Universität Zürich[UZH]

Prospects for direct dark matter detection and neutrinoless double beta decay experiment

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La Thuile
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La Thuile 2017

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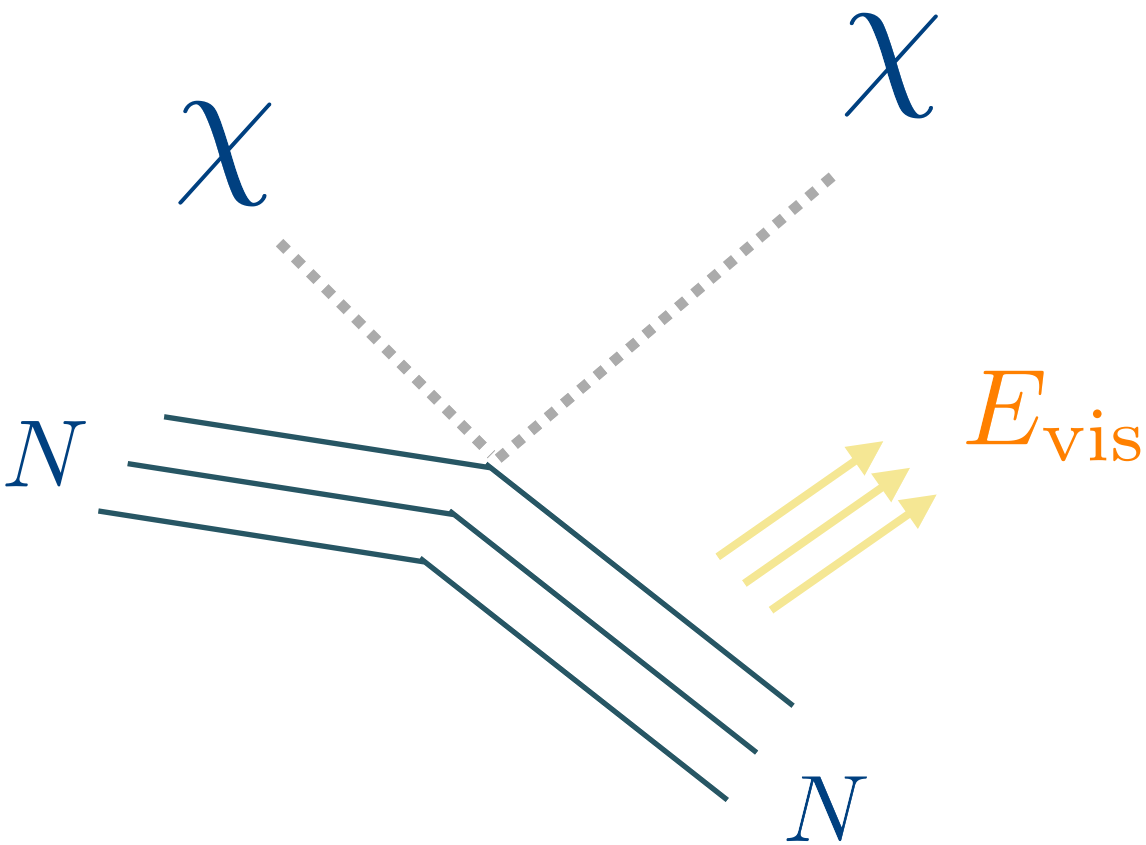
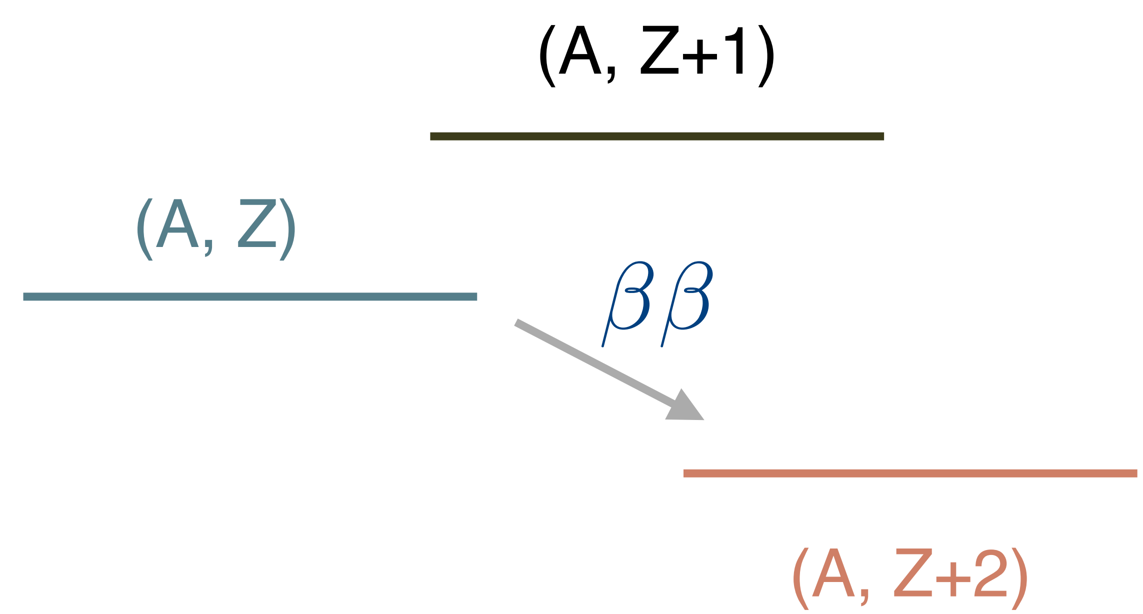
Europe/Rome timezone

Physics aim of dark matter and double beta experiments

- Observe the collision of invisible particles with atomic nuclei

- Observe an extremely rare nuclear decay process





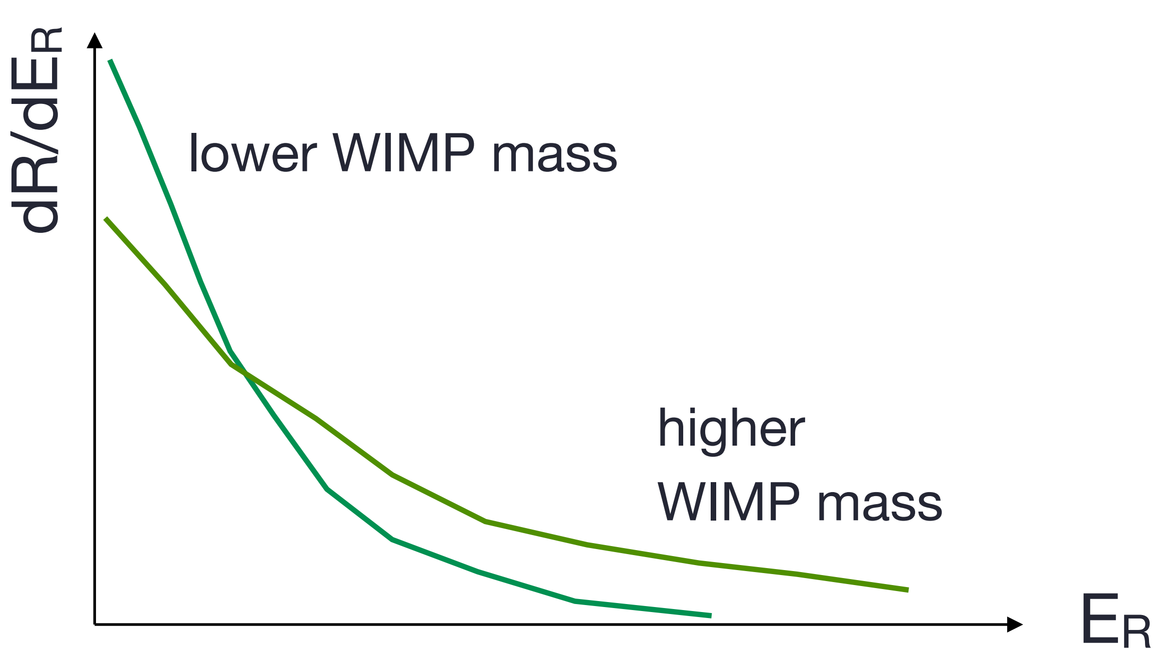
$$E_R = \frac{q^2}{2m_N} < 30\,\text{keV}$$

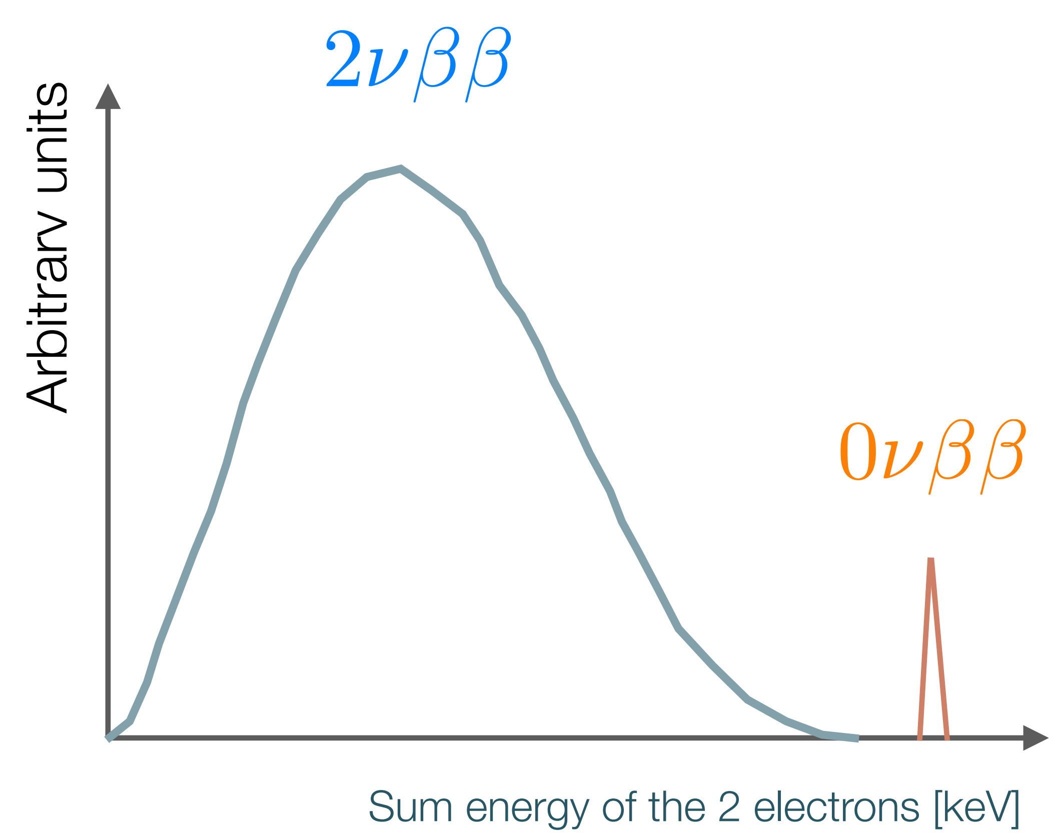
$$T_{1/2}^{0\nu\beta\beta} > 10^{24}\,\text{y}$$

Main characteristics

- Nuclear recoils: ~ keV-scale E_R
- Featureless recoil spectrum
- Very low event rates: < 0.1/(kg y)

- Q-value: ~ MeV-scale
- Peak at the Q-value of the decay
- Very low event rates: <0.1/(kg y)





Main requirements

- Low energy threshold
- Ultra-low backgrounds & nuclear vs. electronic recoil discrimination
- Large detector masses

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{min}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$

- Excellent energy resolution
- Ultra-low backgrounds & gamma/beta discrimination
- Large detector masses and high isotopic enrichment

$$T_{1/2}^{0\nu} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

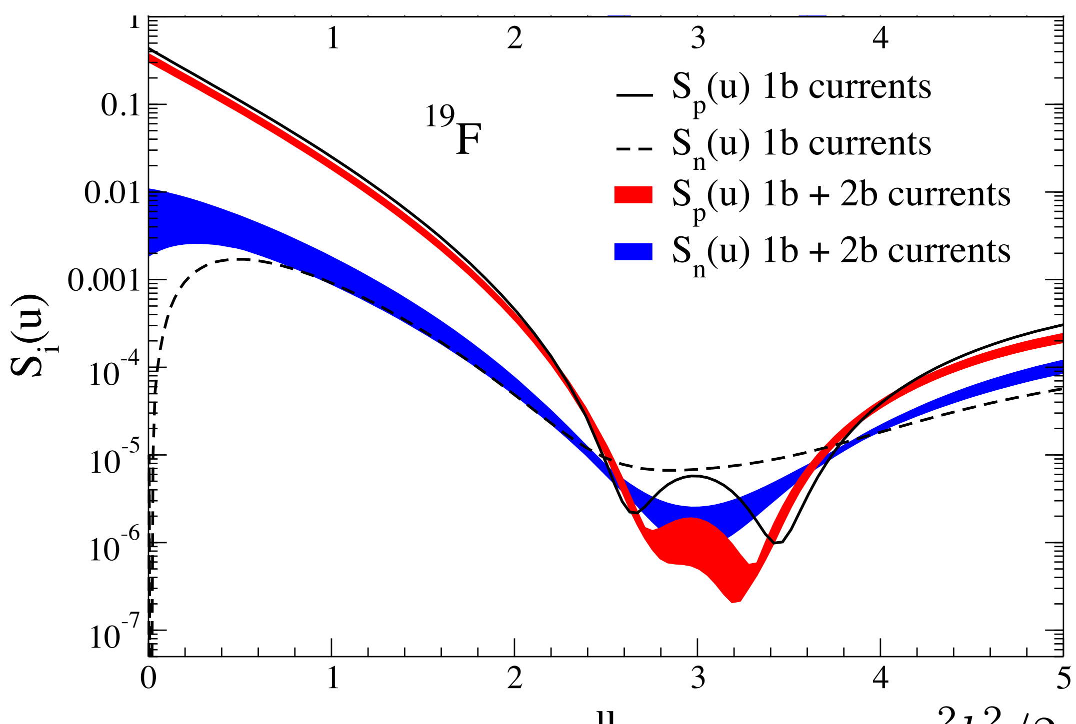
Employed nuclei

Nucleus	Spin	Abund [%]
^{19}F	$1/2^+$	100
^{23}Na	$3/2^+$	100
^{27}Al	$5/2^+$	100
^{29}Si	$1/2^+$	4.7
^{73}Ge	$9/2^+$	7.76
^{127}I	$5/2^+$	100
^{129}Xe	$1/2^+$	26.4
^{131}Xe	$3/2^+$	21.2
^{40}Ar	—	99.6
^{70}Ge, ^{72}Ge, ^{74}Ge, ^{76}Ge	—	
^{124}Xe, ^{126}Xe, ^{128}Xe, ^{130}Xe, ^{132}Xe, ^{134}Xe, ^{136}Xe	—	
…		

Candidate*	Q [MeV]	Abund [%]
^{48}Ca -> ^{48}Ti	4.271	0.187
^{76}Ge -> ^{76}Se	2.040	7.8
^{82}Se -> ^{82}Kr	2.995	9.2
^{96}Zr -> ^{96}Mo	3.350	2.8
^{100}Mo -> ^{100}Ru	3.034	9.6
^{110}Pd -> ^{110}Cd	2.013	11.8
^{116}Cd -> ^{116}Sn	2.802	7.5
^{124}Sn -> ^{124}Te	2.228	5.64
^{130}Te -> ^{130}Xe	2.530	34.5
^{136}Xe -> ^{136}Ba	2.479	8.9
^{150}Nd -> ^{150}Sm	3.367	5.6

Main uncertainties (I)

- Structure factors
- Astrophysics: $\rho, f(v), v_{esc}$

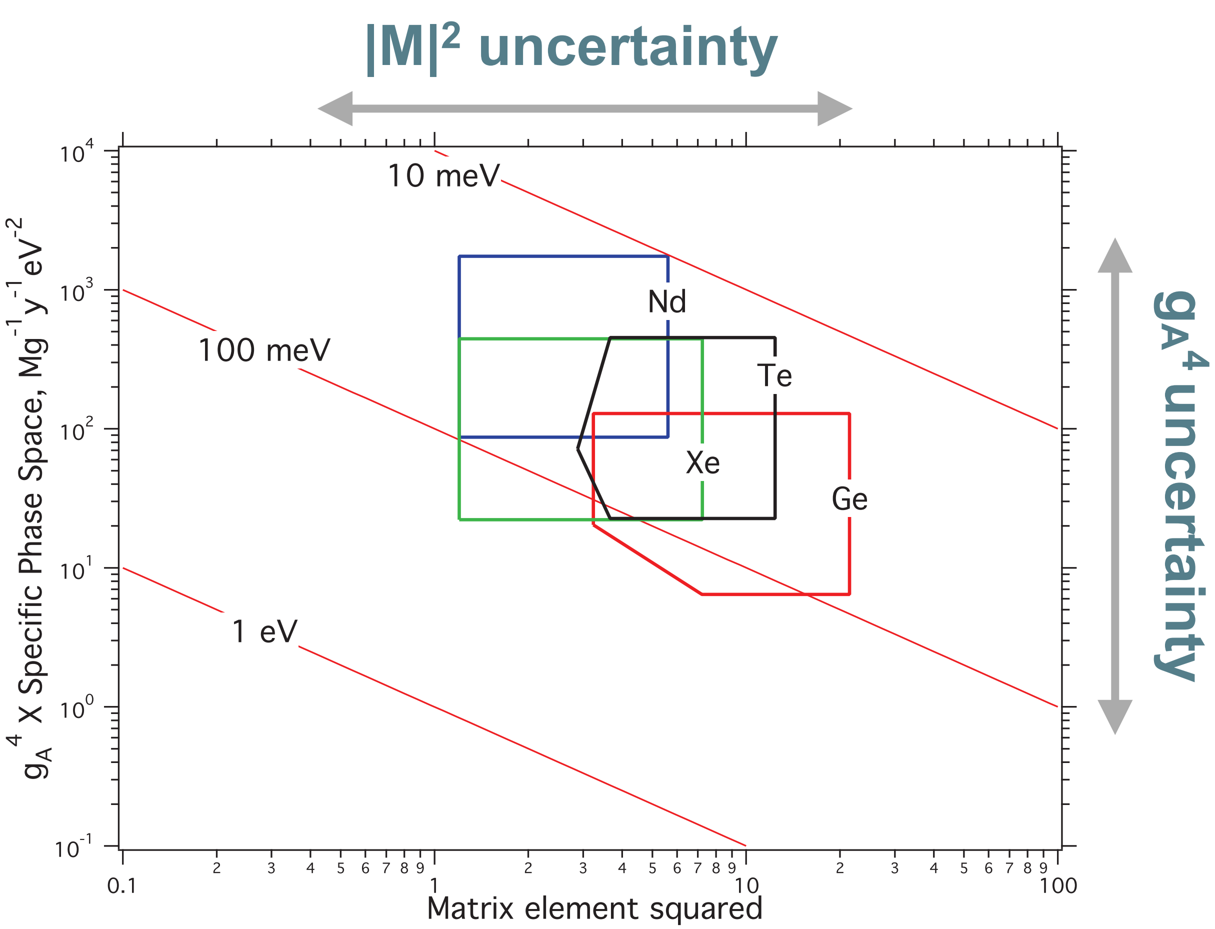


$u = q^2 b^2/2$

P. Klos et al., PRD 88 (2013)

structure factor for ^{19}F uncertainties from WIMP currents in nuclei (in chiral EFT)

- Matrix elements
- Axial-vector coupling (g_A)

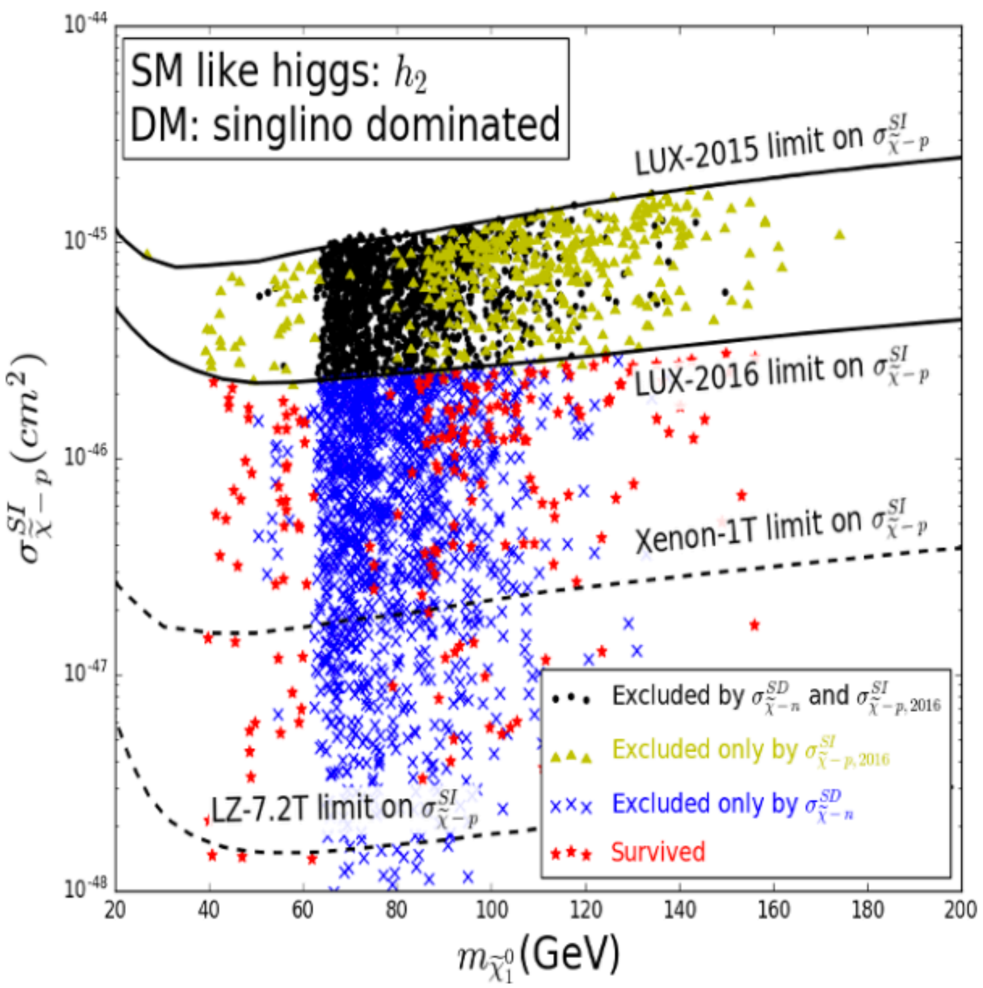


effective value for the axial vector coupling constant g_A: ~ 0.6 - 1.269 (free nucleon value)

R. G. H. Robertson, Mod. Phys. Lett. A28 (2013)

Main uncertainties (II)

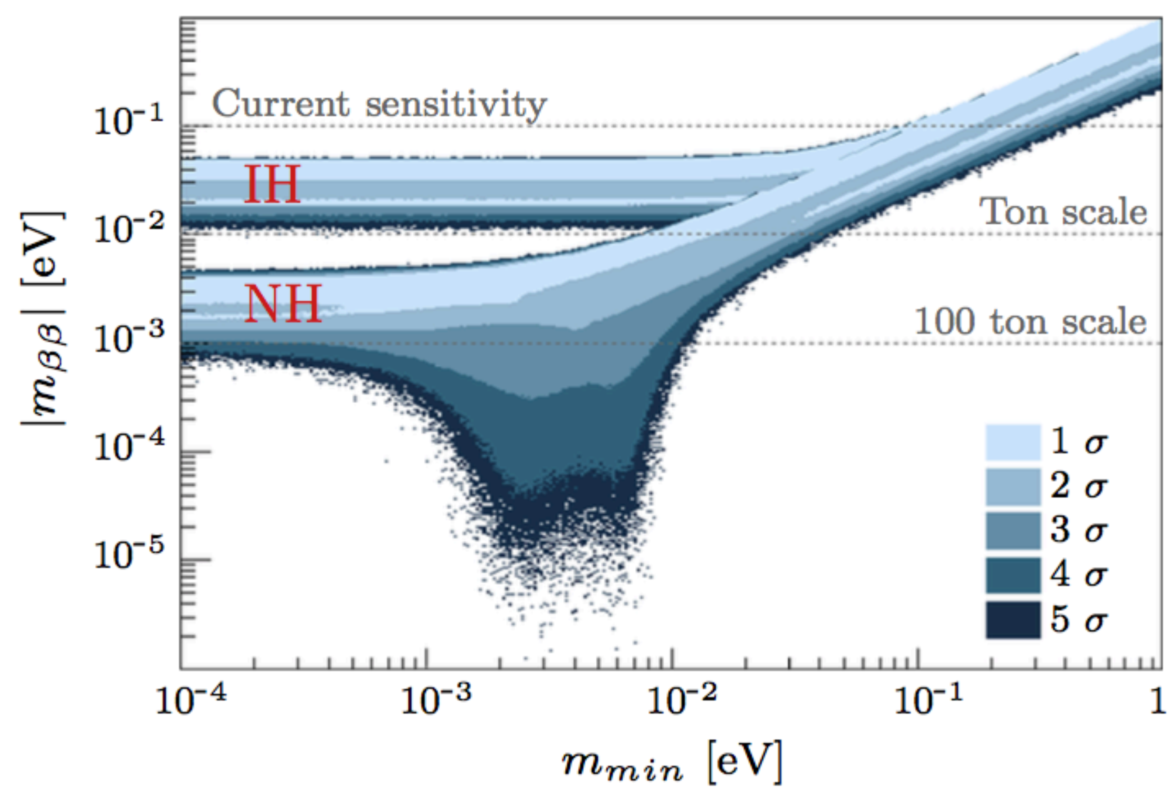
- Mass and cross section of the dark matter particles



Example: Next-to-Minimal MSSM

- Neutrino mass eigenstates and neutrino mixing matrix terms

$$|m_{\beta\beta}| = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$



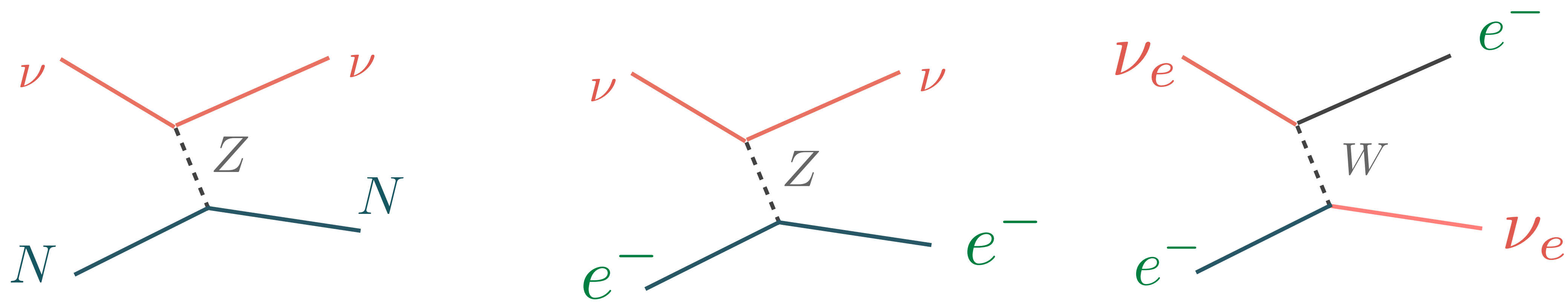
Probability distribution of $m_{\beta\beta}$ via random sampling from the distributions of mixing angles and Δm^2

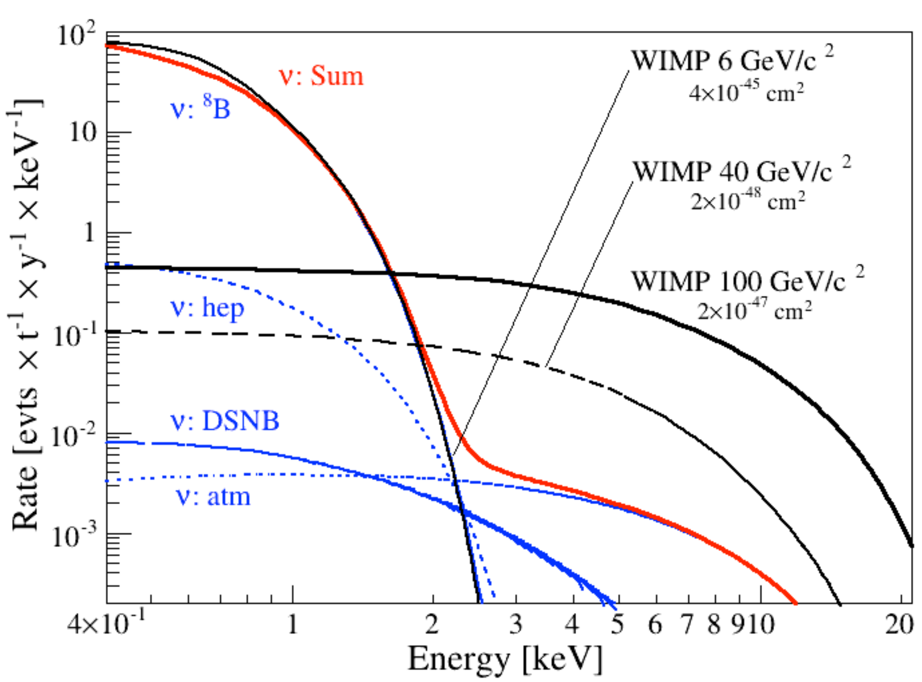
J. Cao et al., JHEP 10 (2016) 136

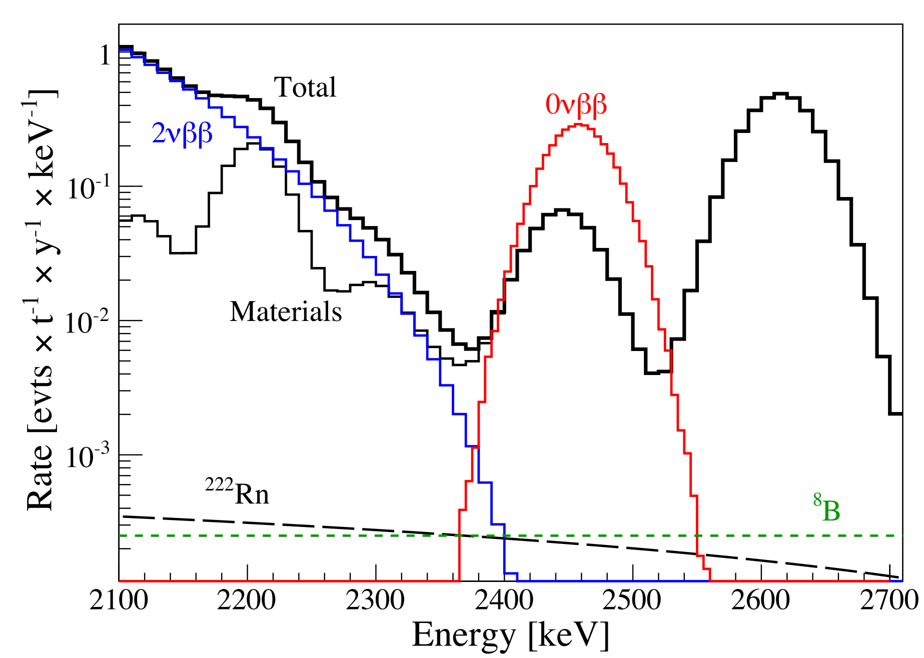
G. Benato, EPJ-C (2015) 75

Backgrounds

- Cosmic rays & cosmic activation of detector materials
- Natural (^{238}U, ^{232}Th, ^{40}K) & anthropogenic (^{85}Kr, ^{137}Cs) radioactivity: γ, e^-, n, α
- Ultimately: **neutrinos (+ $2\nu\beta\beta$-decays, depending on the energy resolution)**

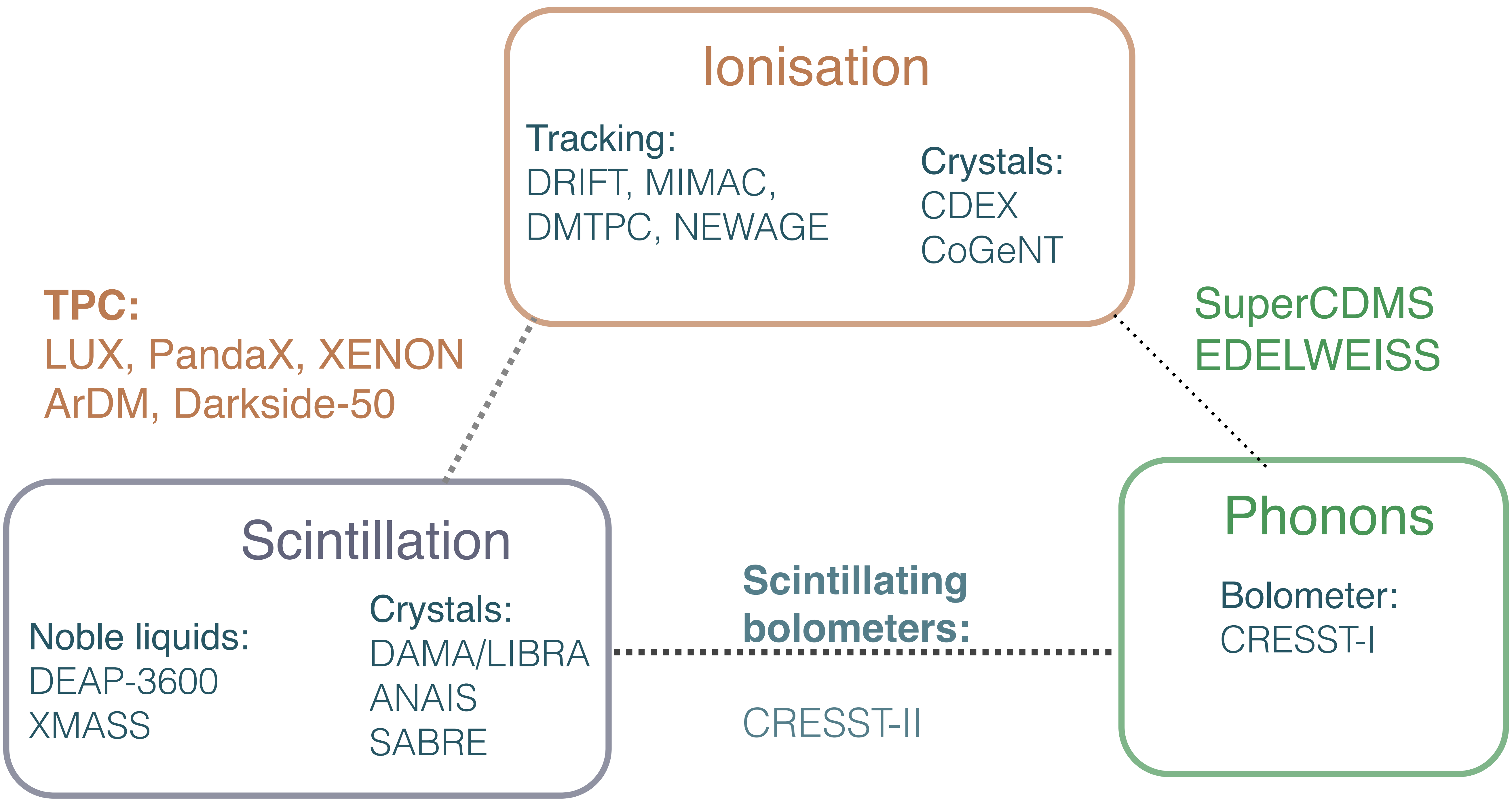




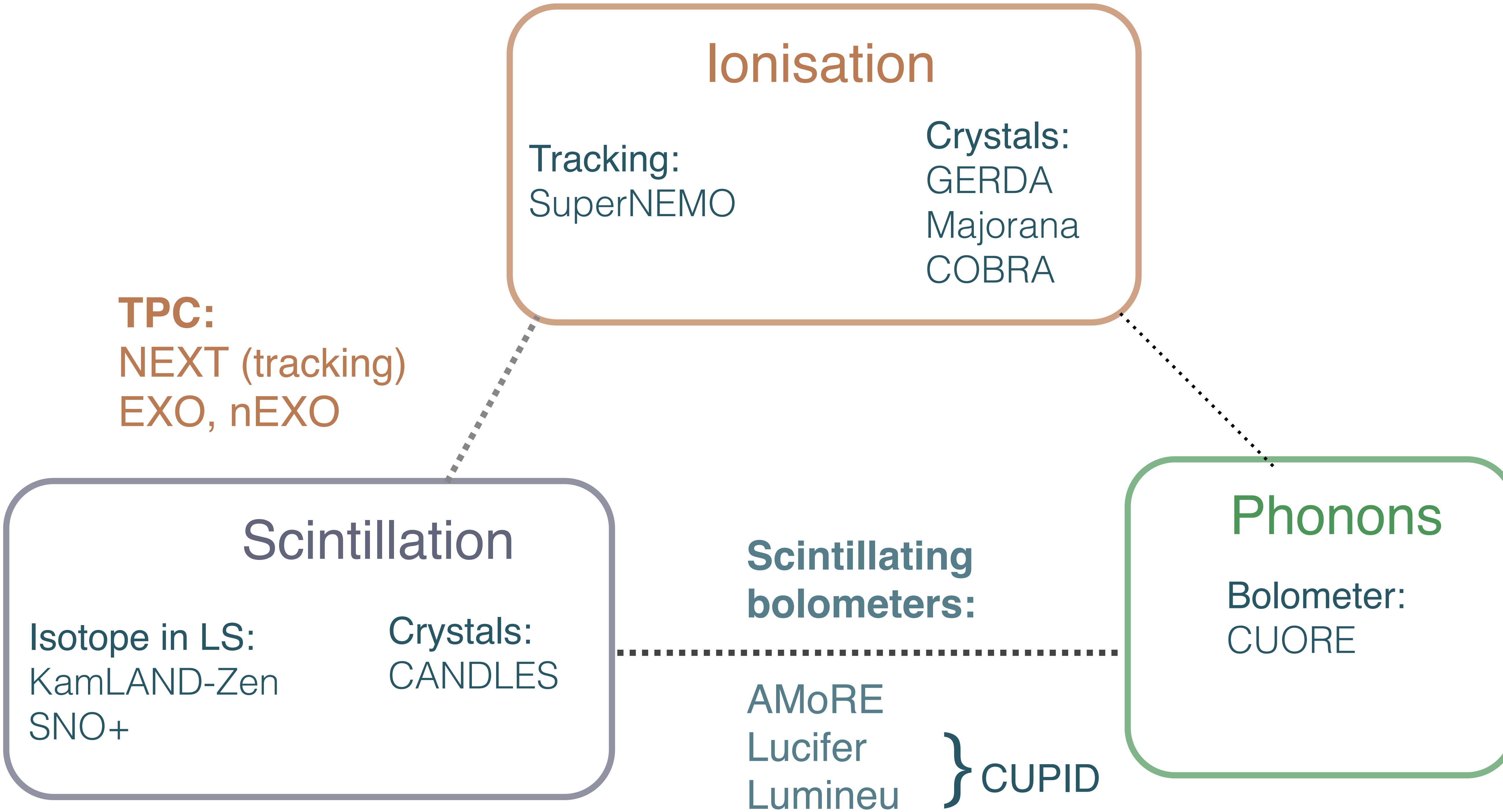


LB et al., JCAP01 (2014) 044

Experimental techniques: dark matter



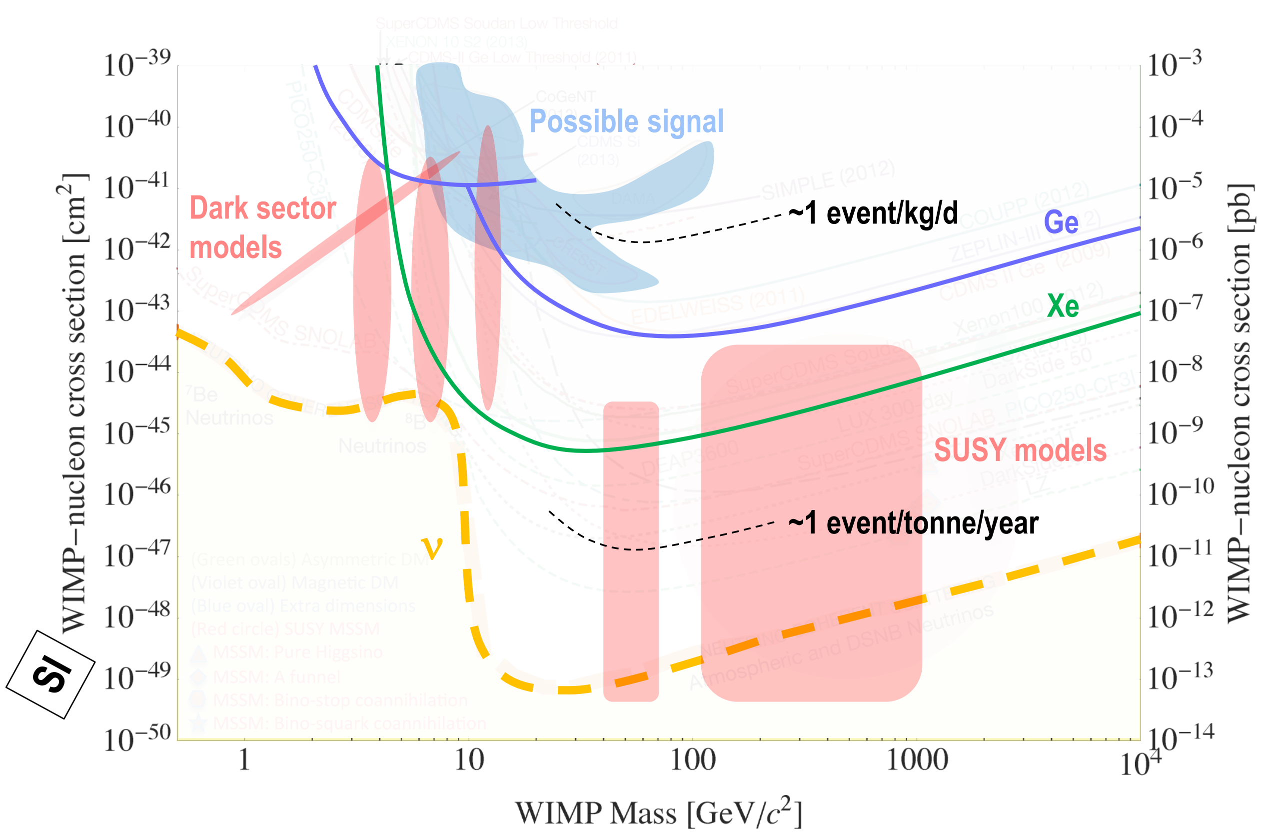
Experimental techniques: double beta

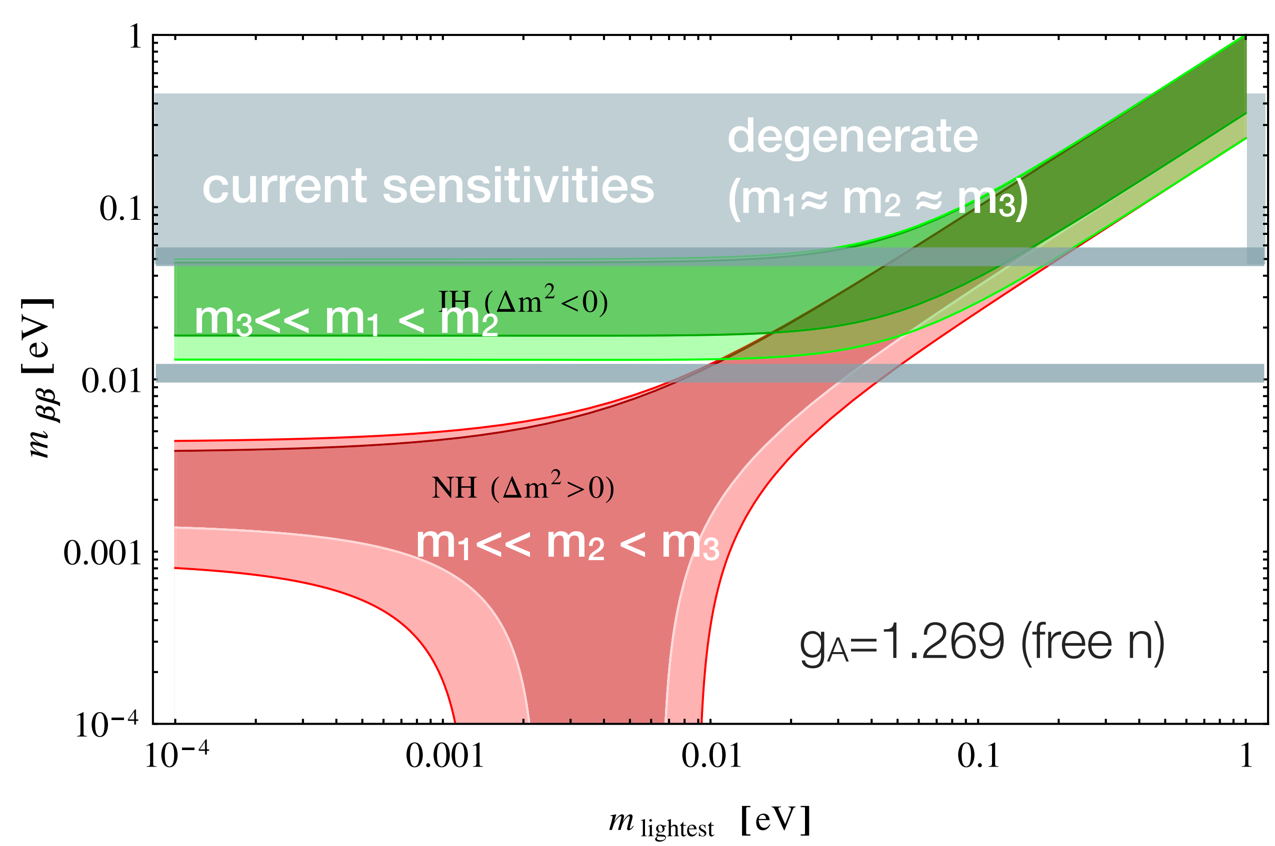


Experimental status: overview

- No evidence for WIMPs
- Several "anomalies", mostly gone

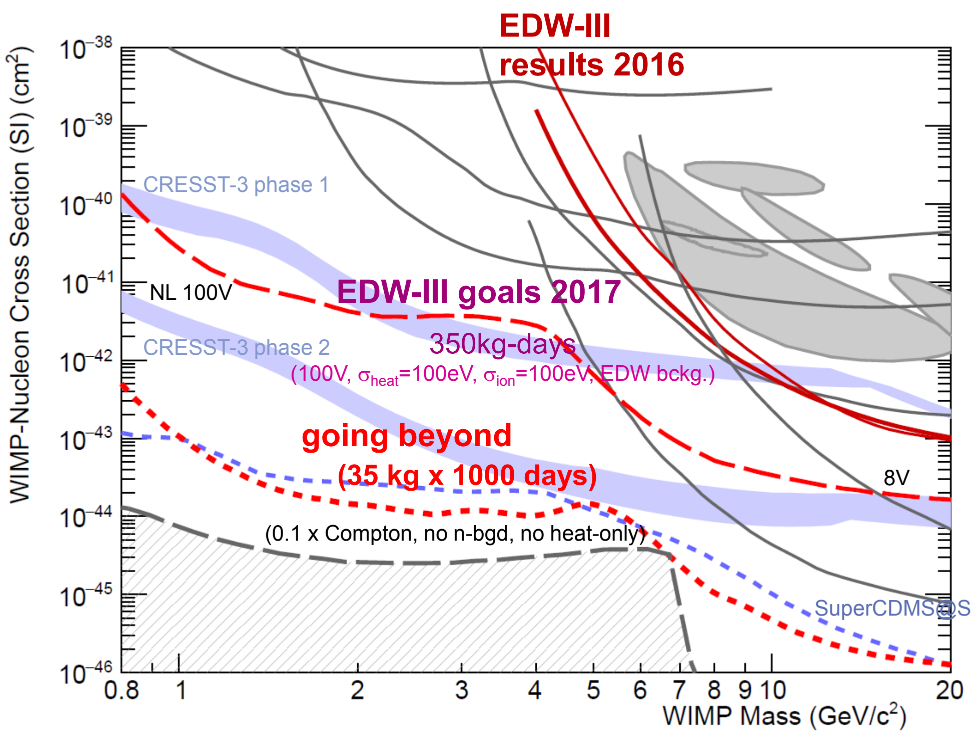
- No evidence for the $0\nu\beta\beta$ decay
- Signal claim by HVKK et al. excluded

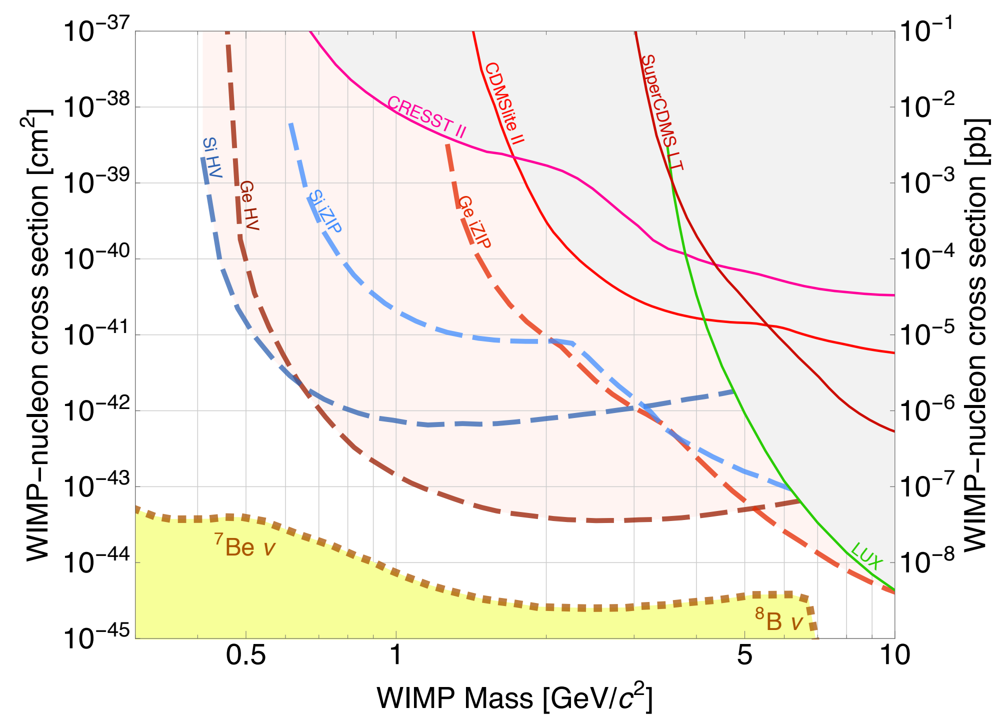




Dark matter: cryogenic detectors at T ~ mK

- Goal: reach energy thresholds ≤ 100 eV
- **Probe low-mass WIMP region (sub-GeV to few GeV)**

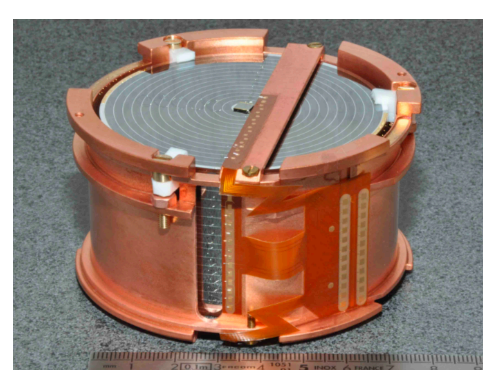




J.Phys.Conf.Ser. 718 (2016)

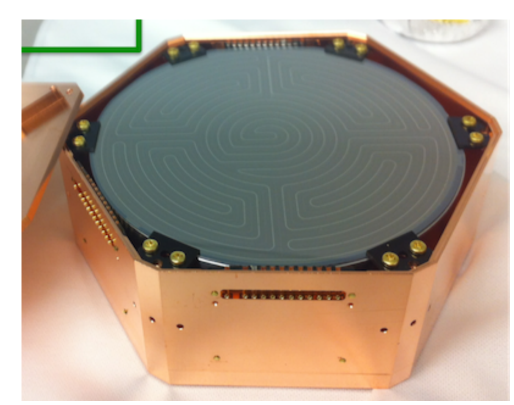
CRESST-III ($CaWO_4$)

EPJ-C C76 (2016) 10



EDELWEISS-III (Ge)

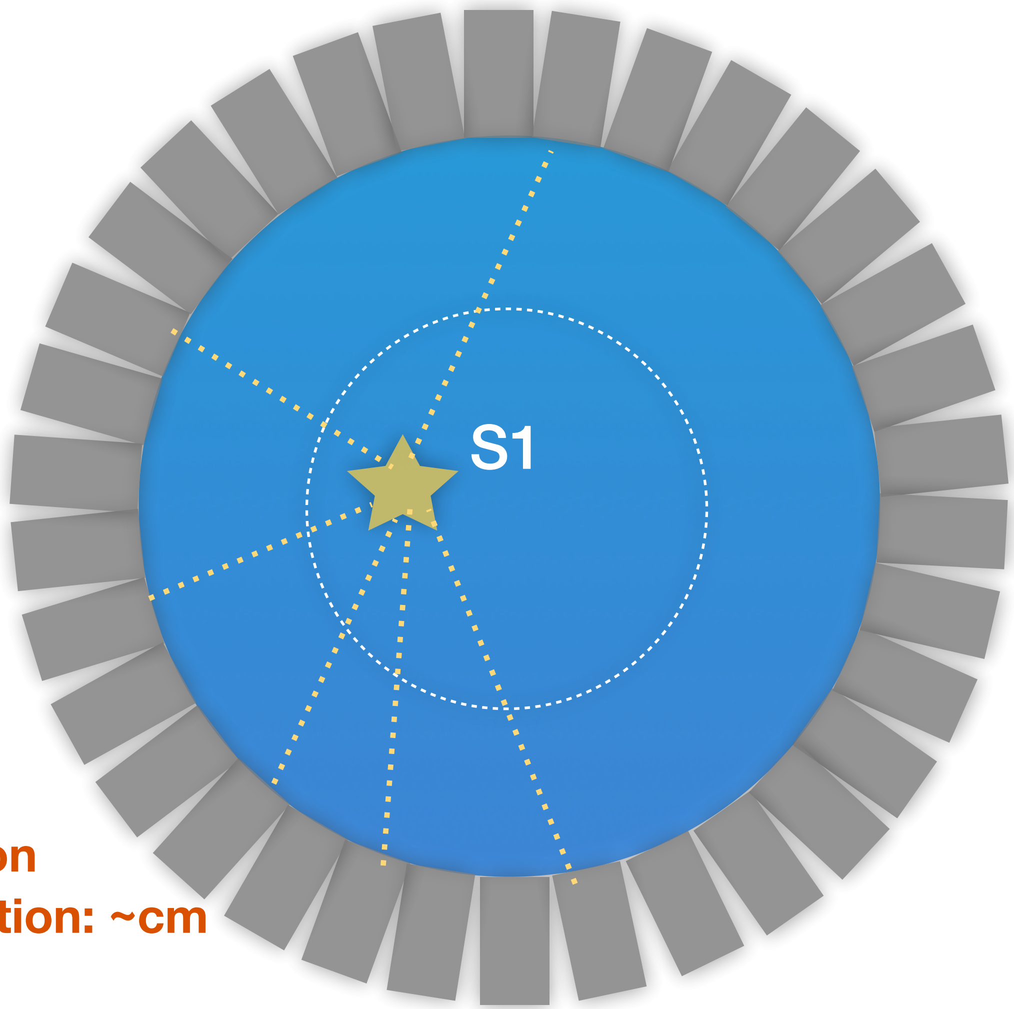
arXiv:1610.00006



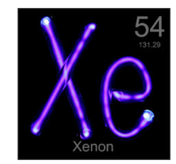
SuperCDMS (Ge, Si)

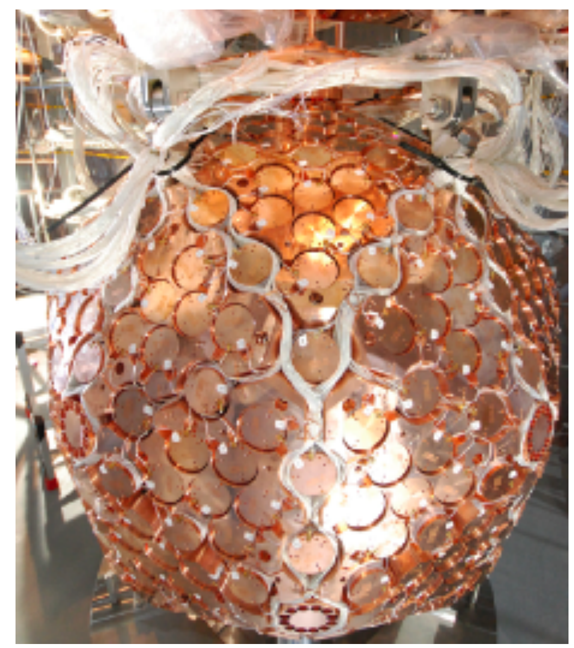
Dark matter: single-phase noble liquid detectors

PMT array



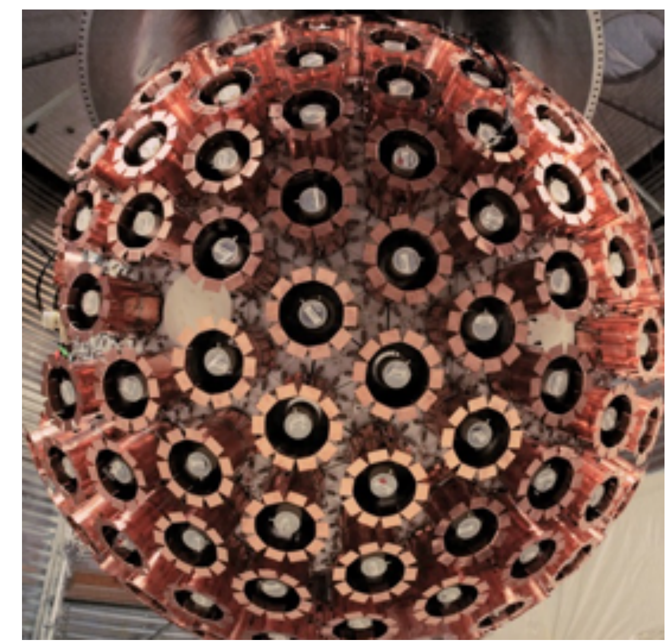
position resolution: ~cm





XMASS at Kamioka:

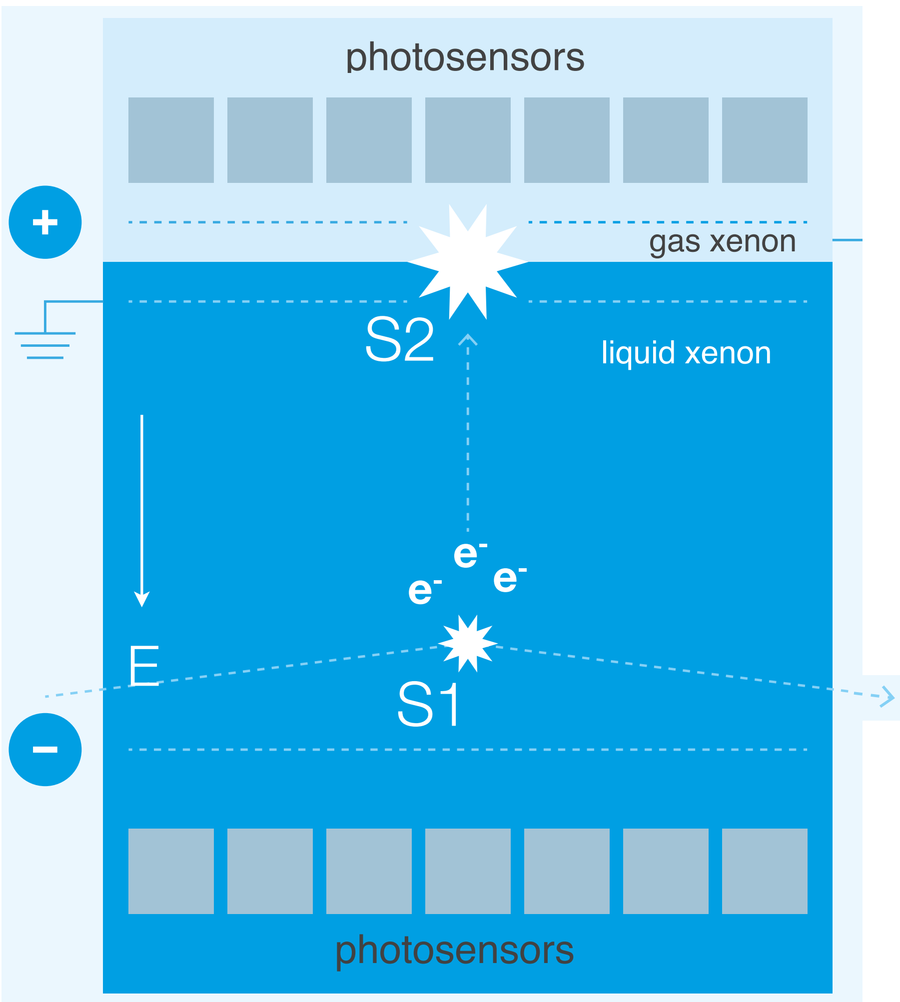
835 kg LXe (100 kg fiducial), single-phase, 642 PMTs
new run since fall 2013
several results

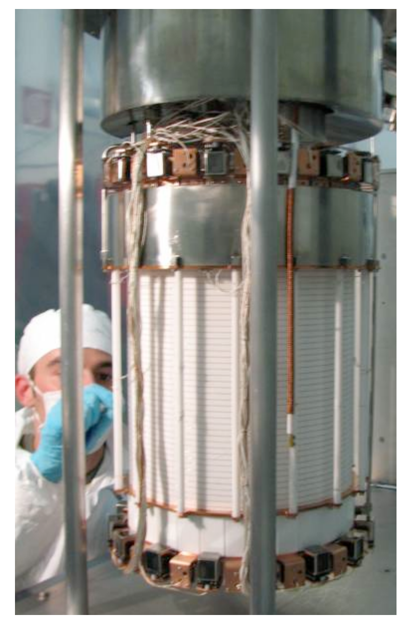


DEAP at SNOLab:

3600 kg LAr (1t fiducial)
single-phase detector
100 t d exposure
first results in 2017

Dark matter: dual-phase noble liquid detectors

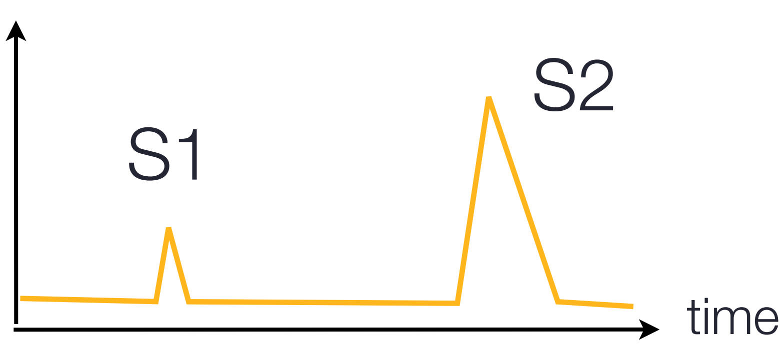




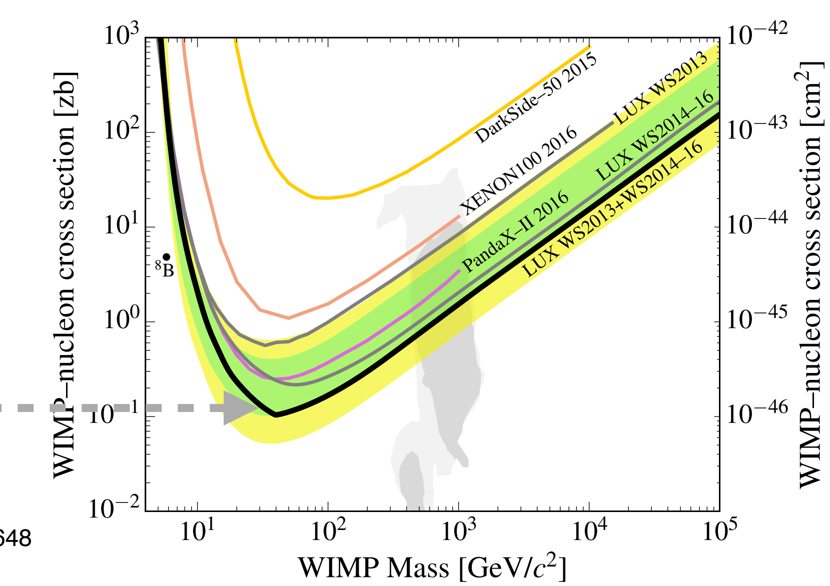
XENON100 at LNGS, LUX at SURF, PandaX at CJPL

DarkSide-50 at LNGS, ArDM at Canfranc

Talk by P. Agnes



Minimum at 0.1 zb

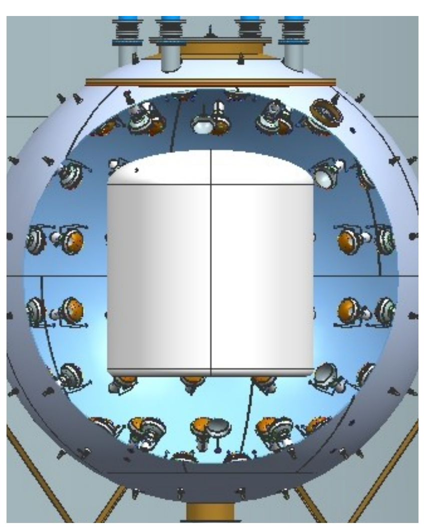


LUX collaboration, PRL 116, 161301 and arXiv:1608.07648
PandaX collaboration: PRL, August 2016

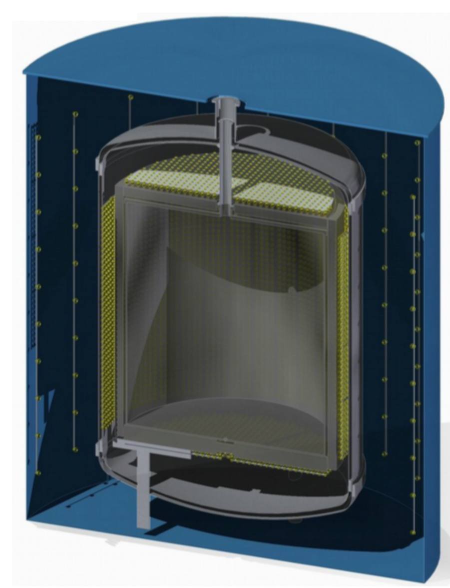
Dark matter: new & future noble liquid detectors

- Acquiring science data: XENON1T 3.2 t LXe   Talk by J. Masbou
- In construction (LXe): LUX-ZEPLIN 7t, XENONnT 7t
- Proposed (LAr): DarkSide-20k, DEAP-50T; Proposed LXe: XMASS 5t
- Design & R&D: DARWIN 50 t LXe; ARGO 300 t LAr, DEAP-50T LAr

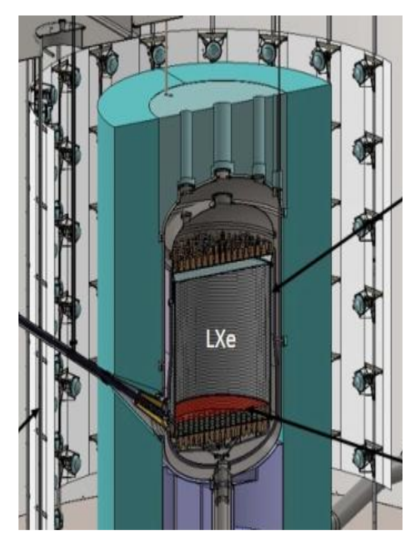
XENONnT: 7t LXe



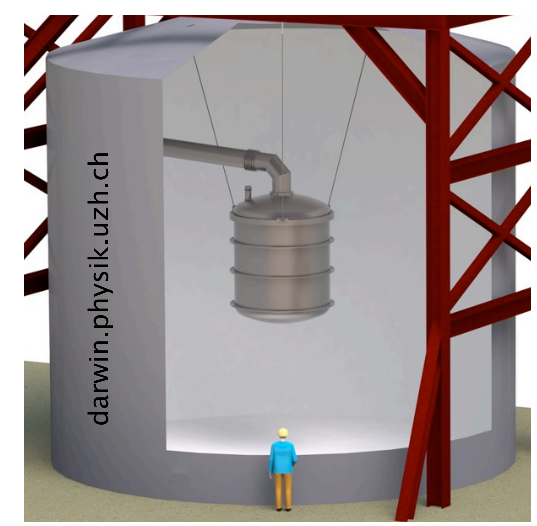
DarkSide: 20 t LAr



DEAP-50T: 50 t LAr



LZ: 7t LXe

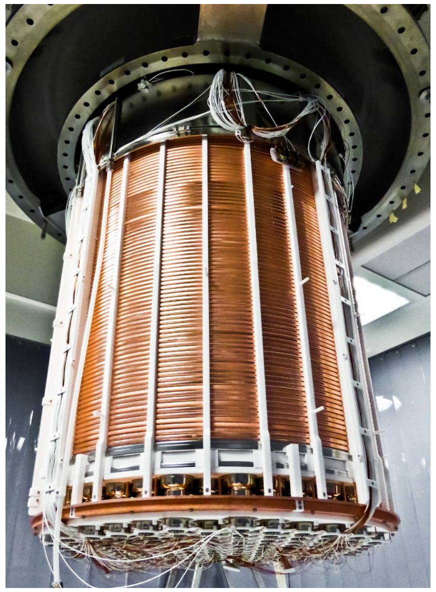
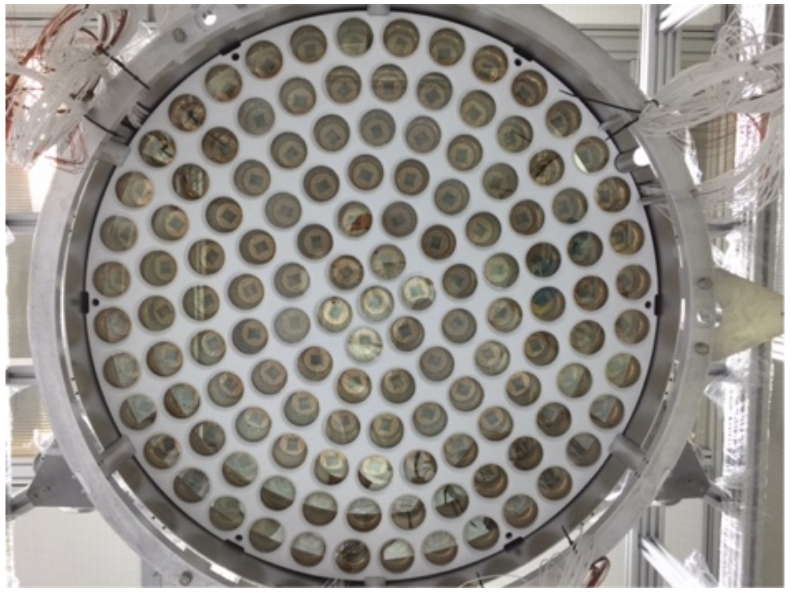
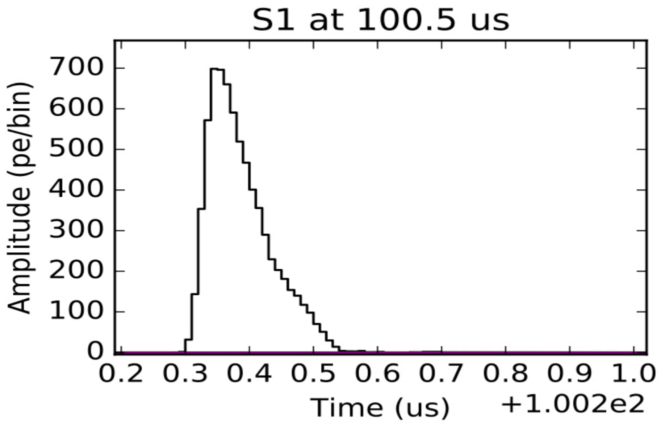


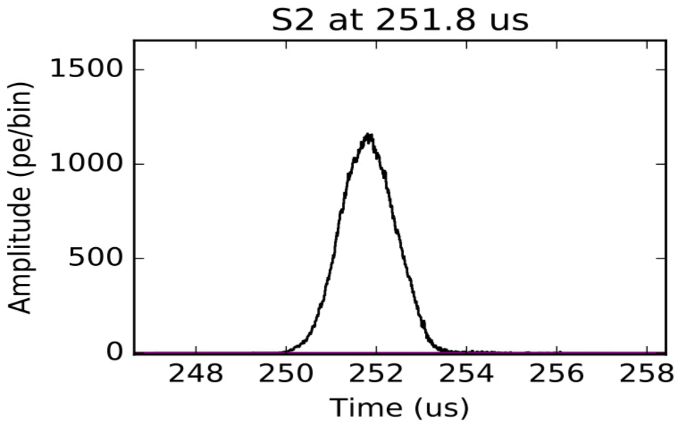
DARWIN: 50 t LXe

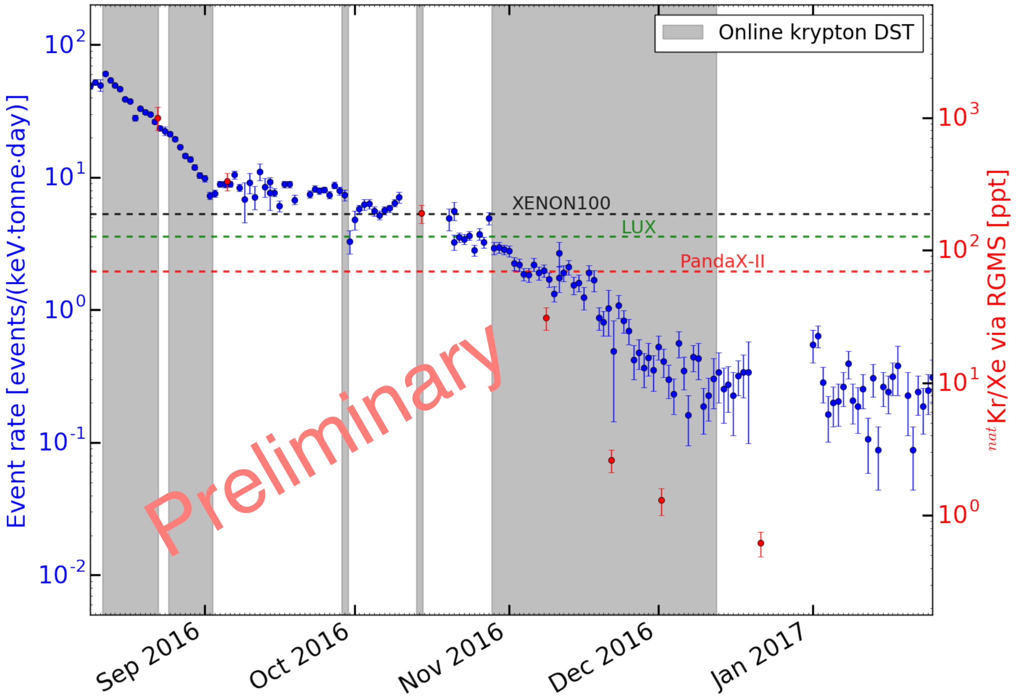
Dark matter: the XENON1T experiment

Talk by J. Masbou

- 3.2 t LXe in total; commissioned & **acquiring science data since December 2016**

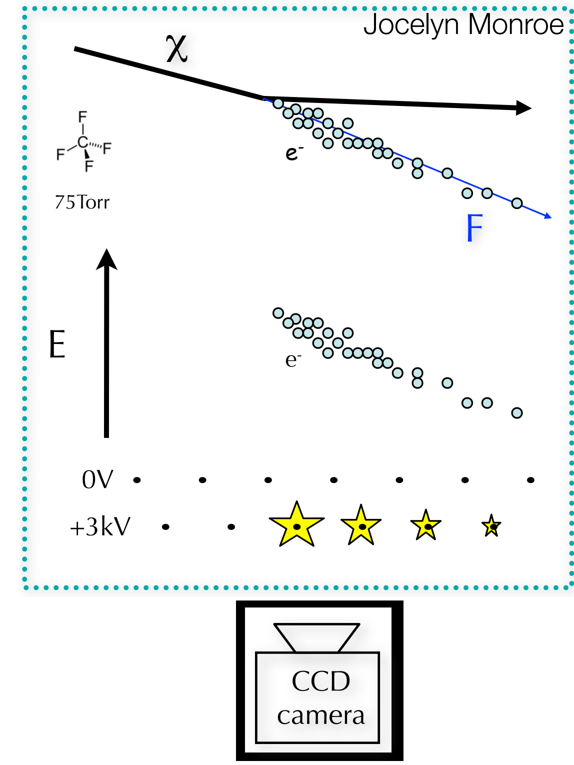







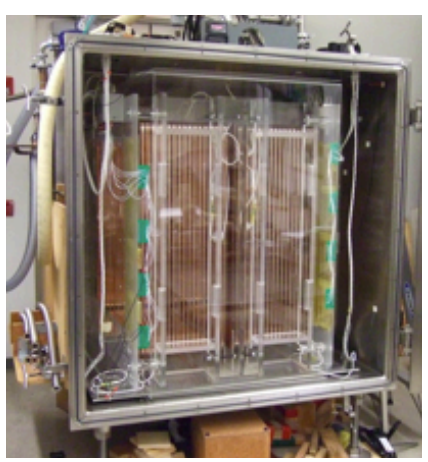


Dark matter: directional detectors

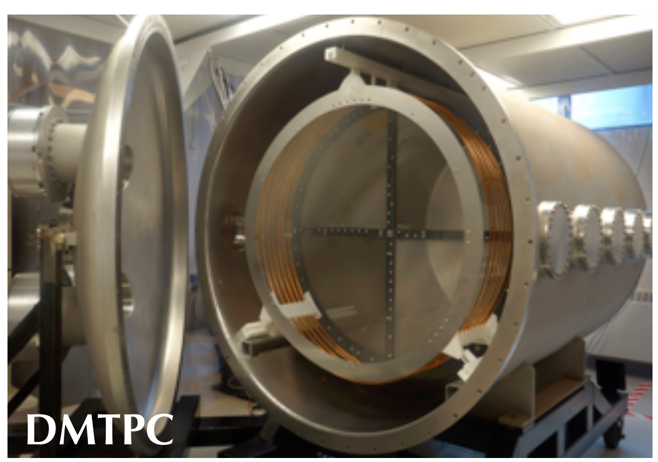
- R&D on low-pressure gas detectors to measure the recoil direction (~30° resolution), correlated to the Galactic motion towards Cygnus
- Challenge: good angular resolution + head/tail at 30-50 keVnr
- **One common technology to be proposed in 2017**



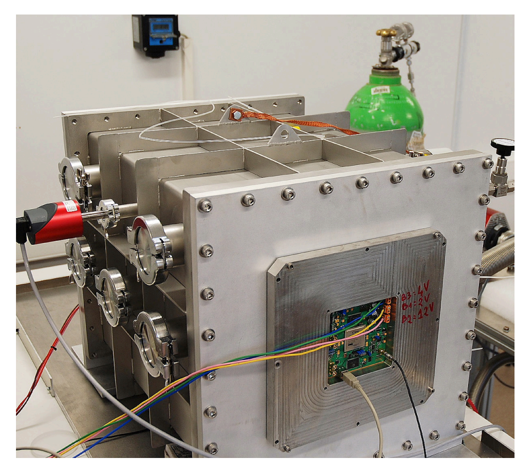
CYGNUS: coordination of directional R&D



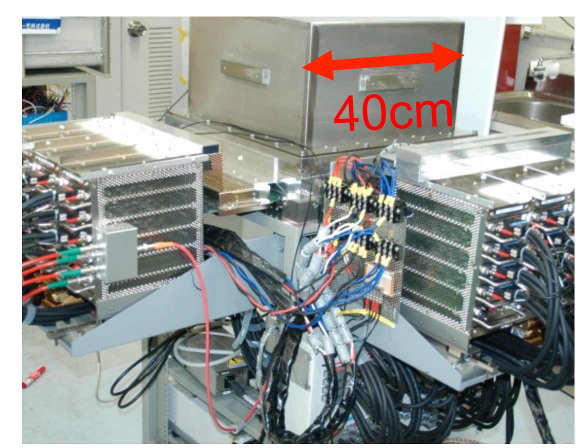
DRIFT, Boulby Mine
1 m^3, negative ion drift
CS_2 +CF_4 gas



DMTPC, MIT
Optical and charge readout
CF_4 gas
commissioning 1 m^3 module



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

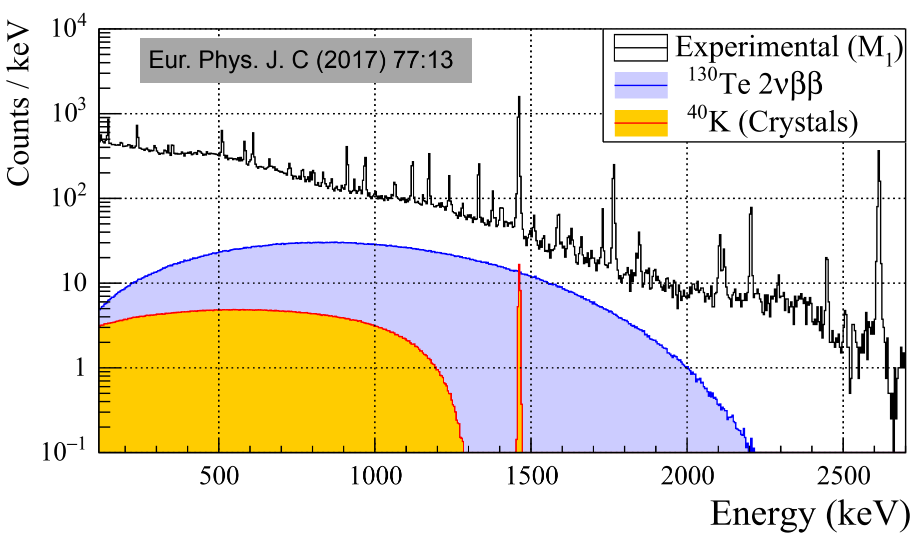


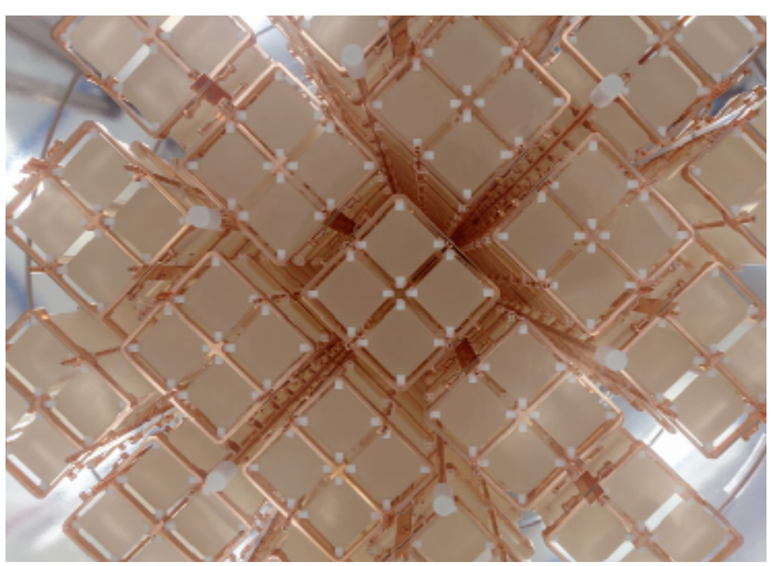
NEWAGE, Kamioka
CF_4 gas at 0.1 atm
50 keV threshold

Double beta: cryogenic detectors at T ~ mK

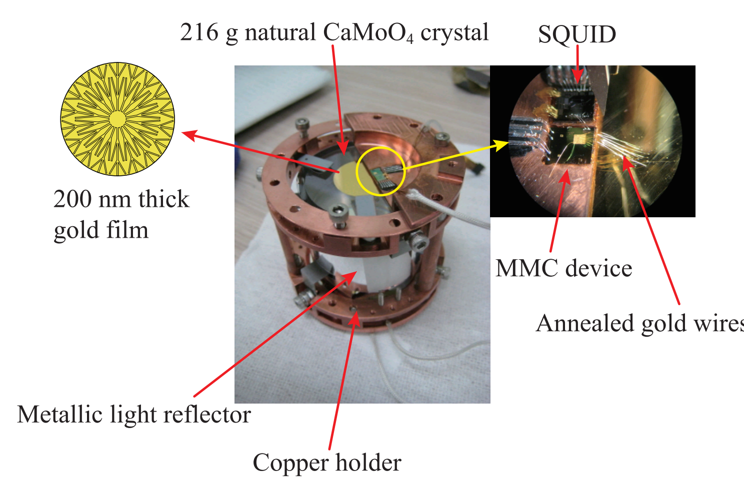
- CUORE: All 988 crystals (206 kg ^{130}Te) built and assembled in towers   Talk by V. Singh
- Cryostat: stable base temperature reached, allows operation of bolometers at 6.3 mK
- Detector installation completed, commissioning now
  - Background goal: 0.01 events/(kg keV y)
  - Energy resolution goal: 5 keV at 2.6 MeV [FWHM]
  - **Sensitivity aim (after 5 y):** $T_{1/2} \sim 9.5 \times 10^{25} y$

$$T_{1/2}^{2\nu\beta\beta} = [8.2 \pm 0.2(\mathrm{stat.}) \pm 0.6(\mathrm{syst.})] \cdot 10^{20}\mathrm{y}$$

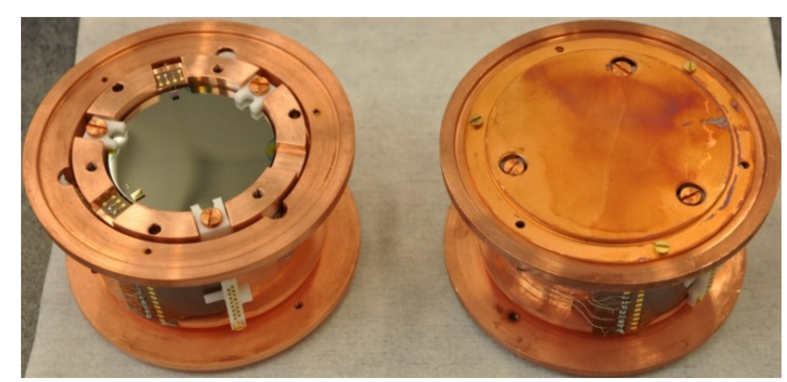




CUORE: TeO_2



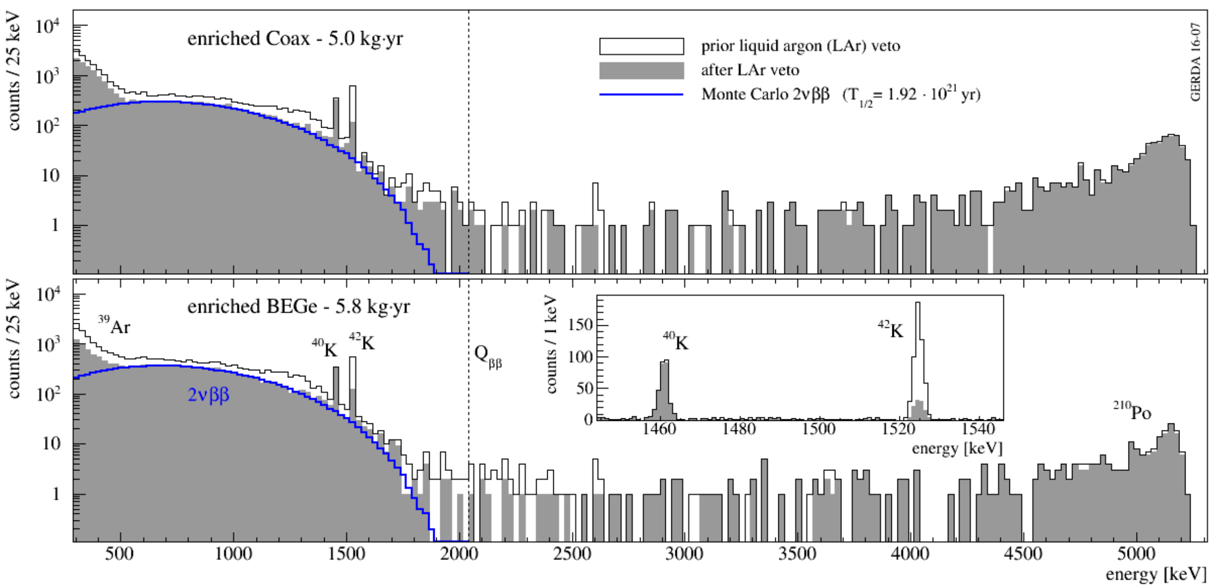
AMoRE: $^{40}Ca^{100}MoO_4$



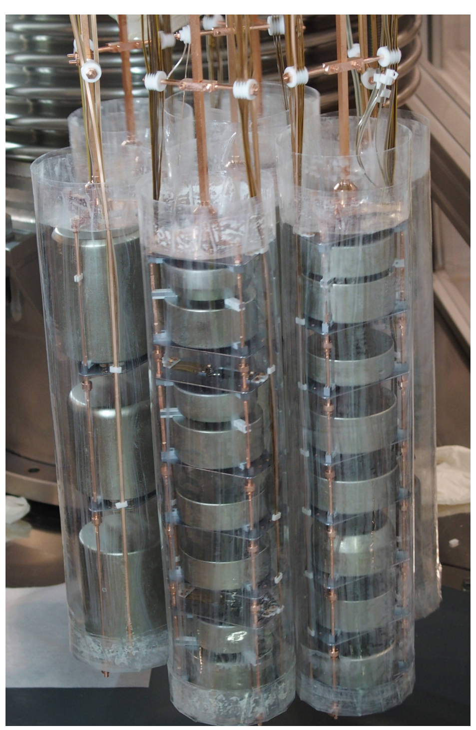
LUMINEU: $Zn^{100}MoO_4$

Double beta: HPGe detectors at 77 K

Talk by M. Misiaszek

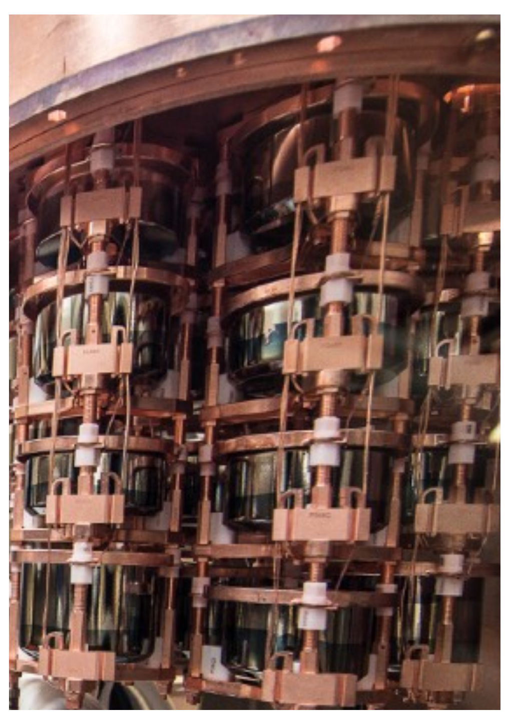


- **GERDA Phase II data: Dec 2015 - June 2016**
- **Background in BEGe detectors:**
  - $(0.7^{+1.1}_{-0.5} \times 10^{-3})$ events/(kg y keV)
- **No hint for a signal and:**
  - **$T_{1/2} > 5.3 \times 10^{25}$ y (90% CL)**
  - $m_{eff} < 0.15$ eV - 0.33 eV
- Manuscript accepted in Nature
- Stable running conditions, currently acquiring data towards the 100 kg y exposure goal
- **GERDA + Majorana = LEGEND: 200 kg stage at LNGS; ton-scale experiment (location tbd)**



GERDA: ^{76}Ge (37 kg HPGe)

arXiv:1703.00570



Majorana: ^{76}Ge (30 kg HPGe)

arXiv:1610.01210

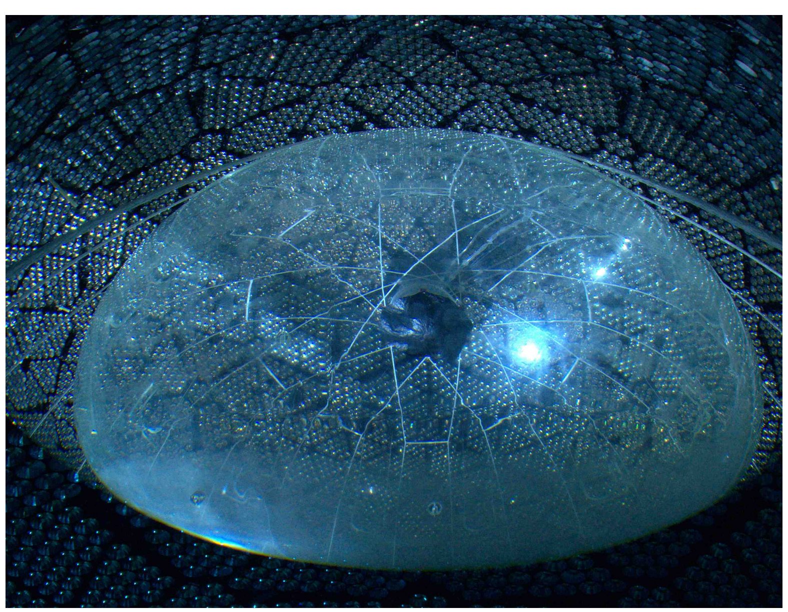
Double beta: liquid scintillators

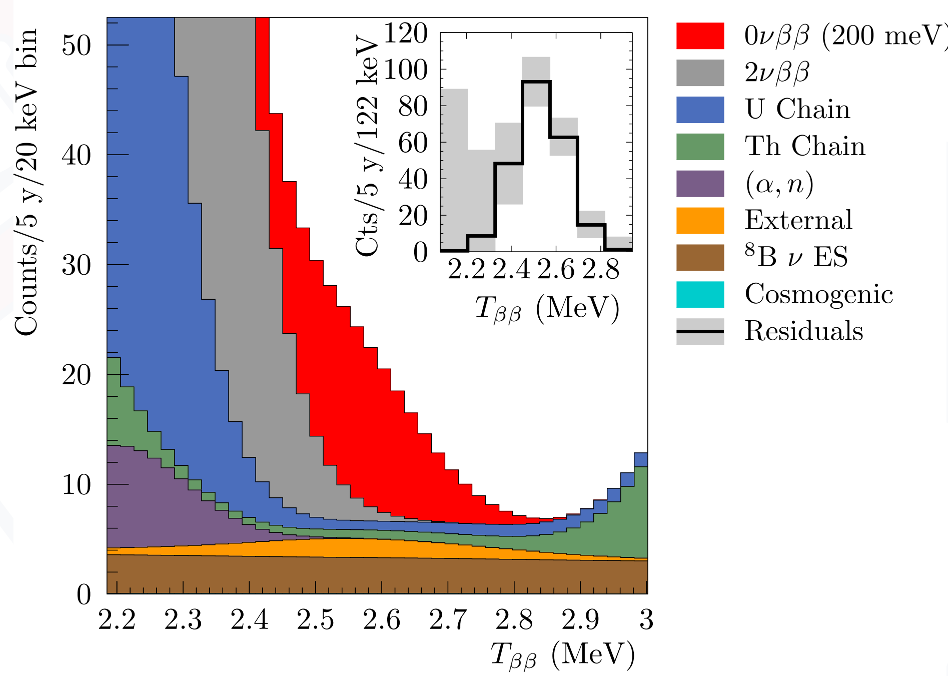
- First phase: 0.3% natural Te (~ 800 kg ^{130}Te)
- **Detector and cavity are filled with light water, data taking ongoing (24/7 shifts)**
- **Commissioning of LS plant ongoing**
- Load 0.3-0.5% Te in 2017
- Future: upgrade PMTs and 3% load -> to cover inverted hierarchy scenario

- Phase 1+2 (179 kg + 383 kg):
- **$T_{1/2}$ > 2.6 x 10^{25} y (90% CL)**

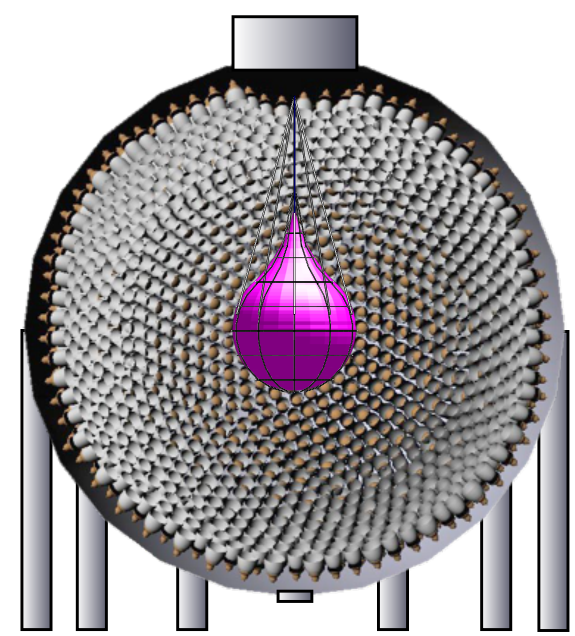
$$m_{\beta\beta} < 0.14 - 0.28\,\mathrm{eV}$$

- Started 800 kg phase
- Sensitivity: 2 x 10^{26} yr after 2 y exposure



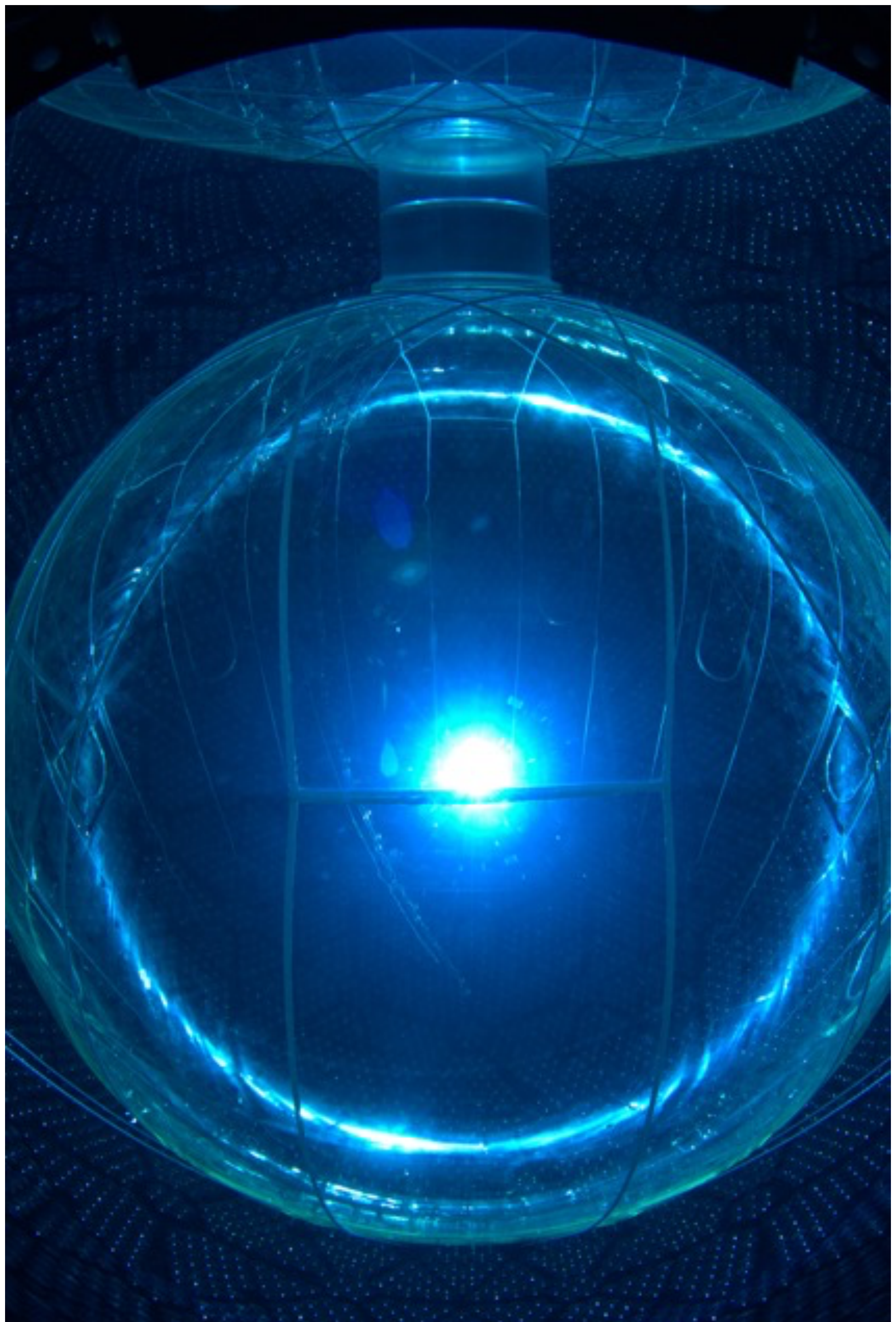


SNO+: ^{130}Te in LS

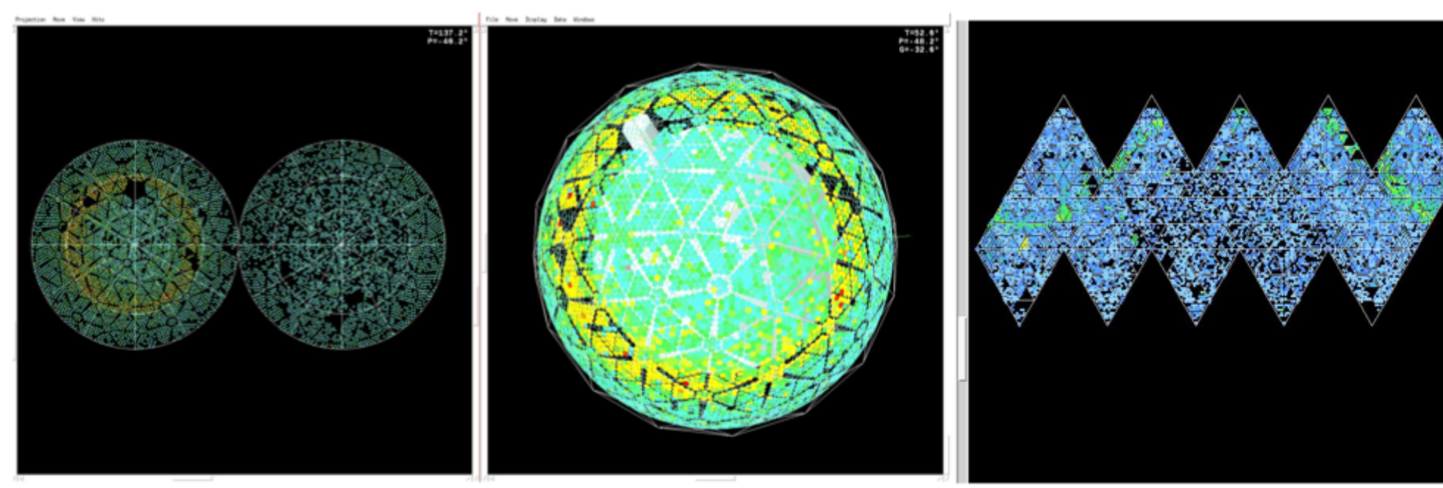


KamLAND-Zen ^{136}Xe in LS

Double beta: SNO+



First neutrino candidate: 2017-02-05, upward-going, no outward-looking PMTs triggered

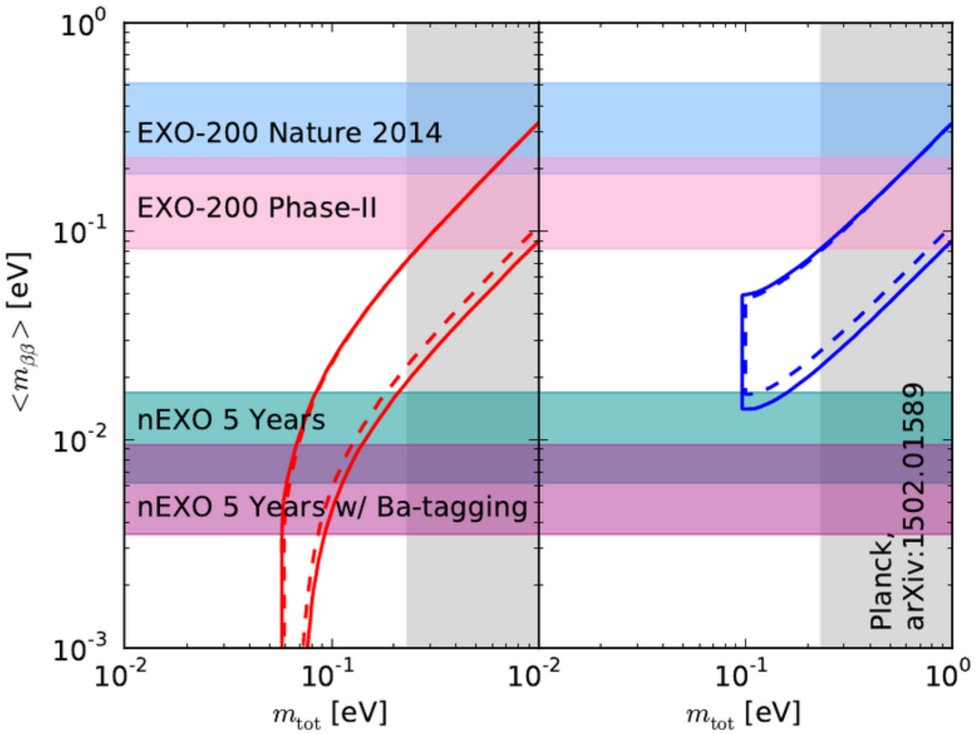


Info from Mark Chen and Nigel Smith

Double beta: xenon TPCs

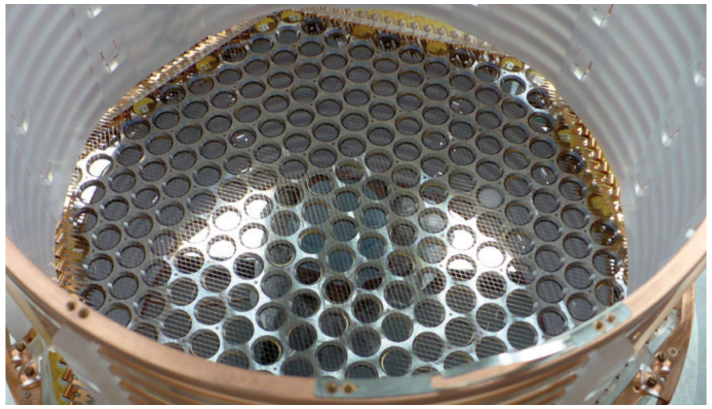
$$T_{1/2}^{0\nu} > 1.1 \times 10^{25}\,\mathrm{y}\,(90\%\mathrm{C.L.})$$

$$m_{\beta\beta} < 0.19 - 0.45\,\mathrm{eV}$$

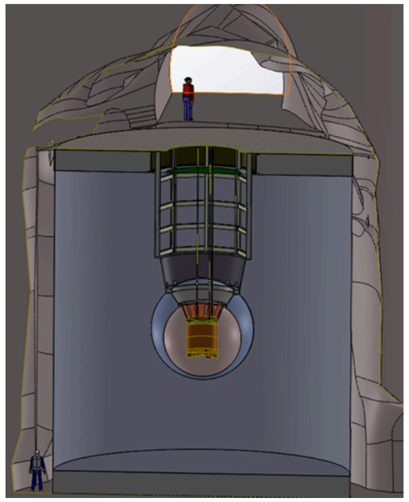


Goal of nEXO: $T_{1/2} \sim 6.6 \times 10^{27} y$

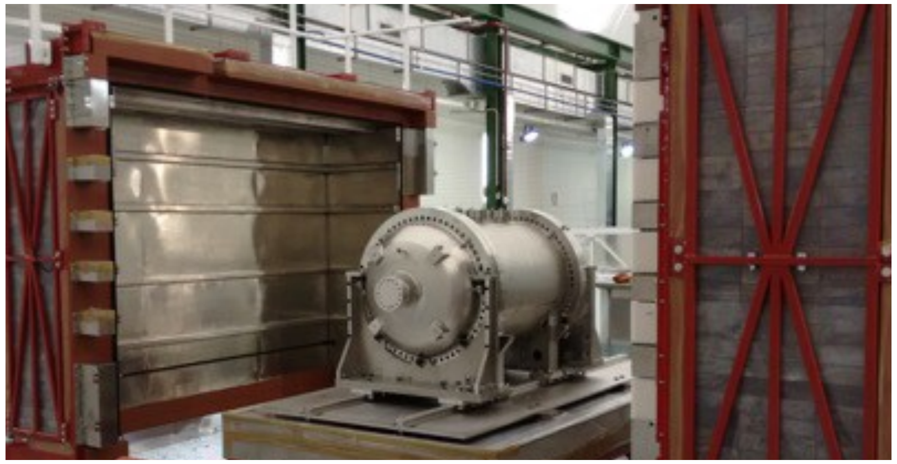
Parameter	nEXO	EXO-200
Fiducial mass (kg)	4780	98.5
Enrichment (%)	80-90	80
Data taking time (yr)	5	5
Energy resolution @ $Q_{\beta\beta}$ (keV)	58	88 (58)
Depth (m.w.e)	6010	1500
Background within FWHM of endpoint (events/yr/mol_{136})	6.1×10^{-4}	0.022 (0.0073)
Background within FWHM of endpoint inner 3000kg (events/yr/mol_{136})	1.6×10^{-4}	



EXO-200 ^{136}Xe



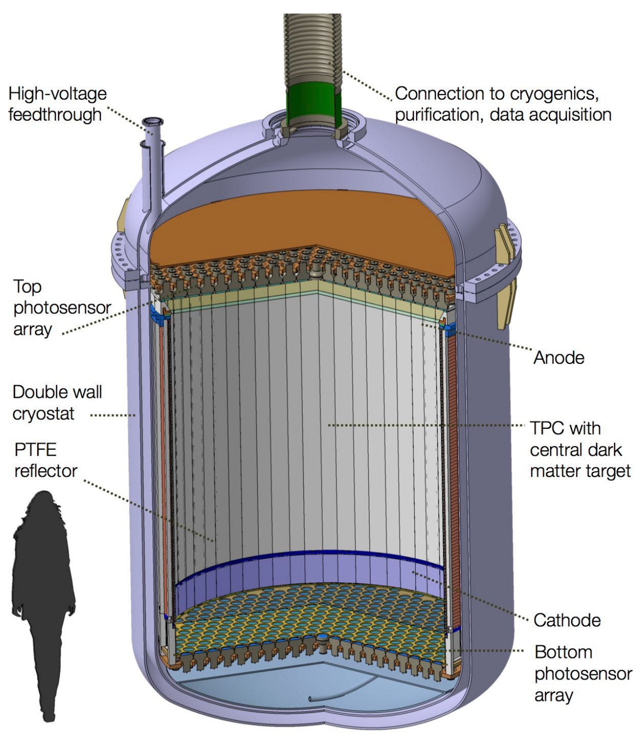
nEXO ^{136}Xe

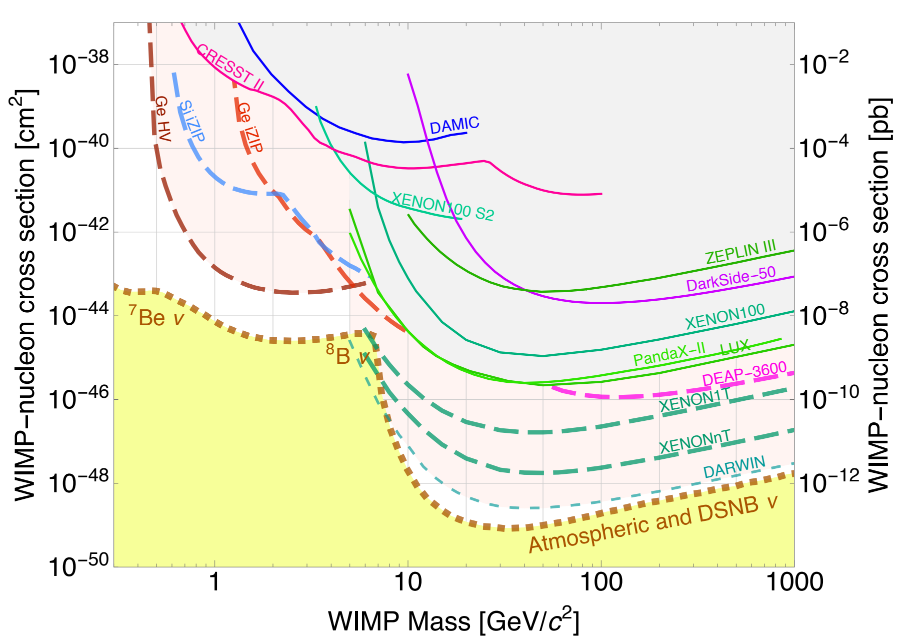


NEXT ^{136}Xe (HP gas) (+tracking)

Can we do both? => DARWIN

- **50 tonnes ^{nat}Xe, 8.9% ^{136}Xe**

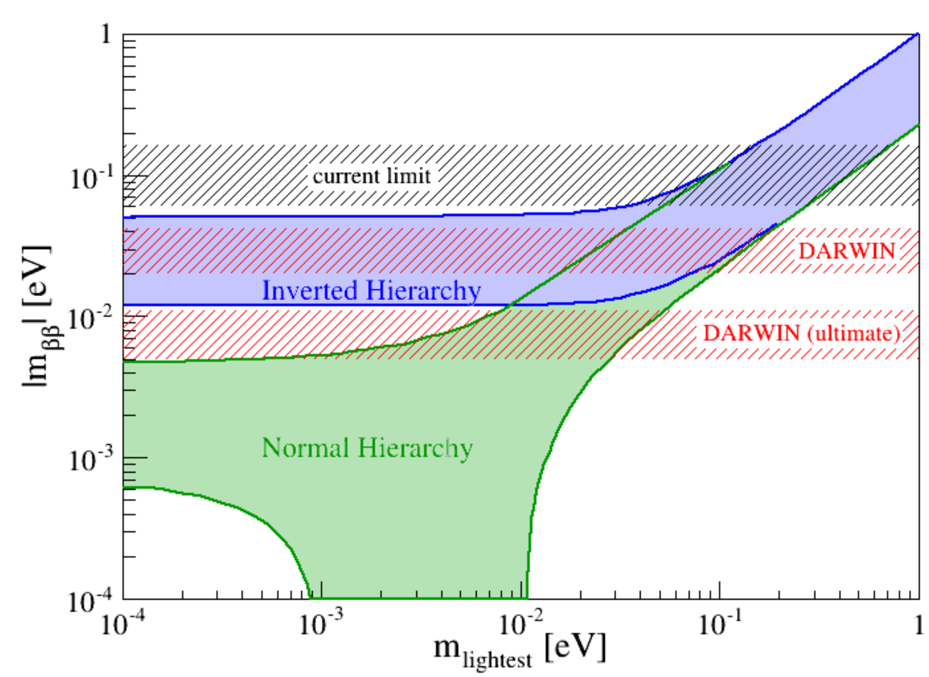




- **Sensitivity (140 t y exposure, ^{nat}Xe)**

$$T_{1/2} \sim 8.5 \times 10^{27} y$$

- Assumptions:
  - ^{222}Rn: 0.1 μBq/kg (~ 0.036 events/(t y))
  - (^{8}B rate is ~ 0.036 events/(t y))
  - sigma/E = 1% at Q-value
  - materials: sub-dominant background source



DARWIN collaboration, JCAP 1611 (2016); LB et al, JCAP 1401 (2014)

L Baudis

Testing WIMPs to the limit

A surface building at Gran Sasso National Laboratory in Italy, which hosts a network of caverns shielded from cosmic radiation.

The DARWIN observatory proposed to be built at Gran Sasso in the mid-2020s promises to be the ultimate dark-matter detector, probing the WIMP paradigm to its limit.

DARWIN, the ultimate dark-matter detector using the noble element xenon in liquid form, will be in a unique position to address these fundamental questions. Currently in the design and R&D phase, DARWIN will be constructed at the Gran Sasso National Laboratory (LNGS) in Italy and is scheduled to carry out its first physics runs from 2024. The DARWIN consortium is growing, and currently consists of about 150 scientists from 26 institutions in 11 countries.

Conclusions

Direct searches for particle dark matter and for the neutrinoless double beta decay share many common features

Due to very low expected event rates:

- large detector masses, ultra-low backgrounds, good energy resolution, particle ID

- in general, dm detectors optimised at keV-scale energies, bb-experiments optimised at MeV-scale energies

So far, no convincing evidence for positive signals, however:

technologies have matured and reached stages where they can be scaled up to *large masses with unprecedented low backgrounds*

- eventually, limited by solar & atm & diffuse supernovae neutrinos

- ideally, large detectors which can search for both signals

The end

Of course, “the probability of success is difficult to estimate, but if we never search, the chance of success is zero”

G. Cocconi & P. Morrison, Nature, 1959

Backup slides

What is the observable decay rate?

Phase space factor | Axial-vector cc | NME

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \frac{|m\beta\beta|^2}{m_e^2}$$

Can be calculated: ~ Q^5 | **Difficult: factor 2-3**

- with the **effective Majorana neutrino mass:**

$$|m_{\beta\beta}| = |U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i(\alpha_1-\alpha_2)} + U_{e3}^2 m_3 e^{i(-\alpha_1-2\delta)}|$$

➡ a coherent sum over mass eigenstates with potentially CP violating phases

➡ = a mixture of m_1, m_2, m_3, proportional to the U_{ei}^2, with α_1,α_2 = Majorana CPV phases

- U_{ei} = matrix elements of the PMNS-Matrix, m_i = eigenvalues of the neutrino mass matrix

Experimental requirements

- Experiments measure the half life of the decay, $T_{1/2}$ with a sensitivity **(for non-zero background)**

$$T^{0\nu}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

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

Minimal requirements:

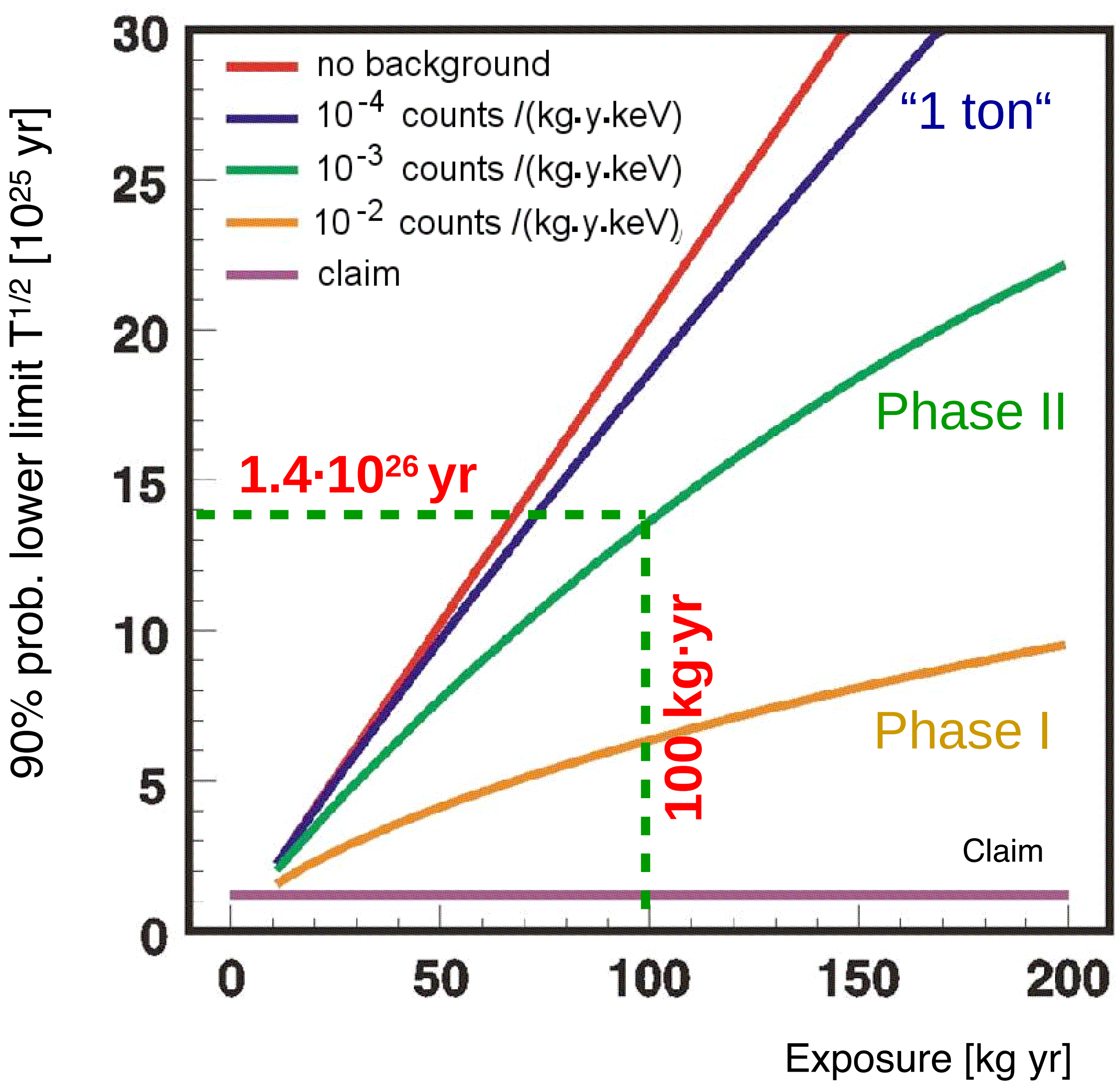
large detector masses
high isotopic abundance
ultra-low background noise
good energy resolution

Additional tools to distinguish signal from background:

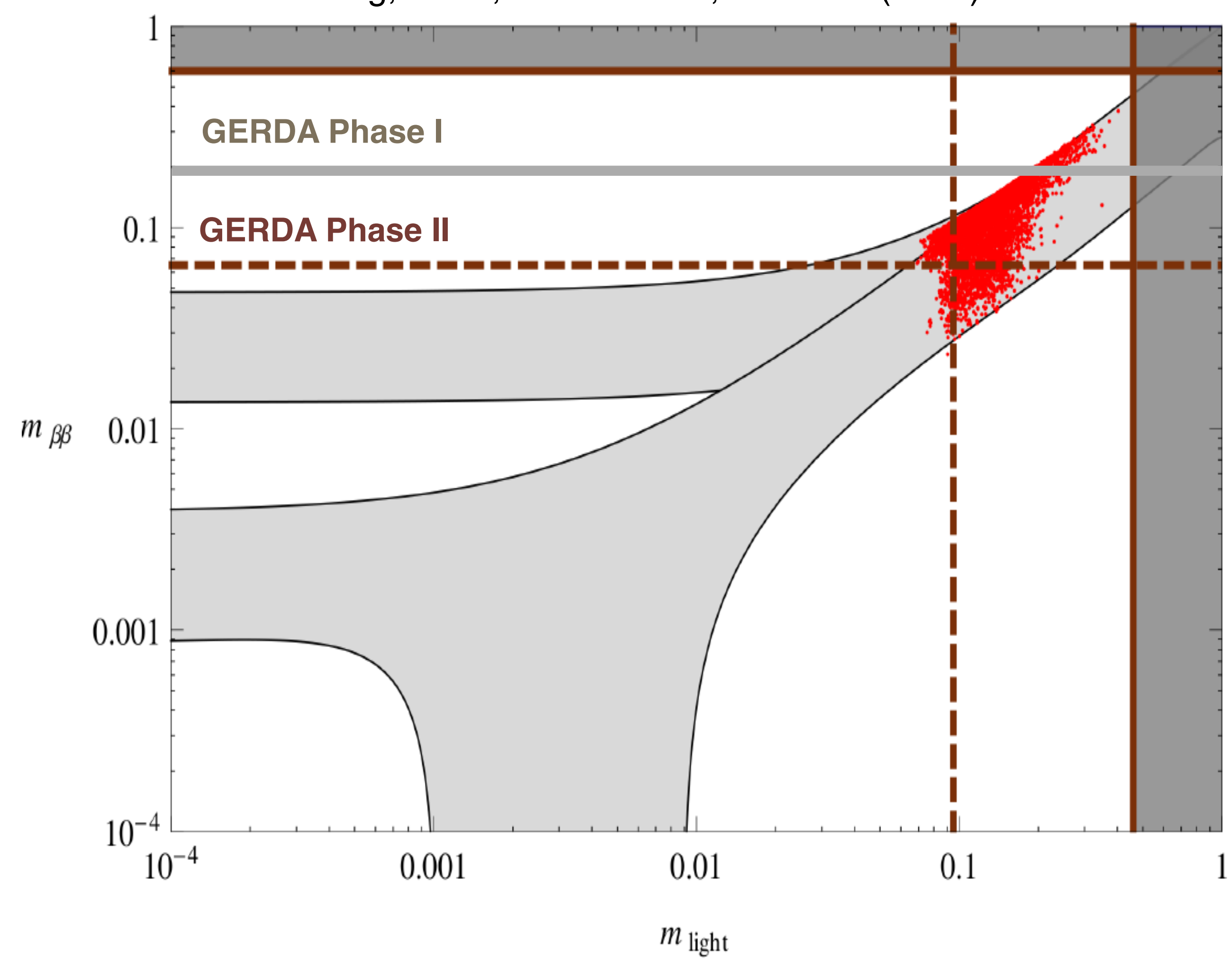
event topology
pulse shape discrimination
particle identification

GERDA phase II and beyond

- Demonstration that a background of ≤ 10^{-3} events/(keV kg yr) is feasible
- Will explore $T_{1/2}$ values in the 10^{26} yr range, probing the degenerate mass region
- A ton-scale experiment (in collaboration with Majorana in the US) is in design phase



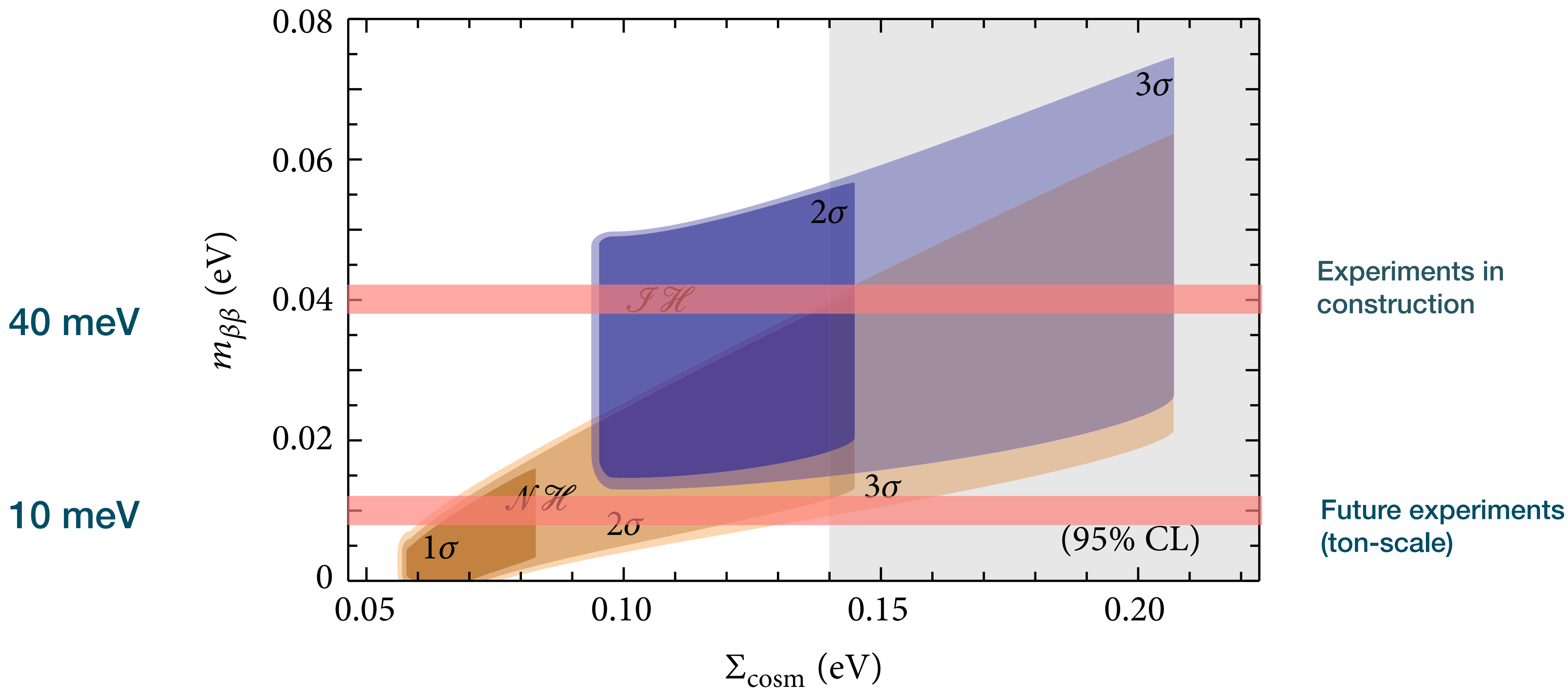
Alonso, Gavela, Isidori,Maiani, JHEP 1311 (2013) 187
Blankenburg,Isidori, Jones-Perez, EPJC 72 (2012) 2126



Theory: neutrino mixing and masses from a minimum principle

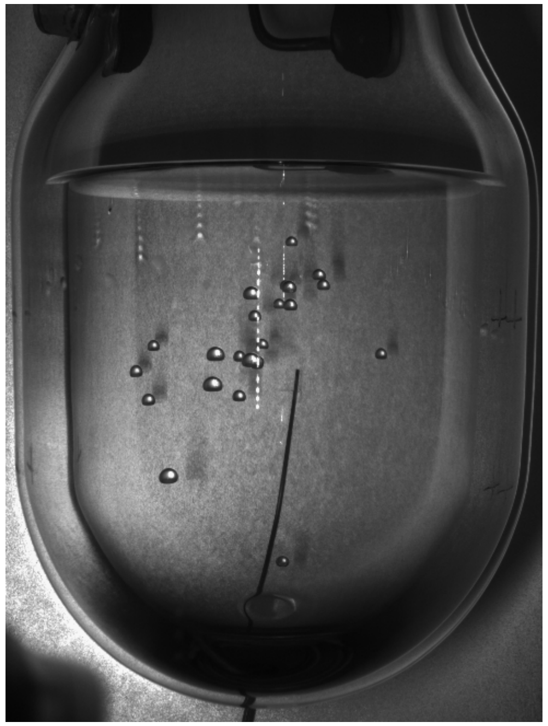
Physics reach

- Ton-scale experiments are required to explore the inverted mass hierarchy scale
- Several other technologies also move into this direction
- ^{76}Ge experiments have the advantage of an excellent energy resolution coupled to ultra-low backgrounds



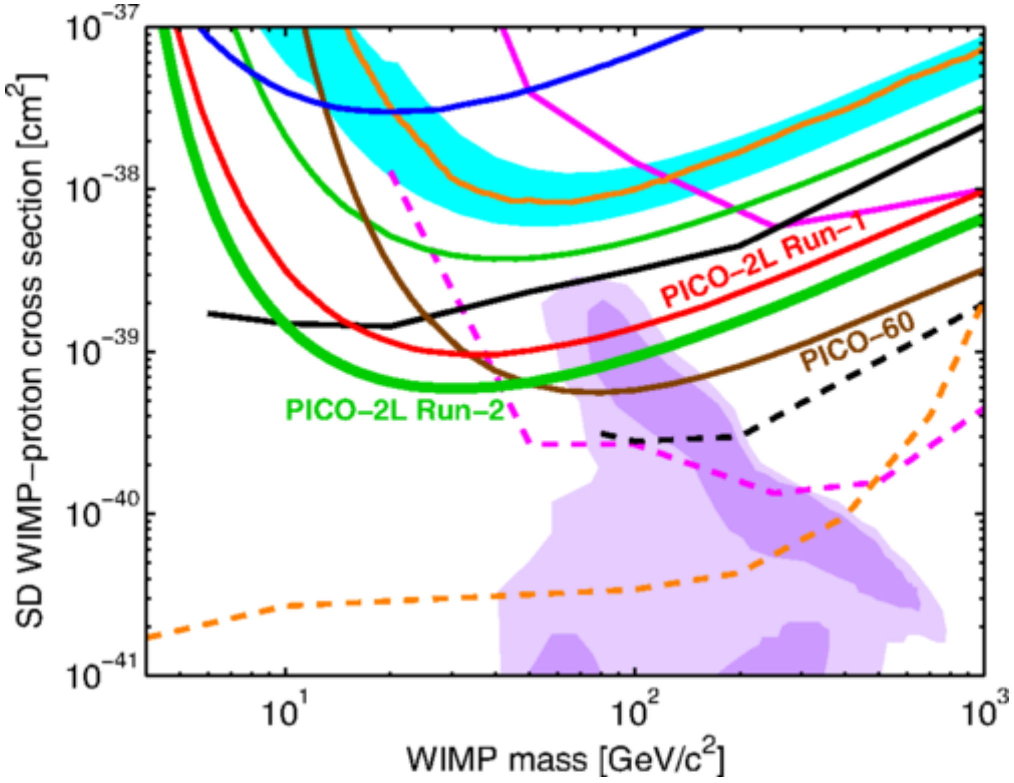
Bubble chambers

- Detect single bubbles induced by high dE/dx NRs in superheated liquid target:
  - acoustic and visual readout; measure integral rate above threshold
  - large rejection factor (~10^{10}) for MIPs; scalable to large masses; high spatial granularity
- New results: PICO-2L (PICASSO + COUP), 2.9 kg C_3F_8 target, best SD WIMP-proton limit
- PICO-60L running since 2016; proposed: PICO-250L C_3F_8 target at SNOLAB

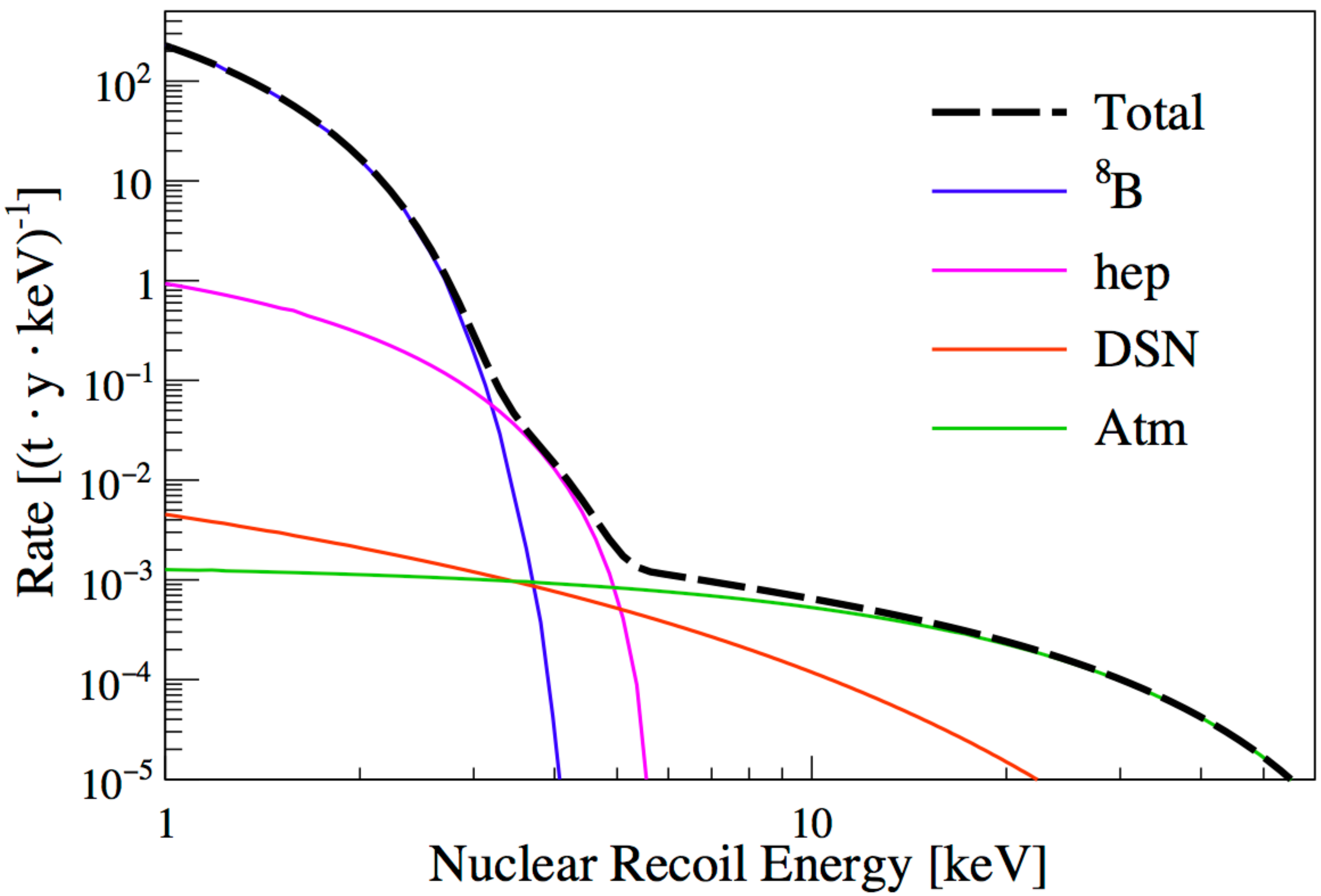


PICO-2L n-calibration

PRD 93, 061101 (2016)



Coherent neutrino-nucleus scatters in XENON1T



- **Total rates:**
- 90 events/(t yr) > 1 keVnr
- 9 x 10^{-2} events/(t y) > 3 keV_{nr}
- 1.8 x 10^{-2} events/(t y) > 4 keV_{nr}
- 1.2 x 10^{-2} events/(t y) > 5 keV_{nr}

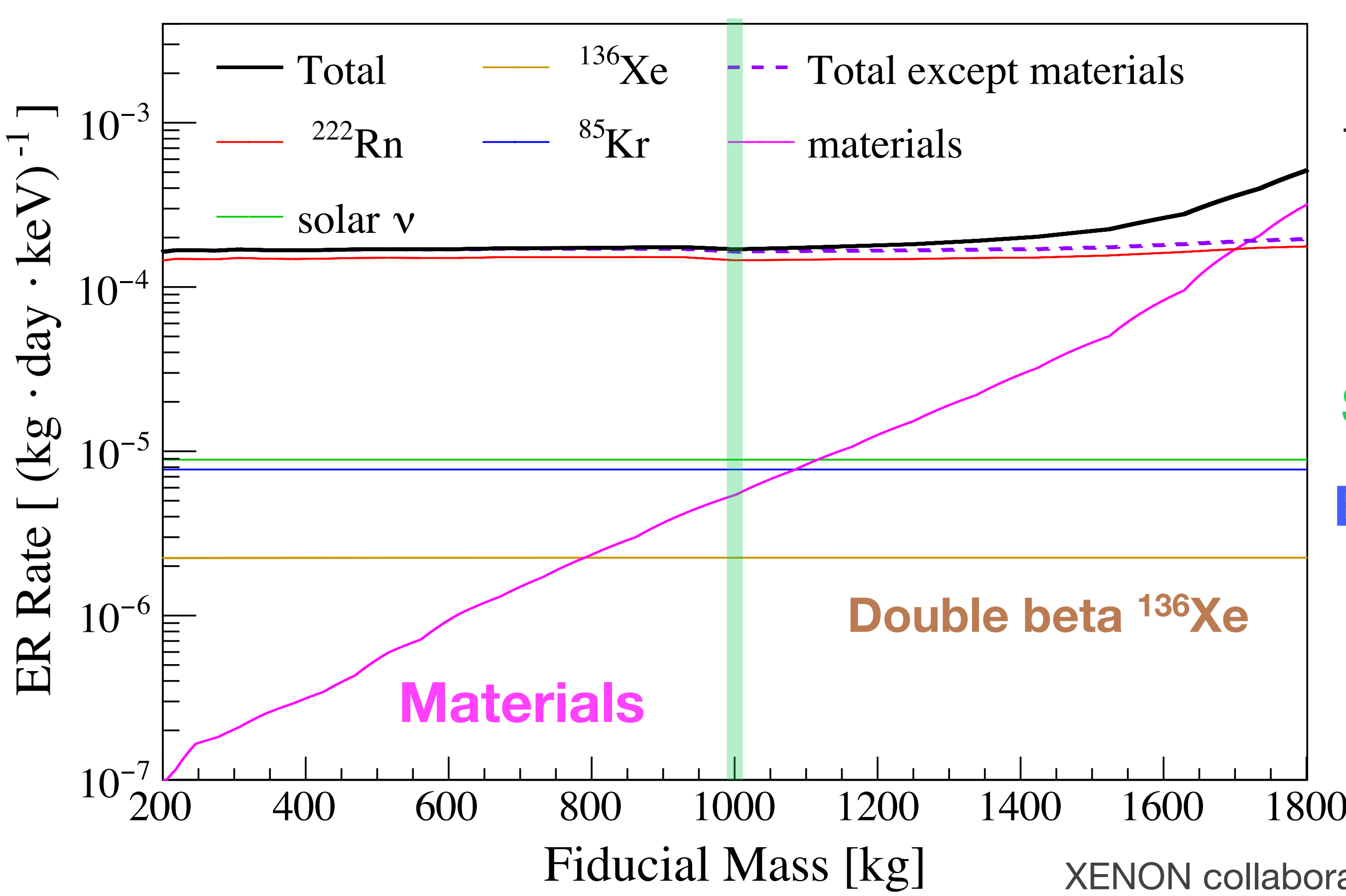
XENON collaboration: JCAP04(2016)027

XENON1T background predictions

- Materials: based on screening results for all detector components
- ^{85}Kr: 0.2 ppt of ^{nat}Kr with 2x10^{-11} ^{85}Kr; ^{222}Rn: 10 μBq/kg; ^{136}Xe double beta: 2.11x10^{21} y
- ER vs NR discrimination level: 99.75%; 40% acceptance for NRs

➡ **Total ERs: 0.3 events/year** in 1 ton fiducial volume, [2-12] keV$_{ee}$

➡ **Total NRs: 0.6 events/year in 1 ton**, [5-50] keV$_{nr}$ (muon-induced n-BG < 0.01 ev/year)



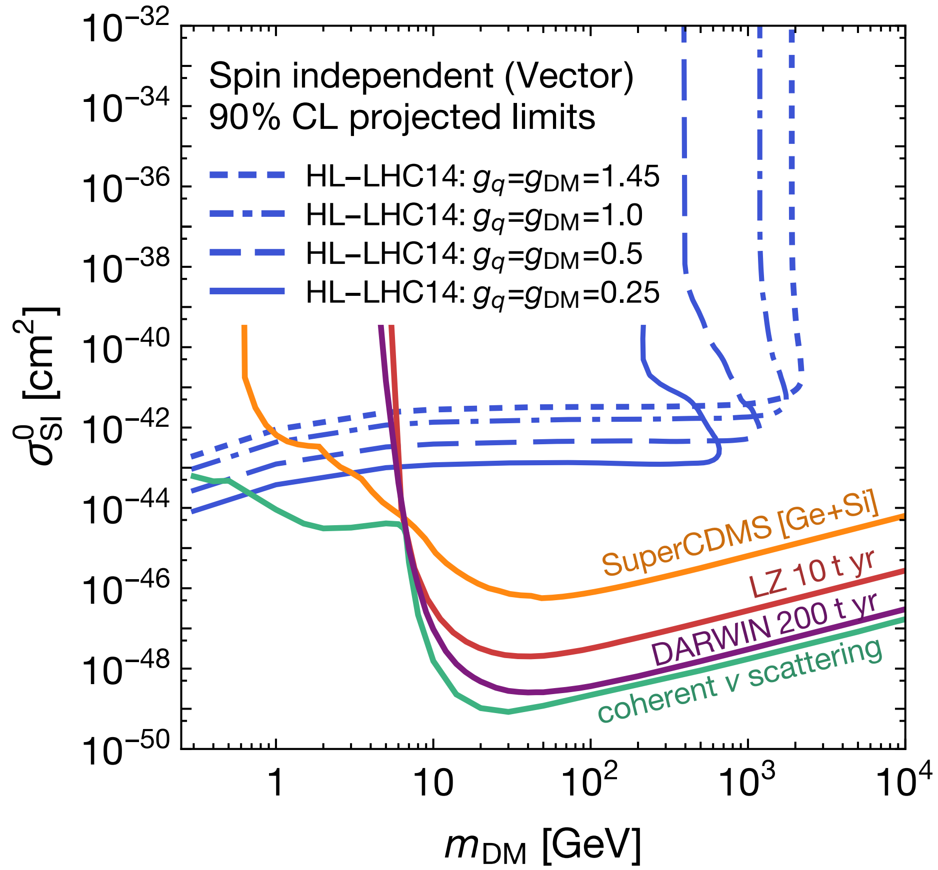
XENON collaboration: JCAP04(2016)027

WIMP physics: complementarity with the LHC

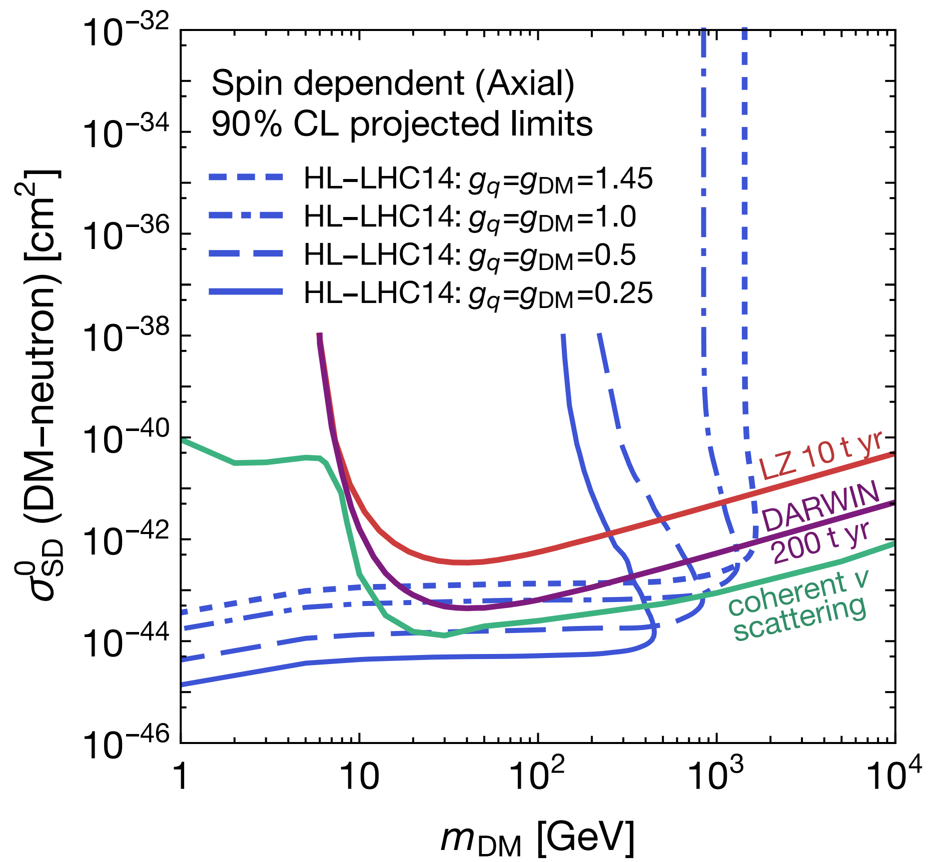
- Minimal simplified DM model with only 4 variables: m_{DM}, M_{med}, g_{DM}, g_q
- Here DM = Dirac fermion interacting with a vector or axial-vector mediator; equal-strength coupling to all active quark flavours

$$\sigma_{\rm DD} \propto \frac{g_{\rm DM}^2 g_q^2 \mu^2}{M_{\rm med}^4}$$

Spin independent



Spin dependent



S. Malik et al., Phys. Dark Univ. 9-10 (2015) 51-58