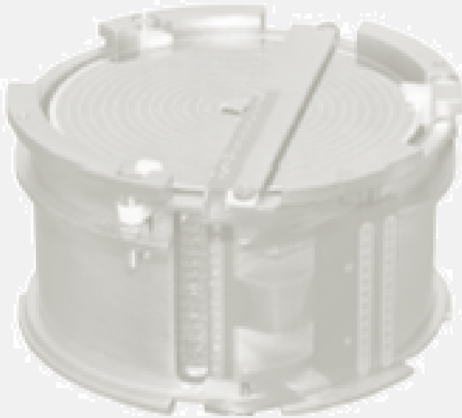
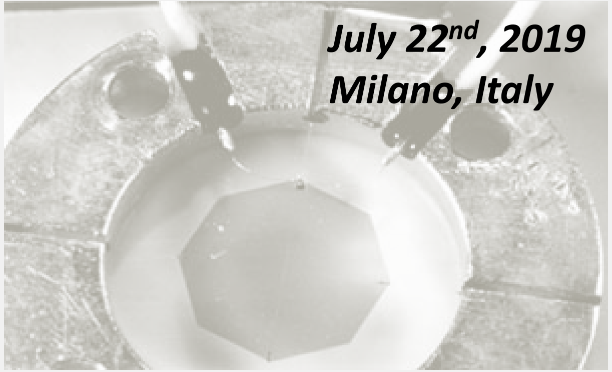
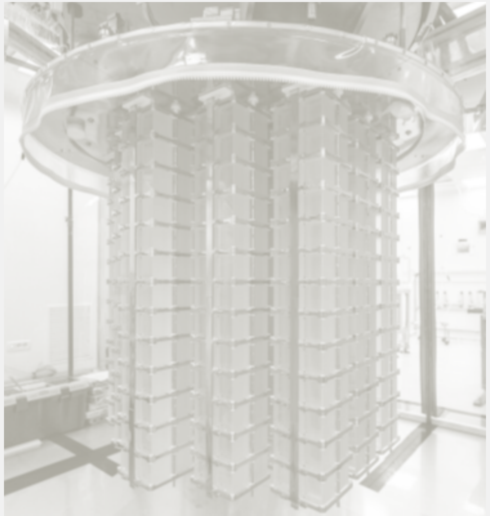
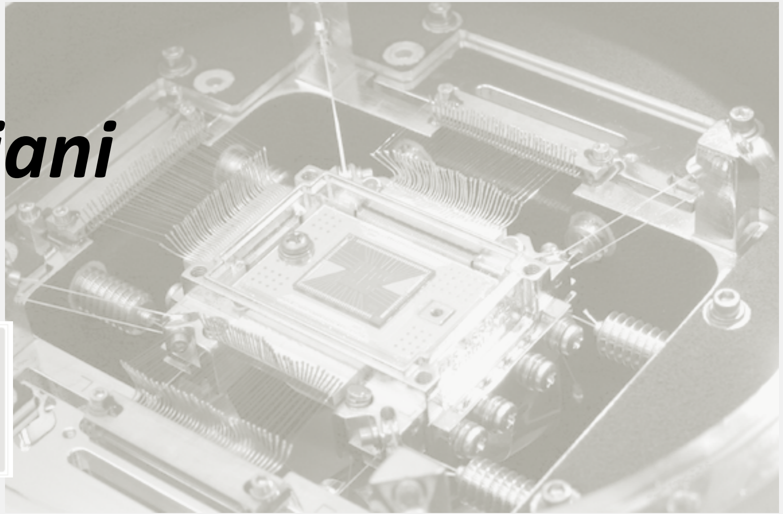




July 22nd, 2019
Milano, Italy

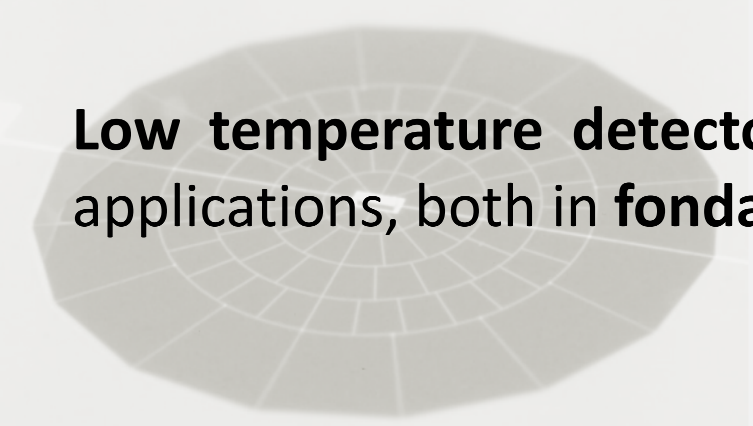
Applications of low temperature detectors

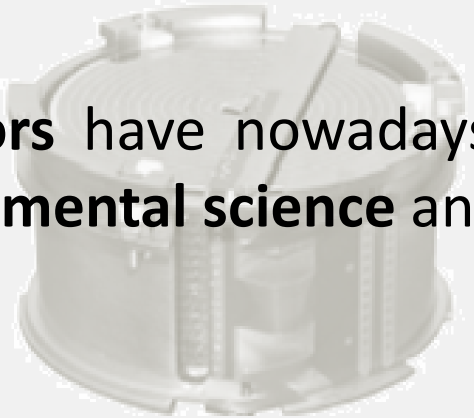


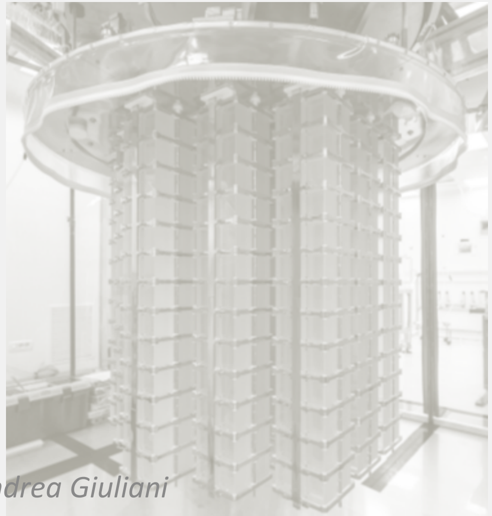

Andrea Giuliani

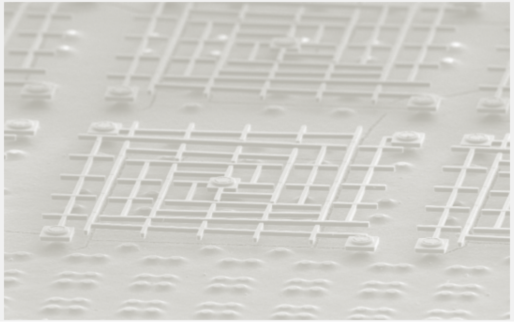


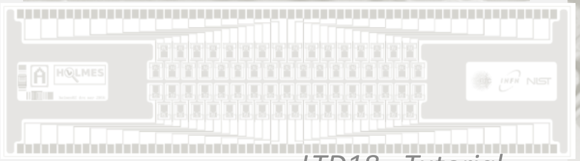
Low temperature detectors have nowadays a wide range of applications, both in **fondamental science** and **technology**

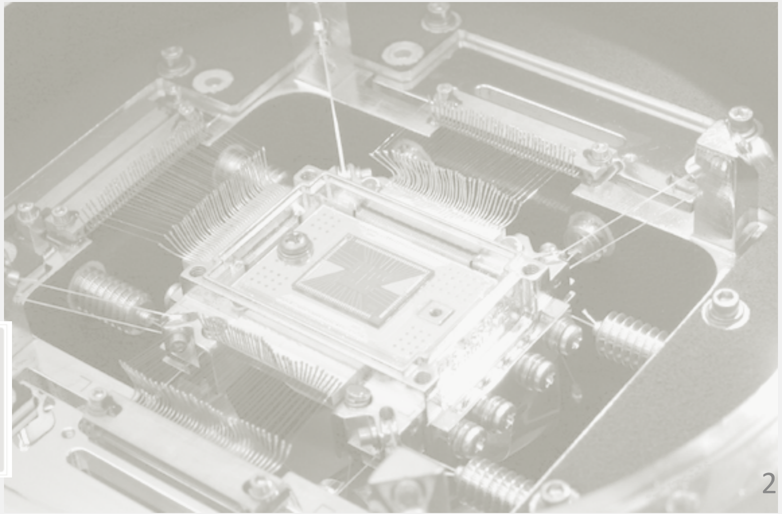












Low temperature detectors have nowadays a wide range of applications, both in **fondamental science** and **technology**

- Astronomy, astrophysics and cosmology
- Dark matter: search for WIMPs, axions and other exotic particles
- Neutrino basic properties
- Nuclear and atomic physics
- Material and life science, cultural heritage, homeland security
- New frontier: quantum technologies

Low temperature detectors have nowadays a wide range of applications, both in **fondamental science** and **technology**

- Astronomy, astrophysics and cosmology
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- New frontier: quantum technologies

The deep roots of bolometry are in astronomy

Samuel P. Langley (1834 – 1906) was an American astronomer, physicist, inventor of the **bolometer**

THE

"BOLOMETER,"

BY

PROF. S. P. LANGLEY,

AMERICAN METROLOGICAL SOCIETY,

DECEMBER, 1880.

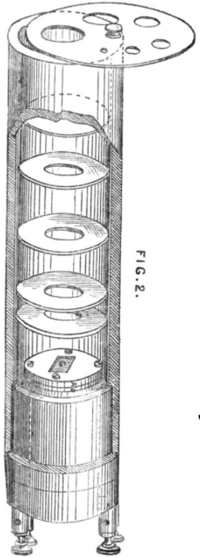
1880

which I have called the Bolometer (βολη μέτρον)

S. Langley, *The bolometer*
Nature, 25, 14-16, 1882

The radiation absorber was a thin iron strip inserted in a Wheatstones's bridge

→ Sensitive to **ΔT ~ 10^{-5} K**



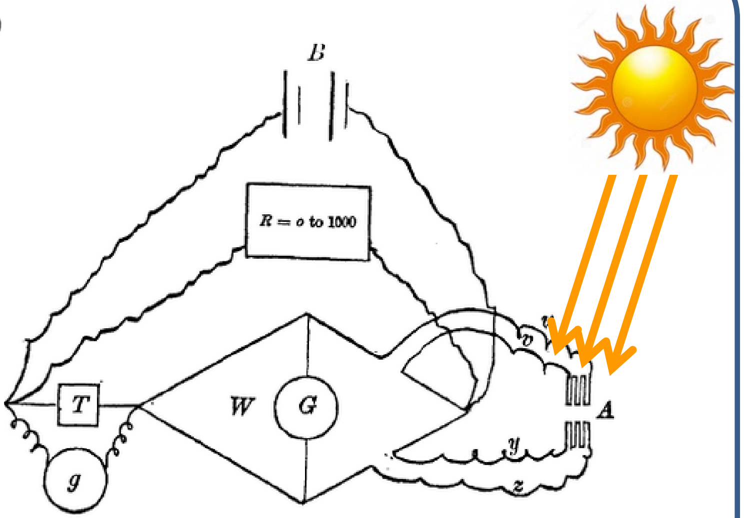


FIGURE 3.

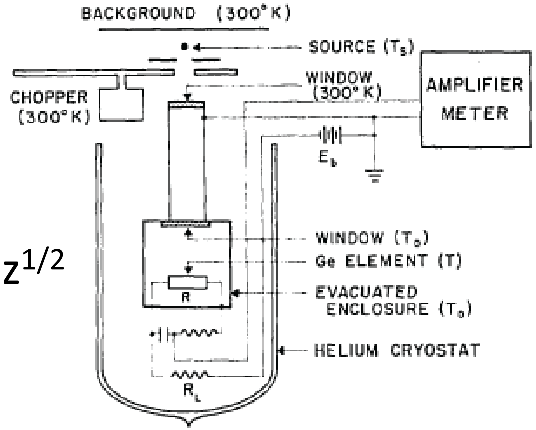
This instrument enabled him to study **solar irradiance far into its infrared region** and to measure the intensity of solar radiation at various wavelengths

The advantage of cooling down: the LTD era

Franck Low develops a bolometer based on a **Ge:Ga thermistor**, cooled at **2 K**
Journal of the Optical Society of America
Vol. 51, Issue 11, pp. 1300-1304 (**1961**)

Low-Temperature Germanium Bolometer

Frank J. Low
Texas Instruments Incorporated, Dallas, Texas
(Received March 29, 1961)



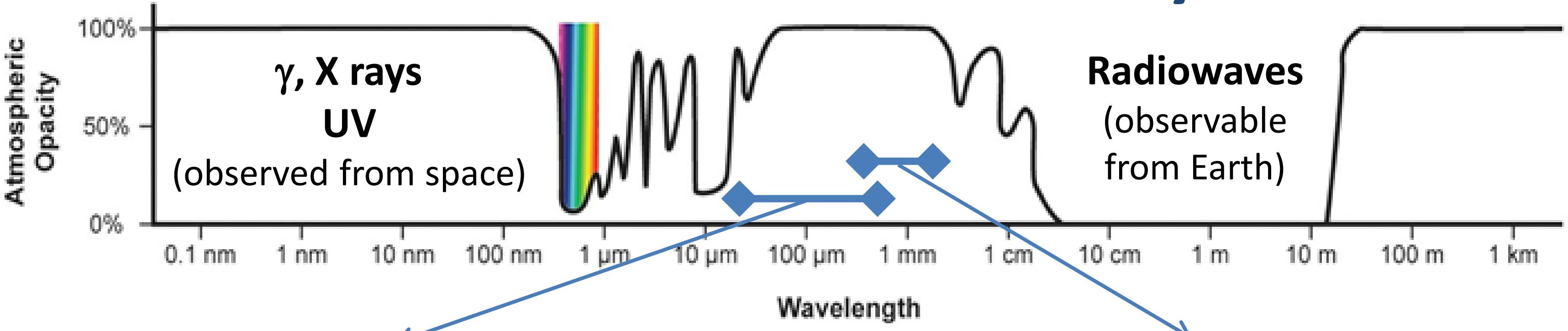
NEP
$\sim 10^{-12}$ W/Hz$^{1/2}$

To avoid IR absorption in lower atmosphere, instruments were placed in aircrafts

Major discoveries in **IR astronomy**:

- Orion Nebula
- IR Cosmic Background
- IR galaxies
- Jupiter and Saturn → internal source of energy

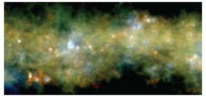
The mm and sub-mm astronomy: science



Far InfraRed (FIR) / sub-mm astronomy

Wavelength range: **50 μm – 850 μm**

- Galaxy formation in the early universe
- Evolution of galaxies
- Star formation
- Chemical composition of atmospheres and surfaces of Solar System bodies
- Molecular chemistry across the universe

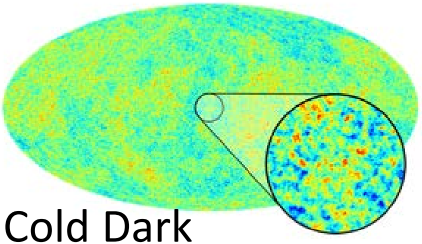


mm astronomy

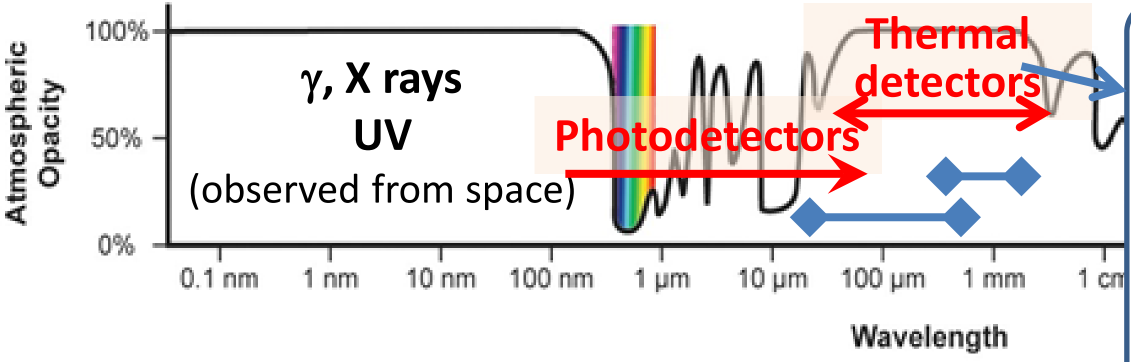
CMB: dE/dλ peaks at **λ = 1.063 mm**

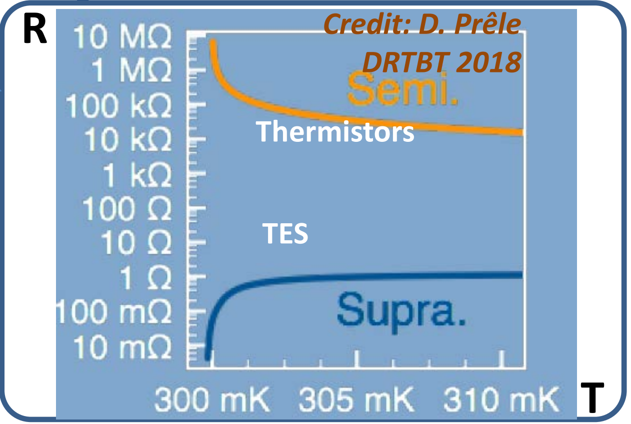
Strong support for:

- the Big Bang model in general
- the ΛCDM ("Lambda Cold Dark Matter") model in particular



The mm and sub-mm astronomy: instruments

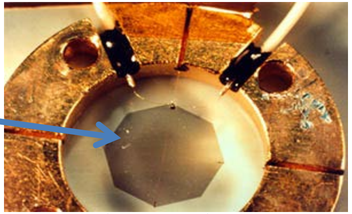




COBE mission (1989-1993) – Demonstrates that CMB has a near-perfect black-body spectrum

FIRAS [0.1 – 10 mm] – Michelson interferometer with **four bolometric detectors**

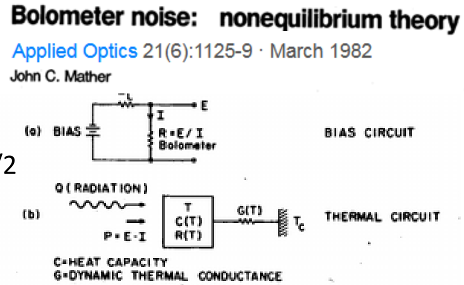
- Composite bolometer
- Absorber: diamond with Cr-Au film
- Si-doped sensor



~ 0.8 cm

T ~ 1.6 – 1.7 K

NEP ~ 4 × 10^{-15} W/$Hz^{1/2}$



John Mather

The mm and sub-mm astronomy: instruments

RECENT PAST

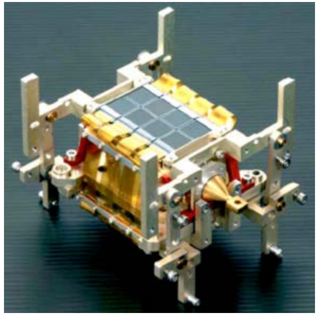
Far InfraRed (FIR) / sub-mm astronomy

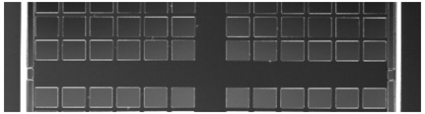
Herschel (2009-2013) -The largest, most powerful infrared telescope ever flown in space

PACS instrument

Two filled Si:P:B bolometer arrays:
32x16 ("red") and 64x32 ("blue, green") pixels

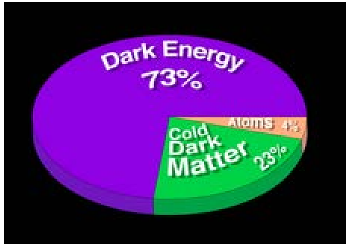
T ~ 0.3 K NEP ~ a few × 10^{-17} $W/Hz^{1/2}$





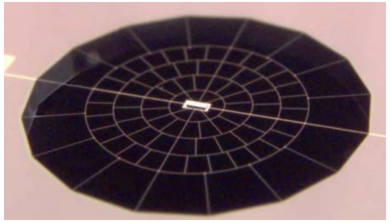
mm astronomy

Planck (2009-2013)
Space observatory that provided the most precise measurements of several key cosmological parameters



High Frequency Instrument (HFI)

52 spider-web bolometers based on NTD Ge thermistors
T ~ 0.1 K



The mm and sub-mm astronomy: instruments

CURRENT EFFORTS

Far InfraRed (FIR) / sub-mm astronomy

SPICA –Final selection mid 2021

Launch in ~ **2032**

3 instruments

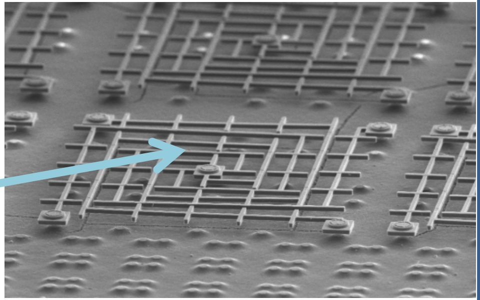
- SMI (Mid-IR)
- Safari (Spectrometer, FIR)
- **Safari-Pol: imaging polarimeter in FIR**

Si doped thermistor technology

T ~ 0.05 K

NEP ~ 10^{-18} W/Hz$^{1/2}$

Each pixel is intrinsically sensitive to polarization



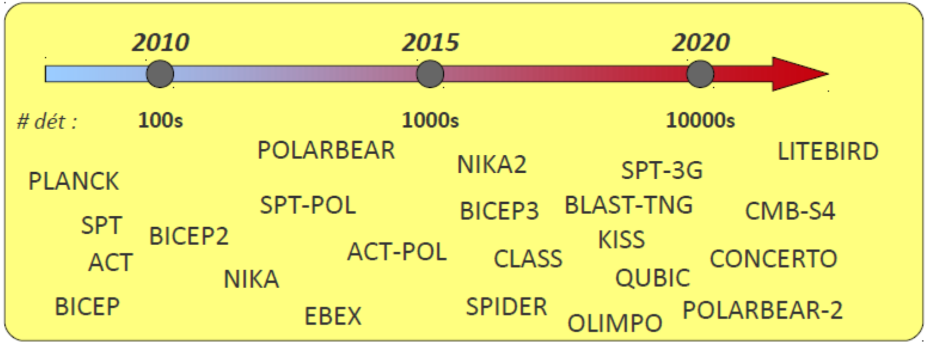
mm astronomy

Holy grail of cosmology:

CMB B-modes polarization

→ gravitational lensing

→ gravitational waves from inflation



Multiplexing

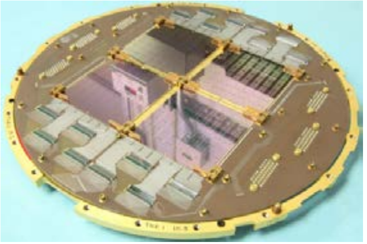
Series production

Emerging technologies:

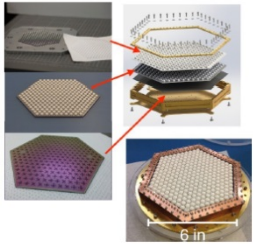
- TES
- MKIDs

The mm and sub-mm astronomy: instruments

CURRENT EFFORTS

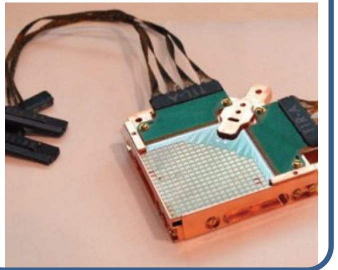


Ti **TES**
256/512 pixels / det

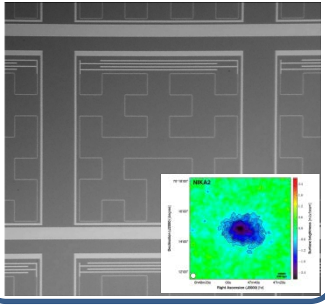


Ti-Au **TES**
271 pixels / module

NbSi **TES**
4 × 250 pixels



LEKID design
600-2000 pixels

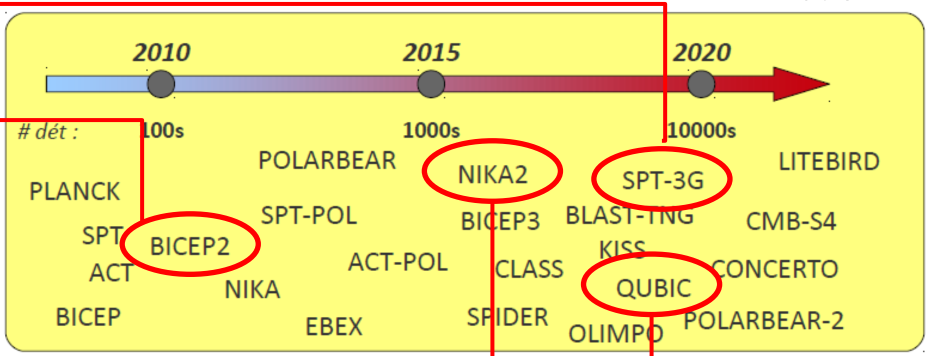


mm astronomy

Holy grail of cosmology:
CMB B-modes polarization

gravitational lensing

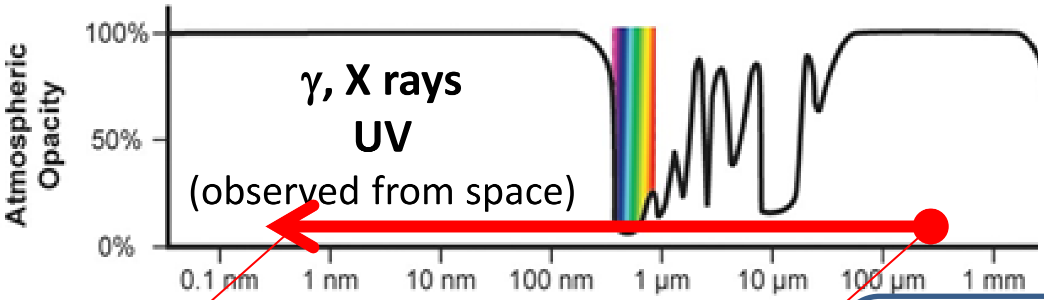
gravitational waves from inflation



Multiplexing
Series production

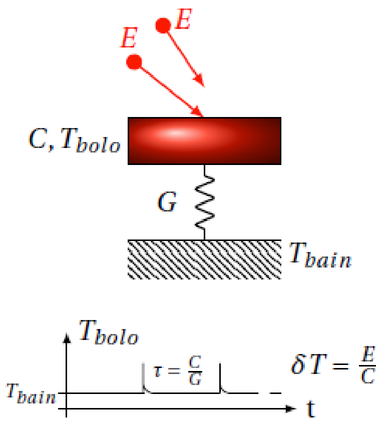
Emerging technologies:
- TES
- MKIDs

From IR to X-rays

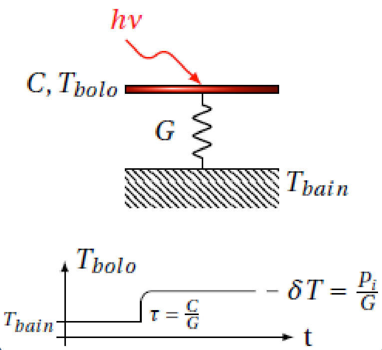


Unlike Bragg spectrometers, possibility to couple **space resolution** with **spectral resolution**

Single photon E> ~1 eV



Flux of photons



Credit: D. Prêle
DRTBT 2018

Thermal detectors as x-ray spectrometers

Journal of Applied Physics 56, 1257 (1984); https://doi.org/10.1063/1.334129

S. H. Moseley and J. C. Mather
Goddard Space Flight Center, Greenbelt, Maryland 20771
D. McCammon
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

Dan McCammon

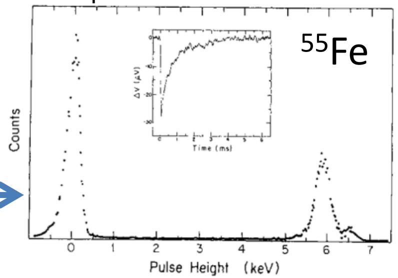
1984

Experimental tests of a single-photon calorimeter for x-ray spectroscopy

Journal of Applied Physics 56, 1263 (1984); https://doi.org/10.1063/1.334130

D. McCammon
Physics Department, University of Wisconsin, Madison, Wisconsin 53706
S. H. Moseley, J. C. Mather, and R. F. Mushotzky
Goddard Space Flight Center, Greenbelt, Maryland 20771

Si-doped thermistor



First energy spectrum with a low temperature calorimeter

X-ray astrophysics with sounding rockets

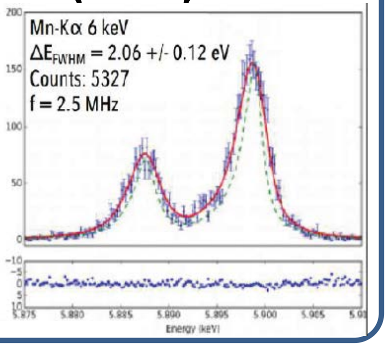
X-ray astrophsyics

Credit: E. Cucchetti DRTBT 2018

X-ray astrophysics deals with galaxy clusters, AGN, SN remnants, binary stars and other « extreme » astrophysical objetcs

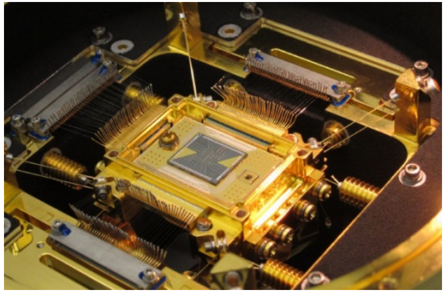
Athena mission (2031)

X-IFU instrument
Bi/Au absorber on
Mo/Au **TES**
3800 channels
2.5 eV FWHM < 7 keV



ASTRO-H (Hitomi) mission (2016)

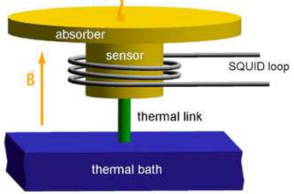
SXS instrument
HgTe asborbers on **Si thermistors**
6×6 channels - 7 eV FWHM in 0.3-12 keV



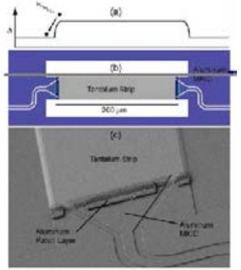
Other possible detector choices

MMCs

2.8 eV FWHM @7 keV



MKIDs

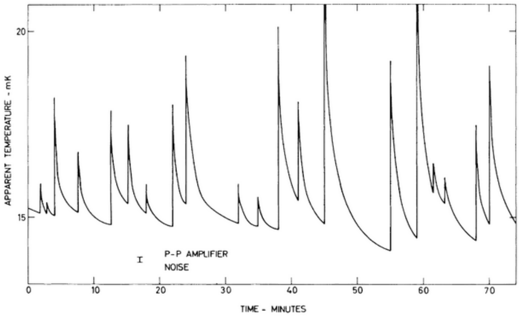


Lynx concept study

A parallel story…

T.O. Niinikoski, 1974

Cosmic ray disturbances in thermometry and refrigeration



T.O. Niinikoski, F. Udo, 1974

CERN internal report

Cryogenic detection of neutrinos?

A. Drukier, L. Stodolsky, 1982

Cryogenic detection of neutral-current neutrino scattering off nuclei

A. Drukier and L. Stodolsky
Phys. Rev. D **30**, 2295 – Published 1 December 1984

M.W. Goodman, E. Witten, 1985

Cryogenic detection of dark-matter candidates

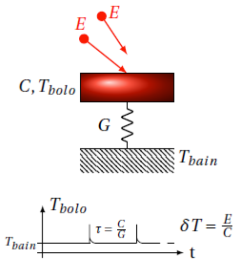
Mark W. Goodman and Edward Witten
Phys. Rev. D **31**, 3059 – Published 15 June 1985

B. Cabrera, L.M. Krauss, F. Wilczek, 1985

Detection of neutrinos more in general

Blas Cabrera, Lawrence M. Krauss, and Frank Wilczek
Phys. Rev. Lett. **55**, 25 – Published 1 July 1985

E. Fiorini, T.O. Niinikoski, 1984



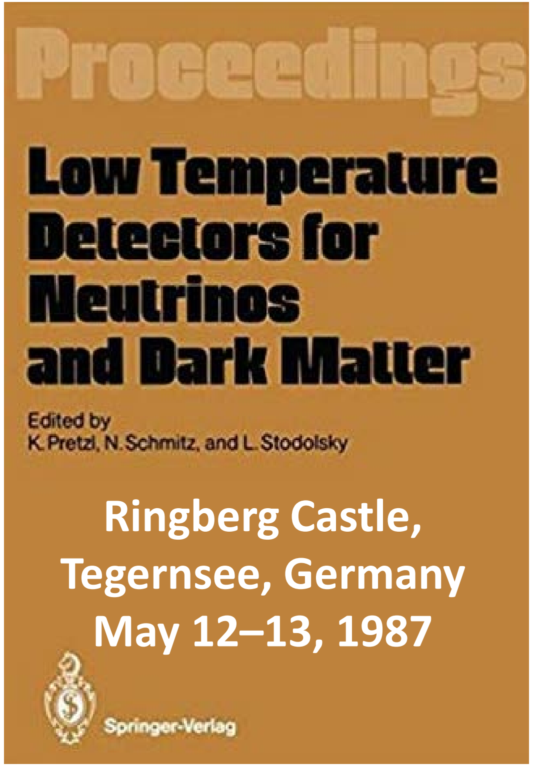
Low-temperature calorimetry for rare decays

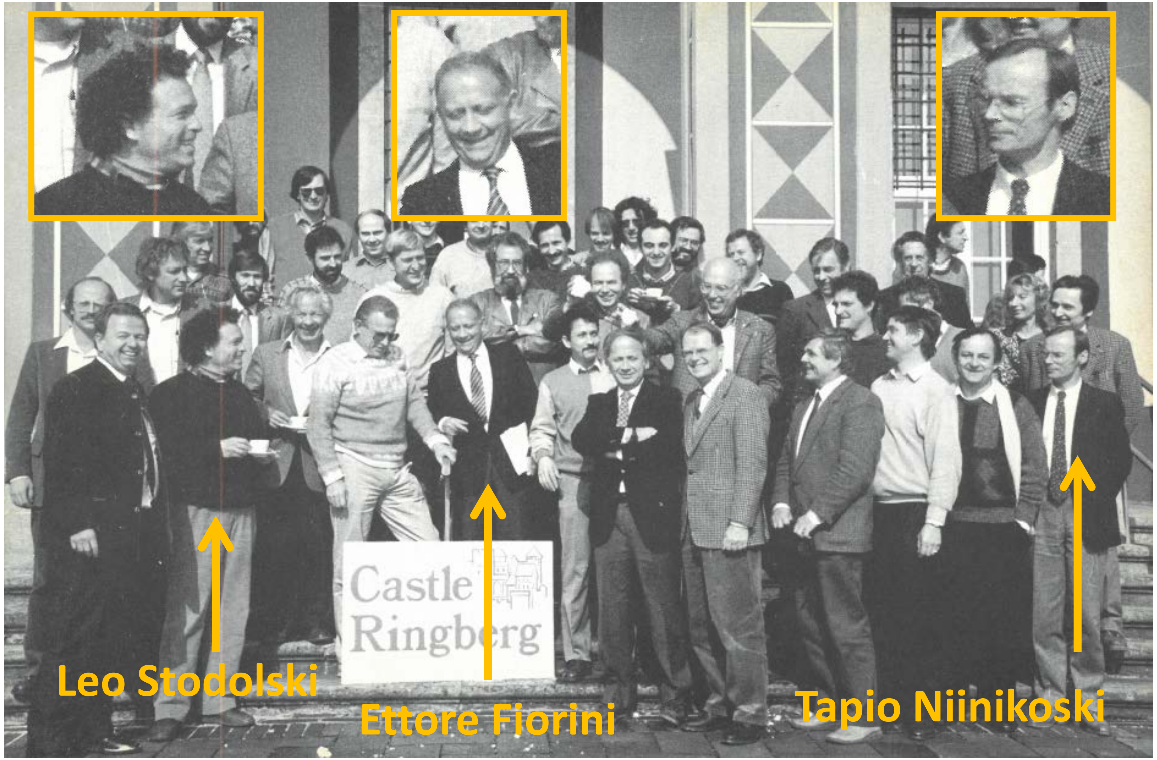
Nuclear Instruments and Methods in Physics Research
Volume 224, Issues 1–2, 1 July 1984, Pages 83-88

Application to ββ decay

Isotope	%	Z	A	$E_{trans.}$ (keV)	Sensitivity (1 yr expos.) (yr)	Present limit (yr)
^{76}Ge	7.67	32	72.59	2041 ± 2.5	1.2×10^{24}	5×10^{22}
^{82}Se	9.19	34	78.96	3009 ± 12	7×10^{22}	3×10^{21}
^{96}Zr	2.8	40	91.22	3356 ± 7	5×10^{23}	---
^{100}Mo	9.62	42	95.94	3033 ± 7	5×10^{24}	2×10^{21}
^{116}Cd	7.58	48	112.4	2808 ± 6	3.8×10^{23}	---
^{124}Sn	5.98	50	118.69	2277 ± 6	1.8×10^{23}	---
^{128}Te	31.79	52	127.6	870 ± 4	5.4×10^{22}	geolog.
^{130}Te	34.49	52	127.6	2534 ± 10	3.0×10^{23}	geolog.
^{136}Xe	8.86	54	131.3	2479 ± 11	9.0×10^{21}	---
^{50}Nd	5.6	60	144.29	3366 ± 8	2.2×10^{23}	2×10^{21}

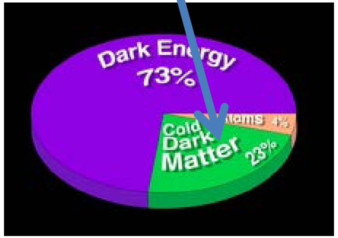
…leading to « LTD1 »



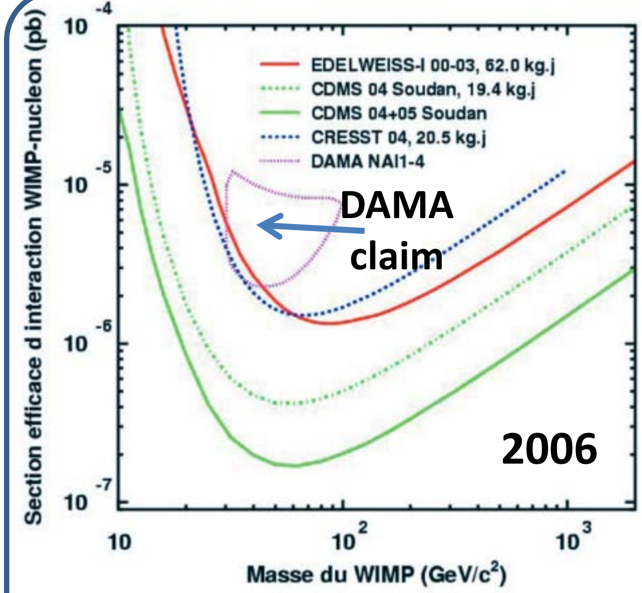


Search for dark-matter candidates

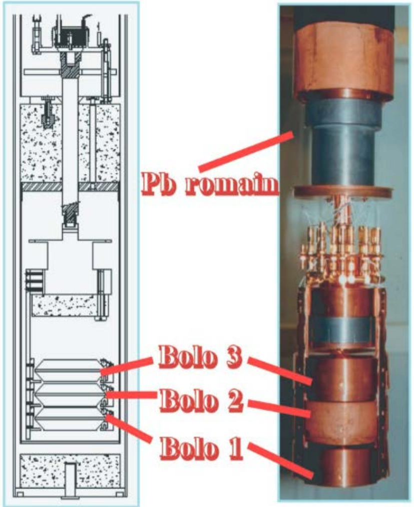
In the nineties of last century, **SUSY** enjoyed a great deal of credit in particle phsyics and the lightest SUSY particle (**neutralino**) was considered the natural dark-mater candidate, as it turned out to have the correct **relic abundance** (« WIMP miracle »).



Intense direct search for **WIMPs** with masses of **~100 GeV**



Promiment role of LTDs, which lead the fields until ~10-15 years ago



A relatively simple 3-bolometer set-up like EDELWEISS-1 has been leader in 2002

Search for dark-matter candidates

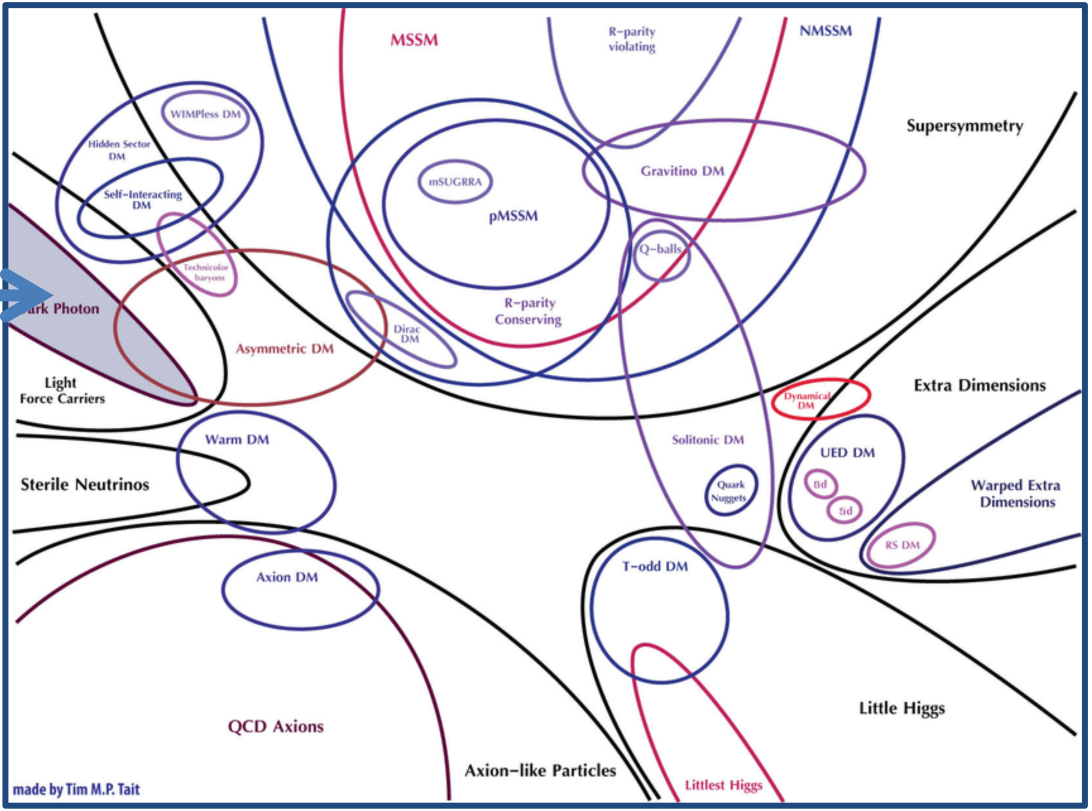
Today's situation

- **No SUSY** particles detected at **LHC**
- **No WIMP direct detection** down to **σ~10^{-46} cm^2**

Plethora of possibilities

- **Liquefied noble-gas detectors** dominate the field above 5 GeV WIMP mass

However, **still an important role for LTDs** (also for axion detection)



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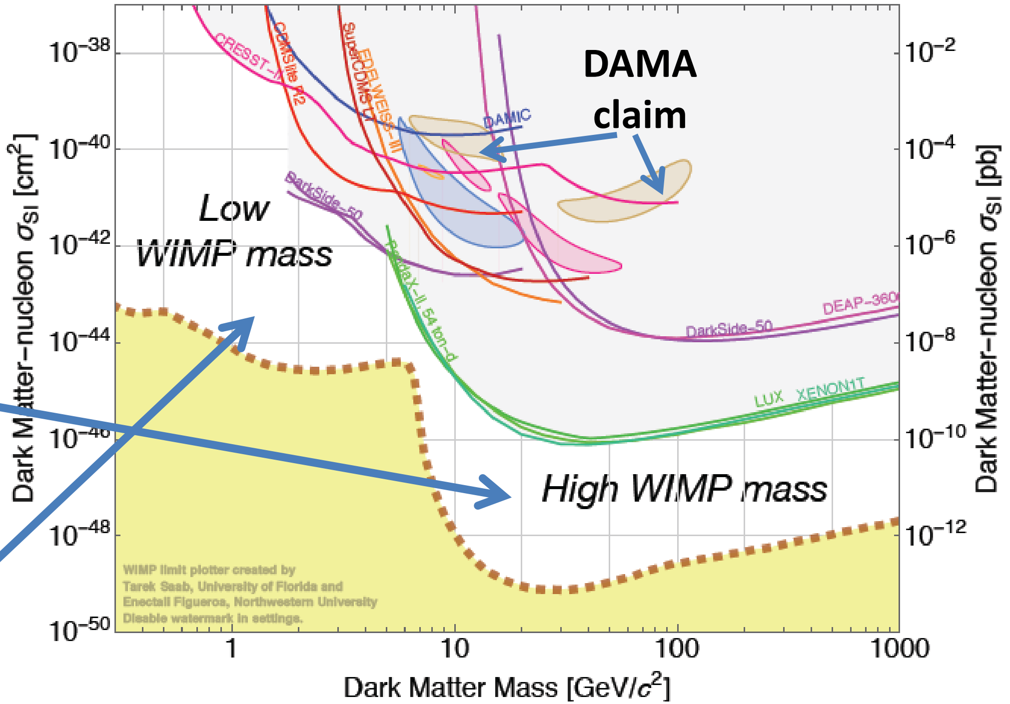
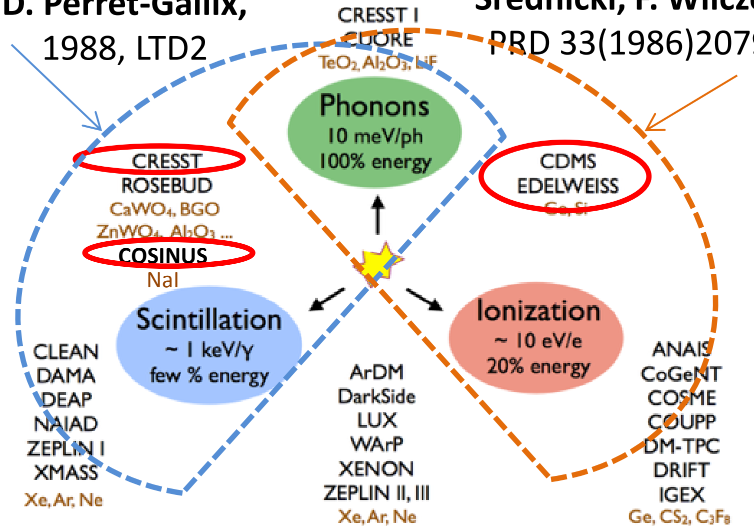


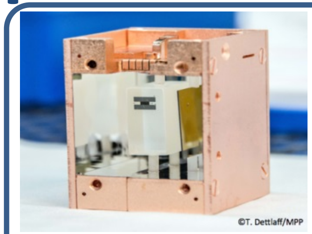
Dark matter experiments with LTDs

- Low energy threshold (≤ 100 eV)
- Low raw background
- Electron/nuclear recoil discrimination
- Large exposures

L. Gonzalez-Mestres, D. Perret-Gallix, 1988, LTD2

L.M. Krauss, M. Srednicki, F. Wilczec PRD 33(1986)2079





CRESST

$CaWO_4$ crystals

24 g

Scintillating bolometer

60 eV threshold on average

30 eV on one detector

EDELWEISS

Ge crystal

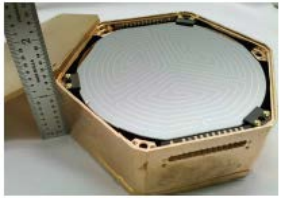
850 g

Ionization + heat

→ Reject surface events by charge collection pattern

36 detectors

→ 20 kg



SuperCDMS

Ge crystal

600 g

Ionization + athermal phonons

→ Reject surface events by phonon signal

15 detectors

→ 9 kg

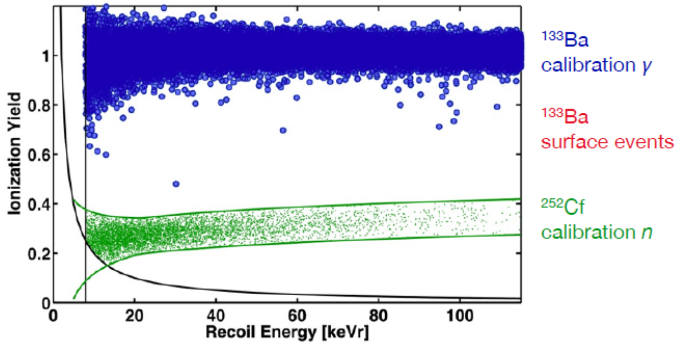
COSINUS: scrutinize DAMA with NaI scintillating bolometers

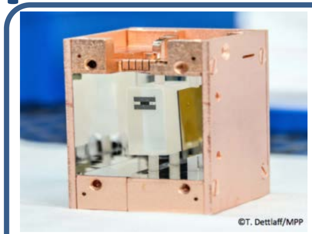
Dark matter experiments with LTDs

- Low energy threshold (≤ 100 eV)
- Low raw background
- Electron/nuclear recoil discrimination
- Large exposures

Discrimination in EDELWEISS

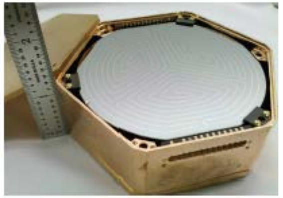
$Y = E_q/E_r$





CRESST
$CaWO_4$ crystals
24 g
Scintillating bolometer
60 eV threshold on average
30 eV on one detector

EDELWEISS
Ge crystal
850 g
Ionization + heat
→ Reject surface events by charge collection pattern
36 detectors
→ 20 kg



SuperCDMS
Ge crystal
600 g
Ionization + athermal phonons
→ Reject surface events by phonon signal
15 detectors
→ 9 kg

COSINUS: scrutinize DAMA with NaI scintillating bolometers

Search for low-mass candidates

Search for low-mass WIMPs

→ **threshold** more important than discrimination → **new strategies**

CRESST – phonons + ~~scintillation~~

Very small Al_2O_3 crystal – 0.49 g – 19.6 eV threshold

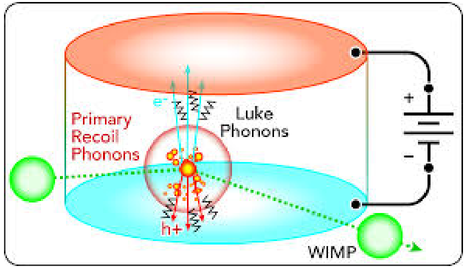
EDELWEISS – phonons + ~~ionization~~

Careful optimization of NTD readout and microphonic noise

Ge crystal – 32 g – 55 eV threshold

SuperCDMS and EDELWEISS – ~~phonons~~ + ionization

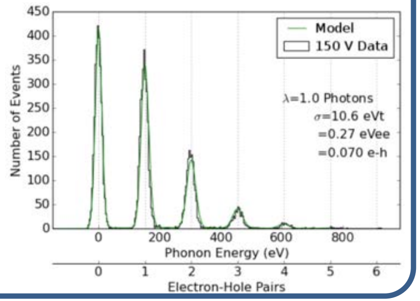
Ionization read by **Neganov-Luke effect** - CDMSLite 56 eVee threshold

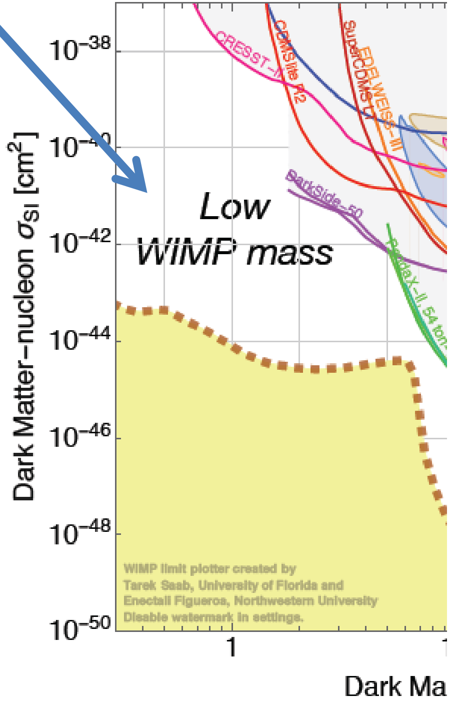


P. Luke

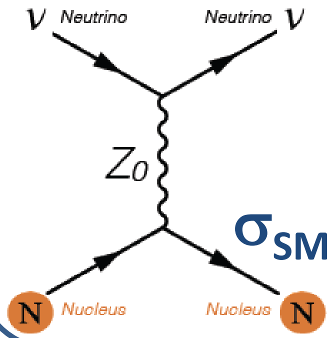
JAP 64(1988)6858

In this context, first observation of **e-h quantization** in Si →





Coherent elastic neutrino-nucleus scattering



Neutrinos scatter **coherently** off **atomic nuclei**

Low momentum transfer

Low neutrino energies

$\sigma_{SM} \propto$ **(Number of neutrons)^2**

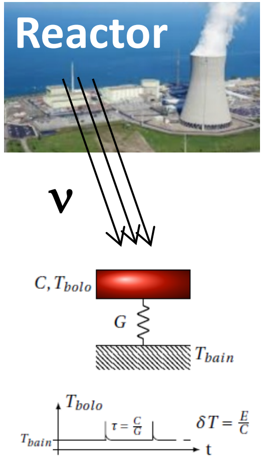
Table-top neutrino experiment!

Detected by COHERENT in 2017 with conventional detectors with relativley high-energy neutrinos

A. Drukier and L. Stodolsky
Phys. Rev. D **30**, 2295 – Published 1 December 1984

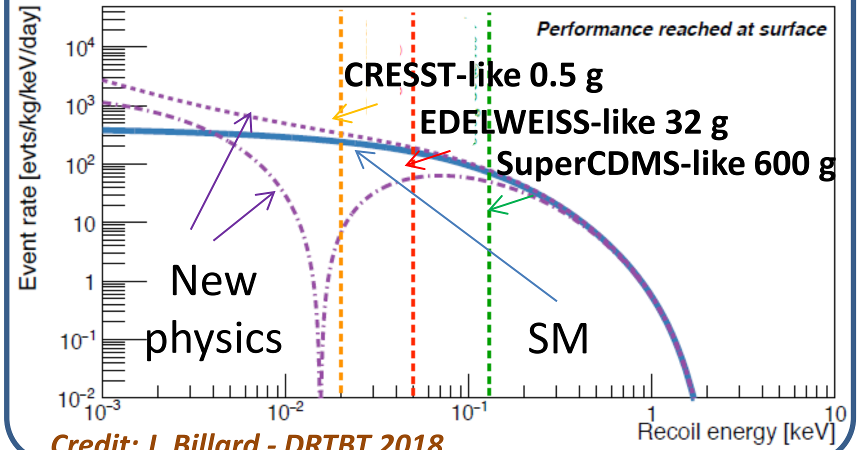
Precision measurements with **LTDs** required for:

- Low energy test of SM
- Physics beyond SM
  - – ν magnetic moment
  - – Non standard ν interaction
  - – Z' boson



O(10 eV) theshold required

WIMP-CEνNS connection



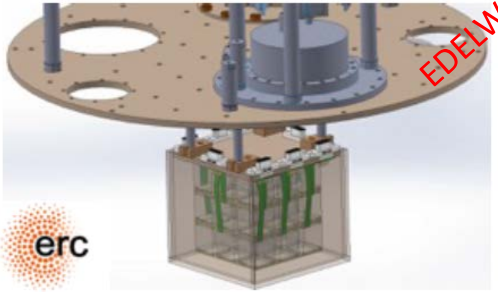
Credit: J. Billard - DRTBT 2018

Coherent elastic neutrino-nucleus scattering

One of the main challenges is **background** → **different strategies**

Ricochet

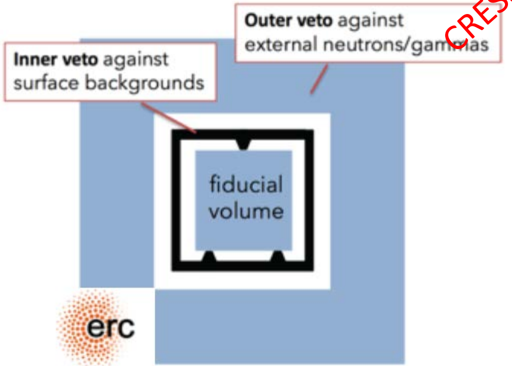
EDELWEISS



- **1 kg array** of detectors (CryoCube) 3×3×3 = 27 crystals of 30 g (Ge & Zn)
- **Nuclear recoil identification** down to O(10) eV threshold

NuCLEUS

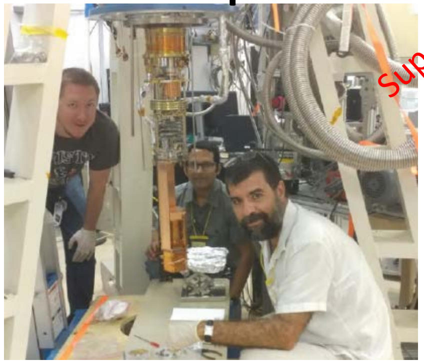
CRESST



- Phase 1: **10 g target mass** 9 $CaWO_4$ and 9 Al_2O_3 crystals
- Outer and inner **vetos**

MINER – phase 1

SuperCDMS



- Use one **SuperCDMS (625 g Ge) detector** in **HV mode**
- Passive and active **shielding**
- **Science run** started

BASKET – Use **lithiated targets** to monitor neutron background in real time

Neutrino mass scale: double beta decay

Neutrinoless double beta decay ($0\nu2\beta$) – Hypothetical rare decay ($T_{1/2}$ > $10^{25\text{-}26}$ y) – **If observed**:

- neutrino and antineutrino coincide (**Majorana fermions**)
- **Lepton number** is not an exact symmetry of Nature

⇒ The most important problem in neutrino physics

In addition, measurement of the **effective Majorana mass** $m_{\beta\beta}$ → **neutrino mass scale**

(A,Z) → (A,Z+2) + 2e$^-$ – a few interesting nuclei

Signature: **peak in the 2e$^-$ spectrum** (Q=2-3 MeV)

LTDs are ideal detectors:

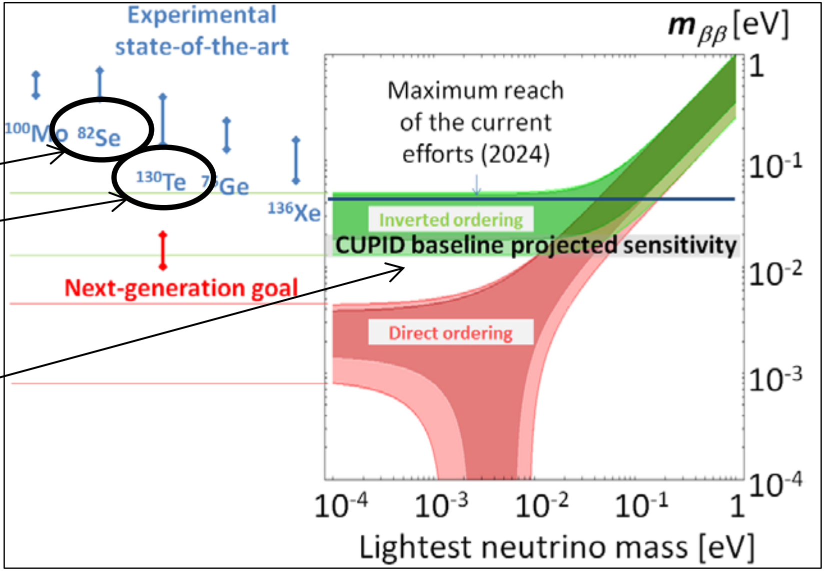
- **High energy resolution**
- **Flexible material choice**
- **Background rejection methods** (hybrid or surface sensitive detectors)
- **Multi-isotope** search in principle

CUPID-0

CUORE

CUPID

AMoRE



LTDs for double beta decay: CUORE and CUPID-0

CUORE

First ton-scale array of cryogenic calorimeters:

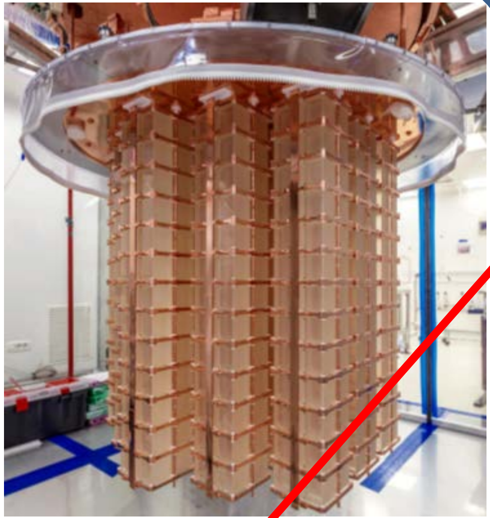
988 TeO_2 crystals

(0.75 kg each)

NTD readout

CUORE cryostat (LNGS)

unprecendented technological challenge



Current results

90% C.I. limits on

Half-life of ^{130}Te:

$\mathbf{T_{1/2} > 1.5\times10^{25}}$ **y**

Effective Majorana mass:

$\mathbf{m_{\beta\beta} < (110 - 520)}$ **meV**

Intrinsic limitations

- surface α background
- low Q (~2.5 MeV) of ^{130}Te $\rightarrow \gamma$ background

Solution

Scintillating bolometers with **Q>3 MeV** candidates

L. Gonzalez-Mestres, D. Perret-Gallix, 1989, Moriond

Milano group

First scintillating bolometer (CaF_2 for $0\nu2\beta$)

Physics Letters B

Volume 420, Issues 1–2, 19 February 1998, Pages 109-113

S. Pirro

Pioneering work

Scintillating double-beta-decay bolometers

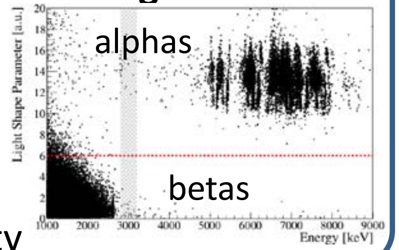
Phys. At. Nucl. 69 (2006) 2109

CUPID-0 evolution of LUCIFER (LNGS)

24× 95%-enriched **$Zn^{82}Se$ scintillating bolometers**

Excellent α rejection, but **intrinsic limitations of ZnSe**

- Low energy resolution
- Difficult crystallization
- Non-excellent radiopurity

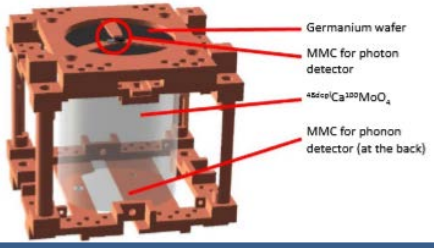


LTDs for double beta decay: the ^{100}Mo way

Mo-based scintillating bolometers to study the candidate **^{100}Mo – Q~3.03 MeV**

AMoRE
MMC readout

AMoRE pilot
6× $Ca^{100}MoO_4$ crystals
1.9 kg total
DONE



AMoRE-I
18× crystals
3 different types
IN PREPARATION

AMoRE-II
200 kg
total mass
PLANNED

LUMINEU → CUPID-Mo – development of the $Li_2{}^{100}MoO_4$ technology – NTD readout

Multiple tests with **natural and enriched crystals** (2014-2017) in LSM and LNGS with outstanding results in terms of:

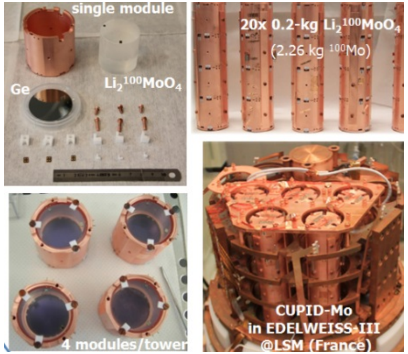
- Reproducibility → excellent performance uniformity
- Energy resolution → ~ **4-6 keV FWHM** at 2615 keV
- α rejection → **> 99.9 %**
- Internal radiopurity → **< 5 μBq/kg in ^{232}Th, ^{238}U; < 5 mBq/kg in ^{40}K**

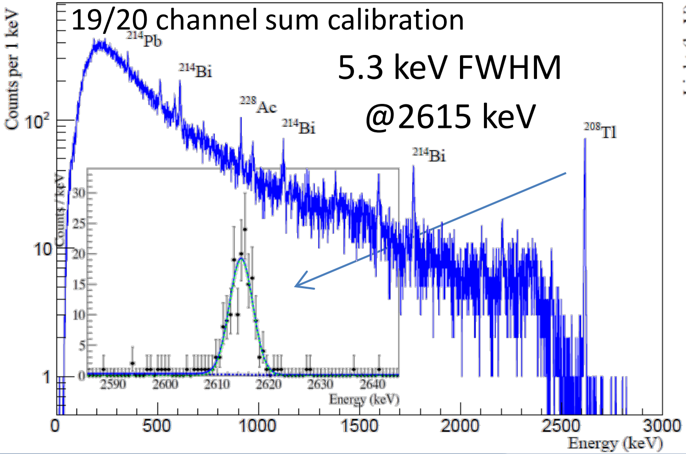
CUPID-Mo pilot experiment

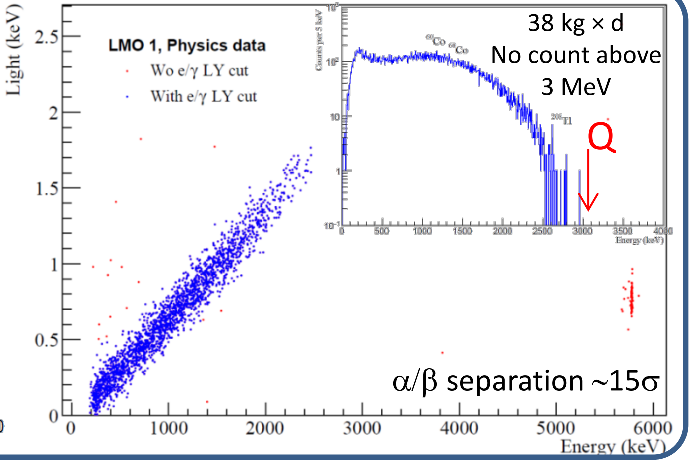
LTDs for double beta decay: CUPID-Mo and CUPID

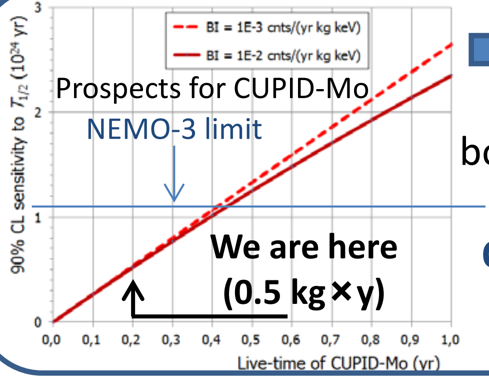
CUPID-Mo

20 scintillating bolometers







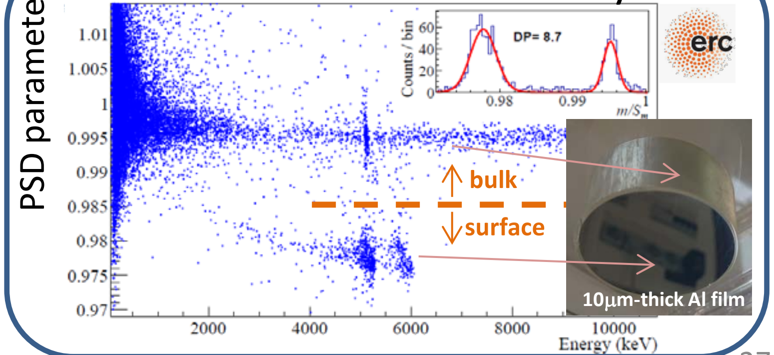


Towards **CUPID**

~1500 Li_2MoO_4 scintillating bolometers in the **CUORE cryostat**

One of the most sensitive $0\nu2\beta$ searches of the next decade

CROSS – surface sensitivity



Neutrino mass: β decay and electron capture

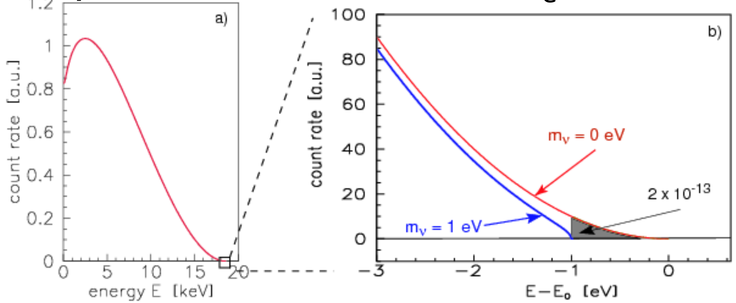
Neutrino mass scale: fondamental parameter of particle physics and cosmology

Model-independent measurement:
kinematics → **Spectral distortion** of the visible energy emitted along with invisible neutrinos

High energy resolution + flexibility in detector material → **LTDs**

$^{187}Re \rightarrow {}^{187}Os + e^- + \bar{\nu}_e$ - Q~2.5 keV
MIBETA-MANU
m_ν < 15.6 eV - **$AgReO_4$ bolometers**
No go for LTDs
→ no convenient Re-based bolometer

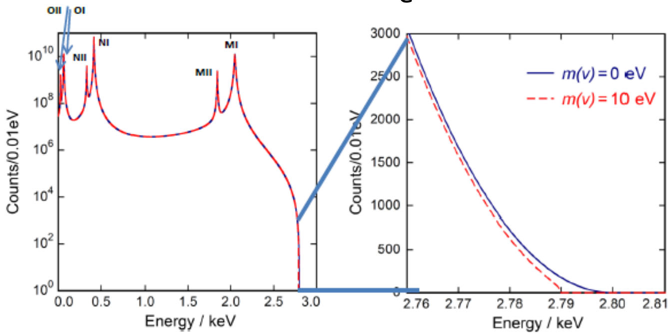
Tritium β decay: $^{3}H \rightarrow {}^{3}He + e^- + \bar{\nu}_e$ - Q~18.6 keV



Best limit (**m_ν** < 2.2 eV) and prospects (**m_ν** < 0.2 eV) with MAC-E filter spectrometers: KATRIN experiment
No go for LTDs → too small fraction of useful events

More promising: **A. De Rújula,** 1981

$^{163}Ho \rightarrow {}^{163}Dy^* + \nu_e$ - Q~2.8 keV



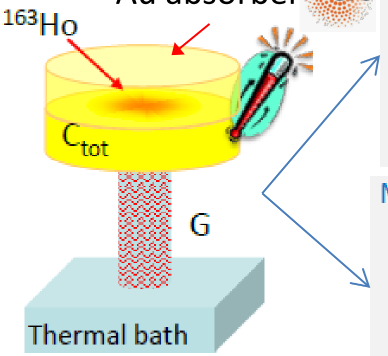
Neutrino mass: electron capture experiments

For **sub-eV sensitivity**: **> 10^{14} events** → total activity ~ 1 MBq
In order to limit pile-up in each pixel → **~ 10^5 pixels**

- Large arrays
- Multiplexing

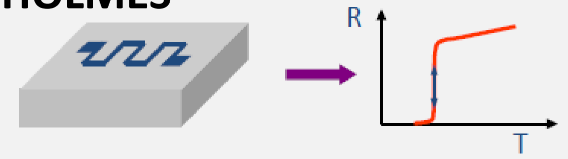
Detector challenges:

- High energy resolution **O(1 eV)**
- Fast risetime **< 1μs**



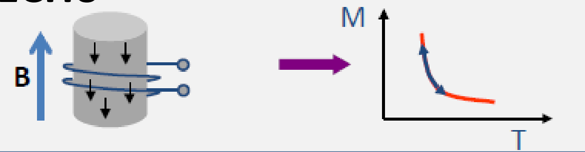
Resistance at superconducting transition,TES

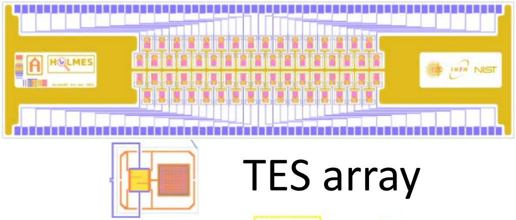
HOLMES



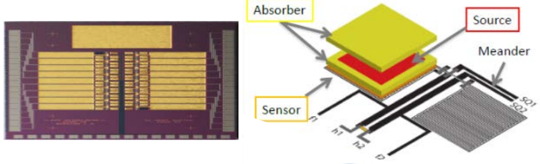
Magnetization of paramagnetic material, MMC

ECHo





TES array



MMC array

Credit L. Gastaldo NEUTRINO 2018

Source challenges:
Production and embedding of the source
1 MBq → **> 10^{17} atoms** – $T_{1/2}$= 4570 y

A combination of technologies for neutrino mass measurement (**including LTDs**) can be used to attempt the detection of **relic neutrinos** – **PTOLEMY**

Low temperature detectors have nowadays a wide range of applications, both in **fondamental science** and **technology**

- Astronomy, astrophysics and cosmology
- Dark matter: search for WIMPs, axions and other exotic particles
- Neutrino basic properties
- Nuclear and atomic physics
- Material and life science, cultural heritage, homeland security
- New frontier: quantum technologies

Low temperature deteys a wide range of applications, both in **fon**nd **technology**

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- Material …
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LTDs will play a relevant role in search for low-mass WIMPs and axions

LTDs will detect and study CEνNS at nuclear detectors
LTDs can dominate $0\nu2\beta$ scenario in the next decade
LTDs can provide a method to improve the present sensitivity on m_ν