Physics of cosmic microwave background anisotropies

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Snowmass at SLAC, March 6, 2013

Overview

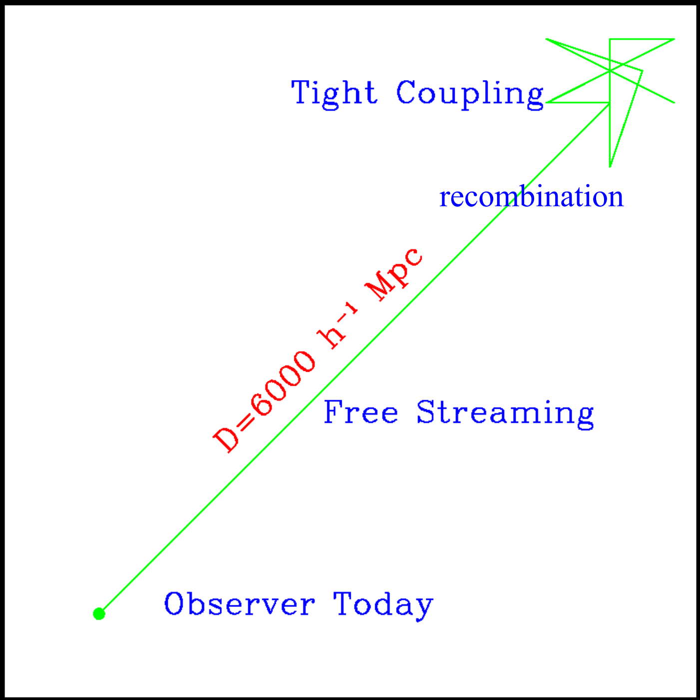
- Basics of CMB physics: temperature, polarization, lensing
- Beyond the standard model: gravity waves, relativistic and massive neutrinos, primordial nongaussianity
- Future of CMB and synergies with LSS

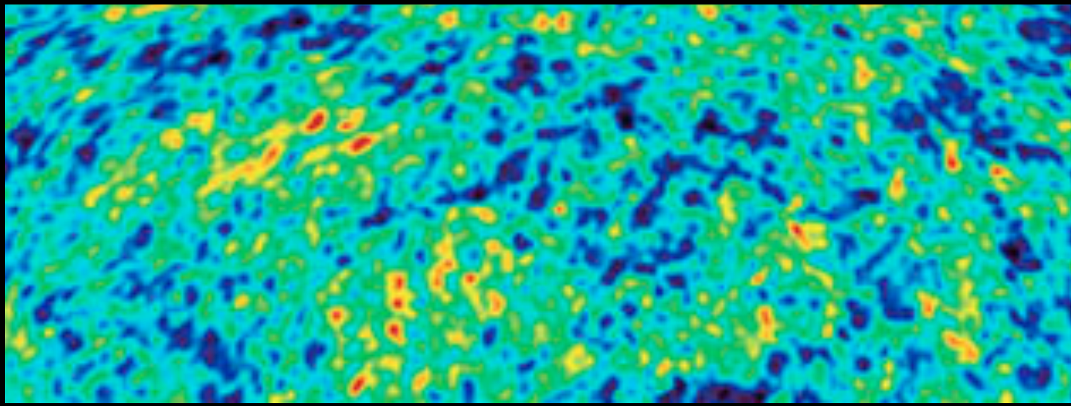
Apologies: this is a science case talk for CMB, not LSS

Primary CMB: temperature

$$\frac{\delta T}{T} = \phi + \frac{\delta_\gamma}{4} + \frac{v_r}{c}$$

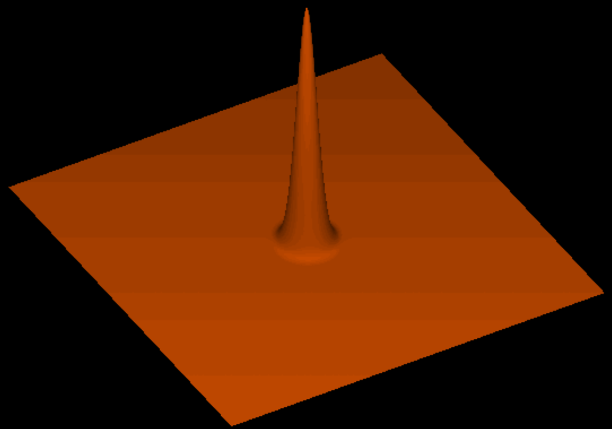
All 3 effects have the same origin



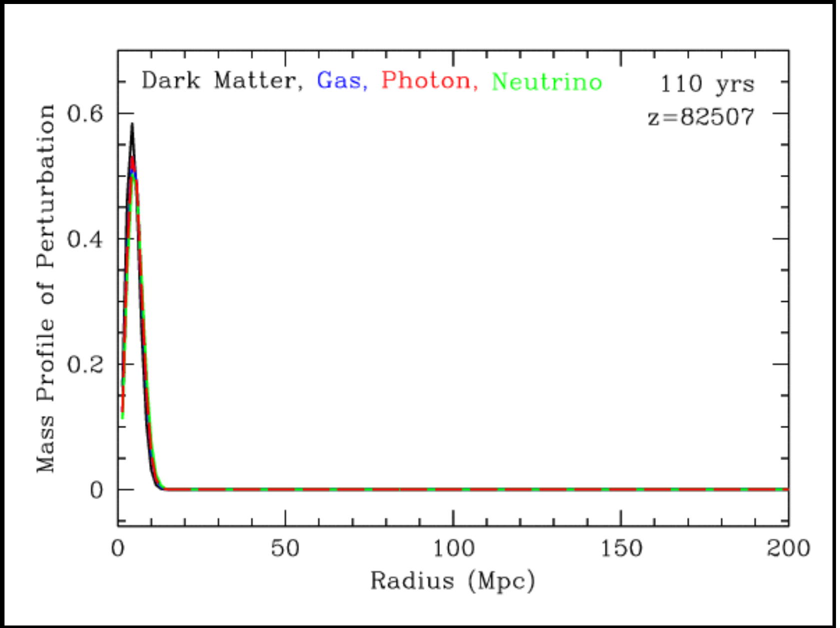


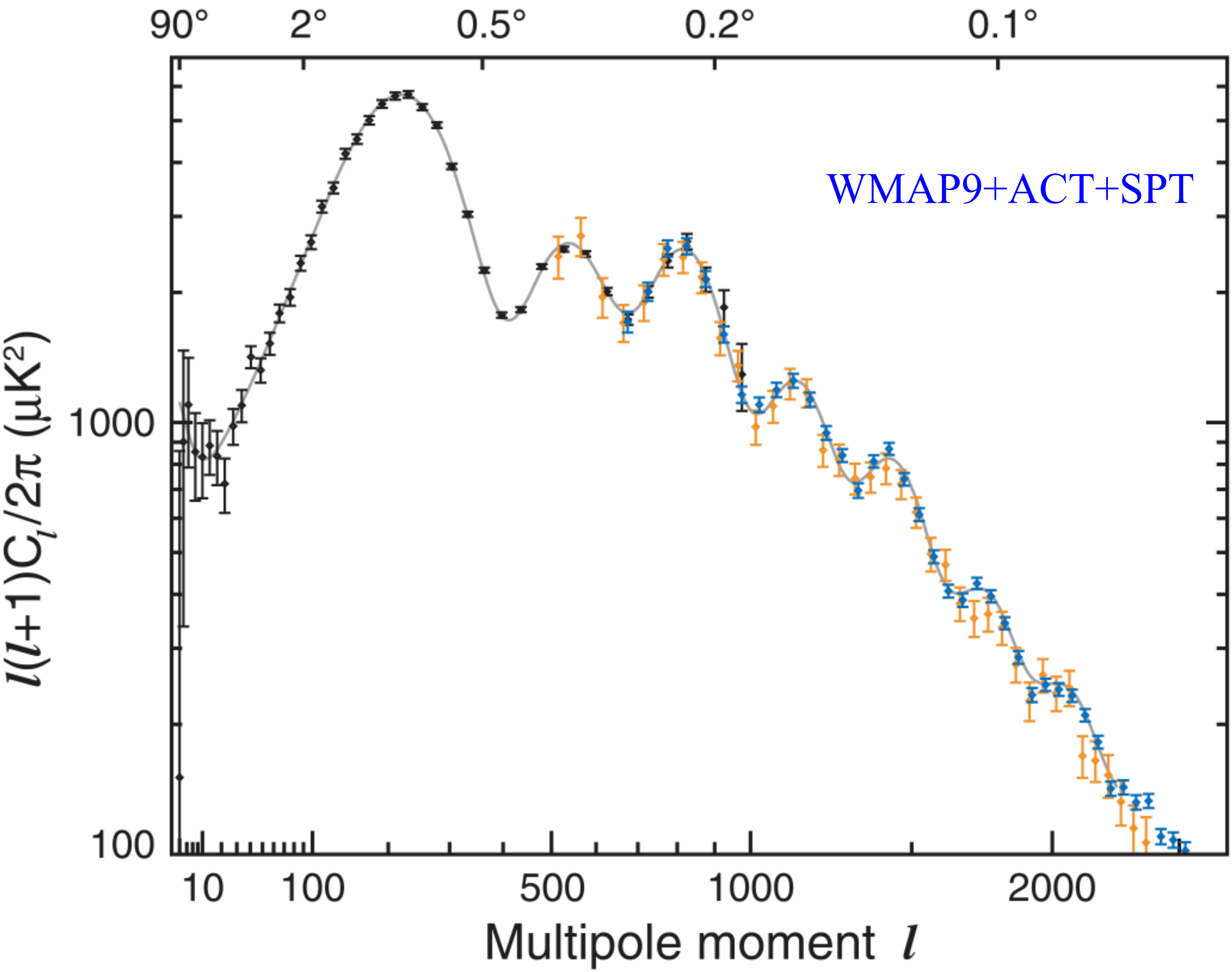
Although there are fluctuations on all scales, there is a characteristic angular scale.

Sound Waves



- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination, z=1100. CMB travels to us from this last scattering surface.
- At recombination sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Seen in CMB as acoustic peaks
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 150 Mpc.




90°
2°
0.5°
0.2°
0.1°
WMAP9+ACT+SPT
$l(l+1)C_l/2\pi$ (μK²)
1000
100
10
100
500
1000
2000
Multipole moment l

What determines the CMB?

- The physics of acoustic peaks depends only on 2 parameters:
- 1) R: baryon to photon density ratio at recombination

$$R \equiv \frac{3\rho_b}{4\rho_\gamma} \approx 0.63\left(\frac{\Omega_b h^2}{0.02}\right)\left(\frac{1000}{1+z}\right)(T_{cmb}/2.7K)^{-4}$$

- 2) z_{eq}: nonrelativistic to relativistic energy density at recombination:

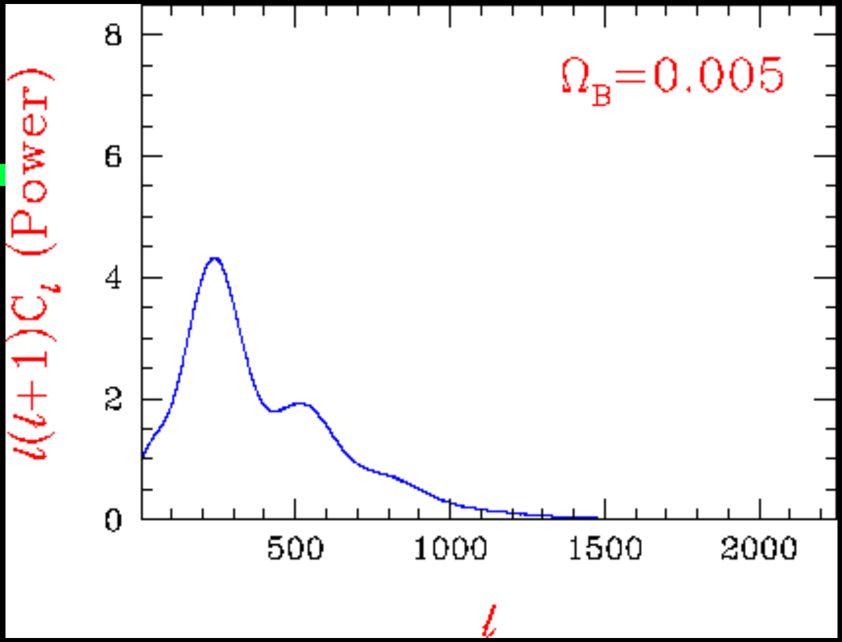
$$1 + z_{\rm eq} = \frac{\Omega_m}{\Omega_r} = \frac{\Omega_m h^2}{\Omega_\gamma h^2}\frac{1}{1+0.2271 N_{\rm eff}}$$

$$\Omega_\gamma h^2 = 2.469 \times 10^{-5}$$

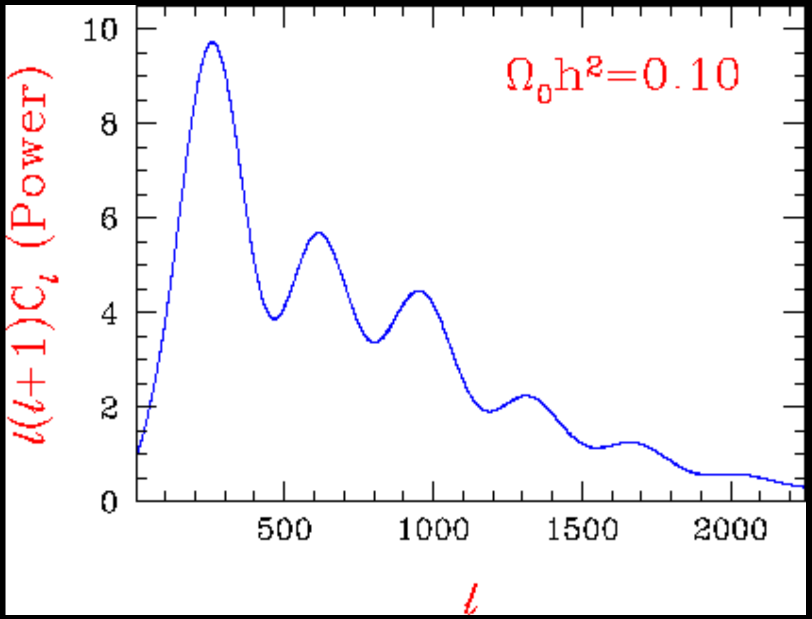
Determined by $\Omega_m h^2$, photon temperature T_{cmb} and number of neutrino families N_{eff}.

Sensitivity to cosmological parameters

Baryon to photon density ratio: difference between even and odd peaks, affects sound speed



Matter to relativistic (photons +neutrinos) ratio: feedback amplification if radiation dominates gravitational potential

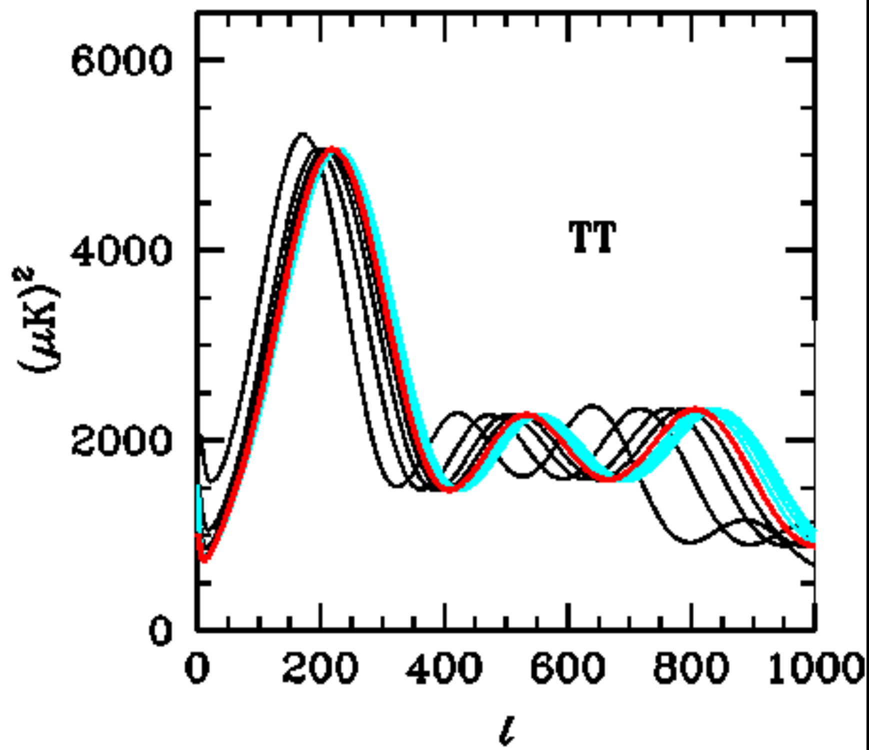


Determining Basic Parameters

Angular Diameter Distance

A physical BAO scale is observed in angle on the sky. The conversion is determined by DLSS: distance to last scattering surface. At this level curvature and dark energy enter only through DLSS

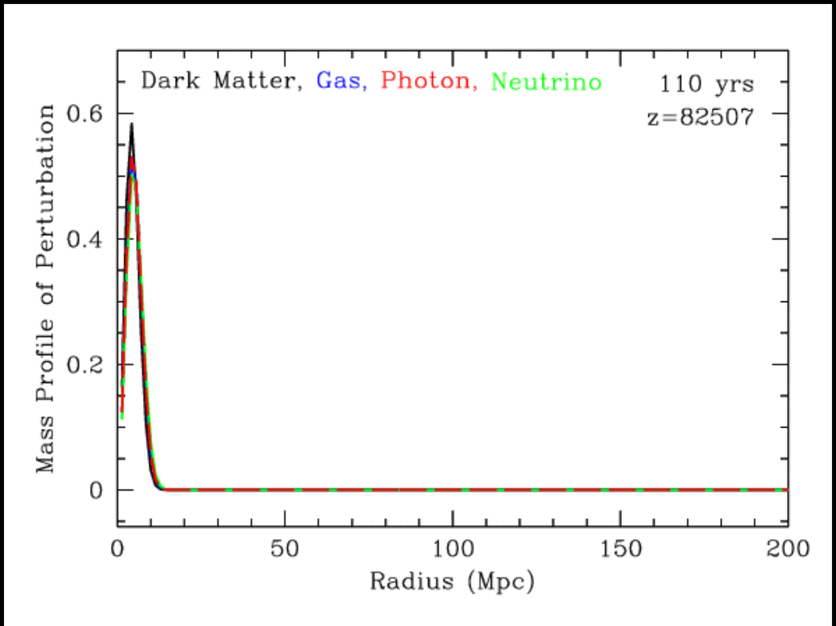
Changing curvature, dark energy density or equation of state moves the peak positions



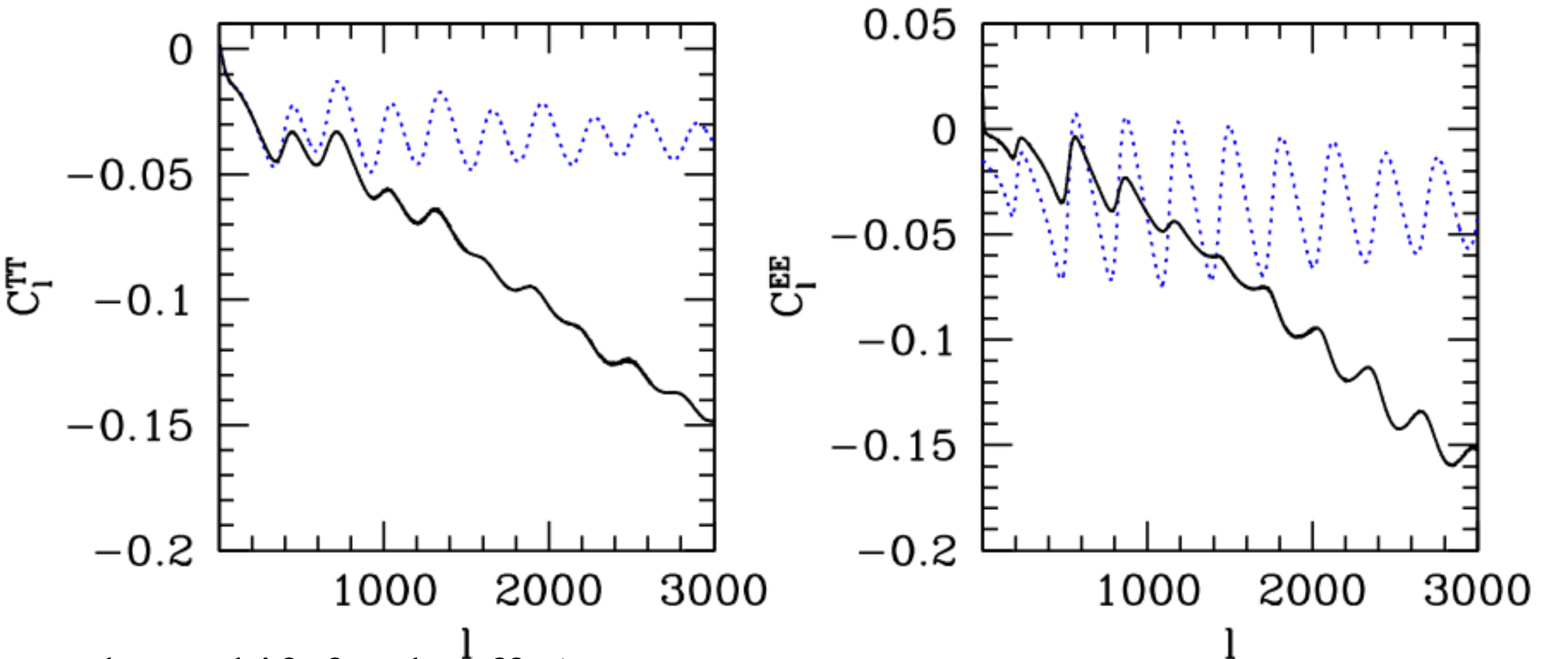
Varying w by 0.2

Are there additional noninteracting relativistic species?

- Standard value N_{eff}=3.04, but modifications possible due to sterile neutrinos, incomplete thermalization, additional rel. dof…
- Non-interacting relativistic particles free stream and create anisotropic stress: signatures at l<200
- They travel with speed of light rather than speed of sound: generate a phase shift in BAO of CMB



How well can we measure N_{eff}?



Phase shift for dNeff=1

Bashinsky & US 2004

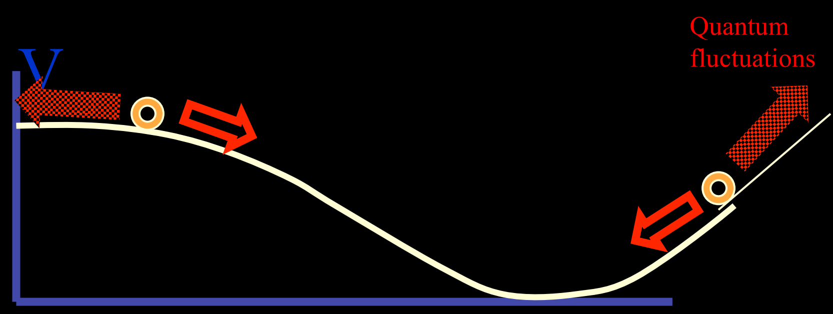
dN_{eff}=0.25 with Planck, 0.05-0.1 with CMBPol

Initial conditions: Inflation

Consider a scalar field with non-zero potential

If V(phi)>> all space and time derivative (squared) terms

$$H^2 = V$$



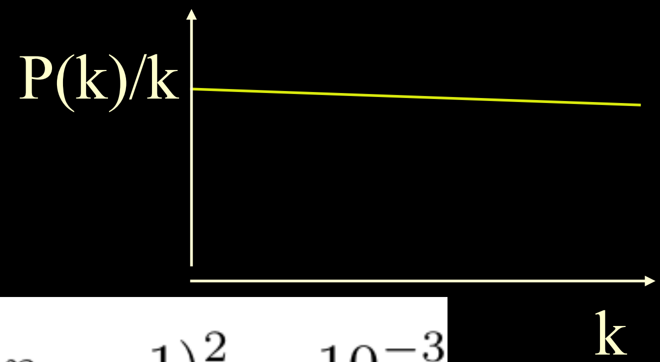
Scalars $P(k) \propto \frac{H^2}{\dot{\phi}}$

Tensors $P_g = \frac{2}{M_{pl}^2}(\frac{H}{2\pi})^2$

Quantum fluctuations converted into classical space-time perturbations of scalars and tensors (gravity waves)

Inflation predictions

- Inflation must end, number of e-folds 50-60
- Predicts almost scale invariant spectrum



$$P(k) \propto k^{n_s}$$

$$|n_s - 1| \sim 10^{-2}, \alpha_s = \frac{dn_s}{d\ln k} \sim (n_s - 1)^2 \sim 10^{-3}$$

- Adiabatic, almost gaussian fluctuations
- Inflation generically predicts zero spatial curvature, some string cosmology models suggest detectable negative curvature
- To measure energy scale of inflation need gravity waves:

  $r=10^{-4}$ $V=3\text{x}10^{15}$GeV (GUT scale 10^{16}GeV)
- Large field (chaotic) inflation predicts tensor to scalar ratio $r>10^{-2}$

CMB Can probe all of these predictions

Gravity waves from Inflation

Each polarization of the GW fluctuates during

inflation by $\frac{1}{M_{PL}}\frac{H}{2\pi}$ ($M_{pl} = 2.4\ 10^{18}$ GeV)

$$P_g = \frac{2}{M_{pl}^2}\left(\frac{H}{2\pi}\right)^2 \qquad \frac{l(l+1)C_l^T}{2\pi} \approx 6\ 10^{-3}\left(\frac{H}{M_{pl}}\right)^2$$

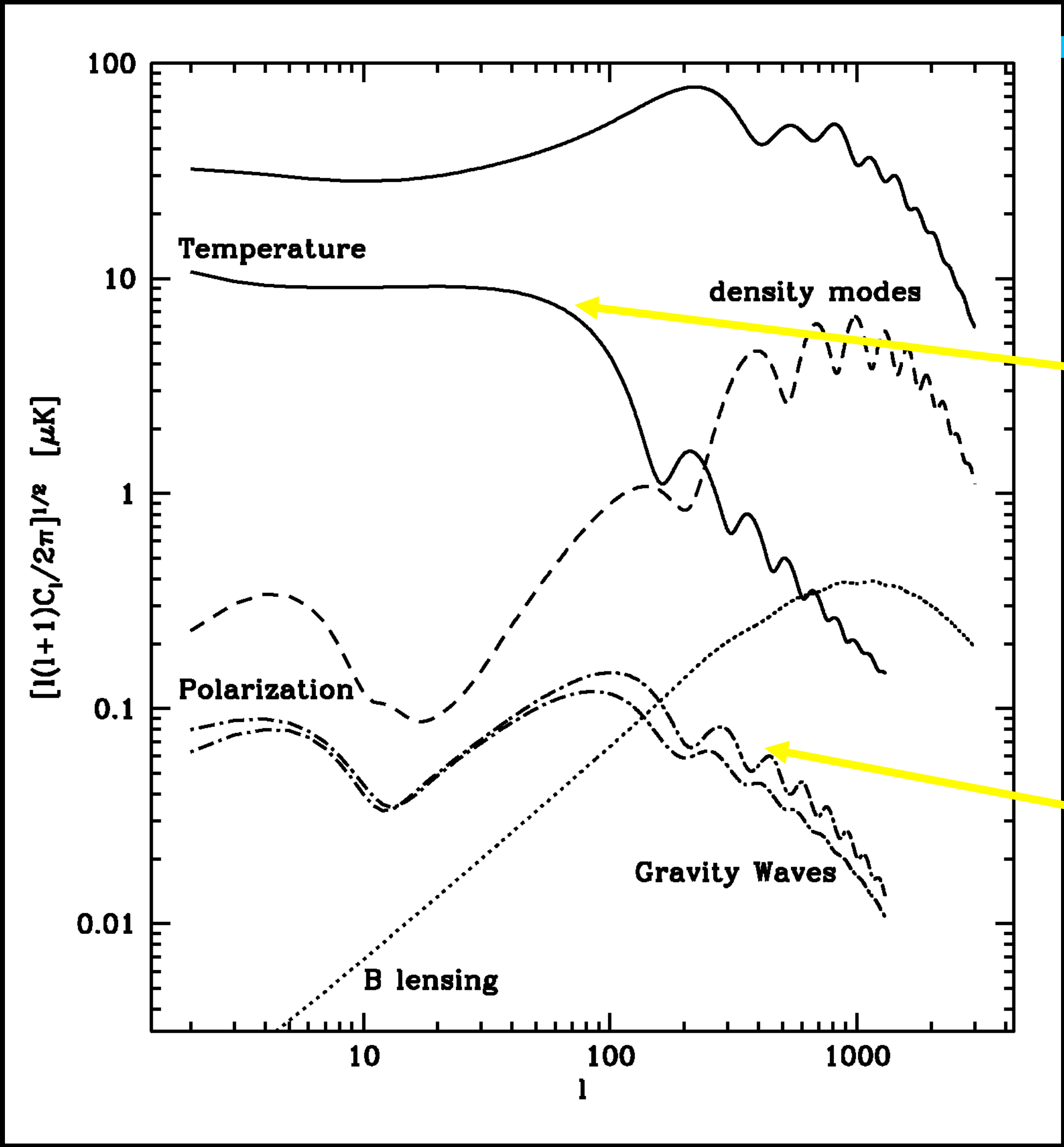
Directly measure the expansion rate during Inflation

If $r \sim 10^{-4}$ $\qquad \frac{H}{M_{pl}} \sim 1.3\ 10^{-6}$

$$V^{1/4} \sim 3\ 10^{15} GeV \qquad M_{unification} \sim 3\ 10^{16}\ GeV$$

Large field (chaotic) inflation predicts $r>10^{-2}$

Anisotropies created by gravity waves

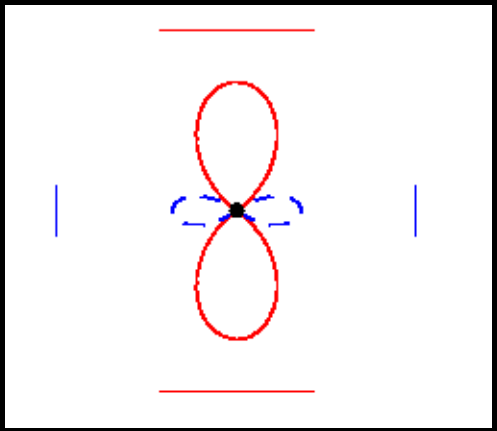


Cannot be observed because of cosmic variance

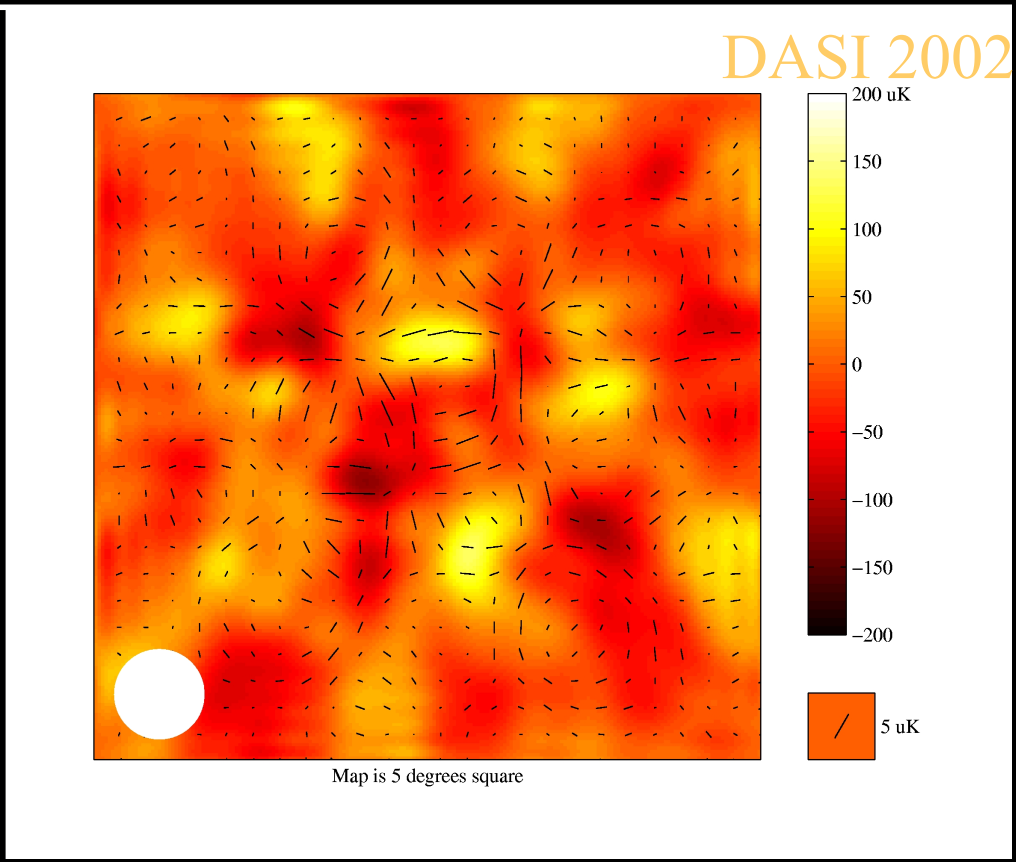
Polarization to the rescue?

The Anisotropies are polarized

To generate polarization need Thomson scattering and quadrupole anisotropy



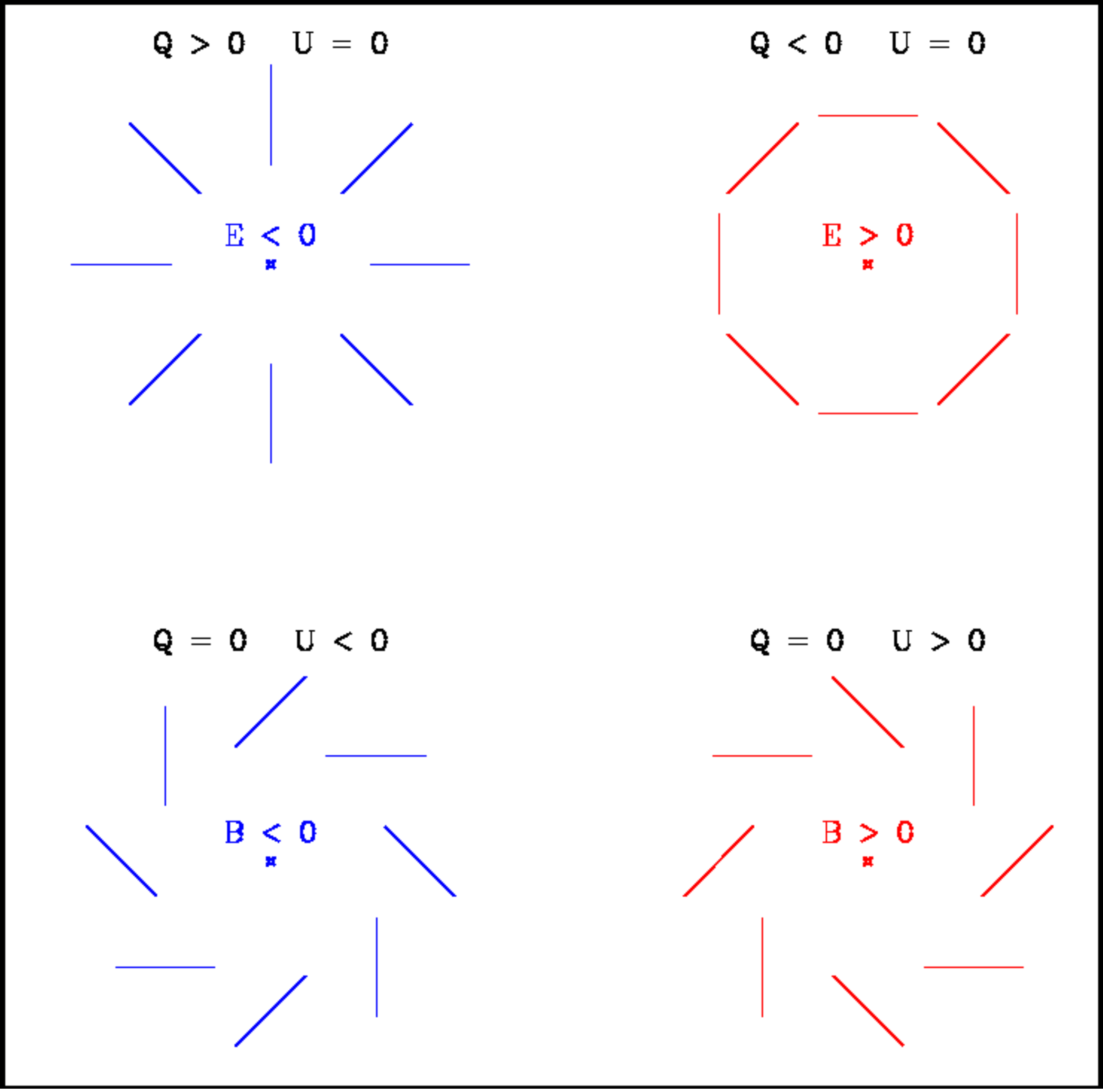
Linear polarization is specified by 2 numbers at each point: Q and U Stokes parameters. Can be decomposed into E and B



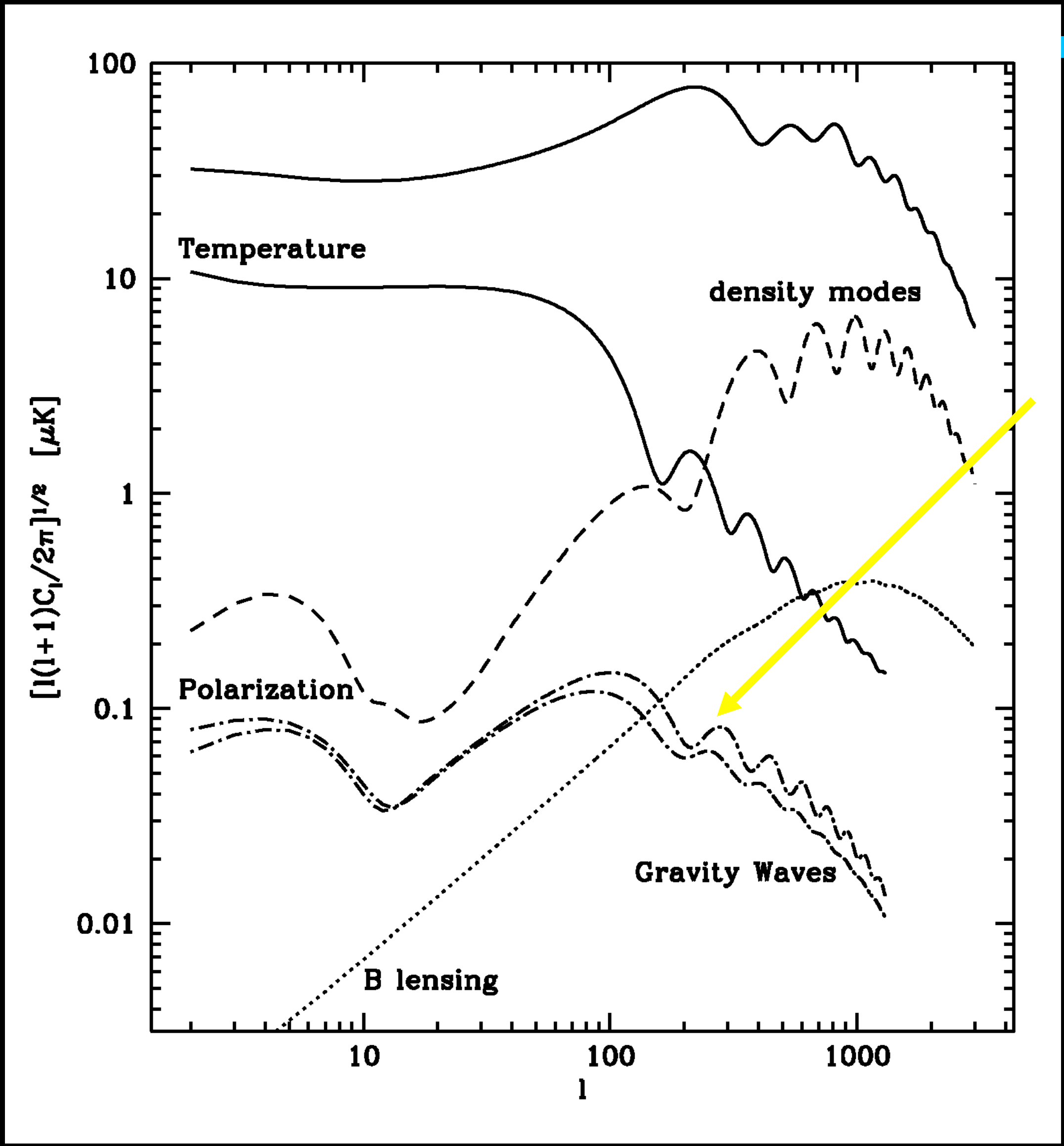
E and B pattern of polarization

Scalar density perturbations have one degree of freedom at each point: E type

Gravity waves have two degrees of freedom at each point and excite both E and B

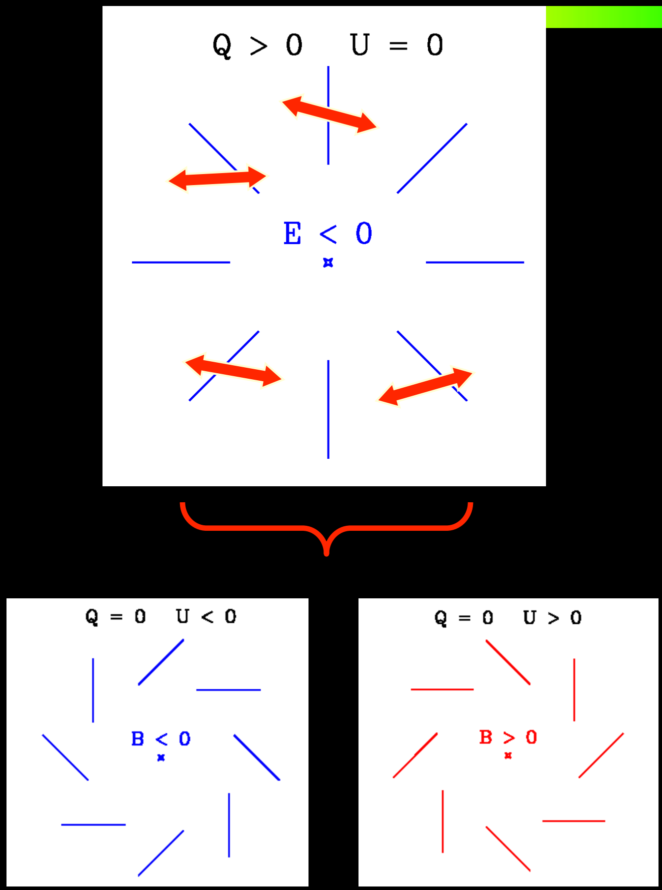


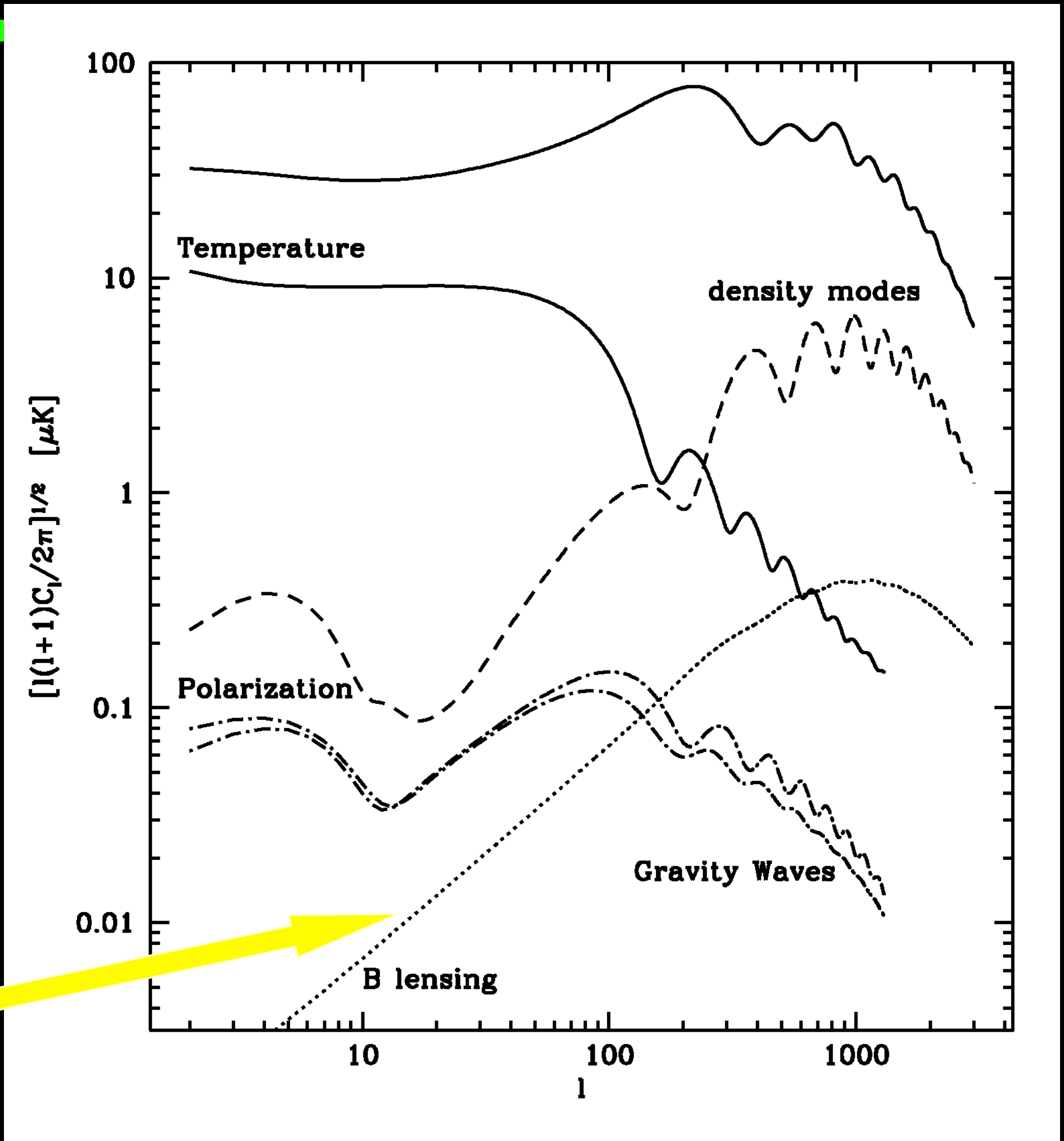
Anisotropies created by gravity waves



No cosmic variance in B polarization: just noise limited

Gravitational Lensing as a nuisance



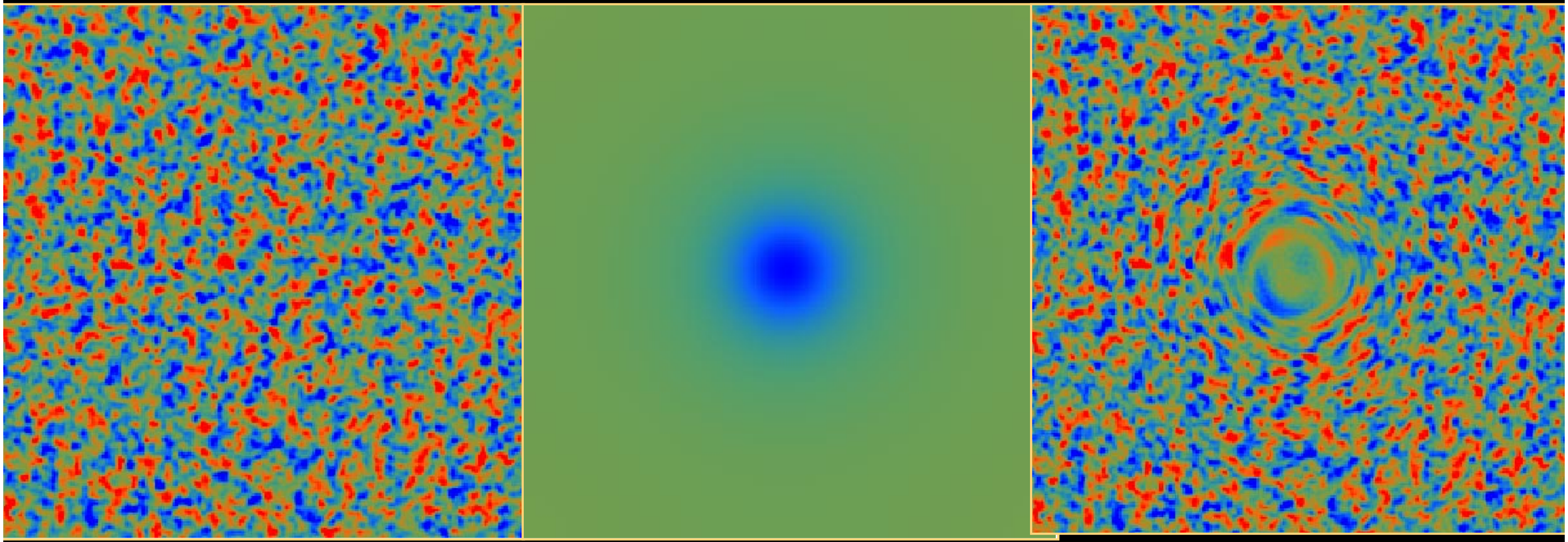


Gravitational lensing is a contaminant to B polarization
Can we remove it?

Effect of gravitational lensing on CMB

$$T_{lensed}(\vec{\mathbf{n}}) = T_{unlensed}(\vec{\mathbf{n}} + \vec{\mathbf{d}}) \qquad \vec{\mathbf{d}} = -2\vec{\nabla}\nabla^{-2}\kappa$$

- Here κ is the convergence and is a projection of the matter density perturbation.



Okamoto and Hu 2002

- Lensing creates magnification and shear

Convergence and shear

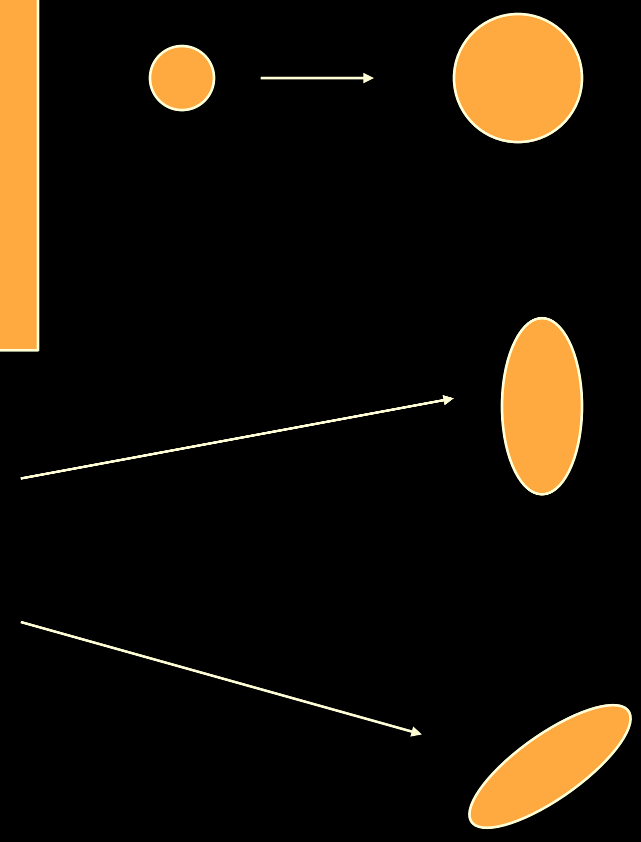
convergence

$$\kappa = \int \frac{(r_{LSS} - r)r}{r_{lSS}} \vec{\nabla}^2 \Phi dr = \frac{3}{2}\Omega_m H_0^2 \int \frac{(r_{LSS} - r)r}{r_{lSS}} dr \frac{\delta}{a}$$

Convergence shear relation in Fourier space

$$\gamma_1(\vec{l}\,) = \kappa(\vec{l}\,)\cos 2\varphi_l$$

$$\gamma_2(\vec{l}\,) = \kappa(\vec{l}\,)\sin 2\varphi_l$$



Gravitational lensing in CMB: reconstruction of lensing

$$\kappa \propto (\nabla_x T)^2 + (\nabla_y T)^2$$
$$\gamma_1 \propto (\nabla_x T)^2 - (\nabla_y T)^2$$
$$\gamma_2 \propto 2(\nabla_x T)(\nabla_y T)$$

Local estimate of typical patch size or shape

Compare to global average

Zaldarriaga & US 1998

$$T_{lensed}(\vec{\vartheta}) = T_{unlensed}(\vec{\vartheta}+\vec{\delta}) \approx T_{unlensed}(\vec{\vartheta}) + \vec{\delta} \bullet \vec{\nabla} T_{unlensed} + \dots$$
$$T_{lensed}(\vec{L}) = T_{unlensed}(\vec{L}) + \sum_l T_{unlensed}(\vec{l})(\vec{L}-\vec{l}) \bullet \vec{l}\,\varphi(\vec{L}-\vec{l}) + \dots$$
$$\vec{\delta}(\vec{l}) = \vec{l}\,\varphi(\vec{l})$$
$$\vec{C} = \left\langle T(\vec{l})T(\vec{l}\,')\right\rangle = C_l \delta_{ll'} + (\vec{l}-\vec{l}\,')(C_l \vec{l} - C_{l'} \vec{l}\,')\varphi(\vec{l}-\vec{l}\,')$$
$$\varphi(\vec{l}) = \frac{1}{2} F_{ll'}^{-1} (\vec{T} C^{-1} \frac{\partial \vec{C}}{\partial \varphi(\vec{l}\,')} C^{-1} \vec{T})$$

Optimal quadratic estimator

Okamoto and Hu 2002

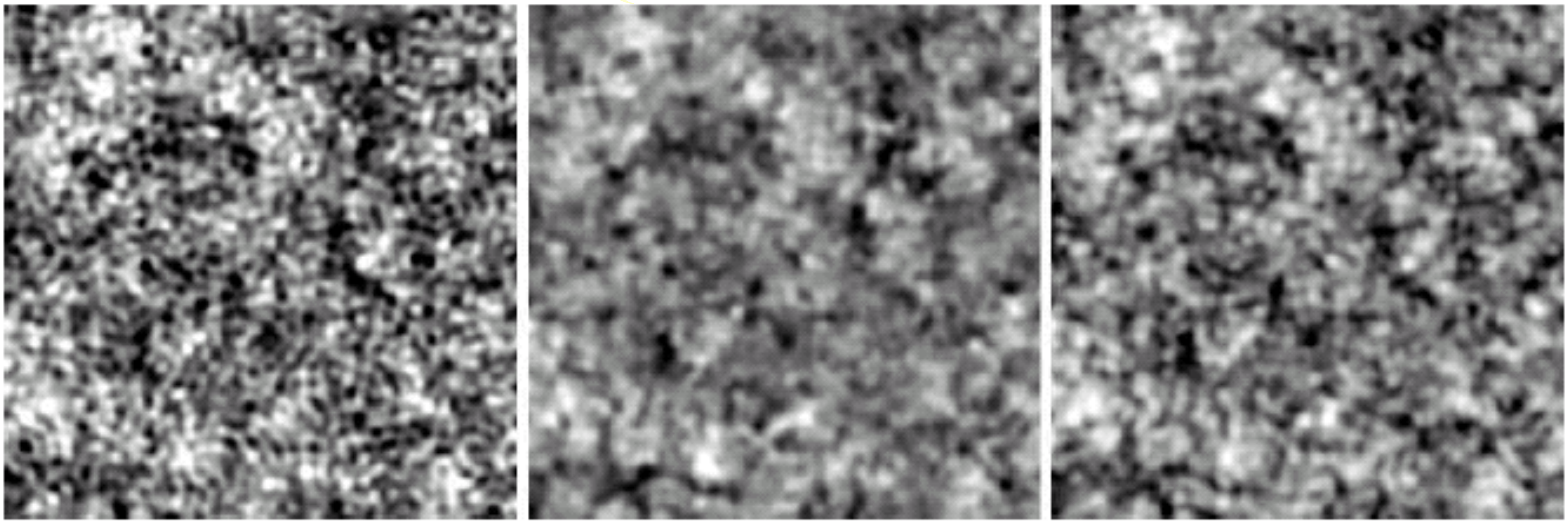
Iterative reconstruction method in polarization

Hirata and US 2003

- For low detector noise main statistical information is provided by B mode polarization:
  → B mode polarization is not present in primary anisotropy (except for non-scalar modes)
  → Therefore with B mode polarization we measure lensing, we are not limited by statistical fluctuations in the primary CMB, rather by noise, systematics, foregrounds, …
- If these issues can be controlled, measuring B mode polarization is the ultimate CMB lensing experiment.

Lensing with CMB polarization

INPUT QUADRATIC ITERATIVE



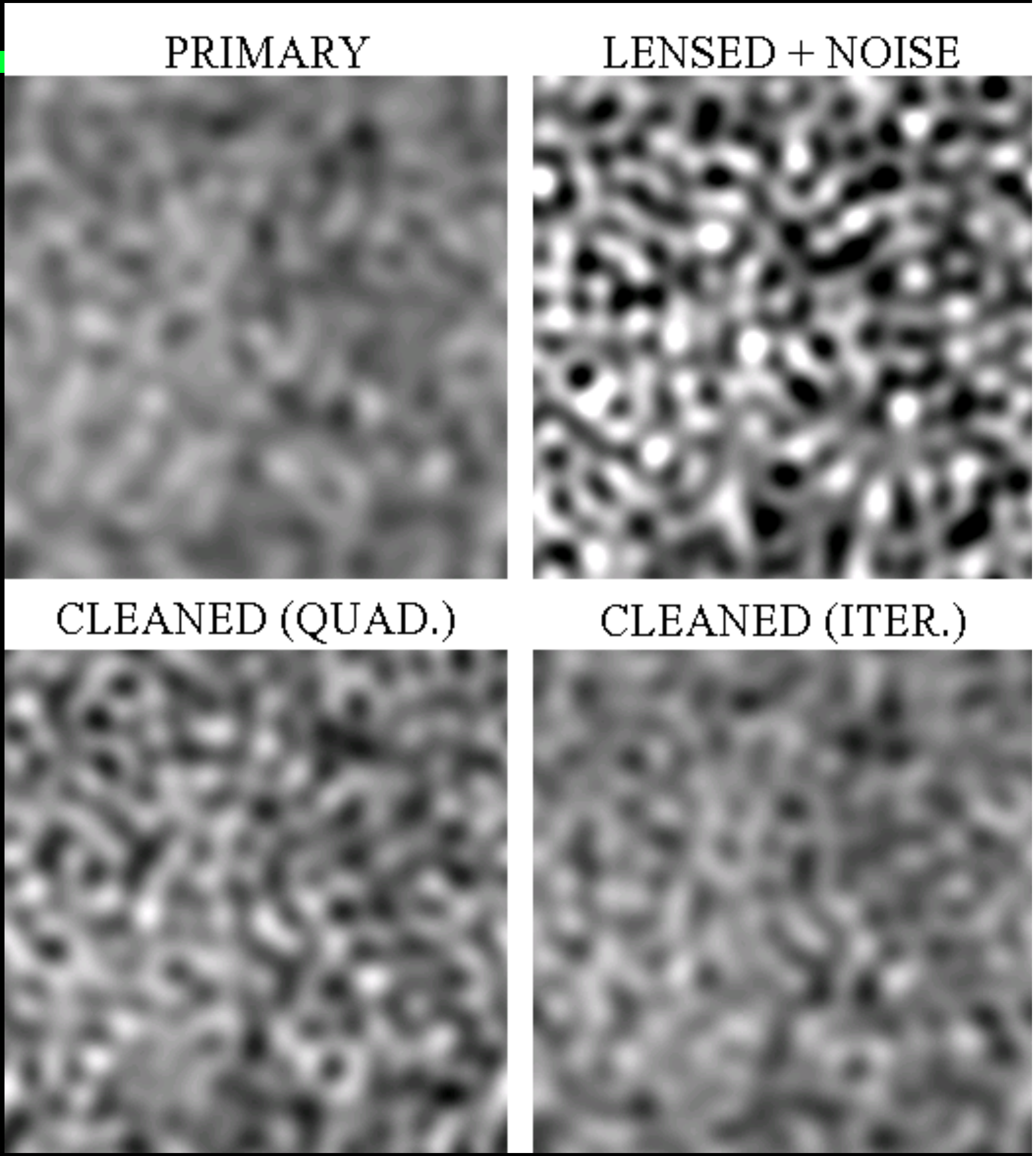
(Hirata & US 2003)

- 1.4 μK arcmin noise
- 4 arcmin beam
- 8.5x8.5 degrees
- Convergence scale -0.12 to +0.12
- S/N>1 on each mode out to L=1000.

B-modes and Gravitational Waves

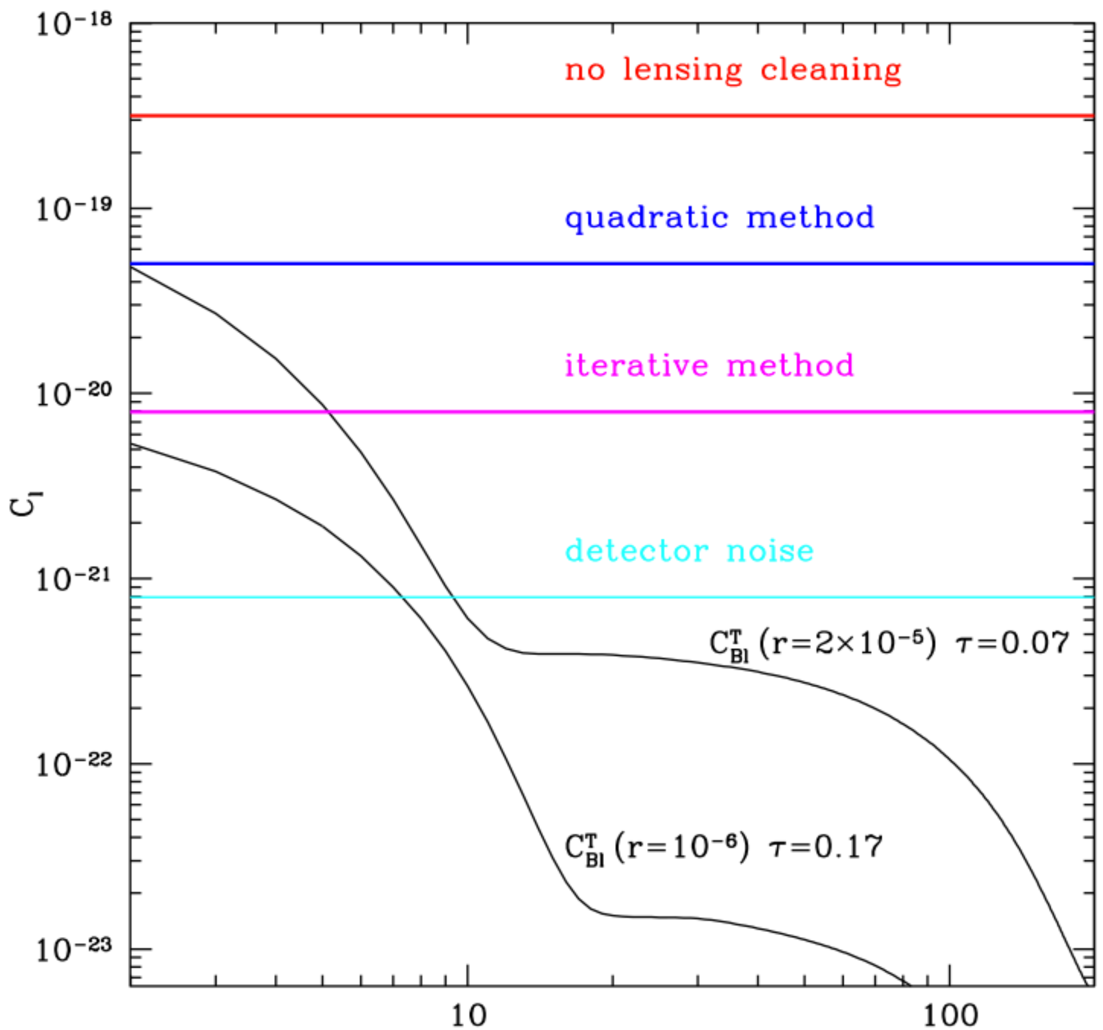
• Another possible application of lensing reconstruction techniques is to separate the lensing B polarization from the inflationary gravitational wave contribution

• Toy simulation at right for 0.5 μK arcmin noise, 4 arcmin beam



US & Hirata (2003)

How well can we delens B polarization?



US & Hirata 2003

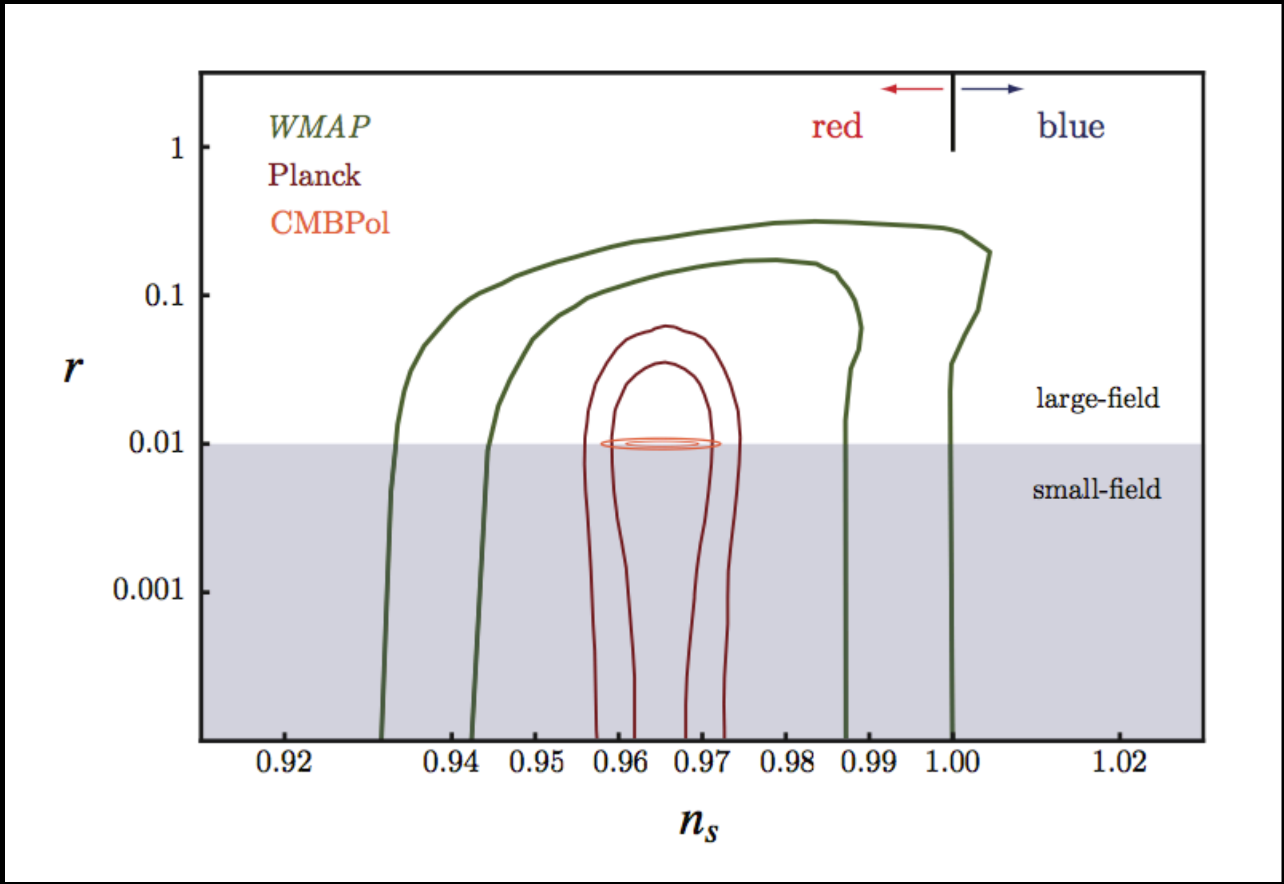
For very low detector noise it can be pushed to $r=T/S=10^{-5}$

$V_{infl}=10^{15}$GeV

If inflation scale is related to unification scale or if inflation is large field (e.g. power law chaotic) we should see gravity waves and its energy scale

The only direct detection of such high energy scale in all of particle physics

Testing inflation with CMBPol

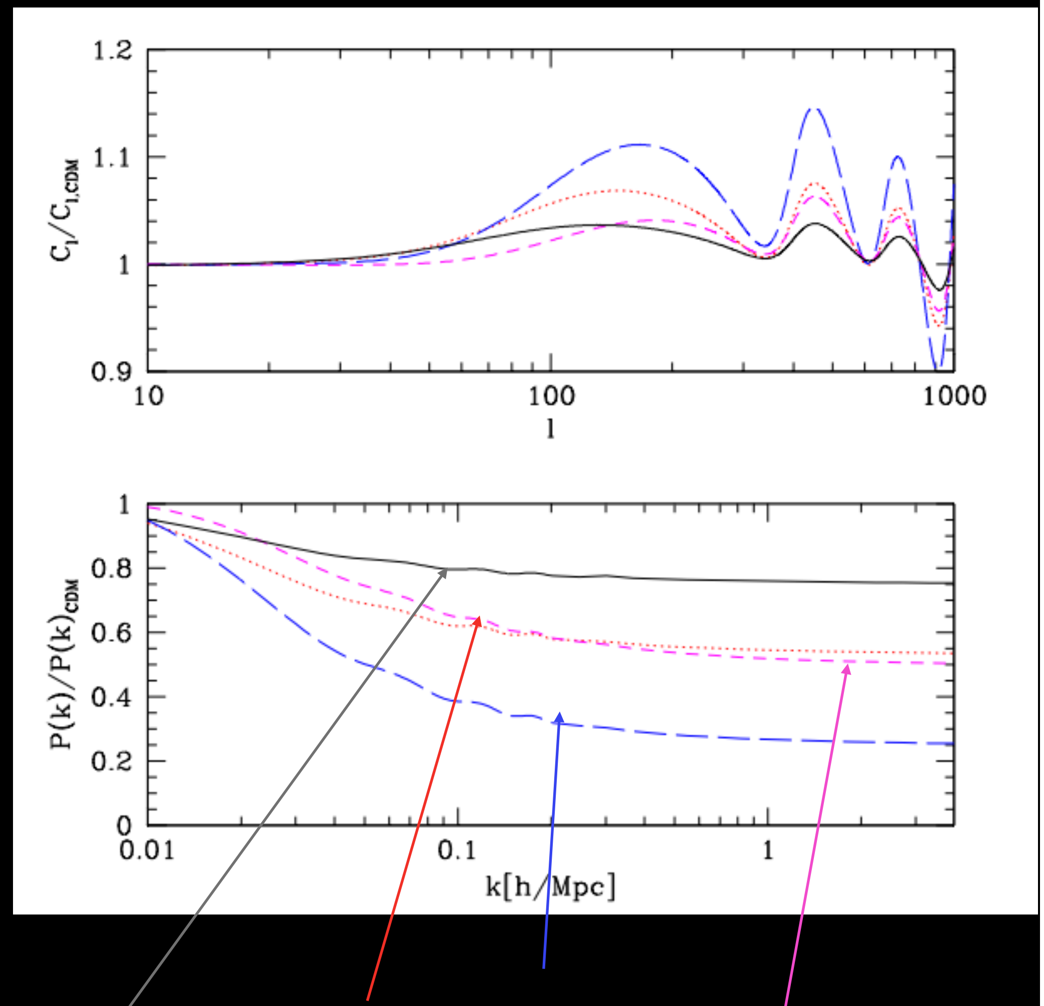


Baumann et al 2008

Also very strong limits on curvature ($6x10^{-4}$), isocurvature, cosmic strings…
This is CMBPol alone: improves further with LSS

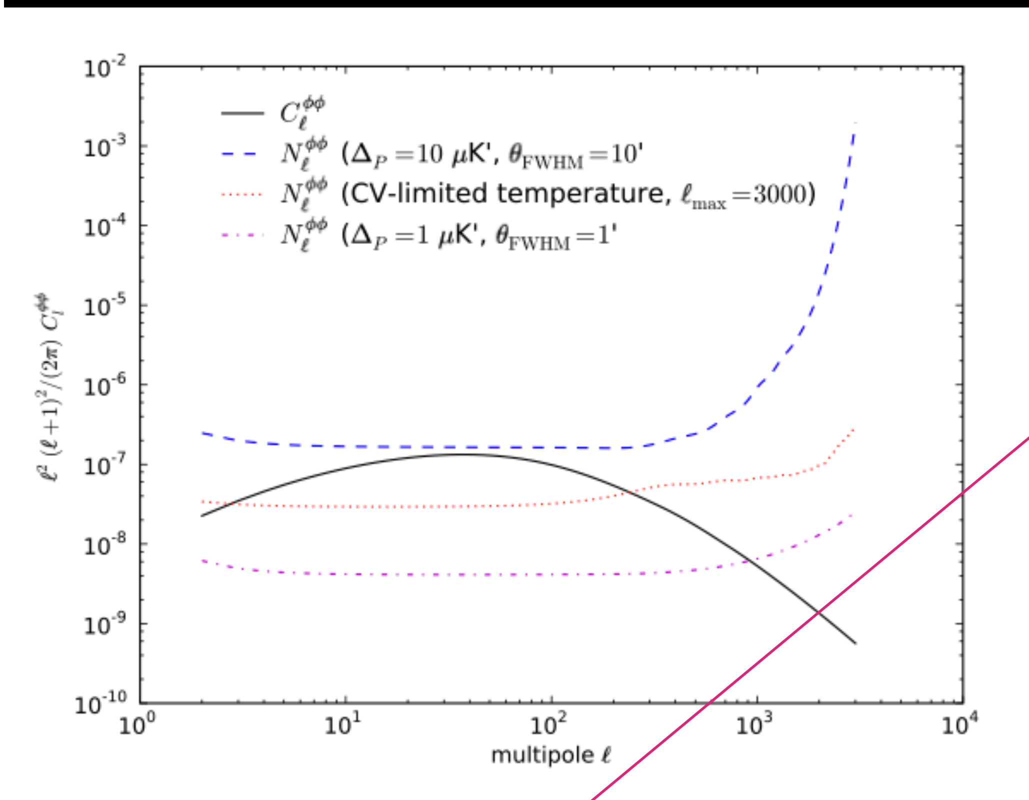
How to measure neutrino mass with CMB?

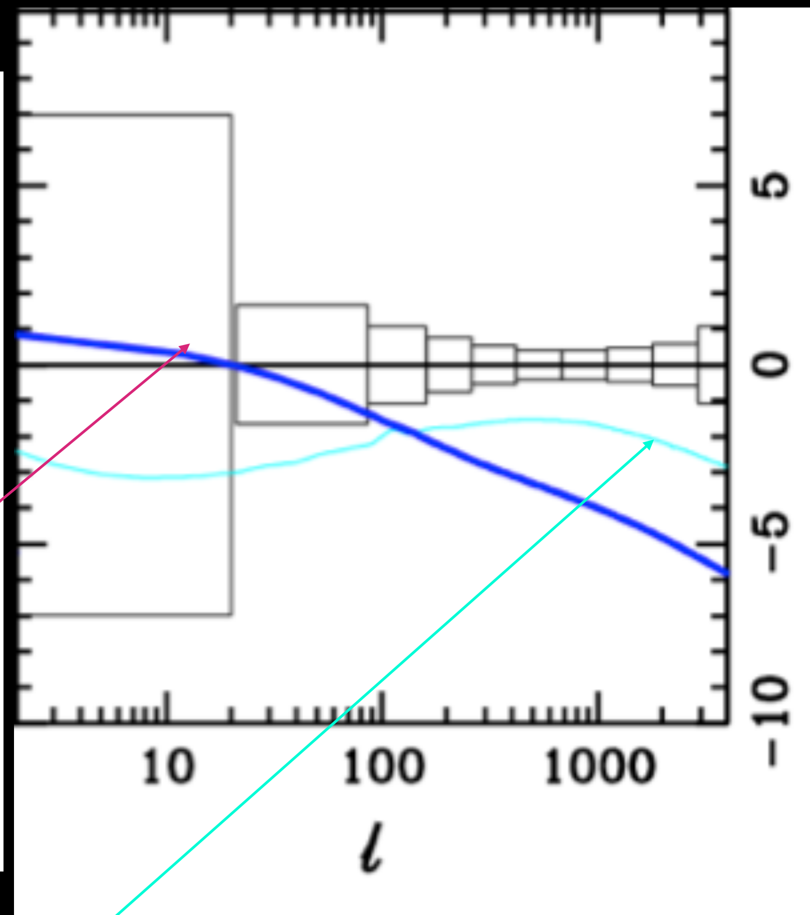
- Neutrino free streaming inhibits growth of structure on scales smaller than free streaming distance
- If neutrinos have mass they contribute to the total matter density, but since they are not clumped on small scales dark matter growth is suppressed
- Minimum signal at 0.06eV level makes 3% suppression in power, mostly at k<0.1h/Mpc



m=0.15x3, 0.3x3, 0.6x3, 0.9x1 eV

How well can we measure weak lensing with CMB?

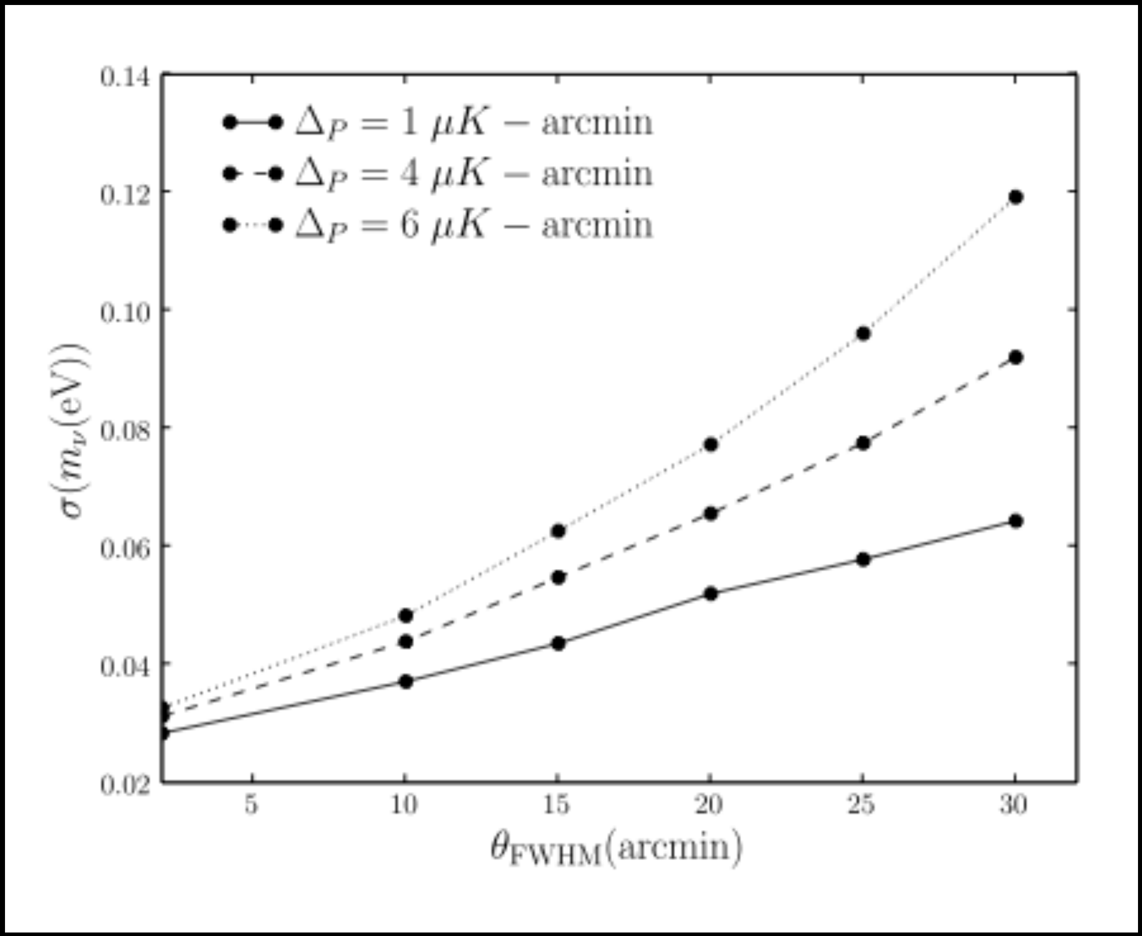




Effect of a 0.1eV massive neutrino Equation of state change Δw=0.2

Kaplinghat etal 2003

Predicted limits on neutrino mass

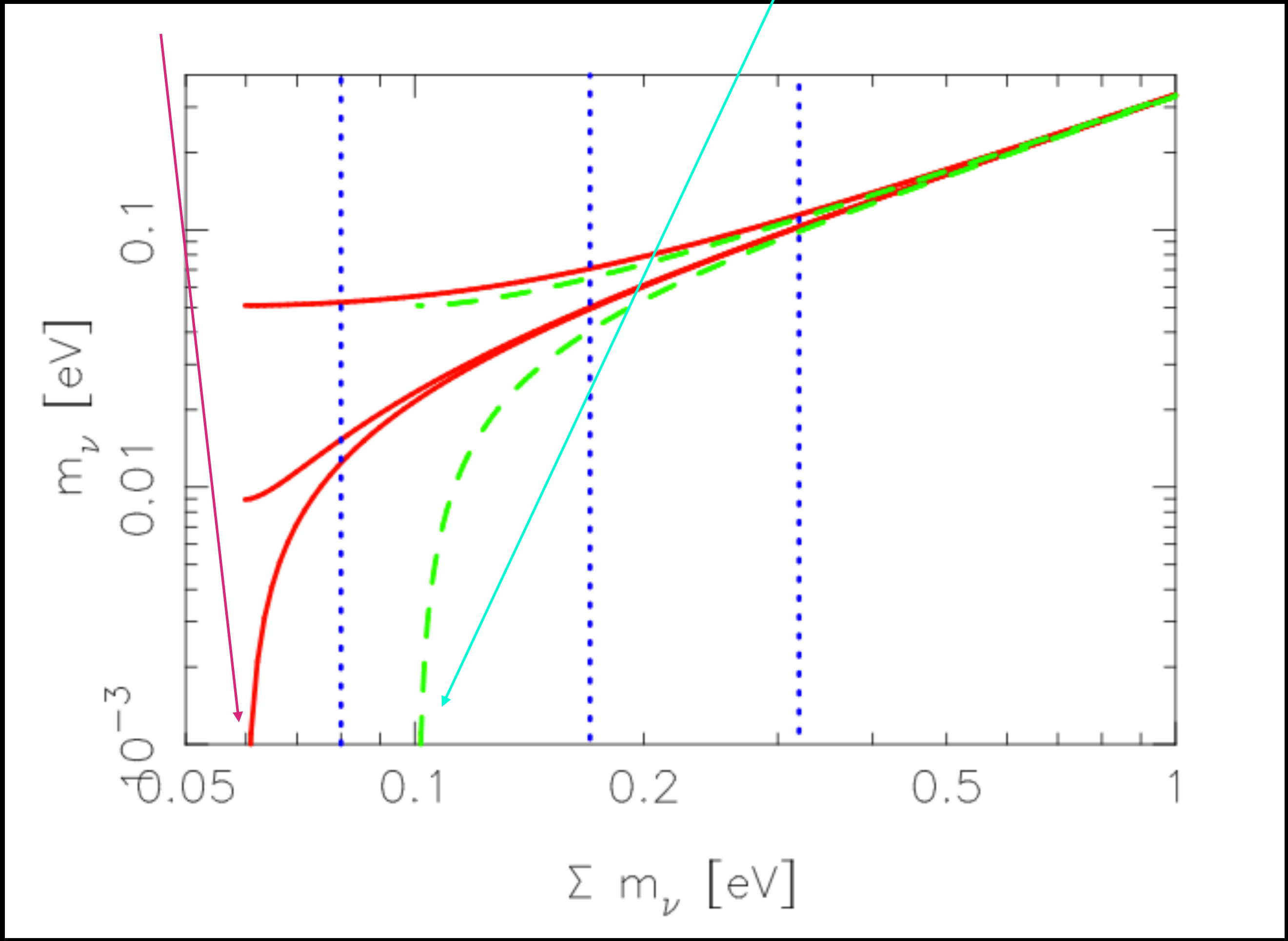


Smith etal 2008

using optimal quadratic estimator, can possibly do better with iterative estimator

One can perhaps reach as low as 0.01-0.02eV on the sum of neutrino mass: guaranteed detection?

Regular or inverted hierarchy?



One needs 0.01eV error on the sum to answer it at 4 sigma, with 0.02eV one can be lucky and have a 3 sigma answer or unlucky and have no answer

CMB polarization: the ultimate weak lensing experiment?

- Cleanest probe of dark matter clustering: largest scales, linear growth, highest redshift, known to be 1100, very few systematics (contrast to galaxy lensing)
- Helps clean out B contamination
- Guaranteed science (eg, neutrino mass detection) even if T/S=0
- Can calibrate LSS weak lensing surveys

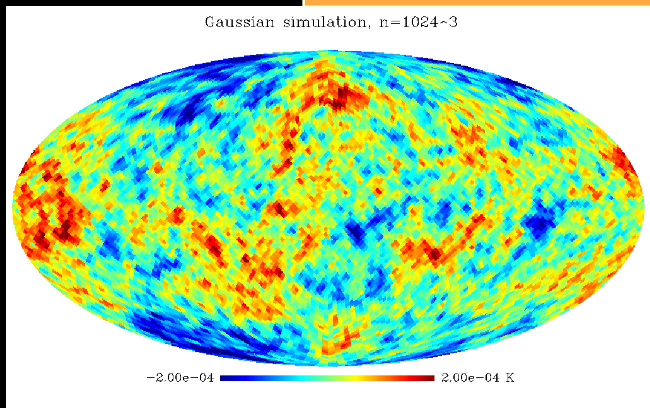
Calibrating weak lensing surveys with CMB lensing

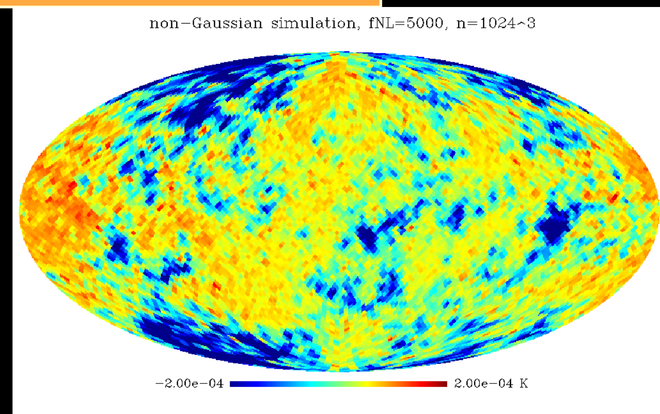
- One of primary concerns for galaxy weak lensing surveys (DES, LSST, Euclid…) is ellipticity-shear conversion bias and photometric redshift calibration bias, both of which appear as a multiplicative factor
- CMB lensing very clean: does not suffer from these and one can use CMB lensing cross-correlation with galaxy lensing to calibrate the galaxy lensing bias (Vallinotto 2012)
- One can further improve by using cross-correlation of each with a galaxy survey (Das & Spergel 2013)
- The gains can be a factor of 10+: for LSSTxCMBPol from 4% to 0.3% calibration (Vallinotto 2012)
- This would allow LSST to do low redshift dark energy science (e.g lensing tomography) that CMB lensing cannot do

Primordial non-gaussianity

- Local model $$\Phi(x) = \Phi_G(x) + f_{NL}\Phi_G^2(x)$$

f_{nl}=0





f_{nl}=5000

- Simple single field inflation predicts f_{nl}<1
- Nonlinear corrections give f_{nl} around 1
- Extensions of simplest inflationary models can give f_{nl}>1
- Search for using bispectrum or 3-point function
- Other non-local configurations of 3 point function possible and predicted by certain models of inflation
- CMBPol is predicted to reach f_{nl} of order 2 for local and 10 for equilateral

Conclusions: why still do CMB in the era of LSS?

- Polarization is the future of CMB
- B polarization and gravity waves: possibility of direct detection of 10^{15}-10^{16} GeV energy scale of inflation
- CMB lensing: arguably the cleanest lensing probe, high signal if using B and E polarization
- Testing inflation, dark energy, neutrino mass and relativistic energy density at an unprecedented level
- Important synergies with LSS (e.g. CMB provides absolute calibration of BAO scale), possibly could even save the day with LSS weak lensing calibration