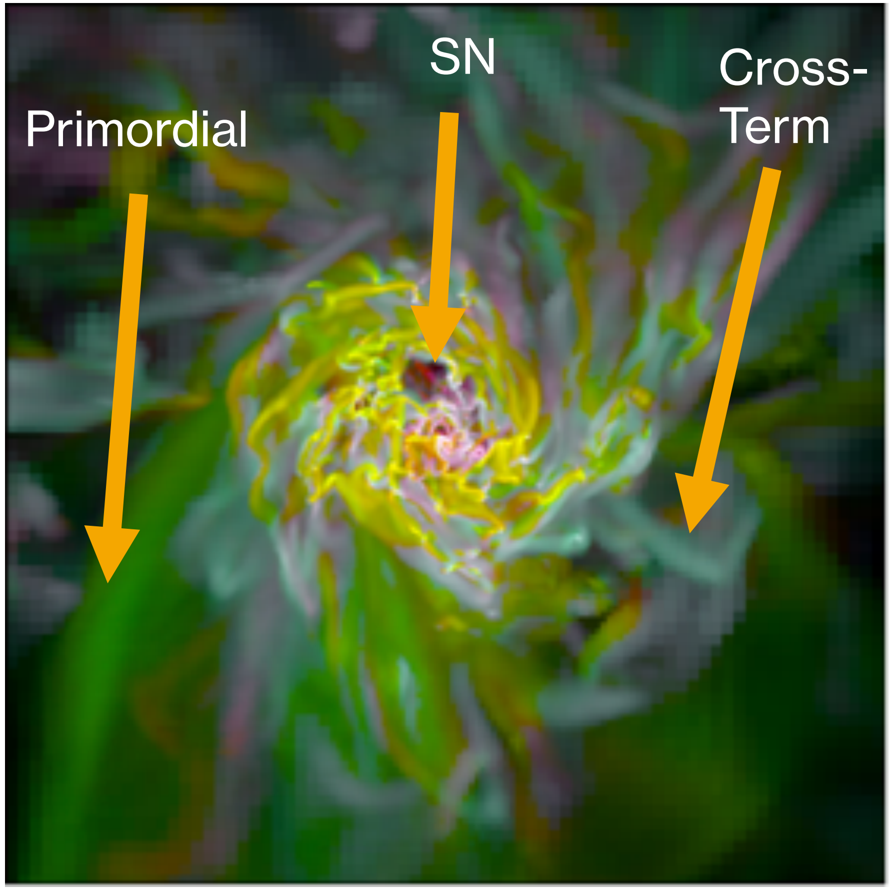


Martin-Alvarez, HK+ 2020

No agreed upon scenario



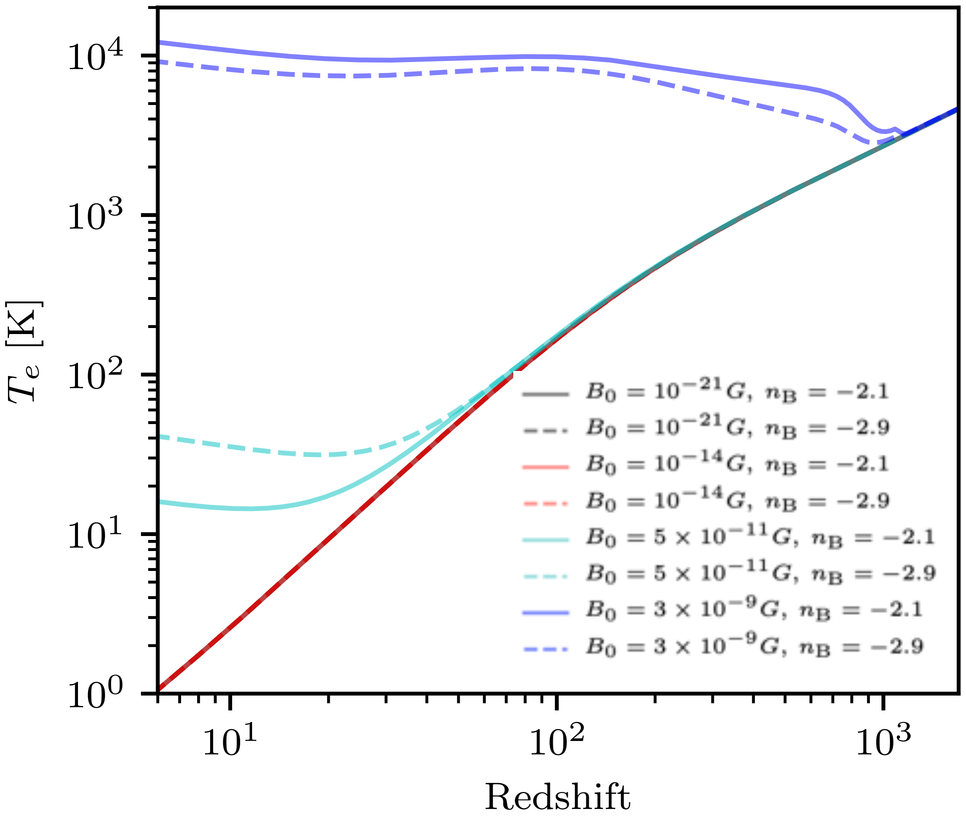
Garaldi+ 2021



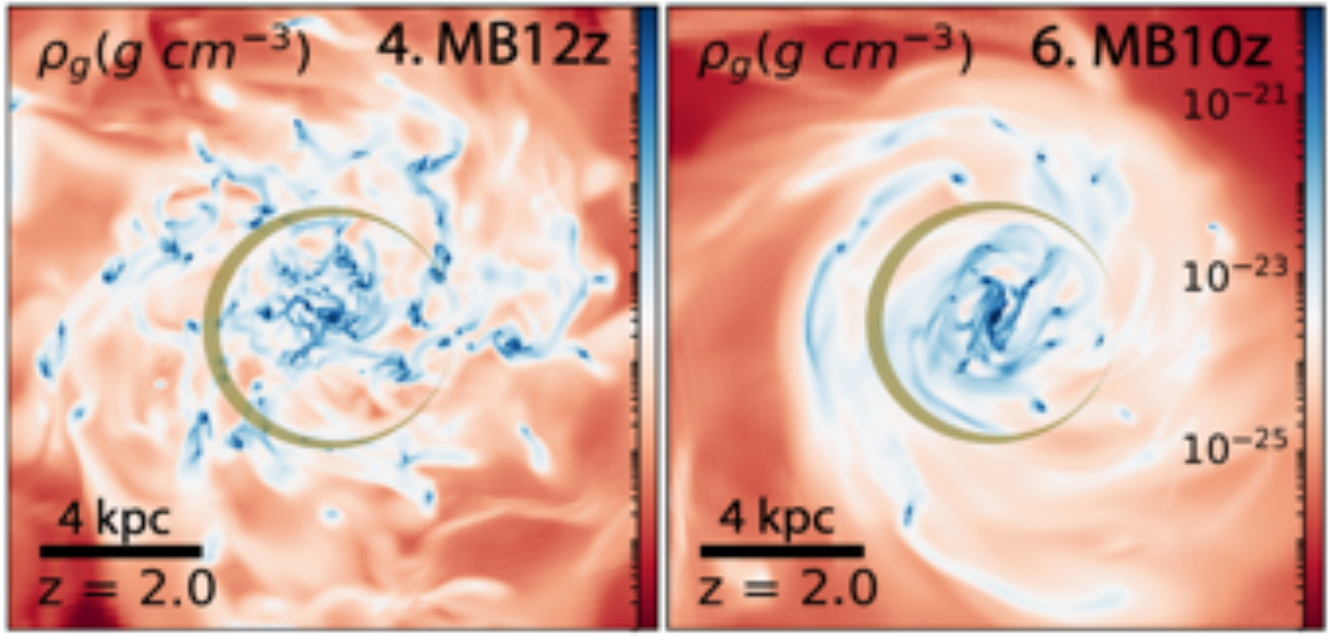
Martin-Alvarez, HK+ 2021

Strong PMFs can drive reionization

Decaying magnetic turbulence + ambipolar diffusion heat the IGM

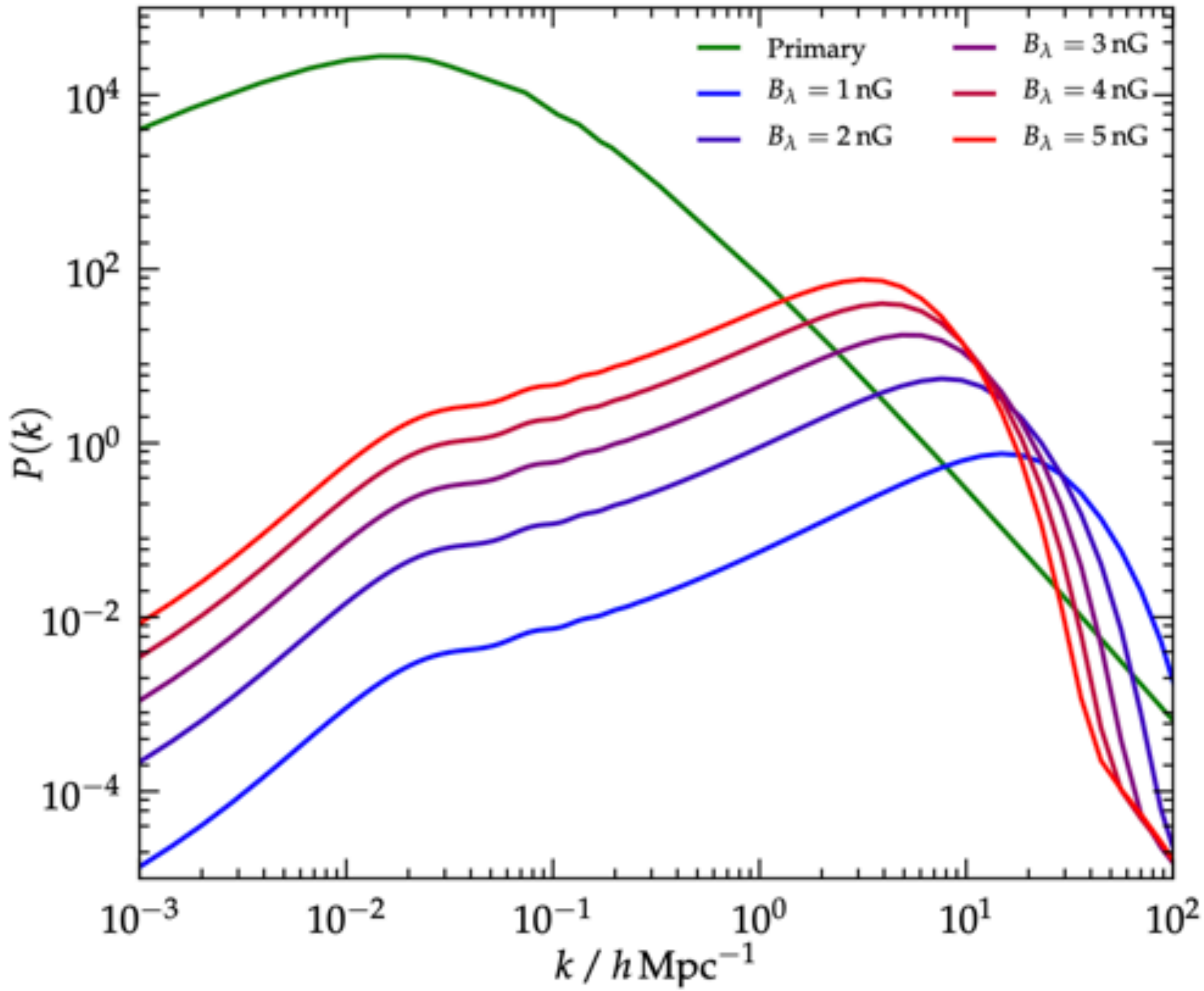


PMFs impact the structure of the ISM



Martin-Alvarez+ 2020

PMFs can modify the matter power spectrum



Shaw+ 2012

How PMFs modify the matter power spectrum (see Kim+ 1996)

Ideal MHD equations:

$$
\begin{aligned}
\partial_t \mathbf{v} + \frac{\dot{R}}{R}\mathbf{v} &= -\frac{\nabla\psi}{R} + \frac{(\nabla\times\mathbf{B}_b)\times\mathbf{B}_b}{4\pi R(t)\rho_b(t)},\\
\partial_t\delta + \frac{\nabla\cdot\mathbf{v}}{R} &= 0,\\
\nabla^2\psi &= 4\pi R^2 G\rho_b\delta,\\
\nabla\cdot\mathbf{B}_b = \nabla\cdot\delta\mathbf{B} &= 0,\\
\partial_t(R^2\mathbf{B}_b) &= 0,\\
\partial_t(R^2\delta\mathbf{B}) &= \frac{\nabla\times(\mathbf{v}\times R^2\mathbf{B}_b)}{R}.
\end{aligned}
$$

Evolution of baryon density perturbations

$$
\frac{\partial^2\delta_b}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial\delta_b}{\delta t} - 4\pi G(\rho_{DM}\delta_{DM} + \rho_b\delta_b) = \frac{\nabla\cdot[(\nabla\times\mathbf{B})\times\mathbf{B}]}{4\pi a^2\rho_b}
$$

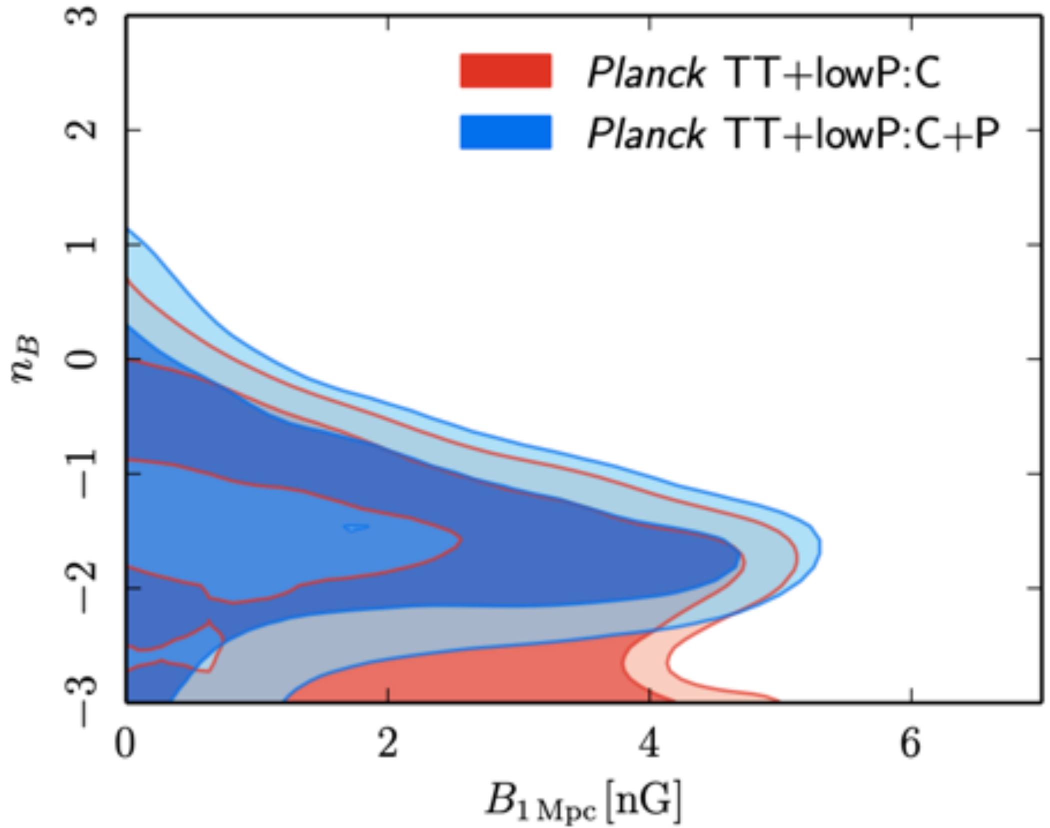
Evolution of DM density perturbations

$$
\frac{\partial^2\delta_{DM}}{\partial t^2} = -2\frac{\dot{a}}{a}\frac{\partial\delta_{DM}}{\delta t} + 4\pi G(\rho_{DM}\delta_{DM} + \rho_b\delta_b)
$$

Constraints from Planck

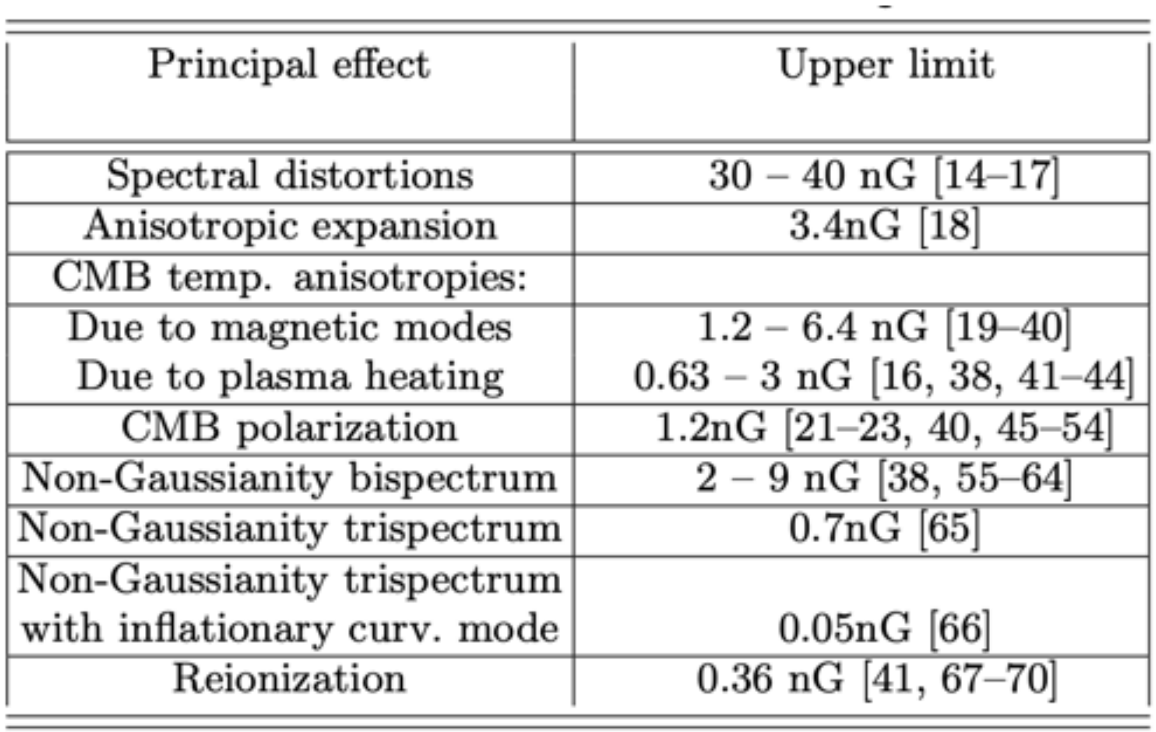
$$P(k) = Ak^{n_B}$$

$$A = \frac{(2\pi)^{n_B+5} B_{1\mathrm{Mpc}}^2}{2\Gamma\left(\frac{n_B+3}{2}\right) k_{1\mathrm{Mpc}}^{n_B+3}}$$



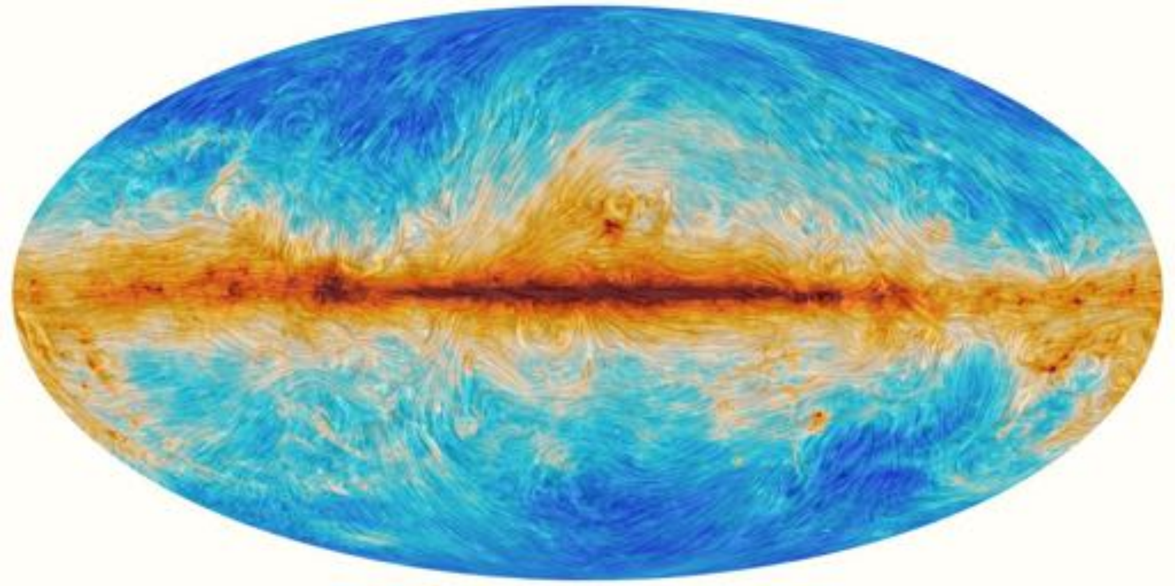
Ade+ 2015

CMB (and other phenomena) puts strong constraints on primordial magnetic fields

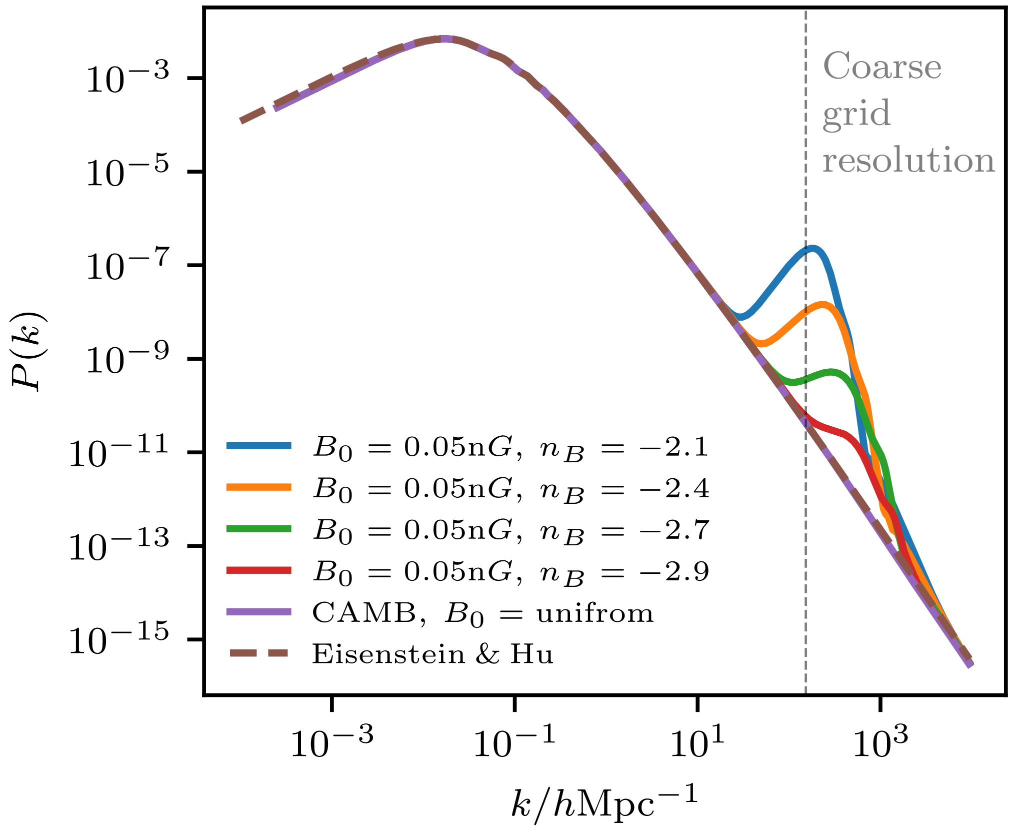


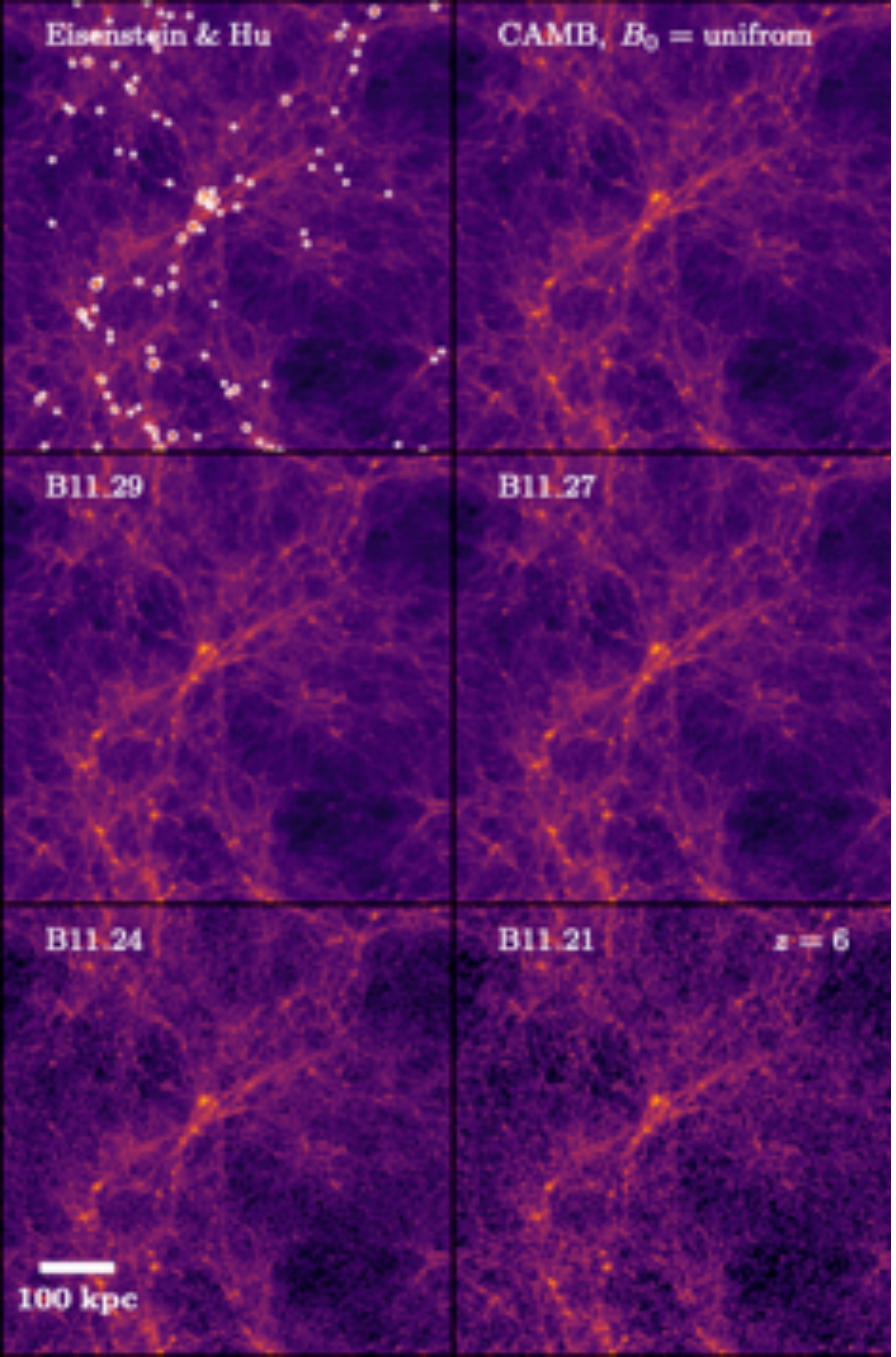
Principal effect	Upper limit
Spectral distortions	30 – 40 nG [14–17]
Anisotropic expansion	3.4nG [18]
CMB temp. anisotropies:	
Due to magnetic modes	1.2 – 6.4 nG [19–40]
Due to plasma heating	0.63 – 3 nG [16, 38, 41–44]
CMB polarization	1.2nG [21–23, 40, 45–54]
Non-Gaussianity bispectrum	2 – 9 nG [38, 55–64]
Non-Gaussianity trispectrum	0.7nG [65]
Non-Gaussianity trispectrum with inflationary curv. mode	0.05nG [66]
Reionization	0.36 nG [41, 67–70]

Jedamzik+ 2018

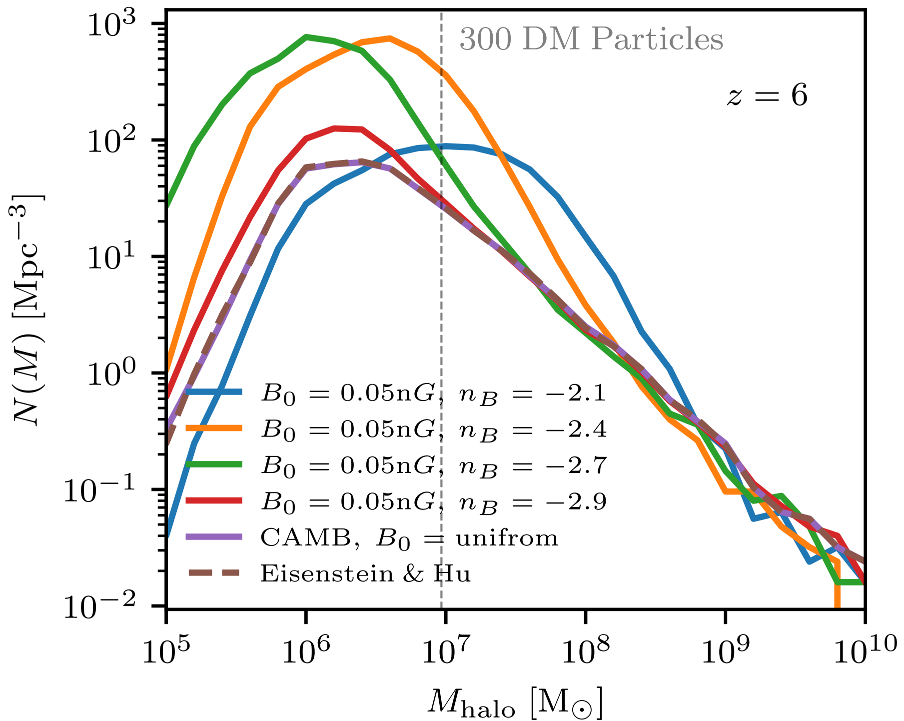


Within the constraints, the impact is primarily in the dwarf galaxy regime

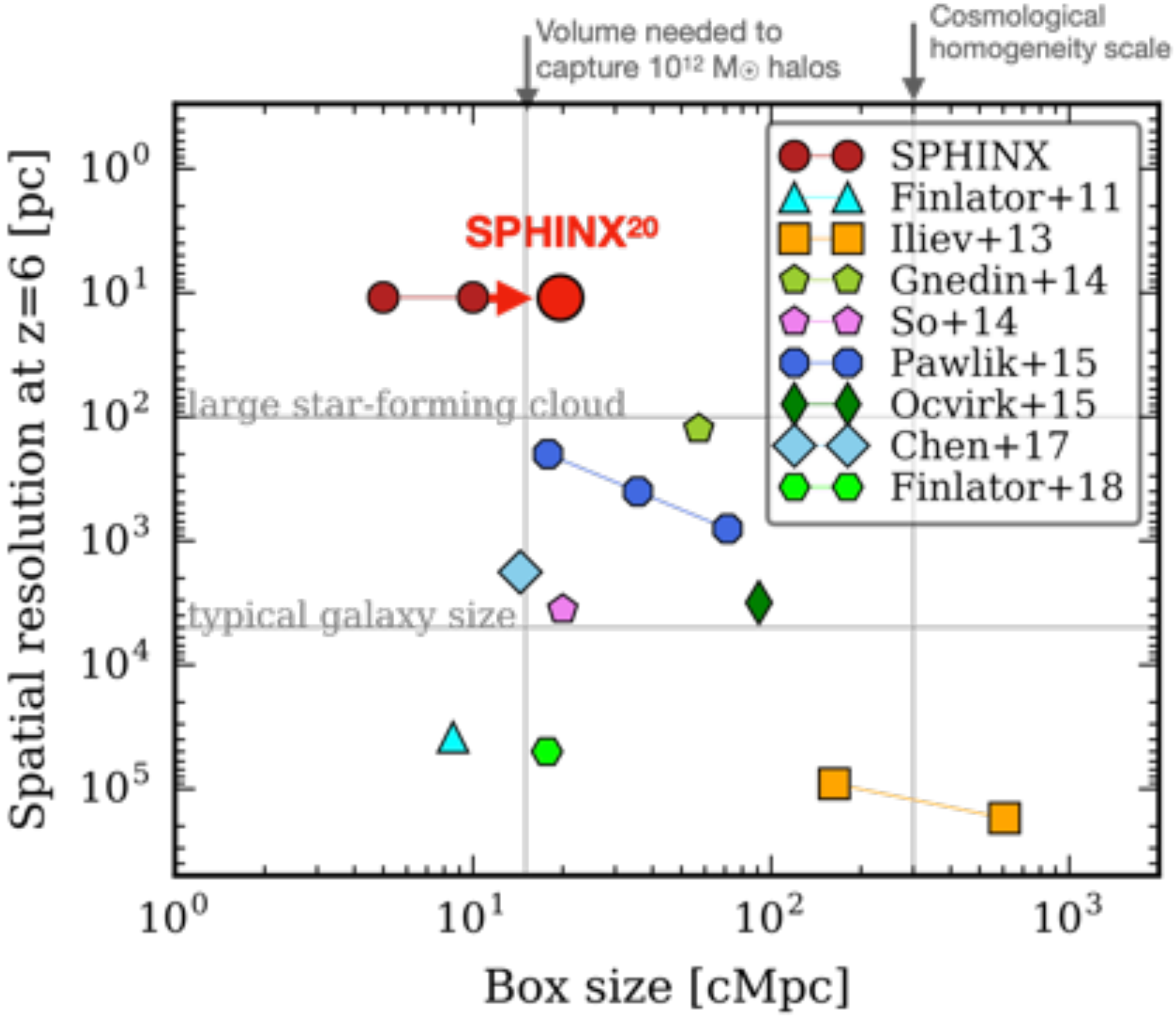

Katz+ 2021



The modified matter power spectrum can drastically alter the DM density field



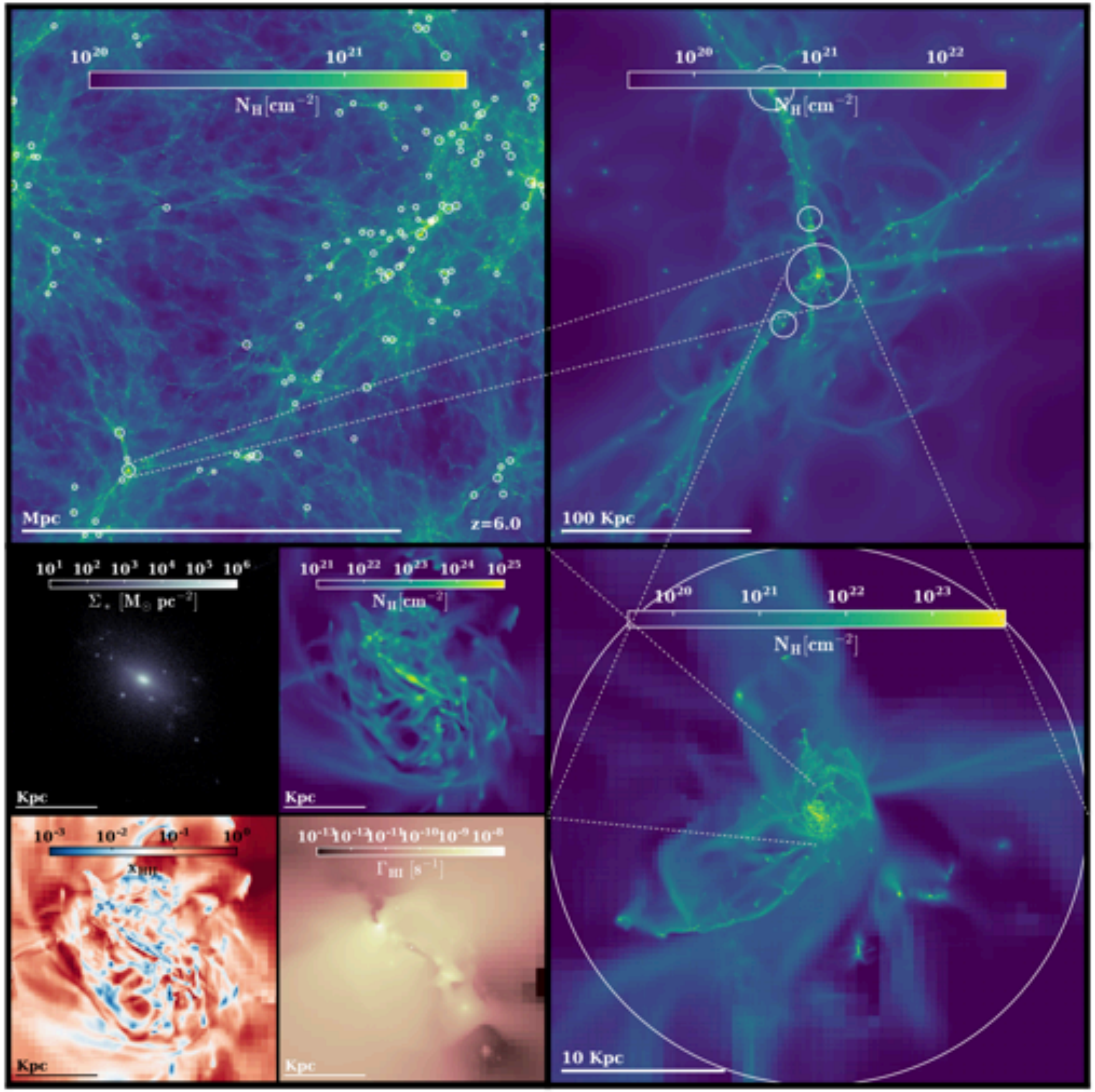
Katz+ 2021



Introducing SPHINX

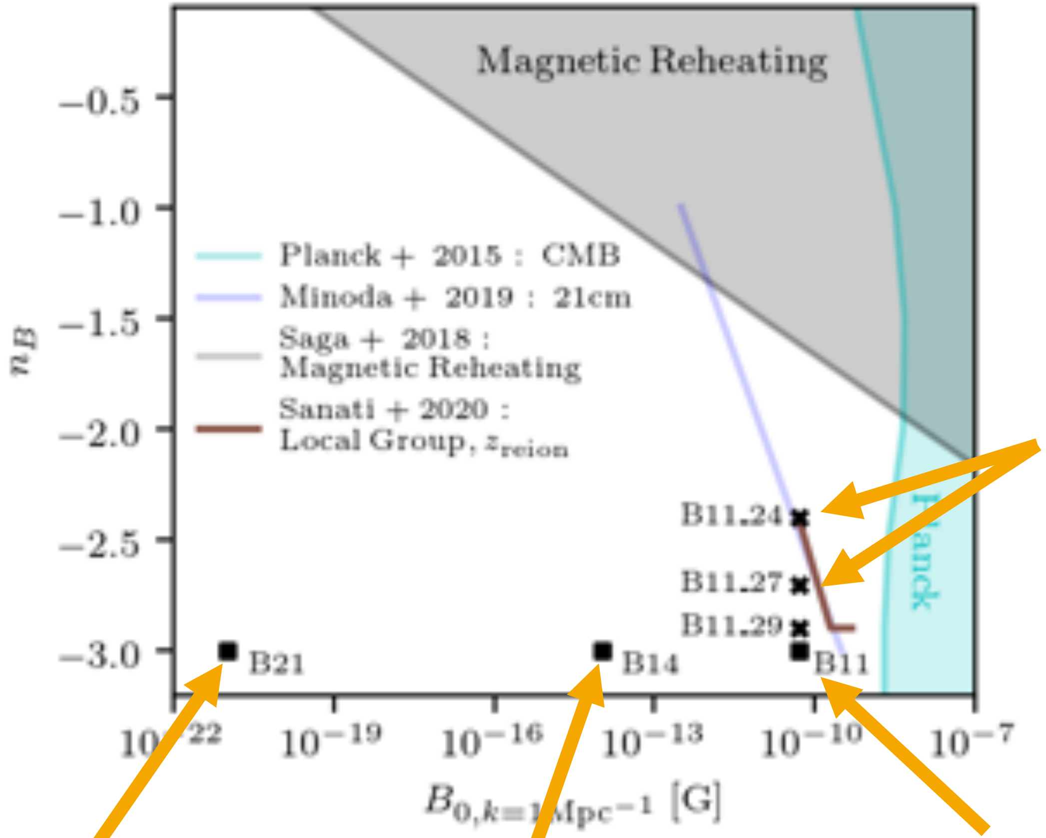
SPHINX-MHD sim details

- Almost identical to the original hi-res version of SPHINX (Rosdahl et al. 2018)
- 5 Mpc box
- 10 pc physical resolution
- 6-species non-equilibrium chemistry and 3-bin radiation transfer
- 1,000 M_{sun} star particles, 3.1e4 M_{sun} DM particles
- Constrained transport ideal MHD
- Star formation criteria and efficiency includes the impact of magnetic fields



6 simulations varying the strength and structure of the primordial magnetic field

$$P(k) = A k^{n_B} \qquad A = \frac{(2\pi)^{n_B+5} B_{1\mathrm{Mpc}}^2}{2\Gamma\left(\frac{n_B+3}{2}\right) k_{1\mathrm{Mpc}}^{n_B+3}}$$

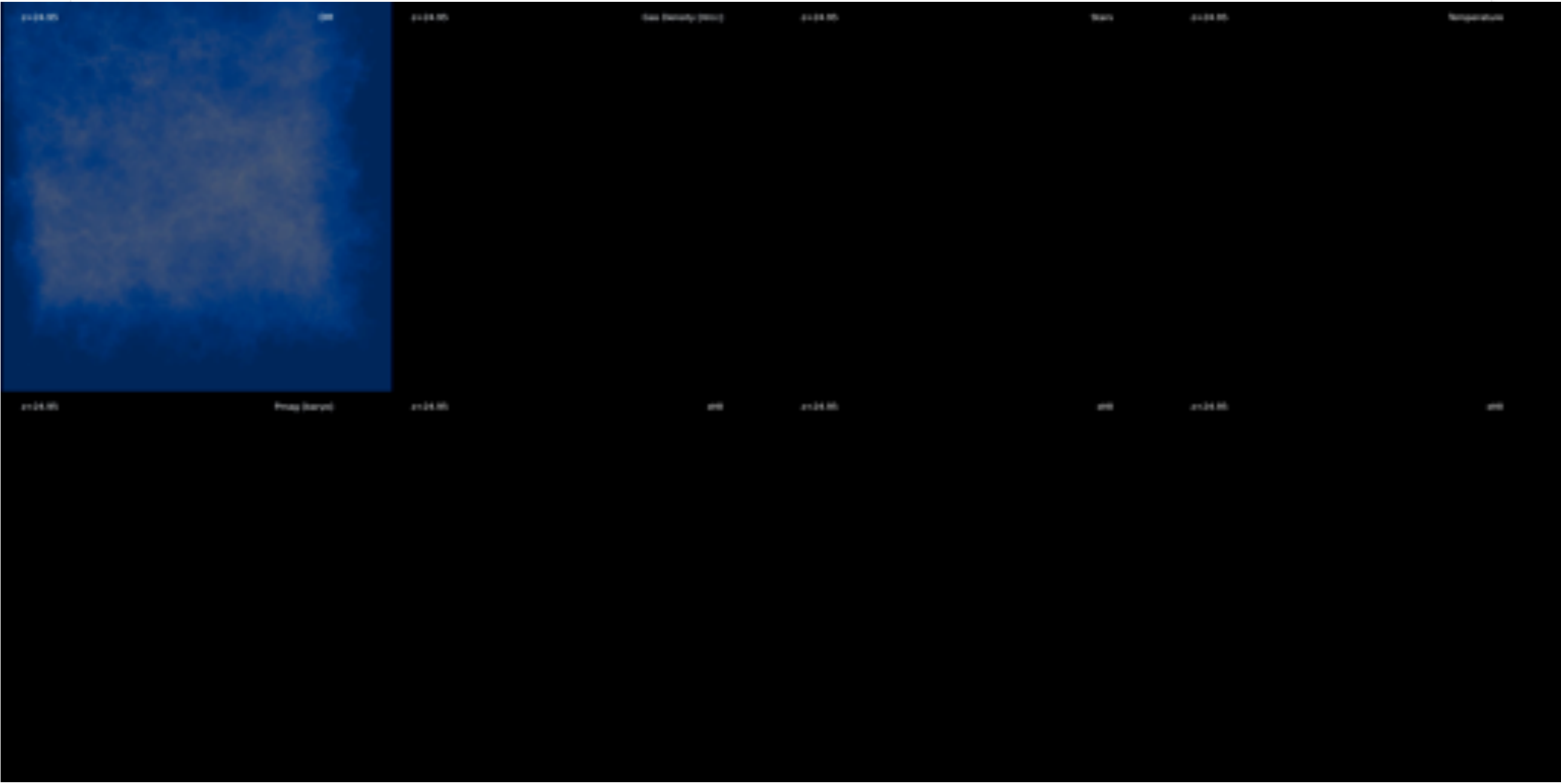


Strong impact on structure formation

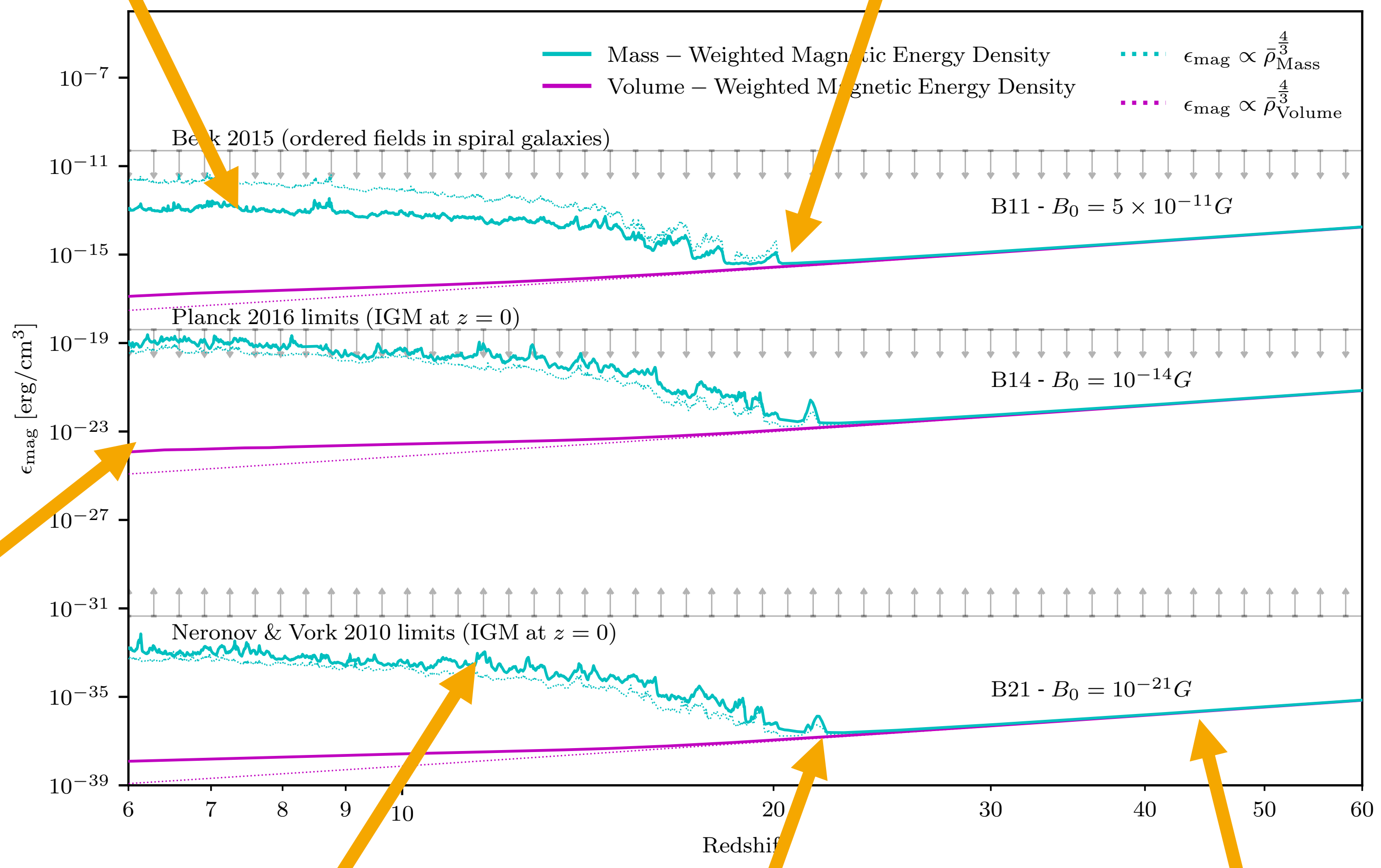
Biermann battery level

Illustris-TNG

Micro-Gauss level fields from compression


DM
Gas Density
Stars
Temperature

Magnetic fields grow due to compression and turbulent/rotational amplification



Saturation

Strong PMFs delay structure formation

Expulsion into the IGM

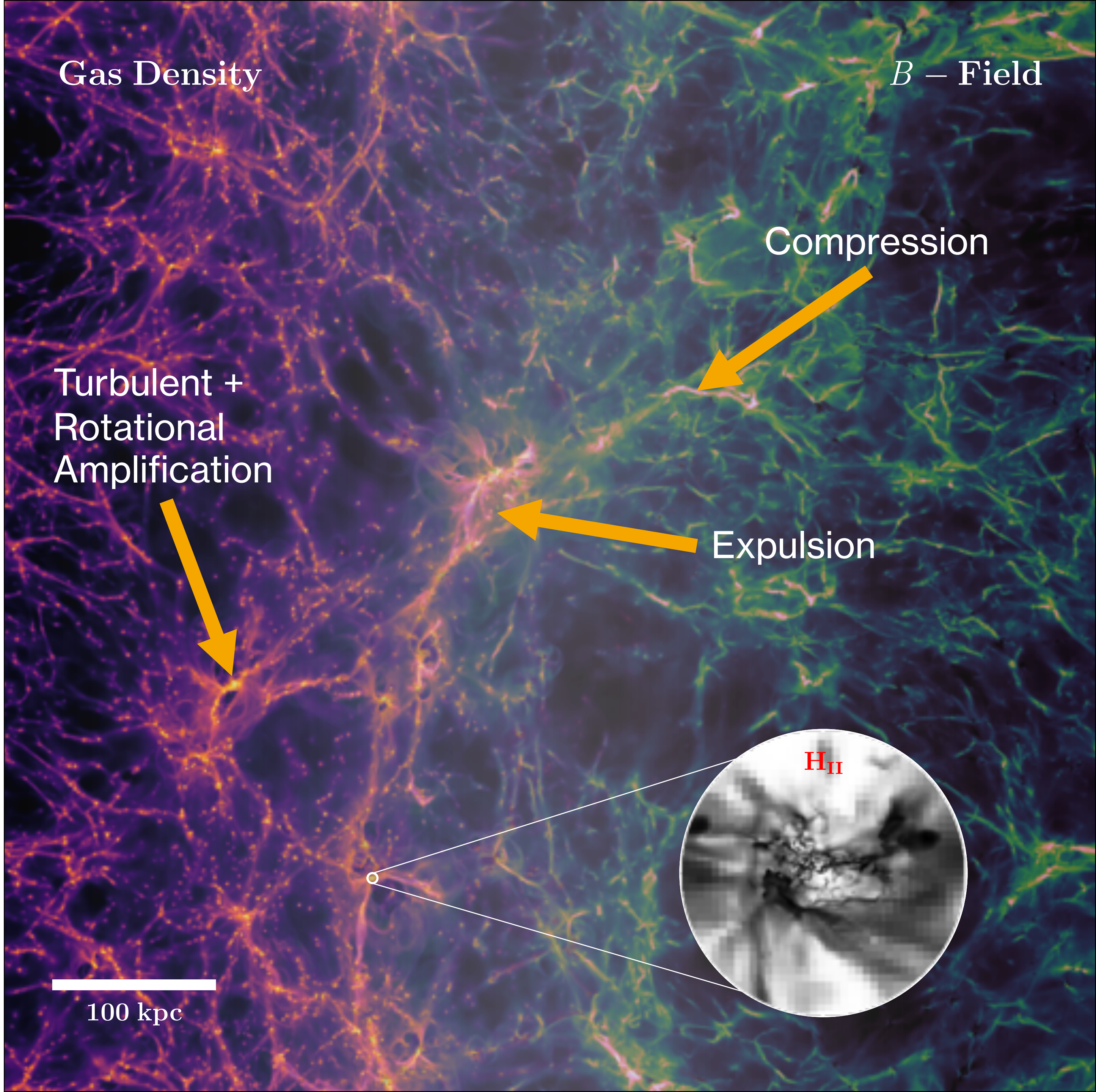
Turbulent + rotational amplification

First structures

Cosmic expansion

PMF amplification follows the ρ –field

- Compressional amplification: $B \sim \rho^{2/3}$ due to flux conservation
- Turbulent and rotational dynamos occur in galaxies
- Amplified magnetic fields are expelled into the IGM



Star formation depends on the local properties of the magnetic field

Can stars form?

$$\lambda_{\mathrm{J,MTT}} = \frac{\pi\sigma_V^2 + \sqrt{36\pi c_{\mathrm{s,eff}}^2 G \Delta x^2 \rho + \pi\sigma_V^4}}{6 G \rho \Delta x},$$

$$c_{\mathrm{s,eff}} = c_{\mathrm{s}}\sqrt{1 + \beta^{-1}},$$

$$\beta = P_{\mathrm{thermal}} / P_{\mathrm{mag}}$$

How efficiently do they form?

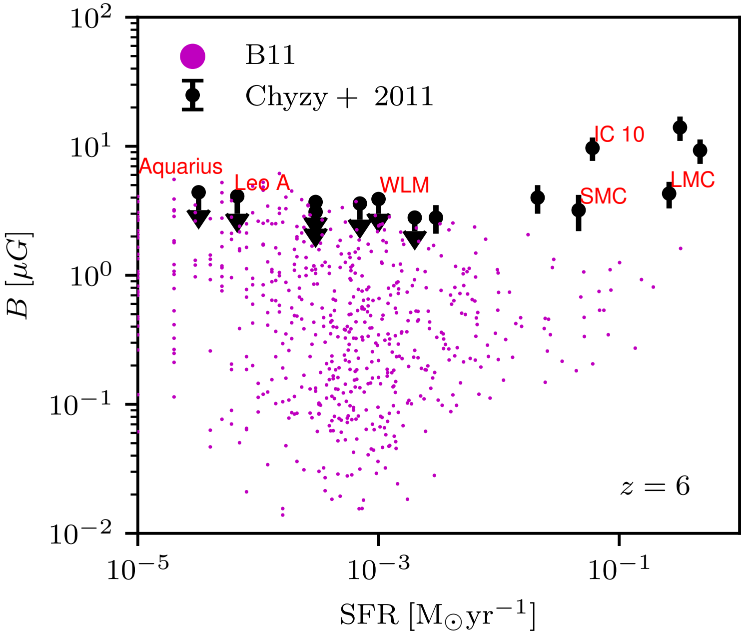
$$\dot{\rho}_{\mathrm{star}} = \epsilon_{\mathrm{ff}} \frac{\rho}{t_{\mathrm{ff}}}$$

$$\epsilon_{\mathrm{ff}} = \frac{\epsilon_{\mathrm{cts}}}{2\phi_t} \exp\left(\frac{3}{8}\sigma_s^2\right)\left[1 + \mathrm{erf}\left(\frac{\sigma_s^2 - s_{\mathrm{crit}}}{\sqrt{2\sigma_s^2}}\right)\right]$$

$$s_{\mathrm{crit}} = \ln\left(0.067\ \theta^{-2} \alpha_{\mathrm{vir}} \mathcal{M}^2 f\left(\beta\right)\right)$$

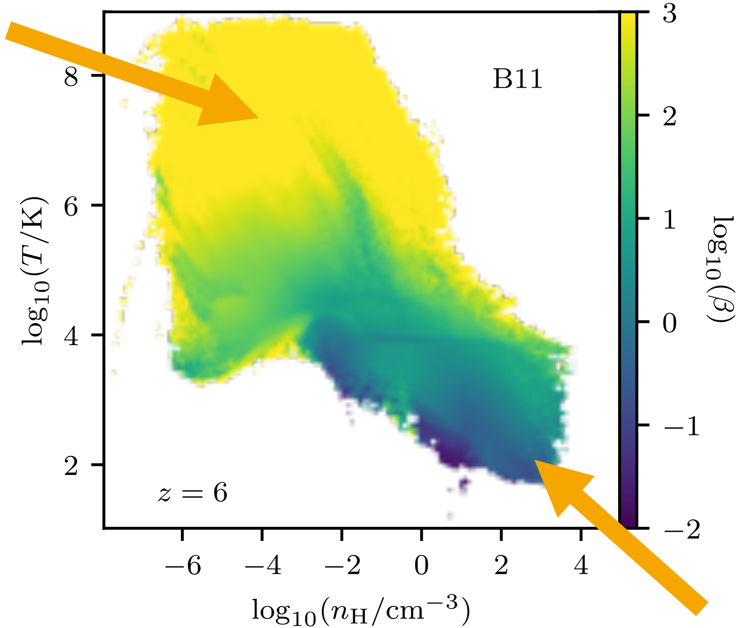
Schmidt 1959, Padoan & Nordlund 2011, Hennebelle & Chabrier 2011, Federrath & Klessen 2012

Our strongest PMFs result in micro-Gauss level B-fields in galaxies and impact star formation



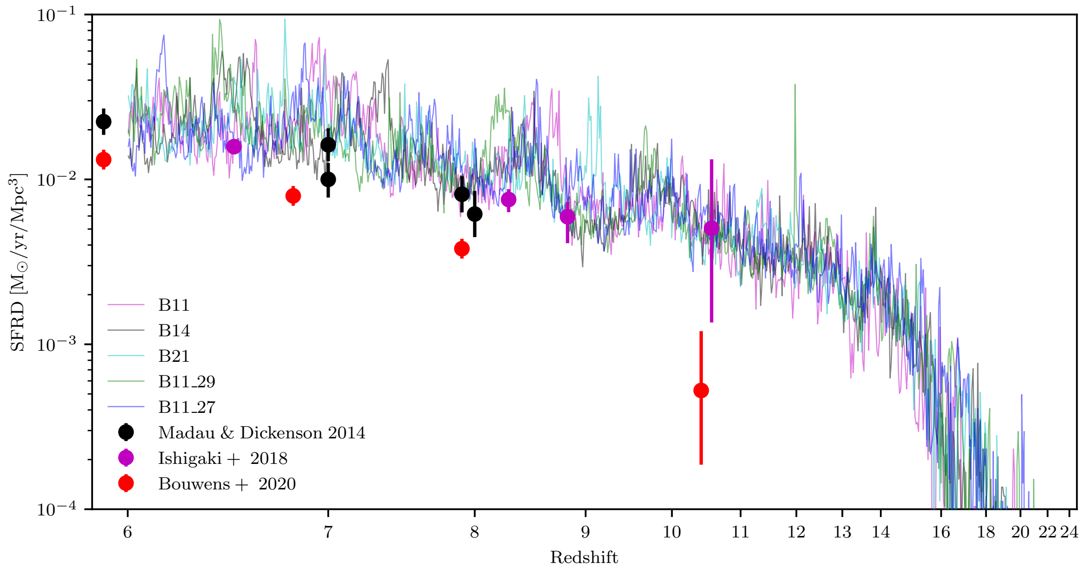
$$c_{\mathrm{s,eff}} = c_{\mathrm{s}}\sqrt{1+\beta^{-1}}$$

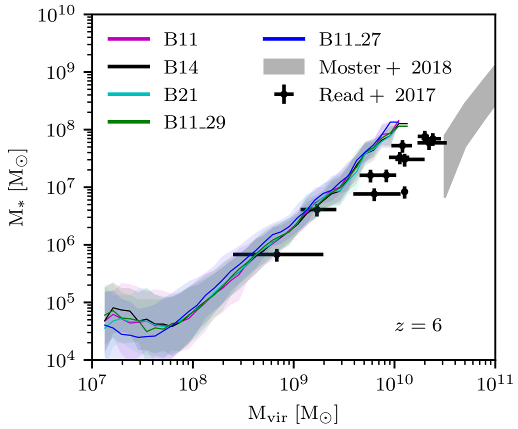
Thermal pressure dominates

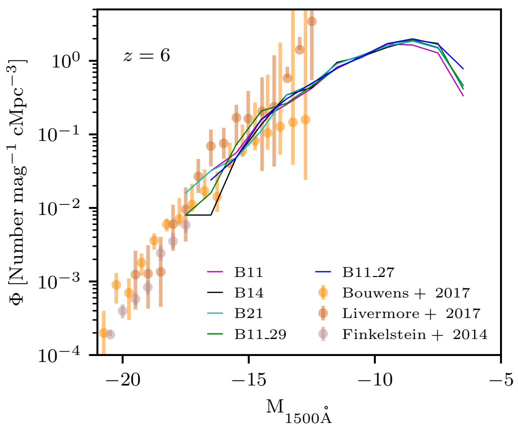


Magnetic pressure dominates

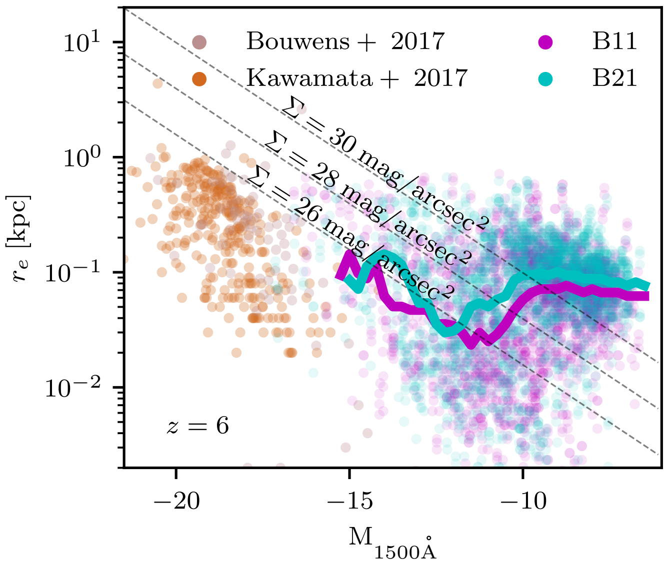
Despite the additional pressure and number of dwarf galaxies, star formation is not strongly impacted

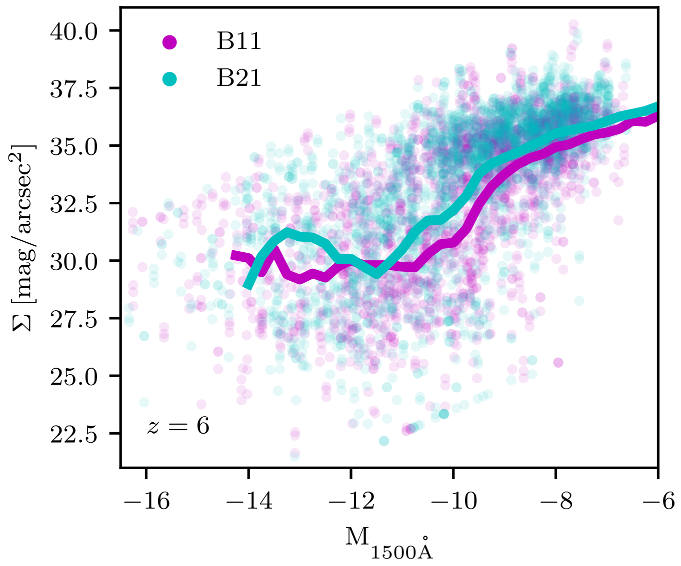


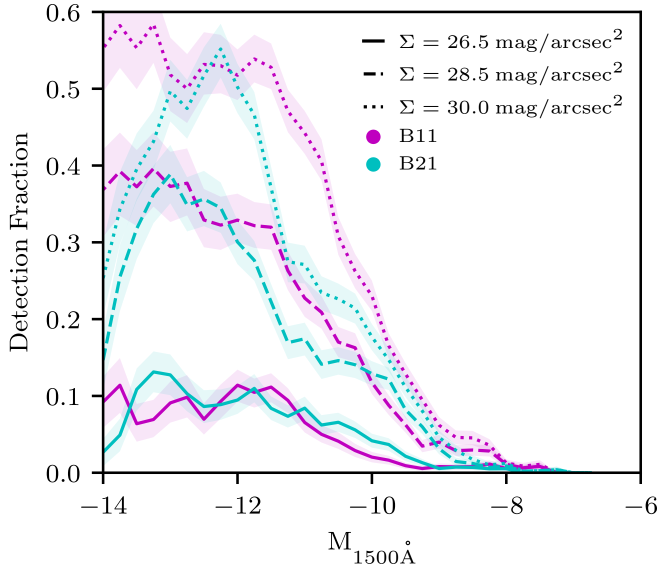


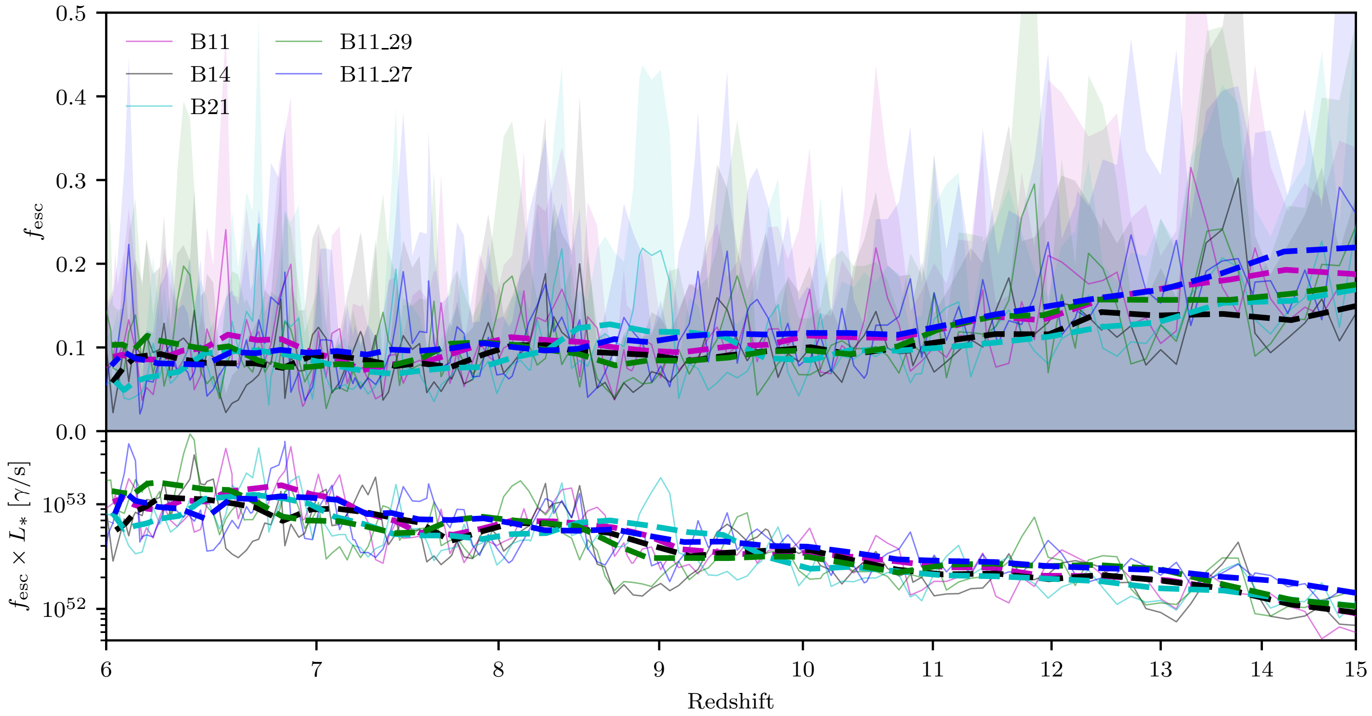


Strong PMFs shrink the effective radii of galaxies and increase their surface brightness



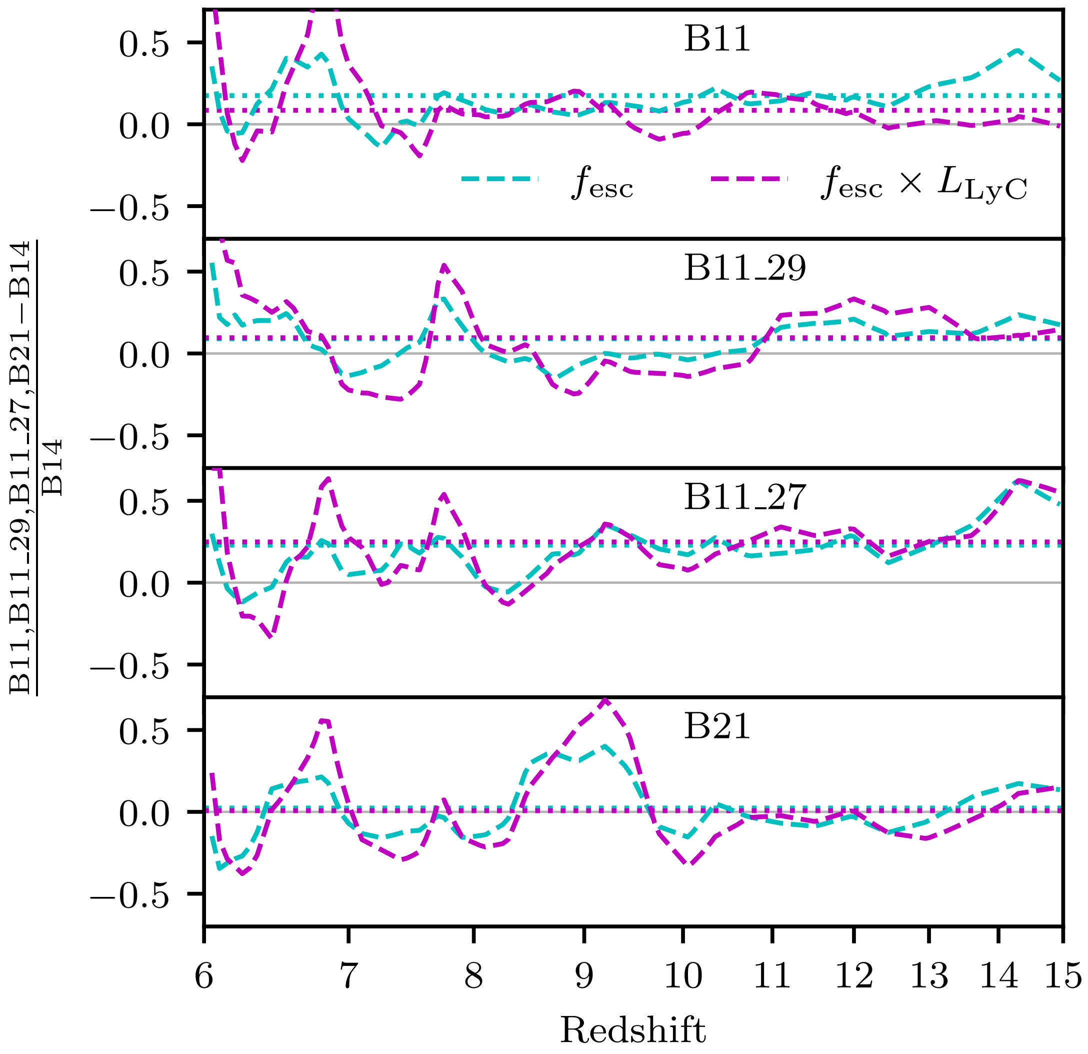




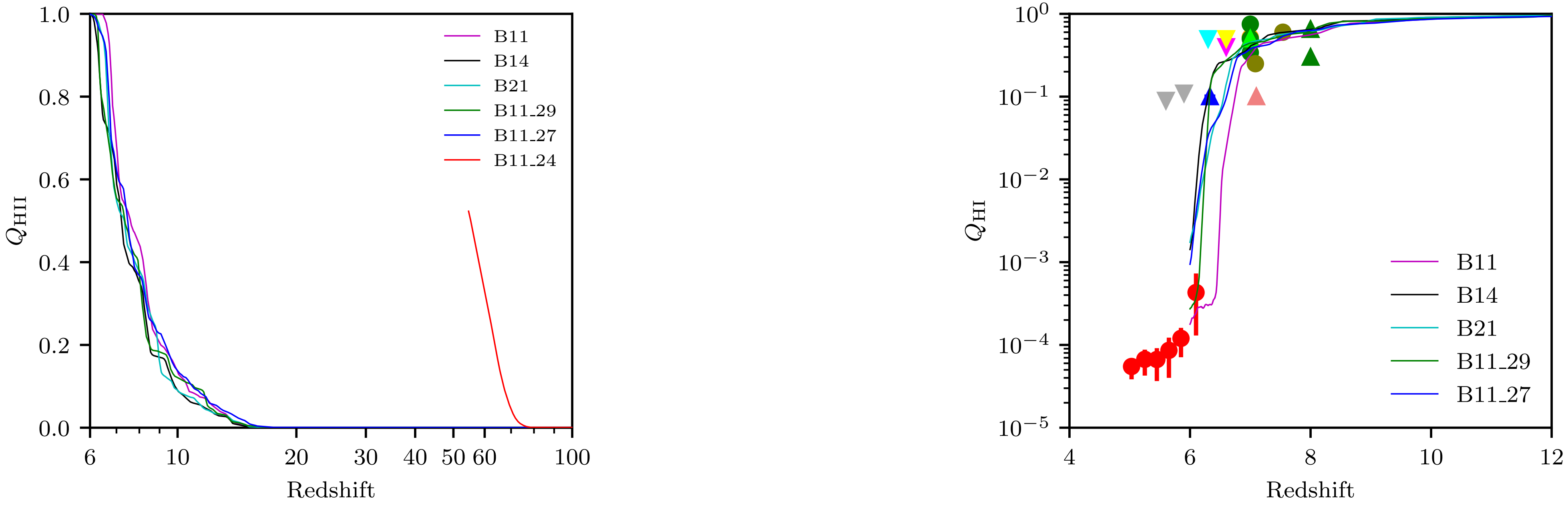


To first order, the LyC escape fractions appear very similar

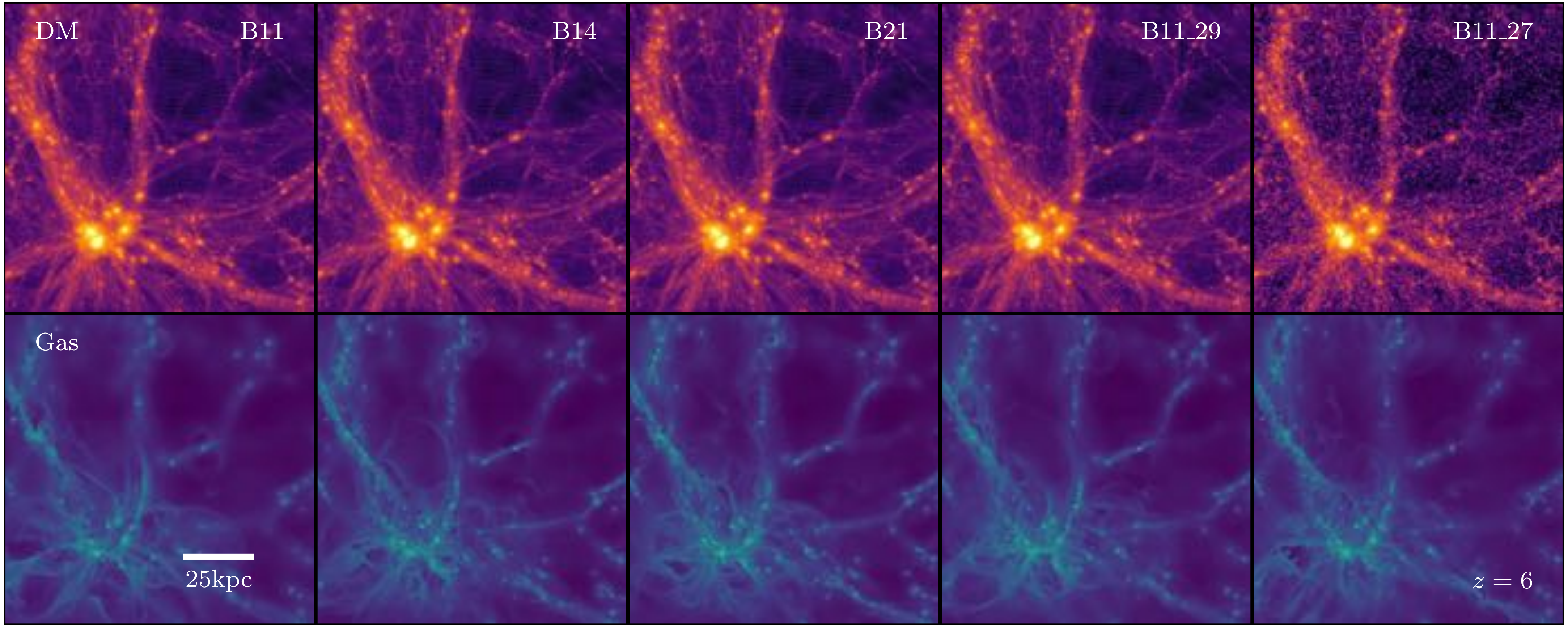
Strong PMFs increase f_{esc} by up to 25%

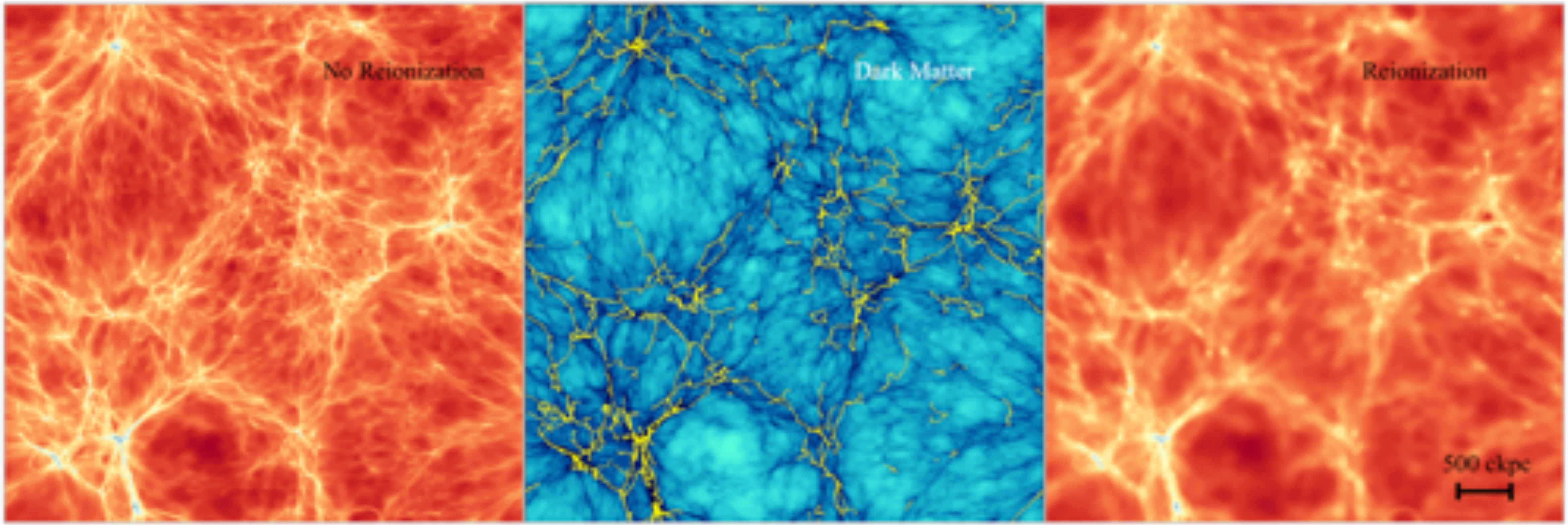


Reionization history is strongly impacted by flat spectral indices



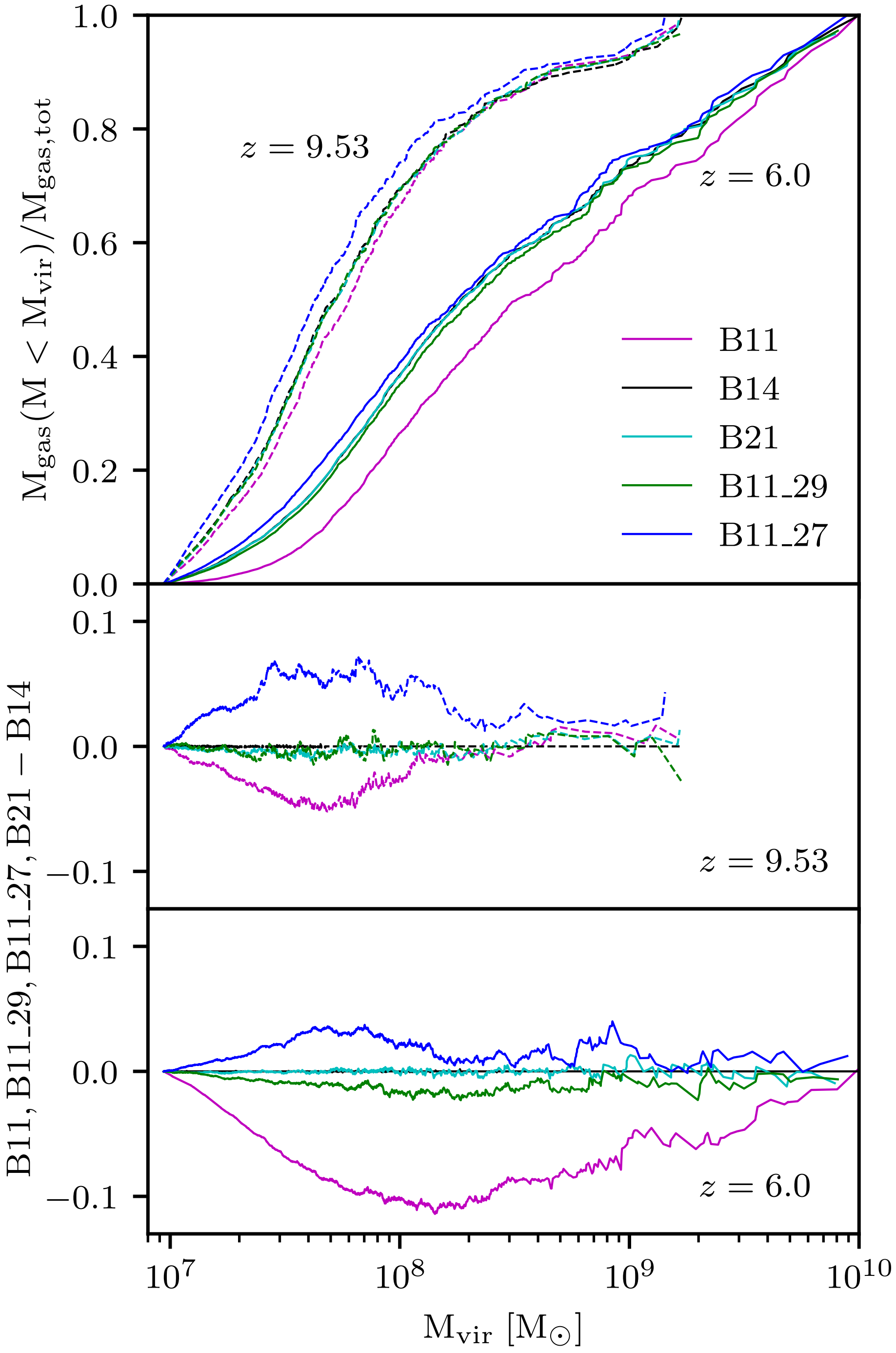
Do PMFs impact the Lya forest?





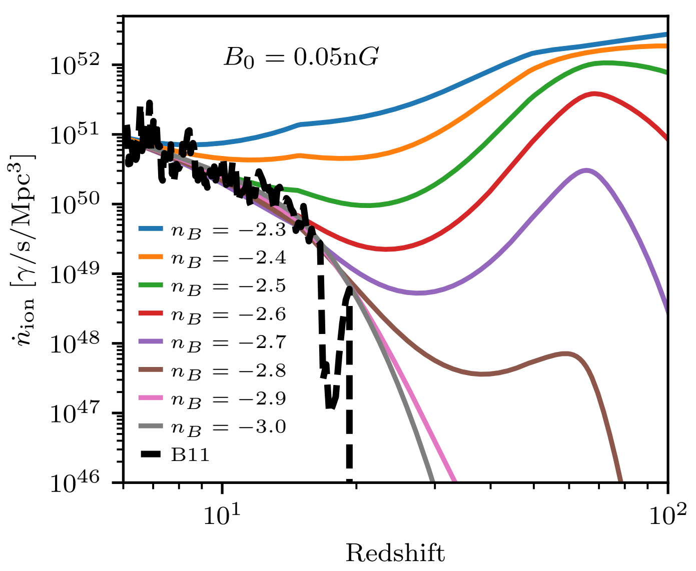
Reionization efficiently smooths the density field

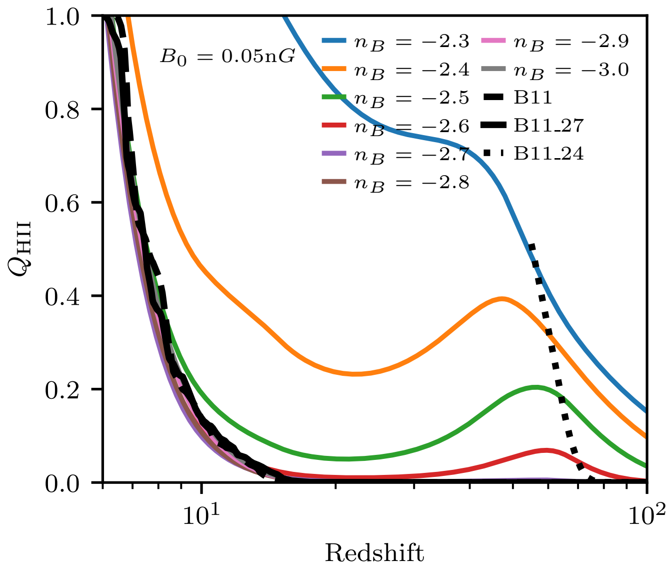
We predict only a very minor impact on the Lya forest

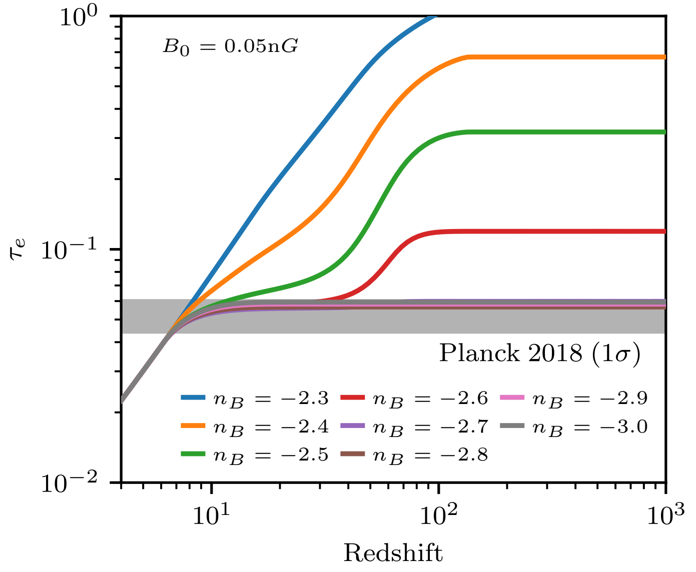


Constraining the properties of PMFs

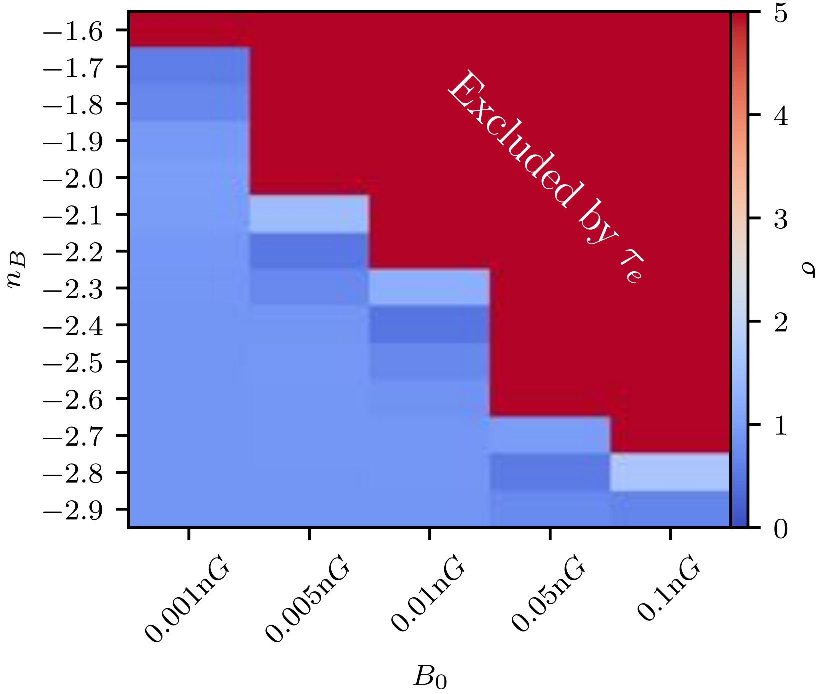
$$\frac{dQ_{\rm HII}}{dt} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H}\rangle} - \frac{Q_{\rm HII}}{\bar{t}_{\rm rec}(C_{\rm HII})}$$

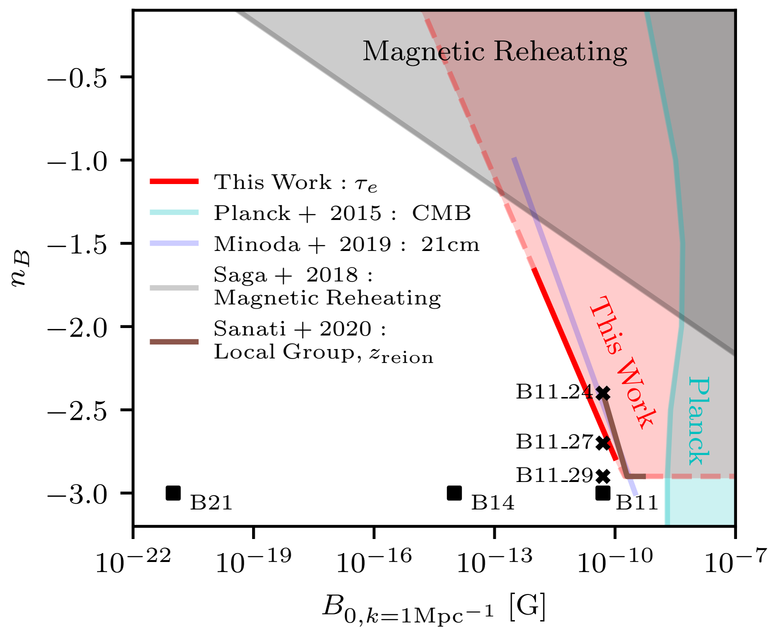






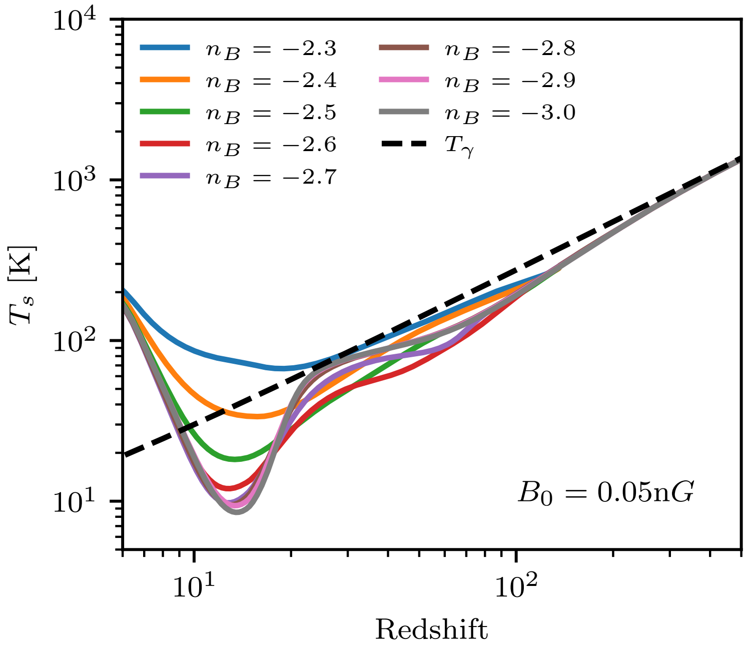
The effective optical depth provides the strongest constraints on PMFs

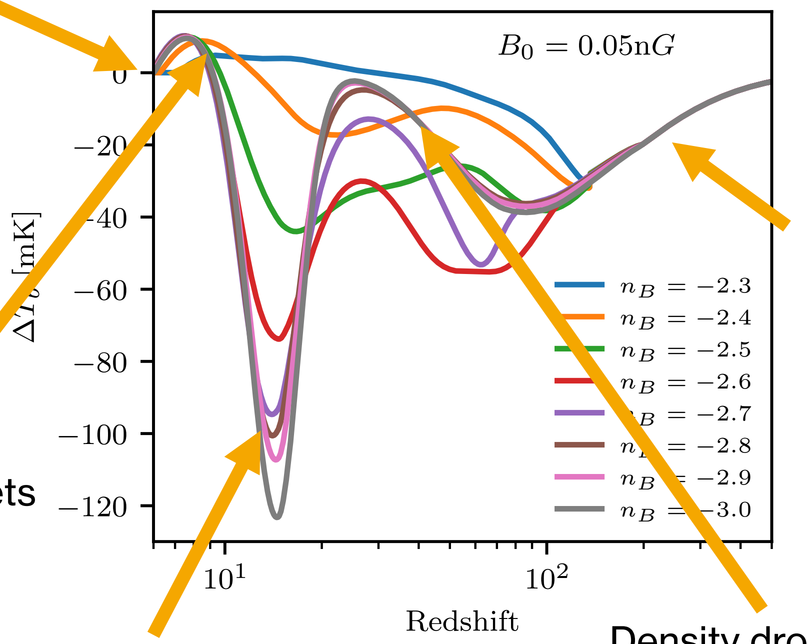




Stronger constraints can come from 21cm observations

$$\Delta T_b = 27 Q_{\rm HI}(1+\delta)\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.016}{\Omega_m h^2}\right)\left(\frac{1+z}{10}\right)^{0.5}\left(1-\frac{T_\gamma}{T_s}\right){\rm mK},$$





Reionization complete

Coupling due to Compton scattering

Adiabatic cooling + collisional coupling

Reionization sets in

Lya and X-ray coupling

Density drop leads to radiative coupling

Conclusions

Reionization + global 21cm signal place strong constraints on the properties of PMFs

The PMFs that we studied don’t strongly impact the stellar properties of reionization era galaxies or the Lya forest

Strong PMFs can shrink the effective radii of by ~44% which changes the size-luminosity relation

LyC escape fractions can increase by up to 25% due to small changes in star formation and ISM properties