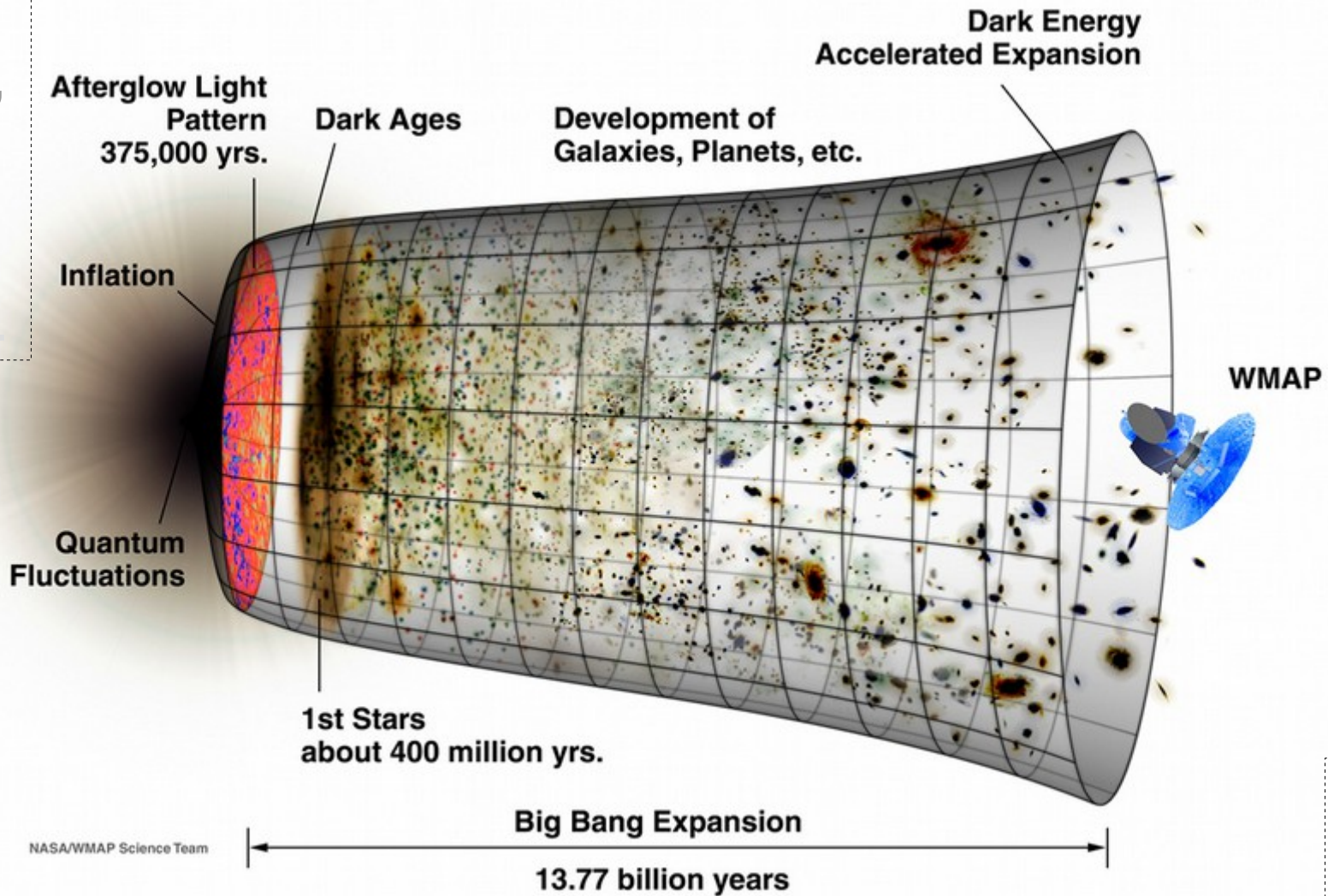


QUBIC,  
mmLab,  
Simons  
Array,  
LiteBIRD,  
CMB  
Stage-IV,  
CORE,  
Planck, ...

# Cosmology



Euclid,  
LSST,  
BOSS

***KEN.GANGA@APC.UNIV-PARIS-DIDEROT.FR***

# Work Force

---

## Today

- Permanent Members
  - 7 CNRS
  - 4 University
  - 2 CEA
  - 1 Observatory
  - 3 Emeritus
- 7 Graduate Students
- 3 Post-Docs (inc. PCCP)
- 4 Associates
- About 20 other admin. & « affiliates »

## 2015

- Permanent Members
  - 7 CNRS Researchers
  - 3 university
  - 1 CEA
  - 1 Emeritus
- 5 Graduate Students
- 4 Postdocs
- 5 Associates

# Project Evolution

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- (e)BOSS work has finished at APC
- Planck has (almost) finished
- DESI work has moved to LPNHE
- SKA work is not being undertaken
- LSST & Euclid work is well-defined & long-term
- LiteBIRD proposals are being submitted
- Simons Array work continues
- QUBIC has begun integration
- Simons Observatory & CMB Stage 4 is being explored



# QUBIC is a spectro-imager



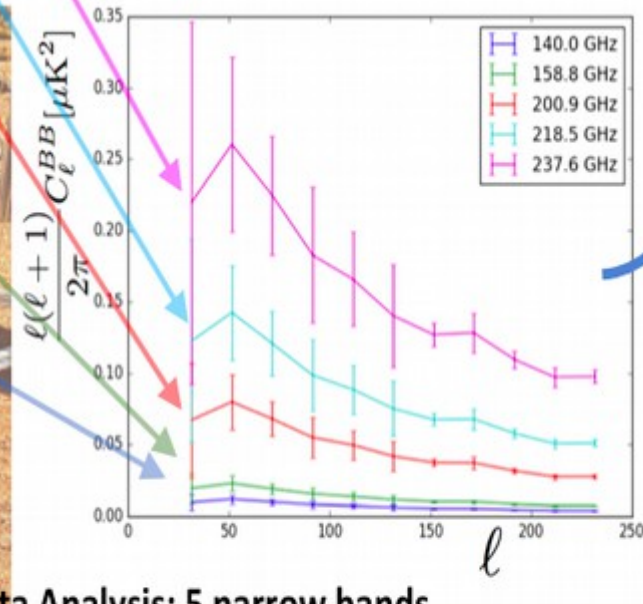
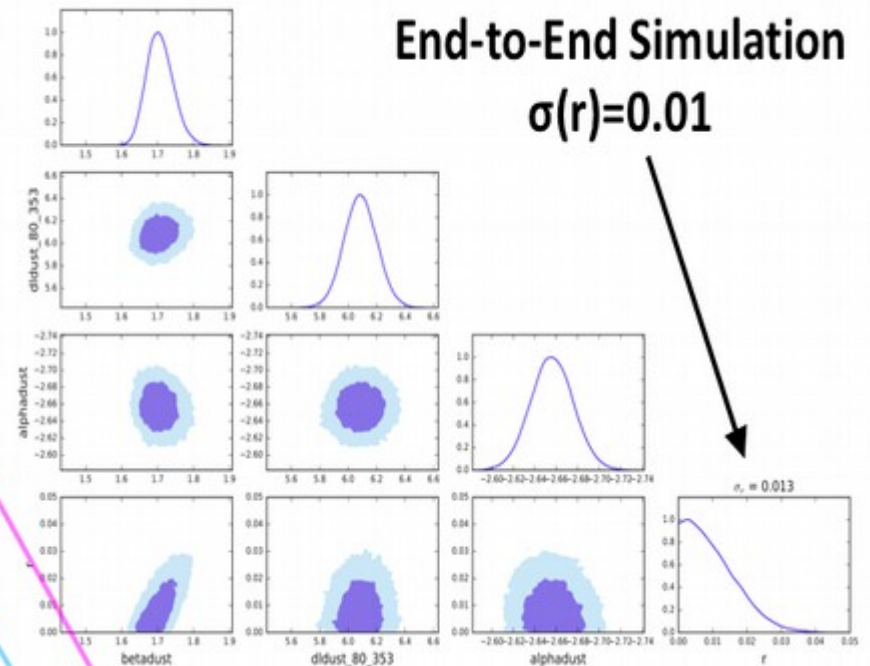
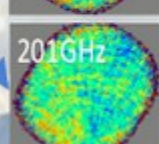
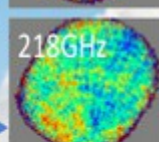
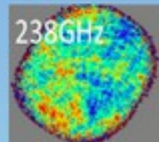
Sky:  
« Infinite # bands »



Instrument:  
2 wide bands

TOD(220 GHz)

TOD(150 GHz)

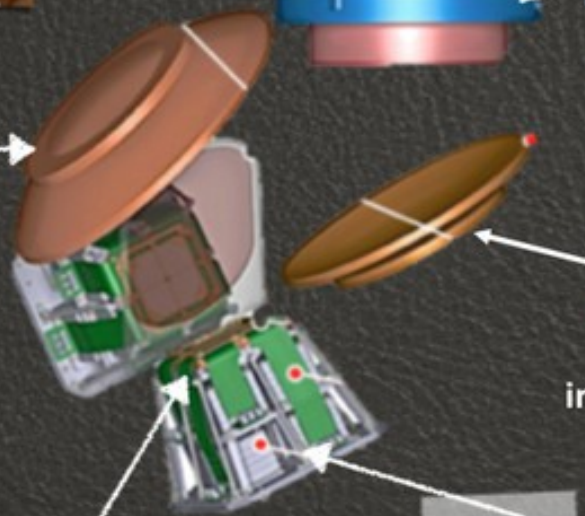


Data Analysis: 5 narrow bands  
=> Increased Spectral Resolution  
=> Improved Dust subtraction

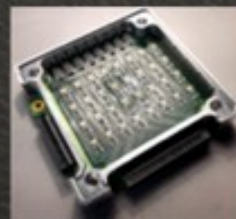




# QUBIC assembly and integration



TES array ready  
(CSNSM/Orsay)



Squid Board  
+ ASIC (APC/Paris)



Calibration mount  
(LAL/Orsay)



# QUBIC Deployment plan

- **2017-2018 : at APC**

- Integration started
- Early 2018: Technological Demonstrator (reduced QUBIC)
  - 1/4 focal plane, 64 horns, small mirrors
- April 2018: Upgrade to full size mirrors and 400 horns

- **2018 : Argentina**

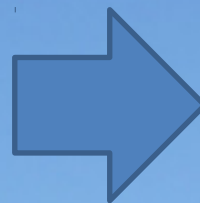
- mid-2018: Integration with mount, Installation on site
- First Light Sept. 2018 with ¼ focal plane

- **2019 : Argentina**

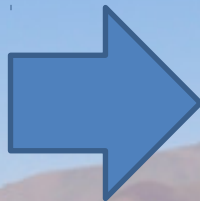
- Upgrade to QUBIC 1<sup>st</sup> module (2 focal planes 150 and 220 GHz)
- First Light March 2019
- Data taking: 2-3 years  $\sigma(r)=0.01$

- **2020-... : QUBIC evolves towards Stage-IV**

- European extension of the collaboration
- Improved designs already being investigated
- Excellent quality site open to development



In-lab Demonstration of  
Bolometric Interferometry



On-Sky Demonstration of  
Bolometric Interferometry



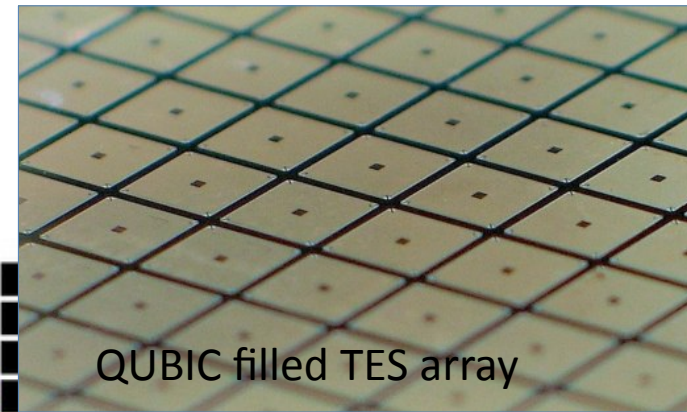
Stage III  
 $\sigma(r)=0.01$



Evolution to Stage IV  
 $\sigma(r)=0.001$

# Millimeter-Wave Laboratory Activities

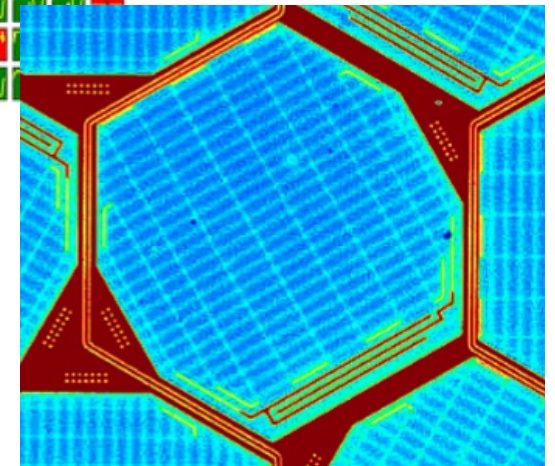
- QUBIC:
  - Instrument definition
  - Detection chain architecture
  - Cold readout electronics
    - Cryogenic SiGe ASIC
    - TDM 128->1:  
**world premiere**
  - TES characterisation
- Polarisation sensitive KIDs
  - Test set-up
  - First samples



QUBIC filled TES array

C fiber signal on  
QUBIC TESs

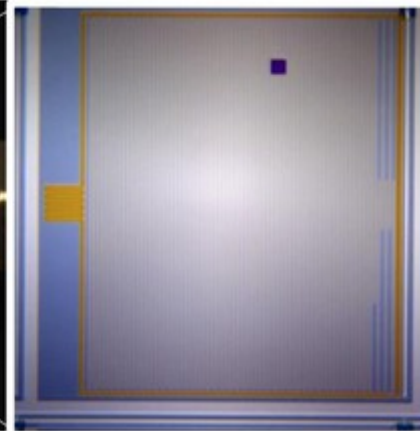
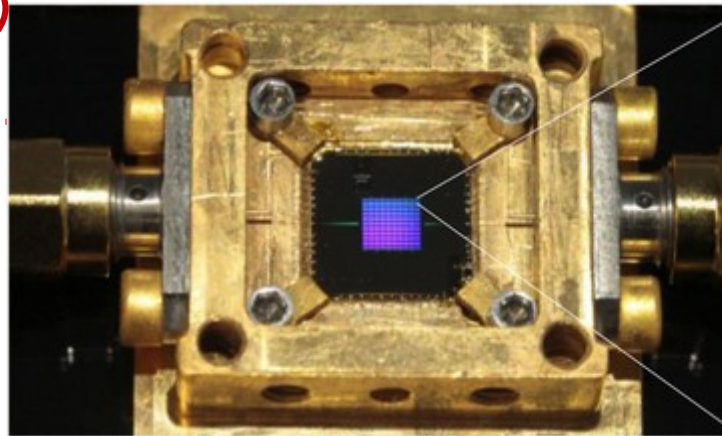
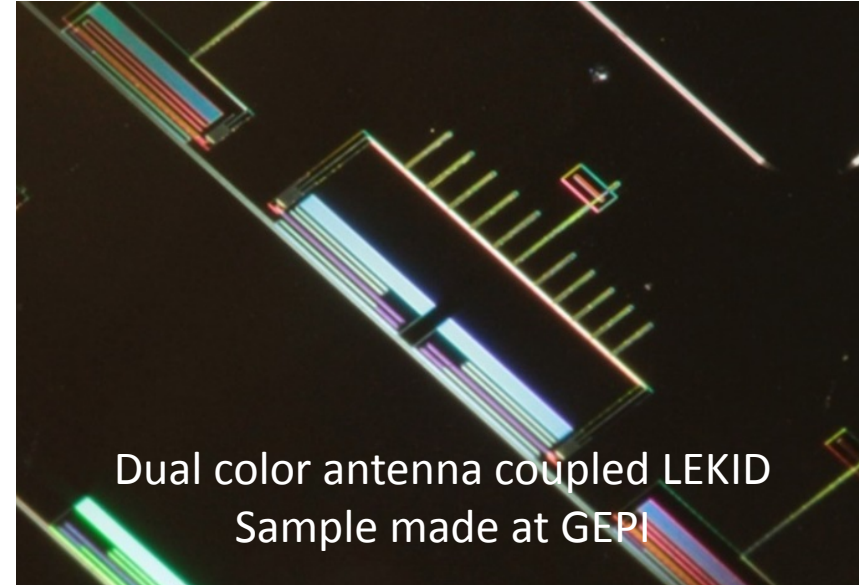
Polarisation  
sensitive LEKIDs





# Millimeter-Wave Laboratory Future

- Faster TDM ASIC
- Antenna coupled multichroic LEKIDs
- Projects:
  - Near term: QUBIC
  - Medium/Long term:
    - ground-based experiment S4-like
    - space mission (LiteBird, CORE)
- Visible and near-IR KIDs
  - GEPI leader



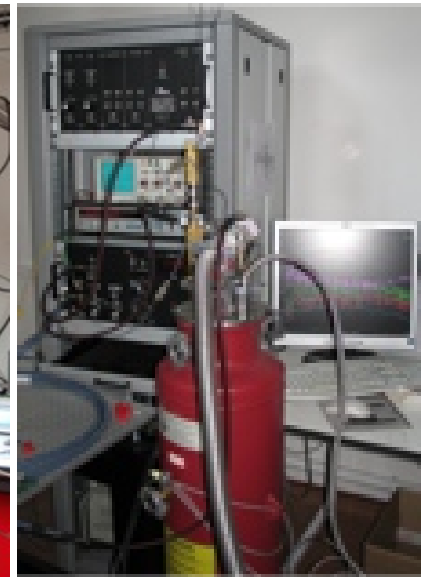


# APC mm lab : ETP, resources, schedule

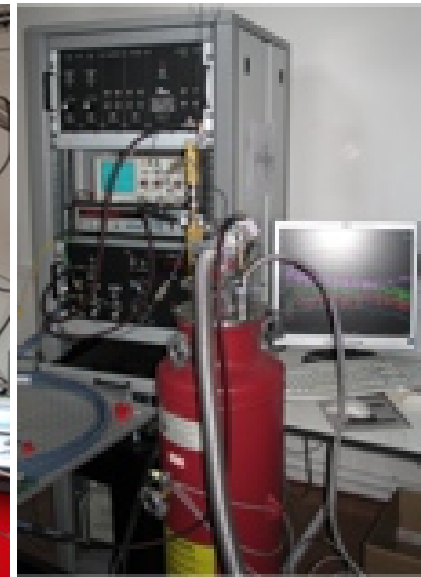
- The team:
  - Permanents: Fabrice Voisin (10%), Damien Prêle (10%), Jean-Pierre Thermeau (40%), Steve Torchinsky (50%), Michel Piat (50%)
  - Postdoc: Maria Salatino
  - PhD student: Alessandro Traini
  - Support of technical services
- Funding: ANR, CNRS, ESA, CNES
- Coming years:
  - QUBIC on site
  - tests and improvement of pol LEKIDs



Dilution  
20mK



$^4\text{He}/^3\text{He}$  system  
280mK



mm cryo  
deepstick 4K



# POLARBEAR (2012-2017)

## Basic facts

- International collaboration: 7 countries, 10 institutes (3 from Europe, 1 from France), ~80 researchers;
- Location: Atacama Desert, Chile;
- Test campaign: 2009-10, White Mountain, California;
- First light in 2012;
- Single frequency, 150GHz, array of ~1,000 polarization-sensitive, TES detectors operating @300mK;
- Telescope: Gregorian, 3 m (effective resolution @150 GHz: 3.5').

## @APC

involved since 2009:

- permanent: R. Stompor (DR1); J. Errard (CR2), M. Le Jeune (IR2);
- membership of the Collaboration Board;
- leadership of the European POLARBEAR effort (3 institutes, ~10 researchers);
- 5 PhD students: past: J. Errard (PhD 2012), G. Fabian (PhD 2013), J. Peloton (PhD 2015), D. Poletti (PhD 2016); current: D. Beck (since 2016), C. Verges (since 2017).
- travel support: PICS: 2012-14, 2017-19; France-Berkeley Fund: 2009-10, 2014-15, LABEX 2016-18.

Scientific production:

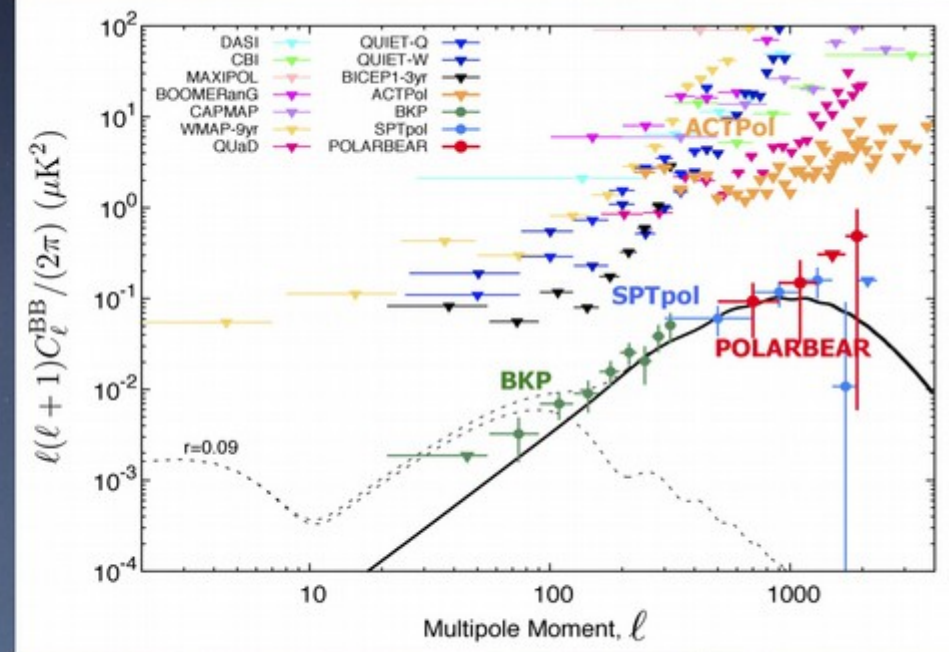
- 7 journal papers, 19 conference papers and proceedings;
- leadership on 2 technical papers (lead authors) and 1 main science paper (corresponding author);
- 12 talks on international conferences and 2 posters;
- 4 PhD theses.



# POLARBEAR (CONT'D):

## main results

- first direct measurement of sub-degree B-modes;
- first reconstruction of lensing potential with CMB polarization only;
- reconstruction of the lensing potential via cross-correlation with CIB.



**Evidence for B-Mode Polarization of the CMB from Cross-correlating Gravitational Lensing with the Cosmic Infrared Background**  
The POLARBEAR collaboration

Phys. Rev. Lett. 112, 131302 (2014)

**Measurement of the Cosmic Microwave Background Polarization Lensing Power Spectrum with the POLARBEAR Experiment**  
The POLARBEAR collaboration

Phys. Rev. Lett. 113, 021301 (2014)

**A Measurement of the Cosmic Microwave Background B-Mode Polarization Power Spectrum at Sub-degree Scales with POLARBEAR**  
The POLARBEAR Collaboration  
The Astrophysical Journal, Volume 794, 171 (2014)

**POLARBEAR Constraints on Cosmic Birefringence and Primordial Magnetic Fields**  
The Polarbear collaboration  
Phys. Rev. D, Volume 92, Issue 12, id.123509 (2015)

**A Second Measurement of the Cosmic Microwave Background B-Mode Polarization Power Spectrum at Sub-degree Scales with POLARBEAR**  
The POLARBEAR Collaboration (2017)

## APC main contributions

### Past:

- participation in instrument deployment and calibration campaigns;
- participation in remote observations;
- TOD characterization and calibration;
- systematics modelling and simulations
- leadership of an end-to-end data analysis pipeline;
- co-leadership of the 2nd analysis paper;
- leadership on two technical papers.

### Current:

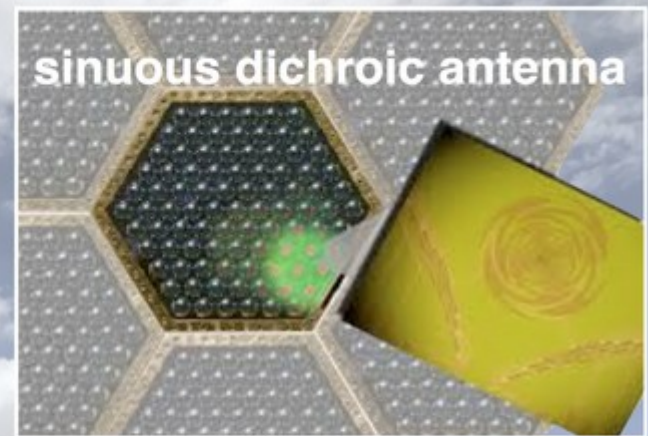
- remote observations;
- foreground cleaning;
- lensing and delensing analysis.



# Simons Array (2018-2020) (= POLARBEAR phase II)

## Basic facts

- “extended POLARBEAR”;
- 3 x 3m Gregorian telescopes ➤ 3.5' @150GHz,
- multifrequency: 95, 150, 220, 270GHz
- ~25,000 multichroic, polarization-sensitive, TES detectors;
- Operations: 2018 till 2020
- Science goals:  $\sigma(r) = O(10^{-2})$ ,  $\sigma(\Sigma m_\nu) = O(40\text{meV})$



+ continuously rotating HWP

**POLARBEAR**  
telescope

95+150GHz

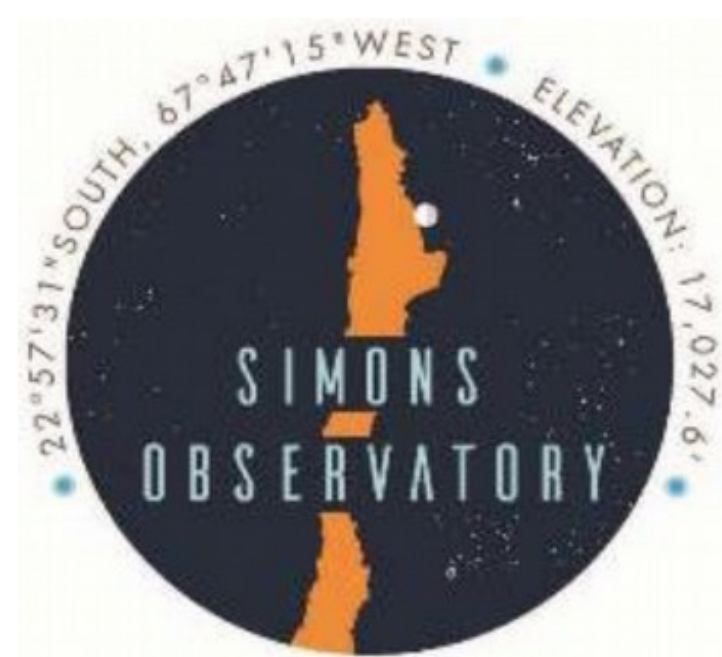
220+270GHz

95+150GHz

## APC involvement

- remote observations;
- pipeline development and validation;
- leadership of the component separation effort (J.Errard);
- co-leadership of the map-making effort (R.Stompor);
- co-leadership of the lensing estimation work (D. Beck).





# Simons Observatory

- A new project supported by Simons Foundation and combining two major current experiments: POLARBEAR/Simons Array and advACT.
- It will feature multiple telescopes with range of apertures (1- 6m) and  $O(10^5)$  multi-chroic detectors.
- It will operate from the Atacama Desert in Chile;
- The first light is expected in 2020.
- It will be a precursor for Stage IV experiments.
- It targets:  $\sigma(r) \ll 10^{-2}$ ,  $\sigma(\Sigma m_\nu) < O(35\text{meV})$ , but it science ranges from clusters to primordial gravitational waves.
- It is an open collaboration actively searching for foreign partners.



@APC

- The PB/SA group at APC involved since 2016 and has an 'essential' member status (absolved of yearly 'buy-in' fees);
- Involved in (co)-coordination of the science activities (membership of the *Scientific Planning and Pipeline and Data Management Committees, coordination of the Working Groups*);
- Discussion started with SO about a potential APC/IN2P3 hardware involvement.
- Could be a stepping stone for the APC, IN2P3 and French CMB community to S4.

# CMB Stage-4

CMB Stage-4 will be the next “stage” of ground-based Cosmic Microwave Background cosmology. Led by the US, it is being planned now.

We remain in contact with the S4 community and attend the preparatory meetings, and hope elements of QUBIC & the mmLab can carve out contributions.

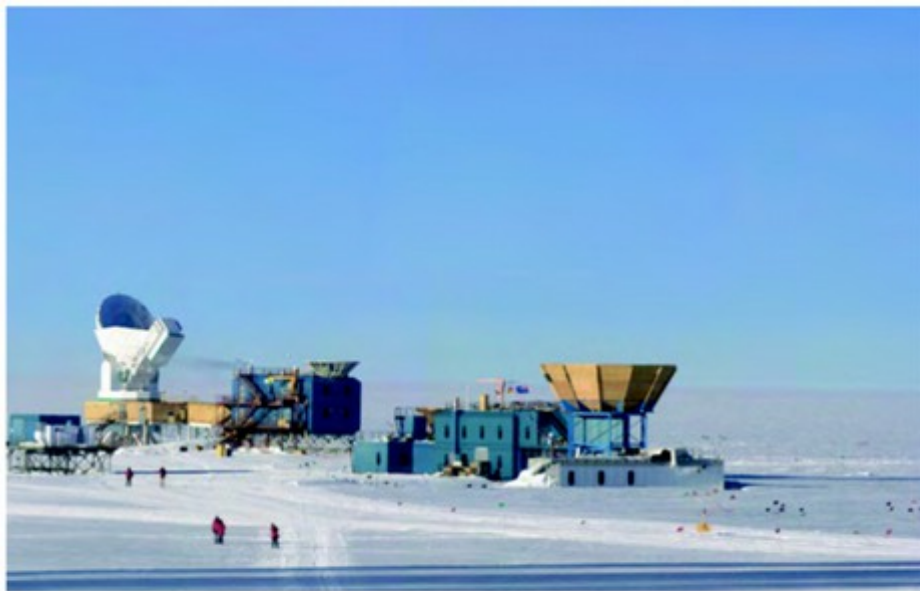


Figure 1: *Left:* the CMB telescope sector at South Pole Station in Antarctica. *Right:* CMB telescopes at Cerro Toco in the Chilean Andes.



# LiteBIRD- CMB polarization satellite mission

JAXA-led CMB polarization mission which is undergoing phase A study in Japan (PI. M. Hazumi) as part of JAXA's strategic mission program. It is expected to be launched as early as in 2026/27.

LiteBIRD is an international collaboration involving researchers from Japan, US (PI: A. T. Lee) and Canada (PI: M. Dobbs).

LiteBIRD's main science objective is to characterize large-scale CMB polarization with unprecedented precision enabling it setting an upper limit on the tensor-to-scalar ratio of  $\sigma(r) \sim 10^{-3}$ .

LiteBIRD is designed to measure what really has to be measured from space, providing opportunities for numerous and fruitful synergies with suborbital CMB and other (21 cm, galaxy survey) efforts.



# LiteBIRD in France

LiteBIRD provides an excellent opportunity for the French CMB community to continue its involvement in cutting-edge, space-based CMB research aiming at some of the most exciting science goals.

Recognizing this, LiteBIRD-France Collaboration constituted itself in March 2017.

It currently involves 10 laboratories in France and ~35 permanent researchers.

A proposal submitted to CNES in September 2017 is currently evaluated. It proposes significant, numerous contributions to the LiteBIRD instruments as well as pipeline development and data analysis. The proposed work builds on unique know-how in space-based CMB programs developed in France as a result of the Planck mission.

LiteBIRD-France collaboration plays also a key-role on the European level spearheading an effort of building an ESA-supported, coordinated European contribution to LiteBIRD under the ESA's Mission of Opportunity program.





# LiteBIRD at APC

At APC the LiteBIRD group is composed of 7 permanent researchers and 2 research engineers.

The involvement of the APC researchers in LiteBIRD dates back to 2014. Since then we have made major contributions to the project via LiteBIRD's Joint Study Groups studying impact of instrumental effects (HWP, etc) and astrophysical foregrounds on performance of the mission.

The APC group has been instrumental in setting up the LiteBIRD-France collaboration and coordinating its work since its inception. APC researchers currently hold co-spokesperson and scientific coordinator functions nationally. We are also well-positioned to play important roles on the European level.

Envisaged hardware contributions from APC are in the area of warm read-out electronics, building on the extensive expertise of the Lab acquired from work on QUBIC and Athena.

We also plan on making significant contributions to a development of data analysis pipeline and data management layer building on our experiences gained from the Planck and POLARBEAR work.





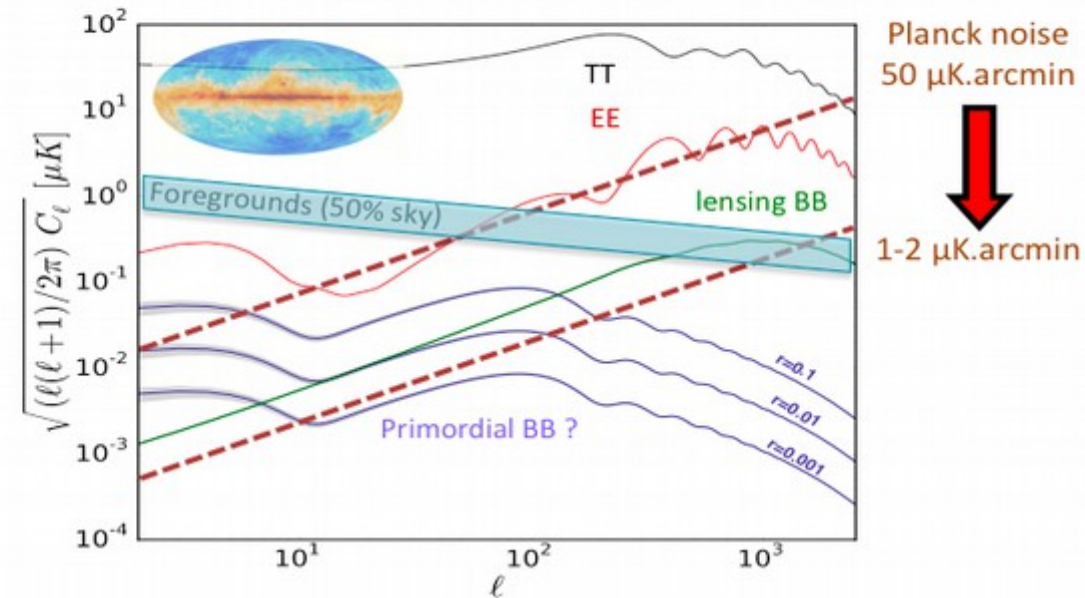
# CORE and "post-CORE-M5" options

## Primordial BB is uncertain (risky target):

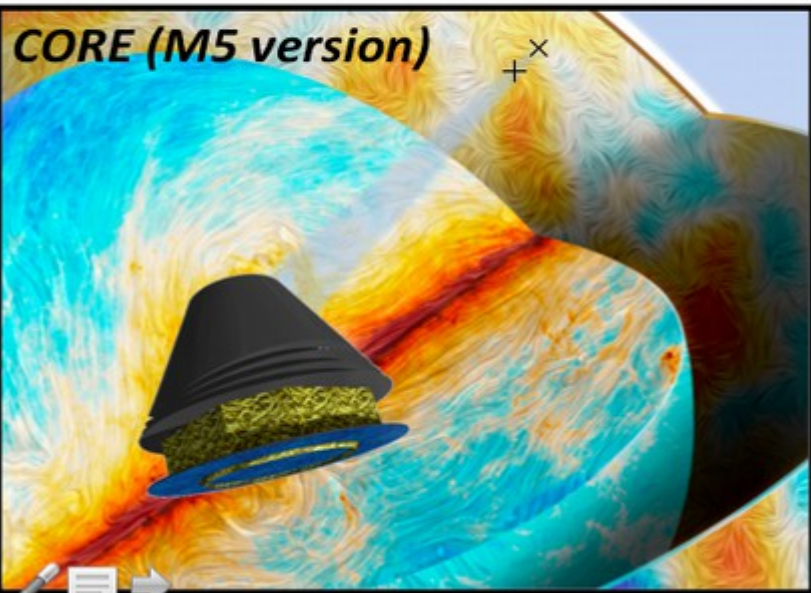
- *foregrounds* are a potential killer at  $l < 10$ ;
- *lensing* and foregrounds are issues at  $l \approx 80$ ;
- $r$  could be  $\ll 0.001$ , beyond detection capability.

## CORE avoids these risks by targeting:

- *primordial B-modes down to fundamental limits, after both de-lensing & foreground subtraction;*
- *guaranteed high-value CMB polarization science;*
- *guaranteed rich legacy.*



CORE (M5 version)



## Status in 2017

CORE did not pass the ESA technical and programmatic screening for M5 in January 2017. The main issue was cost.

Drastic reductions of mirror and focal plane sizes do not solve the issue. An international partner seems necessary.

## Activity for the coming 1-2 years (2018-2019)

Investigate partnership with India for a joint mission to be launched post 2027 (e.g. in  $\approx 2030$ ). Encouraging preliminary contacts in 2017. Involvement of CORE consortium members to NASA CMB Probe study, in preparation for participation in a US-led mission post-2030.



# The APC LSST Team

---

Éric Aubourg — DR CEA — CCS/Lensing/Joint probes

Jim Bartlett — PR P7 — Amas

Josquin Errard — CR — Lensing/Joint probes

Ken Ganga — DR — Joint probes

Cécile Roucelle — MDC P7 — Lensing/Joint probes

Cyrille Doux — thésard — Lensing/Joint probes

Maude Le Jeune — IR — Joing probes

Etienne Marin-Matholaz — IR — CCS

Françoise Virieux — IR — CCS

Begoña Ascaso — Postdoc Marie Curie (fin en 2017)

Mariana Penna-Lima — Postdoc (fin en 2016)

# Recent LSST News

---

- Contribution to the Construction:
  - Camera Command Control System Architecture — Eric Aubourg
  - Development of the Core of the Code — Etienne Marin-Matholaz
    - This provides test-bed support for all sub-systems;
  - Filter changer control system (FCS) development — Françoise Virieux
    - This includes a full-scale model at LPNHE
  - Construction Coordination in France — Eric Aubourg
- Scientific Preparation:
  - Cluster analysis preparation – Bartlett, Penna-Lima, Ascaso
  - Multi-survey lensing analysis preparation & probe combination preparation – Aubourg, Rosset, Ganga, Doux, Penna-Lima, Aubourg



# LSST 2018 –

---

- Construction
  - The project will soon move from construction to integration, and from SLAC to Chile
  - Construction of the filter changer at LPNHE, Filter Change System & Camera Command System
- Scientific Preparation
  - Cluster Cosmology (ANR project led by Bartlett)
  - Preparation of multi-survey joint LSST/Euclid analysis: deblending, combined shear measurement with machine learning (ERC project led by Aubourg)

# Difficulties

---

It is crucial that Etienne Marin-Matholaz's position become permanent.

The CCS development is being done by an APC+SLAC team: there is a significant amount of travel needed, and this need will increase.

There is also not enough financing for scientific preparation meetings (since priority is given to the technical meeting travel budget).

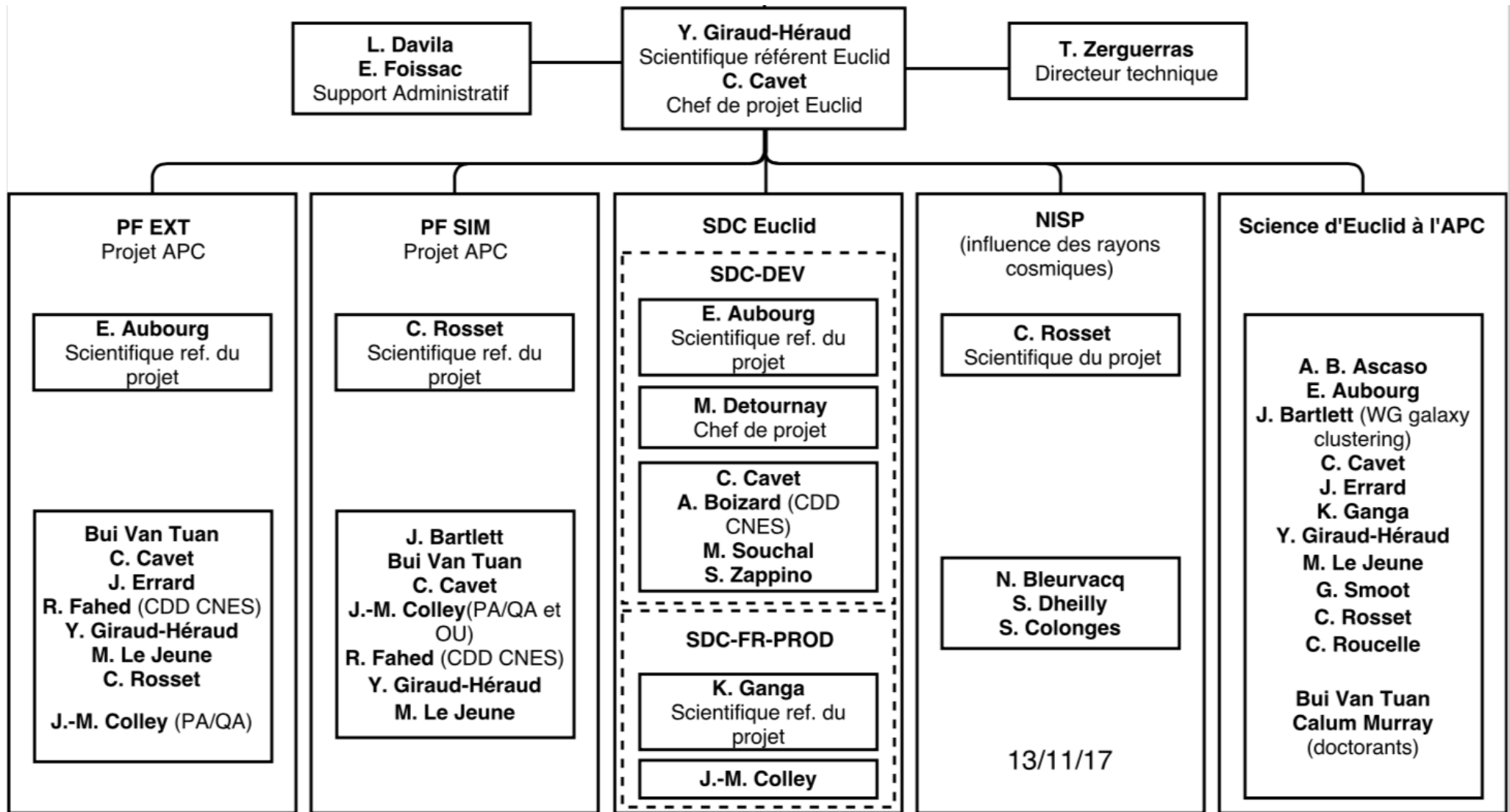


# Euclid

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- ESA's M2 cosmology mission: the near-term successor to Planck.
- Launch expected in 2021, with 7 years of operations.
- APC is contributing to the Euclid External, Simulations, Photometric Redshifts, CMB Cross-Corr...
- Pre-Launch NISP Radiation Testing
- Euclid-France's "Software Development platform" is developed by APC, the IN2P3 and others
- Contributor to Galaxy Cluster Science Working Group
- APC provides the Euclid-France SDC Reference Scientist/CCIN2P3 scientist

# Euclid@APC Organization



Work with  
LSST

Simu-  
lations

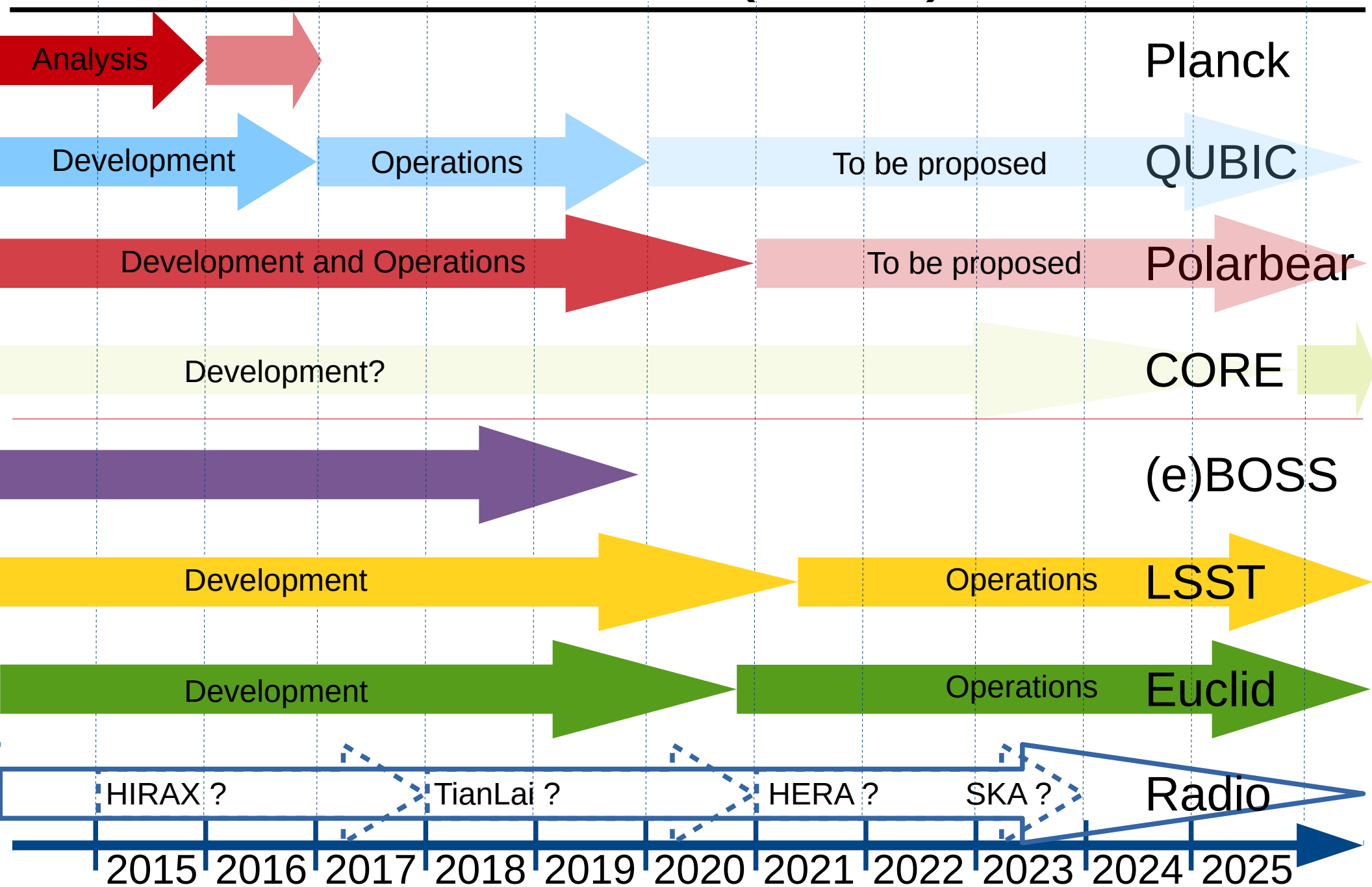
Project  
Support

Cosmic  
Ray Tests

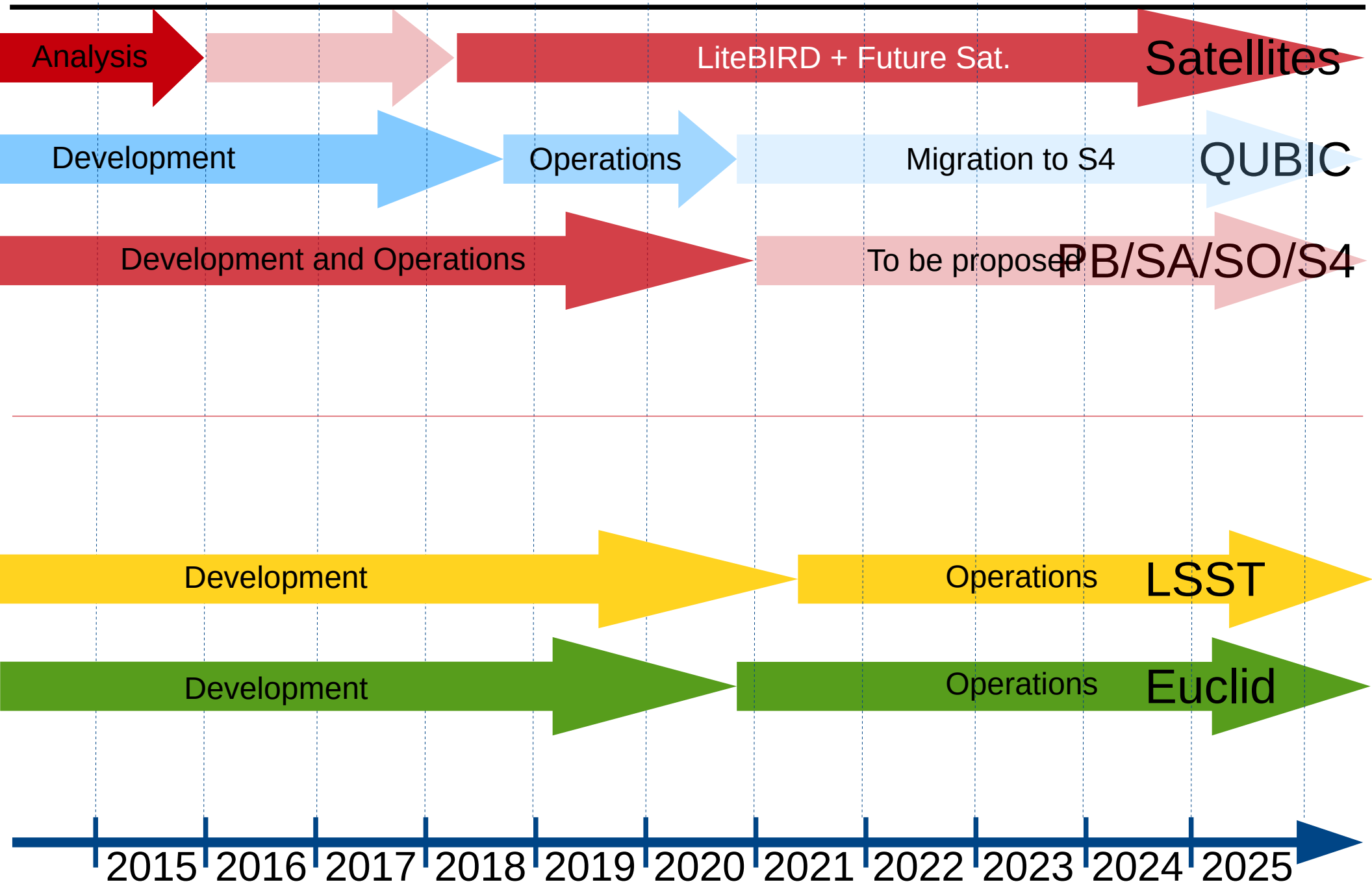
“Science”



# Timeline (2015)



# Timeline (2017)

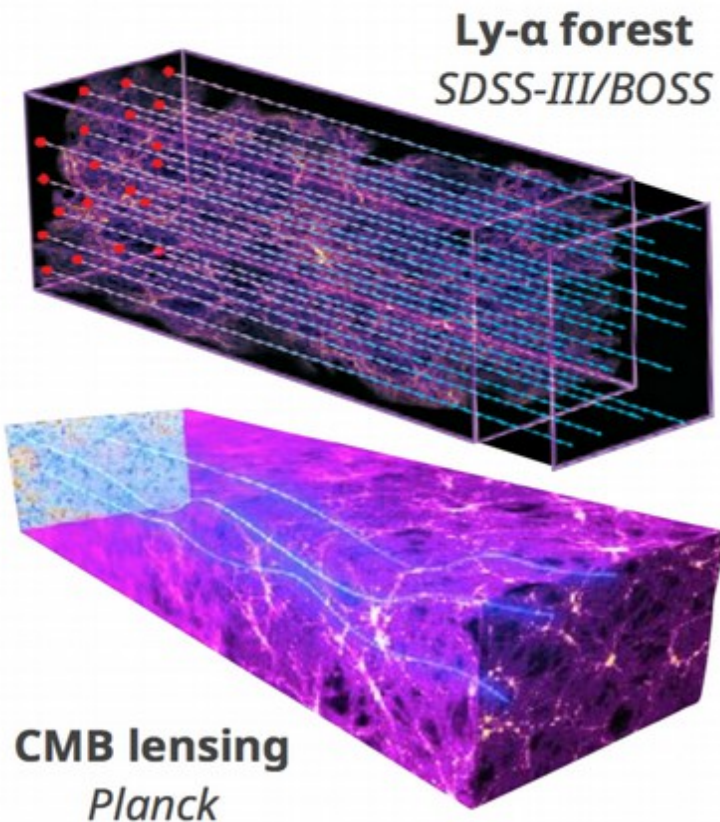




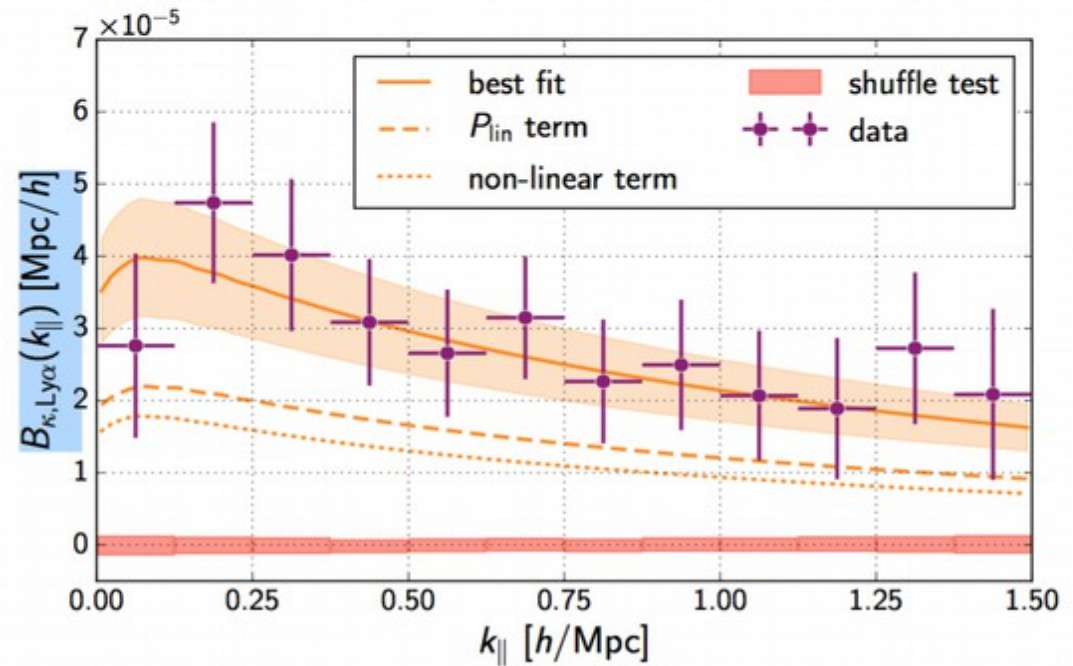
# Cross-correlation studies at APC

Combining multiple cosmological probes can

- reveal new effects : CMB lensing  $\times$  Ly- $\alpha$  forest, kinetic SZ effect
- break degeneracies and improve constraints on cosmological parameters
- test extensions of  $\Lambda$ CDM (forecasts):  $f_{\text{NL}}$ ,  $\Sigma m_{\nu}$ , modified GR



Measuring position-dependent power spectrum



*Doux, Schaan et al., PRD (2016).*

# Summary

---

- The “Low-z” branch of the Cosmology group has stable projects, Euclid & LSST and well-defined roles.
- The CMB branch of the Cosmology group is still “transitioning” from Planck to new projects.
  - QUBIC expects on-site sky data in 2018
  - Analysis involvement in Polarbear is evolving with the experiment to Simons Array. The intention is to contribute on more aspects to Simons Observatory and CMB Stage-4
- APC is leading Europe towards LiteBIRD involvement, and while CORE has not been selected, other possibilities are still being explored



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# Thanks!