Cosmic Recombination in the Presence of Primordial Magnetic Fields

A Brief Overview of PMFs effects on the CMB

B Small-scale density fluctuations due to PMFs

~~C Relieving the Hubble tension by PMFs~~ talk Levon Pogosian

D Towards a complete calculation of the effects of PMFs on recombination

E Comments on results presented by Pranjal Trivedi

Primordial Magnetic Fields and the CMBR:

spectral distortions

plasma heating

TT anisotropies

non-Gaussianity

Principal Efffect		
	Upper Limit	References
spectral distortions	**30-40 nG**	Jedamzik *et al.* 2000 Kunze & Komatsu 2014
plasma heating	**0.63-3 nG**	Sethi & Subramanian 2004 Kunze & Komatsu 2014 Chluba *et al.* 2015 Planck collaboration 2015
direct TT anisotropies	**1.2 - 6.4 nG**	Subramanian *et al.* 1998, 2002, 2003 Yamazaki *et al.* 2010 Paoletti & Finelli 2010 Shaw & Lewis 2010 Caprini 2011 Paoletti & Finelli 2013 Planck collaboration 2015 Zucca *et al.* 2016 Sutton et al. 2017
non-Gaussianity bispectrum	**2-9 nG**	Brown & Crittenden 2005 Seshadri & Subramanian 2009 Caprini *et al.* 2009 Cai *et al.* 2010 Trivedi *et al.* 2010 Brown 2011 Shiraishi *et al.* 2011 Shiraishi & Sekiguchi 2014 Planck collaboration 2015
non-Gaussianity trispectrum	**0.7nG**	Trivedi *et al.* 2012
non-Gaussianity trispectrum with inflationary curvature mode	**0.05nG**	Trivedi *et al.* 2014

small-scale baryon inhomogeneities set the strongest limit :

~0.01nG (phase transiton) 0.1nG (inflation)

K.J. & Saveliev 19

however, old data, and toy model

-> potential for discovery

these are the approximate field strength to explain
cluster magnetic fields without dynamo

Physical conditions shortly before recombination:

the photon mean free path is ~ 1Mpc

large magnetic modes L >> 1 Mpc subject to photon diffusion

small magnetic modes L << 1 Mpc subject to strong photon drag

unlike adiabatic modes, small scale magnetic modes survive Silk damping

the effective speed of sound for small modes is the
small baryonic speed of sound

→ viscous and compressible MHD on small scales

A correlation of magnetic field strength with length scale

shortly before recombination

$$B \approx 0.08\ \mathrm{nG} \left(\frac{L}{\mathrm{kpc}} \right)$$

after recombination

$$B \approx 0.005\ \mathrm{nG} \left(\frac{L}{\mathrm{kpc}} \right)$$

$$\frac{V_A}{L} \approx H$$

Why baryon inhomogeneities on small ~ kpc scales ?

photons are free-streaming on these scales i.e. cs = c/sqrt(3) -> cb

Viscous MHD evolution with free-streaming photon drag:

$$\frac{d\mathbf{v}}{dt} + \left(\mathbf{v}\cdot\nabla\right)\cdot\mathbf{v} + c_s^2\frac{\nabla\varrho}{\varrho} = -\alpha\mathbf{v} - \frac{1}{4\pi\varrho}\left(\frac{1}{2}\nabla\mathbf{B}^2 - \mathbf{B}\cdot\nabla\mathbf{B}\right)$$

the three important terms

$$\frac{d\varrho}{dt} + \nabla\left(\varrho\mathbf{v}\right) = 0$$

Back of the envelope estimate of the inhomogeneities:

initial conditions: zero velocity and homogeneous

schematic Euler and continuity equations

$$dv/dt + v^2/L + c_S^2(\delta\varrho/\varrho)/L = v_A^2/L + \alpha v$$

$$d(\delta\varrho/\varrho)/dt + v/L = 0$$

initially only the terms on the RHS are important

$\boxed{v \simeq v_A^2/(L\alpha)}$ unless pressure forces $\delta\varrho/\varrho \lesssim (v_A/c_s)^2$

$$\rightarrow \delta\varrho/\varrho \simeq vt/L \simeq v_A^2 t/(L^2\alpha)$$

until either decay at $v/L \simeq 1/t$ or pressure force backreaction

$$\rightarrow \delta\varrho/\varrho \simeq \min\left[1, (V_A/V_s)^2\right]$$

scaling confirmed by numerical simulations

K.J. and Abel 2013

It doesn't take much field:

$$c_s = 6.33 \frac{\mathrm{km}}{\mathrm{s}}$$

isothermal speed of sound at recombination

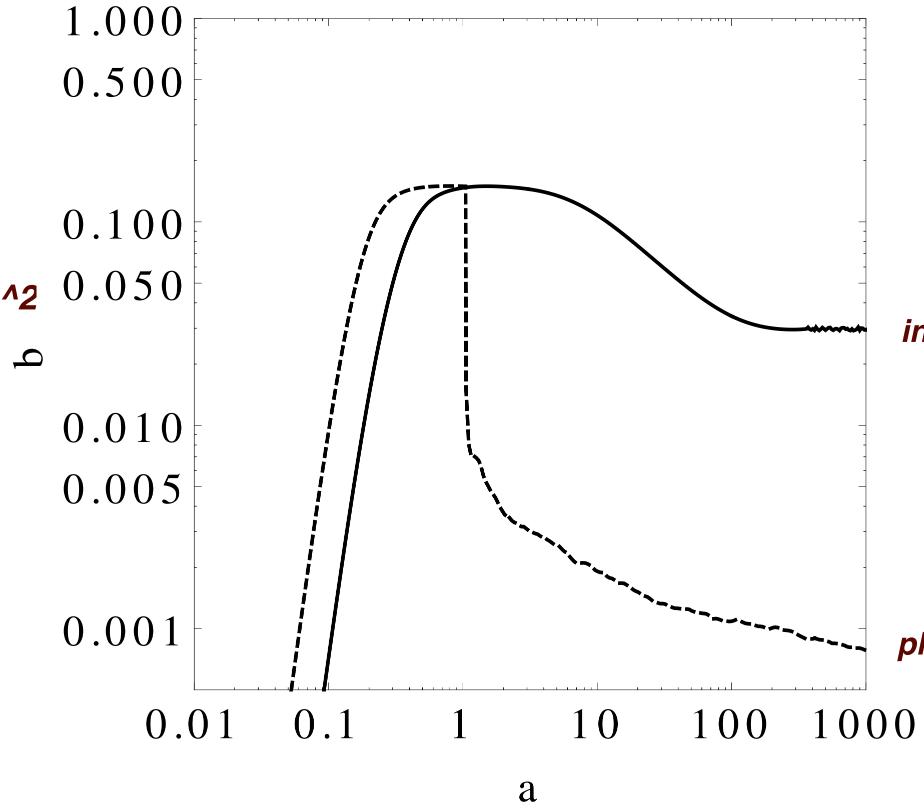
$$v_A = \frac{B}{\sqrt{4\pi\varrho}} = 5.79 \frac{\mathrm{km}}{\mathrm{s}} \left(\frac{B}{0.04\mathrm{nG}} \right)$$

-> order unity density fluctuations for ~ 0.05 nG

First full MHD simulations:

clumping factor:

b = <rho^2-<rho>^2>/<rho>^2



inflationary produced fields

phase transition produced fields

final field 10 pG

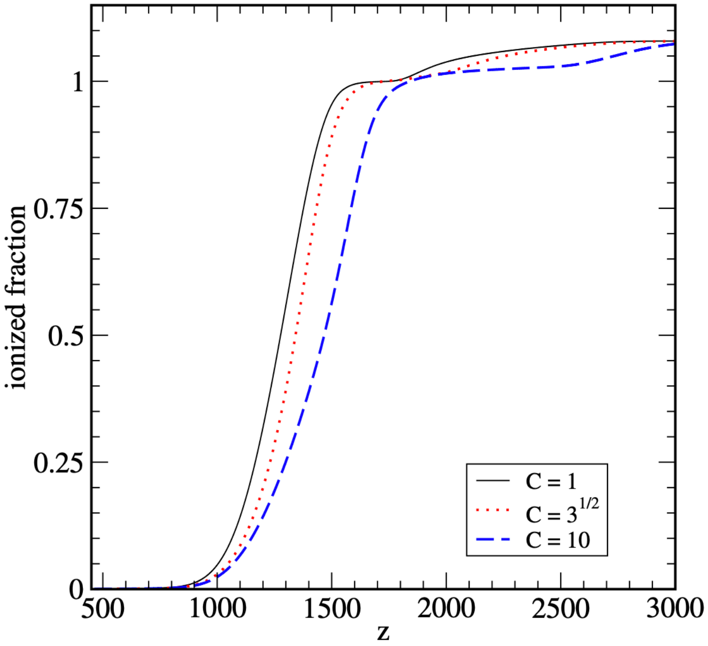
scale factor (a=1 at recombination)

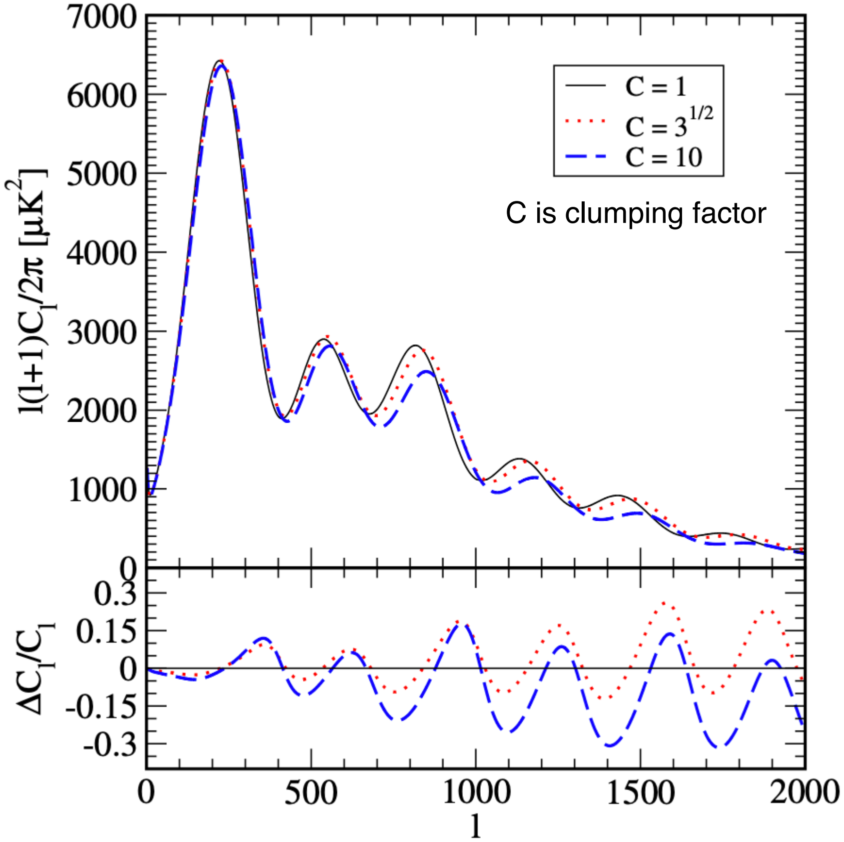
K.J. and Saveliev 2018

Inhomogeneities enhance the recombination rate

$$\frac{\mathrm{dn_e}}{\mathrm{d}t} + 3Hn_e = -C\left(\alpha_e n_e^2 - \beta_e n_{H^0}\mathrm{e}^{-h\nu_\alpha/T}\right)$$

$$\langle n_e^2 \rangle \ > \ \langle n_e \rangle^2$$





C is clumping factor

Jedamzik and Abel, arXiv:1108.2517, JCAP (2013)

Hubble tension

does LCDM need to be amended ?

early time solutions

reduction of sound horizon

late time solutions

increase of distance to last scattering surface

small-scale clumping could relieve the tension

Alternative sources of small-scale baryon clumping:

Enhanced small-scale adiabatic fluctuations do not survive Silk-damping

Extra baryon isocurvature fluctuations violate BBN constraints

B-balls or quark nuggets evaporating before recombination also violate BBN constraints

Baryon inhomogeneities produced by cosmic strings may not reach high volume filling factors

Short falls of the three zone toy models:

- ad hoc baryon density pdf
- no evolution of clumping
- plus new effects found

Towards a complete calculation of PMFs influencing recombination

requires extensive MHD simulations

MHD simulations give you a direct connection between PMF properties and CMB signal

for comparison to CMB requires high accuracy

Cosmic Recombination - a Quick Summary

$$e + H^+ \rightarrow H^0 + \gamma$$

$$e + He^+ \rightarrow He^0 + \gamma$$

- direct recombination into the ground state, immediately ionizes elsewhere -> no net recombination
- ionization into excited states, produces a casade of resonance photons, with the last often a Lyman-alpha photon (i.e. 2p->1s transition). This Lya photon excites a neutral atom elsewhere, The excited 2p atom will to the highest probability be photo-ionized by CMB photons ->no net recombination
- frequent attemps of recombining drives the Lya occupation number to super-thermal values, such that n2p/n1s is out of equilibrium
- there is only one way to have a net recombination, loss of Lya resonance photons, for hydrogen there are two possibilities:
  - a slow two-gamma transition from 2s->1s + 2gamma
  - redshifting of Lya photons out of resonance by Hubble expansion

Inhomogeneous Recombination due to Primordial Magnetic Fields

K.J., T. Abel, and Y Ali-Haimoud astro-ph 2312.11448

Attention: astro-ph/2312.11448v2

physical effects to be considered:

→ clumping of baryons
→ evolution of this clumping
→ Lyman-alpha photon transport
→ locally varying speed of sound of fluid
→ locally varying photon drag on fluid
→ loss of Lya photons due to pecuilar motions

we combined:

→ MHD fluid code ENZO   Greg Bryan et al 2014
coupled to
→ new cosmic recombination code
→ proper Monte-Carlo simulations of Lya loss

we are not aware of any missing physics (so far)

The Monte Carlo simulations:

(1) inject photon from Voigt profile

(2) determine when and where it excites a 2p state

(3) take into account the redshifting between scatterings

(4) determine if the 2p state either (a) spontaneously de-excites into the 1s state

or much less likely

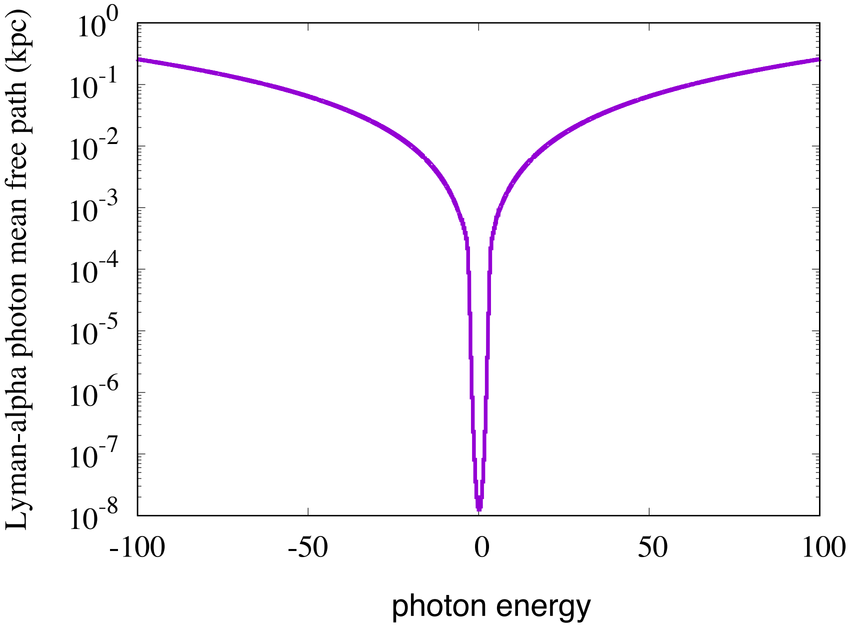
(b) decays via the two-photon transition -> net recombination

(c) gets ionized by a CMB photon -> no net recombination

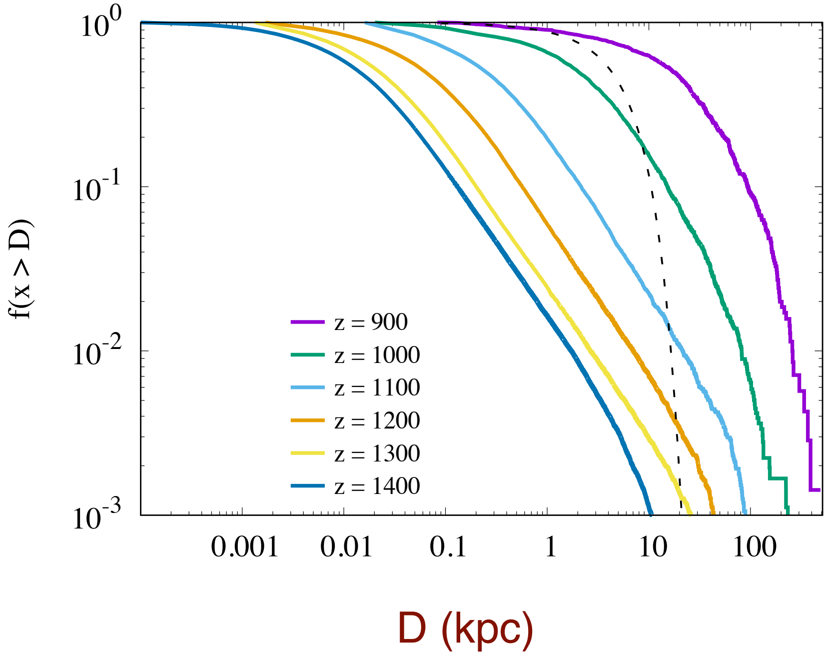
in case (a) go to (5), in case (b) and (c) go to (1) - inject another photon

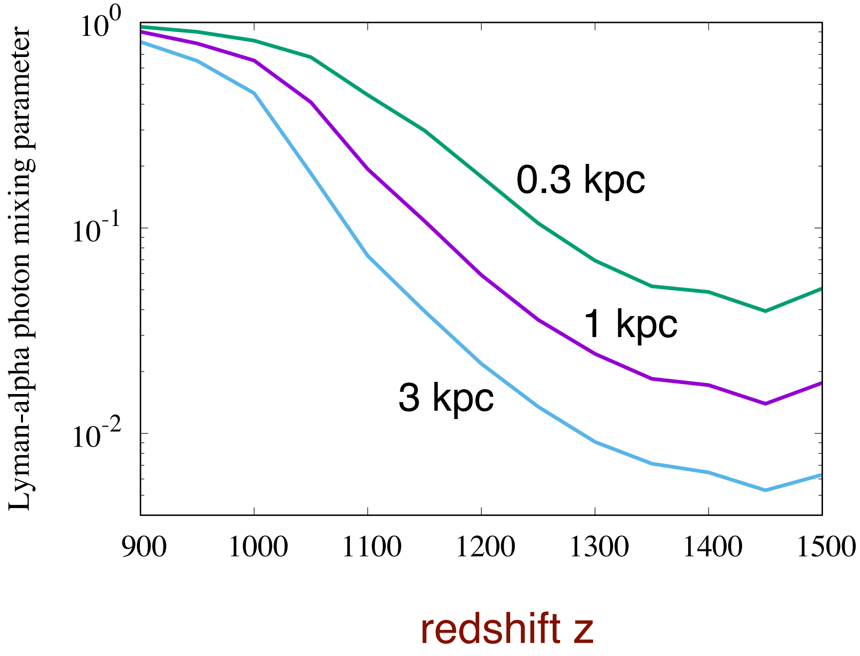
(5) the de-excitement is effectivly scattering.
compute the photon energy and direction
after scattering

photons which are lost to redshifting
get smaller and smaller energy
and do not scatter anymore



Fraction of photons which travel further than D (kpc)





The typical length scale of inhomogeneities is 0.1 - 1 kpc depending on magnetic field strength

-> Lyman-alpha photons mix, recombination not local anymore

The standard recombination equation in a homogeneous Universe:

$$\dot{n}_e\big|_{\rm rec} = -C\left(\alpha_e n_e^2 - \beta_e n_{1s} e^{-E_\alpha/T_\gamma}\right)$$

Peebles C factor ~ 0.02 at redshift 1100

-> recombination delayed

$$C = \frac{\Lambda_{2\gamma}+R_\alpha}{\beta_e+\Lambda_{2\gamma}+R_\alpha}, \qquad R_\alpha = \frac{8\pi H}{\lambda_\alpha^3 n_{1s}}$$

The recombination equation in a clumpy Universe with full Ly-a mixing derived from the Boltzman equation:

$$\dot{n}_e\big|_{\rm rec} = -C^{\rm mix}\left(\alpha_e n_e^2 - \beta_e n_{1s} e^{-E_\alpha/T_\gamma}\right)$$
$$-(1-C^{\rm mix})\alpha_e\left(n_e^2 - \frac{n_{1s}}{\langle n_{1s}\rangle}\langle n_e^2\rangle\right)$$

$$R_\alpha^{\rm mix} \equiv \frac{8\pi H}{\lambda_\alpha^3 \langle n_{1s}\rangle}$$

2nd new term parametrically larger

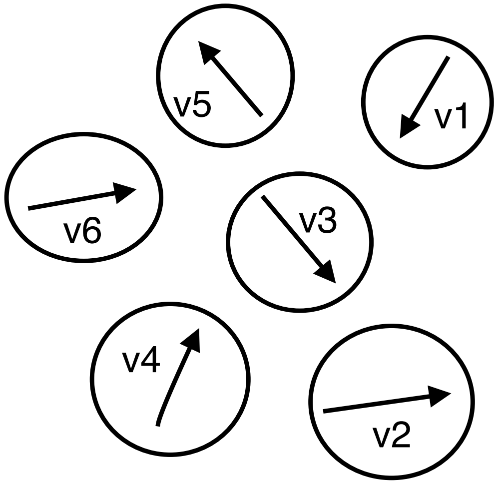
but averages to zero

Peculiar flows and Lyman-alpha escape

limit large length scale of inhomogeneity

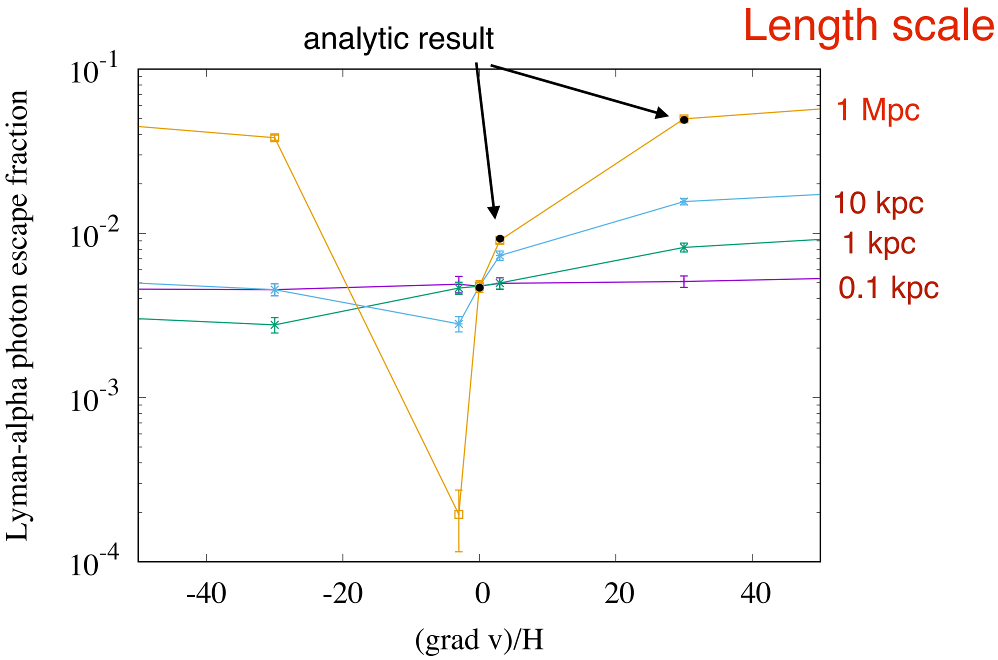
$$C = \frac{\Lambda_{2\gamma}+R_\alpha}{\beta_e+\Lambda_{2\gamma}+R_\alpha}, \qquad R_\alpha = \frac{8\pi H}{\lambda_\alpha^3 n_{1s}}, \qquad H \to H + \nabla\cdot v/3$$

enhancement of
Lyman-a losses



$$(\nabla\cdot v)_{\rm rms} \sim 20H$$

naively C
substantially larger



-> for “larger” B ~ 0.1nG (final field)
extra speed-up of recombination

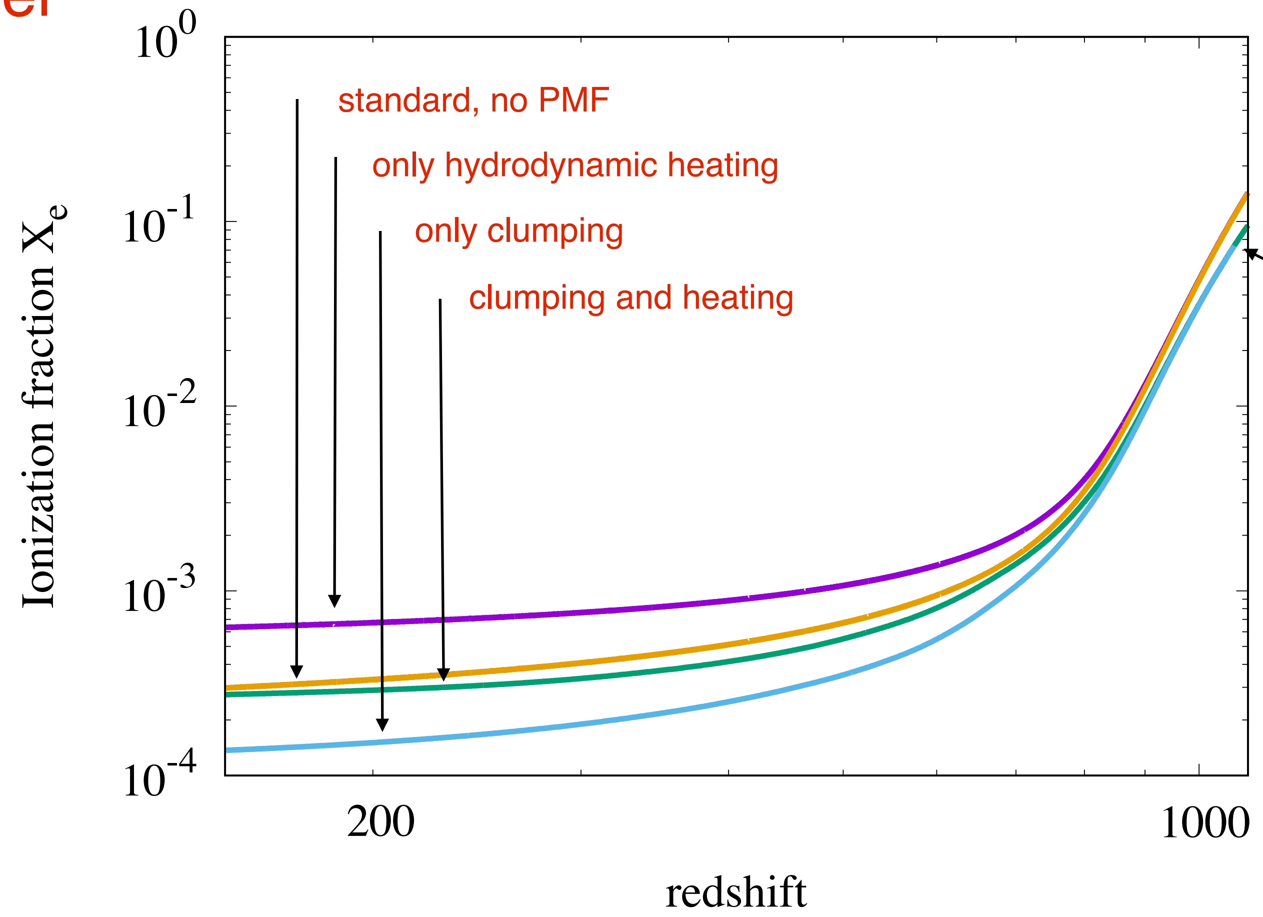
Limits on PMFs from hydrodynamic heating ?

Hydrodynamic heating induces an excess of Xe at z < 800

this may be constrained by the enhanced optical depth

Sethi & Subramanian 04

However

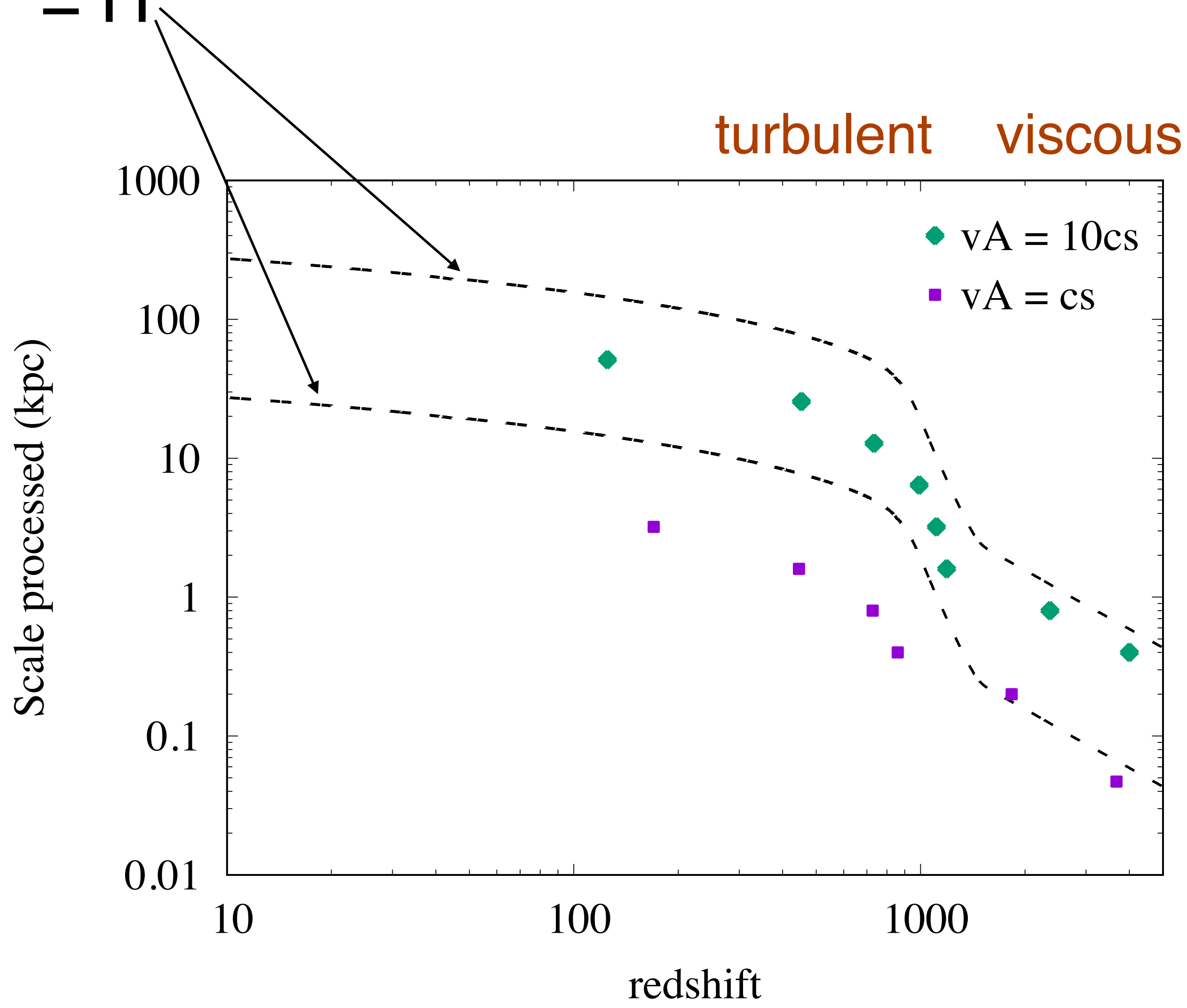


Constraints come from clumping effects at z ~ 1100

When heating and clumping is treated there is no excess in Xe at z < 800

Processing of scales (single mode)

$$\frac{V}{L} = H$$



Processing of modes seems somewhat delayed during turbulence

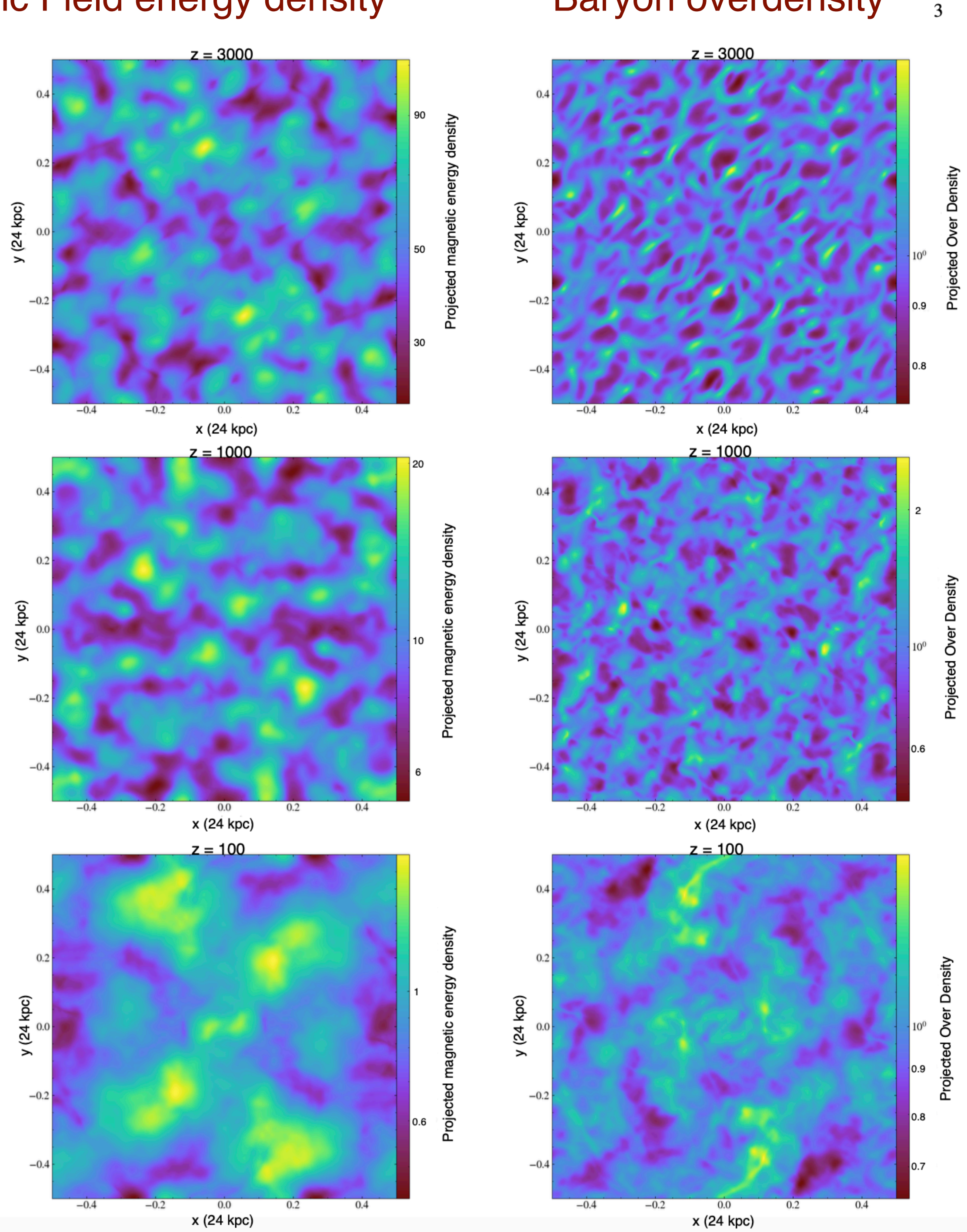
Magnetic Field energy density

Baryon overdensity

initial conditions:
at z = 4500:

— zero velocities
— baryons uniform

Batchelor spectrum
non-helical
Box size 24 kpc

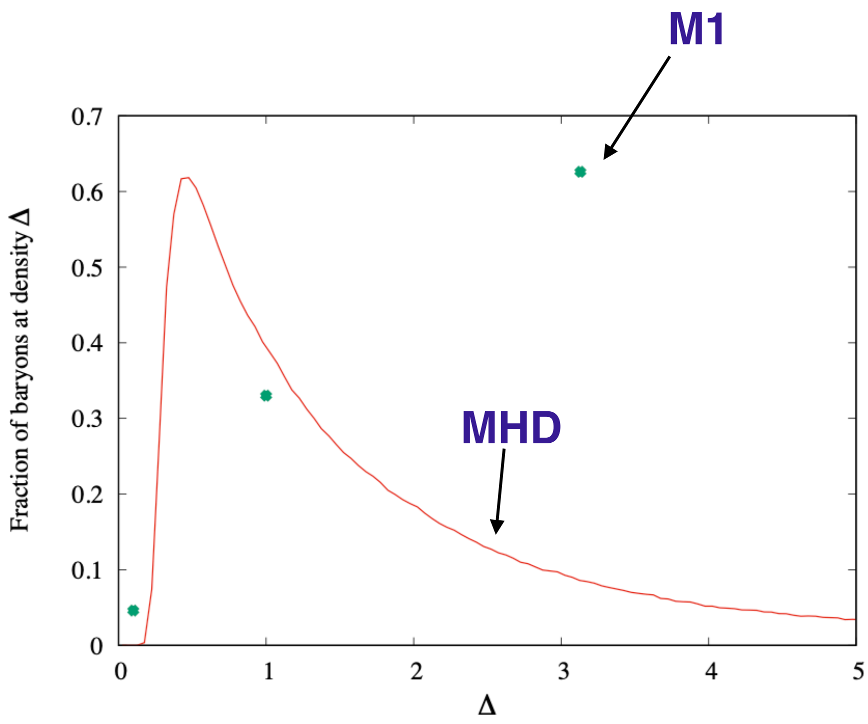


z = 3000

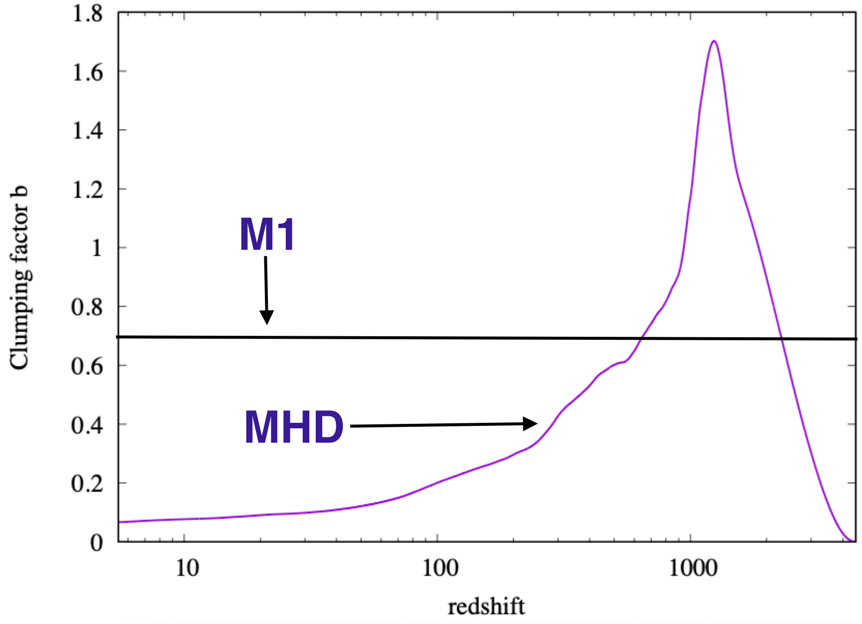
z = 1000

z = 100

Baryon probability distribution function and evolution



Baryon Overdensity



PDF significantly different from 3-zone models

A sample simulation -> general trends

—> initial field 0.52 nG

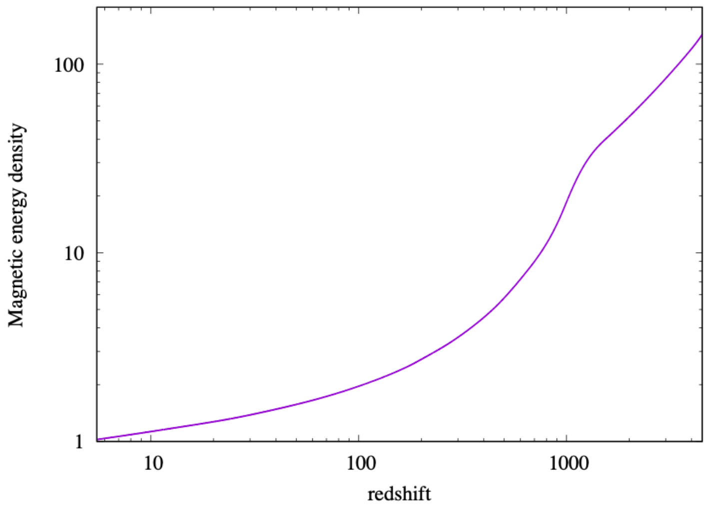
—> Batchelor spectrum

—> all k=1 to 8 modes excited

—> non-helical

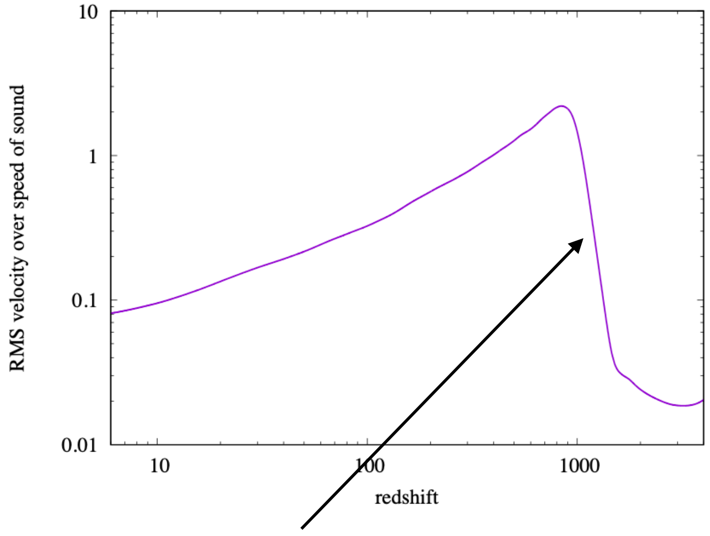
final field 0.043 nG

Magnetic energy density



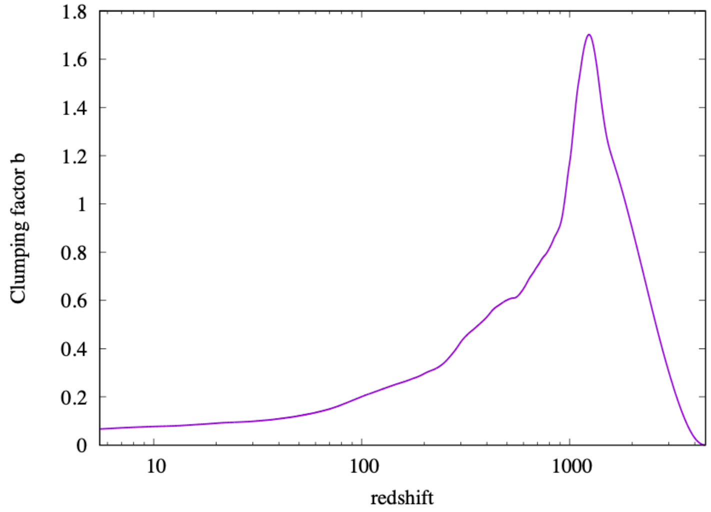
> 99% energy dissipated

RMS velocity over speed of sound

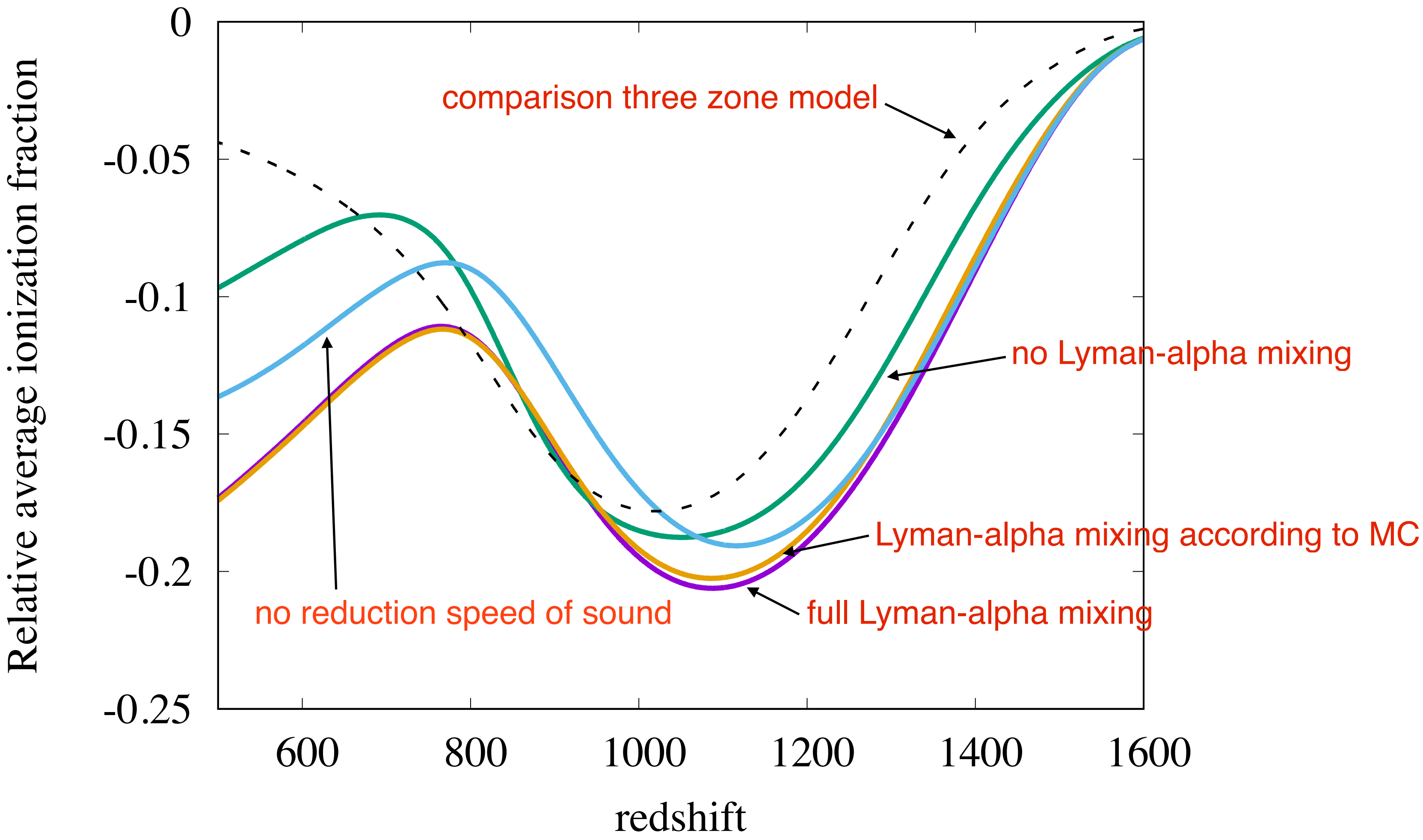


transition from viscous to turbulent regime
at recombination

Clumping factor



Relative change to LCDM ionization fraction



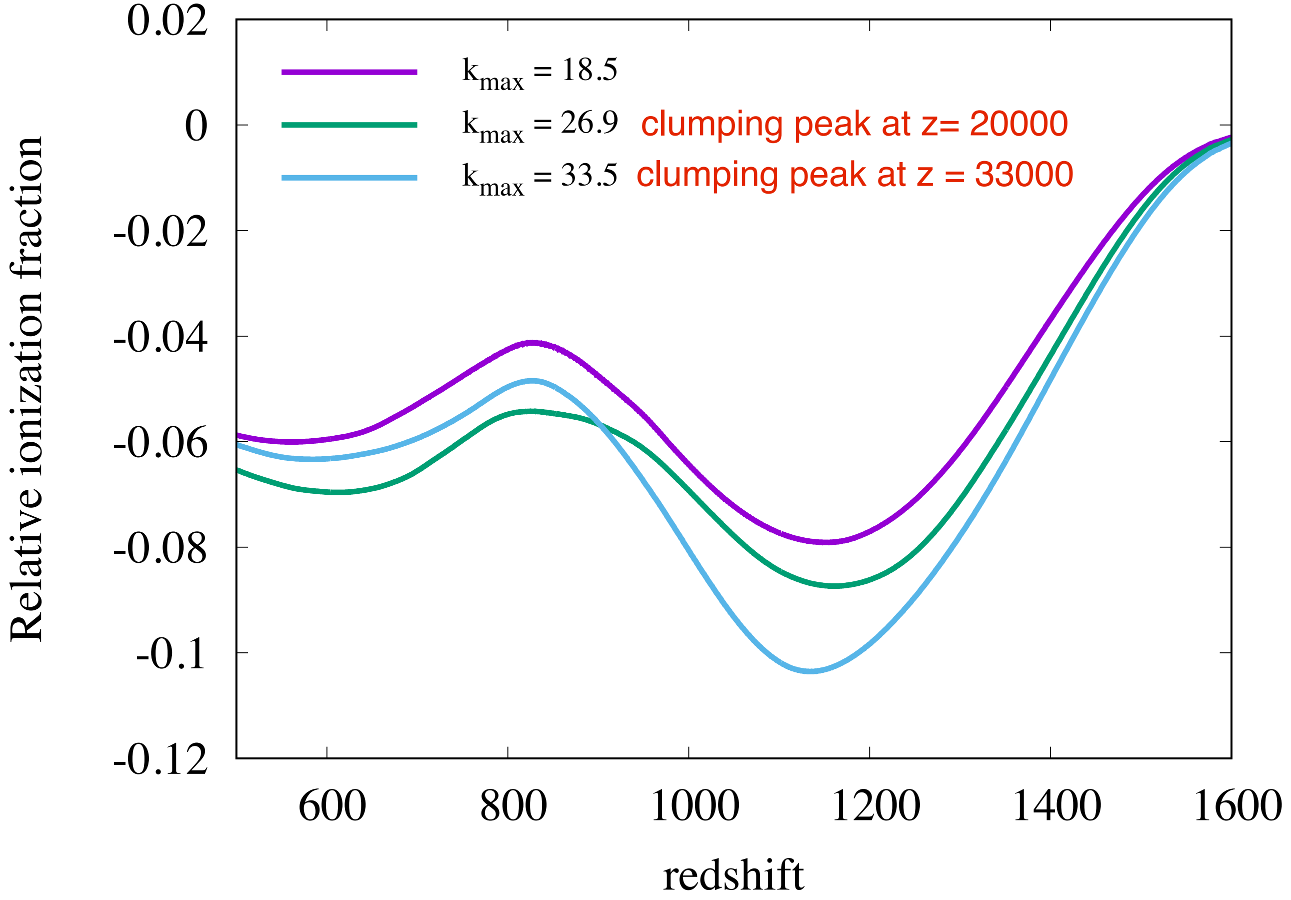
The CMB data is sensitive to such changes

Ultraviolet modes in Batchelor spectrum

modes which have there peak in clumping at z ~ 1000 should be most important

$k_{min} = 4.2$

k = 8.4 clumping peak at z = 1500



Somewhat surprising dependency of results on ultraviolet modes

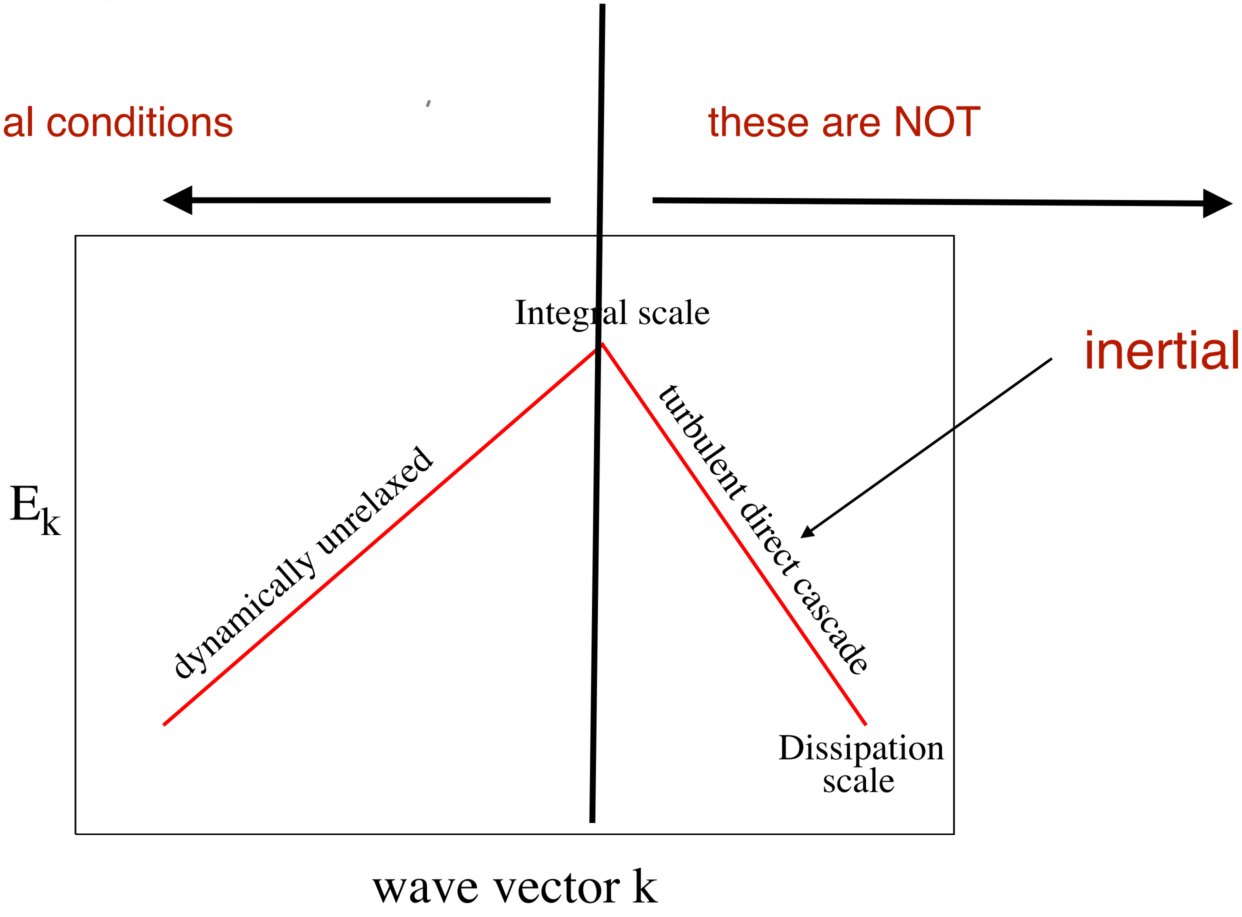
Comments on the results Trivedi, Banerjee, ….

Initial conditions:

The fluid is in a highly viscous state at redshifts z >>10000 Reynolds number R ~ 1

v -> 0, rho-> 0

R ~ 1 -> Integral scale IS THE dissipation scale



these are the initial conditions

these are NOT

inertial range

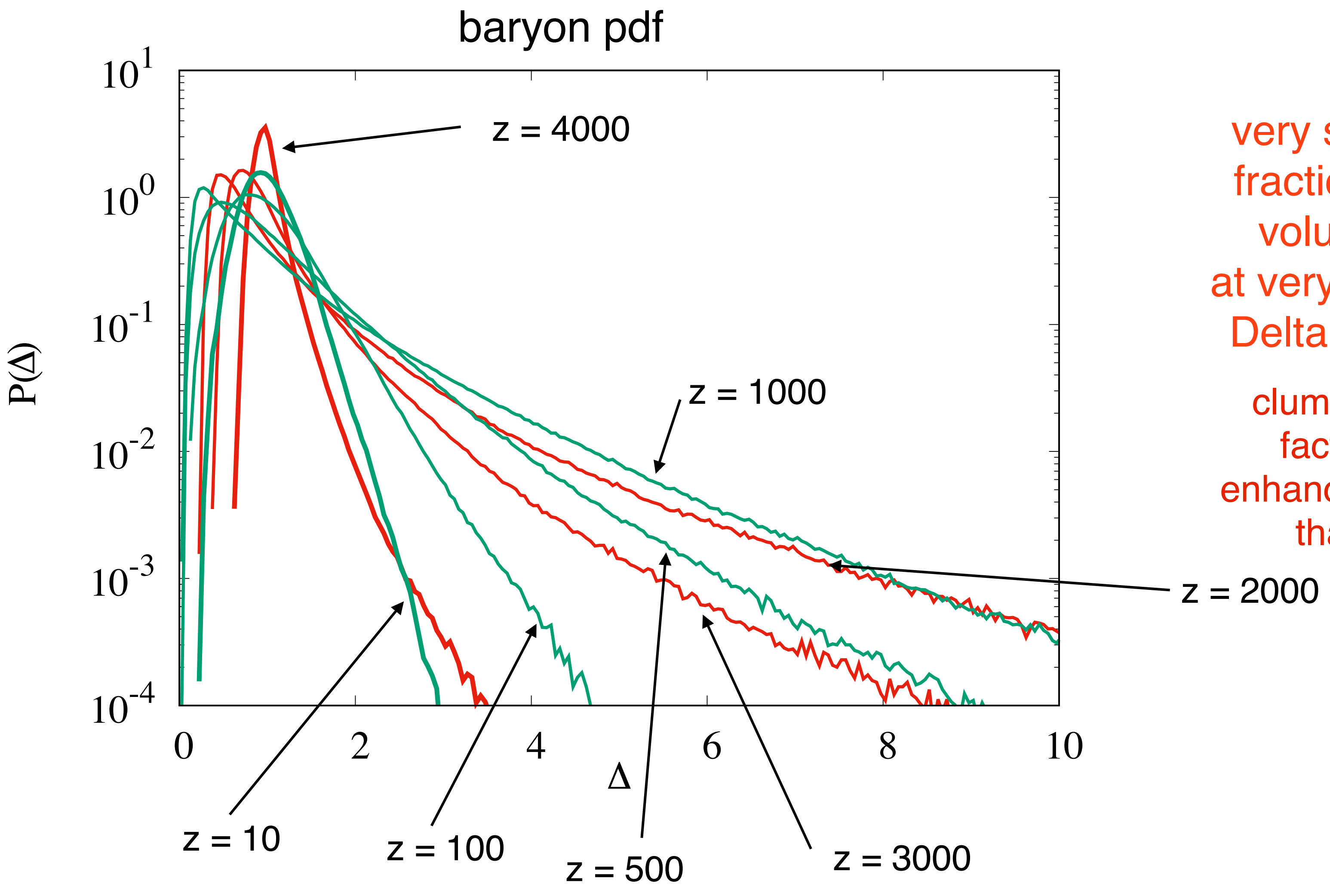
Overdensities Delta we find with ENZO

24 kpc box

256^3

modes resolved by minimum 32 zones

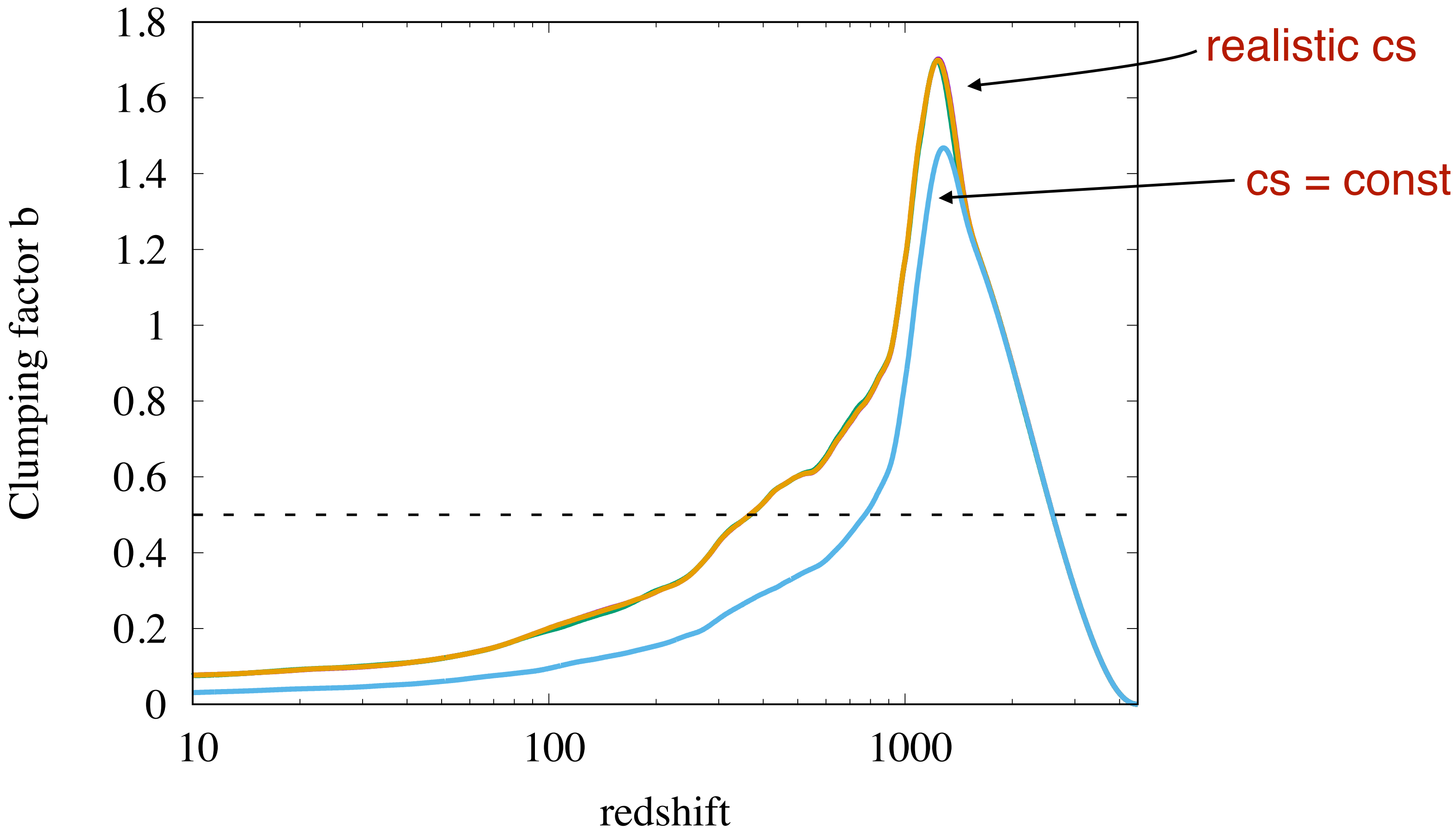
B_ini = 0.52 nG, B_fin = 0.043nG


baryon pdf

very small fraction of volume at very large Delta > 10

clumping factor enhanced by that

Drop of speed of sound during recombination



realistic cs

cs = const

clumping enhanced by drop of speed of sound

…, Trivedi, Banerjee		**K.J., Abel, Ali-Haimoud**
$z = 100 - 5000$		$z = 10 - 4500$
initial conditions with inertial range (waste of CPU power)		initial conditions pure Batchelor
strengths up to 0.2nG		strengths up to 2 nG
512^3		256^3
b_max ~ 0.3		b_max ~ 1.5 for 0.52 nG
Flash code and Pencil code		Enzo code and private code
dissipated energy 70 %		dissipated energy 99%
resolution ?		resolution minimum 32 zones per mode
box size 2.4 kpc	???	box size 24 kpc
cs = constant		varying cs

Resolution: direct comparison of well-defined test runs

Complicating factors of the calculations:

→ many MHD codes can not handle large over-densities

→ only a determination of the baryon pdf and it’s evolution is not sufficient

→ dynamic range of ~50 (at least for scale-invariant fields) required is difficult in 3D (for Batchelor spectrum easier)

→ 2D simulations give largely incorrect results

→ extensive CPU time is needed

→ dependency on UV modes for Batchelor

→ Lyman-alpha transport difficult, but manageable for smaller field strength

→ peculiar velocity effects complicate things for larger field strength

→ code dependency of result ????

The CMB is a relatively clean and precise probe of PMFs

Baryon clumping due to PMFs leaves a distinct impact on the anisotropies in the CMB

It still needs to be theoretically calculated with precision which turns out to be difficult

PMFs are the only well motivated possible partial solution to the Hubble tension