CMB Polarization Experiments

J.-Ch. Hamilton
APC - Paris

CMB Polarization

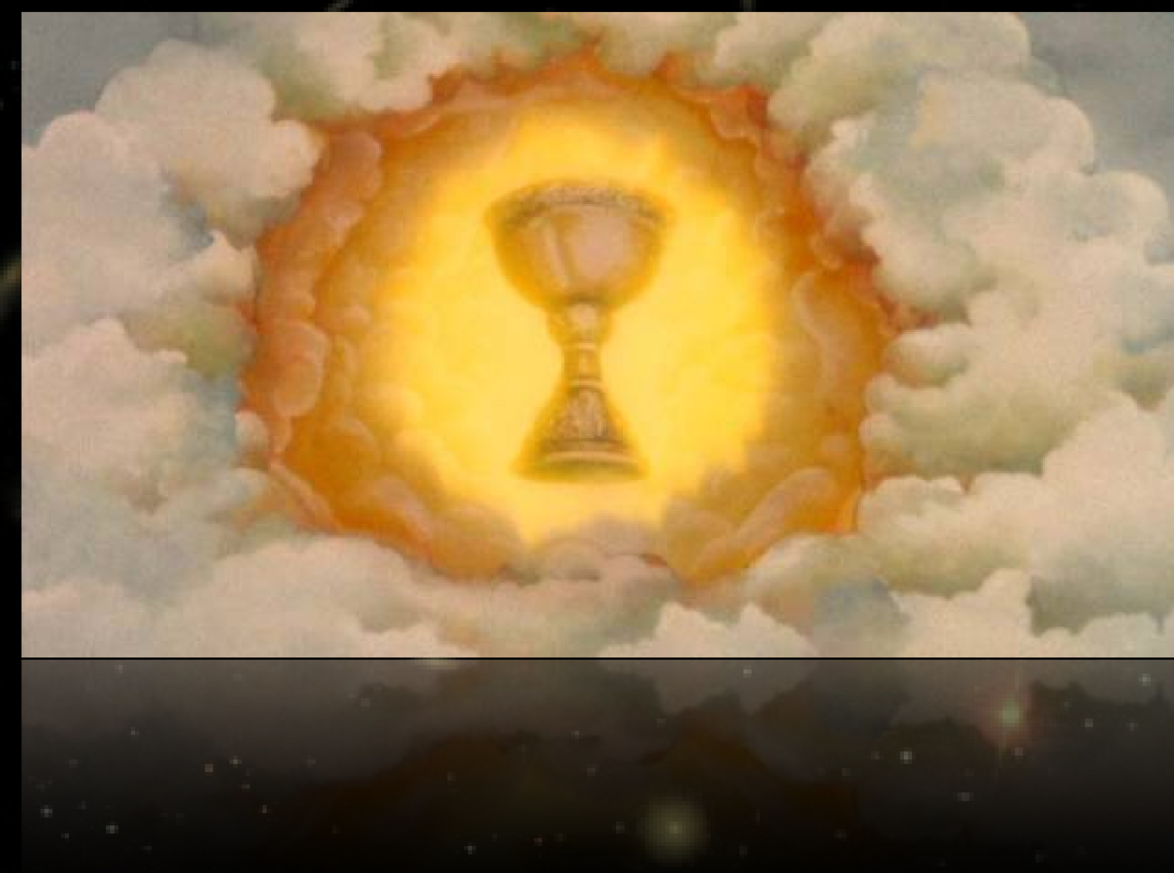
Lecture 1

Lecture 2

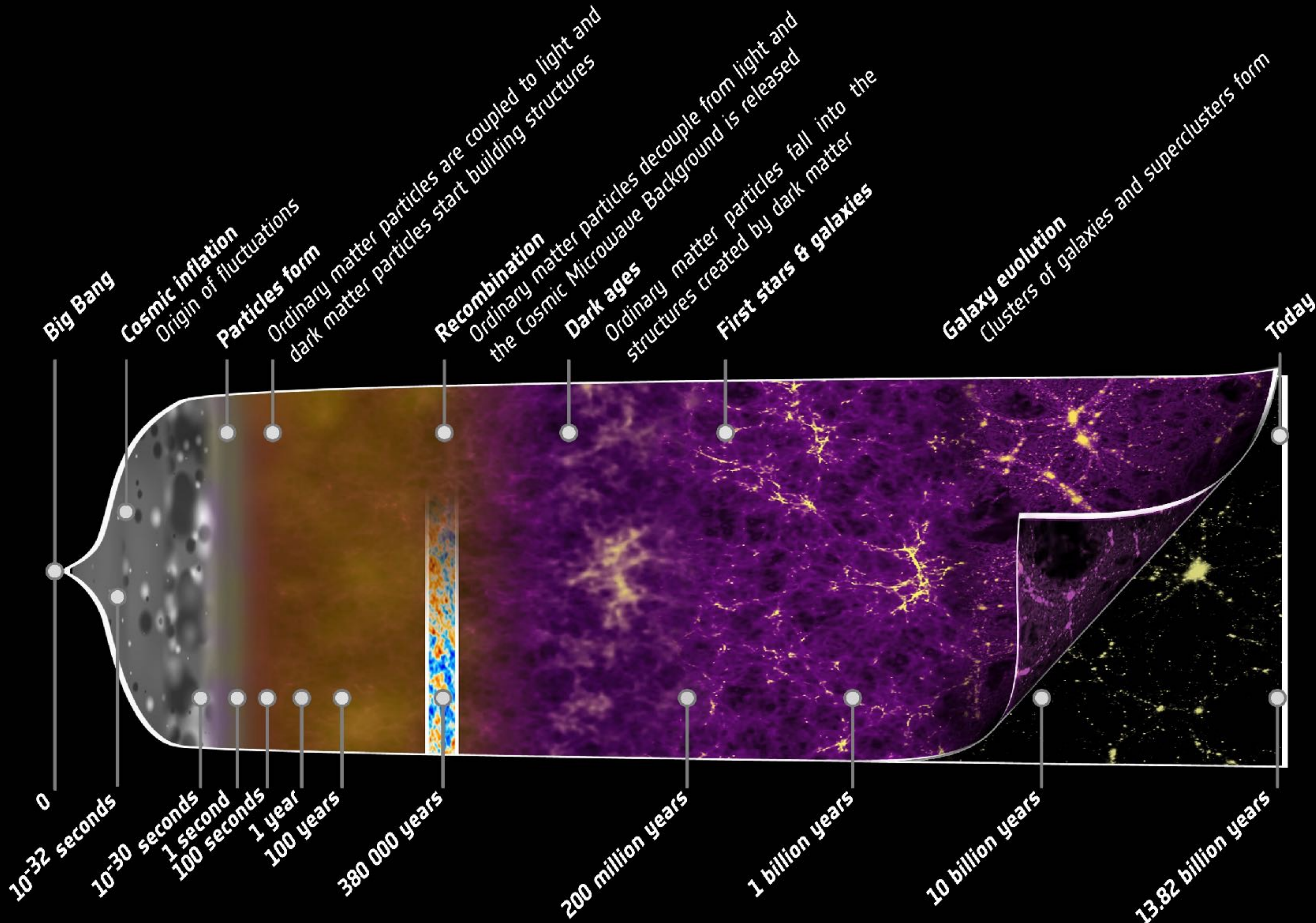
CMB Polarization

Why is this the Holy Grail for cosmology ?

CMB Polarization



Why is this the Holy Grail for cosmology ?

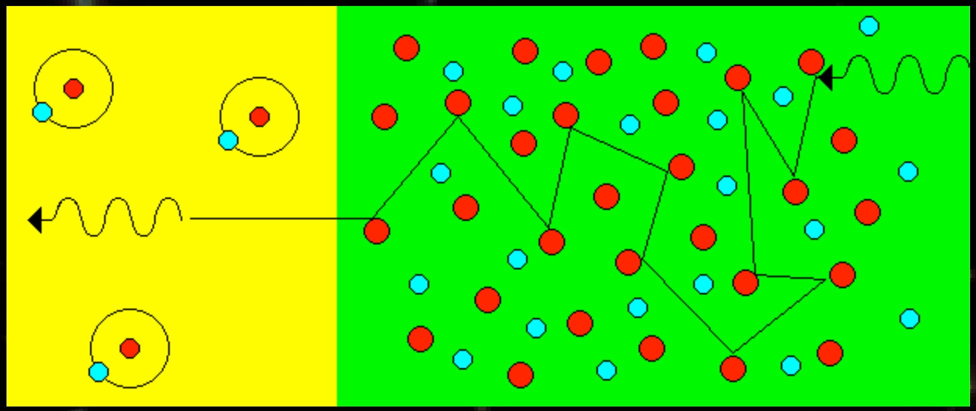

Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

The CMB

- **Matter-Radiation Decoupling:**
  - ★ z=1000: electrons captured by nuclei
  - ★ Universe becomes transparent
  - ★ photons last scatter on electrons
- **Uniform background of photons**
  - ★ Very uniform black-body (10^{-5} primordial perturbations)
  - ★ 3000 K at z=1000
  - ★ 3 K today
  - ★ From all directions in the sky
- **Picture of the Universe at z=1000**
  - ★ Temperature fluctuations ~ 10^{-5}
    - denser = warmer
    - less dense = colder
  - ★ Partially polarized linearly (~10 %)
    - Described with Stokes Parameters maps: I, Q and U

$$
\begin{aligned}
I(\vec{n}) &= \left\langle \left|E_{\parallel}(\vec{n})\right|^2 \right\rangle + \left\langle \left|E_{\perp}(\vec{n})\right|^2 \right\rangle \\
Q(\vec{n}) &= \left\langle \left|E_{\parallel}(\vec{n})\right|^2 \right\rangle - \left\langle \left|E_{\perp}(\vec{n})\right|^2 \right\rangle \\
U(\vec{n}) &= \left\langle E_{\parallel}(\vec{n}) E_{\perp}^{\star}(\vec{n}) \right\rangle + \left\langle E_{\perp}(\vec{n}) E_{\parallel}^{\star}(\vec{n}) \right\rangle
\end{aligned}
$$

The CMB



- **Matter-Radiation Decoupling:**
  - ★ z=1000: electrons captured by nuclei
  - ★ Universe becomes transparent
  - ★ photons last scatter on electrons
- **Uniform background of photons**
  - ★ Very uniform black-body (10^{-5} primordial perturbations)
  - ★ 3000 K at z=1000
  - ★ 3 K today
  - ★ From all directions in the sky
- **Picture of the Universe at z=1000**
  - ★ Temperature fluctuations ~ 10^{-5}
    - denser = warmer
    - less dense = colder
  - ★ Partially polarized linearly (~10 %)
    - Described with Stokes Parameters maps: I, Q and U

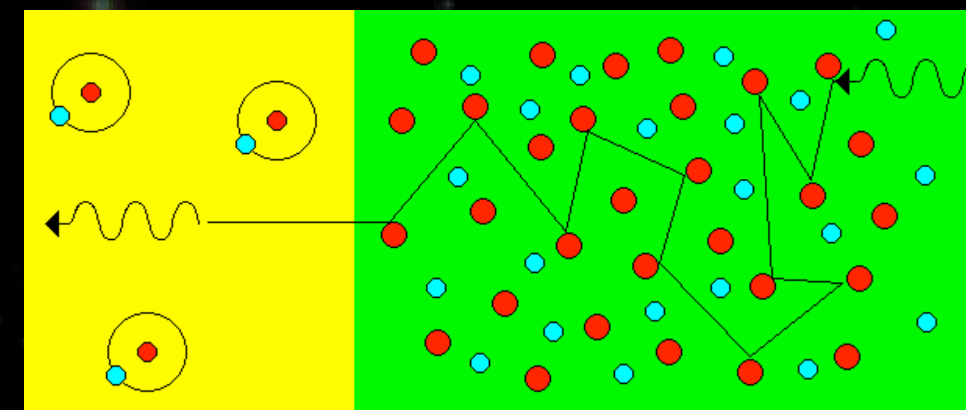
$$
\begin{aligned}
I(\vec{n}) &= \left\langle \left|E_{\parallel}(\vec{n})\right|^2 \right\rangle + \left\langle \left|E_{\perp}(\vec{n})\right|^2 \right\rangle \\
Q(\vec{n}) &= \left\langle \left|E_{\parallel}(\vec{n})\right|^2 \right\rangle - \left\langle \left|E_{\perp}(\vec{n})\right|^2 \right\rangle \\
U(\vec{n}) &= \left\langle E_{\parallel}(\vec{n}) E_{\perp}^{\star}(\vec{n}) \right\rangle + \left\langle E_{\perp}(\vec{n}) E_{\parallel}^{\star}(\vec{n}) \right\rangle
\end{aligned}
$$

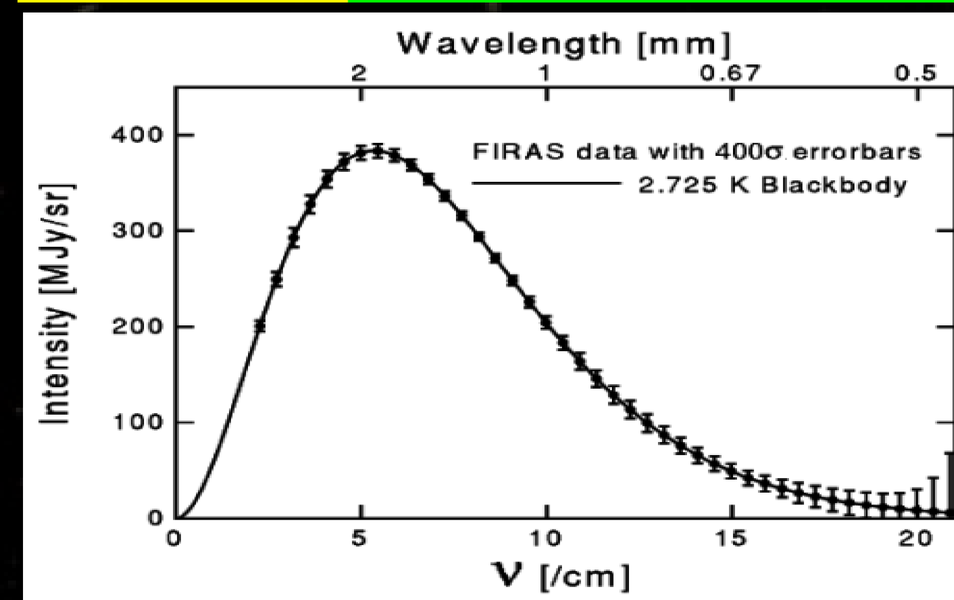
J.-Ch. Hamilton
hamilton@apc.in2p3.fr

The CMB

- Matter-Radiation Decoupling:
  - ★ z=1000: electrons captured by nuclei
  - ★ Universe becomes transparent
  - ★ photons last scatter on electrons
- Uniform background of photons
  - ★ Very uniform black-body (10^{-5} primordial perturbations)
  - ★ 3000 K at z=1000
  - ★ 3 K today
  - ★ From all directions in the sky
- Picture of the Universe at z=1000
  - ★ Temperature fluctuations ~ 10^{-5}
    - denser = warmer
    - less dense = colder
  - ★ Partially polarized linearly (~10 %)
    - Described with Stokes Parameters maps: I, Q and U

$$
\begin{aligned}
I(\vec{n}) &= \left\langle \left|E_{\parallel}(\vec{n})\right|^2 \right\rangle + \left\langle \left|E_{\perp}(\vec{n})\right|^2 \right\rangle \\
Q(\vec{n}) &= \left\langle \left|E_{\parallel}(\vec{n})\right|^2 \right\rangle - \left\langle \left|E_{\perp}(\vec{n})\right|^2 \right\rangle \\
U(\vec{n}) &= \left\langle E_{\parallel}(\vec{n})E_{\perp}^{\star}(\vec{n}) \right\rangle + \left\langle E_{\perp}(\vec{n})E_{\parallel}^{\star}(\vec{n}) \right\rangle
\end{aligned}
$$

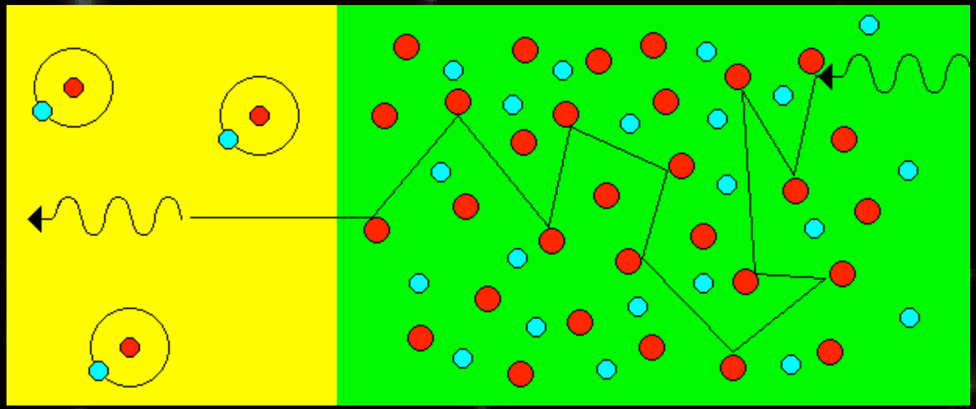


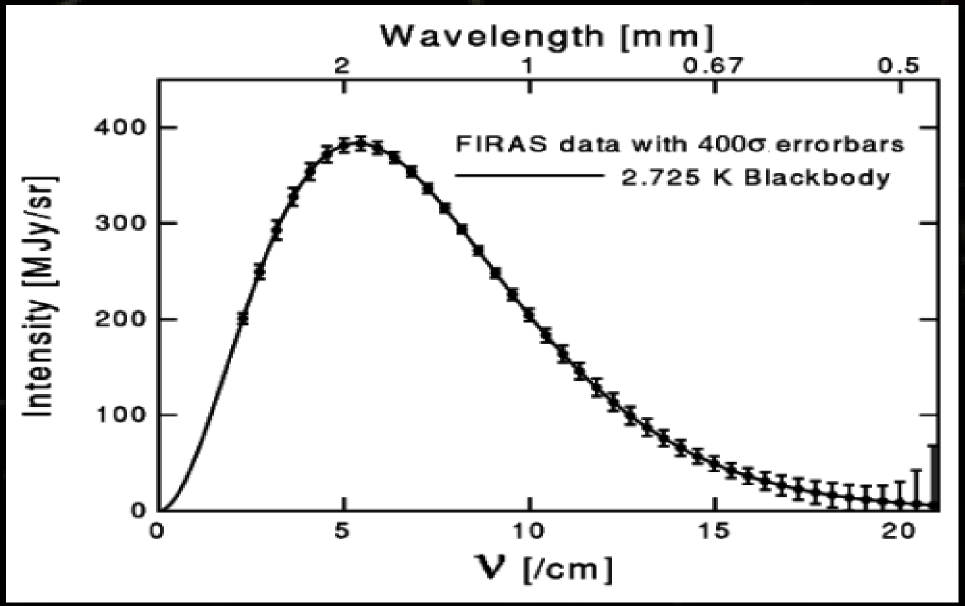


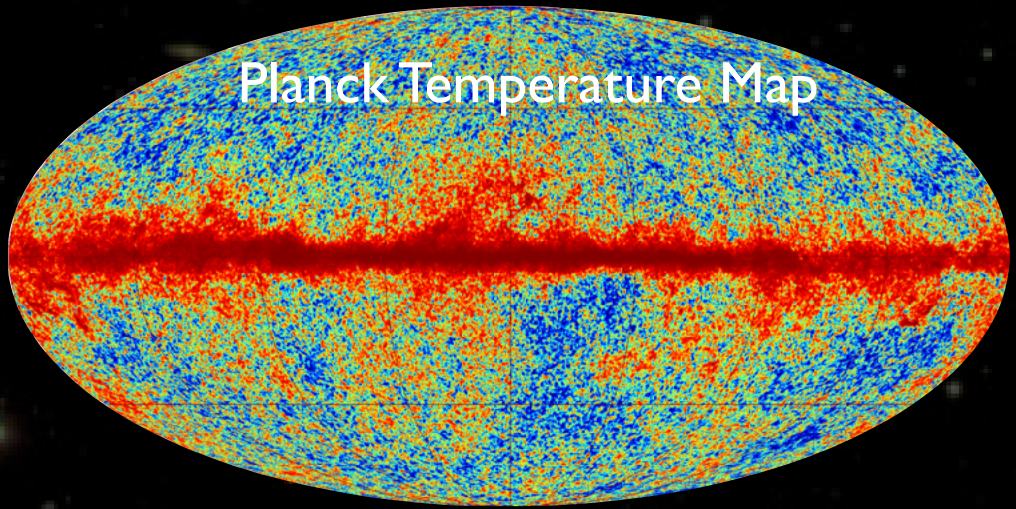
The CMB

- **Matter-Radiation Decoupling:**
  - ★ z=1000: electrons captured by nuclei
  - ★ Universe becomes transparent
  - ★ photons last scatter on electrons
- **Uniform background of photons**
  - ★ Very uniform black-body (10^{-5} primordial perturbations)
  - ★ 3000 K at z=1000
  - ★ 3 K today
  - ★ From all directions in the sky
- **Picture of the Universe at z=1000**
  - ★ Temperature fluctuations ~ 10^{-5}
    - denser = warmer
    - less dense = colder
  - ★ Partially polarized linearly (~10 %)
    - Described with Stokes Parameters maps: I, Q and U

$$
\begin{aligned}
I(\vec{n}) &= \left\langle |E_{\parallel}(\vec{n})|^2 \right\rangle + \left\langle |E_{\perp}(\vec{n})|^2 \right\rangle \\
Q(\vec{n}) &= \left\langle |E_{\parallel}(\vec{n})|^2 \right\rangle - \left\langle |E_{\perp}(\vec{n})|^2 \right\rangle \\
U(\vec{n}) &= \left\langle E_{\parallel}(\vec{n}) E_{\perp}^{\star}(\vec{n}) \right\rangle + \left\langle E_{\perp}(\vec{n}) E_{\parallel}^{\star}(\vec{n}) \right\rangle
\end{aligned}
$$



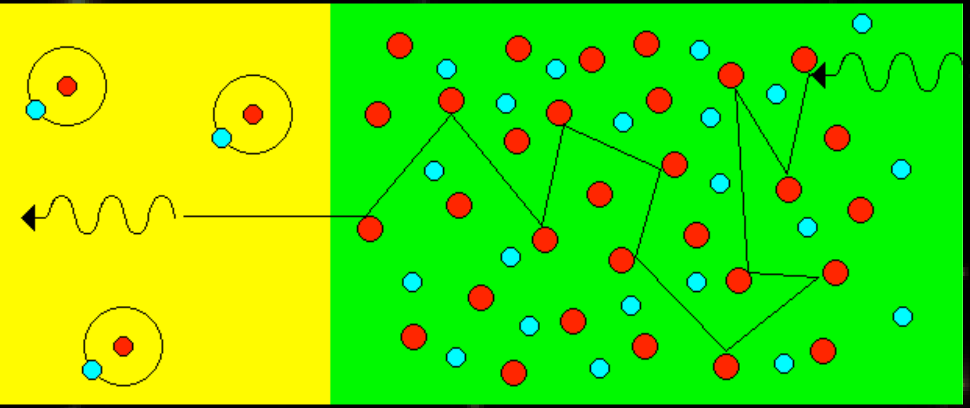


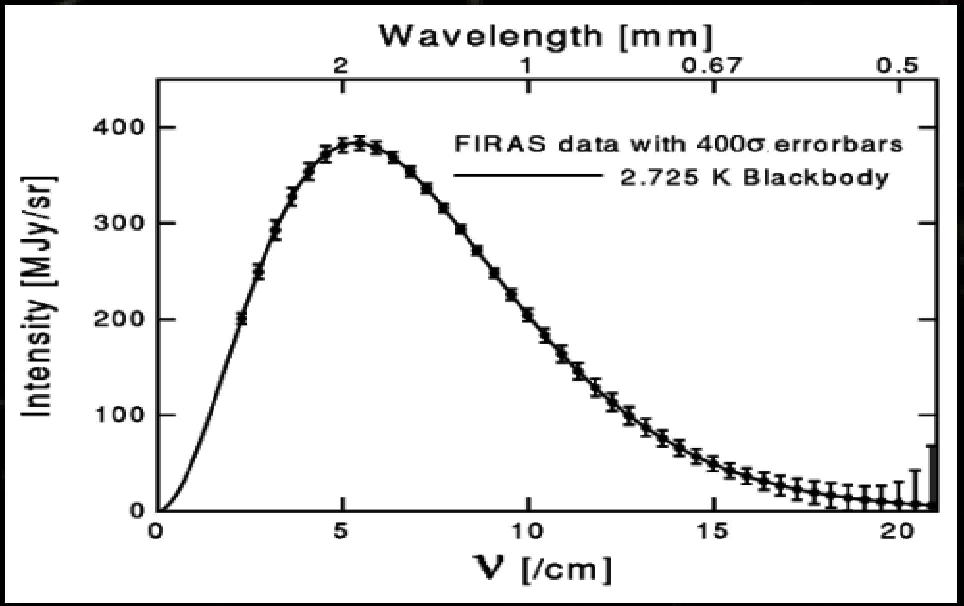


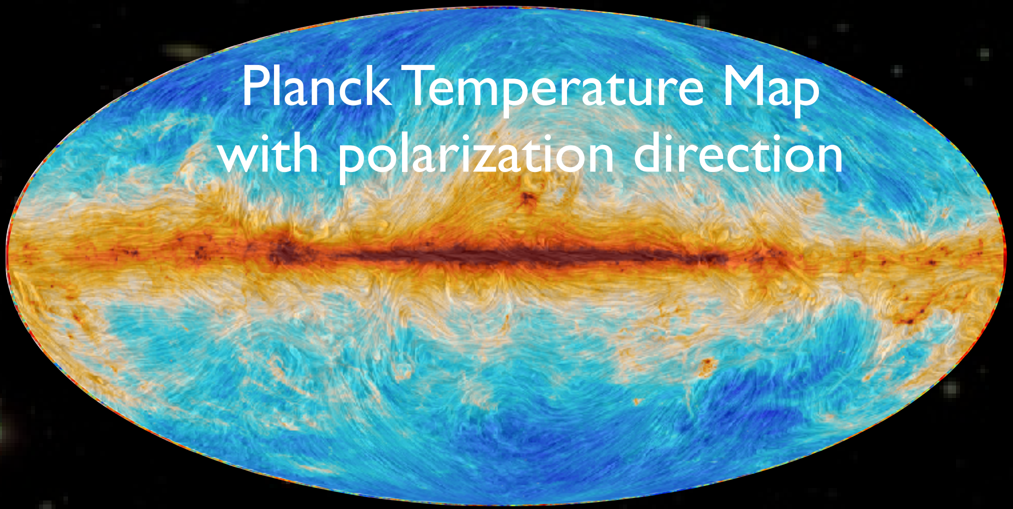
The CMB

- Matter-Radiation Decoupling:
  - ★ z=1000: electrons captured by nuclei
  - ★ Universe becomes transparent
  - ★ photons last scatter on electrons
- Uniform background of photons
  - ★ Very uniform black-body (10^{-5} primordial perturbations)
  - ★ 3000 K at z=1000
  - ★ 3 K today
  - ★ From all directions in the sky
- Picture of the Universe at z=1000
  - ★ Temperature fluctuations ~ 10^{-5}
    - denser = warmer
    - less dense = colder
  - ★ Partially polarized linearly (~10 %)
    - Described with Stokes Parameters maps: I, Q and U

$$
\begin{aligned}
I(\vec{n}) &= \left\langle \left|E_{\parallel}(\vec{n})\right|^2 \right\rangle + \left\langle \left|E_{\perp}(\vec{n})\right|^2 \right\rangle \\
Q(\vec{n}) &= \left\langle \left|E_{\parallel}(\vec{n})\right|^2 \right\rangle - \left\langle \left|E_{\perp}(\vec{n})\right|^2 \right\rangle \\
U(\vec{n}) &= \left\langle E_{\parallel}(\vec{n})E_{\perp}^{\star}(\vec{n}) \right\rangle + \left\langle E_{\perp}(\vec{n})E_{\parallel}^{\star}(\vec{n}) \right\rangle
\end{aligned}
$$



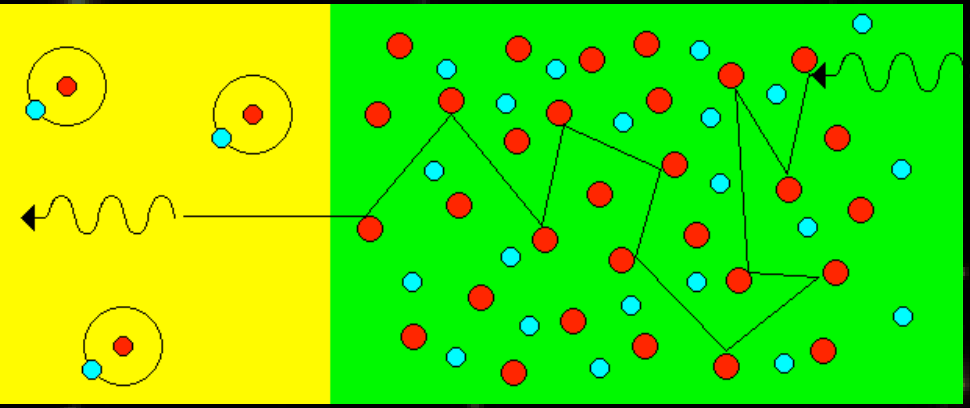


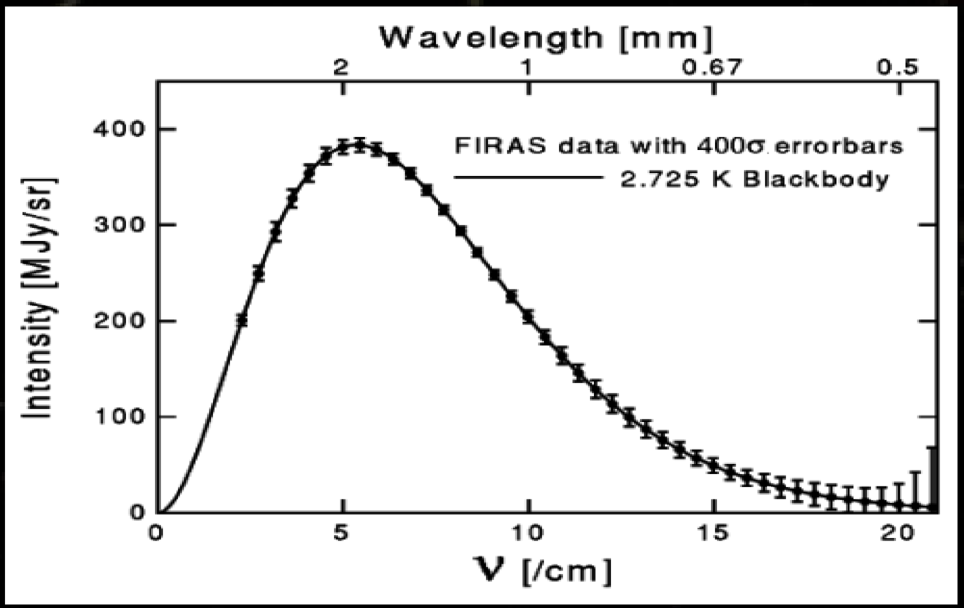


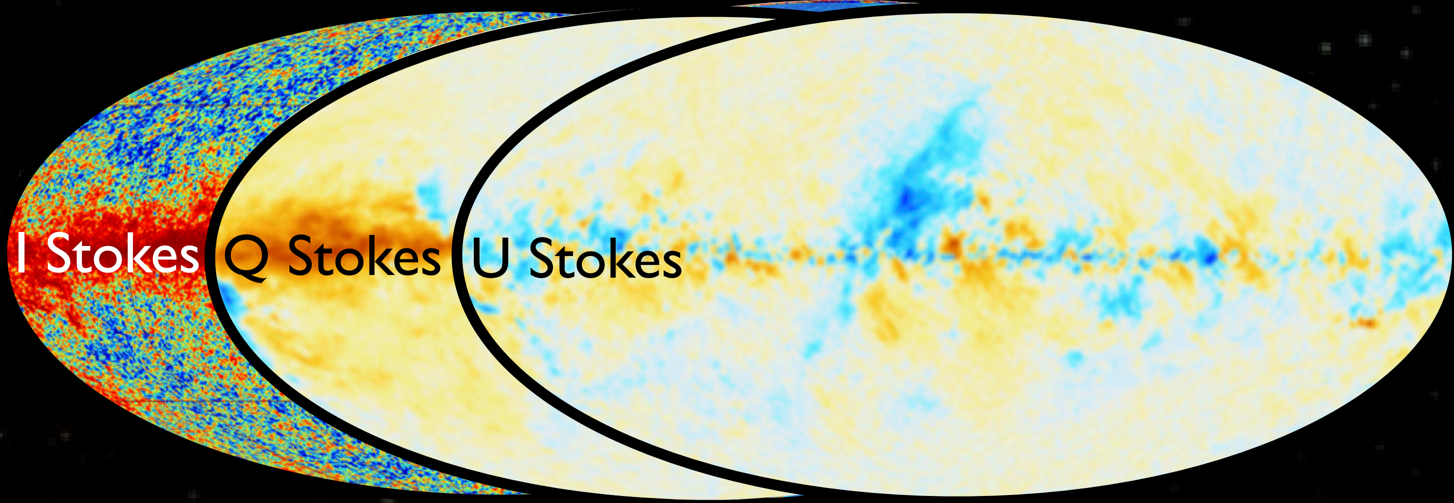
The CMB

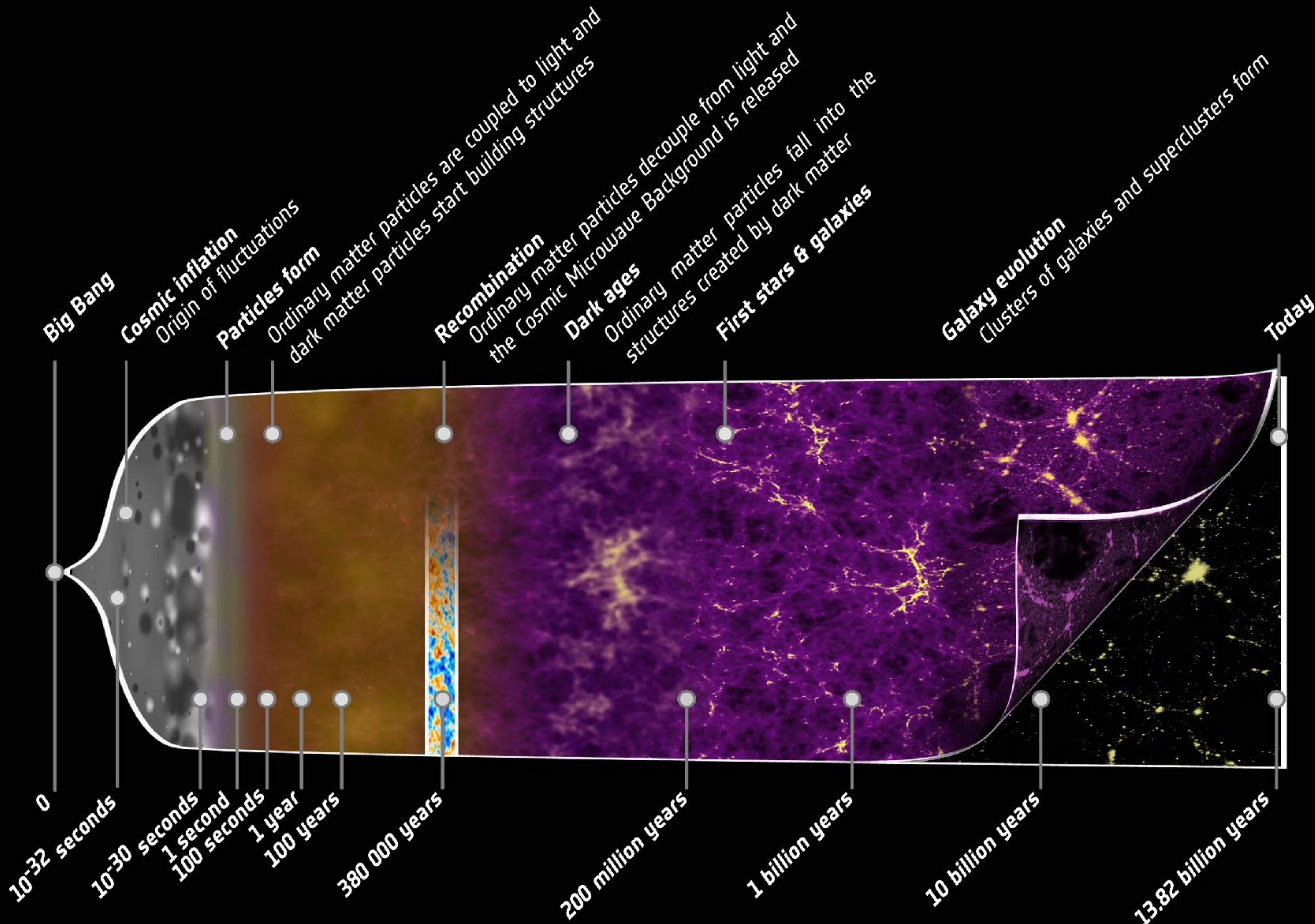
- **Matter-Radiation Decoupling:**
  - ★ z=1000: electrons captured by nuclei
  - ★ Universe becomes transparent
  - ★ photons last scatter on electrons
- **Uniform background of photons**
  - ★ Very uniform black-body (10^{-5} primordial perturbations)
  - ★ 3000 K at z=1000
  - ★ 3 K today
  - ★ From all directions in the sky
- **Picture of the Universe at z=1000**
  - ★ Temperature fluctuations ~ 10^{-5}
    - denser = warmer
    - less dense = colder
  - ★ Partially polarized linearly (~10 %)
    - Described with Stokes Parameters maps: I, Q and U

$$
\begin{aligned}
I(\vec{n}) &= \left\langle \left|E_{\parallel}(\vec{n})\right|^2 \right\rangle + \left\langle \left|E_{\perp}(\vec{n})\right|^2 \right\rangle \\
Q(\vec{n}) &= \left\langle \left|E_{\parallel}(\vec{n})\right|^2 \right\rangle - \left\langle \left|E_{\perp}(\vec{n})\right|^2 \right\rangle \\
U(\vec{n}) &= \left\langle E_{\parallel}(\vec{n}) E_{\perp}^{\star}(\vec{n}) \right\rangle + \left\langle E_{\perp}(\vec{n}) E_{\parallel}^{\star}(\vec{n}) \right\rangle
\end{aligned}
$$

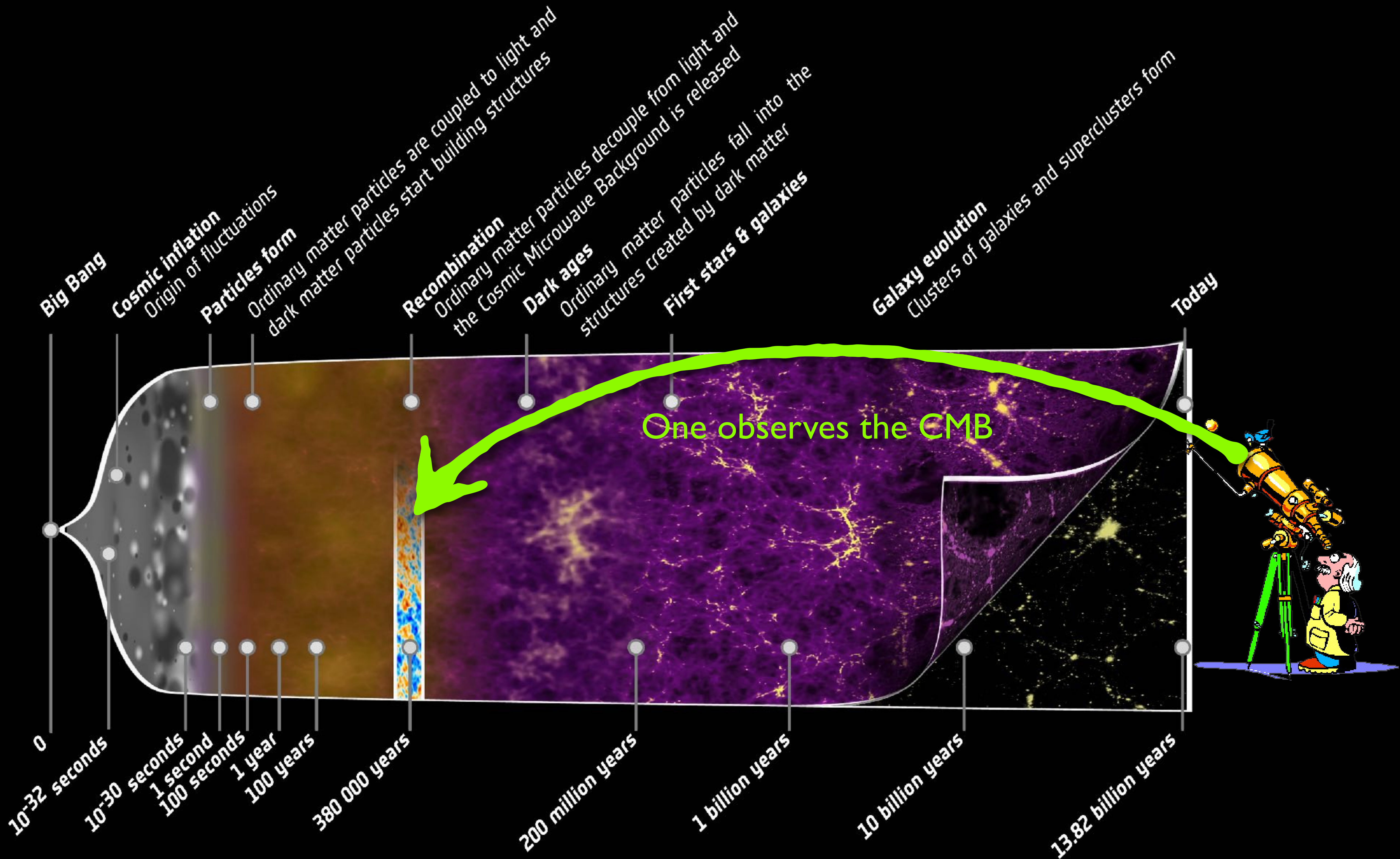




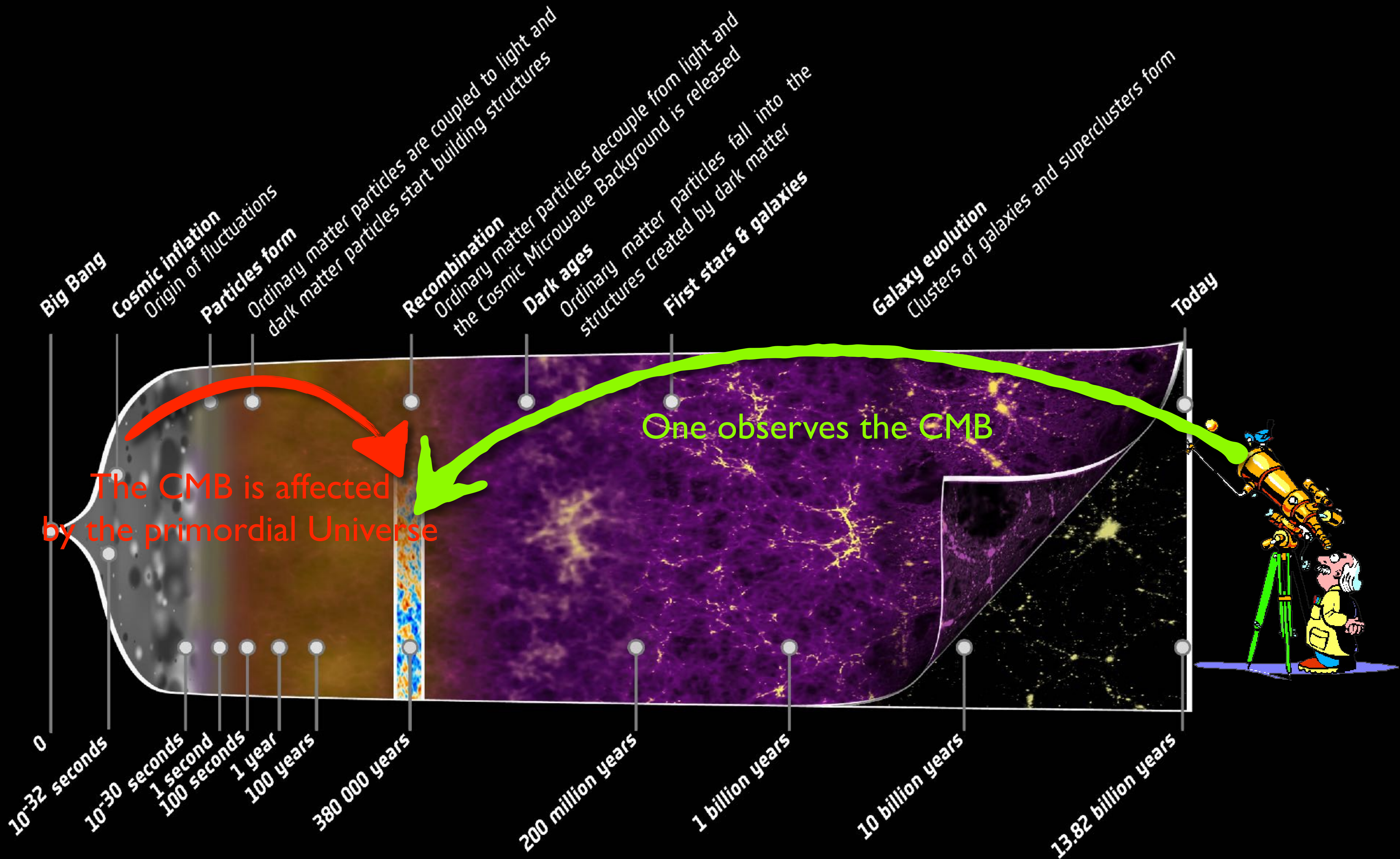




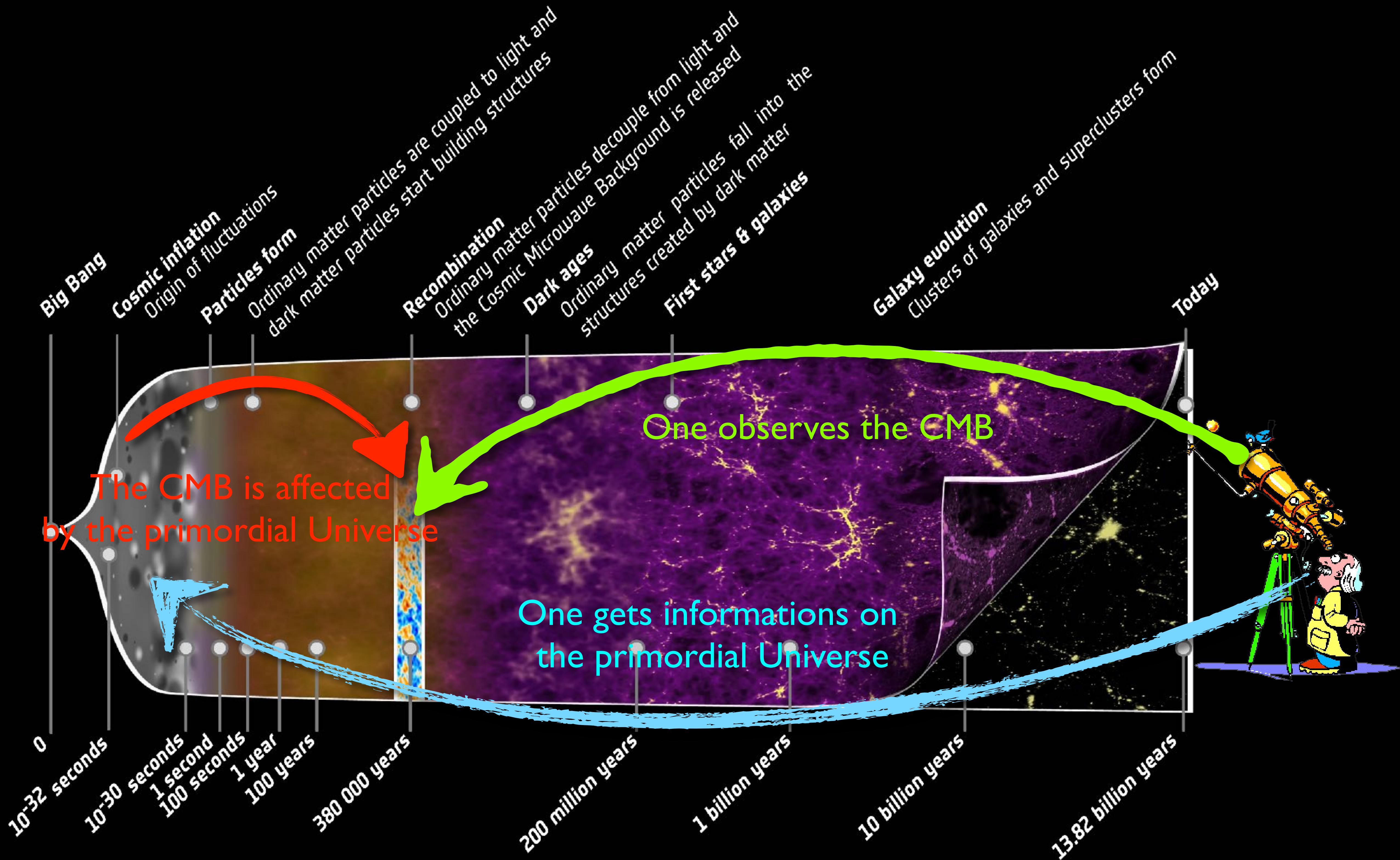
General philosophy: rather simple…



General philosophy: rather simple…



General philosophy: rather simple…



General philosophy: rather simple…

Relating maps to cosmology

- Spherical Harmonics Expansion

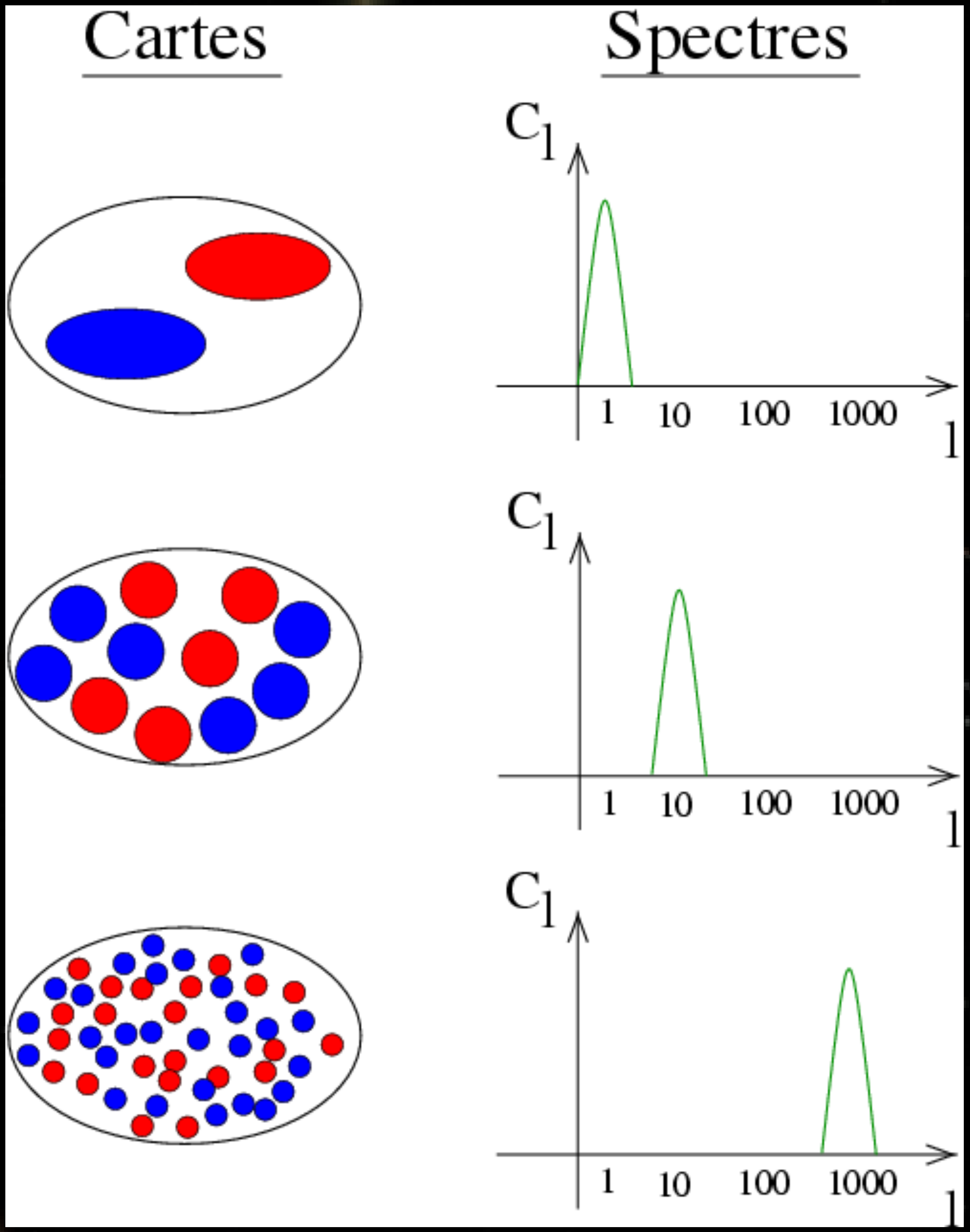
$$\frac{\Delta T}{T}(\theta,\phi)=\sum_{\ell=0}^{\infty}\sum_{m=\ell}^{\ell}a_{\ell m}Y_{\ell m}(\theta,\phi)$$

- Angular power spectrum

$$C_\ell=\frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell}|a_{\ell m}|^2$$

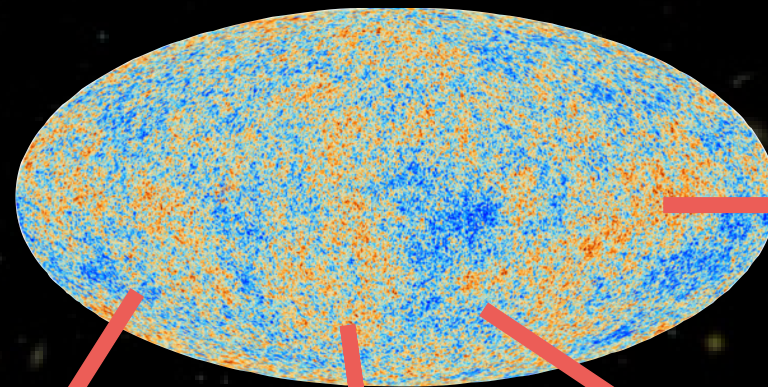
- ℓ is the inverse of an angle

$$\ell=200\leftrightarrow\theta=1\mathrm{deg.}$$

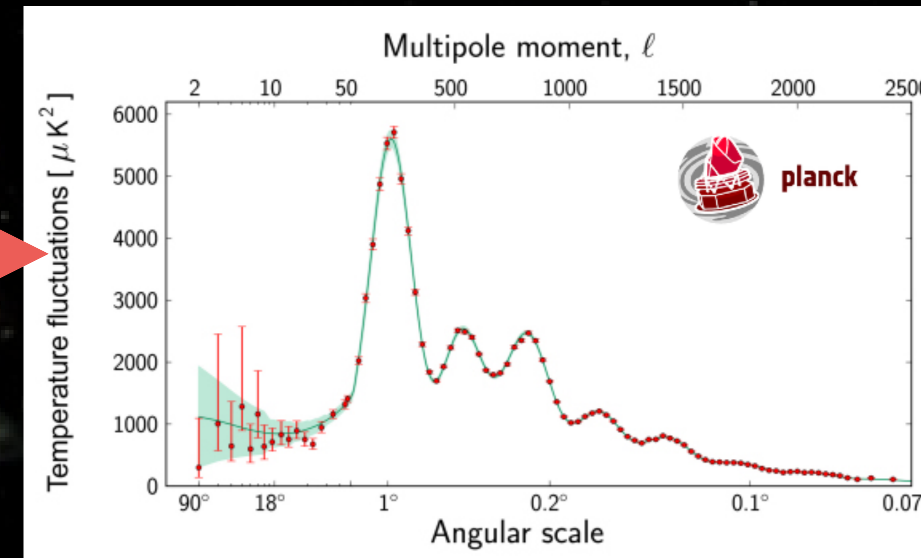


B. Revenu

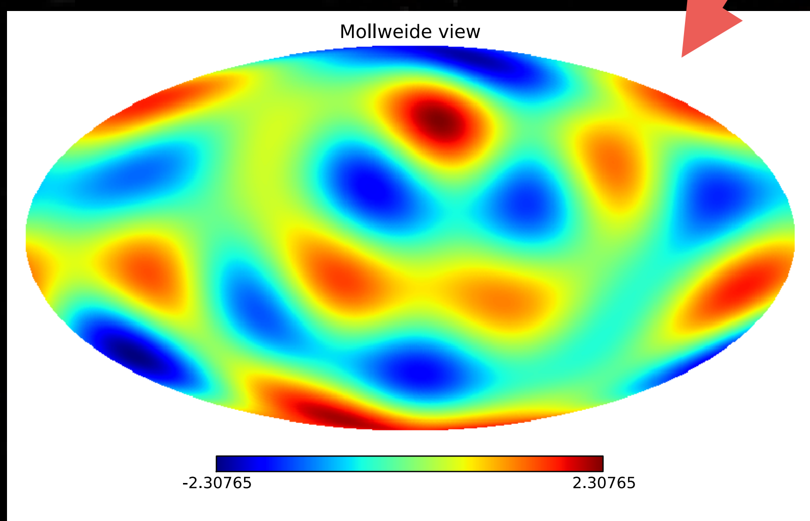
Angular power spectrum C_ℓ

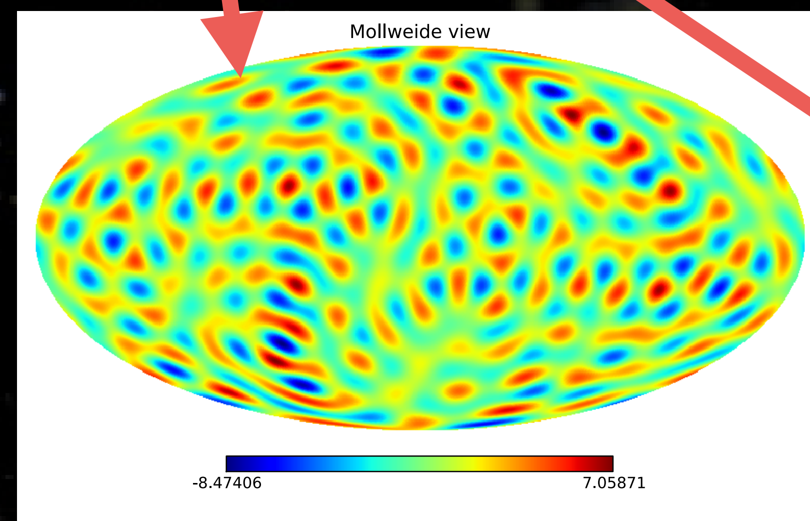


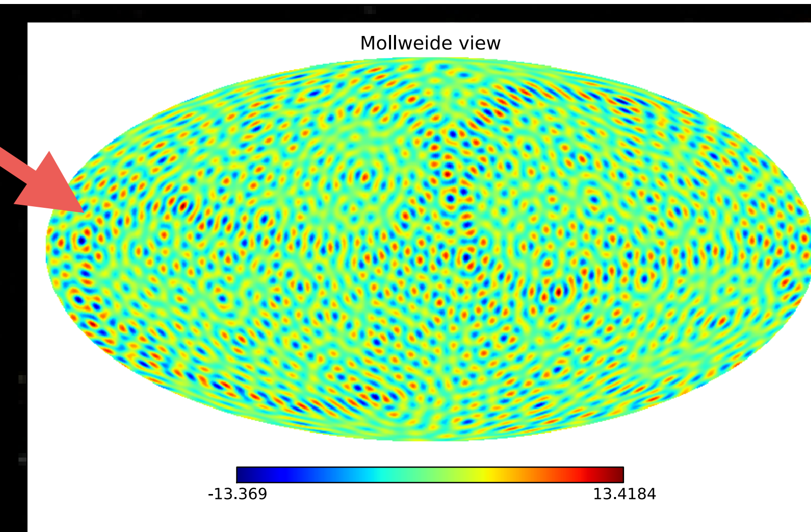
All ℓ

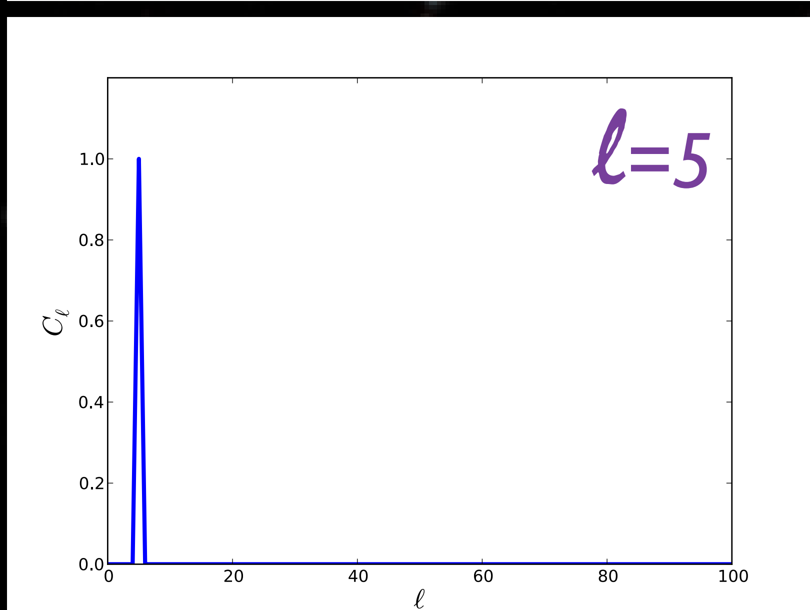


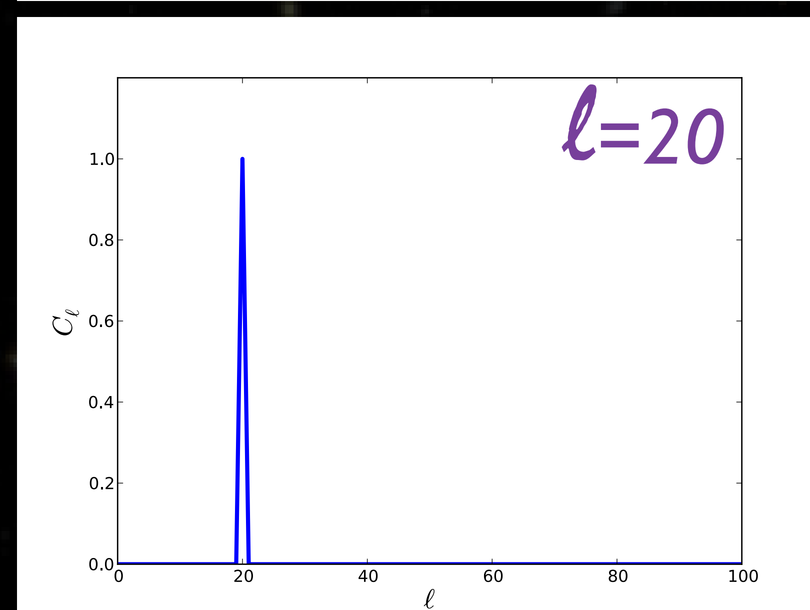
ℓ=5 ℓ=20 ℓ=60

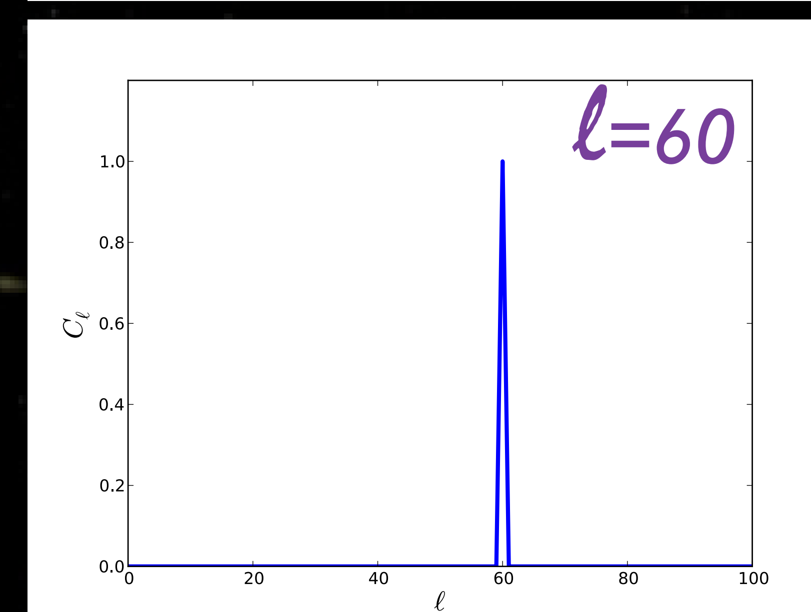








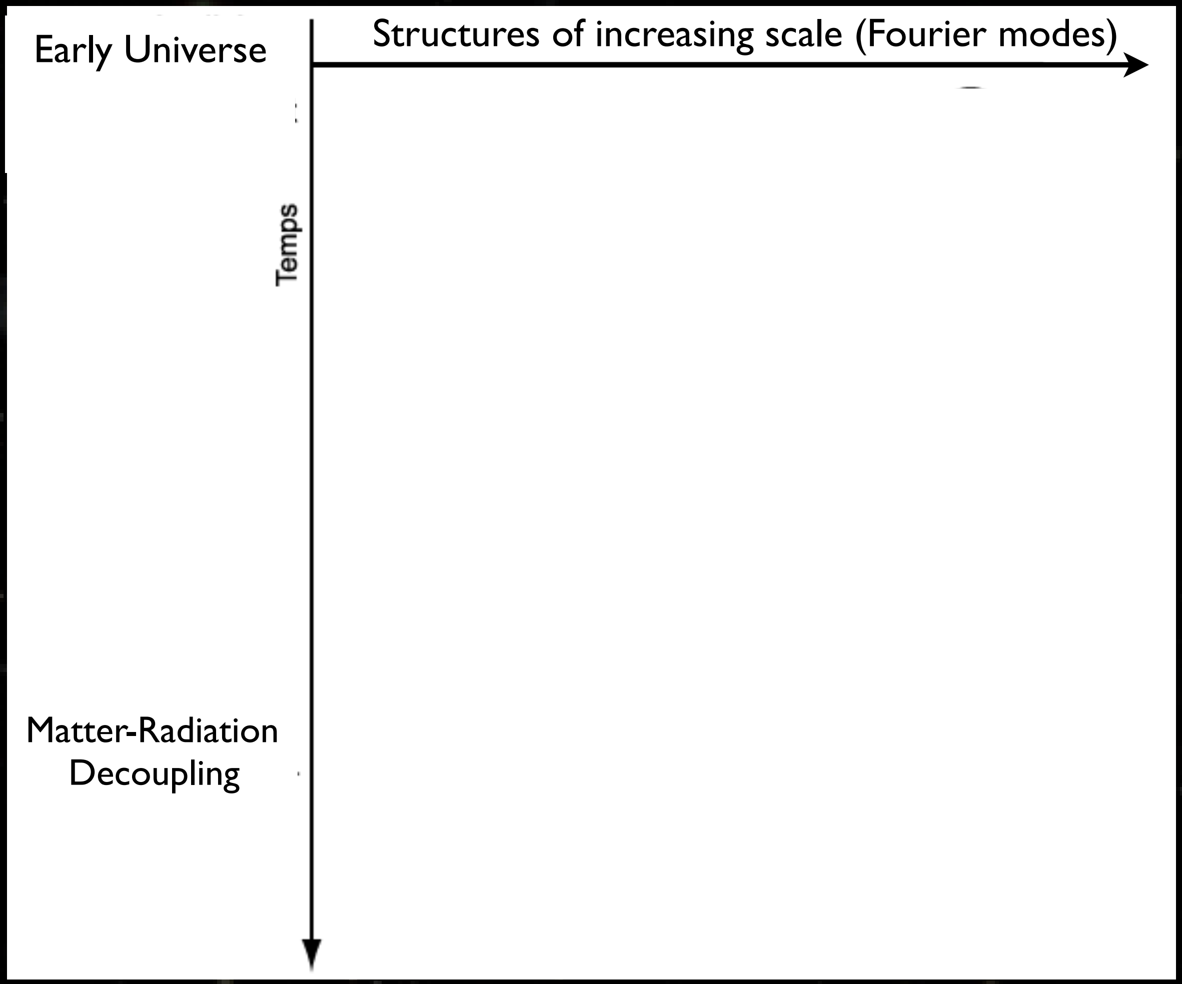




Structures amplitude as a function of their angular size

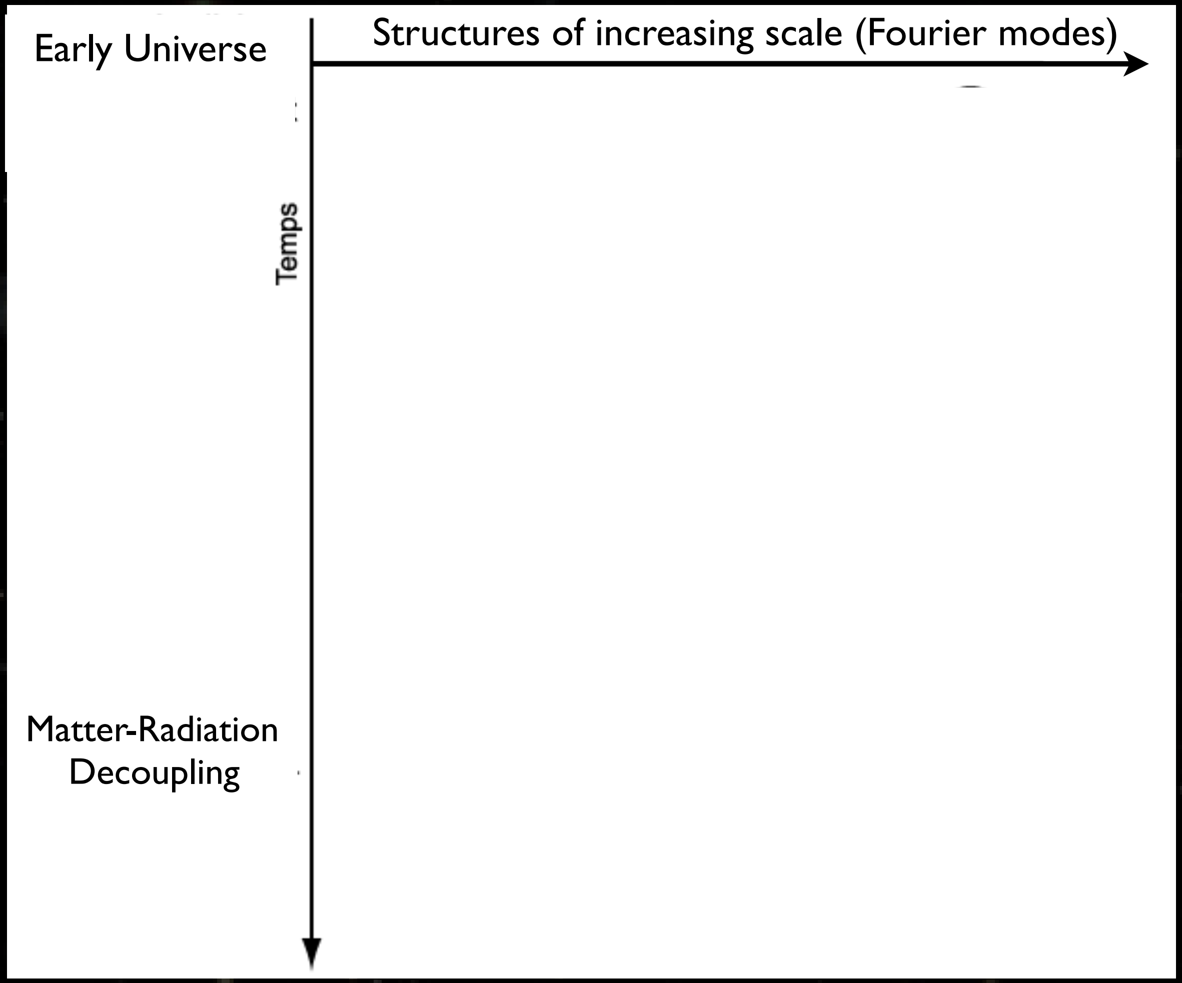
Transfer function: Baryonic Acoustic Oscillations

- (try to) think in Fourier space
  - ★ A structure collapses under its own gravity when larger than Hubble radius
  - ★ Temperature increases inducing more radiation pressure
  - ★ The structure re-expands
  - ★ Oscillations occur at each scale with a phase correlated to the scale
  - ★ Oscillations are frozen at matter-radiation decoupling



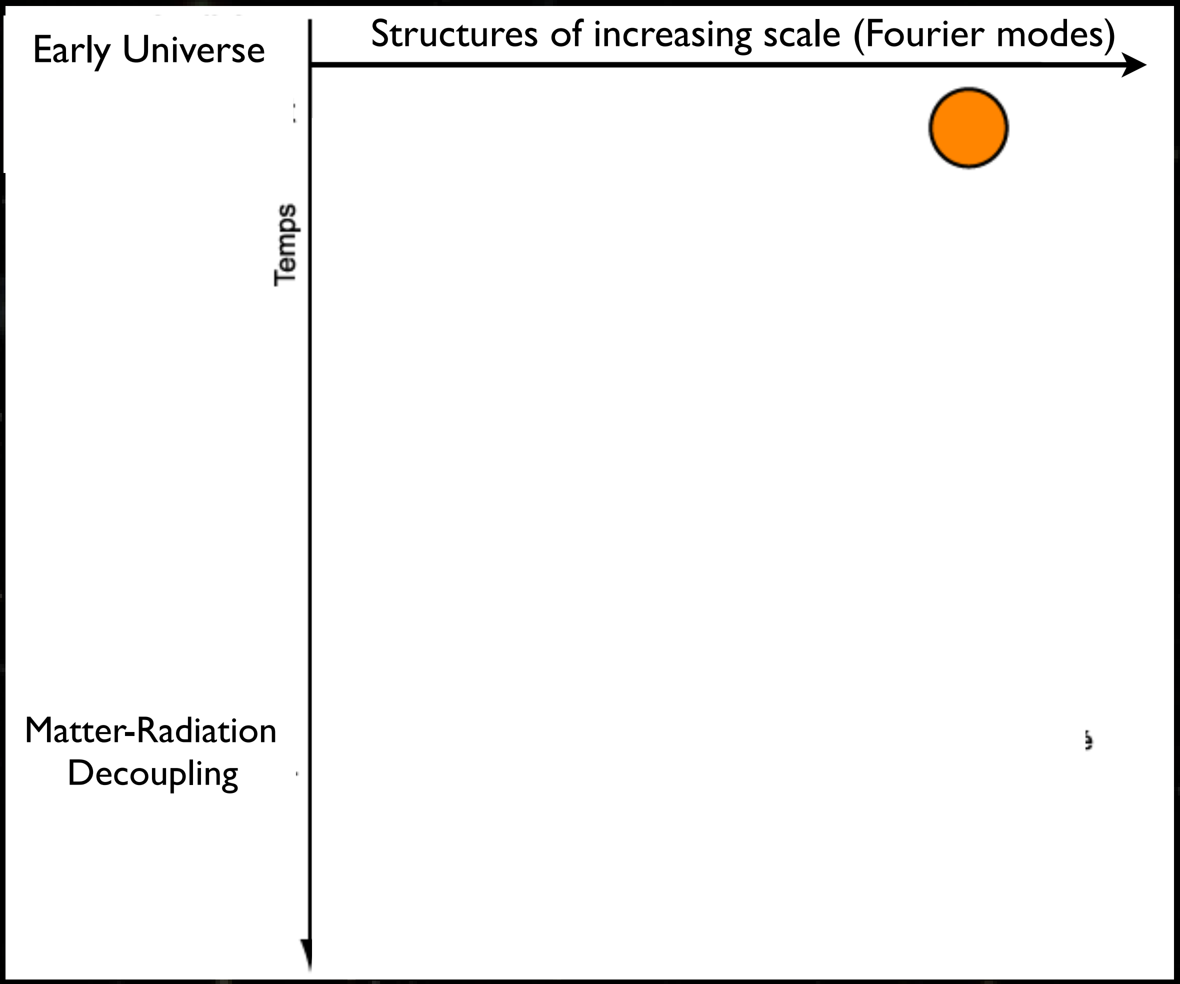
Transfer function: Baryonic Acoustic Oscillations

- (try to) think in Fourier space
  - ★ A structure collapses under its own gravity when larger than Hubble radius
  - ★ Temperature increases inducing more radiation pressure
  - ★ The structure re-expands
  - ★ Oscillations occur at each scale with a phase correlated to the scale
  - ★ Oscillations are frozen at matter-radiation decoupling



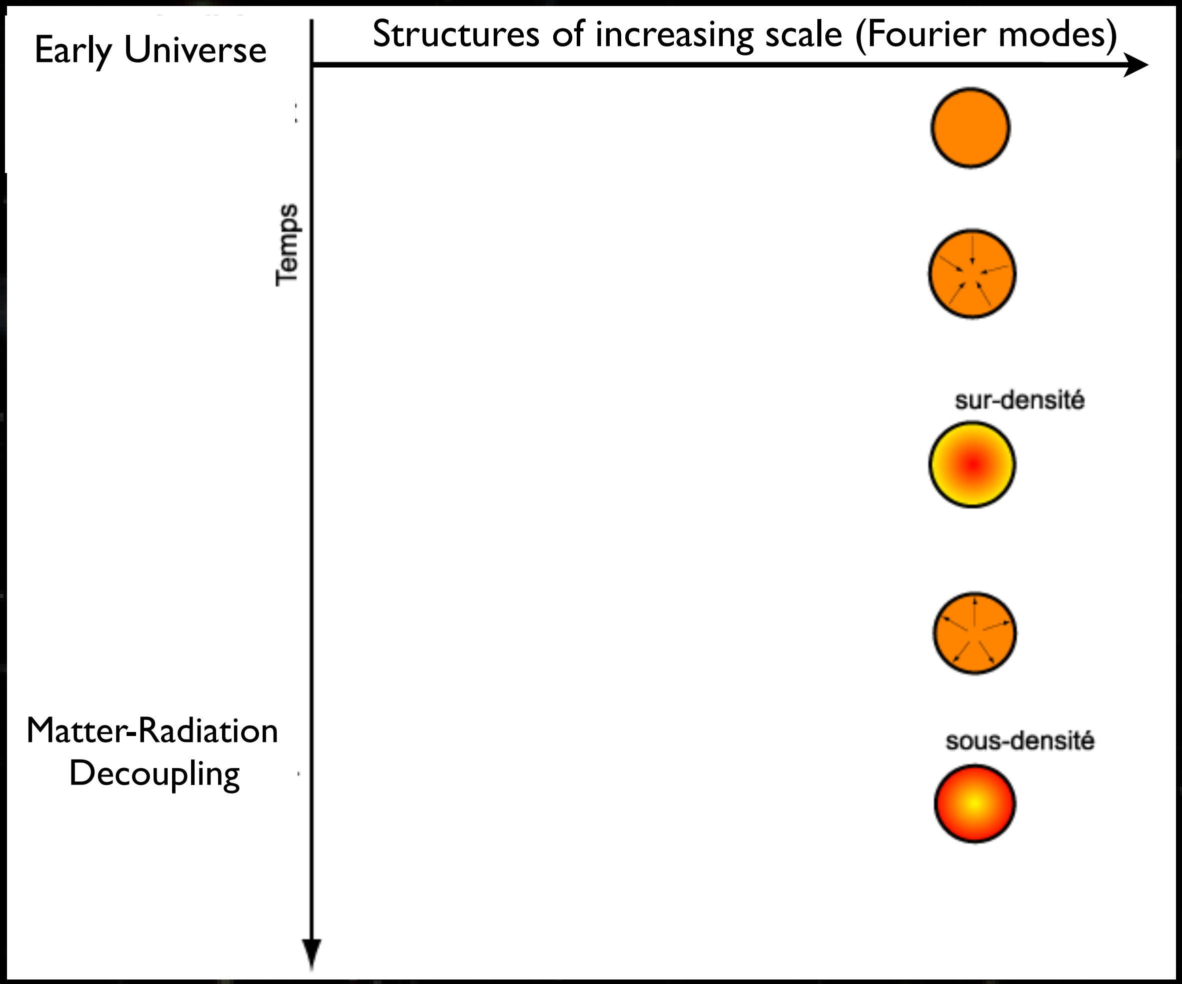
Transfer function: Baryonic Acoustic Oscillations

- (try to) think in Fourier space
  - ★ A structure collapses under its own gravity when larger than Hubble radius
  - ★ Temperature increases inducing more radiation pressure
  - ★ The structure re-expands
  - ★ Oscillations occur at each scale with a phase correlated to the scale
  - ★ Oscillations are frozen at matter-radiation decoupling



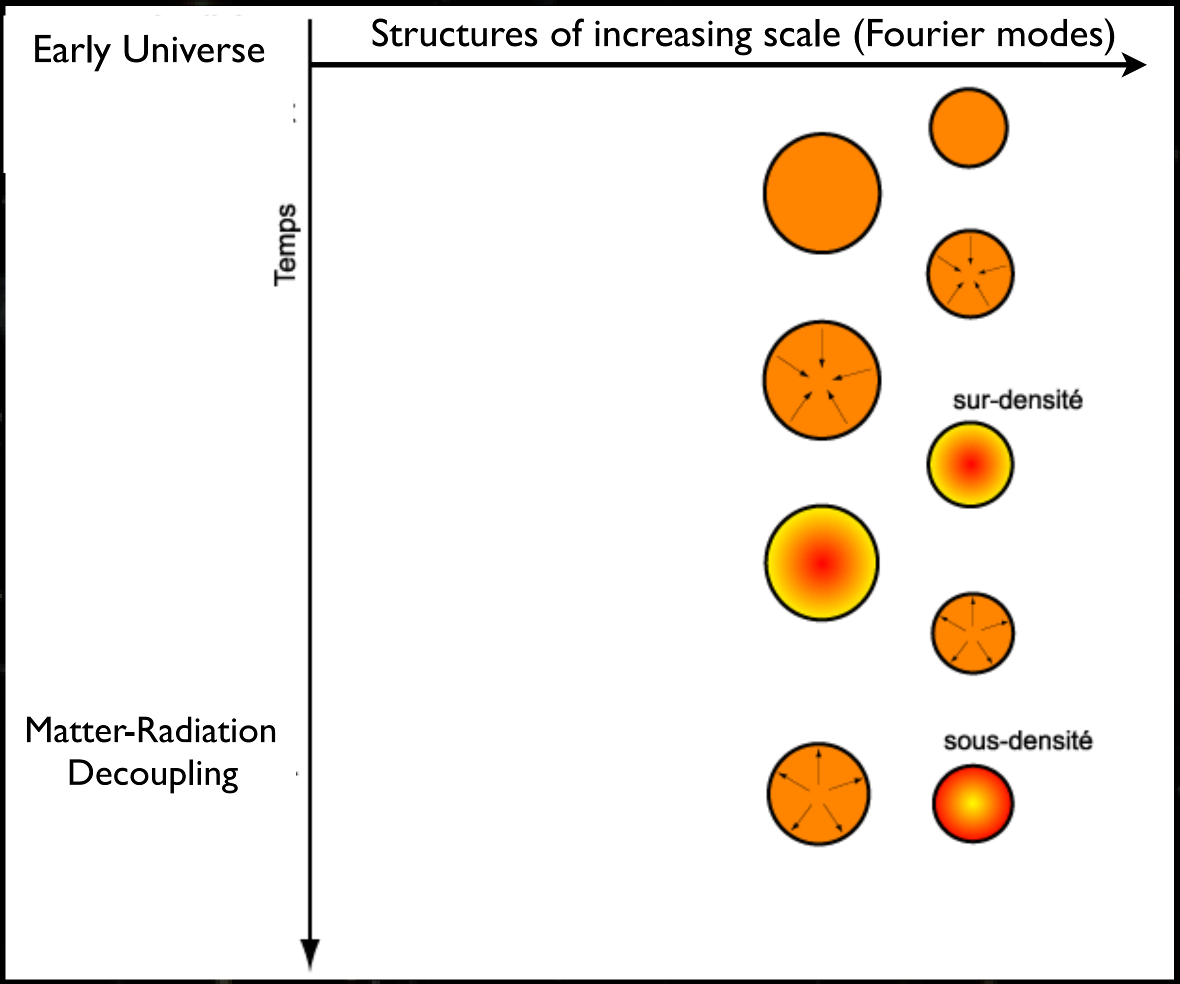
Transfer function: Baryonic Acoustic Oscillations

- (try to) think in Fourier space
  - ★ A structure collapses under its own gravity when larger than Hubble radius
  - ★ Temperature increases inducing more radiation pressure
  - ★ The structure re-expands
  - ★ Oscillations occur at each scale with a phase correlated to the scale
  - ★ Oscillations are frozen at matter-radiation decoupling



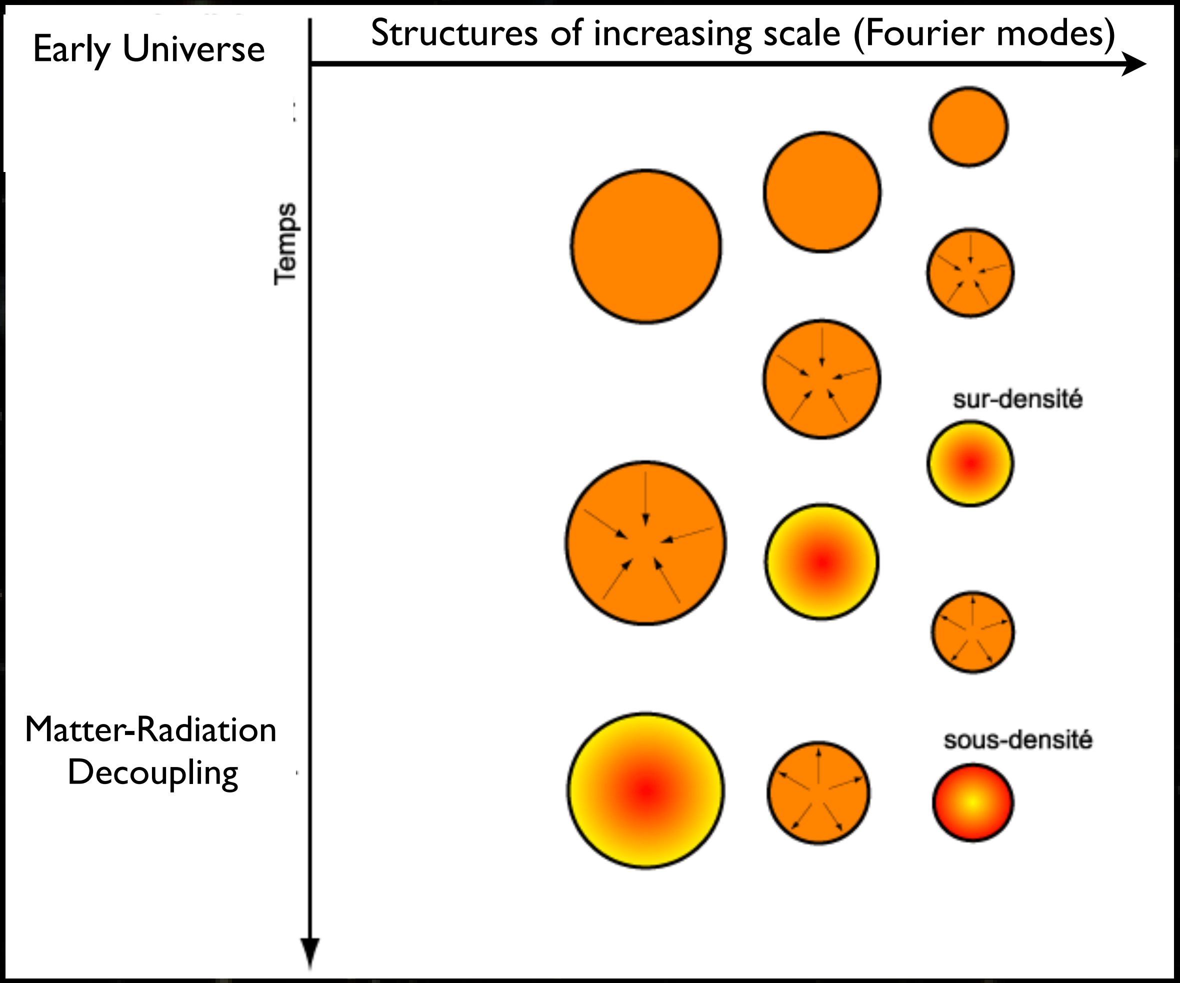
Transfer function: Baryonic Acoustic Oscillations

- (try to) think in Fourier space
  - ★ A structure collapses under its own gravity when larger than Hubble radius
  - ★ Temperature increases inducing more radiation pressure
  - ★ The structure re-expands
  - ★ Oscillations occur at each scale with a phase correlated to the scale
  - ★ Oscillations are frozen at matter-radiation decoupling



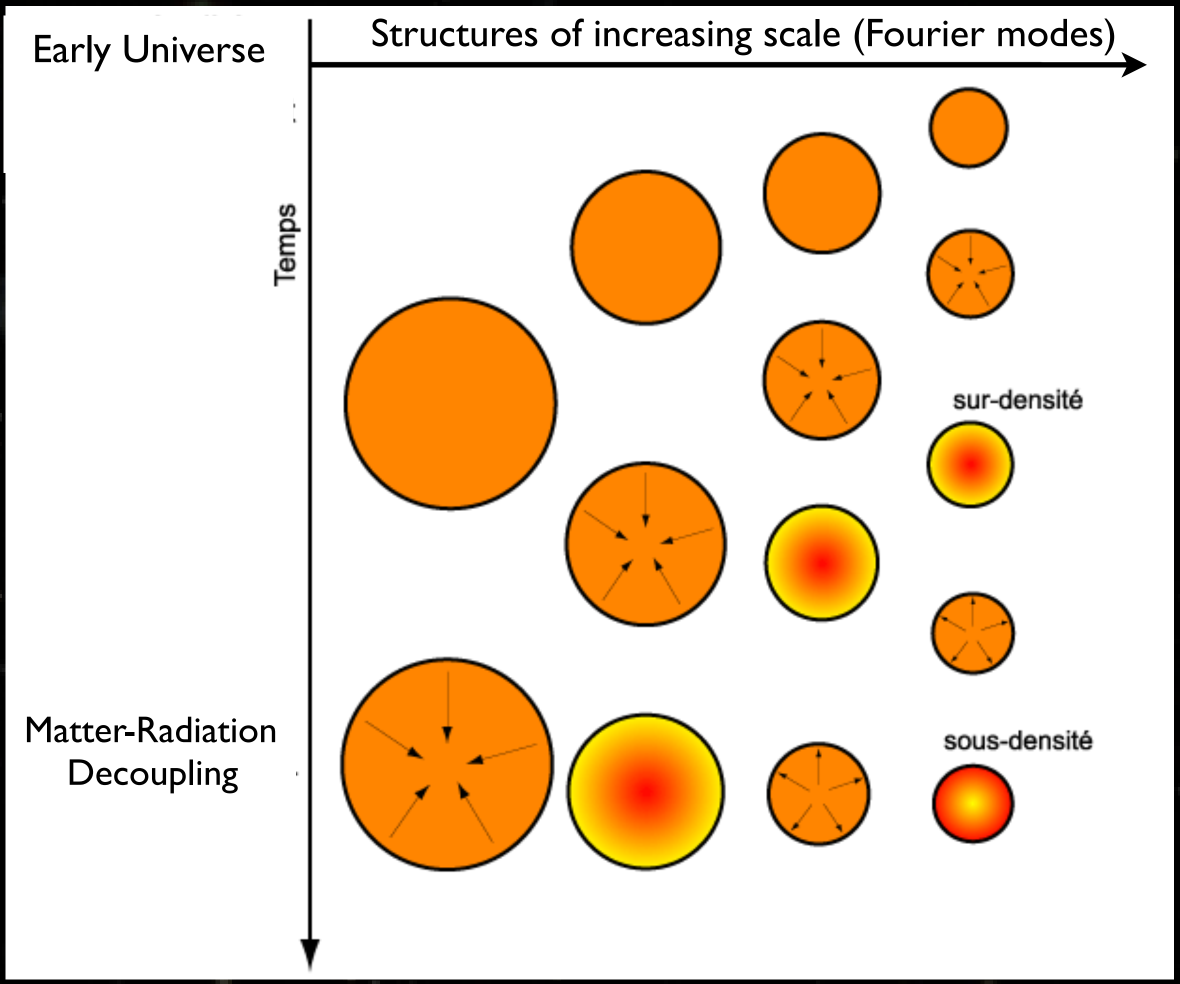
Transfer function: Baryonic Acoustic Oscillations

- (try to) think in Fourier space
  - ★ A structure collapses under its own gravity when larger than Hubble radius
  - ★ Temperature increases inducing more radiation pressure
  - ★ The structure re-expands
  - ★ Oscillations occur at each scale with a phase correlated to the scale
  - ★ Oscillations are frozen at matter-radiation decoupling



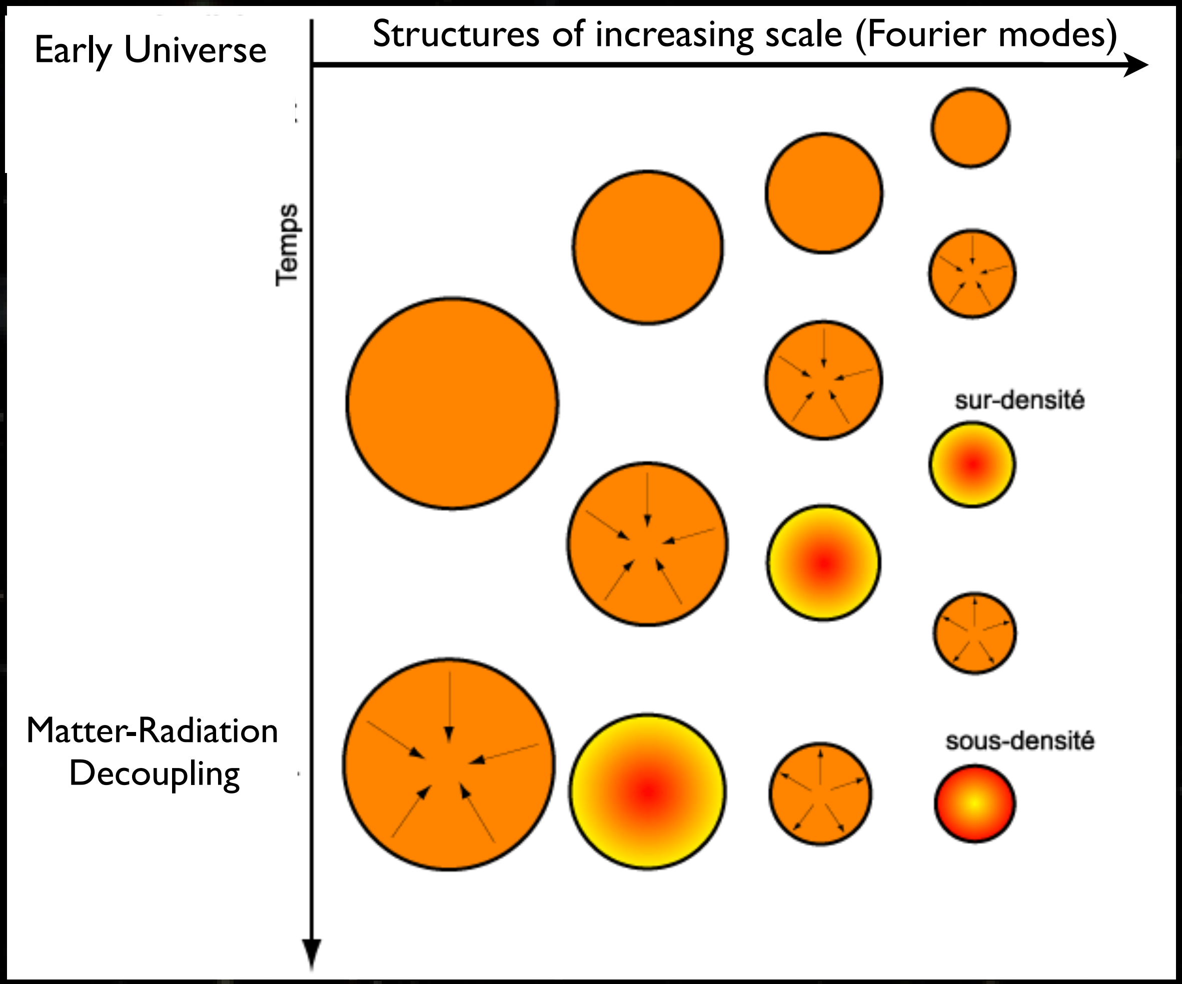
Transfer function: Baryonic Acoustic Oscillations

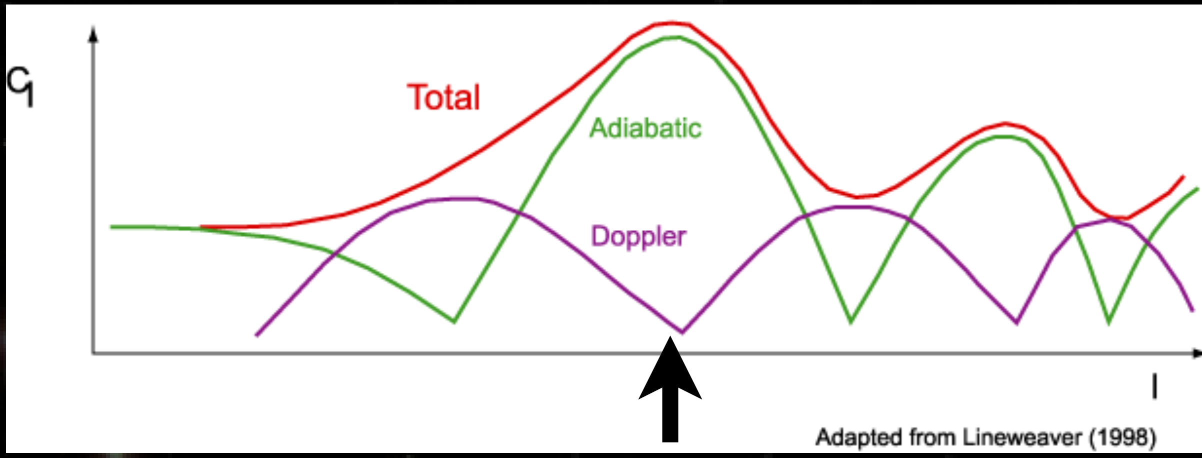
- (try to) think in Fourier space
  - ★ A structure collapses under its own gravity when larger than Hubble radius
  - ★ Temperature increases inducing more radiation pressure
  - ★ The structure re-expands
  - ★ Oscillations occur at each scale with a phase correlated to the scale
  - ★ Oscillations are frozen at matter-radiation decoupling



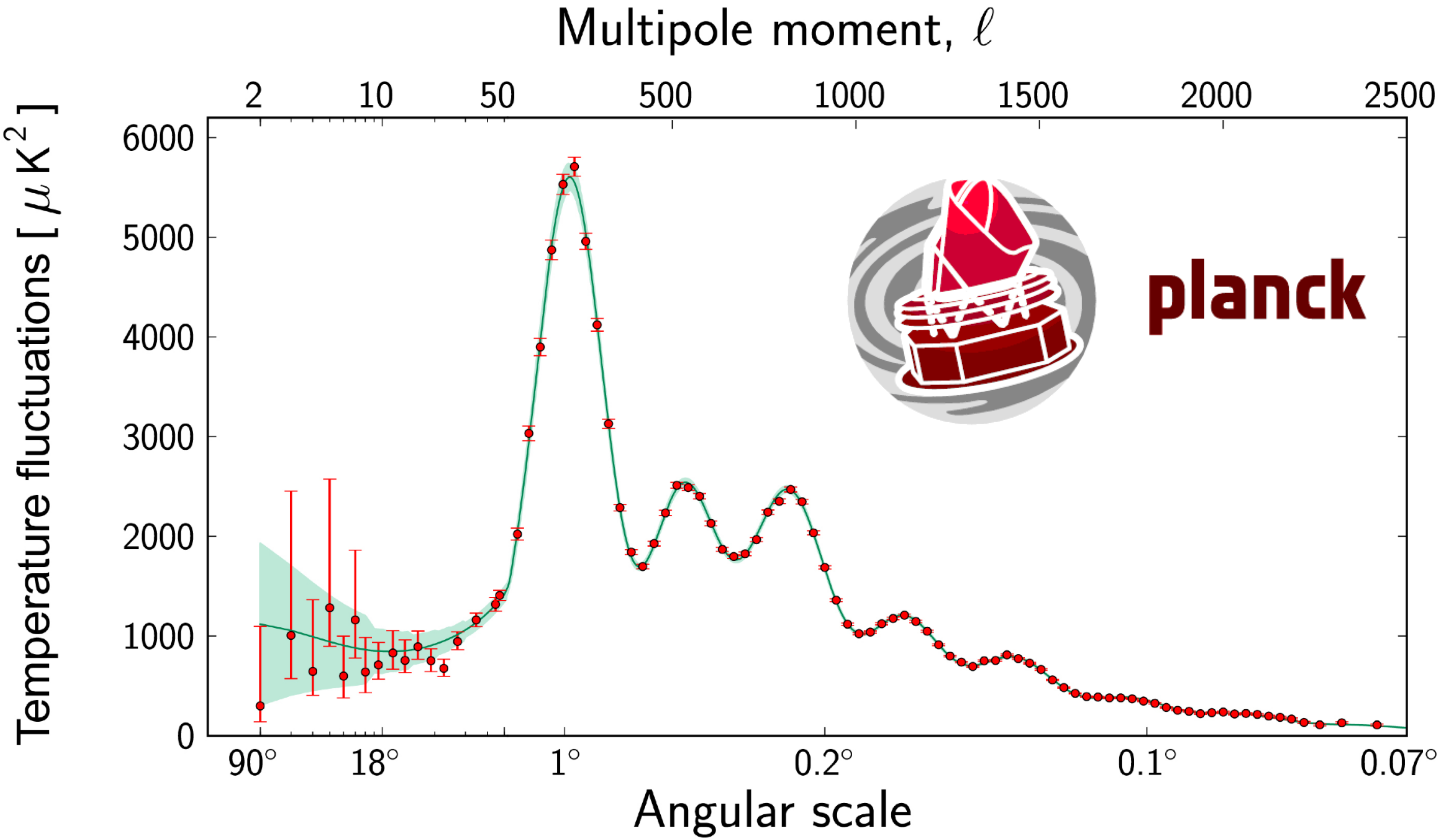
Transfer function: Baryonic Acoustic Oscillations

- (try to) think in Fourier space
  - ★ A structure collapses under its own gravity when larger than Hubble radius
  - ★ Temperature increases inducing more radiation pressure
  - ★ The structure re-expands
  - ★ Oscillations occur at each scale with a phase correlated to the scale
  - ★ Oscillations are frozen at matter-radiation decoupling



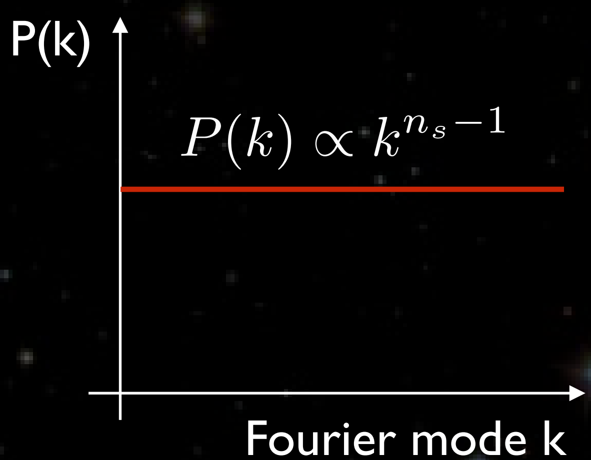


150 Mpc @ z=1000


Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale
planck

Density Field Transfer Function

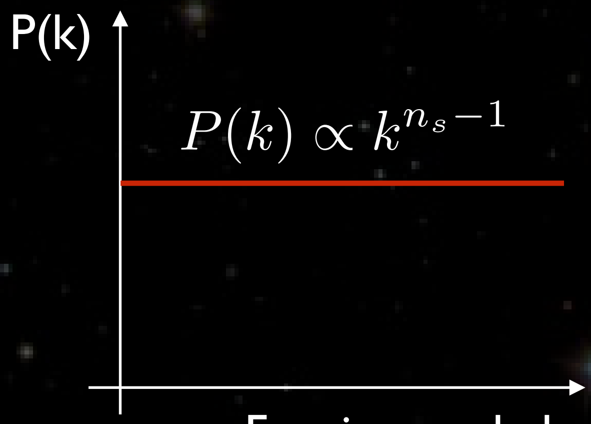
Early Universe
Primordial Density
Fluctuations

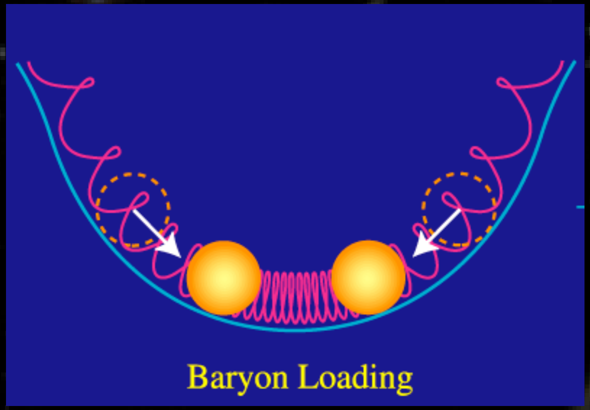


Density Field Transfer Function

Early Universe
Primordial Density
Fluctuations

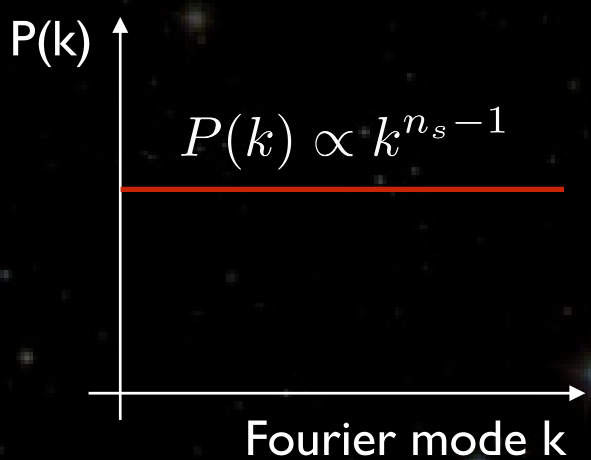
Acoustic
Oscillations

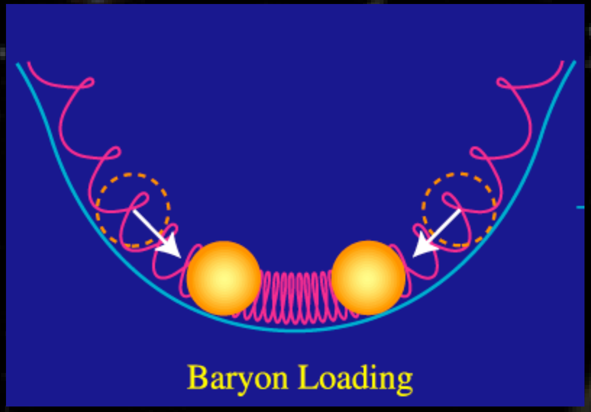


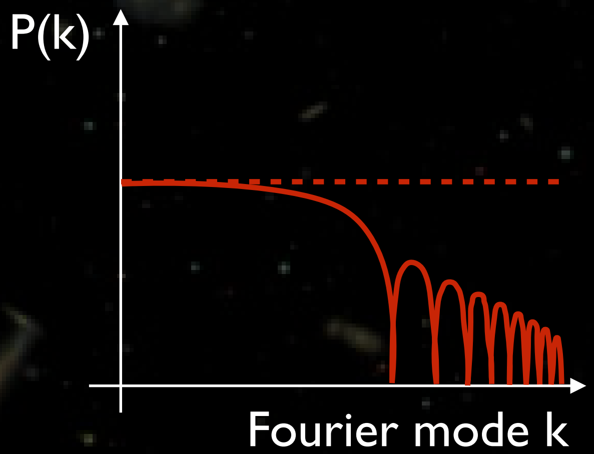


Density Field Transfer Function

Early Universe Primordial Density Fluctuations → Acoustic Oscillations → Evolved power spectrum

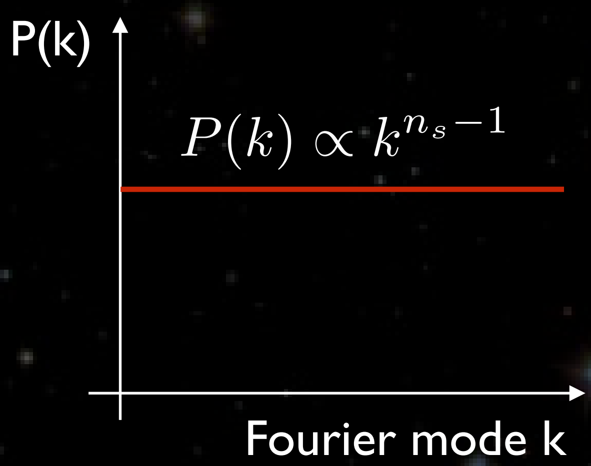


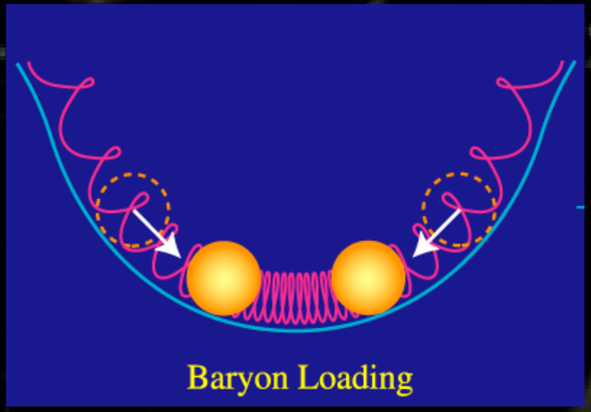


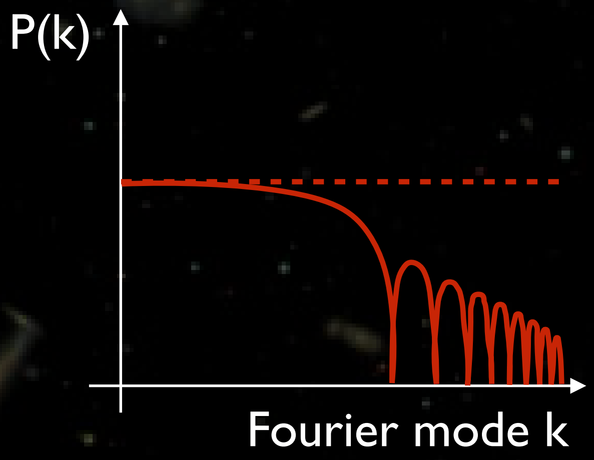


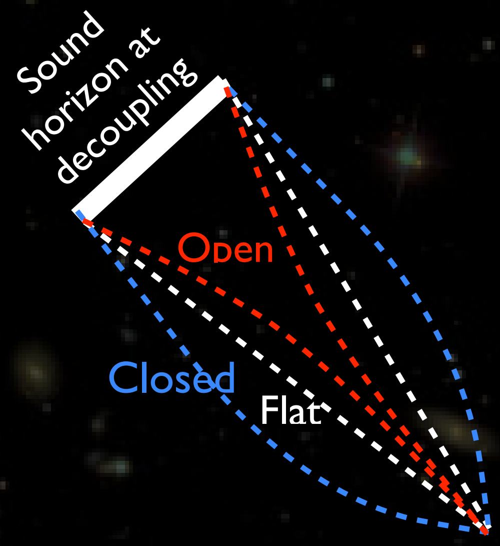
Density Field Transfer Function

Early Universe Primordial Density Fluctuations → Acoustic Oscillations → Evolved power spectrum → Geometry



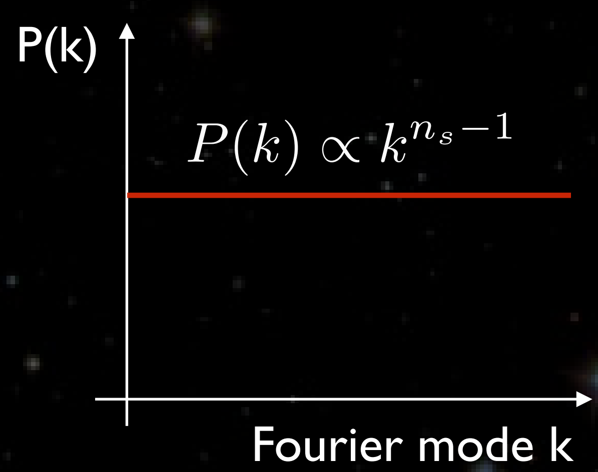




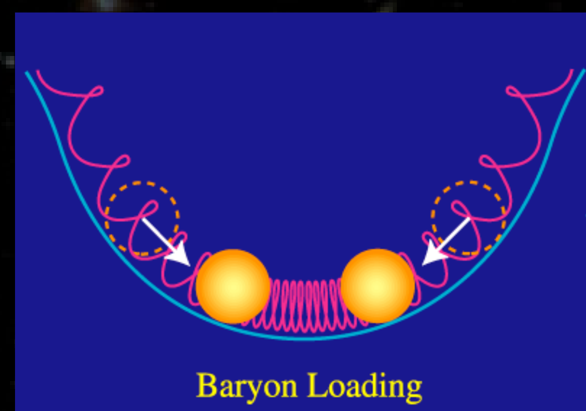


Density Field Transfer Function

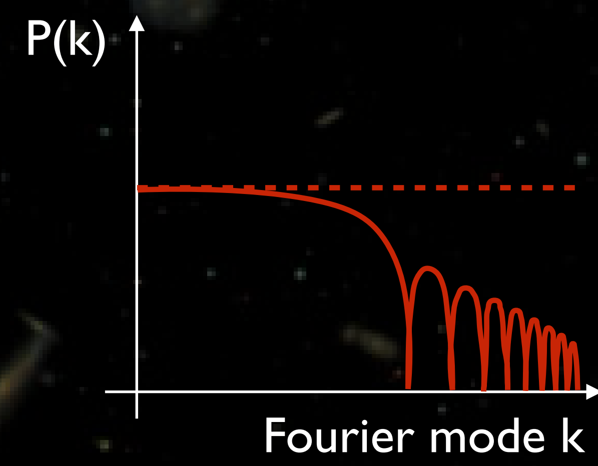
Early Universe Primordial Density Fluctuations



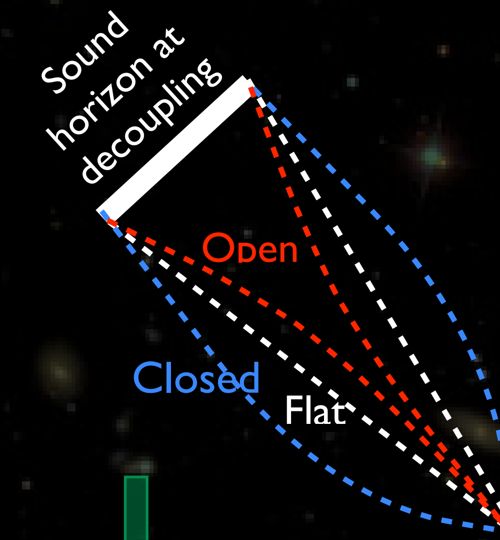
Acoustic Oscillations



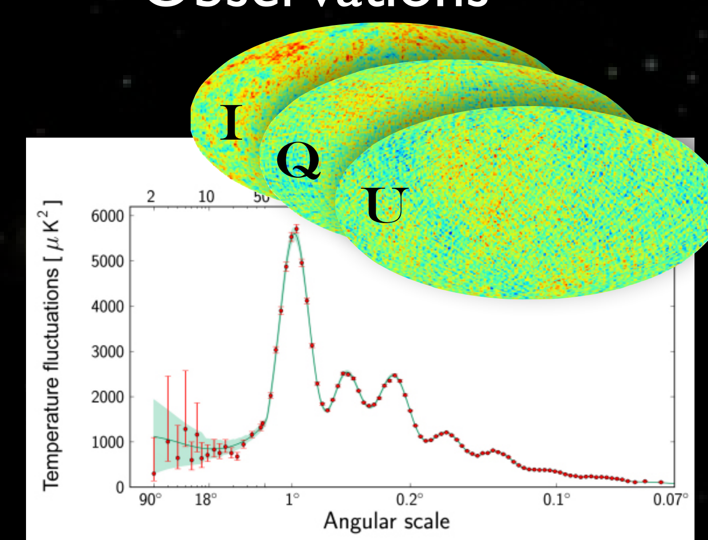
Evolved power spectrum



Geometry

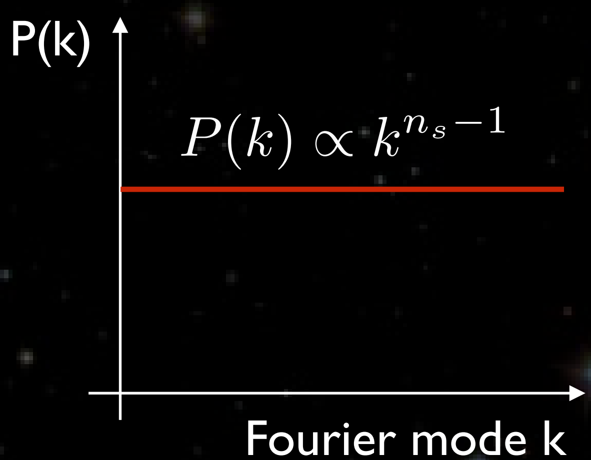


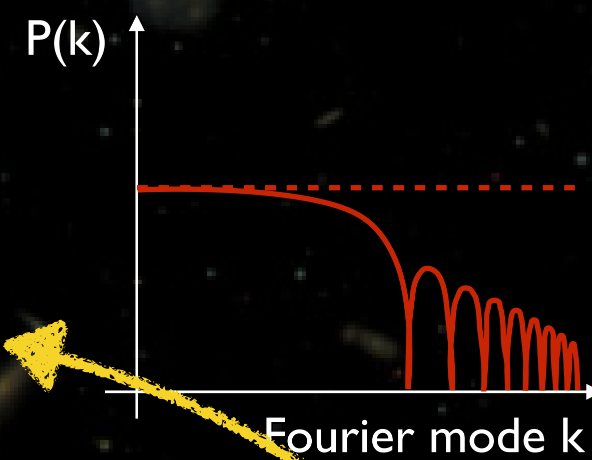
CMB Observations

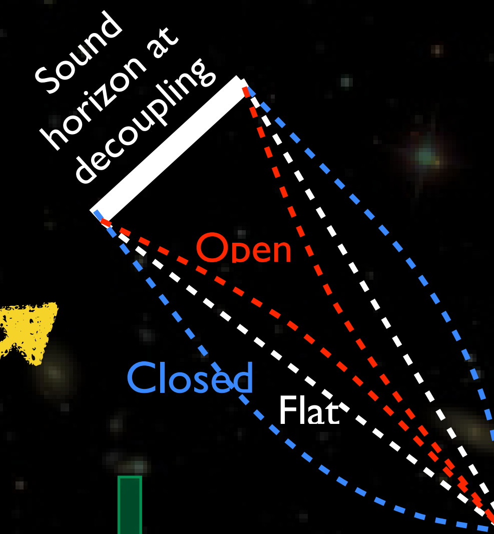


Density Field Transfer Function

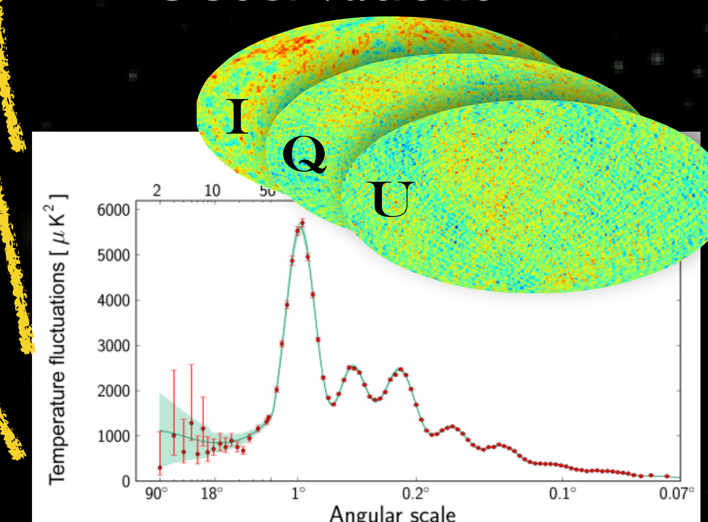
Early Universe Primordial Density Fluctuations → Acoustic Oscillations → Evolved power spectrum → Geometry







CMB Observations



- Perturbations evolve from end of inflation to decoupling due to matter-radiation oscillations.
- The **<u>transfert function</u>** depends upon « simple physics » and cosmological parameters
- Allows to fit both cosmology and primordial spectra (including inflationary physics)

B-modes and Tensors: the holy grail for Inflation

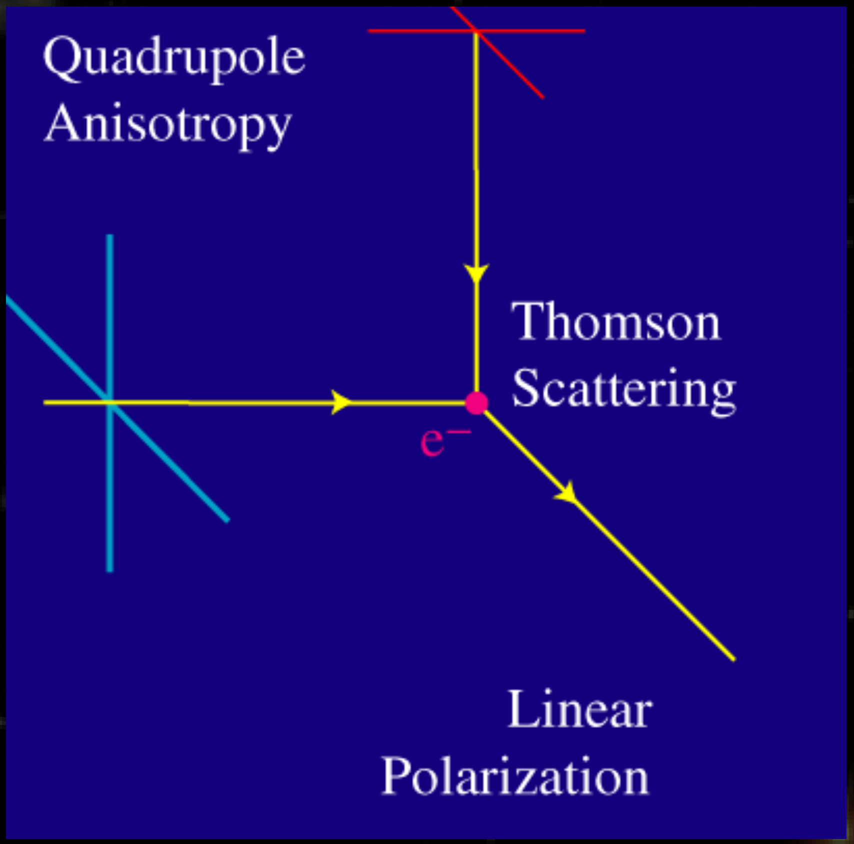
- Why is there CMB polarization ?
- E, B, Q, U, tensors and scalars ?
- Link with inflation ?
- B-modes are the Holy Grail !

B-modes and Tensors: the holy grail for Inflation

- Why is there CMB polarization ?
- E, B, Q, U, tensors and scalars ?
- Link with inflation ?
- B-modes are the Holy Grail !

Origin of CMB Polarization

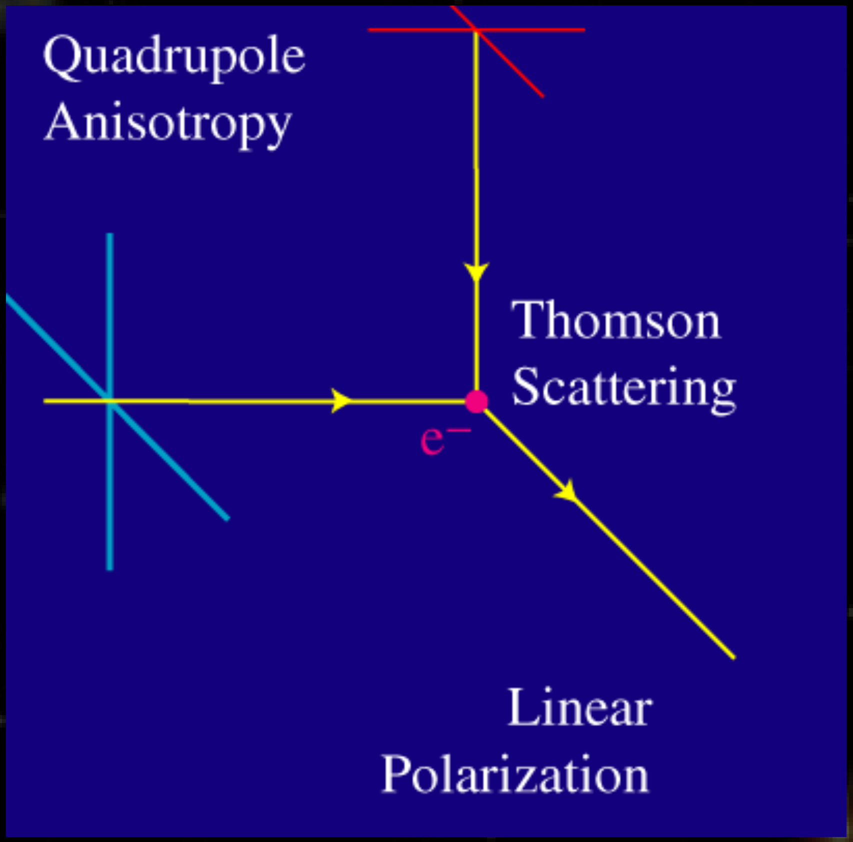
Thomson Scattering on the last scattering surface (at CMB emission)



W. Hu

Origin of CMB Polarization

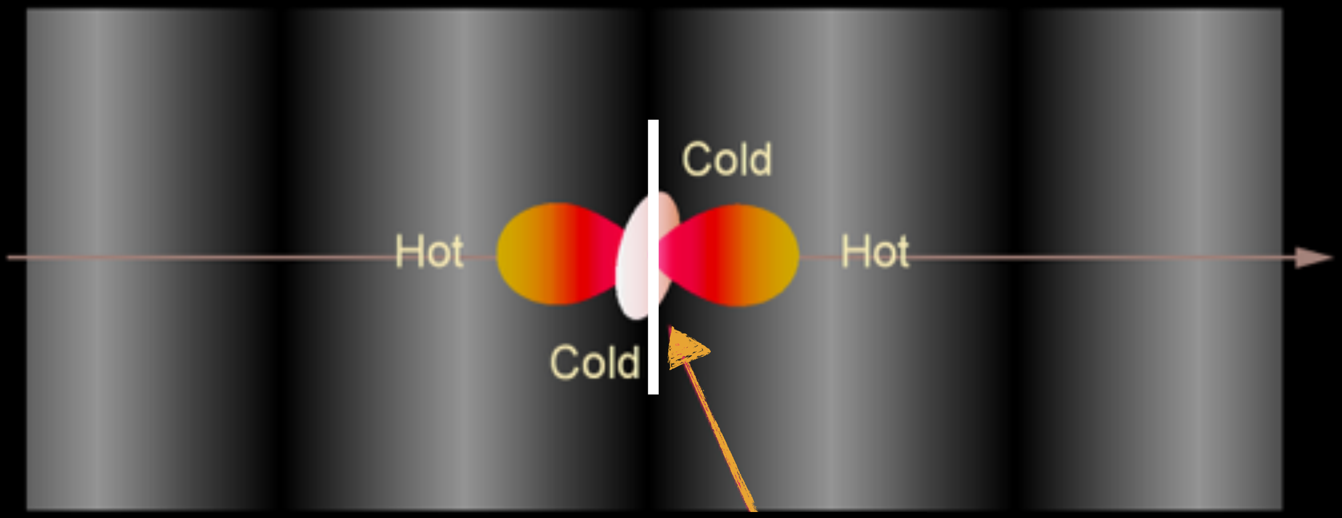
Thomson Scattering on the last scattering surface (at CMB emission)



W. Hu

Anisotropic fluxes on the LSS: E and B modes

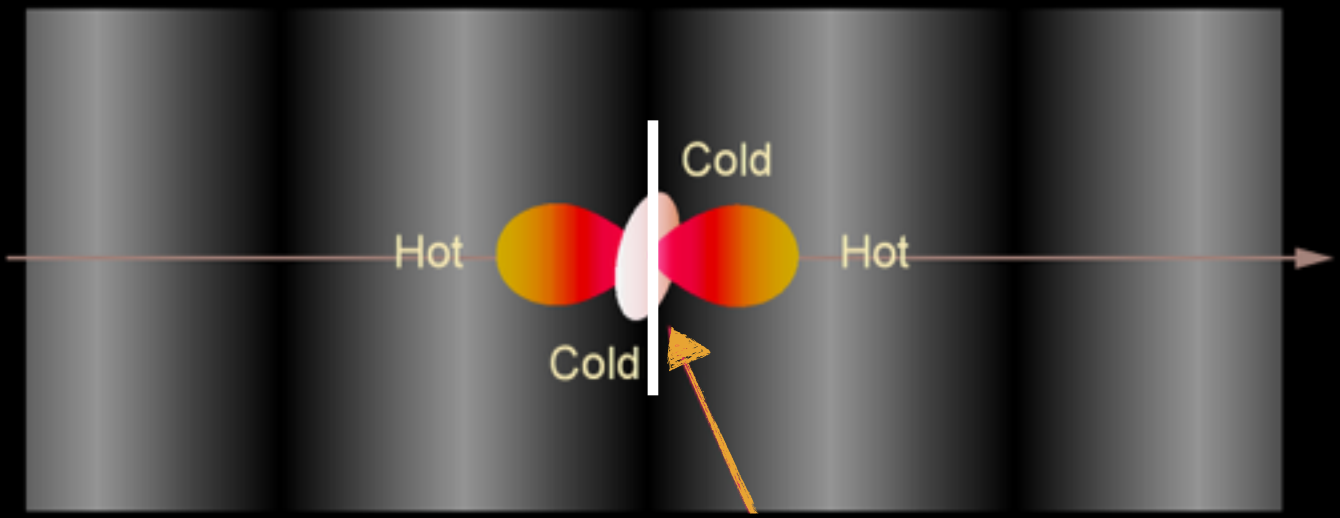
Density Wave (Scalar Perturbations)

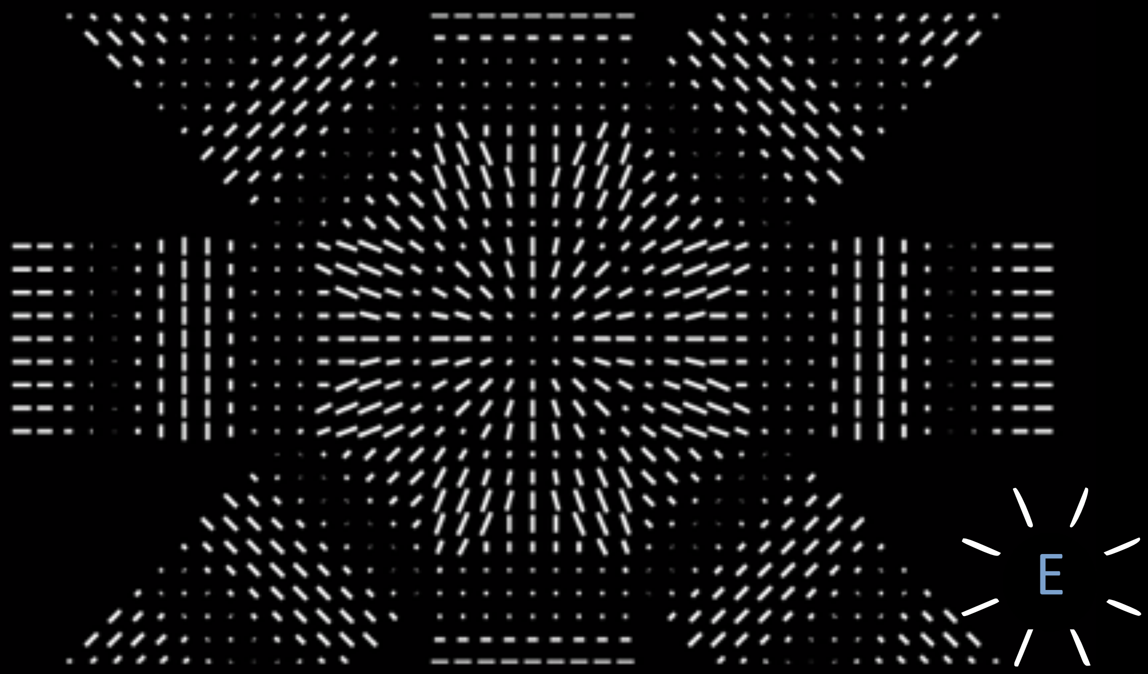


Credit: BICEP Collaboration

Anisotropic fluxes on the LSS: E and B modes

Density Wave (Scalar Perturbations)

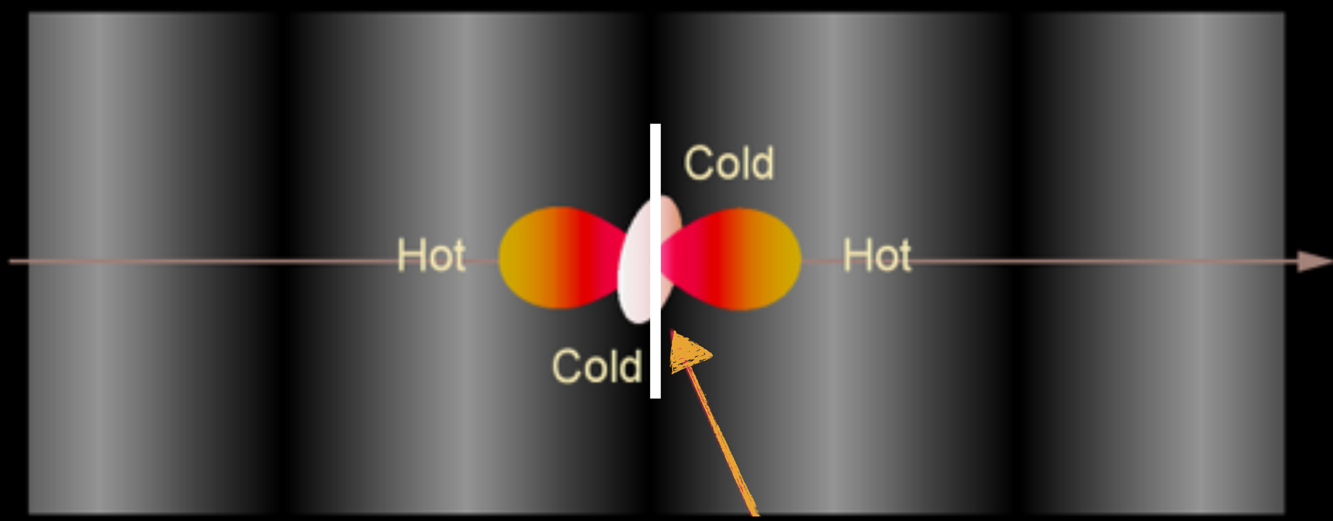


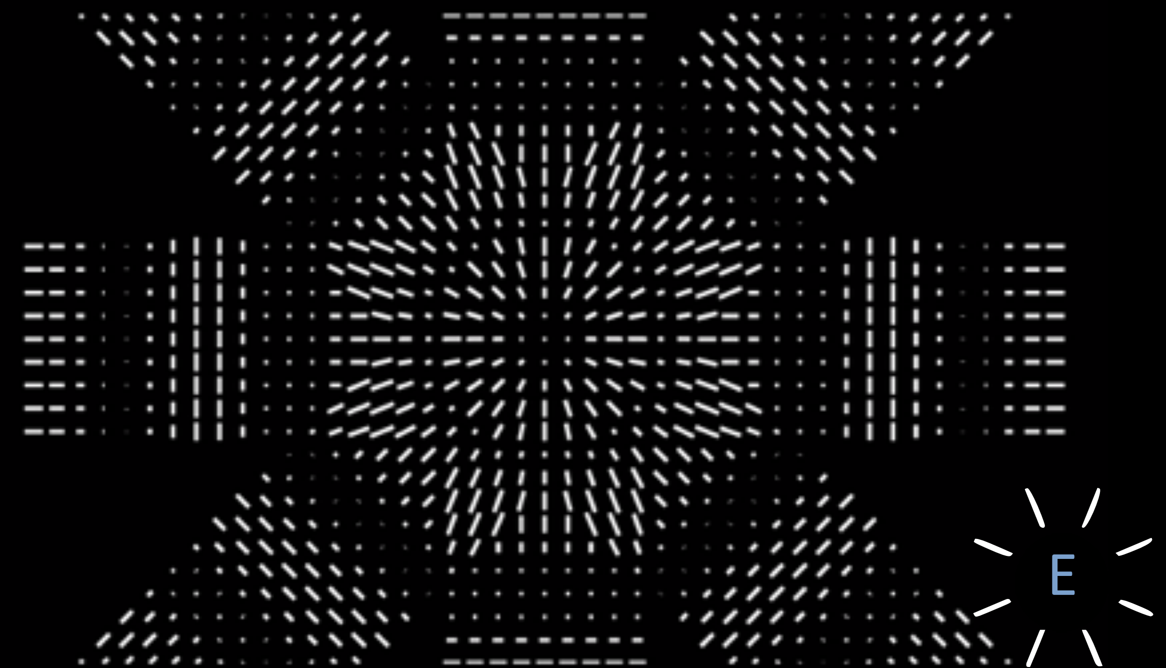


Credit: BICEP Collaboration

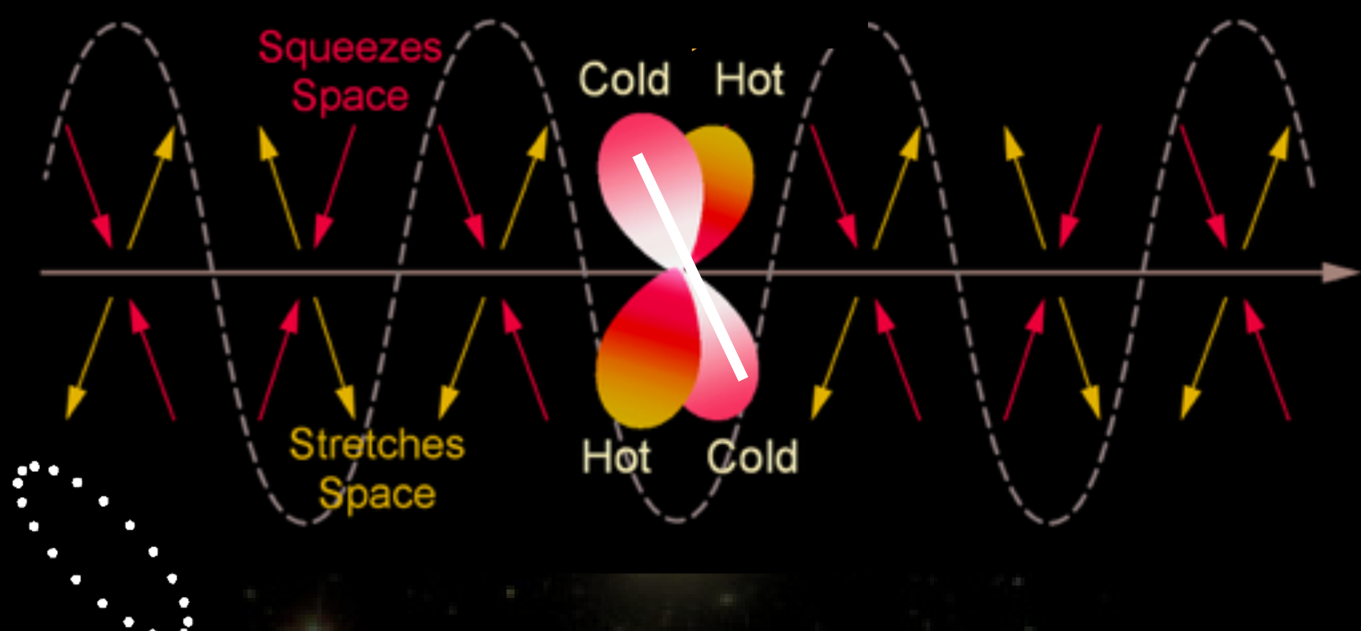
Anisotropic fluxes on the LSS: E and B modes

Density Wave (Scalar Perturbations)





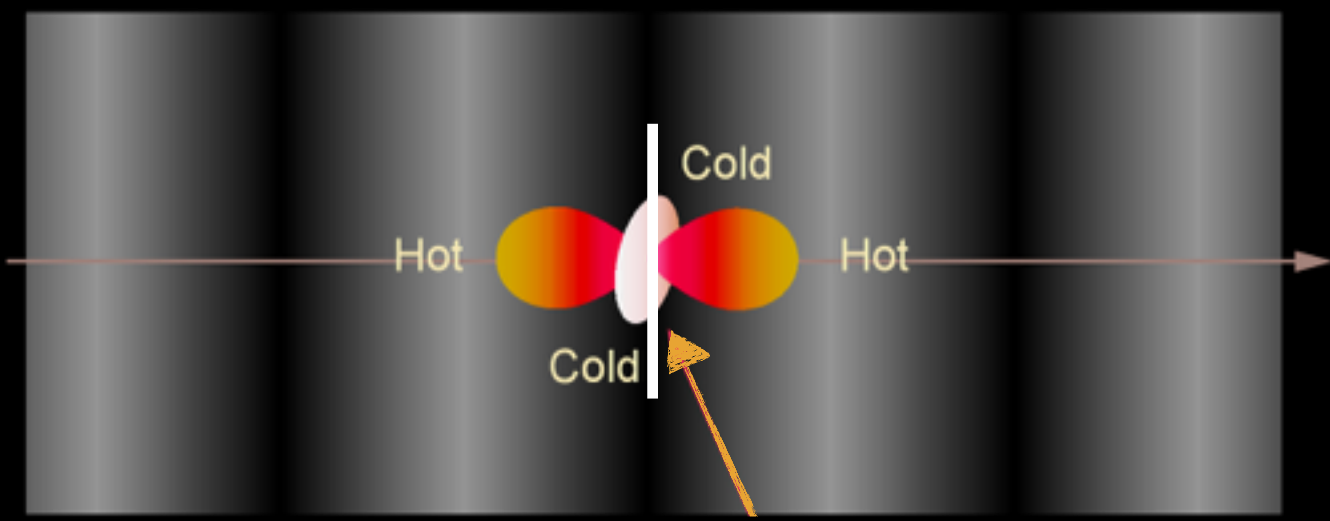
Gravitational Wave (Tensor Perturbations)

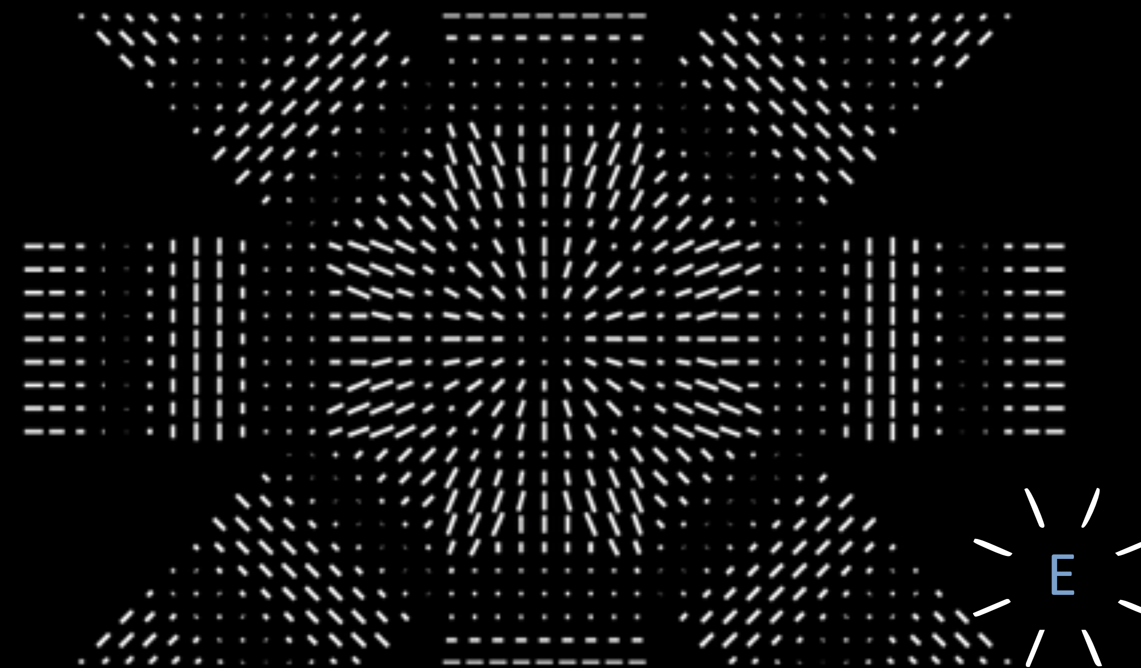


Credit: BICEP Collaboration

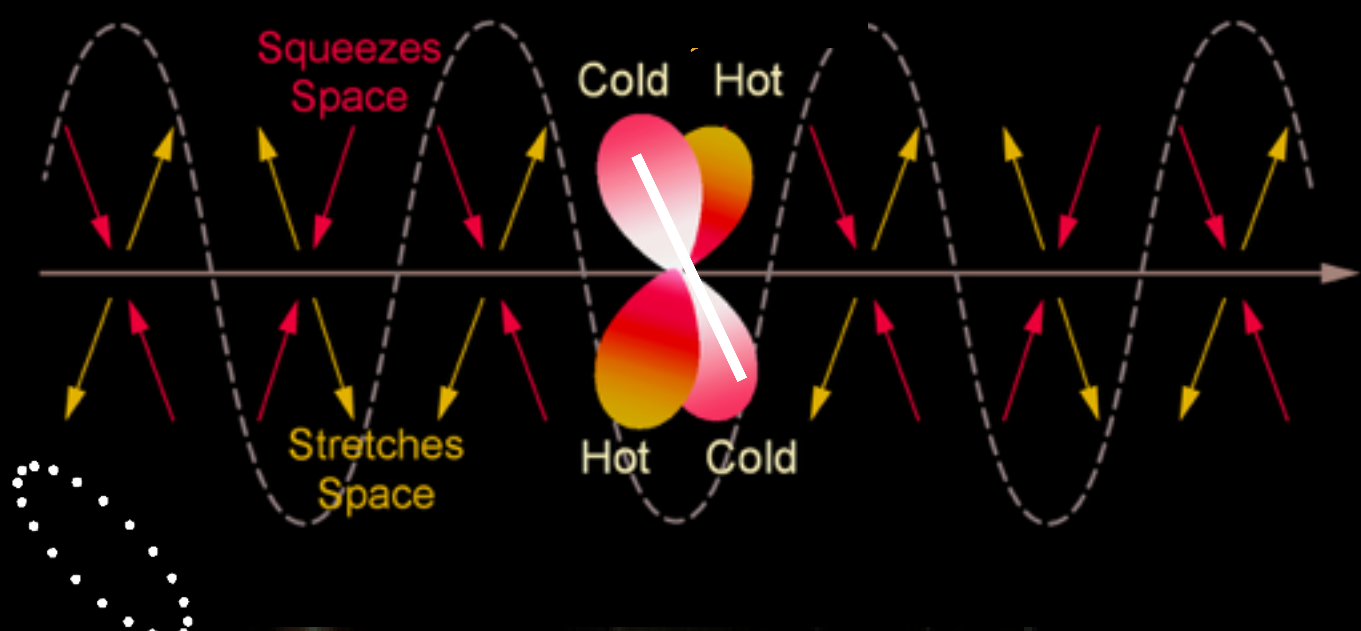
Anisotropic fluxes on the LSS: E and B modes

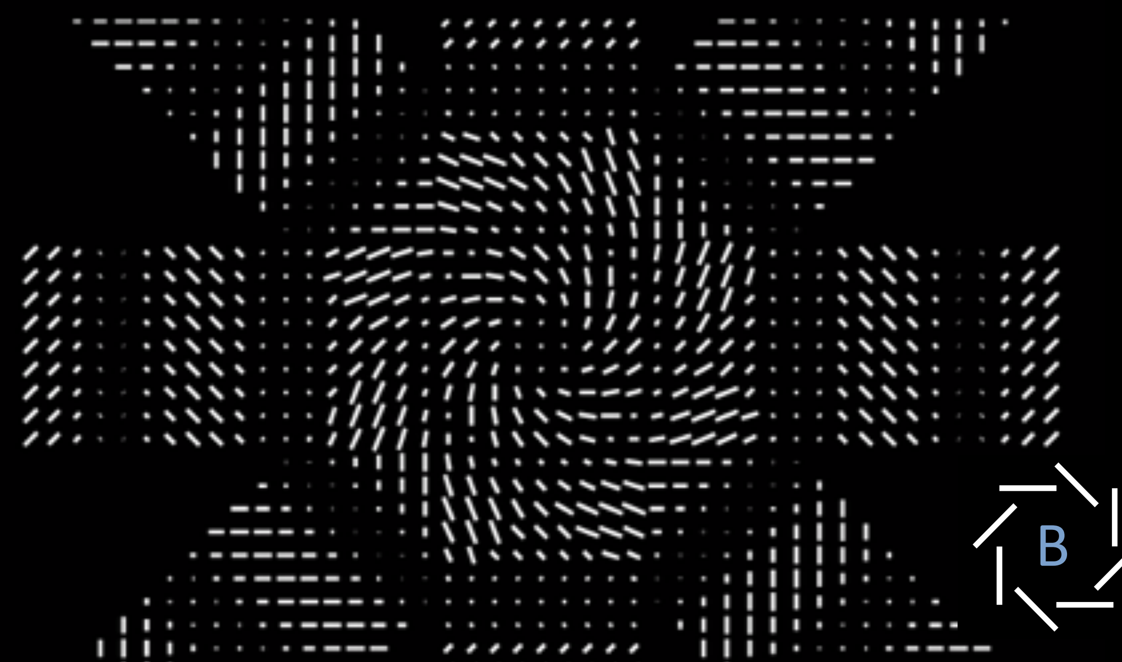
Density Wave (Scalar Perturbations)





Gravitational Wave (Tensor Perturbations)





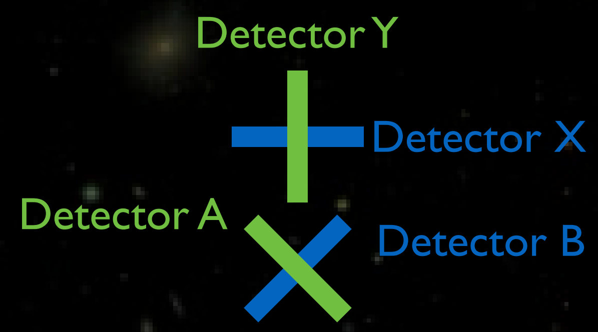
Credit: BICEP Collaboration

Observables are Q and U

- Stokes Parameters (linear pol.)

$$Q(\vec{n}) = \left\langle \left| E_{\parallel}(\vec{n}) \right|^2 \right\rangle - \left\langle \left| E_{\perp}(\vec{n}) \right|^2 \right\rangle \qquad \text{(spin 2)}$$

$$U(\vec{n}) = \left\langle E_{\parallel}(\vec{n}) E_{\perp}^{\star}(\vec{n}) \right\rangle + \left\langle E_{\perp}(\vec{n}) E_{\parallel}^{\star}(\vec{n}) \right\rangle \qquad \text{(spin 2)}$$



- Spin 2 Spherical Harmonics Expansion

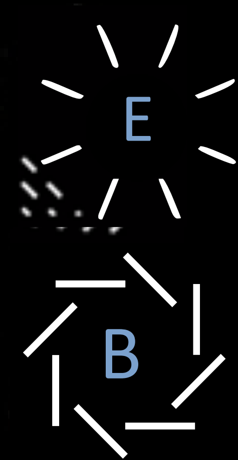
$$Q(\vec{n}) + iU(\vec{n}) = \sum_{\ell m} a_{2,\ell m} \; {}_{2}Y_{\ell m}(\vec{n})$$

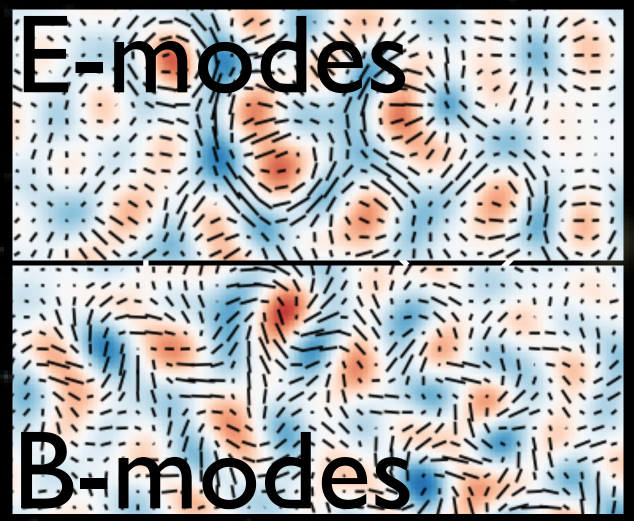
$$Q(\vec{n}) - iU(\vec{n}) = \sum_{\ell m} a_{-2,\ell m} \; {}_{-2}Y_{\ell m}(\vec{n})$$

- Scalar E and B fields

$$a_{E,\ell m} = -\frac{a_{2,\ell m} + a_{-2,\ell m}}{2}$$

$$a_{B,\ell m} = i\frac{a_{2,\ell m} - a_{-2,\ell m}}{2}$$





$$\left.\right\} \quad C_\ell^{TT} \quad C_\ell^{TE} \quad C_\ell^{EE} \quad C_\ell^{BB}$$

Scalar and tensor modes - E & B polarization

- **Scalar perturbations:** $$P_s(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$
  - Density fluctuations
    - Temperature
    - E polarization
    - No B polarization
- **Tensor perturbations:** $$P_r(k) = A_t \left(\frac{k}{k_0}\right)^{n_t}$$
  - Specific prediction from inflation!
    = Primordial gravitational waves
    - Temperature
    - E polarization
    - B Polarization

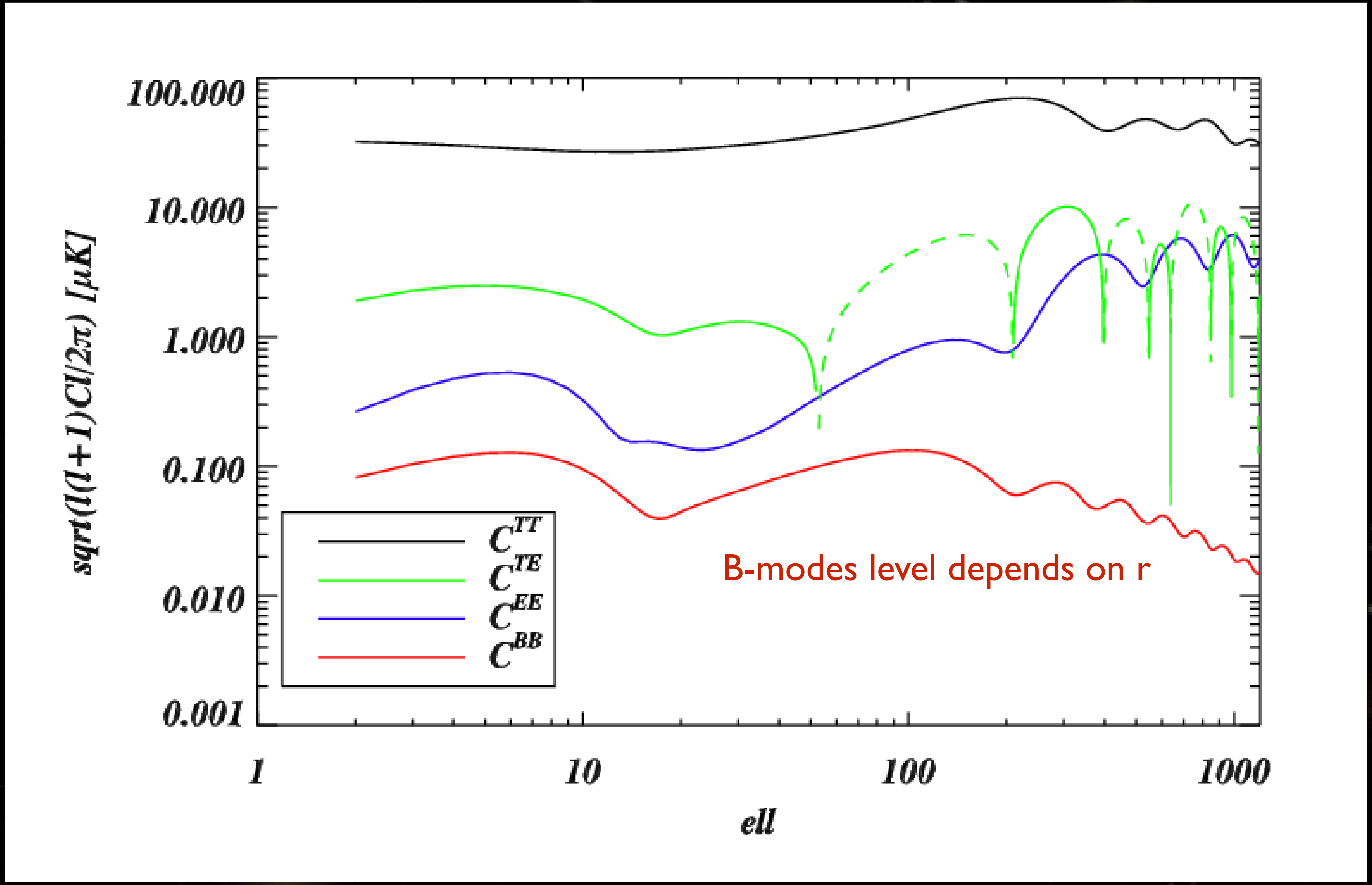
$$r = \frac{P_t(k_0)}{P_s(k_0)}$$

~ ratio between E and B modes

⇒ detect B-modes is :

- Direct detection of tensor modes
- «smoking gun» for inflation (see M. Zaldarriaga's talk)
- Measurement of its energy scale $$V^{1/4} = 1.06 \times 10^{16} \mathrm{GeV} \left(\frac{r_{\mathrm{CMB}}}{0.01}\right)^{1/4}$$

B-modes spectra



NB: No lensing nor dust shown here…

Tensors: window on Inflation Physics

Four important quantities :

- ★ A_s : known
- ★ n_s : known
- ★ A_t or r : unknown
- ★ n_t :unknown, requires exquisite B-modes **measurement**

- Energy scale: $$V^{1/4} = 1.06 \times 10^{16}\mathrm{GeV}\left(\frac{r_{\mathrm{CMB}}}{0.01}\right)^{1/4}$$

- Generic prediction of inflation : $$r = -8n_t$$

coherence test of inflation

- Direct inflaton potential reconstruction (Taylor expansion):

$$V(\phi) \simeq V|_{\phi_{\mathrm{CMB}}} + V'|_{\phi_{\mathrm{CMB}}}(\phi-\phi_{\mathrm{CMB}}) + \frac{1}{2}V''|_{\phi_{\mathrm{CMB}}}(\phi-\phi_{\mathrm{CMB}})^2 + \frac{1}{3!}V'|_{\phi_{\mathrm{CMB}}}(\phi-\phi_{\mathrm{CMB}})^3$$

- ★ A_s related to V'
- ★ n_s related to V''
- ★ *running of* n_s related to V'''
- ★ A_t related to V

inflaton potential shape recovery !
Need accuracy on r
Within reach in the next few years !

Primordial Fluctuations Origin ?

Inflation Predictions

• Flatness, Homogeneity	✔
• Nature of the perturbations: ★ TT peaks at same scales as EE troughs ➡ Adiabatic perturbations	✔
• Spectral index $P(k) \propto k^{n_s - 1}$ ★ Planck TT + WMAP Pol + High ℓ + BAO $n_s = 0.9608 \pm 0.0054\ (7.2\sigma \text{ from } 1)$ ➡ Almost scale invariant spectrum	✔
• Gaussianity ★ No hint for non-Gaussianity (despite impressive efforts)	✔
• Tensor perturbations of the metric	?

Primordial Fluctuations Origin ?

Inflation Predictions

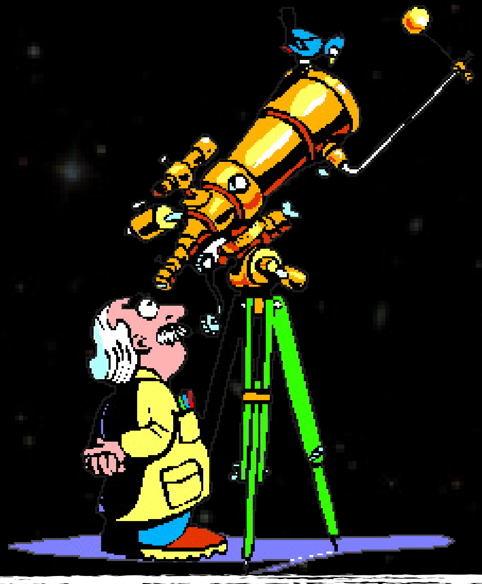
• Flatness, Homogeneity	✔
• Nature of the perturbations: ★ TT peaks at same scales as EE troughs ➡ Adiabatic perturbations	✔
• Spectral index $P(k) \propto k^{n_s - 1}$ ★ Planck TT + WMAP Pol + High ℓ + BAO $n_s = 0.9608 \pm 0.0054 \ (7.2\sigma \text{ from } 1)$ ➡ Almost scale invariant spectrum	✔
• Gaussianity ★ No hint for non-Gaussianity (despite impressive efforts)	✔
• Tensor perturbations of the metric	

Take home message:

Take home message:

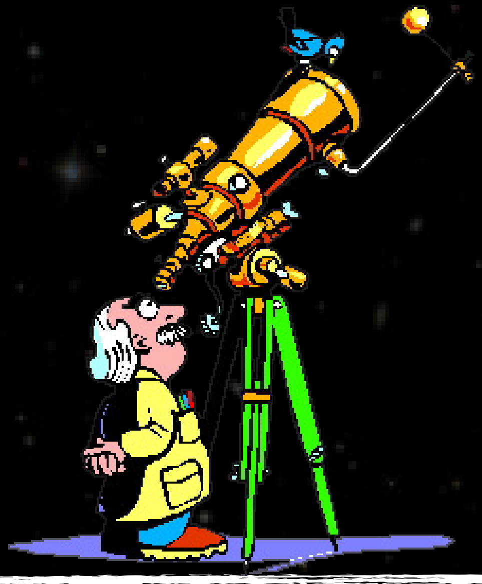
Difficulties in the Quest

- Lensing signal (but LSS and ν !)
- Weakness of Primordial B-modes
- Instrumental Systematics
- Foregrounds



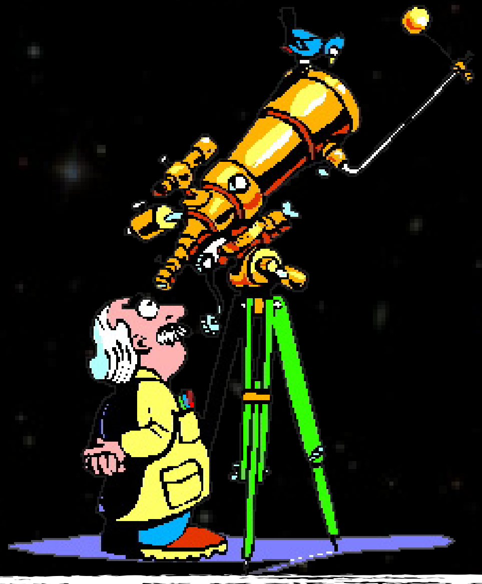
Difficulties in the Quest

- Lensing signal (but LSS and ν !)
- Weakness of Primordial B-modes
- Instrumental Systematics
- Foregrounds



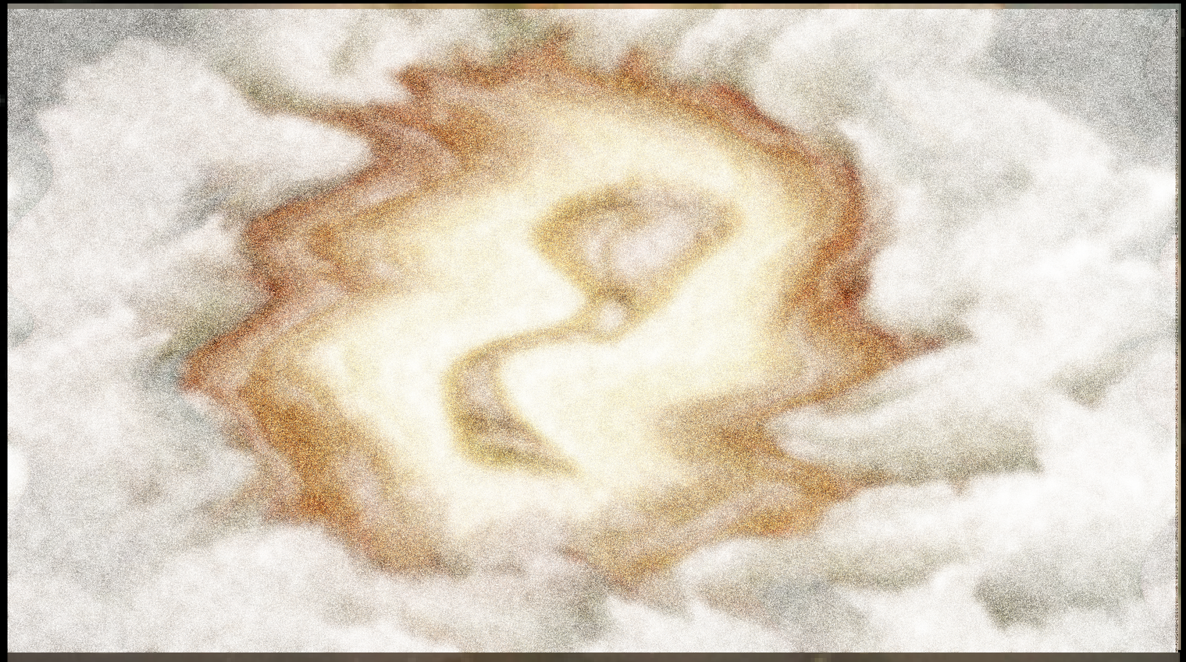
Difficulties in the Quest

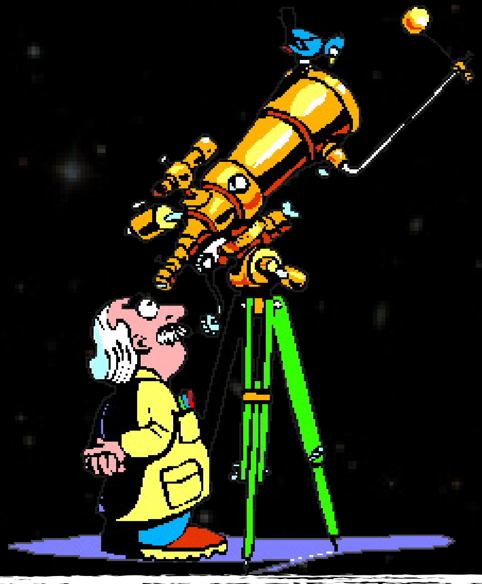
- Lensing signal (but LSS and ν !)
- Weakness of Primordial B-modes
- Instrumental Systematics
- Foregrounds



Difficulties in the Quest

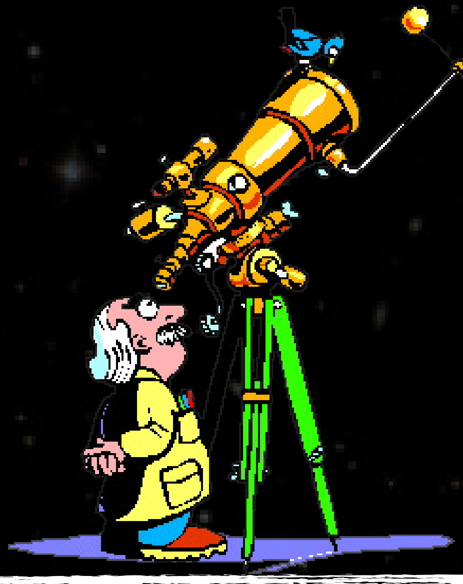
- Lensing signal (but LSS and ν !)
- Weakness of Primordial B-modes
- Instrumental Systematics
- Foregrounds





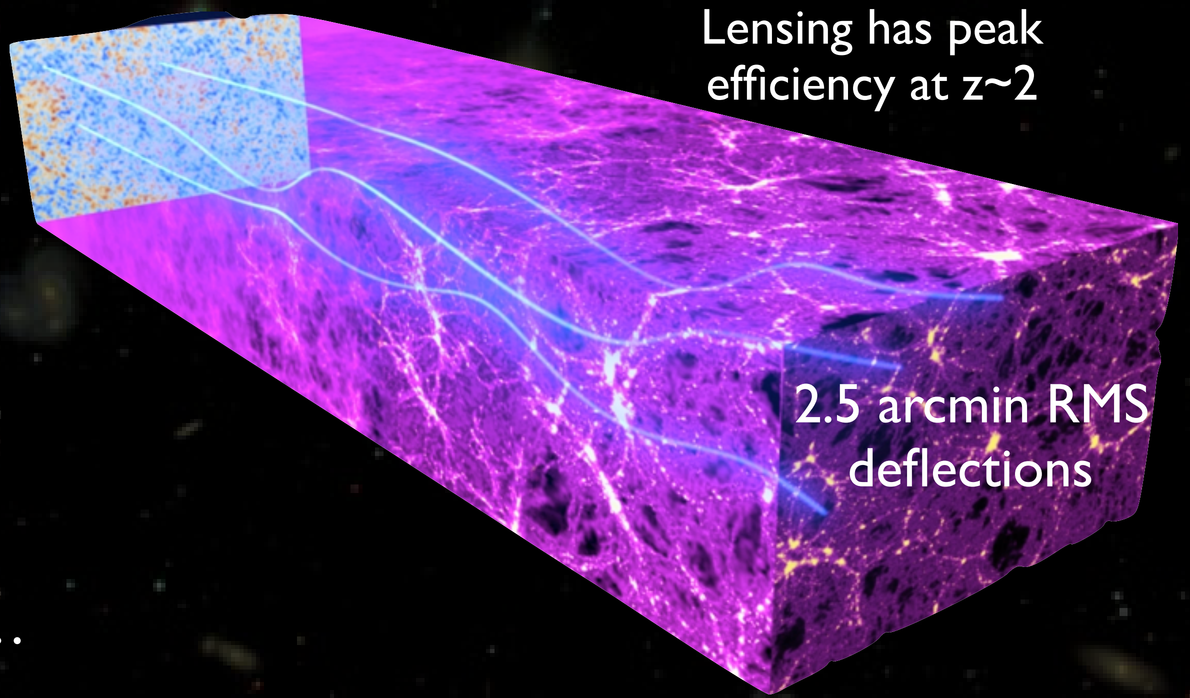
Difficulties in the Quest

- Lensing signal (but LSS and ν !)
- Weakness of Primordial B-modes
- Instrumental Systematics
- Foregrounds



CMB Lensing by large scale structure

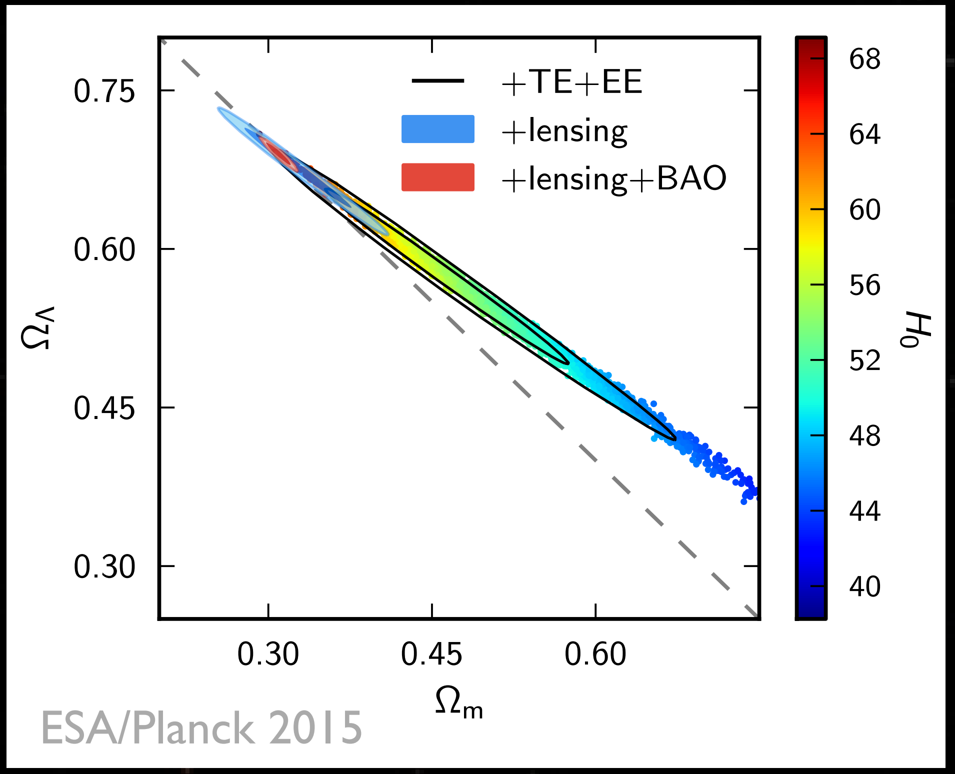
- **Deflection field:**
  - ★ Gradient of redshift-integral of LSS
- **Lensing adds information**
  - ★ lifts geometric CMB degeneracies
    - Curvature, sub-eV neutrino masses, Dark Energy…

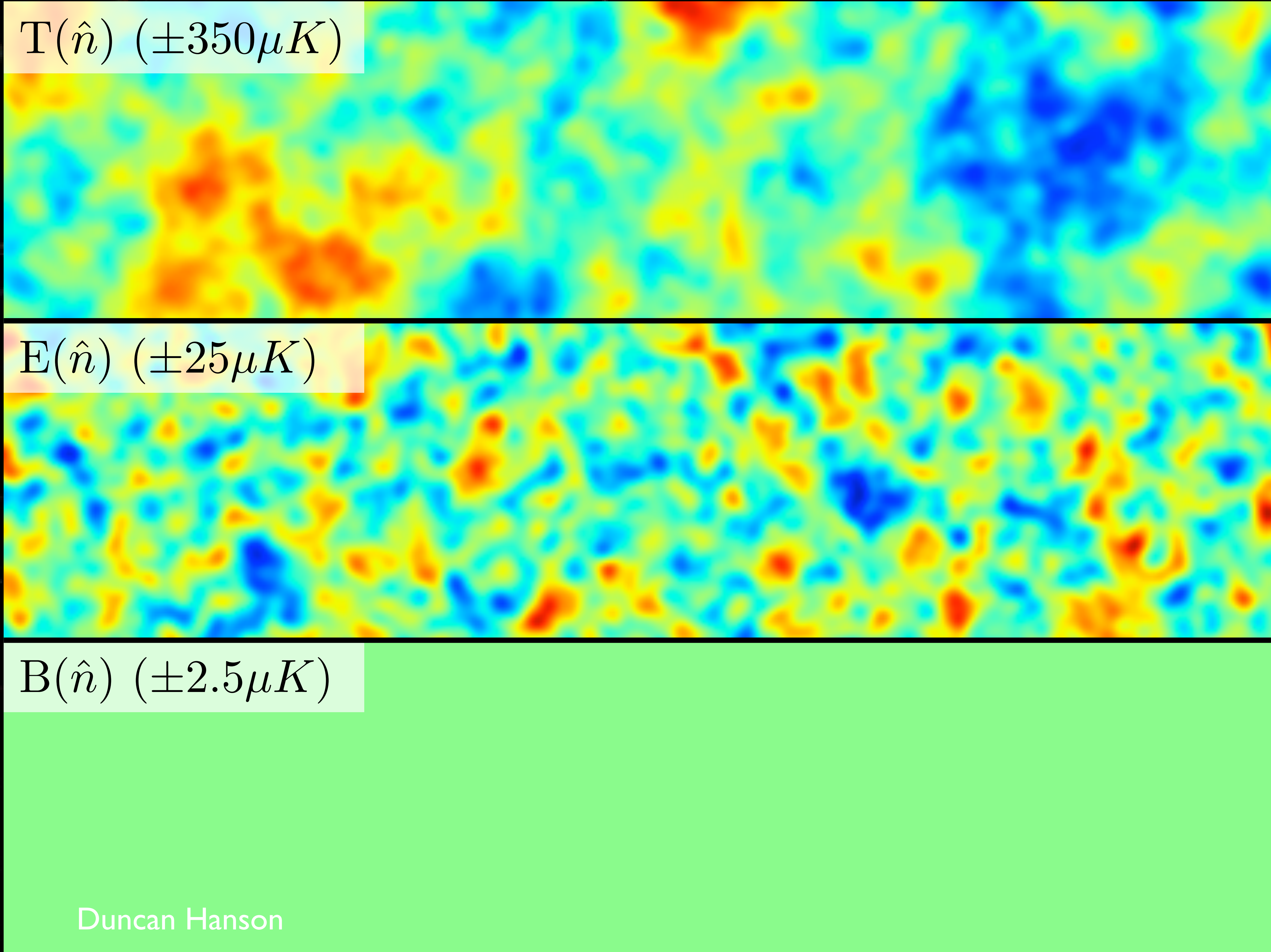


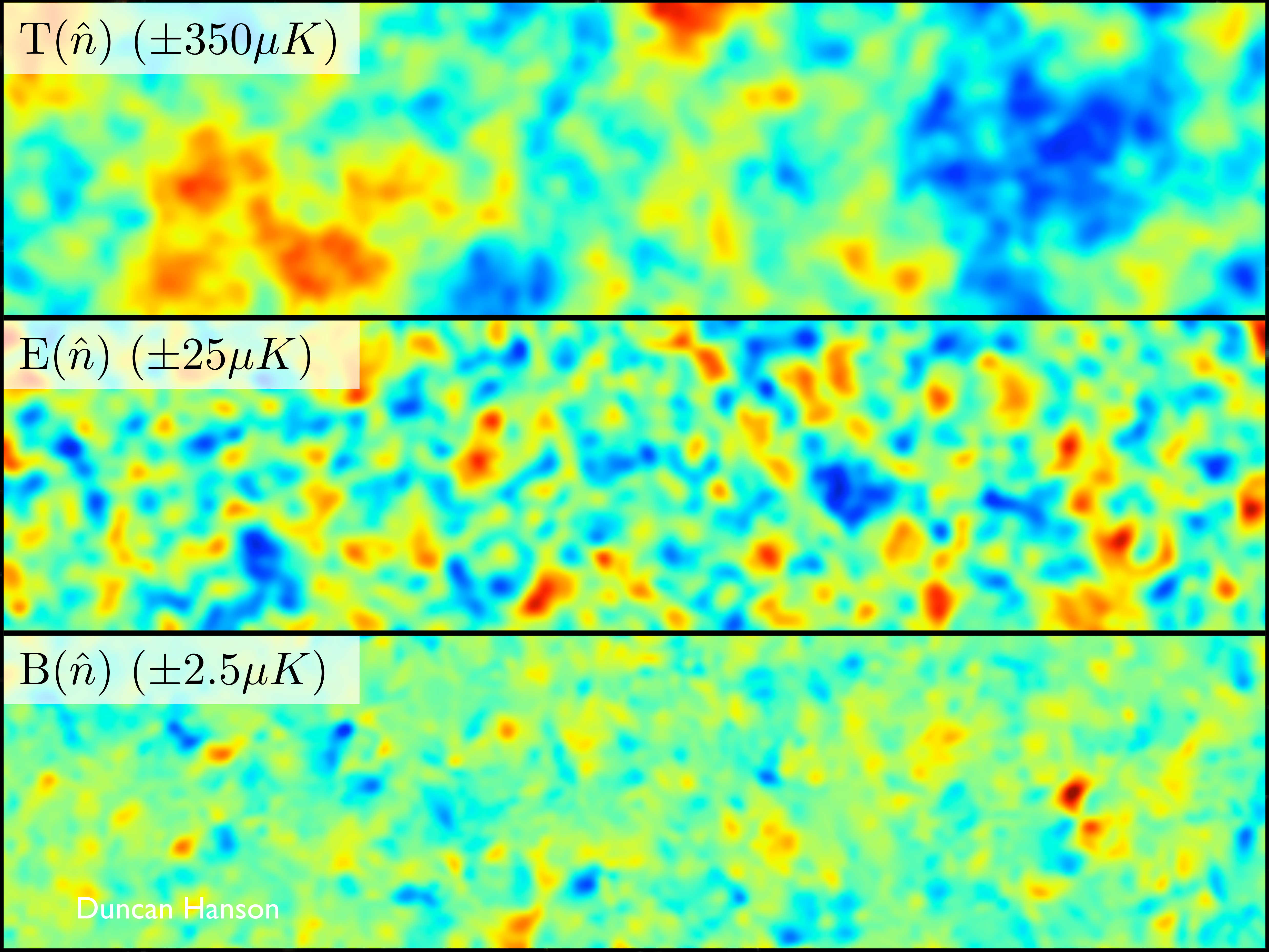
- **Effect on Stokes parameters**

$$\tilde{T}(\vec{x}) = T(\vec{x}+\vec{\nabla}\phi)$$
$$(\tilde{Q}\pm i\tilde{U})(\vec{x}) = (\tilde{Q}\pm i\tilde{U})(\vec{x}+\vec{\nabla}\phi)$$

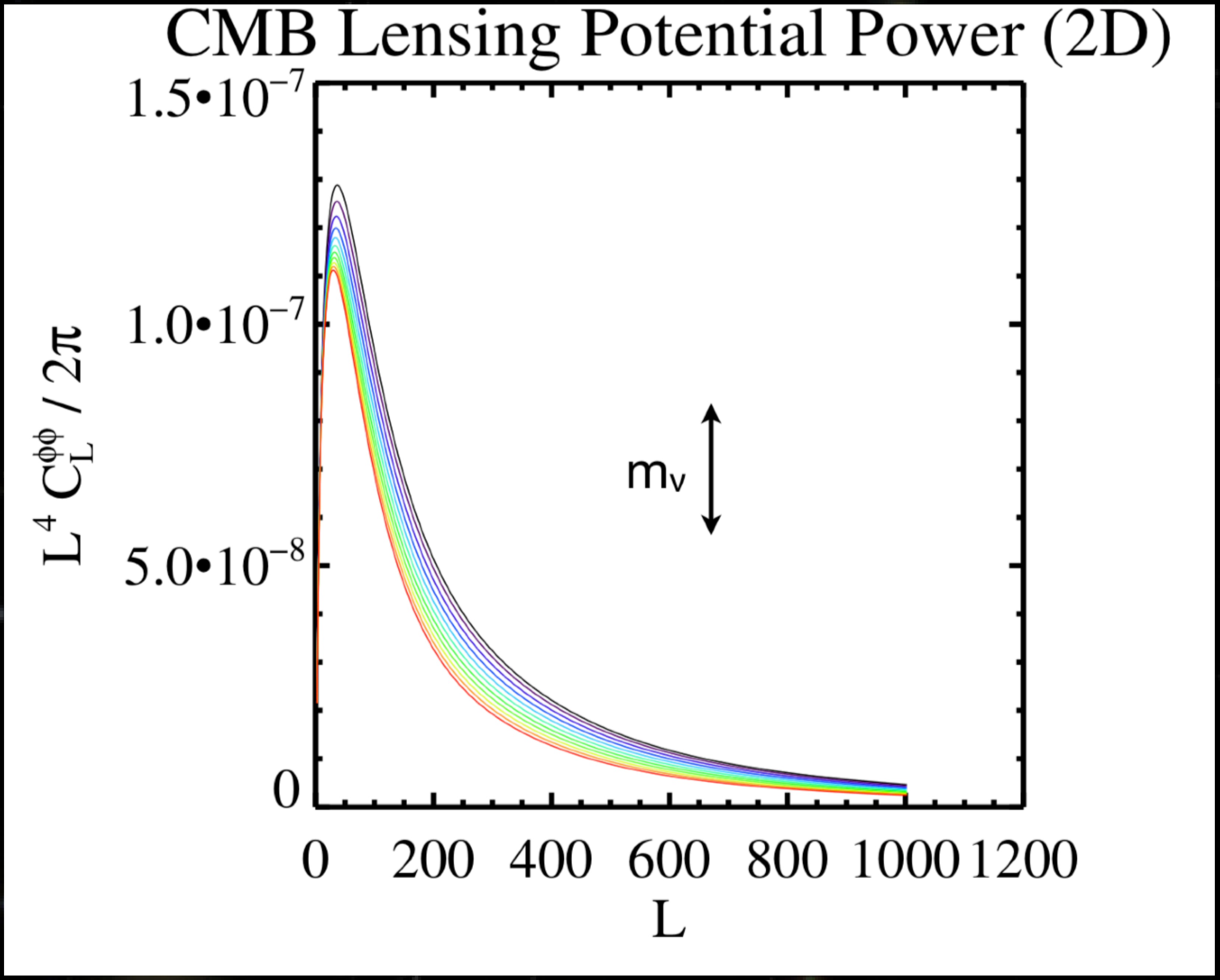
- Smoothes the CMB spectra
- Adds power at arc minutes scales on TT, TE and EE
- Generates « lensing B-modes » from E-modes…




$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
Duncan Hanson

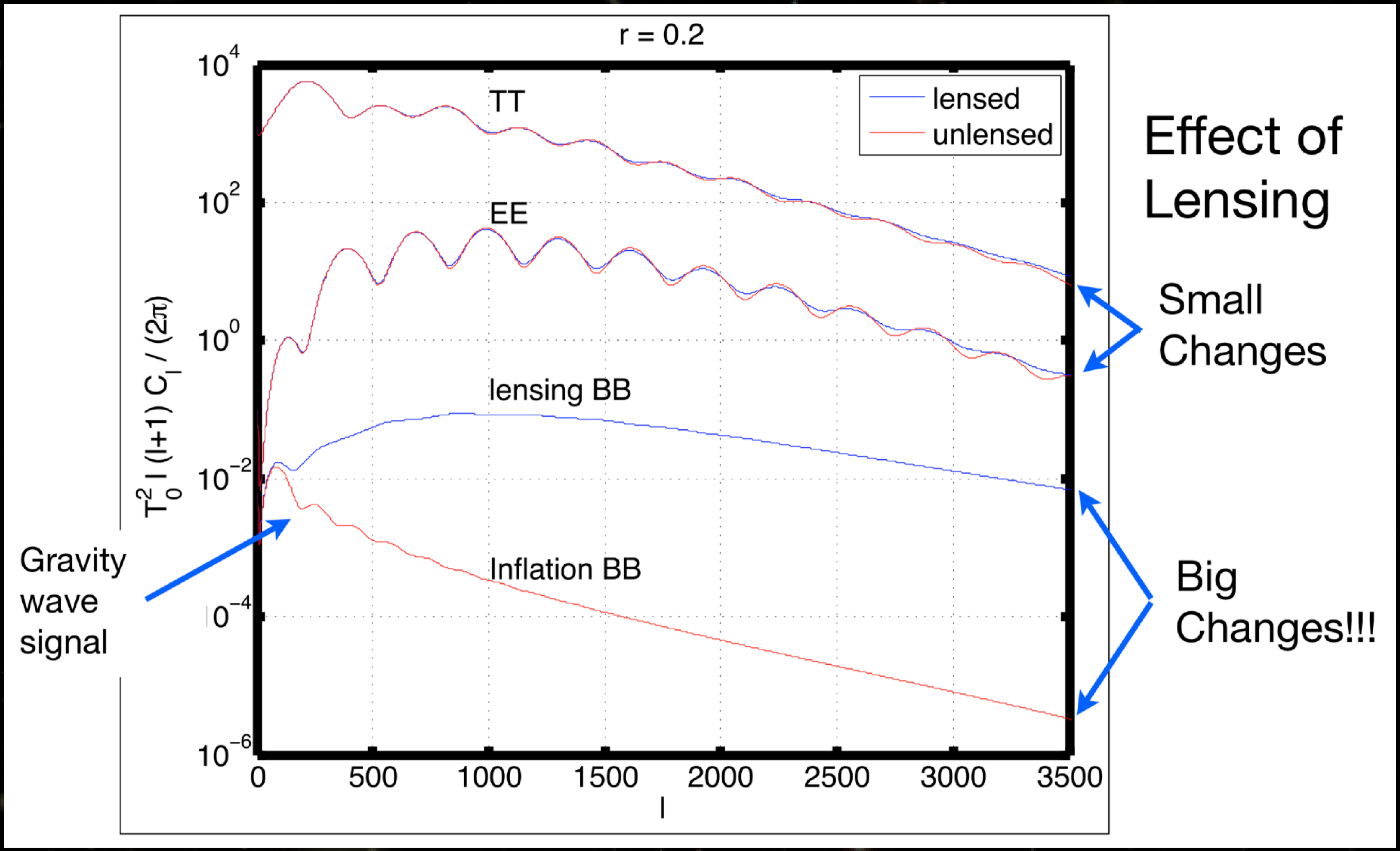

$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$
$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$
$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$
Duncan Hanson

Lensing likely to be the best way of constraining neutrino masses



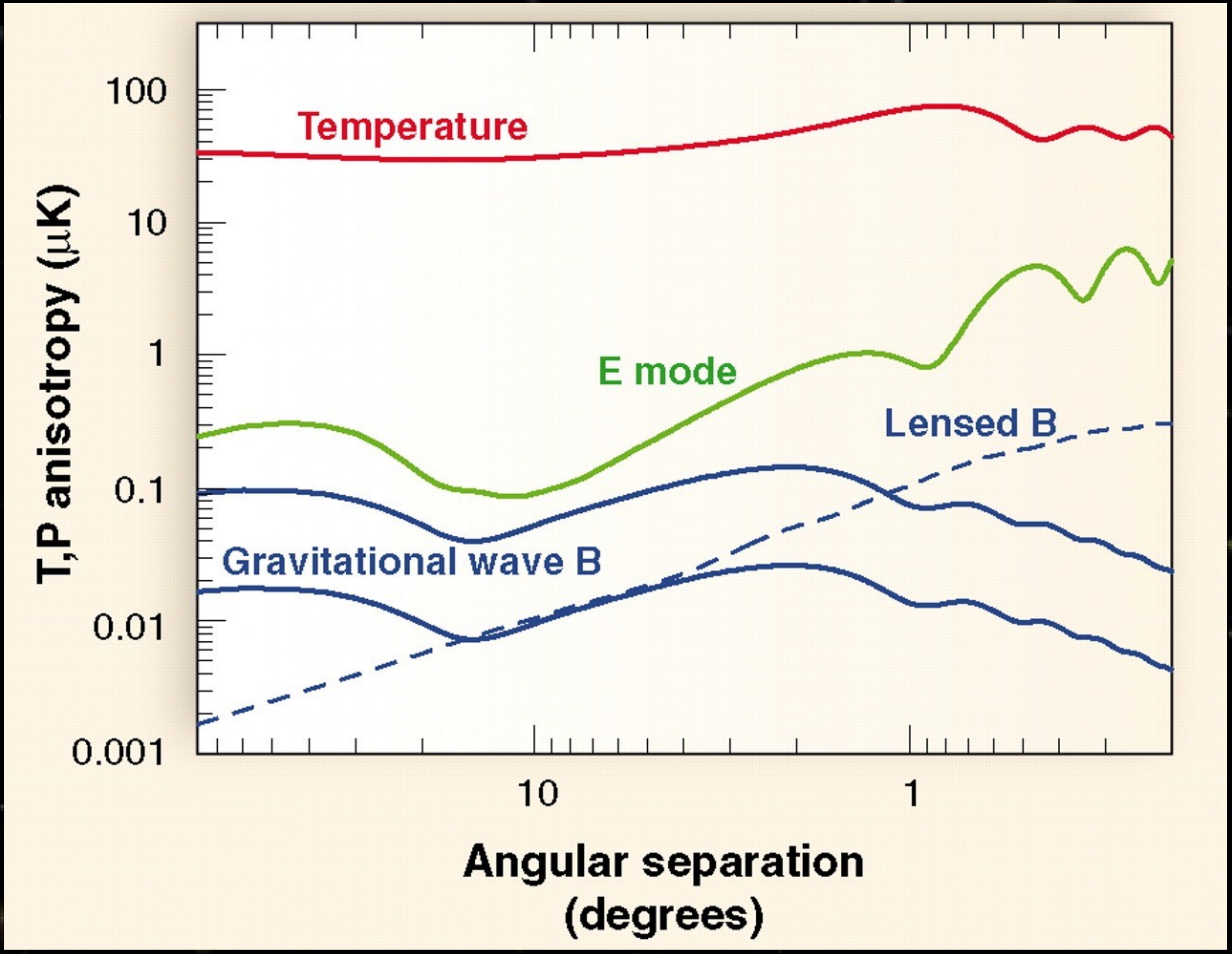
[From Ch. Reichardt @ WIN2017]

Lensing likely to be the best way of constraining neutrino masses

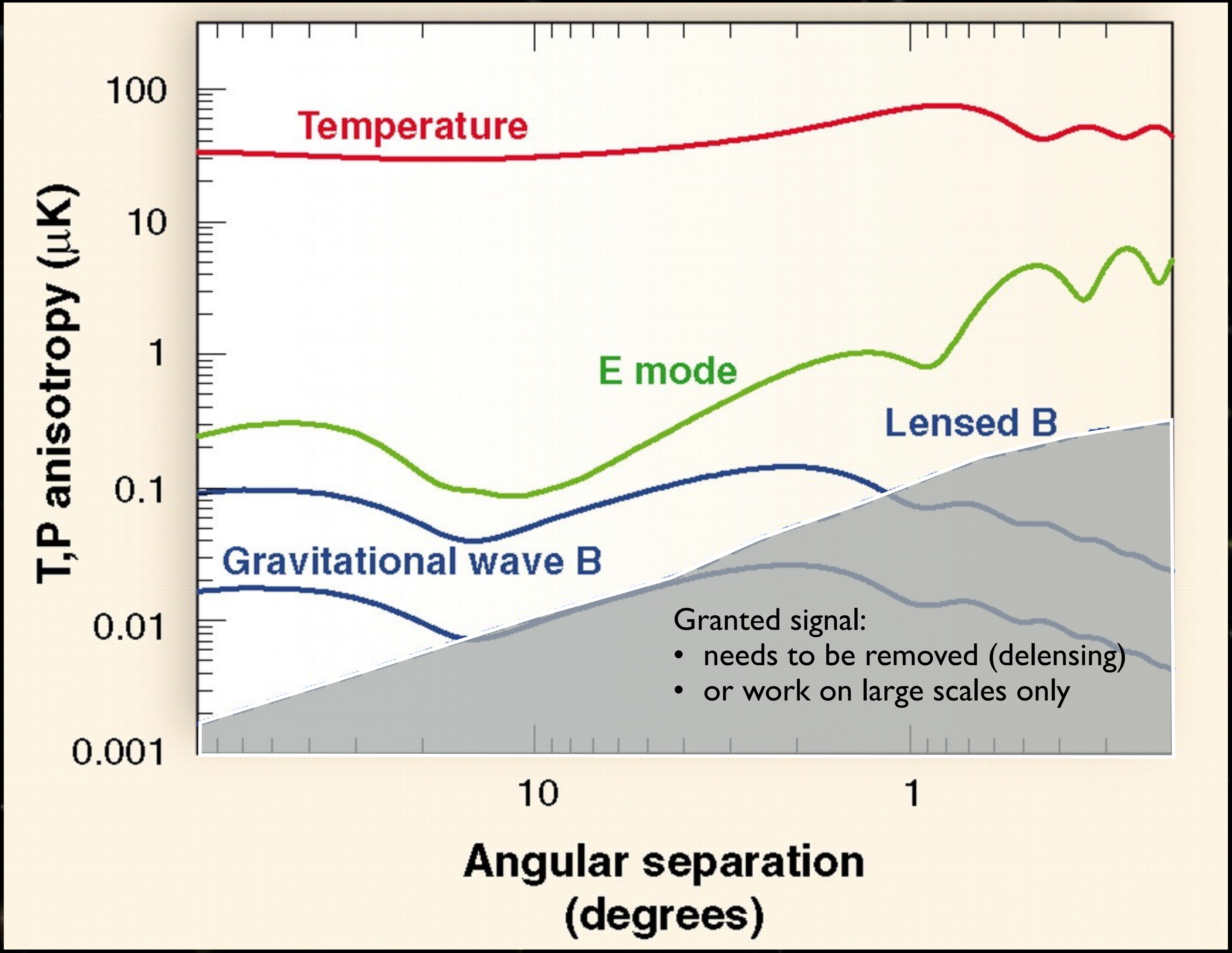


[From Ch. Reichardt @ WIN2017]

Resulting Spectrum

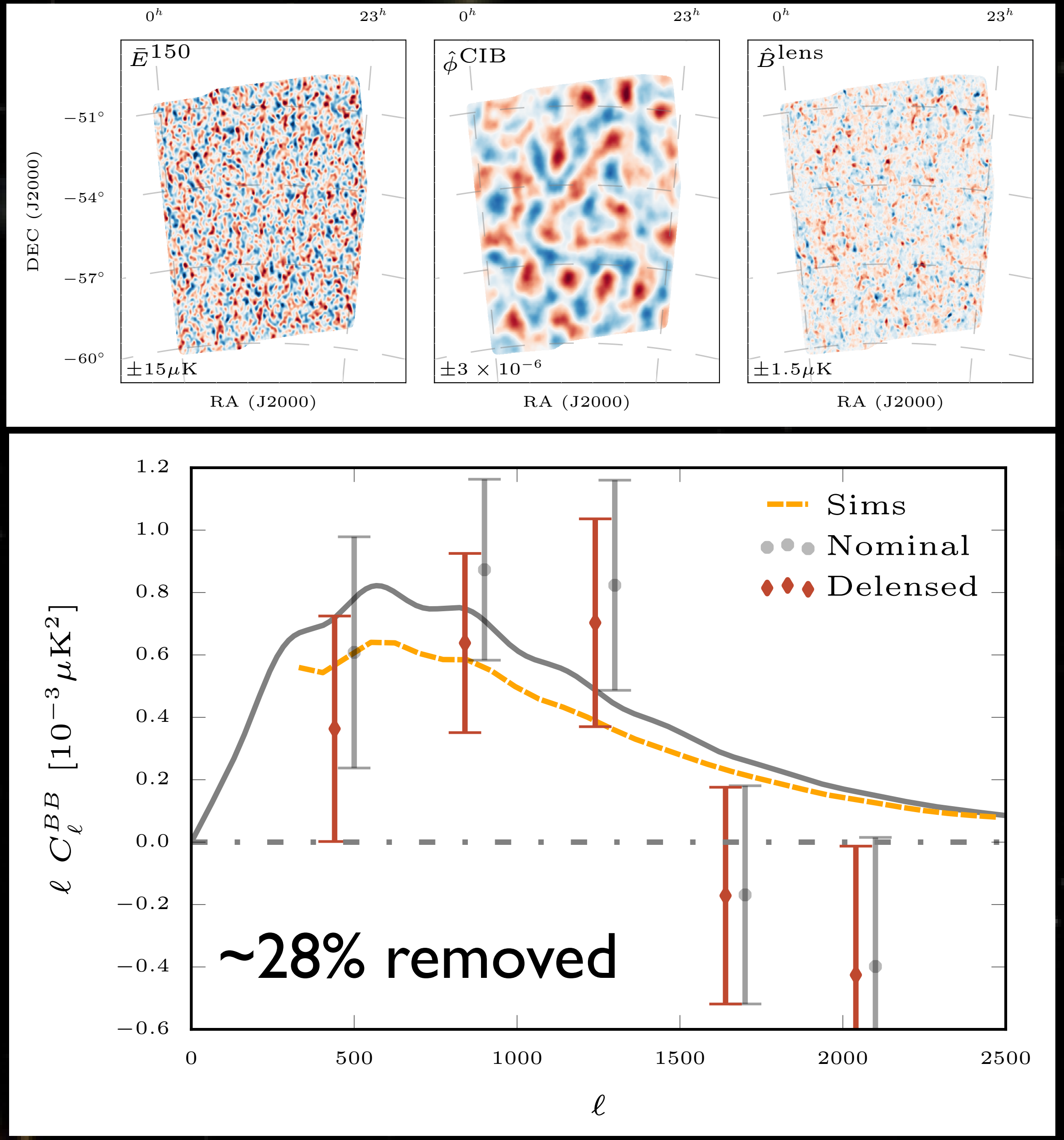


Resulting Spectrum



Delensing

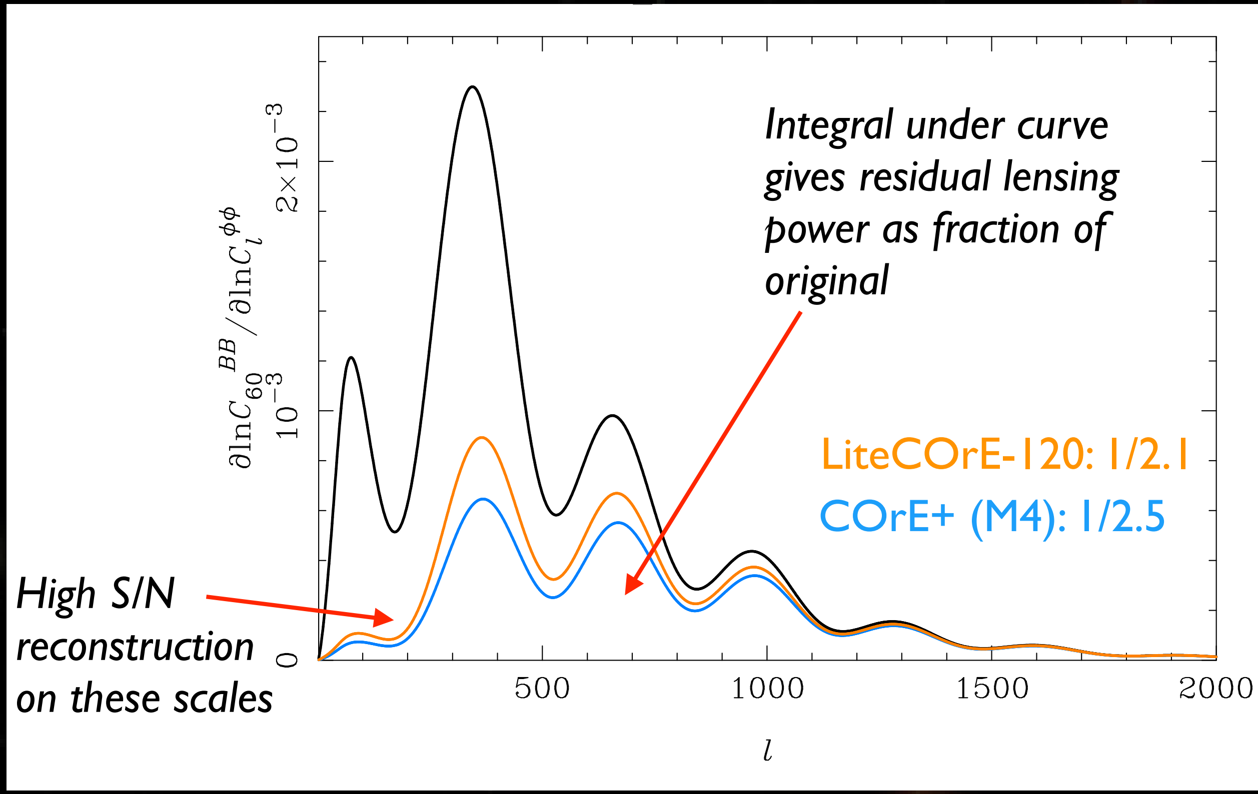
- **Difficulty:**
  - ★ E->B lensing kernel is wide: mixes together small and large scales
- **Needs:**
  - ★ High resolution E maps
  - ★ A lensing model:
    - Internal CMB lensing analysis
    - Large Scale Structure maps (eg. CIB maps)
  - ★ A tough analysis…
- **Results:**
  - ★ promising but not yet there…



Ex: delensing SPTPol data with Herschel CIB [Manzotti et al., 2017]

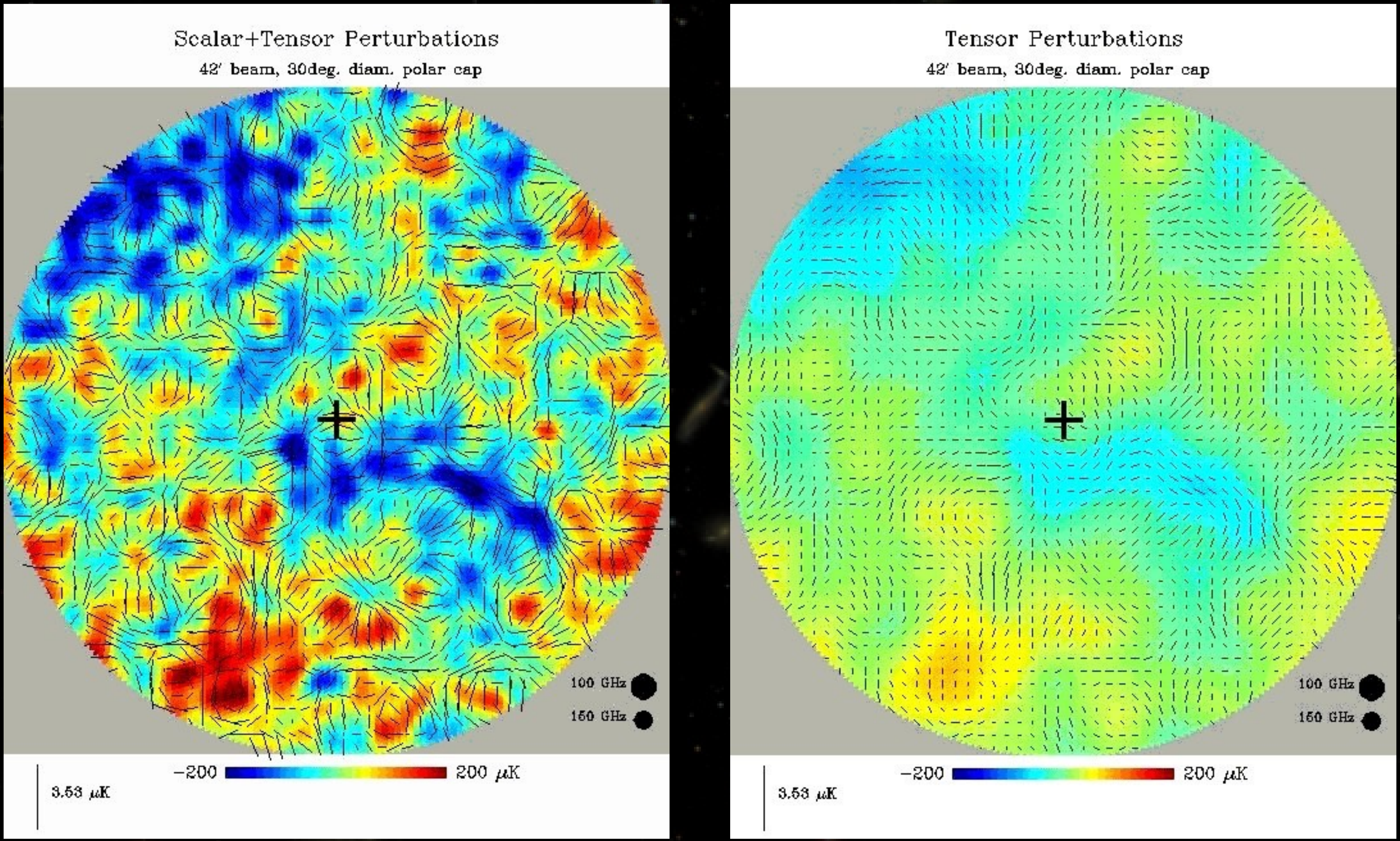
Delensing

- **Difficulty:**
  - ★ E->B lensing kernel is wide: mixes together small and large scales
- **Needs:**
  - ★ High resolution E maps
  - ★ A lensing model:
    - Internal CMB lensing analysis
    - Large Scale Structure maps (eg. CIB maps)
  - ★ A tough analysis…
- **Results:**
  - ★ promising but not yet there…
  - ★ Should improve significantly with future satellite and high-resolution ground based instruments

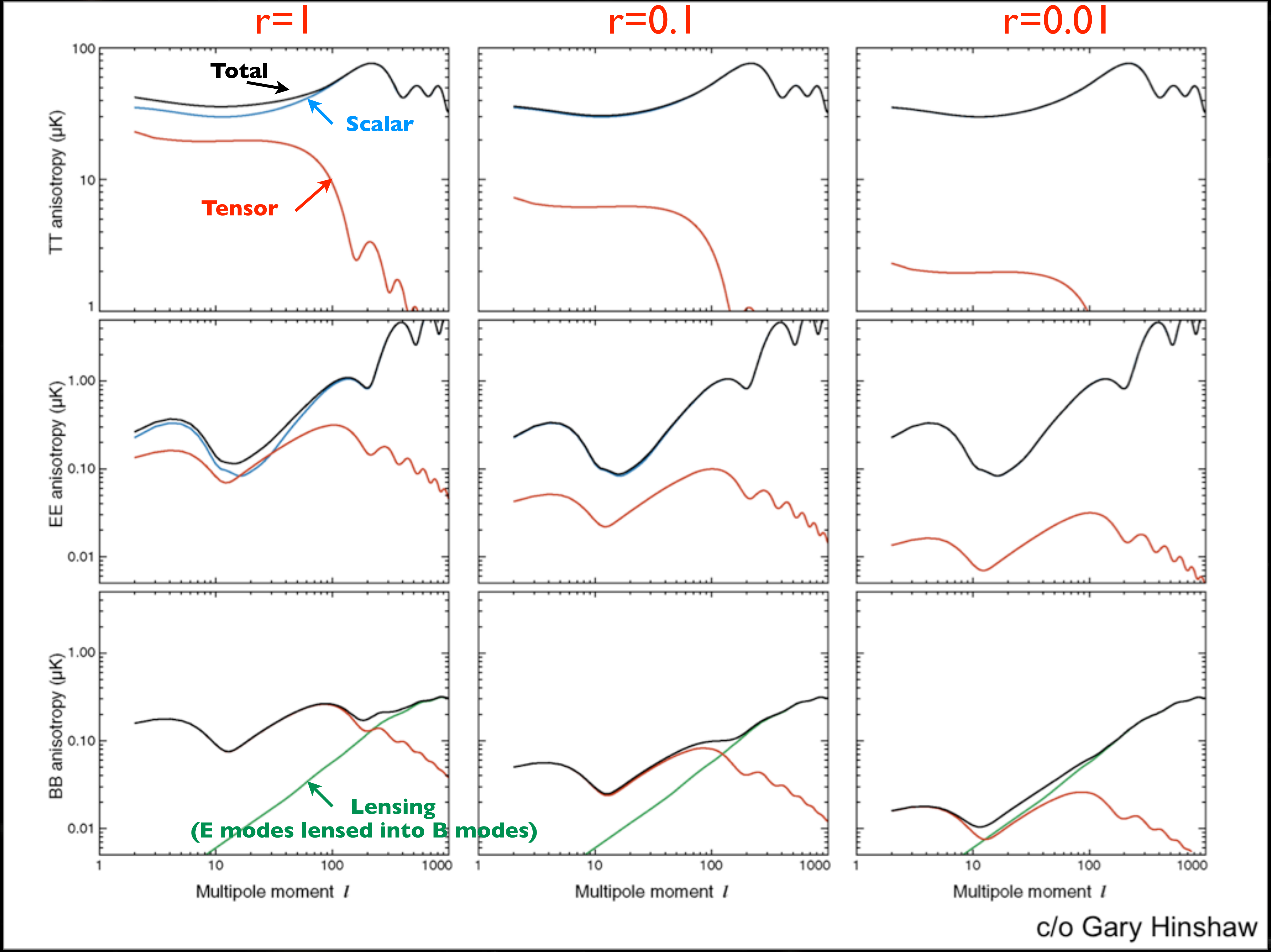


Forecasts with future satellite missions
[From a presentation by A. Challinor -Florence 2016]

Tensors are small



[BICEP]



Only B modes allow to «directly observe» tensor modes

Polarization mixing

- Polarization is the difference between Ex and Ey
  - ★ So if instrument converts Ex in Ey or does not transmit them equally, there is polarization mixing

$$\begin{pmatrix} Ex \\ Ey \end{pmatrix}' = J \cdot \begin{pmatrix} Ex \\ Ey \end{pmatrix}$$

  - ★ According to the definition of the Stokes Parameters $\begin{cases} I &= |Ex|^2 + |Ey|^2 \\ Q &= |Ex|^2 - |Ey|^2 \\ U &= Ex.Ey^\star + Ey.Ex^\star \end{cases}$
  - ★ we get mixing of I, Q and U

$$\begin{pmatrix} I \\ Q \\ U \end{pmatrix}' = M \cdot \begin{pmatrix} I \\ Q \\ U \end{pmatrix}$$

J.-Ch. Hamilton
hamilton@apc.in2p3.fr

Polarization mixing

- If J is Identity, fine… no effect
- In the general case: $$\begin{pmatrix} I \\ Q \\ U \end{pmatrix}' = \begin{pmatrix} a & b & c \\ d & e & f \\ g & h & i \end{pmatrix} \cdot \begin{pmatrix} I \\ Q \\ U \end{pmatrix}$$
- If $J = \begin{pmatrix} \rho+1 & \epsilon \\ -\epsilon & \rho+1 \end{pmatrix}$ then (at 1st order)

$$\begin{pmatrix} I \\ Q \\ U \end{pmatrix}' = \begin{pmatrix} 2\rho+1 & 0 & 0 \\ 0 & 2\rho+1 & 2\epsilon \\ 0 & -2\epsilon & 2\rho+1 \end{pmatrix} \cdot \begin{pmatrix} I \\ Q \\ U \end{pmatrix}$$

- Remember that I >> E >> B
  - ★ Important to avoid leakage of I into Q and U to have ~0 in I→Q,U terms
  - ★ Mixing between Q and U induces leakage of E into B… and so needs to be minimized

Polarization mixing

- Now let's focus on Q and U

$$\begin{pmatrix} Q \\ U \end{pmatrix}' = \begin{pmatrix} 2\rho+1 & 2\epsilon \\ -2\epsilon & 2\rho+1 \end{pmatrix} \cdot \begin{pmatrix} Q \\ U \end{pmatrix}$$

- At the level of E, B spectra:

$$\begin{pmatrix} C_\ell^{EE} \\ C_\ell^{BB} \end{pmatrix}' = \begin{pmatrix} 1+4\rho & 4\epsilon^2 \\ 4\epsilon^2 & 1+4\rho \end{pmatrix} \cdot \begin{pmatrix} C_\ell^{EE} \\ C_\ell^{BB} \end{pmatrix}$$

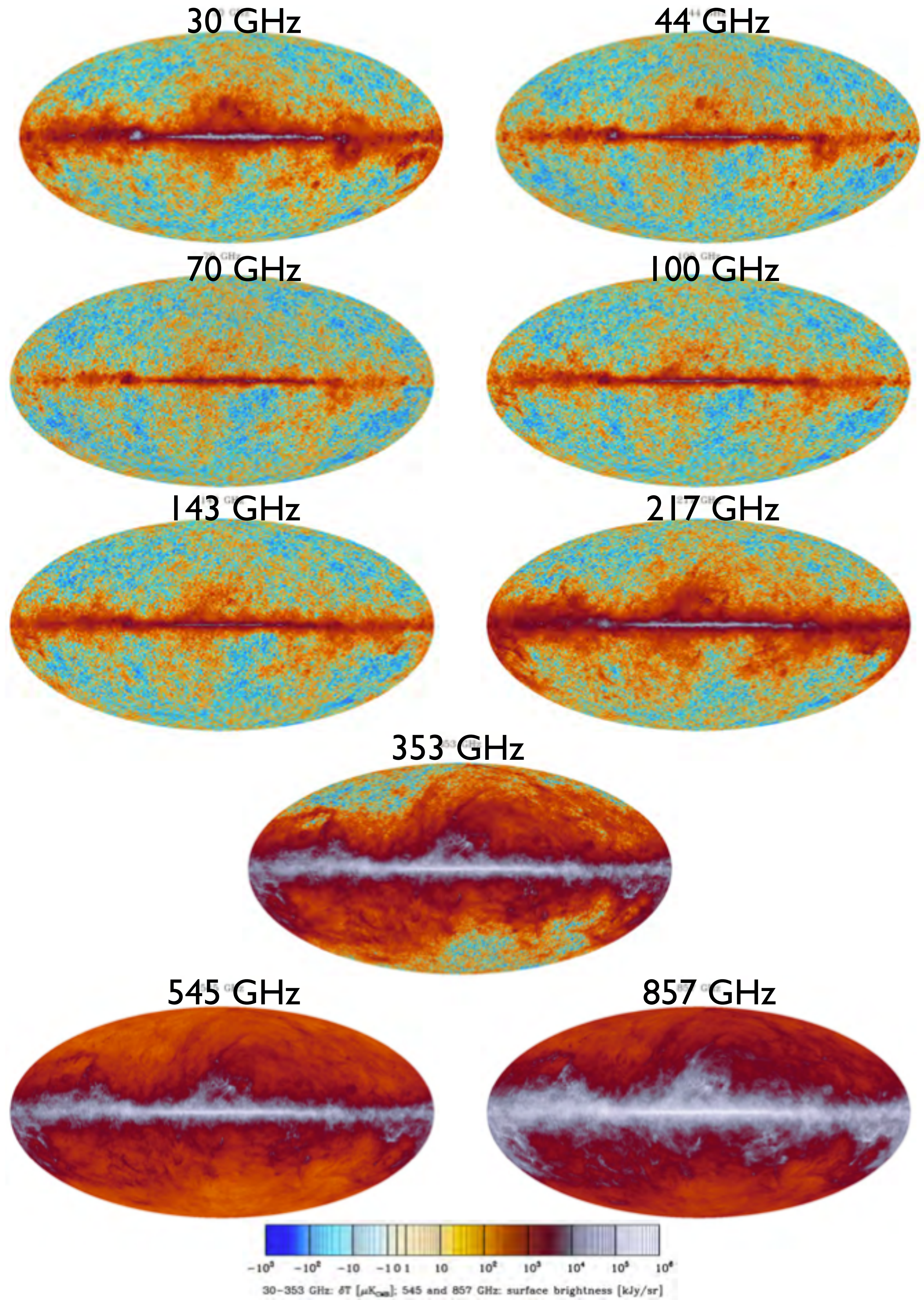
★ Therefore mixing ε needs to be controlled exquisitely to allow for B-mode clean measurement.

★ Typically
- if r=0.1 need better than 5% on cross-polarization
- if r=0.01 need better than 1.5%
- if r=0.001 need better than 0.5%

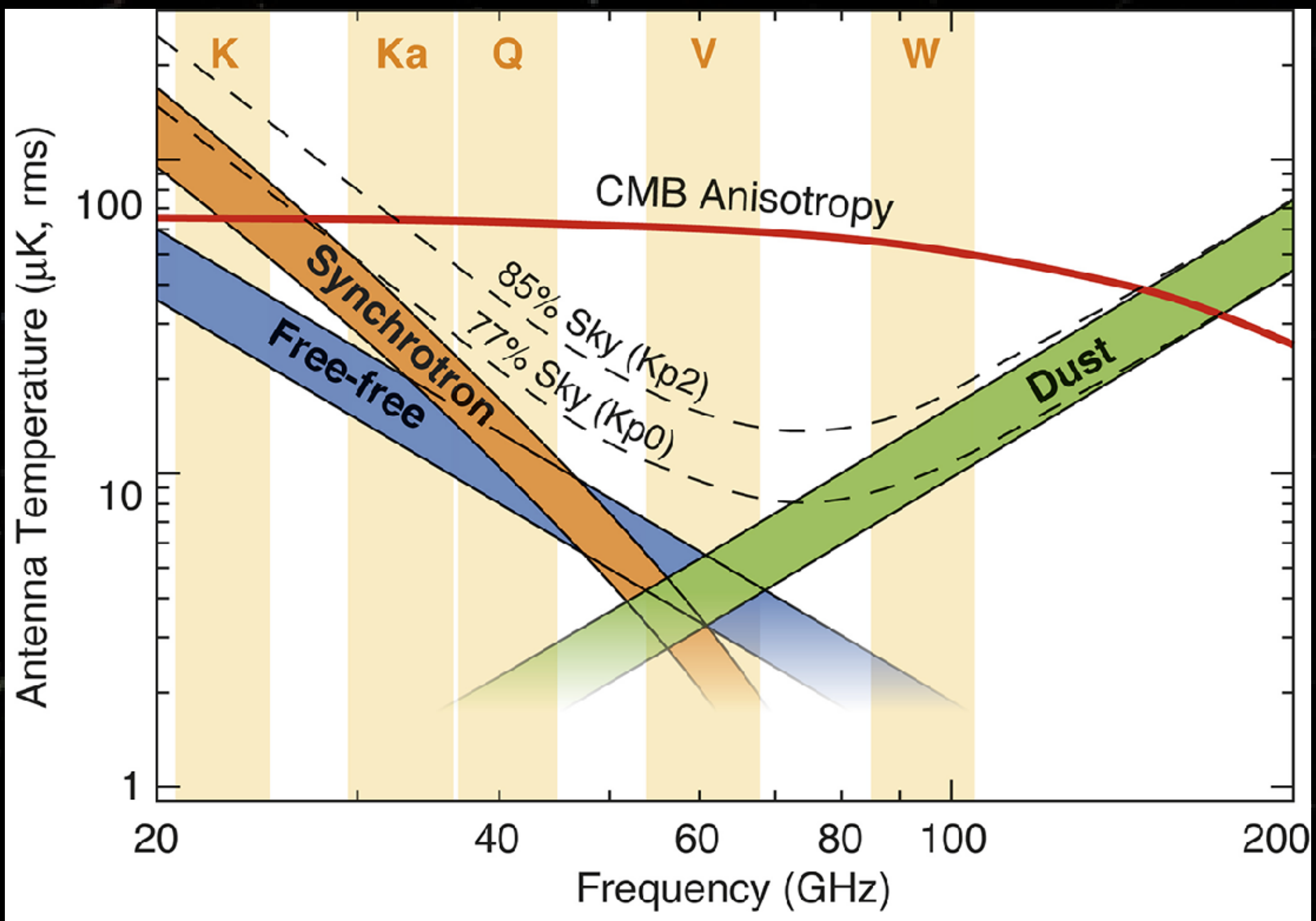
Solutions:
- Care in Instrument Design
- Care in Instrument Fabrication
- Polarization modulation (HWP, …)
- Self-Calibration in Data Analysis

Foregrounds

Temperature Maps from Planck

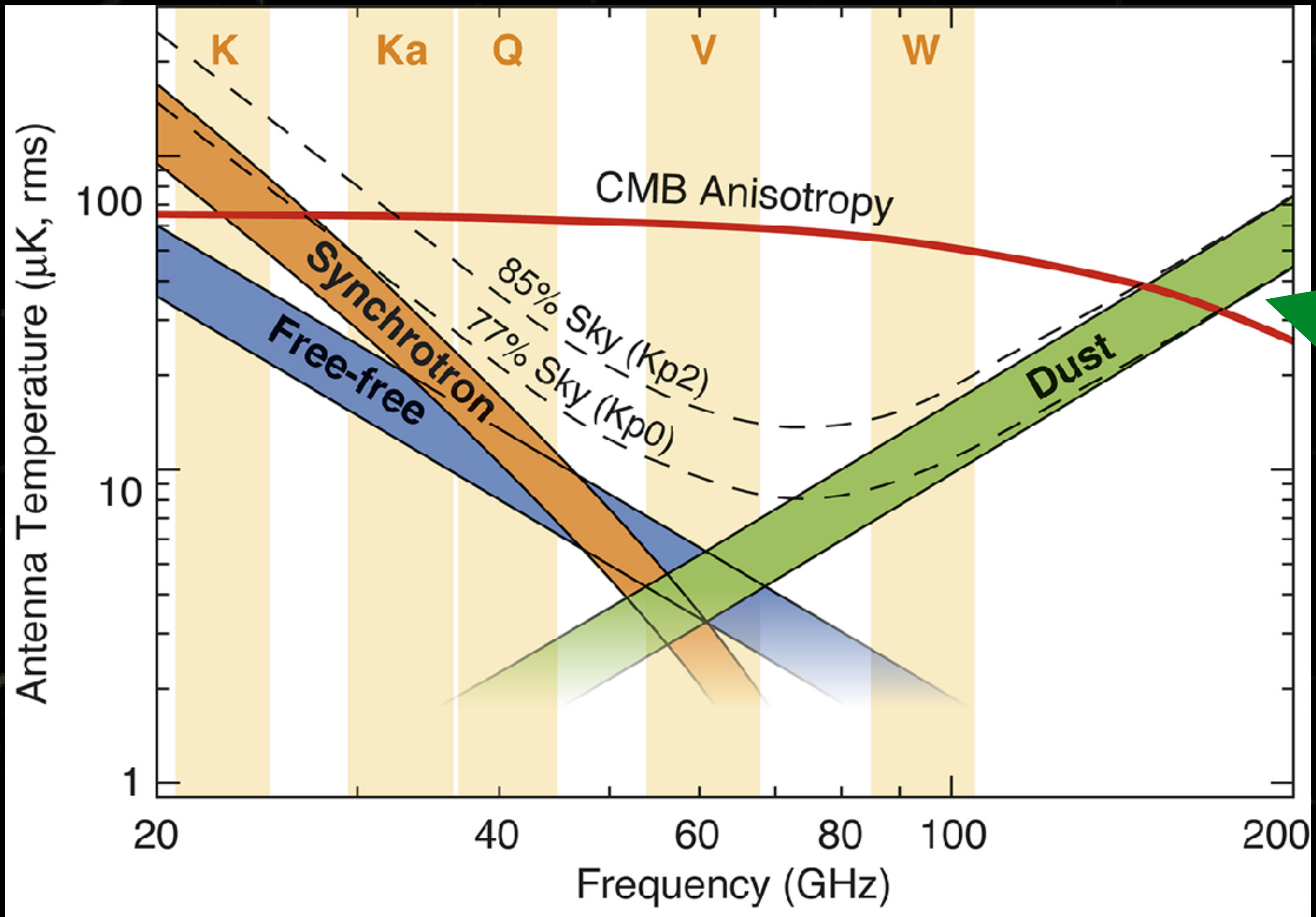


Foregrounds

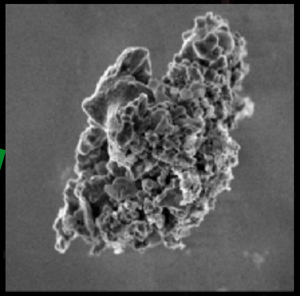


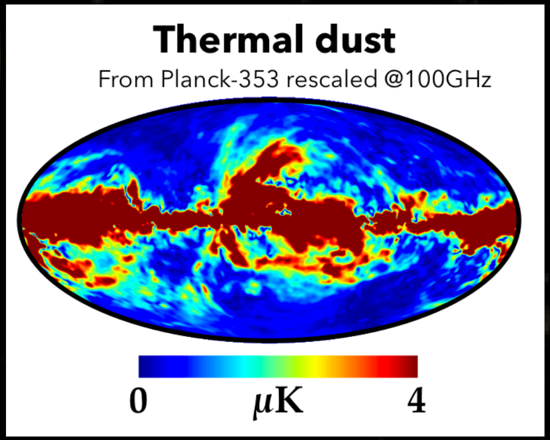
[WMAP]

Foregrounds



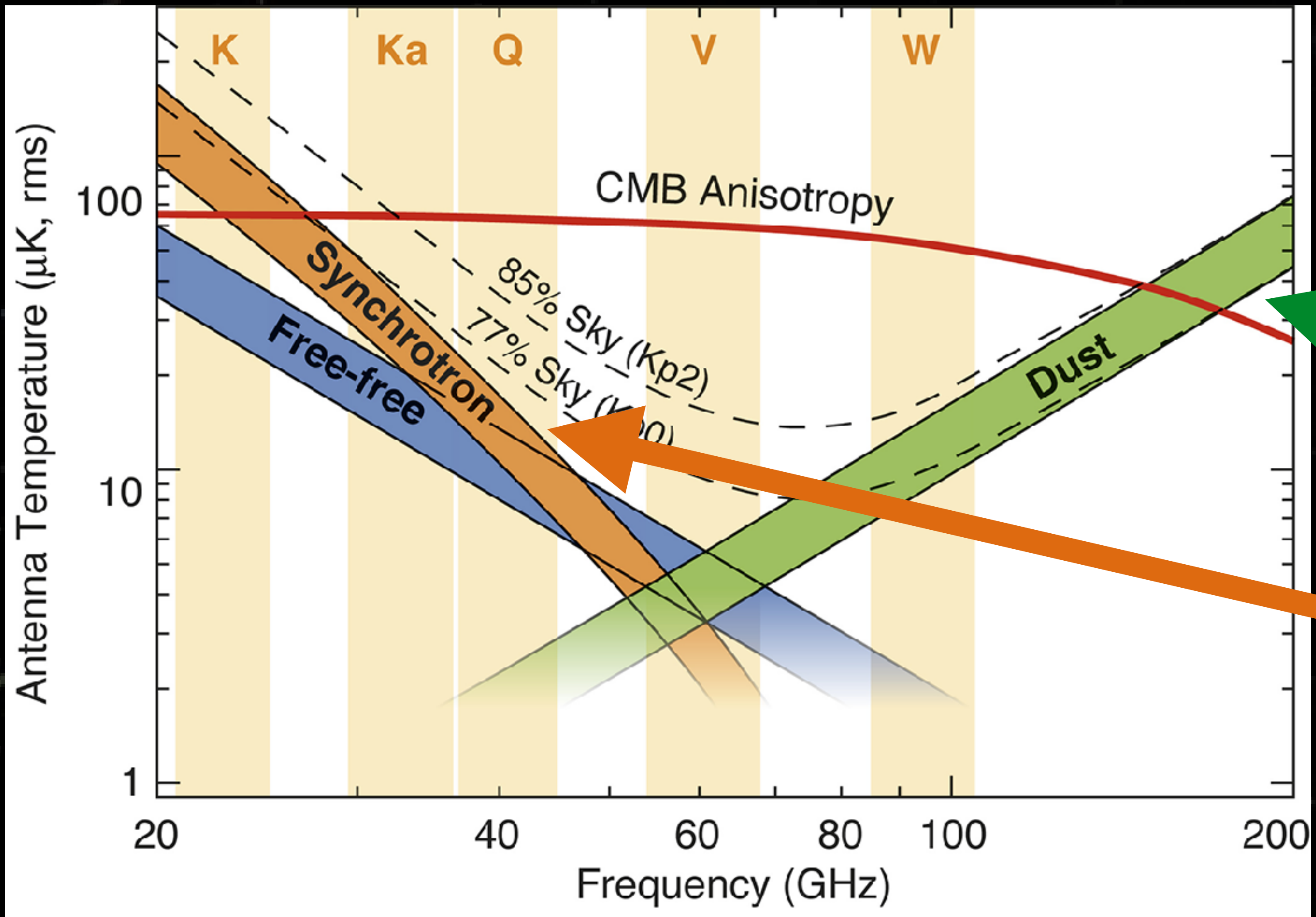
Dust grains



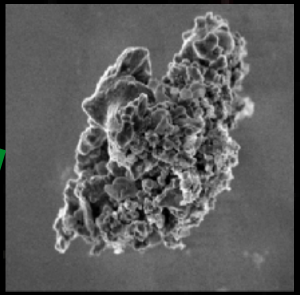


[WMAP]

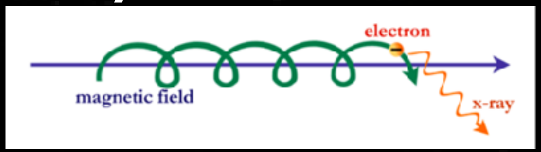
Foregrounds

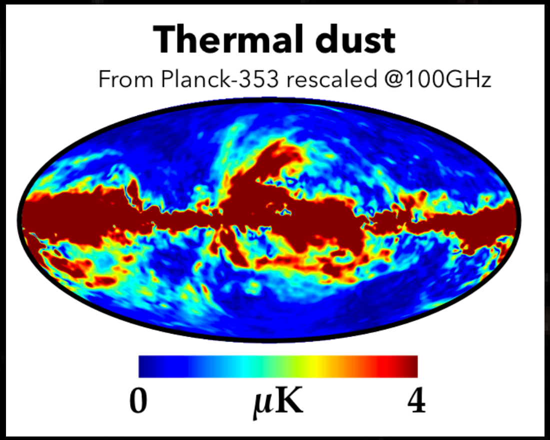


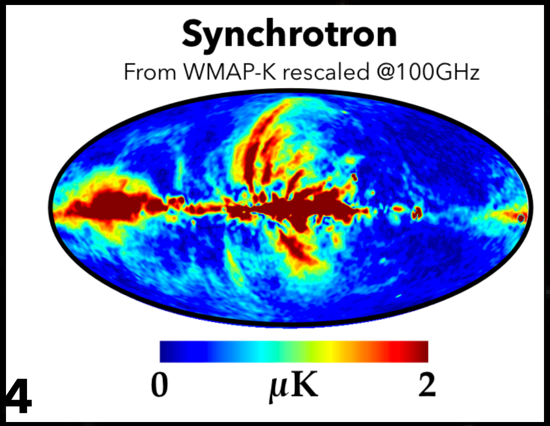
Dust grains



Synchrotron







[Courtesy N. Krachmalnicoff]

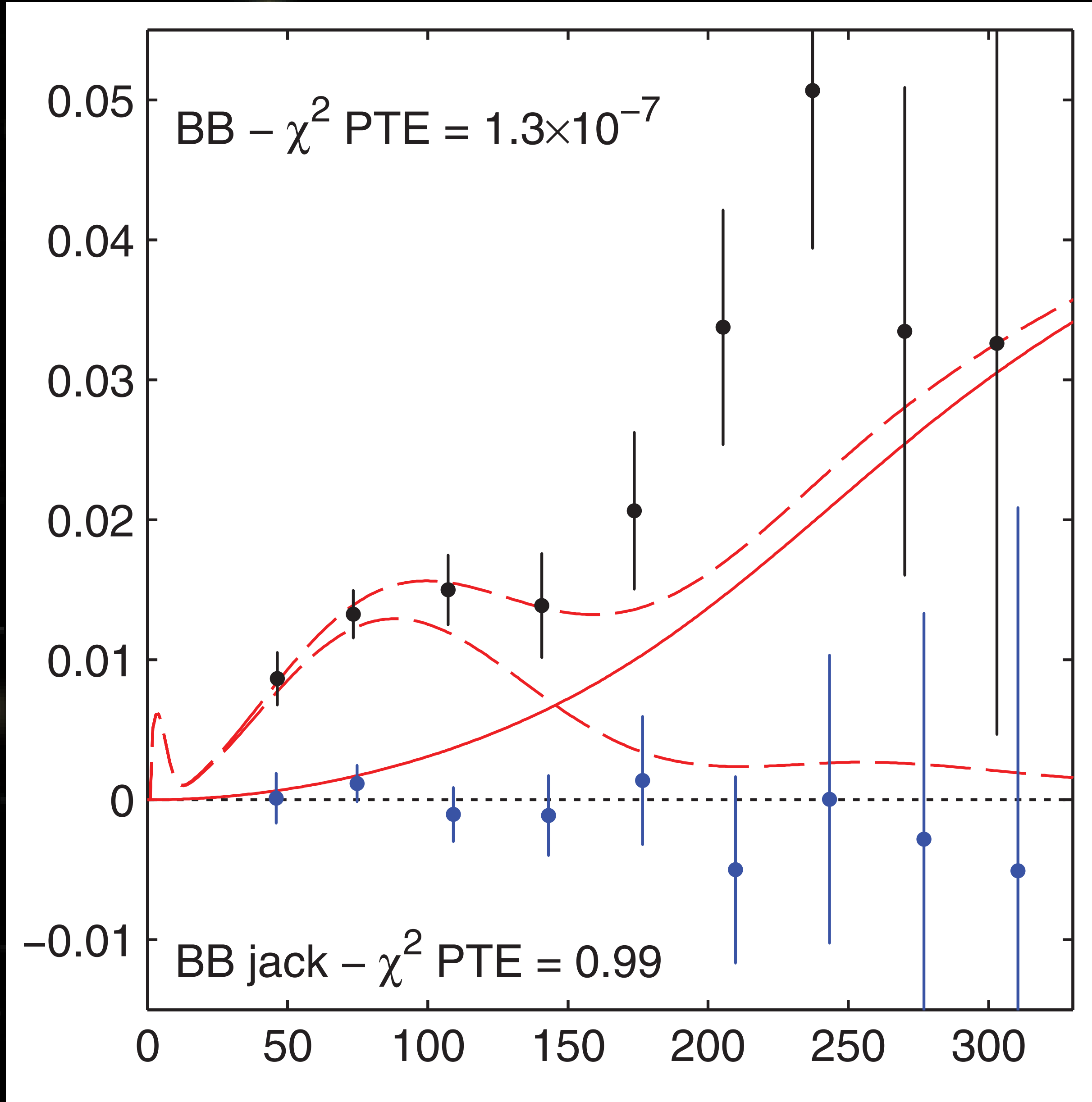
[WMAP]

Dust is heavily polarized :-(

- The BICEP2 saga…

  ★ March 2014:

  - BICEP2 publishes a 5σ detection of primordial B-modes (r~0.2)



[BICEP2 collaboration, PRL 112, 241101 (2014)]

[Courtesy M. Tristram]

Dust is heavily polarized :-(

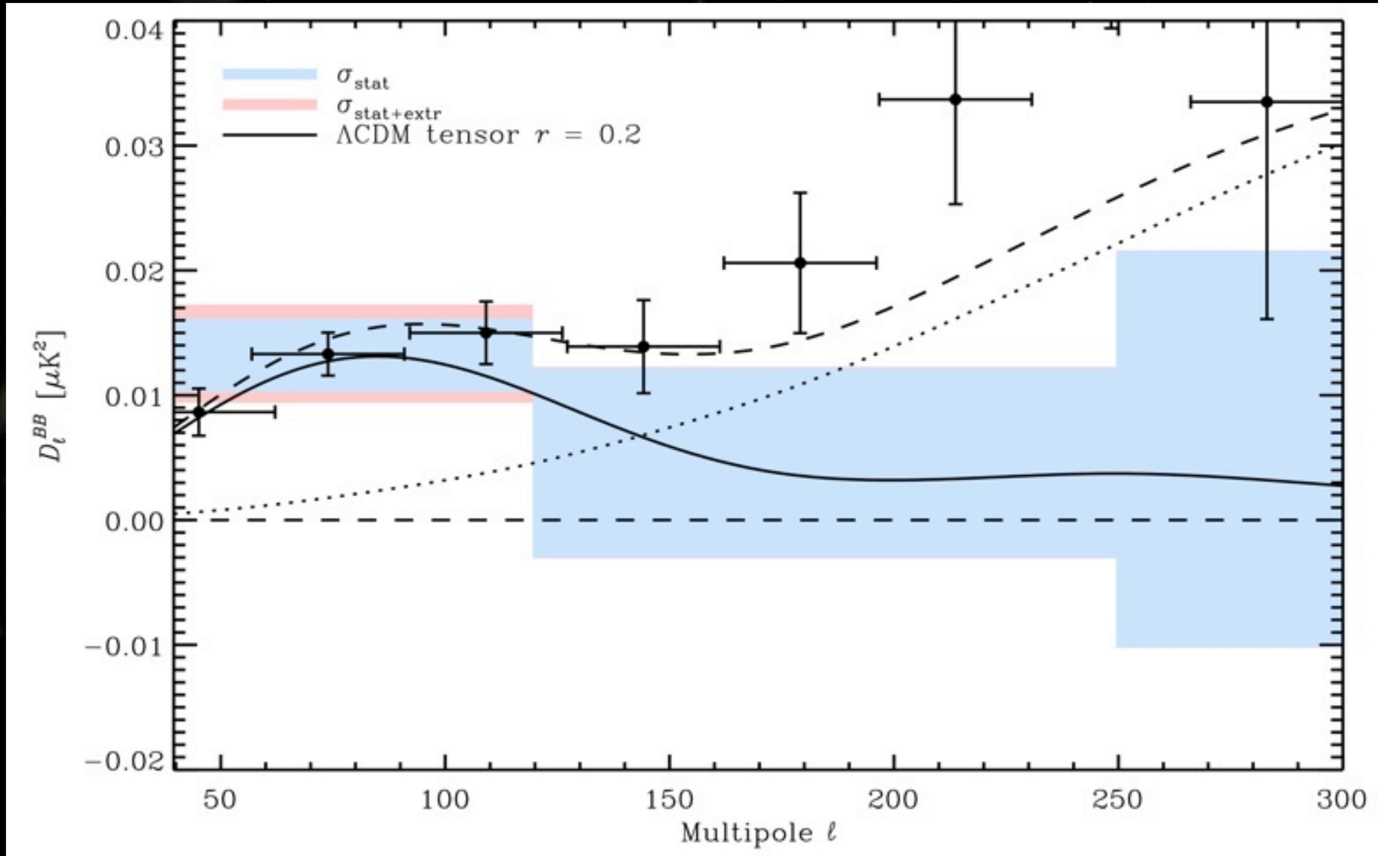
- The BICEP2 saga…

★ March 2014:

- BICEP2 publishes a 5σ detection of primordial B-modes (r~0.2)

★ September 2014:

- Planck shows that most of BICEP2 signal is compatible with amount of dust measured in 353 GHz polarized channel



[Planck Intermediate XXX, arXiv:1409.5738 (2014)]

[Courtesy M. Tristram]

Dust is heavily polarized :-(

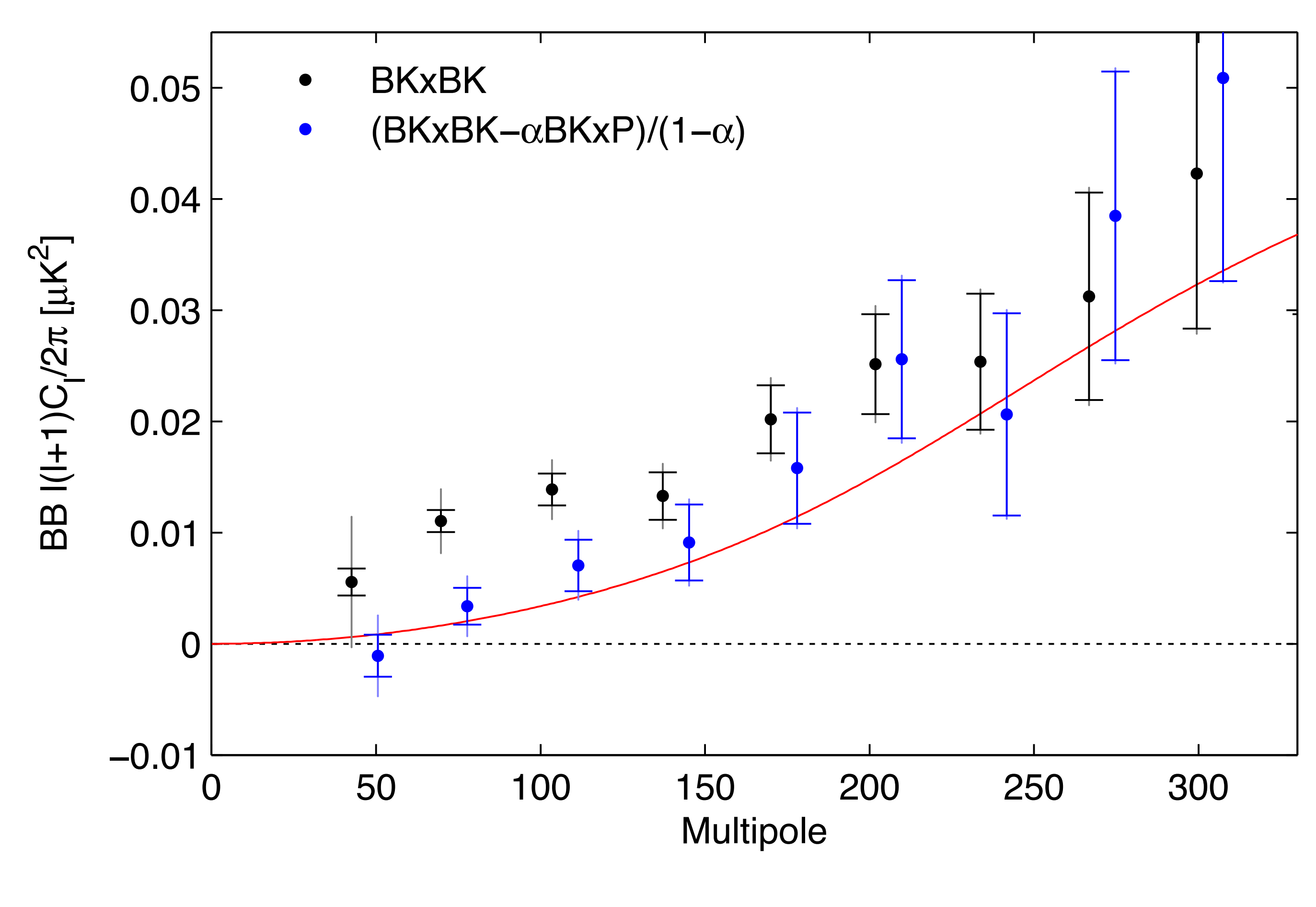
- The BICEP2 saga…

★ March 2014:
- BICEP2 publishes a 5σ detection of primordial B-modes (r~0.2)

★ September 2014:
- Planck shows that most of BICEP2 signal is compatible with amount of dust measured in 353 GHz polarized channel

★ January 2015:
- a joint analysis with Planck and BICEP2/Keck data shows no primordial signal
- r < 0.12 @ 95% C.L.

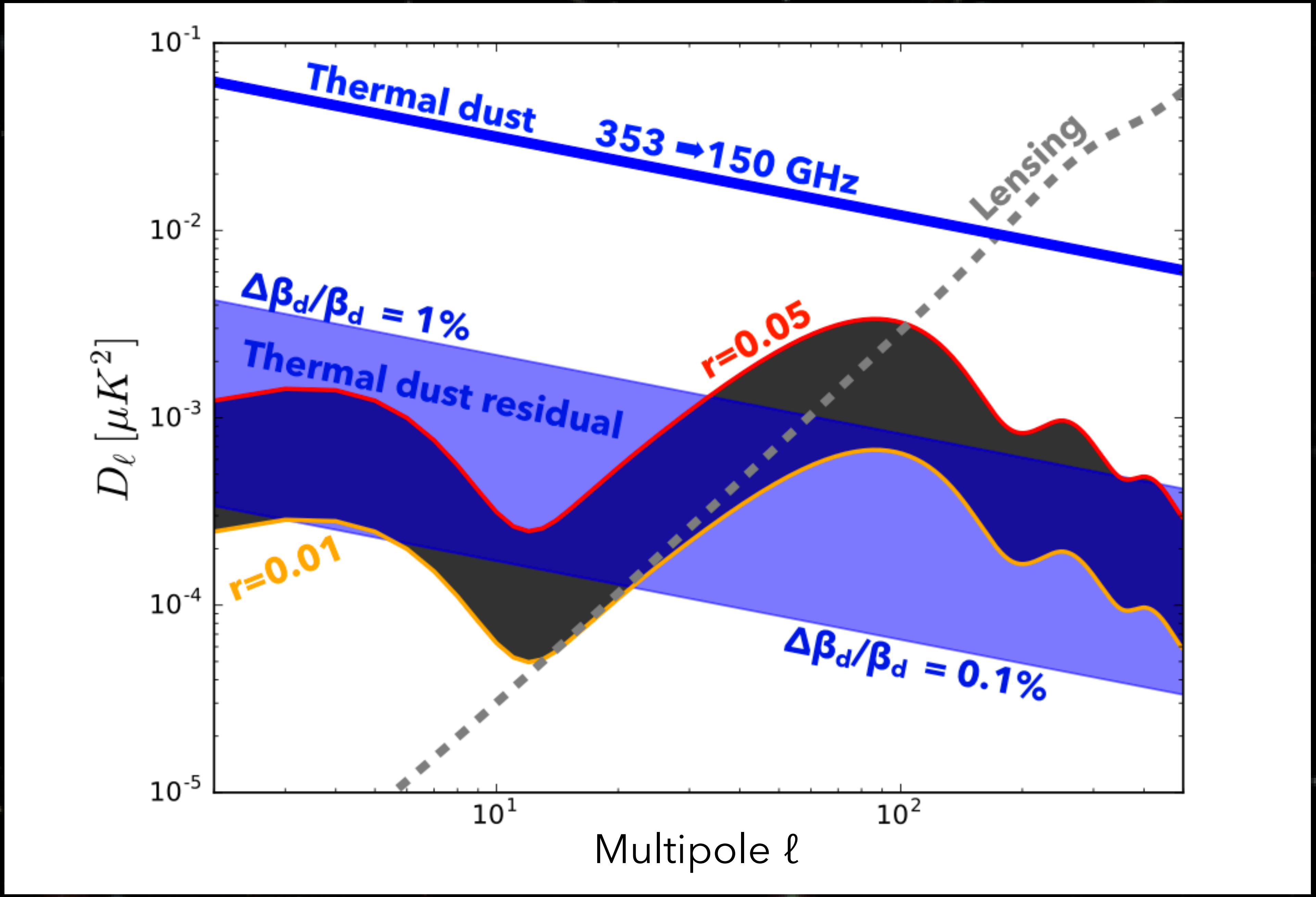
★ Latest limit from BICEP/Planck
- r < 0.07 @ 95% C.L.



[BICEP2/Keck - Planck collaborations, arXiv:1502.00612 (2015)]

[Courtesy M. Tristram]

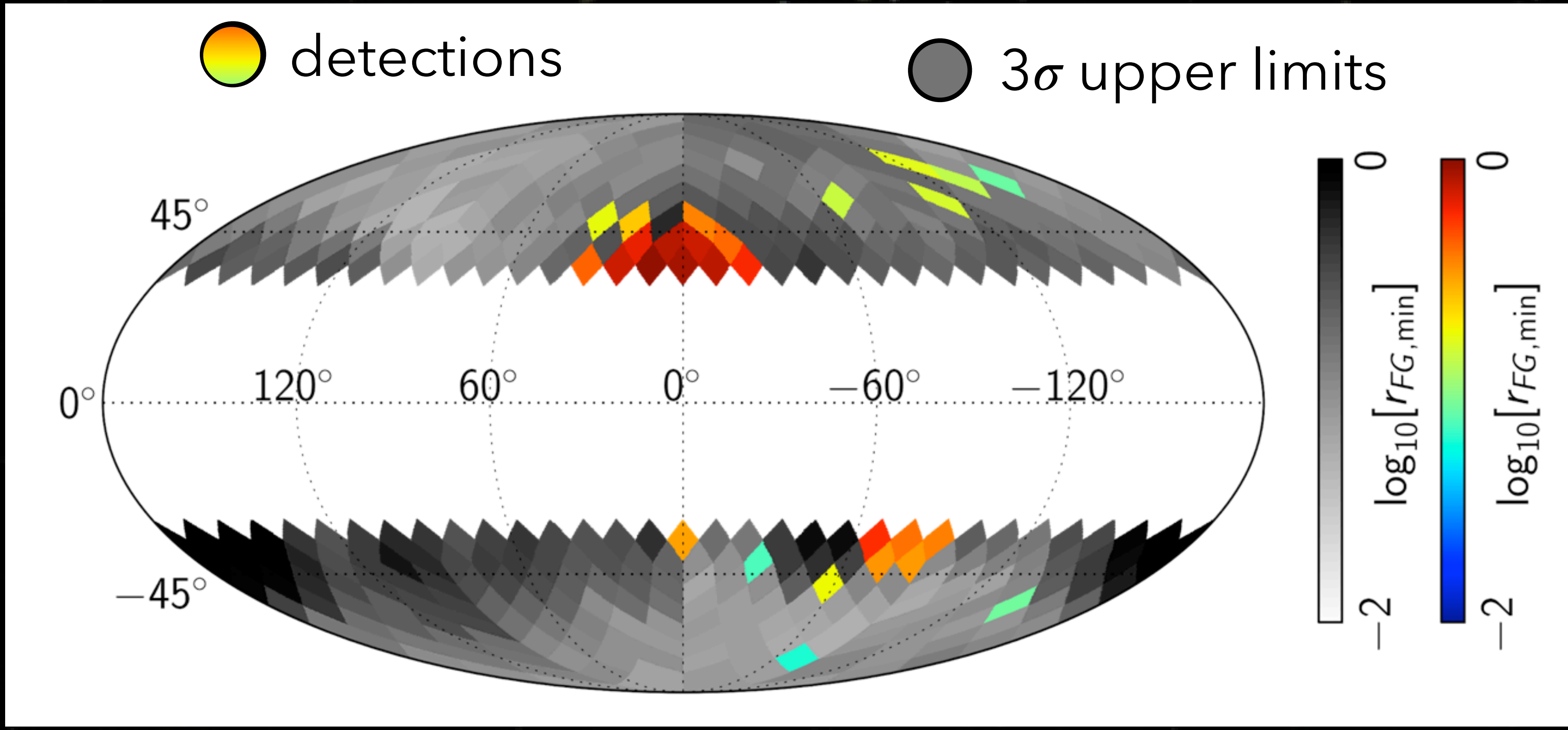
Dust is heavily polarized



[Courtesy N. Krachmalnicoff]

Dust is everywhere…

Dust foreground residual T/S ratio:
$0.05 < r_{FG} < 1.5$



[Krachmalnicoff et al. 2016]

And the same applies for Synchrotron…
[Krachmalnicoff et al. 2018]

Foreground Separation

Sky Model:

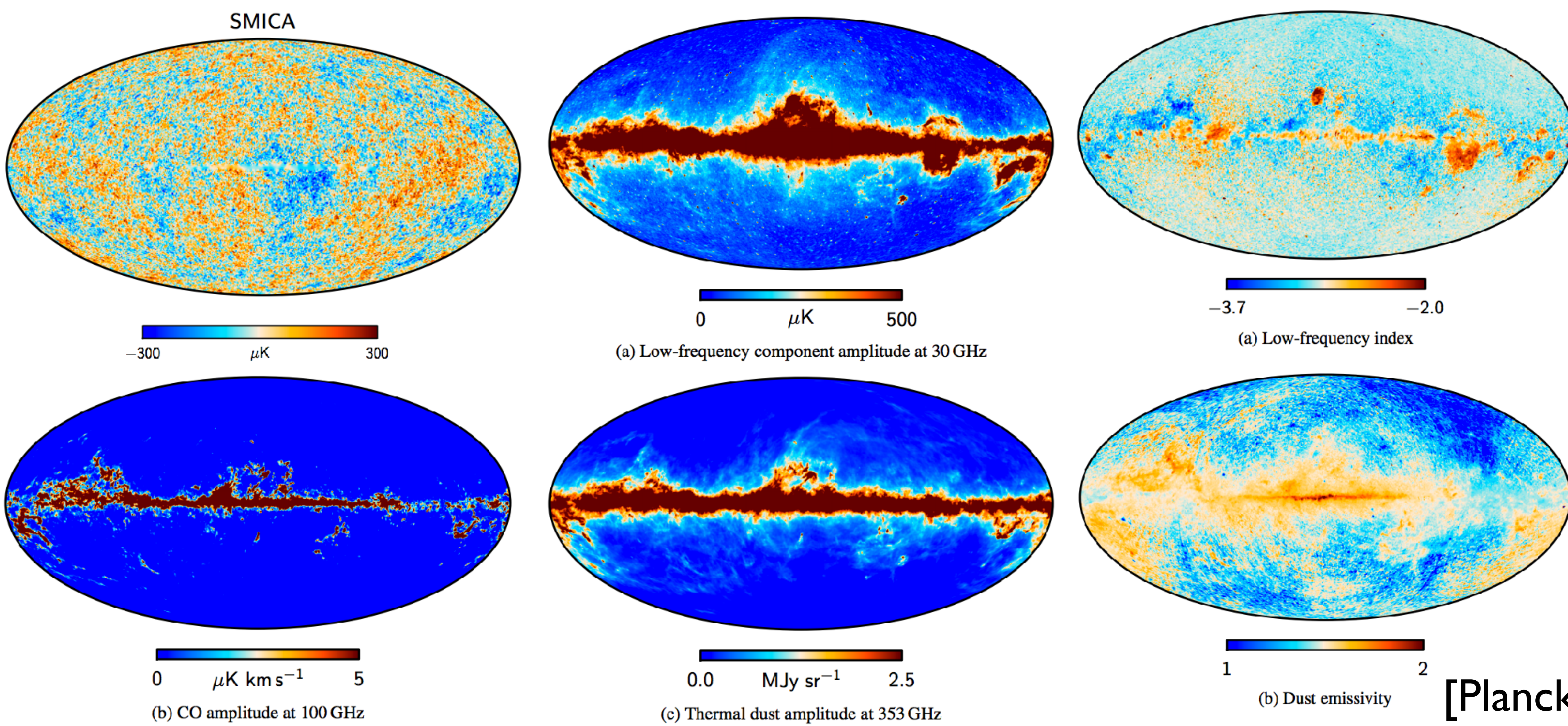
$$\vec{x}_\nu = \vec{x}_{CMB} + \vec{F}_\nu + \vec{n}_\nu$$

With $\vec{F}_\nu = A_\nu \vec{F}$

Solution:

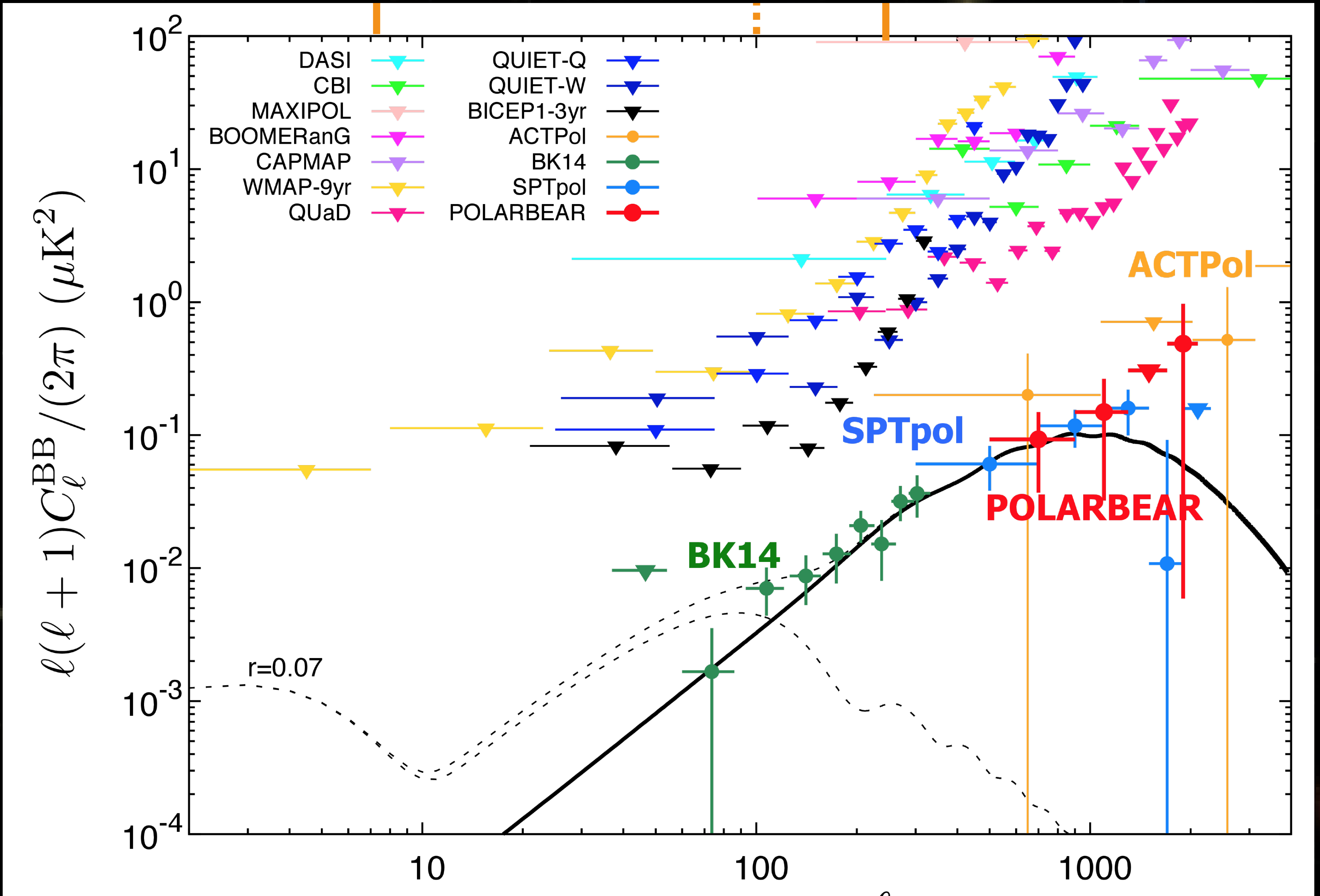
$$\hat{\vec{x}}_{CMB} = \sum_\nu w_\nu \vec{x}_\nu$$

NB: this is simple I.LC., there are more complex algorithms



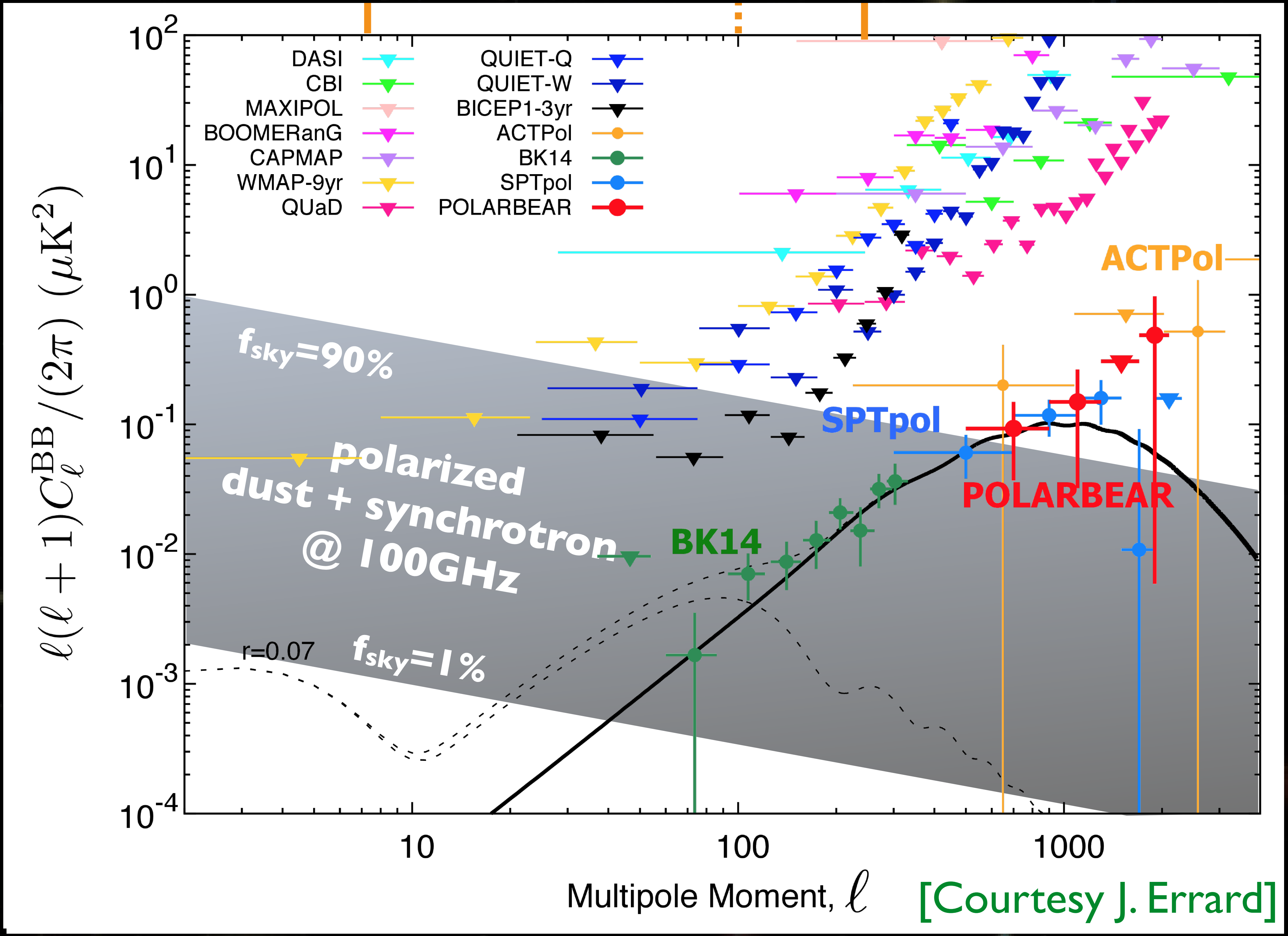
[Planck]

Recent results !!

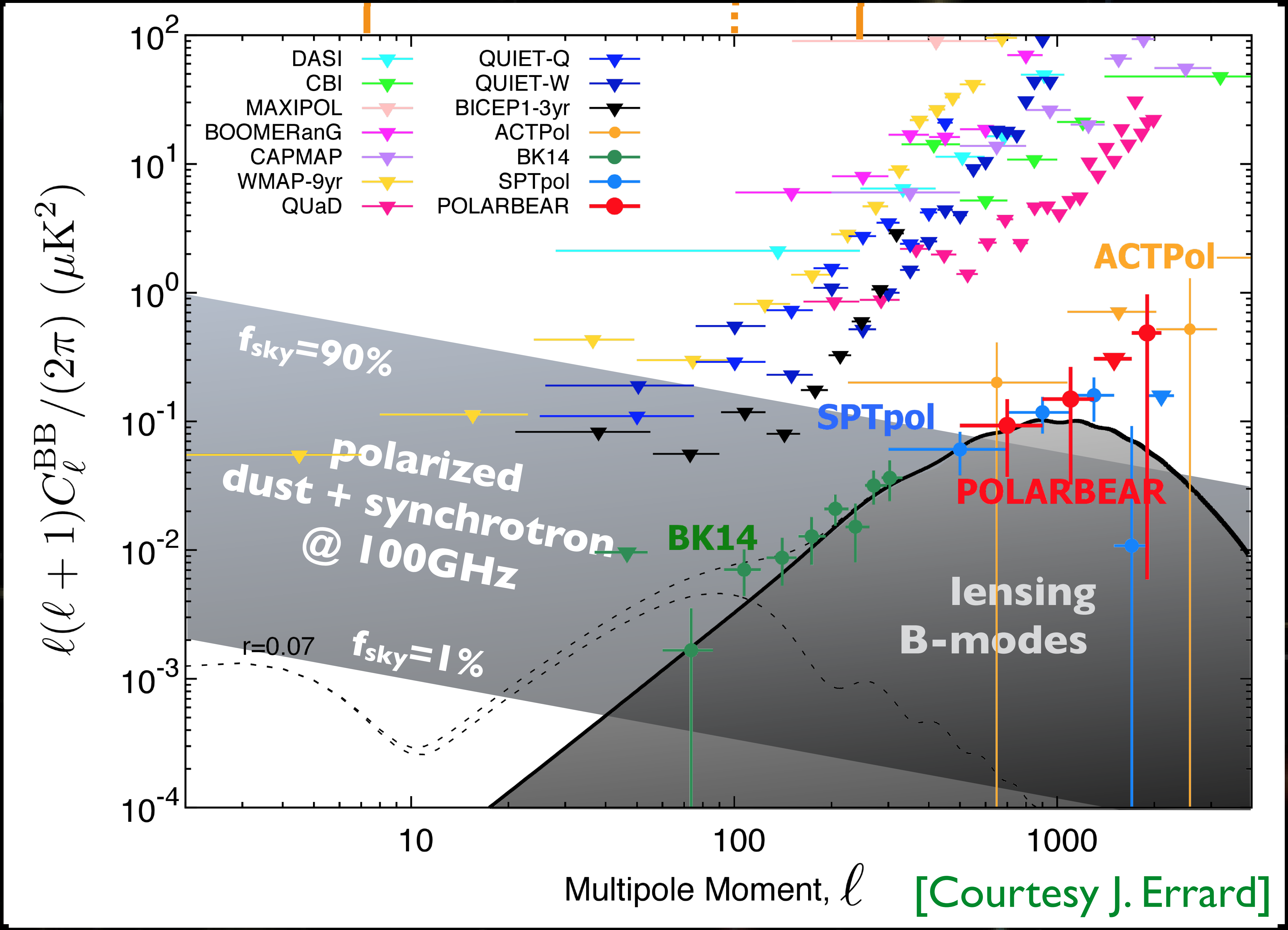


[Courtesy J. Errard]

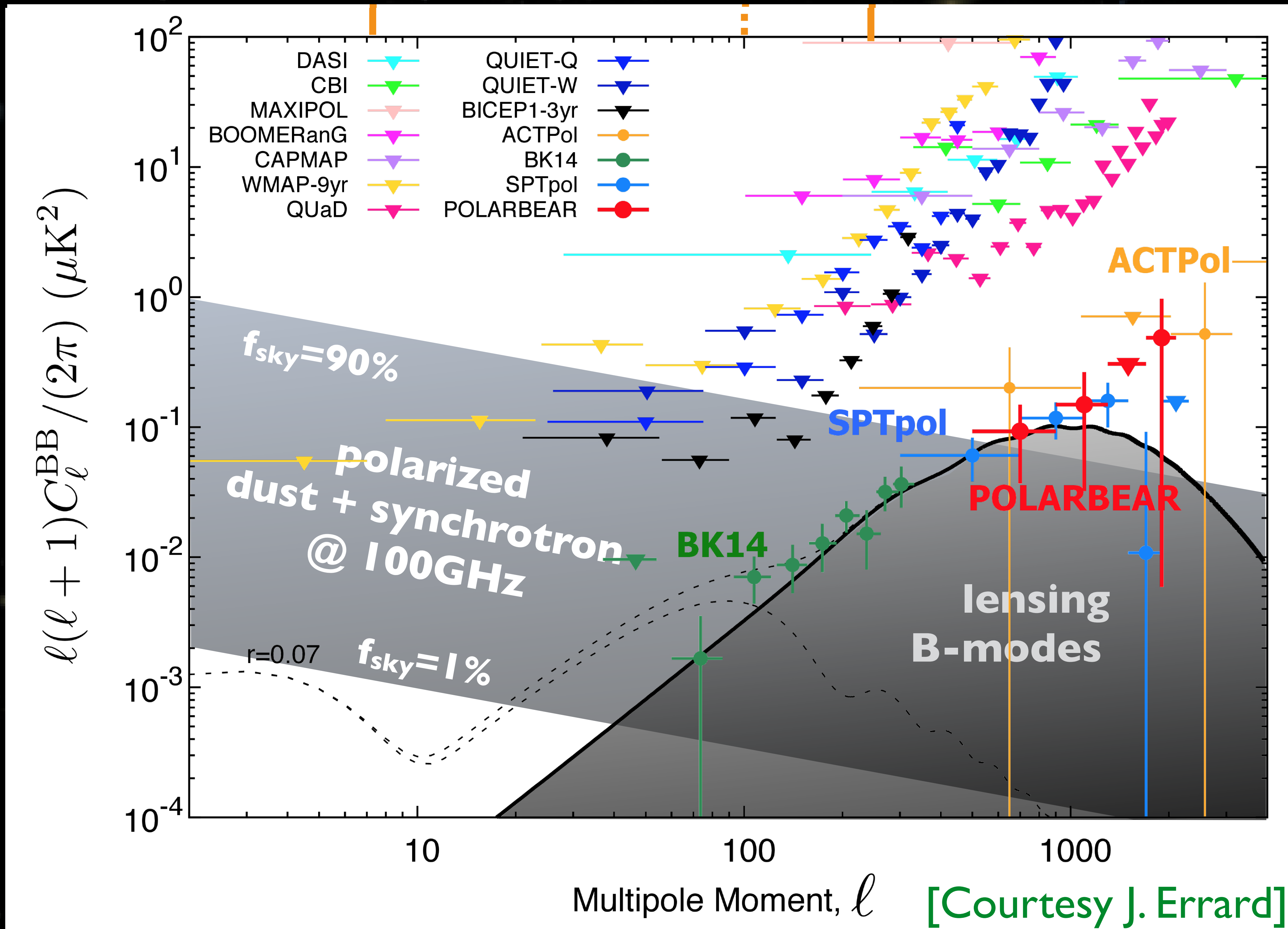
Recent results !!



Recent results !!



Recent results !!



No primordial B-modes yet… Go back to work !

Gracias