The Simons Observatory
and a new framework to constrain cosmic birefringence

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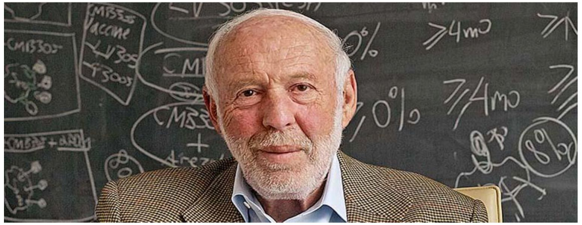
Supervisors : Radek Stompor, Josquin Errard

CMB-France
November 15th, 2021

Simons Observatory (SO)

SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION



SIMONS OBSERVATORY
22°57'31" SOUTH, 67°47'15" WEST
ELEVATION: 17,027.6'
PARQUE ASTRONÓMICO ATACAMA, CHILE

Summer 2019, F2F meeting

Construction of nominal project is funded privately and has already begun. >200 collaborators

Member Institutions

10 Countries
40+ Institutions
306 Researchers

Europe

- **APC – France**
- **IJClab – France**
- Cambridge University
- Cardiff University
- Imperial College
- Manchester University
- Oxford University
- SISSA – Italy
- University of Sussex
- Stockholm University

Middle East

- Tel Aviv

United States

- Arizona State University
- Carnegie Mellon University
- Center for Computational Astrophysics
- Cornell University
- Florida State
- Haverford College
- Lawrence Berkeley National Laboratory
- NASA/GSFC
- NIST
- Princeton University
- Rutgers University
- Stanford University/SLAC
- Stony Brook
- University of California - Berkeley
- University of California – San Diego
- University of Michigan
- University of Pennsylvania
- University of Pittsburgh
- University of Southern California
- West Chester University
- Yale University

Australia

- Melbourne

Canada

- CITA/Toronto
- Dunlap Institute/Toronto
- McGill University
- Perimeter Institute
- University of British Columbia

Japan

- KEK
- IPMU
- Tohoku
- Tokyo
- Kyoto

Chile

- Pontificia Universidad Catolica
- University of Chile

South Africa

- Kwazulu-Natal, SA

French participation

Graduate students:

- Dominic Beck (2016-2019)
- Clara Vergès (2017-2020)
- Hamza El Bouhargani
- Baptiste Jost

Joining students:

- Magdy Morshed
- Arianna Rizzieri
- Raphaël Kou

Permanent researchers:

- James Bartlett (Collaboration Council Oversight Committee)
- Josquin Errard (co-lead of the BB WG, member of TAC)
- Ken Ganga (Talks panel)
- Jean-Baptiste Melin
- Radek Stompor (Membership panel)

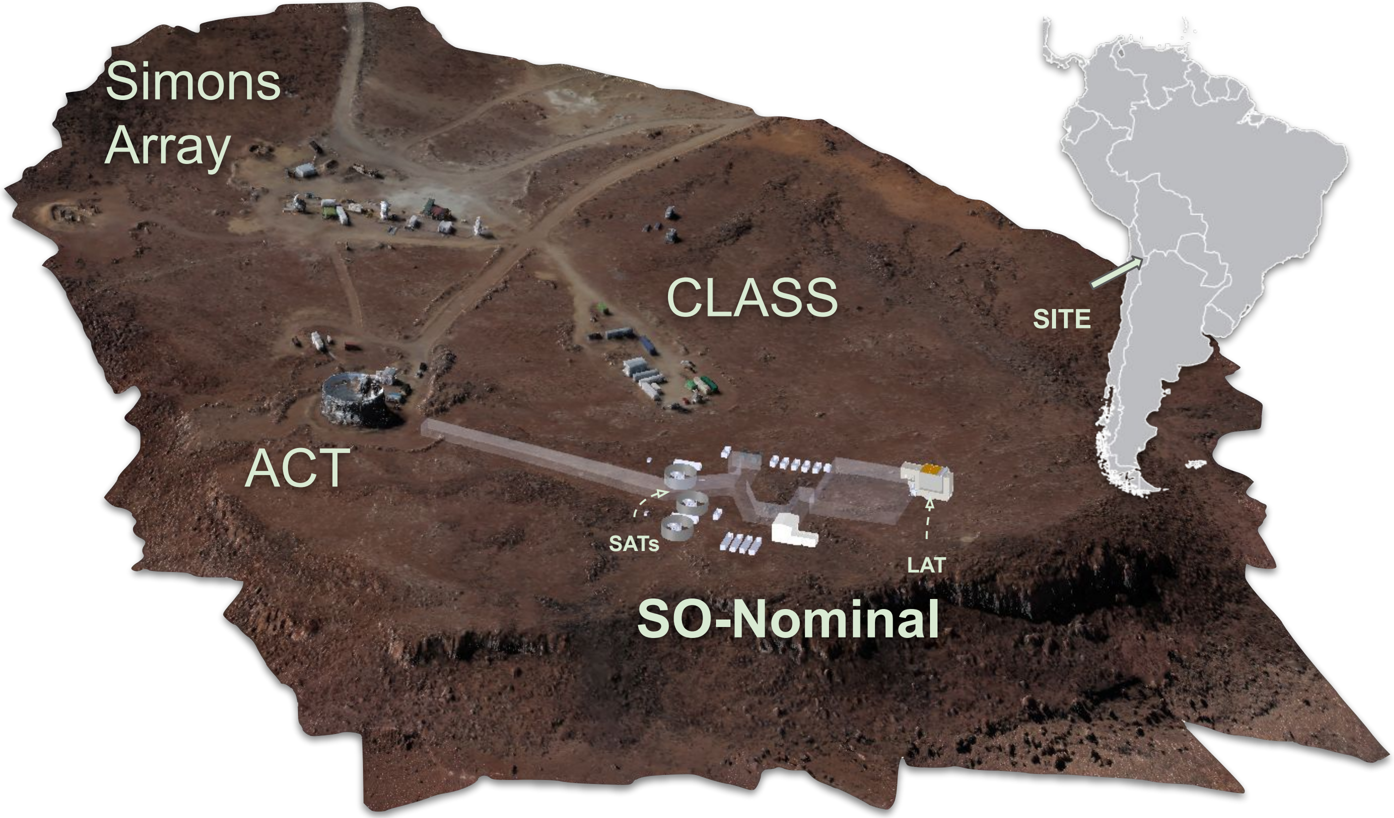
Graduate students:

- Adrien La Posta

Permanent researchers:

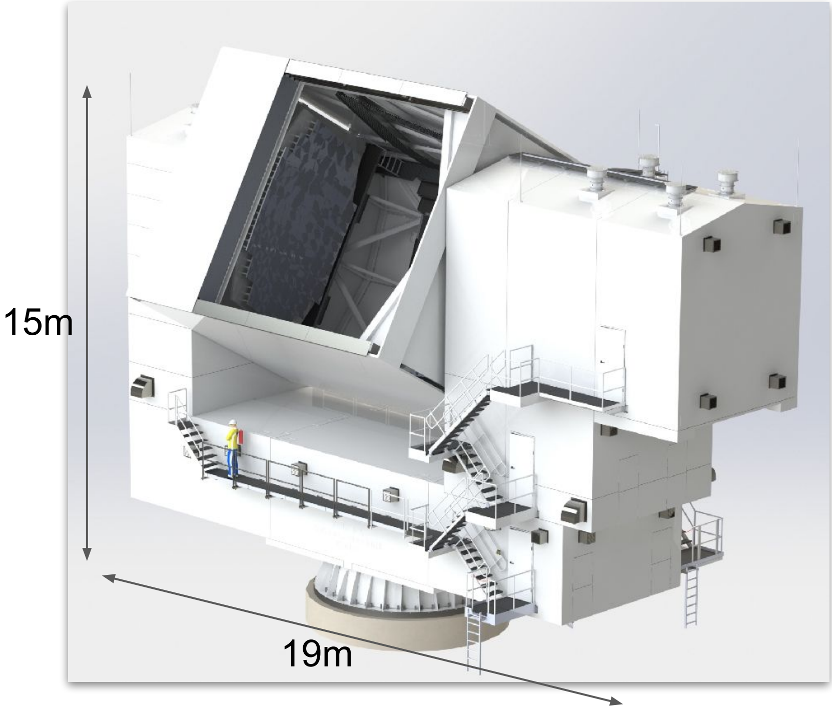
- Thibaut Louis (co-lead of PS WG)
- Xavier Garrido (co-lead of PS WG)

SO Site in Chile: Next to Existing Telescopes



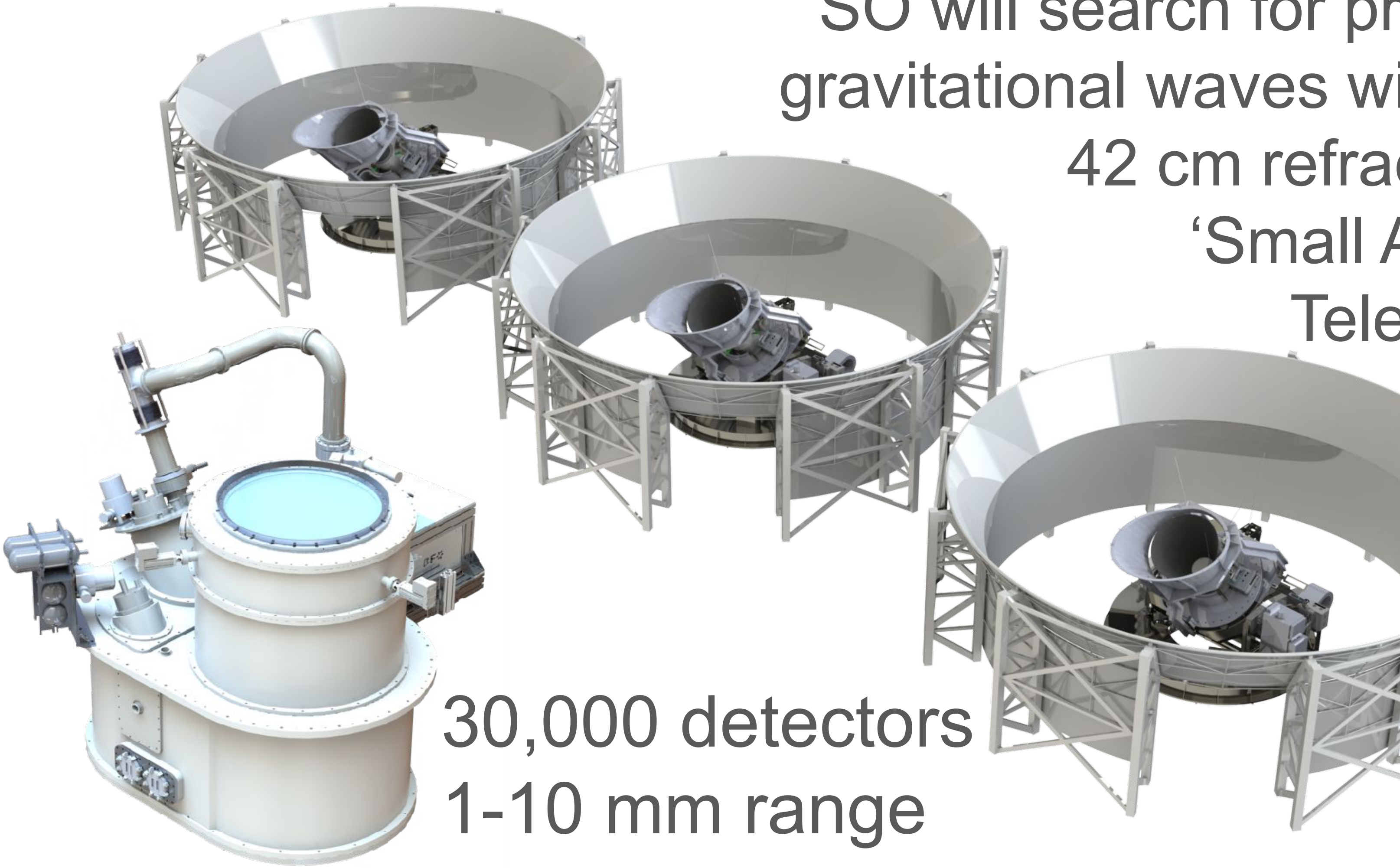
- 5,200 meters
- high and dry
- 23 degree South Latitude
- Established site
- Room for expansion

SO Construction is Underway



- 6-meter-primary mirror
- Detectors measure 6 wavelength bands: 1-10 mm (30-280 GHz)
- >30,000 Transition Edge Sensor detectors
- Arcmin resolution

SO will search for primordial gravitational waves with three 42 cm refractors, or 'Small Aperture Telescopes'



30,000 detectors
1-10 mm range

Recent developments :

Germany, November 3rd

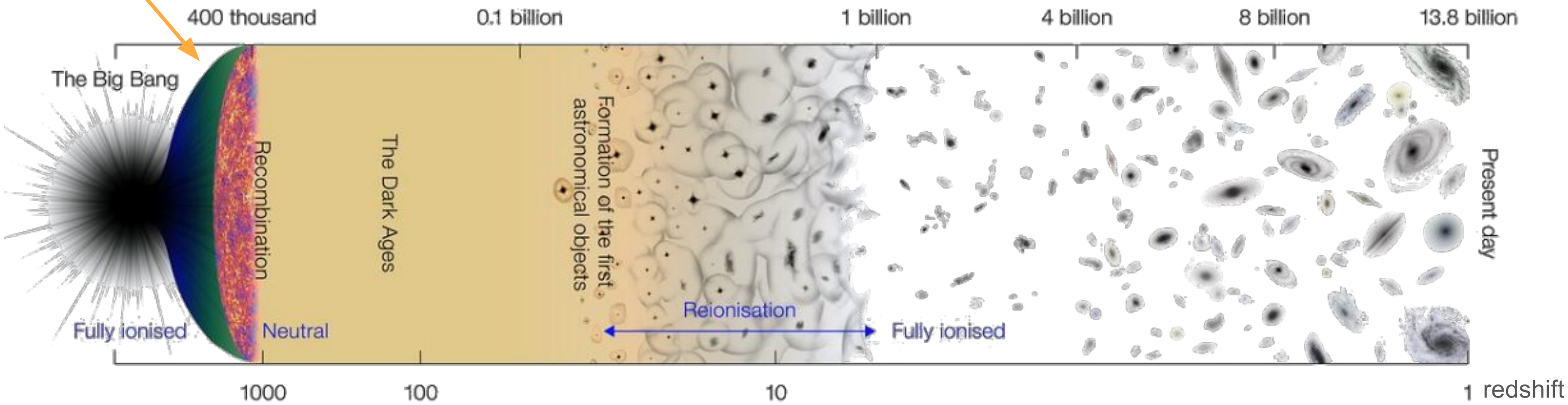
Chile, November 10th

SO Addresses Key Cosmological and Astrophysics Questions

- **Dark matter :** CMB lensing probes
- **Feedback and IGM :** KSZ and TSZ. With LSS surveys can be a novel probe of the inter cluster medium and feedback

- Variable radio sky
- Search for Planet 9
- Galactic Science (Hensley et al 2021)
  - Legacy arcmin-resolution millimeter-wave sky maps
  - Map of large-scale distribution of magnetic fields in the Galaxy

- Gravitational waves, shape of primordial spectrum, non-Gaussianity
- CMB fluctuations sensitive to many possible dark matter properties
- Cosmological model



Credit : ESO

SO Science Goals

From: The Simons Observatory: science goals and forecasts

Peter Ade, et al., JCAP02 (2019) 056

	Parameter	SO-Baseline[a] (no syst)	**SO-Baseline[b]**	SO-Goal[c]	Current[d] (2018-19)	Method	Sec.
Primordial	r	0.0024	**0.003**	0.002	0.03	BB + ext delens	3.4
perturbations	$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	0.4%	**0.5%**	0.4%	3%	$TT/TE/EE$	4.2
	$f_{\mathrm{NL}}^{\mathrm{local}}$	1.8	**3**	1	5	$\kappa\kappa \times$ LSST-LSS + 3-pt	5.3
		1	**2**	1		kSZ + LSST-LSS	7.5
Relativistic species	N_{eff}	0.055	**0.07**	0.05	0.2	$TT/TE/EE + \kappa\kappa$	4.1
Neutrino mass	Σm_ν	0.033	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO	5.2
		0.035	**0.04**	0.03		tSZ-N $\times$ LSST-WL	7.1
		0.036	**0.05**	0.04		tSZ-Y + DESI-BAO	7.2
Deviations from Λ	$\sigma_8(z=1-2)$	1.2%	**2%**	1%	7%	$\kappa\kappa$ + LSST-LSS	5.3
		1.2%	**2%**	1%		tSZ-N $\times$ LSST-WL	7.1
	H_0 (ΛCDM)	0.3	**0.4**	0.3	0.5	$TT/TE/EE + \kappa\kappa$	4.3
Galaxy evolution	η_{feedback}	2%	**3%**	2%	50-100%	kSZ + tSZ + DESI	7.3
	p_{nt}	6%	**8%**	5%	50-100%	kSZ + tSZ + DESI	7.3
Reionization	Δz	0.4	**0.6**	0.3	1.4	TT (kSZ)	7.6

[a] This column reports forecasts from earlier sections (in some cases using 2 s.f.) and applies no additional systematic error.

[b] This is the nominal forecast, increases the column (a) uncertainties by 25% as a proxy for instrument systematics, and rounds up to 1 s.f.

[c] This is the goal forecast, has negligible additional systematic uncertainties, and rounds to 1 s.f.

[d] Primarily from [44] and [287].

[44] BICEP2 and Planck collaborations, Joint Analysis of BICEP2/Keck Array and Planck Data, Phys. Rev. Lett. 114 (2015) 101301
[287] Planck collaboration, Planck 2018 results. VI. Cosmological parameters

Table 9. Summary of SO key science goals. All of our SO forecasts assume that SO is combined with *Planck* data.

SO Schedule as of 2021

Timeline

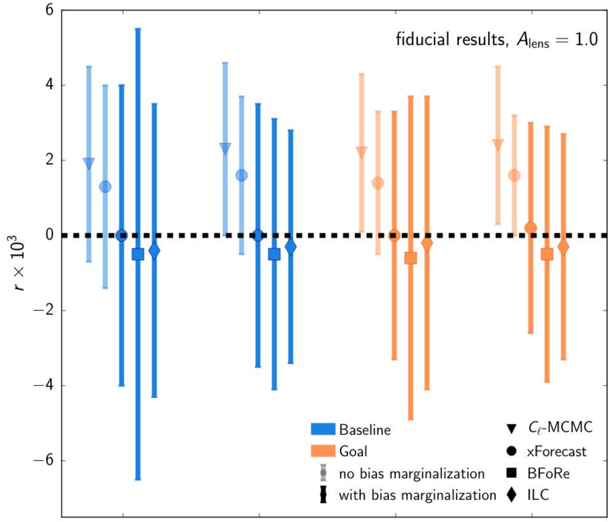
Early ‘21	Mid ‘22	Early ‘23	Mid ‘24
Testing and integration, optical validation	First light for both SAT + LAT	**First** science observations expected	**Full** science observations expected

SAT science : r and birefringence

- We aim at σ(r) ≃ 0.003 without delensing
- Several pipelines are being developed
- Current data challenge to test them

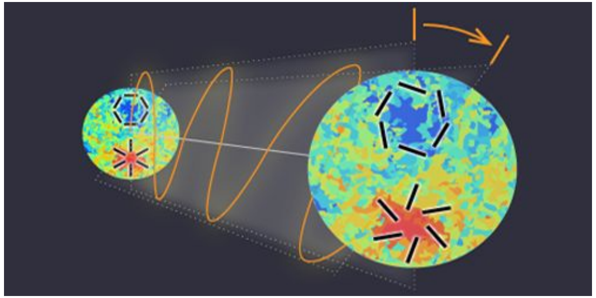
- I generalised parametric component separation (Stompor et al 2016: fgbuster) in order to constrain cosmic birefringence in the presence of foregrounds and instrumental systematic effects

	Method	SO Baseline pess-1/f	SO Baseline opt-1/f	SO Goal pess-1/f	SO Goal opt-1/f
$A_{\rm lens}=1$	C_ℓ-Fisher	$\sigma=2.4$	$\sigma=1.9$	$\sigma=1.7$	$\sigma=1.5$
	C_ℓ-MCMC	1.9 ± 2.6	2.3 ± 2.3	2.2 ± 2.1	2.4 ± 2.1
	xForecast	1.3 ± 2.7	1.6 ± 2.1	1.4 ± 1.9	1.6 ± 1.6
	xForecast[b]	0.0 ± 4.0	0.0 ± 3.5	0.0 ± 3.3	0.2 ± 2.8
	BFoRe[b]	-0.5 ± 5.8	-0.5 ± 3.6	-0.6 ± 4.3	-0.5 ± 3.4
	ILC[b]	-0.4 ± 3.9	-0.3 ± 3.1	-0.2 ± 3.9	-0.3 ± 3.0
$A_{\rm lens}=0.5$	C_ℓ-Fisher	$\sigma=1.8$	**$\sigma=1.4$**	$\sigma=1.2$	$\sigma=0.9$
	C_ℓ-MCMC	1.7 ± 2.1	**2.2 ± 2.0**	2.0 ± 1.7	2.2 ± 1.7
	xForecast	1.3 ± 2.1	**1.6 ± 1.5**	1.3 ± 1.3	1.5 ± 1.0
	xForecast[b]	0.1 ± 3.2	**0.1 ± 2.6**	0.0 ± 2.5	0.3 ± 1.8
	BFoRe[b]	-0.2 ± 5.0	**-0.4 ± 2.6**	-0.6 ± 3.2	-0.5 ± 2.0
	ILC[b]	-0.3 ± 3.0	**-0.3 ± 2.4**	-0.1 ± 2.8	-0.2 ± 2.3



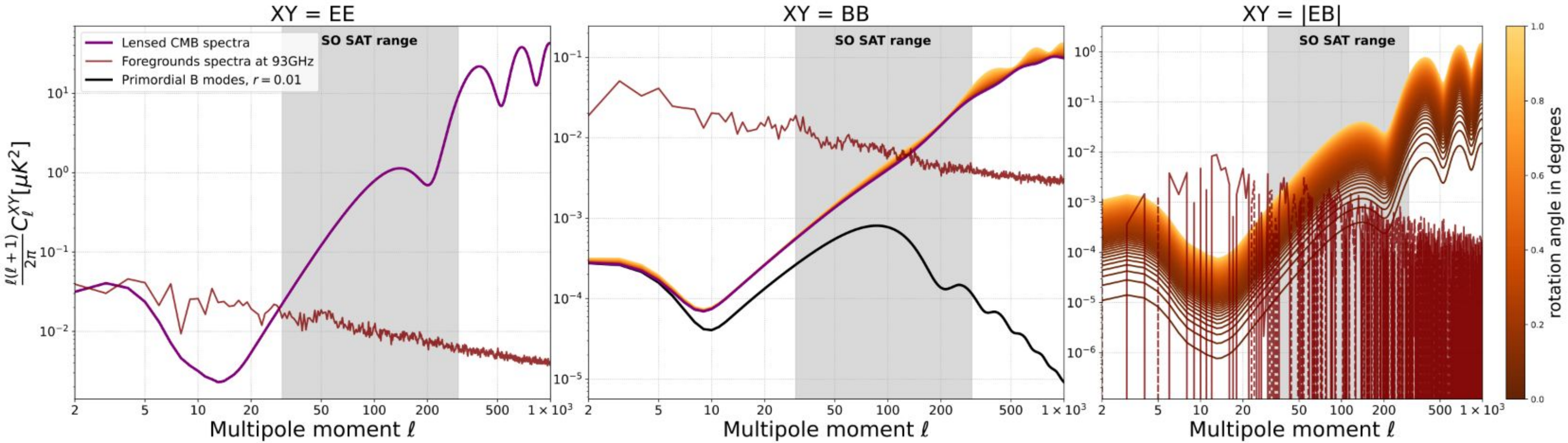
Credit : SO science goals and forecast 2019

Cosmic birefringence



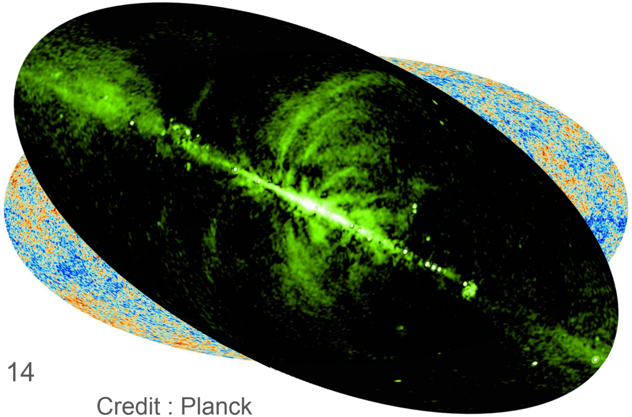
Credit : Minami / Keck

- Birefringence generates non-zero EB
- Could be a hint of photon/axion interaction
- More generally : Chern simons effect or parity violating interactions

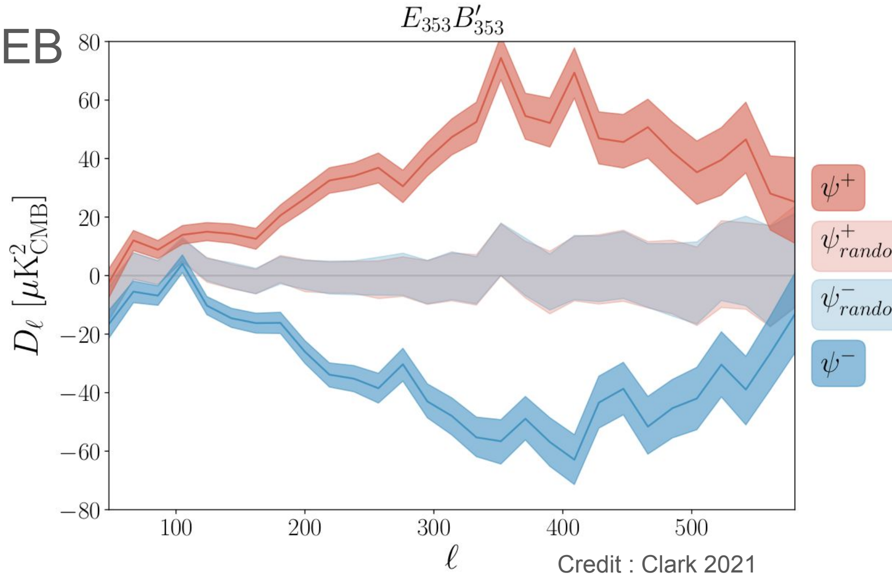


The polarisation angle of the telescope problem

- Miscalibration of the polarisation angle of the telescope degenerate with birefringence angle
- Lift the degeneracy : Minami, Komatsu 2020 uses foregrounds
- Vanishing EB foregrounds spectrum is assumed to fit for miscalibration
- Hint of non-zero birefringence angle β=0.35 ± 0.14° from Planck data
- Clark et al 2021 : non-zero foregrounds EB



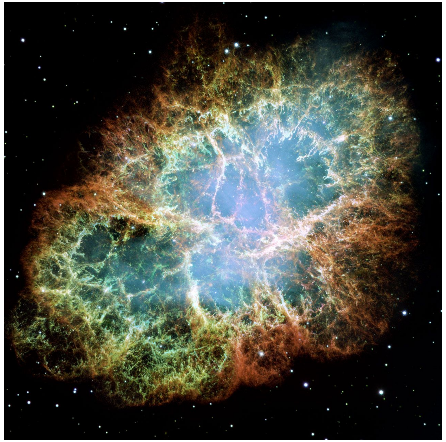
Credit : Planck



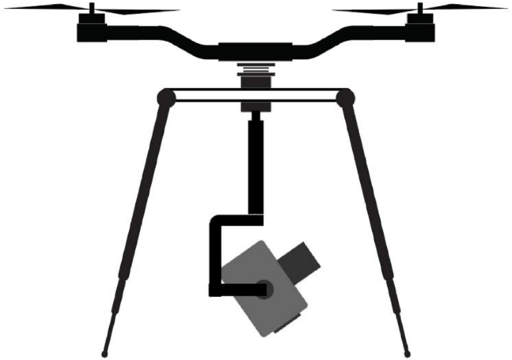
Credit : Clark 2021

Foreground cleaning and instrumental effects

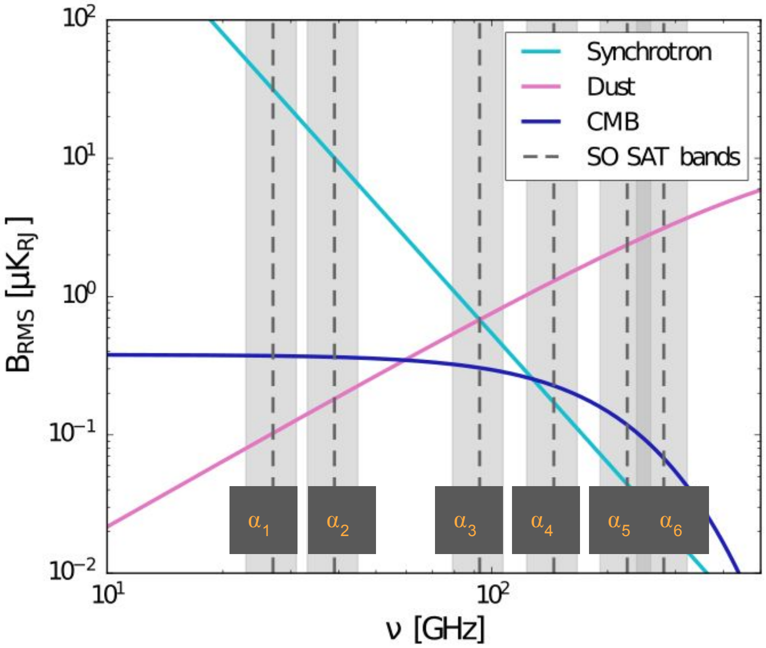
- We develop a method which is agnostic wrt foregrounds EB and uses calibration priors to lift degeneracy.
  - Tau A measurements $\sigma(\alpha) \simeq 0.27°$ (Aumont et al 2020)
  - Wire grid on top of the window $\sigma(\alpha) \simeq 1 - 0.2°$ (Bryan et al 2018)
  - Drone $\sigma(\alpha) \simeq 0.1 - 0.01°$ (Nati et al 2017)
- Frequency dependence of signals
  - Propagation of prior informations



credit : Nasa/Hubble



credit : Nati 2017



credit : SO science goals and forecast

Data model

Miscalibration matrix

$$X(\{\alpha_1, ..., \alpha_n\}) = \begin{pmatrix} cos(2\alpha_1) & sin(2\alpha_1) & & & 0 \\ -sin(2\alpha_1) & cos(2\alpha_1) & & & \\ & & \ddots & & \\ & & & cos(2\alpha_n) & sin(2\alpha_n) \\ 0 & & & -sin(2\alpha_n) & cos(2\alpha_n) \end{pmatrix}$$

Birefringence matrix

$$B(\{\beta_b\}) = \begin{pmatrix} cos(2\beta_b) & sin(2\beta_b) & 0 & 0 & 0 & 0 \\ -sin(2\beta_b) & cos(2\beta_b) & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$d_p = X(\{\alpha_1, ..., \alpha_n\}).A_p(\{\beta_{fg}\}).B(\{\beta_b\}).s_p + n_p$$

$$d_p = \begin{pmatrix} Q_1 \\ U_1 \\ \vdots \\ Q_n \\ U_n \end{pmatrix}_p$$

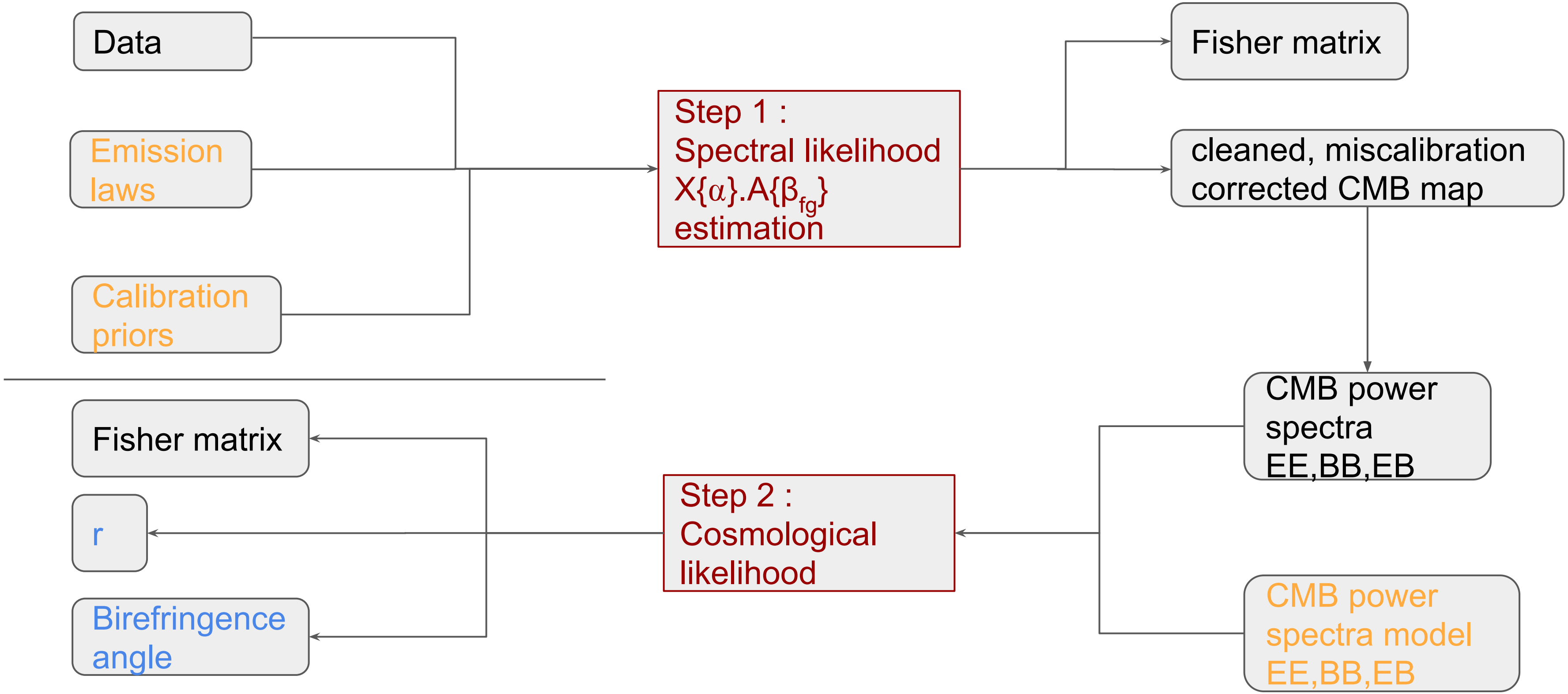
Mixing matrix

$$A(\{\beta_{fg}\}) = \begin{pmatrix} 1 & 0 & A_1^d & 0 & A_1^s & 0 \\ 0 & 1 & 0 & A_1^d & 0 & A_1^s \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & A_n^d & 0 & A_n^s & 0 \\ 0 & 1 & 0 & A_n^d & 0 & A_n^s \end{pmatrix}$$

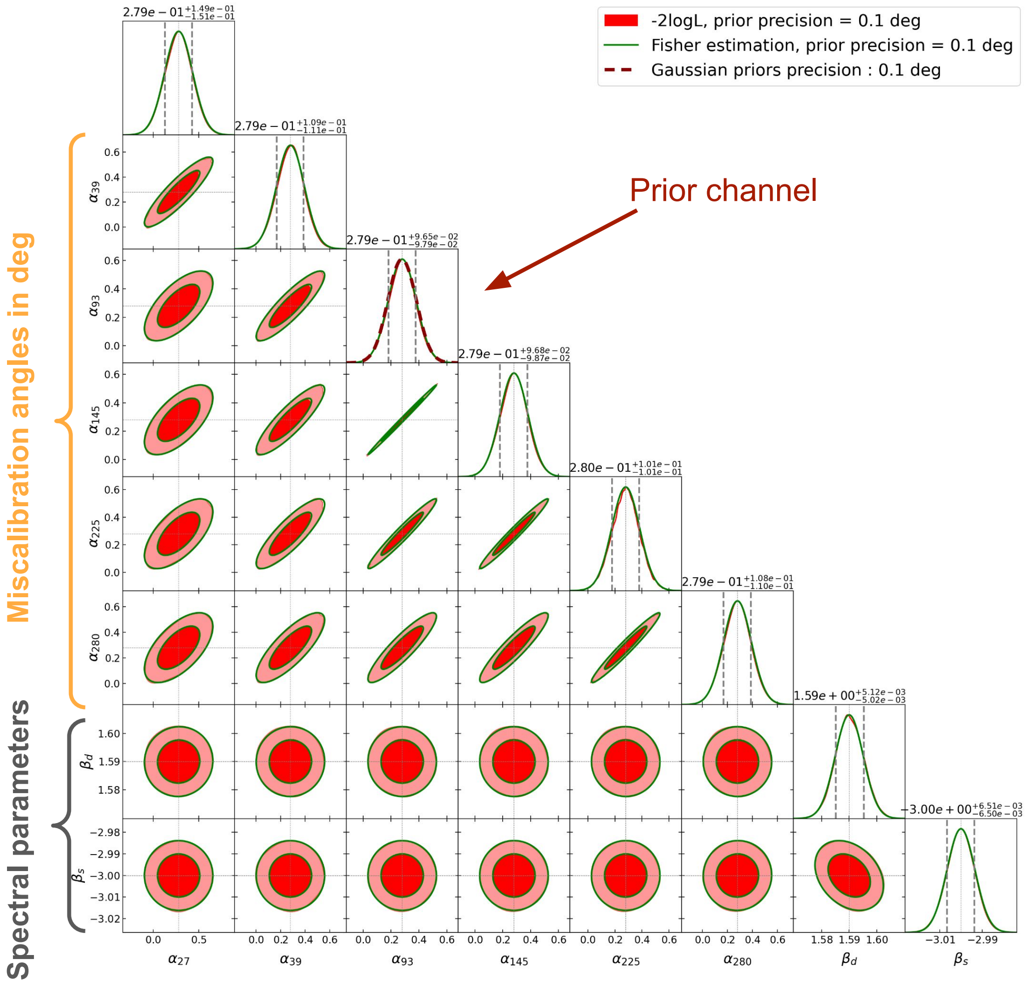
$$s_p = \begin{pmatrix} Q^{CMB} \\ U^{CMB} \\ Q^d \\ U^d \\ Q^s \\ U^s \end{pmatrix}$$

The Pipeline : 2 steps analysis

Jost et al in prep



Forecast case study : SO SAT 0.1 deg prior on 93 GHz

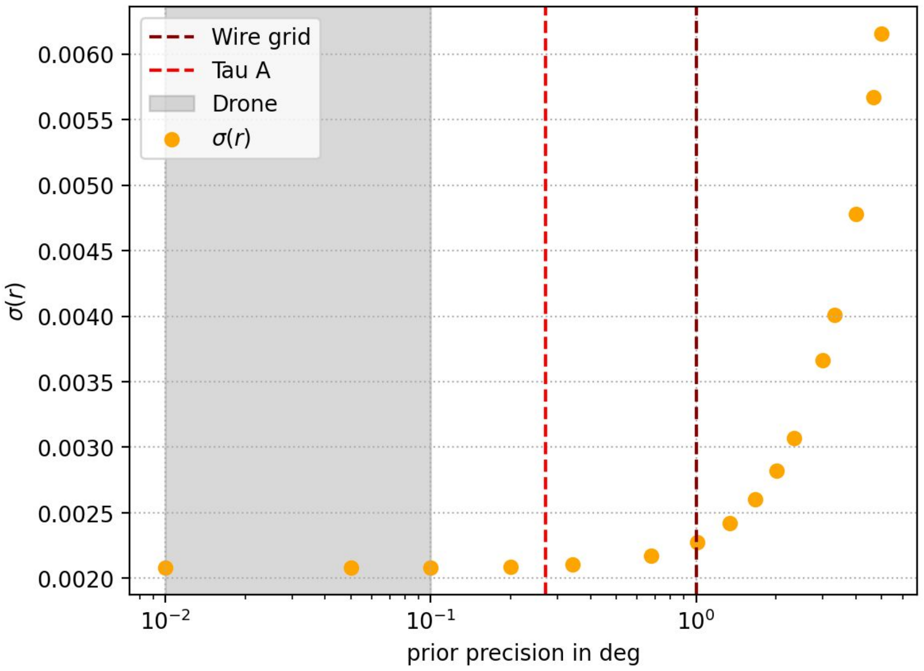


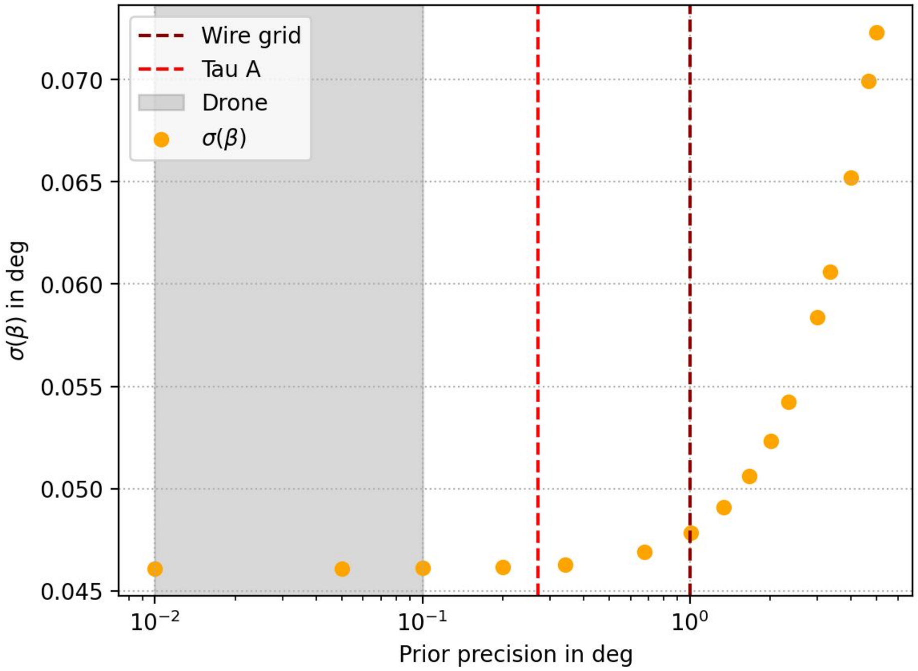
Step 1 :
Spectral likelihood
X{α}.A{β_{fg}}
estimation

- d0s0 pysm model Zonca et al 2021
- baseline white noise, pessimistic 1/f
- Taking advantage of the foregrounds to constrain miscalibration angles : only one prior needed
- We can propagate statistical residuals for the estimation of cosmological parameters

Evolution of precision wrt prior precision (on 93 GHz)

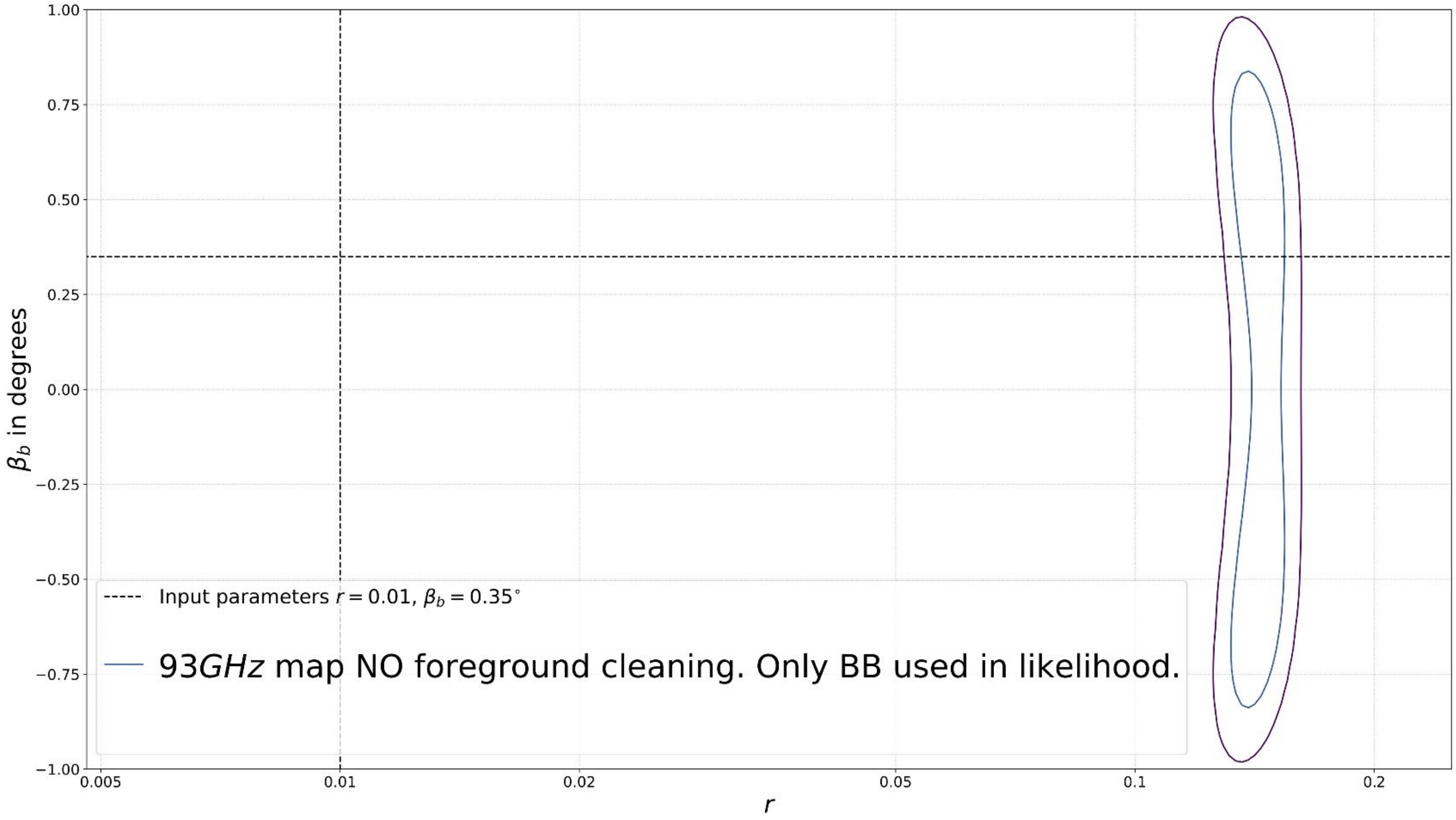
Step 2 :
Cosmological
likelihood





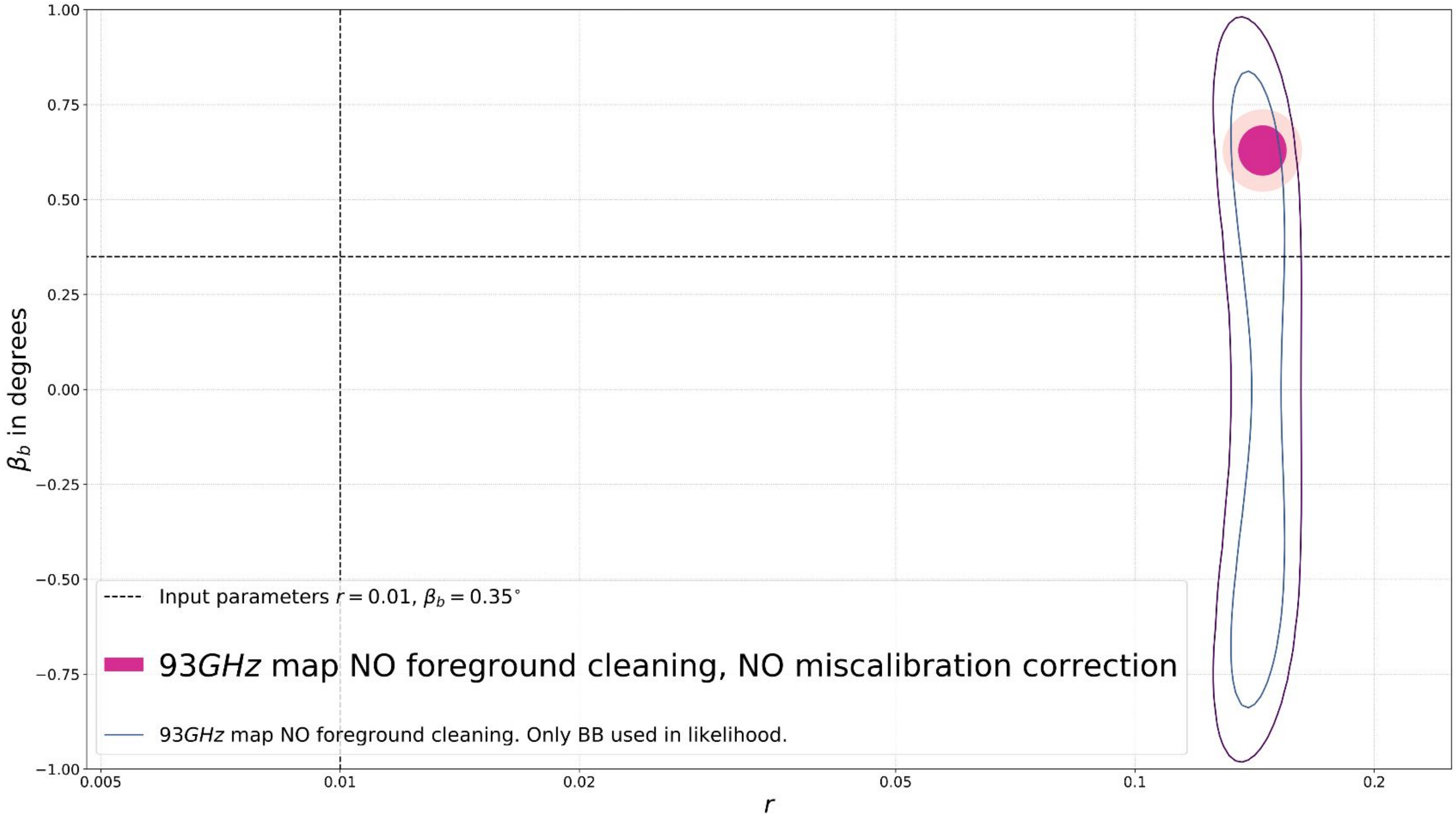
Cosmological likelihood results

Step 2 :
Cosmological likelihood



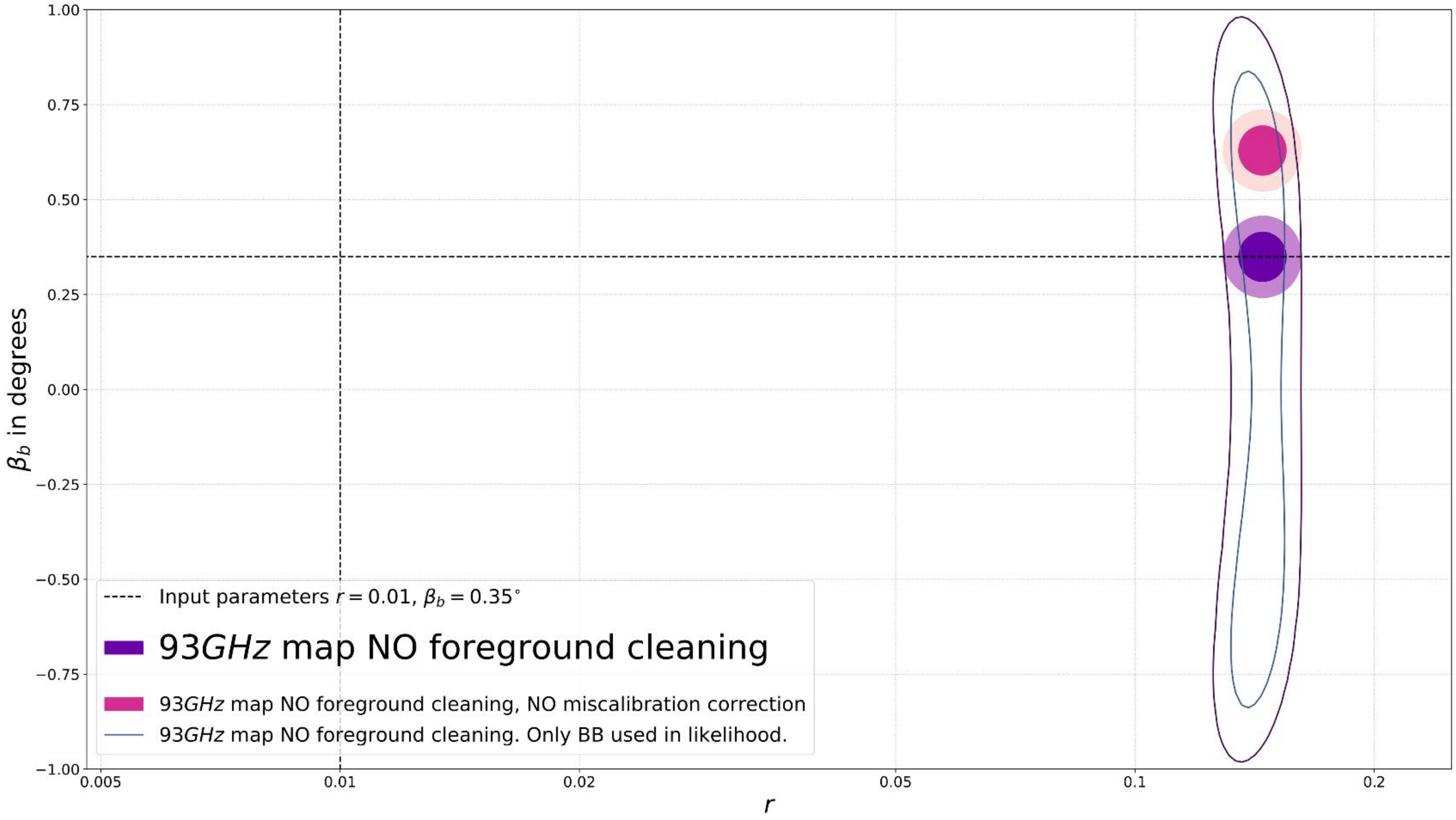
Cosmological likelihood results

Step 2 : Cosmological likelihood



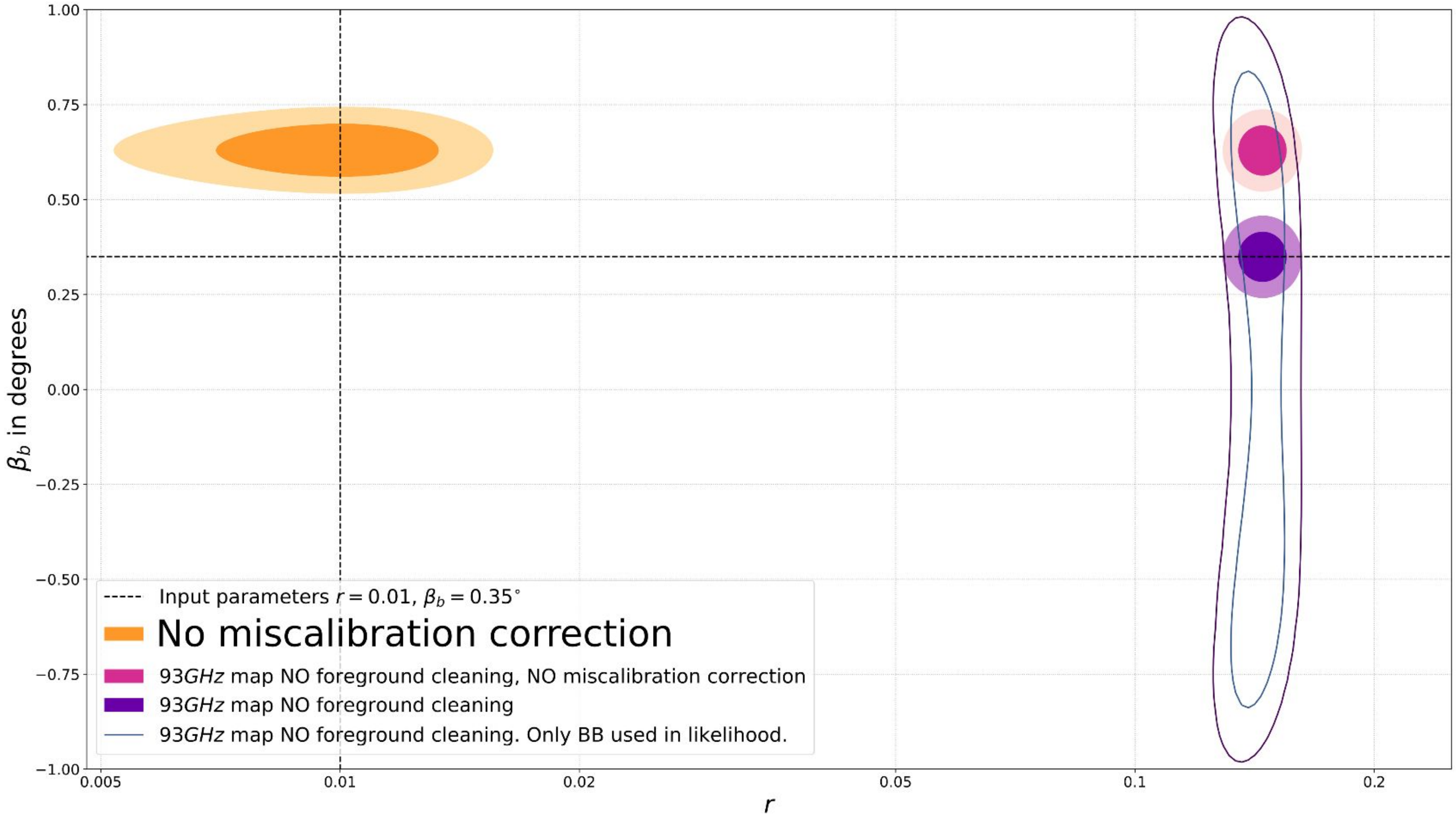
Cosmological likelihood results

Step 2 :
Cosmological likelihood



Cosmological likelihood results

Step 2 :
Cosmological likelihood



Cosmological likelihood results

Step 2 :
Cosmological
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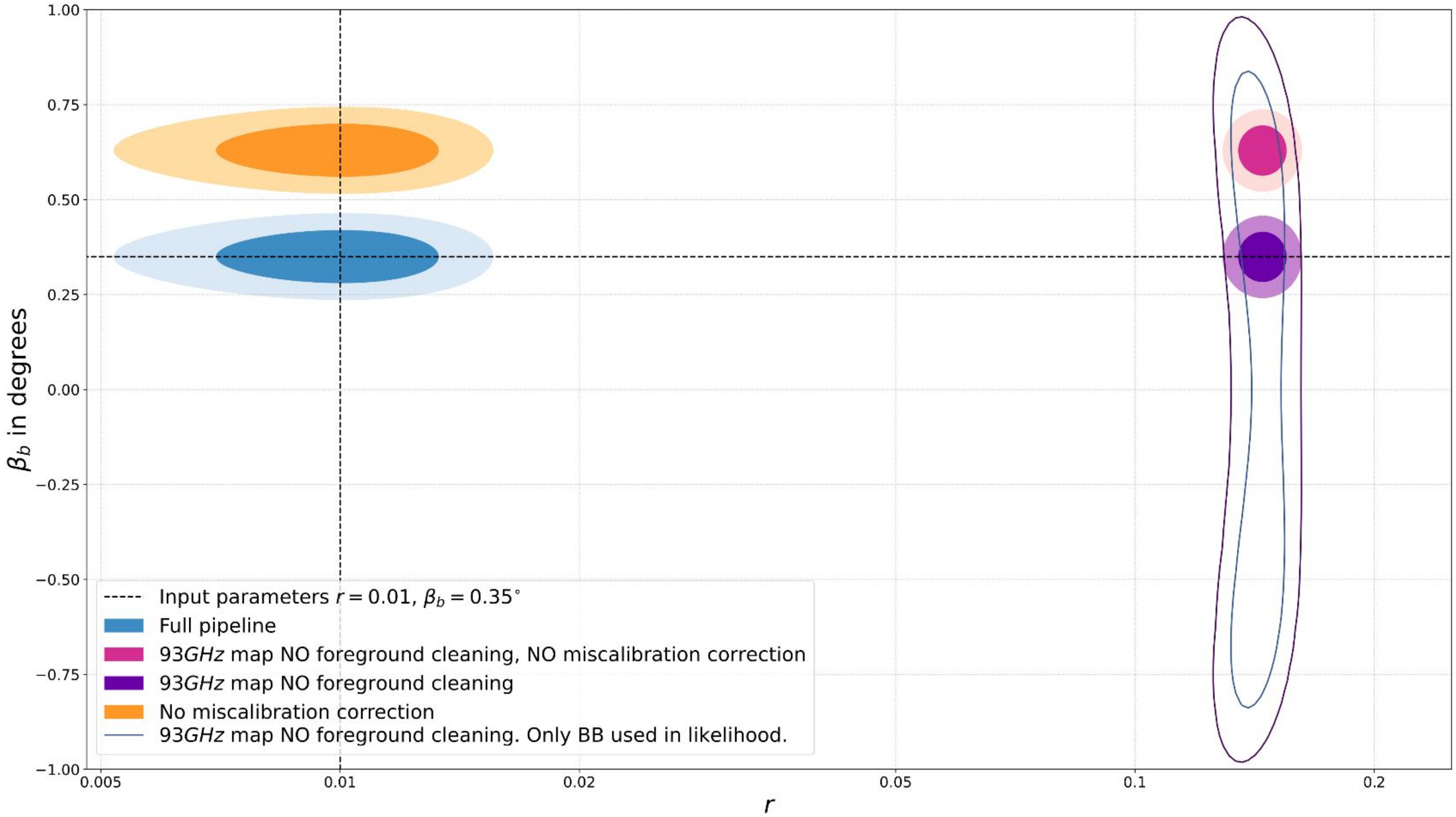

Conclusion :

- Broad science goals (from inflation to Planet 9, and birefringence !) .
- Strong involvement of French groups, well positioned for leading roles in scientific analysis.
- Observations starting soon, stay tuned !
- I developed a new method that with SO observation would improve the constraint cosmic birefringence with a minimum amount of assumption and in a statistically robust framework.
- Jost et al in prep
- Application to existing SO pipelines / test of performances on current data challenge
- LAT extension / SAT+LAT


THANK YOU !