

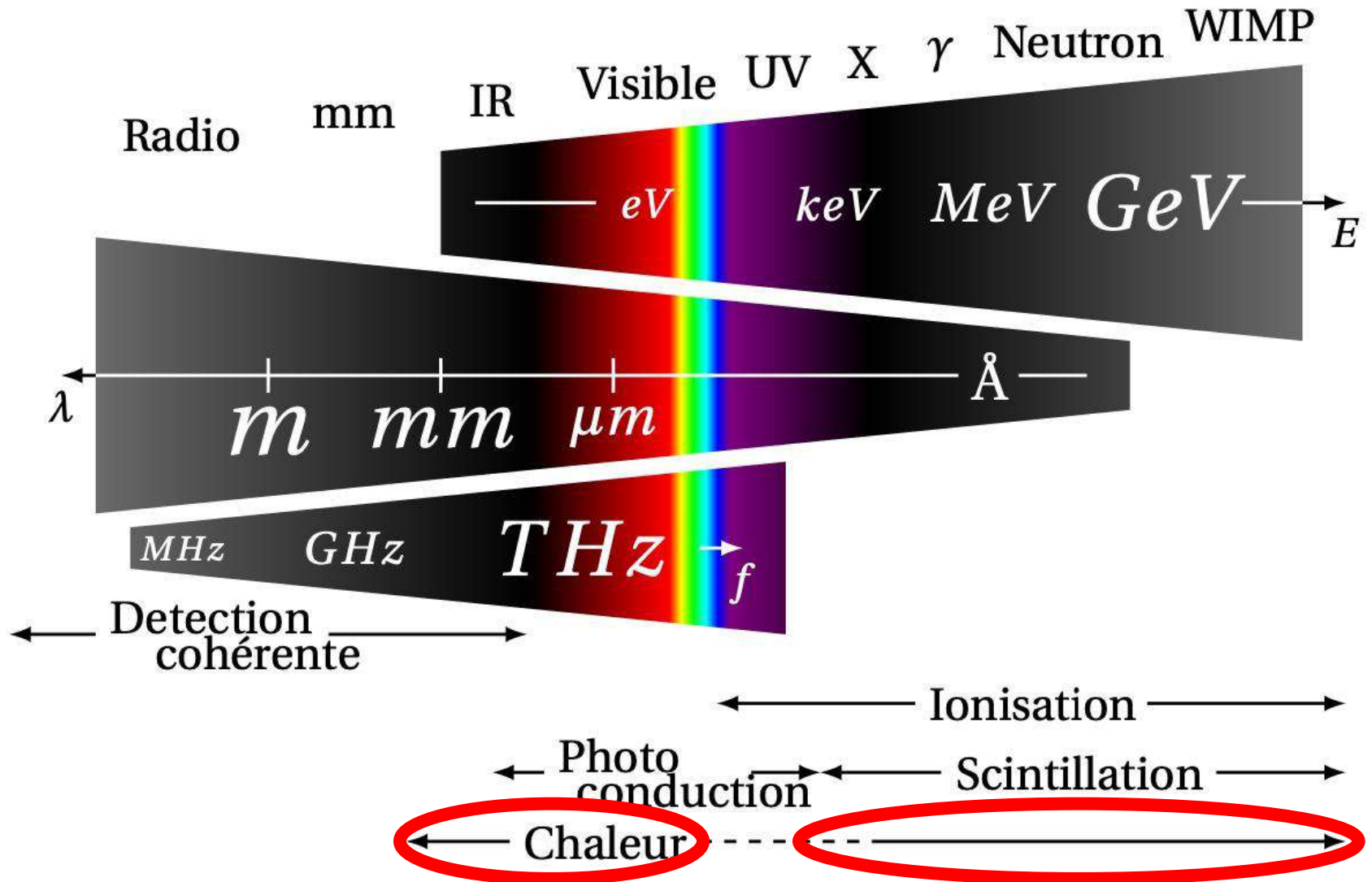
TES en France

détection mm, X et diffusion cohérente de matière noire / neutrinos

Damien PRÊLE - APC
RÉUNION DU GDR DI2I 25 juin 2024 - ORSAY

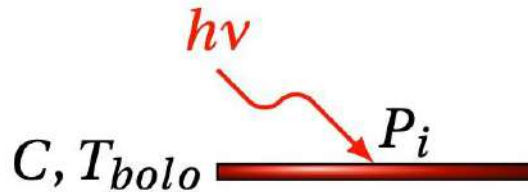


Detection bolométrique/quadratique : P ou E -> **Chaleur**

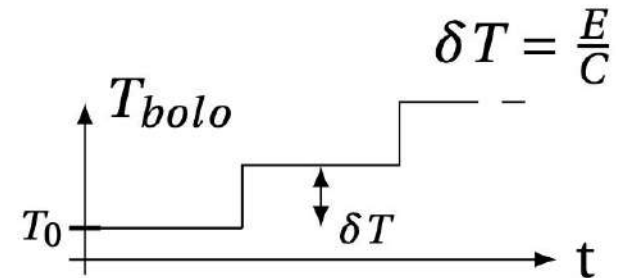
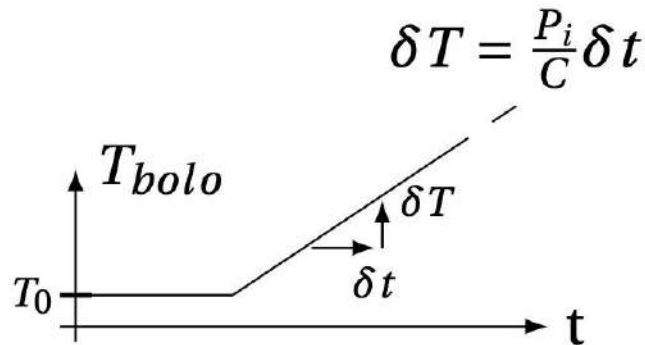
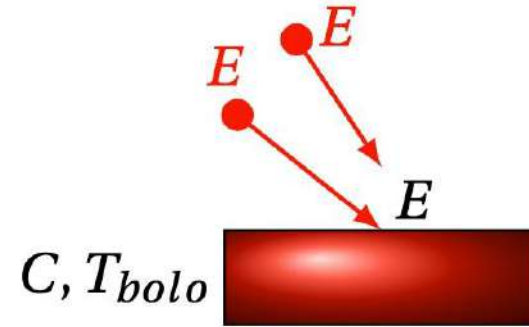


Principe du bolomètre : l'absorbeur

"background" / flux de photon



photons $> eV$ / particules



$$\delta T = \frac{P_i}{C} \delta t$$

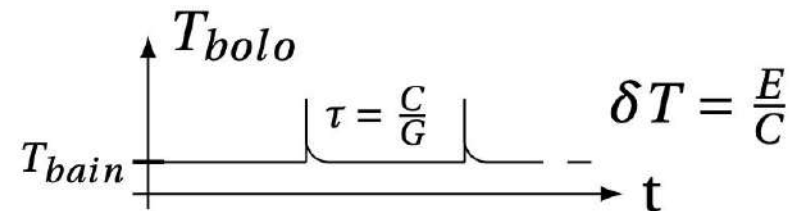
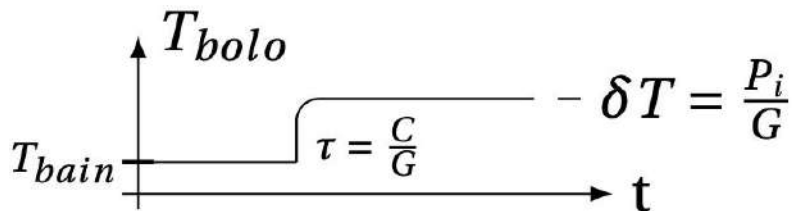
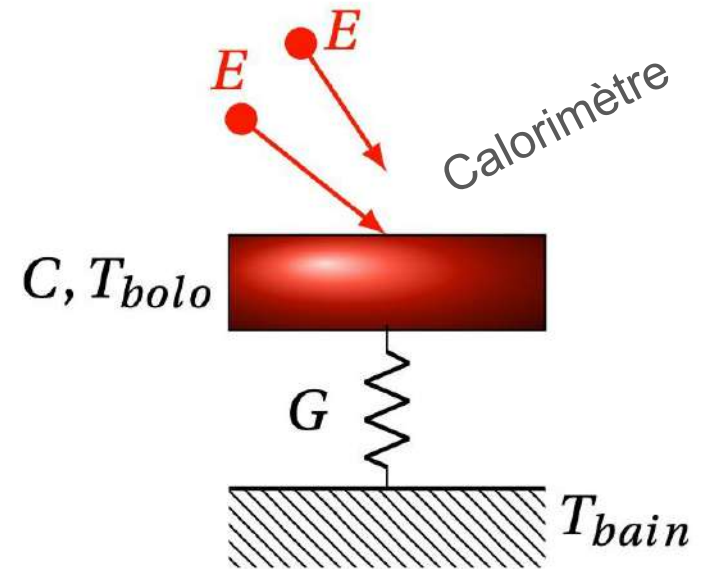
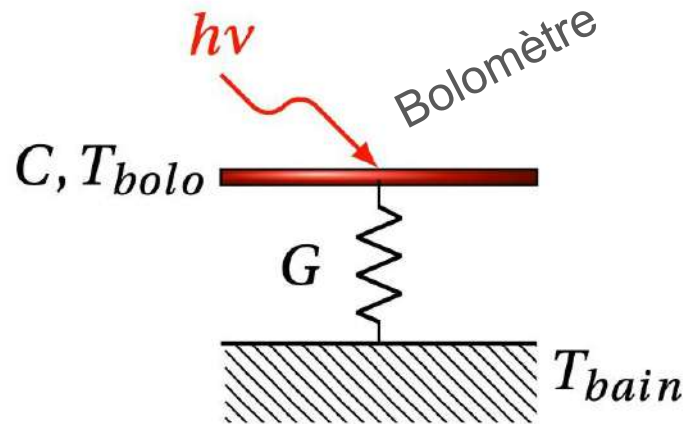
$$\delta T = \frac{E}{C}$$

C capacité calorifique [J/K]; G conductance thermique [W/K]; T_{bolo} Température d'équilibre [K]; T_{bain} Température de bain [K]; E Energie déposée [J]; P_i Puissance incidente [W]; P_J Puissance dissipée par effet Joule [W]

Principe du bolomètre : la "fuite" thermique

"background" / flux de photon

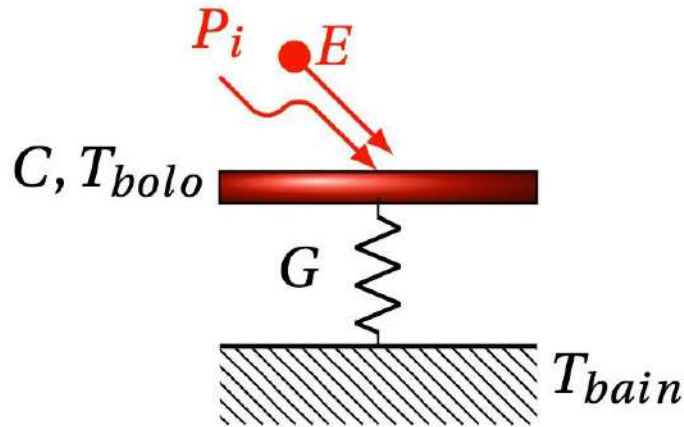
photons > eV / particules



Constante de temps naturel du bolomètre $\rightarrow \tau = \frac{C}{G}$

C capacité calorifique [J/K]; G conductance thermique [W/K]; T_{bolo} Température d'équilibre [K]; T_{bain} Température de bain [K]; E Energie déposée [J]; P_i Puissance incidente [W]; P_J Puissance dissipée par effet Joule [W]

Bruit et basses températures



- ▶ P_i [W] → Puissance incidente (de l'onde)
- ▶ E [J] → Energie déposée (par une particule)
- ▶ C [J/K] → Capacité calorifique du dissipateur couplé au thermomètre
- ▶ T_{bolo} [K] → Température du bolomètre
- ▶ G [W/K] → Conductance thermique
- ▶ T_{bain} [K] → Référence de température

- ▶ Bolometre $\Delta T = P_i / G$

Bruit thermodynamique : $NEP = \sqrt{4k_B T^2 G}$ [W/ \sqrt{Hz}]

- ▶ Calorimetre $\Delta T = E / C$

Fluctuations d'Energie : $\Delta E_{rms} = \sqrt{k_B T^2 C}$ [J]

☞ travailler à basse température

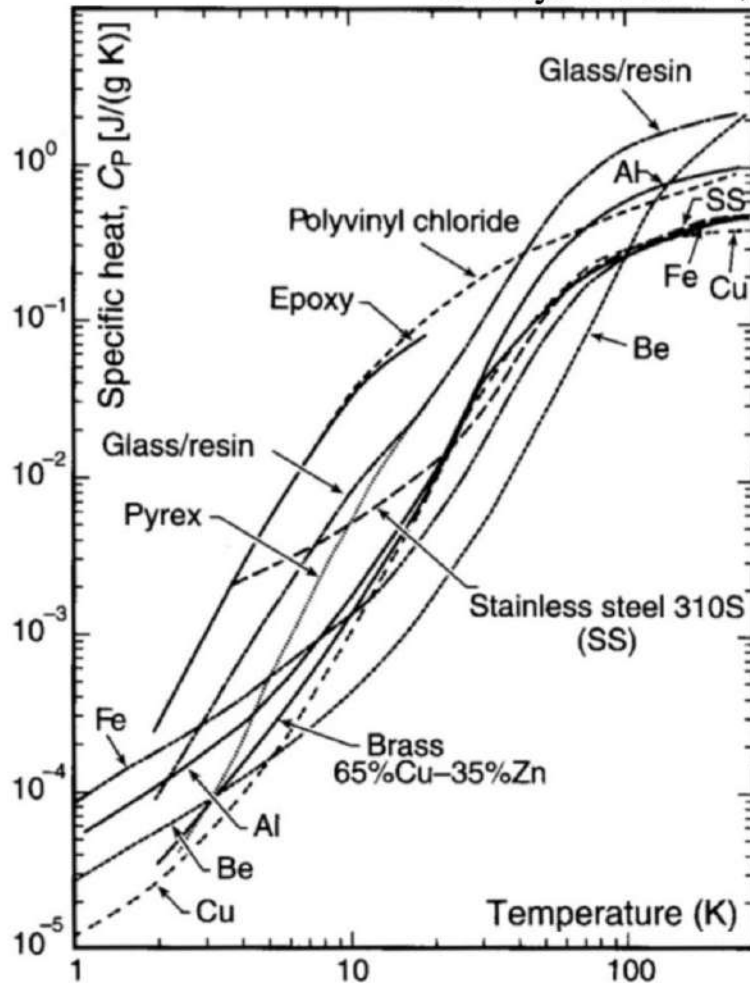
Refroidire pour mieux chauffer : capacité calorifique C [J/K]

$$\delta T \rightarrow \frac{E}{C} = \frac{E}{mc}$$

Chaleur spécifique c [J/gK]

$\div 10 @ 77K$ $\div 1000 @ 4K$

@Tcryo : $c \propto T^3$; $c_{\text{metaux}} \propto T$



"sensitivity of calorimetric can be increased by many orders of magnitude by working at very low T"

Application of Low Temperature Calorimetry to Radioactive Measurements

It is often of importance to determine in absolute measure energy changes connected with radioactive transformations, but only in a few cases has it been possible to employ calorimetric methods for this purpose, since in general the amounts of energy liberated in unit time are too small. The sensitivity of calorimetric measurement can be increased, however, by many orders of magnitude by working at very low temperatures, and it may be worth while to point this out, as low temperature technique is now within the reach of non-specialised laboratories.

Consider a calorimeter consisting of lead. At a temperature of 1.3°, which can easily be obtained with liquid helium, its specific heat is 3,000 times smaller than at room temperature. So the calorimetric sensitivity is increased by this factor if we

take the temperature sensitivity as constant. Using a substance like tungsten, with a higher θ_{Debye} , one can increase this factor still further by one power of 10. If one wishes to measure the heat developed with an accuracy of 1 per cent, the temperature must be allowed to change by $1/10^5$, assuming that the measuring sensitivity is $1/1,000^2 - 1/10,000^2$. The effects can be accumulated over a period of at least ten minutes, as at very low temperatures the thermal insulation can be made nearly perfect, owing to the lack of radiation. Thus, using a calorimeter consisting of 1 cm³ of tungsten, one could measure 10^{-3} cal./sec., which is about 1,000 times more sensitive than in the calorimeter of Meitner and Orthmann¹. So, for example, the total heating effect of 10^{-3} gm. of radium situated within the calorimeter could be determined, or the heating caused by the γ -rays from a source of 0.1 millicurie of radon placed 3 cm. away from the calorimeter.

Cooling the calorimeter below 1° by the magnetic procedure, one can diminish still further the specific heat of the absorbing substance, and at the same time the sensitivity of the temperature measurement is considerably increased by basing it on the susceptibility of the paramagnetic salt, for, in the region where the Curie law holds, the accuracy of temperature measurement is proportional to $1/T^3$. With a substance obeying the T^3 law for the specific heat, therefore, the sensitivity of this method increases with falling temperature with T^{-4} .

The specific heat of a paramagnetic salt, however, does not follow the T^3 law, as its specific heat must necessarily be anomalous in this temperature region². No great increase in sensitivity could therefore be achieved below 1° by working with a calorimeter consisting of the salt alone. But, of course, this does not apply to an appropriate combination of the paramagnetic salt and an absorbing substance of non-anomalous specific heat.

In some preliminary experiments carried out during the past few weeks, Dr. Kurti and I nevertheless worked with the unfavourable case of the salt alone in order to be able to use our ordinary apparatus for magnetic cooling³. We took 1 gm. of iron ammonium alum and cooled it down to 0.05°, which in this case was an advantage solely because of the improved thermal insulation². In spite of the very small absorption coefficient of the substance for γ -rays, and the comparatively low thermometric sensitivity of this particular apparatus, a sharp rise of temperature set in immediately after the substance had been exposed to the γ -radiation of 100 millicuries of radon at a distance of 2.5 cm. (This turned out to be a very convenient way for measuring the specific heat of the salt and we will report soon on the results.) Even in this unfavourable case, we could measure 10^{-3} cal./sec., and it should be possible to measure, in a volume of about 1 cm.³, an evolution of heat of the order of 10^{-11} cal./sec., by using a suitable absorbing substance in combination with the paramagnetic salt and improving the sensitivity of the temperature determination.

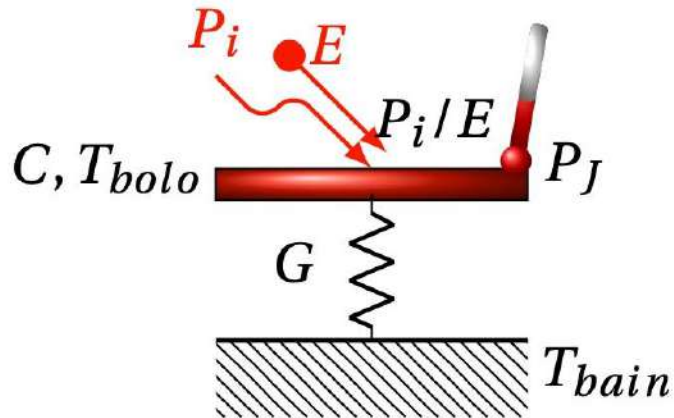
With such increased sensitivity, various problems can be attacked, and experiments in this direction are in progress at the Clarendon Laboratory.

F. SIMON.

Clarendon Laboratory,
Oxford,
March 28.

¹ L. Meitner and W. Orthmann, *Z. Phys.*, **60**, 143: 1930.
² N. Kurti and F. Simon, *Proc. Roy. Soc. A*, **149**, 152: 1935.

Thermometer : Mesure T ... mais **réchauffe** le bolomètre



- ▶ P_i [W] → Puissance incidente (de l'onde)
- ▶ E [J] → Energie déposée (par une particule)
- ▶ P_J [W] → Puissance dissipée par effet Joule dans le thermomètre
- ▶ C [J/K] → Capacité calorifique du dissipateur couplé au thermomètre
- ▶ T_{bolo} [K] → Température du bolomètre
- ▶ G [W/K] → Conductance thermique
- ▶ P_b [W] → Puissance de fuite
- ▶ T_{bain} [K] → Référence de température

Conversion $P \rightarrow T$ $P_i + P_J - G(T_{bolo} - T_{bain}) = C \frac{\partial T}{\partial t}$

ou $E \rightarrow T$ $\frac{\partial E}{\partial t} + P_J - G(T_{bolo} - T_{bain}) = C \frac{\partial T}{\partial t}$

Constante de temps naturel du bolomètre

$$\tau = \frac{C}{G}$$

Les différents type de thermometers :

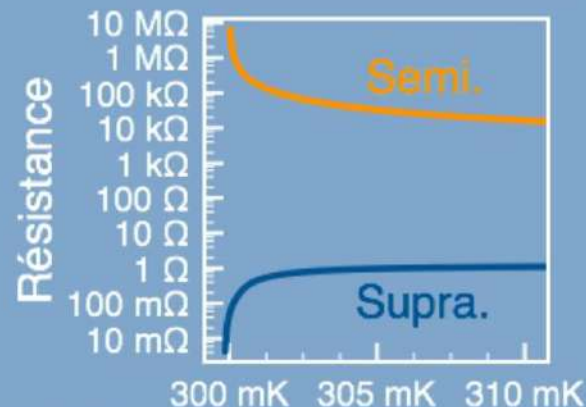
► Résistive (thermistors)

Semi. Haute impédance [$\gg 100 \text{ k}\Omega$]

- Semi. Dopé NTD Neutron Transmuted Doped
- Alliage $\text{Nb}_x\text{Si}_{1-x}$ avec $x < 9\%$

Supra TES / Basse impédance [$< 1\Omega$]

- Alliage $\text{Nb}_x\text{Si}_{1-x}$ avec $x > 13\%$
- MultiCouches Mo-Cu, Mo-Au ...



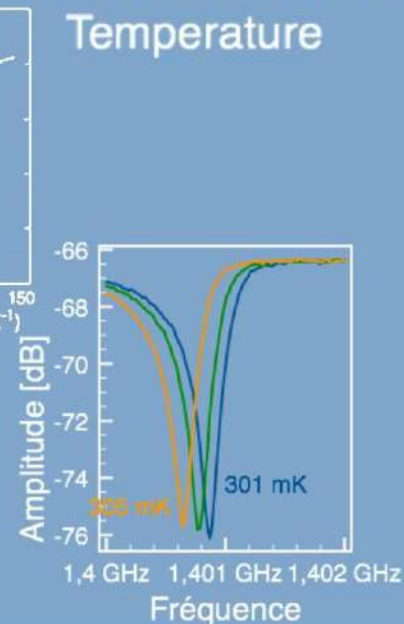
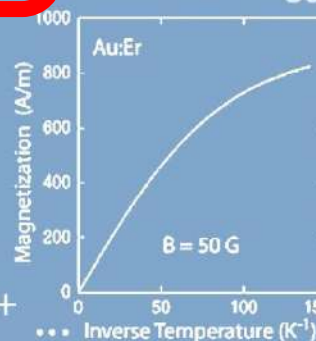
► Magnétique (MMC)

variation aimantation fonction de T
Alliage paramagnétique (orientation des spins d'ions)

Ions Terres rares Er^{3+} , Eu^{3+} , Sm^{3+} , Yb^{3+}

Matrice Métallique Au, Ag ... ou isolant TmAG ...

Exemple : Au:Er (or-erbium) [MMC - M.Rodrigues - DRTBT2012]

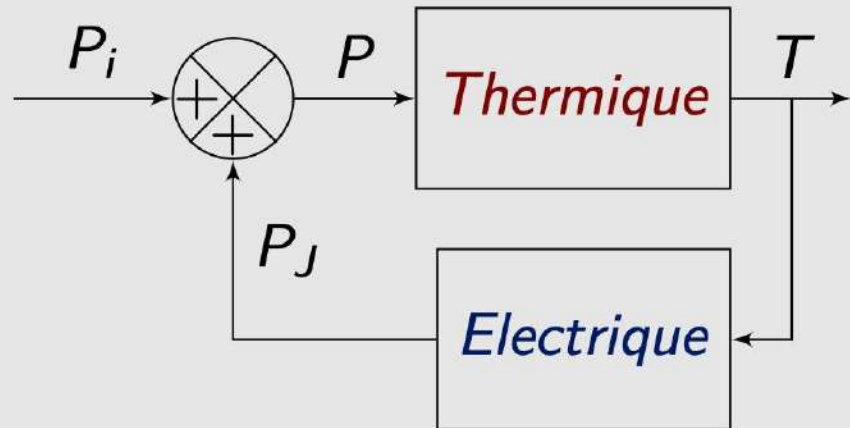


- Inductif → KID "athermique"

Contre-réaction électro-thermique

La "force" et le signe (stabilité) de la contre réaction sont données par le gain de boucle du schéma block :

$$\mathcal{L} = \frac{\partial T}{\partial P} \frac{\partial P_J}{\partial R} \frac{\partial R}{\partial T}$$



$\frac{\partial T}{\partial P}$ - fonction de transfert Thermique du bolomètre $\frac{1}{1+j\omega\tau}$

$\frac{\partial P_J}{\partial T}$ - fonction de transfert Electrique du bolomètre :

$$\frac{\partial P_J}{\partial R} \text{ dépend de la polarisation : } \frac{\partial(RI^2)}{\partial R} = I^2 \text{ ou } \underbrace{\frac{\partial(\frac{V^2}{R})}{\partial R}}_{\text{TES polarisé en V}} = -\frac{V^2}{R^2}$$

$$\frac{\partial R}{\partial T} \text{ pente du thermomètre} = \alpha \frac{R}{T}$$

$$\mathcal{L} = \frac{\partial T}{\partial P} \frac{\partial P_J}{\partial R} \frac{\partial R}{\partial T} = -\frac{P_J \alpha}{G_d T} \frac{1}{1+j\omega\tau}$$

Bolomètre en contre réaction Boucle fermé

$$\frac{\partial T}{\partial P_i} = \frac{1}{1 + j\omega \frac{\tau}{1+|\mathcal{L}|}}$$

Constante de temps accélérée $\tau_{\text{eff}} = \frac{\tau}{1+|\mathcal{L}|}$

En forte contre réaction électro-thermique (TES polarisé en tension et $|\mathcal{L}|$ très grand)

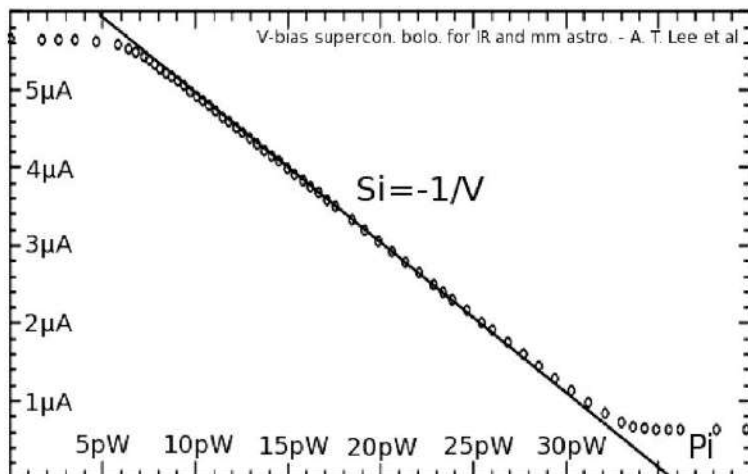
la fonction de transfert $\frac{\partial T}{\partial P} = \frac{1}{G_d(1+|\mathcal{L}|)} \frac{1}{1+j\omega\tau_{eff}} \rightarrow 0$

Le TES est un "thermomètre" qui maintient fixe la température du bolomètre \Rightarrow **asservissement de la température**

Sensibilité $S_I = \frac{\partial I}{\partial P} = \frac{\partial T}{\partial P} \frac{\partial R}{\partial T} \frac{\partial I}{\partial R}$ du TES

$$S_I = \frac{1}{G_d(1+|\mathcal{L}|)} \frac{1}{1+j\omega\tau_{eff}} \times \alpha \frac{R}{T} \times \frac{-V}{R^2} = \boxed{\frac{-1}{V} \frac{|\mathcal{L}|}{1+|\mathcal{L}|} \frac{1}{1+j\omega\tau_{eff}}}$$

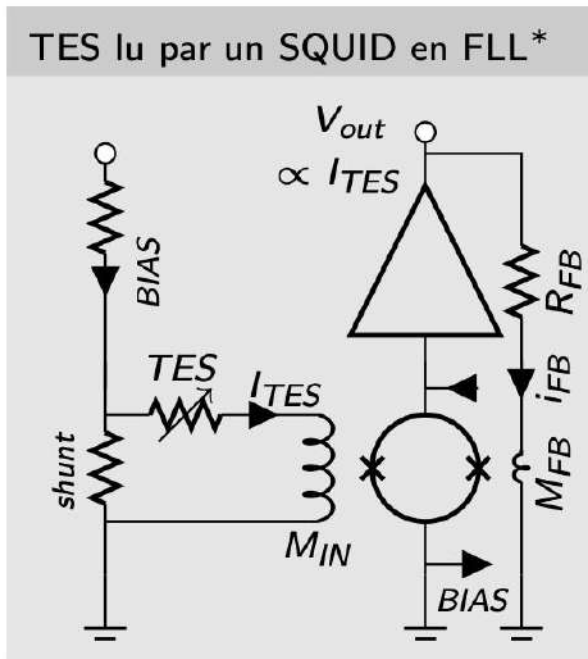
[A/W]




- 1 $S_I = \frac{\partial I}{\partial P}$ linéaire et indépendant du TES
- 2 τ_{eff} = constante de temps accélérée \Rightarrow Bande passante \nearrow

Le circuit de lecture du TES doit assurer la **polarisation en tension** du TES et sa **lecture en courant**.

Le SQUID *Superconducting Quantum Interference Device* permet une lecture en courant du TES sans résistance d'entrée.



- 1 Amplificateur de courant 
(trans-impédance $I \rightarrow V$)
- 2 Réactance nulle \Rightarrow Polarisation en tension
- 3 Fonctionne jusqu'à $\approx 0K$
- 4 Multiplexage possible (marge de bruit et de bande passante)

La caractéristique périodique du SQUID est linéarisée par une boucle de contre-réaction qui fixe le **gain de la chaîne de lecture** à

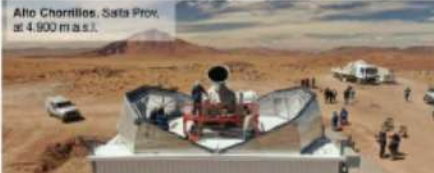
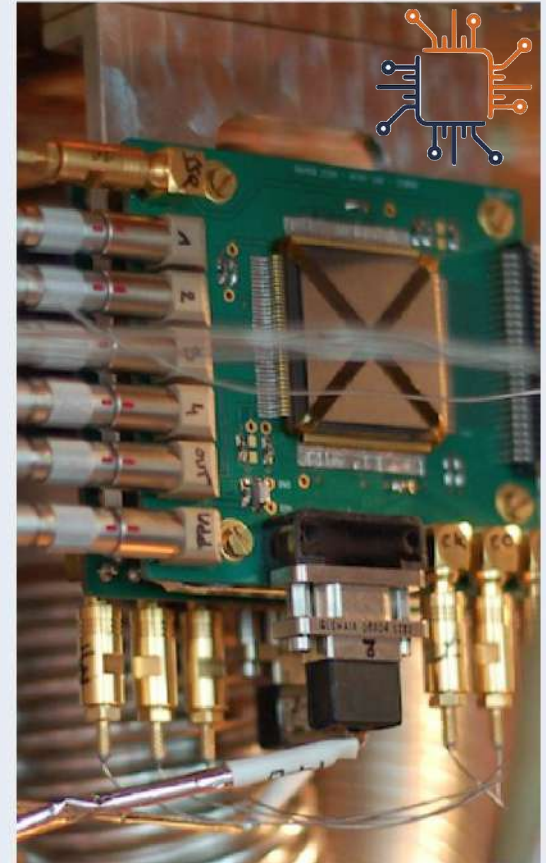
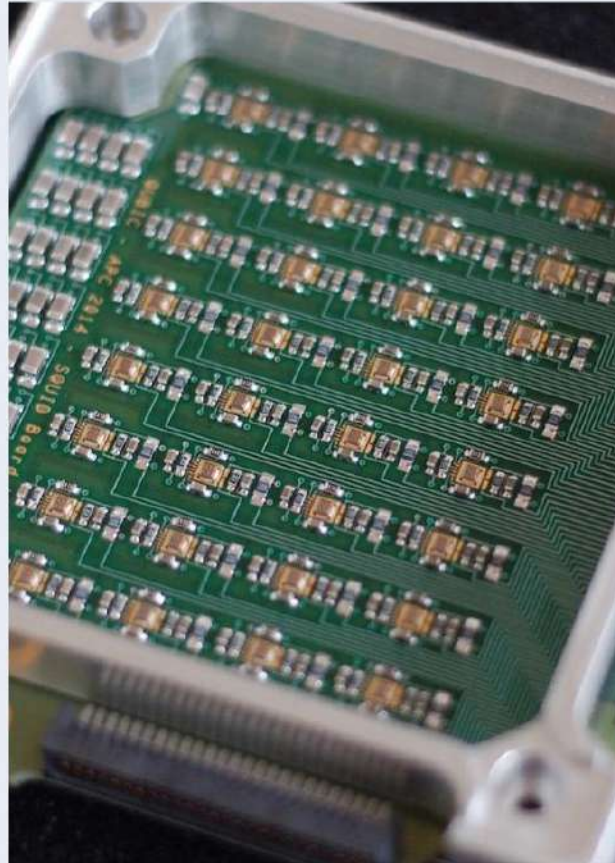
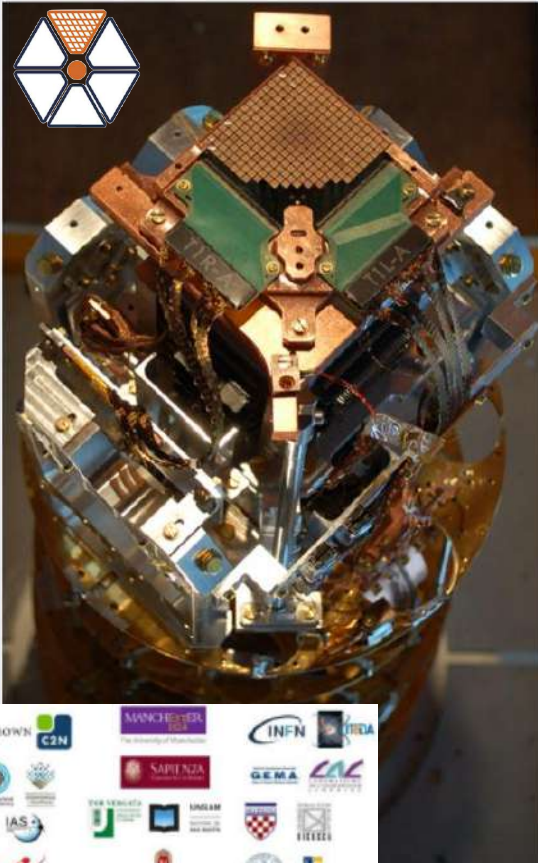
$$\frac{M_{IN}}{M_{FB}} R_{FB}$$

* FLL - Flux Locked Loop = boucle de contre réaction du SQUID en flux

Chaine de detection pour QUBIC (CMB)

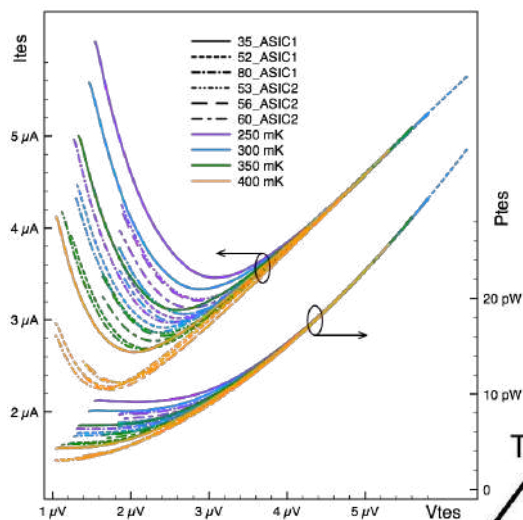
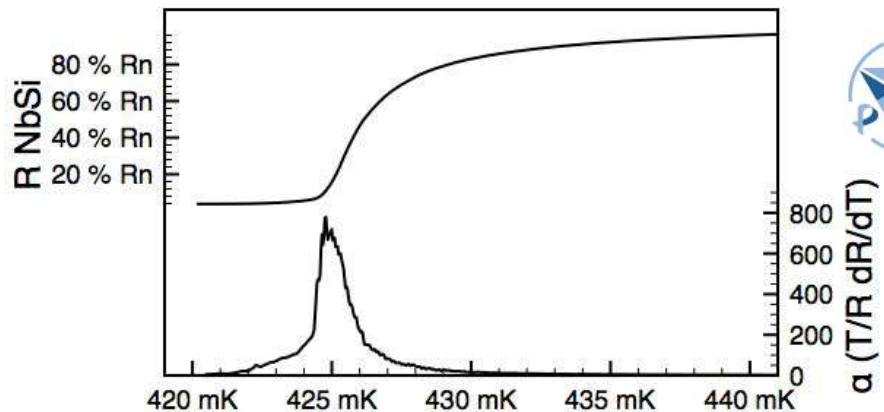
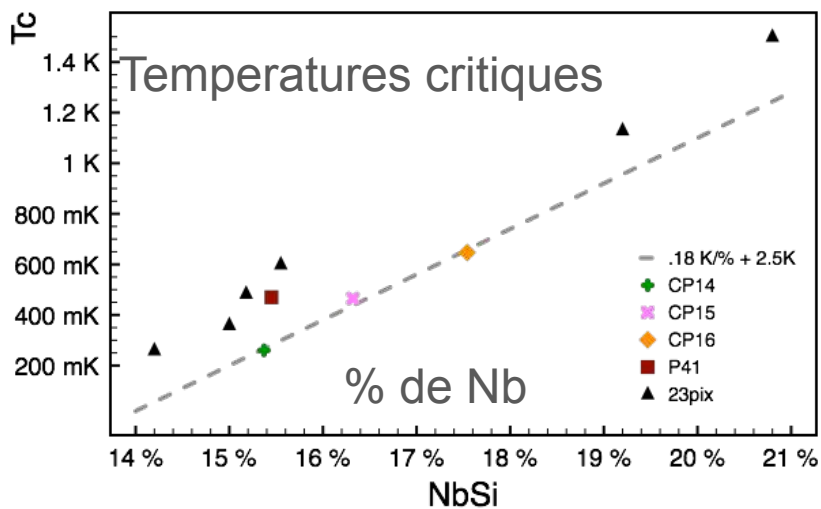


Sub-system : NbSi **TES** (300 mK) + 256 **SQUID**s (1K) + 2 **ASIC**s (40K)

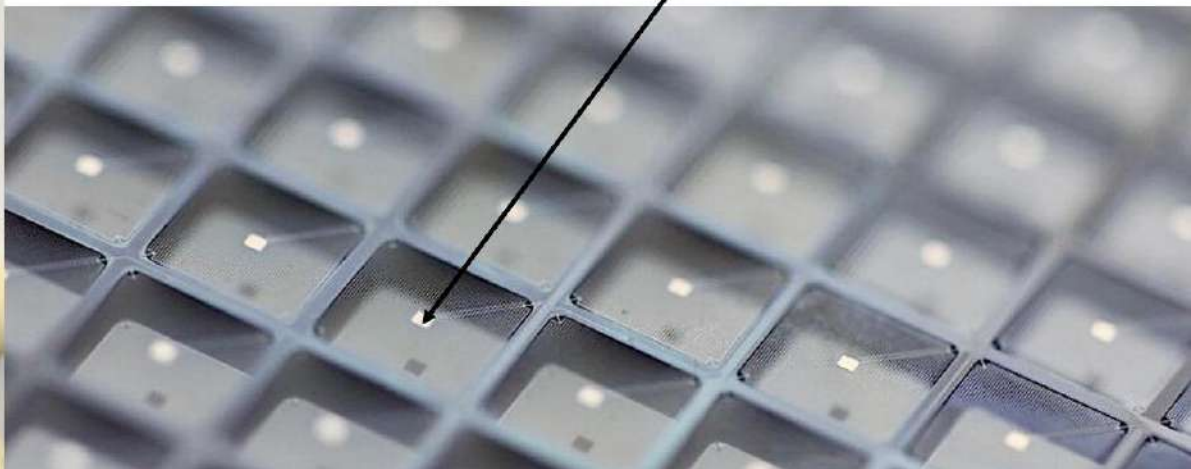
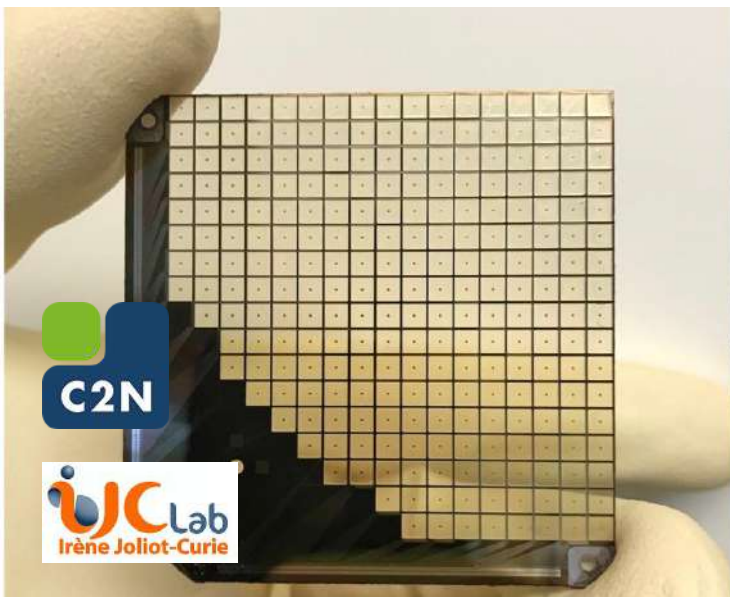


https://apc.u-paris.fr/~prele/TESreadout_PRELE_QUBIC_Rome2016.pdf

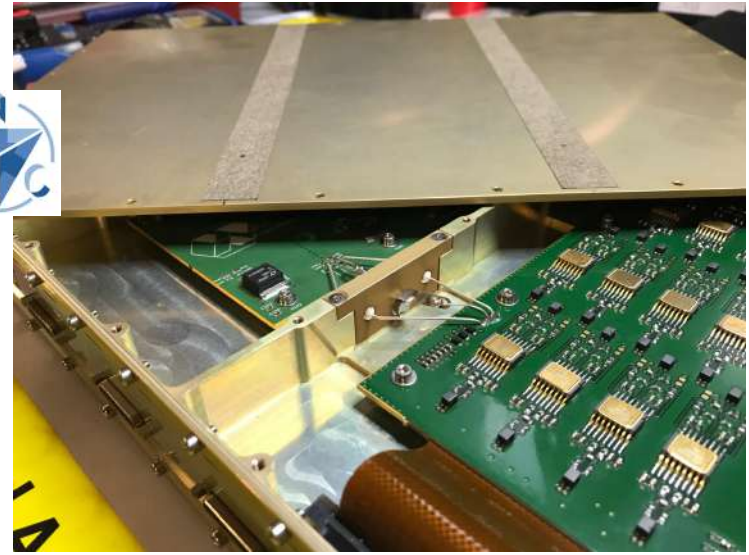
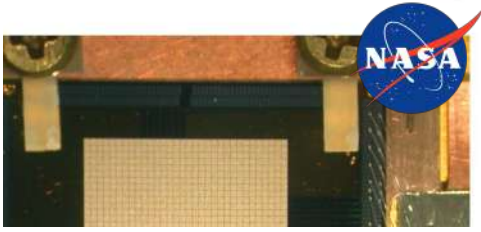
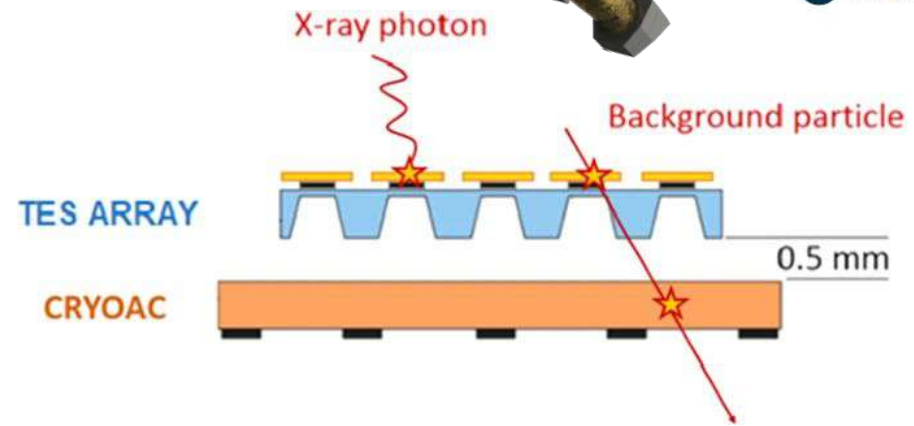
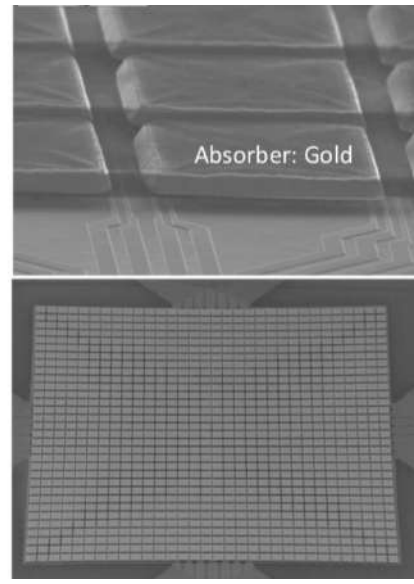
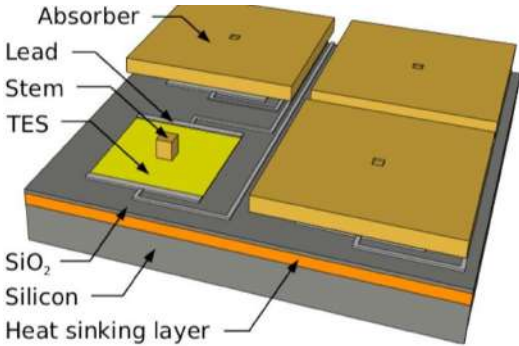
NbSi : supra "ajustable"



Thermomètre supraconducteur

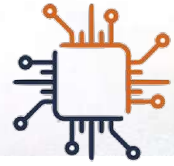


Microcalorimètre supra - X-IFU ATHENA

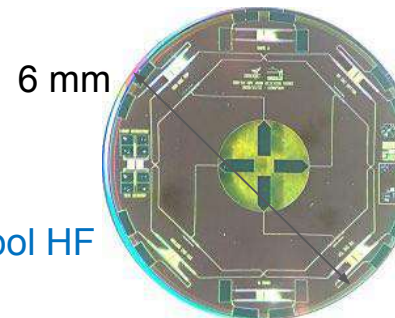


Warm
Front-End
Electronic :

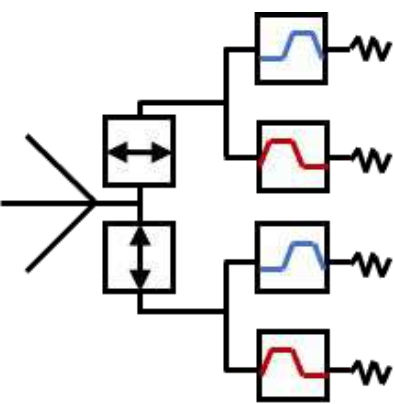
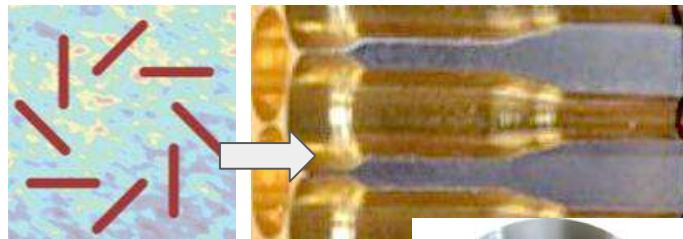
Electronique
ASIC de
lecture et de
polarisation
des TES



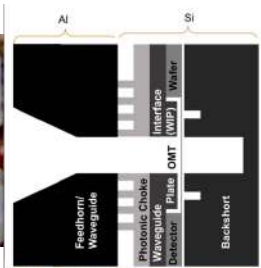
CMB-S4 TES multichroic et multipolar



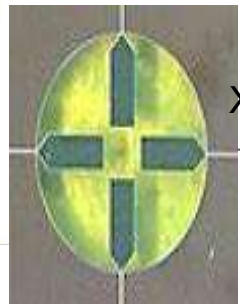
Sky Signal spline-profiled Horn* array



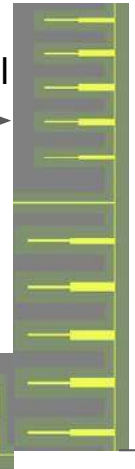
Interfaces layers**



OMT***



Diplexer****



TES Xpol HF

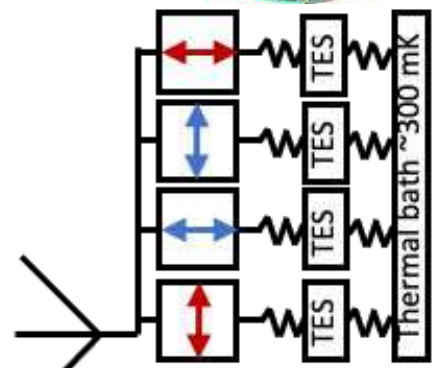
X-pol

Y-pol

TES Ypol LF

TES Xpol HF

TES Ypol HF



- Sensitive to **polarisation** antenna
- Superconducting **Channelizer** / Diplexer
- End line **dissipator** + Thermalization
- **Bolometer** + Superconducting thermometer

*Feedhorn dev. and scalability for SO and beyond - S. M. Simon et al.
 ** Conceptual Design ...for the CMB-S4 survey experiment, D. Barron et al.
 *** JLTP 2022 DOI: 10.1007/s10909-022-02731-x
 ****Multi-Chroic Detectors for Observing the CMB - A. Traini, M. Piat et al.

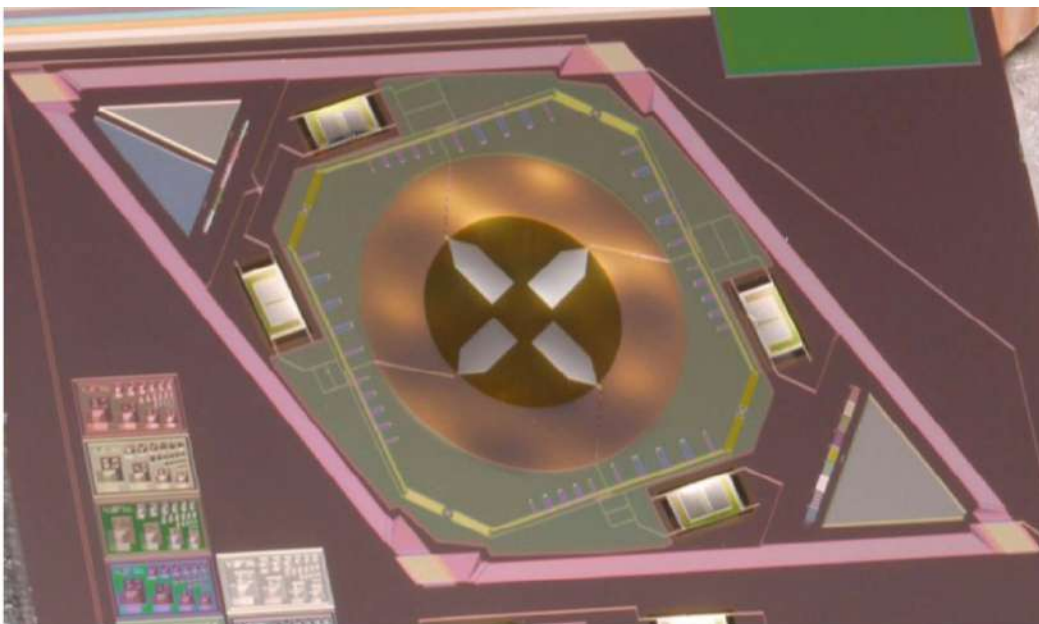
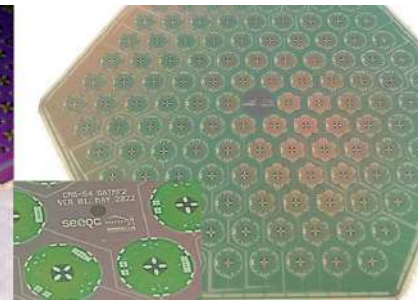
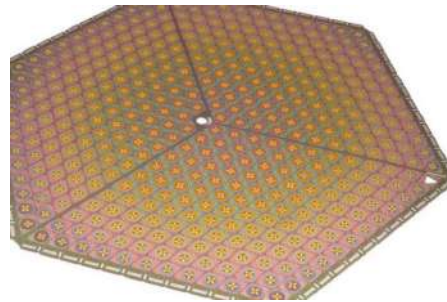
CMB-S4 TES multichroic et multipolar

CMB-S4
Next Generation CMB Experiment

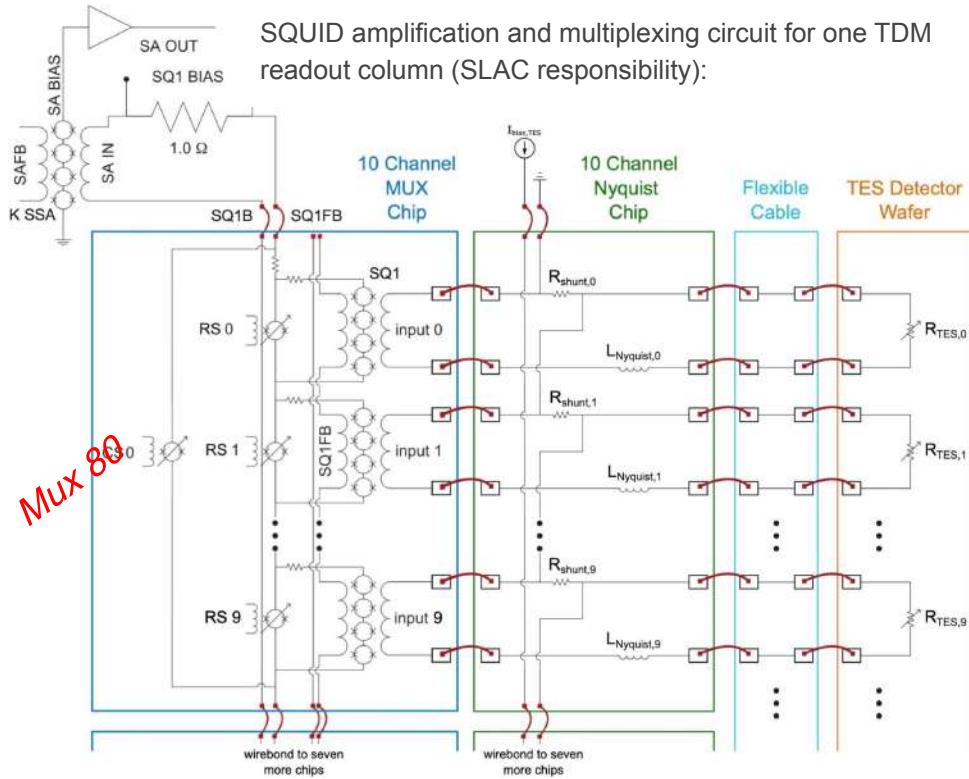
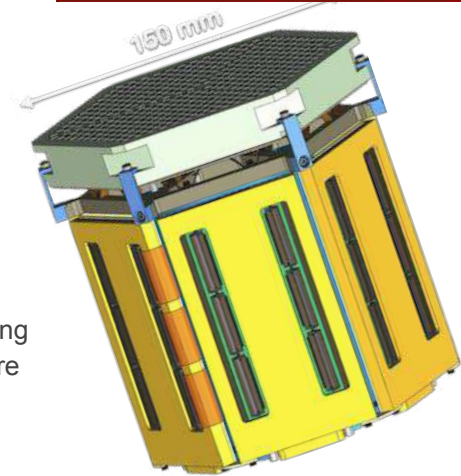
6 fabrication sites : NIST, Argonne, UCB, LBNL/SQC, JPL

SAT : 30/40 GHz, 85/145 GHz, 95/155 & GHz 225/278 GHz

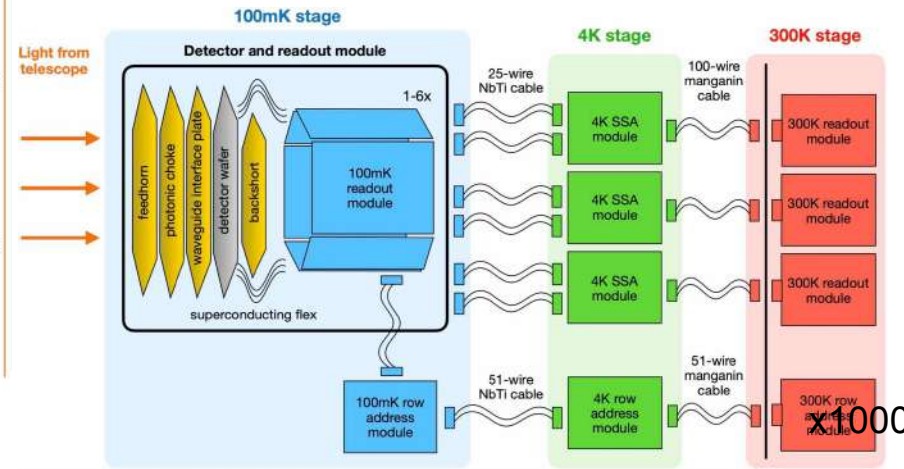
LAT : 20 GHz, 30/40 GHz, 90/150 GHz & 225/278 GHz



CMB S4 detection chain : TES + SQUID TDM + warm readout



Modular readout scheme showing components at each temperature stage and interconnects :



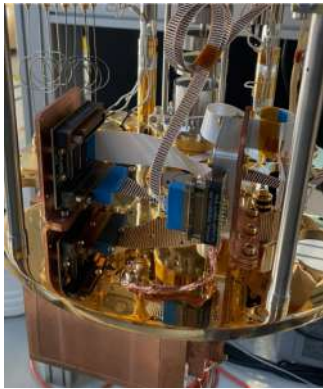
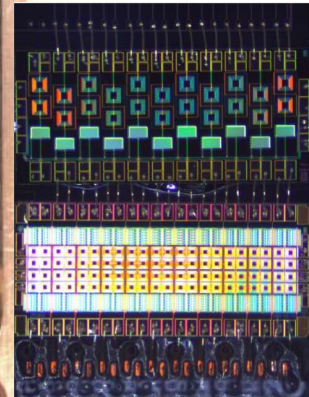
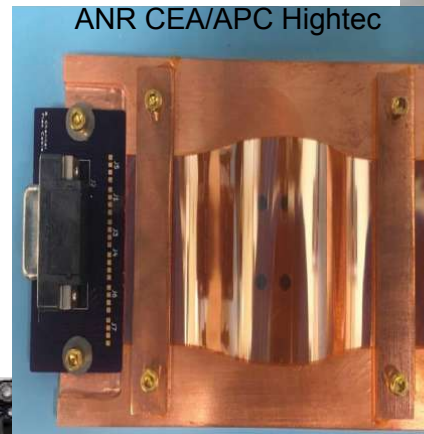
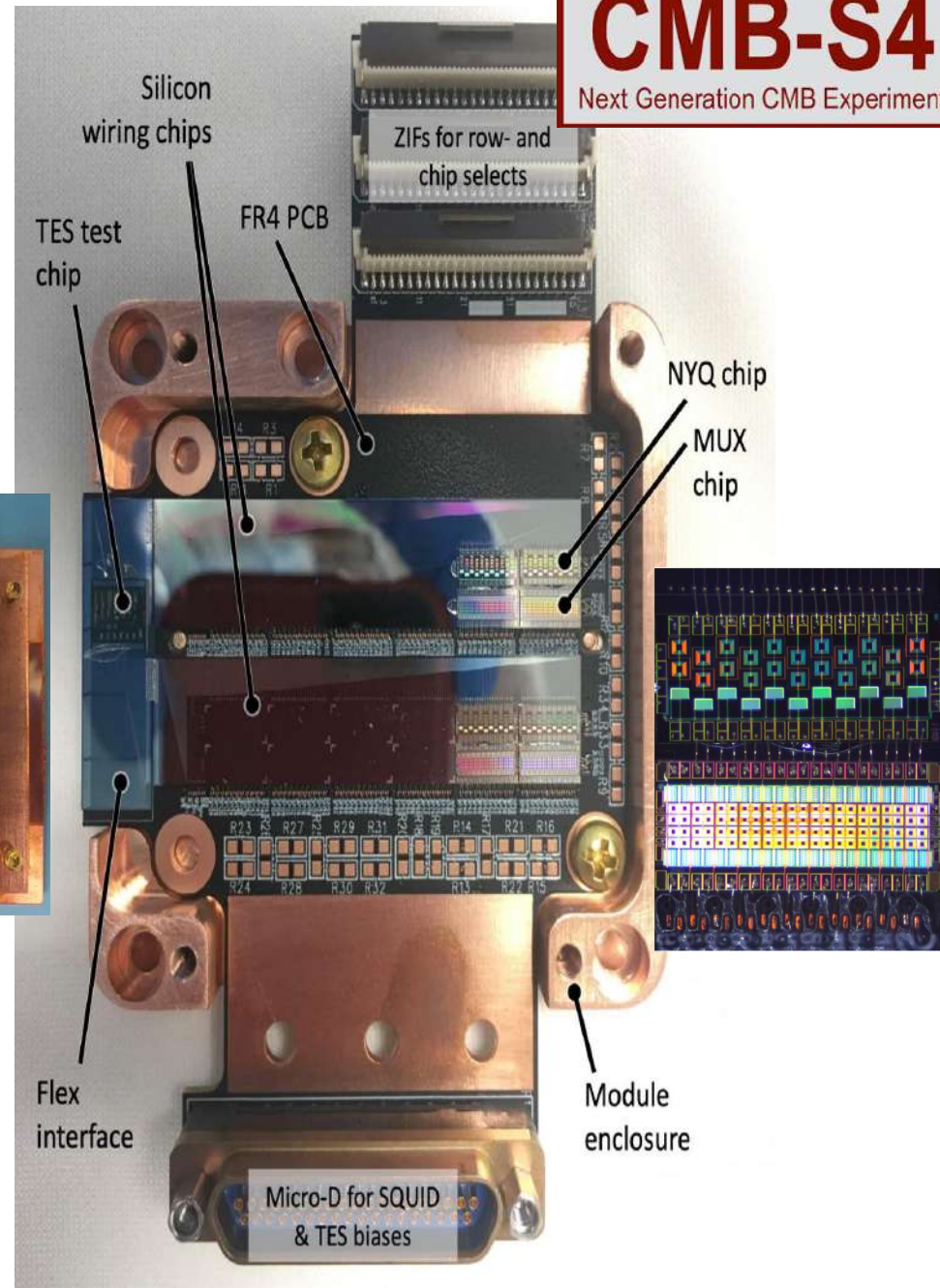
x500

100 mK readout

[readout] CMB-S4 Readout WG Telecon every 2 weeks

- **NIST SQUID** fabrication
- **SLAC** assembly
- **Test :**
 - UIUC
 - FNAL
 - UNM
 - SLAC

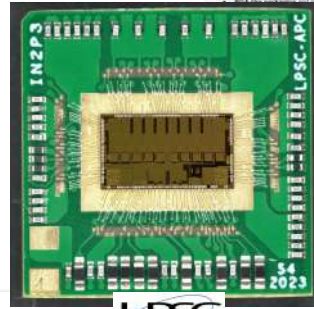
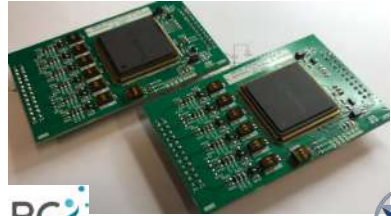
CMB-S4
Next Generation CMB Experiment



Installation d'une chaîne de détection dans une dilution APC



Collaboration IN2P3/SLAC on the detection chain



READOUT-FRONTENDCARD-TO-ASICv3 BOARD INTERFACE
CONTROL DOCUMENT
CMB-S4
CMBS4-doc-xxx-v1

Document release signatures

Released

Prepared by:		
Name(s) and Signature(s)	Role/Organization	Date
Gunter Haller	L2 ReadoutCAM Engineer	
Zeeb Ahmad	L2 Readout Manager	
Damien Prele	APC IN2P3	
Manuel Gonzalez	APC IN2P3	
Approved by:		
Name(s) and Signature(s)	Role/Organization	Date
Approved by:		

DELIVERABLES

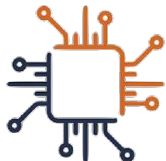
1. WBS 1.04 Readout

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 card
- iii. Functionality/performance test with IN2P3 ASIC daughter board with ASIC_v3 in new 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

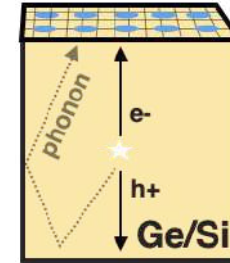
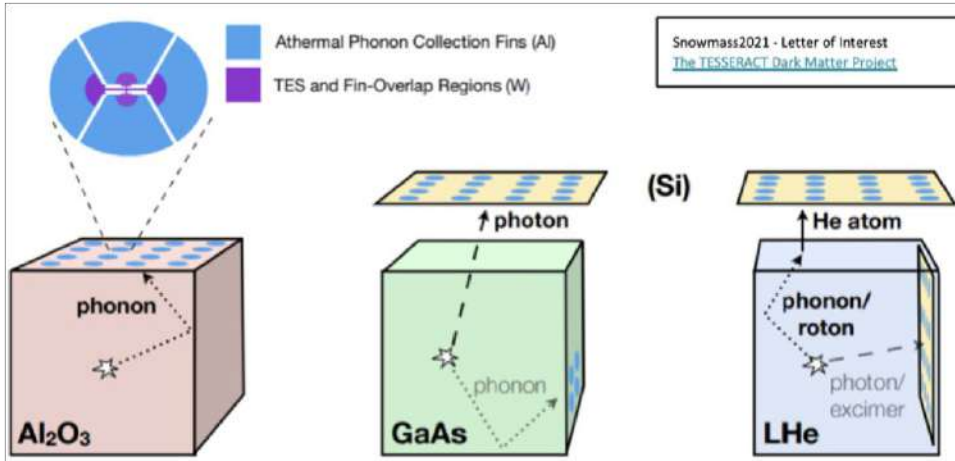
b. IN2P3

- 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.



TESSERACT : Proposal experiment @ LSM

Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets



TESSERACT @ LSM proposal:

- DOE Funding for R&D and project development began in June 2020 (Dark Matter New Initiative)
- One experimental design, and different target materials with complementary DM sensitivity, all using TES
- Includes **SPICE** (Al₂O₃ and GaAs) and **HeRALD** (LHe)
- ~ 40 people from 8 institutions
- ~~Actively searching for an underground lab~~
- **found an underground Lab and new partners**

- Benefit from EDW+Ricochet+CUPID Ge bolometer expertise and low-background cryogenic experience to:
 - **Add the French semiconductor Ge bolometer technology (both LV and HV mode) to the TESSERACT science program**
 - **Deploy** the future TESSERACT experiment **at LSM**
- Achieve leading light DM sensitivities on short time scales
- Benefit from exchange of technologies with US partners



Caltech



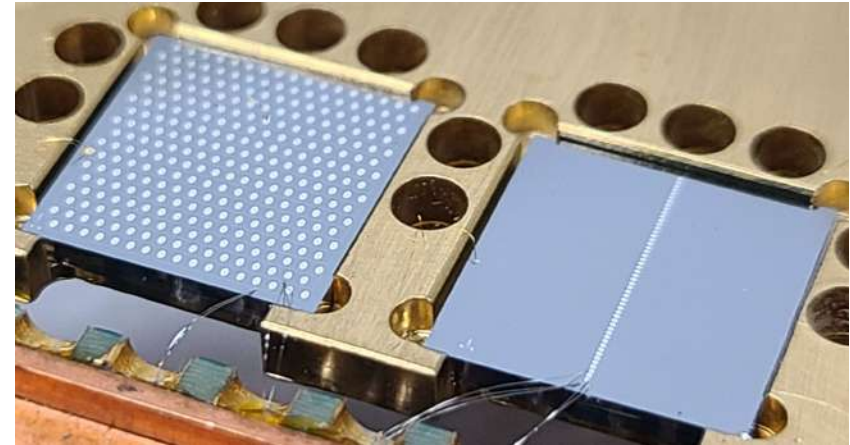
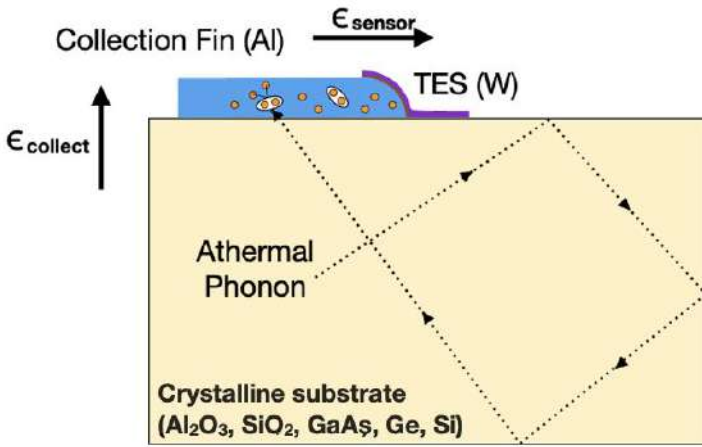
FLORIDA STATE



UMass Amherst



TESSERACT : New generation TES sensors

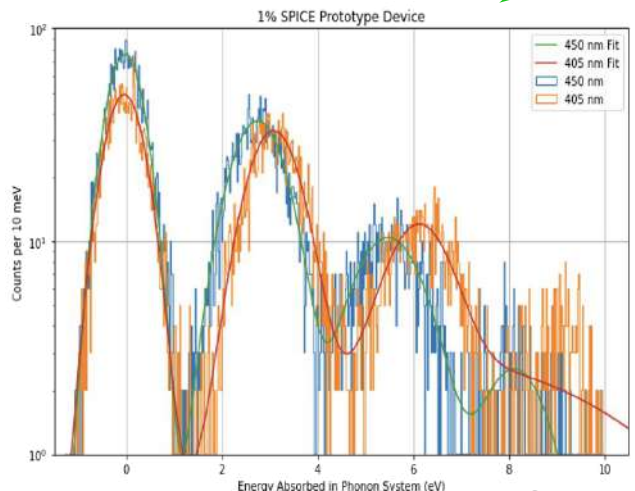


$$\sigma_E \sim \frac{\sqrt{4k_b T_c^2 G (\tau_{collect} + \tau_{sensor})}}{\epsilon_{collect} \epsilon_{sensor}}$$

$$\sigma_E \propto V_{det}^{1/2} T_c^3$$

Energy threshold decreases w/ detector mass

Energy threshold decreases very quickly w/ Tc

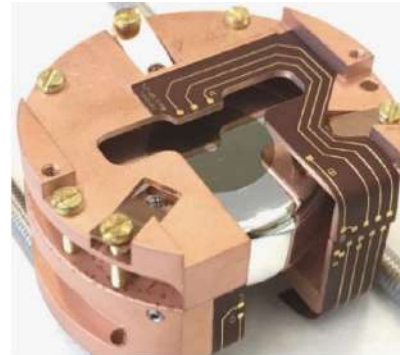


- SuperCDMS TES technology optimized for small volume crystal.
- 273 meV (RMS) leading to eV-scale threshold **already achieved** with a 0.2g Si detector and Tc = 50 mK
- Targeted Tc around 15-20 mK recently achieved
 - **~100 meV threshold achievable on 1 cm3 crystals**
- Next challenge: parasitic power (vibrations, EMI, IR photons) needs to be <aW to fully reach TES sensitivity

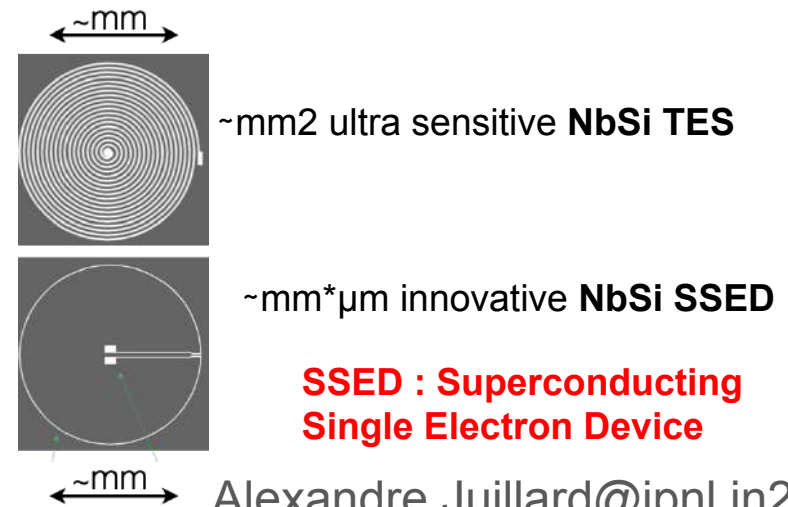
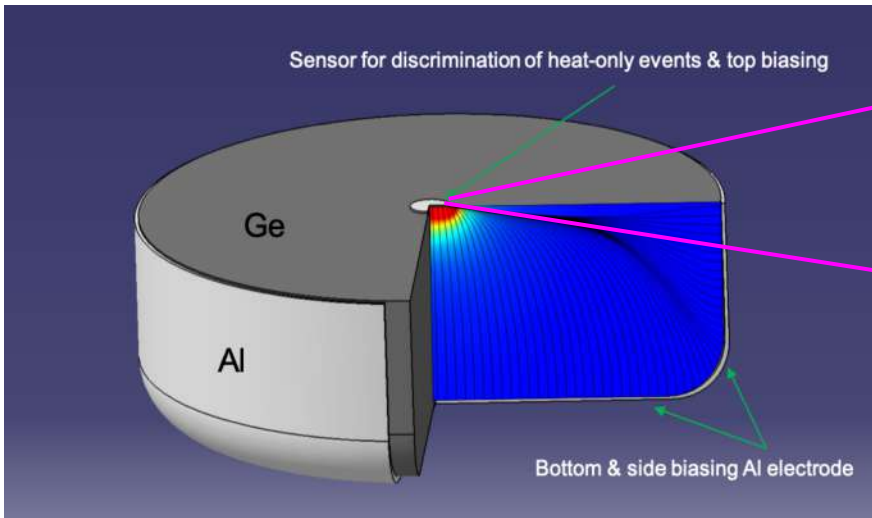


- Low Energy Excess observed in ALL cryo detector are non ionizing (« **heat only** » event)
- **Ionization can be used to reject LEE**
- Huge effort over the past 7 years :
 - from EDWIII $\sigma = 200$ eV to $\sigma = 30$ eV (reached for RICOCHET)
 - **$\sigma = 20$ eV in hand** but hard to do better than 10

- CryoSEL Tricks = use the Luke effect
 - **Concentrate it**
 - **Trigger a « LEE » veto** thermometer
 - single e-h sensitivity possible with a SSED : **Superconducting Single Electron Device**
- Will be used in TESSERACT**

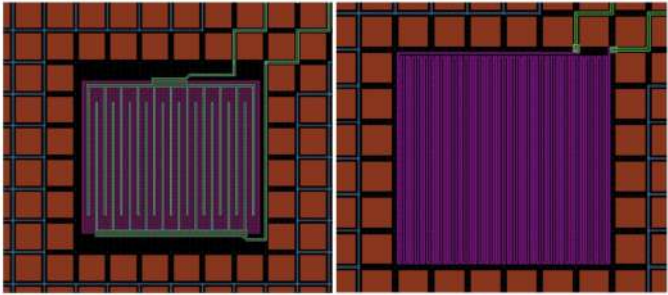


38g Ge CryoSEL prototype



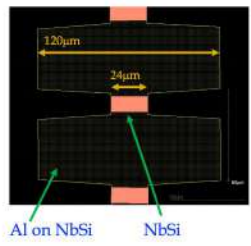


R&D @ IJCLab : NbSi thermal sensor

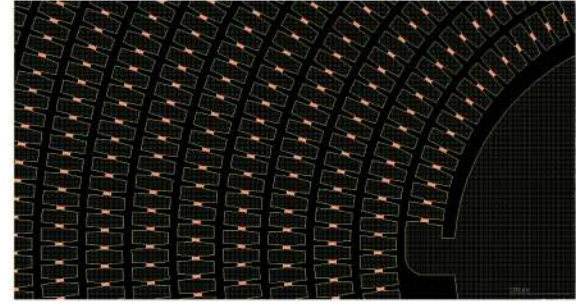


Low Impedance High Impedance

The NbSi phonon-trap design

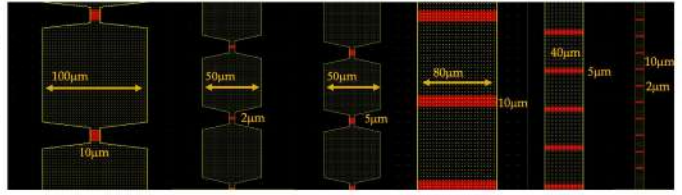


17000 NbSi-Al cells in series to form a spiral

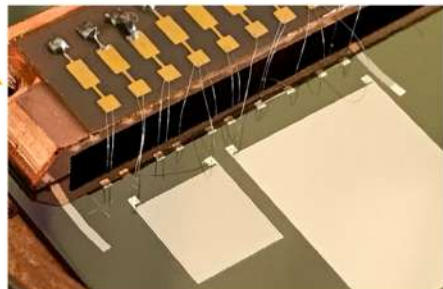
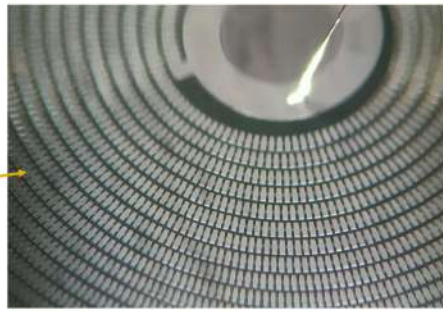
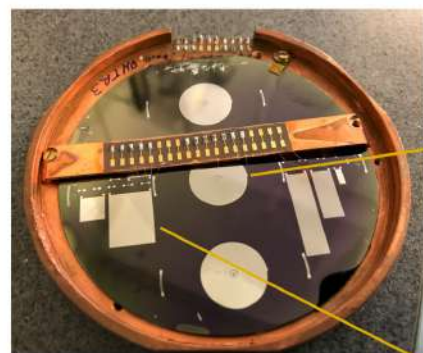


- **Nb_xSi_{1-x}** : Alloy near the **Metal Insulator Transition** or **superconductor**
- > 20 years of development. Co-evap of thin film.
- **Best result in the superconducting mode** (high or low Z)
- **Micro-lithography** (CNRS/C2N) for both **detectors matrix** (QUBIC) and **massive bolometers** (EDELWEISS, CryoSEL, TINY).
- **R&D :**
 - Specific heat minimization → Phonon traps
 - **Low threshold** « metastable » state for heat only event discrimination (Superconducting Single-Electron Device **-SSED-**, CryoSEL ANR project)

Other tested designs ...
10 µm, 5 µm and 2 µm TES



NbSi "PhononTrap" samples

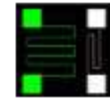


Four Si wafers with several phonon-trap designs were realized
Samples with TES islands ≥ 5 µm are OK
Samples with 2 µm TES have some problems

Optimisation du design des TES US dans le cadre d'une double mesure chaleur/ionisation car il y a competition entre les electrodes et les TES en terme d'absorption de phonon (développement en commun avec les US)

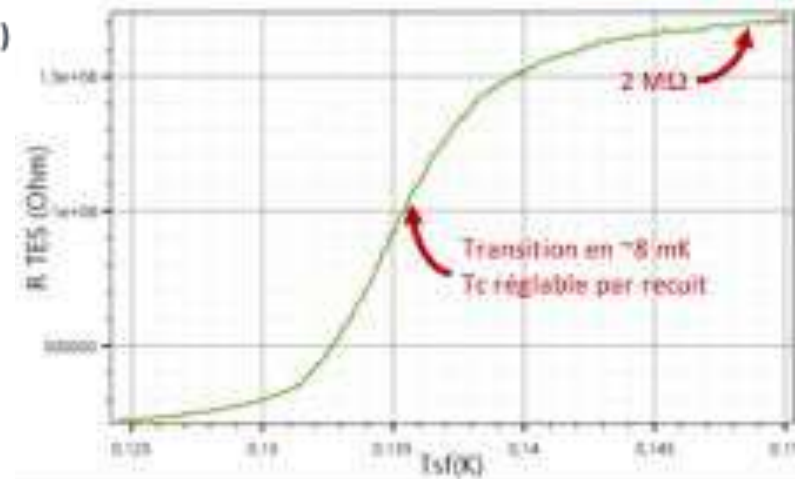
R&D HRTES-X (spectro-imagerie X)

TES NbSi HZ (XdIB, Benjamin Criton, JLS)



Thermomètre à transition supraconductrice haute résistivité (HR-TES)

- Utiliser un **nouveau type** de thermomètre (IJCLab, Orsay) possédant potentiellement les avantages du Si dopé (impédance) et ceux du TES classique (sensibilité)...
- ... dans le cadre de détection X (→ nouveauté).
- Pour cela, notre **innovation** : la contre-réaction électrothermique active (pour contrer le problème du découplage électron-phonon).
- Principe du TES : matériau placé juste à sa transition supraconductrice $\Rightarrow \Delta T = \sim 8 \text{ mK} \rightarrow \Delta R = 2 \text{ M}\Omega$



Objectifs de la R&D

- Modéliser le dispositif et estimer ses performances théoriques
- Puis développer un démonstrateur complet : {déTECTEUR + électronique + banc}, mais de taille réduite (16 voies)

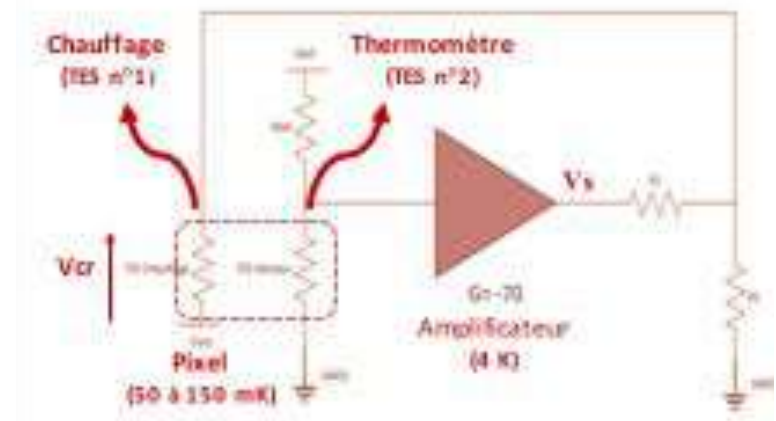
Deux thèses successives

- Galahad Jégo (2016 – 2019)
- Benjamin Criton (2020 – 2023)

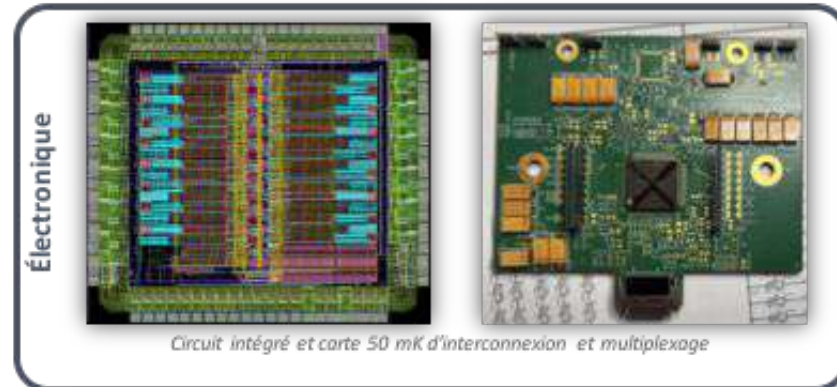
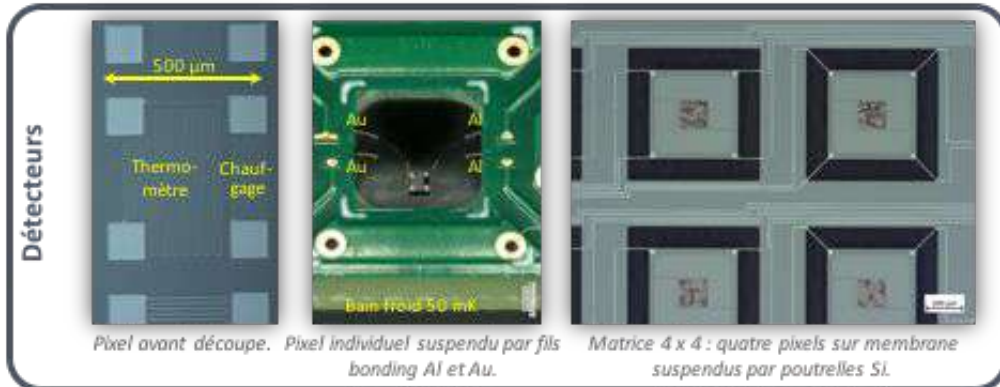
Électronique

Besoins **similaires** au Si dopé, mais avec des **spécificités** :

- le multiplexage passe de 2,5 K à 50 mK
- il multiplexe le signal et la contre-réaction électrothermique.

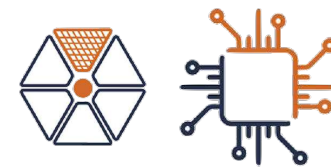
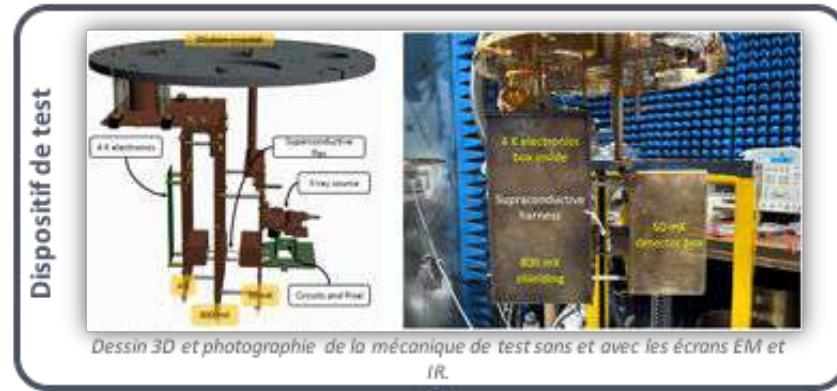


R&D HRTEs-X (spectro-imagerie X)



Développements

- Prototypes de **détecteurs** (fabrication IJCLab) :
 - pixels individuels (Si suspendu par bonding)
 - matrice 4 x 4 pixels (membrane suspendue par poutrelles)
- **Électronique** :
 - ASIC de multiplexage 50 mK,
 - cartes à 50 mK et 4 K (amplification) et 300 K
- **Structure thermomécanique de test** (50 mK – 300 mK – 4 K)



R&D HRTES-X (spectro-imagerie X)

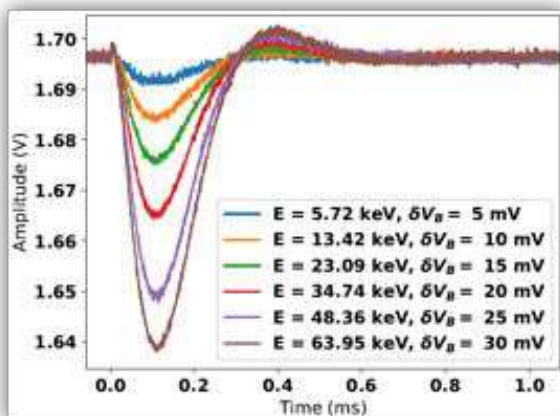
Bilan provisoire

- **Résolution spectrale théorique** après optimisation a été évaluée : 2,1 eV à 6 keV → **état de l'art**
- Le **dispositif de test complet** a été assemblé et les éléments validés individuellement.
- Mais problème de cryogénérateur ⇒ la **résolution spectrale expérimentale** n'a pas encore pu être mesurée.

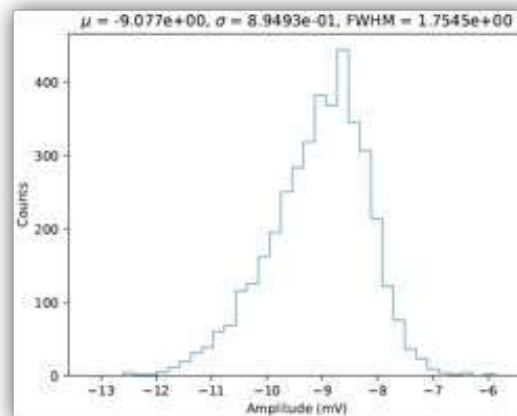
Prochainement

- Le cryogénérateur sera à nouveau opérationnel et les **mesures** pourront reprendre (février ?).
- Une nouvelle R&D Intégration (voir plus loin) offrira un **cadre pour poursuivre** ce développement.

A suivre...

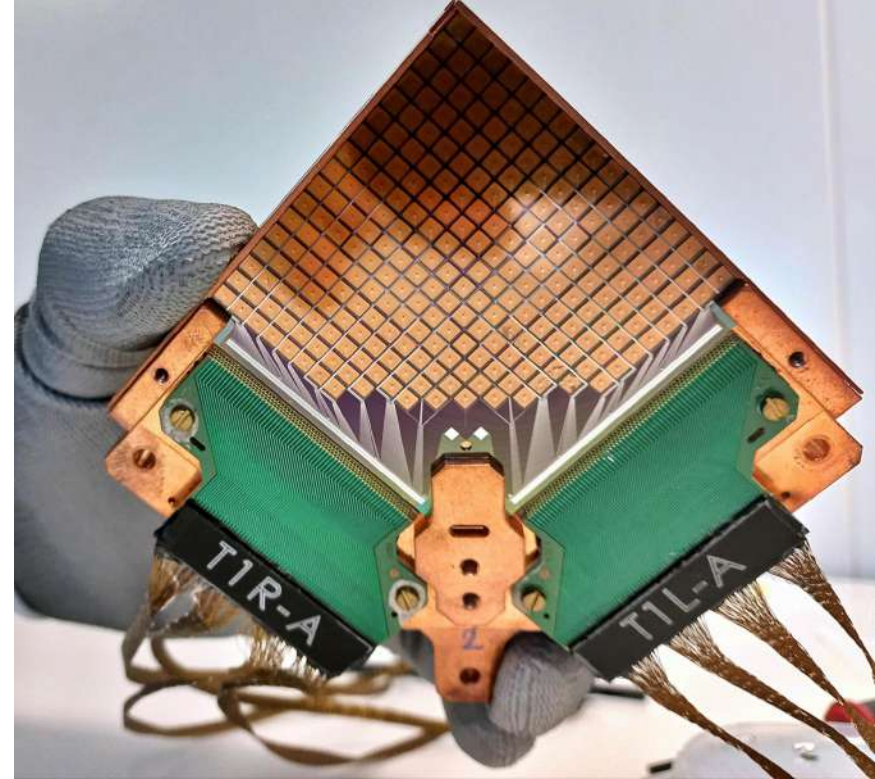


Spectre préliminaire sur pixel d'essai fonctionnel.



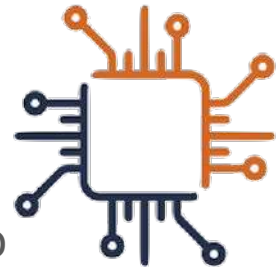
Spectre préliminaire sur pixel d'essai fonctionnel.

Conclusion



- NbSi
 - T_c adjustable \rightarrow 50 mK - qK
 - Facteur de forme \rightarrow 100 m Ω - 2 M Ω

- Matrices de **bolomètre supraconducteur** mm \rightarrow Cosmology CMB
- Matrices de **microcalorimètre X** \rightarrow Astronomie Haute Énergie
- Détecteur de **phonon** - **Cristaux** type Edelweiss \rightarrow DM, WIMP, Neutrino



Et **électronique de polarisation, de multiplexage et de lecture**

Et aussi les flex supra

