# Signature of Cosmic Magnetic Fields in the Polarization of CMB

## CMBR

**Dominant Component is isotropic**

↓

**Lends support to the Hypothesis of homogeneity and isotropy**

**Finer feature**

**Anisotropy**

- **Spatial variation in potential**
- **Velocity fields**
- **Baryon density perturbations**

↕

**Cosmic Magnetic Fields**

↓

**Polarization**

**Thomson Scattering from charges**

**Spectrum**

**Distortion possible due to Re-ionization + compton scattering**

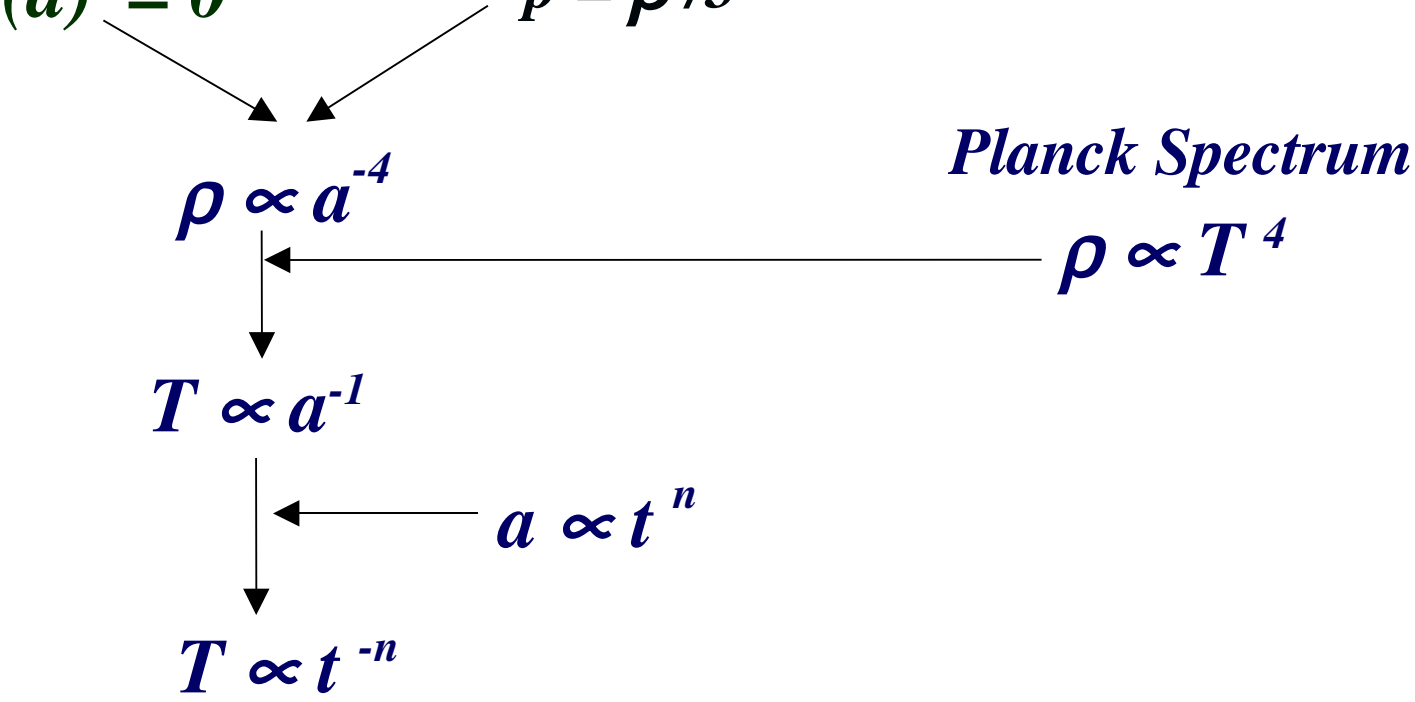
# Time-Temperature Relation

**Continuity Equation for Radiation**

$d(\rho a^3) + p\, d(a)^3 = 0$

**Equation of State for Radiation**

$p = \rho/3$

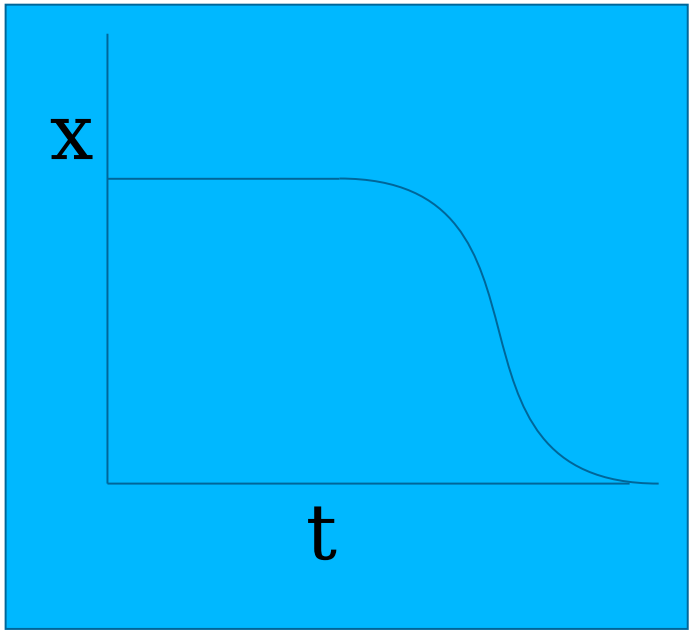



**Photon Temperature very high in the Early Universe**

# Nature of Transition

## Saha Ionization Formula

$$\frac{x^2}{1-x} = \frac{(2\pi m_e kT)^{3/2}}{h^2} \frac{\exp(x/kT)}{N}$$



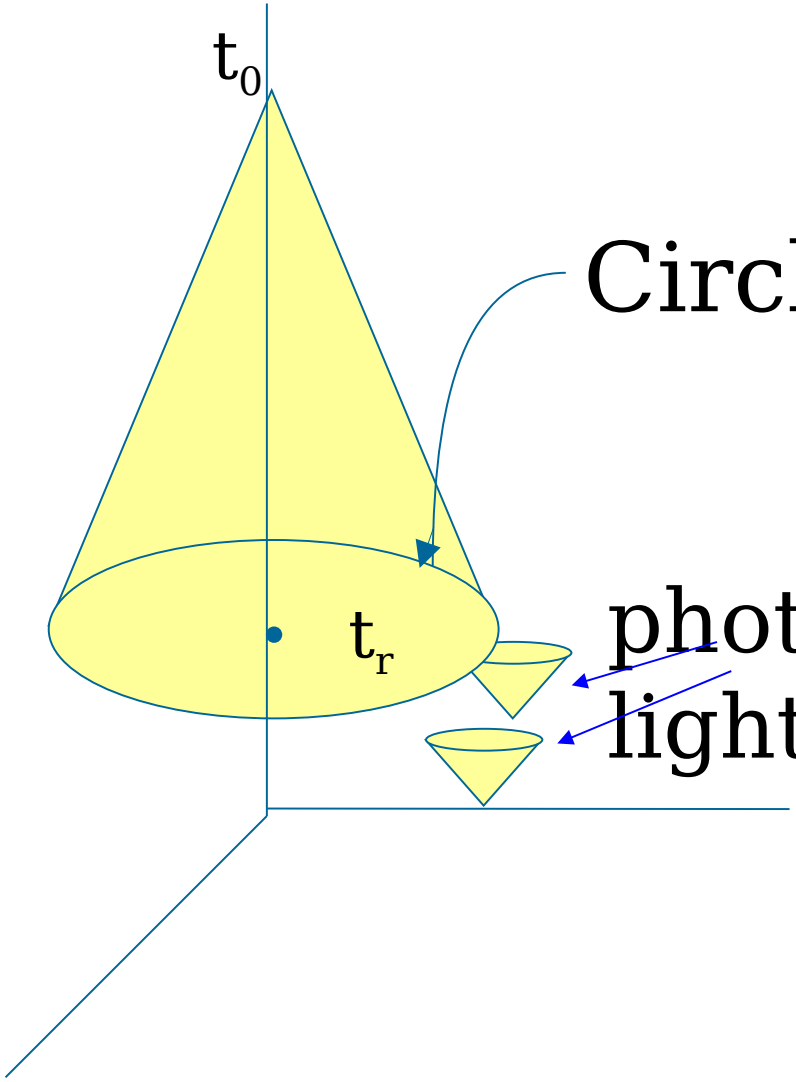

**Transition is rather sharp**

**The epoch of transition well defined**

**Recombination epoch T ~ 3000K**

**Matter in Universe as Plasma before recombination**

# Photon Trajectory - 1 + 2D

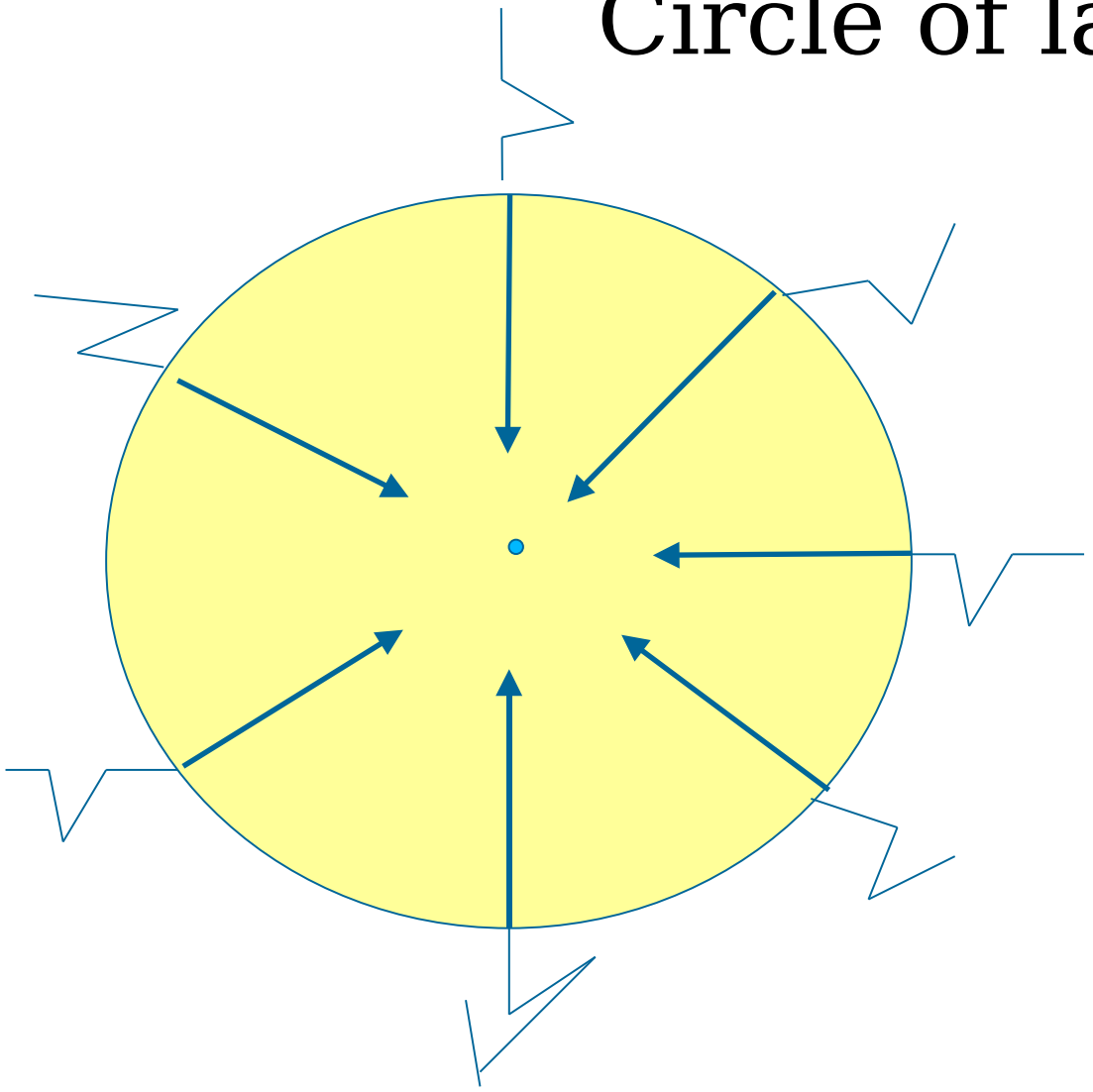



Circle of last scatter

photons scattered alon

light cones

# Circle of last scatter



# Cosmic Microwave Background Radiation

**Nearly Uniform**

**Received from all directions**

**Observed**

Blackbody with T = 2.726 K (observed)

$\lambda_m$ corresponds to **microwave**

**Interpretational**

# ORIGIN OF CMBR

**TILL $t = t_{recom}$ radiation temperature high enough to keep matter in the ionized (PLASMA) form**

**Radiation Interacts strongly with matter**

**r times energy of photons insufficient to keep matter**

↓

Hence transition from PLASMA to NEUTRAL state

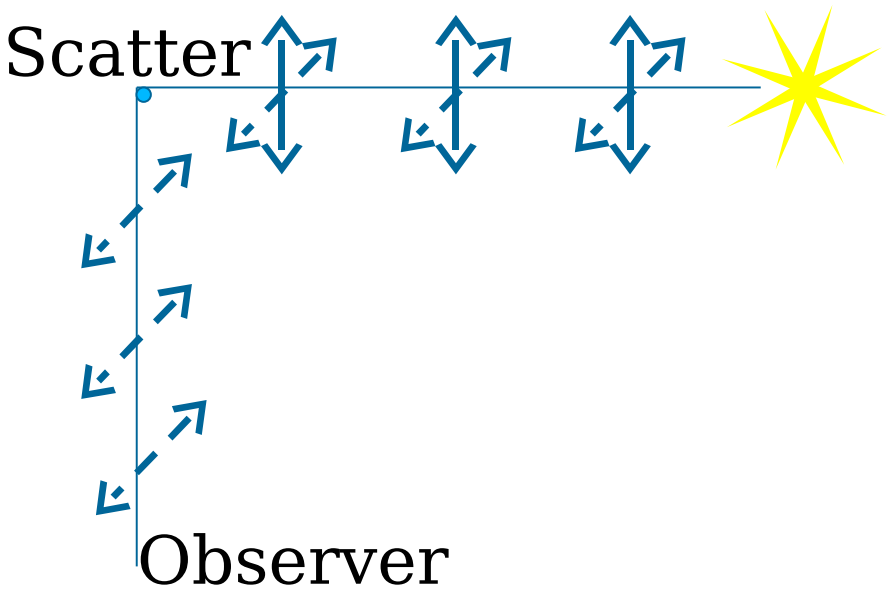
**Interaction of radiation and matter drops abruptly**

**Radiation free streams; received today as CMBR**

**CMBR a strong pillar of HOT BIG BANG MODEL**

# Origin of Polarization

An example from our atmosphere

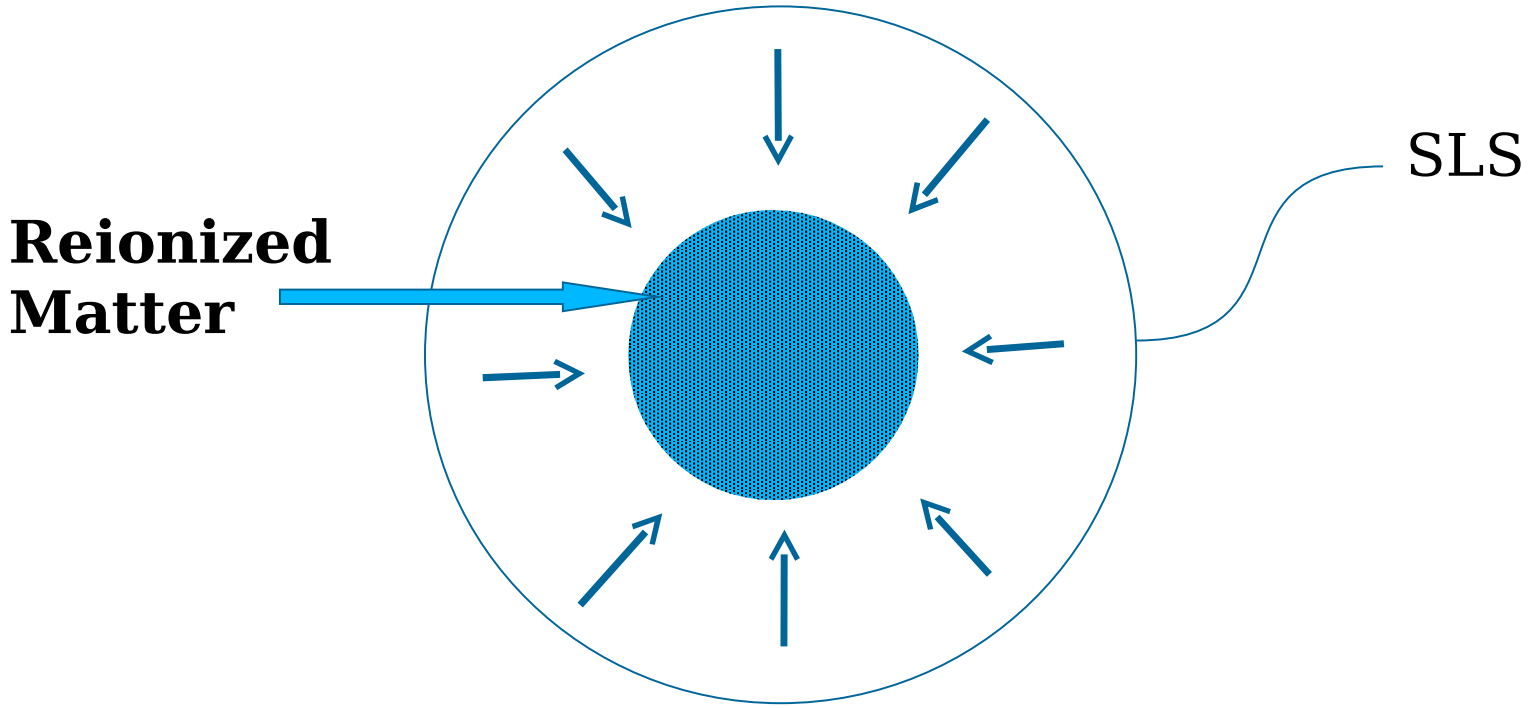



Anisotropic Radiation +Free Charges

**Thomson Scattering**

**POLARIZATION**

# ization in Cosmology - in reionized Univ




he reionized matter is like a cosmological ionosphe

he nature of Polarization sheds light on the details
f reionization

# CMB Polarization :

*Standard case without reionization*

formation in Photons washed out by Scatter

***But***

scattering event on the Surface of Last scat
an anisotropy from the last-but-one-scatter

Leads to polarization of CMBR

# Evolution Equation for Temperature and Polarization Fluctuations

**Boltzman Equation for the CMB Photons** → **Evolution of Temperature and Polarization Fluctuations**

$$< E_i^* \ E_j >$$ **(Intensity Matrix)**

$$\mathbf{T} = \Theta \mathbf{I} + Q\sigma_\mathbf{3} + U\sigma_\mathbf{1} + V\sigma_\mathbf{2} \qquad \Theta = Tr(\mathbf{T}\ \mathbf{I})/2$$

$$\mathbf{T} = \Theta \mathbf{I} + (Q + iU)\mathbf{M}_+ + (Q - iU)\mathbf{M}_- + V\sigma_\mathbf{2}$$

$$\mathbf{M}_+ = (\sigma_\mathbf{3} - i\sigma_\mathbf{1}) \qquad \mathbf{M}_- = (\sigma_\mathbf{3} + i\sigma_\mathbf{1})$$

$$\vec{T} = (\Theta, Q + iU, Q - iU)$$

$$\frac{d}{d\eta}\vec{T} = \frac{\partial}{\partial x}(\vec{T}) + n^i \nabla_i \vec{T} = \vec{C}[\vec{T}] + \vec{G}[h_{\mu\nu}]$$

# Basis Function Expansion

can be expanded in terms of basis functions

are components of a spin-2 field.
e, they cannot be expanded in terms of $Y_{lm}$

functions consist of Spin weighted spheric
onics.
e Temperature, Q and U are not rotationally invar

s to difficulties in superposition for different k's

a rotationally invariant description of polarizatio

# ionally Invariant Description of Polariz

**e spin raising and spin lowering operators**

**te them on Q,U**

**et scalar quantities called E-type and**
**e polarization**

**are scalars E has even parity and B has odd parity**

**raising and lowering are differential operators**

**B are not rotationally invariant combinations of Q a**

**like rotationally invariant combinations of**
**acian like' operations on Q and U.**

$$\Theta = \int \frac{d^3k}{(2\pi)^3} \sum_l \sum_{m=-2}^{2} \Theta_l^{(m)} G_l^m$$

$$Q + iU = \int \frac{d^3k}{(2\pi)^3} \sum_l \sum_{m=-2}^{2} (E_l^{(m)} + iB_l^{(m)})_{+2} G_l^m$$

$$Q - iU = \int \frac{d^3k}{(2\pi)^3} \sum_l \sum_{m=-2}^{2} (E_l^{(m)} - iB_l^{(m)})_{-2} G_l^m$$

**Cosmic Magnetic Fields**

**Divergence free velocity fields**

$$| m | = l \text{ modes}$$

# tatistical Measures of CMBR Polarizatio

$$(2l+1)^2 C_l^{XY} = \frac{2}{\pi} \int dk\ k^2 \sum_{m=-2}^{2} X_l^{(m)}\ {}^*Y_l^{(m)}$$

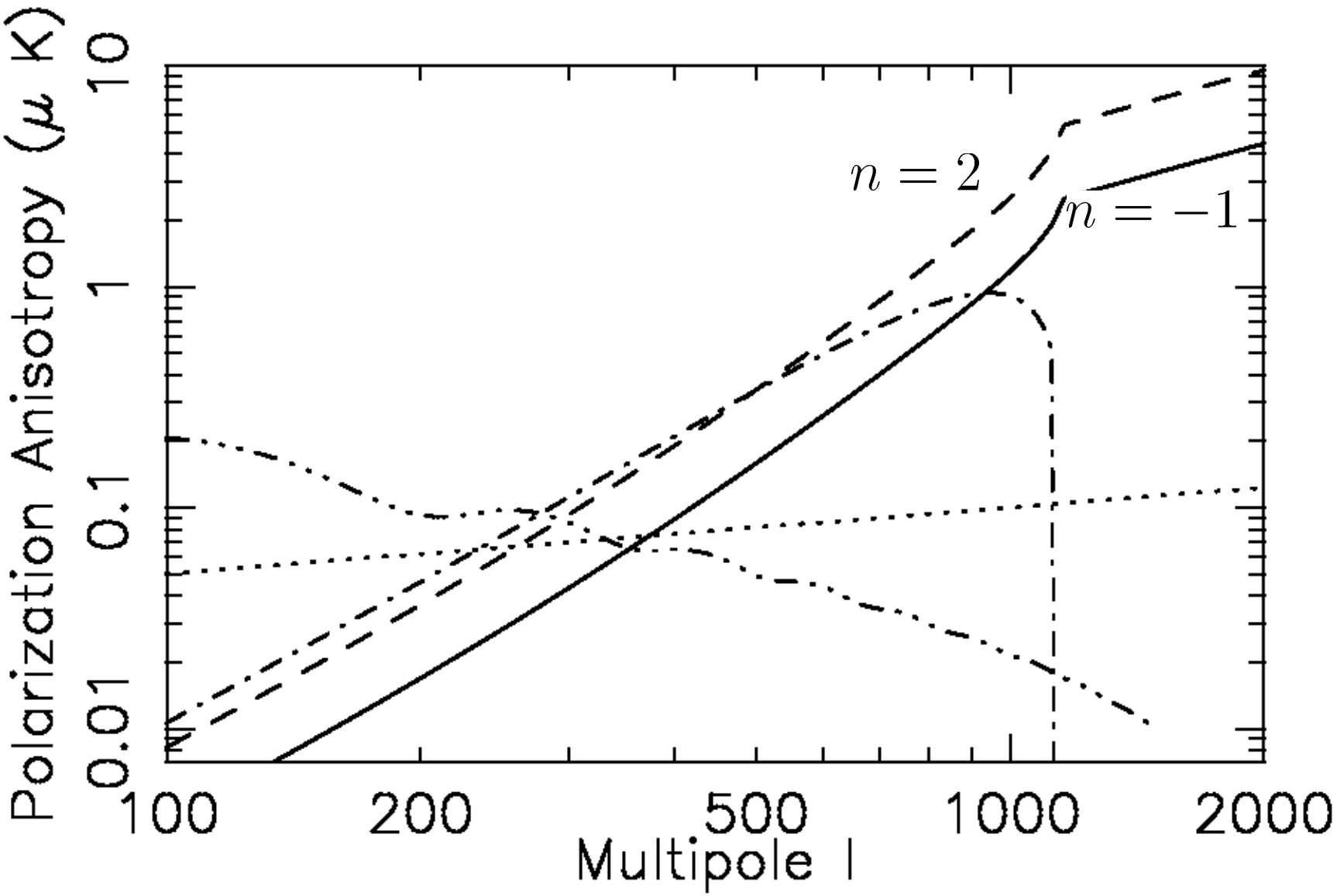
$$C_l^{\Theta\Theta} = 4\pi \int dk\ \frac{k^2}{2\pi^2} \frac{l(l+1)}{2} \langle | \int_0^{\eta_0} d\eta g(\eta_0, \eta) v \frac{j_l(k(\eta_0 - \eta))}{k(\eta_0 - \eta)} |^2 \rangle$$

Similarly $C_l^{E\Theta}$, $C_l^{EE}$ and $C_l^{BB}$

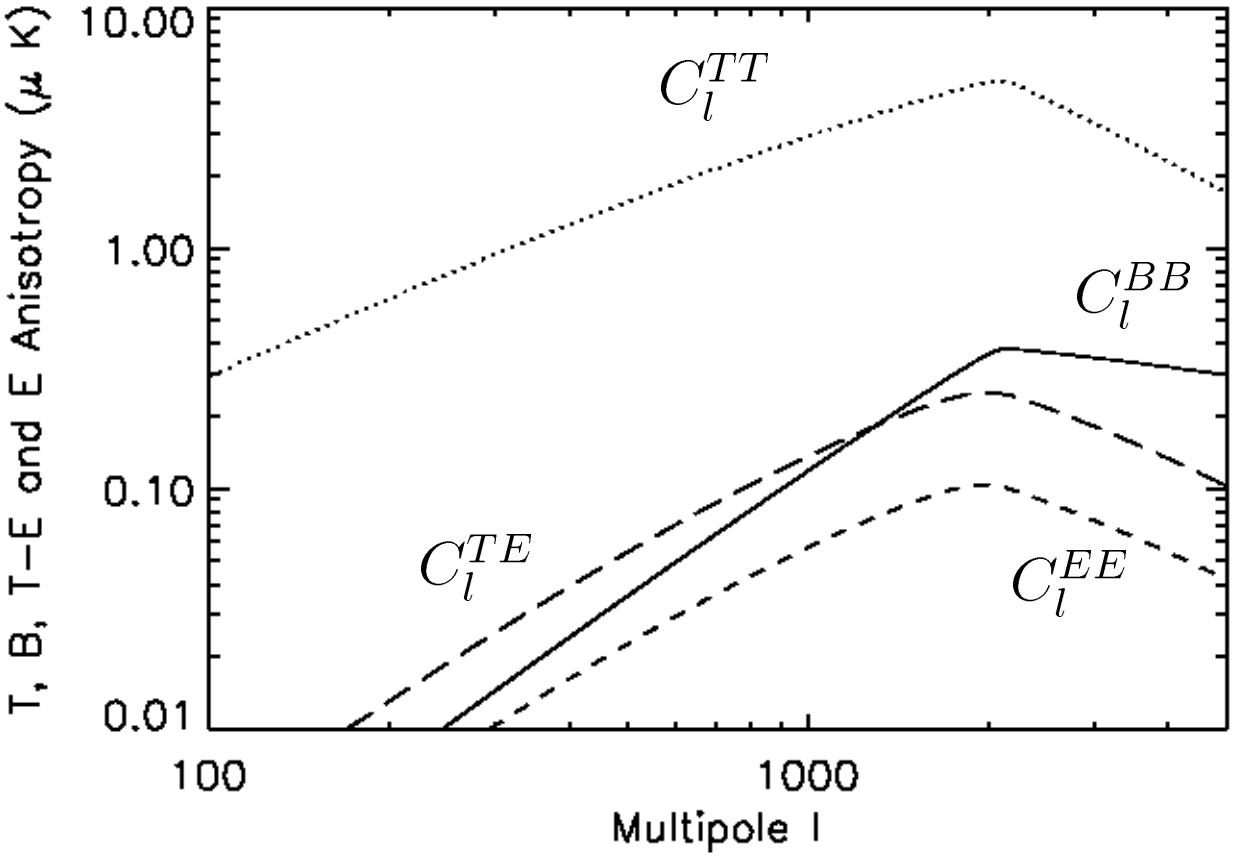
$$g(\eta_0, \eta) = -\dot{\tau} \exp(-\tau) \qquad \tau = \int_{\eta}^{\eta_0} d\eta\ \ n_e \sigma_T a(t)$$

$g(\eta_0, \eta)\ d\eta$:

Probability that the photon received today was last scattered between $\eta$ and $\eta + d\eta$

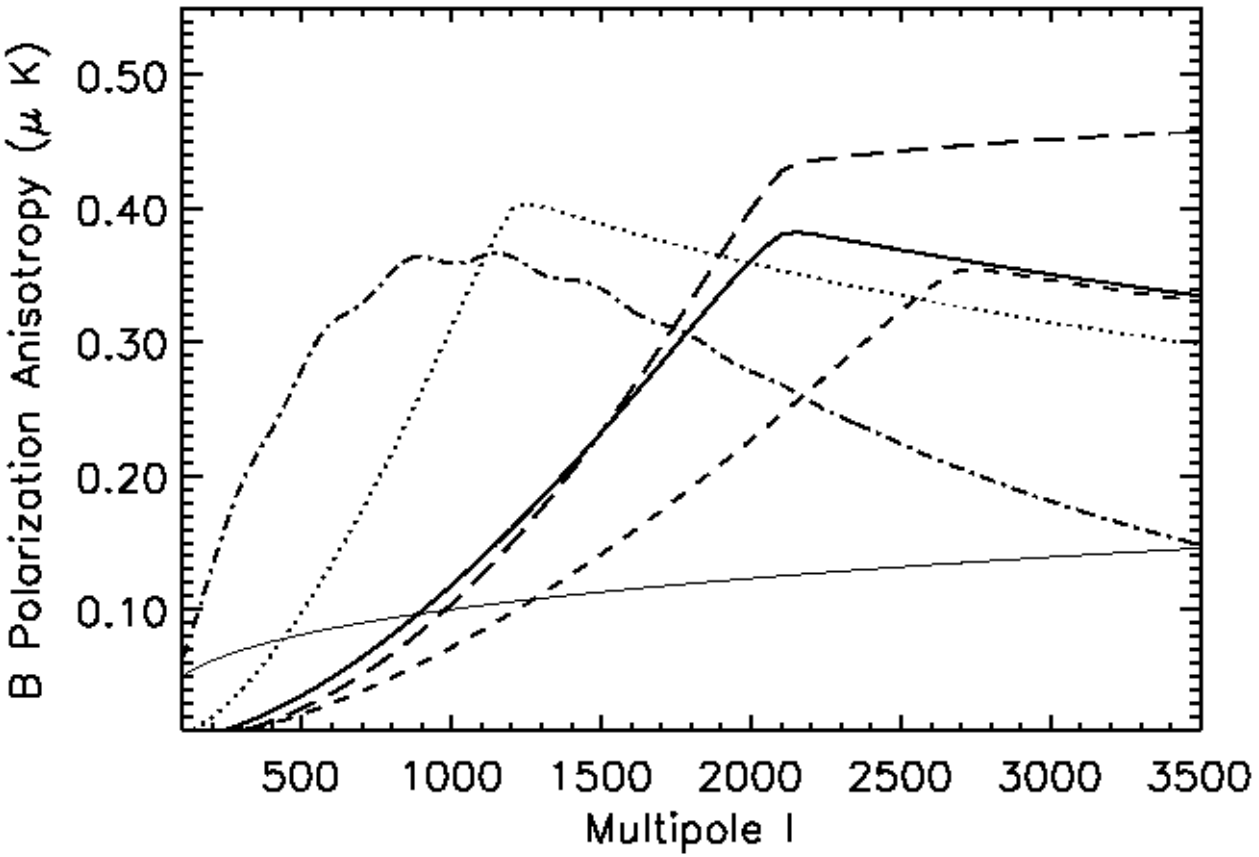



***Phys. Rev. Lett. 87 (2001) 101301***
***TRS and K. Subramanian***




$\Lambda - CDM$ and a nearly scale-invariant Magnetic field Power-spectrum

***Mon. Not. RAS 344 (2003) L31-L35***
***K. Subramanian, TRS and John D. Barrow***

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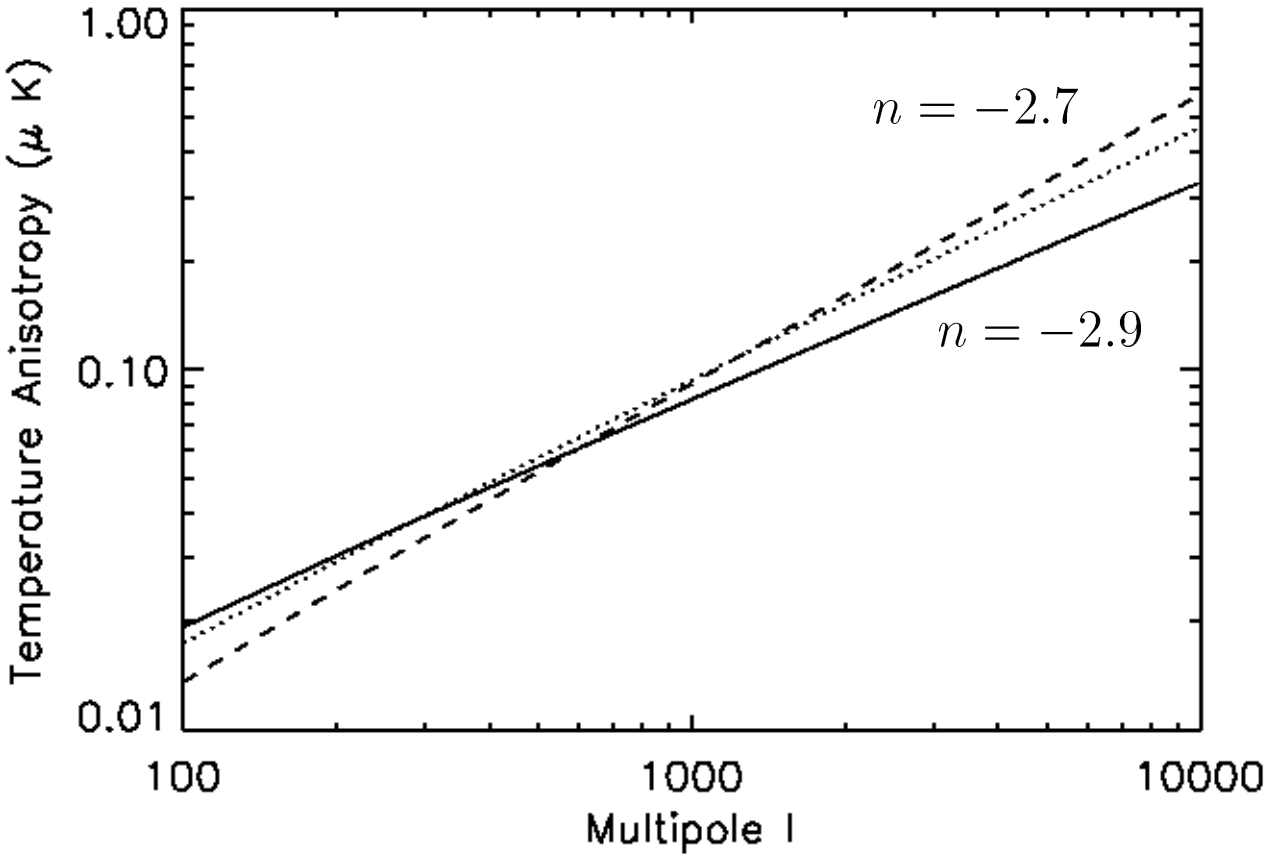


*Phys. Rev. D72 (2005) 023004*
*TRS and K. Subramanian*

# What can CMB Polarization tell us

1: Reionization in the Universe

2: Nature of Cosmological Magnetic Field

3: Imprint of Gravitational Waves

4: Gravitational Lensing of CMB

# Conclusions

**CMB Polarization and Temperature anisotropy Maps can enlighten us about the nature and strength of Cosmic Magnetic Fields**

**The B-B correlation at small angles (large angles) is important**

**A scale invariant Magnetic Field which redshifts to about 3 nano Gauss today can produce micro-kelvin level fluctuations in polarization anisotropy**

**Statistical Properties of the polarization and Anisotropy**