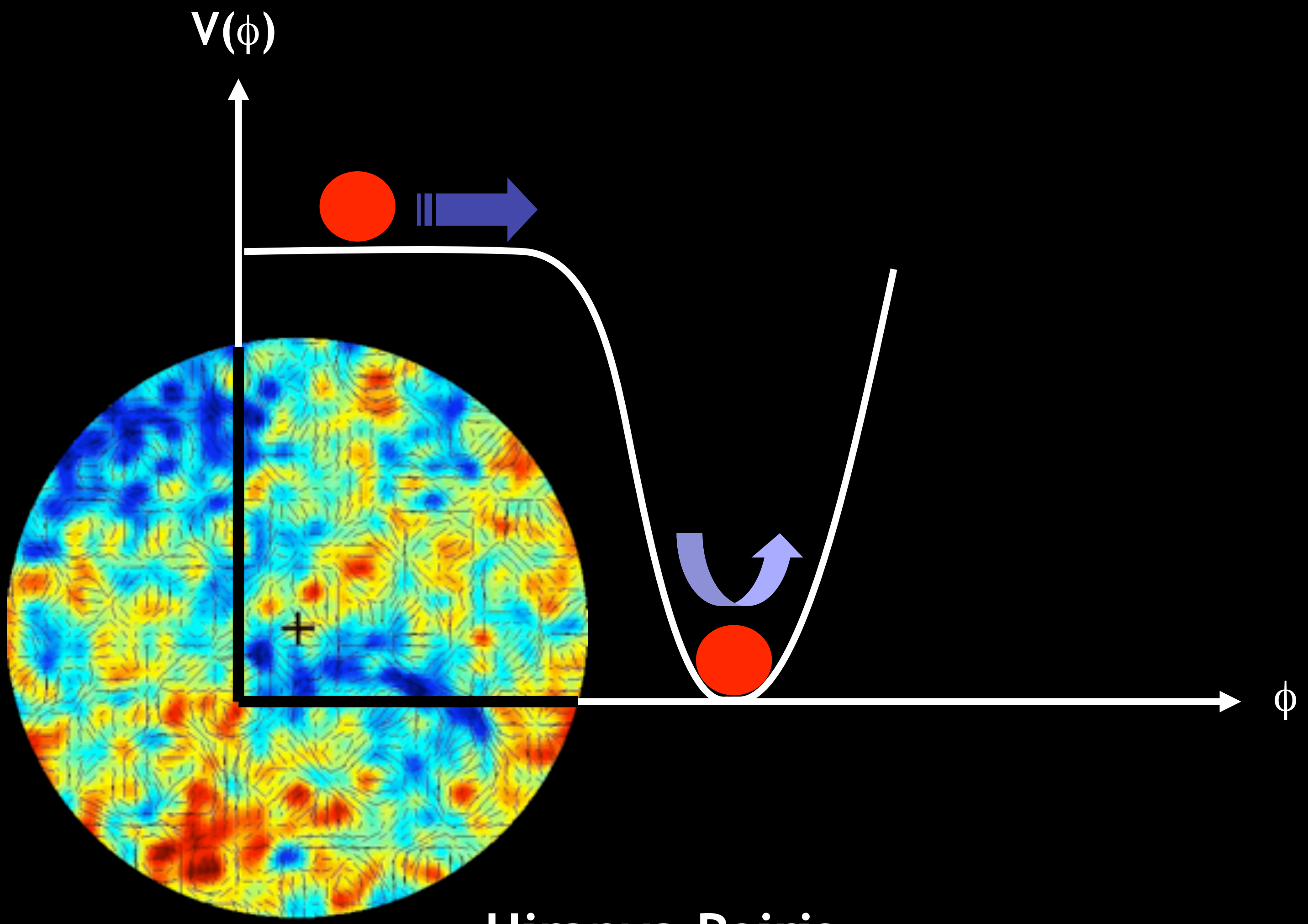
Prospects for CMB observations

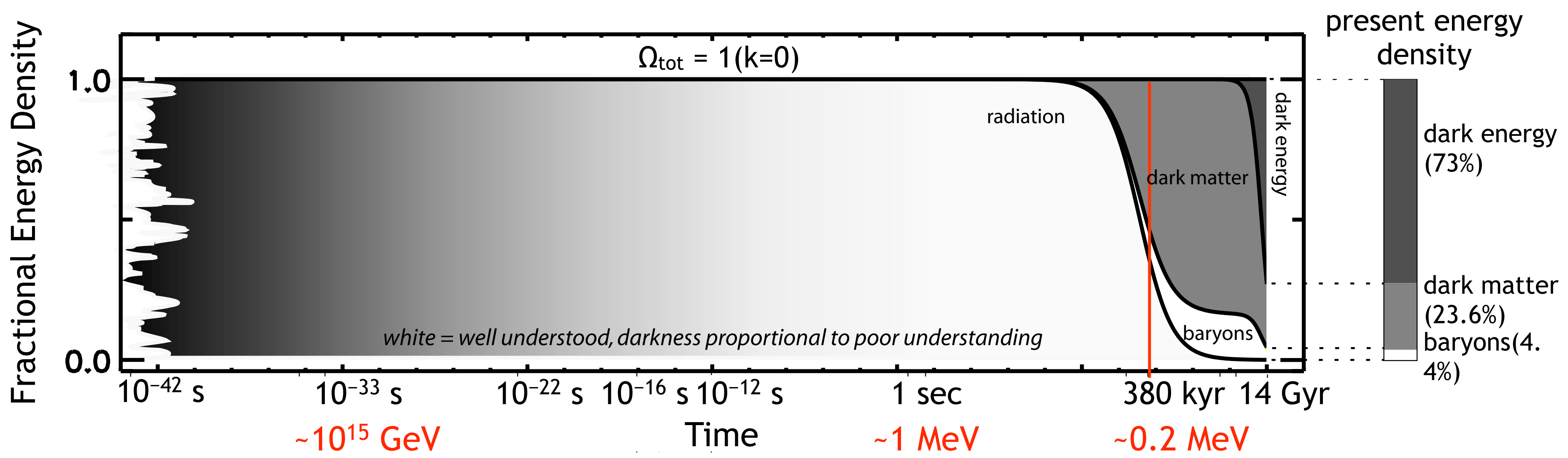


Hiranya Peiris

STFC Halliday Fellow

University of Cambridge

Cosmic History / Cosmic Mystery



Planck
Energy

GUT
symmetry

T=100 TeV
(ILC X 100)

nucleosynthesis

Generation
of primordial
perturbations

Cosmic Microwave
Background Emitted
carries signature of
acoustic oscillations and
potentially primordial
gravitational waves

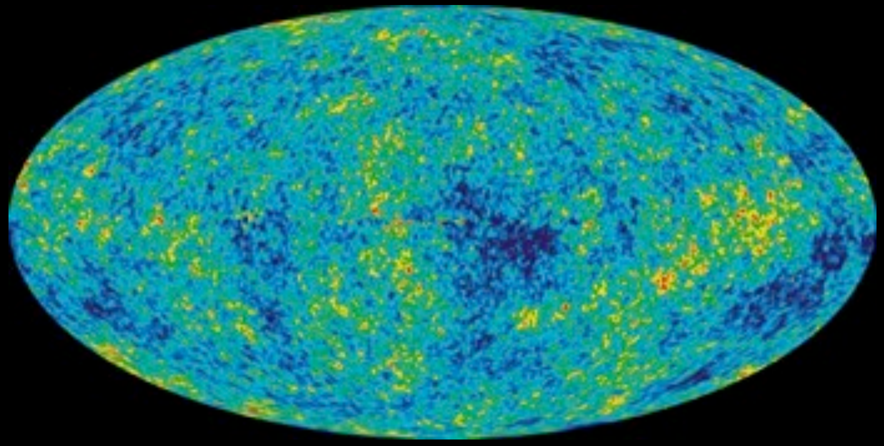
non-linear growth of
perturbations:
signature on CMB
through weak
gravitational lensing

Figure: J. McMahon, adapted by HVP

ΛCDM: The "Standard Model" of Cosmology

Homogeneous background

Perturbations



$$\Omega_b, \Omega_c, \Omega_\Lambda, H_0, \tau$$

$$A_s, n_s, r$$

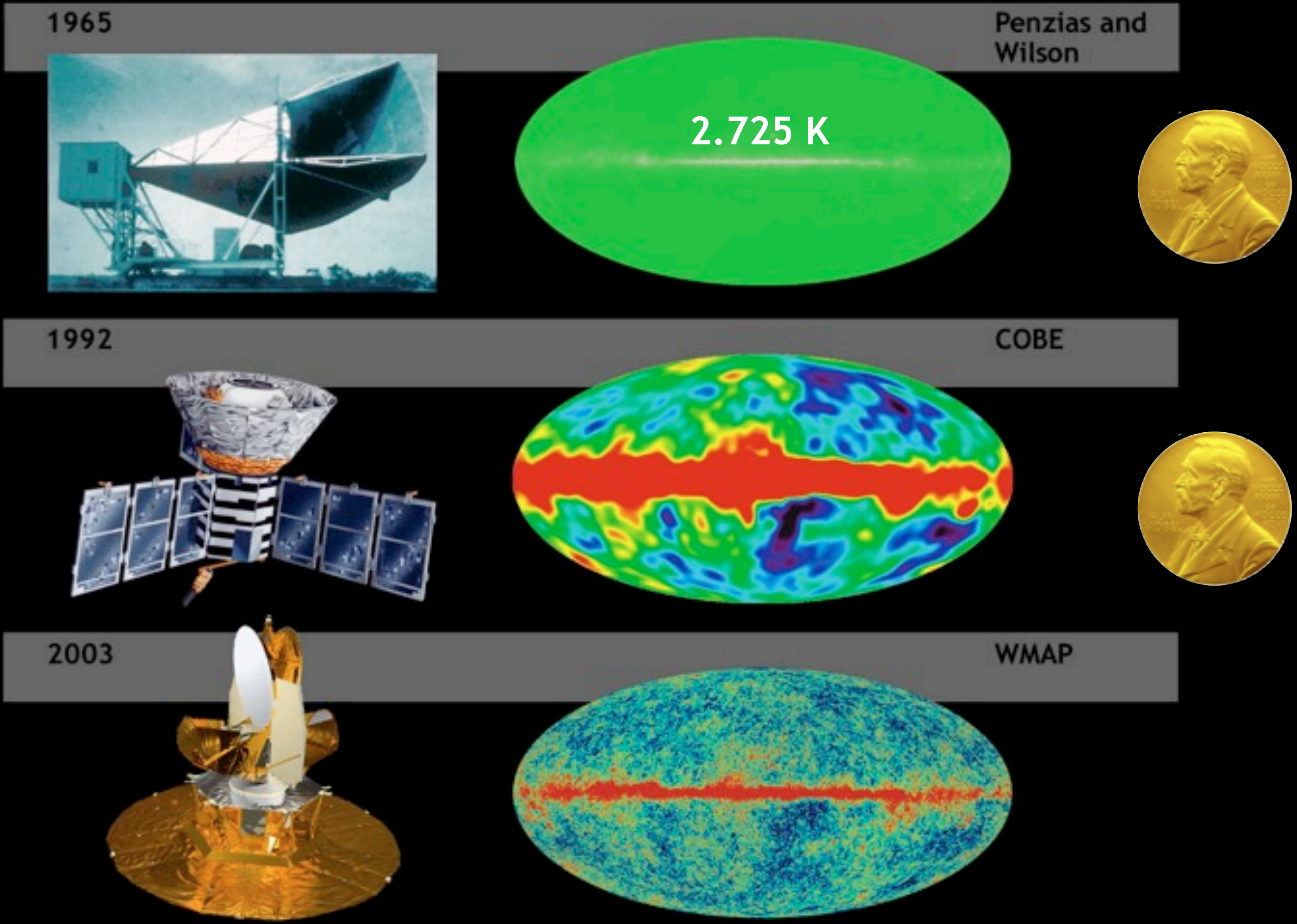
- atoms 4%
- cold dark matter 23%
- dark energy 73%

- nearly scale-invariant
- adiabatic
- Gaussian

Λ? CDM?

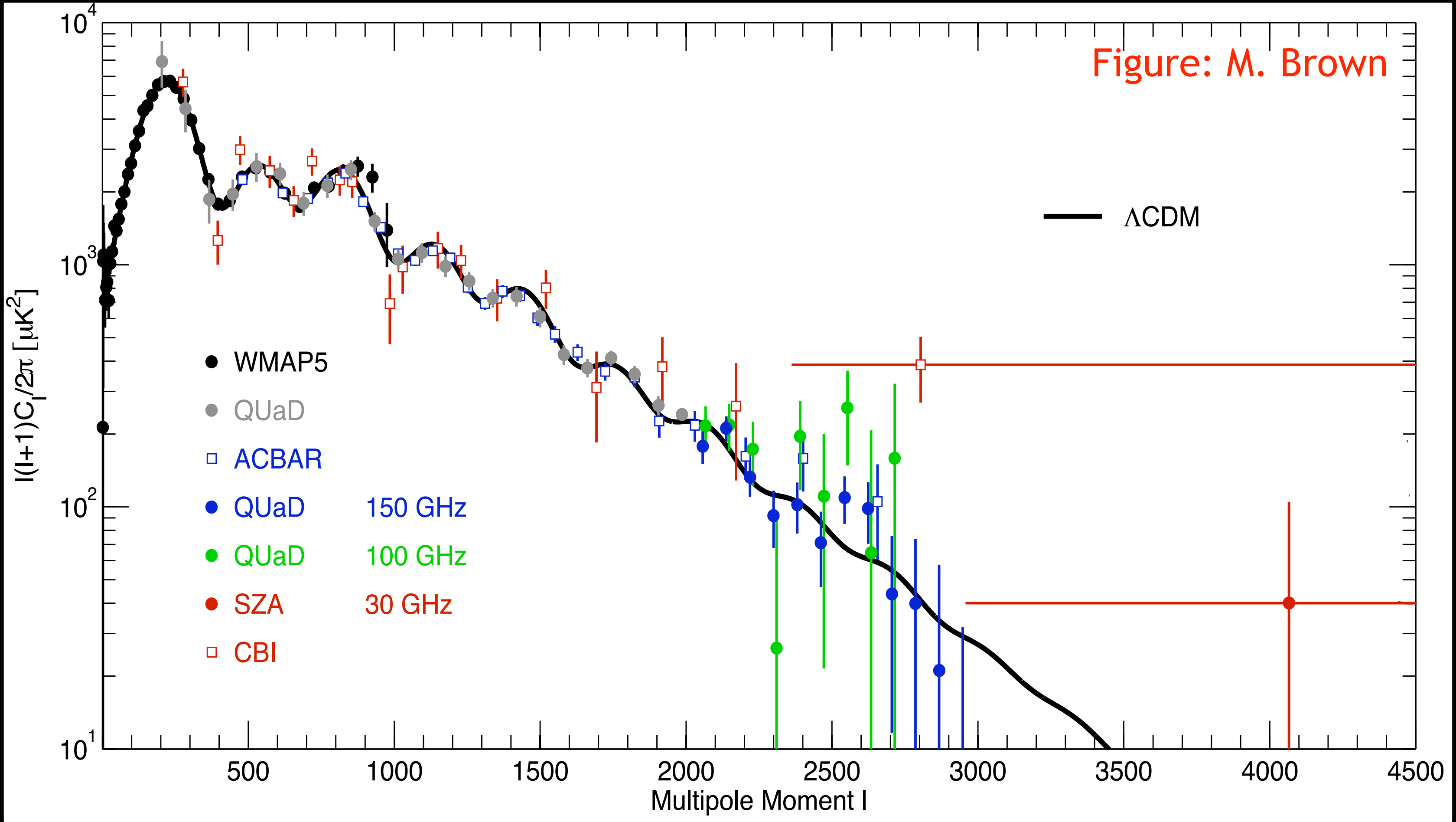
ORIGIN??

History of CMB temperature measurements



TOCO (1998) BOOMERANG (1998, 2003) MAXIMA (2000)
ARCHEOPS (2002) CBI (2002) ACBAR (2002) VSA (2002)

State of the art: temperature



- Sachs-Wolfe plateau and the late time Integrated Sachs-Wolfe effect
- Acoustic peaks at “adiabatic” locations
- Damping tail and photon diffusion
- Weak gravitational lensing (detected in cross-correlation, Smith et al. 2007)

Scalar & tensor power spectra

- For scalar perturbations (left), δ_γ oscillates $\pi/2$ out of phase with $v_\gamma \Rightarrow C_l^E$ peaks at minima of C_l^T

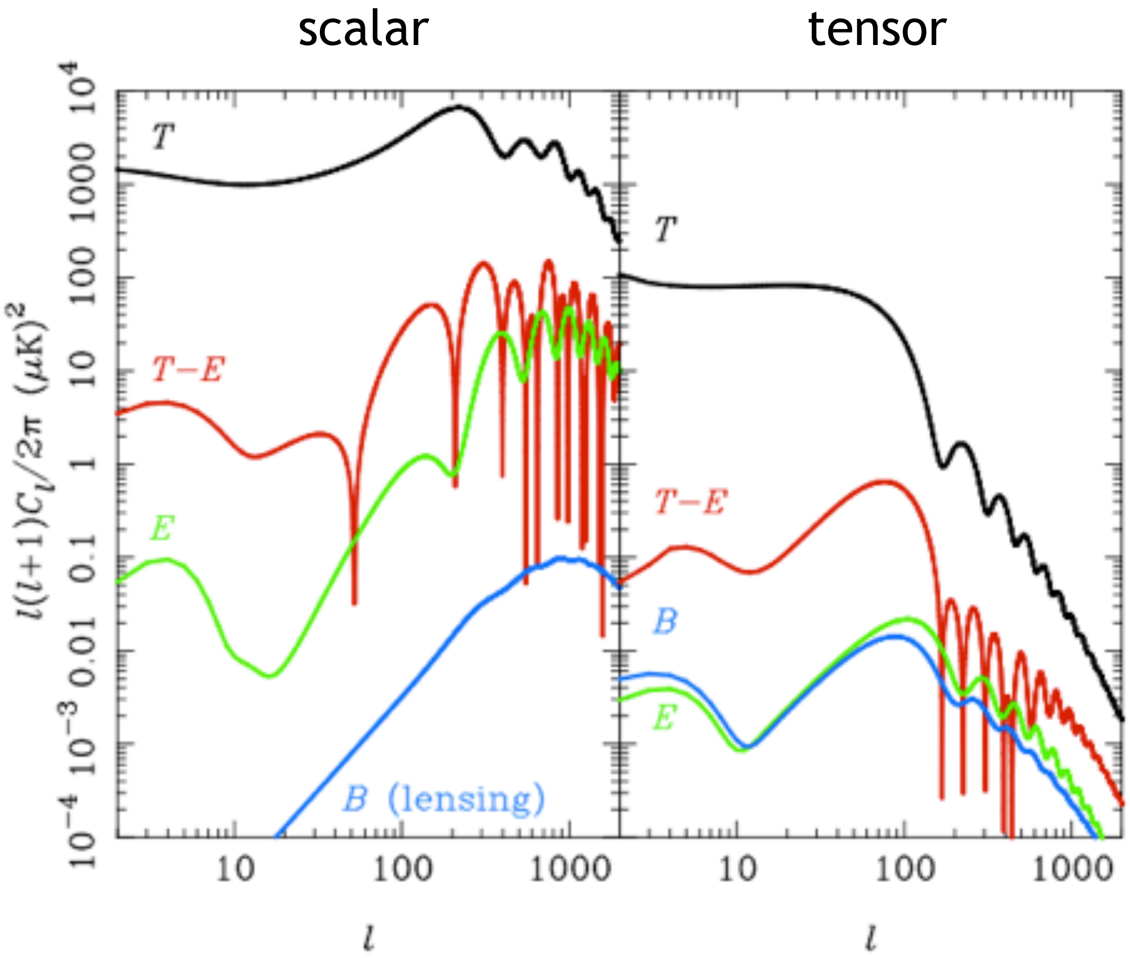
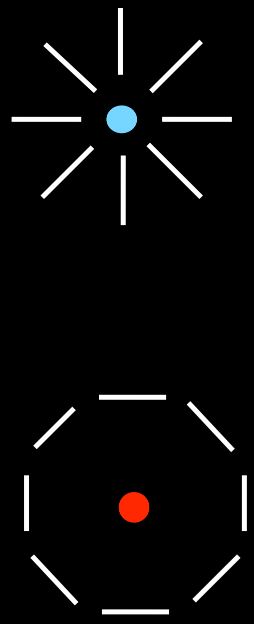


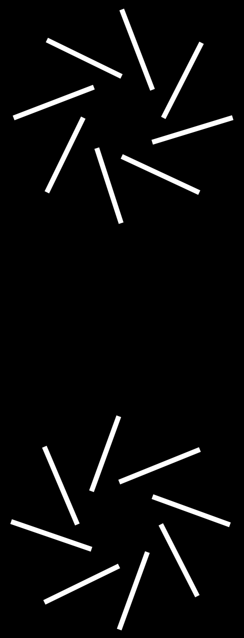
Figure: A. Challinor

Types of CMB polarization

CMB polarization can be decomposed into two orthogonal modes. E-mode is the curl-free mode (“Electric”). B-mode is the divergence-free mode (“Magnetic”).



E-mode

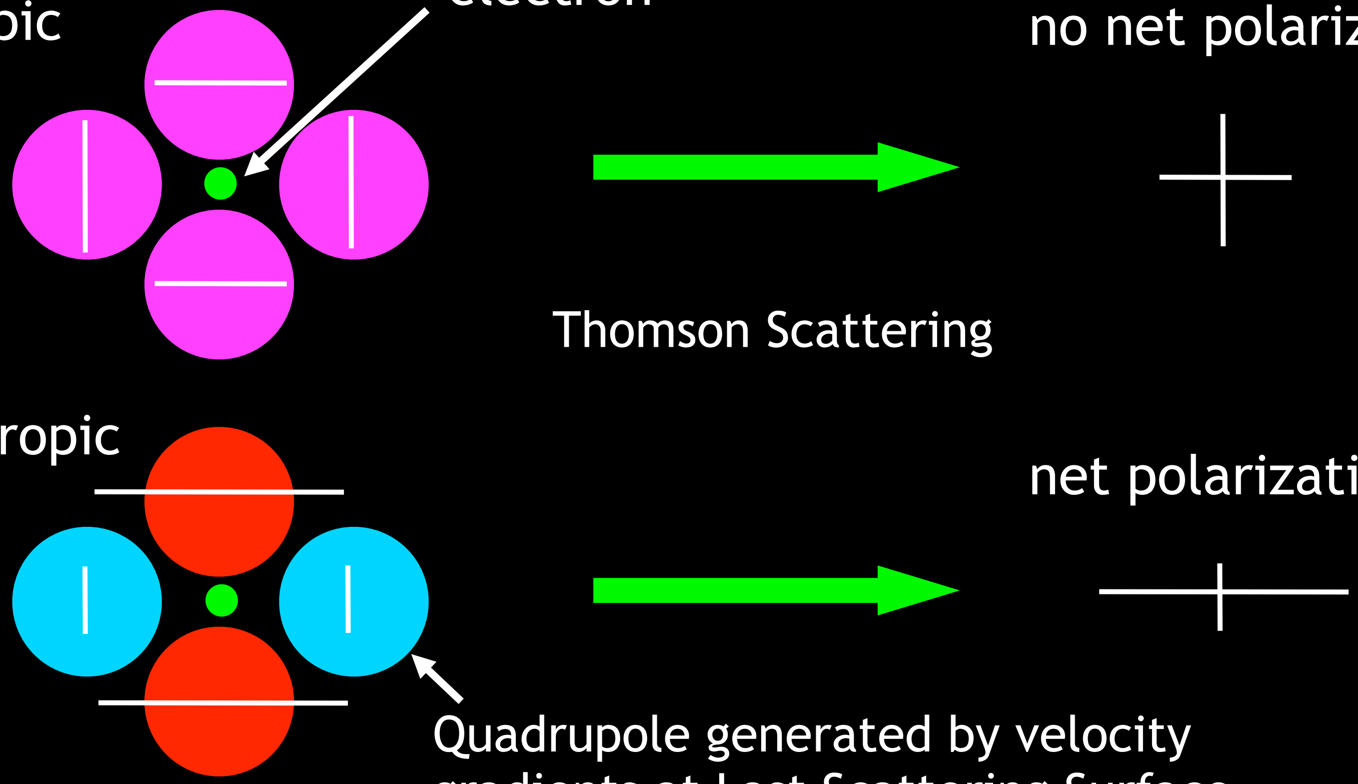


B-mode

B mode discriminates between scalar and tensor perturbations

Generation of CMB polarization

- Temperature quadrupole at the surface of last scatter generates polarization.



isotropic

electron

no net polarization

Thomson Scattering

anisotropic

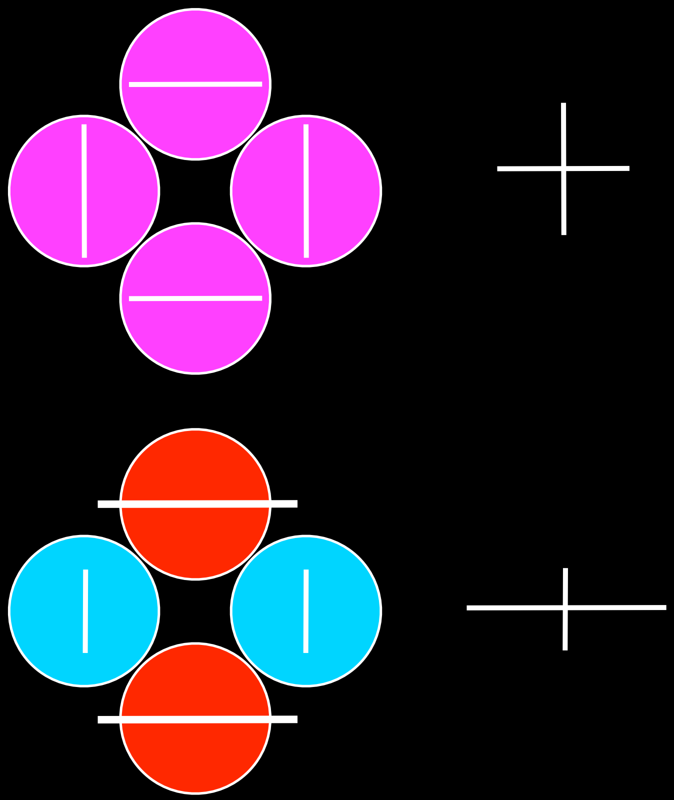
net polarization

Quadrupole generated by velocity gradients at Last Scattering Surface

Temperature-Polarization Correlation

Temperature quadrupole at
z~1089 generates polarization

Radial pattern around cold spots
Tangential pattern around hot spots



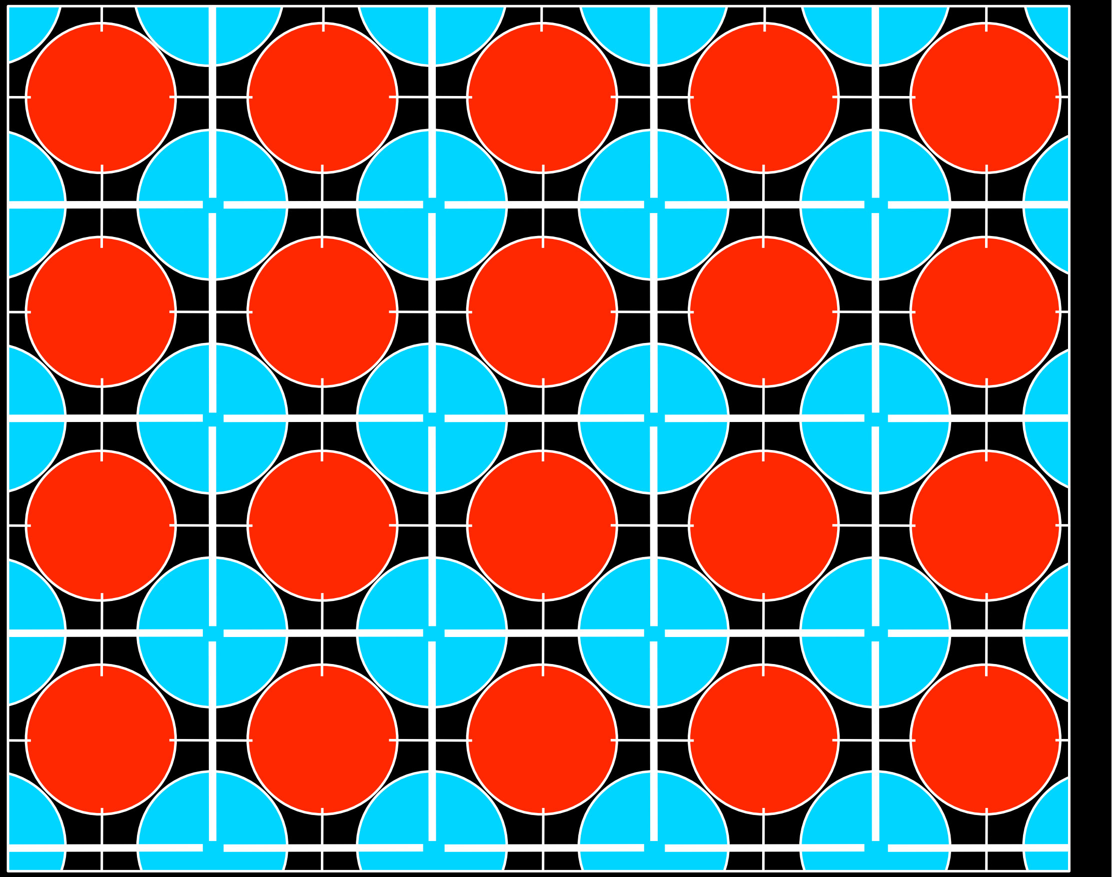


Figure: E. Komatsu

Correlated polarization in real space

- On largest scales, infall into potential wells at last scattering generates e.g. tangential polarization around large-scale hot spots
- Sign of correlation scale-dependent inside horizon

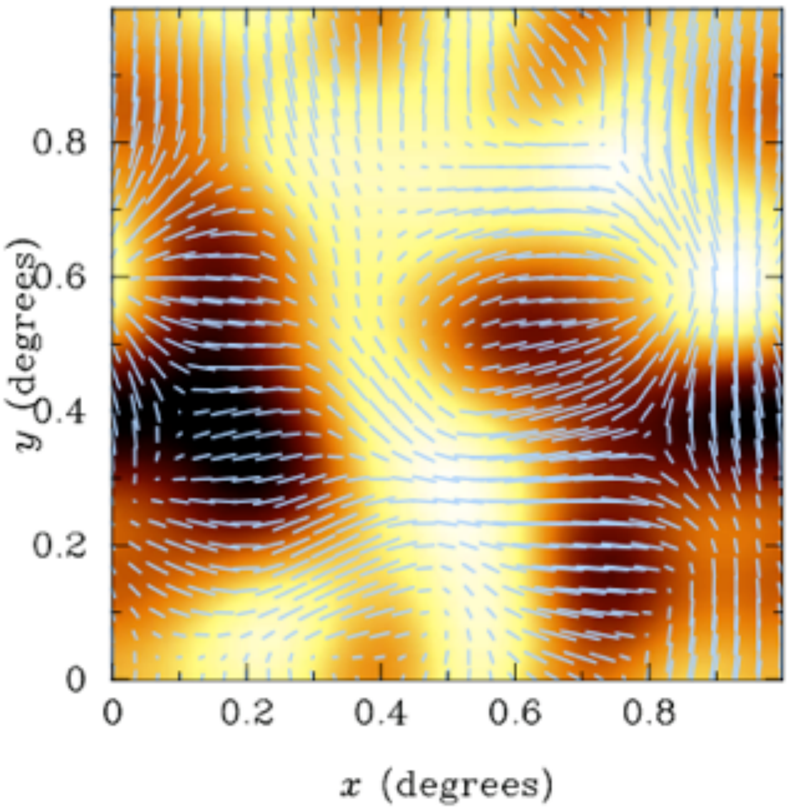


Figure: A. Challinor

Gravitational waves

- Tensor metric perturbations $ds^2 = a^2[d\eta^2 - (\delta_{ij} + h_{ij})dx^i dx^j]$ with $\delta^{ij} h_{ij} = 0$
  - Shear $\propto \dot{h}_{ij}$ gives anisotropic redshifting $\Rightarrow$

$$\Theta(\hat{\boldsymbol{n}}) \approx -\frac{1}{2} \int d\eta \, \dot{h}_{ij} \hat{n}^i \hat{n}^j$$

  - Only contributes on large scales since h_{ij} decays like a^{-1} after entering horizon

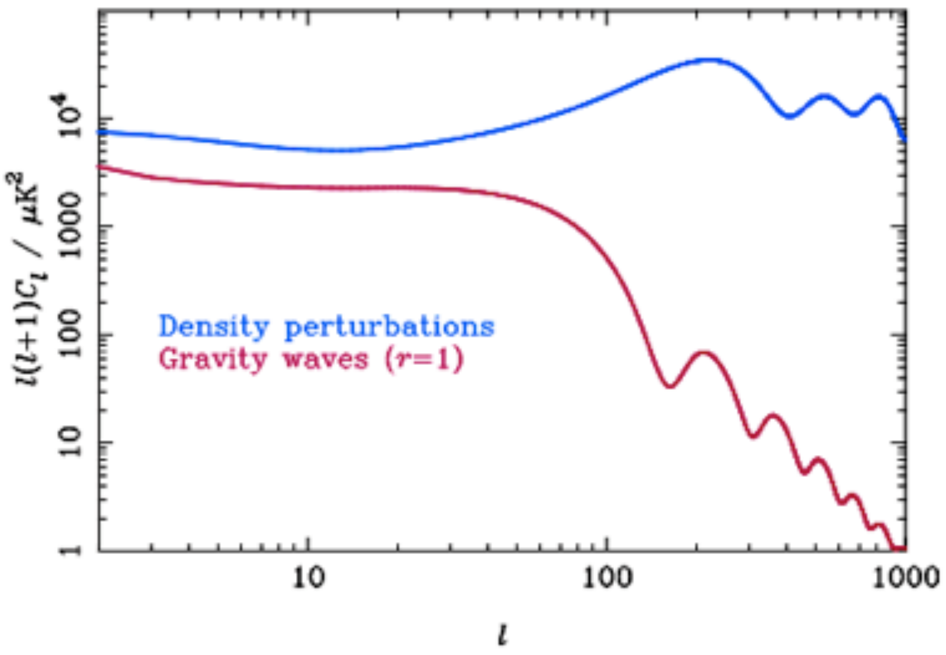
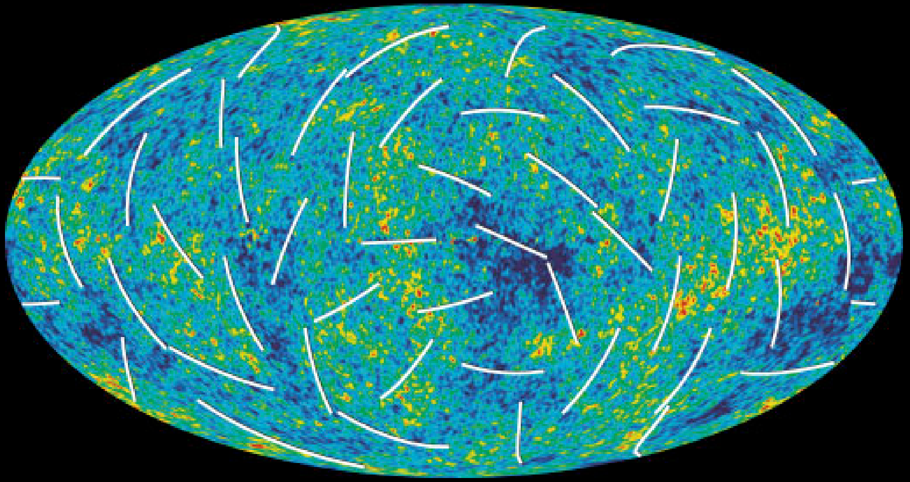


Figure: A. Challinor

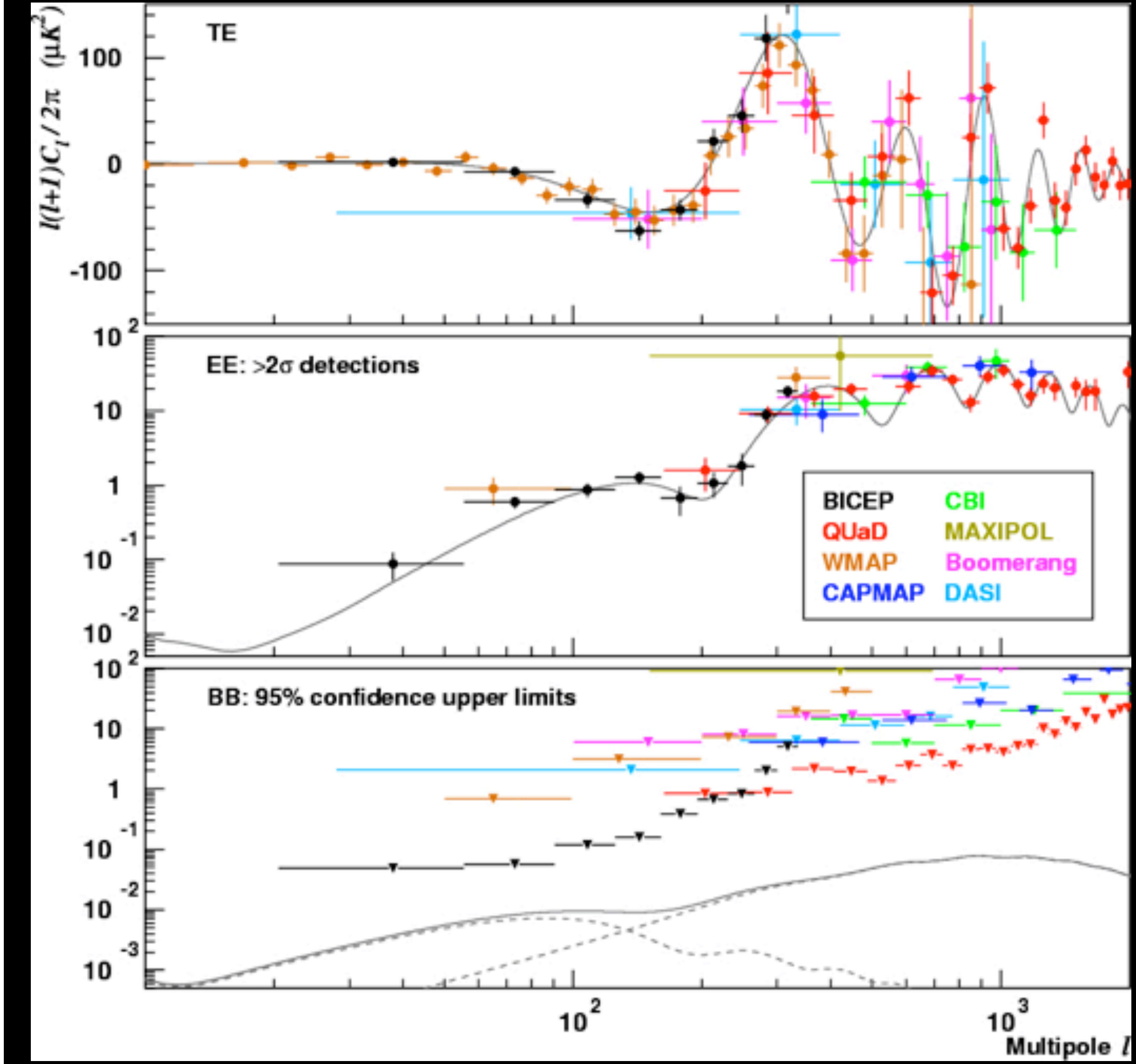
History of CMB polarization measurements



First detected by DASI in 2002

Figure: WMAP Science Team (2006)

State of the art: polarization

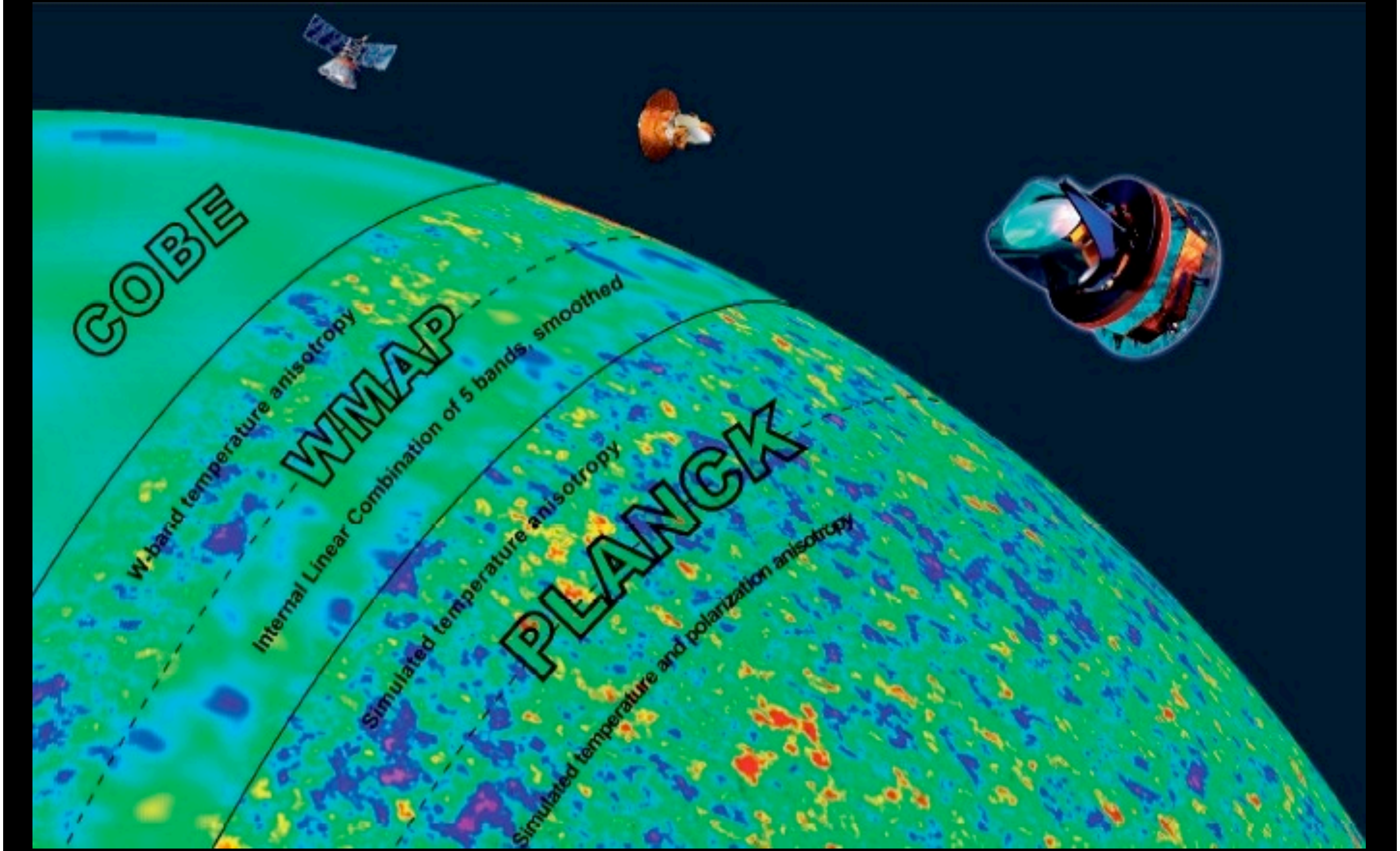


- Acoustic peaks at “adiabatic” locations
- E-mode polarization and cross-correlation with T
- Large angle polarization from reionization
- BICEP limit from BB-alone: T/S < 0.73 (95% CL)

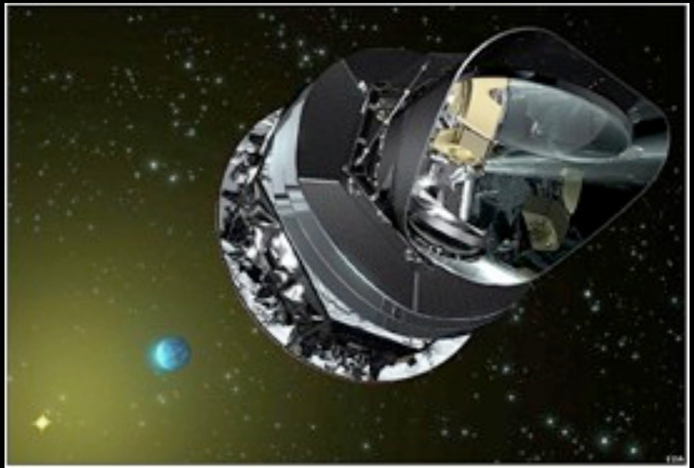
Figure: Chiang et al. (2009)

Planck:

THE NEXT GENERATION



Planck



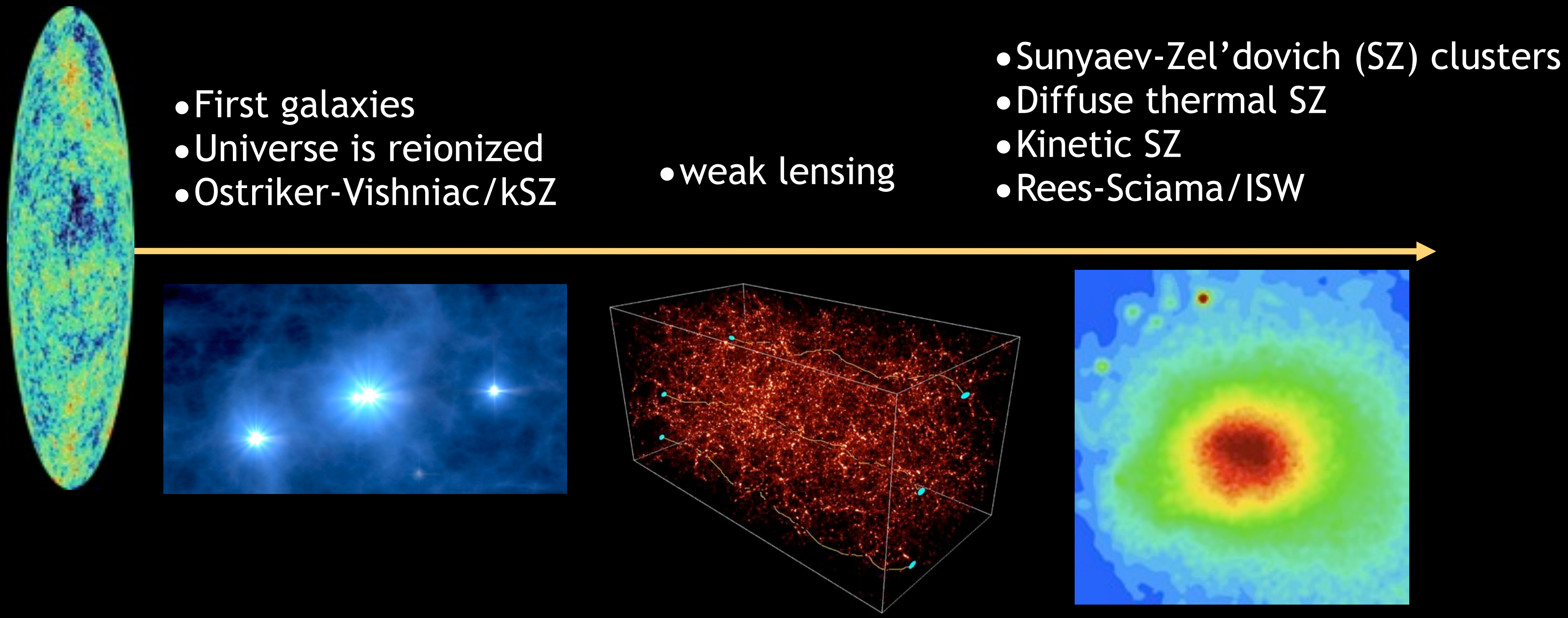
ESA

Extract essentially all information in primary CMB temperature anisotropy; big advance in polarization measurements.

What's next?

Next frontier: secondary anisotropies

Use the CMB as a backlight to illuminate the growth of cosmological structure.



- First galaxies
- Universe is reionized
- Ostriker-Vishniac/kSZ

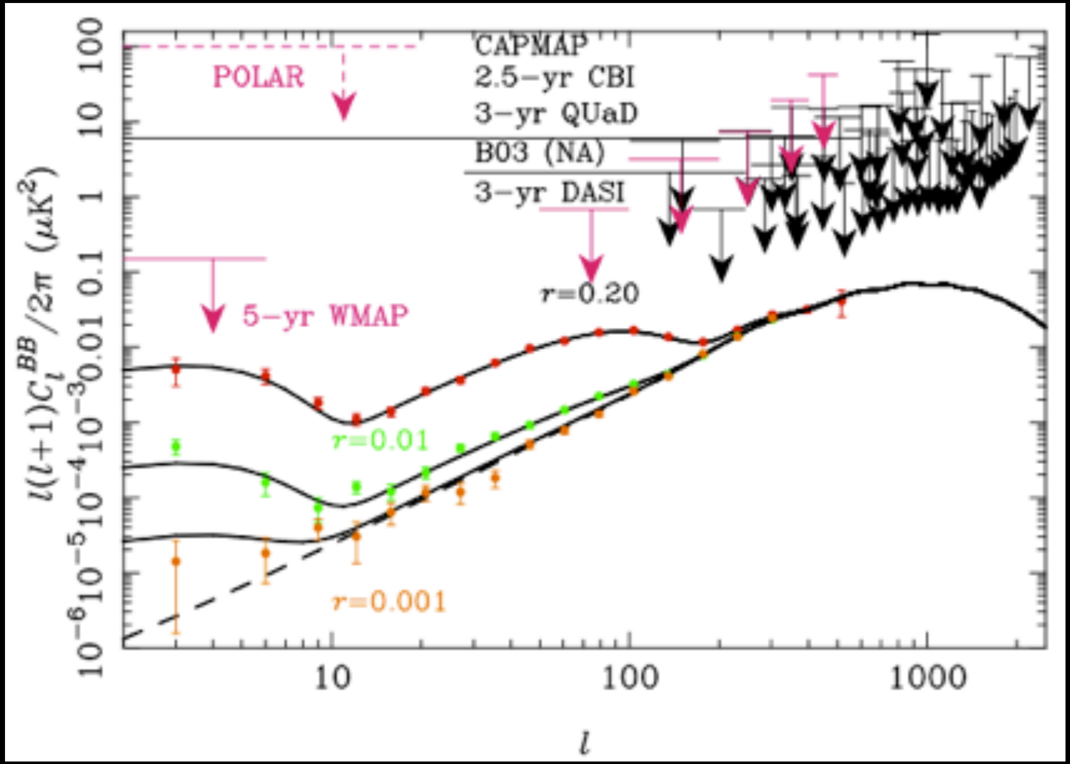
- weak lensing

- Sunyaev-Zel'dovich (SZ) clusters
- Diffuse thermal SZ
- Kinetic SZ
- Rees-Sciama/ISW

Watch this space because experiments like South Pole Telescope & Atacama Cosmology Telescope are well under way.

Figure: L. Verde

Next frontier: polarization



- B-mode polarization circumvents cosmic variance from dominant linear density perturbations; current upper limits (e.g. BICEP) same ballpark as from TT.

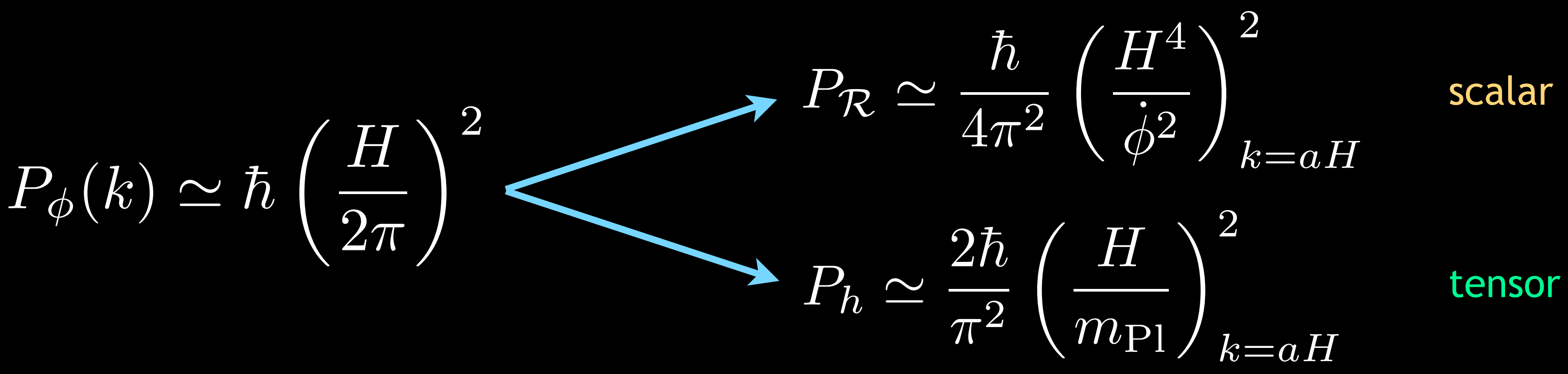
- Next generation (SPIDER, EBEX, QUIET etc) targeting T/S>0.01.

- Requires exquisite control of systematics and removal of polarized Galactic foregrounds.

Figure: A. Challinor

Inflation

- Solves the flatness/horizon problems if the early universe inflates by factor ~10^{30}.
- Cosmological perturbations arise from quantum fluctuations, evolve classically.



$$P_\phi(k) \simeq \hbar \left(\frac{H}{2\pi}\right)^2$$

$$P_{\mathcal{R}} \simeq \frac{\hbar}{4\pi^2} \left(\frac{H^4}{\dot\phi^2}\right)^2_{k=aH}$$

scalar

$$P_h \simeq \frac{2\hbar}{\pi^2} \left(\frac{H}{m_{\rm Pl}}\right)^2_{k=aH}$$

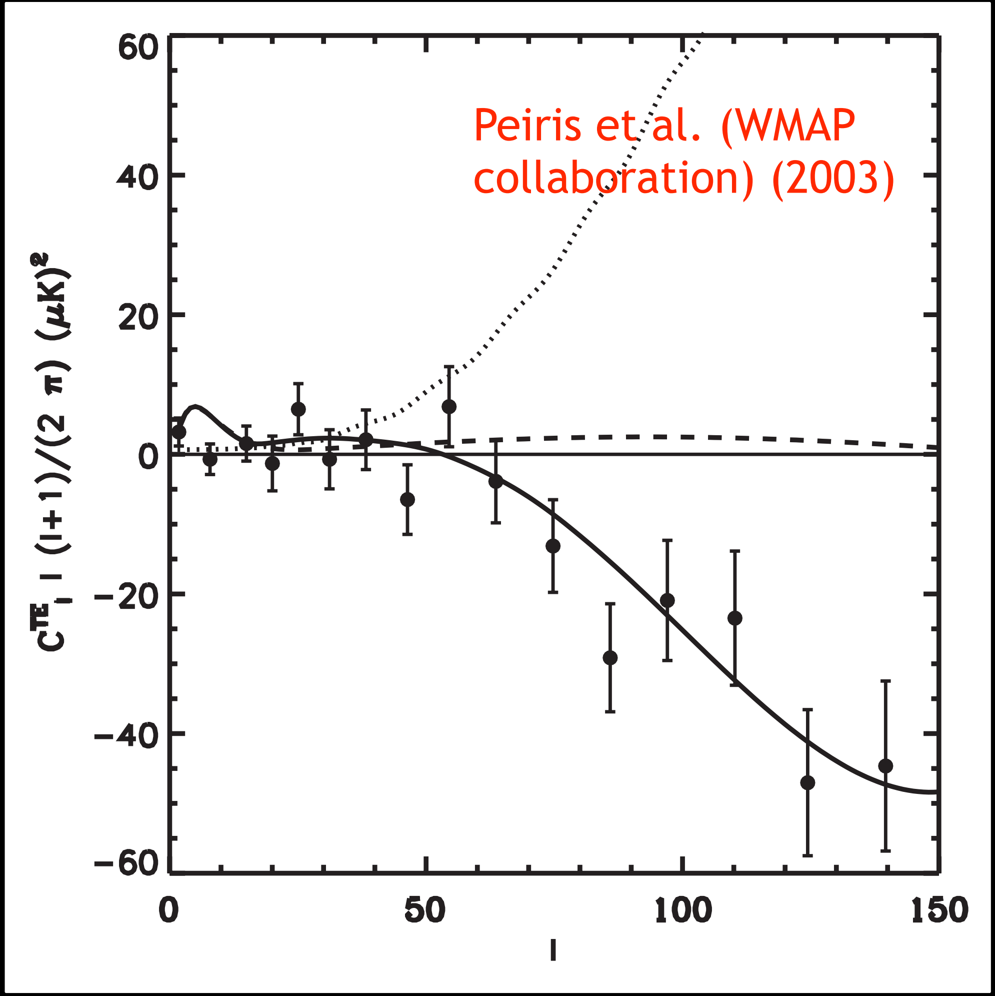
tensor

- Don’t know the dynamics of inflation: parameterize weakly scale-dependent functions with a few numbers to pin down observationally.

$$P_{\mathcal{R}}(k) \simeq A_s \left(\frac{k}{k_0}\right)^{n_s-1} \qquad P_h(k) \simeq A_t \left(\frac{k}{k_0}\right)^{n_t} \qquad r = \frac{P_h(k_0)}{P_{\mathcal{R}}(k_0)}$$

Slow roll inflation consistent with WMAP+

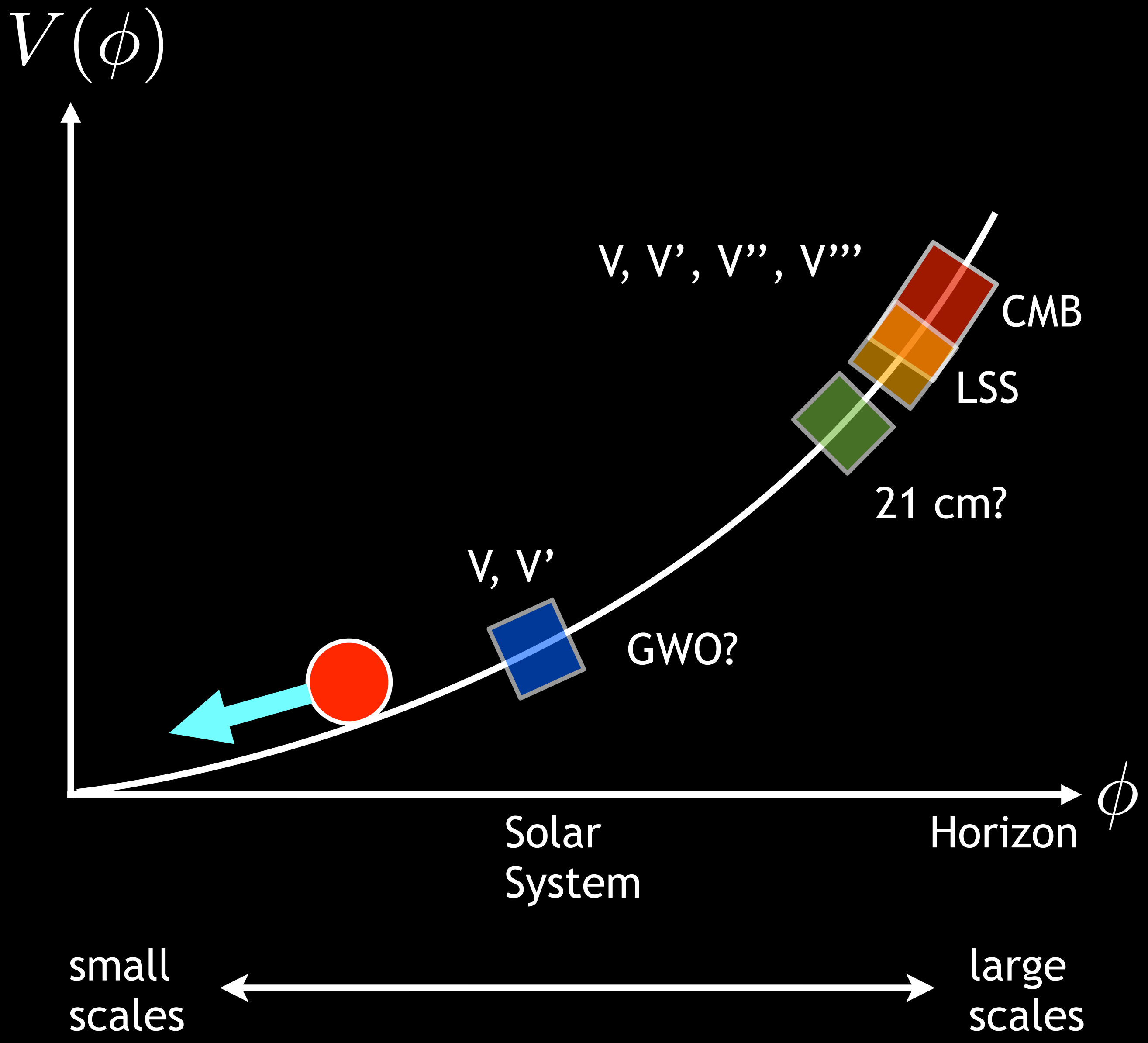
- Superhorizon, adiabatic fluctuations
  - T and E anticorrelated at superhorizon scales
- Flatness tested to 1%.
- Gaussianity tested to 0.1%.
- nearly scale-invariant fluctuations
  - red tilt indicated at ~2.5 σ



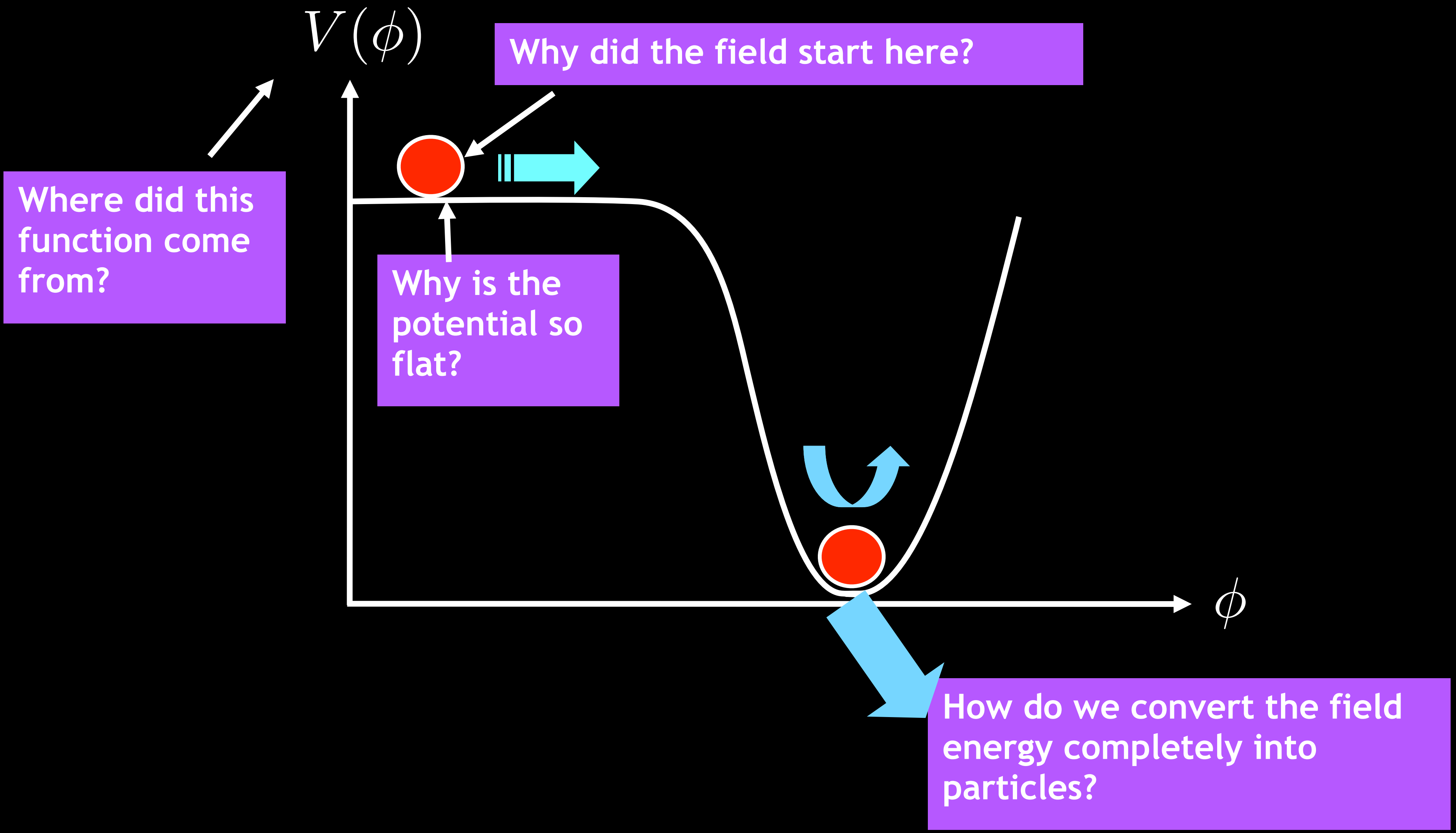
- Still testing basic aspects of inflationary mechanism rather than specific implementation.

Spergel, Verde, Peiris et al. (2003), Komatsu et al. (2003), Peiris et al. (2003), Spergel et al (WMAP Collaboration) (2006), Dunkley et al & Komatsu et al (WMAP Collaboration) (2008)

Fingerprints of the early universe



What is the physics of inflation?



Why did the field start here?

Where did this function come from?

Why is the potential so flat?

How do we convert the field energy completely into particles?

Primordial gravitational waves: a smoking gun

- Temperature only sensitive to scalars. Polarization can differentiate between scalars (density) and tensors (gravitational waves).

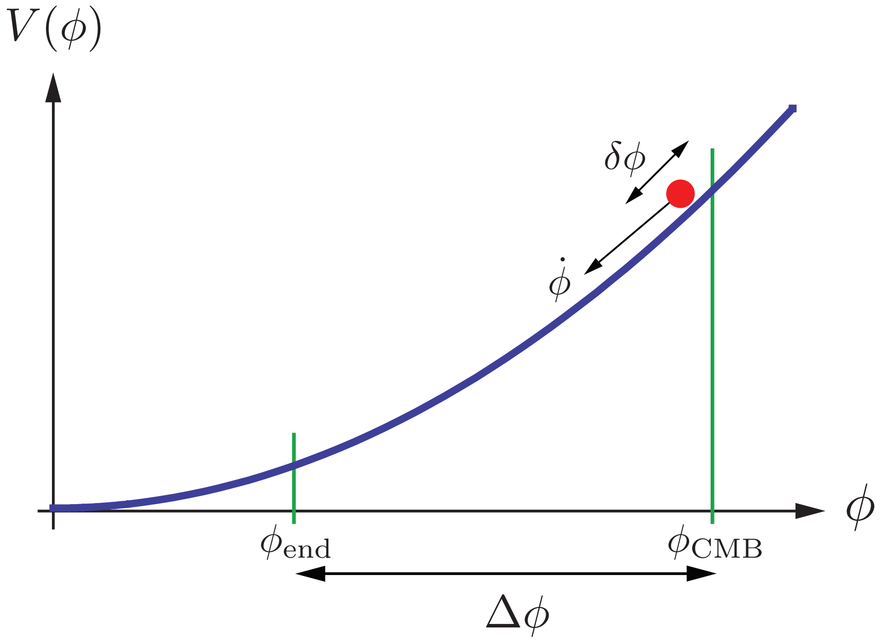
- Current limit $r_{\rm CMB} < 0.2$. "Realistically" observable: $r_{\rm CMB} \geq 0.01$

- Measurement gives two critical pieces of info:

  -energy scale of inflation: $V^{1/4} \sim \left(\frac{r_{\rm CMB}}{0.01}\right)^{1/4} 10^{16}\ {\rm GeV}$

  -super-Planckian field variation: $\frac{\Delta\phi}{M_{\rm Pl}} > \mathcal{O}(1)\left(\frac{r_{\rm CMB}}{0.01}\right)^{1/2}$

Large field inflation



- Important class of models where inflaton is driven by e.g. a monomial potential:

$$V(\phi) \sim \phi^p$$

- Field evolves over a super-Planckian distance during inflation: $\Delta\phi > M_{\mathrm{Pl}}$

- Large amplitude of gravitational waves produced by QM fluctuations.

Image: D. Baumann

Lyth Bound

In a de Sitter spacetime,

tensors: $P_h \propto \dfrac{H^2}{M_{\rm Pl}^2}$ scalars: $P_s \propto H^2 \left(\dfrac{H}{\dot{\phi}}\right)^2$

tensor to scalar ratio: $r \equiv \dfrac{P_h}{P_s} = 8\left(\dfrac{1}{M_{\rm Pl}}\dfrac{d\phi}{dN_e}\right)^2$

where $dN_e \equiv d\ln a = H\,dt = \left(\dfrac{H}{\dot{\phi}}\right) d\phi$

field variation relates to tensor signal: $\dfrac{\Delta\phi}{M_{\rm Pl}} = \displaystyle\int_{\phi_{\rm end}}^{\phi_{\rm CMB}} dN_e \sqrt{\frac{1}{8} r(N_e)}$

Useful if this can be computed from a microscopic theory!

Useful if this can be constrained via observations!

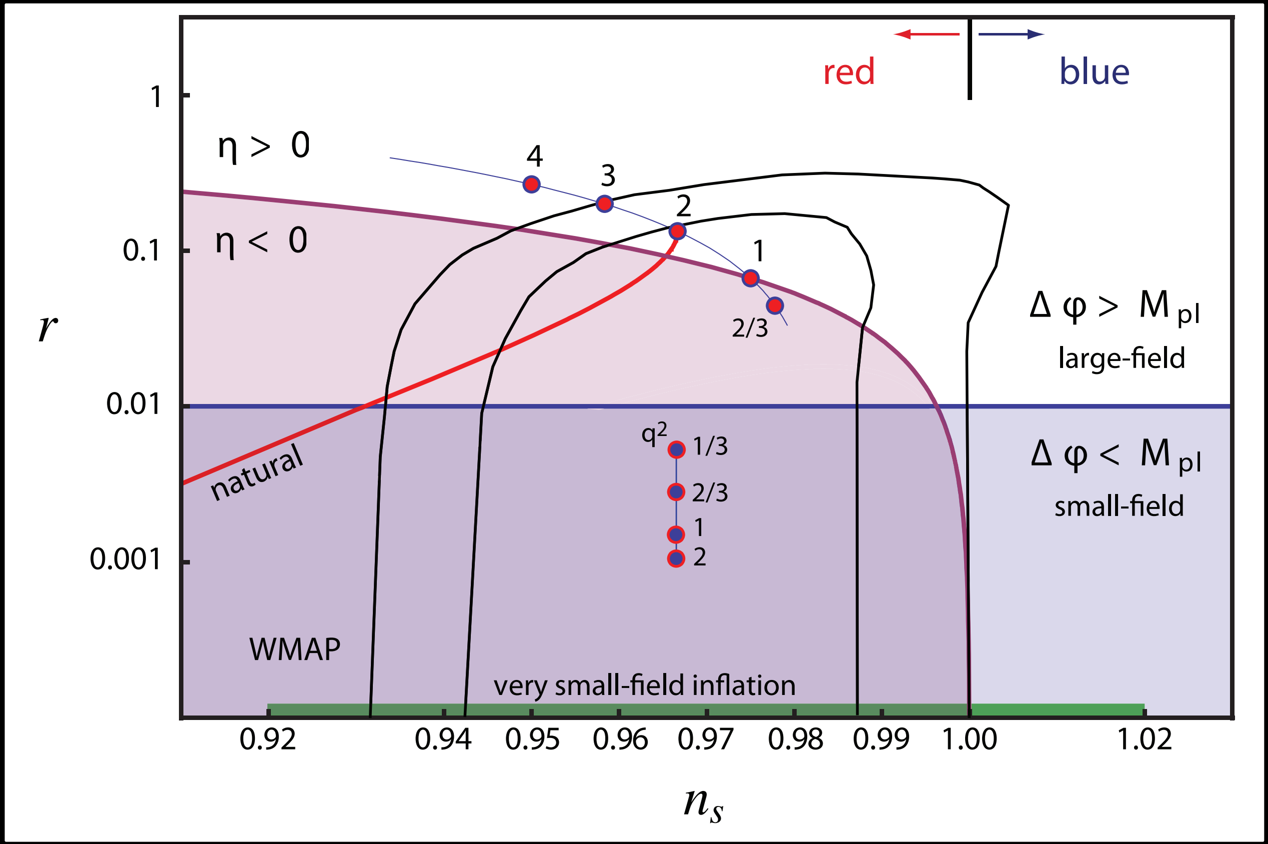
Lyth (1996)

Primordial gravitational waves: the challenges

Gravity's waves are
Traceless; which does not mean they
Can never be found.

Haiku by Peter Coles

Challenge I: what is the amplitude?

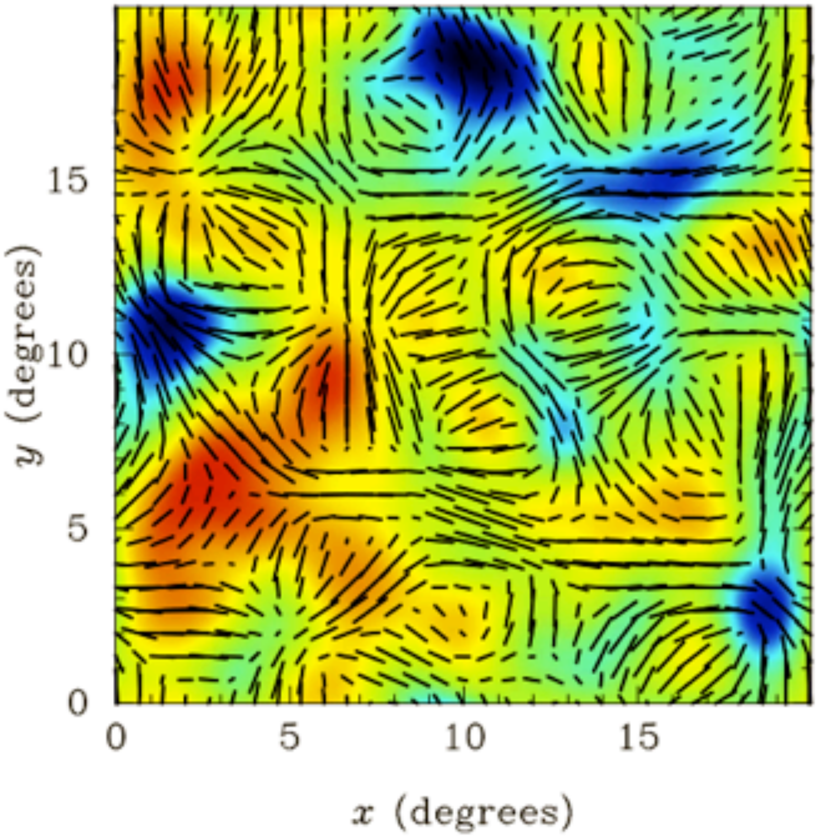


- r determines whether model is large or small field.
- n_s determines whether spectrum is red or blue.
- a combination of n_s and r determines the curvature of the potential η.

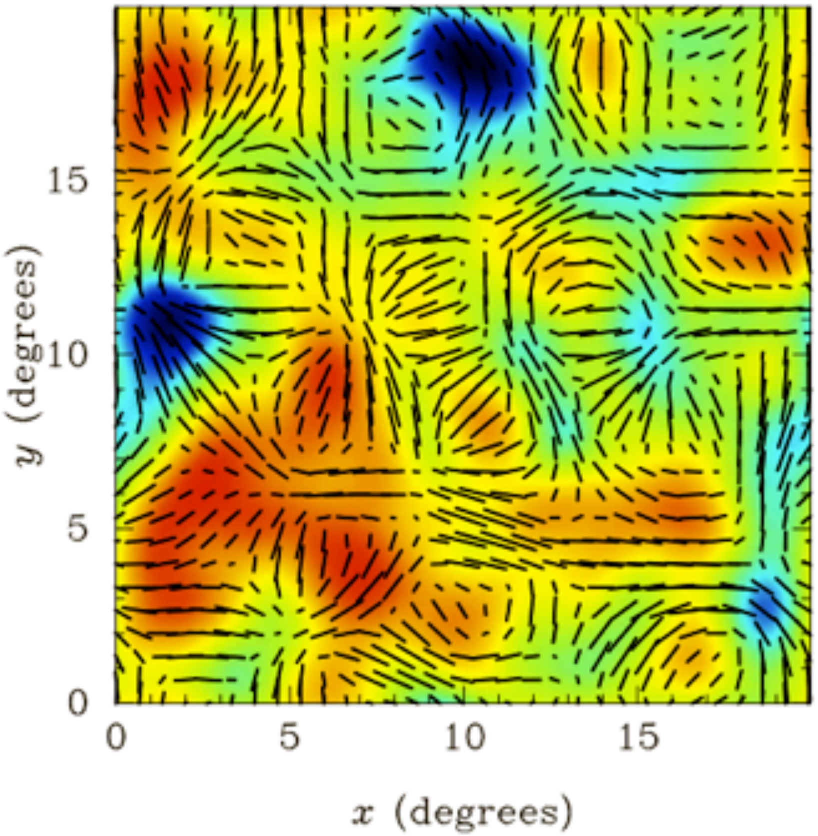
Figure: D. Baumann / CMBPol Mission Study (amended by HVP)

Tensors: B-mode contribution is small!

- R.m.s. B-mode signal from gravity waves $< 200\,\mathrm{nK}$



$r = 0.28$



$r = 0.0$

Figure: A. Challinor

Relative Amplitudes of CMB power spectra

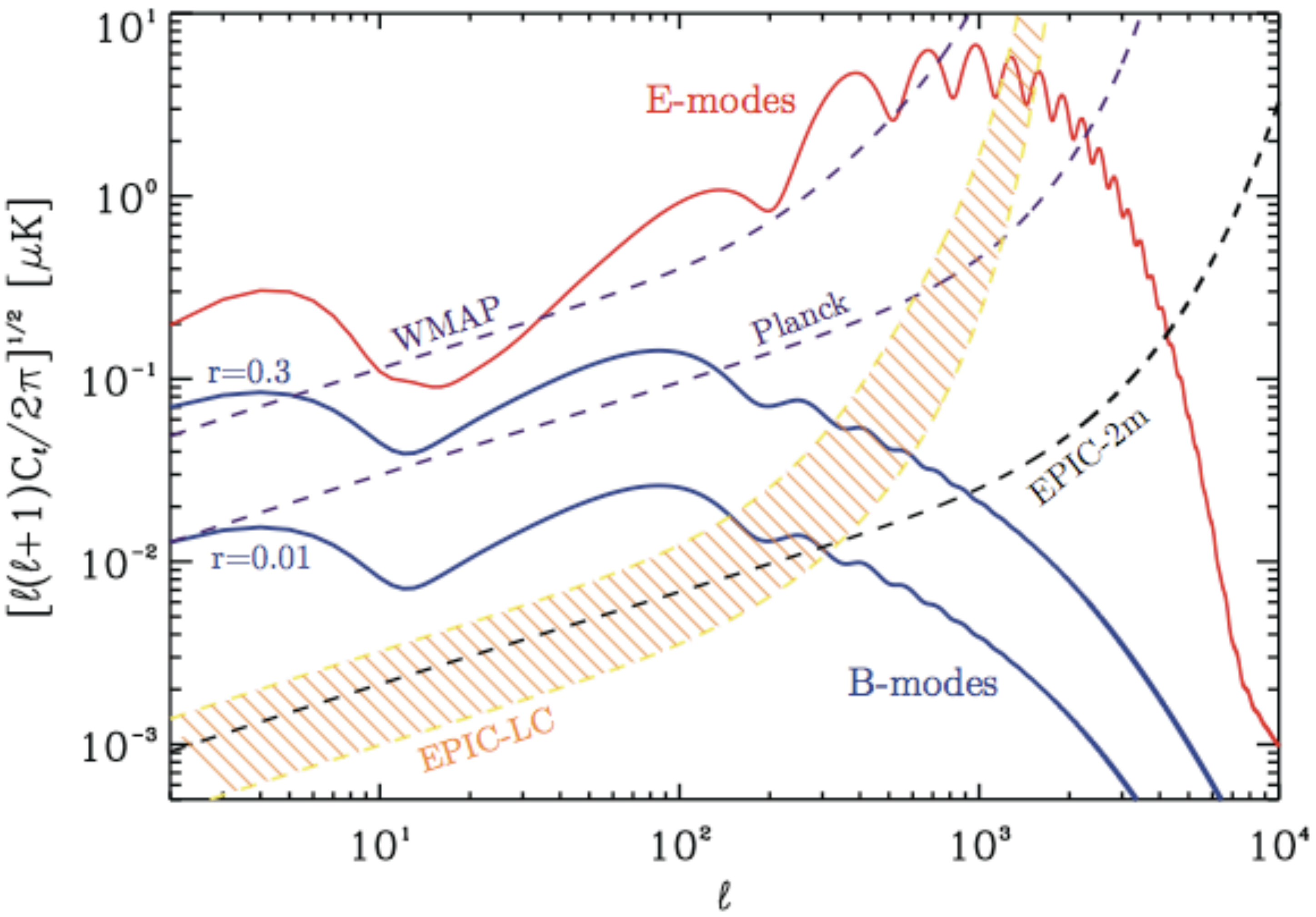


Figure: CMBpol Mission Concept Study

Challenge II: Weak Lensing

- Generated by weak lensing of the E-mode by large scale structure; subdominant on large scales, dominates on small scales. (Seljak & Zaldarriaga 1998)

- Use cross-correlation/ map non-Gaussianity to "de-lens"? (Okamoto & Hu/Lewis/Knox & Song/Smith)

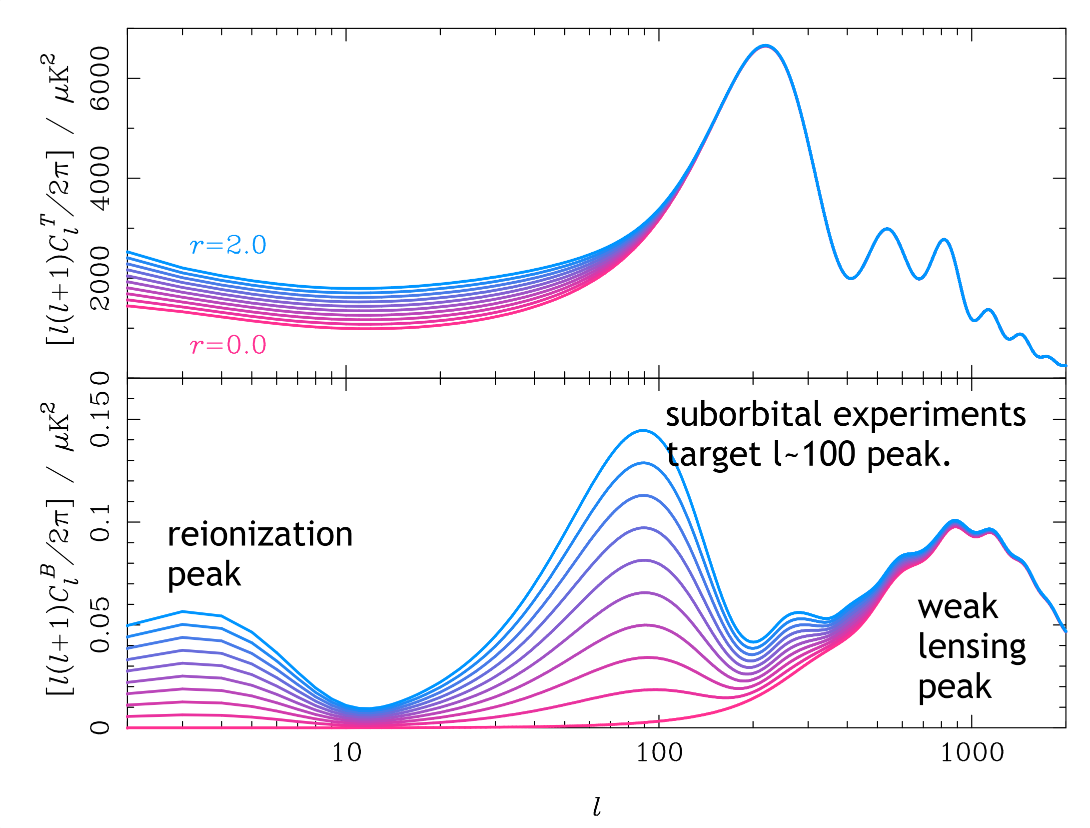


Figure: A. Challinor via A. Jaffe.

Challenge III: Detectors

- Polarization-sensitive bolometers
  - Good above ~ 100 GHz. (e.g. BOOMERanG, DASI)

- HEMT polarimeters
  - Good below ~100 GHz (e.g. WMAP)

Limited by photon shot noise
$$\Delta T_{\rm rms} = \frac{T_{\rm RMS} + T_{\rm receiver}}{\sqrt{\Delta\nu\Delta t}}$$

Need detector arrays to beat down noise limit/detector

Wide frequency coverage to keep foregrounds in check

} heavy!

low l lensing-free → large sky coverage

systematic control → stability

} Space → weight restrictions!

Challenge IV: we live inside a galaxy!

RMS polarized Galactic emission at 1 deg.

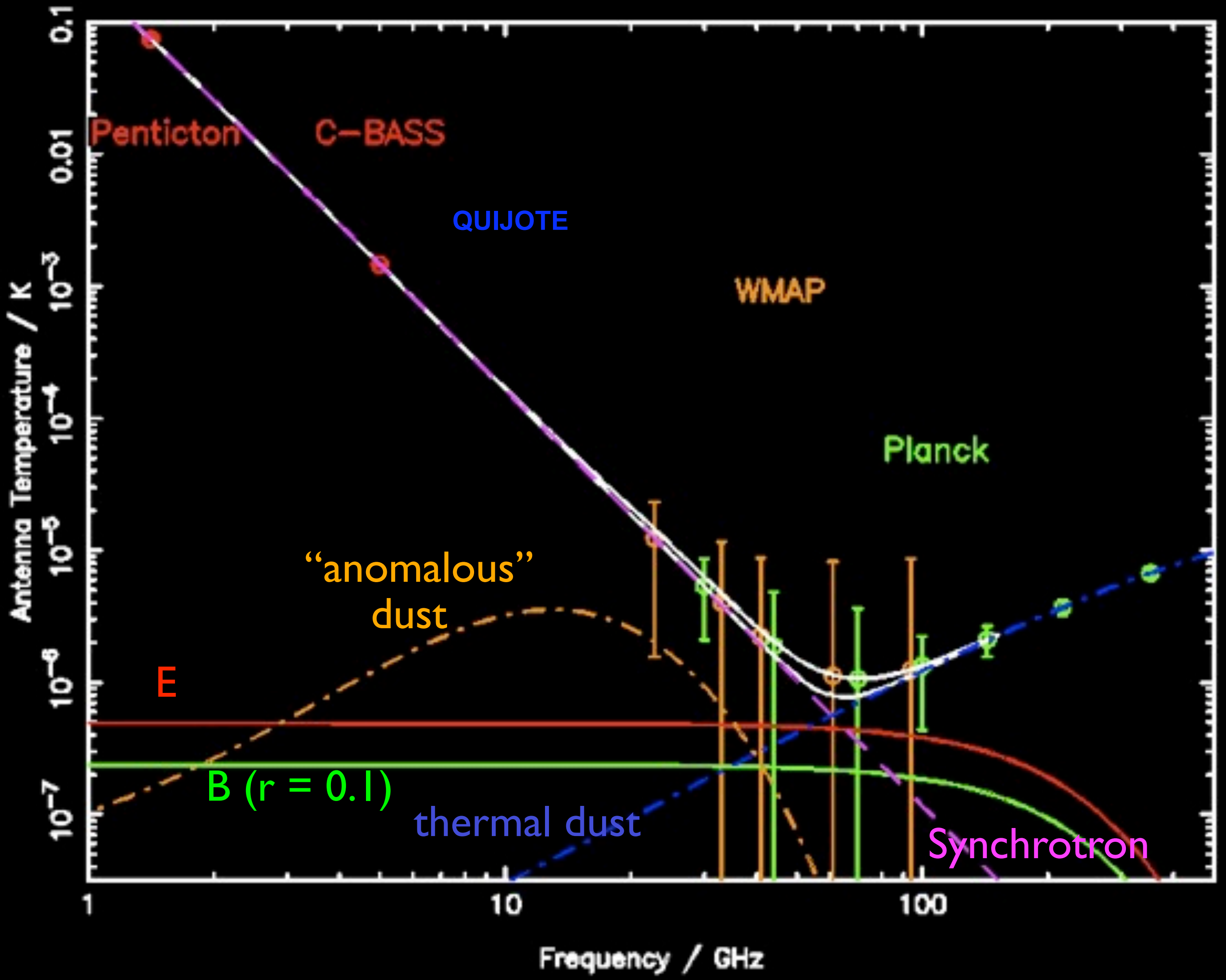
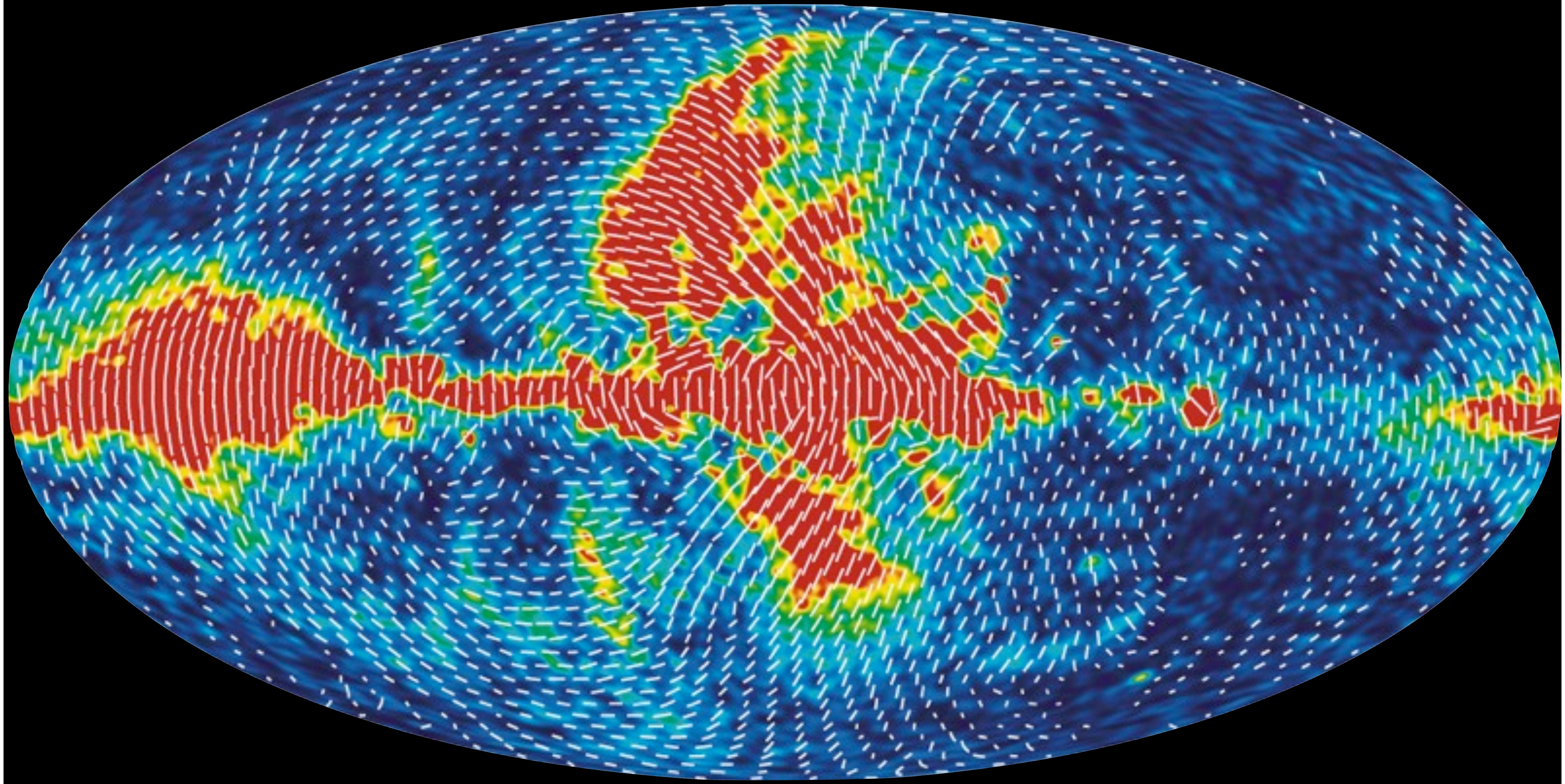


Figure: P. Leahy via A. Jaffe

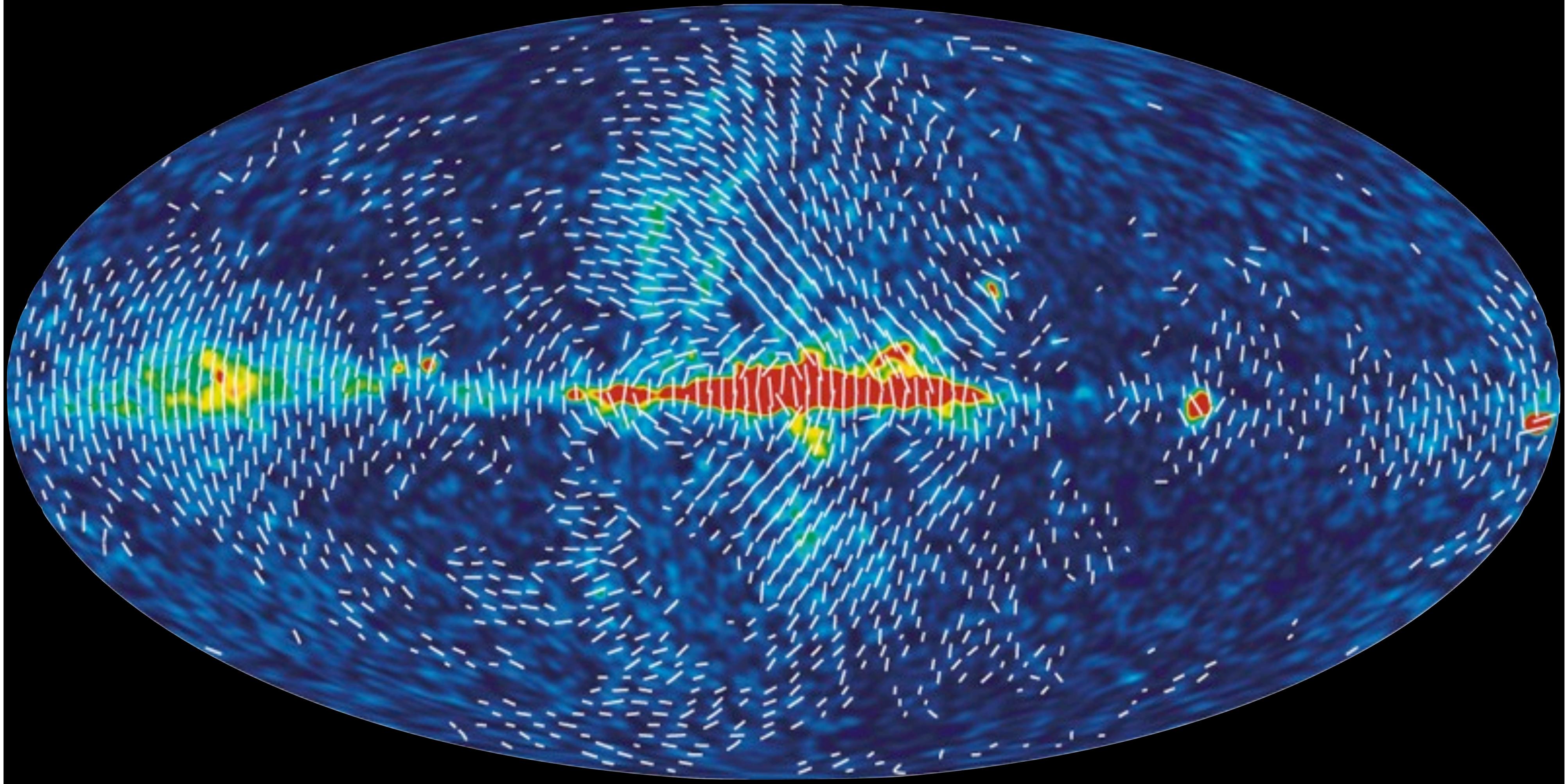
K Band (23 GHz)



Dominated by synchrotron. Note polarization direction perpendicular to magnetic field lines.

Figure: WMAP Science Team (2008)

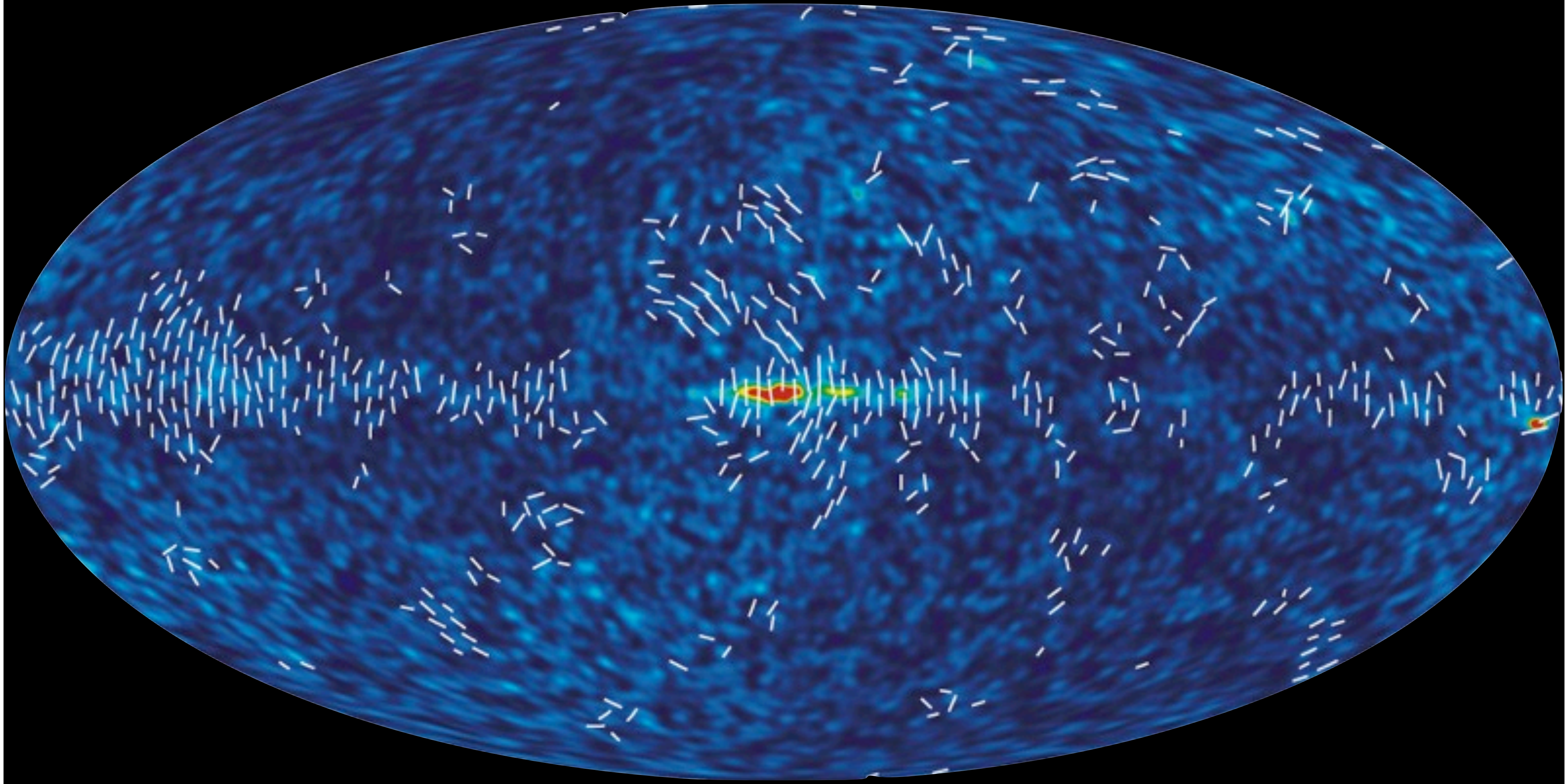
Ka Band (33 GHz)



Synchrotron drops as $\nu^{-3.2}$ from K to Ka.

Figure: WMAP Science Team (2008)

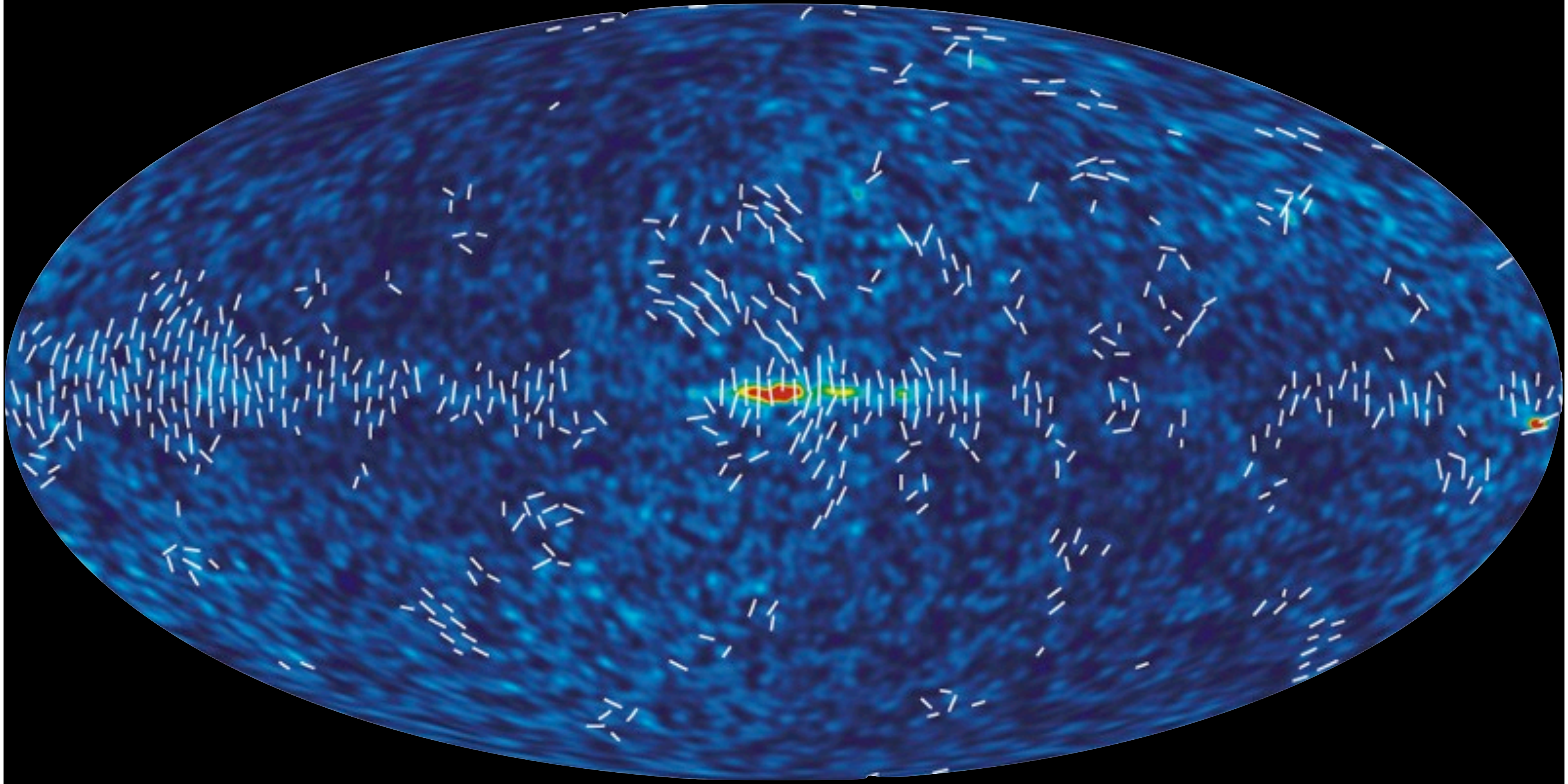
V Band (61 GHz)



Polarized FG emission is lowest in V band (notice noise is larger in ecliptic plane).

Figure: WMAP Science Team (2008)

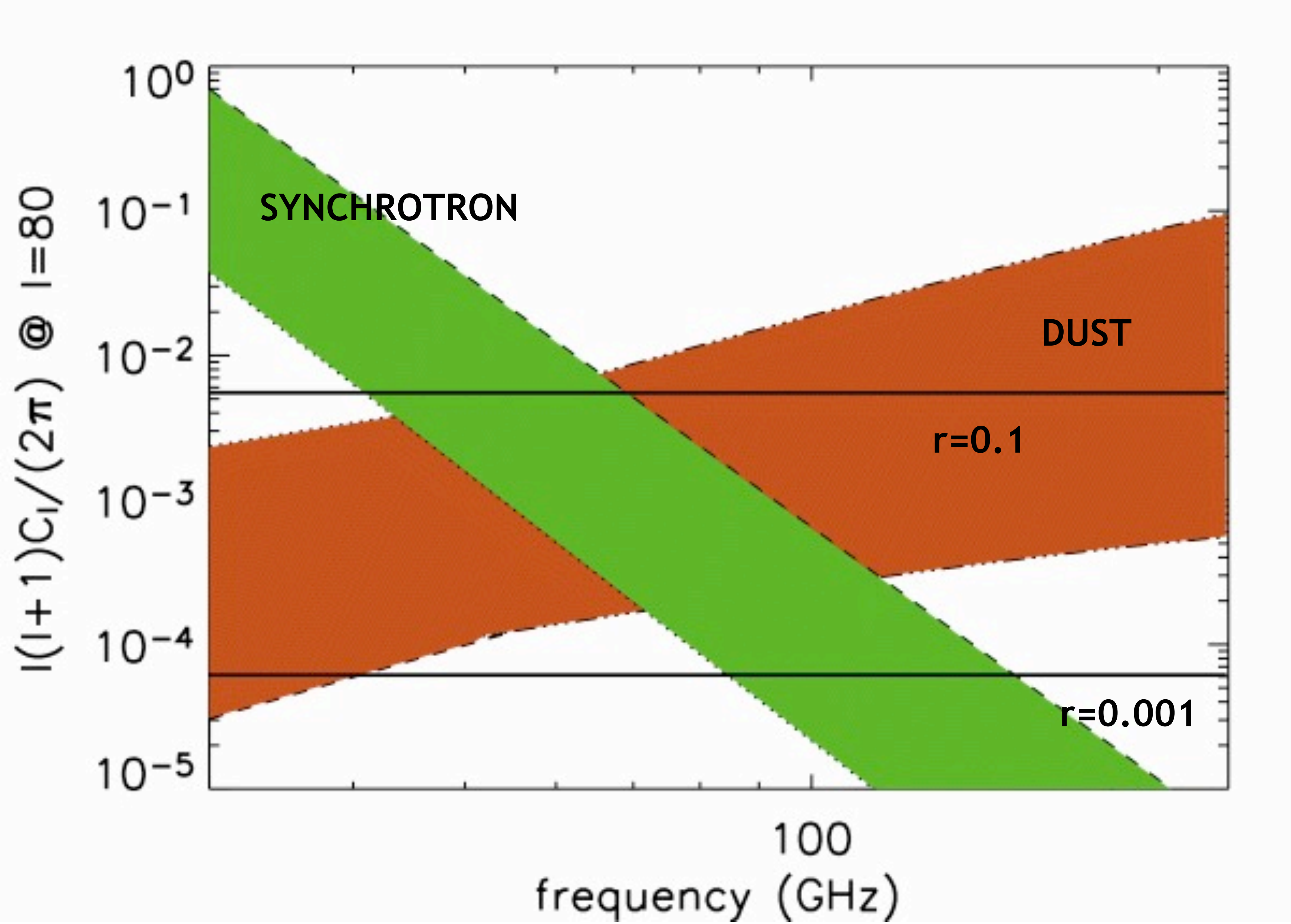
W Band (94 GHz)



Synchrotron smallest in W band, but there may be polarized dust contamination.

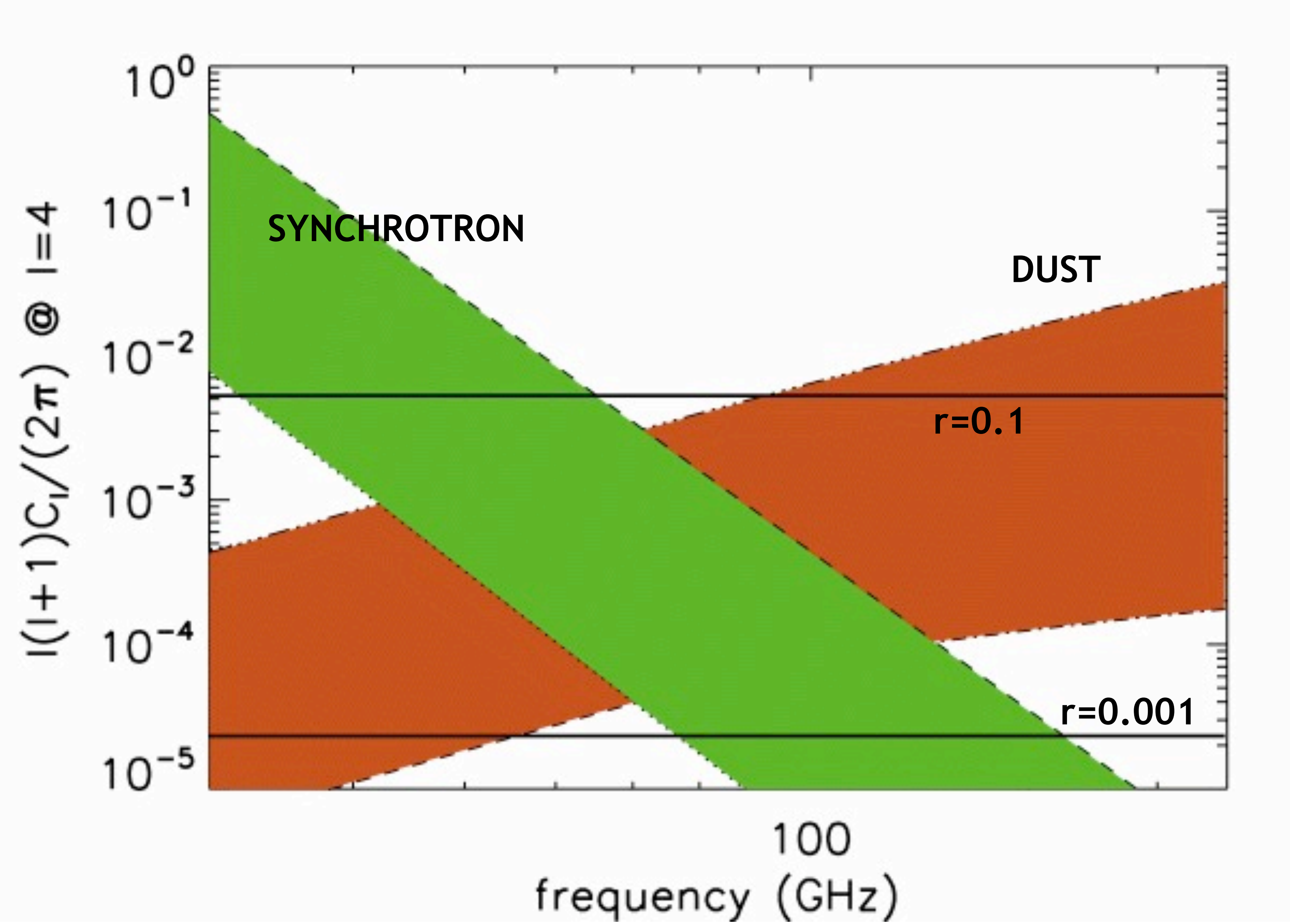
Figure: WMAP Science Team (2008)

Foreground uncertainties vs CMB at l=80



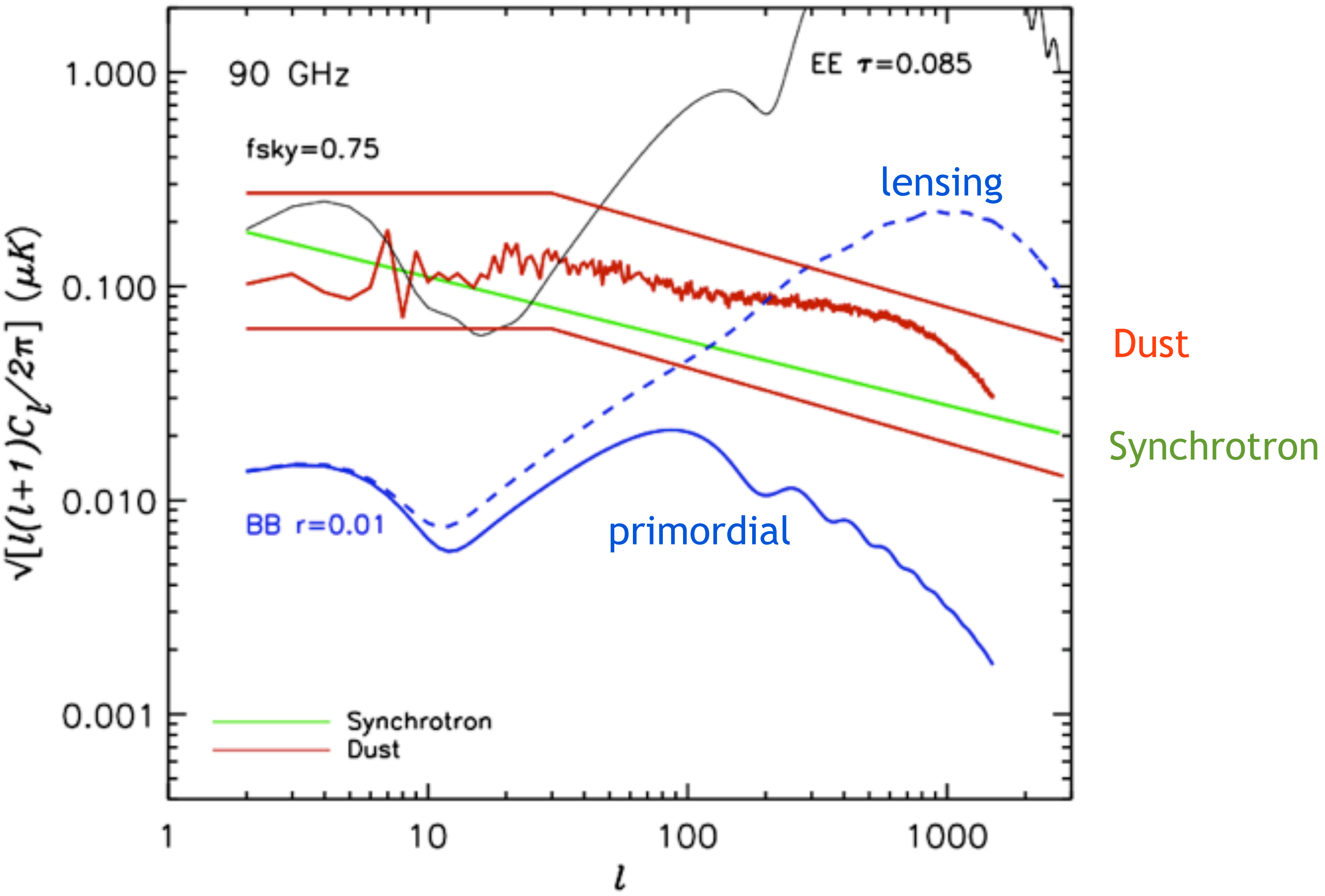
Verde, HVP & Jimenez (2005)

Foreground uncertainties vs CMB at l=4



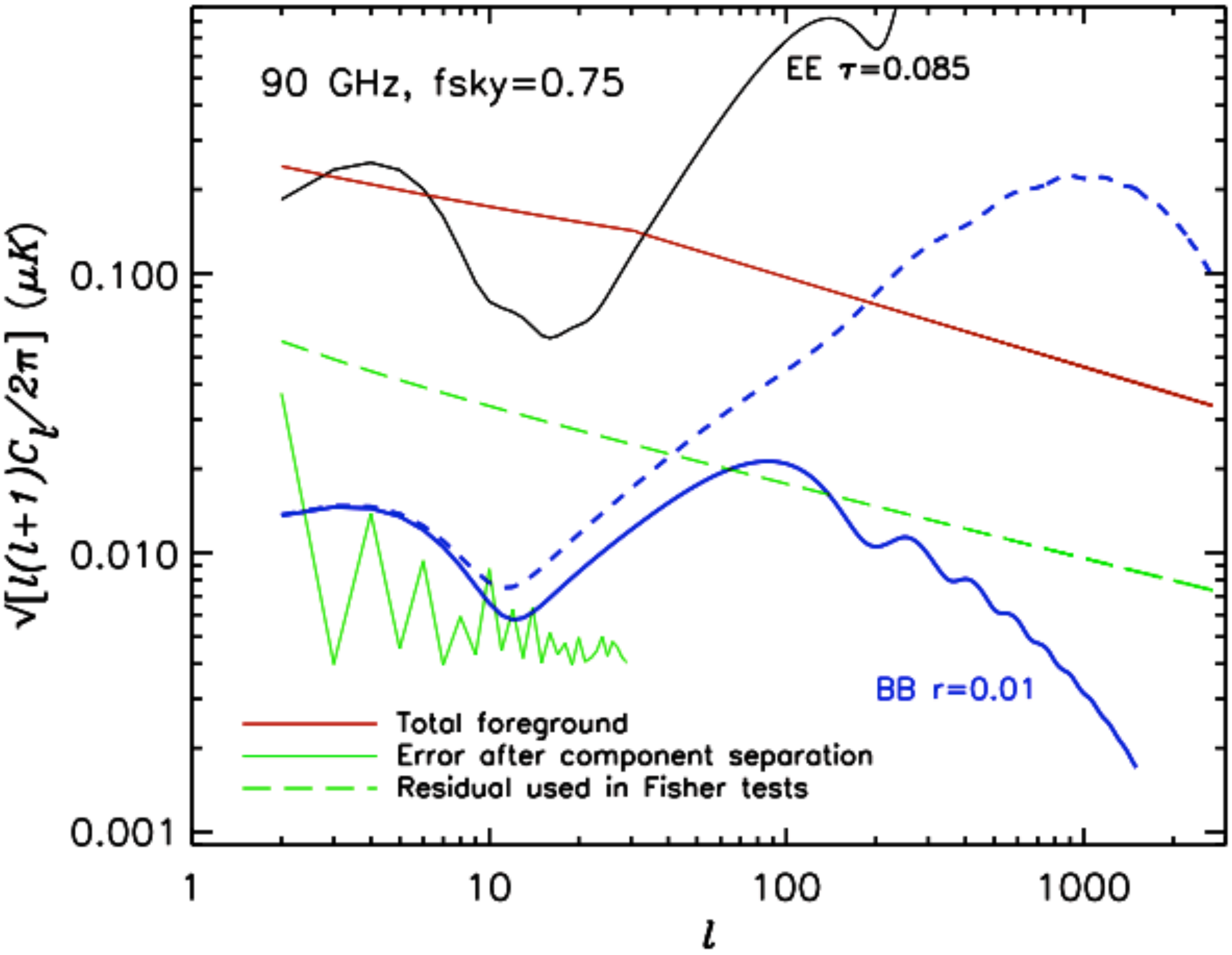
Verde, HVP & Jimenez (2005)

Foregrounds vs CMB at 90 GHz



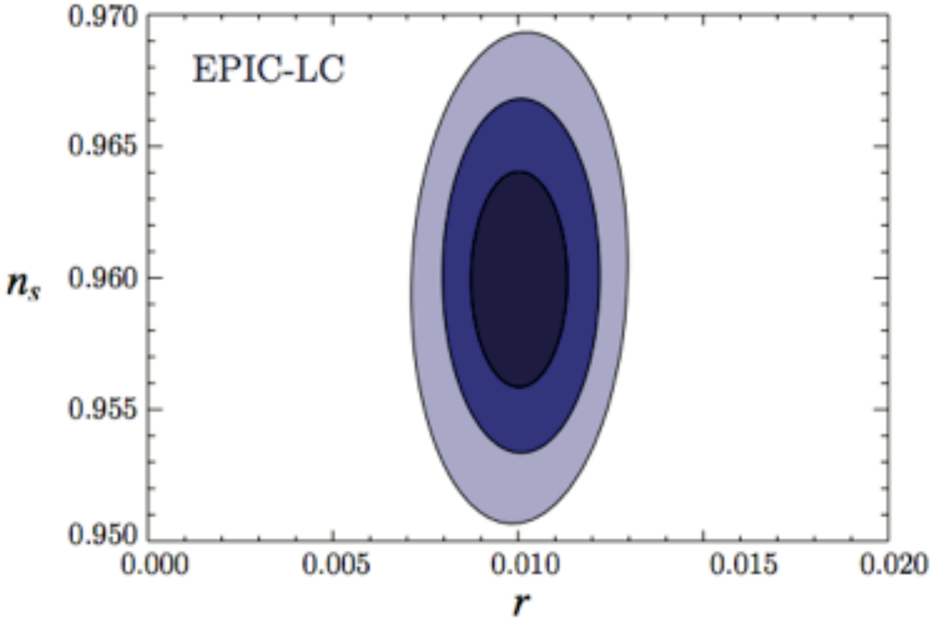
CMBpol Mission Concept Study: Foreground Removal Working Group Report (arxiv: 0811.3915)

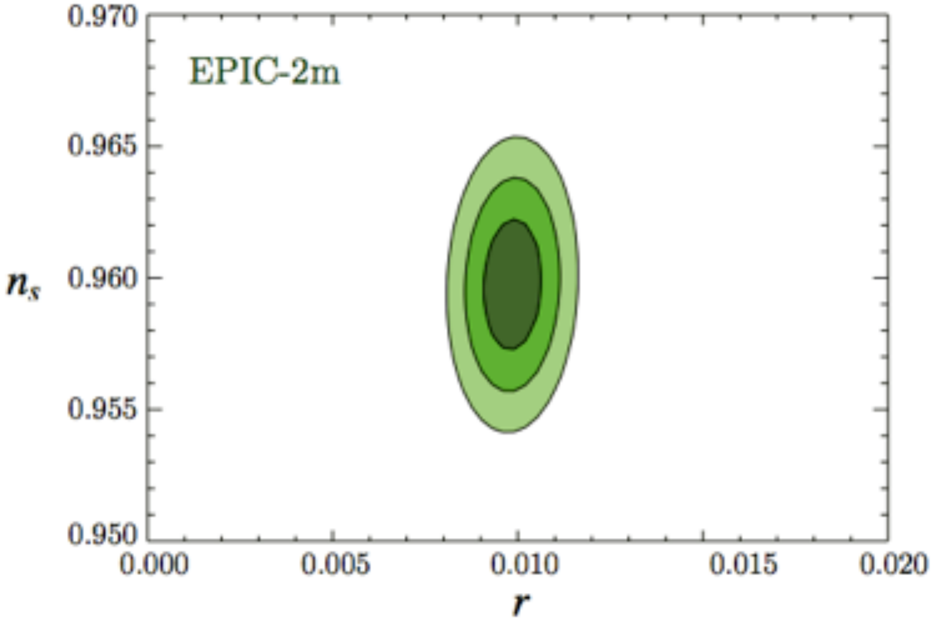
FG cleaning residuals from simulated maps



CMBpol Mission Concept Study: Foreground Removal Working Group Report (arxiv: 0811.3915)

Forecasted CMBpol constraints for r=0.01

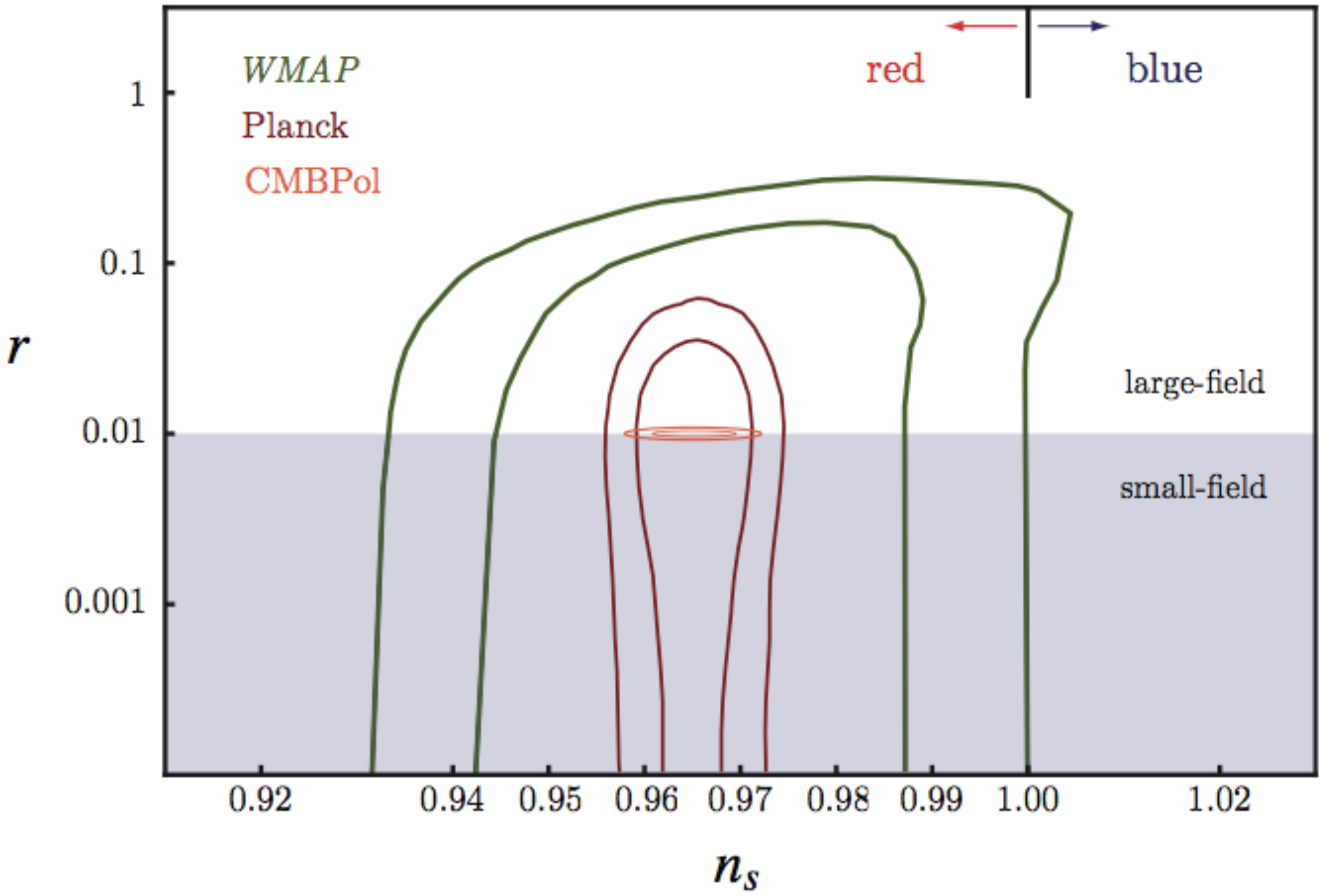




- *EPIC-LC*: “low cost” CMBpol proposal
- *EPIC-2m*: “mid cost” CMBpol proposal

Computed for CMBpol Concept Study by Adshead, Easther, Peiris, Verde (arxiv: 0811.3919)

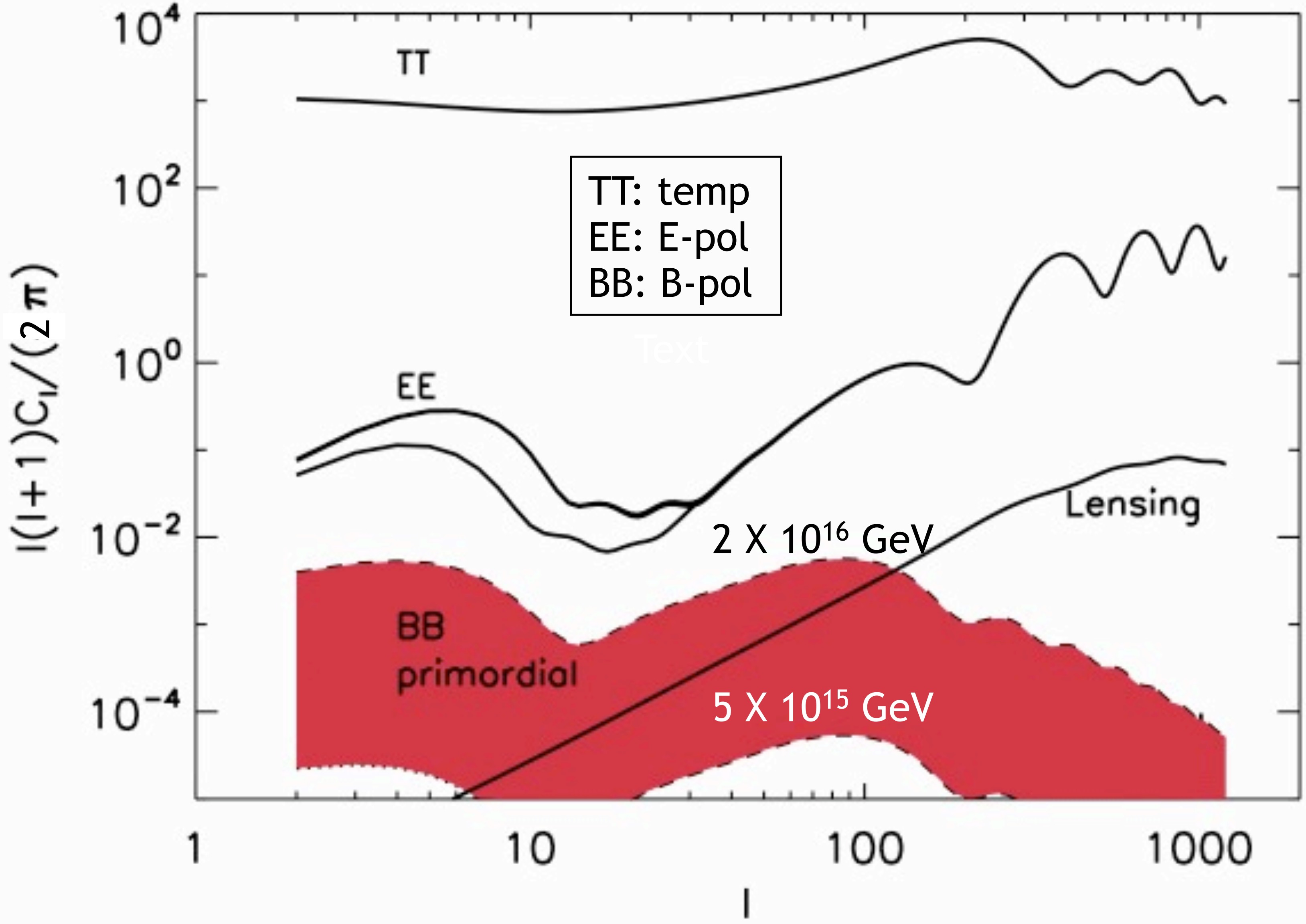
Forecasted CMBpol constraints for r=0.01



CMBpol Mission Concept Study: Inflation Working Group Report (arxiv: 0811.3919)

Approximate range of primordial tensors accessible to upcoming experiments

$$V^{1/4} \simeq 3.3 \times 10^{16} r^{1/4} \text{ GeV}$$



Science enhanced by precision polarization

(a non-comprehensive and idiosyncratic list)

Primordial non-Gaussianity

Gaussian quantum fluctuation	$\delta\eta$
non-Gaussian inflaton fluctuation	$\delta\phi \sim g_{\delta\phi}(\delta\eta + f_{\delta\eta}\delta\eta^2)$
non-Gaussian curvature fluctuation	$\zeta \sim g_{\zeta}(\delta\phi + f_{\delta\phi}\delta\phi^2)$
non-Gaussian CMB anisotropy	$\frac{\delta T}{T} \sim g_T(\zeta + f_{\zeta}\zeta^2)$

Addition of polarization data improves estimator for “f_{NL}” by 160%!

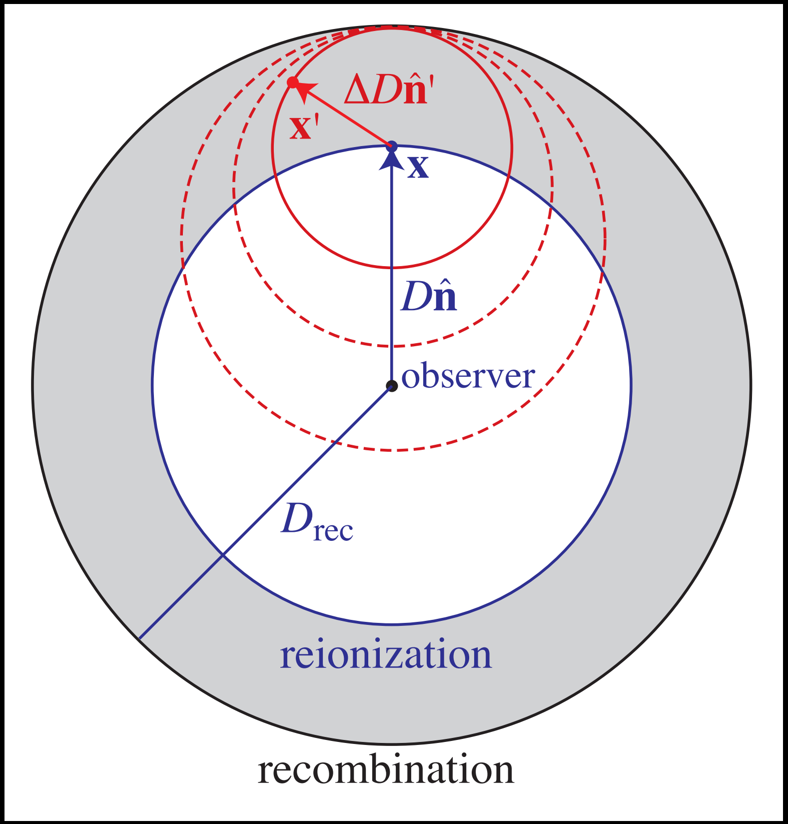
Could be critical in reaching slow roll inflation prediction $f_{NL} \sim 1$.

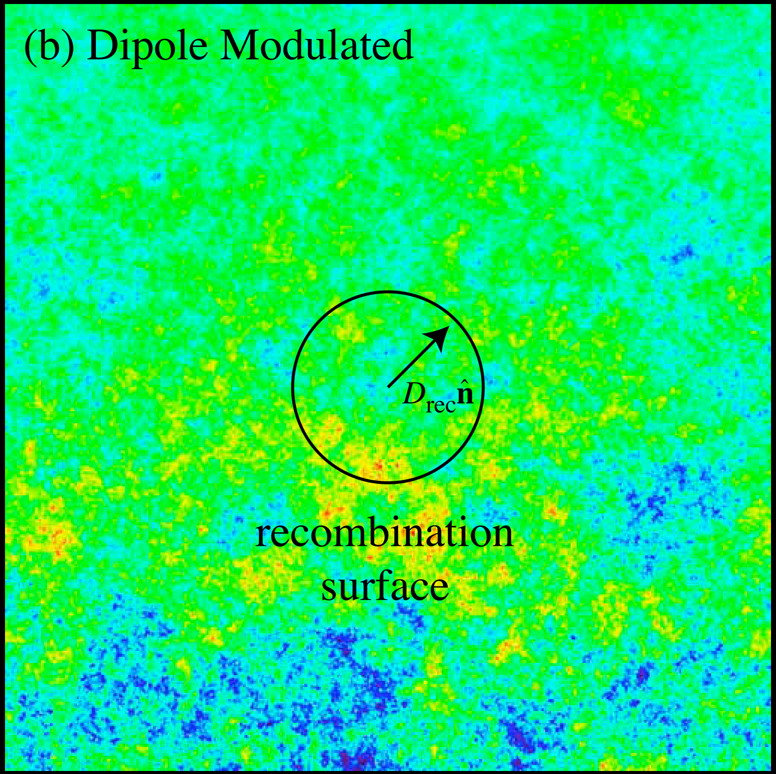
CMBpol Mission Concept Study: Inflation Working Group Report (arxiv: 0811.3919)

CMB Polarization: Testing Statistical Isotropy

- Isotropy “anomalies” identified in WMAP temperature field (e.g. hemispherical asymmetry, quadrupole-octupole alignment)

- Any physical model of temperature anomalies provides testable predictions for statistics of polarization field; goes beyond *a posteriori* inferences.





Dvorkin, Peiris & Hu (astro-ph/0711.2321)

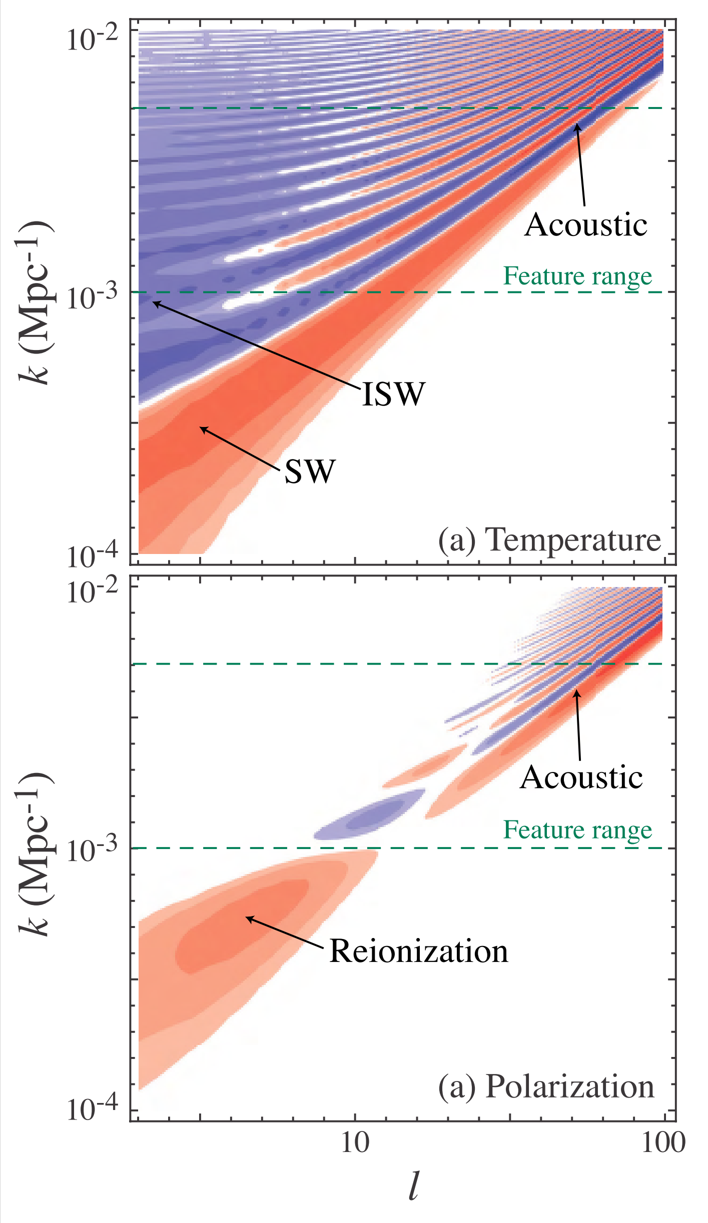
CMB Polarization: Is Potential Smooth?

- “Glitches” in WMAP TT spectrum at large scales: statistics, systematics, or new physics?

- Features in inflationary power spectrum?

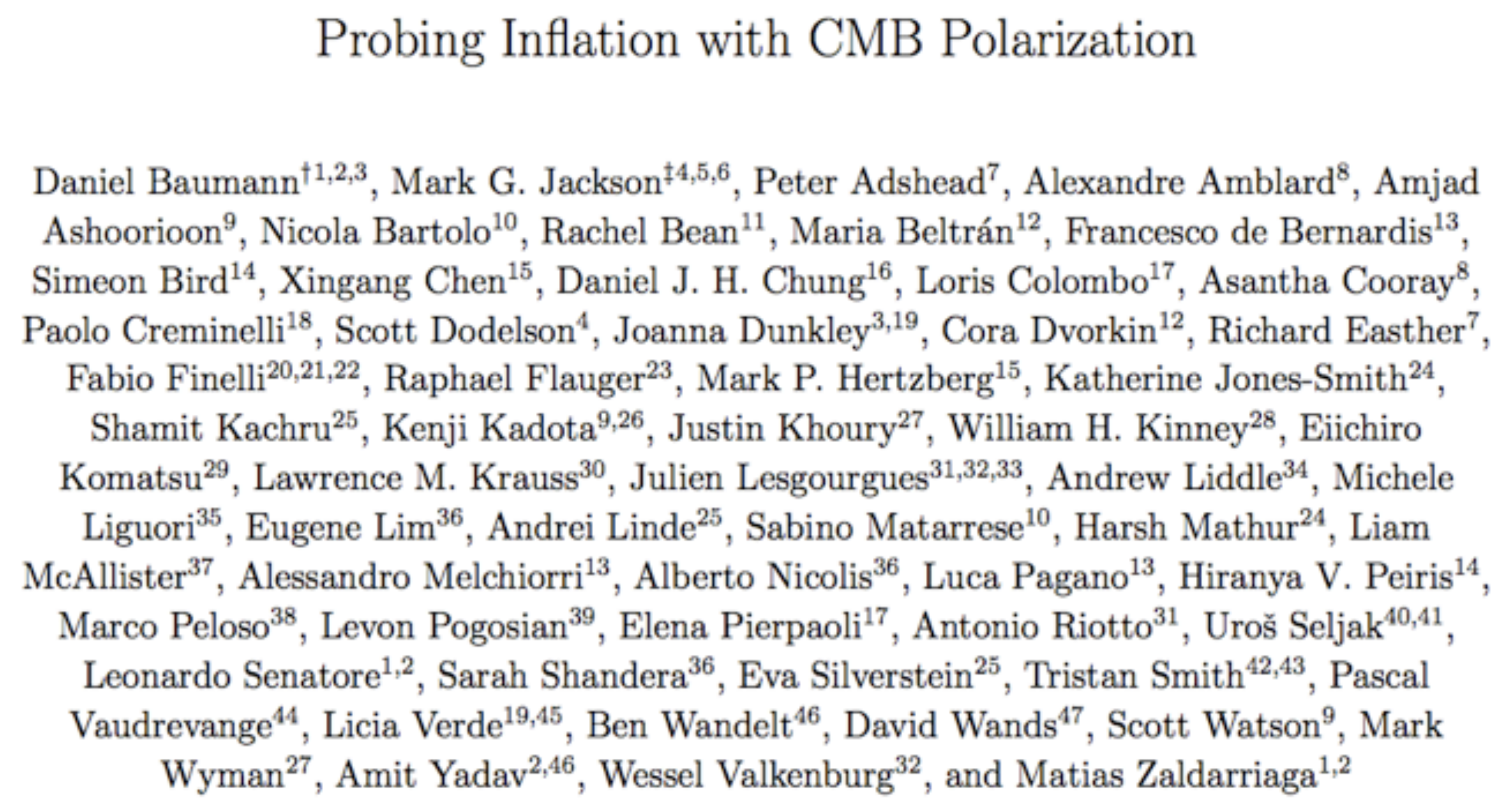
- Test: polarization transfer function narrower than temperature one.

- Disentangle from complex reionization history?



Mortonson, Dvorkin, Peiris & Hu (0903.4920)

For the full science case see...



Probing Inflation with CMB Polarization

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arxiv:0811.3919

Also...

arxiv:0811.3915	Prospects for polarized foreground removal
arxiv:0811.3816	Gravitational lensing
arxiv:0811.3918	Reionization Science with the CMB
arxiv:0811.3920	Foreground Science knowledge

Summary

arxiv:0811.3911
CMBPol Mission Concept Study: A mission to map our origins

Future observational prospects

- Go to small scales. Much better measurements of the primordial scalar power spectrum shape.
  - Planck *l*~3000 (*k*~0.2/Mpc)
  - ACT, SPT *l*~10000 (*k*~0.7/Mpc) [secondary effects]
  - Galaxies *k*~1/Mpc [non-linearity & bias]
  - Lyman alpha *k*~5/Mpc [gas phys. & radiation feedback]
  - Reionization *k*~50/Mpc [much is unknown]
- Detecting gravitational waves.
  - CMB: BICEP, QUIET, ~~CLOVER~~, PolarBeaR, EBEX, SPIDER, Planck, CMBPOL/B-Pol etc... [large scales]
  - GWO: direct detection of primordial gravitational waves (BBO) [solar system scales]
- Detecting primordial non-Gaussianity.
  - Can we detect f_{NL}~1 or f_{NL} >> 1?
  - Can we distinguish shape dependence? scale dependence?

THE END