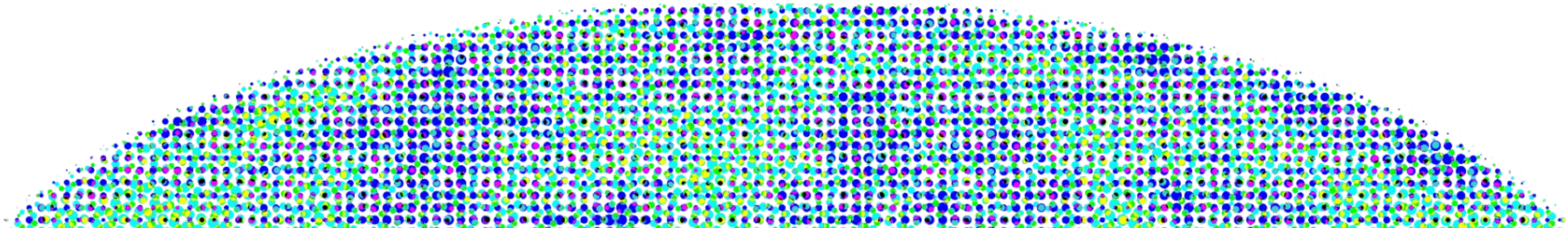
CMB S4

From the next generation cosmology experiment to cryogenic detectors

19 June 2025



Elisa Radjabou

1st Year PhD at APC

Laboratoire AstroParticules et Cosmologie
Sous la direction de Michel Piat et Damien Prêle

On behalf of the CMB S4 collaboration

Presentation outline

- The experiment
- APC contribution
- My PhD subject : Detector and read out modelization and characterisation

Scientific context

From the Big Bang to today

- Inflation

Hot, dense, opaque plasma dominated by photons

- Recombination

380 000y after Big Bang, Universe cools down, and nucleus can catch free electrons → Transparent Universe

- Dark ages

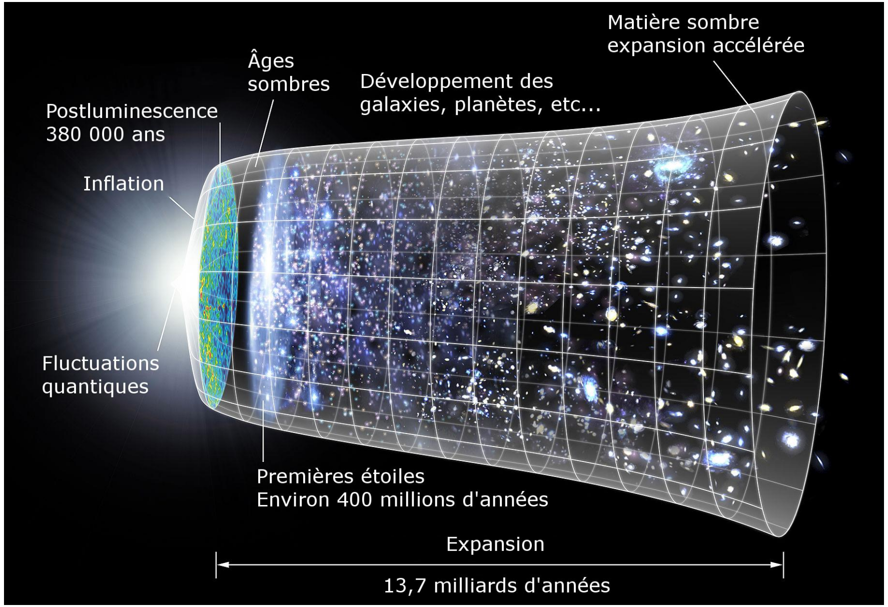
Neutral and cold Universe

- Reionization

Stars radiation ionises matter → plasma

- Millimetric observation

As the Universe expanded, CMB cooled down to T_{CMB} ~ 2,7 K



Cosmic Microwave Background

- Big Bang’s light relic
- Black body spectrum at 3K
- Slightly anisotropic (~µK)

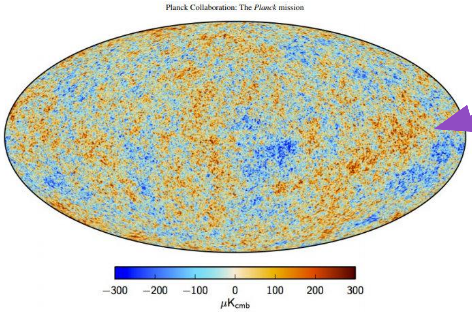
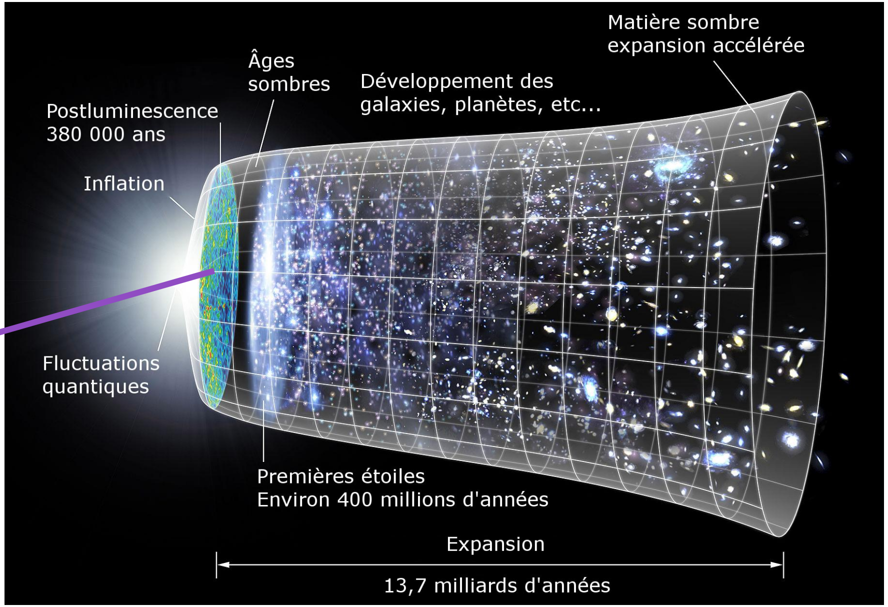


Image of the temperature anisotropies of CMB from the Planck mission (2016)



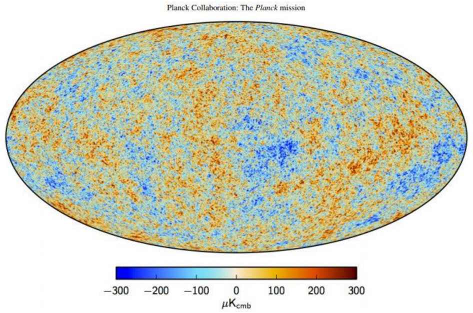
B modes of CMB polarization

Temperature anisotropies

CMB anisotropies have extensively been observed by many space and ground missions

Polarisation modes

New interest in the cosmology community :
B modes of polarisation



- Big Bang scenario
- Hot and dense past
- Inflation
- Galaxy formation and large scale structure
- ...

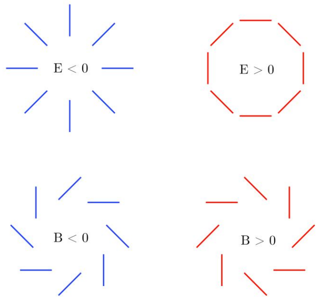
B modes of CMB polarization

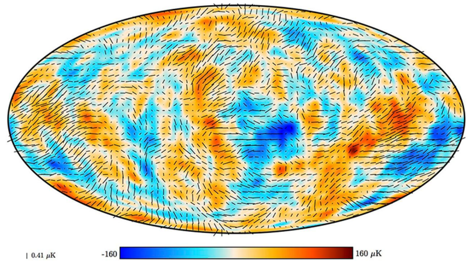
Temperature anisotropies

CMB anisotropies have extensively been observed by many space and ground missions

Polarisation modes

New interest in the cosmology community : B modes of polarisation

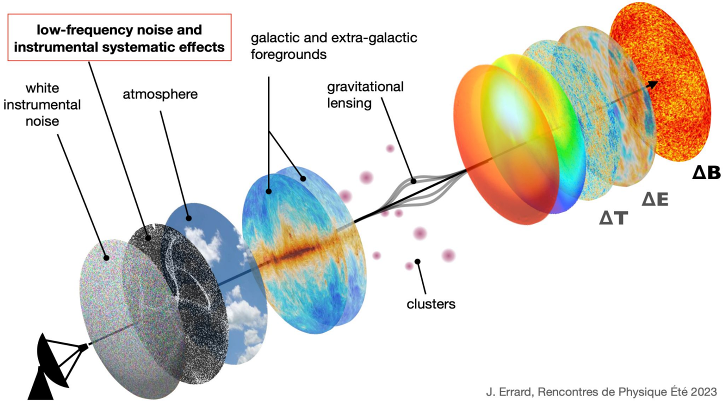




- Inflation
  - ❏ Primordial gravitational waves
  - ❏ Constraints on r
- Neutrino physics, axion dark matter
- Mapping matter
  - ❏ gravitational lensing
- Multi-messenger astronomy

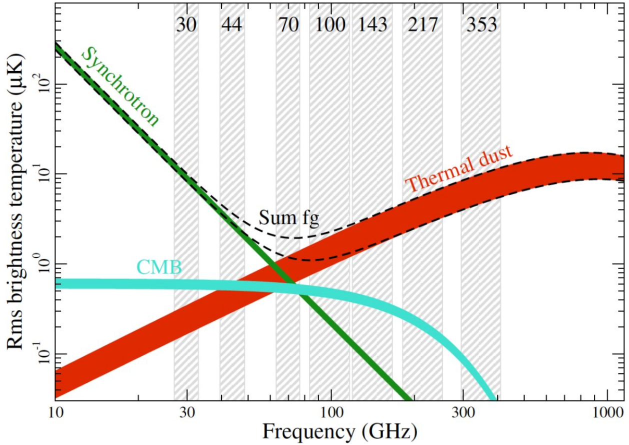
B modes of CMB polarization

CMB Foregrounds



J. Errard, Rencontres de Physique Été 2023

Polarization anisotropy of the CMB foregrounds



Planck Collaboration, Adam, R., Ade, P. A. R., et al. 2015
arXiv:1502.01588

The CMB S4 instrument

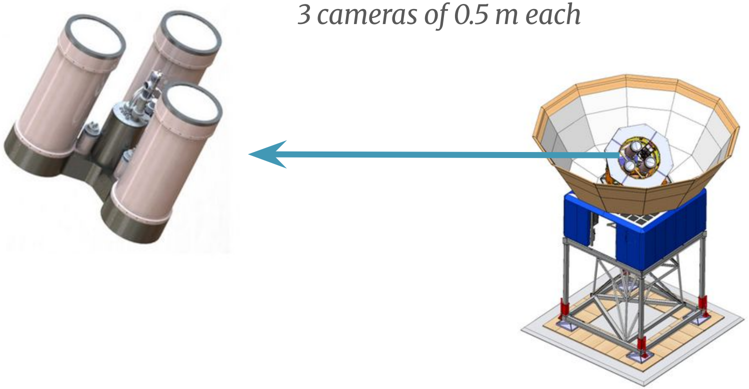
Telescopes with frequency ranging from **20 to 280 GHz** in, to be deployed in Chile

(Final configuration is currently under study)

2 – 9 SAT tubes

D = 56 cm

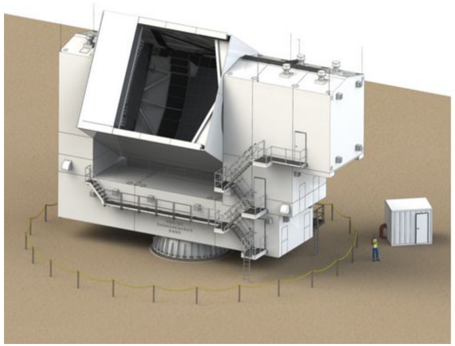
3 cameras of 0.5 m each



1 – 3 LAT

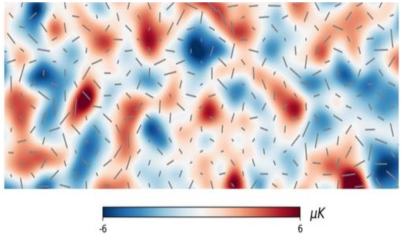
D = 6m

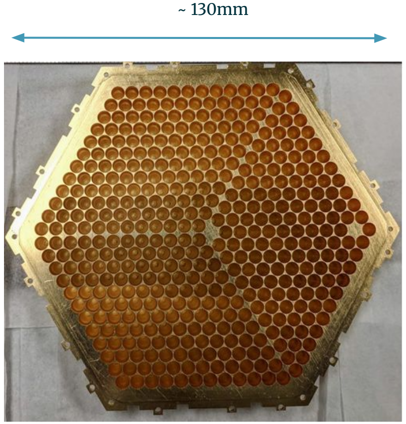
high angular resolution



The detectors

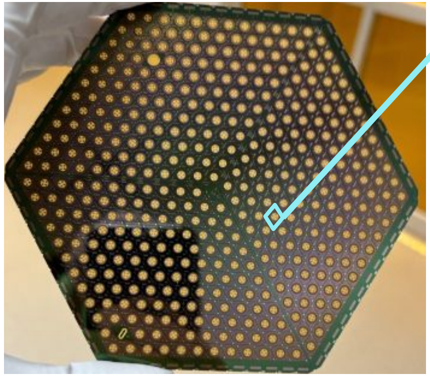
Overview : bolometers array coupled to the sky by antennas and read out in time-division multiplexing



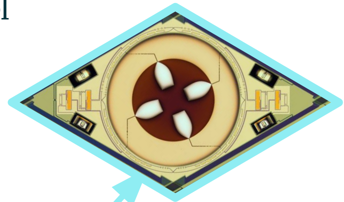


Gold plated Al feedhorn antenna prototype
Simons Observatory

antenna coupled to the wafer



TES array
NIST



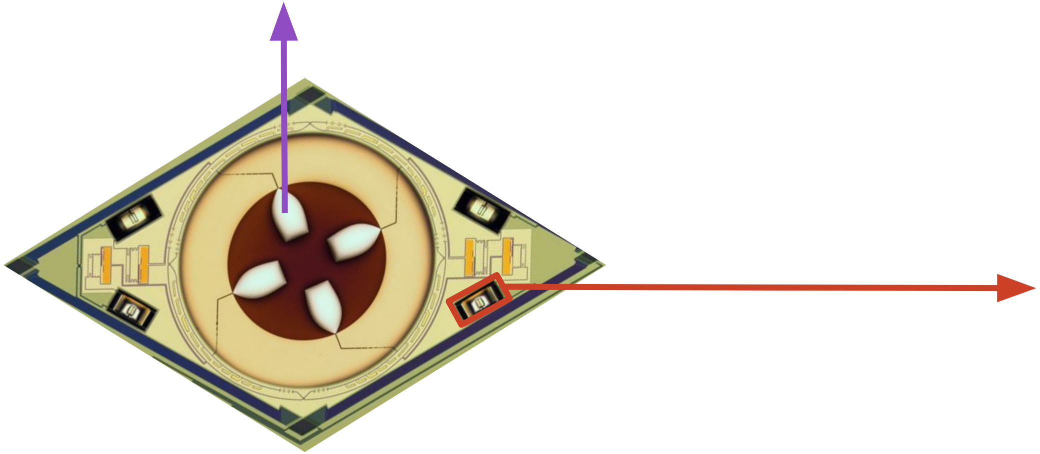
Single pixel
NIST

The detectors

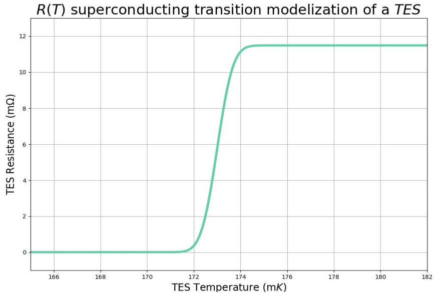
The **OMT** detects the two CMB polarization modes :

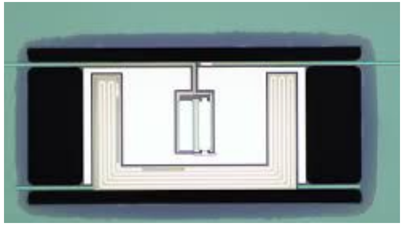
For every polarization we separate in two frequencies

Ortho Mode Transducer OMT



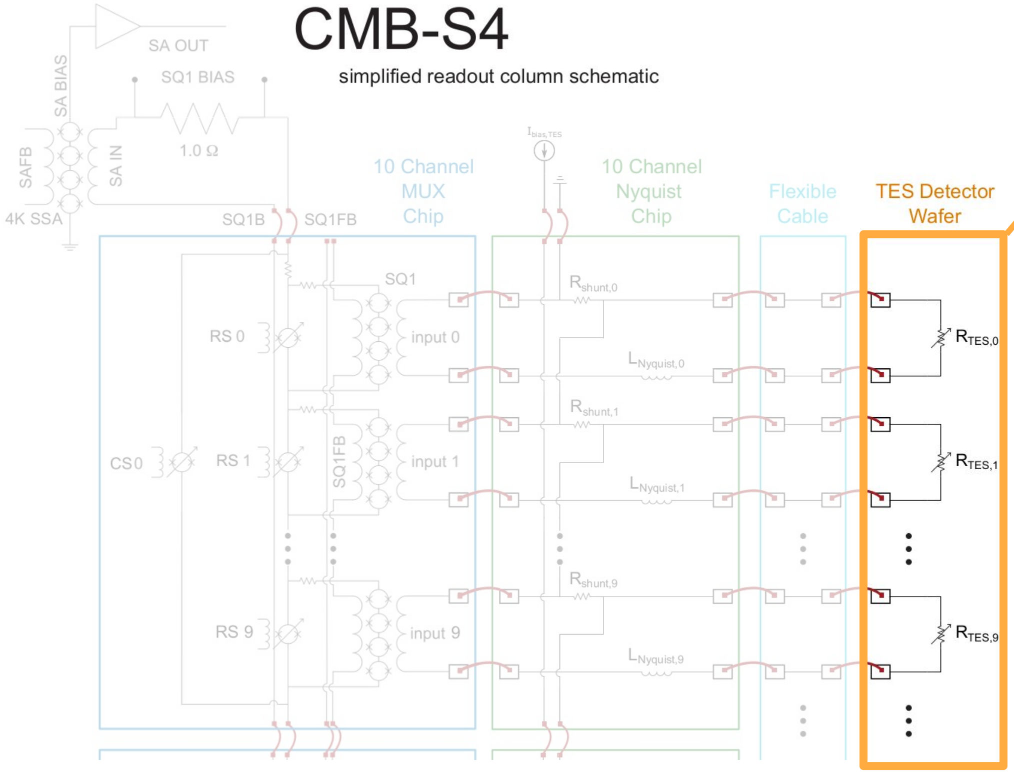
The bolometer **TES** converts the sky signal in current variation





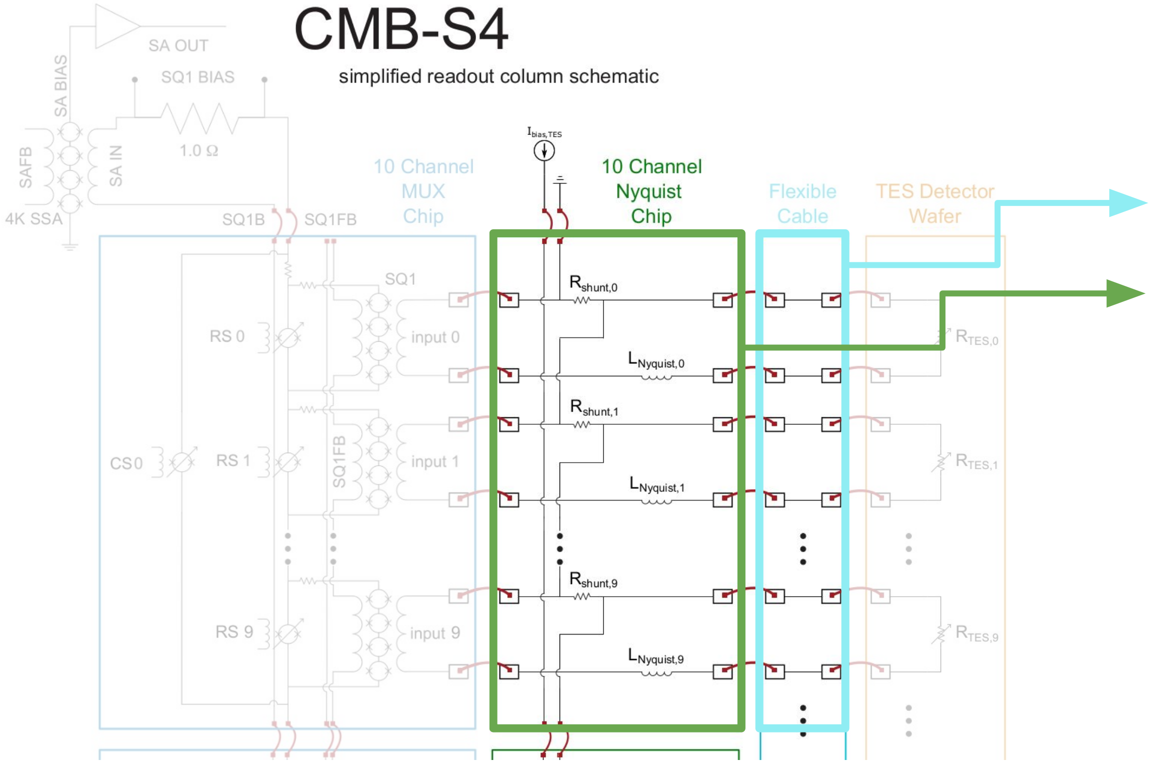
Transition Edge Sensor TES

Cryogenic detectors and read out



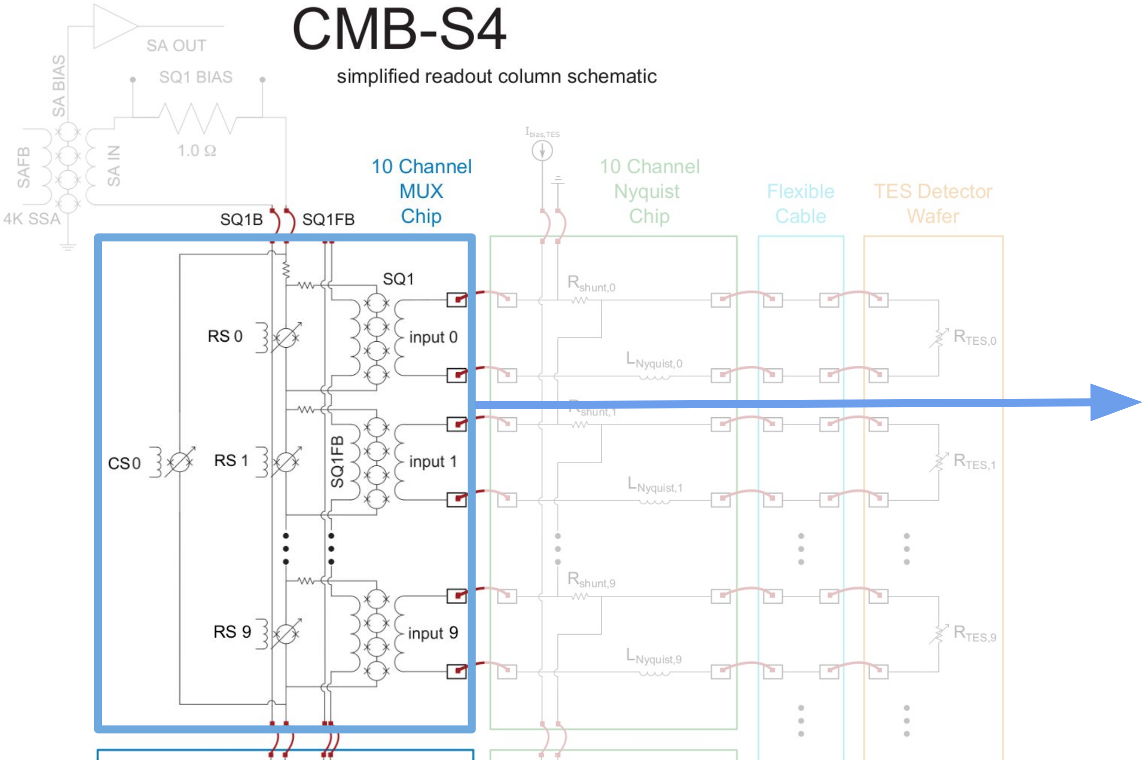
- Transition Edge Sensors **TES** transduce change in optical power to changes in current (100 mK)
- Connected via superconducting flex cables
- Shunted by small resistance
- Signal from each TES is multiplexed by **S**uperconducting **QU**antum **I**nterference **D**evice *SQUIDs* ***SQ1 MUX*** *(100 mK)*
- Signal amplified by an array of SQUIDs ***SSA***
- Pre amplifier at room temperature
- DAC in current for biasing

Cryogenic detectors and read out



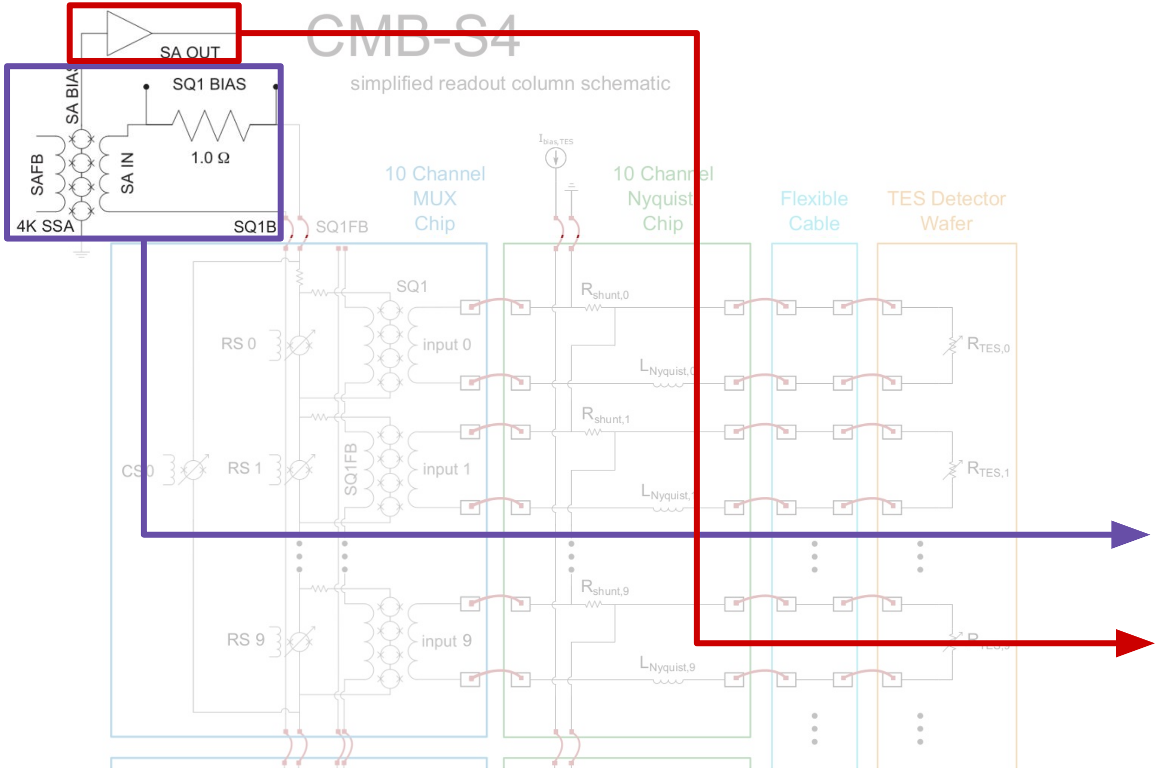
- Transition Edge Sensors **TES** transduce change in optical power to changes in current **(100 mK)**
- Connected via superconducting flex cables
- Shunted by small resistance
- Signal from each TES is multiplexed by **S**uperconducting **QU**antum **I**nterference **D**evice *SQUIDs* ***SQ1 MUX (100 mK)***
- Signal amplified by an array of SQUIDs ***SSA***
- Pre amplifier at room temperature
- DAC in current for biasing

Cryogenic detectors and read out



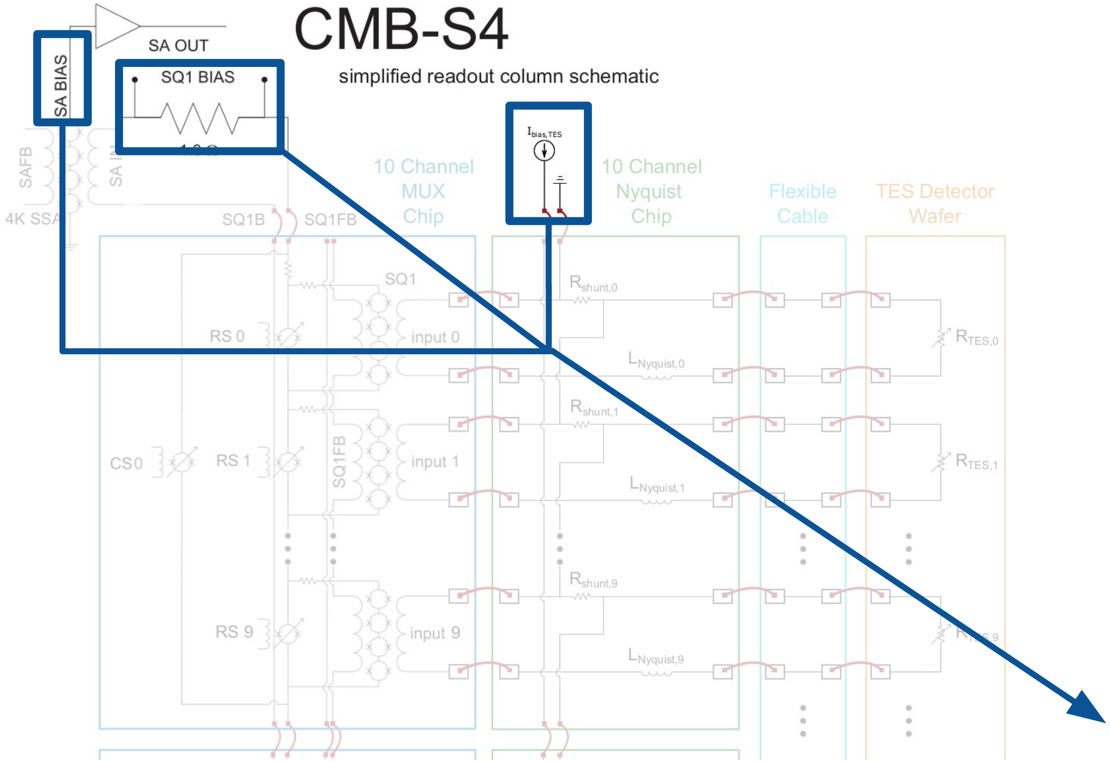
- Transition Edge Sensors **TES** transduce change in optical power to changes in current (100 mK)
- Connected via superconducting flex cables
- Shunted by small resistance
- Signal from each TES is multiplexed by Superconducting QUantum Interference Device *SQUIDs SQ1 MUX (100 mK)*
- Signal amplified by an array of SQUIDs ***SSA*** *(4 K)*
- Pre amplifier at room temperature LNA
- DAC in current for biasing

Cryogenic detectors and read out



- Transition Edge Sensors **TES** transduce change in optical power to changes in current (100 mK)
- Connected via superconducting flex cables
- Shunted by small resistance
- Signal from each TES is multiplexed by Superconducting QUantum Interference Device *SQUIDs SQ1 MUX (100 mK)*
- Signal amplified by an array of SQUIDs *SSA (4 K)*
- Pre amplifier at room temperature *LNA*
- DAC in current for biasing

Cryogenic detectors and read out



- Transition Edge Sensors **TES** transduce change in optical power to changes in current (100 mK)
- Connected via superconducting flex cables
- Shunted by small resistance
- Signal from each TES is multiplexed by Superconducting QUantum Interference Device *SQUIDs SQ1 MUX (100 mK)*
- Signal amplified by an array of SQUIDs ***SSA*** *(4 K)*
- Pre amplifier at room temperature ***LNA***
- DAC in current for biasing

APC contributions

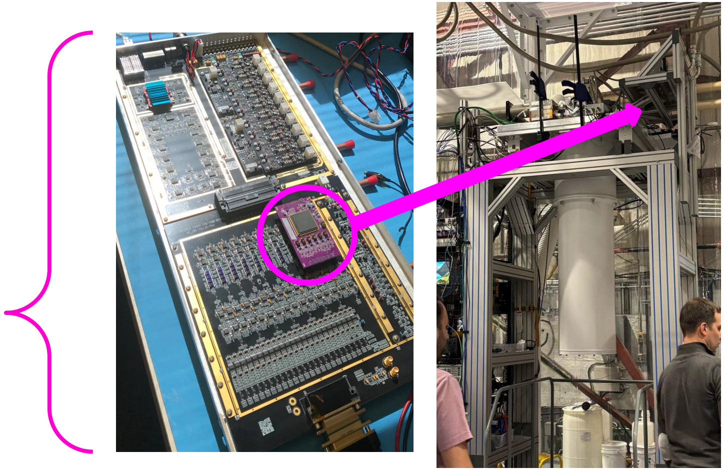
- Meeting at SLAC and LBNL 18-20 March 2025
    - Readout, cryogenics, LaboDRTBT/Cryo facilities, Cryomat, Flex, readout modelization +first SSA coupling with cryogenics results

- CMB S4 Collaboration meeting 24-26 March 2025 at LBNL

- Interdisciplinary Instrumentation Colloquium 19 March 2025 at LBNL (QUBIC/ATHENA/CMB-S4)

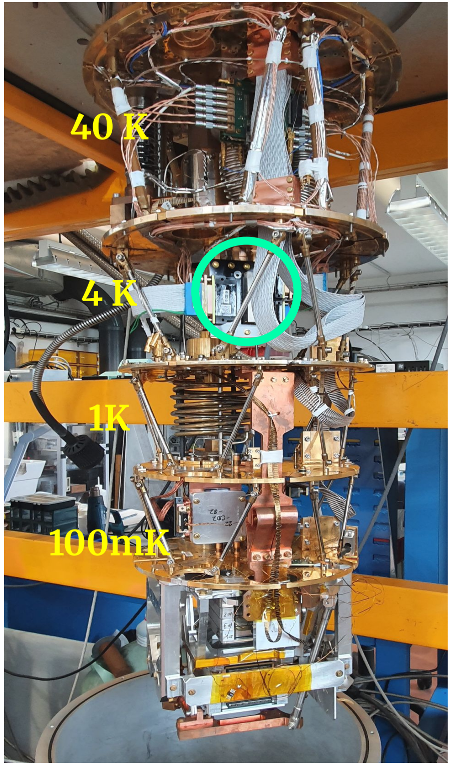
@SLAC

- Commissioning of the **ASIC APC board** on the cryogenic detection chain for CMB-S4



APC contributions

@APC

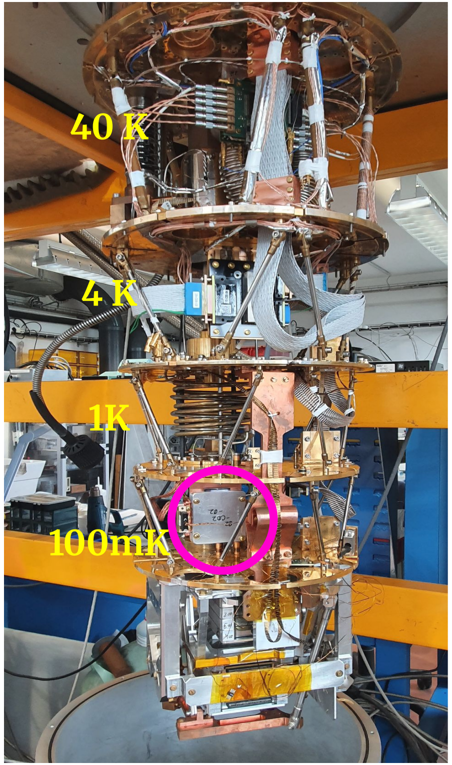


Laboratoire DRTBT - APC

- Installation of the SSA module on the 4K stage in the cryostat
- Assembly of the **SQ1** module on a copper plate and integration on the 100mK stage

APC contributions

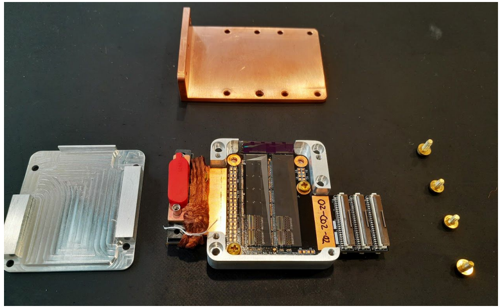
@APC



Laboratoire DRTBT - APC

- Installation of the **SSA** module on the 4K stage

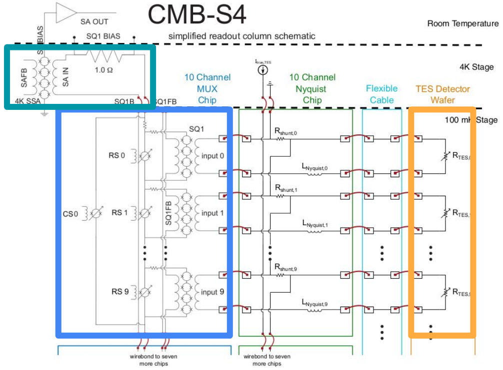
- Assembly of the **SQ1** module on a copper plate and integration on the 100mK stage

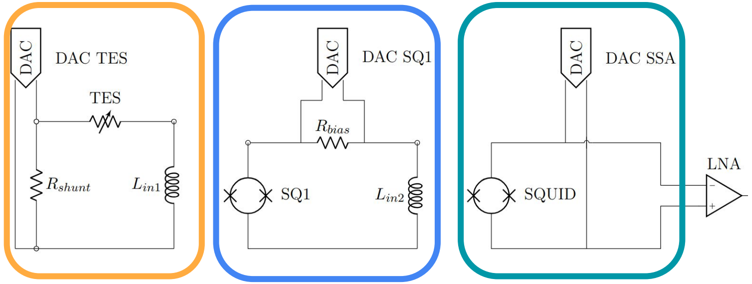


My PhD subject

Title : Characterization and modelization of the detection chain for observation of the cosmic microwave background and the next generation of instruments

- State of the art of TES, SQUIDs physics and TDM for CMB S4
- Modelization of the detection chain
- Find a simplified way to write the noise contributions, and analyse the parameters dependence
    - Modelization of the noise at the entrance of the first SQUID SQ1 : I_{TES}





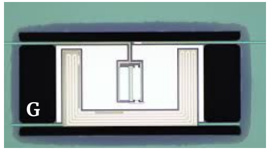
My PhD subject

- Modelization of the current noise at the entrance of the first SQUID SQ1 : I_{TES}
  - Identification of the principal noise contributions as transfer functions :
    - TES and shunt resistance thermal noises (charged carriers agitations)

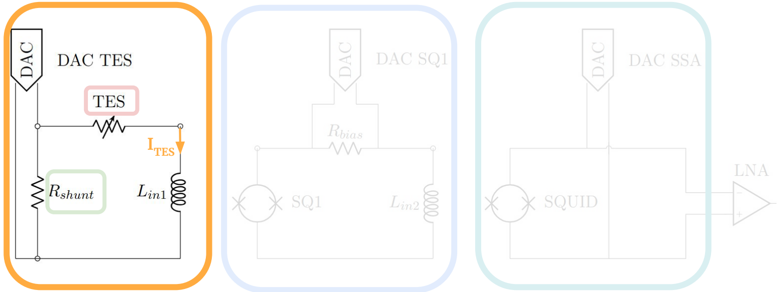
$$\boxed{H_{tes}}(\omega) = K_{tes} \cdot K \frac{1+i\frac{\omega}{\omega_\tau}}{(1+i\frac{w}{\omega_\tau \gamma_t})(1+i\frac{\omega}{\omega_{el}})}$$

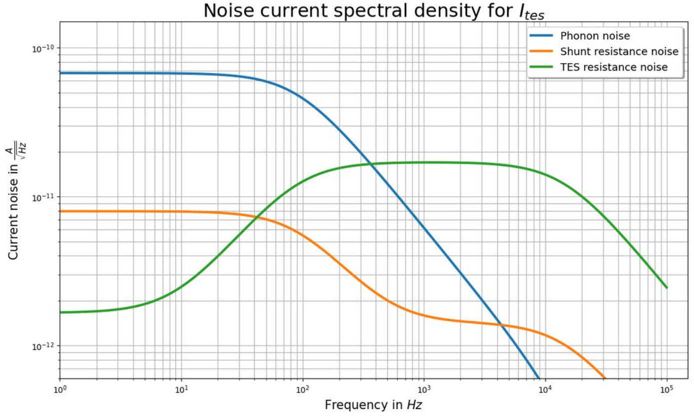
$$\boxed{H_{shunt}}(\omega) = K_L \cdot K \frac{1+i\frac{\omega}{\omega_{eff}}}{(1+i\frac{w}{\omega_{eff}\gamma_l})(1+i\frac{\omega}{\omega_{el}})}$$

    - Phonon noise (exchange of phonons through G)



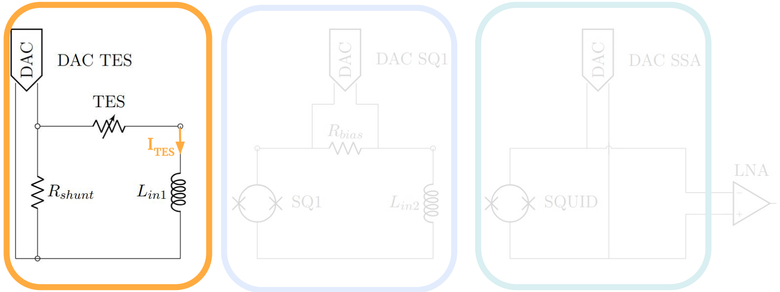
$$H_{ph}(\omega) = K \cdot K_{ph} \frac{1}{(1+i\frac{\omega}{\omega_1})(1+i\frac{\omega}{\omega_{el}})}$$

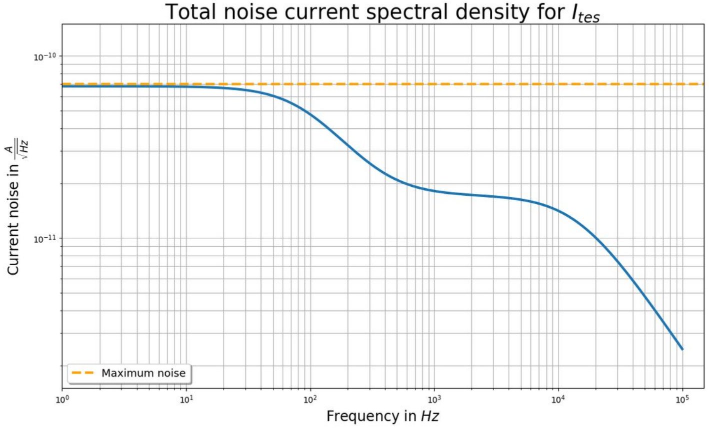




My PhD subject

- Modelization of the noise at the entrance of the first SQUID SQ1 I_{TES} :
  - We can only measure the total noise, not the contribution from every noise source
  - Ability to vary the parameters to analyse the noise
  - Try to match the computed noise current with measurements





What’s next

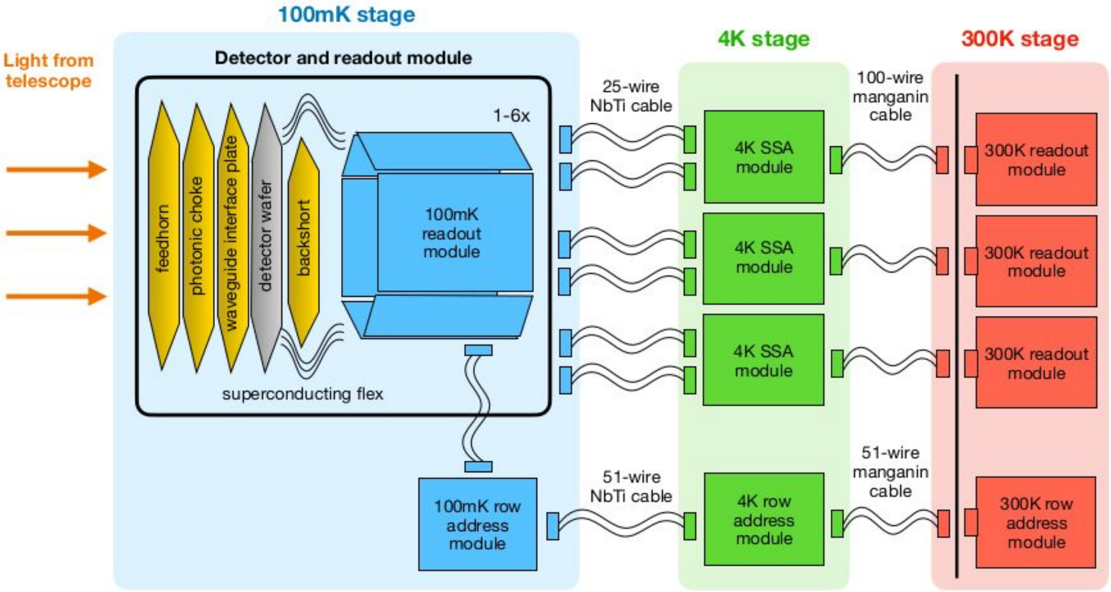
- Presentation and discussion of the model with CMB S4 collaboration (SLAC)
- Integration of the DAC noise (especially at low frequency !)
- Modeling of the rest of the detection chain
- Cryostat operation at 4 K + SSA measurements at 4 K
- Cryostat operation at 100mK + SQ1 measurements at 100mK

Thank you for listening!

Questions ?

Backup slides

Schéma du readout avec ses composants a chaque températures

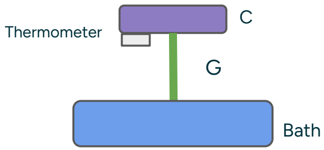


Backup slides : TES stability (NETF)

Electro Thermal Feedback

- The TES current, when red by a thermometer leads to Joule dissipation (of the thermometer), in the bolometer

$$P_i(t) = C\frac{dT}{dt} + P_{bath} - P_{Joule}$$



How to choose the biasing mode ?

If current biased : ($R_{TES} \ll R_{shunt}$) $P_{Joule} = RI^2$

When signal arrives -> T ↗ -> R ↗ -> P_J ↗ -> T ↗ **positive ETF**

If voltage biased : ($R_{TES} \gg R_{shunt}$) $P_{Joule} = \frac{V^2}{R}$

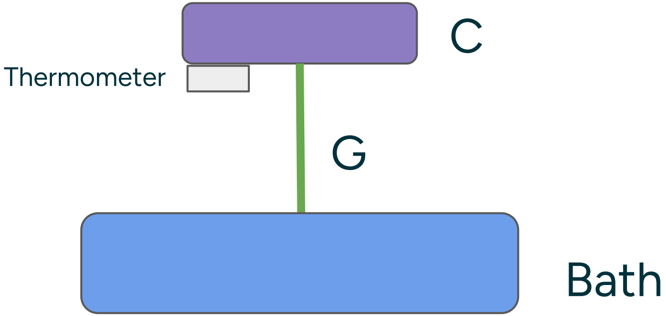
When signal arrives -> T ↗ -> R ↗ -> I ↘ -> P_J ↘ -> T ↘ **negative ETF**

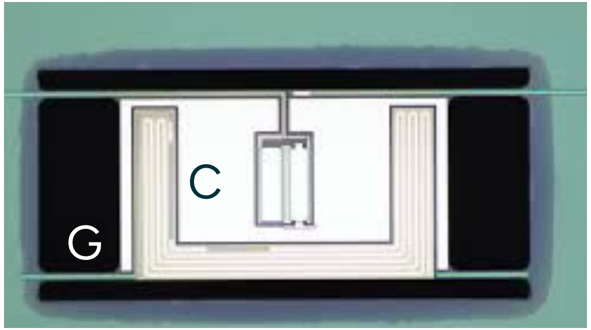
Operated at strong and **negative** Electro Thermal Feedback with voltage bias, thanks to a DAC polarization in current dc, and a shunt resistance, to bias in voltage

Backup slides : TES stability

Electro Thermal Feedback

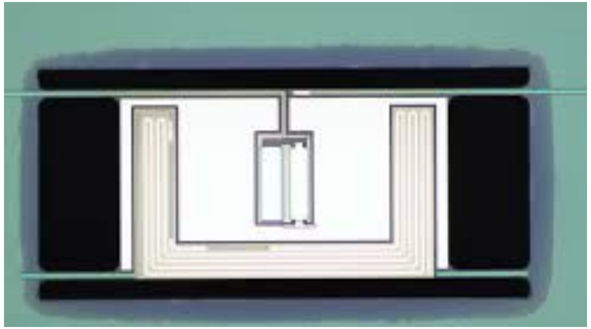
- The TES current, when red by a thermometer leads to Joule dissipation of the thermometer, in the bolometer



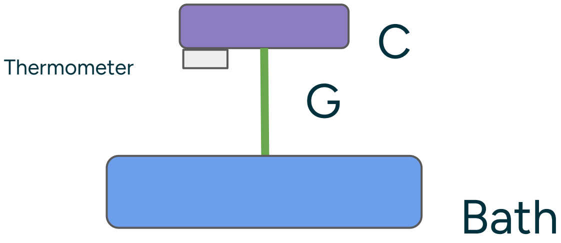


Backup slides : TES stability

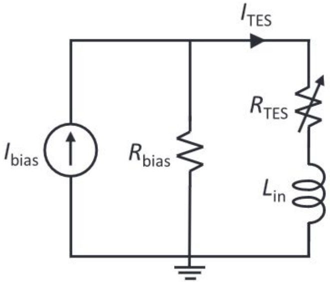
Equivalent diagrams of a TES



Thermal



Electrical



Backup slides : TES equations (1)

The thermal and electrical differential equations that describe the TES are not independent from one another because of cross terms :

Electrical differential equation :

$$L_{eq}\frac{dI_{tes}}{dt} = V^N_{bias} + V^N_{shunt} + V^N_{tes} + V^N_{para} - I_{tes}R_{tes} - I_{tes}\left(R_{shunt} + R_{para}\right)$$

Thermal differential equation:

$$C\frac{dT_{tes}}{dt} = -P_{bath} + P_{Joule} + P_i + P^N_{phonon} + P^N_{tes}$$

After linearization

$$\boxed{\begin{aligned} C\frac{d\Delta T}{dt} &= P_i + P^N_{ph} - I_0 V^N_{tes} + \left(I_0 R_0(2+\beta)\right)\,\Delta I + \left(\alpha\frac{P_{J0}}{T_0} - G\right)\,\Delta T \\ L_{eq}\frac{d\Delta I}{dt} &= V^N_{Load} + V^N_{tes} - \left(R_0(1+\beta) + R_{Load}\right)\,\Delta I - \alpha\frac{R_0 I_0}{T_0}\,\Delta T \end{aligned}}$$

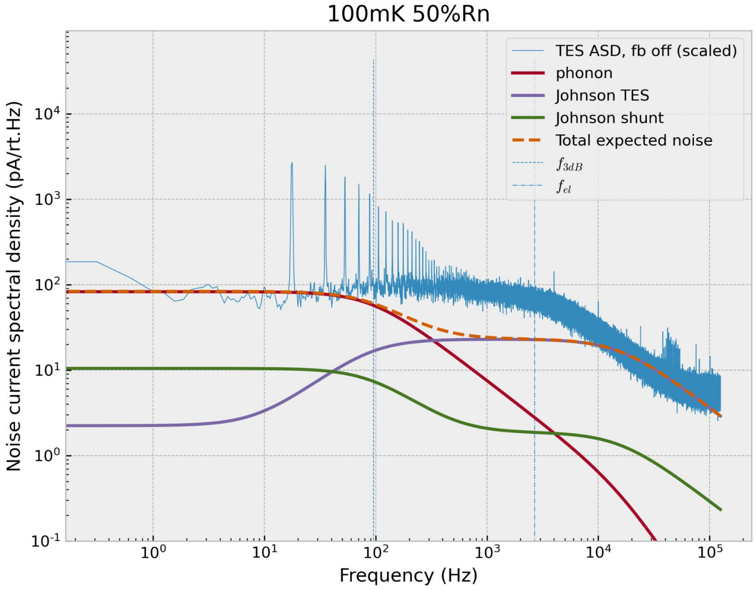
Backup slides : TES equations (2)

Matrix method :

- 2 coupled equations in the matrix form : $\frac{d}{dt}\begin{pmatrix}\Delta I\\ \Delta T\end{pmatrix} = \underbrace{\begin{pmatrix}(-R_0(1+\beta)-R_L)\ \frac{1}{L_{eq}} & -\alpha\ \frac{R_0 I_0}{T_0 L_{eq}}\\ \frac{I_0\ R_0}{C}\ (2+\beta) & \left(\alpha\frac{P_{J0}}{T_0}-G\right)\ \frac{1}{C}\end{pmatrix}}_{\mathbf{M}}\begin{pmatrix}\Delta I\\ \Delta T\end{pmatrix} + \underbrace{\begin{pmatrix}(V_L^N+V_{tes}^N)\ \frac{1}{L_{eq}}\\ (P_i+P_{phonon}^N-I_0V_{tes}^N)\ \frac{1}{C}\end{pmatrix}}_{\mathbf{N}}$
- Fourier Transform of $M_f = \begin{pmatrix}(R_0(1+\beta)+R_L)\ \frac{1}{L_{eq}}+i2\pi f & \alpha\frac{R_0I_0}{T_0L_{eq}}\\ -\frac{I_0R_0}{C}(2+\beta) & \left(-\alpha\frac{P_{J0}}{T_0}+G\right)\ \frac{1}{C}+i2\pi f\end{pmatrix}$
- Go from an equation of this form : $iw\ \overrightarrow{\Delta_f} = M\ \overrightarrow{\Delta_f} + \overrightarrow{N}$, to : $\overrightarrow{\Delta_f} = M^{-1}\ \overrightarrow{N}$, with the inverse of the matrix : $M_f^{-1} = \frac{1}{det(M_f)}\begin{pmatrix}D+iw & -B\\ -C & A+iw\end{pmatrix}$
- And retrieve the whole current variation as a function of TES parameters AND all the noise sources :

$$\Delta I_f = \frac{1}{|det(M_f)|}\left[\left(-\alpha\frac{P_{J0}}{T_0C}+\frac{G}{C}+i2\pi f\right)(V_L^N-V_{tes}^N)\frac{1}{L_{eq}}\right] - \frac{1}{|det(M_f)|}\left[\left(\alpha\frac{R_0I_0}{T_0L_{eq}}\right)(P_i+P_p^N+I_0V_{tes}^N)\frac{1}{C}\right]$$

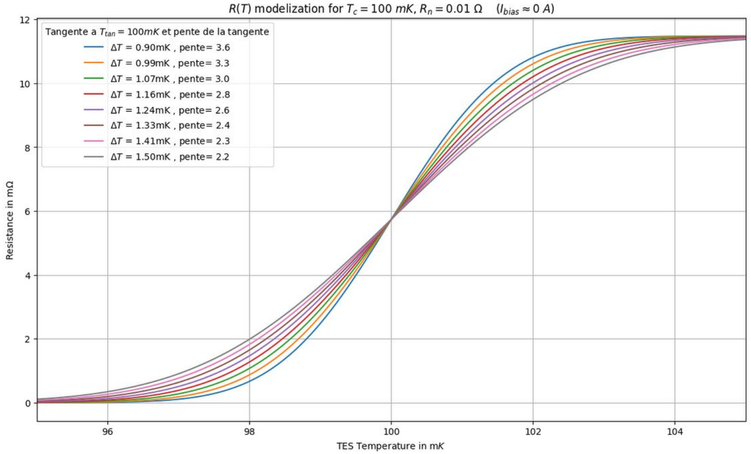
Backup slides : Measurements from SLAC



Still not able to fit perfectly the measured data, many options to explore …

Superconducting transition modelization R(T) influences the predicted data

$$R(T) = \frac{R_n}{2}\left[erf\left(\frac{T-T_c}{\Delta T}\right)+1\right]$$

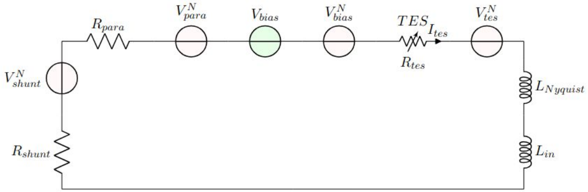


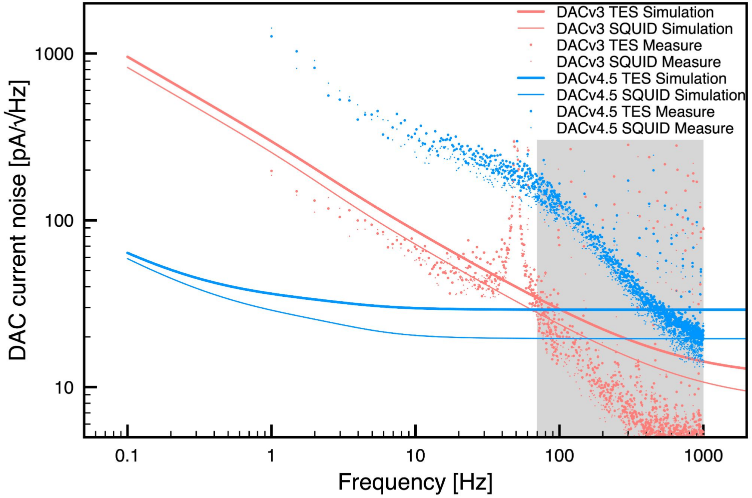
Backup slides : DAC noise

How to add the DAC noise (not white!!!) to the model?

How to define its time dependence ?

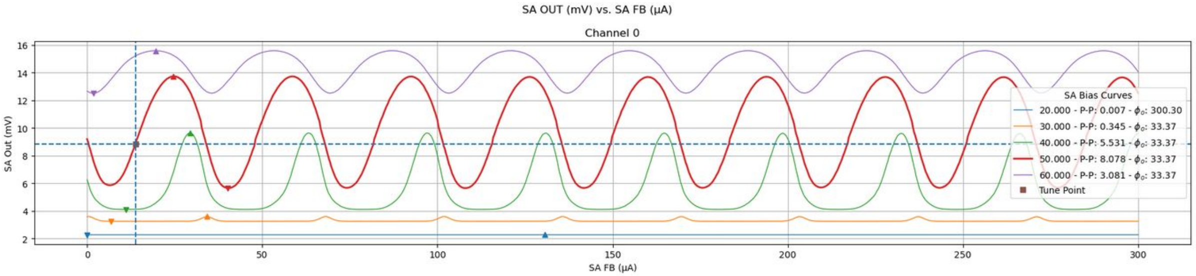
Add DAC noise as a DC generator as for the resistances ?





Backup slides : SLAC results

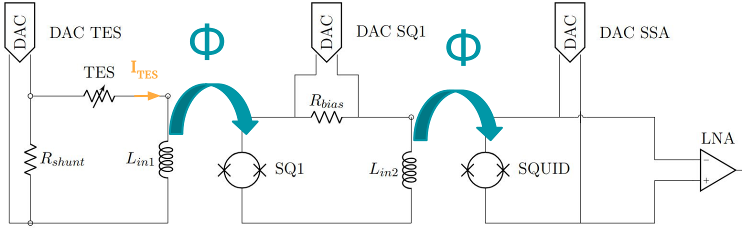
- SSA coupling with cryogenic electronics



Back up slide : SQUID FLL

DC-SQUID operates in a flux-locked loop FLL

- Feedback flux is applied to cancel out any changes in the flux from the input coil L_{in} , thereby maintaining a constant flux Φ in the SQUID (SQ1 and SSA).



- Magnetic flux variation of input coil originate from current variation of the TES from ETF