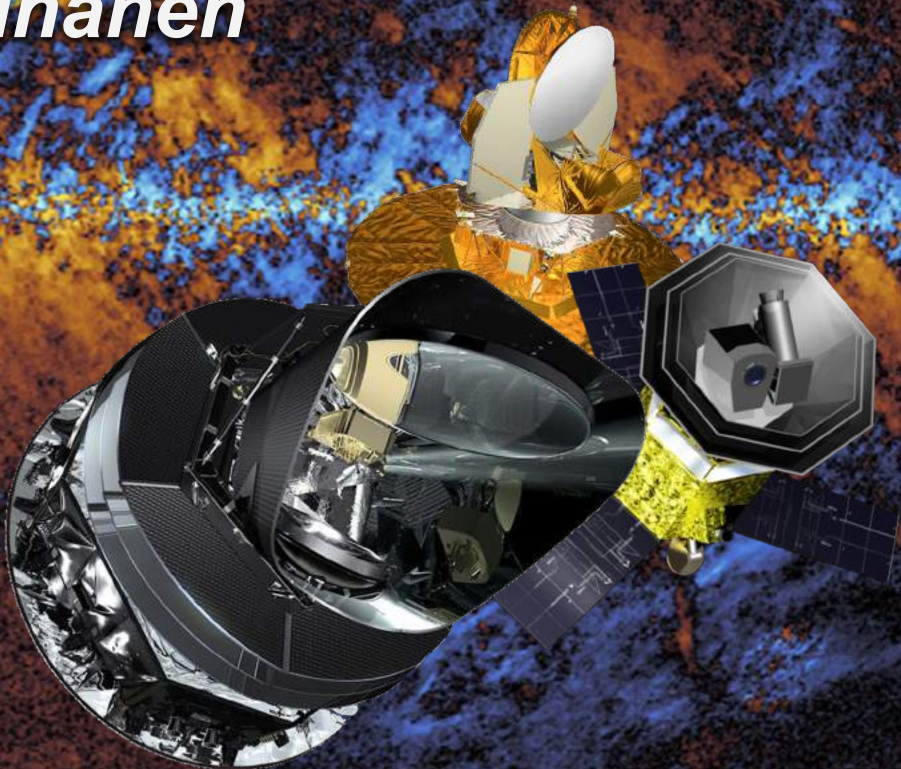
CMB map-making through Gibbs sampling

Elina Keihänen



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BeyondPlanck II. CMB map-making through Gibbs sampling

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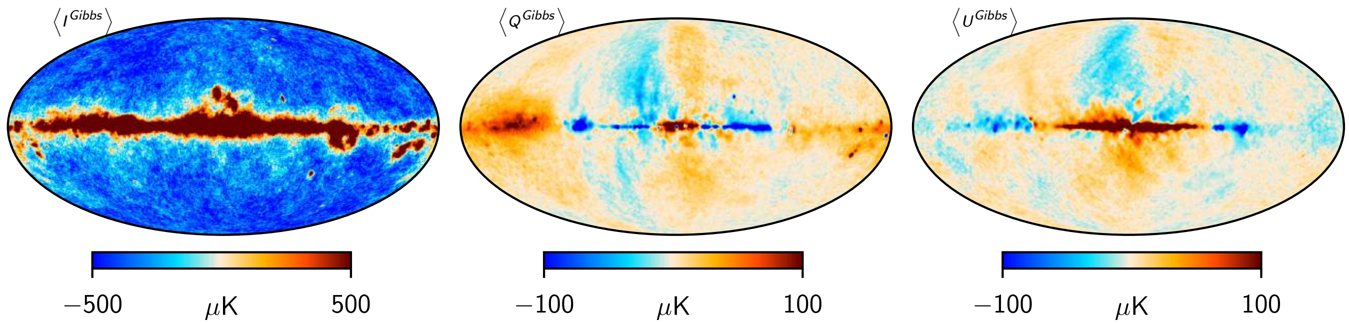
- Paper available online: http://arxiv.org/abs/2011.06024
    - Theoretical background for the map-making algorithm of BeyondPlanck
    - Results based on simulations

What is map-making?

- Map-making:
  - One (heavy) processing step in conventional CMB processing
  - Input: Calibrated time-ordered data (TOI)
  - Output: Frequency maps of in temperature and polarization (CMB+foregrounds)



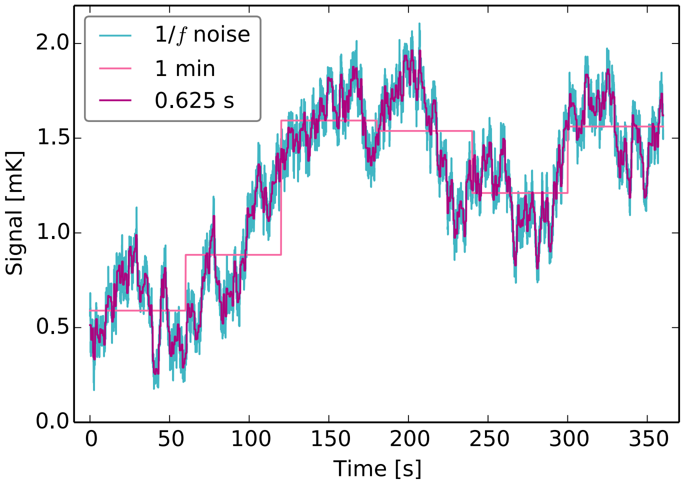
  - Provides input to next processing steps (component separation, cosmological parameters)

- **Removal of correlated noise**

Beyond PLANCK

Map-making methods

- Traditional map-making methods fall into two categories:
  - Maximum-likelihood (GLS) methods
  - Destriping methods
- GLS $$\boldsymbol{m} = (\mathrm{P}^T \mathrm{C}^{-1} \mathrm{P})^{-1} P^T \mathrm{C}^{-1} \boldsymbol{y}$$
- Destriping:
  - Correlated noise modelled as a sequence of offsets, “baselines”
  - Flexibility in terms of mask etc.
  - Baseline length as parameter



- LFI DPC uses Madam destriper for map-making
  - Baseline lengths 0.25-1.0 sec

Map-making through Gibbs sampling

- New: map-making through Gibbs sampling

- "If you cannot beat them, join them"
  - Make correlated noise a Gibbs variable
  - "Noise" = white noise

- Formalism borrowed from destriping

Pointing matrix ↓ baseline-to-TOI ↓

$$\boldsymbol{y} = \mathrm{P}\boldsymbol{m} + \mathrm{F}\boldsymbol{a} + \boldsymbol{n}$$

$\boldsymbol{m}$: Map — **Sampled**

$\boldsymbol{a}$: Noise baseline — **Sampled**

$\boldsymbol{n}$: white noise

Gibbs sampling procedure

- Draw samples from conditional likelihoods

$$\boldsymbol{m}' \leftarrow P(\boldsymbol{m} \mid \boldsymbol{a}; \boldsymbol{y}, \mathsf{C}_w)$$
$$\boldsymbol{a}' \leftarrow P(\boldsymbol{a} \mid \boldsymbol{m}; \boldsymbol{y}, \mathsf{C}_w, \mathsf{C}_a)$$

- Map-making is broken into two manageable steps
  1) Map binning:

$$\boldsymbol{m}' = (\mathsf{P}^T \mathsf{C}_w^{-1} \mathsf{P})^{-1} [\mathsf{P}^T \mathsf{C}_w^{-1} (\boldsymbol{y} - \mathsf{F}\boldsymbol{a}) \quad + \mathsf{C}_w^{-1/2} \omega_1]$$

  2) Correlated noise:

white noise

$$\boldsymbol{b} = \mathsf{C}_w^{-1} (\boldsymbol{y} - \mathsf{P}\boldsymbol{m}') + \mathsf{C}_w^{-1/2} \omega_2 + \mathsf{C}_a^{-1/2} \omega_3$$
$$\boldsymbol{a}' = (\mathsf{C}_w^{-1} + \mathsf{C}_a^{-1})^{-1} \boldsymbol{b}$$

- Solved by pointing period. Baseline length down to 1 sample!
- Maximum-likelihood mode or sampling mode

What to do about gaps?

$$\boldsymbol{a}' = (\mathsf{C}_w^{-1} + \mathsf{C}_a^{-1})^{-1}\boldsymbol{b}$$

- Stationary system can be solved with FFT (Fast Fourier Transform)
- Gaps: data sections that cannot be used in the analysis

$$\mathsf{C}_w \to \infty \quad \Rightarrow \quad \mathsf{C}_w^{-1} = 0$$

- Leads to a non-stationary system (no FFT)
  - Can be solved through CG iteration

Filling the gaps

- Gap filling
  - Make white noise inside gaps a new Gibbs variable
  - Sampling in three steps: sky map, correlated noise, white noise within gaps

$$
\begin{aligned}
\boldsymbol{m}' &\leftarrow P(\boldsymbol{m} \mid \boldsymbol{a}; \boldsymbol{y}, \mathsf{C}_w) \\
\boldsymbol{w}' &\leftarrow P(\boldsymbol{w} \mid \mathsf{C}_w) \\
\boldsymbol{a}' &\leftarrow P(\boldsymbol{a} \mid \boldsymbol{m}, \boldsymbol{w}; \boldsymbol{y}, \mathsf{C}_x)
\end{aligned}
$$

  - Stationary system -> FFT.
  - 5-10 times faster than conjugate-gradient solution
  - Increased memory requirement, increased correlation length

- Commander implements the non-stationary system (memory limitations)

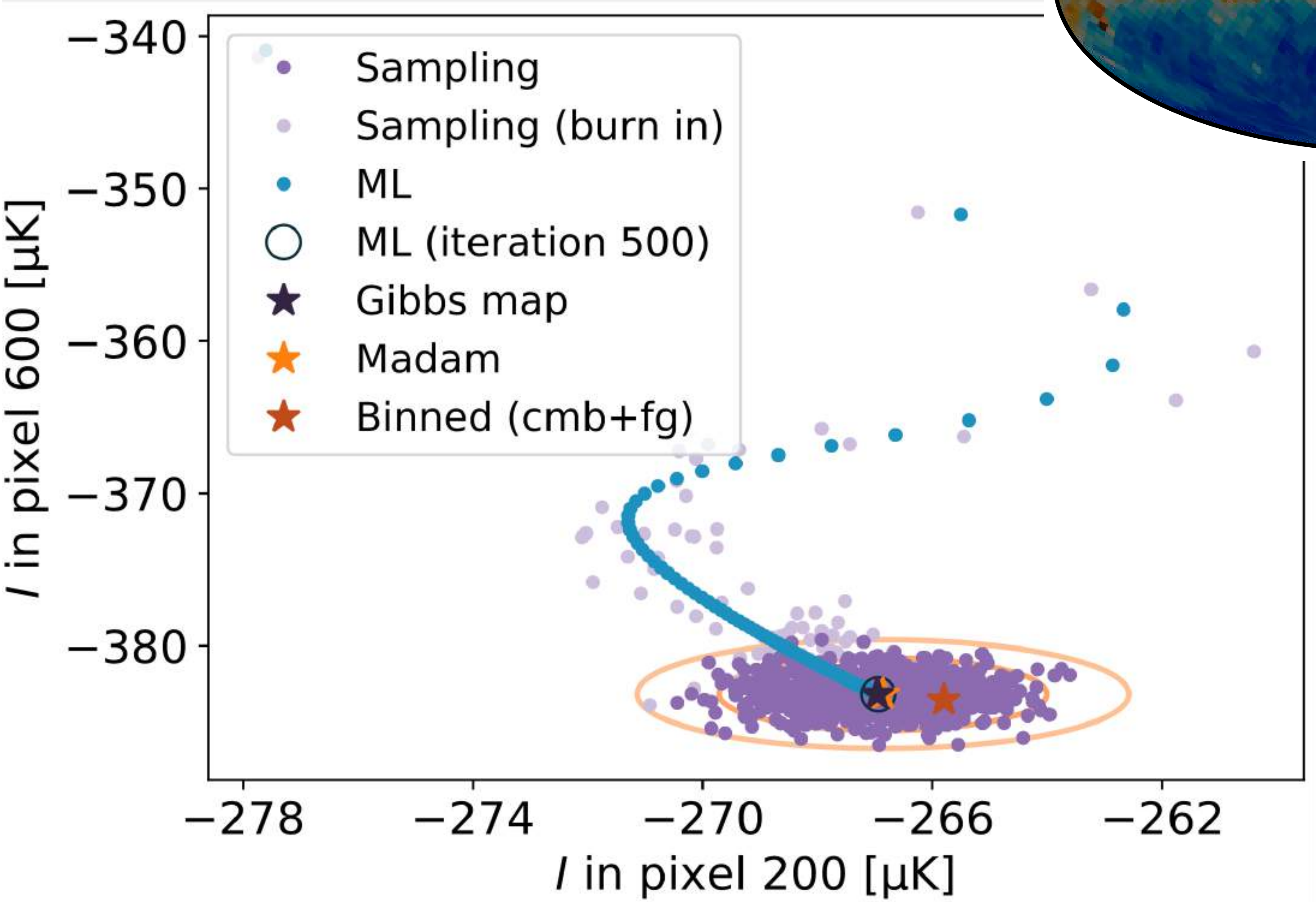
Simulations

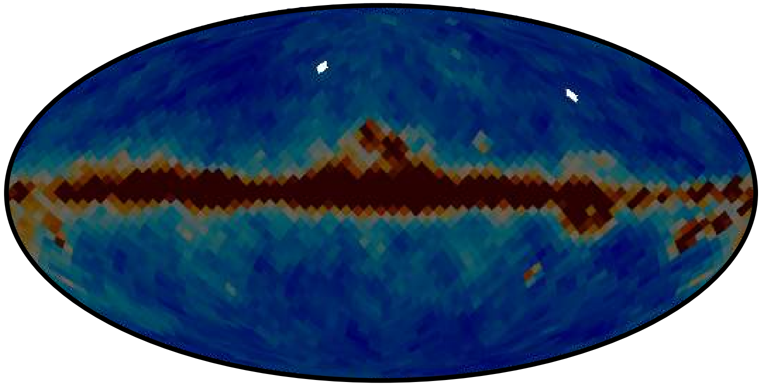
- Test code ("gibbsmap") outside Commander (C++)

- Simulations produced with LevelS
  - 30 GHz, 4 radiometers
  - Noise parameters, beams etc. from Planck 2018 release
  - CMB+astrophysical components
  - correlated + white noise

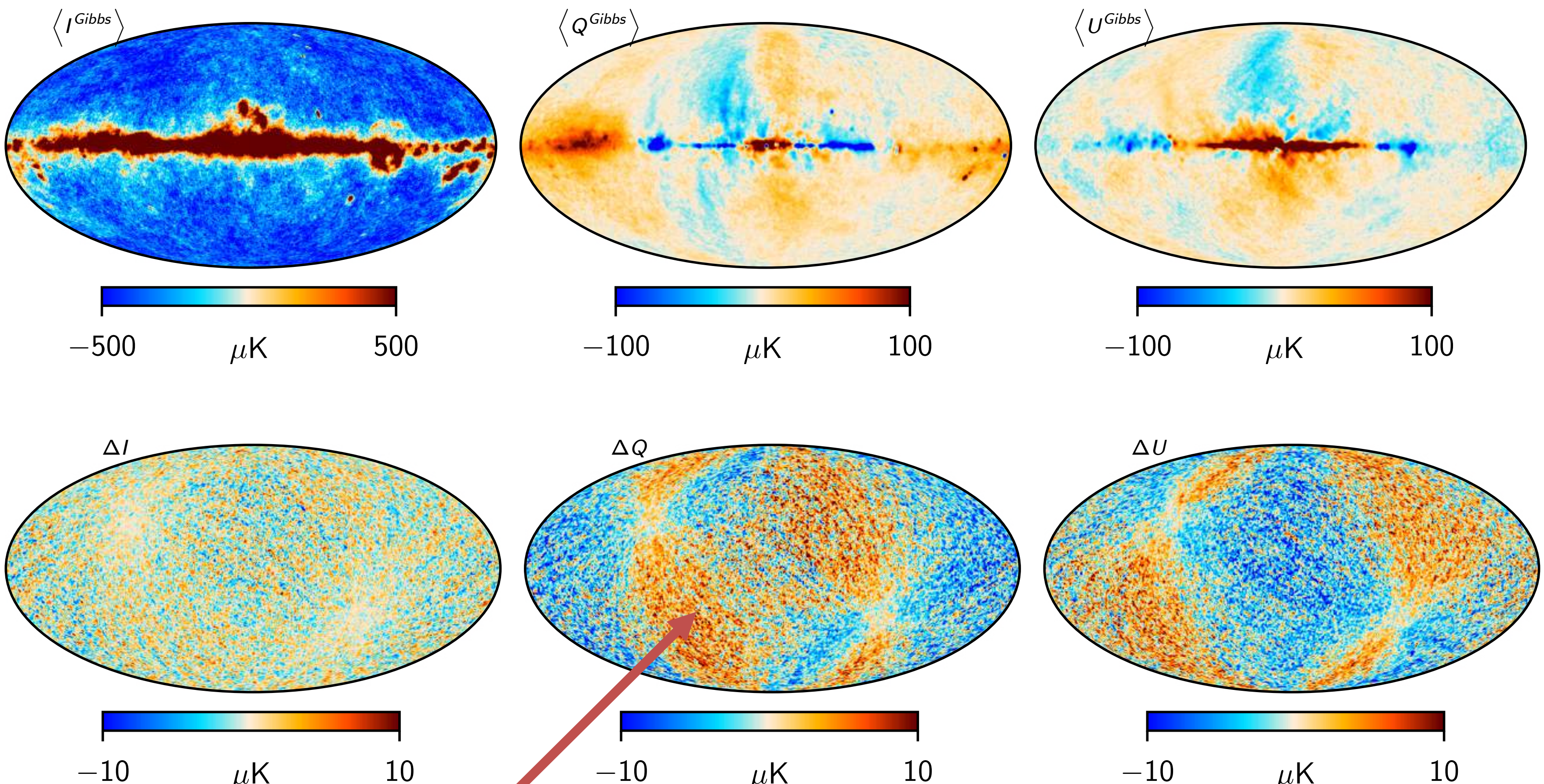
- We run Madam destriper on the same data for reference

Sampling in pixel space



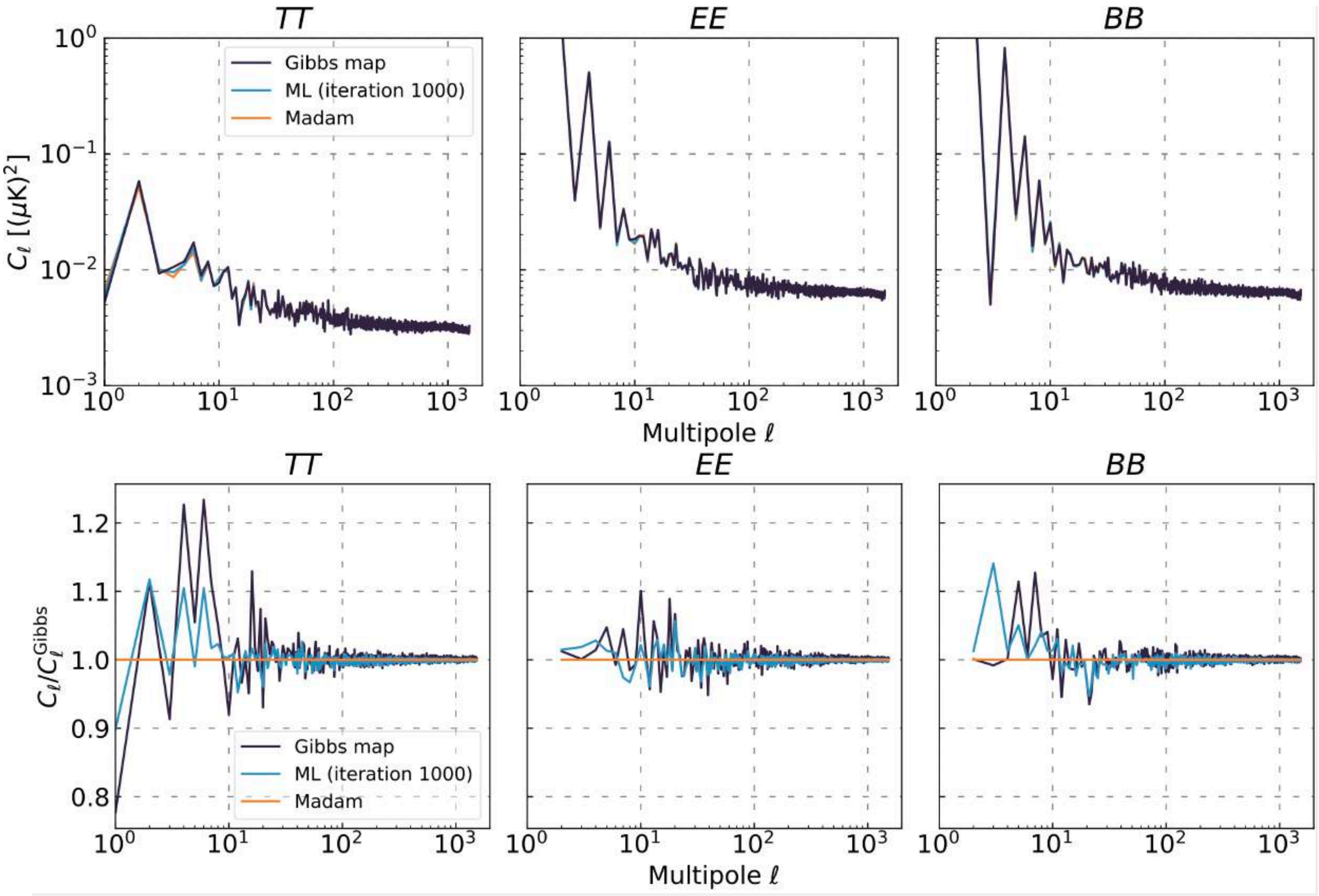


Gibbs map = mean of the Gibbs chain



Bandpass leakage
Cannot be solved in map-making alone.
We need global Gibbs sampling!

Residual noise spectrum

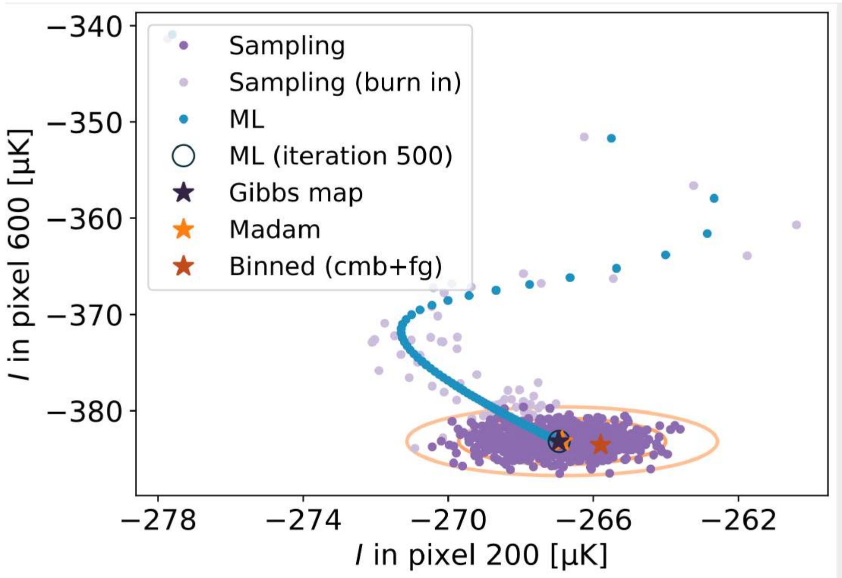


Computational cost

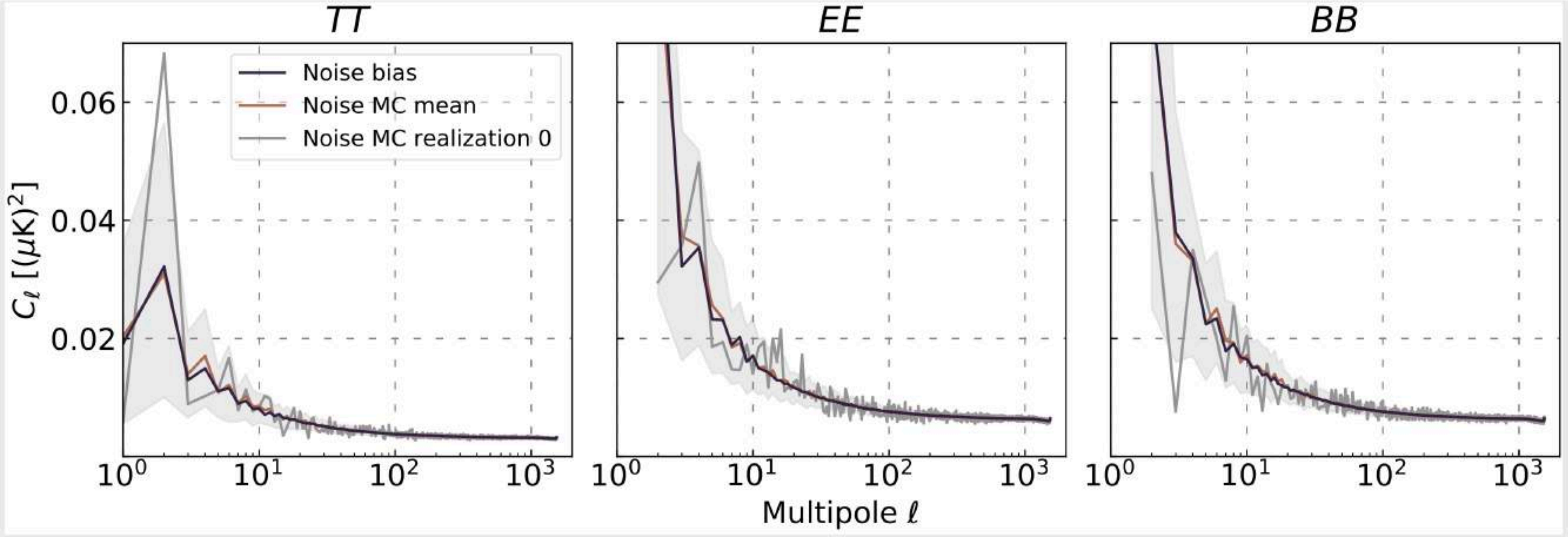
- Madam: 1 hour on 24 cores (27 CPUh)
- Gibbs sampling in *maximum-likelihood mode* (gaps filled):
  107s per sample, 30 hours (720 CPUh) for 1000 samples
- Gibbs sampling in *sampling mode* (gaps filled):
  173s per sample, 2 days (1170 CPUh) for 1000 samples
- Gibbs sampling in maximum-likelihood mode (*no gap filling*, solution of non-stationary system):
  1814 s per sample, 10 days (6000 CPUh) for 500 samples

Why use Gibbs sampling?

- If we get the same results with cheaper methods, what do we need Gibbs sampling for?
  - Residual noise assessment!



Noise bias



100 Monte Carlo realizations: 8 days (wall-clock)
1000 Gibbs steps: 2 days

Why use Gibbs sampling?

- If we get the same results with cheaper methods, what do we need Gibbs sampling for?
  - Residual noise assessment!
  - Opens way for more sophisticated map-making methods (beam deconvolution)
  - Make noise sampling part of a global Gibbs sampling chain (BeyondPlanck!)

Map-making and BeyondPlanck

- Gibbs sampling can be used for map-making and removal of correlated noise
- Conceptual basis for the map-making algorithm employed in BeyondPlanck
- Implementation in BeyondPlanck pipeline: See the talks by Håvard Ihle and Anna-Stiina Suur-Uski tomorrow!

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  - COMPET-4 program
  - PI: Hans Kristian Eriksen
  - Grant no.: 776282
  - Period: Mar 2018 to Nov 2020

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  - ERC Consolidator Grant
  - PI: Hans Kristian Eriksen
  - Grant no: 772 253
  - Period: April 2018 to March 2023
- "*Cosmoglobe*"
  - ERC Consolidator Grant
  - PI: Ingunn Wehus
  - Grant no: 819 478
  - Period: June 2019 to May 2024