Application of Low Temperature detectors in physics :

Past , Present, Future

Ieri, Oggi, Domani

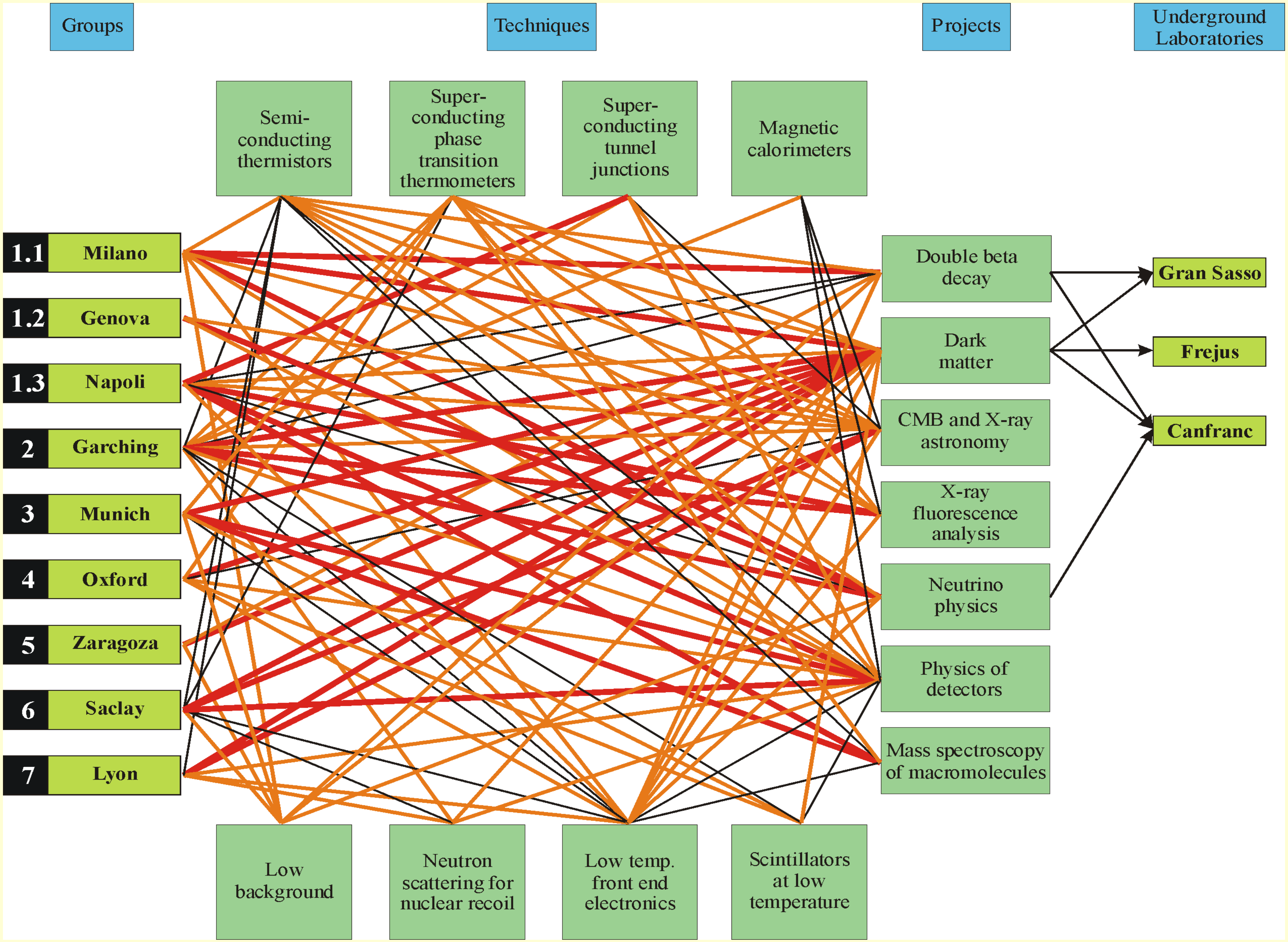
Origin and development of thermal detectors

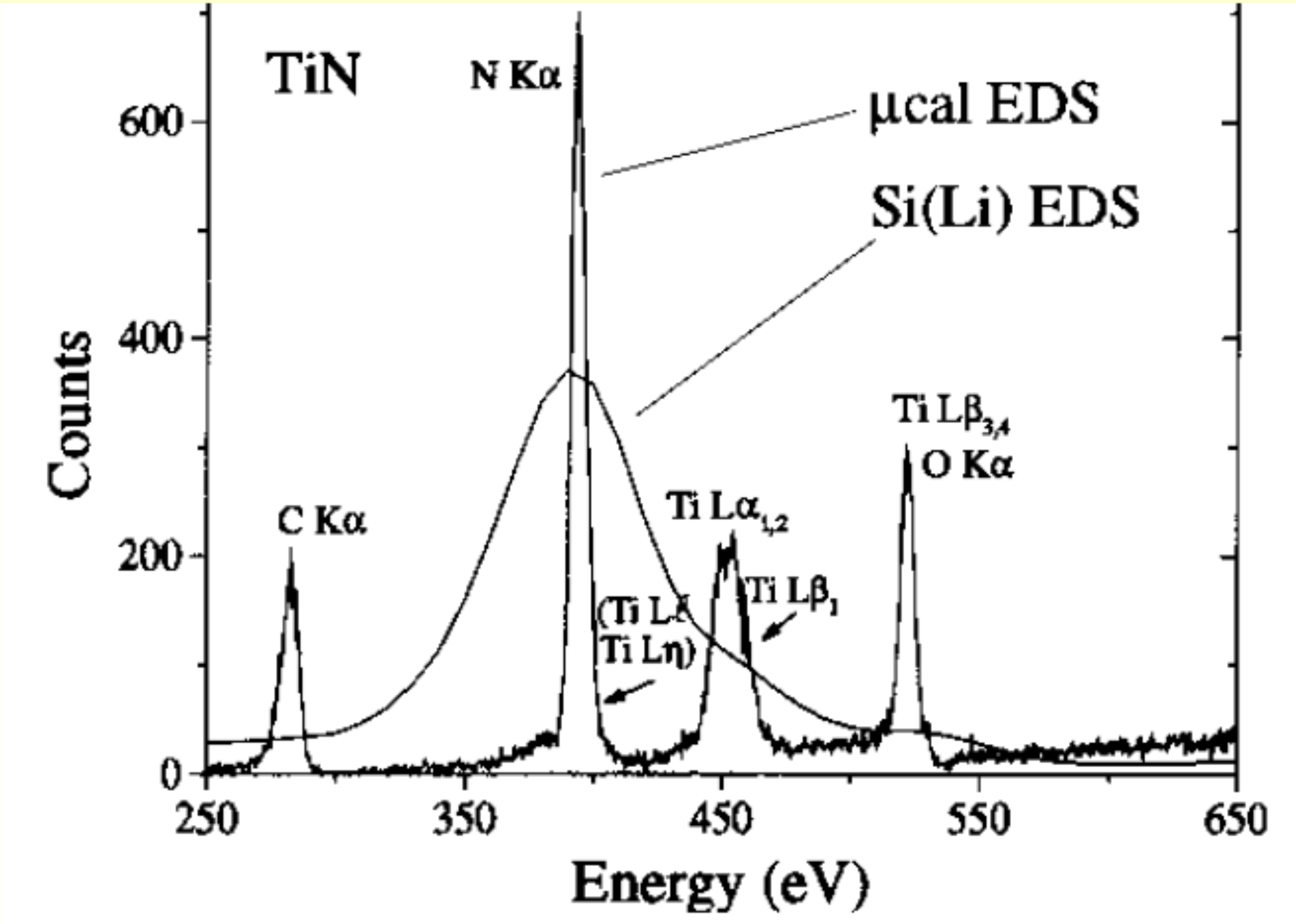
- **Micro and macro-calorimenters:**
  Single beta decay and the neutrino mass
  The second mystery of Ettore Majorana
  The search for direct interactions of WIMPS
- **Expected and unexpected future of cryogenic detectors**
- **Dreams**

S.H.Moseley et LT detectors for astrophysics and ν mass

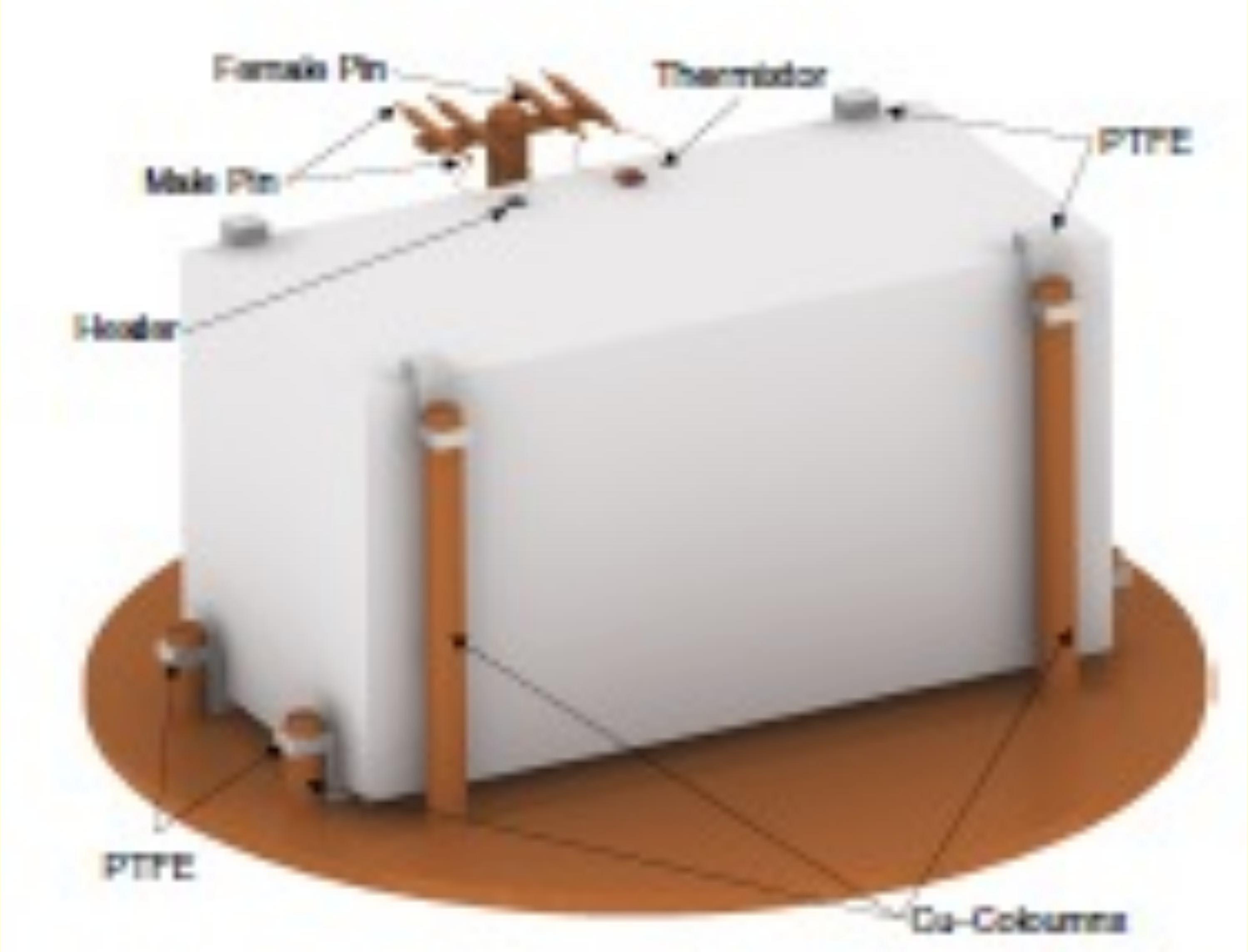
Fiorini and Niinikoski Low temperature detectors for rare events

A. Drukier, L. Stodolsky, => neutrino physics and astronomy


Groups
Techniques
Projects
Underground Laboratories
Semi-conducting thermistors
Super-conducting phase transition thermometers
Super-conducting tunnel junctions
Magnetic calorimeters
1.1 Milano
1.2 Genova
1.3 Napoli
2 Garching
3 Munich
4 Oxford
5 Zaragoza
6 Saclay
7 Lyon
Double beta decay
Dark matter
CMB and X-ray astronomy
X-ray fluorescence analysis
Neutrino physics
Physics of detectors
Mass spectroscopy of macromolecules
Gran Sasso
Frejus
Canfranc
Low background
Neutron scattering for nuclear recoil
Low temp. front end electronics
Scintillators at low temperature


TiN
N Kα
μcal EDS
Si(Li) EDS
Counts
600
400
200
0
Ti Lβ3,4
O Kα
C Kα
Ti Lα1,2
Ti Lβ1
(Ti Lℓ
Ti Lη)
250
350
450
550
650
Energy (eV)

A 2.2 kg TeO_2



Energy resolution of ea crystal of TeO_2 5x5x5 cm^3 (~ 760 g)

:

0.8 keV FWHM @ 46 keV

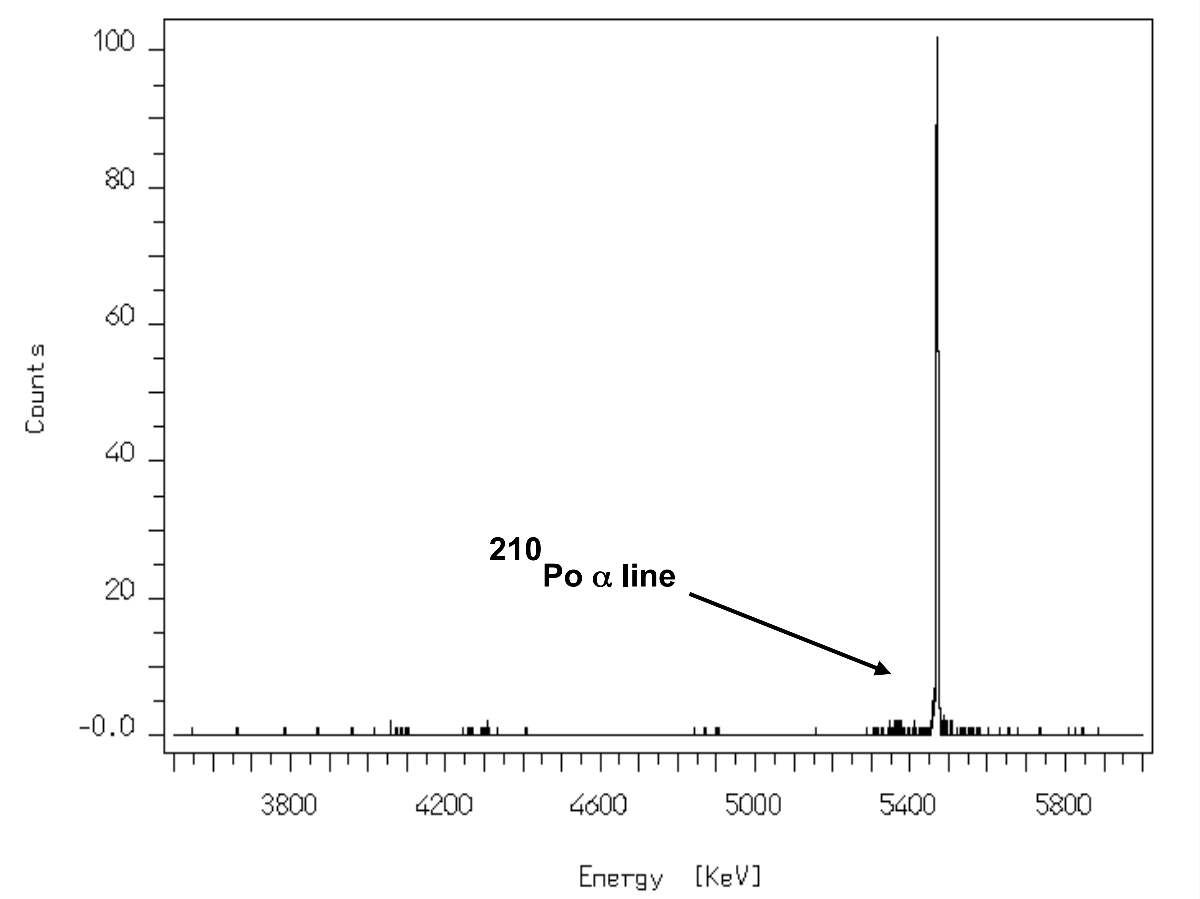
1.4 keV FWHM @ 0.351 MeV

2.1 keV FWHM @ 0.911 MeV

2.6 keV FWHM @ 2.615 MeV

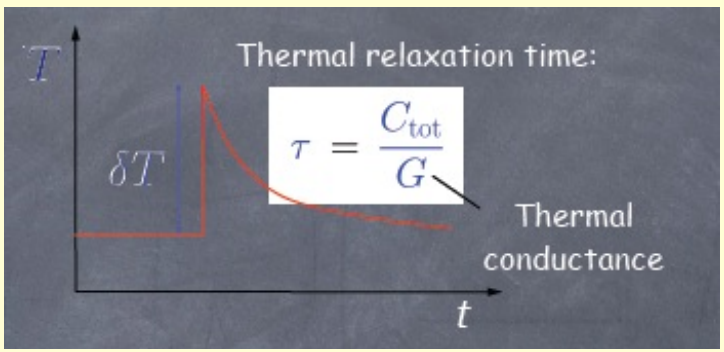
3.2 keV FWHM @ 5.407 MeV

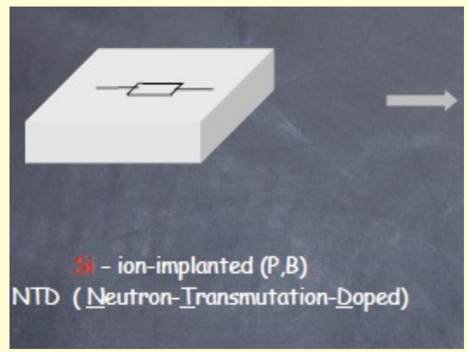
(the best α spectrometer so far

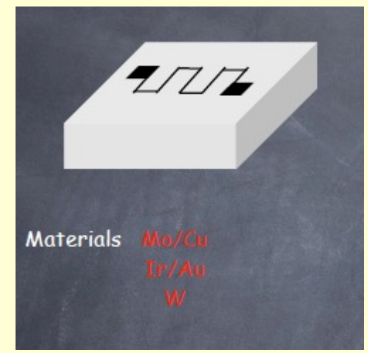


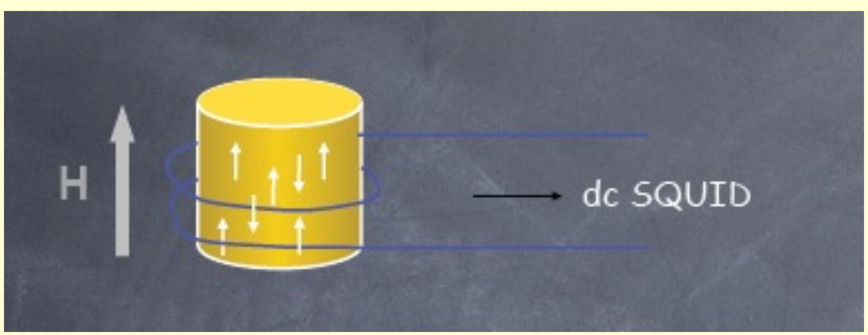
Thermometers

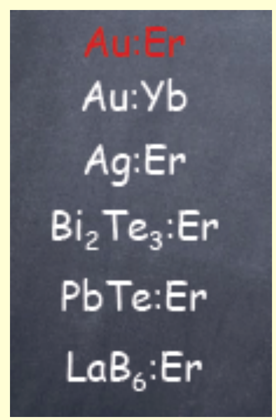
Thermal detectors with NTD Ge sensors
Thermal sensors with doped semiconductors
Superconducting Tunnel Junctions
Superconducting Phase Transition sensors
Superconducting Transition Edge Sensors
Superconducting Kinetic Inductance Devices

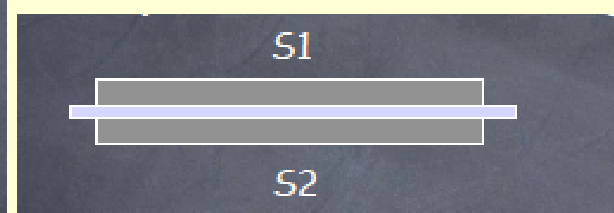






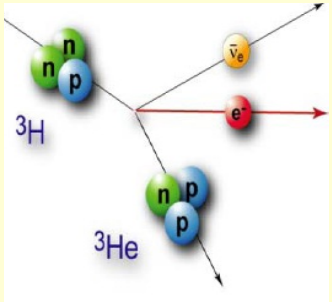




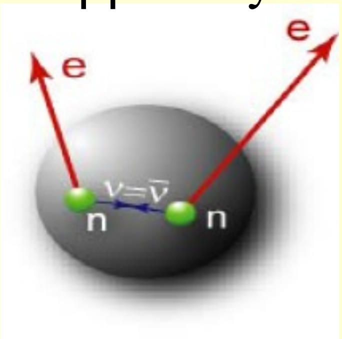


Direct measurement of the neutrino mass

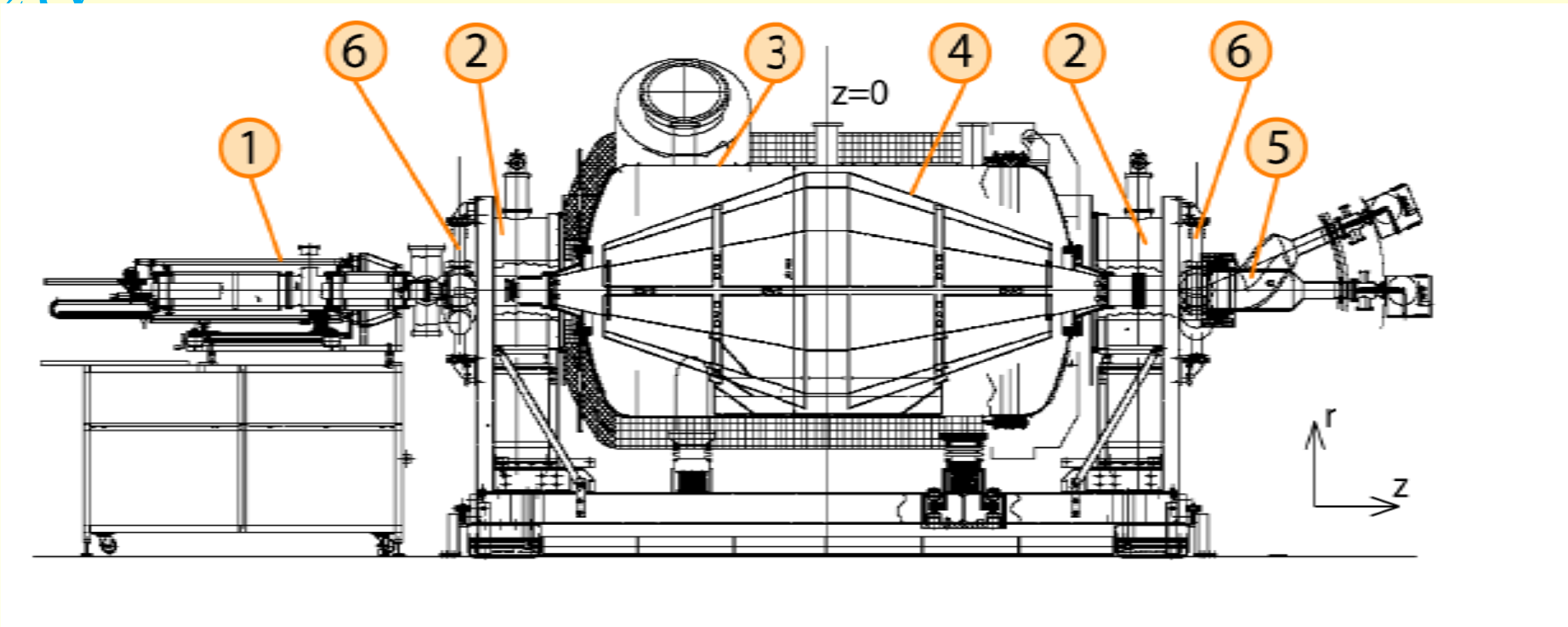
β decay



ββ decay



Beta spectrometers $^3H \Rightarrow {}^3He + e^- + \bar{\nu}_e$ **KATRIN** **2 eV** => 0.2 eV



Thermal detectors for searches on neutrino mass in single β decay

A.Nucciotti

An alternative measurement of the antineutrino mass

$$^{187}Re \Rightarrow {}^{187}Os + e^- + \bar{\nu}_e$$

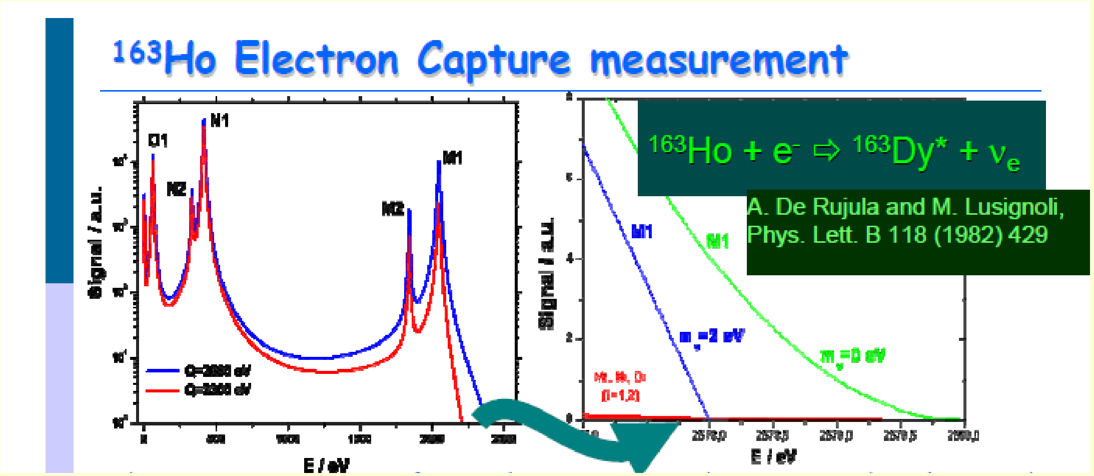
Nucleus with the lowest beta transition energy (**~ 2.5 keV**)

Source **inside the detector** => all energy spent inside the detector is measured

It corresponds to the **entire decay energy** apart the antineutrino one

If the beta decay occurs to an exited state also the **decay of this state is measured**

$$^{163}Os + e^- \Rightarrow {}^{163}Dy + \nu_e$$

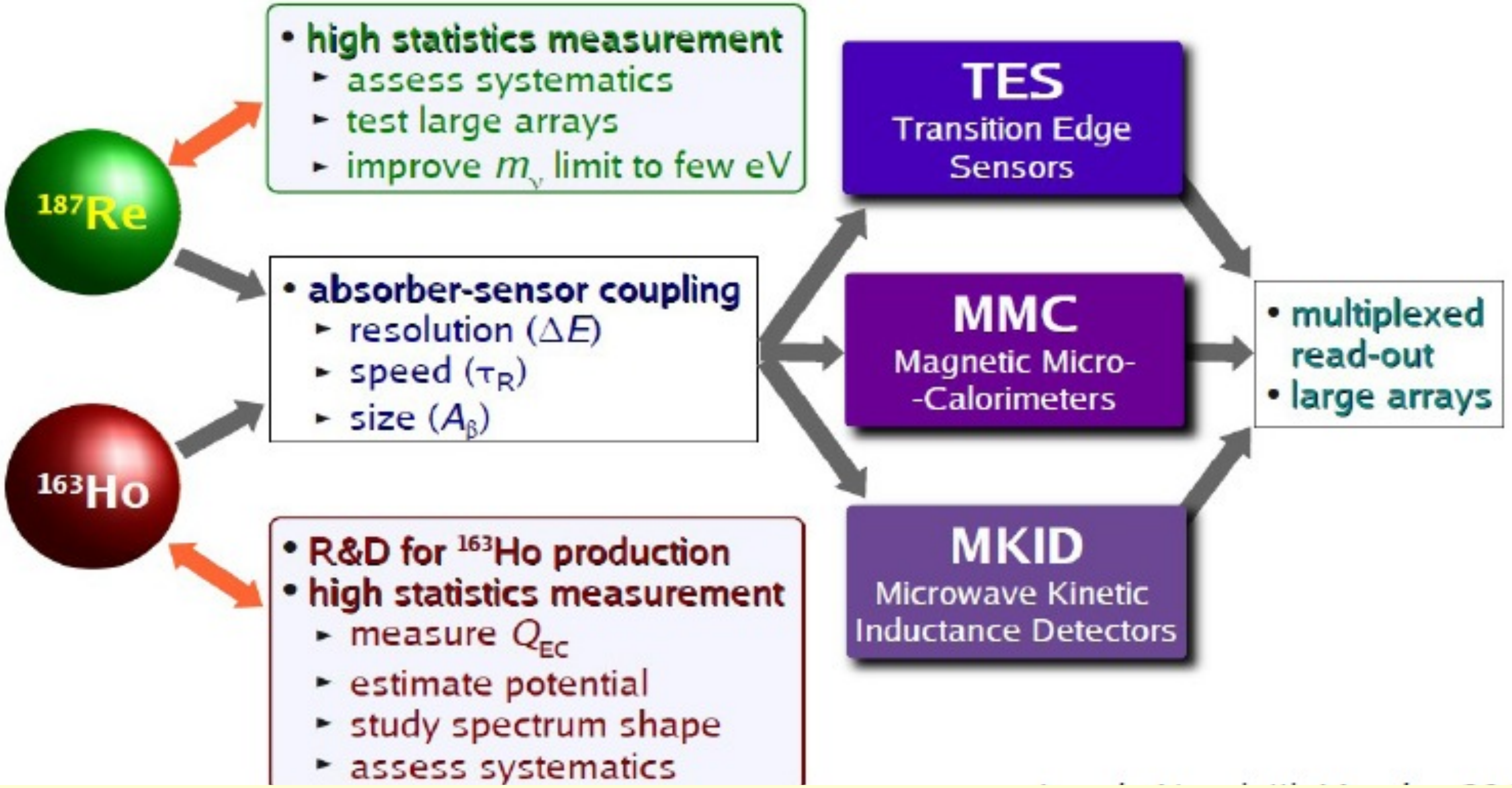


MARE phase 1 / phase 2 objectives

MARE-1 : - collection of activities aiming at isotope / technique selection
- setup of a ^{187}Re experiment with few eV light ν sensitivity

MARE-2 : - full scale experiment with several 10^4 - 10^5 detector pixels aiming at 0.1 eV - 0.2 eV statistical sensitivity

E.Ferri



Milan-NASA- GSFC => 228 **crystals of ~.5mg** of **$AgReO_4$** => .
27 decay/second with implanted Si:P thermistors **(E.Ferri)**.

The Electron Capture Decay of ^{163}Ho to Measure the Electron Neutrino Mass with sub-eV Accuracy (and Beyond)

Massimiliano Galeazzi[a], Flavio Gatti[b], Maurizio Lusignoli[c], Angelo Nucciotti[d], Stefano Ragazzi[d], Maria Ribeiro Gomes[e]

New developments: ECHO

Electron Capture ^{163}Ho Experiment
(Uni Heidelberg, MPIK Heidelberg, Saha Inst. of Nucl. Phys., ISOLDE CERN, Petersburg Nucl. Phys. Inst.)

A non-zero neutrino mass affects the de-excitation spectrum of electron capture decays

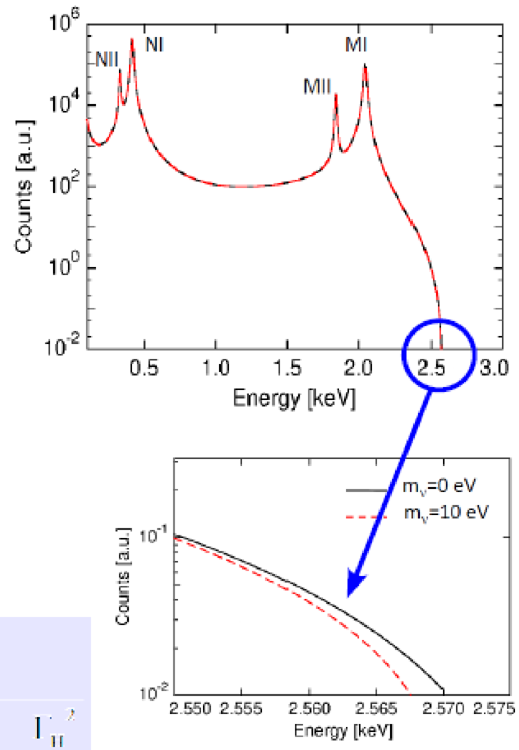
→ calorimetric measurement of the de-excitation energy spectrum

Suitable candidate: **^{163}Ho** → $Q_{EC} \approx 2.5$ keV
$T_{1/2} \approx 4570$ y

$$^{163}_{67}\mathrm{Ho} + e^- \rightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum_H \varphi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}$$



courtesy L. Gastaldo

D.Schmidt, L.Gastaldo

The second mystery of Ettore Majorana

Teoria simmetrica dell'elettrone e del positrone

NOTA DI ETTORE MAJORANA

"Il Nuovo Cimento", vol. 14, 1937, pp. 171-184.

Sunto. — Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di DIRAC ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; né a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di "antiparticelle" corrispondenti ai "vuoti" di energia negativa.

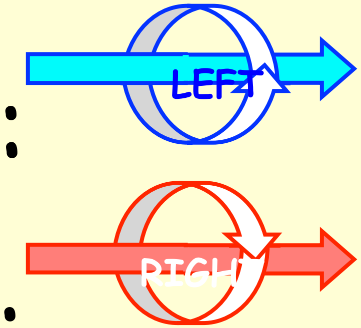
Chi l'ha visto?

Ettore Majorana, ordinario di fisica teorica all'Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marinecci, Viale Regina Margherita 66 - Roma.

Neutrinoless double beta decay and Majorana neutrinos

ν:

$\bar{\nu}$:



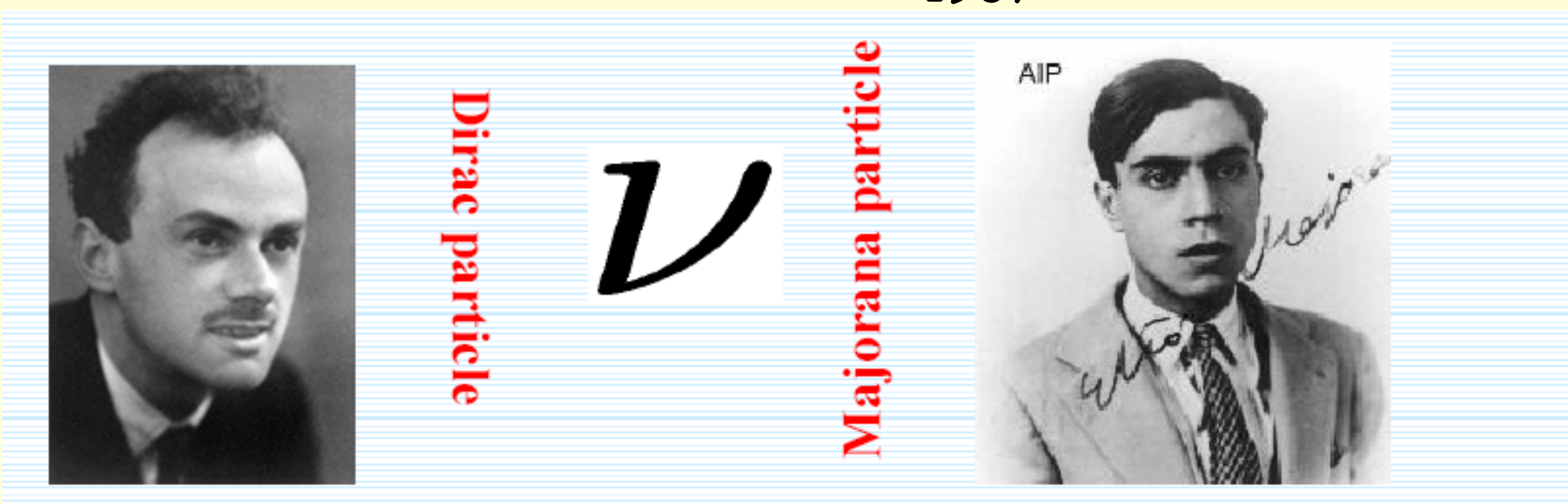
$\nu \neq \bar{\nu}$

$\nu = \bar{\nu}$

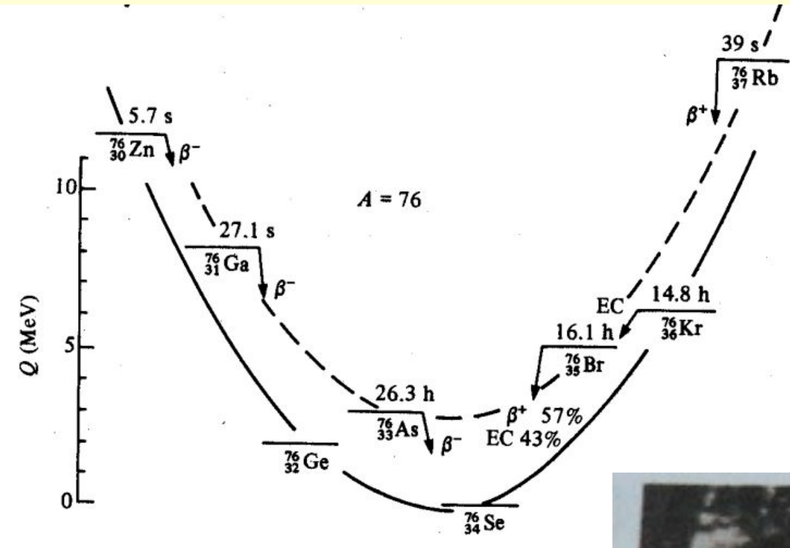
→ →

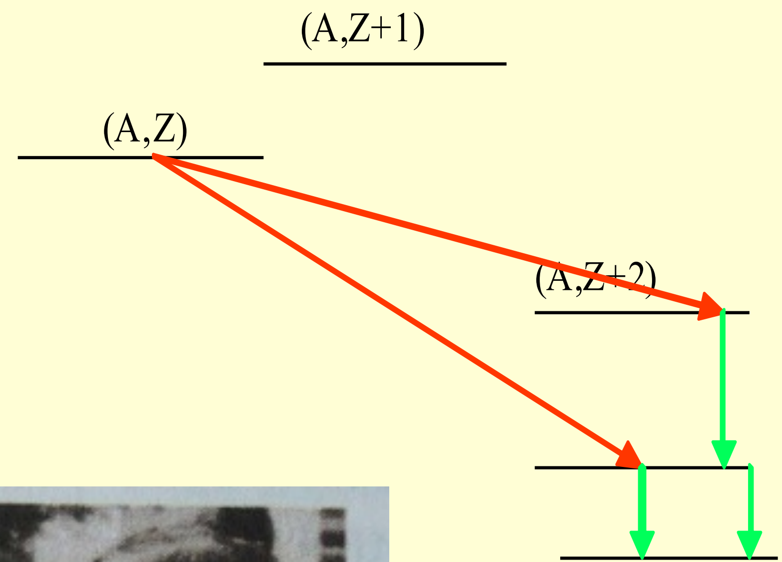
<= =>

Majorana
=>1937

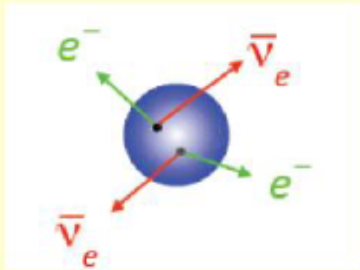


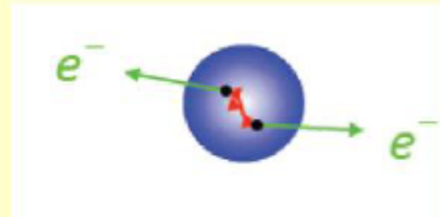
Double beta decay

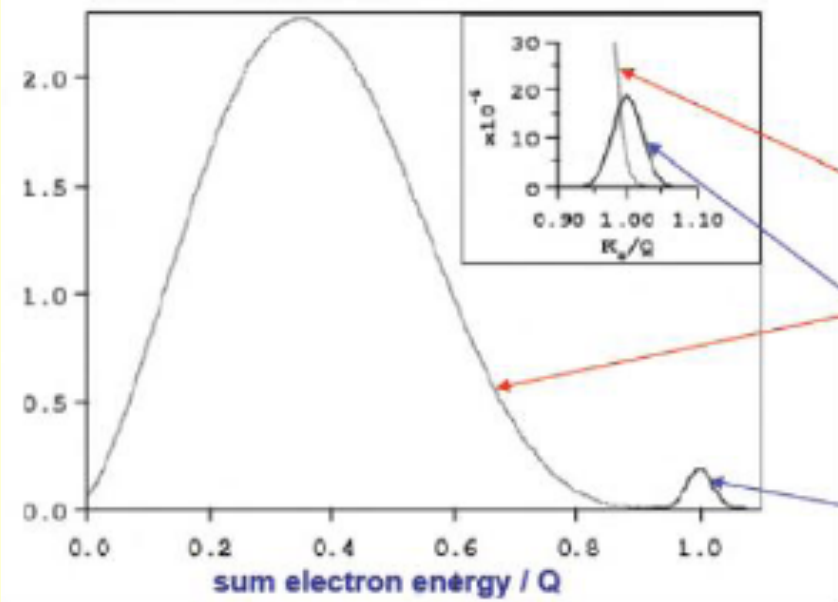




Two neutrino and neutrinoless double beta decay







The shape of the two electron sum energy spectrum enables to distinguish among the most relevant decay modes

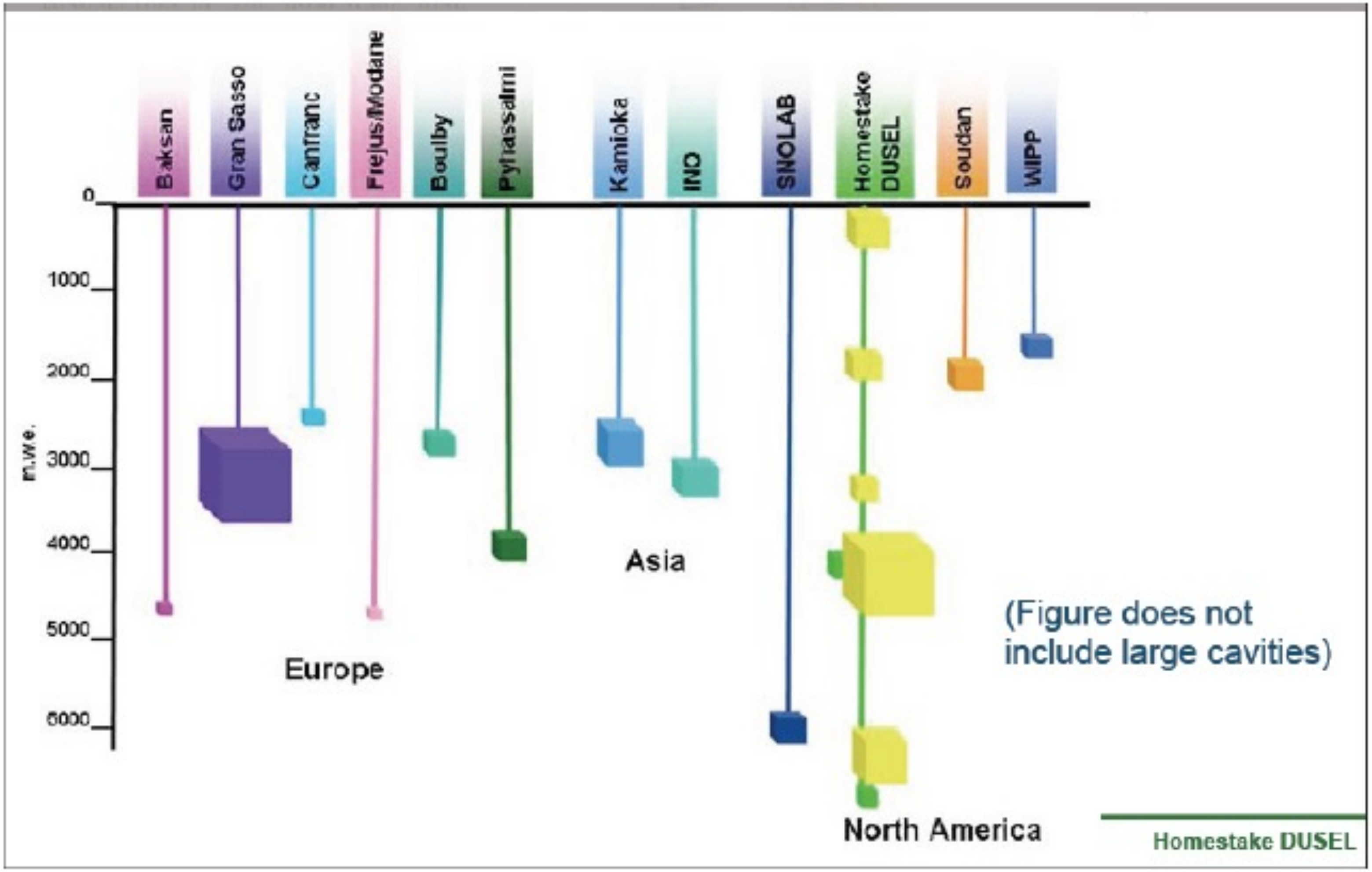
two neutrino DBD
continuum with maximum at ~1/3 Q

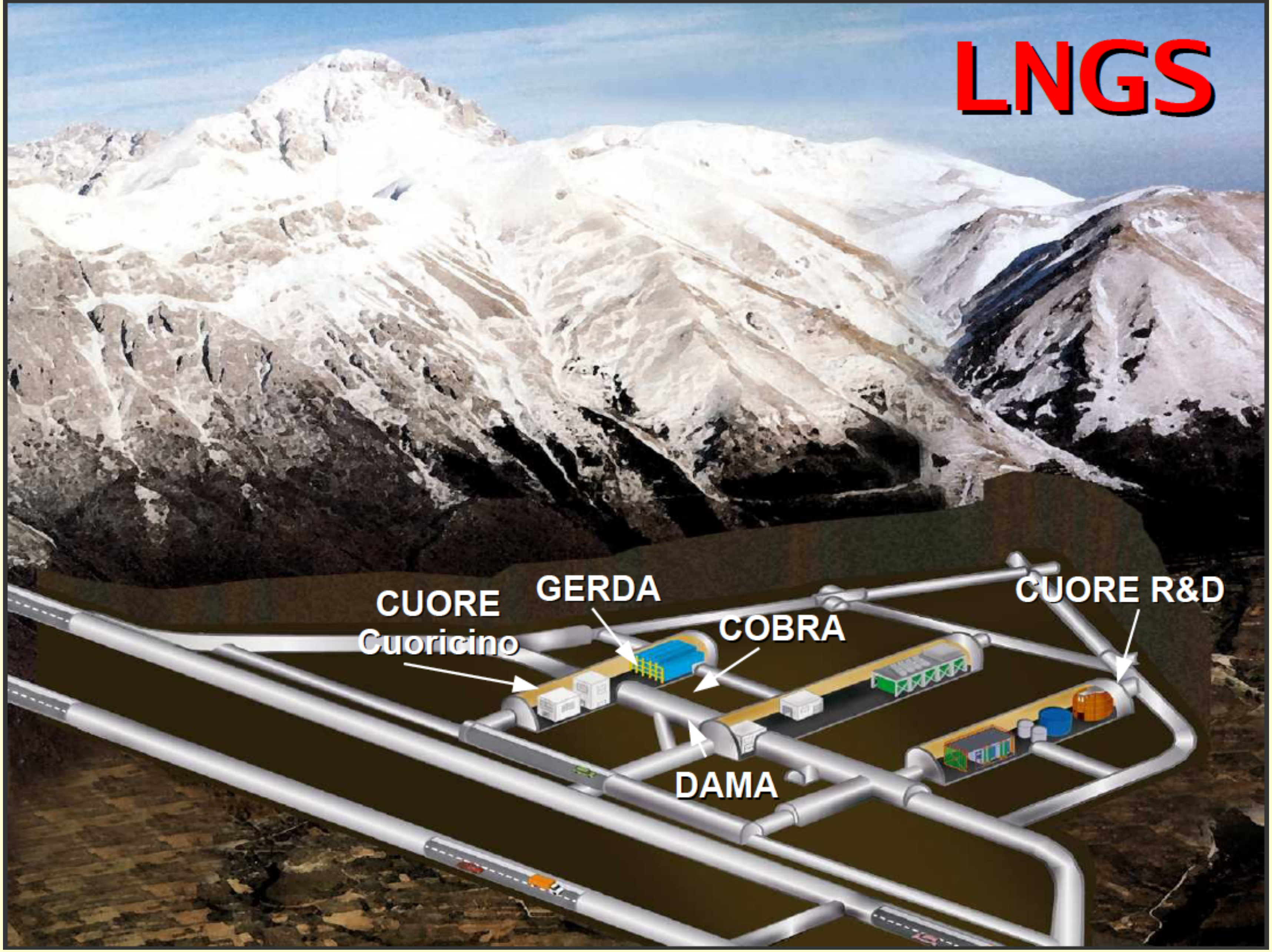
neutrinoless DBD
peak enlarged only by the detector energy resolution

additional signatures:

- single electron energy distribution
- angular distribution
- topology

INTERNATIONAL UNDERGROUND LABORATORIES
(Present and Planned)



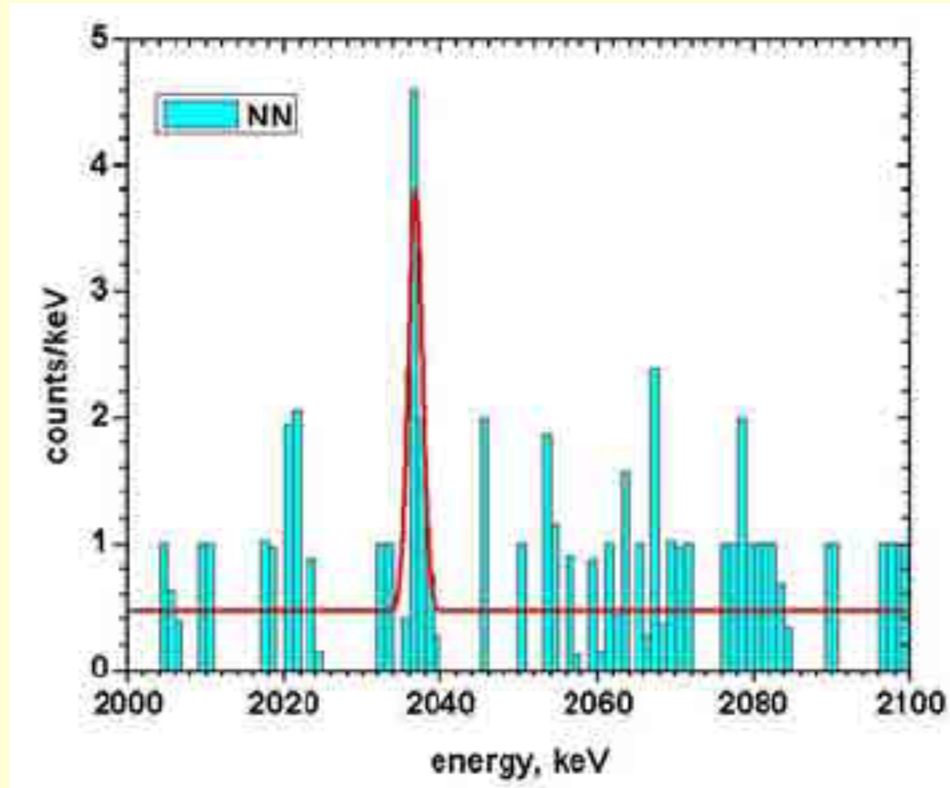

LNGS
CUORE
Cuoricino
GERDA
COBRA
CUORE R&D
DAMA

Possible evidence in $0\nu\beta\beta$ in ^{76}Ge

(H.Klapdor et al)

$$T^{0\nu}_{1/2} = (2.23^{+0.44}_{-0.31}) \times 10^{25}\ \mathrm{y}.$$

$<m_\nu> \sim$ 0.34eV



Present results on neutrinoless DBD

Table I: present results on neutrinoless DBD

Nucleus	Experiment	%	$Q_{\beta\beta}$	Enrich	Technique	$T_{0\nu}$ (y)	$<m_\nu>$
48Ca	Elegant IV	0.19	4271		scintillator	>1.4x1022	20-28
76Ge	IGEX	7.8	2039	87	Ionization	>1.6x1025	.23 – .64
76Ge	Klapdor et al	7.8	2039	87	ionization	1.2x1025	.29-.81
82Se	NEMO 3	9.2	2995	97	tracking	>1.x1023	1.7-4.5
100Mo	NEMO 3	9.6	3034	95-99	tracking	>1x1024	.46-1.1
116Cd	Solotvina	7.5	3034	83	scintillator	>1.7x1023	1.2 – 2.7
128Te	Bernatovitz	34	2529		geochem	>7.7 × 1024	.82-1.9
130Te	Cuoricino	33.8	2529		bolometric	>2.8 x1024	.3-.7
136Xe	DAMA	8.9	2476	69	scintillator	>1.2x1024	.64 -1.6
150Nd	Irvine	5.6	3367	91	tracking	>1.2x1021	14 - ?

EXO $T^{0\nu}_{1/2}$ (136Xe) $> 1.6 \times 10^{25}$ yr correspond $<m_\nu>$ 140–380me

KAMLAND-ZEN $> 3.4 \times 10^{25}$ yr (Fukushima) 120-250

GERDA I ?

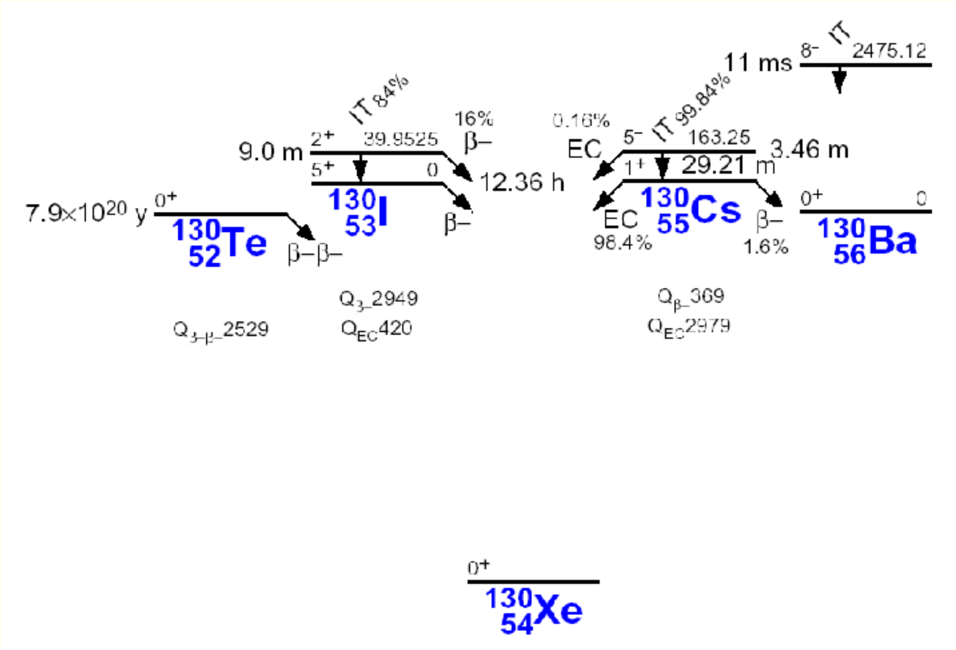
Future experiments on DBD (from Elliott)

Experiment	Isotope	Mass	Technique	Present Status	Location
AMoRE[89,90]	^{100}Mo	50 kg	$CaMoO_4$ scint. bolometer crystals	Development	Yangyang
CANDLES[91]	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL[92]	^{48}Ca	1 ton	CaF_2 scint. crystals	Development	Solotvina
COBRA[93]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0[69]	^{130}Te	11 kg	TeO_2 bolometers	Construction - 2012	Gran Sasso
CUORE[69]	^{130}Te	203 kg	TeO_2 bolometers	Construction - 2013	Gran Sasso
DCBA[94]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Development	Kamioka
EXO-200[57]	^{136}Xe	160 kg	Liq. ^{enr}Xe TPC/scint.	Operating - 2011	WIPP
EXO[70]	^{136}Xe	1-10 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SURF
GERDA[71]	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Operating - 2011	Gran Sasso
GSO[95]	^{160}Gd	2 ton	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Development	
KamLAND-Zen[96]	^{136}Xe	400 kg	^{enr}Xe disolved in liq. scint.	Operating - 2011	Kamioka
LUCIFER[97,98]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Development	Gran Sasso
MAJORANA[77,78,79]	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Construction - 2013	SURF
MOON [99]	^{100}Mo	1 t	^{enr}Mofoils/scint.	Development	
SuperNEMO-Dem[87]	^{82}Se	7 kg	^{enr}Se foils/tracking	Construction - 2014	Fréjus
SuperNEMO[87]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal - 2019	Fréjus
NEXT [82,83]	^{136}Xe	100 kg	gas TPC	Development - 2014	Canfranc
SNO+[84,85]	^{150}Nd	55 kg	Nd loaded liq. scint.	Construction - 2013	SNOLab

NEW SNO+ dissolves **Te** in the scintillator

Searches of ββ decay with thermal detectors

$^{130}Te \Rightarrow {}^{130}Xe + 2e$ a.i,. ~ 34% ΔE = 2527 keV



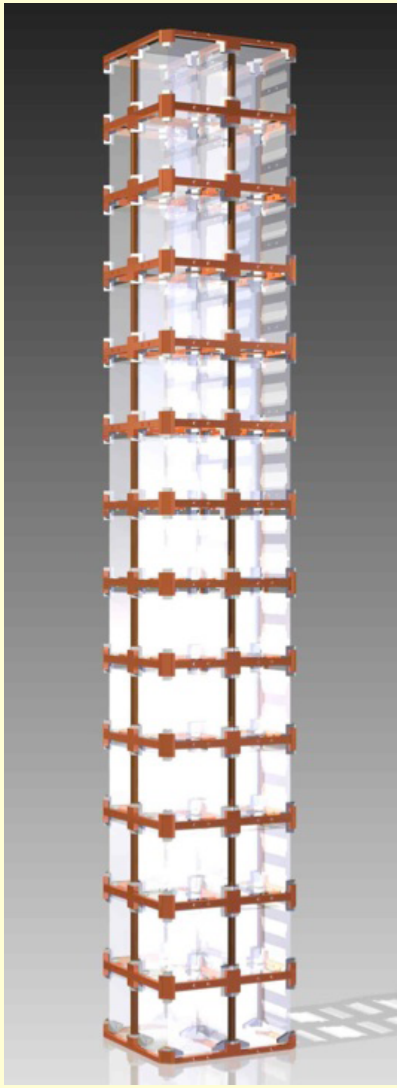
Mibeta (Milan) an array of 20 bolometers of TeO_2 of 320 => **6.8 kg**

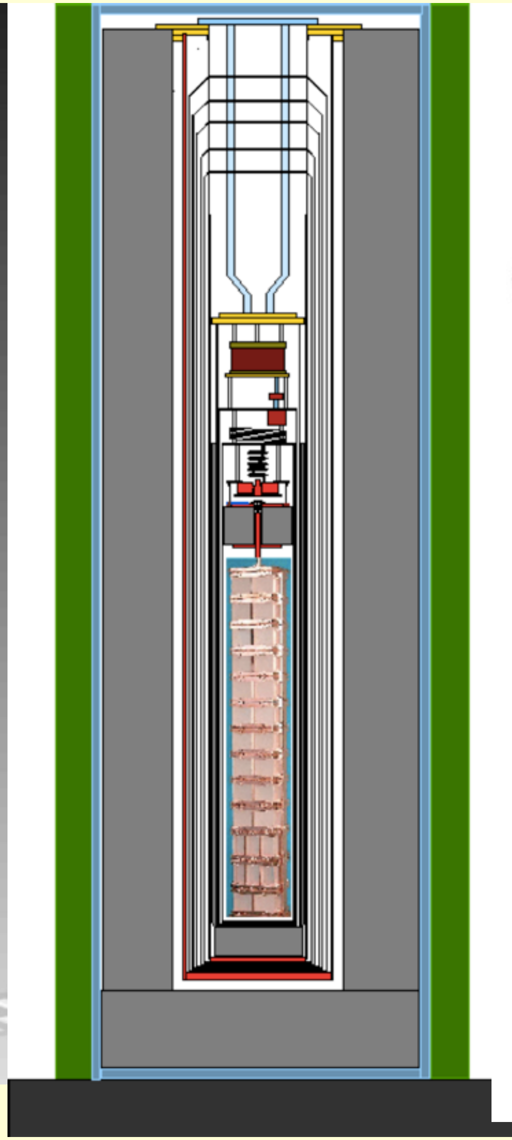
CUORICINO (CUORICINO Coll.) => **40.7 kg**

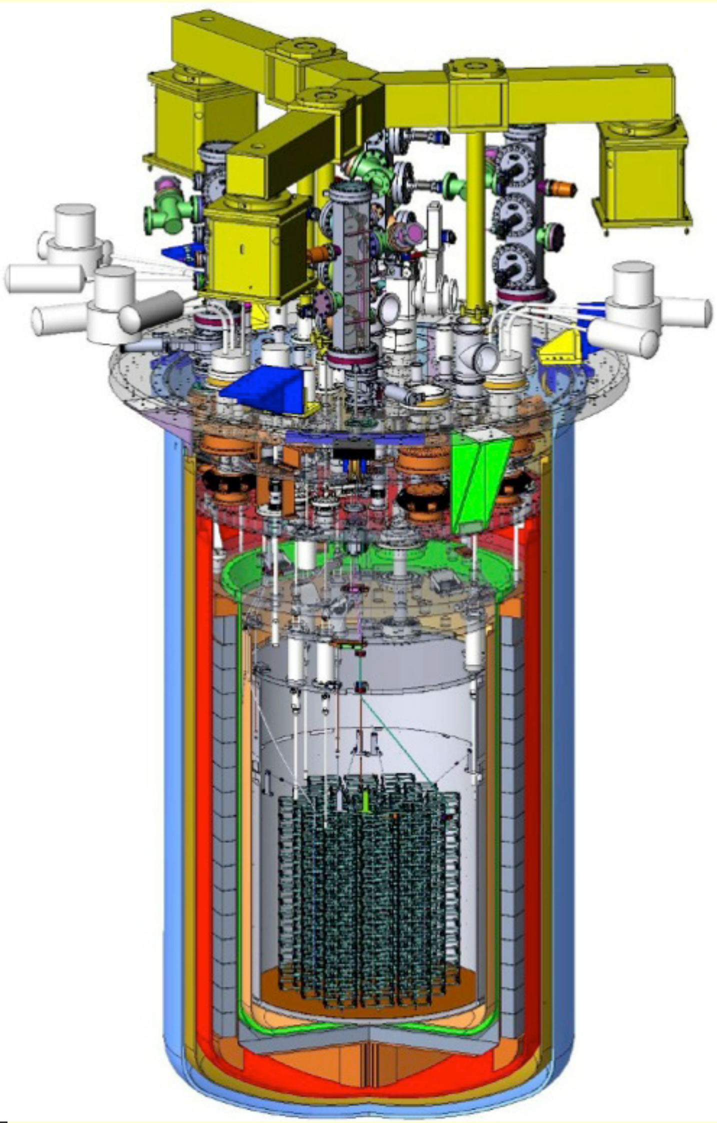
CUORE (CUORE coll) 988 crystals of 750 g => **741 kg**

CUORICINO CUORE0 CUORE

L.Canonica,L.Taffarello







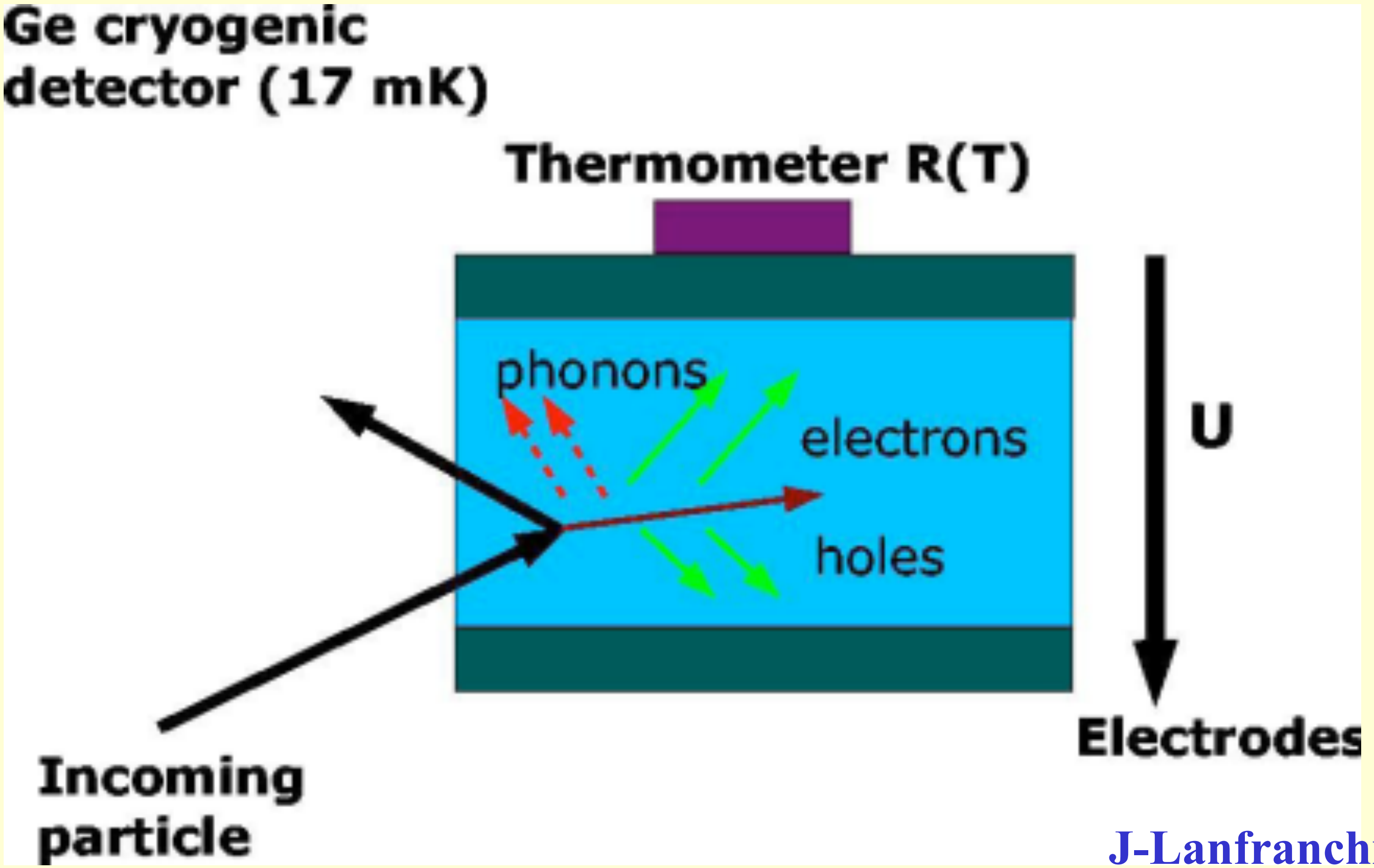
The future

Other possible candidates for ββ decay

Compound	Isotopic abundance	Transiton energy
$^{48}CaF_2$	.0187 %	4272keV
^{76}Ge	7.44 "	2038.7 "
$^{100}MoPbO_4$	9.63 "	3034 "
$^{116}CdWO_4$	7.49 "	2804 "
$^{130}TeO_2$	34 "	2528 "
$^{150}NdF_3$ $^{150}NdGaO_3$	5.64 "	3368“

Searches for **direct interactions** of Weakly Interacting Massive particles (**WIMPS**)

Galactic WIMPs interact on a nucleus depositing **tens to hundreds of keV** of kinetic e nergy to a single nucleus.

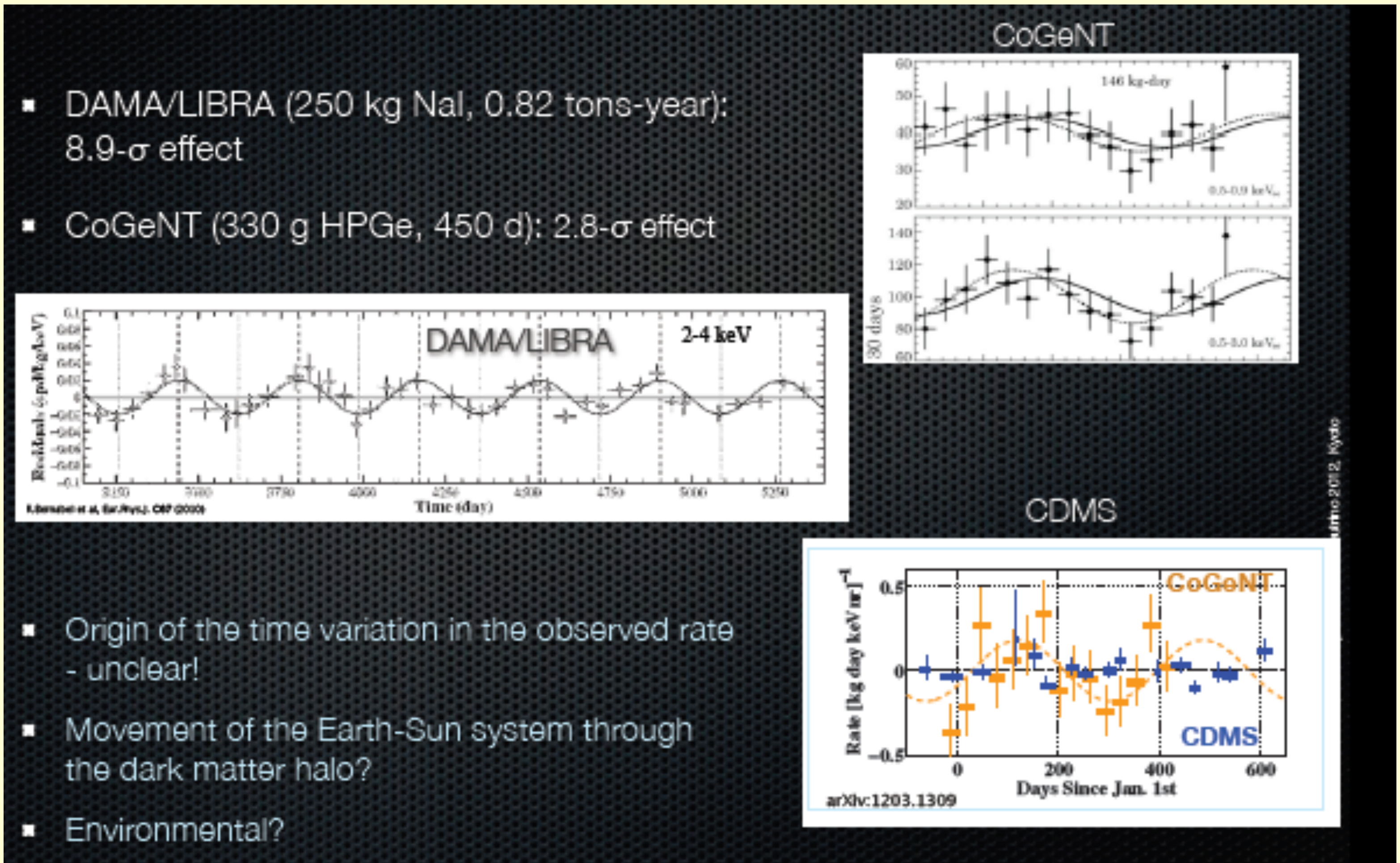


J-Lanfranchi

Evidence of a seasonal variation by DAMA/LIBRA

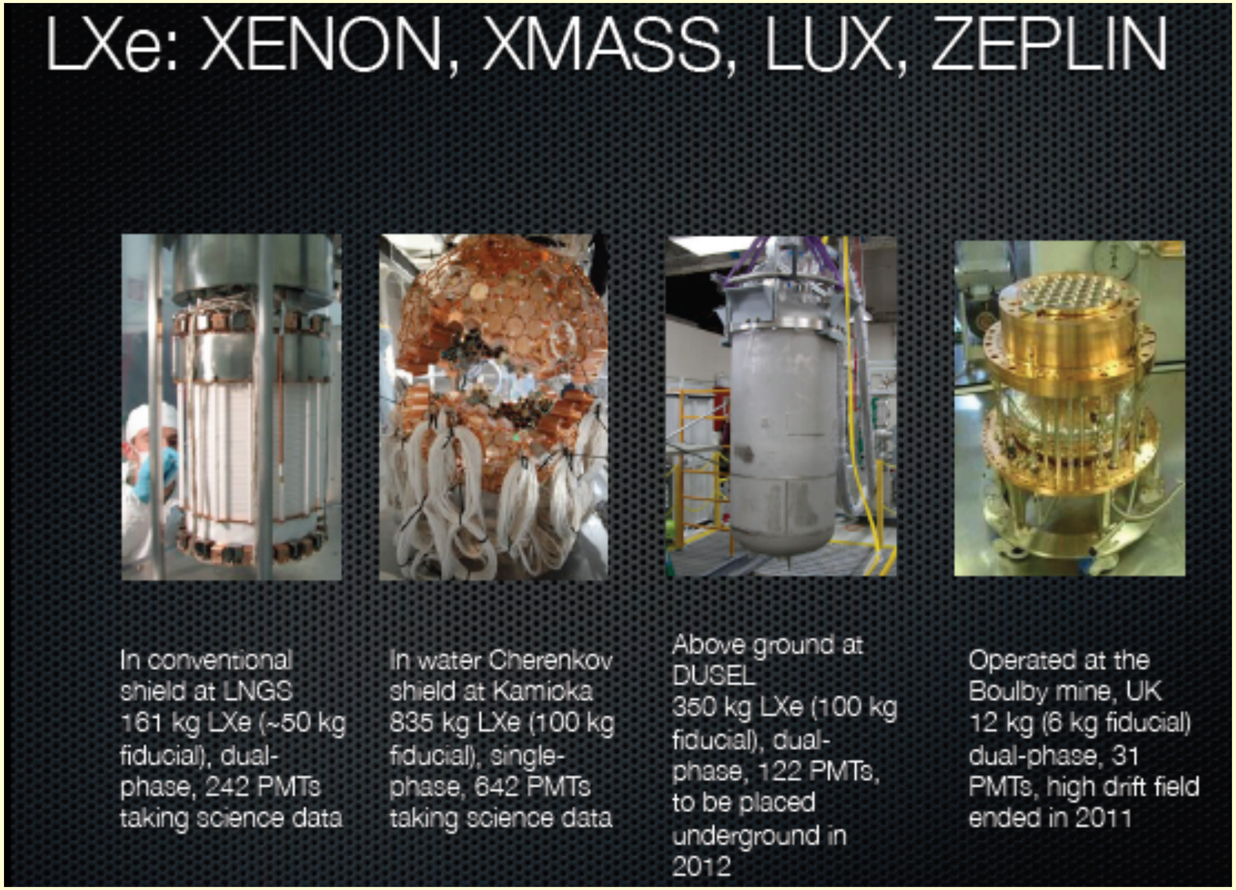
Positive => CRESST,Cogent, CDMS II silicon?

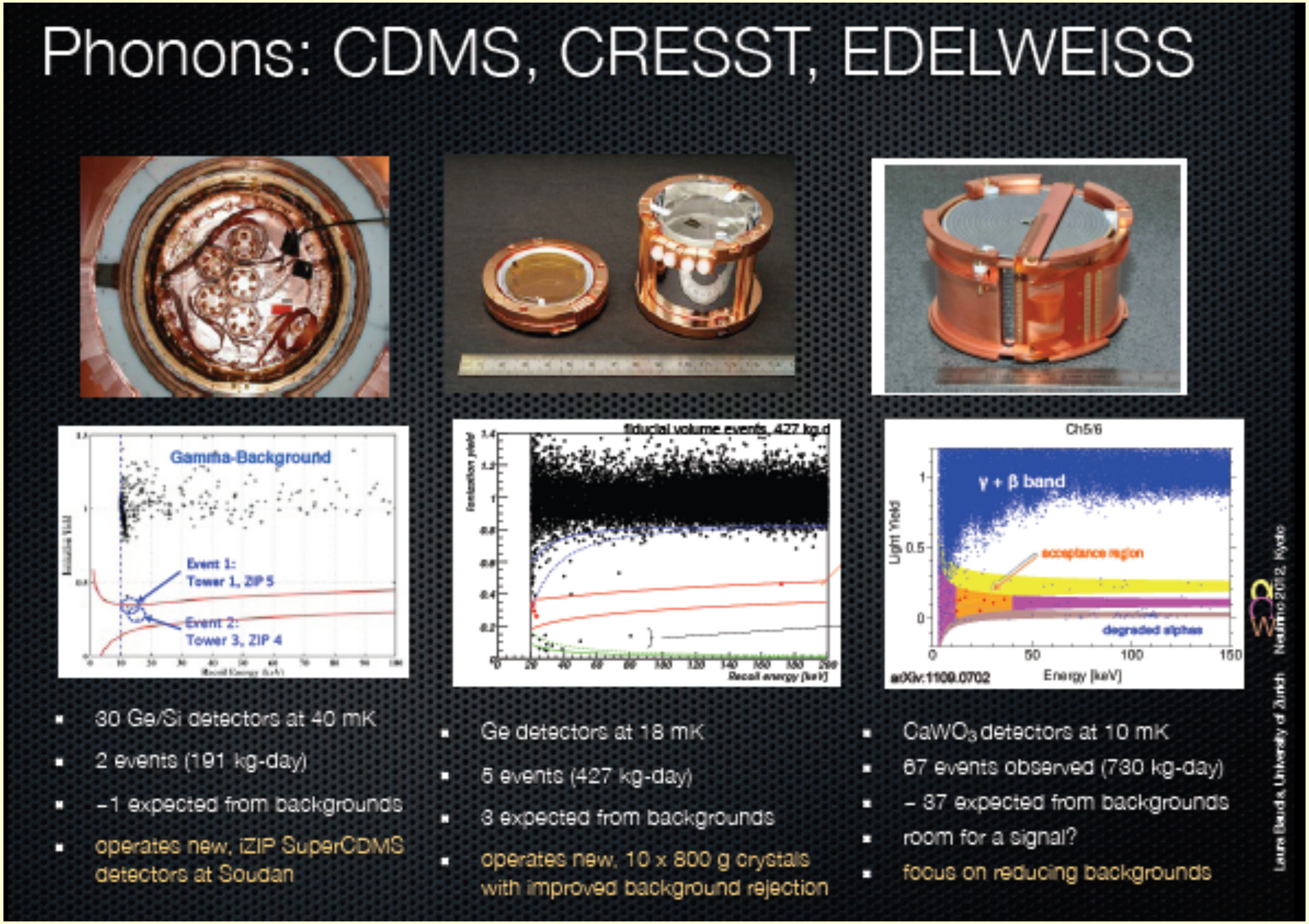
Negative => CDMS II, Xenon100,Picasso, COUPP



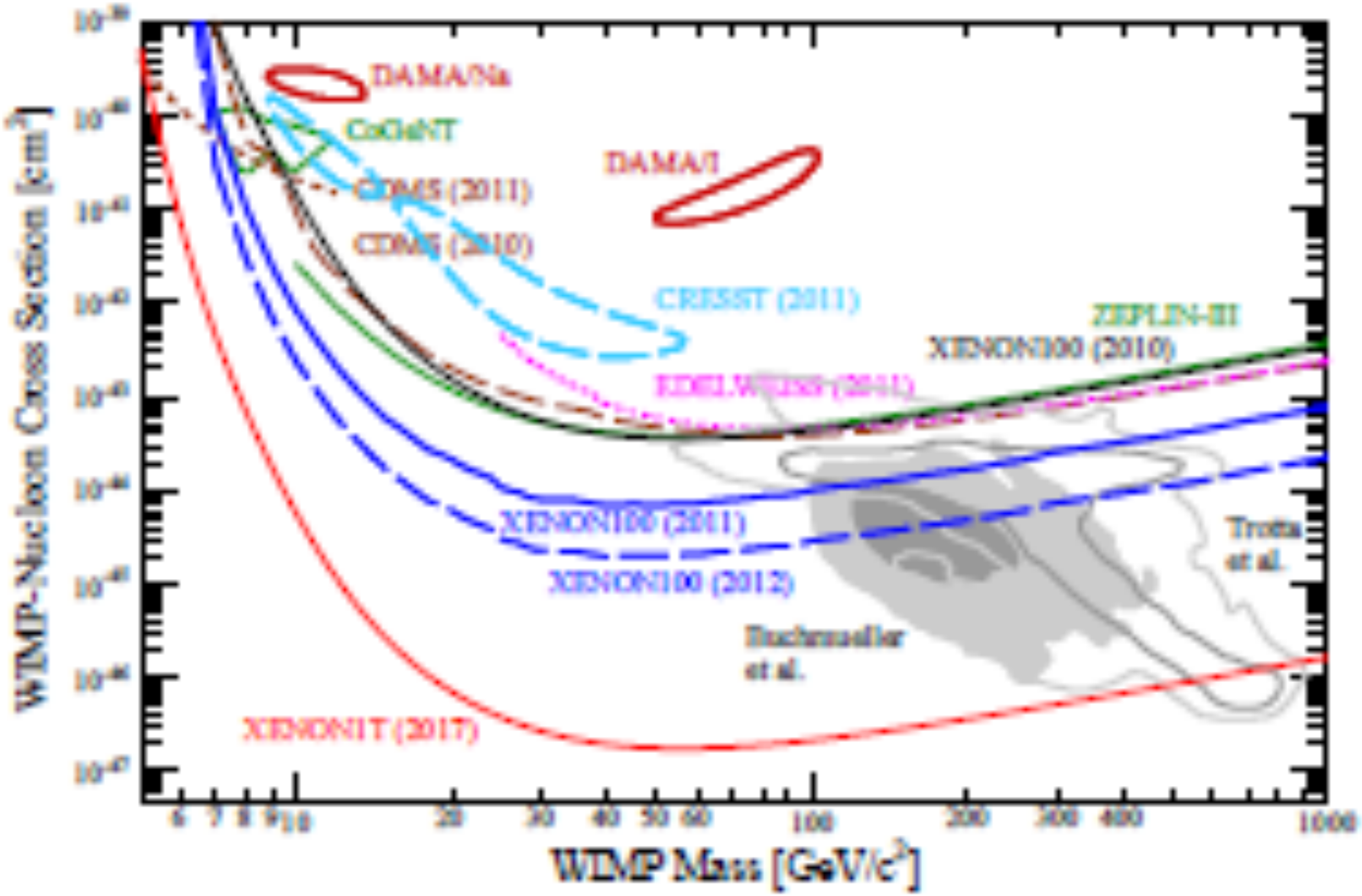
Detectors

=> nuclear emulsions
=> bubbles
=> the human body
=> ionization and scintillation (two phases)
=> LTD's with and without ionization and/or scintillations



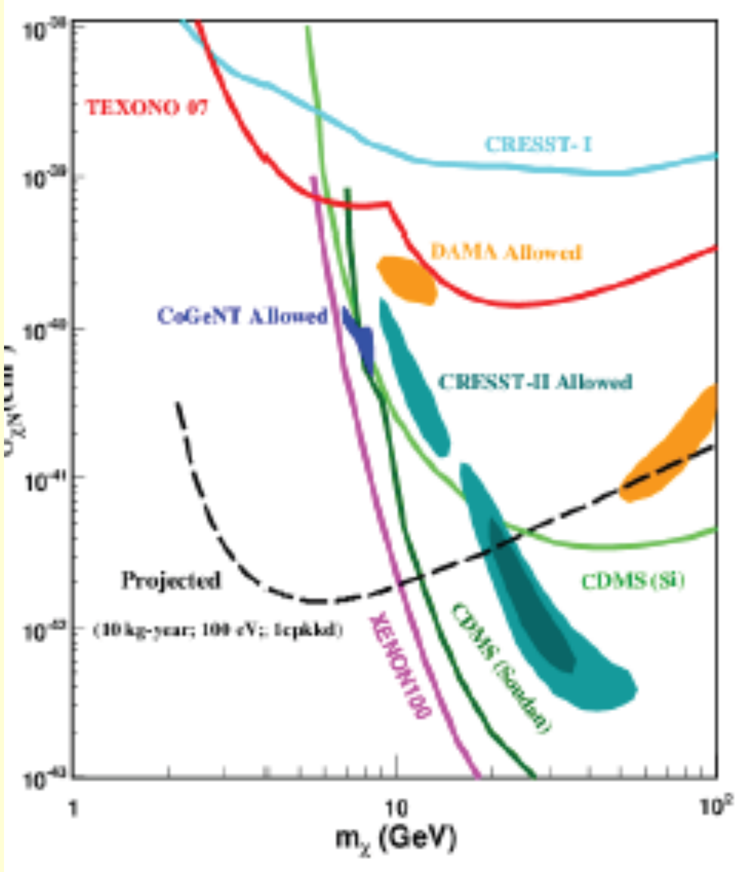


ROSEBUD SrF_2

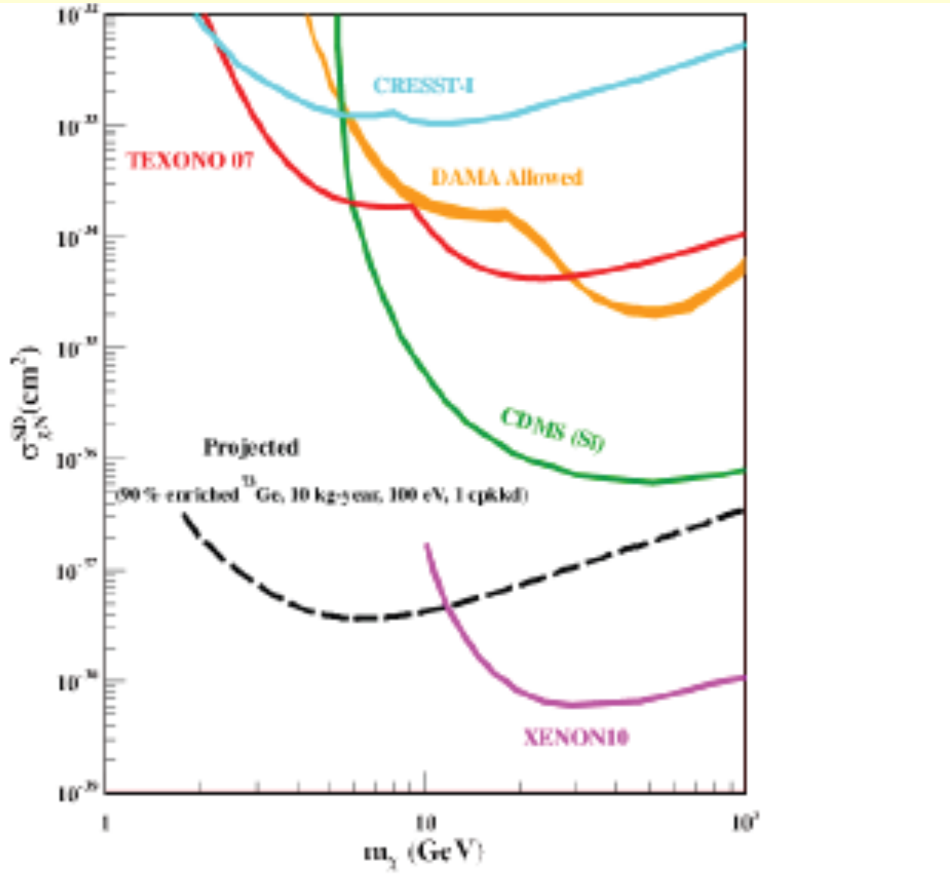


DAMA/Na
CoGeNT
DAMA/I
CDMS (2011)
CDMS (2010)
CRESST (2011)
ZEPLIN-III
XENON100 (2010)
EDELWEISS (2011)
XENON100 (2011)
XENON100 (2012)
Trotta et al.
Buchmueller et al.
XENON1T (2017)
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]
6 7 8 9 10 20 30 40 50 60 100 200 300 400 1000

Spin independent

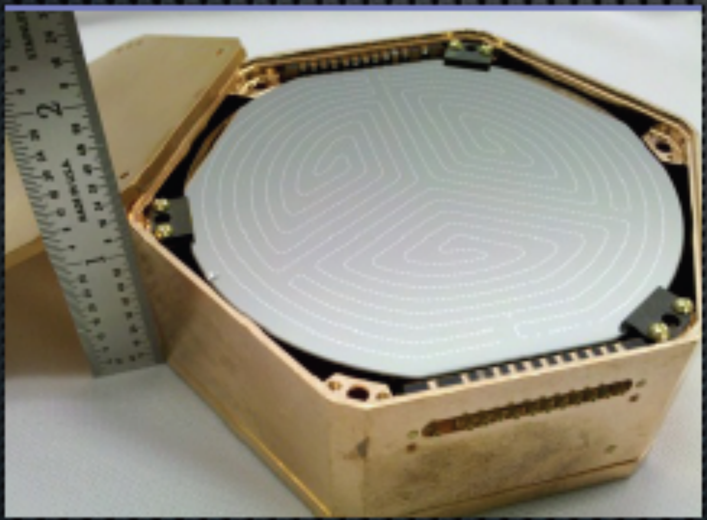


Spin dependent

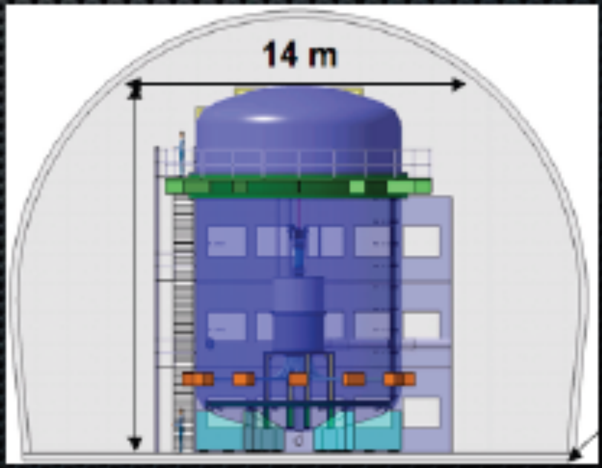


Future Cryogenic Dark Matter Projects

- US/Canada: SuperCDMS (15 kg to 1.5 tons Ge experiment)
- Larger Ge detectors (650g) with improved readout
- To be located at SNOLab



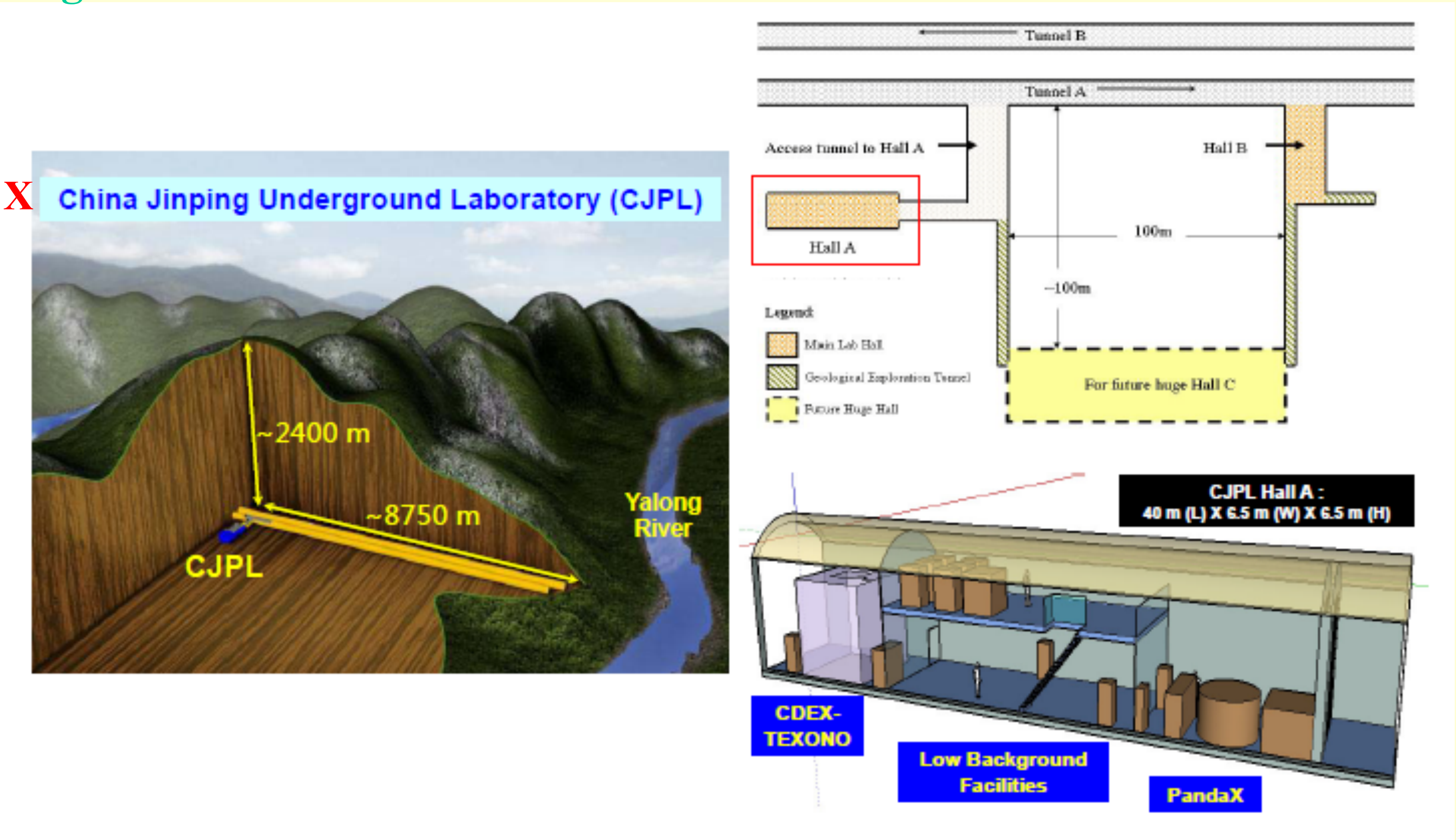
- Europe: EURECA (100 kg to 1.0 ton cryogenic experiment)
- Multi-target approach; EDELWEISS + CRESST
- To be located at the ULISSE Lab (Modane extension) in France



First results on low-mass WIMP from the CDEX-TEXONO experiment at the China Jin ping underground Laboratory

WIMP dark matter from 14.6 kg-day of data taken with a 994 g p-type point-contact germanium detector

X



Reduction of the background in ββ and DM experiments

DM => enhance **nuclear recoil**
reduce **electromagnetic** (e,g etc) contribution
ββ => enhance detection of the **electron pair**
reduce degraded **α particle**

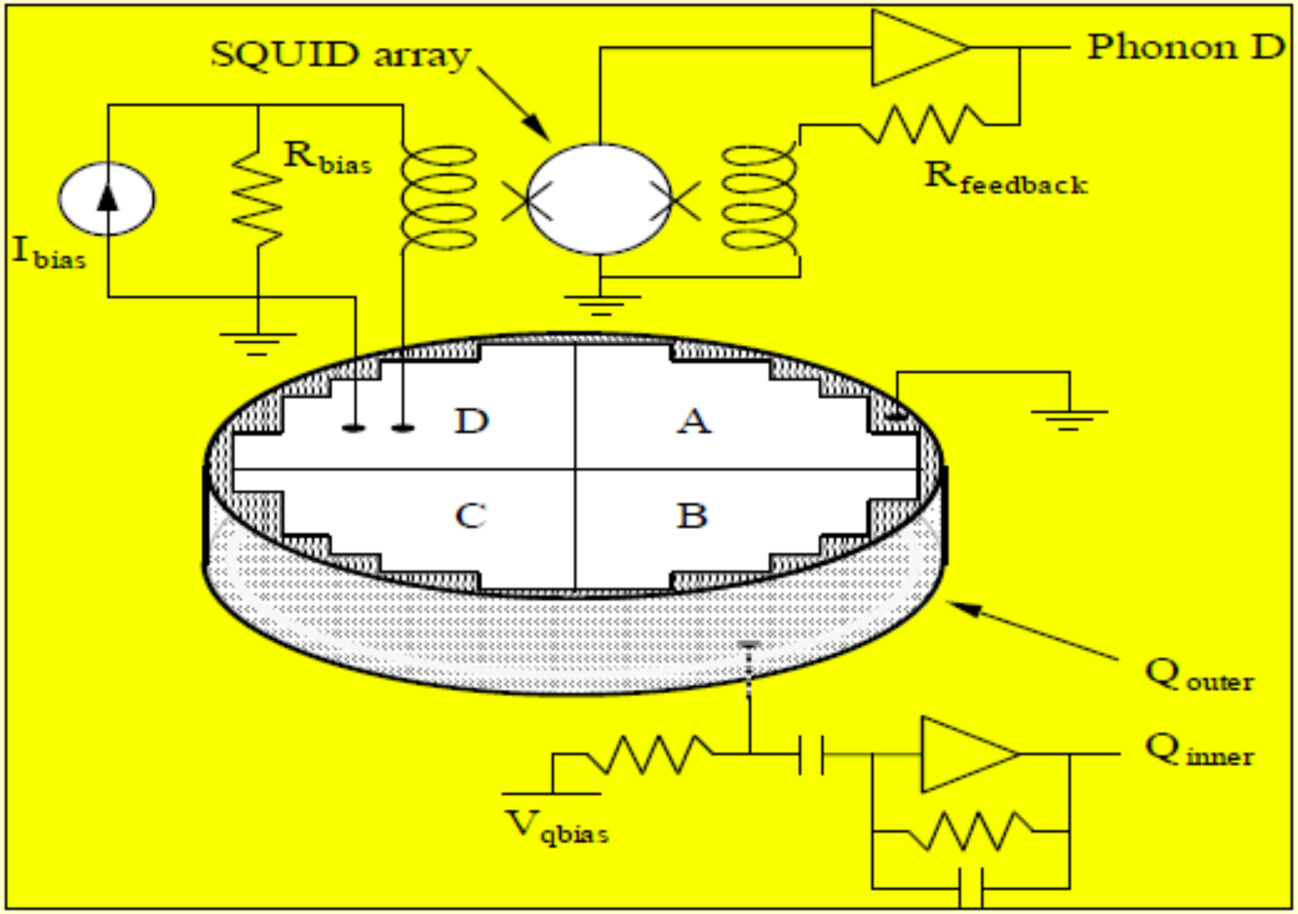
Hybrid techniquest (acting in a different way)
Thermal detector are slow , but
ionization, scintillationa and light are fast
Pulse shape discrimination (even for thermal detectors if associated with a large energy loss by scintillation
Cherenkov light (for TeO_2 detectors for instance
Surface activity reduction for ββ experiments by

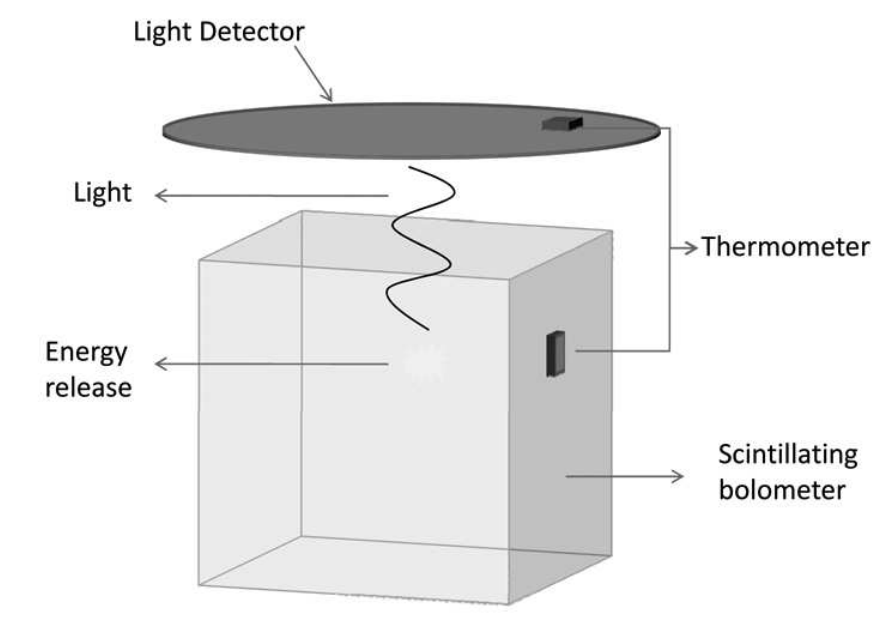
=>Surface-sensitive composite bolometers (eg. thin TeO_2, Ge slabs or NbSi)
⇒Reflecting film and light detector
⇒Cerenkov light at 2.5 Mev 125 photons => 350 eV (in TeO_2)
⇒ Heat + Scintillation or ionization

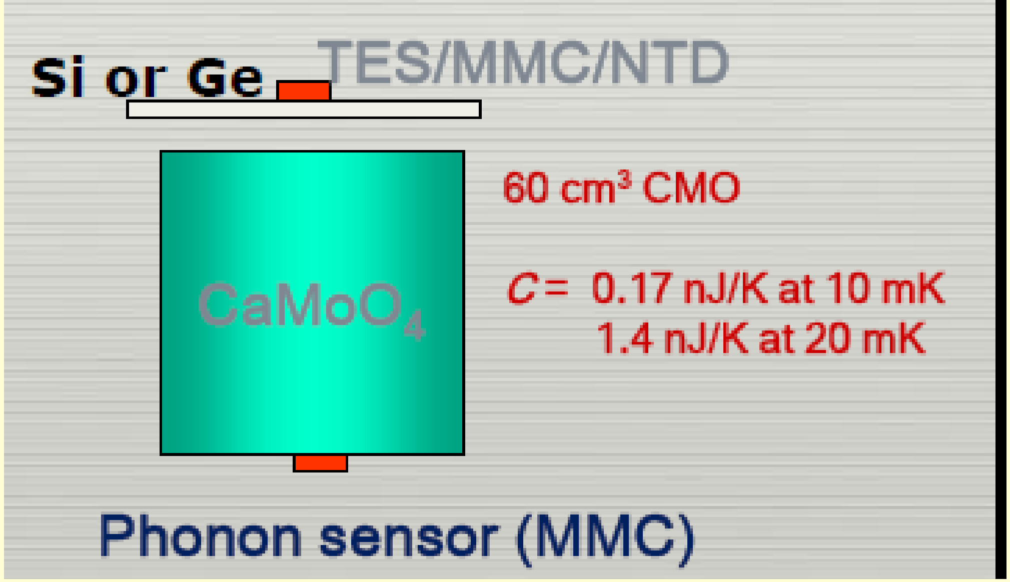
L. Cardani,Geon-Bo Kim

Hybrid techniques

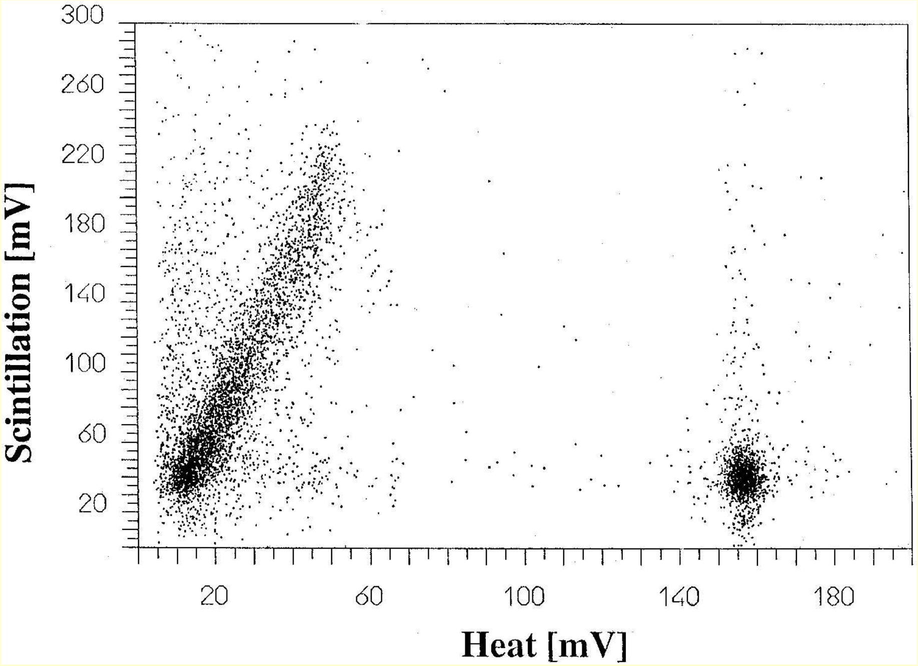
heat + ionization or heat + scintillation





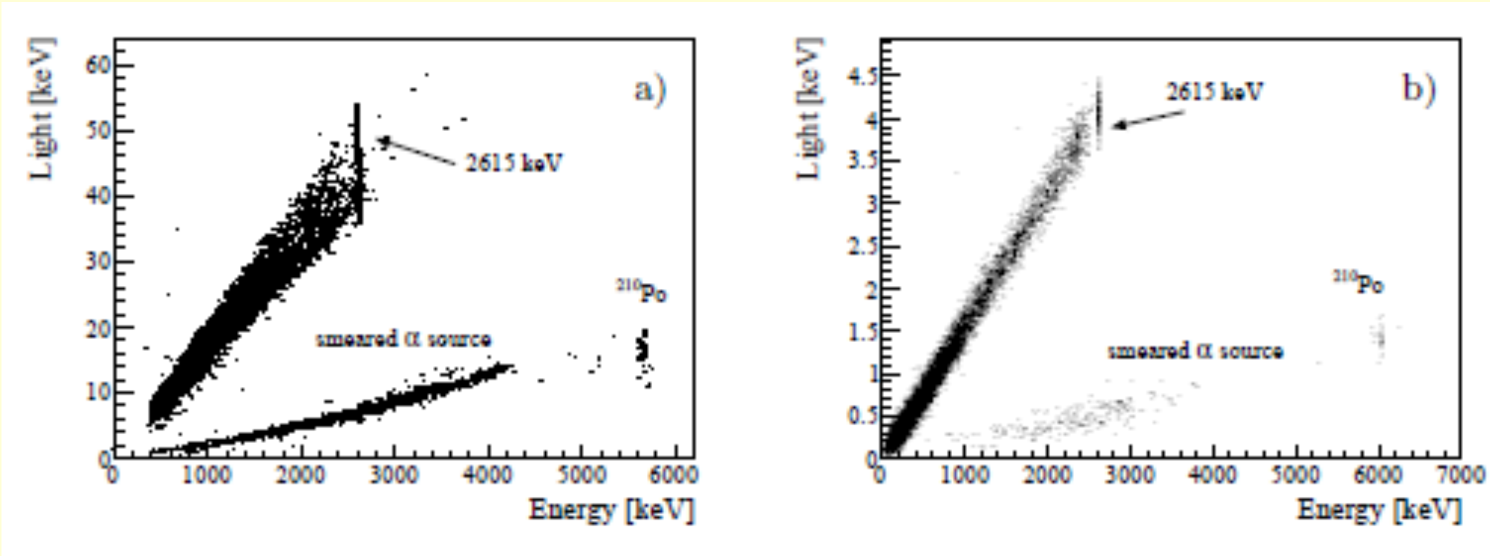


The first **scintillating calorimenter** (CaF_2)

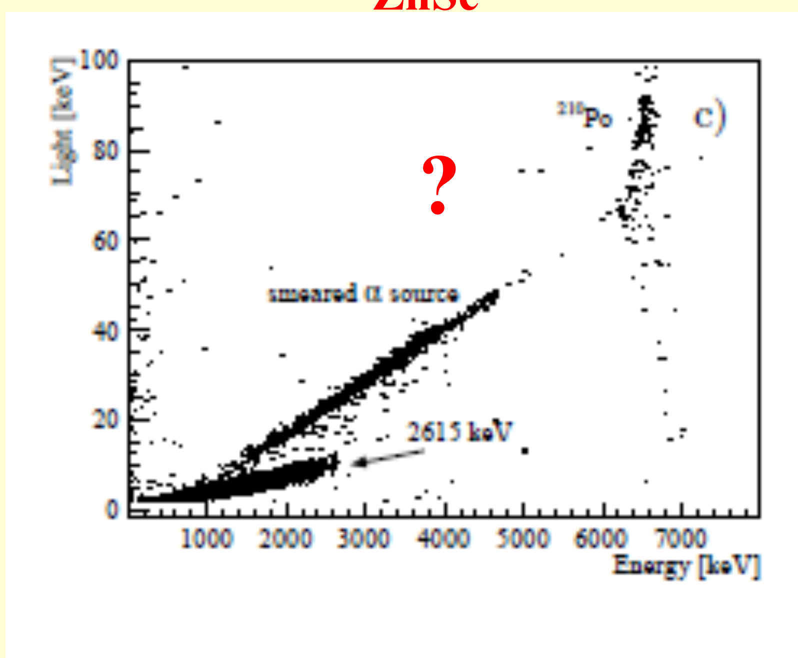


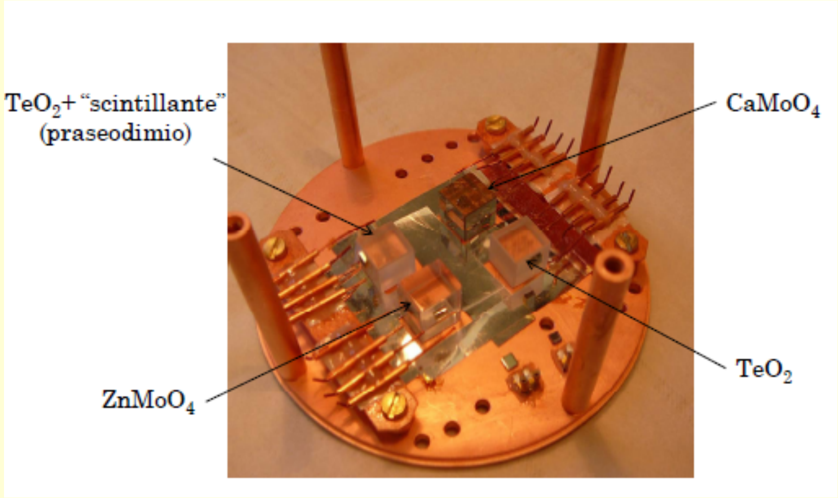
CUORE - LUCIFER

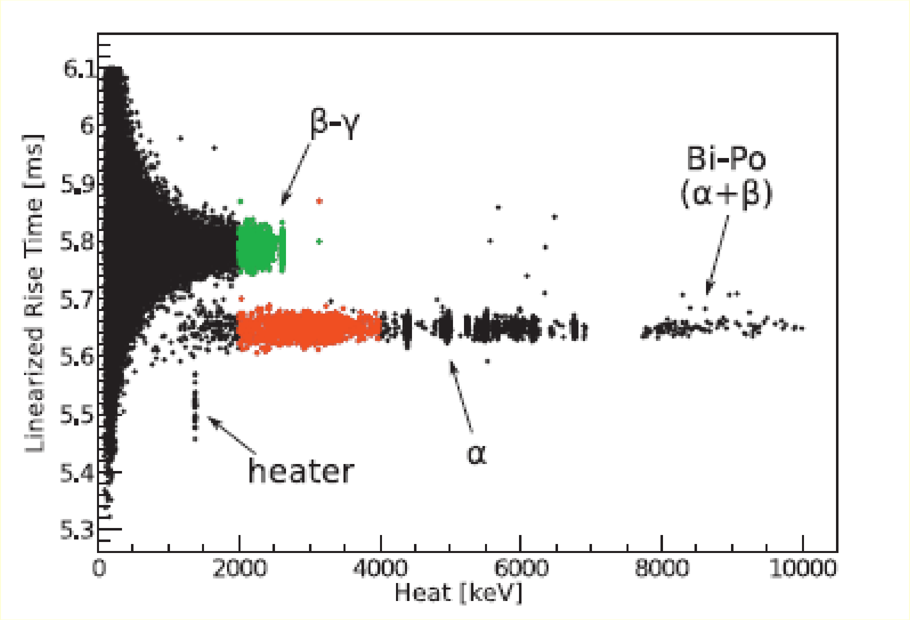
CdWO4 $ZnMoO_4$

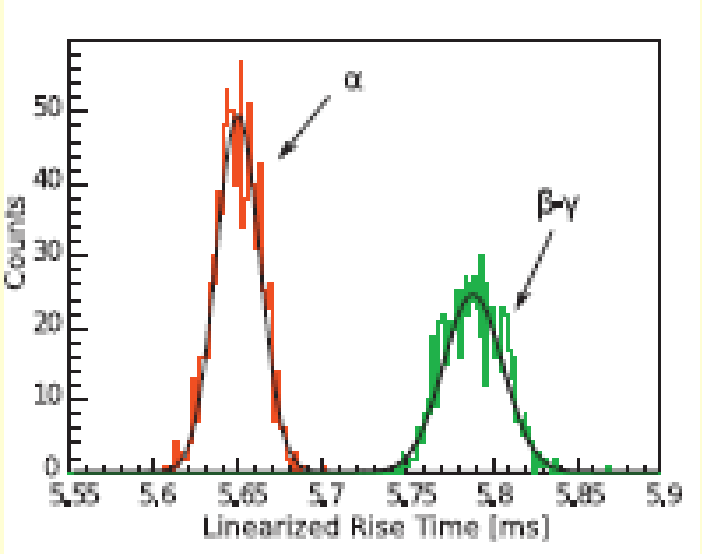


ZnSe




TeO2+ "scintillante"
(praseodimio)
CaMoO4
TeO2
ZnMoO4

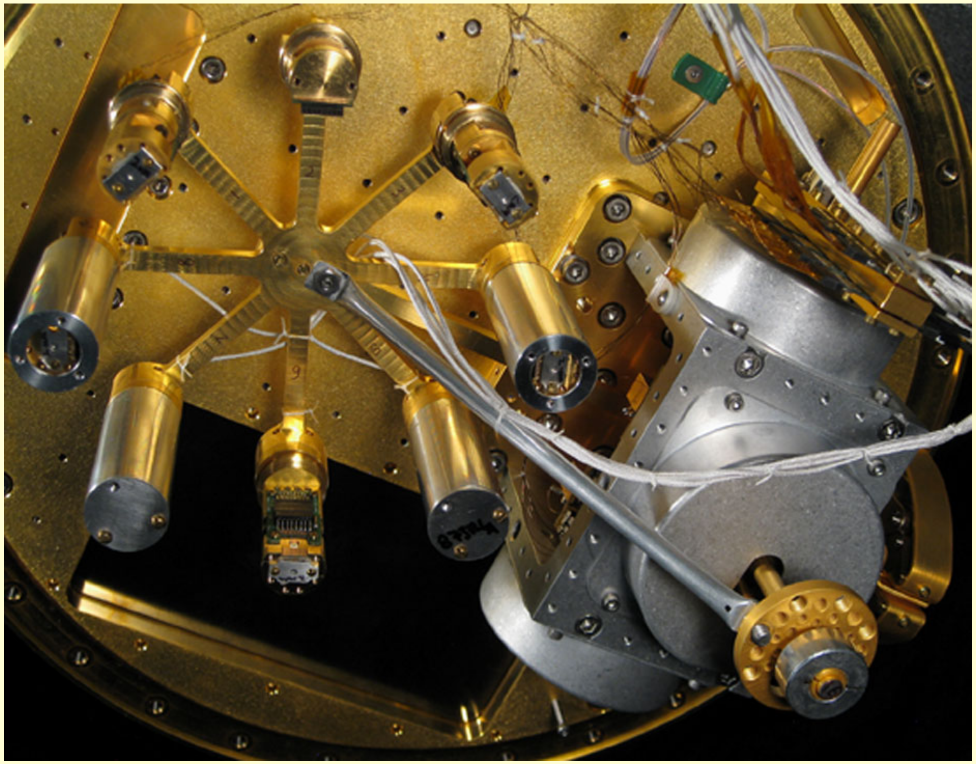

β-γ
Bi-Po
(α+β)
heater
α
Linearized Rise Time [ms]
Heat [keV]


α
β-γ
Counts
Linearized Rise Time [ms]

I miss nuclear physics!

But many relevant results in X and α spectroscopy

D.Benford,D.Schmidt,m.Ploosari,S.Hakateyama,W.Hoon,P.Egelhof,M.Croce.



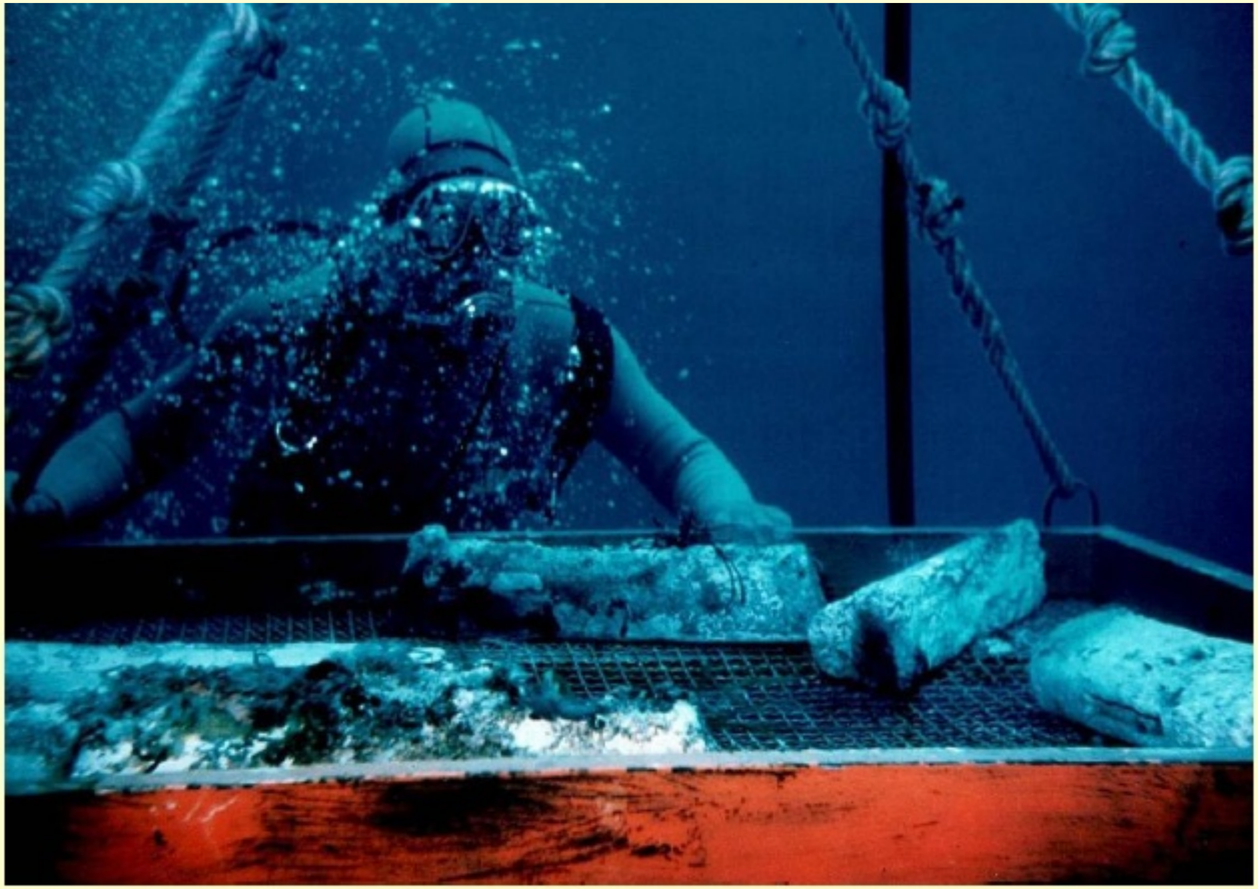
**D.Benford,D.Schmidt,M.Ploosari,
S.Hakateyama,W.Hoon
P.Egelhof,M.Croce.**

Nuclear tables are sometimes **wrong!**

^{209}Bi considered the stable with the higher atomic number => it is not !
Heat+light in Paris and Milan => $\tau \sim 2\ 10^{19}$ years

Archaeometry

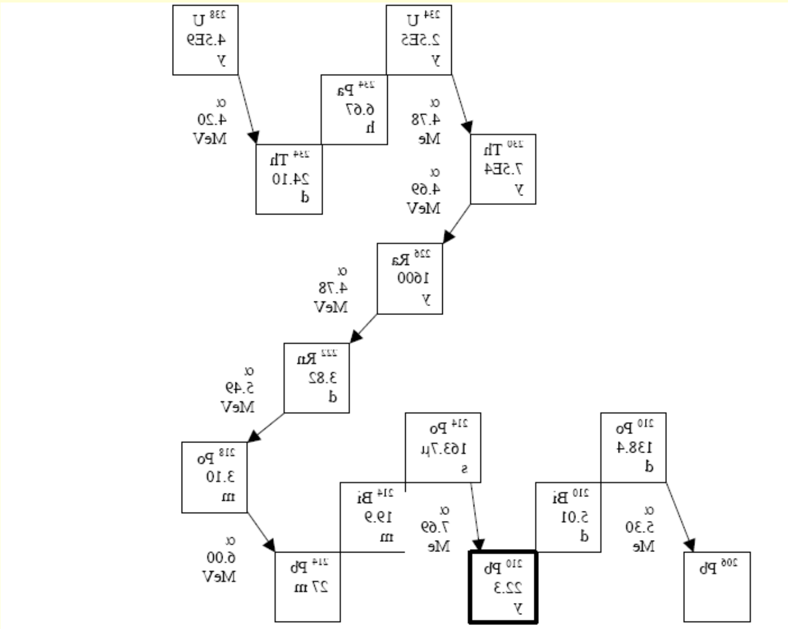
Roman Lead

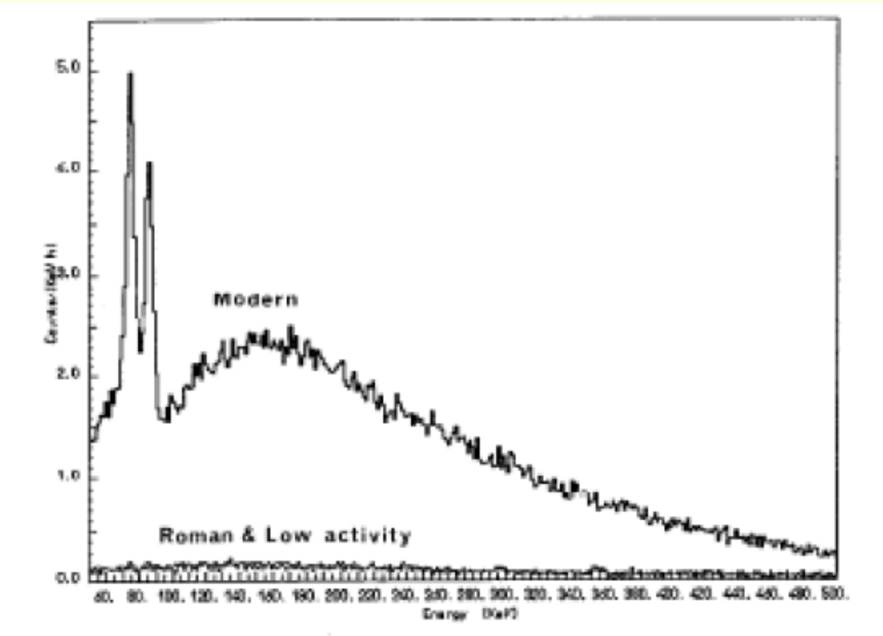


Procured enough for CUORE

Lead is an excellent shielding material , but…

^{210}Pb (22.3 y) => ^{210}Bi => ^{210}Po => ^{206}Pb





Measured thermally => less than 4 mBBq/kg

Isotopic lead geochronology

^{23}U => ^{206}Pb
^{235}U=> ^{207}Pb
^{232} Th° => ^{208}Pb
^{204} Pb (reference)

Coherent elastic neutrino-nucleus scattering

Same technique as for Dark Matter

Not yet found , but **cross section enhanced by coherence**

=> **high intensity π and μ decay-at-rest** (DAR) (maximum neutrino energy ≈52 MeV)

⇒ Maybe also from **SNS** and **Supernovae**

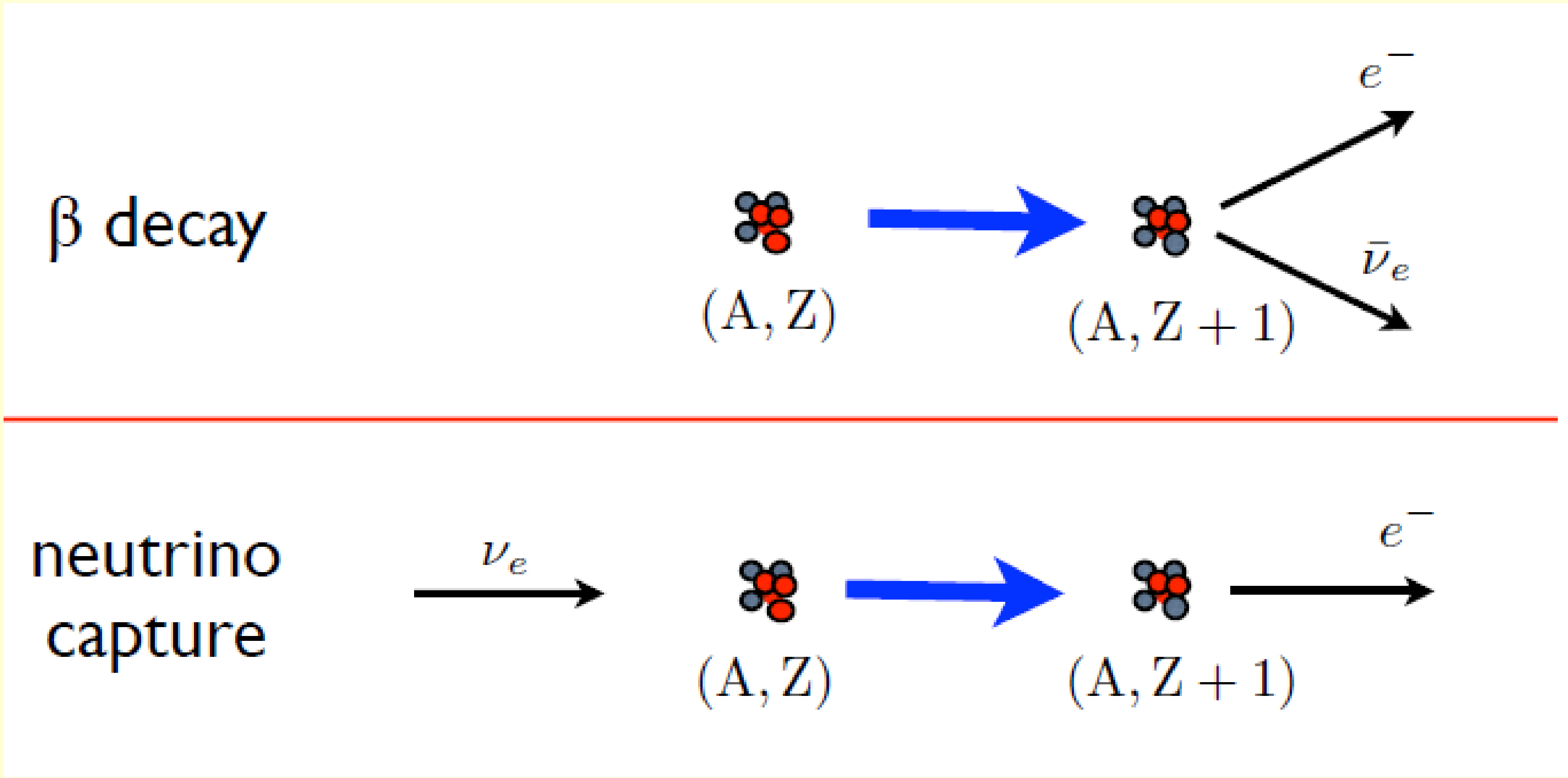
⇒ **Maybe even with reactors**

Texono (with the Taiwan reactor and the Texono-CDEX collaboration in Jinping Underground Laboratory

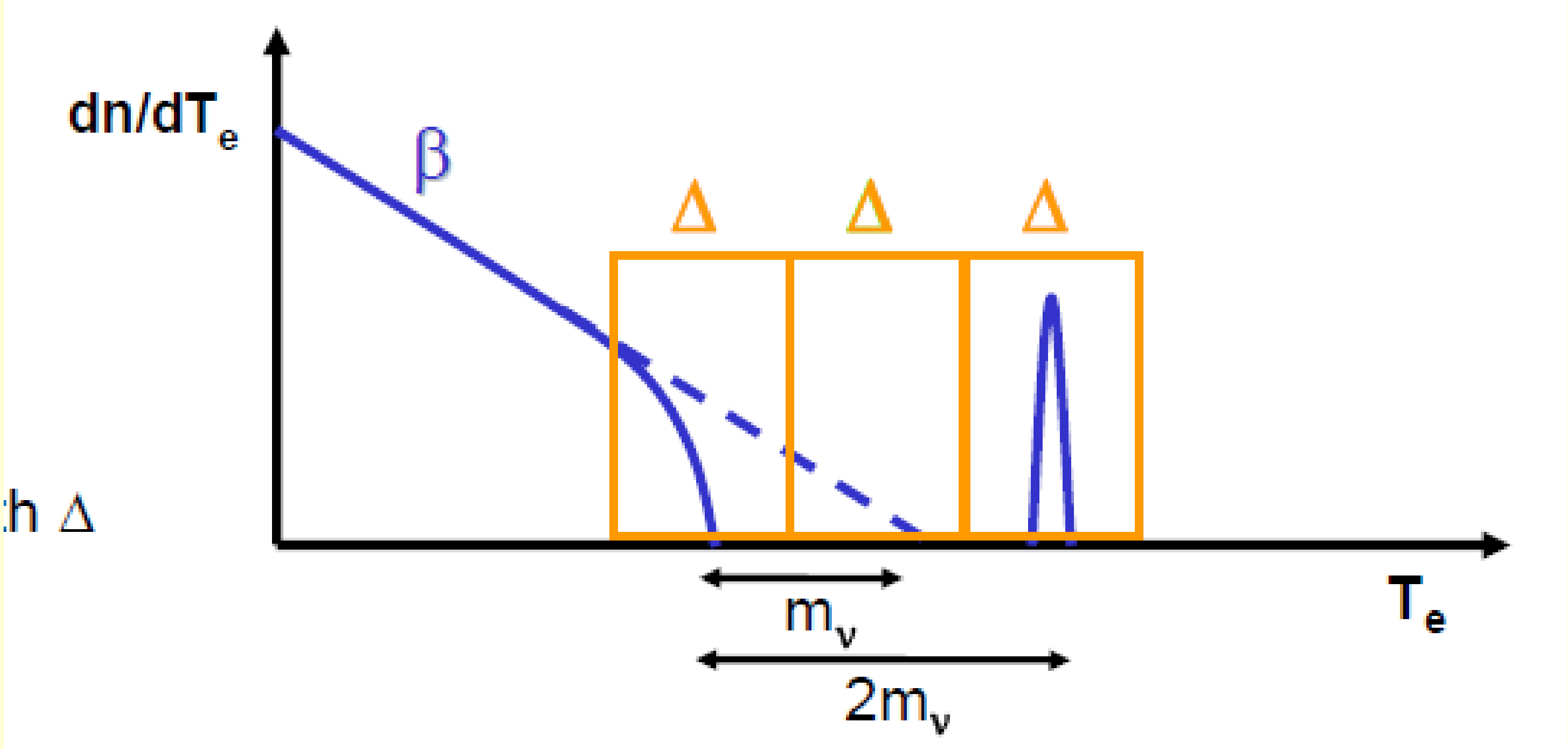
=>Array of small Ge ionisation detectors (better calorimeters!)

DREAM

Detection of relic neutrinos



$$\Omega_\nu h^2 = \frac{\Sigma m_\nu}{93.2 eV}$$



$\nu_e + {}^{3}H \Rightarrow {}^{3}He + e^-$ $\qquad$ $\nu_e + {}^{187}Re \Rightarrow {}^{187}Os + e^-$

Isotope	Decay	Q (keV)	Half-life (sec)	$\sigma_{NCB}(v_\nu/c)$ $(10^{-41}$ cm$^2)$
^{3}H	β^-	18.591	3.8878×10^{8}	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^{9}	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^{7}	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	β^-	2.64	1.3727×10^{18}	4.32×10^{-11}
^{11}C	β^+	960.2	1.226×10^{3}	4.66×10^{-3}
^{13}N	β^+	1198.5	5.99×10^{2}	5.3×10^{-3}
^{15}O	β^+	1732	1.224×10^{2}	9.75×10^{-3}
^{18}F	β^+	633.5	6.809×10^{3}	2.63×10^{-3}
^{22}Na	β^+	545.6	9.07×10^{7}	3.04×10^{-7}
^{45}Ti	β^+	1040.4	1.307×10^{4}	3.87×10^{-4}

NEVER SAY NEVER (James Bond)