Qui Nhơn, Vietnam, July 13th, 2017

POLOCALC

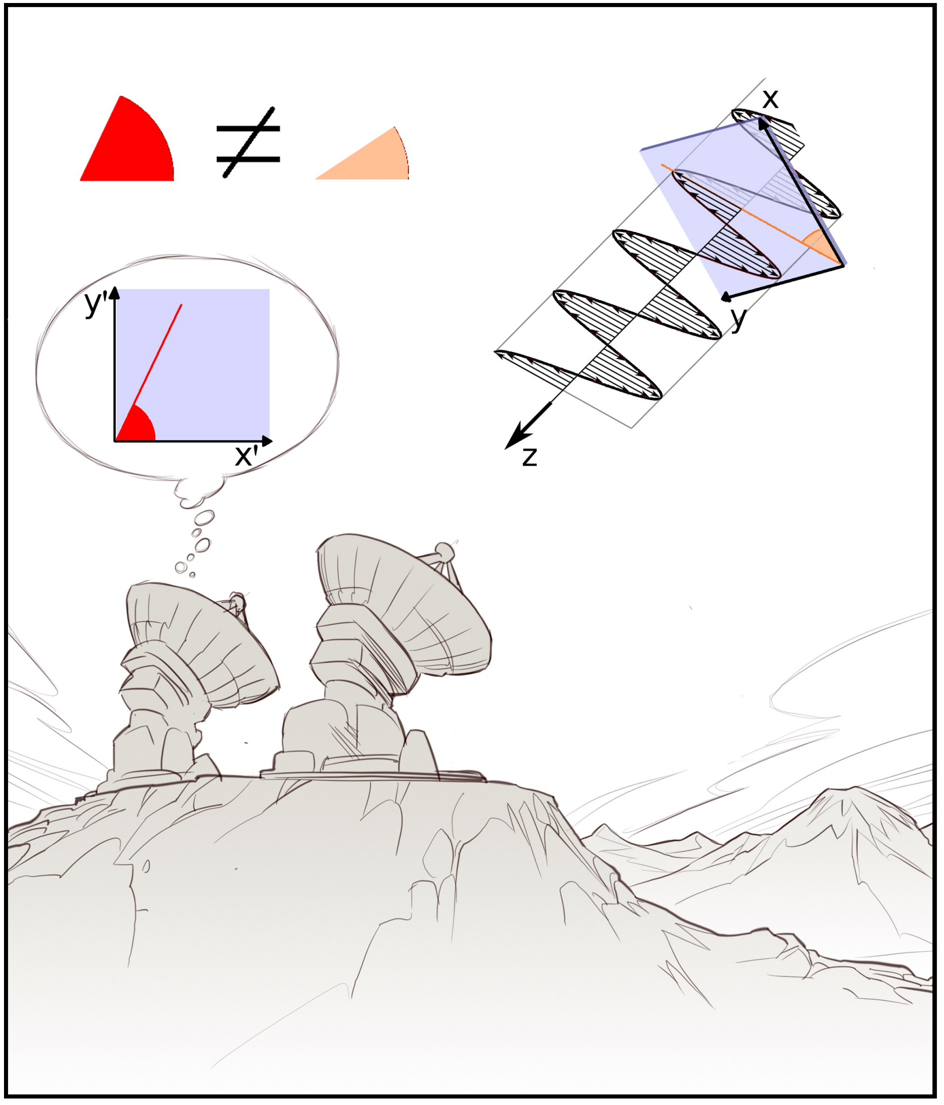
POLarization Orientation CALibator for Cosmology

A Novel Method to Measure the Absolute Polarization Orientation of the Cosmic Microwave Background

Federico Nati, University of Pennsylvania, USA

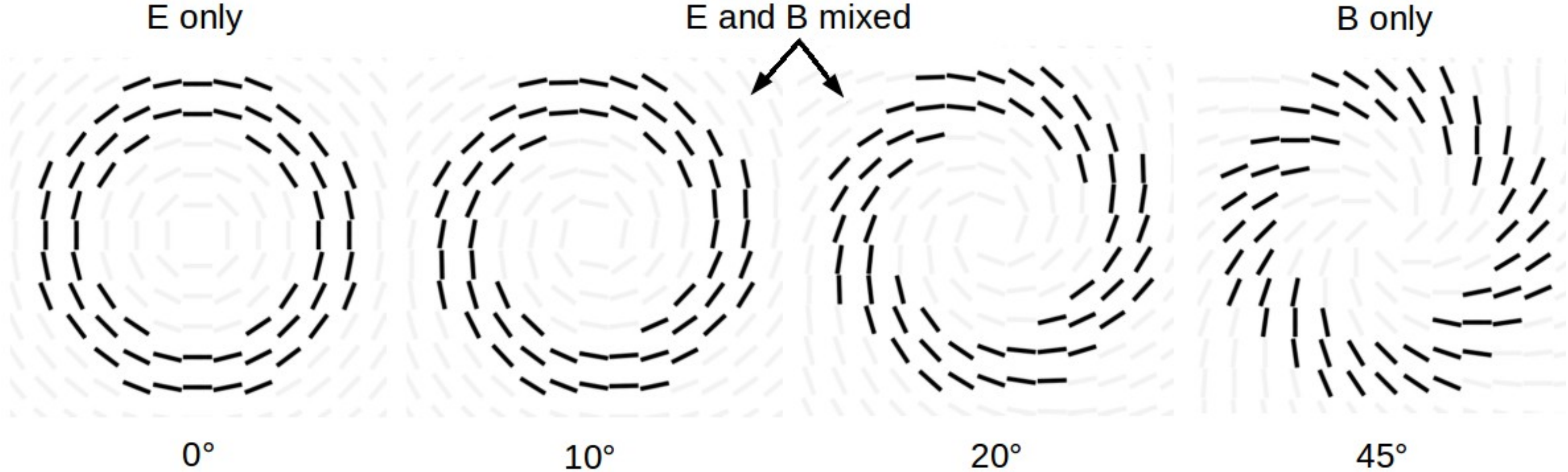
Nati F. et al., *Journal of Astronomical Instrumentation, Volume 6 No.2, 2017*
DOI: 10.1142/S2251171717400086

Absolute Polarization Angle Calibration



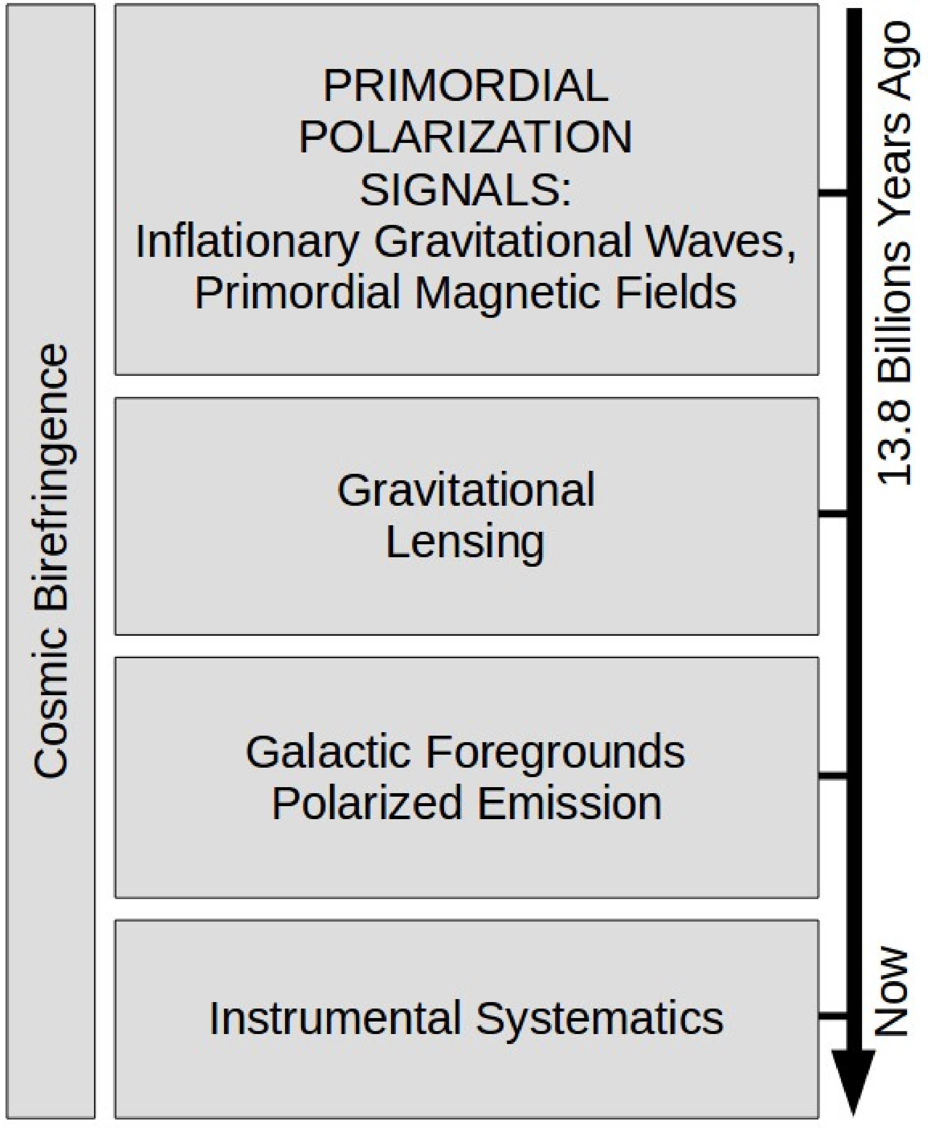
Absolute Polarization Angle Calibration

Absolute Polarization Orientation refers to the polarimeter detectors' direction measured in celestial coordinates. A miscalibration (i.e. a rotation bias for the detector orientation) mixes E and B modes. Such a systematic rotation is degenerate with Cosmic Birefringence (CB or CPR). It also affects other cosmological parameters.



A pure E-mode signal is gradually converted into B-mode by an isotropic rotation of the polarization orientation of 10◦, 20◦ and 45◦. At 45◦ all the E-mode pattern is converted into B-mode

B-Mode History



Absolute Polarization Angle Calibration

- **It is hard!**
- **Uncertainty range:** Existing experimental methods provide accuracy of ~1deg. A miscalibration of 0.5 deg in the polarization orientation translates into a spurious B-mode signal corresponding to a tensor-to-scalar ratio of r ~ 0.01. Smaller values of r will require sub-arcmin accuracy.
- “Self calibration” methods suffer from foreground emission and limit science goals
- **Absolute Polarization Angle is a** small, but critical systematic. Several science goals involved

CMB polarimeters need an indepentent, experimental calibration method with subarcmin accuracy

Why it is hard

Given their typical dimensions, the alignment of detector arrays and cold optics with better than 1 deg accuracy requires a positioning uncertainty smaller than 1mm.

- Microwave detectors must be cooled down from 300 K to 100 mK. Differential contractions of the materials in the cryostat introduce additional misplacements larger than 1 mm. Even with a careful design to mitigate these effects it is hard to fully recover the accuracy, since all the parts must be mounted together at room temperature.
- During operations external pressure and temperature can change, affecting the cryostat internal conditions.
- It is also critical to refer the detector orientation with respect to the telescope and the receiver mount once the cryostat is closed.

As a result, direct polarization angle calibration is not possible with an accuracy better than 1 deg

Current methods

1) Many experiments require the use of polarization modulator systems based on large rotating half wave plates (HWP) or reflective polarization modulators. Thanks to the large filter diameter, in principle they can calibrate the polarization angle with good accuracy. However, ideal, wide-band, optically uniform and thermally stable HWPs do not exist, so they introduce uncontrolled biases degrading the accuracy

2) Thin film polarization grid in front of the receiver can calibrate the absolute polarization orientation of the detectors. However, any strategy based on optical elements placed between the mirrors and the polarimeter does not allow to measure the polarized beam systematics induced by the warm optics

3) Sky sources are used for calibration and beam measurements, but they suffer from frequency dependence and time variability. They are not visible from all observatories and are extended sources. The best candidate is Tau-A, but it is not point-like, its frequency spectrum and polarization direction within the sensitive bands of the polarimeters is not precisely known. It allows an accuracy for the polarization orientation between 1 deg and 0.5 deg

4) Calibration sources placed on the ground or at very low elevation suffer from ground pickup saturates the detectors

Self-Calibration and its limitations

The standard cosmological model predicts that in the early Universe the odd-parity and the even parity signals should be completely unrelated.

This prediction can be used to calibrate CMB polarimeters through a self-calibration method at the expense of losing detection capability on genuine physical quantities. However, the initial assumption is not true in the presence of phenomena that produce non-vanishing TB and EB correlation.

In these cases self-calibration loses accuracy and introduces biases on cosmological parameters. Besides, this method destroys the possibility to measure or to place limits on phenomena that generate TB and EB spectra, like Cosmic Birefringence, Faraday Rotation and chiral gravity models. TB and EB correlations can also be introduced by polarized galactic foregrounds and instrumental systematics.

Absolute Polarization Angle Calibration Requirements

1) Well-characterized polarization sources at **far field distance**: $d_{\mathrm{f}} = \frac{2D^2}{\lambda}$

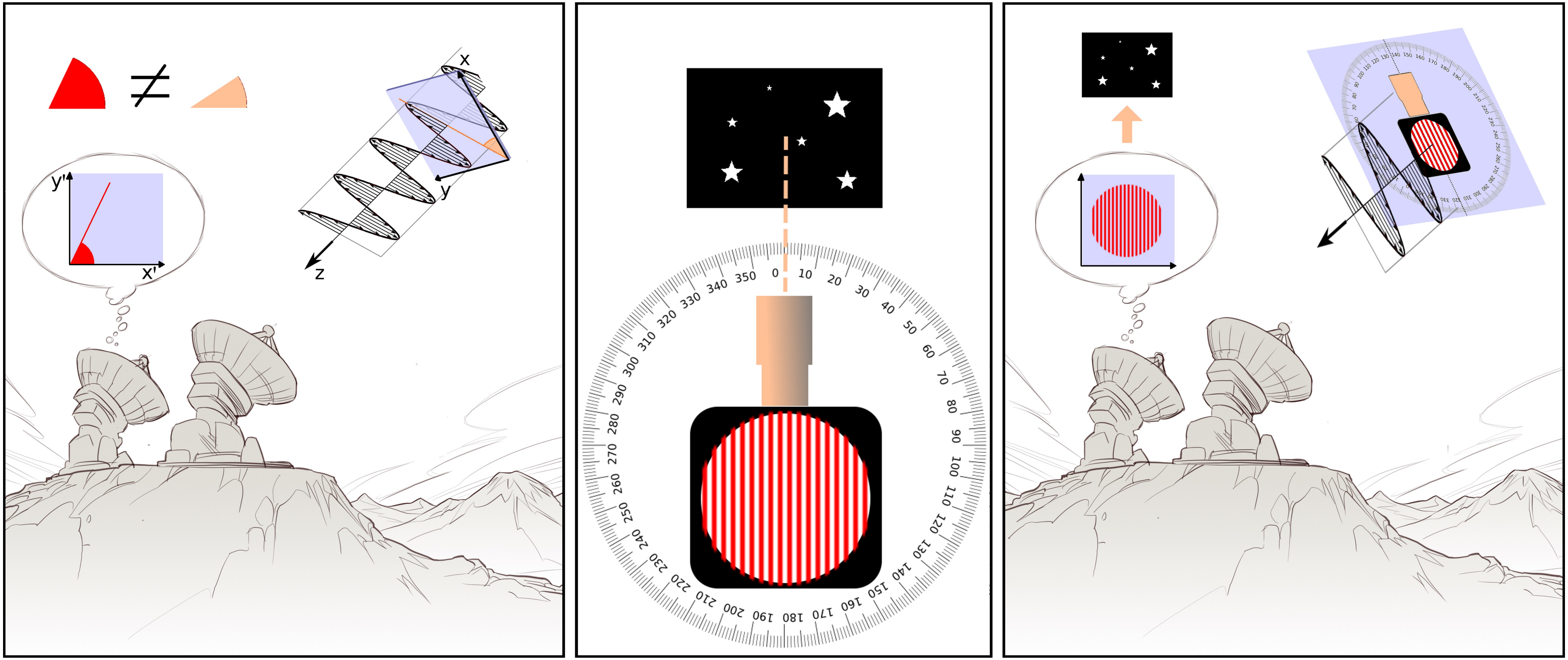
2) The calibration source should be seen at **high elevation angles** to avoid ground and warm air mass signal

3) Calibration of the **full optical chain** (including warm mirrors) and of fully integrated and **cold receivers**, avoiding compensation for mechanical misalignments and differential thermal contractions between laboratory and operating conditions.

Matching these requirements will also provide

- **Systematics control** over thermal, optical or mechanical irregularities of beam filling HWP or polarization filters;
- Measurement of the **polarized beams patterns**, for which a distant artificial source is invaluable;
- Calibration with **no assumptions** on the primordial coupling of intensity and polarization modes, as opposed to the self-calibration methods, thus preventing the induced biases on the cosmological parameters and enabling CB measurements.

POLOCALC Concept

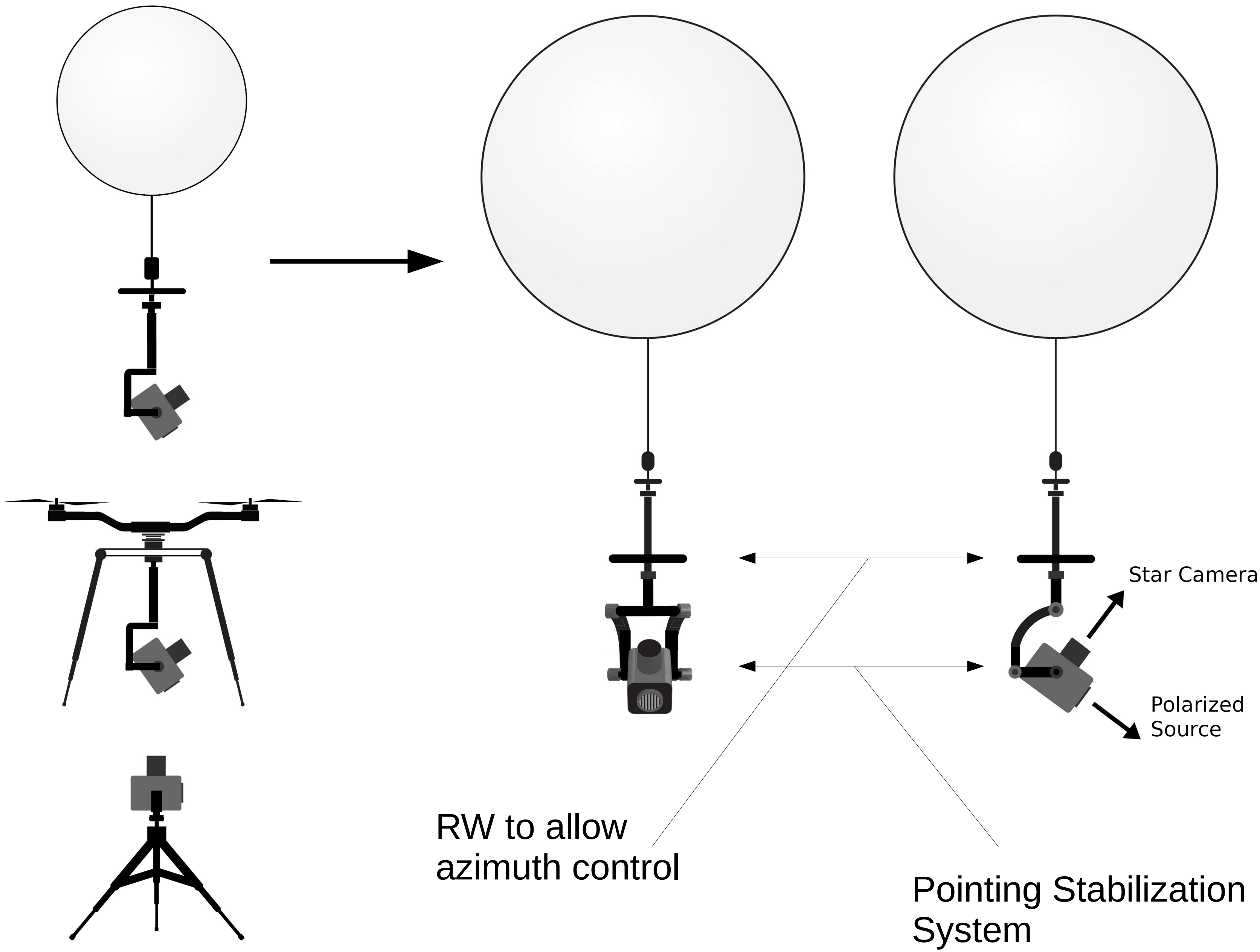


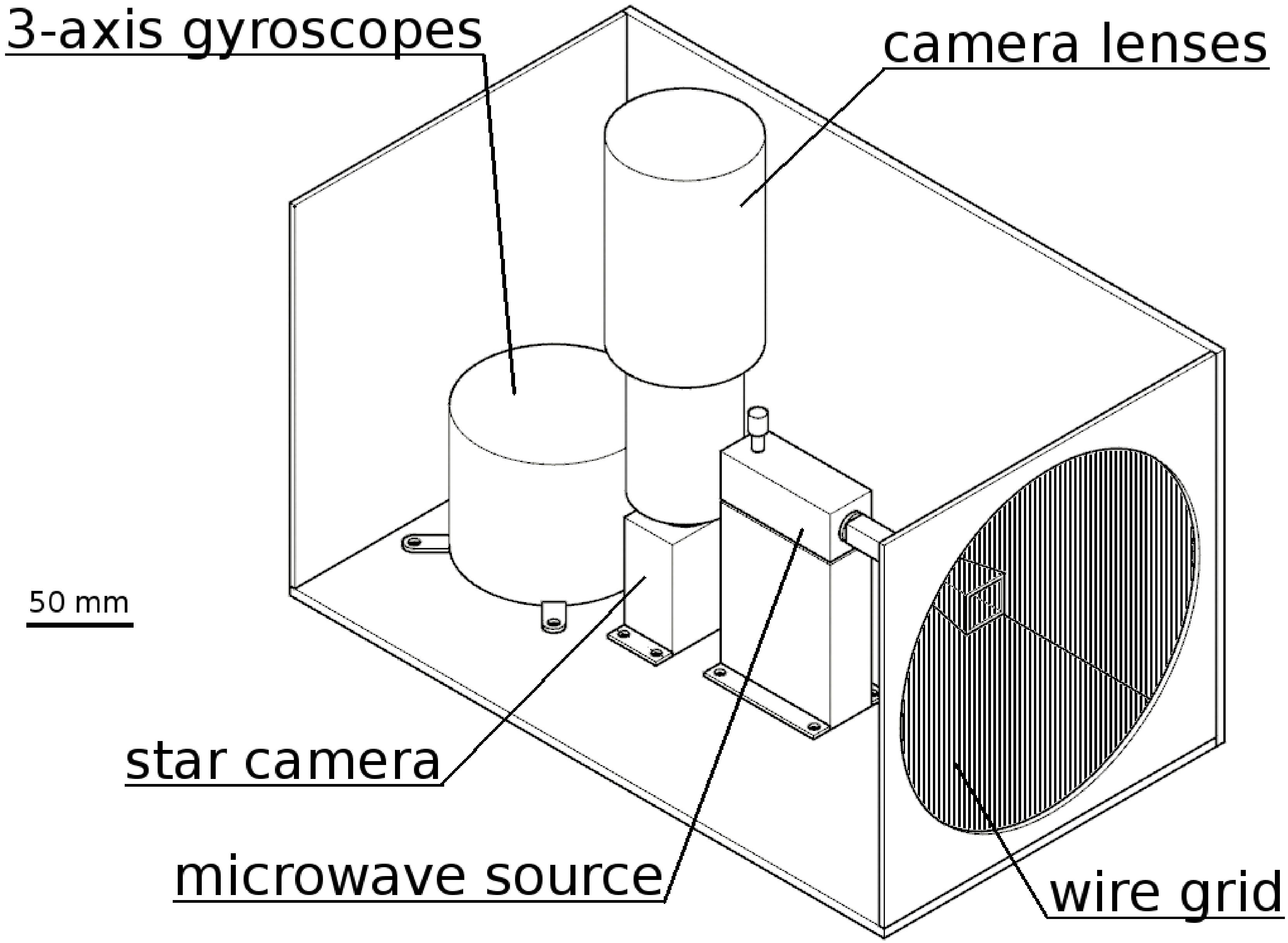
Advantages over existing methods:

1) Far field distance: form 5 km to 36 km
2) High elevation (i.e. > 35 degrees)
3) Fully operative experiments
4) High accuracy between 0.01° and 0.001°
5) Experimental method: no model assumptions

Scientific goals:

I) Inflationary Gravitation Waves
II) Neutrino masses
III) Cosmic Birefringence
IV) Primordial Magnetic Fields


Star Camera
Polarized
Source
RW to allow
azimuth control
Pointing Stabilization
System


3-axis gyroscopes
camera lenses
50 mm
star camera
microwave source
wire grid

Attitude Determination Software and Data Analysis

- STARS (EBEX, Blast-TNG): arXiv:1410.4892
- http://www.astrometry.net/

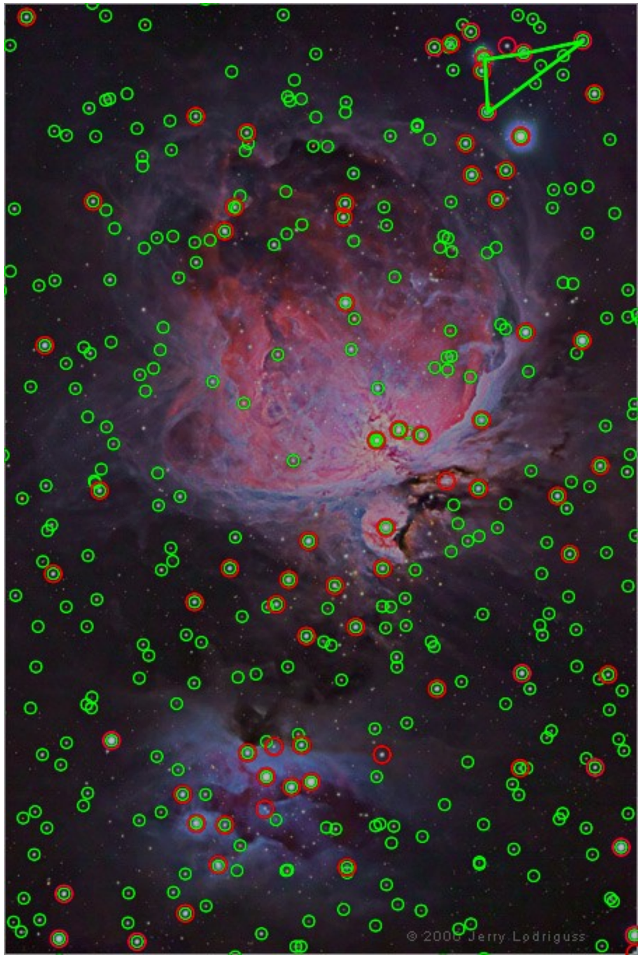
↓

- Data from Star cameras merged with gyros, GPS, housekeeping
- POLOCALC source orientation used to calibrate the telescopes' detectors

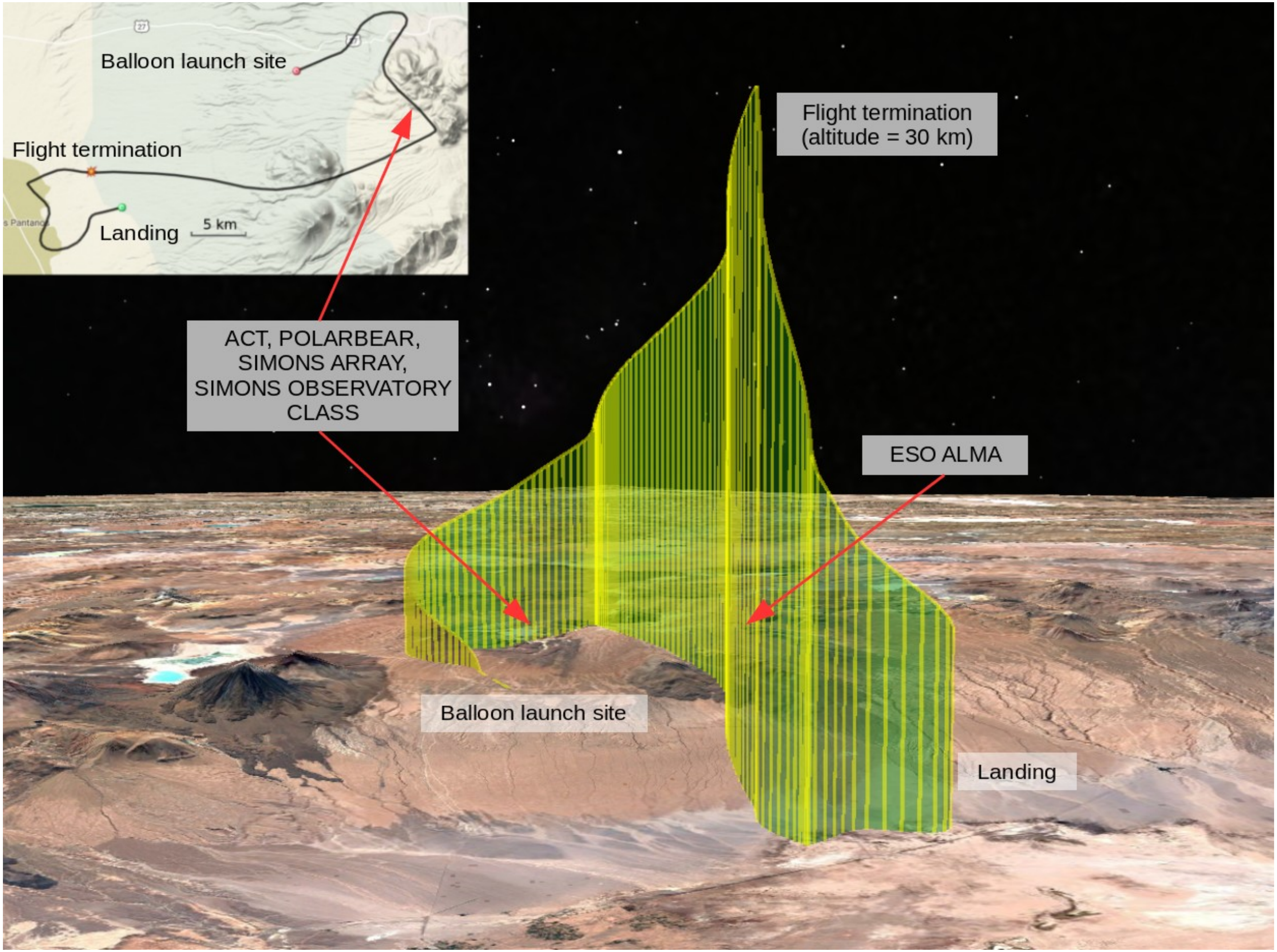
↓

POLOCALC data merged with the data reduction pipelines of the ground experiments

→ Scientific results



Simulation of a ~ 2h flight from http://predict.habhub.org/



POLOCALC Accuracy

Accuracy limited by the uncertainty of the star camera solutions, the mechanical alignment precision of the linear polarization filter direction of the source with the ACS, and the thermal stability and uniformity of the payload.

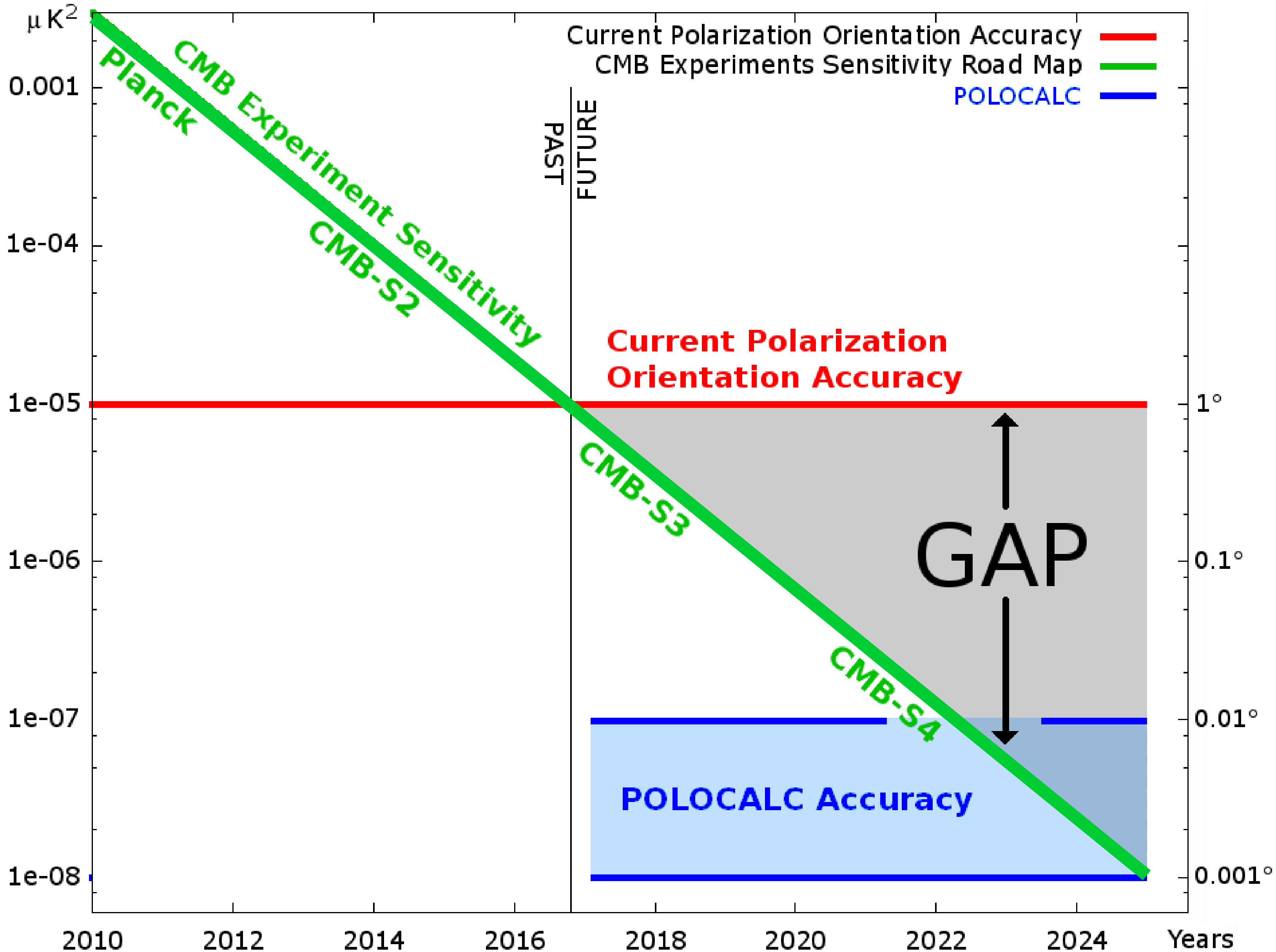
- State-of-the-art ACS accuracy between 0.01 and 0.001 degrees

- The same accuracy range can be achieved for the assembly of the camera and the wire-grid, making use of precise rotary stages, microscopes, and accurate metrology systems.

- Thermal control providing temperature stability between 2 K and 0.2 K, corresponding to an angular misalignment on the order of 0.01 and 0.001 deg respectively.

Note: we can transfer the calibration obtained with POLOCALC among different detectors and telescopes by observing the same sky signals, reducing the risk of calibration mismatch between detectors

Systematics uncertainties limit CMB measurements



Feasibility

- Certainly it is a risky and challenging project
- Main challenges:
  - Light, low consumption payload (< 6 kg, < 20 W)
  - Calibration accuracy
  - Payload stability (attitude, temperature)
  - Balloons are risky
  - Telescope tracking

Compelling contingency plan and risk mitigation

Stabilization

- FreeFly MoVI systems
- M15:
  - 2.5 kg
  - 140x200x165 mm
  - 6.8 kg inner payload
  - powered by its own batteries (several hours of operations)
  - Target mode, remote commands
  - Slew rates up to ~150 deg/s

Power budget

Star Camera	2.9 W
Gyros	5 W
GPS	3 W
Raspberry PI	1 W
Iridium TM	0.5 W
LOS TM	0.2 W
Microwave source	3 W
Reaction wheel	1 W
Thermal control	5 W

↓

Total: ~ 20 W

Battery capacity needed: 3 h flight, 30 W @ 12 V = 2.5 A

↓

Total: 6.8 Ah

Power budget

Lithium battey pack

19.0 Ah, 3.6 V
- -60°C / +85°C
- 33.4 mm x 61.6 mm
- 90 g

With a 4-battery pack:
- 14.4 V
- Pack Weight **360 g**

Example: 3 h flight
30 W @ 12 V = 2.5 A
Total: 6.8 Ah < 19 Ah

Weight budget

Vessel	1000 g
Electronics	100 g
Reaction Wheel	300 g
Microwave source	100 g
Gyroscopes	600 g
Stabilization System	2470 g
Star Camera + Lenses	1000 g
Batteries	360 g

↓

Total: 5930 g **< 6 kg**

Advantages over a CubeSat

(1) Assuming a polar orbit with an altitude of 500 km, a CubeSat-based instrument would be visible from the telescopes in the Atacama Desert for only about 2 minutes in a given orbit and for only a few times each week. The satellite would need to be tracked by the telescopes while it crosses the sky, but the angular speed of the satellite can at times exceed 0.6 ◦ /s, which is a common upper limit for telescope mounts. Therefore, making beam maps will be challenging.

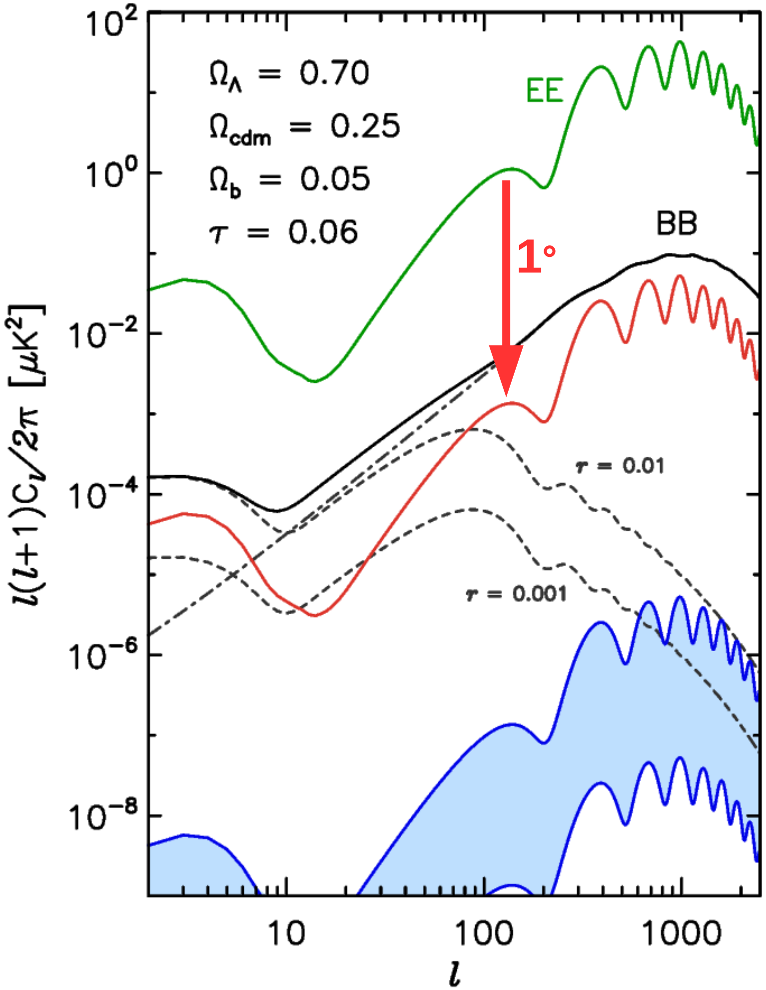
(2) CubeSats pose much stronger limitations in size, weight and power. These constraints limit the cal ibration source technologies that can be used. Also, the broadcast frequency bands are restricted by international regulations, so the available frequencies may not optimally match the spectral bands i the polarimetric receivers.

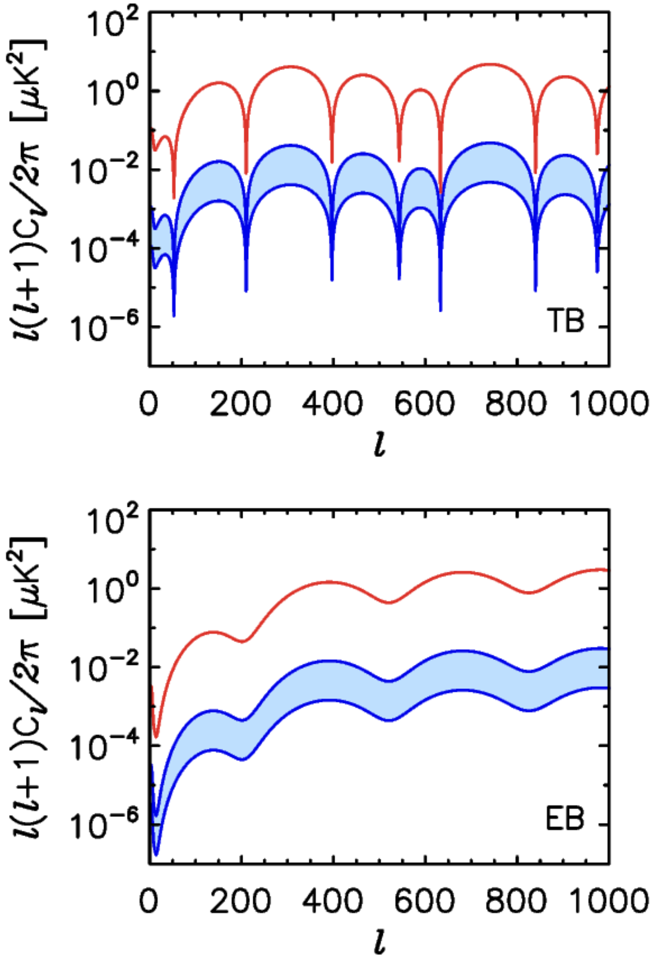
(3) Finally, a satellite is a high risk enterprise, it can be more expensive, and it would not be available immediately.

Scientific impact

I. Inflationary Gravitational Waves (IGW)
II. Lensing and Neutrino masses
III. Cosmic Birefringence
IV. Primordial Magnetic Fields

Simulated impact of POLOCALC



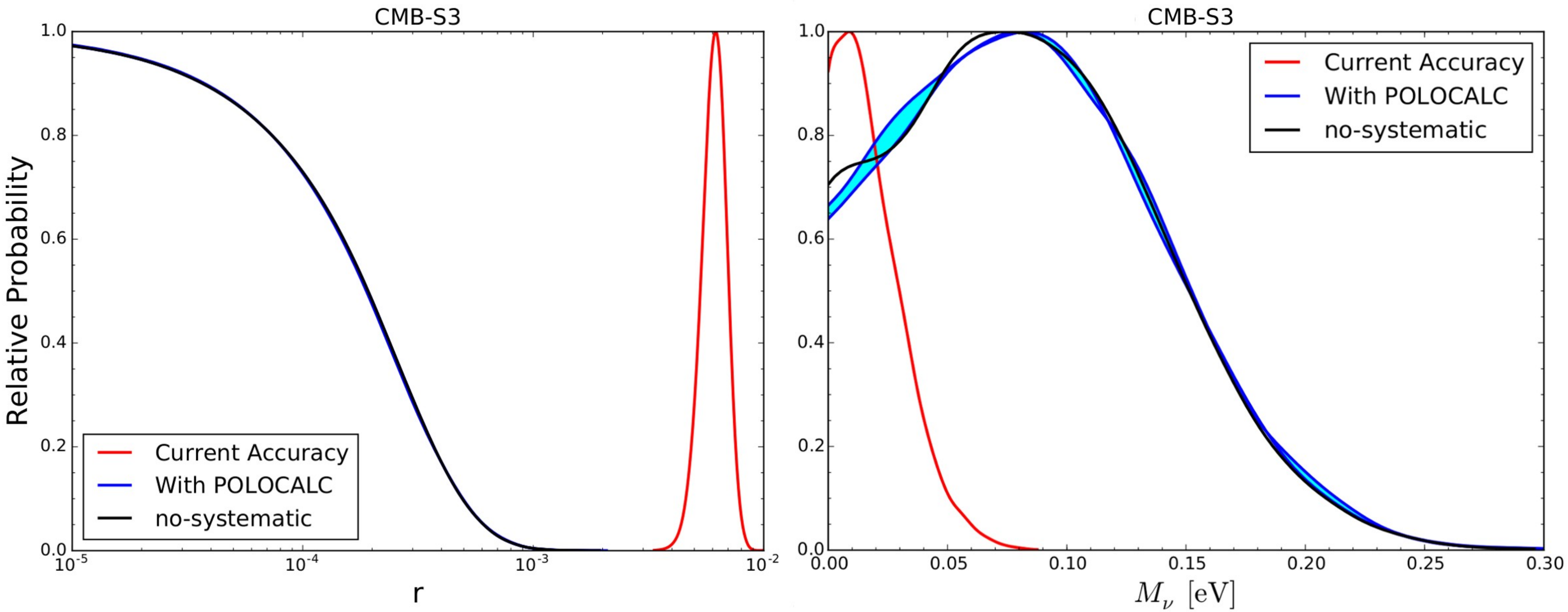


RED: rotation of 1°, corresponding to current accuracy

BLUE: rotation between 0.01° and 0.001°, corresponding to POLOCALC accuracy

Impact on r, neutrino mass, lensing, Cosmic Birefringence, Faraday Rotation from PMF.

Simulated impact of POLOCALC



RED: rotation of 1°, corresponding to current accuracy
BLUE: rotation between 0.01° and 0.001°, corresponding to POLOCALC accuracy

Results from simulated CMB data with noise properties expected for a generic S3 configuration and an ACT mirror size. We input a miscalibration angle and then we analyzed simulated data with COSMOMC as if it was no miscalibration.

Cosmic Birefringence

$$C_\ell'^{TB} = C_\ell^{TE}\sin(2\alpha)$$
$$C_\ell'^{EB} = \frac{1}{2}\left(C_\ell^{EE} - C_\ell^{BB}\right)\sin(4\alpha)$$

POLOCALC would allow accuracy between 0.01 and 0.001 degrees.
Generates TB and EB. Lorentz invariance violation.
Implies fundamental symmetries violation in electromagnetism.
Evidence for Dark Energy, probe of modified gravity, chiral gravity models.

Faraday Rotation and PMFs

POLOCALC would improve accuracy of 2 - 3 order of magnitudes. Measuring Primordial Magnetic Fields through Faraday Rotation would anchor inflationary models and provide evidence of the seeds that originated magnetic fields in large structures.

Conclusion

POLOCALC has the potential to become a rung in the calibration ladder for existing or future CMB experiments observing our novel polarization calibrator. This novel method will enable measurements of the polarization angle for each detector with respect to absolute sky coordinates with unprecedented accuracy.

This project will produce the first independently calibrated measurement of the polarization angles of the CMB light and its contaminants allowing Cosmic Microwave Background polarization experiments to fully mine the cosmic sky.

POLOCALC is described in

Nati F., et al.
"POLOCALC: a Novel Method to Measure the Absolute Polarization Orientation of the Cosmic Microwave Background"

Journal of Astronomical Instrumentation, Volume 6 No.2, 2017
DOI: 10.1142/S2251171717400086