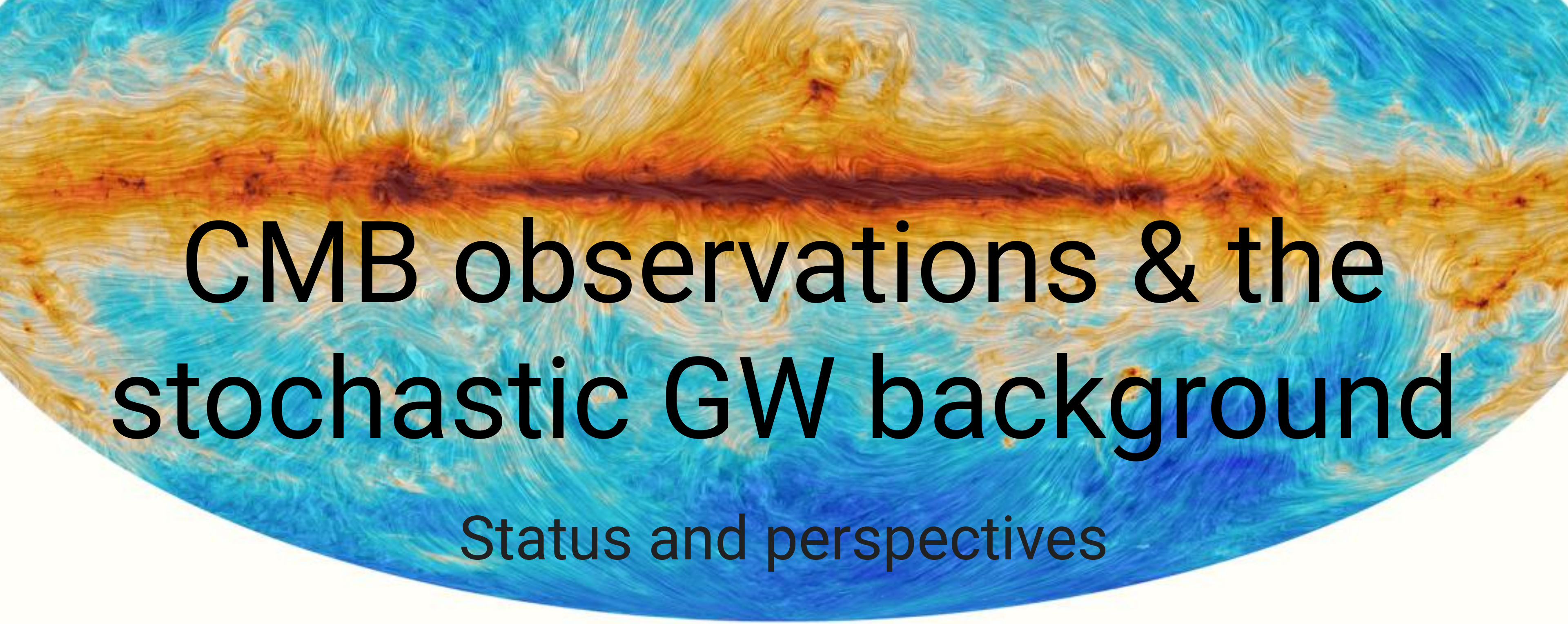


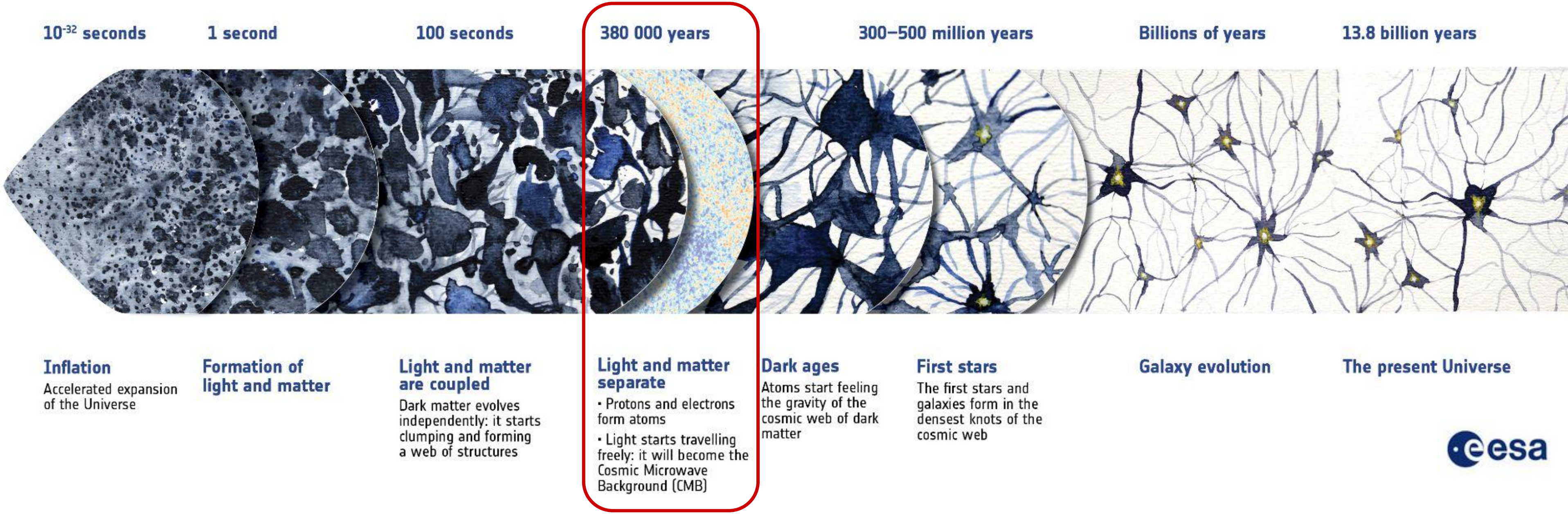
CMB observations & the stochastic GW background

Status and perspectives

Simon Biquard (APC, CNRS)
PhD with J. Errard & R. Stompor
19 Sep 2024

Science from the large scale cosmic microwave background polarization structure

Cosmic history



10^{-32} seconds	**Inflation**	Accelerated expansion of the Universe
1 second	**Formation of light and matter**	
100 seconds	**Light and matter are coupled**	Dark matter evolves independently: it starts clumping and forming a web of structures
380 000 years	**Light and matter separate**	• Protons and electrons form atoms • Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)
	Dark ages	Atoms start feeling the gravity of the cosmic web of dark matter
300–500 million years	**First stars**	The first stars and galaxies form in the densest knots of the cosmic web
Billions of years	**Galaxy evolution**	
13.8 billion years	**The present Universe**	

temperature drops -> recombination (decoupling of photons) -> CMB is released

CMB physics

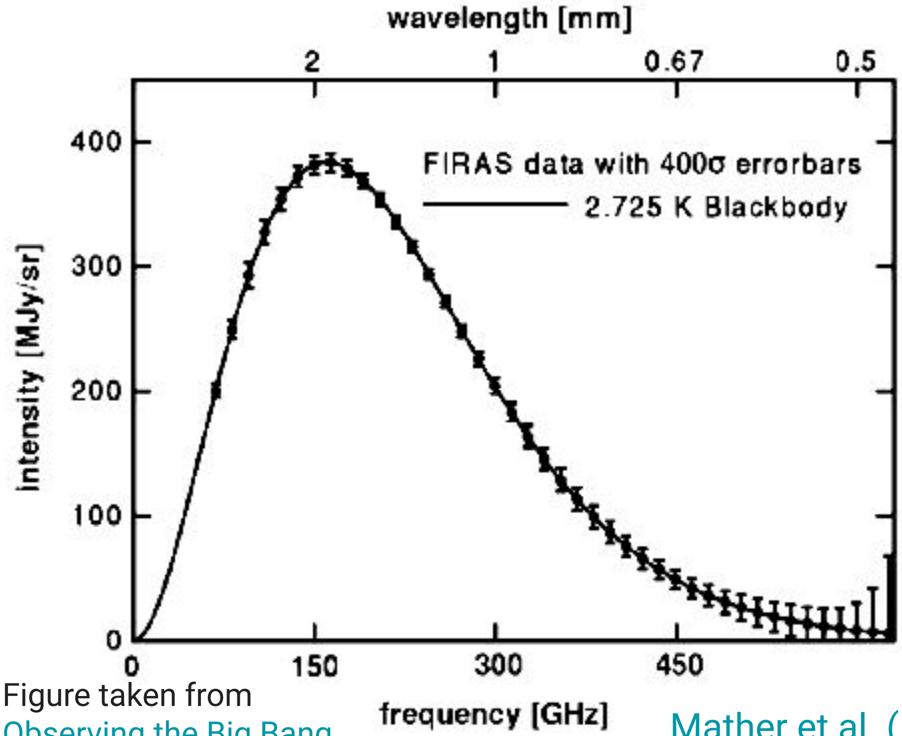
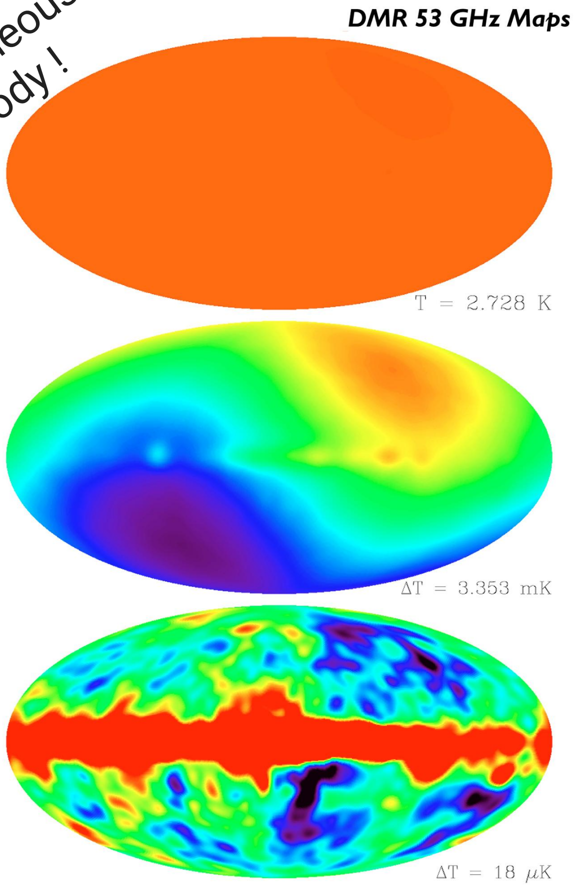


Figure taken from
[Observing the Big Bang](#)

[Mather et al. (1994)](#)
[Bennett et al. (1996)](#)

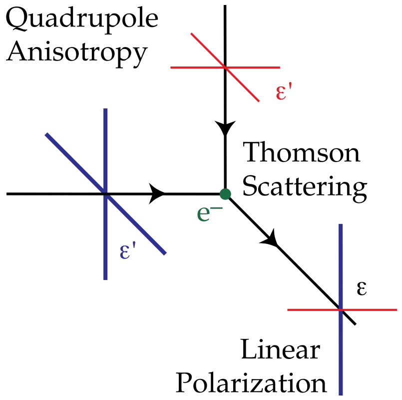
Homogeneous
black-body !



Credits: NASA / Cobe Science Team

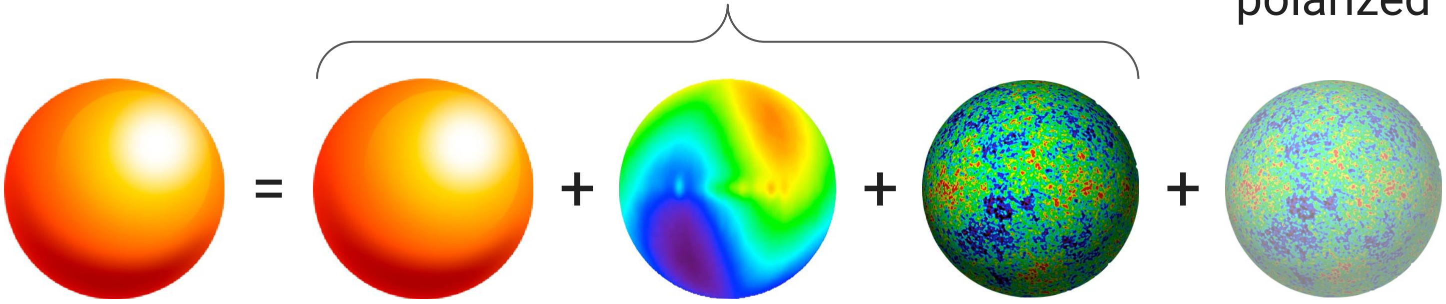
CMB physics

- Solar system peculiar motion -> dipole anisotropy
- Inhomogeneities in the plasma -> temperature anisotropies
- Inhomogeneities + Thomson scattering -> polarization anisotropies



non polarized

polarized



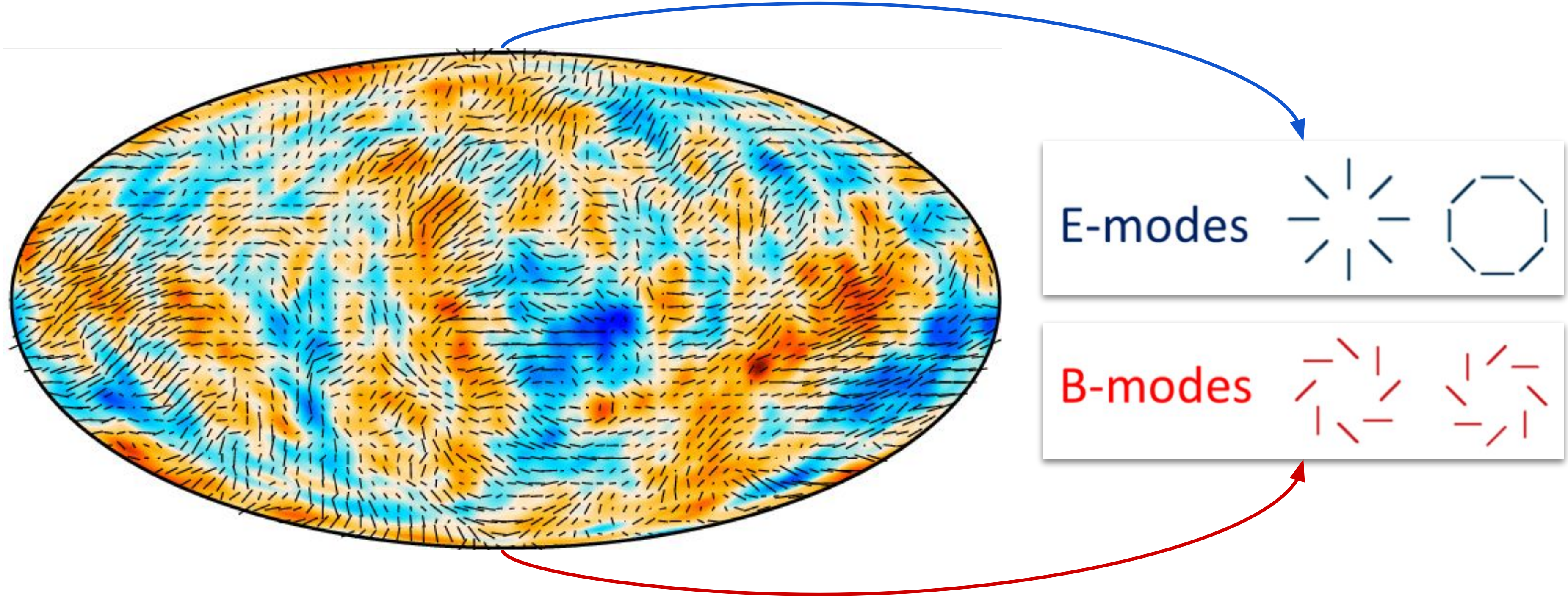
T = 2.7 K

$\Delta T/T \sim 10^{-3}$

$\Delta T/T \sim 10^{-5}$

$\Delta P/T \sim 10^{-6}$

Credits: J. Errard

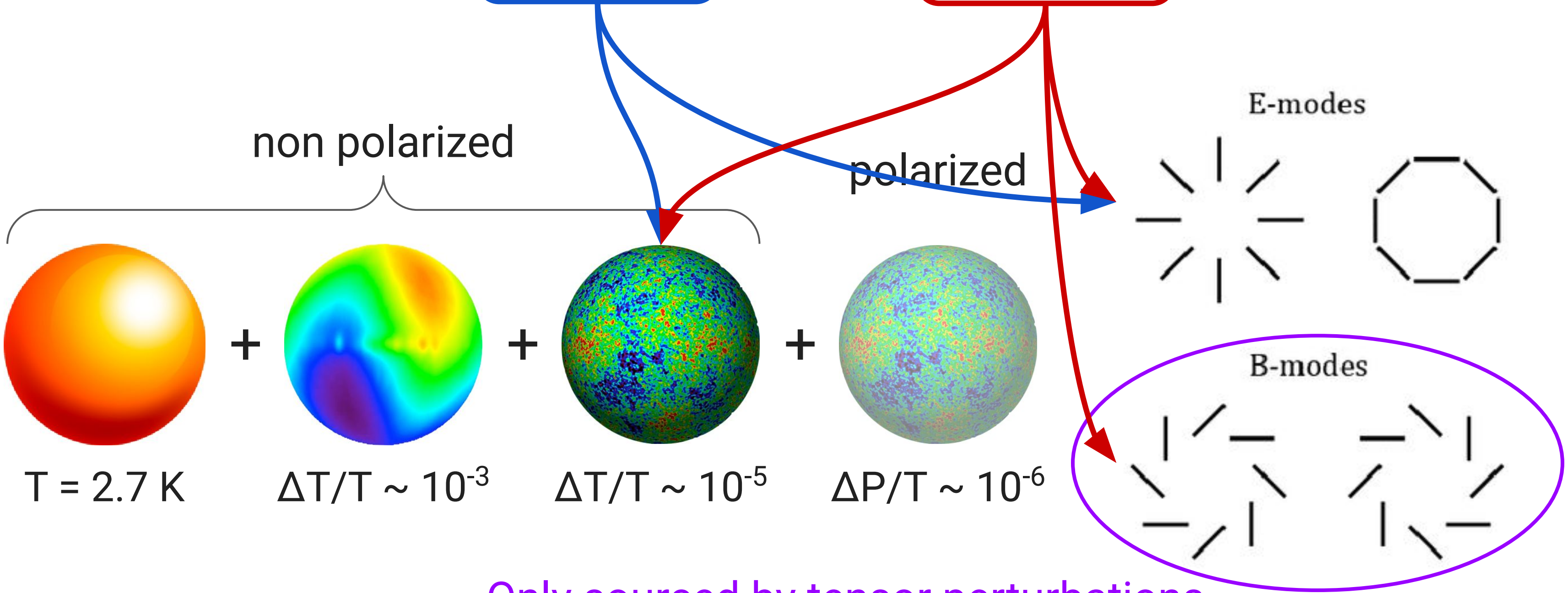


Planck 2018 results I.

CMB polarization superimposed on temperature map (both smoothed to 5°). Credits: Planck collaboration.

CMB physics

$$dl^2 = a^2(t)[1+\boxed{2\zeta(\mathbf{x},t)}][\delta_{ij}+\boxed{h_{ij}(\mathbf{x},t)}]dx^i dx^j$$



non polarized

polarized

$T = 2.7$ K + $\Delta T/T \sim 10^{-3}$ + $\Delta T/T \sim 10^{-5}$ + $\Delta P/T \sim 10^{-6}$

Only sourced by tensor perturbations,
i.e. *primordial gravitational waves* !

Cosmic history

10^{-32} seconds

Inflation
Accelerated expansion of the Universe

1 second

Formation of light and matter

100 seconds

Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures

380 000 years

Light and matter separate
- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter

300–500 million years

First stars
The first stars and galaxies form in the densest knots of the cosmic web

Billions of years

Galaxy evolution

13.8 billion years

The present Universe

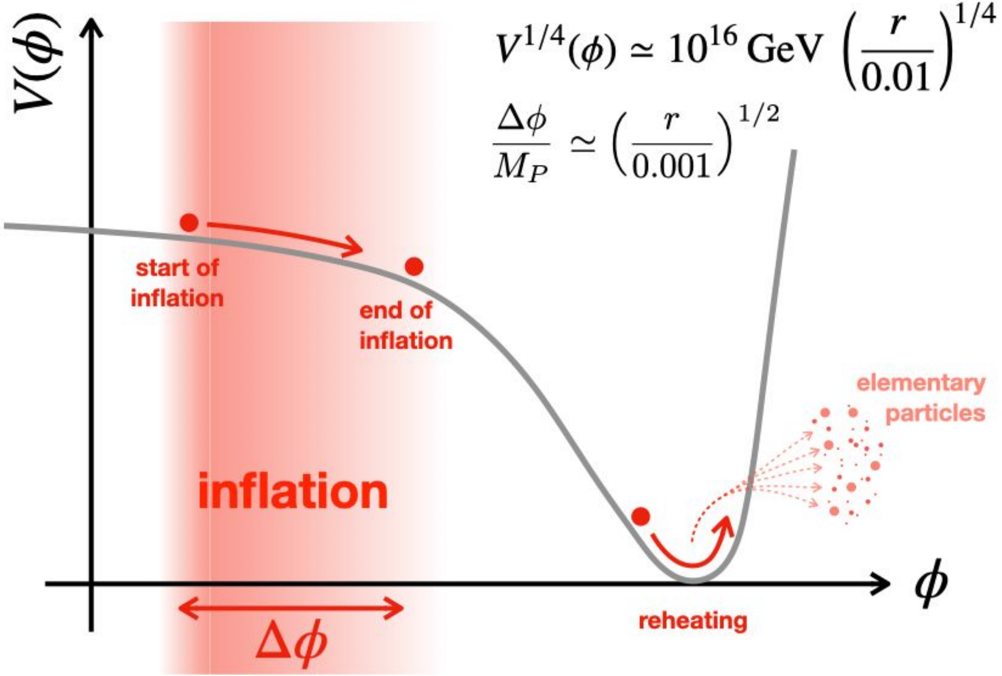
esa

Cosmic inflation

- accelerated expansion of space in the very early universe
- most plausible mechanism for generating 'seeds' of cosmic structure
- observations in agreement with single-field, slow-roll inflation
- also generates primordial GWs
- tensor-to-scalar ratio $r = A_t/A_s$

$$\mathcal{P}_{\mathcal{R}}(k) = A_s\left(\frac{k}{k_0}\right)^{n_s-1}$$

$$\mathcal{P}_{\mathcal{T}}(k) = A_t\left(\frac{k}{k_0}\right)^{n_t}$$

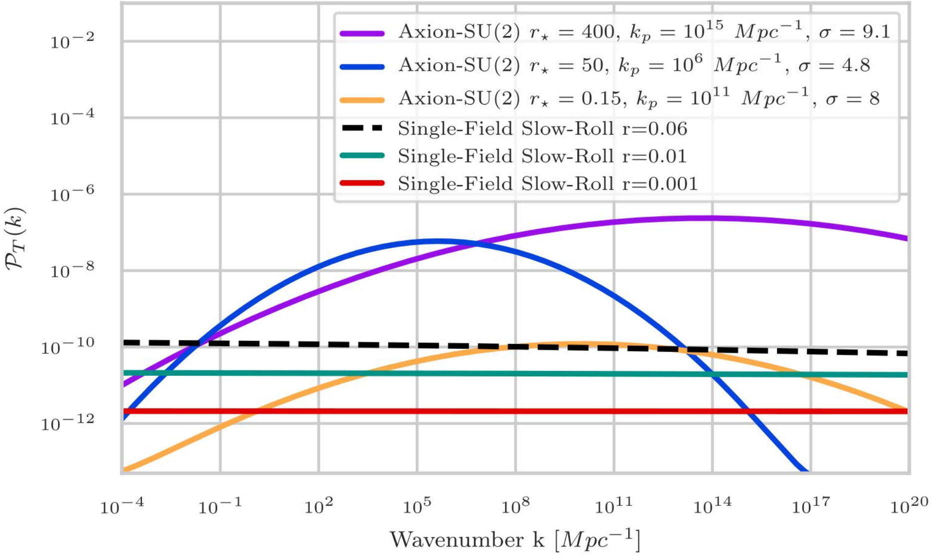


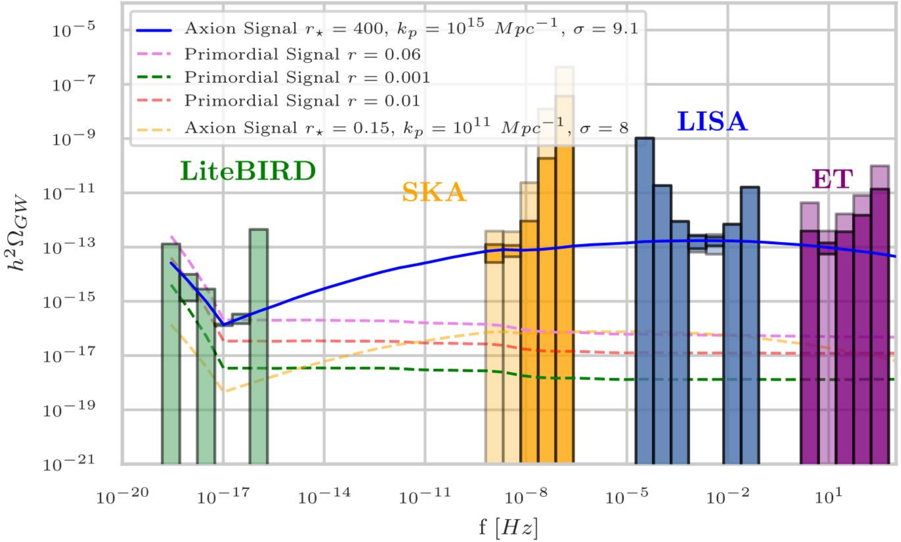
Credits: J. Errard

Planck 2018 results X.

Cosmic inflation

- Possible GW production if e.g. other fields are present during inflation
- Complementarity between CMB, interferometers, pulsar timing arrays

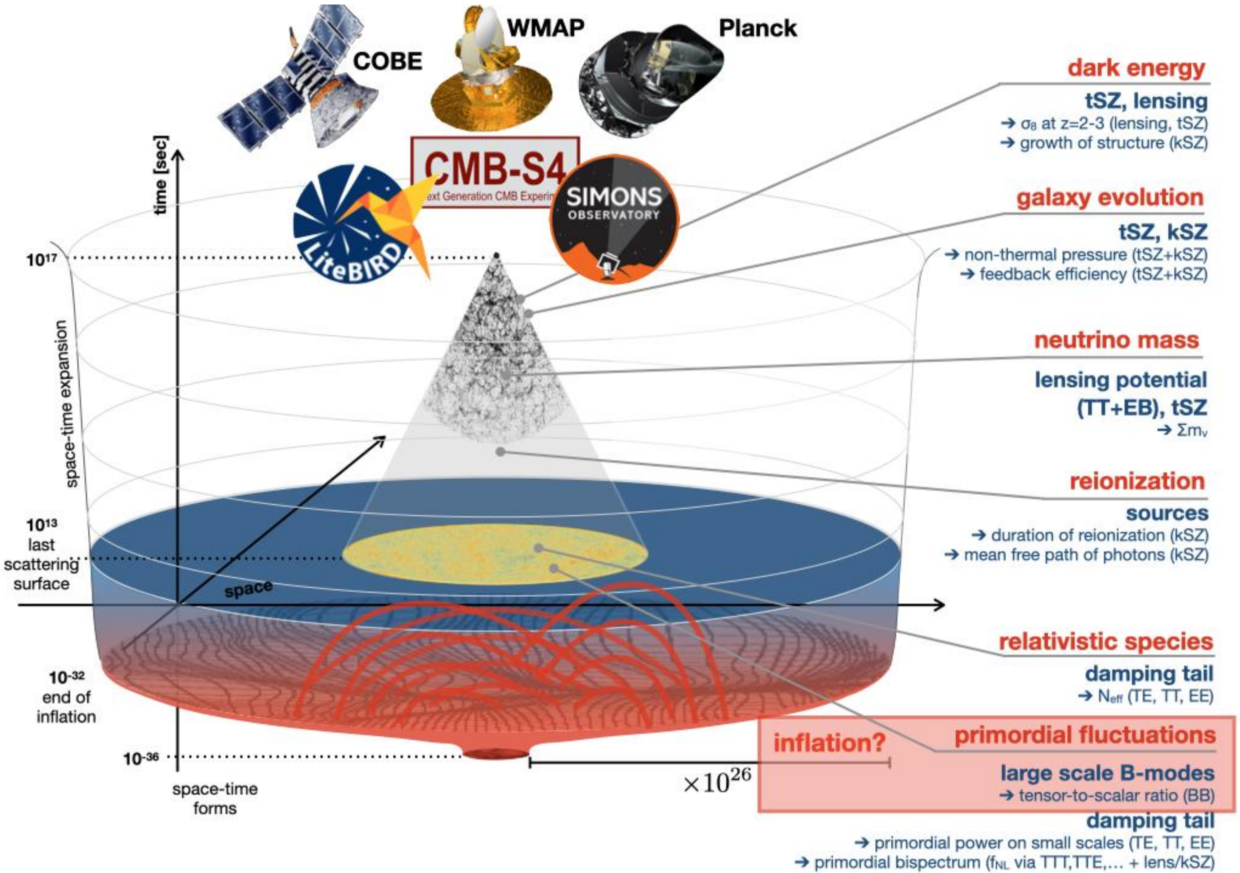




Figures from Campeti et al. (2020)

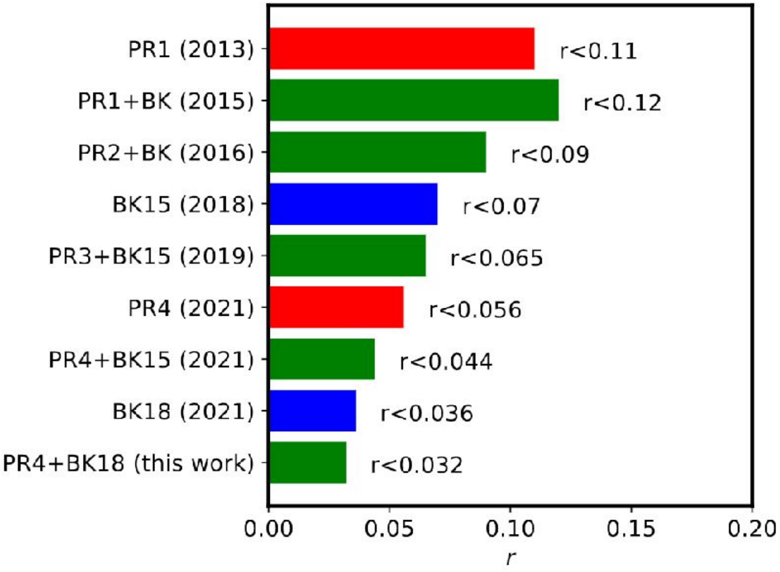
Scientific goals

- Primary anisotropies: early universe
- Secondary anisotropies: late universe (using the CMB as a backlight)

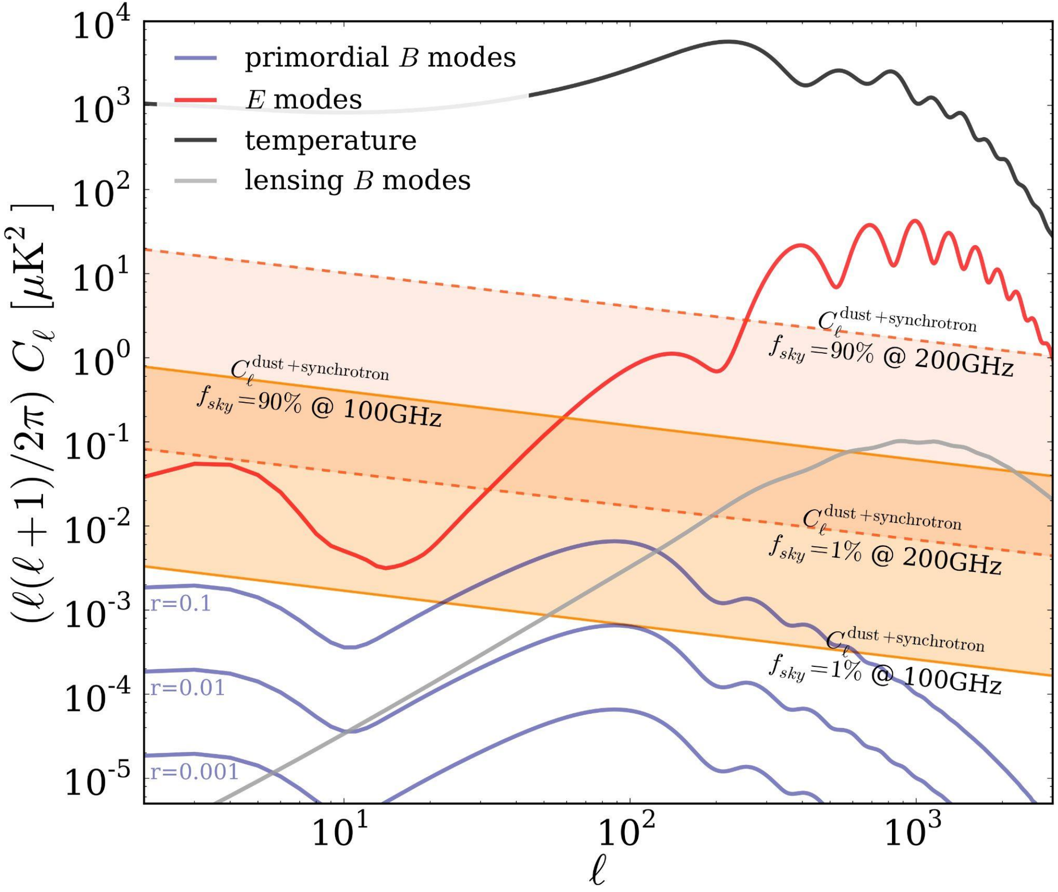


Credits: Josquin Errard

Current constraints on r

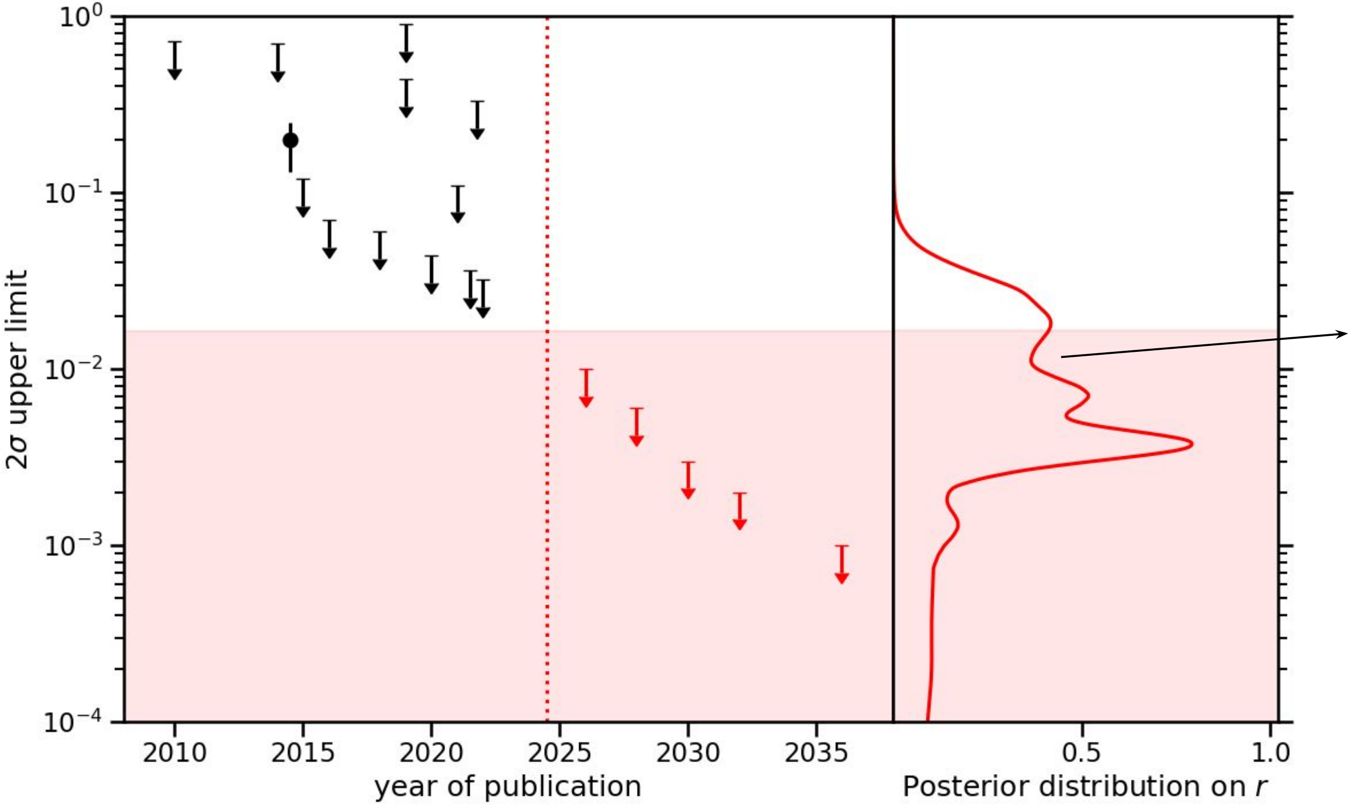


Tristram et al. (2022)



Errard et al. (2016)

Past and forecasted tensor-to-scalar ratio sensitivities

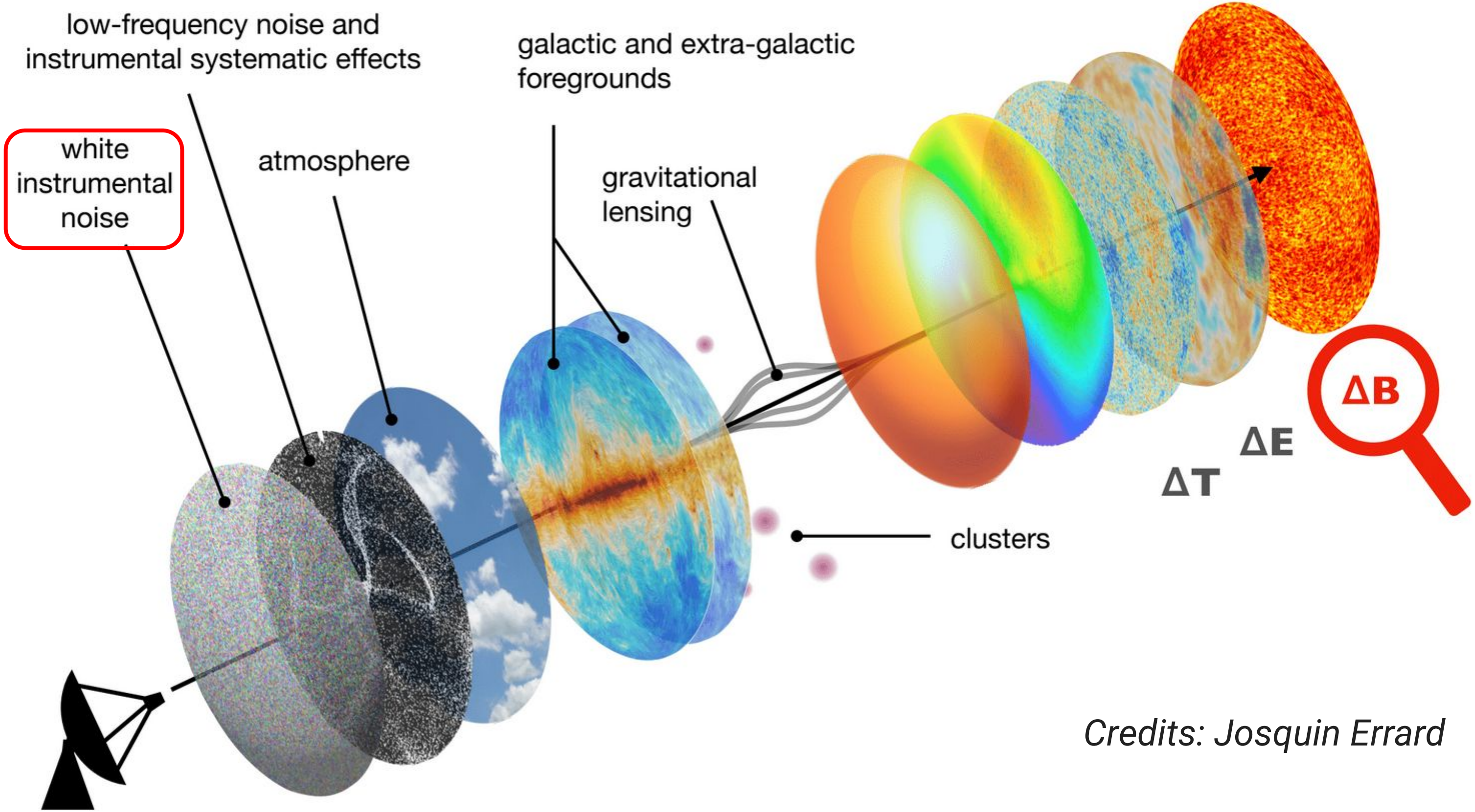


averaged over 283 single-field inflation models

Credits: J. Errard, C. Ringeval, V. Vennin

arXiv:1303.3787
arXiv:2404.10647
arXiv:2404.15089

Observation challenges



Credits: Josquin Errard

Improving the sensitivity

noise of each detector

observed sky area

$$s[\mu\mathrm{K.arcmin}] = \frac{\mathrm{NET}[\mu\mathrm{K}.\sqrt{\mathrm{s}}] \times \sqrt{f_{sky}[\mathrm{arcmin}^2]}}{\sqrt{N_{det} \times Y \times \Delta t[\mathrm{s}]}}$$

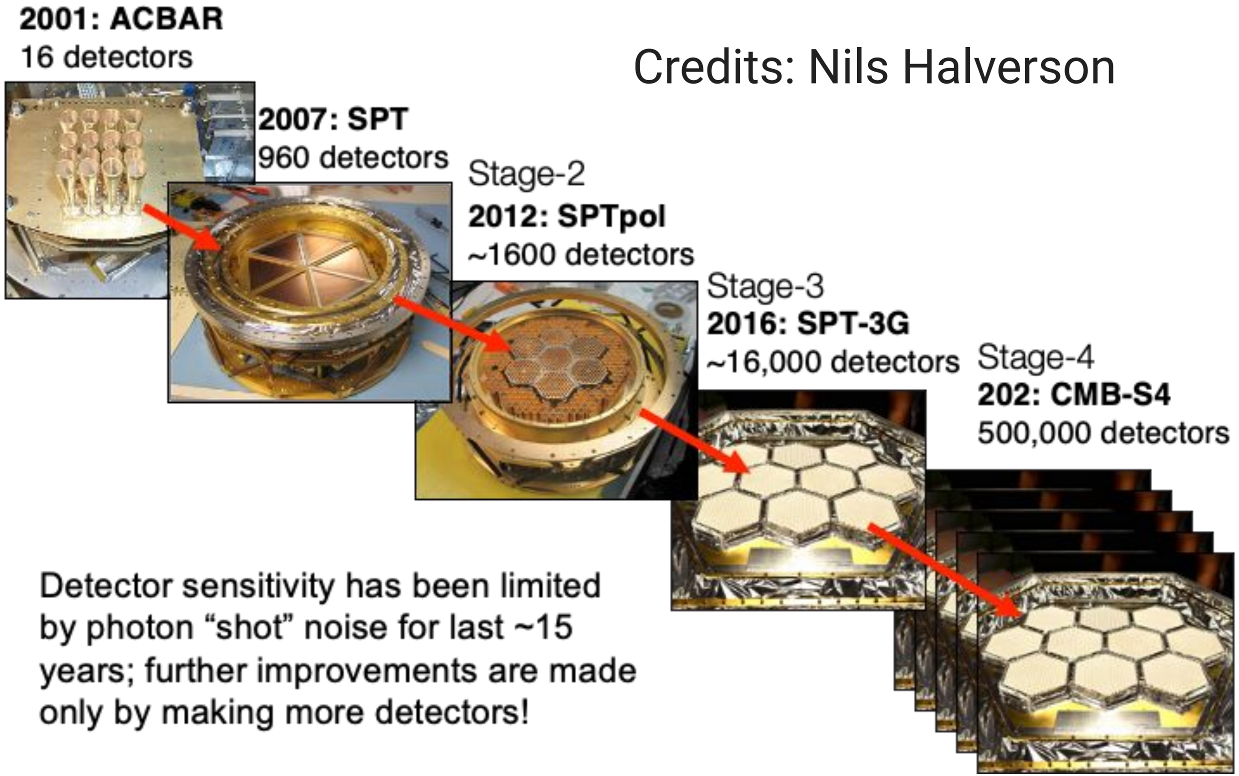
number of detectors

efficiency

integration time

Improving the sensitivity

Credits: Nils Halverson



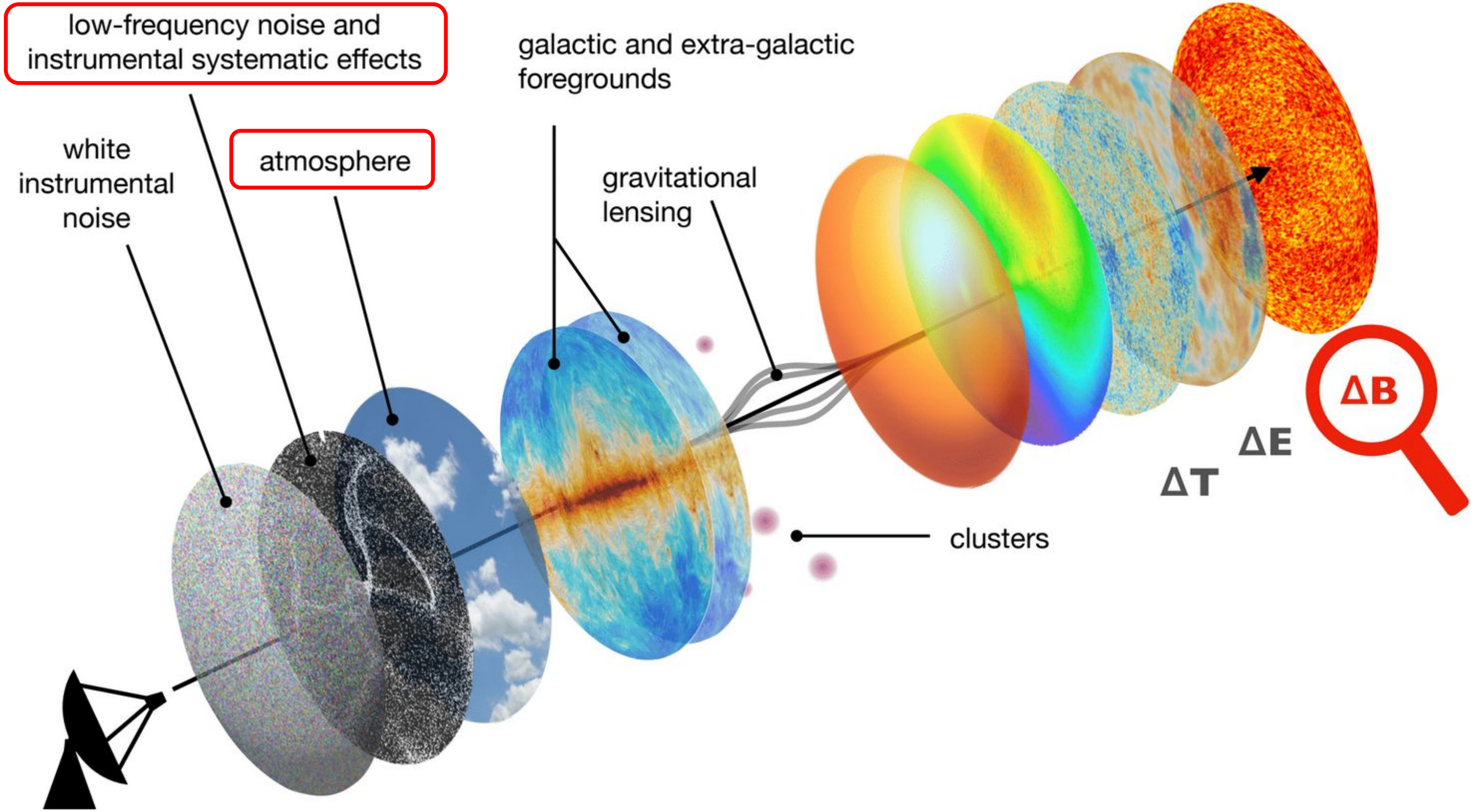
Detector sensitivity has been limited by photon “shot” noise for last ~15 years; further improvements are made only by making more detectors!

Readout challenges!

Simons Observatory:
> dichroic TES sensors
> 1000x multiplexing factor

arXiv:2106.14797

Observation challenges



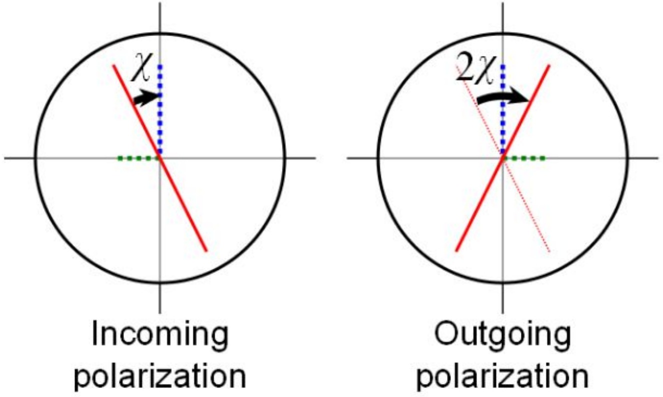
Systematics and 1/f mitigation

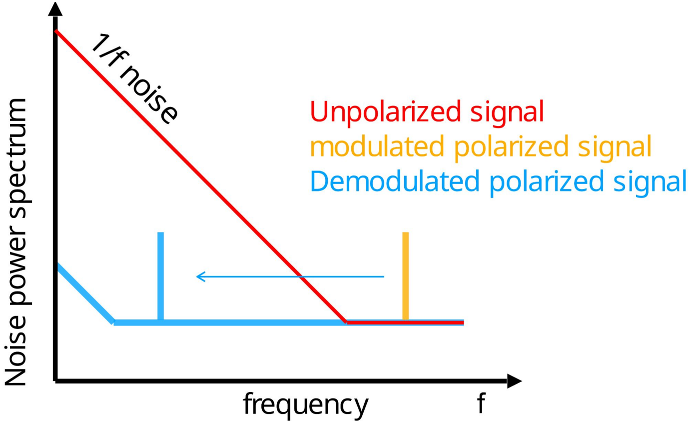
Polarization modulation unit (PMU)
-> commonly a rotating half-waveplate

Telescope observes a polarized source with a rate f_{scan} (depends on scanning strategy).

Data is affected by 1/f noise, especially from the atmosphere, at these frequencies.

Adding a HWP spinning at f_m modulates the incident polarization signal to a frequency of $2f_m$, detected by bolometers at $4f_m$ (>> f_{scan}).





A next-gen CMB instrument: the Simons Observatory

Cerro Toco, Chile, 5,200 meters a.s.l
("high and dry")
> 3 small aperture telescopes (SATs)
> 1 large aperture telescope (LAT)

60,000 TES detectors

6 frequency bands

SATs looking at large scale polarization

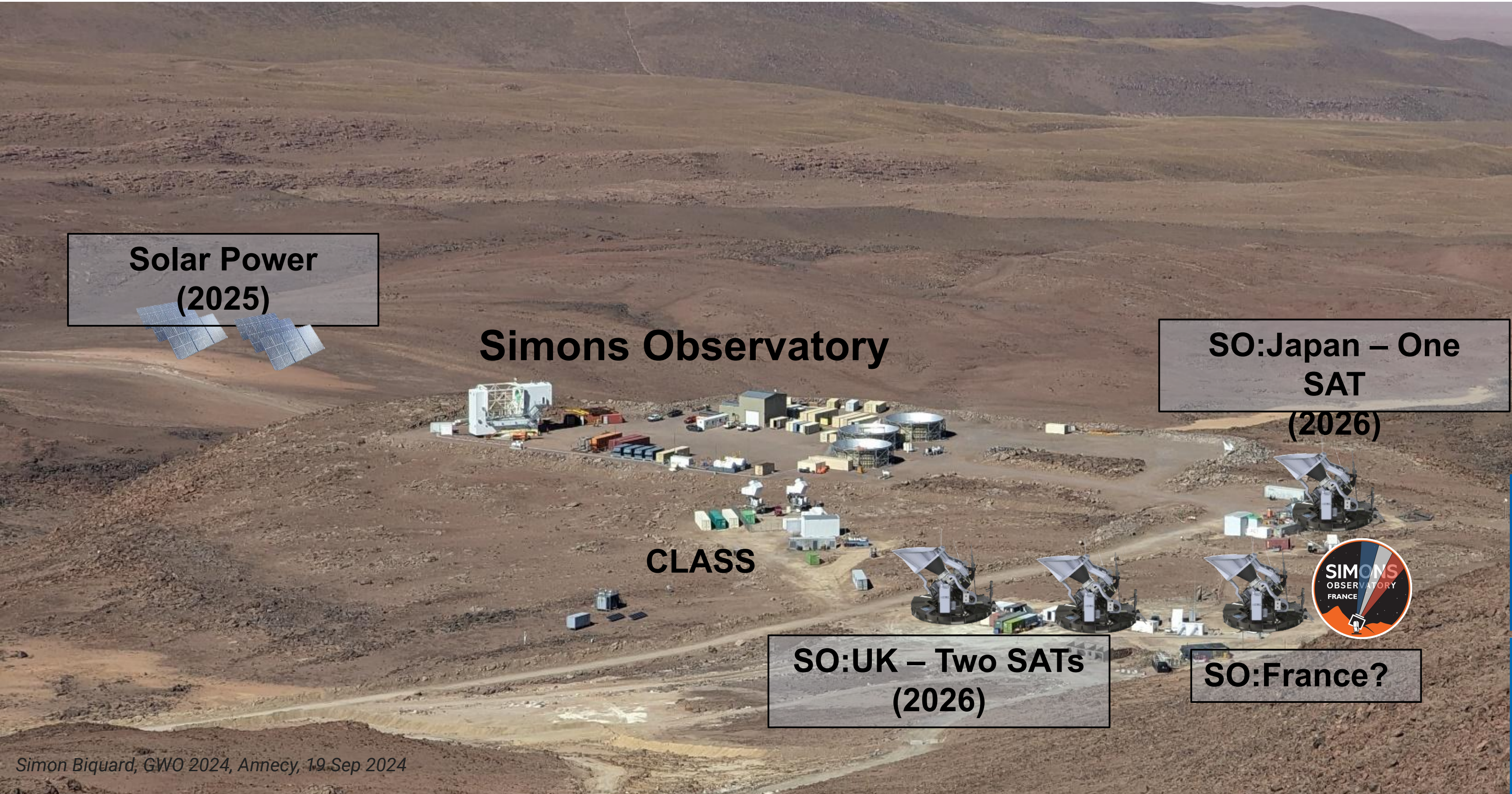
LAT looking at small scale anisotropies over a large sky fraction


Image credits: Nicholas Galitzki


Image credits: Mark Devlin


Image credits: Gabriele Coppi, Rolando Dunner, Federico Nati, Matias Rojas

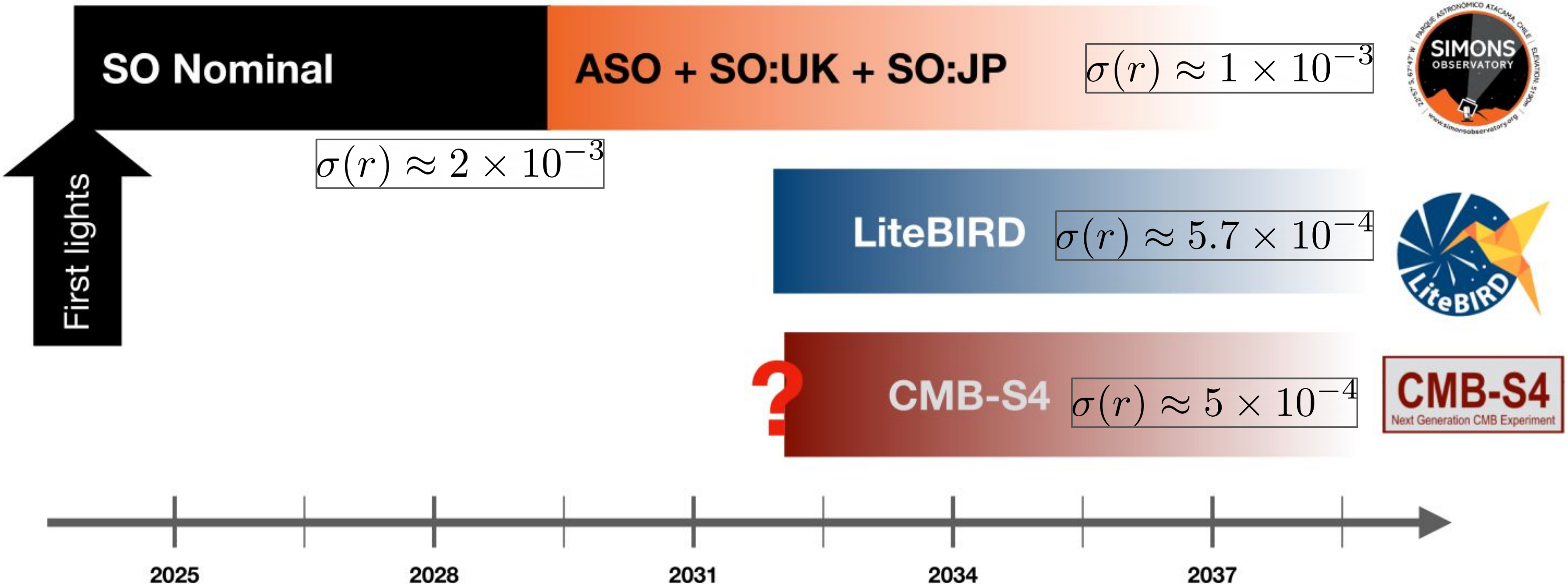
Advanced Simons Observatory



Agencia Nacional de Investigación y Desarrollo
Ministerio de Ciencia, Tecnología, Conocimiento e Innovación
Gobierno de Chile

Ministerio de Bienes Nacionales
Gobierno de Chile

Future observatories



First lights

SO Nominal

$\sigma(r) \approx 2 \times 10^{-3}$

ASO + SO:UK + SO:JP

$\sigma(r) \approx 1 \times 10^{-3}$

LiteBIRD

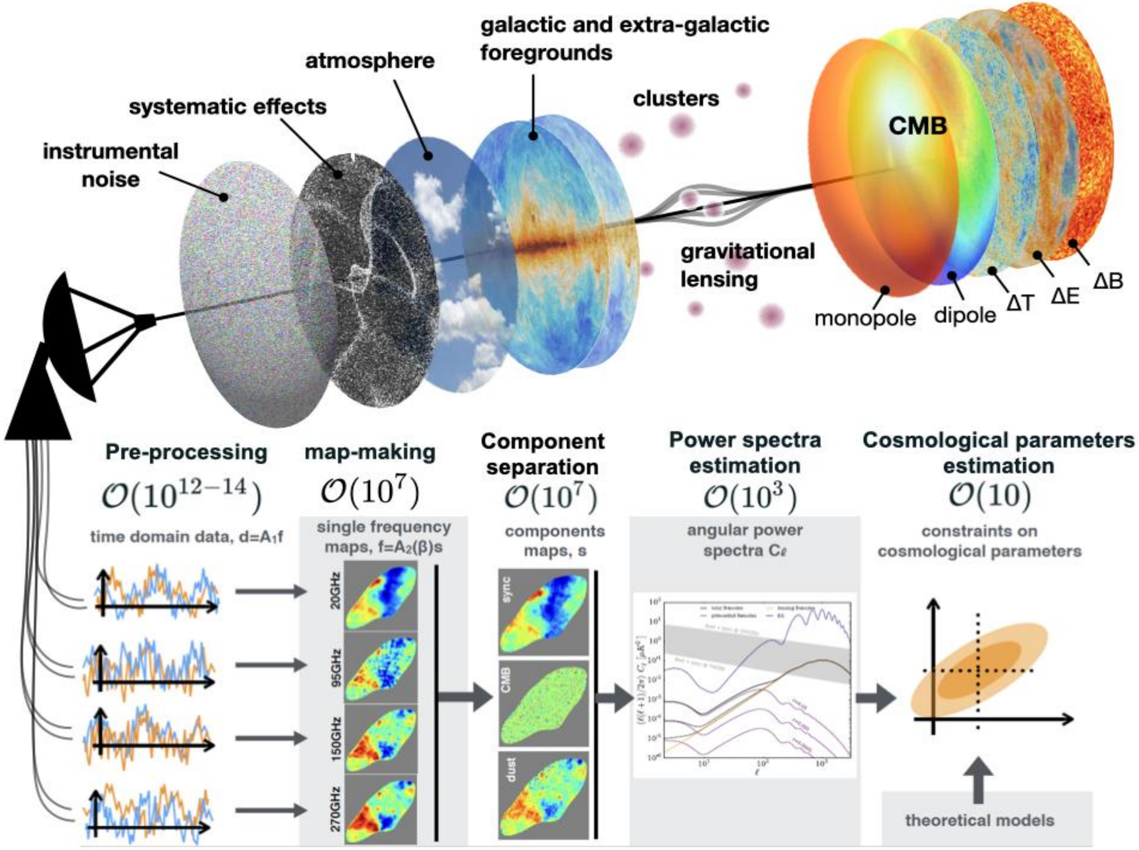
$\sigma(r) \approx 5.7 \times 10^{-4}$

?

CMB-S4

$\sigma(r) \approx 5 \times 10^{-4}$

Credits: Benjamin Beringue



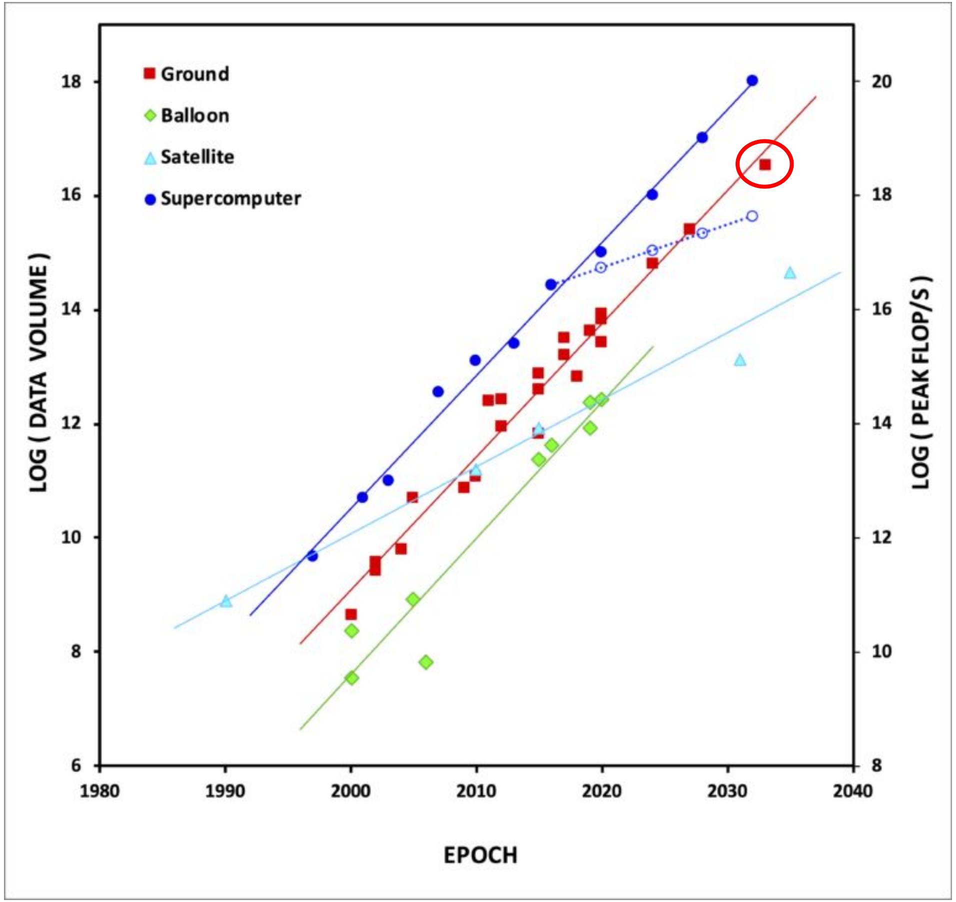
A typical CMB analysis pipeline (credits: J. Errard)

CMB Moore’s law

Moore’s law is ending, CMB data growth is not.

Computational needs: data transfer, storage, reduction, distribution.

Use new architectures, develop more efficient algorithms.

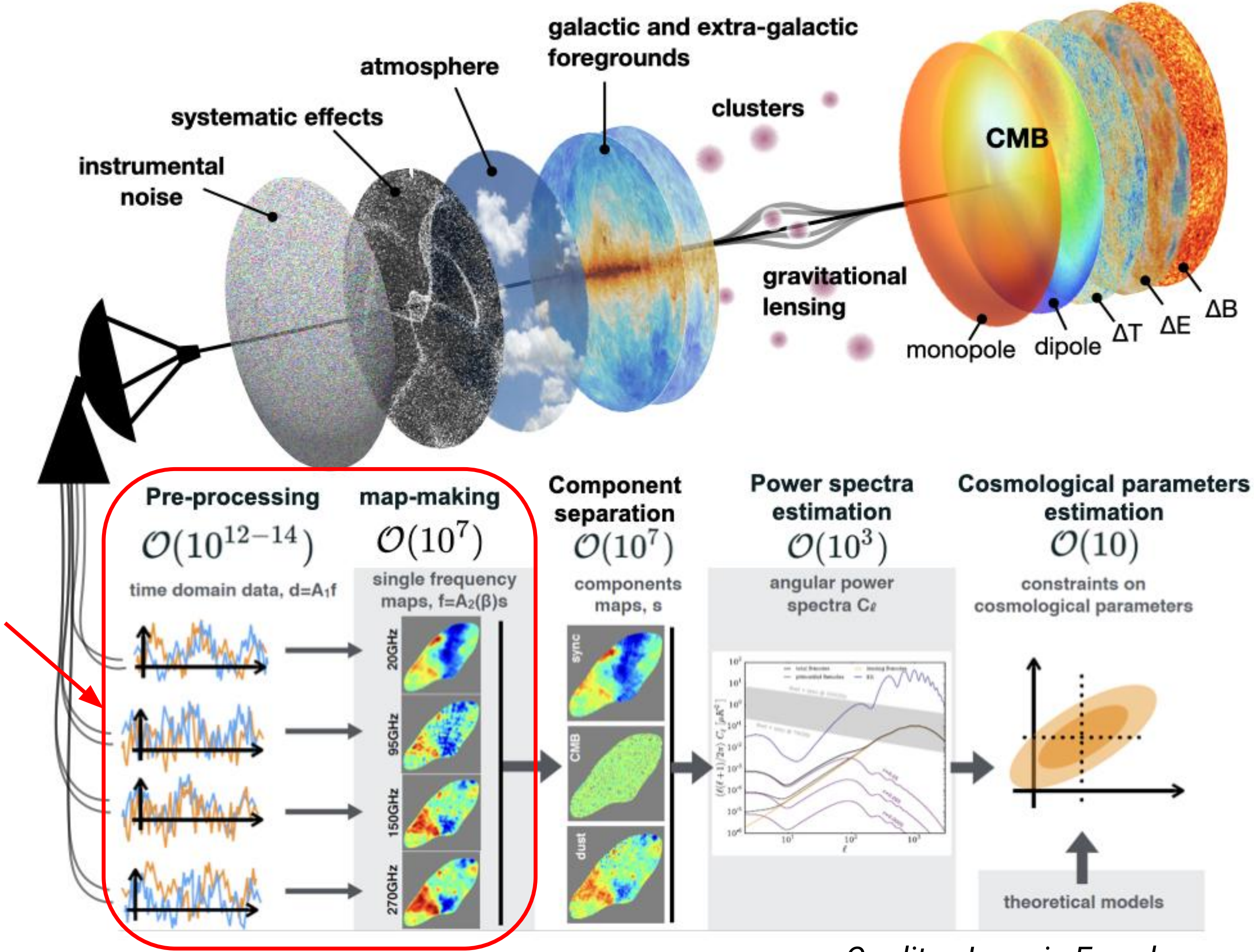


Credits: Julian Borrill

Map-making

map-making = from time-ordered data (TOD) to sky maps at observed frequencies

data <u>reduction</u> step: ~6 orders of magnitude



Credits: Josquin Errard

Simple data model

$$d = Pm + n$$

- d = time-ordered data (all detectors concatenated)
- P = pointing matrix (#samples × #pixels, but sparse)
- m = discretized sky signal (# pixels)
- n = stochastic contribution (noise)

Classic example without/with ideal HWP (no templates):

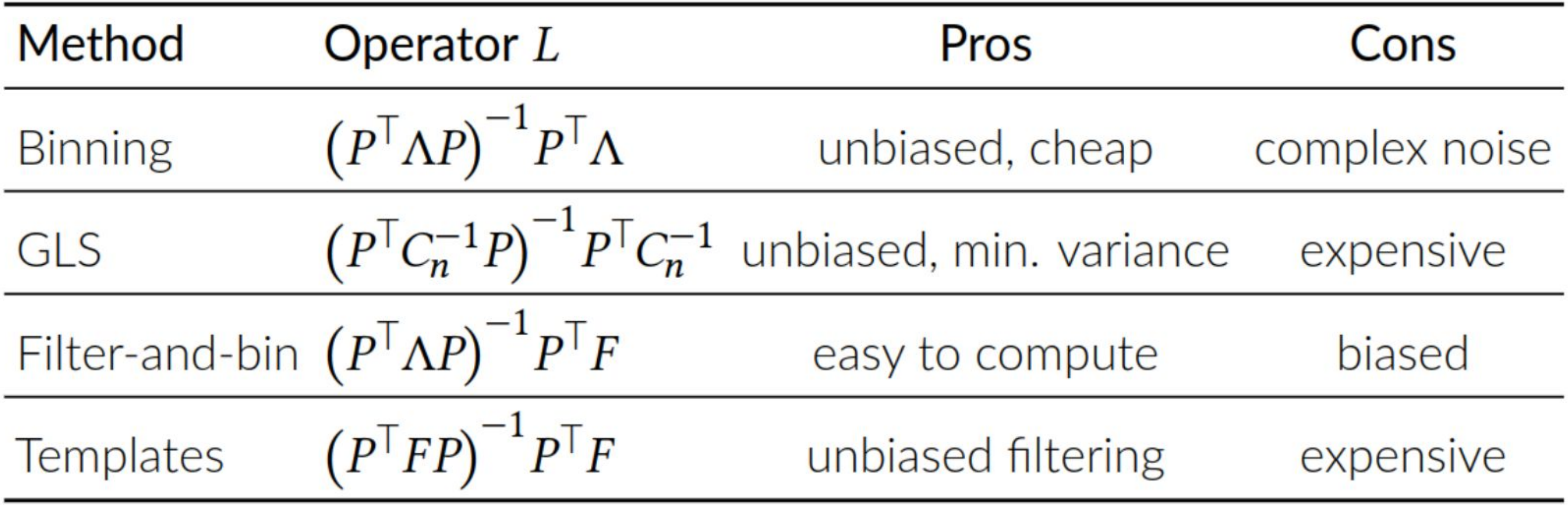
HWP modulation

$$d_t = I_{p_t} + \cos(2\varphi_t) Q_{p_t} + \sin(2\varphi_t) U_{p_t} + n_t$$

$$d_t = I_{p_t} + \cos(2\varphi_t + 4\phi_t) Q_{p_t} + \sin(2\varphi_t + 4\phi_t) U_{p_t} + n_t$$

Different methods for estimating the sky

sky estimate $m = Ld$ <-> linear operation on the TOD



Method	Operator L	Pros	Cons
Binning	$(P^\top \Lambda P)^{-1} P^\top \Lambda$	unbiased, cheap	complex noise
GLS	$(P^\top C_n^{-1} P)^{-1} P^\top C_n^{-1}$	unbiased, min. variance	expensive
Filter-and-bin	$(P^\top \Lambda P)^{-1} P^\top F$	easy to compute	biased
Templates	$(P^\top F P)^{-1} P^\top F$	unbiased filtering	expensive

Λ=diagonal weights, C_n=noise covariance, F=filtering operator

Generic data model

$$d = Pm + Tx + n$$

- m = sky signal
- P = pointing matrix
- columns of T = collection of time-domain templates
- x = template amplitudes
- n = noise (whatever is left)

→ scan-synchronous signal (ground pickup), etc.

Unbiased estimators

$$\hat{m} = \left(P^t F_T P\right)^{-1} P^t F_T d$$

Poletti et al. (2017)

with

$$F_T = W^{-1}\left(I - T(T^t W^{-1} T)^{-1} T^t W^{-1}\right)$$

a filtering and weighting operator which:

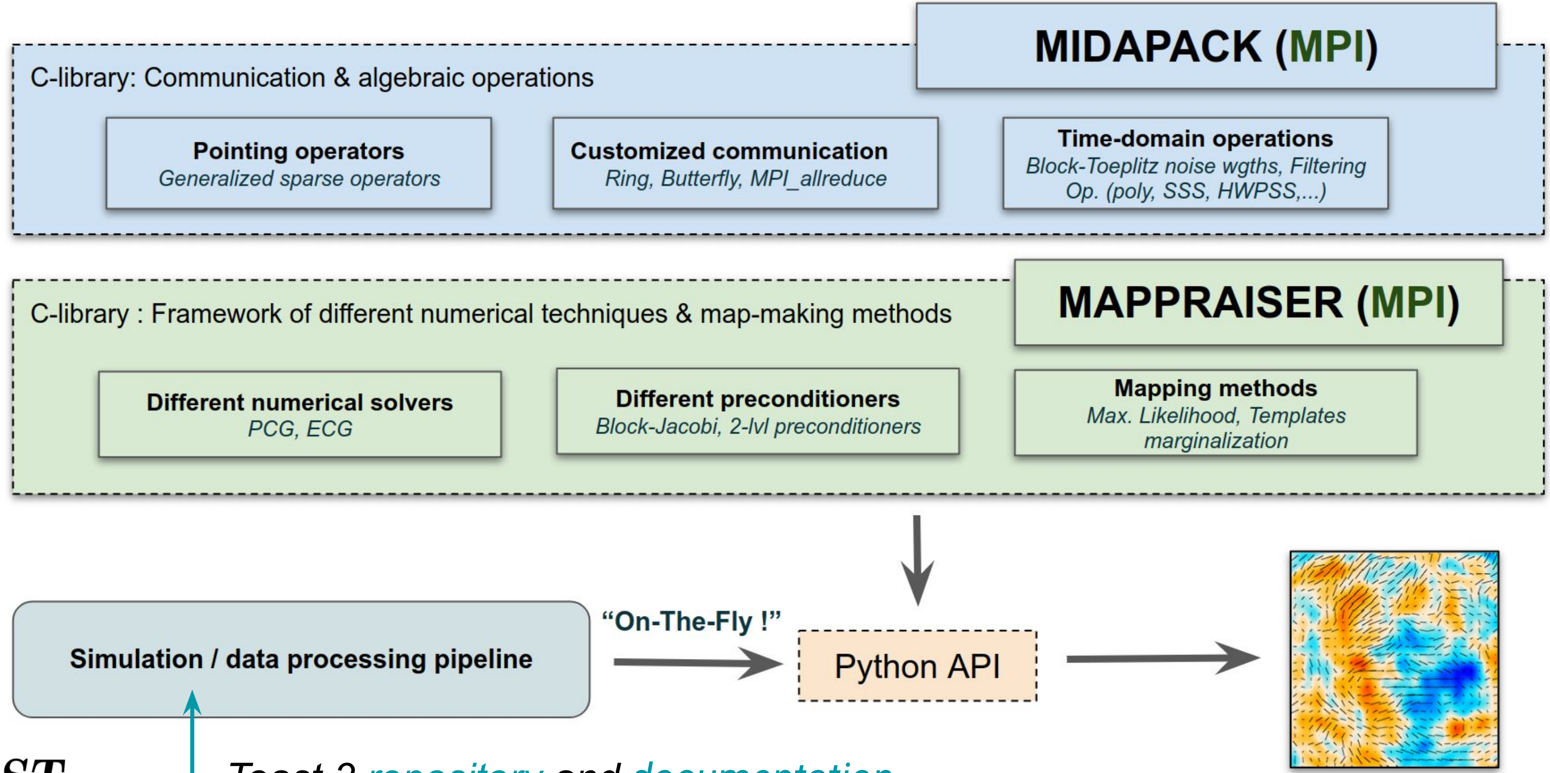
- filters out unwanted signals (linear combinations of columns of T)
- weights orthogonal modes by the weight matrix W

Compute $\hat{m}$ with an iterative solver such as a preconditioned conjugate gradient (PCG).

$Ax = b \leftrightarrow x = A^{-1}b$

Our implementation: MAPPRAISER

paper: El Bouhargani et al. (2022)
GitHub: B3DCMB/midapack



MIDAPACK (MPI)

C-library: Communication & algebraic operations

Pointing operators
Generalized sparse operators

Customized communication
Ring, Butterfly, MPI_allreduce

Time-domain operations
Block-Toeplitz noise wgths, Filtering Op. (poly, SSS, HWPSS,...)

MAPPRAISER (MPI)

C-library : Framework of different numerical techniques & map-making methods

Different numerical solvers
PCG, ECG

Different preconditioners
Block-Jacobi, 2-lvl preconditioners

Mapping methods
Max. Likelihood, Templates marginalization

Simulation / data processing pipeline

"On-The-Fly !"

Python API

TOAST

Toast 3 repository and documentation

Credits: Hamza El Bouhargani

2-lvl *a posteriori* preconditioner

$$M_{2lvl} = M_{BD}(I - AQ) + Q$$
$$Q = Z\left(Z^t AZ\right)^{-1} Z^t$$

Z = deflation matrix

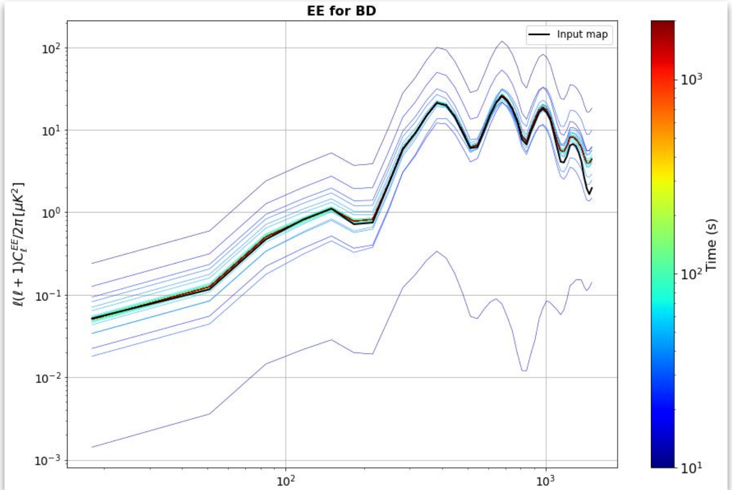
> built from eigenvectors of system matrix

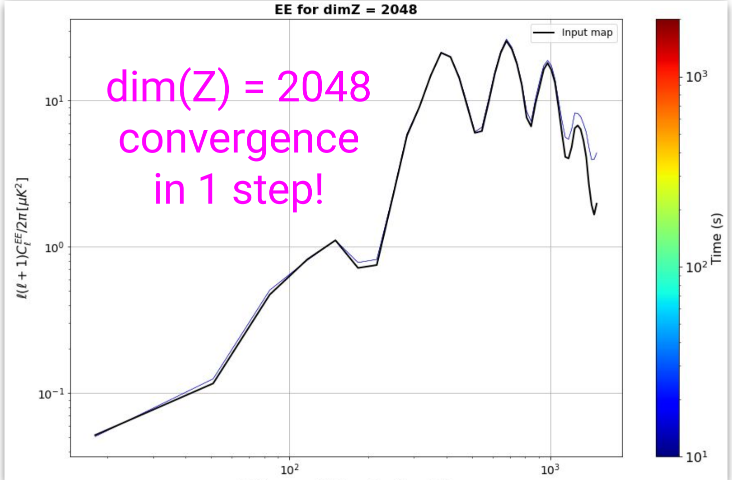
> useful for pixel-pixel covariance matrix

precomputation time ∝ dim *Z*

> reduction?

> [Puglisi et al. (2018)] [Papez et al. (2020)]





dim(Z) = 2048
convergence
in 1 step!

A toolbox for the SciPol project

> Modularity, extensibility, simplicity

```
h = pol @ rot @ hwp @ sampling
solution = ((h.T @ h).I @ h.T)(tod)
```

> Non-ideal optical components (@Ema)

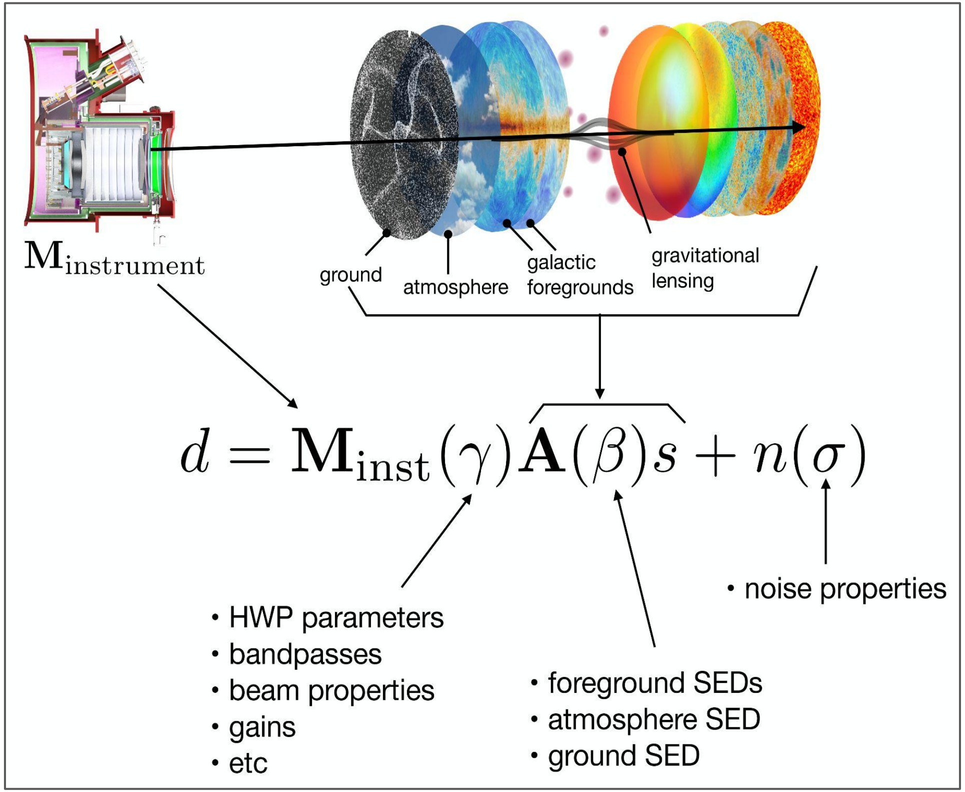
> JAX: Just In Time (JIT) compilation, run the same code anywhere

> 1st steps: “max-L” and “template” map-making (following MAPPRAISER’s formalism)

> Multi-GPU parallelization (soon)

> Framework for robust B-mode analysis

Attempt to tackle the problem mixing instrument+foregrounds+cosmology



$$d = \mathbf{M}_{\rm inst}(\gamma)\overbrace{\mathbf{A}(\beta)s} + n(\sigma)$$

- HWP parameters
- bandpasses
- beam properties
- gains
- etc

- foreground SEDs
- atmosphere SED
- ground SED

- noise properties

Credits: Josquin Errard

Conclusion

CMB can probe the primordial SGWB at very low frequencies through its imprints on the polarization signal (“B modes”).

Many inflation models will be tested in the next 10-15 years, as we push constraints on r to $\lesssim$ 10^-3 (stay tuned for SO results!)

Complementarity between CMB, pulsar timing & interferometry will help us distinguish different models by covering many decades in frequency.

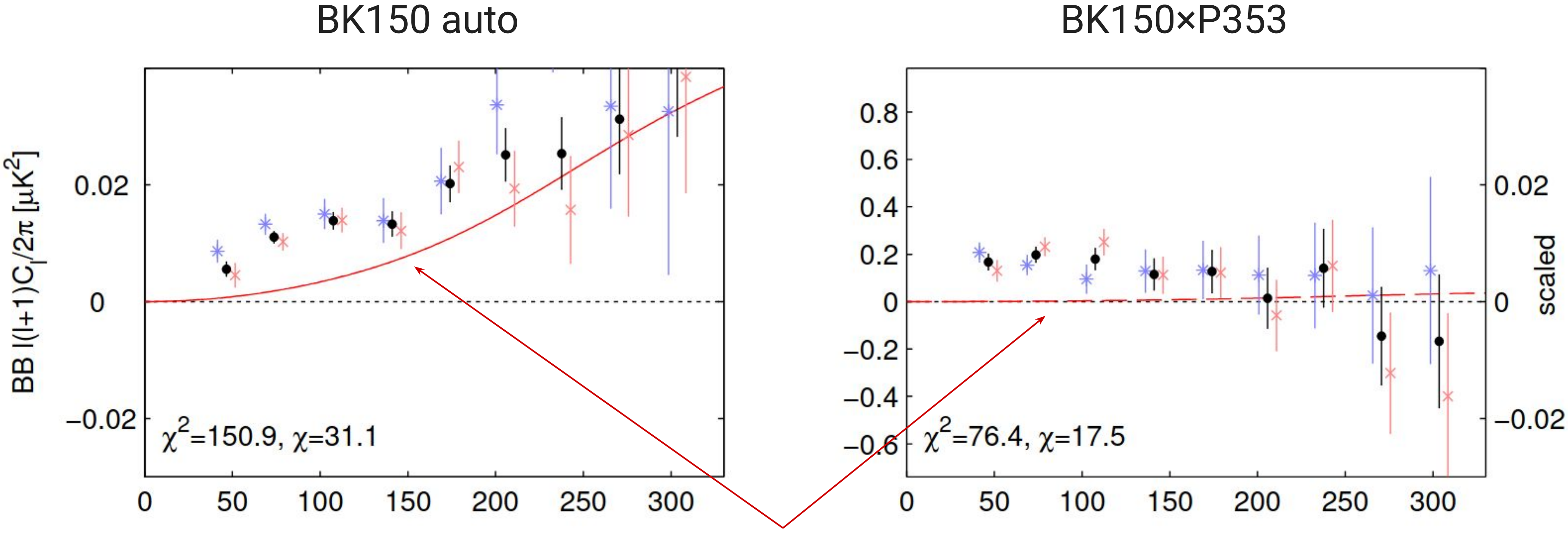
Many observational challenges to analyze the data efficiently and reliably.

With SciPol we hope to build a robust analysis framework, taking into account instrumental and systematic effects.

Backup slides

BICEP + Planck analysis

From Figure 2 of
BKP (2015)



lensed-ΛCDM expectation

BICEP + Planck analysis

Figure 6 of
BKP (2015)

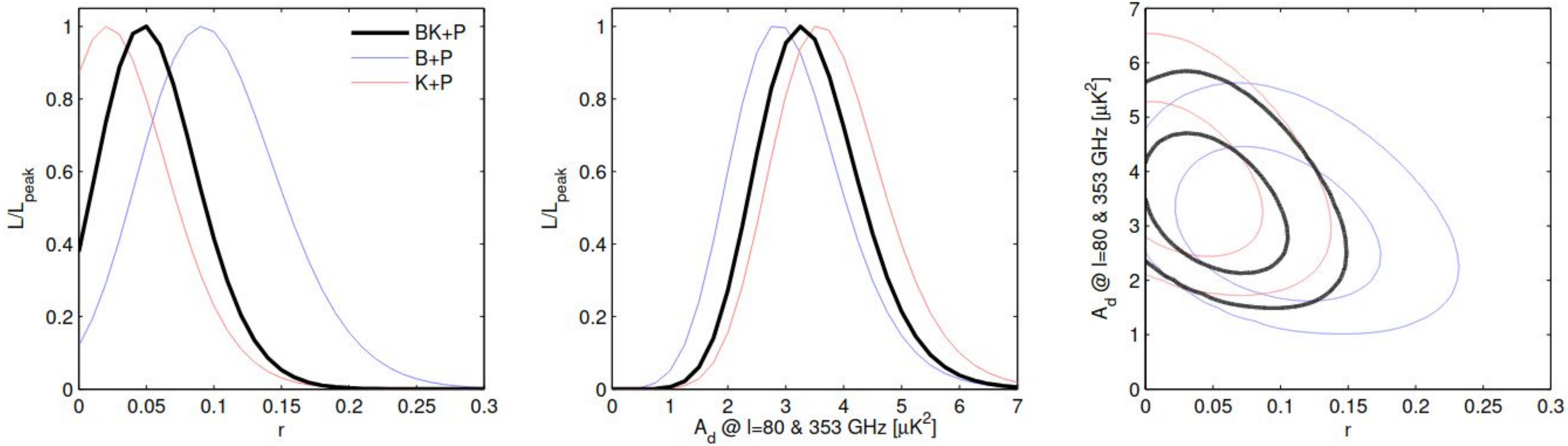
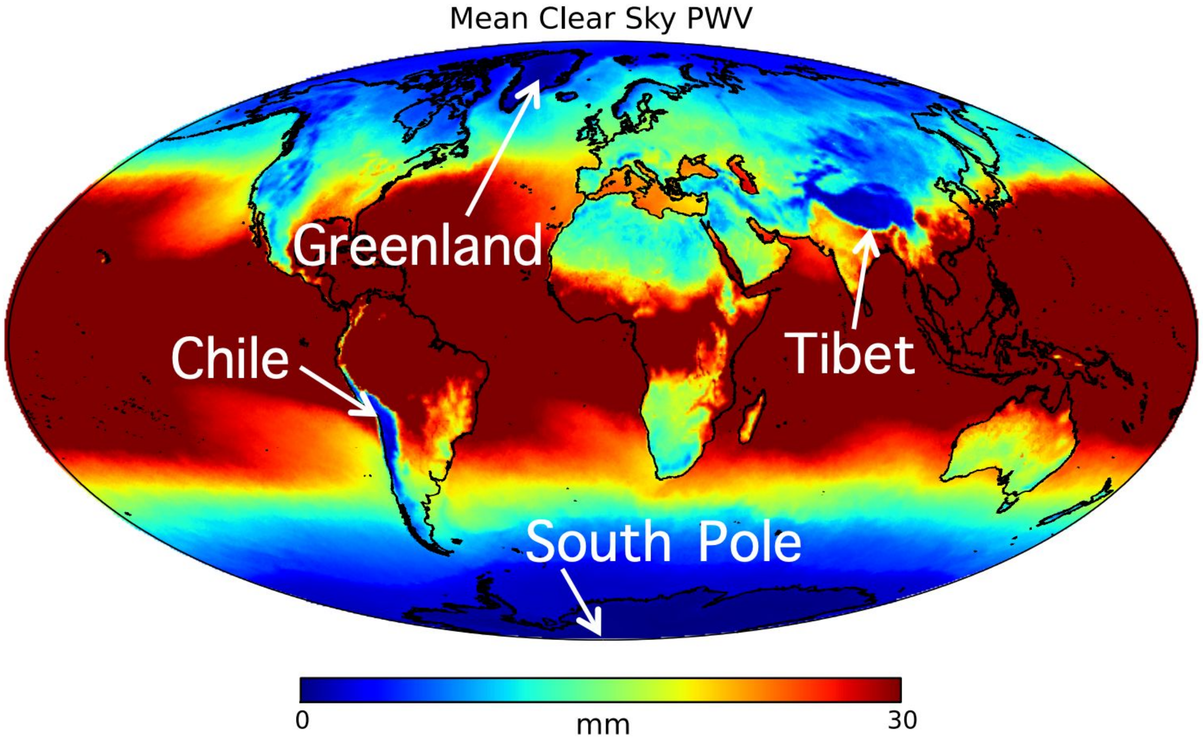
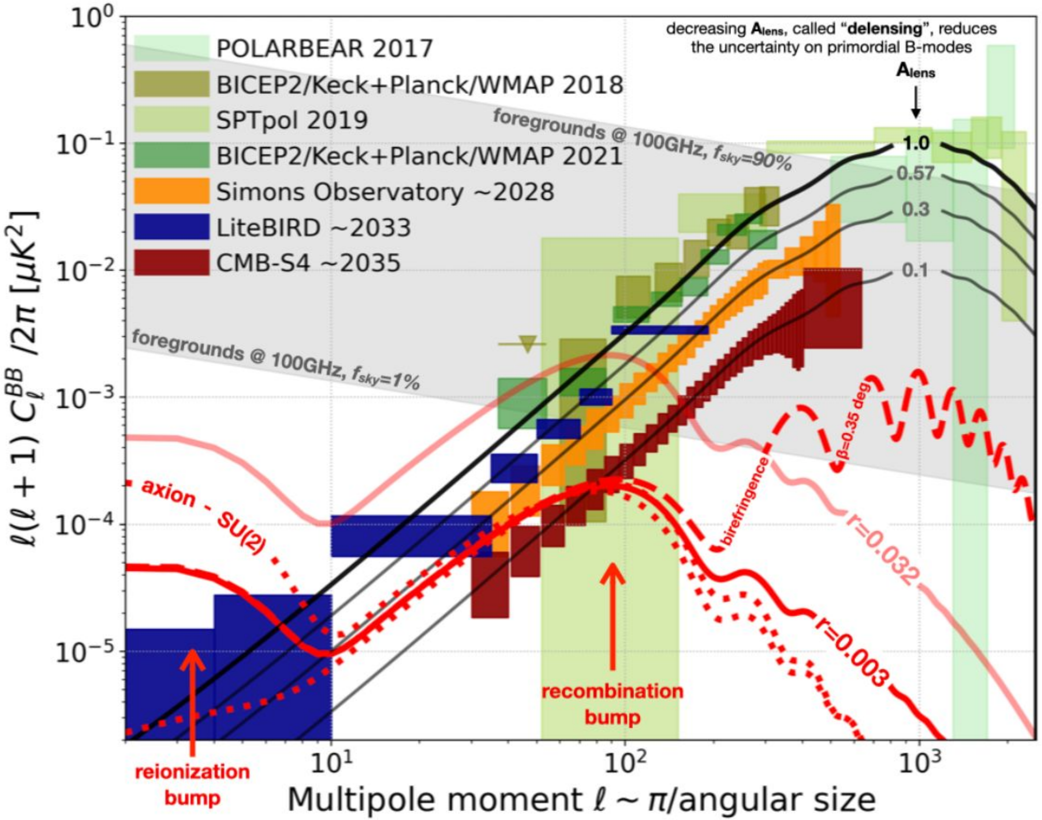


FIG. 6. Likelihood results from a basic lensed-ΛCDM+r+dust model, fitting BB auto- and cross-spectra taken between maps at 150 GHz, 217, and 353 GHz. The 217 and 353 GHz maps come from *Planck*. The primary results (heavy black) use the 150 GHz combined maps from BICEP2/*Keck*. Alternate curves (light blue and red) show how the results vary when the BICEP2 and *Keck Array* only maps are used. In all cases a Gaussian prior is placed on the dust frequency spectrum parameter $\beta_d = 1.59 \pm 0.11$. In the right panel the two dimensional contours enclose 68% and 95% of the total likelihood.

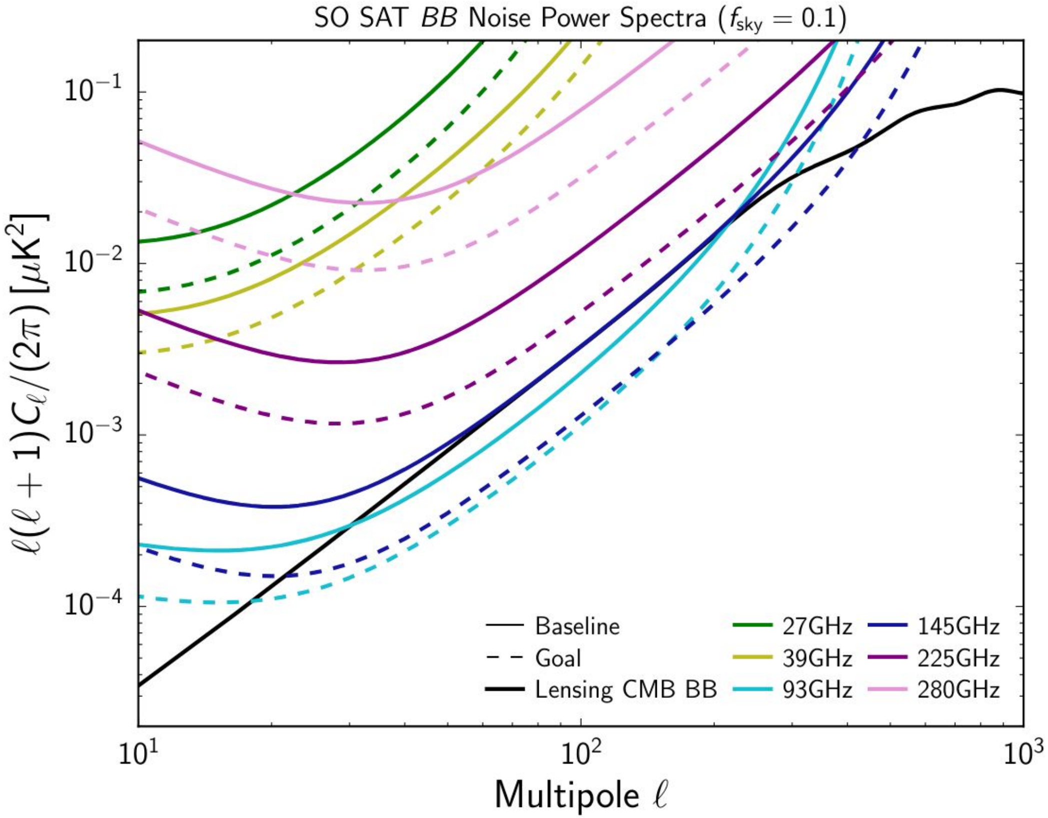
Where to put a CMB experiment ?



Current and forecasted error bars on BB

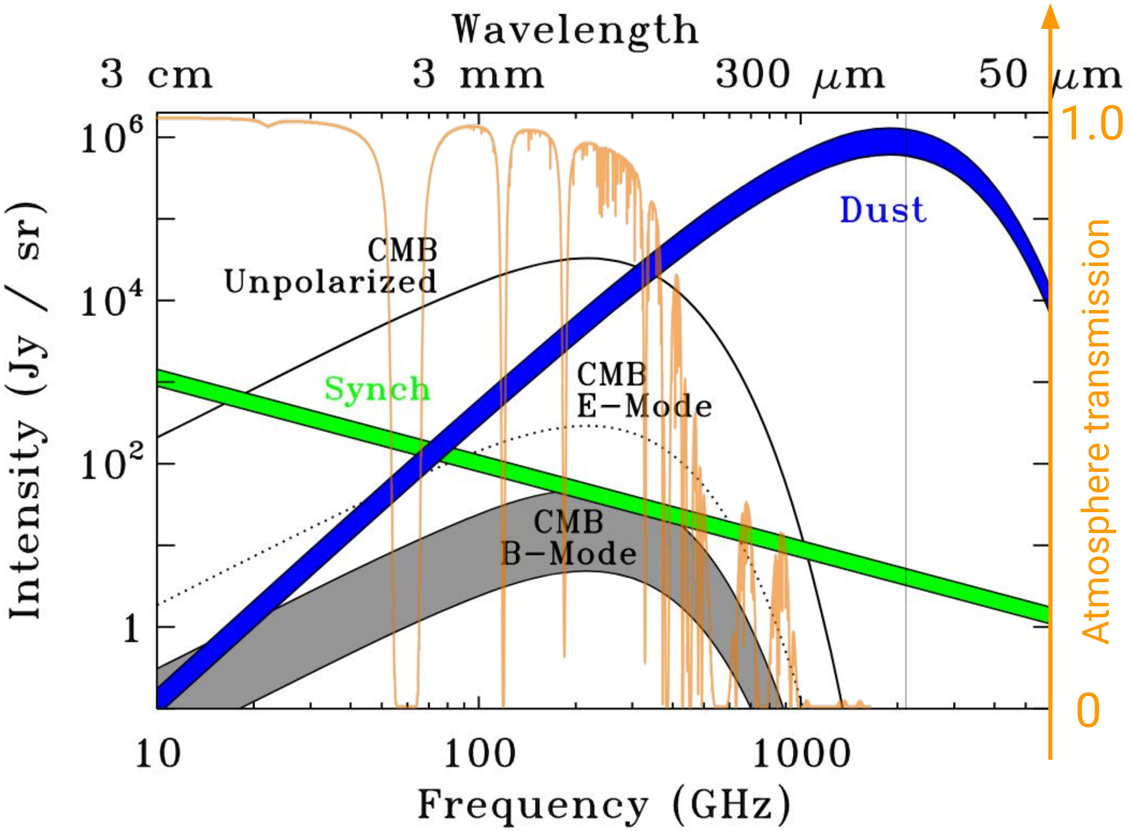


Forecasted SAT noise power spectra (BB)



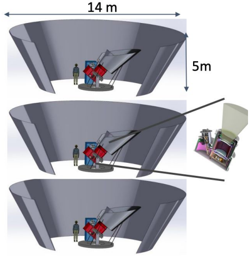
SO Science Goals and Forecasts

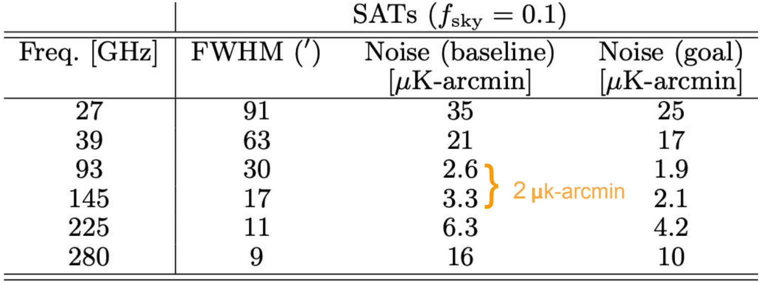
Astrophysical foregrounds for CMB polarization



Adapted from Kogut et al. (2016)
Credits: J. Errard

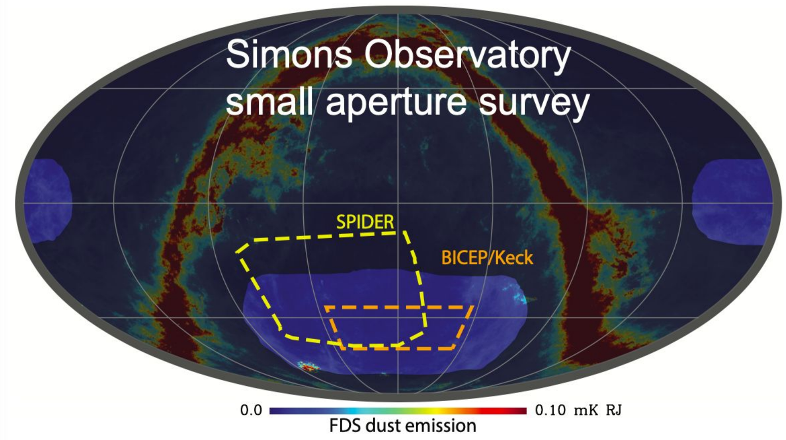
SO Surveys

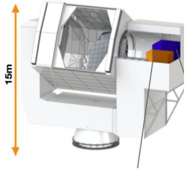


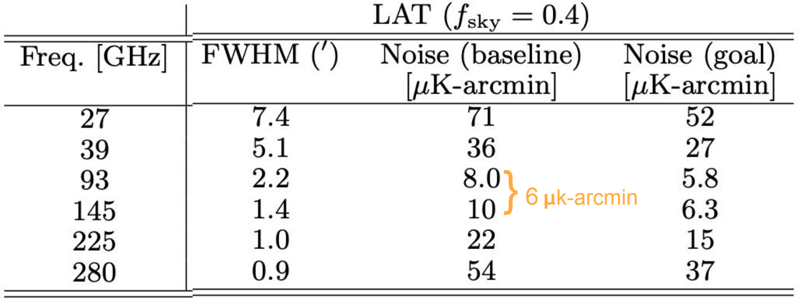


	SATs ($f_{\mathrm{sky}} = 0.1$)		
Freq. [GHz]	FWHM ($'$)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
27	91	35	25
39	63	21	17
93	30	2.6	1.9
145	17	3.3	2.1
225	11	6.3	4.2
280	9	16	10

} 2 μk-arcmin

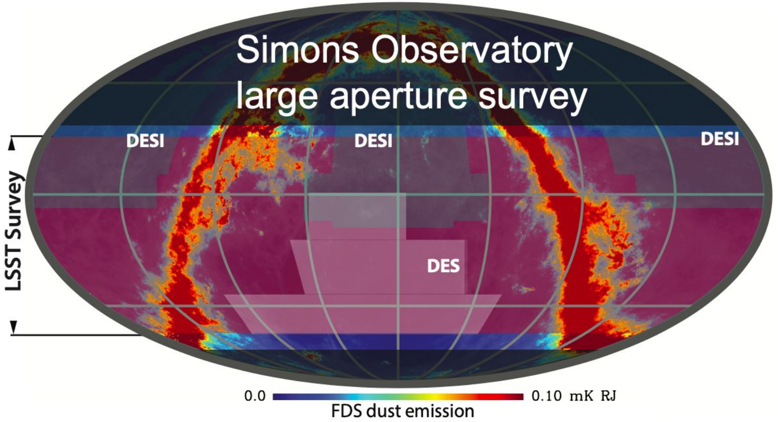






	LAT ($f_{\mathrm{sky}} = 0.4$)		
Freq. [GHz]	FWHM ($'$)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
27	7.4	71	52
39	5.1	36	27
93	2.2	8.0	5.8
145	1.4	10	6.3
225	1.0	22	15
280	0.9	54	37

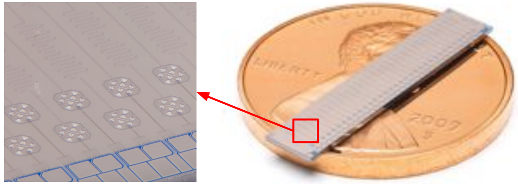
} 6 μk-arcmin



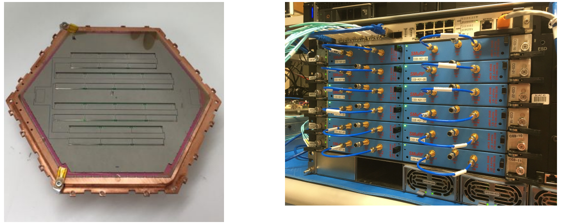
From June, 2020 SO+LSS Zoomference

Simons Observatory Readout and Detectors (1/1)

Readout: SO is developing the microwave SQUID multiplexing (umux) readout with a 1000x multiplexing factor in collaboration with SLAC (warm electronics) and NIST (cold).

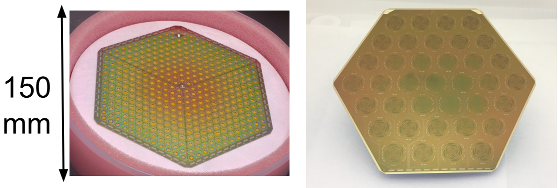


uMux readout channels (left) and NIST uMUX chip with 66 channels (right)

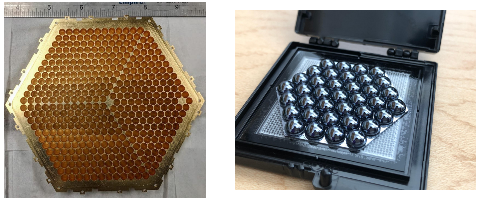


Prototype SO cold readout module with 1848 readout channels (left). SMuRF warm electronics with 12,000 tones (right).

Detectors: SO will use dual-polarization, dichroic TES bolometer detectors spanning 27 - 270 GHz. Each mid-frequency (MF) and high-frequency (HF) array contains ~1700 detectors, with >60,000 detectors total.

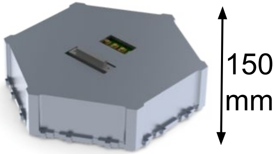


SO MF detector array (left) and LF array (right)

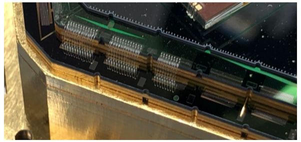


Horn array (left) and lenslet (right) optical coupling for the MF and UFM detector arrays and LF detector array, respectively.

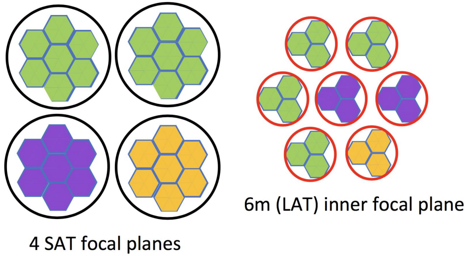
Focal plane design: the universal focal-plane modules, common to both the SATs and LATR, contain the cold readout, detectors, and optical coupling (MF/UHF: horns, LF: lenslets).



universal focal plane (UFM) module



focal plane module detail showing side of horn array, detector stack, and readout.



UFM distribution in the four SATs and LATR.