Simon Prunet, on behalf of the (now extinct) Planck collaboration

Planck: some lessons learned

And others still to be learned

Outline

- Space versus ground, and other evidences
- Planck in a nutshell
- Different views of data analysis
  - The theorist: has The solution ?
  - The painful reality (instrumental, astrophysical, political…)
- Planck ground segment structure, end-to-end simulations, data centers, etc.

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- Space versus ground, and other evidences
- Planck in a nutshell
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Space versus ground

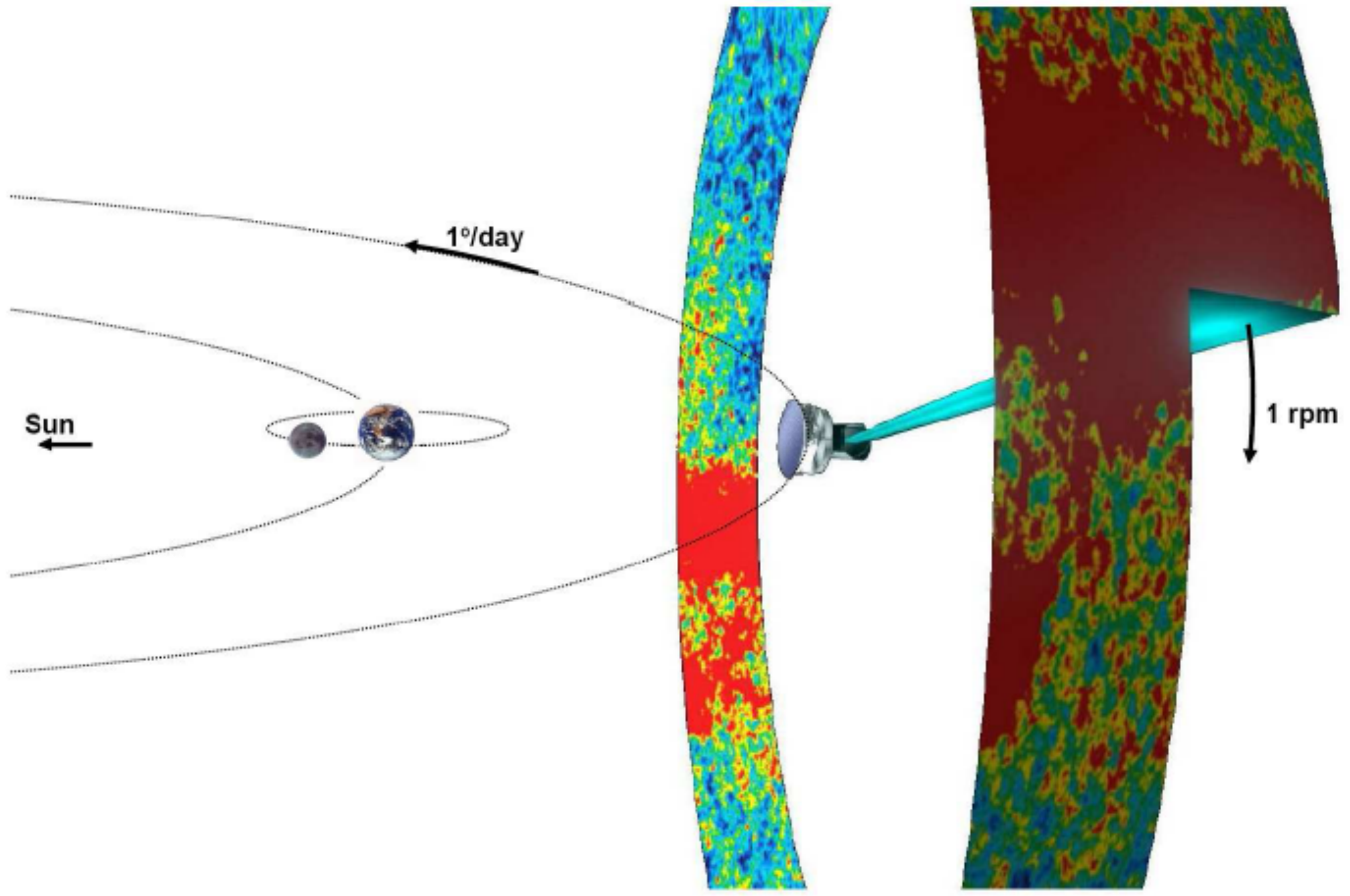
Instrument/payload versus ground segment

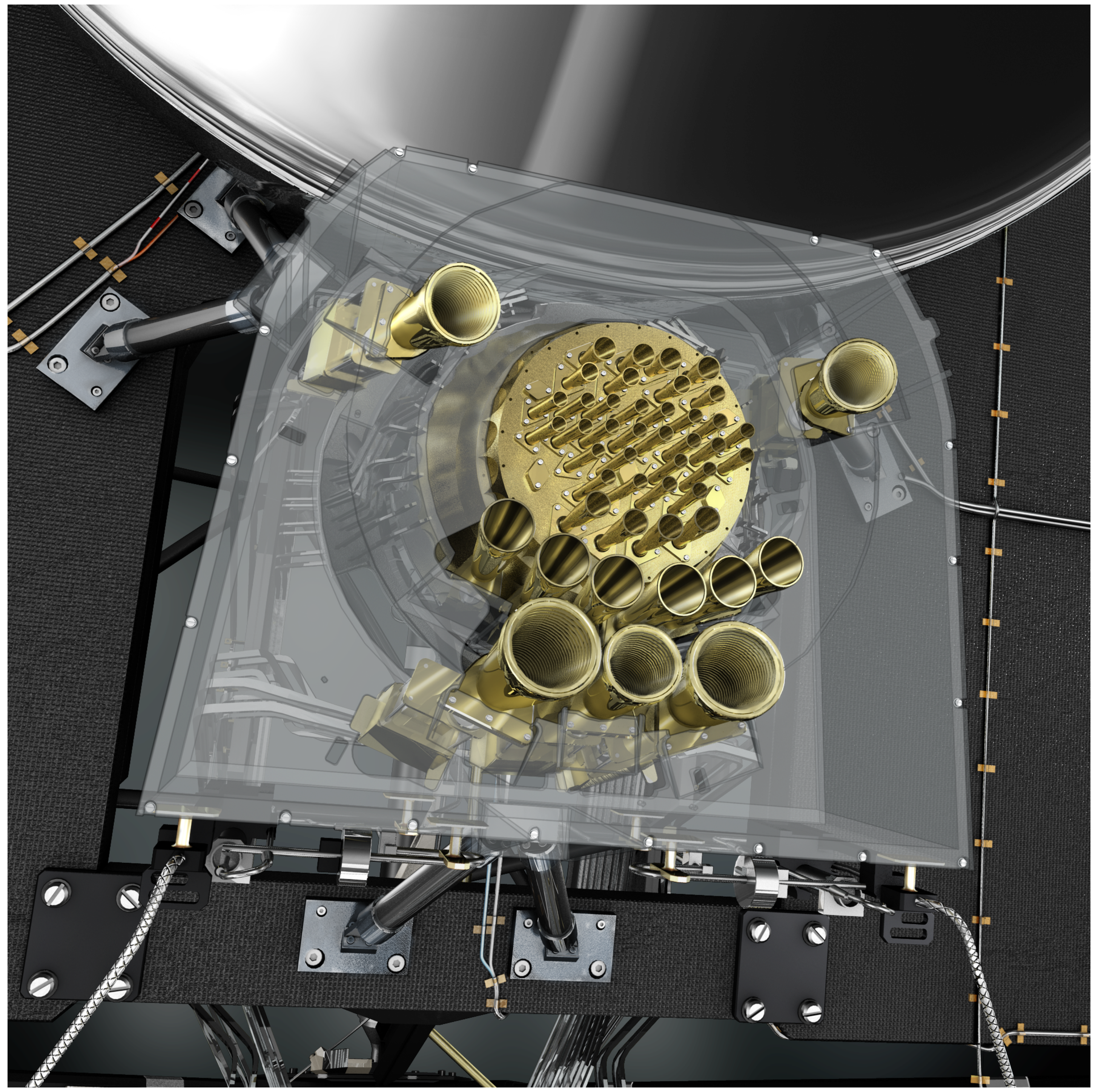
- These might be trivial statements, but you <u>have</u> to remind yourself of them often:
  - A space mission payload, instrument, cannot be fixed after launch (except for HST…)
  - A space mission instrument sub-system cannot be tested after launch, if testing processes have not been designed and built in
- A ground segment can (and will !) be refined (many) many times after launch.
- You prepare years in advance, and think you know your data model… that’s so sweet ! Wait for the data…

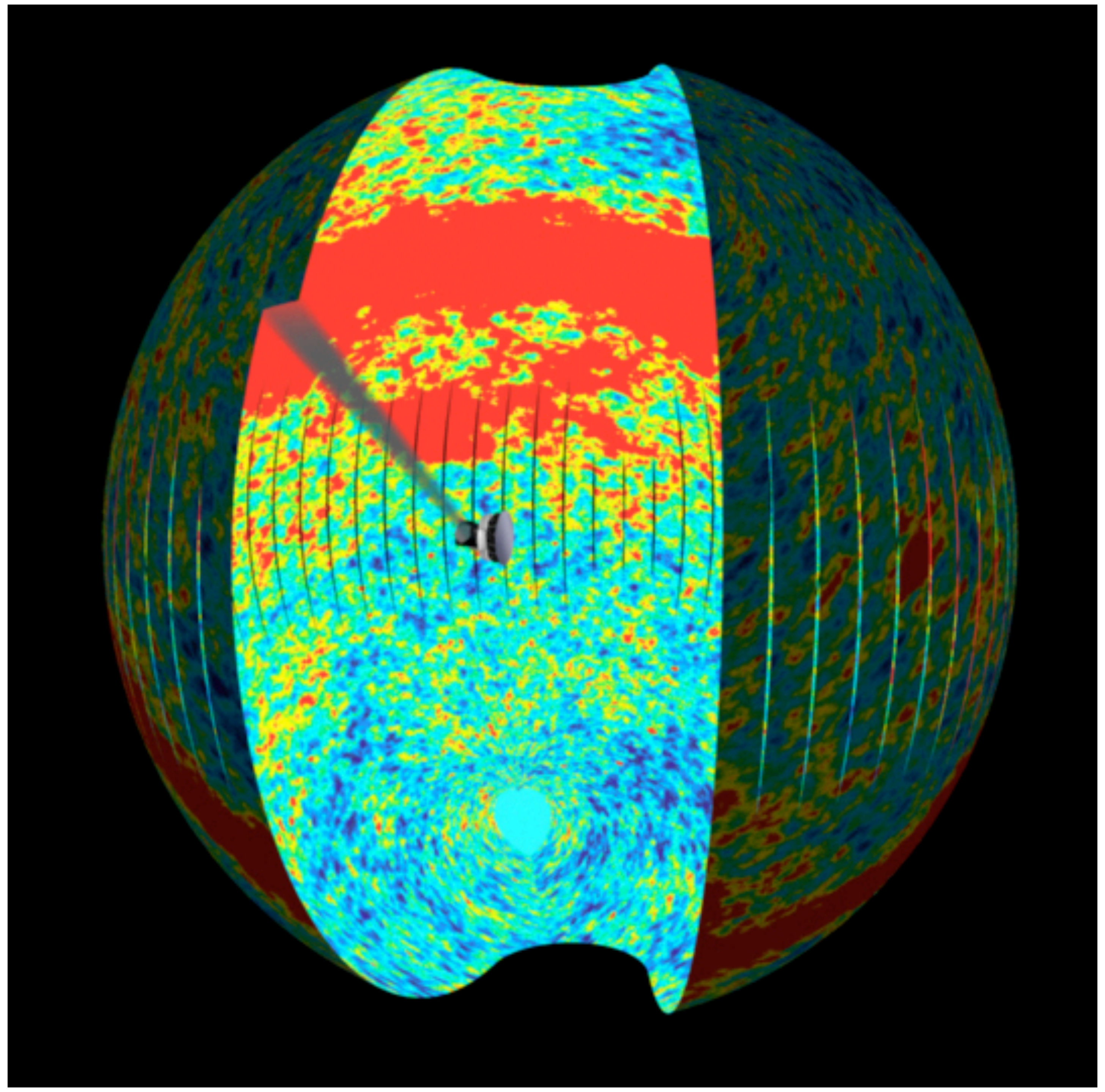
Planck in a nutshell

Legacy mapping of CMB anisotropies, explore all-sky polarisation

- ESA space mission to map CMB temperature anisotropies, launched in 2009
- 1.5m diameter primary, off-axis Gregorian design
- 2 instruments:
    - LFI: 30 to 70 GHz, HEMT technology (same as WMAP), intrinsically polarised
    - HFI: 100 to 857 GHz, Bolometer technology, (first in space), some polarised channels
    - Single pixels with wave guides (feed horns): this is a scanning experiment
    - Produces timelines of data (~ a few tera samples total, plus housekeeping data)







HFi PLANCK

PLANCK LFI

Planck in a nutshell

Planck 2018 results: I Overview and Cosmological Legacy

From timelines to power spectra

HFI Core Team: HFI Data Processing

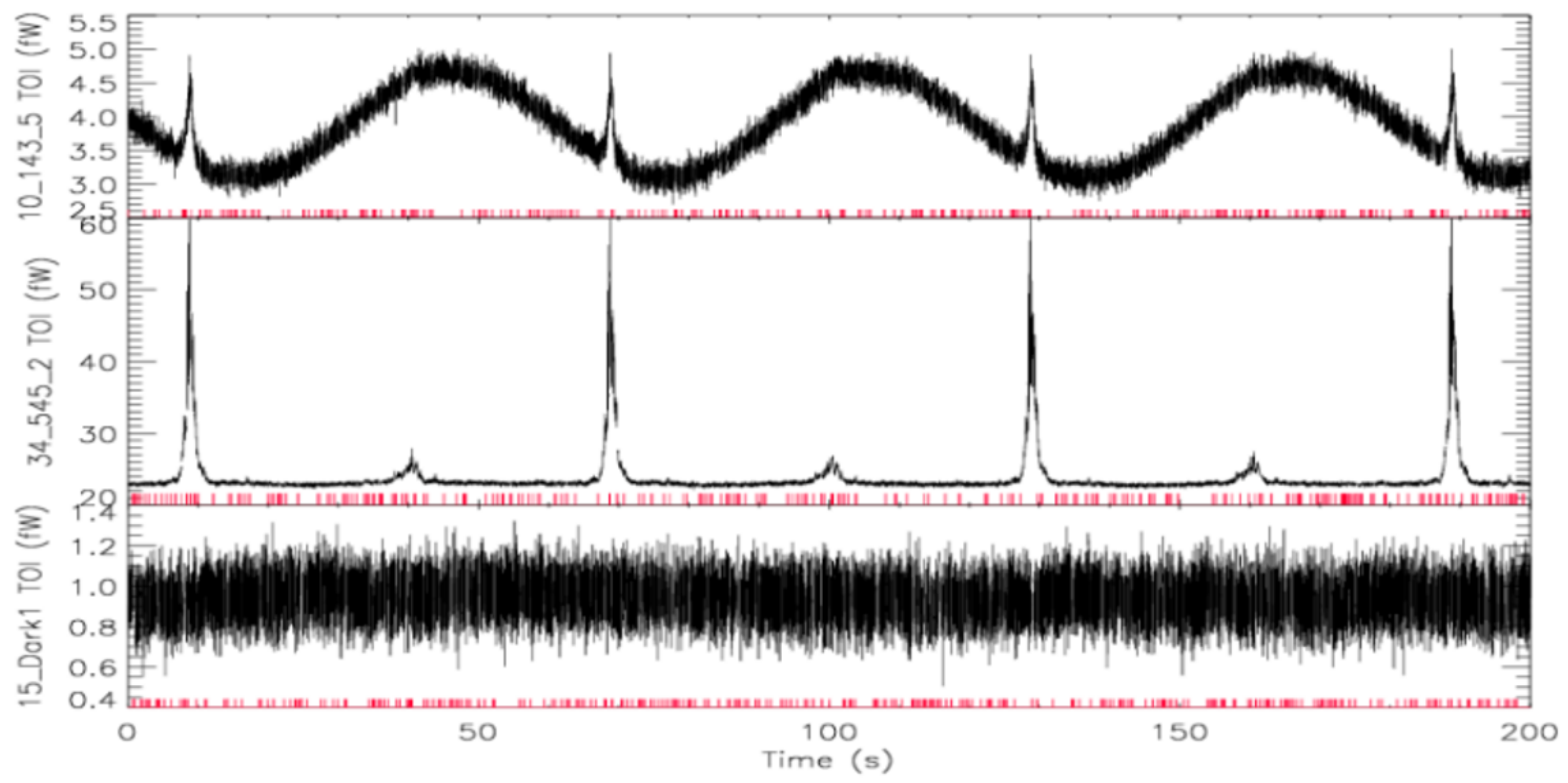
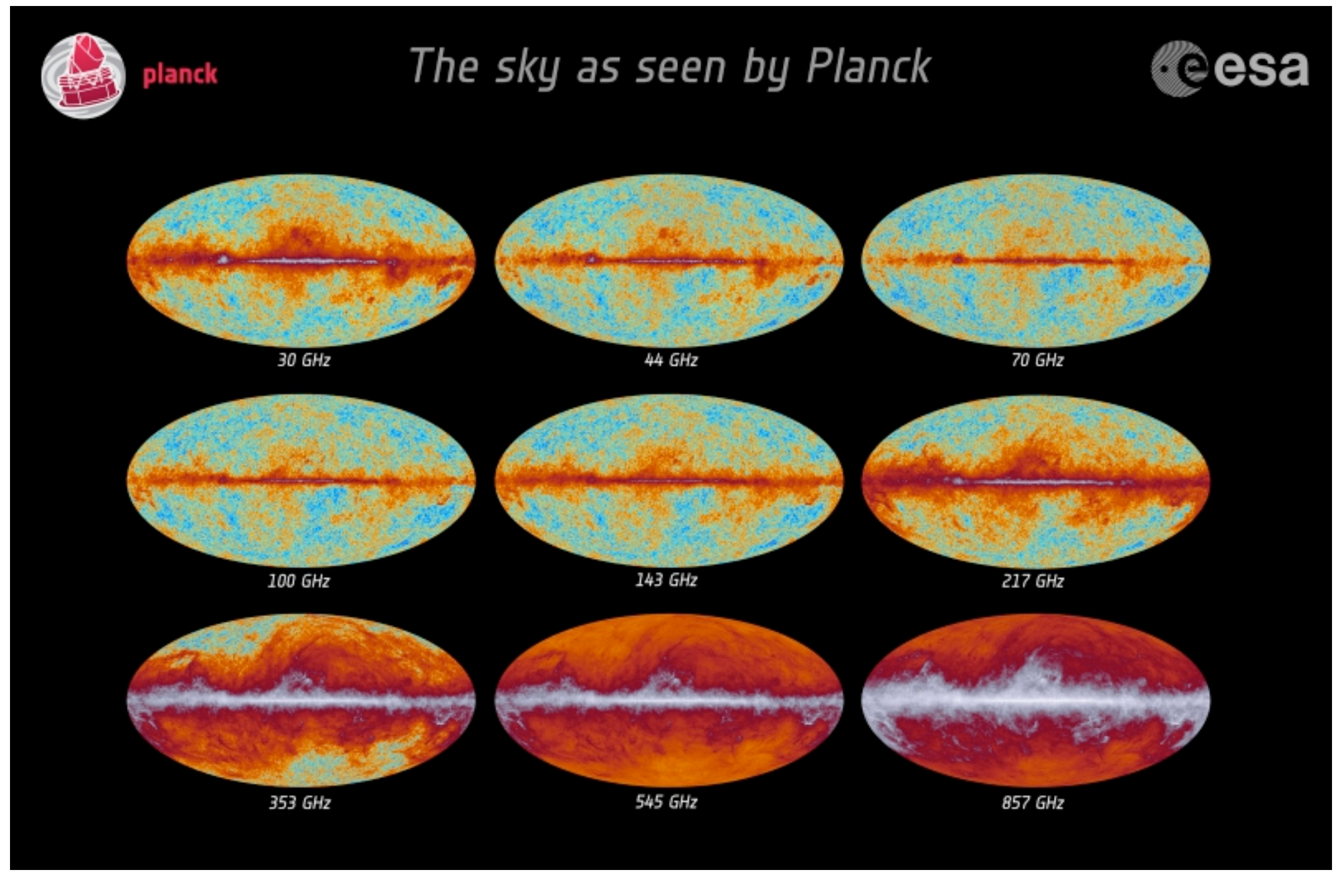


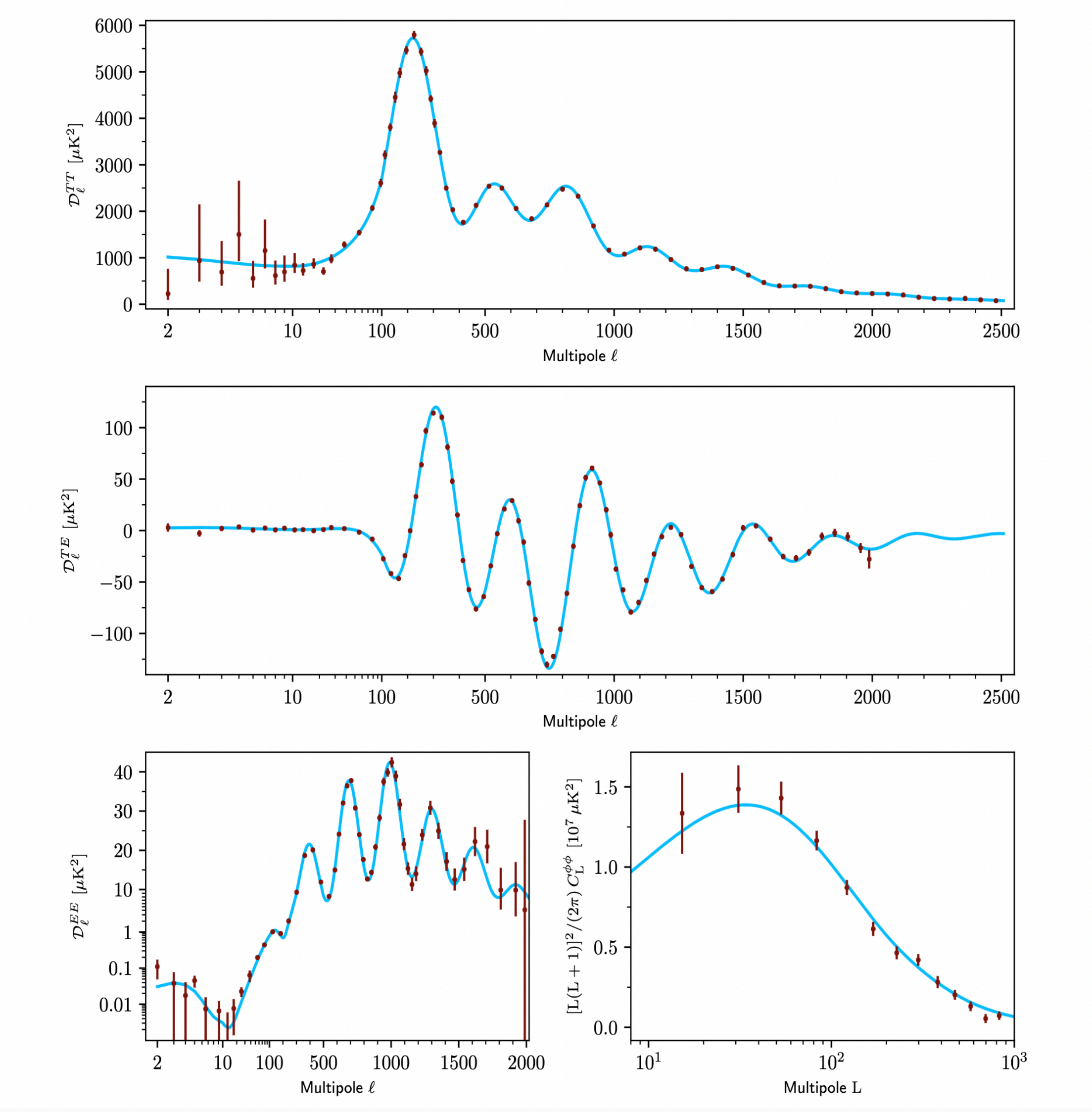
Figure 19. Processed TOI for the same bolometers and time range as shown in Fig. 4. Red samples are considered valid. Times where data are flagged, are indicated by the purple ticks at the bottom of each plot.

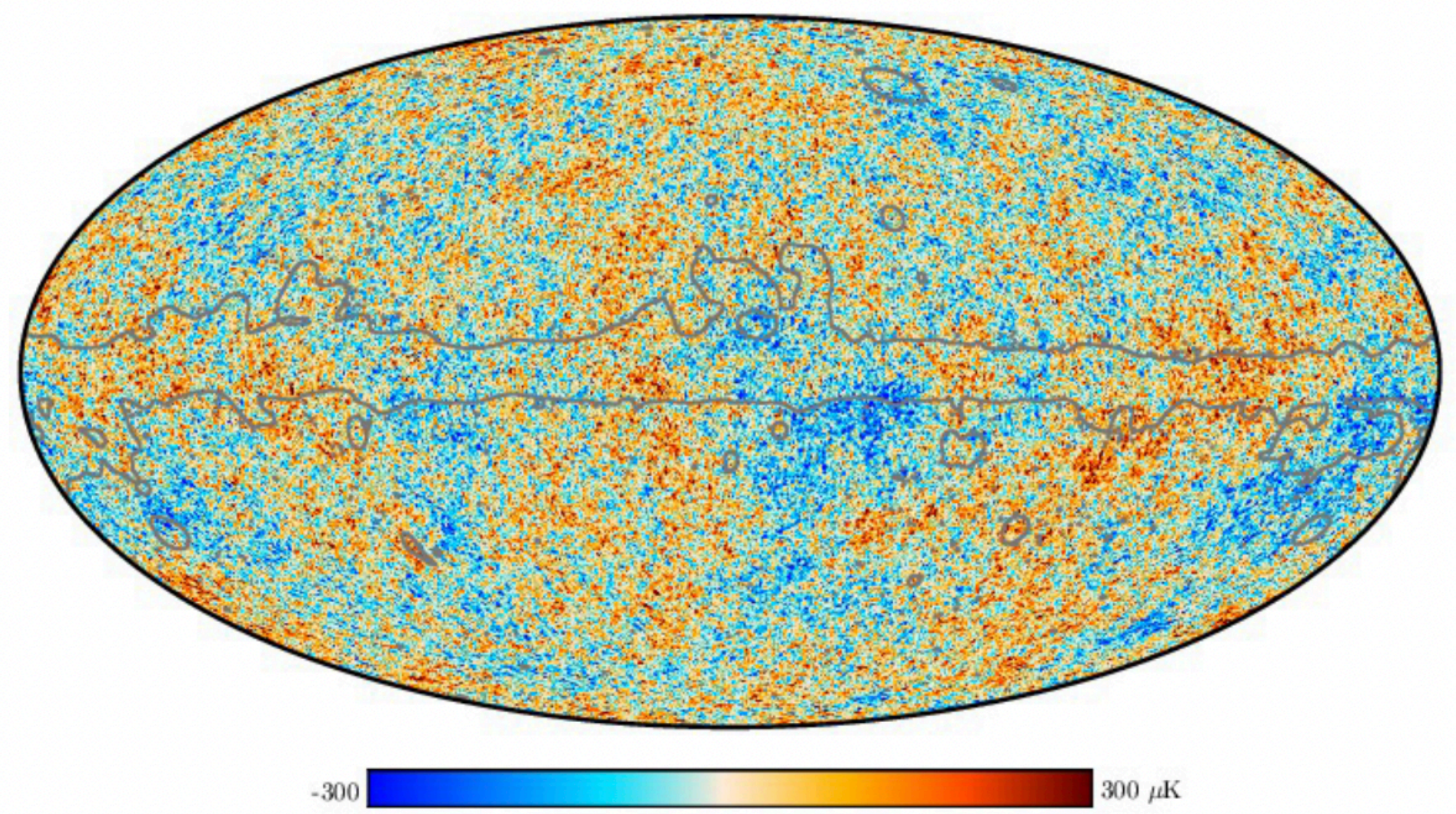
Map making



Components separation

Spectral matching: Planck Likelihood



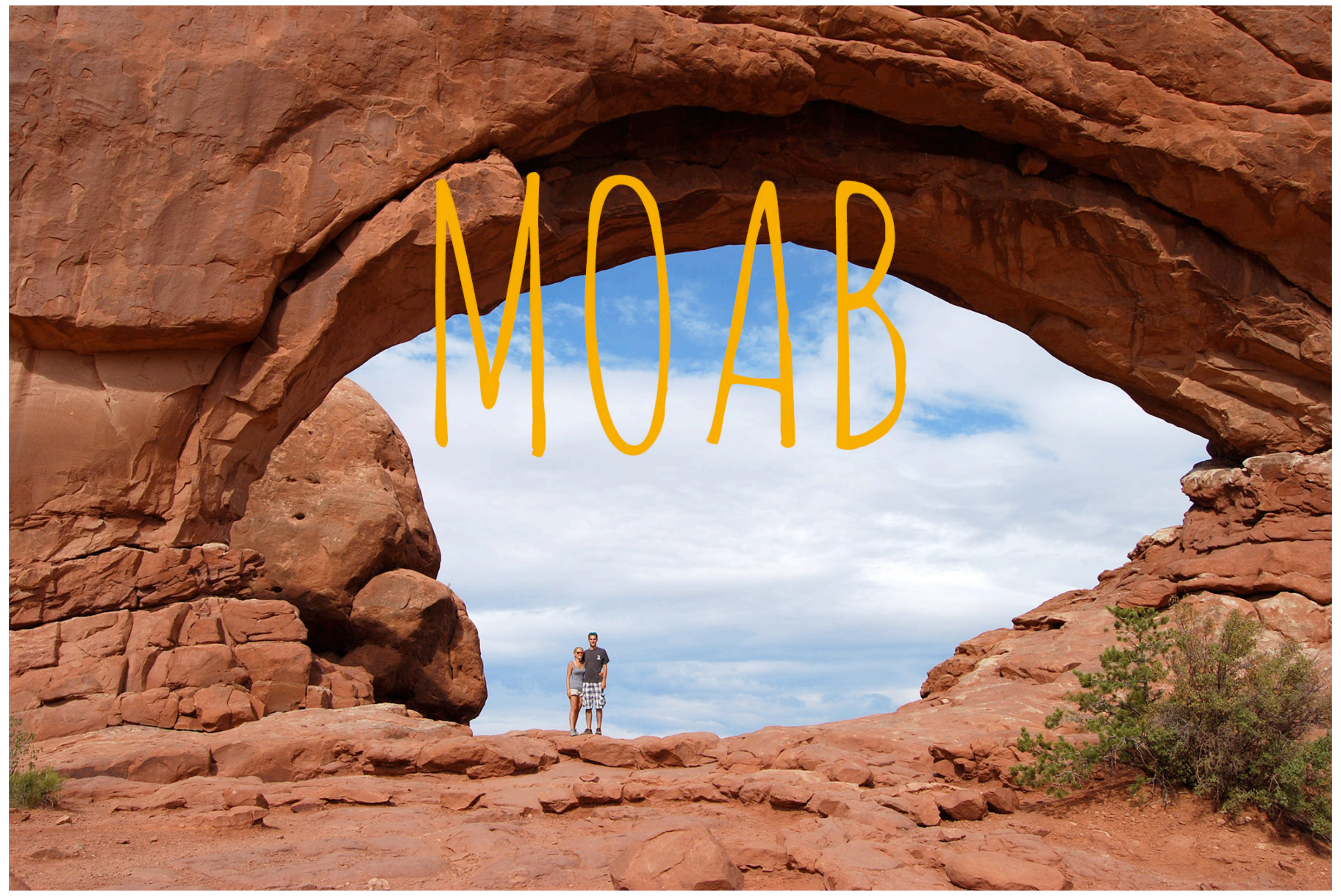


Spectral analysis

Interlude

Theorist versus instrumentalist's view of data processing

- One model, as many parameters as needed
- One data processing
- One Bayesian Code



Mightiest Of All Bayesian codes

- Our instrument is cool and shiny
- It's really, really complicated you know…
- But there's nothing that we can't do with a good digital knife !

Space agency: Kids, please play gently together !!!
And most importantly, according to OUR rules please.

The theorist's view: the MOAB approach

Joint CMB map and power spectrum (and foregrounds, and…) estimation

$$\mathbf{s}_\nu(\theta) = \bar{\mathbf{s}}_\nu(\mathbf{a}_i, \beta_i, g_\nu, \mathbf{m}_\nu, \Delta_\nu) = g_\nu \sum_{i=1}^{N_{\rm comp}} \mathsf{F}^i_\nu(\beta_i, \Delta_\nu)\mathbf{a}_i + \mathsf{T}_\nu \mathbf{m}_\nu,$$

Parametrize component SEDs, amplitude maps, calibration factors, nuisance parameters and templates in the signal

$$\mathcal{L}(\mathbf{a}_i, \beta_i, g_\nu, \mathbf{m}_\nu, \Delta_\nu) \propto \exp\left(-\frac{1}{2}\sum_\nu [\mathbf{d}_\nu - \mathbf{s}_\nu(\theta)]^{\rm T}\mathsf{N}^{-1}[\mathbf{d}_\nu - \mathbf{s}_\nu(\theta)]\right)$$

Express likelihood on all frequency maps

$$\begin{aligned}
\mathbf{a}_i &\leftarrow P(\mathbf{a}_i|\beta_i, g_\nu, \mathbf{m}_\nu, \Delta_\nu, C_\ell)\\
\beta_i &\leftarrow P(\beta_i|\mathbf{a}_i, g_\nu, \mathbf{m}_\nu, \Delta_\nu, C_\ell)\\
g_\nu &\leftarrow P(g_\nu|\mathbf{a}_i, \beta_i, \mathbf{m}_\nu, \Delta_\nu, C_\ell)\\
\mathbf{m}_\nu &\leftarrow P(m_\nu|\mathbf{a}_i, \beta_i, g_\nu, \Delta_\nu, C_\ell)\\
\Delta_\nu &\leftarrow P(\Delta_\nu|\mathbf{a}_i, \beta_i, g_\nu, \mathbf{m}_\nu, C_\ell)\\
C_\ell &\leftarrow P(C_\ell|\mathbf{a}_i, \beta_i, g_\nu, \mathbf{m}_\nu, \Delta_\nu).
\end{aligned}$$

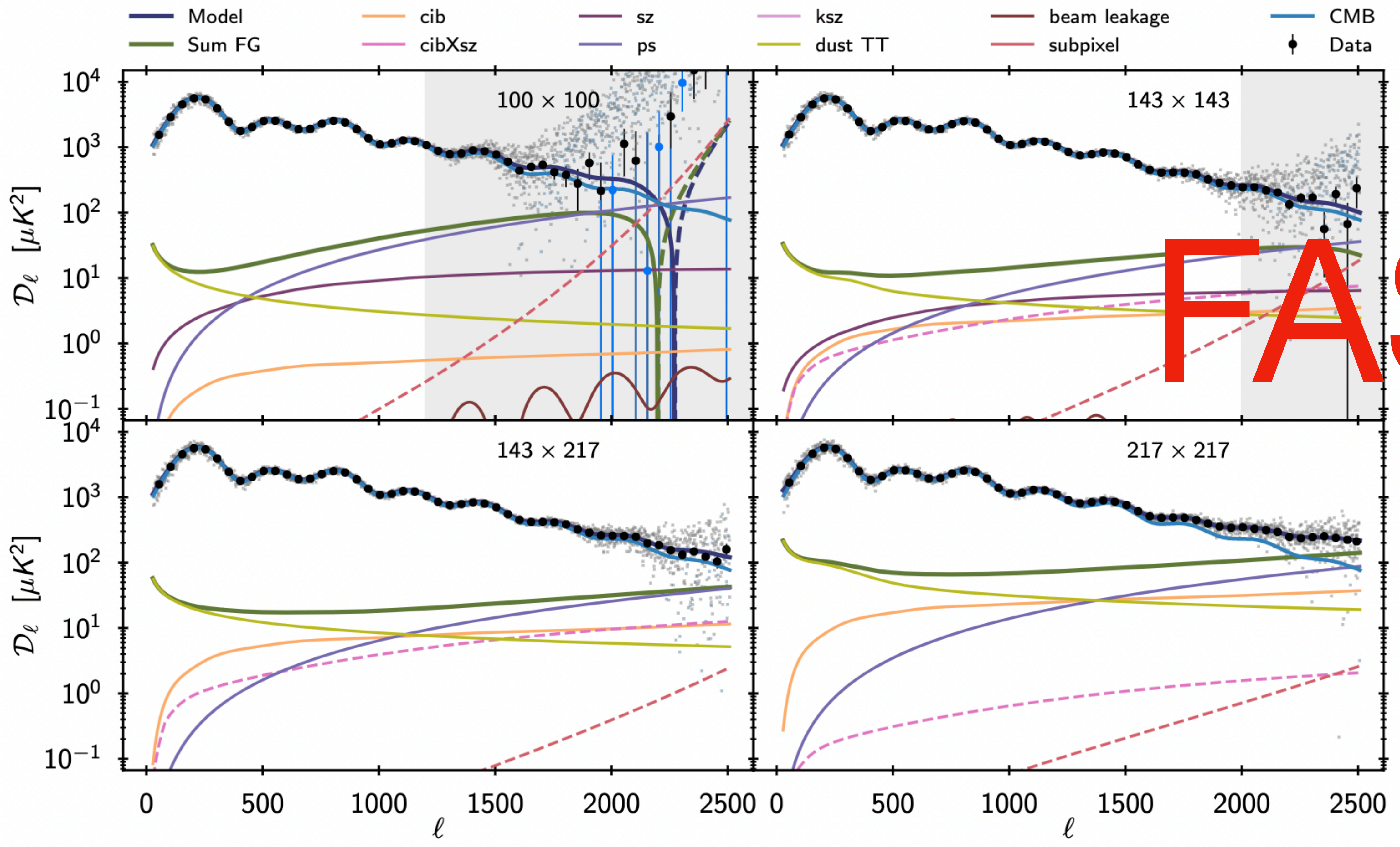
Gibbs sampling craziness !!!
Some of these conditionals allow block sampling

Generally very heavy, most suited for large scales likelihood sampling. Not necessarily most precise, depends on modeling choices…

The theorist had a chat with the instrumental team…

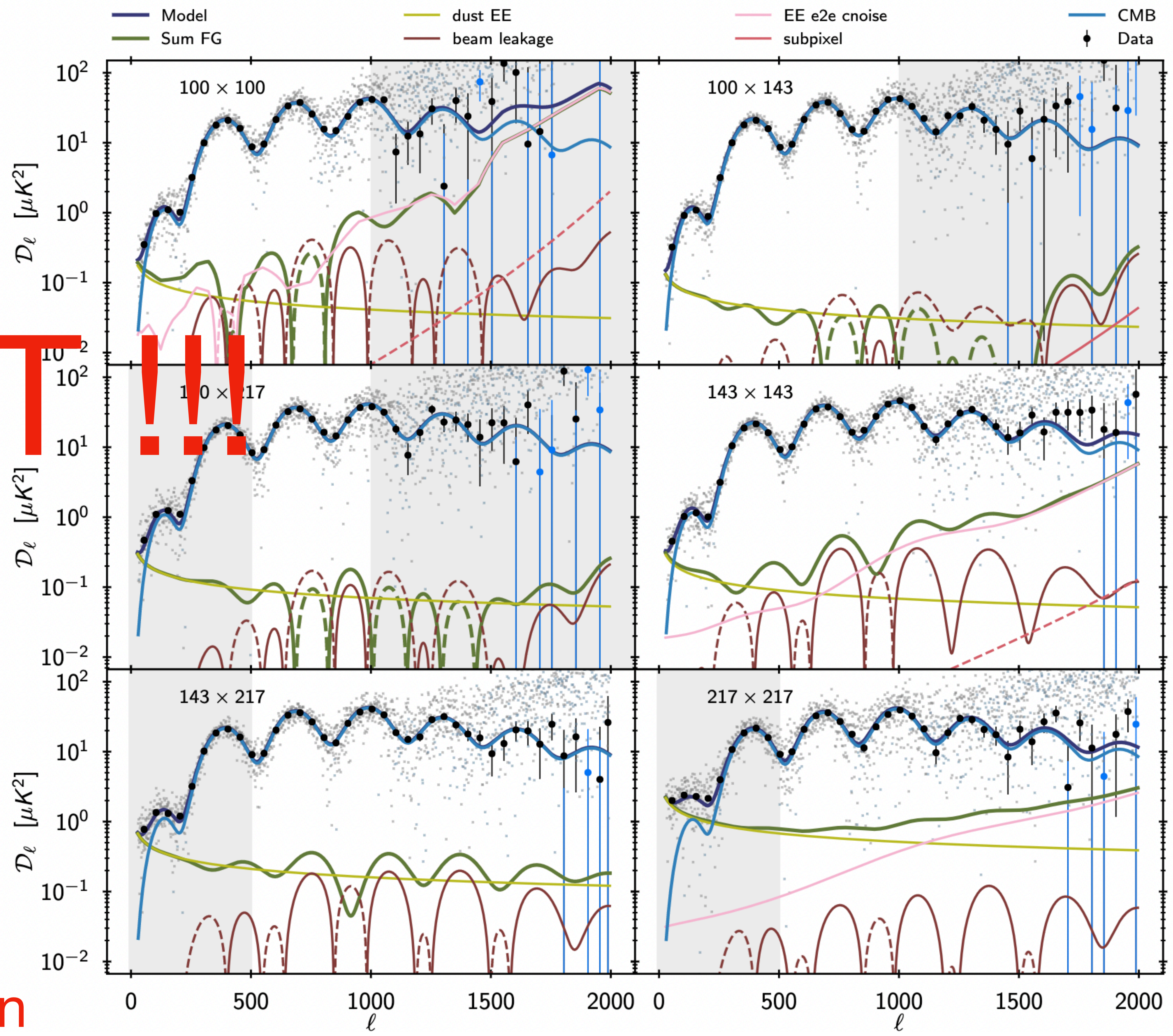
Multi-component, multi-frequency, spectral matching likelihood

Temperature power spectral decomposition



Mix of CMB signal, foregrounds, instrumental and data processing induced colored noise

Polarisation (E modes) power spectral decomposition



FAST !!!

Parametrise the covariances , Gaussian approximation

Are these approaches really different ?

- They all rely on explicit likelihood functions and associated samplings
  - First one models the signal directly with LOTS of parameters
  - Second one compresses data using (approximate) sufficient statistics (empirical power and cross spectra), makes Gaussian approximation on the latter. Much, much faster !
- Compromise between statistical “optimality” and explorative capability
- In general, first approach should be used as a benchmark to test loss of statistical optimality on simulated data, assuming the correct model is known
- Second method allows very large number of iterations, cross-checks, nuisance modeling and marginalization. Allows iterative refinement of astrophysical and instrumental models.
- First method might even fare worse than second method when the data model is not good enough

Use of MOAB as a statistical benchmark on simulated data to validate faster, approximate methods
Use of MOAB on data as a cake icing, at the very end when you understand your data (or never)

A good use of a MOAB

before you forget about it…

Scanning pixel values with correlated noise…

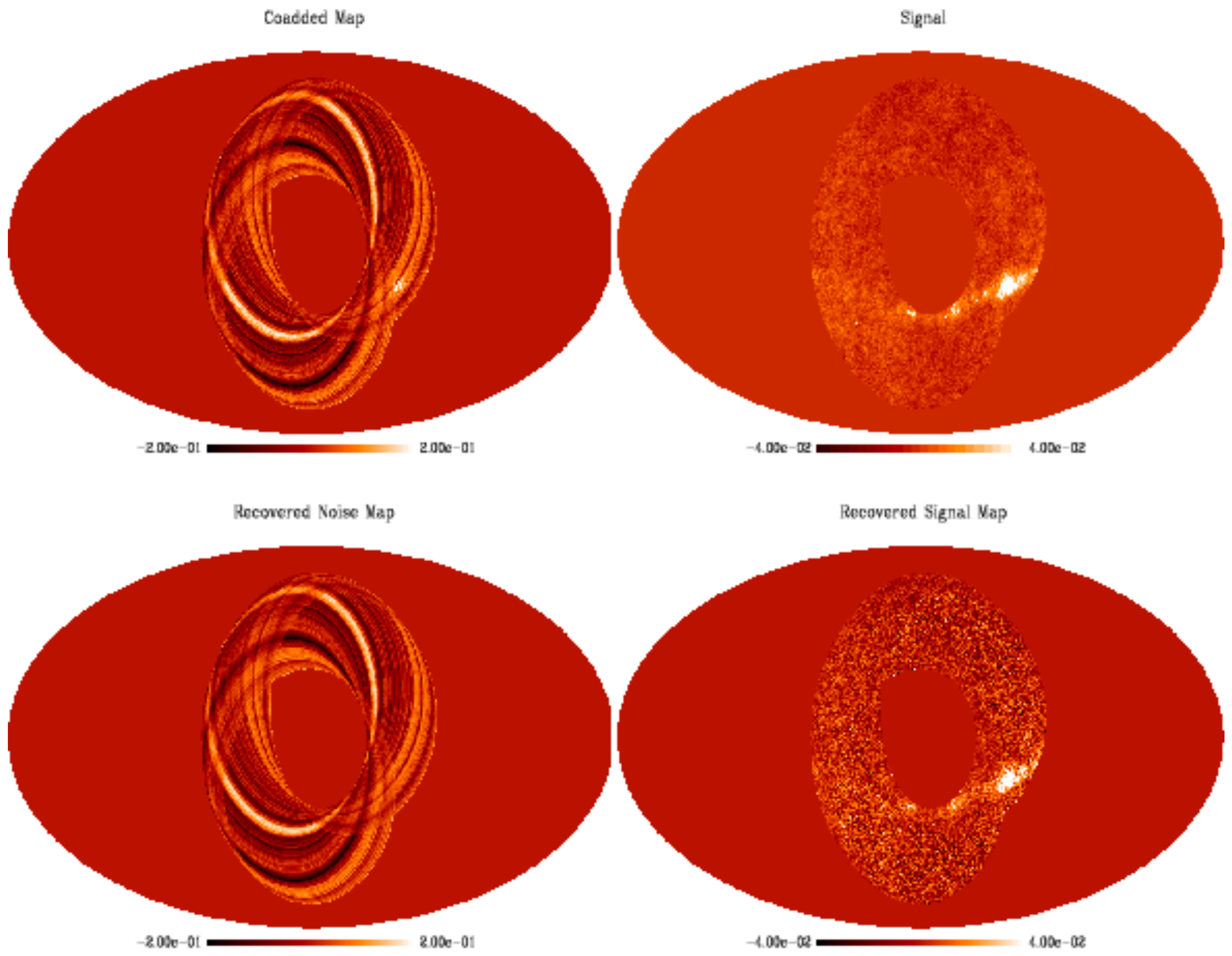
$$d_t = s_t + n_t = \sum_p A_{tp} T_p + n_t$$

Usual minimum variance solution

$$\begin{aligned} \bar{T} &= (A^T N^{-1} A)^{-1} A^T N^{-1} d \\ C_N &= (A^T N^{-1} A)^{-1} \end{aligned}$$

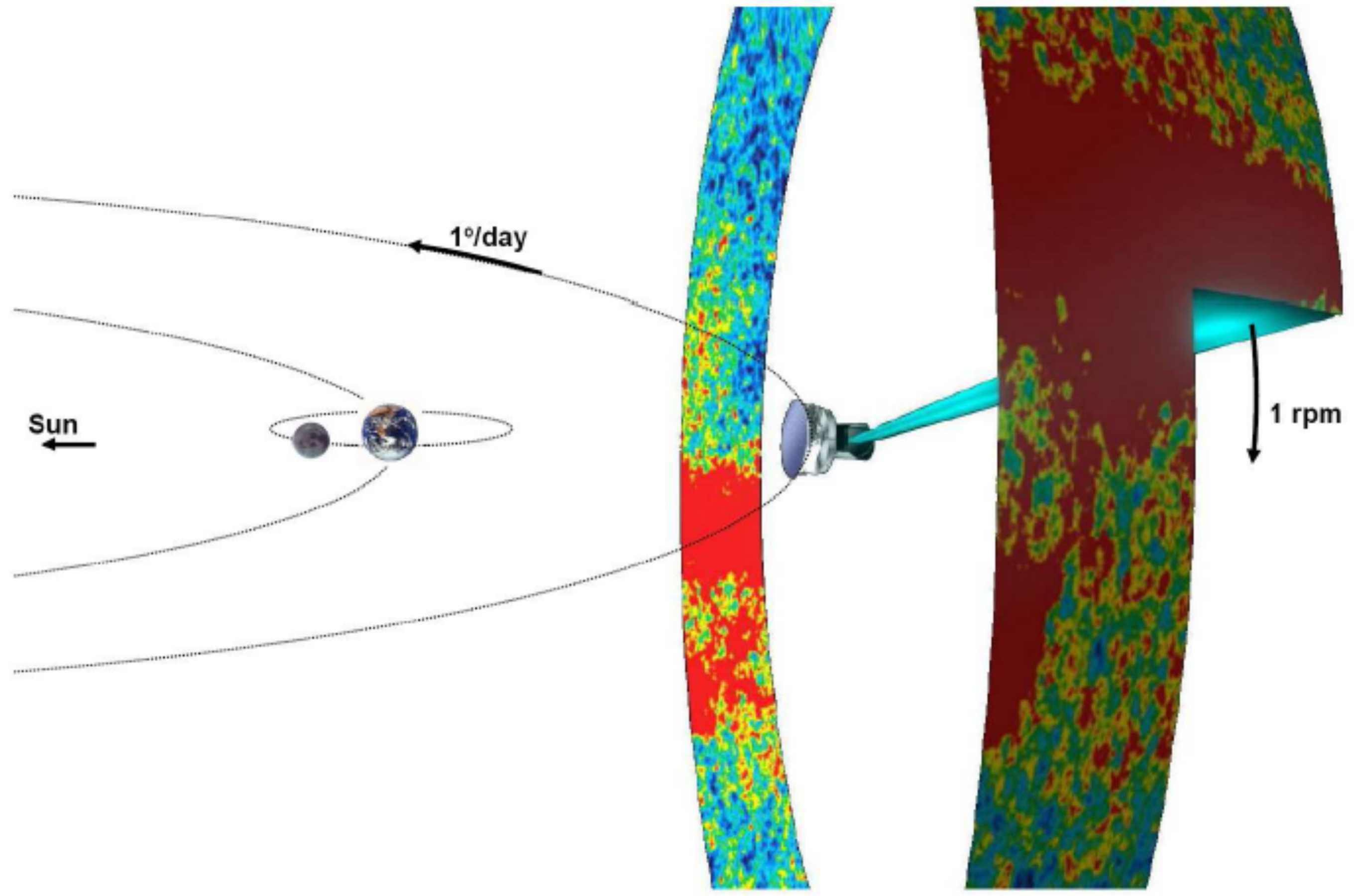
- Multi-detector polarized map-making
- Optimal (generalized least square) for gaussian noise
- Multigrid precond. Conjugate Gradient
  - Piecewise stationary (correlated) noise
  - Naturally deals with uneven coverage/masks
  - Naturally deals with flagged timeline data
- Noise spectral estimation on data
- MPI parallelism, with memory optimization
- Can only be run on massive HPC centers for Planck
- Benchmark for Planck « destriper » solutions

Simulated balloon experiment, pathfinder for Planck

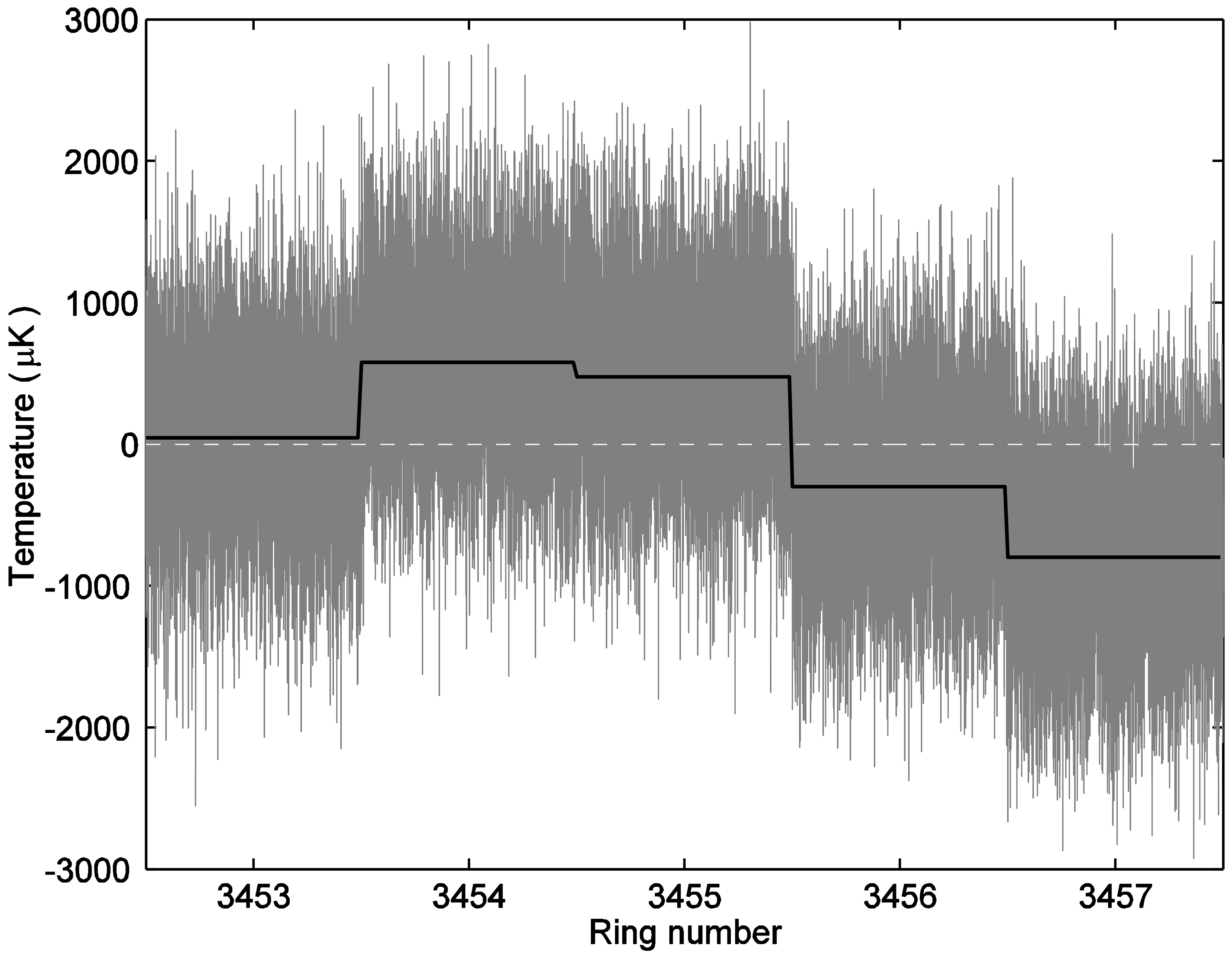


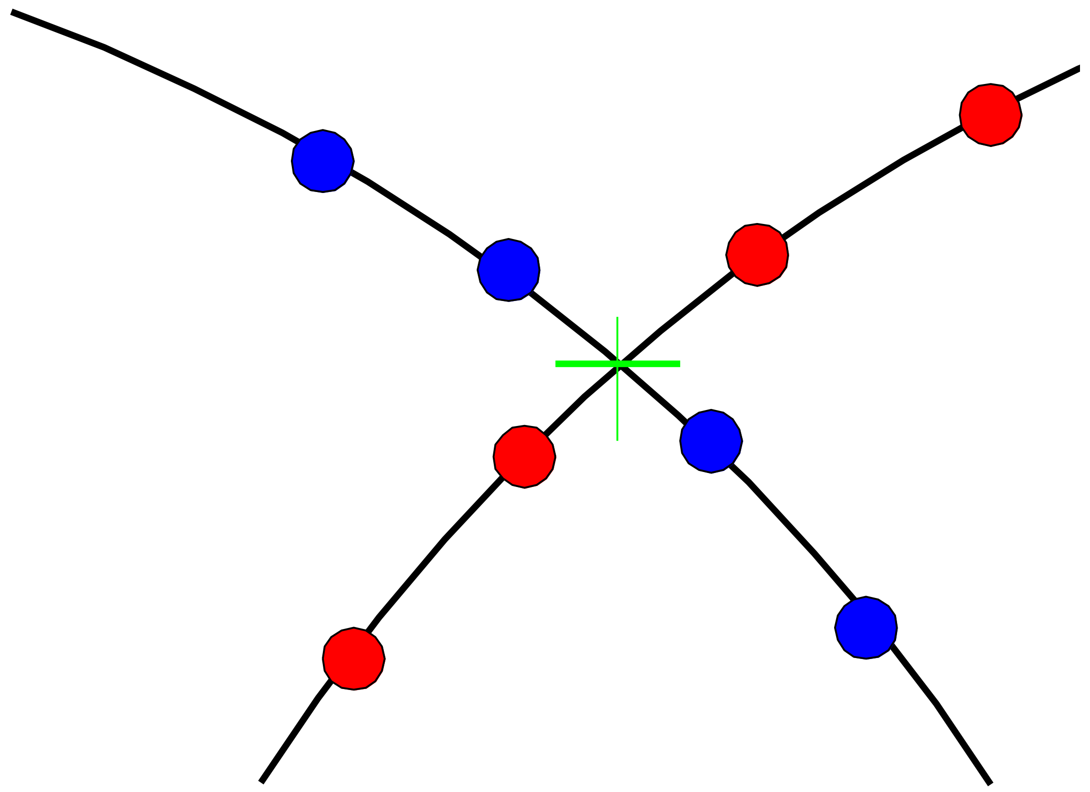
A good use of the MOAB

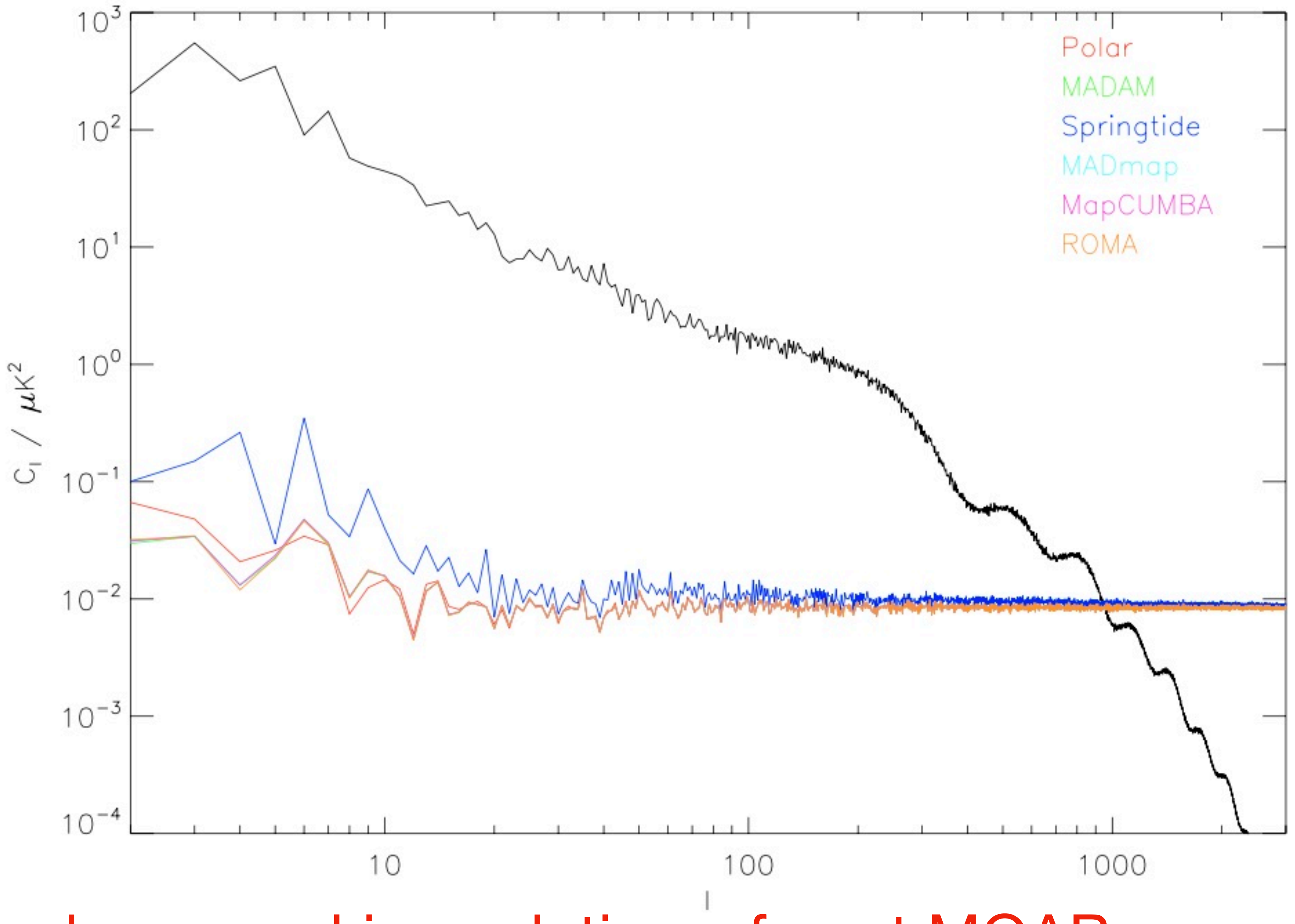
Benchmark for a faster method: destripers



- Successive scanning rings at the same place on the sky can get co-added
- Effective noise level of co-added timeline: white noise plus constant baseline per ring
- Baseline differences can be solved for using ring crossing points (same signal, different baselines)



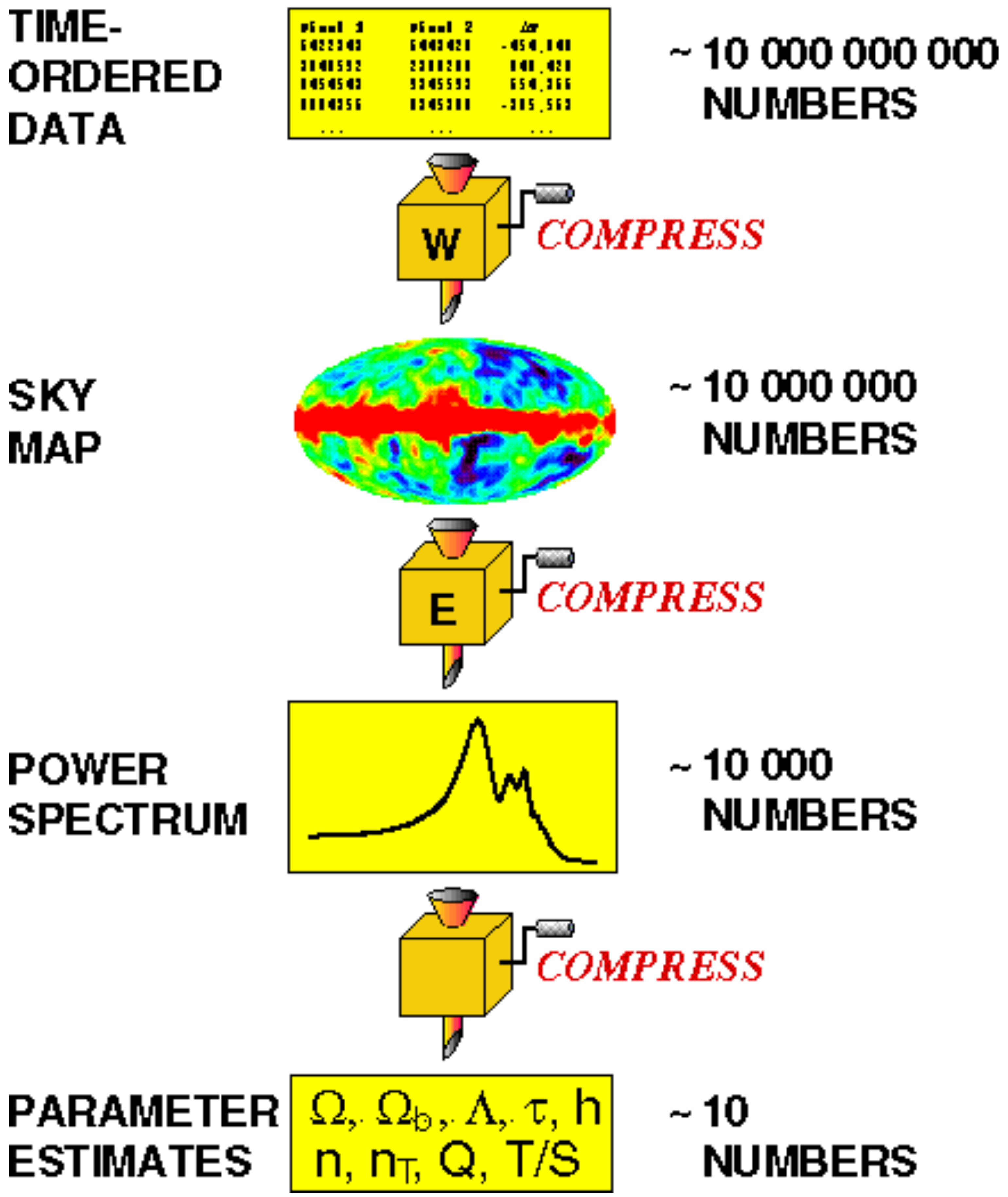




Destripers are nearly optimal map-making solutions: forget MOAB…

Planck HFI data processing

The (simplified) theorist's view



Map-making

Spectral analysis, component separation

Power spectrum estimation

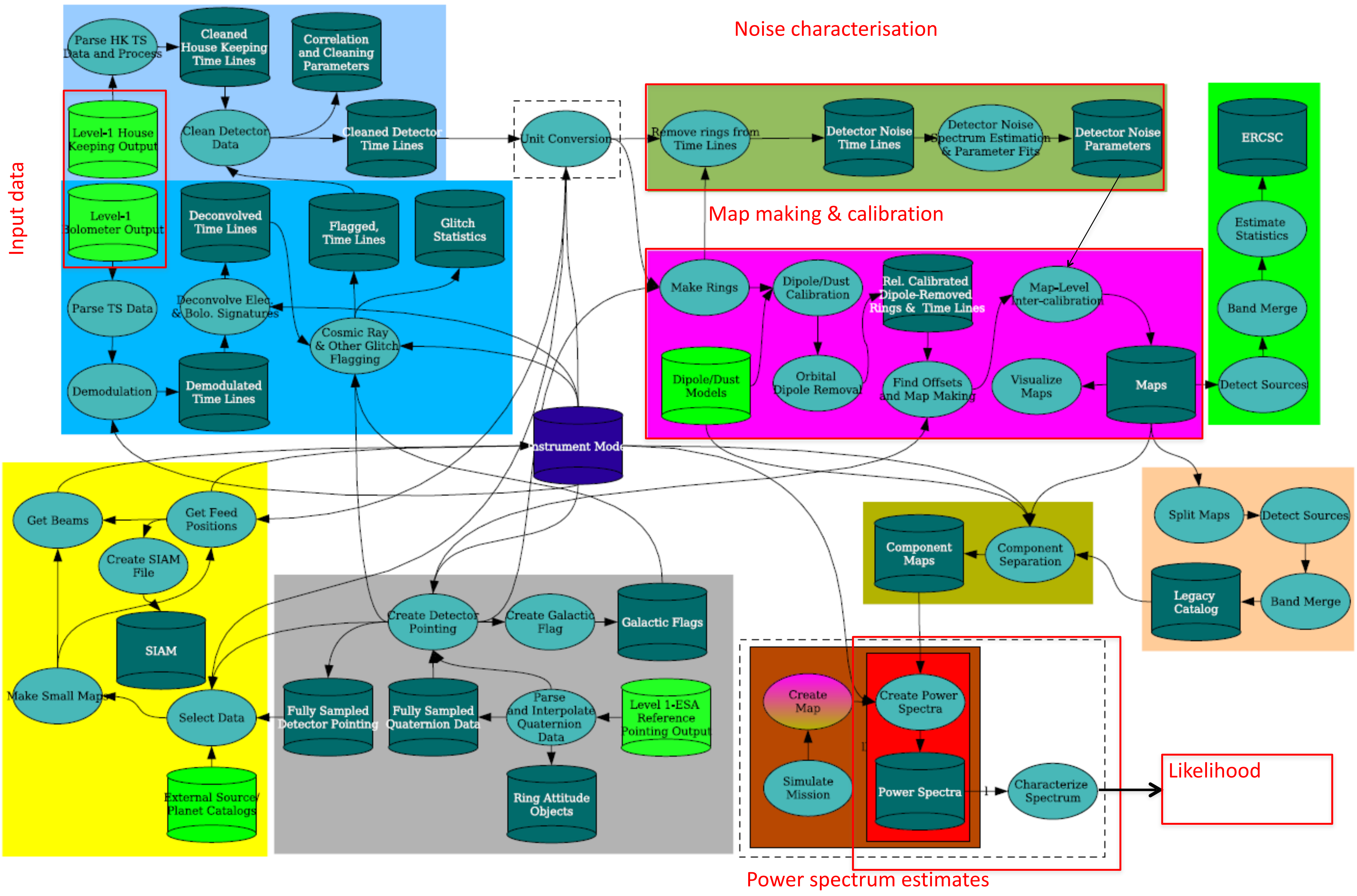
What does "compress" mean ?

- maximum likelihood estimates only
- maximum likelihood estimates followed by Bayesian sampling
- Full Bayesian sampling (MOAB !)

Courtesy M. Tegmark

Planck HFI data processing

Back to the jungle…



Pretend this is somehow a Bayesian hierarchical model…

Add some (overlapping) segments corresponding to labs, countries, etc. and enjoy this fully !

This is part of the lessons still to be learned I guess …

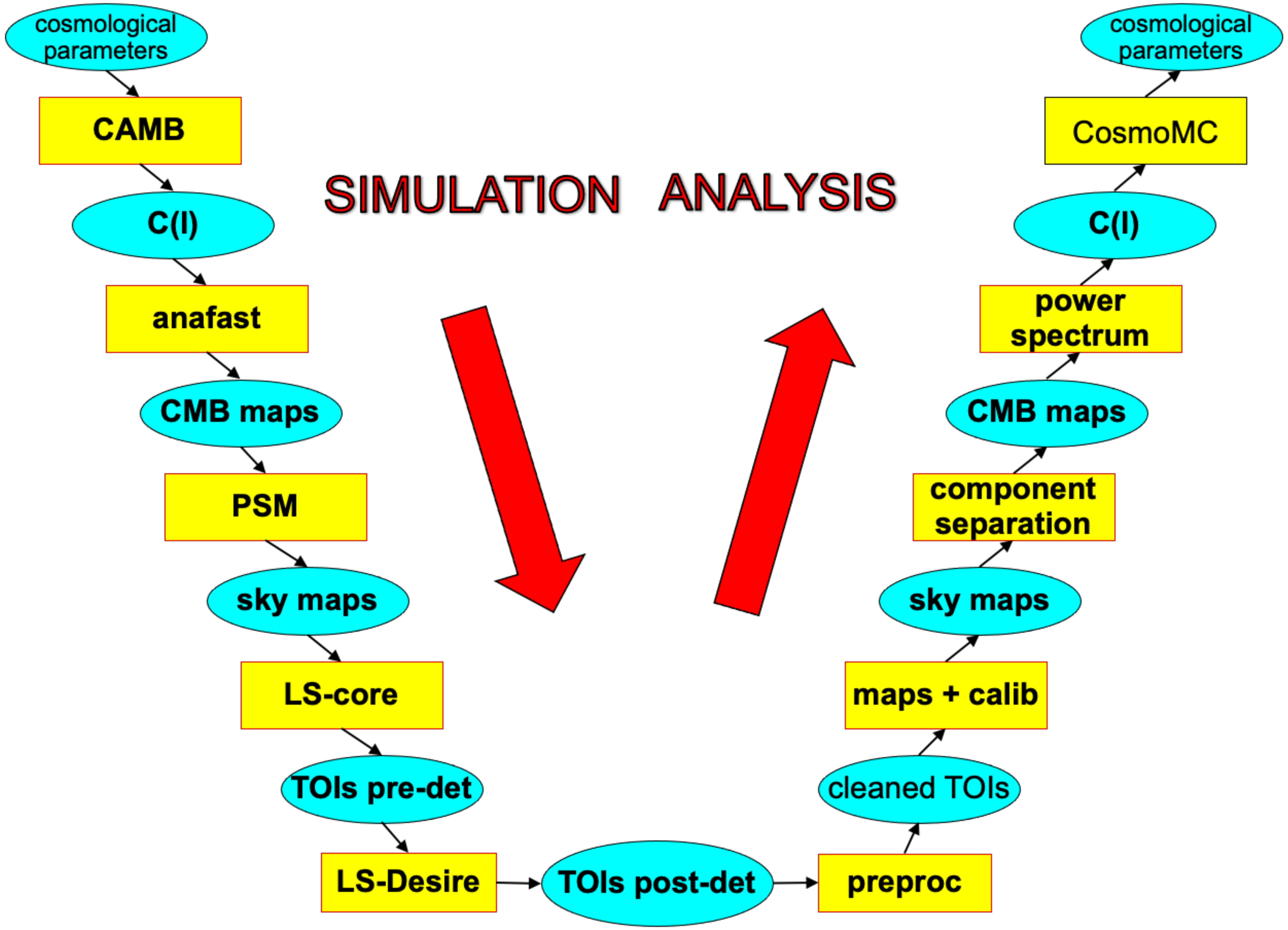
Space versus ground…

An example of screw up

- Electronic R/O chains are often thoroughly checked for their noise properties, response functions, etc.
- Somehow HFI R/O Analog Digital Converters were not properly analyzed… and ended up having non-negligible, unknown non-linearity on the middle range near zero analog signal…
    - Partially accounted for by adjusting a time variable gain model for temperature anisotropies
    - Gain correction model insufficient for very weak polarisation anisotropies
        - Inflight linearity calibration sequence done (but noisy source… hence limited accuracy of the non-linear response)
        - Had to combine correction from sequence above, and residual "gain variation" adjustment to reduce polarisation systematics to acceptable levels, resulting in considerable time spent redeveloping polarized map-making algorithms.
- Two mistakes were done:
    - An electronic component was not properly calibrated before launch
    - An inflight procedure of sufficient accuracy was not built in the electronic R/O unit (which is necessary anyway to monitor for time evolution / degradation)
- Lessons learned:
    - You need to properly calibrate ALL subsystems of the instrumental chain, however unremarkable they may seem (you never completely know in advance which elements will end up giving you headaches…)
    - You need to design internal calibration + quality assessment processes in ALL subsystems, that can be operated via the payload command system
    - Which precision is needed ? That can only be answered by complete propagation of systematic errors (end-to-end simulations including given subsystem perturbations)

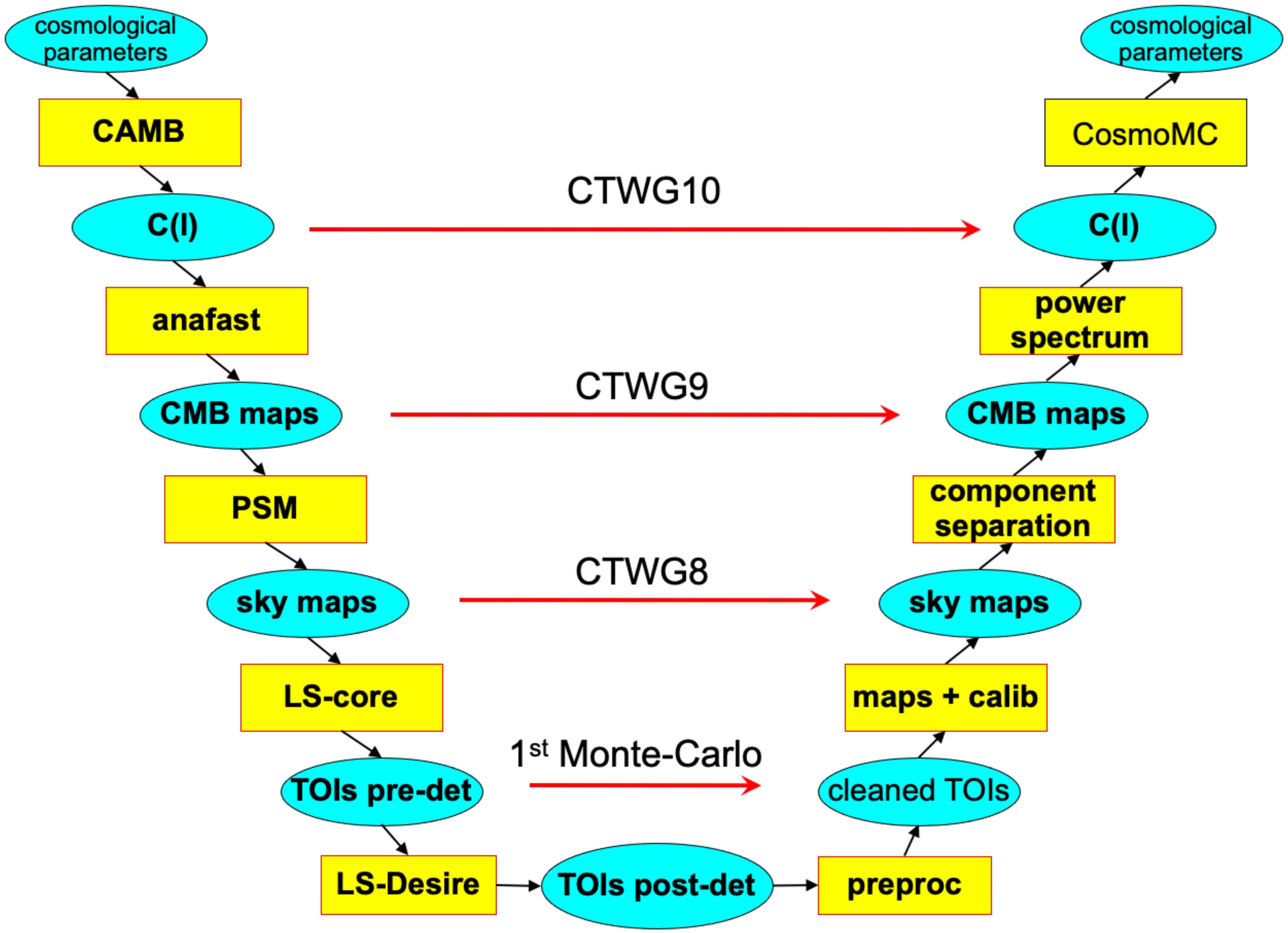
Data processing

End-to-end simulations (early view, but still relevant)



Data processing

End-to-end simulations: short cuts, depending on what needs testing



Data processing

Final remarks

- Data management architecture should be central to your ground segment, not algorithms: algorithms change, you are stuck with your data management scheme (definitely not the naive theorist view)
- Data processing management should include, as much as possible, complete reproducibility (and versioning) of pipeline runs, so that each intermediate product of data processing is totally traceable: > 90% of time lost due to quid pro quo between different teams about what went into a given processed data item (real or simulated). Code and data release versioning is not sufficient !!
- Data quality assessment, editing, flagging, etc. is not the most rewarding of tasks, but it is probably the most important, especially when dealing with low SNR, blended signals where proper statistical characterisation is key
- Every country wants its own data center: that's a bad idea ! Aim for IPAC model if possible (centralised data processing teams and hardware), with access to HPC ressources only for specific, heavy end-to-end simulations.
- Avoid complicated, structural dependencies between DP teams, especially in global iterative schemes. DP teams should not "sit on their own piece of code", everyone should be able to use them in a controlled, documented way. Code redundancy (nice word for unresolved competition) allows some level of debugging, but is very often decreasing overall efficiency.
- HPC power is not key, data and data processing management are.


"That's all Folks!"