Magnetic Fields in the Epoch of Reionization

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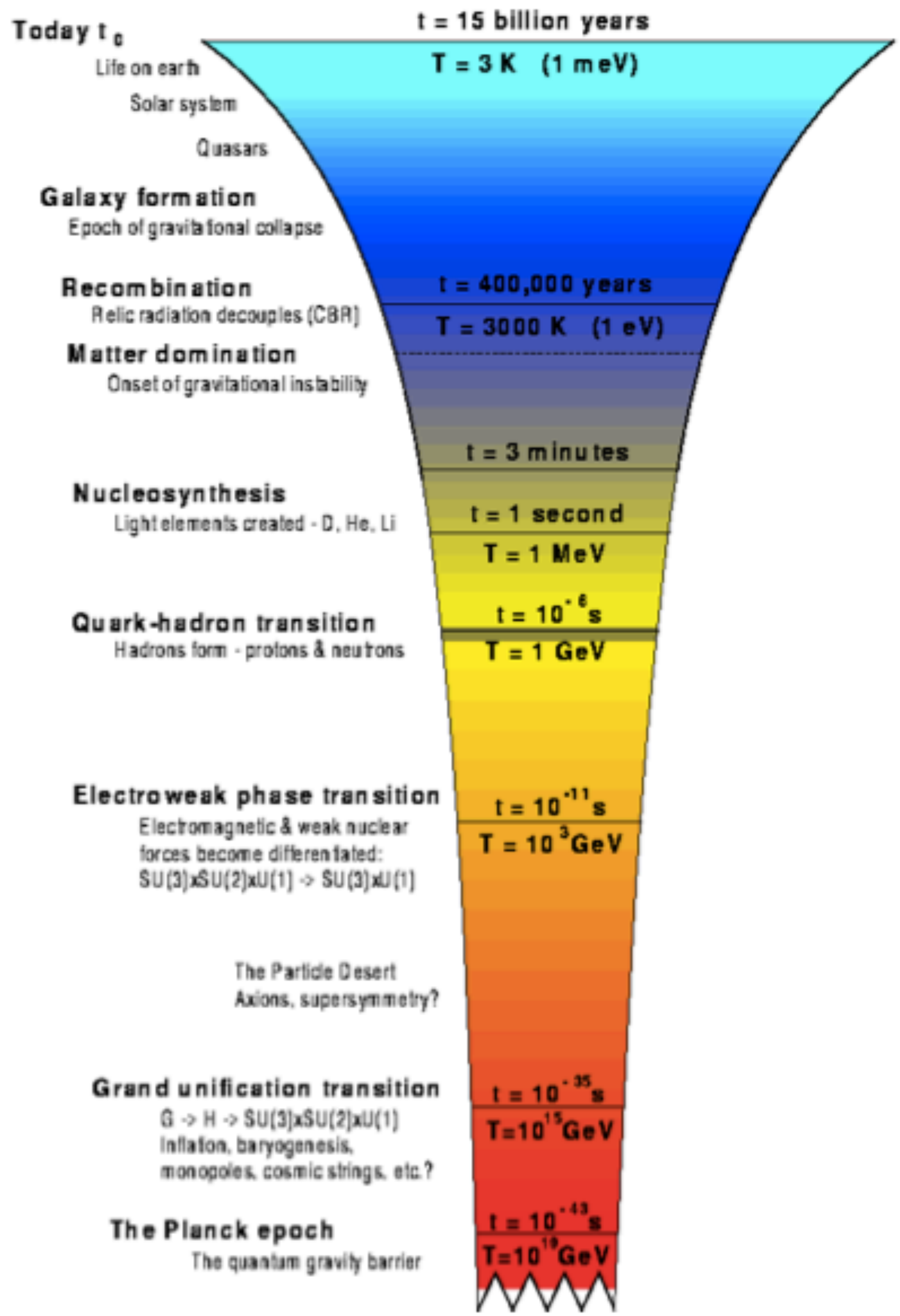
Contents

- Primordial magnetic fields
- Reionization: Observational constraints
- Reionization: Theoretical models
- Primordial magnetic fields: Constraints from the Epoch of Reionization

Reionization as a tool to constrain primordial magnetic fields.

The history of the universe



Primordial fields:

Origin from inflation?

Epoch of inflation:

- Phase of rapid, accelerated expansion in the early Universe.
- Explains why the Universe appears spatially flat.
- Explains the origin of structure -> stretching of quantum fluctuations to scales larger than the Horizon

Magnetic fields formed during inflation naturally reach large scales.

Problem: Symmetries in classical electrodynamics prevent generation of magnetic fields.

Solution: Need to break symmetry. But: Strong parameter dependence and huge uncertainties (50 orders of magnitudes).

review: Grasso & Rubinstein (2001)

Primordial fields:

Origin from phase transitions

Phase transitions in the early Universe:

- Electroweak:
  Separation of electromagnetic and weak force. Unclear whether first- or second-order phase transition.

- QCD:
  Formation of protons and neutrons. First-order phase transition.

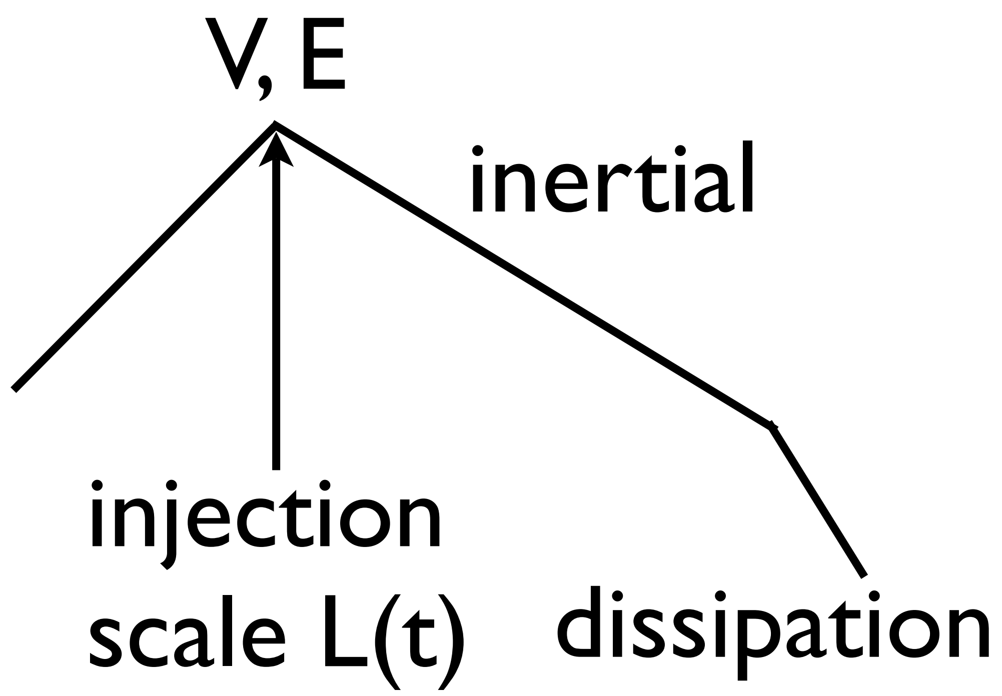
Mechanism: Charge separation due to phase transition, fluid instabilities

Problem: Magnetic field limited to horizon scale (~10 pc for QCD, ~0.01 pc for electroweak phase transition)

see Banerjee & Jedamzik (2004)

Primordial fields:

The inverse cascade

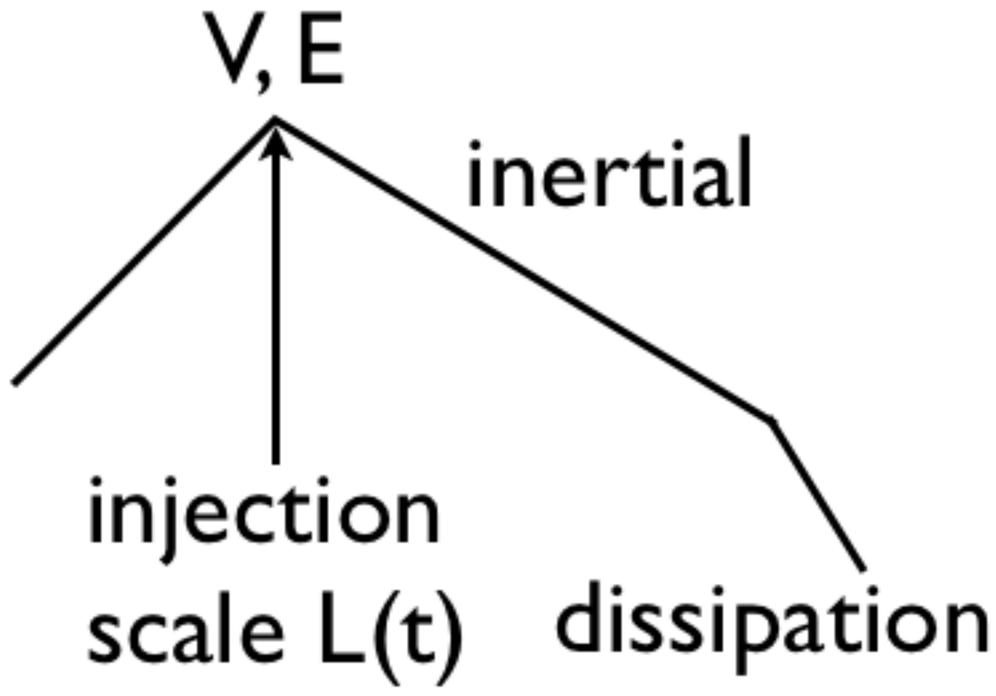


- Injection scale L, velocity V, energy E
- Decay time: tau ~ L / V ~ L / $E^{0.5}$
- Decay law: dE / dt ~ E / tau ~ $E^{3/2}$ / L
- Assumption: $E_l \sim l^{-n}$ for l>L(t). E_l: energy on scale l.
- On scale l: $tau_l \sim l\, E_l^{-1/2} \sim l^{n/2+1}$
- Power-law decay: t ~ tau_l
  => $L(t) \sim t^{2/(n+2)}$
  => $E(t) \sim t^{-2n/(2+n)}$

see Banerjee & Jedamzik (2004)

Primordial fields:

The inverse cascade



- Magnetic helicity as conserved quantity
  => $H \sim L E = const$
  => $E \sim L^{-1}$

- Decay of magnetic energy implies growing coherence length!
  Scaling as if n=1.

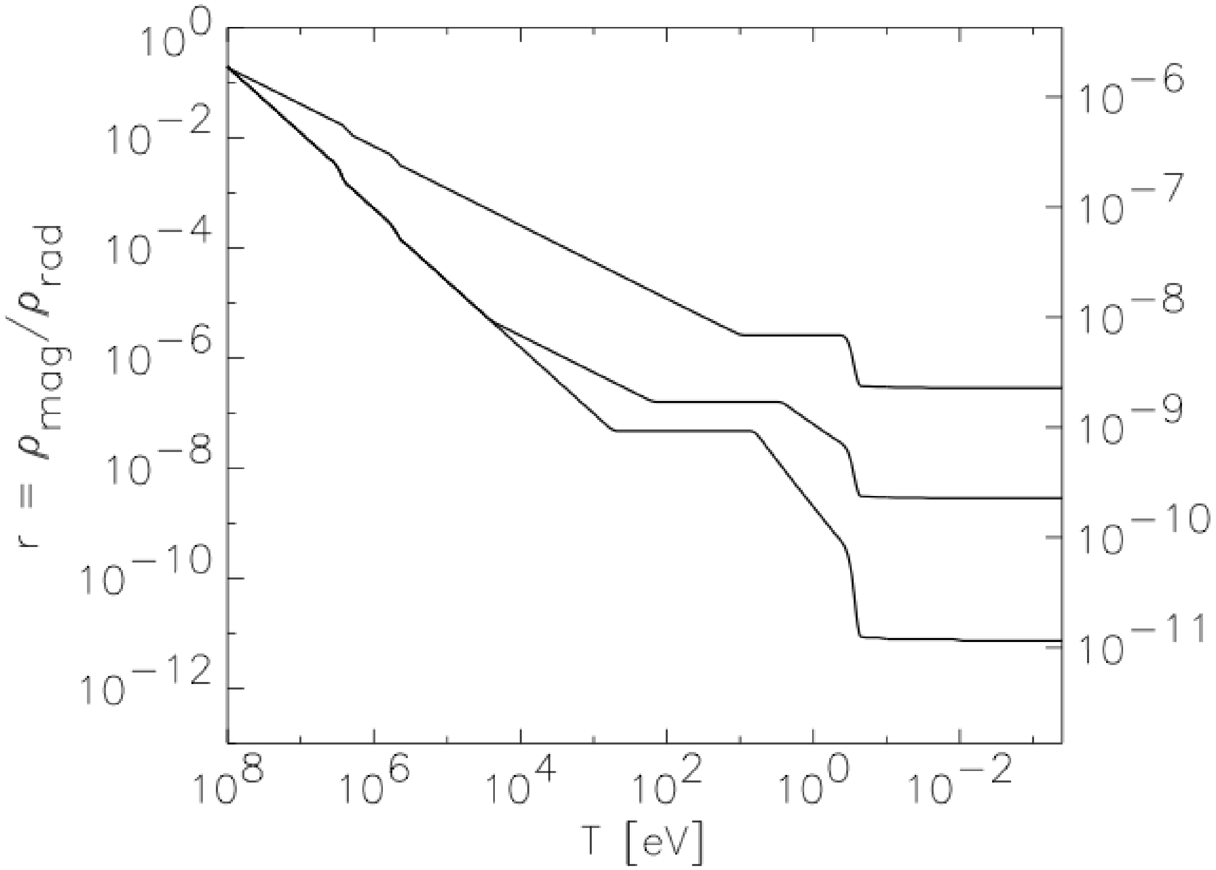
- Then:
  $E(t) \sim t^{-2/3}$
  $L(t) \sim t^{2/3}$

Assumption:
Approximate equipartition between b-field and kinetic energy

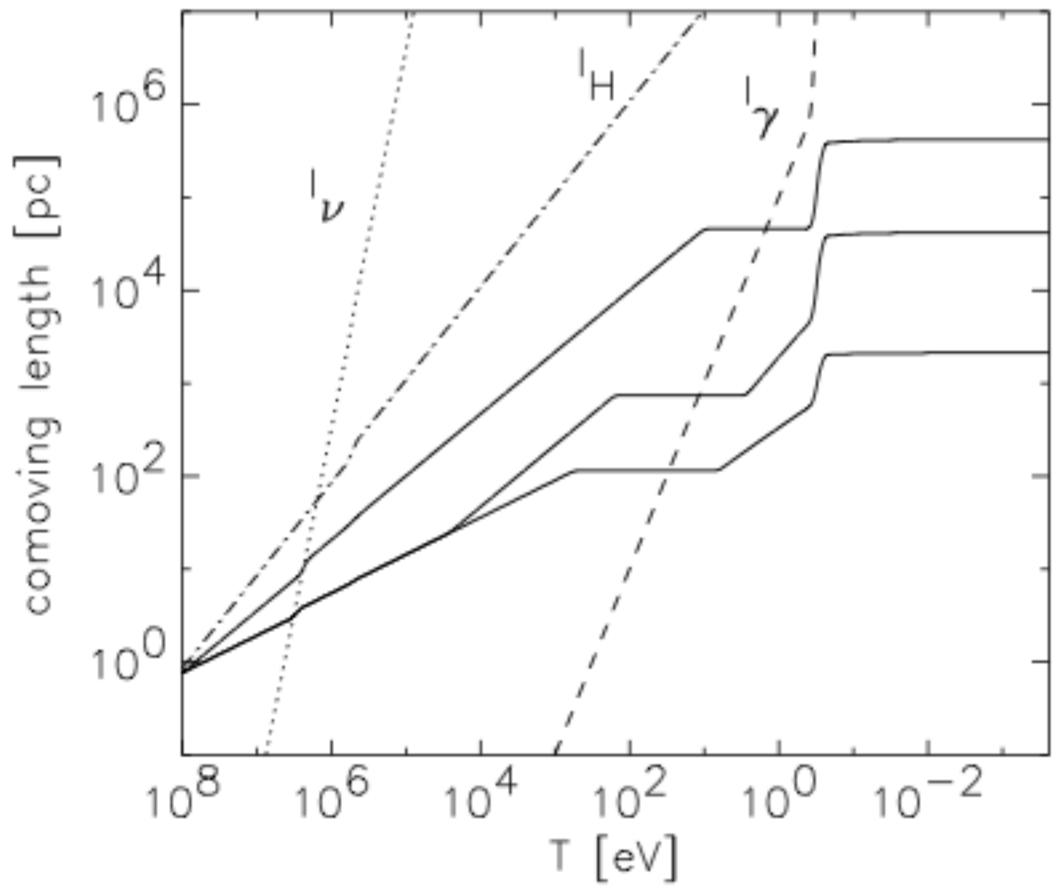
see Banerjee & Jedamzik (2004)

Primordial fields:

Inverse cascade from QCD phase transition



Magnetic energy

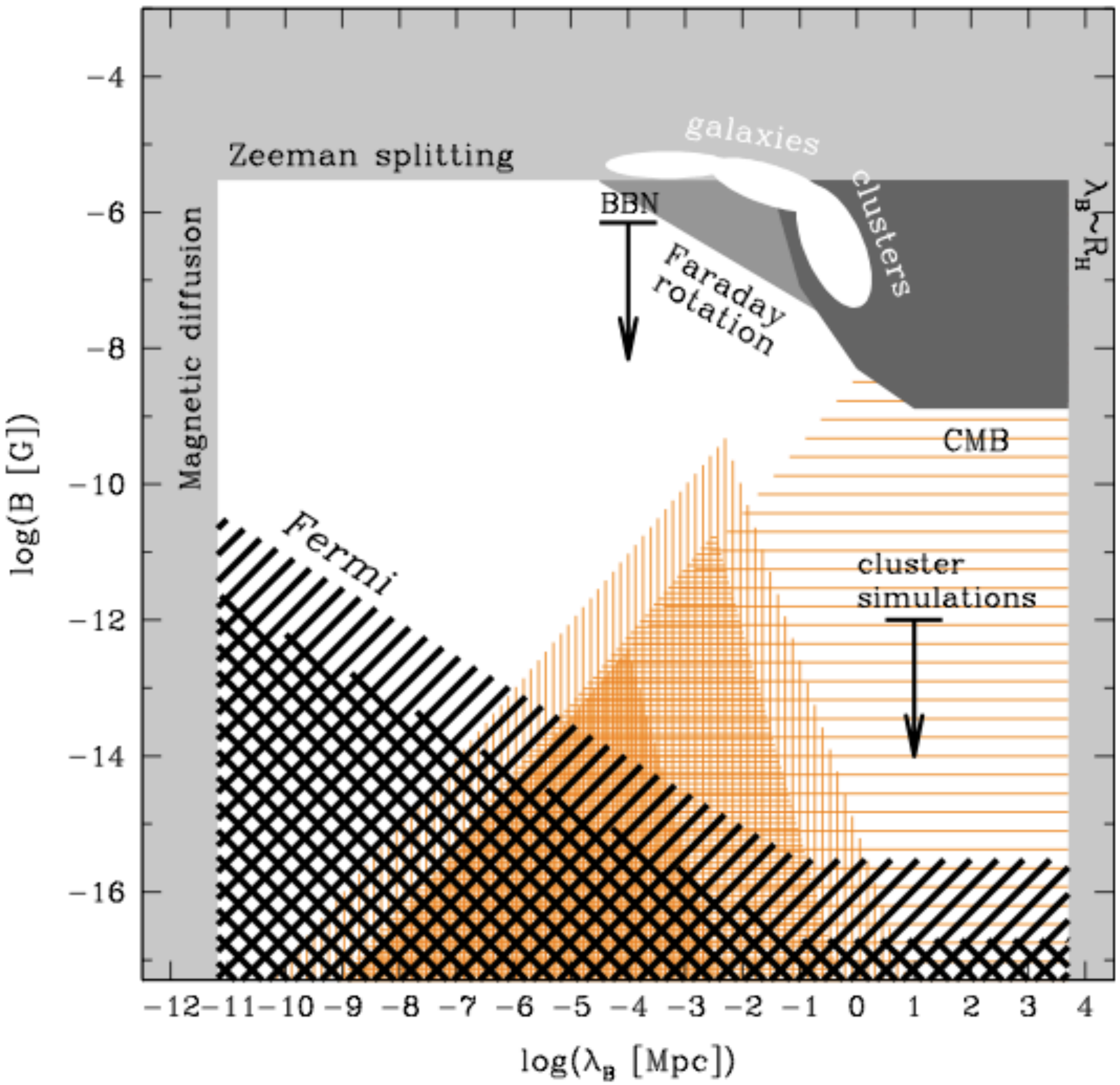


Coherence length

- Co-moving field strength: $B_{co} \sim B_{phys}\ (1+z)^{-2}$.
- Length scales of kpc up to ~Mpc.
- Potentially strong magnetic fields.
- Uncertainty: Initial field strength and helicity.

Primordial fields:

Implications from FERMI?

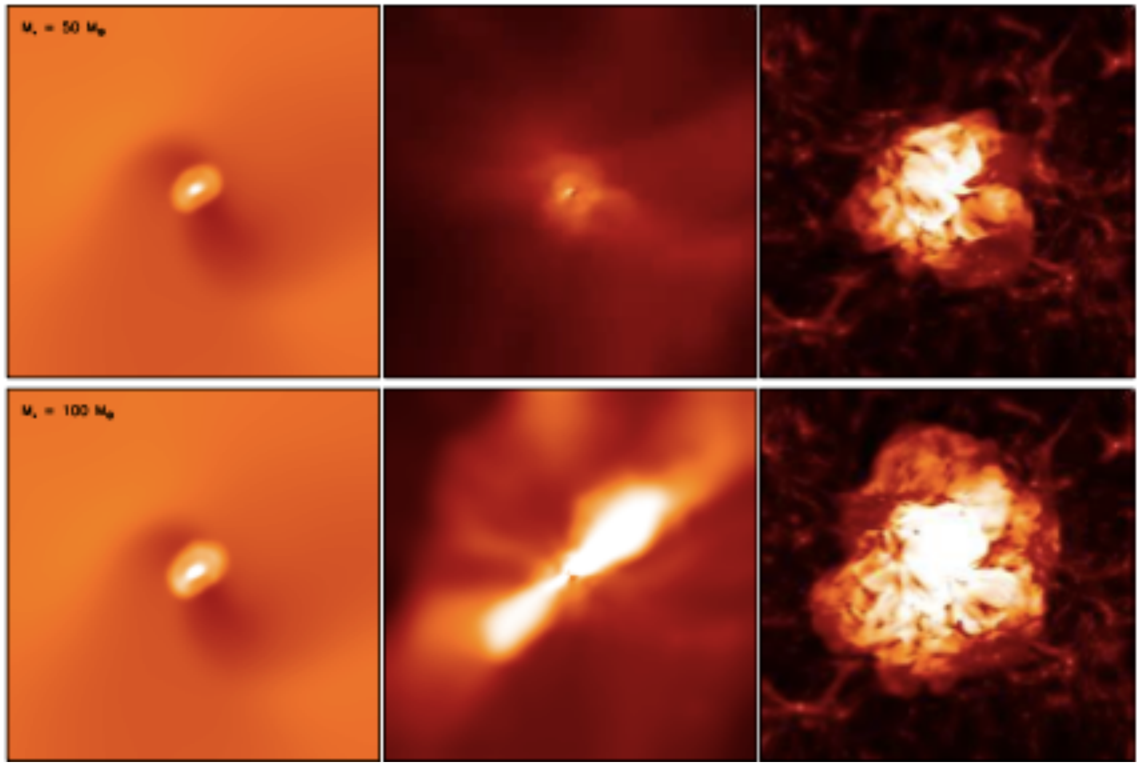


FERMI constraints:
- TeV flux known
- TeV photons interact with EBL, create e^+e^- & subsequent cascade
- Magnetic fields change momentum of e^+e^- and decrease the flux
- Upper limits on GeV data inconsistent with absence of magnetic fields.

Nerenov & Vovk 2010, Science (see also Tavecchio et al. 2010a,b; Dolag et al. 2010)

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:

Quasar absorption spectra

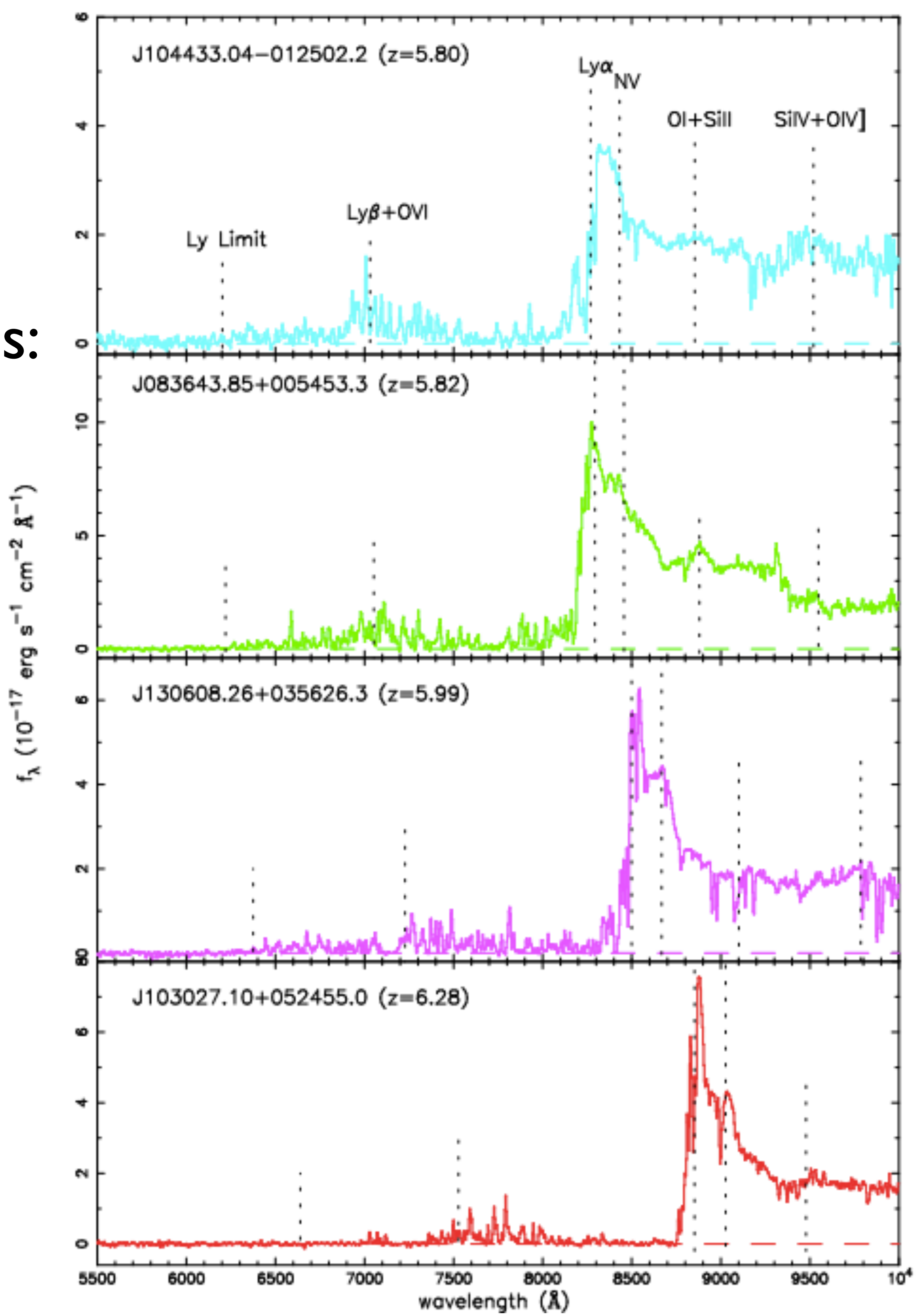
Optical depth for Lyman Alpha photons:

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

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

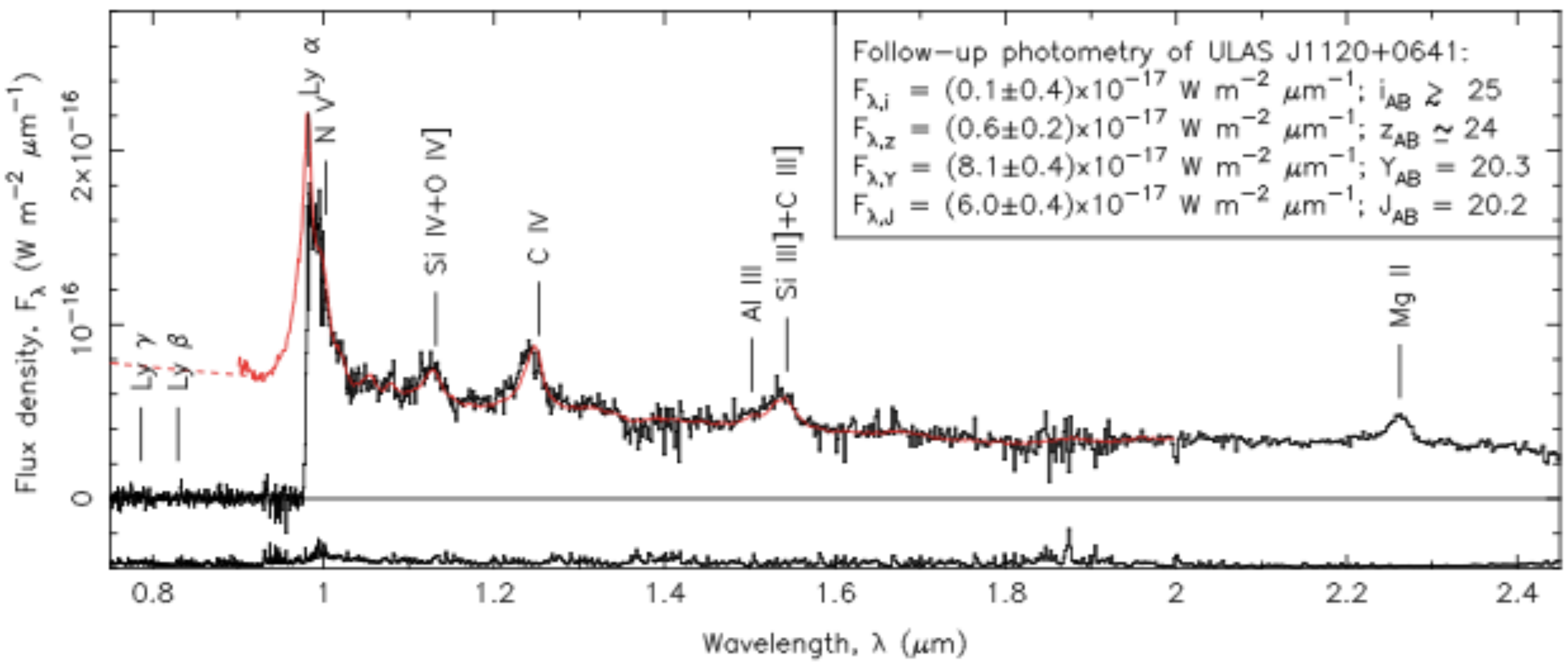
Spectra for z=6.28 quasar consistent with no flux blueward of Lyman Alpha. => End of reionization at z~6.

Becker et al. (2001)

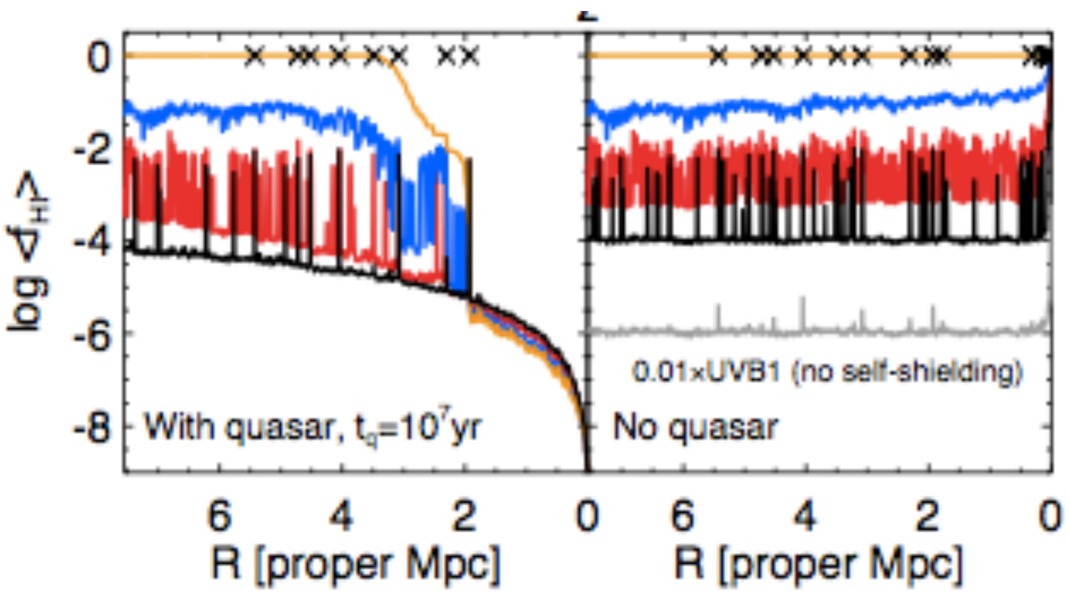


Probing reionization:

A new z~7 quasar.



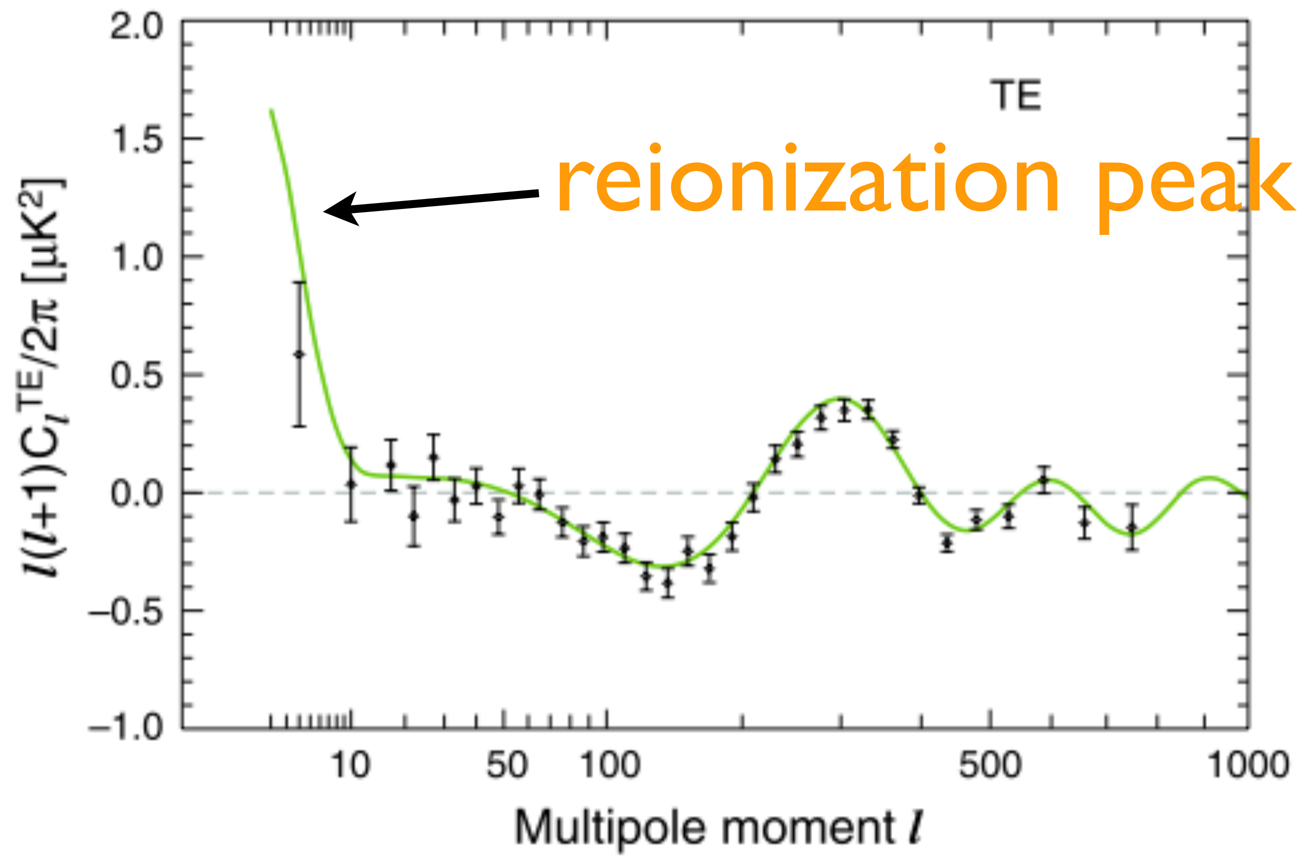
Mortlock et al. (2011): new z=7.085 quasar



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

Probing reionization:

CMB



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

Ionized gas influences CMB via Thompson scattering. Optical depth

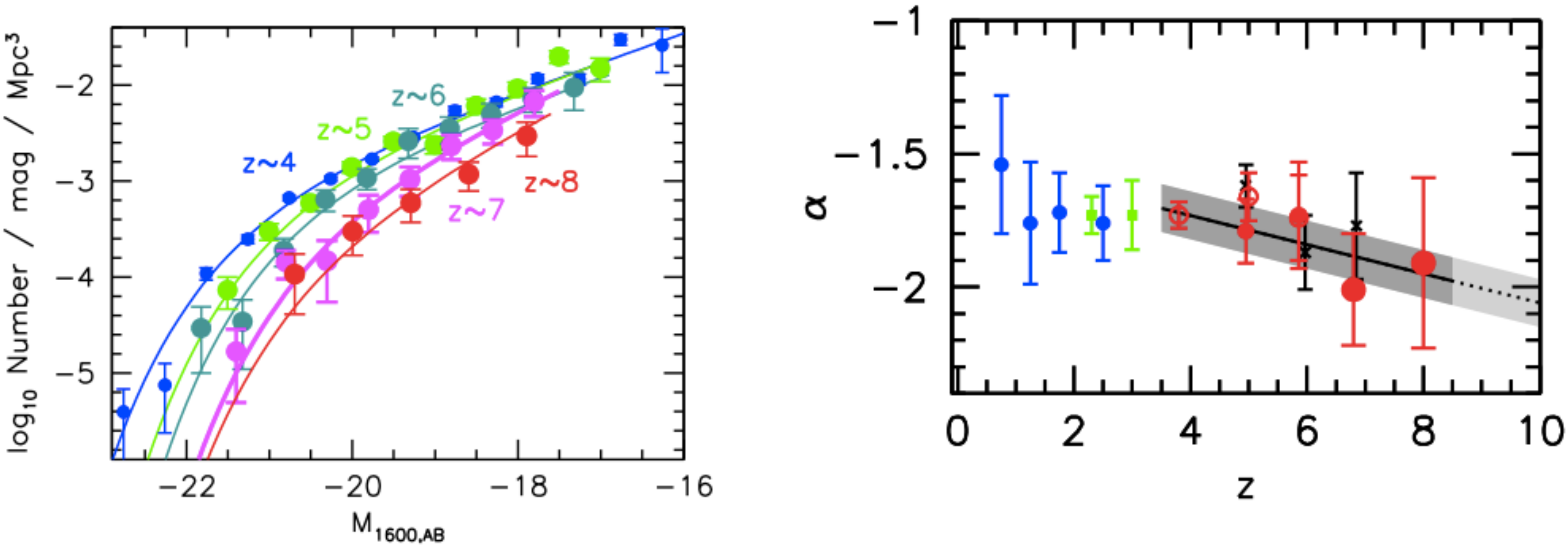
$$\tau = \frac{n_H(0)c}{H_0}\int_{z=0}^{z=z_s} x_{eff}(z)\sigma_T \frac{(1+z)^2}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}}dz,$$

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

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

Probing reionization:

The observed UV luminosity function close to reionization



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

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

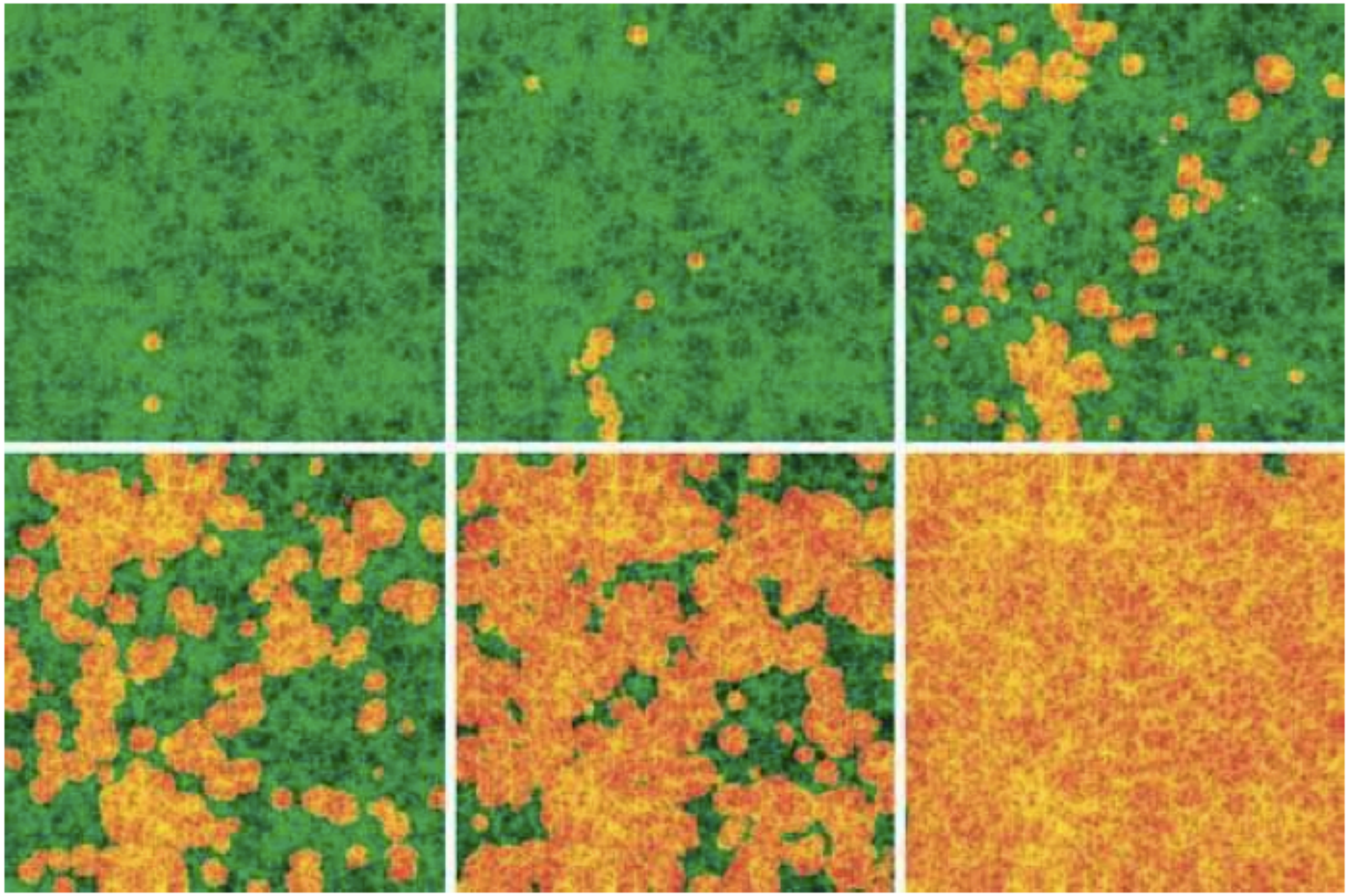
$$M^*_{UV,AB} = (-20.34 \pm 0.11) + (0.28 \pm 0.06)(z-6)$$
$$\phi^* = 10^{-2.90\pm0.09+(-0.04\pm0.05)(z-6)}$$
$$\alpha = (-1.84 \pm 0.05) - (0.05 \pm 0.04)(z-6)$$

Bouwens et al. (2010, 2011)

Reionization:

Simulations

Reionization from the first stars and galaxies: Formation and growth of ionized bubbles, merging of ionized regions.



Iliev et al. (2006): Reionization as an inhomogeneous process (z~18-11).

Building a reionization model:

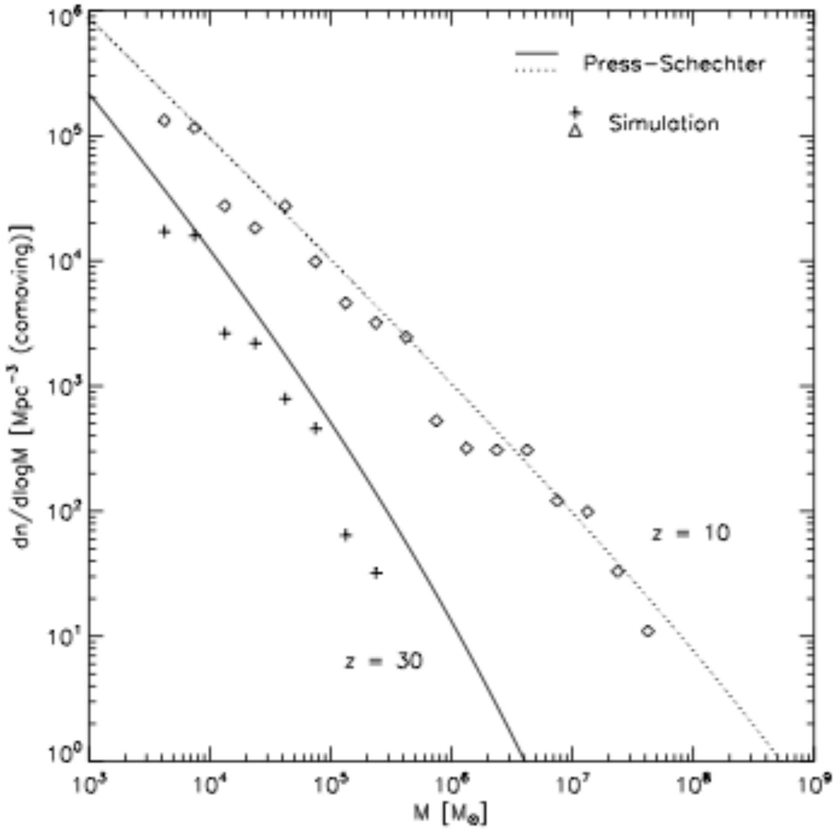
The cosmic star formation rate

Choudhury & Ferrara (2005):

$$\dot{\rho}_{\mathrm{SF}}(z) = \int_z^\infty \mathrm{d}z_c \int_{M_{\min}(z_c)}^\infty \mathrm{d}M\, \dot{M}_{\mathrm{SF}}(M, z, z_c) N(M, z, z_c)$$

star formation rate → $\dot{M}_{\mathrm{SF}}$

halo abundance → N



Greif et al. (2008): Dark matter halos distributed according to Press-Schechter theory.

- Halo abundance can be inferred from Press-Schechter formalism.
- Need to assume star formation efficiency to infer star formation rates.

Building a reionization model:

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.

Building a reionization model:

The production of ionizing photons

- Salpeter IMF: 8% of stellar mass in massive stars (>20 solar)
- End of C-burning phase: 50% converted in helium and carbon
- Mass fraction of 0.7% released as radiation.
- 25% of radiation energy in ionizing photons with mean energy 20 eV.
- For 1 solar mass per year, one thus has 10^{53} photons s^{-1}.

Madau et al. (1998)

Building a reionization model:

The effects of primordial fields

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

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

- **Ambipolar diffusion heating**:
  (Sethi & Subramanian 2005, Pinto, Galli & Bacciotti 2008, Pinto & Galli 2008)

$$L_{\rm AD} = \frac{\eta_{\rm AD}}{4\pi} \left| \left(\nabla \times \vec{B}\right) \times \vec{B}/B \right|^2$$

- **Magnetic Jeans mass**:
  (Subramanian & Barrow 1998)

$$M_J^B \sim 10^{10} M_\odot \left(\frac{B_0}{3~{\rm nG}}\right)^3$$

- **Additional small-scale structure?**
  (Kim et al. 1998)

Ambipolar diffusion

- Ions are coupled to the magnetic field.
- Neutrals are indirectly coupled to the magnetic field by collisions with the ions.
- The coupling is not perfect: Sometimes they diffuse through the field lines
- Magnetic energy can be dissipated by friction between ions and neutrals.

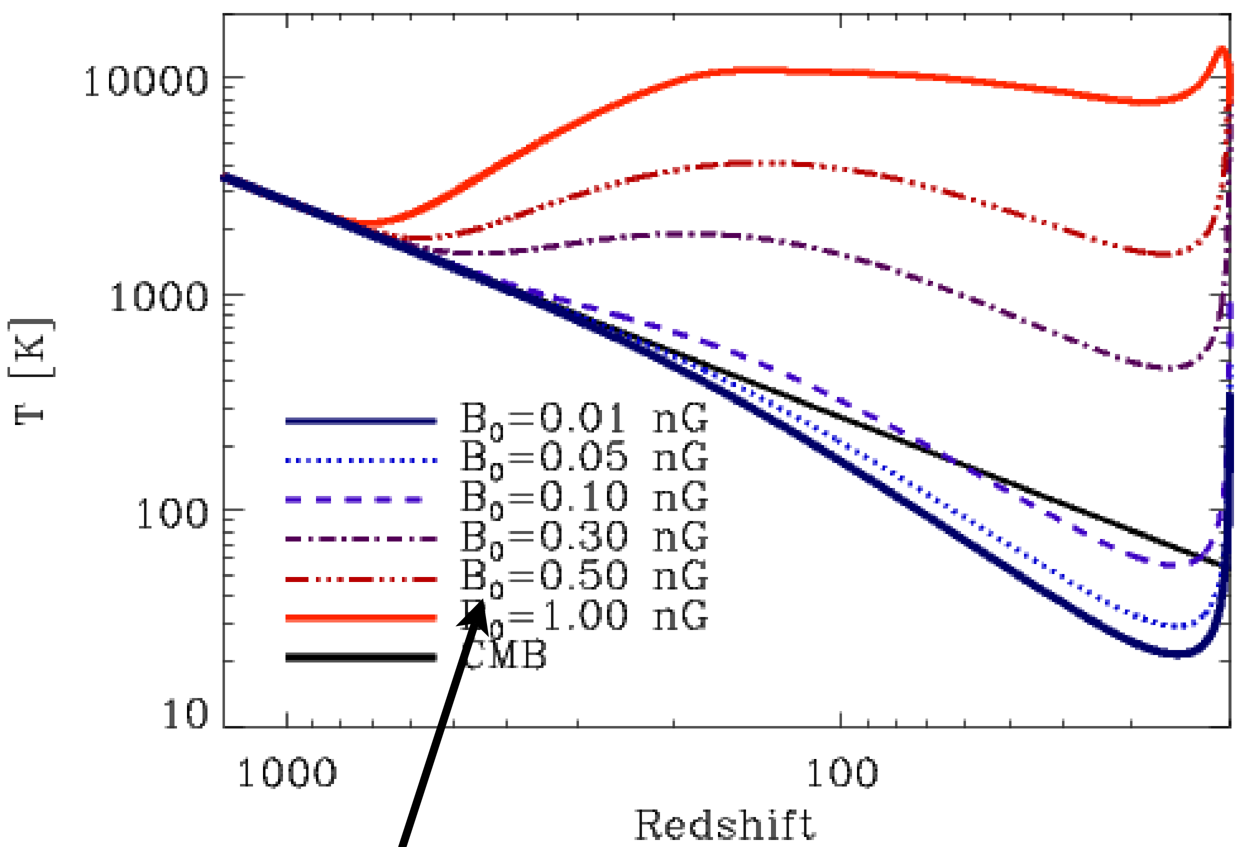
$$L_{\mathrm{ambi}} = \frac{\rho_n}{16\pi^2 \gamma \rho_b^2 \rho_i} \left| \left(\nabla \times \vec{B} \right) \times \vec{B} \right|^2$$

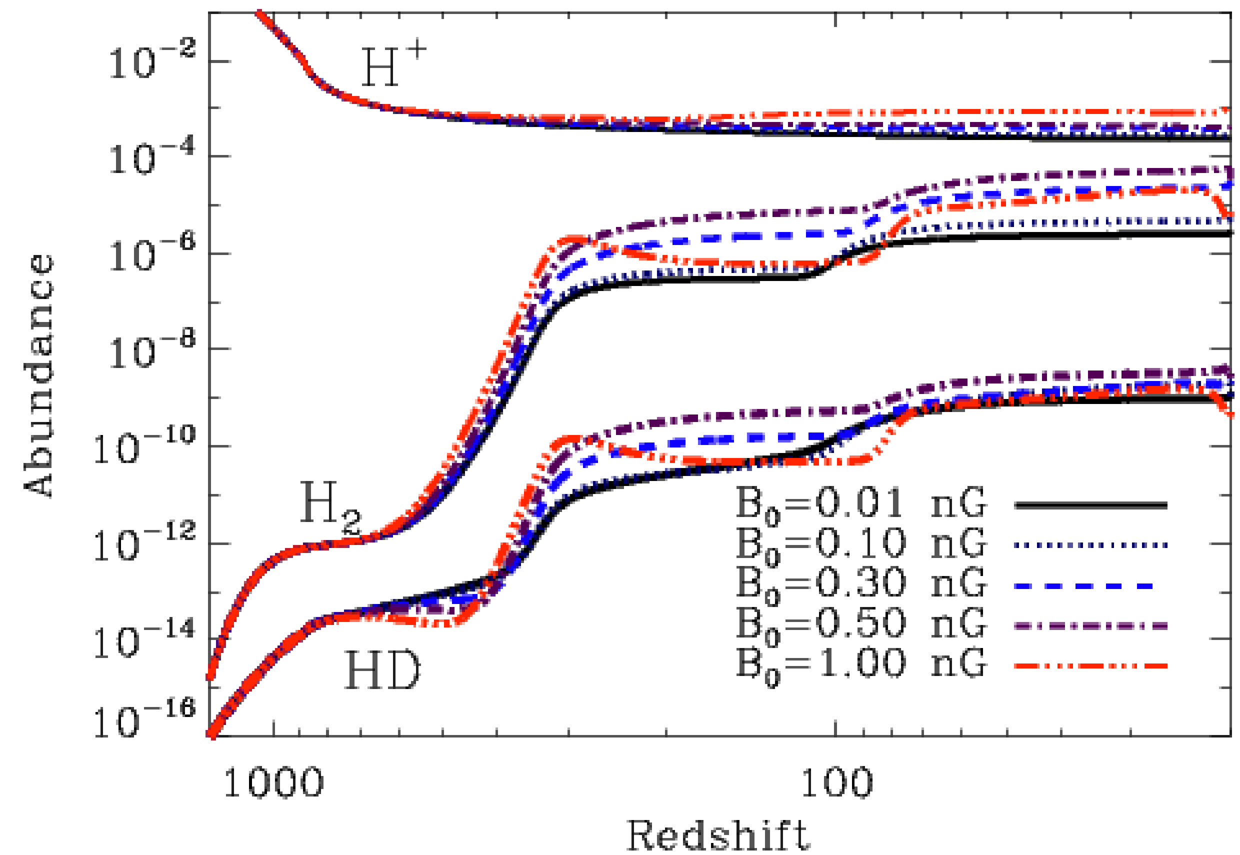
Schleicher, Banerjee & Klessen (2008)

$$\gamma = \frac{\frac{1}{2} n_H \langle \sigma v \rangle_{\mathrm{H^+,H}} + \frac{4}{5} n_{\mathrm{He}} \langle \sigma v \rangle_{\mathrm{H^+,He}}}{m_H \left[n_{\mathrm{H}} + 4 n_{\mathrm{He}} \right]}$$

Ambipolar diffusion:

Implications in the large-scale IGM





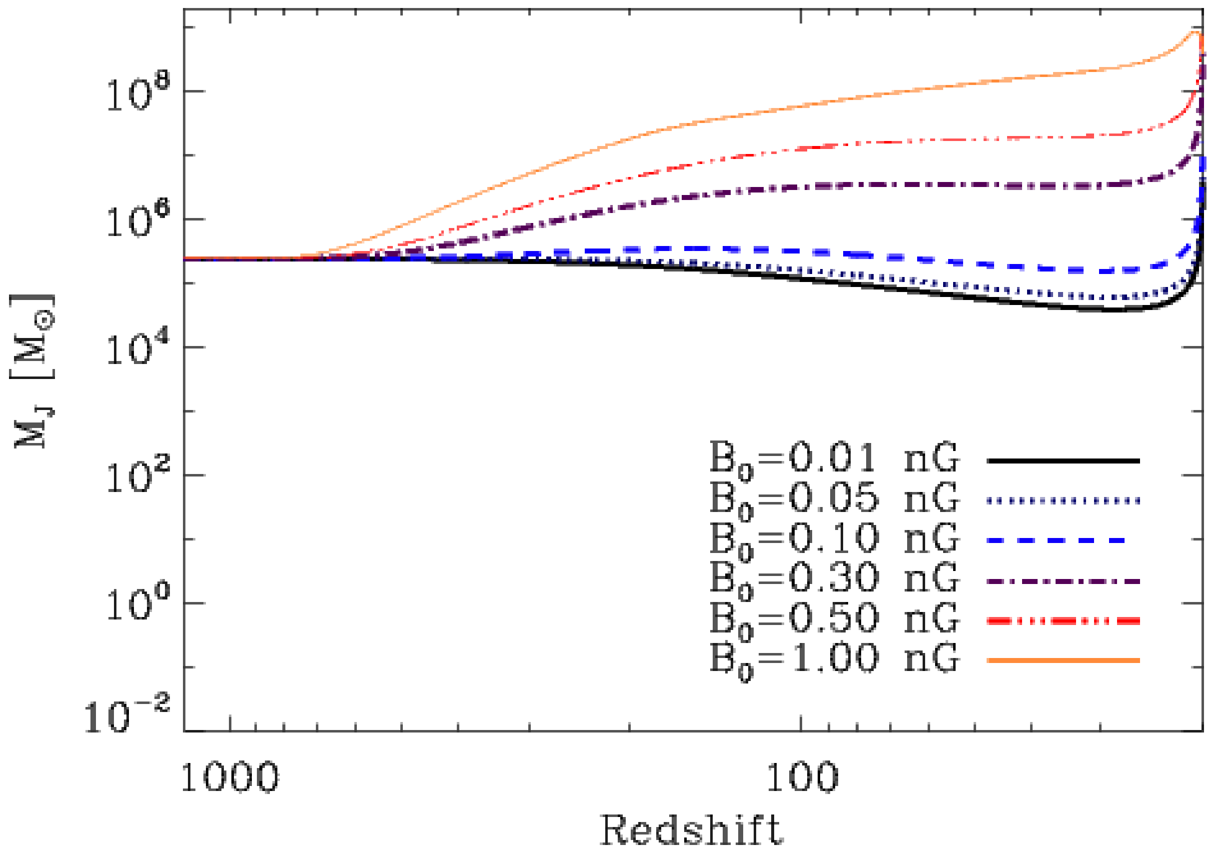
Primordial magnetic fields increase gas temperature and abundance of the main coolants

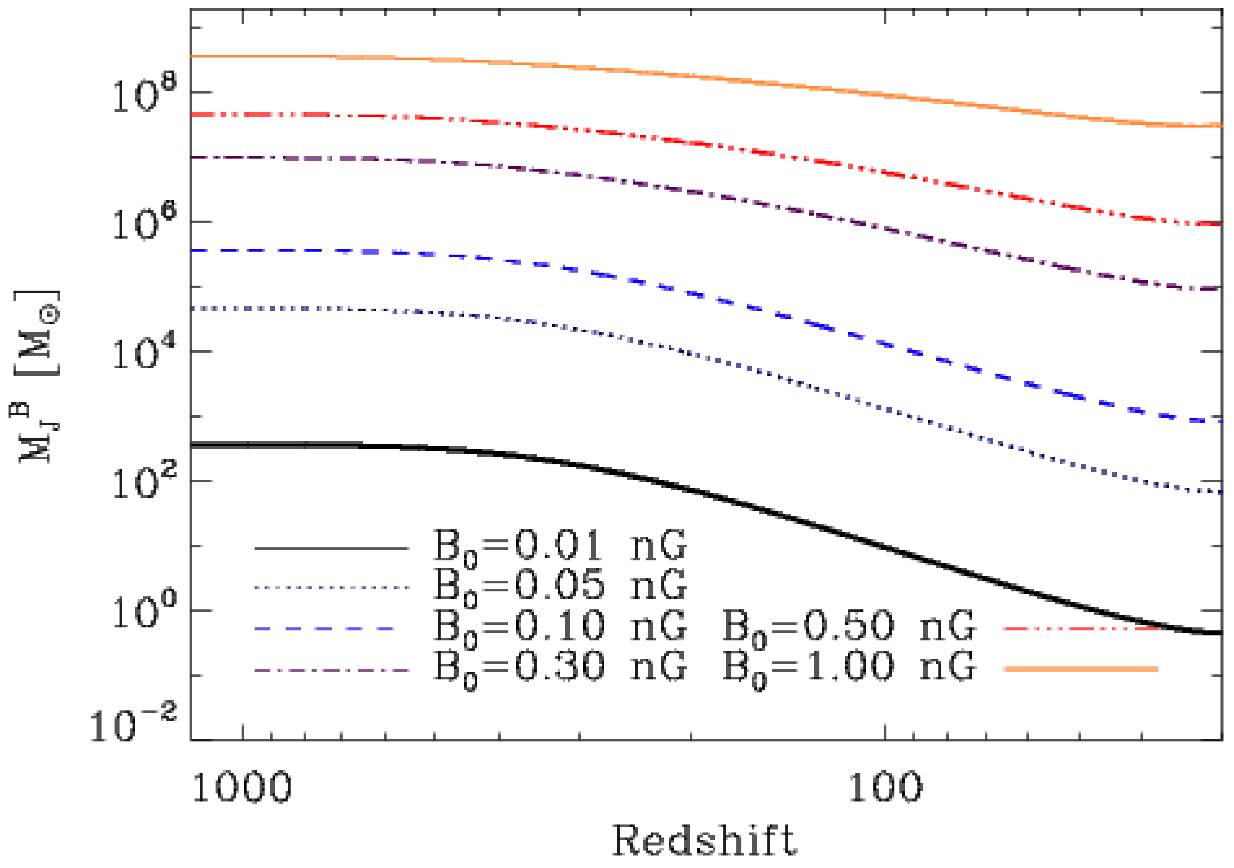
Co-moving field strength: $B_{phys} \sim B_{co} (1+z)^2$.

Schleicher et al. (2009)

Building a reionization model:

The effects of primordial fields





Thermal / magnetic Jeans masses: Critical mass scale for gravity to overcome thermal / magnetic pressure.
Both are significantly increased in the presence of strong magnetic fields.

Schleicher et al. (2009)

Building a reionization model:

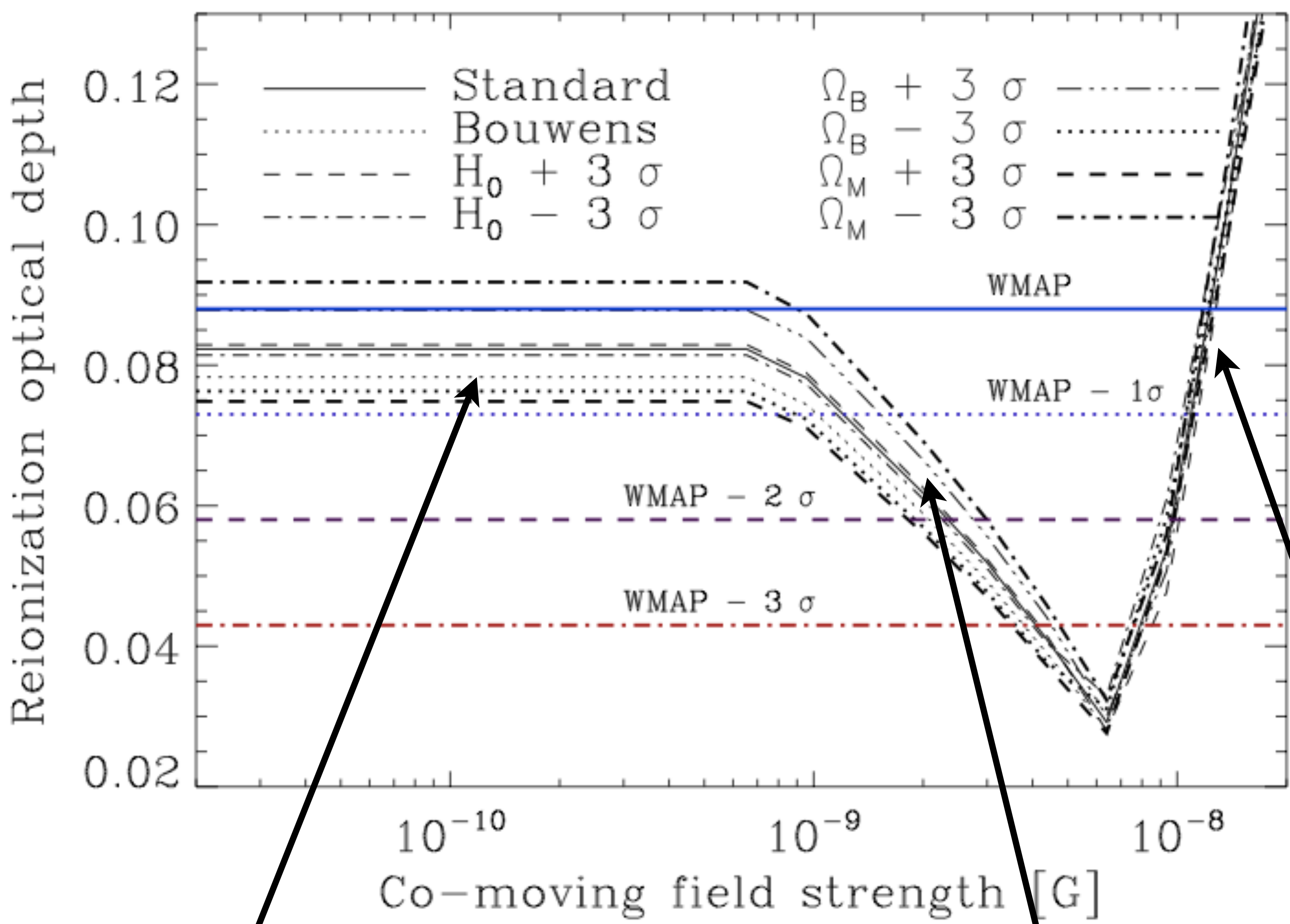
Implications of strong magnetic fields

- 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.
- Follow thermodynamics & chemistry in non-ionized gas.
- Calculate reionization optical depth.

Schleicher, Banerjee & Klessen (2008)

Reionization:

Improved constraints & cosmological uncertainties



Collisional ionization due to heat input via ambipolar diffusion

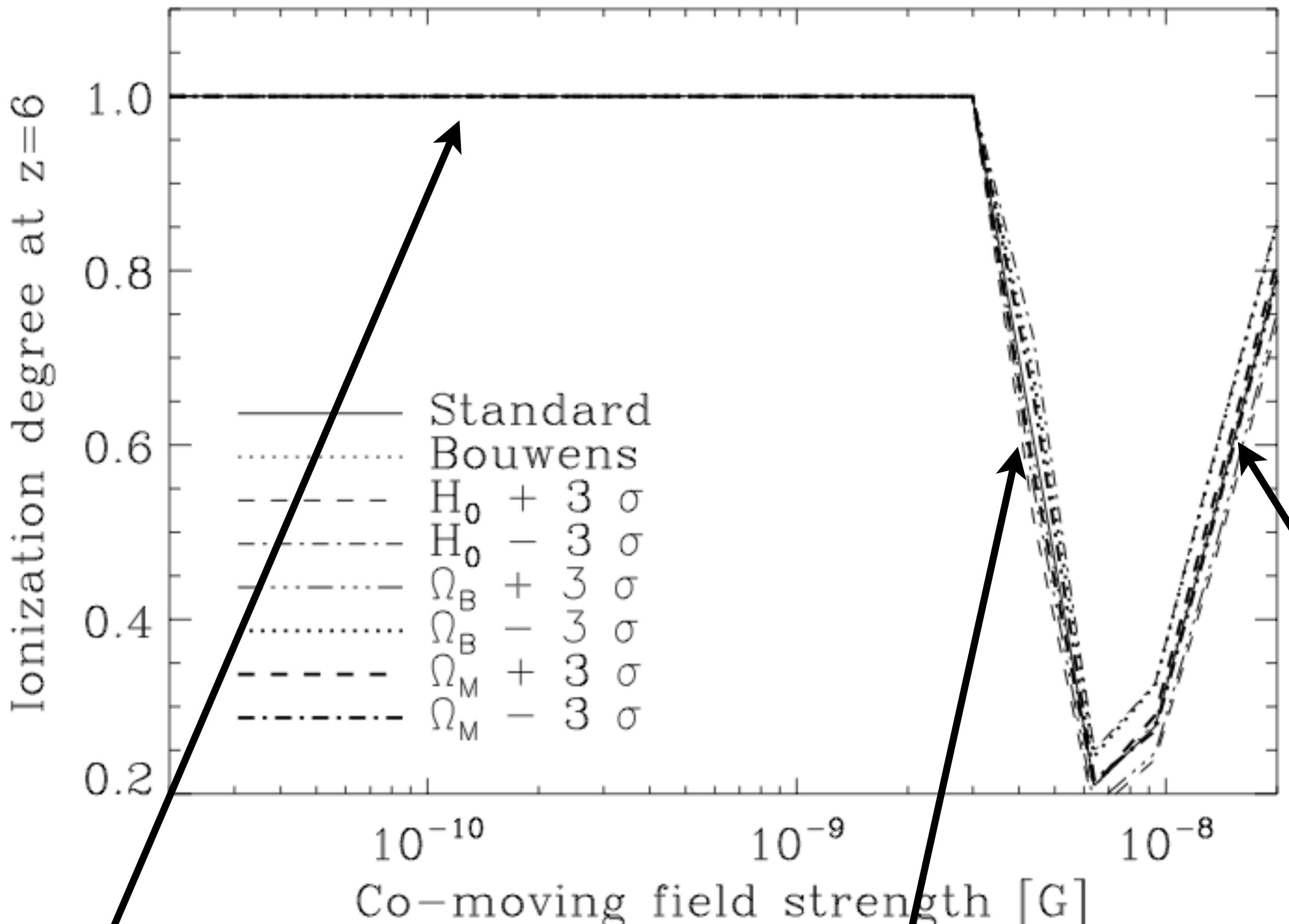
Constant low-luminosity cutoff, M_{UV}=-10

Increased cutoff (magnetic fields)

Schleicher & Miniati, in prep.

Reionization:

Improved constraints & cosmological uncertainties



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

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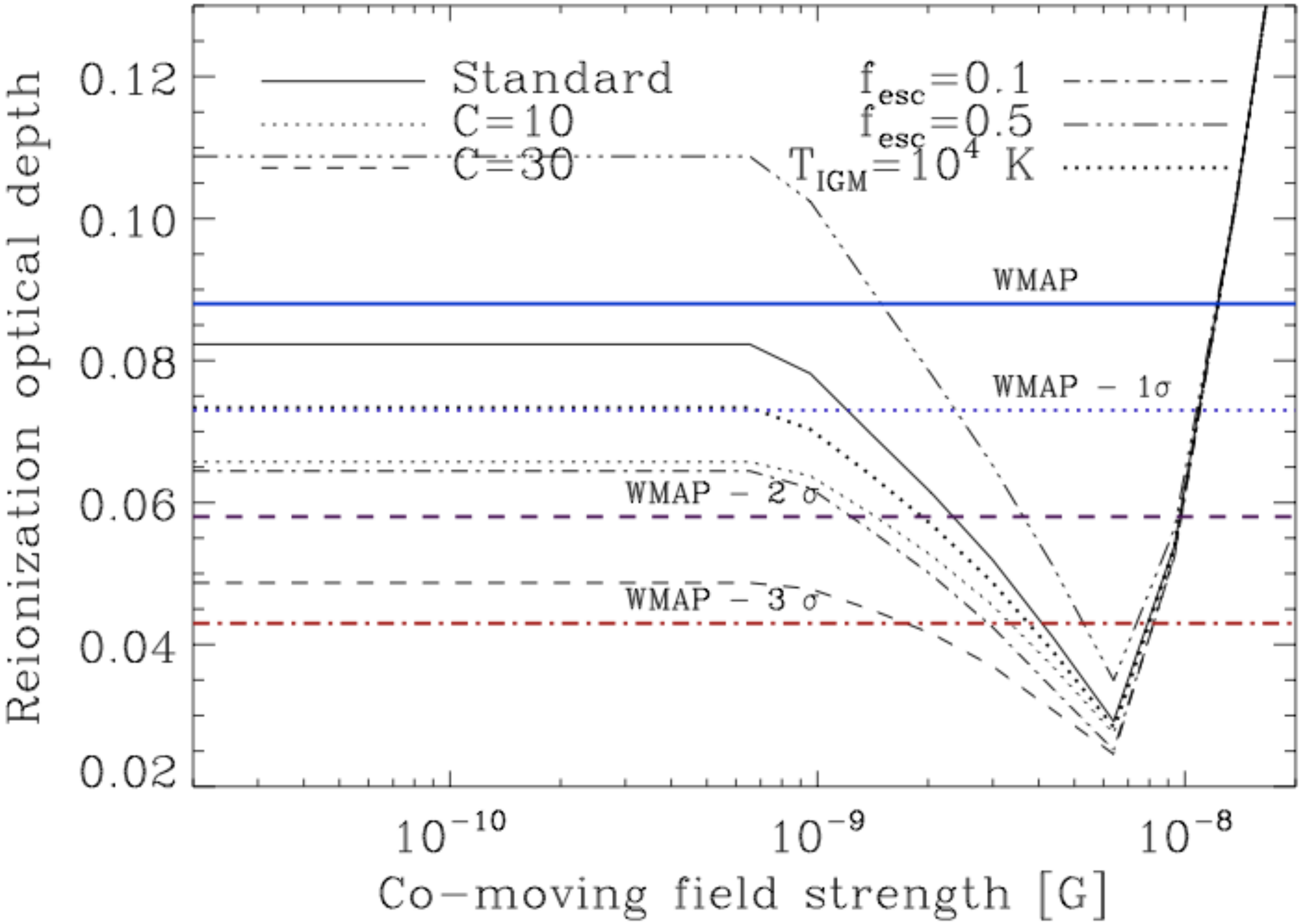
Collisional ionization due to heat input via ambipolar diffusion.

Schleicher & Miniati, in prep.

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, in prep.

Reionization:

Constraints from 21 cm observations: EDGES

Experiment to Detect the Global Epoch of Reionization Signatures

- very simple, low cost 21 cm experiment
- highly complementary to LOFAR / SKA
- high-dynamic-range, standalone radio spectrometer and compact broadband antenna
- measures global 21 cm signal
- second-generation instrument will covers redshifts 6 to 30

Reionization:

Constraints from 21 cm observations: EDGES

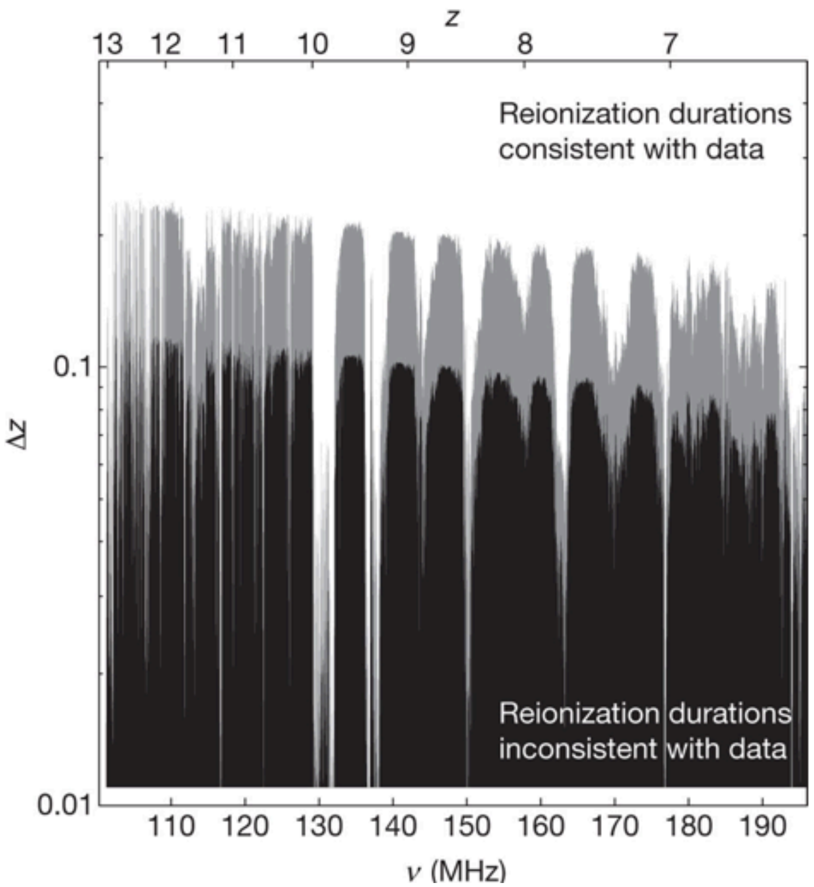
Global 21 cm signal reflects thermal history:

$$\delta T_{21}(\theta, z) \approx 27\,(1+\delta)\,x_{\mathrm{H\,I}}\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\ \mathrm{mK}$$

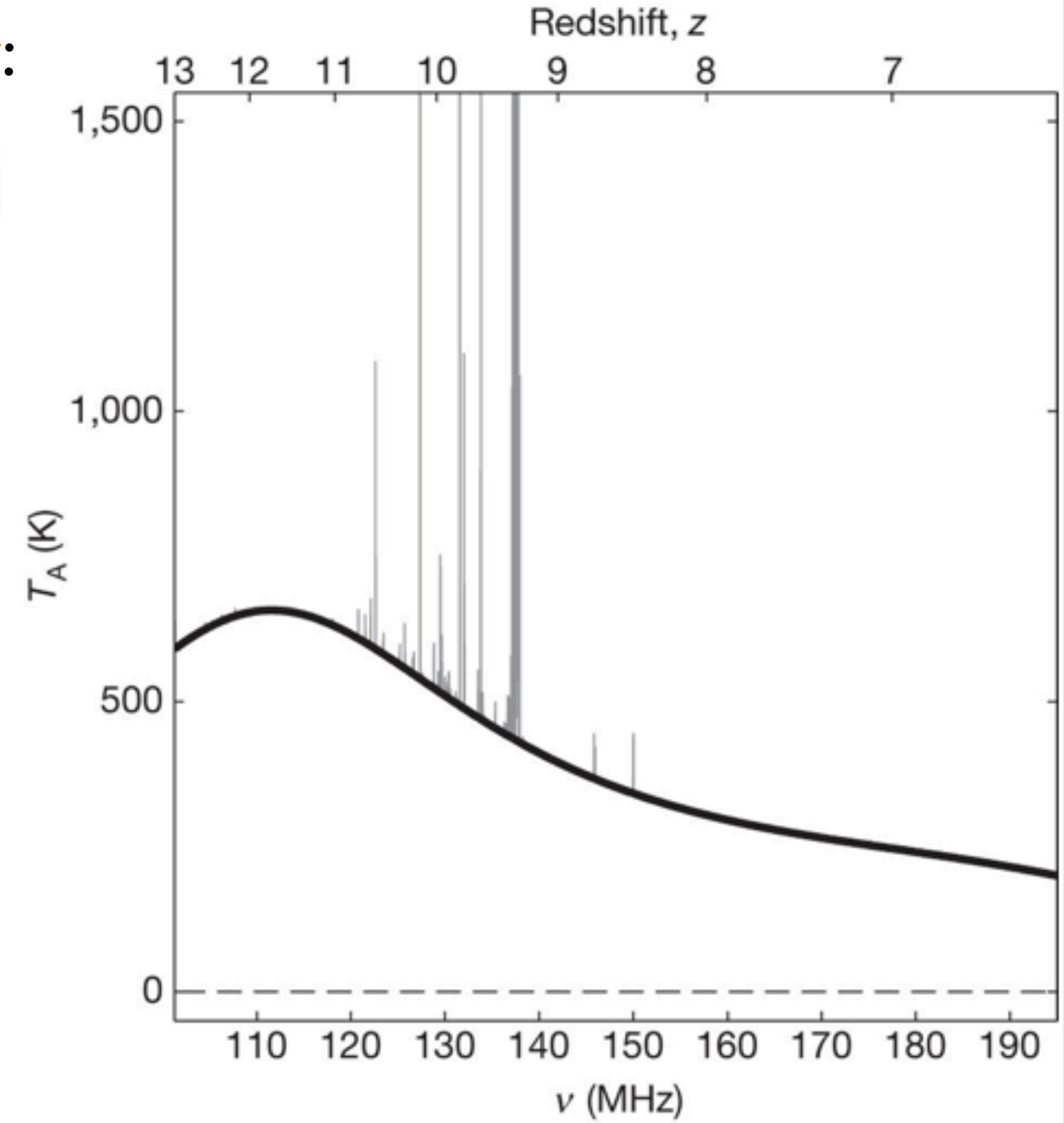
T_S : Spin temperature of hyperfinestructure lines

T_γ : CMB temperature

δ : Local overdensity



Left:
Lower bound on the duration of reionization



measured spectrum:
7<z<13

Bowman & Rogers 2011, Nature

Reionization: LOFAR

- LOFAR: Low-Frequency Array for radio astronomy
- 20000 small antennas, 48 stations all over Europe
- Effective collecting area 1 km^2

LOFAR at Exloo (Netherlands)

- Probing reionization from z=11.4 (115 MHz) to z=6 (200 MHz)
- Focus on spatial structure and 21 cm power spectrum
- Probing the sources of reionization.

Summary and conclusions

- IGM magnetic fields of at least 10^{-15} G indicated by FERMI (lower limit).
- The inverse cascade potentially important for primordial fields.
- Reionization constraints from reionization optical depth and quasar absorption spectra.
- UV luminosity functions observed out to z~8.
- Upper limit of 4-5 nG from reionization constraints.

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