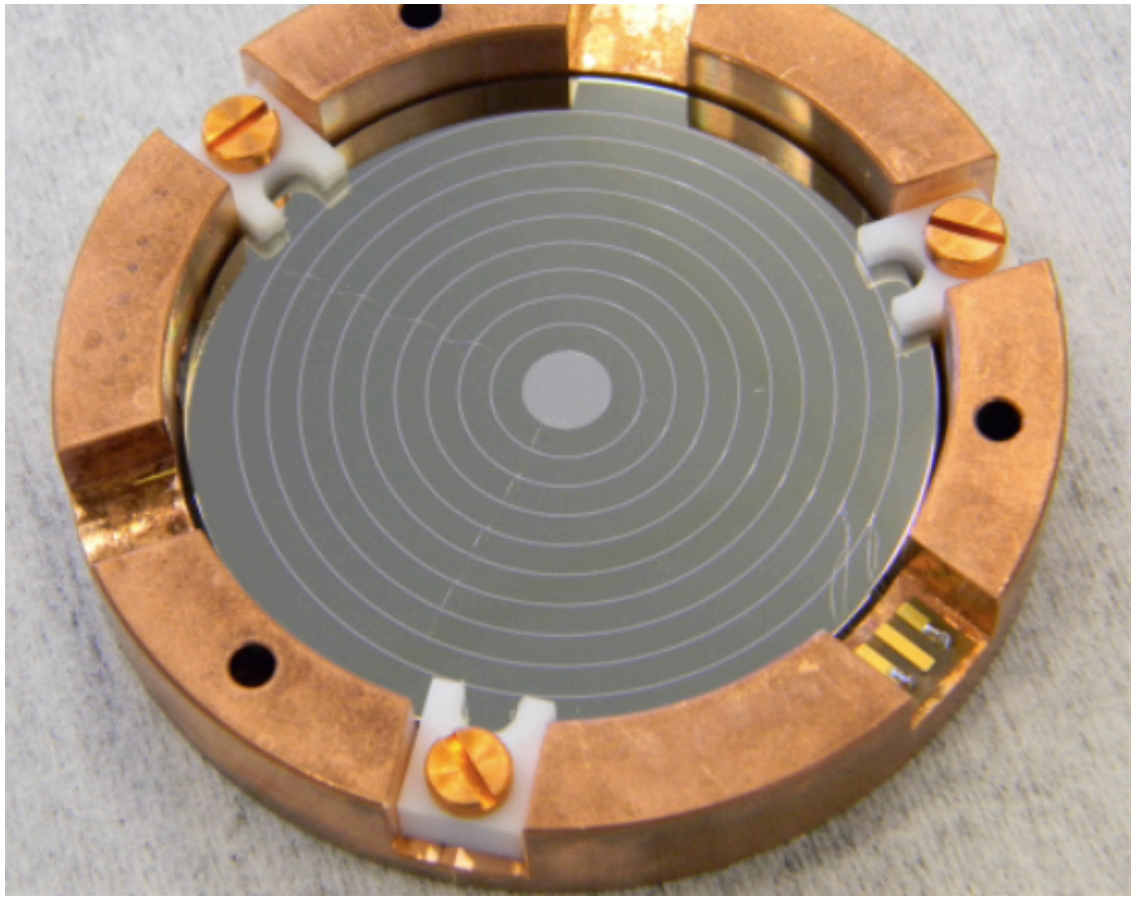
Neganov-Luke assisted Light Sensors



Emiliano Olivieri for the Detector R&D Group at
CSNSM Laboratory (Orsay Campus)

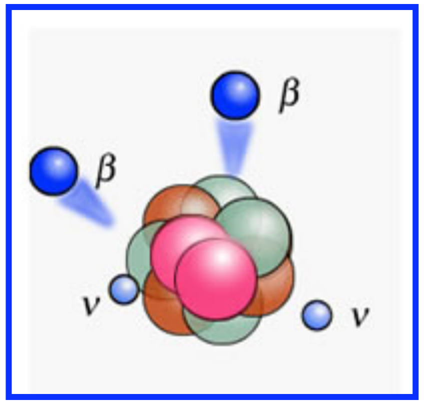
Outline

- Physics background and motivations: the double beta decay (ββ)
- A bolometer in a nutshell...
- The Neganov-Luke Assisted light detector
  - Neganov-Trofimov-Luke effect
  - LukS working regimes
  - The first two prototypes
- Experimental set-up for a complete characterization
- Results and Perspectives
- Conclusions

Rare event search: 0ν-ββ decay

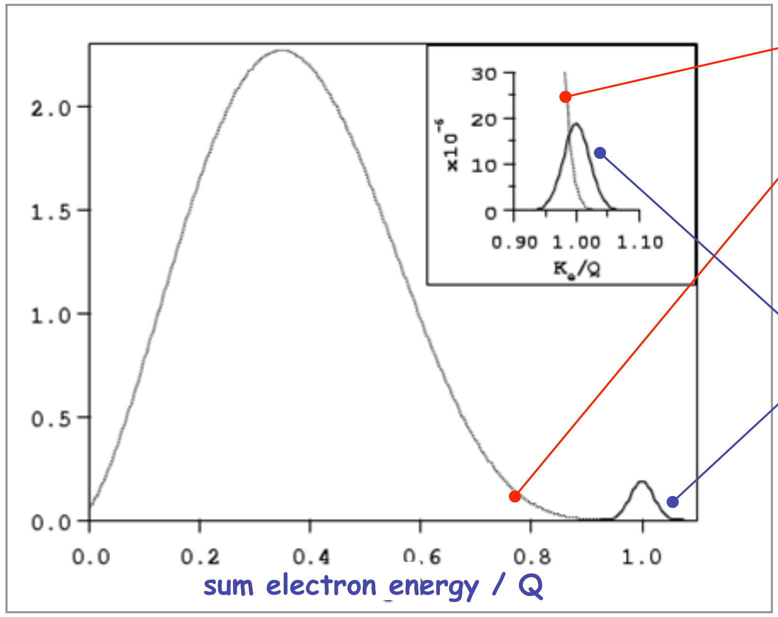
Double Beta Decay (2ν-ββ)

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$



$$[T_{1/2}(2\nu)]^{-1} = G_{2\nu}(Q, Z)|M_{2\nu}|^2$$

The shape of the two electron sum energy spectrum enables to distinguish among the two different discussed decay modes

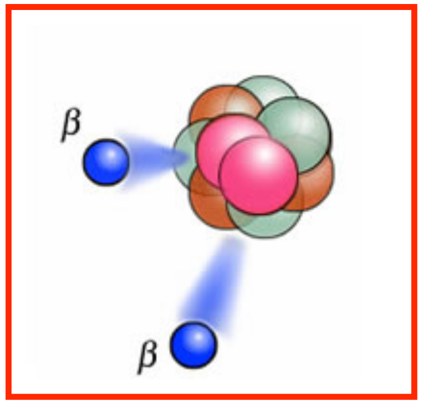


2ν double beta decay continuum with maximum at ~1/3 Q

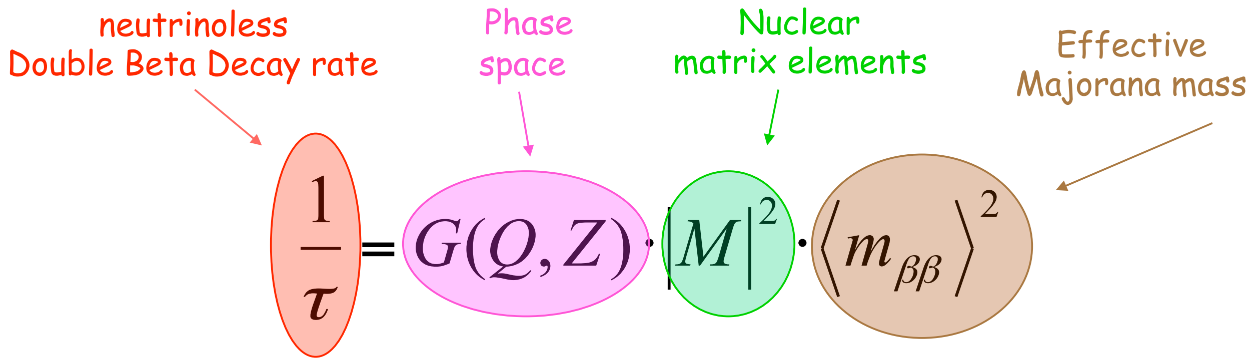
0ν double beta decay peak enlarged only by the detector energy resolution

Neutrino-less Double Beta Decay (0ν-ββ)

$$(A,Z) \rightarrow (A,Z+2) + 2e$$



$$[T_{1/2}(0\nu)]^{-1} = G_{0\nu}(Q, Z)|M_{0\nu}|^2 m_{\beta\beta}^2$$



neutrinoless Double Beta Decay rate

Phase space

Nuclear matrix elements

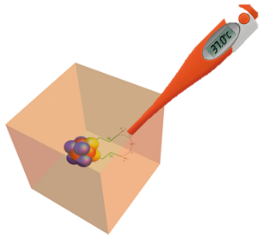
Effective Majorana mass

$$\frac{1}{\tau} = G(Q,Z) \cdot |M|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Absolute Neutrino Mass Scale

The 0ν-ββ candidates

Nucleus	I. A.	Q-value [keV]	Materials successfully tested as bolometers in crystalline form
^{76}Ge	7.8	2039	Ge
^{136}Xe	8.9	2479	NONE
^{130}Te	33.8	2527	TeO_2
^{116}Cd	7.5	2802	$CdWO_4$, $CdMoO_4$
^{82}Se	9.2	2995	ZnSe
^{100}Mo	9.6	3034	$PbMoO_4$, $CaMoO_4$, $SrMoO_4$, $CdMoO_4$, $ZnMoO_4$, Li_2MoO_4, $MgMoO_4$
^{96}Zr	2.8	3350	ZrO_2
^{150}Nd	5.6	3367	NONE → many attempts
^{48}Ca	0.187	4270	CaF_2, $CaMoO_4$



Cuoricino, CUORE

LUMINEU

Orsay, Kiev, Novosibirsk, Como

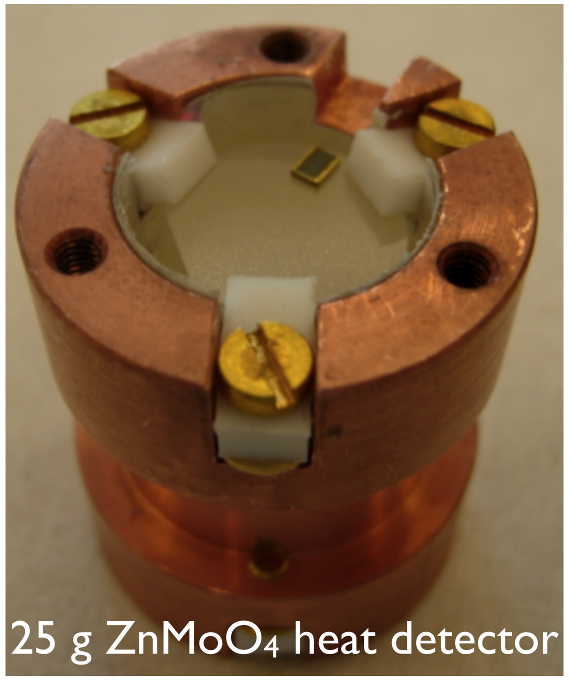
Mass sensitivity:

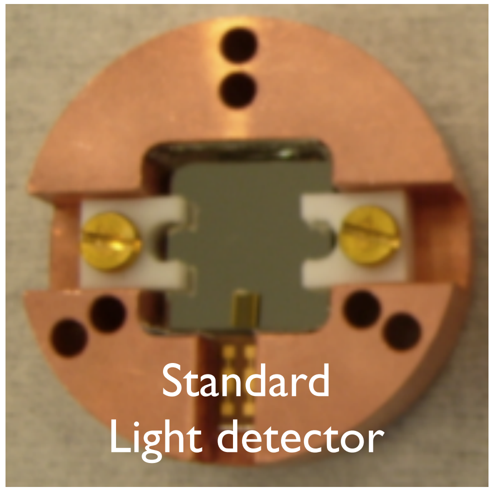
$$\langle m_{\beta\beta}\rangle \propto \left(\frac{b\Delta E}{M t_{live}}\right)^{\frac{1}{4}}$$

ΔE=energy res.
b=bkg in counts/keV/kg/day
M=effective mass
t_{live}=life time

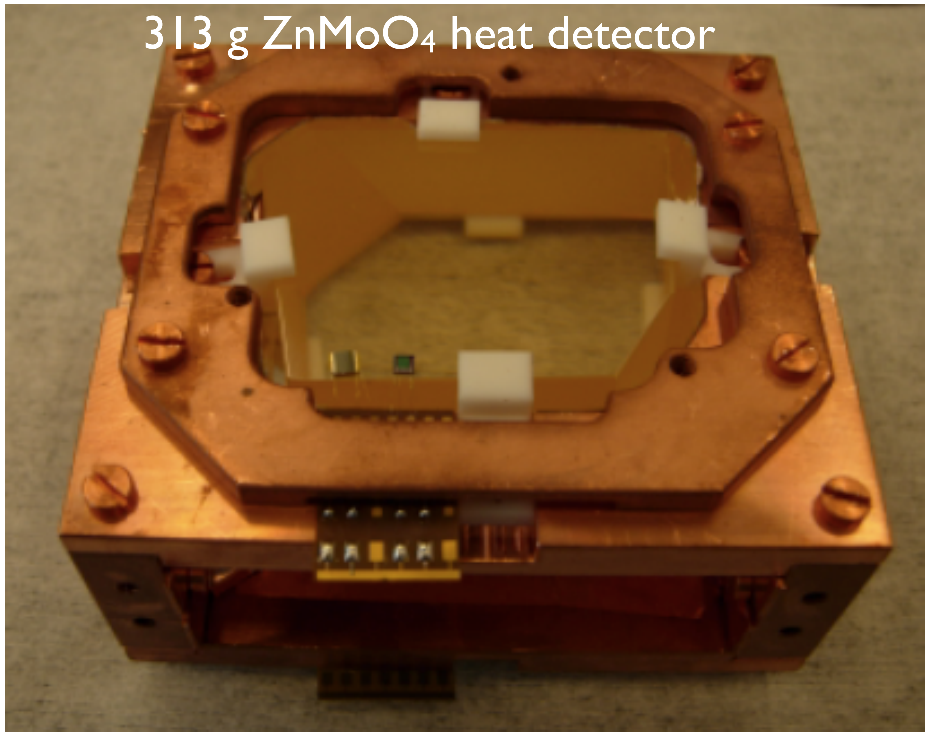
Next future 0ν-ββ experiment...

LUMINEU prototypes

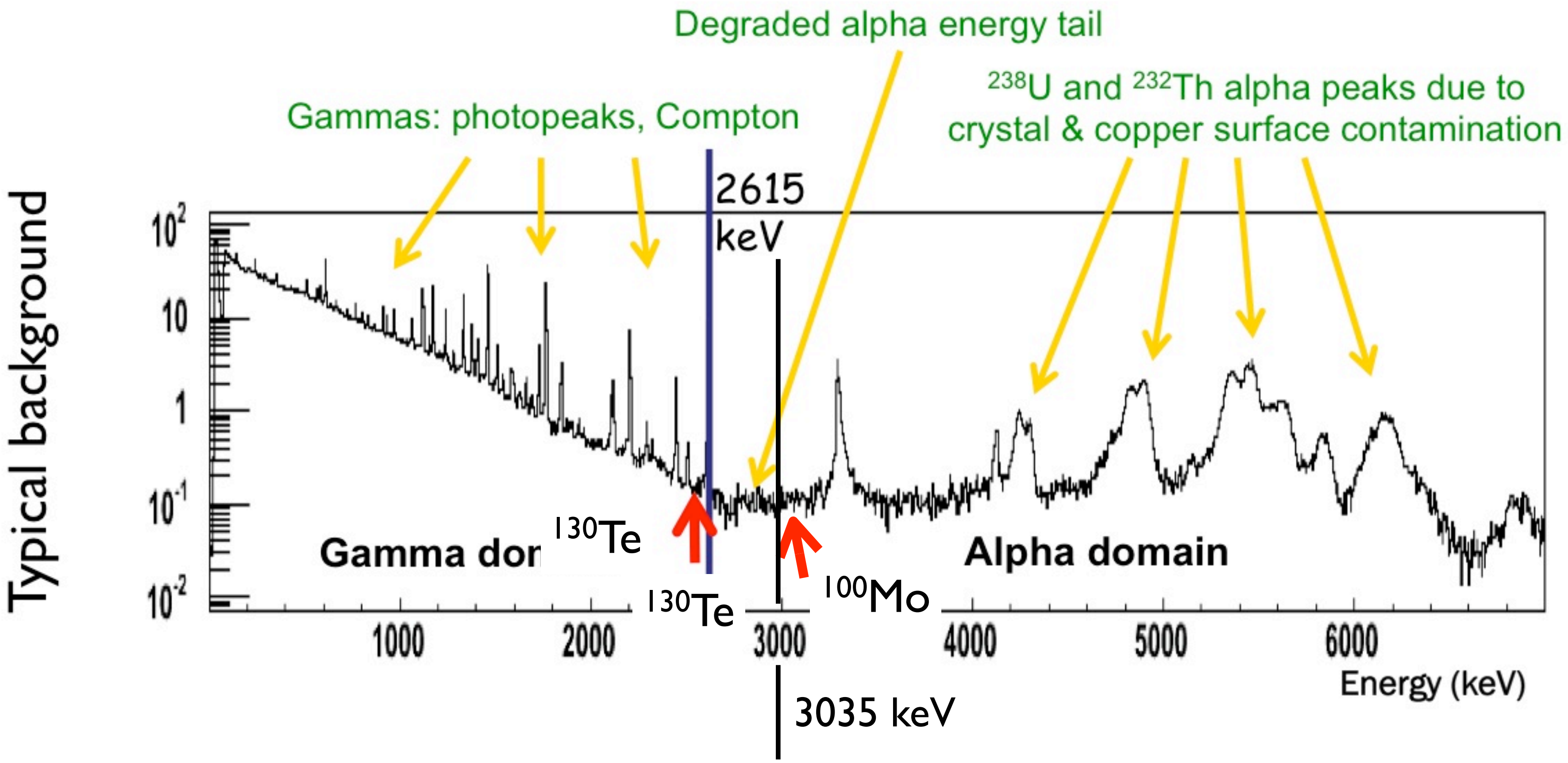




Actually running in LSM. Standard light detector equipped

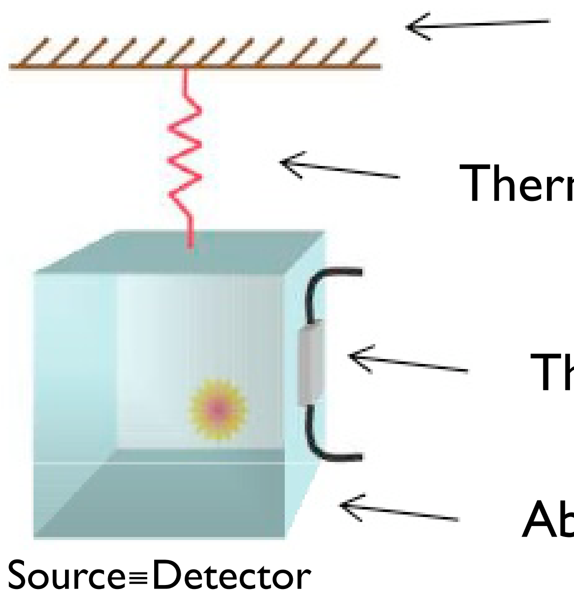


Ready to run in LSM. LukS light detector equipped



A bolometer in a nutshell

Heat



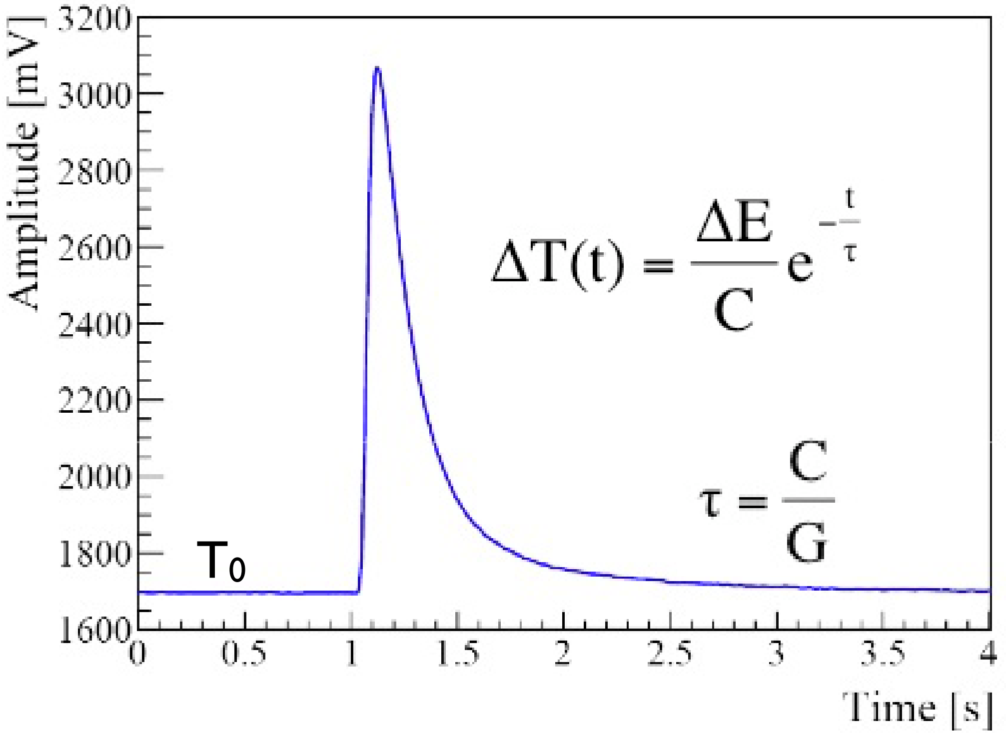
Thermal bath (15 mK): T_0

Thermal link: G

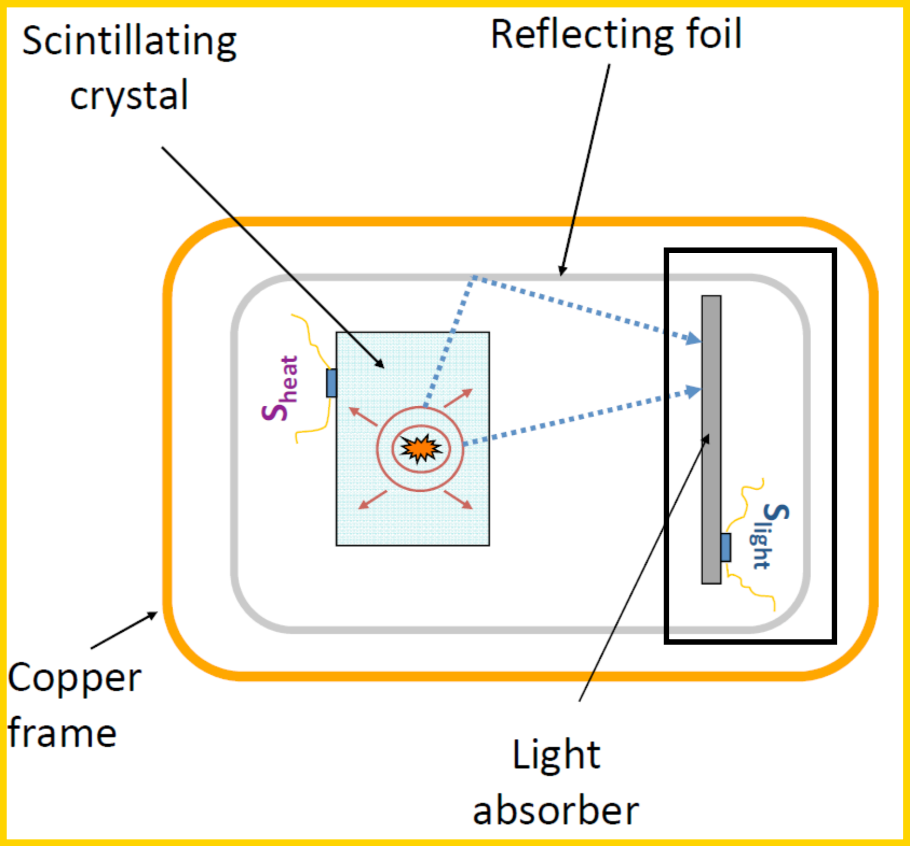
Thermal sensor

Absorber

Source≡Detector



Heat and Light



Scintillating crystal

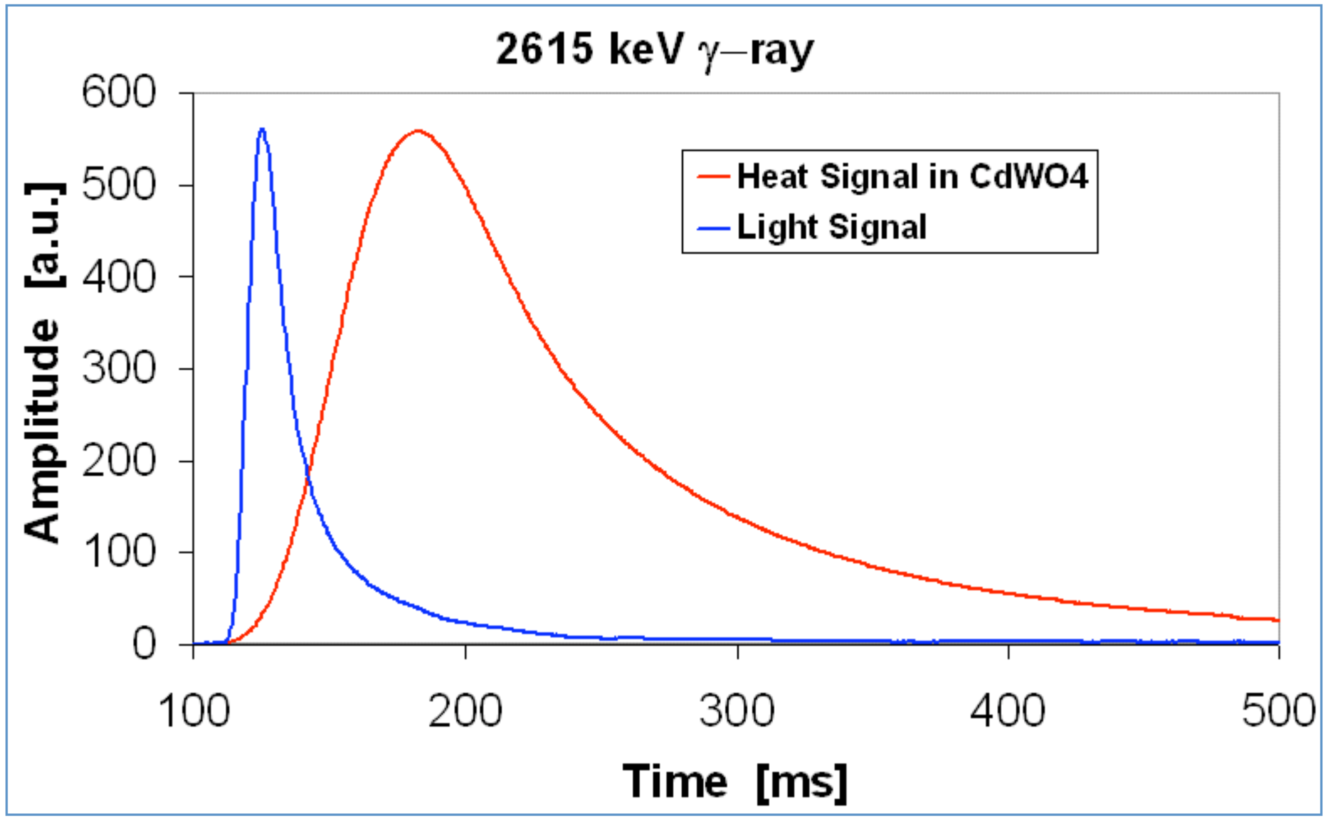
Reflecting foil

S_{heat}

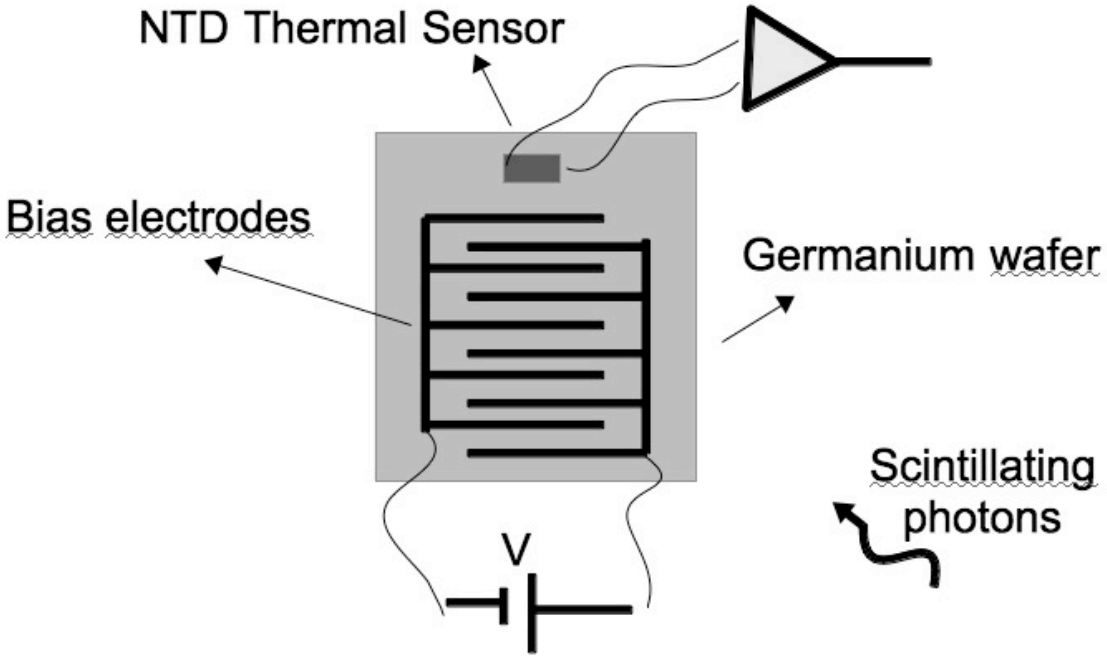
S_{light}

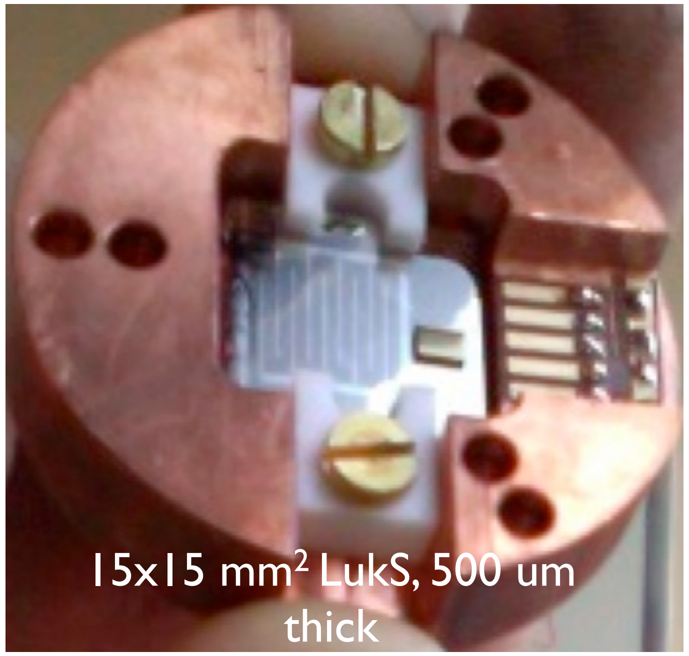
Copper frame

Light absorber

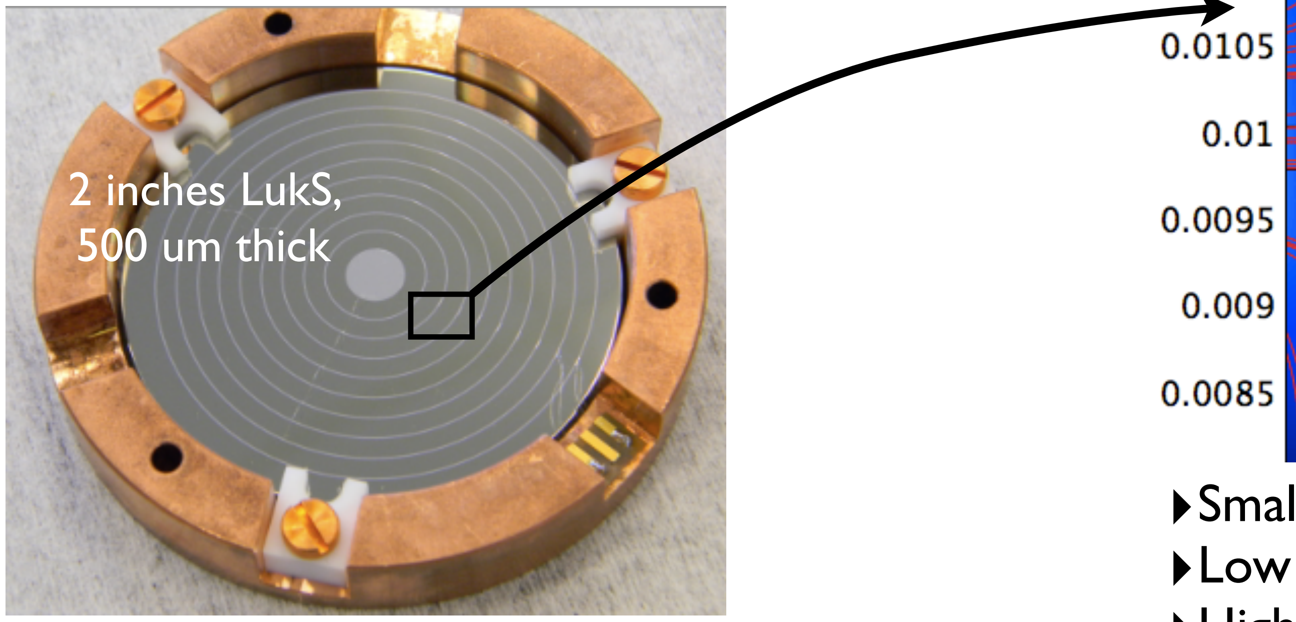


The LukS detector: generalities



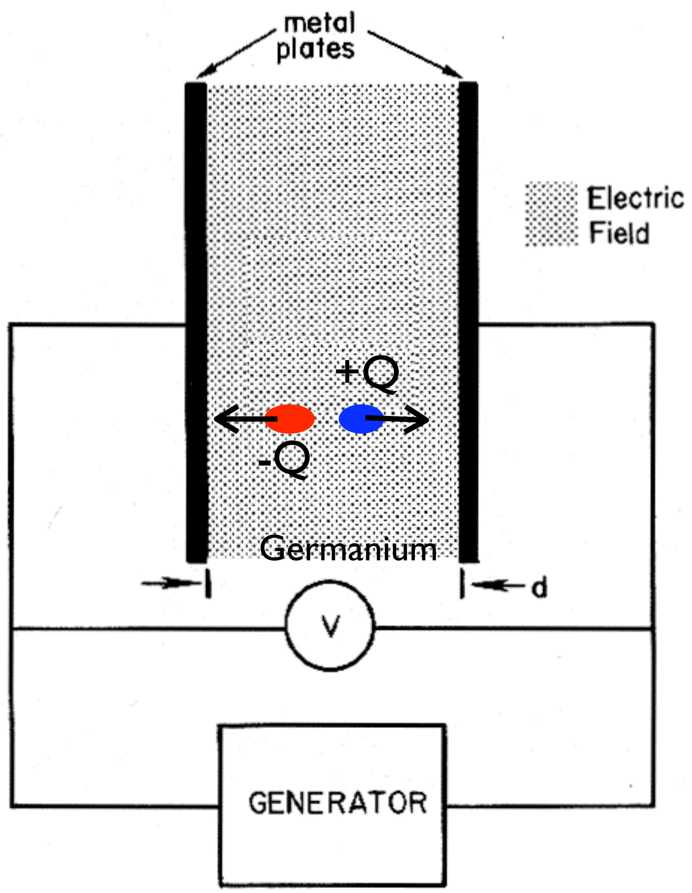

15x15 mm^2 LukS, 500 um thick

Even and odd aluminum annular electrodes respectively connected by bonding aluminum wires. V_{bias} is applied within the two sets (Ex. 10 V)



- Small electrode pitch: short drift path
- Low electric field to reduced leak currents
- High quality substrate: low charge trapping

Neganov-Luke effect



1) Event creates e-h pairs
2) e-h pairs are drifted by E_{bias}
3) Phonon emission while e-h pairs drift. The external generator provide the energy

$$W_{gen} = Q \int_0^d \vec{E} \cdot d\vec{l}$$

$$\boxed{E_{heat} = E_r(1 + qV_{bias}/\varepsilon)}$$

1) The over-heating is proportional to $N_{e\text{-}h} = E_r/\varepsilon$, the number of pairs created by an event of E_r energy.
2) The quantum yield ε depends on the semiconductor (gap) and photon energy. For germanium in X region: ε=3 eV/(e-h). Close to the gap, ε is much lower...
3) By increasing V the heat signal is mainly dominated by the charge creation⇒ beyond the thermodynamic fluctuation limit (Fano fluctuations)

$$\left\langle (\Delta E)^2 \right\rangle = k_B \cdot T_0^2 \cdot C$$

Germanium quantum yield

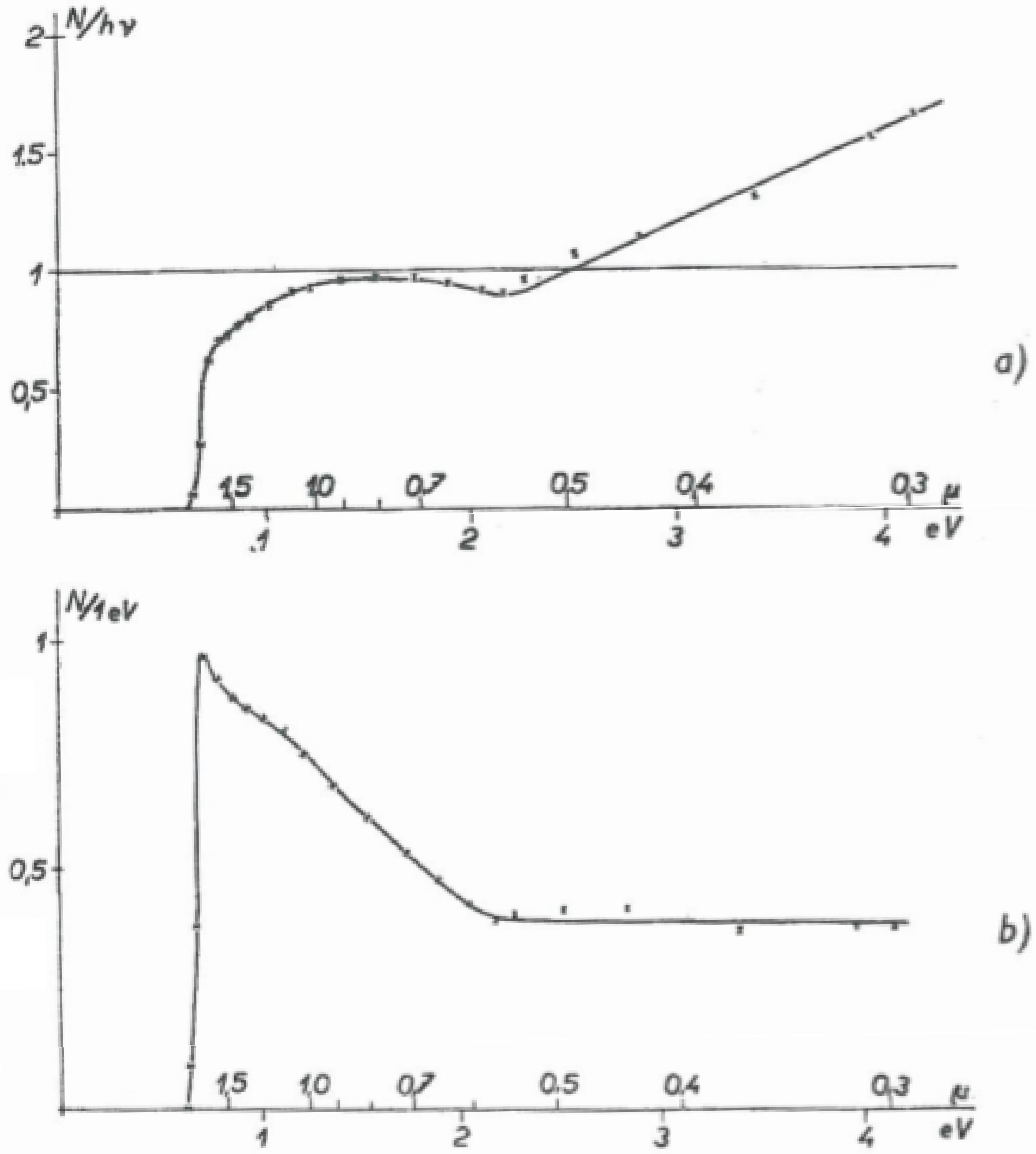
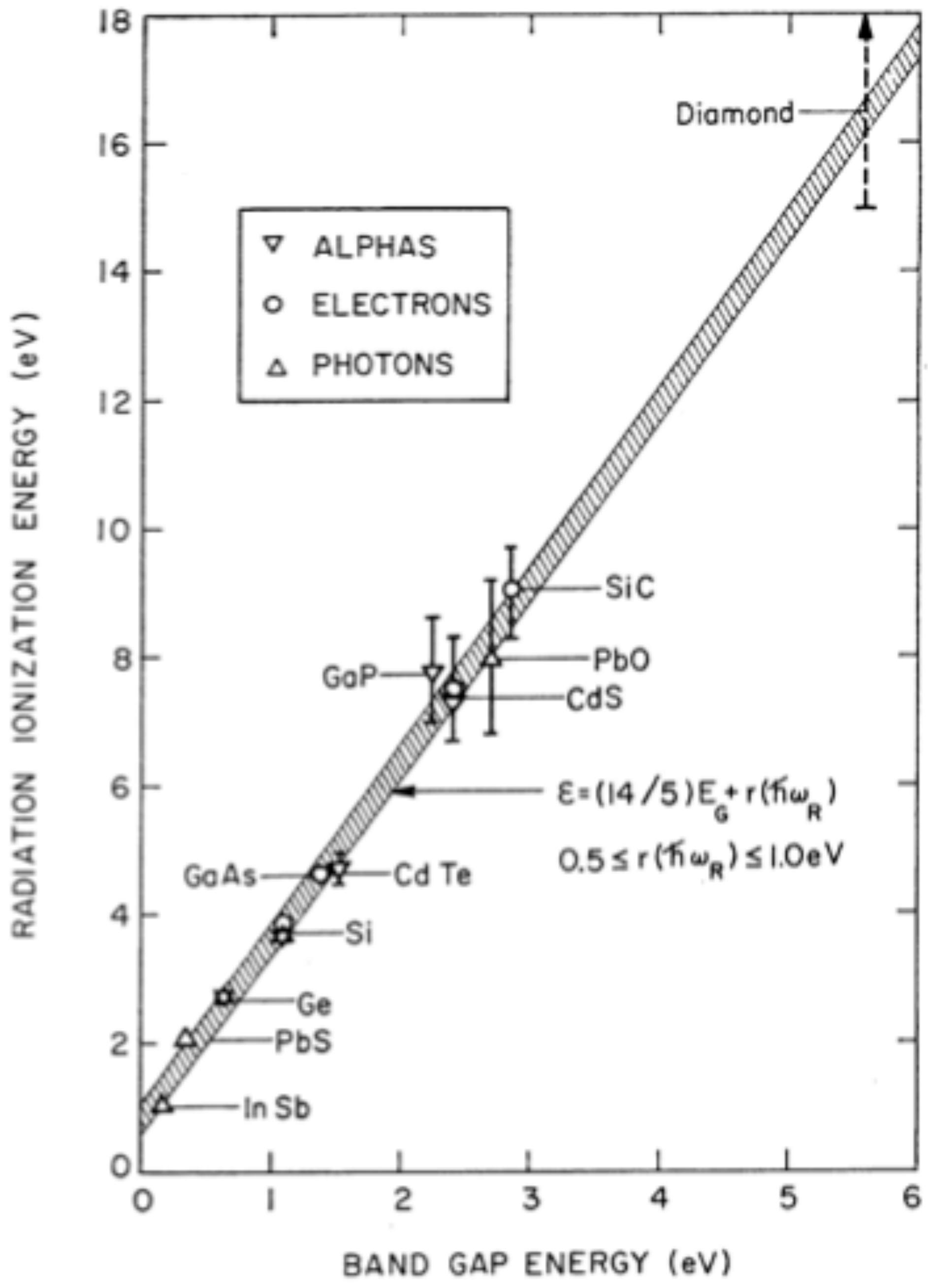


Fig. 1. a) Number of electron-hole pairs generated in germanium by the absorption of one photon as a function of the energy of the incident radiation.

b) Number of electron-hole pairs generated in germanium by the absorption of the total energy of one electronvolt as a function of the energy of the incident radiation.

Neganov-Luke sensor: the two regimes



Two bolometer working regimes:

Prompt Heat Regime

$$E_{heat}=E_r(1+\cancel{qV_{bias}/\varepsilon})$$

Sensitive to thermo-dynamic fluctuation

Fano Regime

$$E_{heat}=E_r(\cancel{1}+qV_{bias}/\varepsilon)$$

Unsensitive to thermo-dynamic fluctuations but statistics of charge carriers

The resolution R (dE/E) is: $R=\sqrt{\frac{Fw}{E}}.$

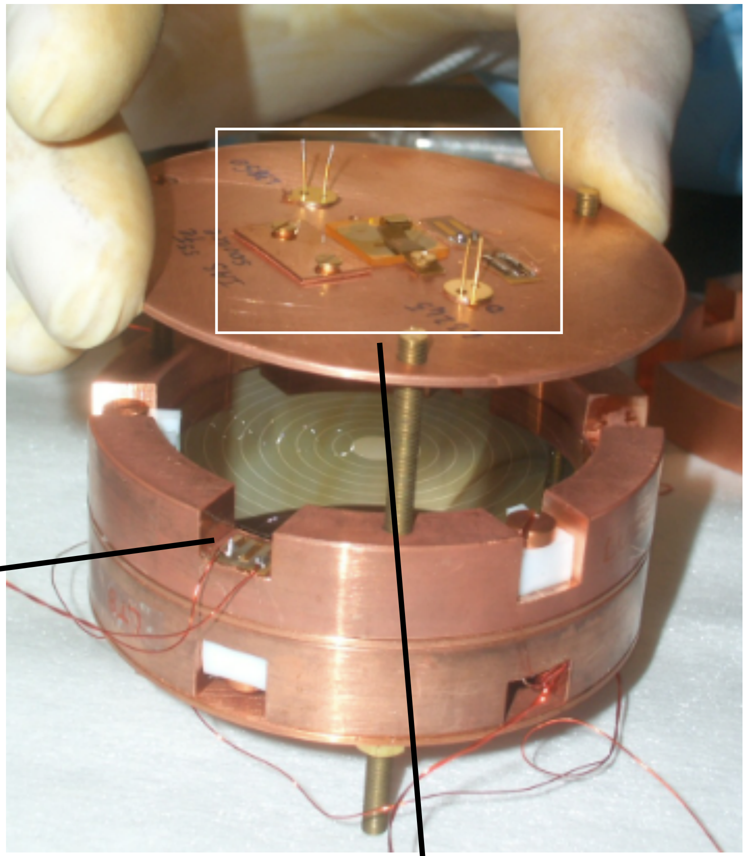
ω is the e-h creation energy. In germanium, it varies between 0.64 and 3 eV, depending on the E of the impinging particle. Fano factor F is material-dependent and in Ge is 0.13

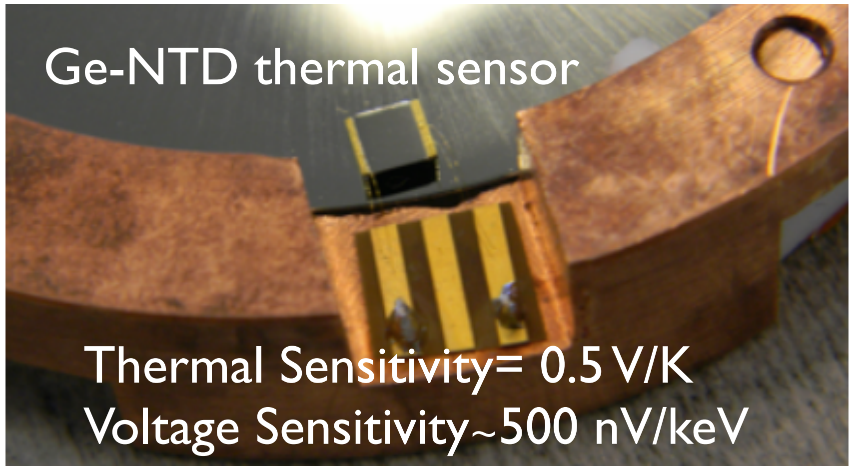
We can increase the heat signal without any limit, increasing V (but dark currents)!

The 2-inches detector

The main questions:

- Baseline noise
- Energy resolution
- Gain under different excitation: X, IR Photons, Visible Photons





Ge-NTD thermal sensor

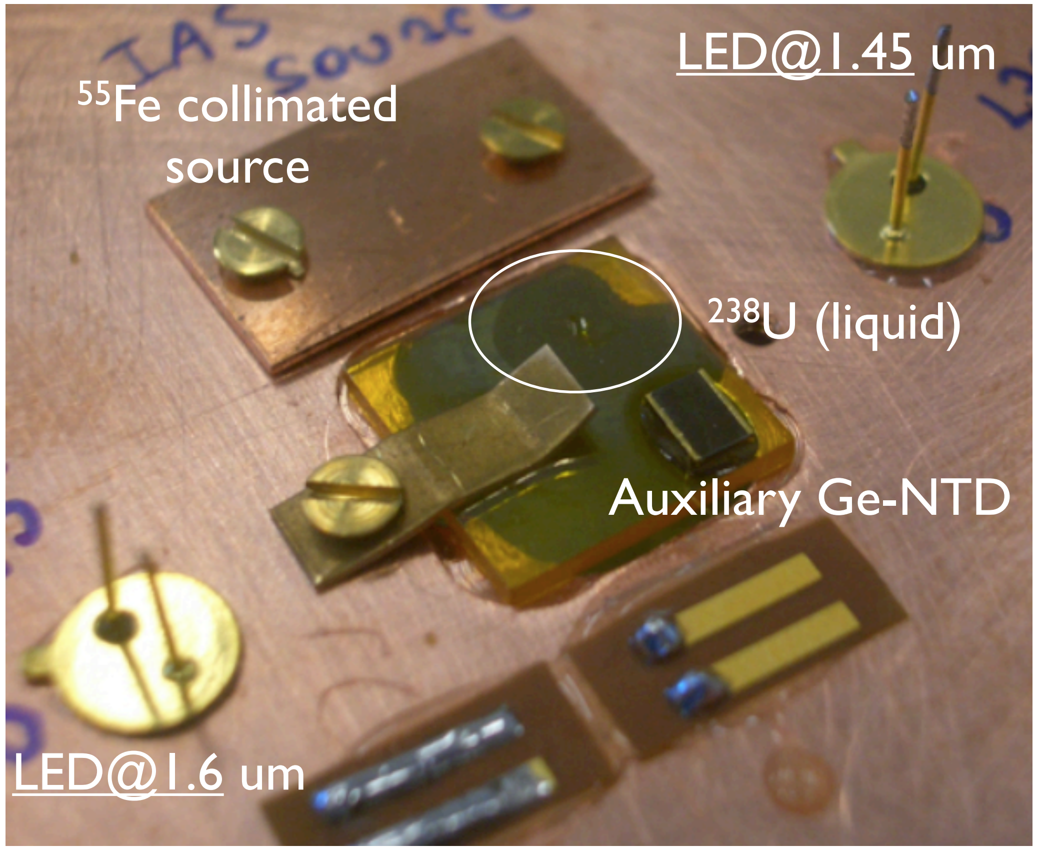
Thermal Sensitivity= 0.5 V/K
Voltage Sensitivity~500 nV/keV

Light emitting source:

- ZnSe crystal which scintillates under ^{238}U liquid alpha source and provide almost 60 keV/alpha
- Tagging of alpha-induced light events via a second Ge-NTD sensor

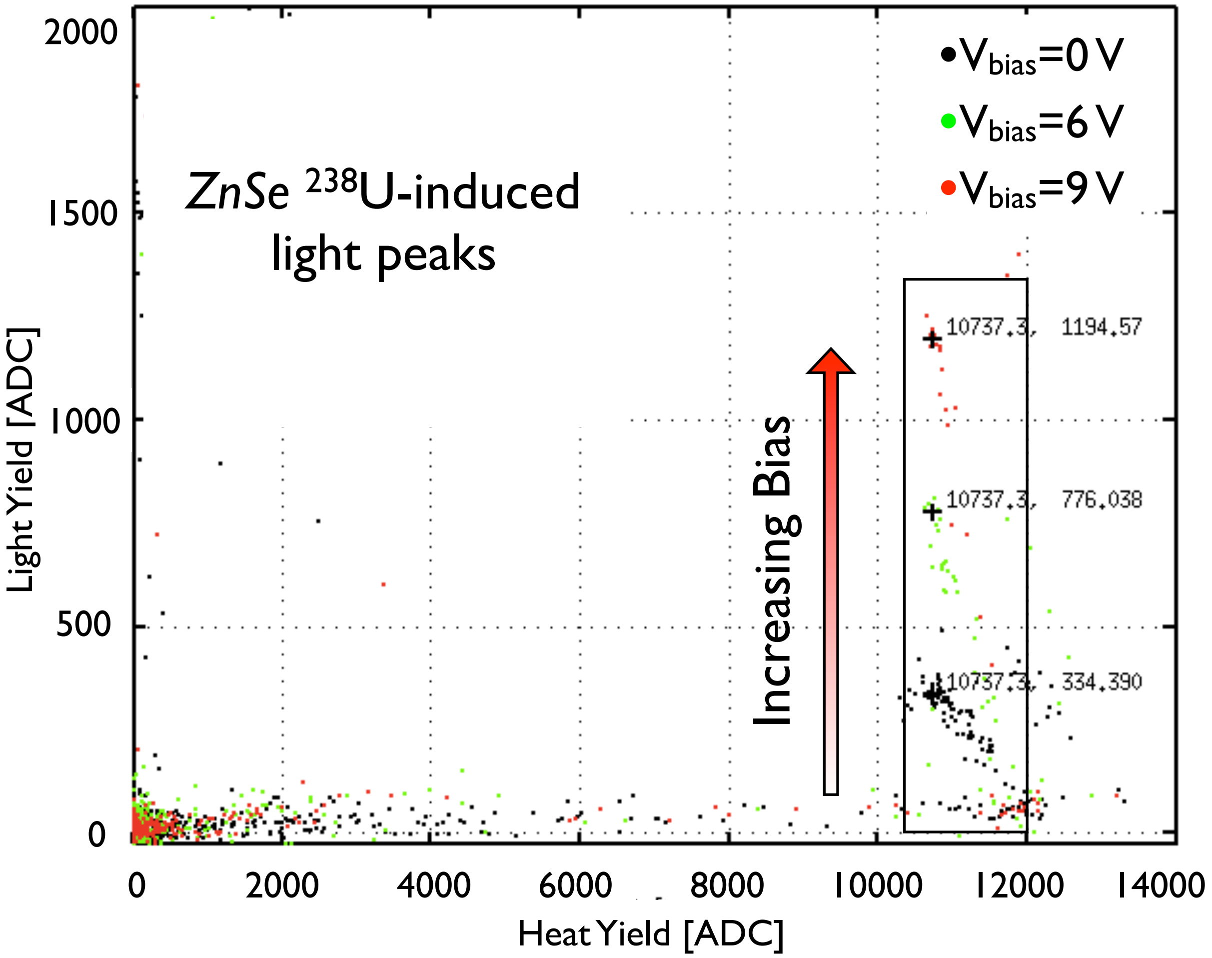
Absolute Calibration Source

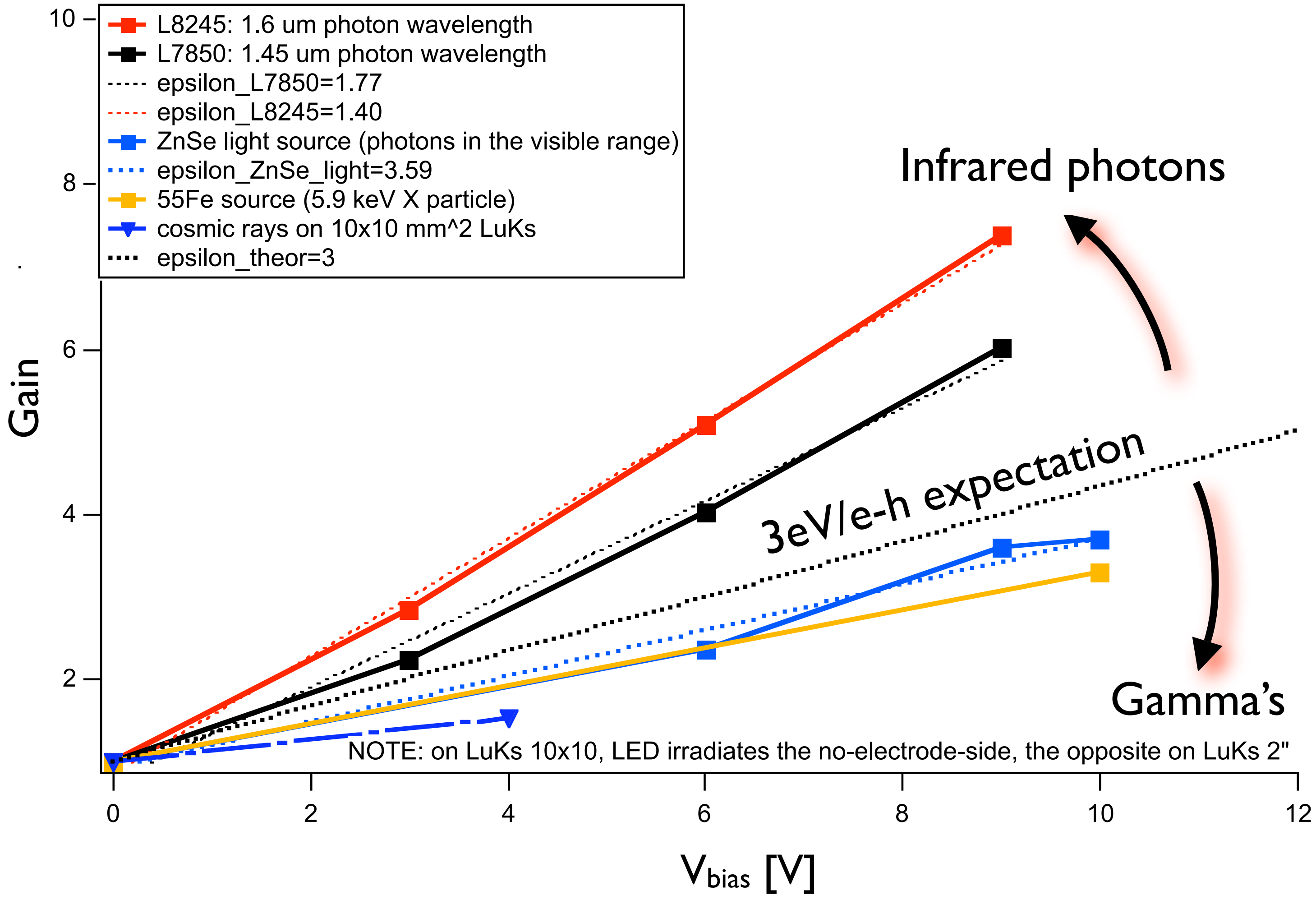
- Collimated ^{55}Fe, which provides 5.9 and 6.4 keV X rays



Results: thermal sensitivity gain

Heat and Light event-by-event scatterplot

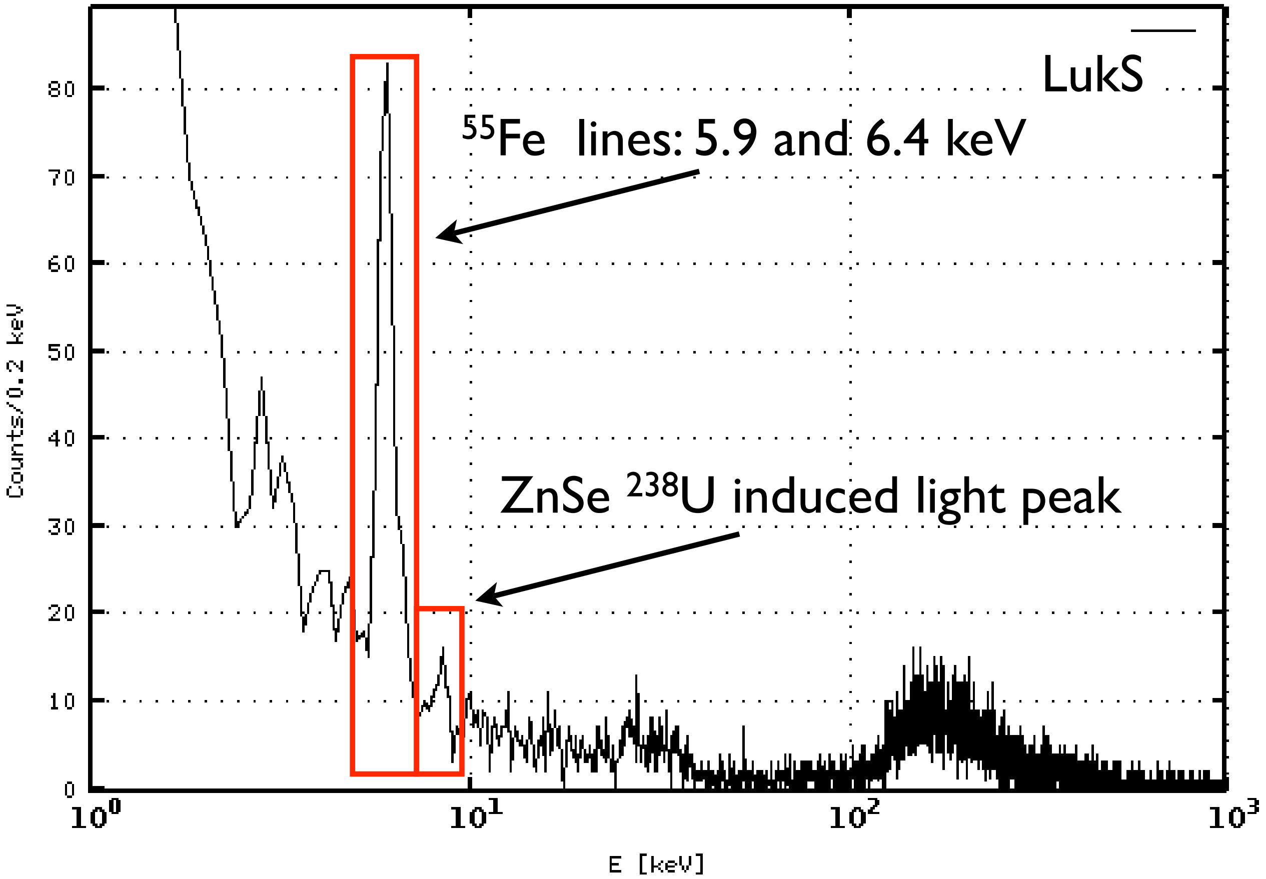




Observations:

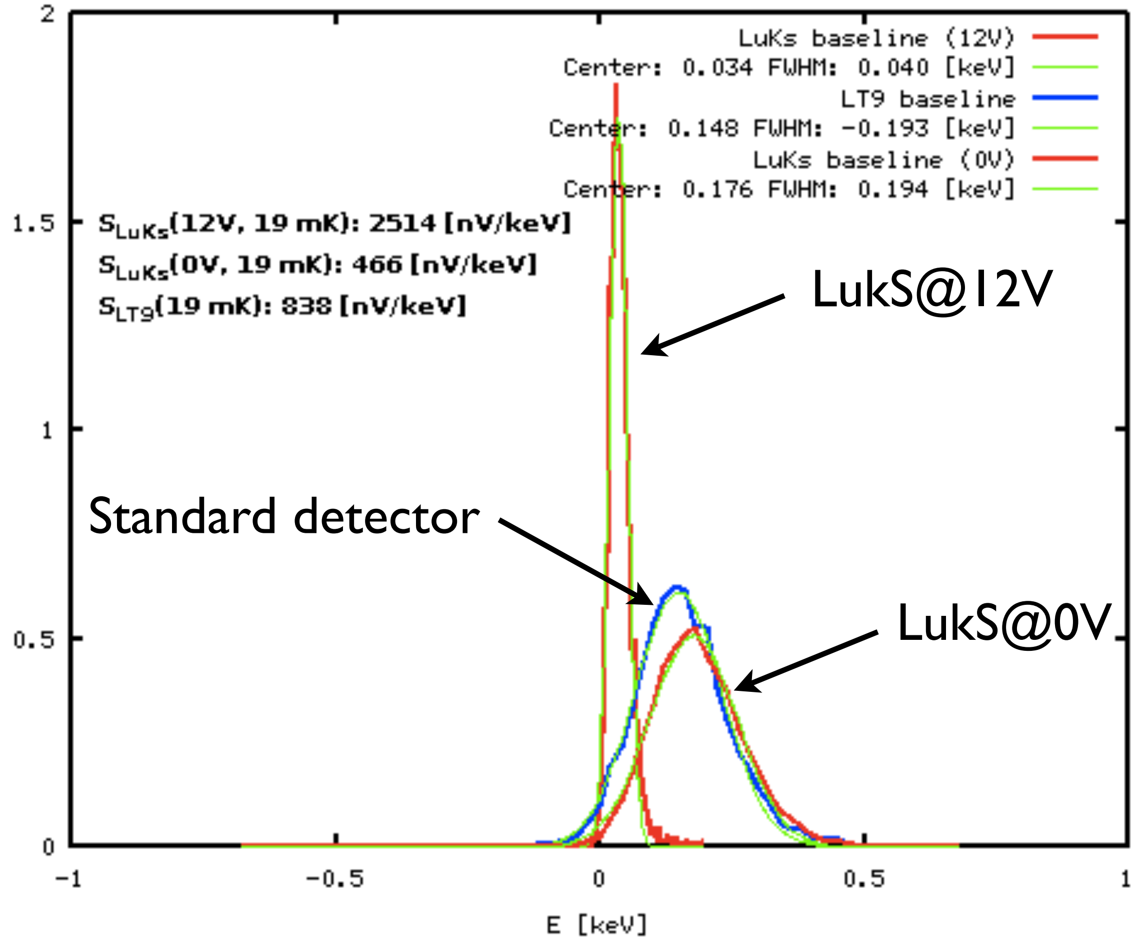
- Charge trapping at surfaces reduces the gain with respect to 3eV/e-h
- Gain depends on the particle/wavelength
- Leakage current appearance at high bias (12V ➟ E_{field}=60V/cm), which at the moment is the only limit to increase the gain!

Results: baseline noise reduction



^{55}Fe lines: 5.9 and 6.4 keV

ZnSe ^{238}U induced light peak



LukS@12V

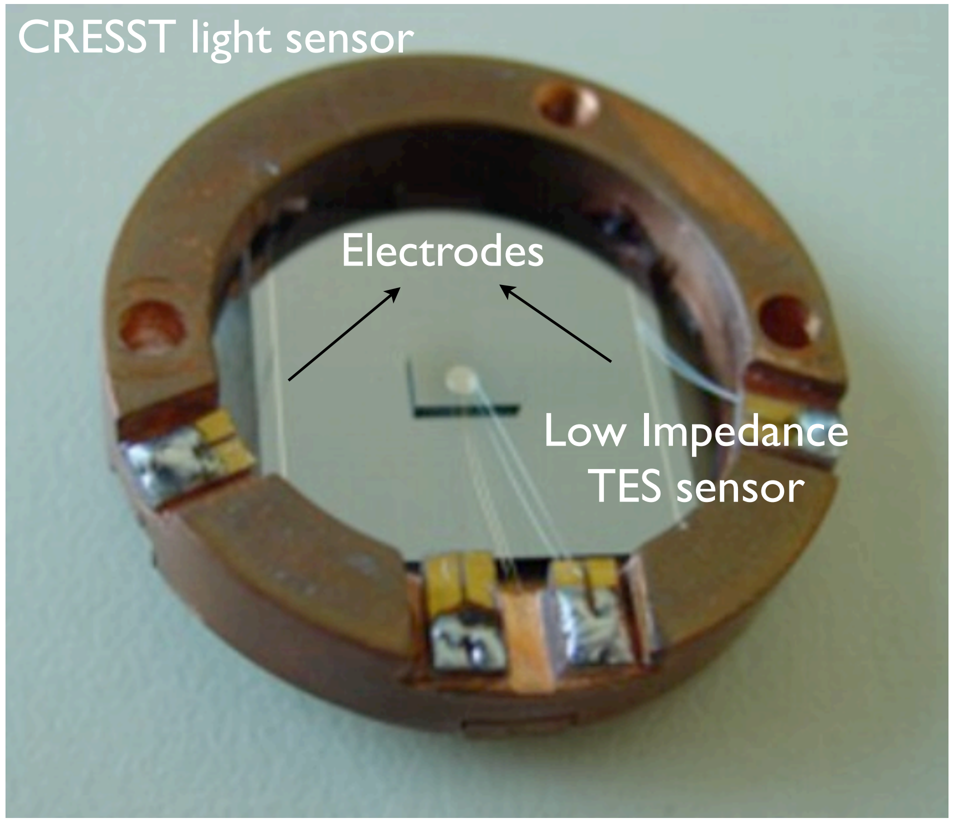
Standard detector

LukS@0V

FWHM baseline noise: from 193 (0 V bias) eV to 40 eV (12V bias)

- Neganov-Luke detector acts as a standard detector with zero bias ⇒ no specific heat added by the electrode deposition
- The baseline noise squeezes due to the sensitivity gain
- Baseline noise reduction well explained by the sensitivity gain due to Neganov-Luke ⇒ no excess noise injected by the electrode bias and no leakage current observed up to 12 V bias!

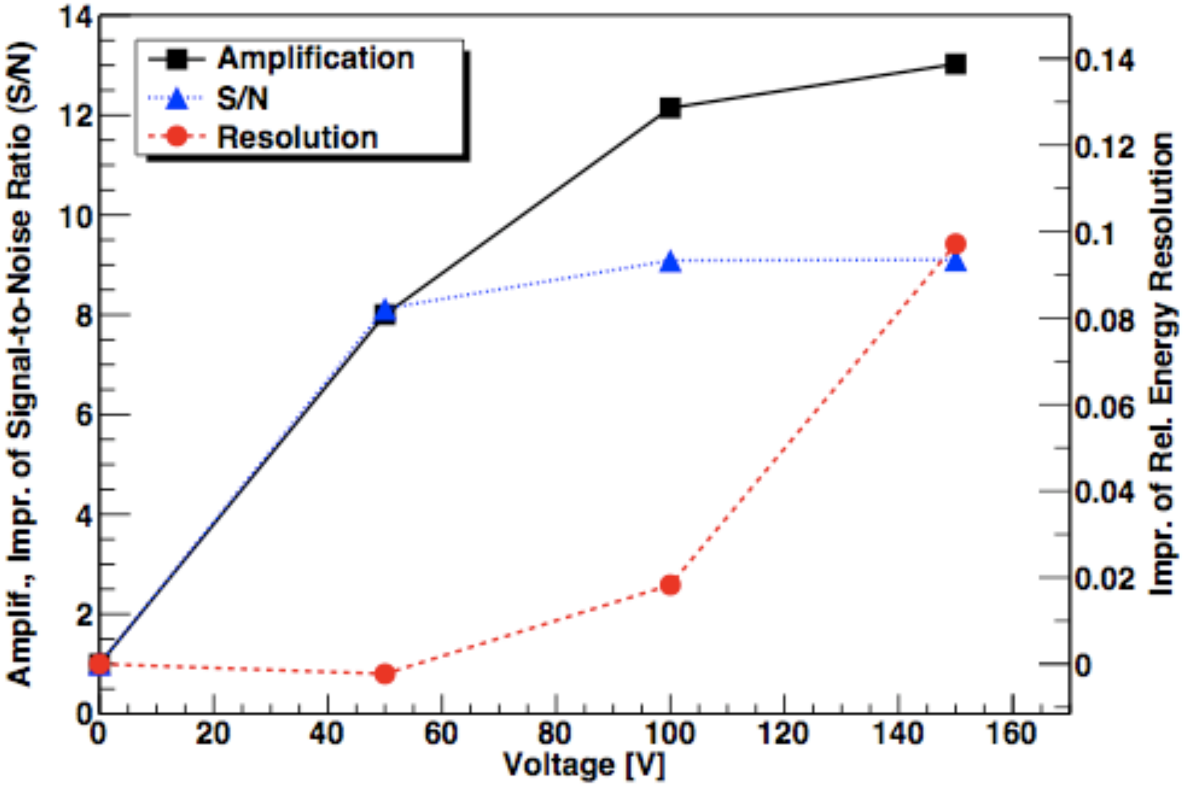
The CRESST and LukS light detector comparison



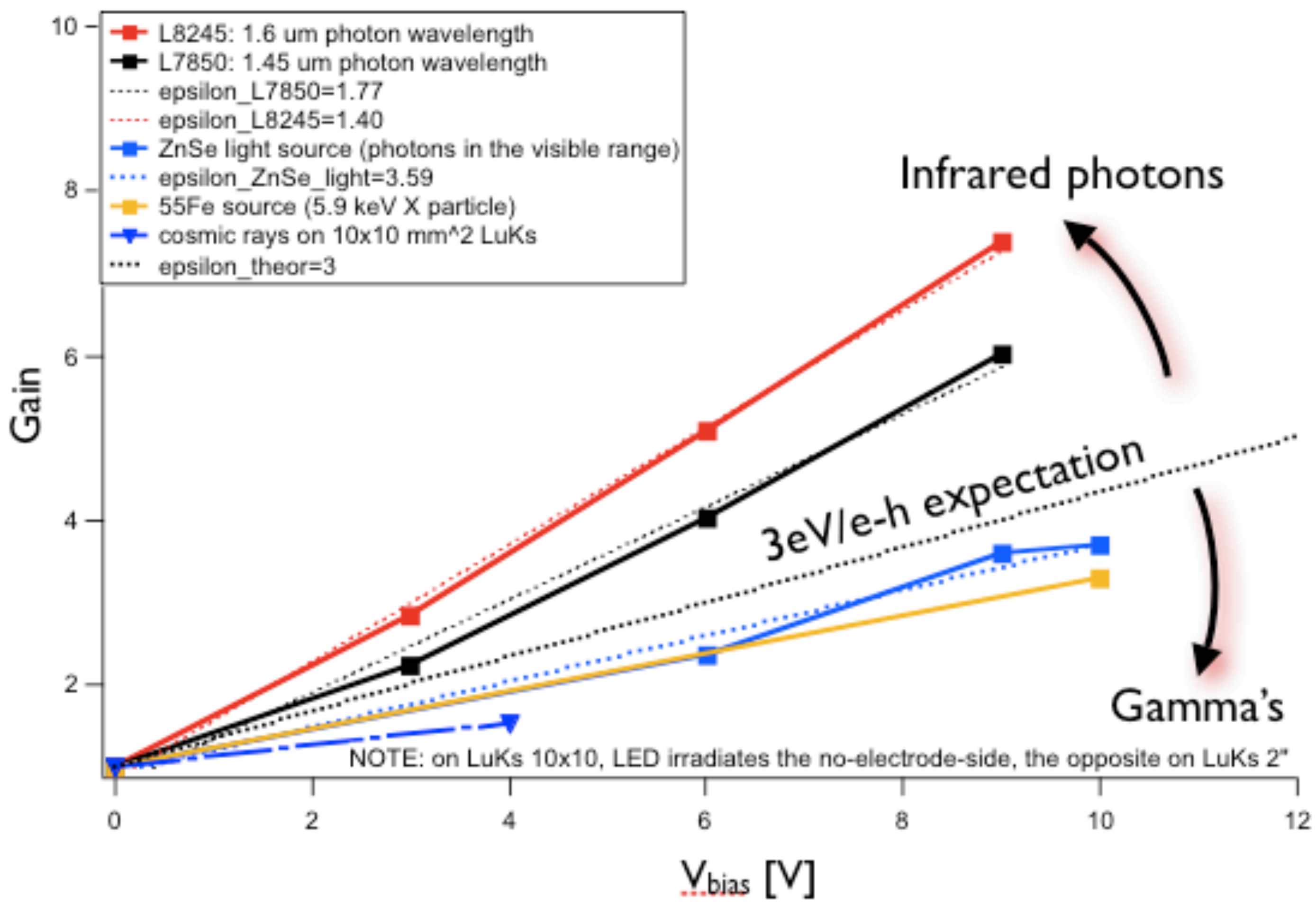
Composite detector

- Evaporation of the Ir-Au-TES onto a small substrate ($3x5x0.5mm^3$) using a shadow mask
- Thermometer is glued onto a Si substrate ($20x20x0.5mm^3$)(absorber)
- Al electrodes are directly evaporated onto the absorber

CRESST LukS

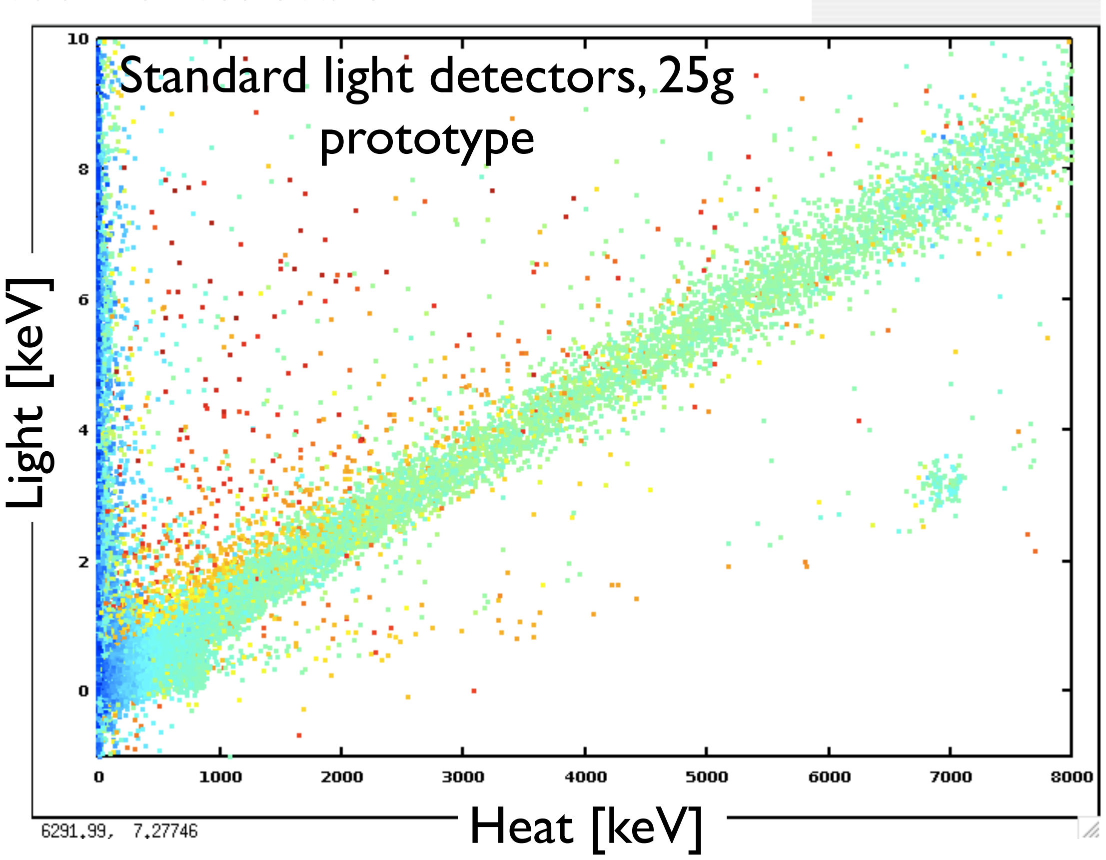


LUMINEU LukS



Next future R&D

- ZnMoO$_4$ large mass experiment for neutrino-less search

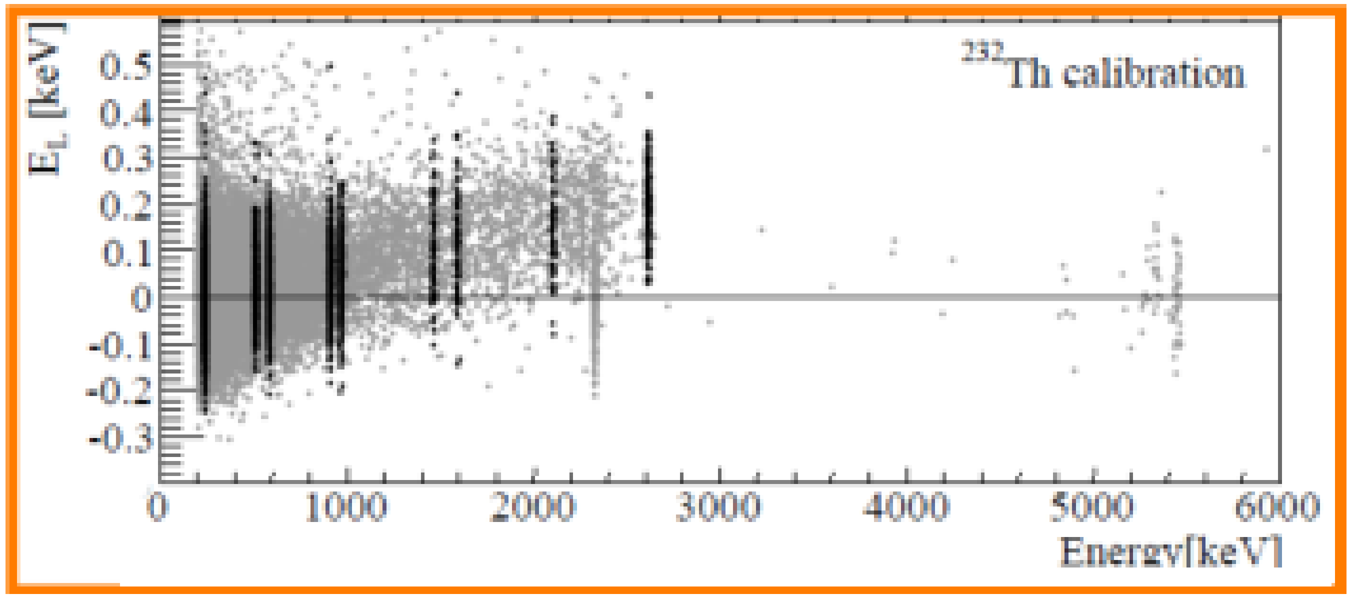


Standard light detectors, 25g prototype

When increasing the scintillating crystal, <u>less light escapes the crystal</u>

A much sensitive light detector is mandatory to scale the detector and LukS detector will fit

- Cherenkov light in TeO2 massive bolometer



arXiv:1106.6286v1

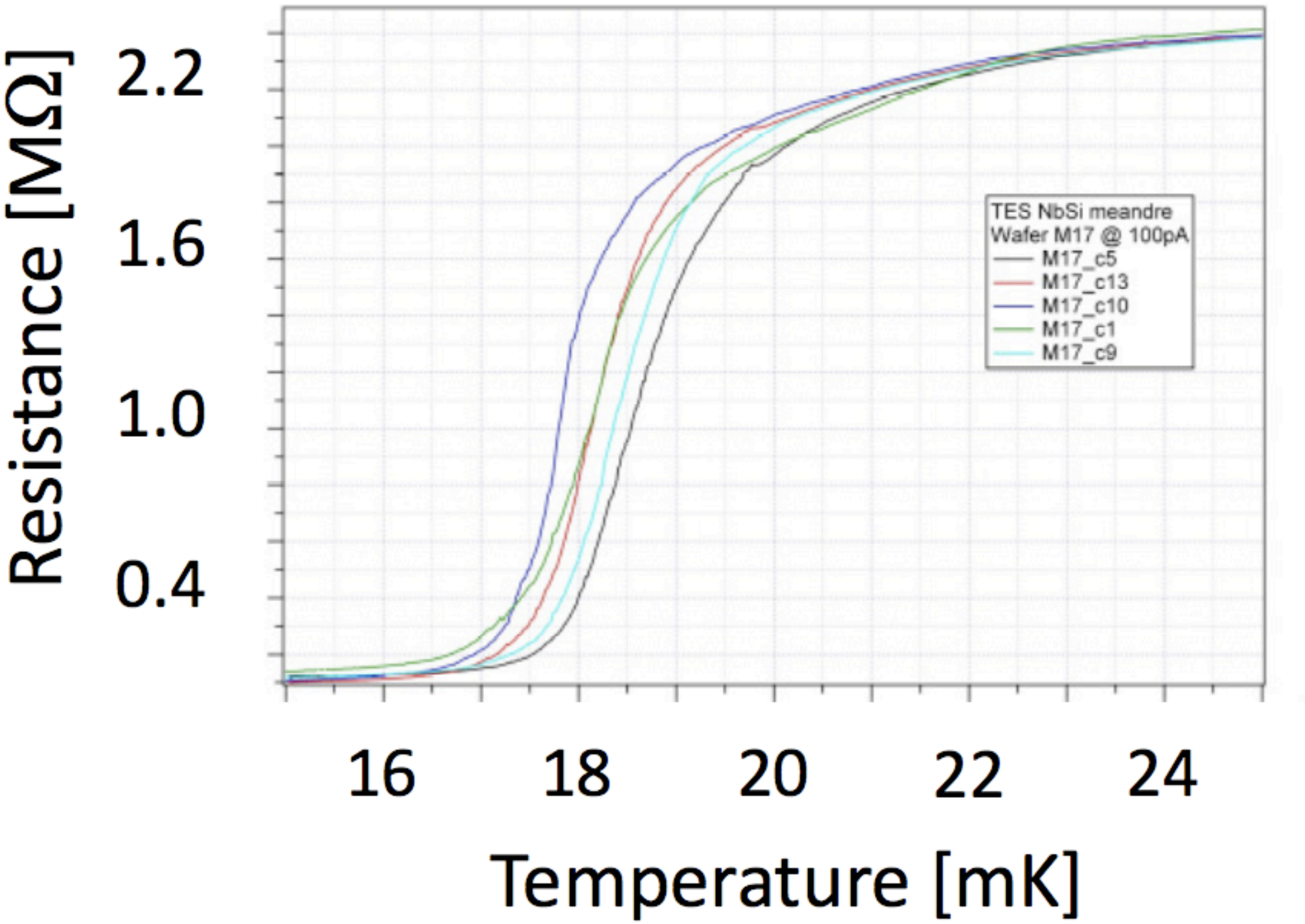
TeO$_2$ do not scintillate but Cherenkov!
There is no enough light resolution for event-by-event discrimination with standard light detector in TeO$_2$!

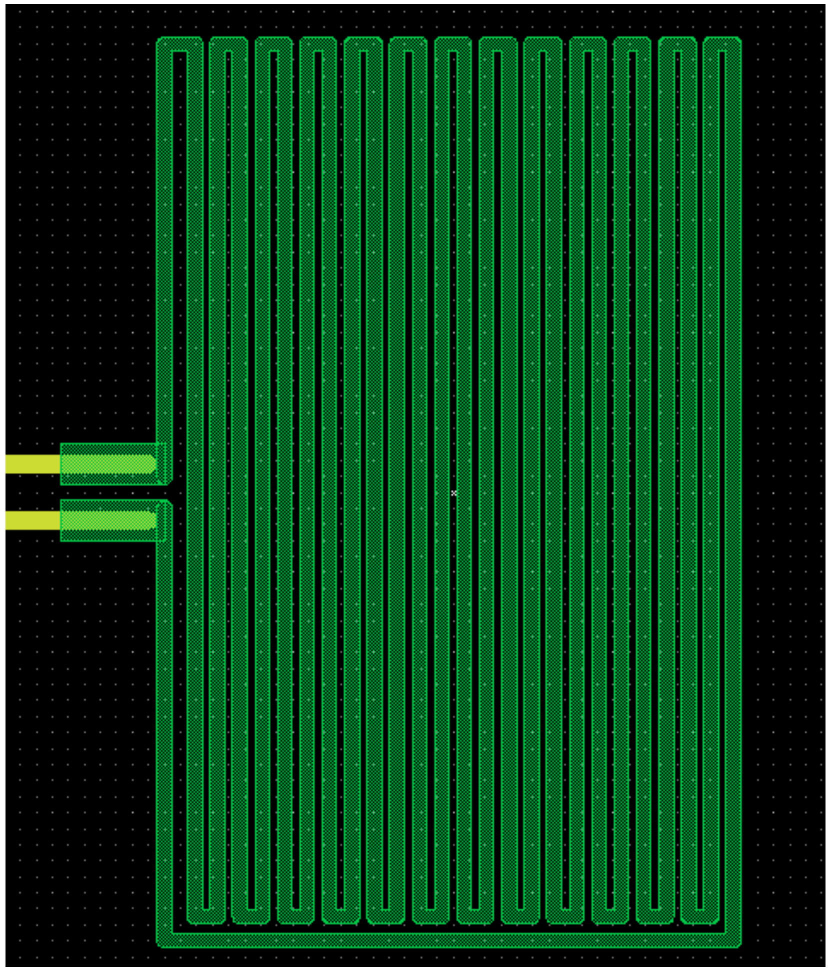
LukS detectors will fit with this set-up

Replace/Re-processing all the standard light detector with Neganov-Luke assisted tecnologie

Next future LukS prototype

High impedance TES sensor, meander shaped.





Conclusions

✓Different geometries of LukS detector have been successfully tested

✓Gap between theoretical and experimental gain: still some charge trapping

✓Sensitivity gain as high as 4 have been obtained

✓Exportable technology on existing light detectors (evaporation of aluminum electrodes)

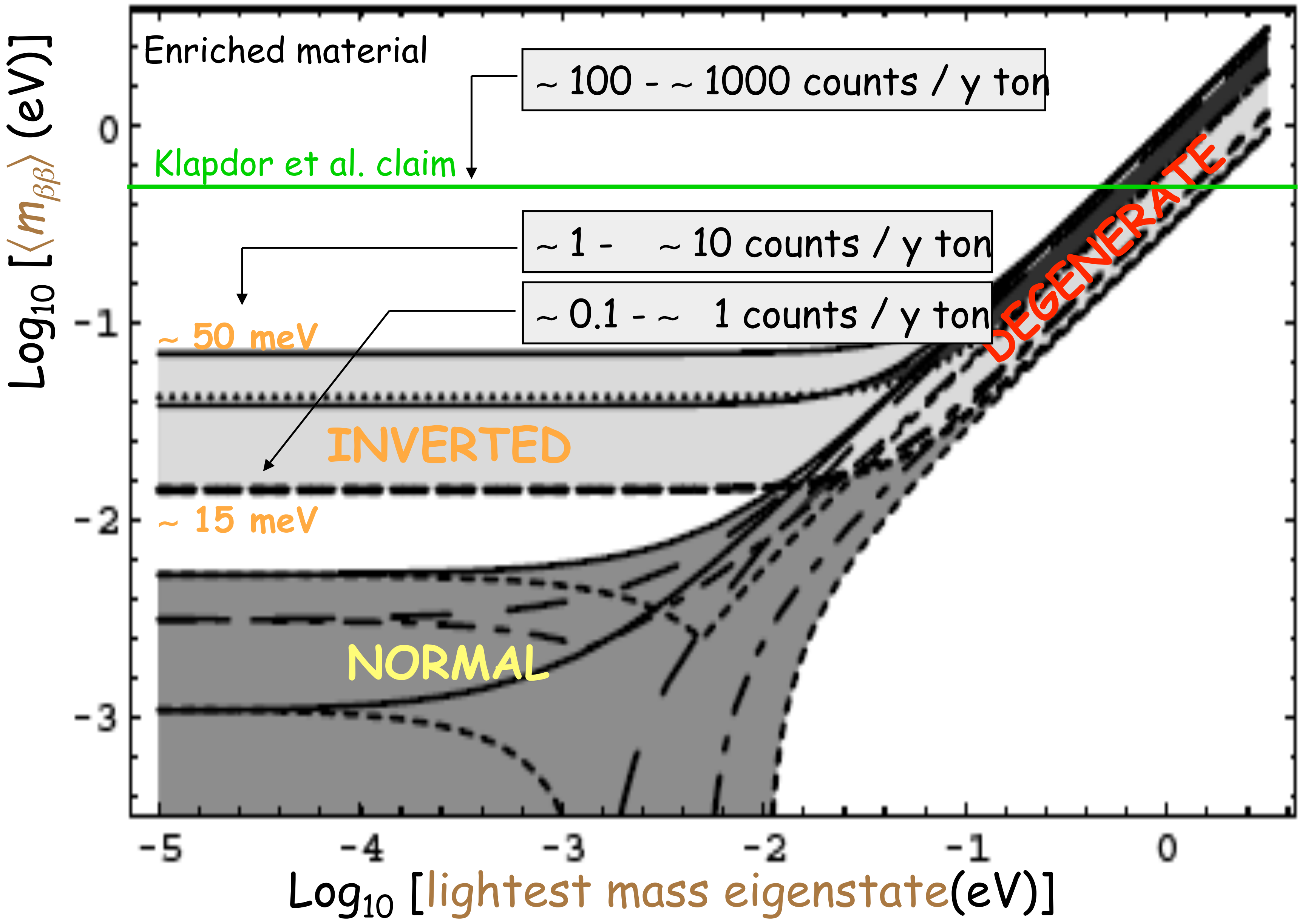
✓New perspectives and possible updates for next generation 0ν-2β experiment

◉Decreasing the electrode pitch to closely obtain the theoretical gain

◉Increasing the V bias, with better control of the leakage current (we have hints...)

◉Testing the High Impedance NbSi TES sensors at the place of "standard" Ge-NTD sensors...

Backup 3


Enriched material
~ 100 - ~ 1000 counts / y ton
Klapdor et al. claim
~ 1 - ~ 10 counts / y ton
~ 0.1 - ~ 1 counts / y ton
~ 50 meV
INVERTED
~ 15 meV
NORMAL
DEGENERATE
0
-1
-2
-3
-5
-4
-3
-2
-1
0
Log10 [⟨mββ⟩ (eV)]
Log10 [lightest mass eigenstate(eV)]