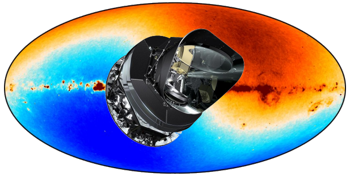
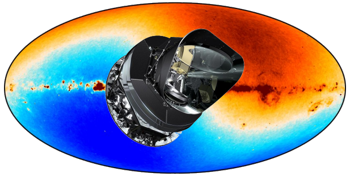


Dipole Based Calibration for Planck

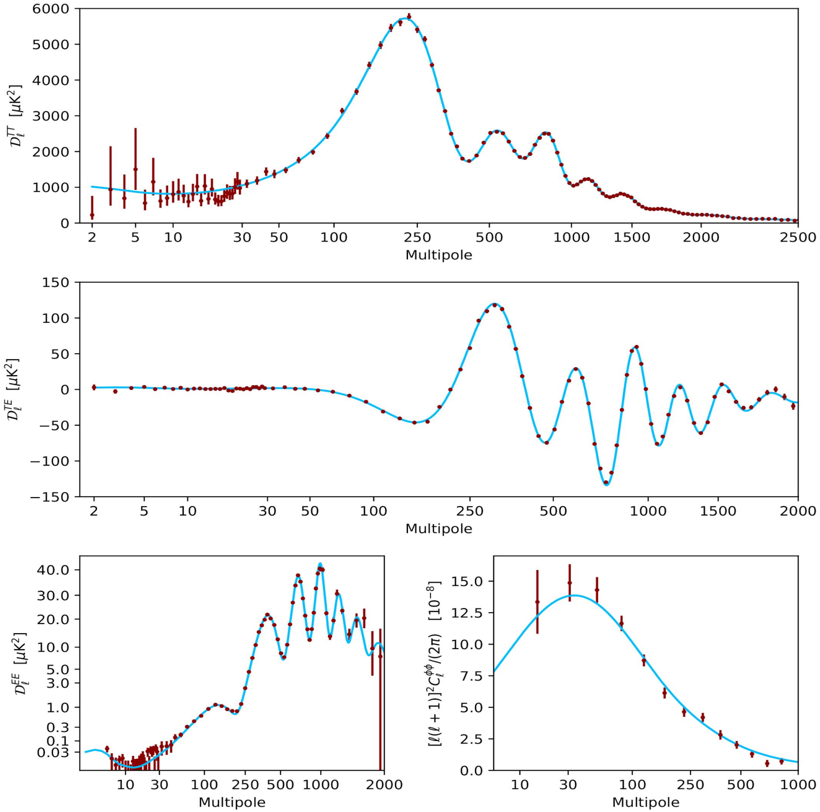
Mathew Galloway
University of Oslo

CMB Cal Workshop, November 2024

Cosmoglobe



The Planck Mission

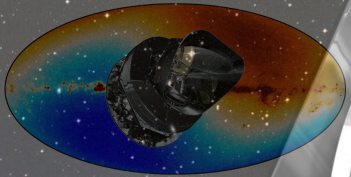


Parameter	Plik best fit
$\Omega_b h^2$	0.022383
$\Omega_c h^2$	0.12011
$100\theta_{MC}$	1.040909
τ	0.0543
$\ln(10^{10} A_s)$	3.0448
n_s	0.96605
$\Omega_m h^2$	0.14314
H_0 [km s^{-1}Mpc^{-1}] . . .	67.32
Ω_m	0.3158
Age [Gyr]	13.7971
σ_8	0.8120
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.8331
z_{re}	7.68
$100\theta_*$	1.041085
r_{drag} [Mpc]	147.049

The Planck Mission

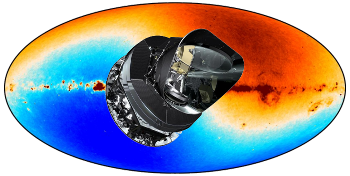
"We just calibrate against Planck…"

-Lots of people, yesterday

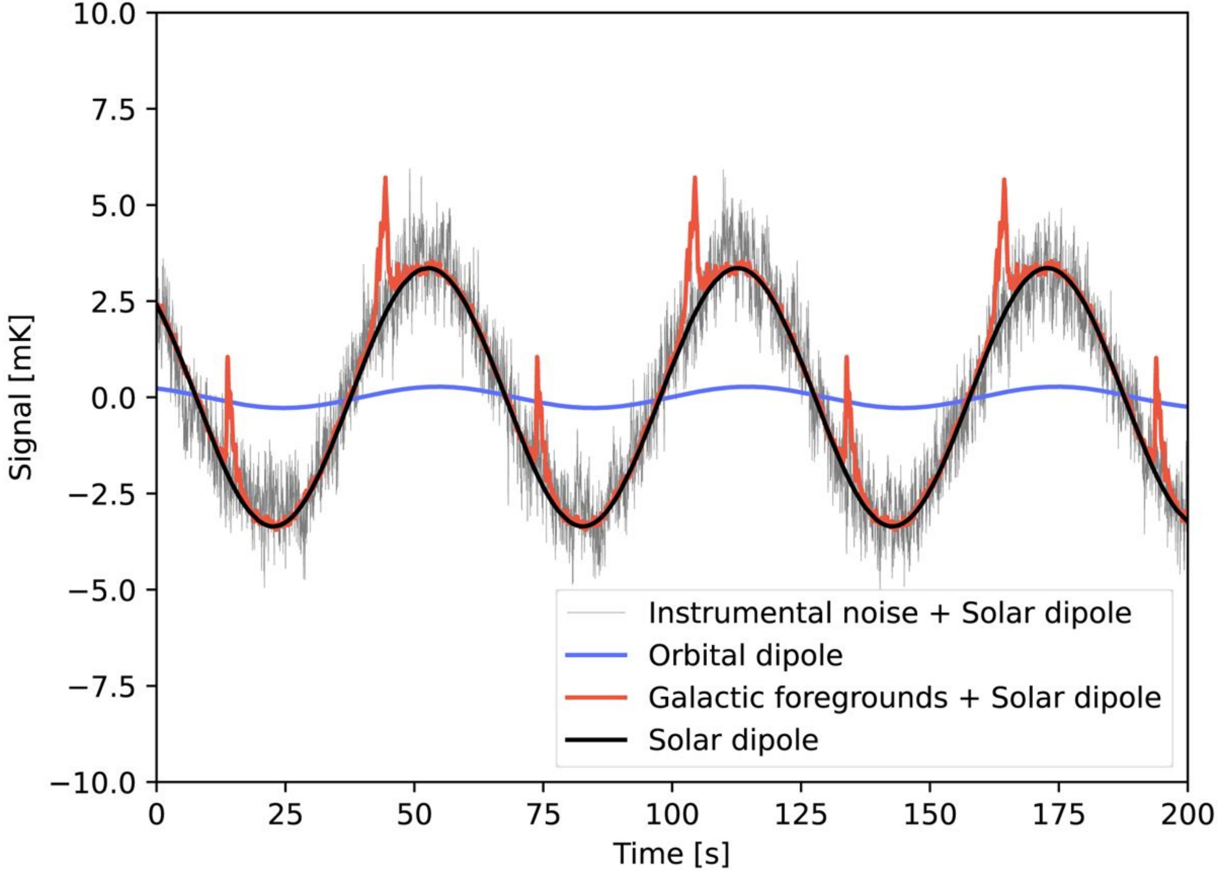


Space: The final frontier

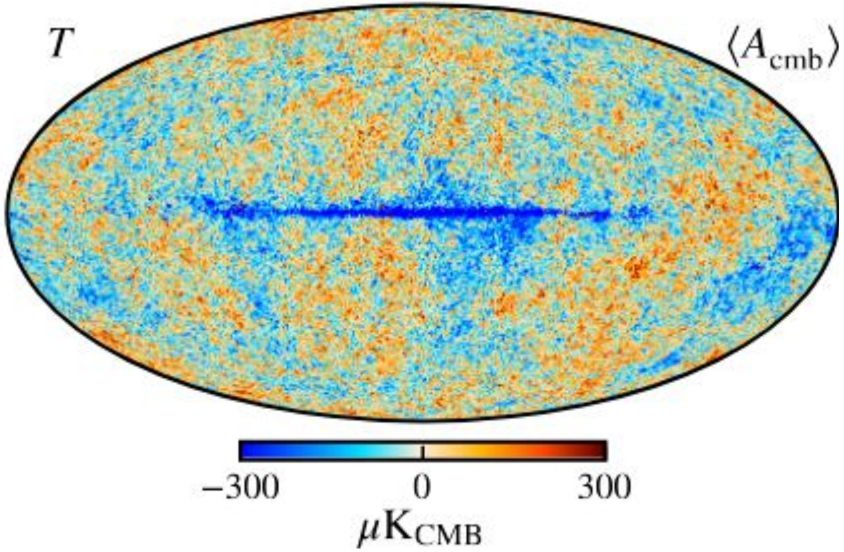
- Hard to produce a calibration source in the far field
  - Formation flying?
  - Planets
  - Bright point sources
- Thermal and radiative environment very different from ground tests
- Sensitivity regime is really hard to probe from the ground
  - Really expensive TVAC chambers
- Only one chance to get it right!

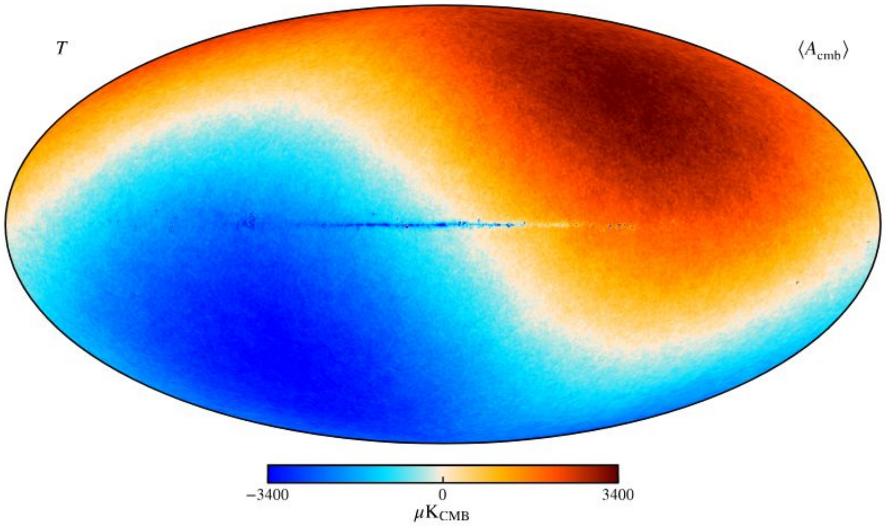


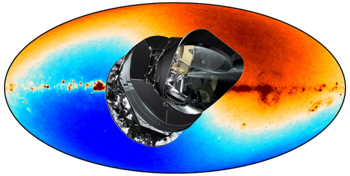
What are we working with?



Solar Dipole



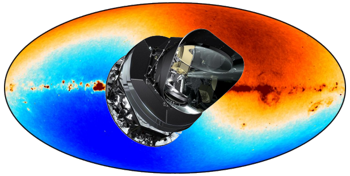




Solar Dipole

- Brightest calibration source we have (other than the monopole which requires absolute DC level to be retained)
- Doppler shift in the CMB
- Amplitude + direction are dependent on the motion of the sun relative to the Universe (not well known)

Pipeline	Amplitude (μK)	Longitude (Deg)	Latitude (Deg)
DR2 [2]	$3364.29 \pm 0.02^{\mathrm{stat}} \pm 0.8^{\mathrm{syst}} \pm 0.74^{\mathrm{FIRAS}}$	$263.914 \pm 0.001^{\mathrm{stat}} \pm 0.013^{\mathrm{syst}}$	$48.2646 \pm 0.0003^{\mathrm{stat}} \pm 0.0019^{\mathrm{syst}}$
DR3 [6]	$3362.08 \pm 0.09^{\mathrm{stat}} \pm 0.45^{\mathrm{syst}} \pm 0.45^{\mathrm{cal}}$	$264.021 \pm 0.003^{\mathrm{stat}} \pm 0.008^{\mathrm{syst}}$	$48.253 \pm 0.001^{\mathrm{stat}} \pm 0.004^{\mathrm{syst}}$
DR4 [7]	3366.6 ± 2.6	263.986 ± 0.035	48.247 ± 0.023
Sroll2 [12]	$3361.90 \pm 0.04^{\mathrm{stat}} \pm 0.36^{\mathrm{syst}}$	$263.959 \pm 0.002^{\mathrm{stat}} \pm 0.017^{\mathrm{syst}}$	$48.260 \pm 0.001^{\mathrm{stat}} \pm 0.007^{\mathrm{syst}}$



Orbital Dipole

- Not a sky-stationary signal (maps don’t look like anything useful)
- Doppler shift because of the Earth’s motion relative to the sun
- Amplitude and direction is very well known and easily predictable (relativistic doppler effect)

$$s^{\mathrm{dip}}(\boldsymbol{x}, t) = T_{\mathrm{CMB}}\left(\frac{1}{\gamma(t)(1-\boldsymbol{\beta}(t)\cdot\boldsymbol{x})} - 1\right)$$

$$\boldsymbol{\beta} = \mathbf{v}_{\mathrm{tot}}/c, \text{ and } \gamma = (1 - |\boldsymbol{\beta}|^2)^{-1/2}$$

- Much weaker than the solar dipole 😢

Gain Estimation Procedure in BeyondPlanck

We decompose the gain into an absolute and a relative term,

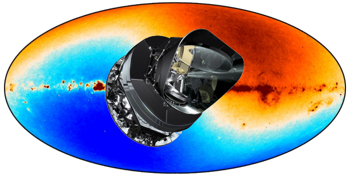
$$g_{q,i} = g_0 + \gamma_{q,i}$$

with the constraint that $$\sum_{q,i} \gamma_{q,i} = 0$$

This turns out to be easier if we also decompose the second term into two parts:

$$g_{q,i} = g_0 + \Delta g_i + \delta g_{q,i}$$

(i indexes detectors and q indexes time)



Gain estimation - Overall gain

- Objective: $P(g_0 \mid \Delta g_i, \delta g_{q,i}, \alpha, \sigma_0, ..., d)$

- Using this approach, we construct our absolute residual:

$$r_{t,i} \equiv d_{t,i} - (g_0 + \Delta g_q + \delta g_{q,i}) s^{\mathrm{tot}}_{t,i} + g_0 s^{\mathrm{orb}}_{t,i} = g_0 s^{\mathrm{orb}}_{t,i} + n_{t,i}$$

- To sample from this (standard univariate gaussian):

$$\hat{g}_0 = \frac{\sum_i (\vec{s}_i^{\mathrm{orb}})^T N_i^{-1} \vec{r}_i}{\sum_i (\vec{s}_i^{\mathrm{orb}})^T N_i^{-1} \vec{s}_i^{\mathrm{orb}}} + \sqrt{\frac{1}{\sum_i (\vec{s}_i^{\mathrm{orb}})^T N_i^{-1} \vec{s}_i^{\mathrm{orb}}}} \cdot \eta$$

Gain Estimation - Per detector gain

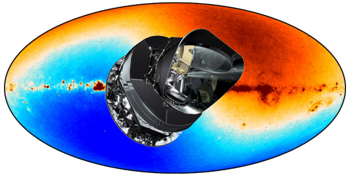
- Same approach, form total signal residual

$$r_{t,i} \equiv d_{t,i} - (g_0 + \delta g_{q,i}) s_{t,i}^{\mathrm{tot}} = \Delta g_i s_{t,i}^{\mathrm{tot}} + n_{t,i}$$

- Subject to additional constraint: $$\sum_i \Delta g_i = 0$$

- Use lagrange multipliers. Some math before we arrive at N+1 coupled equations that can be solved for Δg_i:

$$\begin{bmatrix} (\boldsymbol{s}^{\mathrm{tot}})^T \mathbf{N}_1^{-1} \boldsymbol{s}^{\mathrm{tot}} & 0 & \frac{1}{2} \\ 0 & (\boldsymbol{s}^{\mathrm{tot}})^T \mathbf{N}_2^{-1} \boldsymbol{s}^{\mathrm{tot}} & \frac{1}{2} \\ 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta \hat{g}_1 \\ \Delta \hat{g}_2 \\ \lambda \end{bmatrix} = \begin{bmatrix} (\boldsymbol{r}_1)^{\mathrm{tot}} \mathbf{N}_1^{-1} \boldsymbol{s}_1^{\mathrm{tot}} + \eta_1 \sqrt{(\boldsymbol{s}_1^{\mathrm{tot}})^T \mathbf{N}_1^{-1} \boldsymbol{s}_1^{\mathrm{tot}}} \\ (\boldsymbol{r}_2)^{\mathrm{tot}} \mathbf{N}_2^{-1} \boldsymbol{s}_2^{\mathrm{tot}} + \eta_2 \sqrt{(\boldsymbol{s}_2^{\mathrm{tot}})^T \mathbf{N}_2^{-1} \boldsymbol{s}_2^{\mathrm{tot}}} \\ 0 \end{bmatrix}.$$



Gain Estimation - Time variable gain

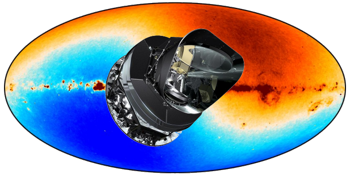
- Again form a residual:

$$r_{t,i} \equiv d_{t,i} - (g_0 + \Delta g_i) s_{t,i}^{\mathrm{tot}} = \delta g_{q,i} s_{t,i}^{\mathrm{tot}} + n_{t,i}$$

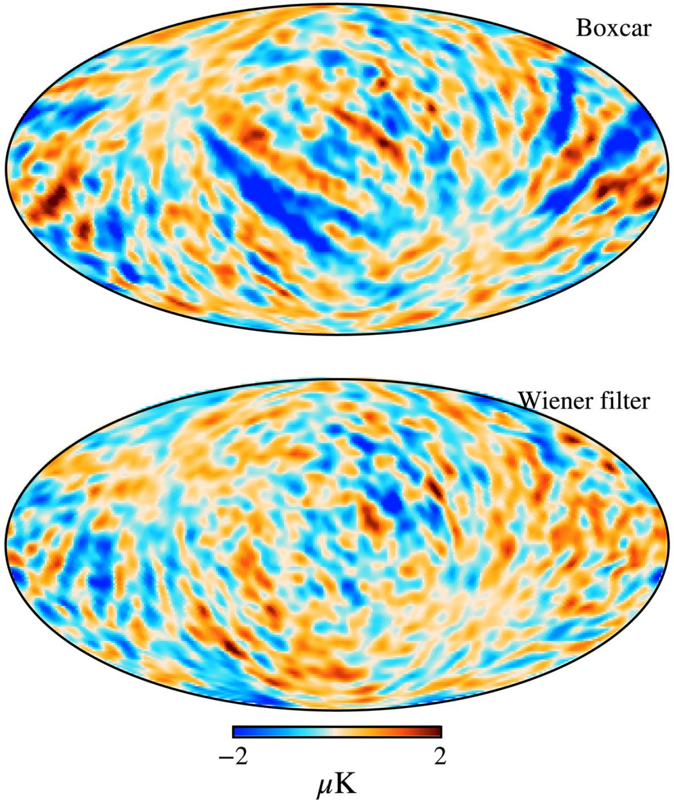
- Then the solution is again

$$\mathsf{T}_i^T N_i^{-1} \mathsf{T}_i \hat{\vec{\delta g}}_i = \mathsf{T}_i^T N_i^{-1} \vec{r}_i + \sqrt{\mathsf{T}_i^T N_i^{-1} \mathsf{T}_i} \cdot \vec{\eta}$$

- Where the matrix T is N_samples x N_chunks, ie. the number of time variable gain samples you are considering
- But, this solves for each chunk independently, leading to non-physical sharp features in the gain



Gain Smoothing



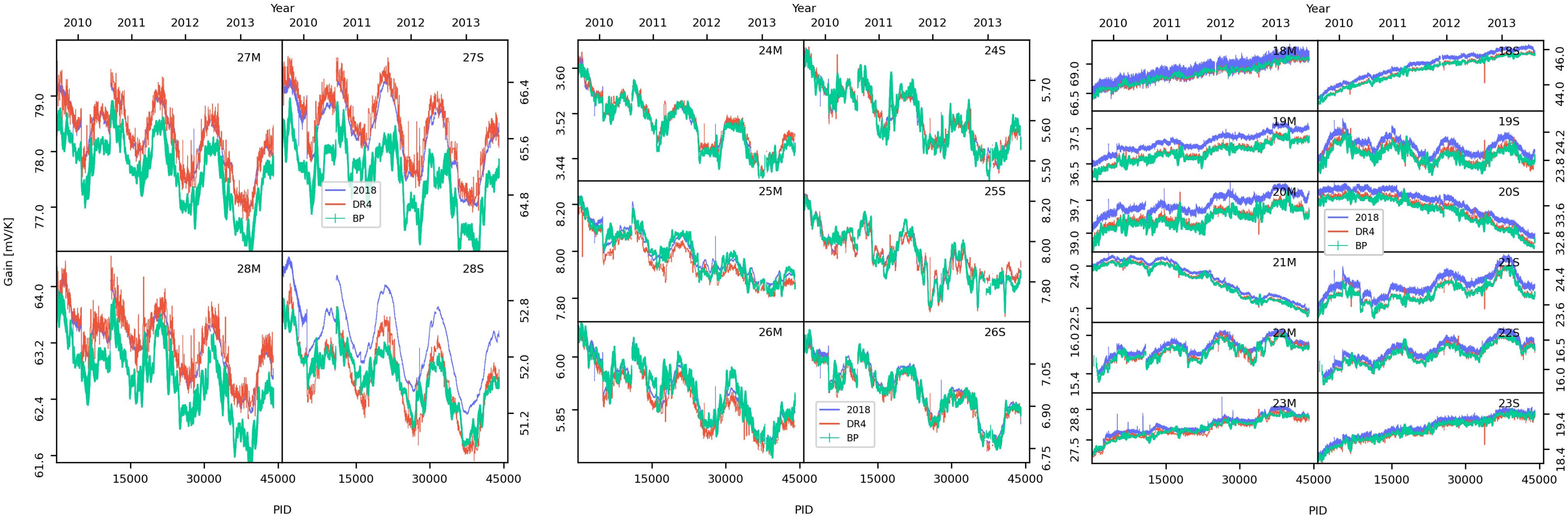
- We want to smoothe the gains between chunks because we believe the underlying processes (temperature, environment, etc.) are smoothly varying
- We can add an underlying model of the correlations between gain samples:

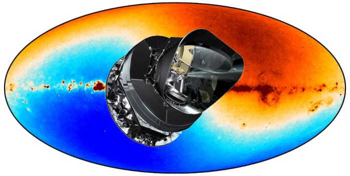
$$\mathsf{G}(f) = \sigma_0 \left(\frac{f}{f_0} \right)^{\alpha}$$

- This lets us draw smoothed samples from

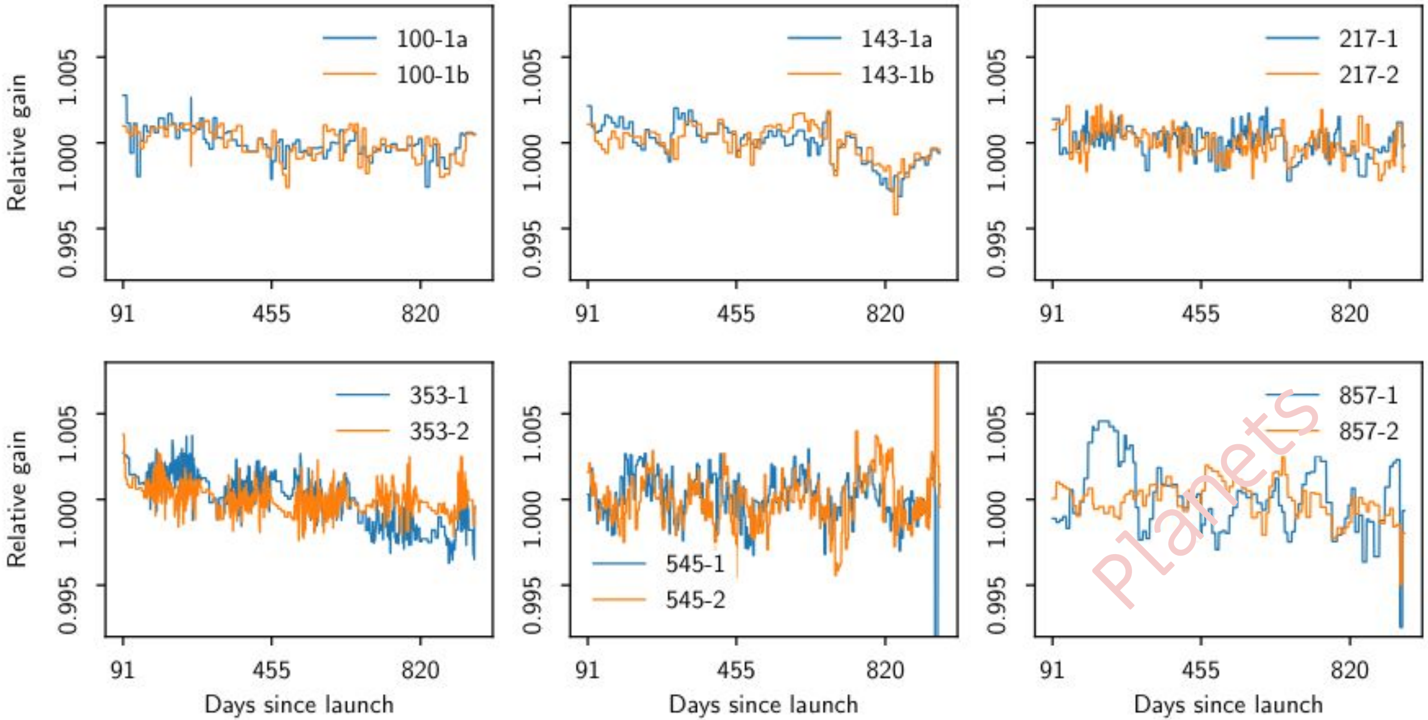
$$(\mathsf{G}^{-1} + \mathsf{T}_i^T N_i^{-1} \mathsf{T}_i) \hat{\vec{\delta g}}_i = \mathsf{T}_i^T N_i^{-1} \vec{r}_i + \mathsf{T}_i^T N^{-1/2} \vec{\eta}_1 + \mathsf{G}^{-1/2} \vec{\eta}_2$$

LFI Gains

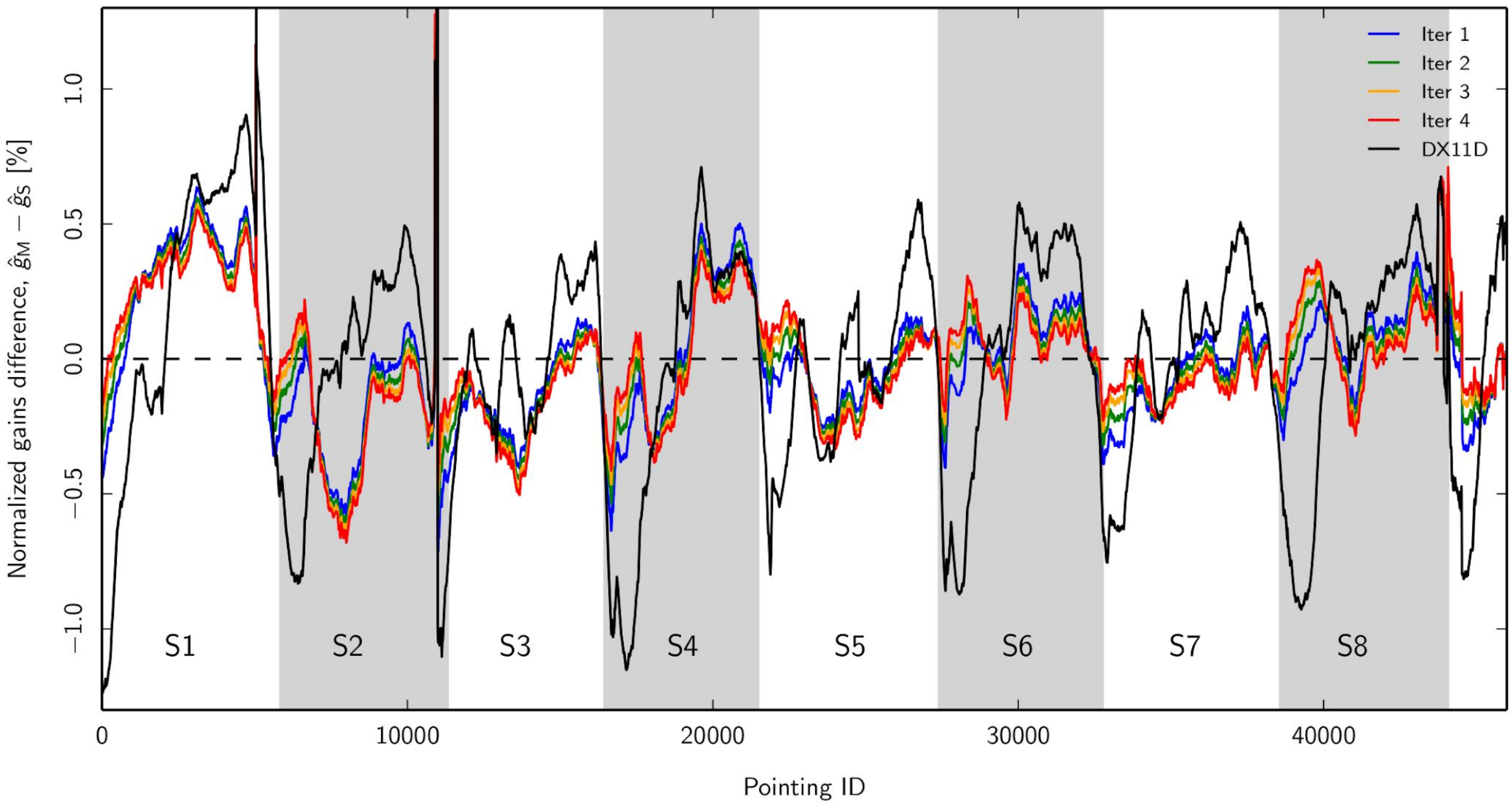

Year
2010
2011
2012
2013
27M
27S
28M
28S
24M
24S
25M
25S
26M
26S
18M
18S
19M
19S
20M
20S
21M
21S
22M
22S
23M
23S
2018
DR4
BP
Gain [mV/K]
15000
30000
45000
PID

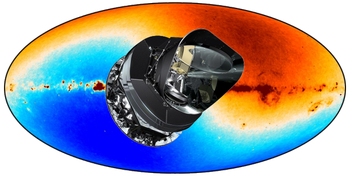


HFI Gains - DR4

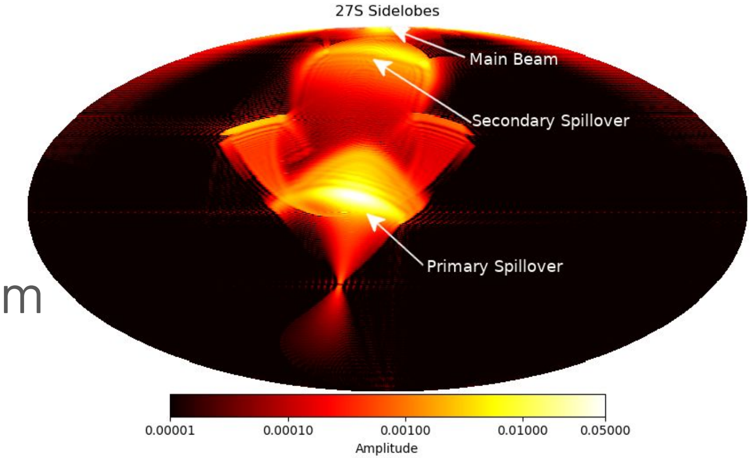


Dependence on the sky model





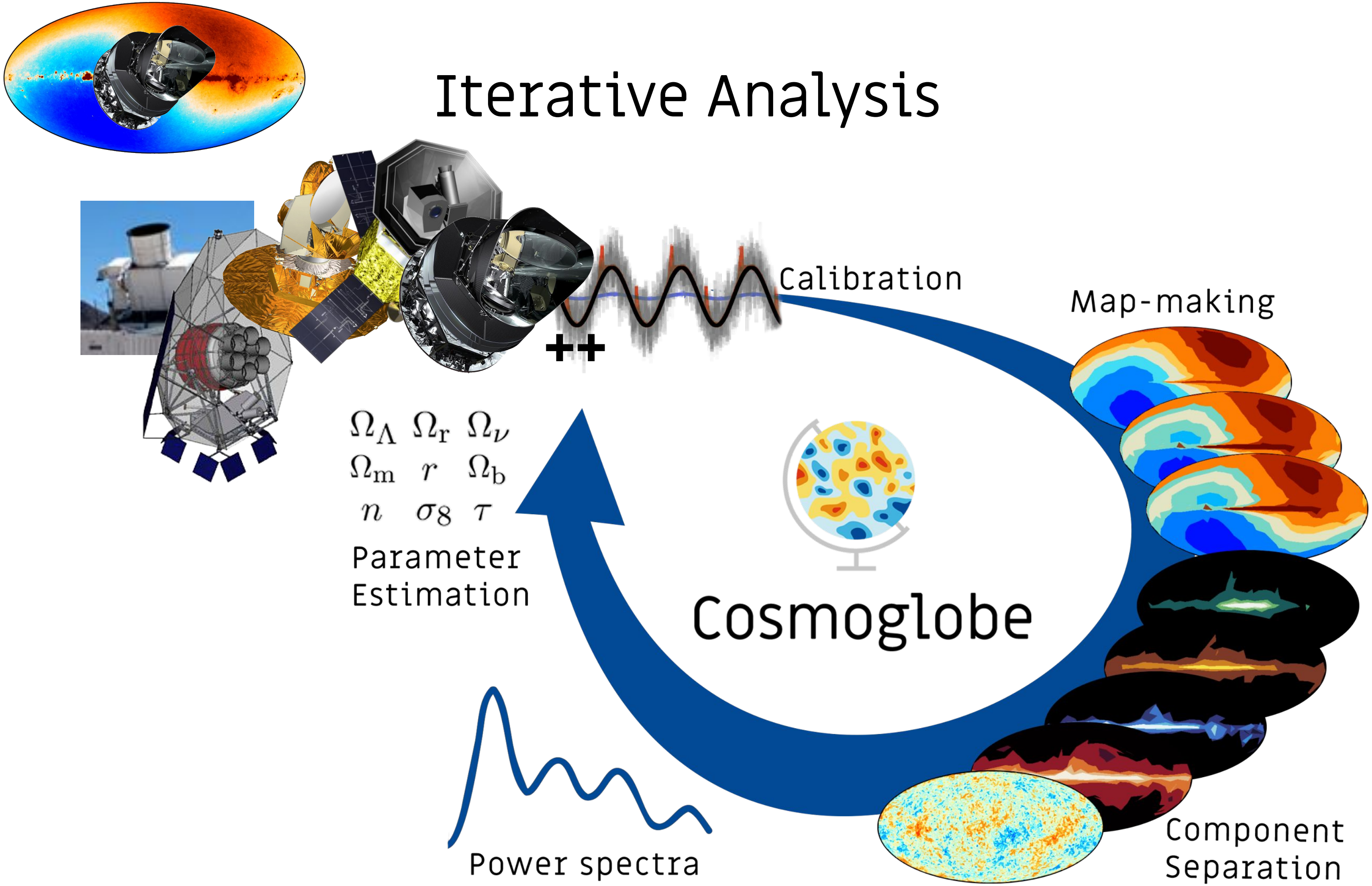
Sidelobes

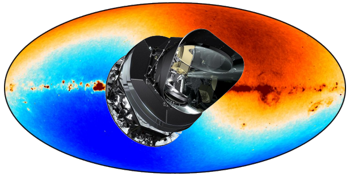


- Detector sensitivity outside main beam
- At the 1-3% level for Planck
- Can mess up your calibration!
- Orbital dipole is especially sensitive + tricky to handle, because you can't simply convolve a beam model with a sky map
- We must replace the simple formula with $\widetilde{D}(\widehat{\boldsymbol{n}}_0) = \int \mathrm{d}\Omega \, B(\widehat{\boldsymbol{n}}, \widehat{\boldsymbol{n}}_0) D(\widehat{\boldsymbol{n}})\,.$
- Because this is a very simple signal, we can break it into 9 distinct precomputable terms:

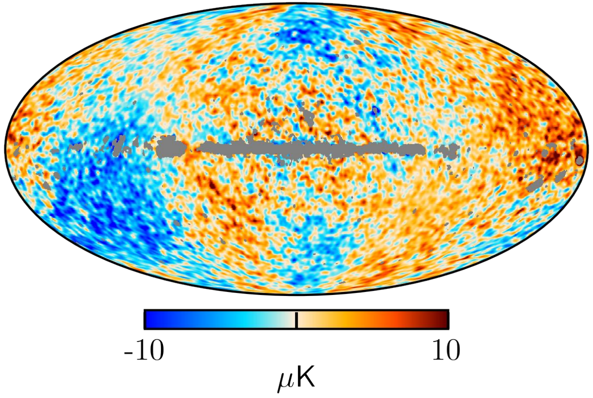
$$\begin{aligned}\widetilde{D} &= T_0 \big[S_x \beta_x + S_y \beta_y + S_z \beta_z \\ &+ q \big(S_{xx} \beta_x^2 + S_{yy} \beta_y^2 + S_{zz} \beta_z^2 \\ &+ 2S_{xy} \beta_x \beta_y + 2S_{xz} \beta_x \beta_z + 2S_{yz} \beta_y \beta_z \big) \big]\,.\end{aligned}$$

Iterative Analysis

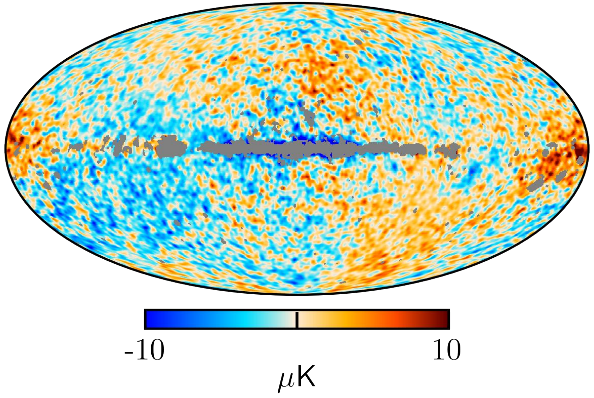




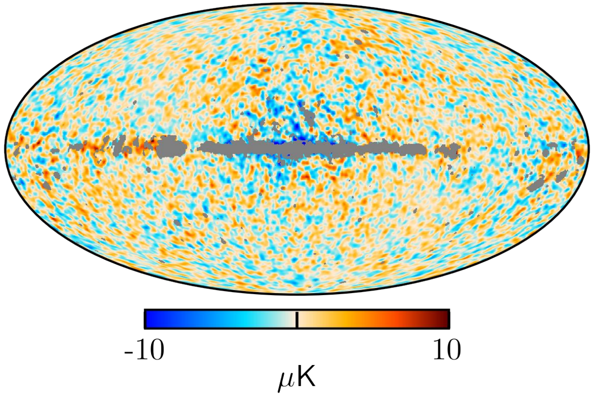
Advantages of joint analysis



Legacy 30 GHz - scaled WMAP K

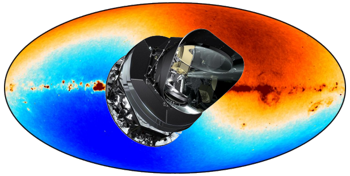


Re-analysis of LFI



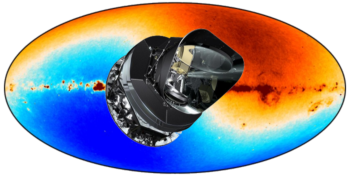
Joint re-analysis of LFI+WMAP

The end-to-end approach is really good at mitigating systematics that traditional pipelines struggle with!



Summary + Conclusions

- On-sky calibration for Planck is done using the orbital and solar dipoles at CMB frequencies, and planets at higher frequencies
- Gains are split into overall calibration and a time varying component
- It is important to smoothe these gains properly to avoid introducing errors
- Dipole-based calibration is sensitive to all the details of your sky and instrument
- Iterative analysis + joint analysis can be powerful ways to constrain all these parameters and get a robust gain solution



More reading

BEYONDPLANCK VII. Bayesian estimation of gain and absolute calibration for cosmic microwave background experiments - A&A 675, A7 (2023)

Planck intermediate results. LVII. Joint Planck LFI and HFI data processing - A&A 643, A42 (2020)

Planck 2018 results. III. High Frequency Instrument data processing and frequency maps - A&A, 2018/32909

Planck 2015 results - VIII. High Frequency Instrument data processing: Calibration and maps - A&A, 594 (2016) A8

Questions?