Planck Simulations

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Roles & Specifications

ROLES

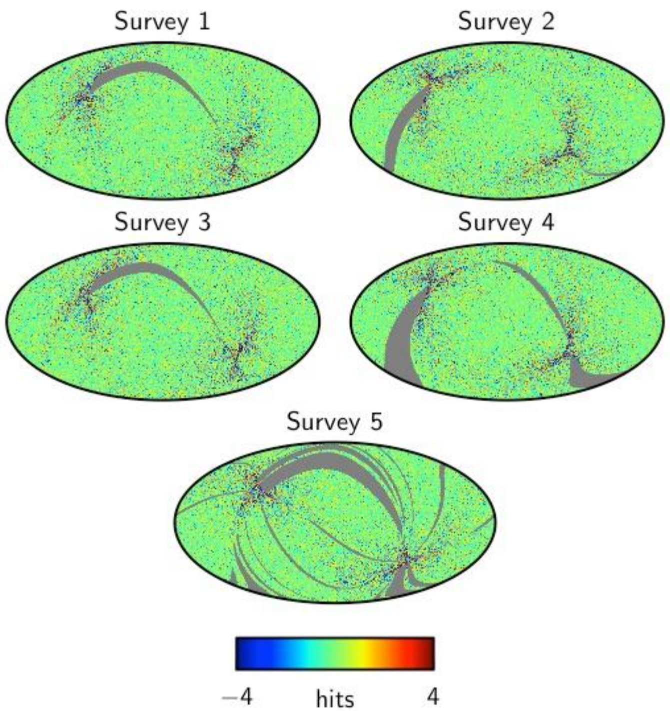
1. Code validation & verification: requires **accurate** fiducial simulation
2. Data uncertainty quantification & debiasing: requires **massive** MC

SPECIFICATION

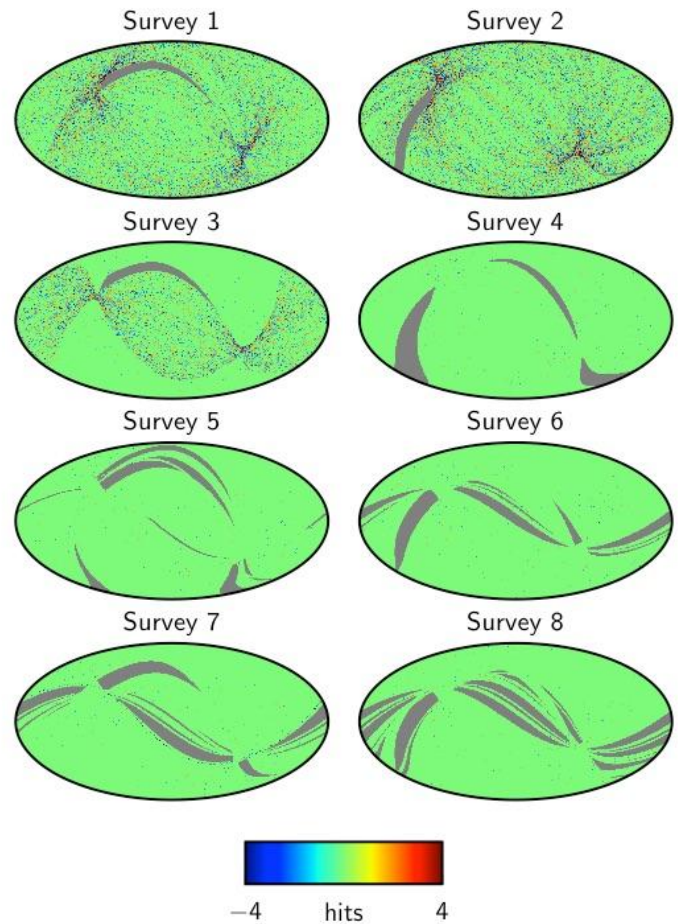
1. Instrument model:
    a. Satellite focal plane, pointing & flags
    b. Detector beams, band-passes & noise
2. Sky model:
    a. Foregrounds
    b. CMB
3. Processing:
    a. Replication of *both* DPC's processing
    b. At massive scale

Focal Plane, Pointing & Flags: TOAST vs DPC Hit Maps

HFI

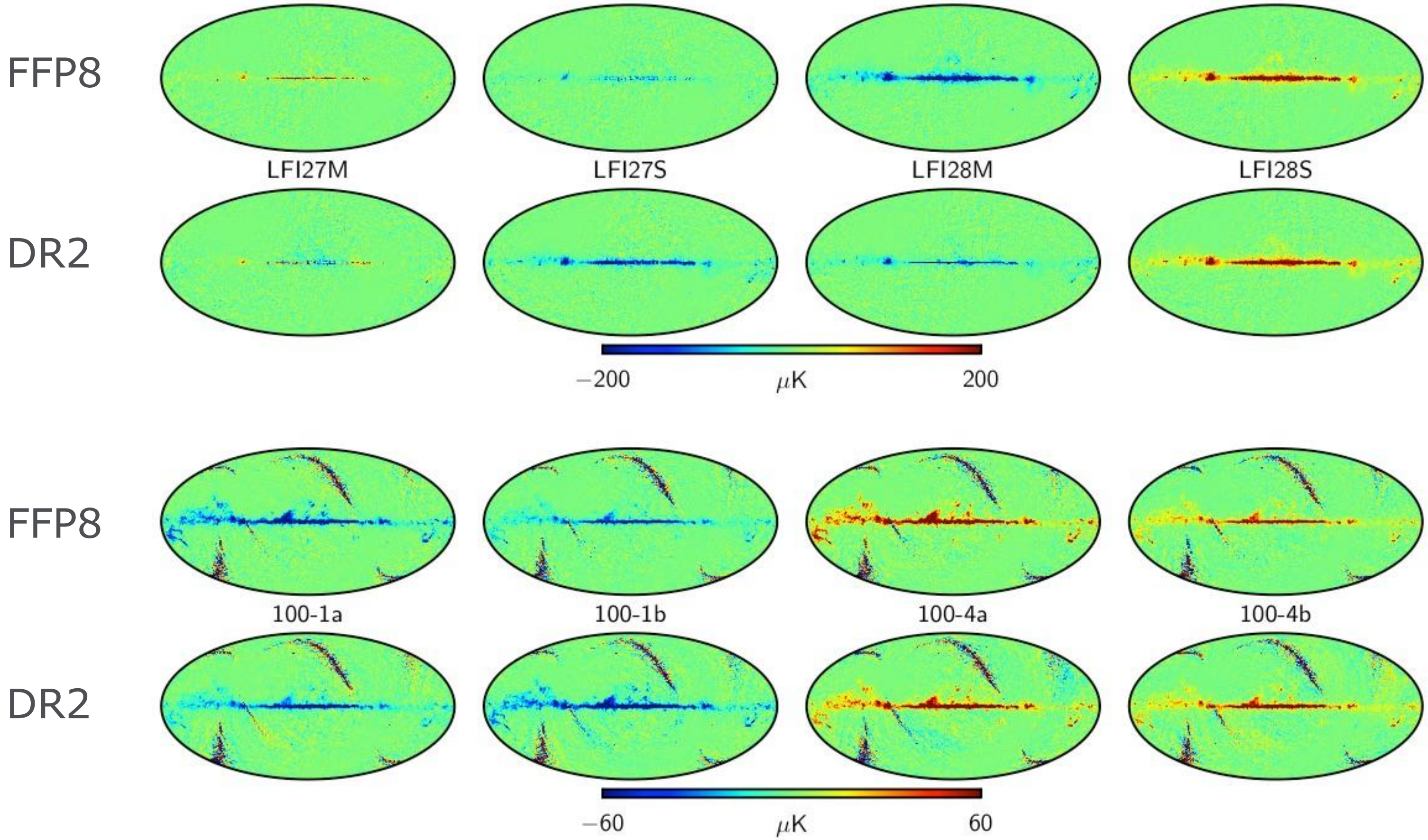


LFI



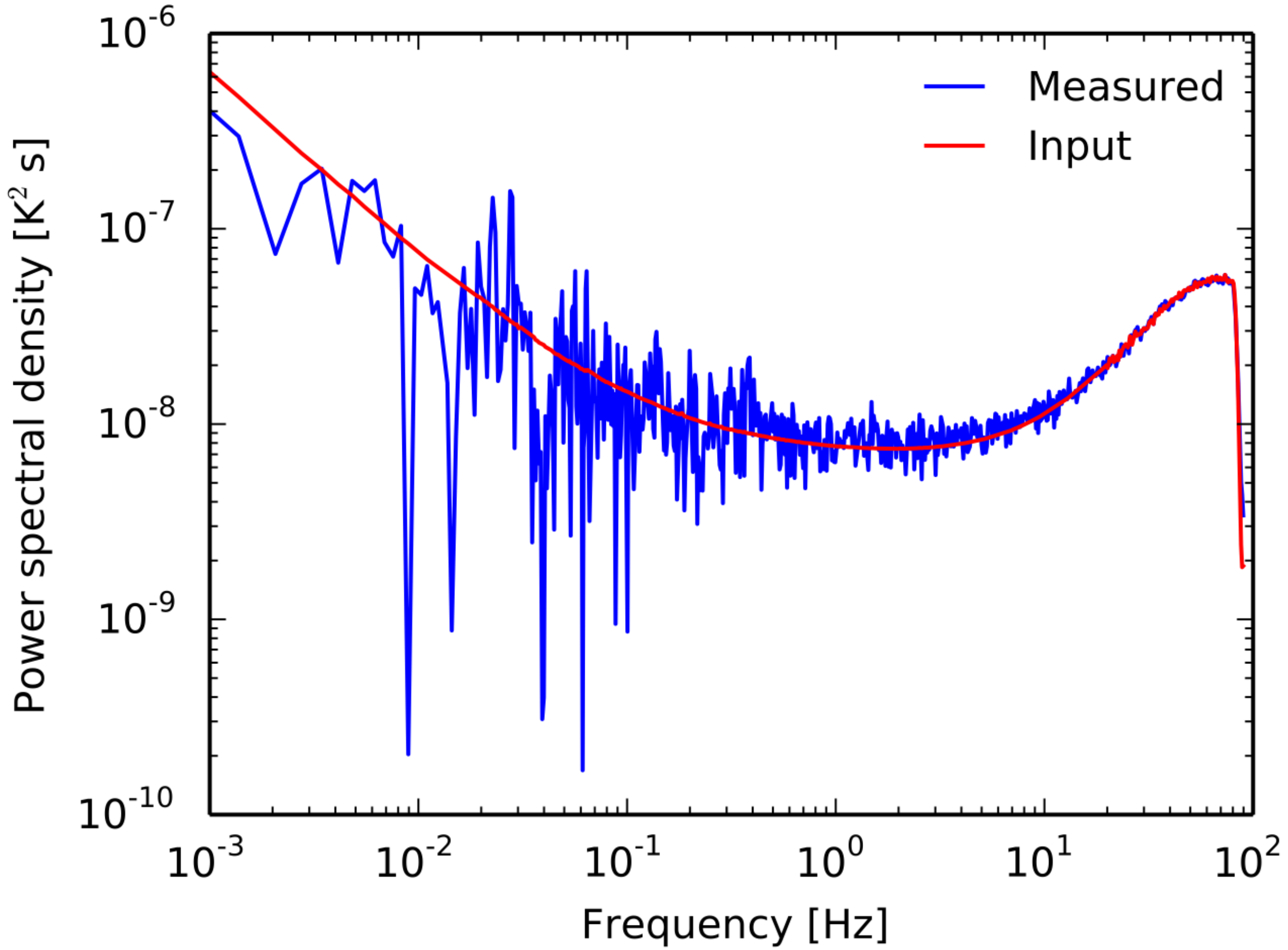
Overall discrepancy in hits: $\Delta T/T \sim 10^{-8}$

Bandpasses: Spurious Component Maps



Noise Estimation

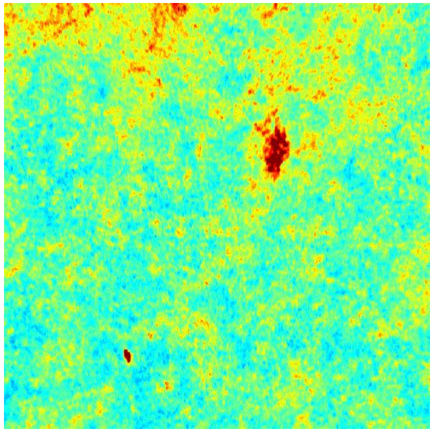
1. Subtract map from time-stream
2. Estimate noise per pointing period
3. Average noise PSD estimates per day



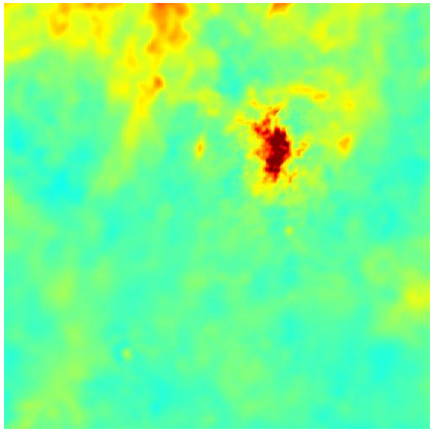
Foregrounds:
Planck Sky Model

Improved 10-component model:

1. CO lines
2. Cosmic Infrared Background
3. Free-free
4. Point Sources (Infrared)
5. Point Sources (Radio)
6. Spinning dust
7. Sunyaev-Zel'dovich (Kinetic)
8. Sunyaev-Zel'dovich (Thermal)
9. Synchrotron
10. Thermal dust



DR1



DR2

Cosmic Microwave Background: Scalar, Tensor & Non-Gaussian

- Start with the Planck 2013 cosmology
- Construct 3 components of CMB sky
    1. Scalar CMB
        a) Lensed
        b) Rayleigh-scattered
        c) Doppler-boosted
        (b–c) } frequency-dependent
    2. Tensor CMB
    3. Non-Gaussian CMB

- Construct total CMB skies for various (r, f_{NL})

$$CMB = CMB_S + \sqrt{r}\, CMB_T + f_{NL}\, CMB_{NG}$$

FFP8 Fiducial Realization

360 timelines:

1. 3 x CMB
2. 2 x Foreground

16 map flavors:

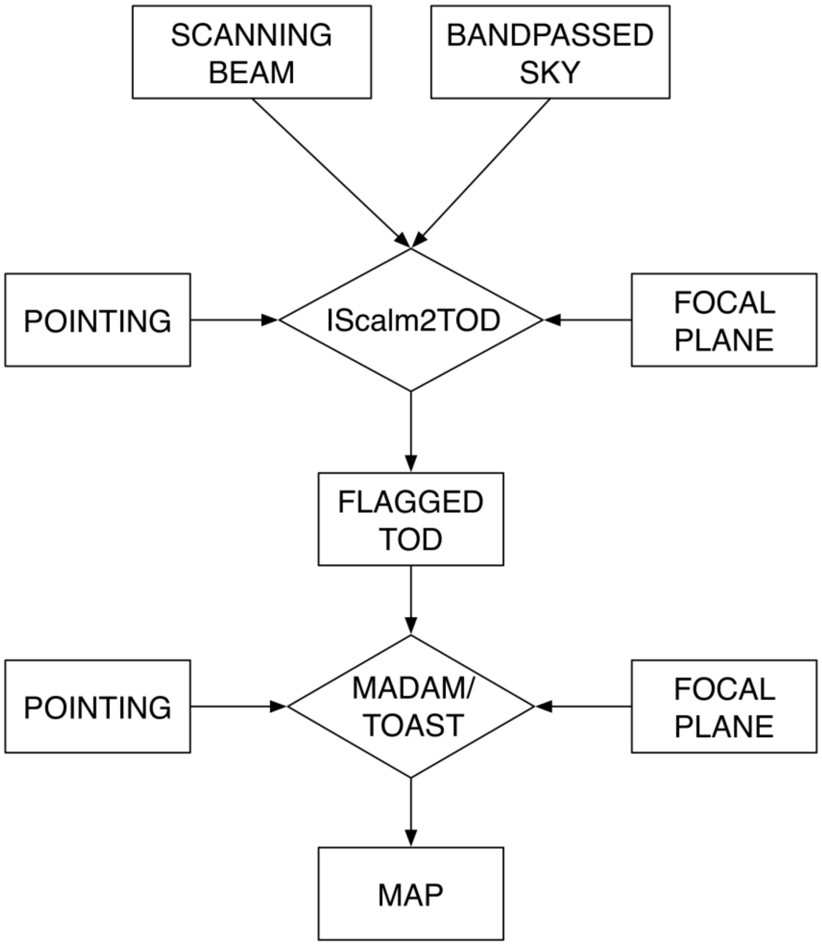
1. 6 x component (CMB, Foreground, Noise)
2. 10 x total: (5 x [r, f_{NL}]) x (2 x FG)

1,134 data combinations:

1. Frequency channel & detset
2. Mission, half-mission, year & survey
3. Full & half-ring

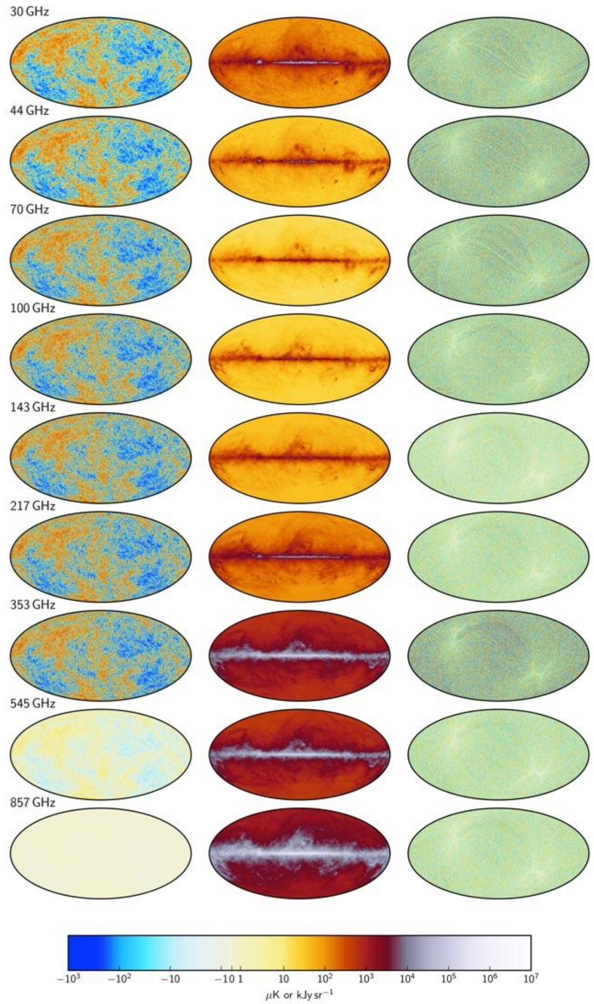
18,144 maps

250K NERSC CPU-hours

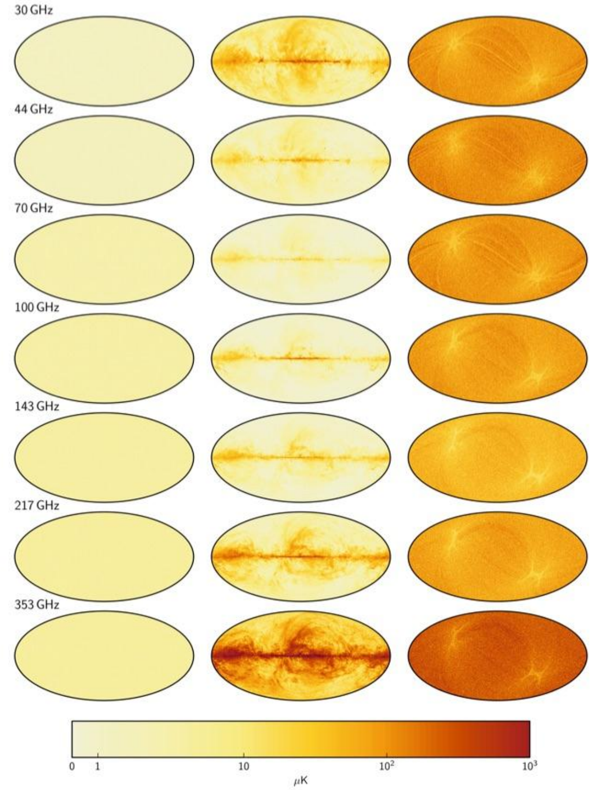


Scalar CMB, Foreground & Noise Maps

Temperature

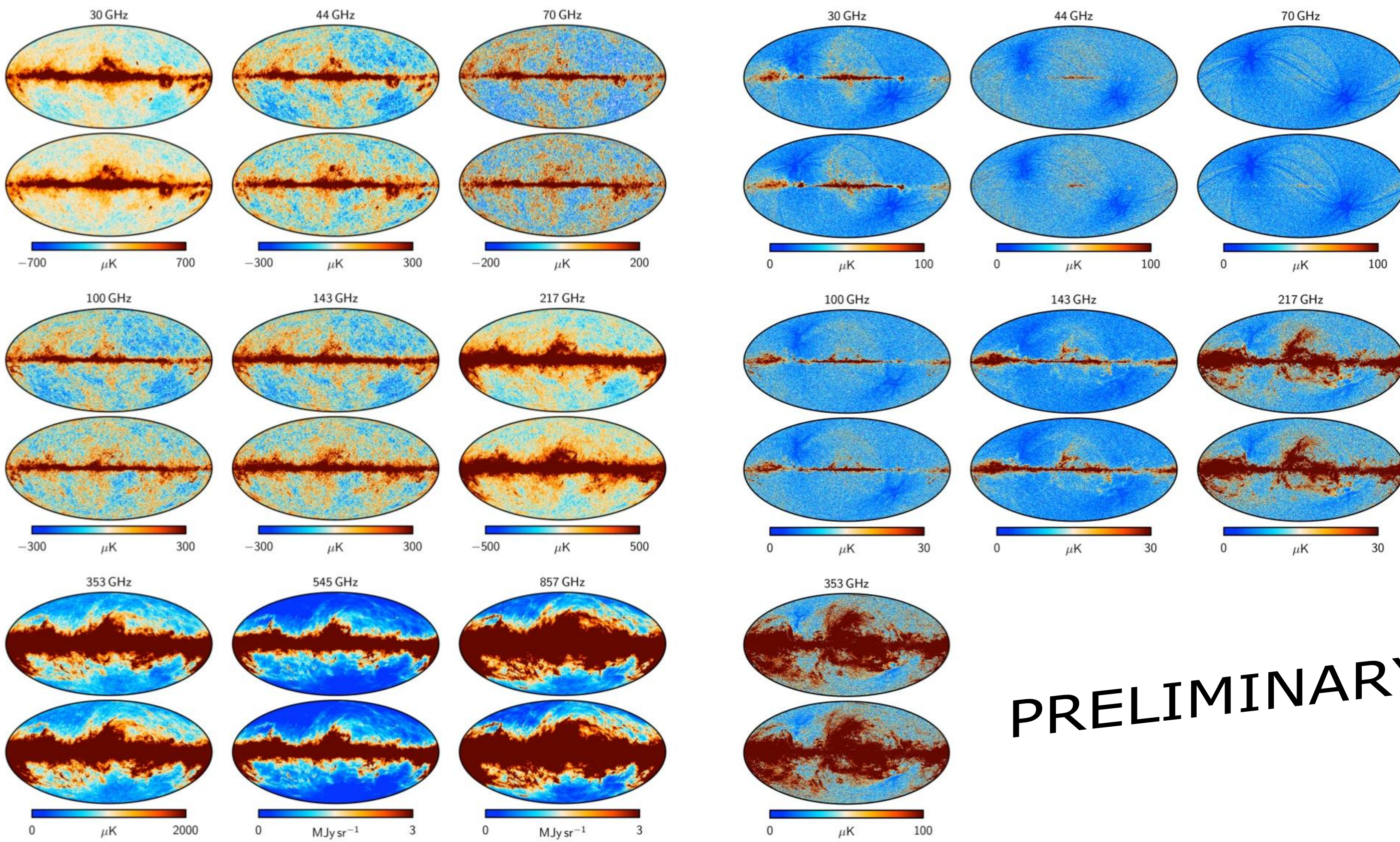


Polarization



Comparison With Real Data

Temperature



Polarization

PRELIMINARY

Noise Monte Carlos

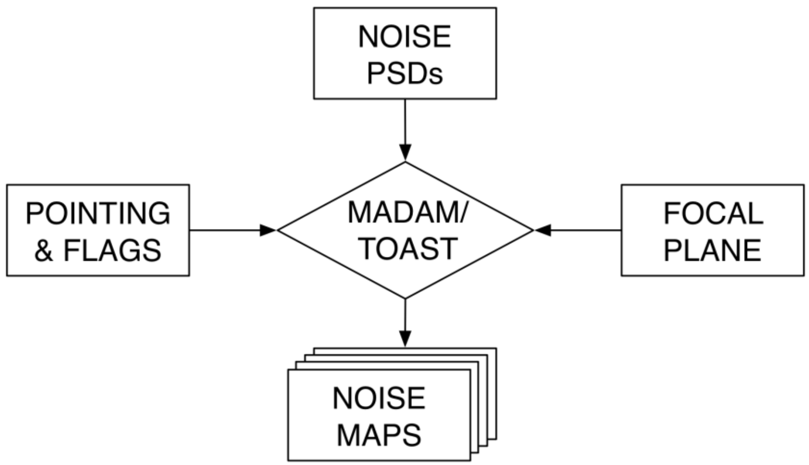
FFP8 contains:

1. 10^4 mission channel full maps
2. 10^3 other full maps
3. 10^2 half-ring maps.

671,400 maps

12M NERSC/CSC CPU-hours

(10K maps/hour)



10,000 Mission Channel Noise Maps

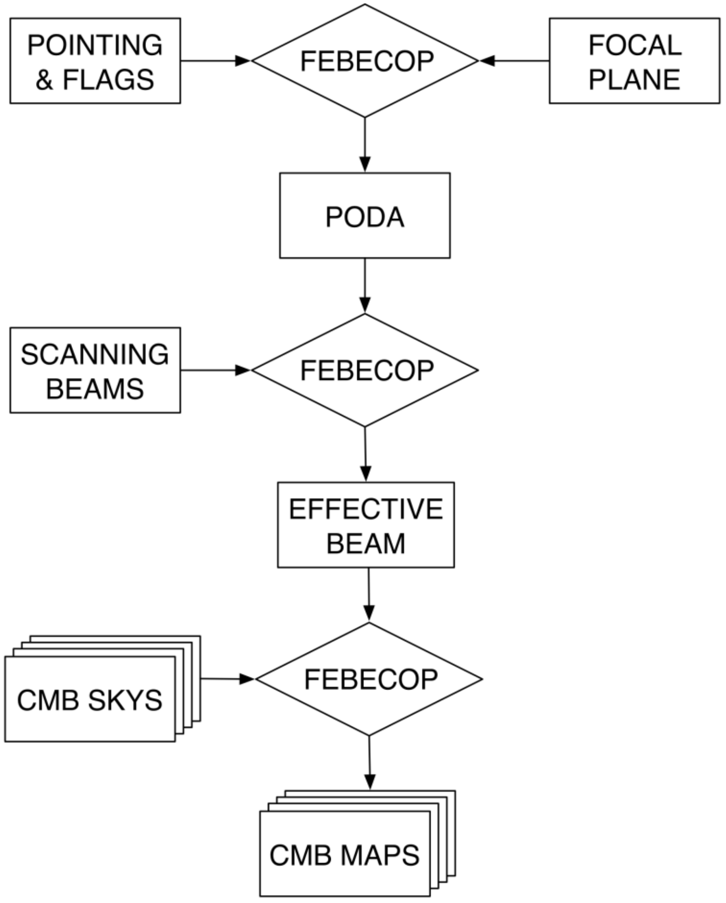
CMB Monte Carlos

FFP8 contains:

1. 10^4 mission channel full maps
2. 10^4 half-mission channel full maps
3. 10^4 mission (some) detset full maps

460,000 maps

8M NERSC CPU-hours

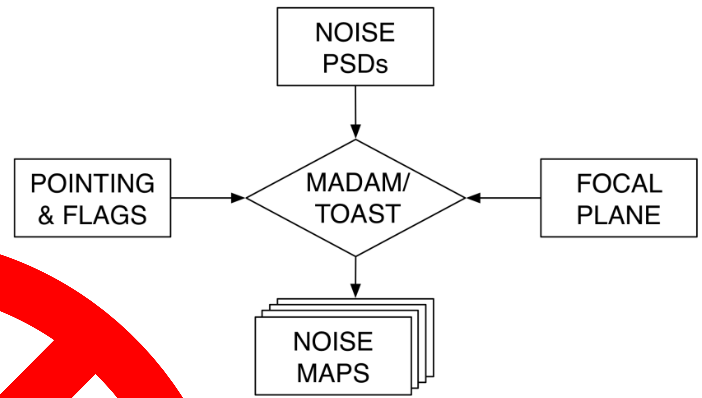


FFP Evolution

FFP1 (2006)	FFP8 (2014)
Single frequency, 12 detectors	All frequencies, 72 detectors
Nominal mission	Full mission
Nominal pointing, no flags	Actual pointing & flags
Common symmetric beam	Individual asymmetric beams
Scalar CMB	Scalar + tensor + non-Gaussian CMB
No foregrounds	Planck Sky Model, with and without band-pass mismatch
Simplest 1/f noise, with the same parameters for all detectors at all times	Measured detector noise PSDs, including time-variation & cross-terms
12 fiducial timelines	360 fiducial timelines & 18,144 maps
No MC	10^4 MC realizations of CMB and noise, reduced to $O(10^6)$ maps
1 map per week on $O(10^3)$ cores	10,000 maps per hour on $O(10^5)$ cores

High Performance Computing Considerations

1. Minimize data movement.
   a. Replace I/O with OTFS
2. Optimize communication.
   a. Data distribution
   b. MPI/OpenMP hybri ation
3. Exploit all levels of para ism
   a. Loop over rea ations
   b. Gang paralle sm
4. Use an appropriate h h pe orm e language.



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.

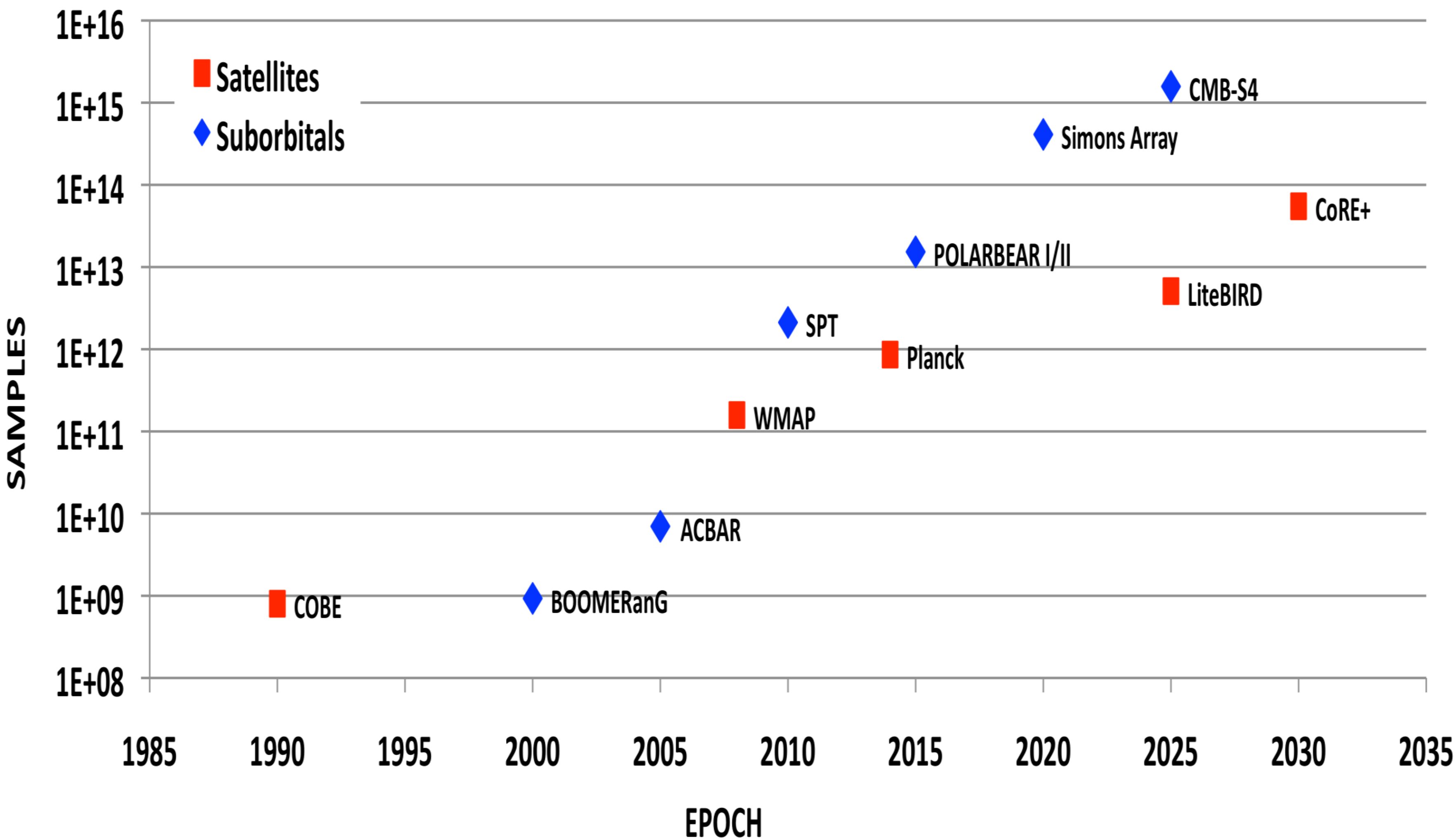
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific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

Post-Planck Simulations

Post-Planck Extensions

- Complementary simulations:
  - Observe the PSM with any experiment's band-passes to generate simulations that can be analyzed
    - in conjunction with equivalent Planck data to leverage its multi-frequency power
    - in conjunction with other experiments to inform coordinated scanning strategies
- Generalized Monte Carlo capabilities:
  - Extend the massively parallel TOAST-based Sim/Map code to other experiments to significantly expand MC set sizes
    - keeping up with Moore's Law is essential & challenging

Exponential Data Scaling



Challenges - Veracity

- Instrument & mission:
  - Capturing all noise correlations
  - Accurate beam representation (side-lobes, polarization)
  - Systematics/residuals
  - Instrument evolution
- Sky:
  - Foreground models & measurements
    - eg. Planck noise residuals corrupting joint analyses (B2P)
  - Atmosphere
    - Sampling weather & observing a time-varying slab

Challenges - Cost

- Context:
  - Continuing exponential growth of data volumes
  - Increasingly challenging HPC architectures
    - power constraints (on data movement especially)
    - end of Moore's Law?
- Chasing efficiency:
  - Extend on-the-fly capability to beam-convolved sky signals, maybe to MC maps themselves.
  - Incorporate more systematic effects (or their residuals)
  - Develop general OTFS interfaces, including to python prototypes
  - Develop and implement efficient data formats

Conclusions

- Simulations play a critical role in CMB science:
  - Instrument design
  - Mission planning
  - Data analysis
- By identifying the need early and investing in a long-term plan to address it, Planck has developed an incomparable simulation capability.
  - Required both the right technology and the right skills
- This capability can and should be part of Planck's legacy to the CMB community.