Universität Zürich[UZH]

DARWIN-LXe: a future large dark matter and neutrino observatory at LNGS

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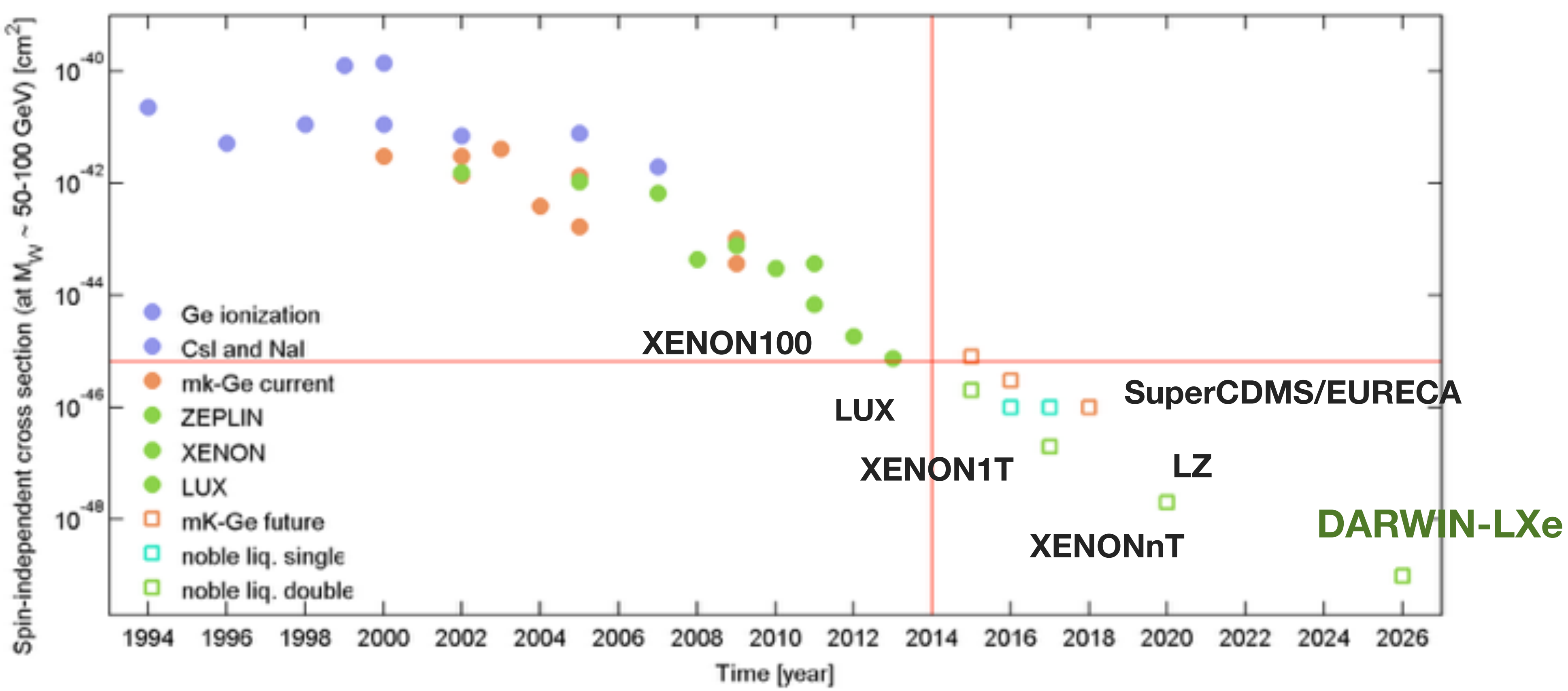
Assergi, April 28, 2015

DARWIN

darwin-observatory.org

DARWIN-LXe General Goals

- Build a dark matter detector capable of exploring the experimentally accessible parameter space for WIMP dark matter
- Base this detector on a TPC filled with Xe in its liquid form, a concept successfully proven by the ZEPLIN, XENON, PandaX, and LUX programs
- Reach a low energy threshold and an absolute ultra-low background, and probe a variety of physics channels

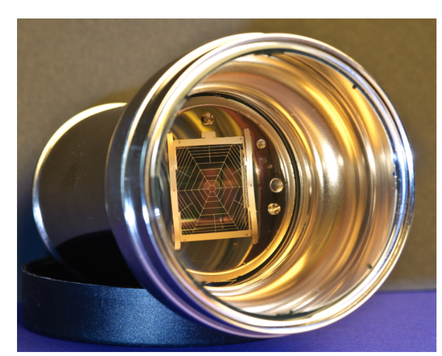


DARWIN-LXe Science Goals: Overview

- **Probe WIMP-nucleon interactions for WIMP masses above 6 GeV/c^2**
  - via spin-independent, spin-dependent and inelastic interactions
  - probe even lower WIMP masses by using the charge signal alone
- **Look for signatures of DM scattering off electrons**
- Detect solar neutrinos: pp-neutrinos via nu-e scattering, ^{8}B coherent nu scattering
- Search for the neutrinoless double beta decay in ^{136}Xe
- Probe interaction of solar axions and axion-like particles, via the axio-electric effect
- Probe sterile neutrinos with masses in the > 10 keV range
- Probe bosonic SuperWIMPs via their absorption by Xe atoms

DARWIN-LXe TPC *baseline* concept

- 30-50 tons LXe in total
- ~ few x 10^3 photosensors
- >2 m drift length
- >2 m diameter TPC
- PTFE walls with Cu field shaping rings
- Background goal: dominated by neutrinos



3-inch PMT, R11410-21

4-inch PMT

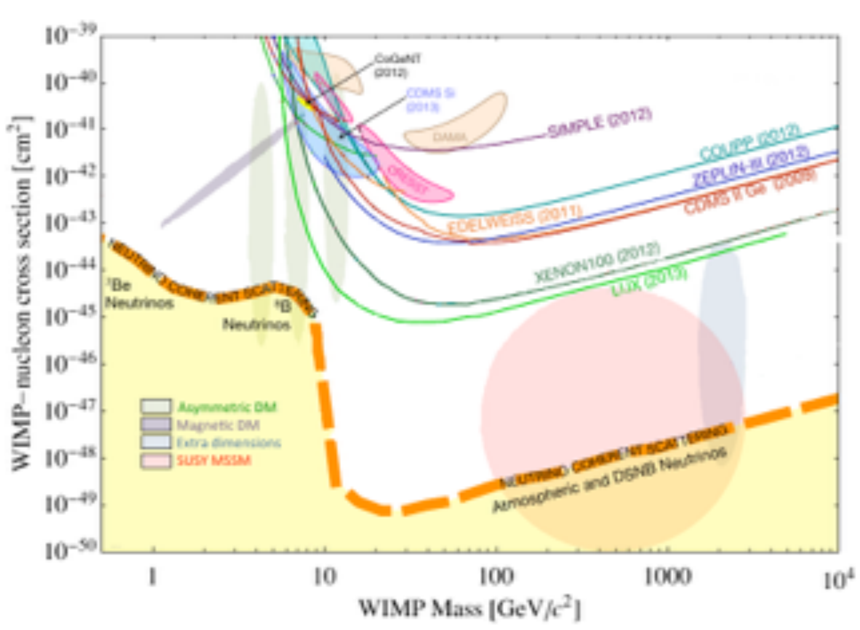
Science reach: WIMP physics with xenon

Probe WIMP-Xe interactions via:

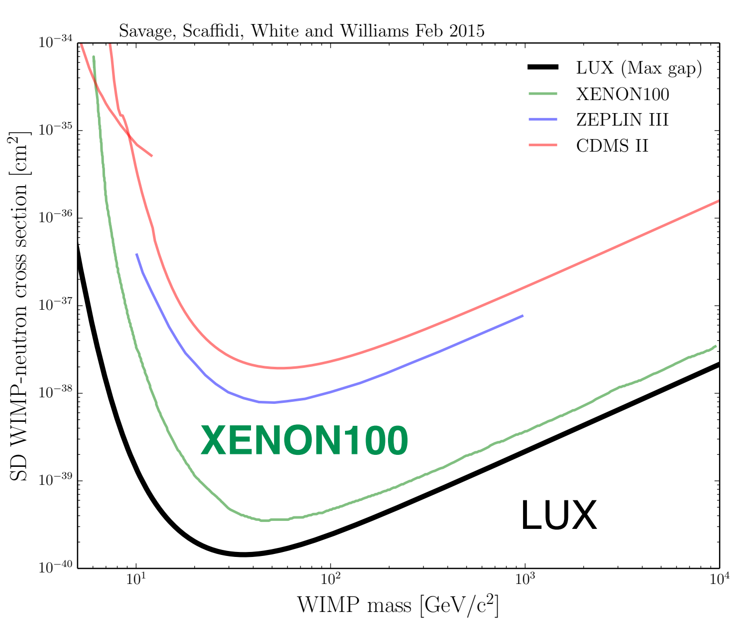
- spin-independent elastic scattering: ^{124}Xe, ^{126}Xe, ^{128}Xe, ^{129}Xe, ^{130}Xe, ^{131}Xe, ^{132}Xe (26.9%), ^{134}Xe (10.4%), ^{136}Xe (8.9%)
- spin-dependent elastic scattering: ^{129}Xe (26.4%), ^{131}Xe (21.2%)
- inelastic WIMP-^{129}Xe and WIMP-^{131}Xe scatters $\chi + ^{129,131}Xe \rightarrow \chi + ^{129,131}Xe^* \rightarrow \chi + ^{129,131}Xe + \gamma$

1 ns, 0.5 ns　　40 keV, 80 keV

SI, elastic WIMP-nucleus

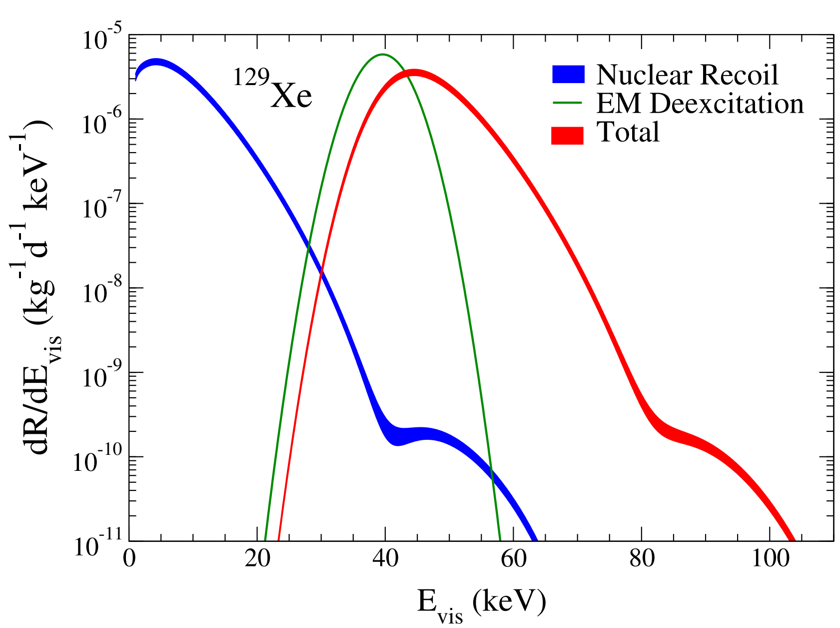


SD, elastic WIMP-nucleus



C. Savage et al, arXiv:1502.02667

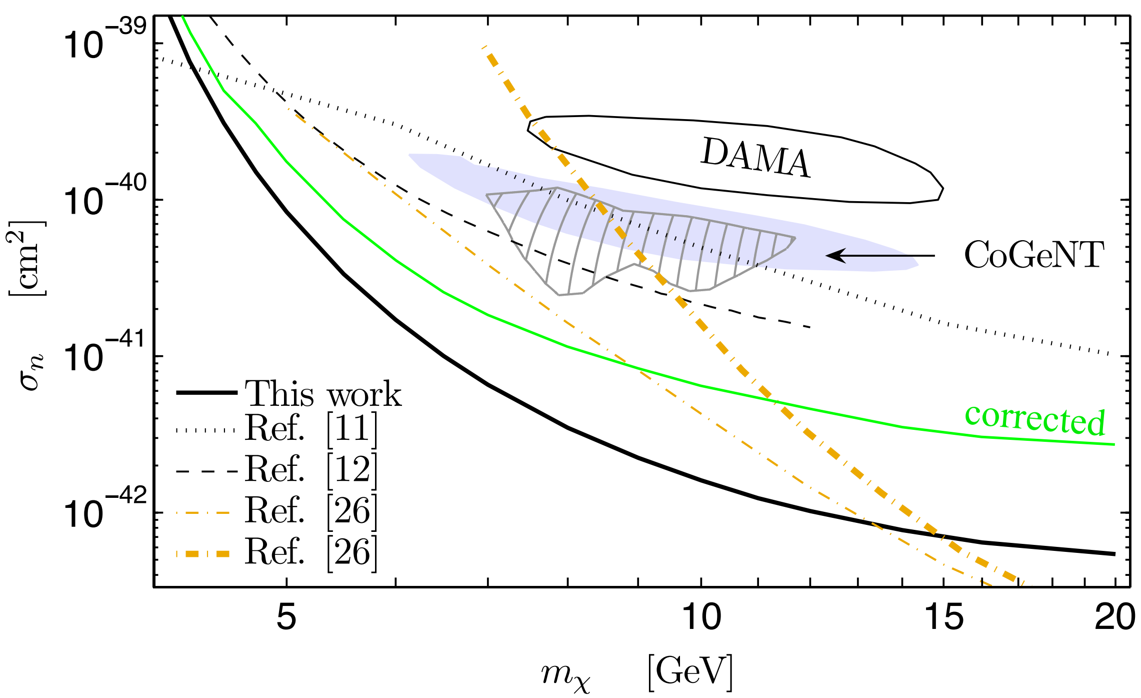
SD, inelastic WIMP-nucleus

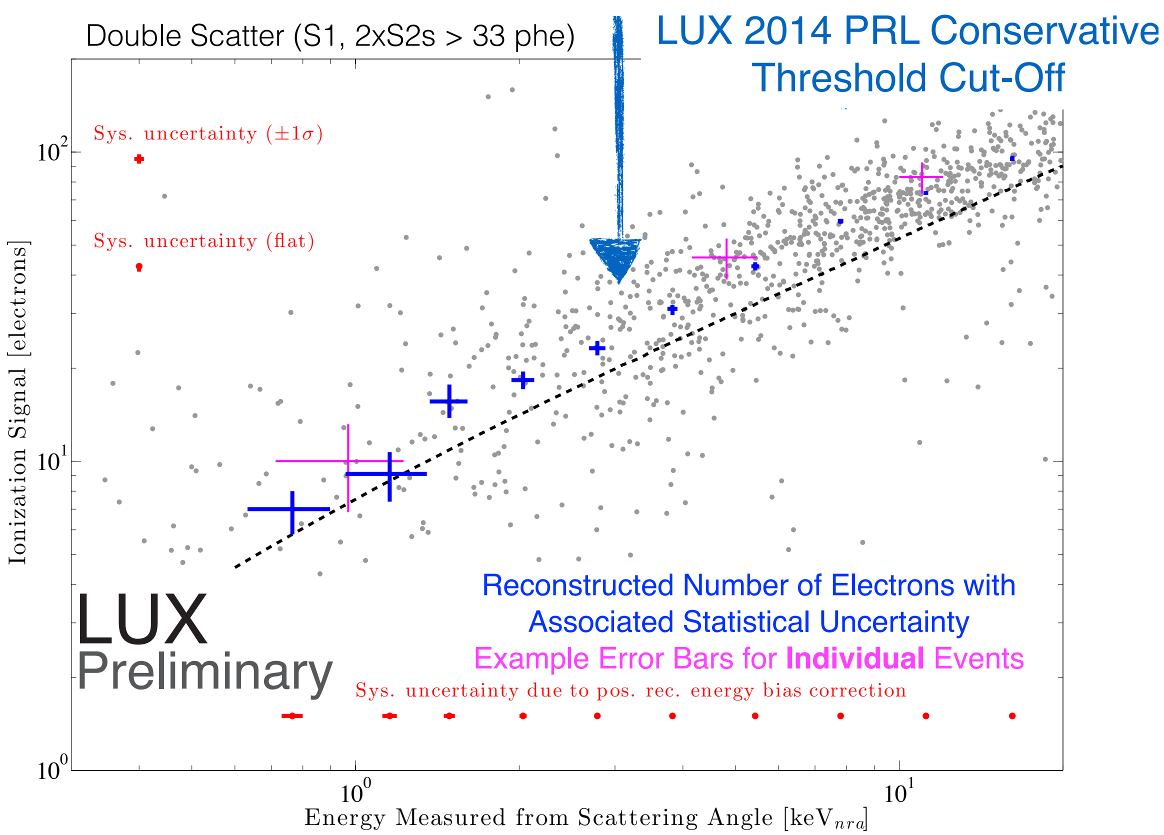


L. Baudis et al, Phys. Rev. D 88, 115014 (2013)

Physics reach: low WIMP masses

XENON 10 result, PRL107/110



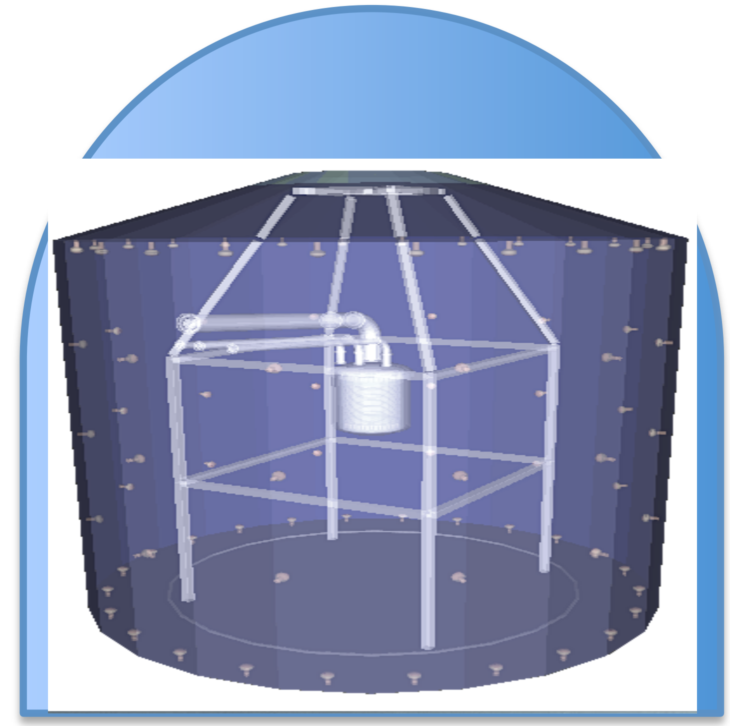


- Achieve a lower energy threshold for NRs if the energy is measured by the S2 signal (e$^-$), with ~ 20-25 PE per extracted e$^-$ in the gas phase
- **XENON10: threshold of E_{nr} ~ 1 keV reached**
- **XENON100: analysis ongoing**
- Loss of S2/S1 discrimination: sensitivity reduction by ~ factor 100, compared to higher WIMP masses; acceptable because at low WIMP masses the solar neutrinos will dominate the NR rate
- **LUX (APS2015): ionization signal absolutely measured below 1 keVnr**

Backgrounds

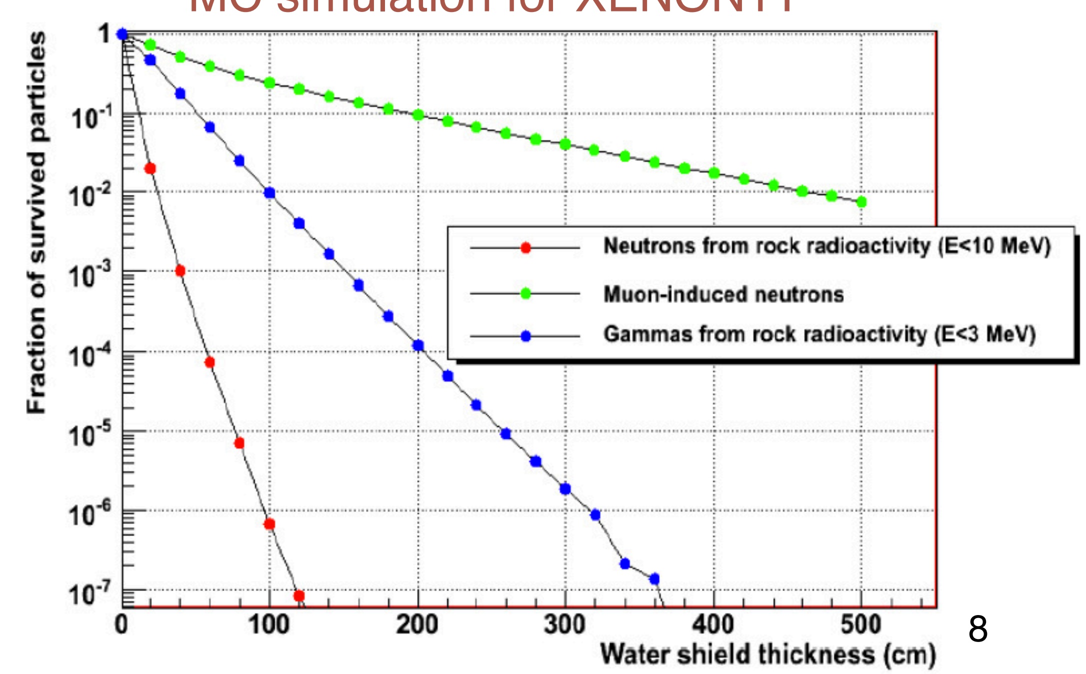
Backgrounds: nuclear recoils

- **Radiogenic** goal: <7 x 10^{-4} events/(t y)
  - active LS veto around cryostat under study
- **Cosmogenic** (MC: 7.3 x 10^{-10} n/(cm^2 s) for E_n > 10 MeV)
  - <0.01 events/(t y) in XENON1T/nT shield
  - **<<0.003 events/(t y) in 14 m diameter water shield**
- **XENON1T muon veto performance must be improved by ~ a factor of 10 (very conservative)**
- Alternative: line the experimental hall with muon veto (multi-layered proportional tubes, as in Soudan Lab)



DARWIN-LXe in 14 m ø water Cherenkov shield

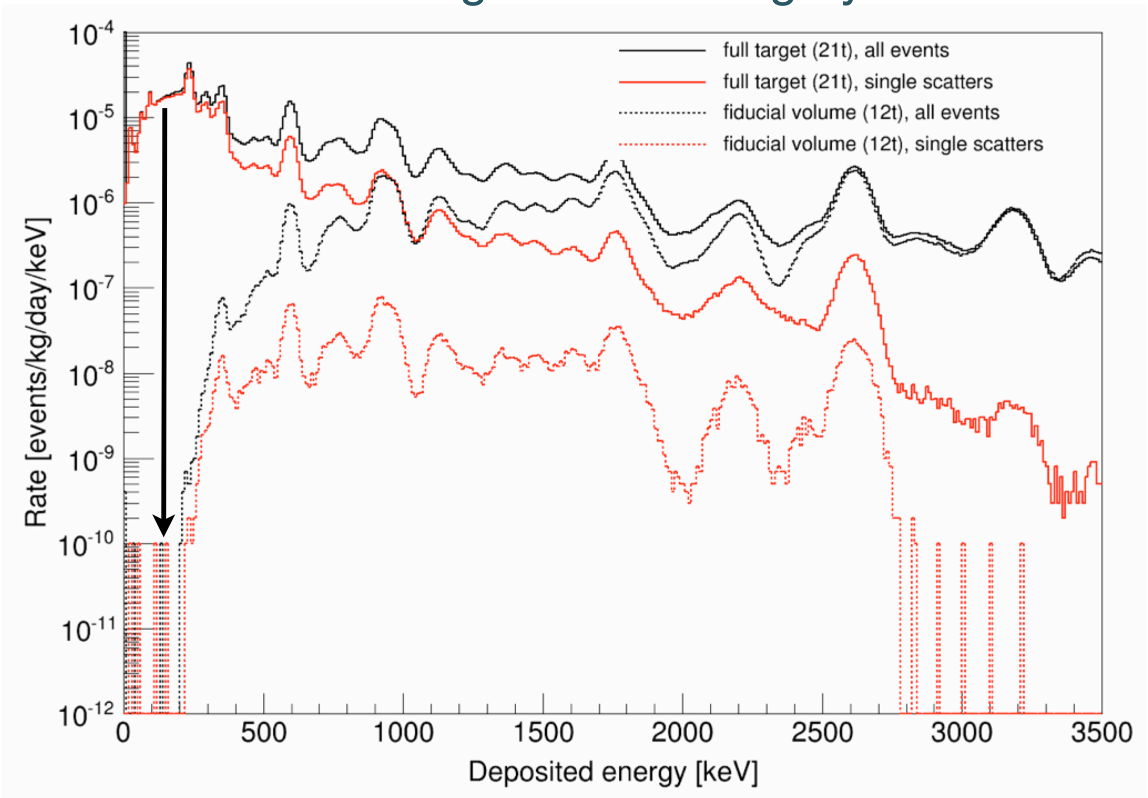
MC simulation for XENON1T



Backgrounds: electronic recoils

- Materials (cryostat, photosensors, TPC)
- ^{222}Rn in LXe
- ^{nat}Kr in LXe (^{nat}Kr contains 2 x 10^{-11} ^{85}Kr)
- ^{136}Xe double beta decay
- Solar neutrinos (mostly pp, ^{7}Be)

Materials: strong self-shielding by dense LXe



Channel	Before discr	After discr (99.98%)
pp + ^{7}Be neutrinos	95	0.488
Materials	1.4	0.007
^{85}Kr in LXe (0.1 ppt ^{nat}Kr)	40.4	0.192
^{222}Rn in LXe (0.1 μBq/kg)	9.9	0.047
^{136}Xe	56.1	0.036

1 t x yr exposure, 2-30 keVee

200 t x yr exposure 4-50 keVnr, 30% acceptance

Backgrounds: electronic recoils

- Materials (cryostat, photosensors, TPC)
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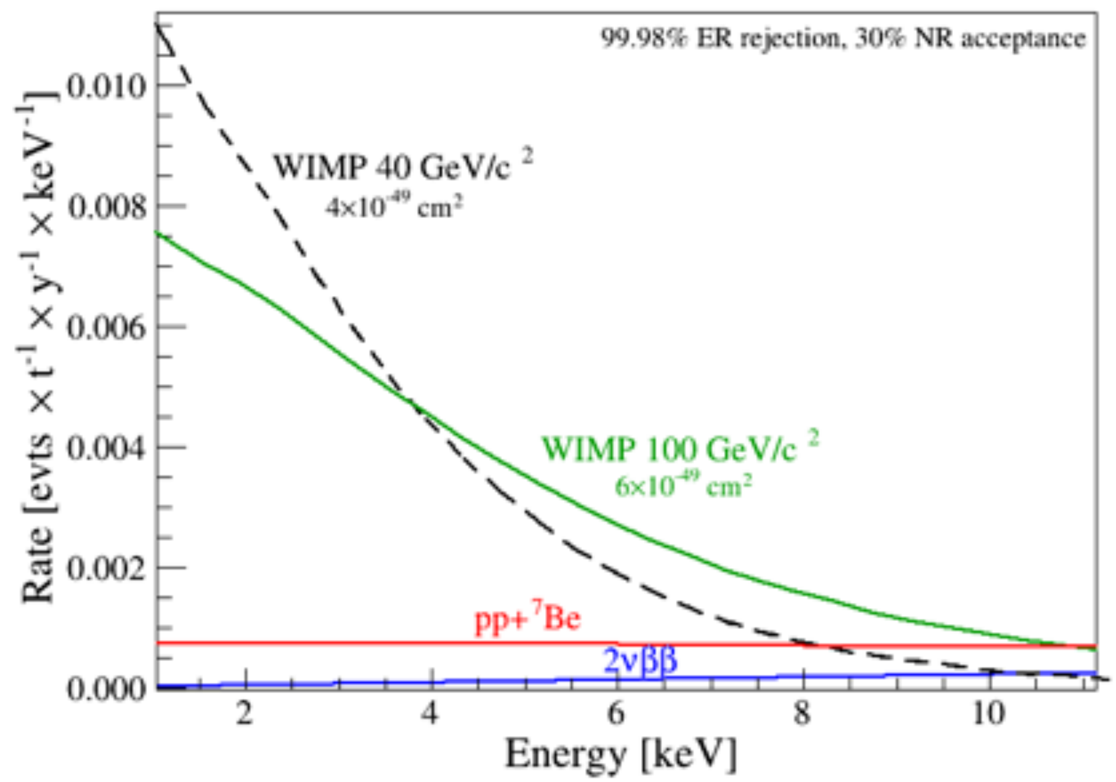
WIMPs and ER backgrounds



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1 t x yr exposure,
2-30 keVee

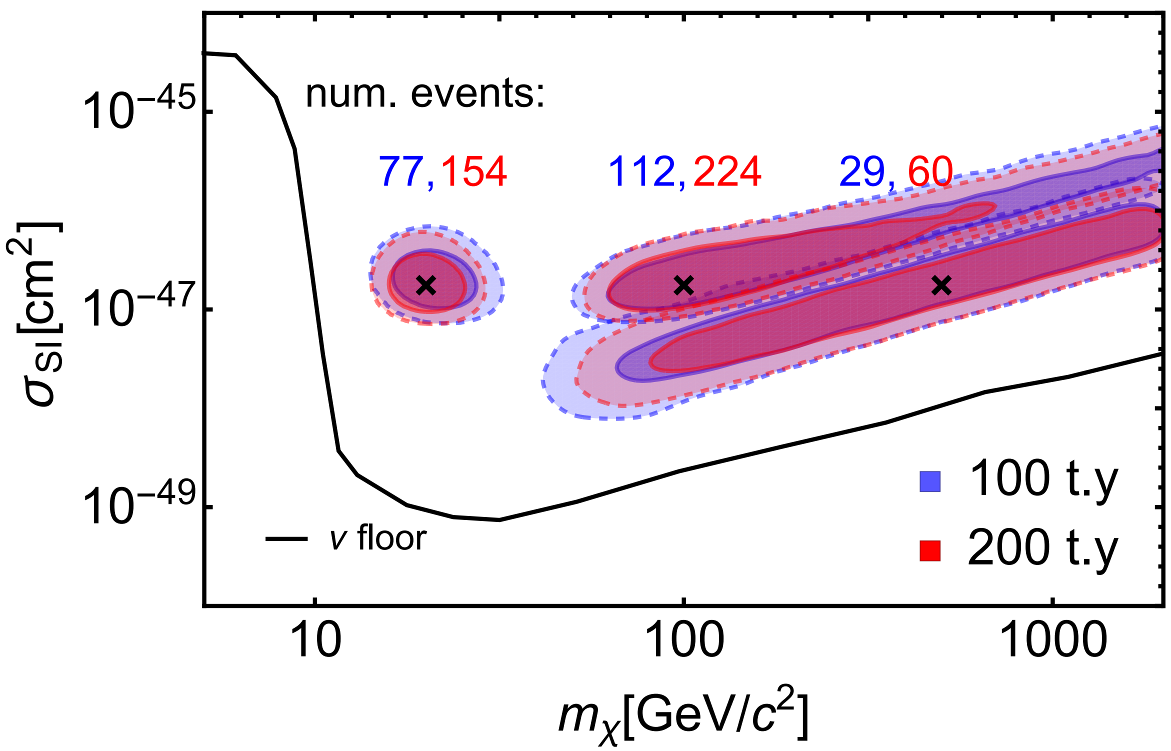
200 t x yr exposure
4-50 keVnr, 30% acceptance

WIMP physics

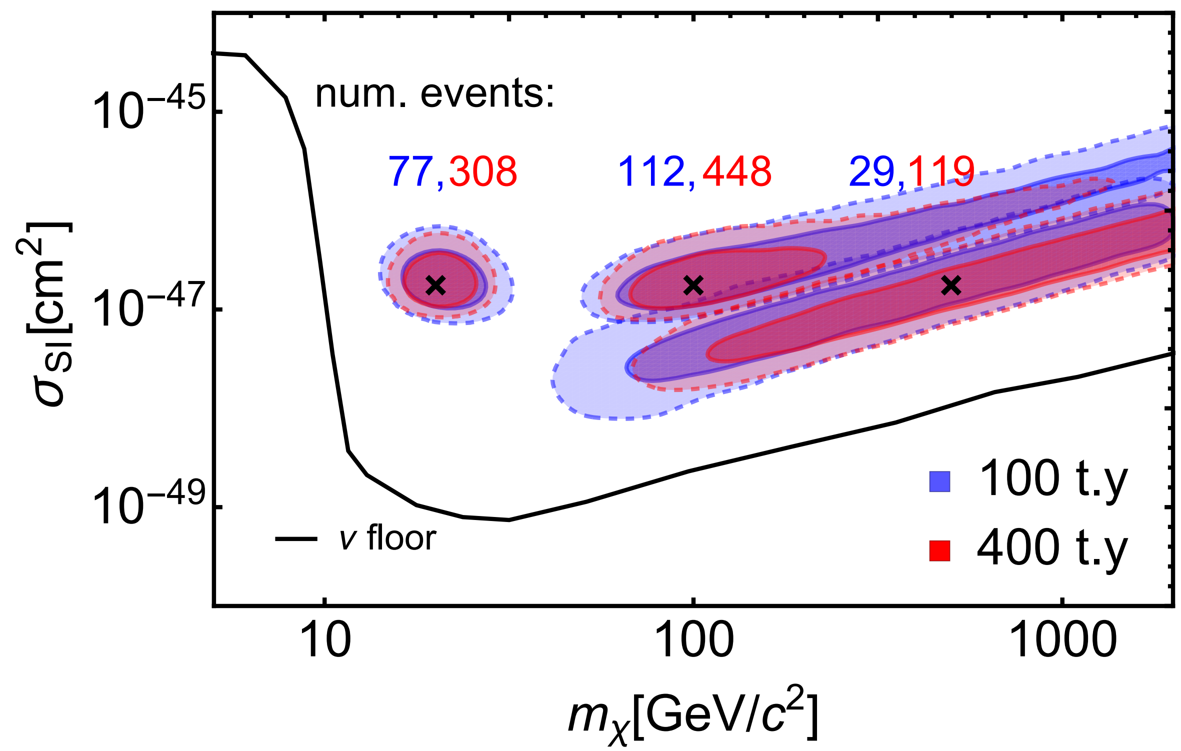
WIMP physics: spectroscopy

- Capability to reconstruct the WIMP mass and cross section for various masses (**20, 100, 500 GeV/c²**) and a spin-independent cross section of 2×10^{-47} cm² (assuming different exposures)

Exposure: 100 t y; 200 t y



Exposure: 100 t y; 400 t y



1 and 2 sigma credible regions after marginalizing the posterior probability distribution over:

$$v_{esc} = 544 \pm 40\,\mathrm{km/s}$$

$$v_0 = 220 \pm 20\,\mathrm{km/s}$$

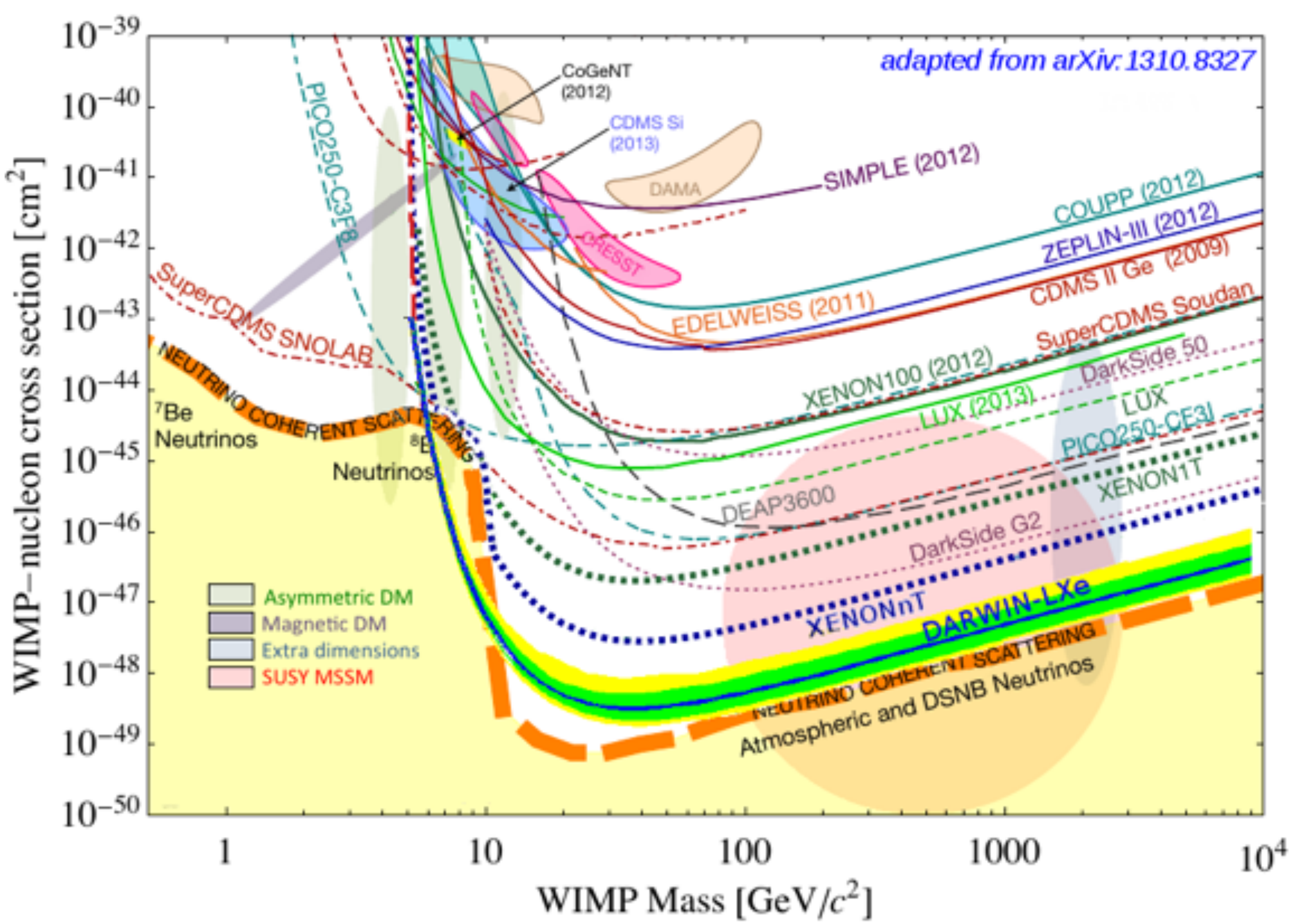
$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$$

Update: Newstead et al., PHYSICAL REVIEW D 88, 076011 (2013)

WIMP physics: sensitivity

- E = [3-70] pe ~ [4-50] keV_{nr}

200 t y exposure, 99.98% discrimination, 30% NR acceptance, LY = 8 pe/keV at 122 keV



Note: “nu floor” = 3-sigma detection line at 500 CNNS events above 4 keV

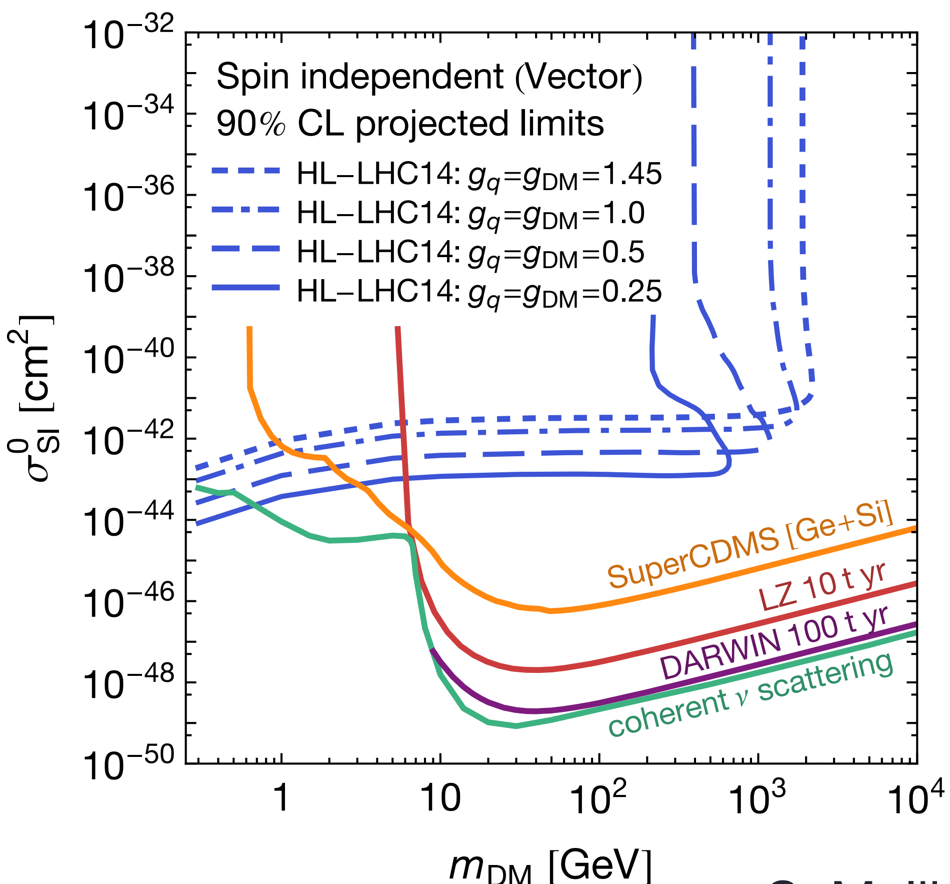
WIMP physics: complementarity with the LHC

- Minimal simplified DM model with only 4 variables: m_{DM}, M_{med}, g_{DM}, g_q

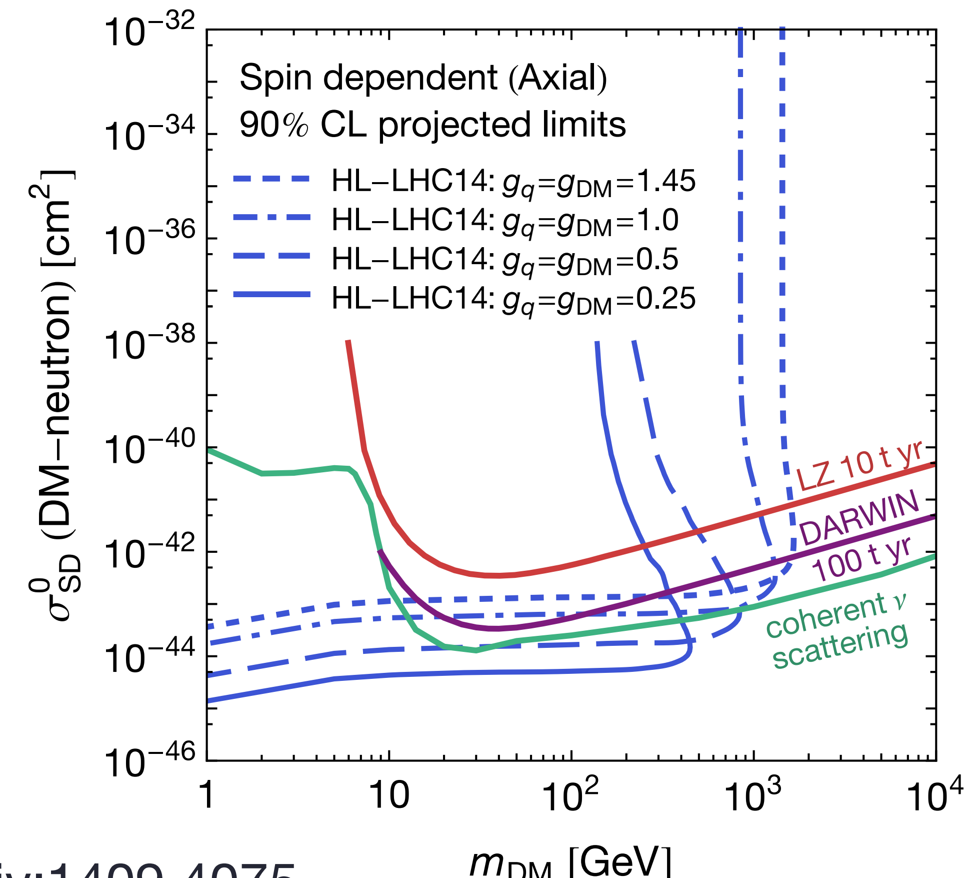
- Here DM = Dirac fermion interacting with a vector or axial-vector mediator; equal-strength coupling to all active quark flavours

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

Spin independent



Spin dependent



S. Malik et al., arXiv:1409.4075

Technical challenges

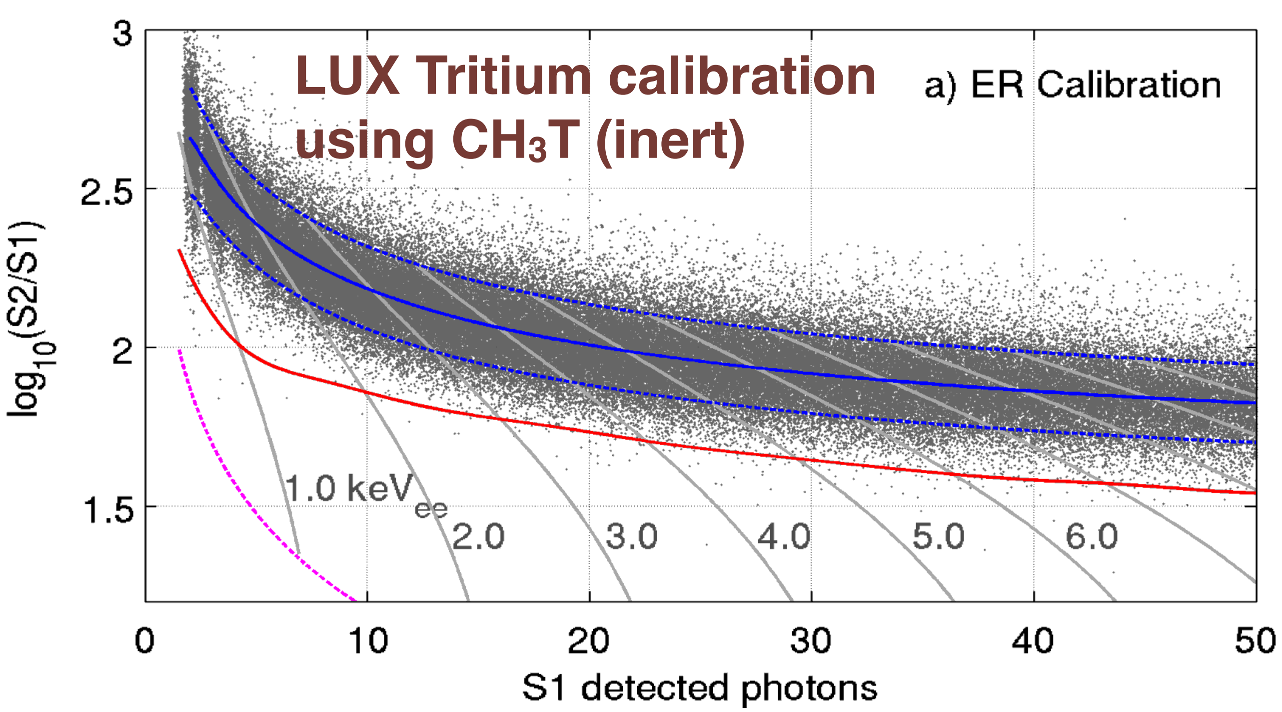
Technical challenge: discrimination

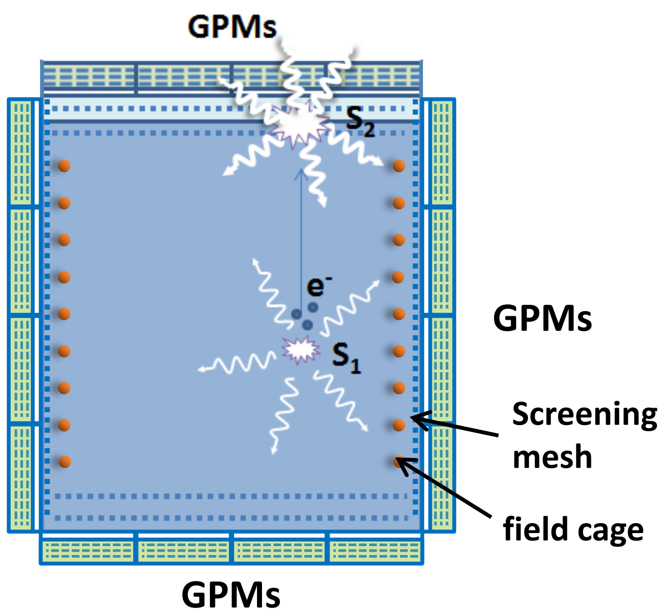
- **A level of 99.98% needs factor of 5 improvement w.r.t. XENON100**

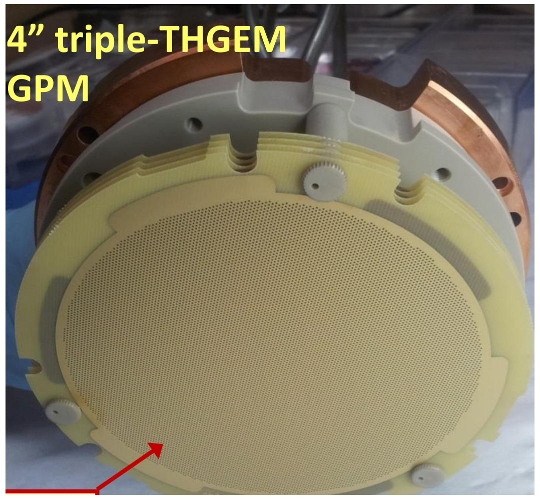
➡ high light yield - R&D for high (4-pi) coverage with photosensors is ongoing; options are high QE PMTs, SiPMs and/or GPMs; single-phase TPC

➡ **strong R&D program in place**

➡ high stats ER band calibrations - internal sources, for instance tritiated methane à la LUX; also ^{220}Rn





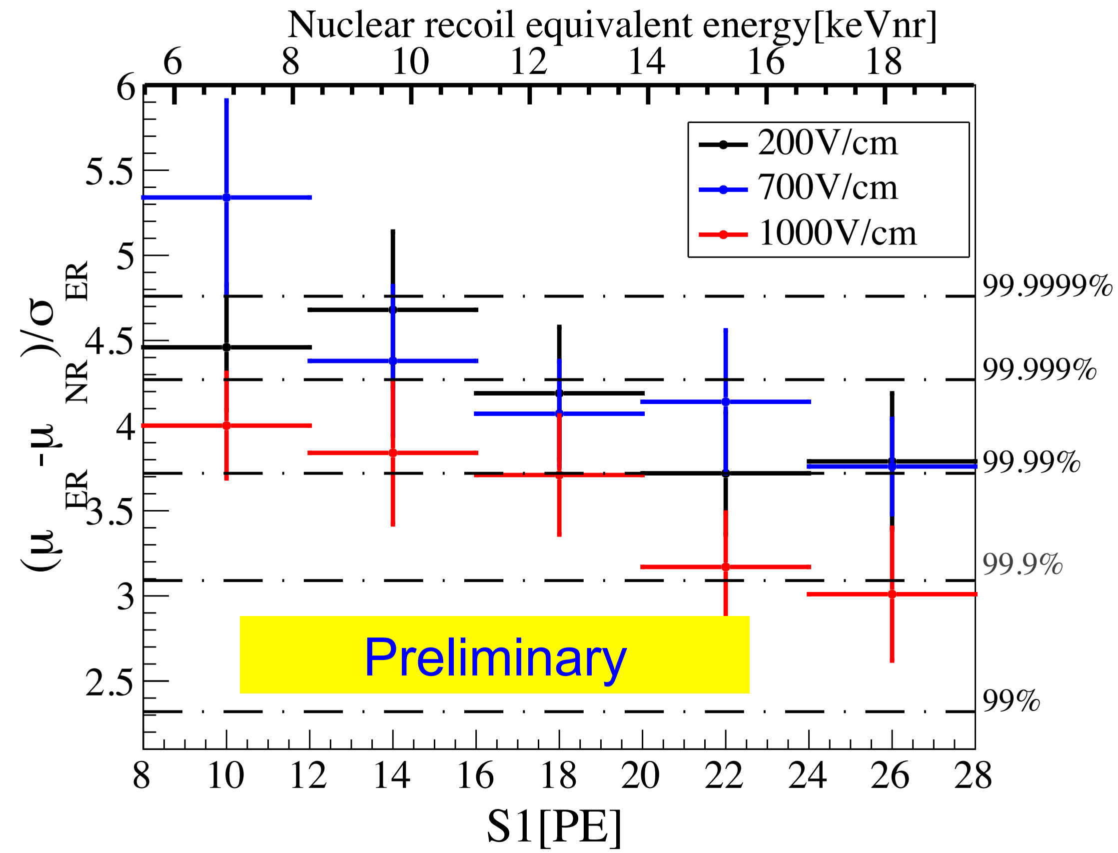


A. Breskin, L. Arazi: bialkali GPM stable operation at gain of 1e5

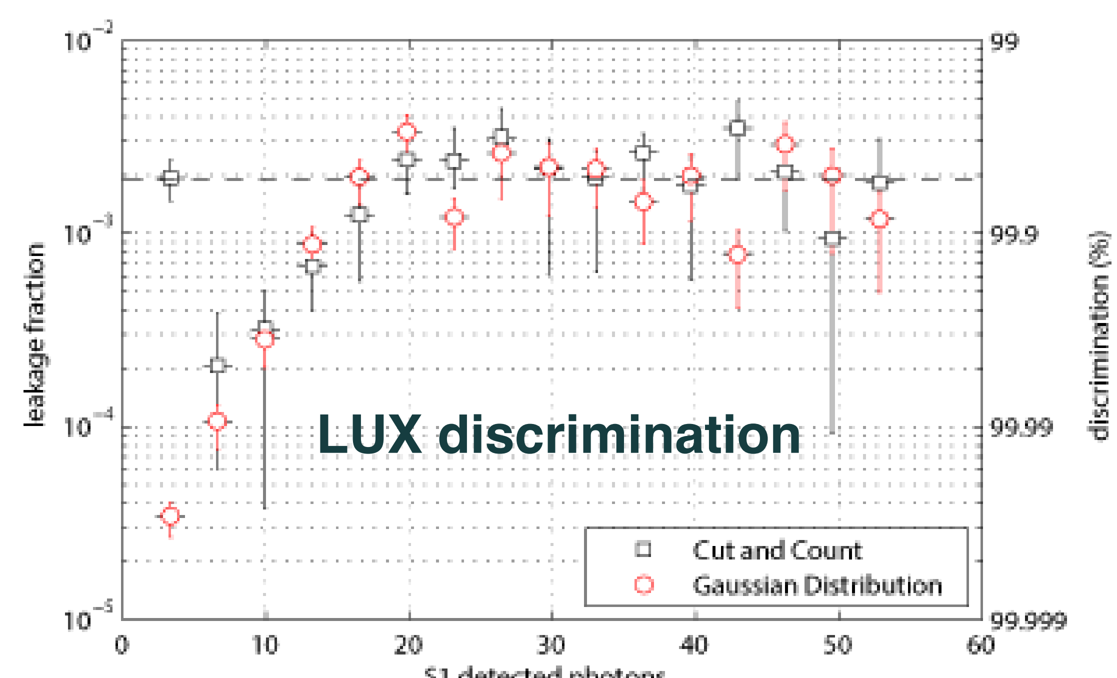
Technical challenge: discrimination

K. Ni, AP2014

- **Best value in LXe by ZEPLIN-III, 99.987%**
- LUX: 99.9% - 99% (at 50% NR acceptance)
- K. Ni: ER power > 10^5 at 50% acceptance
  - **weak dependance on field strength, but field uniformity crucial**

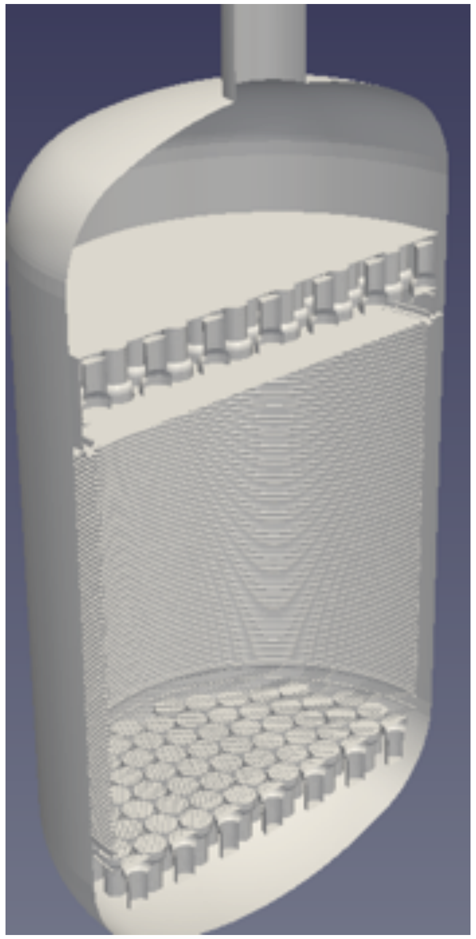


	Field (kV/cm)	Light yield (pe/keVee, for 122 keV at zero field)	Energy ROI (keVnr)	NR acceptance	ER rejection power
ZEPLIN-II	1.0	1.1	14-58	50%	98.5%
XENON10	0.73	5.4	4.5~26.9	45%~49%	99.9~99.3%
ZEPLIN-III	3.4	3.1-4.2	7-35	~50%	99.987%
XENON100	0.53	3.8	6.6-43.3	60%~20%	99.75%
LUX	0.18	8.8	3-27	50%	99.9~99%

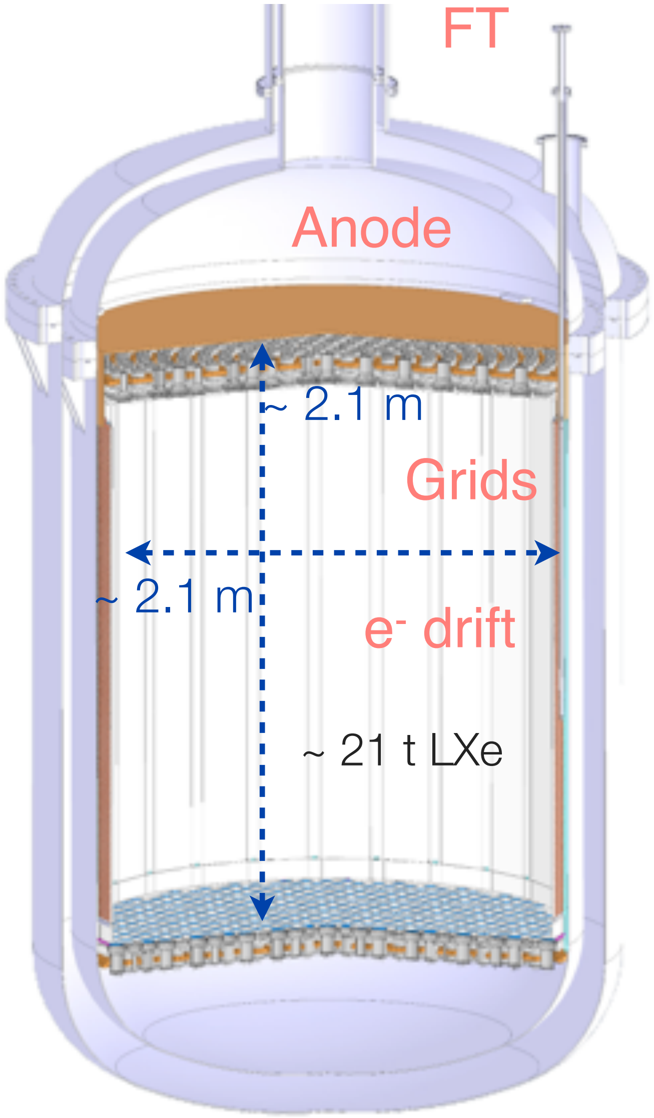


Technical challenge: HV, drift field

- Electron drift length of > 2 m, high purity, and uniform field at the 1% level
- HV to bias the cathode must be -100 to -200 kV to have a drift field of 0.5 - 1 kV/cm
    - build long, >2m TPC demonstrator(s)
- Robust, and transparent grid or wire electrodes with >2 m diameter
- Challenge is to combine thin wires O(100 μm) to ensure high LCE
    - build shallow, >2m diam. TPC demonstrator(s)
- Very precise, 3D field simulations based on the BEM technique



Geometry in the BEM simulation software



Technical challenge: liquid target

- Procurement, storage, cooling, high-speed purification of 30-50 t of LXe
  - **coordinate procurement among institutions, funding agencies and companies**
- Storage: à la ReStoX, developed for XENON1T/nT, acts as a demonstrator
  - **possible solution: a network of connected ReStoX, with a main storage directly connected to the cryostat**
  - **study a different mechanism for recovery, based on gravity (recuperation pipe below cryostat)**

ReStoX: can store up to 7.6 t of xenon

Max heat leak: ~50 W

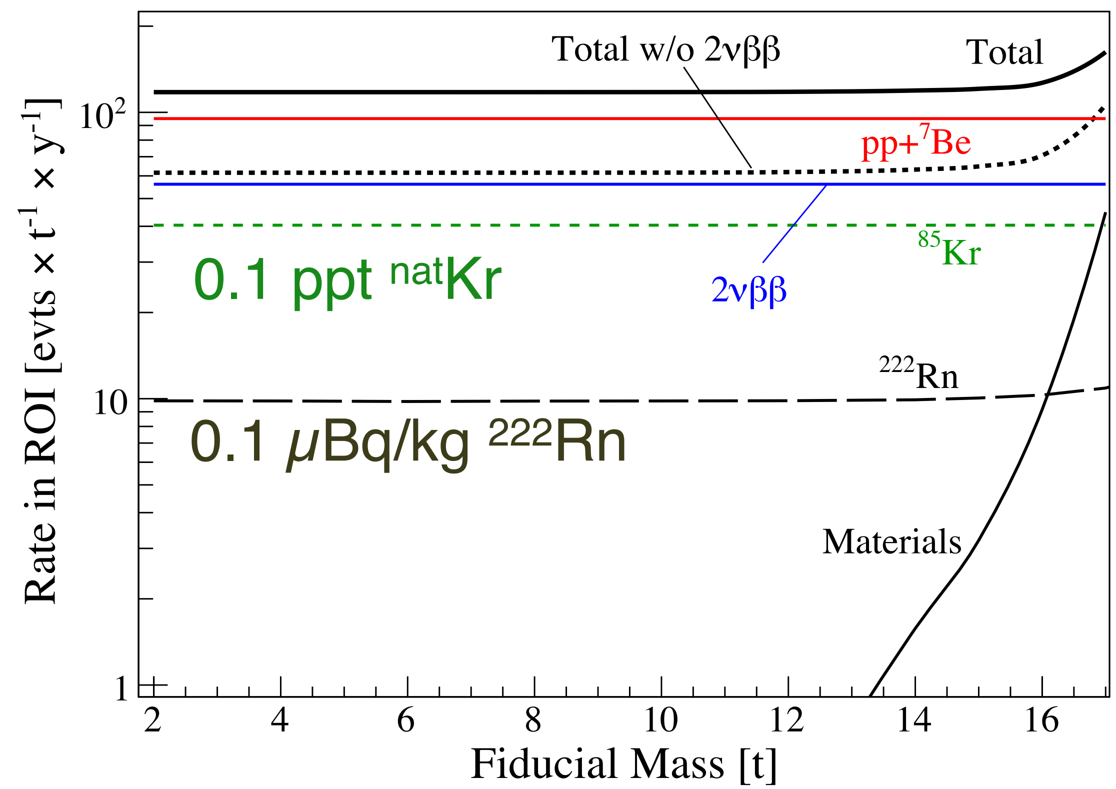
Technical challenge: backgrounds

- **ER dominance by solar neutrinos needs:**

  ➡low intrinsic levels of ^{85}Kr and ^{222}Rn

- **^{85}Kr: 0.1 ppt ^{nat}Kr (0.2 ppt ^{nat}Kr** => same background level as solar neutrinos)
  - **0.2 ppt is goal for XENON1T, factor 20 better than this already achieved by Münster group*: separation factor > 120000!)**

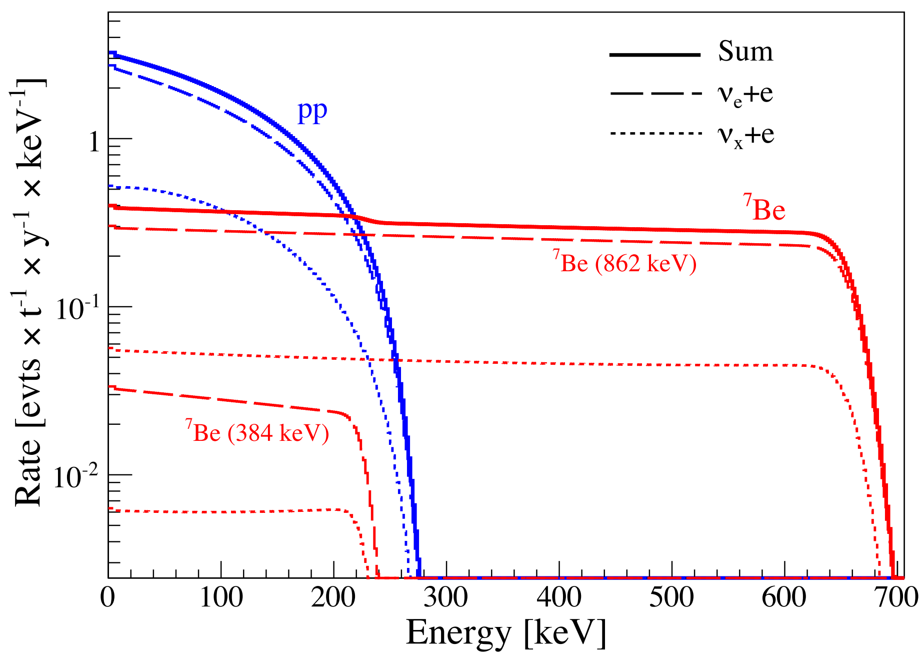
- **^{222}Rn: 0.1 µBq/kg (1 µBq/kg** => same background level as solar neutrinos)
  - **1 µBq/kg is goal for XENON1T): control Rn levels with low-emanation materials & cryogenic distillation (use different vapour pressure), adsorption**

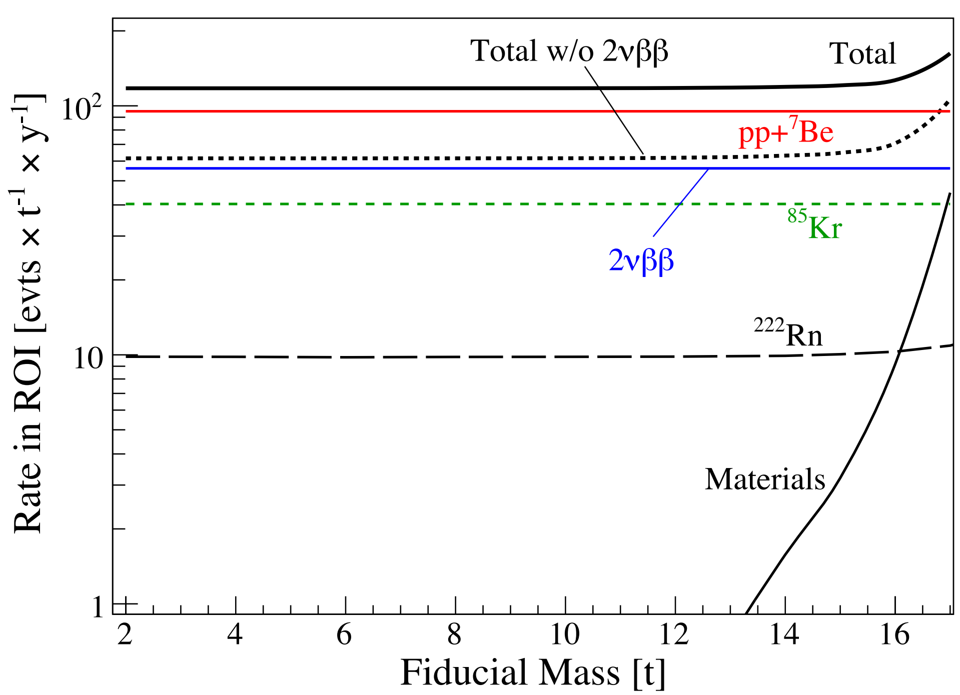


*M. Murra, Münster, DPG 2015: Purified liquid out: ^{nat}Kr/Xe < 26e-15 = 26 ppq (90% CL); measured with MPIK RGMS system

Other physics channels

Physics reach: solar neutrinos $\nu + e^- \rightarrow \nu + e^-$





Details see: L. Baudis et al, JCAP01 (2014) 044

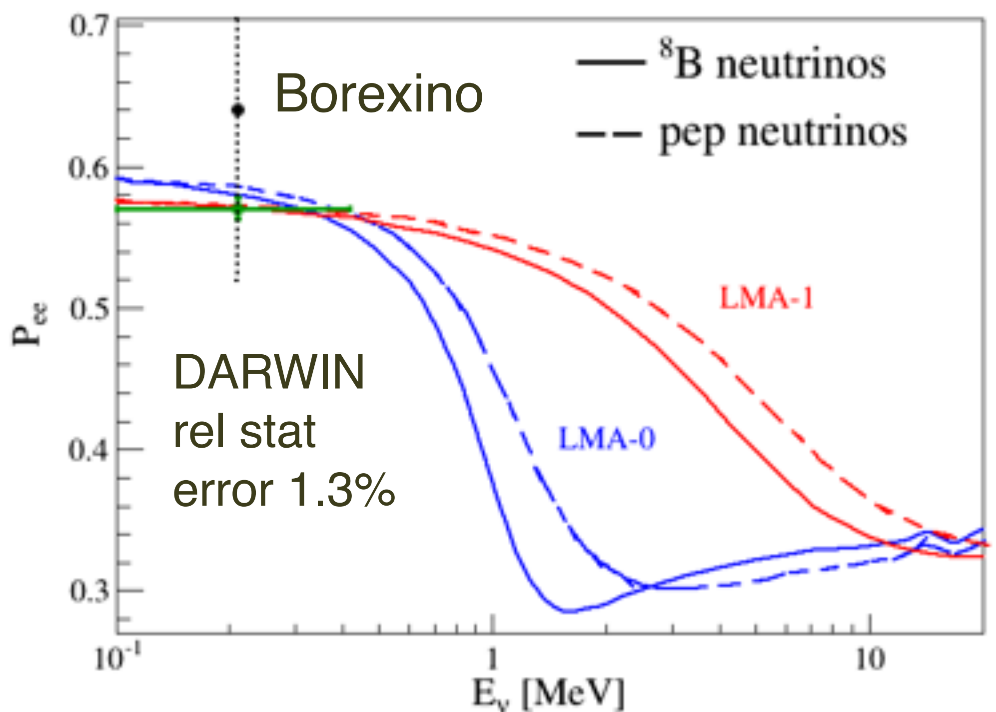
- Rate of solar neutrinos > 2 keV

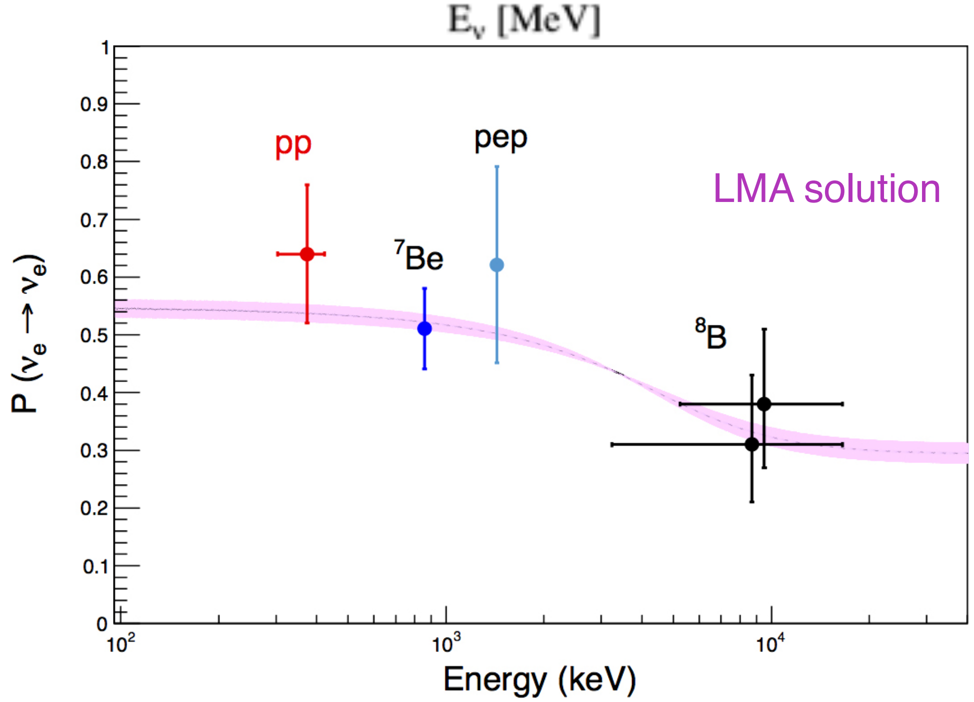
$$R_{pp} \simeq 1.05 \text{ events}/(\text{t d})$$

$$R_{^7Be} \simeq 0.51 \text{ events}/(\text{t d})$$

- **pp neutrinos (2-30 keV):**
  - 1714 events/(20 t x yr)
- **^{7}Be neutrinos (2-30 keV):**
  - 214 events/(20 t x yr)
- ^{220}Rn: 0.1 μBq/kg; ^{nat}Kr: 0.1 ppt
- Reach ~ 1% precision after 5 years

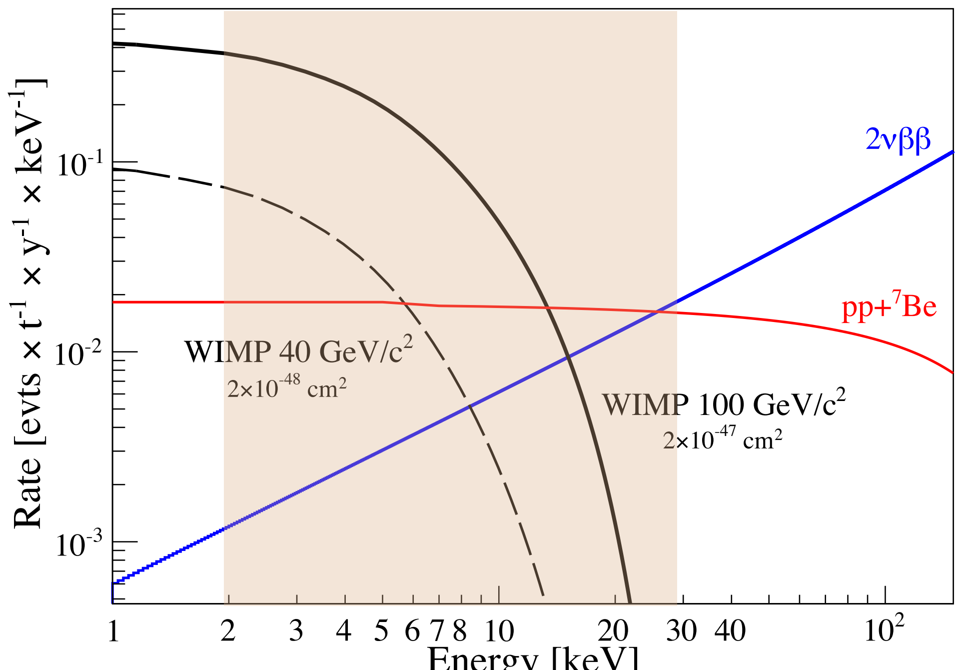
Physics reach: solar neutrinos $\nu + e^- \rightarrow \nu + e^-$



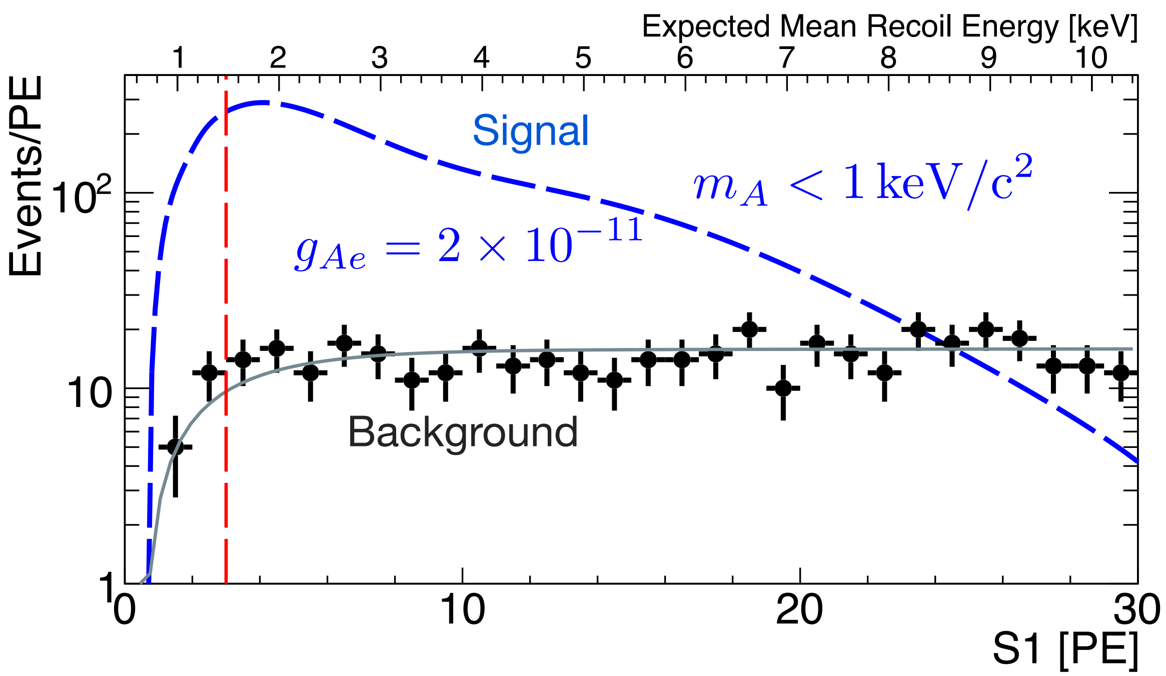


Borexino, Nature 512 (2014) 383

- Reach ~ 1% precision after 5 years
- Test different oscillation scenarios, for instance non-standard neutrino interactions that can modify the P_{ee} of electron neutrinos as a fct of energy
- Even higher stats can be reached with:
  - increased energy range (Xe depleted in ^{136}Xe)
  - larger fiducial mass

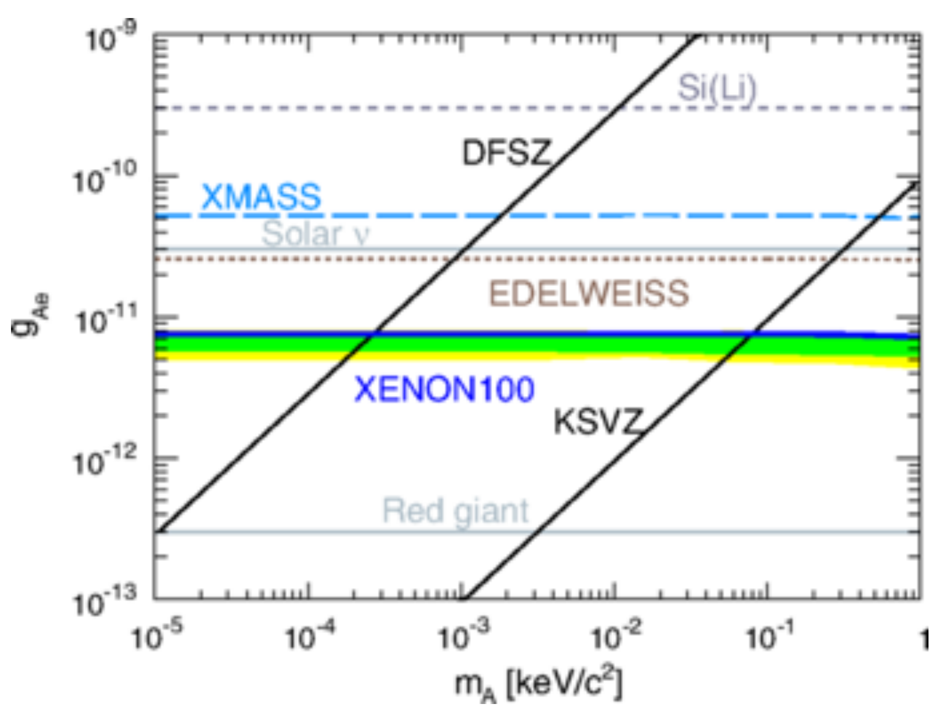


Physics reach: solar axions



Look for solar axions via their couplings to electrons, g_{Ae}, through the axio-electric effect

$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta_A}\frac{3E_A^2}{16\pi\alpha_{em}m_e^2}\left(1 - \frac{\beta_A^{2/3}}{3}\right)$$

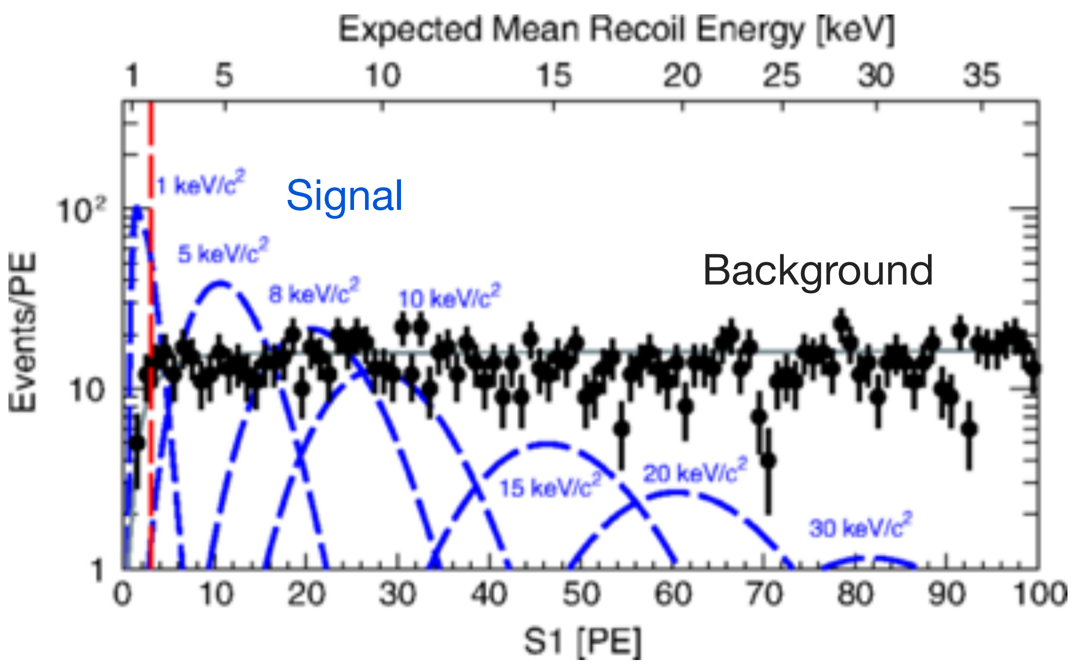


$$\phi_A \propto g_{Ae}^2 \Longrightarrow R \propto g_{Ae}^4$$

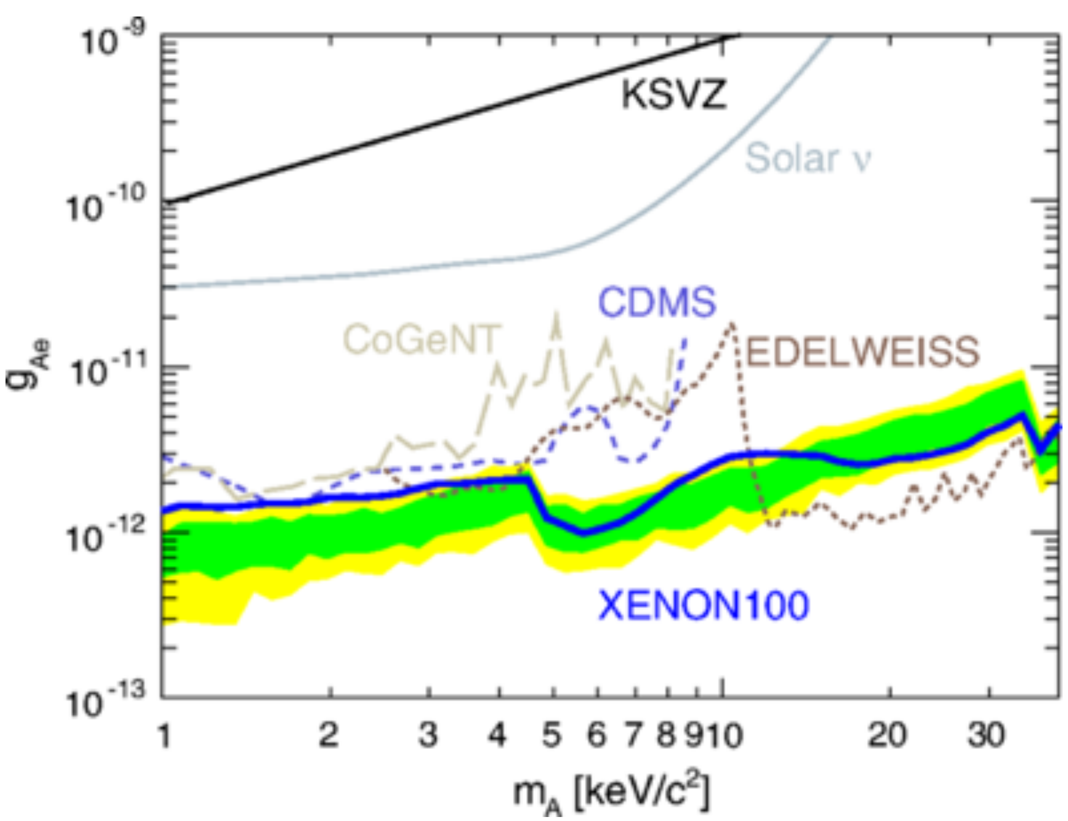
- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs
- **Factor of ~10 improvement with DARWIN**

XENON, Phys. Rev. D 90, 062009 (2014)

Physics reach: galactic axion-like particles (ALPs)



XENON, Phys. Rev. D 90, 062009 (2014)



Look for ALPs via their couplings to electrons, g_{Ae}, through the axio-electric effect

Expect line feature at ALP mass

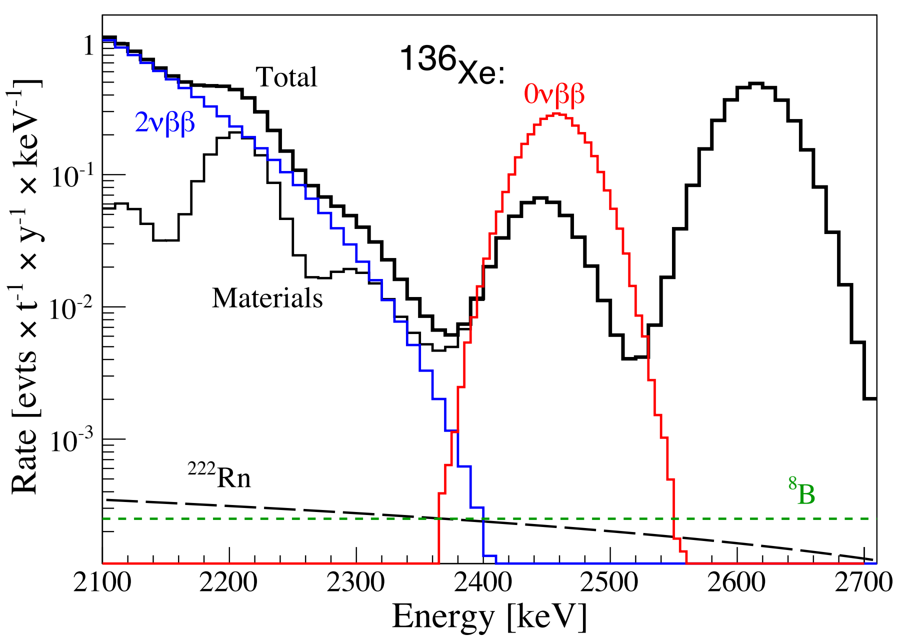
assume $\rho_{dm} = 0.3$ GeV/cm^3

$$\phi_A = c\beta_A \times \frac{\rho_{\rm dm}}{m_A}$$

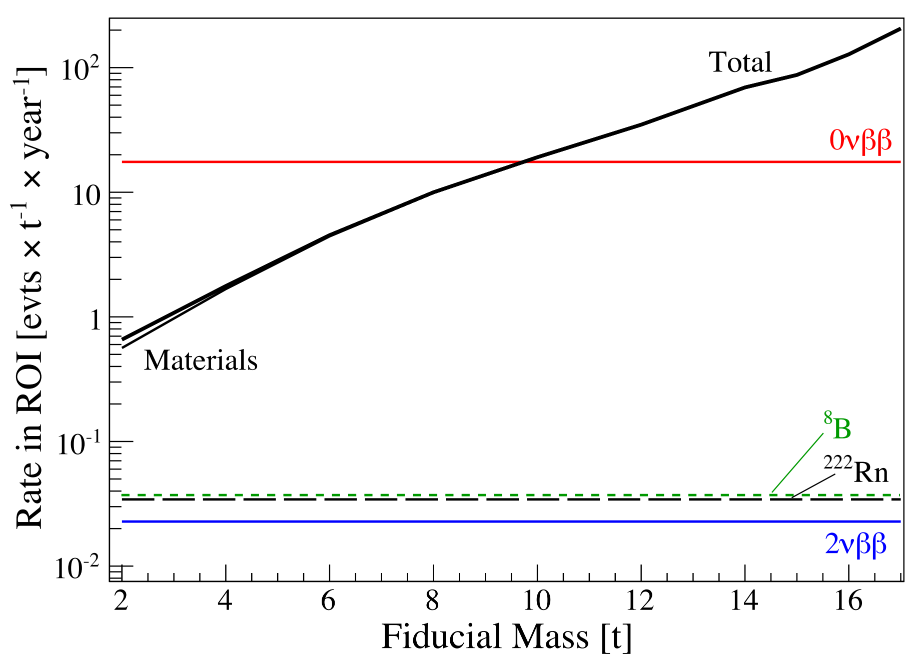
$$R \propto g_{Ae}^2$$

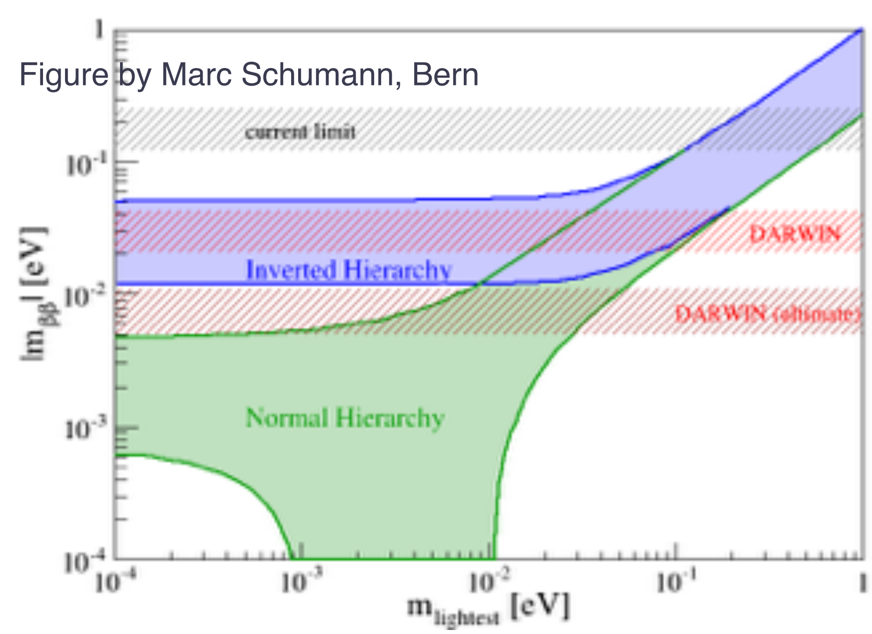
- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs
- **Factor of ~100 improvement with DARWIN**

Physics reach: double beta decay

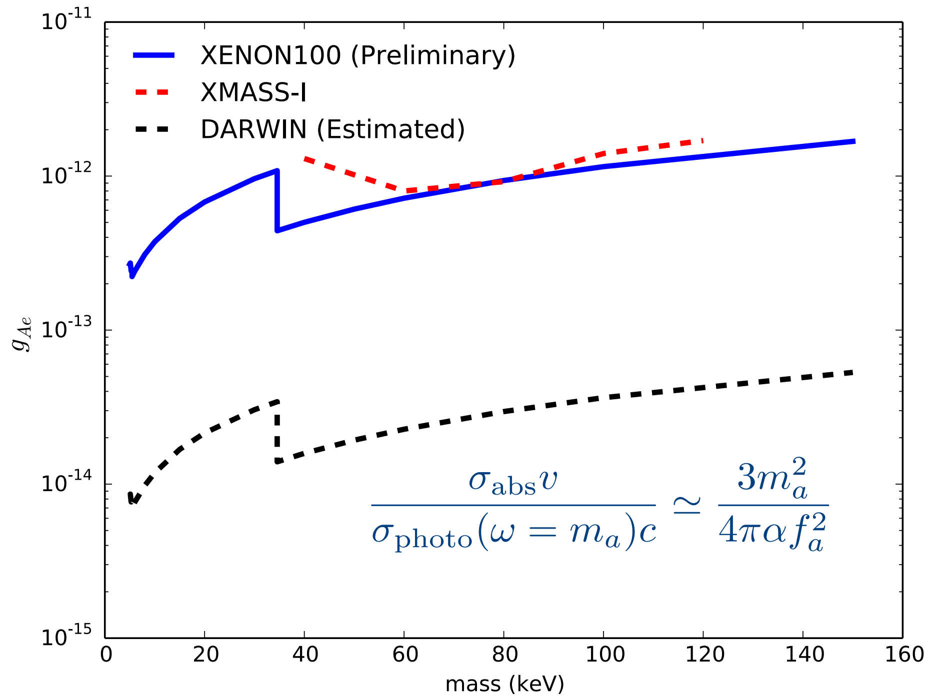


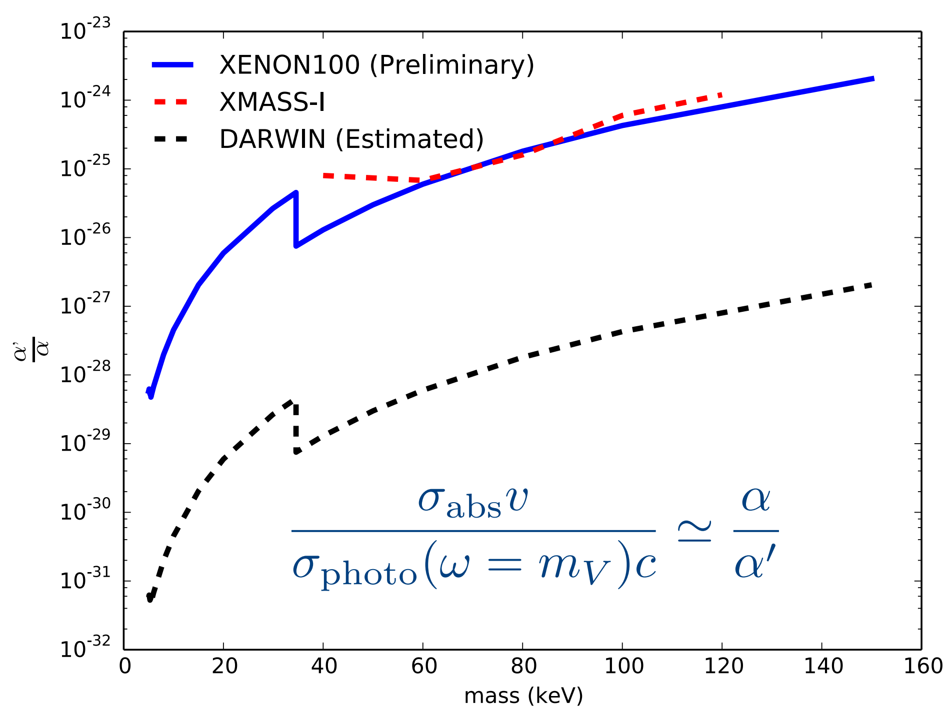
- ^{136}Xe: Q-value = 2458.7 ± 0.6 keV
- Fiducial mass of 6 t of xenon
- sensitivity to the neutrinoless double beta decay of ^{136}Xe:
- **$T_{1/2}$ > 5.6 x 10^{26} yr (95% CL) in 30 t yr**
- **$T_{1/2}$ > 8.5 x 10^{27} yr (95% CL) in 140 t yr,** assuming negligible backgrounds from detector materials





Physics reach: bosonic SuperWIMPs





- Bosonic, light, super weakly interacting cold dark matter (mass in the 10-100 keV range)
- Scattering cross section is many orders of magnitude below the weak-scale cross section, but such particles could be absorbed in LXe and produce a detectable signal
- **Signature: a line at the rest mass of the boson**

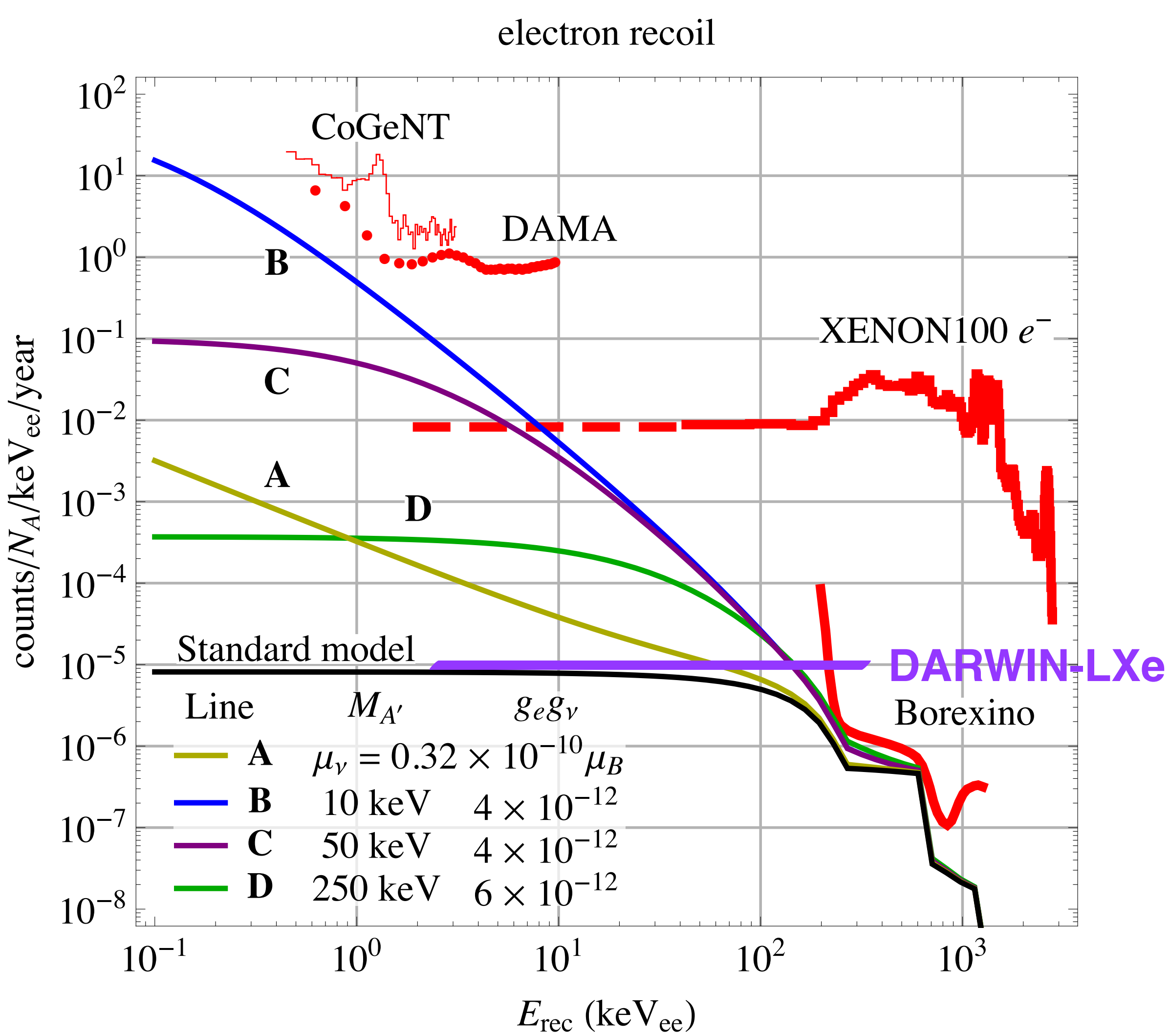
axial-vector $$R \simeq \frac{1.2 \times 10^{19}}{A} g_{aee}^2 \frac{m_a}{\rm keV} \frac{\sigma_{\rm photo}}{\rm b} \,{\rm kg}^{-1}\,{\rm d}^{-1}$$

$$g_{aee} = \frac{2m_e}{f_a}$$

vector $$R \simeq \frac{4 \times 10^{23}}{A} \frac{\alpha}{\alpha'} \frac{\rm keV}{m_V} \frac{\sigma_{\rm photo}}{\rm b} \,{\rm kg}^{-1}\,{\rm d}^{-1}$$

M. Pospelov, A. Ritz, M. Voloshin, PRD 78, 2008

Physics reach: heavy sterile neutrinos



Exploring ν signals in dark matter detectors

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- DARWIN-LXe can explore physics scenarios in which neutrino interactions with electrons are enhanced due to BSM processes:
  - new interactions between neutrinos and e^- mediated by a very light or massless particle (these would dominate the SM rates at low energies relevant for DD)
- A: nu with magnetic moment of 0.32 x 10^{-10} μ^B
- B, C, D: A'-mediated nu-e^- scattering (sterile neutrinos heavier than ~ 10 keV)
- A' is a new light gauge boson ("dark photon") that has a small kinetic mixing with the photon

Risks, costs, requests, timeline, consortium

Technical risks

- A good mix of scaling up our present know-how (XENON10->XENON1T/nT) and higher risk activities, with well-established fallbacks
- **Lower risk:**
  - cooling, purification and storage of large amount of cryogenic liquids - experience from GERDA and XENON1T/nT at LNGS
- **Higher risk:**
  - development of alternative signal readout methods (some technologies seem promising, but were not yet demonstrated to be practical in large noble-liquid detectors)
  - development of single-phase TPC
  - use of stable, high drift field (1 kV/cm)
  - development of 4-pi readout

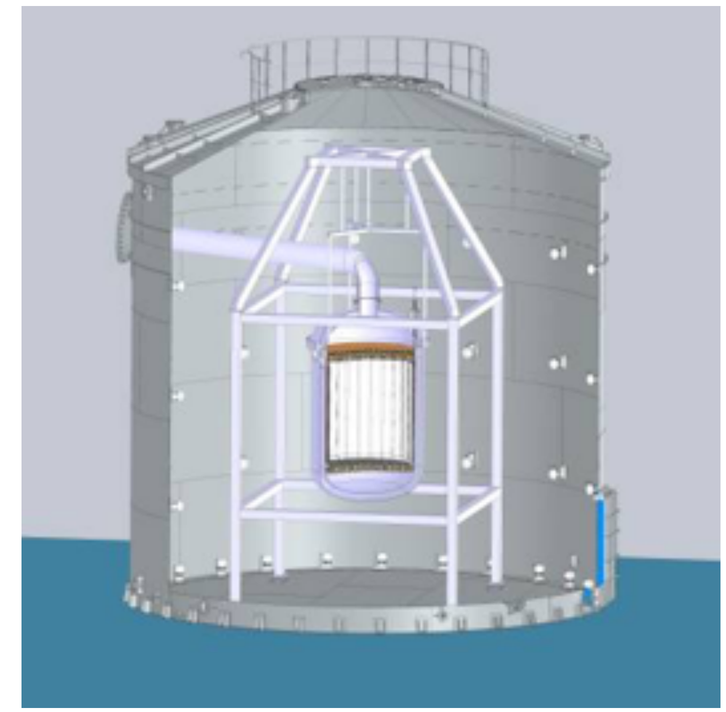
Estimated Construction/Investment Costs

- The costs will be dominated by the costs of LXe, followed by the ones of the photosensors, cryostat, electronics, etc
- Here an example, based on extrapolating the XENON1T/nT costs

Item	Total costs [in 10^6 CHF]
Photosensors, 1000 units	7.0
Xenon, 30 t	22.5
Detector (TPC, grids, HV)	1.5
Cryostat	4.5
Cryostat support	0.5
Cherenkov shield	0.5
Water tank	0.4
Xenon storage	1.6
Infrastructure	1.4
Electronics, DAQ, cables	1.8
Calibration system	0.3
Slow control	0.3
Screening (HPGe, ICP-MS)	0.4
LXe purification (Rn, Kr)	1.5
Demonstrator vertical (drift, HV)	0.5
Demonstrator horizontal (grids)	0.5
Sum	54.2

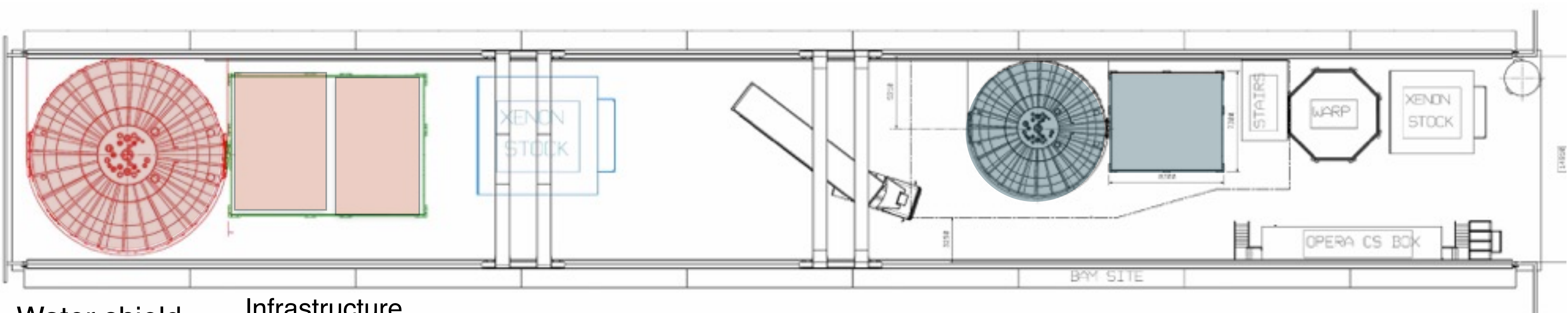
Requests for laboratory space

- Minimum water tank dimensions: 14 m diameter
- Space in Hall B (that belonged to ICARUS)
- Or space in Hall C (Borexino shield or other), or Hall A



Example: space in hall B

DARWIN-LXe **XENON1T/nT**



Water shield
14 m ø

Infrastructure
building
+ clean room

Xe storage

Estimated timescale

2010 - 2013

First R&D phase, Aspera funded

June 2013: Aspera final report

2014 - 2018

R&D and design study

2018: CDR/TDR

2018 - 2020

Engineering studies

2018-19: demonstrators at home institutions

2020: construction/integration at UL

2020 - 2030

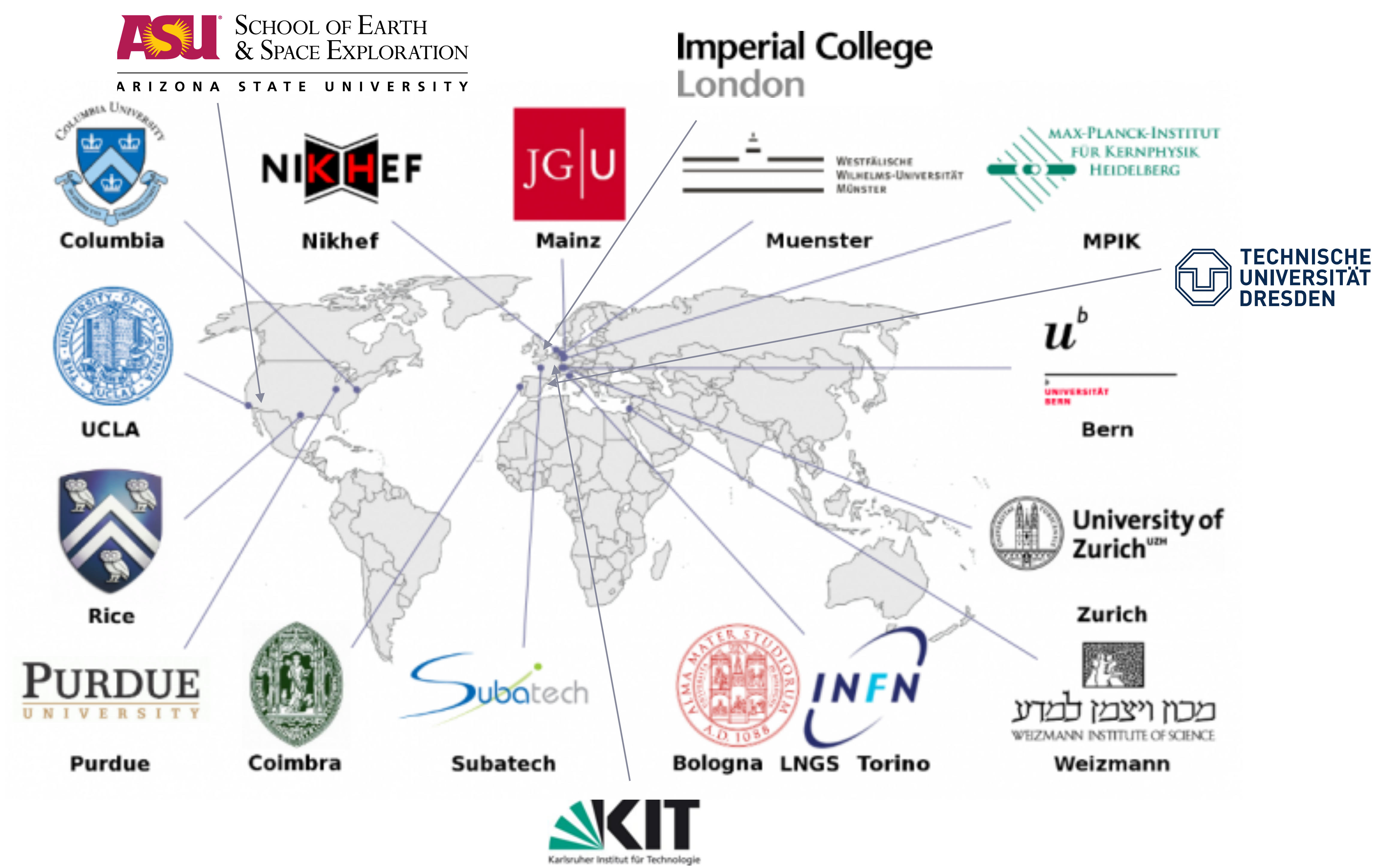
Construction, commissioning, science run

2020: construction/integration at UL

2021: commissioning

2022: physics runs

The DARWIN-LXe consortium



In total: 22 groups from 9 countries

Outlook

End