

# Bicep-II detection of CMB B-modes

Ade et al. arXiv :1403.3985 (63 citations after 8 days)

New York Times :

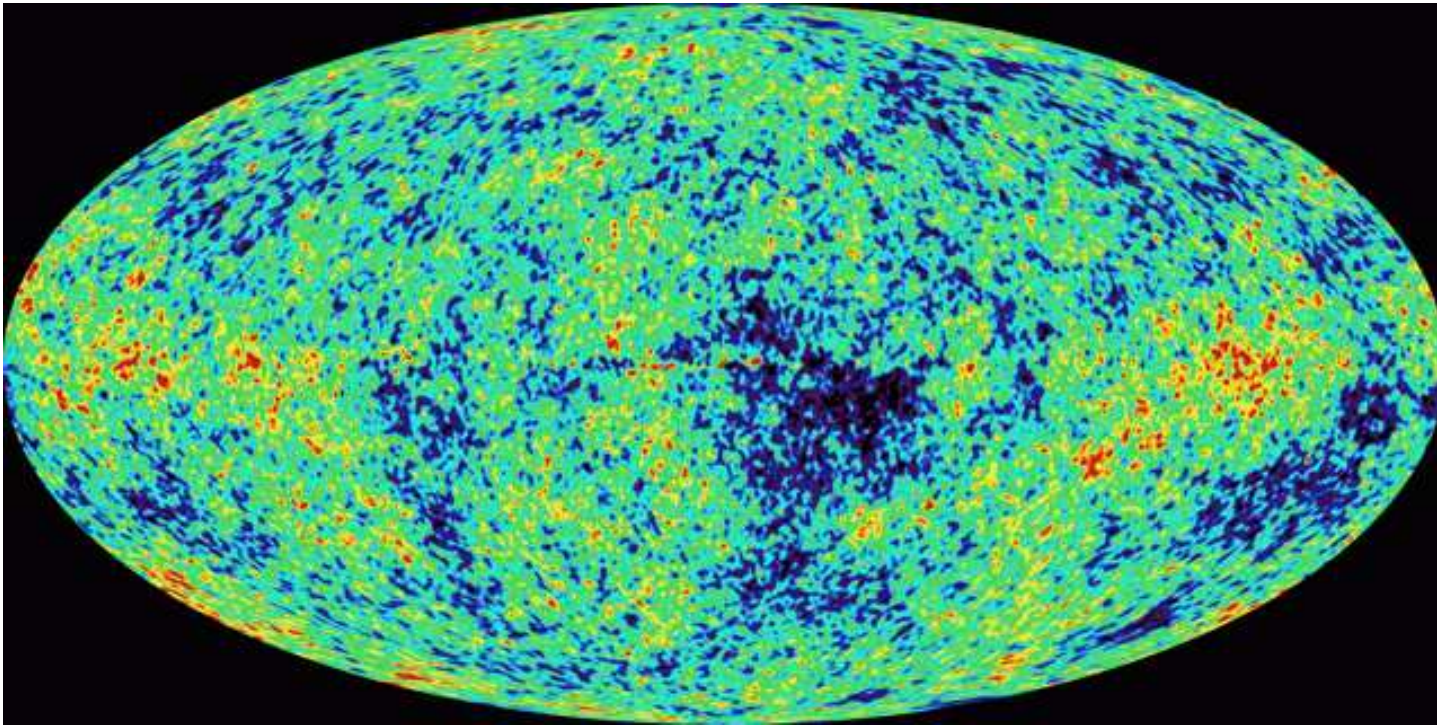
“Space Ripples Reveal Big Bang’s Smoking Gun”



# Bicep telescope at South Pole



# WMAP all sky temperature map



$$T_0(1 + 10^{-5})$$

$$T_0(1 - 10^{-5})$$

Thermal spectrum :  $T_0 = 2.728K$ ,  $kT = 2.348 \times 10^{-4}eV$

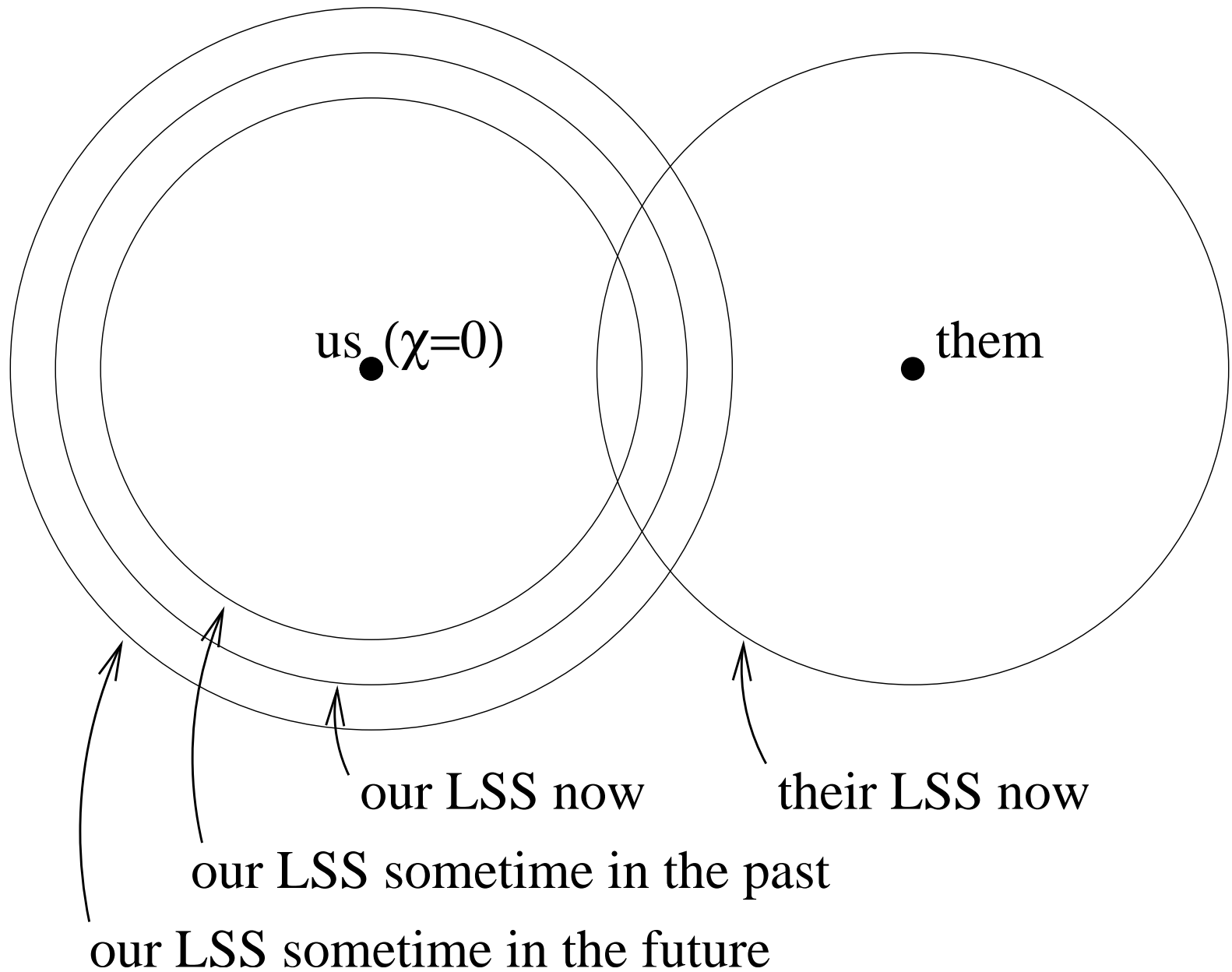
Photons last scattered (on electrons) when

redshift= $z \sim 1080$      $t \sim 4 \times 10^5\text{yr}$ ,     $kT \sim 0.2eV$

Present distance to Last Scattering Surface (LSS) :

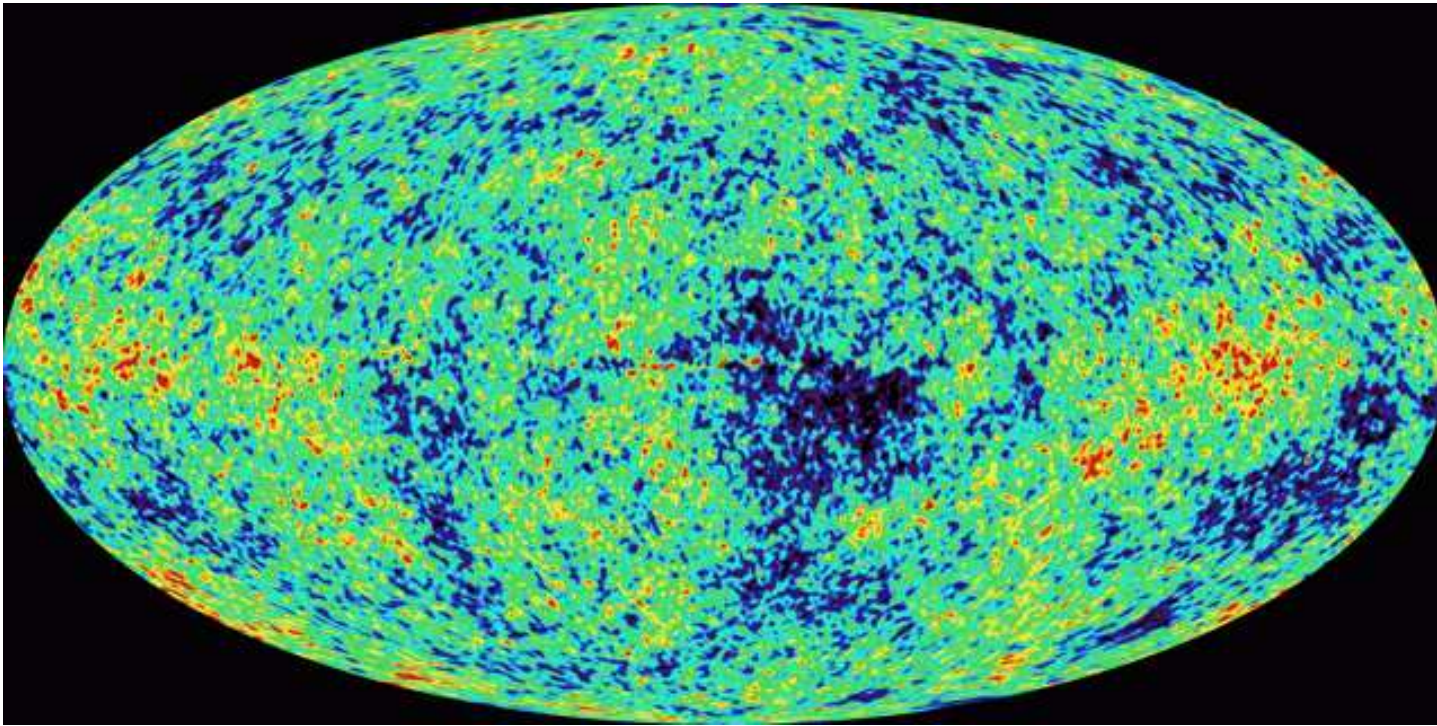
$$D(z = 1080) = 14.3Gpc \quad (\Omega_\Lambda = 0.73, \Omega_M = 0.27)$$

# Last scattering surface





# Origin of temperature anisotropies



Large ( $>1$ deg) **cold** regions :

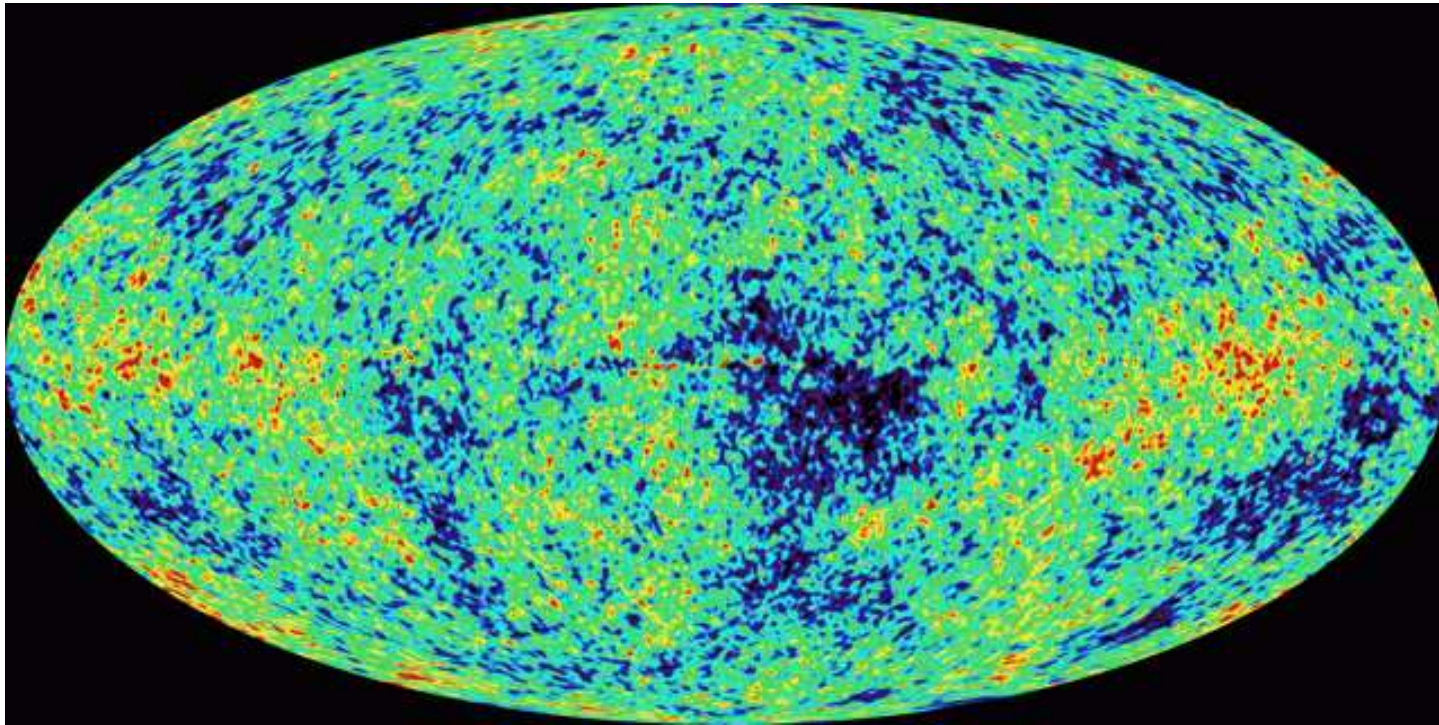
potential **wells** on LSS (concentrations of DM+baryons)

Small ( $<1$ deg) **cold** regions :

regions where the plasma is **colder** than average

OR falling toward mass concentration **behind** the LSS.

# Origin of temperature anisotropies



Large ( $>1$ deg) **hot** regions :

potential **hills** on LSS (deficits of DM+baryons)

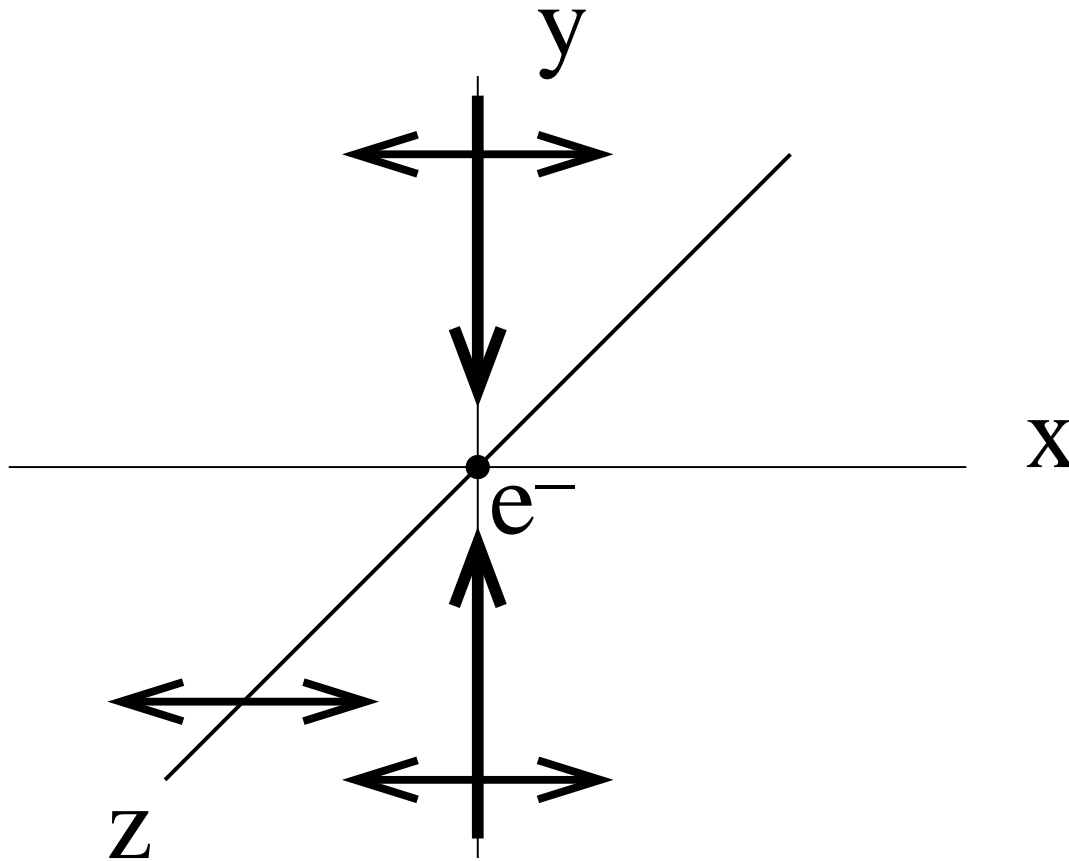
Small ( $<1$ deg) **hot** regions :

regions where the plasma is **hotter** than average

OR falling toward mass concentration **in front of** the LSS.

# Thomson scattering polarizes photons

Compton scattering just before recombination ;  
LSS= $xy$ -plane ; Observer on  $z$  axis

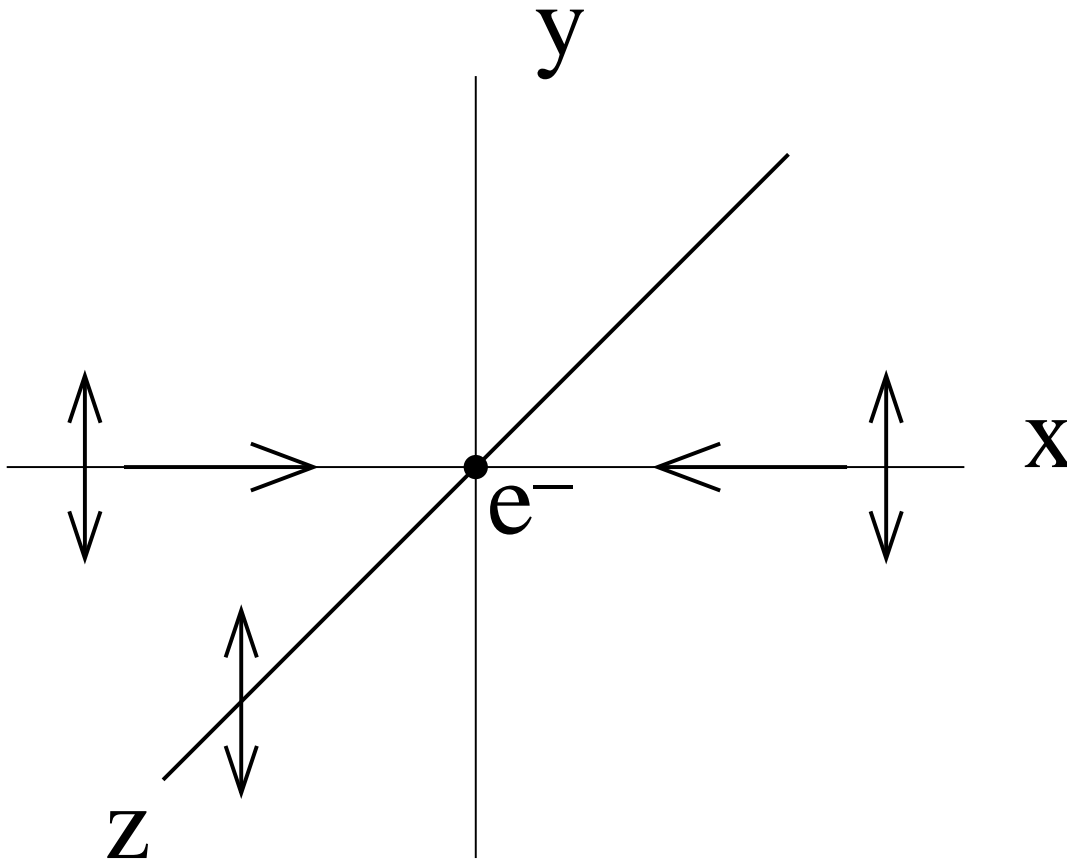


photon flux( $\pm y$  directions)

$\Rightarrow$  photon polarization observed in  $x$  direction

# Thomson scattering polarizes photons

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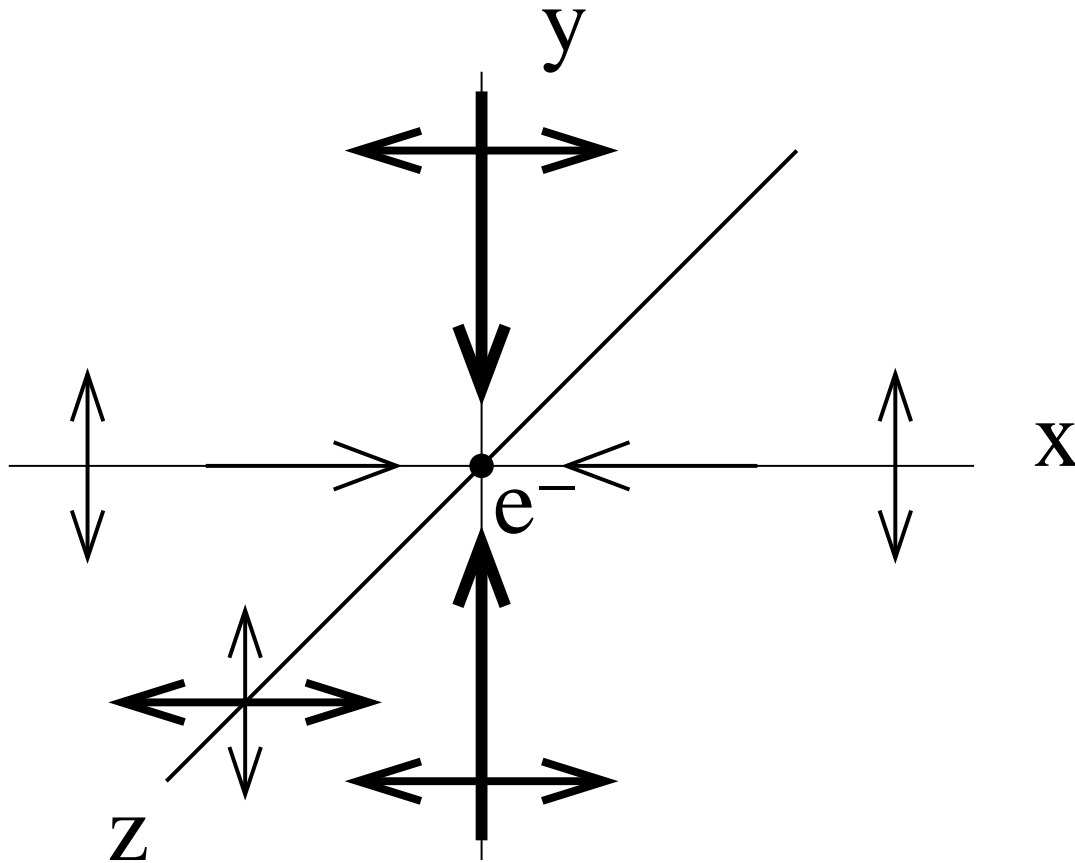
photon flux( $\pm x$  directions)

$\Rightarrow$  photon polarization observed in  $y$  direction



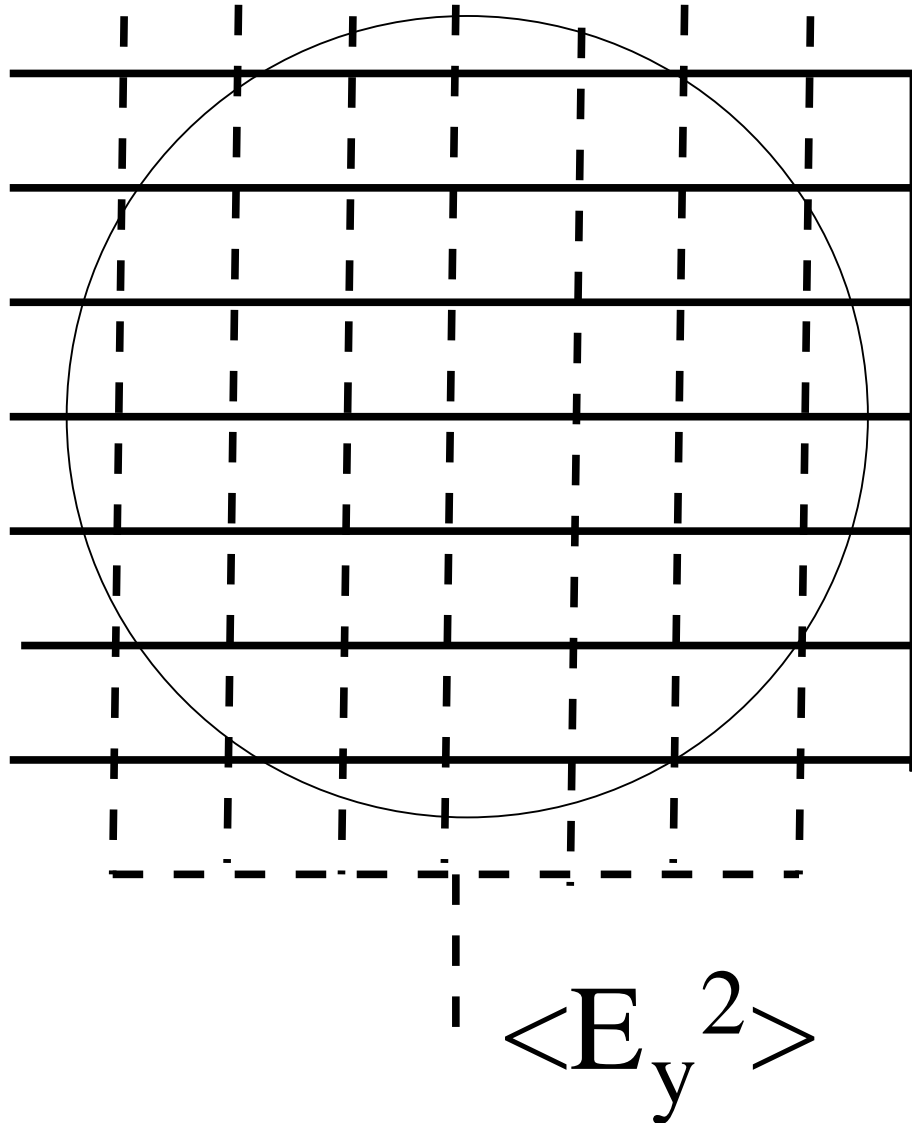
# Inhomogeneities $\Rightarrow$ linear polarization

Compton scattering just before recombination ;  
LSS= $xy$ -plane ; Observer on  $z$  axis



photon flux( $\pm y$  directions)  $>$  photon flux( $\pm x$  directions)  
 $\Rightarrow$  photon polarization observed in  $x$  direction

# Telescope focal plane pixels

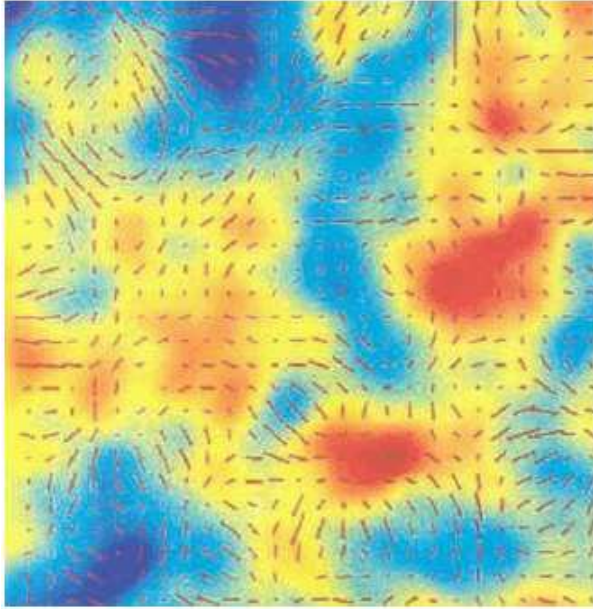


$$\langle E_x^2 \rangle$$

Compare signals in  
orthogonal bolometers

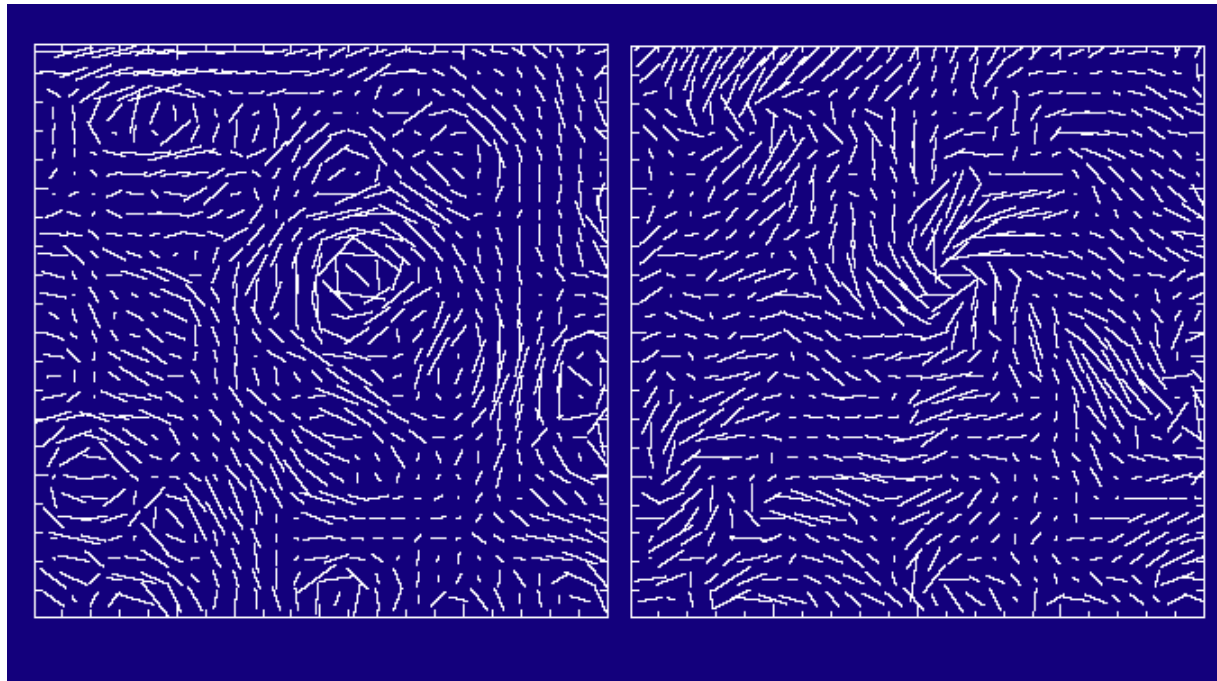
Systematics :  
relative sensitivity,  
orientation, and pointing  
of bolometer pairs.

# Temperature and polarization maps



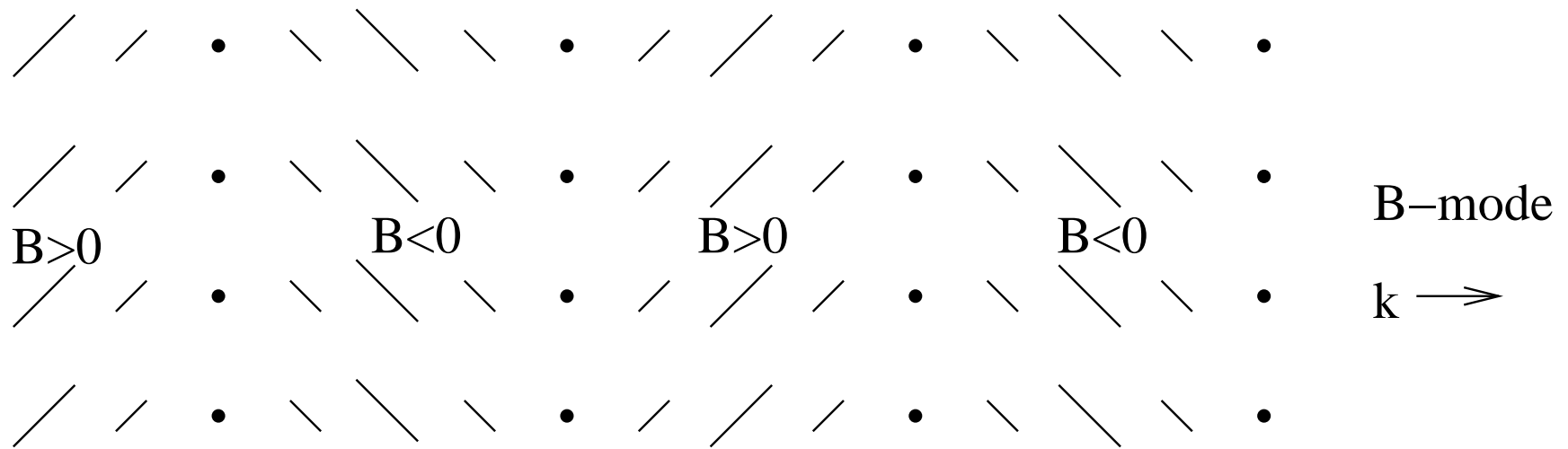
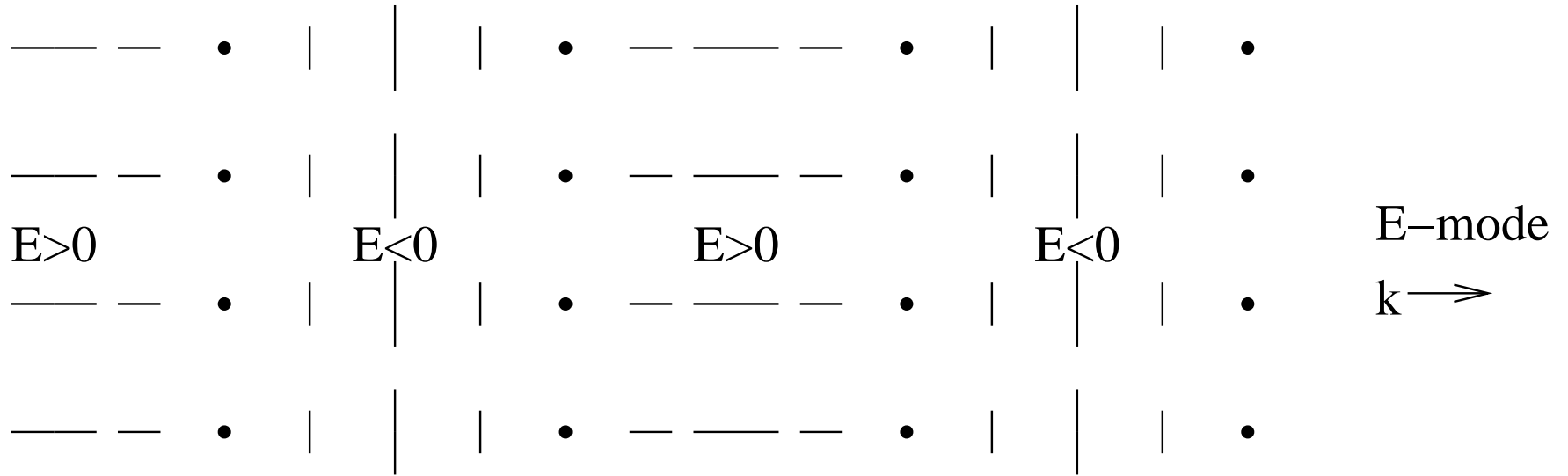
Simulated Temperature and polarization map.  
Line length  $\propto$  polarization

Sum of  
E modes

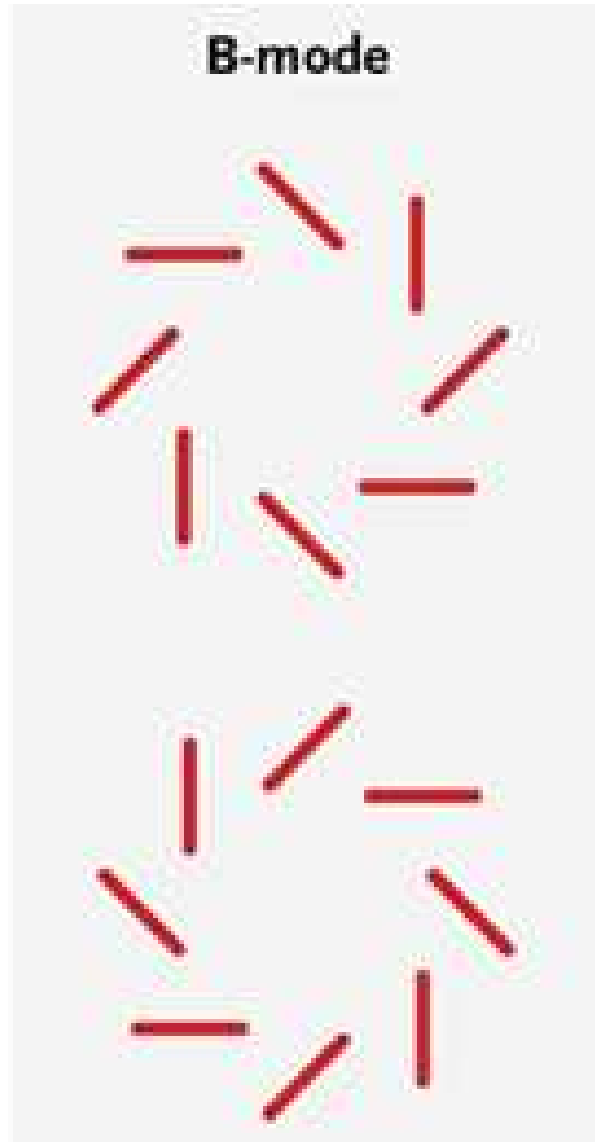
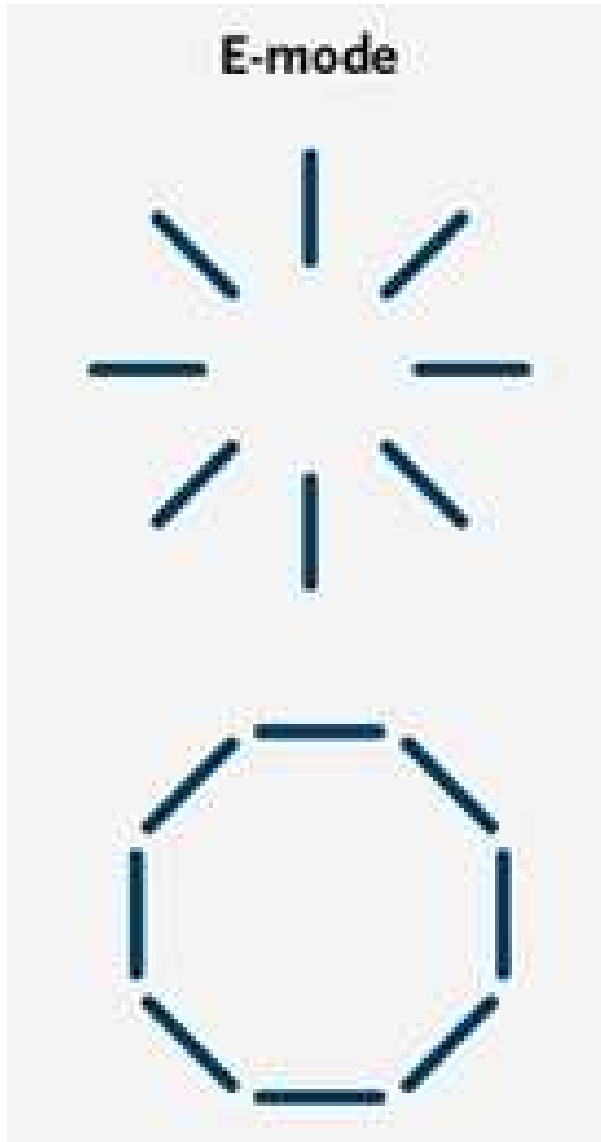


Sum of  
B modes

# E (0, 90deg) and B ( $\pm 45$ deg) modes for $\vec{k}$



# superimpose E- or B-modes



Wave packets



# Polarization from $(\rho, v)$ inhomogeneities

Things that make the pre-recombination plasma move :

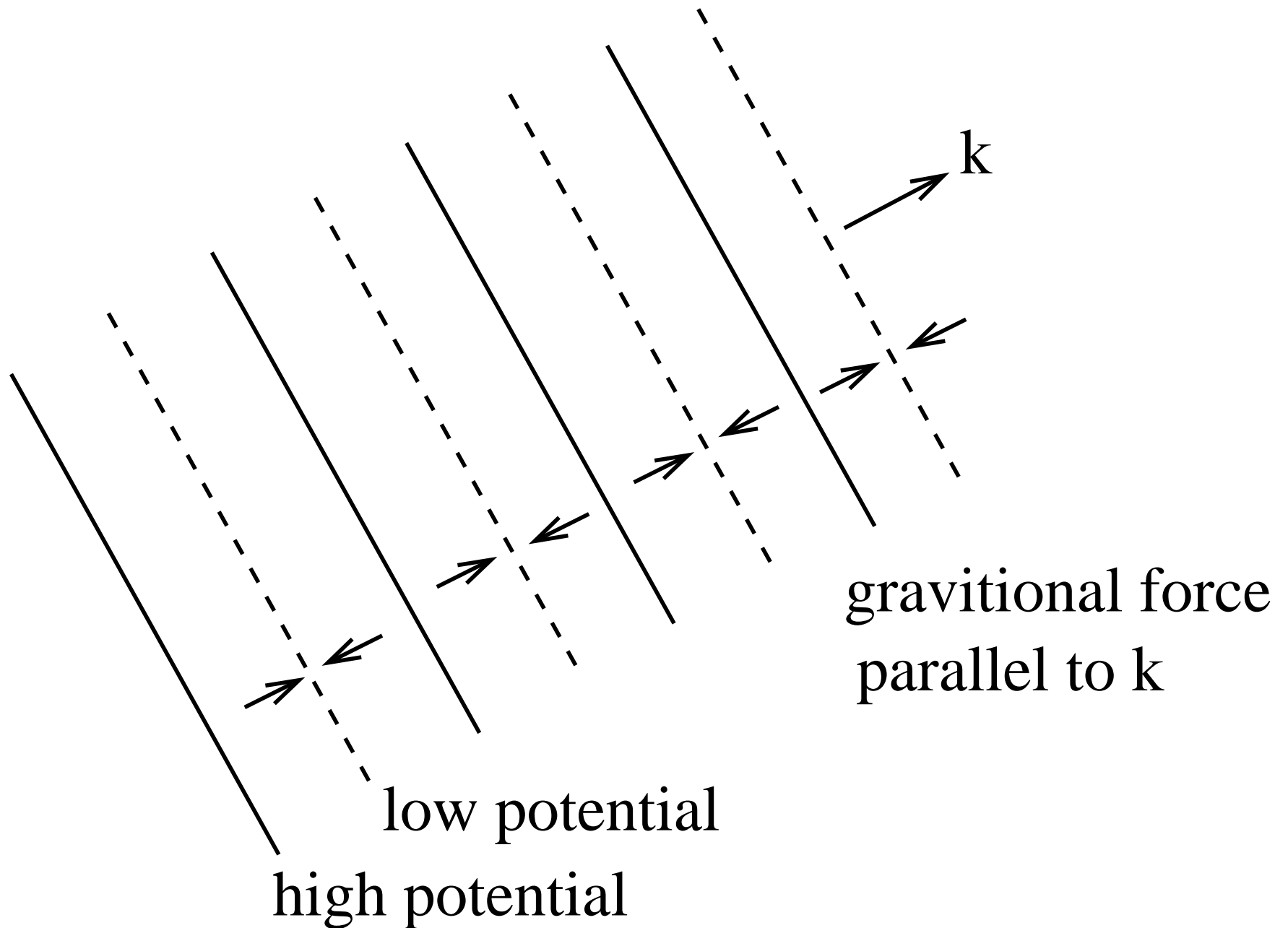
Movement parallel to  $\vec{k}$

- gravitational potential gradient
- pressure gradient

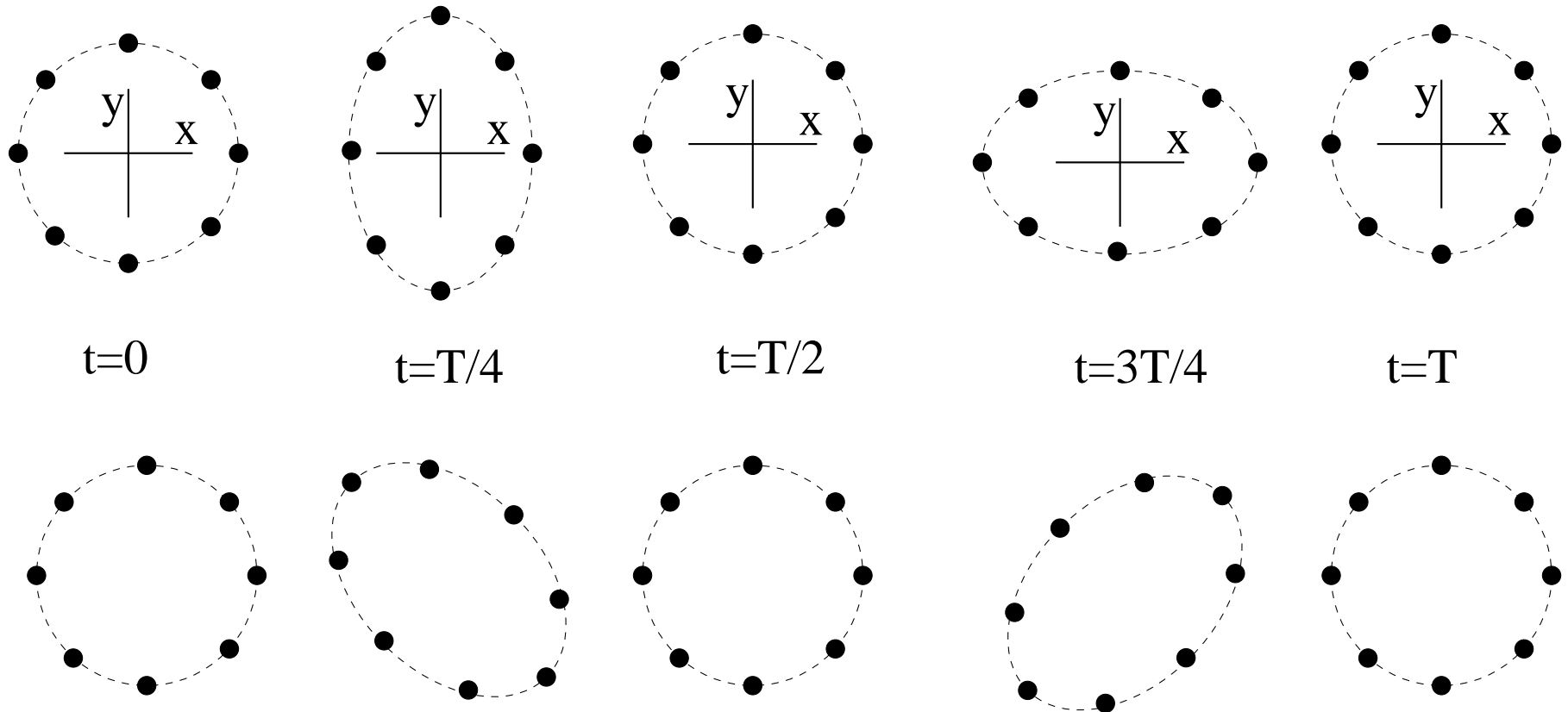
Movement perpendicular to  $\vec{k}$

- gravitational waves

# Response of particles to periodic potential

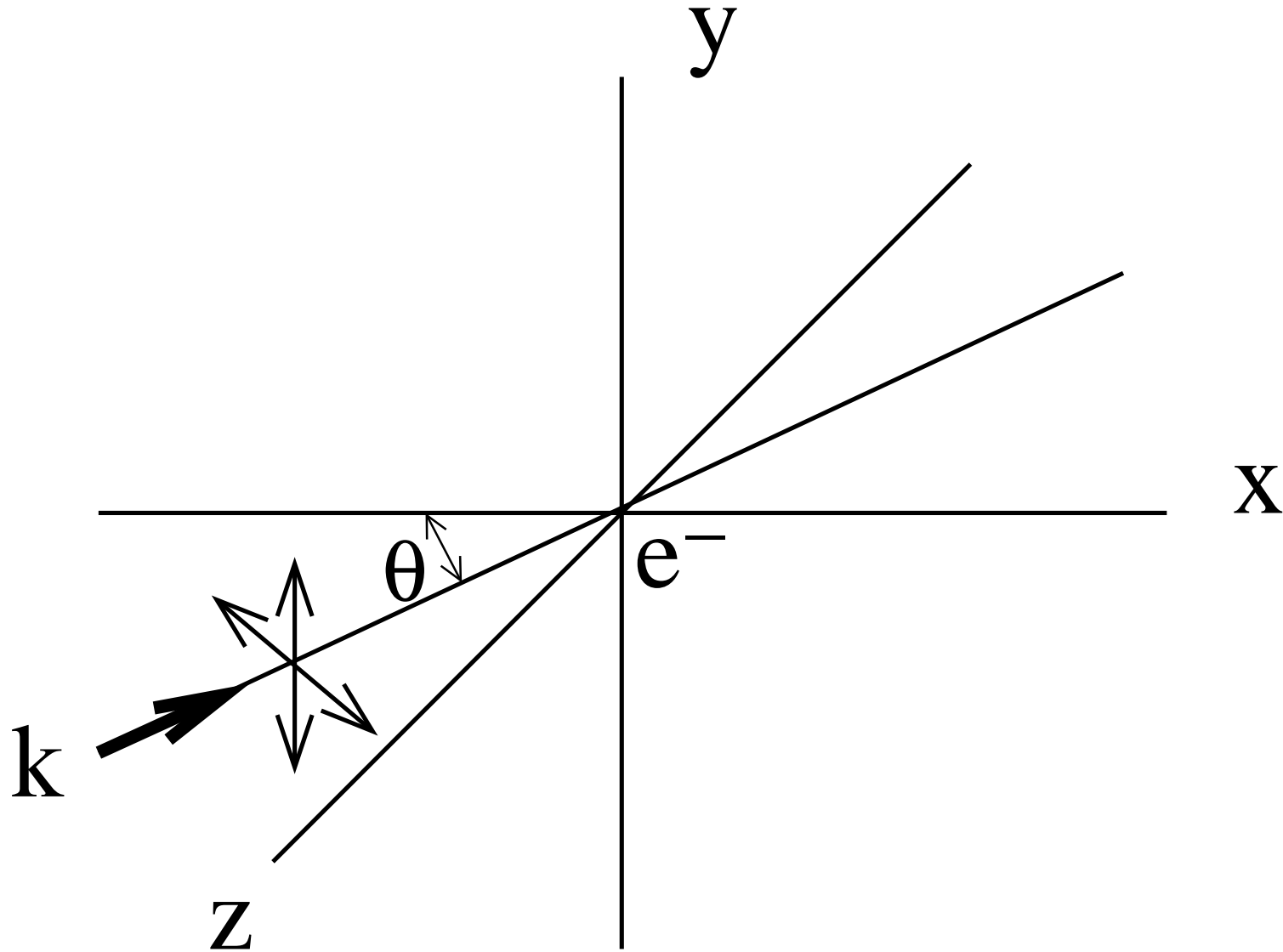


# Response of free particles to G-wave



Two modes ; Movement perpendicular to  $\vec{k}$

# G-wave on LastSS



# perturbation → polarization mode

To find what polarization modes are produced by a perturbation mode, project  $\vec{k}$  and induced plasma movement onto LastSS.

- Potential perturbation

plasma movement parallel to  $\vec{k}$

⇒ E mode

- Gravitational wave

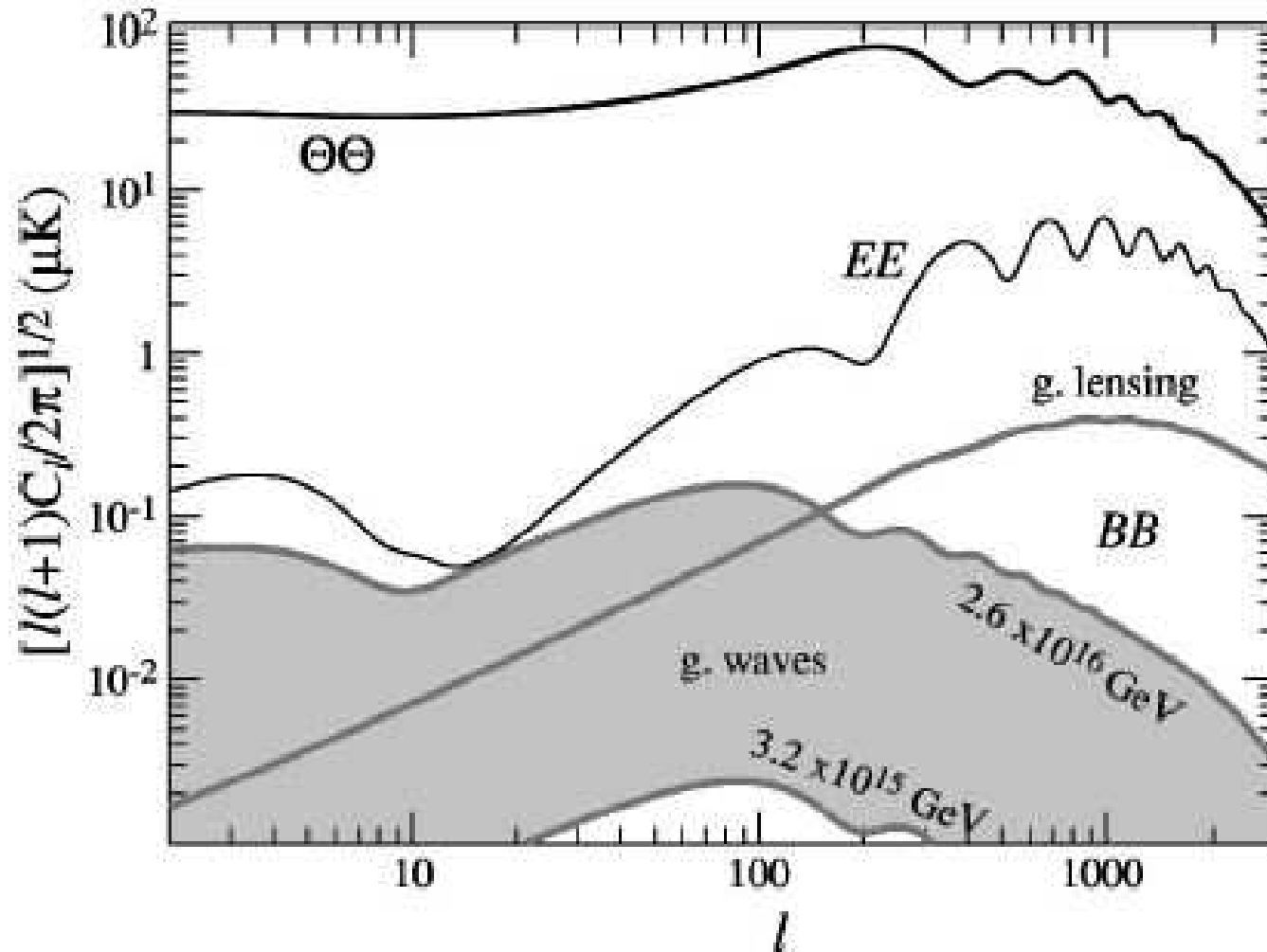
plasma movement perpendicular to  $\vec{k}$

⇒ E and/or B mode

(depending on relative orientation)



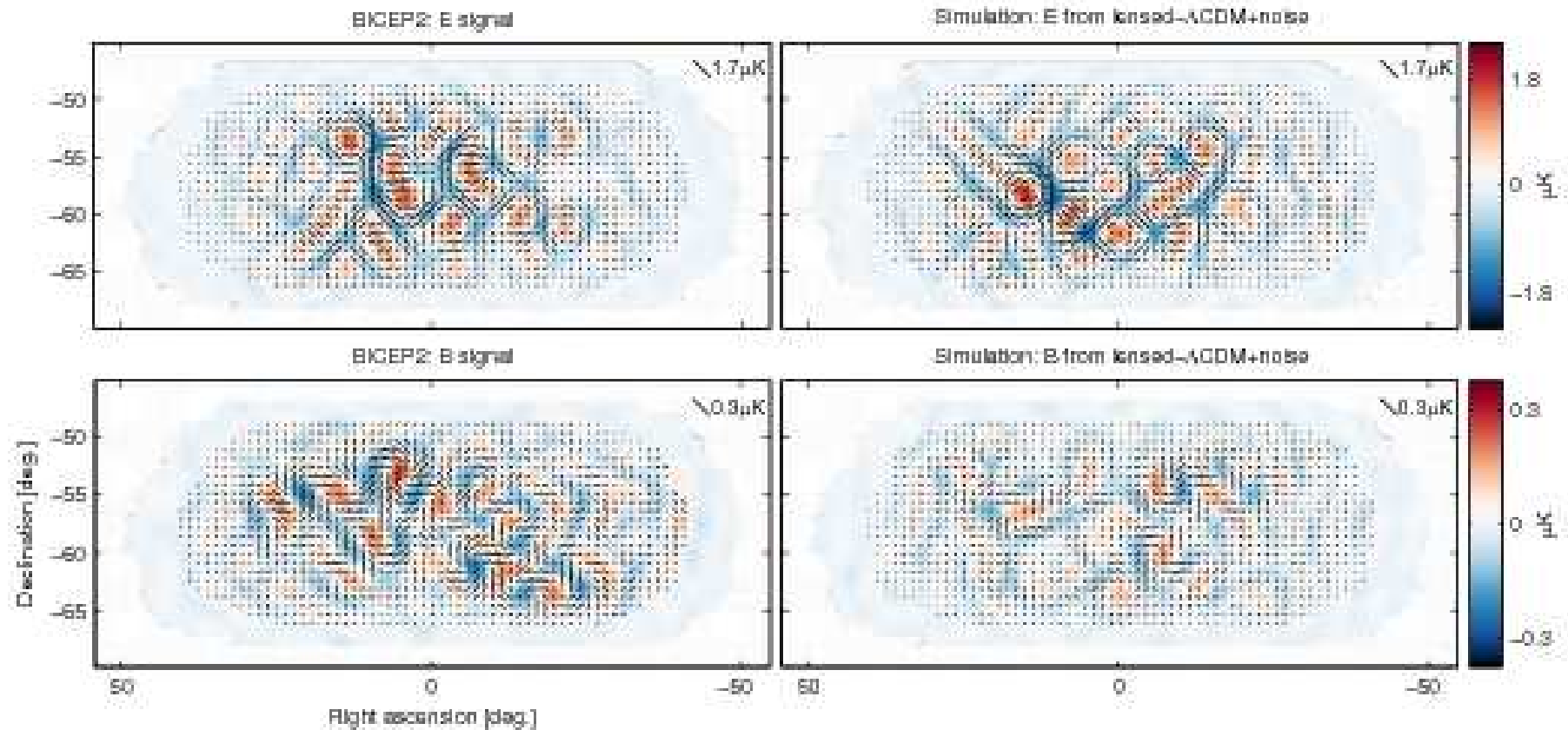
# B modes from inflation



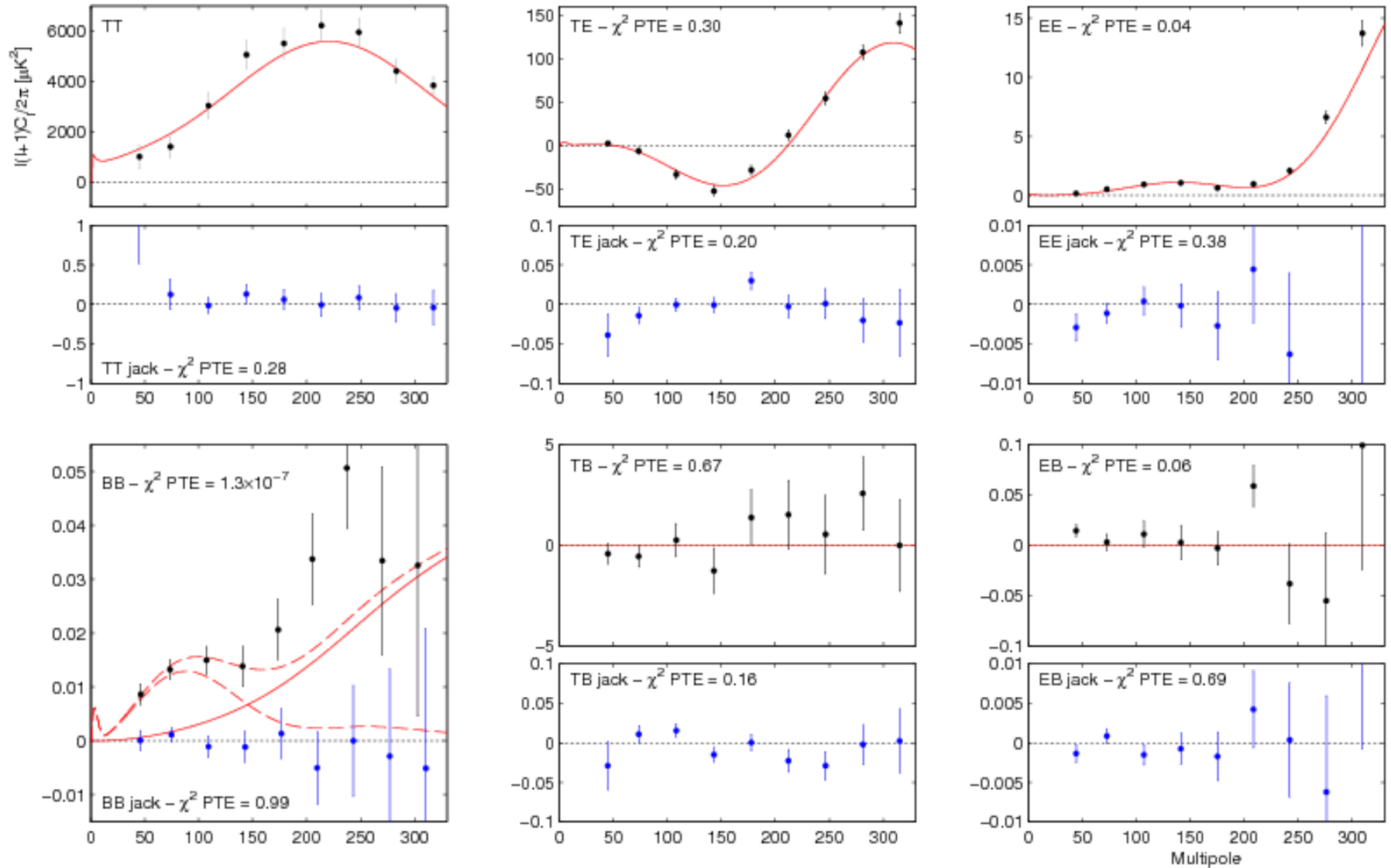
Power at  $l \sim 100$  proportional to  $E_{inflation}$ .

Background : gravitational lenses between us and LastSS cause E-modes to leak into B-modes.

# Biceps2 E and B maps



# Bicep2 power spectra



$\Rightarrow E_{inflation} \sim 10^{16} \text{ GeV}$  ( $\sim$ grand unification energy)