Extracting Science from the Planck Mission

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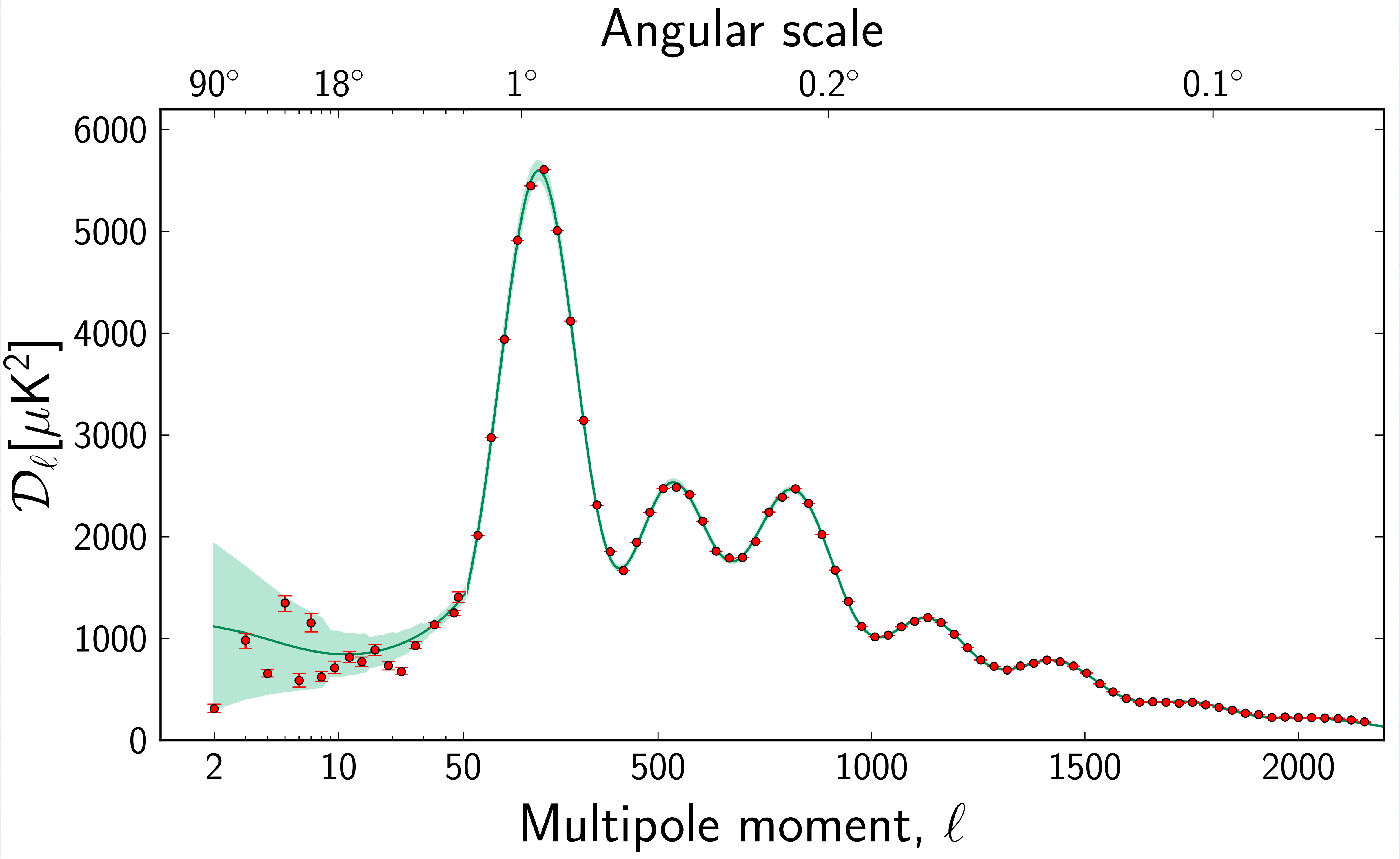
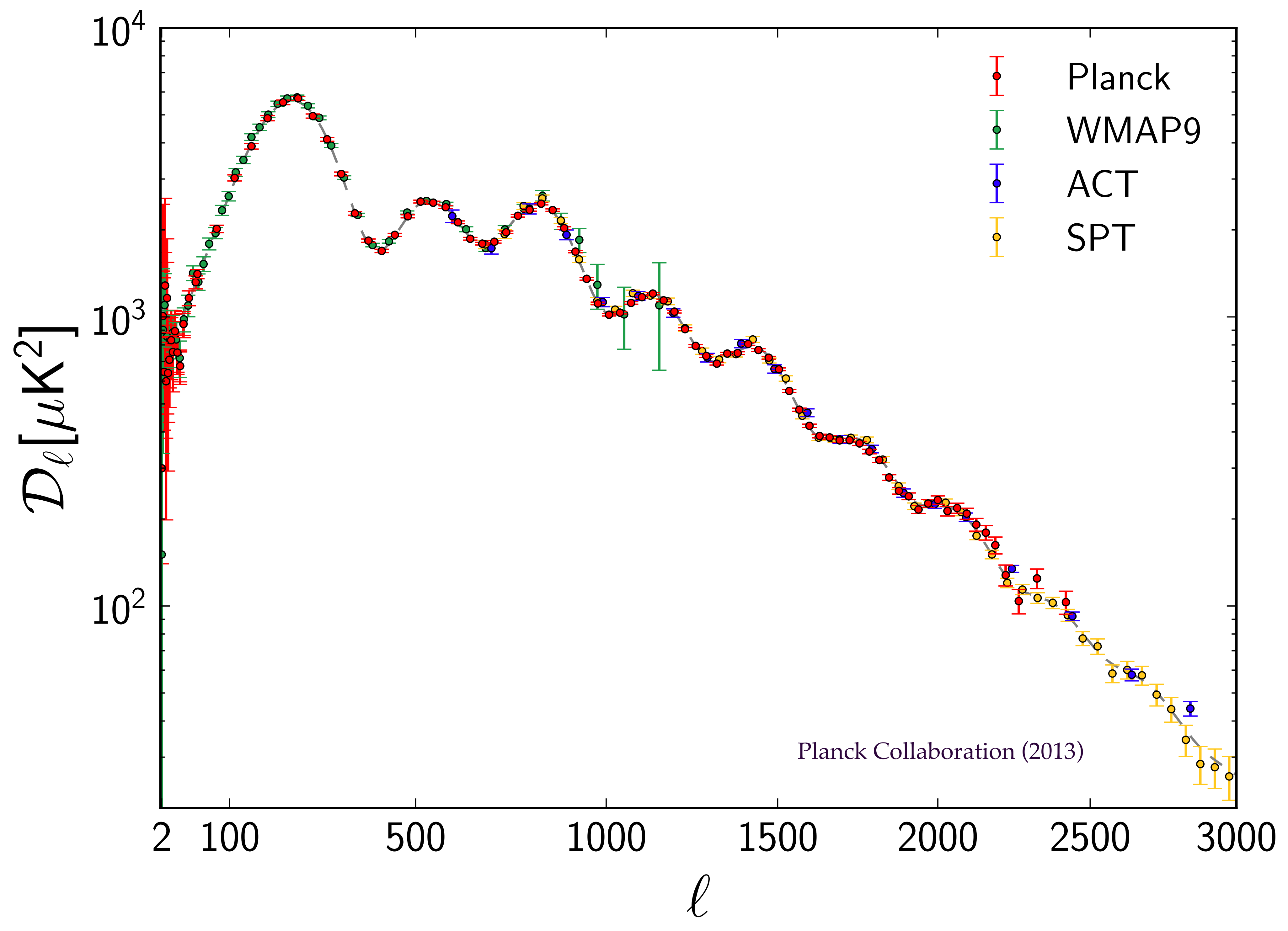
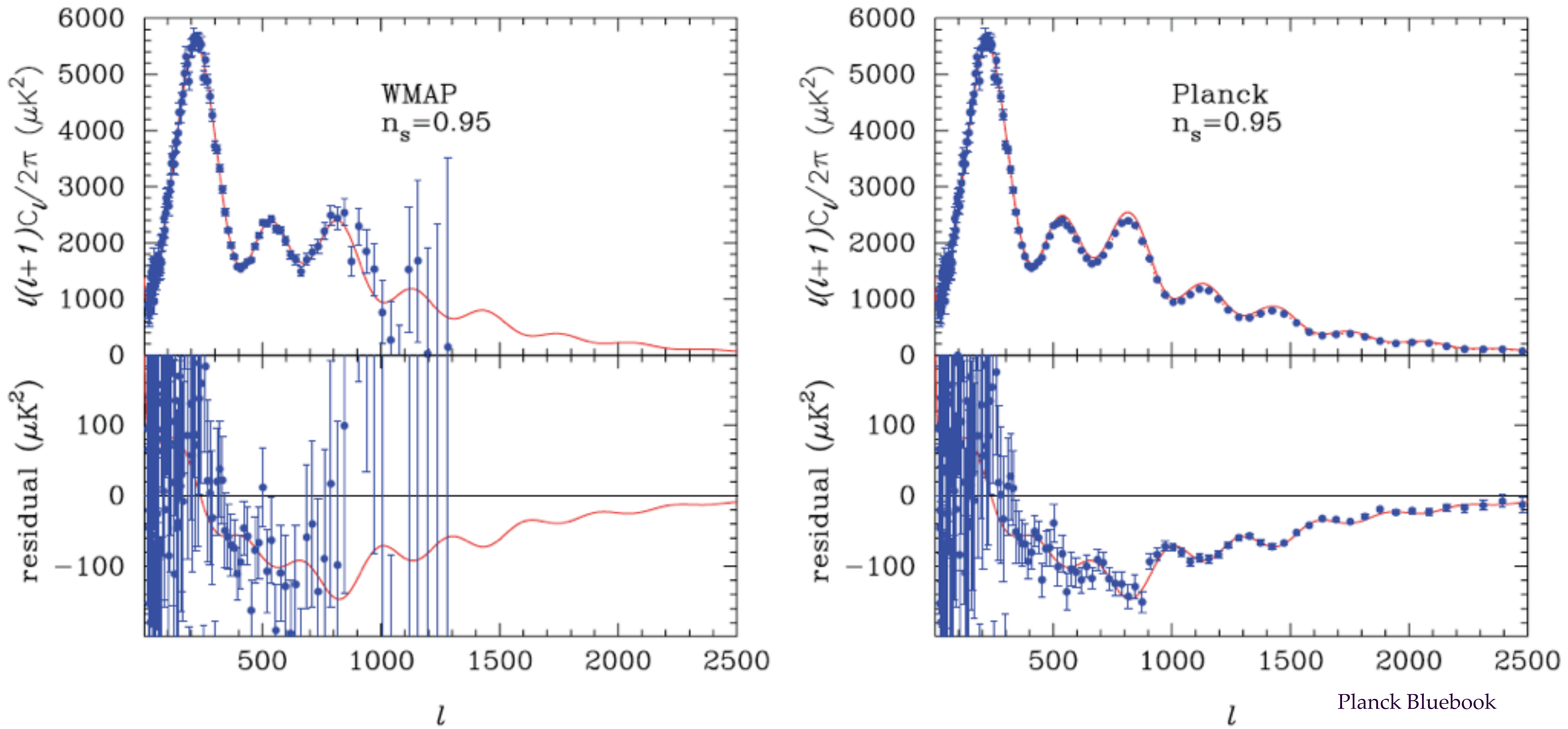
Temperature Power Spectrum



Temperature Power Spectrum



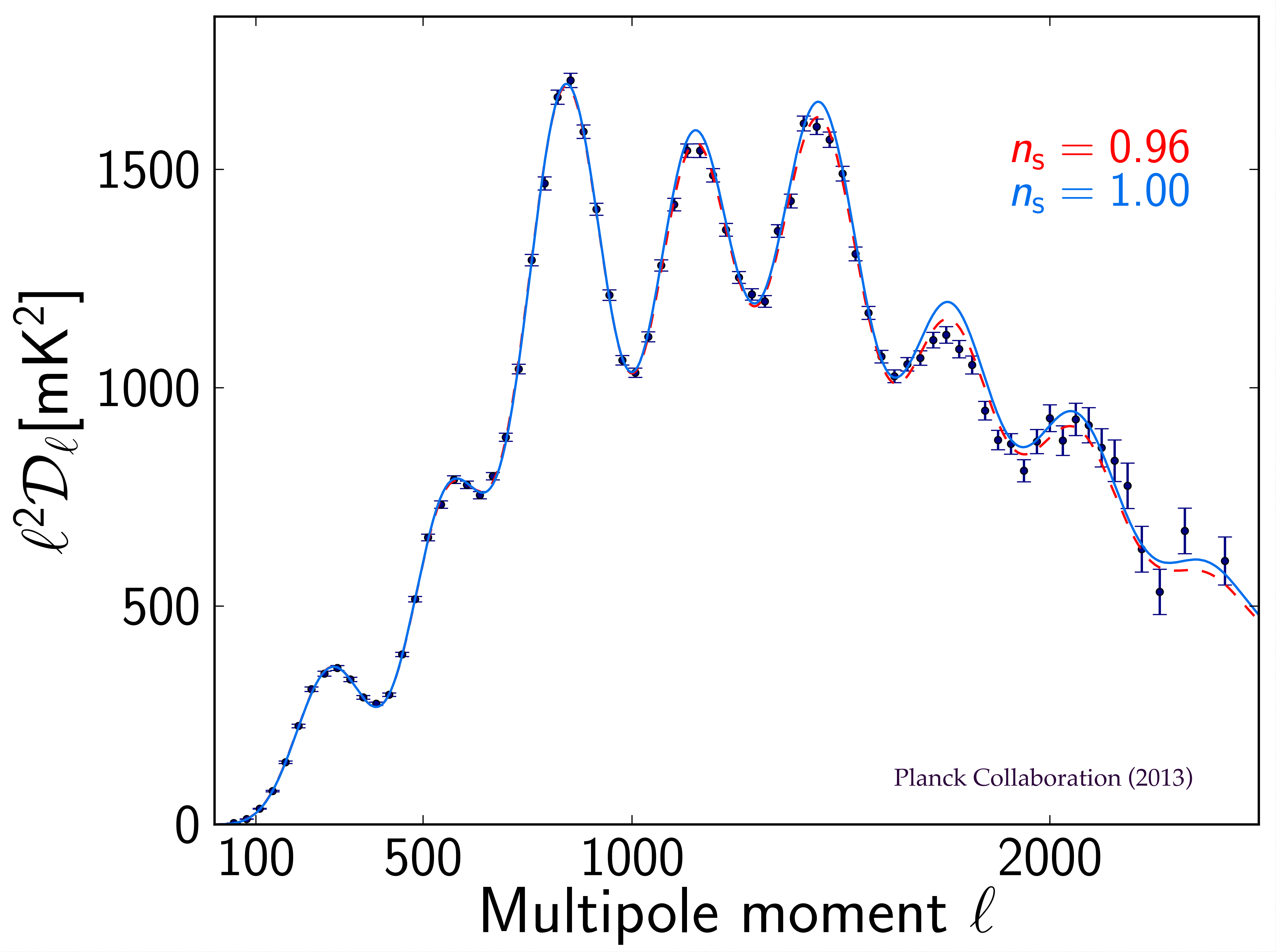
Motivation for Accuracy



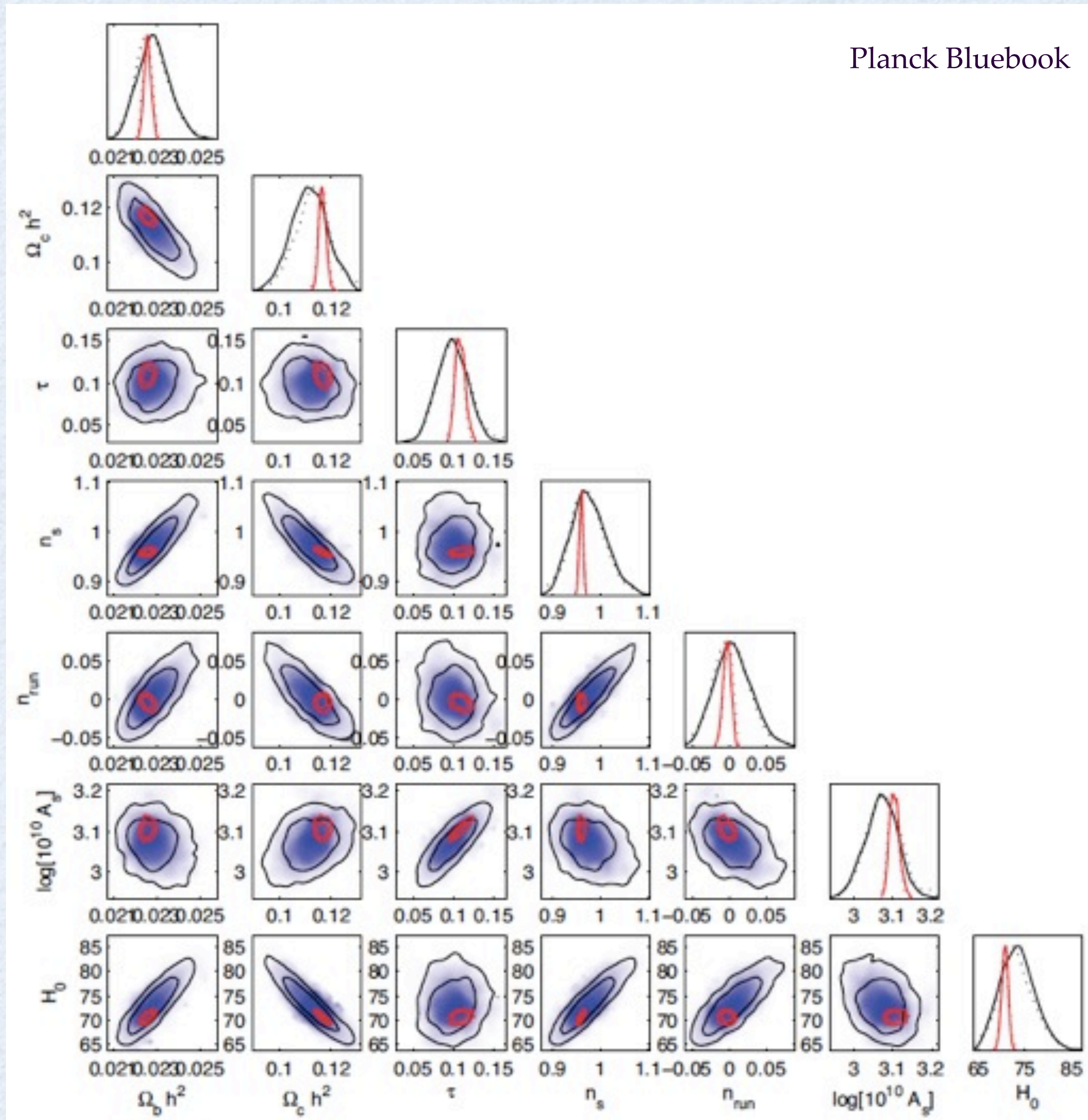
Planck Bluebook

How well WMAP and Planck rule out n_s=1

Motivation for Accuracy



Planck: Parameters Goal



- 3-10 x improvement in cosmological parameters

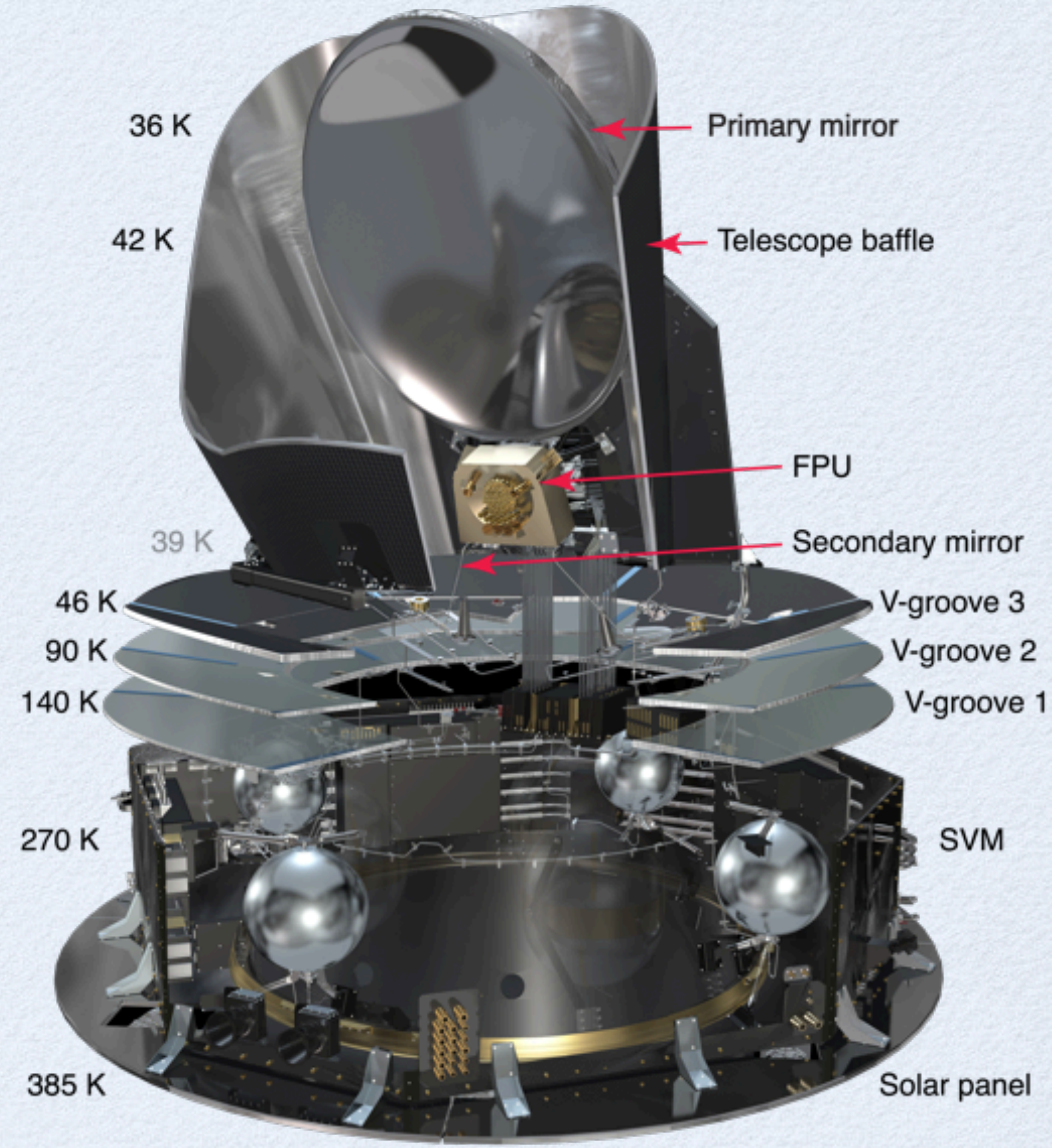
Timeline

- Launched with Hercshel
  - 14 May 2009
- First Light Survey
  - 13-27 Aug 2009
- Early release
  - 11 Jan 2011
- First cosmology release
  - 21 Mar 2013

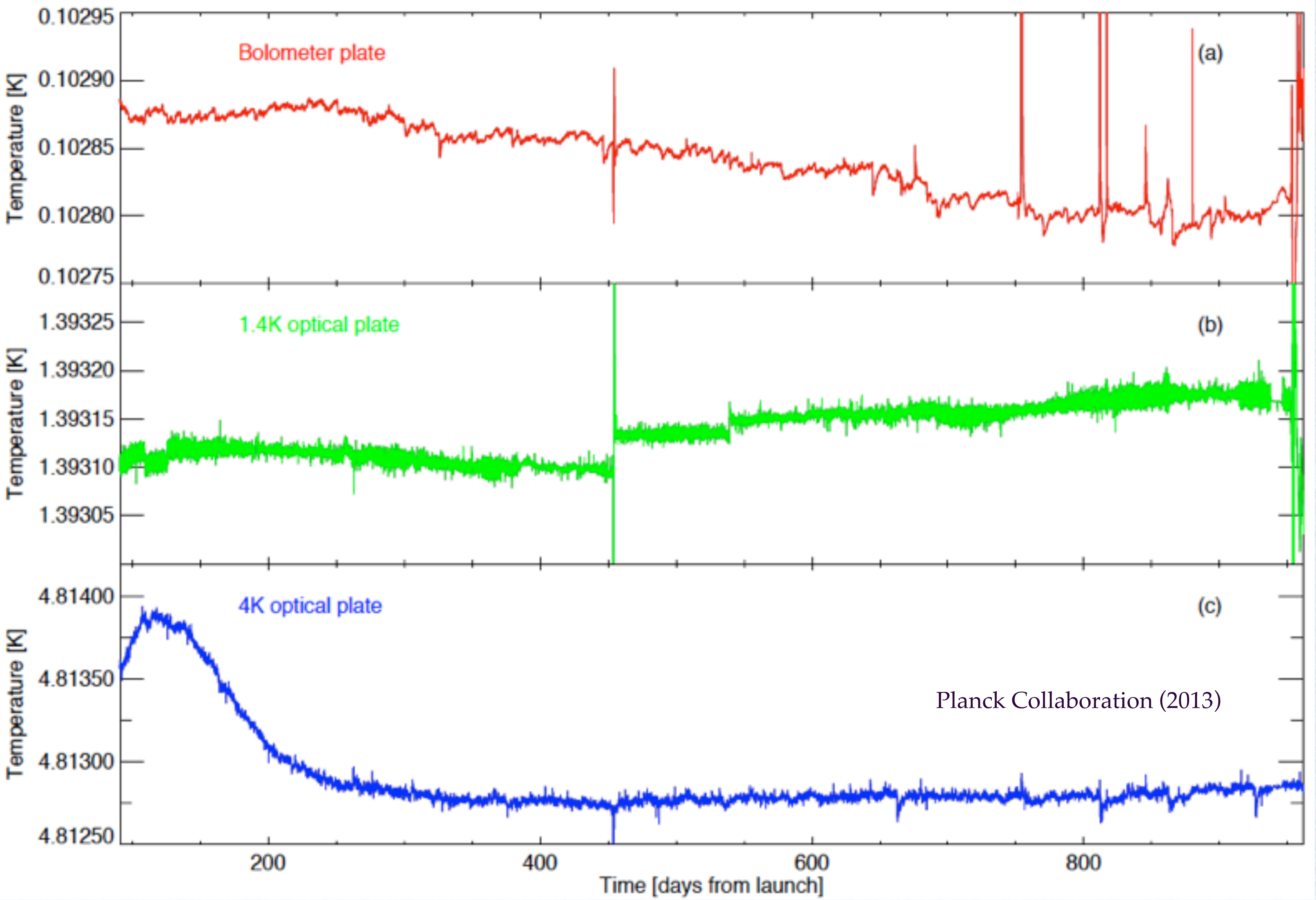
Credit: ESA

Coolest Satellite in Space!

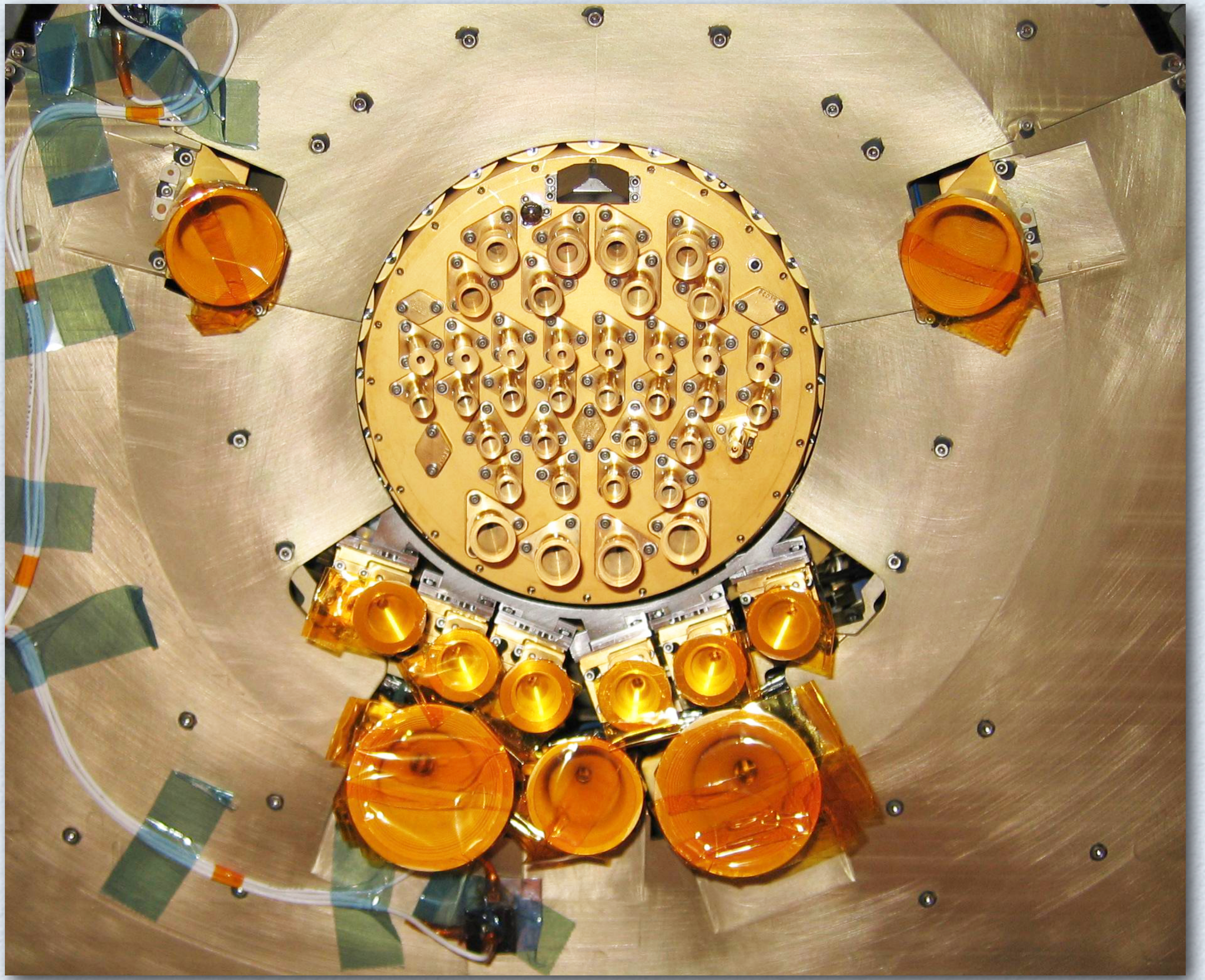
- H_2 Sorption cooler
  - LFI FPU to < 20K
  - pre-cool lower stages
- ^{4}He J-T cooler
  - HFI FPU and LFI reference loads to < 5K
  - only moving part
- Dilution cooler
  - HFI bolometers to 0.1K



Cool and Stable

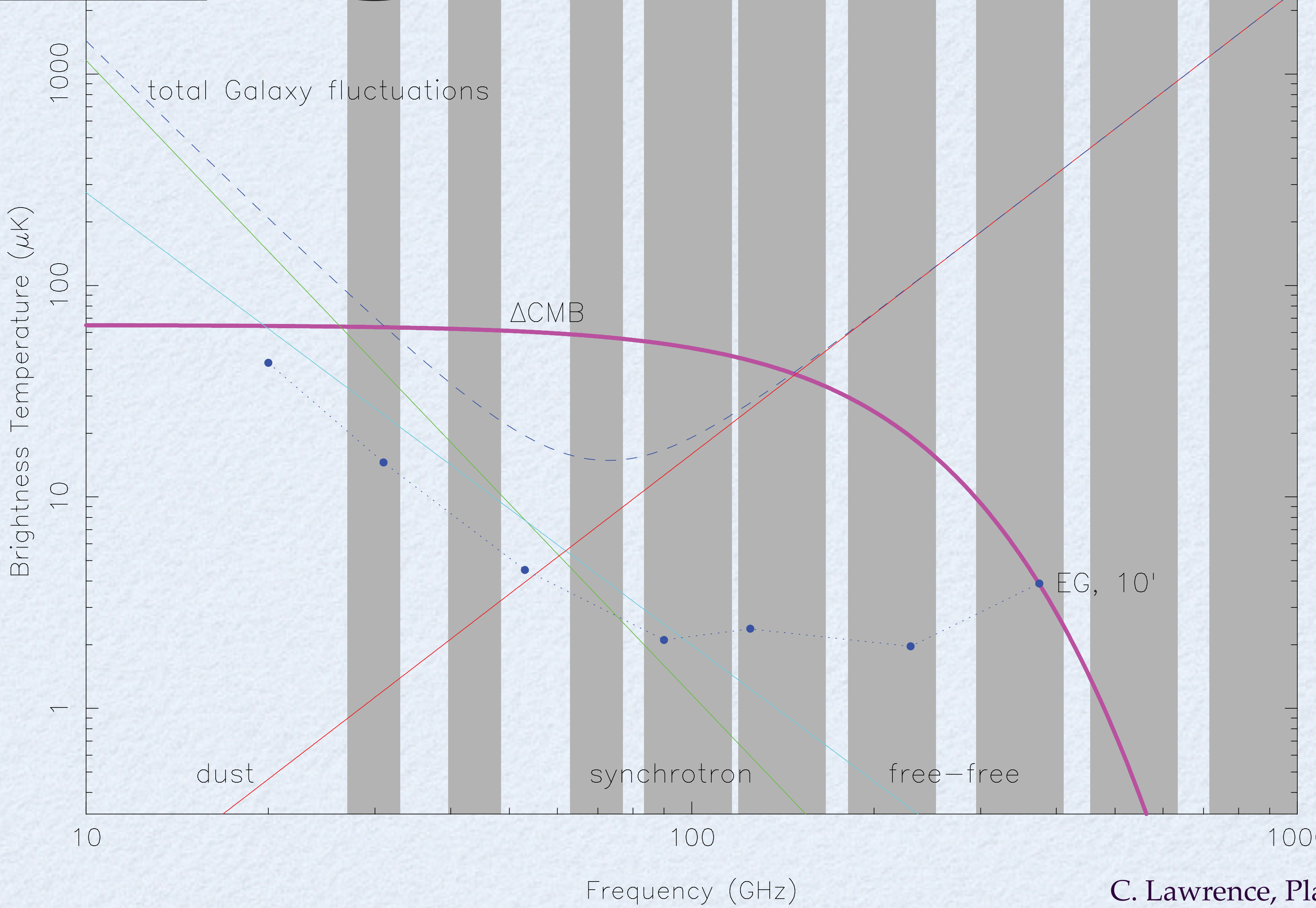


Planck Focal Plane



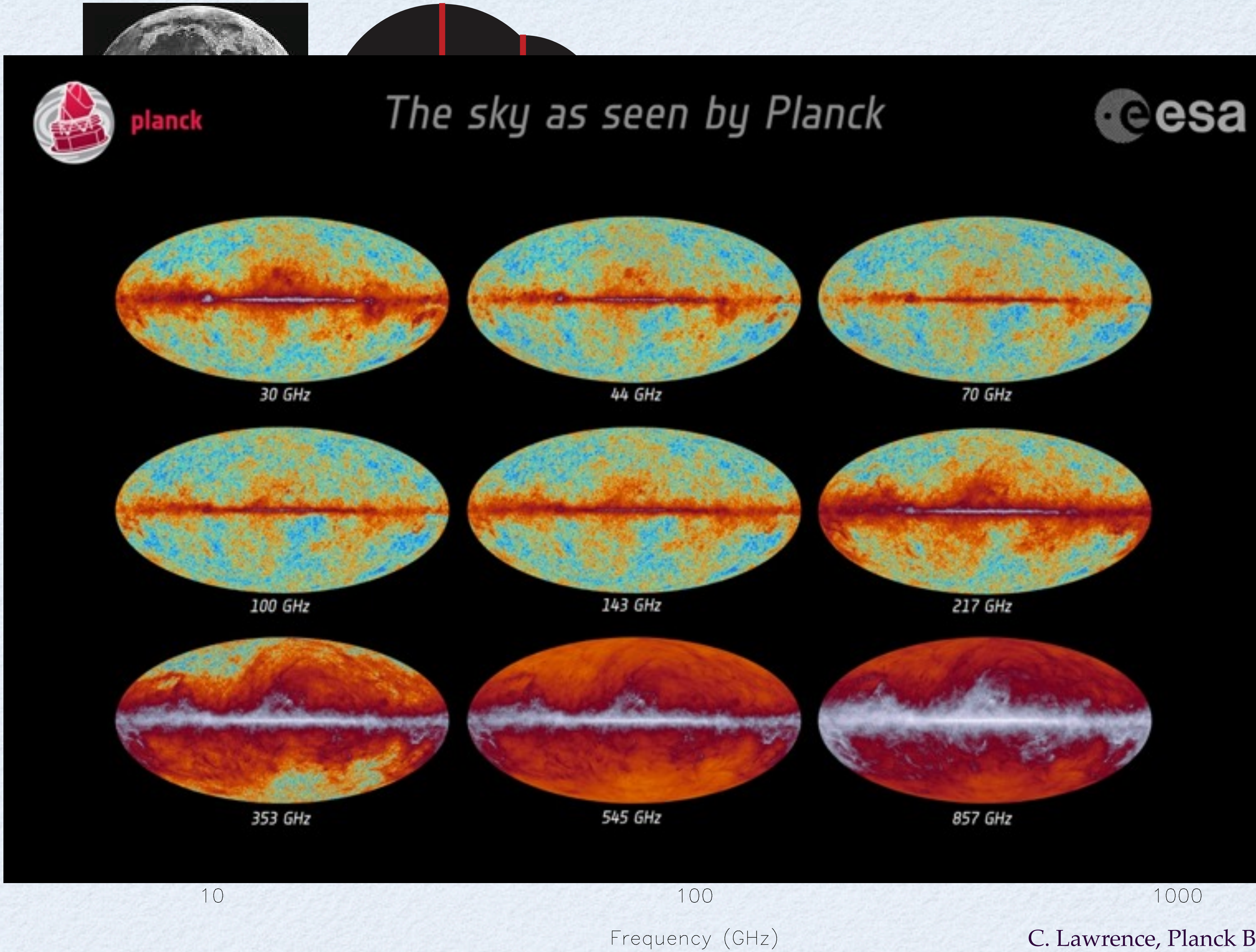
Credit: ESA, HFI & LFI consortia

Nine Frequency All Sky Survey



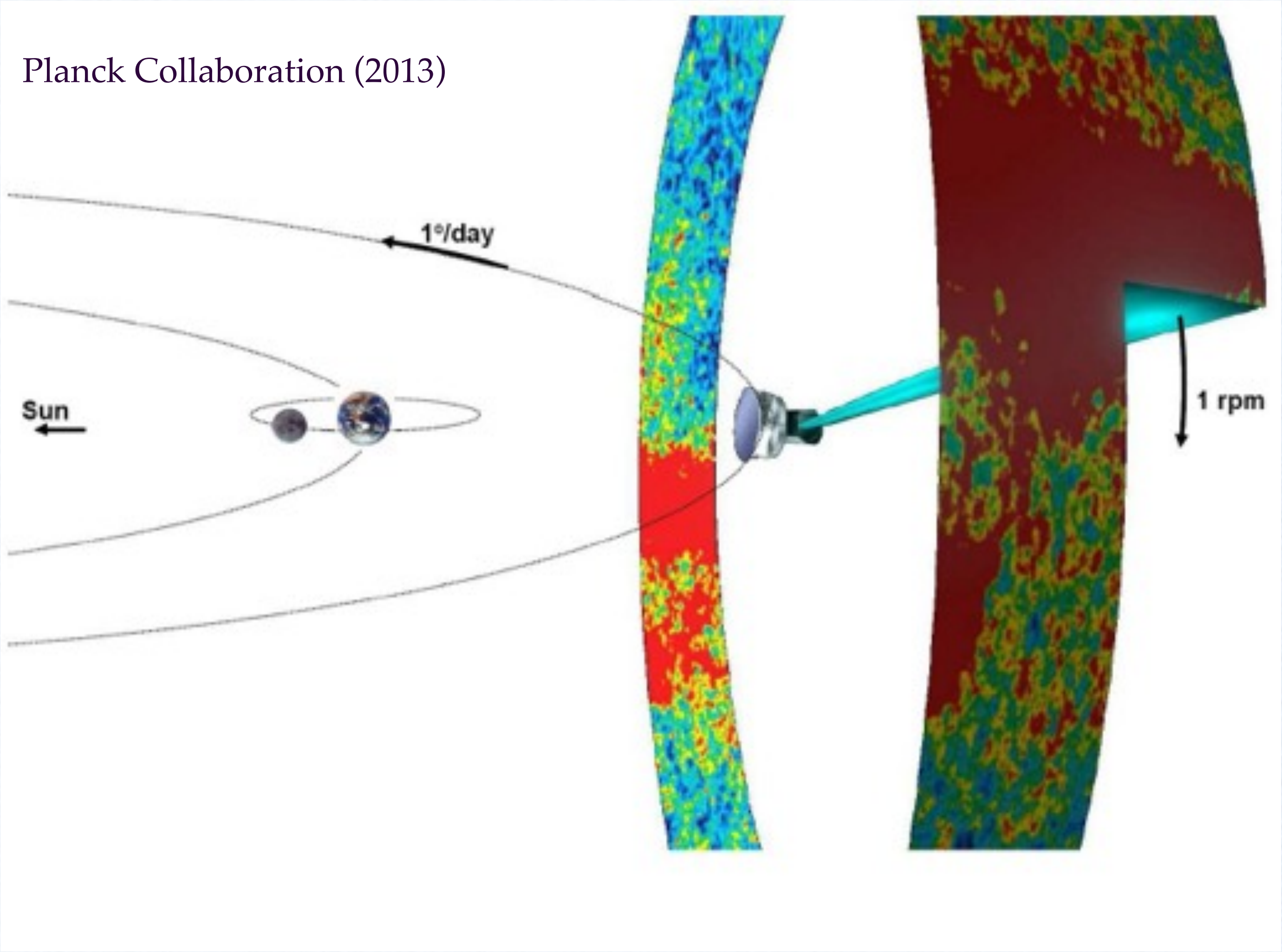
C. Lawrence, Planck Bluebook

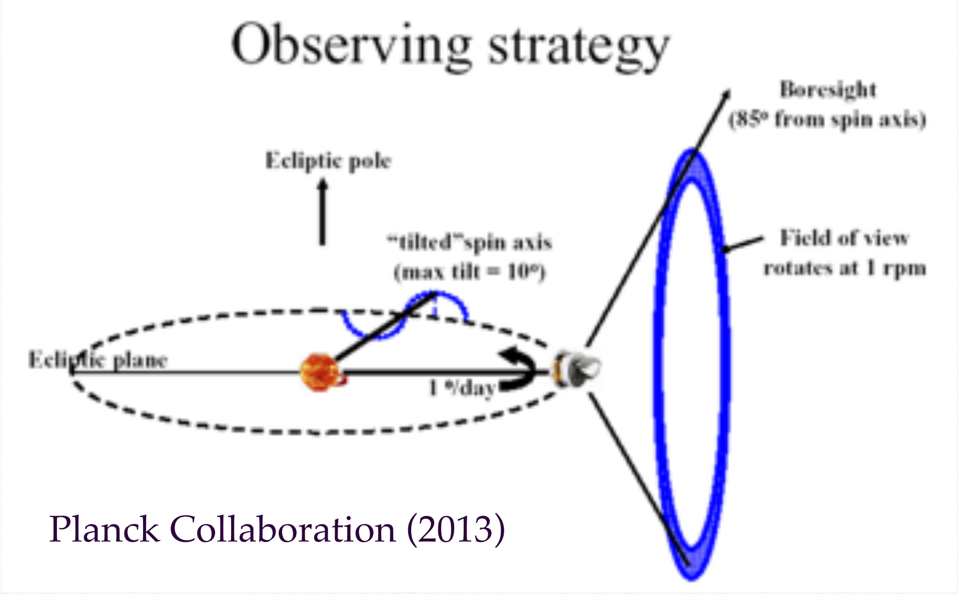
Nine Frequency All Sky Survey



C. Lawrence, Planck Bluebook

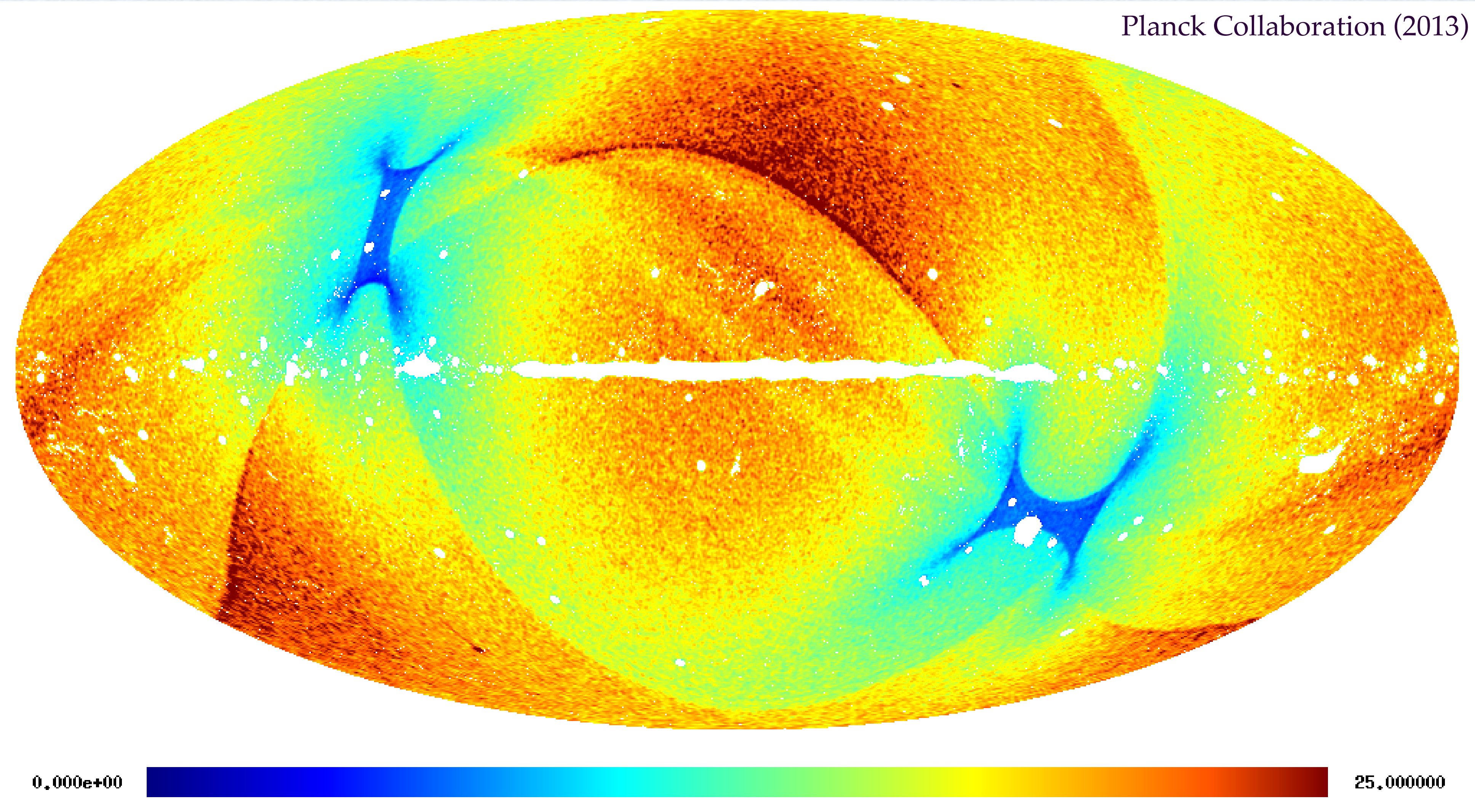
Scanning Strategy



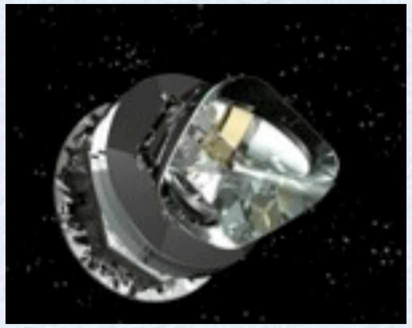


White Noise Level

- SMICA noise map, RMS noise is ~17μK



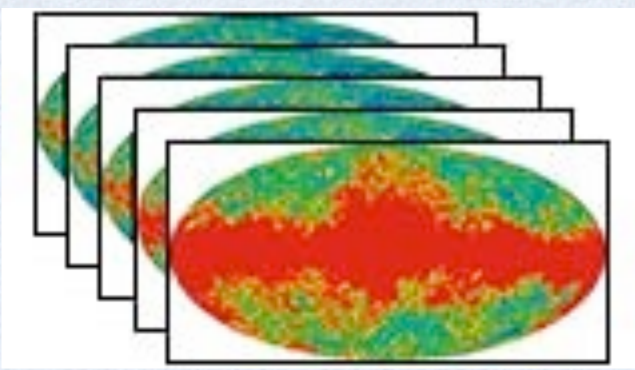
Analysis in a Nutshell



Preprocessing, deglitching, ...

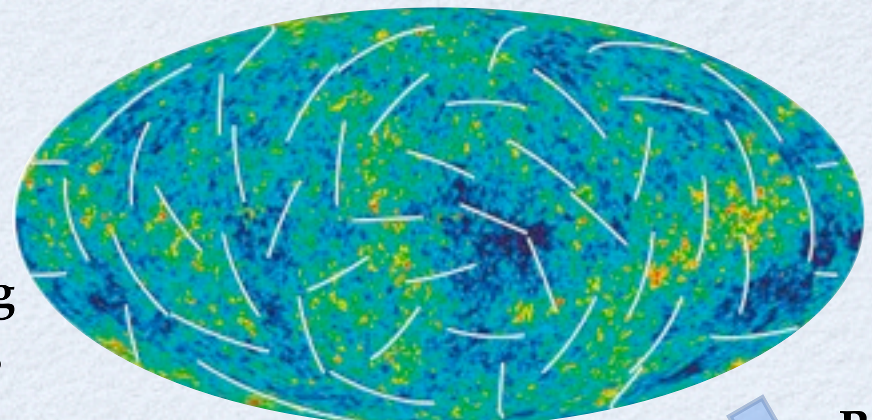
Long chain of data processing centers in Australia, France, Italy, USA, ...

Partial deconvolution and Map Making



Foreground cleaning w/ or w/o templates

Credit: K.Gorski
Images: LAMBDA & ESA



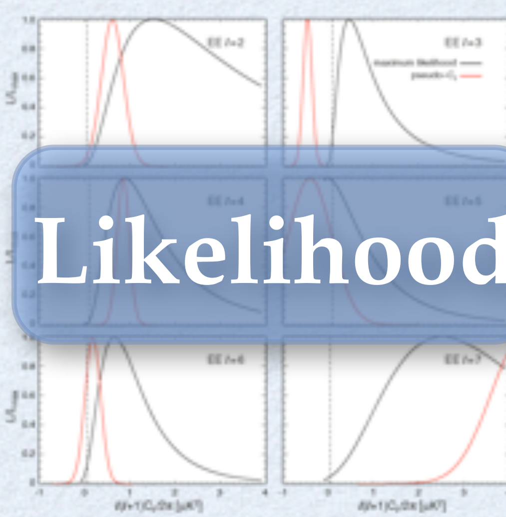
Non-Gaussianity
Statistical Isotropy

Pseudo C_l

MCMC

MCMC

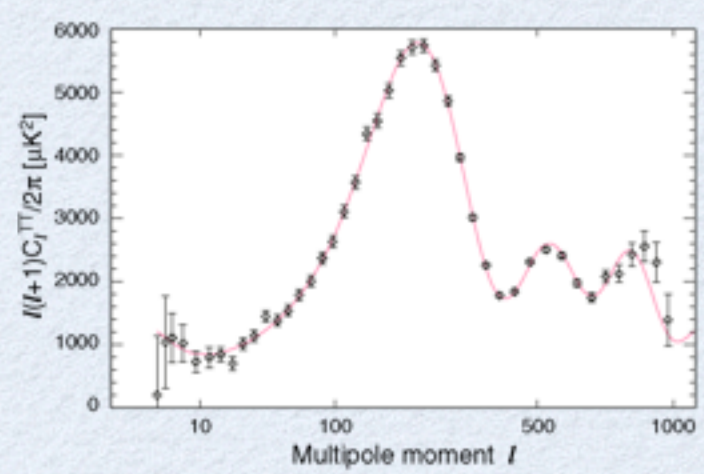
n_s Ω_b σ_8 Ω_0 h τ



Likelihood

Low multipoles

Cosmology Model



Extended Analyses

- Non-Gaussianity of CMB anisotropy
- Statistical anisotropy of CMB
- Reconstruction of Primordial power spectrum
- Reconstruction of lensing potential
- Possibly more to follow...

Redundancy in Analyses

- Redundancy in observation
  - detectors visit each direction at different times
- Multiplicity of methods
- Comparison of LFI and HFI
  - a big plus point for Planck
- Simulations
  - realistic simulations to track systematic effects
  - total 250,000 maps simulated, largest in CMB analyses!

Map Making

- Linear convolution equation with Gaussian noise

$$\mathbf{d} \;=\; \mathbf{K}\cdot\mathbf{m} \;+\; \mathbf{n}$$

- Log-Likelihood

$$\ln[\mathfrak{P}(\mathbf{d}|\mathbf{m})] \;=\; -\frac{1}{2}\Big((\mathbf{d}-\mathbf{K}\cdot\mathbf{m})^T\cdot\mathbf{N}^{-1}\cdot(\mathbf{d}-\mathbf{K}\cdot\mathbf{m}) + \mathrm{Tr}[\ln\mathbf{N}]\Big)$$

- Maximum Likelihood Solution

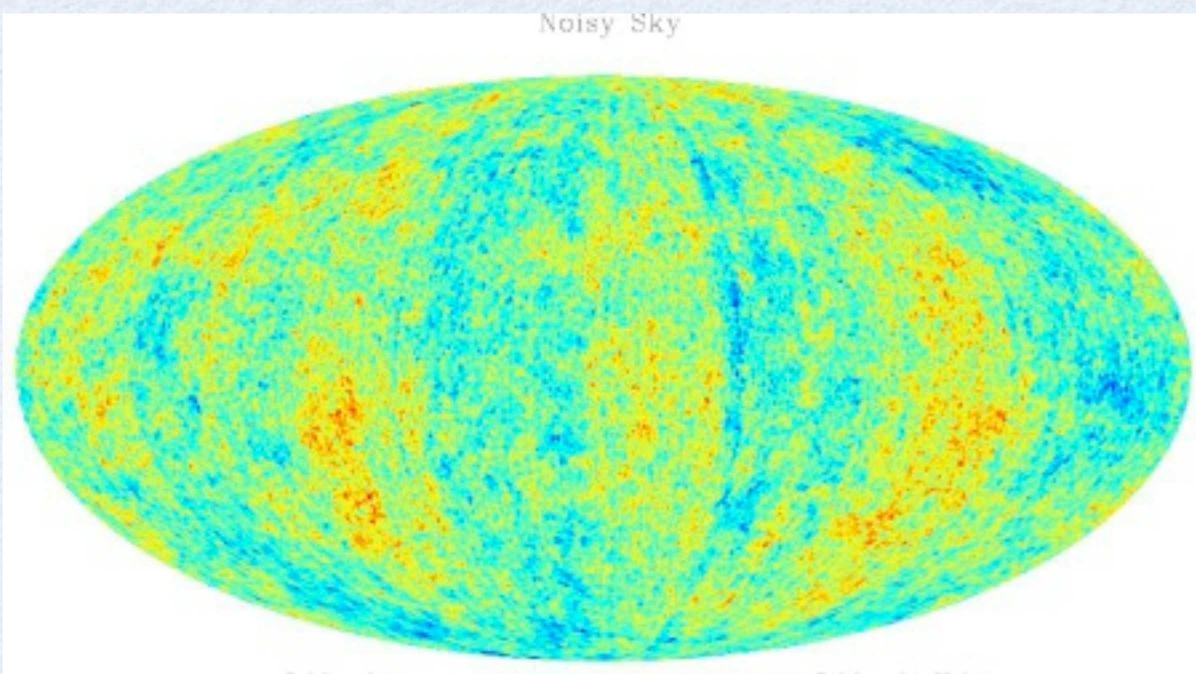
$$\hat{\mathbf{m}} \;=\; \left(\mathbf{K}^T\,\mathbf{N}^{-1}\,\mathbf{K}\right)^{-1}\,\mathbf{K}^T\,\mathbf{N}^{-1}\cdot\mathbf{d}$$

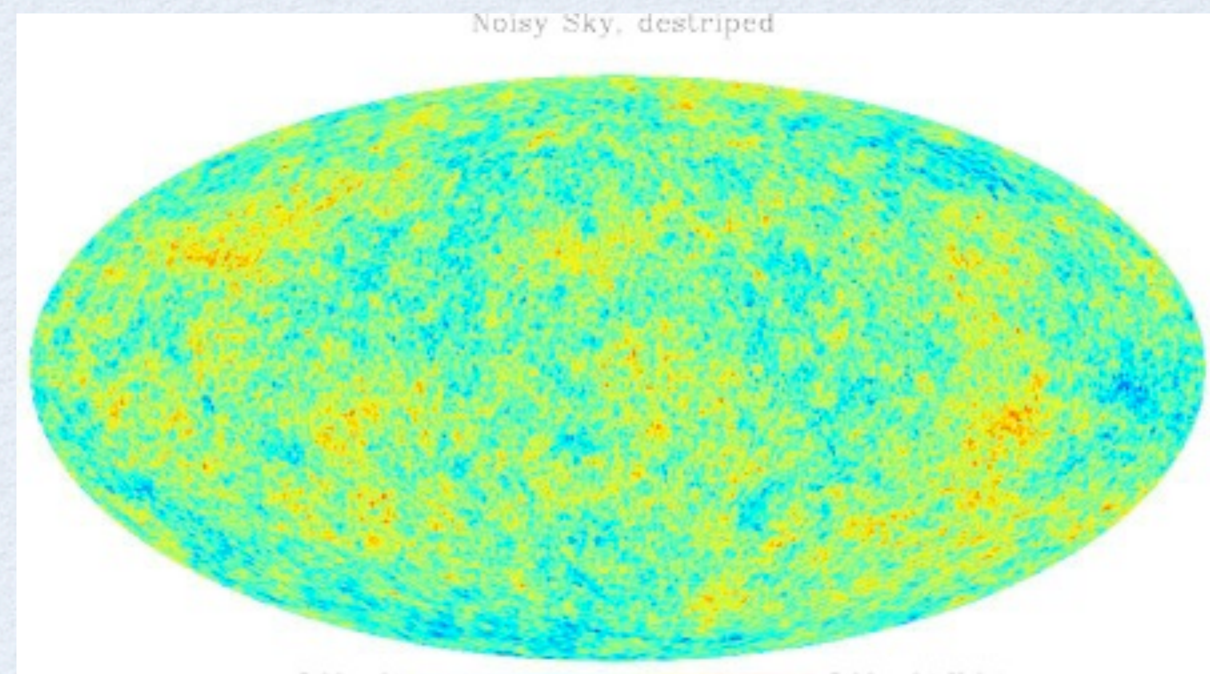
- Final noise covariance matrix of the solution

$$\mathbf{\Sigma} \;=\; \left(\mathbf{K}^T\,\mathbf{N}^{-1}\,\mathbf{K}\right)^{-1}$$

Map Making

- Optimal (a Generalized Least Square solution)
  - computationally expensive
- Destriping
  - cleverly remove 1/f noise “offsets”

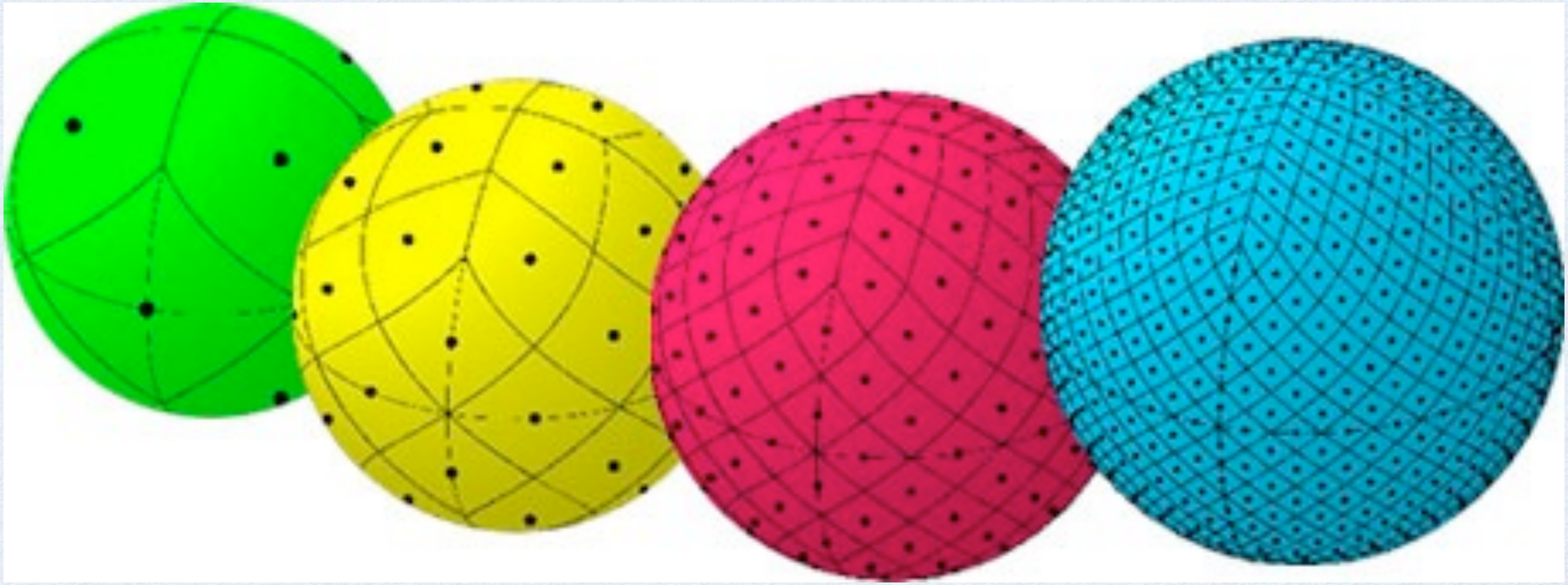




http://www.helsinki.fi/~tfo_cosm/destriping.html

HEALPix

- Hierarchical Equal Area isoLatitude Pixelization

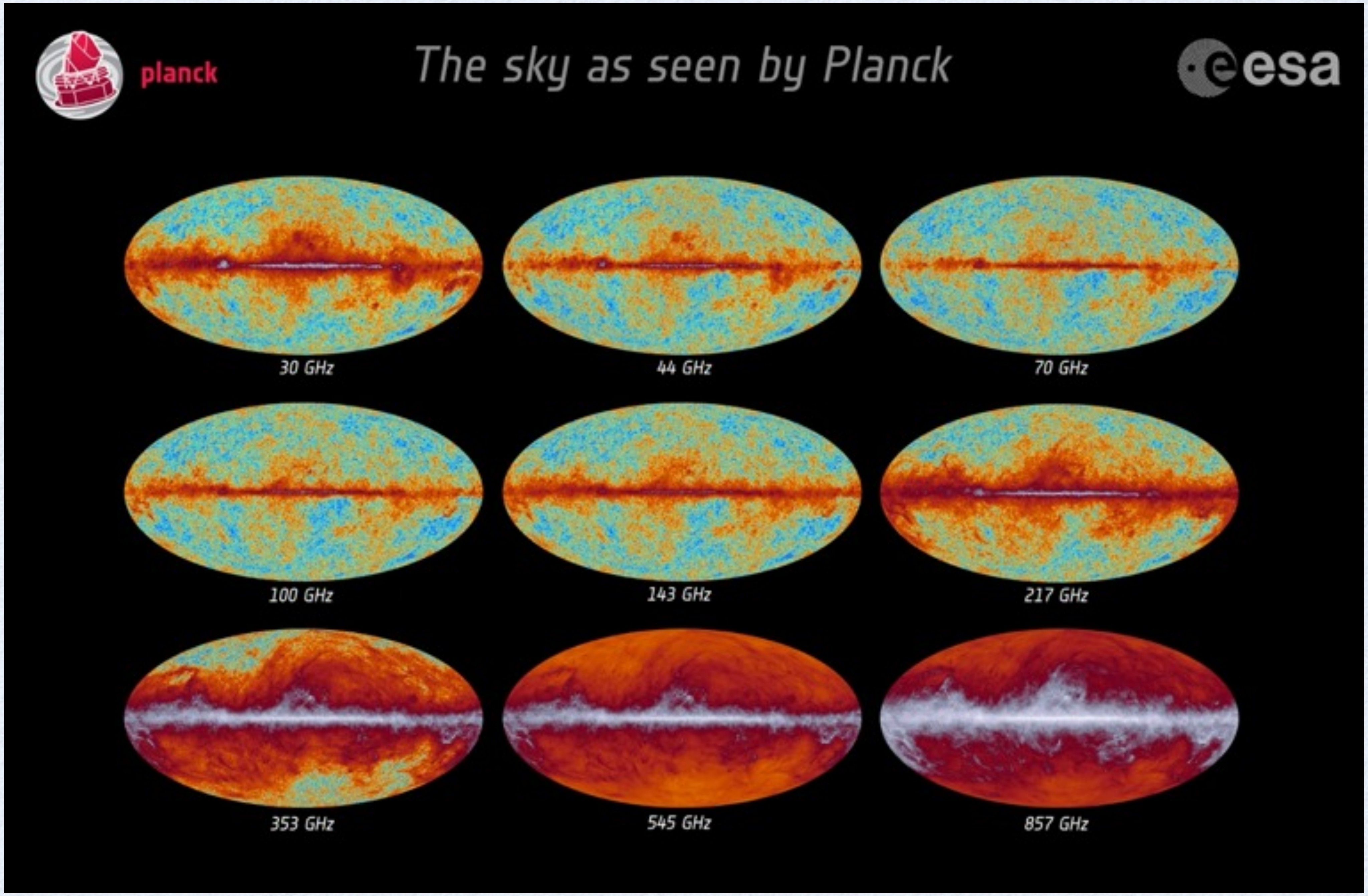


http://healpix.jpl.nasa.gov/

Gorski et al. (2005)

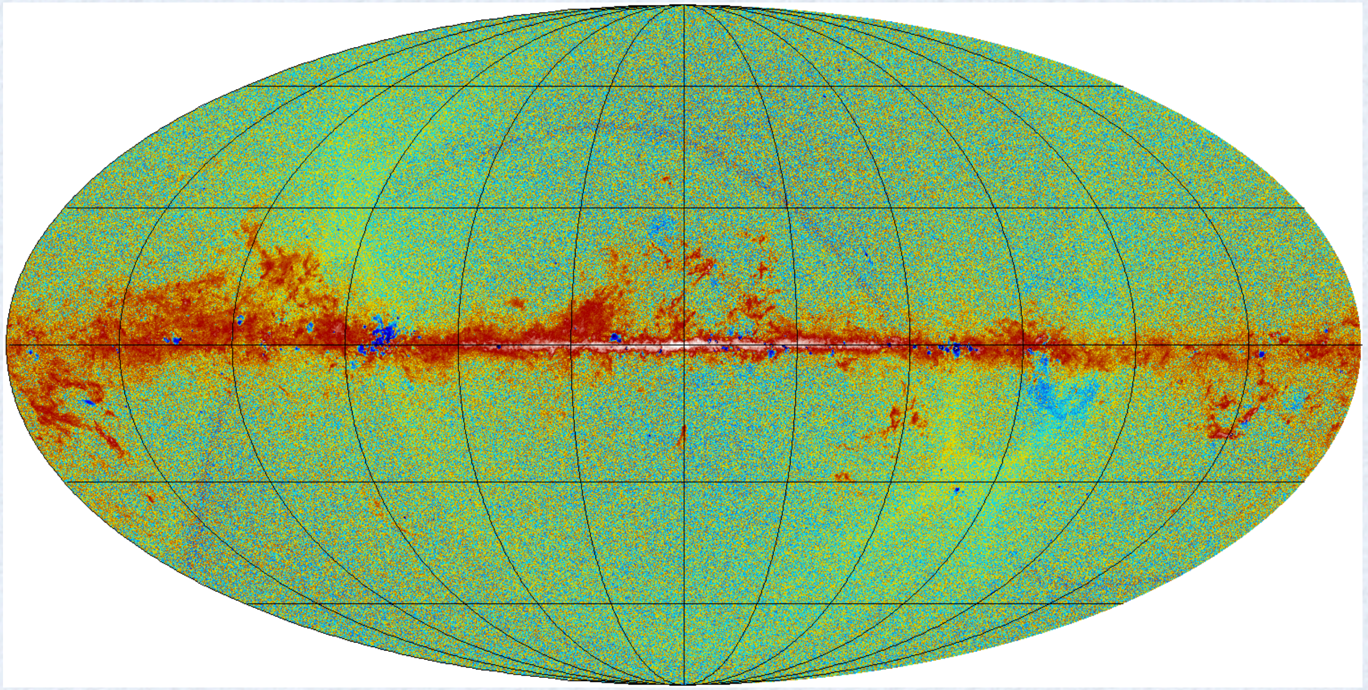
Planck Maps

Planck Maps

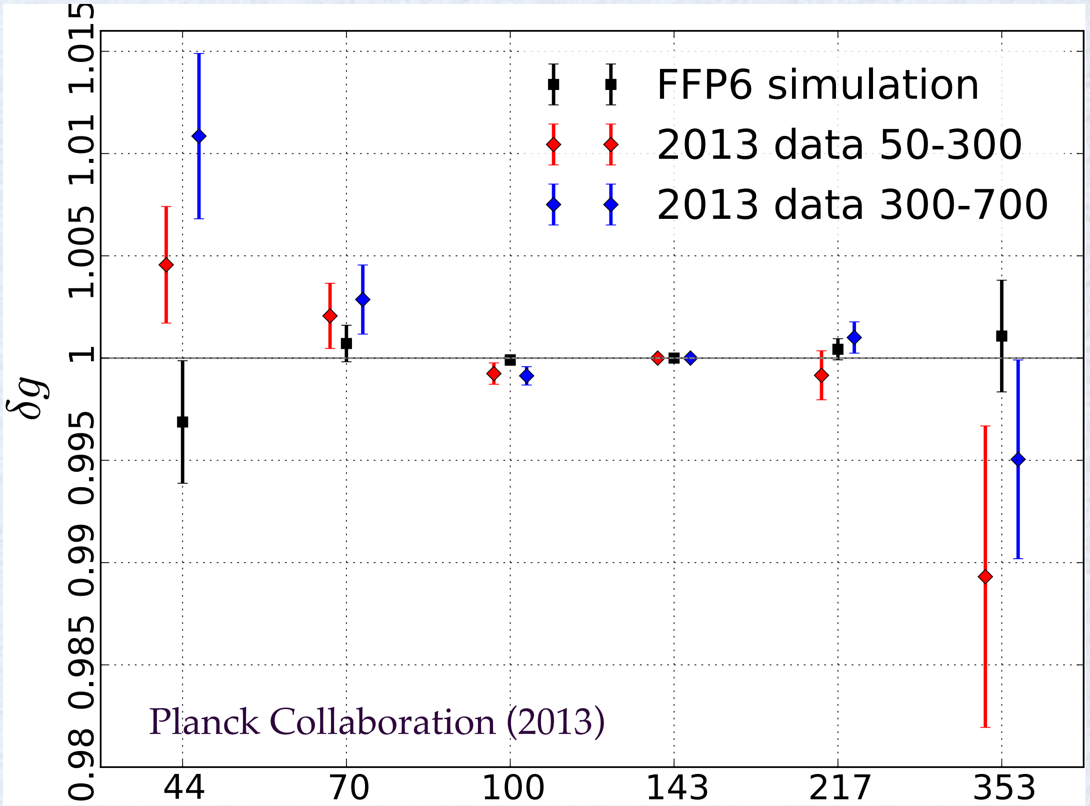


planck
The sky as seen by Planck
esa
30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz

Inter-frequency Consistency



100GHz - 70GHz



Gain factor required to match 143GHz for two multipole ranges

Component Separation

$$d_\nu = b_\nu * \left(\sum_c A_{\nu c} s_c \right) + n_\nu$$

convolution

component maps

beam

observed map

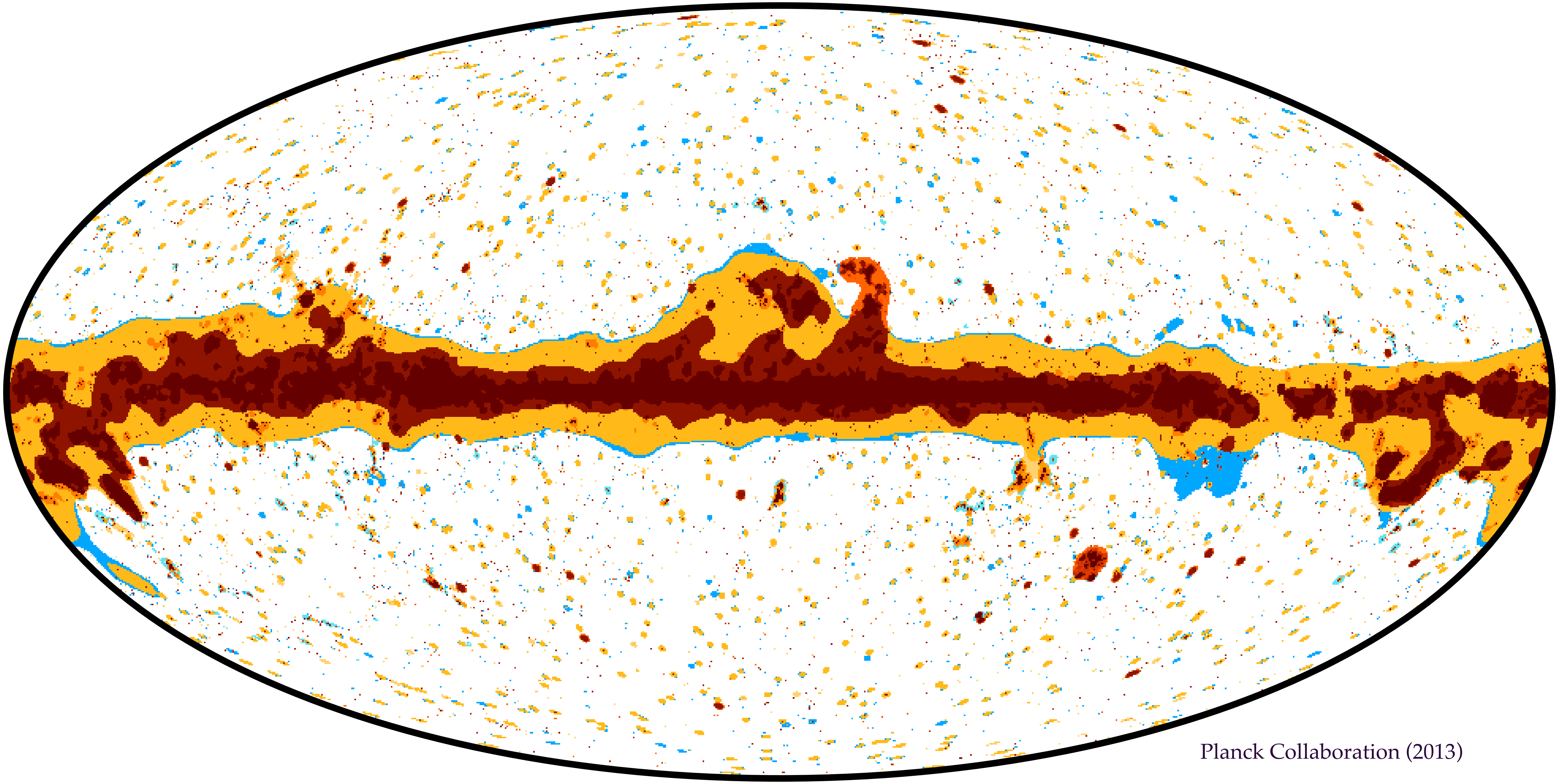
mixing matrix

noise

Leach et al. (2008)
A&A 491, 597

	Channels used	Components modelled	Resources and runtime
COMMANDER	WMAP, PLANCK 30–353 GHz,	CMB, dust, sync, FF, mono-,dipoles	1000 CPU h, 2 day
CCA	PLANCK, Haslam 408 MHz	CMB, dust, sync, FF	70 CPU h, 1.5 day
GMCA	PLANCK, Haslam 408 MHz	CMB, SZ, sync., FF	1200 CPU h, 6 day
FastICA	143–353 GHz	Two components (CMB and dust)	21 CPU min, 20 s
FastMEM	PLANCK	CMB, SZ, dust, sync, FF	256 CPU h, 8 h
SEVEM	PLANCK	CMB	30 CPU h, 30 h
SMICA	PLANCK, WMAP	CMB, SZ, dust, total galaxy	8 CPU h, 4 h
WI-FIT	70–217 GHz	CMB	400 CPU h, 8 h

Masking Scheme



Planck Collaboration (2013)

Power Spectrum Estimation

- Low multipoles

$$p(\mathbf{d}|C_\ell) = \frac{\exp[(-(1/2)\mathbf{d}^T\mathbf{C}^{-1}\mathbf{d}]}{\sqrt{\det\mathbf{C}}}$$

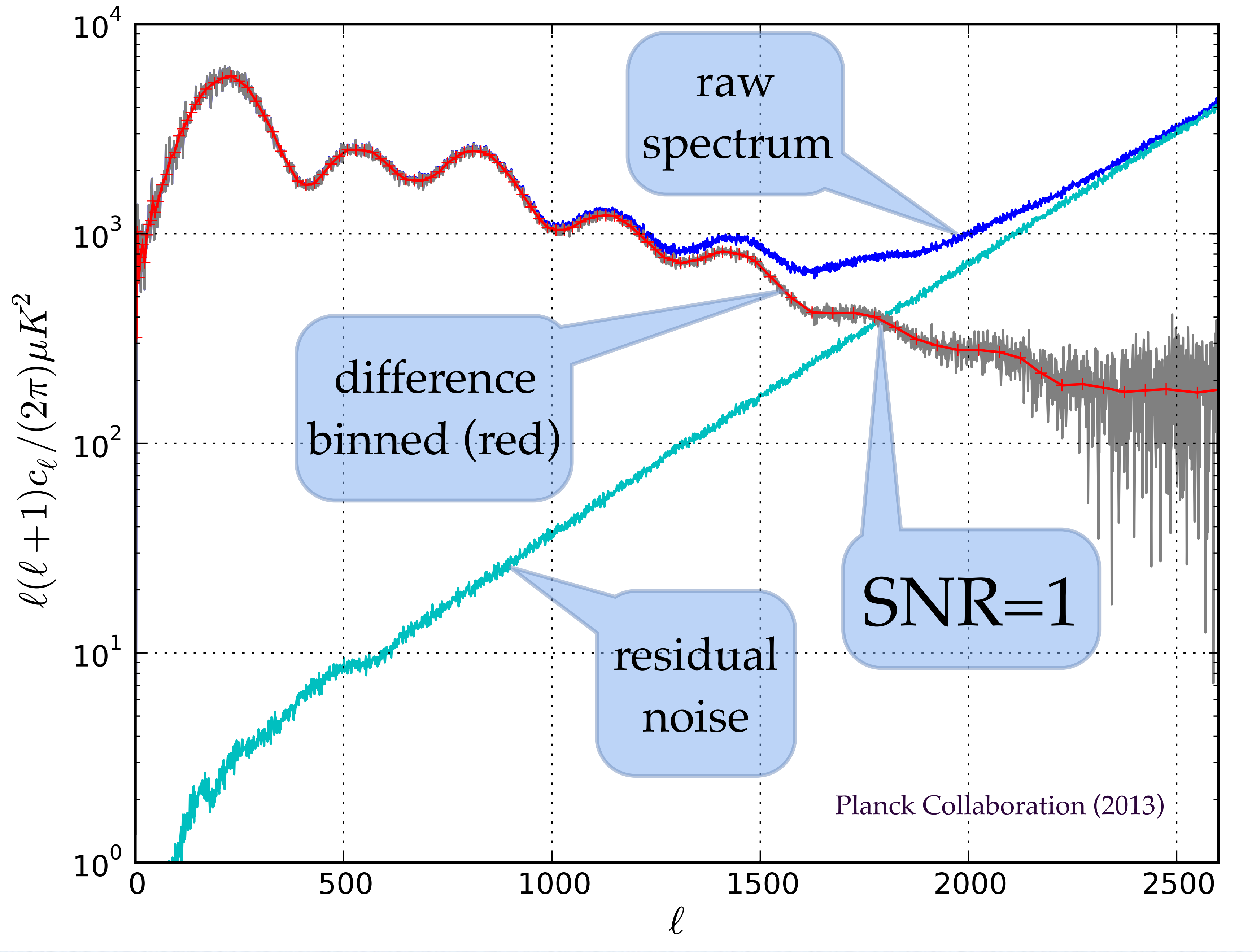
$$\mathbf{C}(C_\ell) = \mathbf{S}(C_\ell) + \mathbf{N}$$

  - MCMC likelihood analysis
    - can incorporate full noise covariance matrix (at low-res)
    - also separates components at the same time
  - Computationally expensive
- High multipoles

$$C_l^{\rm obs} := \frac{1}{2l+1}\sum_{m=-l}^{l}|a_{lm}^{\rm obs}|^2$$

  - Pseudo-C_l estimator
    - power spectra of harmonic transforms of observed CMB sky
  - must account for systematic effects of beam

Power Spectrum and Residual



Systematic Effects: Beam

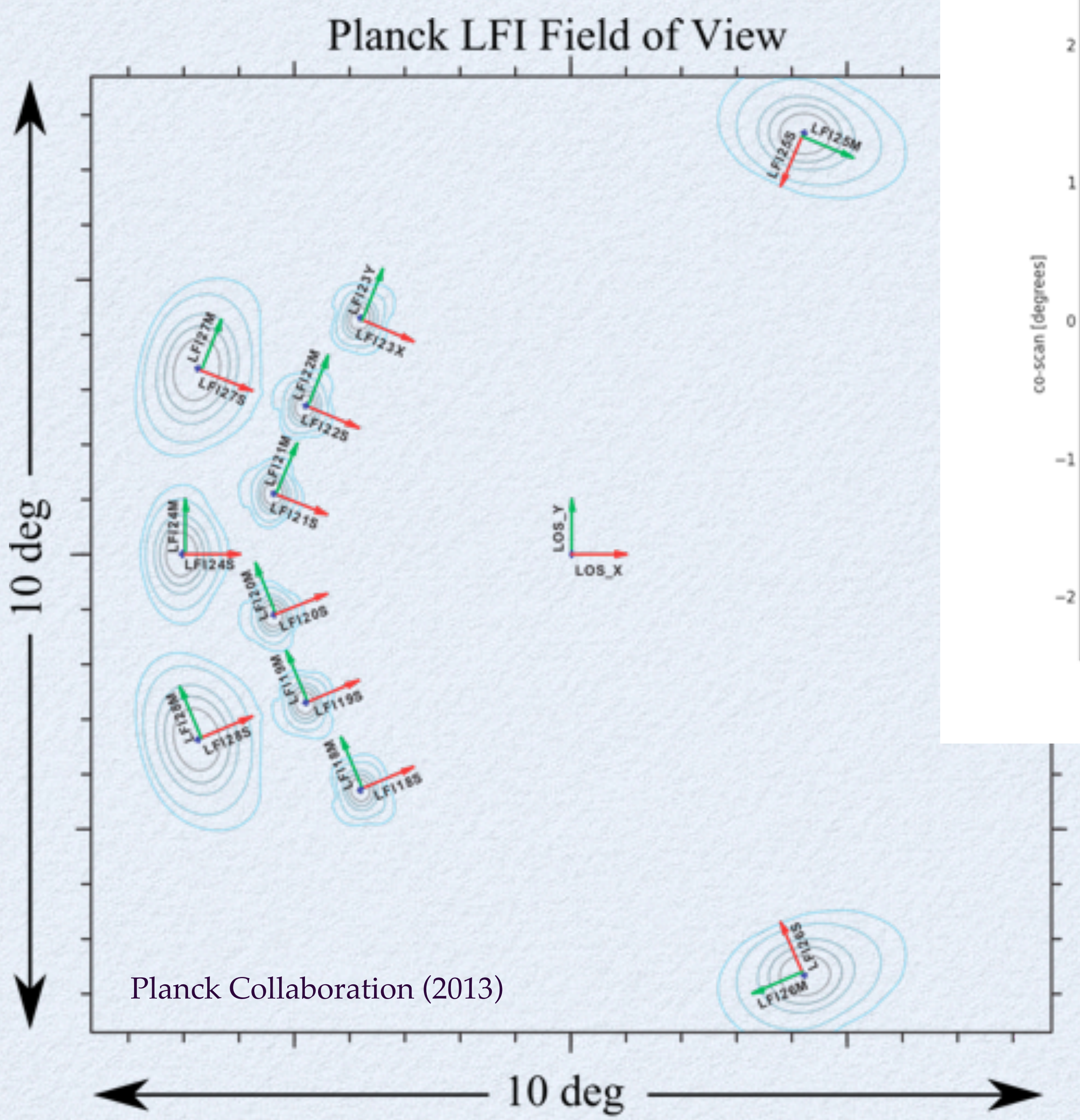
- Precision is meaningful only if all the systematic effects are taken into account
  - Beam is the most important of all, because:

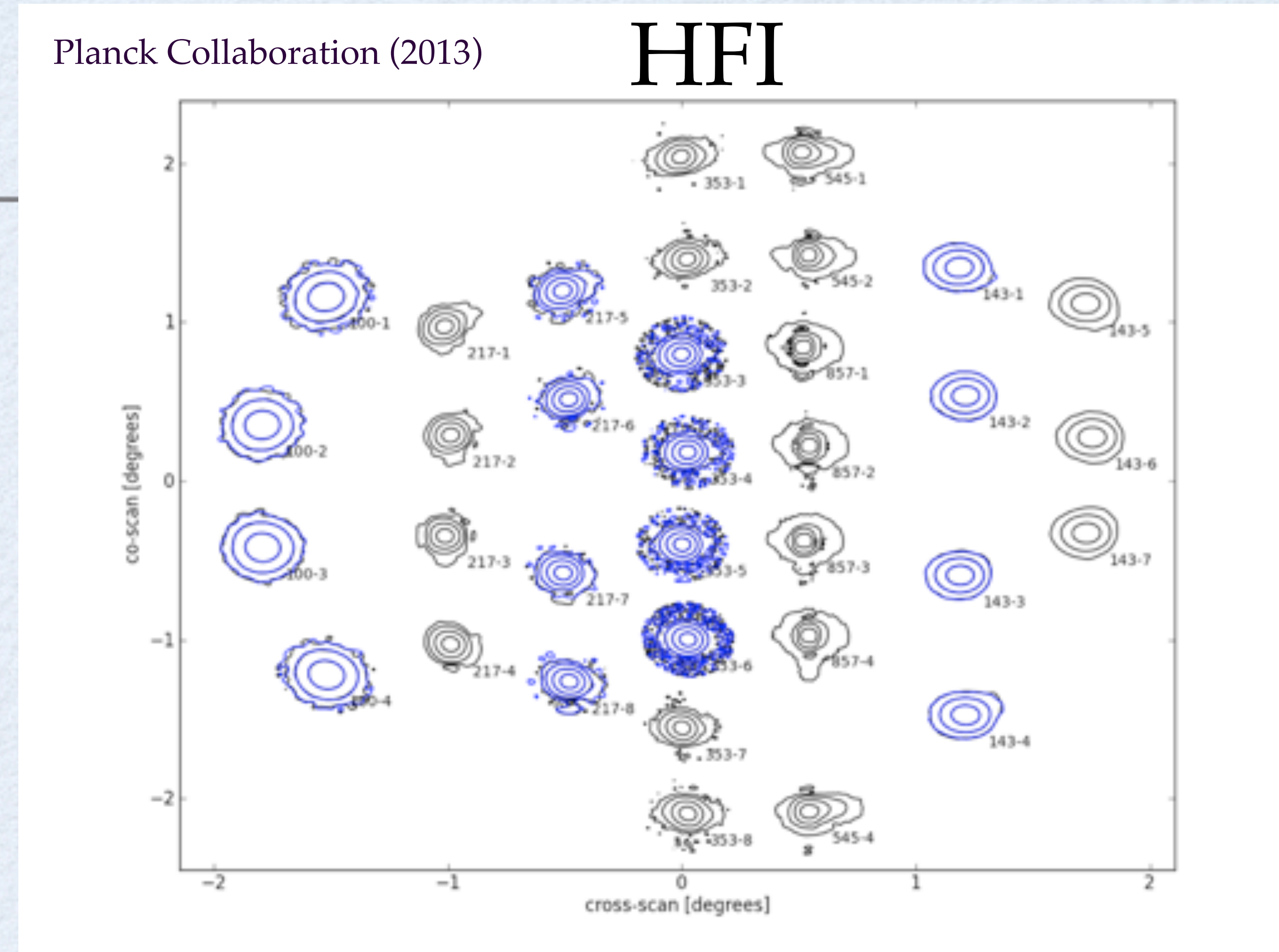
$$\Delta T^{\rm obs}(\hat{\mathbf{q}}) \;=\; U(\hat{\mathbf{q}}) \int_{4\pi} {\rm d}\Omega_{\hat{\mathbf{q}}'}\, B(\hat{\mathbf{q}}, \hat{\mathbf{q}}')\, \Delta T(\hat{\mathbf{q}}') \;+\; n(\hat{\mathbf{q}})$$

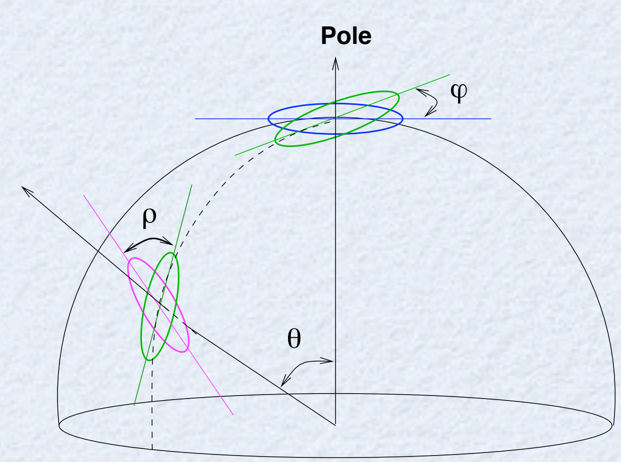
mask — beam — noise

- Two major tasks:
  - beam fitting (& incorporate uncertainties in analyses)
  - accounting for the effect of beam asymmetry

Beams are Asymmetric

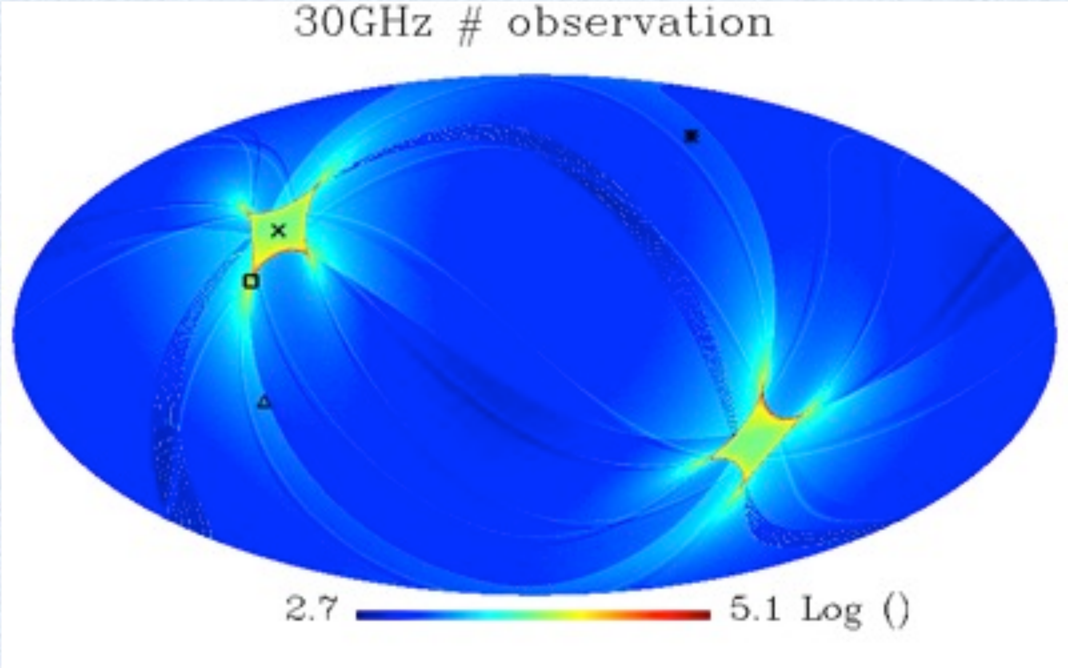




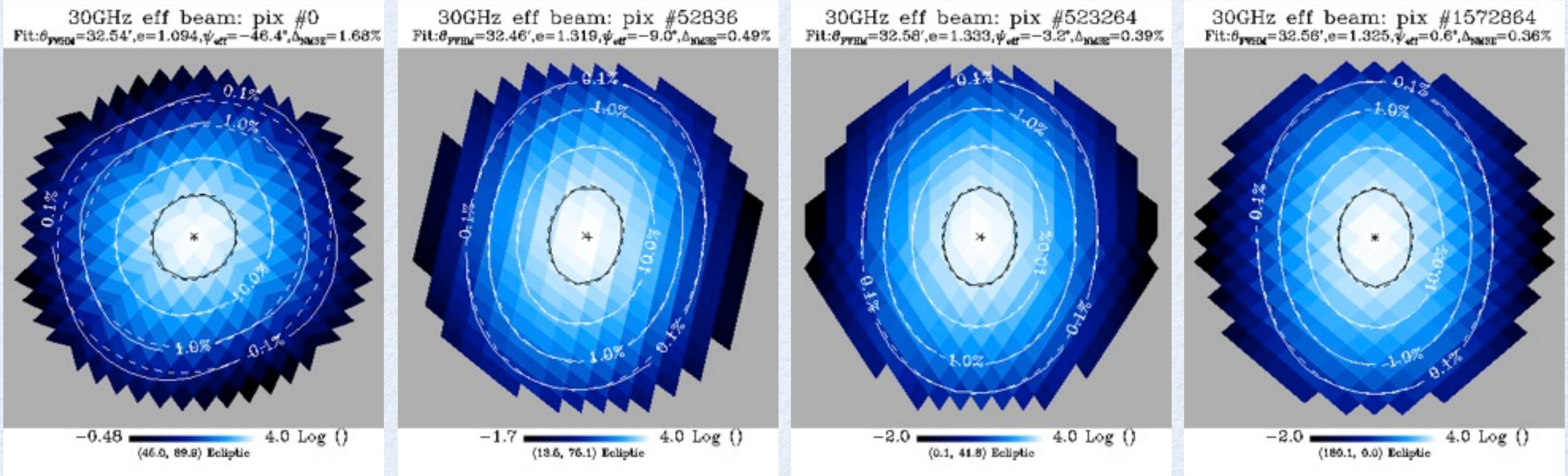


Mitra et al (2004)

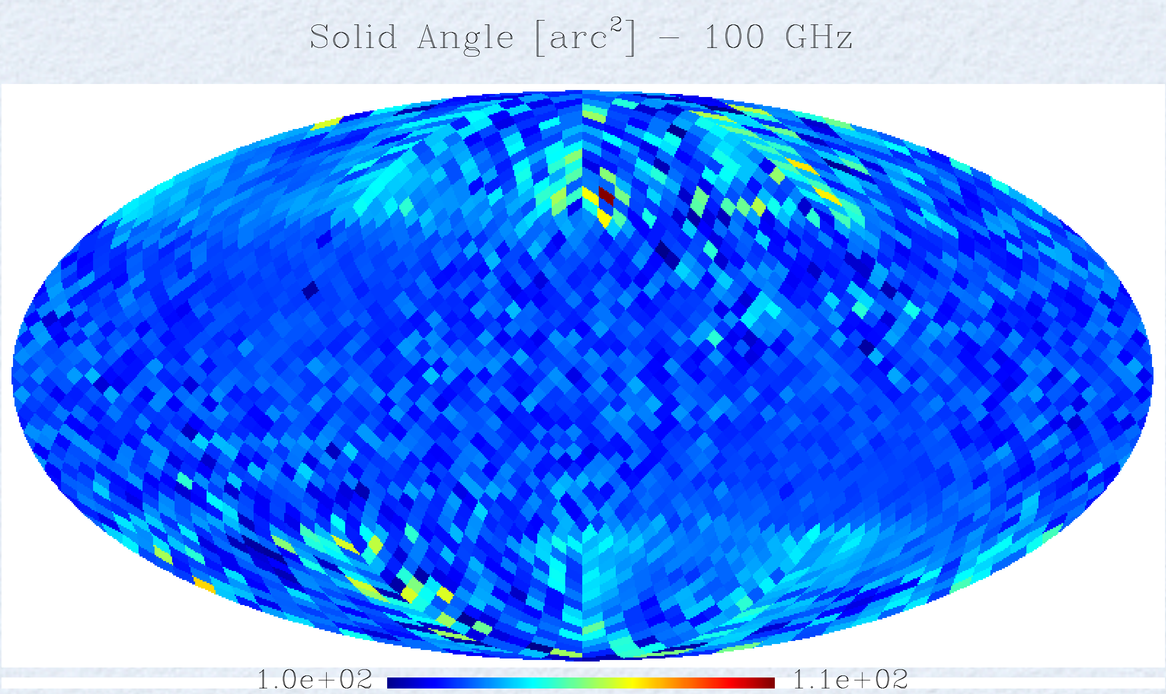
Planck Effective Beams

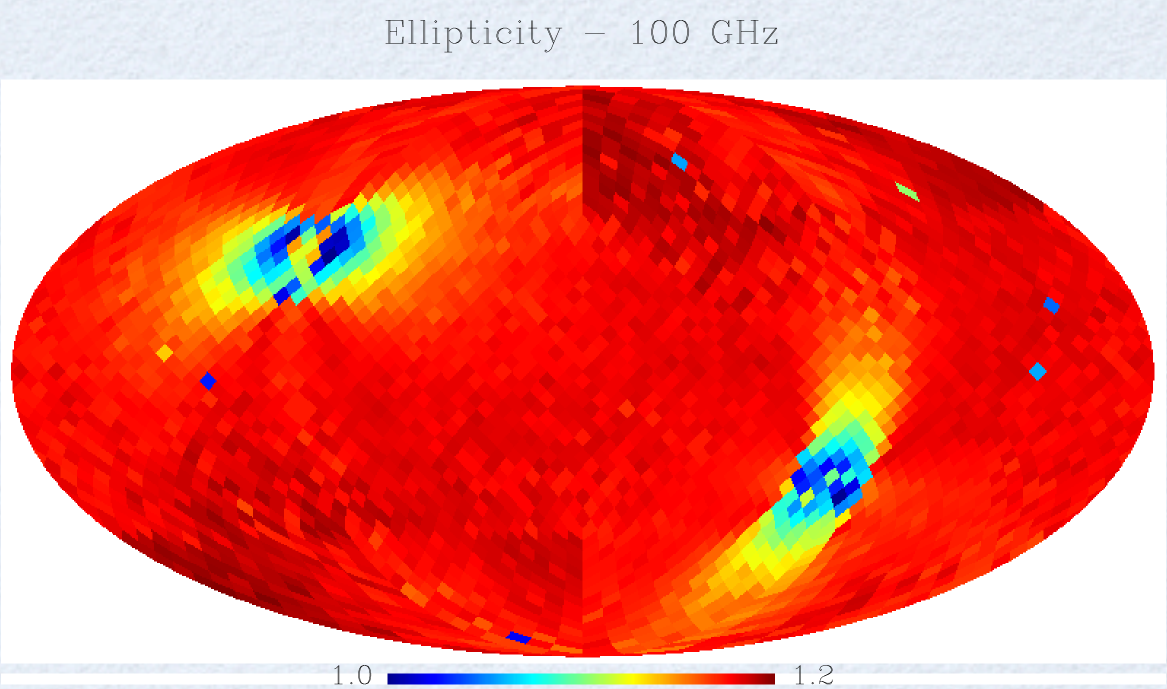


Mitra et al., ApJS 193, 5 (2011)



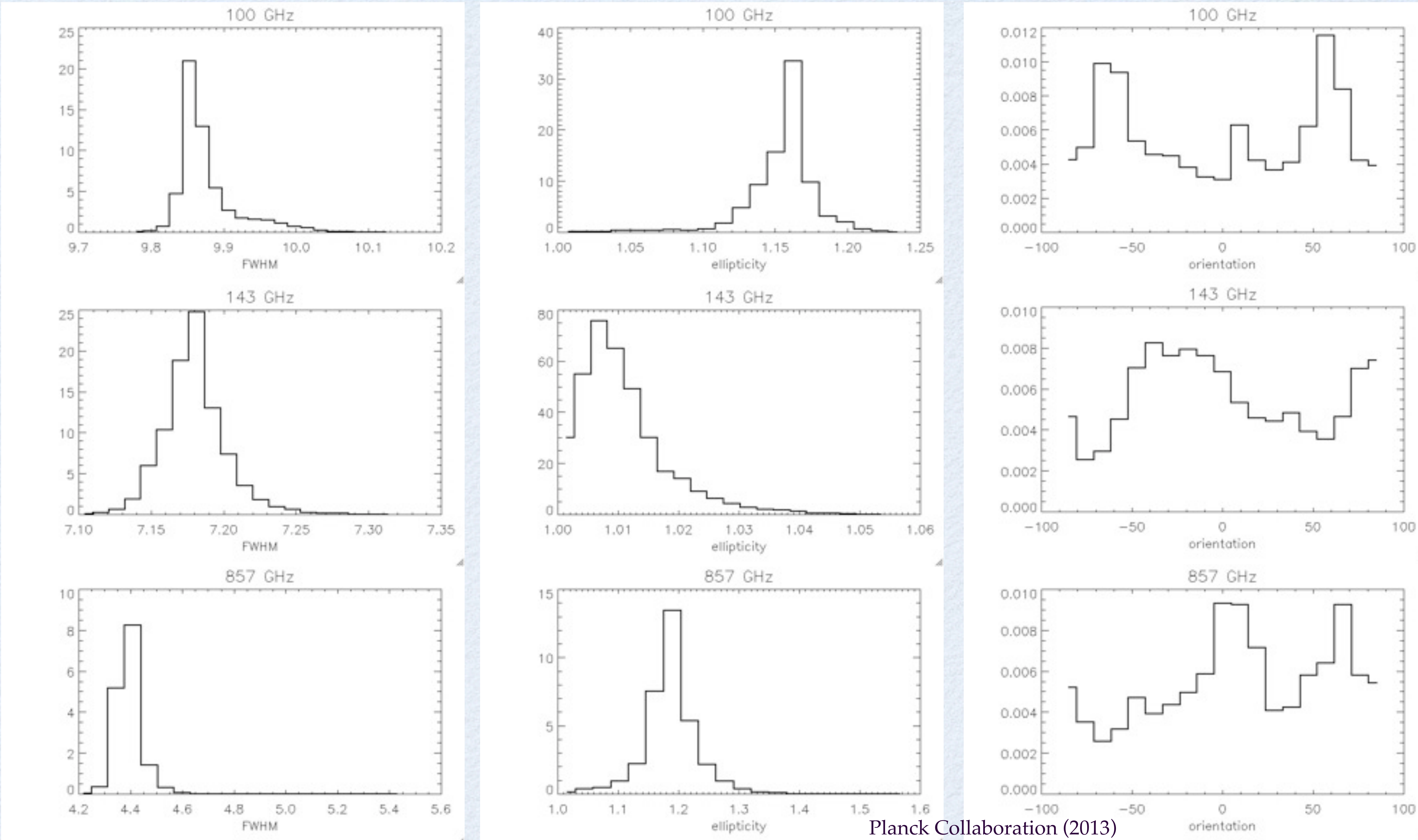
variation of beams across the sky





Planck Collaboration (2013)

Effective Beam Statistics

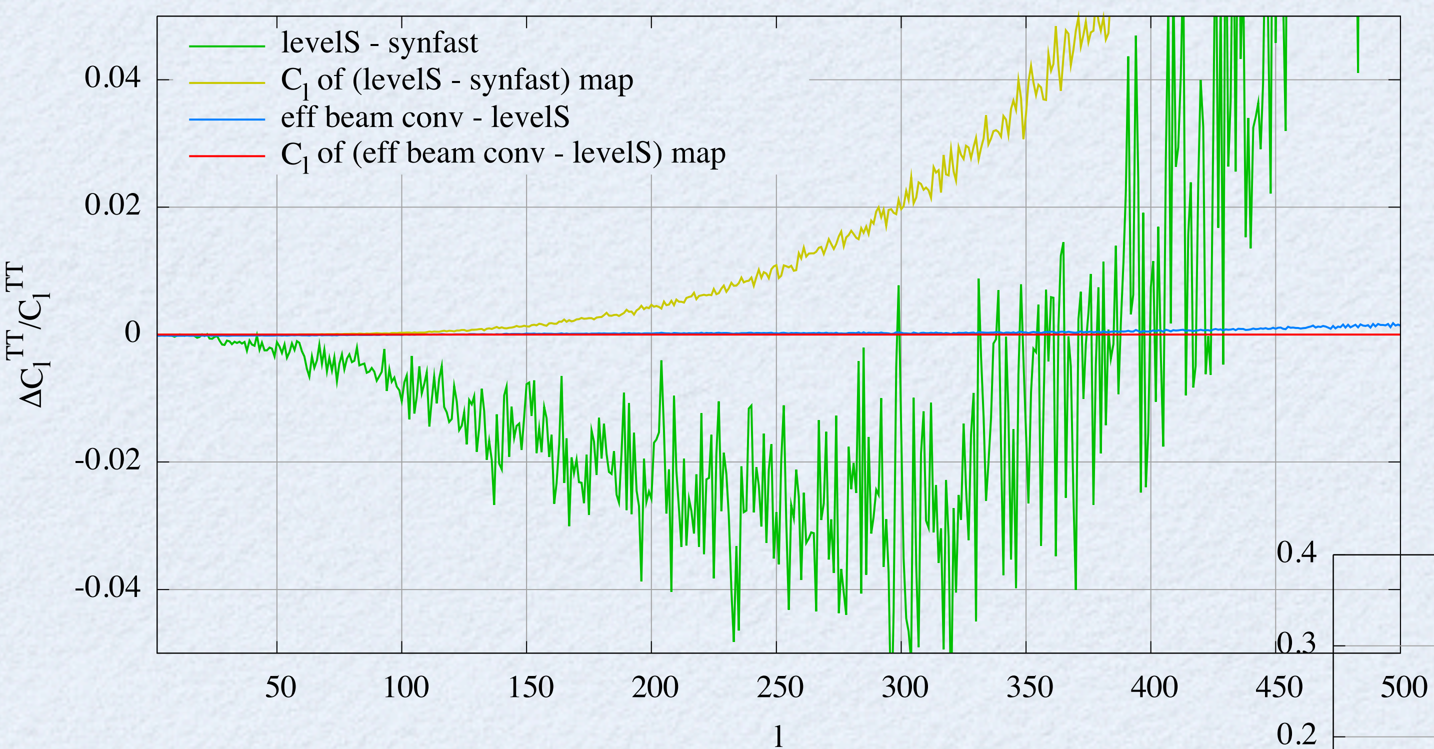


Planck Collaboration (2013)

Effect and Accuracy

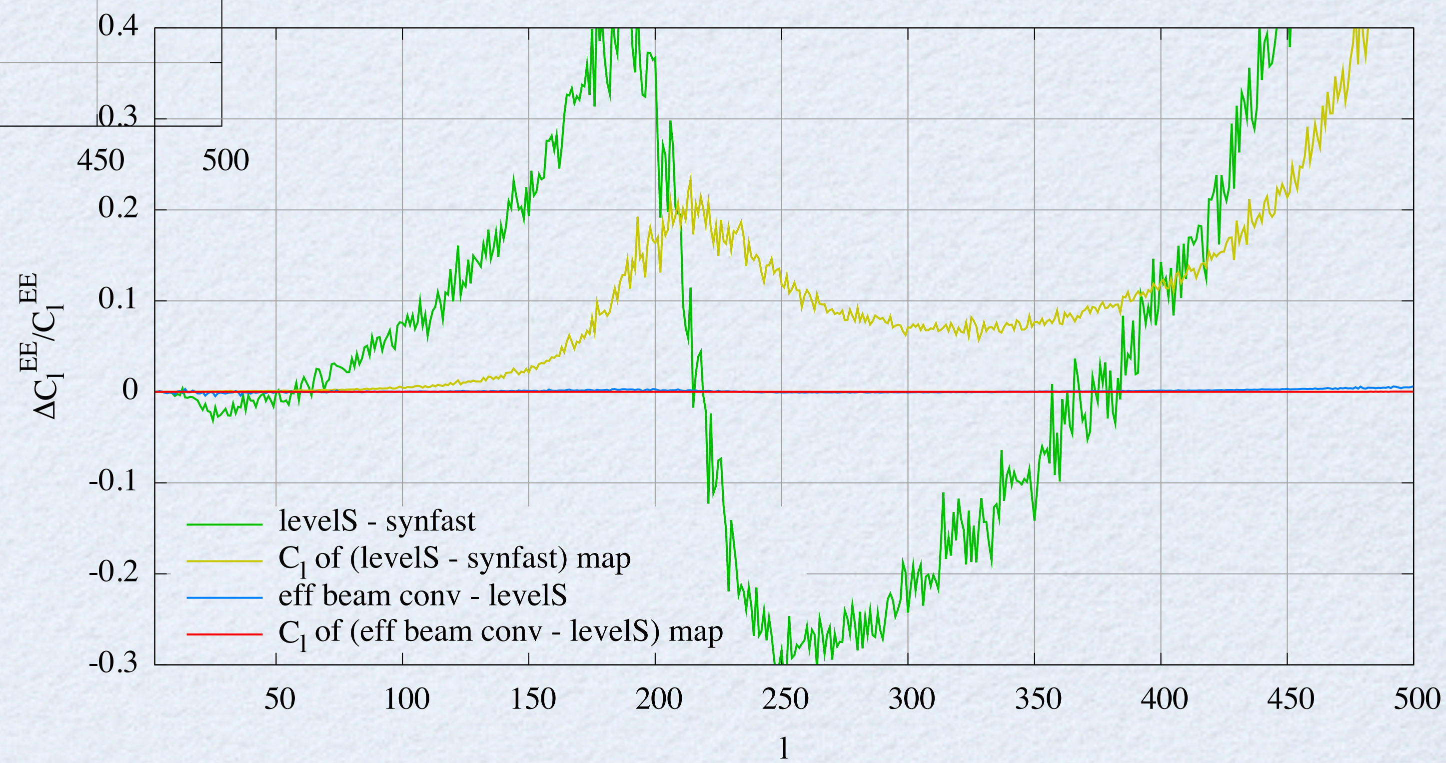
- Comparison with existing Planck simulations

Comparison of Angular Power Spectra for LFI 30GHz



Mitra et al., ApJS 193, 5 (2011)

Fractional difference between Angular Power Spectra for LFI 30GHz



Conclusion

- CMB observation is leading precision cosmology
- Planck produced ultimate temperature anisotropy maps & promises good polarization measurement
- Data analysis is challenging for small errorbars!
  - large volume of interconnected and correlated data
  - all systematics have to be accounted for
    - * beam asymmetry is important & we have taken care of it
- Look forward to the polarization results in 2014

Thank you!