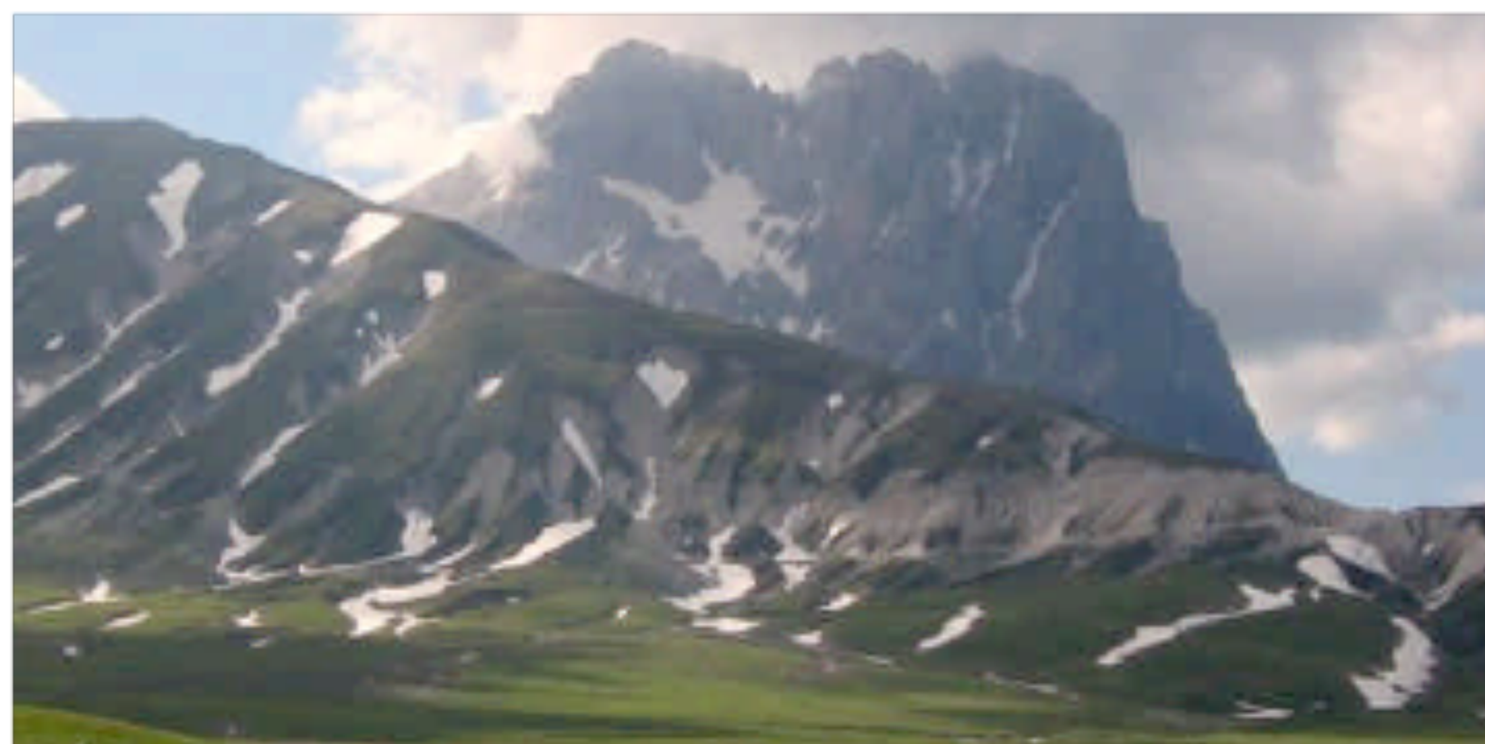
Highlights from the XENON dark matter search



Laura Baudis
University of Zurich

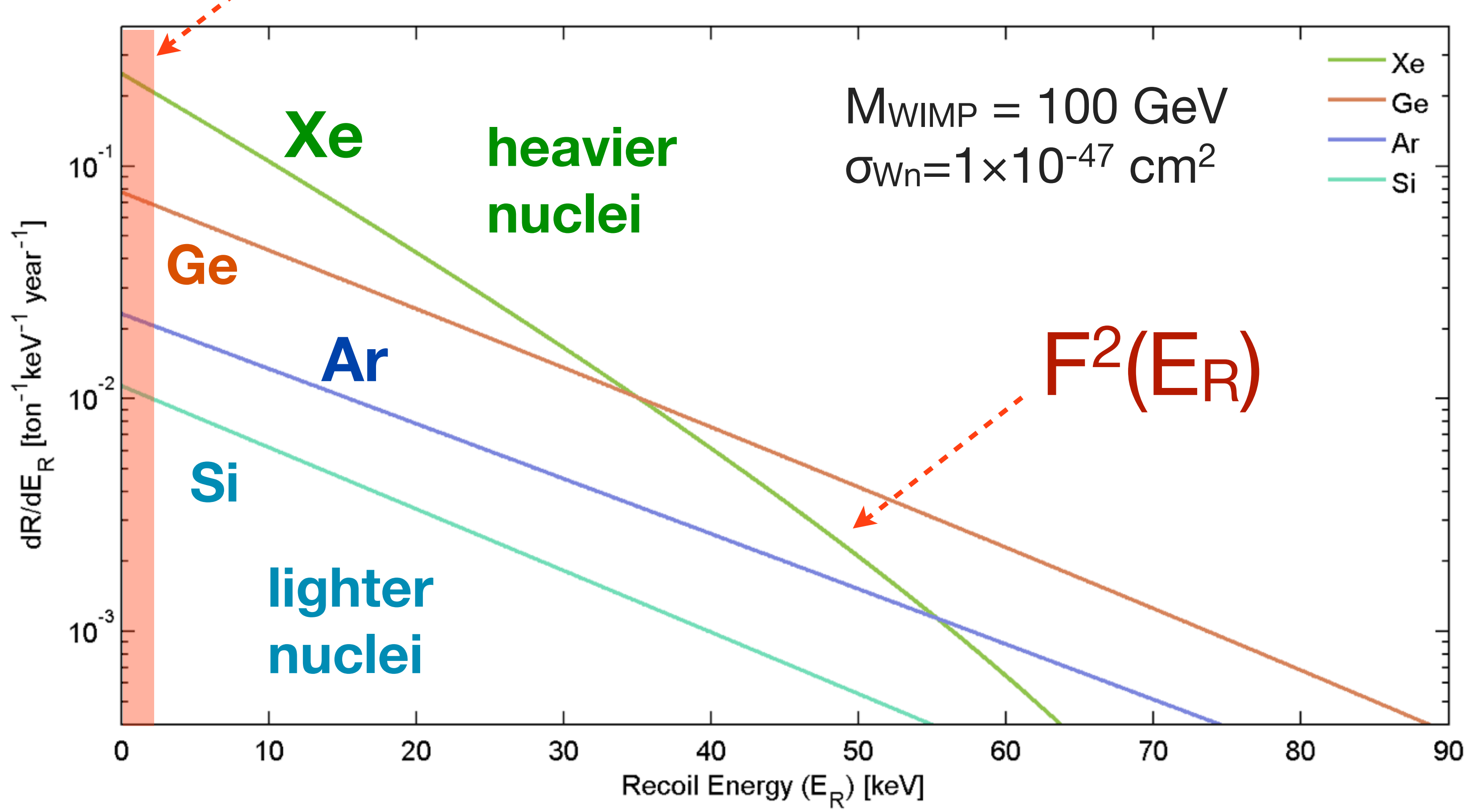
The spacetime odyssey continues
Stockholm, June 3, 2015

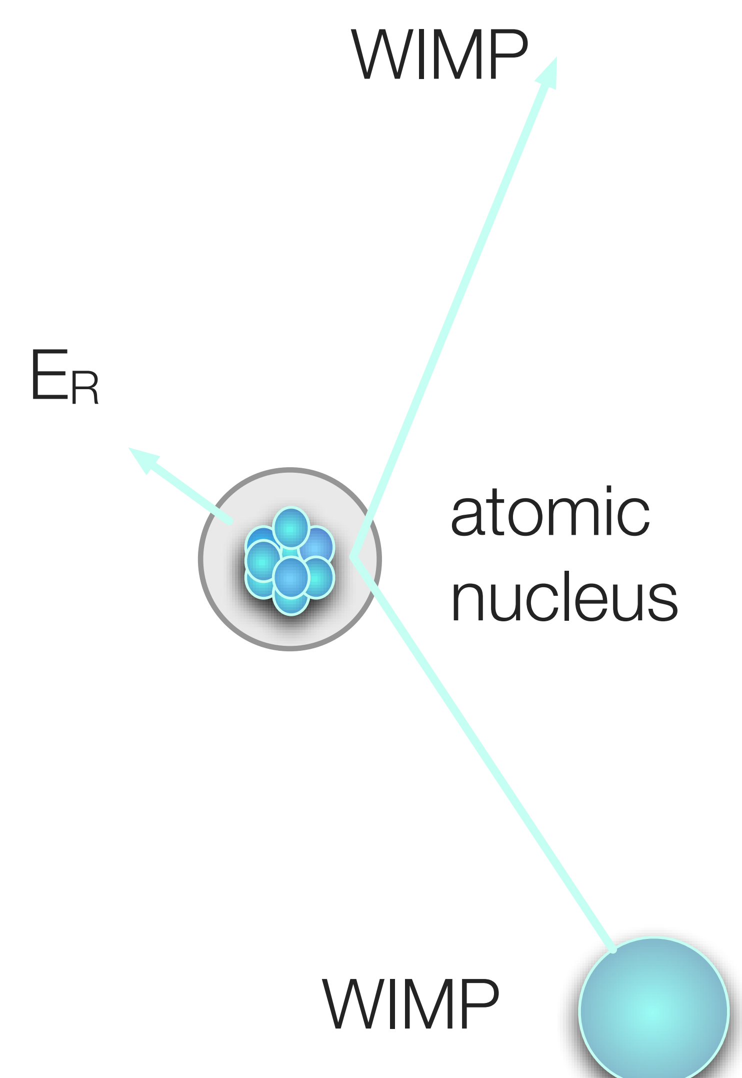
Physics goal of the XENON programme

- Detect WIMP-xenon collisions

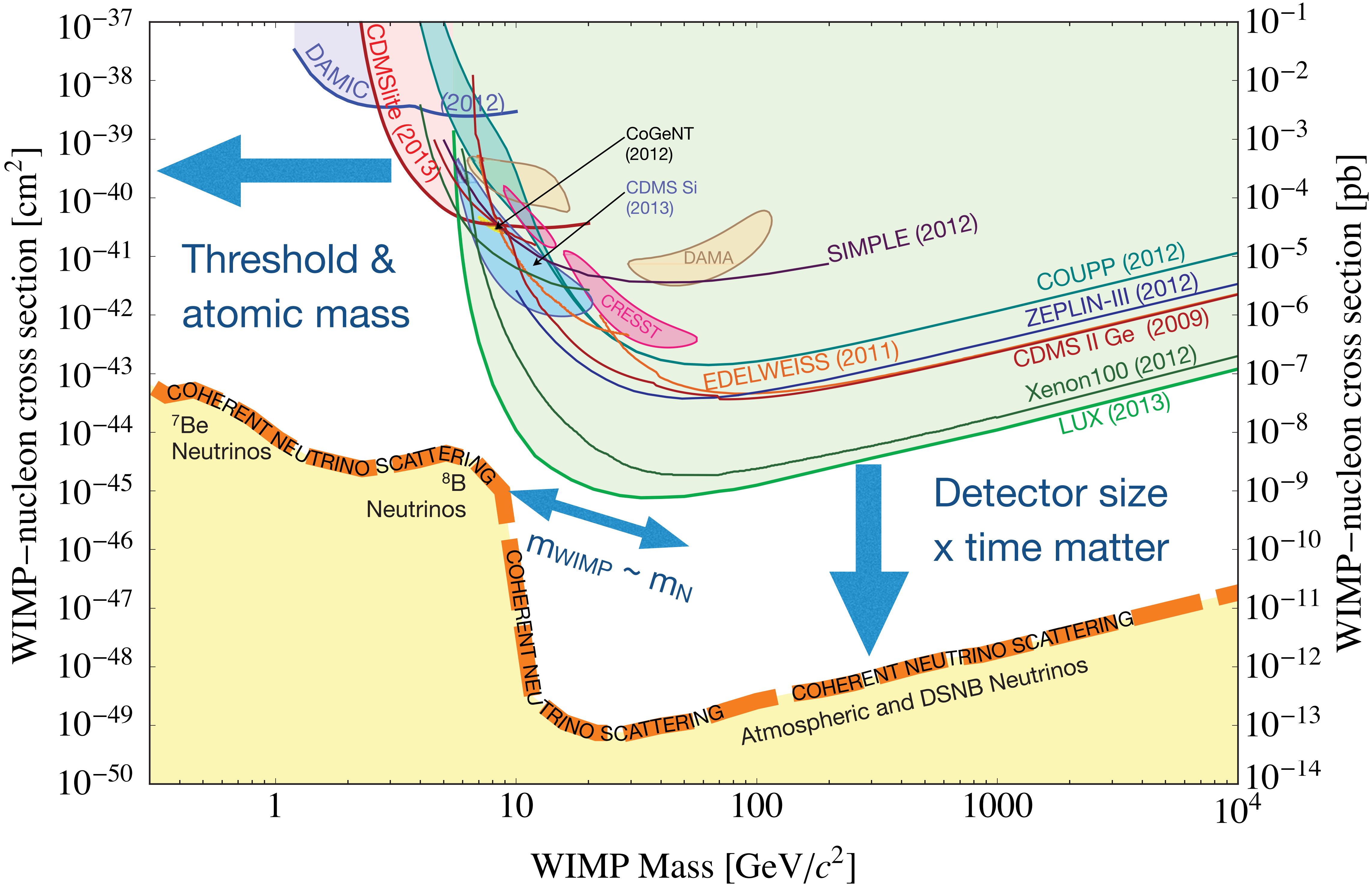
$$R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$

$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu^2}}$$





The WIMP landscape in 2015



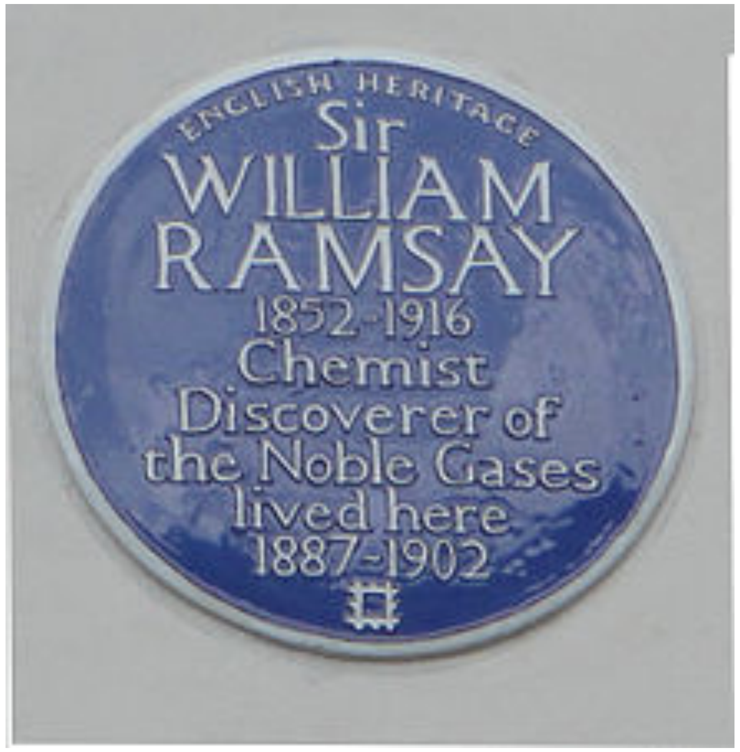
Noble gases in Mendeleev’s Periodic Table

Ueber die Beziehungen der Eigenschaften zu den Atomgewichten der Elemente. Von D. Mendelejeff. — Ordnet man Elemente nach zunehmenden Atomgewichten in verticale Reihen so, dass die Horizontalreihen analoge Elemente enthalten, wieder nach zunehmendem Atomgewicht geordnet, so erhält man folgende Zusammenstellung, aus der sich einige allgemeinere Folgerungen ableiten lassen.

			Ti = 50	Zr = 90	? = 180
			V = 51	Nb = 94	Ta = 182
			Cr = 52	Mo = 96	W = 186
			Mn = 55	Rh = 104,4	Pt = 197,4
			Fe = 56	Ru = 104,4	Ir = 198
			Ni — Co = 59	Pd = 106,6	Os = 199
H = 1			Cu = 63,4	Ag = 108	Hg = 200
	Be = 9,4	Mg = 24	Zn = 65,2	Cd = 112	
	B = 11	Al = 27,4	? = 68	Ur = 116	Au = 197?
	C = 12	Si = 28	? = 70	Sn = 118	
	N = 14	P = 31	As = 75	Sb = 122	Bi = 210?
	O = 16	S = 32	Se = 79,4	Te = 128?	
	F = 19	Cl = 35,5	Br = 80	J = 127	
Li = 7	Na = 23	K = 39	Rb = 85,4	Cs = 133	Tl = 204
		Ca = 40	Sr = 87,6	Ba = 137	Pb = 207
		? = 45	Ce = 92		
		?Er = 56	La = 94		
		?Yt = 60	Di = 95		
		?In = 75,6	Th = 118?		

1. Die nach der Grösse des Atomgewichts geordneten Elemente zeigen eine stufenweise Abänderung in den Eigenschaften.
2. Chemisch-analoge Elemente haben entweder übereinstimmende Atomgewichte (Pt, Ir, Os), oder letztere nehmen gleichviel zu (K, Rb, Cs).
3. Das Anordnen nach den Atomgewichten entspricht der *Werthigkeit* der Elemente und bis zu einem gewissen Grade der Verschiedenheit im chemischen Verhalten, z. B. Li, Be, B, C, N, O, F.
4. Die in der Natur verbreitetsten Elemente haben *kleine* Atomgewichte

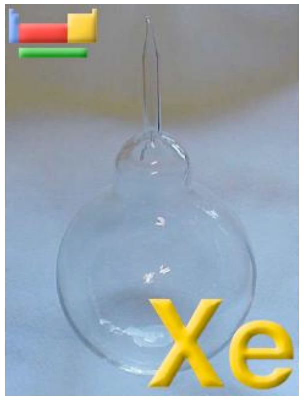
Discovered later by William Ramsay, student of Bunsen and professor at UC London
1904 Nobel Prize in Chemistry



"in recognition of his services in the discovery of the inert gaseous elements in air, and his determination of their place in the periodic system".

Argon: “the inactive one”, neon: “the new one”, krypton: “the hidden one”, **xenon: “the strange one”**

Why xenon for direct dark matter detection?



- Dense, homogeneous target with self-shielding; fiducialization
- Large detector masses feasible at moderate costs
- High light (40 photons/keV) and charge (W_{LAr} = 24 eV, W_{LXe} = 15 eV) yields

Properties [unit]	**Xe**	**Ar**	**Ne**
Atomic number:	54	18	10
Mean relative atomic mass:	131.3	40.0	20.2
Boiling point T_b at 1 atm [K]	165.0	87.3	27.1
Melting point T_m at 1 atm [K]	161.4	83.8	24.6
Gas density at 1 atm & 298 K [$\mathrm{g\,l^{-1}}$]	5.40	1.63	0.82
Gas density at 1 atm & T_b [$\mathrm{g\,l^{-1}}$]	9.99	5.77	9.56
Liquid density at T_b [$\mathrm{g\,cm^{-3}}$]	2.94	1.40	1.21
Dielectric constant of liquid	1.95	1.51	1.53
Volume fraction in Earth's atmosphere [ppm]	0.09	9340	18.2

W. Ramsay: "These gases occur in the air but sparingly as a rule, for while argon forms nearly 1 hundredth of the volume of the air, neon occurs only as 1 to 2 hundred-thousandth, helium as 1 to 2 millionth, krypton as 1 millionth and xenon only as about 1 twenty-millionth part per volume. *This more than anything else will enable us to form an idea of the vast difficulties which attend these investigations*. "

WIMP physics with xenon

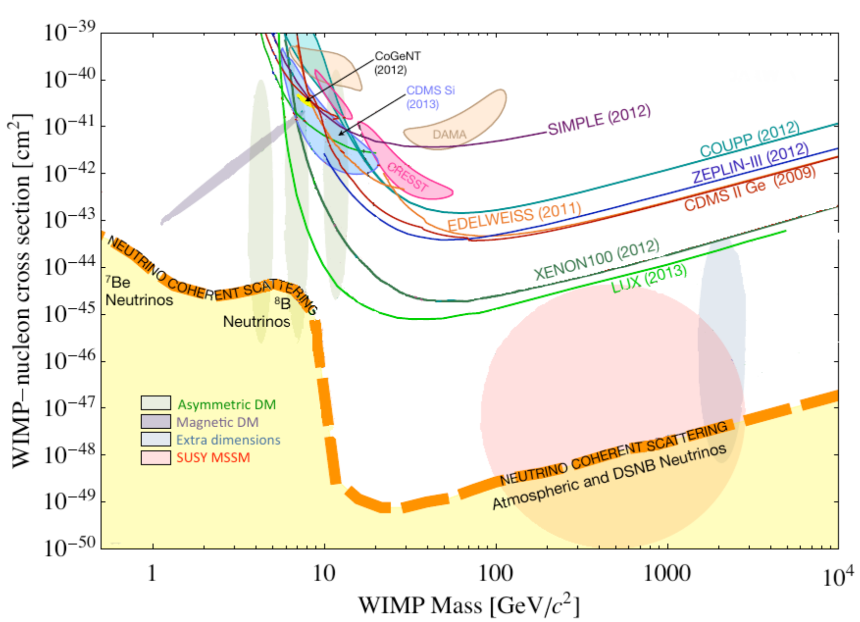
Probe WIMP-Xenon interactions via various channels:

- 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

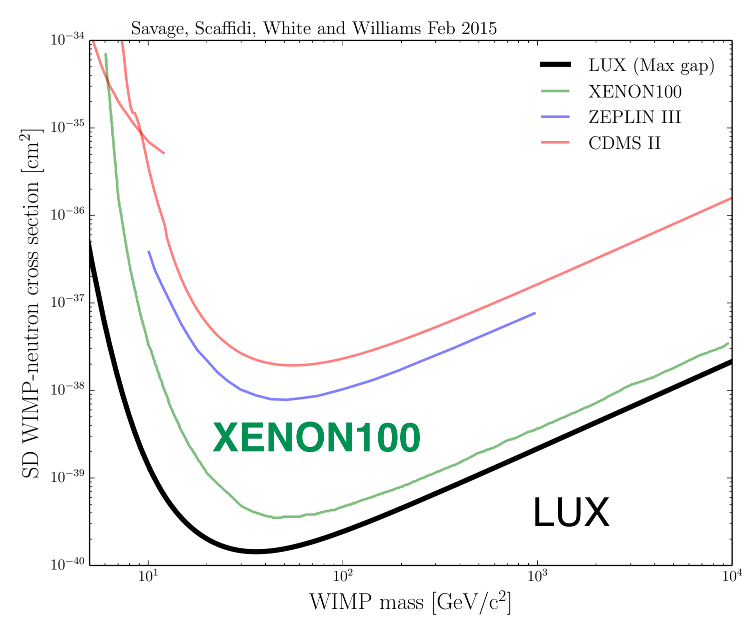
40 keV, 80 keV

SI, elastic WIMP-nucleus



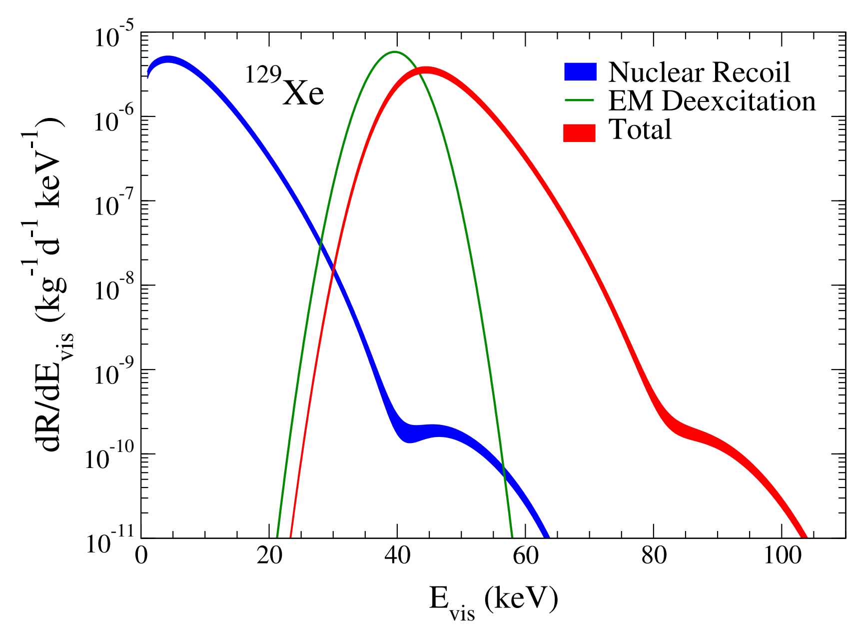
arXiv:1310.8327

SD, elastic WIMP-nucleus



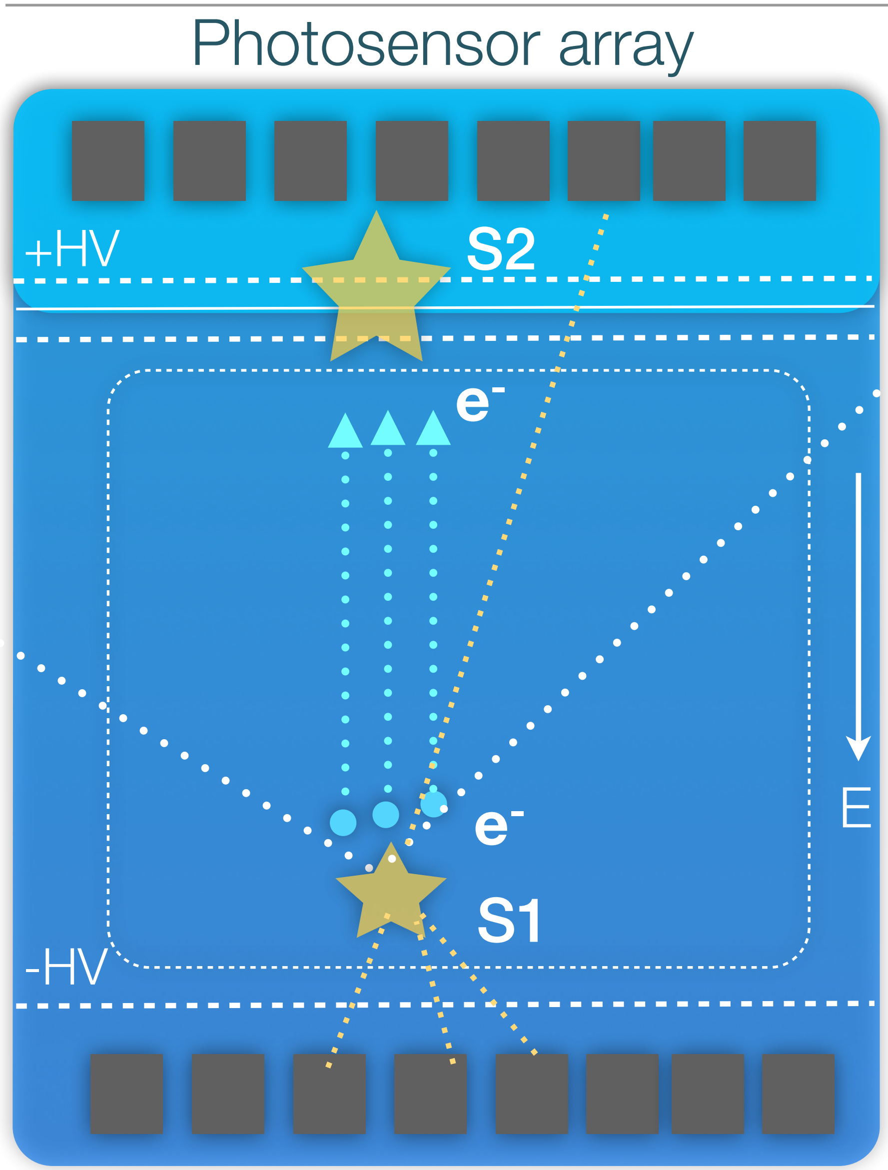
C. Savage et al, arXiv:1502.02667

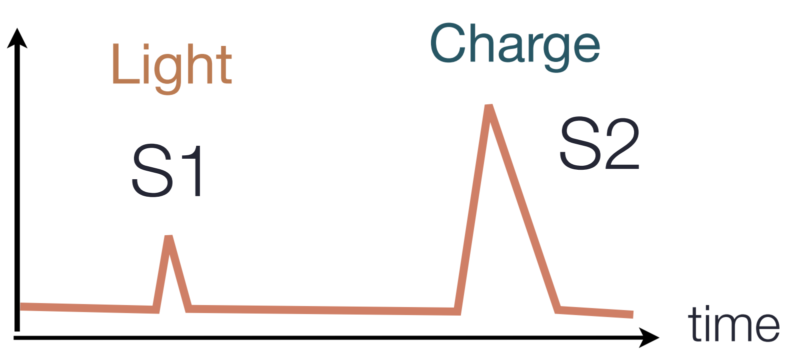
SD, inelastic WIMP-nucleus



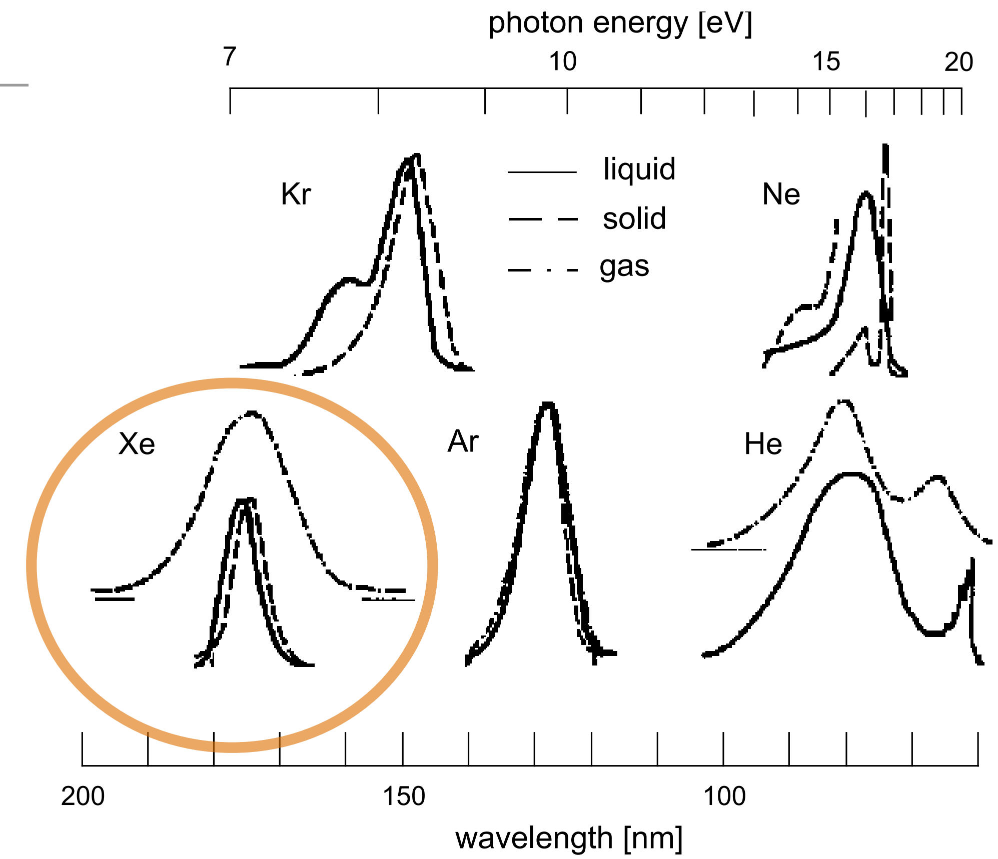
L. Baudis et al, Phys. Rev. D 88, 115014 (2013)

The xenon time projection chamber

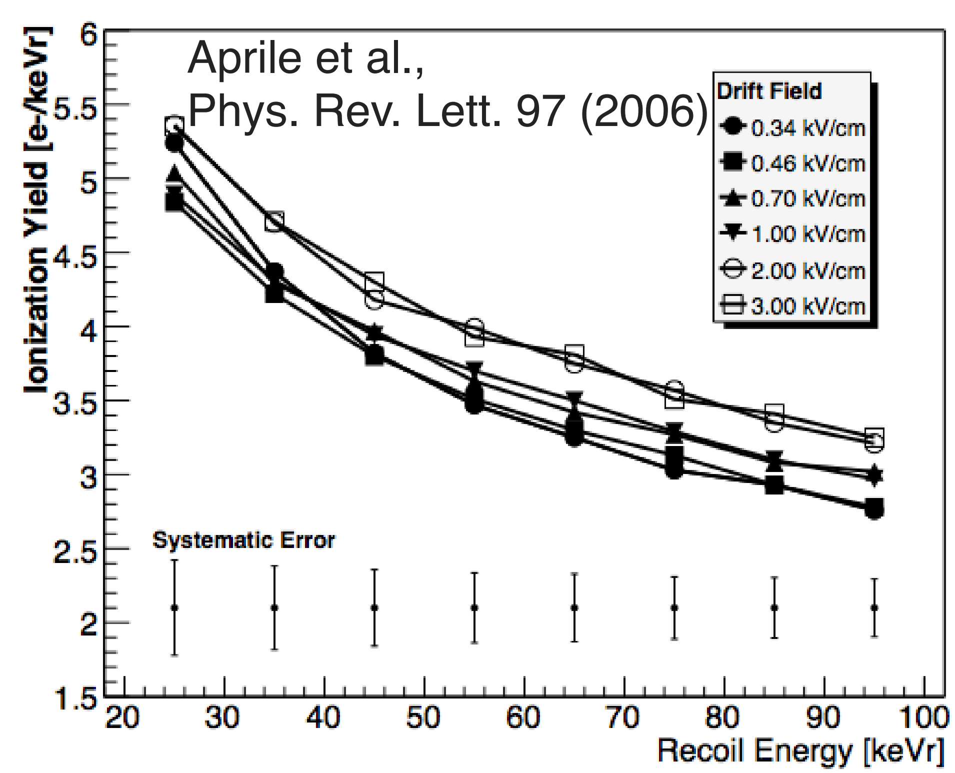




Light

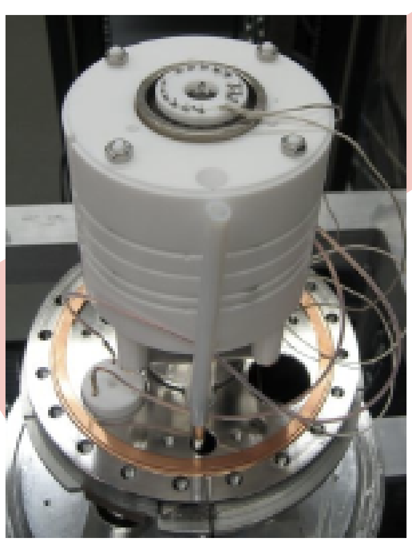


Charge



The XENON Programme

XENON R&D



ongoing

XENON10

2005-2007

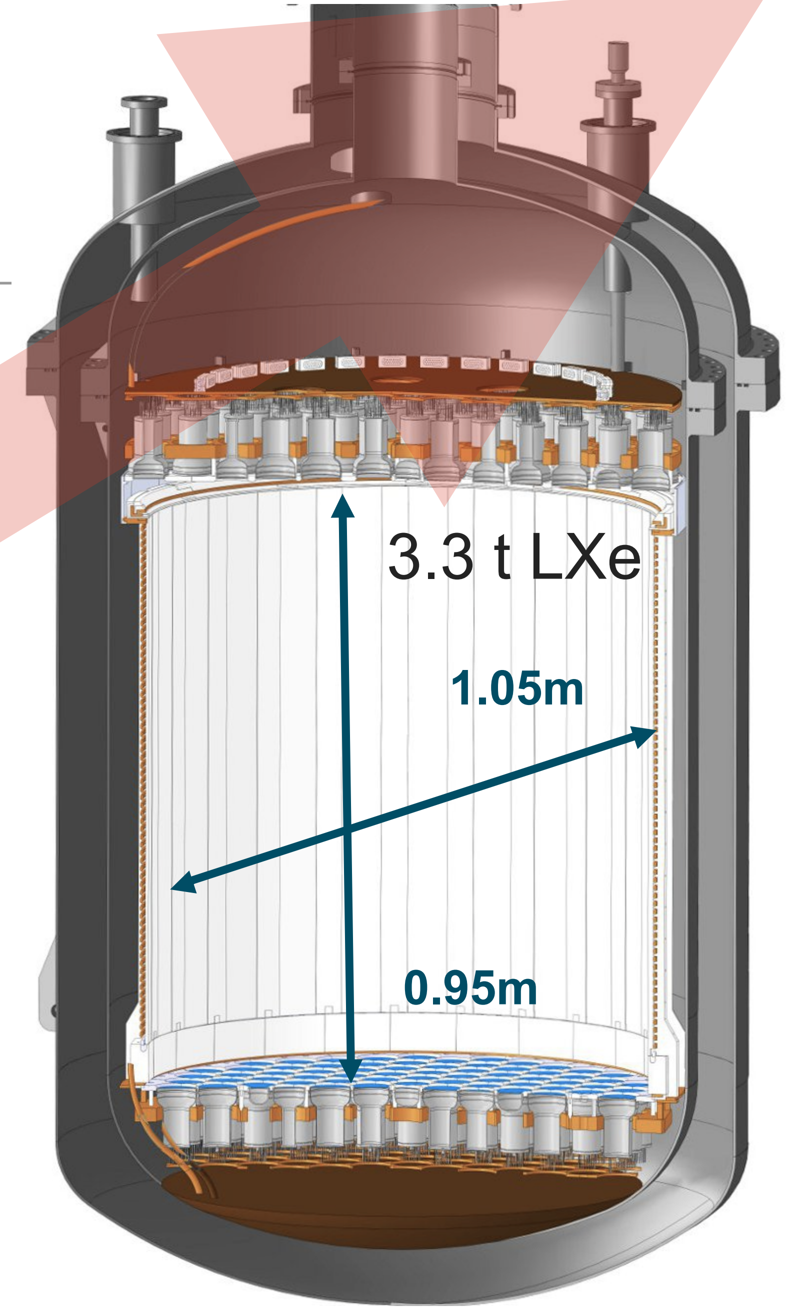
PRL100
PRL101
PRD 80
NIM A 601

XENON100

2008-2015
taking calibration data

PRL105
PRL109
PRL111
…

XENON1T/nT



2013-2020

XENON1T(nT): under construction at LNGS

The XENON Programme

XENON10

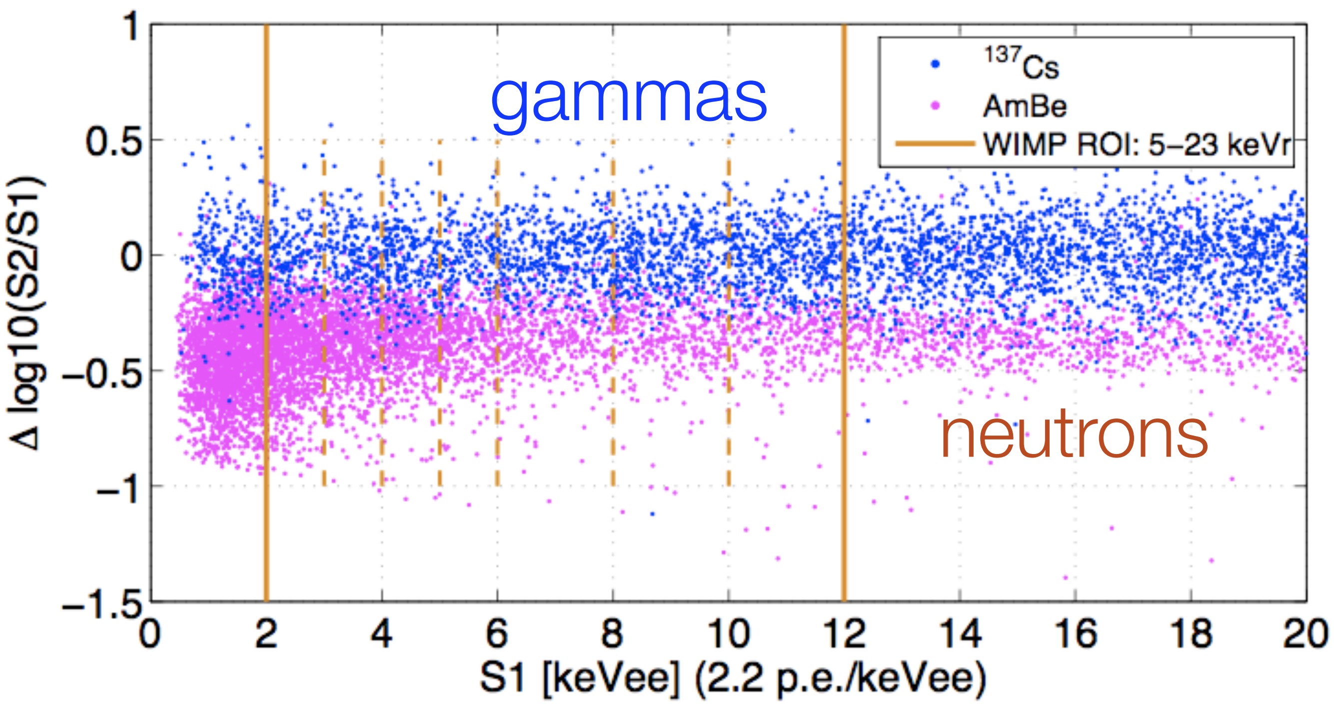
XENON100

XENON1T/nT

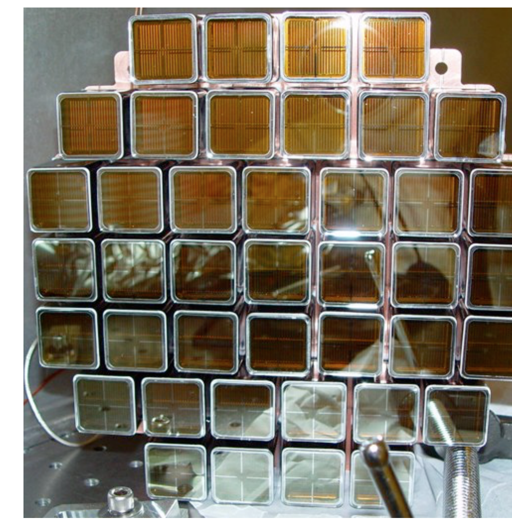
XENON10/XENON100: conventional shield, onion-like structure

XENON1T/nT: large water Cherenkov shield

The XENON10 experiment: 2005-2007



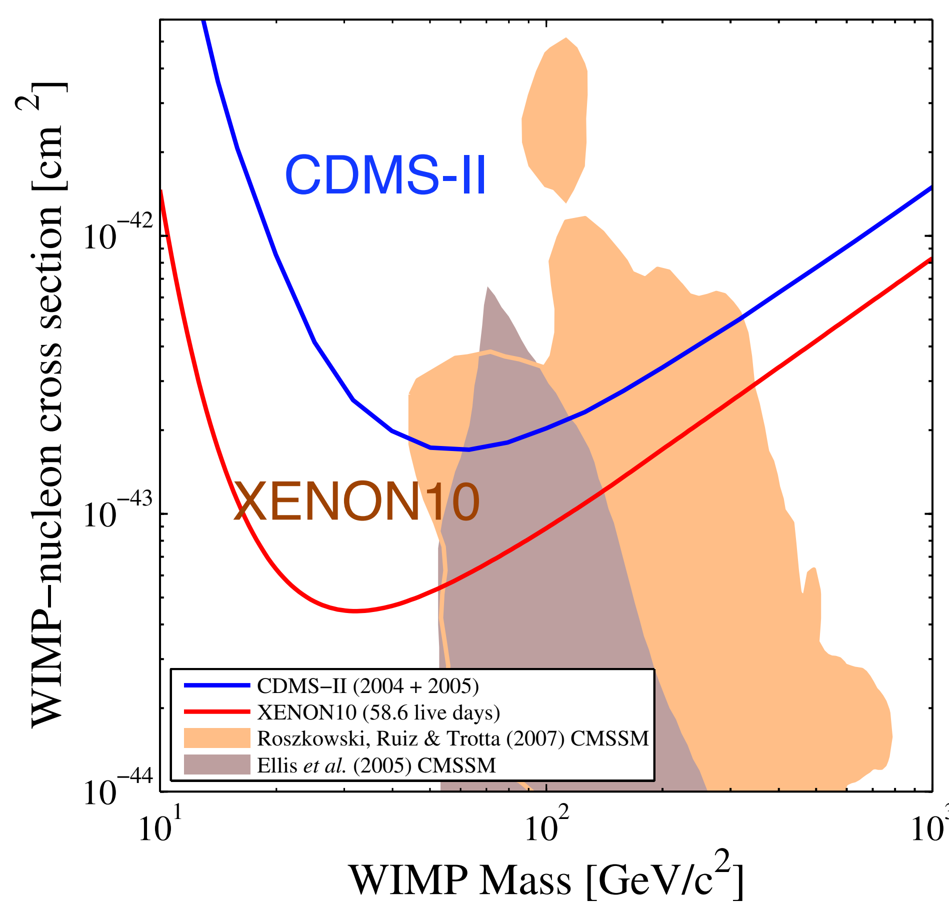
- 22 kg LXe in total
- 20 cm diam, 15 cm drift
- 89 1-inch PMTs
- 0.73 kV/cm drift field



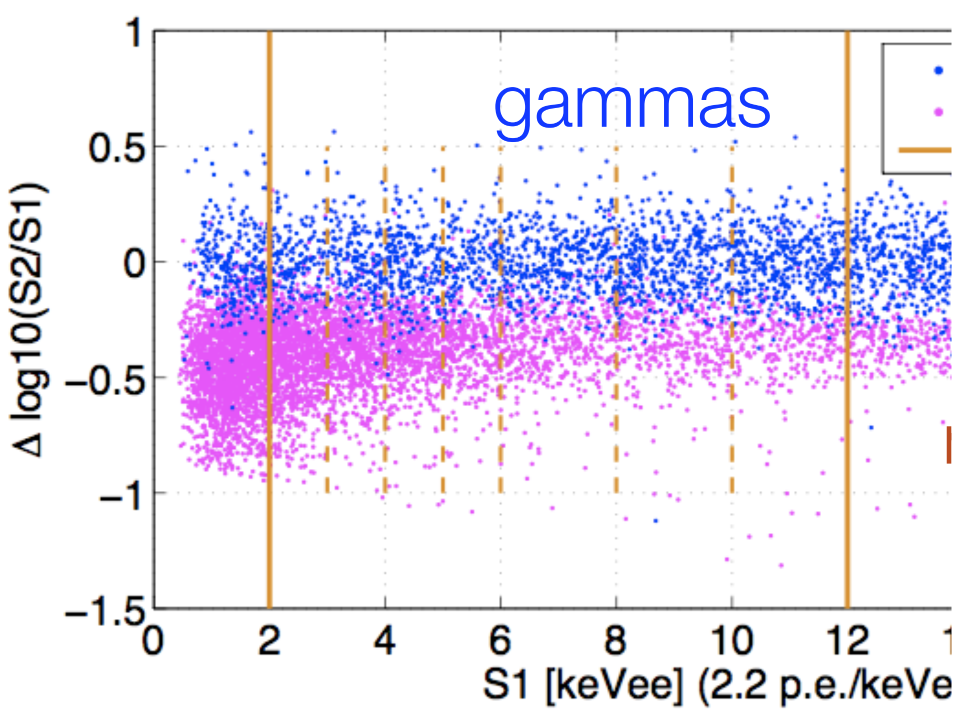
PRL **100,** 021303 (2008) PHYSICAL REVIEW LETTERS week ending 18 JANUARY 2008

First Results from the XENON10 Dark Matter Experiment at the Gran Sasso National Laboratory

J. Angle,[1,2] E. Aprile,[3,*] F. Arneodo,[4] L. Baudis,[2] A. Bernstein,[5] A. Bolozdynya,[6] P. Brusov,[6] L. C. C. Coelho,[7] C. E. Dahl,[6,8] L. DeViveiros,[9] A. D. Ferella,[2,4] L. M. P. Fernandes,[7] S. Fiorucci,[9] R. J. Gaitskell,[9] K. L. Giboni,[3] R. Gomez,[10] R. Hasty,[11] L. Kastens,[11] J. Kwong,[6,8] J. A. M. Lopes,[7] N. Madden,[5] A. Manalaysay,[1,2] A. Manzur,[11] D. N. McKinsey,[11] M. E. Monzani,[3] K. Ni,[11] U. Oberlack,[10] J. Orboeck,[2] G. Plante,[3] R. Santorelli,[3] J. M. F. dos Santos,[7] P. Shagin,[10] T. Shutt,[6] P. Sorensen,[9] S. Schulte,[2] C. Winant,[5] and M. Yamashita[3]



The XENON10 experiment: 2005-2007



PRL 100, 021303 (2008) PHYSICAL REVIEW LET

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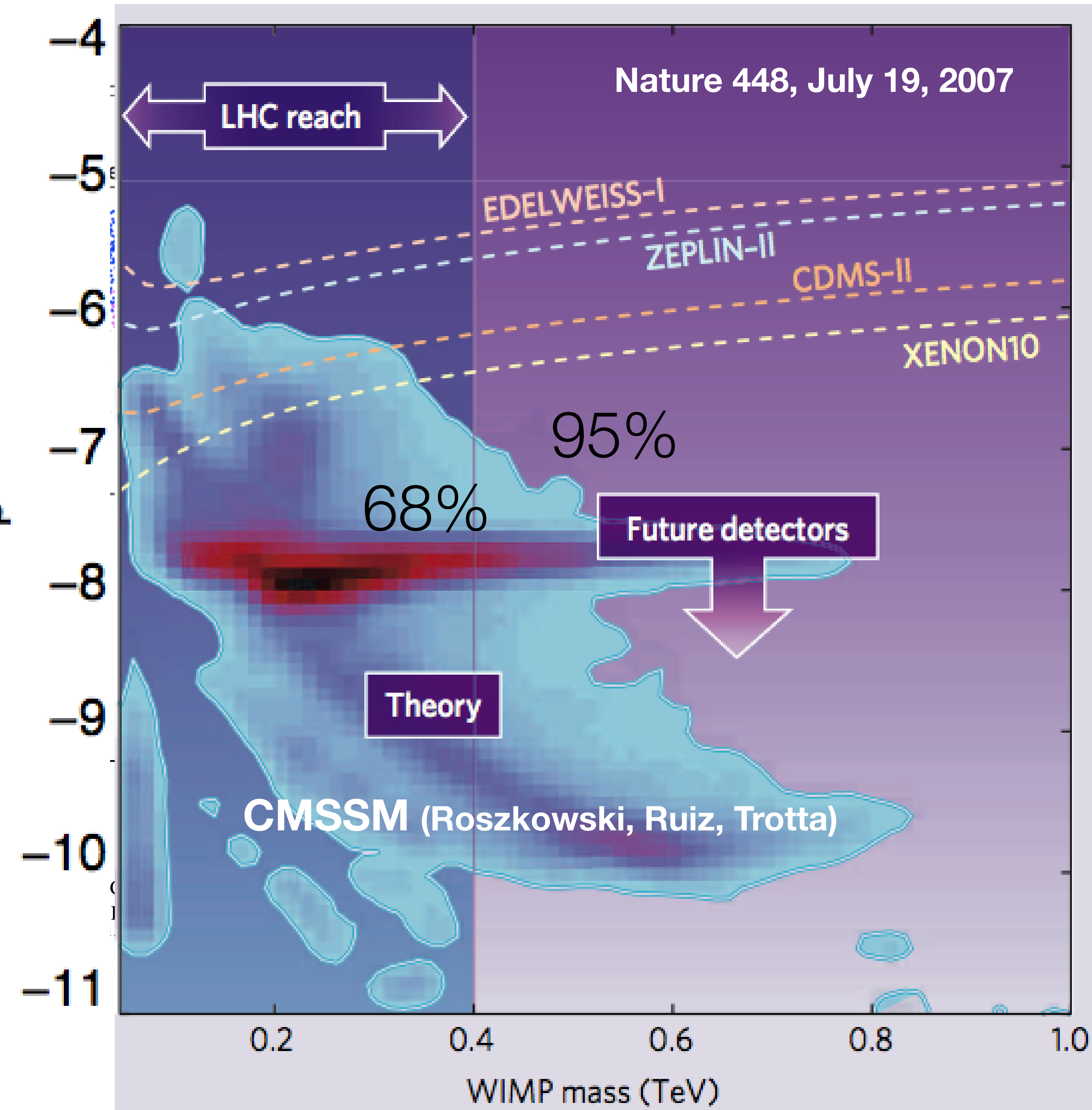


The XENON10 Collaboration

LNGS, May 2006

The XENON100 experiment: 2008-2015

- Double phase time projection chamber with 161 kg (30-50 kg) of LXe total (fiducial), at LNGS
- 30 cm e^- drift length, 30 cm diameter
- 2 arrays of 1-inch, low-background PMTs + LXe veto
- Low radioactivity - screened/selected - materials

Instrument described in:
Astroparticle Physics 35, 2012

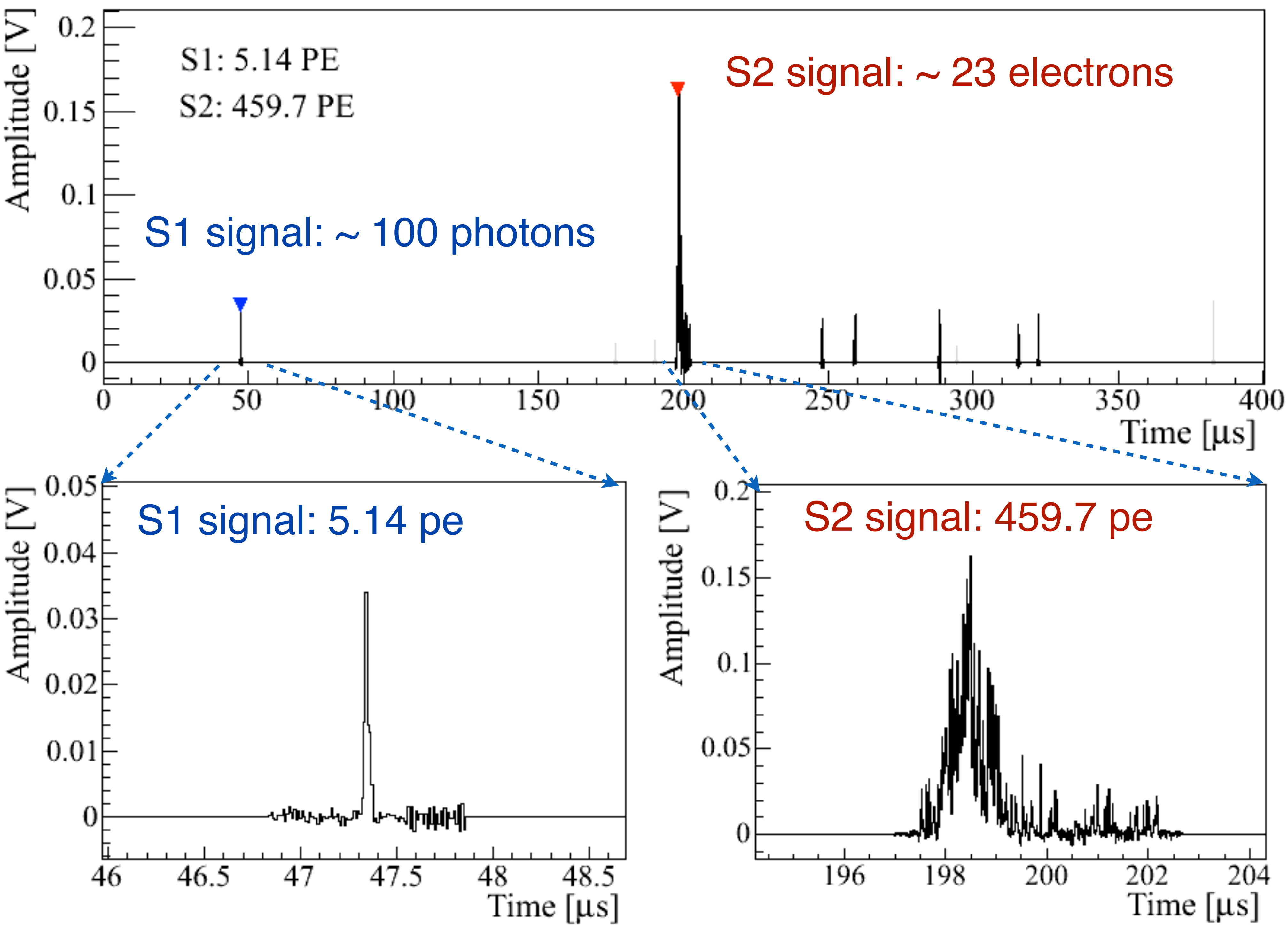
Material screening results in:
JINST 6, 2011

Detailed analysis paper:
Astroparticle Physics 54, 2014

Top array: 98 PMTs

Bottom array: 80 PMTs

Example of a low-energy event waveform

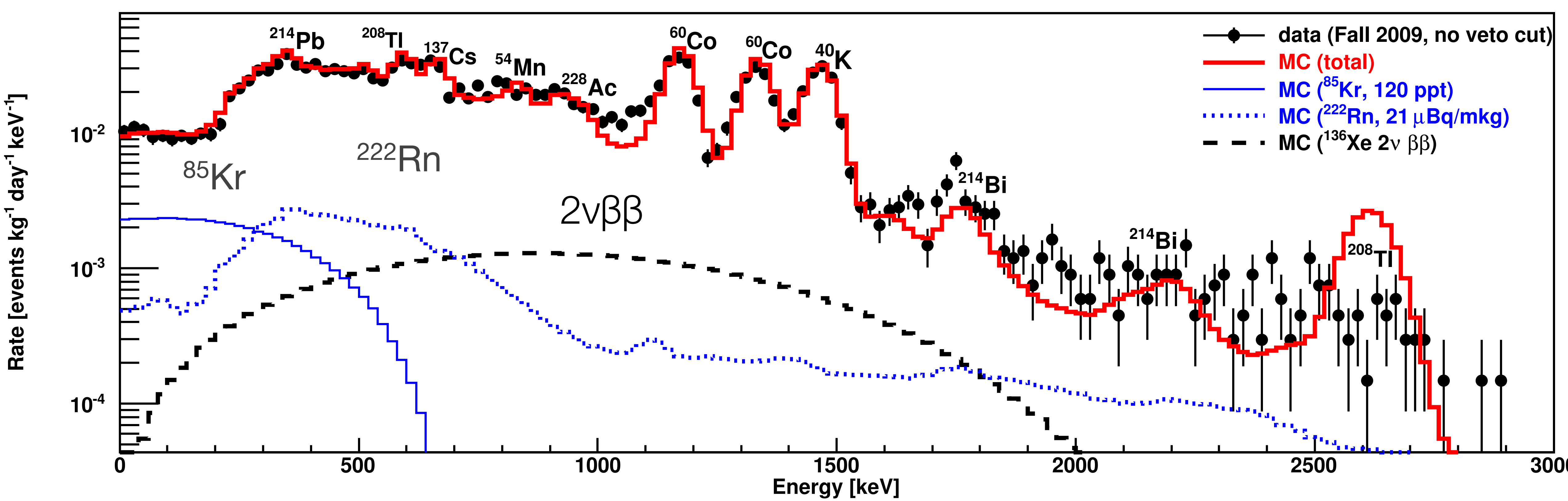


The measured background in XENON100

- **Data** and **MC** (Run 07; no MC tuning; before the active LXe veto cut)
- Region above ~ 1500 keV: saturation in the PMTs
- The background meets the design specifications: 5.3 x 10^{-3} events/(kg keV day)

➡ **100 times lower than in XENON10**

Aprile et al., XENON100 collaboration, PRD 83, 082001 (2011)



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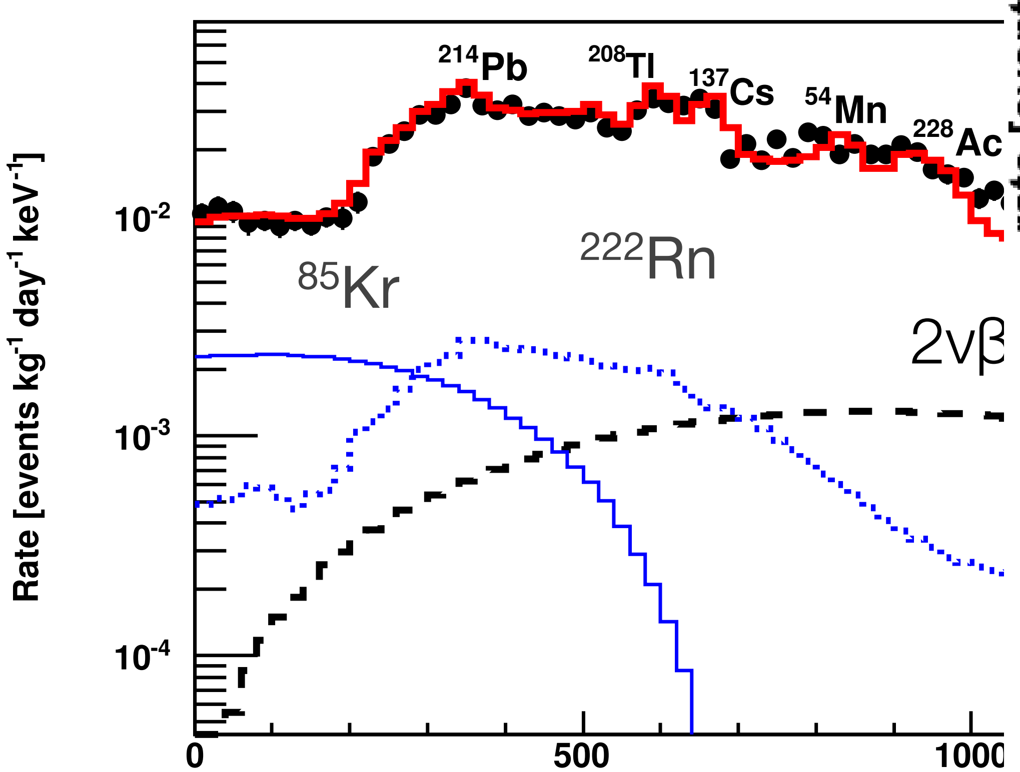
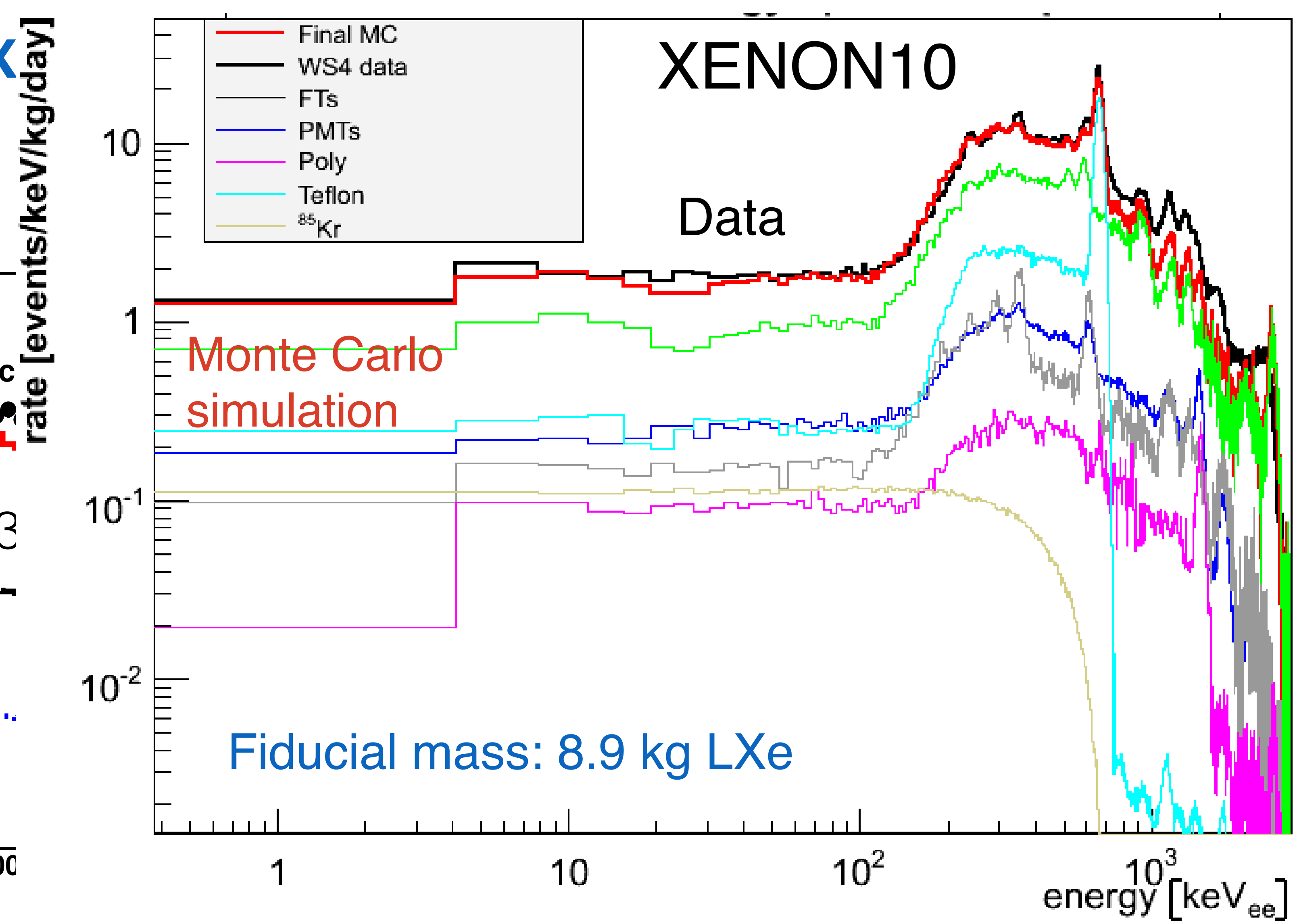
- **Data** and **MC** (Run 07; no MC tuning; before the active LXe veto cut)
- Region above ~ 1500 keV: saturation in the PMTs
- The background meets the design specifications: 5.3 x 10^{-3} events/(kg keV day)

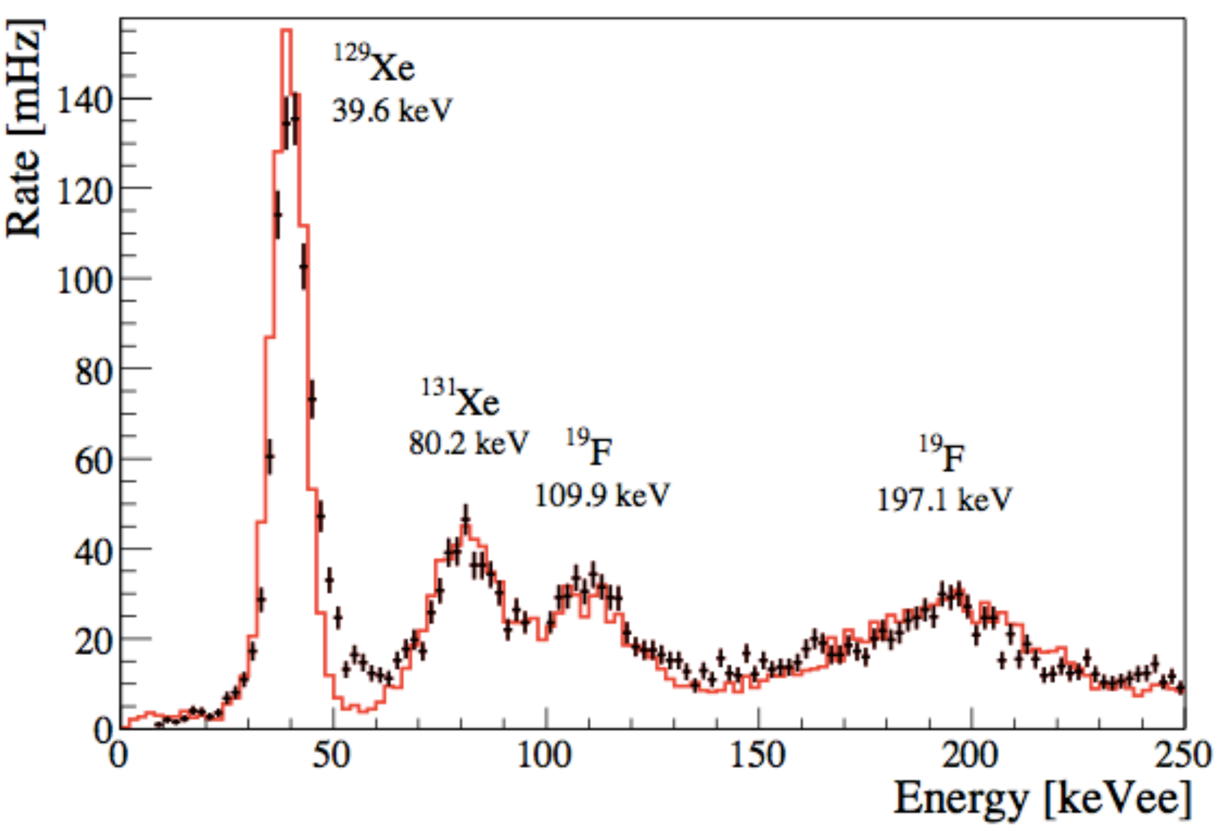
➡ **100 times lower than in X**

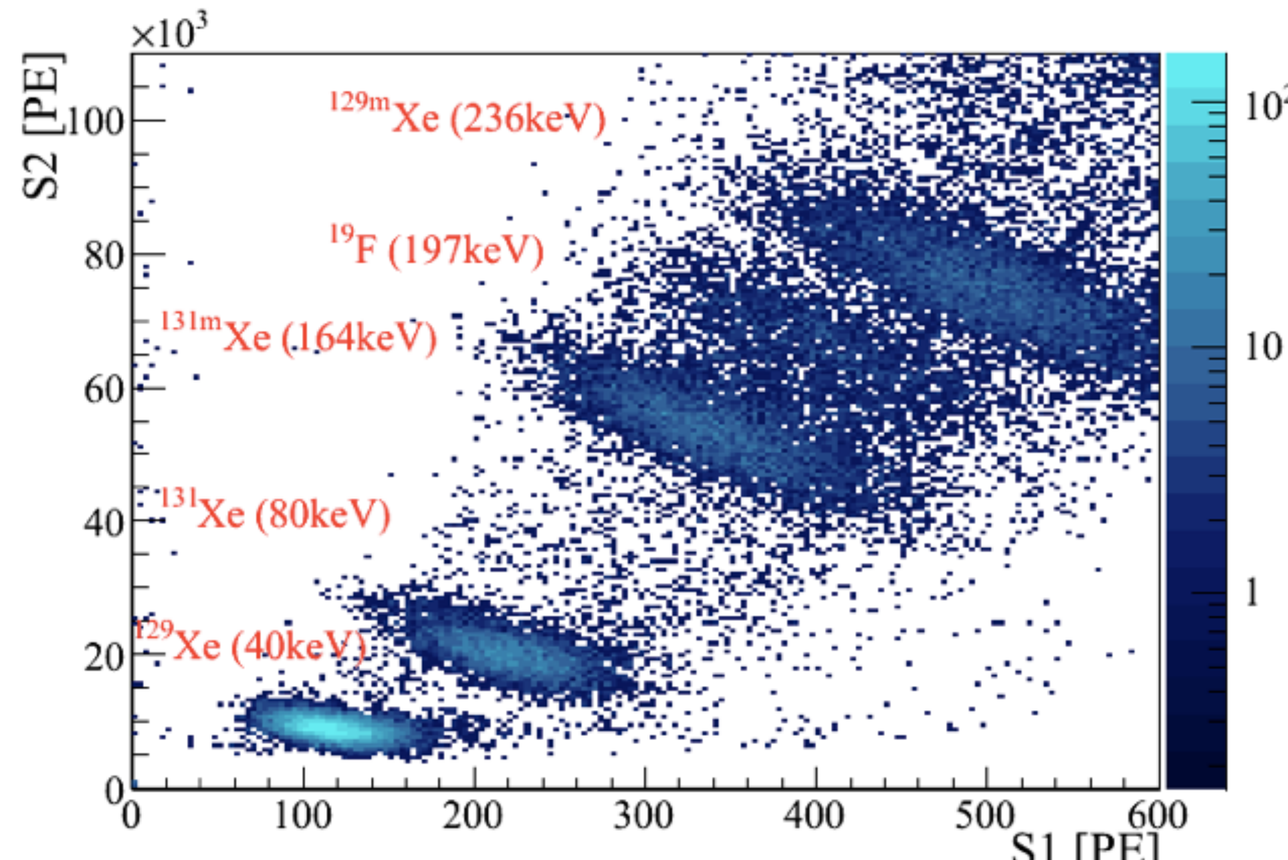




Gammas from neutron calibrations

- AmBe (~ MeV neutrons) data to map the nuclear recoil band, 220 n/s
- Inelastic n-scattering on Xe: $^{129,131}Xe + n \rightarrow {}^{129,131}Xe + n + \gamma$ (40 keV, 80 keV)
- Inelastic n-scattering on F (in PTFE): $^{19}F + n \rightarrow {}^{19}F + n + \gamma$ (110 keV, 197 keV)
- Also Xe n-activation lines: ^{129m}Xe (236 keV) and ^{131m}Xe (164 keV)





All gammas from the neutron irradiation of XENON100 are used to check/correct signal dependency with position and also to infer the LY at 122 keV

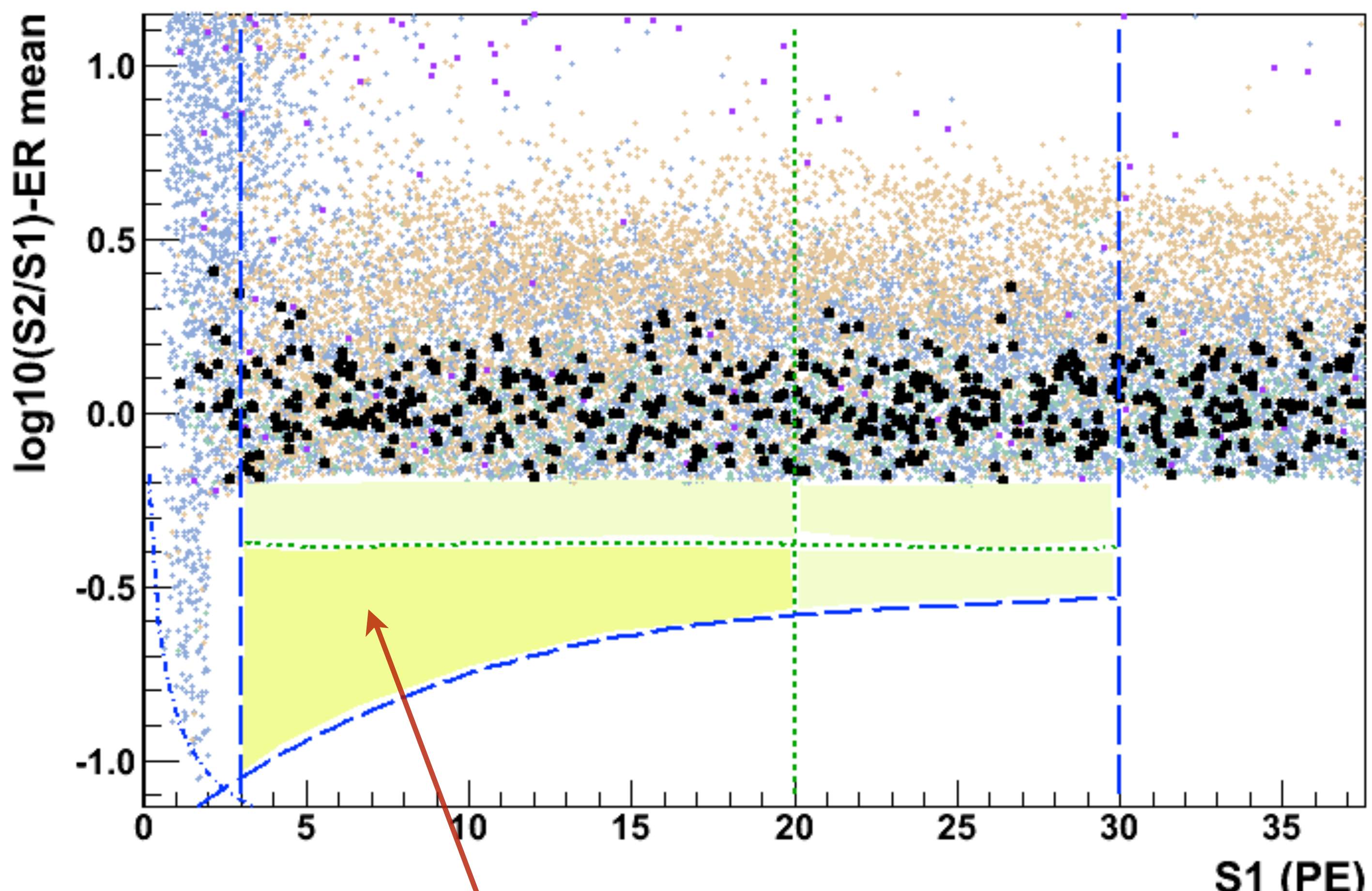
Background prediction for Run10

- Expected background in: 34 kg inner region, 224.6 live days, 99.75% rejection of electronic recoils

- Electronic recoil background:
  - 0.79±0.16 events
  - from ER calibration data, scaled to non-blinded ER band background data

- Nuclear recoil background
  - 0.17+0.12-0.07 events
  - from cosmogenic and radiogenic neutrons

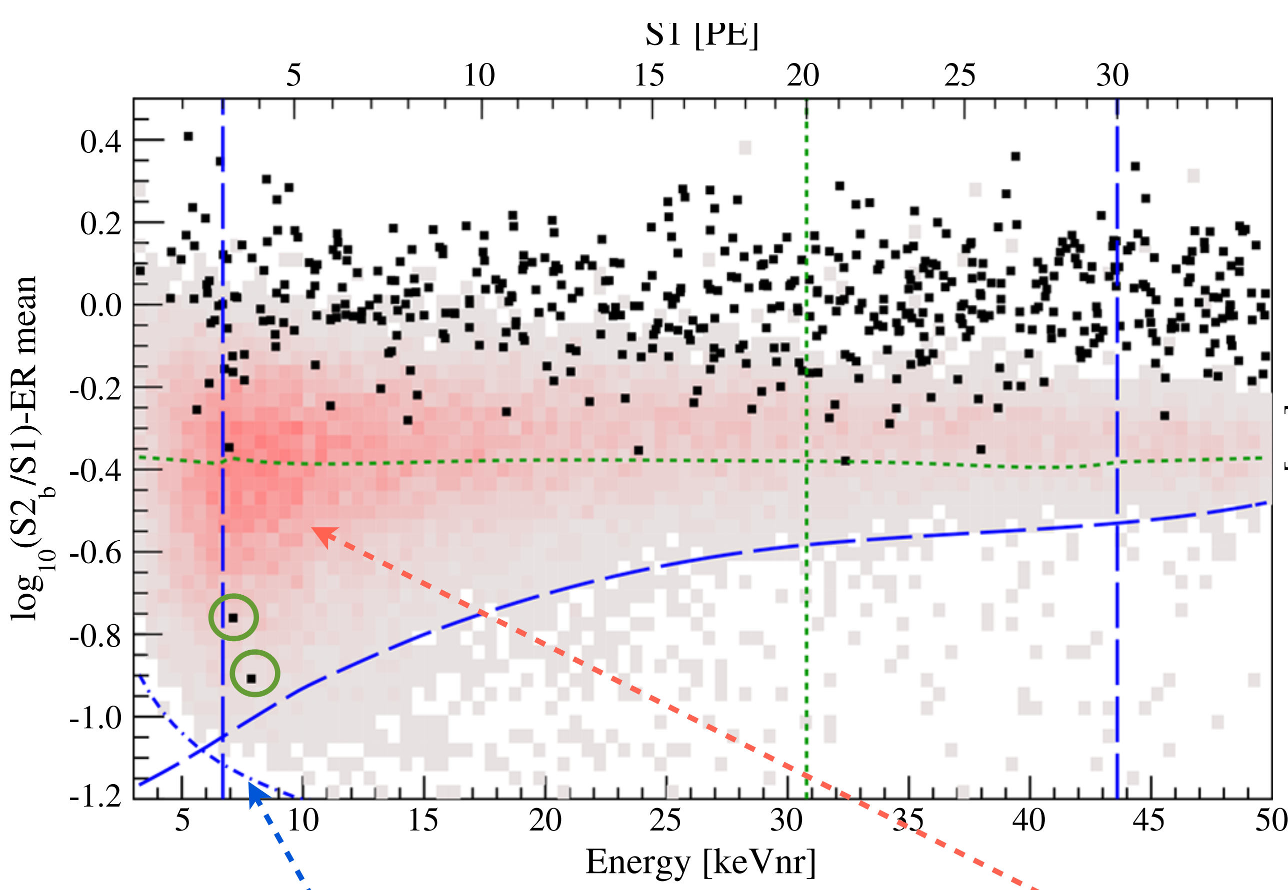
- Total: 1.0±0.2 events

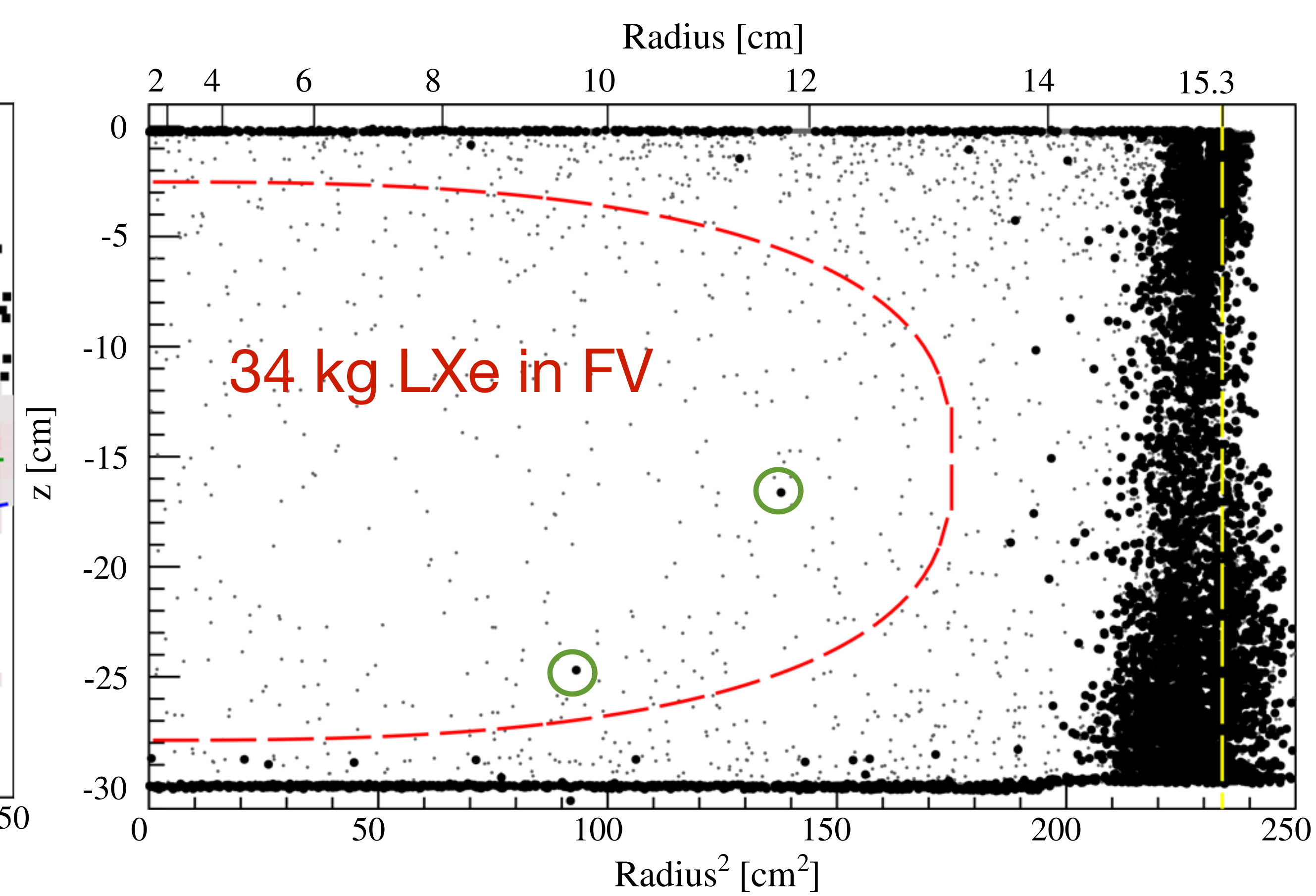


- *benchmark WIMP region (not used in PL analysis)*

After unblinding the previous dark matter run

- Two events observed in signal region (there is a 26.4 % chance for upward fluctuation): at 7.1 keV$_{nr}$ (3.3 pe) and at 7.8 keV$_{nr}$ (3.8 pe) (note: zero events below 3 pe)
- Both events at *low S2/S1 with respect to* NR *calibration data*
- Visual inspection: waveforms of high quality





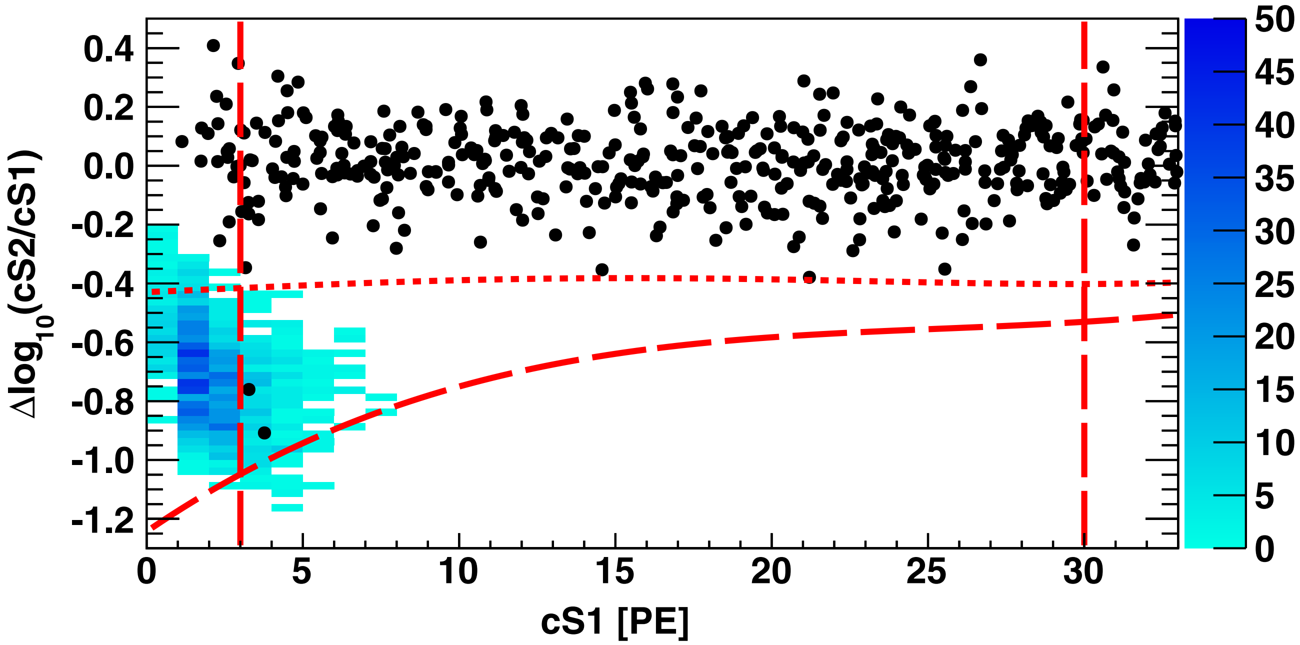
S2 threshold (150 pe)

AmBe n-calibration data

XENON100 predictions for light WIMPs

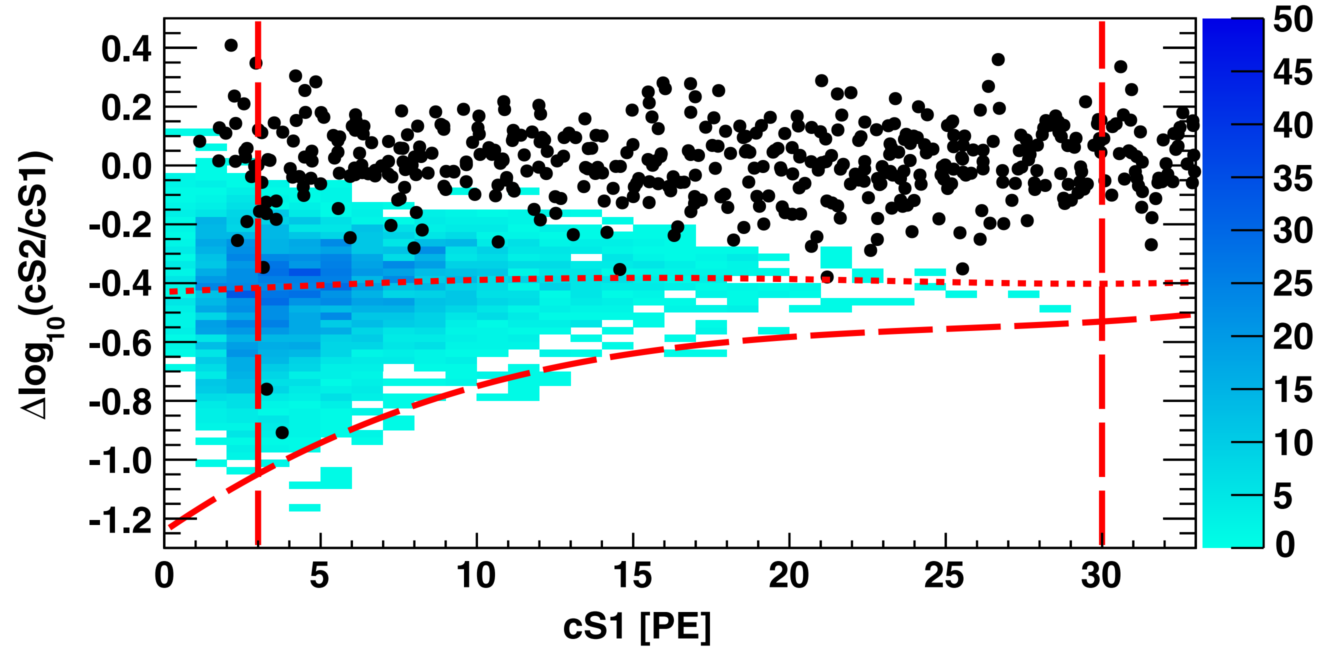
- Past signal claims of other experiments in XENON100 data

WIMP with m_W = 8 GeV



WIMP-nucleon cross section : 3×10^{-41} cm^2

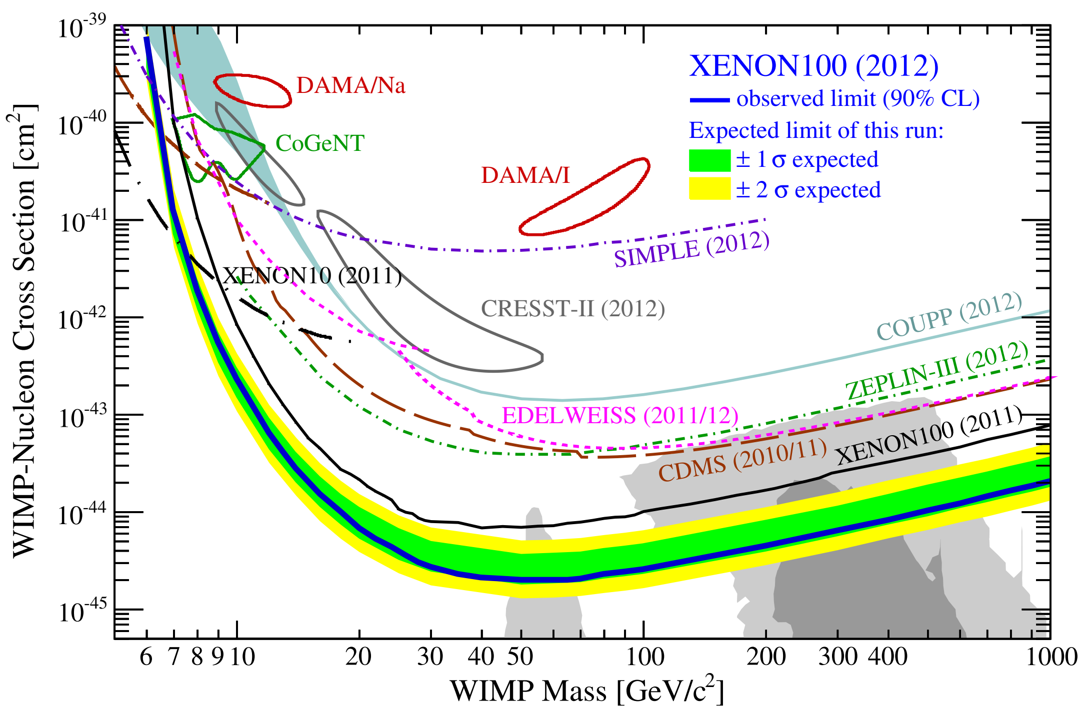
WIMP with m_W = 25 GeV



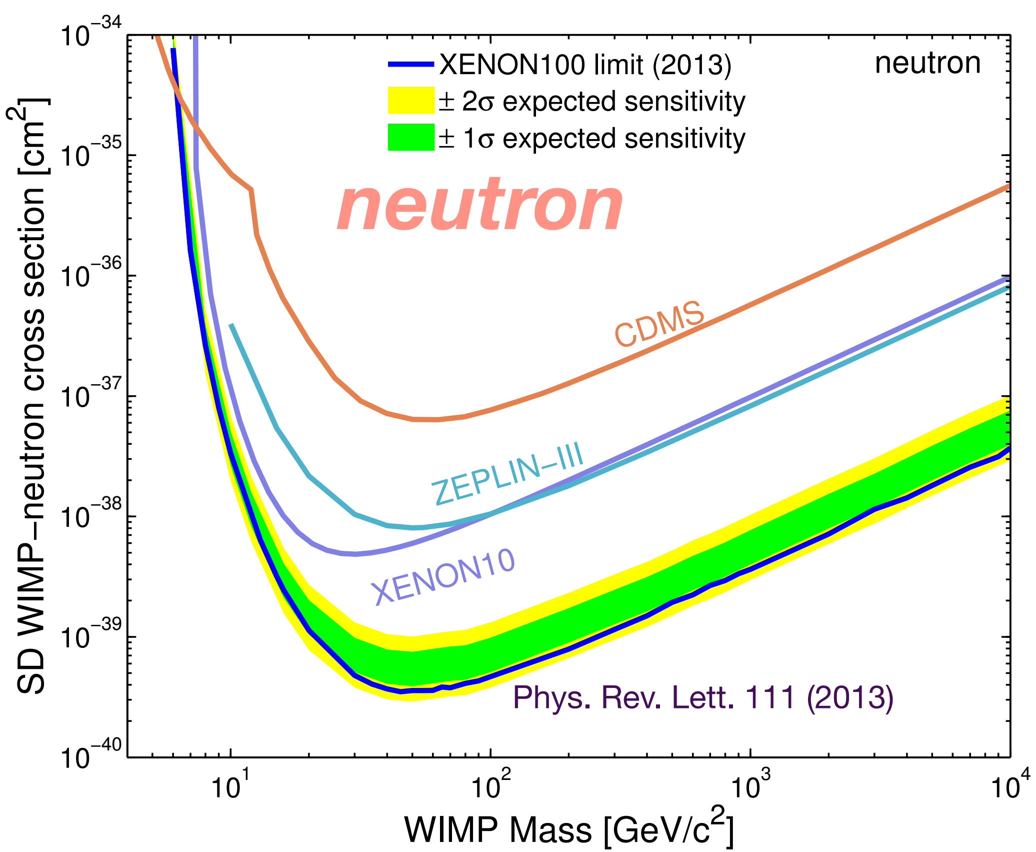
WIMP-nucleon cross section : 1.6×10^{-42} cm^2

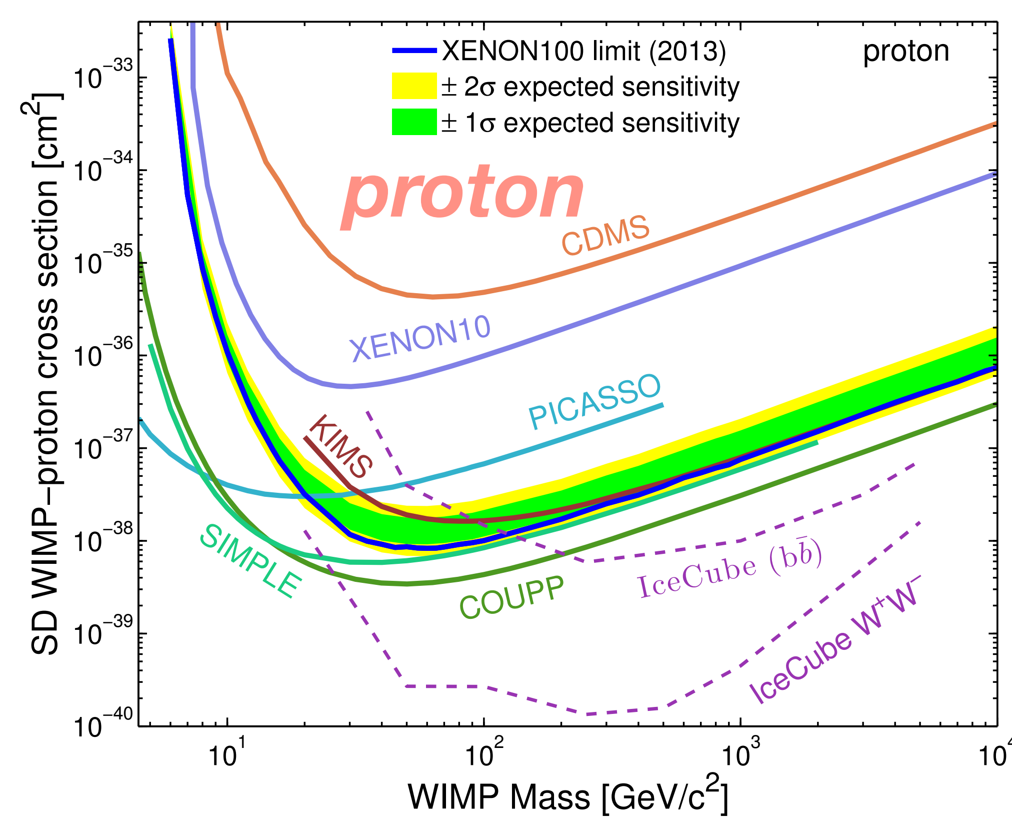
E. Aprile et al (XENON), PRD 88, 2013

WIMP results from XENON100

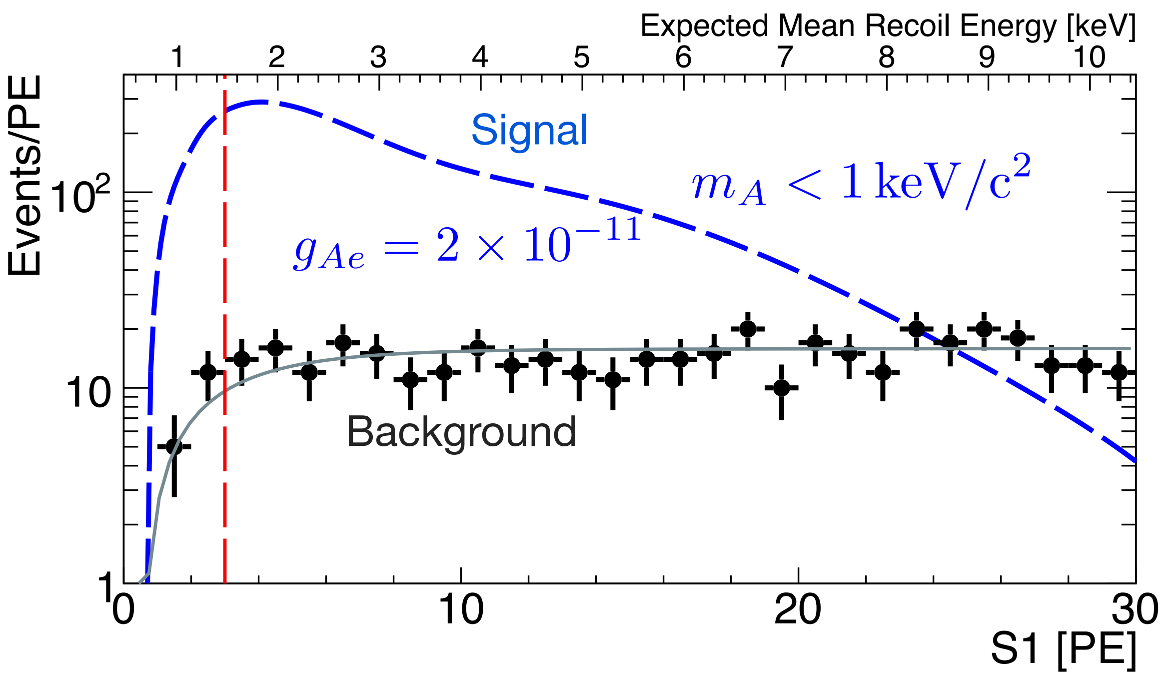


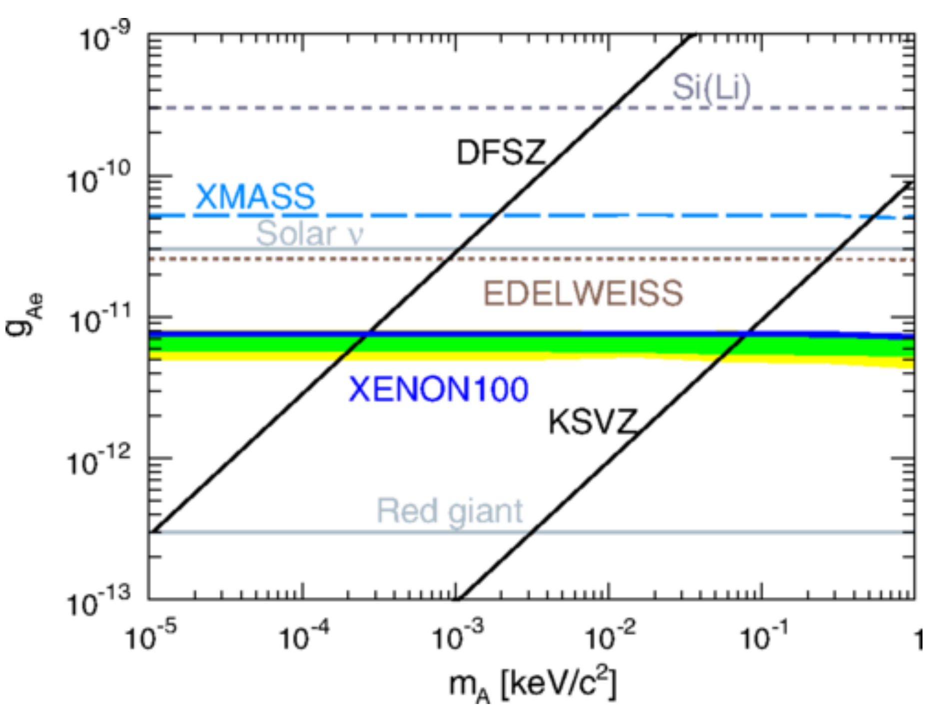
- Ultra-low background and design sensitivity achieved
- Background: ~ 5 x 10^{-3} events/(kg d keV)
- No evidence for WIMP dark matter
- Upper limits on SI, SD WIMP-nucleon cross sections (PRL 109, PRL 111)





Solar axions with XENON100





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

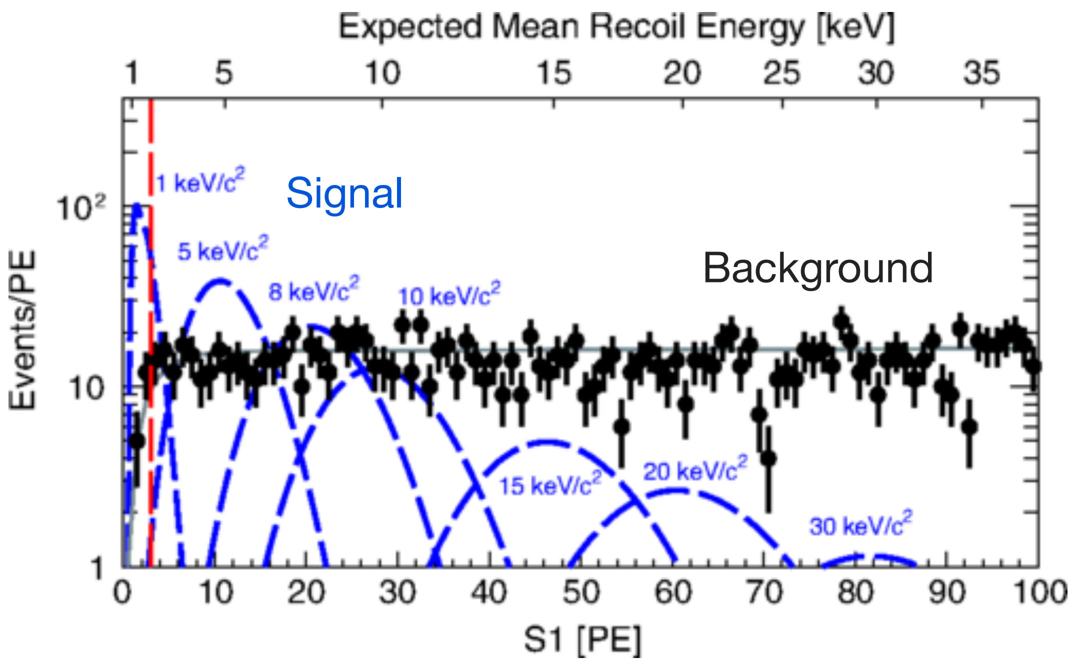
$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta_A}\frac{3E_A^2}{16\pi\alpha_{em}m_e^2}\left(1 - \frac{\beta_A^{2/3}}{3}\right)$$

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

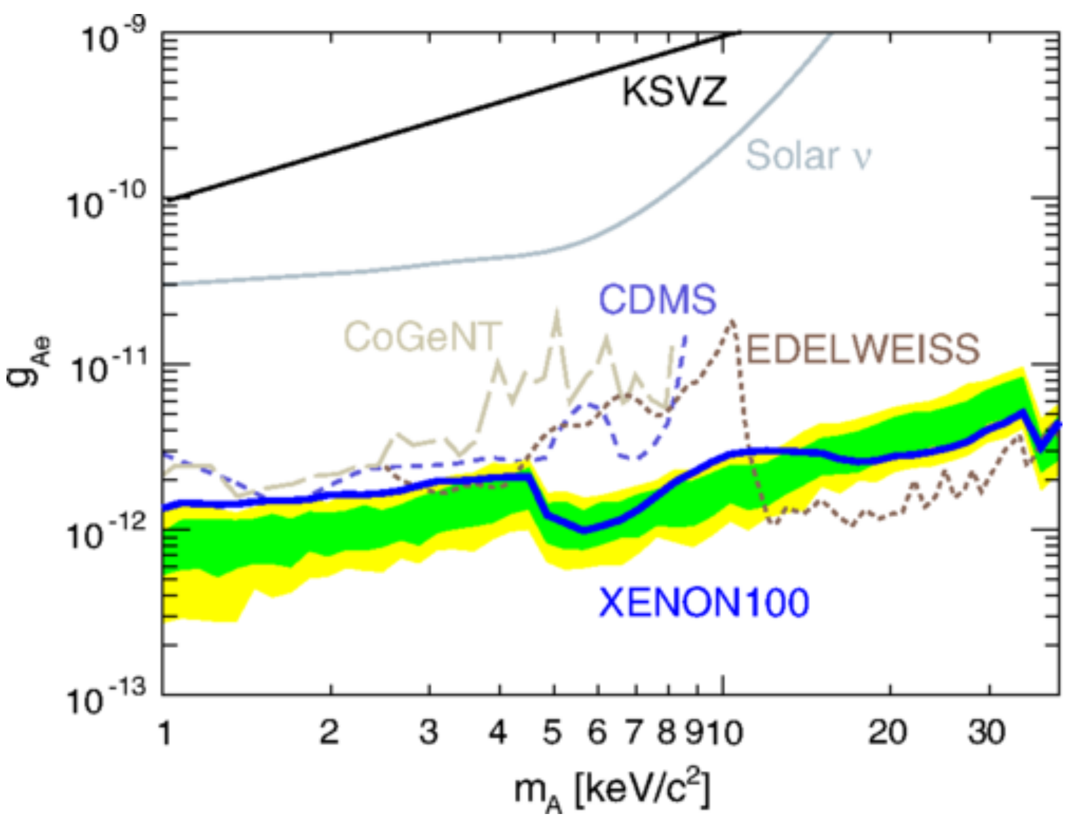
- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs (LB et al., PRD 87, 2013; arXiv:1303.6891)

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

Galactic axion-like particles with XENON100



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 $\rho_0 = 0.3\,\mathrm{GeV/cm^3}$

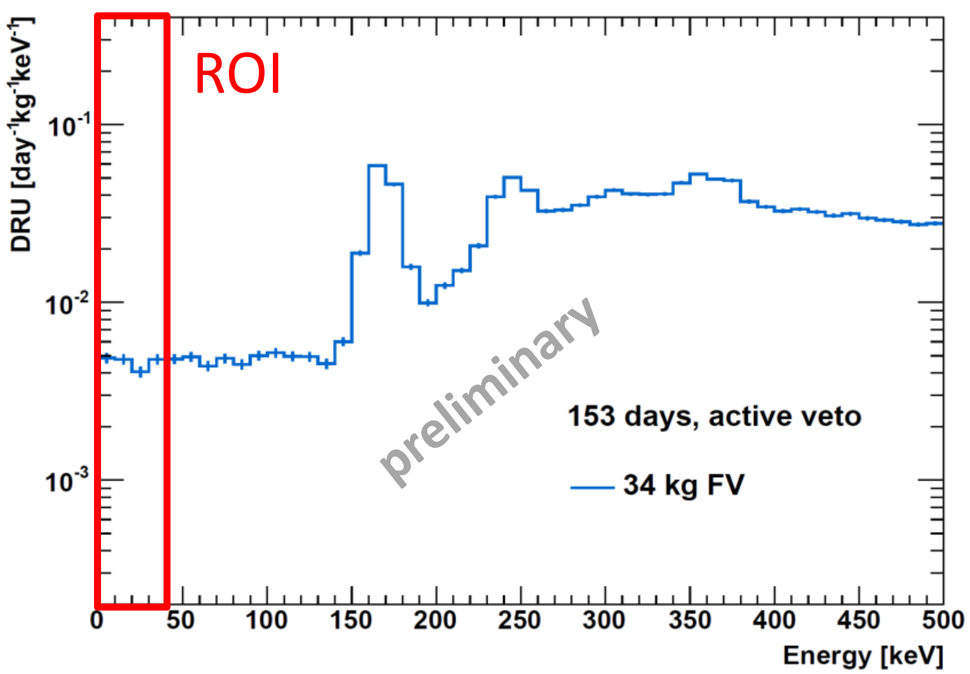
$$\phi_A = c\beta_A \times \frac{\rho_0}{m_A}$$

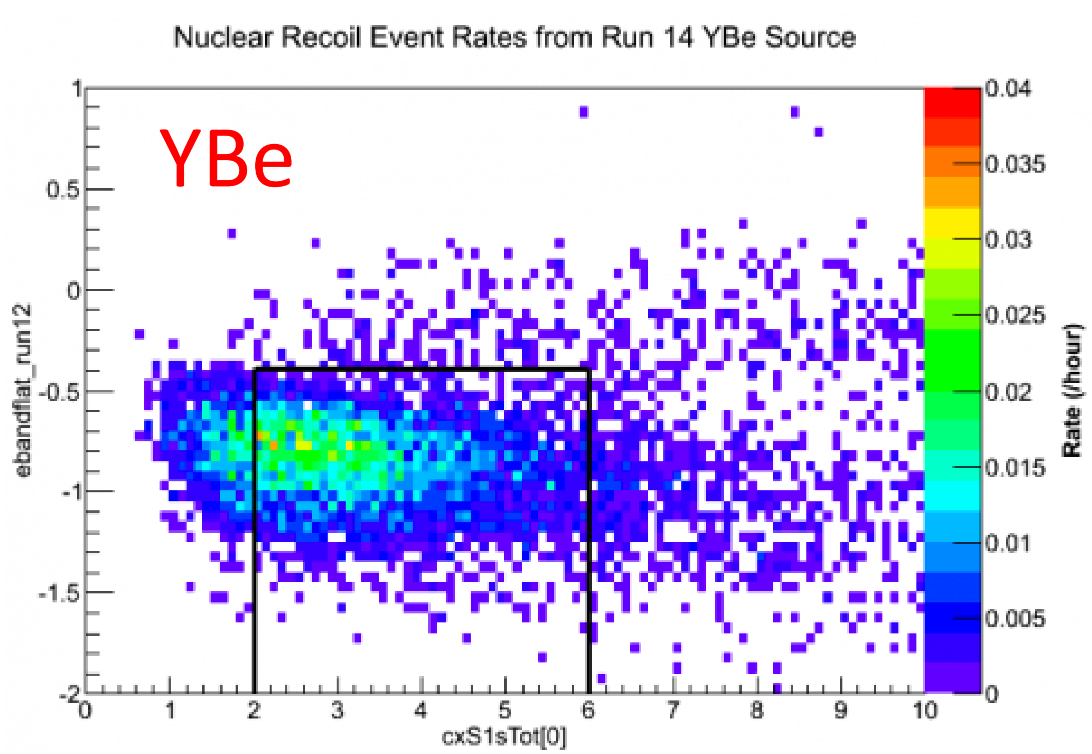
$$R \propto g_{Ae}^2$$

- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs (LB et al., PRD 87, 2013; arXiv:1303.6891)

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

Upcoming results from XENON100





- Search for annual modulation (2 papers submitted)
- Analysis of 153 live days of blinded dark matter search data close to unblinding; search for inelastic scattering on ^{129}Xe, search for low-mass WIMPs
- Calibration measurements:
  - probe lowest nuclear recoil energies (max at 4.5 keVnr) with YBe source placed inside the shield; more than 80 live days collected and clear signal due to neutron scatters observed
  - currently ^{83m}Kr, ^{220}Rn calibration run & analysis
- XENON100 is also used as a test facility for XENON1T/nT: novel online radon purification technique, by cryogenic distillation (Rn has 10 x lower vapour pressure than xenon) verified

The XENON collaboration

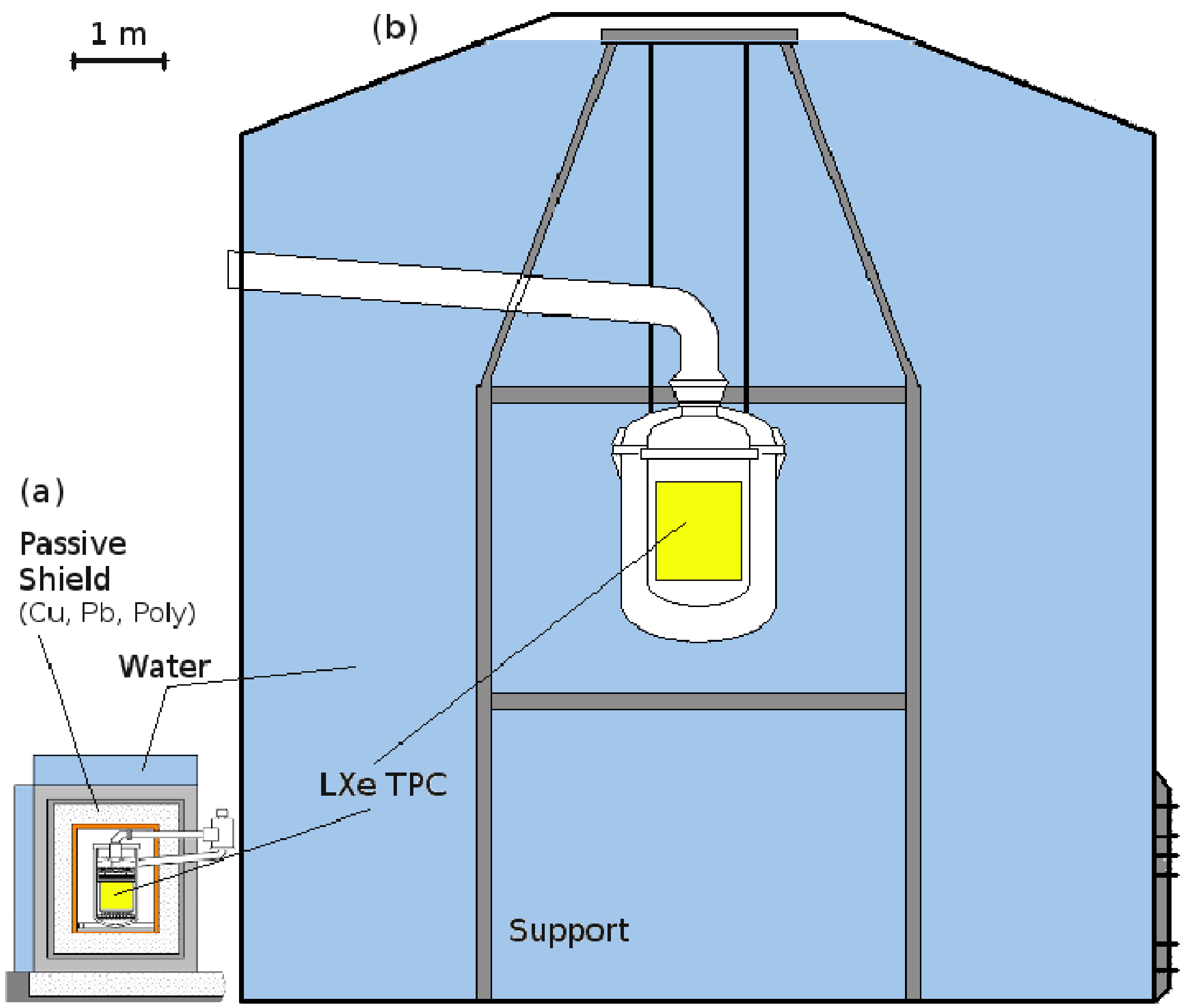
LNGS, November 2014

Columbia Rice UCLA Zürich Coimbra LNGS INFN SJTU Purdue Rensselaer Chicago

Bologna Subatech Münster Heidelberg Nikhef Weizmann Mainz Bern Stockholm University NYU Abu Dhabi

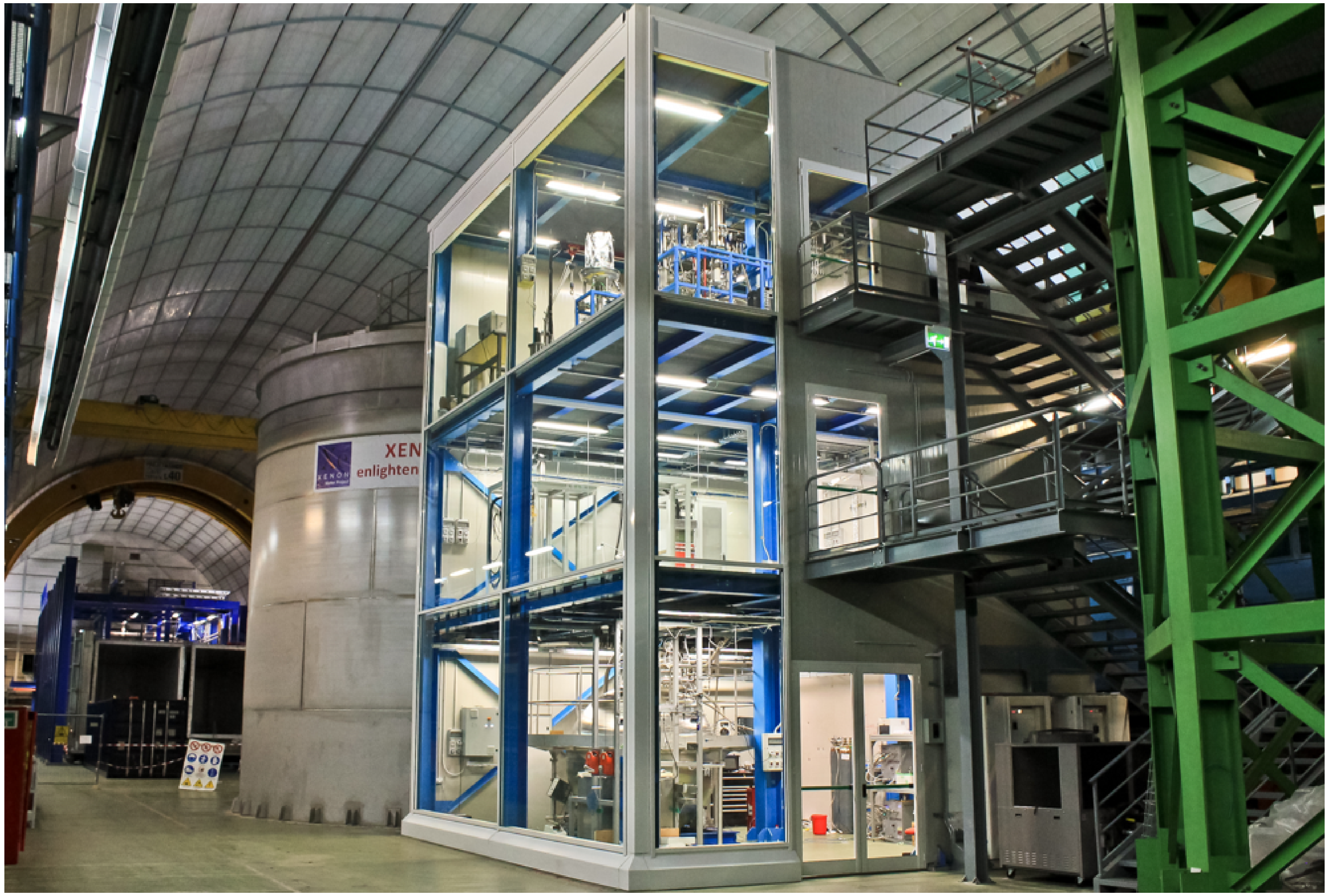
From XENON100 to XENON1T in numbers

	XENON100	XENON1T
Total LXe mass [kg]	161	3300
Background [dru]	5 x 10^{-3}	5 x 10^{-5}
^{222}Rn [µBq/kg]	~ 65	~ 1
^{nat}Kr [ppt]	~120	~0.2
e- drift [cm]	30	100
Cathode HV [kV]	-16	-100



The XENON1T experiment

- Under construction at LNGS since autumn 2013; commissioning planned for late 2015
- Total (active) LXe mass: 3.3 t (2 t), 1 m electron drift, 248 3-inch PMTs in two arrays
- Background goal: 100 x lower than XENON100 ~ 5×10^{-2} events/(t d keV)



XENON1T: status of construction work

- Water Cherenkov shield built and instrumented
- Cryostat support, service building, electrical plant completed
- Several subsystems (cryostat, cryogenics, storage, purification, cables & fibres, pipes) installed/ being tested underground

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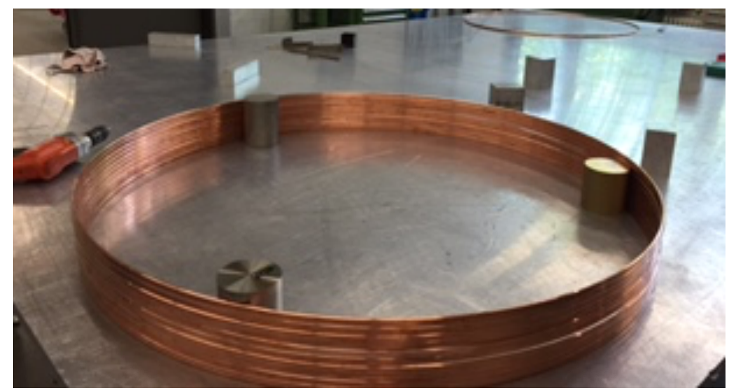
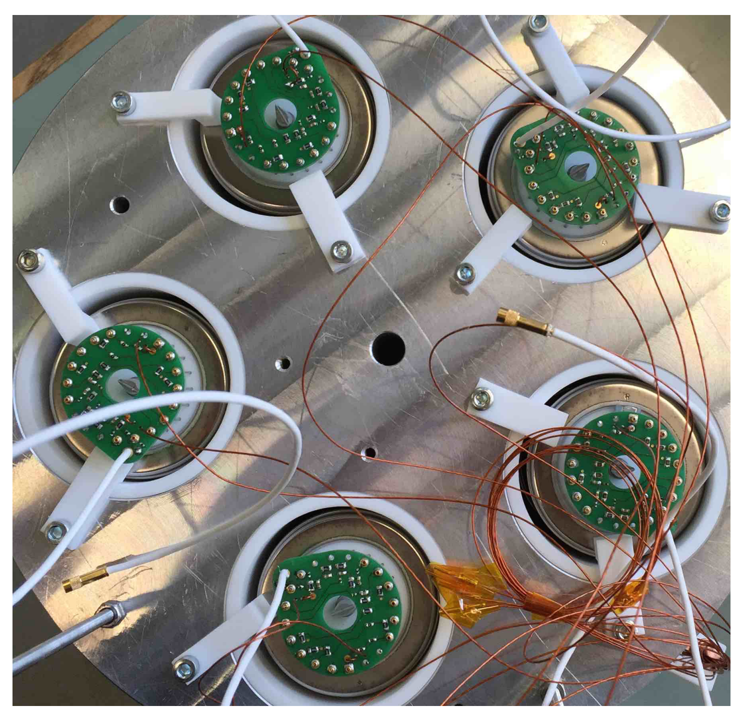
The XENON1T inner detector

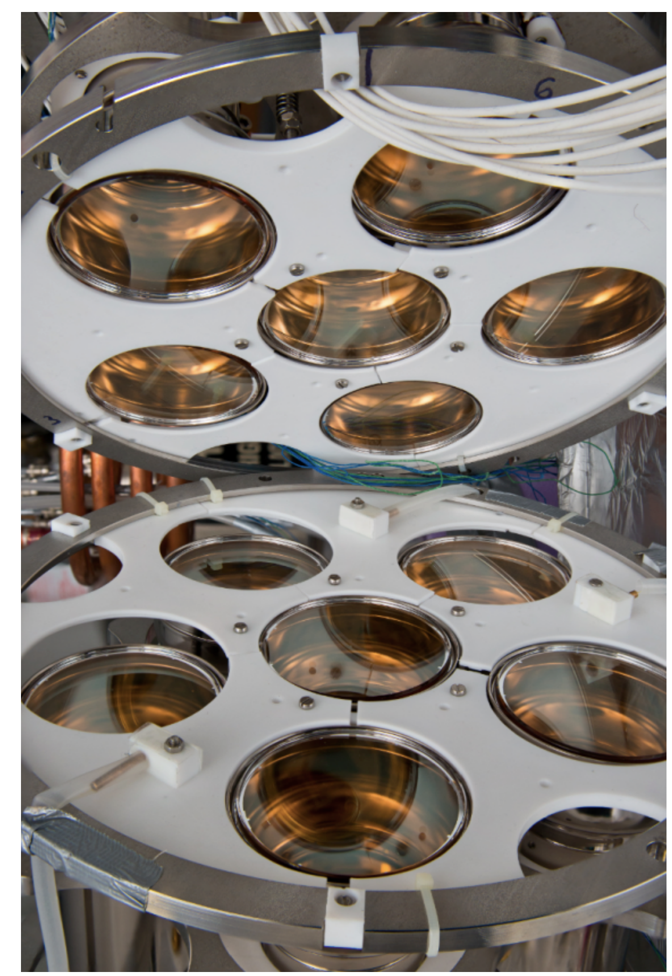
- PMTs are screened with HPGe, then tested in cold gas and - a subsample - in LXe
- TPC design is finalised, currently under prototyping, materials being screened

The TPC





PMT and final bases & cables tests in liquid xenon

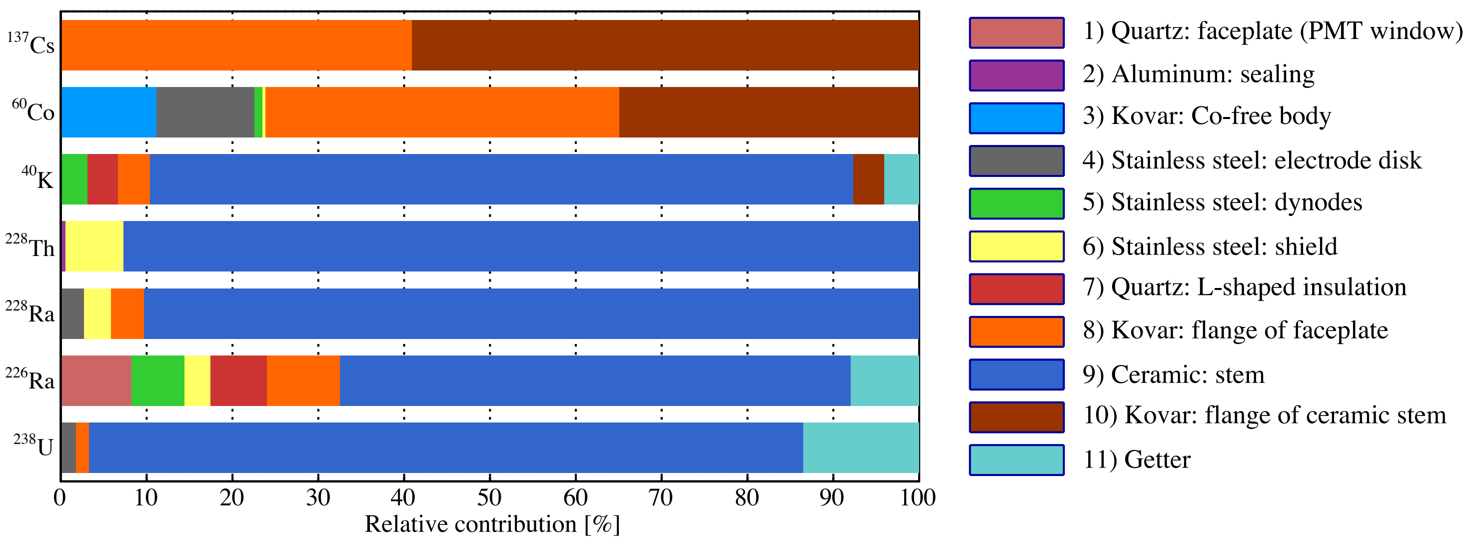


PMT tests at -100 C

The XENON1T photosensors

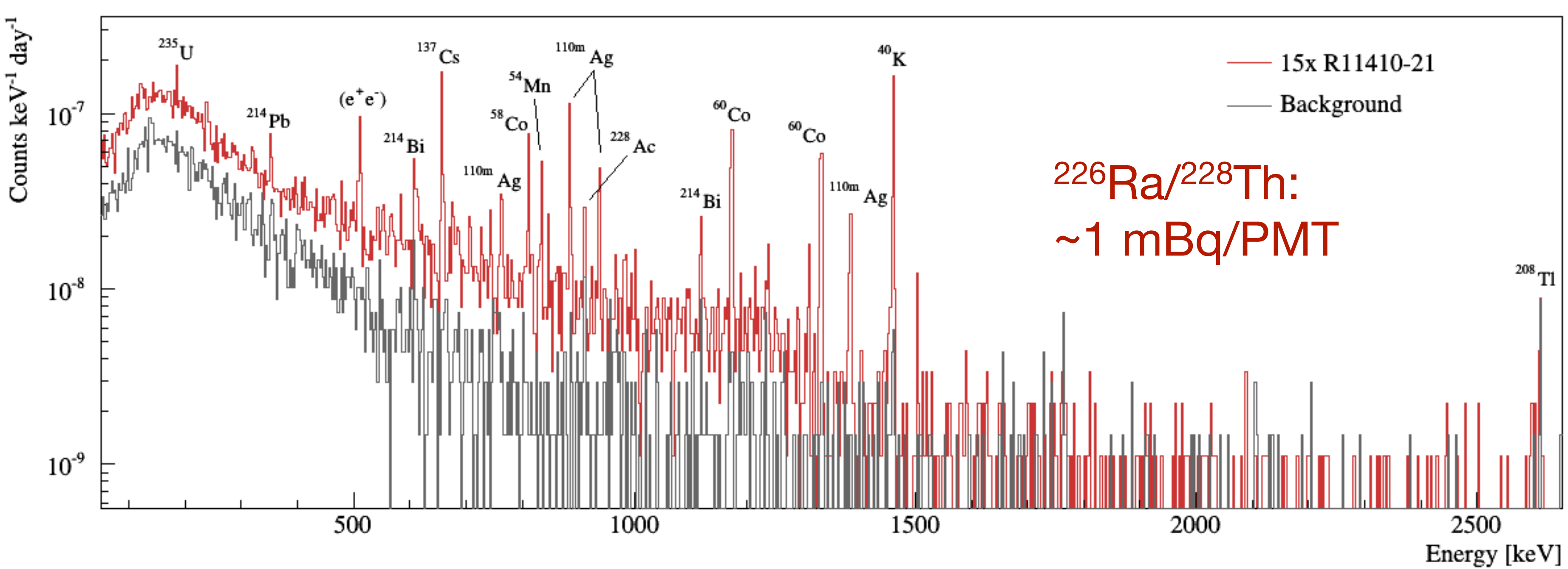
R11410-21 3-inch PMTs; average QE at 175 nm: 36%, average gain: 2 x 10^6 at 1500 V

Material screening/selection for PMT production



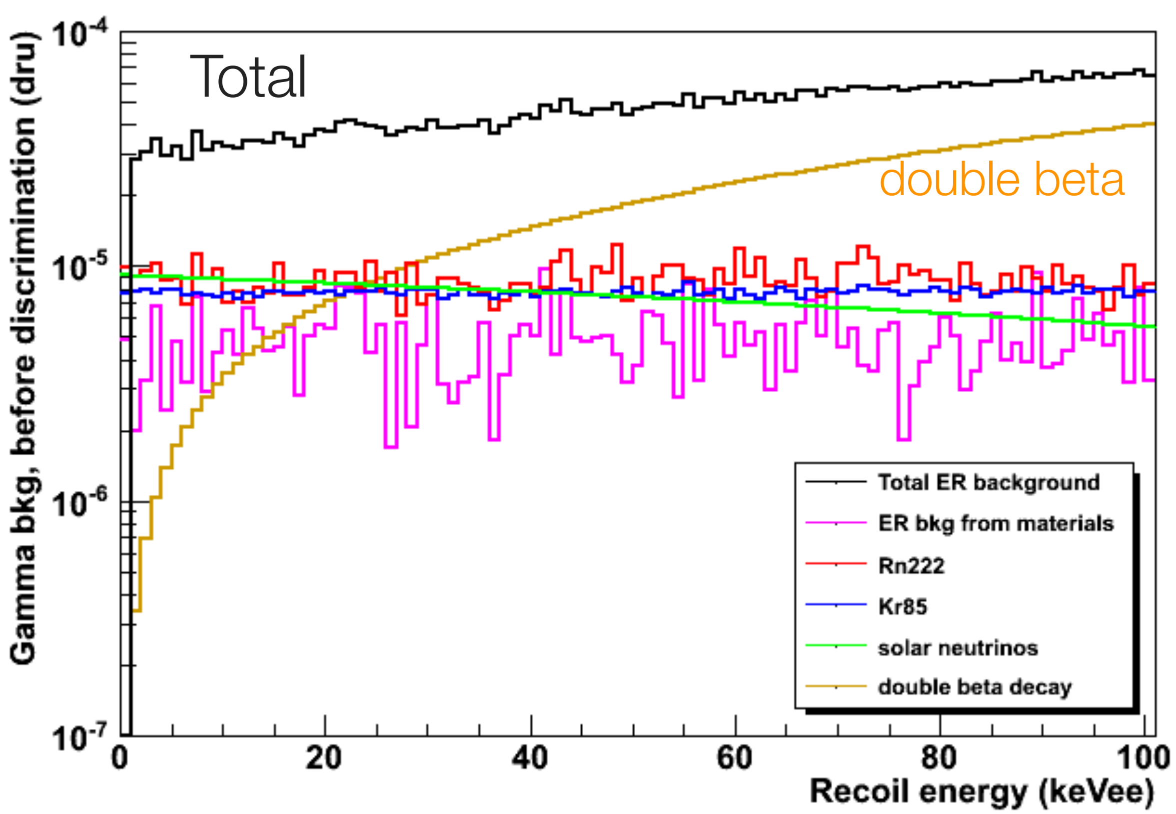
Screening of final product

XENON collaboration, arXiv:1503.07698v1

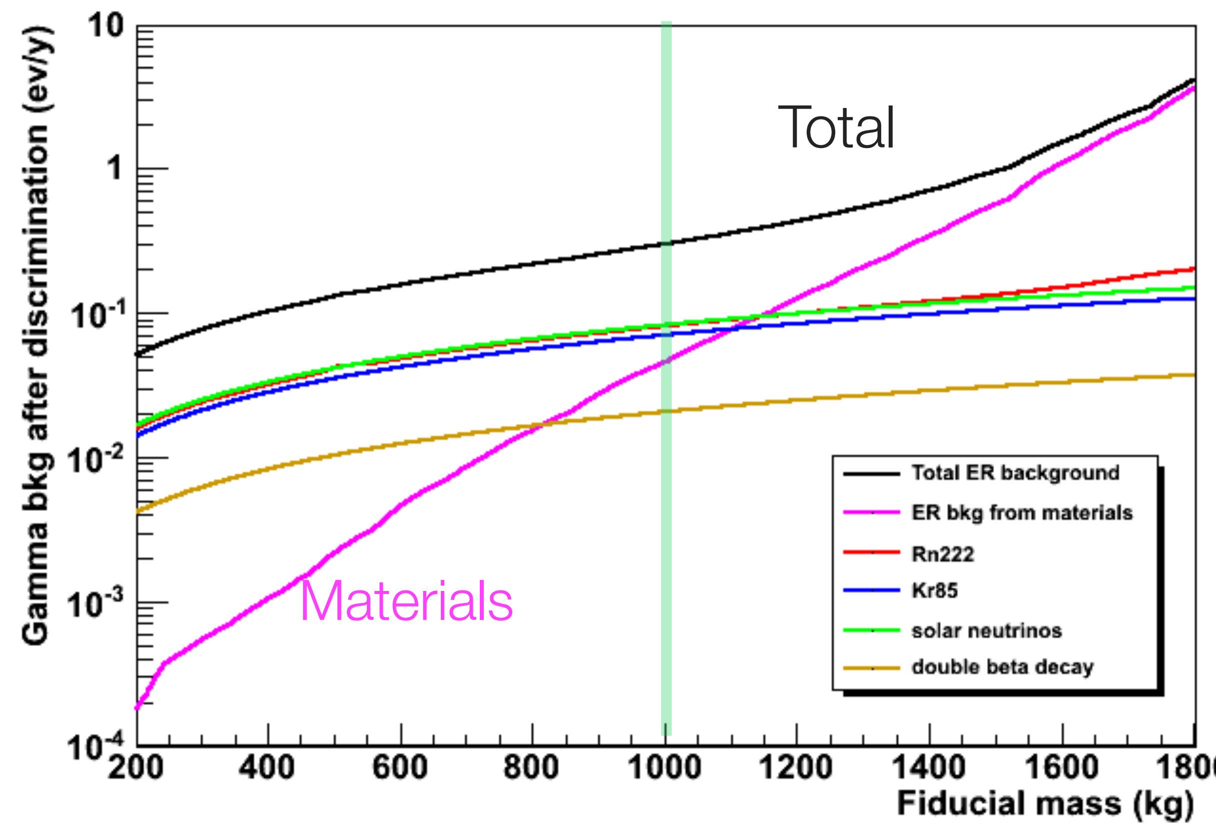


XENON1T background predictions

- Materials background: based on screening results for all detector components
- ^{85}Kr: 0.2 ppt of ^{nat}Kr with 2x10^{-11} ^{85}Kr; ^{222}Rn: 1 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: 0.2 events/year in 1 ton, [5-50] keV$_{nr}$ (muon-induced n-BG < 0.01 ev/year)



Background rate from various components

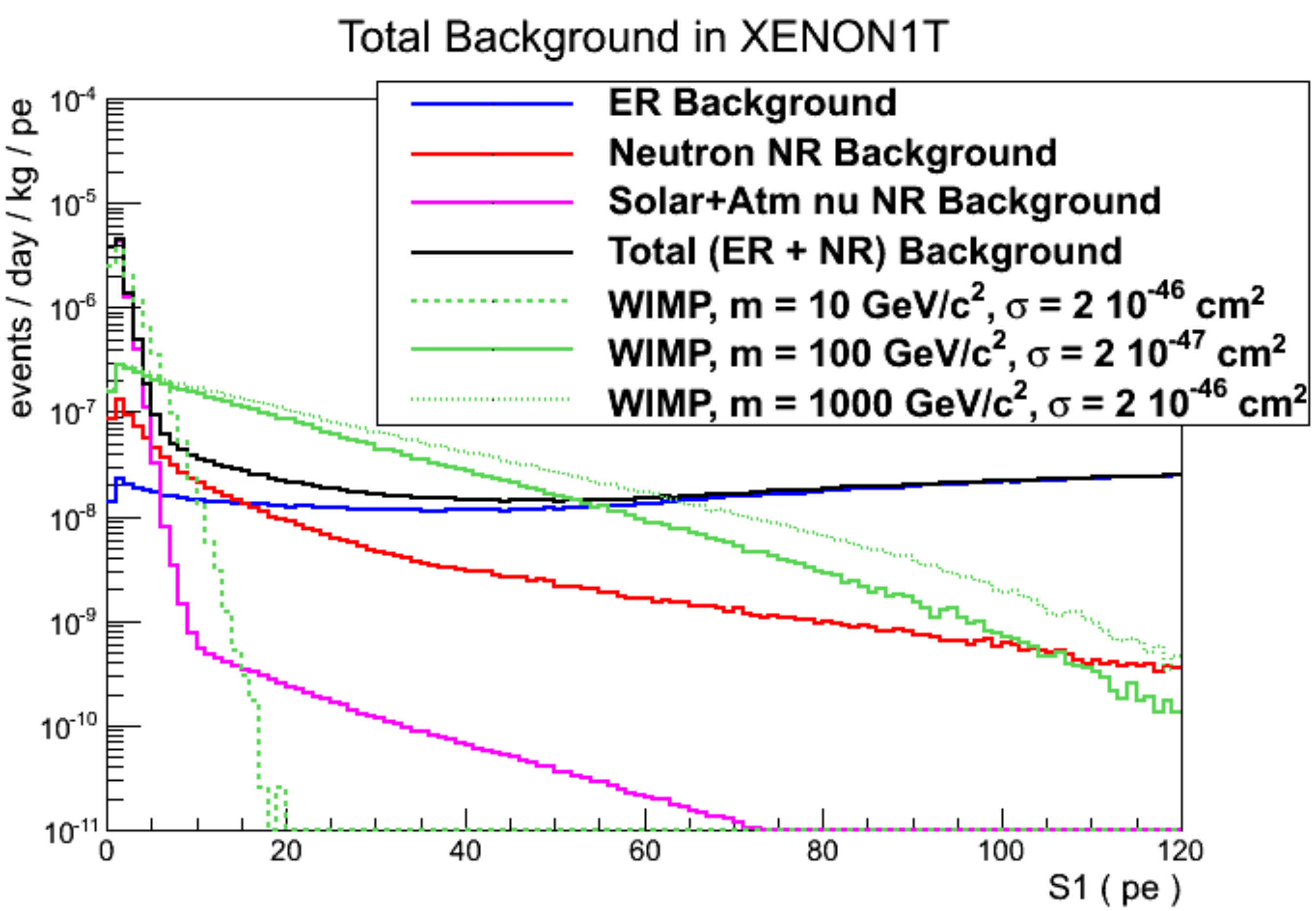


Background versus fiducial LXe mass

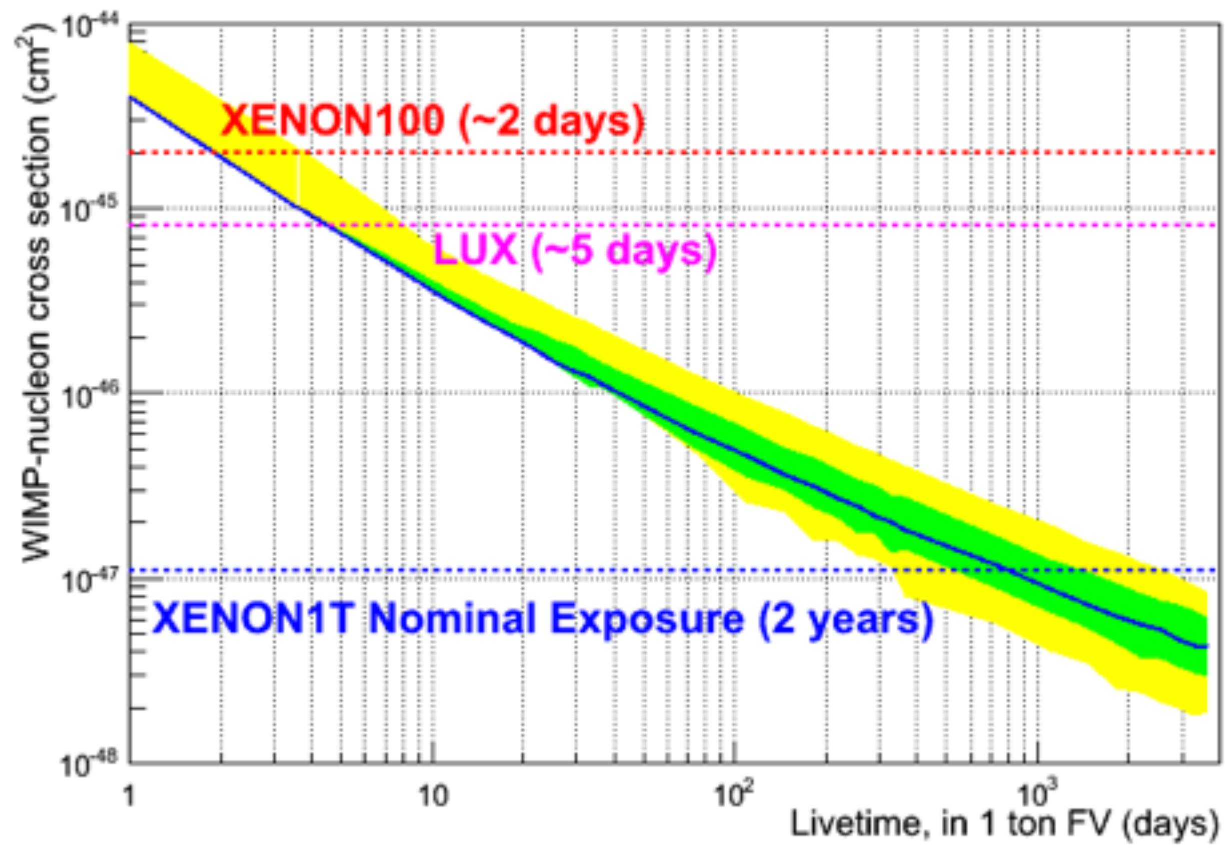
XENON1T backgrounds and WIMP sensitivity

Single scatters in 1 ton fiducial
99.75% S2/S1 discrimination
NR acceptance 40%
Light yield = 7.7 PE/keV at 0 field
L_{eff} = 0 below 1 keVnr

WIMP mass: 50 GeV
Fiducial LXe mass: 1 t
Sensitivity at 90% CL



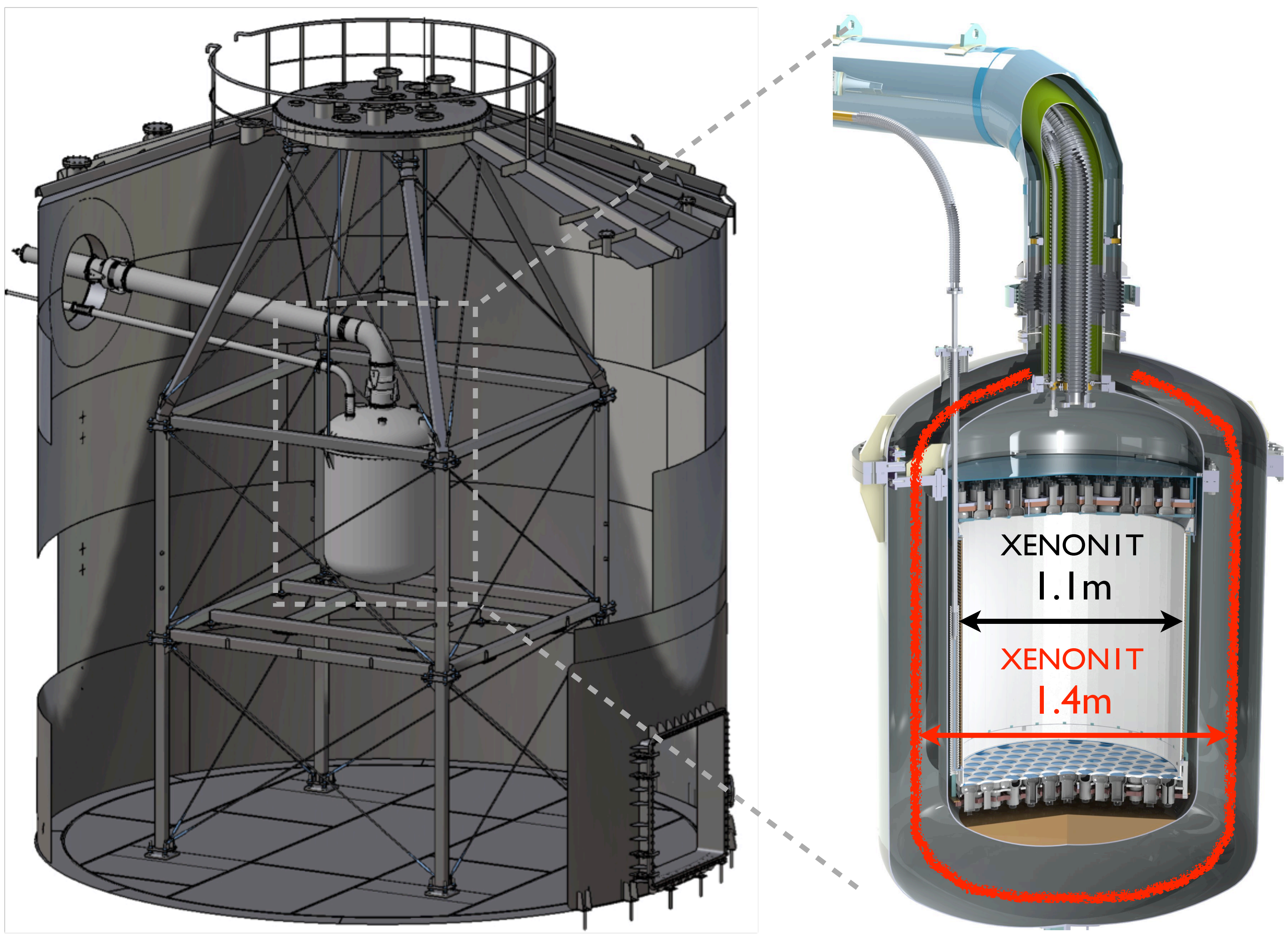
ER + NR backgrounds and WIMP spectra



Sensitivity versus exposure (in 1 ton fiducial mass)

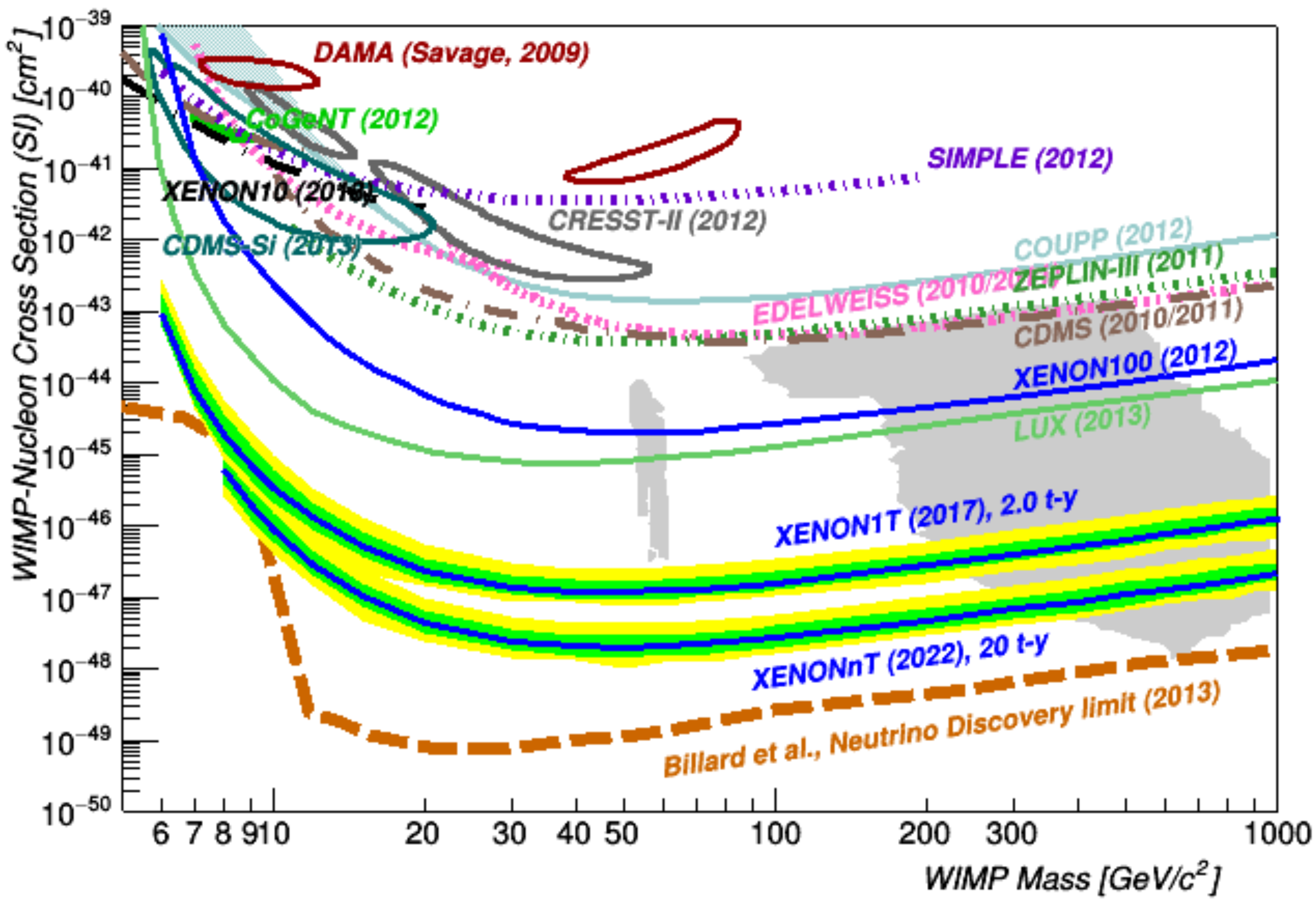
XENONnT: 2018-2020

- Plan: double the amount of LXe (~7 tons), double the number of PMTs
- XENON1T is constructed such that many sub-systems will be reused for the upgrade:



- Water tank + muon veto
- Outer cryostat and support structure
- Cryogenics and purification system
- LXe storage system
- Cables installed for XENONnT as well
- More LXe, PMTs, electronics will be needed

XENONnT WIMP sensitivity

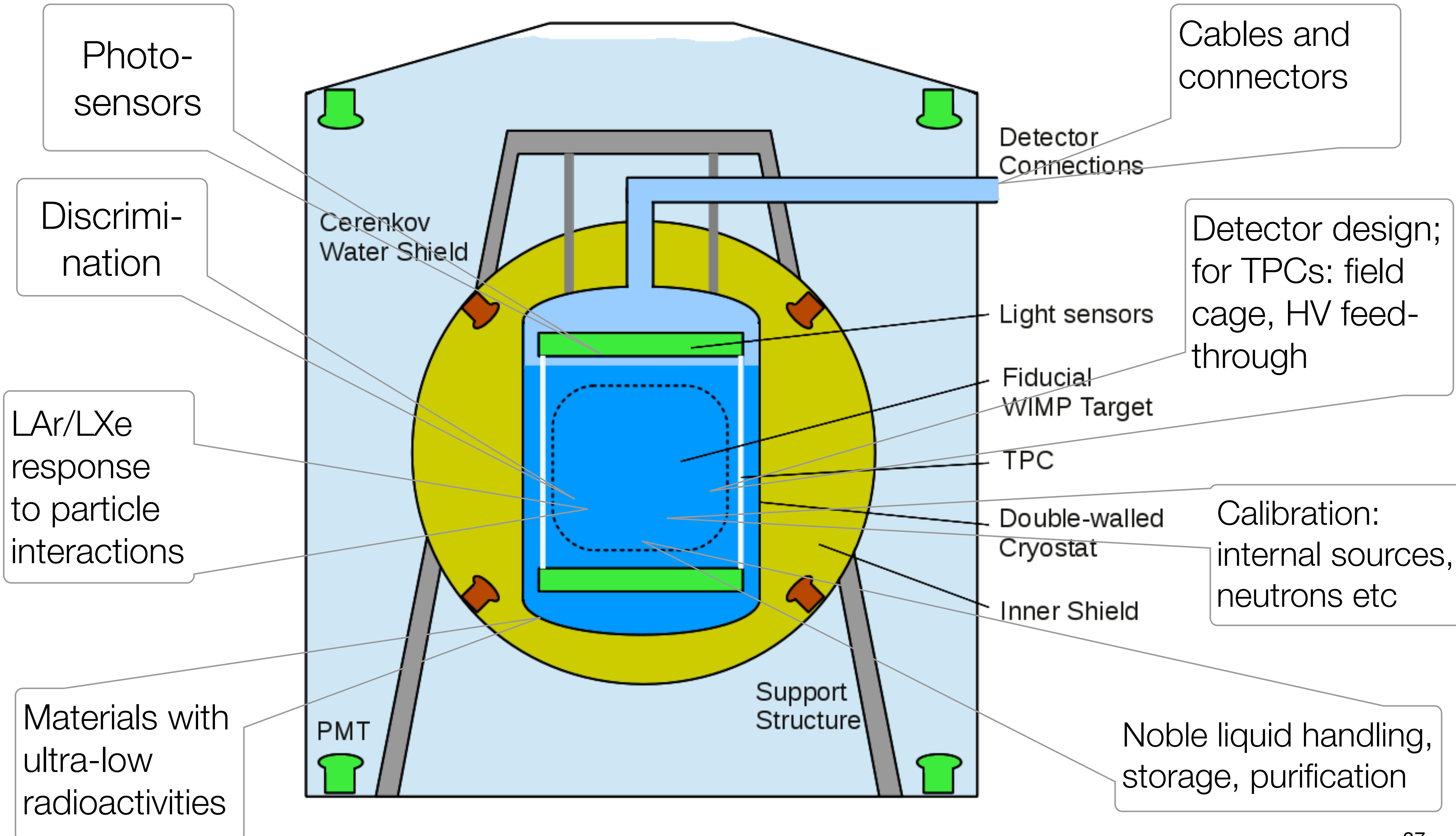


DARWIN Dark matter WIMP search with noble liquids

darwin-observatory.org

- R&D and design study for 30-50 tons LXe detector
- ~ few x 10^3 photosensors
- >2 m drift length
- >2 m diameter TPC
- PTFE walls with Cu field shaping rings (baseline scenario, 4-π readout under study)
- Background goal: dominated by neutrinos
- Physics goal:
  - WIMP spectroscopy
  - many other channels (pp neutrinos, double beta decay, axions and ALPs, bosonic SuperWIMPs…)

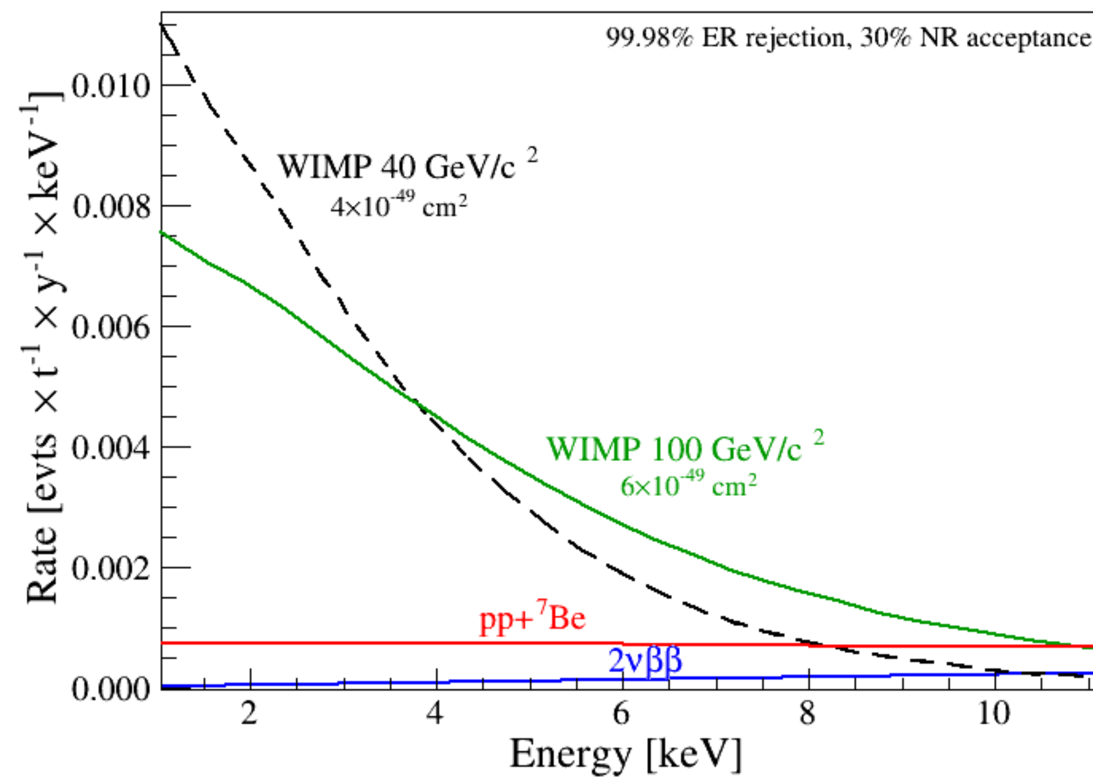
Strong R&D programme required



Backgrounds: electronic recoils

- Materials (cryostat, photosensors, TPC)
- ^{222}Rn in LXe: **0.1 μBq/kg (1 μBq/kg** => same background level as solar neutrinos)
- ^{nat}Kr in LXe: **0.1 ppt ^{nat}Kr (0.2 ppt ^{nat}Kr** => same background level as solar neutrinos)
- ^{136}Xe double beta decay
- Solar neutrinos (mostly pp, ^{7}Be)

WIMPs and backgrounds



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

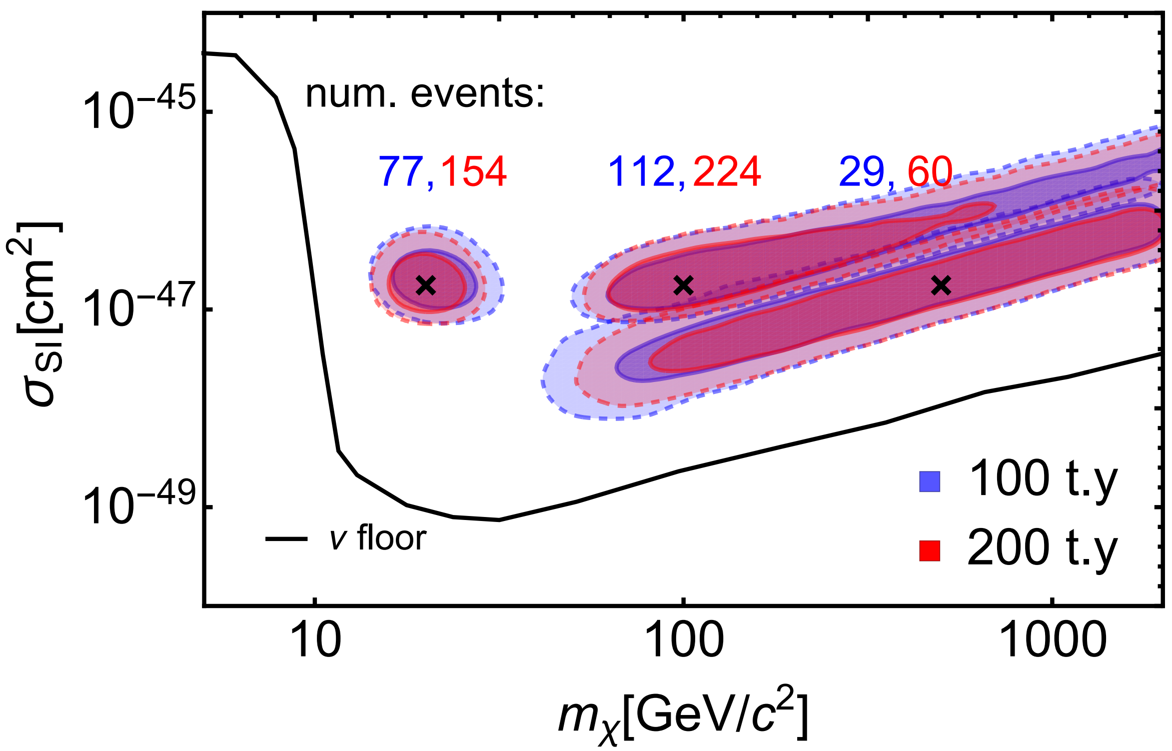
1 t x yr exposure,
2-30 keVee

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

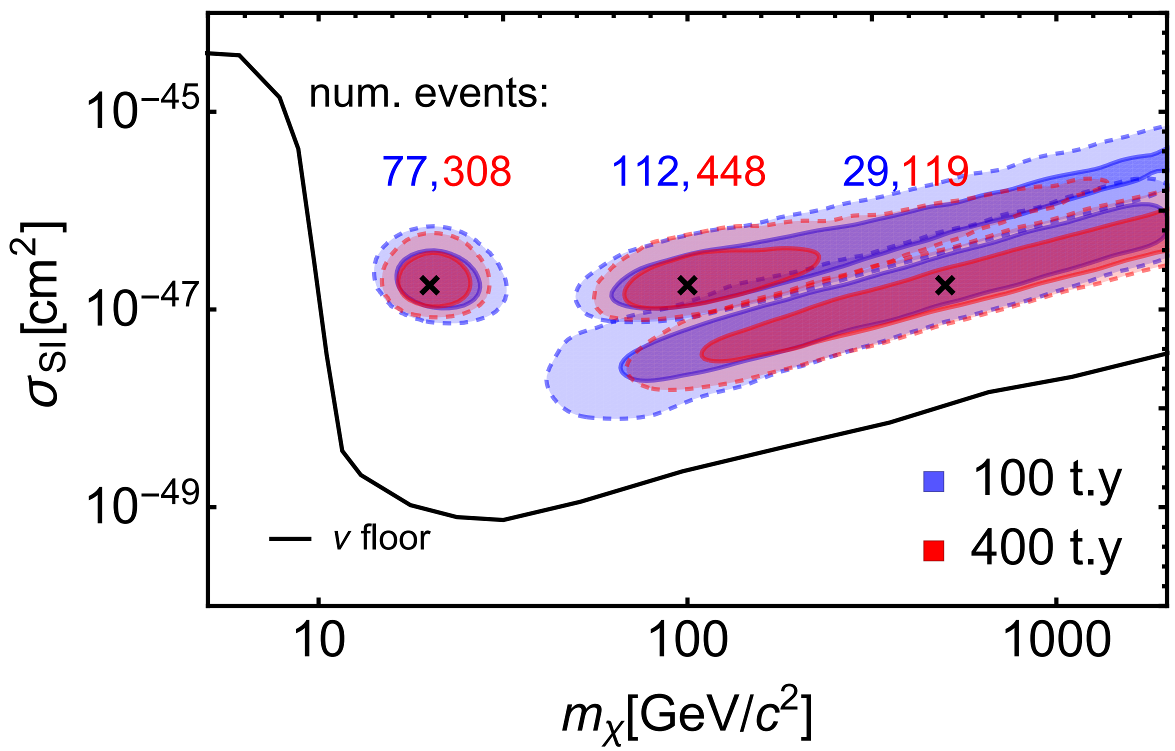
WIMP physics: spectroscopy

- 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:

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

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

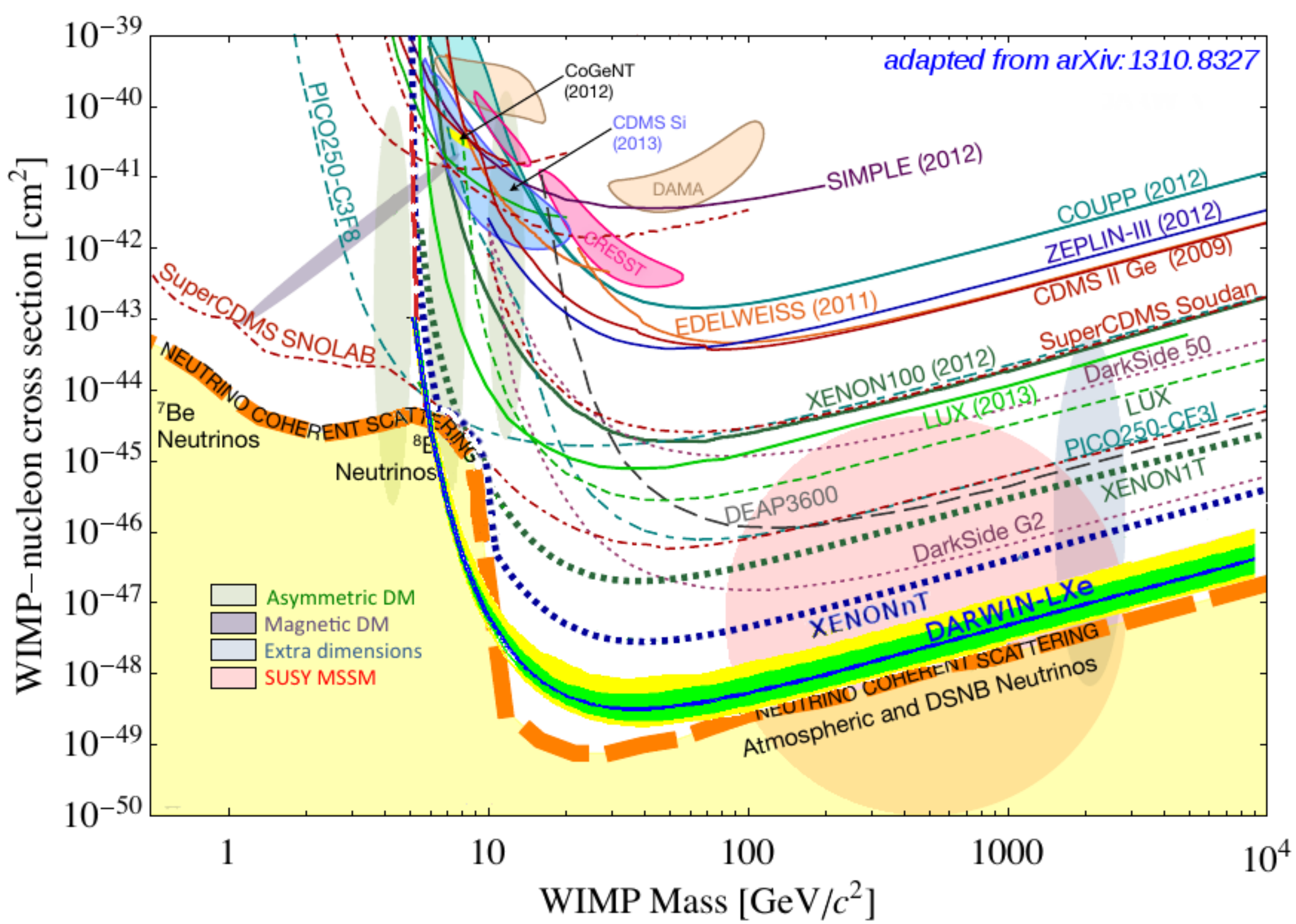
$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$$

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

Sensitivity for spin-independent cross sections

- 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



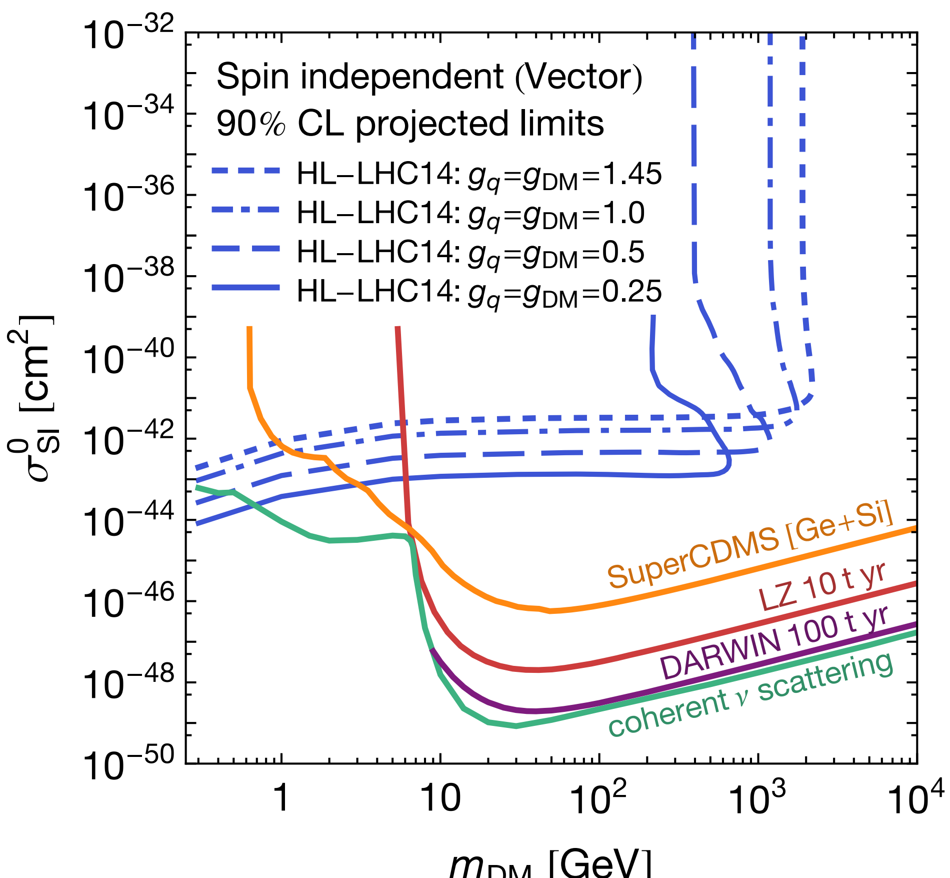
Note: "nu floor" = 3-sigma detection line at 500 CNNS events above 4 keV

Complementarity with the LHC

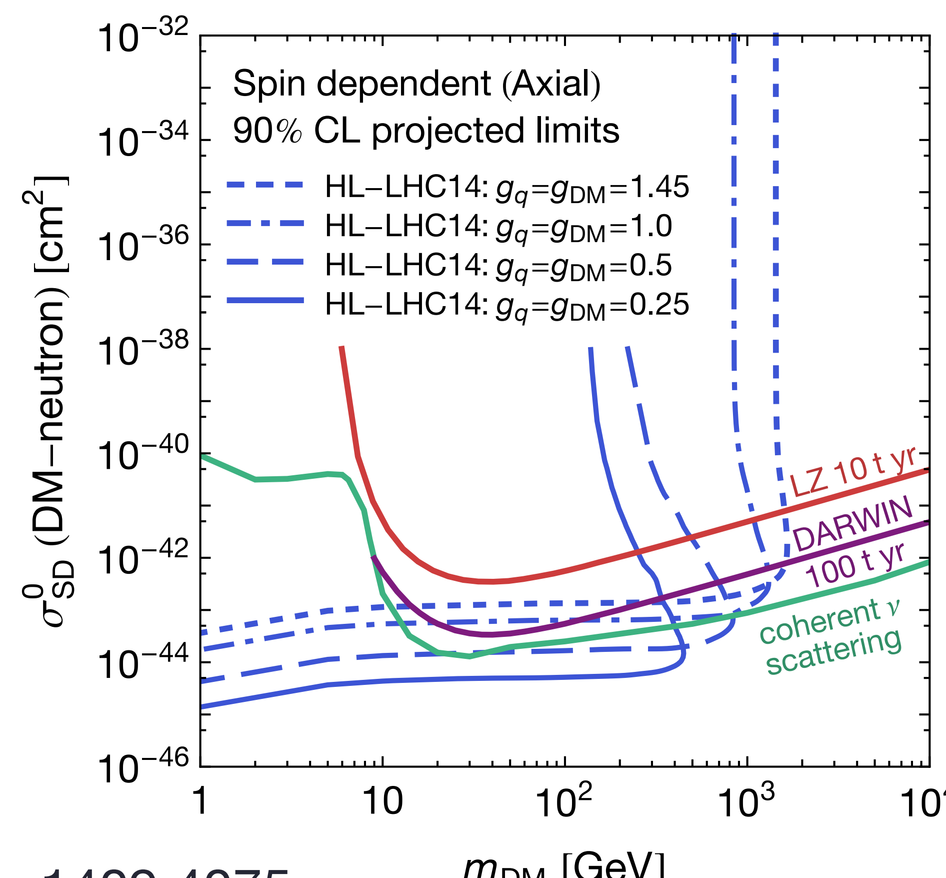
- Minimal simplified DM model with only 4 variables: m_{DM}, M_{med}, g_{DM}, g_q
- Here DM = Dirac fermion interacting with a vector or axial-vector mediator; equal-strength coupling to all active quark flavours

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

Spin independent



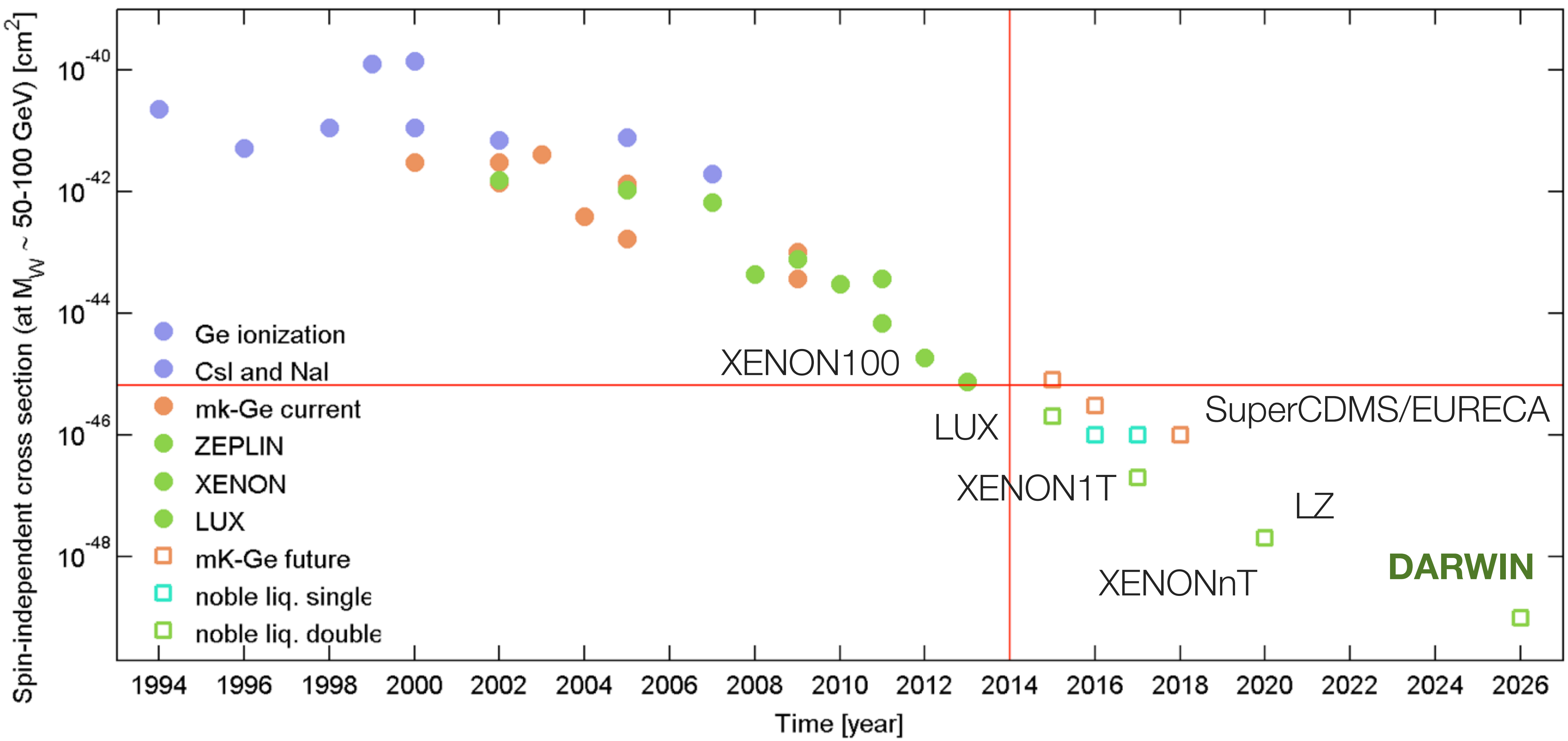
Spin dependent



S. Malik et al., arXiv:1409.4075

Evolution of the experimentally probed WIMP-nucleon cross section

- Sensitivity at WIMP masses above ~ 6 GeV/c^2 is clearly dominated by *noble liquid (Xe) time projection chambers*



Update from Physics of the Dark Universe 1, 94 (2012)

Summary

- New particles with masses and cross sections at the electroweak scale still viable candidates for galactic dark matter
- Liquid xenon based experiments offer great sensitivity over a wide range of masses
- XENON100 has reached its design sensitivity for medium-heavy WIMPs, and it can also probe other type of interactions (axions, ALPs, light WIMPs)
- XENON1T is well under construction at LNGS & various home institutions, integration of all sub-systems is planned for fall 2015, with commissioning ~ late 2015
- XENONnT is proposed as a fast upgrade to XENON1T, with a factor of 10 increase in sensitivity
- DARWIN - an R&D and design study for a third-generation, ‘ultimate’ WIMP dark matter detector - would operate a 30 - 50 t LXe detector, with the goal of probing the experimentally accessible parameter space for masses >~ 10 GeV & spectroscopy
- It could also detect pp-neutrinos in real time, with high stats, possibly coherent neutrinos scattering, axions, ALPs, bosonic SuperWIMPs, etc

The end