``Polarization of 21 cm Radiation from the Epoch of Reionization."

Daniel Babich and Abraham Loeb.

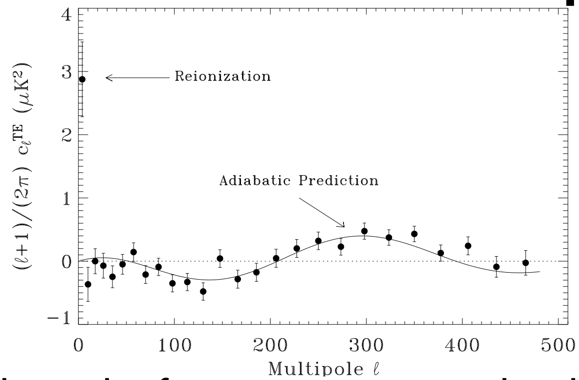
Daniel Grin
Journal Club
Nov. 18th, 2005.


CMBFAST
CMB ANISOTROPIES
EPISODE II
ATTACK OF THE C_l ONES
CMB ANISOTRPOIES EPISODE II ATTACK OF THE POWER SPECTRUM ONES
MATIAS ZALDARRIAGA UROS SELJAK CHUNG-PEI MA WAYNE HU
STEVEN WEINBERG MAX TEGMARK EDMUND BERTSCHINGER
and NAOSHI SUGIYAMA PRODUCED BY KRIS STANEK and MATIAS ZALDARIAGGA
DIRECTED BY ANDREW FRIEDMAN, HARVARD UNIVERSITY, SPRING 2003
CMB

Outline

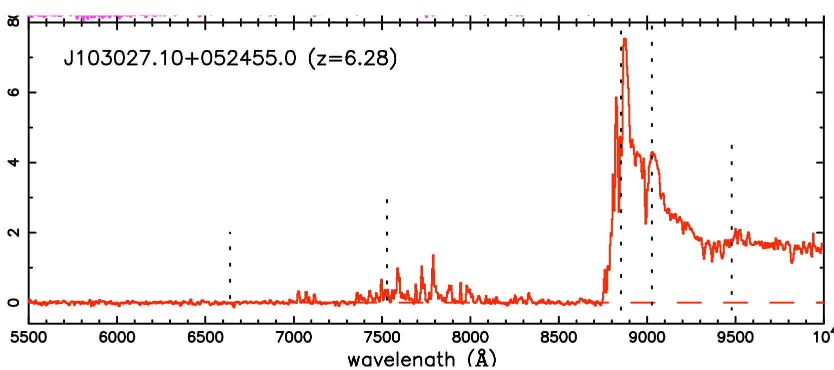
- How do we know reionization happened?
- Review of 21 cm physics.
- Cosmology with 21 cm line.
- What could polarize 21-cm at high-z?
- Results and Discussion: Attck of the $C_l$ones.

Reionization: It Happens



- Reionization cuts short the free-streaming epoch, when monopole temperature perturbations at decoupling are converted to higher multipole temperature anisotropies. Thus the dumping of power from large to small scales is cut short, leading to a peak in TT and TE autocorrelation functions at large angular scales. From this effect, WMAP team inferred $\tau \approx 0.17 \rightarrow 11 < z_r < 30$.

- Gunn-Peterson trough (blank spectral region blueward of Lyman α in QSO rest frame) indicates presence of HI in diffuse IGM beyond $z \approx 6$.



Physics of the 21 cm line:

Evolution of the Spin Temperature

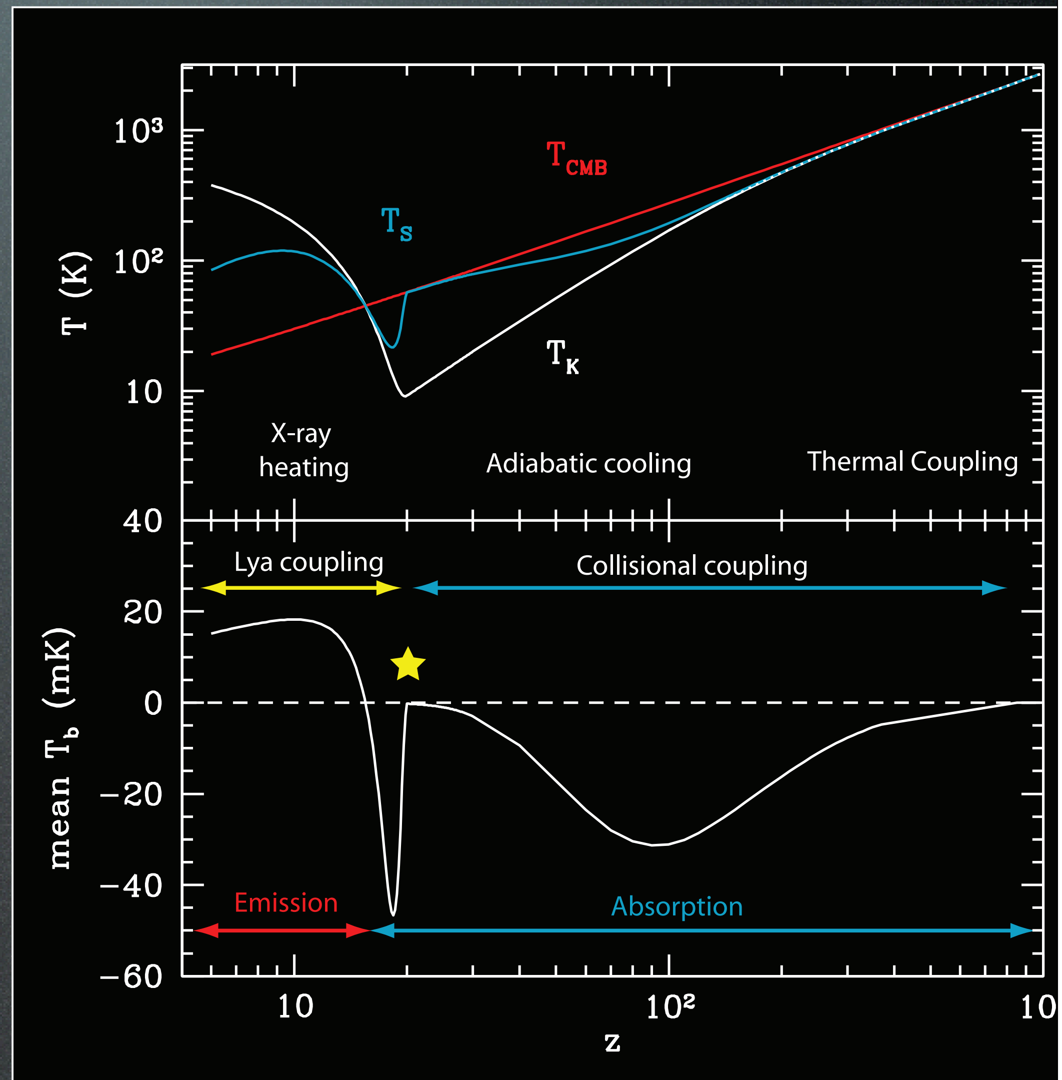
(Attractive plot courtesy of J. Pritchard)

- Evolution of the gas kinetic temperature T_K : Scattering off residual e^- locks T_K to T_{CMB} until $z \approx 200$, at which point e^- are too sparse for CMB photons and gas to stay in equilibrium. When the first ionizing sources (Pop III stars, QSOs) turn on $(z \approx 20)$, the gas is heated so $T_K > T_{CMB}$.

- Collisions couple the spin temperature, defined by

$$\frac{n_1}{n_0} = 3e^{-hc/(\lambda k T_s)}$$, to the

kinetic temperature until $z \approx 70$, after which the collision rate falls below the Hubble rate, and the spin temperature "tries" to track T_{CMB} until the first sources turn on.



Wouthuysen-Field Effect/Zeeman Splitting

- HI is seen in absorption until $z \approx 20$: $T_b = \tau \left(\frac{T_s - T_\gamma}{1+z} \right)$
- Sources produce anisotropic radiation field, leading to anisotropic F=1 population$\rightarrow$ radiative transfer + coupling to CMB photons yields polarized signal.
- Large optical depth to Lyα scattering isotropizes most incoming radiation. Bluer photons are less likely to be isotropized, but they are also less likely to interact with HI and pump F=1 state: Negligible polarization signal.
- Zeeman Splitting may also polarize emission (Furlanetto/Cooray 2004), but given theoretical/observational constraints on B-field in IGM, this effect would be undetectable.

Challenges

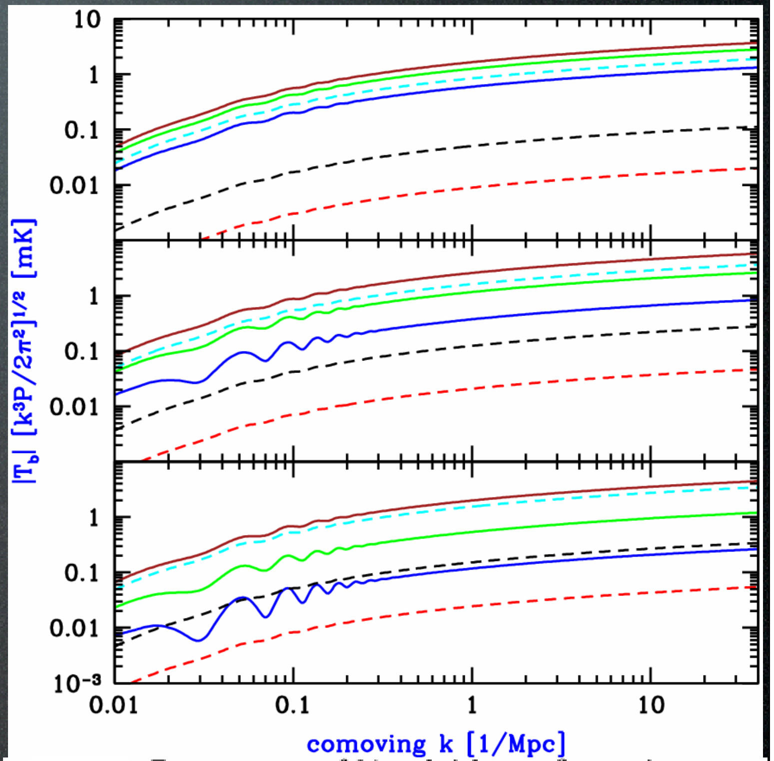
- Foregrounds: Galactic synchrotron radiation, extragalactic radio sources, terrestrial radio broadcasting. (10 K vs 10 mK signal in ΔT_b)
- Foreground frequency dependence is smooth, whereas 21-cm emitters/ absorbers will show sharp frequency dependence (cutting over to a different distance)--> Could be used to extract 10 mK signal in spite of 10 K foreground. (Fluctuation can be extracted)
- Measurement of $l \approx 100 - 1000$ moments requires large collecting area (LOFAR, SKA, PAST).

The promise of high-z cosmology with the 21 cm line

- Possibility of multi-band ($20 < z < 200$) 21 cm absorption maps. $P(k)$ could be measured at small scales: $\frac{d \ln n_s}{d \ln k} \neq 0?$

- Measurement of $P(k, z)$ could identify baryon oscillations imprinted at CMB decoupling. Could provide a standard ruler for measurement of w(z) of dark energy.

- Measurement of ΔT_b during the epoch of reionization could tell us about spatial distribution of ionizing sources. Careful analysis could separate out physics (linear power spectrum) from astrophysics (distribution of ionizing sources).



. Power spectra of 21cm brightness fluctuations versus wavenumber. We show the three power spectra that are separately observable, P_{μ^4} (upper panel), P_{μ^2} (middle panel), and P_{μ^0} (lower panel). In each case we show redshifts 150, 100, 50 (solid curves, from bottom to top), 35, 20, and 15 (dashed curves, from top to bottom).

Whence Polarization? Thompson Scattering

- Polarization is produced by Thomson scattering of incoming 21 cm photons.
- Scattered isotropic radiation is not polarized.
- $$\frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi} \left|\vec{\epsilon}_i \cdot \vec{\epsilon}_f\right|^2,$$
  so the re-scattered radiation is polarized only if incoming radiation has a quadrapole moment.
- 21-cm radiation will be polarized for the same reason the CMB is polarized!

Whence Polarization? Thompson Scattering

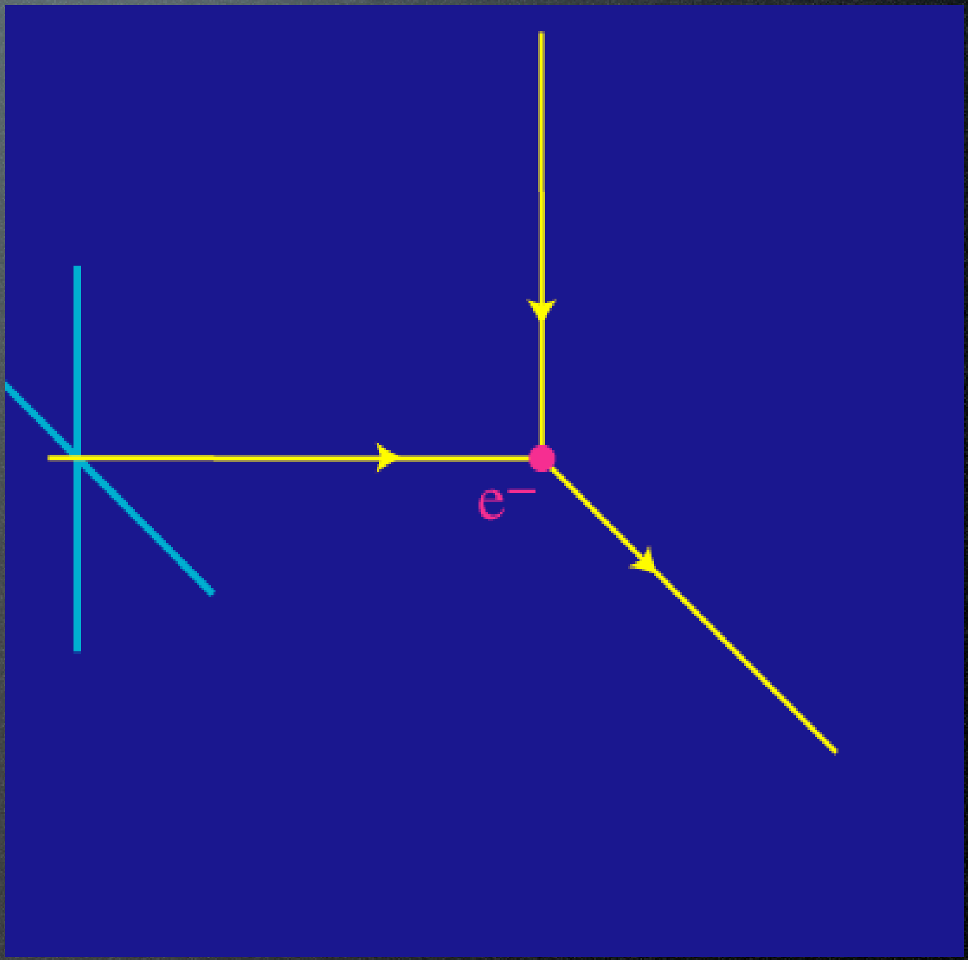
- Polarization is produced by Thomson scattering of incoming 21 cm photons.

- Scattered isotropic radiation is not polarized.

- $$\frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi}\left|\vec{\epsilon}_i \cdot \vec{\epsilon}_f\right|^2,$$

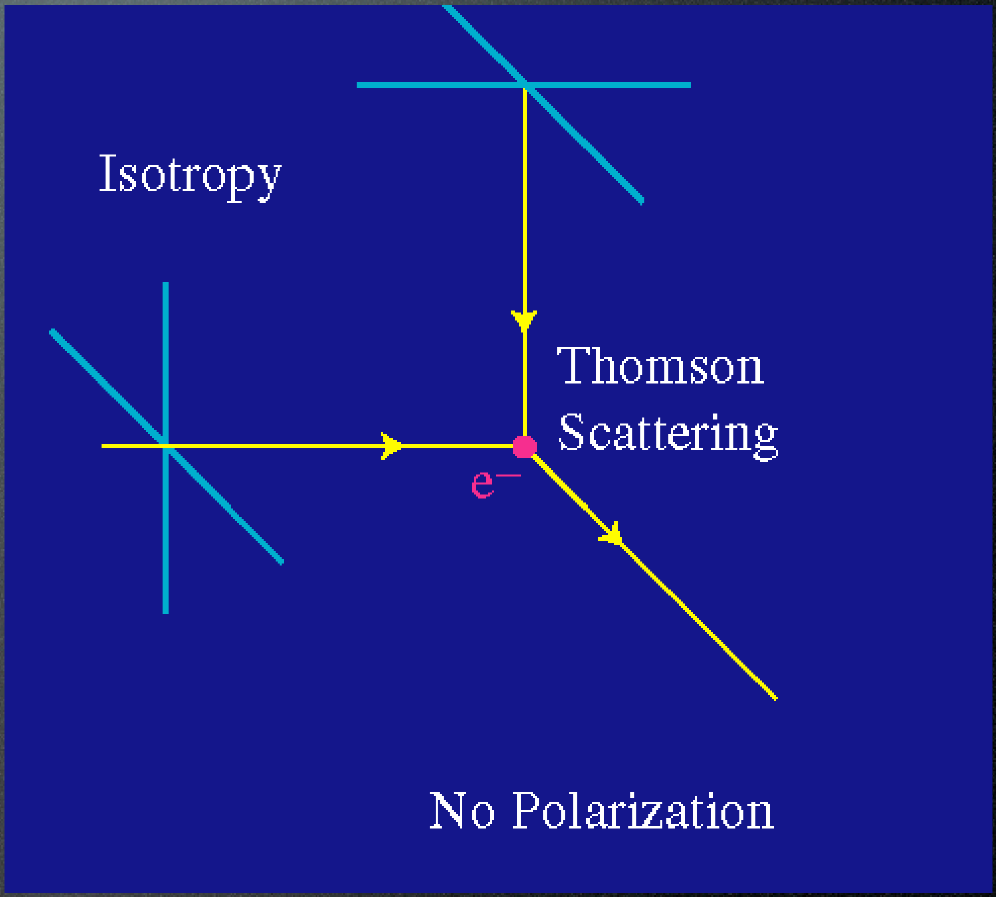
  so the re-scattered radiation is polarized only if incoming radiation has a quadrapole moment.

- 21-cm radiation will be polarized for the same reason the CMB is polarized!



Whence Polarization? Thompson Scattering

- Polarization is produced by Thomson scattering of incoming 21 cm photons.
- Scattered isotropic radiation is not polarized.
- $$\frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi}\left|\vec{\epsilon}_i \cdot \vec{\epsilon}_f\right|^2,$$
  so the re-scattered radiation is polarized only if incoming radiation has a quadrapole moment.
- 21-cm radiation will be polarized for the same reason the CMB is polarized!



Whence Polarization?
Thompson Scattering

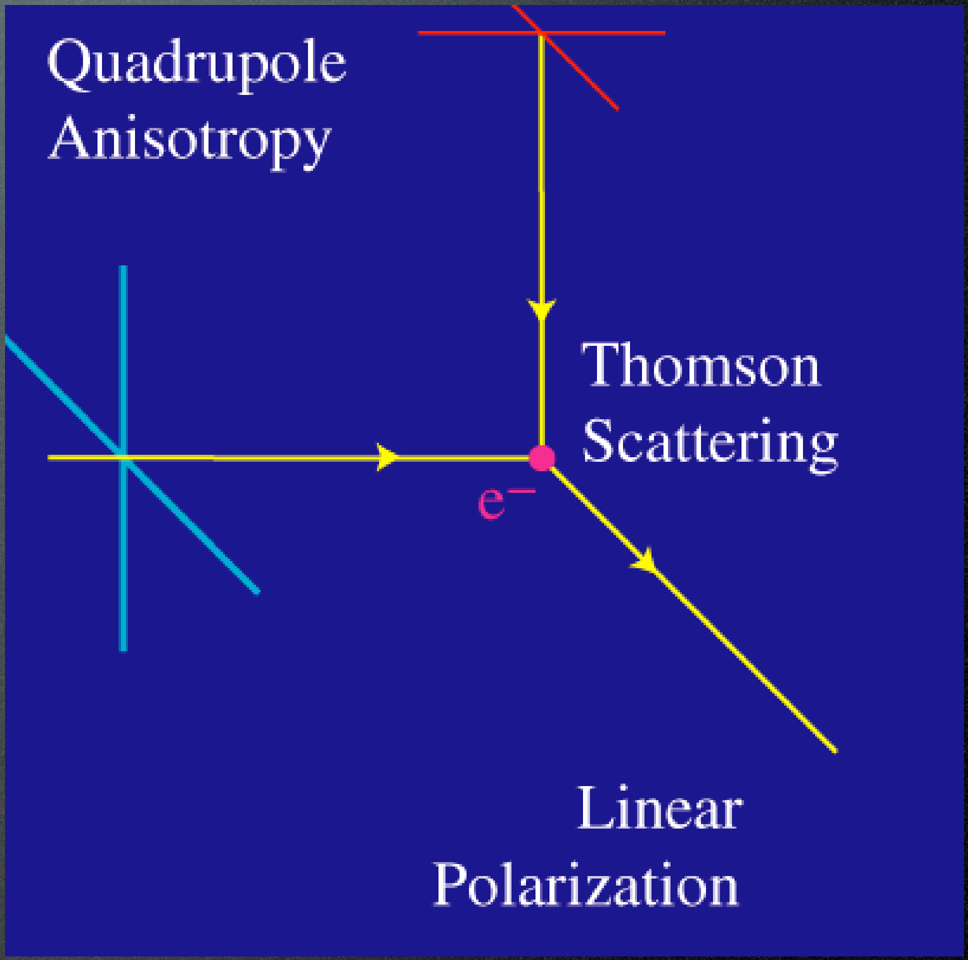
- Polarization is produced by Thomson scattering of incoming 21 cm photons.

- Scattered isotropic radiation is not polarized.

- $$\frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi} \left|\vec{\epsilon}_i \cdot \vec{\epsilon}_f\right|^2,$$

  so the re-scattered radiation is polarized only if incoming radiation has a quadrapole moment.

- 21-cm radiation will be polarized for the same reason the CMB is polarized!



How reionization polarizes 21-cm radiation

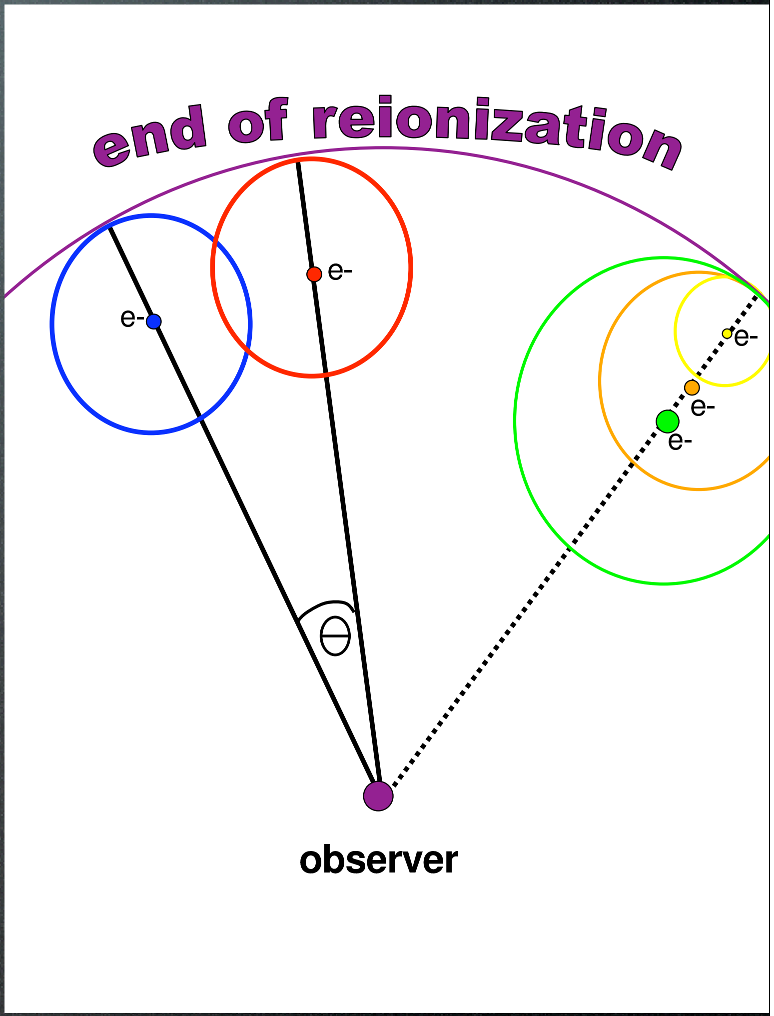
- Reionization produces free e^- that "see" a temperature quadrapole because the emitting HI gas is inhomogeneous:
  1) Baryons are inhomogeneously distributed.
  2) Reionization occurs at slightly different times in different directions $\delta x_{HI} \neq 0$.

- Because these arise from temperature/density perturbations (scalar quantities), the polarization will E-mode. This could be used to control for foregrounds and instrumental effects.

Polarization Power Spectra

- Applying preceding results for $\delta T_b(z)$ in the post-reionization limit of $T_s >> T_{CMB}$, keeping only terms linear in the perturbations, projecting to obtain the quadrapole component, and integrating over k, the authors obtain an expression for the familiar looking

$$C_l^E(\nu) = \frac{2}{\pi} \int k^2 dk \left[\overline{x}_{HI}^2 P_\delta(k) + P_{x_{HI}}(k)\right] \times \left[\Delta_l^E(k,\nu)\right]^2$$



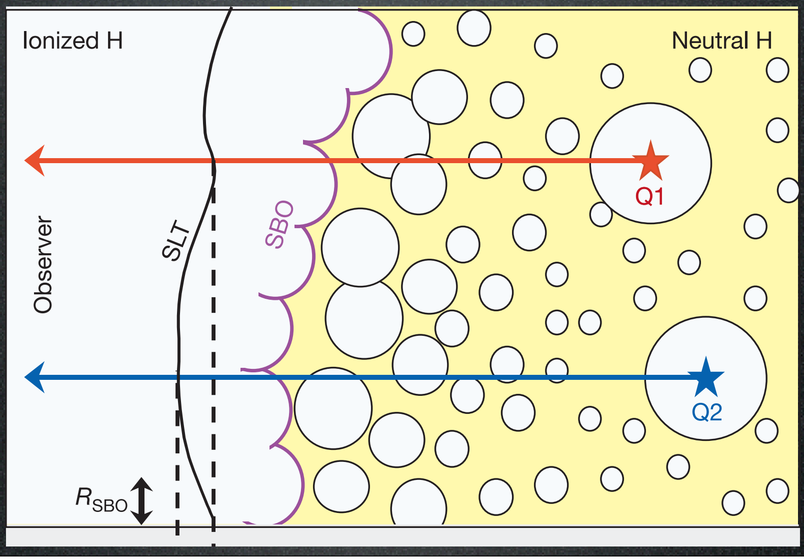
Dealing with fluctuations in ionization fraction

- Modeling of spatial variation in ionized fraction is complicated by astrophysical uncertainties such as poor knowledge of ionizing source population and of radiative transfer of ionizing radiation between bubbles and neutral regions.

- By focusing on signal emitted at the epoch of reionization, relatively robust predictions can be made by applying Press-Schechter formalism to calculate size and number density of HI bubbles right before they overlap (reionization). This yields a characteristic bubble size of $70h^{-1}Mpc$ and power spectrum

$$P_x(k) = \frac{1}{\bar{n}} e^{-k^2 R^2}$$

- For $z_e > z_r$, $x_{HI} = 1$ everywhere and Poisson fluctuations disappear.



Why Bother?

- Polarization of high-z 21 cm emission is a unique signature of reionization.
- Known E-mode, achromatic signature of reionization induced polarization can improve subtraction of foregrounds from measurements of ΔT_b. (Faraday issue)

Results in Baryon Fluctuation Dominated Regime

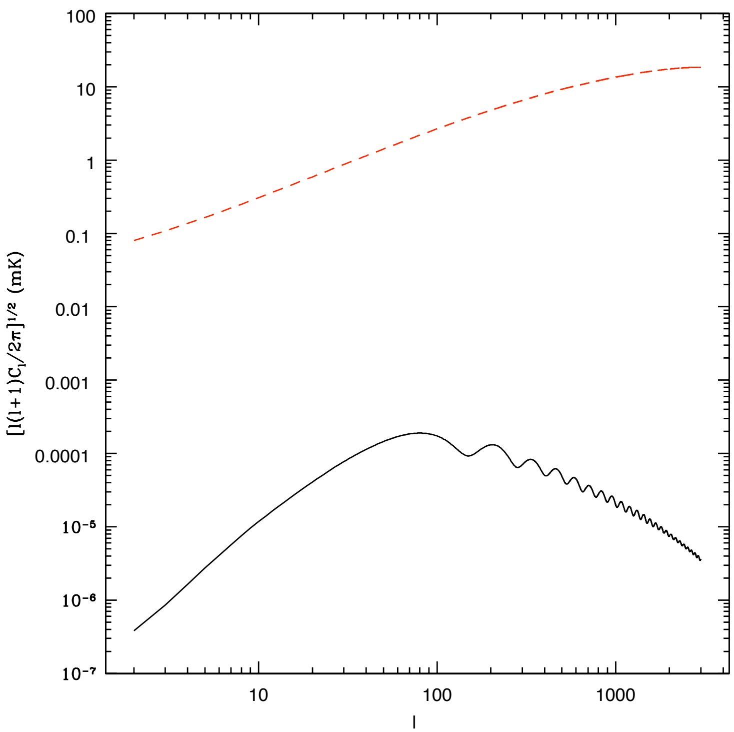


FIG. 2.— The brightness temperature (red, dashed) and polarization (black, solid) due to baryon density fluctuations for emission redshift of $z_E = 20$ and reionization redshift $z_R = 17$.

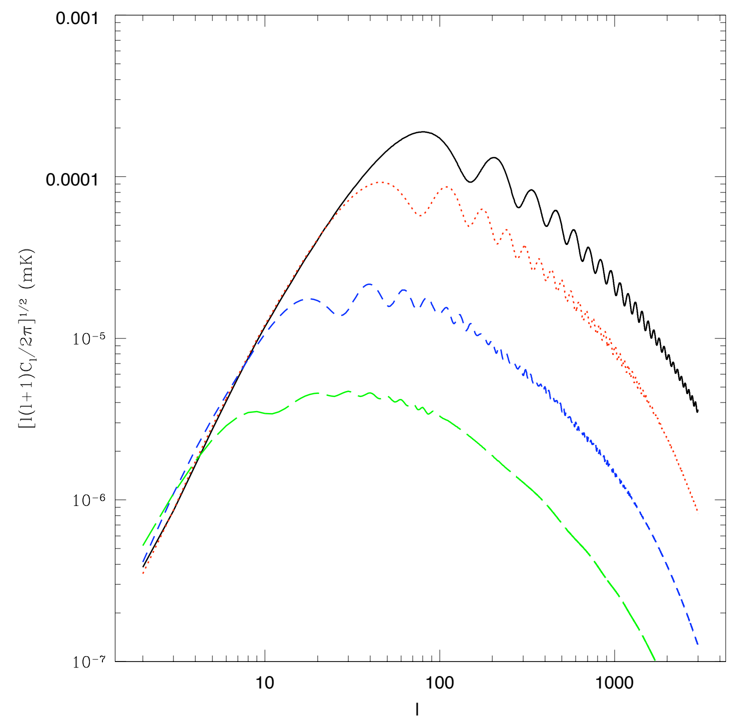


FIG. 3.— The polarization power spectrum sourced by baryon density fluctuations for an emission redshift $z_E = 20$ and reionization redshift $z_R = 17$ (black, solid), $z_R = 15$ (red, dotted), $z_R = 10$ (blue, dashed) and $z_R = 6$ (green, long dashed).

Reionization history is treated simply as a step function

Effect of Reionization History on Results

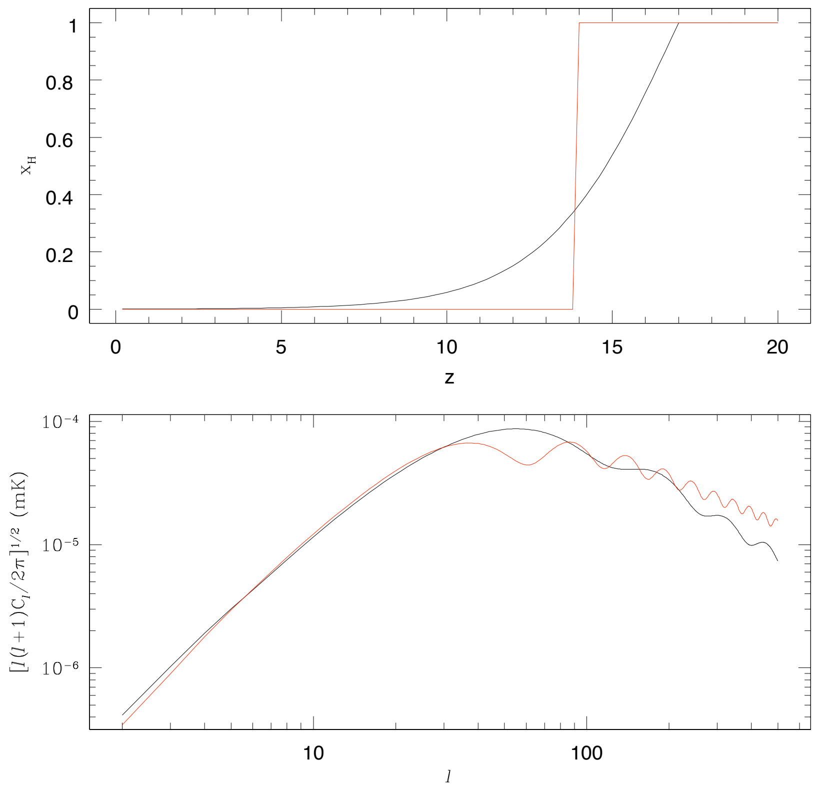


FIG. 4.— Top Panel: The gradual and instantaneous reionization histories appropriate for the polarization power spectra displayed in the botton panel. Bottom Panel: The polarization power spectra are displayed for the instantaneous and gradual reionization histories assuming that the 21cm fluctuations are sourced by density inhomogeneities. The color coding is the same in both panels.

Polarization due to baryon density: Discussion

- Standard CDM transfer function for baryons used.
- Wiggles present in C_l^E but not C_l^T. Wiggles in $C_{l,21cm}^E$ not analogous to photon-baryon fluid oscillations imprinted on $C_{l,2.7K}^E$.
- Free streaming monopole becomes quadrapole--Small scale features come from projecting oscillating modes onto a sky map---See Figure.
- Reionization history affects structure of higher order peaks in baryon sourced power spectra. These are well below current detection limits, but perhaps a next-generation experiment could disentangle reionization history through polarization peak structure.
- As distance to reionization becomes larger relative to distance to emission, visibility function is more peaked as function of η, so a smaller range of wave-numbers k contribute to the line of sight projection. The oscillation of the Bessel function doesn't have a chance to washed by integration, and peak structure is more pronounced.

Results in Poisson Fluctuation dominated Regime

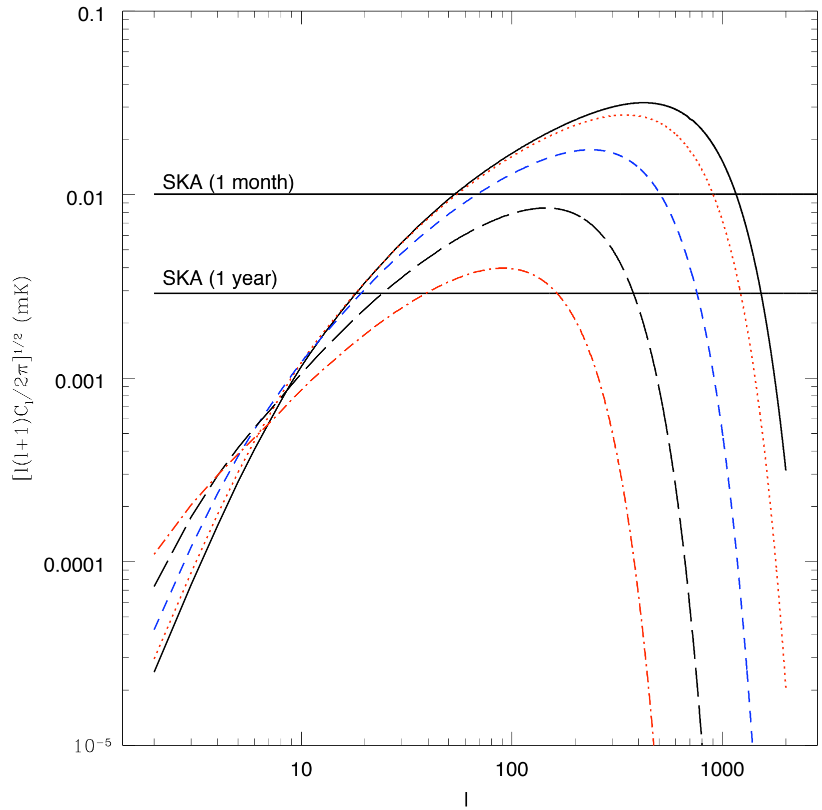


FIG. 5.— The polarization power spectrum sourced by Poisson fluctuations of H II regions for an emission and reionization redshift $z_E = z_R = 30$ (black, solid), $z_E = z_R = 25$ (red, dotted), $z_E = z_R = 17$ (blue, dashed), $z_E = z_R = 10$ (black, long dashed) and $z_E = z_R = 6$ (red, dot dashed). The theoretical detection threshold of SKA is also shown for a 1 month integration time and a 1 year integration time with a bandwidth of 0.4 MHz.

Polarization due to Poisson Fluctuations

- Earlier reionization means smaller bubbles--> More bubbles, few fluctuations in number of HII regions: Expect polarization correlation power to fall with higher redshift.

- Figure belies this expectation! What's going on?

- Visibility function sharply rises at high redshift, and this effect is more dramatic than the fall in power due to lower Poisson fluctuations. The higher density of free electrons at higher redshift increases $\tau_{Thompson}$ and thus the amplitude of polarization power spectra.

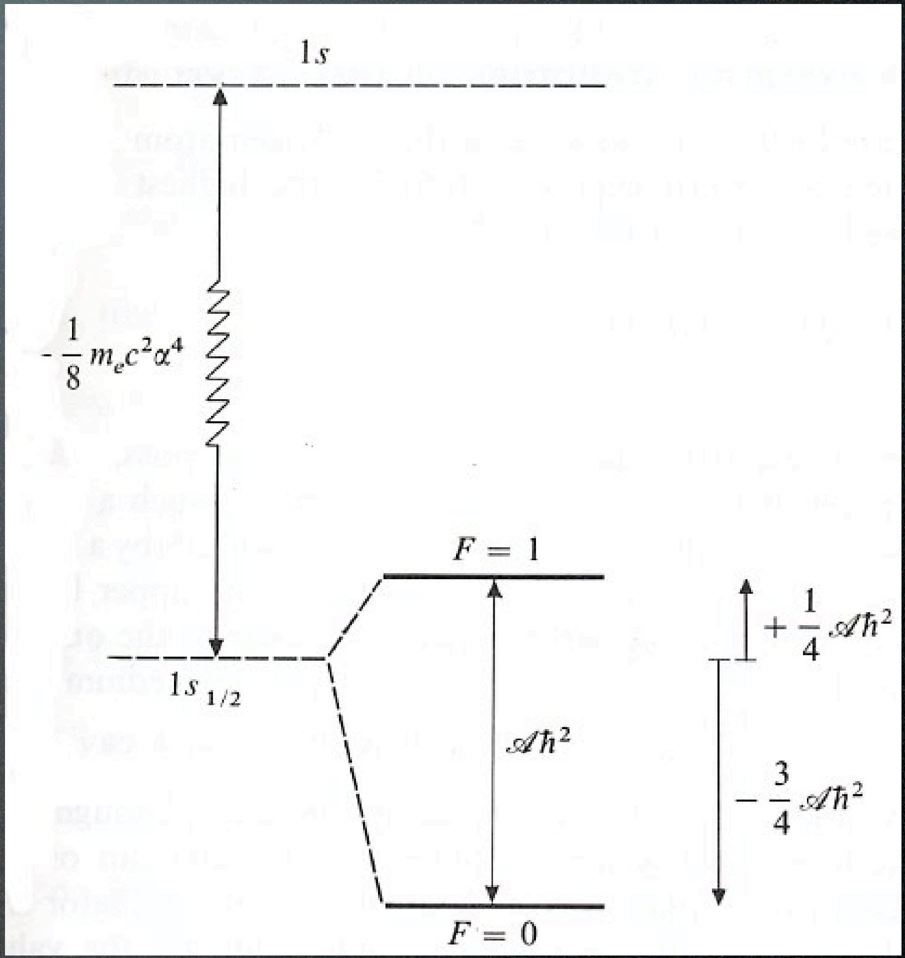
- Polarization signature of reionization could be detected by SKA, LOFAR, and MWA at a variety of redshifts. SKA could even detect $z_r = 6$.

- Reionization redshift is equal to emission redshift, so photons have no time to free-stream and carry power from lower to higher multipoles. Looking at the line of sight integral in an appropriate limit shows that when reionization and emission redshifts are the same, projected anisotropies do not have a multiple-peak structure.

Physics of the 21 cm line:
Hyperfine Splitting in Neutral Hydrogen.

- Fine Structure: Spin orbit coupling and relativistic effects lower energy of HI ground state.
- Addition of nuclear and electron spin yield F=1 triplet and F=0 singlet combined spin states.
- Hyperfine splitting: F=1 state (anti-parallel e and p magnetic moments) is less affected by SO interaction, higher energy than F=0 state.
- Transition between F=1 and F=0 states is a magnetic dipole transition, yields 21 cm line:

$$\nu = 1420.405751768 \pm 1 Mhz$$



Whence Polarization?

Intrinsically Polarized Sources?

B. Zeeman Splitting.

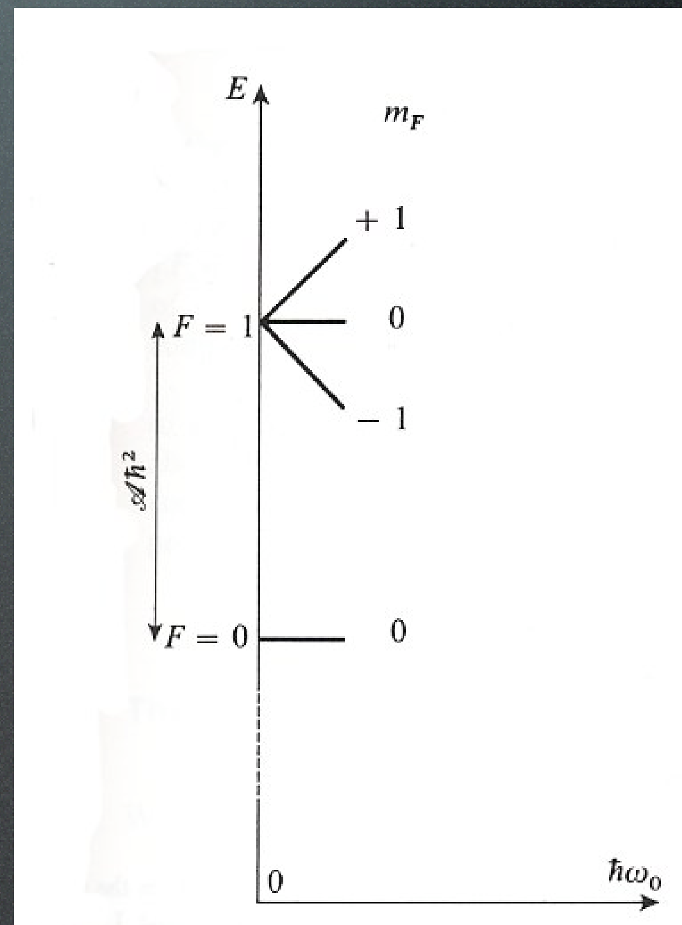
- Application of external B-field will split degenerate F=1 triplet.
- $(F = 1, m_F = 0) \rightarrow F = 0$ feature is undisturbed.
- $(F = 1, m_F = \pm 1) \rightarrow F = 0$ picks up an energy splitting:

$$\nu = \nu_0 \pm \frac{eB}{4\pi m_e c}$$

- The $m_f = \pm 1$ line produces left and right handed circular polarizations of the 21-cm line with differential polarization measure

$$\Delta T_{LR} = 28\ s^{-1} \Delta T^{'}(\nu) \frac{\hat{n} \cdot \vec{B}}{10\mu G}$$

- Mpc-scale HII regions surrounding QSOS at $z \geq 6$ could polarize 21-cm radiation.
- To be detected with SKA, would require $B \geq 100\mu G$,orders of magnitude above theoretical predictions (Furlanetto/Loeb 2001) and Faraday-rotation determined upper limits on extragalactic B-field.

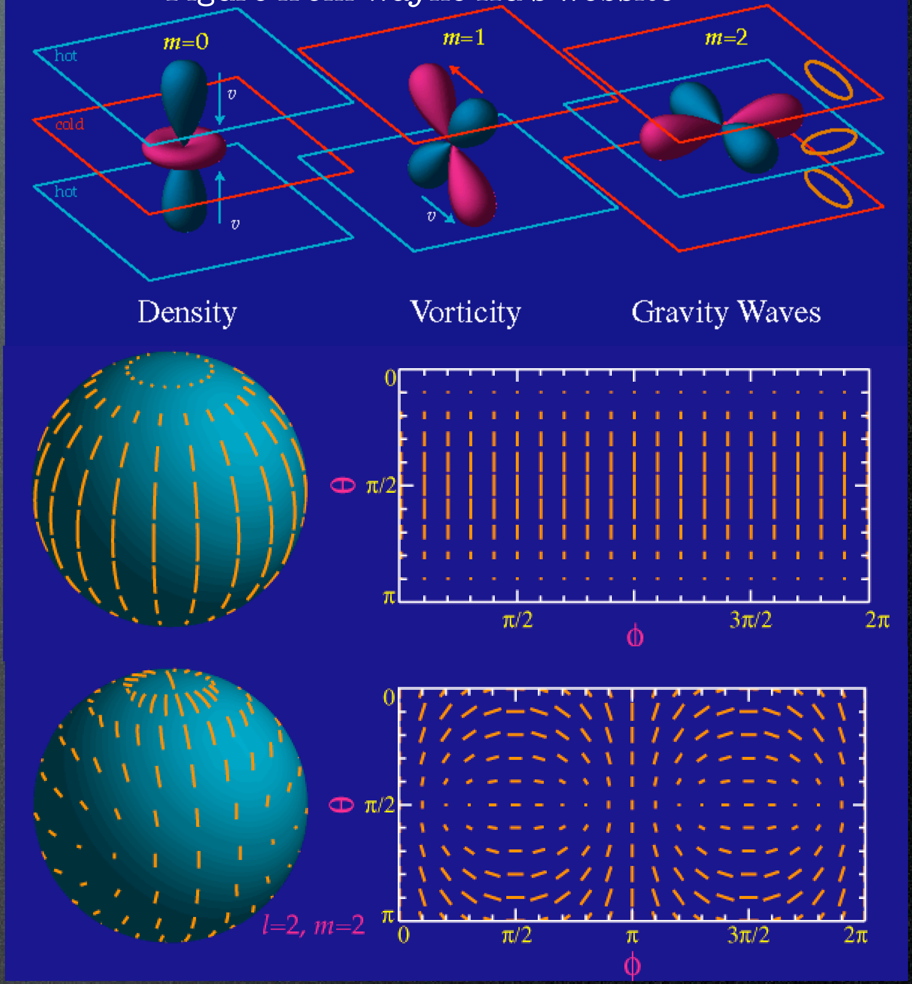


Parity of Polarized 21-cm emission

- B-modes may be produced by lensing, but are small in amplitude (Zaldarriaga and Seljak 1998).

- B-modes may be produced by Faraday rotation of 21-cm emission by B-field in Galactic ISM and IGM--Frequency dependence of Faraday rotation known. This effect could theoretically be removed. (analagous to how galactic synchrotron emission is removed from WMAP data)

Figure from Wayne Hu's website



Messy Stuff:
Boltzmann Equation and Line of Sight Formalism

- Transfer Function $\Delta_P(k,\nu)$ relates initial density inhomogeneity field to observed correlations between polarization on different parts of sky.

- Conserving particle number in an expanding universe and adding a source/sink term for Thompson scattering yields Boltzmann Equation for. Solution requires use of tensor harmonics (Kamionkowski, Kosowski, Stebbins) or spin-weighted spherical harmonics (Seljak and Zaldarriaga) and is

$$\Delta_l^E(k,\nu) = \frac{3}{4}\sqrt{\frac{(l+2)!}{(l-2)!}}\int_0^{\eta_R} d\eta \frac{g(\eta)}{\eta^2 k^2} j_l(k\eta)\Pi(k,\eta,\nu)$$

, where the effect of Thompson scattering (and reionization) is included through the visibility function

$$g(\eta) = \frac{d\tau}{d\eta}e^{-\tau(\eta)}$$

,

and Π is the quadrapole component of the incident fluctuation in 21 cm brightness temperature.