Direct Dark Matter Search With The XENON Experiment

26th Rencontres de Blois

Particle Physics and Cosmology

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on behalf of the XENON collaboration

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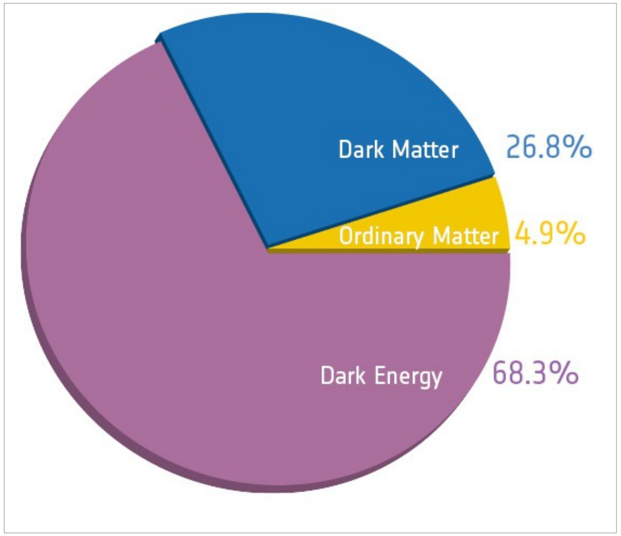
18 May to 23 May 2014

What do we hunt: (WIMP) Dark Matter

Astrophysical hints for Dark Matter:

- Rotation curves in galaxies
- Newest CMB result from Planck satellite (2013)[1]



What is Dark Matter?

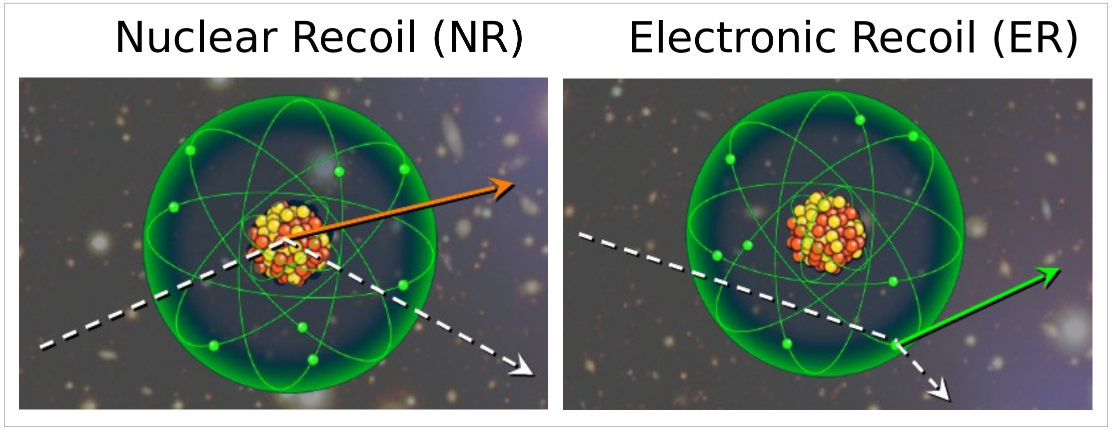
→ Known particles are ruled out
→ On the electro-weak scale

WIMP Dark Matter:

→ ***W***eakly ***I***nteracting ***M***assive ***P***articles

How to find such a mysterious particle?

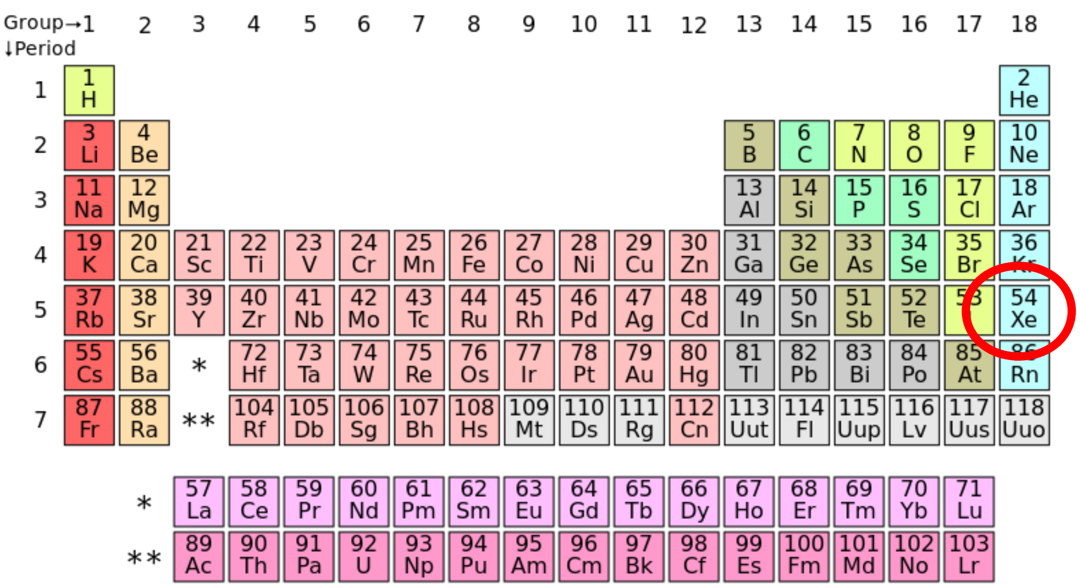
→ Direct Dark Matter search with liquid xenon
→ Search for nuclear recoils
(WIMP-nucleon interaction)

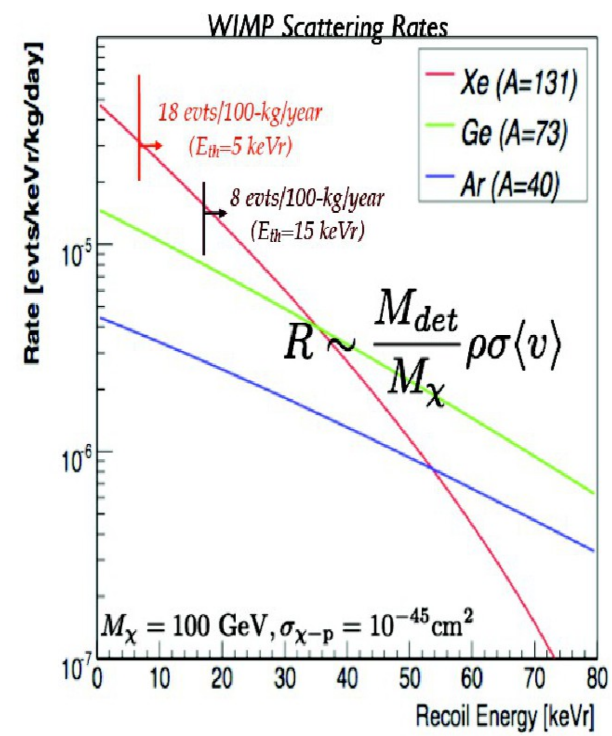


1) preprint: arXiv:1303.5062

XENON Dark Matter Project

Xenon as detection medium:





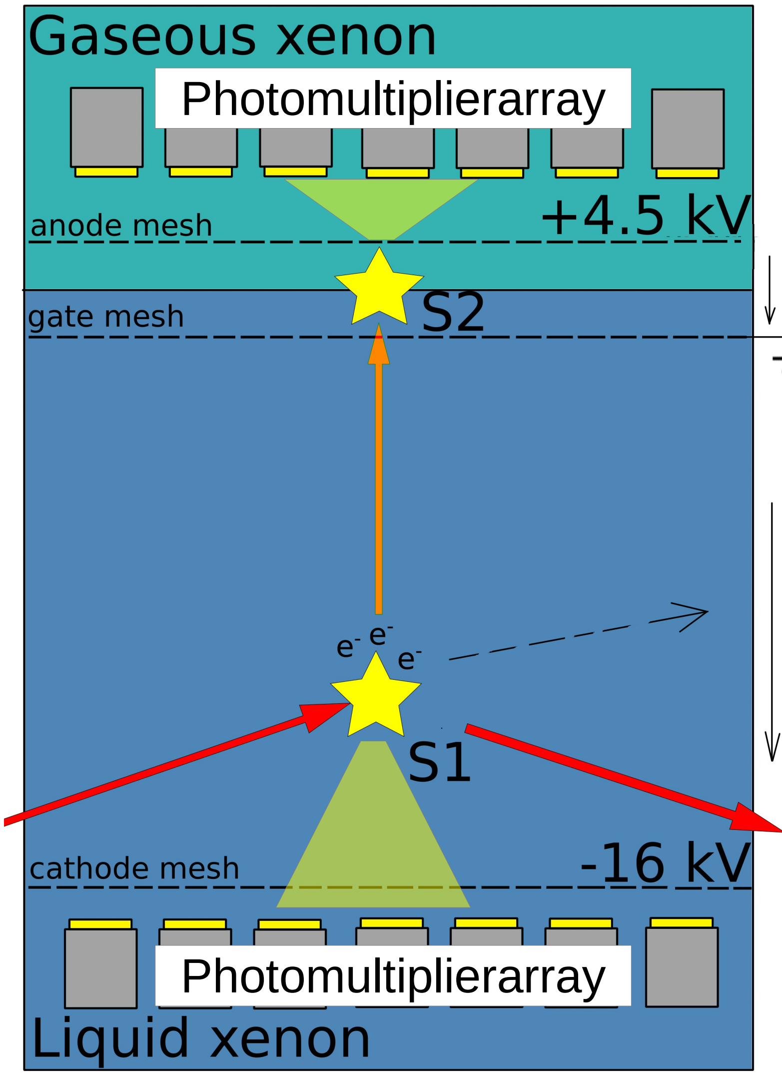
WIMP scattering rates for different detector materials

Detection medium: (liquid) xenon

- High density: ρ = 2.8 kg/l
- High mass number: A = 131 (→ $\sigma \sim A^2$) for coherent scatter
- Even/odd (stable) isotopes
- Radioactive impurities can be removed (e.g.^{85}Kr)

- Increase interaction probability
- Self-shielding properties
  → Definition of a fiducial volume
- Test Dark Matter models:
  → Spin dependent analysis
  → Spin independent analysis
- Easy to scale up!
  → Future detector design

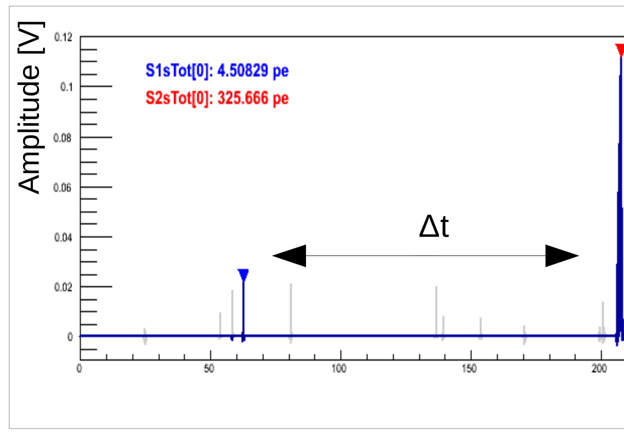
Detection principle of a two phase time projection chamber (TPC)



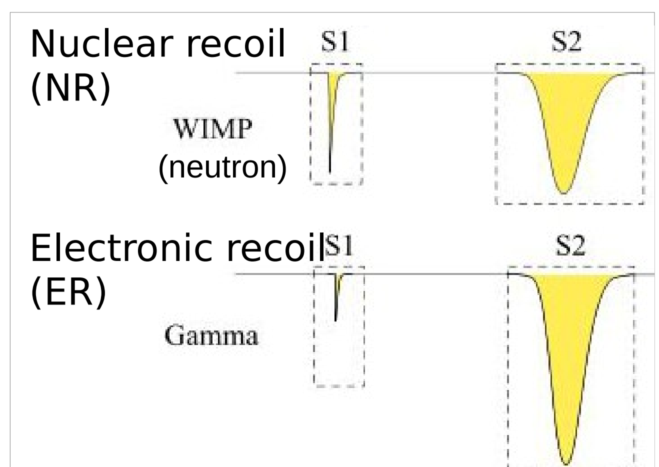
X/Y position from top array

S1:
- → Photons (λ = 178 nm) from scintillation process
- → Detected by PMTs (bottom array, mainly)

S2:
- → Ionisation process frees electrons
- → Electrons drift upwards
- → Extracted in gaseous phase
- → Proportional scintillation light



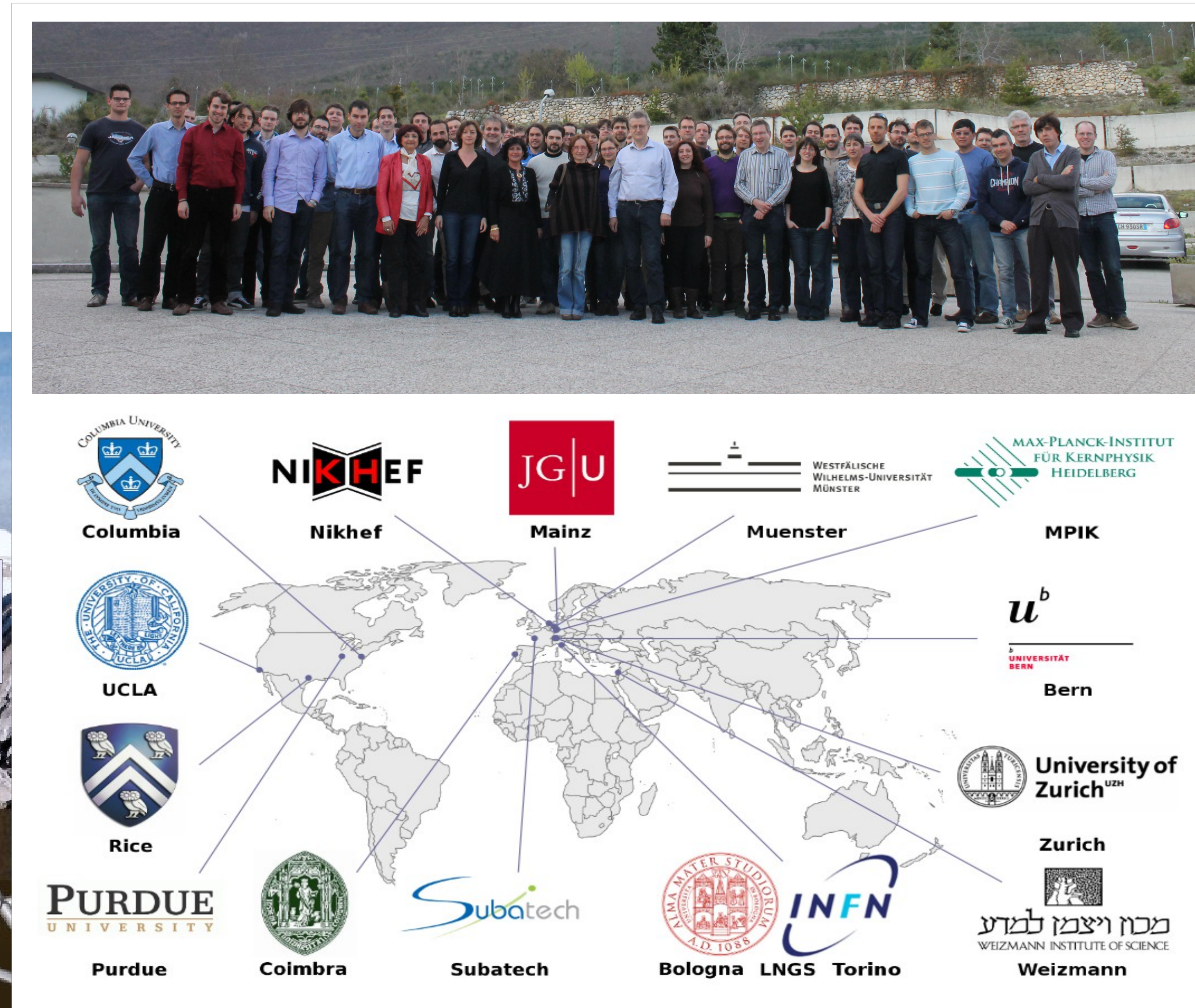
Z position from S1 to S2 difference



3D Position reconstruction!

The Xenon Dark Matter Project:

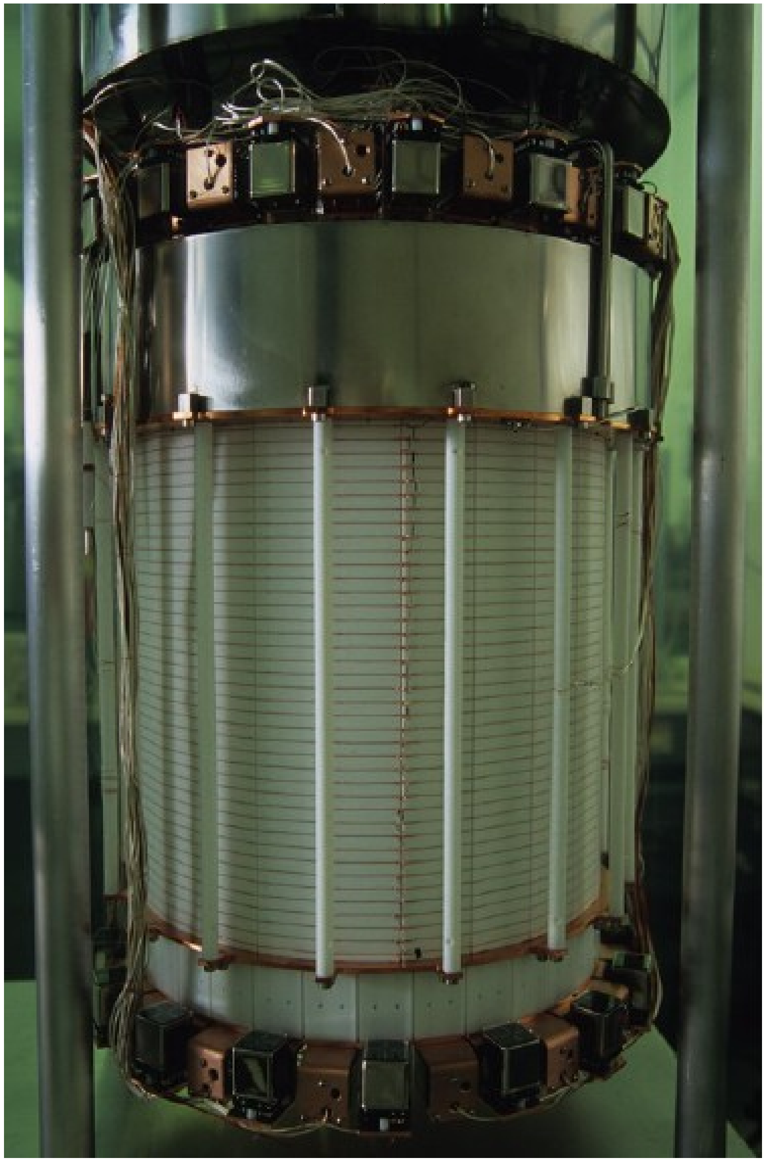
Laboratori Nationali del Gran Sasso (Italy)



World wide XENON Collaboration

The XENON100 Time Projection Chamber (TPC)

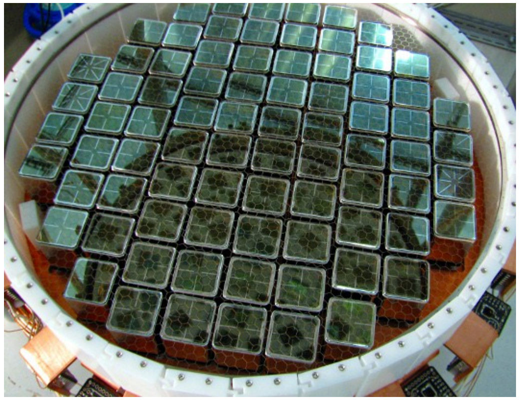
E. Aprile et al. (XENON100), Astroparticle Physics 35, 573 (2012)



XENON100 Time Projection Chamber

242 (1") Photomultiplier (PMTs):
- → 98 PMTs on the top array
- → 80 PMTs on the bottom array
- → 64 PMTs in the veto

Top PMT array



Bottom PMT array

Detection material: 161 kg liquid xenon (-91°C)
→ Target mass: ~ 62 kg

TPC: 30 cm height / 30 cm diameter

All used materials: Low radioactive

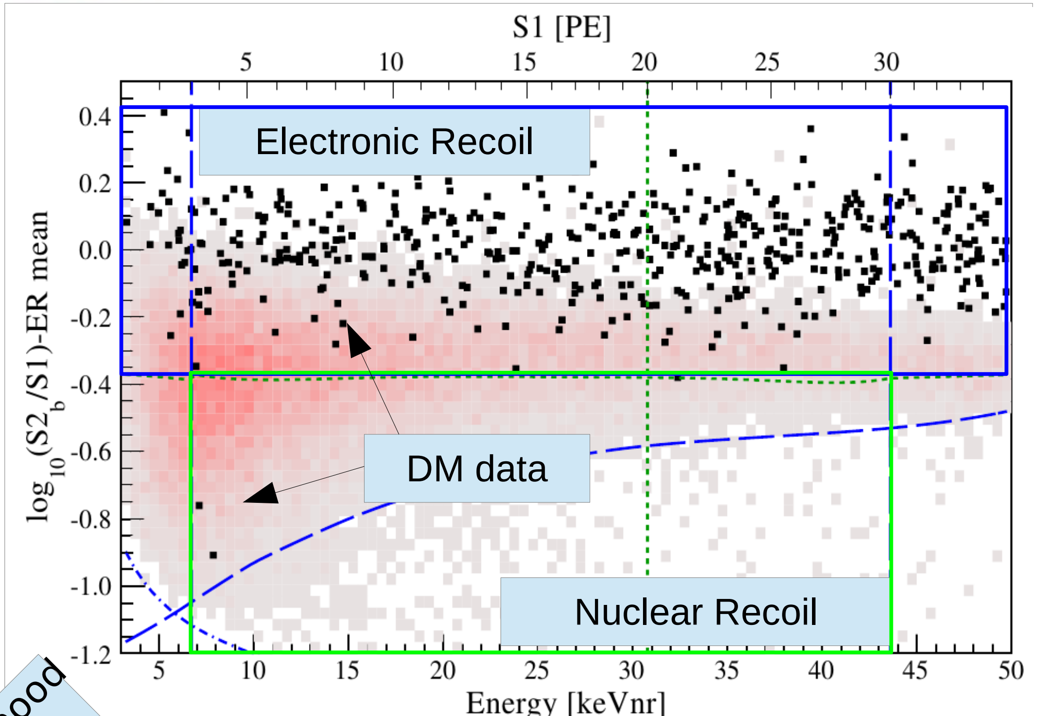
Multilayer passive shield: Cu, PE, Pb, H_2O

XENON100 Result in 2012 – Spin Independent:

During 2011/2012: 225 live days of data

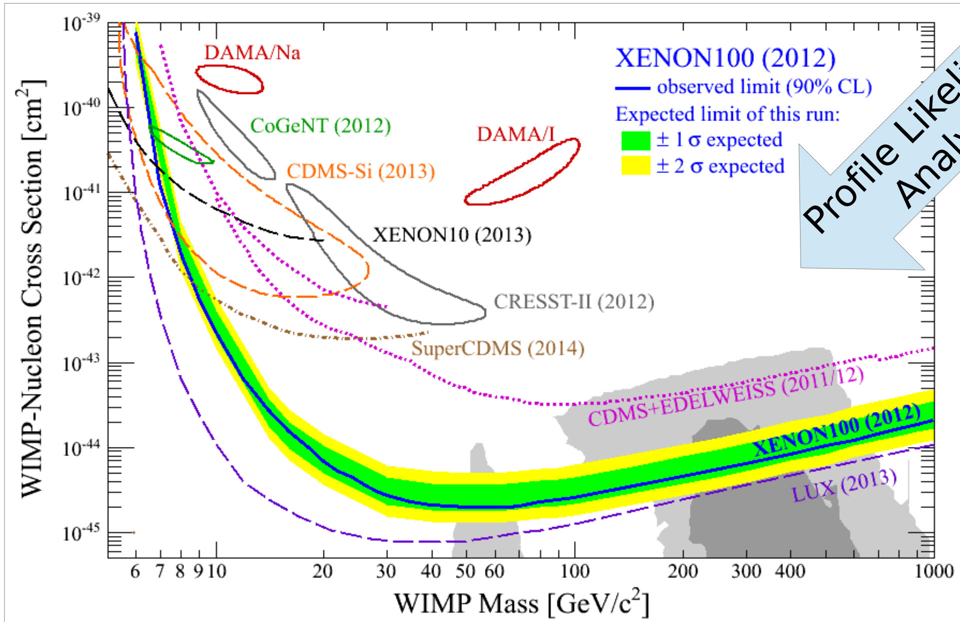
Two observed events are not enough!

- Events within benchmark region for dark matter search (green box)
- No excess due to Dark Matter signal (p-value: >= 5 %)
- Background fluctuation to two events is possible by 26.4%



Event distribution in flatten space

Profile Likelihood Analysis



Exclusion limit of 225 days of Dark Matter data taking

Lowest WIMP-Nucleon Cross-section[1]:

$m_\chi = 55$ GeV/c^2

$\sigma < 2.0 \times 10^{-45}$ cm^2 (90 % C.L.)

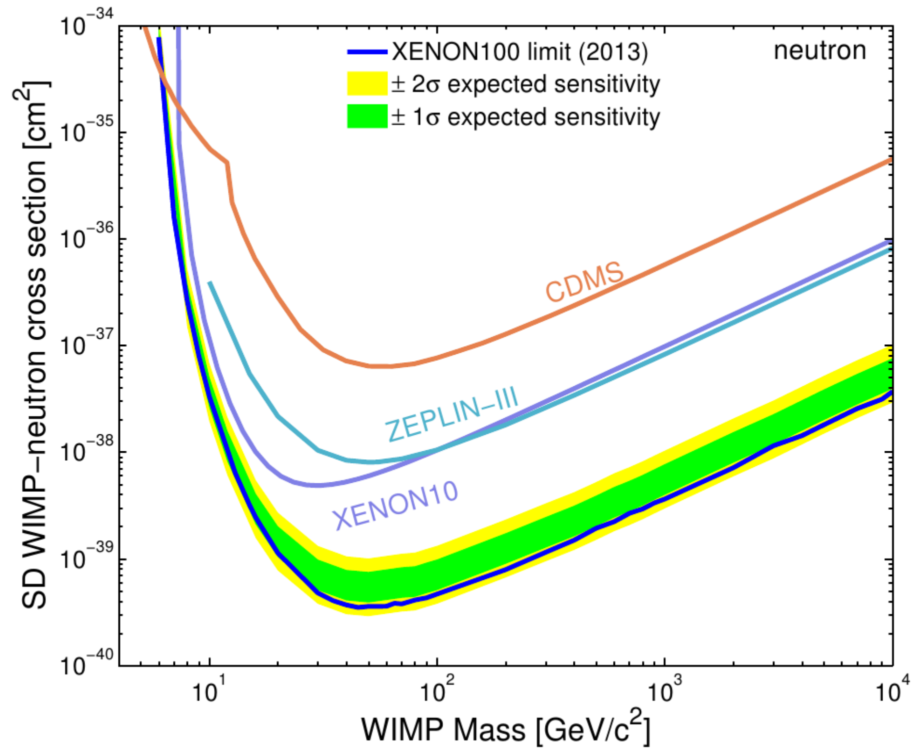
1) E. Aprile et al. Phys. Rev. Lett. 109, 181301 (2012)

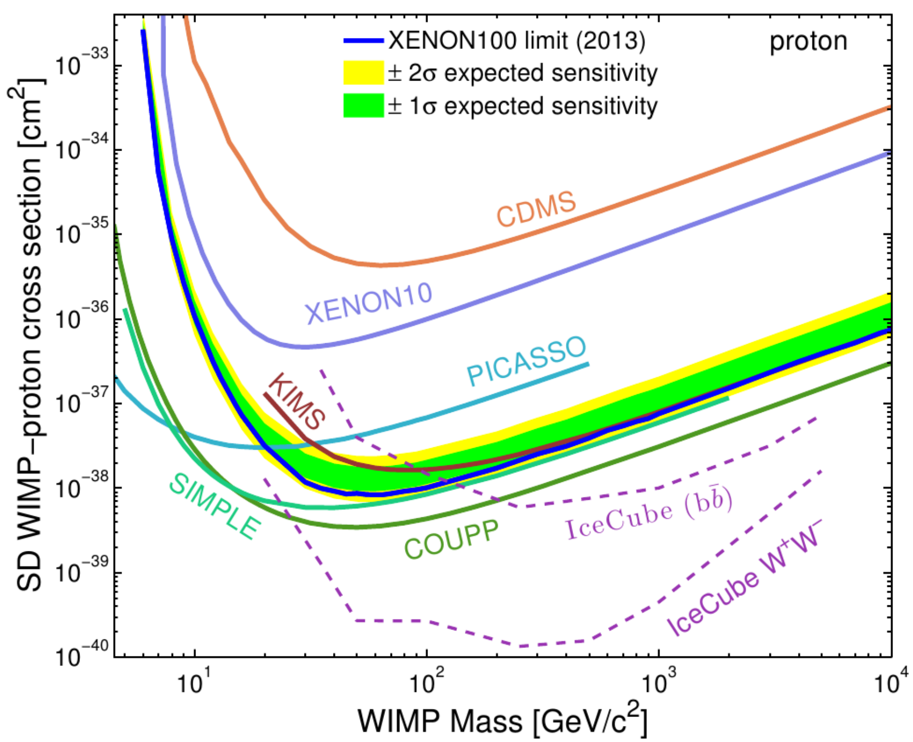
XENON100 Result – Spin Dependent:

Odd xenon isotopes:

- ^{129}Xe (26.2 %)
- ^{131}Xe (21.8 %)

→ WIMP Dark Matter could couple spin dependent!





WIMP-Neutron cross-section (Menendez):[1, 2]

$m_\chi = 45\ GeV/c^2$

$\sigma < 3.5 \times 10^{-40}\ cm^2$

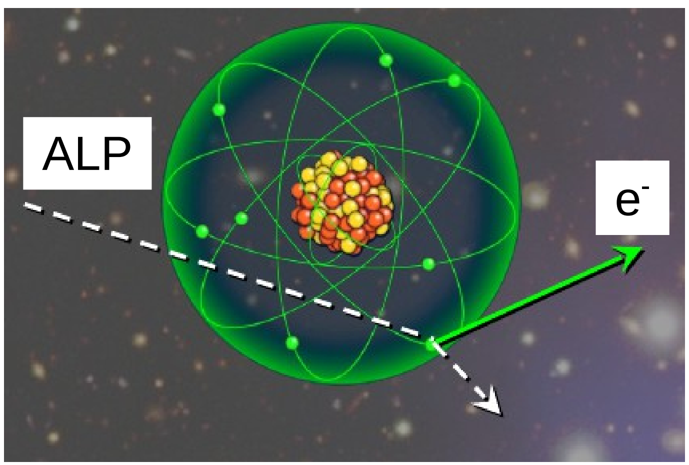
1) E. Aprile, M. Alfonsi, K. Arisaka et al, Phys. Rev. D 88, 012006 (2013)

2) J. Menendez, D. Gazit, and A. Schwenk, Phys.Rev. D86, 103511 (2012), arXiv:1208.1094

XENON100 Result 225 live days – Axion Dark Matter:

Axions and axion-like particles (ALPs) couple:

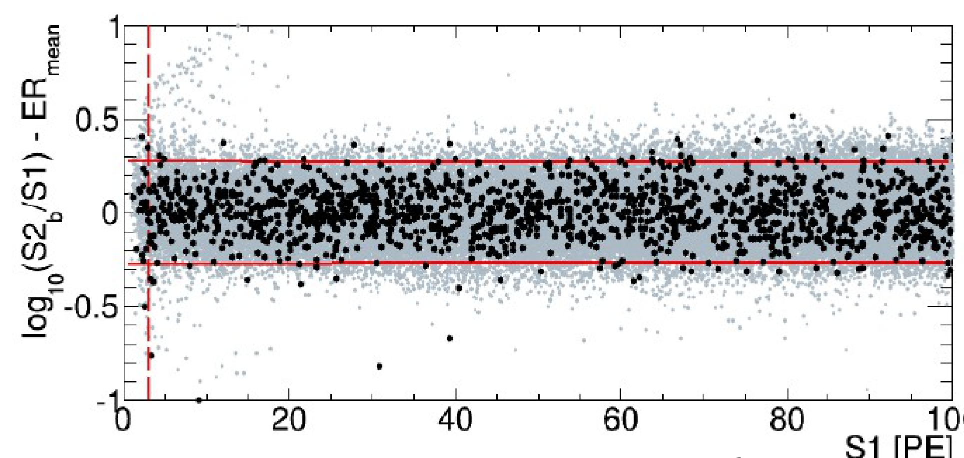
- Photons ($g_{A\gamma}$)
- Electrons (g_{Ae}) → **Search: Scattered electrons**
- Nuclei (g_{AN})



Axions ionize xenon

Test different Axion/ALP models:
→ Solar axions
→ Galactic ALPs

Careful data selection:

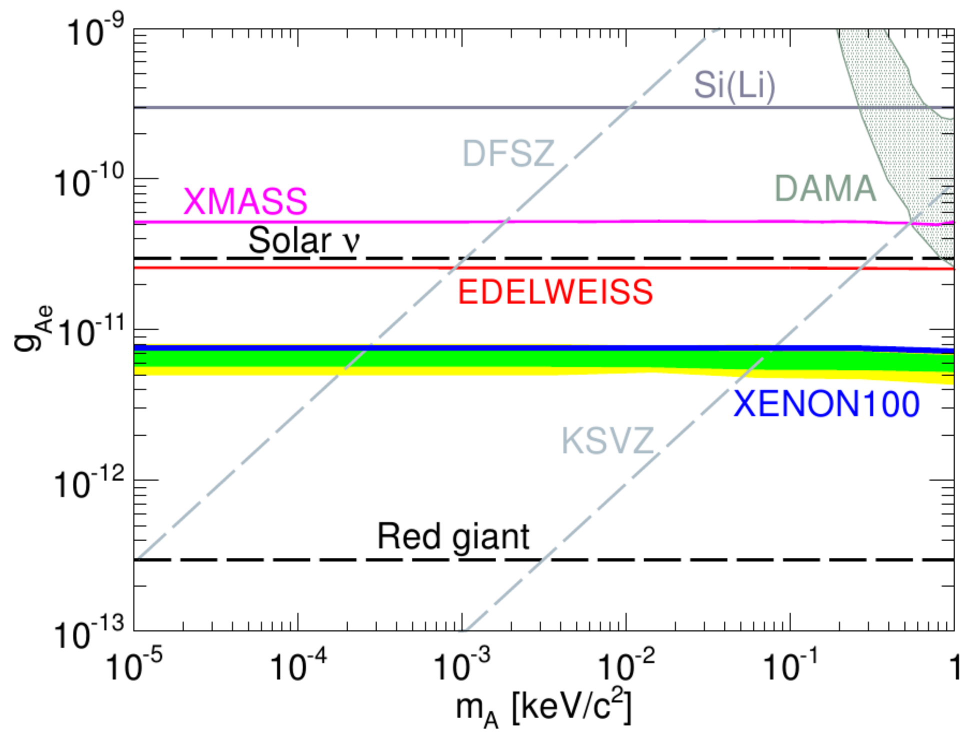


Data selection for axion Dark Matter analysis[1]

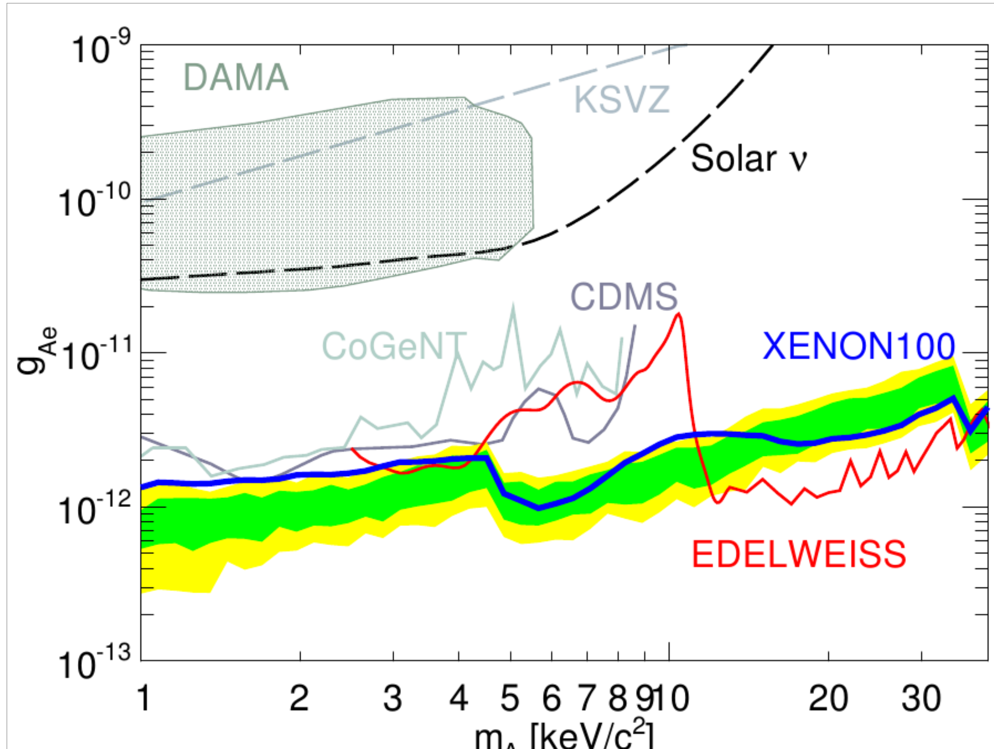
→ Select electronic recoil band

E. Aprile, F. Agostini, M. Alfonsi et al. preprint: arxiv:1404.1455

XENON100 Result 225 live days – Axion Dark Matter:



Solar Axions: Exclusion limit for g_{Ae} with XENON100



Galactic Axions: Exclusion limit for g_{Ae} with XENON100

Solar axions with m < 1 keV/c^2:
→ $g_{Ae} > 7.7 \times 10^{-12}$ excluded (90 % C.L.)

Galactic axions with m = 5 – 10 keV/c^2:
→ $g_{Ae} > 1 \times 10^{-12}$ excluded (90 % C.L.)

(Assuming ALPs constitute all of the galactic Dark Matter.)

E. Aprile, F. Agostini, M. Alfonsi et al. preprint: arxiv:1404.1455

AmBe souce/MC simulation: Data matching

→ Neutron calibration of XENON100 with AmBe

Idea: Get a proper description of XENON100 by an improved simulation and test

Ingredients:

- Measured AmBe source (160 +- 4 n/s) at the PTB/Germany
- Complete XENON100 description (detector + shield)
- Q_y, Threshold, detection resolution and acceptance (S1) from XENON100 detector

How to do (I):

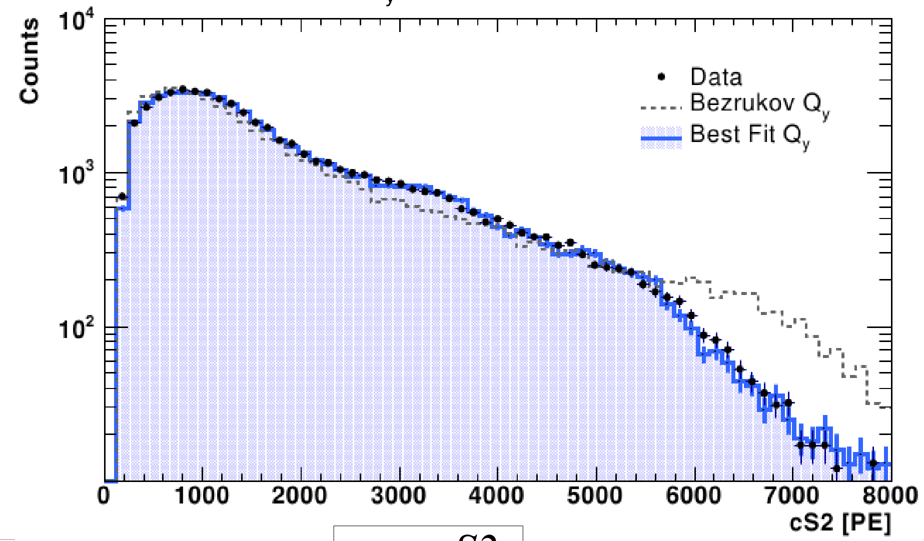
→ Take direct measured L_{eff}

→ Reproduce S2 spectrum

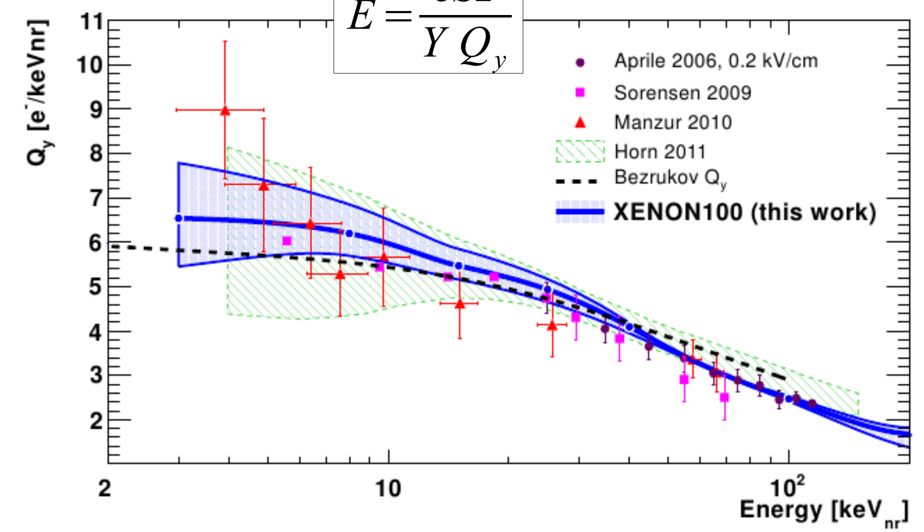
→ Best Fit Q_y

Conversion between Q_y ↔ keV_{nr}

S2 spectrum: Best Fit Q_y fits data



$$E = \frac{cS2}{Y\,Q_y}$$



Q_y conversion to deposited (NR) energy

E. Aprile, M. Alfonsi, K. Arisaka et al. , Phys. Rev. D 88, 012006 (2013)

AmBe souce/MC simulation: Data matching

How to do (II):

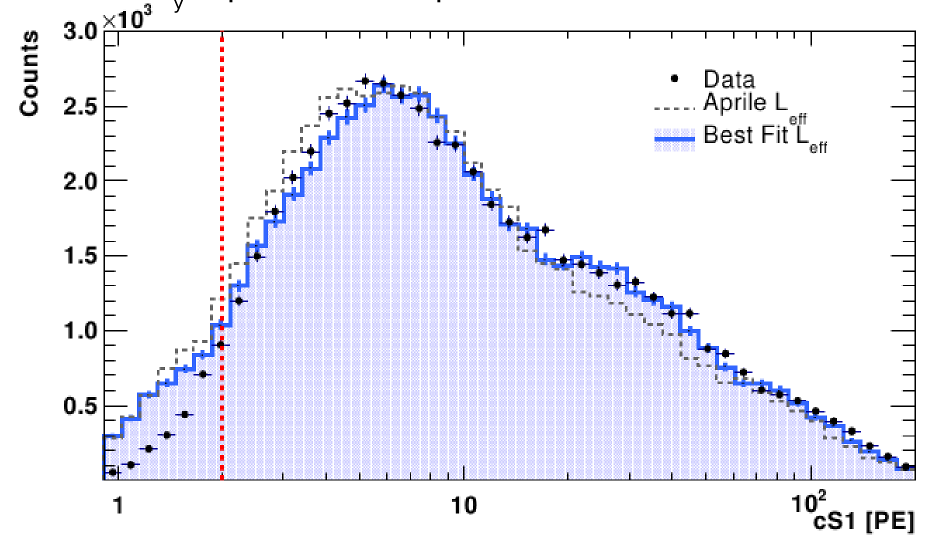
→ Use Best Fit Q_y

→ Reproduce S1 spectrum

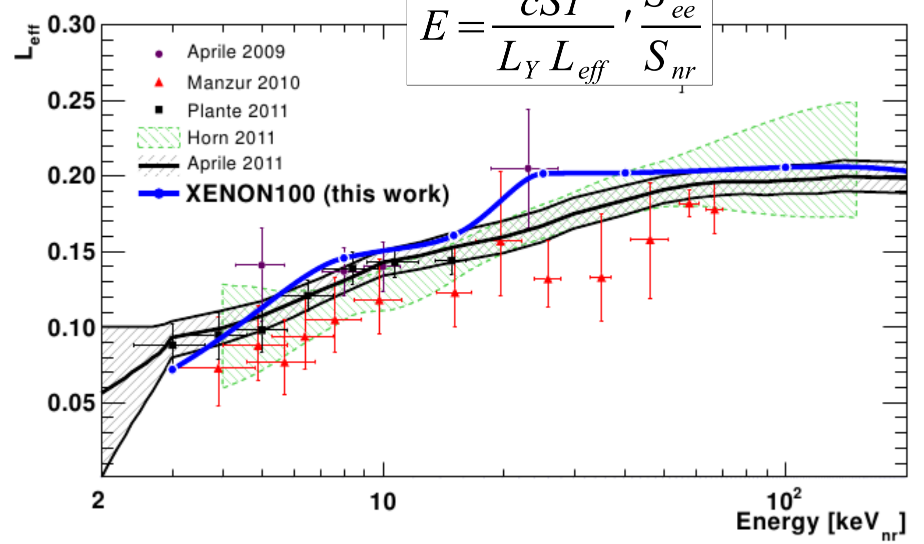
→ Get a new L_{eff}

- Fit the whole spectrum down to 2 PE (~5 keV)
- L_{eff} from best fit matches the previous 'direct' measurements
- Results of XENON100 remain unchanged using this L_{eff}

Best Fit Q_y repreduce S1 spectrum



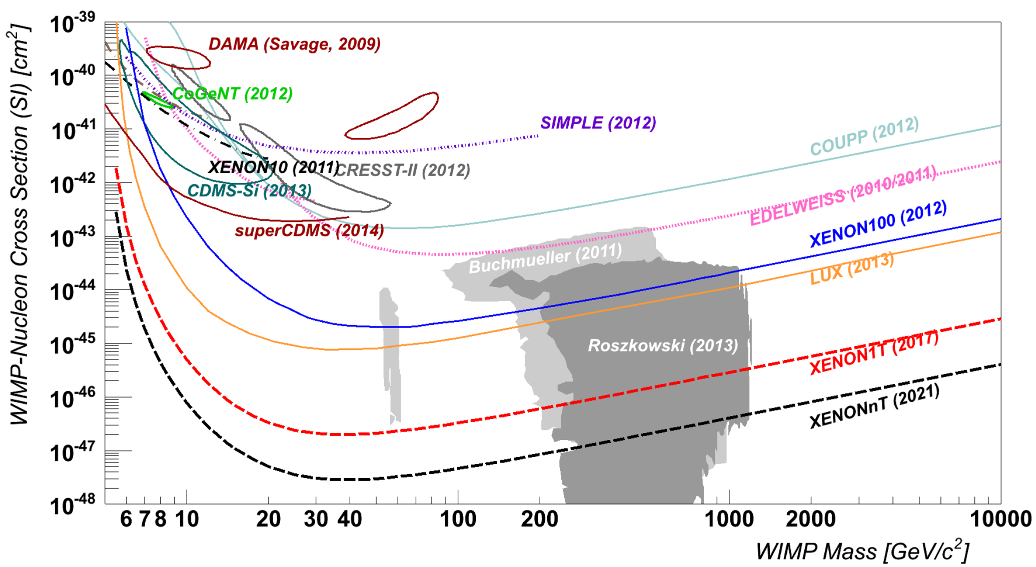
$$E = \frac{cS1}{L_Y L_{eff}}, \frac{S_{ee}}{S_{nr}}$$



Compare data and MC: L_{eff} fits XENON100

E. Aprile, M. Alfonsi, K. Arisaka et al. , Phys. Rev. D 88, 012006 (2013)

We need more! – XENON1T:

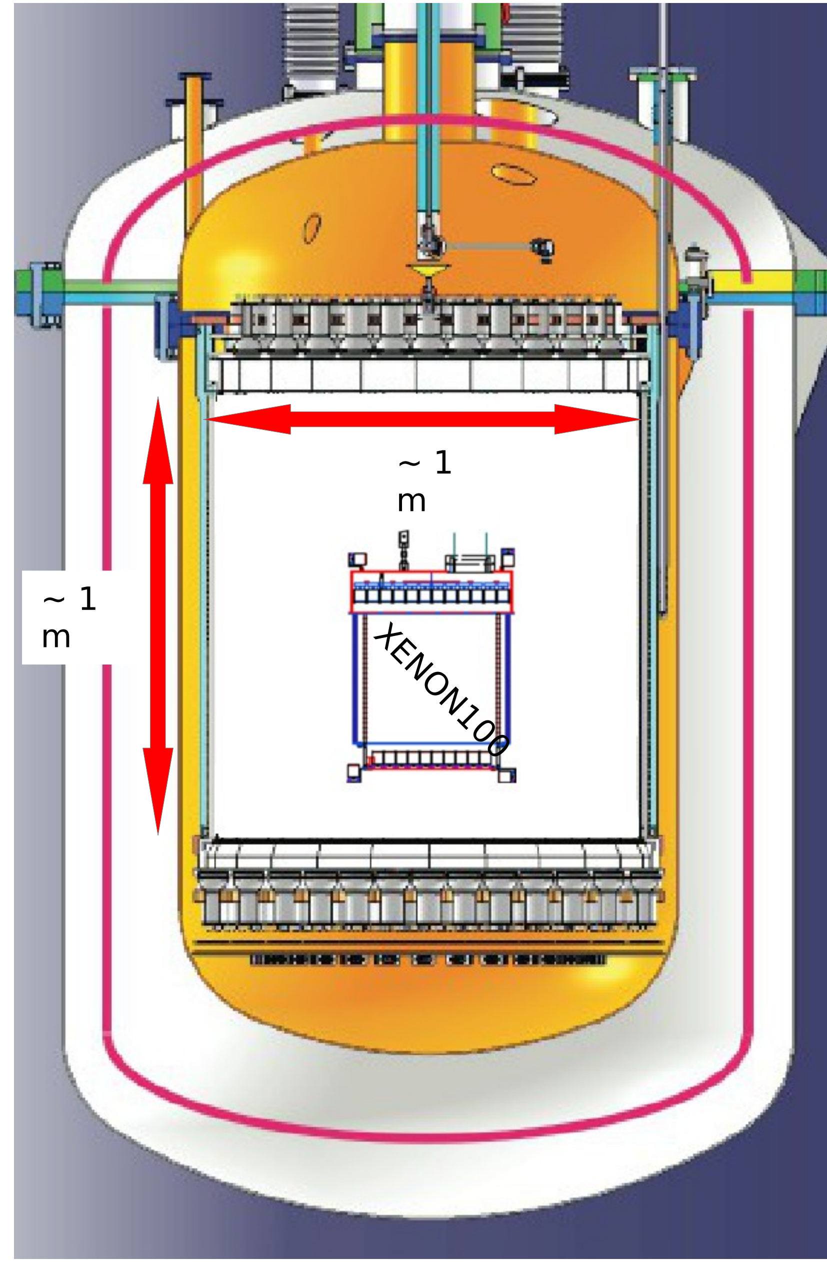


Outlook Exclusion limits

No WIMP Dark Matter found yet!

Increase the fiducial volume by building a bigger TPC and cryostat!

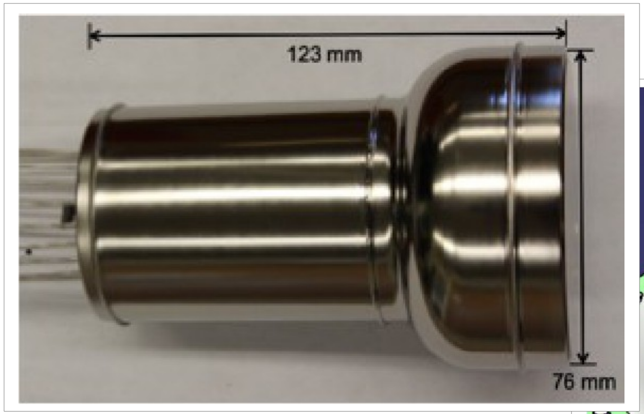
XENON100 → **XENON1T** → *XENONnT*



XENON1T TPC with XENON100 TPC inside

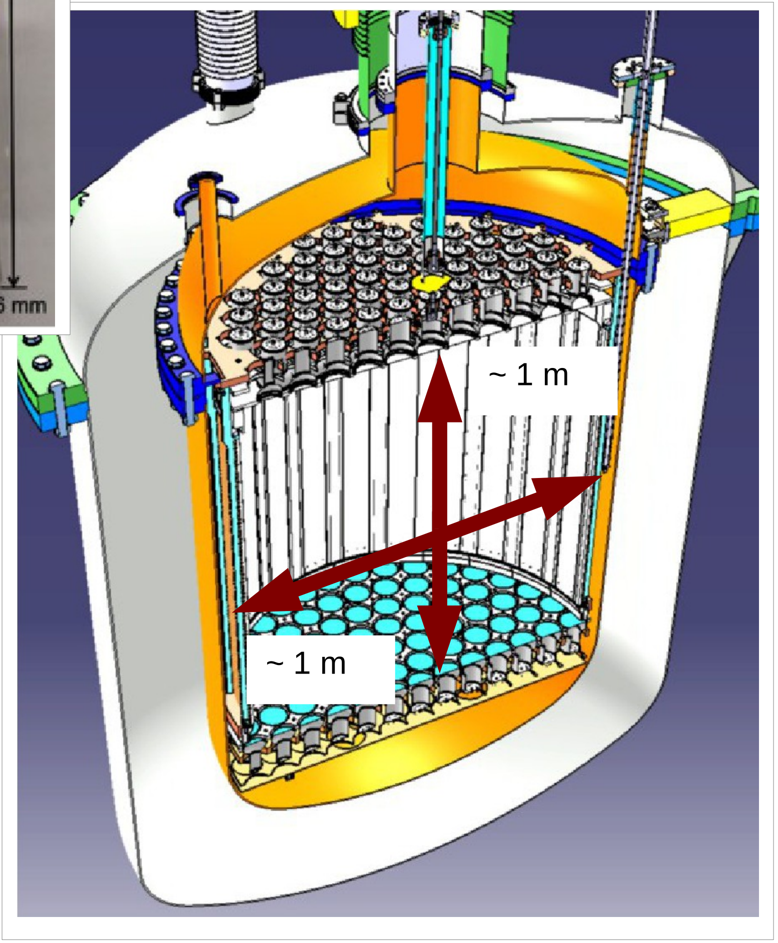
XENON1T: TPC

→ Projected with ~ 3 tons LXe!
- Inside TPC: ~ 2 tons
- Fiducial volume: ~ 1 ton
- Drift length (electrons): 1 m
- Driftfield up to 100 keV



→ Photomultipliers:
- 248 of 3” R11410-21 PMTs1
- Low background + high QE (36 %)

→ Background reduction:
- Careful material selection/screening for cryostat and TPC
- Reduced intrinsic background: ^{85}Kr and ^{222}Rn
- Active water cherenkov muon veto

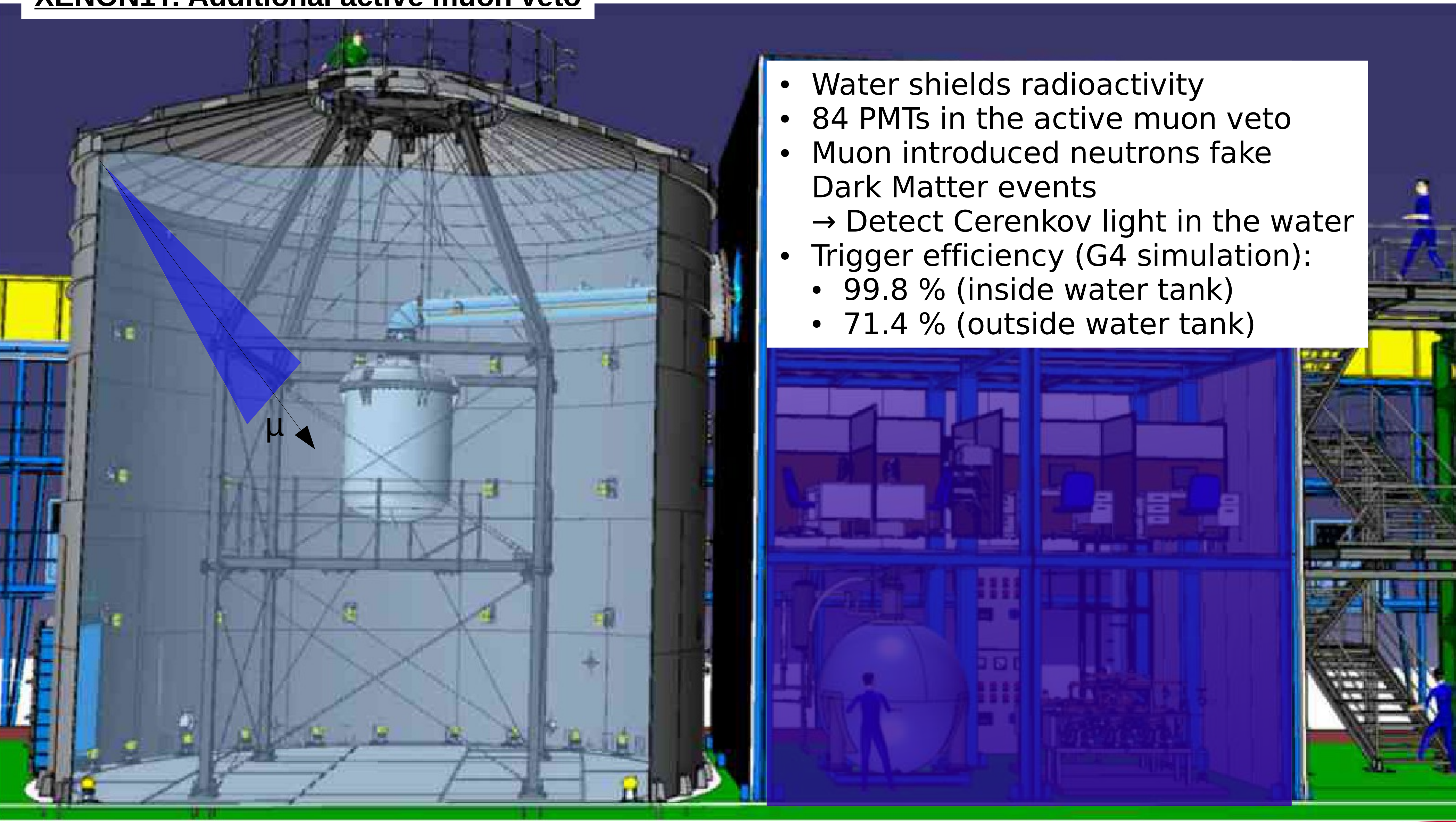


100x lower background!

→ Goal: < 1 events/y

1) JINST 8, P04026 (2013)

XENON1T: Additional active muon veto



- Water shields radioactivity
- 84 PMTs in the active muon veto
- Muon introduced neutrons fake Dark Matter events
  → Detect Cerenkov light in the water
- Trigger efficiency (G4 simulation):
  - 99.8 % (inside water tank)
  - 71.4 % (outside water tank)

XENON Dark Matter Project

Summary:

XENON100

→ Well tested and detailed understanding of the detector

→ Ready to test Dark Matter models

- Lowest exclusion limit in 2012 (SI)
- Lowest exclusion limit in 2013 for SD (neutrons)
- First results for Axions/ALPs interactions in XENON100
- AmBe souce/MC matching results
- Annual modulation results in XENON100 coming soon
- Develop and test alternative analysis methods, e.g. Bayesian approach

Stay tuned!!!

XENON1T

→ XENON1T is under construction!

→ Water tank construction already finished

- Suppress background by a factor 100
- Increase detection probability by a larger amount of xenon
- Active muon veto
- Sensitive to $2x10^{-47}cm^2$
- First data in 2015

The next level XENON - TPC for Dark Matter detection is coming!

XENONnT

→ Future update for XENON1T

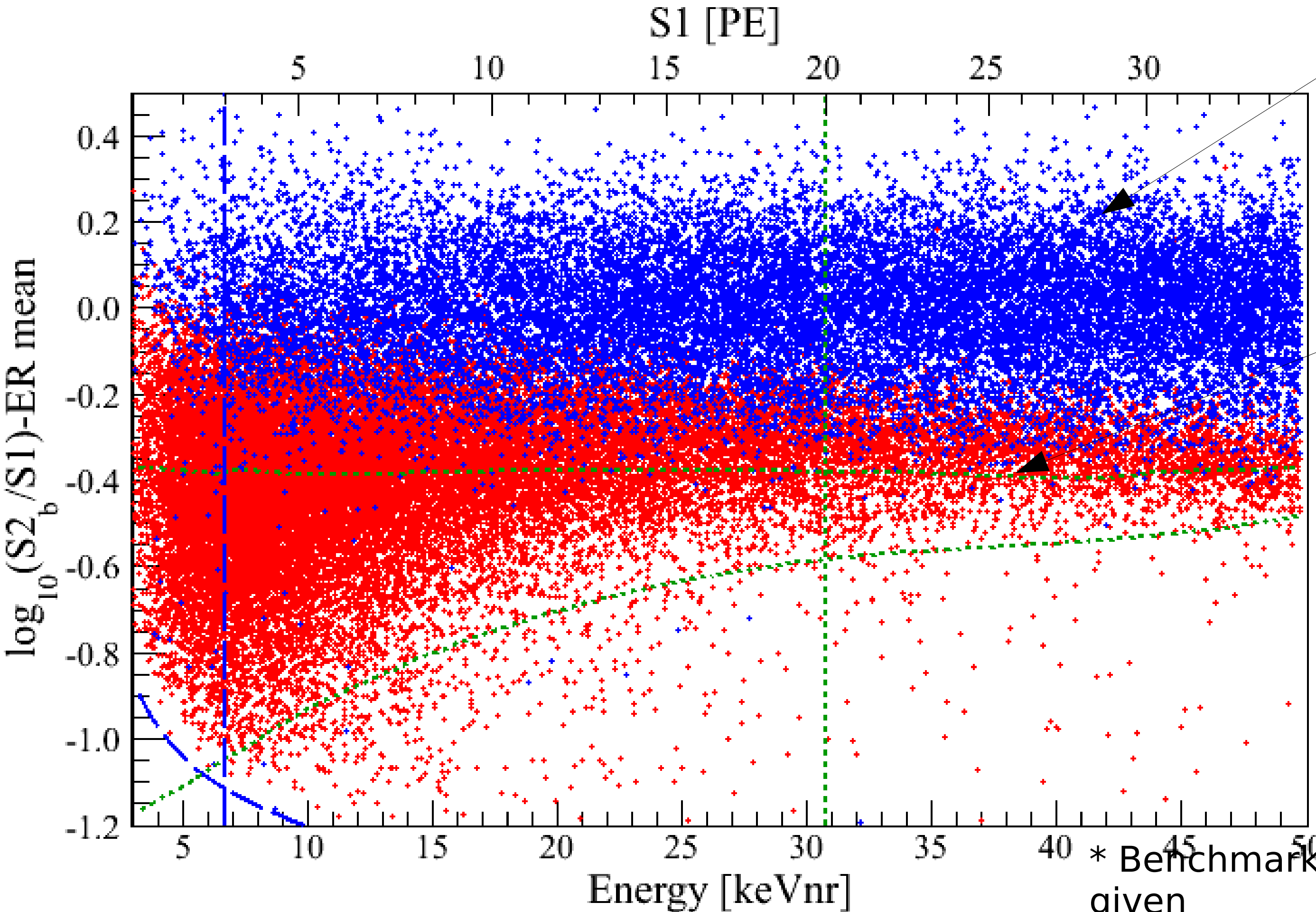
→ Sensitive to $2x10^{-48}cm^2$

Located in Hall B @LNGS

Thanks for your attention

Backup: Background in XENON100

- Detector design: Careful material selection
- Low level ^{222}Rn (62.9 µBy/kg and ^{85}Kr (19.4 ppt)
- Different calibrations are done during the operation



* Benchmark region and given

Background in XENON100: NR and ER

→ Interactions from gamma's and electrons: ^{60}Co, ^{232}Th

ER background*: 0.79 ± 0.16

→ Interactions from neutrons: AmBe source

NR background*: $0.17^{+0.12}_{-0.07}$

Background expectation in total*: 1.0 ± 0.2

* Benchmark region and given exposure

E. Aprile et al. Phys. Rev. Lett. 109, 181301 (2012)

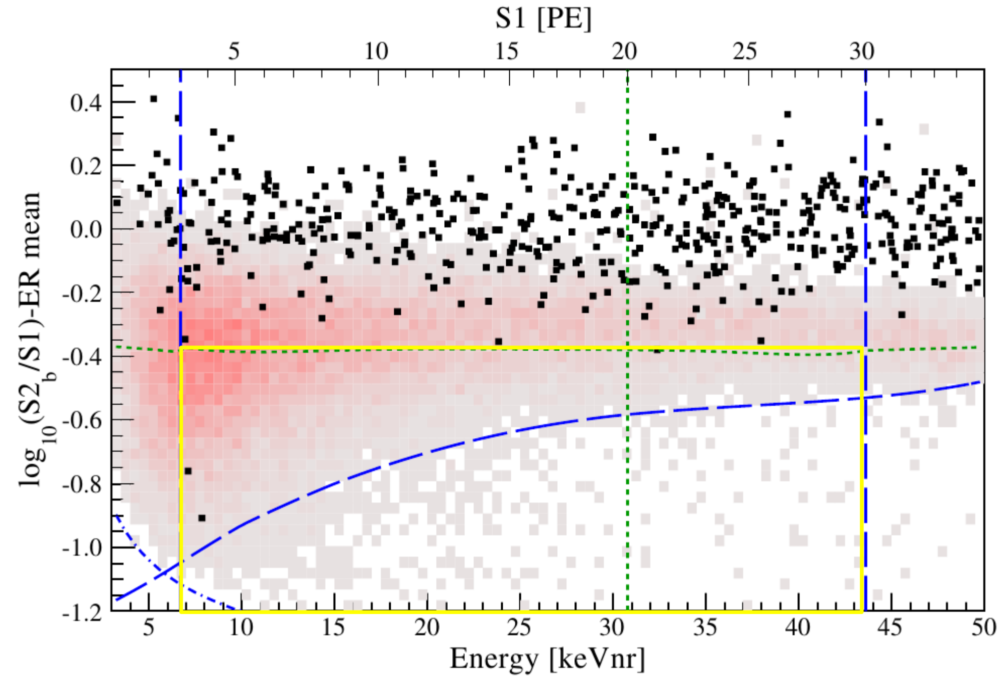
Backup: XENON100: 225 live days data

Data in flatten space after a cut based analysis

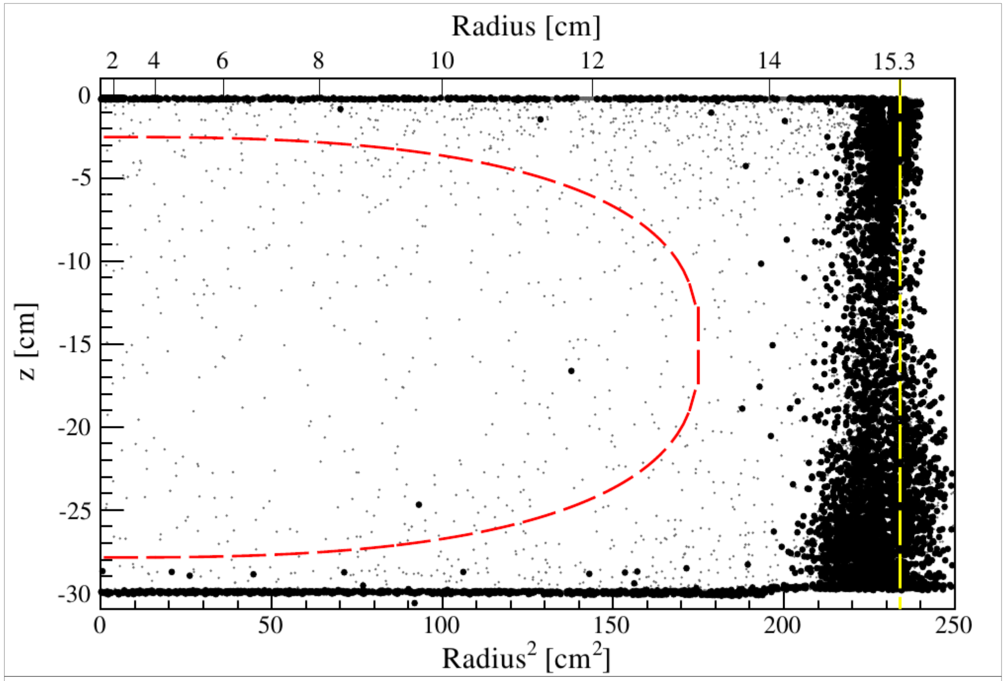
- Nuclear Recoil
- Electronic Recoil
- Dark Matter Data
  → Benchmark region (yellow box)

Background expectation in total*: 1.0 ± 0.2

- Events distributed in the TPC
  → Fiducial volume (34 kg)



Event distribution in flattened space



Event distribution in the TPC

Unblinding[1]: Two events observed!

Profile Likelihood[2] analysis to „test events"

1) E. Aprile et al. Phys. Rev. Lett. 109, 181301 (2012)

2) E. Aprile et al. (XENON100), Phys. Rev. D 84, 052003 (2011)

* Benchmark region and given exposure

Backup: Axion Dark Matter

Solar axions/ALPs:
- Production in the sun
- Compton scattering
- axio-recombination
- axio-deexcitation

Galactic axions/ALPs:
- non-thermal production mechanism in the early universe
- Dark Matter (part of)

Axions and ALPs couple by axio-electric effect!
→ *Axion/ALPs are „absorbed“*

Cross-section:

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

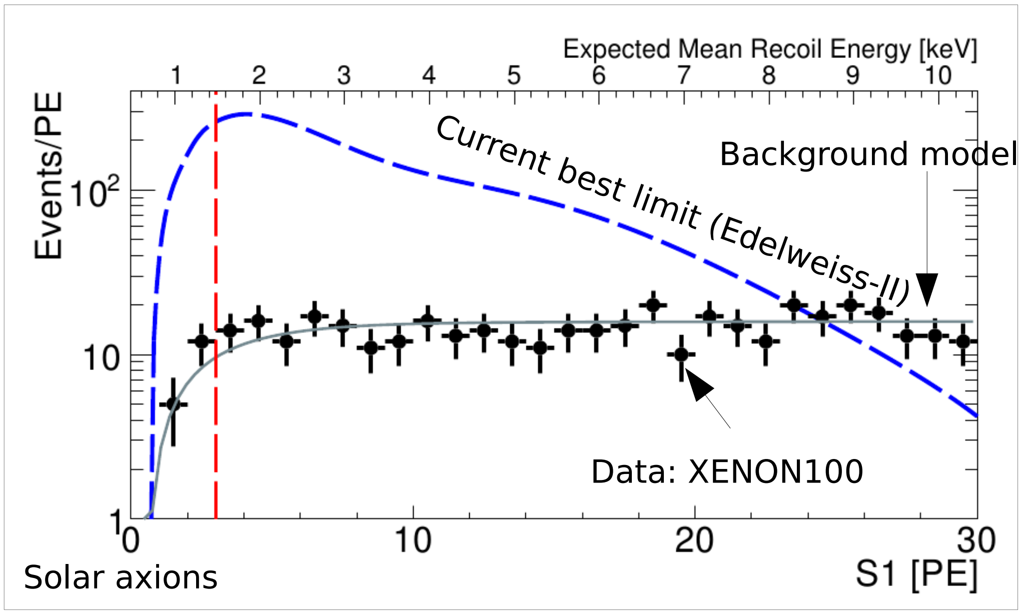
photo-electric cross-section: $\sigma_{pe}(E_A)$; axion energy: E_A; axion speed: β_A; fine structure constant: α_{em}; electron mass: m_e

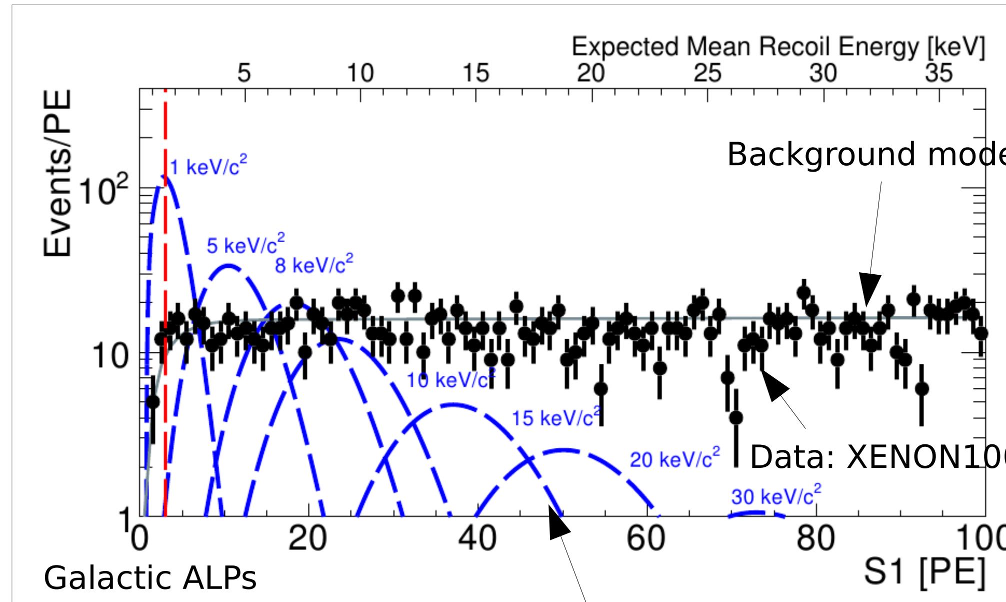
& Solar axions/ALPs: Axion flux ∝ g^2_{Ae} = $\frac{dR^{solar}}{dE_R} \propto g^4_{Ae}$

& Galactic ALPs: $\phi_{ALP} = \frac{c\,\beta\,\rho_{DM}}{m_{ALP}}$ = $\frac{dR^{DM}}{dm_{ALP}} \propto g^2_{Ae}$

Backup: Axion Dark Matter

Event distributions: Solar axions & galactic ALPs





Expected signal of various ALP masses for g_{Ae} =

Backup: Intrinsic Background in XENON1T

^{222}Rn impurity:
→ Removal system to achieve < 1 µBq/kg
→ Absorbtion tower (Alternatives are discussed)

carbonaceous filter material

^{85}Kr impurity:
→ Cryogenic distillation colum
for Kr removal
→ Removal system to archive
^{nat}Kr/Xe < 1 ppt
→ Aim: 3 kg/h xenon (8.7 SLP
→ Fully integrated in XENON1T

Cryogenic distillation in Heidelberg/Germany

Backup: XENON1T – Watertank: Overview and Status

Located in Hall B @LNGS

Water tank facts:

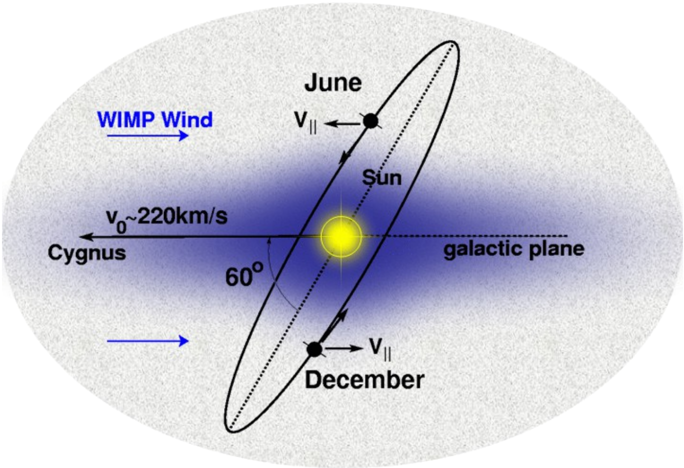
- 10 m height
- 10 m in diameter
- 84 PMTs
- Reflective foil inside the water tank

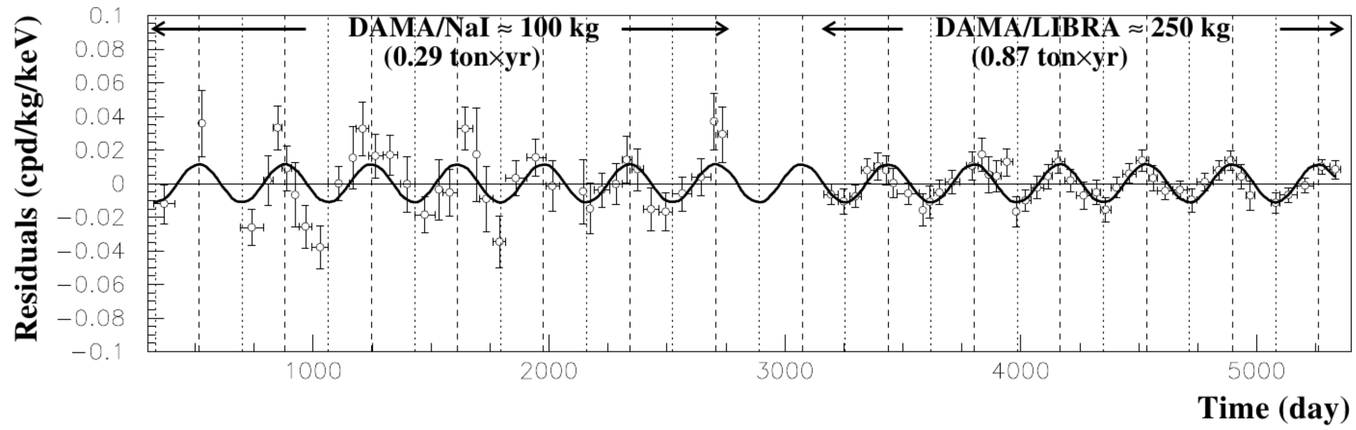
Construction finished!
&
Reflective foil is clad to the roof

Next:

- Installation of the PMTs
- Cladding the wall and bottom
- Installation of the cryostat and the TPC
- First test in fall 2015

XENON100: Annual modulation

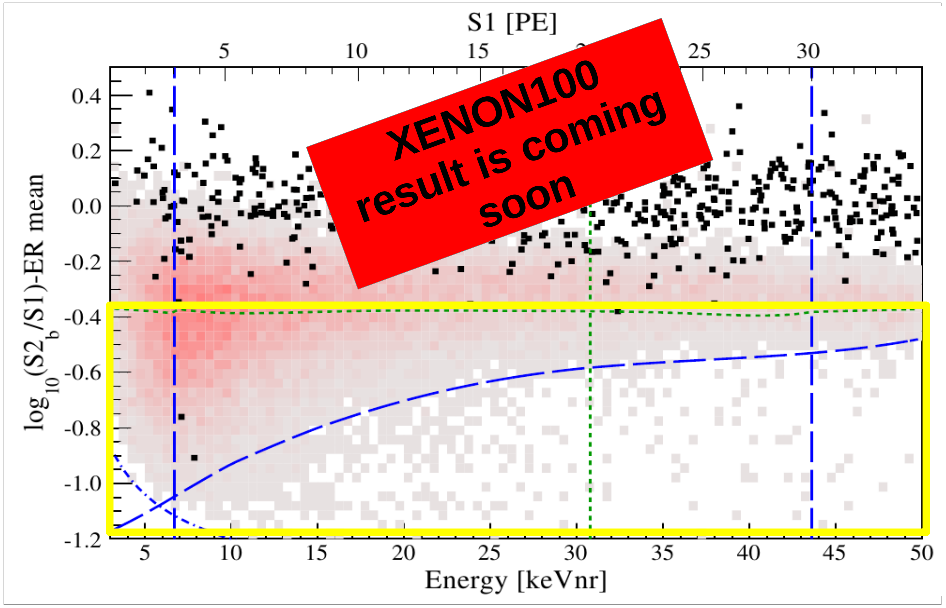




DAMA/LIBRA[1] observe annual modulation from Dark Matter particles in the Galactic Halo
(2 – 6 keV)

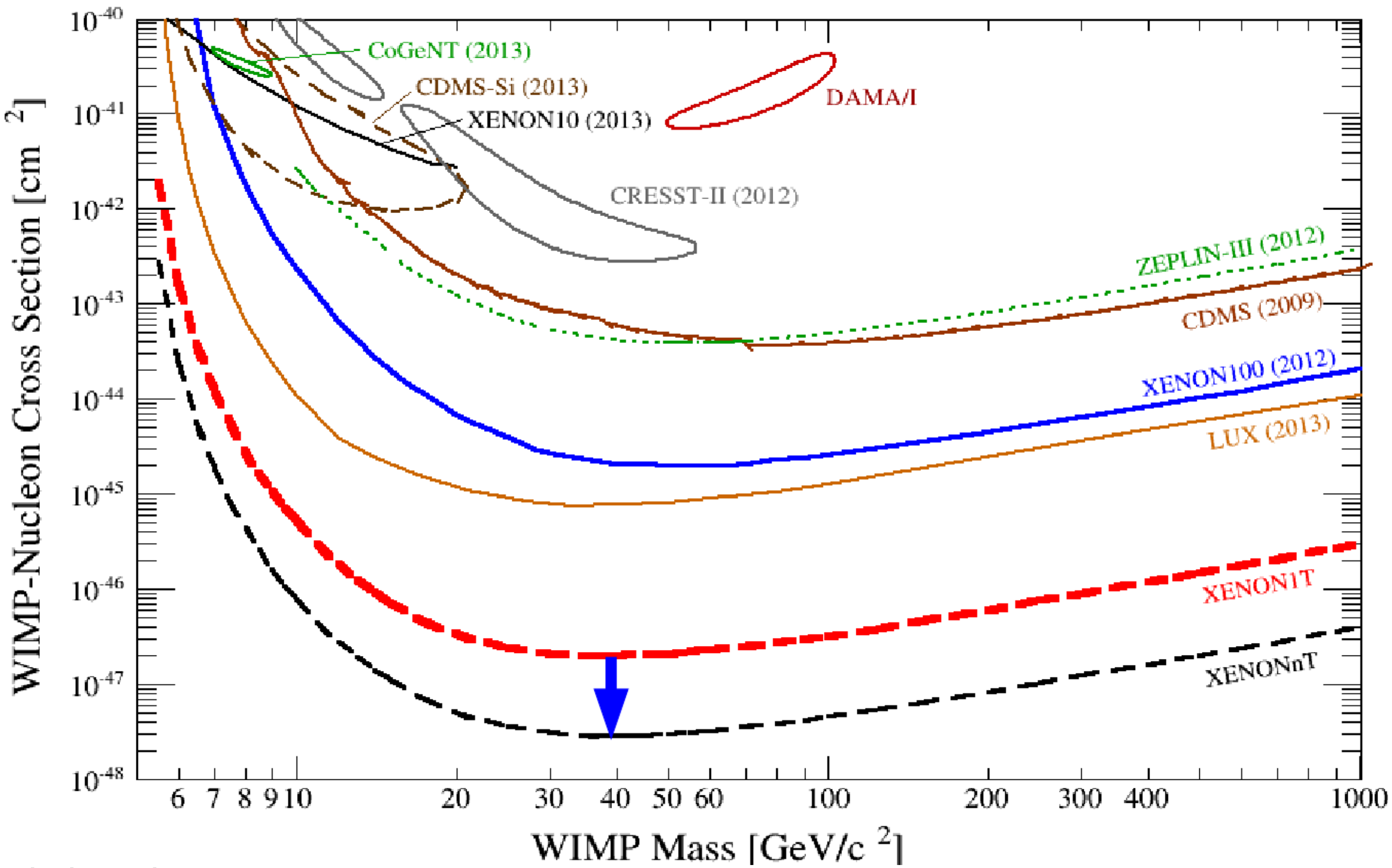
Detection material:
~ 250 kg highly radio-pure NaI (Tl) crystals

Is there also an annual modulation in XENON100?
→ 225 live days of data
→ Data taking period: > 1 year
→ Analysis threshold of XENON100 is lower!



1) R. Bernabei, P. Belli, A. Di Marco, „DAMA/LIBRA results and perspectives“, preprint: arXiv:1301.6243

What comes next? The future of the XENON DARK MATTER Project



Limit update: XENONnT

XENON1T can be updated:

- More xenon
- Bigger TPC in the same cryostat

XENONnT

Sensitivity Goal:

$\sigma = 2 \times 10^{-48}$ cm²