Primordial magnetic fields: Cosmological implications

based on *Sethi and Subramanian, JCAP, 2009*
Sethi, Haiman, and Pandey, ApJ, 2010
Pandey and Sethi, ApJ, 2011
Pandey and Sethi, ApJ, 2012

March 12, 2013

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1. Primordial magnetic fields: Motivation

- Scalar and tensor perturbation were generated at the time of inflation. Is it not conceivable that a process existed then (breaking of conformal invariance?) that led to the generation of magnetic fields? (Turner and Widrow 1988, Ratra 1992)

- Magnetic field coherent at scales $\gtrsim 10\,\mathrm{kpc}$ exist in galaxies and clusters of galaxies. Can they be explained using amplification of a small seed magnetic field $\lesssim 10^{-20}\,\mathrm{G}$ using dynamo mechanism? Not clear. Evidence of μG magnetic field at $z \simeq 2$ and synchrotron emission at super-cluster scales favour primordial field hypothesis.

- Magnetic fields of strength $\simeq 10^{-9}\,\mathrm{G}$ interesting from the point of view of observed fields in galaxies, clusters of galaxies and cosmology.

2. Direct probe of magnetic field at large scales

- Detection of synchrotron radiation from structures larger than clusters (e.g Kim et al. 1989). Difficult as the gas density falls and diffuse low-surface brightness emission is difficult to image with radio interferometers.
- `Correlation of Faraday rotation of high redshift radio sources`: Such correlation can reveal the presence of magnetic field coherent on very large scales ($> 100\,\mathrm{Mpc}$) (e.g. Kollat 1998, Sethi 2003). Not possible so far owing to lack of homogeneous samples of Faraday rotation measurement. Upcoming interferometers such as LOFAR will create such a sample with 10^5 sources. This is one of the primary goals of SKA, which will be able to reliably observe 10^7 Faraday rotations.

3. Tangled Magnetic fields

- Statistically homogeneous and isotropic tangled magnetic fields:

$$\langle \tilde{B}_i(\mathbf{q}) \tilde{B}_j^*(\mathbf{k}) \rangle = \delta_D^3(\mathbf{q}-\mathbf{k}) \left(\delta_{ij} - k_i k_j / k^2\right) M(k) \quad (1)$$

- The magnetic fields are further assumed to be Gaussian and therefore their statistical properties are completely described by power spectrum: $M(k)$ with

$$M(k) = A k^n \quad (2)$$

  with the spectral index of power spectrum $n \gtrsim -3$.

- *Time evolution*: In an expanding universe: $Ba^2 = \text{const}$, flux-frozen: $B\rho^{-2/3} = \text{const}$

- *Normalization*: Normalized to the present, B_0 refers to RMS using the cut-off scale $k_c = 1\,\mathrm{Mpc}^{-1}$.

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HI signal: ΛCDM

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4. Early structure formation with tangled magnetic fields

- Magnetic fields generate density perturbations in the post-recombination era (Wasserman 1978).
- For nearly scale-invariant power spectrum of magnetic fields, the matter power spectrum $P(k) \propto k$. At scales corresponding to $k \lesssim 1\,\mathrm{Mpc}^{-1}$ this could dominate over the inflation-era produced density perturbations.
- **Important scales**: Comoving

$$\begin{aligned} k_{\mathrm{max}} &\simeq 235\,\mathrm{Mpc}^{-1}\left(\frac{10^{-9}\,\mathrm{G}}{B_0}\right) \\ k_{\mathrm{J}} &\simeq 15\,\mathrm{Mpc}^{-1}\left(\frac{10^{-9}\,\mathrm{G}}{B_0}\right) \end{aligned} \qquad (3)$$

  k_{J} is independent of time.

- Magnetic fields can aid early structure formation. How early and at what scales?

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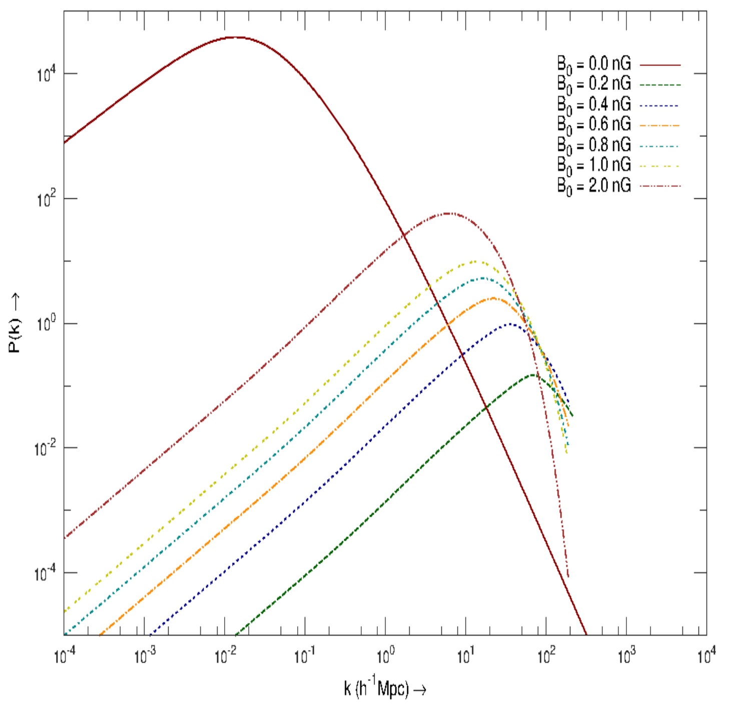
5. Matter power spectrum



(Gopal and Sethi 2003)

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6. Post-recombination effects of magnetic fields

- *Early structure formation*: The redshift of collapse depends strongly on the spectral index of magnetic field power spectrum. All models other than nearly scales invariant $n \simeq -3$ are ruled out by these considerations. The collapse redshift is not sensitive to the value of the magnetic field.

- *Dissipation of magnetic fields*: Tangled magnetic fields can dissipate by ambi-polar diffusion and decaying turbulence in the post-recombination era. This can lead to an altered ionization and thermal history (Sethi and Subramanian 2005).

- *Molecular Hydrogen formation*: Can be significantly altered in the IGM and in the collapsing haloes (Sethi, Nath, and Subramanian 2008, Schicheler et al. 2009, Sethi, Haiman, Pandey 2010)

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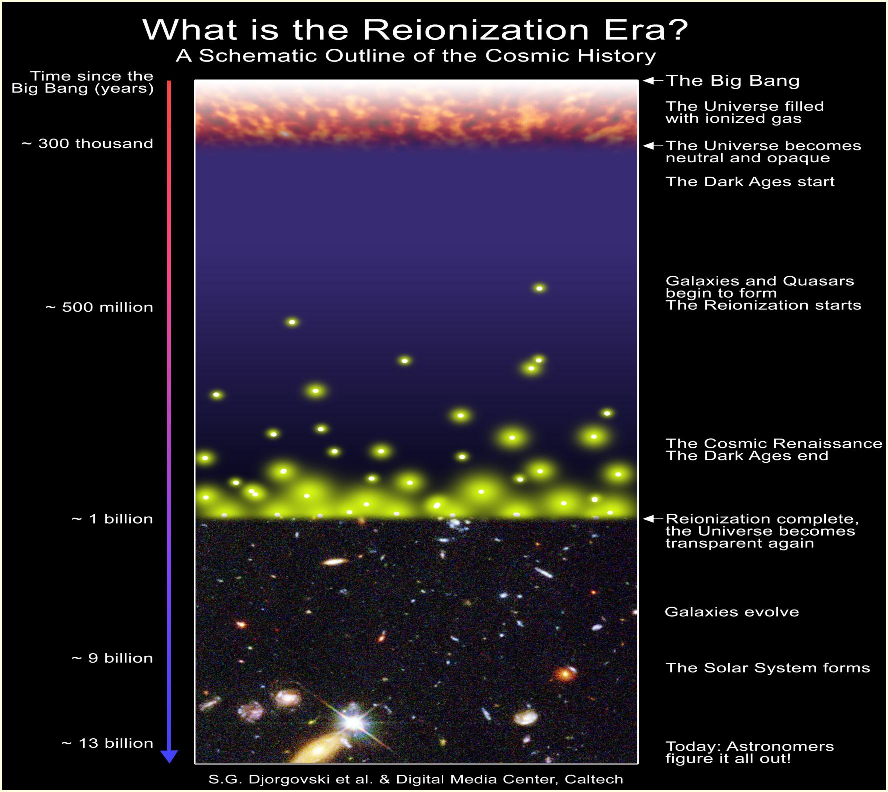
7. The post-Recombination Era



S.G. Djorgovski et al. & Digital Media Center, Caltech

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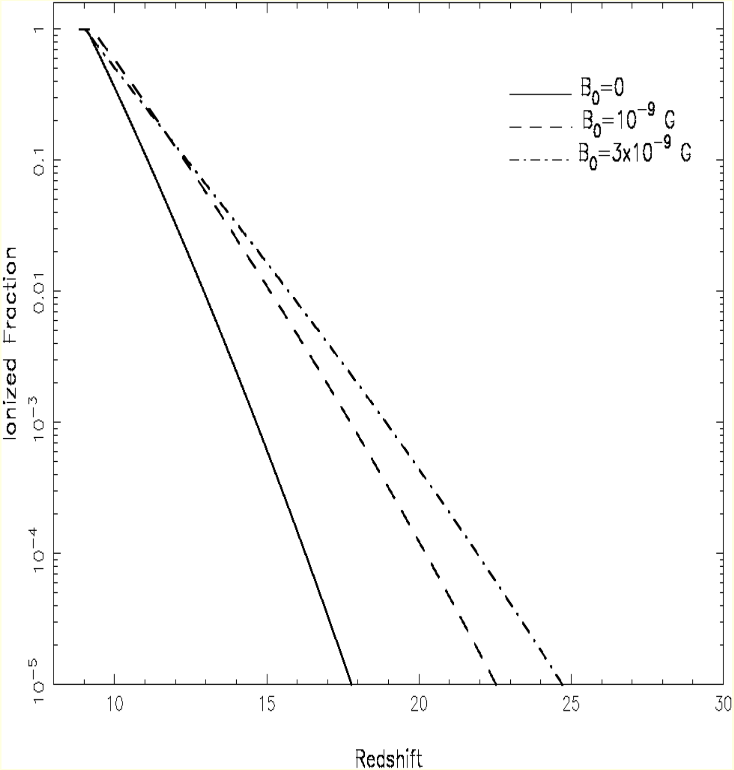
8. Primordial magnetic fields and reionization: semi-analytic models

- Press-Schechter formalism to determine the mass function. Most haloes are close to 1–σ in this case as opposed to the usual case.
- Choose halo UV luminosity, clumping factor, to solve for the radius of evolving Stromgren sphere around each source.
- Compute the evolution of ionized fraction.
- Normalize to WMAP results.
- **magnetic field v/s the usual case**: $f_{\rm eff} f_{\rm esc} \simeq 0.01$ in the usual case. It could be two orders of magnitude smaller for $B_0 \simeq 3 \times 10^{-9}\,$G.

9. Ionization History



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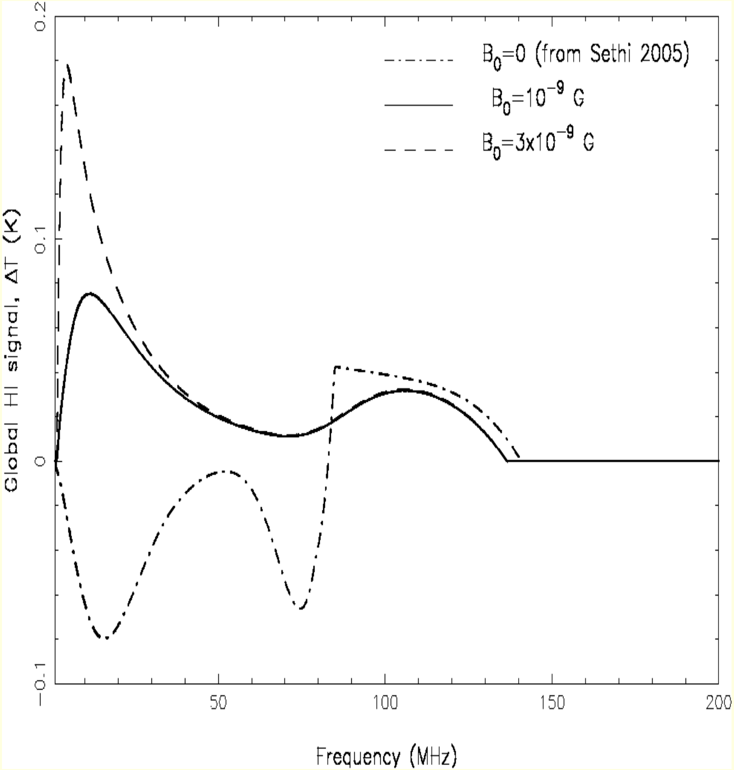
10. Global HI signal



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11. Fluctuating component of HI signal

- **Two point correlation function**:

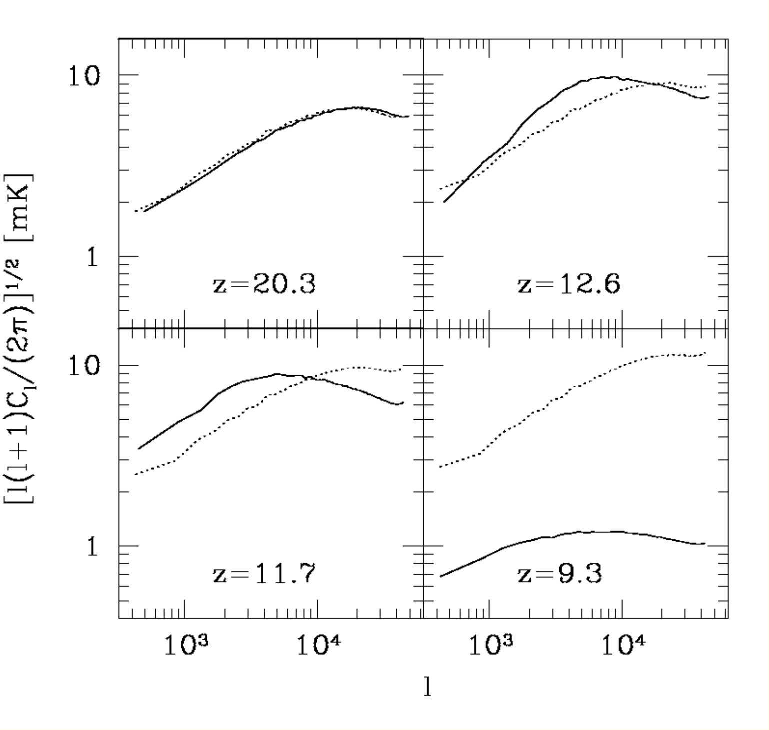
$$C(r_{12},\theta) = T_0^2\left(\xi_{xx}\xi_{\delta\delta}(r_{12},\theta,z) + \xi_{xx} - \bar{x}_{\mathrm{H}}^2\right) \qquad (4)$$

  T_0 is the global HI signal. $\xi_{\delta\delta}(r_{12},\theta,z)$ is the HI density correlation function, which is the same as density correlation function (Bias $b = 1$ assumed throughout).

- $\xi_{xx} = \langle x_{\mathrm{H}}(\mathbf{r_1})x_{\mathrm{H}}(\mathbf{r_2})\rangle$ is computed by assuming the HII regions to be non-overlapping spheres of different sizes.

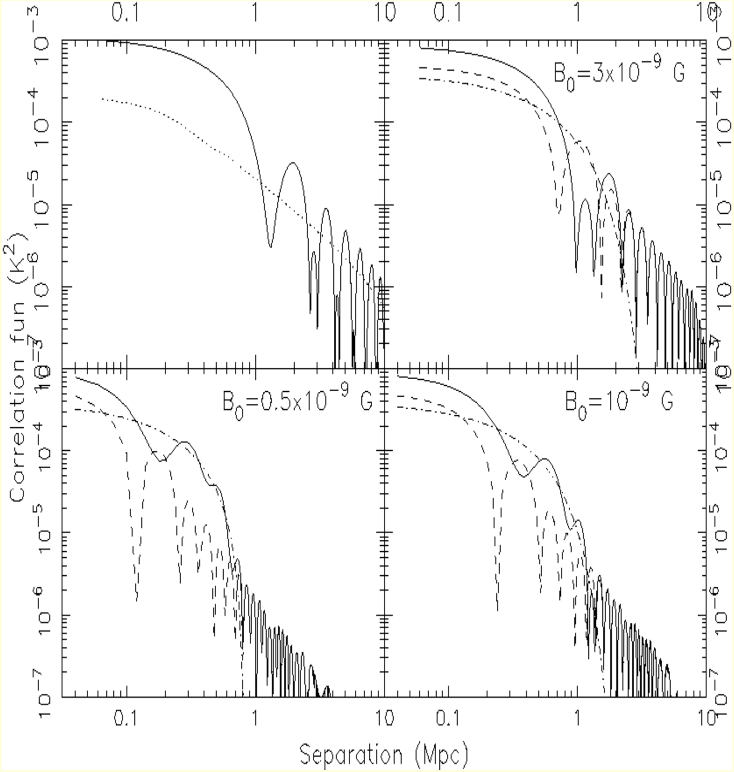
- **Distribution of bubble sizes**: (a) the centers of bubbles are uncorrelated and (b) the centers of bubbles are correlated according to the large scale density field.

12. HI signal: ΛCDM



(Mellema et al 2006)

13. Fluctuating component of HI signal



14. Detectability of the signal

- Upcoming radio interferometers, MWA, LOFAR, have angular resolution $\simeq 2$–$4'$ (4–8 Mpc). It is too coarse to detect the primordial B induced HI signal.
- *Indirect detection*: If magnetic fields played an important role in ionizing the universe, then at the scales probed by MWA, LOFAR, only HI density perturbation will be observed. It would indicate a source of reionization more homogeneous than predicted by ΛCDM model.
- Future radio interferometer has the sensitivity and the resolution to detect this signal. (SKA might also directly detect primordial fields by Faraday rotation studies of 10^7 radio sources).

15. Magnetic fields and molecular Hydrogen formation

- The H^- channel dominates the H_2 formation:

$$\begin{aligned} \mathrm{H} + \mathrm{e} &= \mathrm{H}^- + \gamma \\ \mathrm{H}^- + \mathrm{H} &= \mathrm{H}_2 + \mathrm{e} \qquad (5) \end{aligned}$$

- `Important destruction mechanisms`:

$$\mathrm{H}^- + \mathrm{H} = 2\mathrm{H} + \mathrm{e} \qquad (6)$$

$$\mathrm{H}_2 + \mathrm{e} = 2\mathrm{H} + \mathrm{e} \qquad (7)$$

$$\mathrm{H}_2 + \mathrm{e} = \mathrm{H} + \mathrm{H}^- \qquad (8)$$

$$\mathrm{H}_2 + \mathrm{H} = 3\mathrm{H} \qquad (9)$$

Destruction rates increase with temperature; rate (8) also depends on density and increases with density.

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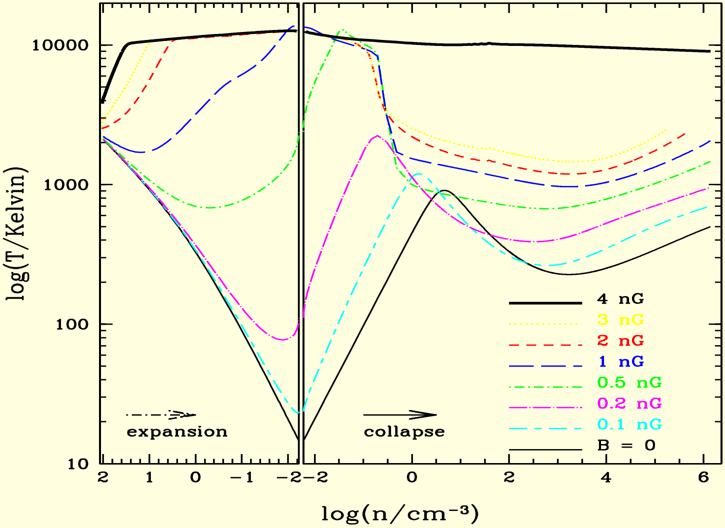
16. Thermal evolution: collapsing halo



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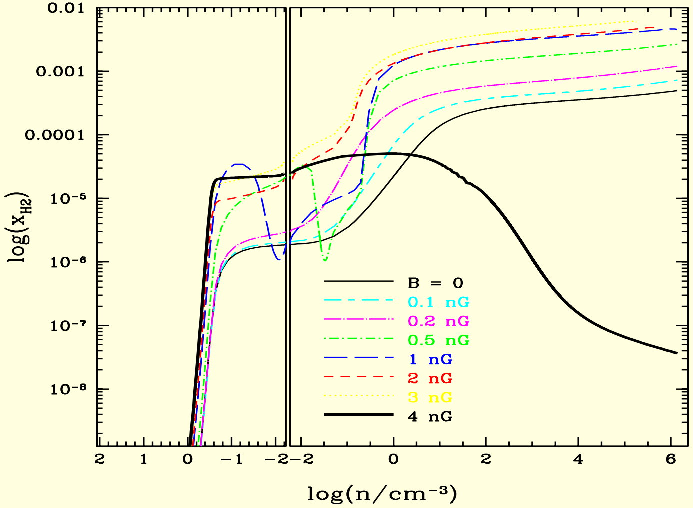
17. Formation of molecular hydrogen: collapsing halo



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18. Formation of first SMBHs

- Presence of quasars at $z \simeq 6$ indicates SMBHs of $\geq 10^9\,\mathrm{M}_\odot$ at $t \leq 1$ billion yrs.

- Simulations suggest masses of first stars $\simeq 100\,\mathrm{M}_\odot$, or the first black holes would be of similar masses. Accretion times scales to form $10^9\,\mathrm{M}_\odot$ black holes comparable to the age of the universe. Cooling to 300 K also results in low accretion rates.

- Preventing cooling of collapsing halo to $n \simeq 10^3\,\mathrm{cm}^{-3}$ might results in a black holes of mass $\geq$ a few $\times\, 10^4\,\mathrm{M}_\odot$ (Shang et al. 2010).

- Magnetic fields provide one such mechanism.

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19. Weak Gravitational lensing and cosmology

- Unbiased probe of all matter (dark plus luminous); is a 'linear' probe of 'non-linear' structures.

- **Power spectrum of convergence**:

$$P_\kappa(\ell) \propto \int dz \left(\frac{g(z)}{a(z)}\right)^2 P_\delta(\ell/r(z), z) \qquad (10)$$

  $g(r)$: redshift distribution of sources. $P_\delta(\ell/r)$: matter power spectrum at $k = \ell/r$.

- **More complications**: redshift distribution of sources, field of view (CFHTLS wide, 57 square degrees), point spread function (future space based survey SNAP)

- **Present data**: CFHTLS wide. Shear statistics from 1 arcmin to 4 degress.

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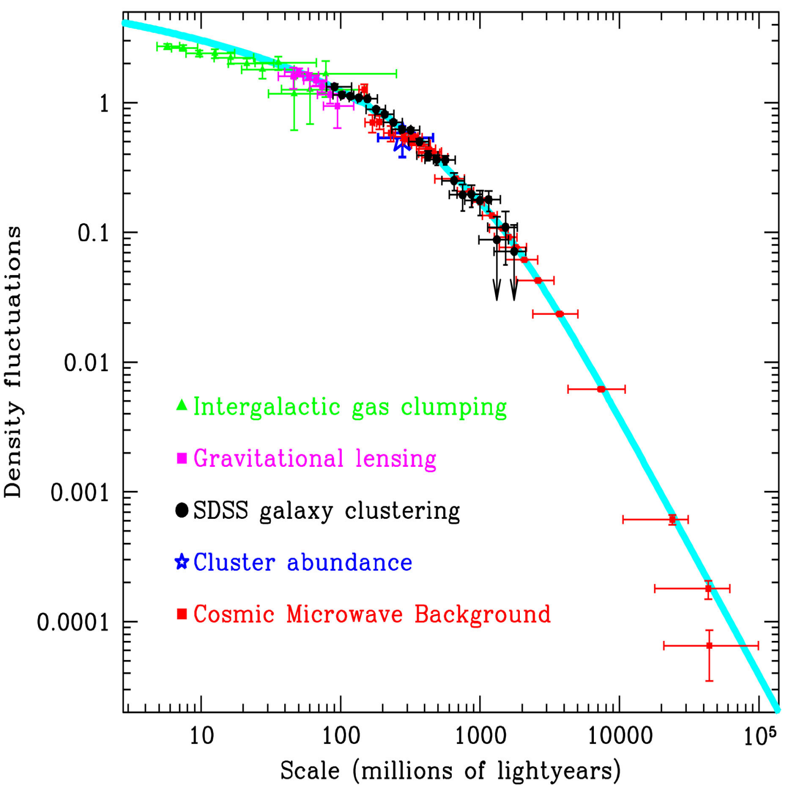
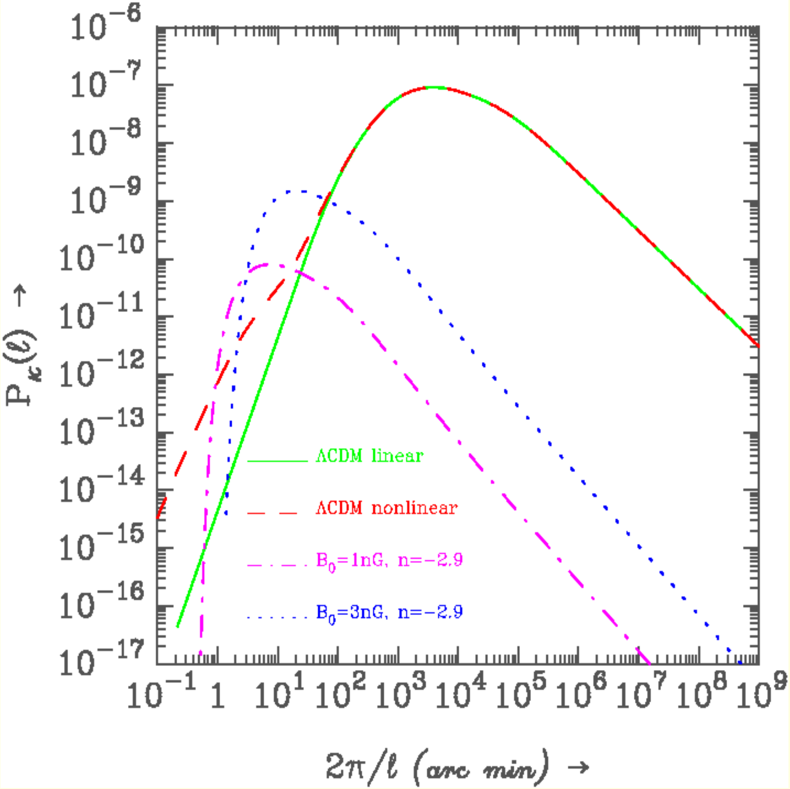
20. Power Spectrum estimation: present status



21. Cosmological weak lensing: power spectrum



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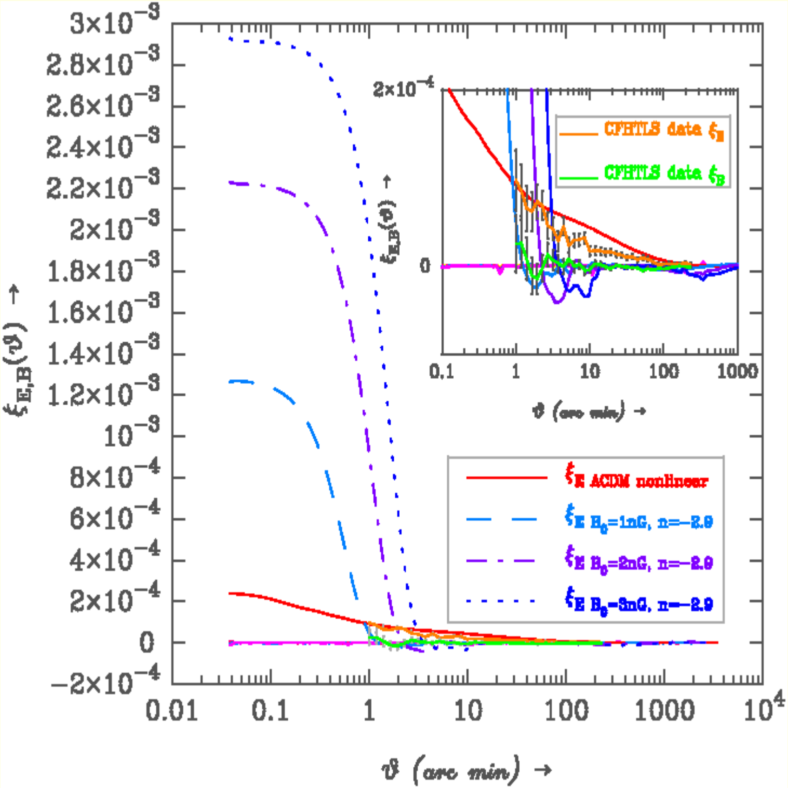
22. Cosmological weak lensing: correlation function



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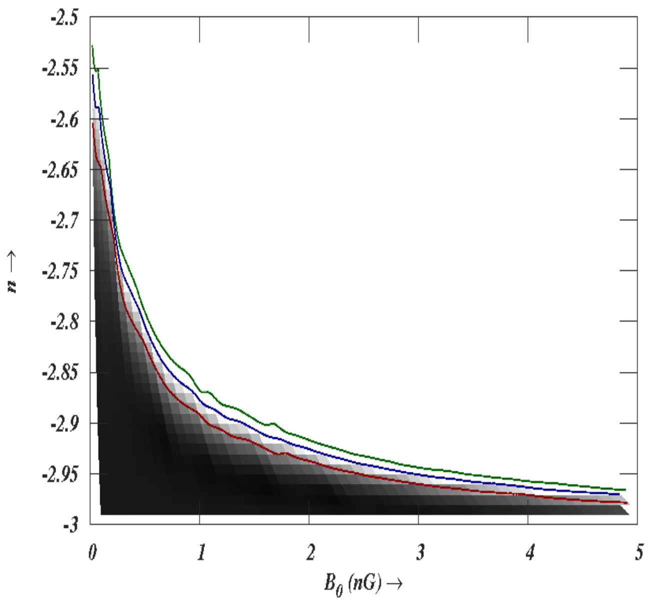
23. Constraints on Primordial magentic fields



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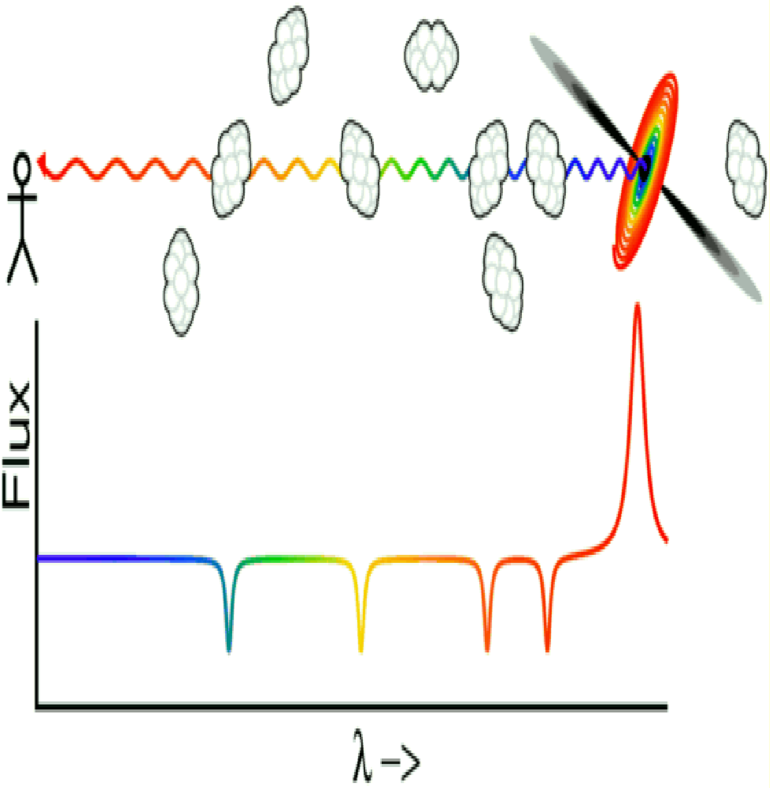
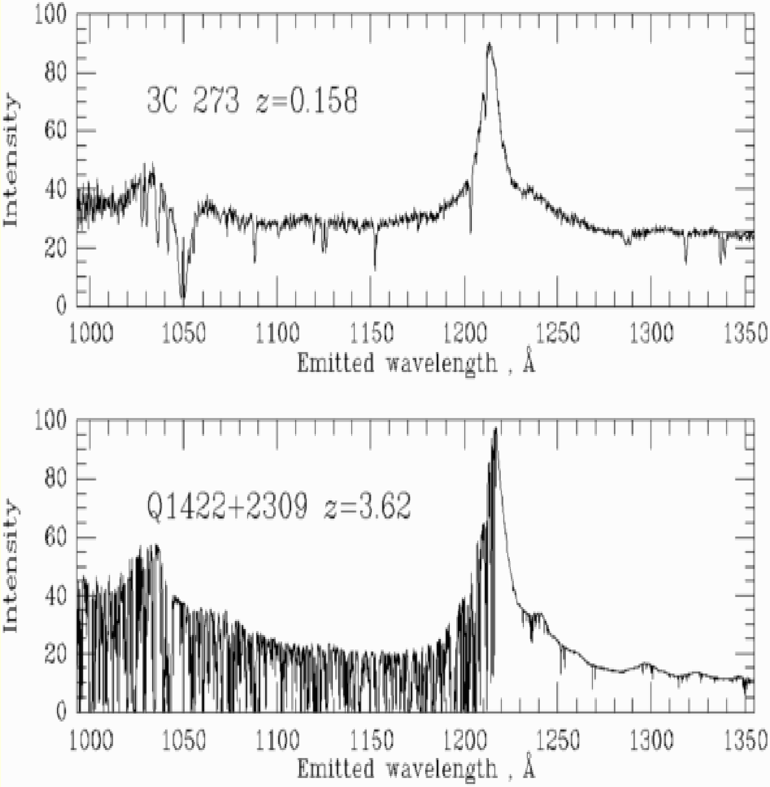
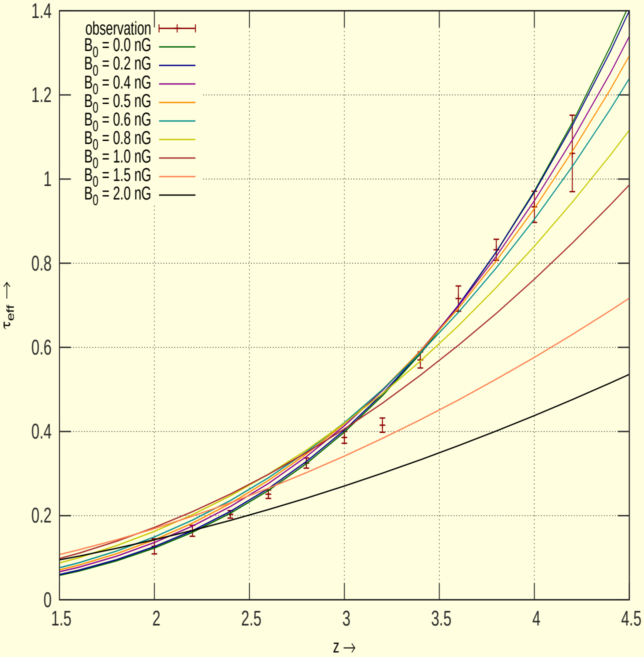
24. Lyman-alpha clouds



25. Lyman-alpha clouds: line of sight density



26. Lyman-clouds clouds: observables



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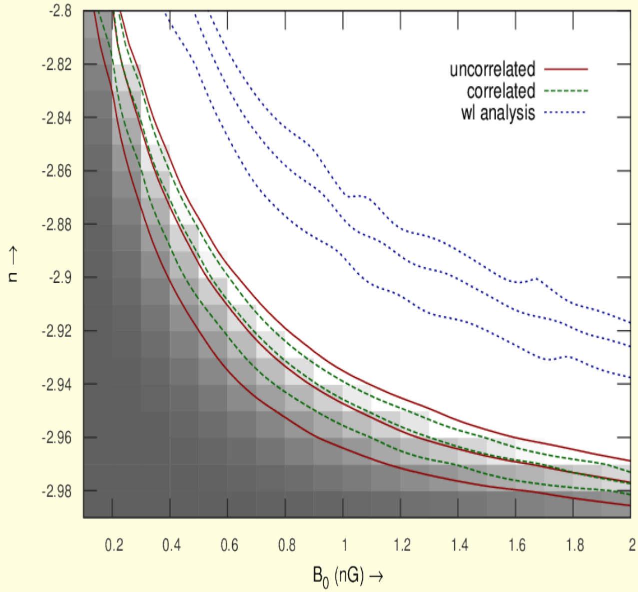
27. Constraints on primordial magnetic fields



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28. Conclusions

- Primordial tangled magnetic fields can cause formation of first structures in the universe
- Magnetic field-induced reionization leaves generic detectable signatures
- Magnetic field dissipation in the post recombination era could provide probes for 'dark age' in the universe.
- Formation of first SMBH might be influenced by the presence of primordial magnetic fields
- Present cosmological weak lensing amd Lyman-alpha clouds data puts strong constraints on primordial field strength and spectral index.