THE ROLE OF LOW TEMPERATURE DETECTORS IN NEUTRINO PHYSICS

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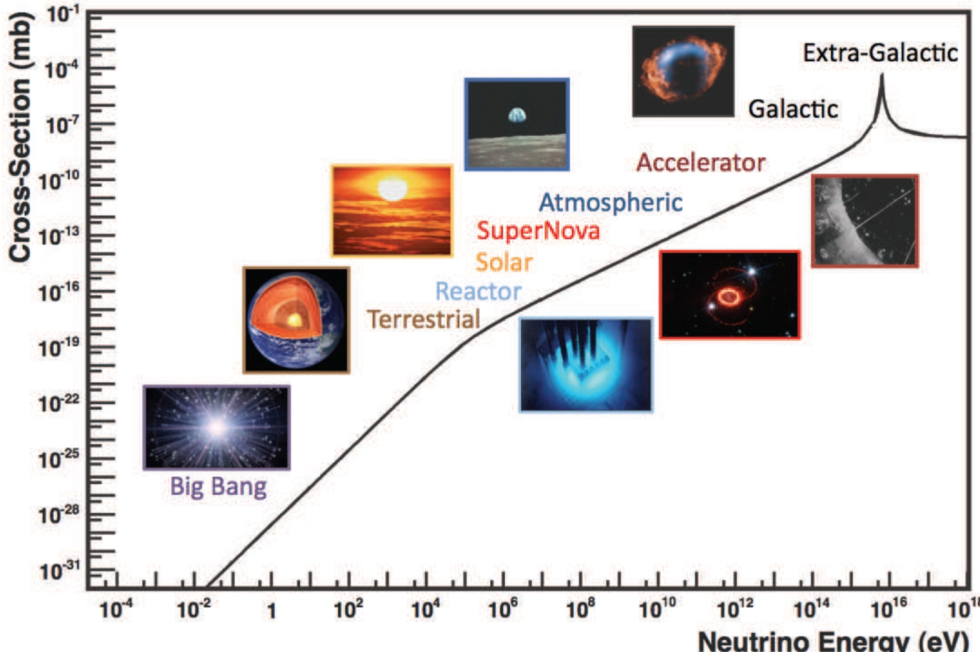
Neutrinos are...

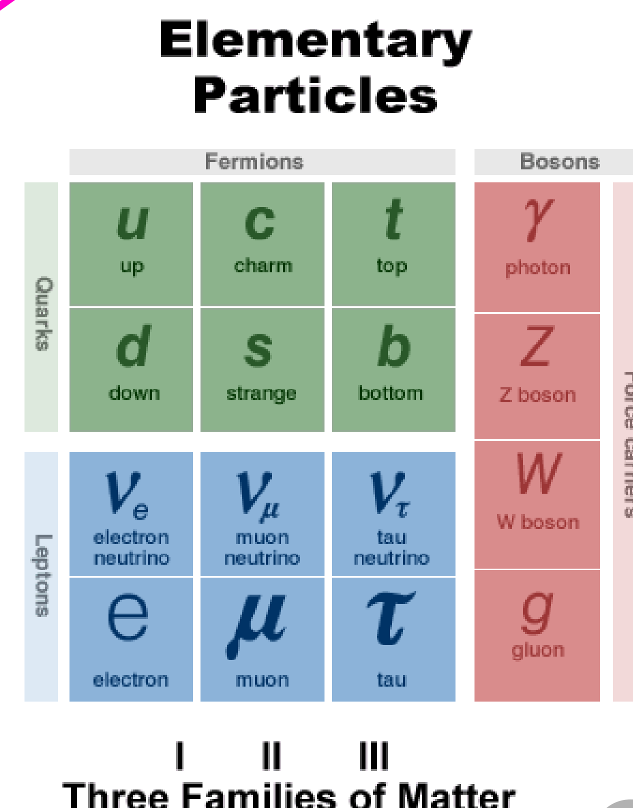


FUNDAMENTAL PARTICLES

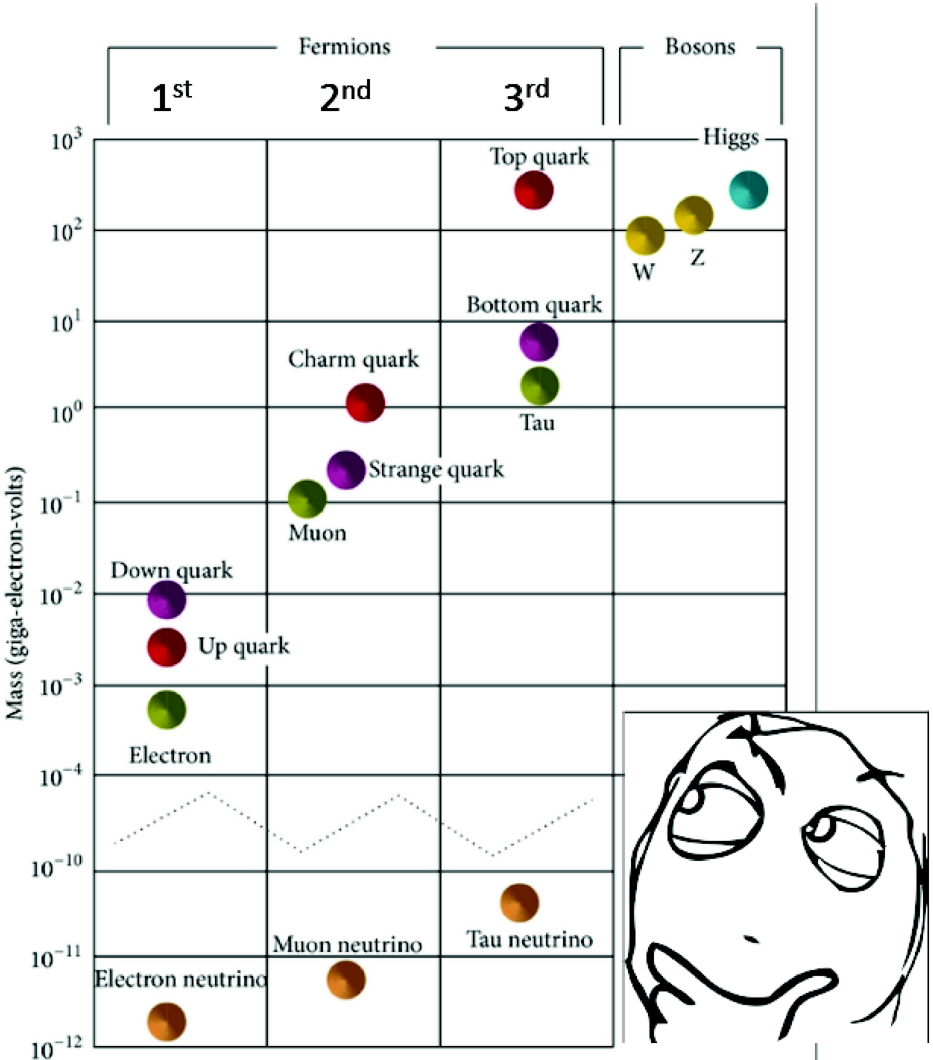
ABUNDANT

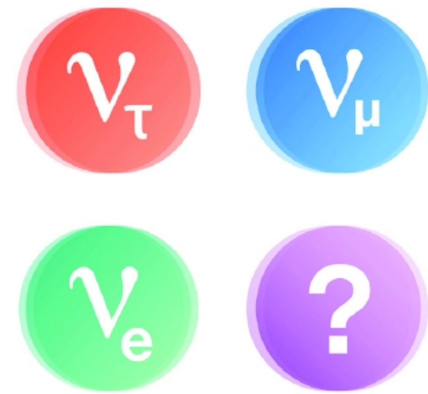
DIVERSE

ELUSIVE



Mysteries about Neutrinos



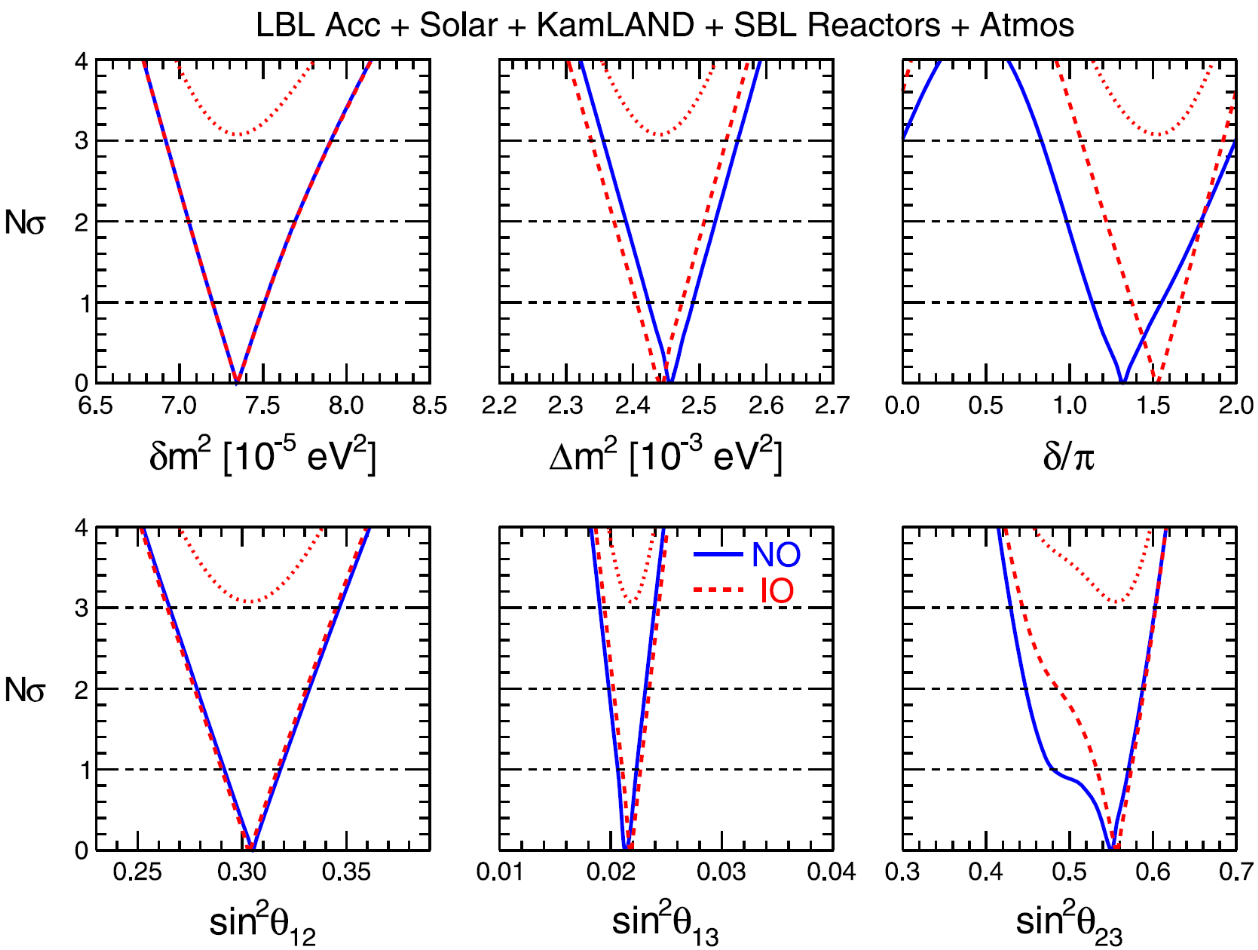


- Why are neutrinos so light?
- Are neutrinos their own anti-particles?
- Is there a fourth neutrino type?
- Are there non-standard interactions?

Current knowledge on neutrino properties

Neutrinos have mass and mix

From oscillation experiments:



Capozzi et al., Prog. Part. Nucl. Phys. 102 (2018) 48

neutrino mixing matrix

neutrino mass eigenstate

$$|\nu_l\rangle = \sum_k U_{lk} |\nu_k\rangle$$

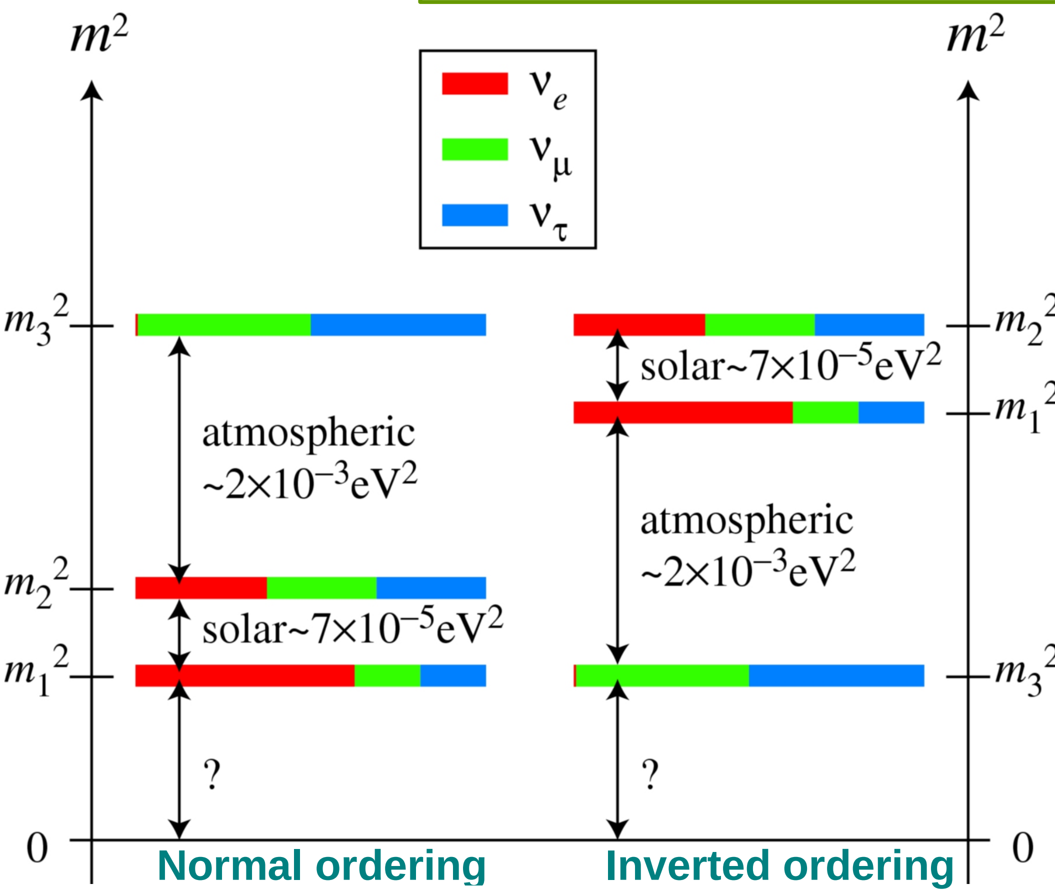
neutrino flavor weak eigenstate

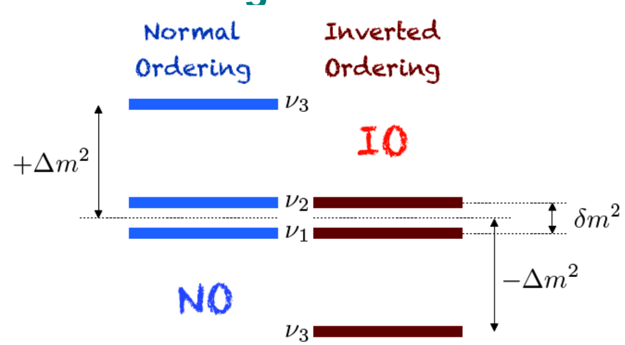
- **2 mass square differences**
- **3 mixing angles**
- **hints of CPV**
- **indications in favor of Normal Ordering**

$$\Delta m^2 = (\Delta m^2_{13} + \Delta m^2_{23})/2$$

Neutrino masses

There are at least 3 massive neutrinos





neutrino mixing matrix

neutrino mass eigenstate

$$|\nu_l\rangle = \sum_k U_{lk} |\nu_k\rangle$$

neutrino flavor weak eigenstate

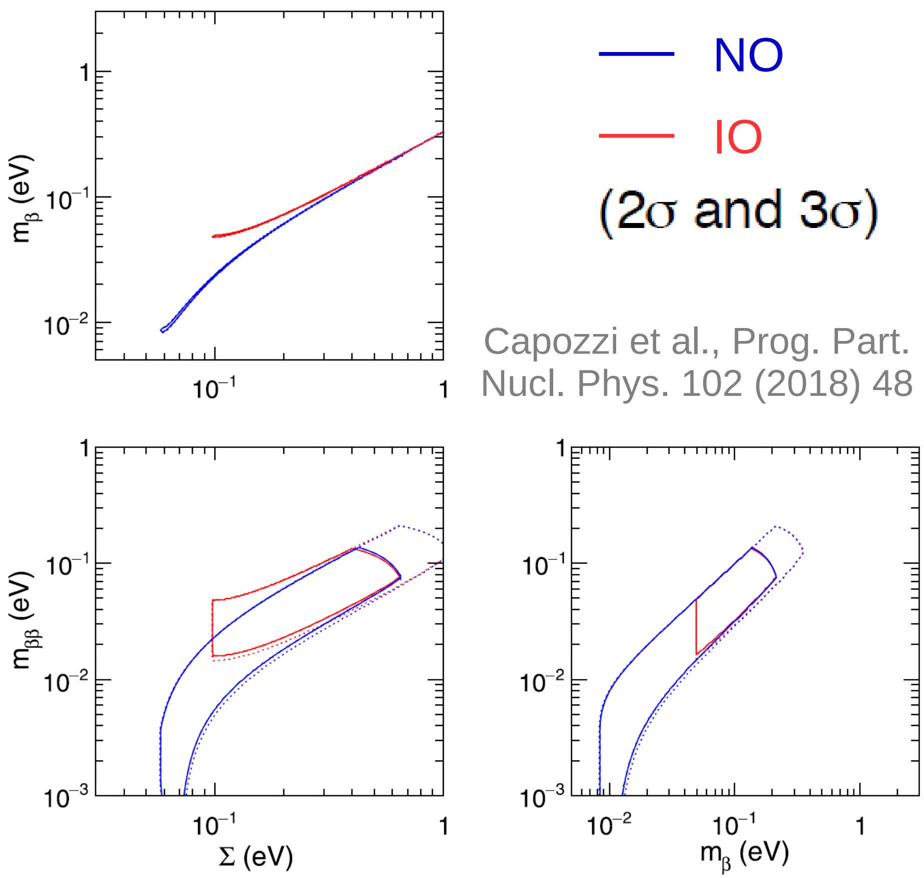
mass eigenstates: ν_1, ν_2, ν_3

Missing puzzle pieces:

- mass scale (i.e. mass of the lightest ν)
- mass ordering
  - $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 \approx m_2$?
- Dirac or Majorana particle?
- CP violation in the lepton sector

Neutrino mass observables

Tool	Measured quantity	Sensitivity (eV) present	Sensitivity (eV) future	model dependency
Cosmology (CMB only)	$m_\Sigma \equiv \sum m_i$	0.6	0.06	yes
0ν double beta decay	$m_{\beta\beta} \equiv \lvert \sum m_i \lvert U_{ei} \rvert^2 e^{i\alpha_i} \rvert$	0.1	0.01	yes
Beta decay	$m_\beta \equiv \left(\sum m_i^2 \lvert U_{e\,i} \rvert^2 \right)^{1/2}$	2	0.2	no



Capozzi et al., Prog. Part. Nucl. Phys. 102 (2018) 48

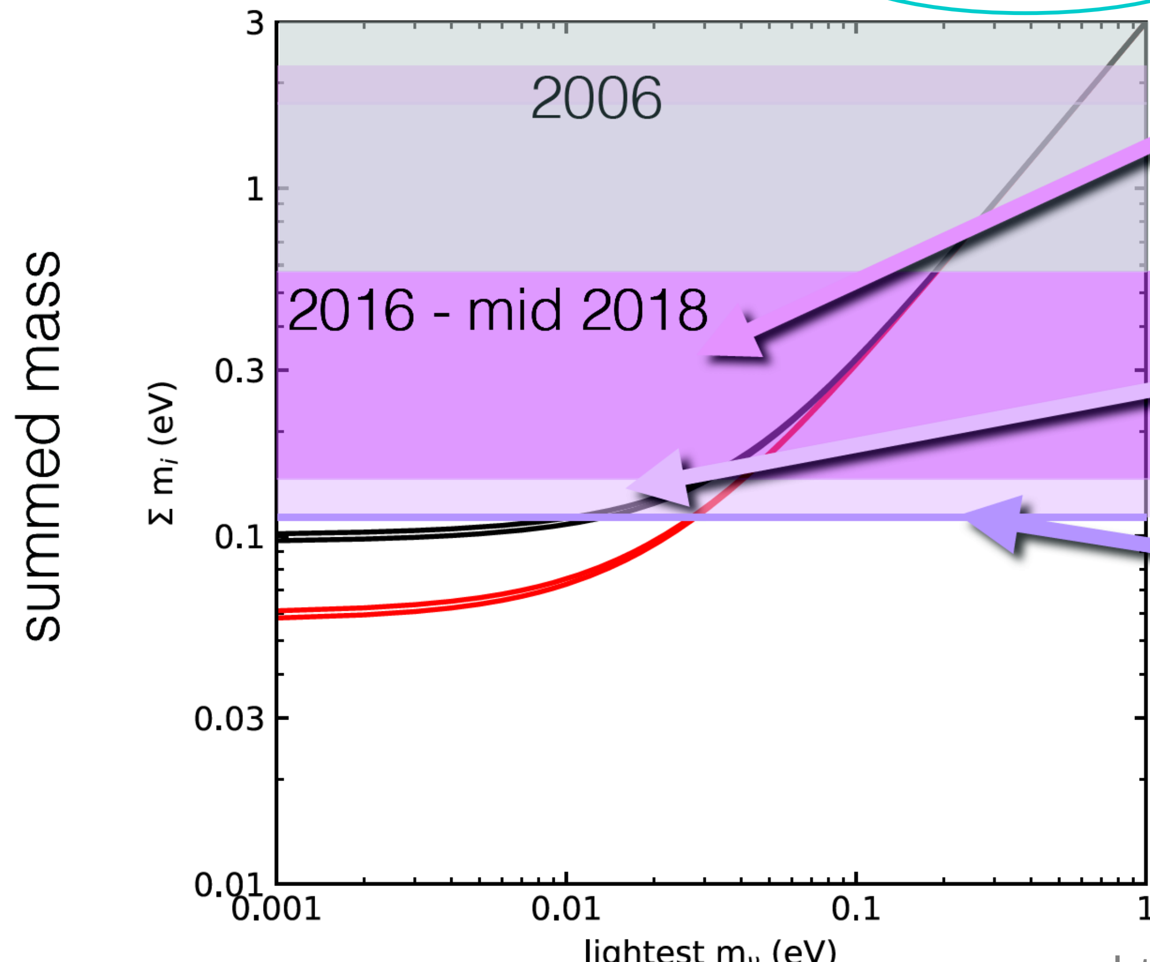
Complementarity of informations from experimental observables

Neutrinos from Cosmology

Summed mass of active neutrinos have specific effects on Cosmic Microwave Background anysotropies and on Large Scale Structure formation

Model dependence

95%CL upper bounds on $\Sigma_i m_i$ for 7 parameters



CMB only: Planck,
w/o high-l polarisation and lensing…
$\Sigma_i m_i$ < 590 to 140 meV (95%CL)

CMB + conservative LSS :

- Planck 2016 {TT+SIMLow+lensing} + BAO: $\Sigma_i m_i$ < **170 meV** (95%CL)
- Planck 2016 {TTTEEE+SIMLow} + BAO: $\Sigma_i m_i$ < **120 meV** (95%CL)

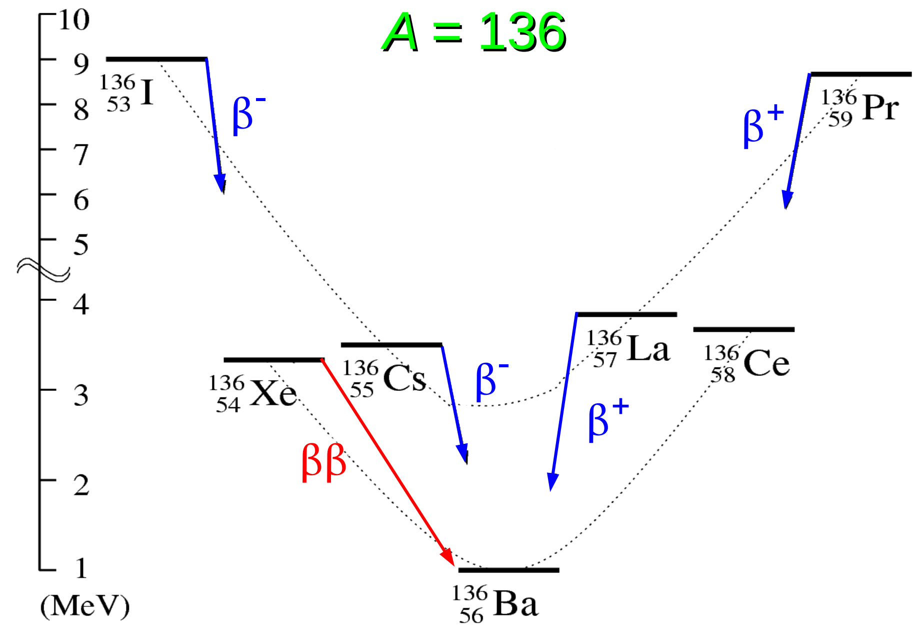
- Planck 2015 + Lyman-α: $\Sigma_i m_i$ < **120 meV** (95%CL)

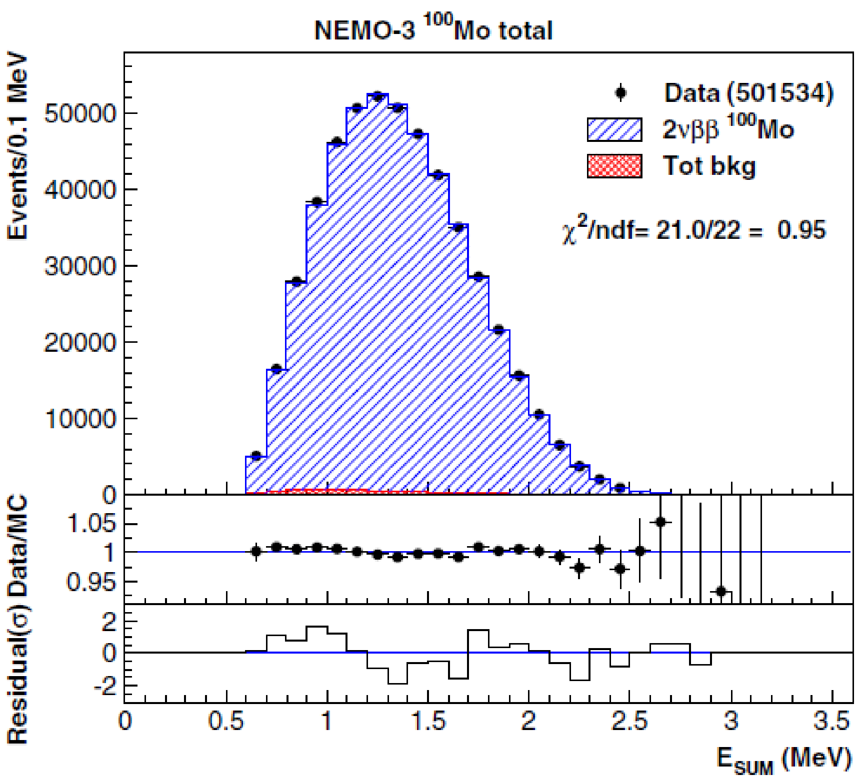
[Planck col.] 1605.02985; Cuesta et al. 2016;
Palanque-Delabrouille et al. 1506.05976;
Vagnozzi et al. 1701.08172;
PDG "Neutrino Cosmology" [JL & Verde]

J. Lesgourgues, Neutrino 2018
http://doi.org/10.5281/zenodo.1287028

Double Beta Decay

second order weak decay
of **even-even nuclei**
in *A* even multiplets
^{48}Ca, ^{76}Ge, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe ...

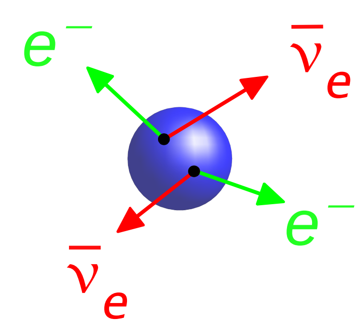




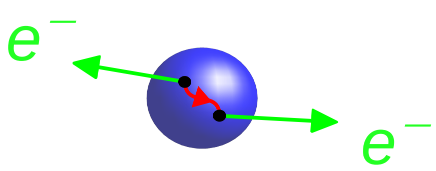
Arnold et al., Eur. Phys. J. C79(2019) 440

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

- allowed by the Standard Model
- observed with $\tau_{1/2} > 10^{18}$ years

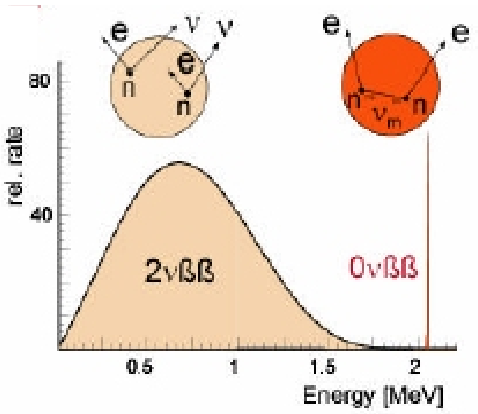


Neutrinoless Double Beta Decay



$0\nu\beta\beta$: $(A, Z) \rightarrow (A, Z+2) + 2e^-$

- not allowed in Standard Model (ΔL=2)
- expected $\tau_{1/2} > 10^{25}$ years



✔ **The decay occurs only if neutrinos are Majorana particles**

✔ The decay rate depends on the "**effective Majorana mass**"

$$0\nu\beta\beta \Leftrightarrow \begin{array}{c} m_\nu \neq 0 \\ \nu \equiv \bar{\nu} \end{array}$$

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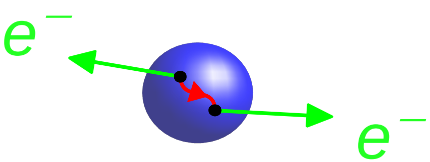

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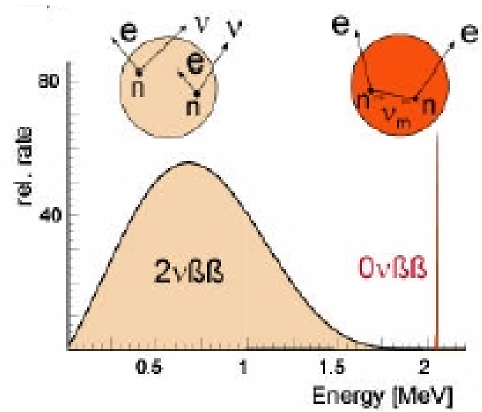

✔ The decay occurs only if neutrinos are **Majorana** particles

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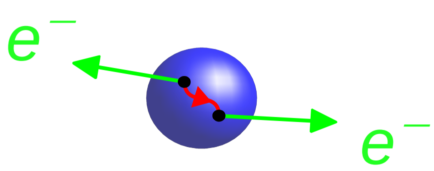
$$0\nu\beta\beta \Leftrightarrow \begin{matrix} m_\nu \neq 0 \\ \nu \equiv \bar{\nu} \end{matrix}$$

$0\nu\beta\beta$ is a test for Lepton Number Violation at low energy

Lepton Number Violation is a necessary condition for Leptogenesis (matter – antimatter asymmetry of the Universe)

Neutrinoless Double Beta Decay



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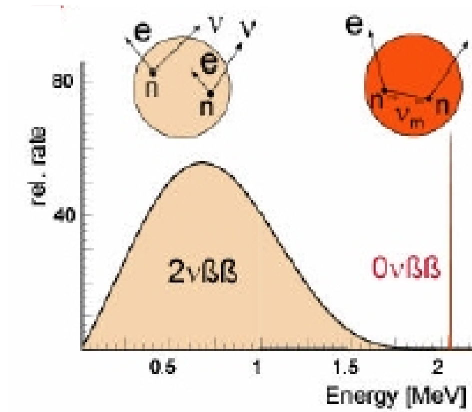

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✔ The decay rate depends on the "**effective Majorana mass**"

$0\nu\beta\beta \Leftrightarrow$ $m_\nu \neq 0$, $\nu \equiv \bar{\nu}$

light Majorana ν mediated $\beta\beta$-0ν decay rate: $$\frac{1}{\tau^{0\nu}_{1/2}} = \frac{|m_{\beta\beta}|^2}{m_e^2} \cdot F_N$$

- phase space $G^{0\nu}(Q_{\beta\beta},Z) \propto Q_{\beta\beta}^{\,5}$ can be calculated with reasonable accuracy

- matrix element $|M^{0\nu}|$ contains details of **nuclear physics** → source of uncertainties (a factor $\approx$3)

nuclear factor of merit

$$F_N \equiv G^{0\nu}(Q_{\beta\beta}, Z)\,|M^{0\nu}|^2$$

phase space

matrix element

0νββ experimental sensitivity

$$S^{0\nu}(\tau_{1/2}) \propto \epsilon \cdot \frac{\eta}{A} \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}} \qquad bkg \neq 0$$

ε	detector efficiency	**ΔE**	FWHM resolution
η	0νββ isotope abundance	**M**	total active mass
A	atomic mass	**t_{meas}**	measuring time

bkg background @ ROI in counts/keV/kg/y

For bkg = 0:

$$S^{0\nu}(\tau_{1/2}) \propto \frac{\epsilon\, \eta}{A} M\, t_{meas}$$

$$m_{\beta\beta} \propto \sqrt{1/\tau^{0\nu}_{1/2}}$$

$0\nu\beta\beta$ experimental sensitivity

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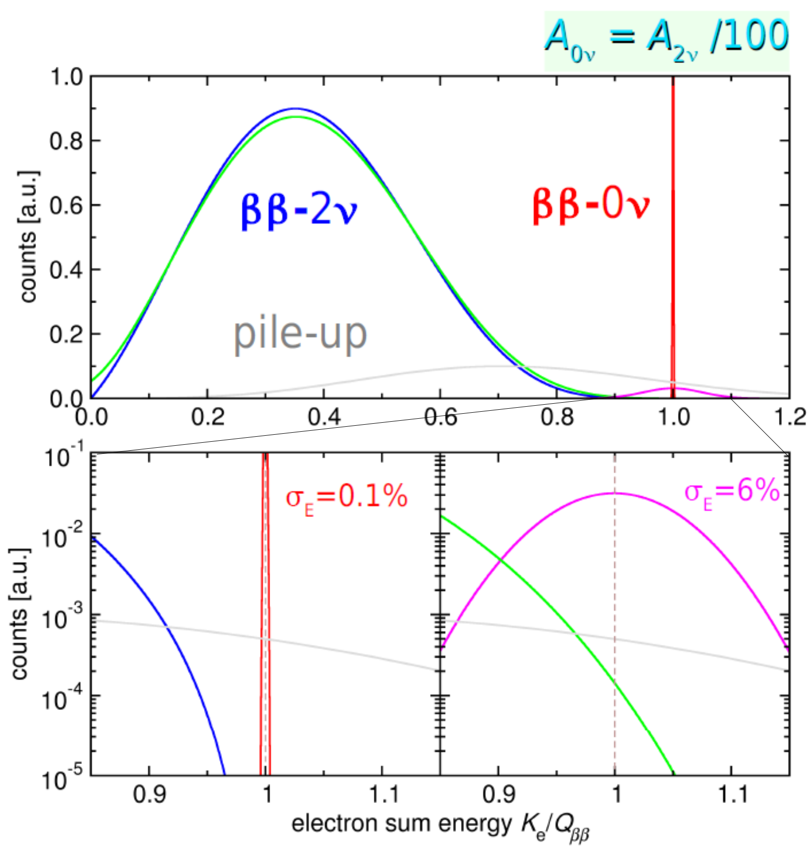
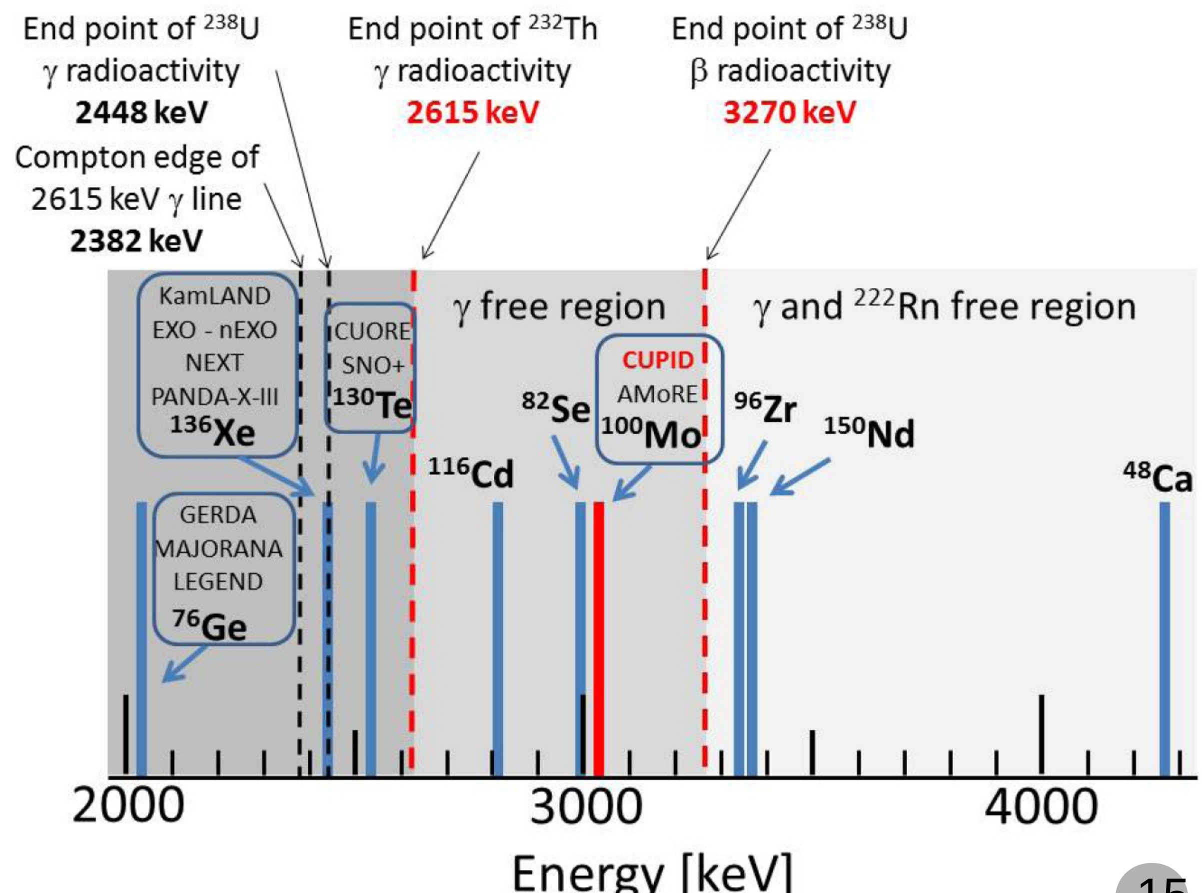
2ν rate in ROI

Isotope	$Q_{\beta\beta}$ [keV]	η [%]	$T^{2\nu}_{1/2}$ [y]	$R_{2\nu}(50\,\mathrm{keV})$ [c/y/ton_iso]	$R_{0\nu}(m_{\beta\beta}=50\,\mathrm{meV})$ [c/y/ton_iso]	$R_{0\nu}(m_{\beta\beta}=10\,\mathrm{meV})$ [c/y/ton_iso]
^{48}Ca	4274	0.2	4.4×10^{19}	4.0×10^{-2}	1.4–23.1	0.1–0.9
^{76}Ge	2039	7.6	1.8×10^{21}	2.5×10^{-2}	1.2–12.2	0.05–0.5
^{82}Se	2996	8.7	9.2×10^{19}	6.8×10^{-2}	4.4–38.7	0.2–1.5
^{96}Zr	3348	2.8	2.3×10^{19}	1.3×10^{-1}	3.9–50.7	0.2–2.0
^{100}Mo	3034	9.6	7.1×10^{18}	6.8×10^{-1}	8.9–71.3	0.4–2.9
^{116}Cd	2814	7.5	2.8×10^{19}	2.1×10^{-1}	6.8–23.8	0.3–1.0
^{130}Te	2528	34.2	6.8×10^{20}	1.3×10^{-2}	3.6–24.9	0.1–1.0
^{136}Xe	2458	8.9	2.1×10^{21}	4.8×10^{-3}	2.5–14.0	0.1–0.6
^{150}Nd	3368	5.6	8.2×10^{18}	2.3×10^{-1}	9.1–42.7	0.4–1.7

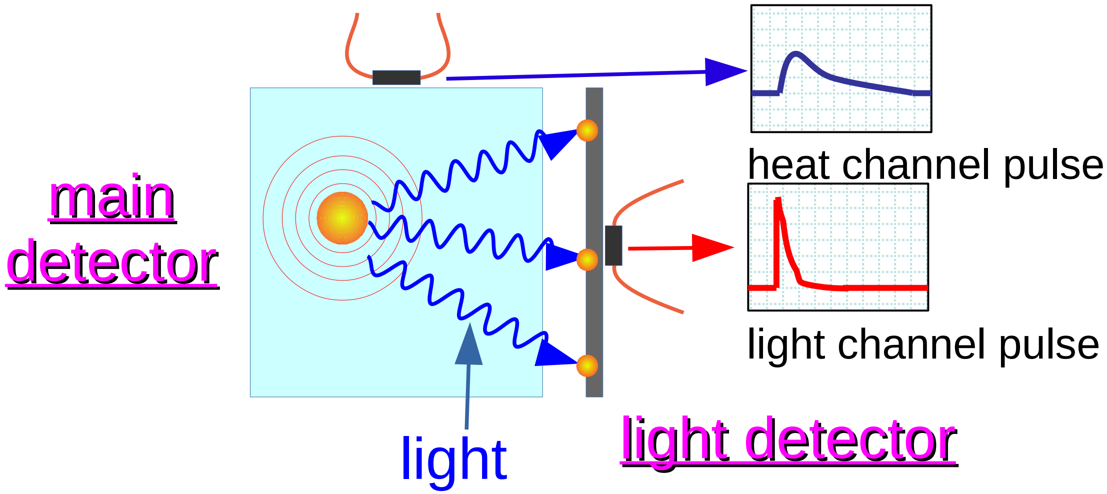
0νββ detection techniques "MUSTs"

- ✔ **Negligible radioactive background**
- ✔ **Large detector mass**
- ✔ **High energy resolution**
- ✔ **Favorable 0νββ candidate (high $Q_{\beta\beta}$, large $R_{0\nu}/R_{2\nu}$ in the ROI)**





LTDs for 0νββ searches



Example of double read-out
(phonons + scintillation photons)

- ✔ excellent energy resolution
- ✔ true calorimeters
- ✔ wide material choice
- ✔ low threshold
- ✔ high efficiency
- ✔ large masses
- ✔ radiopure absorbers
- ✔ fully sensitive to recoils
- ✔ segmentation to reduce background
- ✔ double-readout detectors with particle identification capabilities (i.e. e/γ - recoil, e/γ - α)

Most common thermometer technologies:

- Neutron Transmutation Doped Ge (NTD)
- Transition Edge Sensors (TES)
- Metallic Magnetic Calorimeters (MMC)
- Microwave Kinetic Inductance Det (MKIDs)

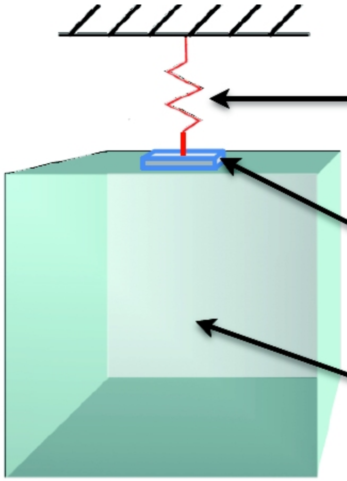
- ✗ slow time responses
- ✗ fully sensitive to surface radioactivity
- ✗ difficult to reduce close materials (holders, wires, cryostats,...)
- ✗ not easy to run stable

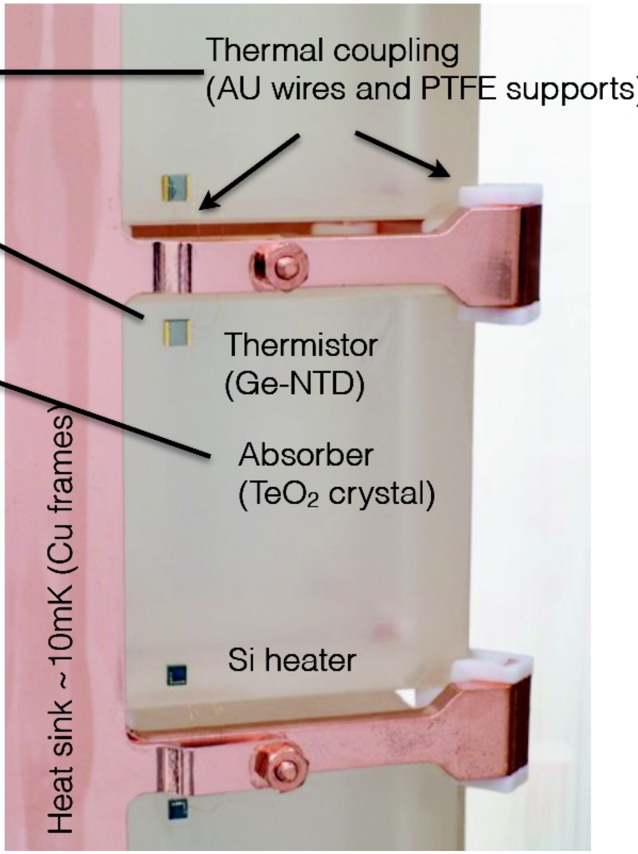
The CUORE TeO_2 thermal detectors

Cryogenic Underground Observatory for Rare Events

TeO_2 absorbers + Ge-NTD thermistors:

T ~ 10 mK
ΔT/ΔE ~ 0.1 mK/MeV
ΔV/ΔE ~ 0.3 mV/MeV
τ = C/G ~ 1 s
C ~ 2×10^{-9} J/K
FWHM ~ 0.2 %





^{130}Te as ββ0ν candidate

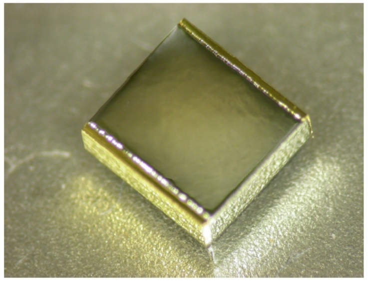
- high natural isotopic abundance: **34.2 %**
- transition energy: **Q = 2527.52 keV**

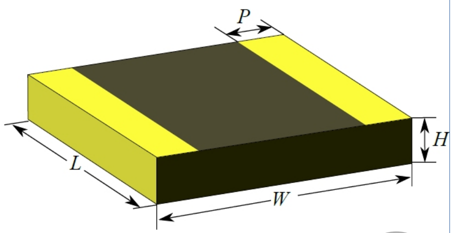
TeO_2 Absorbers

- low specific heat
- large crystals available
- radiopure

Ge-NTD thermistors

- ✔ high dynamic range
- ✔ high linearity
- ✗ microphonic
- ✗ slow





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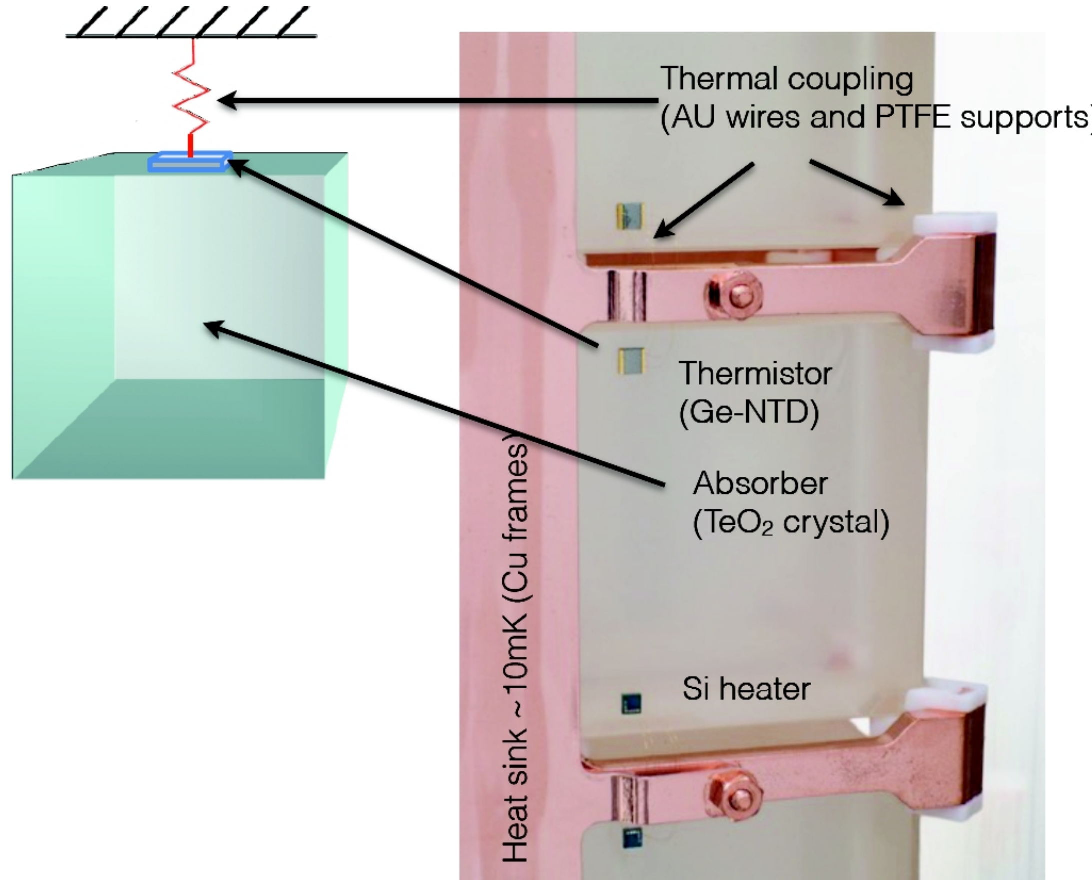
High energy resolution

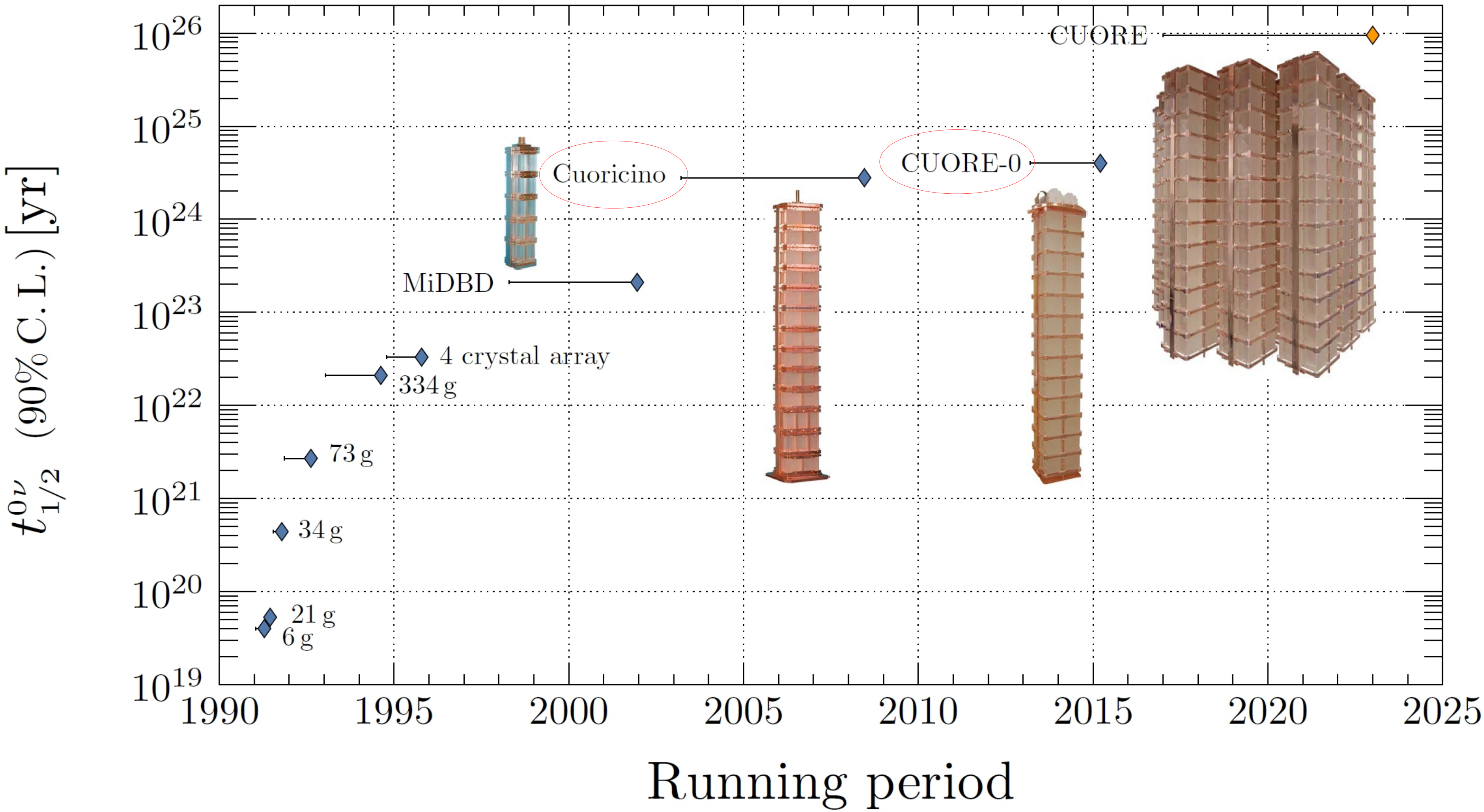


Radiopurity of close materials

→ strict control of the contamination content of Cu, PTFE, Ge-NTDs, Si heaters, PEN wires and TeO_2 crystals themselves

TeO_2 arrays evolution (mass scalability)

CUORE is the latest evolution of a long series of TeO_2 detector arrays



CUORE projected sensitivity (5 years): $S^{0\nu}(\tau_{½}) = 9 \times 10^{25}$ y (90% C.L.)

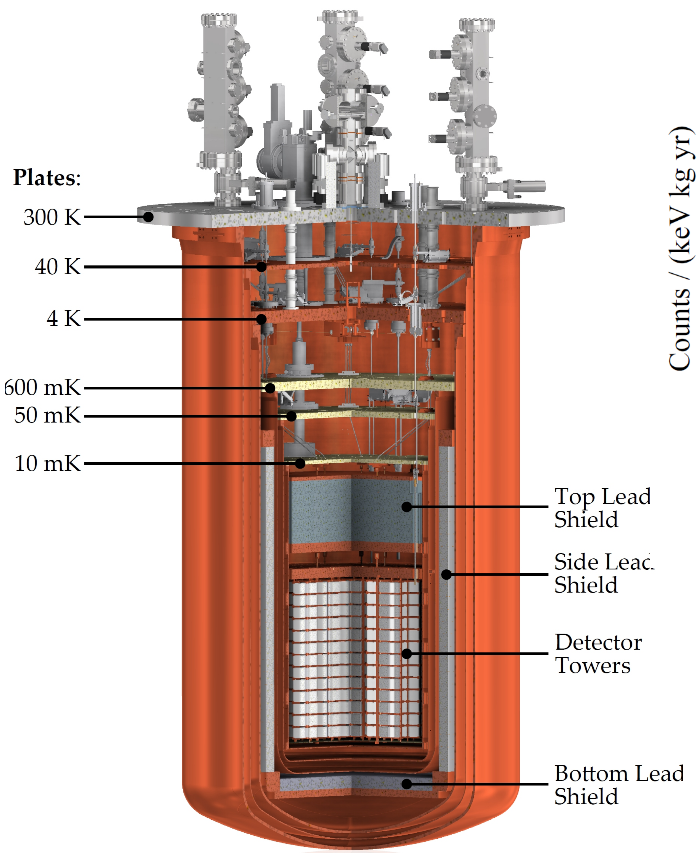
Eur. Phys. J. C 77 (2017) 532

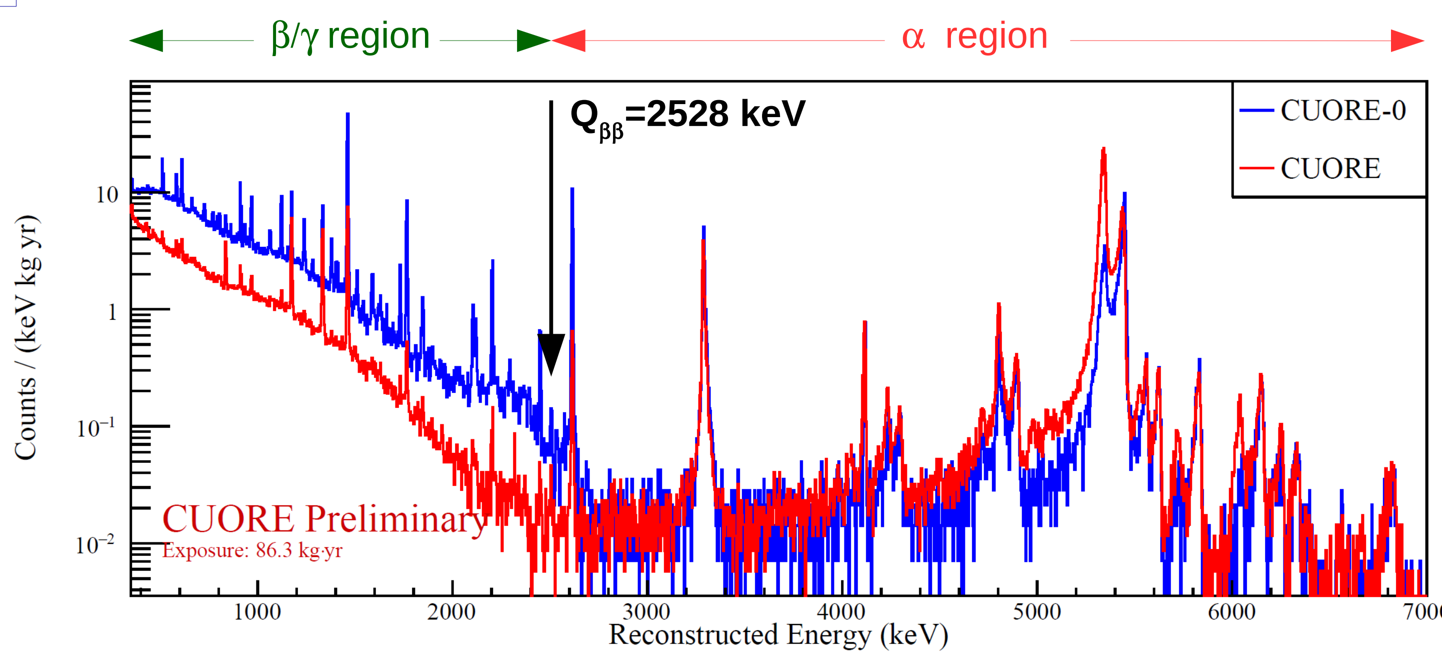
CUORE first results

Background Index is consistent with expectations:
BI ~ 10^{-2} counts/keV/kg/y

Phys. Rev. Lett. 120 (2018) 132501
Eur. Phys. J. C 77 (2017) 543

CUORE cryogenic system:
the most powerful cryostat
ever commissioned





CUORE count rate in the ROI is dominated by surface contaminations (alpha background)

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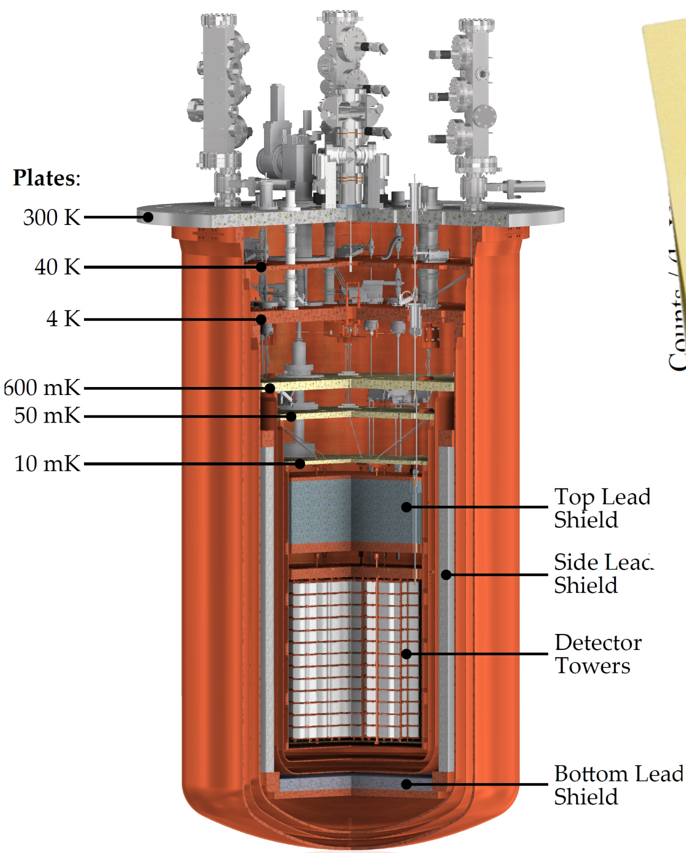
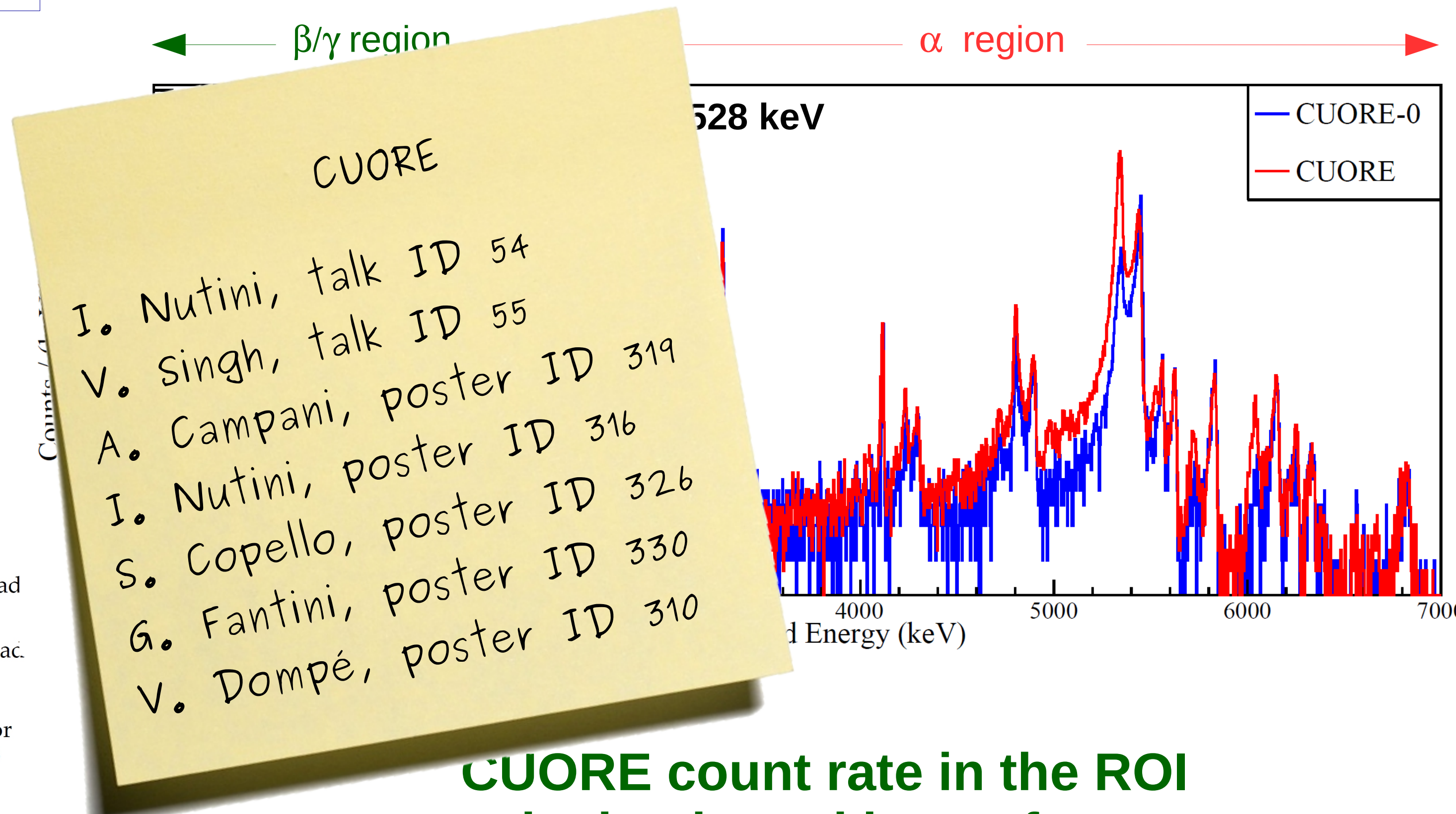




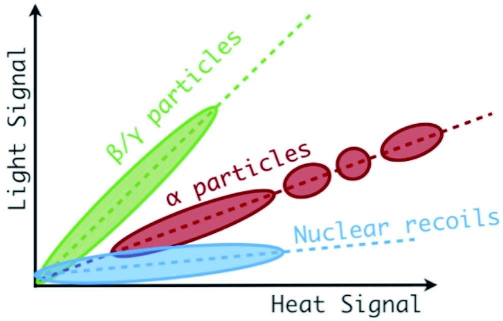
CUORE count rate in the ROI is dominated by surface contaminations (alpha background)

CUPID

CUORE Upgrade with Particle IDentification

- Scintillating crystals and light detectors operated @ 10mK
- Absorbers may be grown from various ββ emitters
- Availability of isotopes with $Q_{\beta\beta}$ in the γ-free region (^{82}Se, ^{100}Mo)
- Excellent energy resolution at $Q_{\beta\beta}$ (< 1%)
- Particle ID capability in the heat and light channels

possible only with LTDs



CUPID (background abatement)

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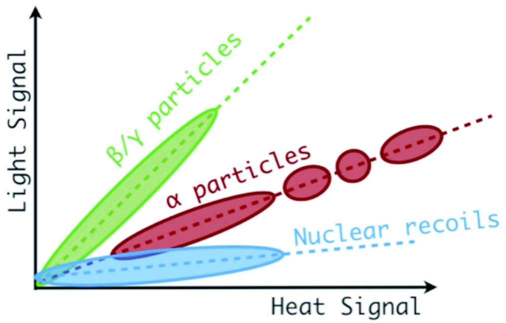


Nucleus	A.I.	Q-value	Good materials
	[%]	[keV]	
^{76}Ge	7.8	2039	Ge
^{130}Te	33.8	2527	TeO2
^{116}Cd	7.5	2802	CdWO4 CdMoO4
^{82}Se	9.2	2995	ZnSe
^{100}Mo	9.6	3034	PbMoO4 CaMoO4 SrMoO4 CdMoO4 ZnMoO4 Li2MoO4 MgMoO4
^{96}Zr	2.8	3350	ZrO2
^{150}Nd	5.6	3367	NONE
^{48}Ca	0.187	4270	CaF2 CaMoO4

CUPID: the present ...

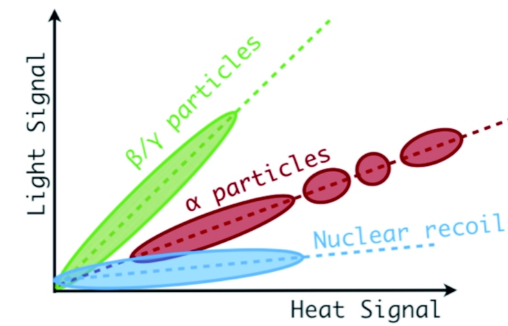
<u>C</u>UOR… …cle <u>ID</u>entification

CUPID-0

L. Cardani,
talk ID 197

- Scintillating crystals a… …d @ 10mK
- Absorbers may be gro… …ers
- Availability of isotopes… …on (^{82}Se, ^{100}Mo)
- Excellent energy resolu…
- Particle ID capability in… …ls

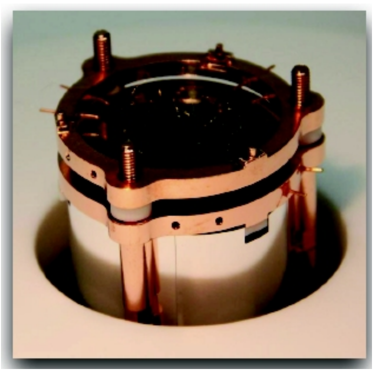
possible only with LTDs



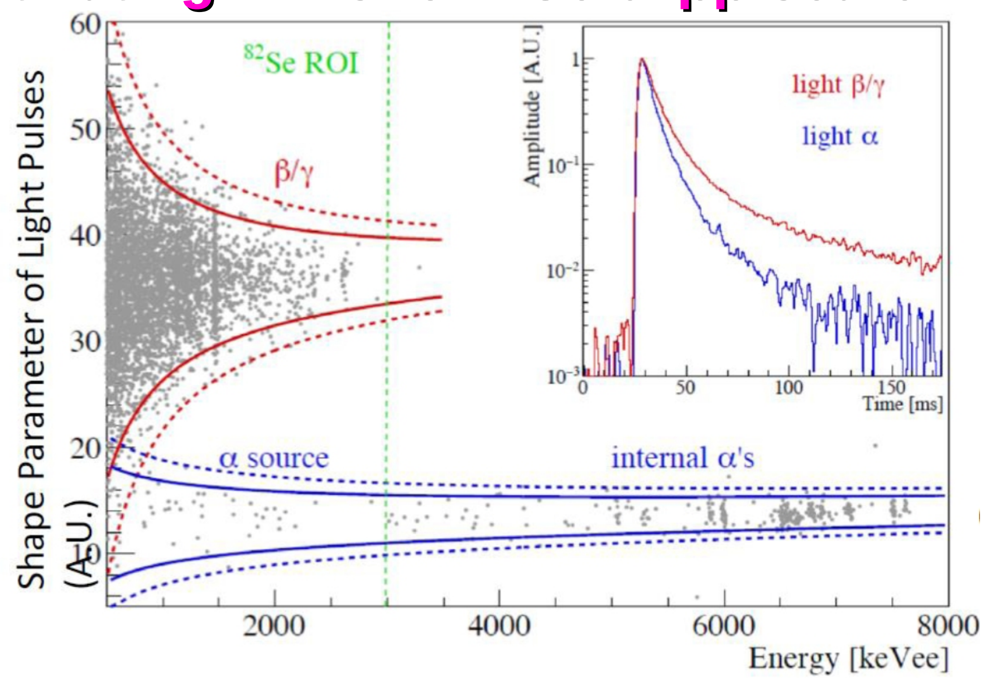
CUPID-0: the first array of scintillating LTDs for ^{82}Se 0νββ search

Zn^{82}Se (95% enrich)

- NTD thermistor (phonons)
- Ge-wafer + NTD (light)



ROI bkg: 3.5 × 10^{-3} c/keV/kg/y
best ever achieved with LTDs



CUPID: the present ...

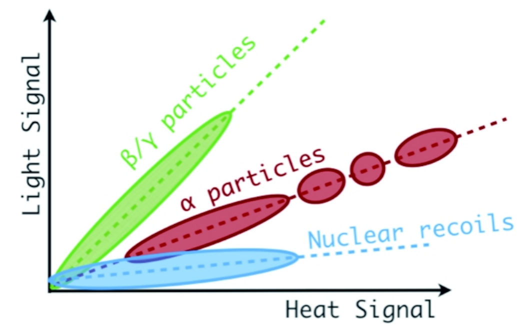
CUOR[...]cle IDentification

- Scintillating crystals a[...]d @ 10mK
- Absorbers may be gro[...]ers
- Availability of isotopes[...]on (^{82}Se, ^{100}Mo)
- Excellent energy resolu[...]
- Particle ID capability in[...]is

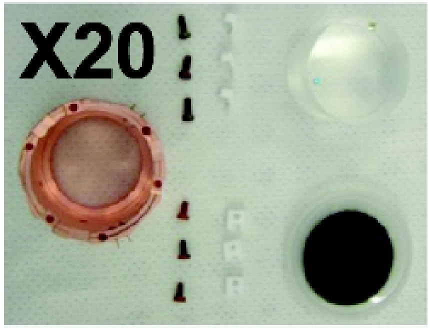
CUPID-Mo

D. Poda,
poster ID 379

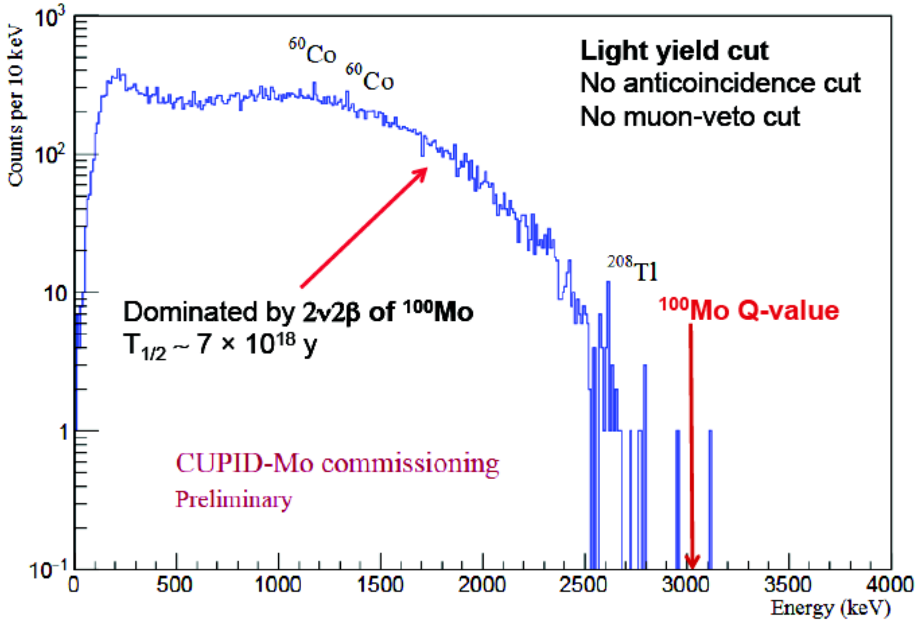
possible only with LTDs



CUPID-Mo: 20 $Li_2{}^{100}MoO_4$ (96% enrich) operated in EDELWEISS setup



- NTD thermistor as phonon sensor
- Ge-wafer with SiO coating + NTD as light detector



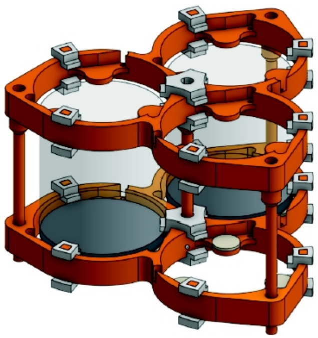
CUPID: the future

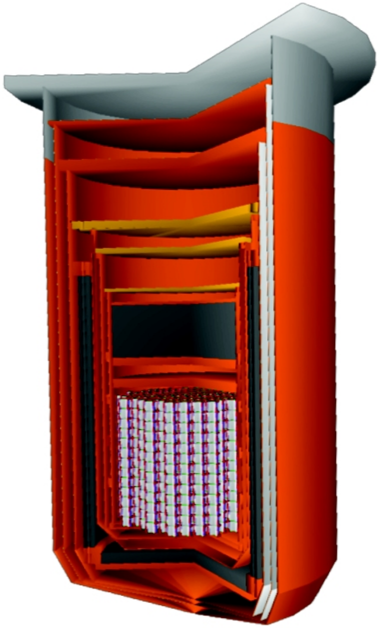
CUORE Upgrade with Particle IDentification

Goal: **explore the entire inverted ordering neutrino mass region down to 10 meV**
Strategy: **merge the CUORE cryogenic infrastructure with CUPID particle ID**
Option for multiple isotopes with the same technique

Active background rejection to reach almost zero-background condition
Expected BI 10^{-4} counts/keV/kg/y in the ROI

Baseline: $Li_2{}^{100}MoO_4$ scintillating absorbers (1500 crystals for 250 kg of ^{100}Mo)
NTD-Ge phonon sensors
Ge wafer + NTD-Ge light detector





TDR and construction readiness in 2021

CUPID CDR available soon

CUPID: the future

CUORE Upgrade with Particle IDentification

Goal:

Stra

Opti

Activ

Basel

TDR an

CUPID

Other light detector technologies like Neganov-Luke-assisted NTDs, Transition Edge Sensors (TES) and microwave Kinetic Inductance Detectors (KID) are under study for their superior signal-to-noise ratio and speed.

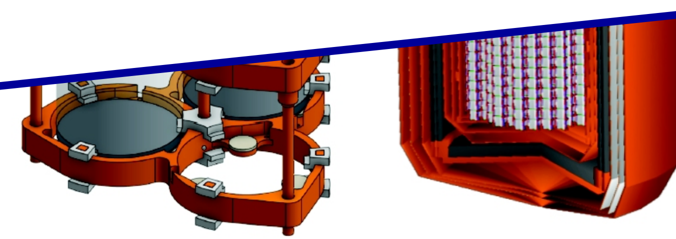
These technologies might be suitable also to read the feeble Cerenkov light emitted by TeO_2 enriched detectors (CUPID alternative solution).

L. Gironi et al., Phys. Rev. C 94 (2016) 054608
D.R. Artusa et al., Phys. Lett. B 767 (2017) 321
L .Bergé et al., Phys. Rev. C 97 (2018) 032501
K. Schaeffner et al., Astrop.Phys.69 (2015) 30

0 meV

D

)



CUPID: the future

CUORE Upgrade with Particle IDentification

Goal: explo... meV

Stra... D

Opti...

Other light detector technologies like Neganov-Luke-assisted NTDs, Transition Edge Sensors (TES) and microwave ... ectors (KID) are under study for their ... al-to-noise ratio

Activ...

Basel... e a ... en ... olu

...16) ...201 ...8) ...201

TDR an...

CUPID ...

CALDER

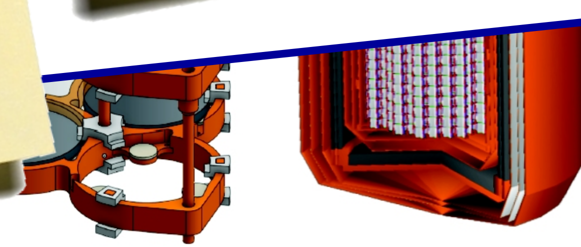
N. Casali, talk ID 143

CROSS

H. Khalife, poster ID 47
P. Carniti, poster ID 390

R&Ds

V. Singh, poster ID 248
J. Zhang, poster ID 329
G. Wang, poster ID 269



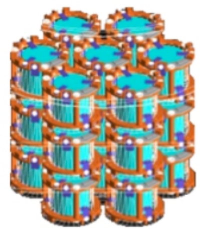
AMoRE

<u>A</u>dvanced <u>Mo</u>-based <u>R</u>are process <u>E</u>xperiment

$^{40}Ca^{100}MoO_4$

~ 1.5 kg

AMoRE Pilot



$^{40}Ca^{100}MoO_4$

~ 5 kg

AMoRE-I

$X^{100}MoO_4$

200 kg

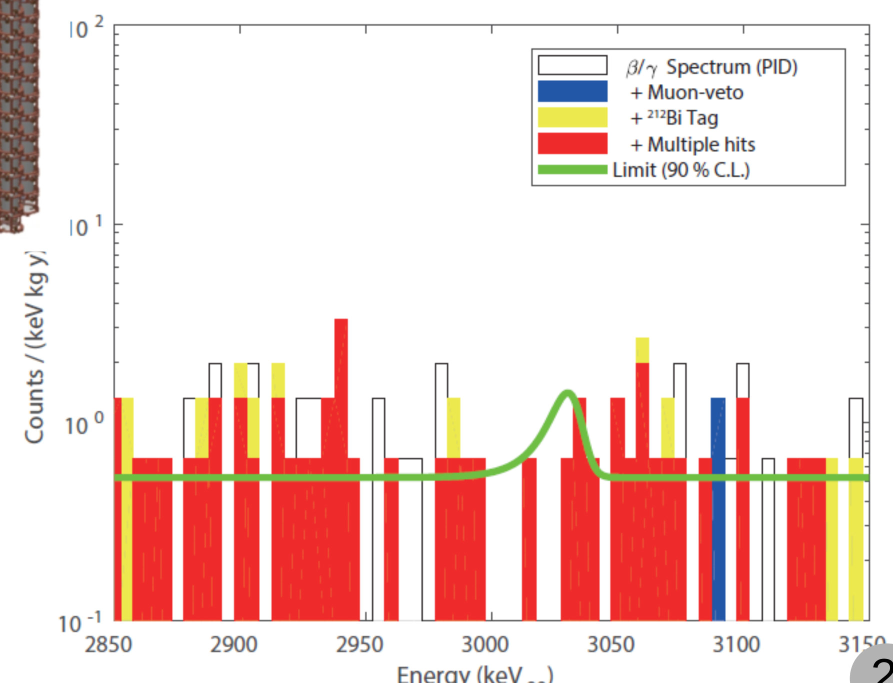
AMoRE-II

ckky : counts/ (keV kg year)

	AMoRE-Pilot	AMoRE-I	AMoRE-II
Crystal Mass (kg)	1.5	5	200
Backgrounds(ckky)	~ 10^{-2}	~ 10^{-3}	10^{-4}
$T_{1/2}$(year)	1.0×10^{24}	8.2×10^{24}	8.2×10^{26}
m_{bb} (meV)	380-719	130-250	13-25
Schedule	2017	2018	2020-2023

AMoRE pilot:
6 detector modules with
$^{48depl}Ca^{100}MoO_4$ absorbers

- MMC as phonon sensor
- Ge-wafer + MMC as light detector



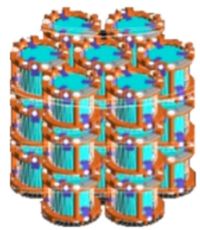
AMoRE

Advanced Mo-based Rare process Experiment

$^{40}Ca^{100}MoO_4$

~ 1.5 kg

AMoRE Pilot



$^{40}Ca^{100}MoO_4$

~ 5 kg

AMoRE-I

$X^{100}MoO_4$

200 kg

AMoRE-II

AMoRE pilot:
6 detector modules with $^{48depl}Ca^{100}MoO_4$ absorbers

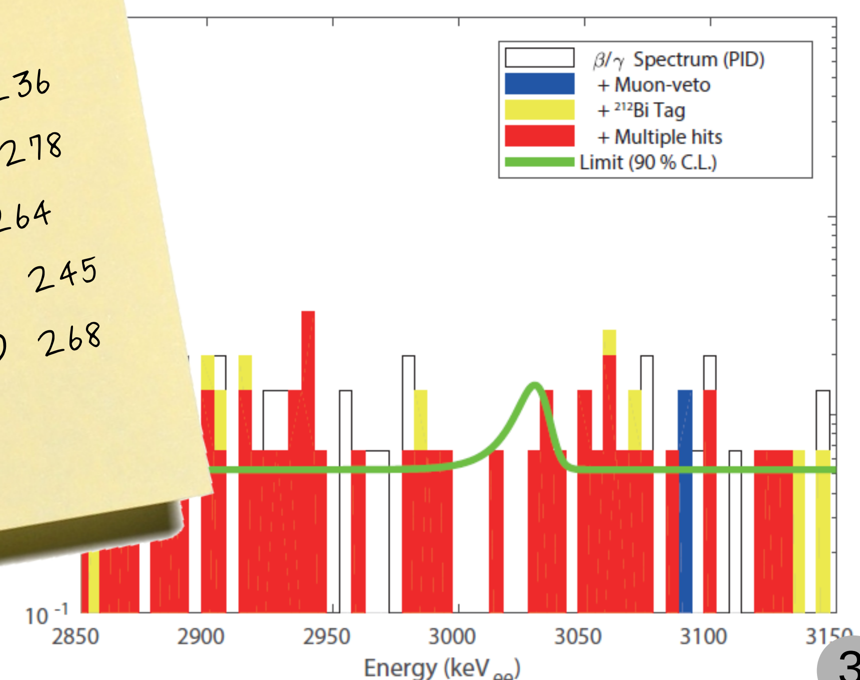
ckky : counts/ (keV kg year)

	AMoRE-Pilot	AMoRE-I	AMoRE-II
Crystal Mass (kg)	1.5	5	
Backgrounds(ckky)	~ 10^{-2}		
$T_{1/2}$(year)	1.0×10^{24}		
m_{bb} (meV)	380-719		
Schedule	2017		

AMORE

C.S. Khang, talk ID 236
D. Kwon, poster ID 278
K. Woo, poster ID 264
H.B. Kim, poster ID 245
S.G. Kim, poster ID 268

- MMC as phonon sen
- Ge-wafer + MMC as

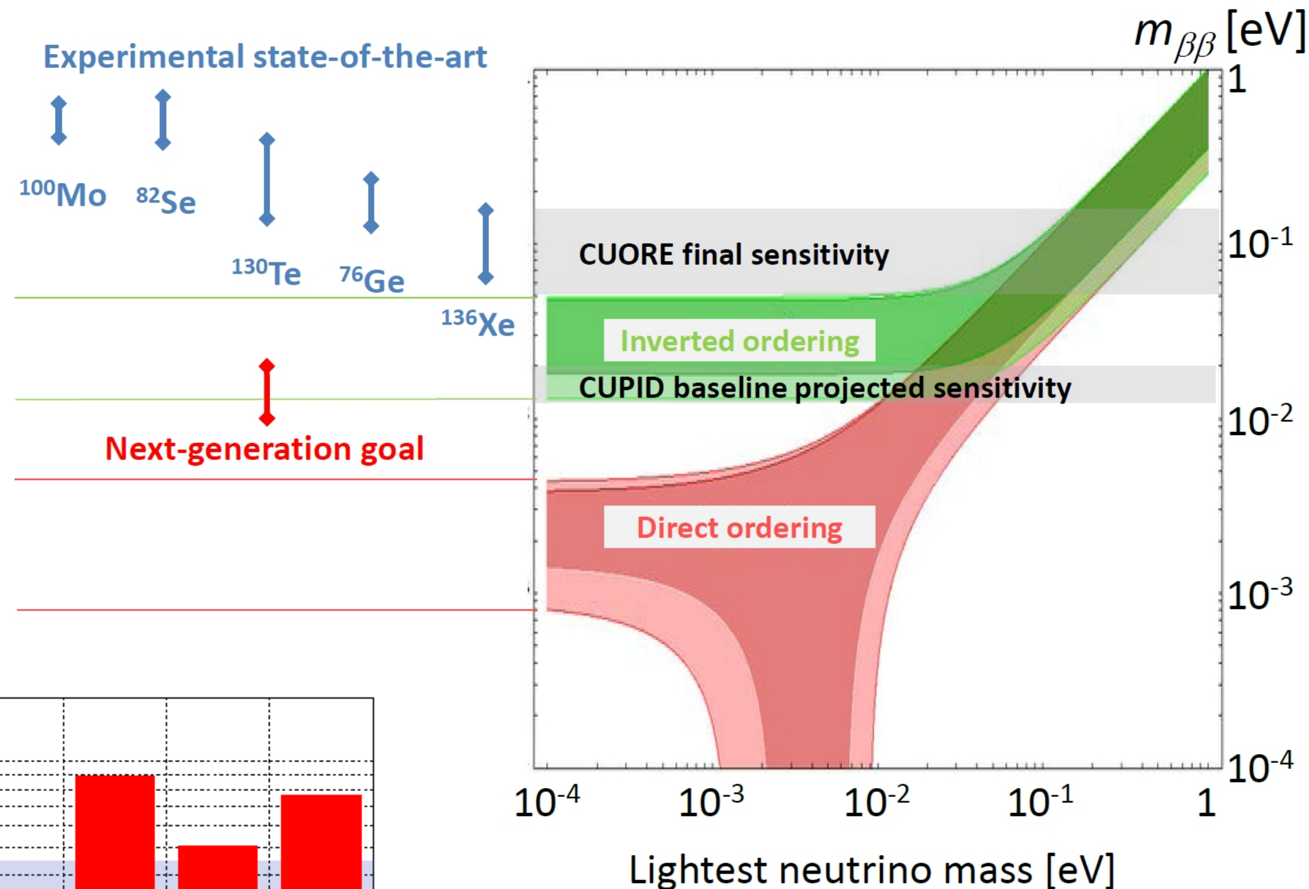


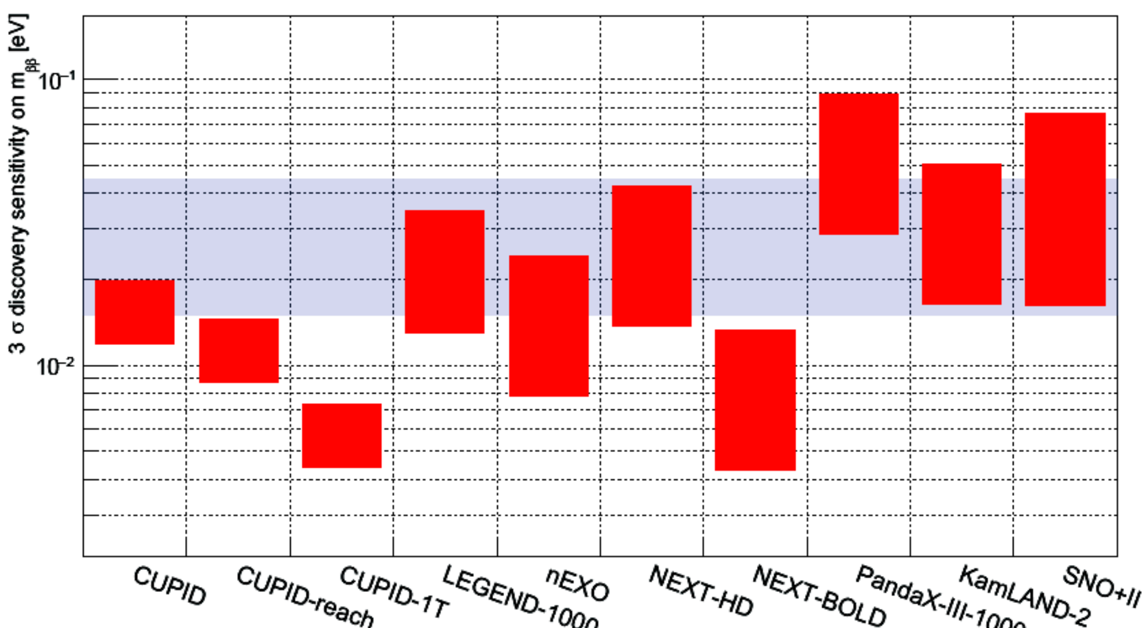
$0\nu\beta\beta$ searches: outlook

Present results

Proposed experiments

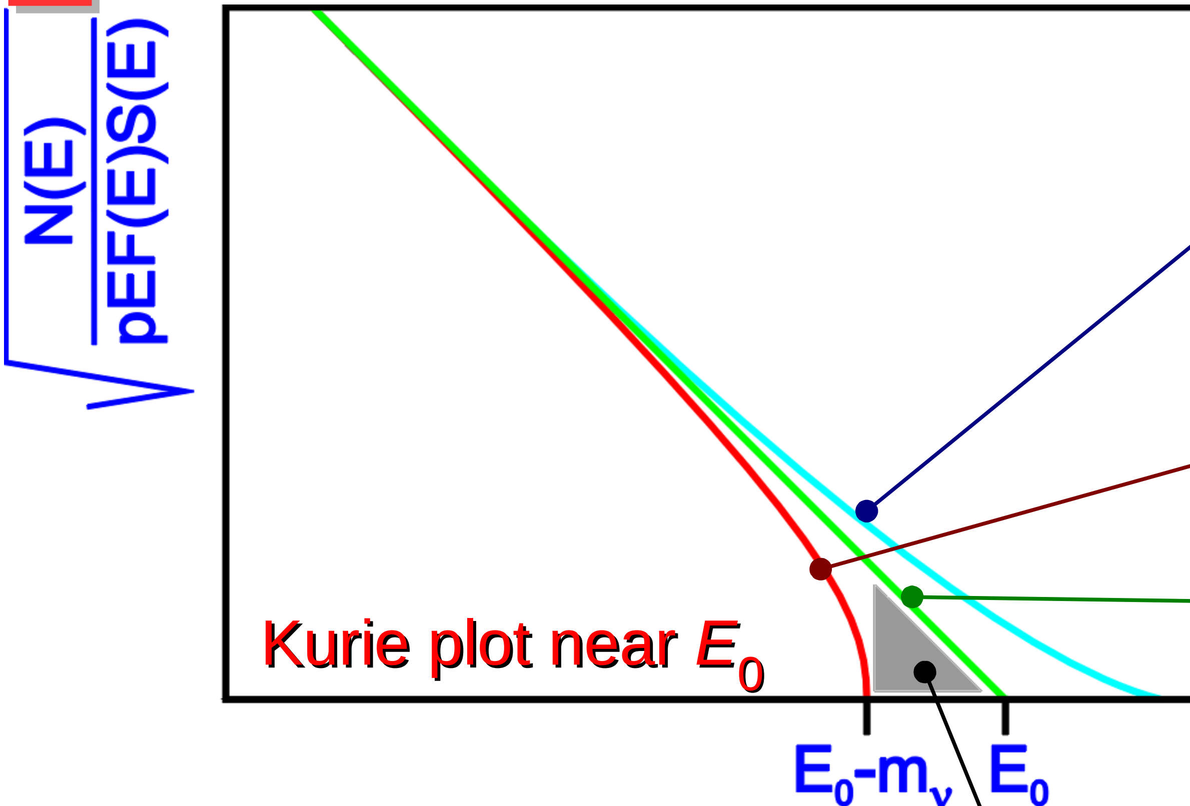
Far future





Discovery potential of proposed projects

Direct neutrino mass measurement



effect of:
- detector energy resolution
- background counts
- other systematics...

effect of $m_\nu \neq 0$

$N(E_\beta, m_{\bar{\nu}_e}=0)$

fraction F of decays below the end-point

$$F(\delta E) = \int_{E_0-\delta E}^{E_0} N(E_\beta, m_{\bar{\nu}_e}=0)\, dE \approx \left(\frac{\delta E}{E_0}\right)^3$$

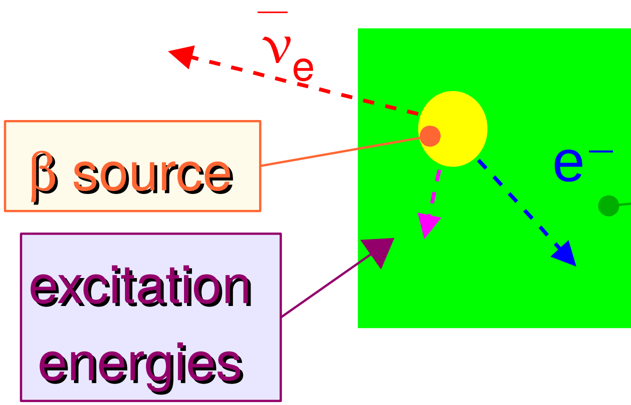
for ^{3}H β-decay $F(10\ \text{eV}) \approx 2 \times 10^{-10}$

General experimental requirements

- low endpoint energy E_0
- high statistics at the β spectrum end-point
- high energy resolution ΔE
- high signal-to-background ratio at the end-point
- small systematic effects

Direct neutrino mass measurement with LTDs

Calorimeters: source ⊆ detector



β calorimeter
ideally measures all the energy E released in the decay except for the $\bar{\nu}_e$ energy: $E=E_0-E_\nu$

Calorimeters measure the entire spectrum at once

use low E_0 β decaying isotopes to achieve enough statistics close to E_0

e.g. ^{187}Re: E_0 = 2.47 keV $\Rightarrow F(\delta E=10\ \text{eV}) \approx (\delta E/E_0)^3 = 7\times 10^{-8}$

Drawback:

Arrays of microcalorimeters (~ µg)

Pile-up
time unresolved superposition of β decays
for a source activity A_β, a time resolution τ_R
and an energy resolution function $R(E_\beta)$

$$N^{exp}(E_\beta) \approx (N(E_\beta) + \tau_R A_\beta \cdot N(E_\beta) \otimes N(E_\beta)) \otimes R(E_\beta)$$

Precursor ^{187}Re experiments

MANU (1999)
Genova

1 crystal of metallic Re: 1.6 mg

^{187}Re activity $\approx$ 1.6 Hz

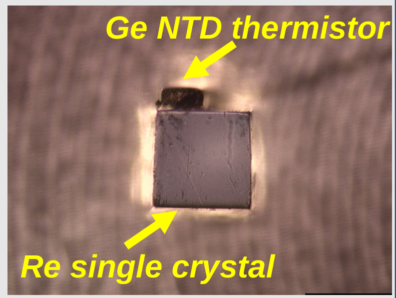
Ge-NTD thermistor

ΔE=96 eV FWHM

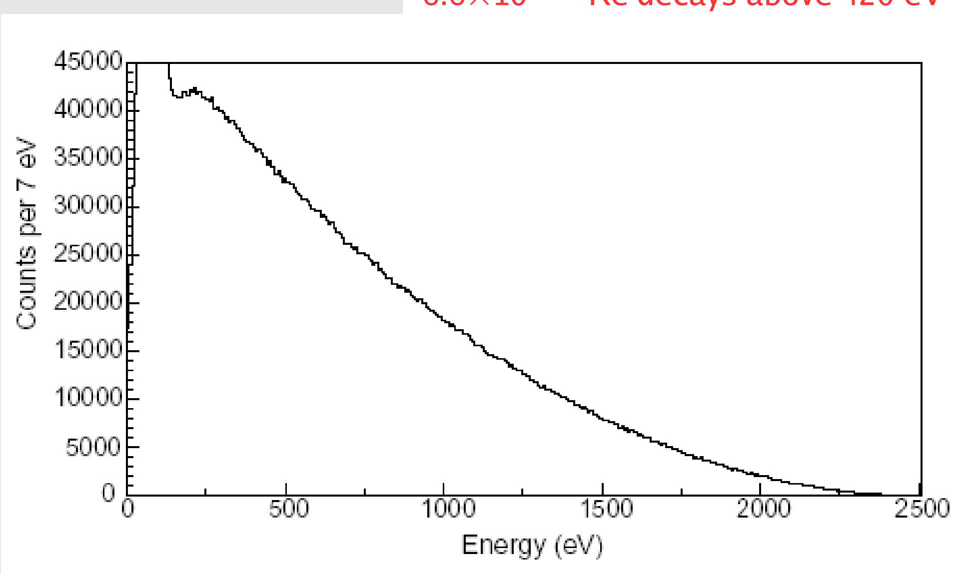
0.5 years live-time

$m_\nu^2 = 462\ ^{+579}_{-679}\ \mathrm{eV}^2$

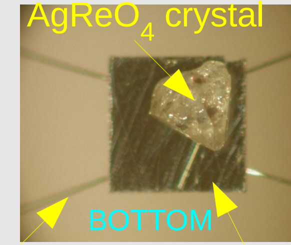
$m_\nu < 26$ eV (95 % C.L.)



6.0×10^6 ^{187}Re decays above 420 eV

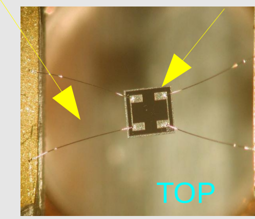


MIBETA (2002-2003)
Milano, Como, Trento



Al bonding wires

Si thermistor



10 $AgReO_4$ crystals: 2.71 mg

^{187}Re activity = 0.54 Hz/mg

Si thermistors (ITC-irst)

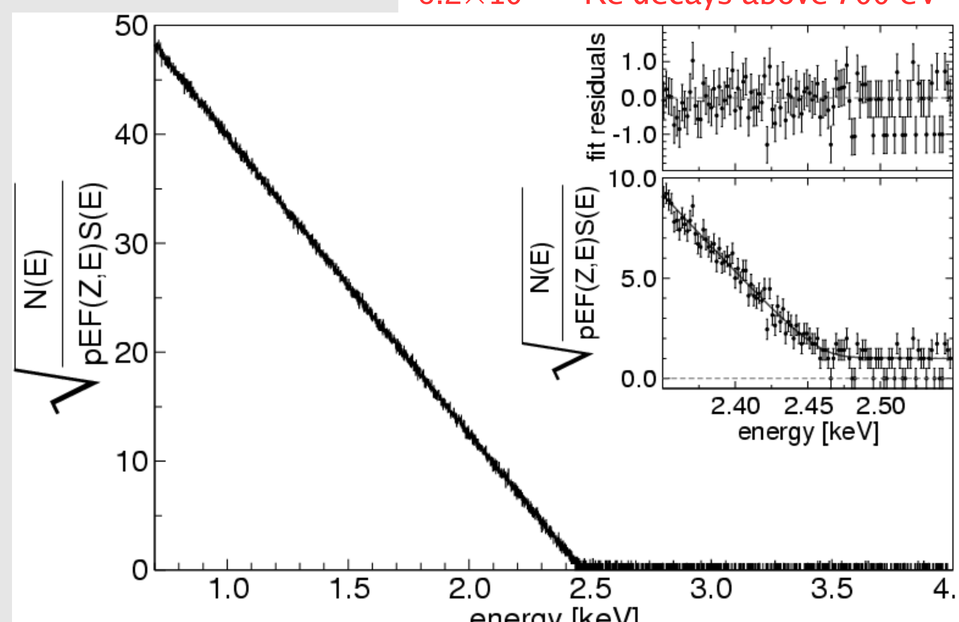
ΔE= 28.5 eV FWHM

0.6 years live time

$m_\nu^2 = -112 \pm 207_{stat} \pm 90_{sys}\ \mathrm{eV}^2$

$m_\nu < 15$ eV (90 % C.L.)

6.2×10^6 ^{187}Re decays above 700 eV



MS et al., Nucl. Instr. Meth. A 520 (2004) 125

Precursor ^{187}Re experiments

MANU (1999)
Genova

1 crystal of metallic Re: 1.6 mg

^{187}Re activity $\approx$ 1.6 Hz

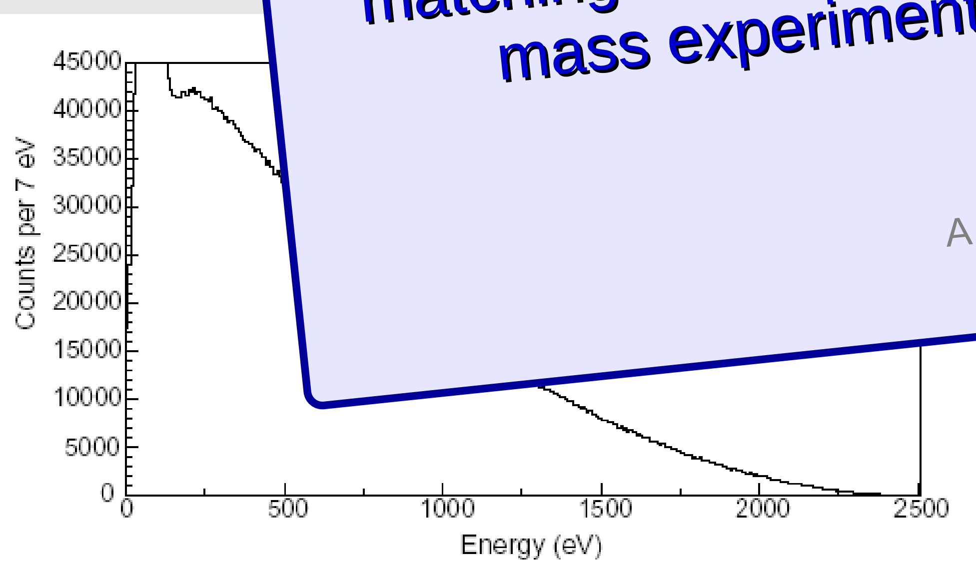
Ge-NTD thermistor

ΔE=96 e

0.5 years

m_{ν}^2 = 46

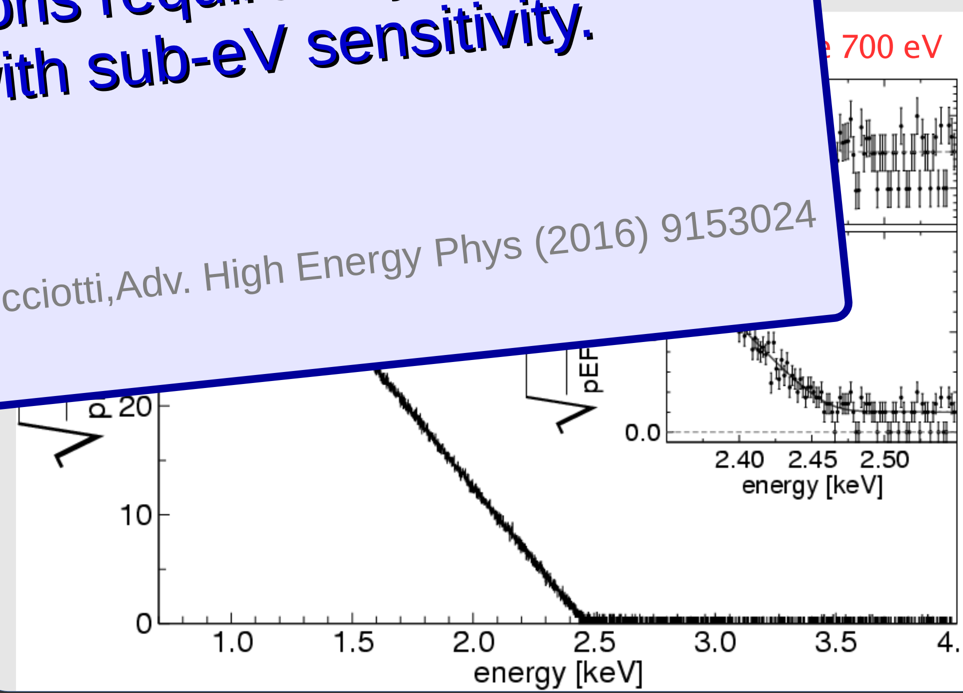
m_{ν} < 26 e



MIBETA (2002-2003)
Milano, Como, Trento

10 $AgReO_4$ crystals: 2.71 mg

^{187}Re activit



The ^{187}Re project MARE was abandoned due to the impossibility to fabricate rhenium microcalorimeters matching the specifications required by a neutrino mass experiment with sub-eV sensitivity.

A. Nucciotti, Adv. High Energy Phys (2016) 9153024

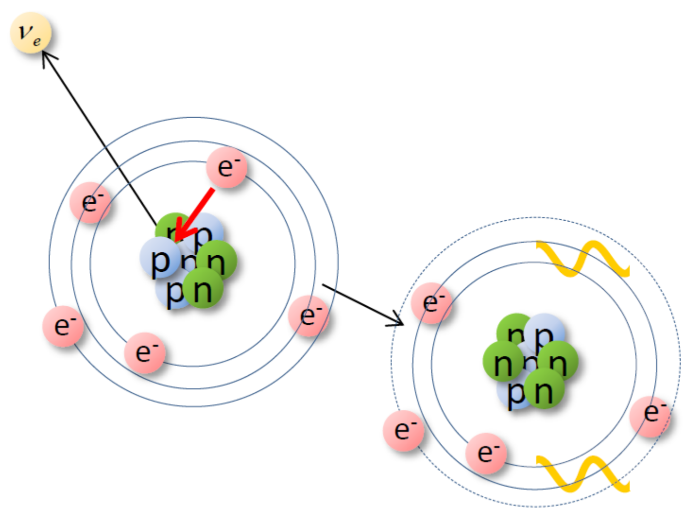
MS et al., Nucl. Instr. Meth. A 520 (2004) 125

Electron capture calorimetric experiments

$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

electron capture from shell ≥ M1

A. De Rújula and M. Lusignoli, Phys. Lett. B 118 (1982) 429



$m(\nu_e) < 225$ eV

Springler et al.,
Phys. Rev. A 35 (1987) 679

Atomic de-excitation:

- X-ray emission
- Auger electrons
- Coster-Kronig transitions

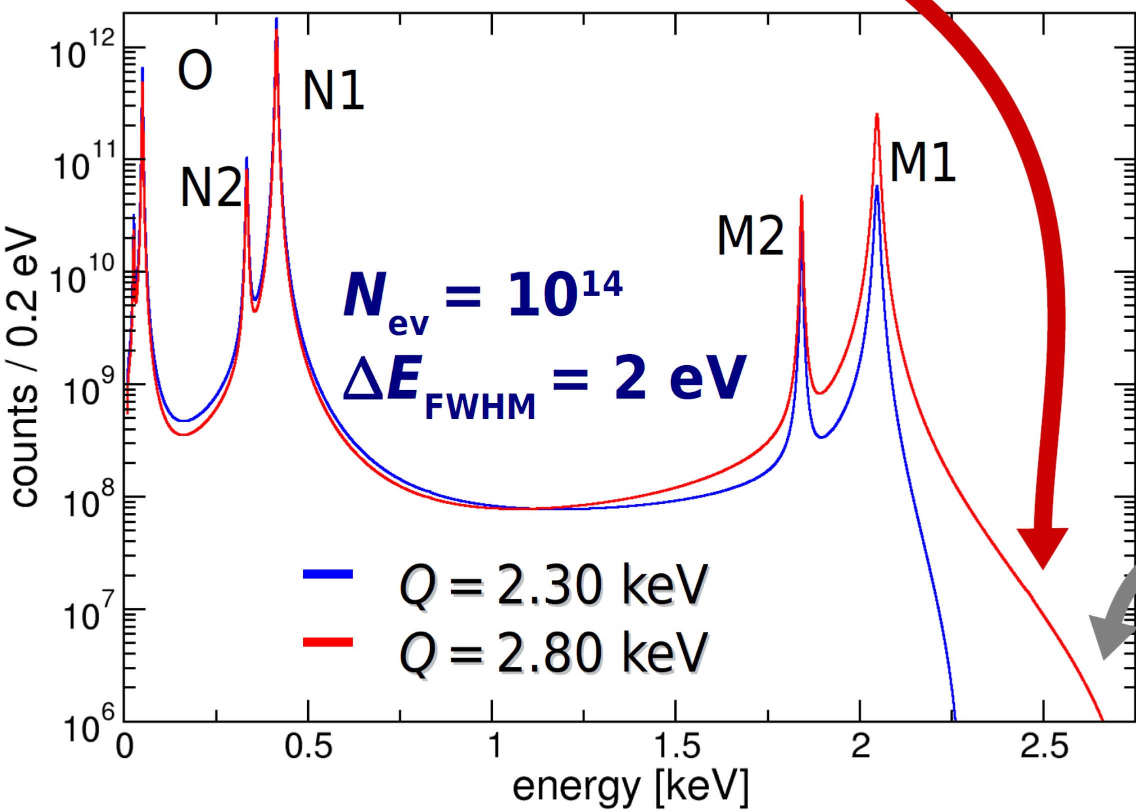
- **calorimetric measurement of Dy atomic de-excitations**
- ***Q* = 2.83 keV** (determined with Penning trap in 2015)
  - end-point rate and **ν mass sensitivity** depend on ***Q* – *E*$_{M1}$**
- **$\tau_{1/2}$ ≈ 4570 years** → 2×10^{11} ^{163}Ho nuclei ↔ 1Bq

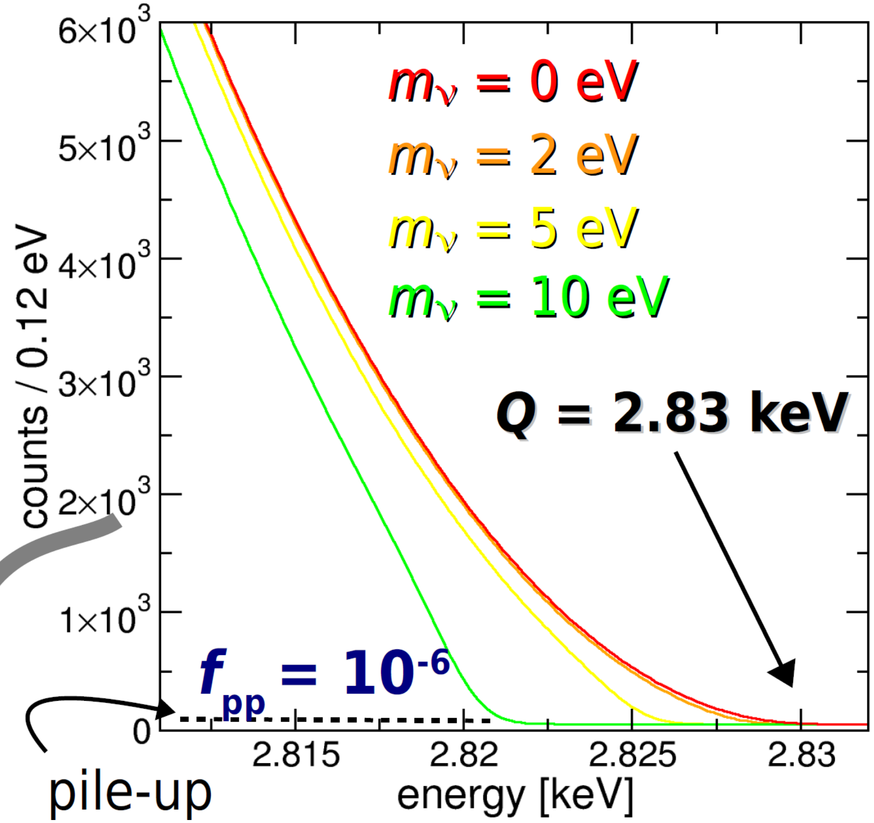
Thanks A.Nucciotti, L.Gastaldo

^{163}Ho calorimetric spectrum

Effect of the neutrino mass at the end-point of the de-excitation spectrum

$$N(E_c) = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2 - \boldsymbol{m_\nu}^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$

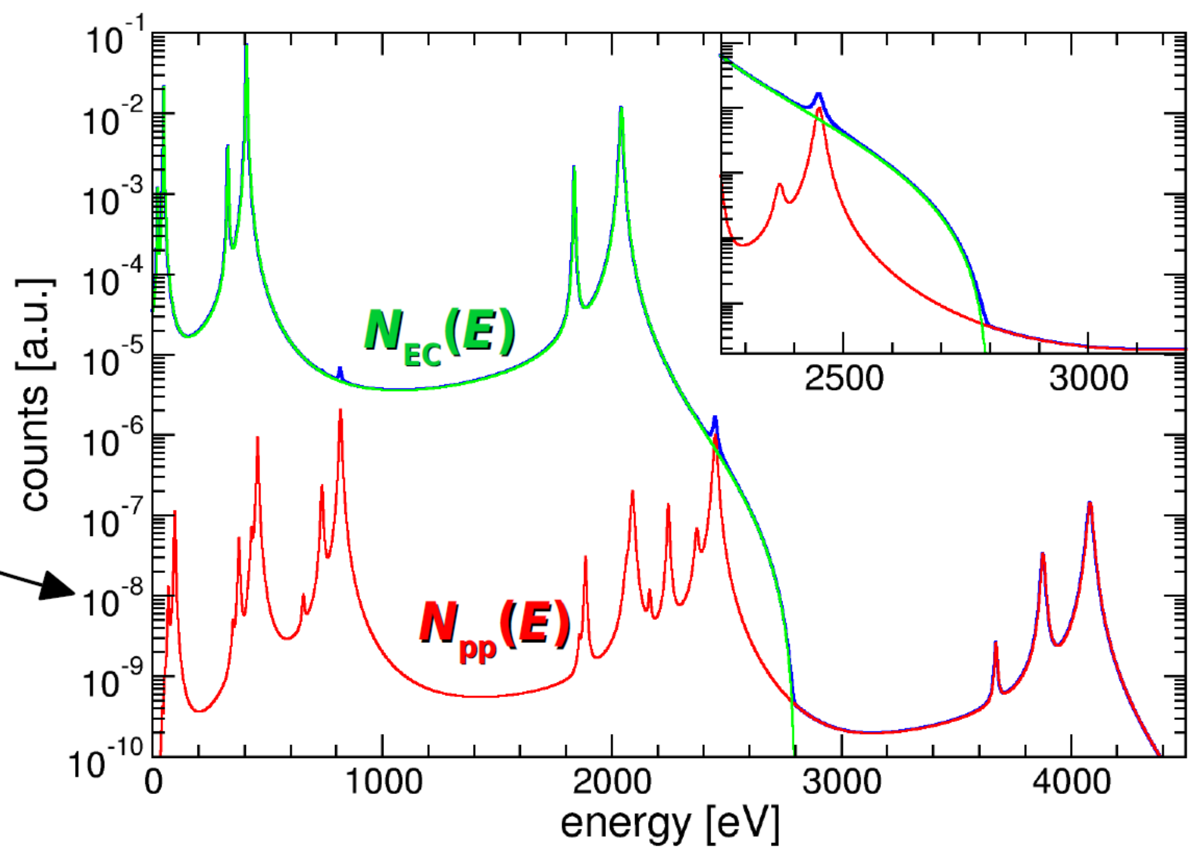




Pulse pile-up effect

- calorimetric measurement ↔ **detector speed is critical**
- accidental coincidences → complex pile-up spectrum
  - $N_{pp}(E) = f_{pp}\, N_{EC}(E) \otimes N_{EC}(E)$ with $f_{pp} \approx A_{EC}\, \tau_R$

A_{EC} EC activity per detector
τ_R time resolution (≈rise time)



Q = 2800 eV
$f_{pp} = 10^{-4}$

$N_{EC}(E)$ without higher order processes (shake up / shake off)

Calorimetric m_ν measurement detector “MUSTs”

For a statistical sensitivity on m_ν of ~1 eV

- ✔ High statistics at the end-point region: $N_{ev} > 10^{13}$
- ✔ Unresolved pile-up fraction $f_{pp} < \sim 10^{-4}$
- ✔ High energy resolution $\Delta E_{FWHM} < 3$ eV
- ✔ Low background level $\sim 10^{-4}$ c/eV/det/day

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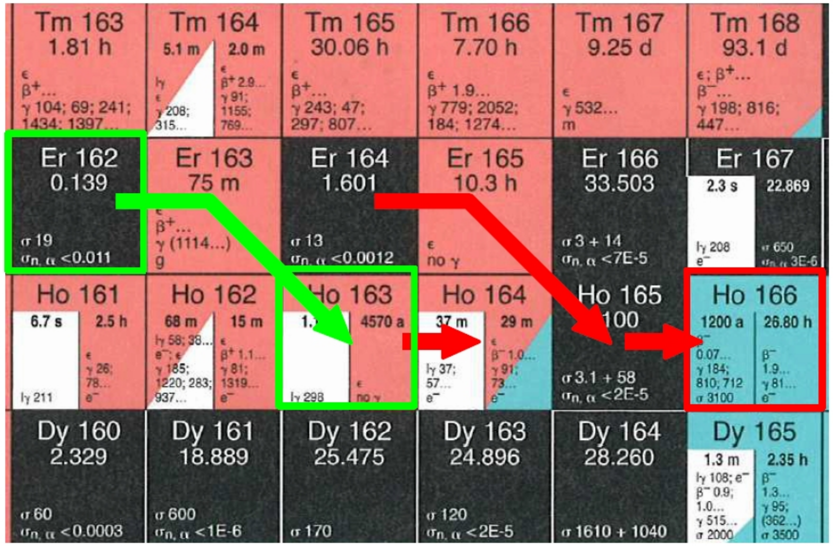
- ✔ Low background level $\sim 10^{-4}$ c/eV/det/day

Challenges:

- ^{163}Ho production

^{162}Er (n,γ) ^{163}Er $\sigma_{thermal} \approx 20$b

^{163}Er → ^{163}Ho + ν_e $\tau_{1/2}^{EC} \approx 75$min



neutron activation

Calorimetric m_ν measurement detector “MUSTs”

For a statistical sensitivity on m_ν of ~1 eV

- ✔ High statistics at the end-point region: $N_{ev} > 10^{13}$
- ✔ Unresolved pile-up fraction $f_{pp} < \sim 10^{-4}$
- ✔ High energy resolution $\Delta E_{FWHM} < 3$ eV
- ✔ Low background level ~ 10^{-4} c/eV/det/day

Challenges:

- ^{163}Ho production
- Detector technology (ECHo, HOLMES)

Calorimetric m_ν measurement detector "MUSTs"

For a statistical sensitivity on m_ν of ~1 eV

- ✔ High statistics at the end-point region: $N_{ev} > 10^{13}$
- ✔ Unresolved pile-up fraction $f_{pp} <\sim 10^{-4}$
- ✔ High energy resolution $\Delta E_{FWHM} < 3$ eV
- ✔ Low background level ~ 10^{-4} c/eV/det/day

Challenges:

- **^{163}Ho production**
- **Detector technology (ECHo, HOLMES)**
- **Construction of high performing detector arrays**

Calorimetric m_ν measurement detector "MUSTs"

For a statistical sensitivity on m_ν of ~1 eV

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Challenges:

- ^{163}Ho production
- Detector technology (ECHo, HOLMES)
- Construction of high performing detector arrays
- ^{163}Ho embedment in the detectors

Calorimetric m_ν measurement detector "MUSTs"

For a statistical sensitivity on m_ν of ~1 eV

- ✓ High statistics at the end-point region: $N_{ev} > 10^{13}$
- ✓ Unresolved pile-up fraction $f_{pp} < \sim 10^{-4}$
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Challenges:

- ^{163}Ho production
- Detector technology (ECHo, HOLMES)
- Construction of high performing detector arrays
- ^{163}Ho embedment in the detectors
- Stable measurement in a low background environment

Calorimetric m_ν measurement detector "MUSTs"

For a statistical sensitivity on m_ν of ~1 eV

- ✓ High statistics at the end-point region: $N_{ev} > 10^{13}$
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Challenges:

- ^{163}Ho production
- Detector technology (ECHo, HOLMES)
- Construction of high performing detector arrays
- ^{163}Ho embedment in the detectors
- Stable measurement in a low background environment
- Theoretical shape of the ^{163}Ho spectrum

→
Faessler et al., Phys. Rev. C 91 (2015) 045505
De Rujula et al., JHEP 05 (2016) 015
Brass et al., Phys. Rev. C 97 (2015) 054620

Detector technology

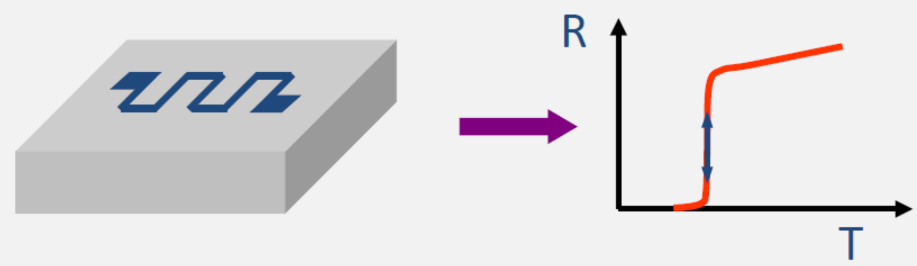
HOLMES

M. Faverzani, talk ID 404
A. Puiu, talk ID 393
E. Ferri, poster ID 408
M. Borghesi, poster ID 398
M. DeGerone, poster ID 389
A. Giachero, poster ID 397

ECHo

F. Mantegazzini, talk ID 149
F. Mantegazzini, poster ID 342
O. Sander, poster ID 317
A. Refenberger, poster ID 260

Resistance at superconducting transition,TES



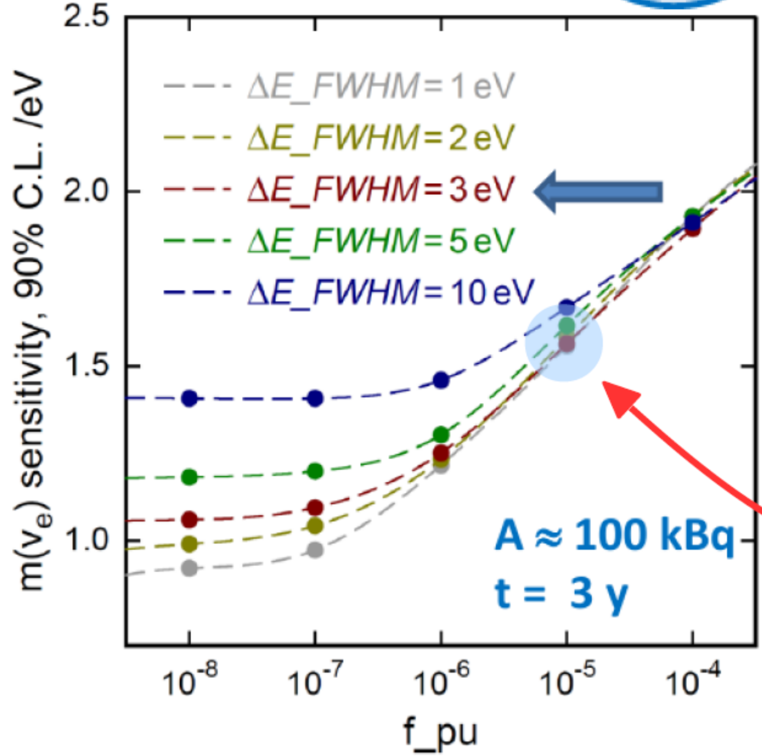
K.D. Irwin and G.C. Hilton, Topics in Applied Physics 99 (2005) 63

Magnetization of paramagnetic material, MMC

A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics 99 (2005) 63

Expected sensitivity of ^{163}Ho m_ν experiments

ECHo-100k (2018 – 2021)

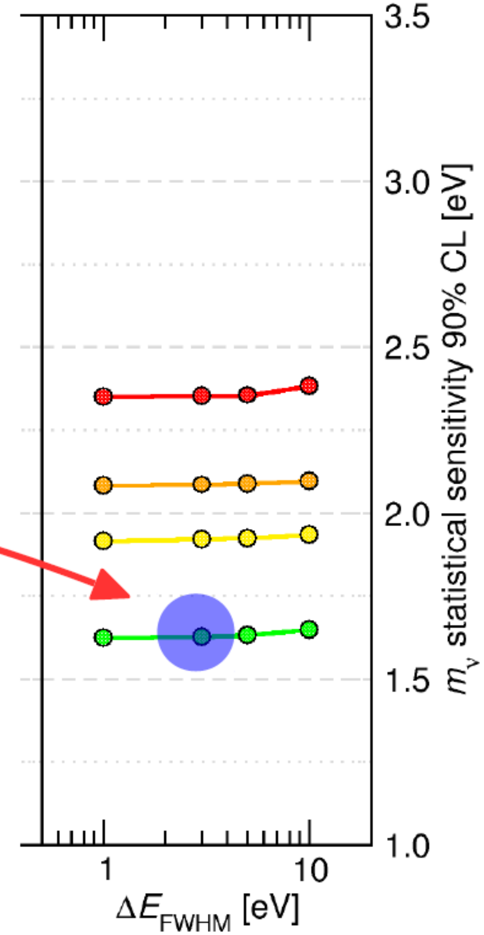


$m(\nu_e) < 1.5$ eV 90% C.L.

Activity per pixel 10 Bq
Number of detectors 12000
Readout: microwave SQUID multiplexing

$N_{det}t_M$ = 1000 det × 3 y

A_{EC} = 300 c/s/det

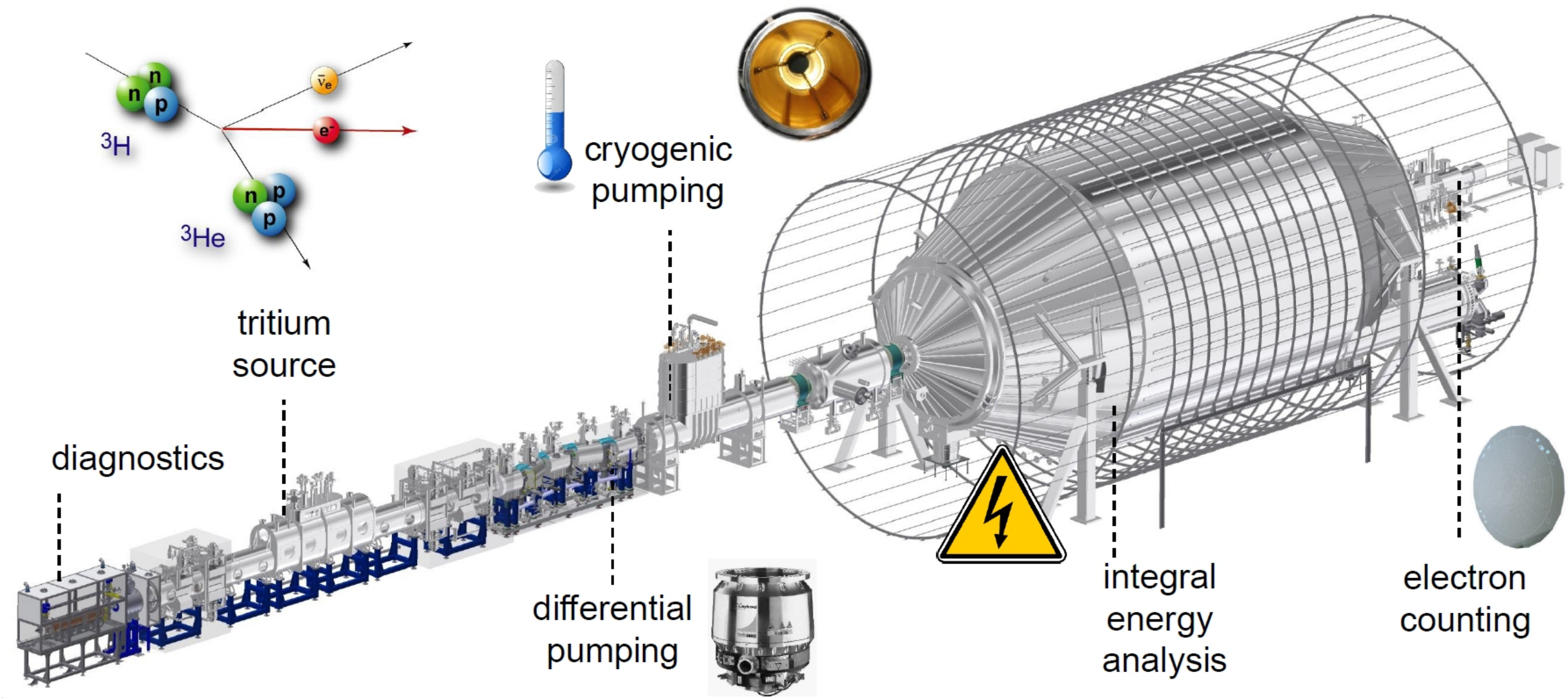


… to be compared with KATRIN

current upper limit on anti-neutrino mass from spectometer experiments: 2.2 eV

KATRIN overview: 70 m long beamline

Karlsruhe Institute of Technology



sensitivity goal: 0.2 eV

first results to be published soon

Neutrinos and the precision era

Oscillation experiments have entered the precision era

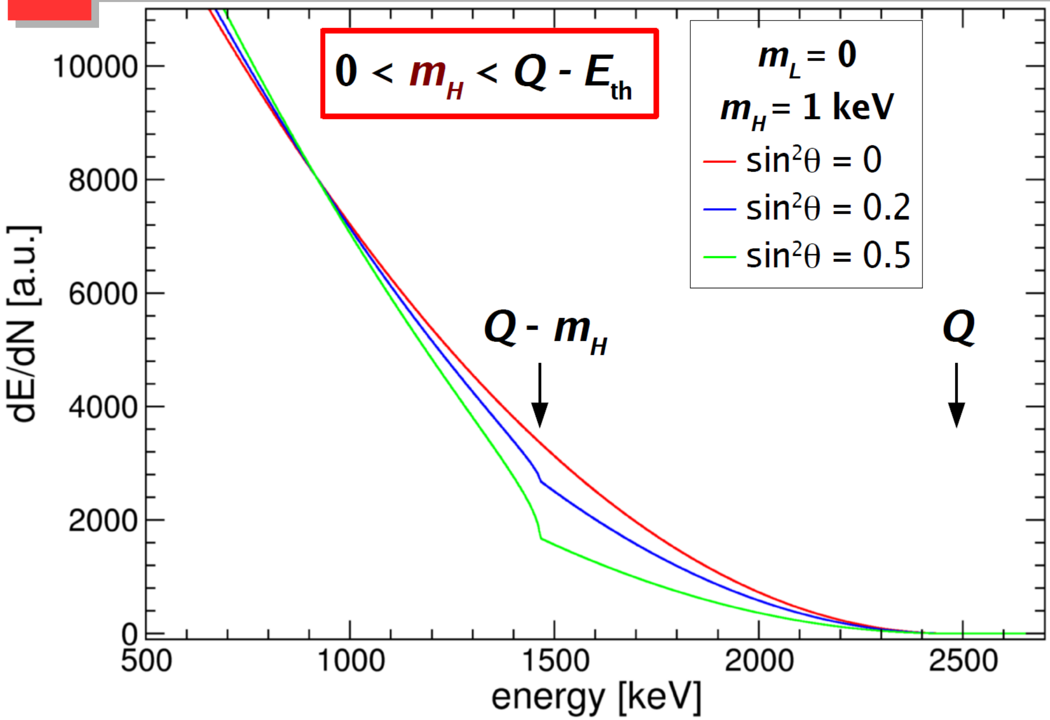
Neutrinos and the precision era

Oscillation experiments have entered the precision era

Future goals are:

- Establishing the robustness of the three-flavor oscillations with respect to new physics beyond the Standard Model

Sterile neutrinos with LTDs

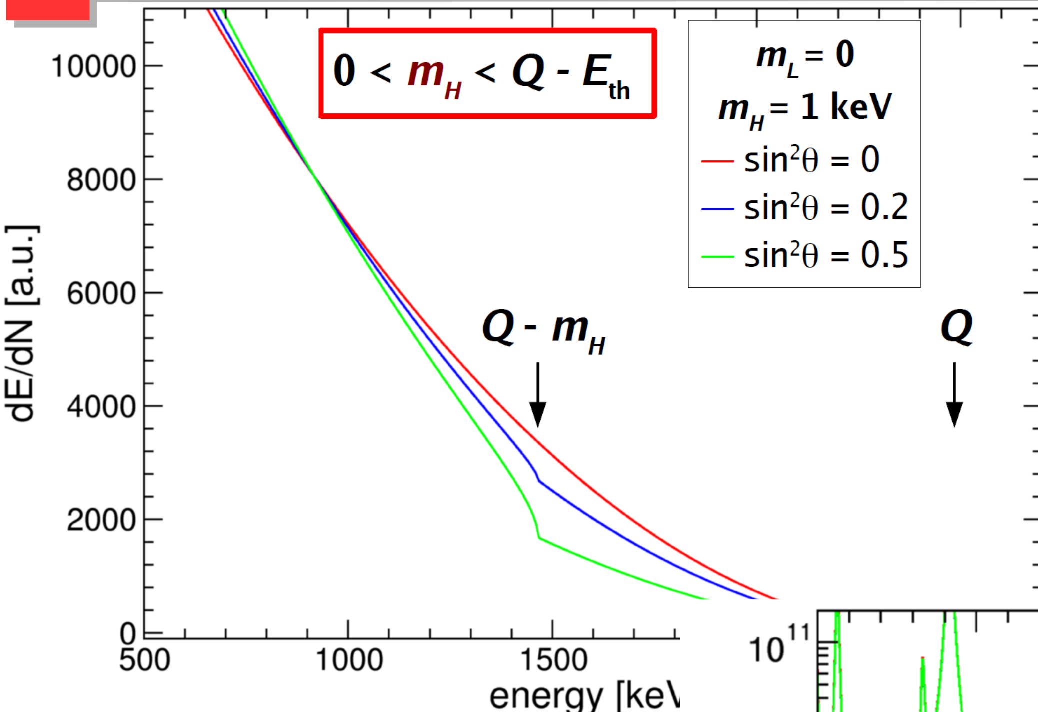


Heavy neutrino emission in ^{187}Re β decay

$$\nu_e = \nu_L \cos\theta + \nu_H \sin\theta$$

$$N_\beta(E, m_L, m_H, \theta) = \cos^2\theta N_\beta(E, m_L) + \sin^2\theta N_\beta(E, m_H)$$

Sterile neutrinos with LTDs

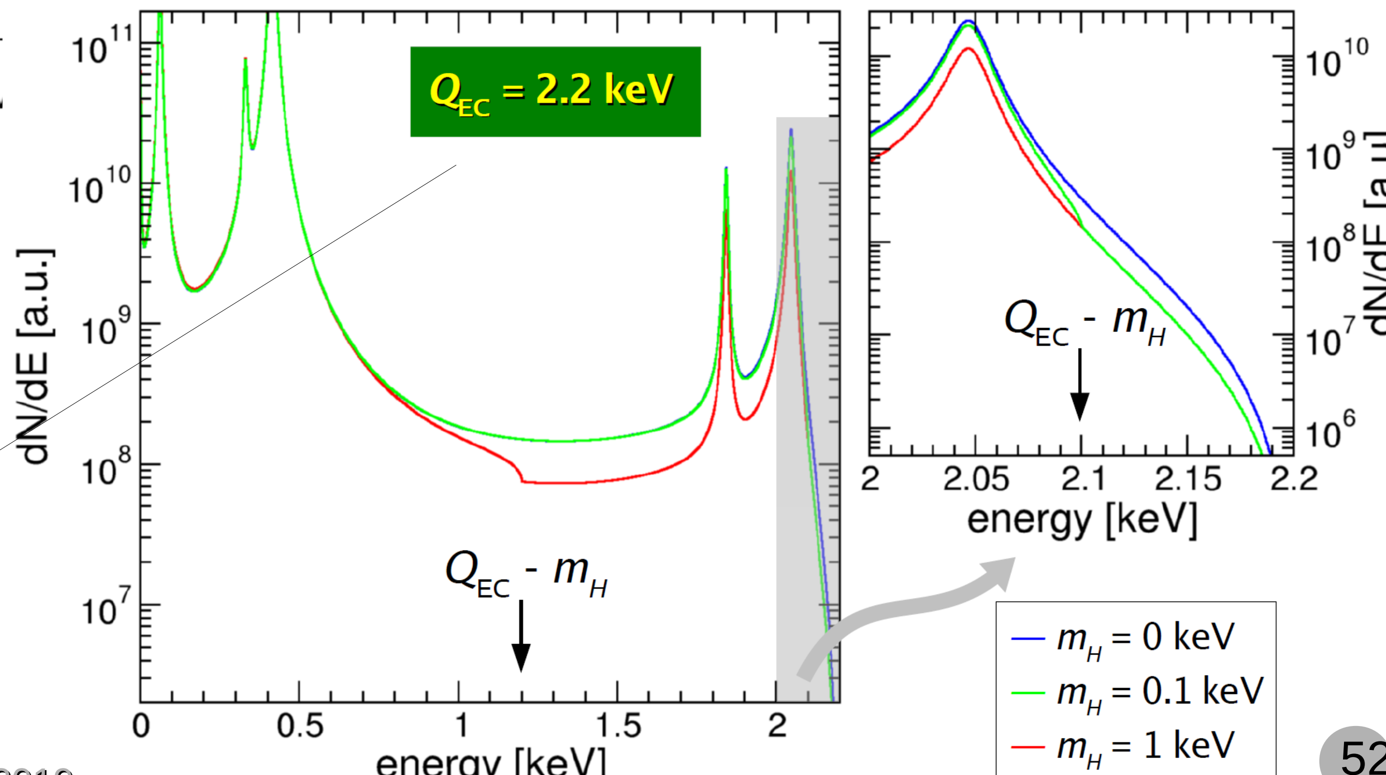


Heavy neutrino emission in ^{187}Re β decay

$$\nu_e = \nu_L \cos\theta + \nu_H \sin\theta$$

Heavy neutrino emission in ^{163}Ho EC decay

calculation to be updated with actual Q-value



Neutrinos and the precision era

Oscillation experiments have entered the precision era

Future goals are:

- Establishing the robustness of the three-flavor oscillations with respect to new physics beyond the Standard Model
- **Determination of the CP-violating phase and the neutrino mass ordering**

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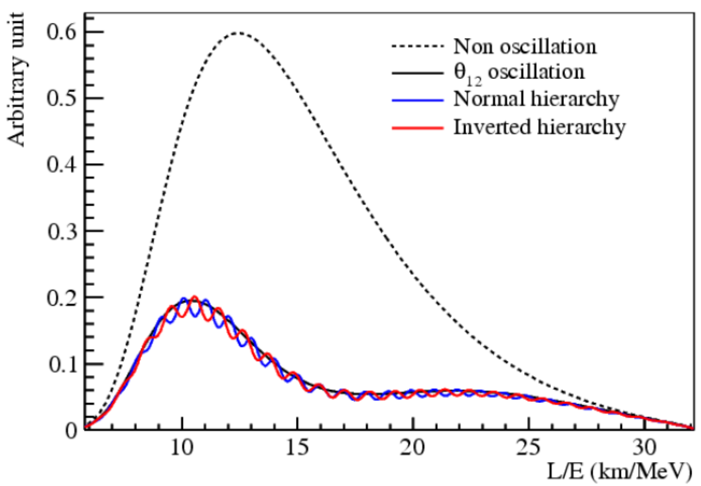
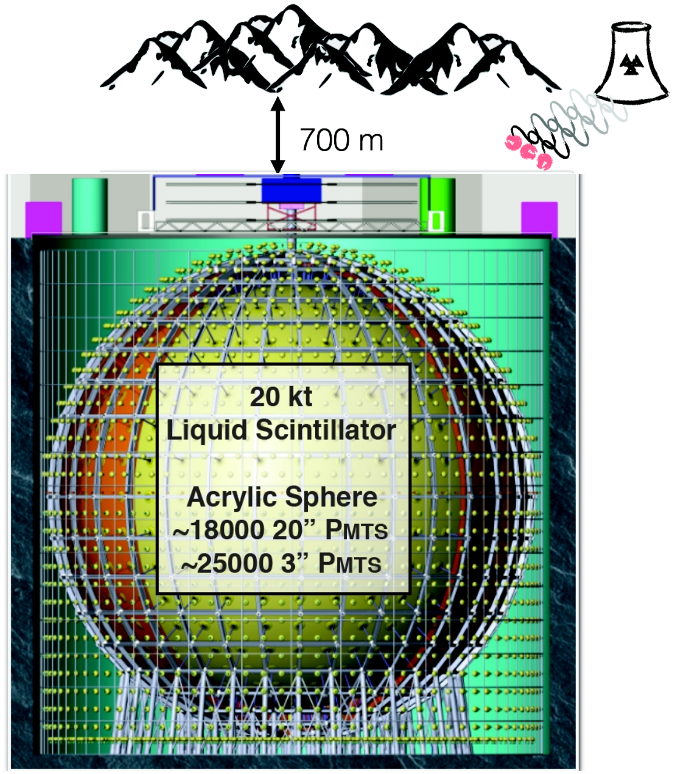


e.g.: JUNO
J. Phys. G 43 (2016) 030401



Neutrinos and the precision era

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Future goals are:

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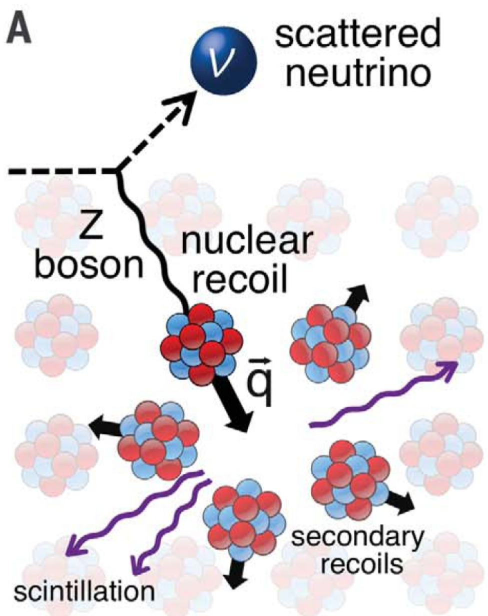
- Determination of the CP-violating phase and the neutrino mass ordering

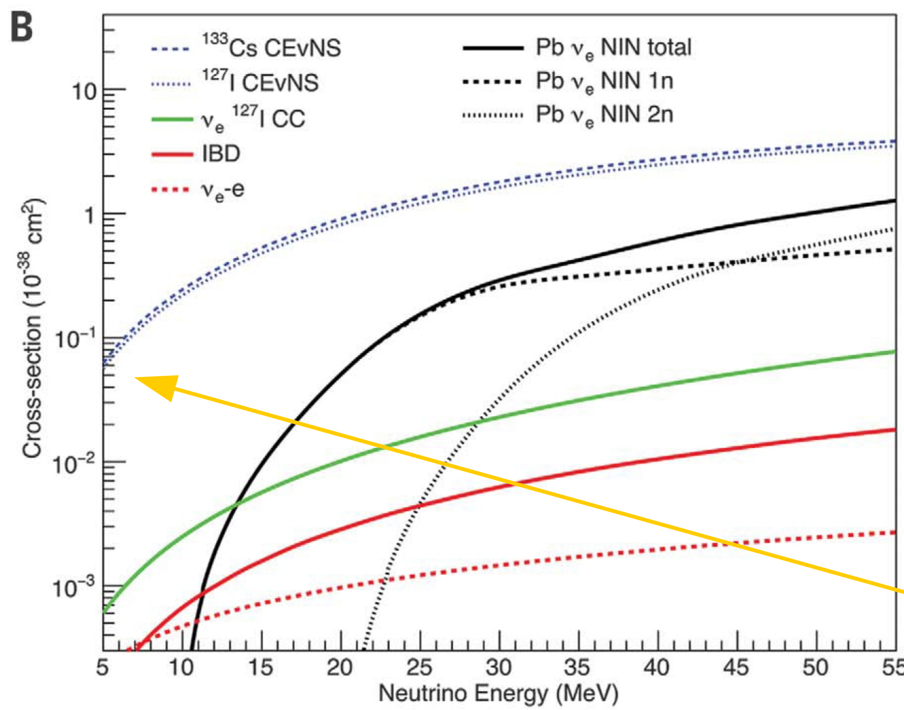
Additional interactions beyond the SM ones affecting the neutrino sector – Non Standard Interactions (NIS) – may have severe consequences on future experiments.

Pilar et al., Phys. Rev. D 94 (2016) 055005

→ **Scattering experiments are important to constrain this scenario**

Coherent elastic ν-nucleus scattering (CEνNS)





CEνNS

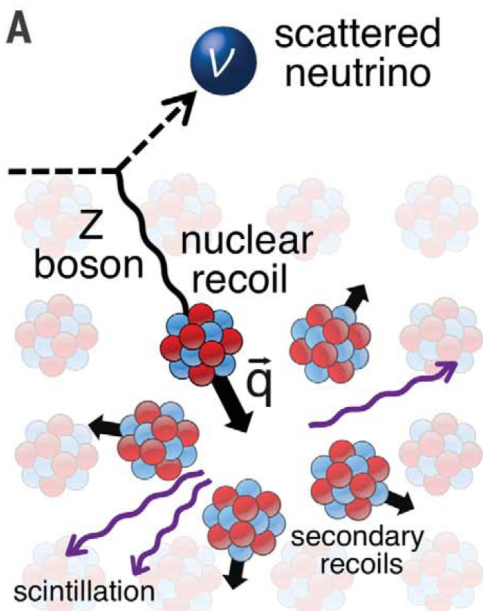
strongly enhanced cross-section

Inverse Beta Decay

no energy threshold

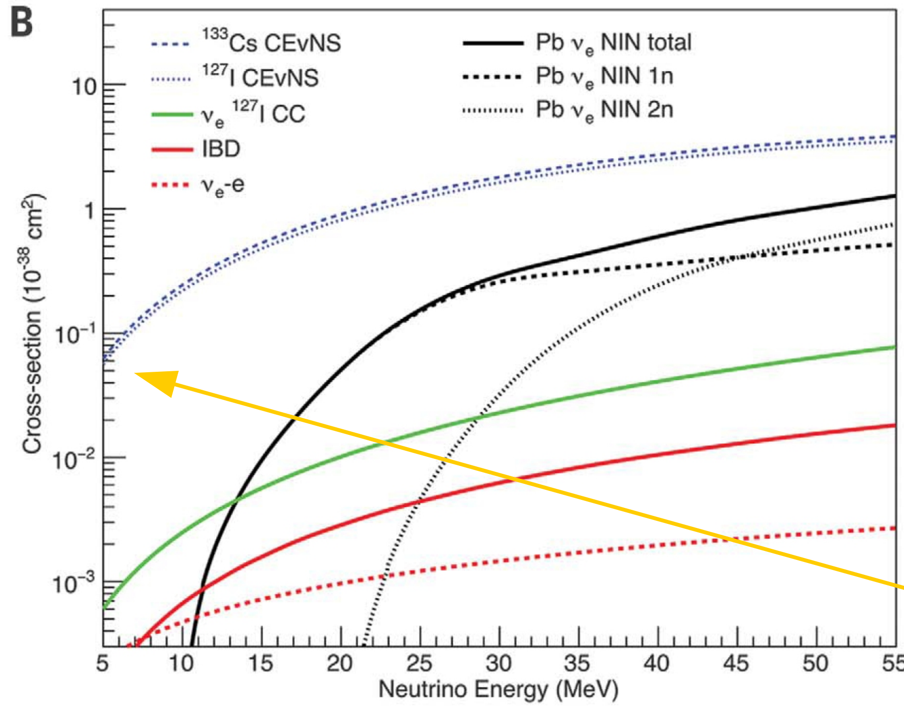
Challenge:
very low energy nuclear recoils

Coherent elastic ν-nucleus scattering (CEνNS)



Challenge: very low energy nuclear recoils

Akimov et al., Science 357 (2017) 1123



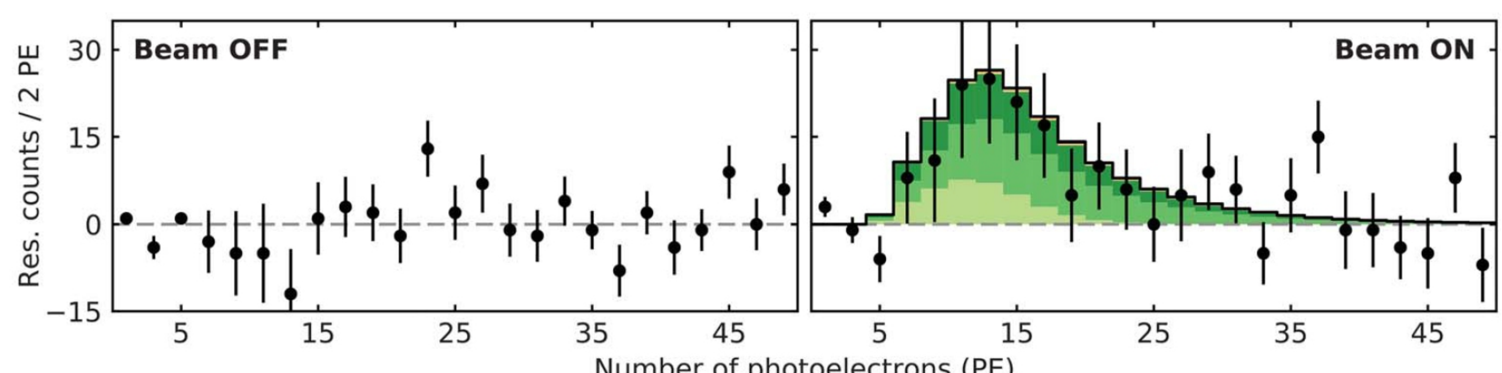
CEνNS

strongly enhanced cross-section

Inverse Beta Decay

no energy threshold

First observation by COHERENT
@ neutron spallation source (Oakridge)
with 14.6 kg CsI[Na] scintillating crystals + PMTs



CevNS with LTDs

Goal: study neutrino physics at low energy with high precision

COHERENT – great! | Why NU–CLEUS ?

Error budget

Observed:	134±22 events
Expected (SM):	173±48 events

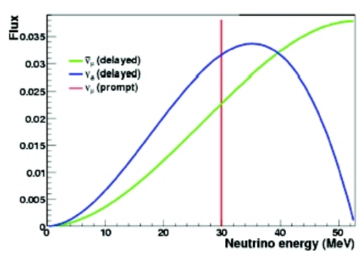
stat. **16%**

syst. **30%**

Aims for few percent level

Neutrino source

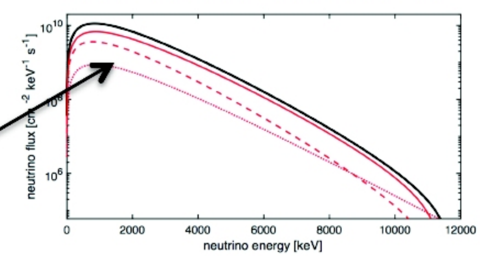
Stopped-pion-source



Nuclear power reactor

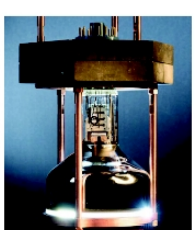
Reactor neutrino physics!

Low energy neutrinos



Detector

"conventional"



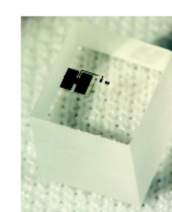
15cm

Threshold:
A few keV

cryogenic detector

Threshold:
A few 10's of eV

5mm

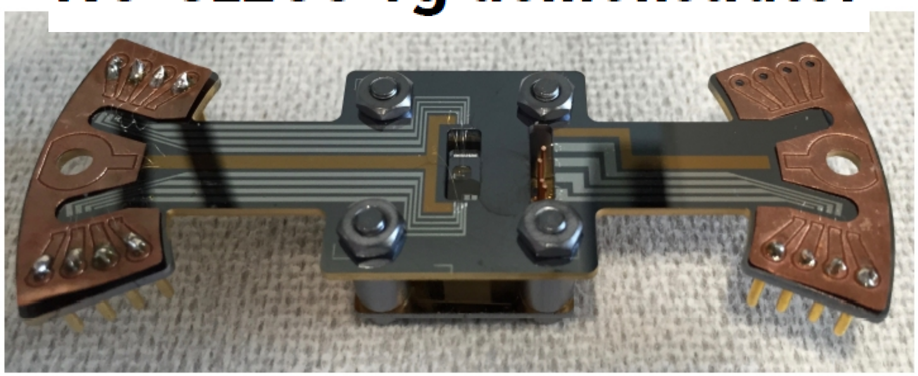


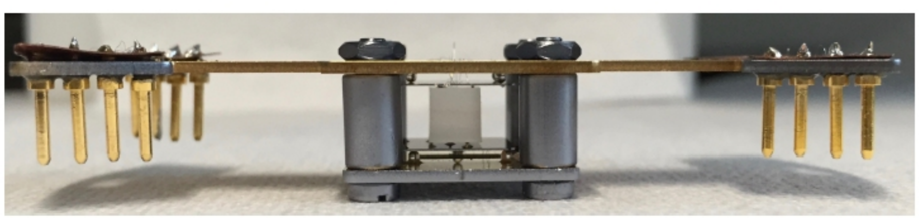
Raimund Strauss, GSSI Seminar, 2018

ν-CLEUS

NU-CLEUS detector prototype:
0.5 g Al_2O_3 detector

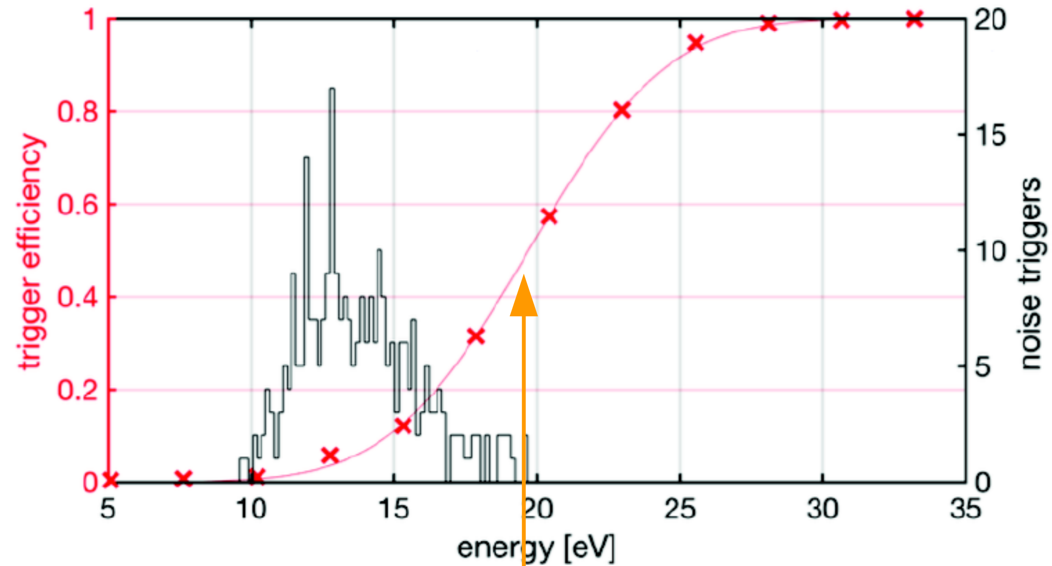
NU-CLEUS 1g demonstrator





- Sapphire and $CaWO_4$ crystals
- Flexible Si wafers as inner veto detectors

Trigger Efficiency



Strauss et al., Phys. Rev. D 96 (2017) 022009

E_{th} = 19.7 ± 1 eV

ν-CLEUS

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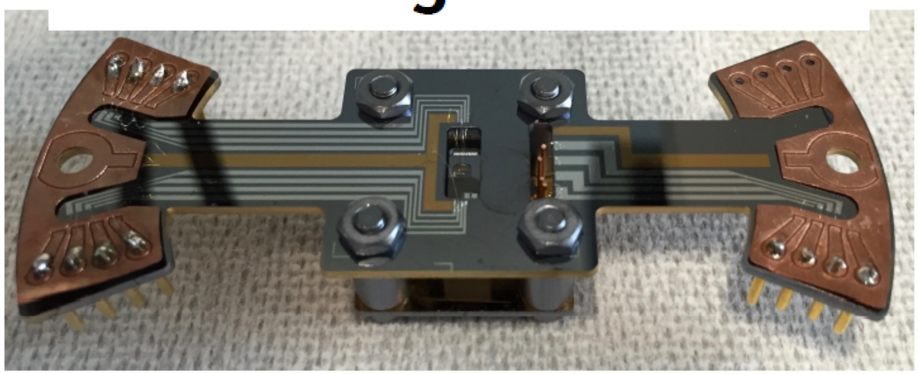
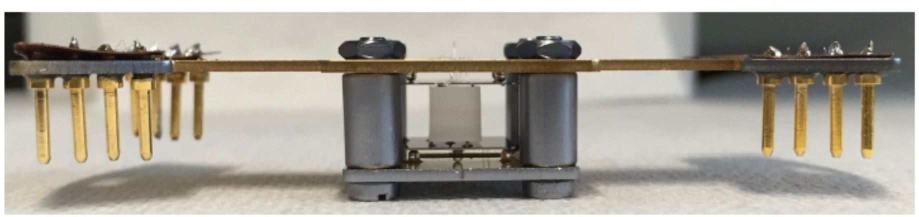
0.5 g Al_2O_3 detector

NU-CLEUS 1g demonstrator





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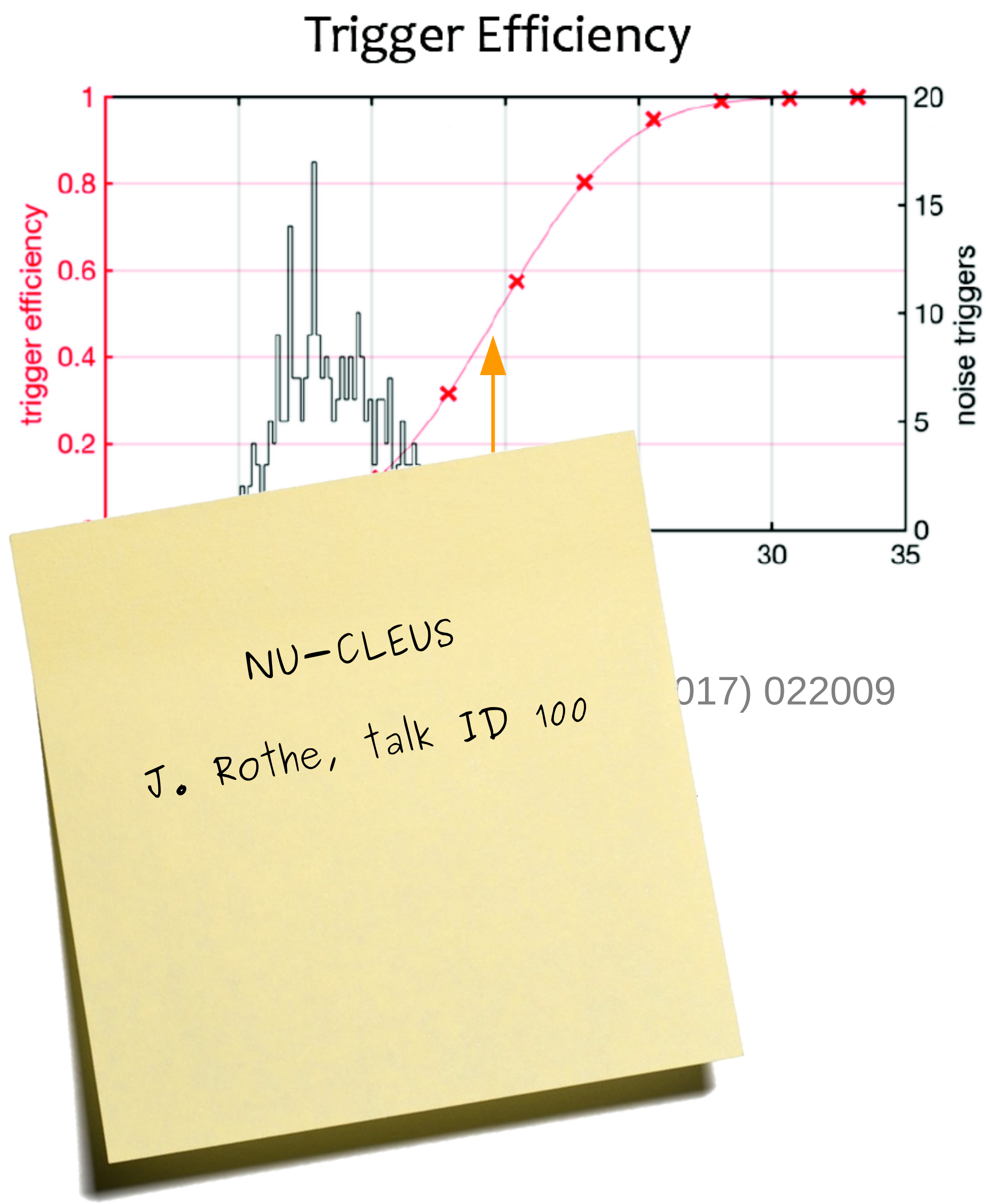
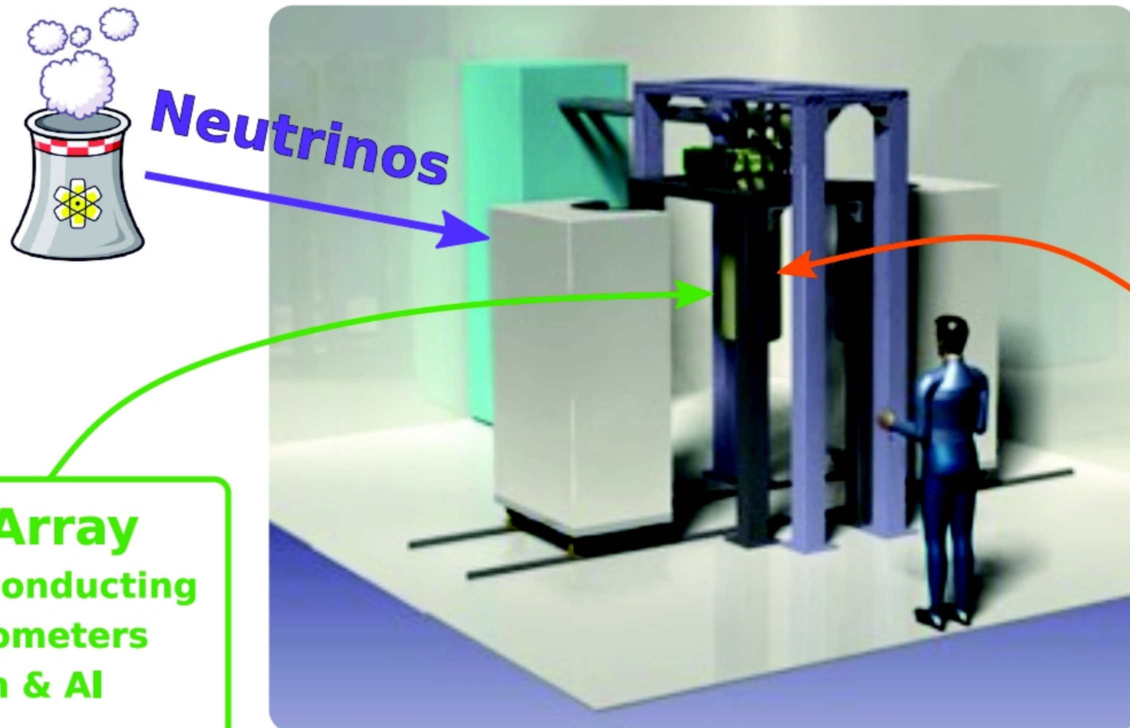


017) 022009

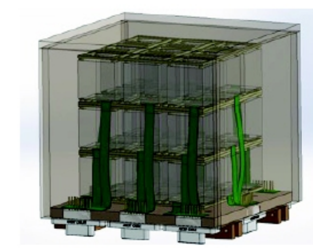
RICOCHET

Proposal paper: "The first low-energy kg-scale CEνNS neutrino observatory combining multi-target and multi-technology cryogenic detectors", J. Billard et al., J. Phys. G (2017) [arXiv: 1612.09035]



Q-Array
Superconducting bolometers
Zn & Al

CryoCube
Semi-conducting & superconducting bolometers
Ge & Zn



RICOCHET
A Coherent Neutrino Scattering Program

UMASS AMHERST · NÉEL institut · THE UNIVERSITY of WISCONSIN MADISON · NORTHWESTERN UNIVERSITY · MIT · JINR · IPNL · LPSC Grenoble · CSNSM

T. Salagnac

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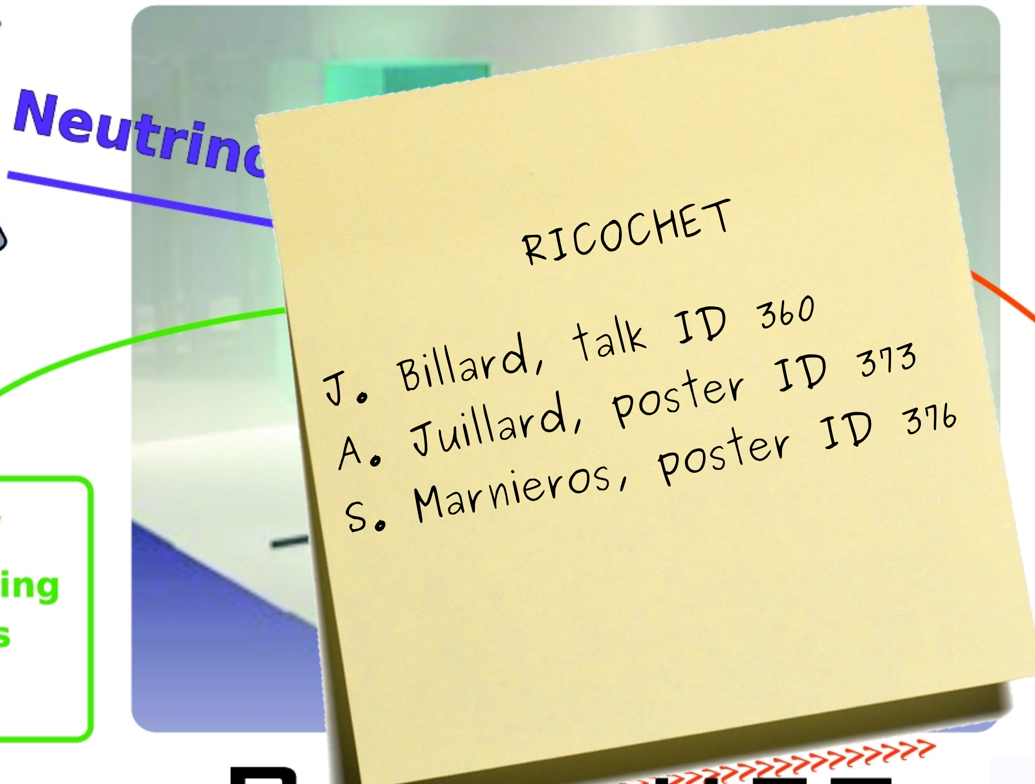

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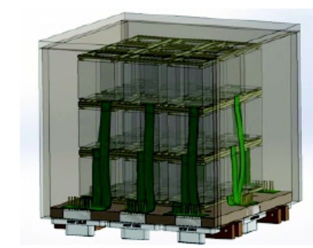
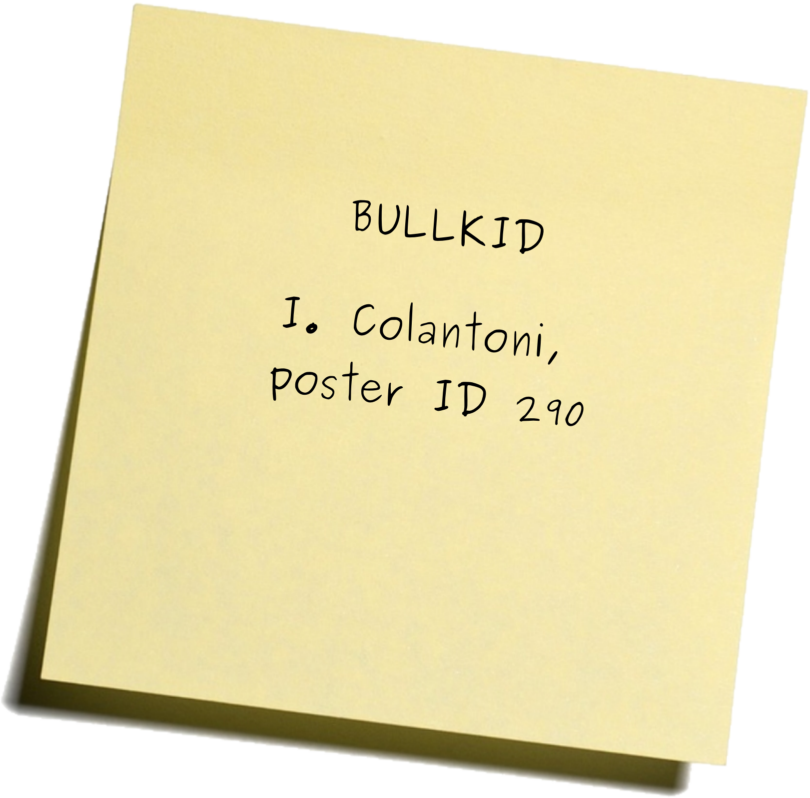


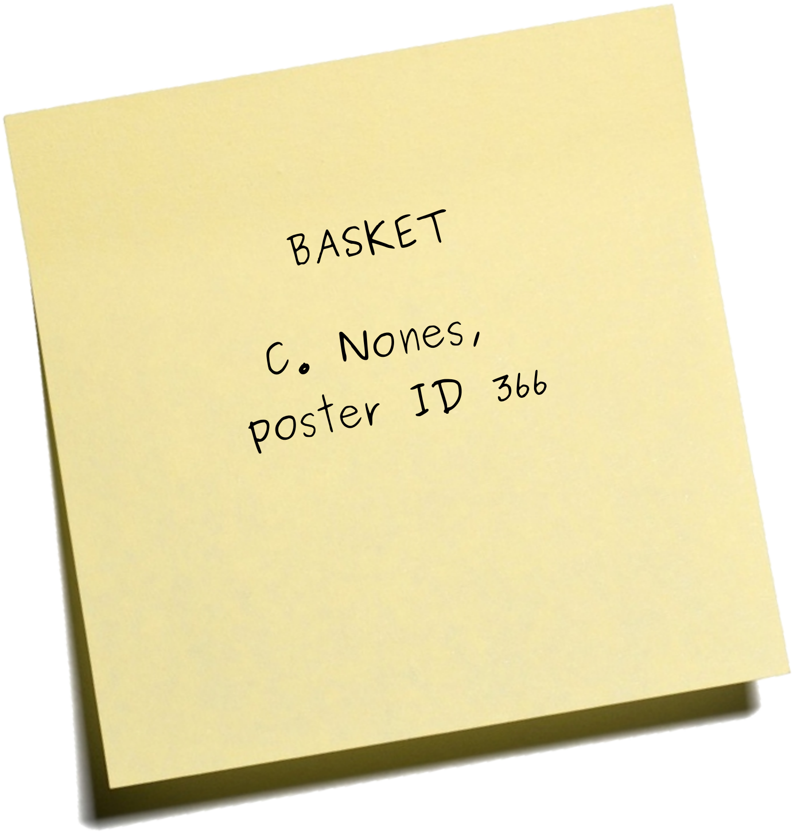
RICOCHET
A Coherent Neutrino Scattering Program

T. Salagnac

CevNS with LTDs

Other ongoing detector developments:





Conclusions

Low Temperature Detectors have become mature devices with strong potentialities in neutrino physics experiments.

Ongoing R&Ds will surely confirm the leading role of this technique also for next generation experiments!

Conclusions

Low Temperature Detectors have b
strong pote

THANKS!

… and apologies for those contributions I forgot to mention...