INSTITUT FÜR ASTROPHYSIK GÖTTINGEN

Magnetic Fields in the Epoch of Reionization and the First Galaxies

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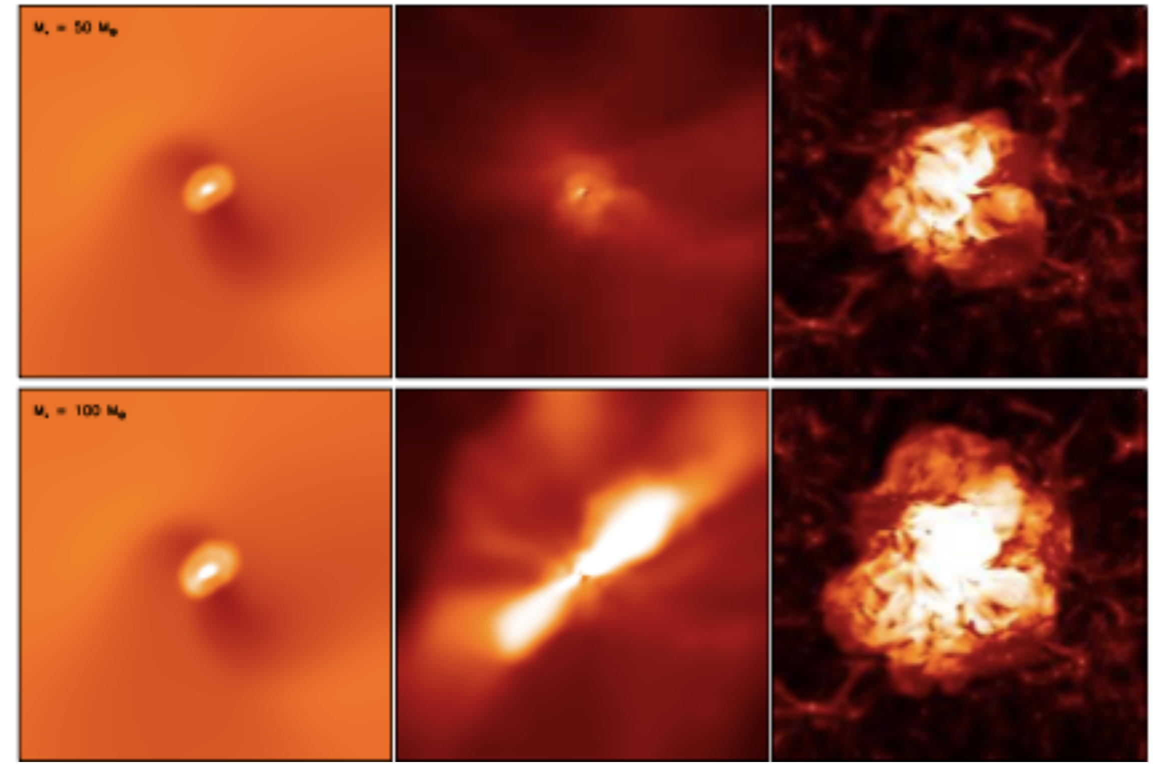
Contents

- Reionization constraints:
  - Observations
  - Implications of magnetic fields
  - Upper limits
- Magnetic field amplification during structure formation
  - The small-scale dynamo
  - Amplification during gravitational collapse
  - Resolution requirements

Reionization:

What is it?

- After cosmic recombination, the Universe is neutral and atomic.
- Today, the gas in the intergalactic medium is highly ionized.
- The transition presumably was due to ionizing photons from the first sources of light ...
- How can we probe the transition from atomic to ionized gas?



Greif et al. (2009):
The onset of reionization

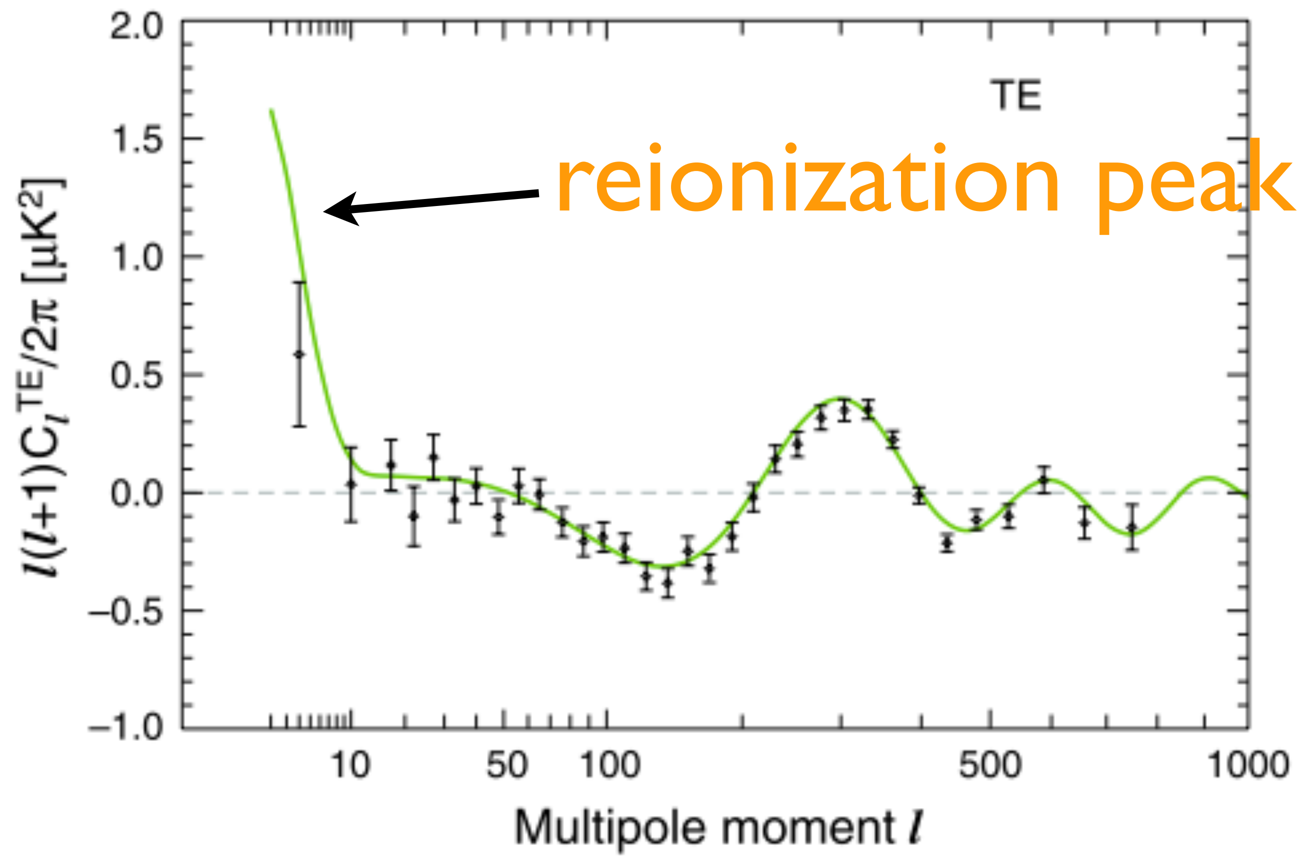
Probing reionization:

CMB

Ionized gas influences CMB via Thompson scattering. Optical depth

$$\tau = \frac{n_H(0)c}{H_0}\int_{z=0}^{z=z_s} x_{eff}(z)\sigma_T \frac{(1+z)^2}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}}dz.$$

e.g. Schleicher, Banerjee & Klessen (2008)



Larson et al. (2011): WMAP 7 TE spectrum

- Primary anisotropies are suppressed as exp(-tau).
- Large-scale polarization increases
  -> Temperature - polarization (TE) power spectra peak at low l.

Probing reionization:

Quasar absorption spectra

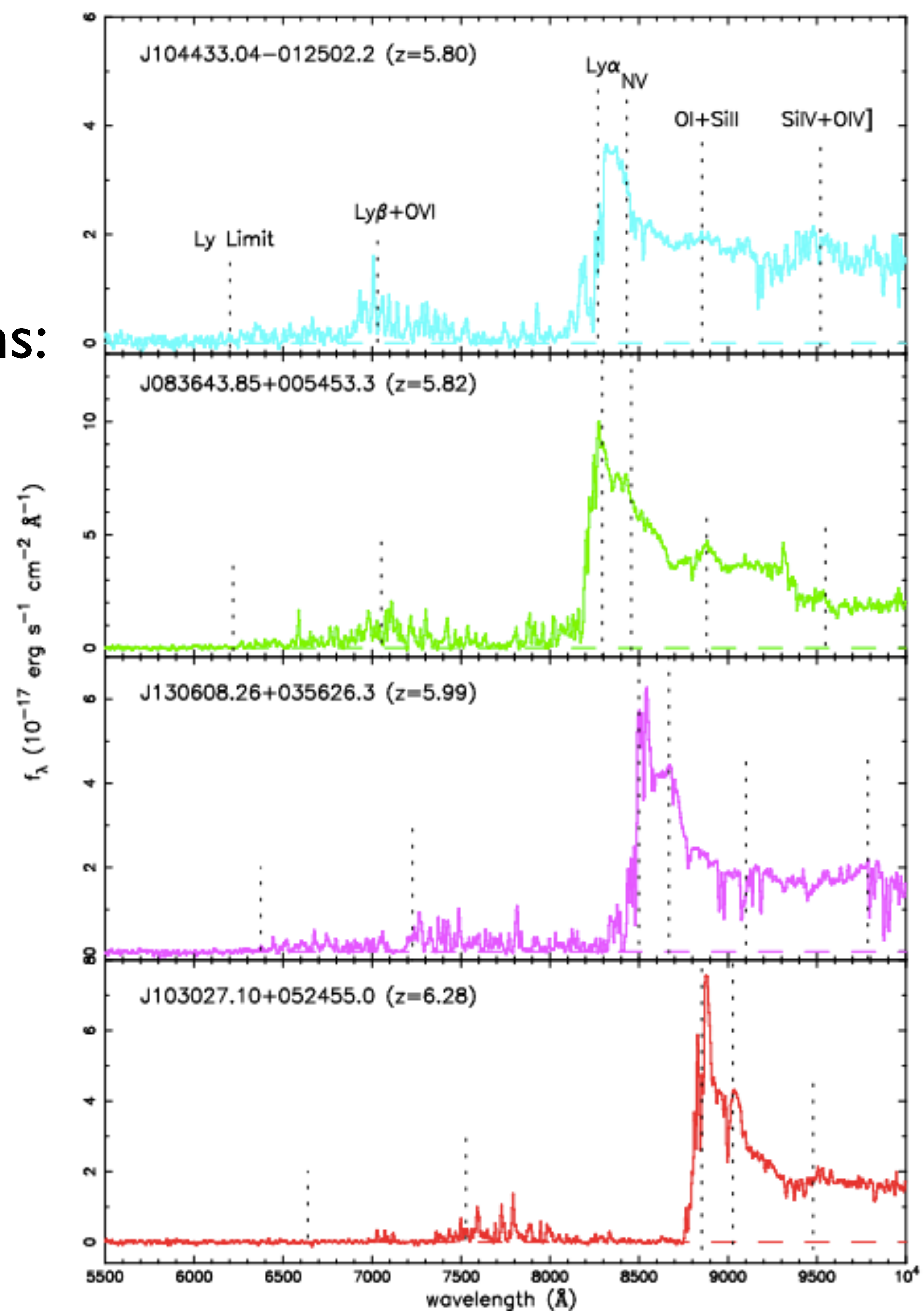
Optical depth for Lyman Alpha photons:

$$\tau_{GP}(z) = 1.8\times10^5 h^{-1}\Omega_M^{-1/2}\left(\frac{\Omega_b h^2}{0.02}\right)\left(\frac{1+z}{7}\right)^{3/2}\left(\frac{n_{\rm HI}}{n_{\rm H}}\right)$$

Small neutral fraction sufficient to absorb Ly Alpha photons.
Higher-frequency photons redshifted through Ly Alpha line!

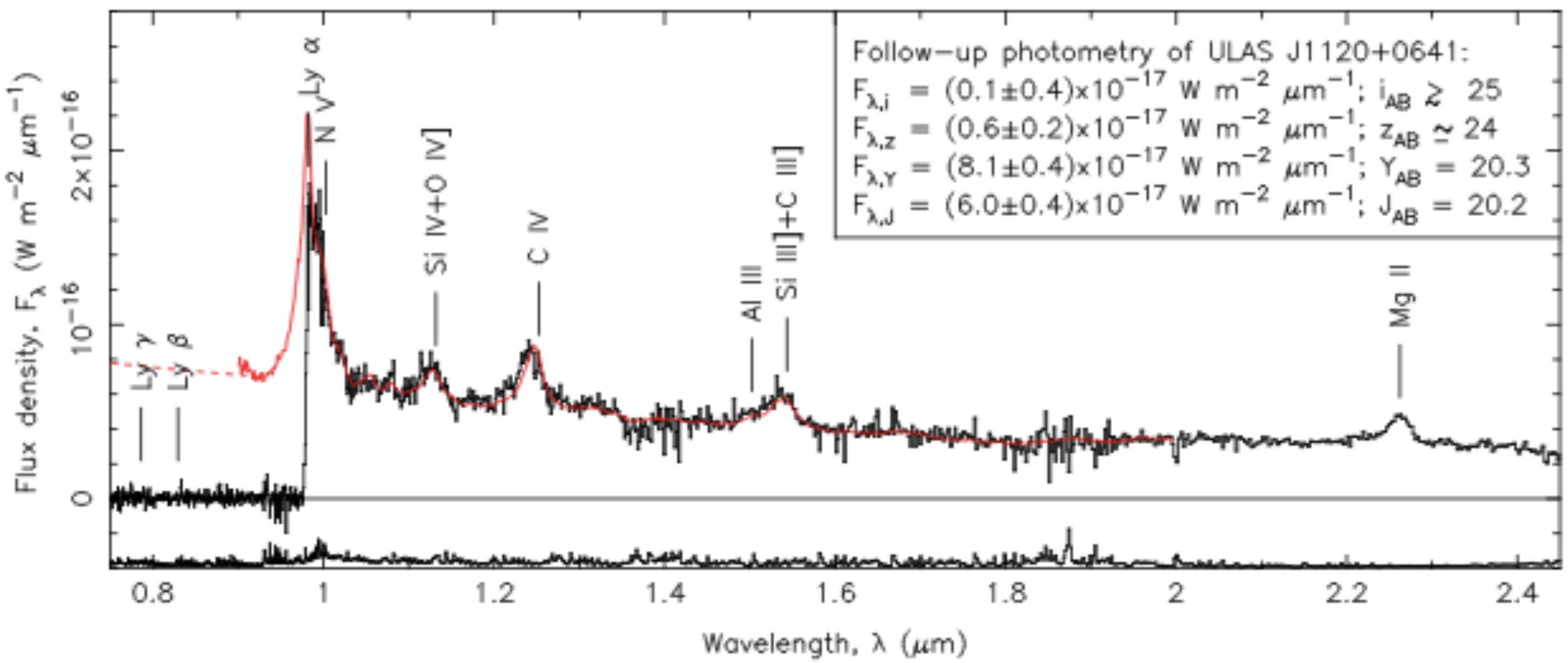
Spectra for z=6.28 quasar consistent with no flux blueward of Lyman Alpha. => End of reionization at z~6.

Becker et al. (2001)

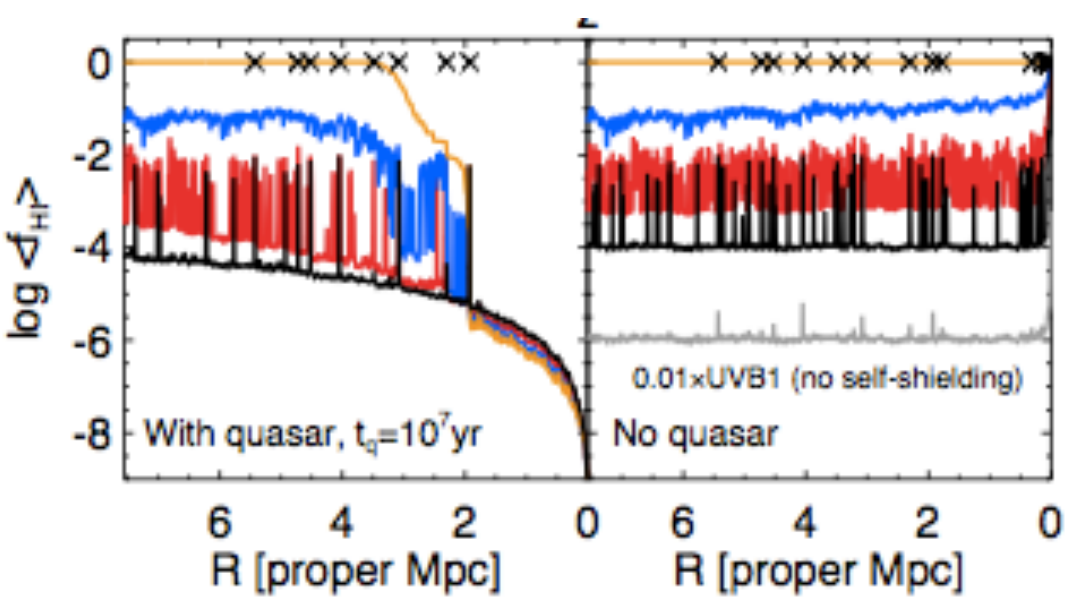


Probing reionization:

A new z~7 quasar.



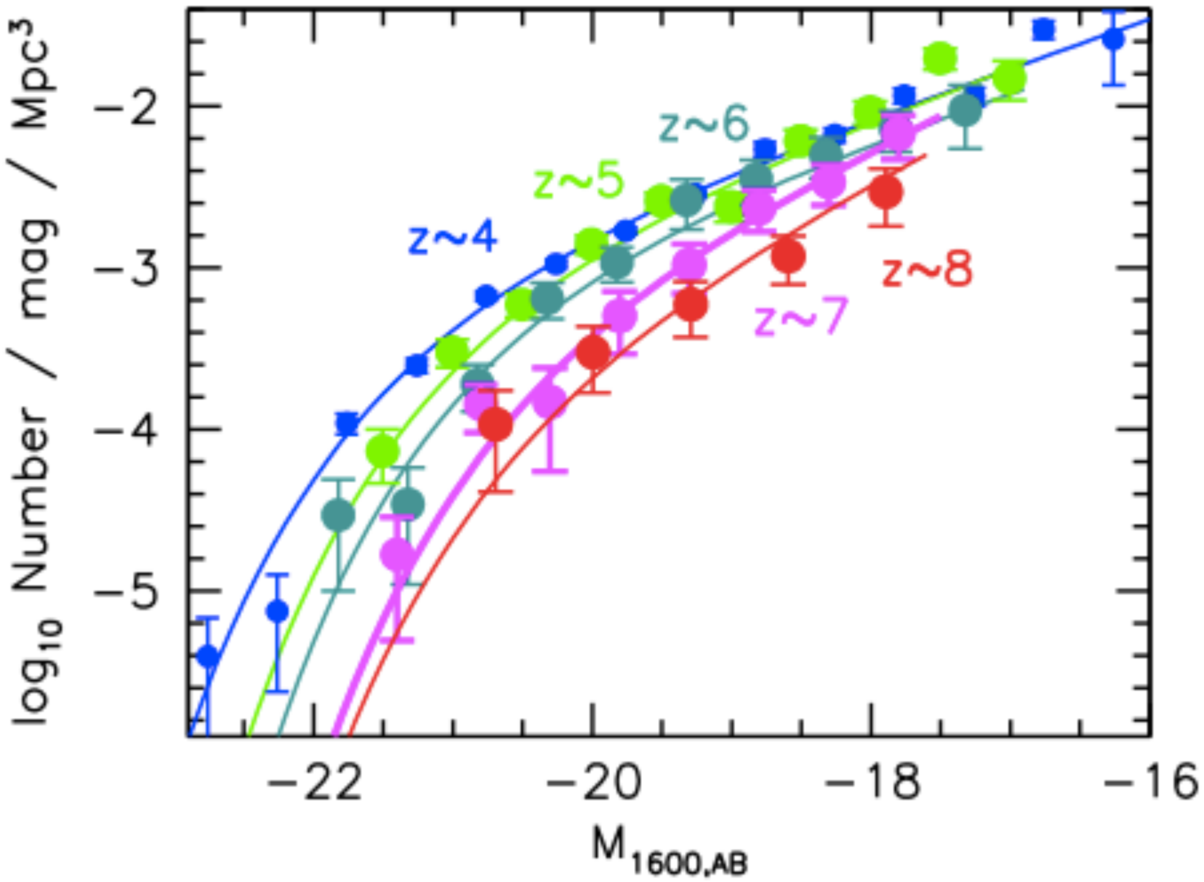
Mortlock et al. (2011): new z=7.085 quasar

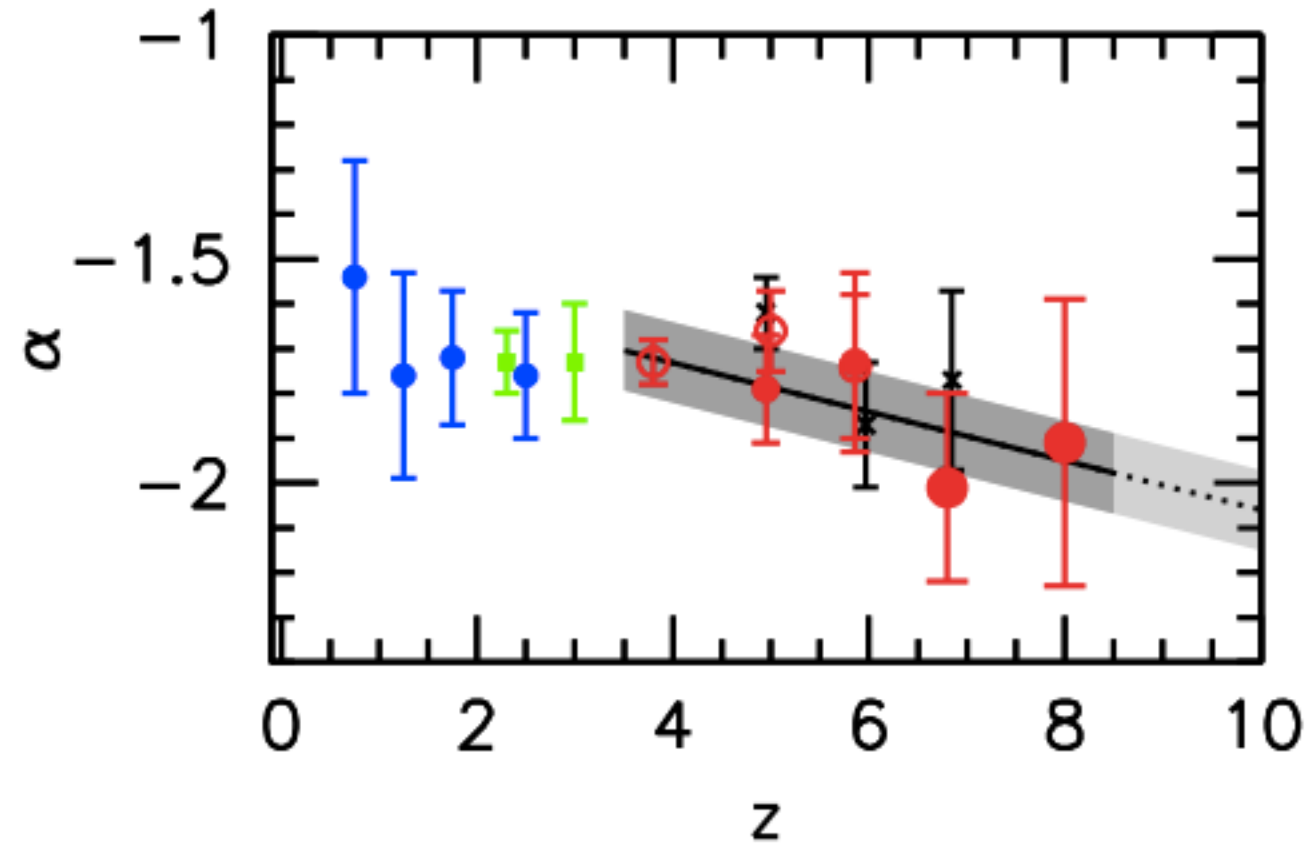


Left: Modeling of HI fraction (Bolton et al. 2011). Implied values of 10^{-3}-10^{-4}.

Probing reionization:

The observed UV luminosity function close to reionization





Left: Observed UV luminosity function. Right: Faint-end slopes vs. redshift.

Schechter function: $n_{SCH}(M_{UV}) = \Phi^* \frac{\ln(10)}{2.5} 10^{-0.4(M_{UV}-M^*_{UV})\alpha} \exp(-10^{-0.4(M_{UV}-M^*_{UV})})$

$$M^*_{UV,AB} = (-20.34 \pm 0.11) + (0.28 \pm 0.06)(z-6)$$
$$\phi^* = 10^{-2.90\pm0.09+(-0.04\pm0.05)(z-6)}$$
$$\alpha = (-1.84 \pm 0.05) - (0.05 \pm 0.04)(z-6)$$

Bouwens et al. (2010, 2011)

Modeling reionization:

The evolution of the ionized volume fraction

$$\frac{dQ_{\rm H\,II}}{dt} = \frac{\dot{n}_{\rm ion}}{\bar{n}_{\rm H}} - \frac{Q_{\rm H\,II}}{\bar{t}_{\rm rec}}$$

Q: ionized volume fraction.

Production rate of UV photons: SFR f_{esc} 10^{53} photons s^{-1}

Recombination timescale: Clumping factor, IGM temperature

Madau et al. (1999)

Evolution equation for the ionized volume fraction.

Modeling reionization:

The effects of primordial fields

- **Magnetic Jeans mass**: $M_J^B \sim 10^{10} M_\odot \left(\frac{B_0}{3\ \mathrm{nG}}\right)^3$

  (Subramanian & Barrow 1998)

- **Ambipolar diffusion heating**: $L_{\mathrm{AD}} = \frac{\eta_{\mathrm{AD}}}{4\pi} \left|\left(\nabla \times \vec{B}\right) \times \vec{B}/B\right|^2$

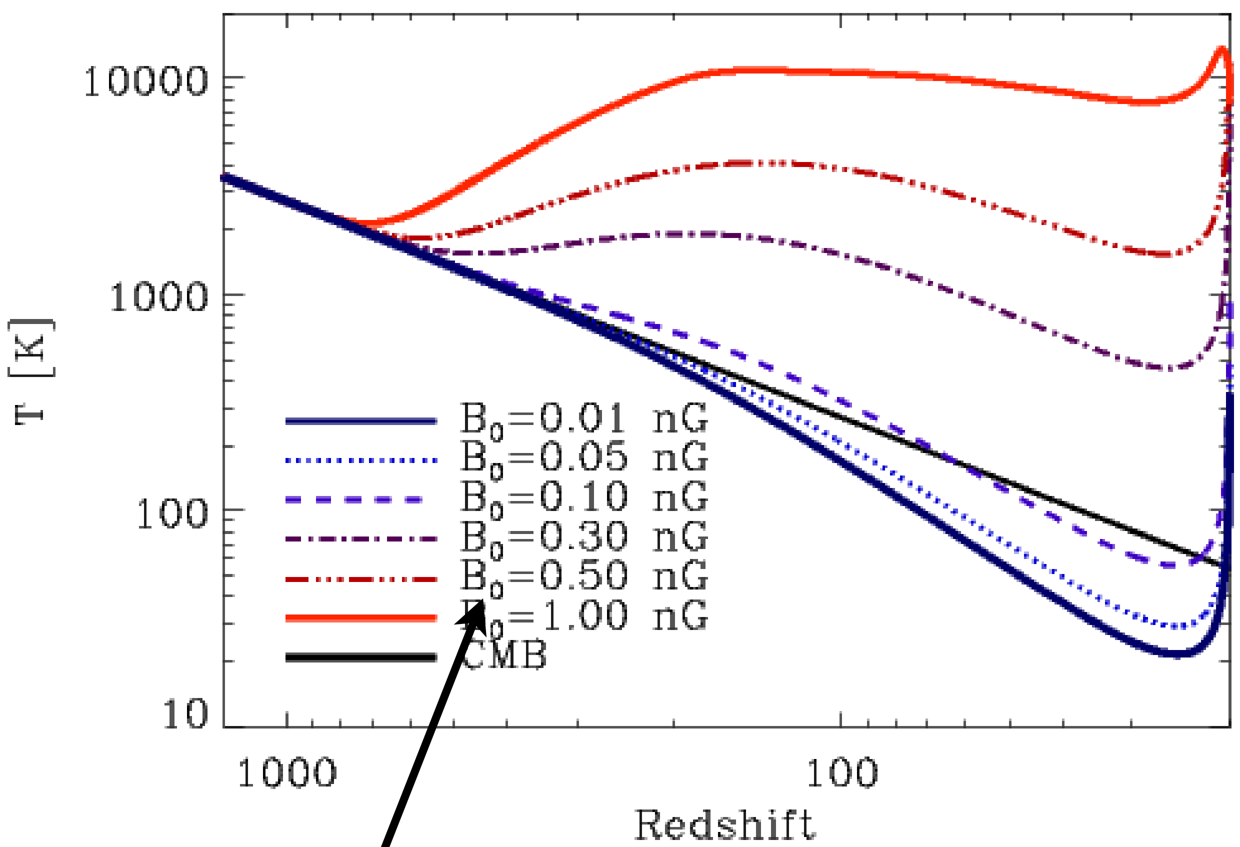
  (Sethi & Subramanian 2005,
  Schleicher, Banerjee & Klessen 2008)

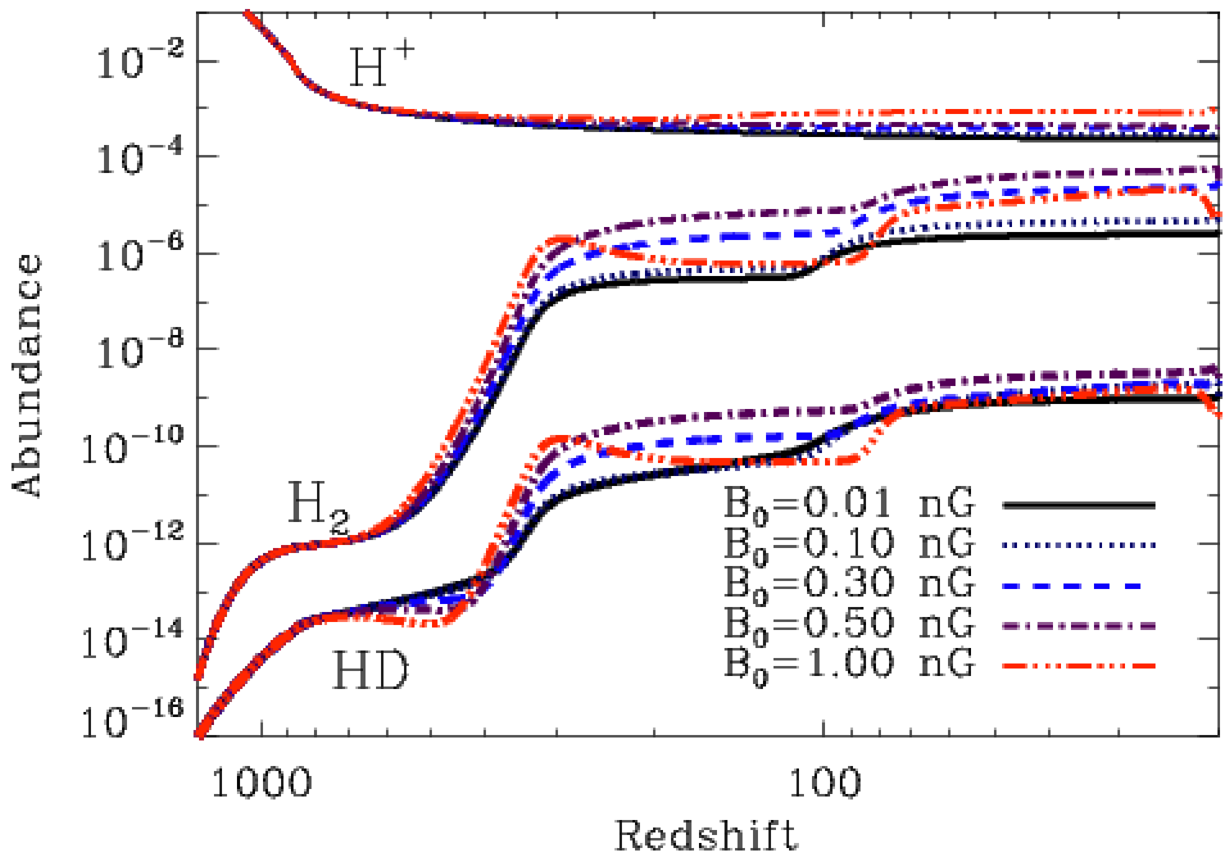
- **Smallest scale**:
  (Jedamzik et al. 1998,
  Subramanian & Barrow 1998)

$$k_{\max} \sim 234\ \mathrm{Mpc}^{-1} \left(\frac{B_0}{1\ \mathrm{nG}}\right)^{-1} \left(\frac{\Omega_m}{0.3}\right)^{1/4} \times \left(\frac{\Omega_b h^2}{0.02}\right)^{1/2} \left(\frac{h}{0.7}\right)^{1/4},$$

Ambipolar diffusion:

Implications in the large-scale IGM





Primordial magnetic fields increase gas temperature and abundance of the main coolants

Co-moving field strength: $B_{phys} \sim B_{co}\,(1+z)^2$.

Schleicher et al. (2009)

Building a reionization model:

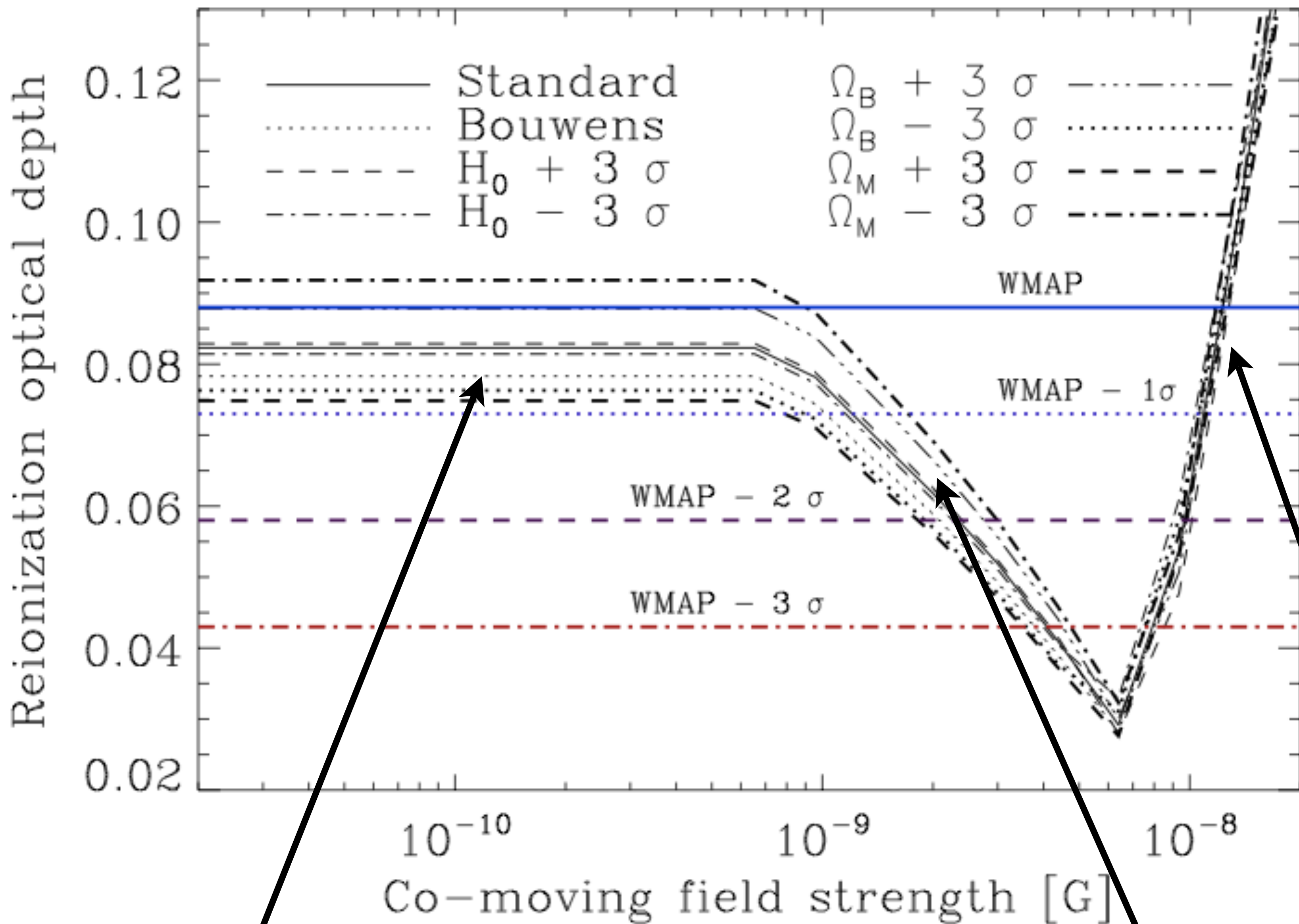
Implications of strong magnetic fields

- Calculate cosmic star formation rate using the observed UV luminosity function.
- Determine low-mass cutoff based on magnetic field strength.
- Follow the evolution of the ionized volume fraction.
- Calculate the reionization optical depth.

Schleicher, Banerjee & Klessen (2008);
Schleicher & Miniati (2011)

Reionization:

Magnetic field constraints & cosmological uncertainties



Constant low-luminosity cutoff, M_{UV}=-10

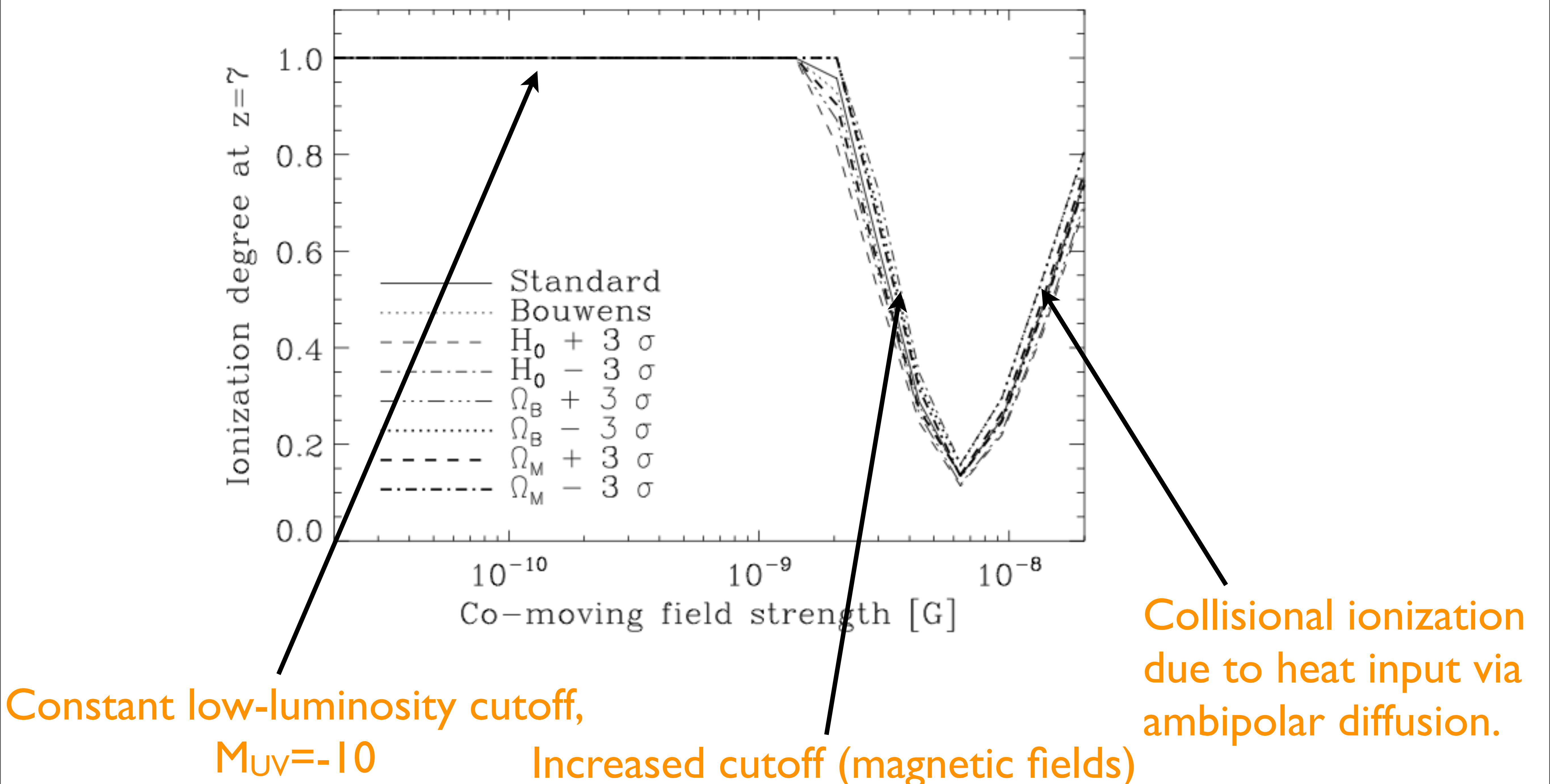
Increased cutoff (magnetic fields)

Collisional ionization due to heat input via ambipolar diffusion

Schleicher & Miniati (2011)

Reionization:

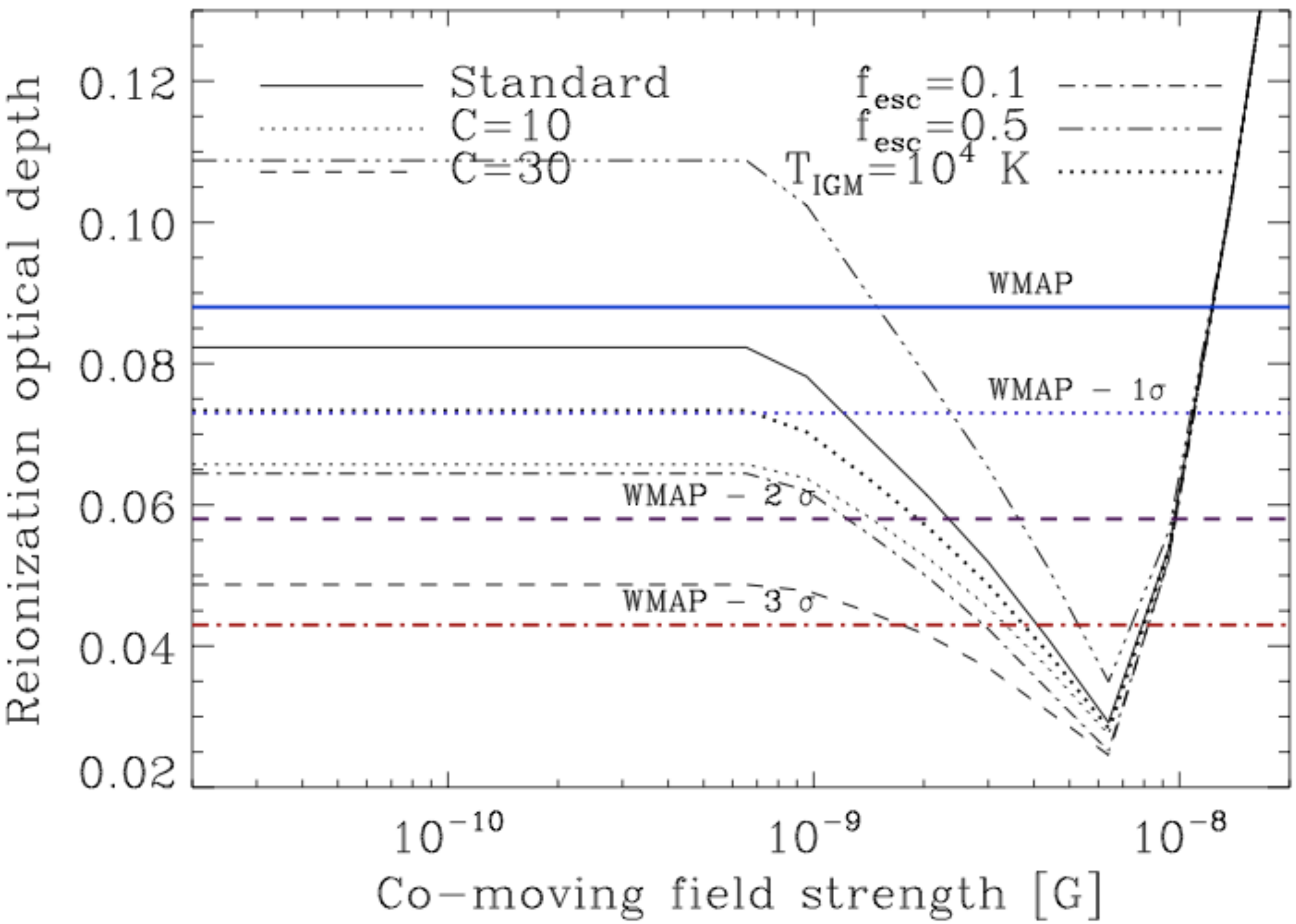
Improved constraints & cosmological uncertainties



Schleicher & Miniati (2011)

Reionization:

Improved constraints & parameter uncertainties



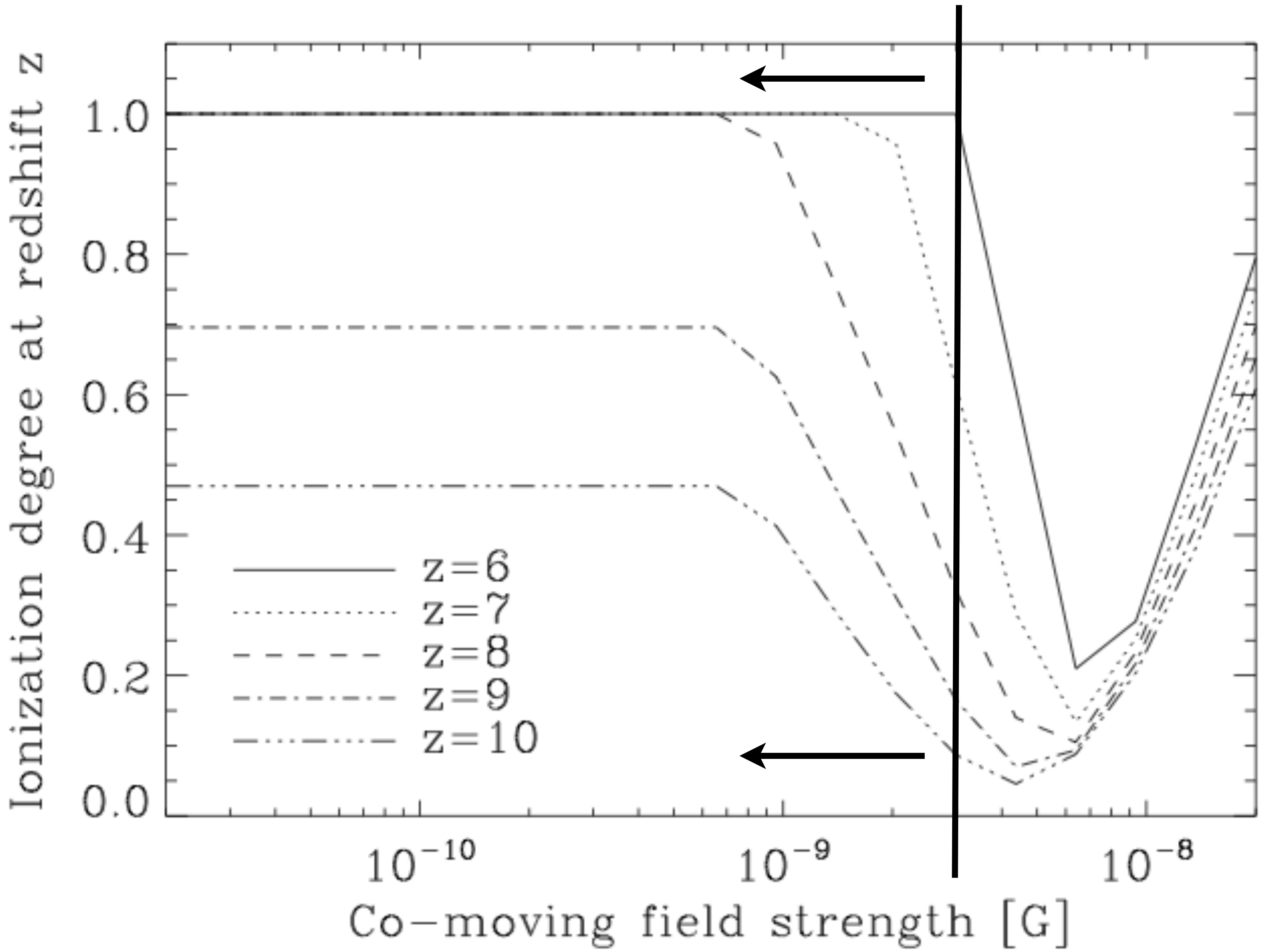
Significant uncertainties due to escape fraction, clumping factor and IGM temperature.

Upper limit on magnetic field strength of ~5 nG (co-moving).

Schleicher & Miniati (2011)

Reionization:

Future improvements



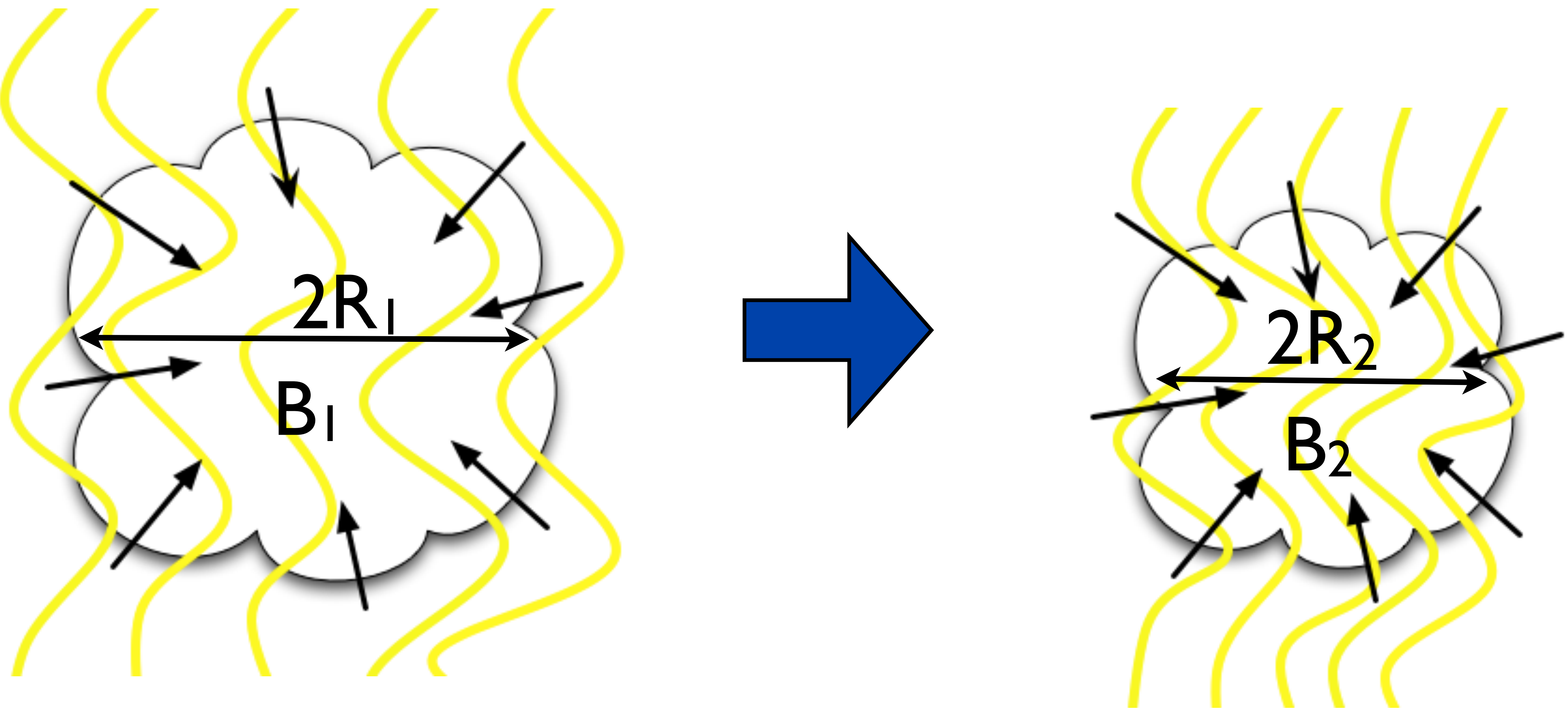
High ionization degrees at z>7 implying stronger constraints.

Low ionization degree at z~8 could indicate strong magnetic fields.

Schleicher & Miniati (2011)

Magnetic fields in the first galaxies:

Magnetic field amplification during collapse



flux conservation:

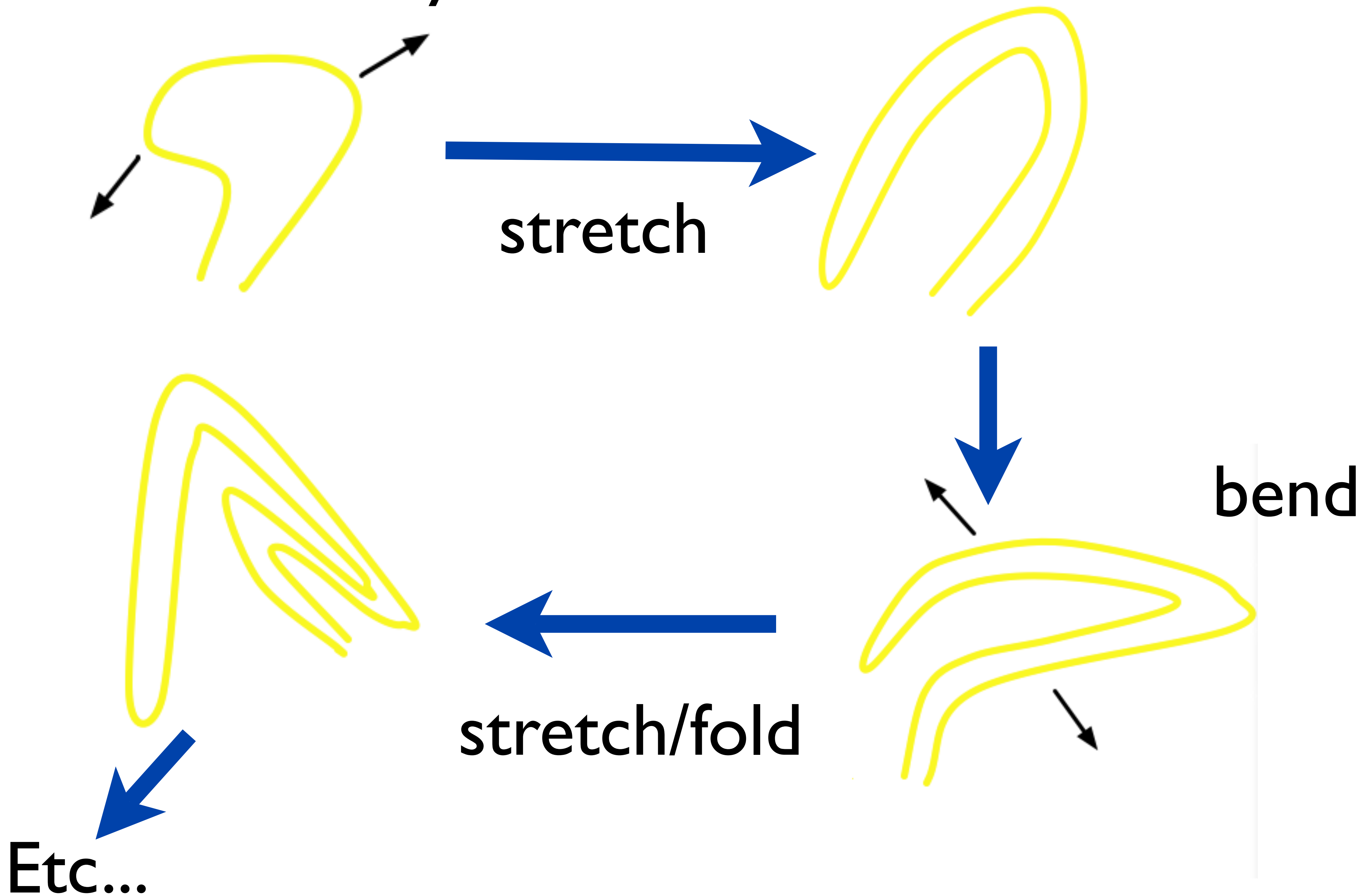
$R_1^2 \, B_1 = R_2^2 \, B_2$

density ~ R^{-3}

-> B ~ density$^{2/3}$

Magnetic fields in the first galaxies:

The small-scale dynamo

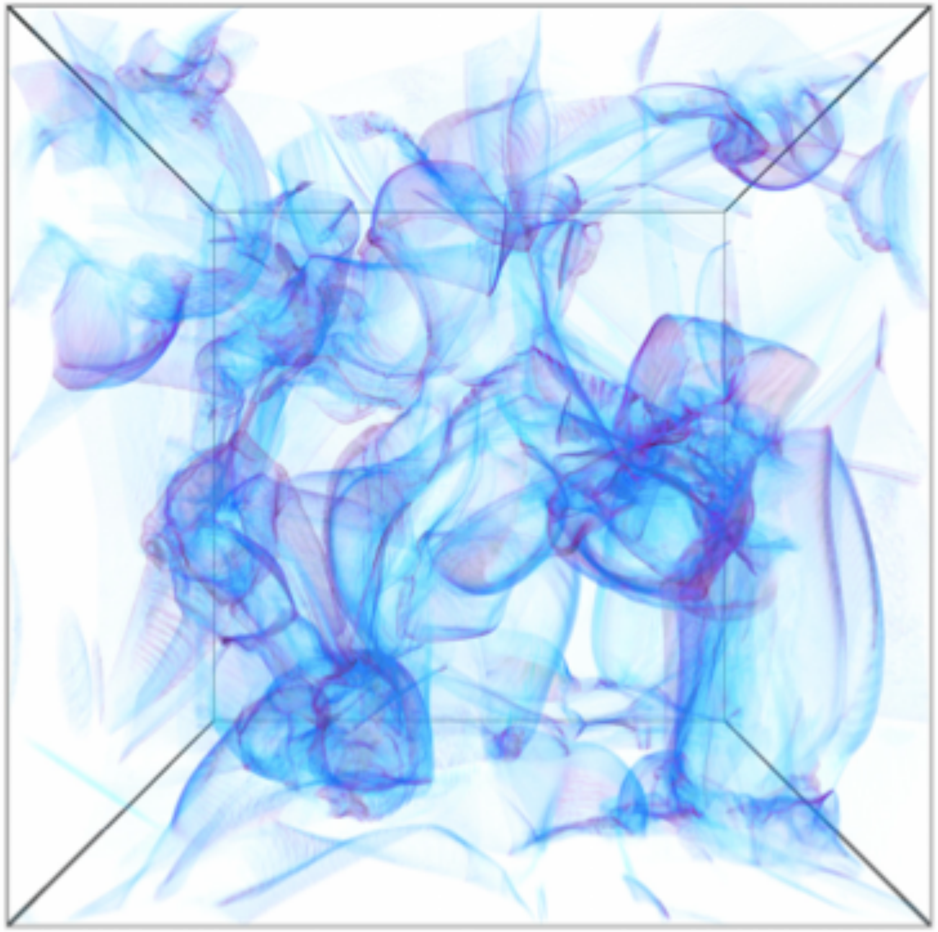


Amplification via stretch-and-fold

see Schleicher, Banerjee, Sur, Arshakian, Klessen, Beck & Spaans (2010)

Magnetic fields in the first galaxies:

The small-scale dynamo



Schmidt et al. (2009)

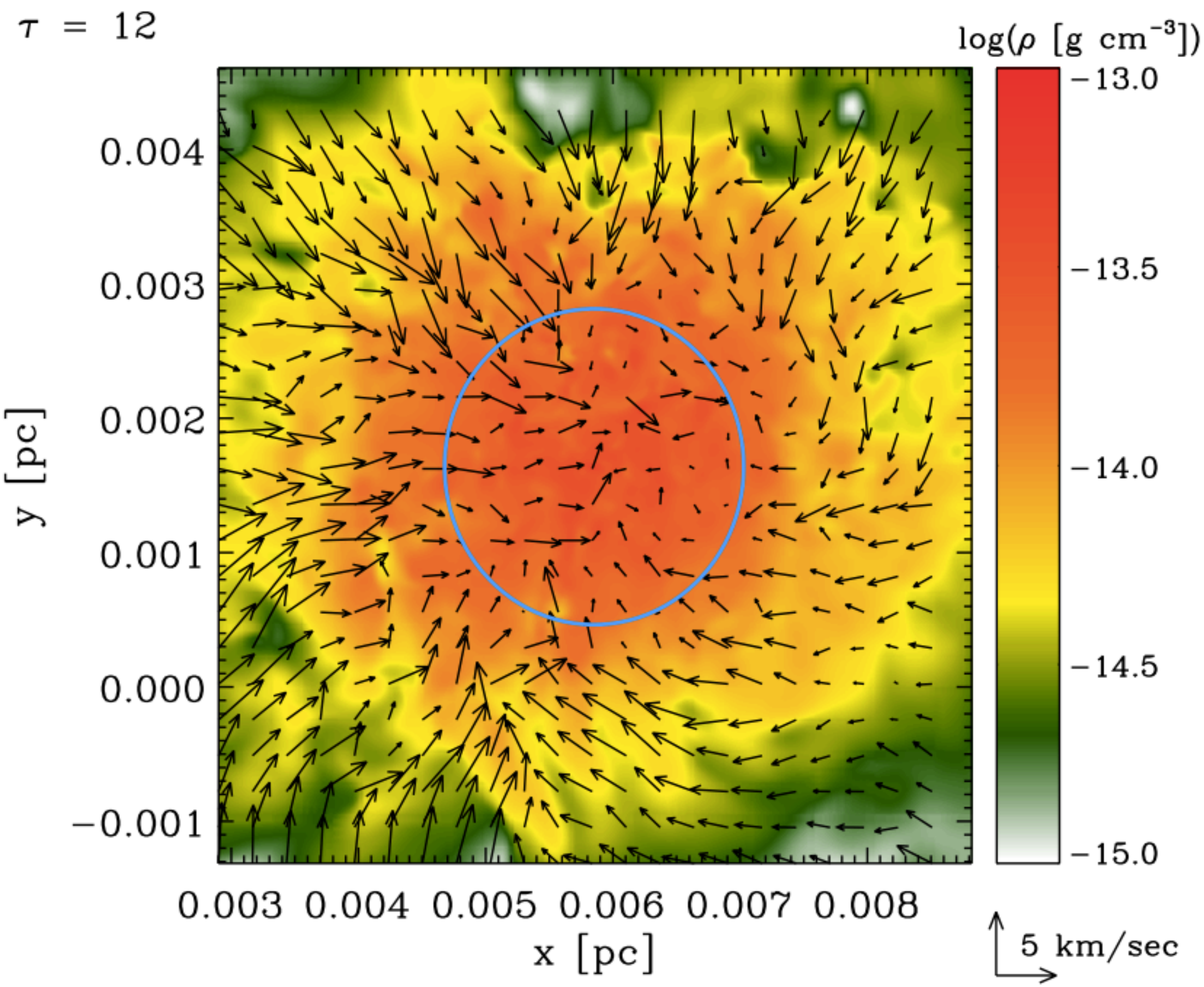
Turbulent scaling laws:
$v \sim l^{1/3}$ (Kolmogorov)
$v \sim l^{1/2}$ (Burgers)
Realistic turbulence often inbetween, with comparable amounts of rotation and compression

Variation of growth rate with Reynolds-number:
Gamma~$Re^{1/2}$ (Kolmogorov)
Gamma~$Re^{1/3}$ (Burgers)

Schober, Schleicher, Federrath, Banerjee & Klessen, in prep.
See also Subramanian (1998) for Kolmogorov turbulence.

Magnetic fields in the first galaxies:

The small-scale dynamo in collapsing clouds

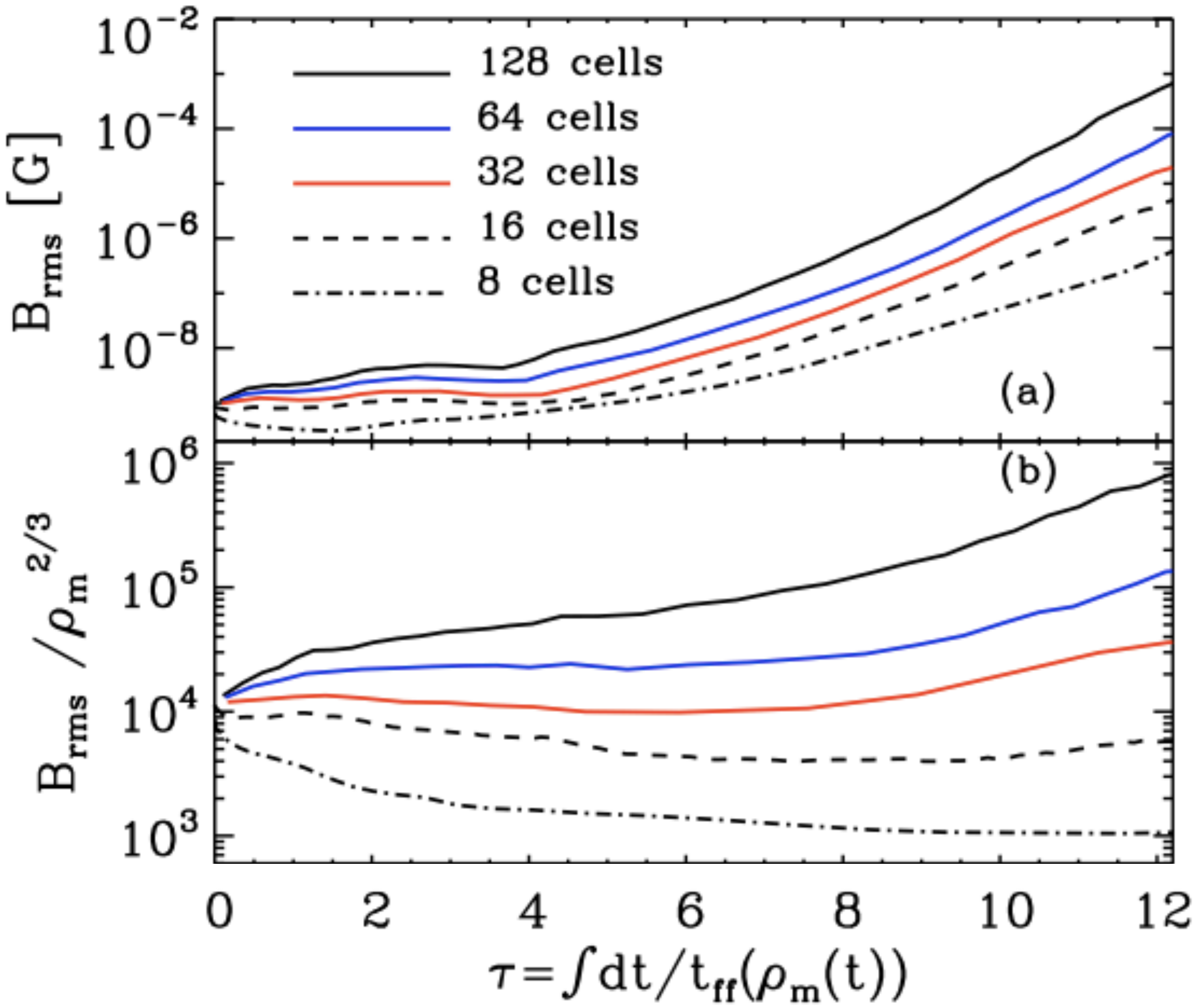


- Motions dominated by infall on large scales.
- Formation of a turbulent core in the center.
- Core size comparable to Jeans length.

Sur et al. (2010), Federrath et al. (2011)

Magnetic fields in the first galaxies:

The small-scale dynamo in collapsing clouds

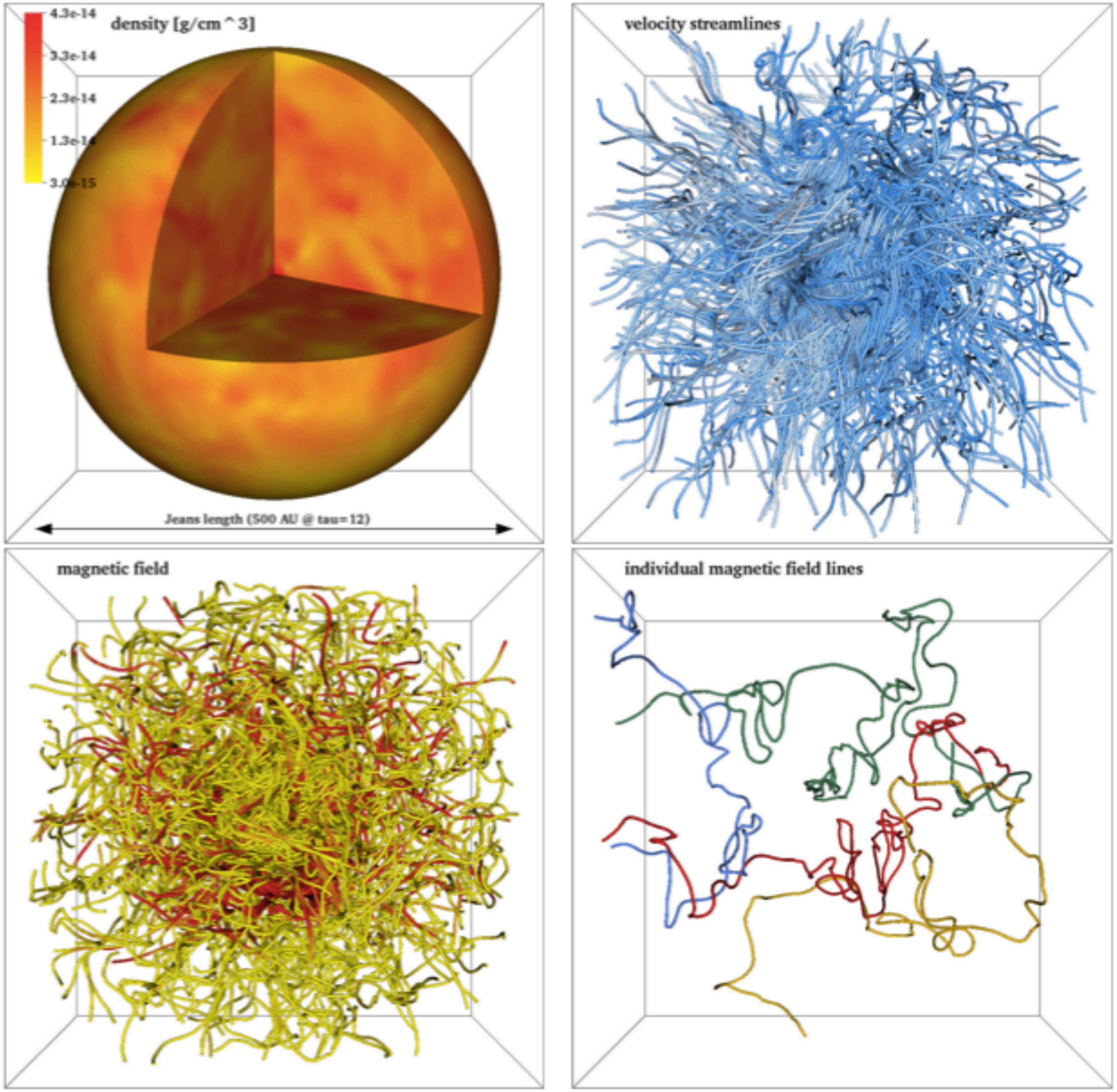


Sur et al. (2010),
Federrath et al. (2011)

More efficient magnetic field amplification at higher resolution
-> dependence on Reynolds number and numerical diffusivity
(see Brandenburg & Subramanian 2005)

Star formation Then:

Turbulence and magnetic field structure

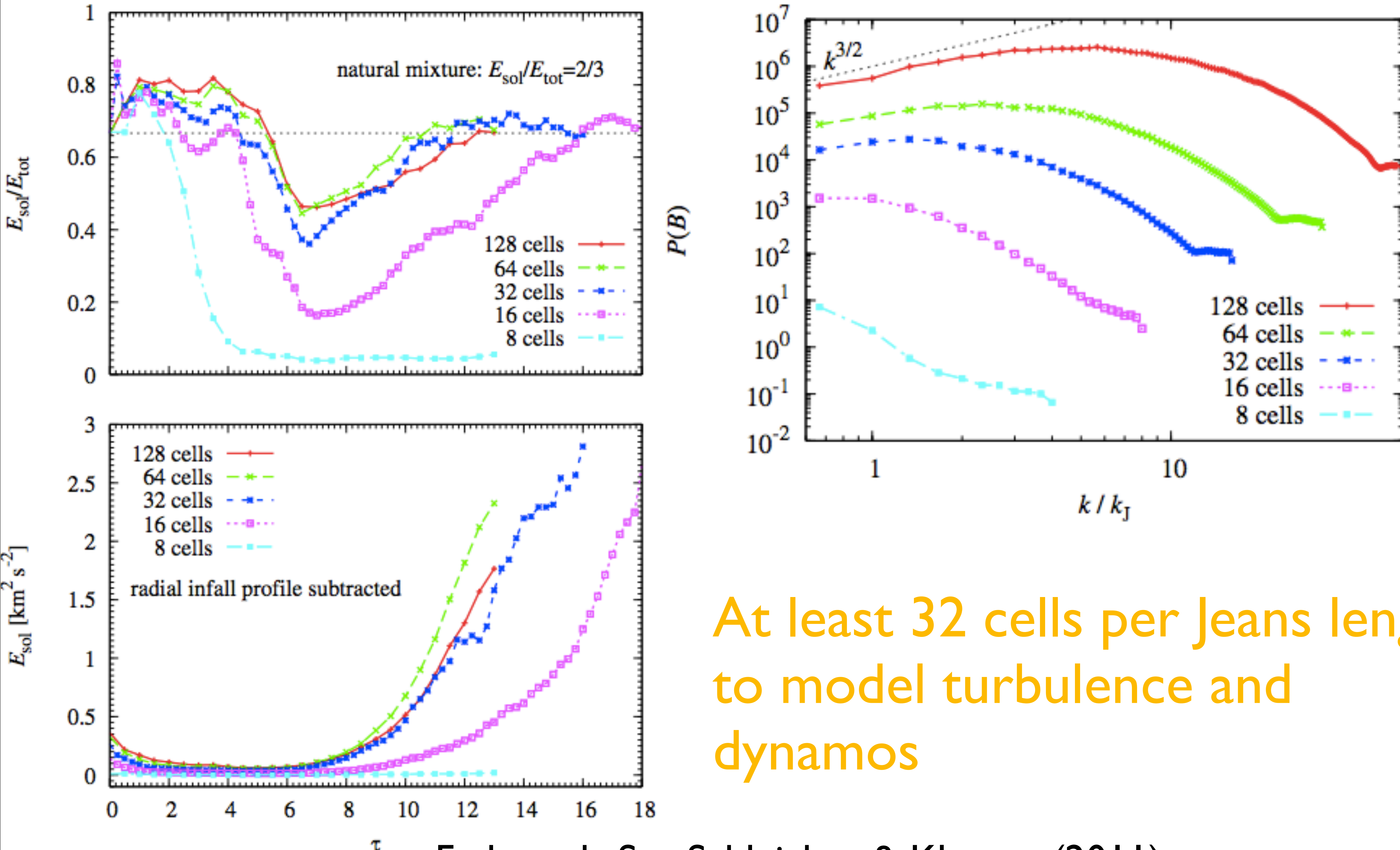


Federrath, Sur, Schleicher & Klessen (2011)

- Magnetic field enhanced by turbulence and compression
- Highly tangled magnetic field structure
- Still reflecting density distribution due to compression

Star formation & magnetic fields:

Turbulent properties and a critical resolution



At least 32 cells per Jeans length to model turbulence and dynamos

Federrath, Sur, Schleicher & Klessen (2011)

FLASH WORKSHOP 2012

Hamburger Sternwarte, Feb. 15/16

Workshop on the MHD-Code FLASH

- Organizers: R. Banerjee, D. Schleicher
- Idea: Learn about new developments with FLASH, exchange of modules, new collaborations.
- Possible topics: Radiative transfer, feedback / subgrid modeling, new solvers, new modules, visualization, data formats.
- Contact: banerjee@hs.uni-hamburg.de, dschleic@astro.physik.uni-goettingen.de

Summary and conclusions

- Reionization constraints from reionization optical depth and quasar absorption spectra.
- UV luminosity functions observed out to z~8.
- Magnetic pressure may set low-mass galaxy cutoff for strong primordial fields.
- Upper limit of 2-3 nG from reionization constraints.

- First galaxies: Magnetic field amplification by the small-scale dynamo.
- Strong dependence on the Reynolds number of the gas.