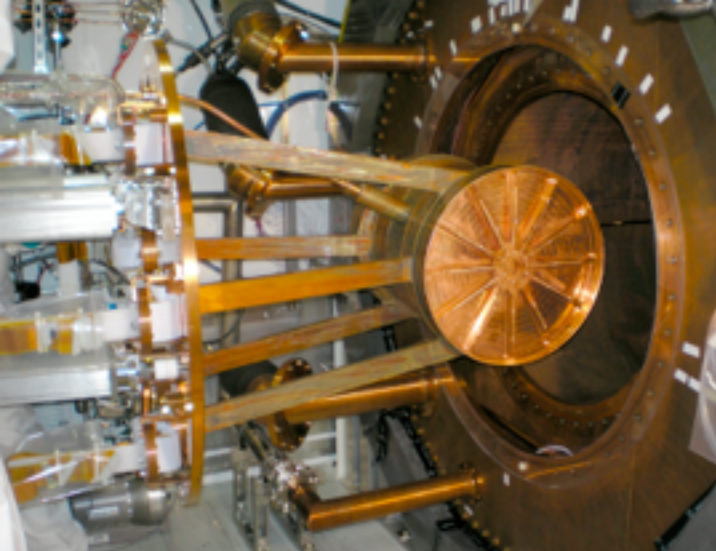
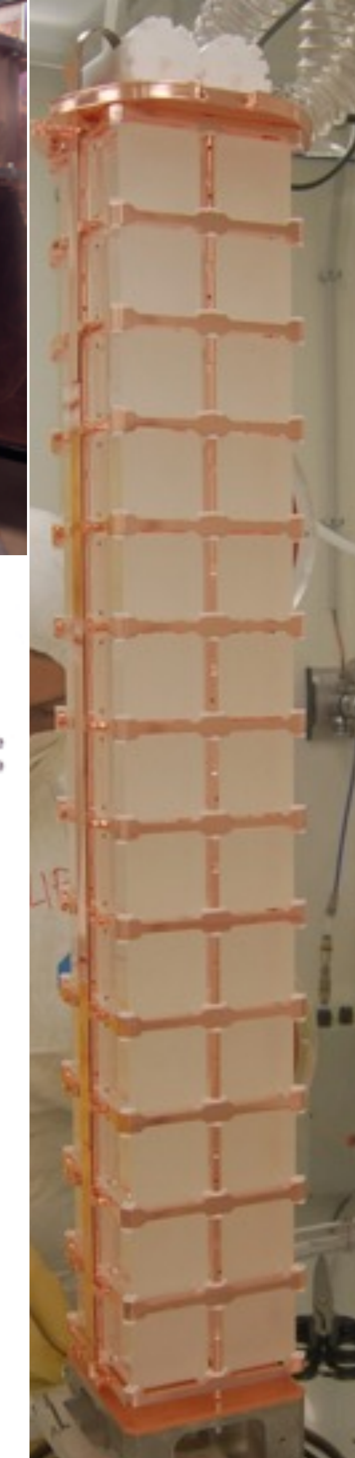




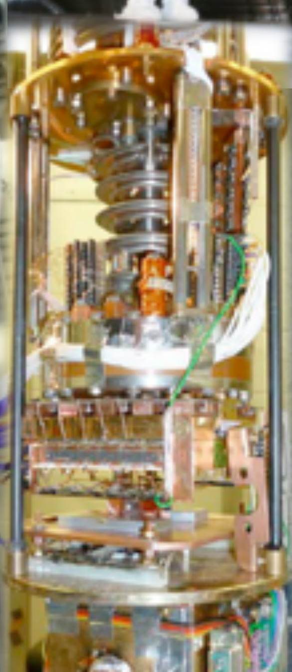
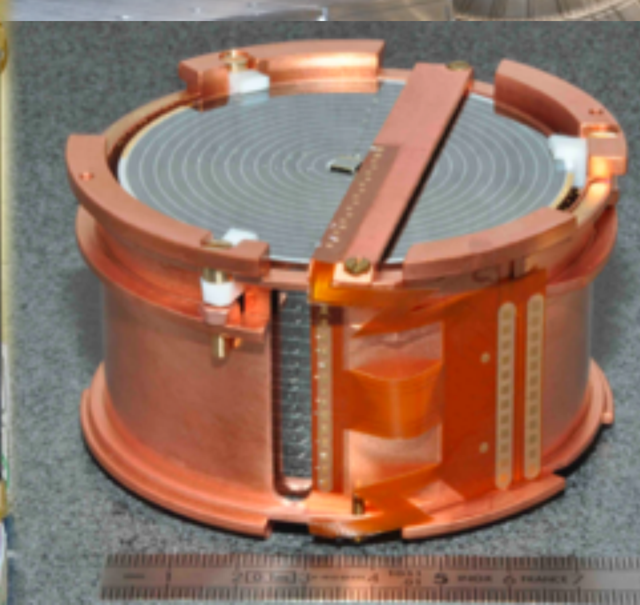
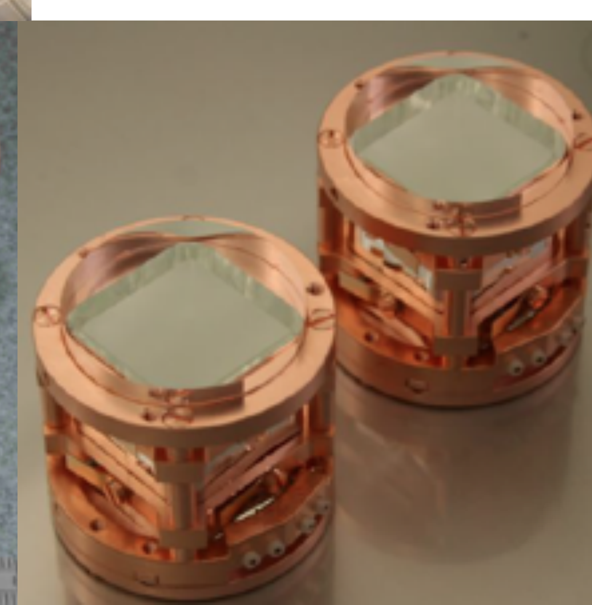
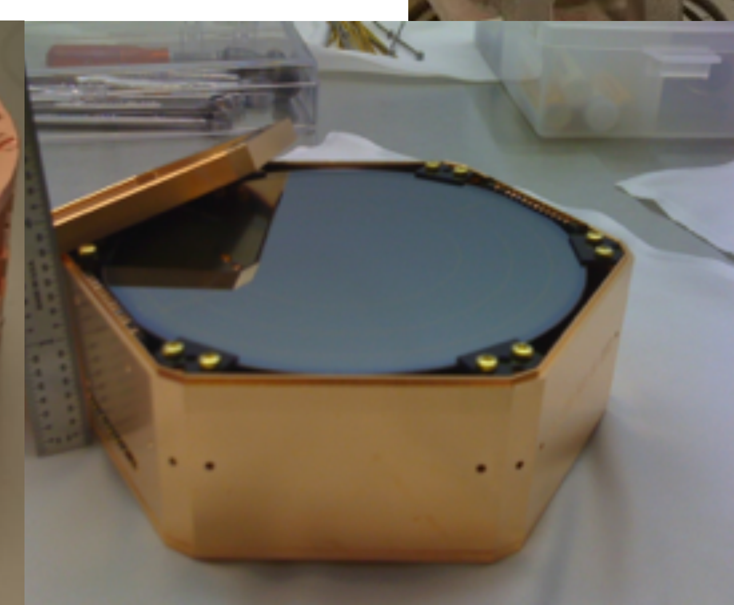



Future rare event challenges

Oliviero Cremonesi

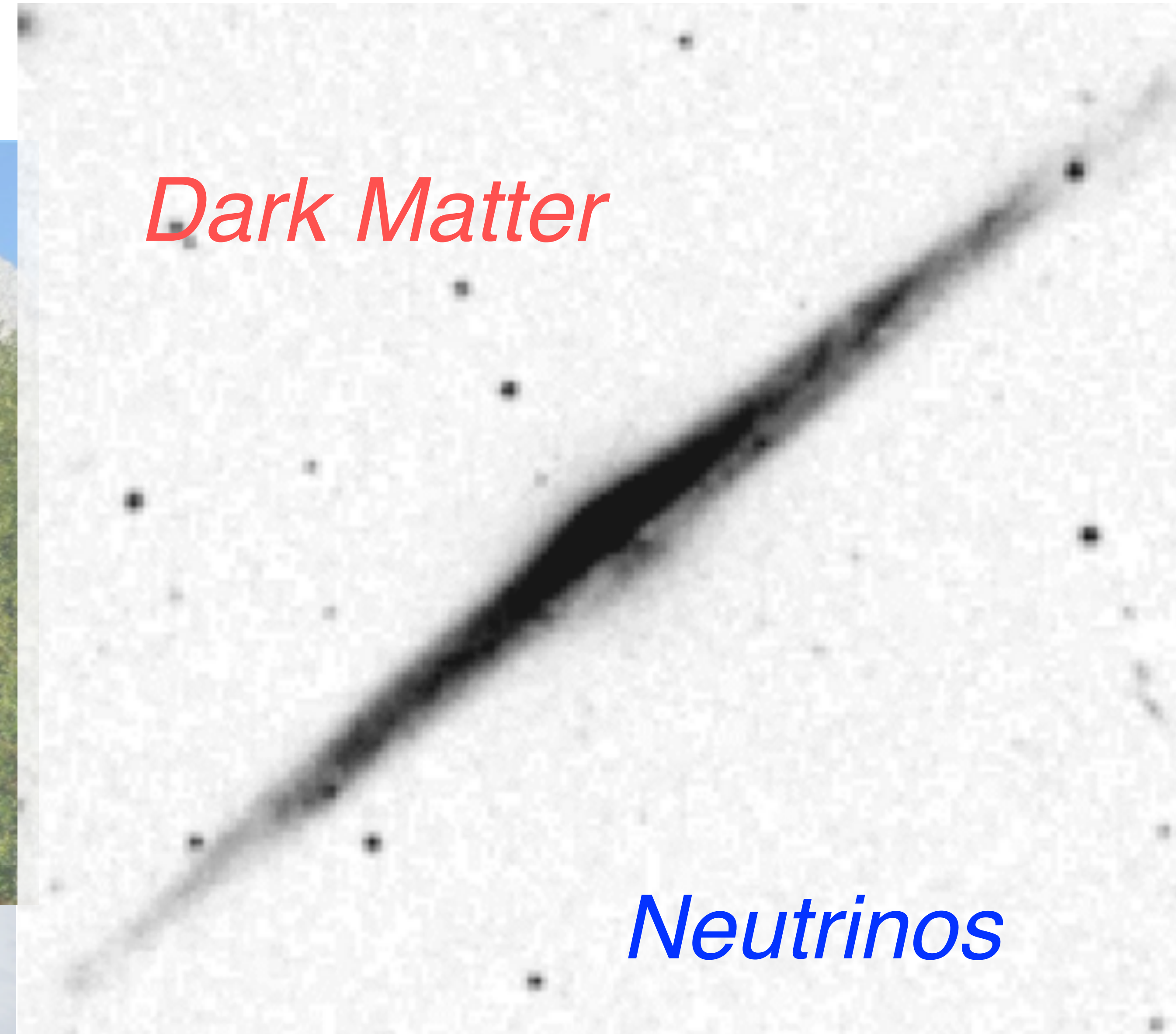
INFN, Sezione di Milano Bicocca

IFD2015
December 16-18, 2015
Turin, Italy

Rare events: few selected items

Neutrinoless ββ



Neutrino mass

Rare events

- Different (compelling) physics cases

- Common features

Low rate (few counts/year)		Low background
Random process	→	Signature
No "beam off"		
Limited information		

Rare events

A continuous quest for

- best performance ⟷ new technologies

with the constraints imposed by the need of

- larger scales ⟷
  - space and cost
  - long running times
- low background
  - severe material assay
  - underground location
  - shields and vetos
  - …

New experiments aim at the best sensitivity and depend on the parallel evolution of all these aspects

Background: a common enemy

- It is the common denominator (or better enemy) to all rare event experiments
- It is the experimental factor which most severely affects (limits) the experimental sensitivity

Main sources:
- Environmental radioactivity
- Radioactivity of the detector and surrounding materials
- Cosmic rays and their secondary reactions
- Specific to each detecting technique

Mitigations:
- Underground operation (and preparation)
- Material assay
- Phased approach
- … but also signatures and technological improvements →
  - pulse shape analysis
  - hybrid techniques
  - special detecting techniques

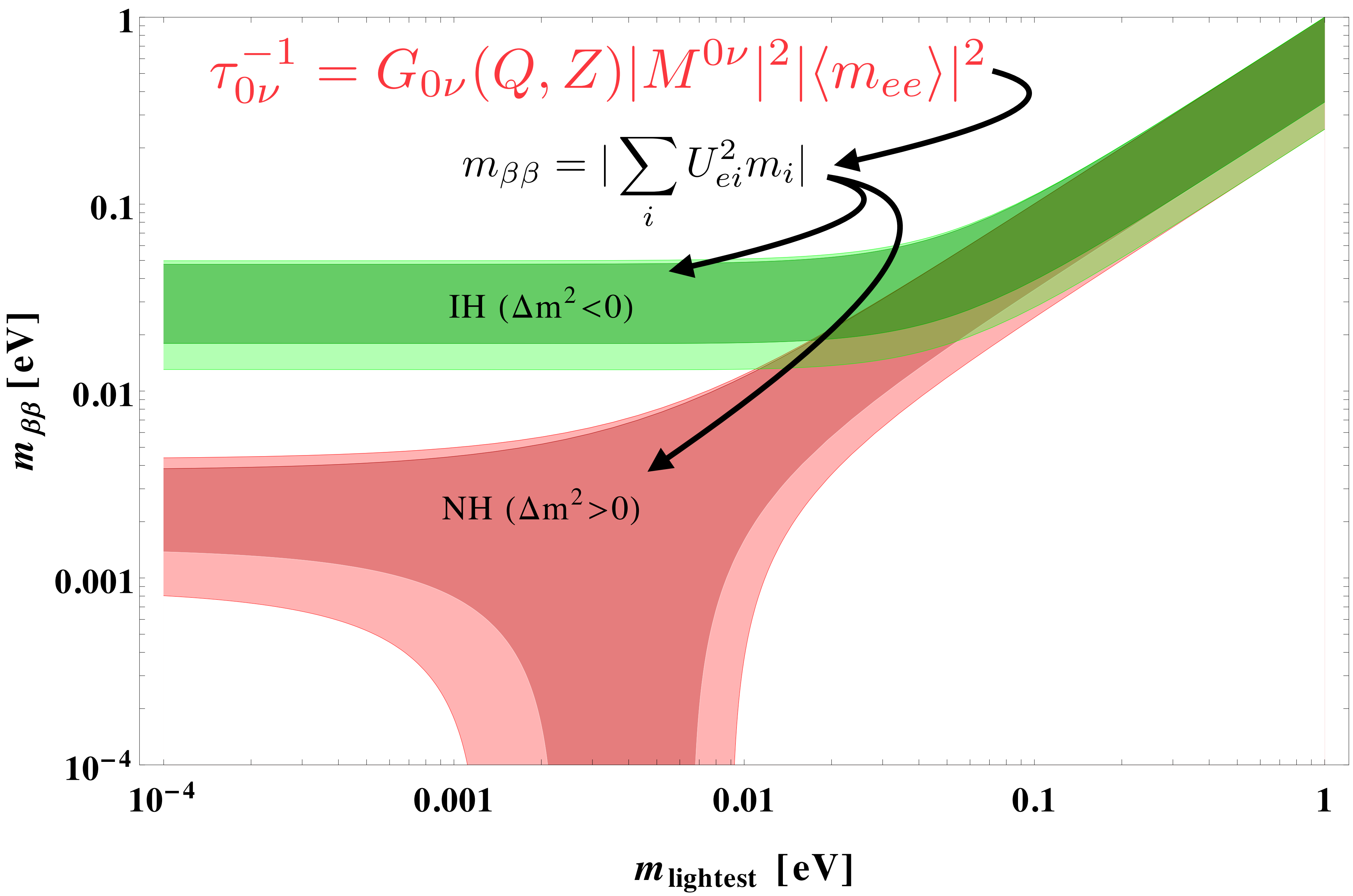
- **It is the true challenge of all future approaches**

Neutrinoless double beta decay

Three light ν's: the "standard" plot

Experimental parameters are pictured as a function of the lightest mass eigenvalue:

- S.Pascoli, S.Petcov, Phys.Atom.Nucl. 66 (2003) 444, arxiv:0111203
- R.Mohapatra et al., arXiv:0510213
- A.Strumia and F.Vissani, IFUP-TH/2004-1; arXiv:0606054



Bands arise from specific experimental and theoretical uncertainties:

- darker: Majorana phases range
- light: mixing parameter uncertainties

- G.L Fogli, et al, PRD 78 033010 (2008), arXiv:0805.2517v3

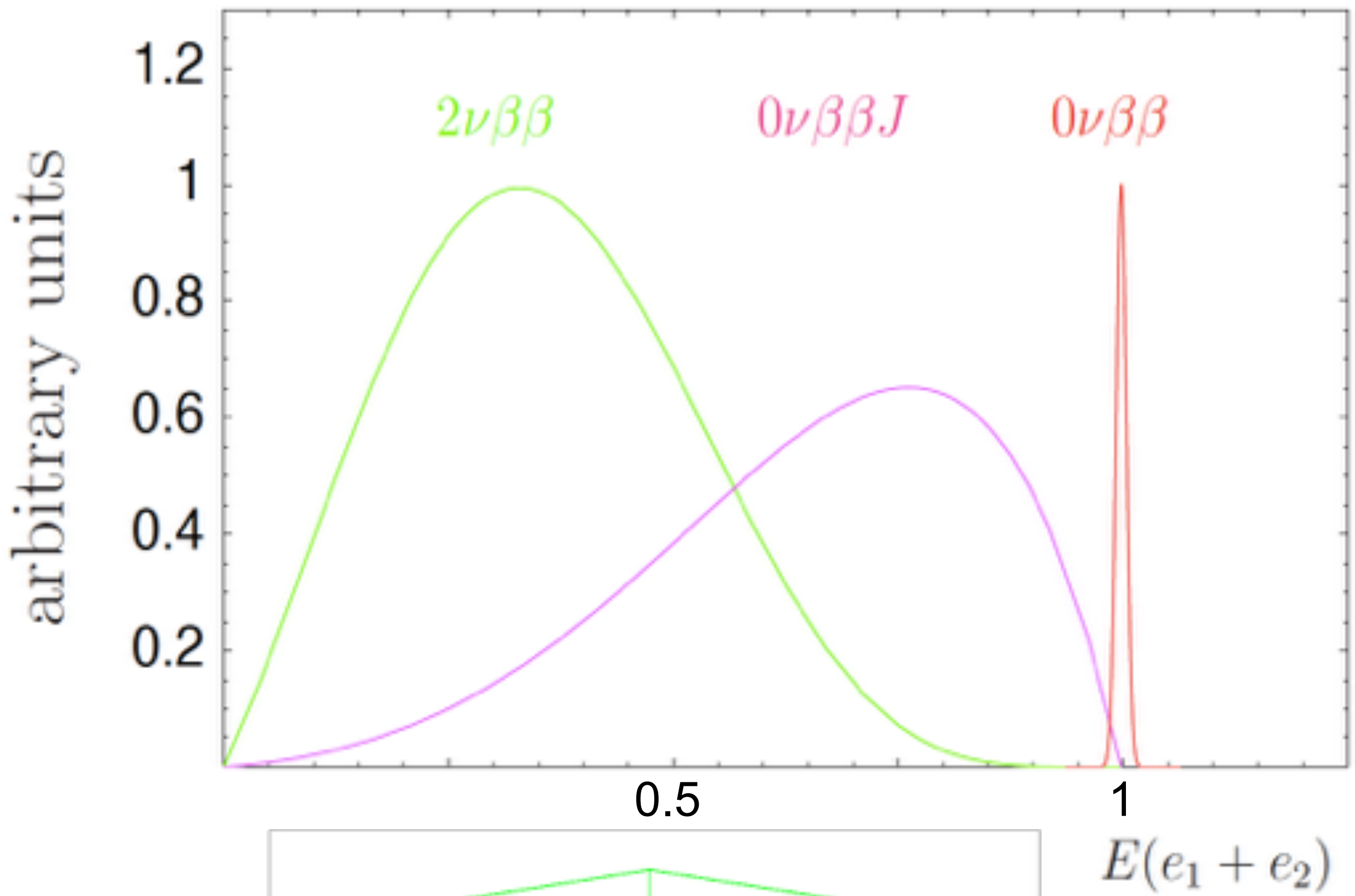
S. Dell'Oro, S. Marcocci, F. Vissani, Phys. Rev. D90, 033005 (2014)

Experimental signature of ββ(0ν)

(A,Z) → (A,Z+2)$^{++}$ + 2 e-

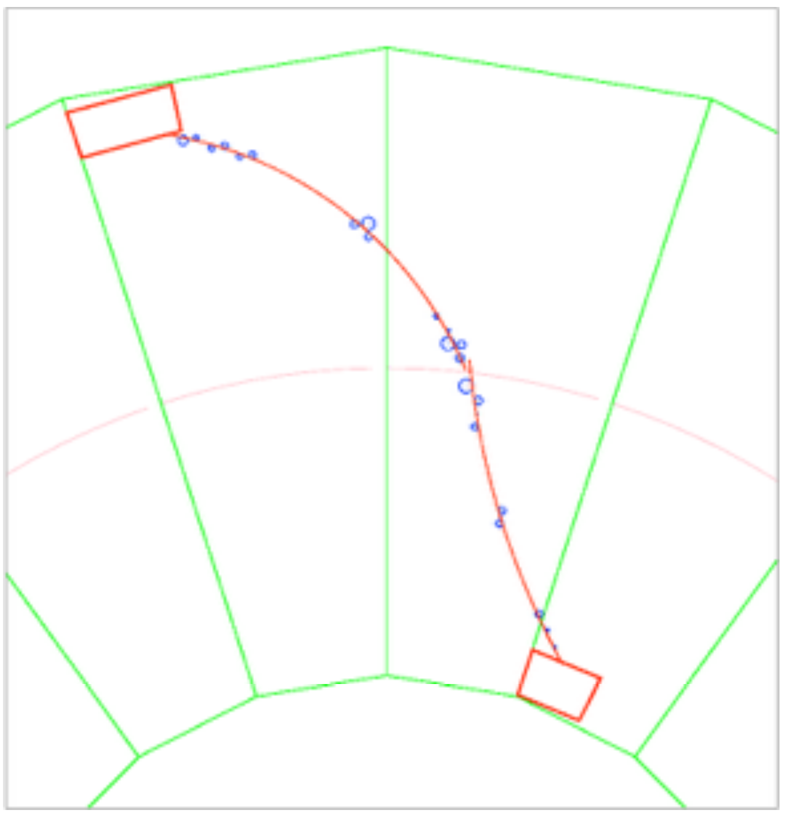
- A new (ionised) isotope
- Two electrons

Main signature:
- 0νββ exhibits a **peak at Q** in the two e$^-$ energy sum spectrum over 2νββ tail (and background contributions)



Additional informations:
- Single electron energy spectrum
- Angular correlation between the two electrons
- Daughter nuclear species

⟶ Track and event topology
⟶ Time Of Flight



- Can allow to disentangle decay modes
- Can help reducing backgrounds

Moreover, to cure NME systematics:
- study as many as possible different isotopes

Experimental sensitivity

The number of background events expected along the experiment lifetime is

$$N_B = bkg \cdot \Delta E \cdot M \cdot t_{meas}$$

Two cases are then possible depending on the extent of the background:

$$N_B >> 1 \longrightarrow S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

$$N_B < 1 \longrightarrow S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A} M \cdot t_{meas}$$

generally named **"zero background"** condition

N_{nuclei}	number of active nuclei in the experiment
t_{meas}	measuring time [y]
M	detector mass [kg]
ε	detector efficiency
i.a.	isotopic abundance
A	atomic number
ΔE	energy resolution [keV]
bkg	background [c/keV/y/kg]

By inserting the proper nuclear factor of merit is then possible to get the **sensitivity on the effective neutrino Majorana mass**

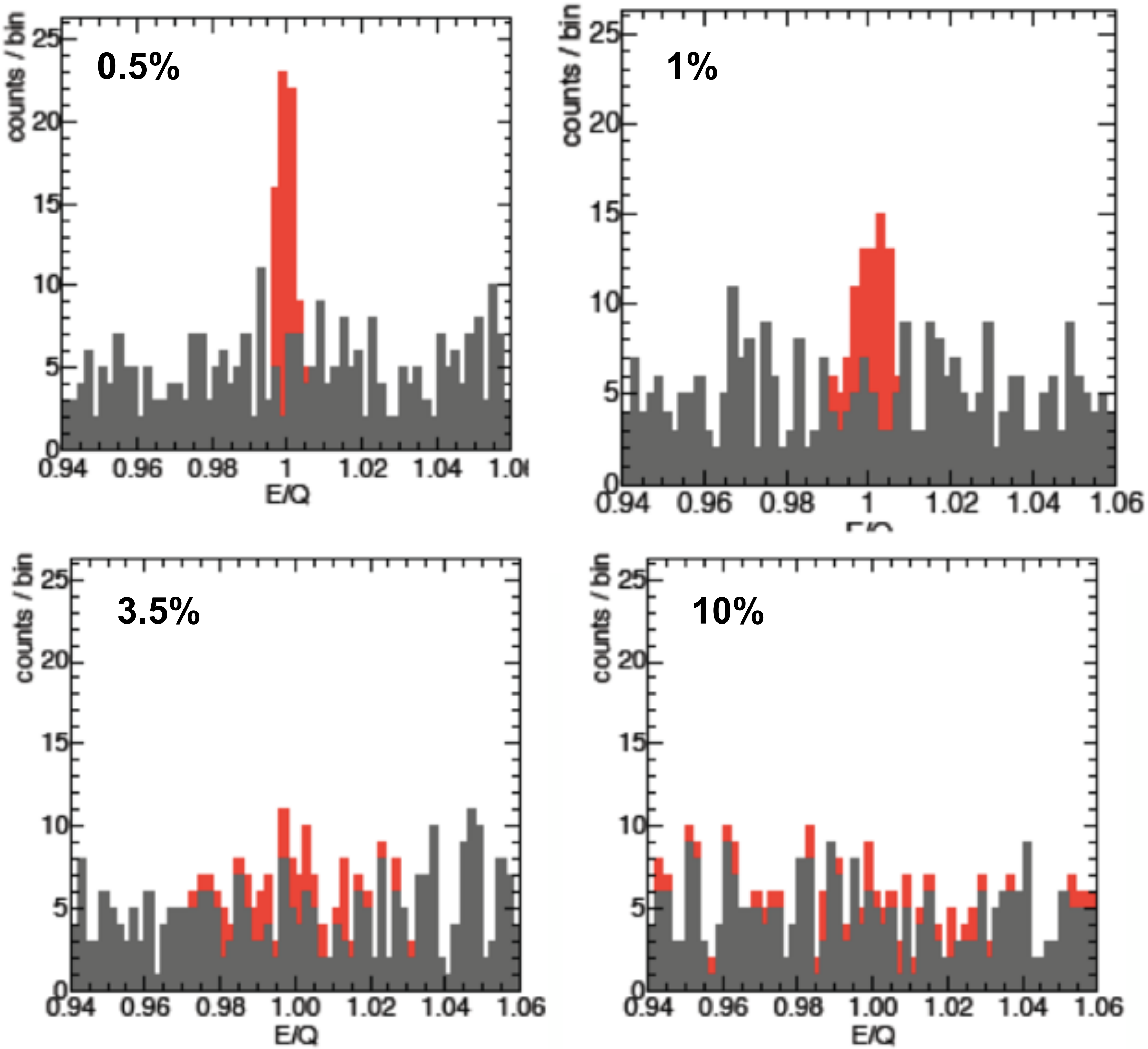
$$\frac{1}{S^{0\nu}_{1/2}(m_{ee})} \propto \sqrt{S^{0\nu}_{1/2} \cdot G^{0\nu}} |M^{0\nu}|$$

Despite their simplicity these formula's outline the dependence of the sensitivity on the critical experimental parameters: **Mass, Measure Time, Energy resolution, Background and Isotope choice**

Energy resolution

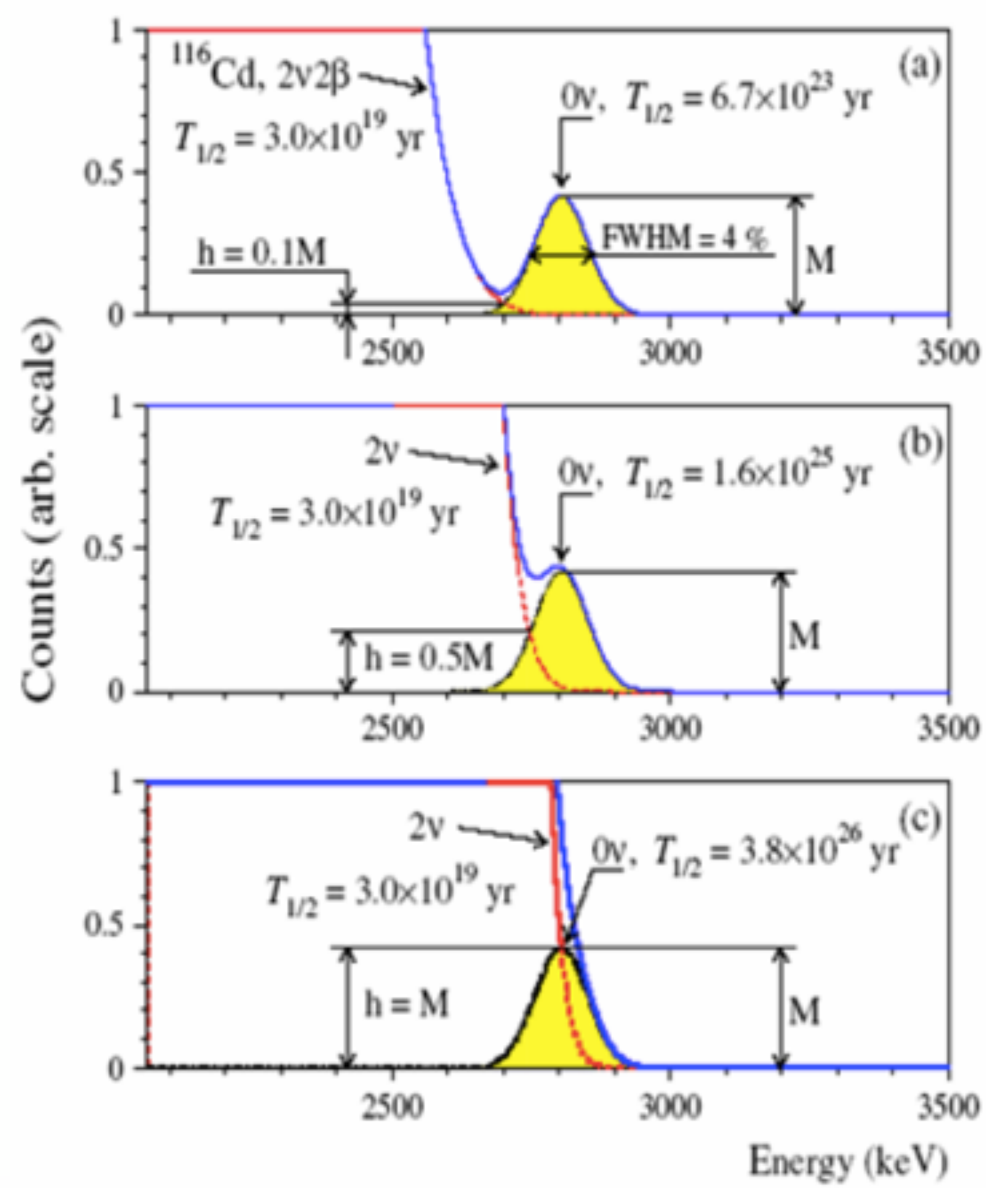
Signal 50 events
$T_{1/2} = 5 \cdot 10^{25}$ yr
t = 1 yr

M = 1ton
B = 1 count/ton/keV/yr



from JJ Gomez-Cadenas

- **Strong influence on**
  - discovery power
  - background
    - irreducible ββ(2ν)
    - background disentanglement



Background

The background index in the ROI is the most critical of the parameters driving the sensitivity.

- Radioactivity
- Cosmogenic activation
- μ−induced reactions
- **2 neutrino double beta decay**
- **...**

Strategies:

"Brute force": directly reduce intrinsic, extrinsic, & cosmogenic activities

- Select and use ultra-pure materials
- Minimize all passive (non "source") materials
- Avoid material re-contamination (machining, manipulation, storage)
- Fabricate ultra-clean materials (underground fab if needed)
- **Go deep — reduced μ's & related induced activities**
- Rank materials: build an accurate Background budget (MC model)

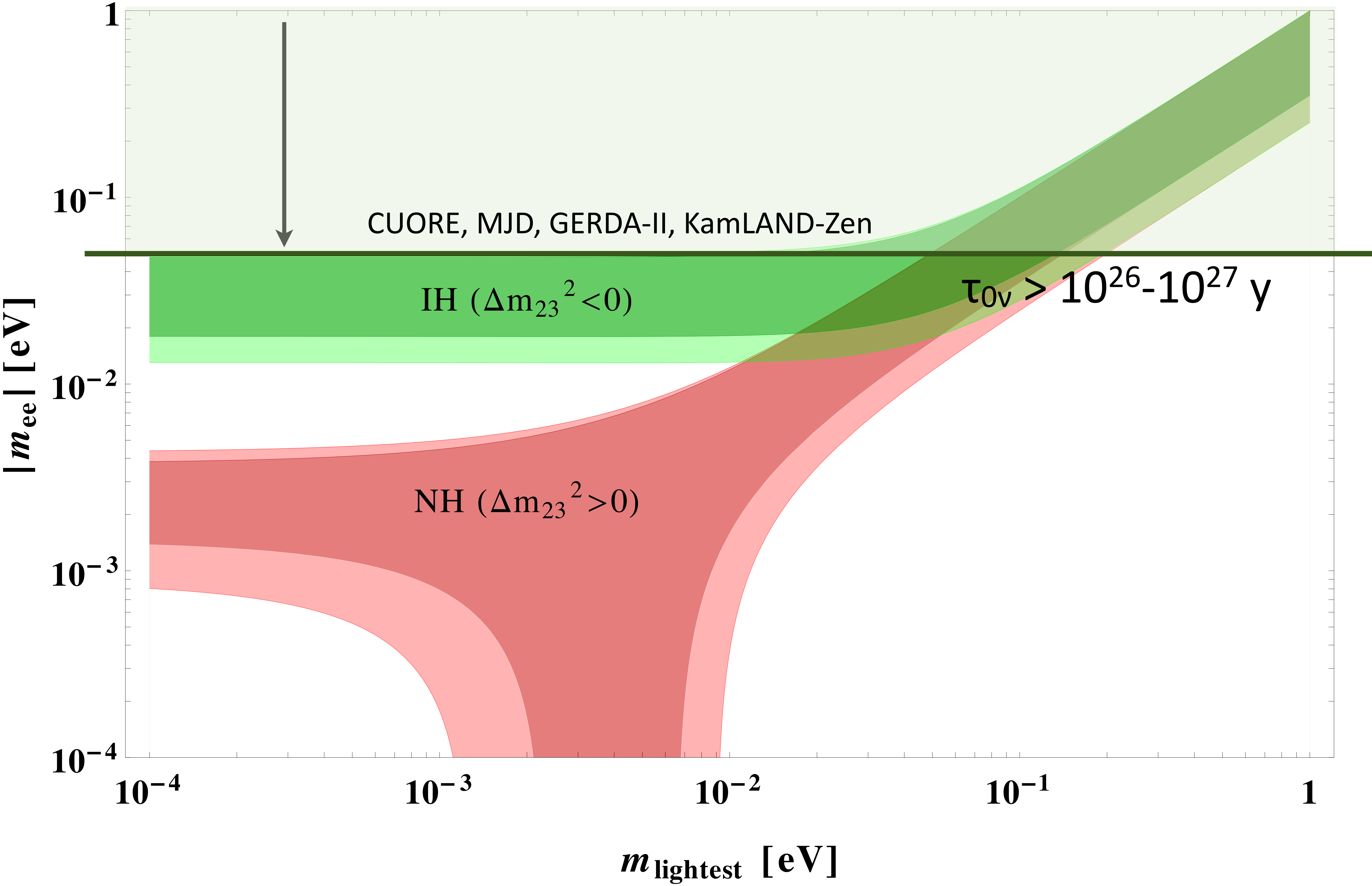
Discrimination techniques

- Energy resolution
- Active veto detector
- Tracking (topology)
- Particle ID, angular, spatial,time correlations
- Fiducial Fits
- Granularity (arrays)
- Pulse shape discrimination (PSD)
- Ion Identification

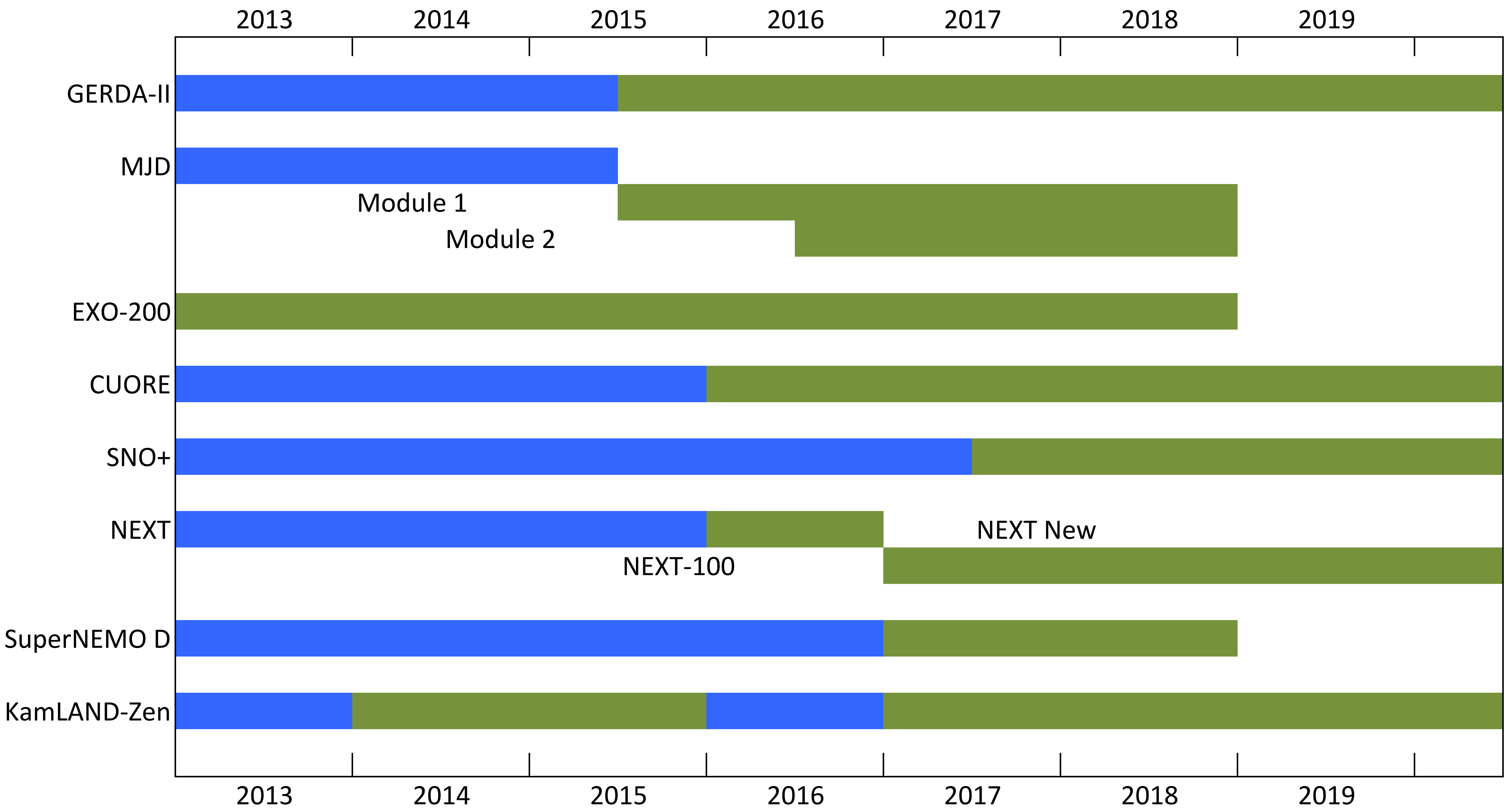
→ **Both approaches are generally needed**
→ **Specific and intense R&D's needed**

Methods	
TPCs (liquid, gas)	^{136}Xe
Doped Liquid Scintillators	^{136}Xe,^{130}Te
Solid state detectors	^{76}Ge, ^{116}Cd
Bolometers (+ enhancements)	^{130}Te, ^{82}Se,^{100}Mo, ^{116}Cd
Foils with tracking chambers	^{82}Se, ^{150}Nd, ^{100}Mo

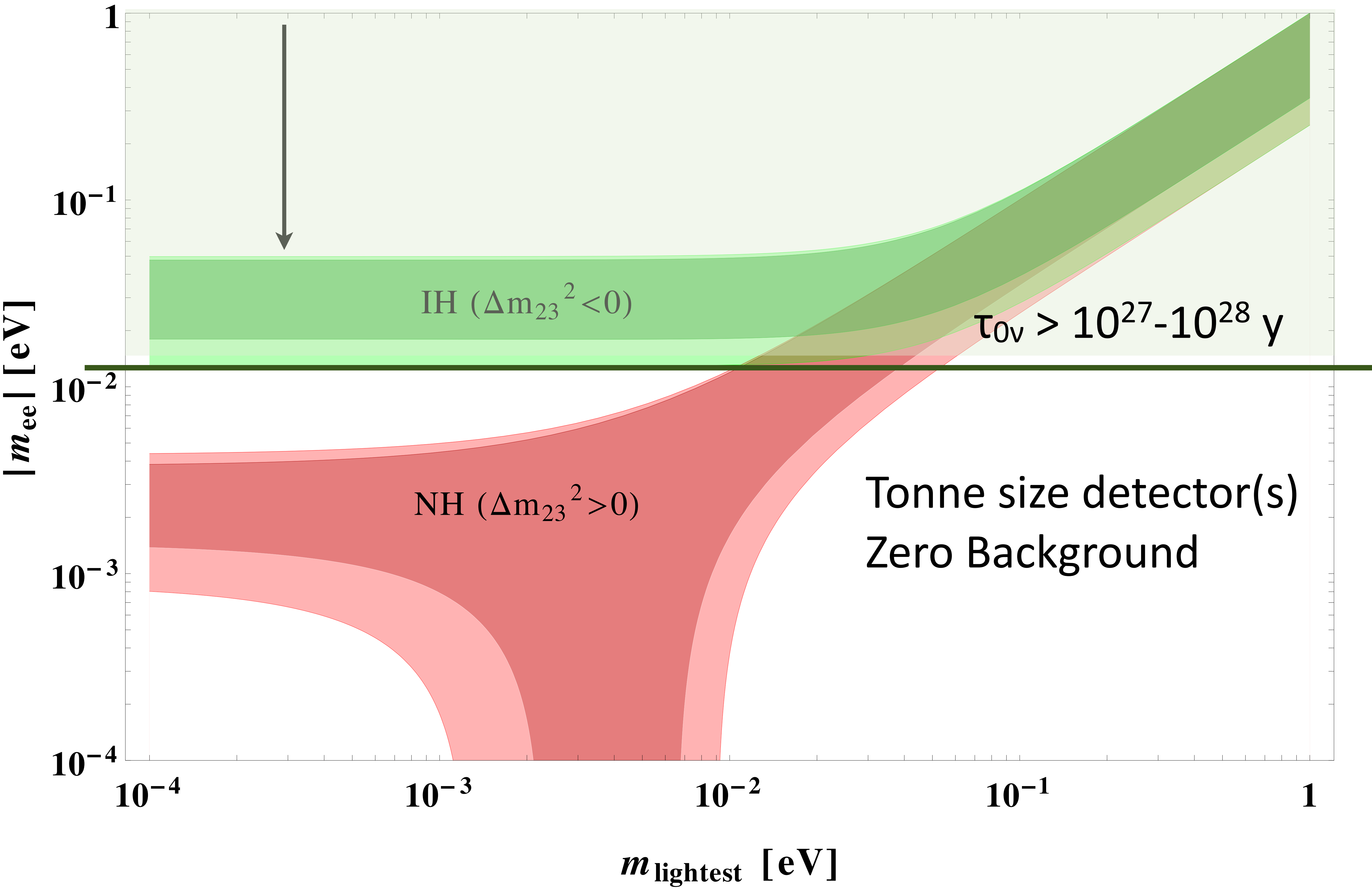
Status: present/near future



Synopsis


2013
2014
2015
2016
2017
2018
2019
GERDA-II
MJD
Module 1
Module 2
EXO-200
CUORE
SNO+
NEXT
NEXT New
NEXT-100
SuperNEMO D
KamLAND-Zen
2013
2014
2015
2016
2017
2018
2019

Future challenge



Future challenge

Active international collaborations aiming at a next generation experiment with sensitivities $T_{1/2} \sim 10^{27}$-10^{28} yr (→ multi-ton, low background)

Isotope	Experiment	Description
^{76}Ge	GERDA & MAJORANA	Large Scale Ge, O(tonne) HPGE crystals
^{82}Se	SuperNEMO	Se foils, tracking and calorimeter, 100 kg scale
^{136}Xe	nEXO	Liquid TPC, 5 tonnes
	NEXT/BEXT	High pressure gas TPC, tonne scale
	KamLAND2-Zen	^{136}Xe in scintillator
^{130}Te	CUPID	Bolometers with light sensor (also ^{82}Se, ^{116}Cd, ^{100}Mo)
	SNO+ II	^{130}Te in scintillator

- Additional efforts underway: AMoRE, CANDLES, PandaX III, CDEX 1T, COBRA
- In most cases a phased approach is proposed (stepwise increments)
- Isotope enrichment requires time and money

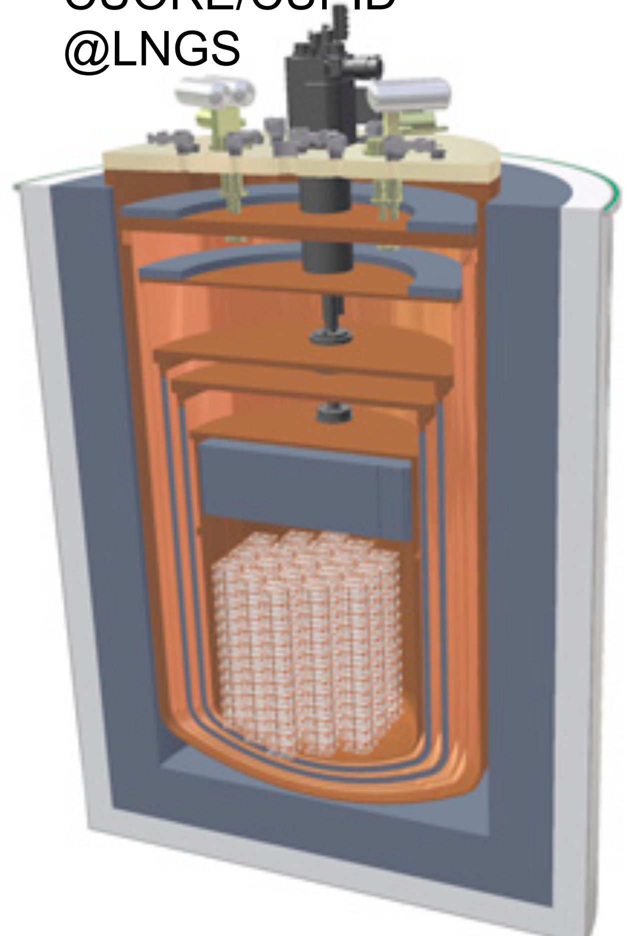
- Potential underground lab sites (increasing number): SNOLAB, JingPing, Gran Sasso, SURF, CanFranc, Frejus, Kamioka, ANDES, Y2L

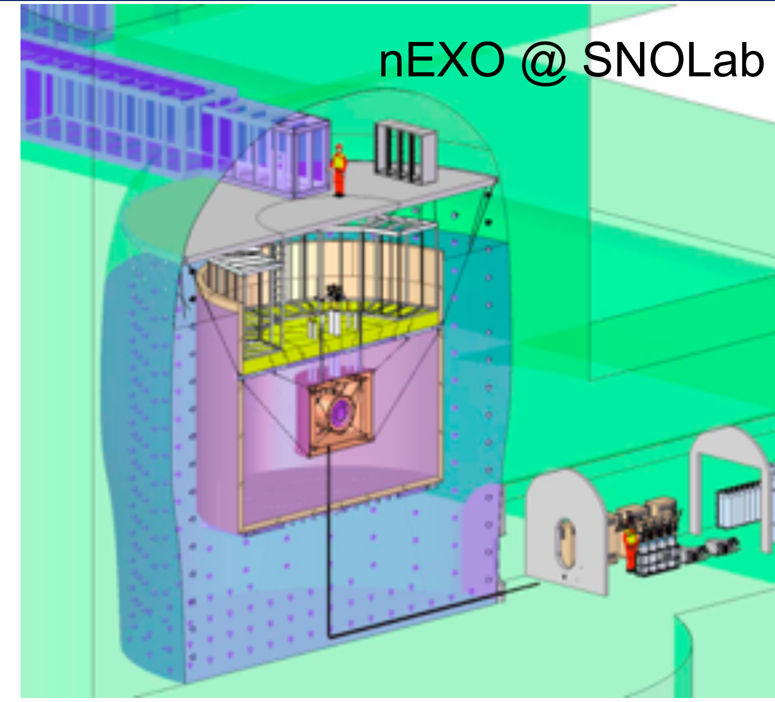
DBD future

MAJORANA-Demonstrator @ SURF

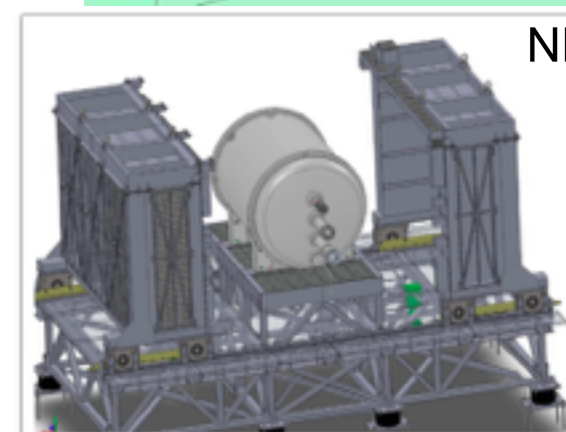
GERDA-II @ LNGS

CUORE/CUPID @LNGS

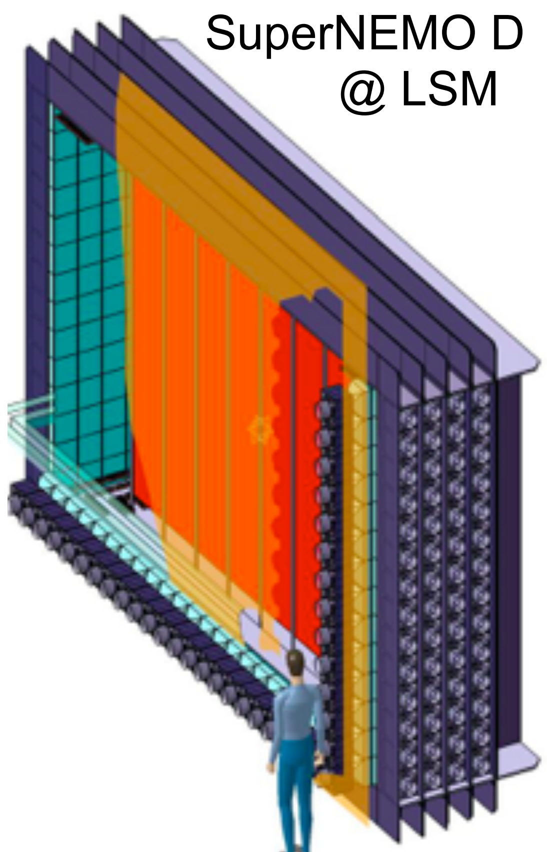




NEXT/BEXT @LSC



SuperNEMO D @ LSM



KAMLAND-Zen @ Kamioka

SNO+ @ Sudbury

Sensitivity revisited

Biassoni et al., arXiv:1310.3870

$z = \eta \cdot \varepsilon / A$

$N_B >> 1$

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

$N_B \leq O(1)$ → "zero background"

$$S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A} M \cdot t_{meas}$$

By generalizing:

- $n' = M \cdot z$
- $B' = B/z$

and re-defining

1. **$x' \equiv n' \cdot T \equiv$ S(cale)**
2. **$y' \equiv B' \cdot \Delta \equiv$ P(erformance)**

$T \equiv t_{meas}$
$B \equiv$ bkg
$\Delta \equiv \Delta E$
$\eta \equiv$ a.i.

we completely get rid of the "z" block and get an effective and objective comparison

The condition

$N_B = (B' \cdot \Delta E) \cdot (n' \cdot T) = x' \cdot y' = P \cdot S$

is a lin in log-log scale

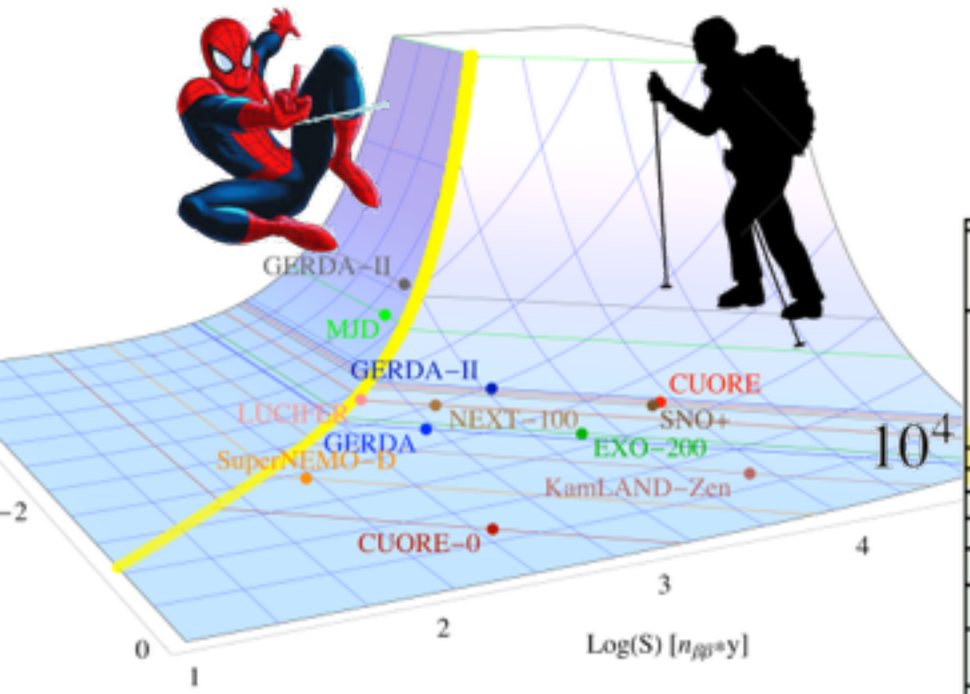
Meaning:

$n' \equiv$ number of "effective" moles of ββ isotope
$B' \equiv$ background rate normalized to the number of "effective" moles of ββ isotope

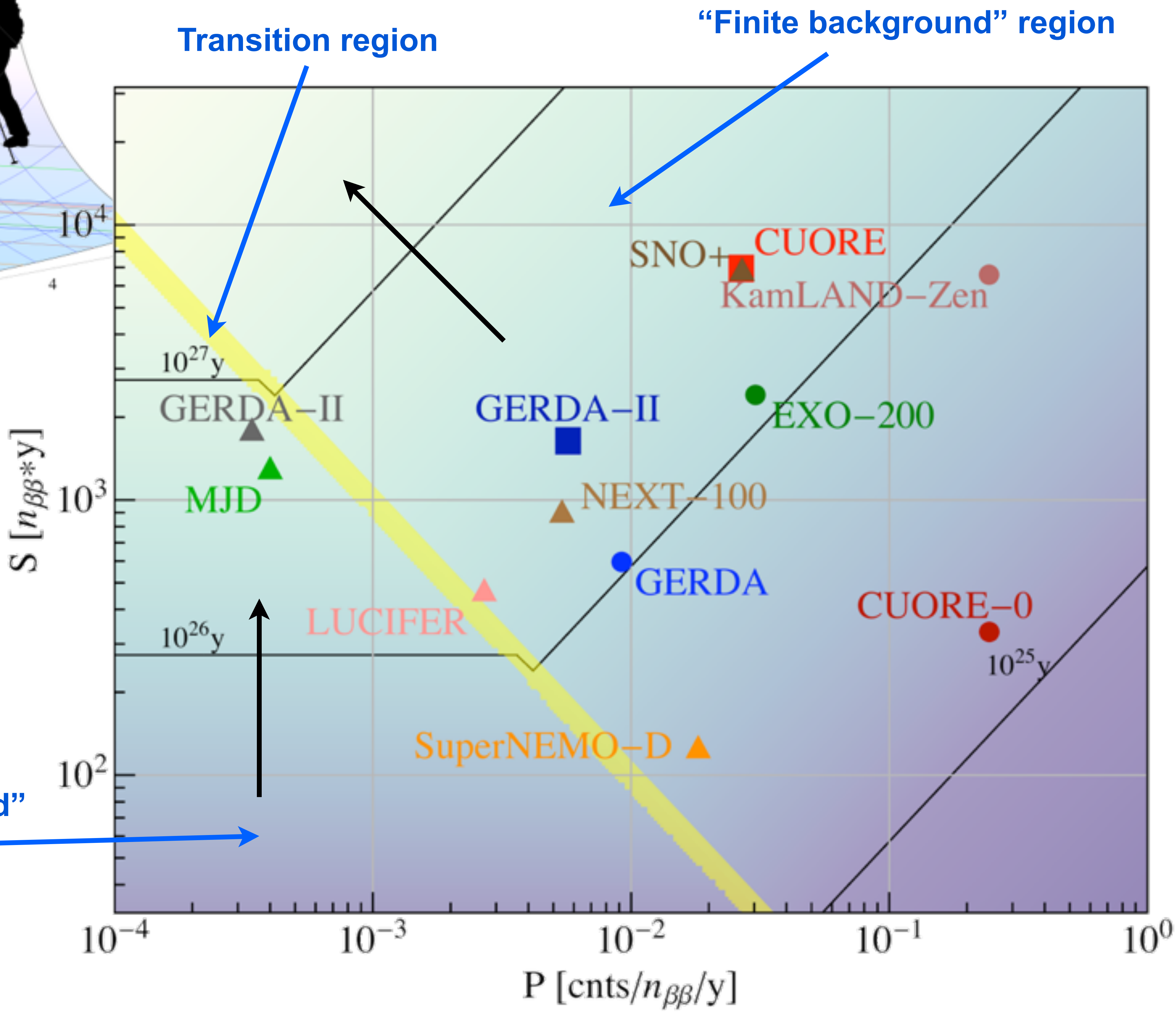
- Sensitivity estimates depend obviously on the assumptions for the the expected performance and scale of the experiments.
- For the major upcoming experiments, in some cases they are measured with pilot experiments, in others they are modeled through Monte Carlo simulations
- In all cases the actual values will be soon measured when the experiments will start taking data.

The sensitivity hill

Biassoni et al., arXiv:1310.3870



Direction of maximum increase of F^{0v}



Fixed budget

- **On a large scale, factors like cost and time can become important.**
- Enrichment is a common request. Let's assume it accounts for half of the cost.
- Let's also assume g_A=1.25 and request a background level such to maintain each isotope in the ZB condition.
- What is the reach of a 100M € experiment?

		Bkg [c/keV/kg/y]	FWHM [keV]	M_{iso} [ton]	$T^{1/2}_{0\nu}$ (ZB) [yr]	$<m_{\beta\beta}>$ [meV]	a.i. [%]	Cost(iso) [€/g]	Prod. [ton/y]	Cost(nat) €/g	M_{tot} [ton]
MAGE	76Ge	8,4E-05	3	0,71	6,99E+27	19	7,8	70	165	1,2	0,79
CUPID ZnSe	82Se	1,56E-05	10	0,71	6,32E+27	12	9,2	70	2275	0,8	1,28
CUPID ZnMO4	100Mo	1,94E-05	9	0,5	3,63E+27	15	7,6	100	266000	0,02	1,15
CUPID CdWO4	116Cd	3,19E-05	6	0,33	2,09E+27	26	9,6	150	22200	0,06	1,05
CUPID TeO2	130Te	8,35E-06	5	3,85	2,34E+28	6	34,2	13	150	0,03	4,79
SNO++	130Te	1,93E-07	270	3,85	5,37E+27	12	34,2	13	150	0,03	3,85
nEXO+	136Xe	5,52E-07	58	6,25	2,09E+28	7	8,9	8	50	1,2	6,25
Kam-Zen	136Xe	1,28E-07	250	6,25	1,25E+28	9	8,9	8	50	1,2	6,25
BEXT	136Xe	2,13E-06	15	6,25	1,25E+28	9	8,9	8	50	1,2	6,25

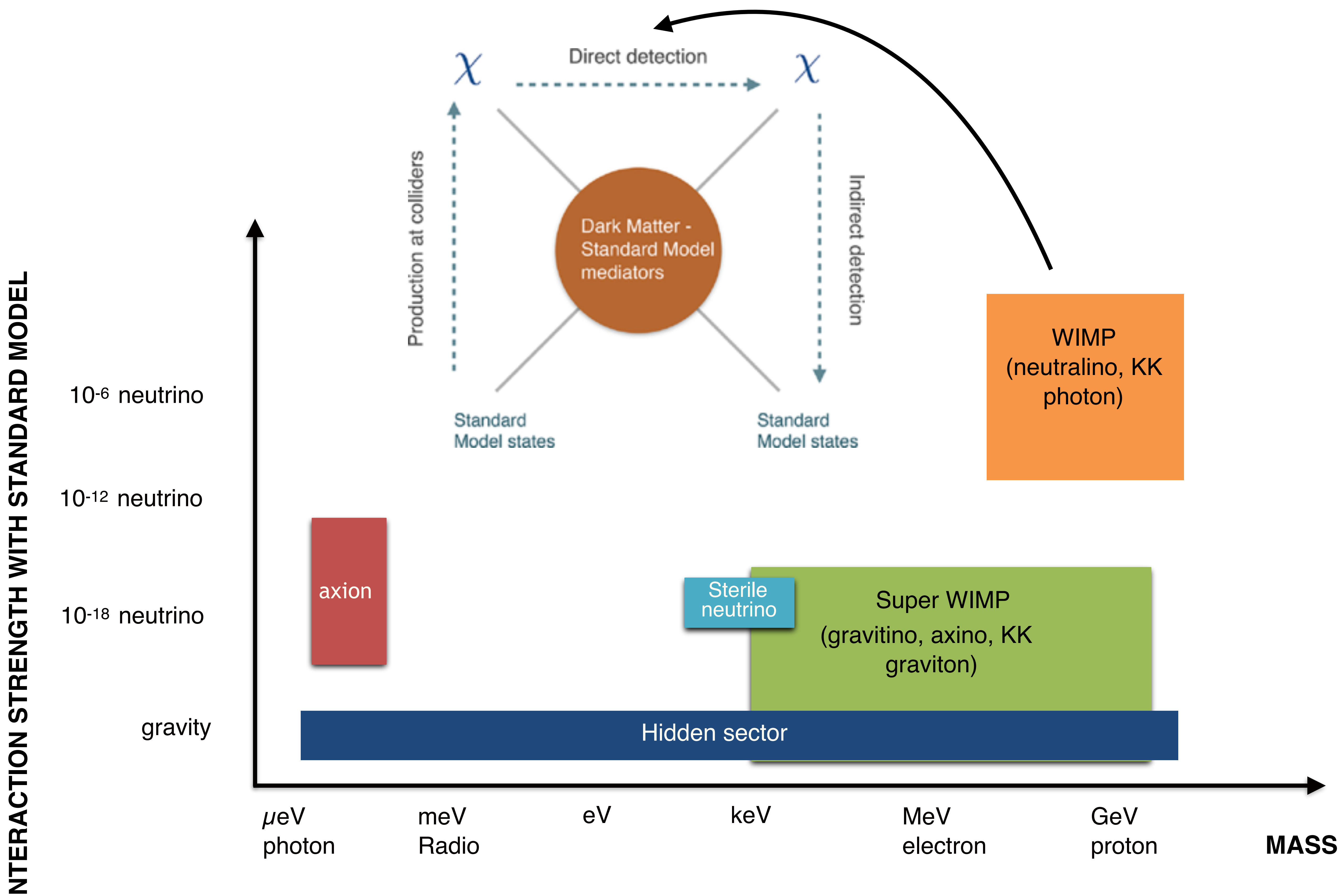
Fixed $<m_{\beta\beta}>$ sensitivity

- Let's revers our argument and design an experiment with a sensitivity $<m_{\beta\beta}>$=10 meV (g_A=1.25 and a background level such to maintain each isotope in the ZB condition)
- What is its scale and cost?

		Bkg [c/keV/kg/y]	FWHM [keV]	M_{iso} [ton]	$T^{1/2}_{0\nu}$ (ZB) [yr]	Cost(iso) [M€]	a.i. [%]	Cost(iso) [€/g]	Prod. [ton/y]	Cost(nat) €/g	M_{tot} [ton]
MAGE	76Ge	2,29E-05	3	2,62	2,57E+28	184	7,8	70	165	1,2	2,92
CUPID ZnSe	82Se	9,68E-06	10	1,03	9,16E+27	72	9,2	70	2275	0,8	2,07
CUPID ZnMO4	100Mo	7,73E-06	9	1,13	8,19E+27	113	7,6	100	266000	0,02	2,88
CUPID CdWO4	116Cd	4,27E-06	6	2,24	1,4E+28	336	9,6	150	22200	0,06	7,81
CUPID TeO2	130Te	2,27E-05	5	1,27	7,72E+27	17	34,2	13	150	0,03	1,76
SNO++	130Te	1,21E-07	270	5,53	7,72E+27	72	34,2	13	150	0,03	6,15
nEXO+	136Xe	9,36E-07	58	3,32	1,11E+28	27	8,9	8	50	1,2	3,68
Kam-Zen	136Xe	1,3E-07	250	5,53	1,11E+28	44	8,9	8	50	1,2	6,14
BEXT	136Xe	2,17E-06	15	5,53	1,11E+28	44	8,9	8	50	1,2	6,14

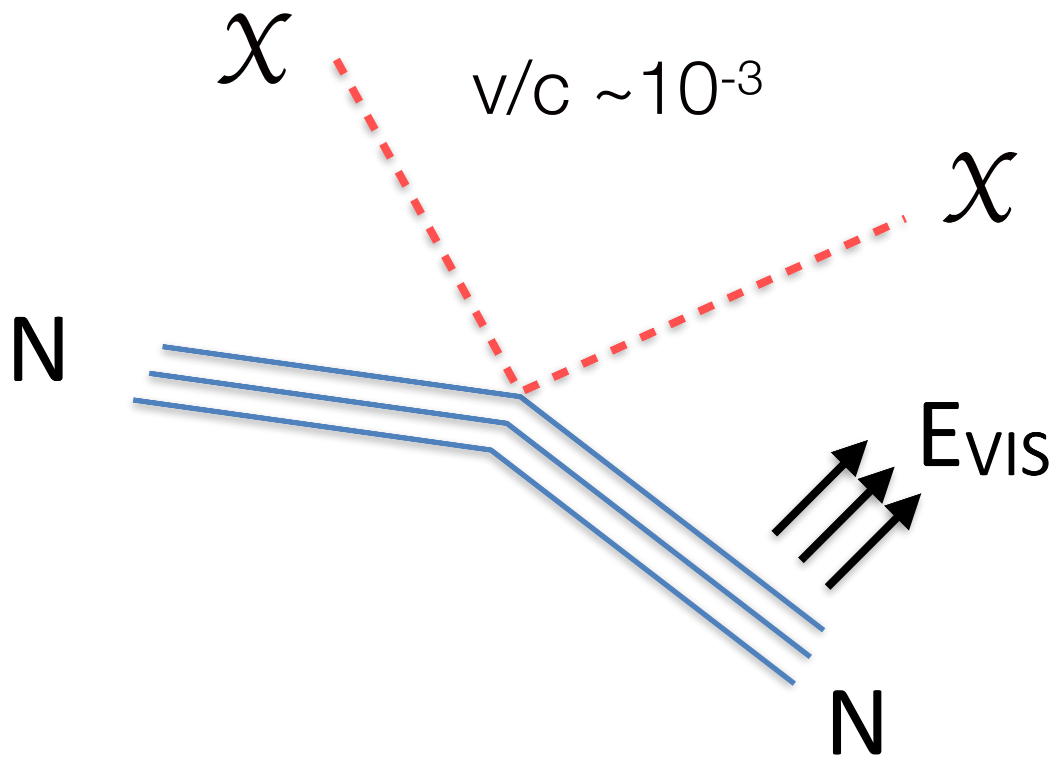
Dark Matter

What do we know about?



WIMP detection it in the lab?

- By searching for collisions of invisibles particles with atomic nuclei => E_{vis} (q ~ tens of MeV)
- Need *very low energy thresholds*
- Need *ultra-low backgrounds*, good background understanding (no "beam off" data collection mode) and discrimination
- Need *large detector masses*

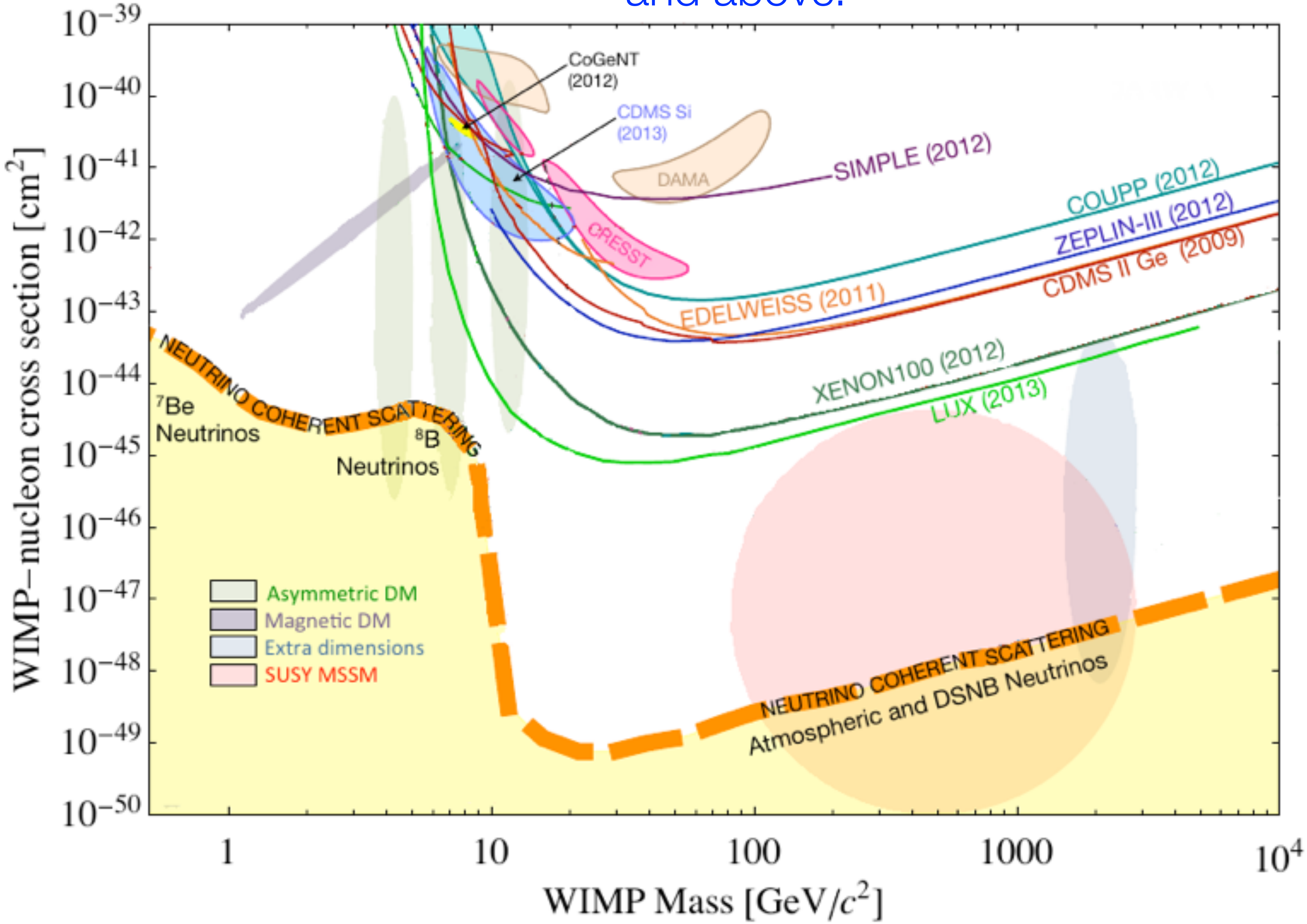


$$E_R = \frac{q^2}{2m_N} < 100keV$$

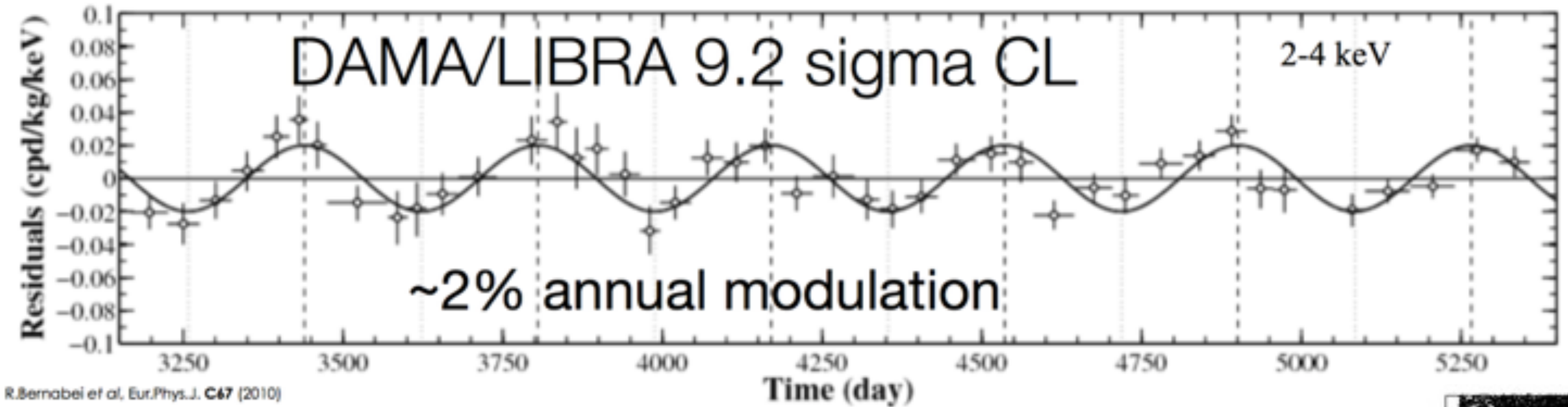
The WIMP landscape

"Anomalies" at low WIMP masses

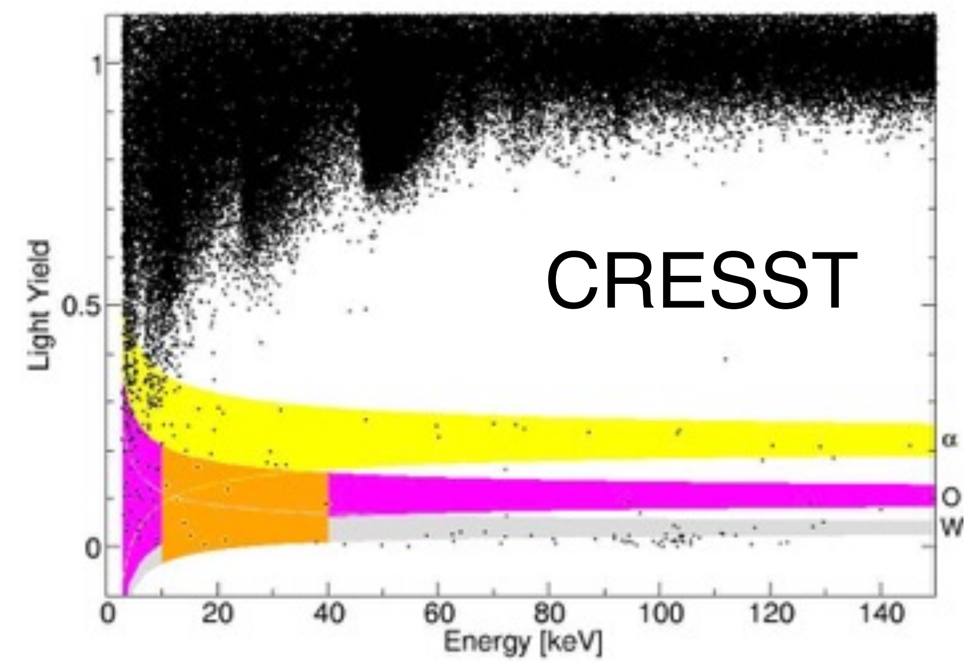
Sensitivity to masses up to 10 TeV and above!

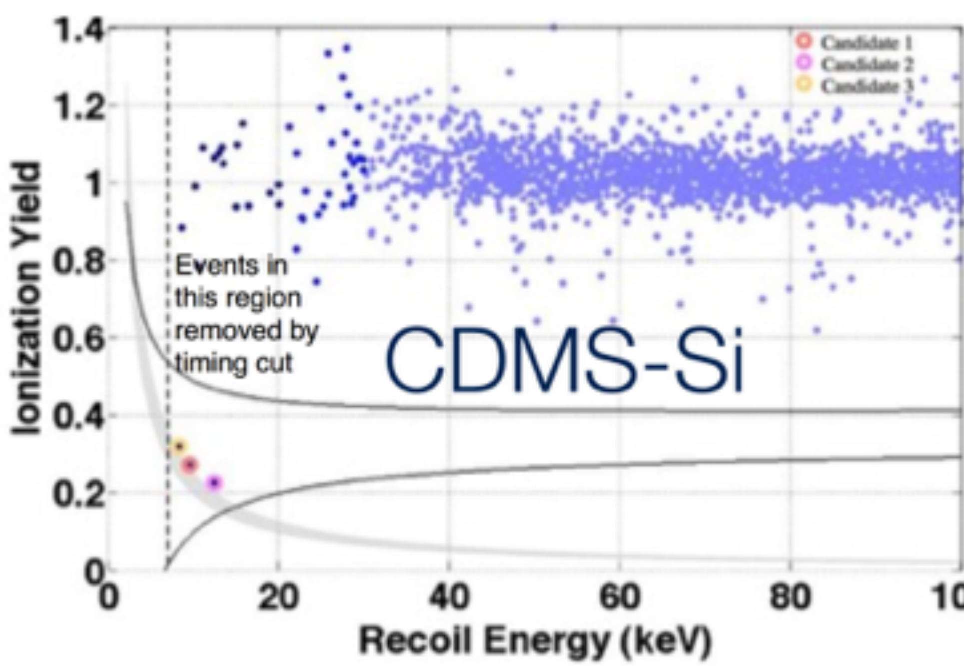


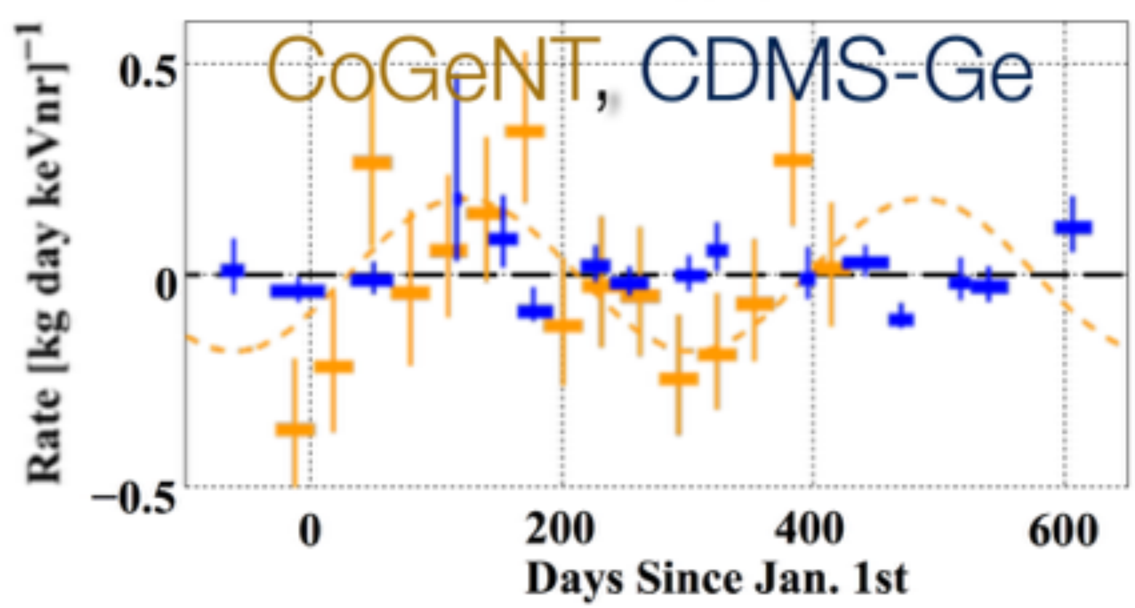
Low mass WIMPs: observed?



CDMS-Si, DAMA/LIBRA,CoGeNT, CRESST: excess of events above the *known* backgrounds





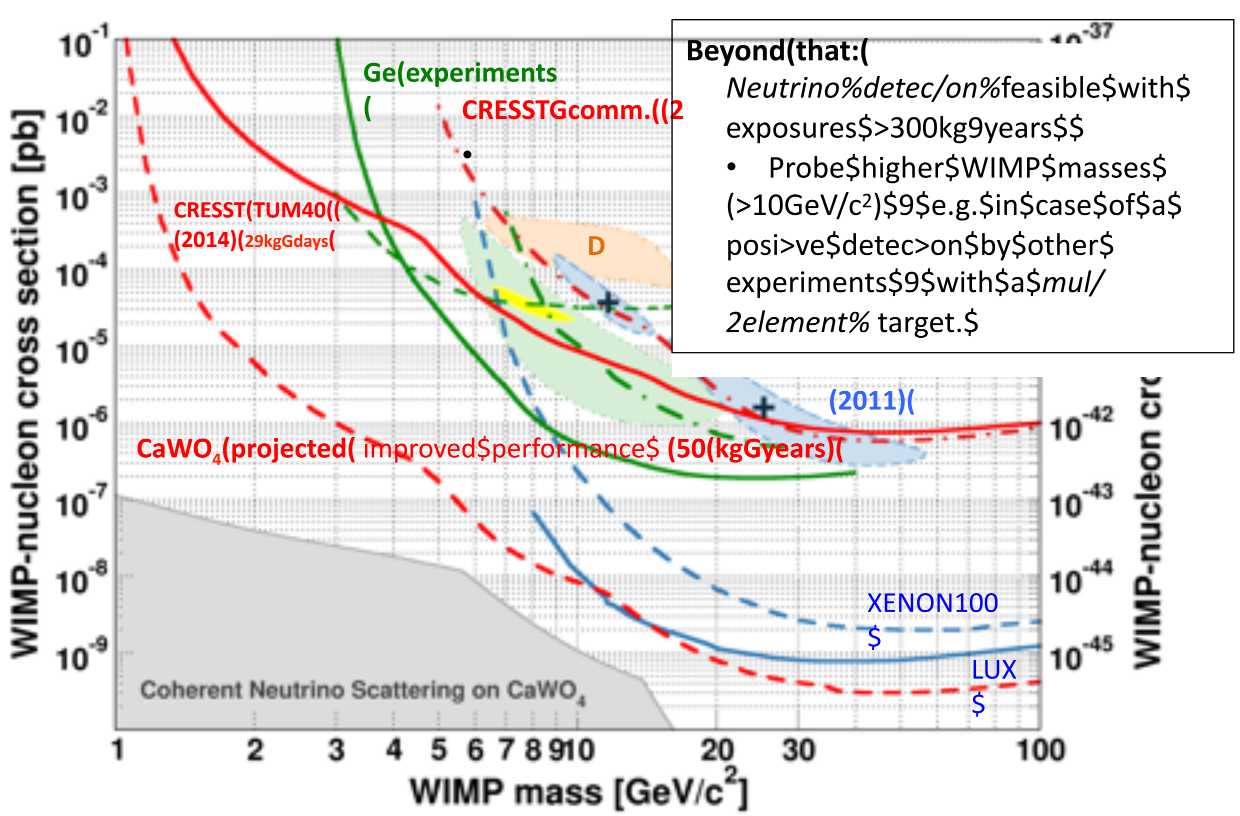


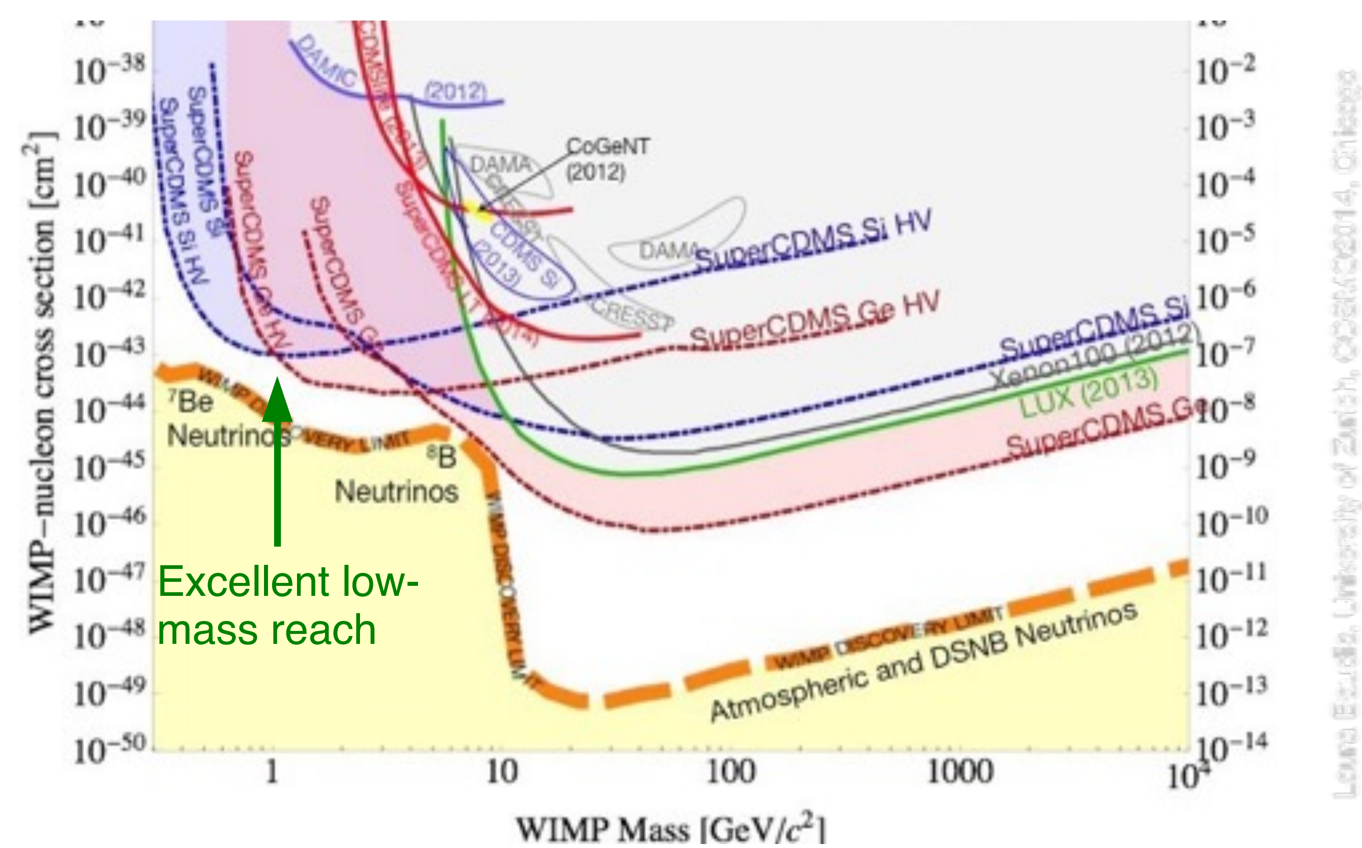
DM experiments

Experiment	Technique	Lab	Isotope/Mass	Since
SuperCDMS	LowT	SNOLAB	92 kg Ge, 11 kg	
CRESST	LowT	LNGS	5kg CaWO4	2013→
Edelweiss	LowT	LSM	30 kg Ge	2014→
DAMIC	CCD	SNOLAB	100 g Si	2015→
COUPP	Bubble	SNOLAB	60 kg CF_3I	→2014
PICASSO/PICO	Bubble	SNOLAB		
Xmass	LXe SP	Kamioka	835/150 kg	2013→
CLEAN	LAr SP	SNOLAB	500/100 kg	2014→
DEAP	LAr SP	SNOLAB	3600/1000 kg	2014→
XENON100	LXe TPC	LNGS	161/50 kg	2013→
LUX	LXe TPC	SURF	370/100 kg	2013→
PANDAX	LXe TPC	CJPL	125/37 kg	2014→
ArDM	LAr TPC	LSC	850/100 kg	2014→
DarkSide	LAr TPC	LNGS	50/33 kg depl.	2014→

Future Cryogenic Experiments at T~ mK

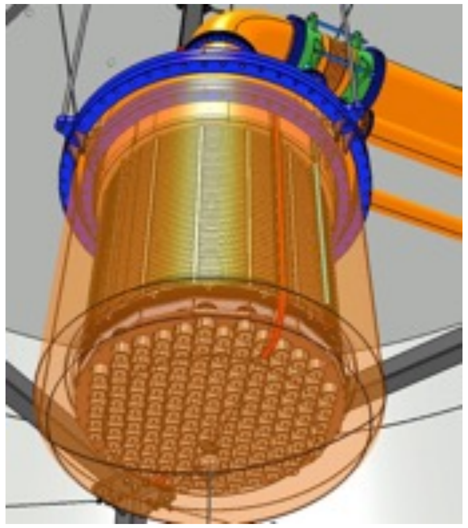
- SuperCDMS at SNOLab: approved by NSF&DoE
- Collaboration between SuperCDMS and EURECA, at the ~100 kg level
- (cryostat can house up to 400 kg target material)
- Multi-target approach ($CaWO_3$, Ge), start data taking in 2018 Reach for SI cross sections: $8x10^{-47}$ cm^2



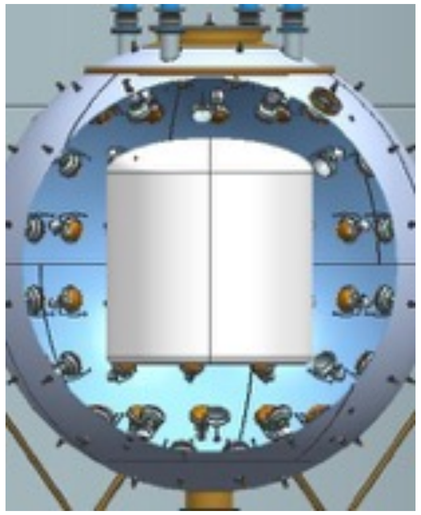


Future noble liquid detectors

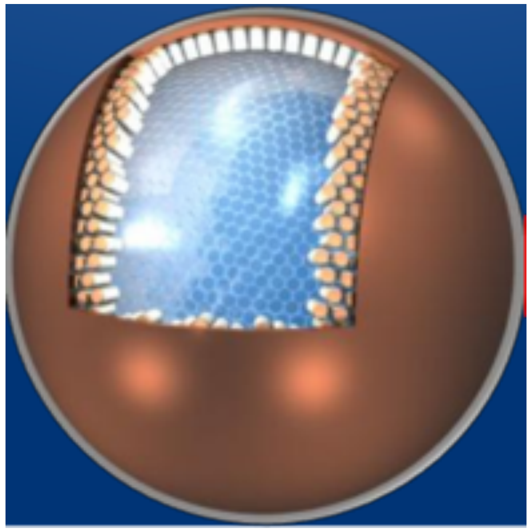
- **Under construction**: XENON1T at LNGS, 3.1 t LXe in total
- **Future:** LUX-ZEPLIN (7 t LXe) (approved by NSF&DoE), XENONnT (n=6-7 t LXe) (to be proposed), XMASS (5 t LXe), DarkSide (5 t LAr) (R&D funds)
- **Design and R&D:** “ultimate detector” DARWIN (~20 t LXe and/or 50 t LAr)



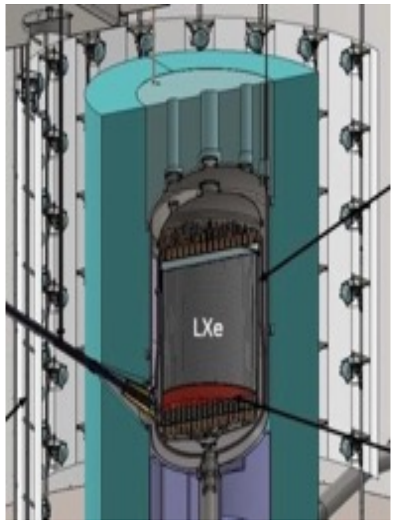
XENON1T: 3.3 t LXe



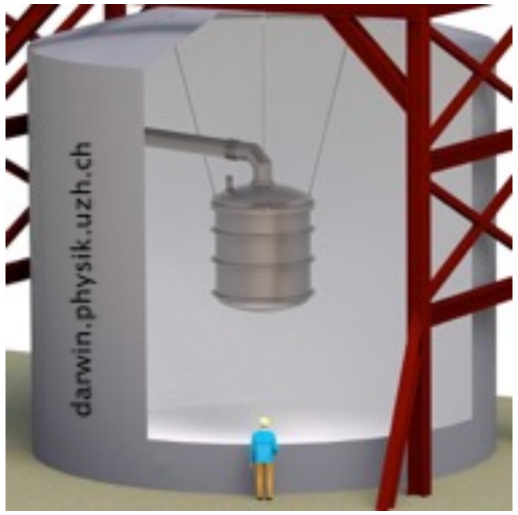
DarkSide: 5 t LAr



XMASS: 5t LXe



LZ: 7t LXe

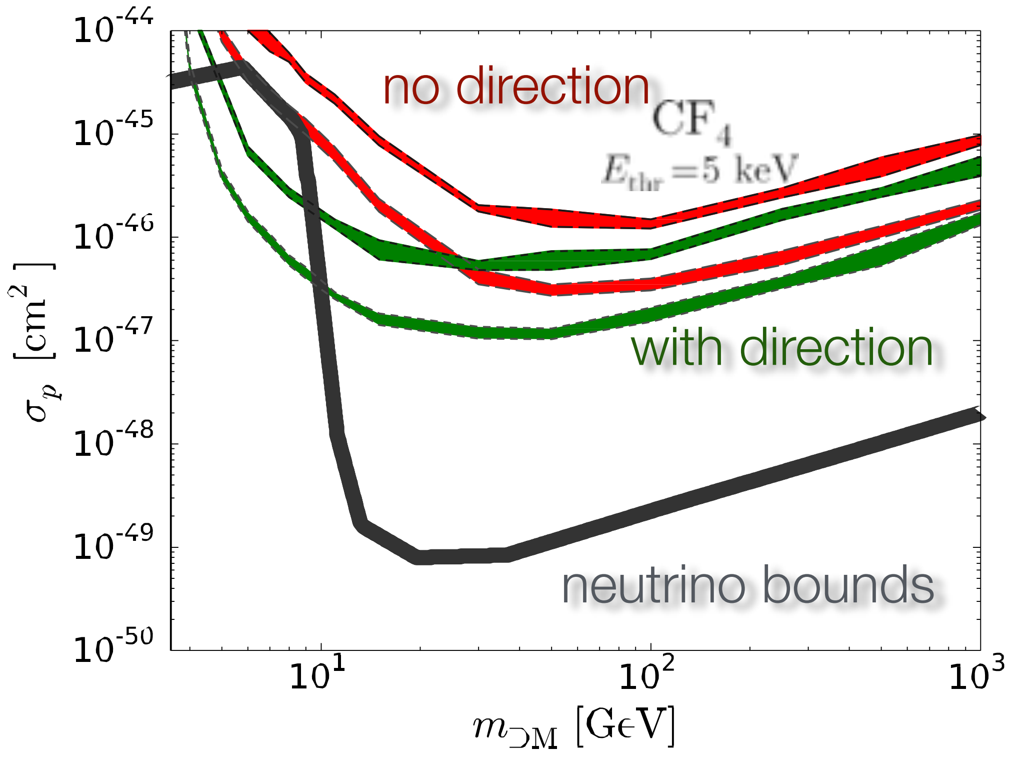


DARWIN: 20 t LXe/LAr

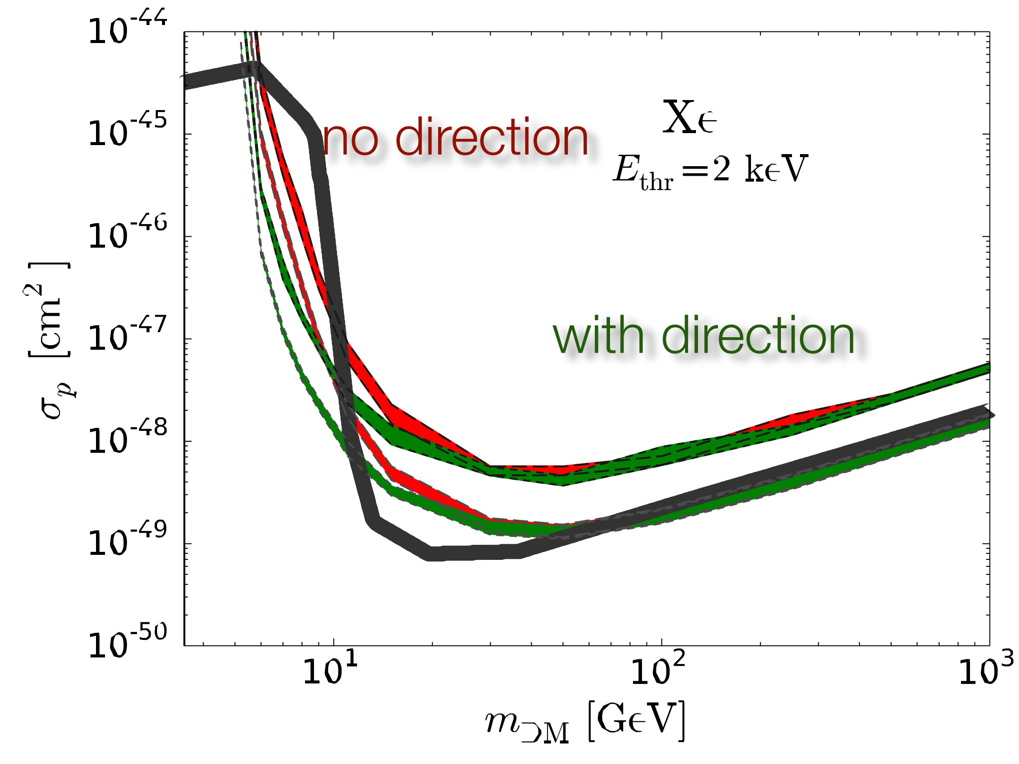
Directional information

- Yes, but mostly for low WIMP masses
- Many directional techniques currently in R&D phase
- Might be difficult to reach the 10^{-48} - 10^{-49} cm^2 cross section with this technique

36.6 t yr exposure, 500 (solar) nu events

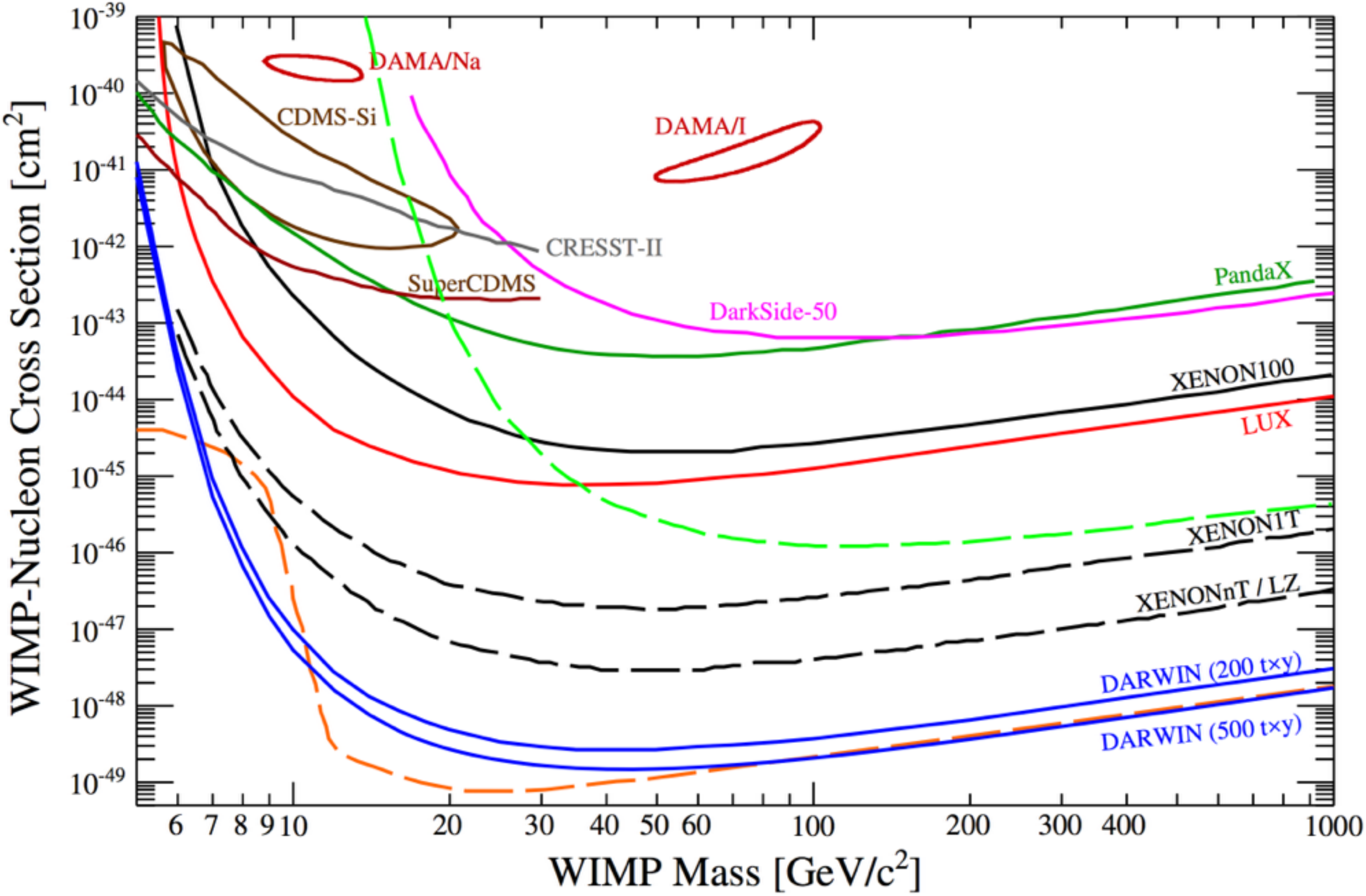


367 t yr exposure, 500 nu events



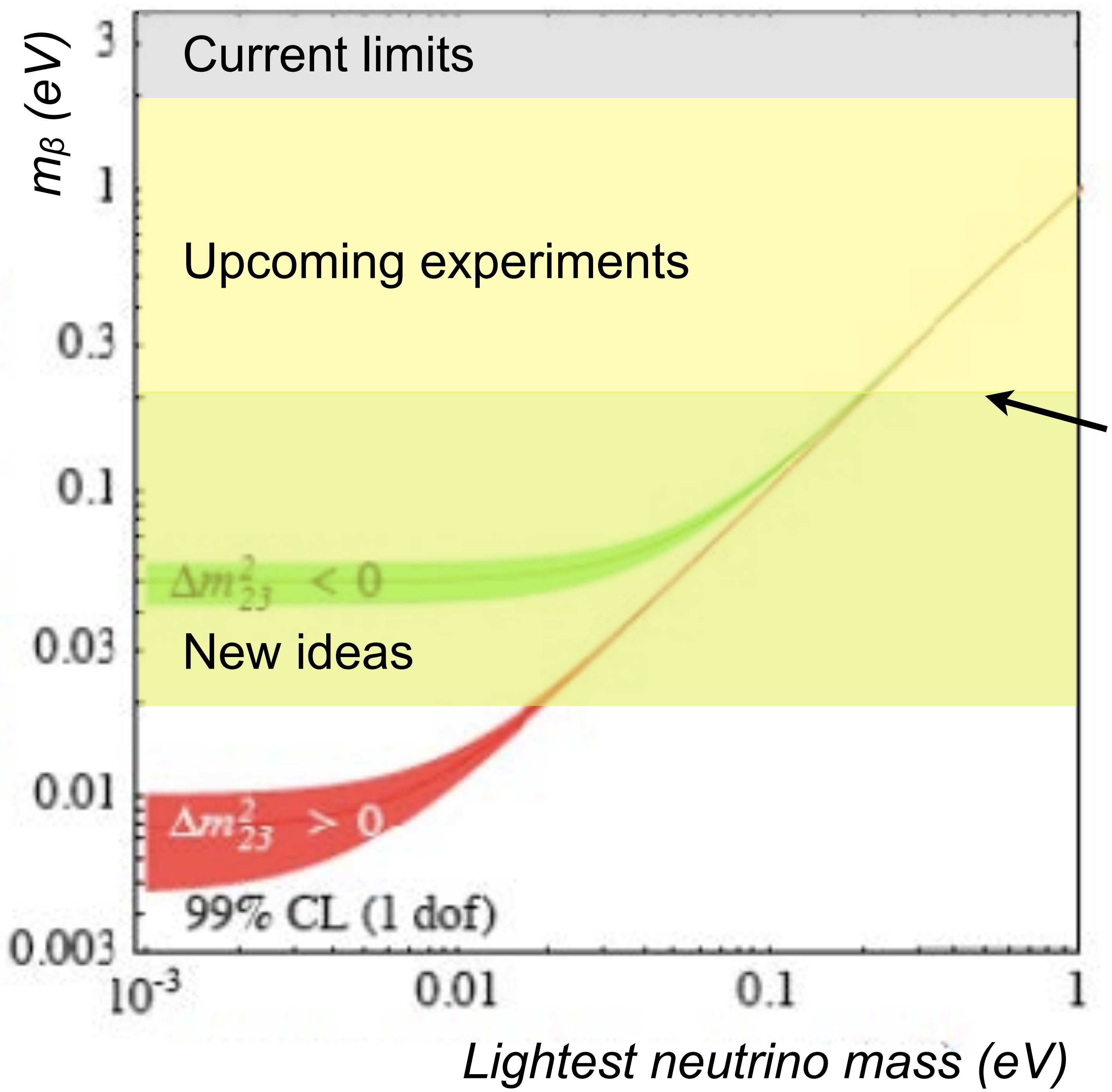
P. Grothaus, M. Fairbairn, J. Monroe, arXiv: 1406.5047

Perspectives



Direct neutrino mass measurements

Direct measurements of neutrino mass



- Neutrinos excluded as Dark Matter
- Distinguish between hierarchical and degenerate scenario, impact on structure formation
- Resolve neutrino mass hierarchy

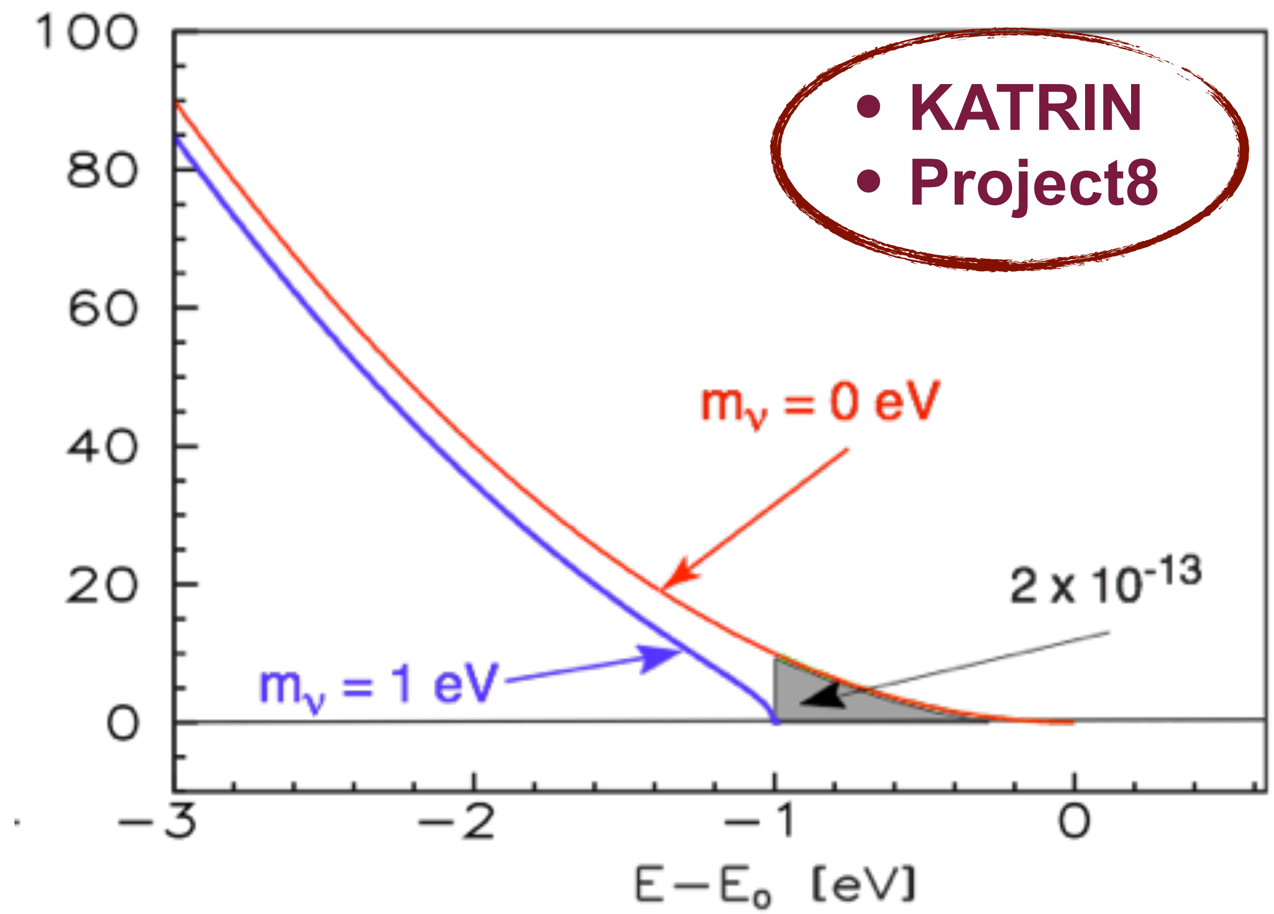
- Kinematic determination of the neutrino mass is the only model independent measurement

Direct measurements of neutrino mass

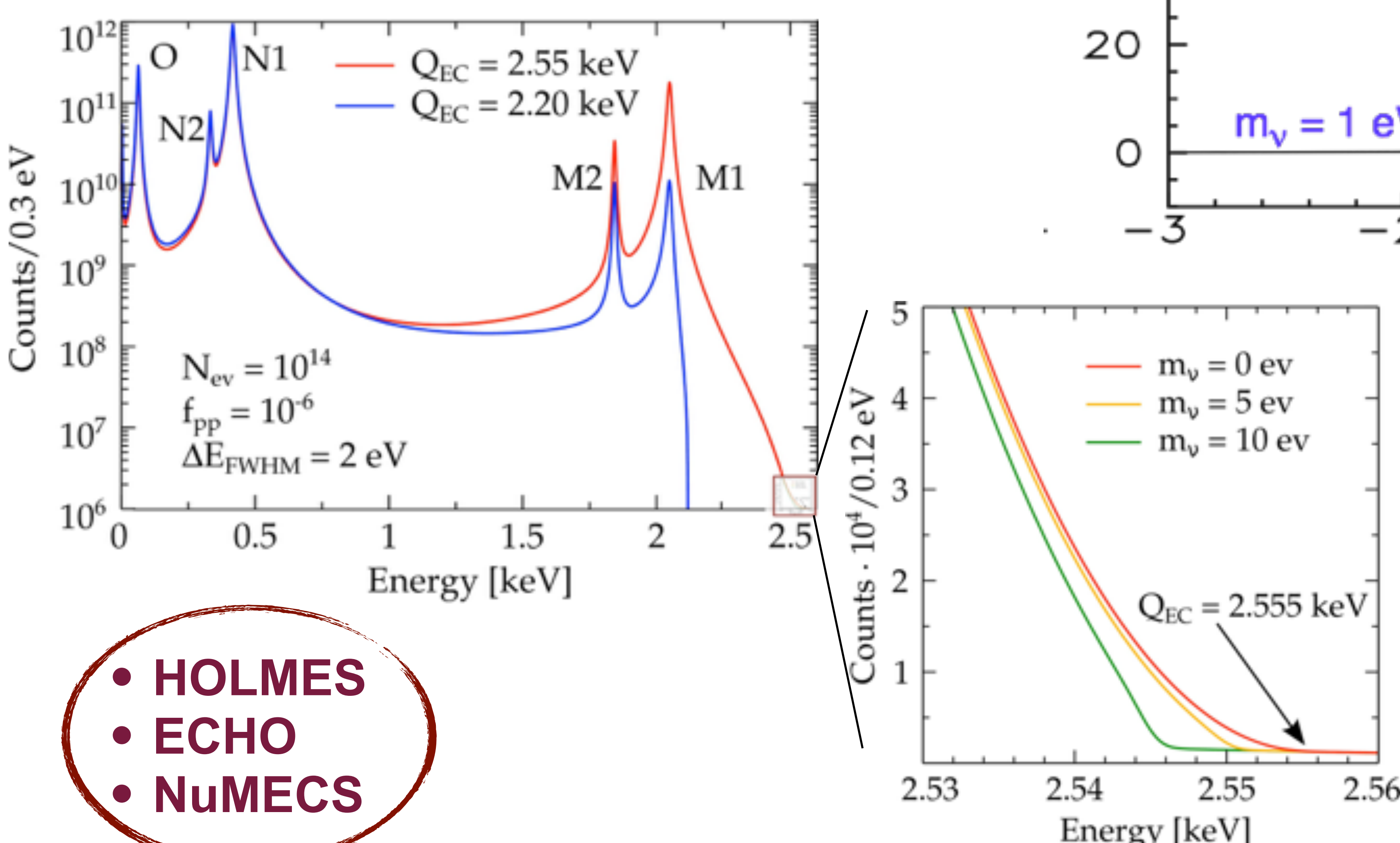
Kinematics of weak decays

- nuclear beta decays
  - single beta (^{3}H, ^{187}Re, ...)
  - EC (^{163}Ho)
- use only energy and momentum conservation
- no further assumptions

- Electron + nuclear recoil
- The observable is the square of the effective electron neutrino mass



- **KATRIN**
- **Project8**

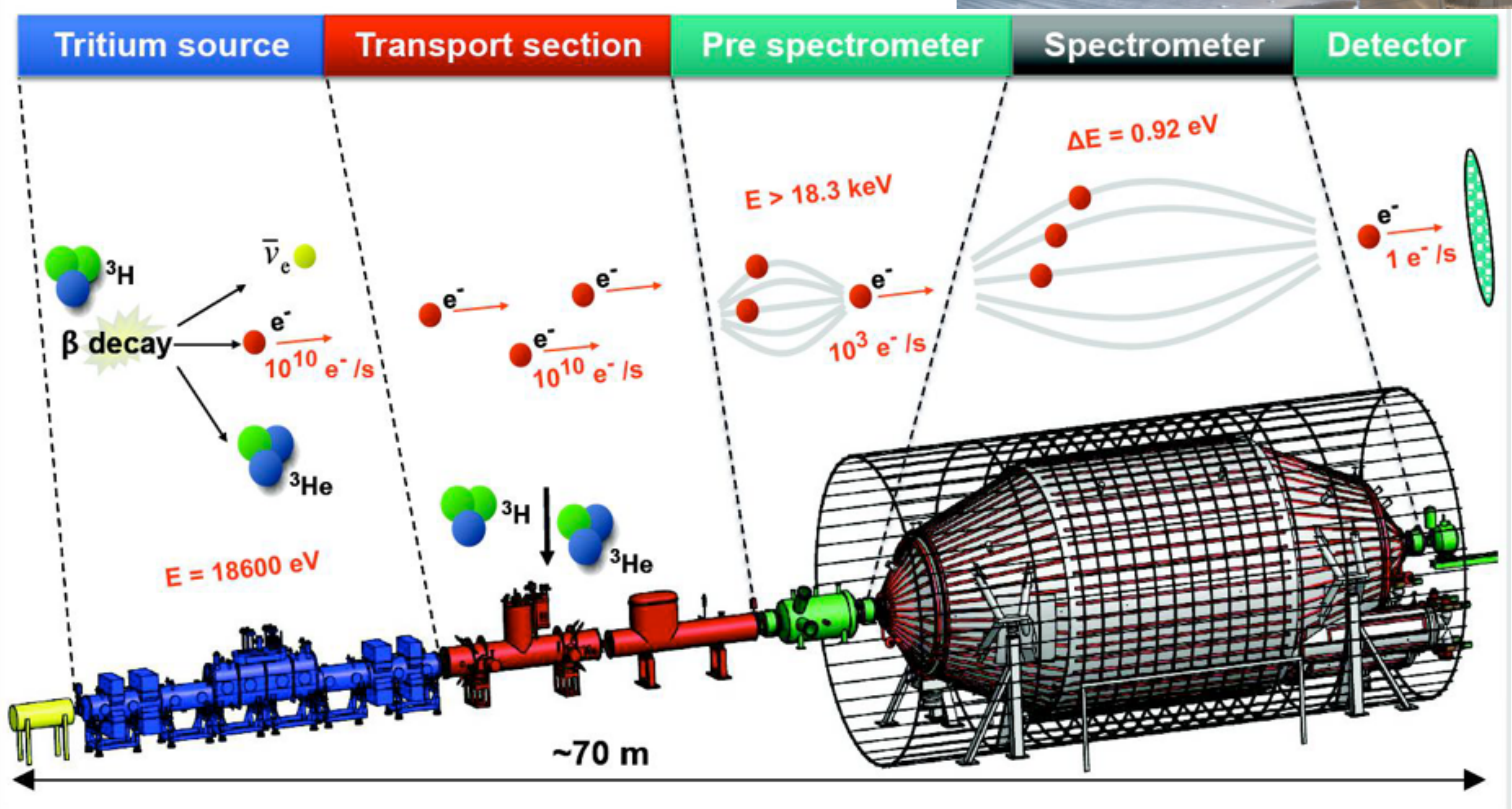


- **HOLMES**
- **ECHO**
- **NuMECS**

- A. De Rujula and M. Lusignoli, Phys. Lett. B 118 (1982) 429
- Addendum: arXiv:1305.4857v1

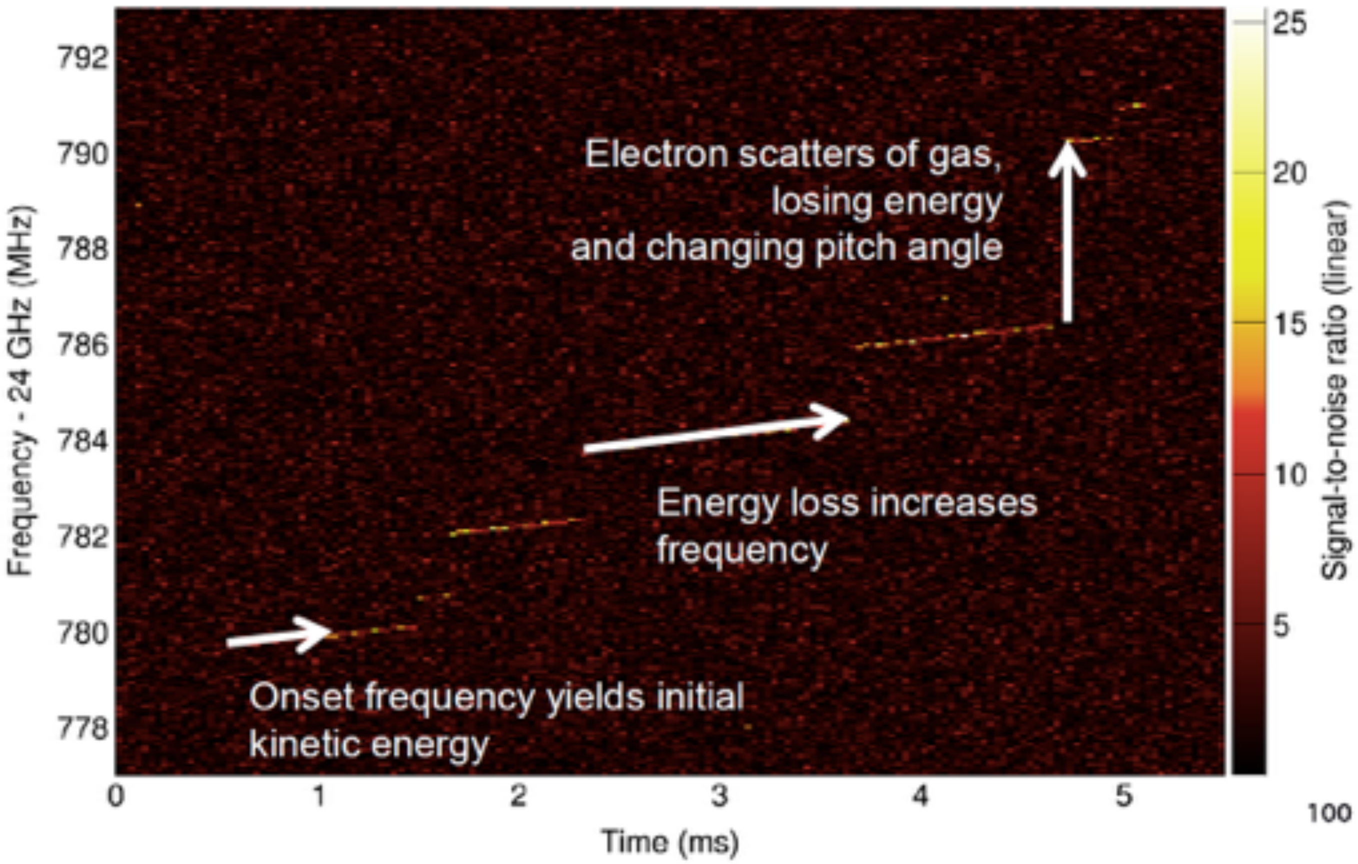
KATRIN

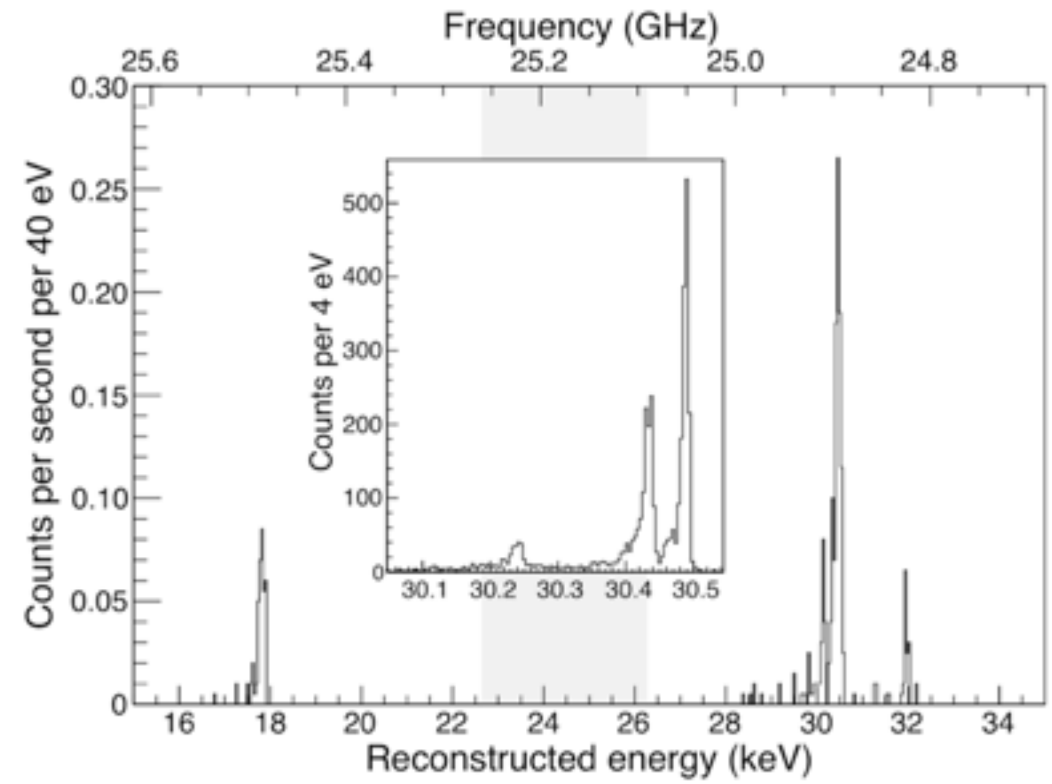
- Large electrostatic spectrometer with gaseous ^3H source (Q=18.6keV)
- Expected statistical sensitivity: **m_{ν_e} < 0.2 eV 90% CL**
- Expected start of data taking in **2016**



Project8

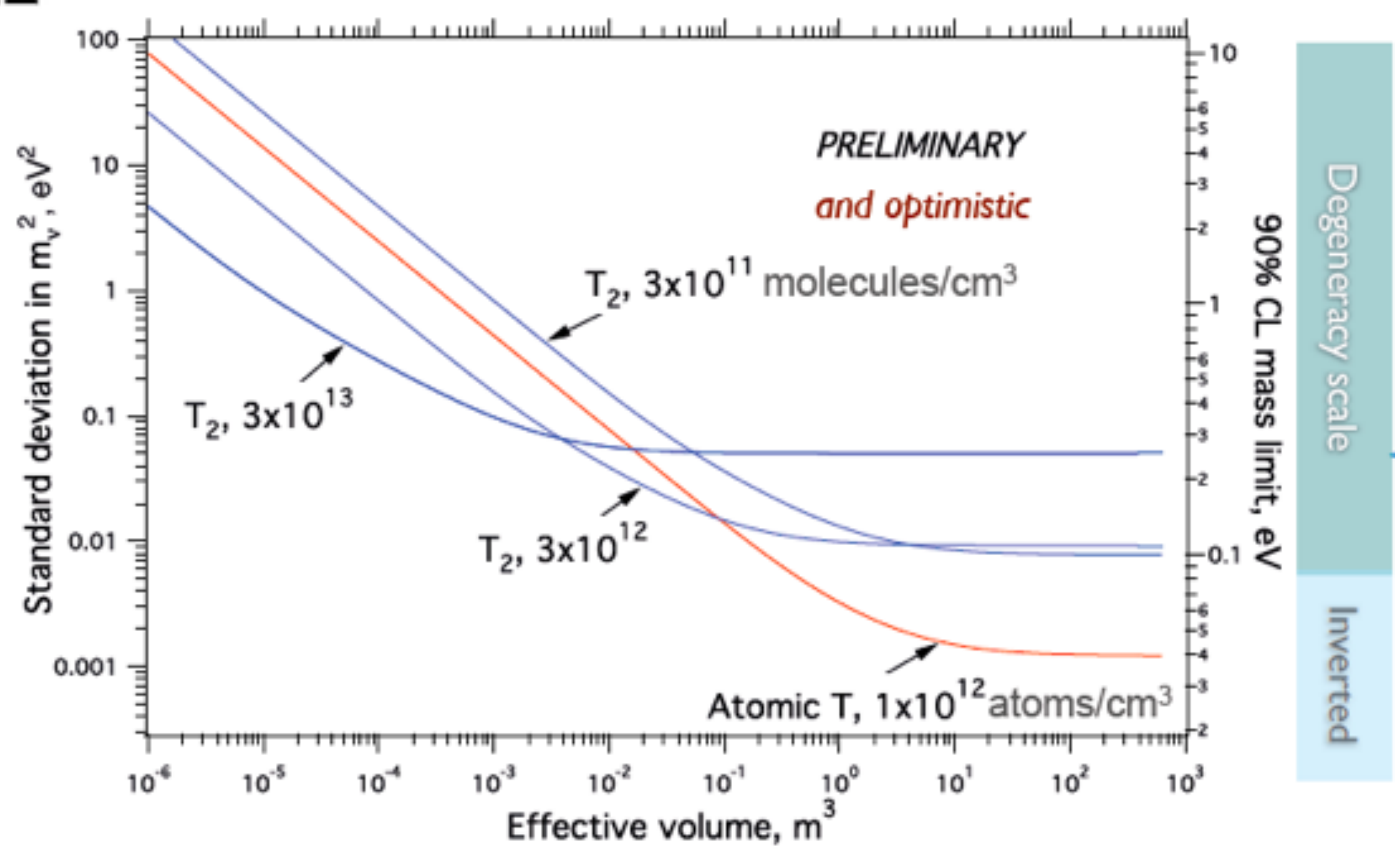
First measured electron and spectra (summer 2014)





Program:

- Use CRES to measure electron energies
- Improve Energy Resolution
- Measure the tritium spectrum



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

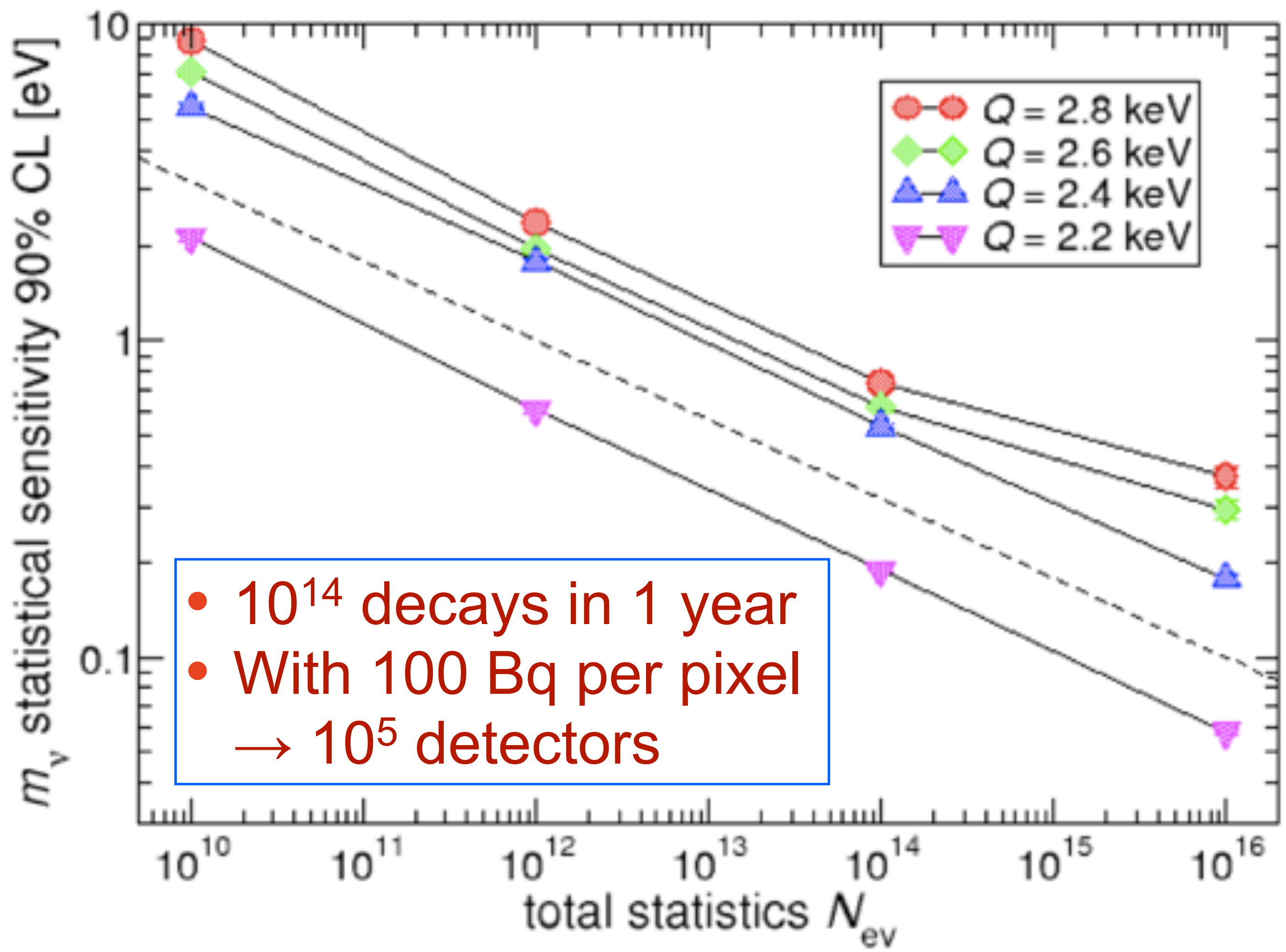
- Calorimetric measurement of ^{163}Dy atomic de-excitation (mostly non-radiative)
- Rate at end-point and ν mass sensitivity depend on Q

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

  - Missing precise measure of Q_{EC} = 2.2-2.8 keV.
  - $\tau_{1/2} \approx$ 4570 years: few active nuclei needed

- Advantages:
  - Source = detector
  - All energy is detected
  - No molecular final states
  - Self-calibrating
- Challenges:
  - ΔE_{FWHM} < 10 eV
  - τ_{rise} < 1 μs to avoid background due to pile-up
  - Clean isotope production and incorporation
  - Huge arrays needed (high speed MUX, data handling)

M. Galeazzi et al., arXiv:1202.4763v2



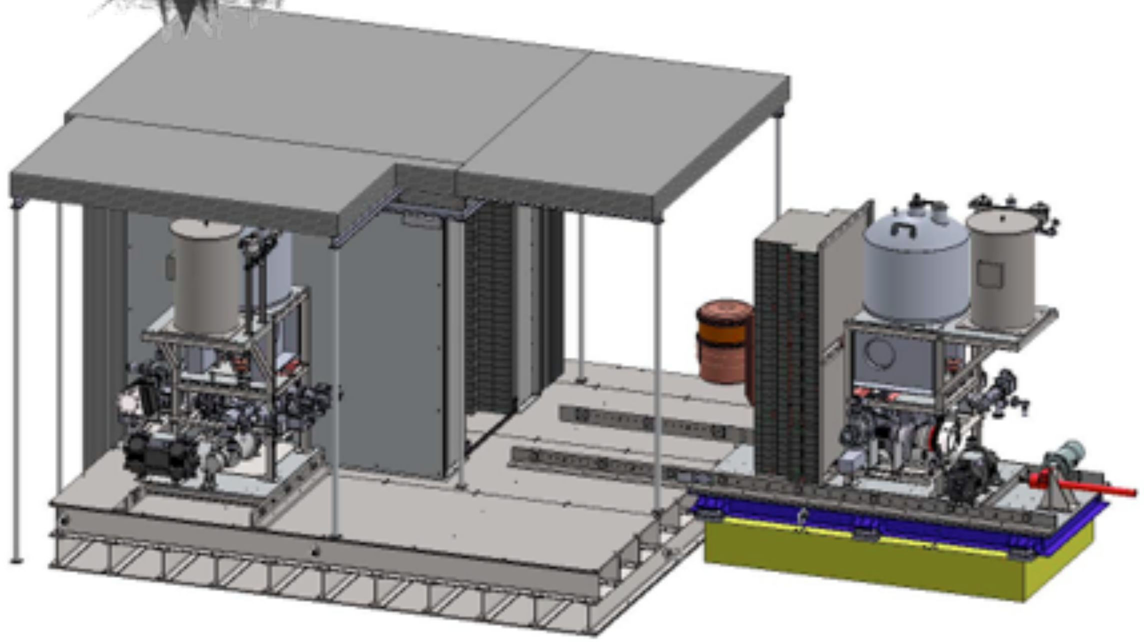
Conclusions

- Rare event searches have a strong scientific motivation
  - Neutrinoless double beta decay is still the only practical approach to the question of the neutrino nature
  - Neutrino mass value and origin is an indispensable piece of information
  - WIMP searches are quickly reaching the parameter regions dominated by neutrino scattering
  - Observed anomalies in the WIMP low mass region need to be confirmed/ understood
- Next generation experiments are mostly based on consolidated technologies properly scaled to match the needed sensitivity
- The true challenge is the reduction of the background i.e. the clear identification of a weak signal with a blurred signature
- In this respect new technological improvements can make the difference and foster new enhanced approaches
- On the other hand, background issues cover all the aspects of the experiment and require specific technologies, know-how and resources
- The quest for a clean (radio-pure), quick and large scale production of specific isotopes is also a challenge
- All future experiments are aiming at ton-size scales. Cost and time are correspondingly increasing and a new challenge is raising: competition.

Backup slides

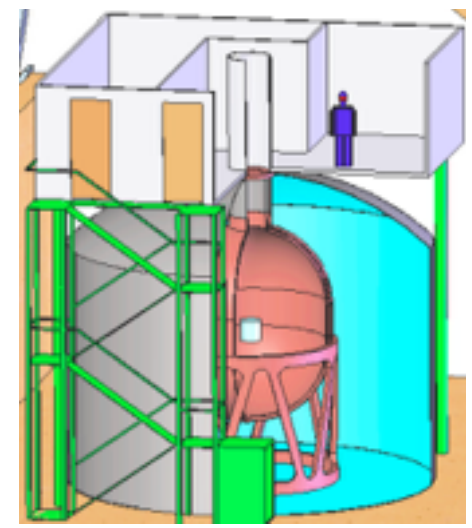
MAGE

MAJORANA



MJD:
- Modules of ^{enr}Ge housed in high-purity
- electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module:
- Total 40 kg (29 kg enr.)

GERDA



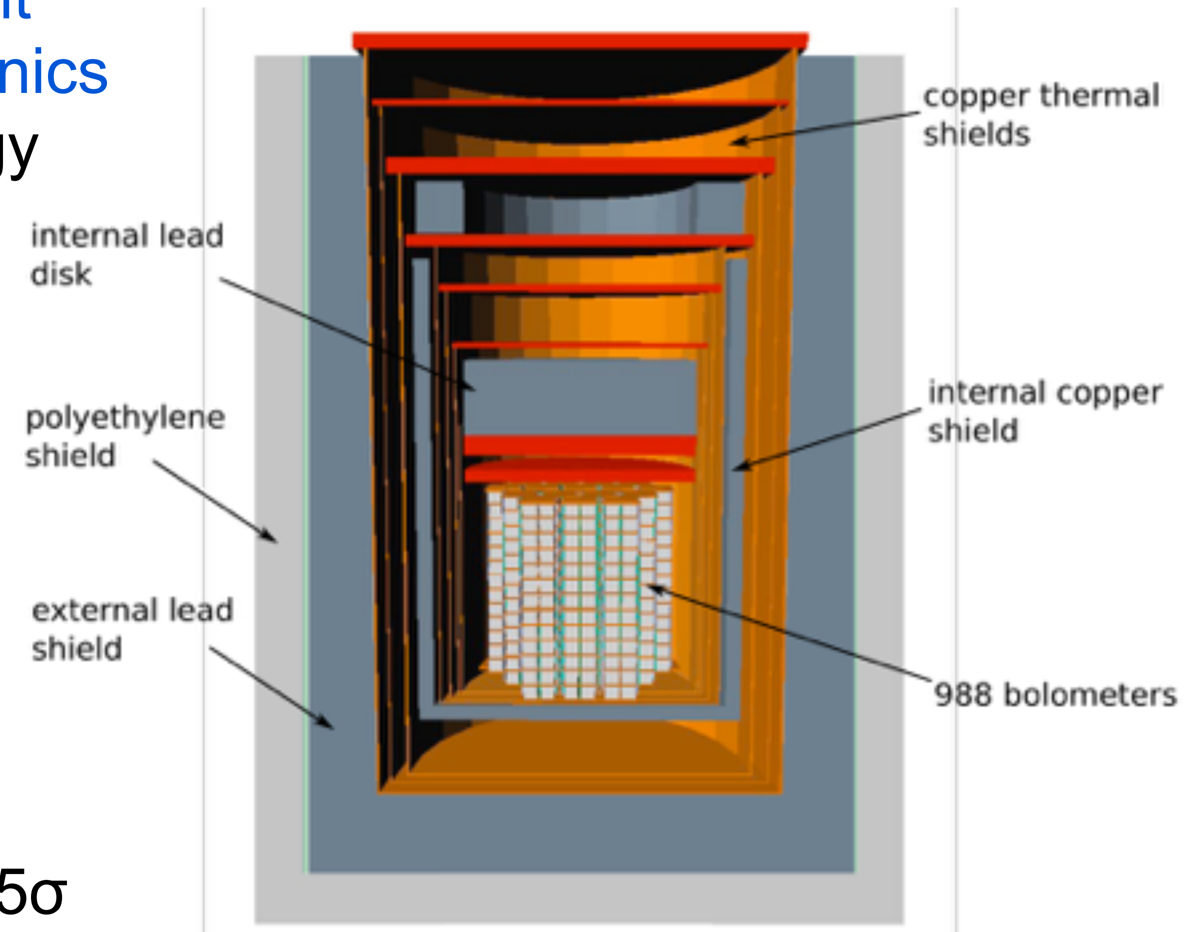
GERDA:
- ‘Bare’ enrGe array in liquid argon
- Shield: high purity liquid Argon / H2O
- Phase I (2013): 21.6 kg·yr
- Phase II (2015): add ~20 kg new detectors - Total ~40 kg
- Joint Cooperative Agreement:
- Open exchange of knowledge & technologies (e.g. MaGe, R&D)

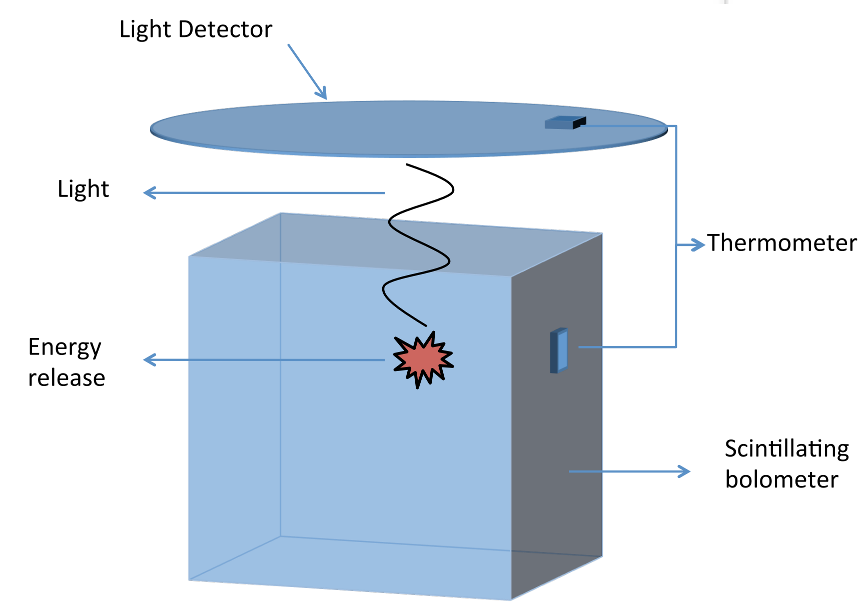
Intention is to merge for Large Scale Ge.
Select best techniques developed and tested in GERDA and MAJORANA

CUPID: CUORE Upgrade with Particle IDentification

- White papers: arXiv:1504.03599, arXiv:1504.03612
- Artusa, D.R. et al. Eur.Phys.J. C74 (2014) 10, 3096, arXiv:1404.4469

- Next-generation bolometric tonne-scale experiment
- Based on the CUORE design and CUORE cryogenics
  - Largest cryostat and DU built; mature technology
  - 988 enriched (90%) crystals, PID with light detection
- 4 options considered:
  - $^{130}TeO_2$: phonons + Cherenkov detector
  - $Zn^{82}Se$, $Zn^{100}MoO_4$, $^{116}CdWO_4$: phonons +scintillation
- Aim for zero-background measurement
- Sensitivity to entire IH region
  - CUORE geometry and background model
    - 99.9% α rejection @ >90% signal efficiency (5σ separation of α and β)
  - 5 keV FWHM resolution
  - **Challenge: nearly zero background measurement: background goal <0.02 events / (ton-year)**
  - Half-life sensitivity (2-5)×10^{27} years in 10 years (3σ)
  - $m_{\beta\beta}$ sensitivity 6-20 meV (3σ)





α/β discrimination

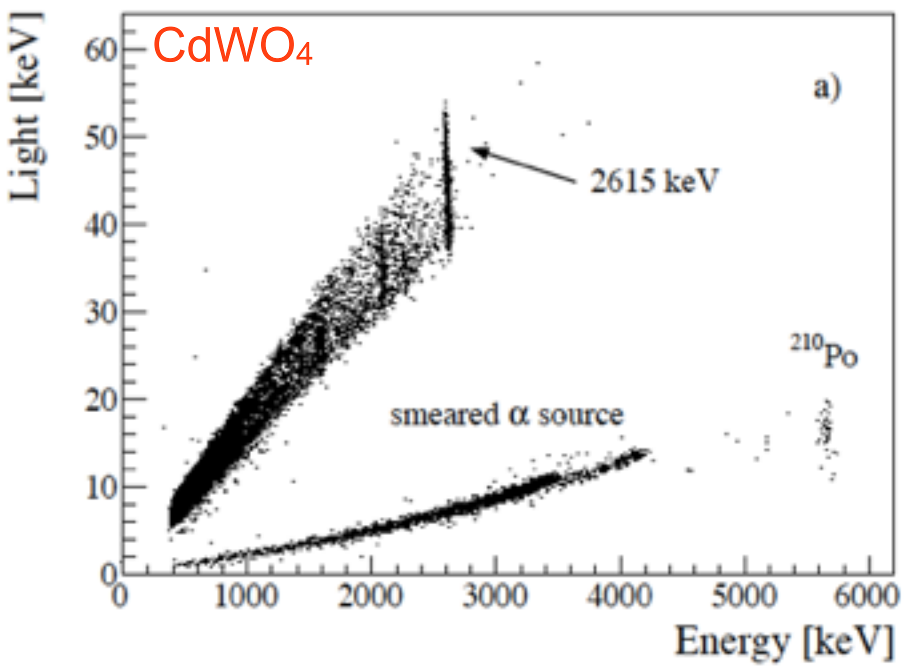
from: D.R.Artusa et al., arXiv:1404.4469 [hep-ex]

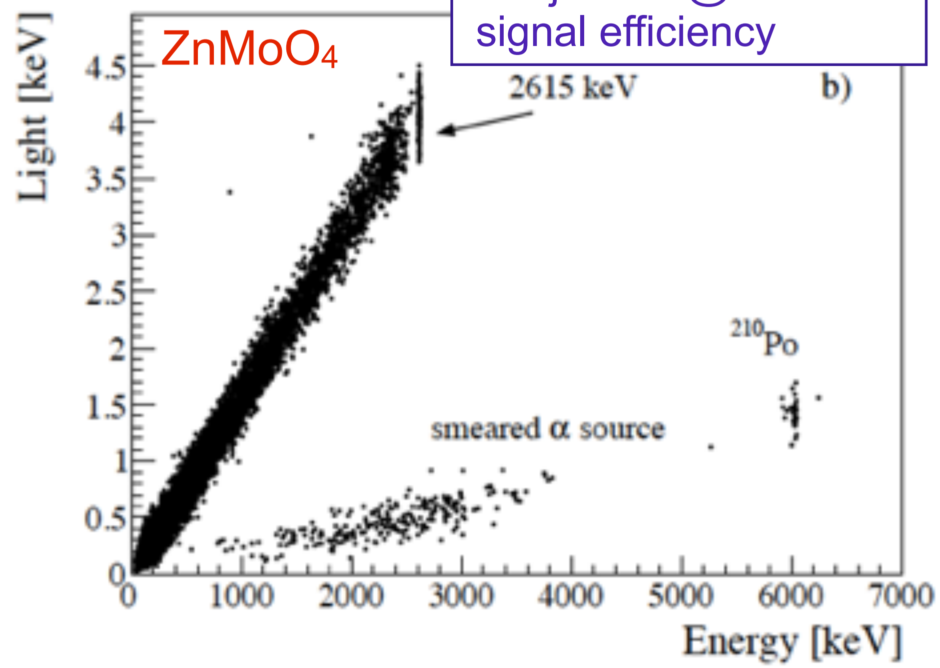
Demonstrated >99.9% α rejection @ >90% signal efficiency

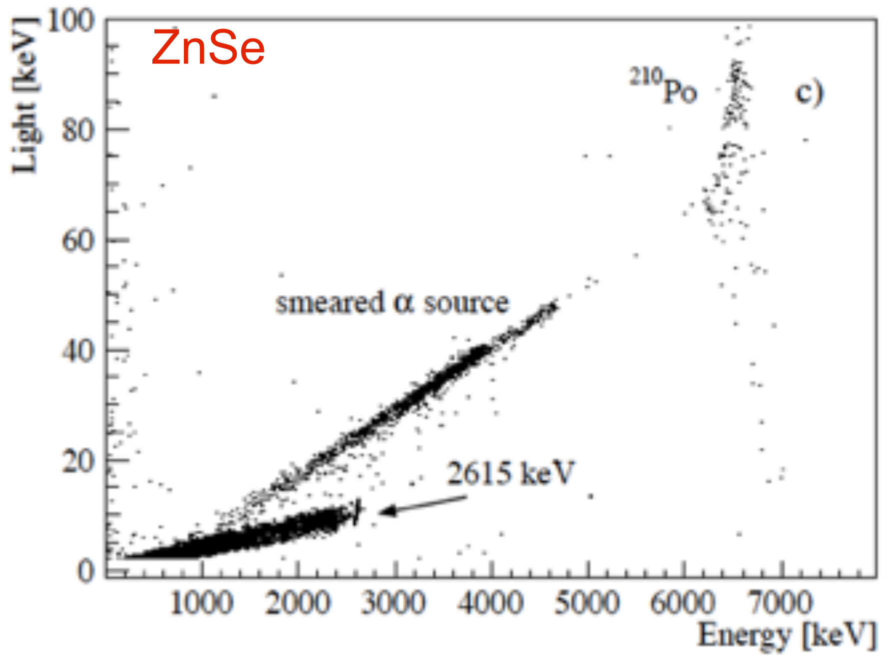
Cherenkov light or scintillation to distinguish α from β/γ:

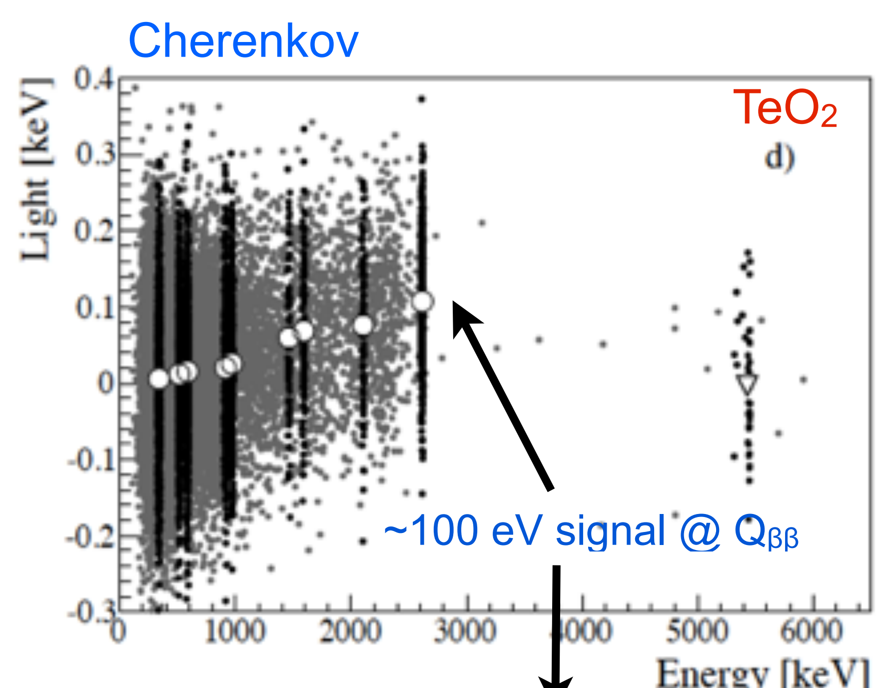
- $^{130}TeO_2$, $Zn^{82}Se$, $^{116}CdWO4$ and $Zn^{100}MoO_4$
- more rejection power needed

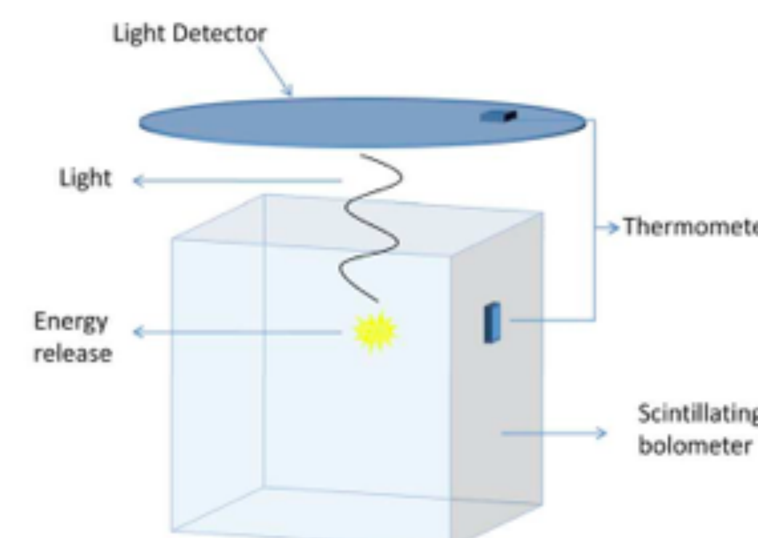
Critical element: light detector









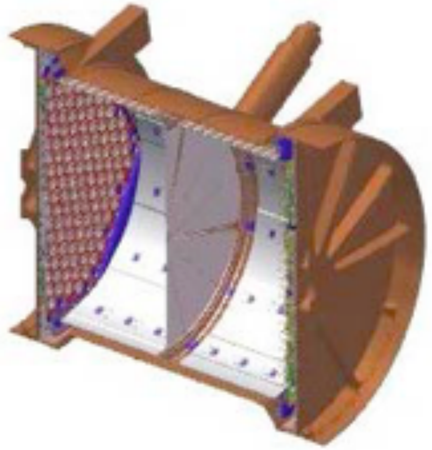


Requires ~20 eV resolution for >99.9% α rejection @ >90% signal efficiency

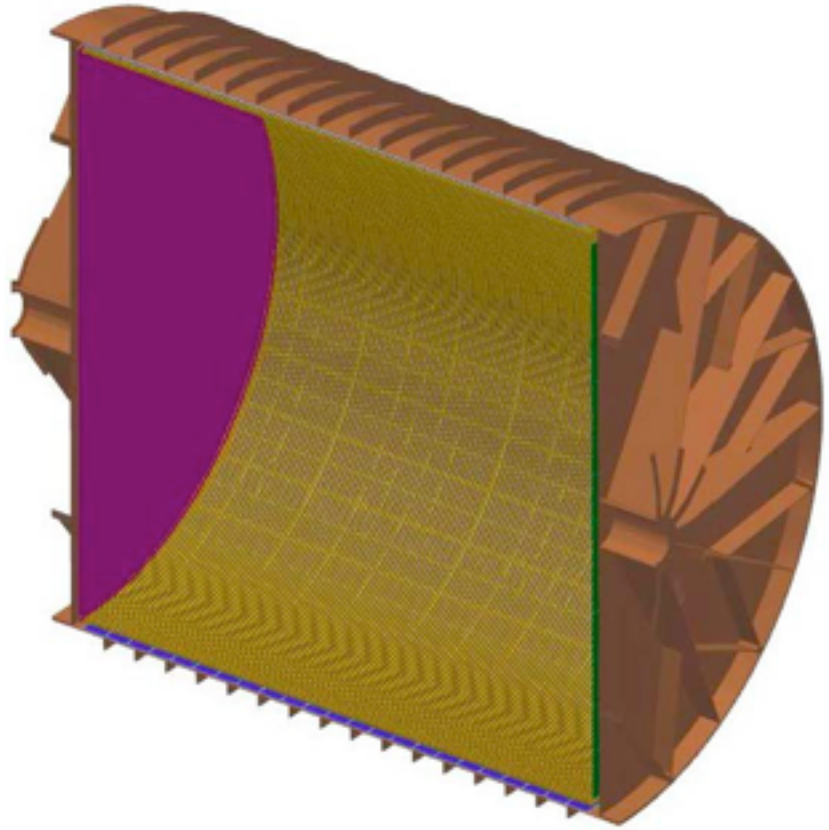
(a) C. Arnaboldi et al., 34, 143 (2010)
(b) J. Beeman et al., Phys. Lett. B 710, 318 (2012)
(c) C. Arnaboldi et al., 34, 344 (2011)
(d) J. Beeman et al., Astropart. Phys. 35, 558 (2012)

nEXO

EXO-200:
- ~150 kg enriched LXe detector
- operation 2011-2014 @ WIPP



nEXO:
- ~5,000kg LXe detector
- pre-conceptual stage
- based @ SNOLAB



Concept
- Large ultra-pure volume of enriched liquid ^{136}Xenon
- Contaminants removed by filtering
- Use ultra-low radioactivity material around the LXe
- Then rely on self-shielding

- Measure ionization e-
- Reconstruct position on segmented anode (wires or pads/strips)
- Excellent multi-pulse separation

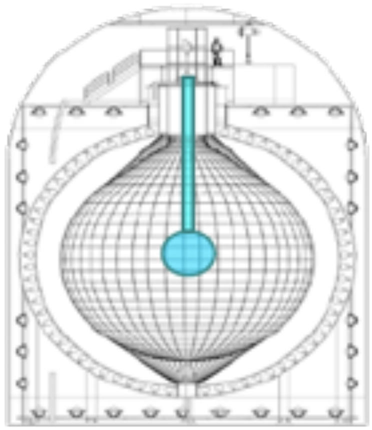
- Measure scintillation photons
- Timing for drift direction position reconstruction
- Achieve excellent energy resolution combining with charge measurement

Based on the successful operation of EXO-200

KamLAND-Zen program

KamLAND-Zen Phase 1 | KamLAND-Zen Phase 2 | KamLAND-Zen2 | KamLAND2-Zen?

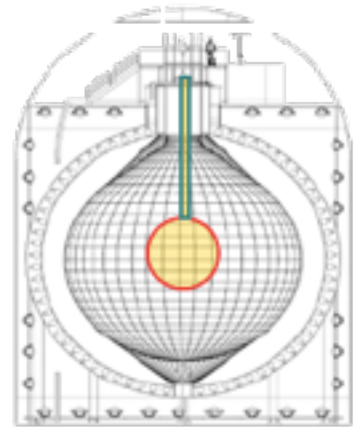
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 202?



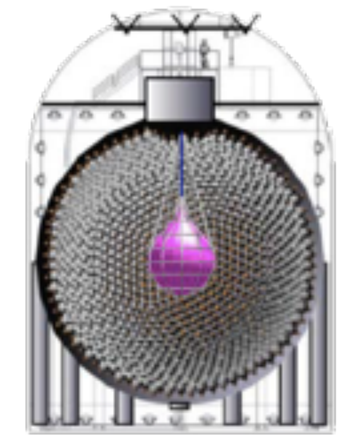
MIB: ~Φ3.12m
Livetime 112.3 days.
^{136}Xe ~320kg(91%)
FV: ^{136}Xe 125 kg.

- LS & ^{136}Xe Purification
- More ^{136}Xe

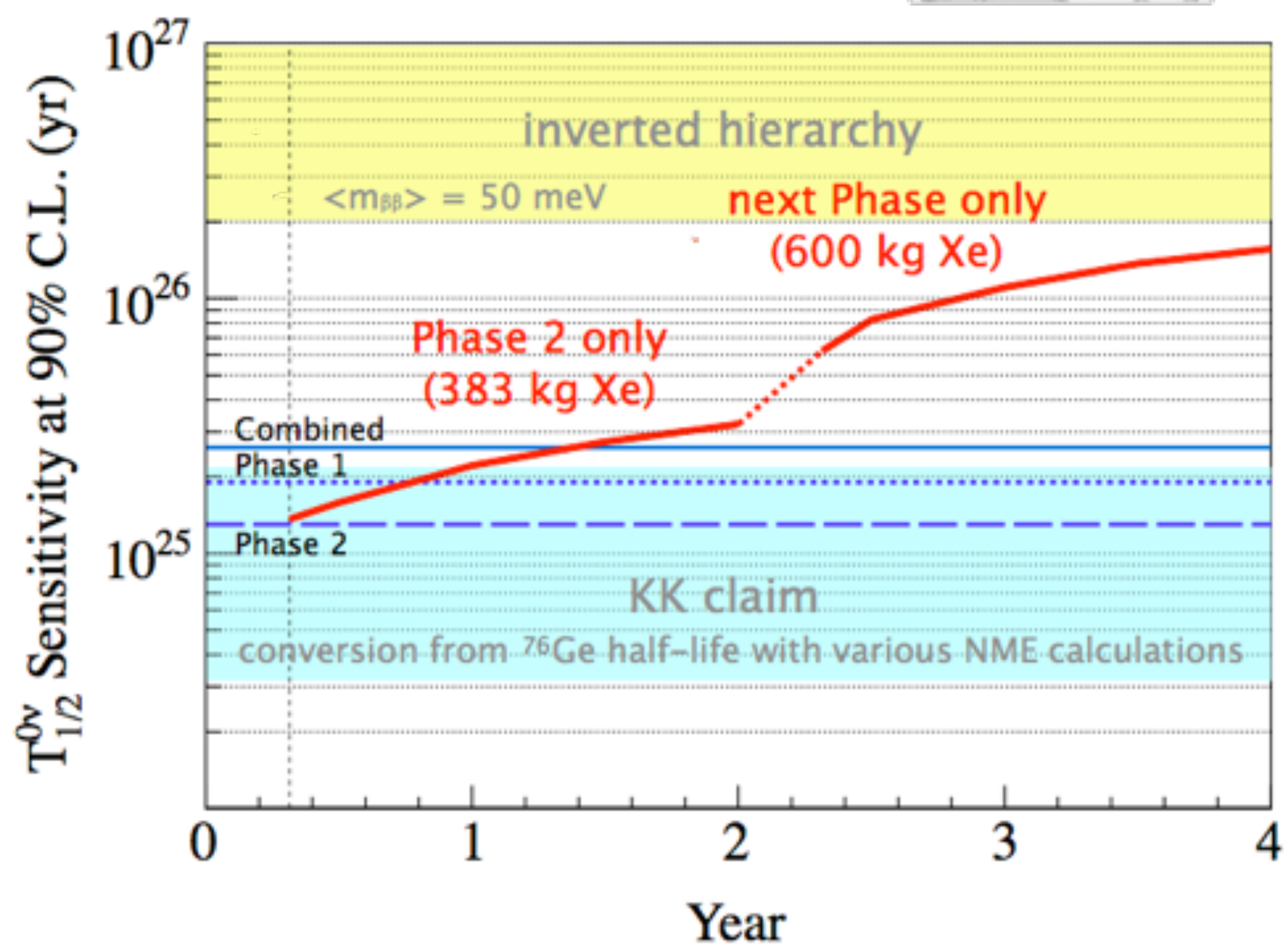
Livetime >600days.?
^{136}Xe ~383kg(91%)



MIB: ~Φ4m
^{136}Xe ~700kg(91%)
5 years



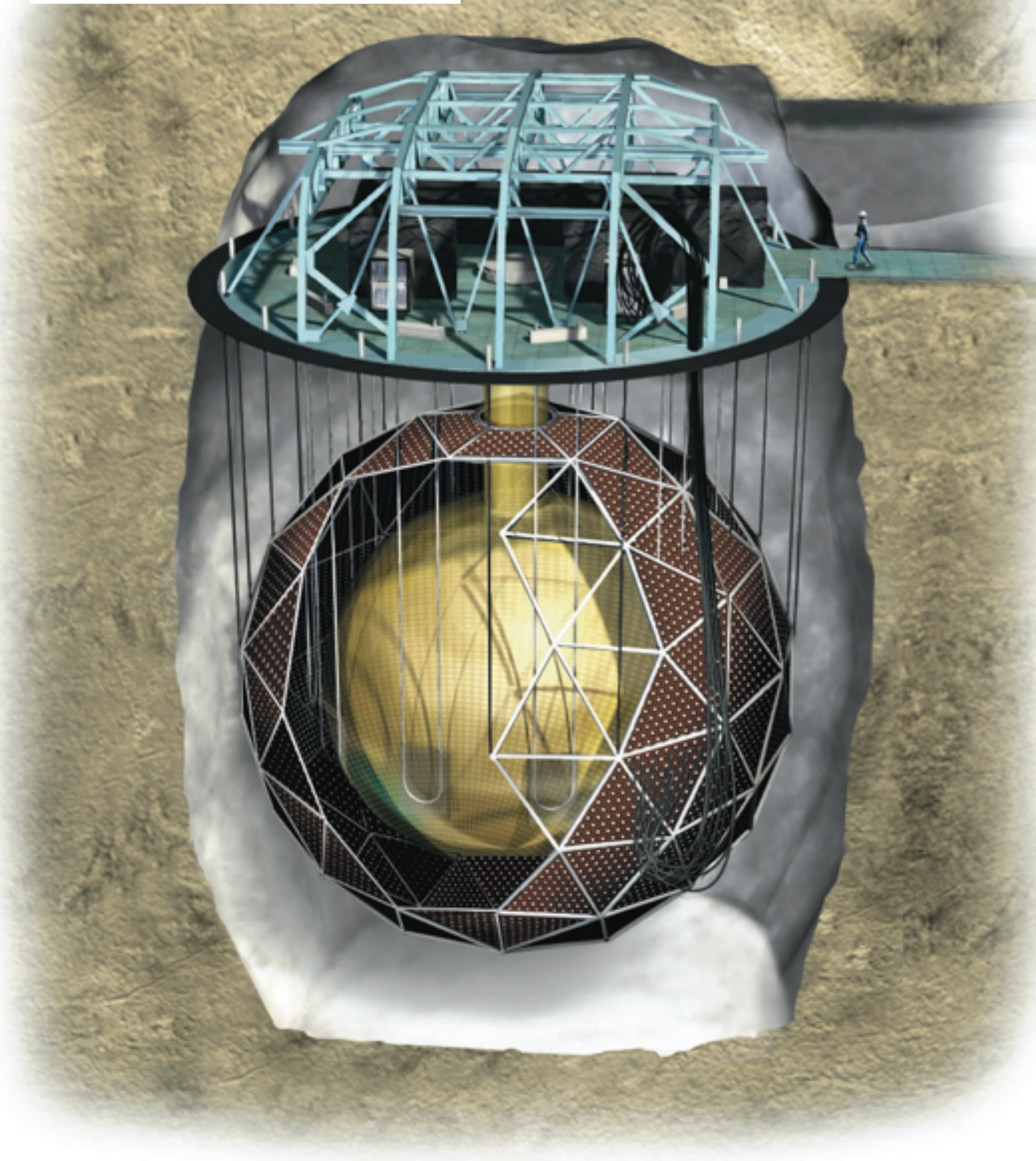
- 2014: KamLAND-Zen w/ lower ^{110m}Ag
  - Just resumed with 380 kg
- 2017: KamLAND-Zen 700 kg
  - with clean mini-balloon
- Future: KamLAND-Zen2
  - high QE PMT
  - high yield LS
  - light concentrator
  - σ_E(2.6 MeV) < 2.5%
- Super-KamLAND-Zen



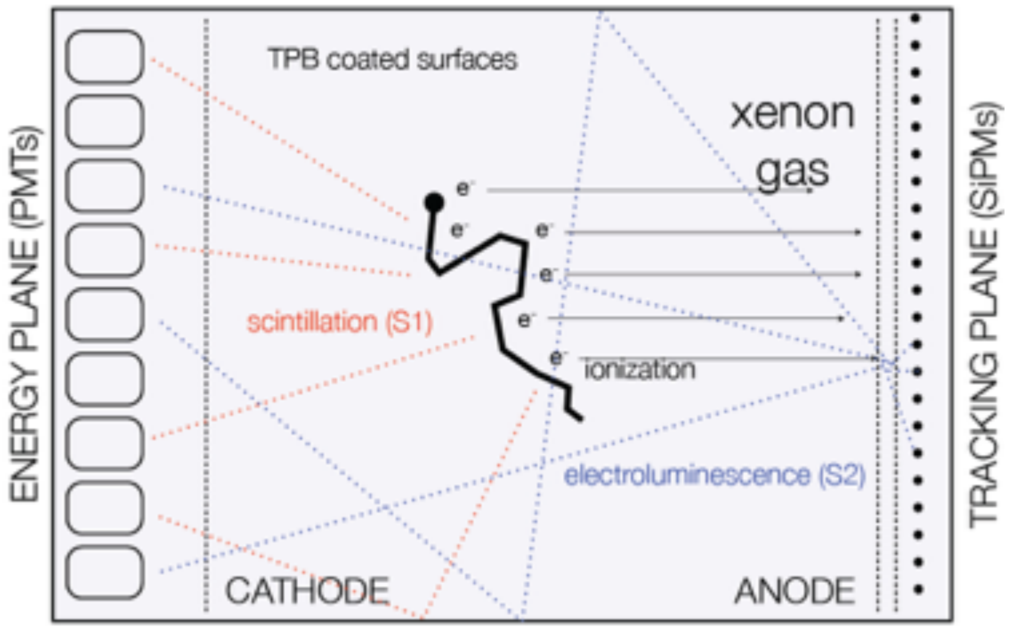
SNO+

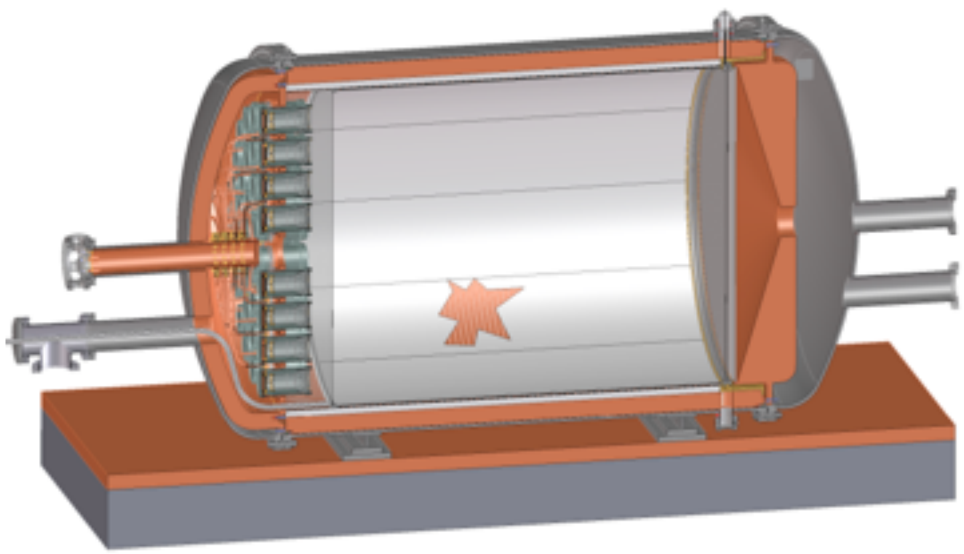
- SNO heavy water replaced by 780 tonnes of liquid scintillator
  - ~9500 PMTs
  - 1700 + 5700 tonnes ultra-pure water shielding
  - New rope net to hold down the 6m radius acrylic vessel
  - 6800' underground in SNOLAB

- Stable loading of aqueous $Te(OH)_6$ in SNO+ scintillator with good optical properties achieved by BNL
- 780 tonne detector and high 130Te isotopic abundance gives large isotope mass
  - 0.3 – 0.5% Te (by weight) in SNO+ Phase I is 2.34 – 3.9 tonnes of Te or 800 – 1333 kg of ^{130}Te
  - Percent level loading is feasible
  - 3% Te in SNO+ Phase II would give 8 tonnes of ^{130}Te

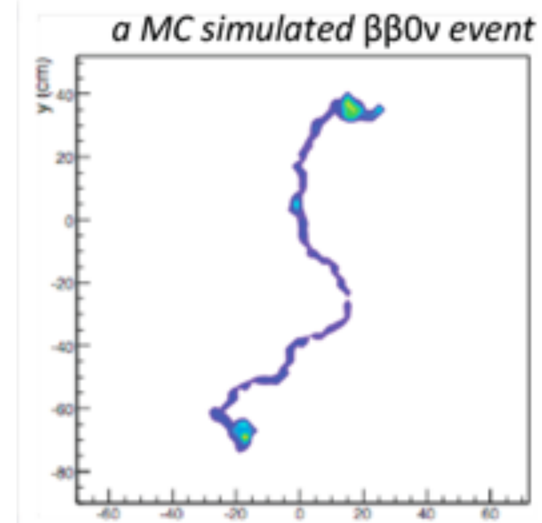


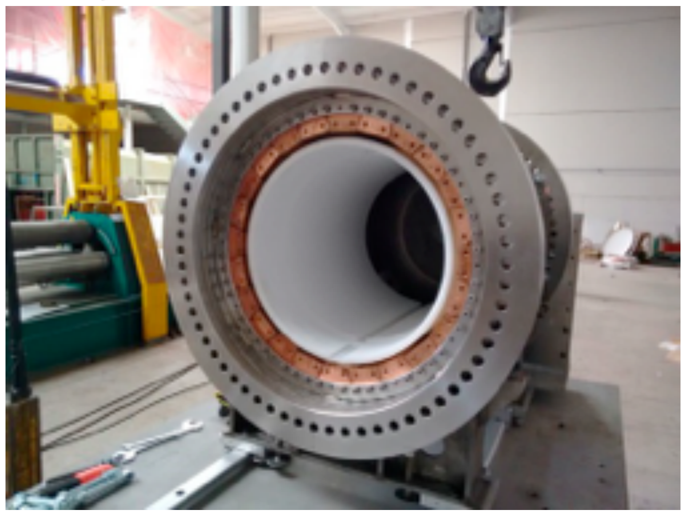
NEXT



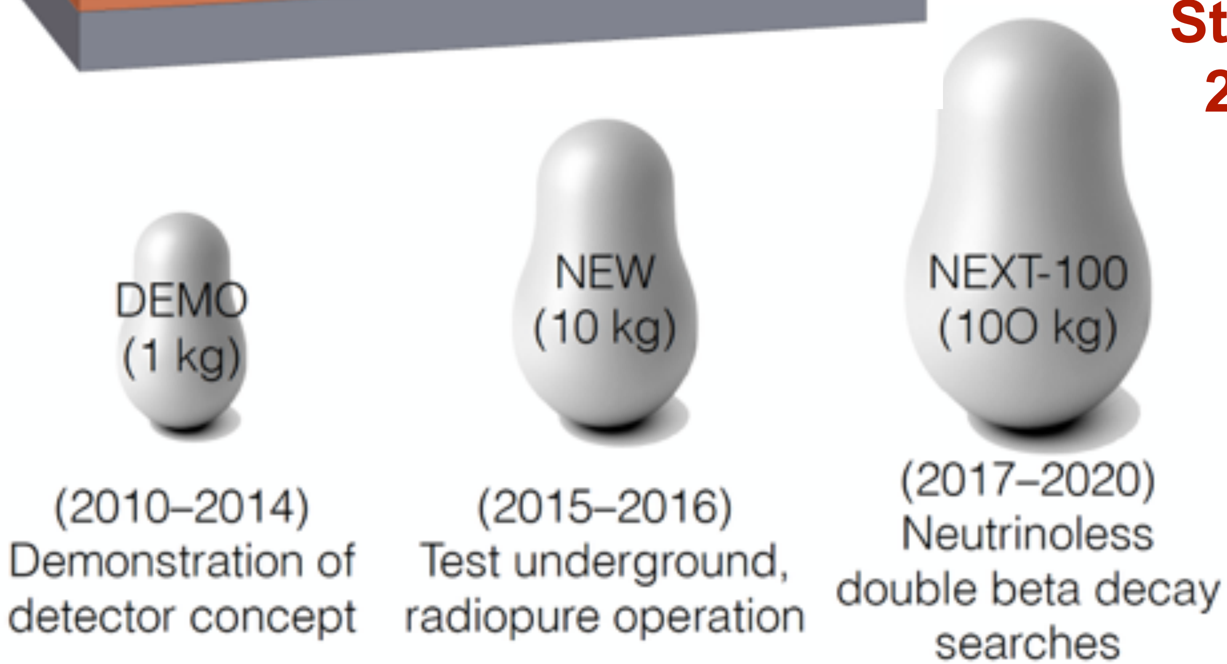


- High Pressure Xenon (HPXe) TPC operating in EL mode.
- Filled with 100 kg of Xenon enriched at 90% in ^{136}Xe (in stock) at a pressure of 15 bar.
- Event energy is integrated by a plane of radiopure PMTs located behind a transparent cathode (energy plane), which also provide t_0.
- Event topology is reconstructed by a plane of radiopure silicon pixels (MPPCs) (tracking plane).





Start operation 2nd half 2016



90% sensitivities

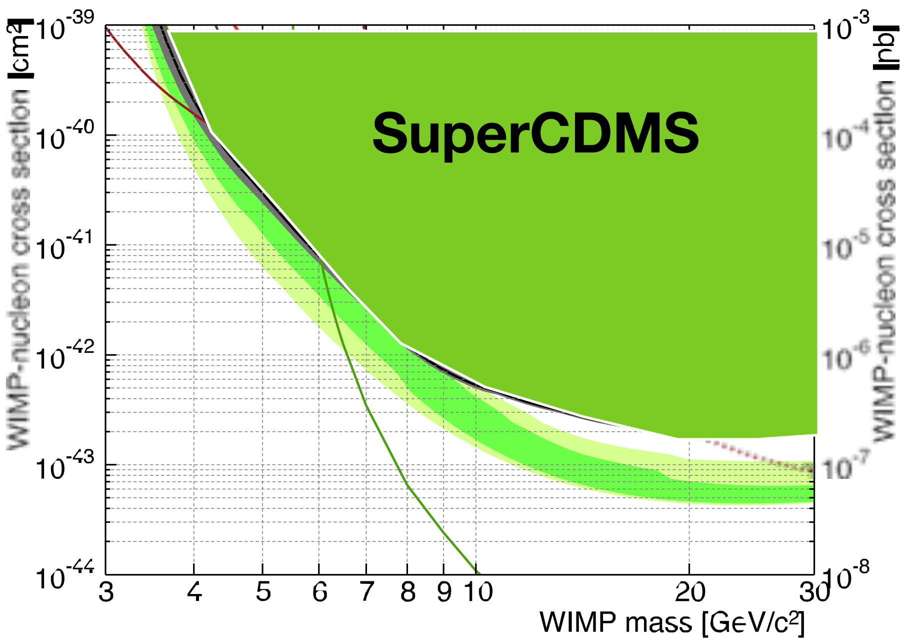
	Isotope	Q	FWHM	B_{iso}	Performance	Scale/time	counts [1y]	Sensitivity [90% CL]	$<m_{\beta\beta}>$ [meV]
CUORE0	130Te	2527	5	1,7E-01	1,6E-01	7,3E+01	11,7	**9,2E+24**	**290**
CUORE	130Te	2527	5	2,9E-02	2,67E-02	1,4E+03	37,1	**9,82E+25**	**89**
GERDA-I	76Ge	2039	4,5	2,3E-02	1,09E-02	1,2E+02	1,4	**4,59E+25**	**237**
GERDA-I up	76Ge	2039	3	4,1E-02	1,27E-02	2,9E+01	0,4	**2,05E+25**	**354**
GERDA-II	76Ge	2039	3	1,2E-03	3,63E-04	2,9E+02	0,1	**2,62E+26**	**99**
K-Zen	136Xe	2458	243,2	9,8E-03	3,23E-01	1E+03	332,9	**2,43E+25**	**213**
K-Zen 2	136Xe	2458	243,2	3,1E-04	1,04E-02	1,2E+03	12,4	**1,46E+26**	**87**
EXO-200	136Xe	2458	80,9	2,8E-03	4,36E-02	4,1E+02	17,7	**4,14E+25**	**163**
EXO-200 2	136Xe	2458	57,8	1,2E-03	1,37E-02	4,1E+02	5,6	**7,39E+25**	**122**
MJD	76Ge	2039	3	1,2E-03	3,68E-04	2,4E+02	0,1	**2,22E+26**	**108**
SuperNEMO D	82Se	2997	138,6	1,1E-04	4,21E-03	2,3E+01	0,1	**2,09E+25**	**209**
SNO+	130Te	2527	267,3	3,7E-04	1,29E-02	1,3E+03	16,2	**1,35E+26**	**76**
NEXT	136Xe	2458	19,7	8E-04	8,56E-03	1,7E+02	1,4	**5,98E+25**	**136**
CUPID(TeO2)	130Te	2527	5	1,1E-03	1,03E-03	3,59E+03	3,7	**8,03E+26**	**31**
CUPID(ZnMoO4)	100Mo	3034,4	5	1,1E-03	1,46E-03	2,5E+03	3,7	**5,69E+26**	**38**
CUPID(Li2MoO4)	100Mo	3034,4	5	1,1E-03	1,12E-03	3,3E+03	3,7	**7,37E+26**	**33**
CUPID(CdWO4)	116Cd	2813,5	5	1,1E-03	2,34E-03	1,6E+03	3,7	**3,54E+26**	**63**
K-Zen II	136Xe	2458	243,2	2E-04	6,56E-03	1,9E+03	12,4	**2,31E+26**	**69**
nEXO	136Xe	2458	57,8	3,8E-05	4,19E-04	1,3E+04	5,3	**2,36E+27**	**22**
SNO+ 2	150Nd	3367	229	1,8E-03	1,18E-01	4,3E+02	50,4	**2,59E+25**	**224**
SuperNEMO	82Se	2997	138,6	1,1E-04	4,21E-03	4,6E+02	1,9	**1,42E+26**	**80**

NME's from J. Barea and F. Iachello, Phys. Rev. C 79 (2009) 044301

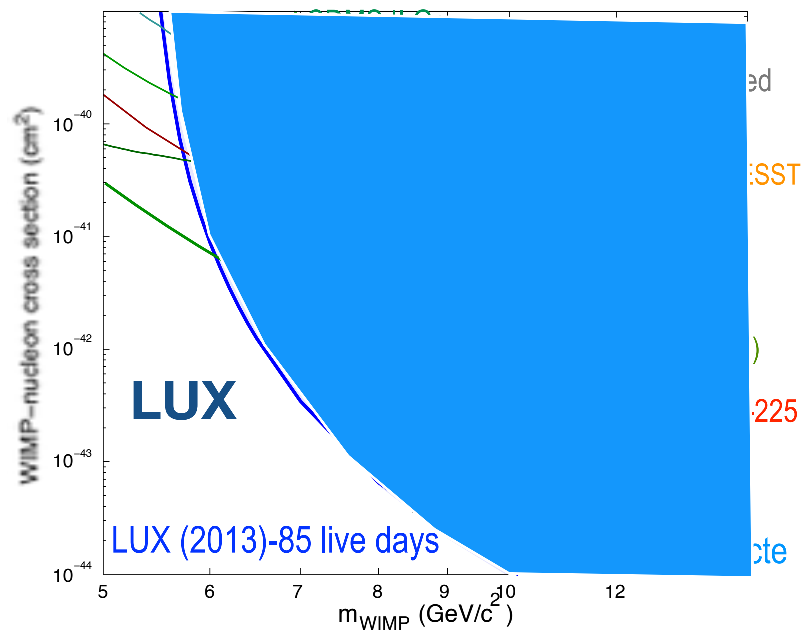
Low mass region

Heavily constrained by CDMS-Ge, XENON10, XENON100, LUX, EDELWEISS, CRESST, CoGeNT, PandaX,…

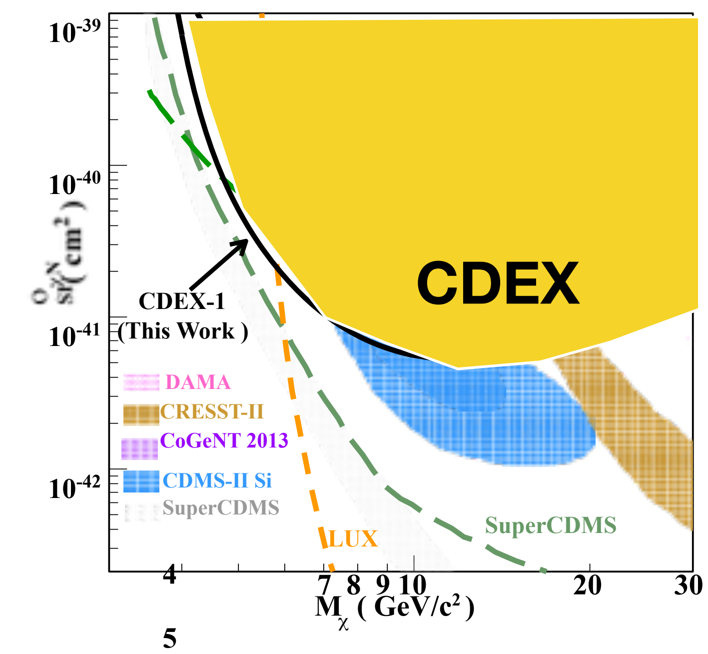
CDMS, PRL 112, 2014

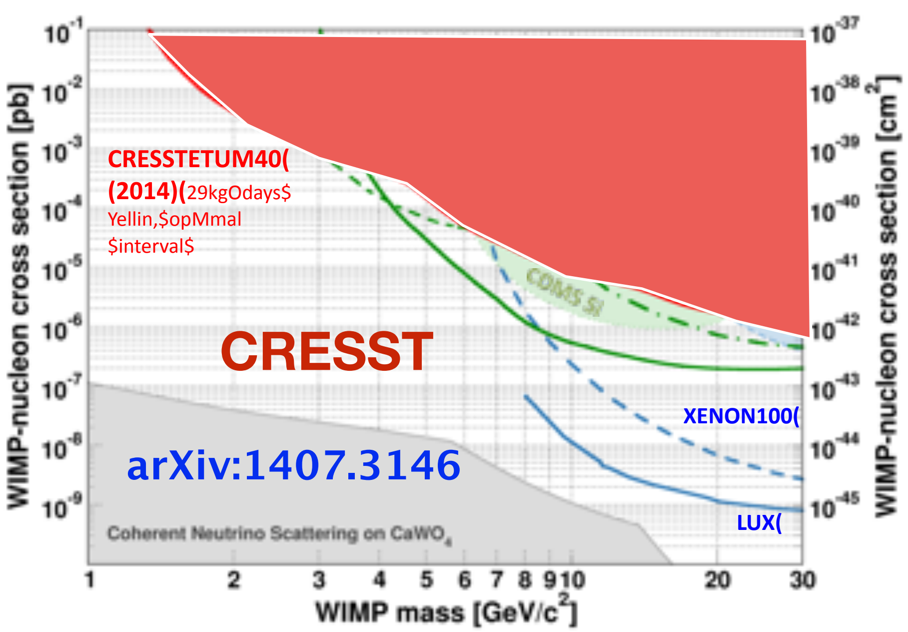


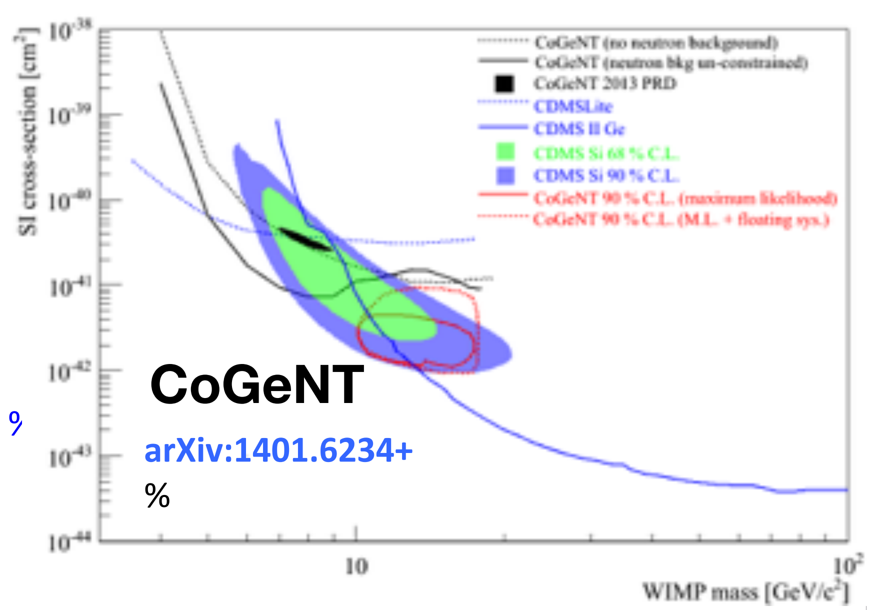
LUX, PRL, arXix: 1310.8214

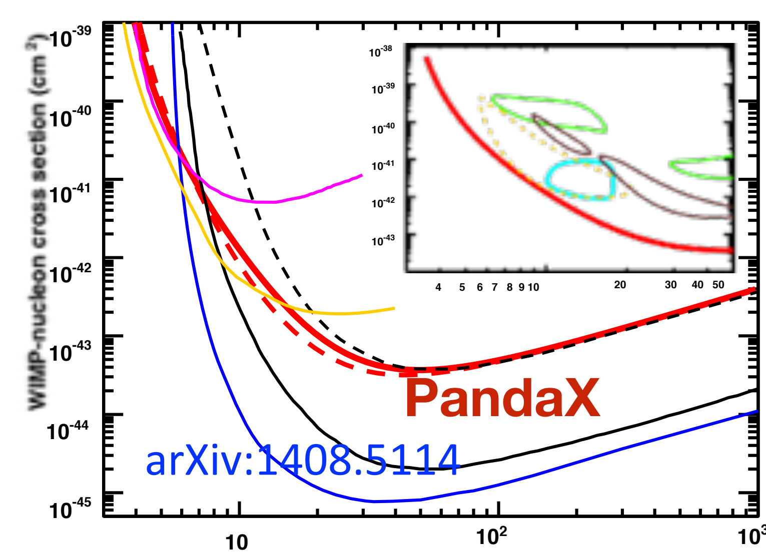


CDEX, arXiv:1404.4946



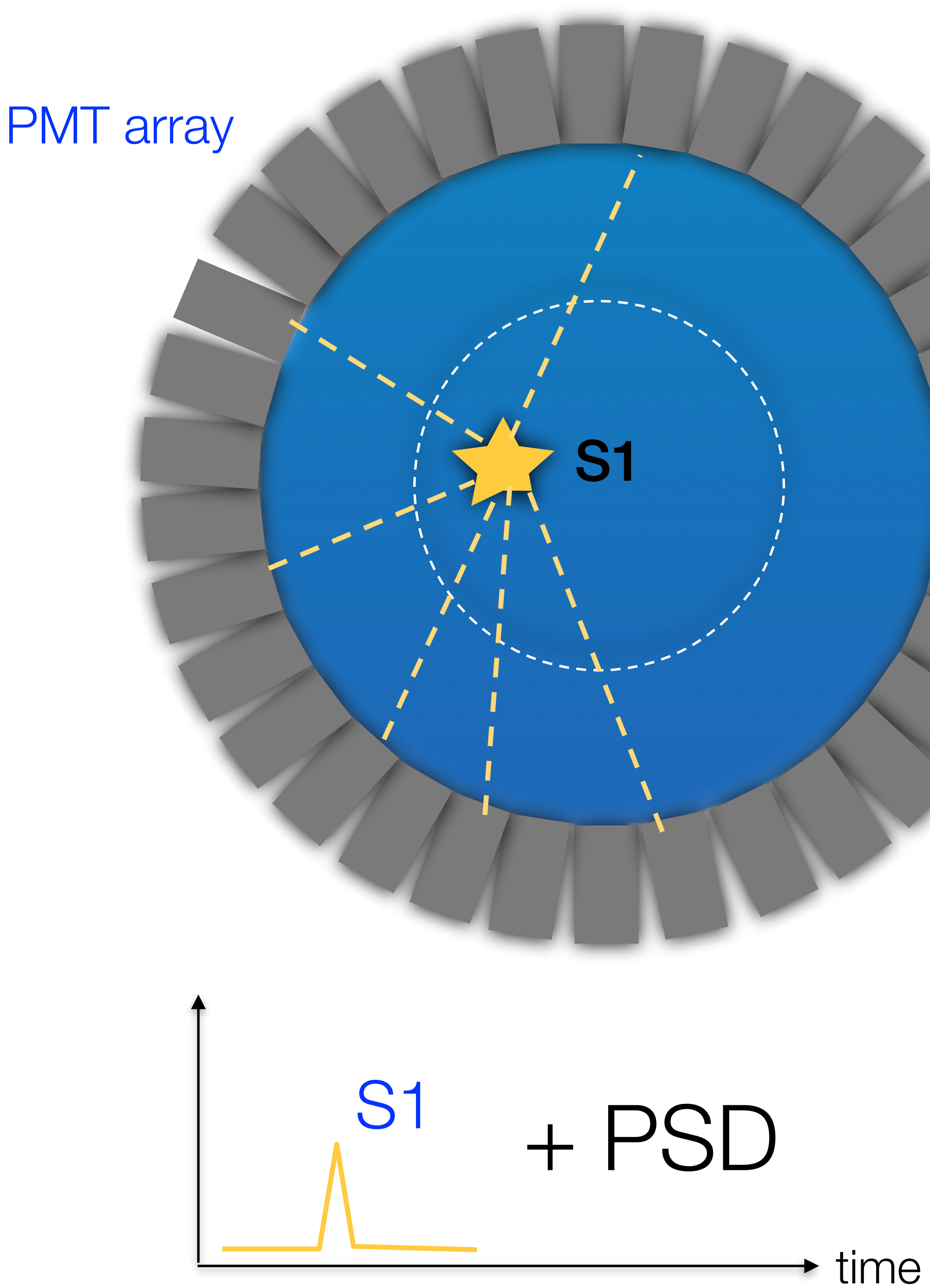




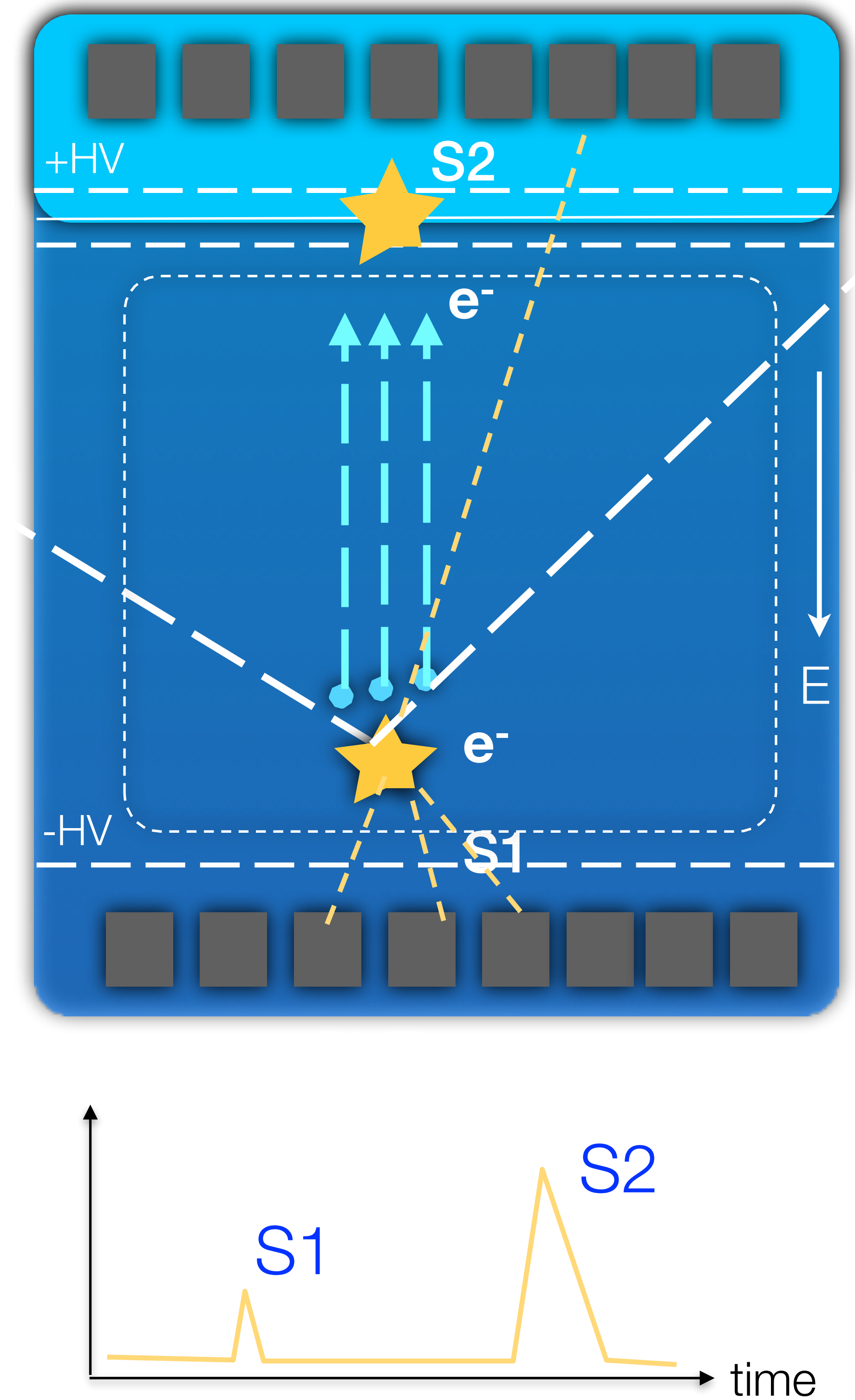


Noble liquid detector concepts

Single phase

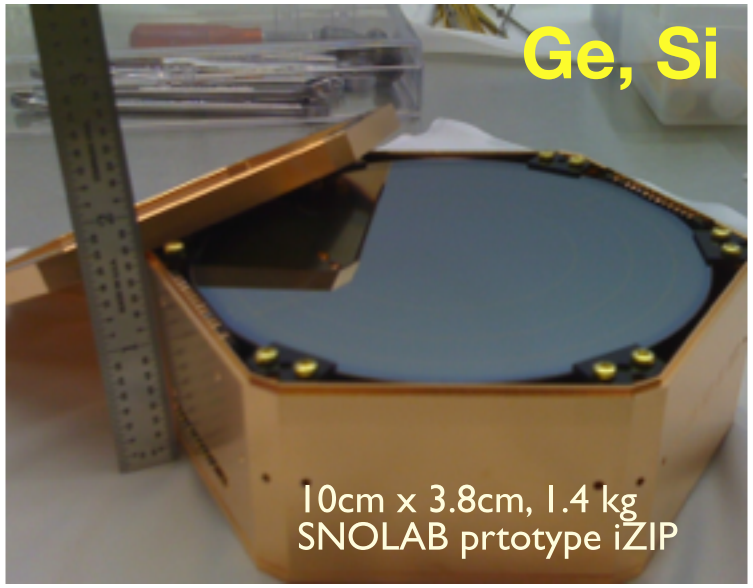


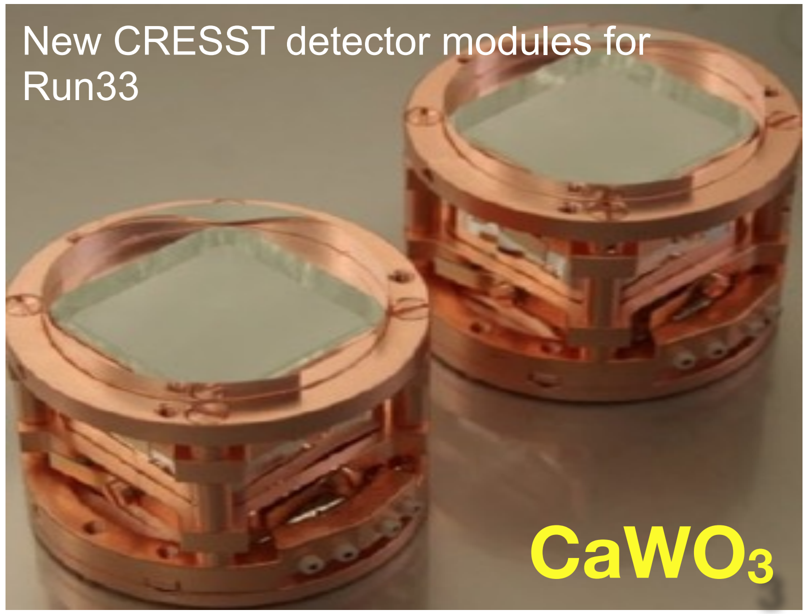
Double phase TPC

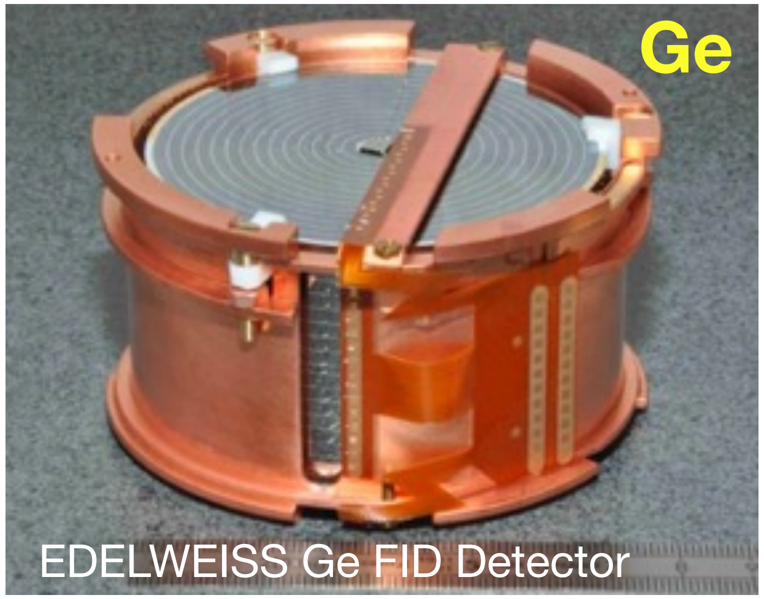


Cryogenic experiments

Absorber masses from ~ 100 g to 1400 g







SuperCDMS

new, leading results at low masses

proposed for SNOLAB:
Std: ~92 kg Ge, 11 kg Si
Lite: 5 kg Ge, 1.2 kg Si

CRESST

18 $CaWO_3$ detector modules (5 kg) installed at LNGS in 2013

low-background run in 2014, recent results and taking more data

EDELWEISS-III

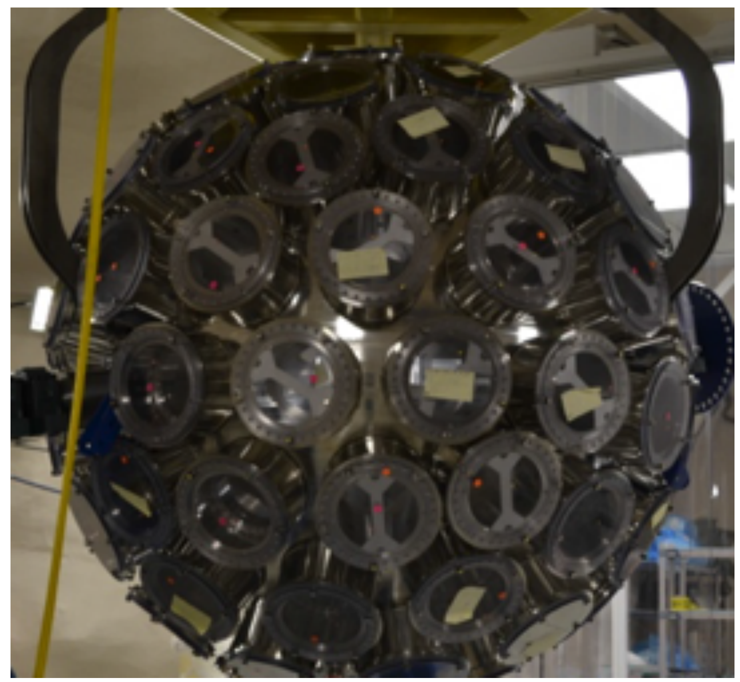
new run with 36 Ge FID800 (~ 30 kg) detectors since June 2014

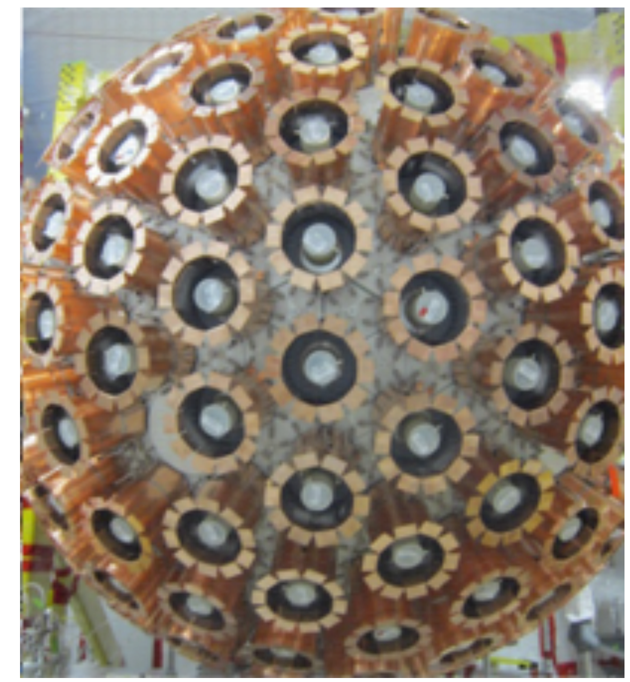
End 2014/early 2015: reach 3000 kg x d (125 live days)

2016: reach 1.2 ton x days (500 live days)

Xe and Ar single-phase

XMASS at Kamioka (LXe), DEAP and CLEAN at SNOLab (LAr)





XMASS at Kamioka:

835 kg LXe (100 kg fiducial),
single-phase, 642 PMTs
unexpected background found
detector refurbished
new run since Nov 2013

CLEAN at SNOLab:

500 kg LAr (150 kg fiducial) single-phase open volume *under construction*
to run in 2014

DEAP at SNOLab:

3600 kg LAr (1t fiducial) single-phase detector *under construction*
first data expected in fall 2014

Ar and Xe TPCs

XENON100 at LNGS:

161 kg LXe
(~50 kg fiducial)

242 1-inch PMTs
since 2013

LUX at SURF:

370 kg LXe
(100 kg fiducial)

122 2-inch PMTs
physics run and first results in 2013
new run in 2014

PandaX at CJPL:

125 kg LXe
(37 kg fiducial)

143 1-inch PMTs
37 3-inch PMTs
first results in August 2014

ArDM at Canfranc:

850 kg LAr
(100 kg fiducial)

28 3-inch PMTs
in commissioning
to run 2014

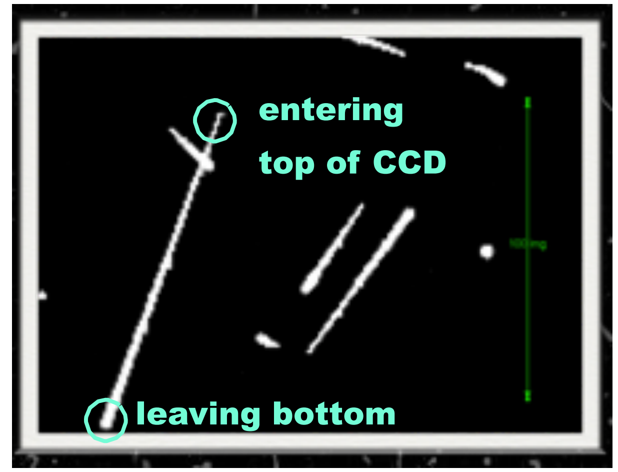
DarkSide at LNGS:

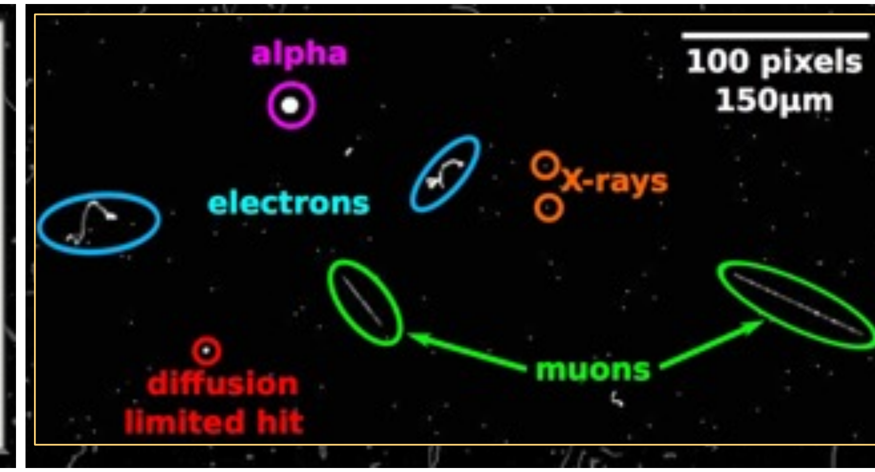
50 kg LAr (dep in ^{39}Ar)
(33 kg fiducial)

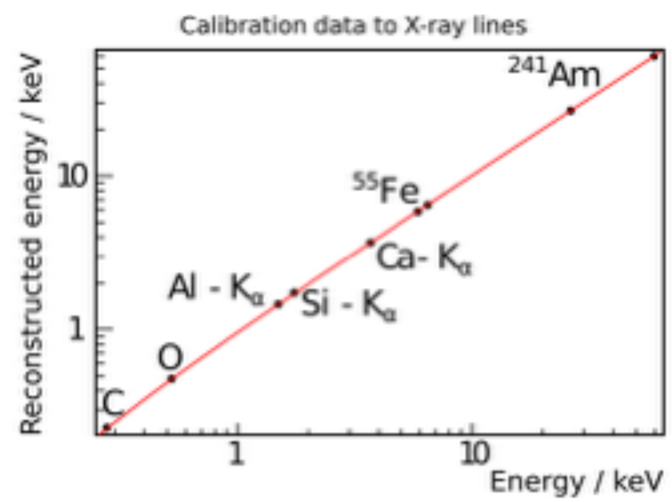
38 3-inch PMTs
first data with non-depl Ar in 2014

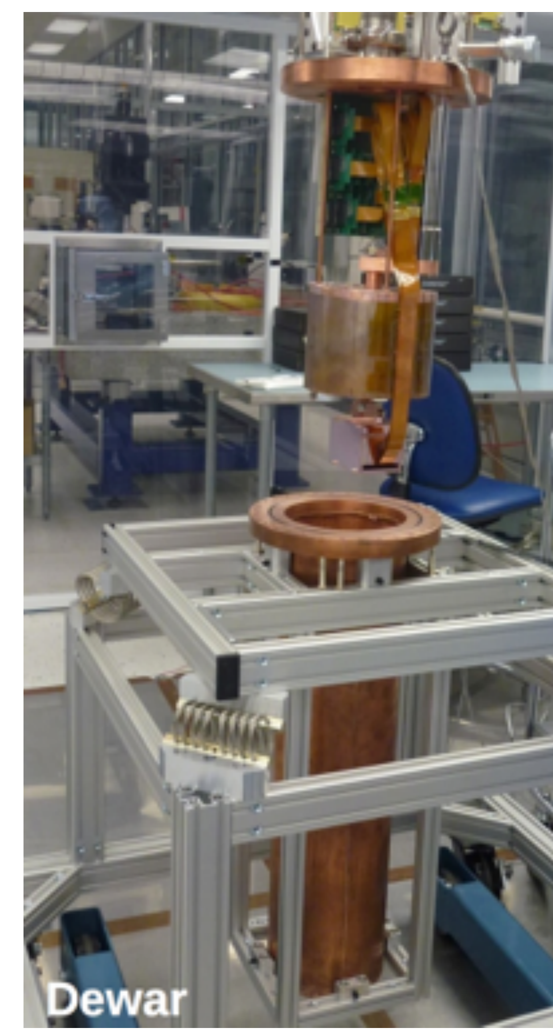
CCDs for low-mass WIMPs: DAMIC

- Particle identification
- Fiducialisation to reject surface events (X-rays)
- DAMIC100 (100 g Si active mass) under construction at SNOLAB; results in 2015

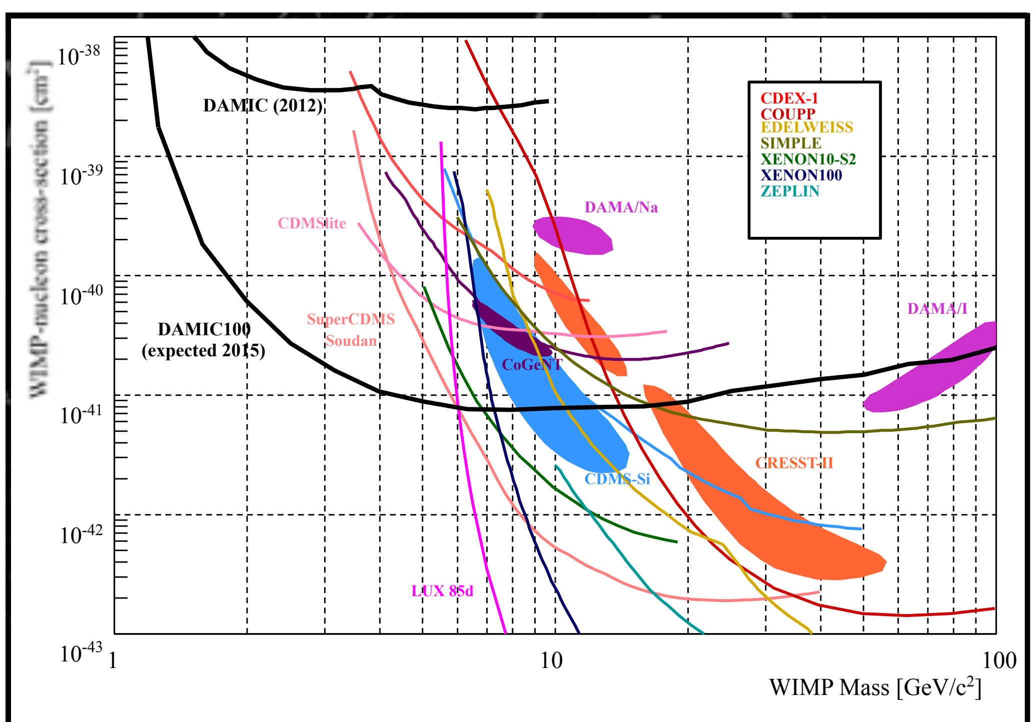


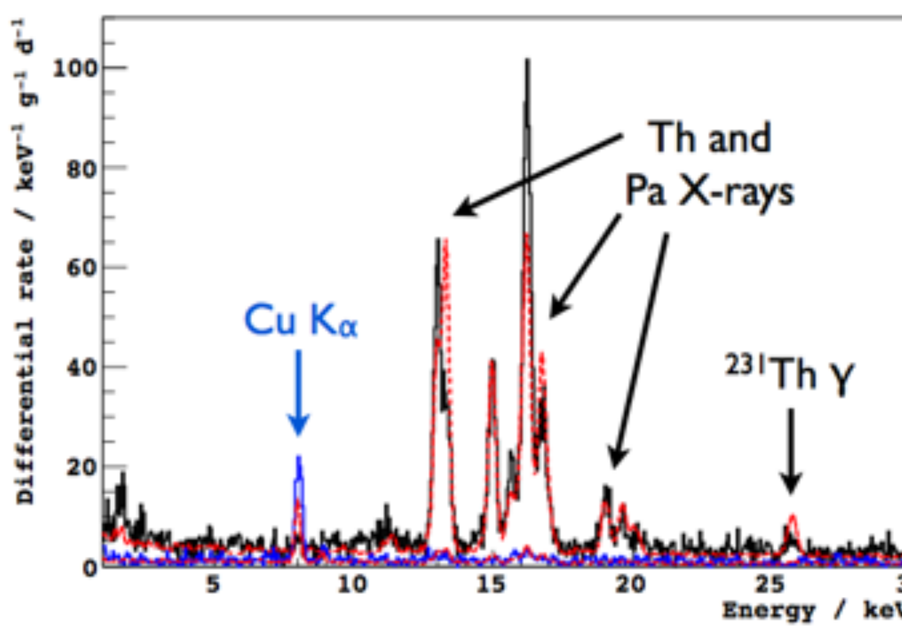






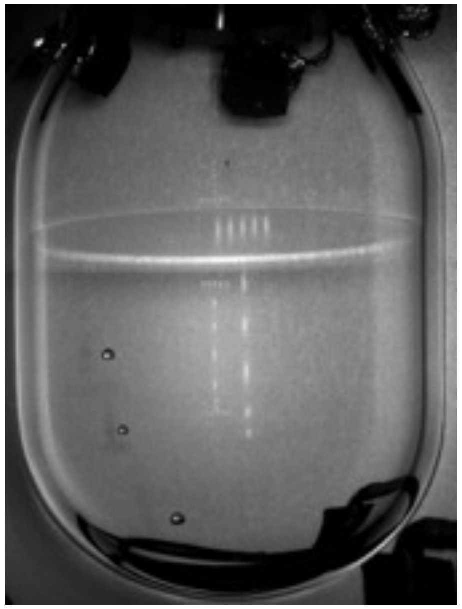
2012 DAMIC limit 107 g-days with 0.04 keV energy threshold Phys.Lett. B711 (2012) 264-269





Bubble chambers

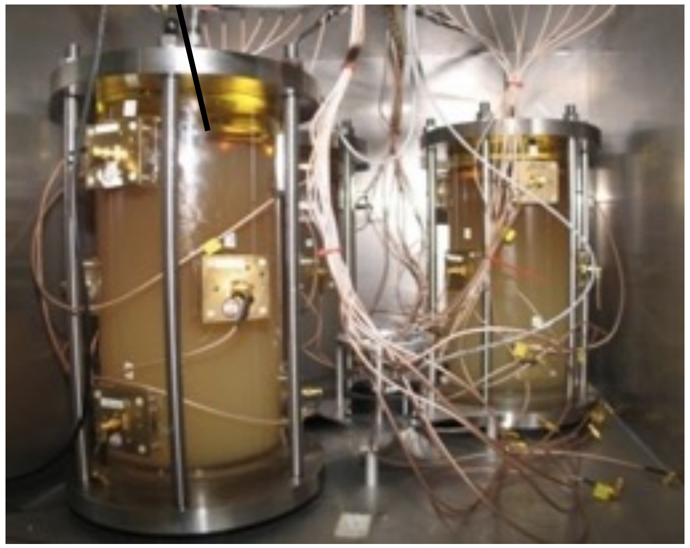
- Detect single bubbles induced by high dE/dx nuclear recoils in heavy liquid bubble chambers (with acoustic, visual or motion detectors)
- Large rejection factor for MIPs (10^{10}), scalable to large masses, high spatial granularity
- Existing detectors: SIMPLE, COUPP, PICASSO, PICO 2L
- Future: PICO (PICASSO + COUPP) -> 250 l detector detector at SNOLAB, C3F8 with 3 keV threshold
- MOSCAB: CSN2 R&D



n-induced event (multiple scatter)

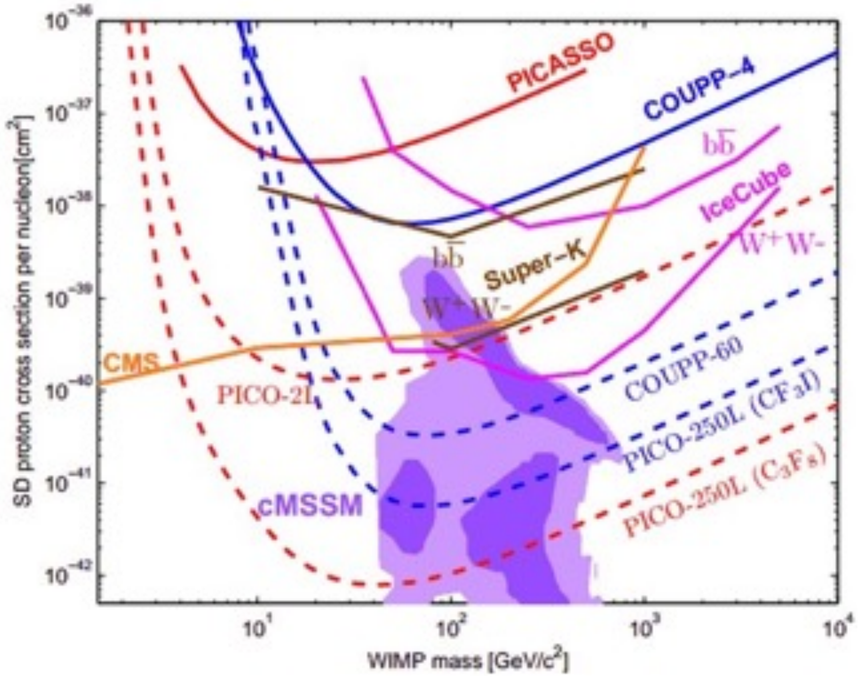
WIMP: single scatter

COUPP 60 kg CF_3I detector installed at SNOLAB; physics run until May 2014



PICASSO at SNOLAB

PICO 2L



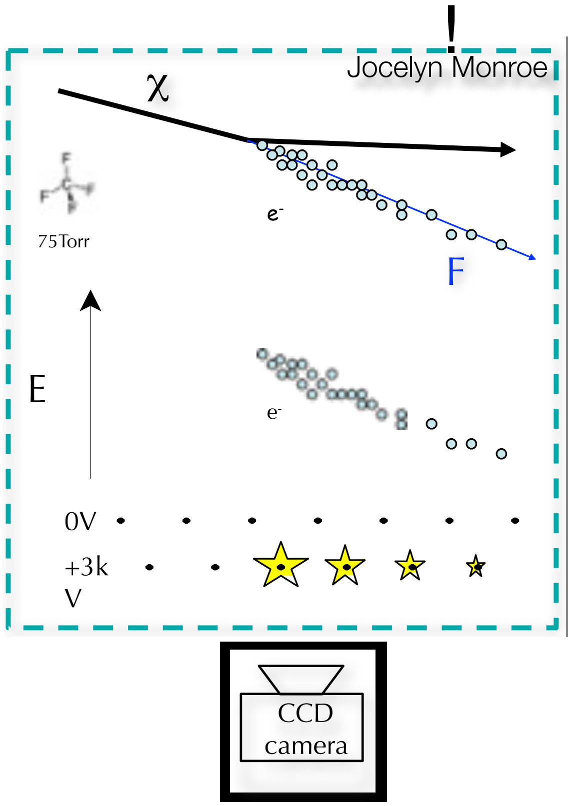
Spin-dependent limits

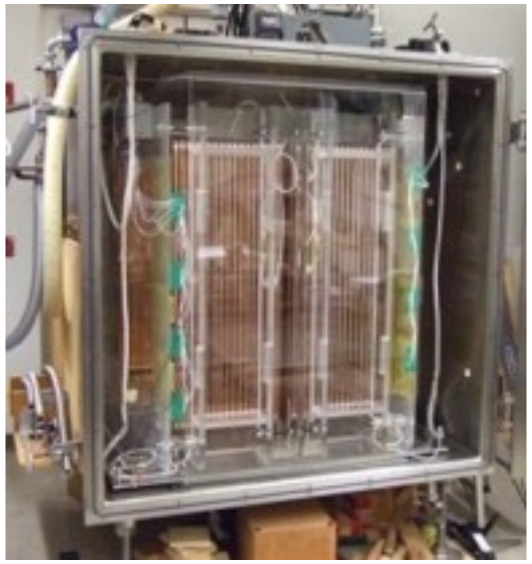
Recoil range << 1 μm in a liquid - very high dE/dx

Directional detectors

R&D on low-pressure gas detectors to measure the recoil direction, correlated to the galactic motion towards Cygnus

Challenge: good angular resolution + head-tail at E_{thr} (~30-50 keV)



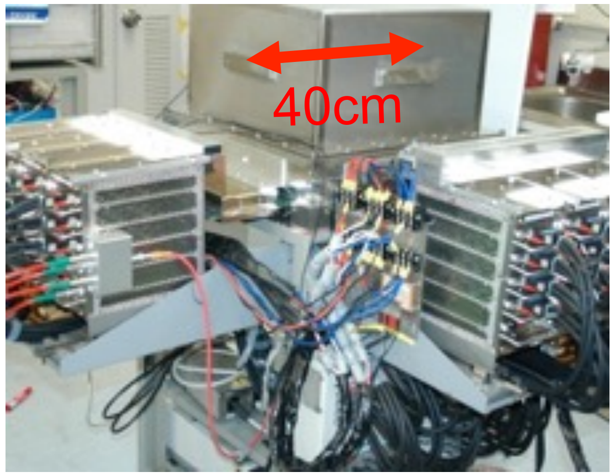


DRIFT, Boulby Mine
1 m3, negative ion drift
CS_2, CF4, O2 gas
DRIFTIII plans:
24 m^3 (3 x 8 m3 cells)
at Boulby
4 kg target mass

DMTPCino TPC at MIT
CCD readout
1 m3 prototype, CF4 gas
commissioning fall 2014

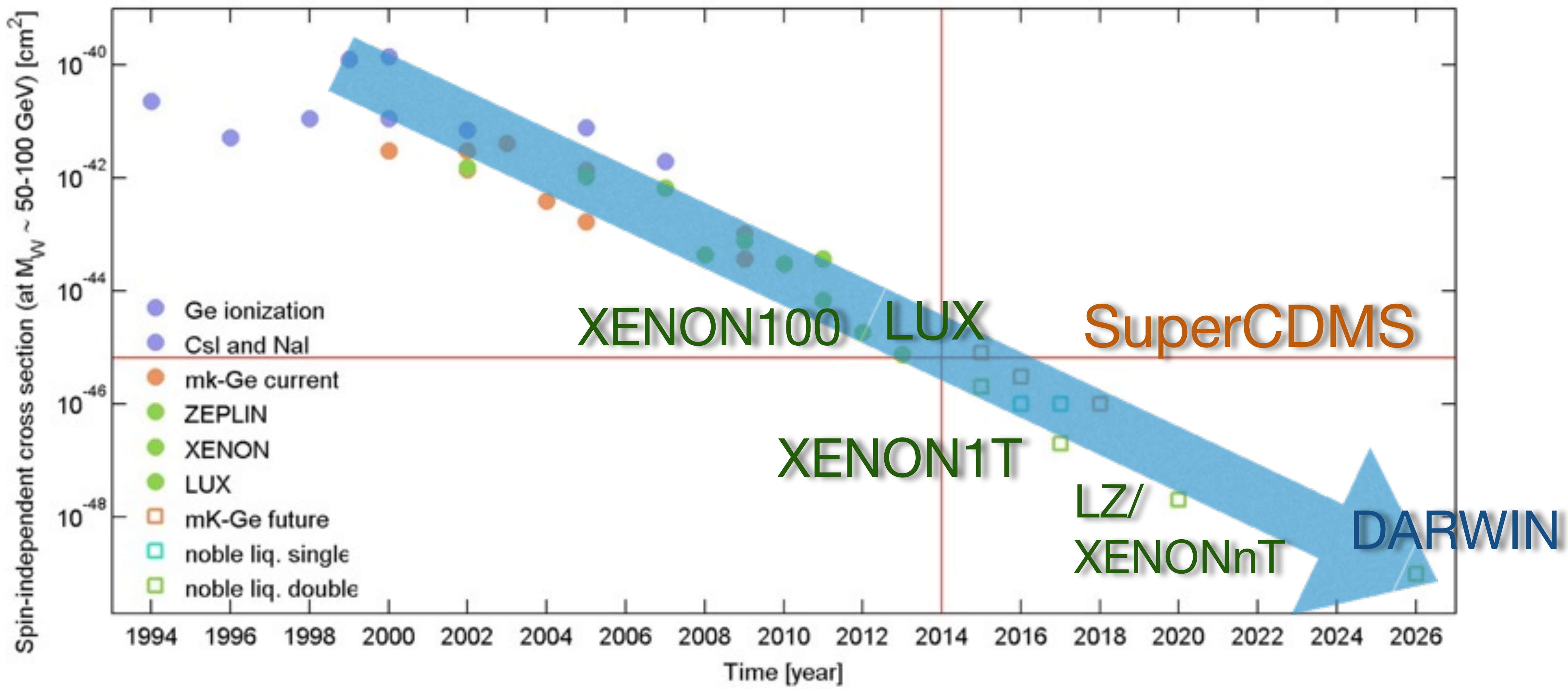
MIMAC 100x100 mm^2
5l chamber at Modane
CF_4, CHF_3, H gas

NEWS: Nuclear Emulsion WIMP Search: CSN2 R&D for directional detection with nuclear emulsions



NEWAGE, Kamioka
CF_4 gas at 0.1 atm
50 keV threshold

WIMP perspectives



About a factor of *10 increase in sensitivity every 2 years*
Who knows! Perhaps (hopefully?!) by 2026…

KATRIN

A very difficult experiment
- Huge dimensions
- A lot of technical challenges

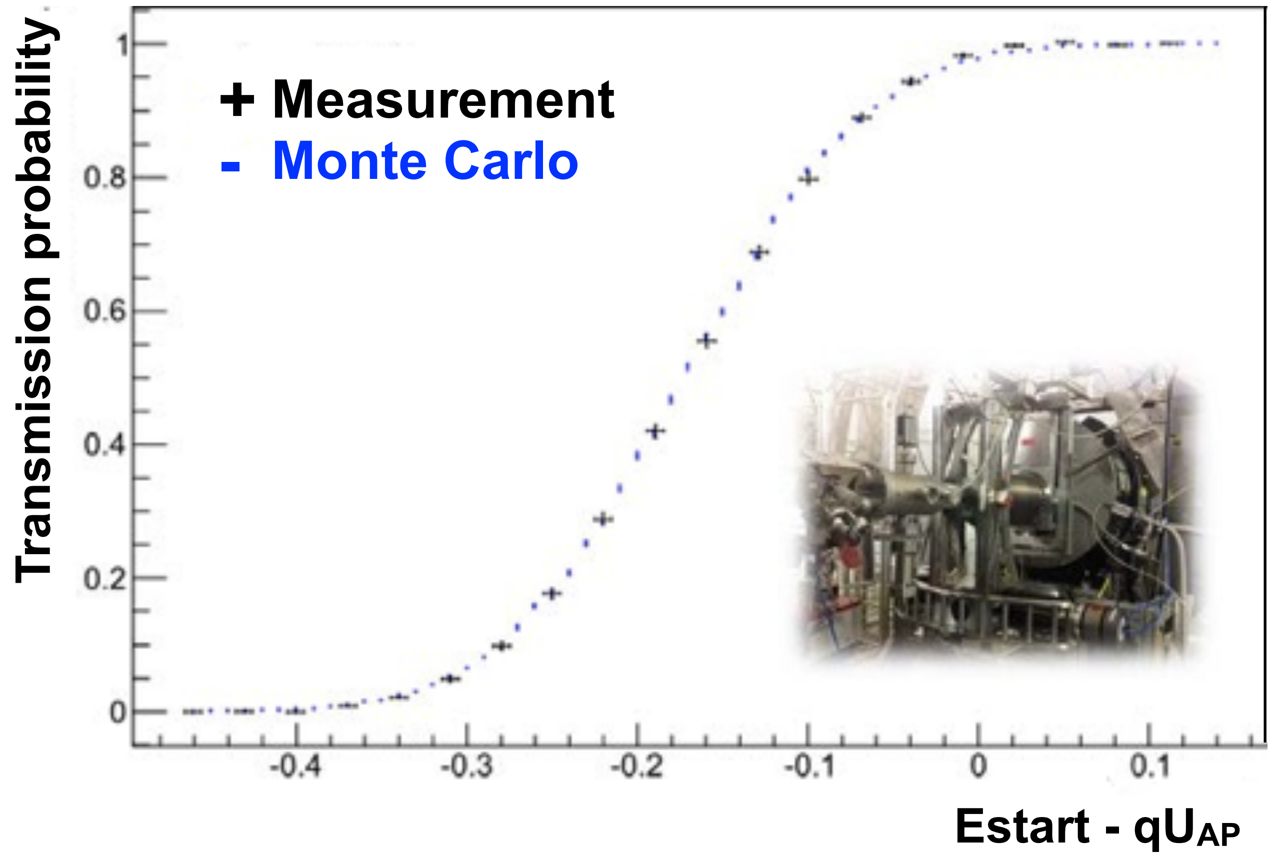
A long journey preluding to a long preparation phase

Nov. 25, 2006

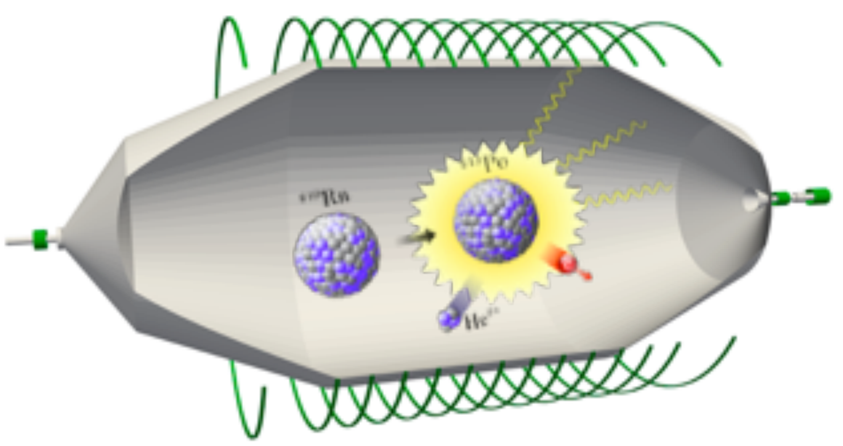
KATRIN progress

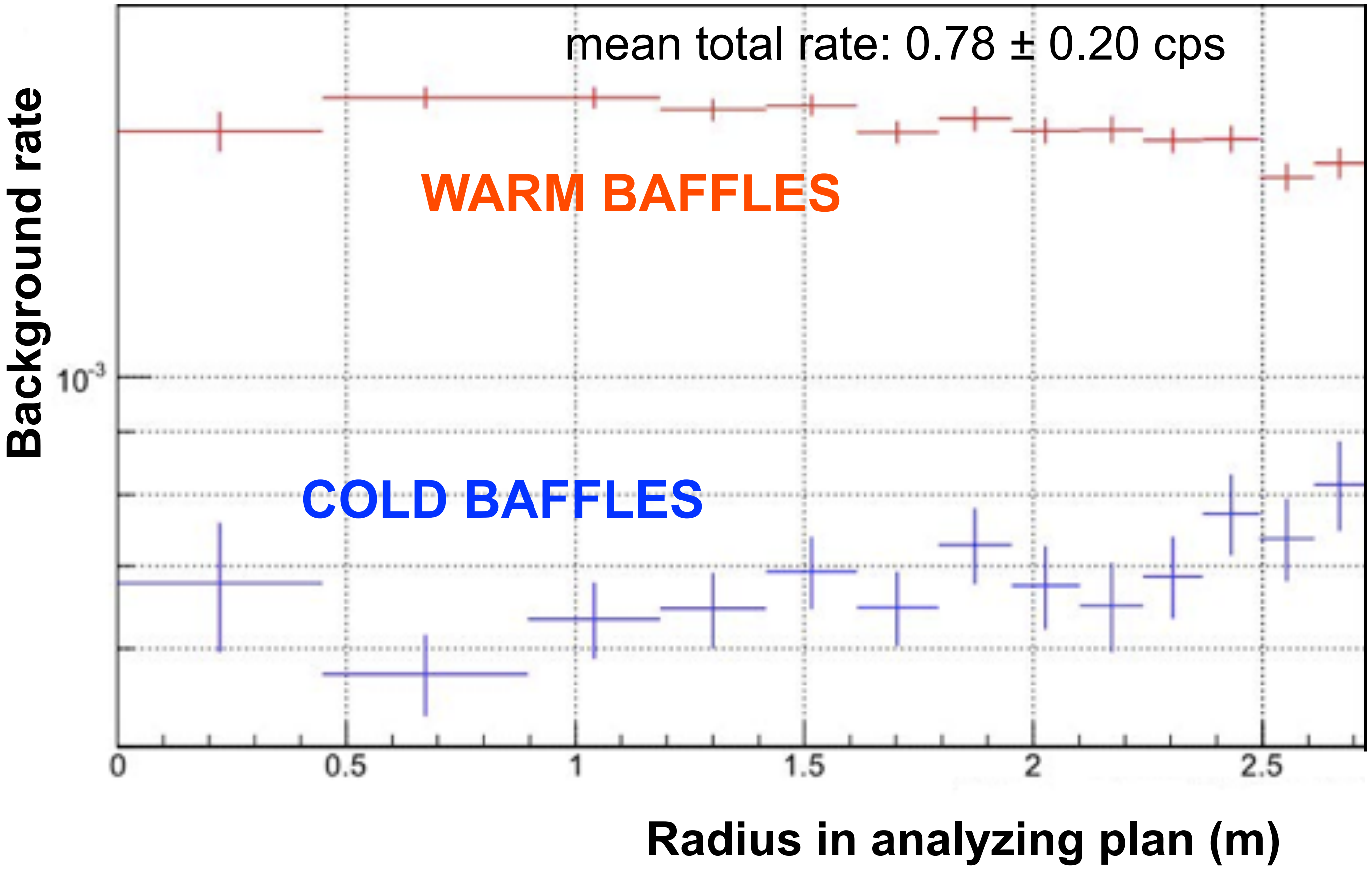
Commissioning of the main spectrometer completed in 2014

Spectrometer transmits electrons as expected !



Background rate of order Hz (10 mHz desired). Greater reduction of backgrounds to come





- Elimination of Rn with liquid-nitrogencooled baffles
- Electrostatic shielding of electrons ejected from the spectrometer hull by muons

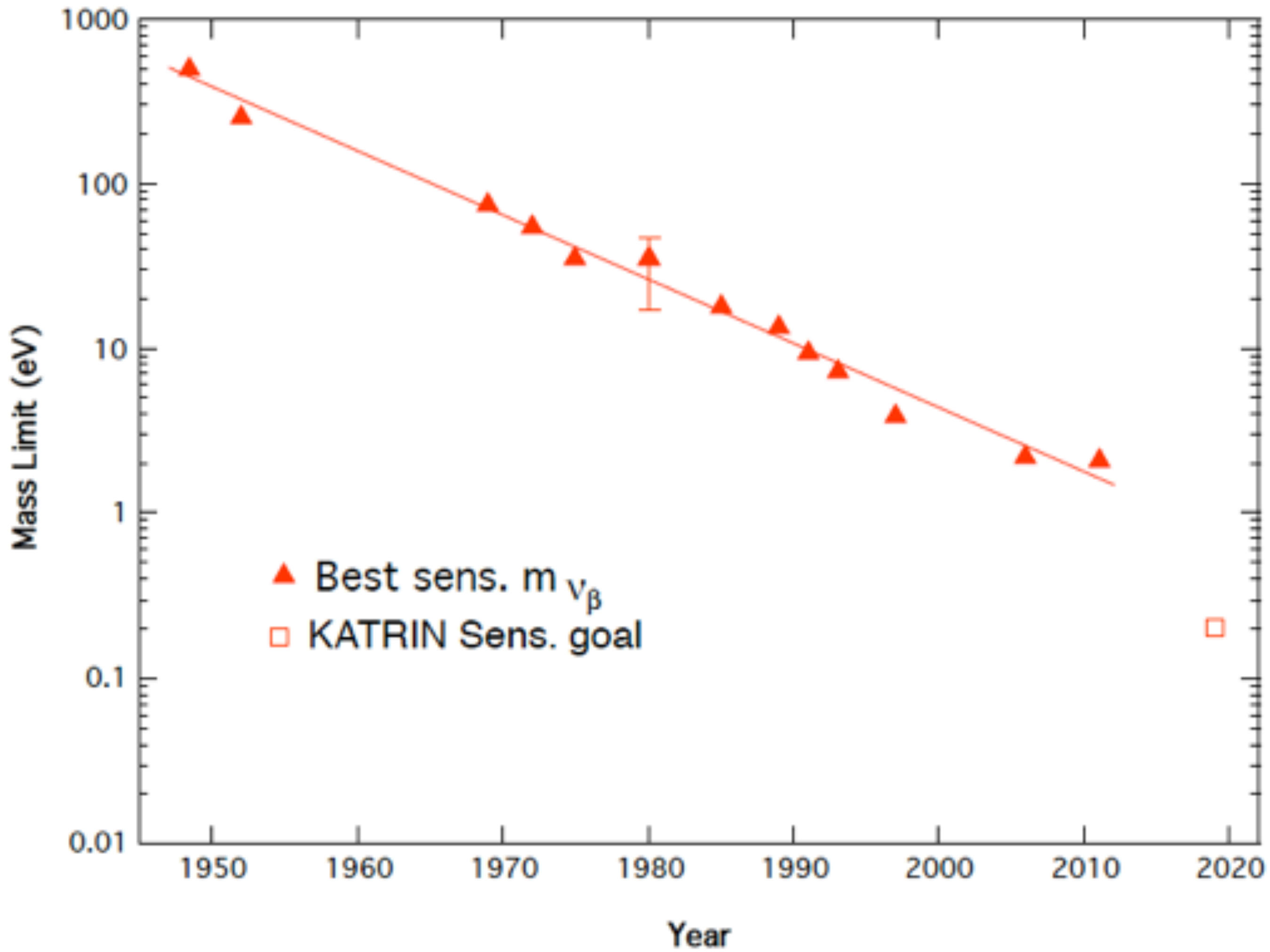
KATRIN sensitivity

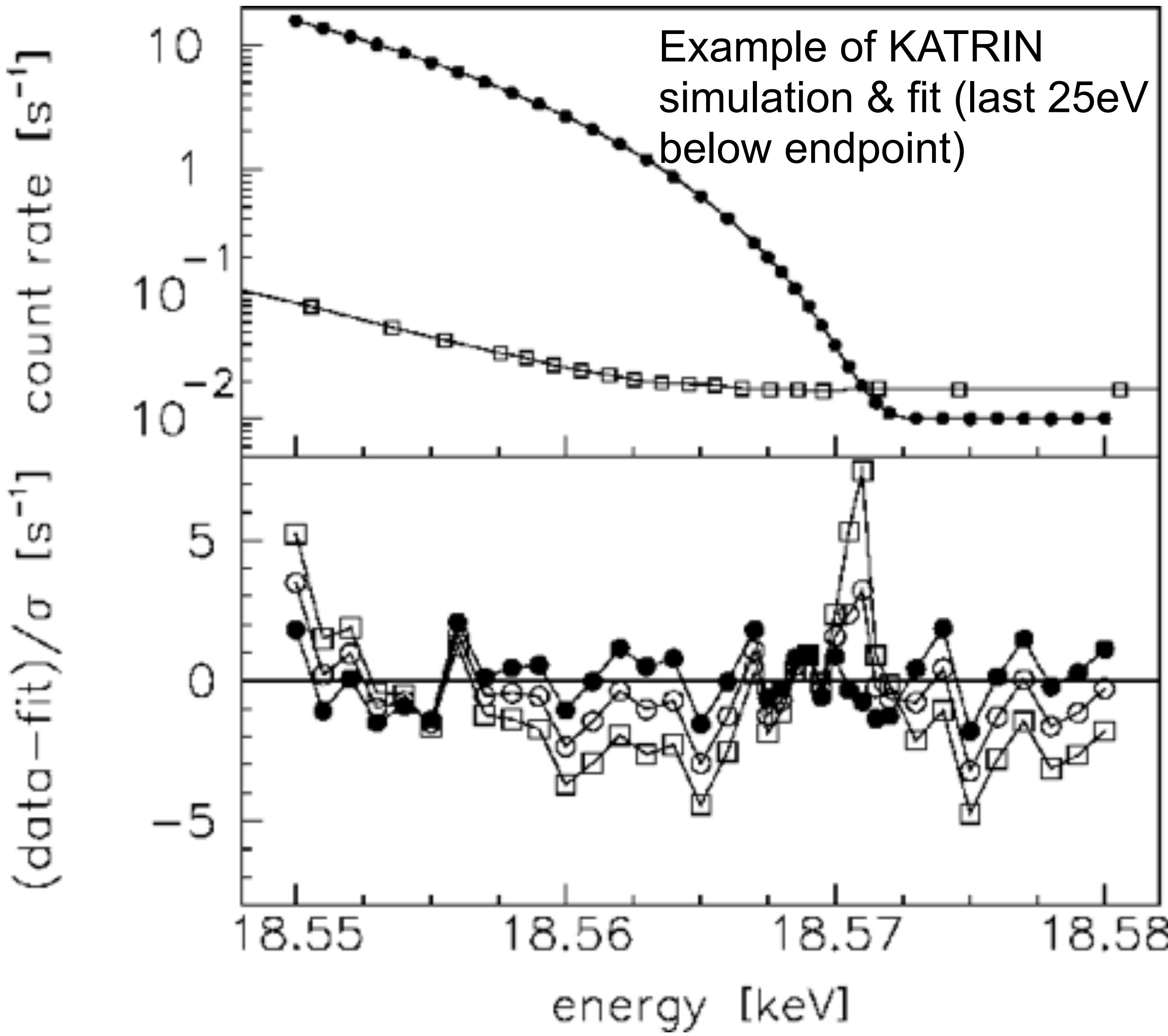
- Run time: 5 years (3 years of beam time)
- m_ν sensitivity improved by one order of magnitude.

  m_ν < 0.2eV (90%CL)
- Discovery potential:

  m_ν = 0.3eV (3σ)

  m_ν = 0.35eV (5σ)





- Sensitivity is still limited by statistics

  $\sigma_{stat} = 0.018\ eV^2$

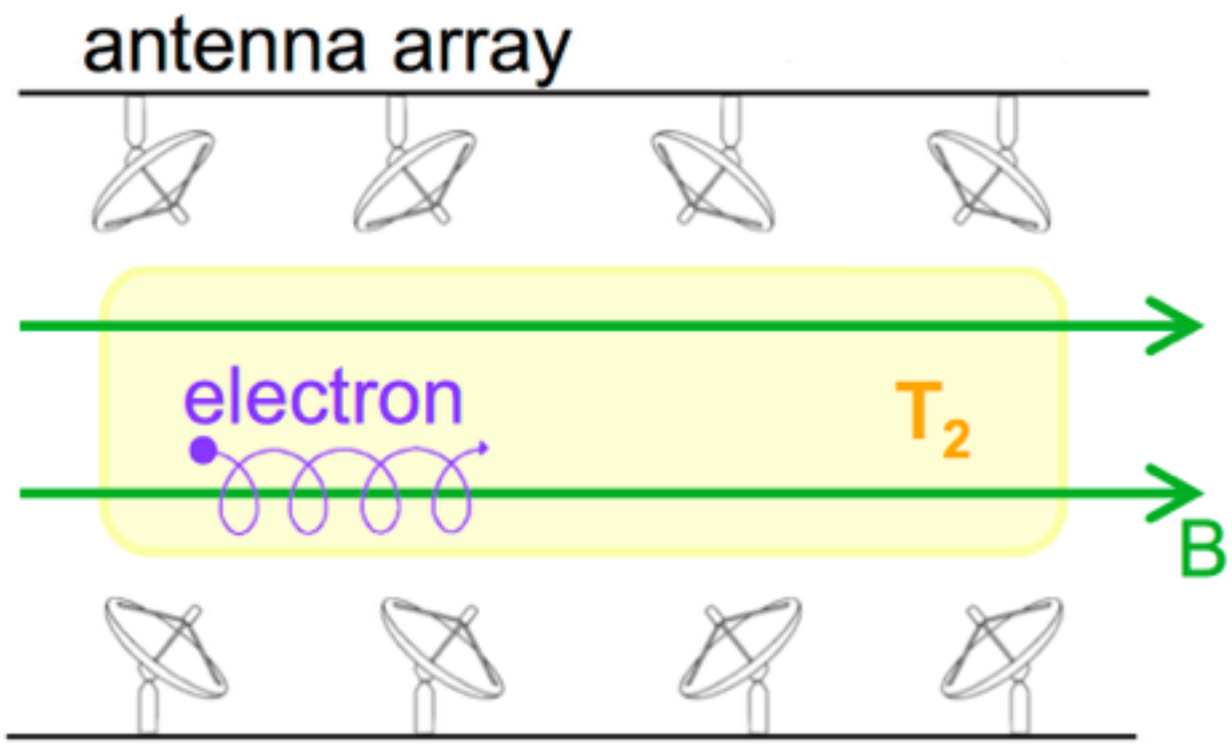
  $\sigma_{syst} = 0.017\ eV^2$

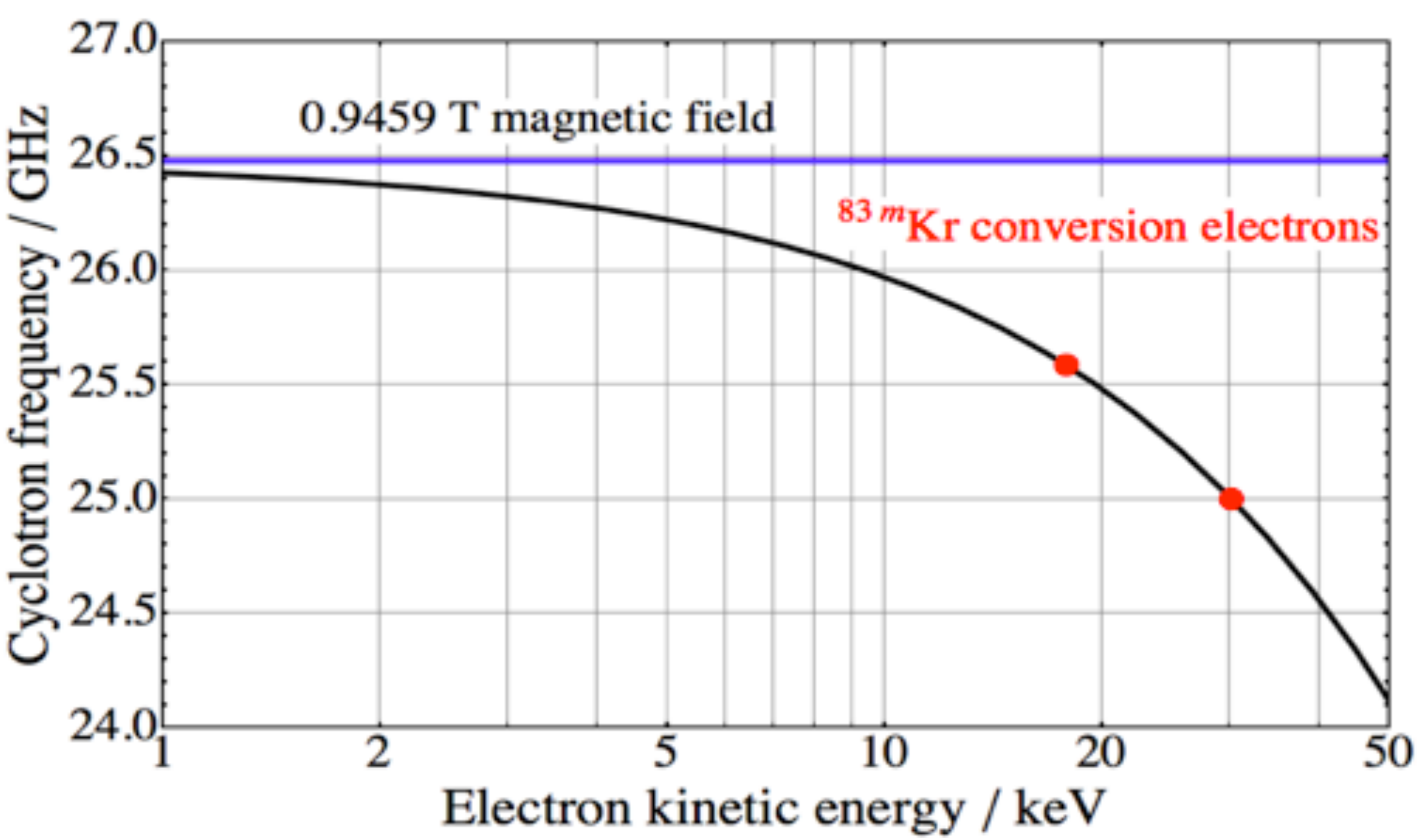
Project8

Cyclotron Radiation Emission Spectroscopy

- Fill a volume with tritium gas
- Add magnetic field
- Decay electrons spiral around field lines
- Detect the cyclotron radiation

- Non-destructive measurement of electron energy
- Novel technology with promising future perspectives





The frequency of the emitted radiation depends on the relativistic boost

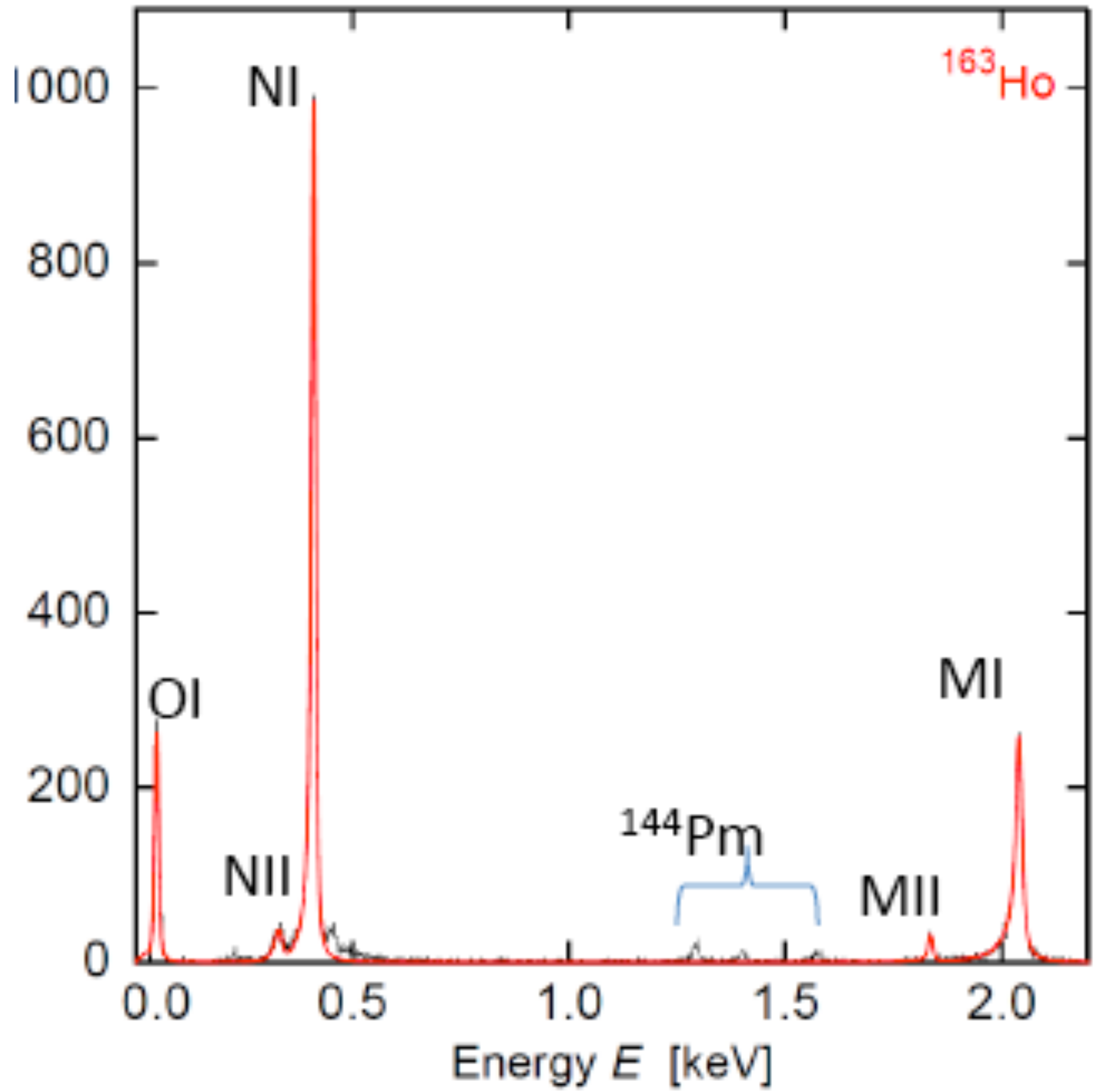
$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

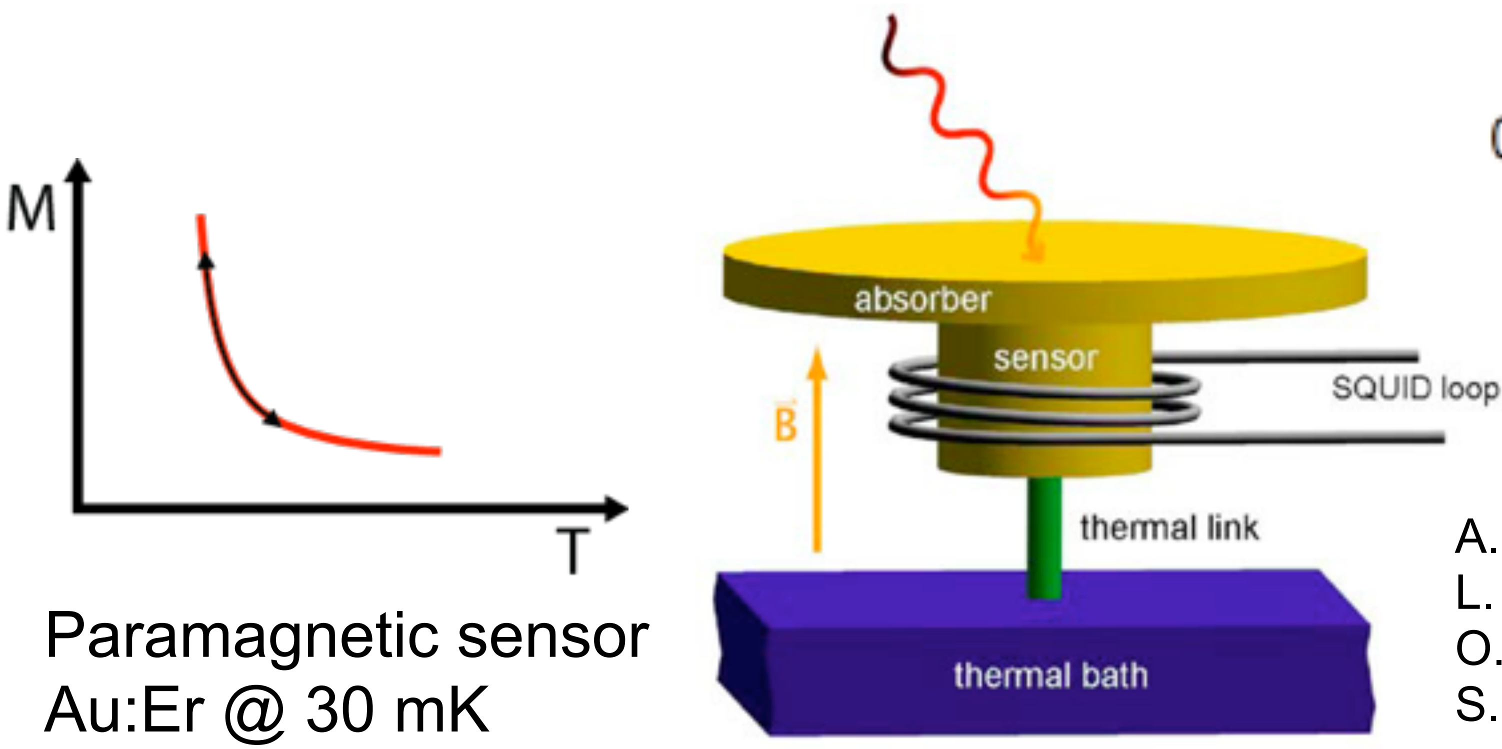
Test measuremet with ^{83m}Kr IC line

ECHo

Heidelberg (Univ., MPI-K), U Mainz, U Tubingen, TU Dresden, U Bratislava, INR Debrecen, ITEP Moscow, PNPI St Petersburg, IIT Roorkee, Saha Inst. Kolkata

- Metallic magnetic calorimeters (MMC)
- Fast rise times (τ = 130 ns), good energy resolutions (7.6 eV @ 6keV), and linearity demonstrated
- Microwave Multiplexing techniques (RF-SQUID)





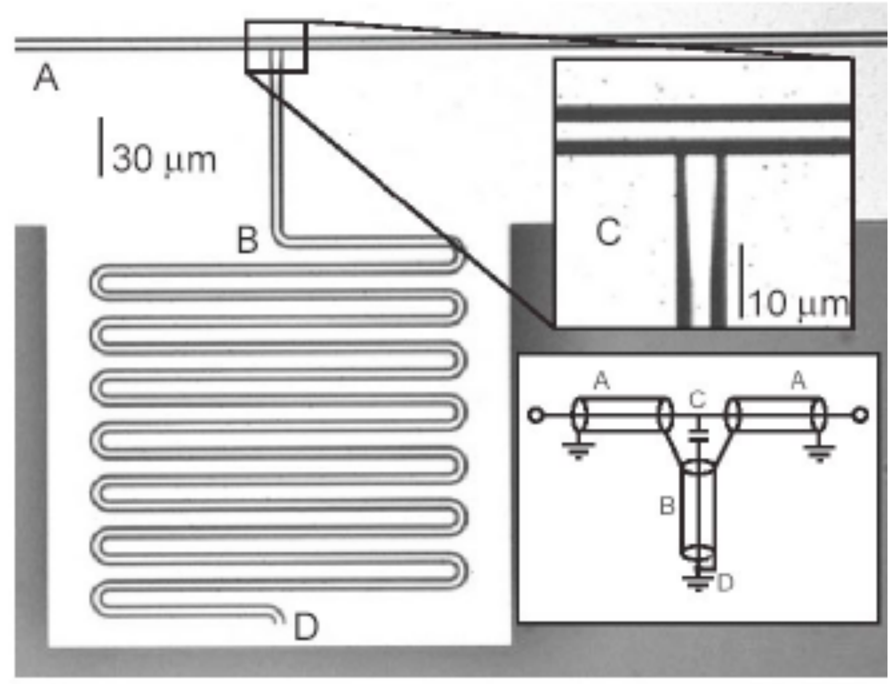
Paramagnetic sensor
Au:Er @ 30 mK

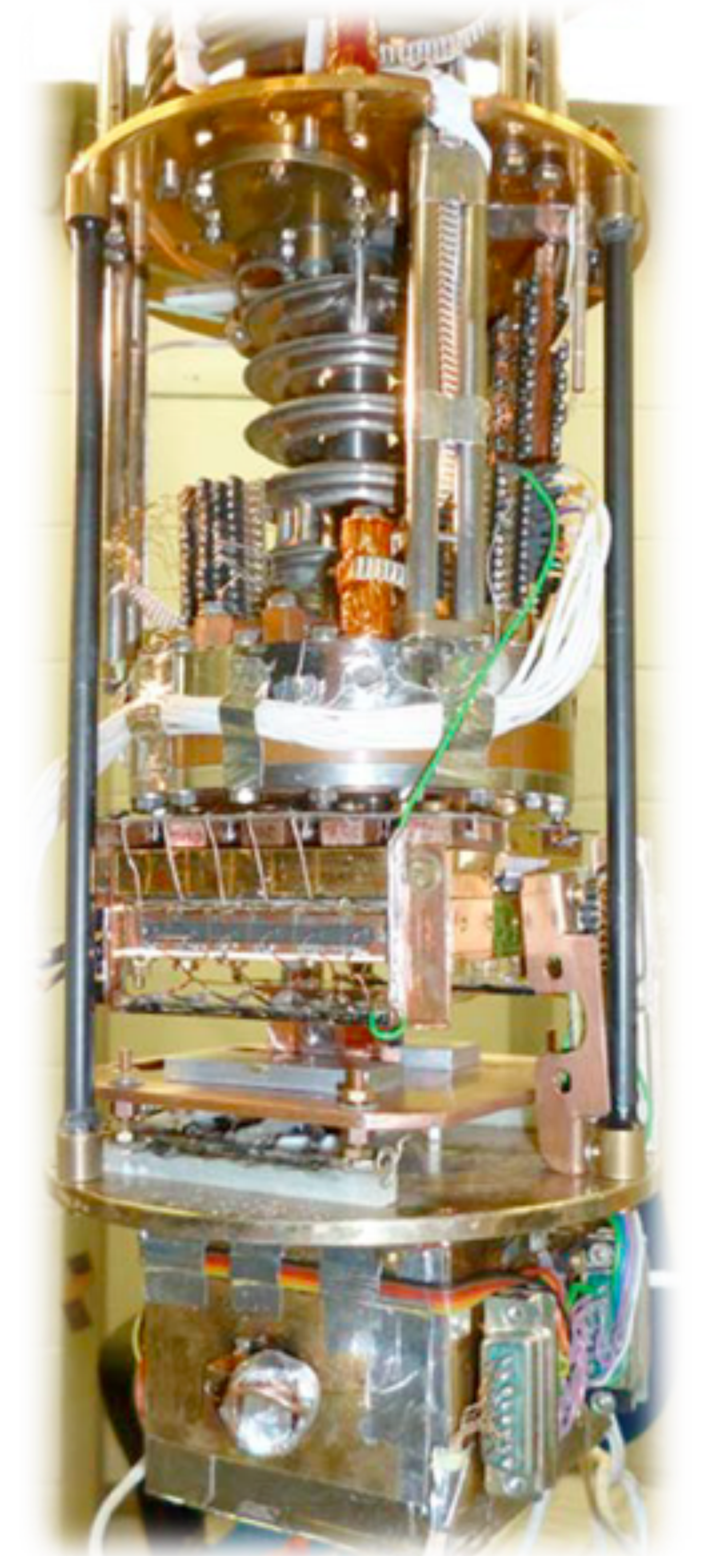
A. Fleischmann et al., AIP Conf. Proc. 1185, 571, (2009)
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)
O. Ranitzsch et al., JLTP 167, 1004 (2012)
S. Kempf et al, JLTP 10.1007/s10909-013-1041-0

HOLMES

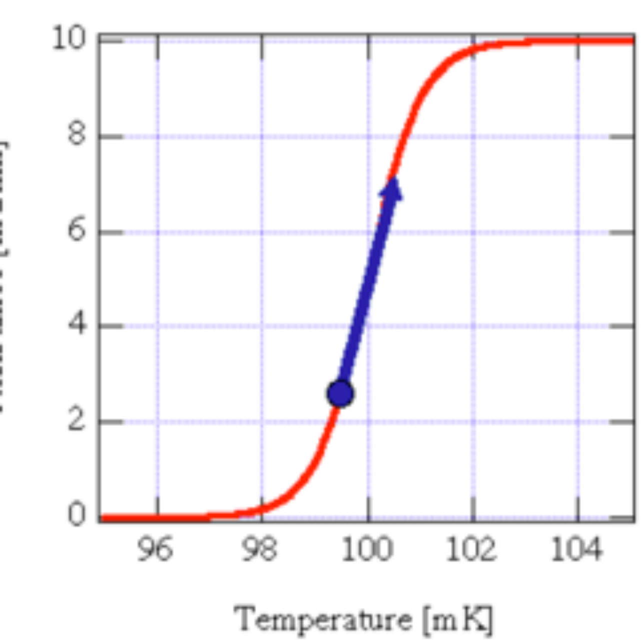
U Milano-Bicocca, INFN Milano/Genova/ Roma, U Lisboa, U Miami, NIST, JPL

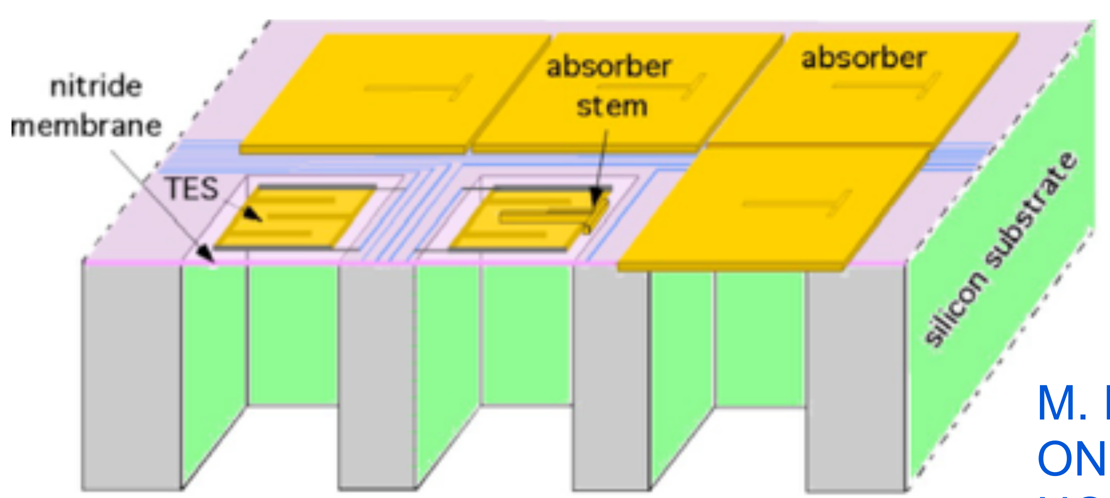
- Transition-Edge Sensors (TES)
- ^{163}Ho implanted Au absorbers
- Microwave Multiplexing with Kinetic Inductance Detectors (MKIDs).
- Successful funding received for 10^3 channels





- 6.5×10^{13} nuclei per detector (300 Bq)
- $\Delta E \approx 1$eV and $\tau_R \approx 1\mu s$
- 1000 channel array
- 6.5×10^{16} ^{163}Ho nuclei (≈18µg)
- 3×10^{13} events in 3 years



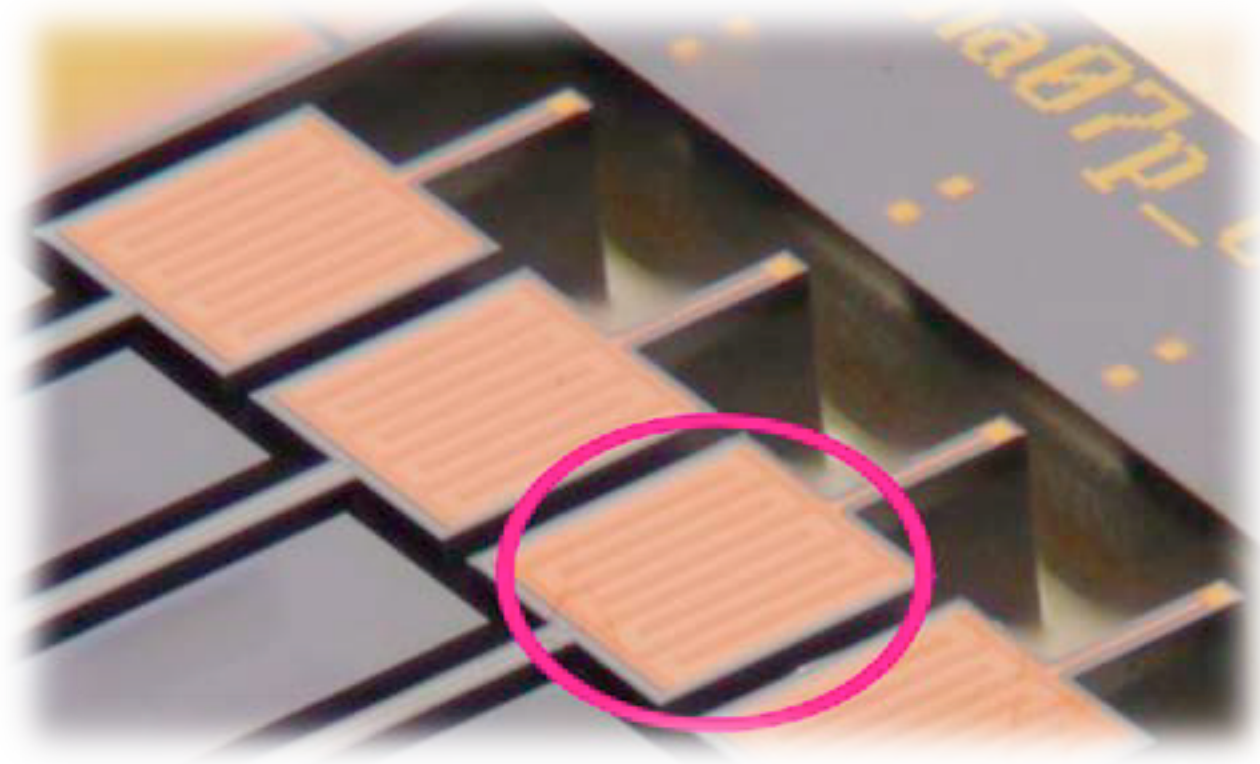


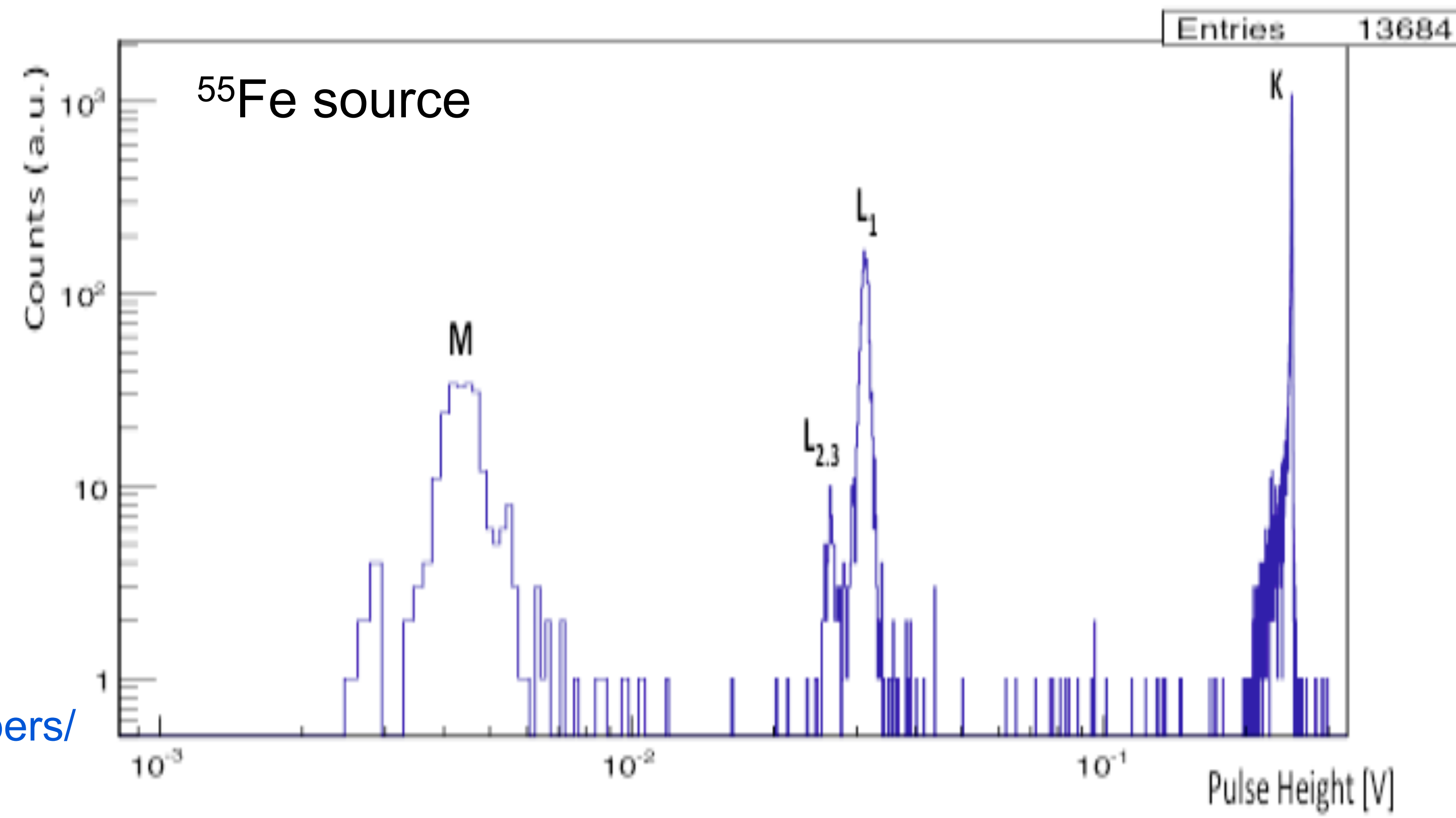
M. Ribeiro Gomes et al., IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

NuMECS

Los Alamos, NIST, U Madison and others

- Transition-Edge Sensors (TES)
- Good energy resolution (6 eV @ 6 keV with ^{55}Fe surrogate).
- Concentration on high purity ^{163}Ho production – proton activation of dysprosium
- Show scalability through a demonstrator experiment with $4 \cdot 10^{24}$ TES array of Ho-implanted detectors with RF-SQUID multiplexing





J.W. Engle et al. NIM B 311 (2013) 131–138
http://fsnutown.phy.ornl.gov/fsnufiles/positionpapers/FSNu_Project8.pdf