”Fgfit” pixel-based foreground subtraction code for experimental design applications

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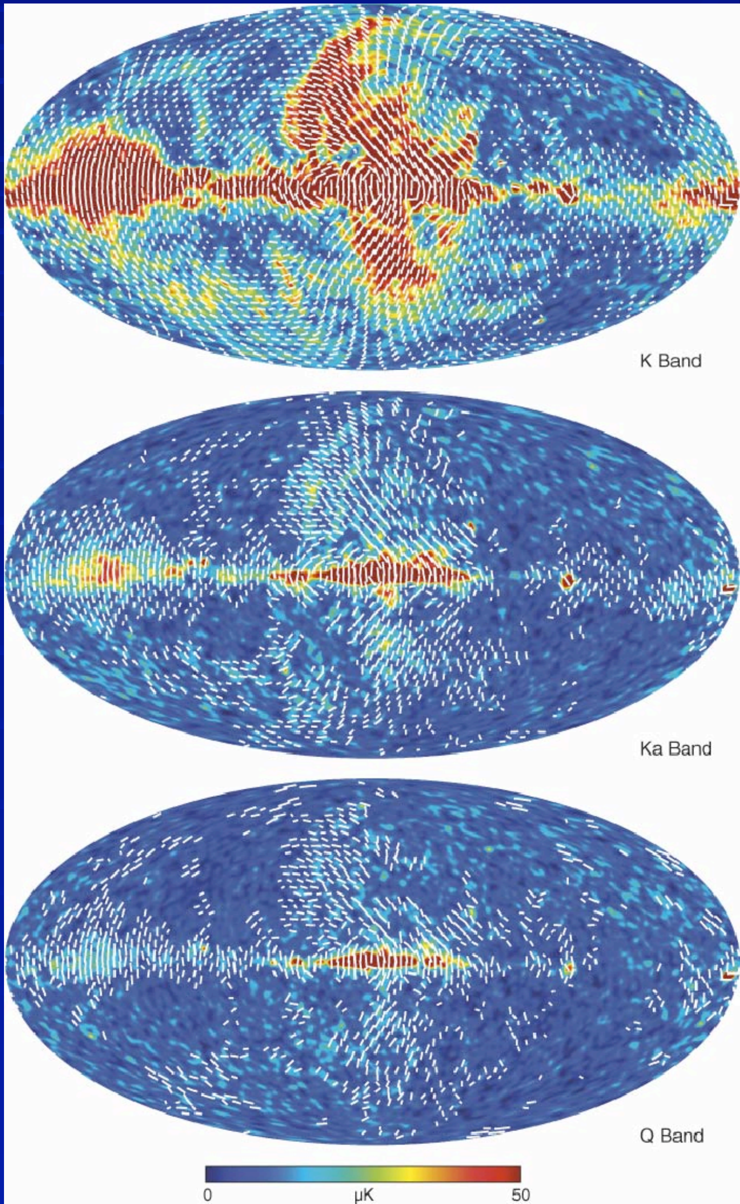
See Eriksen, Dickinson, Lawrence, Baccigalupi, Banday, Górski, Hansen, Lilje, Pierpaoli, Seiffert, Smith and Vanderlinde 2006, ApJ, 641, 665 for details of fitting algorithm and example application to WMAP/Planck simulation.

CMBpol workshop, Fermilab, 23-26th June, 2008.

Foregrounds!

- Foregrounds are probably *the* main problem for B-modes
  - Synchrotron ~10% polarized on average!
  - Dust ~5% polarized on average.
  - At least others are minimally polarized
  - magneto-dipole dust emission? (we hope not!)
- 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!



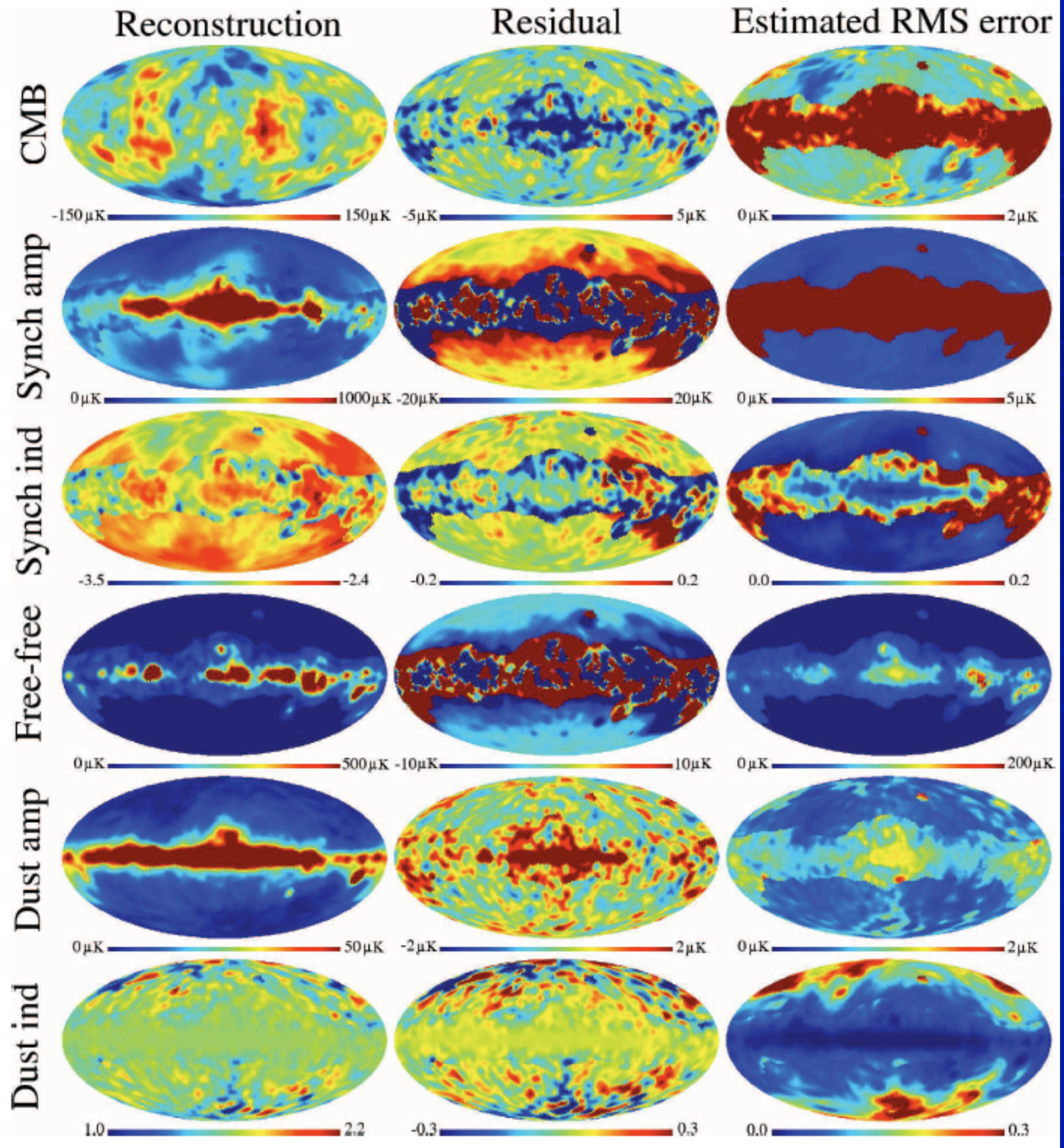
Component separation

- Many methods
  - Blind (e.g. ILC, ICA)
  - Semi-blind (e.g. SMICA, ICA-variants)
  - Template fitting (e.g. WIFIT)
  - Parametric fitting (e.g. FGFIT, Commander)
- Propagation of error bars is critical, especially for B-modes
  - 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
- Bandpass (color) need to be included
  - FGFIT & Commander can do this

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).
  - Get individual foreground parameters and maps for free
  - Full-sky analysis via low/high resolution analysis
  - Propagation of errors thru power spectrum possible.

- Hans-Kristian Eriksen will show results using Commander - a more superior (Gibbs) sampling code that can do the same thing but go directly to power spectrum (with full propagation of errors)



Eriksen et al. (2006)

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 ~1 min running on 256 3GHz processors (COSMOS at JPL)
  - Fix the foreground model, or try a few variations on typical foreground contamination at high Galactic latitudes.
  - Try different parameterizations of model to fit to (modelling errors)
  - Should be good enough to see “which design is best”.
    - Suited for detailed experimental design study

Nominal foreground model

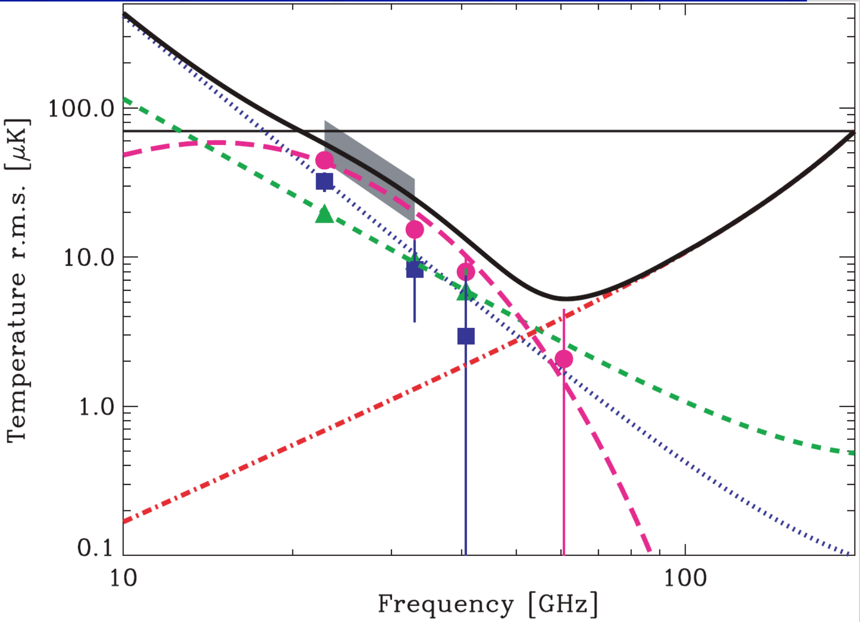
- ”Nominal” sky model, for 2 degree FWHM pixels.
  - Based on WMAP analyses (e.g. Davies et al. 2006).

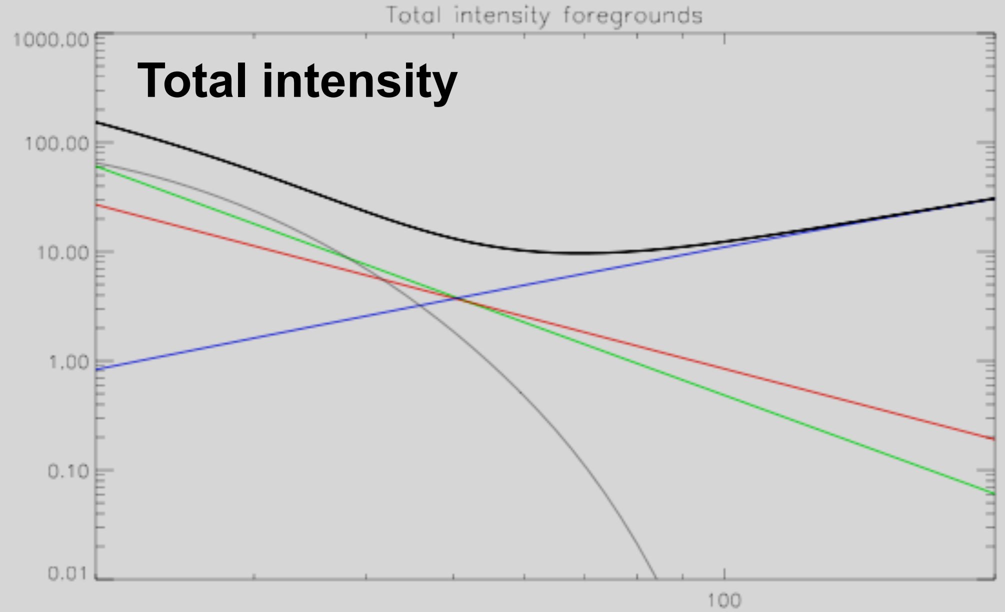
Component	Total-intensity (μK)	Spectrum ν^{β}	Polarization fraction
CMB	70 (r.m.s)	0 (T_{CMB})	1%
Noise	(varies)	(varies)	(varies)
Synchrotron	40 @ 23GHz	-3.0	10%
Free-free	20 @ 23GHz	-2.14	1%
Vib. Dust	15 @94GHz	FDS99 model 8 (~+1.7)	5%
Spinning dust	50 @ 23GHz	WNM (Draine & Lazarian, 1998a)	2%

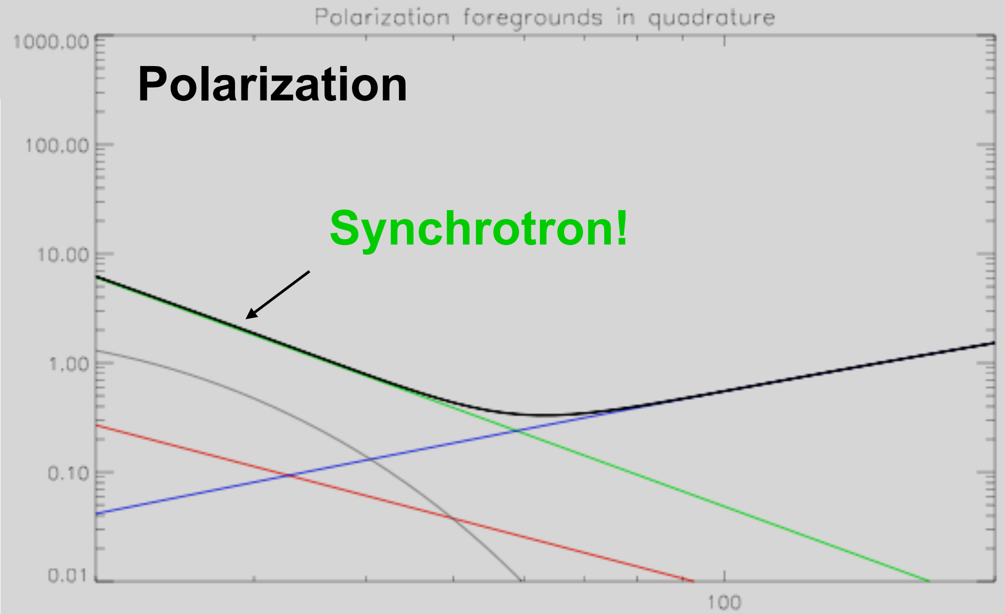
Nominal Foreground Model.

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

Davies et al. (2006)







3 EPIC designs

- Assumes 30% bandwidth, 2xnoise for 1-yr mission, except option 3 (4-yr)
  - Noise levels from Jamie Bock scaled from 7arcmin pixel to 2degrees.
  - Fgfit takes into account effective frequencies (assuming top-hat bandpass)
- #1. 6 channels:
  - 40, 60, 90, 135, 200, 300 GHz.
- #2. 7 channels:
  - 60, 75, 90, 115, 150, 200, 300 GHz.
  - More channels in key range, rely on WMAP (8-yr) for at 23, 33, 41 GHz?
  - Should also consider *Planck* LFI (30,44 GHz).
- #3. 8 channels (4m option):
  - 30, 45, 70, 100, 150, 220, 340, 500 GHz.

Basic results

(average of 1000 realizations of CMB & noise)

EPIC design	Average Q/U CMB Error (μK)
EPIC #1 (40-300GHz, 6 channels)	0.108 μK
EPIC #2 (60-300GHz, 7 channels)	0.114 μK
EPIC #3 (30-500GHz, 8 channels)	0.0755 μK
EPIC #2 + 30GHz channel	0.0962 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!

Planck vs NTD vs TES

(nK!)

Table 2.2.2 Estimated Sensitivities After Foreground Removal

Case	Planck	EPIC/NTD	EPIC/TES
No foregrounds	325	35	11
β_s and β_d fixed	592	77	26
β_s and β_d fitted in 15° pixels	595	81	26
β_s and β_d fitted in 10° pixels	599	85	28
β_s and β_d fitted in 5° pixels	621	108	34
β_s and β_d fitted in 2° pixels	751	203	62

(Bock et al.)

Fits are for single pixels.
Sensitivity increases significantly (factor ~3) by fitting spectral indices over larger pixels
Even worst case can reach r~0.01 (Bock et al.) (via "Knox" formula)

What does it mean?

- Much better than *Planck* by factor >10 in ΔT.
- EPIC frequency designs are within a factor of ~2 only
- TES better than NTD by factor ~3-4 in ΔT.
- Factor of ~3 worse when fitting spectral parameters at 2deg pixel scale

- #1 marginally better noise level even with 1 less channel than #2
  - "Low" frequency channel (40GHz) is important.
- #2 with WMAP (6-yr actually) has virtually no discernable effect on performance!
  - EPIC outperforms WMAP many times over!
  - Maybe *Planck* would do better (I should try this!)
- #3 significantly better (as you would expect!)

- Modelling errors?
  - Synchrotron sp. Index variations (ok here) and curvature / spectral breaks
    - CD to include curvature into Planck Sky Model
    - Polarized anomalous (spinning dust) emission? Probably ok.
    - Include ancillary data e.g. C-BASS, Planck 353GHz etc.
    - E.g. see http://www.astro.caltech.edu/cbass/

WMAP7 vs WMAP9

- Repeated similar analysis to see impact of WMAP9 vs WMAP7 for *Planck*
  - *Planck* ~1.55 μK.
  - *Planck*+WMAP7 ~1.40 μK (11% improvement)
  - *Planck*+WMAP9 ~1.35 μK (15% improvement on *Planck* or 4% improvement on *Planck*+WMAP7)

Including Design constraints

- Need to include realities such as
  - Focal plane area
  - Total power consumption
- Assuming fixed N_{feed} too simplistic (Amblard et al.)
- Calculate sensitivites 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

Frequency range (1)

- Lowest frequency is strongest constraint (larger feed)
  - BUT, is very important for foreground subtraction
- Larger frequency better in most cases with simple model!
  - (e.g. Amblard et al. 2006)
  - Modelling errors are key to defining this better!
  - Ground-based or WMAP/*Planck* may be important (particularly *Planck* at 353GHz)

Freq range (GHz)	Q,U error (μK)
30-250	2.40
40-200	2.82
50-150	3.88
60-100	11.7

Constant signal-to-noise ratio, 7 frequencies, logarithmic spacing

Frequency range (2)

- 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
  - WMAP/*Planck*/other data will help (should be included)

Conclusions

- FGFIT (single pixel mode) is very useful for doing comparisons between experimental designs
  - Also useful for full-sky simulations
  - E.g. foreground cleaned CMB map with errors!
- Experimental constraints have to be folded in
  - ~40-350GHz is widest frequency range we should consider
- Modelling errors are the biggest unknown
  - Updated PSM coming soon (CD will provide maps)
- Commander (Gibbs sampling code) superior for getting absolute errors (e.g. on r)
  - Full propagation of errors naturally to power spectrum (see Hans-Kristian Eriksen's talk)

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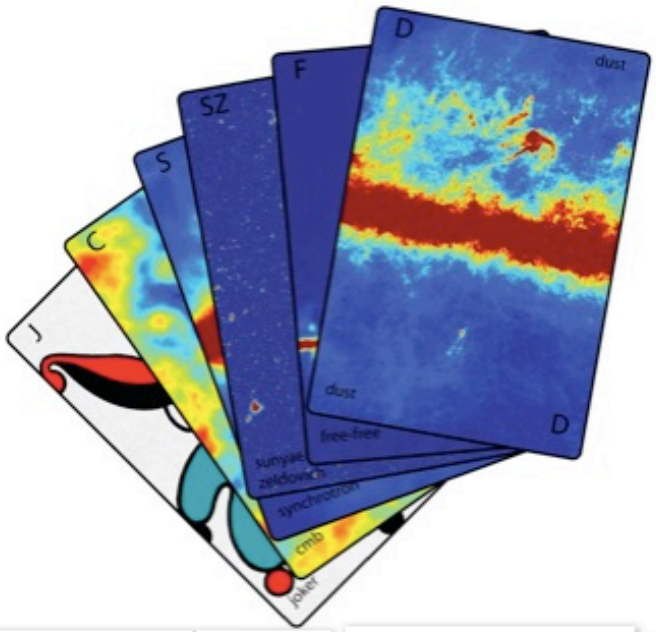
CMB component separation and the physics of foregrounds



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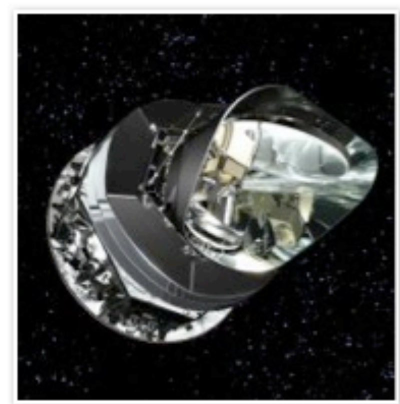

http://planck.ipac.caltech.edu/content/ForegroundsConference/Home.html