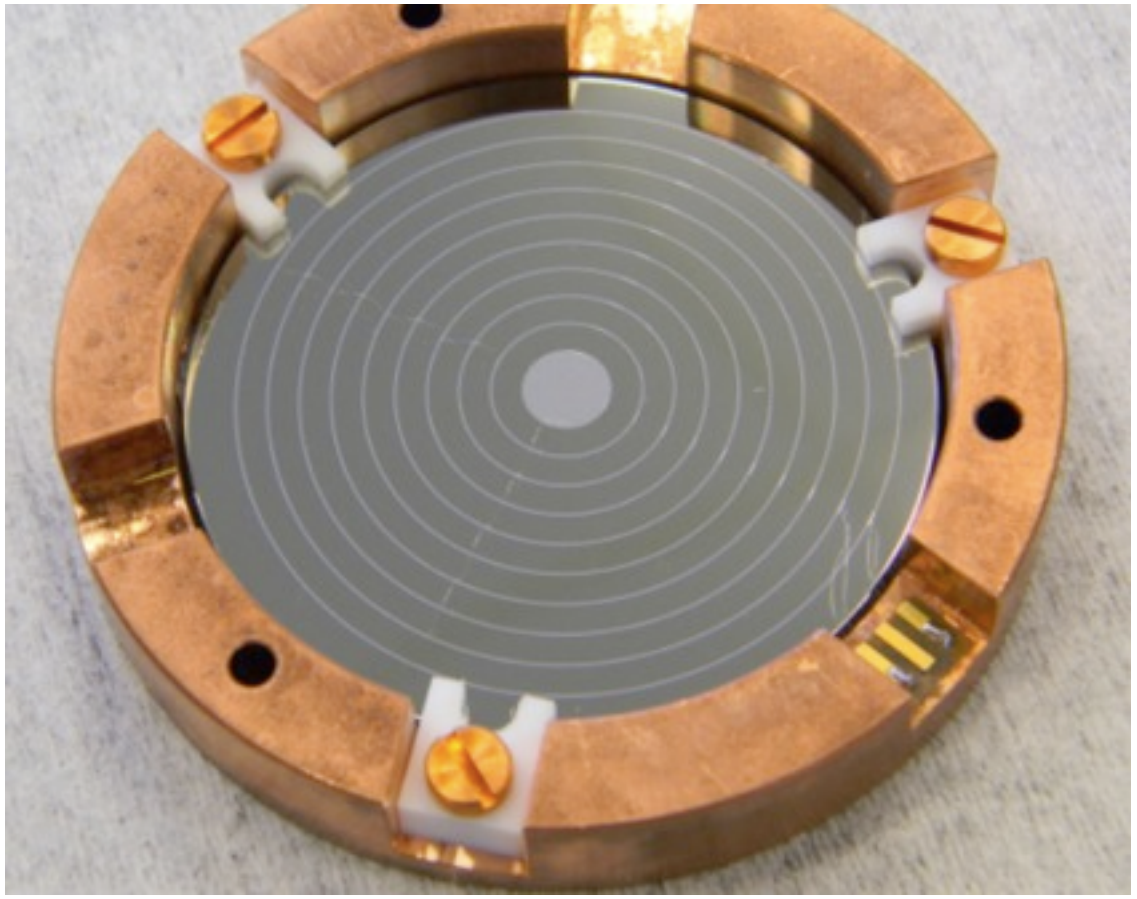
Neganov-Luke assisted Light Sensors



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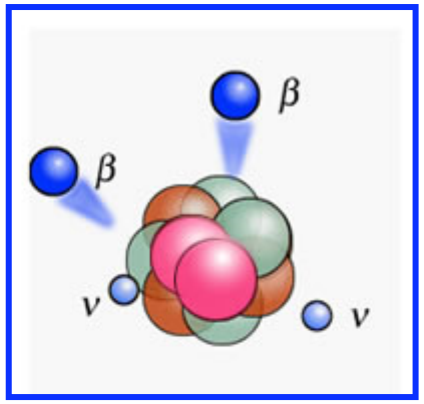
Outline

- Physics background and motivations: the double beta decay (ββ)
- Tailored detectors for 0ν-ββ decay
- A bolometer in a nutshell...
- The Neganov-Luke Assisted light detector
- Experimental set-up for a complete characterization
- Results and Perspectives
- Conclusions

Rare event search: 0ν-ββ decay

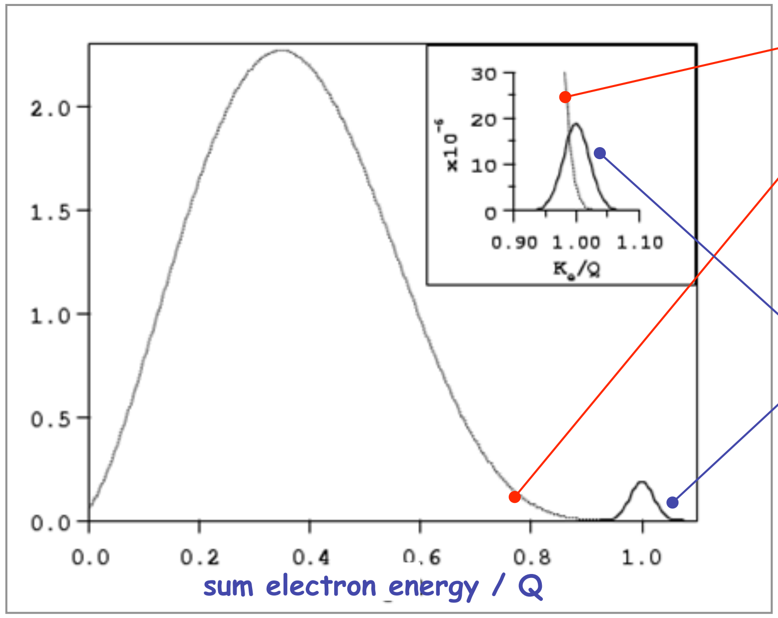
Double Beta Decay (2ν-ββ)

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



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

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

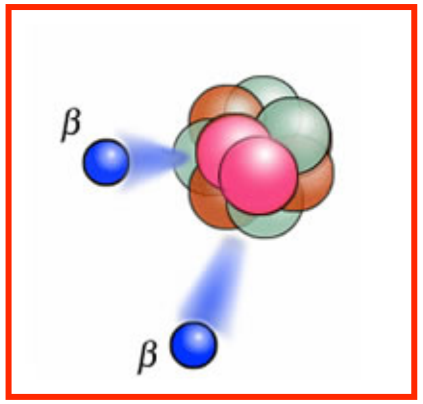


2ν double beta decay continuum with maximum at ~1/3 Q

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

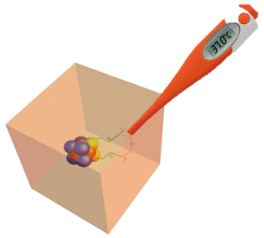
Effective Majorana mass

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

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

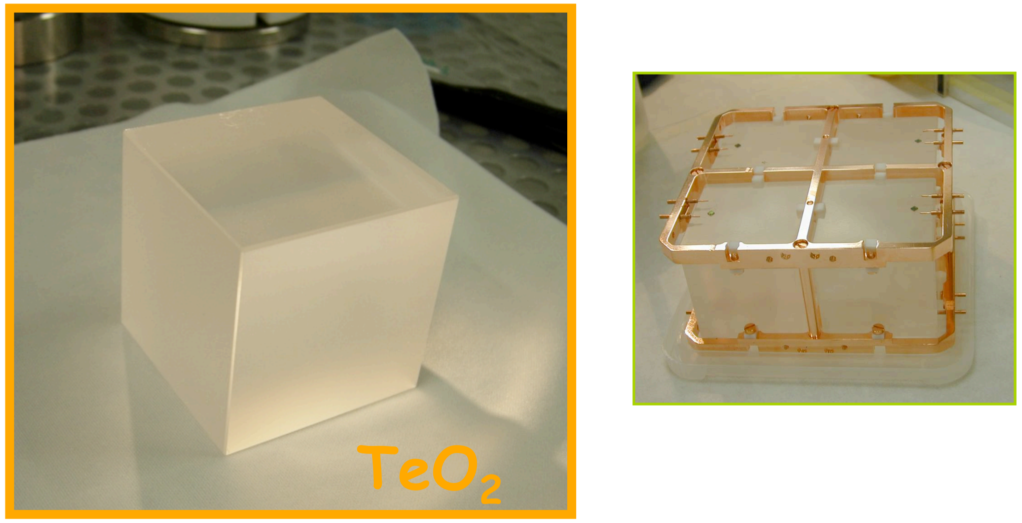
Mass sensitivity:

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

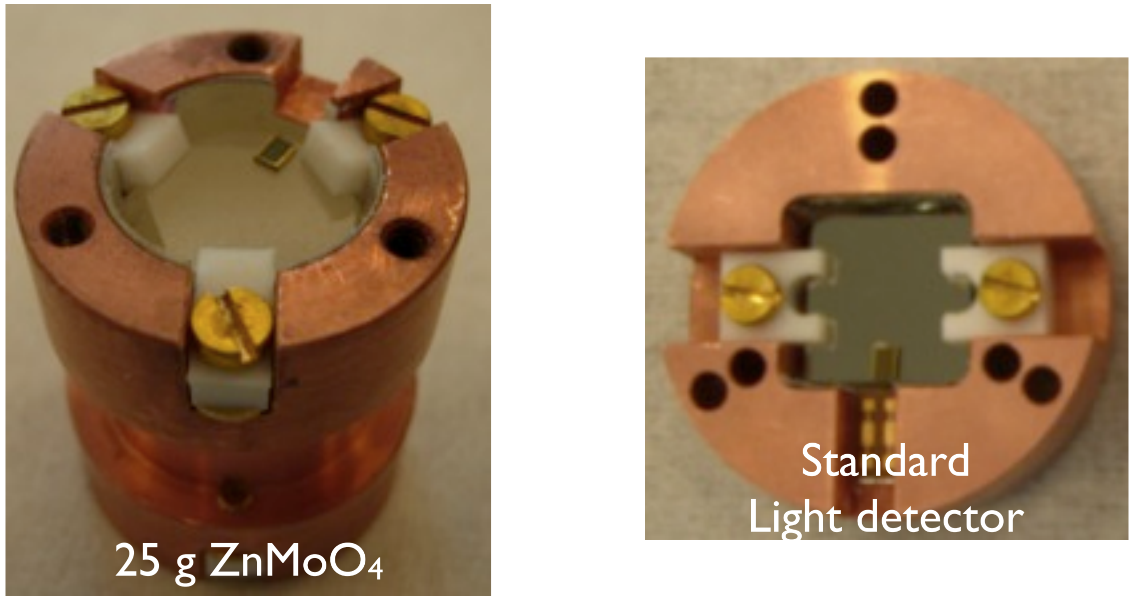
ΔE=energy res.
b=bkg in counts/keV/kg/day
M=effective mass
t_{live}=life time

Next future 0ν-ββ experiment...

CUORICINO and CUORE...

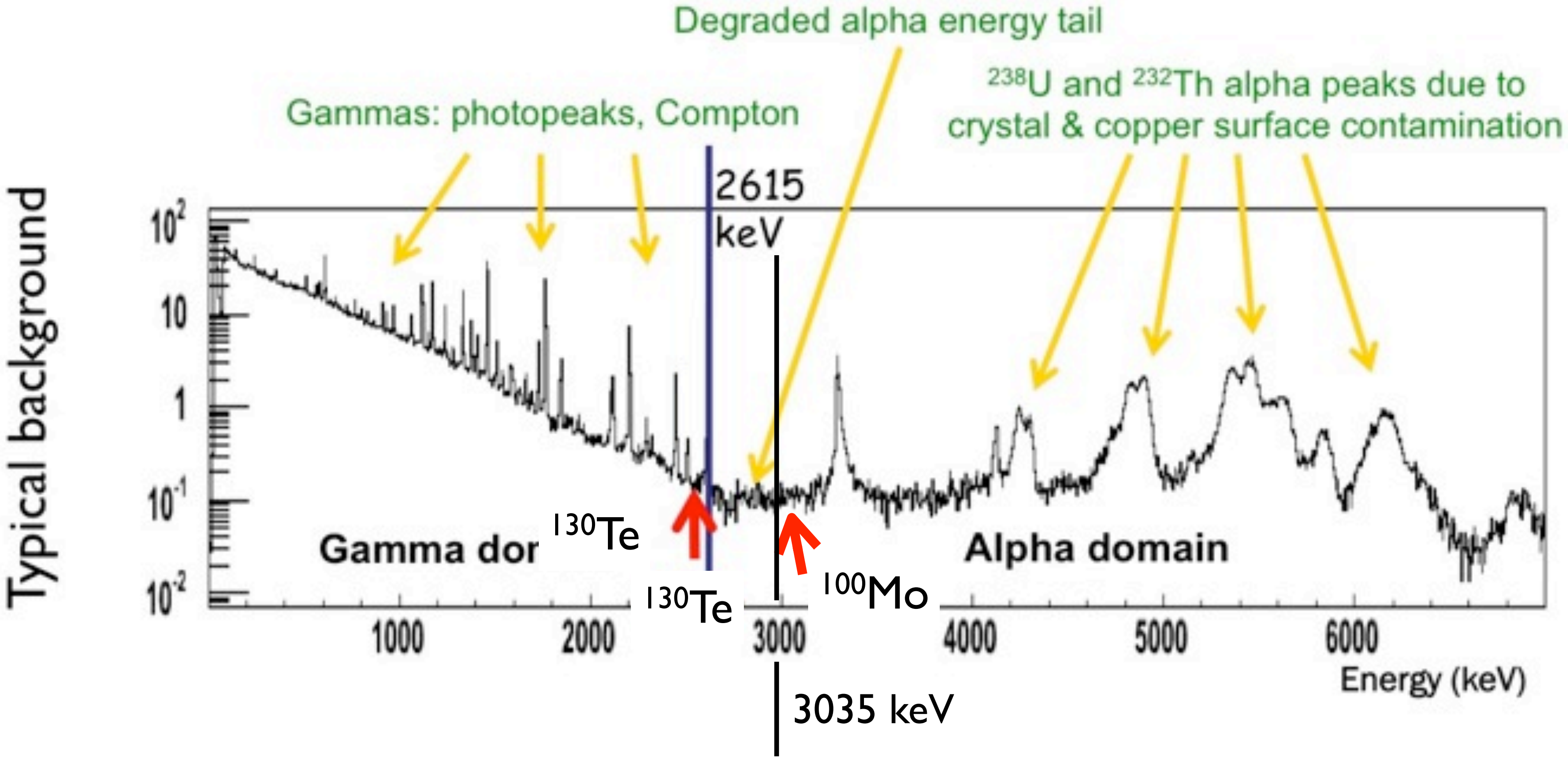


988 x TeO_2 simple-yield bolometers
(1-ton) at 20 mK



Light and heat yield bolometer
400g detector ready to run in LSM

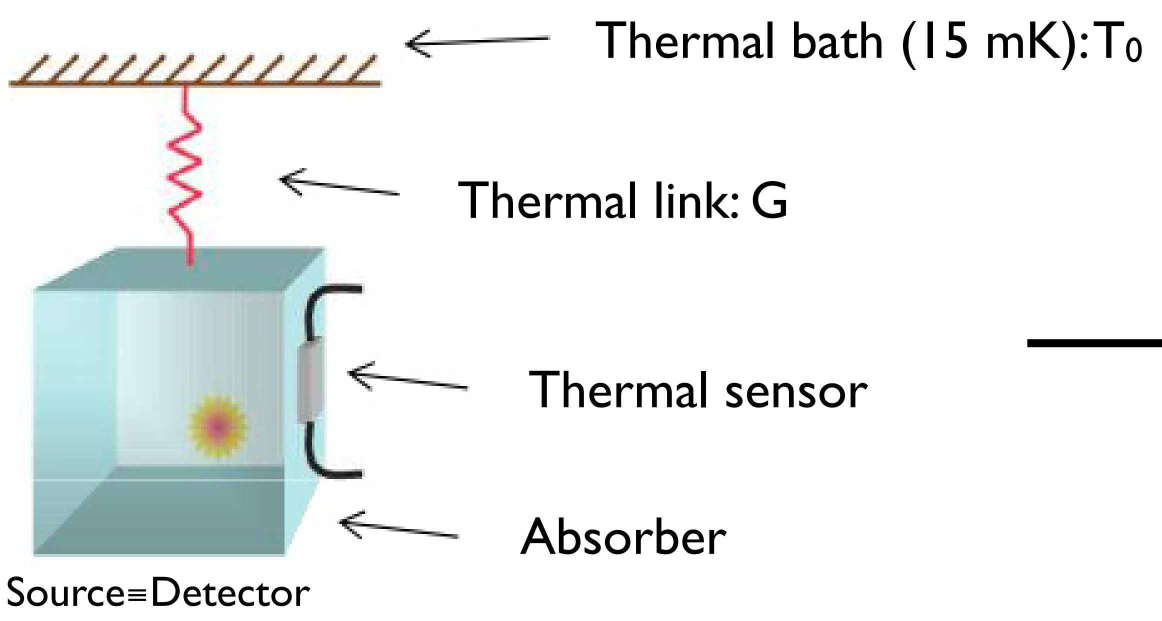
...and **LUMINEU**

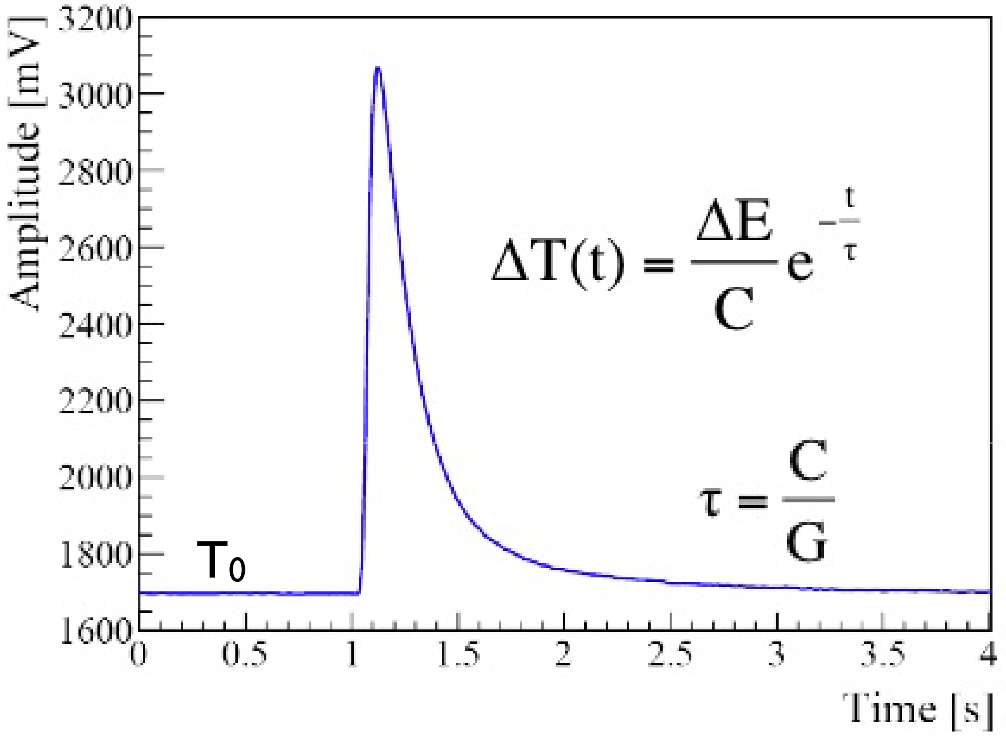


Background Requirements for the next future experiments: 1-10 evt/ ton/y

A bolometer in a nutshell

Heat

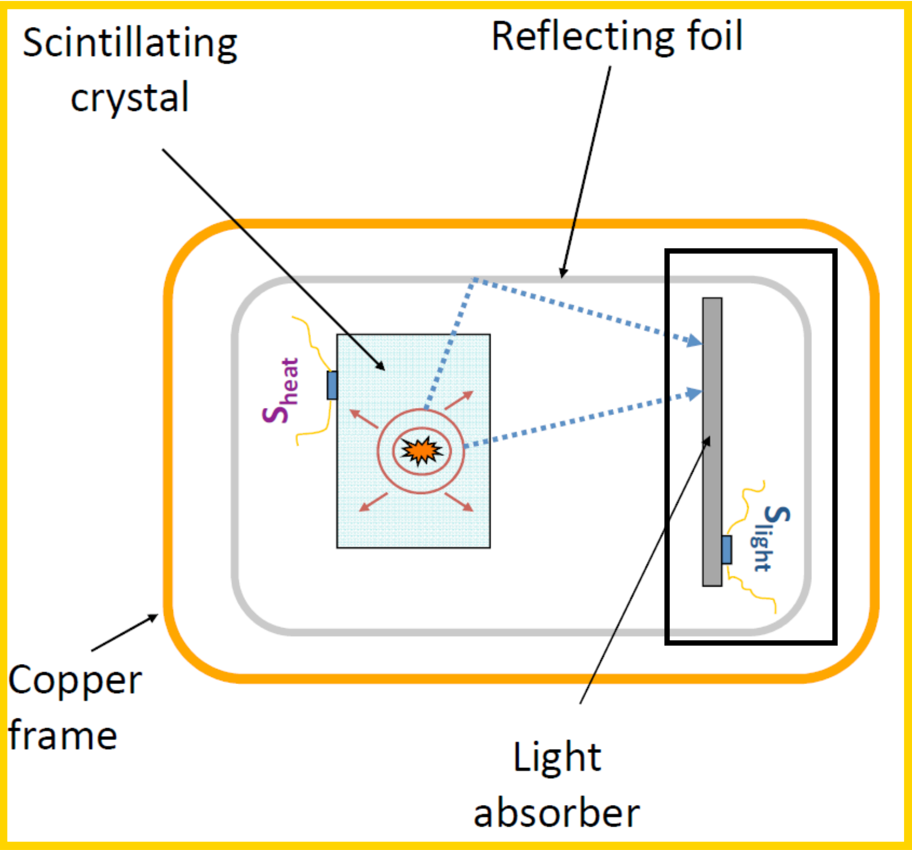


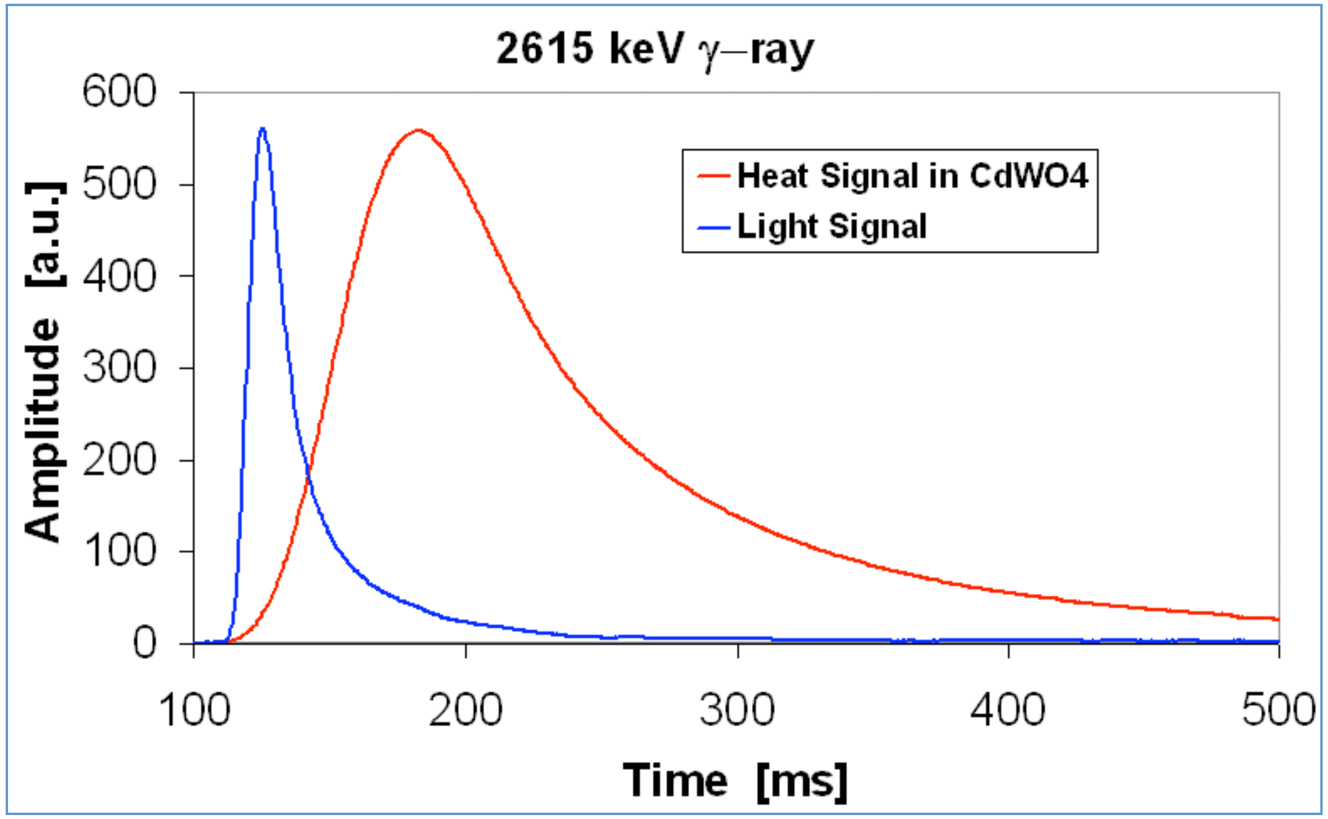


$$\Delta T(t) = \frac{\Delta E}{C} e^{-\frac{t}{\tau}}$$

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

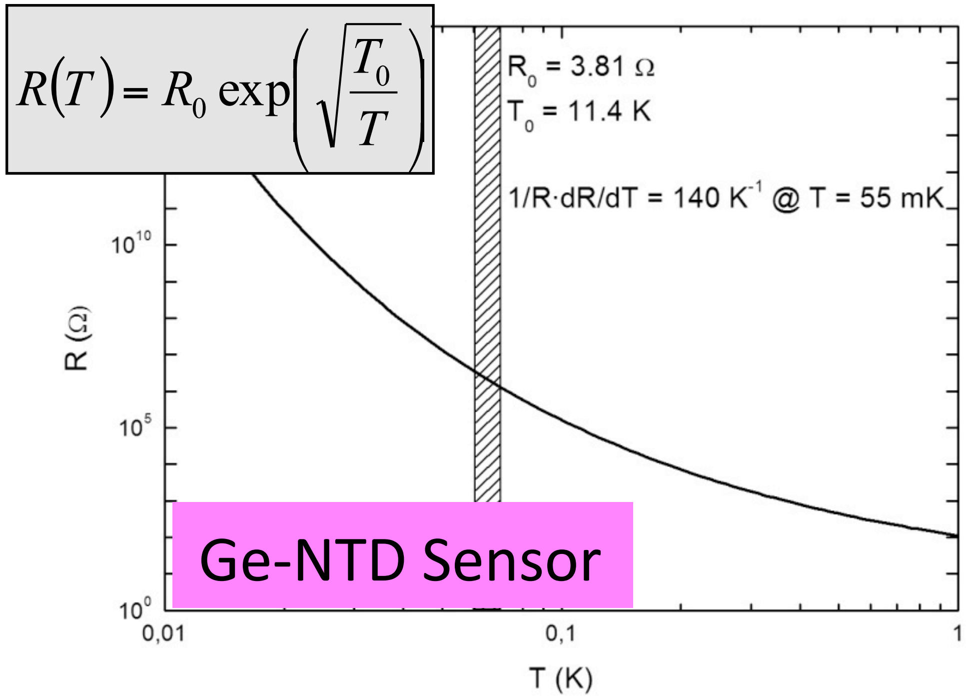
Heat and Light



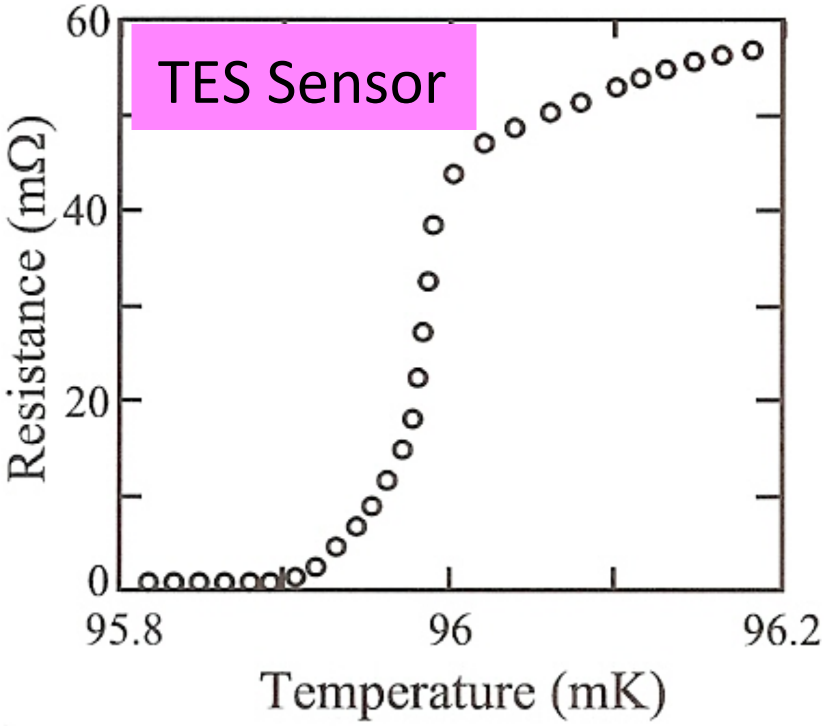


Thermal sensors for bolometers

Dis-entangled bolometer components



$$R(T) = R_0 \exp\left(\sqrt{\frac{T_0}{T}}\right)$$



The Signal S(V) is in first approx. : $S(V) = E_{particle} \times Gain_{therm} \times Gain_{electric}$

Absorber

Sensor

Bolometer

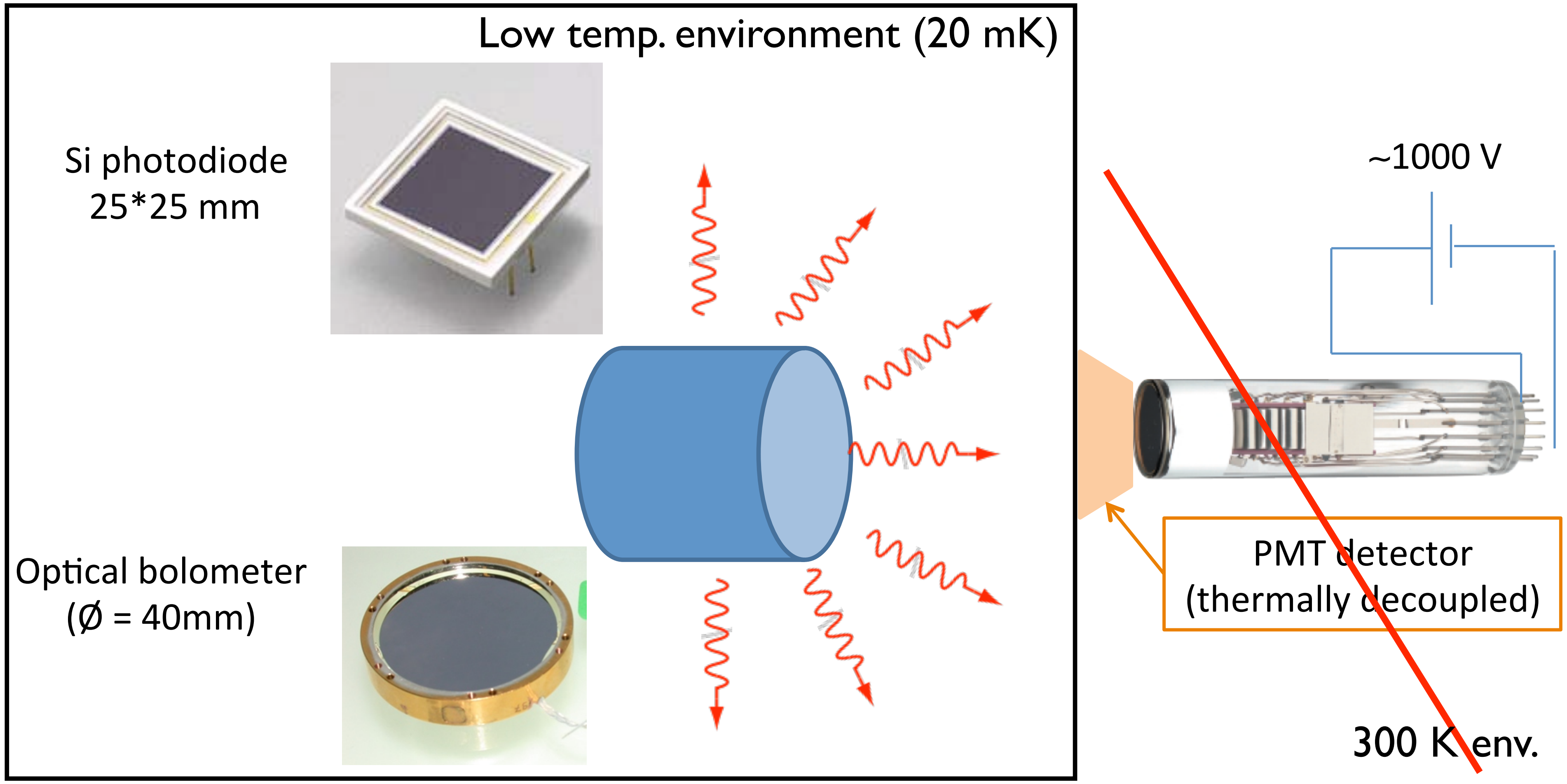
Benefits

- High energy resolution (as low as 3eV)
- Large domain of application: particle physics, astronomy, biology, fundamental physics
- Scalability
- Source-fitting

Drawbacks

- poor time resolution (few µs max)
- cryogenic temperatures
- reproducibility
- microphonic noise affected

Searching for light detector...



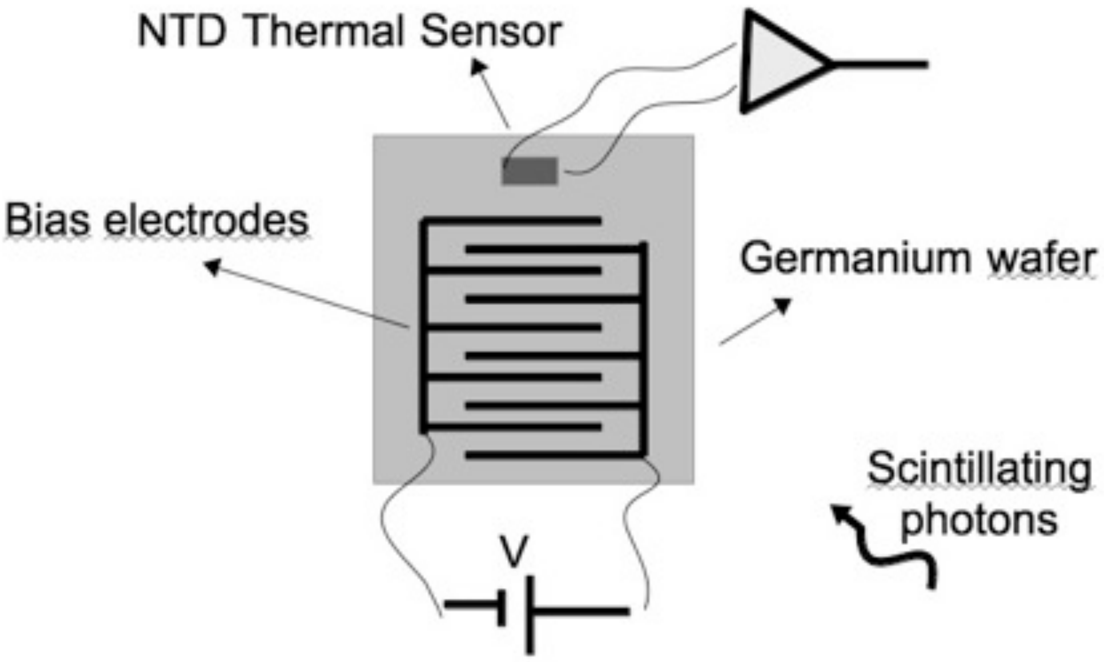
	Sensibility NEP $(W/\sqrt{Hz})$	Quantum efficiency	Absorbtion band	Time resolution (s)
PMs	10^{-16} à 300K 10^{-18}refroidis	~25%	Vis et UV	~10^{-9}
Photodiodes	~~10^{-14}~~	~80%	NIR-UV	~10^{-6}
Bolometer	10^{-17}	~100%	1eV-10keV	10^{-3}-10^{-2}

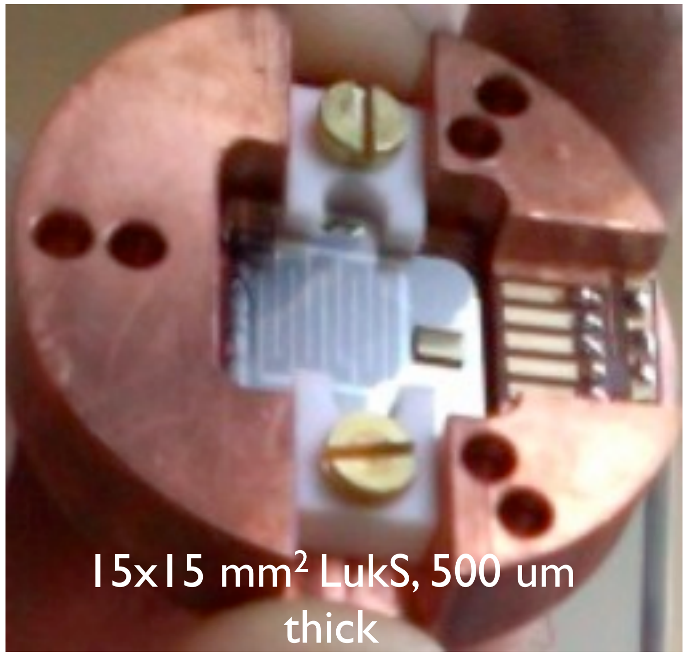
Scintillation
at 300K

Low
Temperature
detection

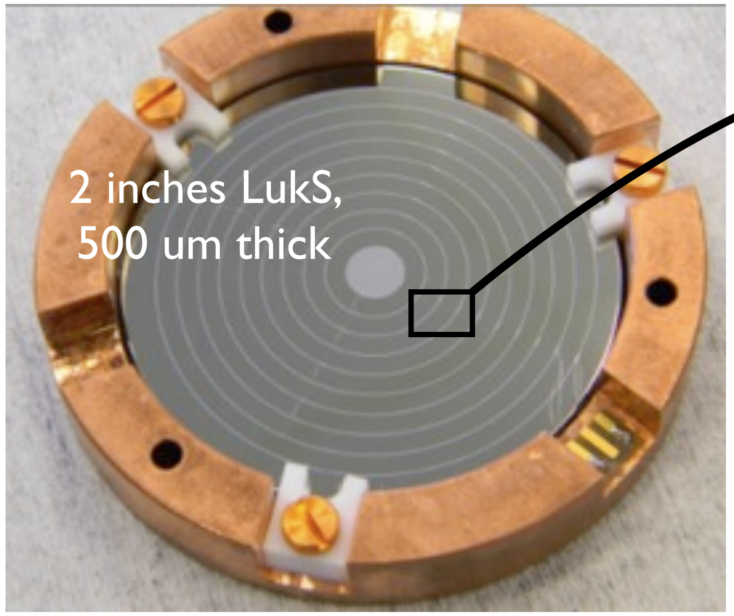
- ✓ Light detector facing directly the main bolometer
- ✓ Absolute light calibration using source ^{55}Fe (6 keV)

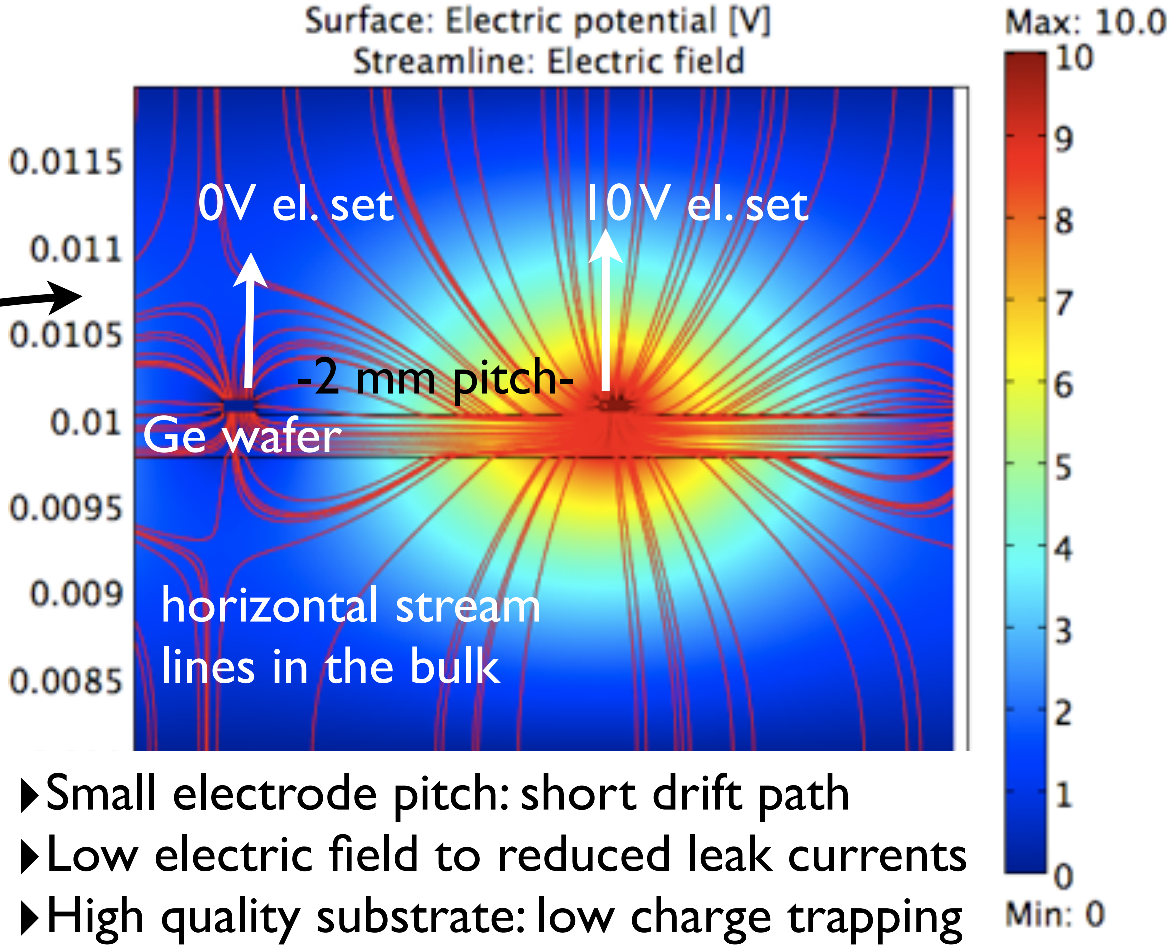
The LukS detector: generalities




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)

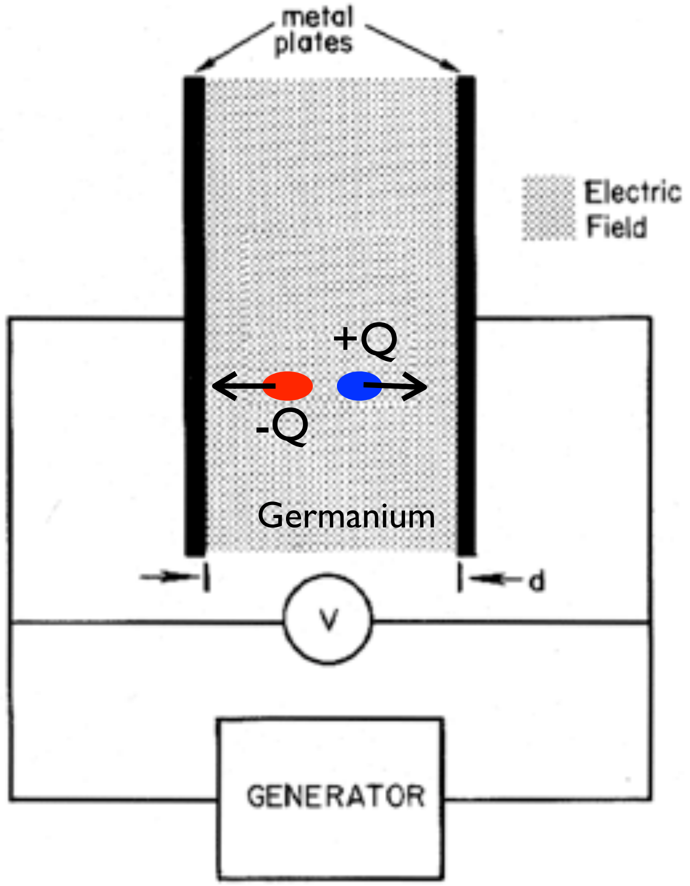

2 inches LukS, 500 um thick



horizontal stream lines in the bulk

- 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

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

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 efficiency ε depends on the semiconductor (gap). For germanium: $\varepsilon = 3$ eV/(e-h)
3) By increasing V the heat signal is mainly dominated by the charge creation $\Rightarrow$ beyond the thermodynamic fluctuation limit (Fano fluctuations)

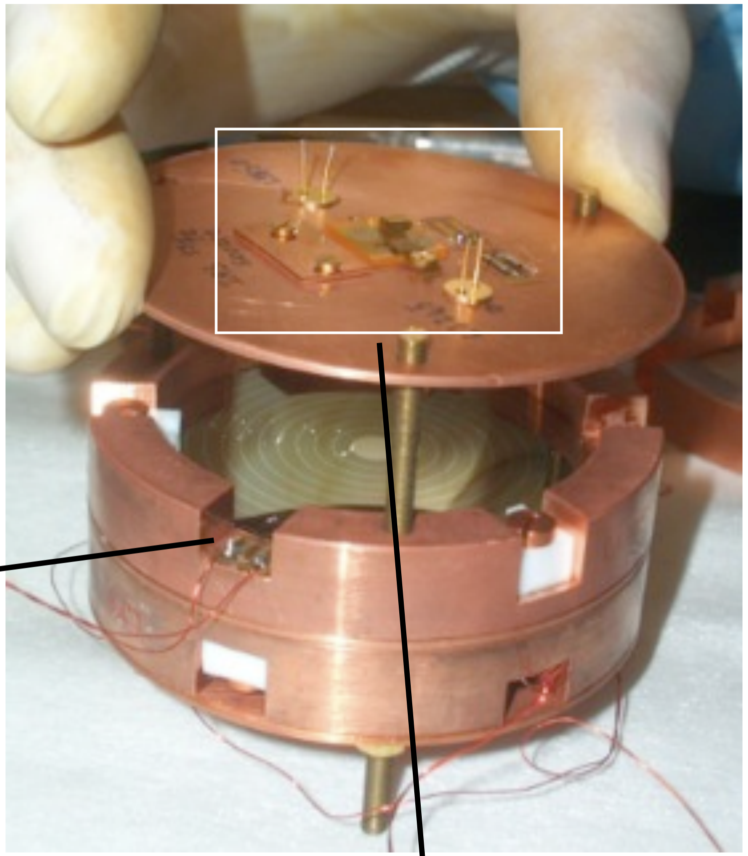
$$E_{heat} = E_r(1 + qV_{bias}/\varepsilon)$$

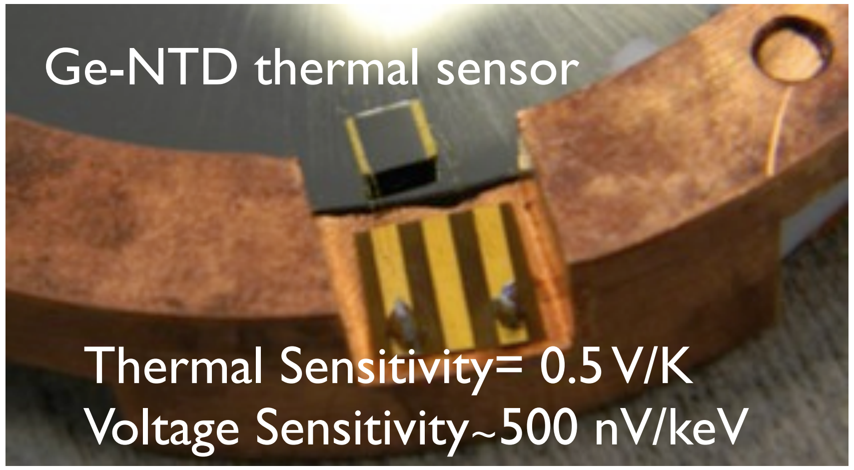
We can increase the heat signal without any limit, increasing V!

The 2-inches detector

The main questions:

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





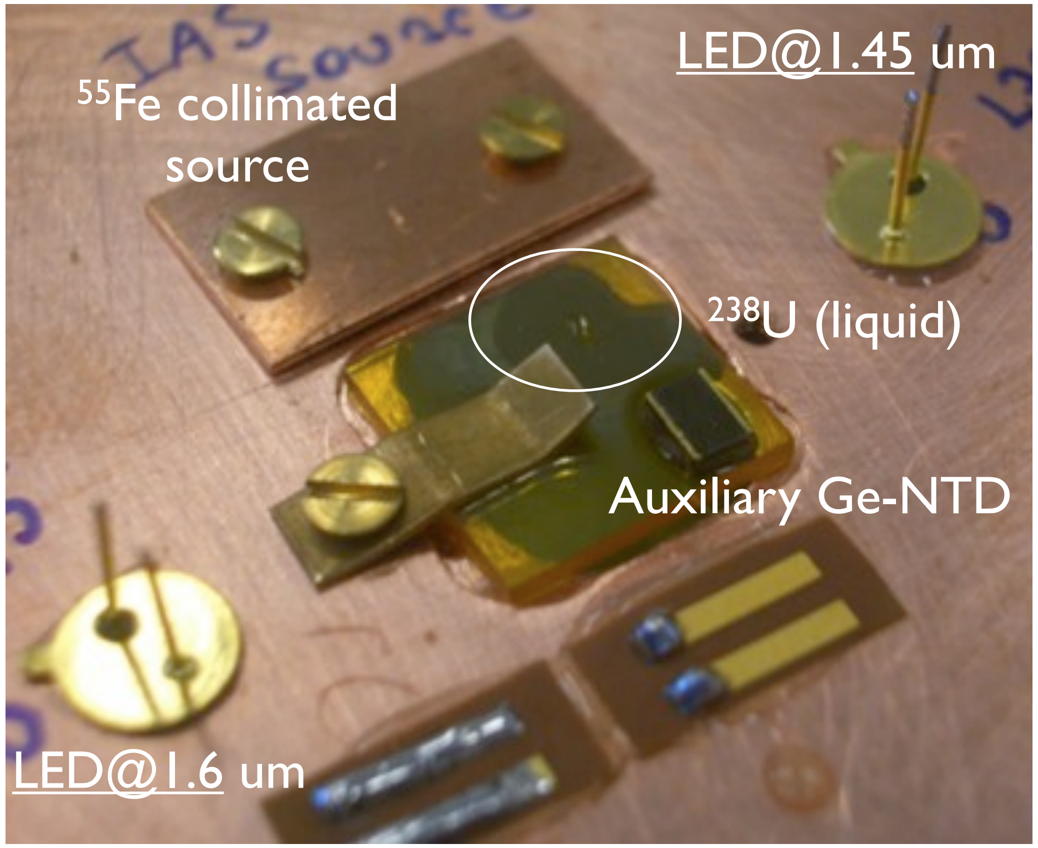
Thermal Sensitivity= 0.5 V/K
Voltage Sensitivity~500 nV/keV

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

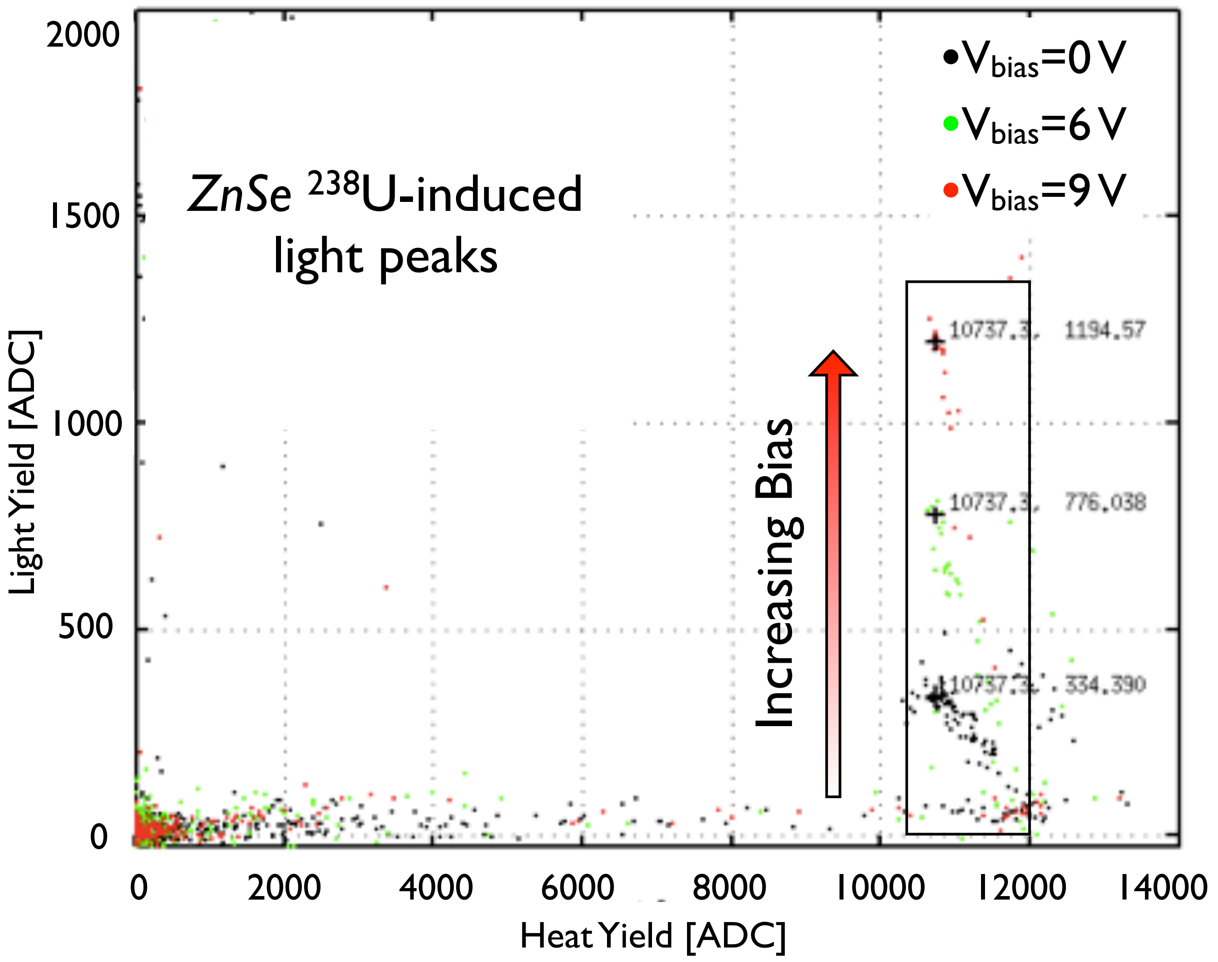
Absolute Calibration Source

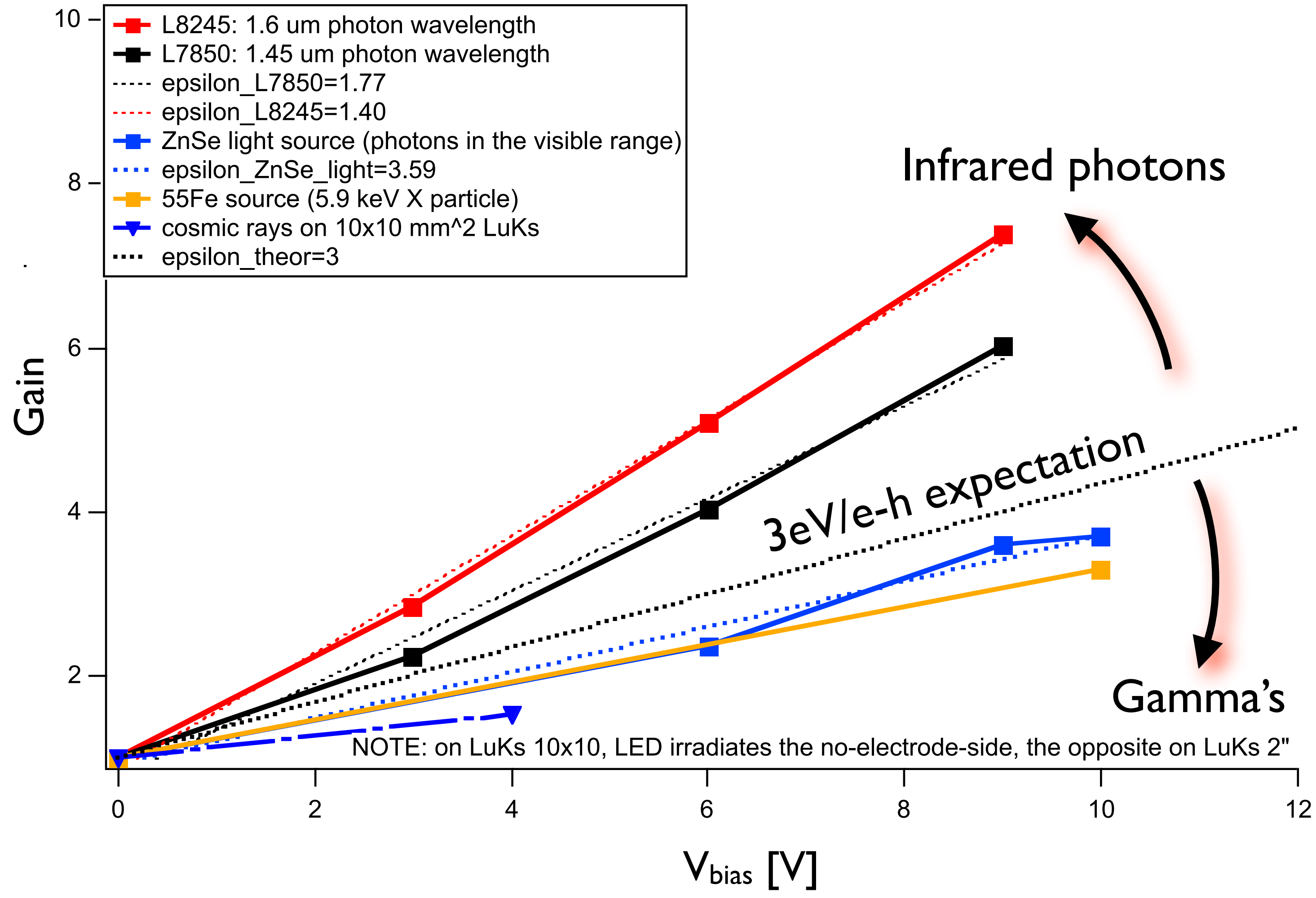
- Collimated ^{55}Fe, which provides 5.9 and 6.4 keV X rays



Results: thermal sensitivity gain

Heat and Light event-by-event scatterplot

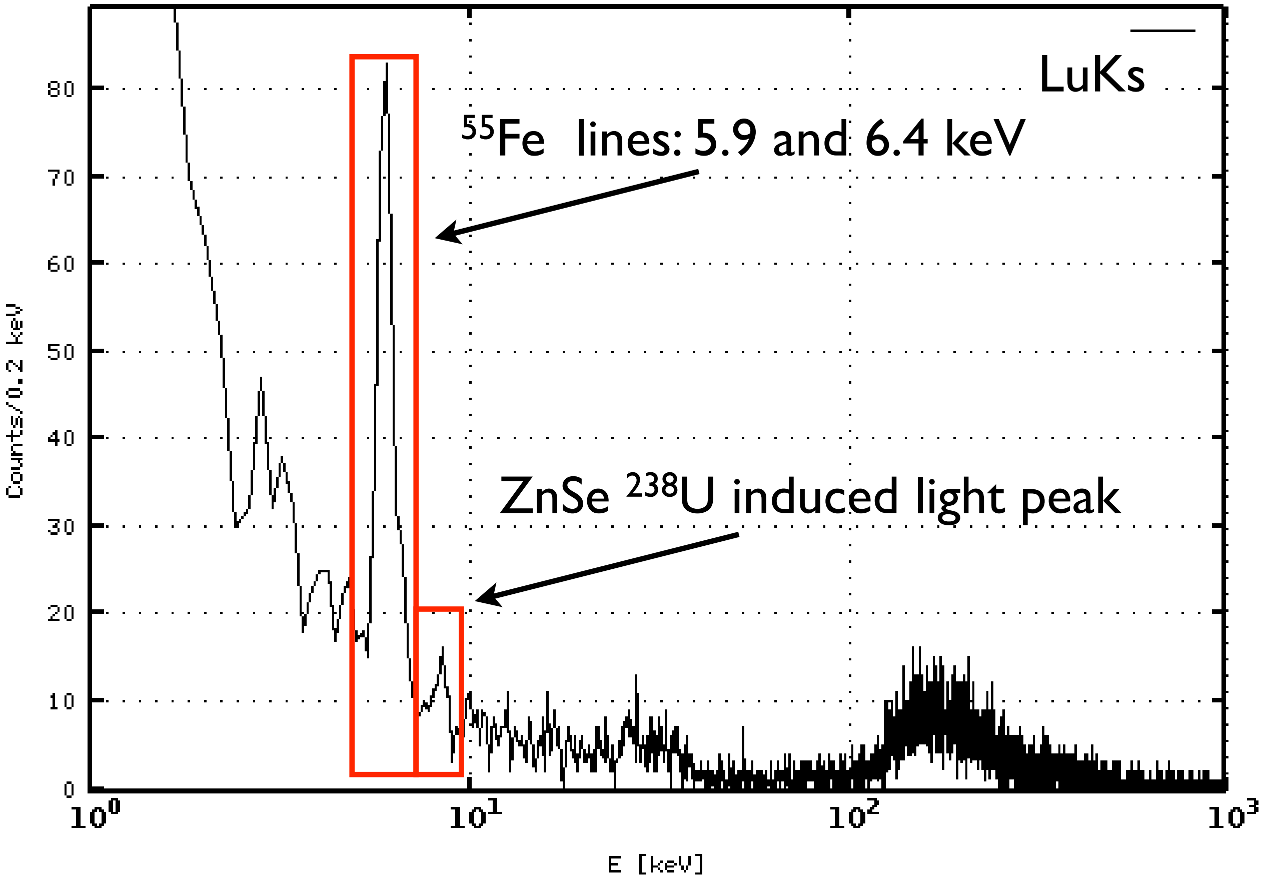




Observations:

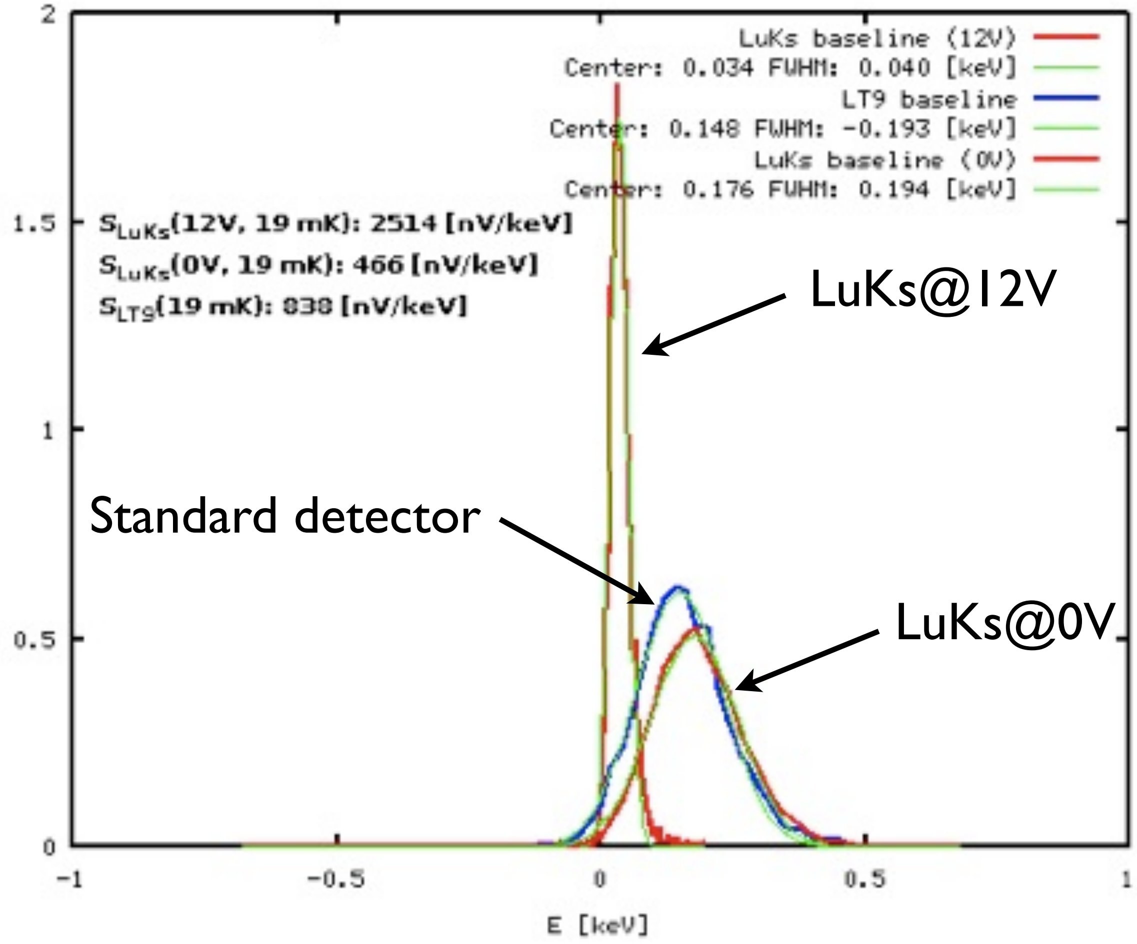
- Charge trapping at surfaces reduces the gain with respect to 3eV/e-h
- Gain depends on the particle/wavelength
- Leakage current appearance at high bias (12V➡E_{field}=60V/cm), which at the moment is the only limit to increase the gain!

Results: baseline noise reduction



^{55}Fe lines: 5.9 and 6.4 keV

ZnSe ^{238}U induced light peak



LuKs@12V

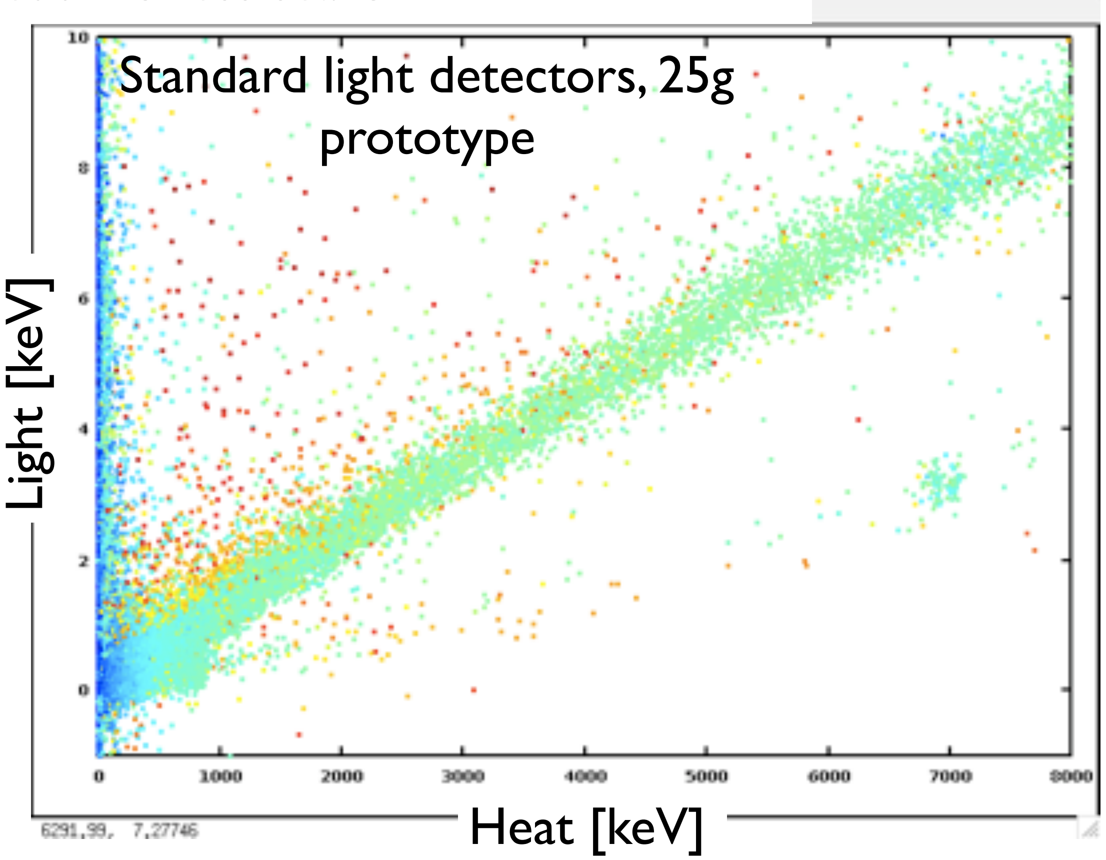
Standard detector

LuKs@0V

- 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 12V bias!

Next future R&D

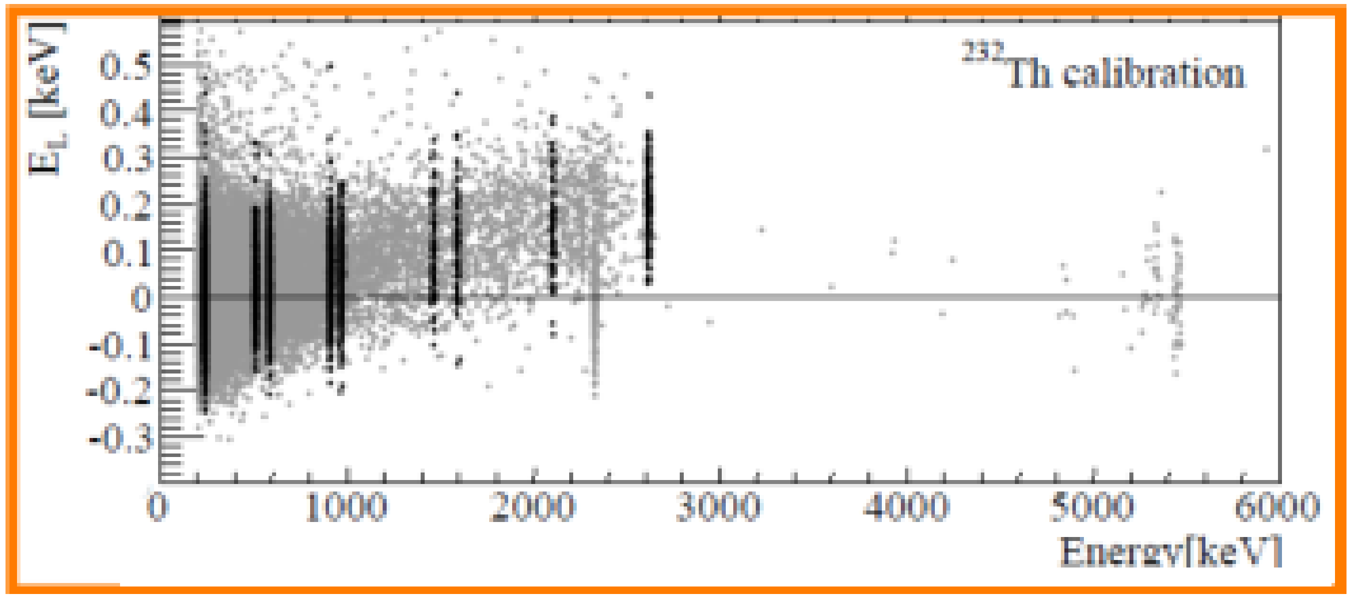
- $ZnMoO_4$ large mass experiment for neutrino-less search



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

<u>A much sensitive light detector is mandatory to scale the detector and LuKs detector will fit</u>

- Cherenkov light in TeO2 massive bolometer



arXiv:1106.6286v1

TeO_2 do not scintillate but Cherenkov!
There is <u>no enough light resolution</u> for event-by-event discrimination with s<u>tandard light</u> detector in TeO_2!
<u>LuKs detectors will fit with this set-up</u>

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

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 1

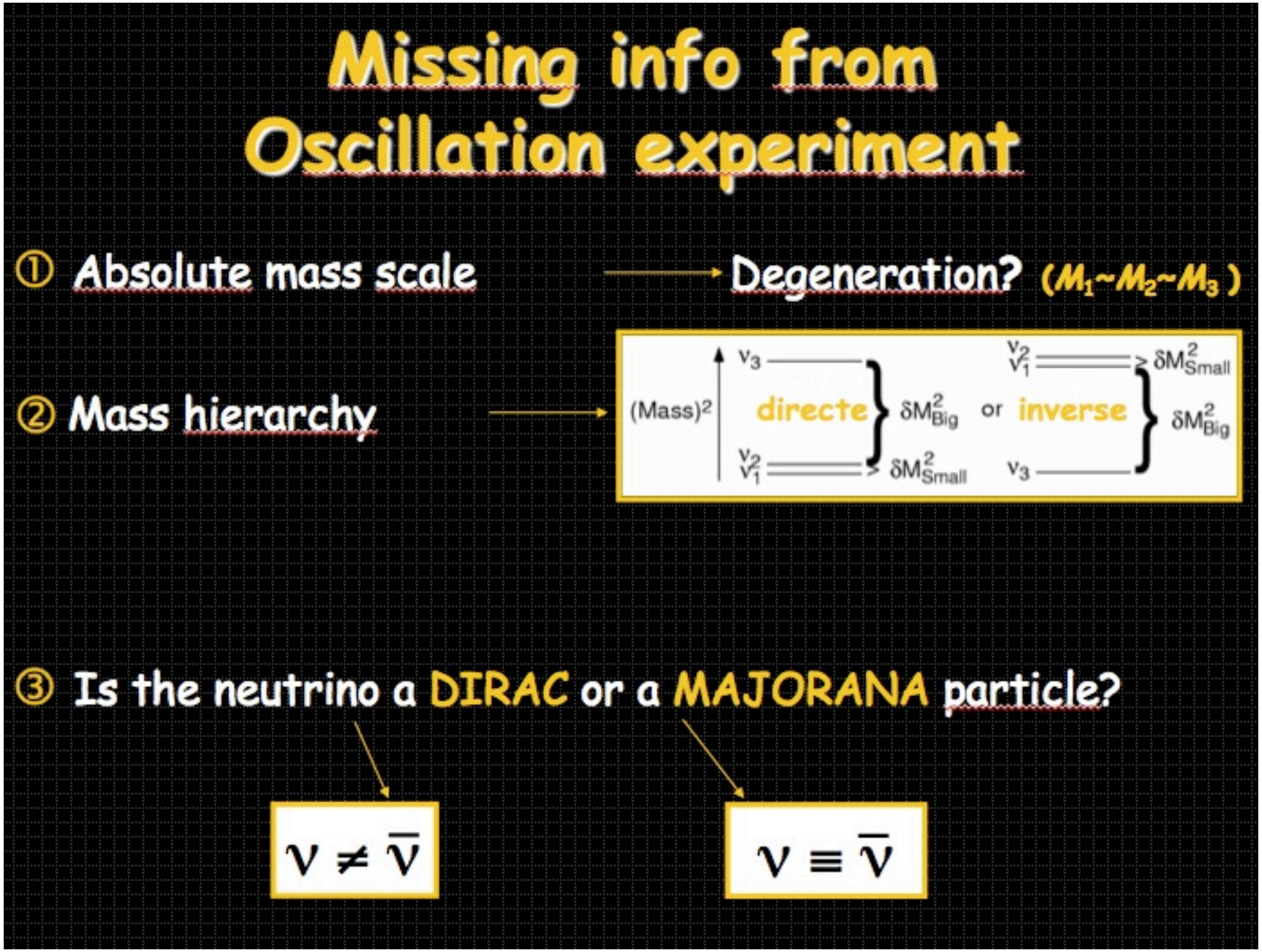
Détecteur	Produits de l'interaction	Dépense énergétique par quantum d'information (QE).
Scintillateur	Photons visibles	**100 eV→1 keV**
Compteur proportionnel	Ions	**10 eV→30 eV**
Semi-conducteur	Paires électrons-trous	**3 eV-4 eV**
STJ : Jonction tunnel supra	Quasi-particules (« paires de Cooper » brisées)	10^{-3} eV
Bolomètre à cible isolante	Phonons	**10^{-5} eV à 10^{-4} eV**
Bolomètre à cible métallique	Excitation d'électrons de conduction	**<< 10^{-5} eV**

🟦 Cold detectors

Statistic contribution to ultimate resolution

$$\Delta E \big/ E \approx 1/\sqrt{n} \quad \mathit{with} \quad n = E \big/ QE$$

Backup 2



Missing info from Oscillation experiment

① Absolute mass scale → Degeneration? (M_1~M_2~M_3)

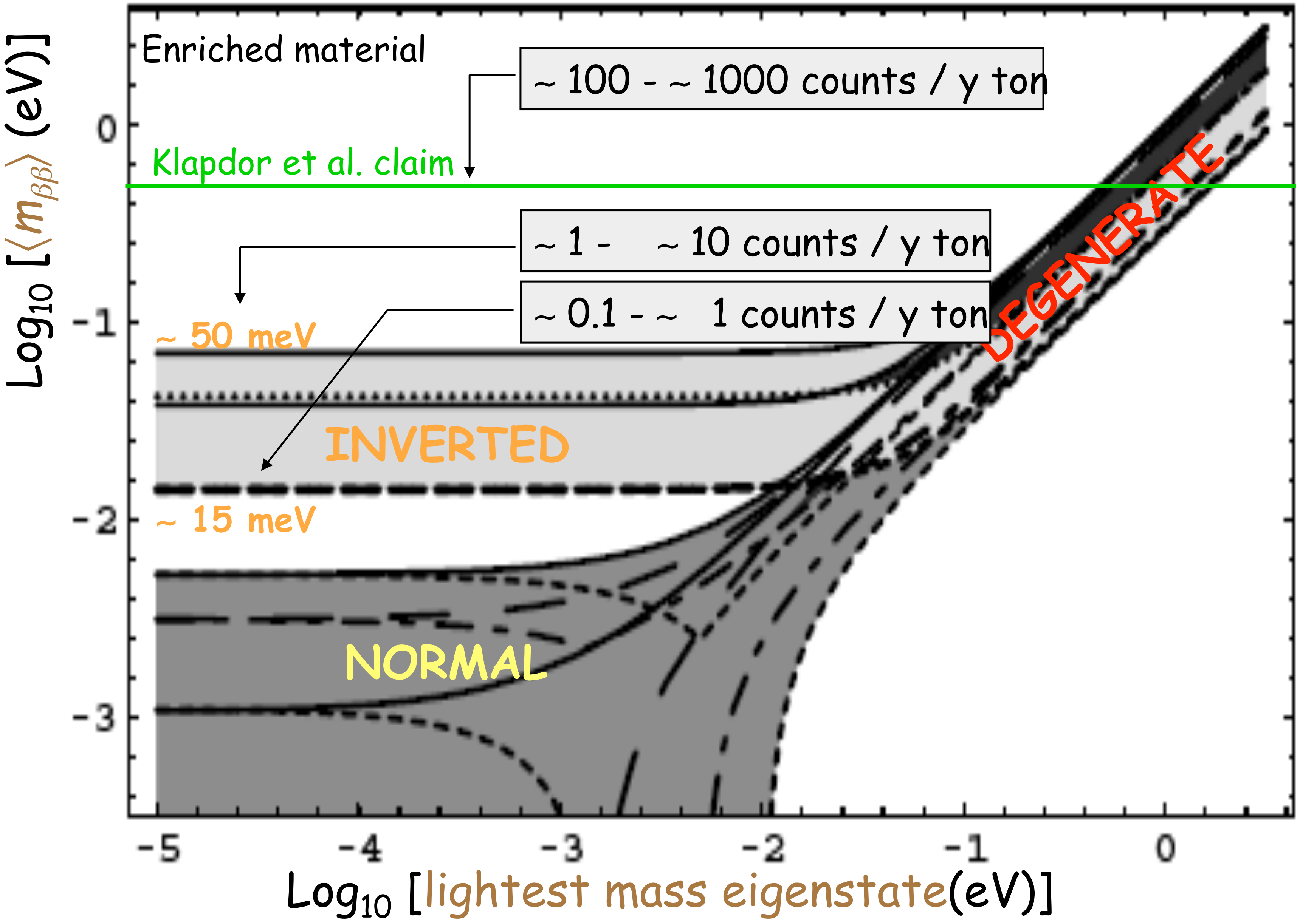
② Mass hierarchy →

③ Is the neutrino a DIRAC or a MAJORANA particle?

$\nu \neq \bar{\nu}$

$\nu \equiv \bar{\nu}$

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
~ 15 meV
INVERTED
NORMAL
DEGENERATE
0
-1
-2
-3
-5
-4
-3
-2
-1
0
Log$_{10}$ [$\langle m_{\beta\beta} \rangle$ (eV)]
Log$_{10}$ [lightest mass eigenstate(eV)]