Title: A new probe of primordial magnetic fields at high redshift

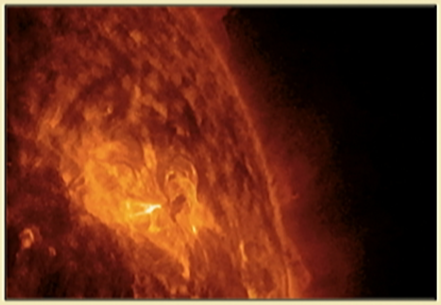
Date: Jun 14, 2016 05:15 PM

URL: http://pirsa.org/16060011

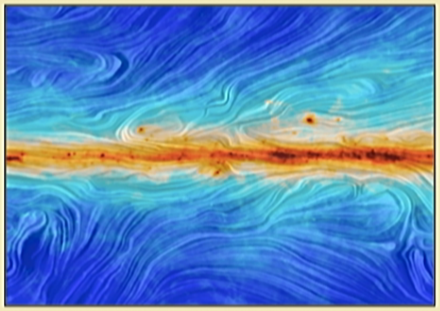
Abstract: I will present a novel method for probing extremely weak large-scale magnetic fields in the intergalactic medium prior to the epoch of reionization. This method relies on the effect of spin alignment of hydrogen atoms in a cosmological setting, and on the effect of magnetic precession of the atoms on the statistics of the 21â€“cm brightnessâ€“temperature fluctuations. It is intrinsically sensitive to magnetic fields weaker than 10^{-19} Gauss in physical units, and thus has a potential to reach many orders of magnitude below the current constraints on primordial magnetic fields. I will discuss the physical mechanism, lay out the estimator formalism that enables searches with future 21-cm tomographic surveys, and present forecasts for detecting magnetic fields in the high-redshift universe using this method.

Why PMFs?

- MFs are ubiquitous.
- Origin of seed fields?
- PMFs = new window into physics of the early universe.
- Predictions: 10^{-30}-10^{-15} G



credits: NASA/SDO/Goddard



credits: ESA/Planck Collaboration

Current constraints

- ✓ CMB spectral distortions:

  COBE/FIRAS <4nG [Kunze & Komatsu, 2013]

- ✓ CMB anisotropies:

  Planck <5nG [Planck 2015 results. XIX.]

- ✓ Large scale structure:

  Lyman-α forest, halo abundance, tSZ <1.5-4.5nG [Kahniashvili et al, 2013]

- ✓ Blazar observations:

  Fields in local voids $>10^{-15}$ G [Neronov & Vovk, 2010]

This work

New method that proposes the use of 21-cm tomography to probe miniscule-strength large-scale magnetic fields *directly* in the high-z IGM.

This work

New method that proposes the use of 21-cm tomography to probe miniscule-strength large-scale magnetic fields *directly* in the high-z IGM.

Can reach $B<10^{-21}$ Gauss comoving!

[1410.2250 & 1604.06327]

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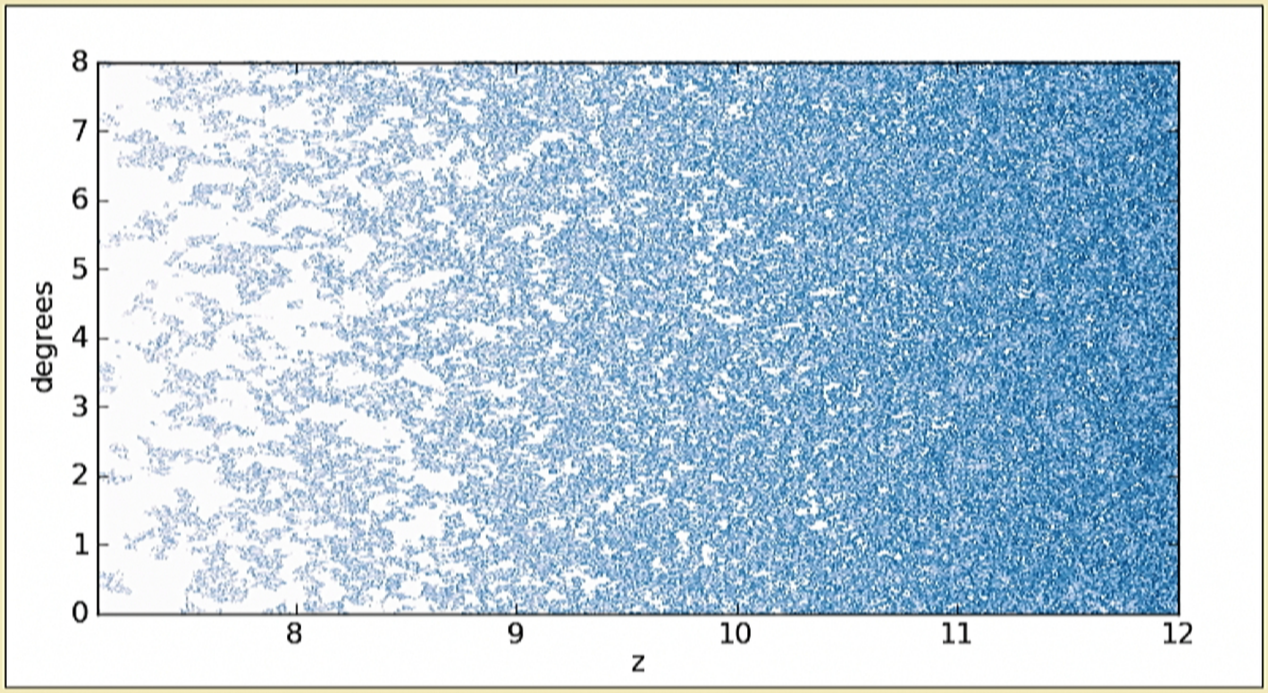
Outline

- 21-cm tomography
- Hyperfine structure of hydrogen and magnetic fields
- Part I: Microphysics
- Part II: Estimator for magnetic field
- Sensitivity forecasts

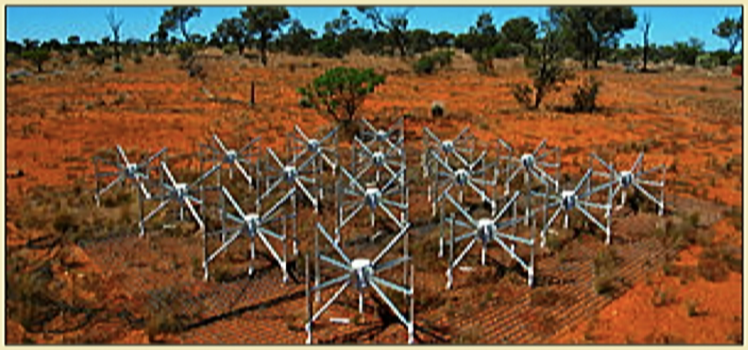
21-cm tomography



Credit: PAPER collaboration

21-cm tomography

Many low-ν radio arrays are under construction
to perform the first 21-cm tomography surveys:

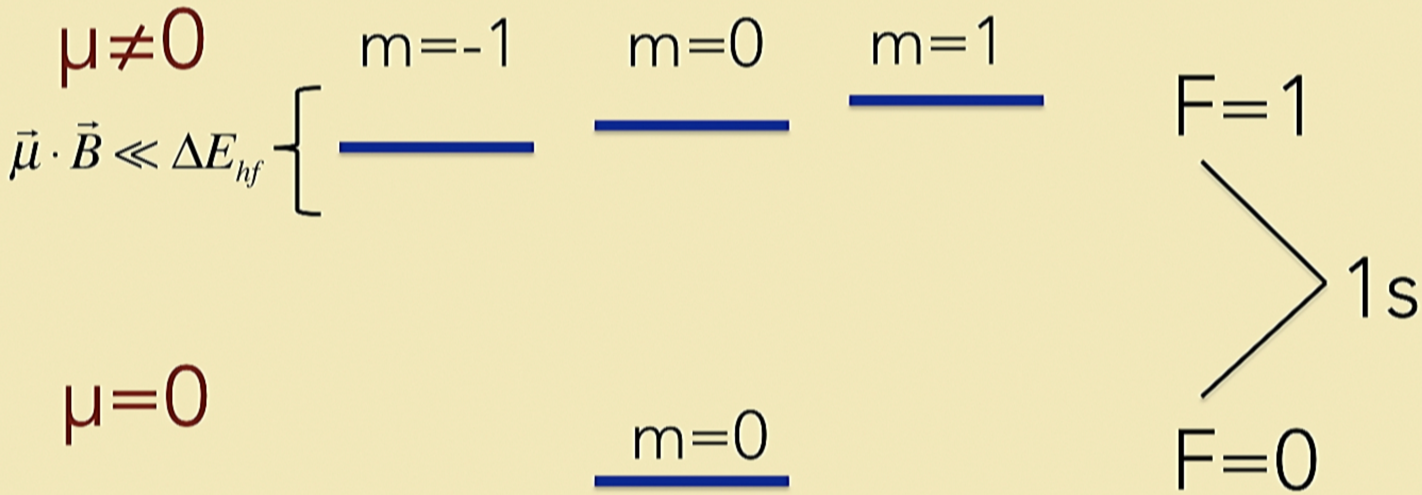


MWA

HERA

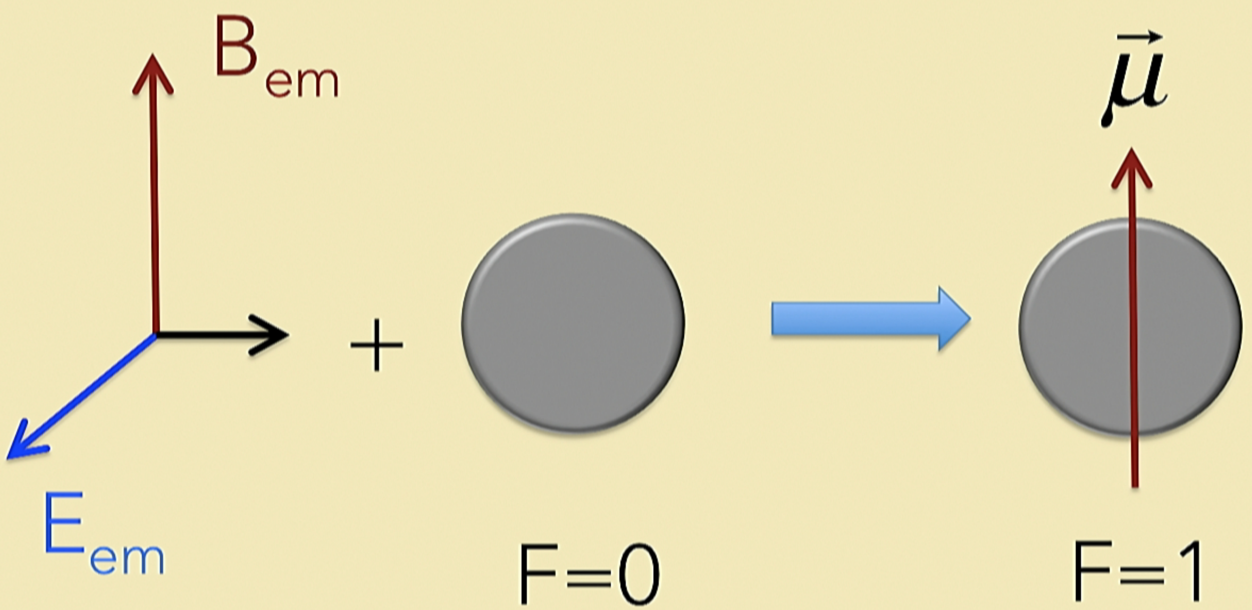
PAPER

Hyperfine structure in the presence of B



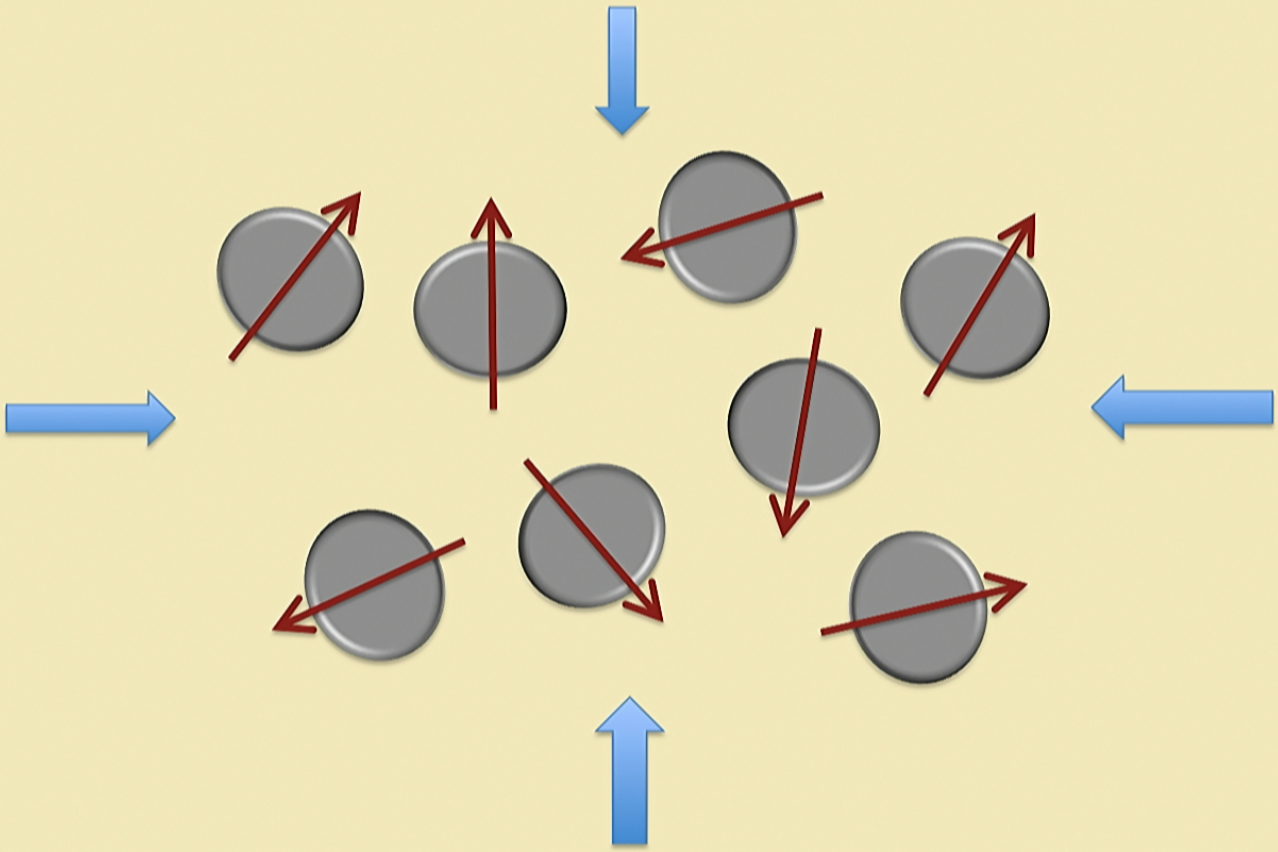
Triplet has a net magnetic moment

Zeeman splitting and precession



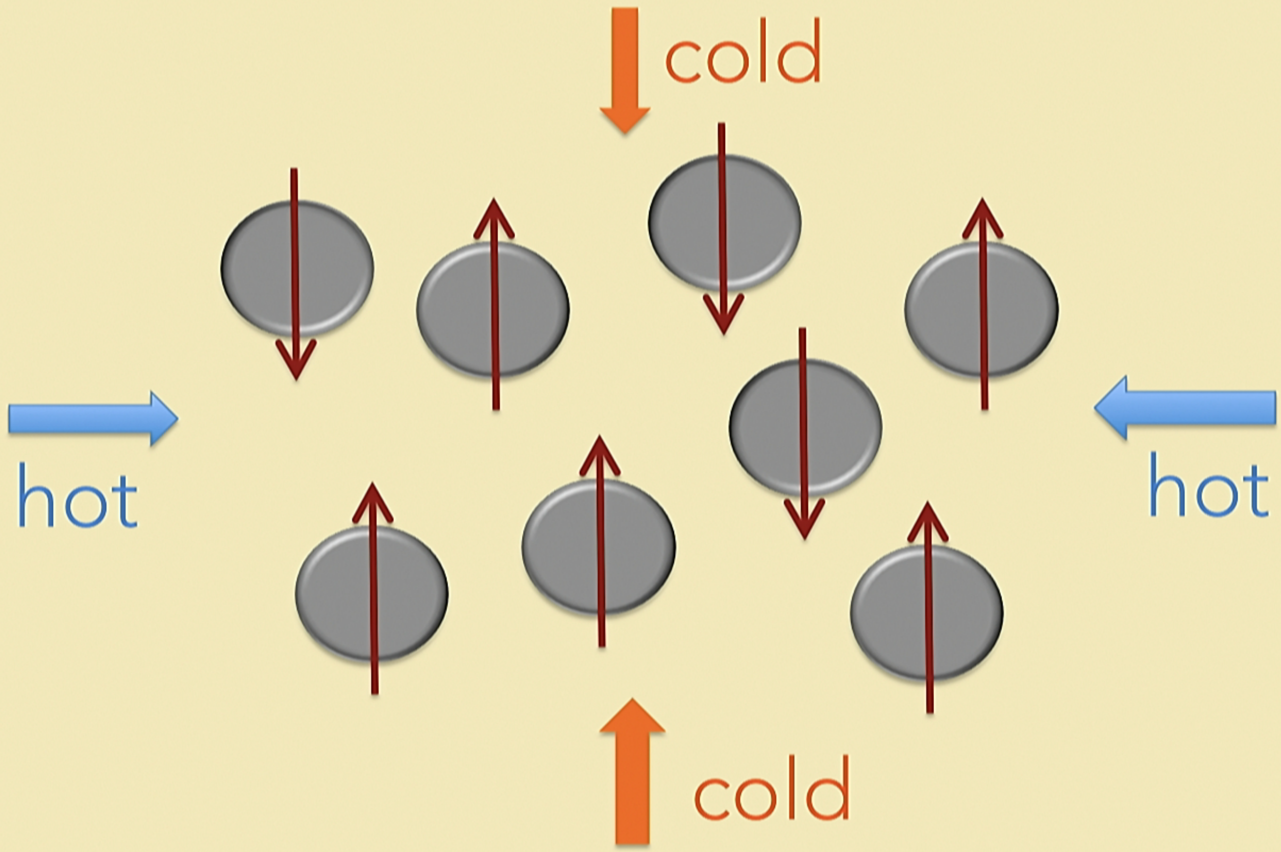
Triplet will preferentially emit perpendicular to μ

Ground state unpolarized



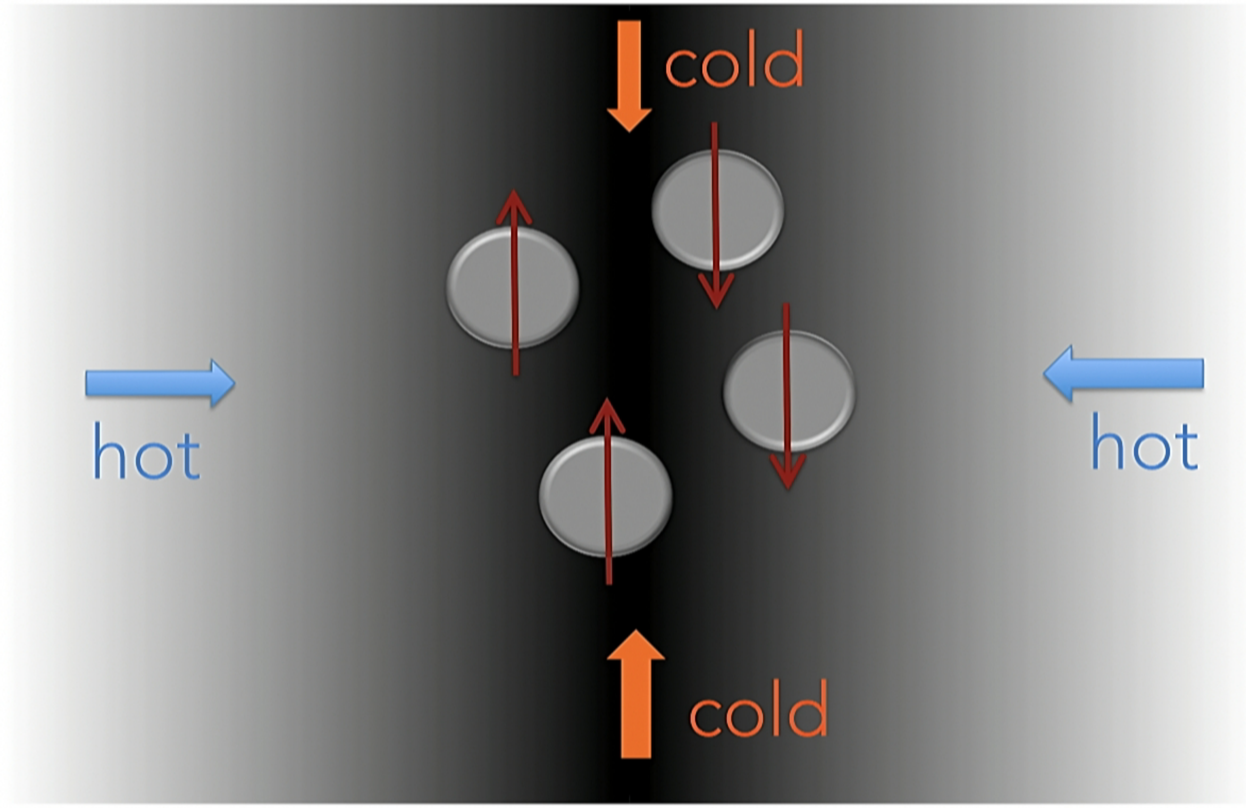
Isotropic bath of 21cm radiation

Ground state alignment

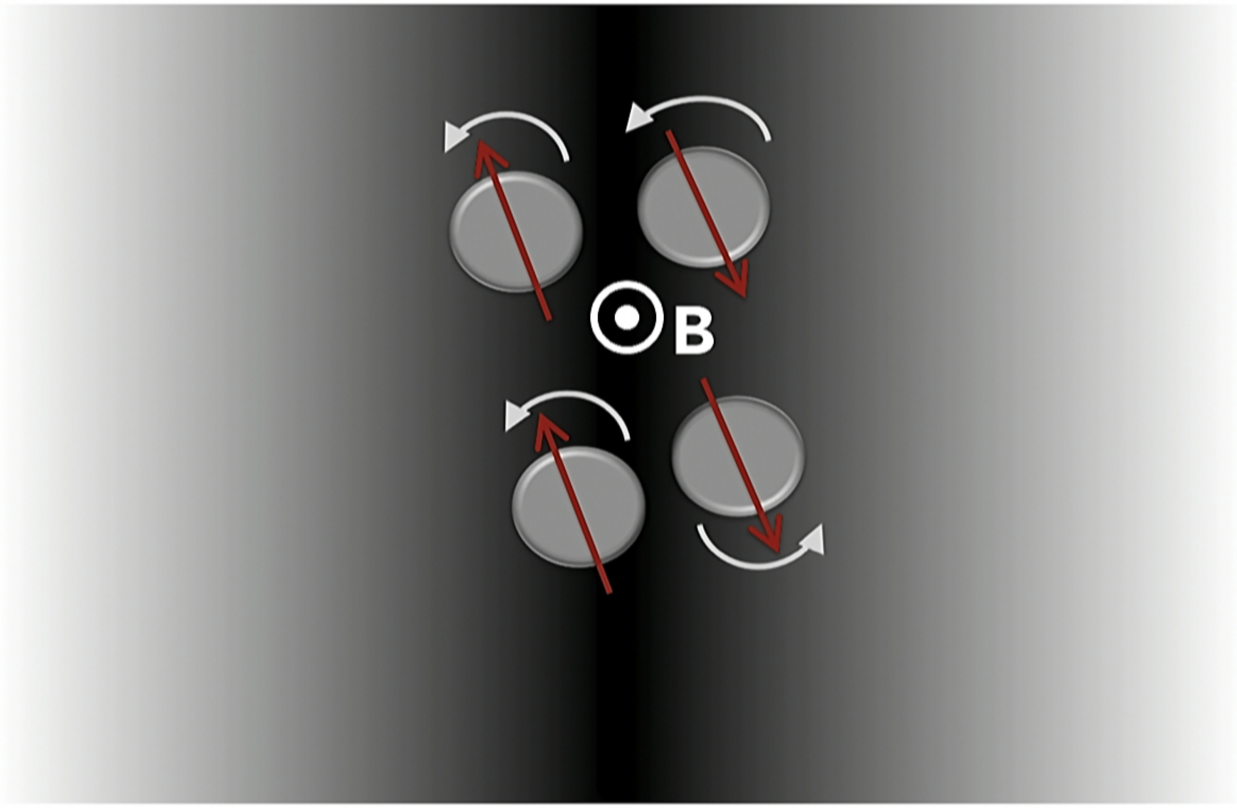


Quadrupolar anisotropy

Spin alignment in inhomogeneous universe



Precession in an external magnetic field



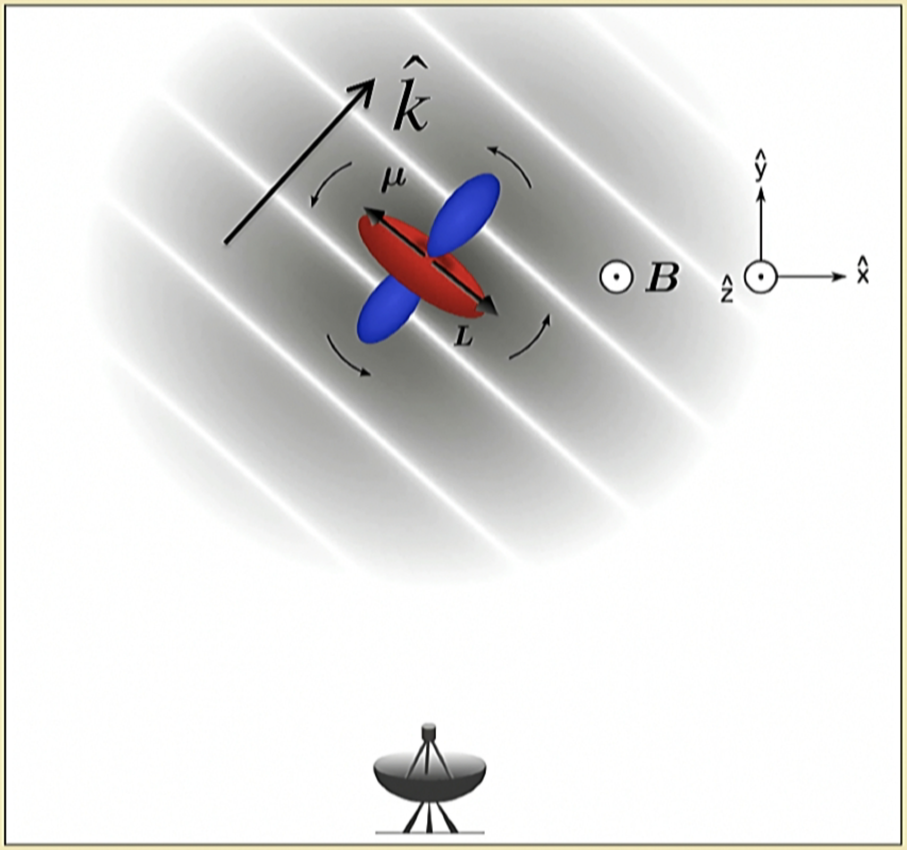
Back of the envelope…

$z \sim 20:$

$t \approx 30000\,yr$

$\omega_L = \frac{eg}{2m_e} B$

$\theta_B = \omega_L t$



Saturation limit:

$\theta_B \sim 1$

$B < 10^{-19}\,Gauss$

Part I: Microphysics

✓ Standard calculation keeps track only of the singlet and the total triplet population, to obtain spin temperature:

$$\frac{n_{F=1}}{n_{F=0}} = 3e^{-68\,mK/T_S}$$

$T_S < T_{CMB}$ (Absorption)

$T_S > T_{CMB}$ (Emission)

✓ To describe precession, need to keep track of the **entire atomic density matrix** (including the off diagonal terms) and track coupled evolution of 21-cm radiation's phase-space density matrix and atomic density matrix.

Part I: Microphysics

Include:

✓ Radiative transitions

✓ Atomic collisions

✓ Lyman-α pumping

✓ **Magnetic fields**

$$T(\widehat{\mathbf{n}},\vec{k}) = \left(1-\frac{T_\gamma}{T_{\rm s}}\right) x_{1\rm s}\left(\frac{1+z}{10}\right)^{1/2}$$
$$\times\left[26.4\ {\rm mK}\left\{1+\left(1+(\widehat{\mathbf{k}}\cdot\widehat{\mathbf{n}})^2\right)\delta(\vec{k})\right\} - 0.128\ {\rm mK}\left(\frac{T_\gamma}{T_{\rm s}}\right)\right.$$
$$\times x_{1\rm s}\left(\frac{1+z}{10}\right)^{1/2}\left\{1+2\left(1+(\widehat{\mathbf{k}}\cdot\widehat{\mathbf{n}})^2\right)\delta(\vec{k})\right.$$
$$\left.\left.-\frac{\delta(\vec{k})}{15}\sum_m \frac{4\pi}{5}\frac{Y_{2m}(\widehat{\mathbf{k}})\,[Y_{2m}(\widehat{\mathbf{n}})]^*}{1+x_{\alpha,(2)}+x_{{\rm c},(2)}-imx_{\rm B}}\right\}\right]$$

Venumadhav, Oklopcic, VG, et al (2014)

Part I: Microphysics

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- ✓ Atomic collisions
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Spin temperature — CMB temperature

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Rates of depolarization/precession

Venumadhav, Oklopcic, VG, et al (2014)

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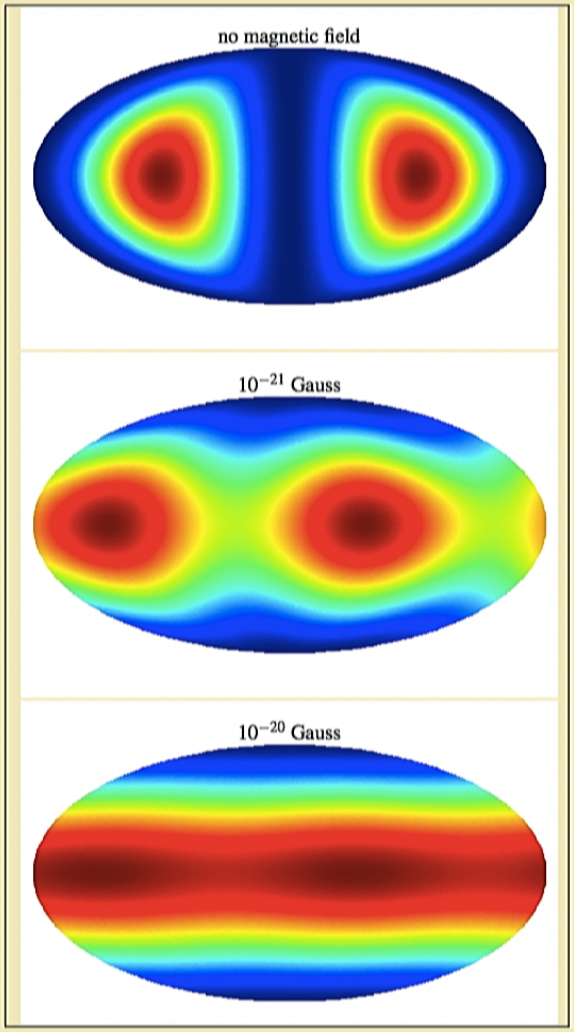
$$G(\widehat{\mathbf{k}}) \equiv \frac{\partial T}{\partial \delta}(\widehat{\mathbf{k}},\delta=0) \qquad T^S(\vec{k}) = G(\widehat{\mathbf{k}})\delta(k)$$

$$\left\langle T_0(\vec{k})T_0^*(\vec{k}')\right\rangle \equiv (2\pi)^3\delta_D(\vec{k}-\vec{k}')P_0^S(\vec{k})$$
$$= (2\pi)^3\delta_D(\vec{k}-\vec{k}')G_0^2(\widehat{\mathbf{k}})P_\delta(k)$$

To evaluate these expressions, need:

- ✓ Spin temperature
- ✓ IGM kinetic temperature
- ✓ Lyman-α flux evolution

← 21CMFAST



Saturation →

VG et al (2016)

Part II: Estimator formalism

- ✧ Homogenous MF introduces a preferred direction (anisotropy).
- ✧ Stochastic MF produces correlation between Fourier modes (statistical anisotropy).

VG et al (2016)

Part II: Estimator formalism

unknown ⟶ $B(z) = B_0(1+z)^2$

observable ⟶ $T(\vec{r}) = T^S(\vec{r}) + T^N(\vec{r})$

$$T^S(\vec{r}) = T_0^S(\vec{r}) + B_0(\vec{r})\frac{T_0^S}{\partial B_0}(\vec{r})$$

$$T(\vec{k}) = T_0^S(\vec{k}) + \int d\vec{r} e^{-i\vec{k}\cdot\vec{r}} B_0(\vec{r})\frac{\partial T_0^S}{\partial B_0}(\vec{r})$$

$$= T_0^S(\vec{k}) + \frac{1}{(2\pi)^3}\int d\vec{k}_1 B_0(\vec{k}_1)\frac{\partial T_0^S}{\partial B_0}(\vec{k}-\vec{k}_1)$$

VG et al (2016)

Part II: Estimator formalism

$$\left\langle T(\vec{k})T^*(\vec{k}')\right\rangle = (2\pi)^3\delta_D(\vec{k}-\vec{k}')P_{\rm null}(\vec{k}) + B_0(\vec{k}-\vec{k}')$$
$$\times\left[P_\delta(k')G_0^*(\widehat{\mathbf{k}}')\frac{\partial G_0}{\partial B_0}(\widehat{\mathbf{k}}') + P_\delta(k)G_0(\widehat{\mathbf{k}})\frac{\partial G_0^*}{\partial B_0}(\widehat{\mathbf{k}})\right]$$

Quadratic estimator (model-independent):

$$\widehat{B}_0^{\vec{k}\vec{k}'}(\vec{K}) = \frac{T(\vec{k})T^*(\vec{k}')}{P_\delta(k')G_0^*(\widehat{\mathbf{k}}')\frac{\partial G_0}{\partial B_0}(\widehat{\mathbf{k}}') + P_\delta(k)G_0(\widehat{\mathbf{k}})\frac{\partial G_0^*}{\partial B_0}(\widehat{\mathbf{k}})} \qquad \vec{K} = \vec{k}-\vec{k}'$$

MVQE variance (noise power spectrum):

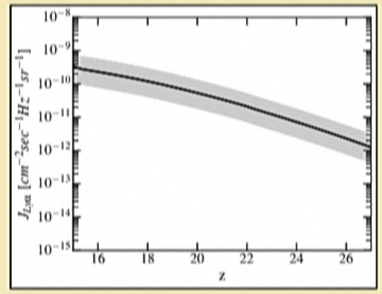
$$\left(P^N_{B_{0,i}}(\vec{K})\right)^{-1} = \int k^2 dk \sin\theta_k d\theta_k d\phi_k \;\; \frac{\left(P_\delta(k')G_0^*(\widehat{\mathbf{k}}')\frac{\partial G_0}{\partial B_i}(\widehat{\mathbf{k}}') + P_\delta(k)G_0(\widehat{\mathbf{k}})\frac{\partial G_0^*}{\partial B_i}(\widehat{\mathbf{k}})\right)^2}{2(2\pi)^3 P_{\rm null}(\vec{k})P_{\rm null}(\vec{k}')}$$

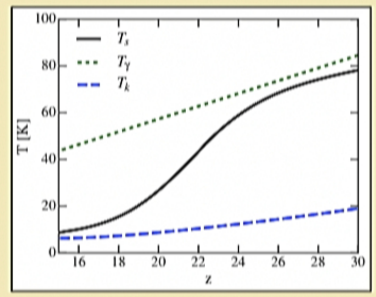
VG et al (2016)

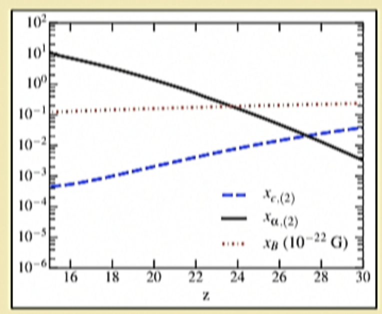
Sensitivity forecasts

Assume:

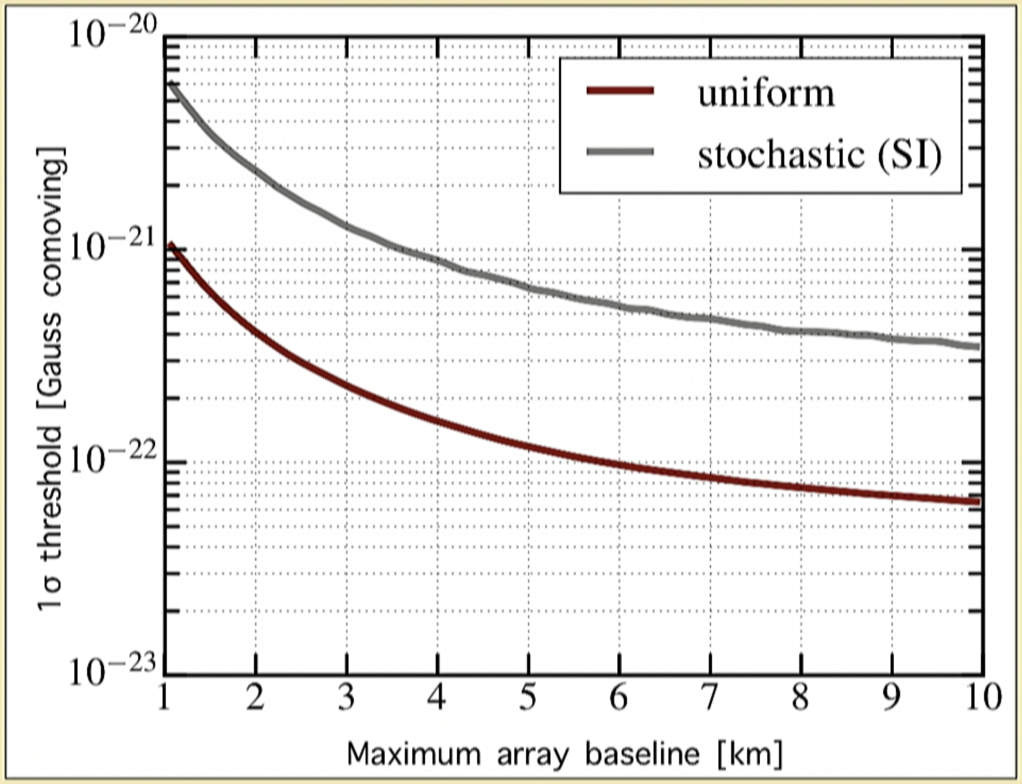
- Consider two cases: a uniform and a field with SI power spectrum.
- Reasonable reionization history.
- Noise from galactic foreground: $T_{sky} = [0.21(1+z)]^{2.55}$
- Experiment = array of dipoles in a compact grid configuration
- Observe z=15-25, FOV=1 sr, integration time = 3 years







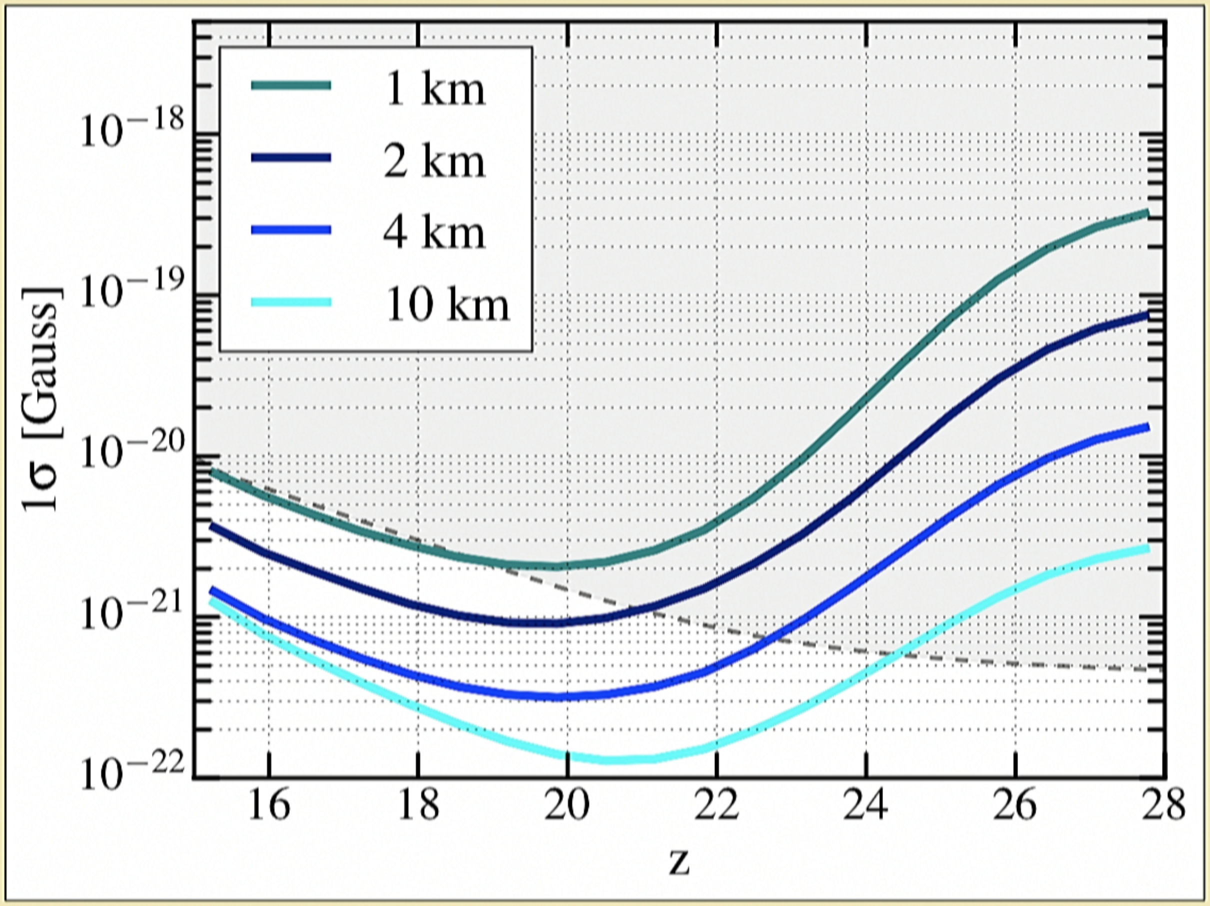
Forecasts: results



- compact grid of dipoles
- z=15-25
- FOV=1 sr
- 3 years

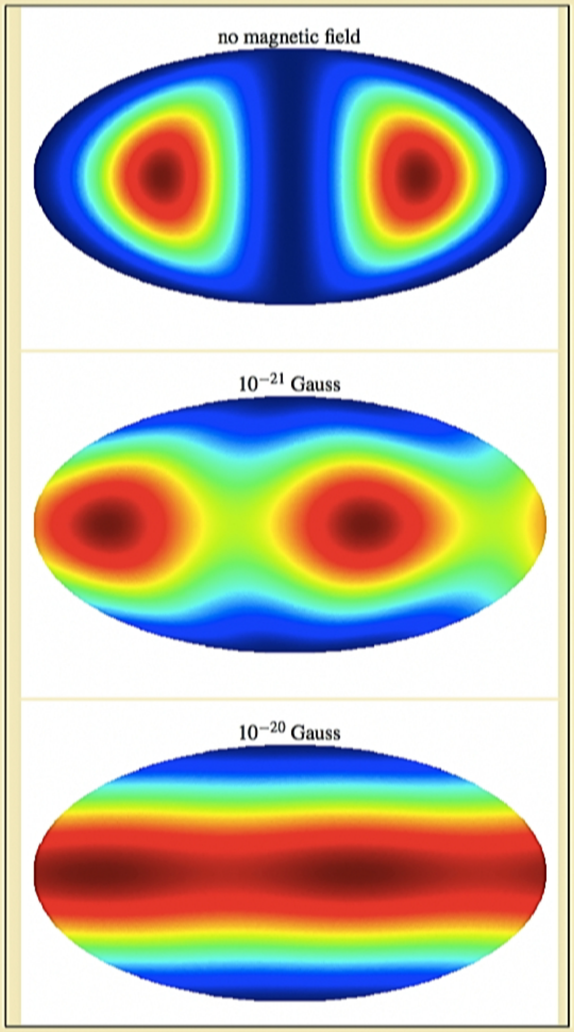
$$B(z) = B_0(1+z)^2$$

VG et al (2016)


1 km
2 km
4 km
10 km
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
1σ [Gauss]
16
18
20
22
24
26
28
z

VG et al (2016)

Saturation →



VG et al (2016)

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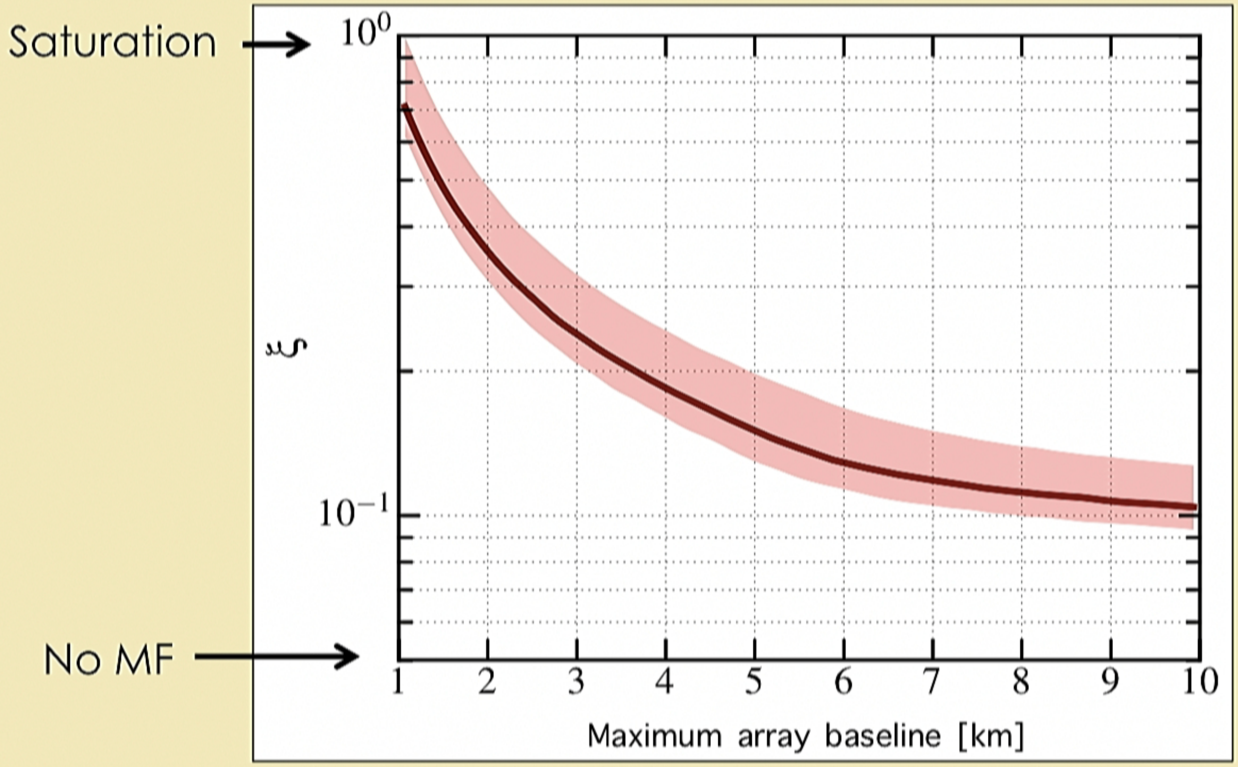

compact grid of dipoles

z=15-25

FOV=1 sr

3 years

VG et al (2016)

$$P^S(\vec{k}) = (1-\xi)P^S(\vec{k}, B=0) + \xi P^S(\vec{k}, B \to \infty)$$

Summary

- ✓ Exquisitely sensitive new probe of large-scale magnetic fields in the pre-reionization IGM.
- ✓ Array of dipoles with ~a square kilometer collecting area can reach 1-sigma sensitivity to 10^{-21} Gauss comoving ~ 10 oom below CMB constraints!