Planck component separation with Commander

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for the Planck collaboration

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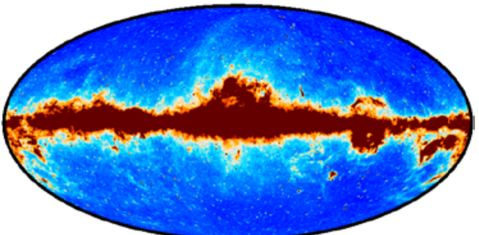
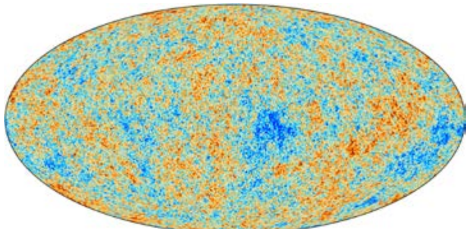
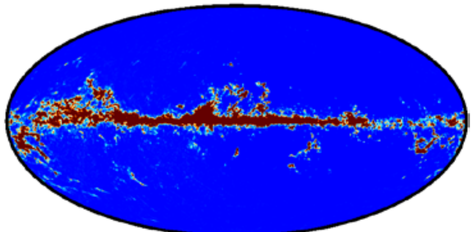
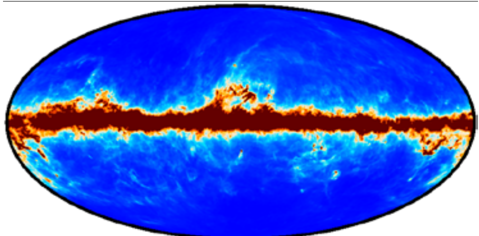
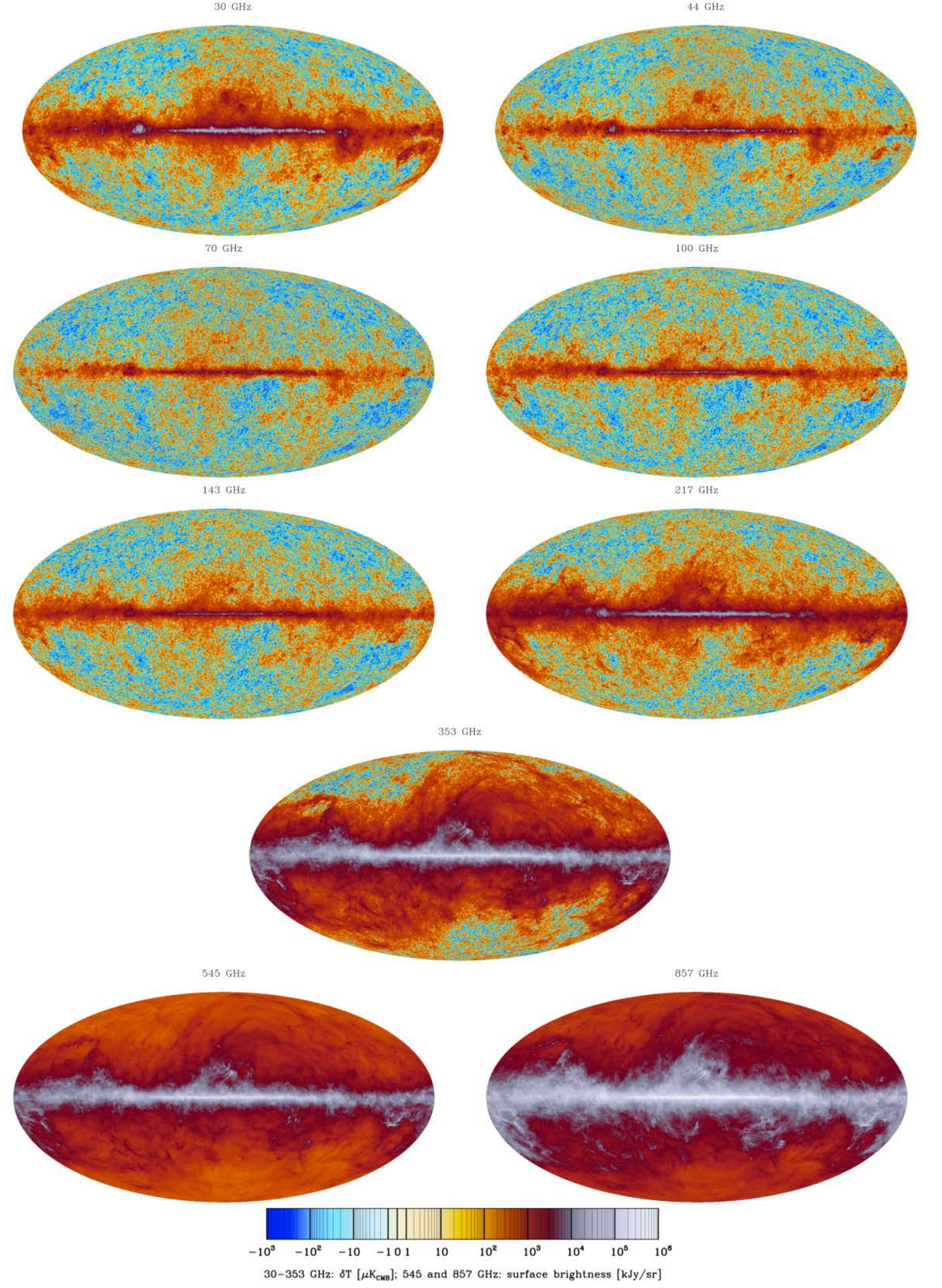





The problem

- We need to separate the CMB from the foregrounds

The solution

- We have observations at multiple frequencies



The Bayesian approach

- Assume we have data, **d**, that can be described by some parametric model, for instance

$$\mathbf{d} = \mathbf{s} + \mathbf{f} + \mathbf{n}$$

  where
  - **s** is the cosmological signal
    - Often assumed to be a Gaussian field with power spectrum C_l
  - **f** are foregrounds and/or systematics
  - **n** is instrumental noise

- What most cosmological experiments (and data analyses) attempt to estimate is really the *joint posterior* in some form or other,

$$P(\mathbf{s}, C_\ell, \mathbf{f}|\mathbf{d})$$

  - If we can find this, we also know all marginals, like P(C_l | **d**) and P(**s** | **d**), which describes the main cosmological results

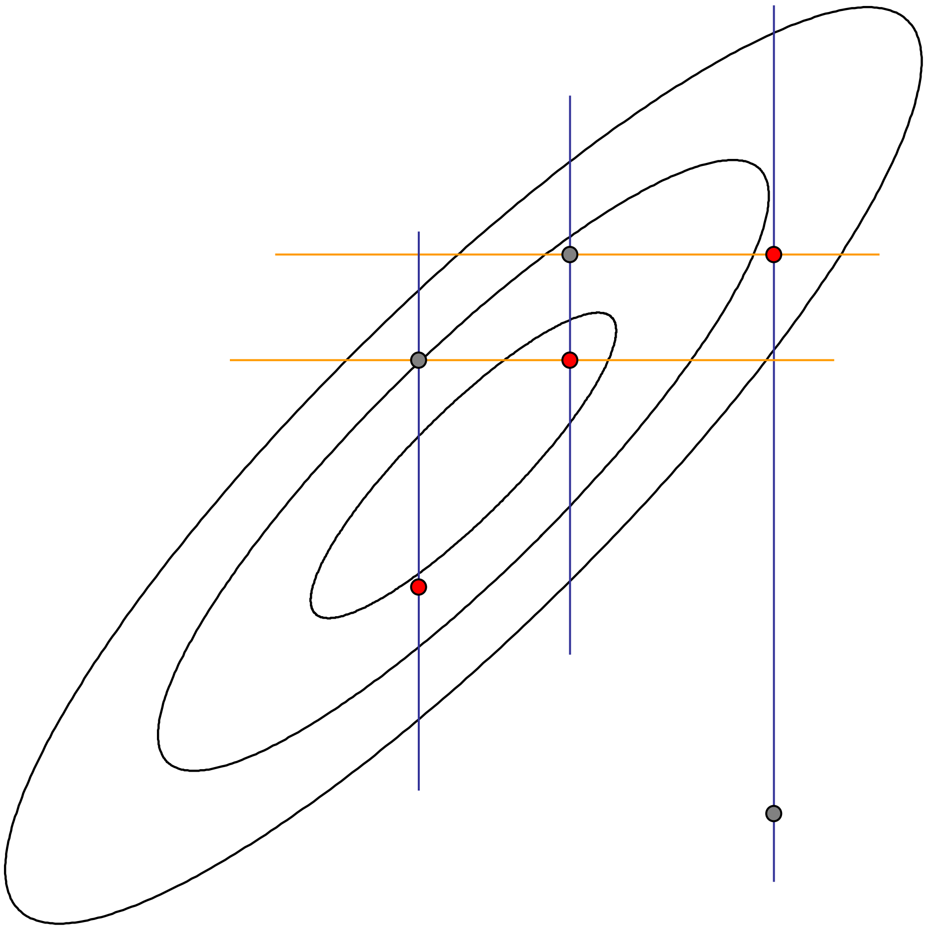
- But how do we compute this for modern data sets?
  - The observations consists of millions of data points
  - The models have millions of free parameters
  - The probability distributions are typically non-Gaussian and strongly coupled

Gibbs sampling

- *Gibbs sampling:* Sample from joint distribution by cycling through conditionals

- Consider simple two-dimensional example, P(x, y)
  - Choose arbitrary initial point
  - Sample y from P(y|x)
  - Sample x from P(x|y)
  - Iterate
- This is a special case of Metropolis-Hastings, and guaranteed to converge to the right answer

- Why is this useful?
  - Because conditionals are often much simpler than the joint distribution
  - Complicated distributions can be build up by Gaussians, inverse gammas etc...



Signal model

- We use the seven lowest Planck frequencies, from 30 to 353 GHz
- A wide range of physical effects are relevant in this range
  - CMB, synchrotron, free-free, AME, haze (?), CO, thermal dust, SZ, CIB, extragalactic sources...
- Adopt the following model for *diffuse* Galactic analysis:

$$
\begin{aligned}
d_\nu(p) = \; & A_{\mathrm{cmb}}(p) && \text{CMB} \\
& + A_{\mathrm{lf}}(p) \left(\frac{\nu}{\nu_{0,\mathrm{lf}}}\right)^{\beta(p)} && \text{Low-frequency component} \\
& + A_{\mathrm{d}}(p) \left(\frac{\nu}{\nu_{0,\mathrm{d}}}\right)^{\beta_{\mathrm{d}}(p)} \frac{e^{\frac{h\nu_{\mathrm{d}}}{kT_{\mathrm{d}}(p)}} - 1}{e^{\frac{h\nu}{kT_{\mathrm{d}}(p)}} - 1} && \text{Thermal dust} \\
& + A_{\mathrm{co}}(p) h(\nu) && \text{CO} \\
& + n_\nu(p) && \text{Noise}
\end{aligned}
$$

$\Rightarrow$ four amplitude parameters + three spectral parameters per pixel (+ C_l's for A_{cmb})

Priors

- Fitting seven free parameters to seven frequencies is difficult – need priors

- Choose to impose priors on spectral parameters only

  – Low-frequency component:
    - Prior is only needed in low S/N regions $\Rightarrow$ high Galactic latitudes
    - Synchrotron is dominant emission effect $\Rightarrow$ $\beta = -3 \pm 0.3$

  – Thermal dust component:
    - Priors informed by an initial MCMC run at high latitudes
      – Fitting only a single value for dust emissivity and temperature
    - $\beta_{\mathrm{d}} = 1.6 \pm 0.1\,, \quad T_{\mathrm{d}} = 18 \pm 0.05\mathrm{K}$
      – Dust temperature essentially fixed to 18K, but is allowed to float slightly to accommodate extremely high S/N objects in the Galactic center

  – CO component:
    - Assume constant line ratios, fitted to high S/N objects
    - *h*(217 GHz) = 0.6,   *h*(353 GHz) = 0.3, all others set to zero

- *Planck is strong enough to not require amplitude priors!*

The CMB Gibbs sampler

- For this model, the Gibbs sampling algorithm looks like:

$$\begin{aligned} \mathbf{A} &\leftarrow P(\mathbf{A}|C_\ell, \mathbf{f}, \mathbf{d}) \\ \mathbf{f} &\leftarrow P(\mathbf{f}|\mathbf{A}, C_\ell, \mathbf{d}) \\ C_\ell &\leftarrow P(C_\ell|\mathbf{A}, \mathbf{f}, \mathbf{d}) \end{aligned}$$

- Iterate this chain, remove the first few samples due to burn-in, and compute summary statistics

- All that remains is to write down the individual conditionals

Conditional distributions

- Amplitudes can be described by a multivariate Gaussian, and is given by a Wiener filter plus a fluctuation term,

$$(\mathbf{S}^{-1} + \mathbf{N}^{-1})\mathbf{A} = \mathbf{N}^{-1}\mathbf{d} + \mathbf{S}^{-1/2}\omega_1 + \mathbf{N}^{-1/2}\omega_2$$

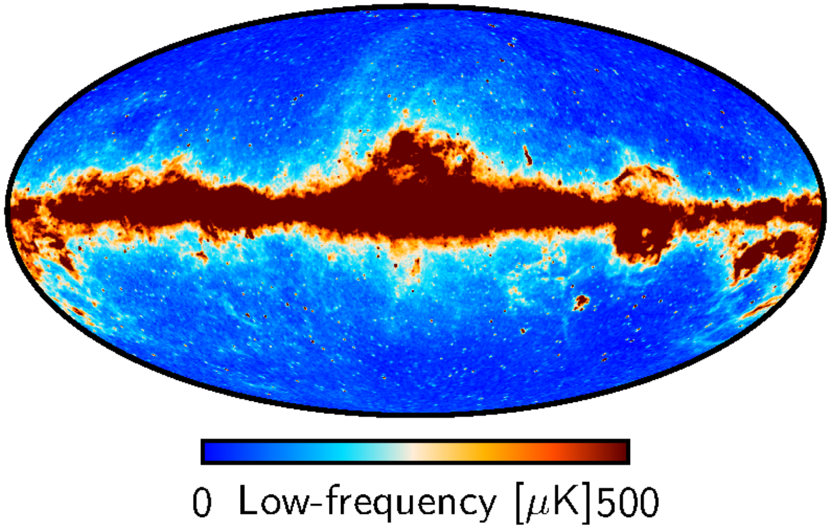
- Spectral parameters must be computed directly from the chi-square

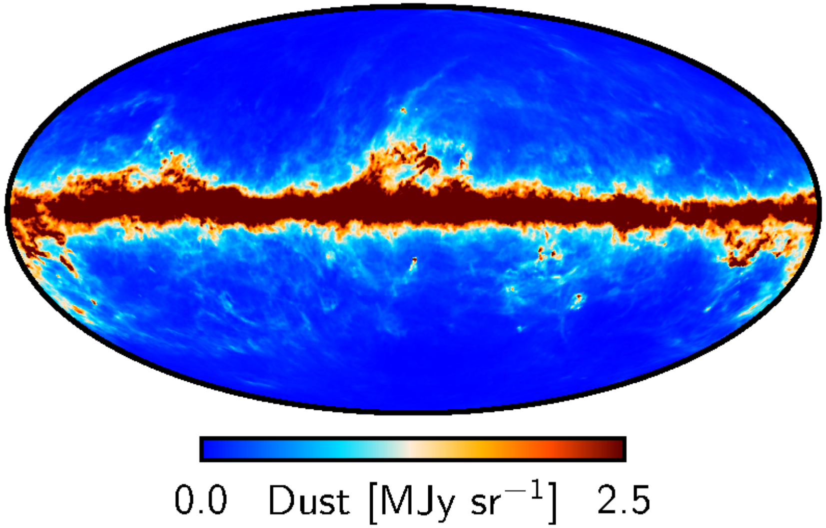
$$\text{-2ln}\,\mathcal{L}(\beta) = (\mathbf{d} - \mathbf{A}\nu^{\beta})^t\mathbf{N}^{-1}(\mathbf{d} - \mathbf{A}\nu^{\beta})$$

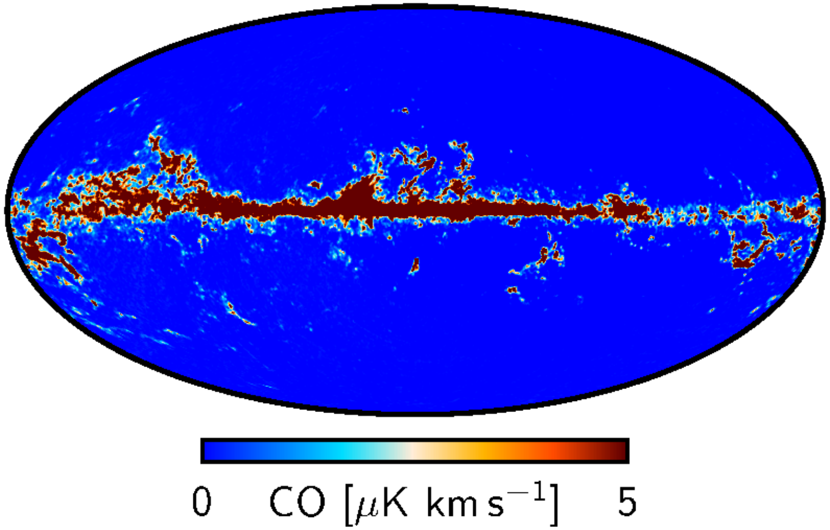
- Angular power spectra are given by an inverse Gamma distribution

$$C_\ell = \frac{\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2}{\sum_{i=1}^{2\ell-1} \omega_i}$$

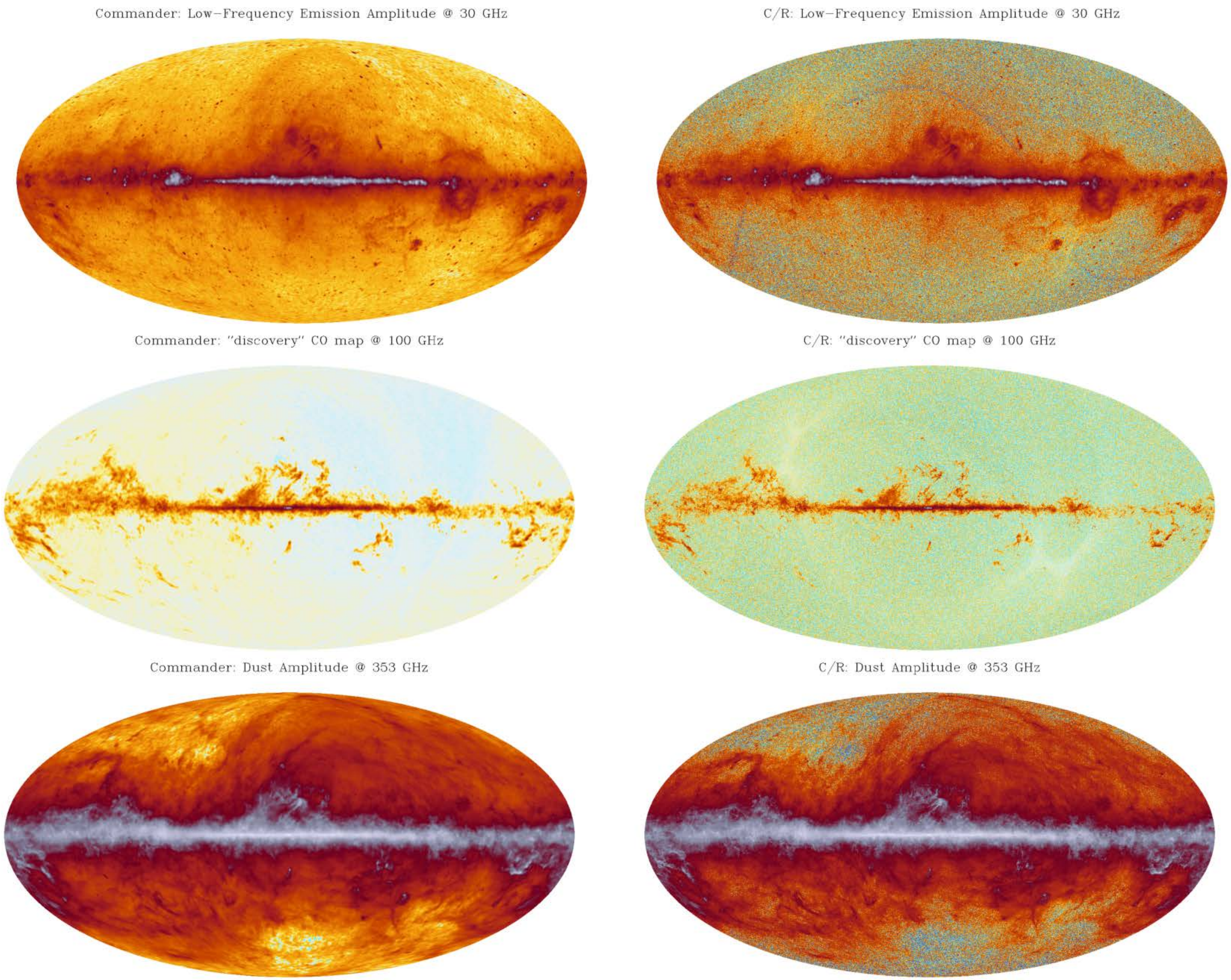
Astrophysical components from Planck



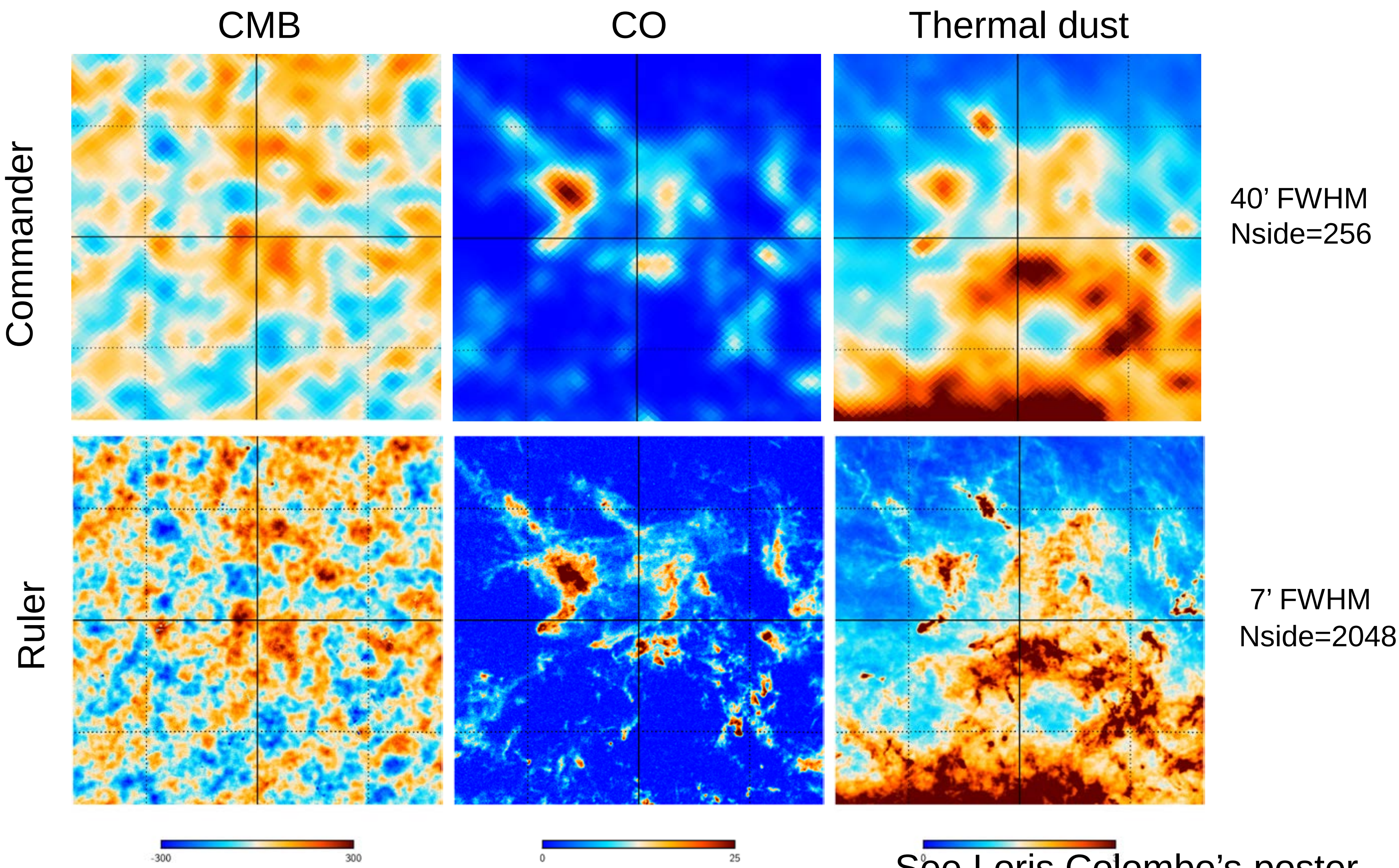




Low- and high-resolution maps

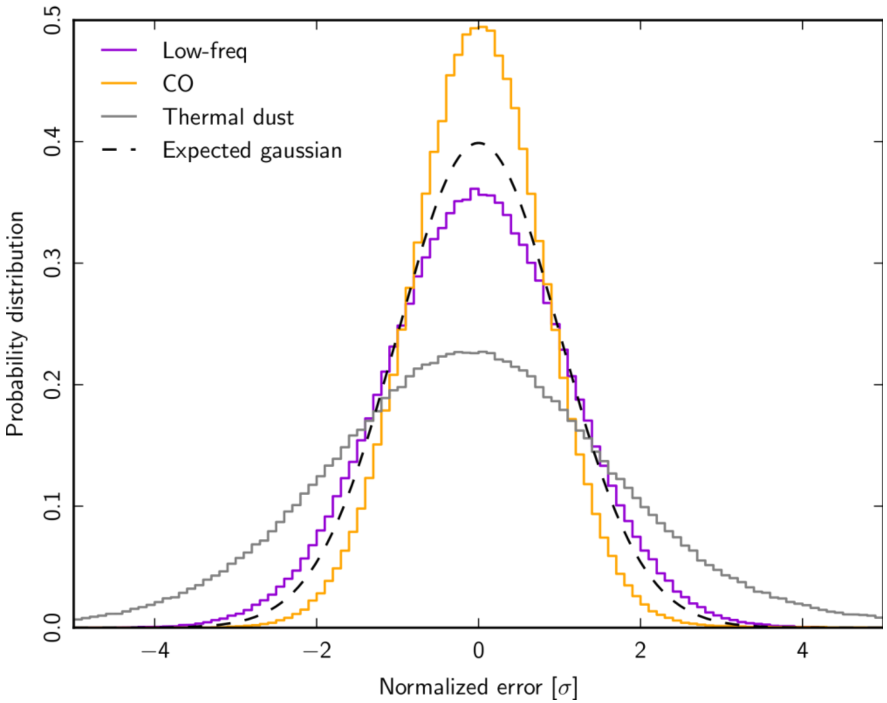


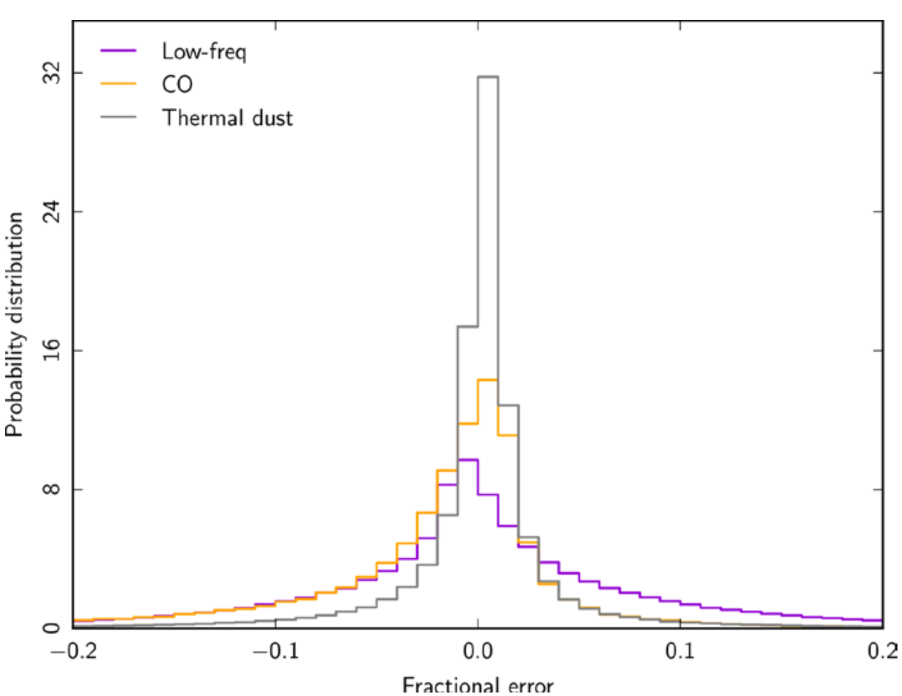
Low- and high-resolution maps



See Loris Colombo's poster

Validation by simulations





$$\text{Norm. error} = \frac{\text{output} - \text{input}}{\text{estimated uncertainty}}$$

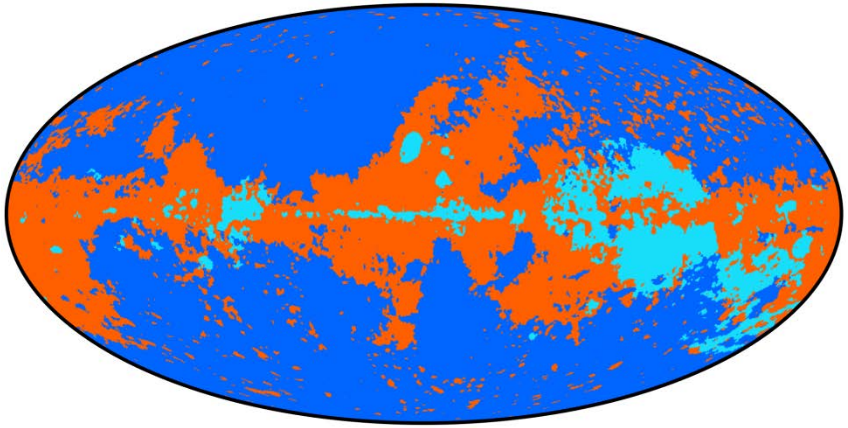
$$\text{Frac. error} = \frac{\text{Output} - \text{Input}}{\text{Input}}$$

- Largest bias is 3% for the CO component
- Uncertainties for low-frequency and CO components accurate to 13%
- Thermal dust uncertainty underestimates true error by a factor of 2 due to unmodelled CIB fluctuations

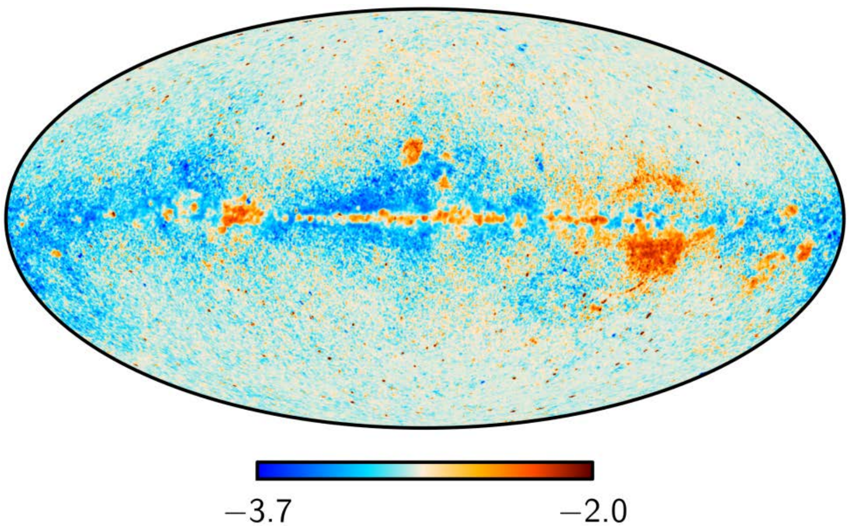
Validation by simulations

Dominant components at 30GHz

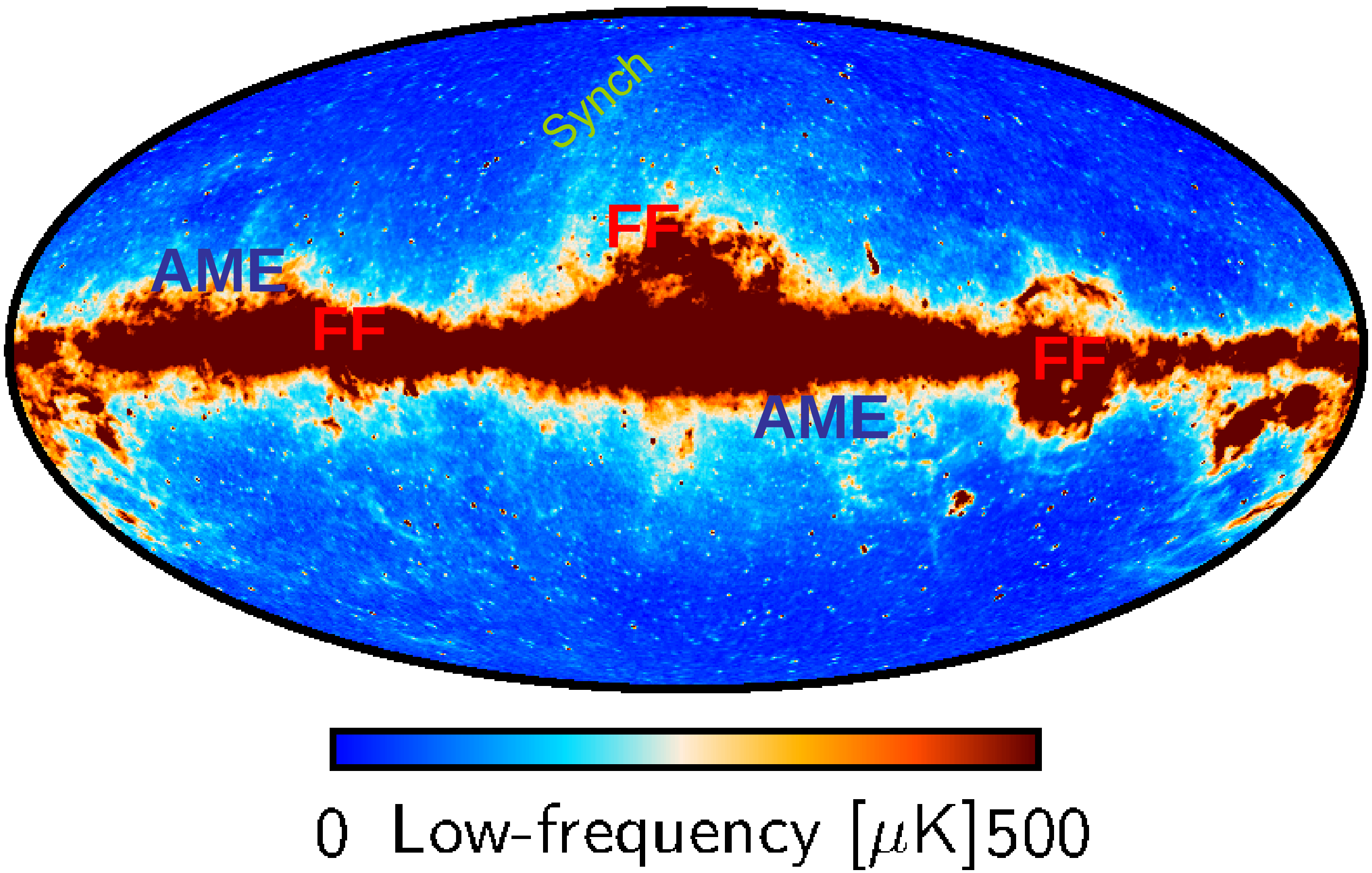
- Orange: AME
- Cyan: Free-free
- Purple: Synchrotron



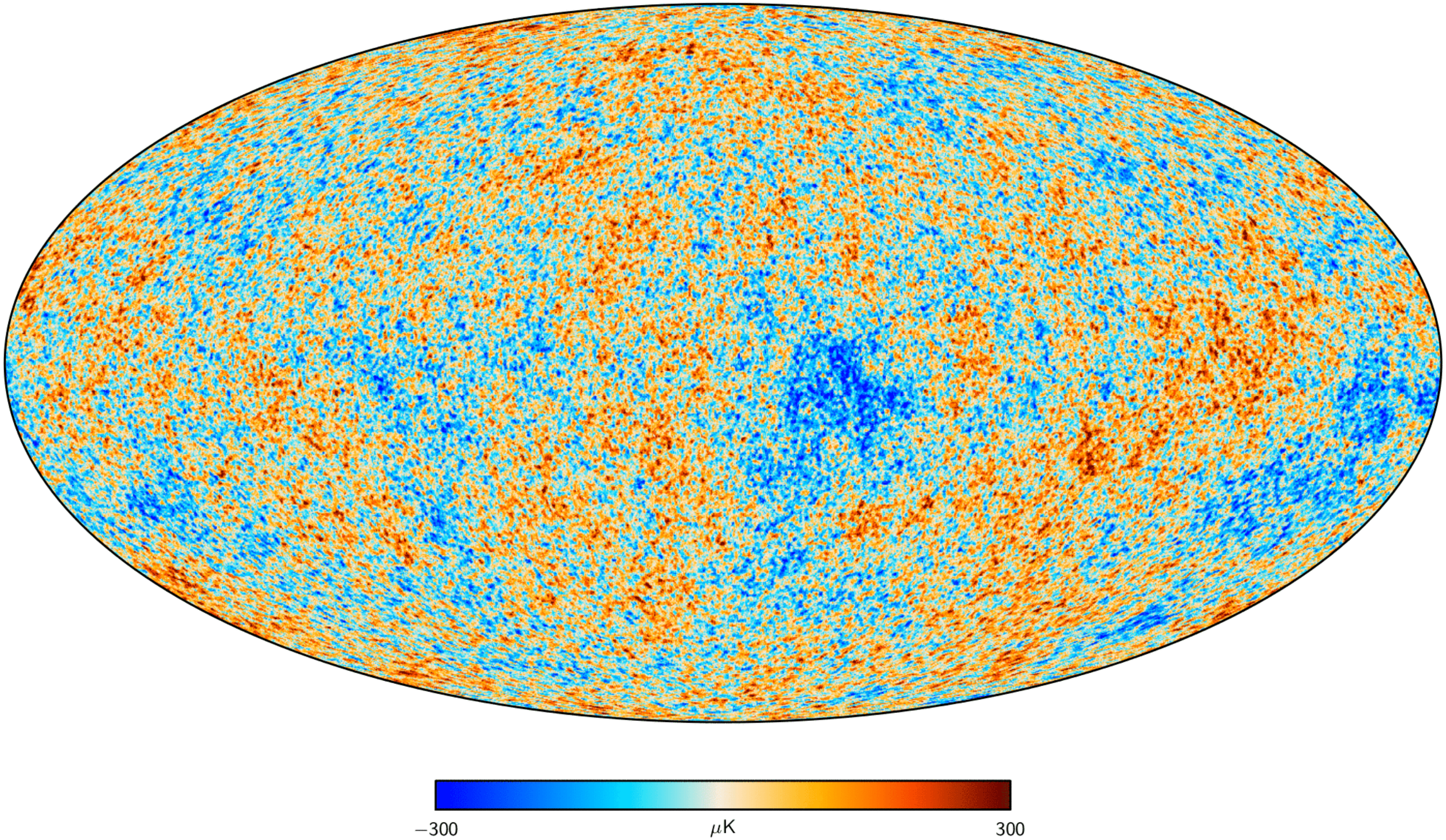
- Low-freq spectral index



Low-frequency power law index

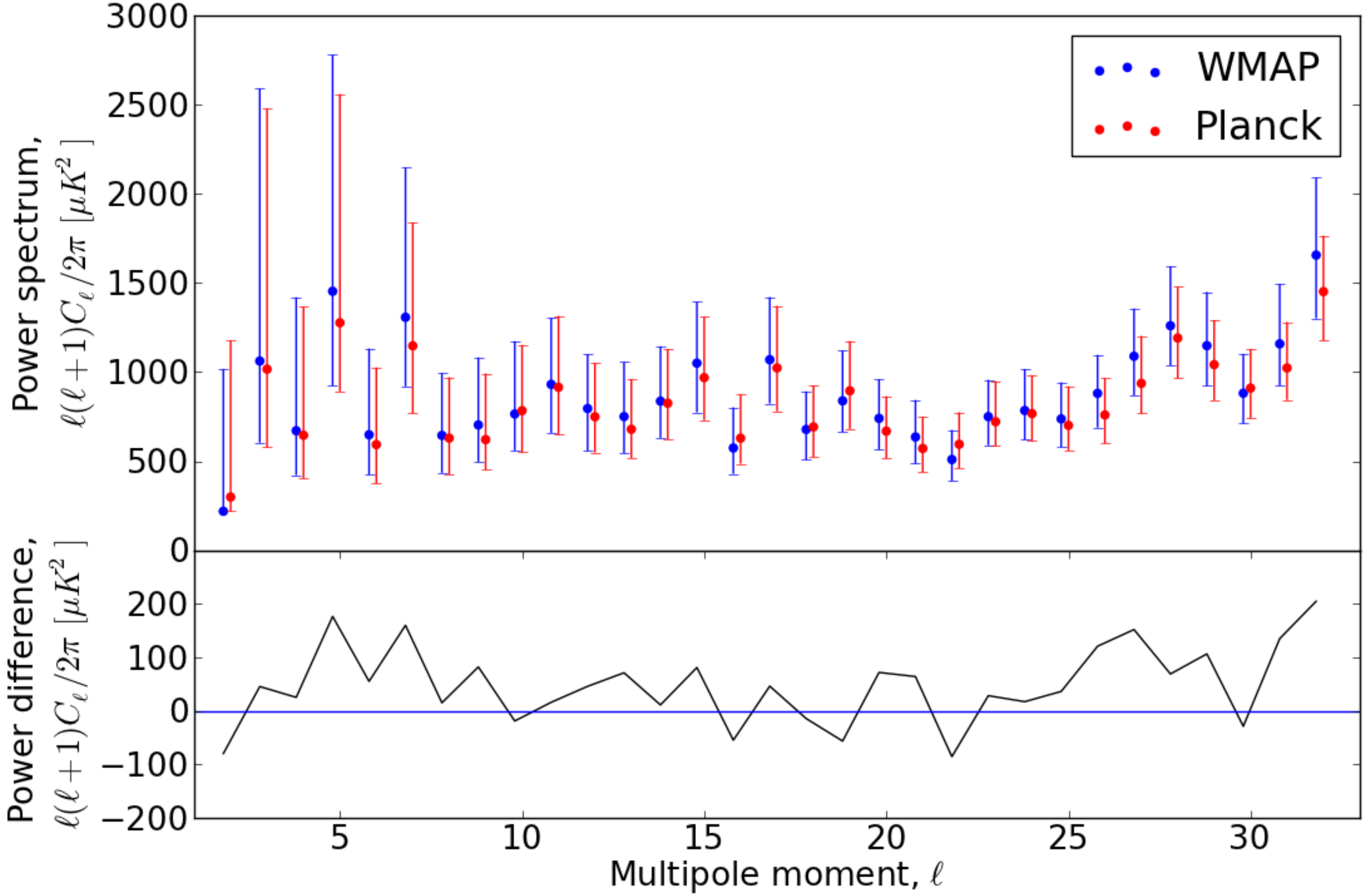


Planck CMB sky samples



Constrained realization in a 13% Galactic mask

The low-*l* CMB power spectrum



Defines the low-*l* Planck likelihood through a Blackwell-Rao estimator

See Eirik Gjerløw's poster

Summary and outlook

- Major strengths of the Bayesian approach:
  - Relies on a well defined and transparent physical data model
  - Easy to impose priors whereever necessary
  - Seamless end-to-end propagation of both foreground and systematic uncertainties
  - Allows naturally for joint CMB and total intensity analysis
- Commander-Ruler in the 2013 Planck data release:
  - Defines the low-l Planck likelihood up to l=49
  - Provides full-sky low-frequency component, CO and thermal dust maps, including spectral parameters
- An extended low-frequency analysis of synchrotron, free-free and AME is expected to be released in the near future
- Already working on high-*l* extensions for 2014 data release
  - Faster algorithms
  - Sampling of SZ clusters and (hopefully) CIB fluctuations

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

References

- CMB Gibbs sampling
  - Jewell et al 2004; Wandelt et al 2004; Eriksen et al 2004
- CMB + foregrounds Gibbs sampling
  - Eriksen et al 2008
- Planck results
  - Planck 2013 results. XII. Component separation
  - Planck 2013 results. XV. CMB power spectrum and likelihood