Low Temperature Detectors
for
Neutrino Physics

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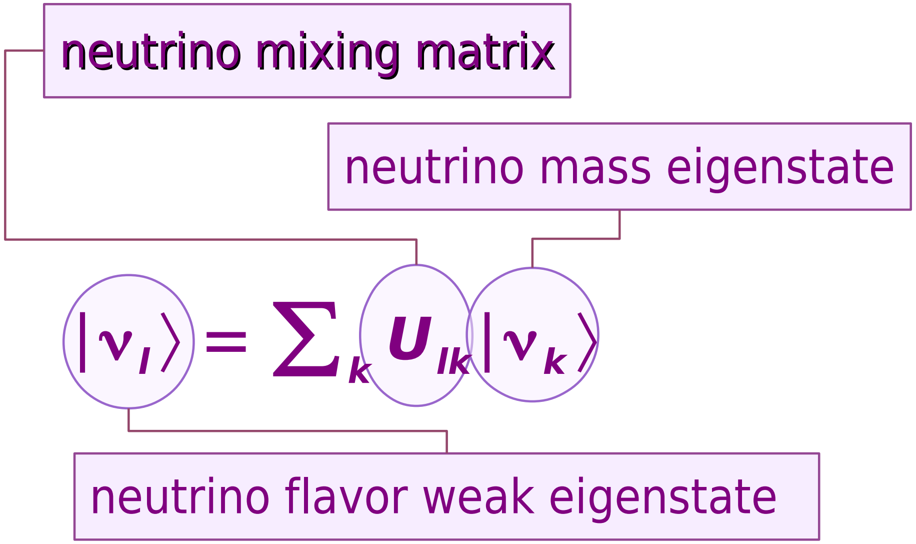
15th International Workshop on
Low Temperature Detectors

Outline

- neutrino properties
  - ☐ open questions
  - ☐ anomalies
  - ☐ unobserved phenomenologies
- experimental tools for the challenge
  - ☐ role of low temperature detectors (LTD)
- neutrinoless double beta decay searches
- direct neutrino mass measurements
- coherent scattering experiments

Neutrino properties

- neutrinos are massive fermions
- there are 3 active neutrino flavors
- neutrino flavor states are mixtures of mass states

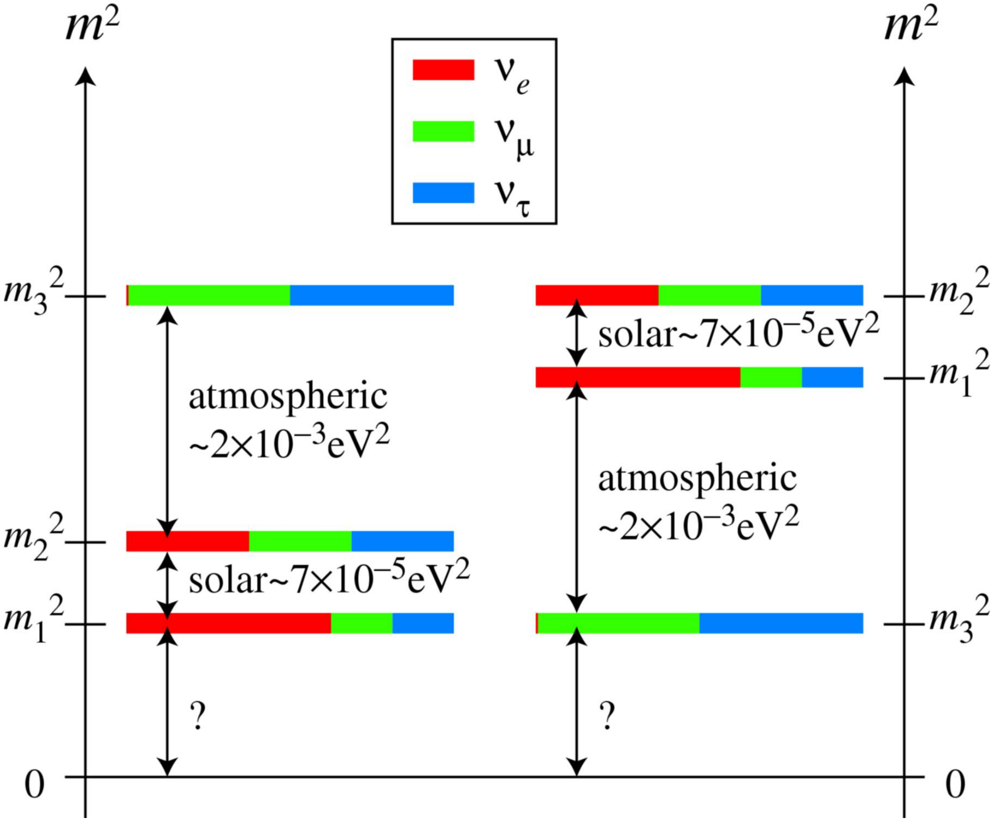


neutrino mixing matrix

neutrino mass eigenstate

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

neutrino flavor weak eigenstate



→ neutrino oscillation experiments measure

$$\Delta m_{ik}^2 = |m_i^2 - m_k^2|$$

$$\sin^2 2\vartheta_{ik} = f(|U_{lk}|^2)$$

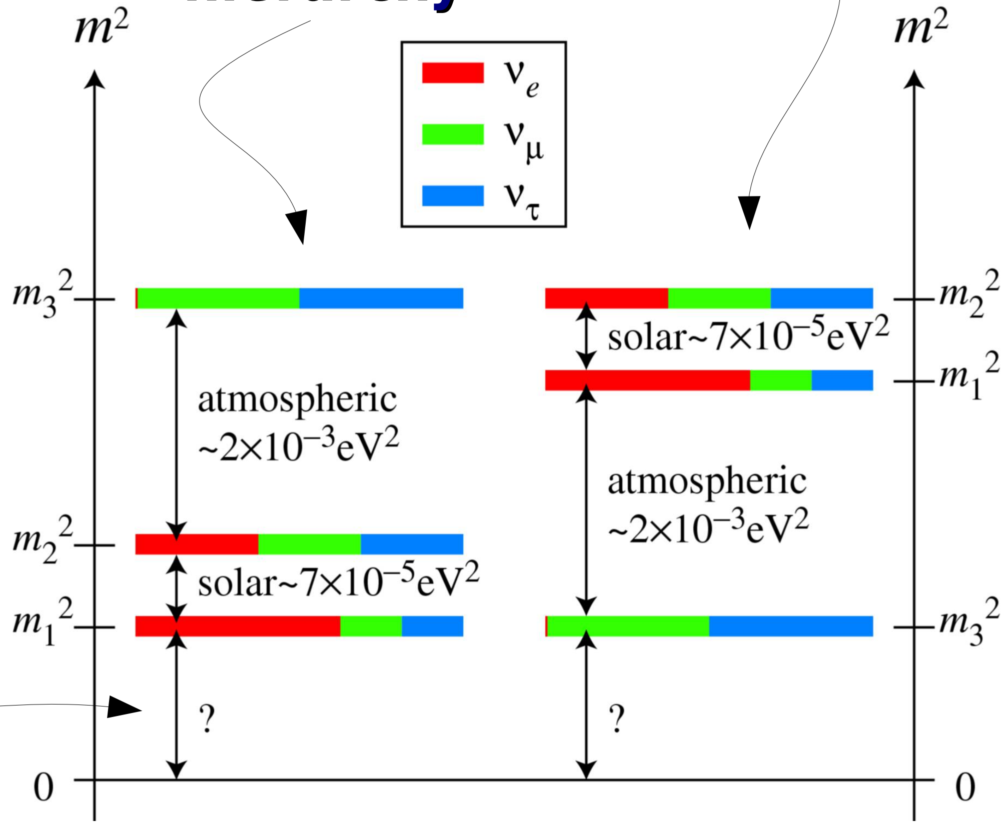
Neutrino open questions

- mass scale: i.e. mass of the lightest ν
- degenerate ($m_1 \approx m_2 \approx m_3$) or hierarchical masses
  - mass hierarchy: $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 \approx m_2$?
- $\nu = \bar{\nu}$? i.e. Dirac or Majorana particle?
- CP violation in the lepton sector

inverted hierarchy

normal hierarchy

mass scale



Anomalies and unobserved phenomenologies

- there are **anomalies** in data from
  - past reactor oscillation experiments (reanalyzed)
  - short baseline accelerator oscillation experiments (LSND, MiniBOONE)
  - solar experiment calibration with neutrino sources (GALLEX)
- call for 4th neutrino mass state ν_4 → sterile neutrino

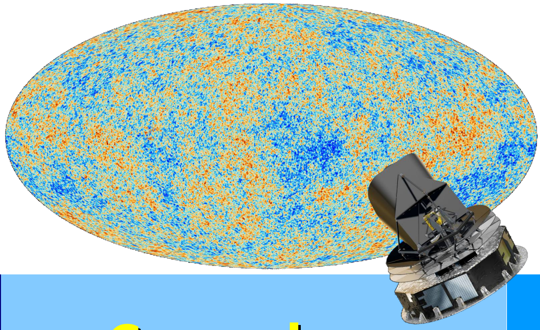
$$\Delta m^2 \approx 1 \text{ eV} \quad \text{and} \quad \sin^2 2\theta \gtrsim 0.1$$

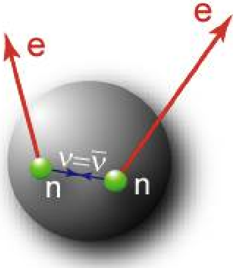
- Sterile (Right Handed) neutrinos are a natural extension to the Standard Model to include the mass of active neutrinos (νMSM)
  - sterile neutrino in the keV mass range are perfect candidate as Warm Dark Matter (WDM) particles
- **Standard Model also predicts**:
  - coeherent neutrino scattering on nuclei → never observed!
  - cosmic neutrino background (CνB) → never observed!

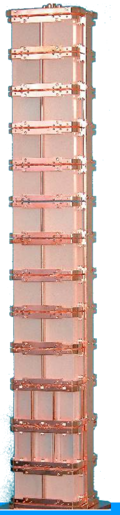
→ neutrinos probe physics beyond Standard Model

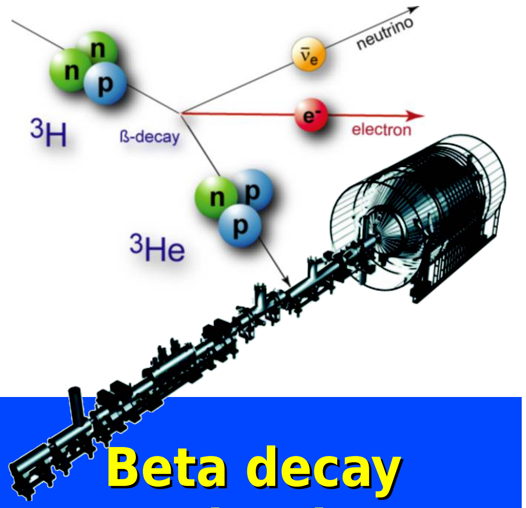
Experimental tools / 1

three complementary tools available
→ low temperature detectors play key role
(E. Fiorini and T. Niinikoski, Nucl. Instrum. and Meth. 224, p.83 (1984))



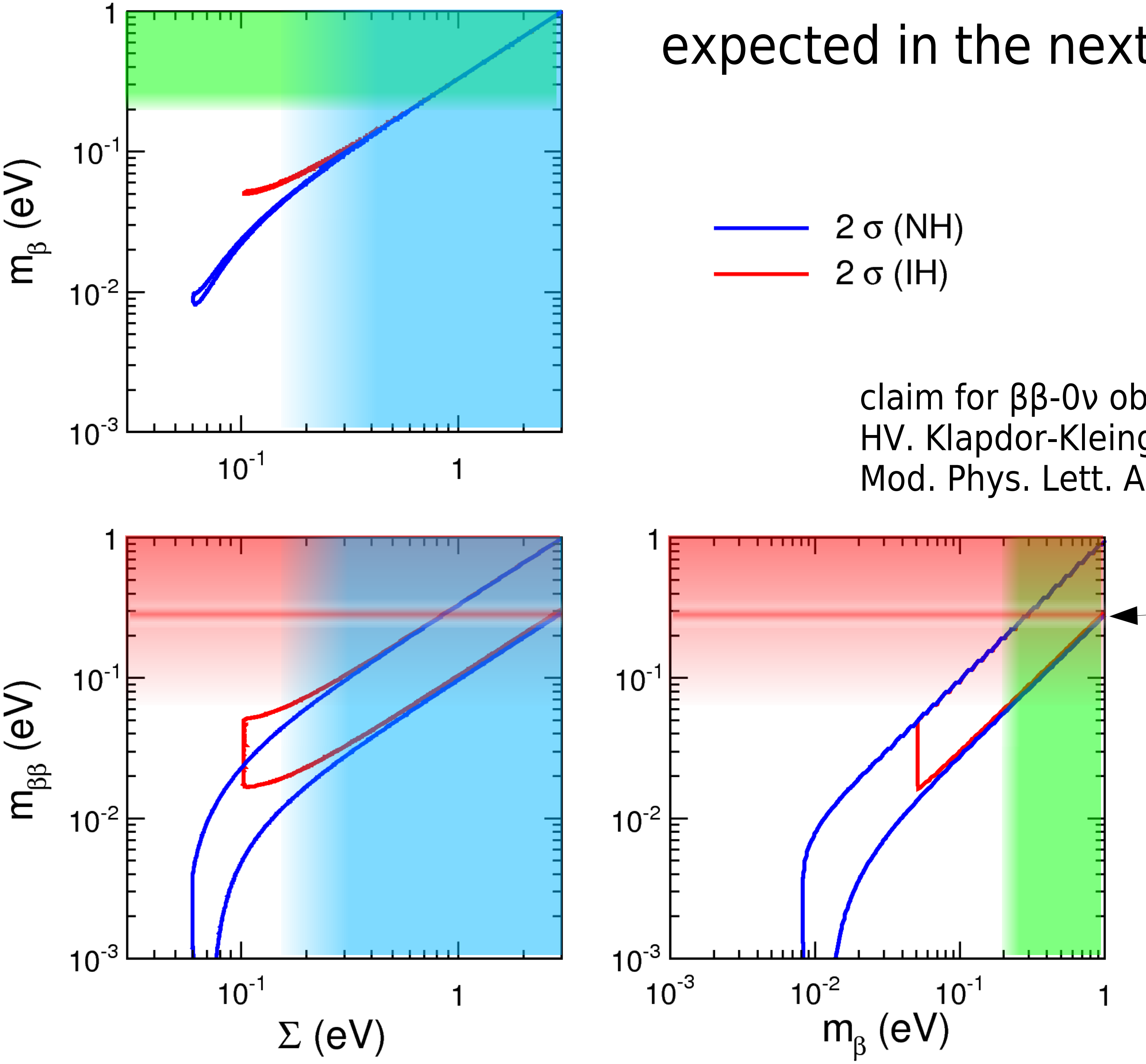






tool	**Cosmology CMB+LSS+...**	**Neutrinoless Double Beta decay**	**Beta decay end-point**
observable	$m_\Sigma=\Sigma_k m_{\nu_k}$	$m_{\beta\beta}=\lvert\Sigma_k m_{\nu_k} U_{ek}^2\rvert$	$m_\beta=(\Sigma_k m_{\nu_k}^2\lvert U_{ek}\rvert^2)^{1/2}$
present sensitivity	≈0.1 eV	≈0.1 eV	2 eV
future sensitivity	**0.01 eV**	**0.01 eV**	**0.2 eV**
model dependency	yes ☹	yes ☹	no ☺
systematics	large ☹	yes 😐	large ☹

The Challenge: mass hierarchy

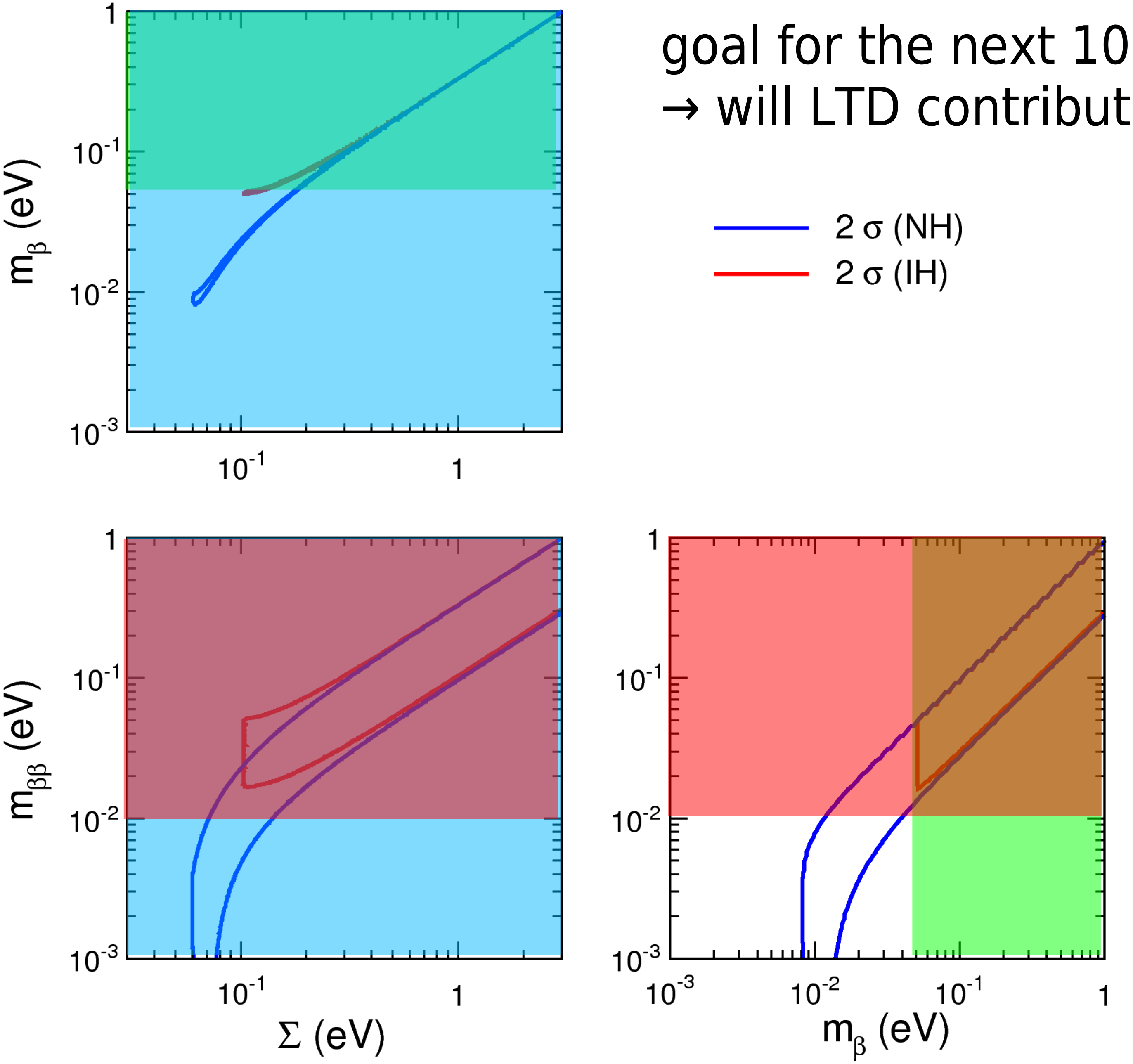


expected in the next ≈5 years

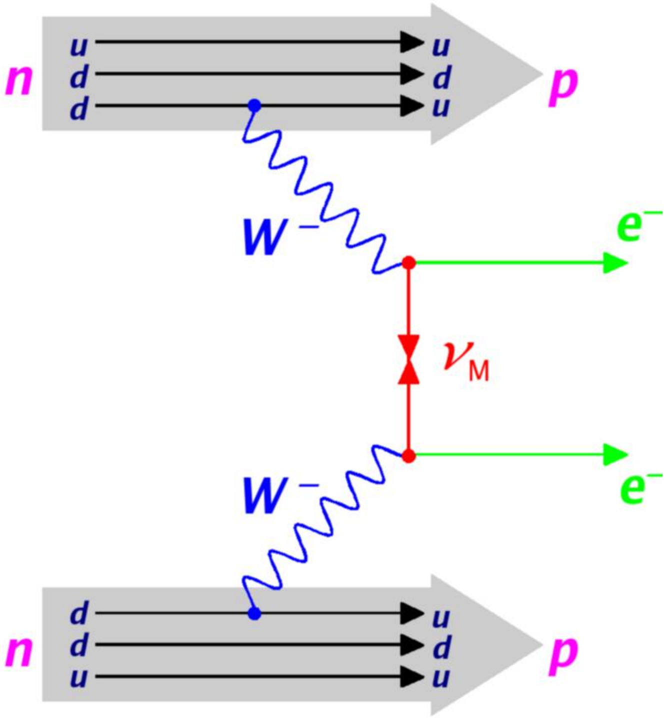
claim for ββ-0ν observation in ^{76}Ge
HV. Klapdor-Kleingrothaus et al.
Mod. Phys. Lett. A, 21 (2006) 1547

The Challenge: mass hierarchy

goal for the next 10-20 years
→ will LTD contribute?



ββ-0ν and neutrino properties



- a virtual neutrino is exchanged
  - neutrino must have **mass** to allow helicity non conservation ⇒**$\Delta H=2$**
  - neutrino must be a **Majorana particle** to allow **lepton number violation** ⇒**$\Delta L=2$**

$$\beta\beta\text{-}0\nu \iff \begin{matrix} m_\nu \neq 0 \\ \nu \equiv \bar{\nu} \end{matrix}$$

▲ these conditions hold even if **other mechanisms** are possible and may dominate

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

nuclear structure factor

$$F_N \equiv \underbrace{G^{0\nu}}_{\text{phase space}}(Q_{\beta\beta}, Z)\,|\underbrace{M^{0\nu}}_{\text{nuclear matrix element}}|^2$$

effective neutrino Majorana mass

$$\langle m_\nu \rangle \equiv \left| \sum_k m_{\nu_k} \underbrace{\eta_k}_{\text{CP phases}} |\underbrace{U_{ek}}_{\text{neutrino mixing matrix}}|^2 \right| \equiv m_{\beta\beta}$$

ββ-0ν and neutrino properties / 2

$$\frac{1}{\tau_{1/2}^{0\nu}} = \frac{m_{\beta\beta}^2}{m_e^2} \cdot F_N$$

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

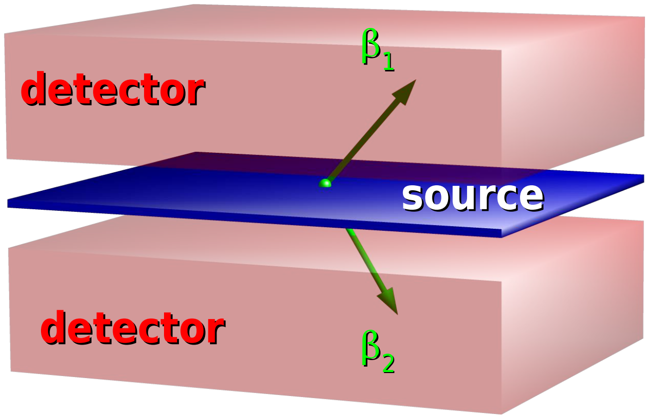
- **Model dependencies**
  - ββ-0ν always needs Majorana neutrinos to happen
  - ββ-0ν lifetime $\tau_{½}^{0\nu}$ measures $m_{\beta\beta}$ only for the light Majorana neutrino exchange mechanism
- **Systematics**
  - uncertainties in $|M^{0\nu}|$
- **Solutions**
  - study as many isotopes as possible
  - analyze topology and energy spectrum of emitted electrons
  - … hope for Majorana neutrinos

Experimental approaches for ββ-0ν

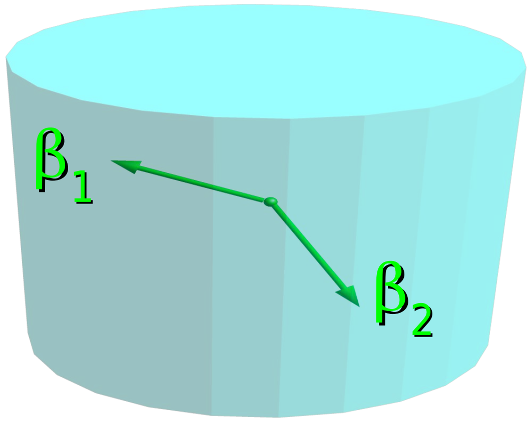
Source ⊆ detector (calorimetry)

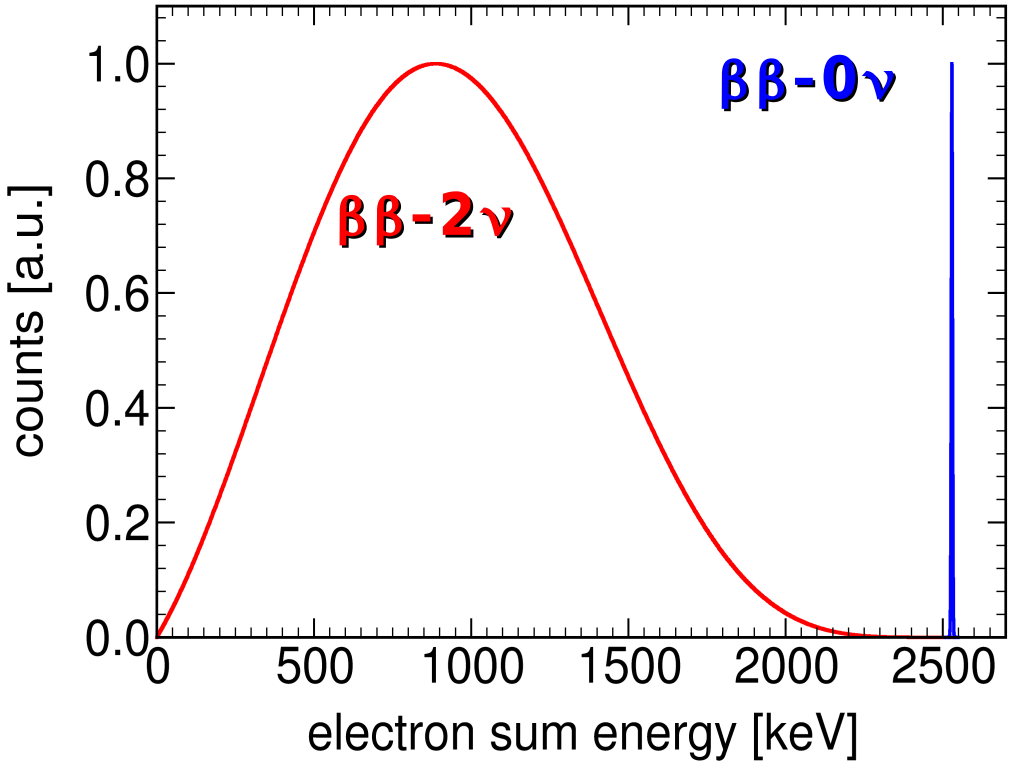
- detector measures sum energy $E = E_{\beta_1} + E_{\beta_2}$
  - ββ-0ν signature: a peak at transition energy $Q_{\beta\beta}$
- scintillators, **bolometers**, semiconductor diodes, gas chambers
  - **large masses**
  - **high efficiency**
  - **many isotopes possible**
- depending on technique
  - **high energy resolution** (bolometers, semiconductors)
  - moderate topology recognition (Xe TPC, semiconductors)

Source ≠ detector ...



detector



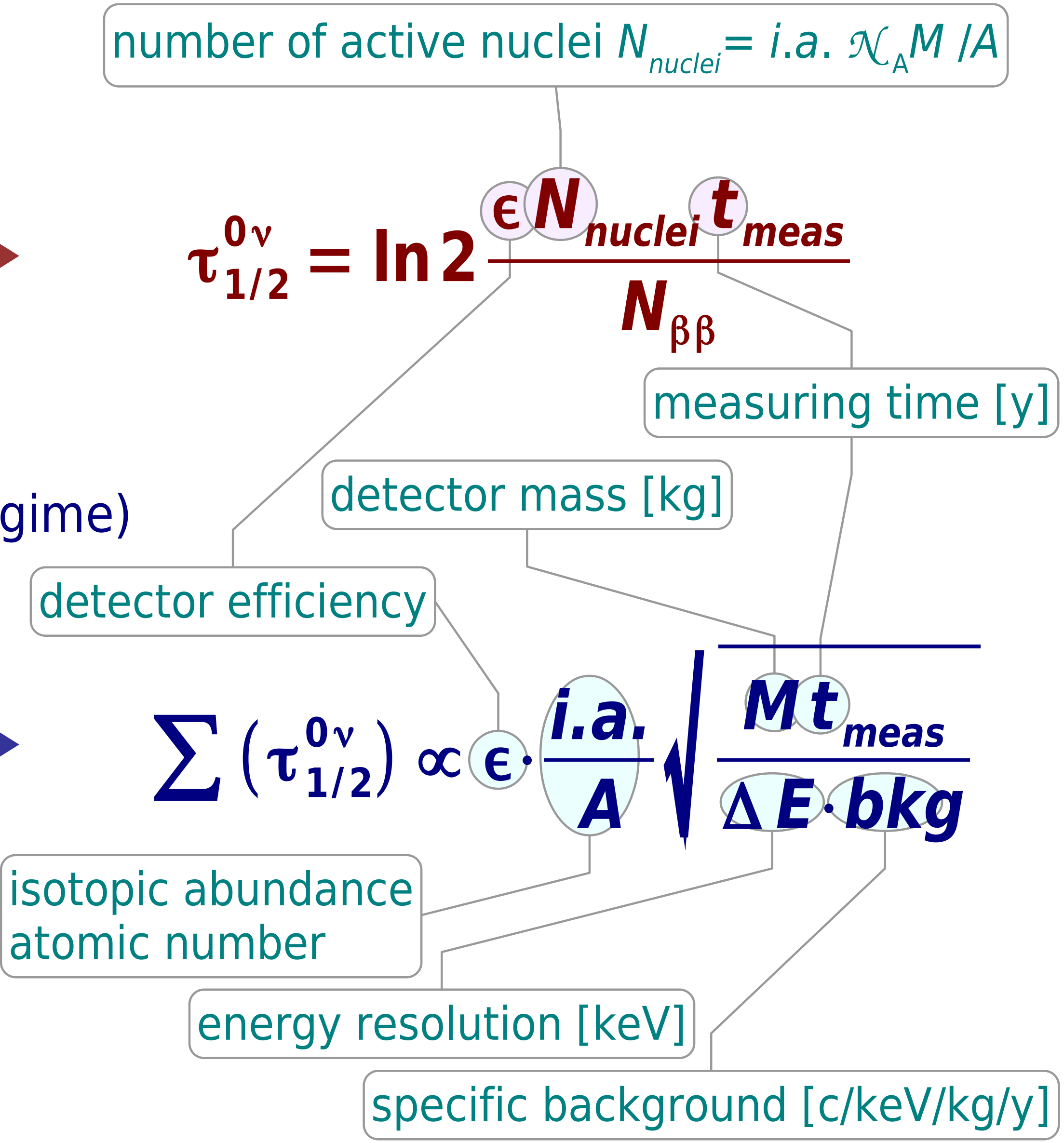


Experimental sensitivity for ββ-0ν

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

Experimental ββ-0ν rate

- with $N_{\beta\beta}$ decays observed



$$\tau^{0\nu}_{1/2} = \ln 2 \frac{\epsilon N_{nuclei} t_{meas}}{N_{\beta\beta}}$$

number of active nuclei $N_{nuclei} = i.a.\ \mathcal{N}_{A} M / A$

measuring time [y]

detector mass [kg]

detector efficiency

Experimental sensitivity to $\tau_{½}^{0\nu}$

- with no decay observed (Gaussian regime)
  - $N_{\beta\beta} \leqslant (bkg \cdot \Delta E \cdot M \cdot t_{meas})^{½}$ at 1σ

$$\Sigma(\tau^{0\nu}_{1/2}) \propto \epsilon \cdot \frac{i.a.}{A} \sqrt{\frac{M t_{meas}}{\Delta E \cdot bkg}}$$

isotopic abundance
atomic number

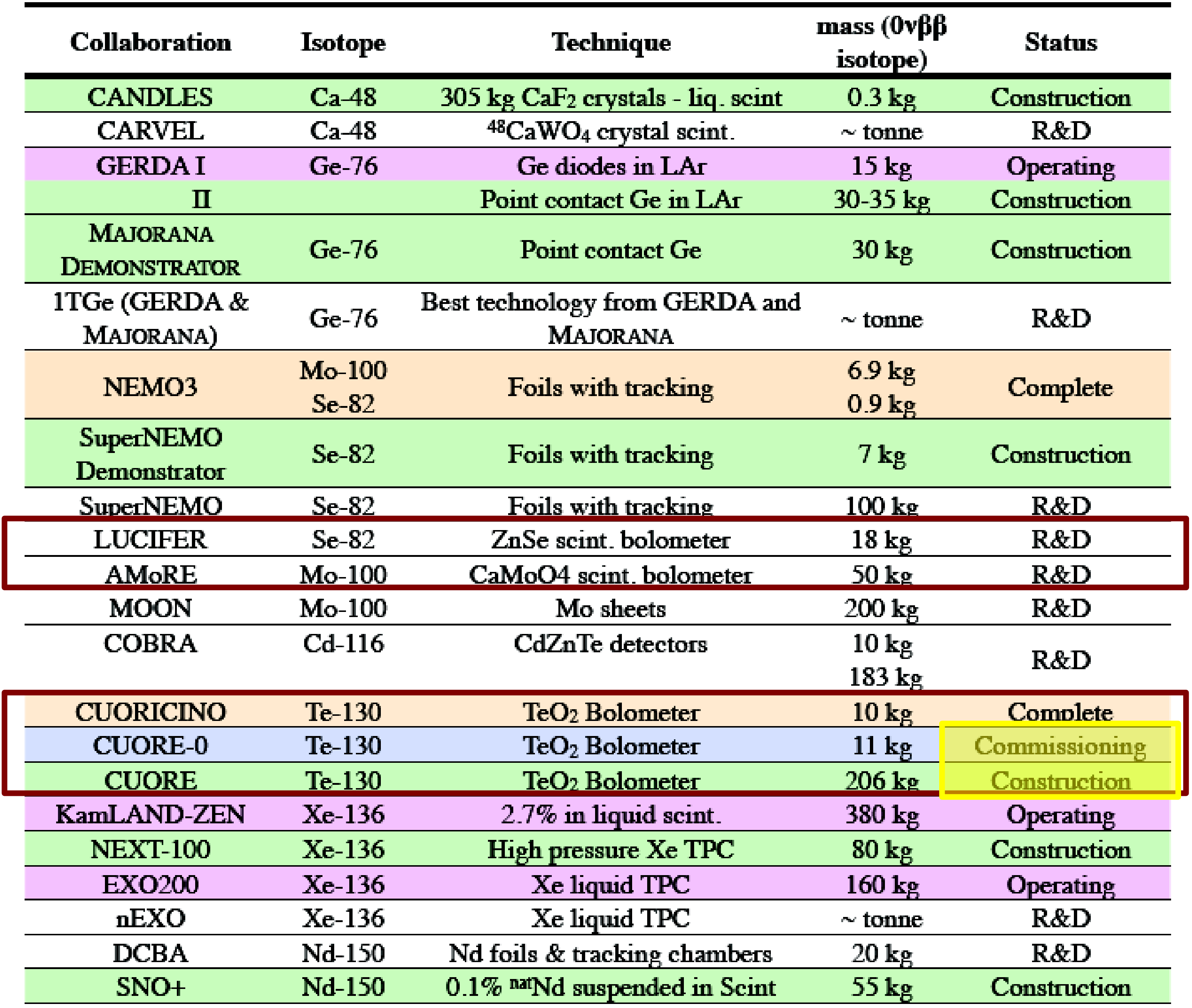
energy resolution [keV]

specific background [c/keV/kg/y]

- for $bkg=0 \Rightarrow N_{\beta} \leqslant 1.13$ at 68%

$$\Sigma(\tau^{0\nu}_{1/2}) \propto \frac{\epsilon\, i.a.}{A} M t_{meas}$$

Experiments: running, commissioning, R&D, ...



Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ tonne	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Operating
II		Point contact Ge in LAr	30-35 kg	Construction
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	30 kg	Construction
1TGe (GERDA & MAJORANA)	Ge-76	Best technology from GERDA and MAJORANA	~ tonne	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	CaMoO4 scint. bolometer	50 kg	R&D
MOON	Mo-100	Mo sheets	200 kg	R&D
COBRA	Cd-116	CdZnTe detectors	10 kg 183 kg	R&D
CUORICINO	Te-130	TeO_2 Bolometer	10 kg	Complete
CUORE-0	Te-130	TeO_2 Bolometer	11 kg	Commissioning
CUORE	Te-130	TeO_2 Bolometer	206 kg	Construction
KamLAND-ZEN	Xe-136	2.7% in liquid scint.	380 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	80 kg	Construction
EXO200	Xe-136	Xe liquid TPC	160 kg	Operating
nEXO	Xe-136	Xe liquid TPC	~ tonne	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D
SNO+	Nd-150	0.1% ^{nat}Nd suspended in Scint	55 kg	Construction

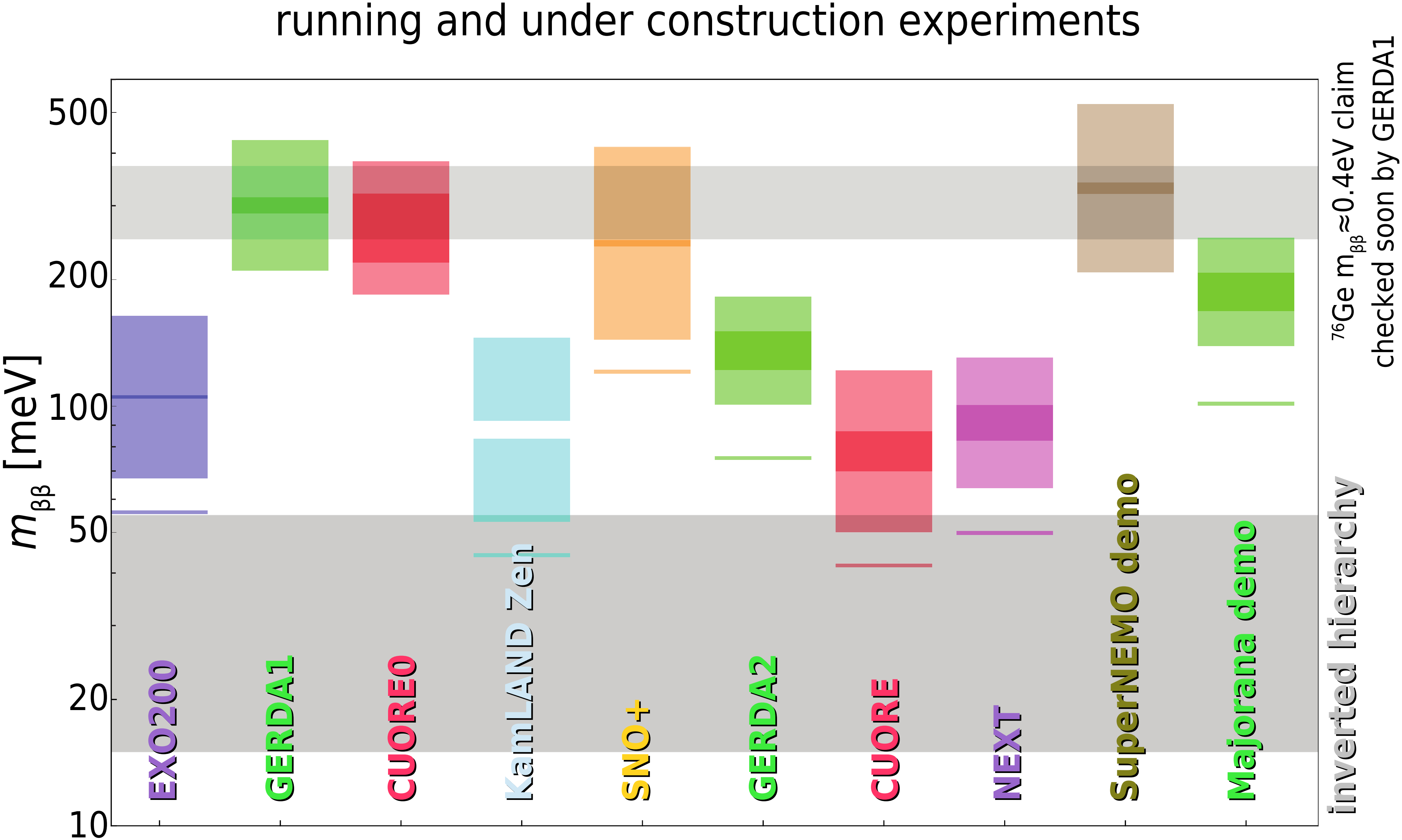
all calorimeters
except
NEMO3
SuperNEMO
MOON
DCBA

L. Cardani, talk, Fri 11:15
G.B. Kim, talk, Fri 11:30
M. Loidl, poster, Mon 210
M. Mancuso, poster, Tue 107
S. Di Domizio, poster, Fri 21

L. Canonica, talk, Fri 10:15
E. Ferri, poster, Fri 300
L. Taffarello, poster, Fri 210

adapted from J. Wilkerson @NUMASS2013

Sensitivity reach



adapted from JJ Gomez-Cadenas, Riv. Nuovo. Cim. 35 (2012) 29

Thermal detectors for ββ-0ν searches

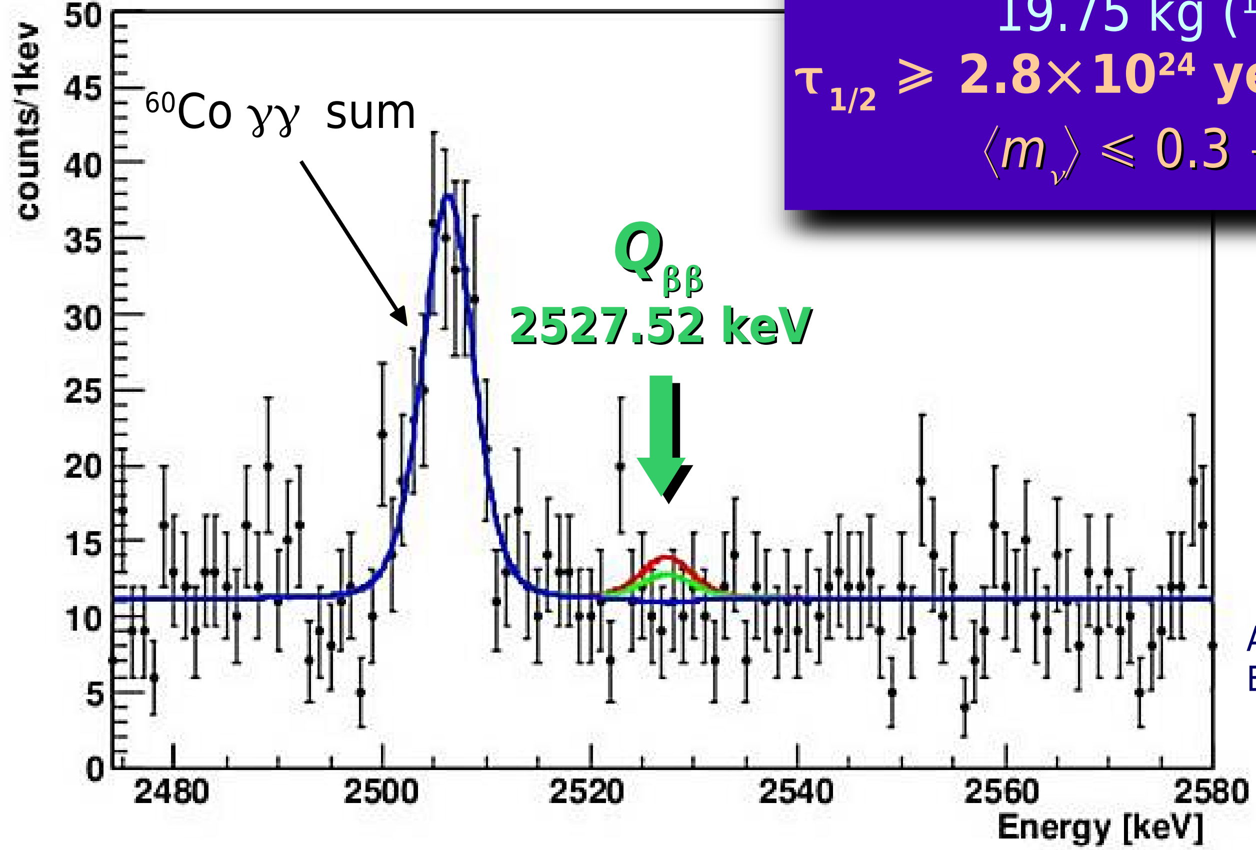
- ▲ true calorimeters
- ▲ high energy resolution
- ▲ large masses
- ▲ material choice
  - high *Q* above environmental γ (>2615 keV) or β (>3270 keV)
  - high natural abundance (or low enrichment cost)
  - good for particle identification by PSD and/or simultaneous light detection
- ▼ slow → ββ-2ν pile-up background

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

CUORICINO final results

- duty cycle ~45% (RUN II 05/2004-06/2008)
- total exposure **19.75 kg (^{130}Te) × years**
- energy resolution FWHM ΔE = 8 keV at $Q_{\beta\beta}$ (σ_E=1.3‰)
- anti-coincidence applied to reduce surface U/Th background and external γs
- background mainly from U/Th on Cu and TeO_2 surfaces (α and β)
  - $b \approx 0.169$ c/keV/kg/y at $Q_{\beta\beta}$

anti-coincidence sum spectrum
19.75 kg (^{130}Te) × y
$\tau_{1/2} \geqslant 2.8\times10^{24}$ years at 90% C.L.
$\langle m_\nu \rangle \leqslant 0.3 \div 0.7$ eV *



^{60}Co γγ sum

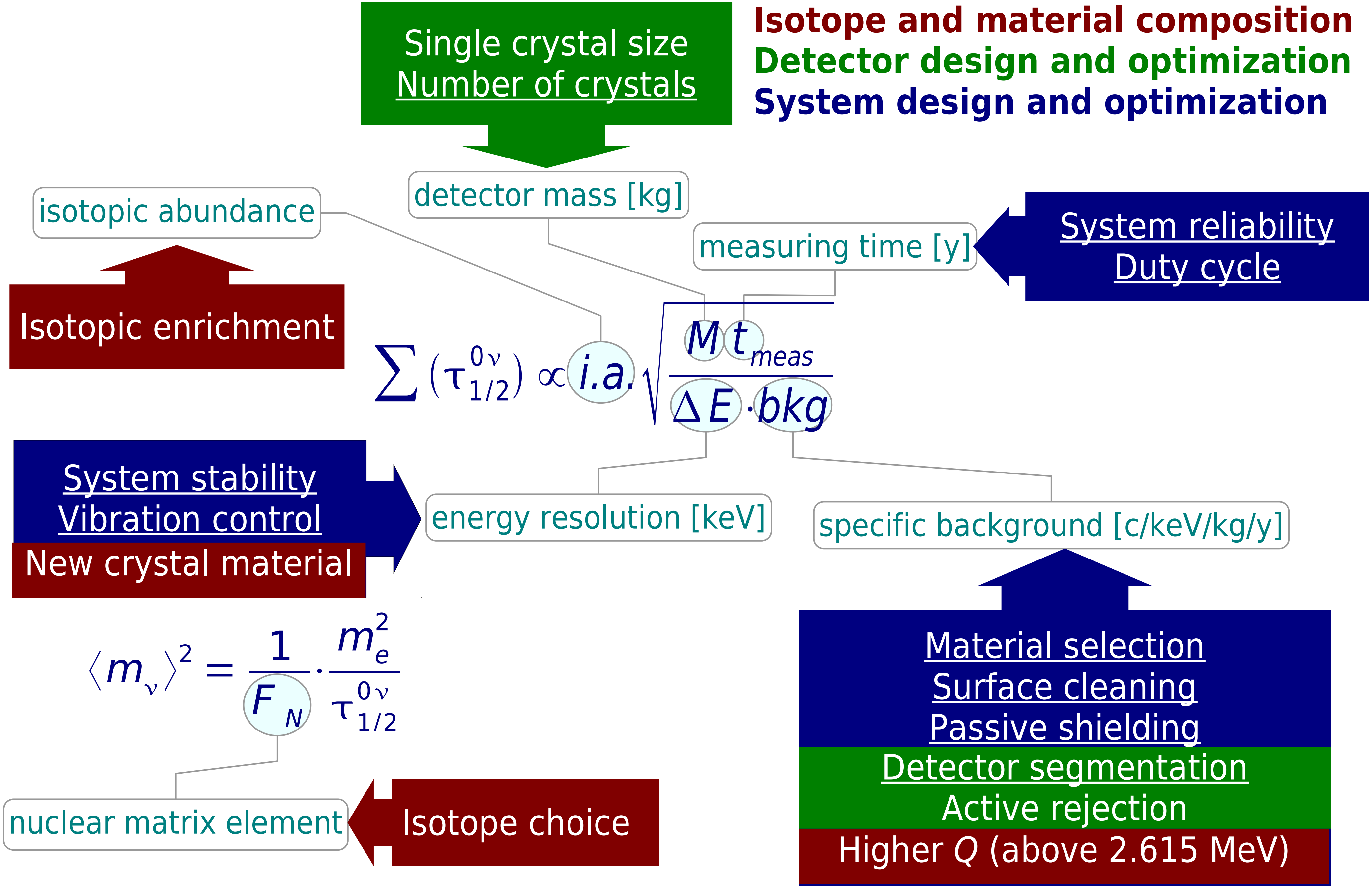
$Q_{\beta\beta}$
2527.52 keV

* Nuclear Matrix Elements from
1 Šimkovic et al., PRC 77 (2008) 045503
2 Civitarese et al., JoP:Conference series 173 (2009) 012012
3 Menéndez et al., NPA 818 (2009) 139
4 Barea and Iachello, PRC 79 (2009) 044301

A. Arnaboldi et al., Phys. Rev C, 78 (2008) 035502
E. Andreotti et al.. Astropart. Phys. 34 (2011) 822

How to improve CUORICINO sensitivity on ββ-0ν

Isotope and material composition
Detector design and optimization
System design and optimization



Single crystal size
Number of crystals

detector mass [kg]

isotopic abundance

Isotopic enrichment

measuring time [y]

System reliability
Duty cycle

$$\sum\left(\tau^{0\nu}_{1/2}\right) \propto i.a.\sqrt{\frac{M\,t_{meas}}{\Delta E\cdot bkg}}$$

System stability
Vibration control
New crystal material

energy resolution [keV]

specific background [c/keV/kg/y]

Material selection
Surface cleaning
Passive shielding
Detector segmentation
Active rejection
Higher *Q* (above 2.615 MeV)

$$\langle m_\nu\rangle^2 = \frac{1}{F_N}\cdot\frac{m_e^2}{\tau^{0\nu}_{1/2}}$$

nuclear matrix element

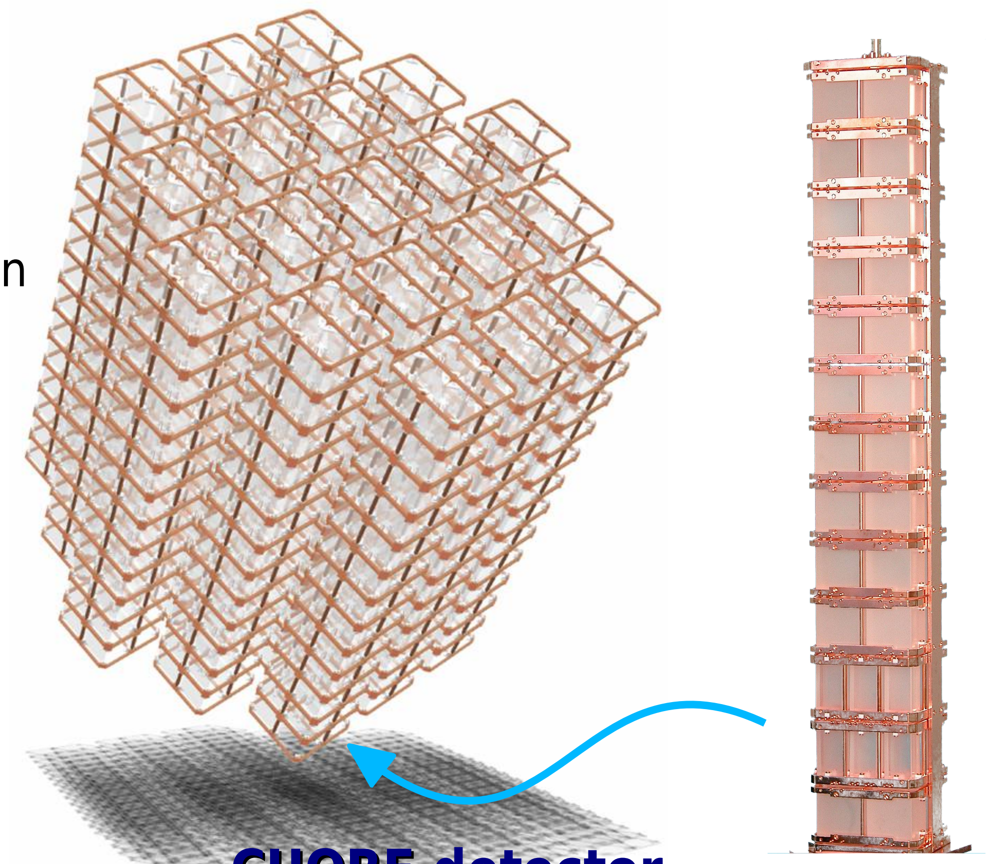
Isotope choice

CUORE (vs. Cuoricino)

- **CUORE**: Cryogenic Underground Observatory for Rare Events
- improve ×10 the Cuoricino sensitivity on $\langle m_\nu \rangle$
- i.e. improve ×100 the Cuoricino sensitivity on $\tau_{1/2}$

$$\sum\left(\tau^{0\nu}_{1/2}\right) \propto \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

  - increase total detector mass M ×18
    - 988 crystal natural $\mathbf{TeO_2}$ 750 g crystals ⇒ total mass 740 kg TeO_2 ⇒ 206 kg of ^{130}Te
  - increase measuring time t_{meas} ×5
    - improve duty cycle
  - reduce background bkg ÷100
    - improve shielding and material selection
    - better surface cleaning
    - improve detector design
    - use coincidence cuts



Cuoricino: ≈1 CUORE tower

CUORE detector

19 *towers* – 52 detectors each

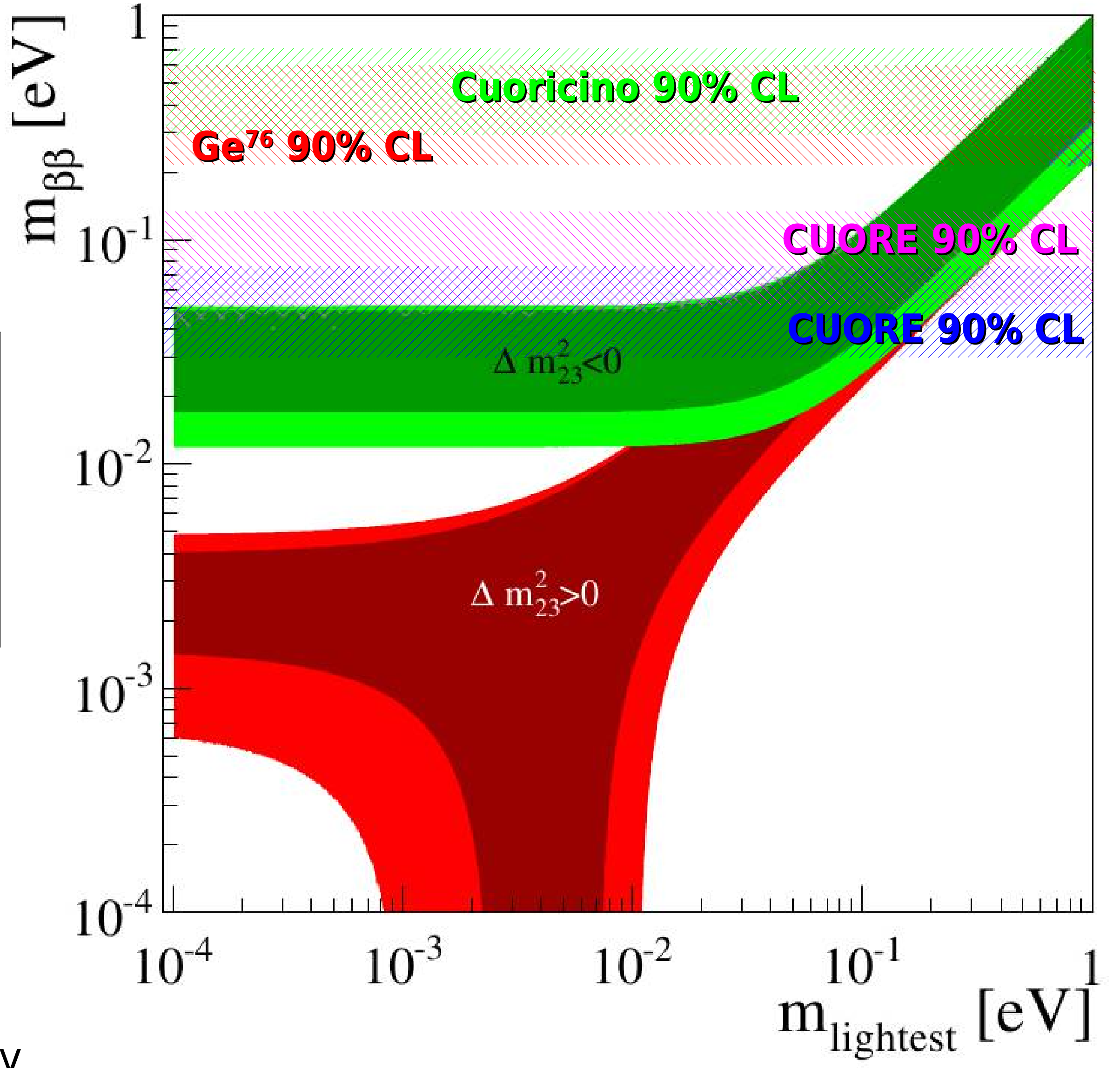
CUORE sensitivity potential

- sensitivity depends strongly on **background** level
- **NME uncertainties** broaden the sensitivity expectations *

90% CL sensitivity in 5 years

bkg [c/keV/kg/y]	DE [keV]	$t_{1/2}^{0\nu}$ [y]	$\langle m_\nu \rangle$ [meV]
0.01	5	1.0×10^{26}	50 ÷ 129
0.001	5	2.8×10^{26}	30 ÷ 77

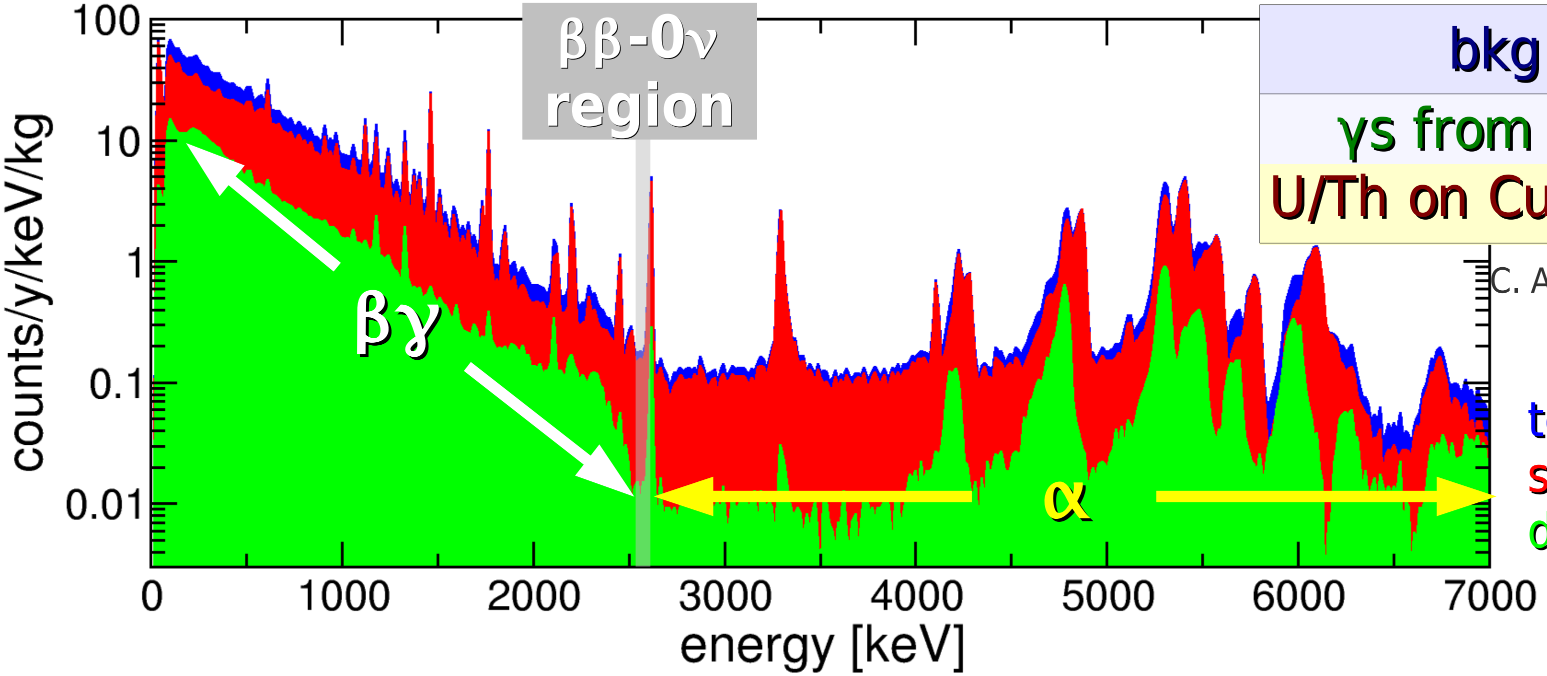
Nuclear Matrix Elements from:
Poves et al., NPA 818 (2009) 139; Faessler et al., JoP G: Nucl. Part. Phys. 39 (2012) 124006; Fang et al. , PRC 83 (2011) 034320; Suhonen et al., JoP G: Nucl. Part. Phys. 39 (2012) 124005; Iachello et al., PRC 87 (2013) 014315; P.K. Rath et al., Phys. Rev. C82 064310 (2010); T. R. Rodriguez et al., Phys. Rev. Lett 105 252503 (2010)



* **NME uncertainties** can be reduced by observing ββ-0ν in many different isotopes

F. Alessandria et al., *Sensitivity and Discovery Potential of CUORE to Neutrinoless Double-Beta Decay*, arXiv:1109.0494v3 [nucl-ex]

Understanding CUORICINO (and LTDs...) background



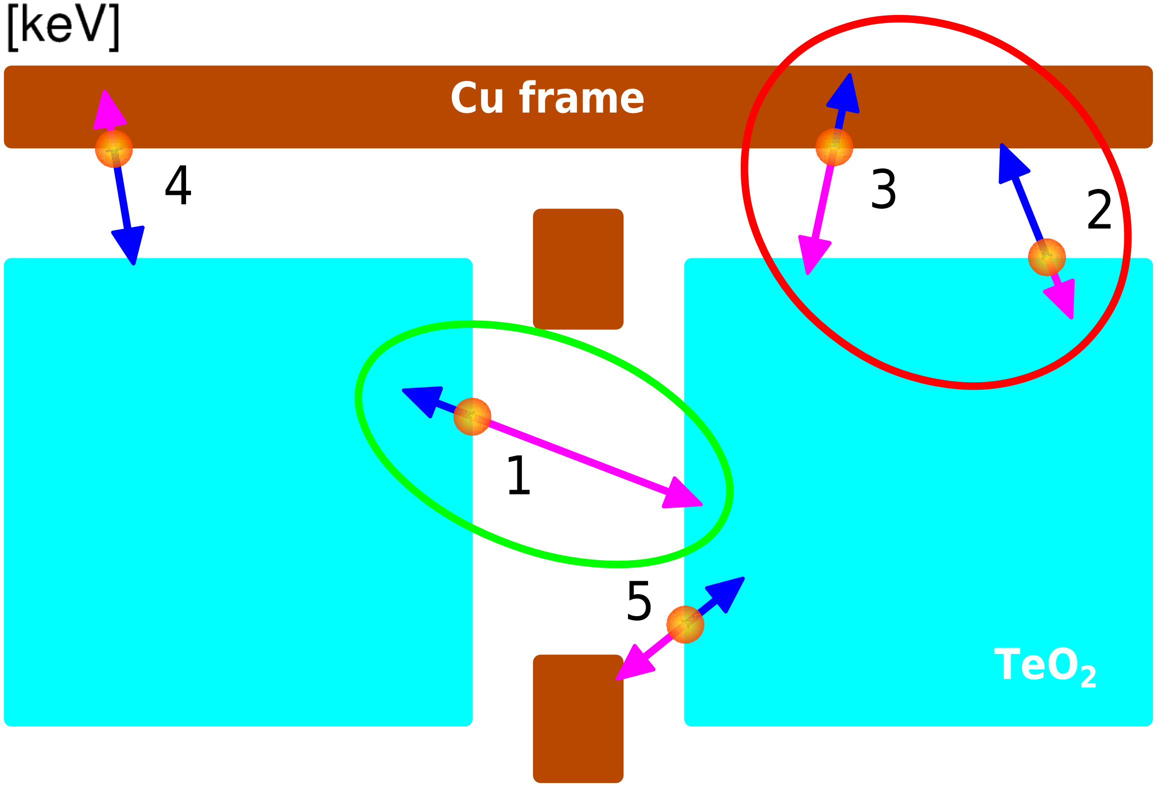
bkg sources	at Q_{bb}
γs from external Th	30%
U/Th on Cu/TeO_2 surfaces	70%

C. Arnaboldi et al., PRC78(2008)035502

↑ recoiling daughter nucleus; E_{recoil}

● parent nucleus

↓ α; E_α



1 discarded by coincidence cut

2 peak at E_α with tail

3 broad distribution up to E_α

4 broad distribution up to E_{recoil}

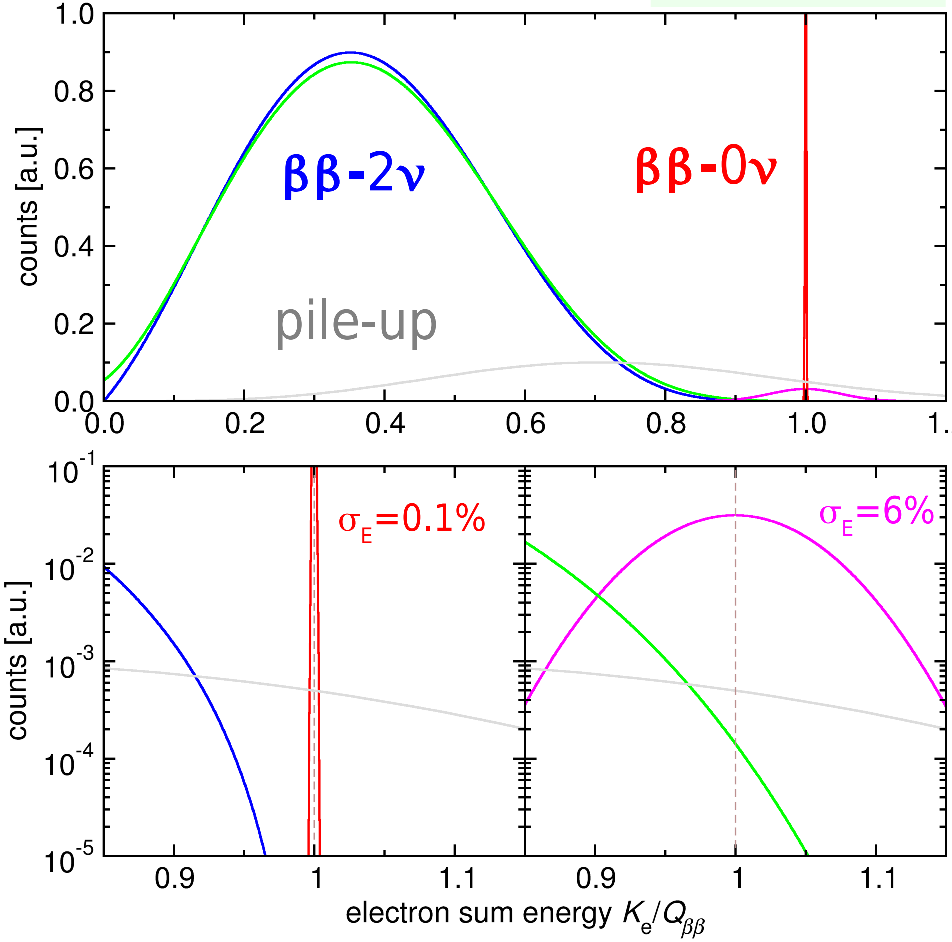
5 broad peak around E_{recoil}

$E_{recoil} \approx 0.02 E_\alpha \approx 100$ keV

Background in LTDs

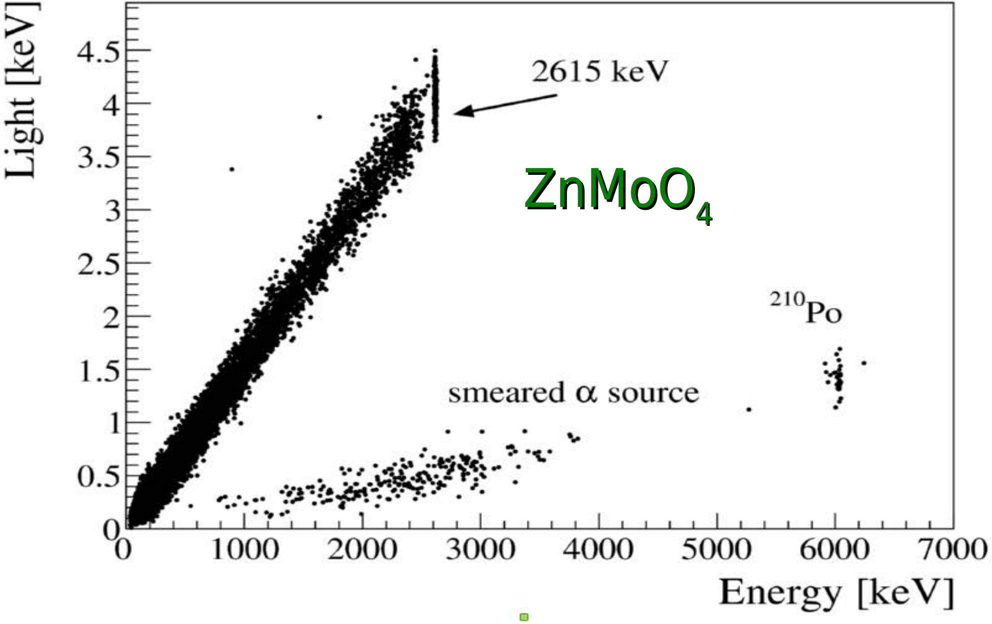
- **main background sources in LTDs**
  - α/γ/β in the detector
  - γ/β from bulk of neighbor materials
  - α from surfaces
  - intrinsic internal backgrounds → ββ-2ν and ββ-2ν pile-up
- **to reduce non-intrinsic backgrounds**
  - material selection and cleaning
  - choose high Q → only α
  - use α/β discrimination techniques

$A_{0\nu} = A_{2\nu}/100$

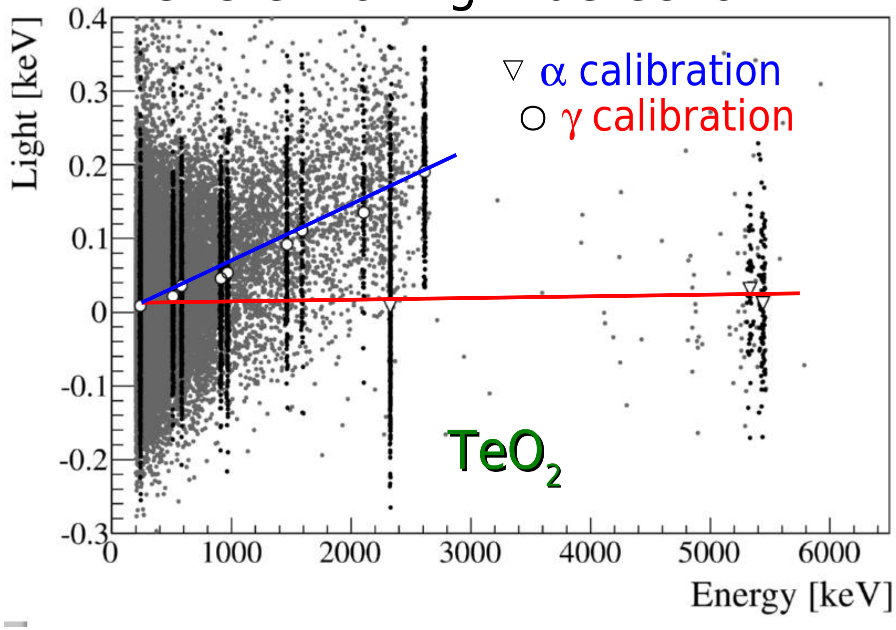


Background reduction techniques with LTDs

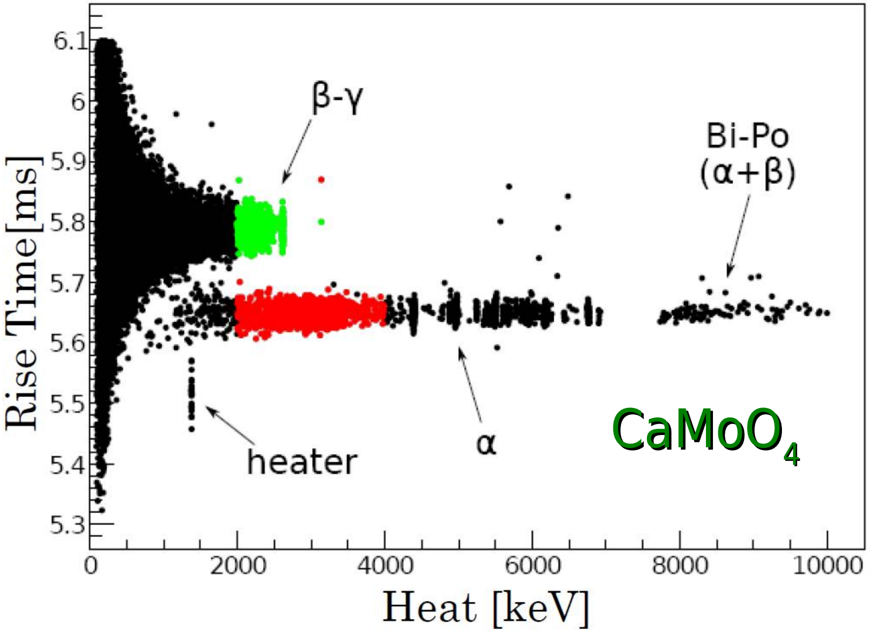
Scintillation light detection



Cherenkov light detection



Pulse shape discrimination



and more...

- **AMoRE** → CaMoO$_4$
- **LUCIFER** → ZnSe
- **LUMINEU** → ZnMoO$_4$
- **Caldera**

Exploring the Inverted Hierarchy with LTDs

Detector:
M =1 ton
5x5x5 cm^3 detectors
t_M = 10 y
ΔE = 5 keV
I.A. = 90%
τ_{rise} = 1 ms (time resolution)
α discrimination power = 99.9%

background: 2 hypothesis

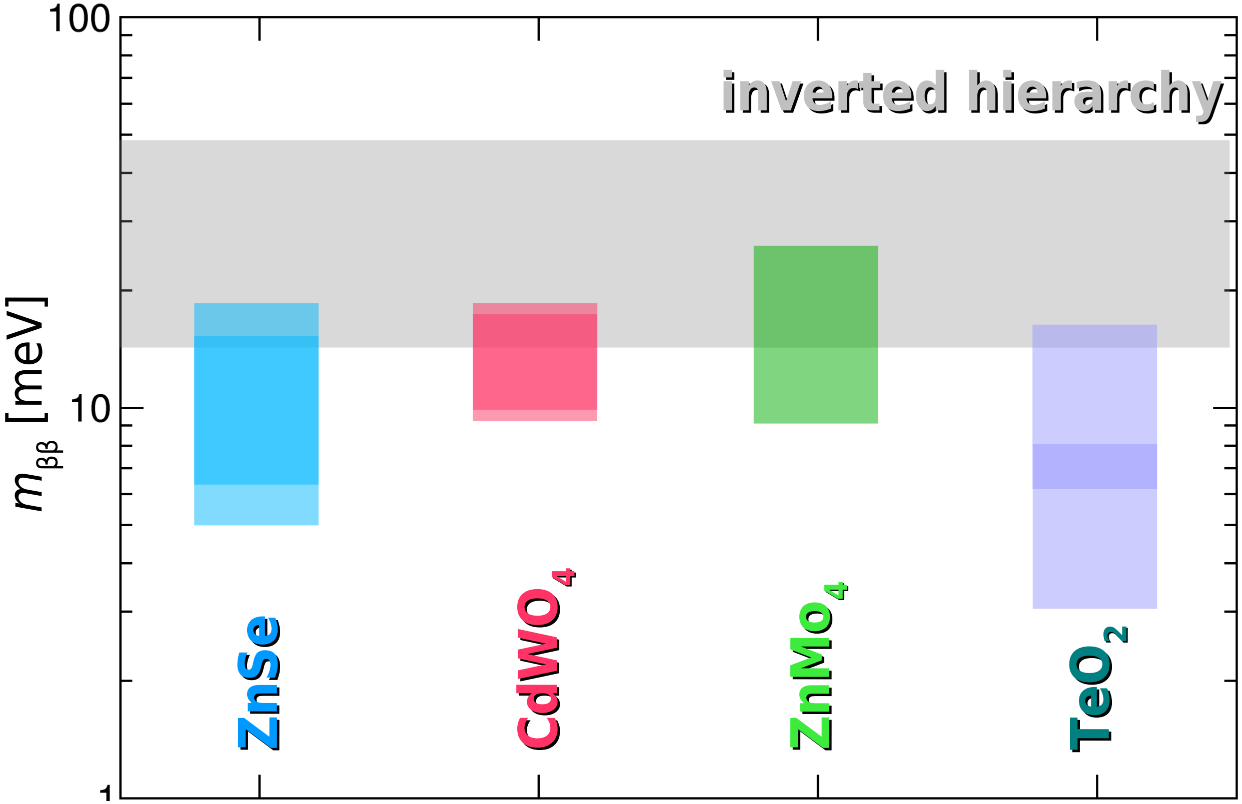
- maximum between 0.1 c/ton/y and ββ-2ν pile-up
- only ββ-2ν pile-up

(ββ-2ν background is negligible with ΔE = 5 keV)

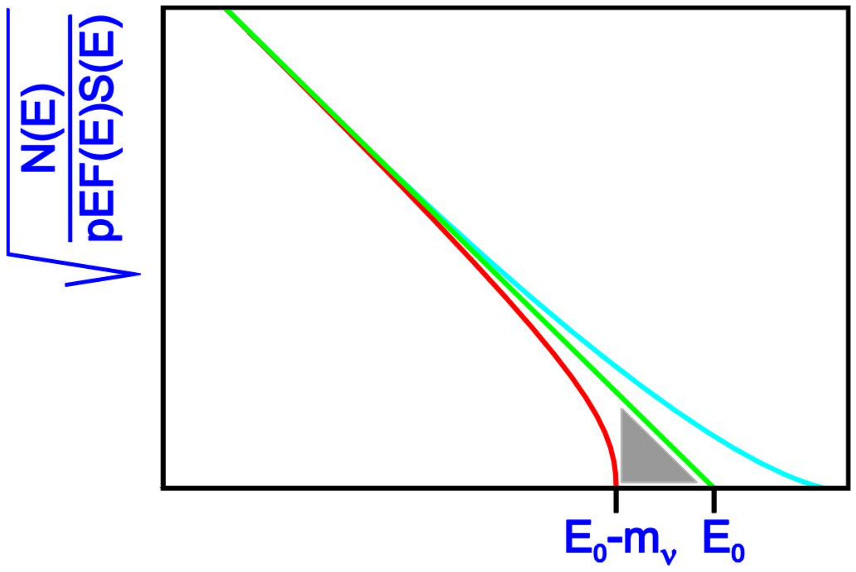
→ **90% C.L. limits** using Poisson statistics

		bckg [c/ton/y]	$\tau_{0\nu}$ [y]	$m_{\beta\beta}$ min [meV]	$m_{\beta\beta}$ max [meV]
ZnSe	82	1.0E-01	6.5E+27	6	19
CdWO4	116	1.0E-01	3.0E+27	10	18
ZnMoO4	100	1.5E+00	1.4E+27	9	25
TeO2	130	1.0E-01	6.6E+27	6	16

		bckg 2ν (1ms) [c/ton/y]	$\tau_{0\nu}$ [y]	$m_{\beta\beta}$ min [meV]	$m_{\beta\beta}$ max [meV]
ZnSe	82	2.7E-02	1.0E+28	5	15
CdWO4	116	7.0E-02	3.4E+27	9	17
ZnMoO4	100	1.5E+00	1.4E+27	9	25
TeO2	130	5.0E-04	2.7E+28	3	8



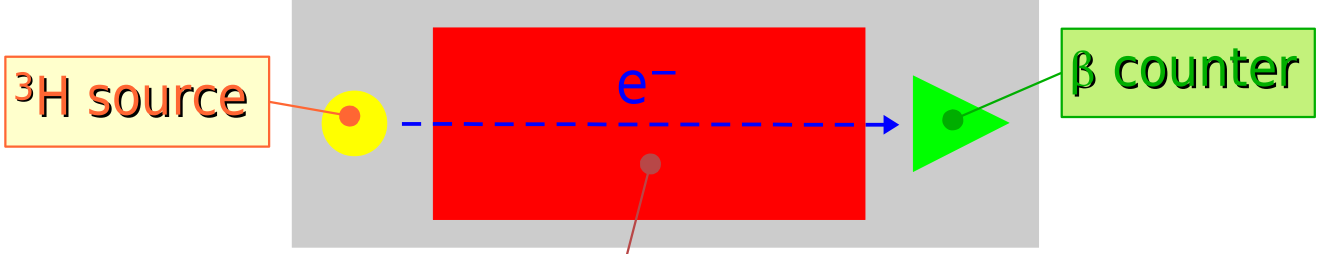
Direct neutrino mass measurements



- **kinematics of weak decays**
  - nuclear beta decays
  - use only energy and momentum conservation
  - no further assumptions
- **time of flight measurements**
  - ν from supernovae
  - use $E^2 = p^2c^2 + m_\nu{}^2c^4$ and hypothesis on emission time distribution
  - sensitivity limited to ≈1 eV (SN1987 → $m_\nu \lesssim 6$ eV)

Experimental approaches

Spectrometers: source ≠ detector

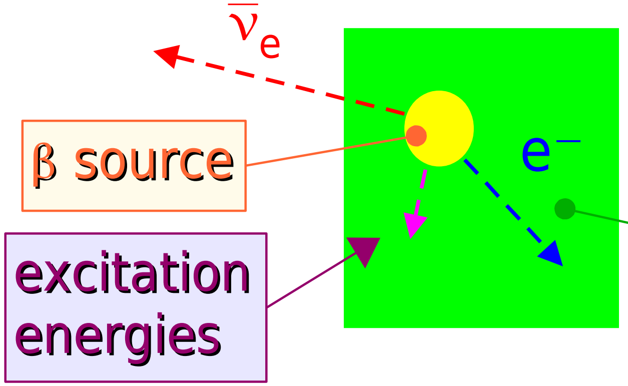


β analyzer

differential or integral spectrometer: βs from the ^{3}H spectrum δE are magnetically and/or electrostatically selected and transported to the counter

- ▲ high statistics
- ▲ high energy resolution
- ▼ large systematics
  - ► source effects
  - ► decays to excited states
- ▼ background

Calorimeters: source ⊆ detector



β calorimeter

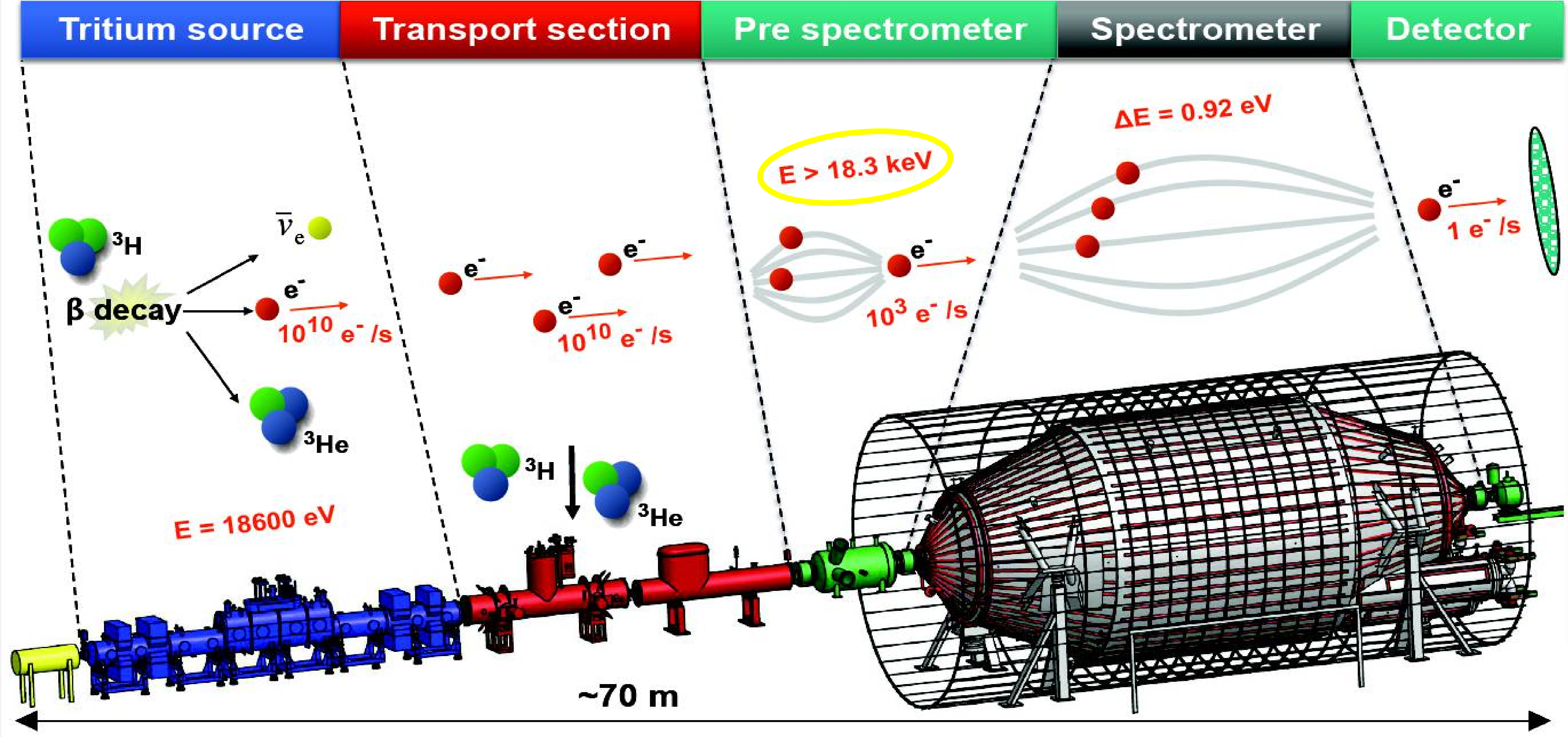
ideally measures all the energy E released in the decay except for the $\bar{\nu}_e$ energy: $E=E_0-E_\nu$

- ▲ no backscattering
- ▲ no energy losses in the source
- ▲ no atomic/molecular final state effects
- ▲ no solid state excitation
- ▼ limited statistics
- ▼ pile-up background
- ▼ spectrum related systematics

Spectrometers future: KATRIN

large electrostatic spectrometer
with **gaseous ^{3}H source (E_0=18.6keV)**

- expected statistical sensitivity
  $m_{\nu e}$ < 0.2 eV 90% CL
- start data taking in **2014/2015**



Calorimeter statistical sensitivity

resolving time τ_R analysis interval ΔE

source activity A_β number of detectors N_{det}

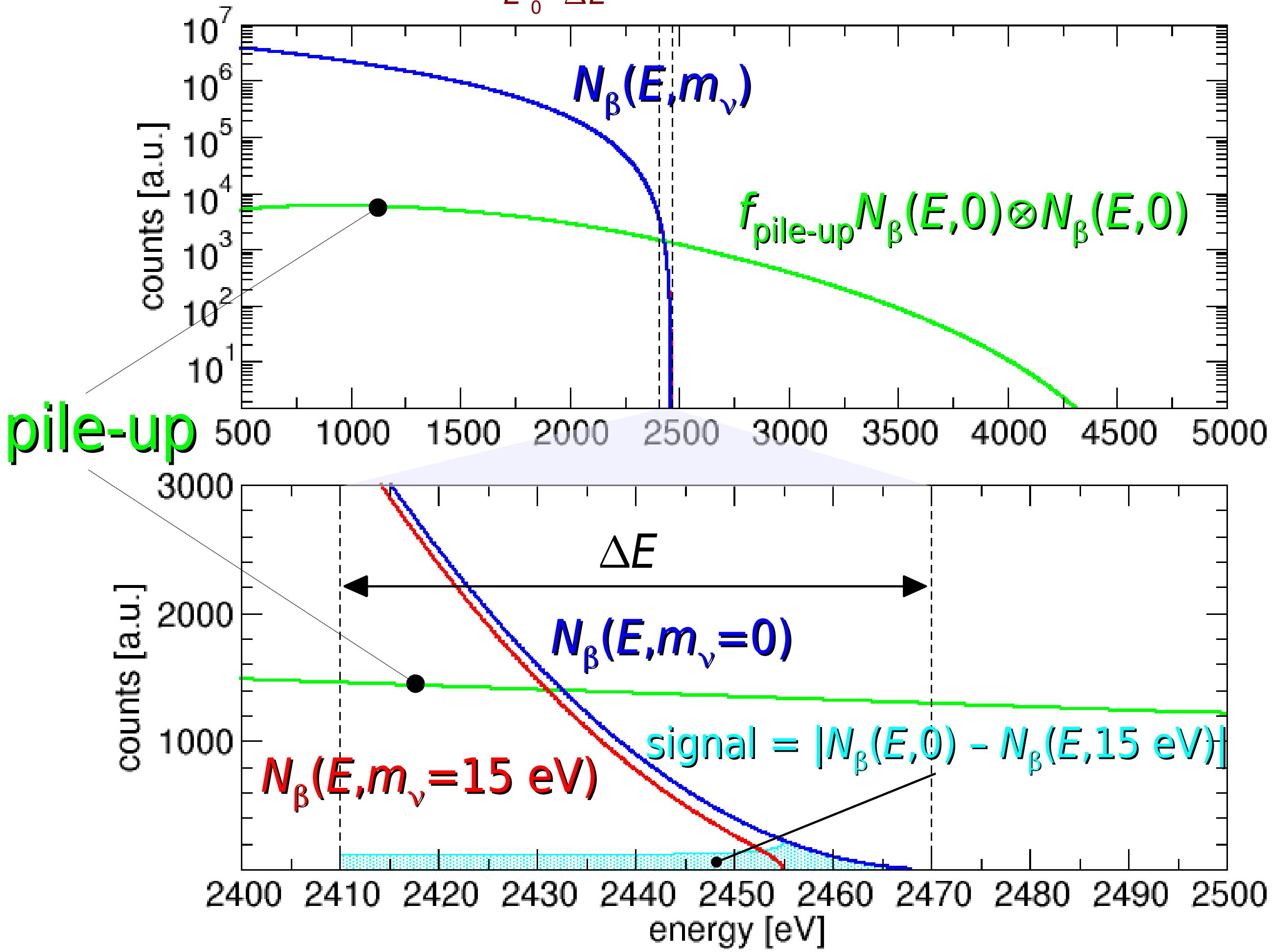
pile-up fraction $f_{pile-up}=\tau_R A_\beta$

experimental exposure $t_M=T\times N_{det}$

$$N_\beta(E,m_\nu)\approx\frac{3}{E_0^3}(E_0-E)^2\sqrt{1-\frac{m_\nu^2}{(E_0-E)^2}}$$

$$F_{\Delta E}(m_\nu)=A_\beta N_{det}\int_{E_0-\Delta E}^{E_0} N_\beta(E,m_\nu)dE \qquad F_{\Delta E}(0)\approx A_\beta N_{det}\frac{\Delta E^3}{E_0^3}$$

→ **^{187}Re E_0=2.5keV**



$f_{pile-up}=\tau_R A_\beta \ll \frac{\Delta E^2}{E_0^2}$ negligible pile-up

$$\Sigma_{90}(m_\nu)\approx 0.89\sqrt[4]{\frac{E_0^3\Delta E}{A_\beta t_M}}$$

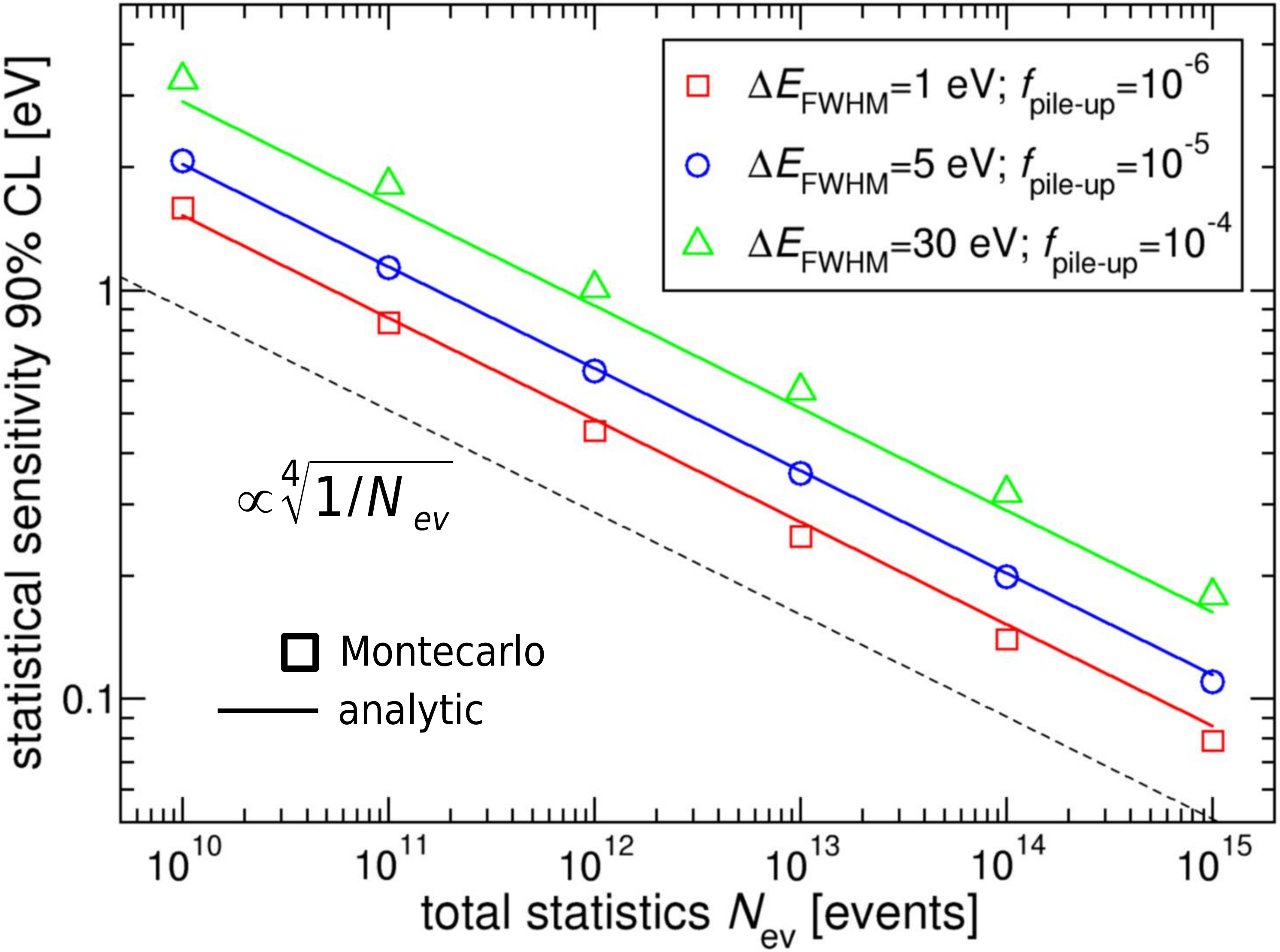
experimental challenges

- ▸ energy resolution ΔE_{FWHM}
- ▸ time resolution τ_R
- ▸ exposure $t_M = N_{det}\times T$
- ▸ single channel activity A_β

^{187}Re experiment statistical sensitivity / 1

^{187}Re past mesurements

- total statistics $N_{ev} \approx 10^7$ events



A.Nucciotti et al., Astropart. Phys., 34 (2010) 80 (arXiv:0912.4638v1)

^{187}Re experiment statistical sensitivity / 2

exposure required for 0.2 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	1	1	0.2×10^{14}	7.6×10^{5}
10	1	1	0.7×10^{14}	2.1×10^{5}
10	3	3	1.3×10^{14}	4.1×10^{5}
10	5	5	1.9×10^{14}	6.1×10^{5}
10	10	10	3.3×10^{14}	10.5×10^{5}

***bkg* = 0**

5000 pixels/array
8 arrays
10 years
400 g ^{nat}Re

exposure required for 0.1 eV m_ν sensitivity

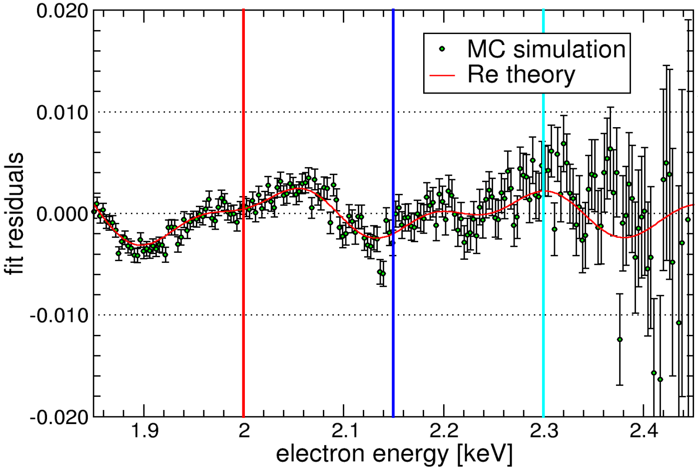
A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	0.1	0.1	1.7×10^{14}	5.4×10^{6}
10	0.1	0.1	5.3×10^{14}	1.7×10^{6}
10	1	1	10.3×10^{14}	3.3×10^{6}
10	3	3	21.4×10^{14}	6.8×10^{6}
10	5	5	43.6×10^{14}	13.9×10^{6}

20000 pixels/array
16 arrays
10 years
3.2 kg ^{nat}Re

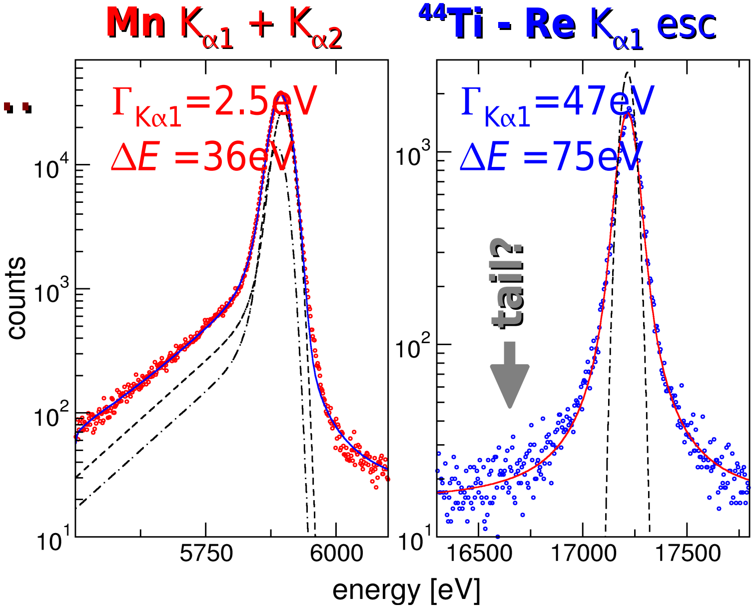
Rhenium experiment status and future

- Re detector development → to date no satisfactory results with Si or Ge thermistors, TES, MMCs... in about **20 years** of testing
  - no clear understanding of Re absorber physics
  - purity and superconductivity?
  - extra *C* due to nuclear quadrupole moment?
- low specific activity → “large” masses → fabrication issues
- possible large systematics
  - Beta Environmental Fine Structure (BEFS)
  - spectral shape
  - detector response function
- **future of Re experiments is not very bright...**

AgReO4 detectors cannot provide the perfomances needed for **sub-eV sensitivity**
E.Ferri, talk Fri 11:15



BEFS in ^{187}Re
$N_{ev} = 10^{10}$
ΔE = 5 eV
$f_{pp} = 10^{-5}$



Electron capture end-point experiment / 1

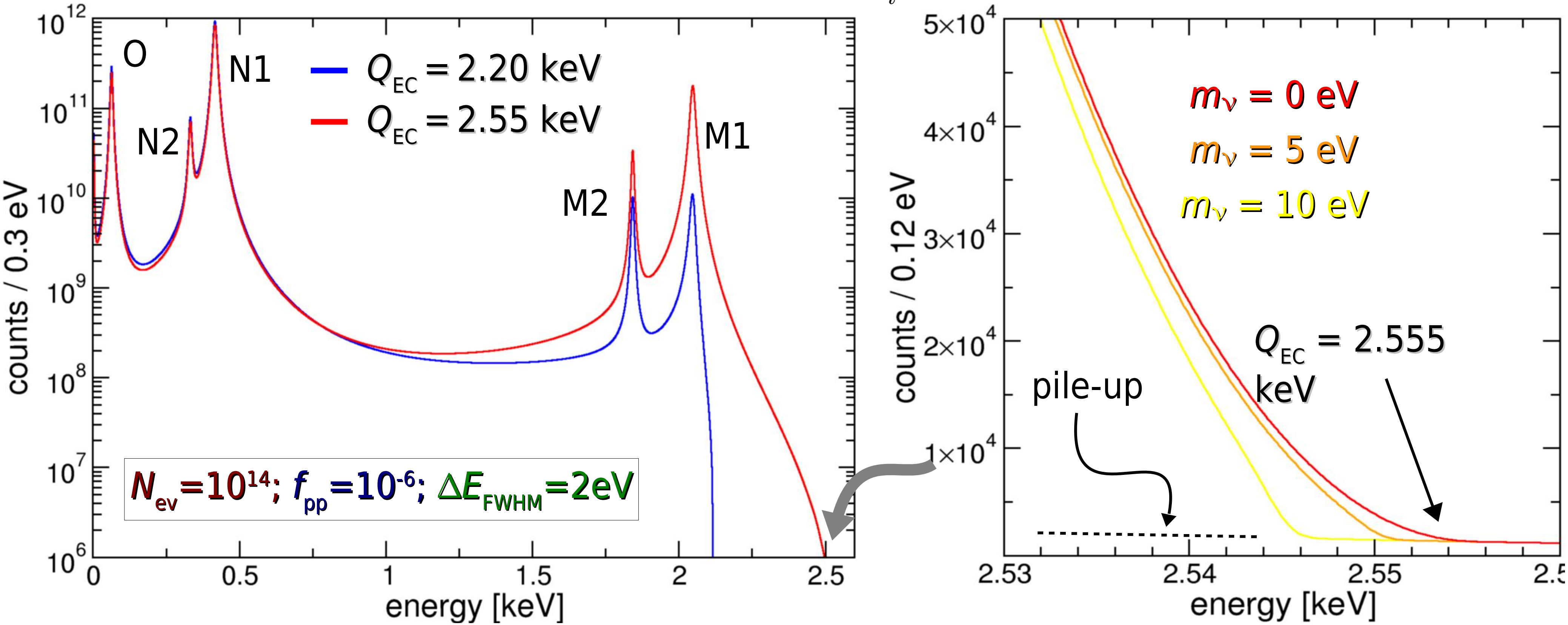
$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e$

electron capture from shell ⩾ M1

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

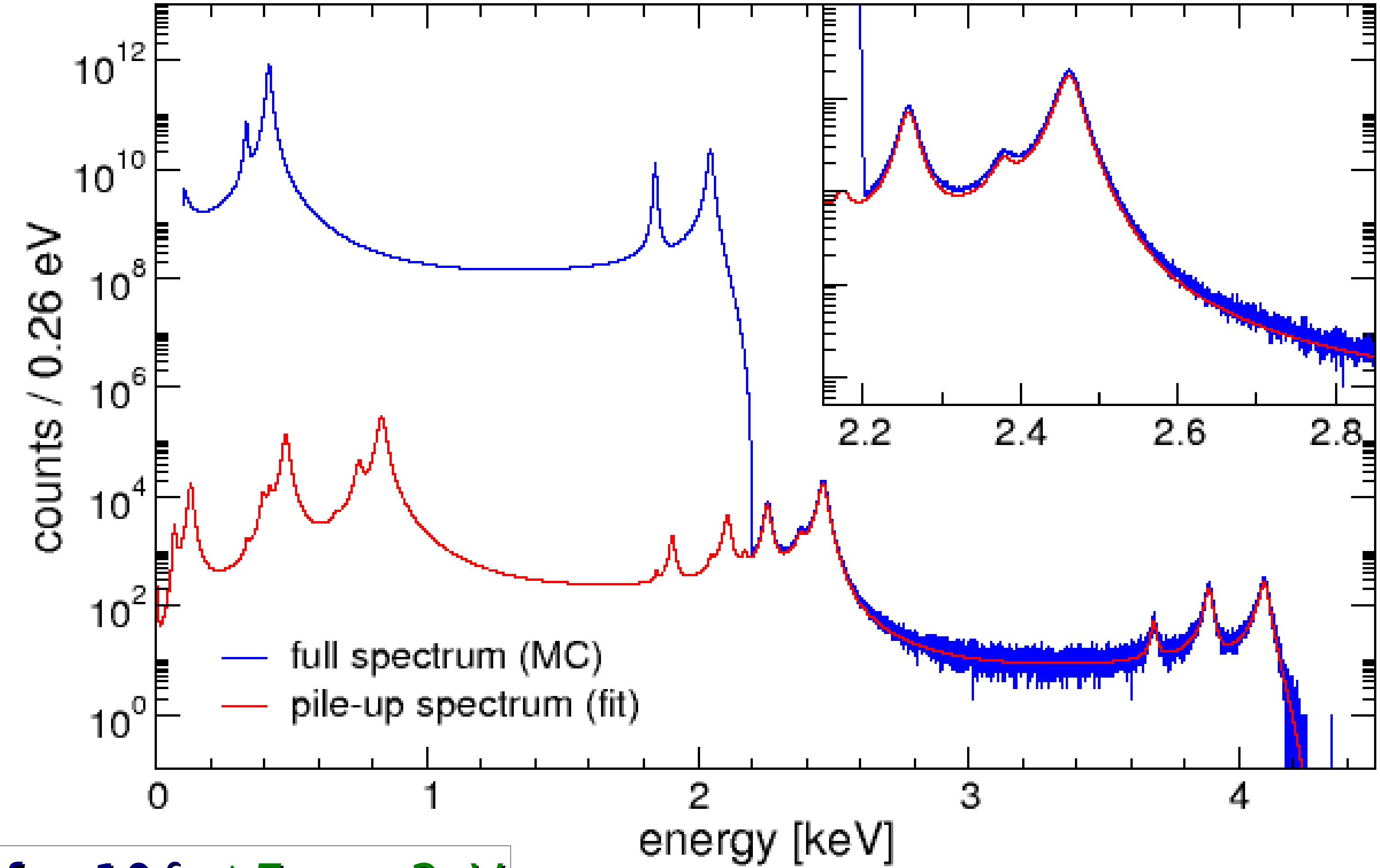
- calorimetric measurement of Dy atomic de-excitations (mostly non-radiative)
- rate at end-point and ν mass sensitivity depend on Q
  - ▸ Measured: Q_{EC} = 2.2÷2.8 keV. Recommended: Q = 2.555 keV
- $\tau_{1/2}$ ≈4570 years: few active nuclei are needed

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



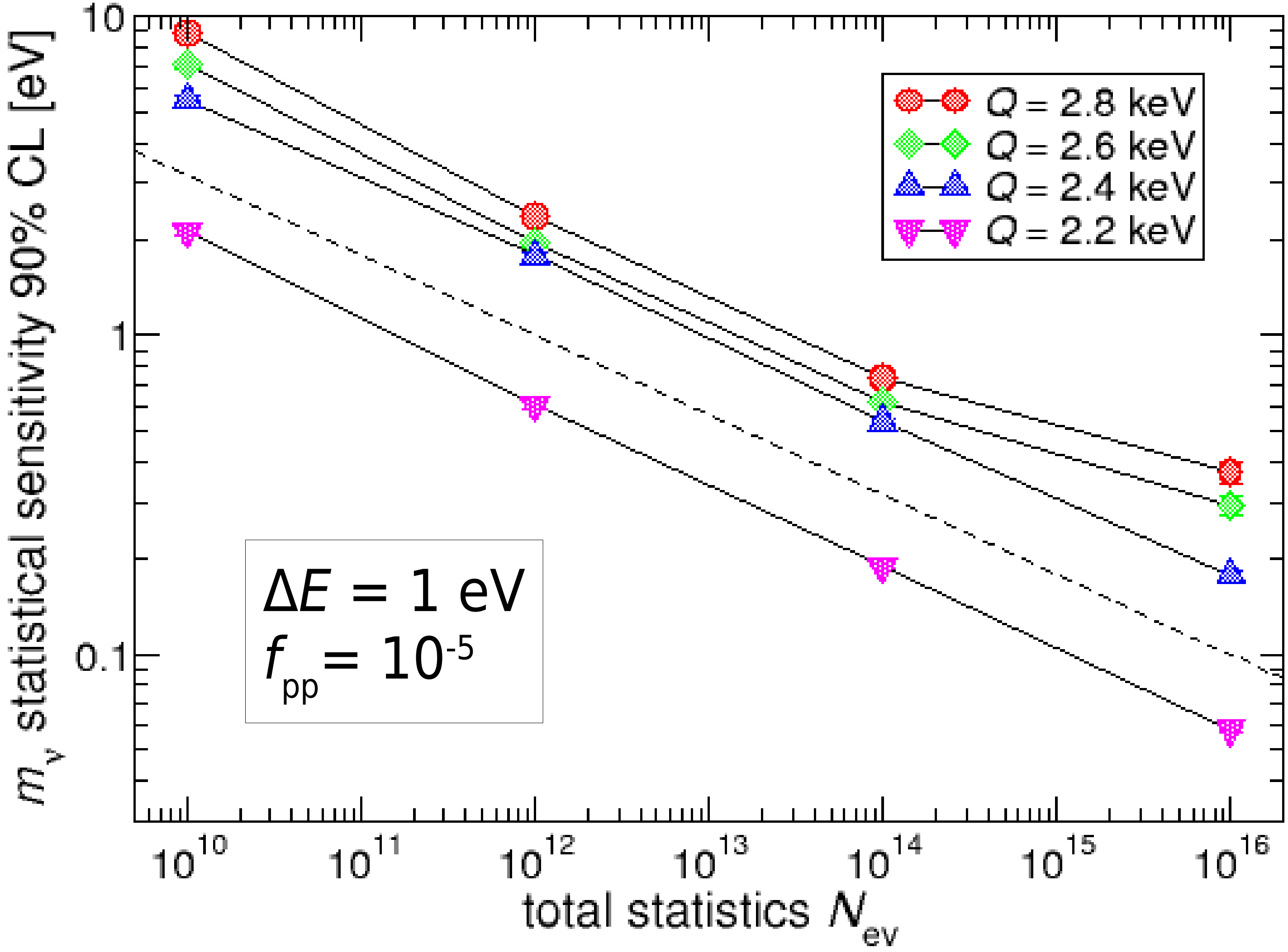
Electron capture end-point experiment / 2

- no direct calorimetric measurement of Q so far
- Q and atomic de-excitation spectrum poorly known
- complex pile-up spectrum



$N_{ev}=10^{14}$; $f_{pp}=10^{-6}$; $\Delta E_{FWHM}=2\text{eV}$

Statistical sensitivity: Montecarlo simulations



M. Galeazzi et al., submitted to PRD, arXiv:1202.4763v2

^{163}Ho experiment statistical sensitivity / 1

exposure required for 0.2 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	1	1	2.8×10^{13}	9.0×10^{5}
1	0.1	1	1.3×10^{13}	4.3×10^{5}
100	0.1	1	4.6×10^{13}	1.5×10^{4}
10	0.1	1	2.8×10^{13}	9.0×10^{4}
10	1	1	4.6×10^{13}	1.5×10^{5}

exposure required for 0.1 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	0.1	0.3	1.2×10^{14}	3.9×10^{6}
100	0.1	0.3	6.4×10^{14}	2.0×10^{5}
100	0.1	1	7.4×10^{14}	2.4×10^{5}
10	0.1	1	4.5×10^{14}	1.5×10^{6}
10	1	1	7.4×10^{14}	2.4×10^{6}

Q_{EC} = 2200 eV
***bkg* = 0**

5000 pixels/array
3 arrays
1 year
$\approx 2\times10^{17}$ ^{163}Ho nuclei

5000 pixels/array
4 arrays
10 years
$\approx 3\times10^{17}$ ^{163}Ho nuclei

^{163}Ho experiment statistical sensitivity / 2

exposure required for 0.2 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	1	1	3.8×10^{15}	1.2×10^{8}
1	0.1	1	1.6×10^{15}	5.3×10^{7}
100	0.1	1	9.8×10^{15}	3.1×10^{6}
10	0.1	1	3.8×10^{15}	1.2×10^{7}
10	1	1	9.8×10^{15}	3.1×10^{7}

Q_{EC} = 2800 eV

***bkg* = 0**

60000 pixels/array

5 arrays

5 year

≈4×10^{18} ^{163}Ho nuclei

exposure required for 0.1 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	0.1	0.3	2.6×10^{16}	8.2×10^{8}
100	0.1	0.3	1.9×10^{17}	5.9×10^{7}
100	0.1	1	1.6×10^{17}	5.0×10^{7}
10	0.1	1	6.1×10^{16}	1.9×10^{8}
10	1	1	1.6×10^{17}	5.0×10^{8}

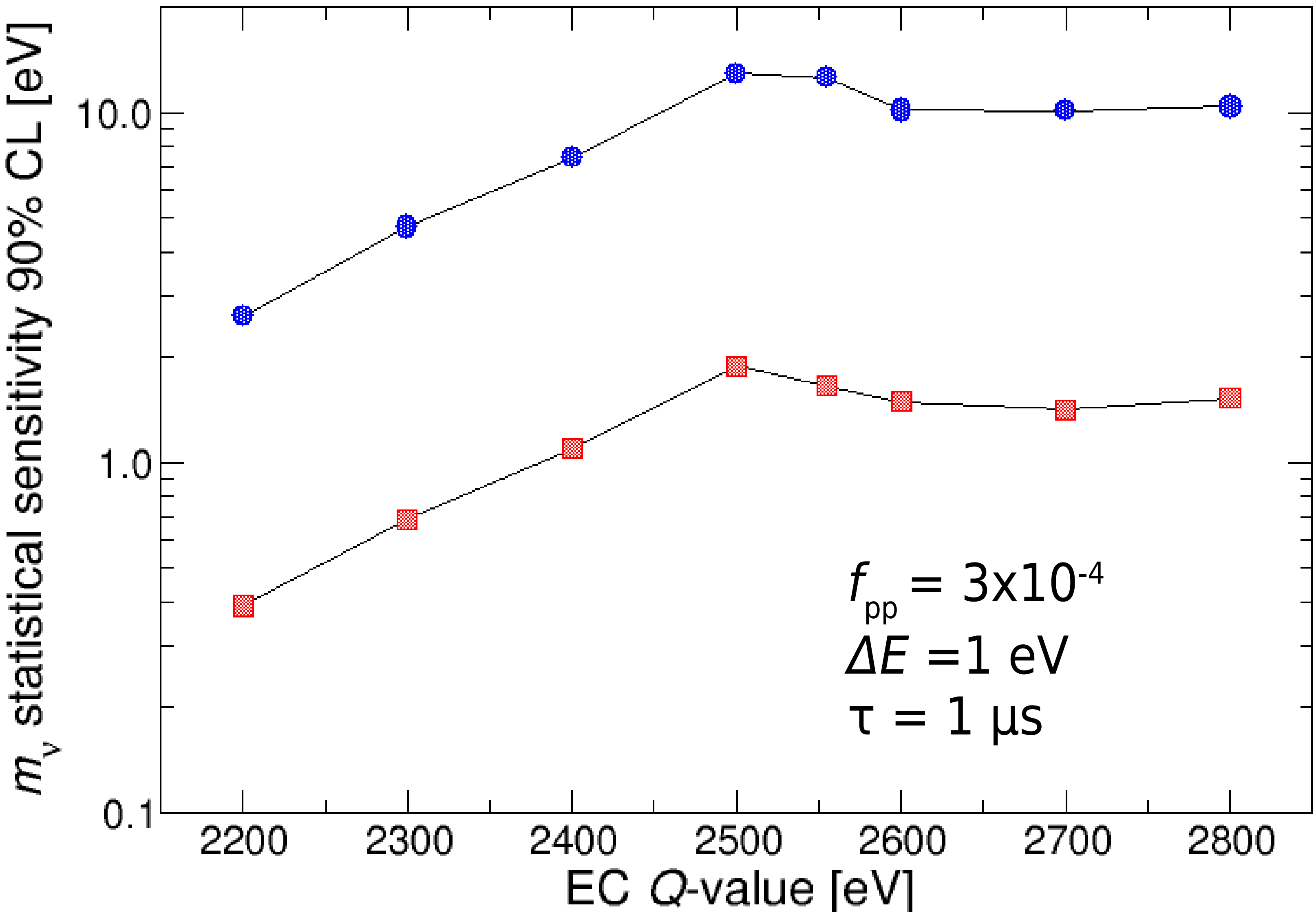
60000 pixels/array

100 arrays

10 years

≈8×10^{19} ^{163}Ho nuclei

Small scale mid term ^{163}Ho experiments



$f_{pp} = 3\text{x}10^{-4}$
ΔE =1 eV
τ = 1 μs

16 channels
t_M=1 month
A=300Hz/ch
→ 10^{10} decays

1000 channels
t_M=3 years
A=300Hz/ch
→ $3\text{x}10^{13}$ decays

Holmium experiment status

- **^{163}Ho seems to be better than ^{187}Re**
  - higher specific activity → don't need an Holmium detector
  - *self calibrating* → better systematics control
  - but
    - higher *Q* → maybe less sensitive
    - pile-up spectrum
    - chemical effects on *Q*
- (at least) **two LTD projects**
  - ECHO (L.Gastaldo, talk Fri 11:45; P. Ranitzsch, port Fri 305)
  - MARE (E.Ferri, talk Fri 11:15; M. Galeazzi, post Fri 109; G. Pizzigoni, post Fri 208; M. Ribeiro post Fri 306)
- **common technical challenges**
  - clean ^{163}Ho production
  - ^{163}Ho incorporation
  - large channel number → high speed MUX
  - data handling (processing, storage, ...)

^{163}Ho production and incorporation

GJ Kunde post. Fri 209
M Ribeiro post. Fri 306
G Pizzigoni post. Fri 208

^{163}Ho production by nuclear reaction

- high yield
- low by-products contaminations (in particular ^{166m}Ho, β $\tau_{½}$=1200y)
- not all cross sections are well known
  - → neutron activation of enriched ^{162}Er (nuclear reactor)
  - → spallation with *p* on W/Ta (ISOLDE@CERN)
  - → ^{163}Dy(p,n)^{163}Ho E_p=10 MeV (direct, low yield)
  - → ^{nat}Dy(α,xn)^{163}Er and ^{159}Tb(^{7}Li, 3n)^{163}Er

^{163}Ho Separation from Dy, Er and more ...

- radiochemistry
- magnetic mass separation
- resonance ionization laser ion source

^{163}Ho incorporation in detector absorber

D Schmidt talk Tue
M Croce talk Fri 14:15
M Galeazzi post Fri 109

- implantation (+magnetic separation)
- film deposition
- liquid drop drying

GJ Kunde post. Fri 209

particle	*p*	*n* 10^{14} n/cm2/s	*p* 16 MeV	*p* 24 MeV	*α* 40 MeV	*α* 40 MeV
target	W/Ta	^{162}Er	^{nat}Dy	^{nat}Dy	^{nat}Dy	^{161}Dy
^{163}Ho prod rate [nuclei/h]	10^{14}	$10^{13\text{-}15}$/ mg ^{162}Er	10^{14}	10^{15}	10^{13}	10^{10}

U. Koester @NuMass 2013

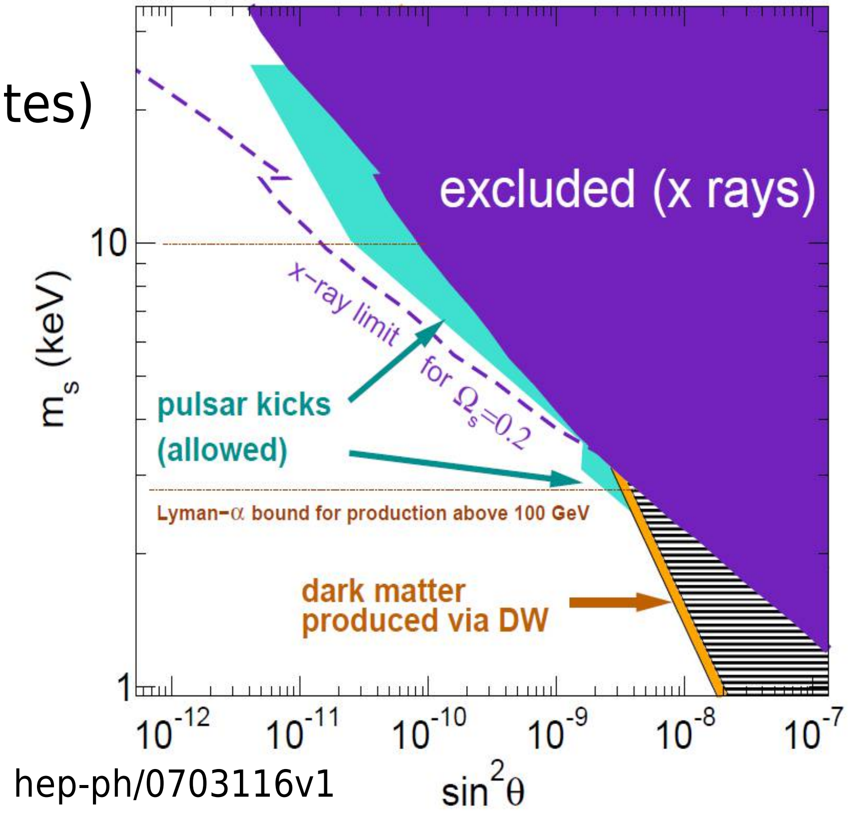
Sterile neutrinos

- **two mass ranges of interest for LTDs**
  - ▸ low mass (1eV) → coherent scattering
  - ▸ keV mass → beta decay kink searches

- **keV mass sterile neutrinos as Warm Dark Matter**
- why WDM?
  - ▸ fixes some problems with ΛCDM at small scales
    - cusped halo profiles
    - overabundant sub-galactic structures (satellites)
- limits from astrophysics observations
  x-ray from sterile neutrino decay

C. Destri, H. J. de Vega, N. G. Sanchez, New Astronomy 22, 39 (2013)

C. Destri, H. J. de Vega, N. G. Sanchez, arXiv:1301.1864.



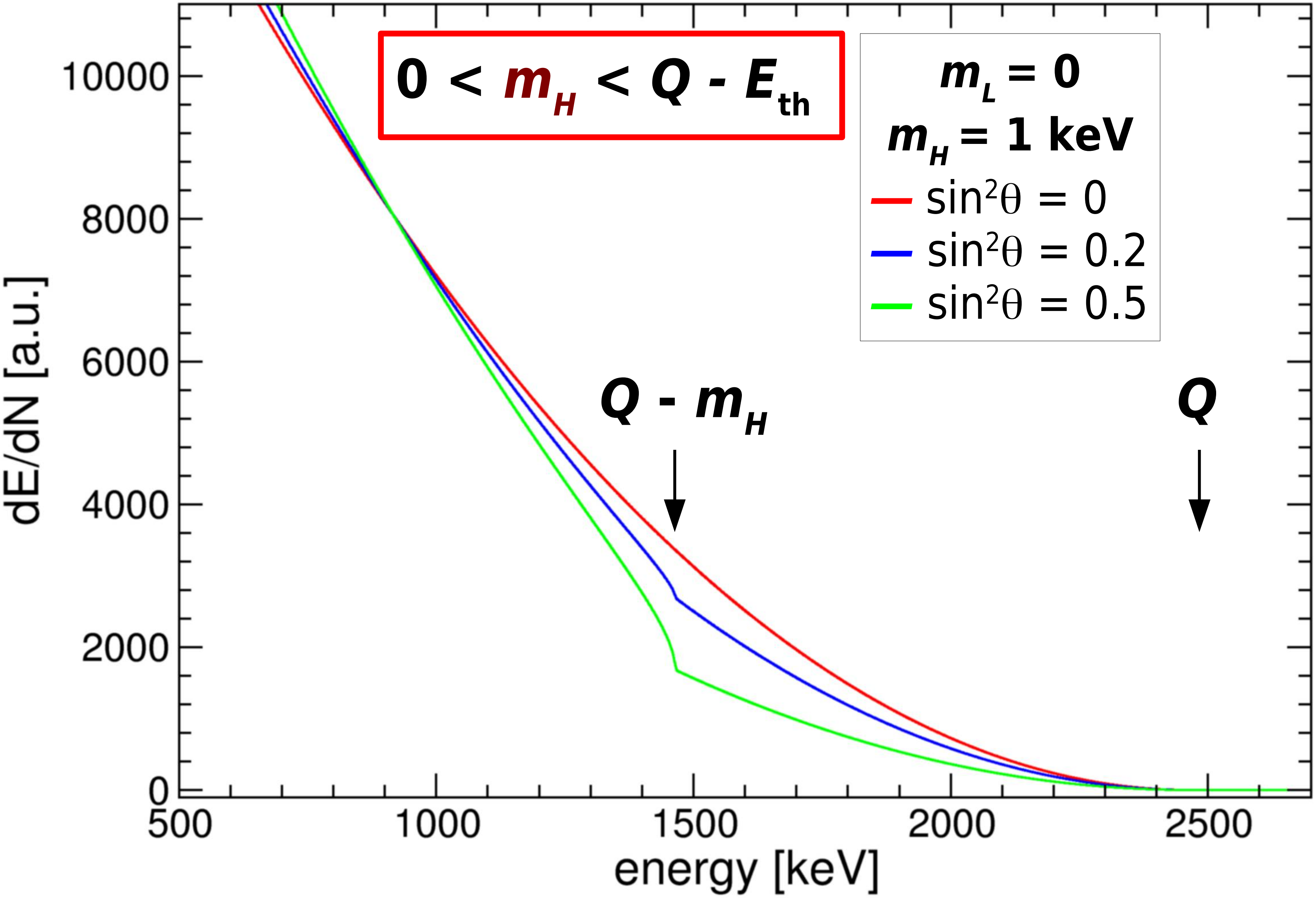
A. Kusenko, hep-ph/0703116v1

Searches for sterile neutrinos in β decay

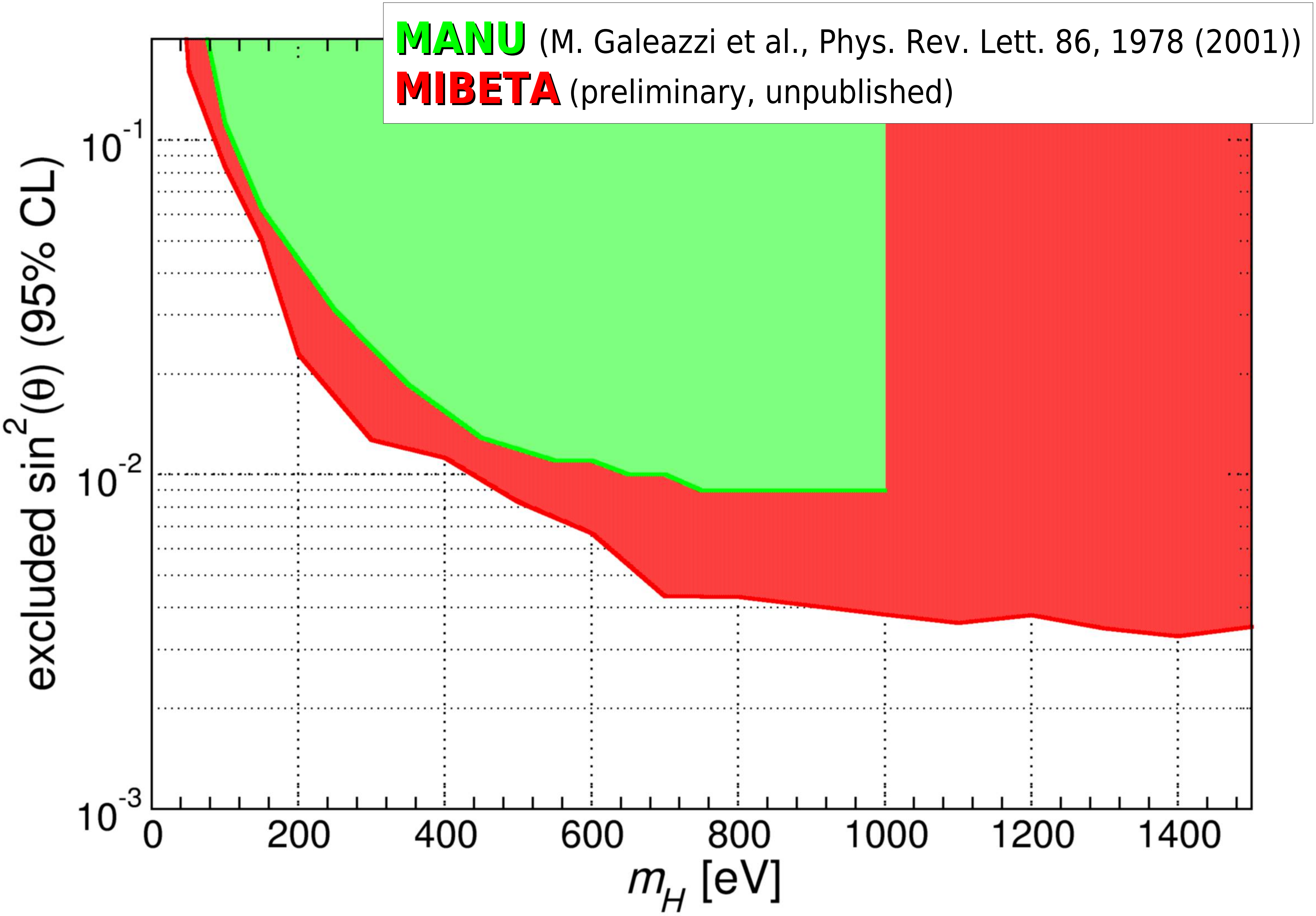
heavy neutrino emission in ^{187}Re β decay

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

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


$0 < m_H < Q - E_{th}$

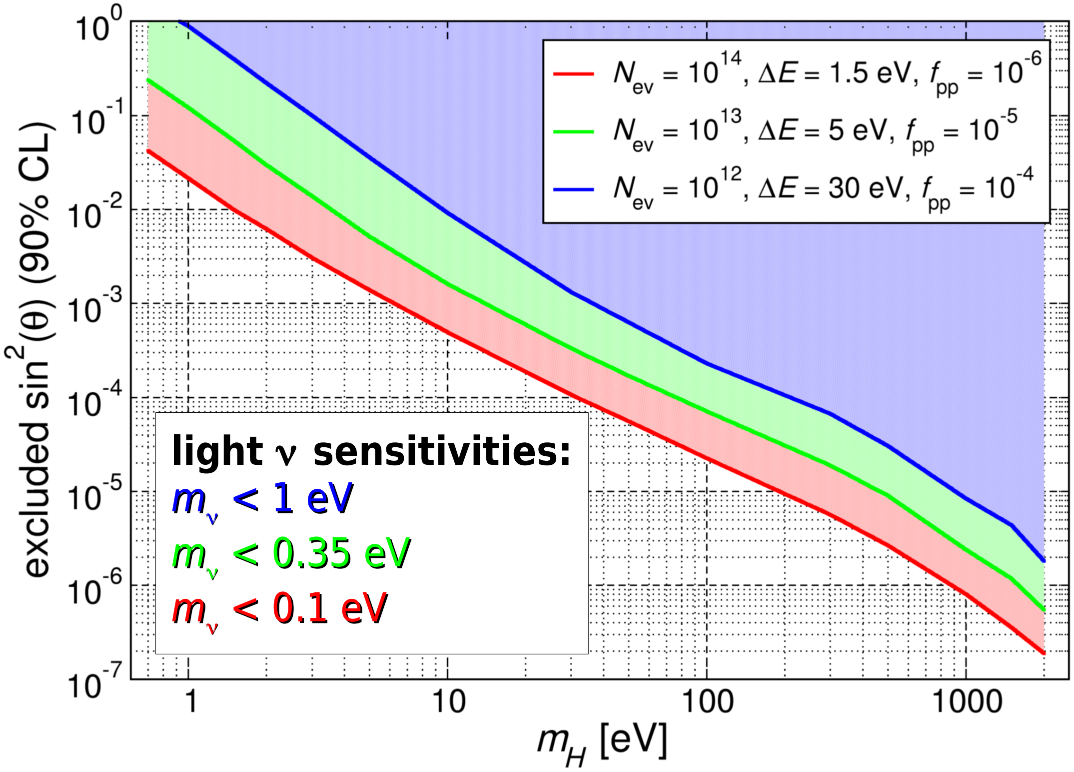
Sterile neutrino emission in ^{187}Re decay



MANU (M. Galeazzi et al., Phys. Rev. Lett. 86, 1978 (2001))

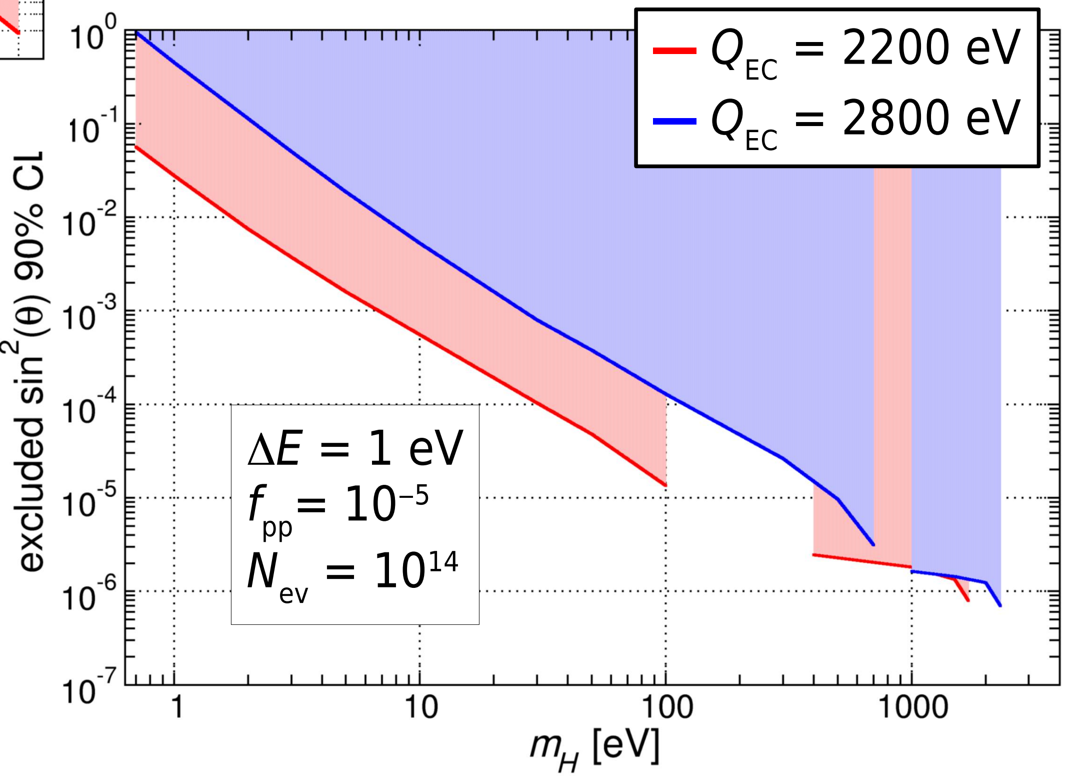
MIBETA (preliminary, unpublished)

Sterile neutrino search with MARE or ECHO



← ^{187}Re

^{163}Ho →



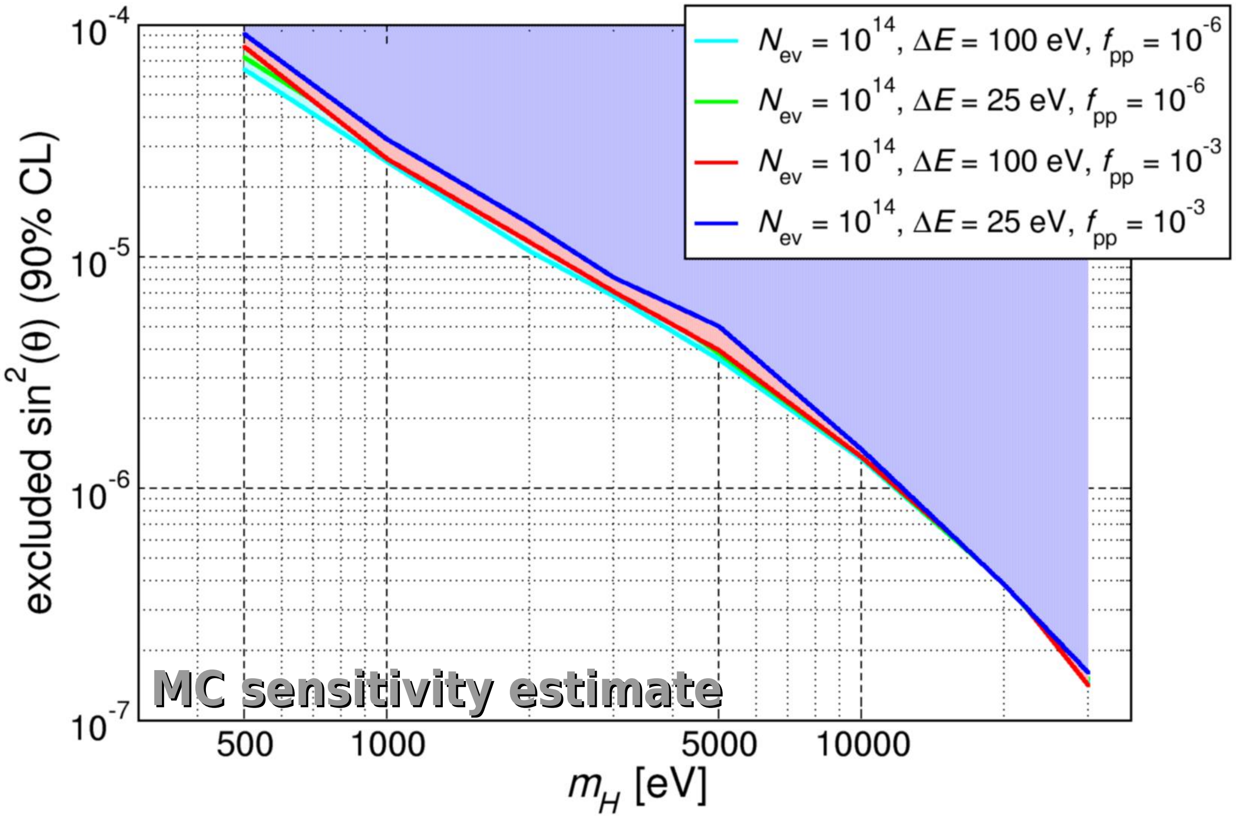
$$\sum\nolimits_{90}\left(\sin^2(\theta)\right) \approx 1/\sqrt{N_{ev}}$$

Sterile neutrino emission in other β decays

$$^{107}\mathrm{Pd} \rightarrow {}^{107}\mathrm{Ag} + e^{-} + \bar{\nu}_e$$

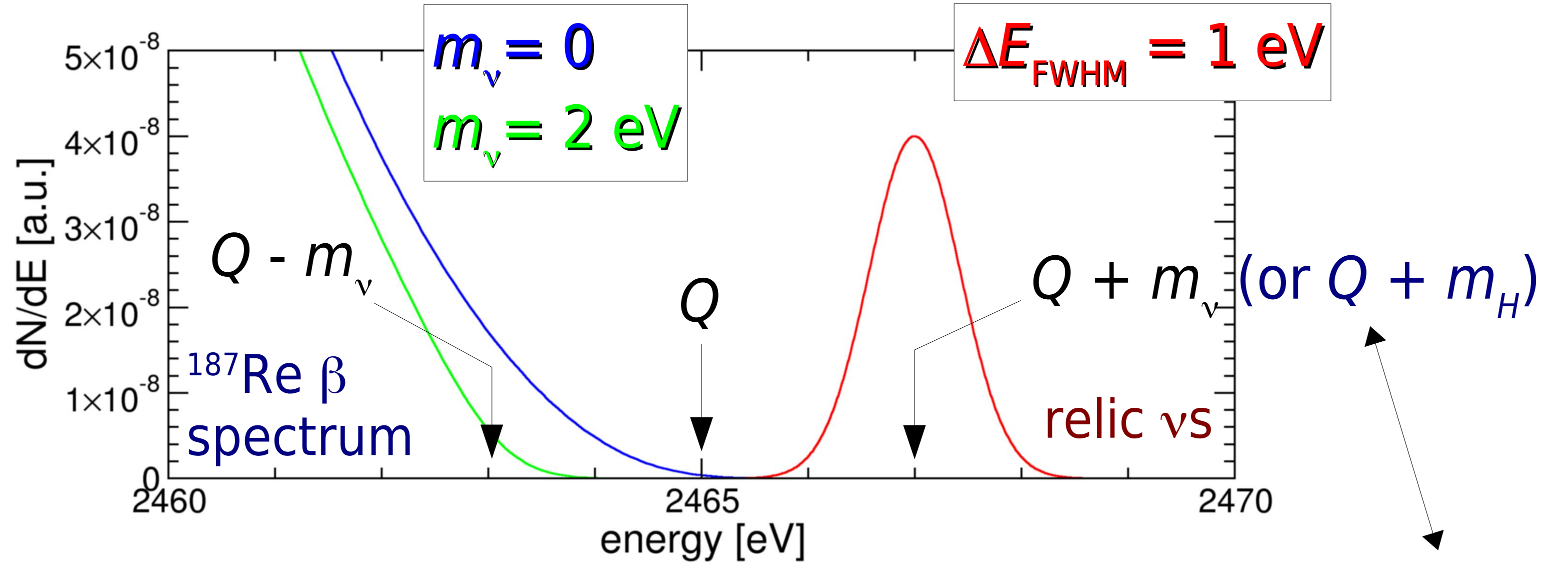
- $5/2^{+} \rightarrow 1/2^{-}$ unique first forbidden
- end point E_0 = 35 keV
- half-life time: $\tau_{1/2} = 6.5 \times 10^{6}$ y
- Production: ^{106}Pd(n,γ)

- Why **thermal microcalorimeters**?
  - Not for energy resolution, not for speed
  - Full energy detection against systematics
- Need a **good compound** to make thermal microcalorimeters
- Possible issues:
  - Detector size for full β containment
  - Background



1000 pixels/array
300 dec/s per pixel
4 arrays
3 years

Cosmic neutrino background detection



Interaction rates in **KATRIN** and **MARE**	**relic ν_e (CνB)**	**isotope mass**	**rate**	**sterile ν_H m_H = 1 keV**
$\nu + {}^3H \rightarrow {}^3He + e^-$	$0.1\ y^{-1}\ g^{-1}$ (1)	100 μg	$10^{-5}\ y^{-1}$	$100\ \sin^2\theta\ y^{-1}\ g^{-1}$ (4)
$\nu + {}^{187}Re \rightarrow {}^{187}Os + e^-$	$10^{-10}\ y^{-1}\ g^{-1}$ (2)	1000 g	$10^{-7}\ y^{-1}$	$10^{-7}\ \sin^2\theta\ y^{-1}\ g^{-1}$
$\bar{\nu} + e^- + {}^{163}Ho \rightarrow {}^{163}Dy^*$	$10^{-5}\ y^{-1}\ g^{-1}$ (3)	100 μg	$10^{-9}\ y^{-1}$	$10^{-3}\ \sin^2\theta\ y^{-1}\ g^{-1}$ (5)

ν densities

CνB: $n_\nu \approx 55\ \nu_e/cm^3$ *

WDM: $n_\nu \approx 3\times10^5\ \nu_H/cm^3$

Q_{EC} = 2.5 keV

* without clustering (→ 10^2-10^6 increase)

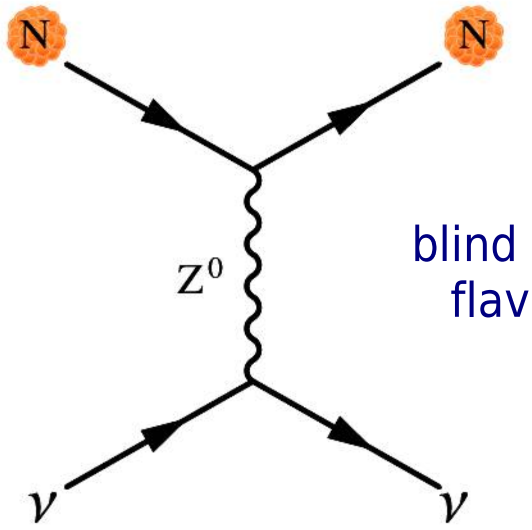
(1) R.Lazauskas et al., J. Phys. G: Part. Phys. 35, 025001 (2008)
(2) A.G.Cocco et al., J. Cosmol. Astropart. Phys. 06, 15 (2007)
R.Hodak et al., Progr. in Part. and Nucl. Phys. 66, 452 (2011)
(3) M.Lusignoli, M.Vignati, Phys. Lett., B697, 11 (2011) (arXiv:1012.0760 [hep-ph])
(4) W.Liao, Phys. Rev., D82, 73001 (2010)
Y.F.Li, Z.Z.Xing, Phys. Lett. B695, 205 (2011)
(5) Y.F.Li, Z.Z.Xing, arXiv:1104-4000 [astro-ph]

Coherent scattering

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} M_A Q_W^2 (1 - \frac{M_A T}{2E_\nu^2}) F(q^2)^2$$

$$Q_W = N - Z(1 - 4\sin^2\theta_W)$$

$$T_{\max} \le \frac{E_\nu}{1 + \frac{M_A}{2E_\nu}}$$



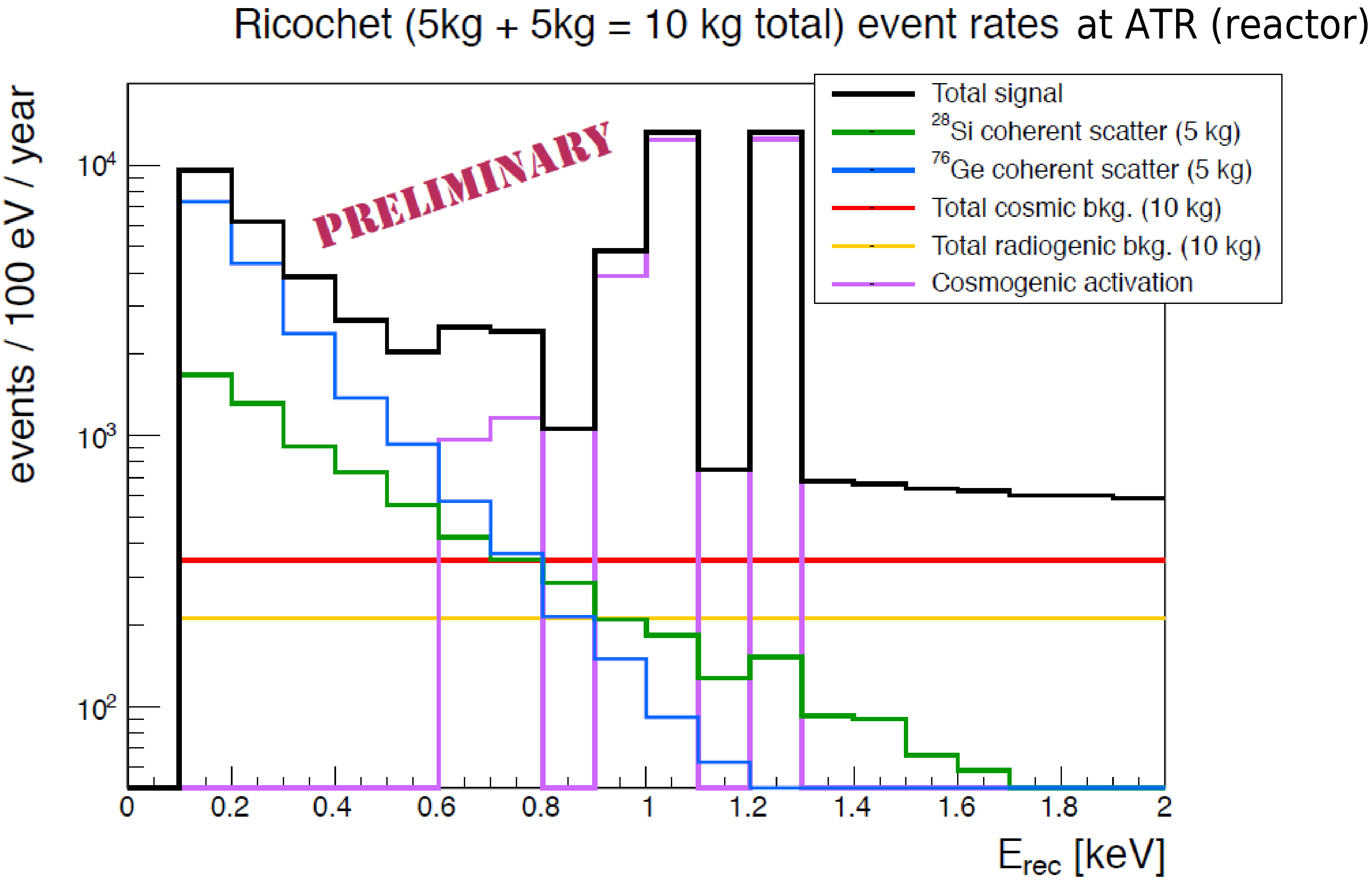
blind to ν flavor

- **predicted by Standard Model** but never observed
- cross section coherent enhancement (≈N^2)
- low energy nuclear recoil → use LTDs!
  - test for physics beyond SM at low momentum transfer
  - ν detection
    - → short distance low energy oscillations → sterile νs
    - → supernovae ν detection
    - → ν magnetic moment measurement

Coherent scattering LTD experiments

- **Ricochet program**
- test SM model and search for sterile ν with oscillations
- few option under study
  - SuperCDMS low threshold (100 eV) optimized Si and Ge detectors at nuclear reactor (M. Pyle, talk Fri 8:30)
  - very low threshold (10 eV) 10^4 pixel array of ≈10 g Si or Ge with Electron Capture source

Ricochet at a nuclear reactor



→ coherent scattering detection
→ search for non standard interactions
→ search for sterile neutrinos by moving the detector

Ricochet with an electron capture source

Source	Half-Life	Progeny	Production	E_ν
^{37}Ar	35.04 days	^{37}Cl	^{40}Ca(n,α)^{37}Ar	811 keV (90.2%), 813 keV (9.8%)
^{51}Cr	27.70 days	^{51}V	n capture on ^{50}Cr	747 keV (81.6%), 427 keV (9%), 752 keV (8.5%)
^{65}Zn	244 days	^{65}Cu	n capture on ^{64}Zn	1343 keV (49.3%), 227 keV (50.7%)

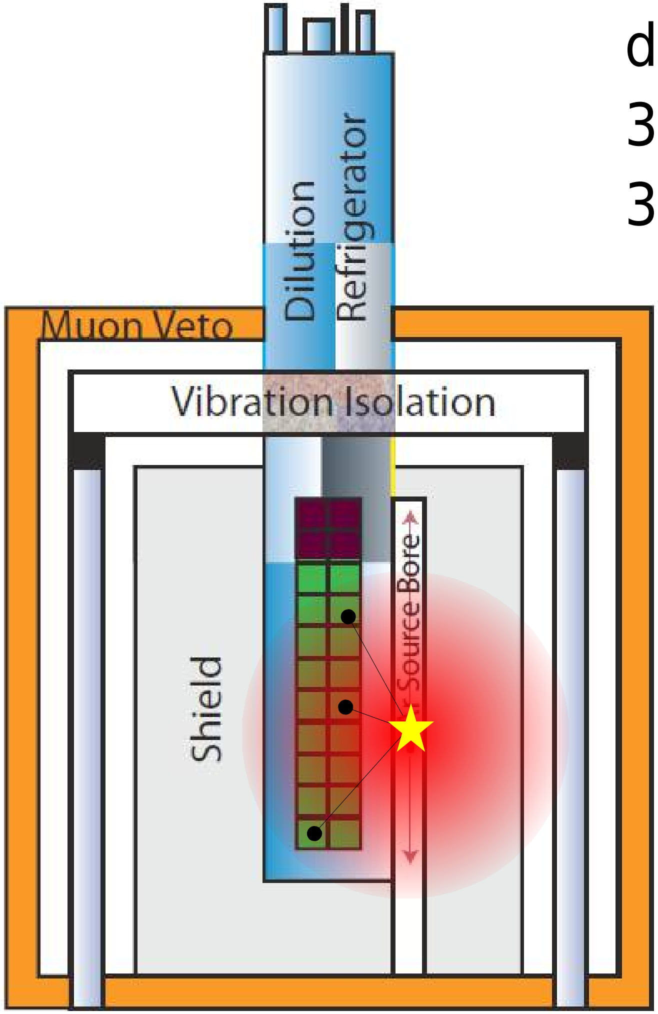
detector: 10^4 pixel

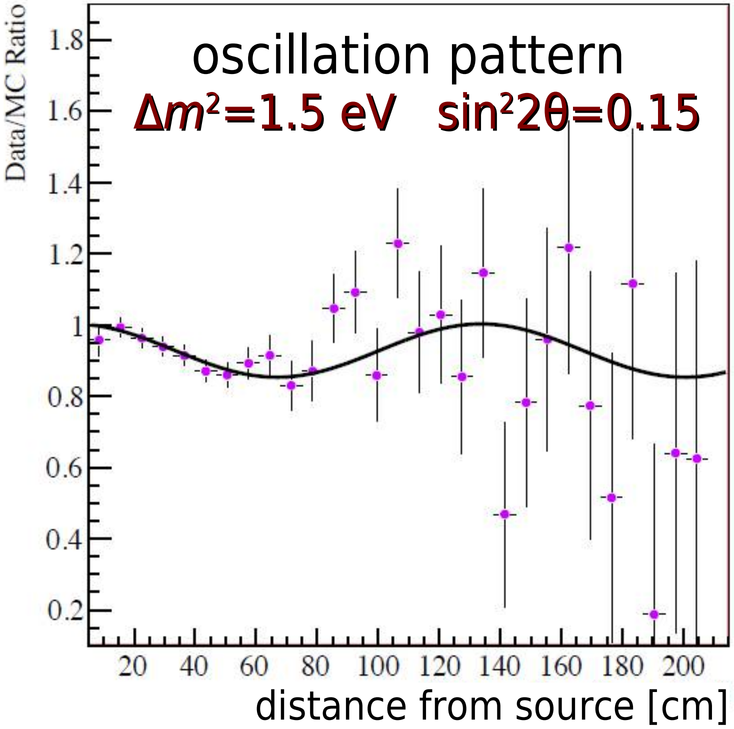
→ 500kg Si (or 200kg Ge)

deep underground site and bkg=1 c/kg/day

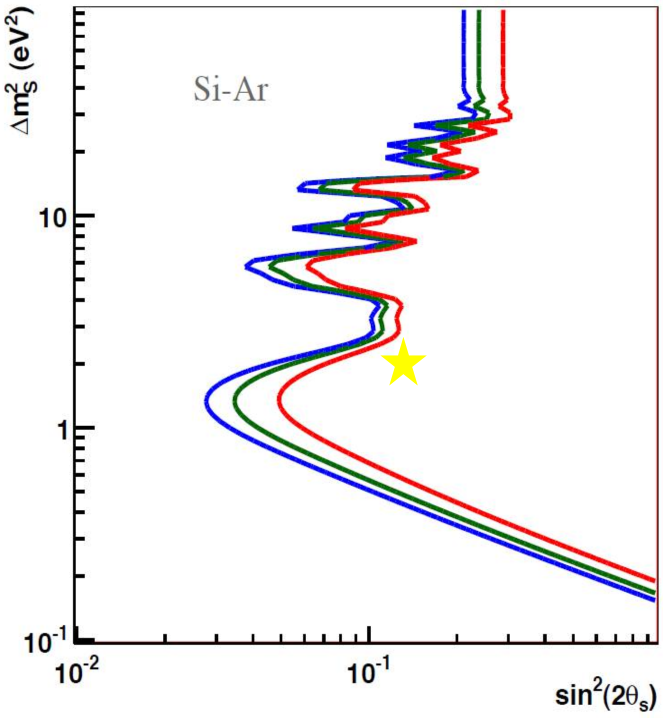
37Ar source 5MCi → 800 keV ν

300 days exposure




oscillation pattern

Δm^2=1.5 eV $\sin^2 2\theta$=0.15

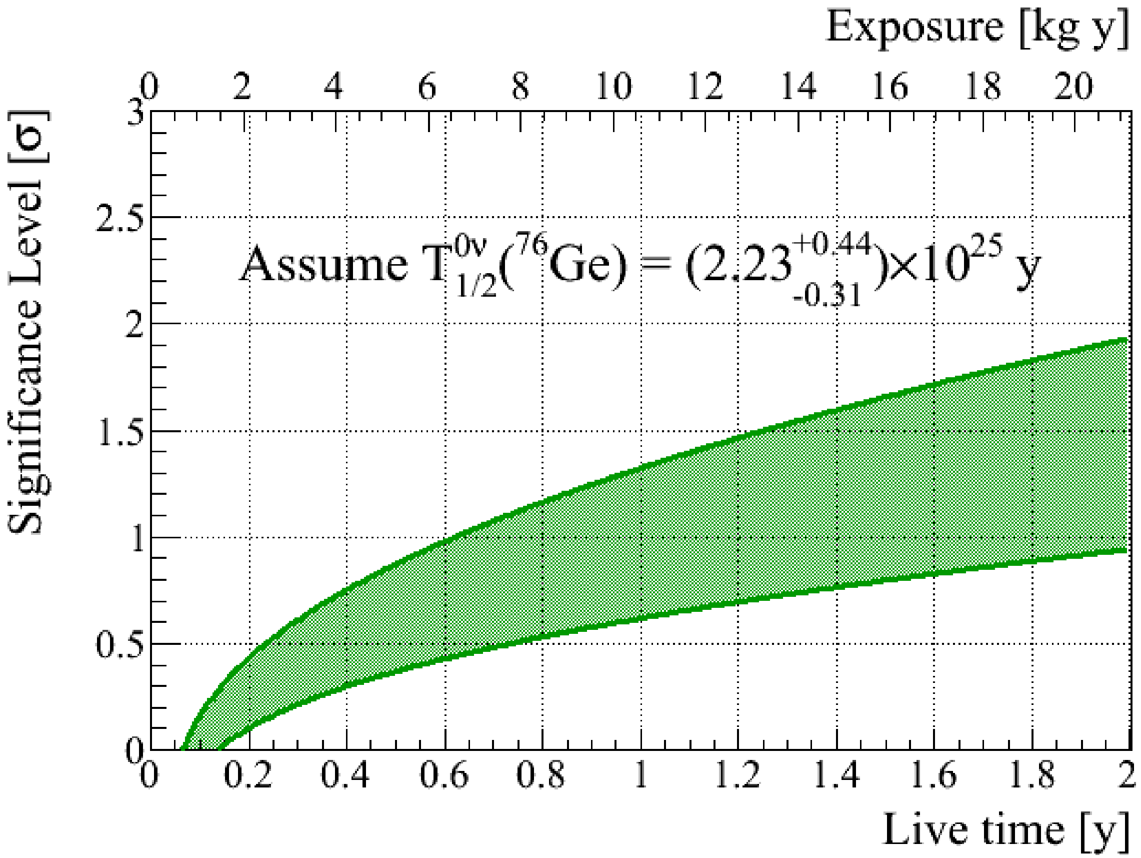


Conclusions

- **Neutrino physics has still many urgent open questions**
- **Many complementary approaches should be pursued**
- Low temperature detectors do play a key role in neutrino physics
- For next generation experiments the technical challenge is becoming daunting (as for other techniques...)
- The effort will require always larger collaborations

Backups...

Checking Heidelberg claim



Significance level at which CUORE-0 can observe a DBD signal consistent with the claim in ^{76}Ge (KK-HK), assuming 0.05 c/keV/kg/y background

- The inner band corresponds to the best-fit value of the claim; the range arises from the “1σ” range of QRPA NME calculations in A. Faessler et al., Phys. Rev. D79 (2009) 053001
- The outer band also includes the 1σ error on the ^{76}Ge claim

b = 0.05 c/keV/kg/y, *T* = 2 y

$T_{1/2}$ sensitivity = 5.9 x 10^{24} y (90% CL)

$<m_{ee}>$ < (204 ÷ 533) meV