Stringent Limits on Cosmic Magnetic Fields from the CMBR

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Motivation

- the early Universe may well be magnetized
- observations of TeV blazars indicate the likely presence of an intergalactic magnetic field

$$B \gtrsim 10^{-15}\mathrm{Gauss}$$

- primordial magnetic fields of

$$B \sim 3 \times 10^{-12}\ \text{Gauss}$$

would be sufficient to explain cluster magnetic fields

Known Sources of impact on the CMBR

- Faraday rotation
- dissipation of magnetic fields and μ and y blackbody spectral distortions
- direct generation of anisotropies below the Silk scale
- dissipation of magnetic fields shortly after recombination and changes in the Thomson optical depth
- non-Gaussian signatures (i.e bispectrum and trispectrum)
- reionization

Known CMB Limits on Scale-Ivariant primordial magnetic fields

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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
reionization	**0.36nG**	Sethi & Subramanian 2005 Schleicher *et al.* 2011 Vasiliev & Sethi 2014 Pandey *et al.* 2015 Bonvin *et al.* 2013

Damping of pre-existing magnetic fields

- Pre-existing magnetic fields excite fluid motions
- These fluid motions are broken up into smaller and smaller eddies until they are damped by dissipation
- in this way the magnetic field energy is also drained
- magnetic diffusion is unimportant due to the high number of charged carriers
- due to the existence of radiation the speed of sound v_s is large and the evolution is incompressible

The fully turbulent regime

$$
\begin{aligned}
\frac{d\mathbf{v}}{dt} + (\mathbf{v}\cdot\nabla)\cdot\mathbf{v} &= \eta\nabla^2\mathbf{v} - \frac{1}{4\pi(\varrho+p)}\mathbf{B}\times(\nabla\times\mathbf{B}) \\
\frac{d\mathbf{B}}{dt} &= \nabla\times(\mathbf{v}\times\mathbf{B})
\end{aligned}
$$

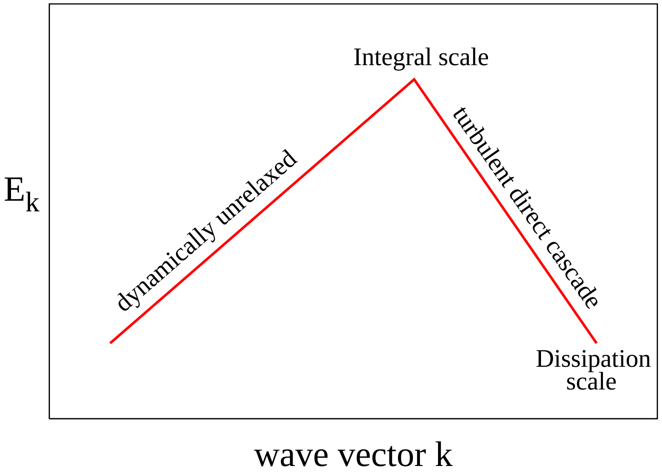
- The Alfven velocity: $v_A = \frac{B}{\sqrt{4\pi(\varrho+p}}$
- When fully turbulent, on larger scales, away from the dissipation scale, $v_A \approx v$
- The time needed to excite an eddy is given by $t_{\mathrm{eddy}} \approx L/v_A$

→ Eddies on scale L are excited when $v_A/L \approx H$

The integral scale

The integral scale L is defined by the condition

$$v_A/L \approx H$$

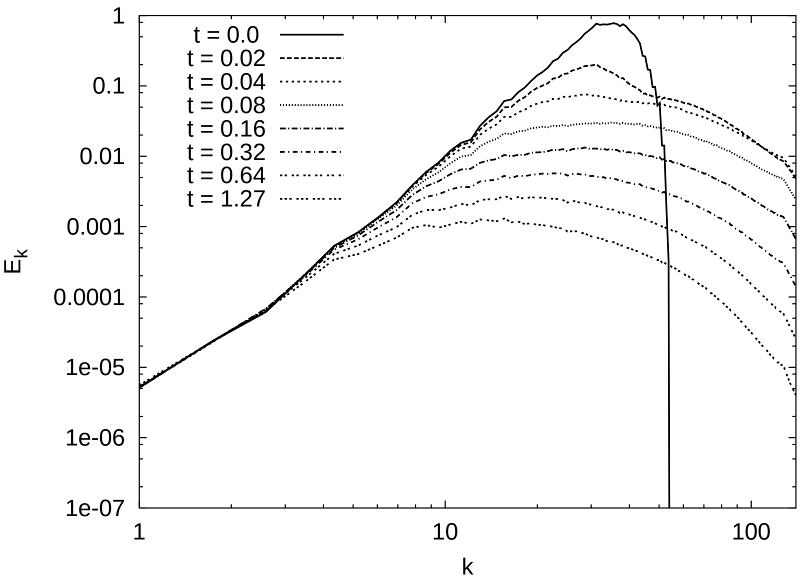


The growth of the integral scale

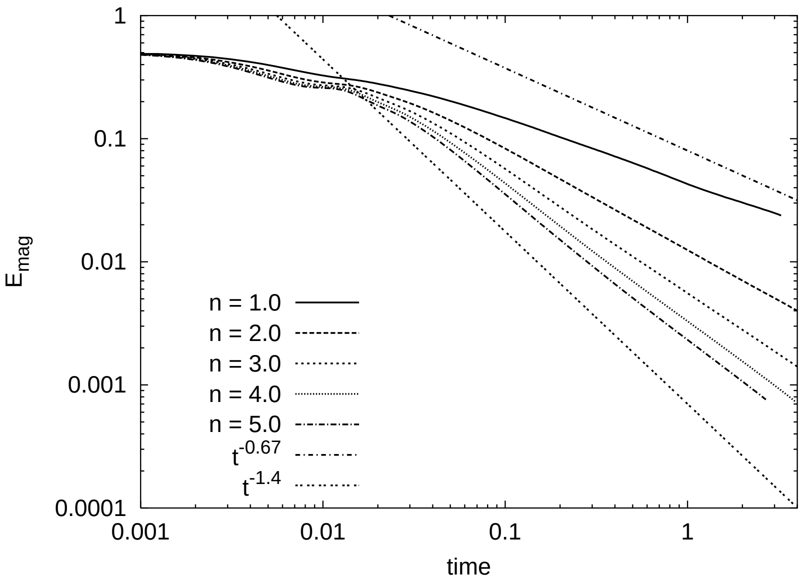
$$\frac{t_{\mathrm{eddy}}}{t_{\mathrm{Hubble}}} \approx \frac{L/v_{\mathrm{A}}}{t_{\mathrm{Hubble}}} \propto \frac{a}{a^2} \propto 1/a$$

Comparison to numerical simulations

Spectrum with time



Energy with time



Banerjee & K.J. 2004, Saveliev, K.J., & Sigl 2013

The growth of the integral scale after recombination

$$\frac{t_{\text{eddy}}}{t_H} \approx \frac{L/v_{\text{A}}}{t_H} \propto \frac{a/1/a^{1/2}}{a^{3/2}} \propto a^0$$

→ after recombination essentially no more evolution

→ what has not dissipated until recombination will remain to today

Predicted correlation length of primordial magnetic fields:

$$B_0 \lesssim 5 \times 10^{-12}\,\text{Gauss}\left(\frac{L_c}{\mathrm{kpc}}\right)$$

But wait ?

Magnetic fields on scales 1-10 kpc around recombination, that's below the photon mean free path ~ 2 Mpc at recombination

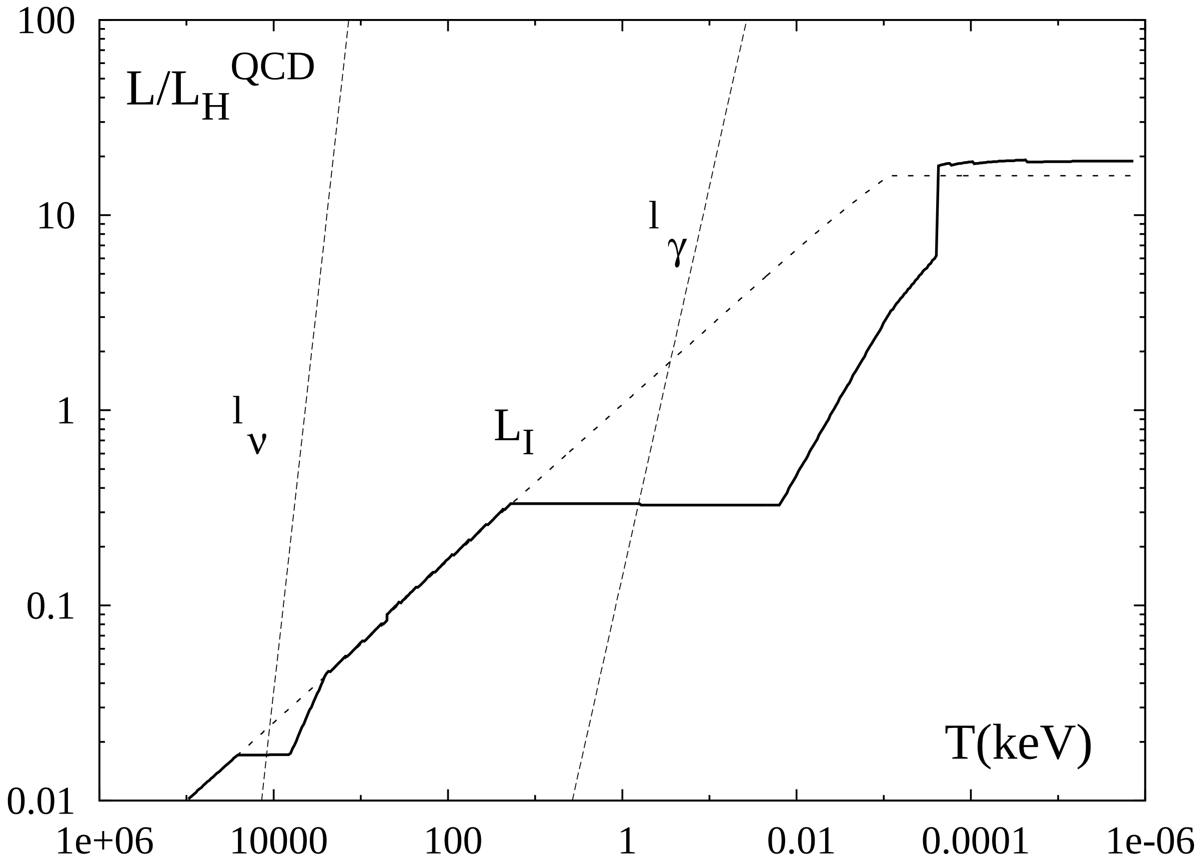
$\rightarrow$ Photons do not participate in the fluid motions

MHD with strong photon drag

$$\frac{d\mathbf{v}}{dt} + (\mathbf{v}\cdot\nabla)\cdot\mathbf{v} \;=\; -\alpha\mathbf{v} - \frac{1}{4\pi\varrho}\mathbf{B}\times(\nabla\times\mathbf{B})$$

- with strong photon drag only the RHS is important
- velocities $v \approx \frac{v_A^2}{L\alpha}$ are excited
- the magnetic energy dissipation $\dot{E} \sim -\alpha v^2 \sim \frac{v_A^4}{L^2\alpha}$ counterintuitively is smaller for larger drag α

The Evolution of the Magnetic Coherence Length



But wait again ?

Since photons do not participate anymore in the fluid motions the speed of sound is the much smaller baryonic one

$v_A \simeq v_s$ when $B \simeq 5 \times 10^{-11}$ Gauss

$\rightarrow$ Very weak magnetic fields on $\sim$kpc scales can excite density fluctuations

Production of density fluctuations before recombination

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

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

- Very quickly small velocities $v \approx \frac{v_A^2}{L\alpha}$ are produced
- from the continuity equation one finds $\frac{\delta\varrho}{\varrho} \simeq \frac{Vt}{L} \simeq \frac{v_A^2 t}{L^2\alpha}$
- when the pressure term becomes important, i.e. $V_s^2(\delta\varrho/\varrho)/L \simeq \alpha v$
- $\rightarrow \delta\varrho/\varrho \simeq \frac{L\alpha v}{v_s^2} \simeq \frac{v_A^2}{v_s^2}$, but never much larger than 1 K.J. & Abel 2013

A "new" effect: Inhomogeneous recombination

recombination in inhomogeneous environment

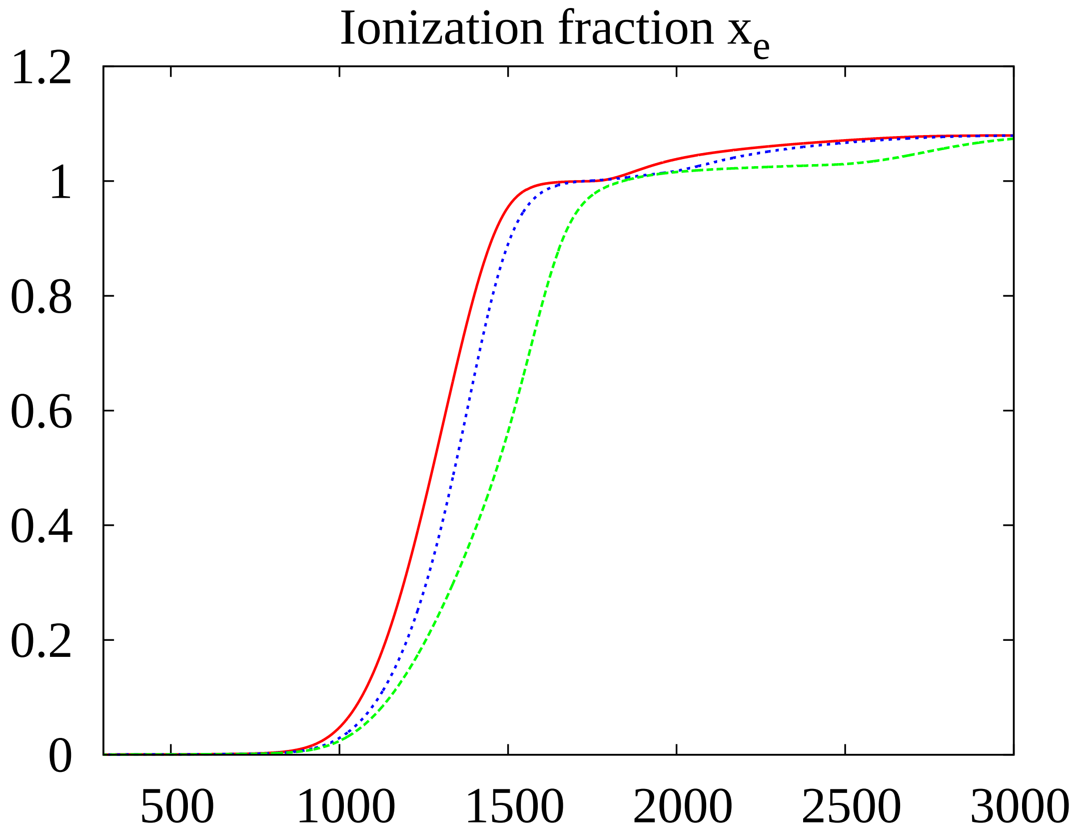
$$\frac{d\langle n_{H0}\rangle}{dt}\Big|_{inhomo} =$$

$$\alpha_e\langle n_e n_p\rangle - \beta_e\langle n_{1s}\rangle \exp\left(\frac{-E_{\nu\alpha}}{kT}\right) \neq \frac{d\langle n_{H0}\rangle}{dt}\Big|_{homo}$$ since

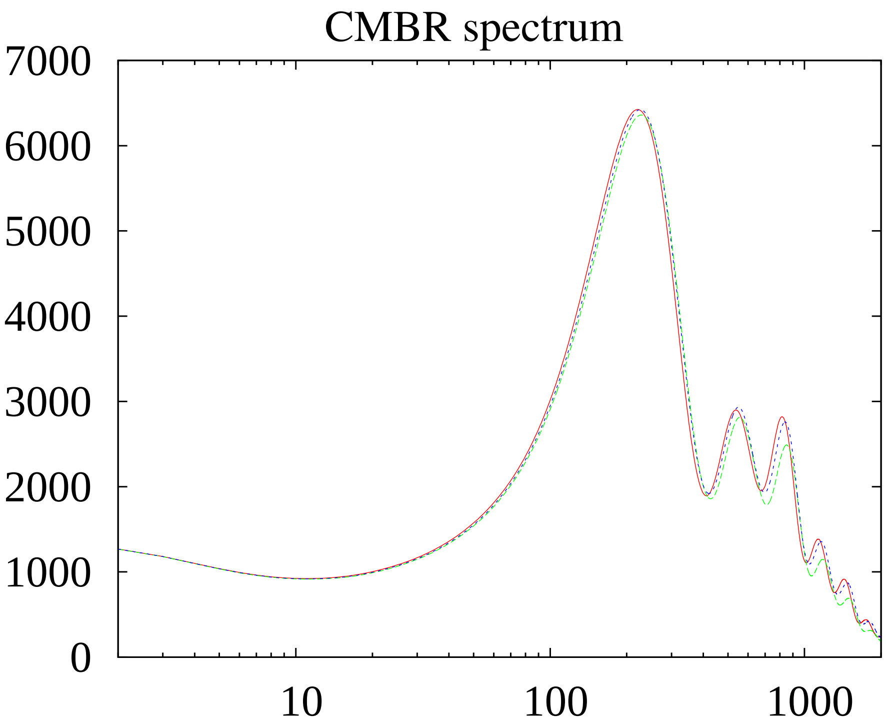
$$\langle n_e n_p\rangle \neq \langle n_e\rangle\langle n_p\rangle$$

A "new" effect: Inhomogeneous recombination

$$\left(\frac{\delta\varrho}{\varrho}\right)_{rms} = 0,\ \sqrt{3},\ 10$$

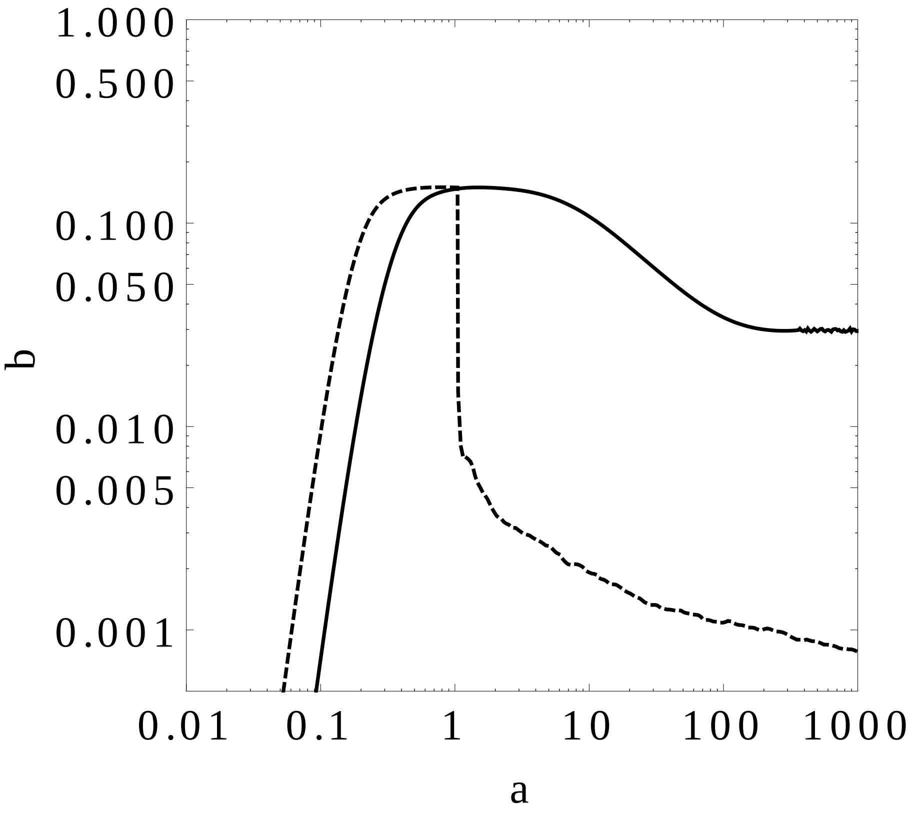


A "new" effect: Inhomogeneous recombination



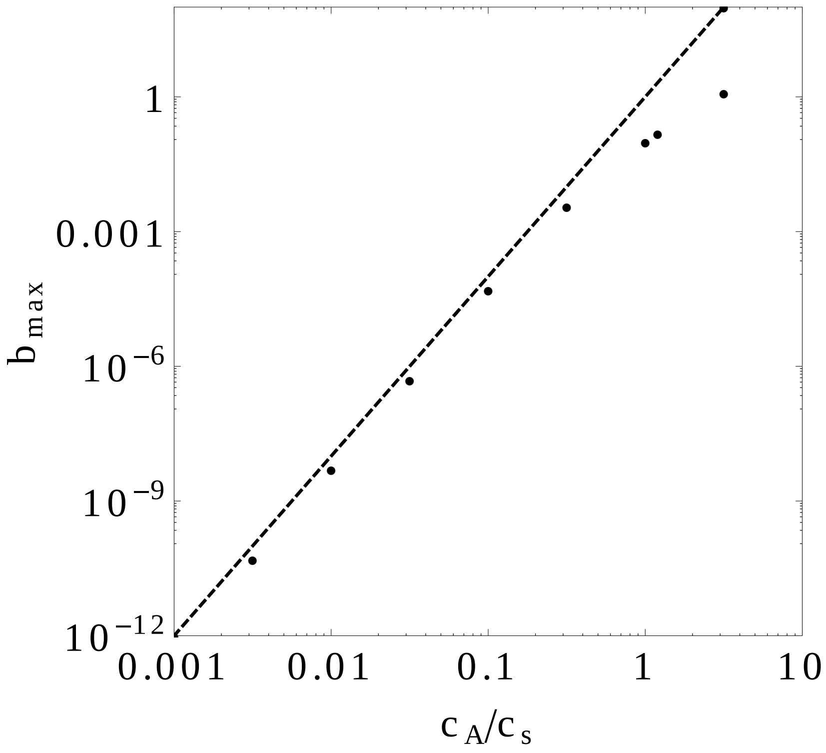
- earlier recombination, peaks shift to higher l
- enhanced Silk damping

Numerical simulations of compressible MHD before recombination

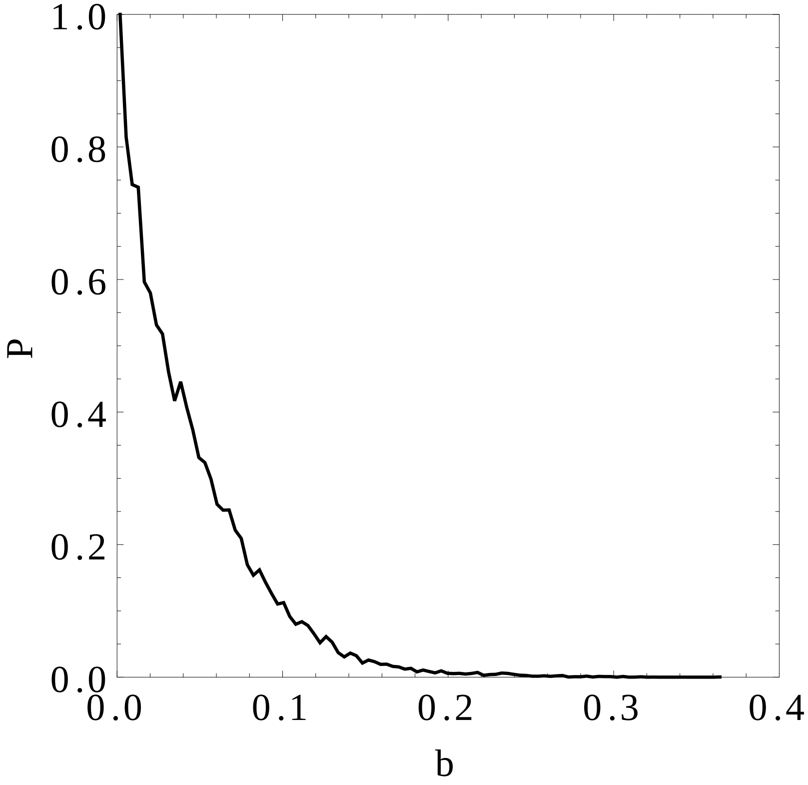


clumping factor $b = \frac{(\langle \varrho - \langle \varrho \rangle \rangle)^2}{\langle \varrho \rangle^2}$

Density fluctuations as a function of v_A



The marginalized probability for clumping from Planck data



Resulting limits on primordial magnetic fields

stringent new limits on primordial magnetic fields
from inhomogeneous recombination

$B \lesssim 0.0089$ nG (total field) at 95% confidence
for causual spectra

$B \lesssim 0.047$ nG
for scale-invariant spectra

K.J and A. Saveliev, Phys.Rev.Lett. (2019)