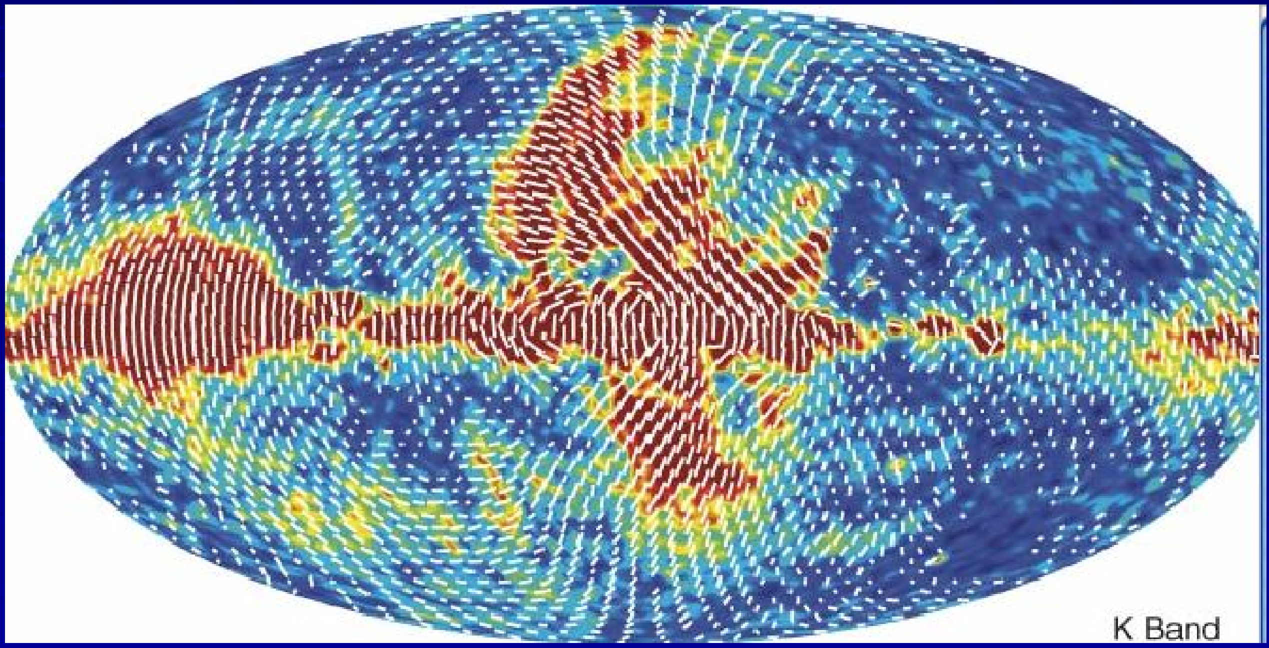
Foreground measurements for future high-sensitivity CMB experiments

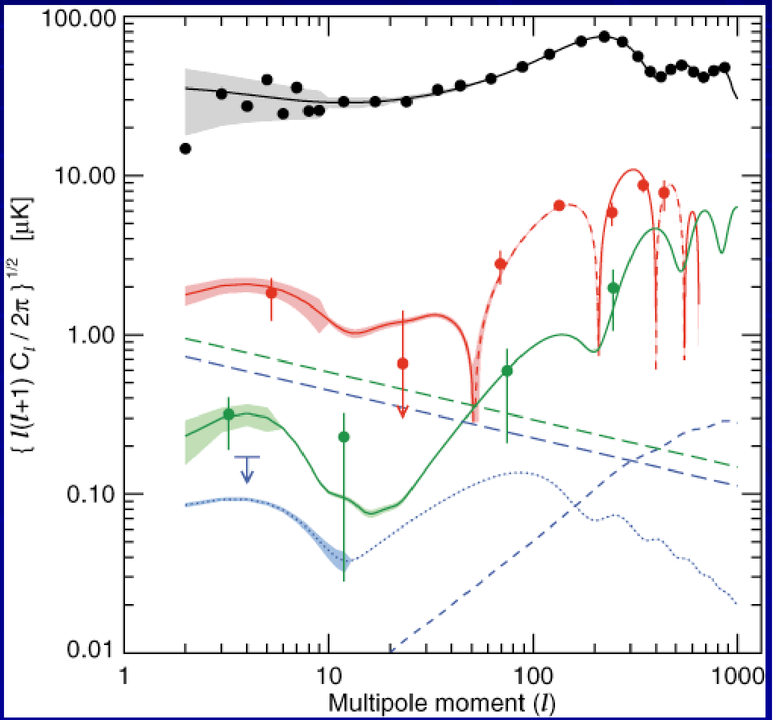
Clive Dickinson (IPAC/Caltech/JPL)



For many more talks (!) see
http://planck.ipac.caltech.edu/content/ForegroundsConference/Home.html

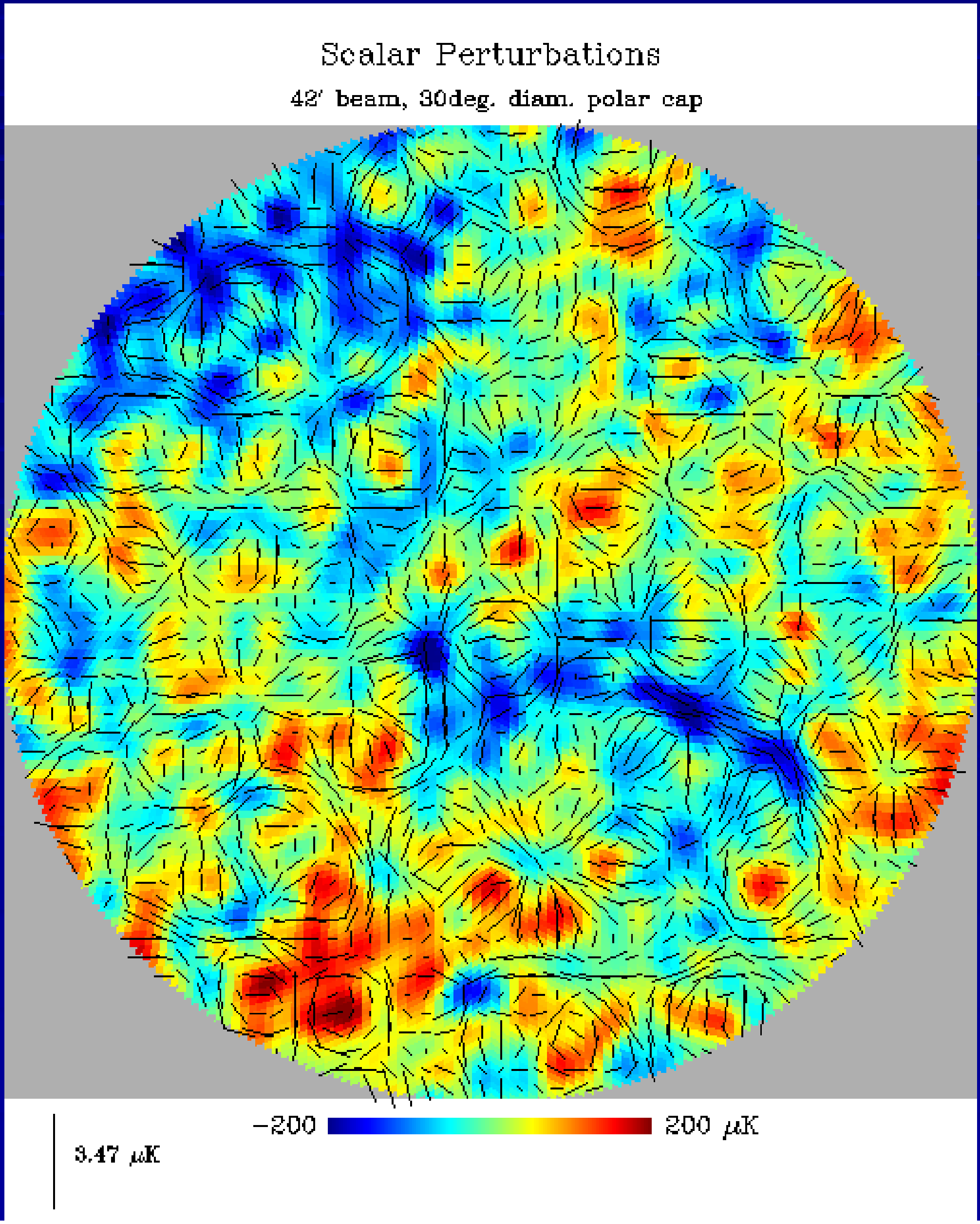
Future of CMB cosmology

- Lots more science to do with CMB
  - WMAP has measured ~10% of information content in CMB (“Charles Lawrence”, Pasadena July ‘08)
  - Small angular scales
    - l=>500
    - “CBI/ACBAR excess” (l=2000-4000)
    - Sunyaev-Zeldovich effect
  - Non-Gaussianity signatures (from maps!)
    - Non-standard cosmology
    - Topology, cosmic strings, textures, mag fields + more!
- Polarization!
  - E-modes: cosmological parameters, reionization history
  - B-modes: gravitational waves (inflation), lensing
    - Energy scale of inflation (~10^{16} GeV?)
  - Signal is very faint!!!



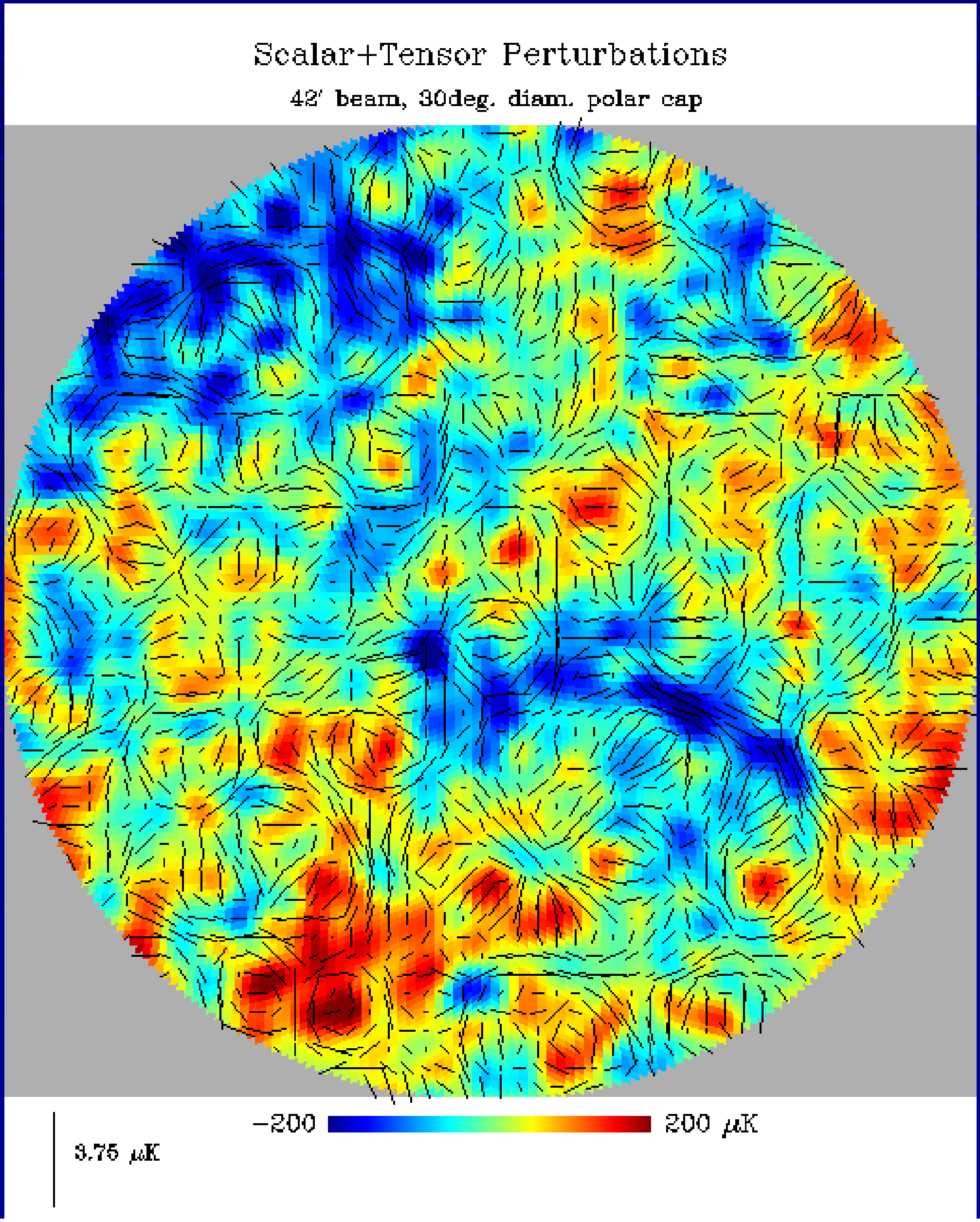
WMAP3

CMB field with no tensor modes (r=0)



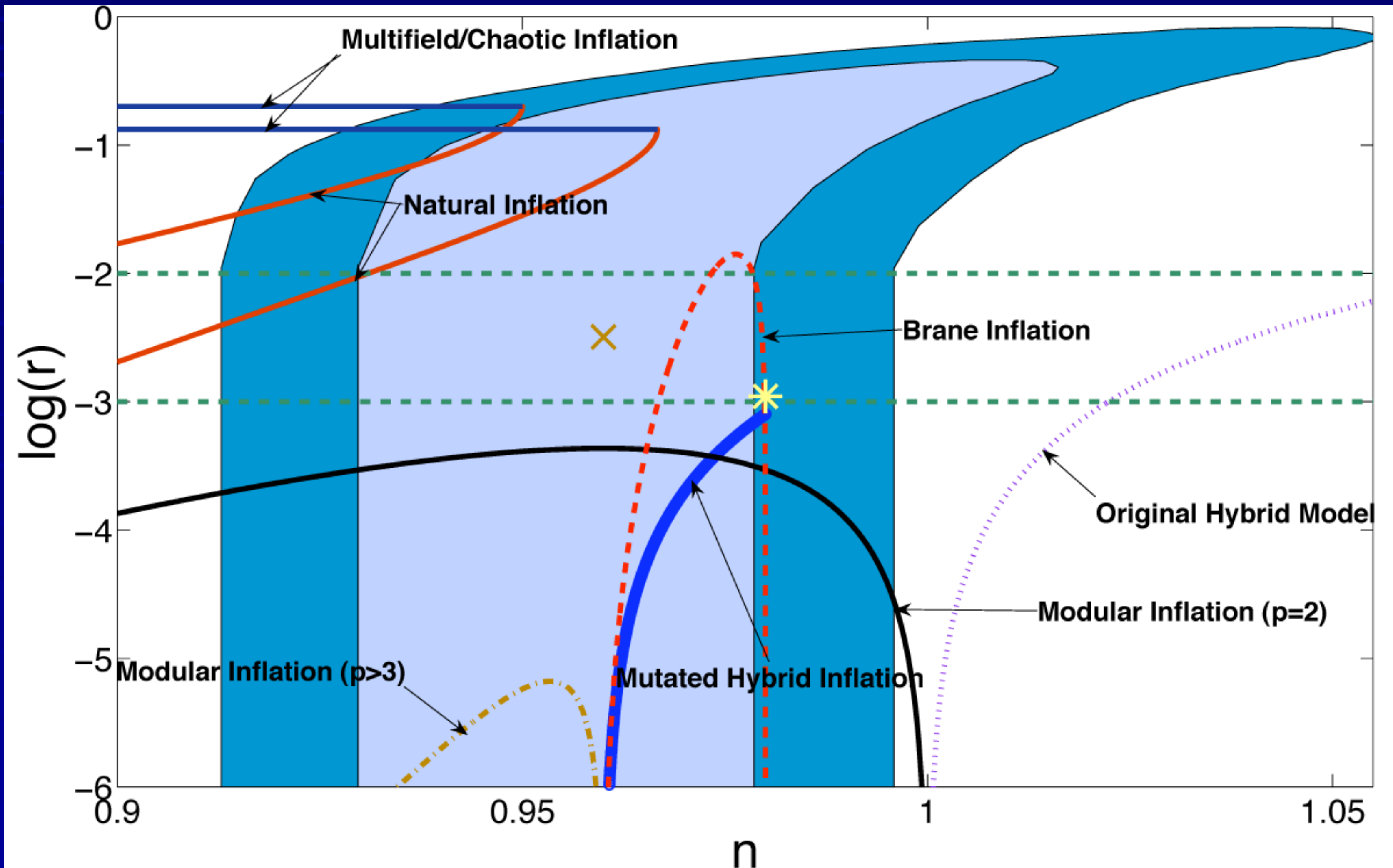
Eric Hivon

CMB field with tensor modes (r=0.3)



Eric Hivon

Inflationary parameters: n, r



Lyth (2002)

Lots of upcoming experiments!

QUIET	Atacama	2008	45, 90	JPL MMIC HEMT
BICEP2	South Pole	2009	150 (+100, 220)	JPL ACB
Planck	L2	2009	30 - 350	JPL Polarized Bolometer
EBEX	Antarctic Balloon	2010	150 - 300	UCB Bolo. + Wire Grid
SPIDER	Australia	2010	100, 150, 220	JPL ACB
Polar Bear	Atacama	2010	100, 150, 220	UCB ACB
Clover	Atacama	2010	100, 150, 220	UK ACB

+ more!
+ *funded* foreground-dedicated experiments!!

(Lange, Pasadena July '08)

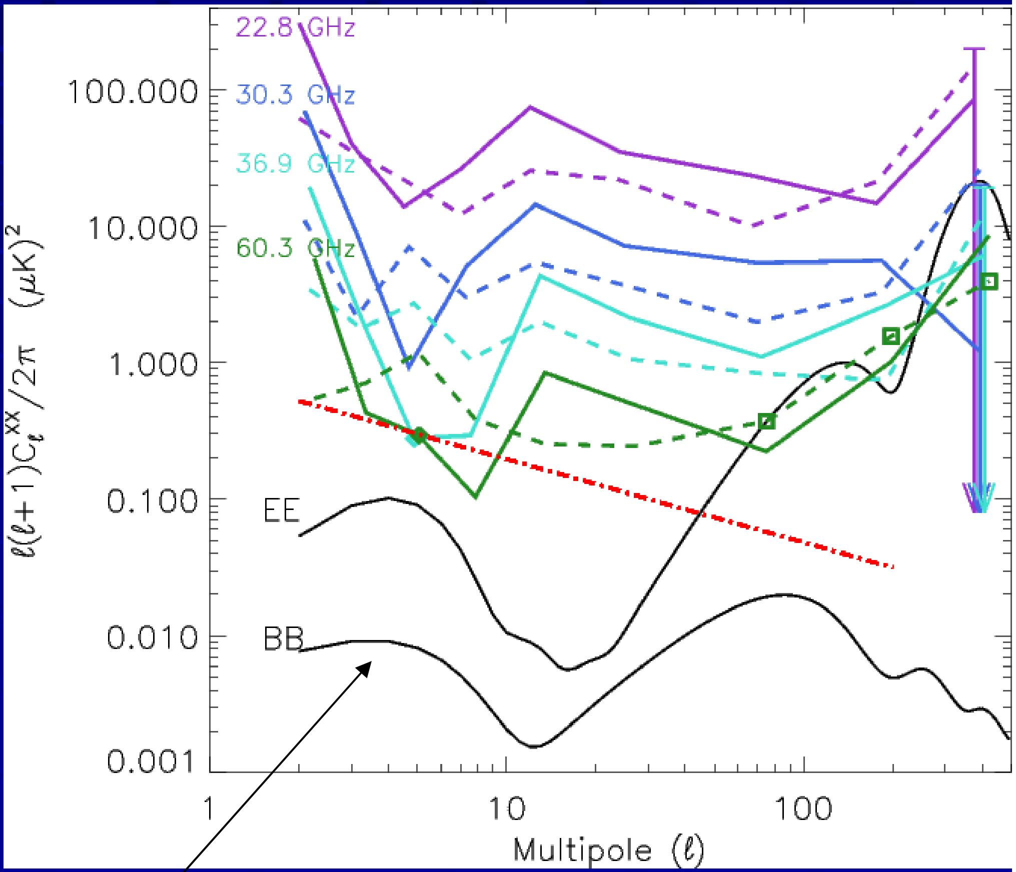
Diffuse foregrounds!

- Foregrounds will be the main limitation, particularly for B-modes
  - Synchrotron from e^- spiralling in B-field ~10-20% polarized on average!
  - Thermal dust from non-spherical grains ~5% polarized on average.
  - Spinning dust? (~3% polarized?)
  - Magnetic dust emission? (highly polarized!)
- At large angular scales
  - noise *will* be sub-dominant
  - foreground subtraction critical
  - Propagation of error bars!
- Masking will help, but at l~10, cosmic variance is serious!

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

WMAP Polarization foregrounds

- Over large areas of Sky diffuse foregrounds dominate the cosmological signal!
- No detailed model of foregrounds (spectral or spatial!)
  - 1st order estimates
- B-modes could be much weaker than this!

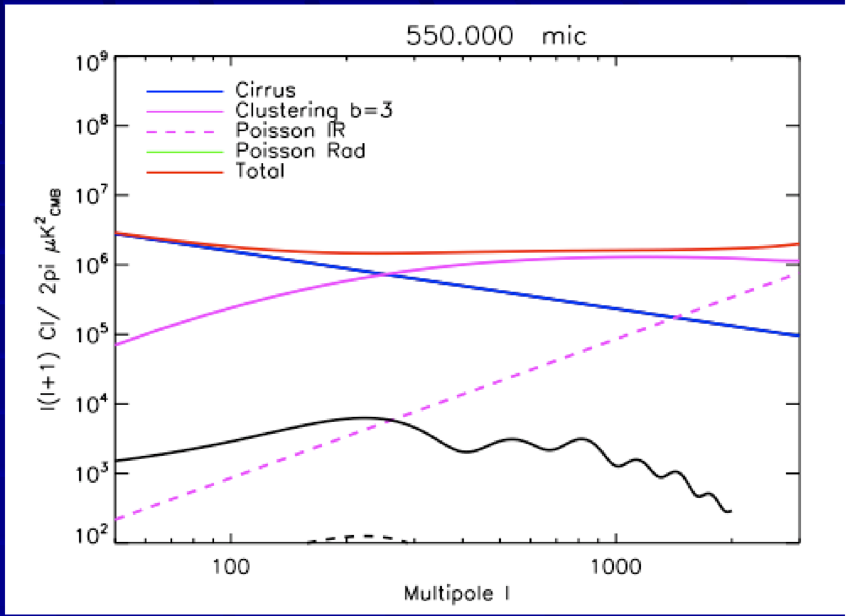


Page et al. (2007)

r=T/S=0.18 (near current upper limit!)

Small angular scales - galaxies!

- At l>~1000, extragalactic sources (Galaxies) are dominant foreground at all relevant frequencies
  - At high frequencies (Planck HFI), CIB dominates the dust cirrus!
- Require detailed statistics (cannot mask everything!)
  - Source counts
  - Frequency distributions
- Need high angular resolution, large-area surveys (~10-500GHz)
  - E.g. ATCA 20G, GBT 30GHz etc.
  - Focal-plane arrays! (e.g. OCRA-C)



G. Lagache (Pasadena July '08)

CMBpol foregrounds

- CMBpol (or Bpol) will be the next generation CMB experiment (~2020-2025, maybe)
- Foregrounds will be the ultimate limit of CMB measurements (e.g. Weiss report)
  - Knowledge of foregrounds critical
  - CMBpol workshop(s) to investigate these limitations
  - Bottom line: r~0.01 ok, r~0.001 maybe
- CMBpol also "needs" ancillary science (Stephen Meyer, CMBpol workshop)
  - Provide wider science goals for ~$600M !!
    - E.g. magnetic field, SNRs, HII regions, cold dust, dust polarization, molecular clouds 3-D Galactic model, Solar System etc etc…
      - 16 WG7 (Galactic science) projects in *Planck*!! (see *Planck* blue book) 1
      - Entire conference last week here at Caltech!

What do we know in polarization???

- Very little!
- At least 2 components
  - Synchrotron
    - Mostly WMAP K-band
    - Expect some curvature from power-law
  - Thermal dust
    - ~4-5% polarized from Archeops (Ponthieu et al. 2005)
- Future all-sky survey are urgently needed!
  - ~5-500GHz (many channels)
  - *Planck* will give us the 1st detailed picture! (~2012-2013)

QuickTime™ and a
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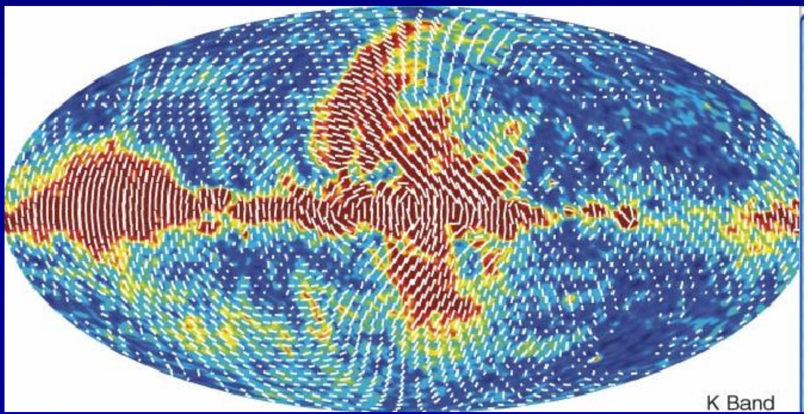

C-BASS

- C-Band (5GHz) All-Sky Survey
  - Total-intensity and polarization
  - 1GHz bandwidth correlation polarimeter & radiometer
  - Full-sky, <0.1mK noise per beam (~1°)
  - Observations 2009 (California) & 2010 (SA)

QuickTime™ and a
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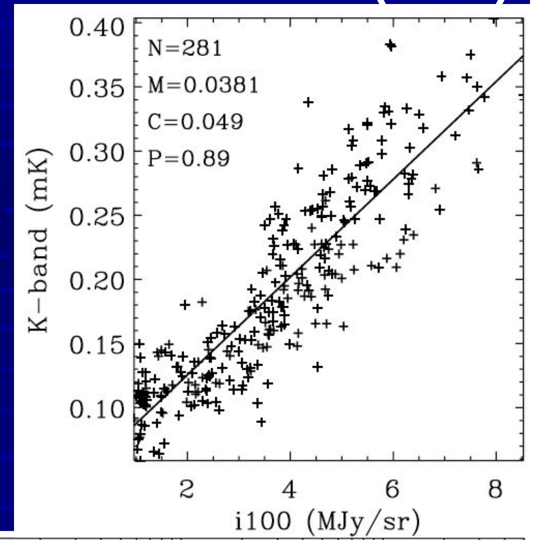
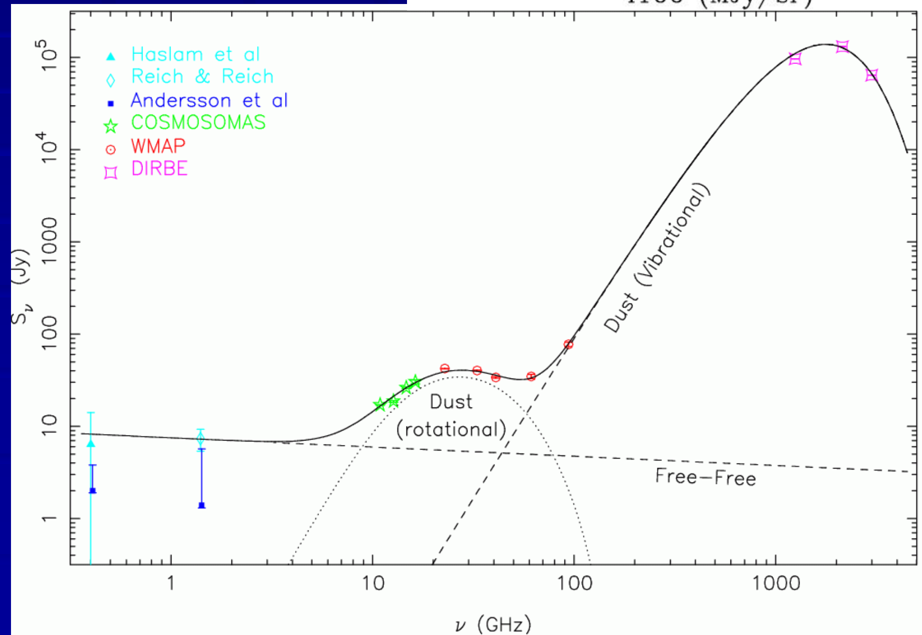
are needed to see this picture.

Expect surprises!

- Anomalous dust-correlated emission
  - New component seen at 10-60GHz (many papers!)
  - Maybe spinning dust
    - Few % polarized
- CIB
  - IR emission from population of dusty galaxies
- Others?
  - Magneto-dipole emission?
  - Fullarenes?
  - Hot free-free?
  - Cold dust?
  - Others???

Davies et al. (2006)





Watson et al. (2005)

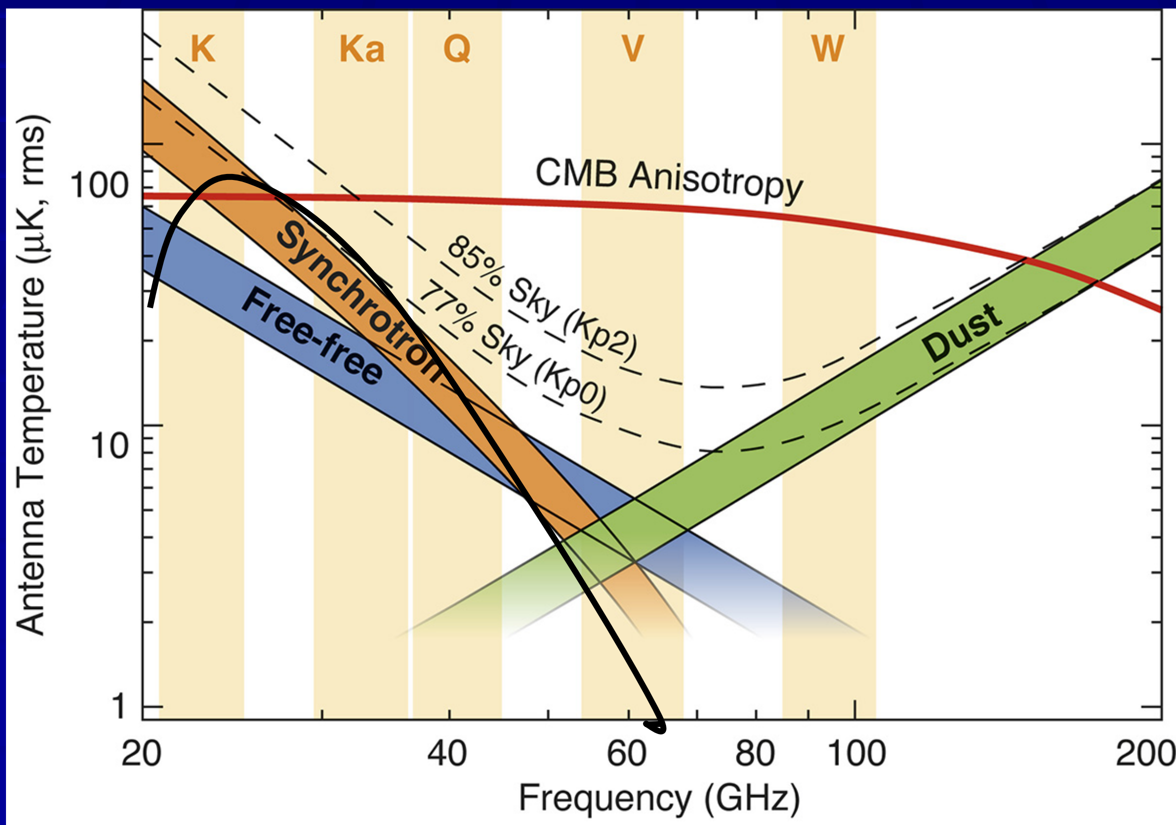
Need detailed 5-60GHz measurements!

Component separation

- Many methods
  - Blind (e.g. ILC, ICA)
  - Semi-blind (e.g. SMICA, ICA-variants)
  - Template fitting (e.g. WMAP, WIFIT)
  - Parametric fitting (e.g. FGFIT, Commander)
- Propagation of error bars is critical, especially for B-modes
  - Experimental forecasts should be done with codes that propagate errors (few codes can do this properly!)
  - Pixel-based codes are the only way (“Lyman Page”)
- Modelling errors are particularly difficult
  - Requires prior knowledge of foregrounds!
  - Bandpass (color) effects need to be included
- FGFIT & Commander can do this (Eriksen et al. 2006, 2008)

Spectral discrimination

- Need lots of frequencies covering a range of frequencies in and around ~70-80GHz



WMAP

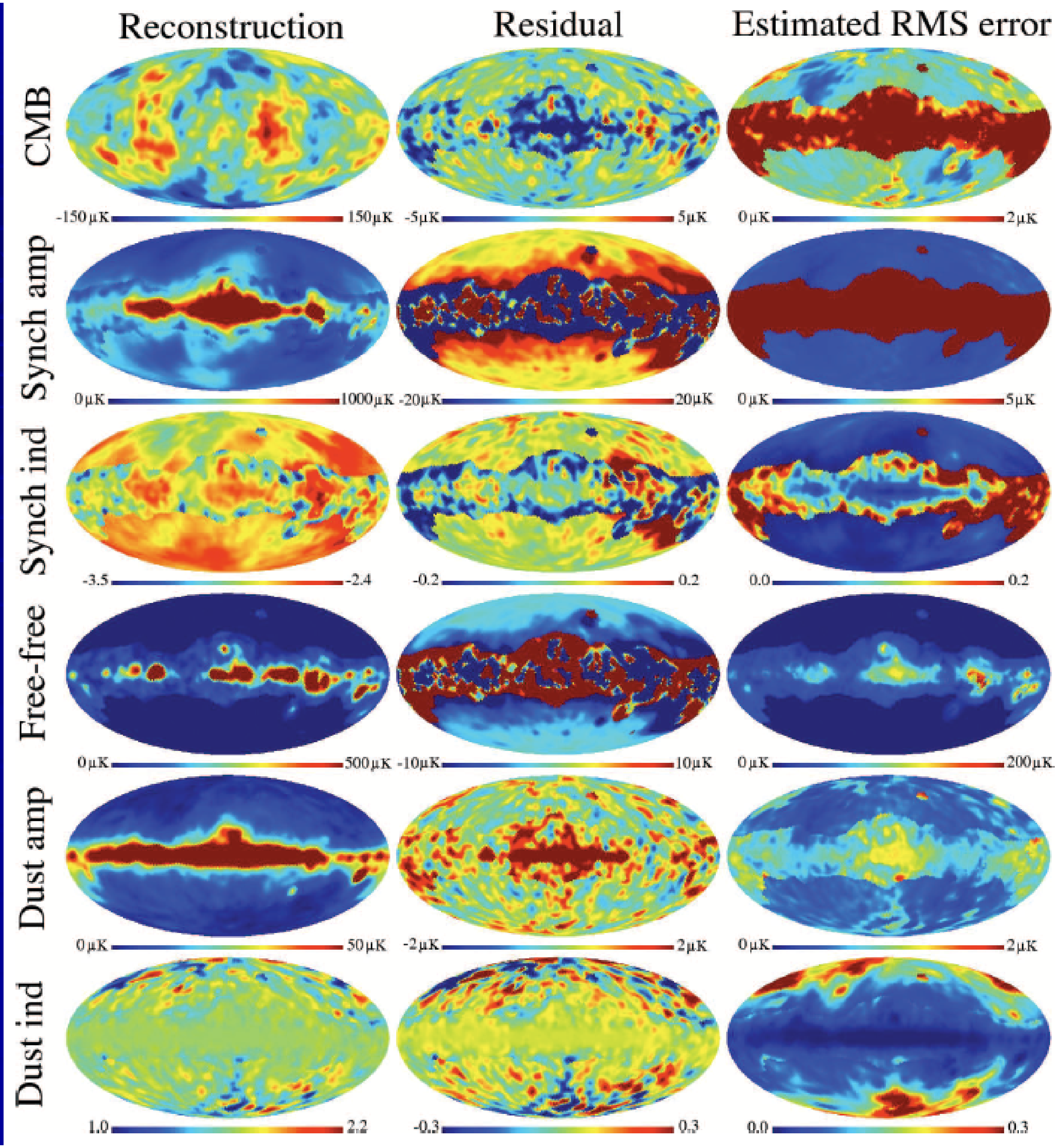
FGFIT Method: Basic idea

- FGFIT is a pixel-by-pixel "maximum-likelihood" estimator
  - MCMC to sample full likelihood (see Eriksen et al. 2006)
    - Assume uncorrelated Gaussian data

$$\ln \mathcal{L} = -\frac{1}{2}\sum_{\nu=1}^{N}\left[\frac{d_\nu - S_\nu(\theta)}{\sigma_\nu}\right]^2 = -\frac{1}{2}\chi^2.$$

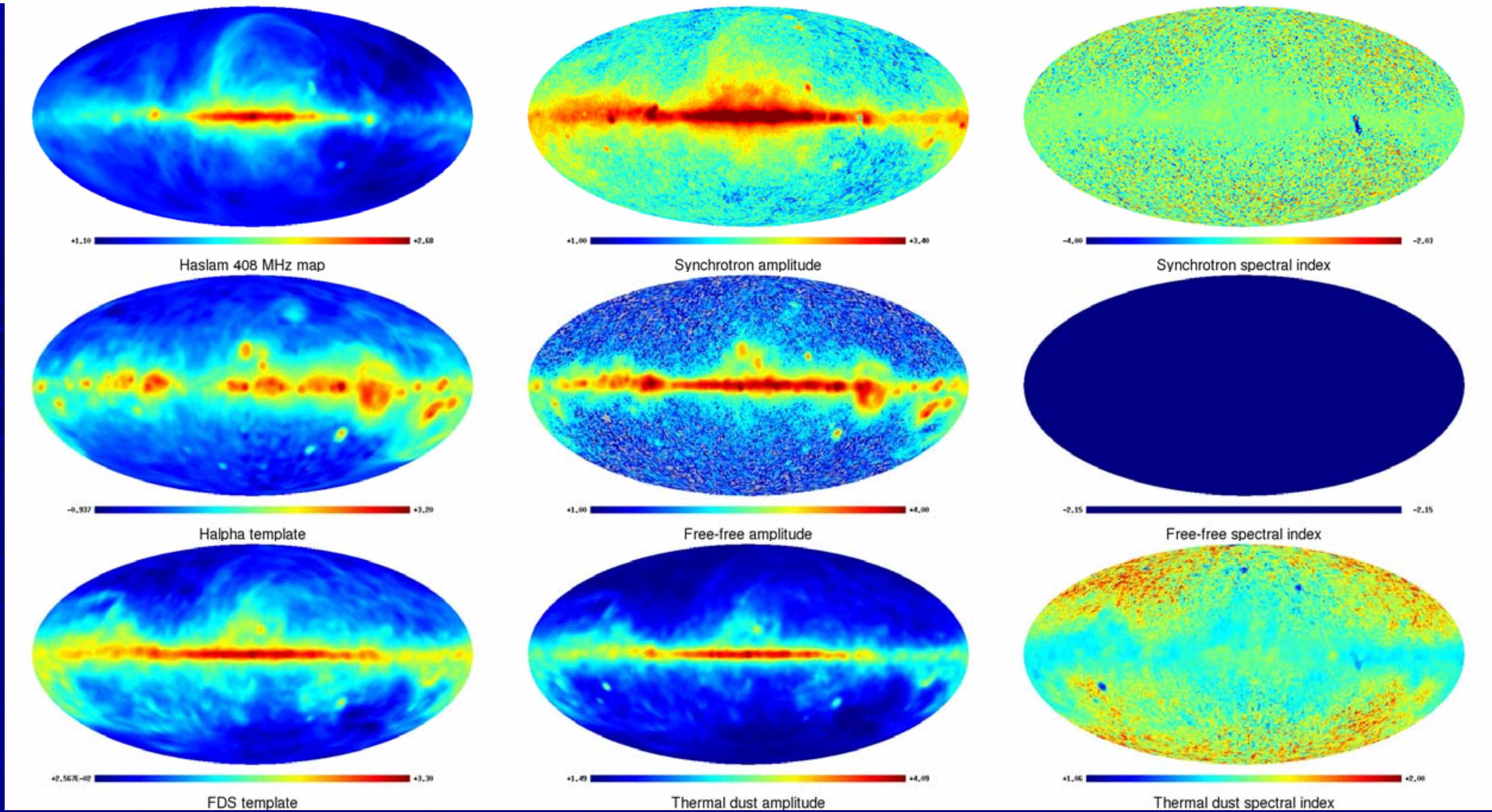
    - Fit CMB, sych power-law, dust model etc. at each pixel
  - Parallel code to distribute pixels over many processors
  - Most powerful when considering many frequency channels at high signal-to-noise ratios (c.f. template fitting).
    - Need more channels than fitted parameters! (ideally >10)
  - Propagation of errors to CMB amplitudes

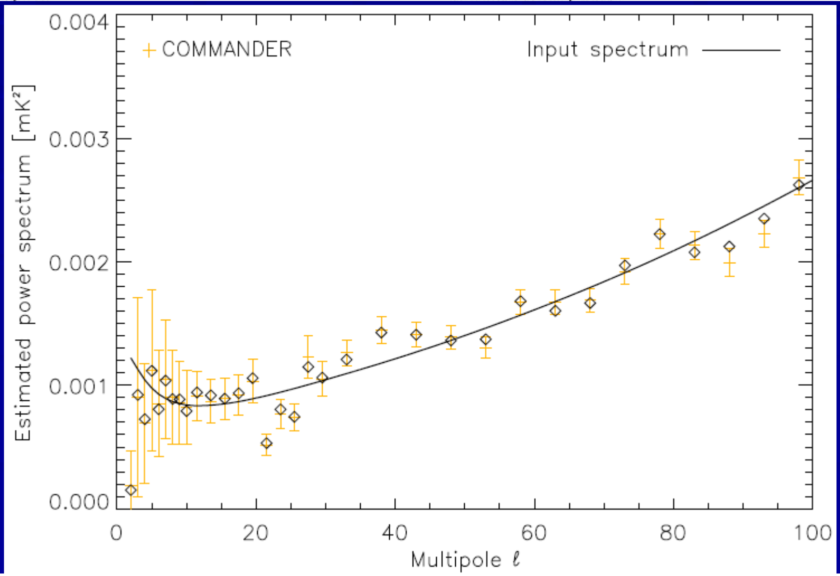
- Commander (Gibbs sampling) does the same thing but can fit the CMB Cl's at the same time! (Eriksen et al. 2008)
  - Likelihood for each CMB Cl



FGFIT

Eriksen et al. (2006)





Planck WG2 challenge

Commander

Experimental Forecasts: Single pixel fits

- We want to know what is the optimal design (frequency coverage, no. of channels, sensitivity distribution etc…).
  - Difficult question -> large parameter space! (on-going study with C. Lawrence, M. Seiffert, H.K. Eriksen, K. Gorski & JPL group)
    - (also see Amblard, Cooray, Kaplinghat, 2007, Phys. Rev. D75, 083508)

- Simulations based on a single (I,Q,U) pixel only! ("fgfit_pix")
  - Computationally fast - 1000 realizations of CMB/noise in few mins running on 256 3GHz processors (COSMOS at JPL)
  - Vary CMB and noise for each realization
  - Good enough to see "which design is best".
    - Critical for future CMB satellites!
    - FGFIT is well suited for detailed experimental design study

Nominal foreground model

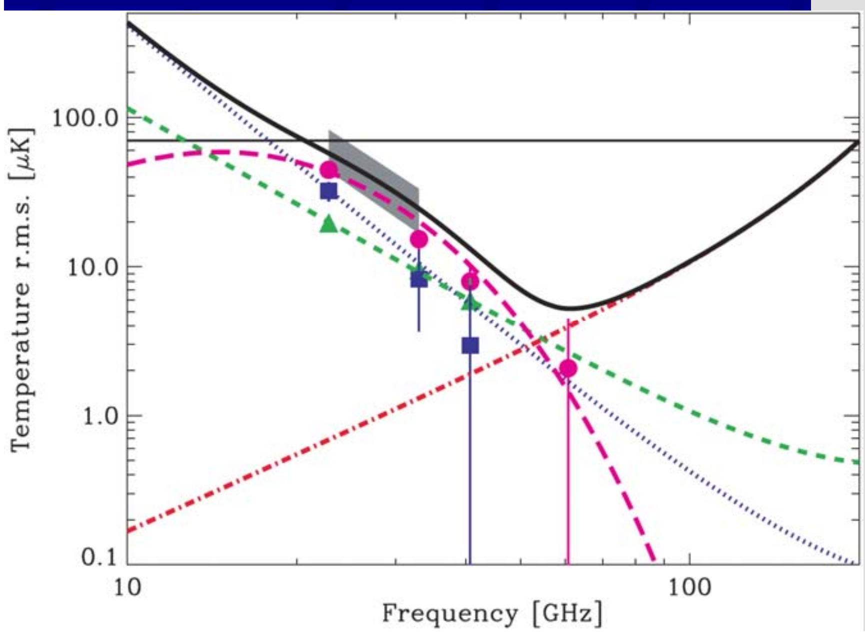
- ”Nominal” sky model, for 2° FWHM pixels.
  - Based on WMAP analyses (e.g. Davies et al. 2006).

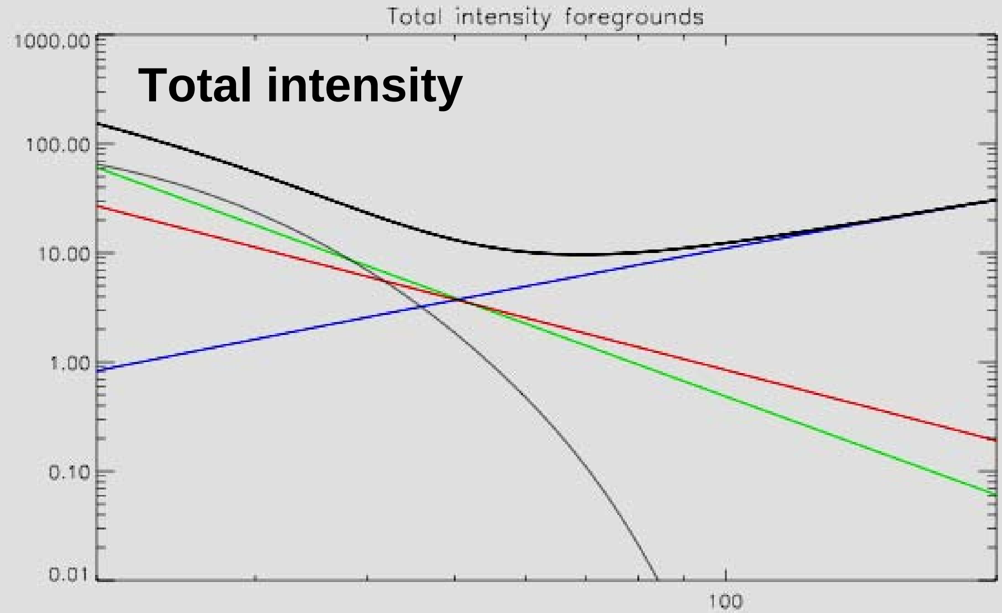
Component	Total-intensity (μK)	Spectrum ν^{β}	Polarization fraction
CMB	70 (r.m.s)	0 (T_{CMB})	1%
Noise	(varies)	(varies)	(varies)
Synchrotron	40 @ 23GHz	-3.0	10%
Free-free	20 @ 23GHz	-2.14	1%
Vib. Dust	15 @94GHz	FDS99 model 8 (~+1.7)	5%
Spinning dust	50 @ 23GHz	WNM (Draine & Lazarian, 1998a)	2%

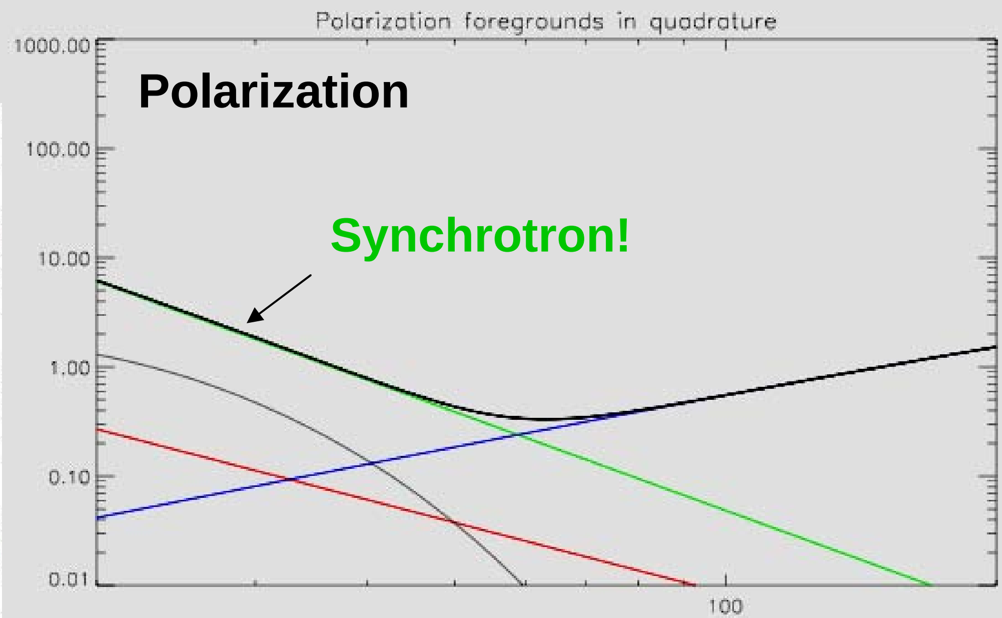
Nominal Foreground Model.

Fitted for synch & dust only (amplitude & spectral index)

Davies et al. (2006)







FGFIT applied to EPIC (Bock et al.)

(average of 1000 realizations of CMB & noise)

EPIC design	Average Q/U CMB Error (μK)
EPIC #1 (40-300 GHz, 6 channels)	0.108 μK
EPIC #2 (60-300 GHz, 7 channels)	0.114 μK
EPIC #3 (30-500 GHz, 8 channels)	0.075 μK
EPIC #2 + 30 GHz channel	0.096 μK
EPIC #2 + WMAP 6-yr K-band	0.110 μK

c.f. *Planck* (for 6 frequencies), at this resolution, gives ~1.6μK error in Q/U.
-> factor of ~15 better than Planck in ΔT!

Can reach r~0.01 without too much difficulty (Bock et al. EPIC report)
CMBpol studies - can we get down to r~0.001 or below? (difficult)

Including Design constraints

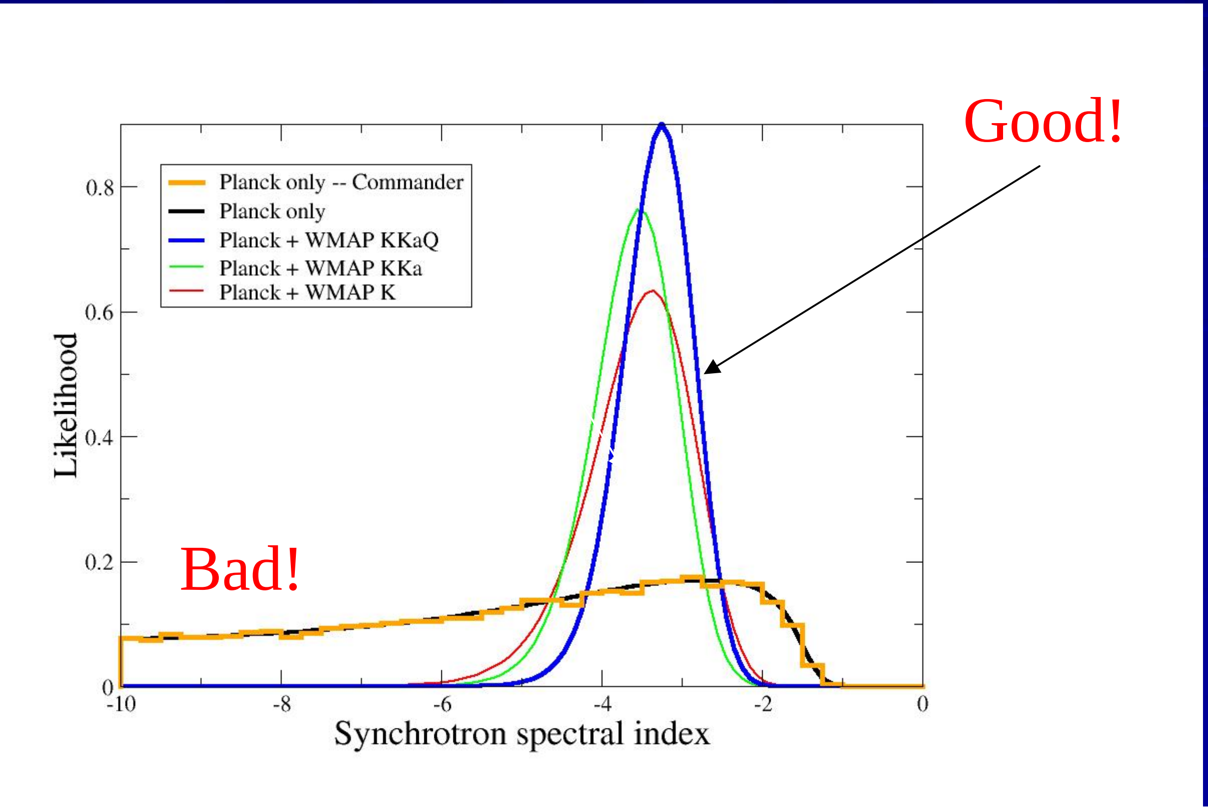
- Need to include realities such as
  - Focal plane area
  - Total power consumption
- Assuming fixed N_{feed} too simplistic (Amblard et al.)
  - Prefers too wide a frequency range!
- Calculate sensitivities based on these constraints
  - Requires “shape” of sensitivity to be known a priori (e.g. constant signal-to-noise ratio)
  - Scale N_{feed} based on this to full up focal-plane and/or power limitation
  - Typically focal-plane area is the limitation

Example: Optimal frequency range?

- Constant signal-to-noise ratio (all channels)
- Keep end of frequency range fixed and vary the other
  - 200GHz fixed. Optimum ν_{min} ~40GHz
  - 30GHz fixed. Optimum ν_{max} ~350GHz
- Modelling errors probably worse than this
  - ~40-350GHz is likely the maximum range that we should consider for a satellite mission with feed horns
  - We still need the wider frequency range to test this!
    - WMAP/*Planck*/other data will help (should be included)
  - Ground-based experiments at 30GHz and lower!!
    - E.g. C-BASS, GEM-P, QUIJOTE
    - For 10-30GHz we need focal plane arrays for sensitivity!!!

Why "low" frequencies?

- Foregrounds minimum at ~70GHz
  - Not much leverage to lower frequencies!
  - Synchrotron spectral indices & curvature!
  - Anomalous dust and/or other components?!



Hans-Kristian Eriksen

Conclusions

- Foregrounds are ultimate limit for CMB measurements
  - Need high sensitivity & many frequency channels
  - Detailed understanding of foreground components
  - Modelling errors are the biggest unknown
- Foregrounds science will be important for CMBpol
  - Already important for *Planck* (see blue book)
- FGFIT is very useful for doing comparisons between experimental designs
  - Commander (Gibbs sampling code) superior for getting absolute errors (e.g. on r)
- Experimental constraints have to be folded into experimental forecasts
  - Perhaps ~40-350GHz is about the frequency range we should consider for CMBpol
  - BUT, ancillary science at >350GHz also important (c.f. *Planck*)
  - 5-30GHz ground-based surveys are needed!

But, we're not there yet!

- Still largely dominated by sensitivity
- QuAD 100/150GHz show no foregrounds in clean area of sky (K. Ganga, Pasadena '08), but need to go ~100 times deeper and possibly more!

QuAD collaboration