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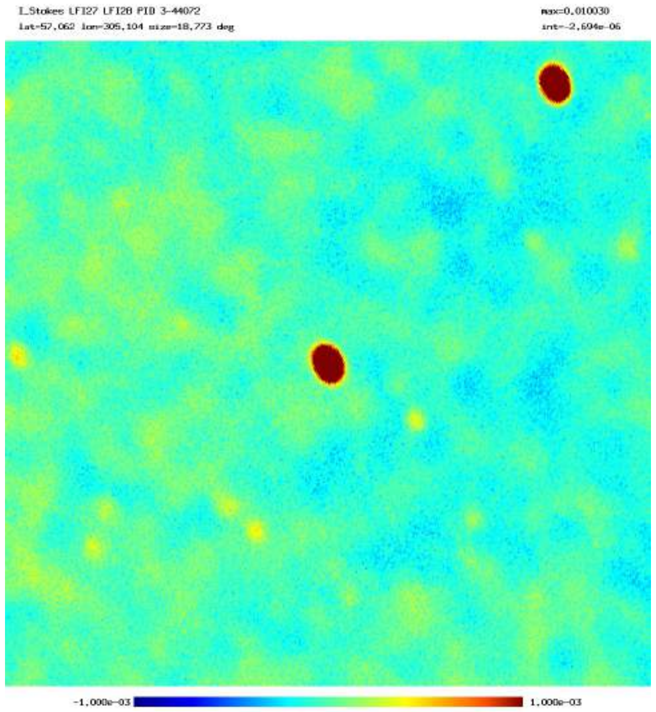
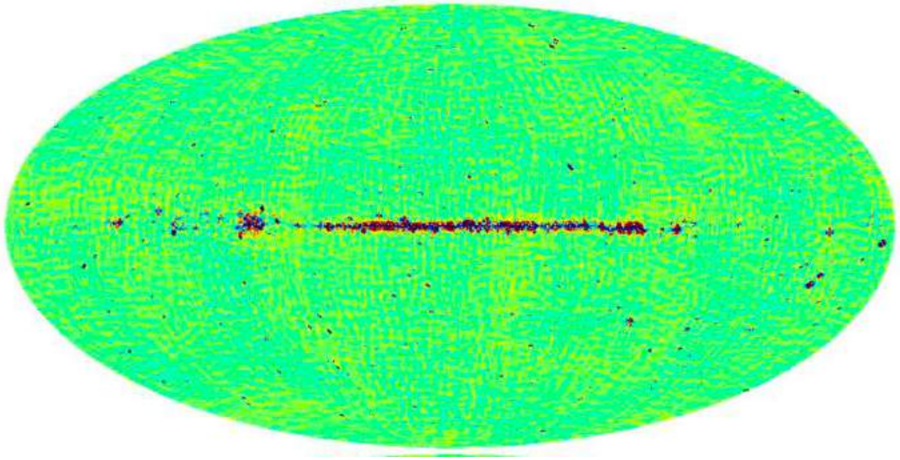
Beam deconvolution with ArtDeco

Beam asymmetry

- Signal collected from a finite area
- Beam asymmetries complicate the analysis of CMB data
  - Distortion of the frequency map
  - Complicates the analysis of null maps
  - Non-uniform effective beam
- Beam shape mismatch is a source of temperature-to-polarization leakage.

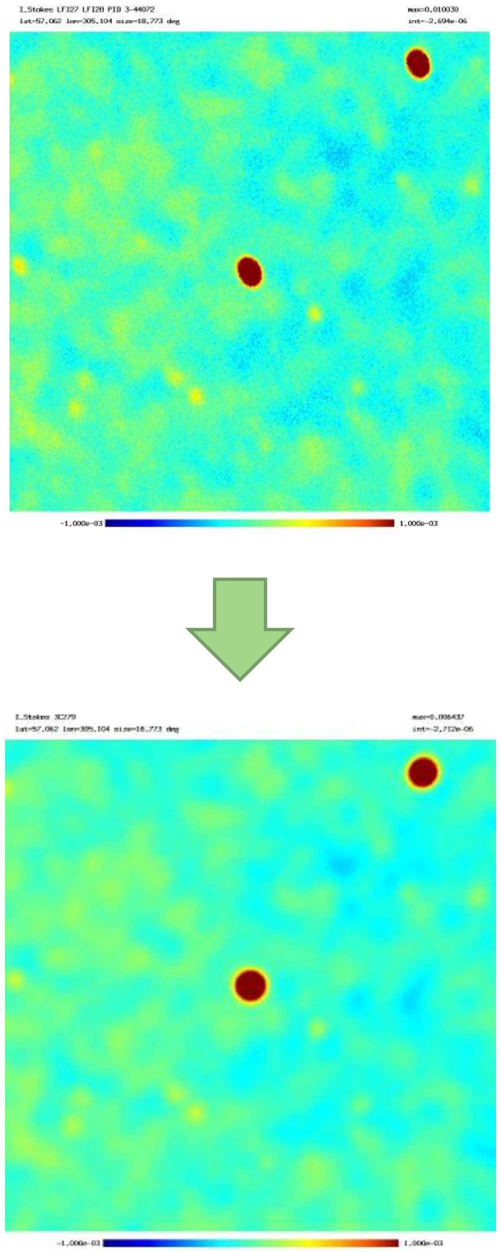




ArtDeco deconvolver

- ArtDeco deconvolution map-making code for correction of beam asymmetry
- Further developments:
  - Application to power-spectrum estimation
  - Gibbs sampling (BeyondPlanck)

- E. Keihänen and M. Reinecke,
  ArtDeco: a beam-deconvolution code for absolute cosmic microwave background measurements.
  Astronomy and Astrophysics, 548:A110, 2012



Beam convolution formalism

$$t_j = \sum_{slmk} a_{slm} b^*_{slk} D^{l*}_{mk}(\omega_j) + n_j$$

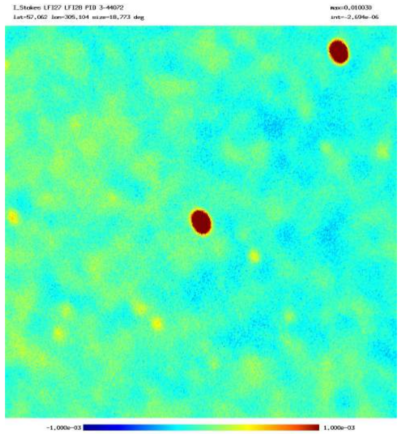
$$\begin{aligned}
a_{slm} &= \text{sky} \\
b^*_{slk} &= \text{beam} \\
D^{l*}_{mk}(\omega_j) &= \text{Wigner matrix} \\
\omega_j &= \{\varphi_j, \theta_j, \psi_j\} = \text{pointing} \\
n_j &= \text{noise} \\
s &= \text{spin index: } s = 0\,\text{(temperature)},\ s = \pm 2\ \text{(pol)}
\end{aligned}$$

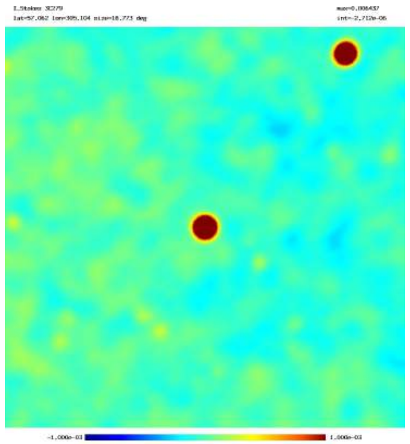
Linear fit to determine a_{slm} .

smoothing window

A beam-symmetrized map is constructed as

$$\begin{aligned}
T(\theta,\varphi) &= \sum_{lm} a_{0lm} w(l)\, {}_0Y_{lm}(\theta,\varphi) \\
(Q+iU)(\theta,\varphi) &= \sum_{lm} a_{2lm} w_p(l)\, {}_2Y_{lm}(\theta,\varphi)
\end{aligned}$$





3D maps and Wigner transform

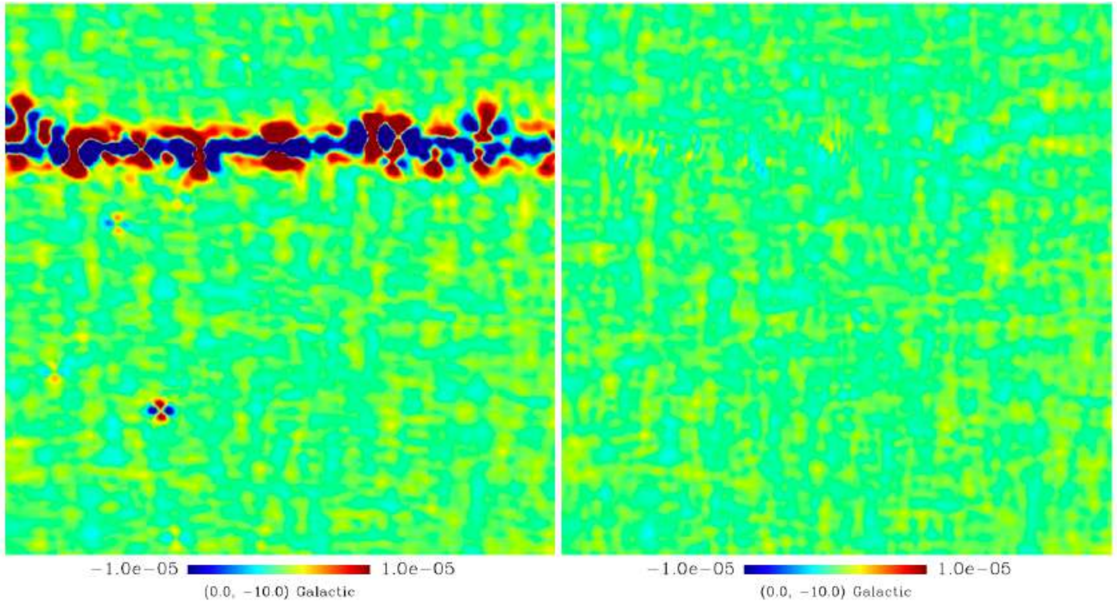
A key element in ArtDeco algorithm is the concept of **3D map**.

- A 3D map is constructed by coadding TOI (time-ordered data) samples with same pointing $\{\varphi_j, \theta_j, \psi_j\}$ (in some binning).
- Compression factor ~100 -> 1GB / radiometer (all Planck LFI data 30 GB)
- 3D map is a 3-dimensional “data cube”, only non-empty cells stored
  - Keeps the information of beam orientation
  - Input to beam deconvolution
- *Wigner transform:* $W^l_{mk} = \sum_{\varphi,\theta,\psi} D^l_{mk}(\varphi,\theta,\psi) T(\varphi,\theta,\psi)$

  3D equivalent of Healpix map <-> spherical harmonics expansion
- ArtDeco code makes use of the Libsharp library

Simulation results

Q polarisation



deconvolution

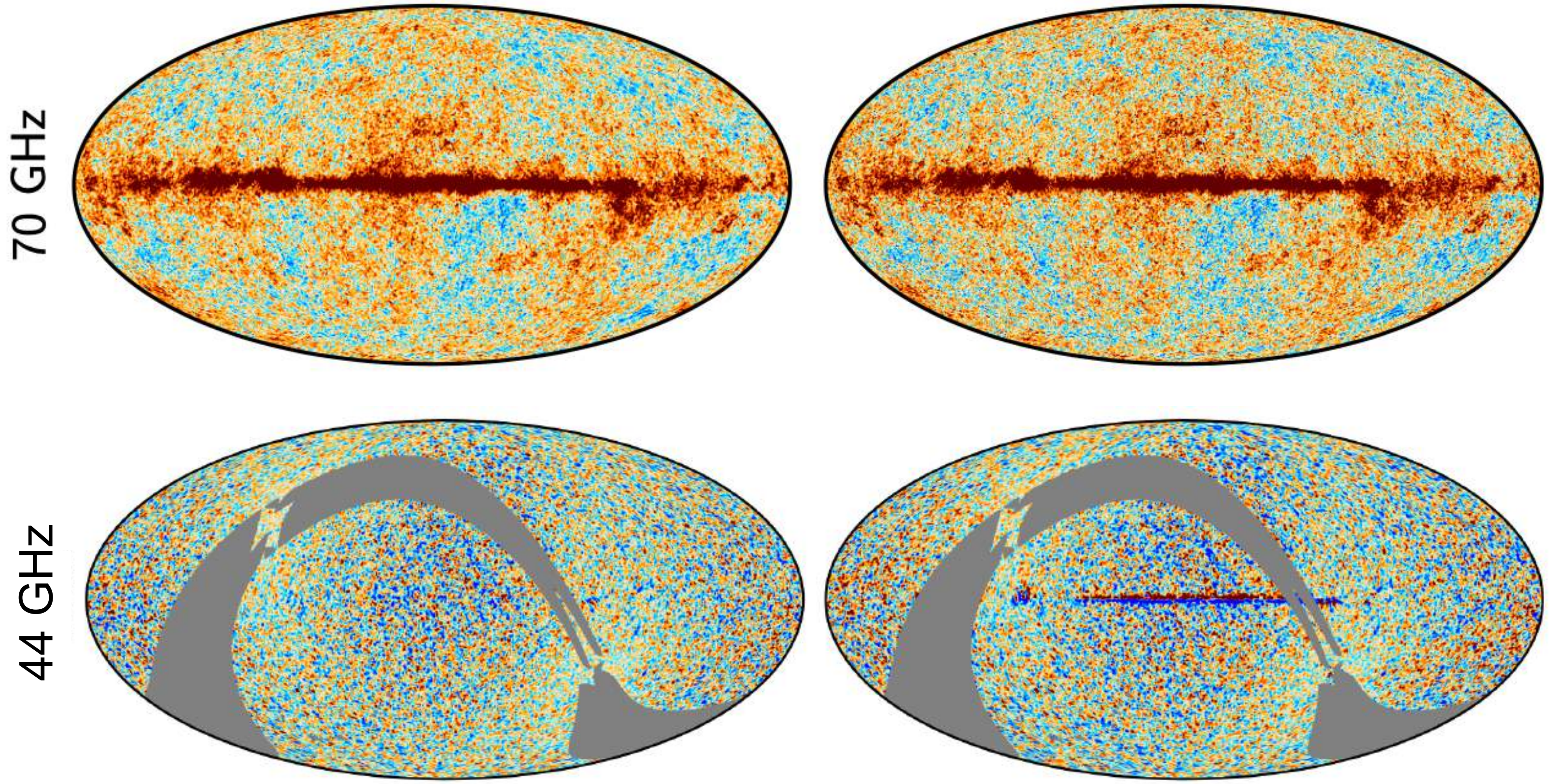
Removal of temperature leakage!

Simulation with unpolarized foregrounds and identical bandpasses:

All foreground signal in the Q map is leakage via beam-shape mismatch.

Application to Planck LFI data

deconvolved



Odd-even survey difference (temperature)

Requirements: Can I use this for my experiment?

- Must obey the data model: $$t_j = \sum_{slmk} a_{slm} b^*_{slk} D^{l*}_{mk}(\omega_j) + n_j$$
- Inputs:
  - Time-ordered data, compressed to a 3D map,
    n ≈ white noise
  - Known beam shapes:
    Beam = linear instrument response, rotates with the focal plane
- Full sky coverage **not** required
- Outputs:
  - Harmonic expansion of the beam-free sky (temperature+polarisation)
    From these one can construct a map with symmetric Gaussian effective beam

Performance considerations

- Total cost of deconvolving all of Planck LFI 70 GHz data (6 radiometers) up to multipole to ℓ_{max} =1500:
  5 hours on 24 cores (120 CPU hours)
- Scales linearly with number of detectors
- Scales as $\ell_{\text{max}}^2 \cdots \ell_{\text{max}}^3$
- Code available at http://sourceforge.net/projects/art-deco/

Deconvolution and Gibbs sampling

Deconvolution and Gibbs sampling

- Beyond PLANCK project (talk by H.K. Eriksen on Monday) has implemented a global Gibbs sampling framework for joint analysis of CMB+astrophysical+ instrument parameters, and applied it to Planck LFI.
- Opens the possibility of including beam-deconvolution as one Gibbs sampling step, combining it with foreground cleaning and removal of correlated noise.
- 3D maps...
  - retain the information on beam orientation (important for deconvolution)
  - are detector-specific = not subject to bandpass mismatch.
- Each 3D map can be handled like a separate frequency map
  - Natural domain for component separation

Simulation

- Four Planck 30 GHz radiometers
- CMB + 3 foreground components (sync, free-free, spinning dust) + noise (correlated+white)
- Realistic beams

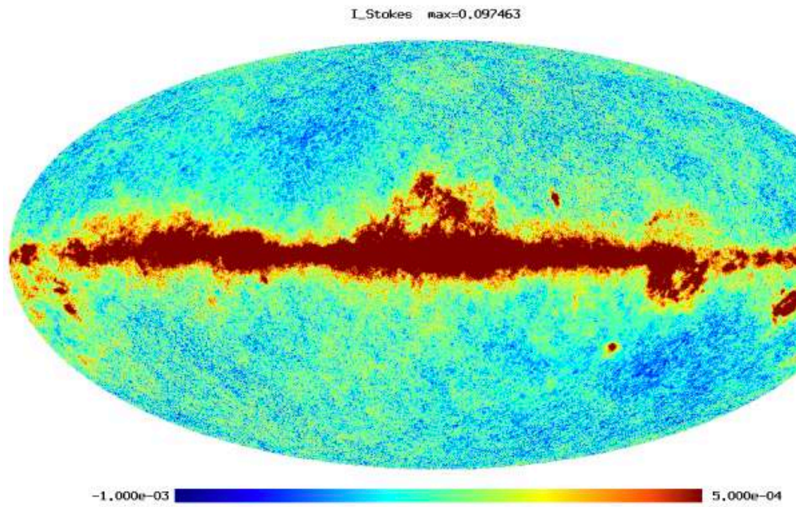
- Data model:

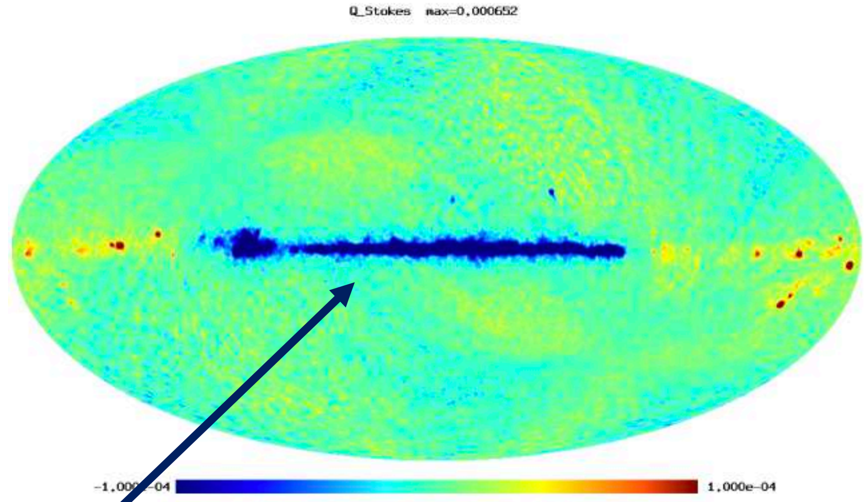
$$t_j = \sum_{slmk} a_{slm} b^*_{slk} D^{l*}_{mk}(\omega_j) + \sum_p c_p F(\omega_j) + n_j^{\mathrm{corr}} + n_j^{\mathrm{white}}$$

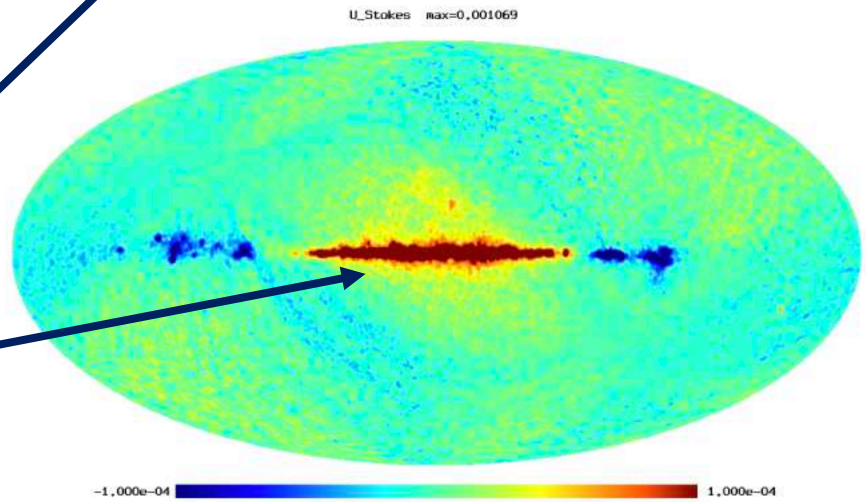
CMB

Simple foreground model:
F = foreground template (3D map, beam convolved)
c_p = amplitude (one coefficient per radiometer and per component, 12 in total)

Direct map-making







Simulation with
un-polarized foregrounds

leakage
bandpass & beam

Gibbs sampling procedure

Data model:

$$t_j = \sum_{slmk} a_{slm} b^*_{slk} D^{l*}_{mk}(\omega_j) + \sum_p c_p F(\omega_j) + \cancel{n_j^{\text{corr}}} + n_j^{\text{white}}$$

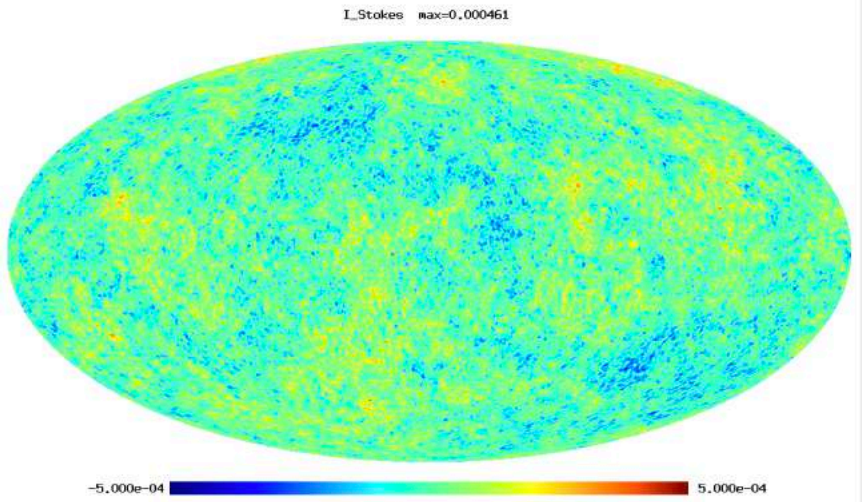
CMB

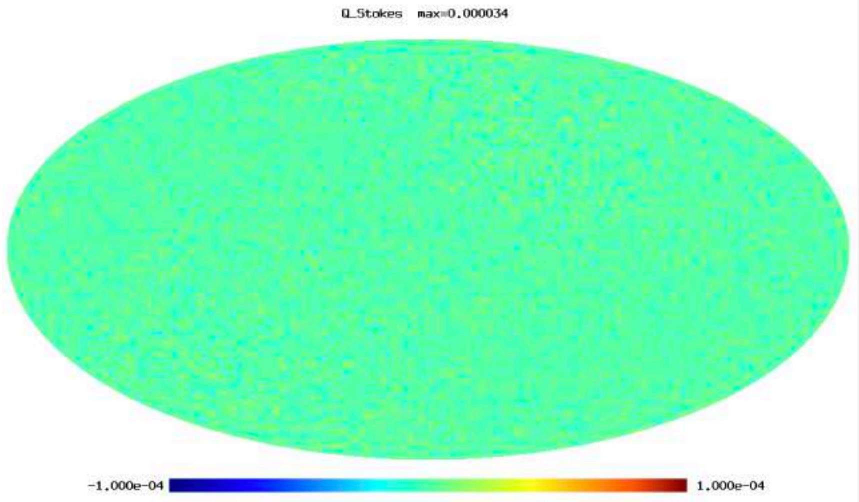
Foreground model

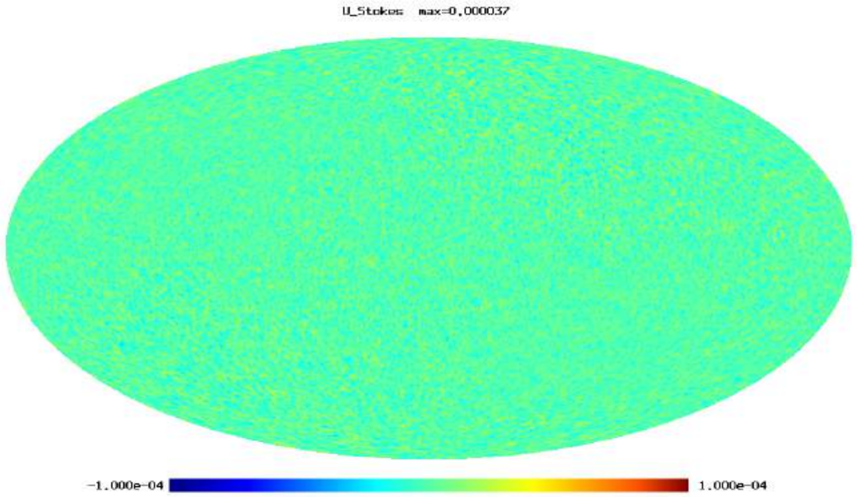
$$\begin{aligned}
\boldsymbol{a}' &\leftarrow P(\boldsymbol{a} \mid \boldsymbol{c}, \boldsymbol{n}_{\text{corr}}, \boldsymbol{y}) \\
\boldsymbol{c}' &\leftarrow P(\boldsymbol{c} \mid \boldsymbol{n}_{\text{corr}}, a, \boldsymbol{y}) \\
\cancel{\boldsymbol{n}'_{\text{corr}}} &\cancel{\leftarrow P(\boldsymbol{n}_{\text{corr}} \mid \boldsymbol{a}, \boldsymbol{c}, \boldsymbol{y})}
\end{aligned}$$

Need more data to break the degeneracies!

Deconvolution+fg cleaning







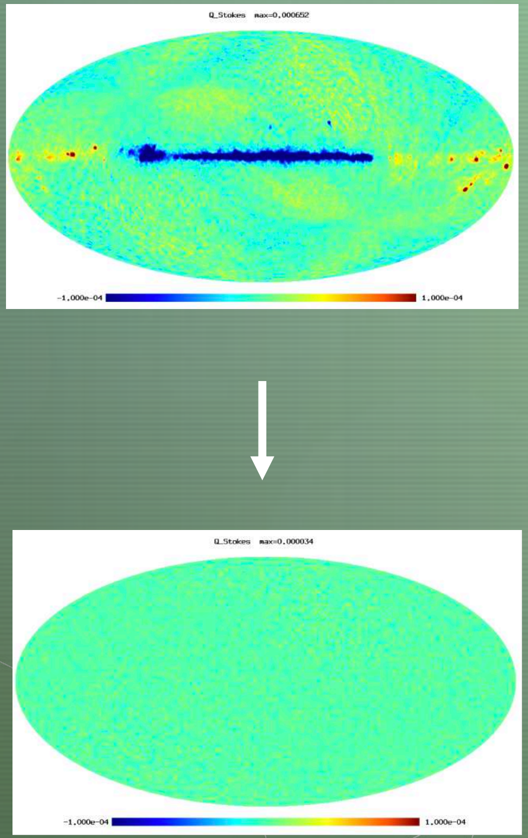
Foreground contamination + leakage removed!

Prospects and computational cost

- We have demonstrated that incorporating full beam deconvolution into a Gibbs sampling framework is fully feasible
- 14 Gibbs steps: 2 hours on 24 cores (1 node)
    - x 1000 (100 x data volume, 140 steps) = 8 days on 10 nodes

Summary

- Beam asymmetry is a source of leakage of temperature signal into polarisation
- ArtDeco is a beam-deconvolution code for correction of beam asymmetry effects
- We have demonstrated that beam-deconvolution can be incorporated into a Gibbs sampling framework (BeyondPlanck)
  -> Simultaneous correction of bandpass and beam leakage



References

- E. Keihänen and M. Reinecke. ArtDeco: a beam-deconvolution code for absolute cosmic microwave background measurements. Astronomy and Astrophysics, 548:A110, 2012
- E. Keihänen, K. Kiiveri, V. Lindholm, M. Reinecke, and A.-S. Suur-Uski, Impact of beam deconvolution on noise properties in CMB measurements: Application to Planck LFI. Astronomy and Astrophysics, 587:A27, 2016
- E. Keihänen, K. Kiiveri, H. Kurki-Suonio, and M. Reinecke.
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  Monthly Notices of the Royal Astronomical Society, 466:1348, 2017
- E. Keihänen, V. Lindholm, M. Lopez-Caniego, M. Maris, M. Reinecke, and A.-S. Suur-Uski. Beam-deconvolved Planck LFI maps. Astronomy and Astrophysics, 632:A1, 2019
- Beyond PLANCK: https://beyondplanck.science