IN2P3 activities and developments for CMB-S4

Manuel Gonzalez

on behalf of the CMB-S4@IN2P3* team and with many inputs from the CMB-S4 collaboration

*Horacio Arnaldi[(1)], James Bartlett [(1)], Olivier Bourrion[(4)], Andrea Catalano[(4)], Céline Combet[(4)], Jacques Delabrouille[(2)], Elena de la Hoz[(2)], Cyrille Doux[(4)], Josquin Errard[(1)], Ken Ganga[(1)], Xavier Garrido[(3)], Manuel Gonzalez[(1)], Jean-Christophe Hamilton[(1)], Sophie Henrot-Versillé[(3)], Julius Hrivnac[(3)], Marine Kuna[(4)], Fabian Lambert[(4)], Sotiris Loucatos[(1)], Thibaut Louis[(3)], Juan Macías Pérez[(4)], Frédéric Mayet[(4)], Jerôme Odier[(4)], Julien Peloton[(4)], Laurence Perotto[(4)], Michel Piat[(1)], Damien Prêle[(1)], Fatah Rarbi[(4)], Radek Stompor[(2)], Jean-Pierre Thermeau[(1)], Steve Torchinsky[(1)], Matthieu Tristram[(3)], Christophe Vescovi[(4)]

(1) AstroParticule et Cosmologie (APC)

(2) Centre Pierre Binétruy (CPB)

(3) Laboratoire de Physique de 2 infinis, Iréne Joliot-Curie, (IJCLab)

(4) Laboratoire de Physique Subatomique et Cosmologie, (LPSC)

Who Am I

Manuel Gonzalez
Postdoc at APC since 2020
CMB-S4 project and collaboration member

Experience relevant to CMB-S4

- Development and operation of cryogenic instruments
- Microfabrication of superconducting devices
- Design and test of cryogenic readout chains
- Modelling of TES and SQUID readout
- Experience in TES readout for QUBIC and ATHENA

Member of the ATHENA X-IFU detection chain and CMB-S4 readout WGs

CMB-S4@IN2P3

- For the last several years, there has been a **community at IN2P3** interested to participate to CMB-S4 (periodic meetings).
- In 2020 CMB-S4 was identified as a **priority prospective** for IN2P3.

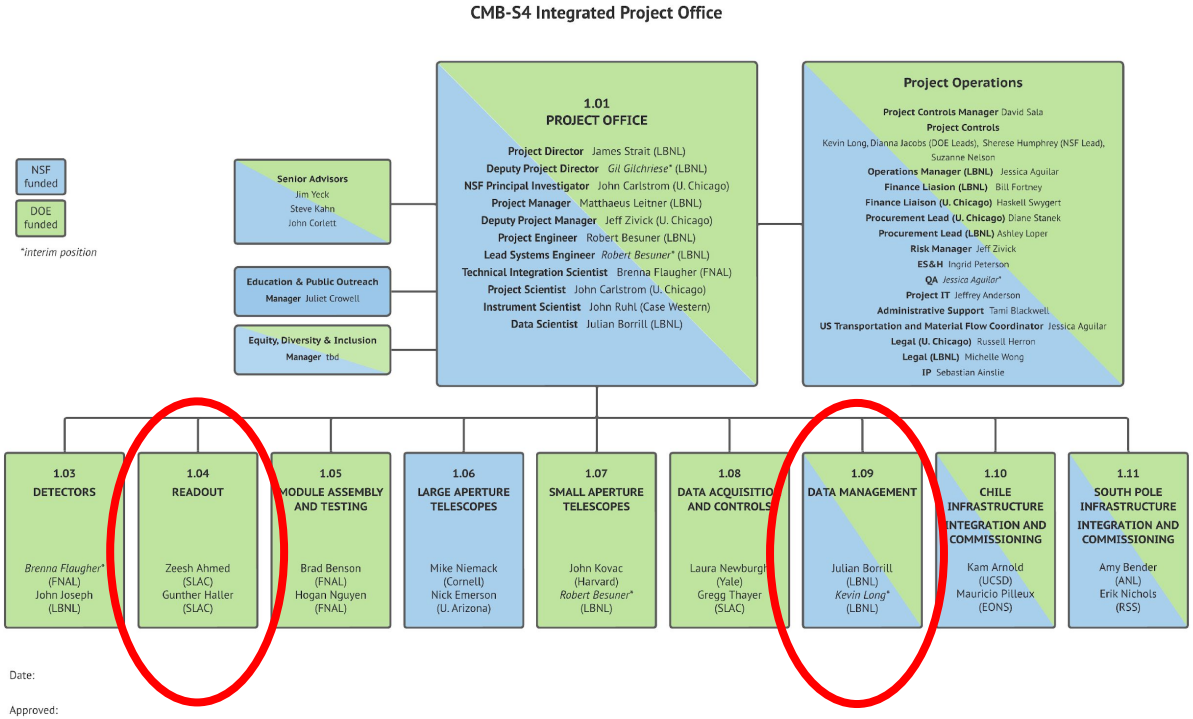
  "Develop a project plan based on the required expertise and identified resources for a French contribution to the CMB-S4 project."

- Two general areas of common interest were identified:

  detection chain and **data management.**

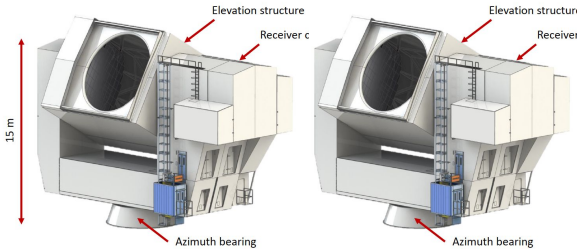
- During the last two years we have worked to formalize and consolidate the potential contributions.
- In 2023, CMB-S4 was added as an annex to a Cooperative Research and Development Agreement (**CRADA**) between LBNL and IN2P3.

CMB-S4@IN2P3

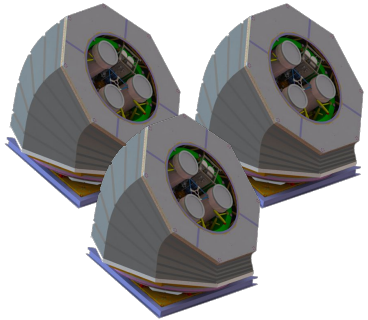


Commitment in the **CRADA** for the next 3 years in Readout and Data Management

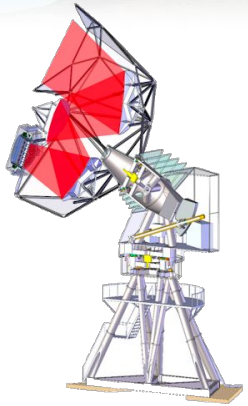
CMB-S4 instrument overview



Two Chile LATs



Three South Pole SATs



One South Pole LAT

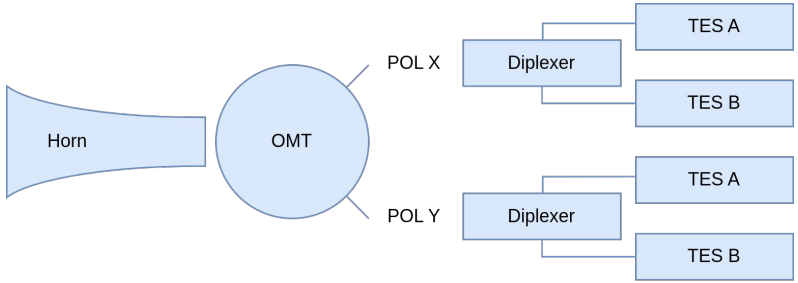
All instruments:

- Use two-polarization, dichroic pixels… *except the ULF on the SPLAT which is single-color.*
- Use 100mK TES bolometers with a time-division multiplexed readout.
- Share the same band implementations (on the wafer) for LF and HF channels.

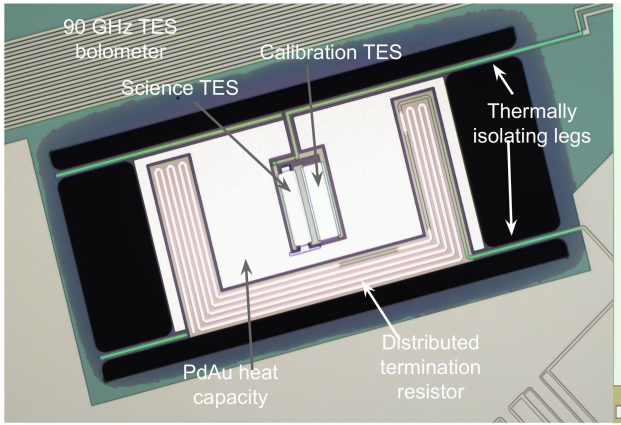
All LATs:

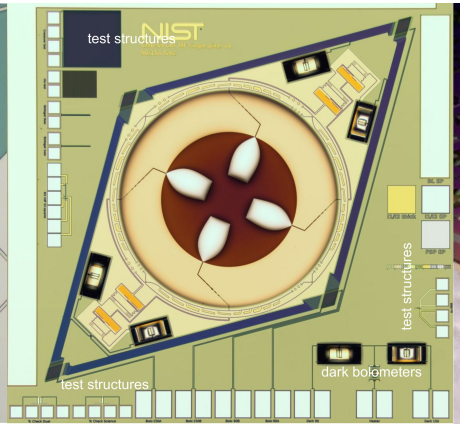
- Share the same MF band implementations
- Use the same basic cryostat and optics tube design (with small modifications)

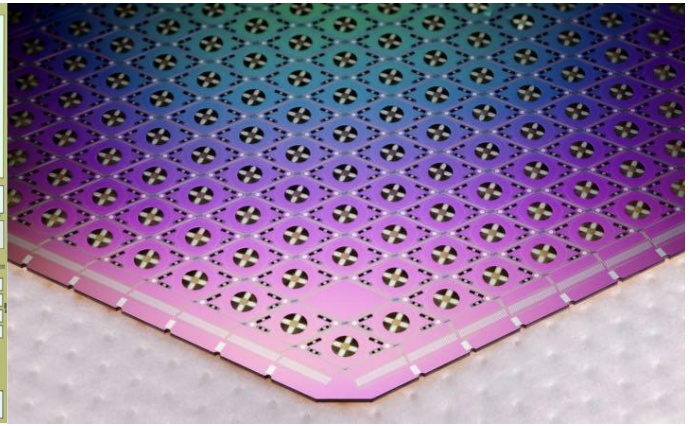
CMB-S4 detectors



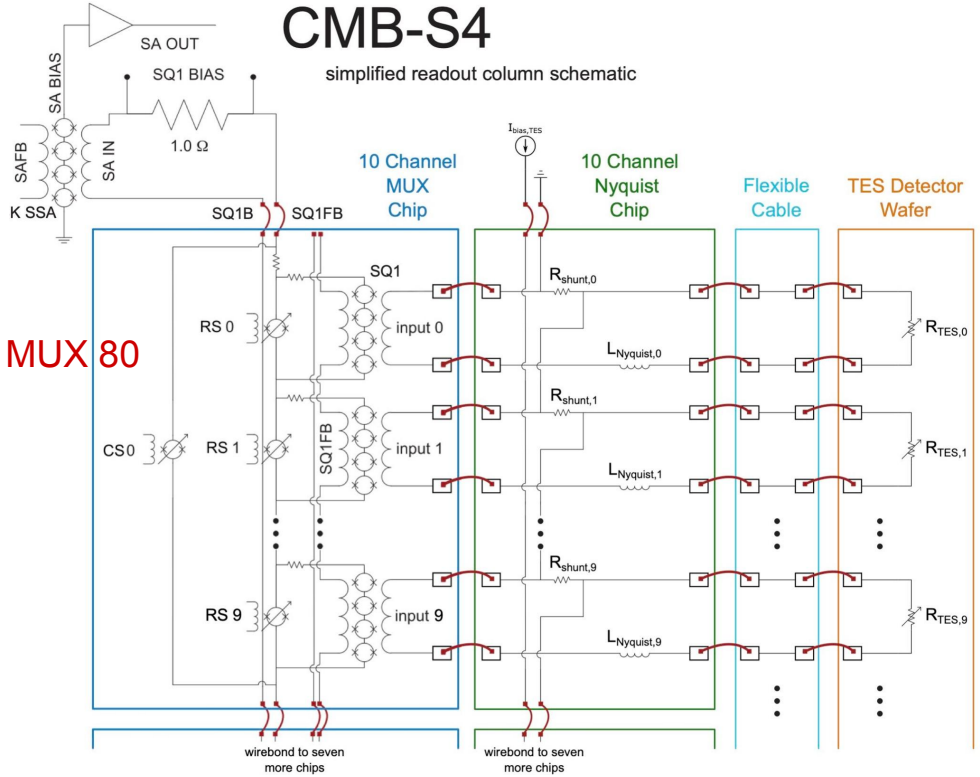
- Horn coupled TES bolometers
- Dichroic and dual-polarization pixels
- 500,000 TES in total
- Photon noise limited
- Dual Tc
- Time-division multiplexing (MUX 80)
- Proven technology from stage-3
- 6 fabrication sites
- 5 test sites

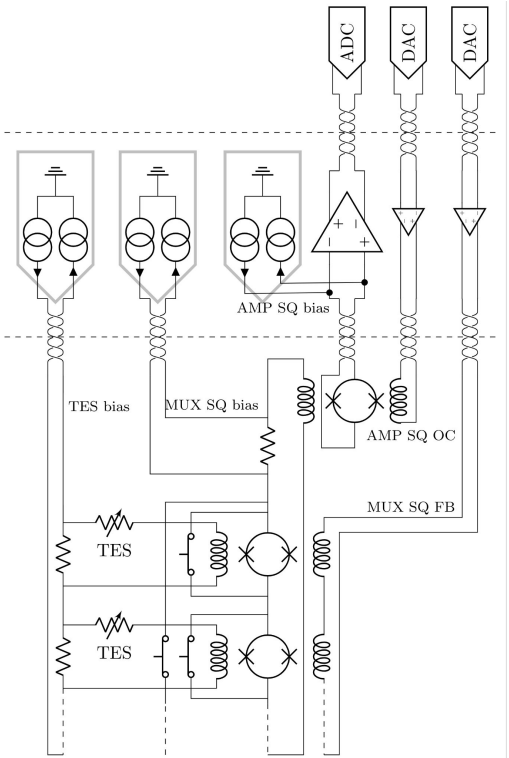




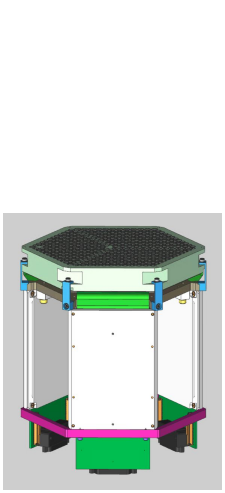


Time-division multiplexing





Readout subsystem



Light from telescope

100mK stage

Detector and readout module

feedhorn

photonic choke

waveguide interface plate

detector wafer

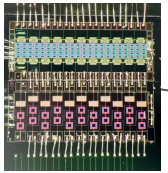
backshort

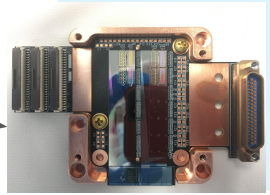
1-6x

100mK readout module

superconducting flex

SQUID multiplexer and TES bias chips





100mK row address module

Contains SQUID Series Array Amplifier

25-wire NbTi cable

51-wire NbTi cable

4K stage

4K SSA module

4K SSA module

4K SSA module

4K row address module

Cryogenic cabling

100-wire manganin cable

51-wire manganin cable

300K stage

300K readout module

300K readout module

300K readout module

300K row address module

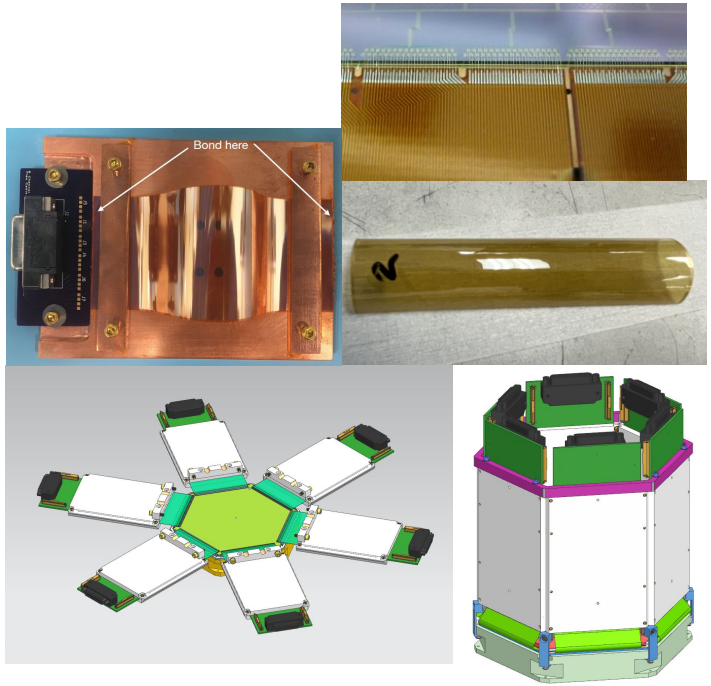
Warm electronics modules

Superconducting Flex

- Development led by CEA
- Production planned to be carried by two companies Hightec and Cicor/Microtech.
- Flexible
- Superconducting
- Low parasitic resistance ($\ll 1 m\Omega$)
- High yield (~100%)

AI assisted **visual inspection** tool to be developed

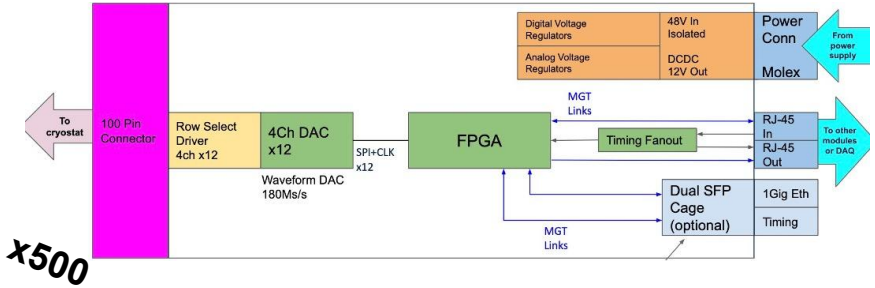
Cryogenic tests to be performed at APC/Cryo-MAT

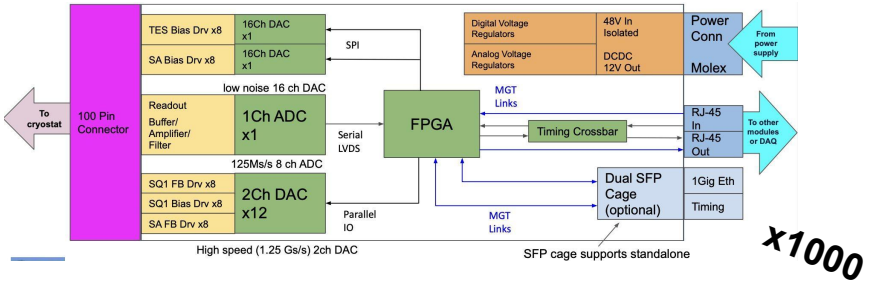


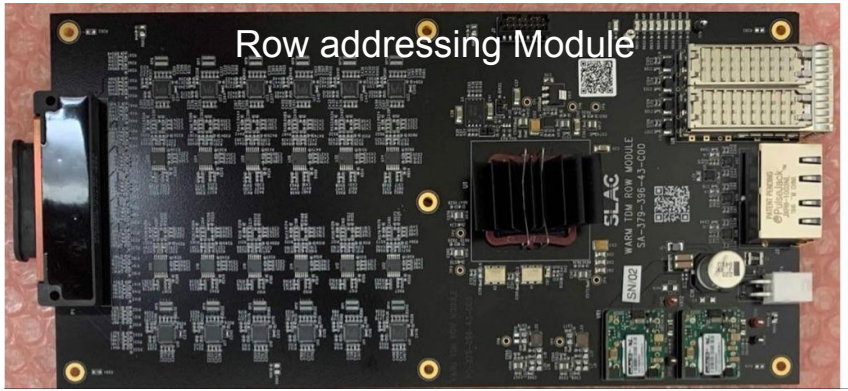
CEA-Irfu: Xavier de la Broïse, Jean-Luc Sauvageot, Jean-Baptiste Melin, Etienne Burtin, Sotiris Loucatos
CNRS-In2p3-APC: Damien Prêle, Manuel Gonzalez, Michel Piat, Jean-Pierre Thermeau

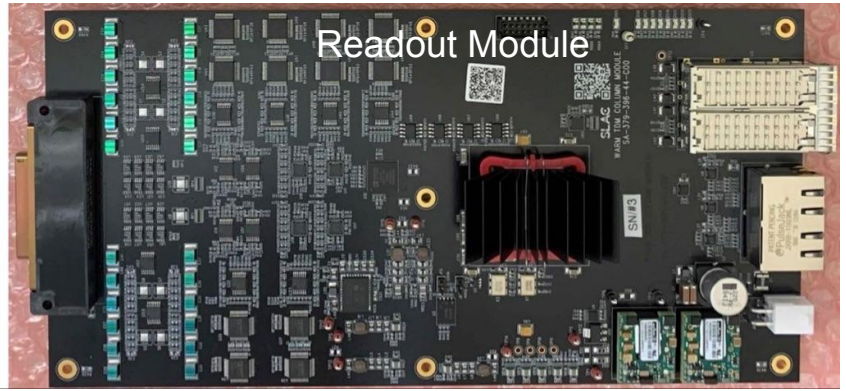
Warm readout

This subsystem is under SLAC responsibility



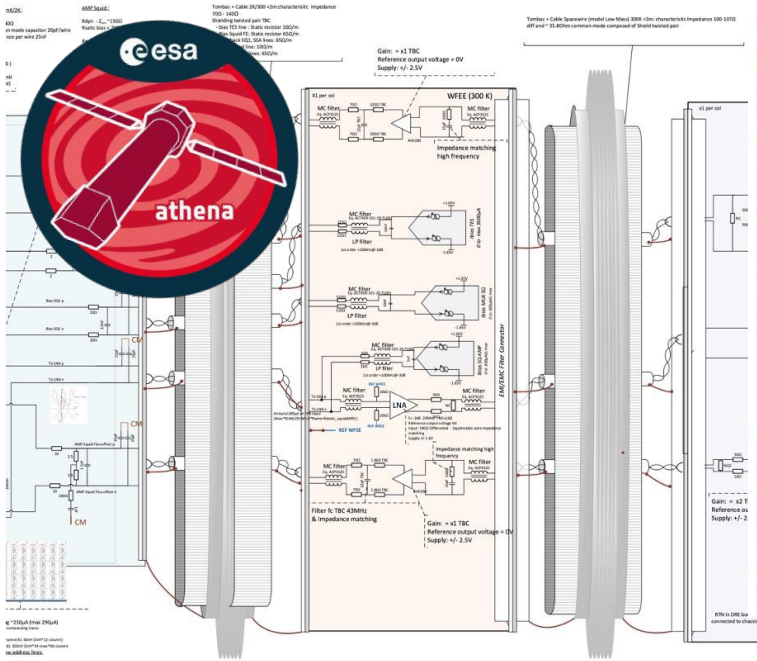






Warm readout background

Front-end readout ASIC family designed for ATHENA X-IFU



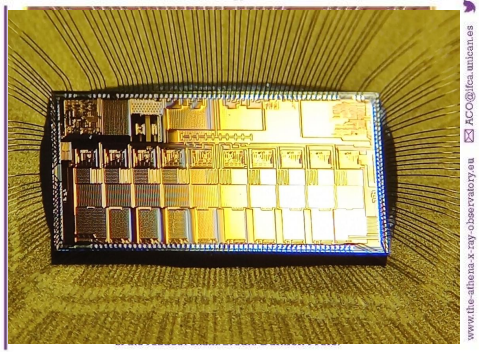
Specific Integrated Circuit for the X-IFU Warm Front-End Electronics

Damien Prêle (APC, Paris) on behalf of the WFEE and X-IFU detection chain team.

The X-IFU (X-ray Integral Field Unit) instrument of the Athena mission is designed to operate with 3168 superconducting microcalorimeters (read out by Transition Edge Sensors - TES) cooled to 50 mK, providing an imaging spectrometer for X-ray astronomy. The unprecedented spectral resolution of 2.5 eV up to 7 keV requires low noise readout electronics. Located immediately outside the cryostat, the Warm Front End Electronics (WFEE) is a key component of the readout electronics.

The WFEE amplifies the detection chain signal, adjusts the operating points of the cryogenic devices (Superconducting QUantum Interference Devices - SQUIDs), and feeds through the TES bias and feedback loop. Using Frequency Domain Multiplexing (FDM, see Athena Nugget #25 for more details), 40 microcalorimeters are read out per channel and 40 carriers between 1 to 5 MHz are injected to 40 sensors. As a result, the detected X-ray pulses are transposed into 40 different frequencies. Ultimately, about one hundred channels are needed for the full readout of the TES array.

To meet the energy resolution of the cryogenic sensors, the WFEE, like the whole readout chain, has to exhibit ultra-low noise and extremely small gain-drift. At the same time, the size, the mass, and the dissipation must be minimized as required for a space mission. For this reason, an Application-Specific Integrated Circuit (ASIC) has been designed for the WFEE. "350 nm BiCMOS SiGe" ASIC technology is used for the core of the WFEE. "350nm" corresponds to the minimum gate size of MOS transistors. "BiCMOS" means that both bipolar transistors and complementary (N and P) MOS transistors can be built using this technology. Finally, "SiGe" indicates that Silicon-Germanium alloy is used to make the base-emitter junction of the bipolar transistor. Such a hetero-junction increases the speed of the transistors allowing the design of a wide-band amplifier covering the frequency range of the carriers used for the FDM. The micro-photograph illustrates an ASIC chip design for the WFEE. Eight independent readout channels will be integrated on a chip of one square centimetre.



The noise degradation of WFEE is minimized by reducing any parasitic resistance and thanks to fine-tuning of the transistors biasing to operate in an optimal noise condition.

The gain drift is also a significant contributor to the energy resolution budget. At large time scale (> 1s), the thermal drift is the main cause of electronic parameter shifts. The entire circuit is based on a specific design including thermal compensation techniques.

The WFEE with its custom designed ASIC is a compact, light-weight component with minimal power consumption and it delivers the high performance required for Athena's X-IFU readout electronics.

IFU | Project: ATHENA X-IFU | Ed.: DID 1.2 | Rev.: 0 | Date: 20/04/2022 | Format: custom | Page

Athena X-ray Observatory
@AthenaXobs
ACO@ifca.unican.es
www.the-athena-x-ray-observatory.eu

IN2P3 contributions: warm readout

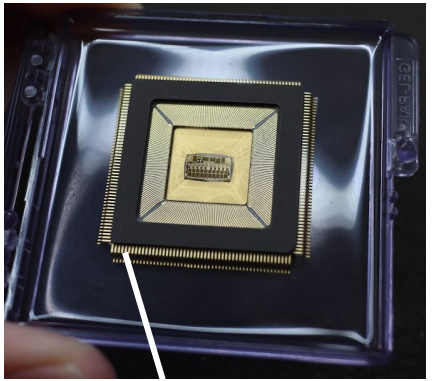
- The objectives have been identified in the CRADA
- A real ongoing collaboration with SLAC, multiple visits and biweekly meetings
- First hardware to be delivered mid December

DELIVERABLES

1. WBS 1.04 Readout
   - a. DOE
     - i. Front-End module schematic/layout/fab with ASIC front-end board
     - ii. Functionality/performance test with IN2P3 ASIC daughter board with ASIC_v3 in CQFP208 package on front-end card
     - iii. Functionality/performance test with IN2P3 ASIC daughter board with ASIC_v3 in new smaller package on front-end module (same daughter board foot-print and IO)
     - iv. Modification of warm readout module (schematic/layout/fab) to incorporate In2P3 ASIC daughter board with ASIC_v4
     - v. Functionality/performance test of readout module with In2P3 ASIC daughter board with ASIC_v4
   - **b. IN2P3**
     - i. Schematic/layout/fab/bench test of **ASIC daughter board with ASIC_v3** in CQFP208 package for front-end module
     - **ii. Package ASIC** in new smaller package
     - **iii. Schematic/layout/fab/bench test of ASIC daughter card** with ASIC_v3 in new smaller package for front end module
     - **iv. Design/fab/test ASIC_vS4**
     - v. Schematic/layout/fab/bench test of ASIC daughter card with ASIC_vS4 in new smaller package for warm readout module.

Front-end readout daughter board

Drop-in integrated circuit for analog readout.
Bias and amplification for 2 TDM columns.
Initially developed for X-ray TES readout (ATHENA)
Fully differential, low noise and low thermal drift.



Daughter board based on current package.

- Currently in fabrication
- **To be delivered next week**
- First tests planned for december

2 x **LNA** 20 MHz 0.7 nV/√Hz
2 x DC DAC for **SQ1 bias**
2 x DC DAC for **SSA bias**
2 x DC DAC for **TES bias**
DACs controlled through I2C

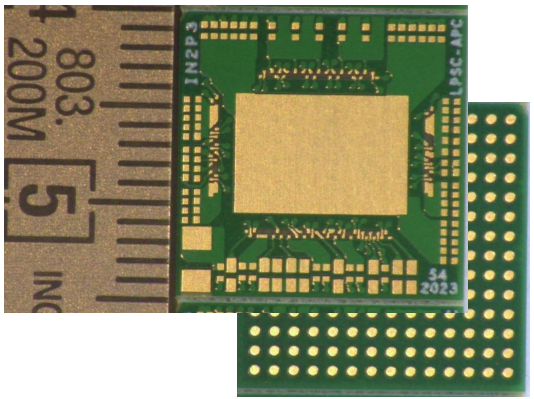
Design of new compact BGA package

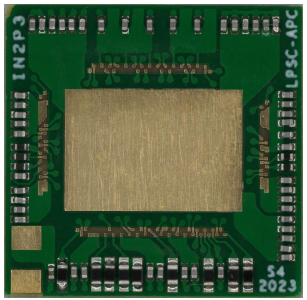
1.5 cm PCB with glued and bonded ASIC naked die and passive components
Compact system in package of the ASIC as a BGA*
In preparation for 4 ASICs integration in one board

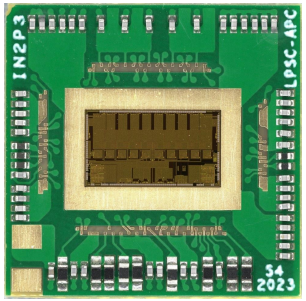
*Ball Grid Array - BGA : chip carrier, surface-mount packaging

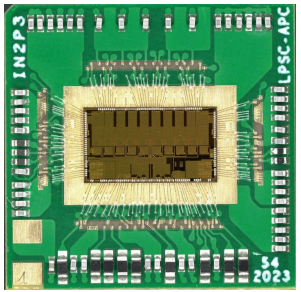
Company	Work	Delay
PCB electronics (french company)	**PCB Fabrication**	4 weeks
LPC Clermont-Ferrand (IN2P3 Lab)	**Soldering** - Passive components	2 weeks
C4PI @IPHC (IN2P3 Lab)	**wire bonding** - Chip on Board	2 weeks
Itancia	Solder Bump	6 weeks

WE ARE HERE

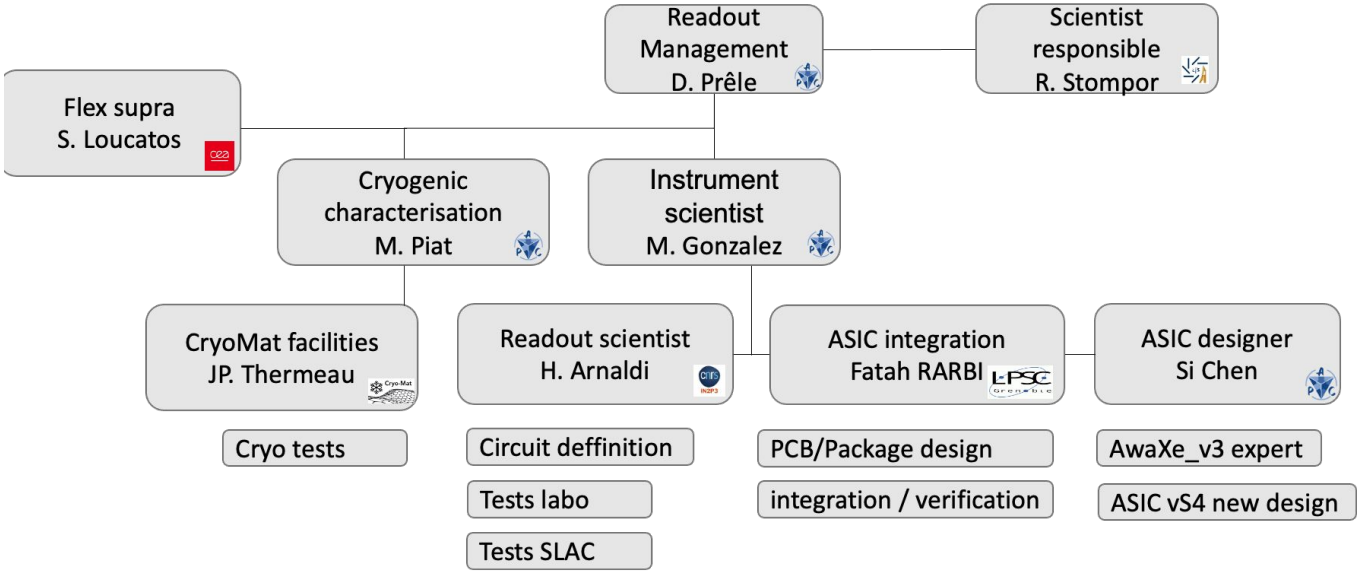




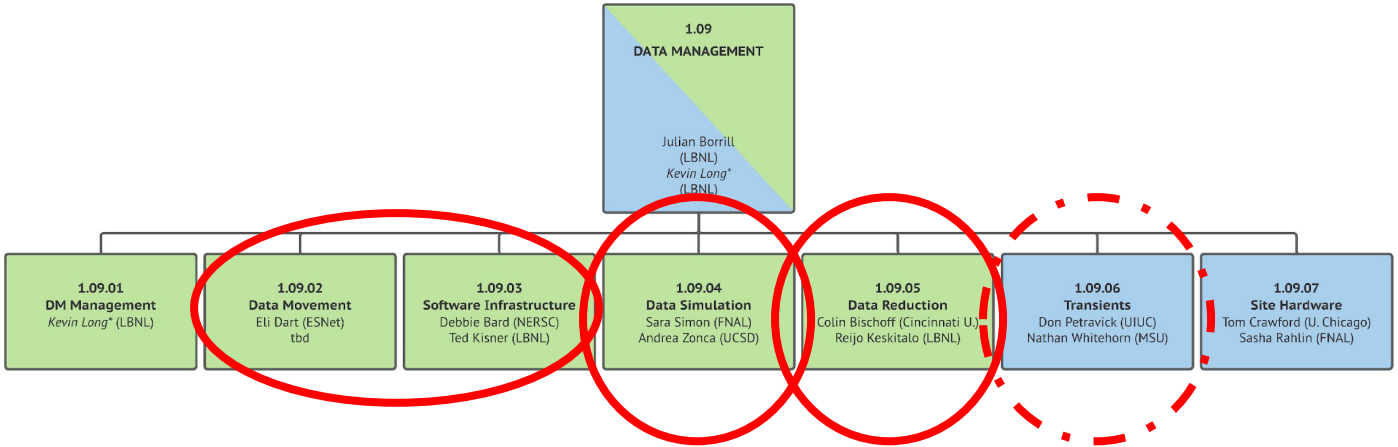




CMB-S4 readout in France organization



Data management



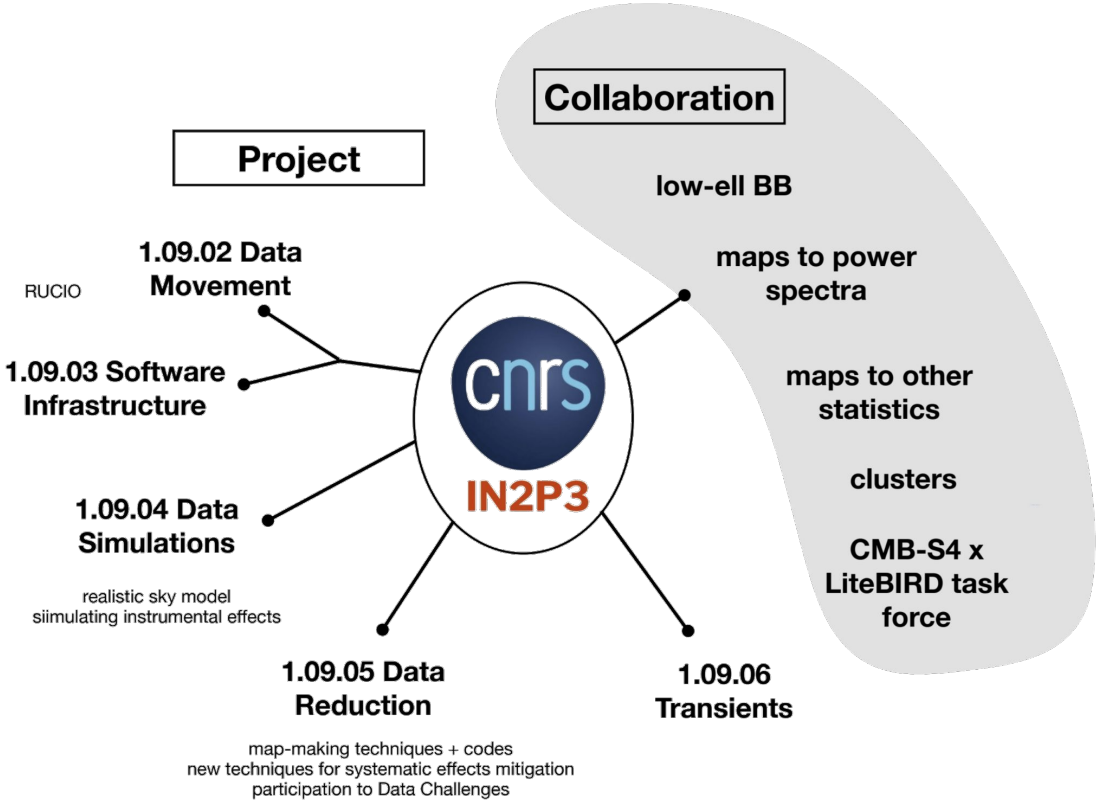
Currently considered in CRADA:

- 1.09.02. Data Movement
- 1.09.03. Software Infrastructure
- 1.09.04. Data Simulations
- 1.09.05. Data Reduction

Longer term and not included in CRADA at this time:

- 1.09.06. Transients

IN2P3 contributions DM & collaboration



- RUCIO infrastructure for data movement and metadata tracking
- Simulations of realistic sky models and instrumental effects
- Map-making and systematics
- FINK7 for transient candidates
- CPB can host IN2P3 researchers working on CMB-S4 at Berkeley or Stanford.

- Capitalizing on software development for, and access to the real data of, Simons Observatory.

Conclusions and way forward

- Strong interest of the IN2P3 community on the CMB-S4 science and instrumental developments
- The French contributions are being formalized and the activities for the next three years are being defined
- Cohesive effort to capitalize the development for other CMB projects
- Articulated activities between IN2P3 labs and CEA on readout
- Strong collaboration with SLAC
- First French CMB-S4 hardware to be delivered next week
- We need to start thinking about the production phase

IN2P3 contributions: 1.09.02 and 1.09.03

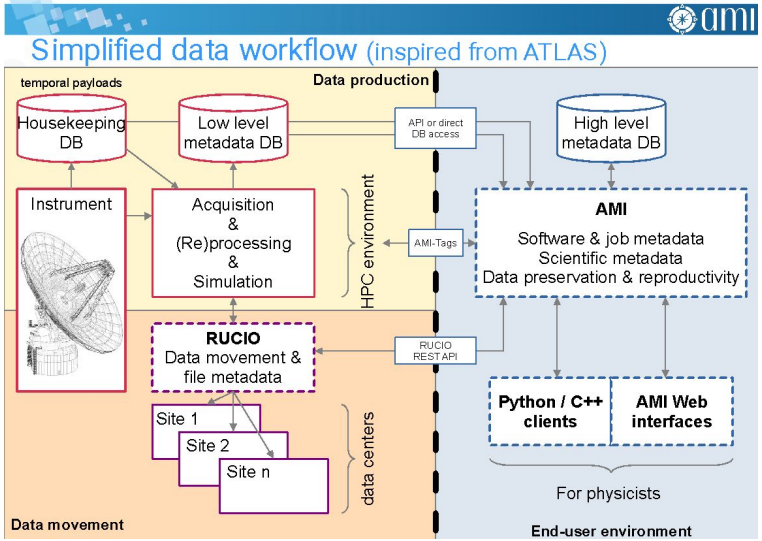
Data movement (1.09.02) and **Software infrastructure** (1.09.03) – these tasks cover all data storage and (local) data movement infrastructure for the project work and the collaboration. Led by Ted Kisner (LBL) and Debbie Bard (NERSC) at the Project Office level.

Our potential contributions:

- implementing the Atlas Metadata Interface (AMI) for tracking and managing the CMB-S4 database on the metadata level, (LPSC)
- porting and adapting RUCIO as an actual data movement tool originally developed for ATLAS.

Specific, level 4 and 5 tasks covering these contributions are:

- Registration for Data Movement, 1.09.02.01;
- Data and Metadata Indexing, 1.09.03.01.3;
- Tracking of Workflows and Data Products, 1.09.03.04.2.



AMI team@LPSC

IN2P3 contributions: 1.09.04

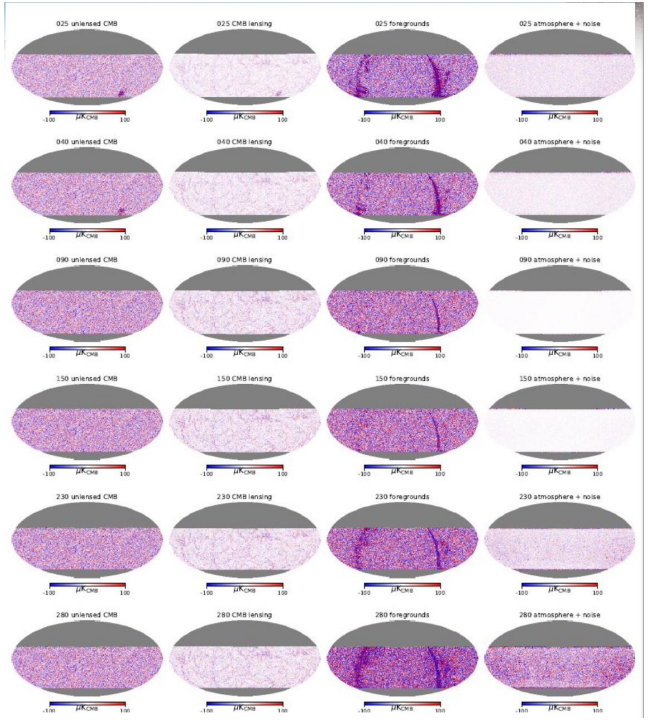
Data Simulations (1.09.04) – development and implementation of progressively more realistic, in terms of data volumes and complexity of numerical tools, and production of data sets with increasing level of realism to validate design choices, set requirements, and demonstrate data analysis tools.

This effort is led at the Project Office by Andrea Zonca (UCSD) and Sara Simon (Fermilab).

The specific areas we plan on contributing to are:

- development, implementation and validation of new sky, realistic sky models;
- development, implementation and validation of numerical modules simulating instrumental effects.

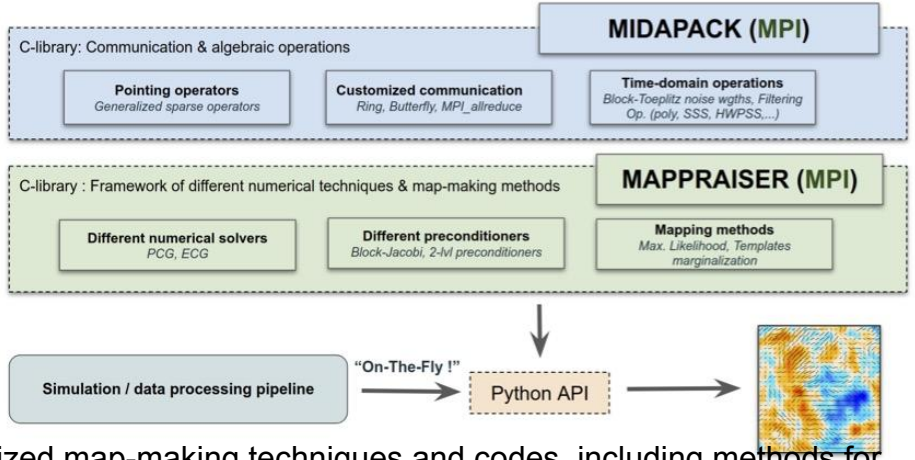
These correspond to WBS Level 4 tasks: 01.09.04.02-04.



IN2P3 contributions: 1.09.05

Data Reduction (1.09.05) – development and implementation of progressively more capable, precise, and efficient numerical tools for characterization of the raw CMB-S4 data and of reducing them to more manageable, pixel-domain objects, together with their sufficient statistical characterization, including residual systematic effects.

The leads of this effort are Reijo Keskitalo (LBNL) and Colin Bischoff (Cincinnati).



The specific contributions we envisage here include:

- development, implementation, and validation of new generalized map-making techniques and codes, including methods for statistical characterization of all the derived pixel domain products;
- development, implementation, and validation of new techniques for systematic effects mitigation;
- application of the developed tools to the project-wide Data Challenges as those become available, starting with DC0 which will become available this summer.

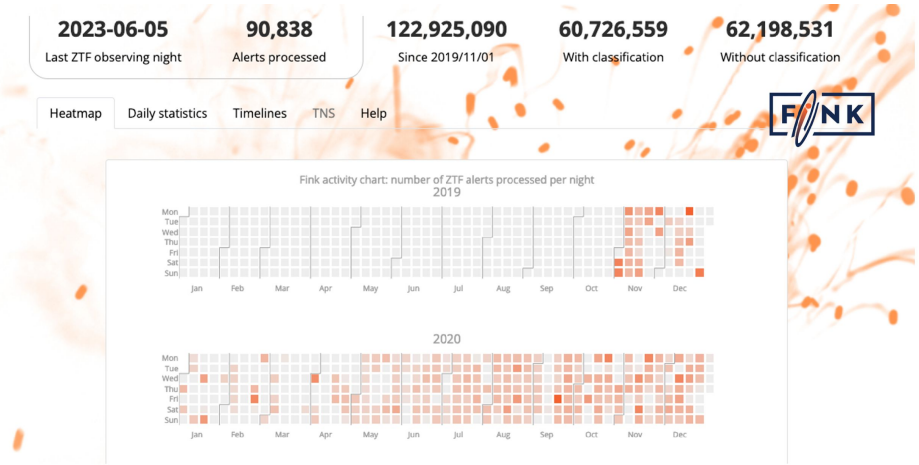
These contributions correspond to the level 4 tasks 1.09.05.03 and 1.09.05.04 in the WBS. We expect to play eventually coordinating role on some of these tasks.

IN2P3 contributions: others

Transients (1.09.06):

The real-time event detection software, FINK7, (J.Peloton, IJCLab). FINK is one of the leading so-called brokers, selected for use by Rubin Observatory and is currently validated on data of Zwicky Transient Factory.

The proposed work would include extending the software to allow for an efficient, candidate event; determination in microwave band and porting and maintaining it in the CMB-S4 software infrastructure.



IN2P3 contributions: Collaboration work

Low-ell BB: working toward developing tools and techniques appropriate for the B-mode detection, using predominantly data from Small Aperture Telescopes envisaged to operate from the South Pole. The work of this AWG will be a key for constraining the physics of inflation and therefore fundamental physics laws at the extremely high energies.

Maps to power spectra: working on techniques and software for CMB power spectrum estimation and targeting Large Aperture Telescopes (high resolution/large sky coverage). This AWG will play a key role in constraining the properties of relativistic particles present in the Universe, including neutrinos, and those from beyond the standard model of particle physics.

Maps to other statistics: working on higher order statistics, which will allow to improve on the constraints on inflation (via e.g., delensing and constraints on primordial non-Gaussianity) and provide clues about the nature of dark energy via characterization of the kinematic and thermal Sunyaev-Zel'dovich effects.

Clusters: studying the properties of clusters and therefore contributing to the constraints on cosmology from clusters.

Joint LiteBIRD CMB-S4 Task Force: exploring synergies between the two experiments.