Direct Dark Matter Search with the XENON Dark Matter Project

"Effective Theories and Dark Matter"
Johannes-Gutenberg Universität Mainz

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on behalf of the XENON collaboration

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16th to 23th March 2015

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

XENON Dark Matter Project

PRISMA

Motivation: Dark Matter (I)

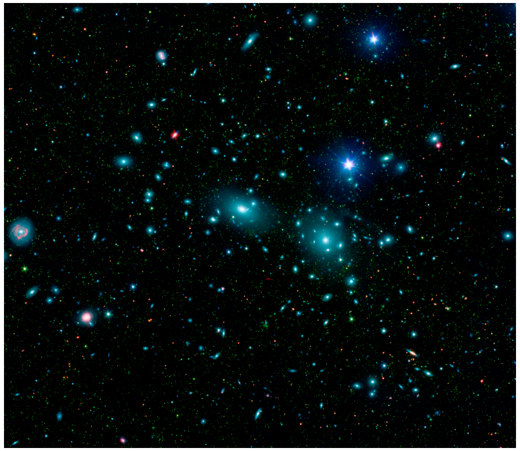
Evidences for Dark Matter for 80 years now

1933: Fritz Zwicky's "missing mass problem"

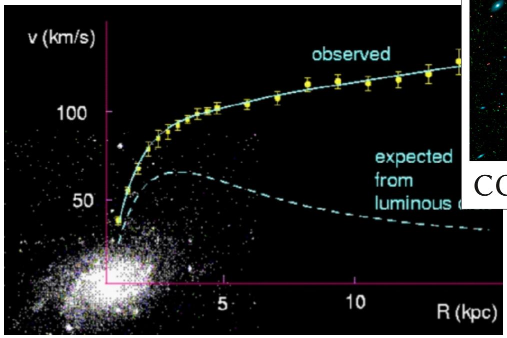
1966: Vera Rubin Study of rotation curves

... Observation techniques development

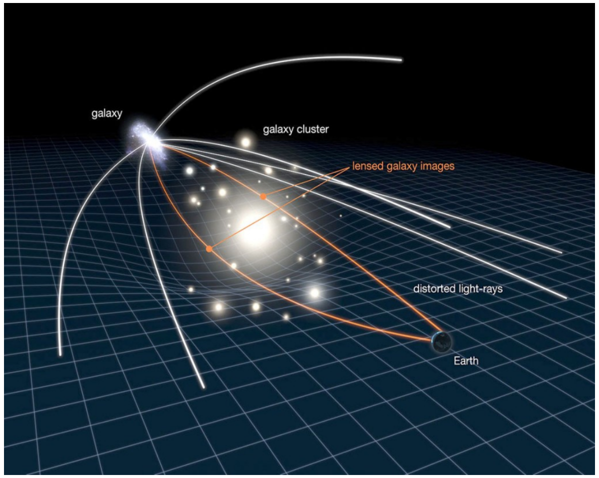
2013: Planck Satellite mission Dark Matter in the CMB

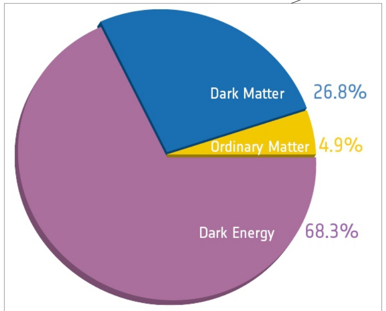


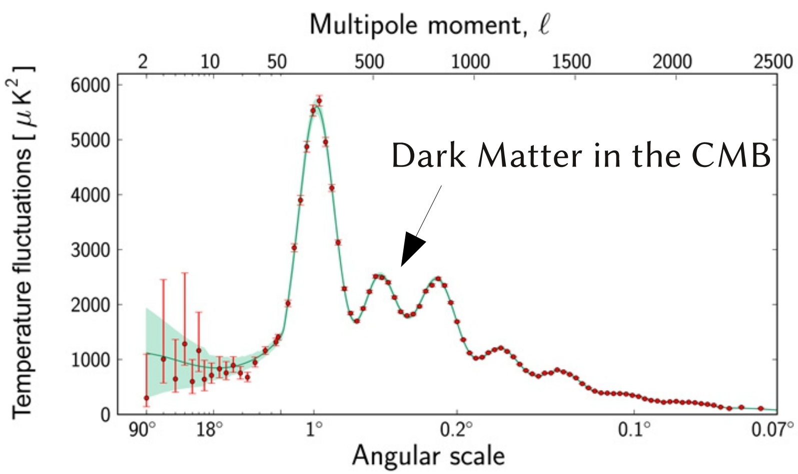
COMA Cluster in 2007



Observation vs. theory







Temperature fluctuations in the CMB

Motivation: Dark Matter (II)

What do we know from Cosmology?

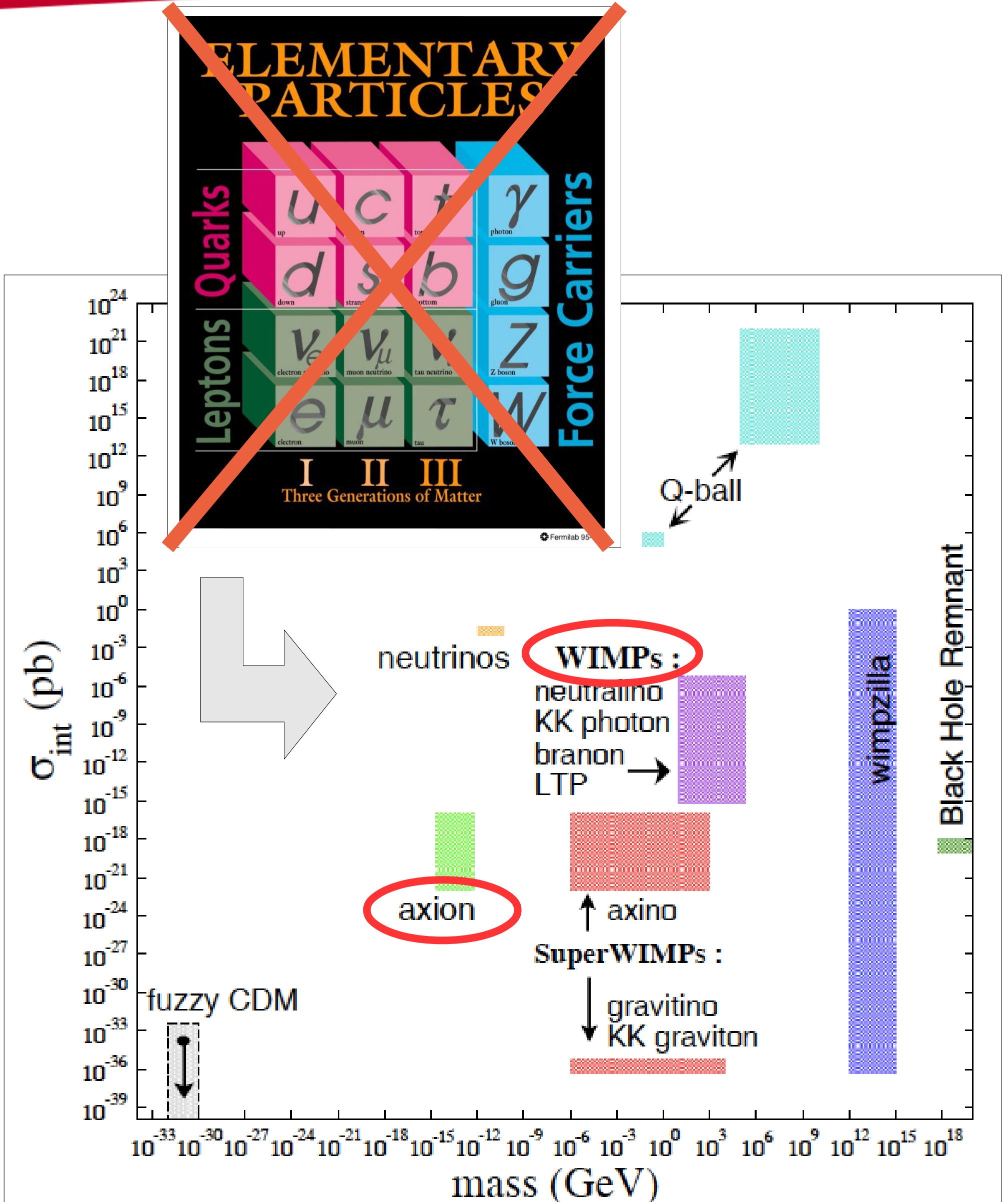
- Dark Matter is stable/long-lived
- All known particles are ruled out! (non-baryonic particle)
- It's “dark” ⟶ Electrically neutral

At least Dark Matter is a placeholder nowadays!

The XENON Dark Matter Projects:

Look for Weakly Interacting Massive Particles (WIMPs)

Other hypothesis can be tested:
⟶ Axions and Axion-like particles

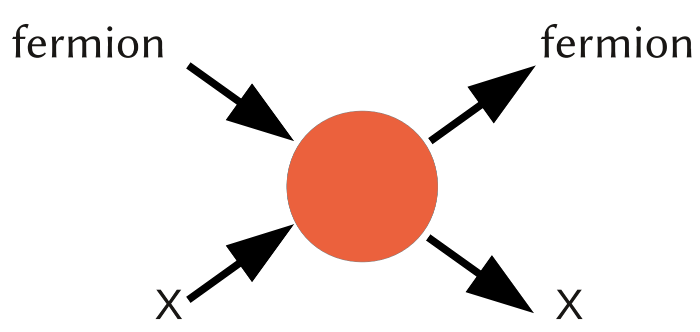


Different theories for Dark Matter particles[1)]

1) Gardner, Susan et al. Prog.Part.Nucl.Phys. 71 (2013)

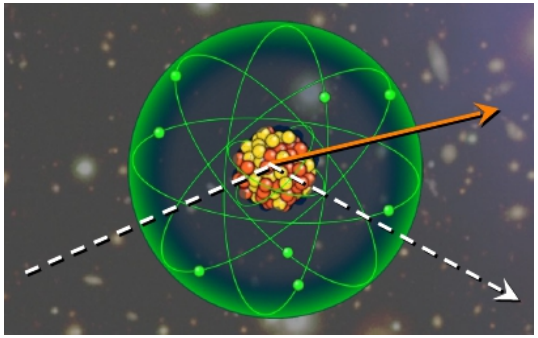
Dark Matter Search (I):

- **Direct Dark Matter** search
- Search for nuclear recoils (WIMP-nucleon interaction)
- Search for electronic recoils (WIMP-electron interaction)
- NR/ER is also used for detector calibration

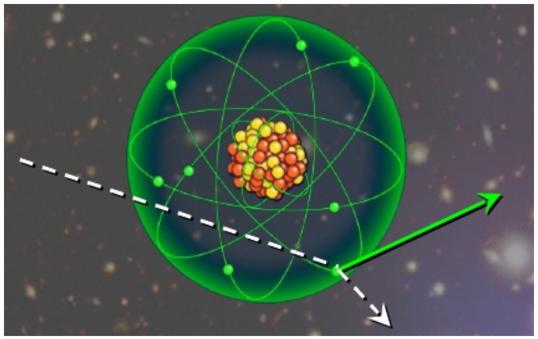


Elastic scatter:

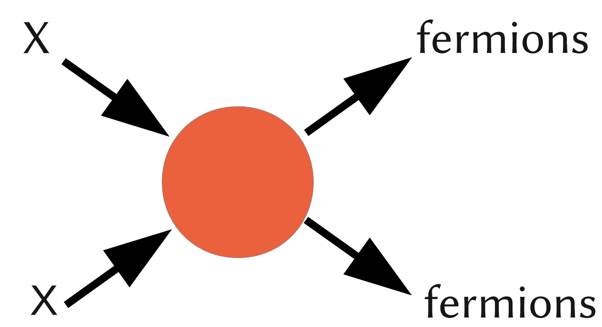
Nuclear Recoil (NR)



Electronic Recoil (ER)

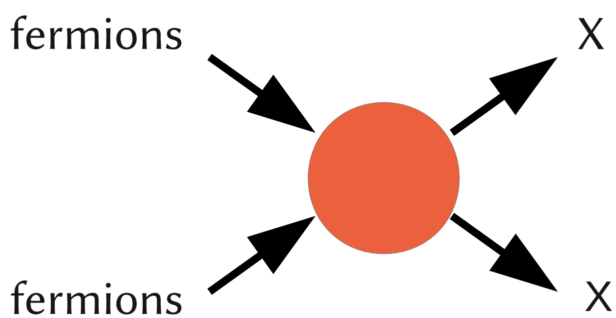


Indirect Dark Matter search:



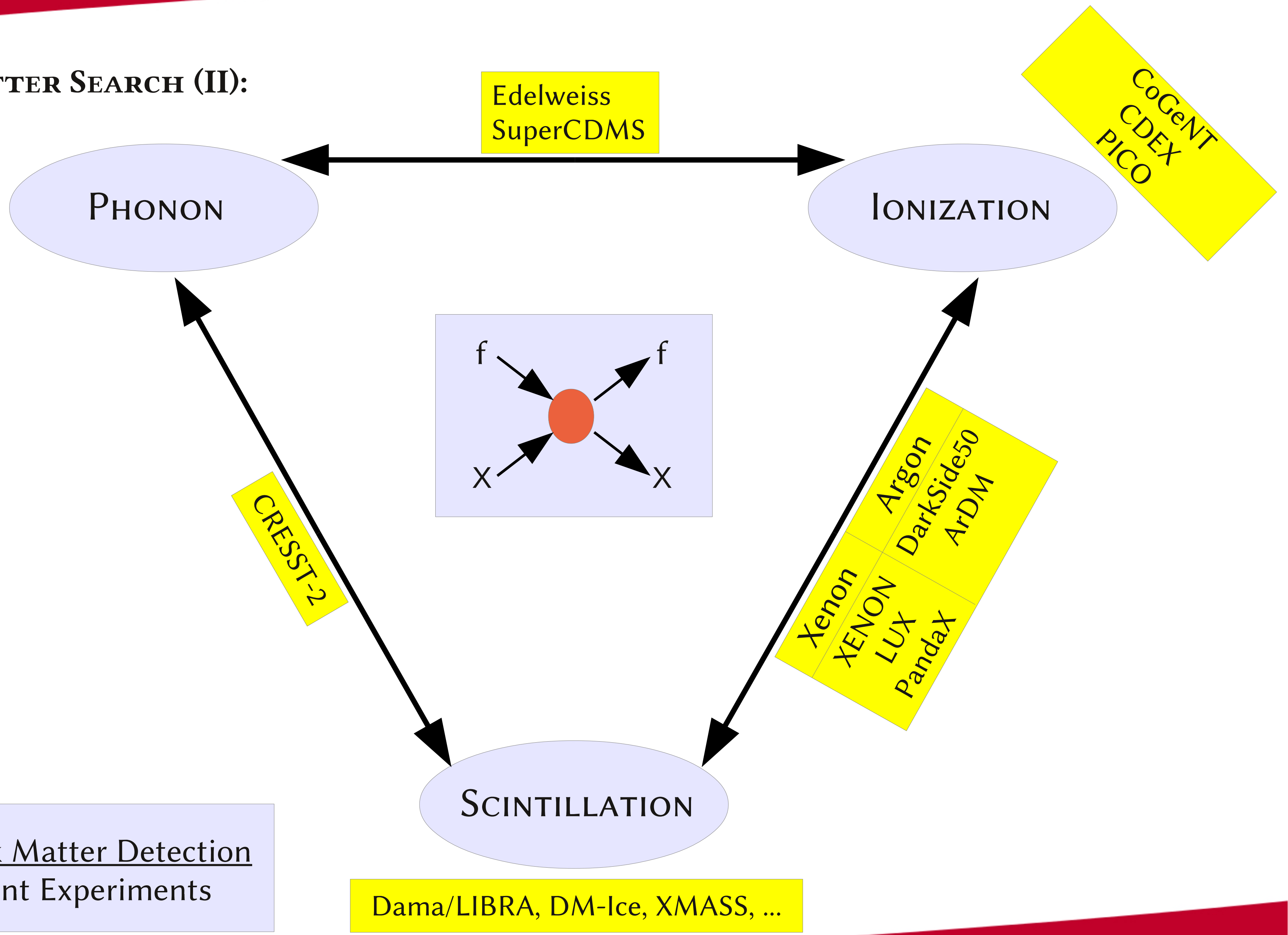
IceCube, ANTARES, H.E.S.S.

Dark Matter production:



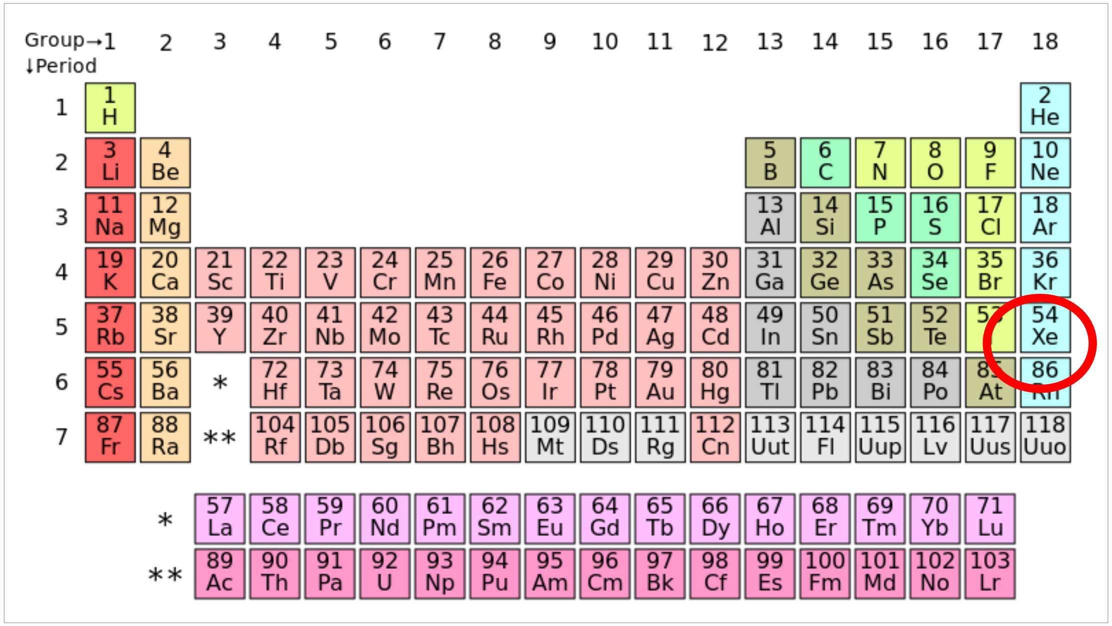
LHC

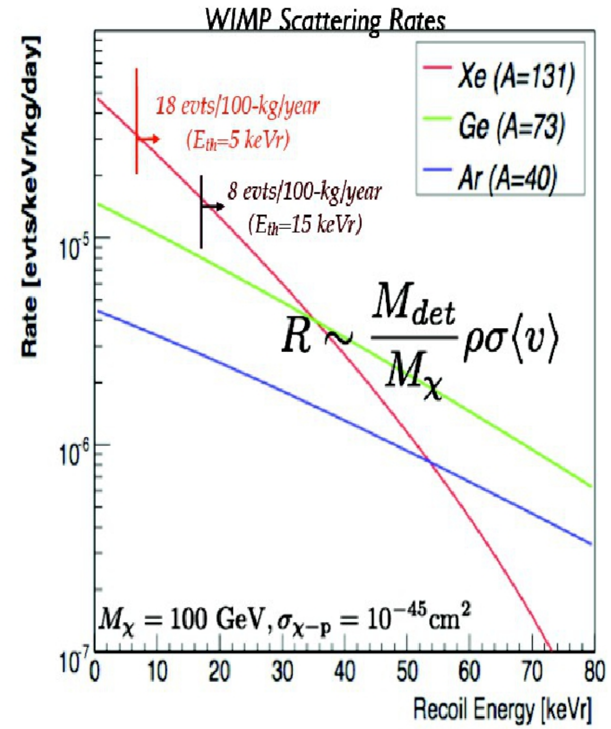
DARK MATTER SEARCH (II):



Direct Dark Matter Detection
with different Experiments

Xenon as Detection Material





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

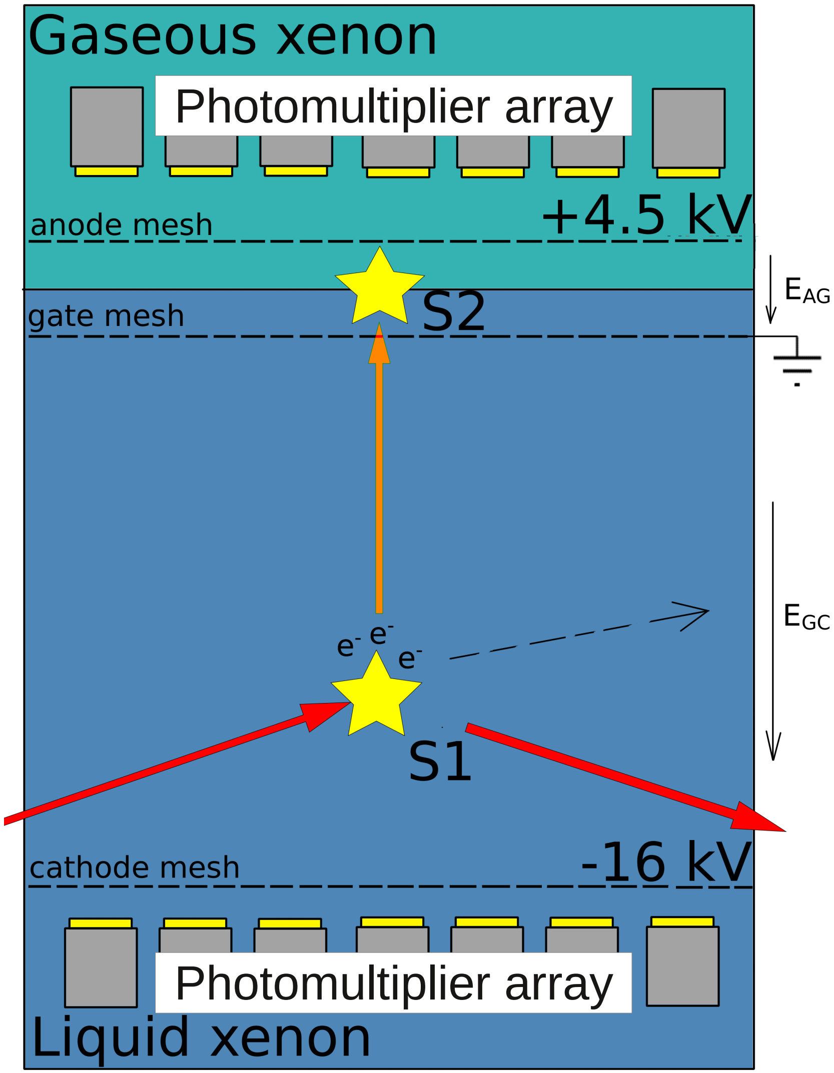
} Increase interaction probability

} Self-shielding properties
⟶ Definition of a fiducial volume

- Even/odd (stable) isotopes. } Test spin depended Dark Matter models
- Radioactive impurities (^{85}Kr, ^{222}Rn, ^{136}Xe unstable ⟶ 2ν2β)

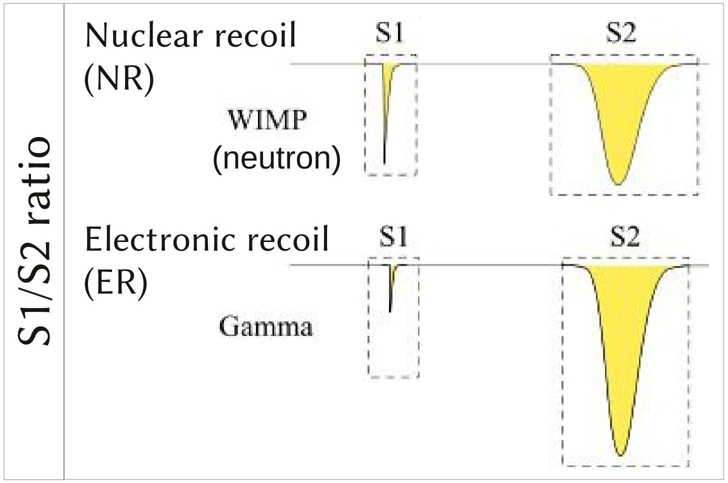
"Easy" to scale up!
⟶ Future detector design

Operation Principle of a Two-Phase Time Projection Chamber (I)

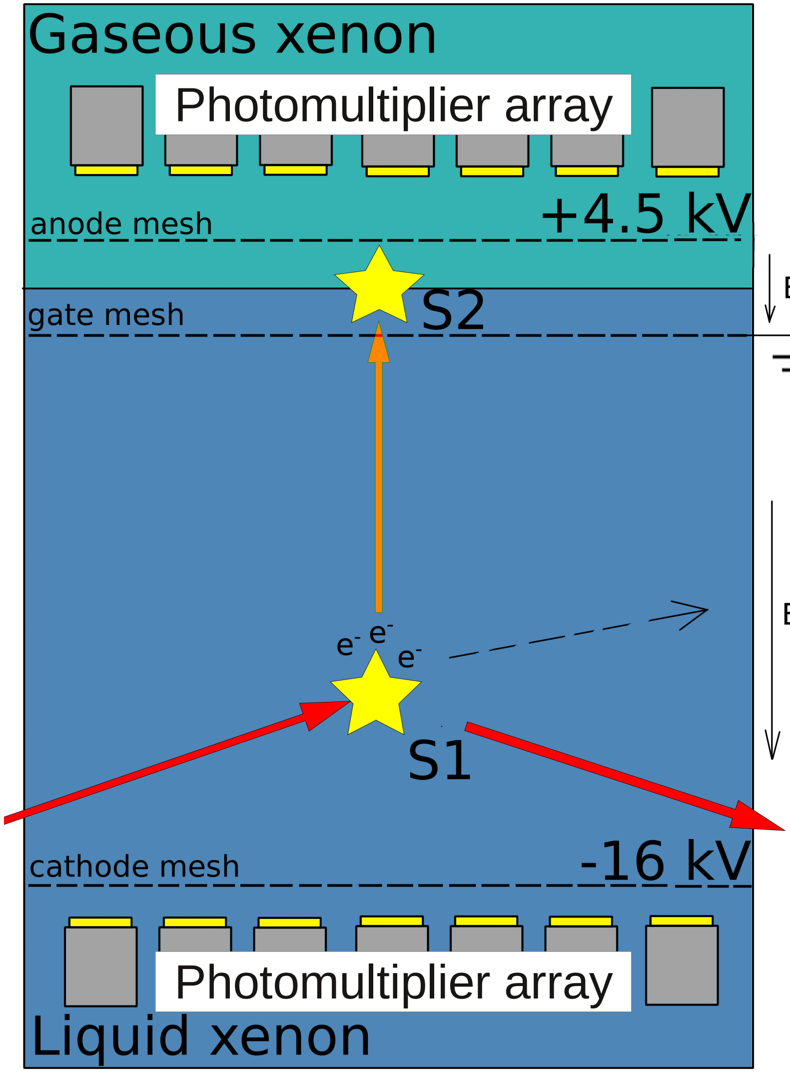


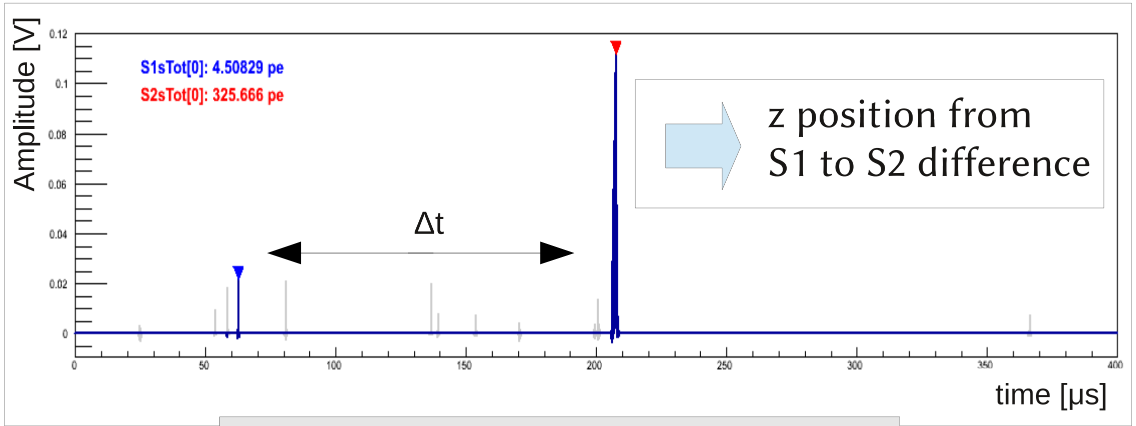
S1:
→ Photons (λ = 178 nm) from scintillation process
→ Detected by PMTs

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



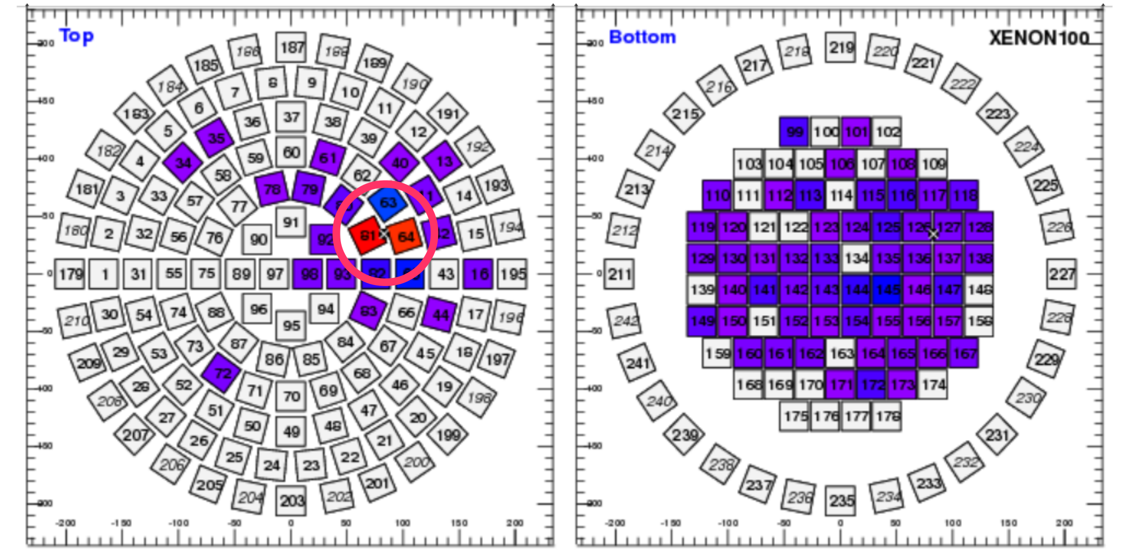
Operation Principle of a Two-Phase Time Projection Chamber (II)





z position from S1 to S2 difference

3D position reconstruction!

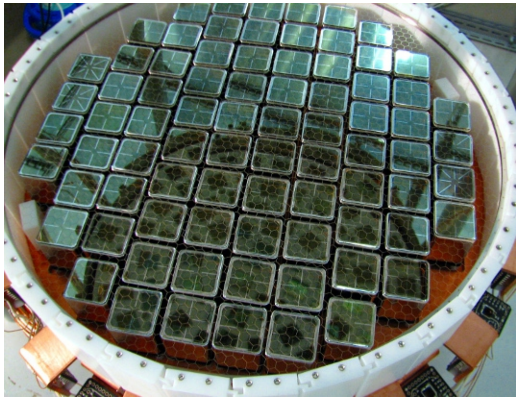


S2 hit-pattern for x/y position

The XENON100 Time Projection Chamber (TPC)

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


Top PMT array

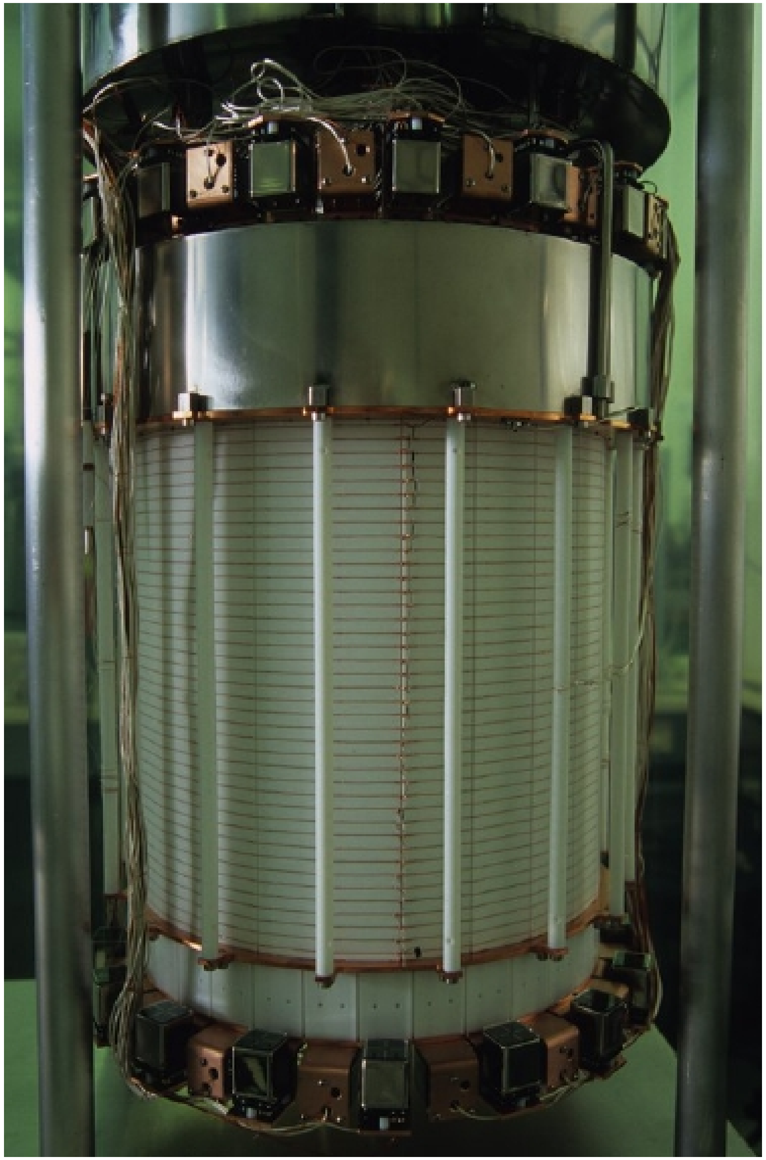

Bottom PMT array

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

TPC: 30 cm height / 30 cm diameter

All used materials: Low radioactive

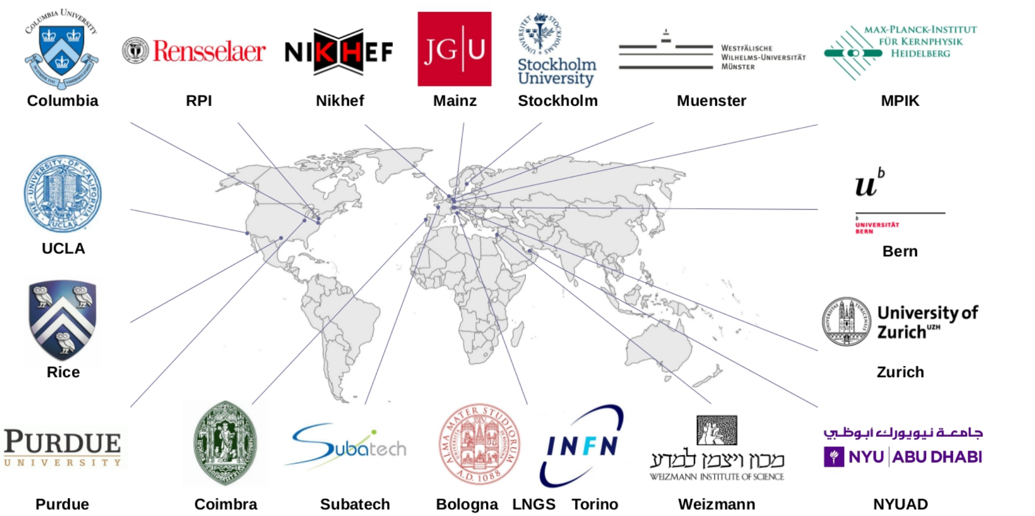
Multilayer passive shield: Cu, PE, Pb, H_2O


XENON100 Time Projection Chamber

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

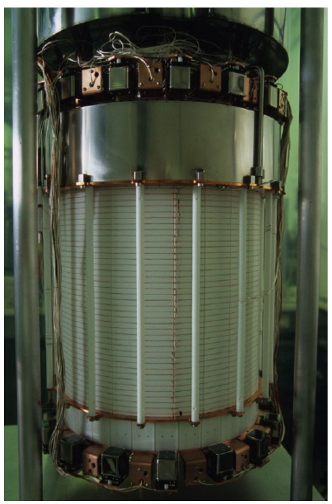
The XENON Dark Matter Project

– World Wide Collaboration –



HowTo: Find Dark Matter

1) Take a TPC



2) Calibrate your PMTs

Blue LEDs illuminate the TPC (weekly)

3) Estimate the electron life time

Source: ^{137}Cs (weekly)

4) Be sure what you measure!

NR calibration: AmBe (before/after data taking)

ER calibration: ^{232}Th, ^{60}Co (weekly)

5) Waiting...

Dark Matter Data (~ 5 days a week)

HowTo: Find Dark Matter

Raw data

?

^{241}AmBe
^{60}Co
^{232}Th

DM
^{137}Cs

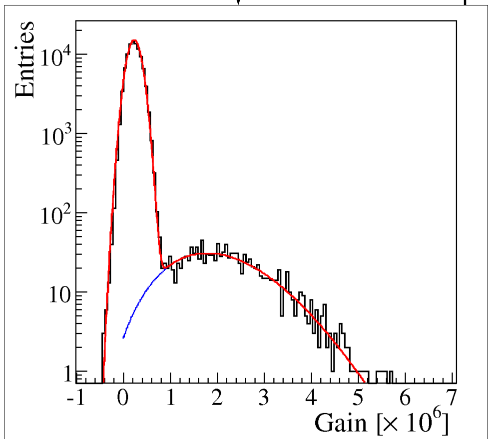
Raw Data Processor

Reduced Data Set

LED

LED calibration software

gain



Gain spectrum of a single PMT

Required: Dedicated data analysis!

Detector working conditions

Many cuts & acceptances

ER background model

Signal model

Neutron response

Full detector simulation (MC)

Ongoing work

Results

Test Dark Matter Models (e.g.):
⟶ Spin in-/dependent WIMPs
⟶ Axions search

XENON100: Energy Calibration

→ S1 and S2 signals correspond to a measured energy quantity in eV

S1 signal: $\boxed{E = \frac{S1^*}{L_Y \, L_{eff}} \frac{S_{ee}}{S_{nr}}}$

Electric field suppression factor for ER/NR

Light yield → pe/keV$_{ee}$

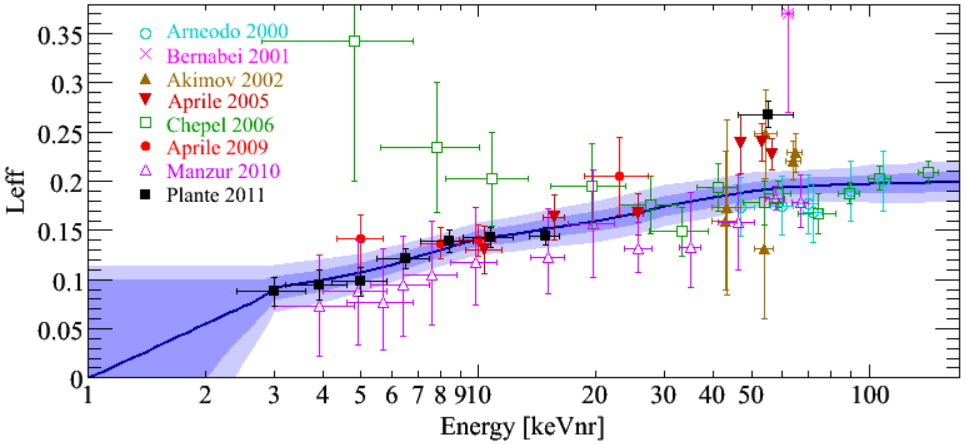
Detector parameter in XENON100

S2 signal: $\boxed{E = \frac{S2^*}{Y \, Q_y}}$

Single electron gain

Charge yield → e$^-$ /pe

Relative scintillation efficiency:



Relative scintillation efficiency from scattering experiments

Energy calibration with e.g. 40 keV, 80 keV, 164 keV line of activated xenon for S1 signals

* S1 and S2 signals are drift-time and volume corrected in further use

DATA MATCHING: XENON100 (I)

– XENON100 Data Matching –

→ Neutron calibration of XENON100 with ^{241}AmBe

Idea: Get a proper description of XENON100 by a simulation

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):

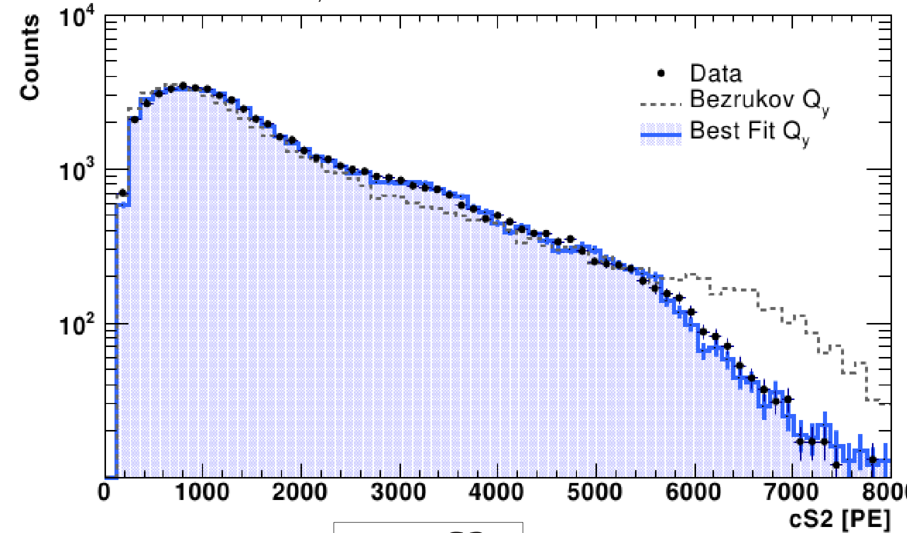
→ Take direct measured L_{eff}

→ Reproduce S2 spectrum

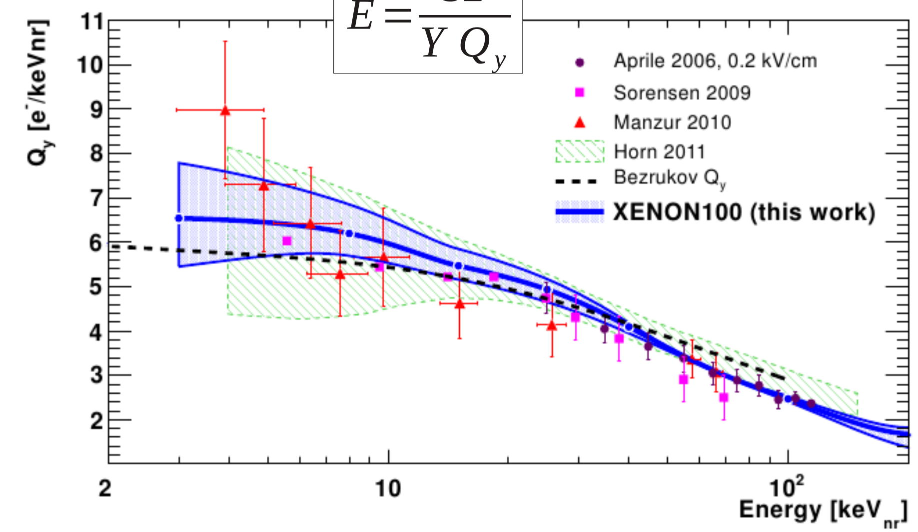
→ Best Fit Q_y

Conversion between $Q_y \leftrightarrow keV_{nr}$

S2 spectrum: Best Fit Q_y fits data



$$E = \frac{S2}{Y\,Q_y}$$

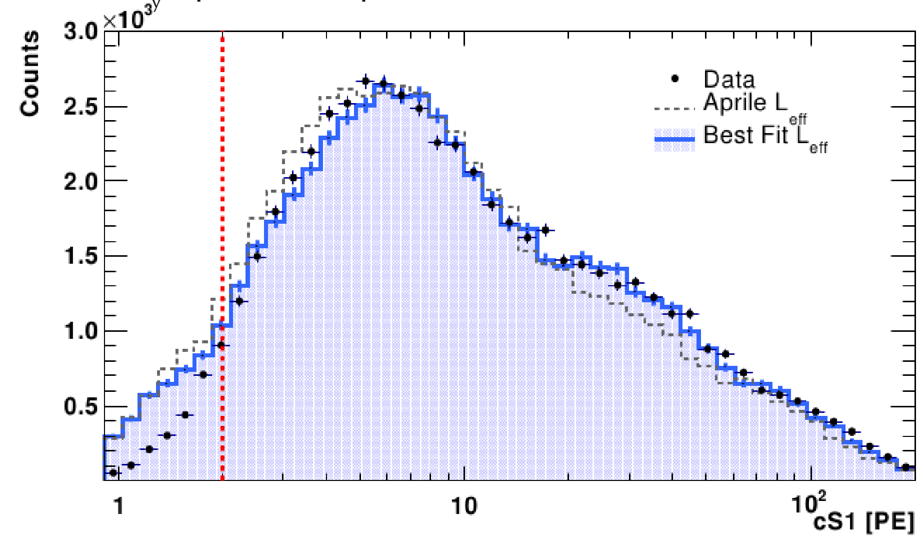


Q_y conversion to deposited (NR) energy

DATA MATCHING: XENON100 (II)

– XENON100 Data Matching –

Best Fit Q_y repreduce S1 spectrum



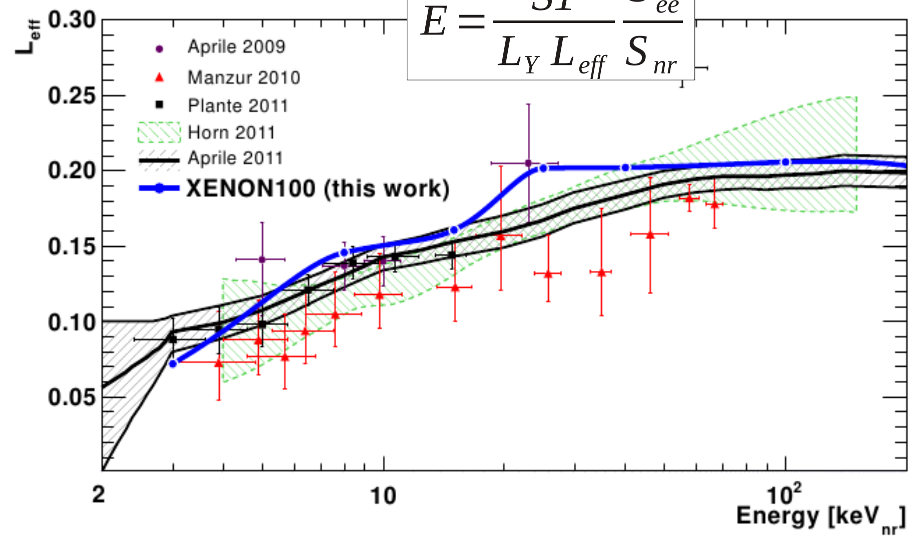
<u>How to do (II):</u>

⟶ Use Best Fit Q_y

⟶ Reproduce S1 spectrum

⟶ Get a new L_{eff}

$$E = \frac{S1}{L_Y\, L_{eff}} \frac{S_{ee}}{S_{nr}}$$



Compare data and MC: L_{eff} fits XENON100

- 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}

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

XENON100: Profile Likelihood

Full Likelihood function[1)] for m_χ and σ_χ

$$\mathscr{L} = \underbrace{\mathscr{L}_1(\sigma, N_b, \epsilon_s, \epsilon_b, \mathcal{L}_{\mathrm{eff}}, v_{\mathrm{esc}}; m_\chi)}_{\text{XENON100 measurement}} \times \underbrace{\mathscr{L}_2(\epsilon_s) \times \mathscr{L}_3(\epsilon_b) \times \mathscr{L}_4(\mathcal{L}_{\mathrm{eff}})}_{\text{Additional uncertainties}}$$

Parameter of interest: σ_χ

Nuisance parameters are *profiled out*

Analysis is done in flatten space

Background predictions from

- Electronic recoil (data)
- Monte Carlo simulation (NR)

From *no observation* an upper exclusion limit is calculated!

$\mathscr{L}_2(\epsilon_s) \times \mathscr{L}_3(\epsilon_b)$

Control measurements of signal and background data:
$\longrightarrow$ Determine the probabilities ε_b and ε_s to find an event

$\mathscr{L}_4(\mathcal{L}_{\mathrm{eff}})$

Relative scintillation efficiency $\mathcal{L}_{\mathrm{eff}}$ not available below 3 $\mathrm{keV}_{\mathrm{nr}}$

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

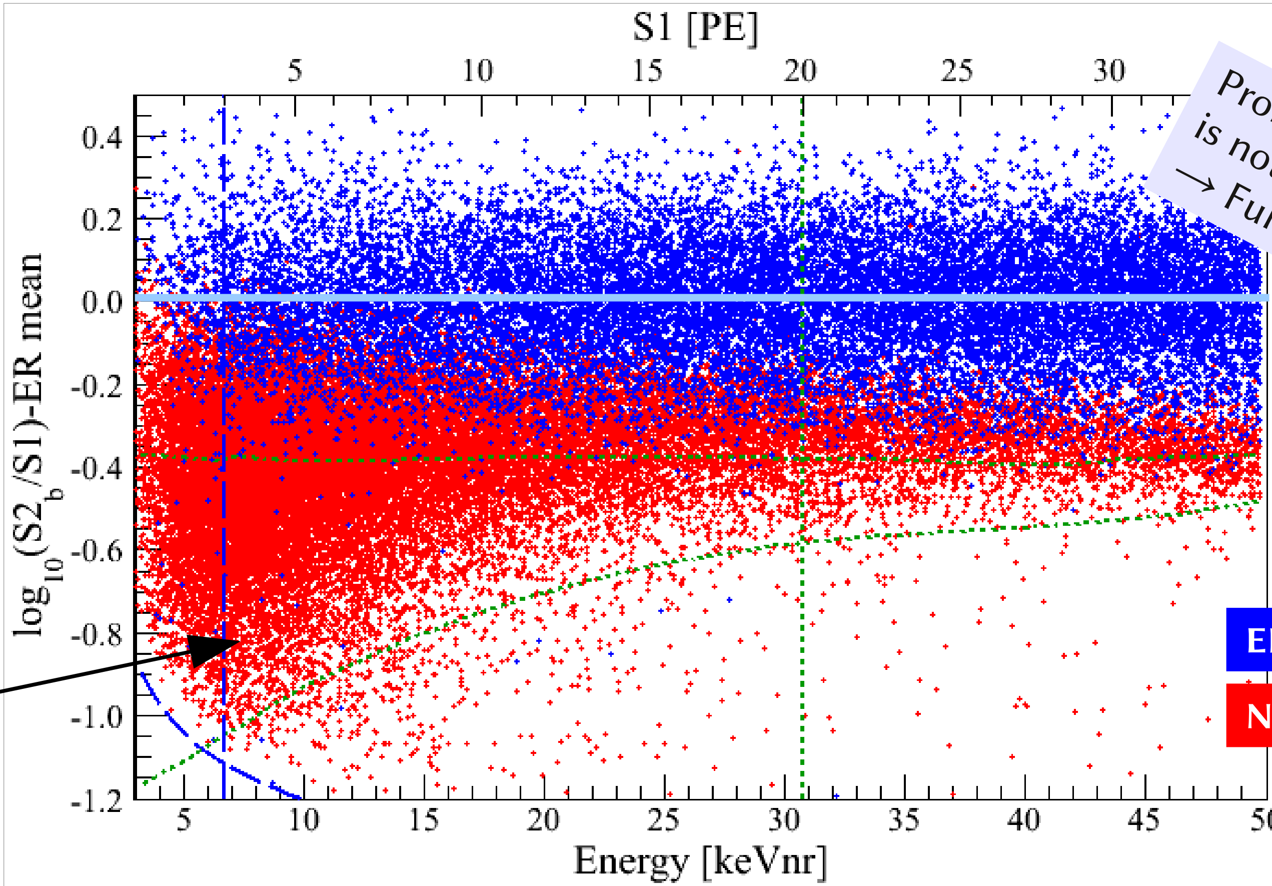
ANALYSIS: XENON100 (I)

– Background Expectation for 225 days –

Demand:

- Detector design: Careful material selection
- Low level ^{222}Rn (62.9 µBq/kg) and ^{85}Kr (19.4 ppt)

Discrimination space:



Background in XENON100: NR and ER from 225 life days

Profile Likelihood analysis is not limited to signal region!
→ Full discrimination space

ER calibration data: $^{232}Th/^{60}Co$

NR calibration data: $^{241}AmBe$

Signal region

ER background: 0.79 ± 0.16 events

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

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

Analysis: XENON100 (II)

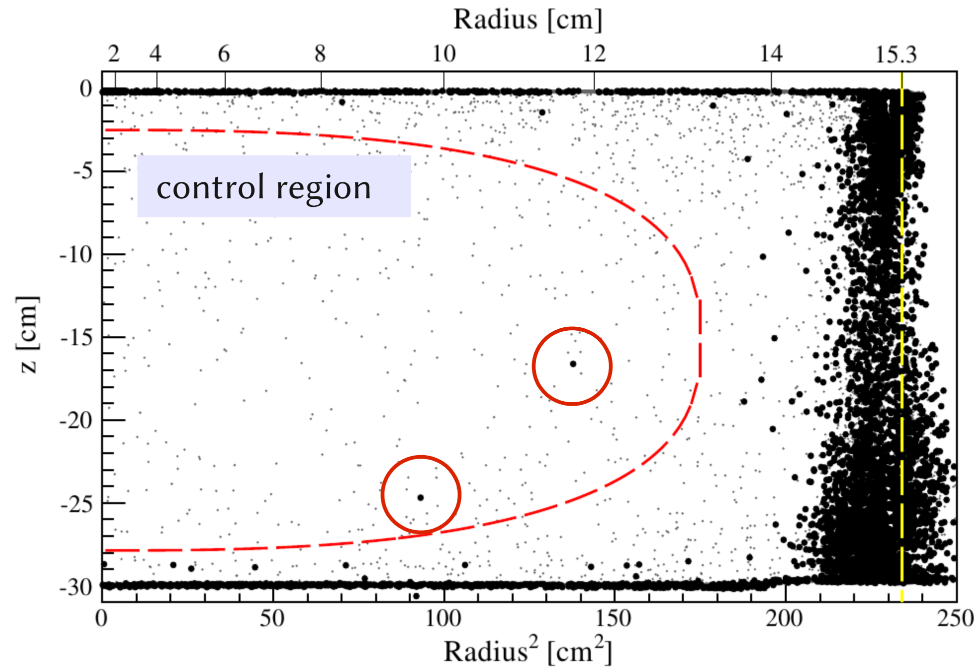
– Spin-independent –

<u>During 2011/2012:</u> 225 live days of data

Total background expectation: 1.0±0.2

Two observed events are not enough compared with expected background.

⟶ Background fluctuation to two events is possible by 26.4%



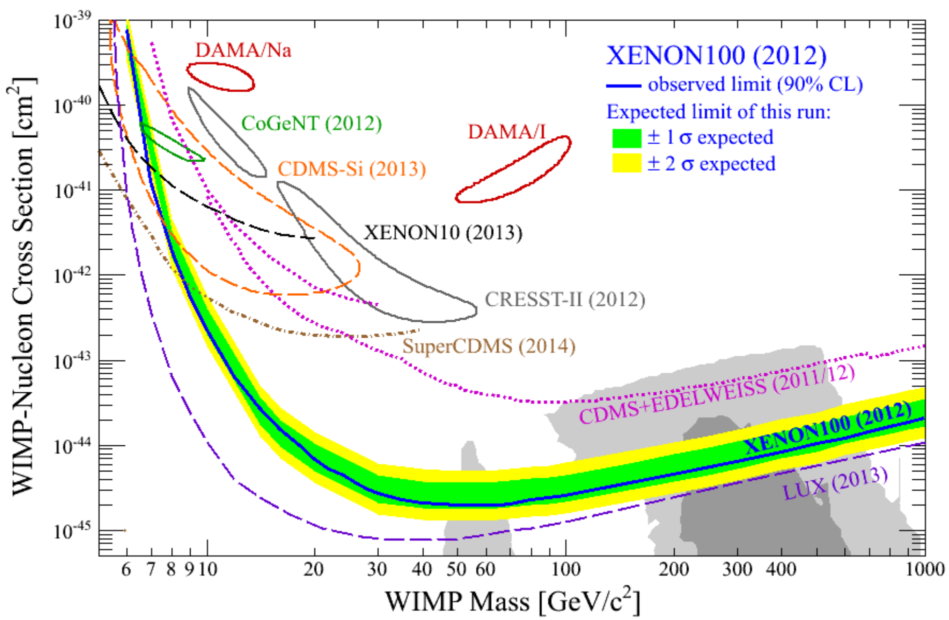
Event distribution

Profile Likelihood Analysis

Lowest WIMP-Nucleon Cross-section[1]:

m_χ = 55 GeV/c²

σ < 2.0 x 10^{-45} cm² (90% C.L.)



Exclusion limit of 225 days of Dark Matter data taking

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

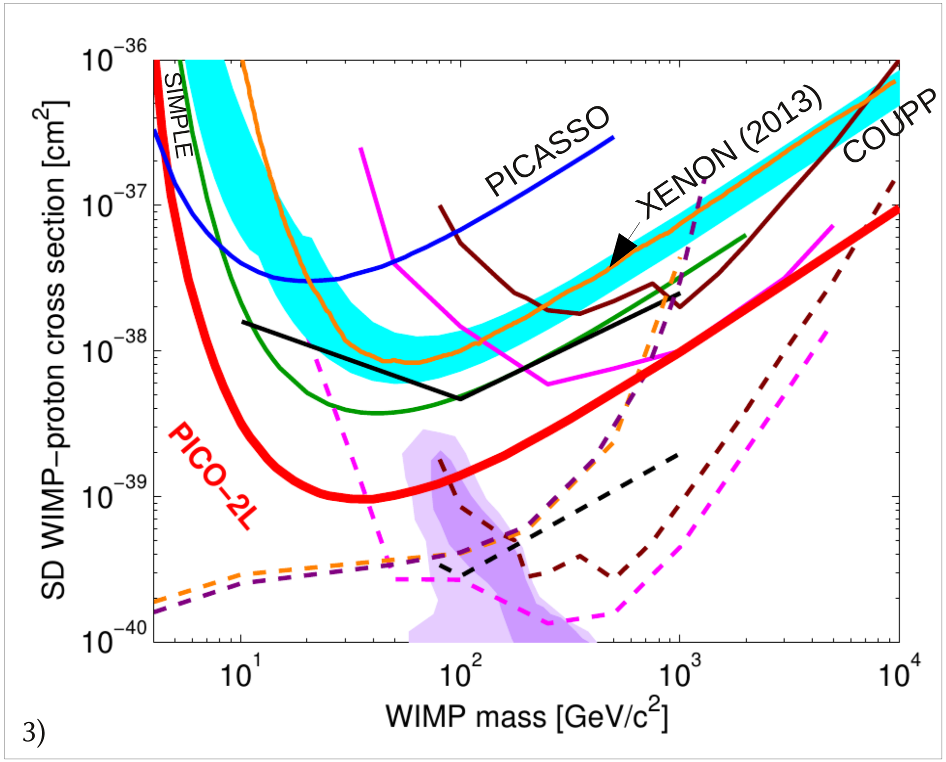
Analysis: XENON100 (III)

– Spin-dependent –

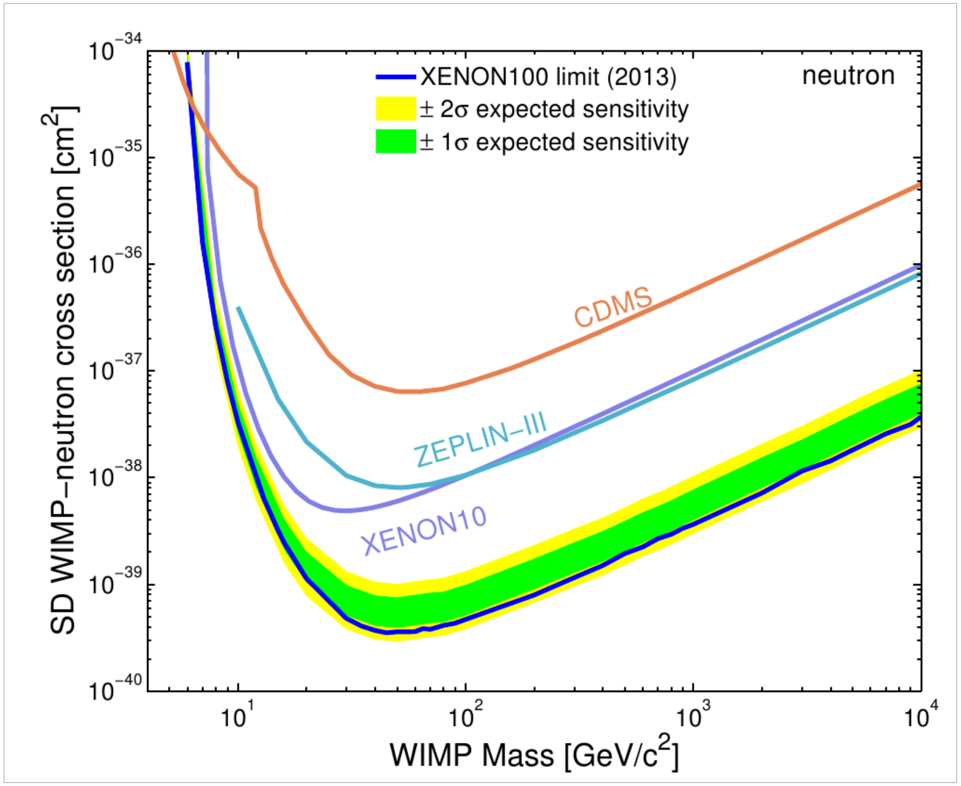
Odd xenon isotopes:

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

→ WIMP Dark Matter could couple in a spin dependent way!



3)



WIMP-Neutron cross-section[1]

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

$\sigma < 3.5 \times 10^{-40}$ cm²

by using a nuclear model of Menendez[2]

1) E. Aprile et al, Phys. Rev. D 88, 012006 (2013)

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

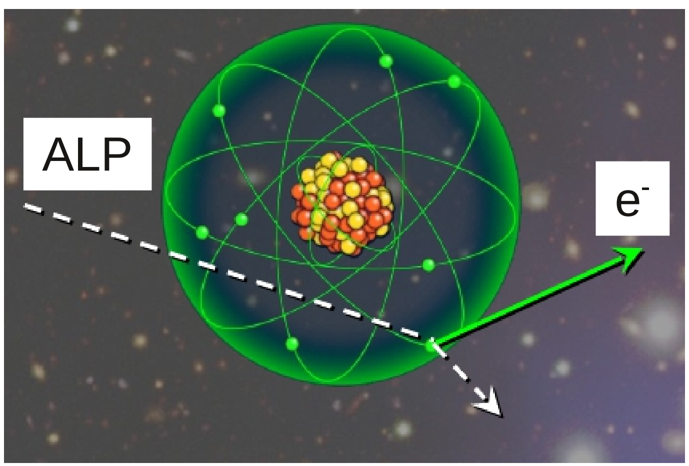
3) SNO Collaboration (C. Amole (Queen's U., Kingston) et al.). e-Print: arXiv:1503.00008 (2015)

Analysis: XENON100 (IV)

– Axion Search in XENON100 –

Axions and axion-like particles (ALPs) may couple with:

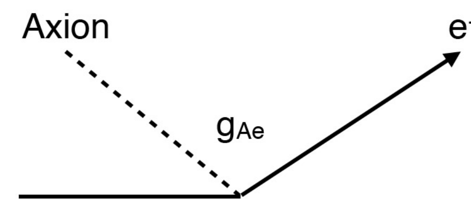
- Photons ($g_{A\gamma}$)
- Electrons (g_{Ae}) ⟶ **Search: Scattered electrons**
- Nuclei (g_{AN})



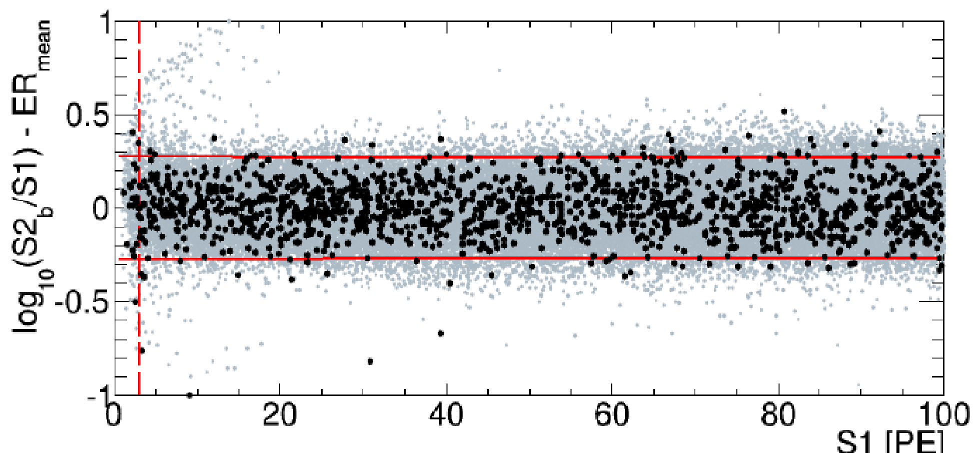
Axions ionize xenon

Test different axion/ALP models:

→ Solar axions
→ Galactic ALPs



Careful data selection from 225 days of data:



Data selection for axion Dark Matter analysis[1]

→ Select electronic recoil band

[1] E. Aprile et al. Phys.Rev. D90 (2014) 6, 062009

Analysis: XENON100 (V)

– Axion Search in XENON100 –

Solar axions:

- 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:

photo-electric cross-section

Axion energy

Axion velocity

$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{g_{Ae}^4}{\beta_A}\frac{3E_A^2}{16\pi\alpha_{EM}m_e^2}\left(1-\frac{\beta_A^{2/3}}{3}\right)$$

fine structure constant

electron mass

&

Solar axions:

Axion flux ∞ g^2_{Ae}

=

$$\frac{dR^{solar}}{dE_R} \propto g_{Ae}^4$$

&

Galactic ALPs:

$$\Phi_{ALP} = \frac{c\beta\rho_{DM}}{m_{ALP}}$$

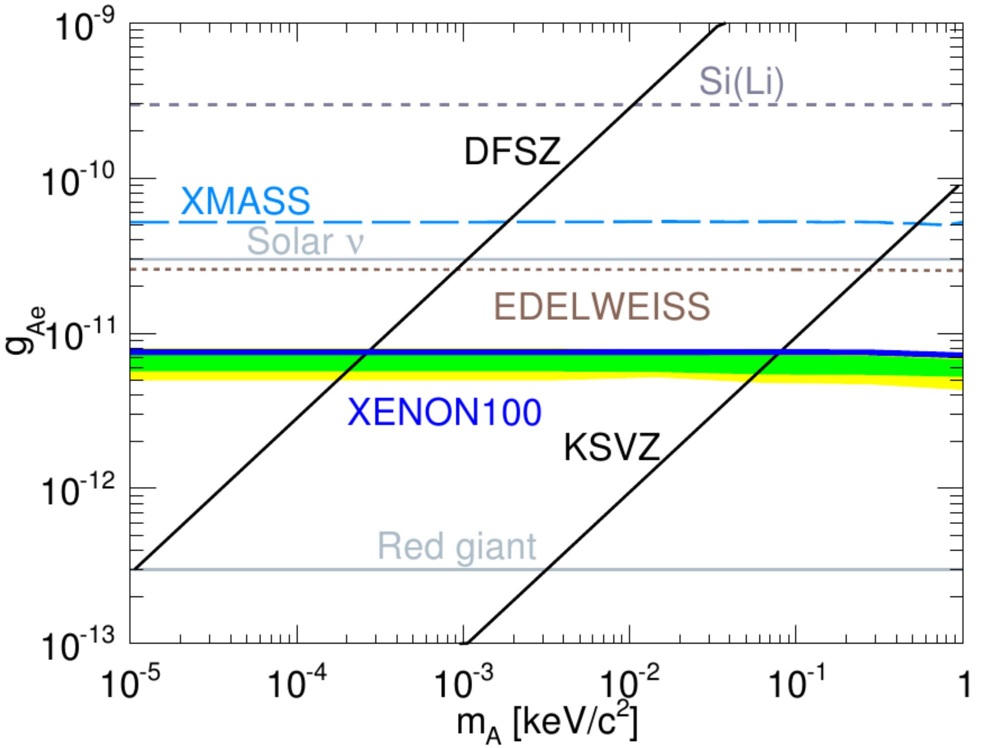
=

$$\frac{dR^{DM}}{dm_{ALP}} \propto g_{Ae}^2$$

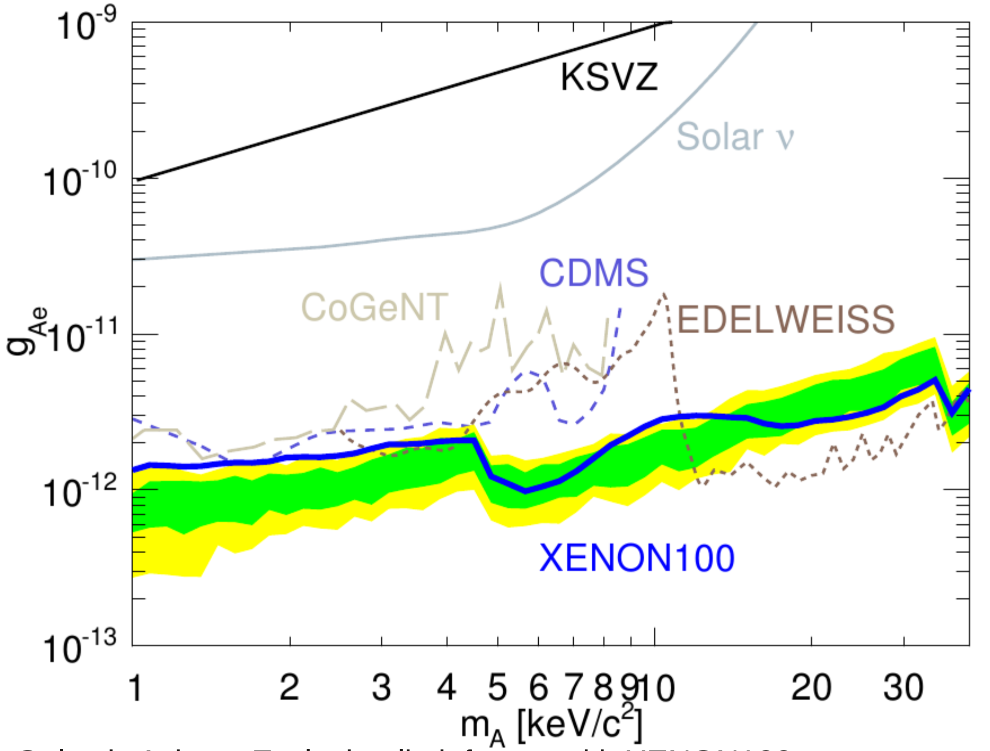
E. Aprile et al. Phys.Rev. D90 (2014) 6, 062009

Analysis: XENON100 (VI)

– Axion Search in XENON100 –



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:
$\longrightarrow$ $g_{Ae} > 7.7 \times 10^{-12}$ excluded (90 % C.L.)

Galactic axions with m = 5 – 10 keV/c^2:
$\longrightarrow$ $g_{Ae} > 1 \times 10^{-12}$ excluded (90 % C.L.)
(Assuming ALPs constitute all of the galactic Dark Matter.)

E. Aprile et al. Phys.Rev. D90 (2014) 6, 062009

Status: ^{88}YBe Calibration

– Low energetic neutron calibration –

<u>AmBe source:</u>

$\longrightarrow$ Broad neutron recoil energy spectrum

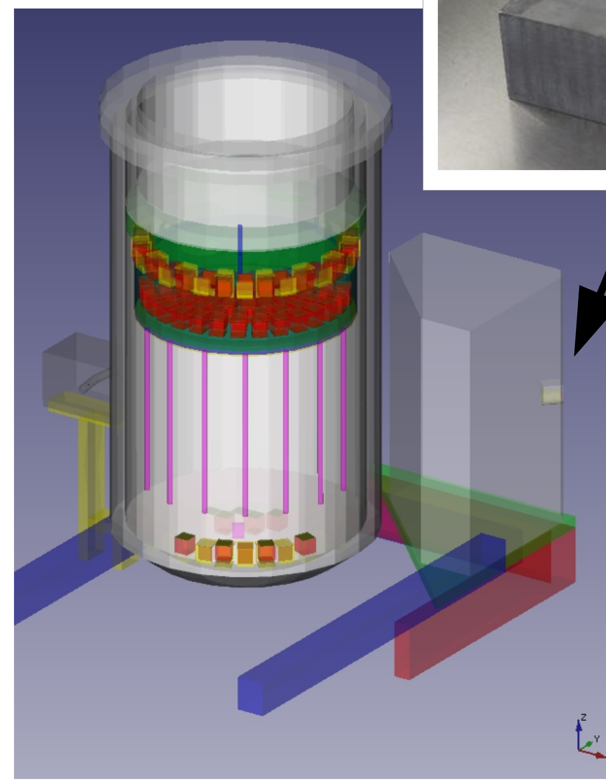
<u>Aim:</u>

$\longrightarrow$ Test a mono-energetic neutron source

$$^{88}\mathrm{Y} \xrightarrow{\gamma\,=\,1.836\ \mathrm{MeV}} {}^{9}\mathrm{Be} \qquad Q_{\mathrm{Be}} = 1.666\ \mathrm{MeV}$$

$$^{9}\mathrm{Be} \longrightarrow {}^{8}\mathrm{Be} + n$$

Photo disintegration process



<u>Calibration:</u>

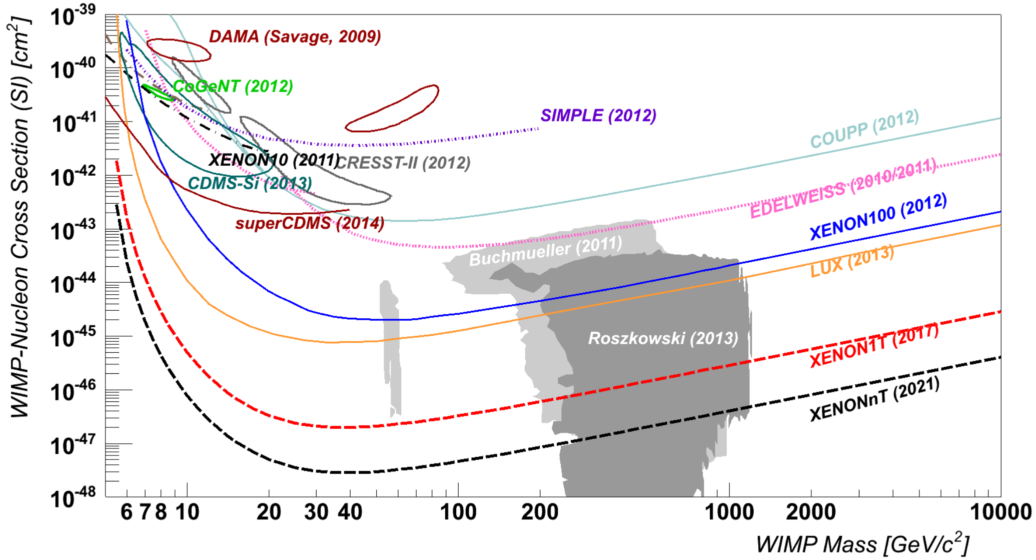
- Neutron energy: 152 keV
- Source strength: 170 n/s (5 MBq)
- Source is mounted in BeO housing

<u>Lead shield is necessary:</u>

- Neutron creation also includes γ with ~1.836 MeV
  $\longrightarrow$ Additional ER Background!

Data analysis is ongoing!

XENON1T: The next Level

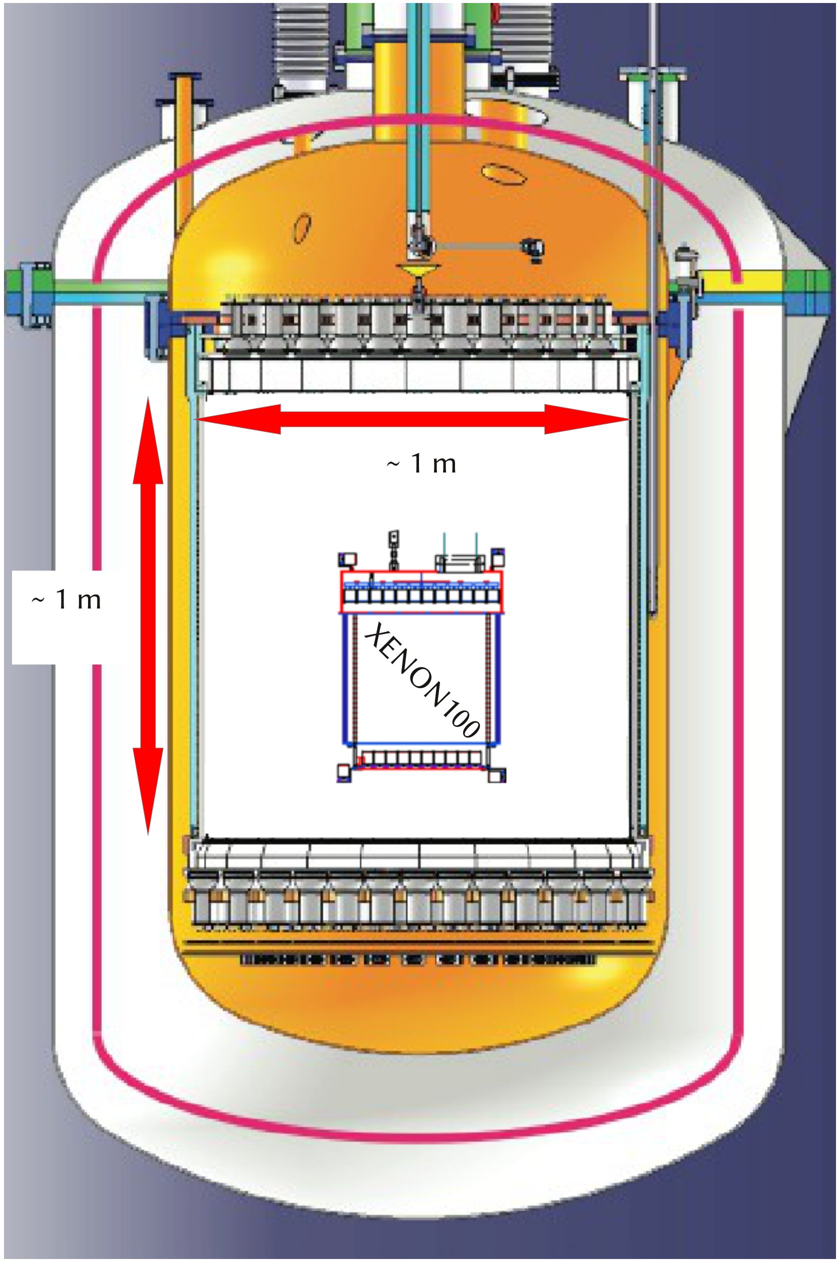


Outlook Exclusion limits

No WIMP Dark Matter found yet!

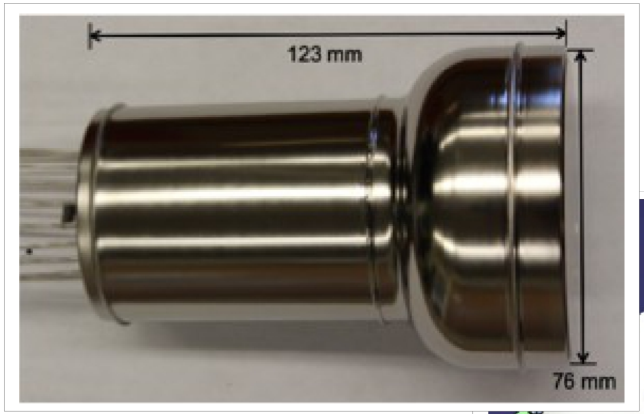
<u>Increase the target mass</u>
⟶ Background reduction
⟶ Increase sensitivity

XENON100 ⟶ **XENON1T** ⟶ *XENONnT*



XENON1T TPC with XENON100 TPC for size comparison

XENON1T: The TPC



⟶ Designed with ~ 3.3 tons LXe!

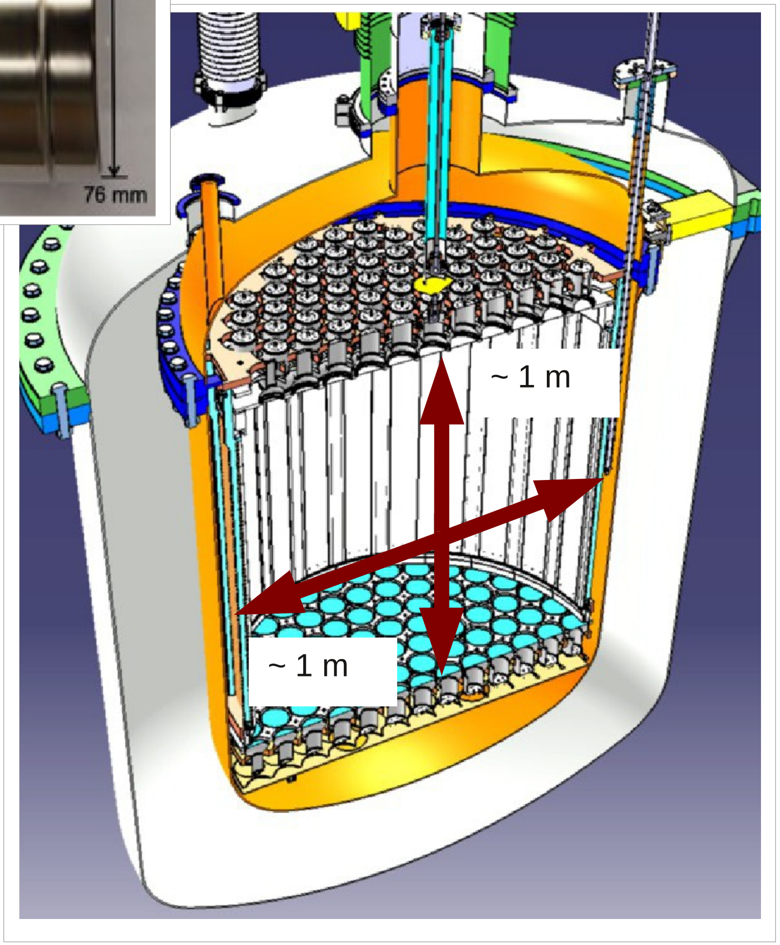
- Inside TPC: ~ 2 tons
- Fiducial volume: ~ 1 ton

⟶ Photomultipliers:

- 248 of 3” R11410-21 PMTs[1)]
- Low background + high QE (35 %)

⟶ Background reduction:

- Careful material selection/screening of cryostat and TPC

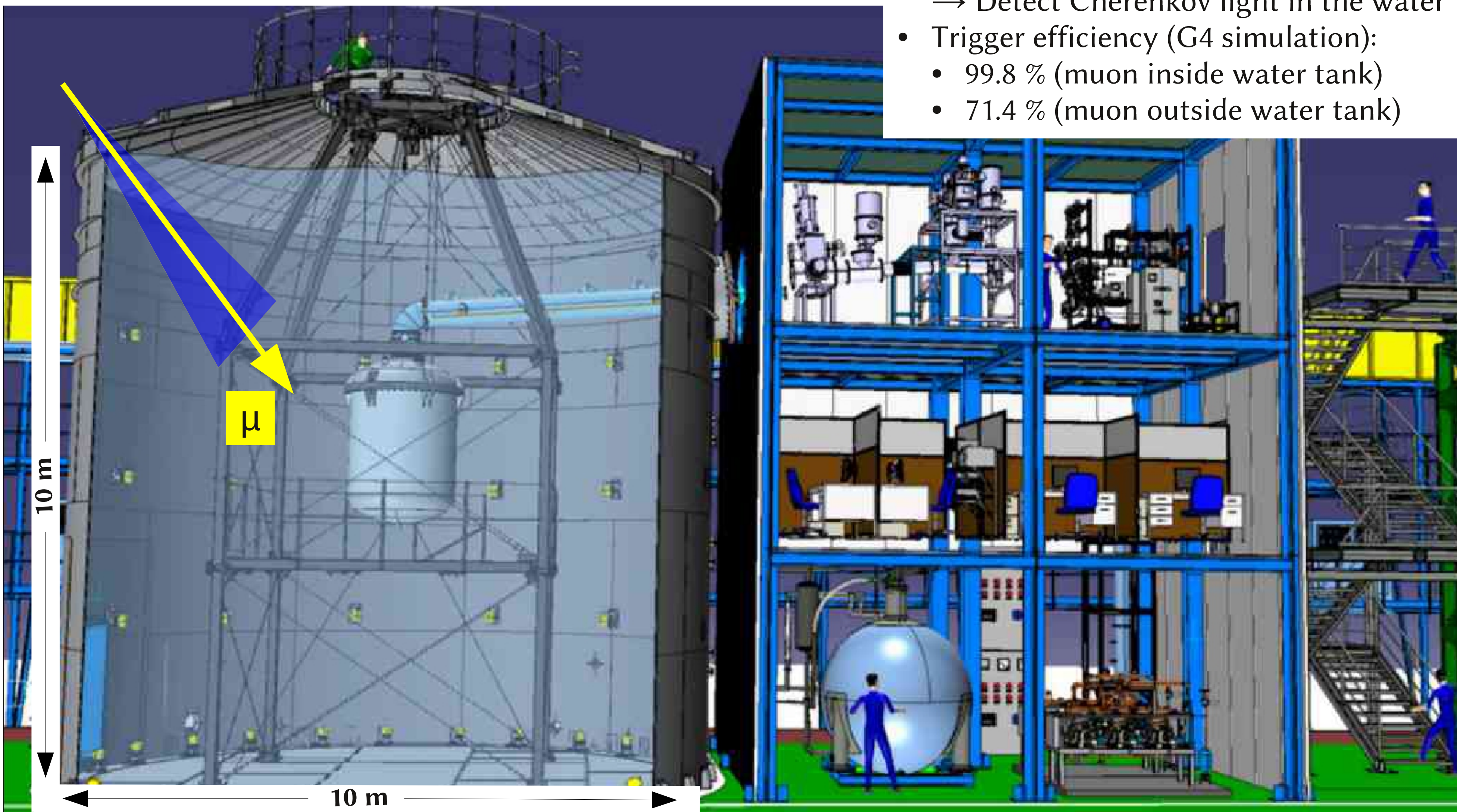


100x lower background!

1) JINST 8, P04026 (2013)

XENON1T: Water Cherenkov Muon Veto

– Active Muon Veto[1] –



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

1) E. Aprile et al., JINST 9, P11006 (2014)

XENON1T: Current Status@LNGS – Hall B

XENON1T: ReStoX

– **Re**covery and **Sto**rage of **X**enon –

Storage

- 7.6 tons xenon (liquid or gaseous)
- Up to 72 bar!
- Liquid Nitrogen cooling system
  - (two redundant)
- Store xenon at room temperature

Recovery

- Recovery:
  - TPC maintenance
  - Emergency (~3 h)
- Keep xenon clean
- Pre-purified xenon for TPC filling

Slow Control

- Constant temperature control
- Control condenser
- Cooling power: > 2 kW

__Status:__

- Two cooling tests are finished

__Next:__

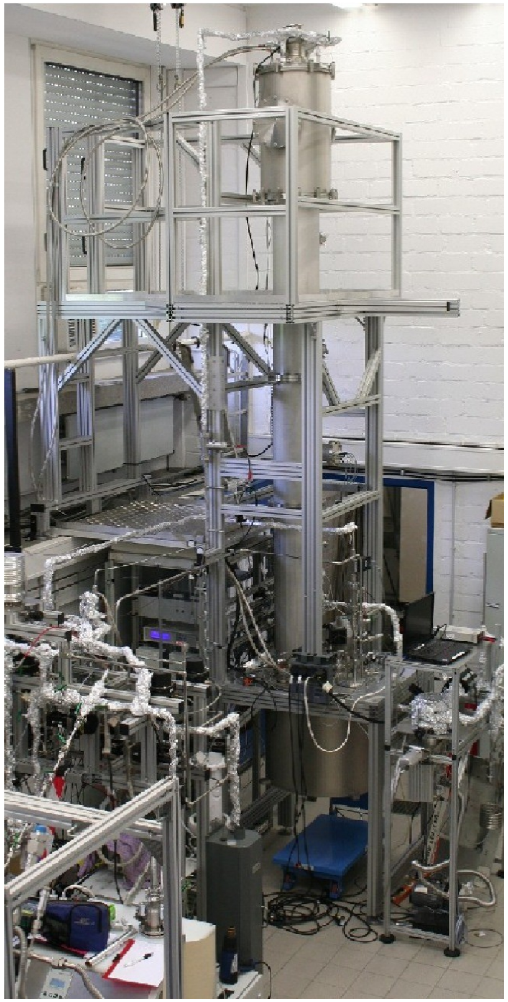
- Test with xenon in the sphere
- Test fast recovery of tons of LXe

XENON1T: Intrinsic background reduction

Gas purification system for XENON1T

→ In between ReStoX and TPC
→ Detailed gas analysis possible

Future Upgrade: ^{222}Rn removal system


Kr Column

^{85}Kr impurity:

- Cryogenic distillation column for Kr removal
- Removal system to achieve: ^{nat}Kr/Xe < 0.2 ppt
- Aim: 3 kg/h xenon
- Fully integrated in XENON1T
- Column height: 5 m

XENON1T: Cryogenic System

- Pulse tube refrigerators (PTRs) keep xenon at operation temperature (- 91° C)
- Heat load up to 50 W
  (Not including the xenon gas circulation of the purification system)
- Two redundant PTR cooling systems (200 W)
- Emergency liquid nitrogen (LN2) system for up to 48 hours of cooling

XENON1T: The Outer Vessel & TPC

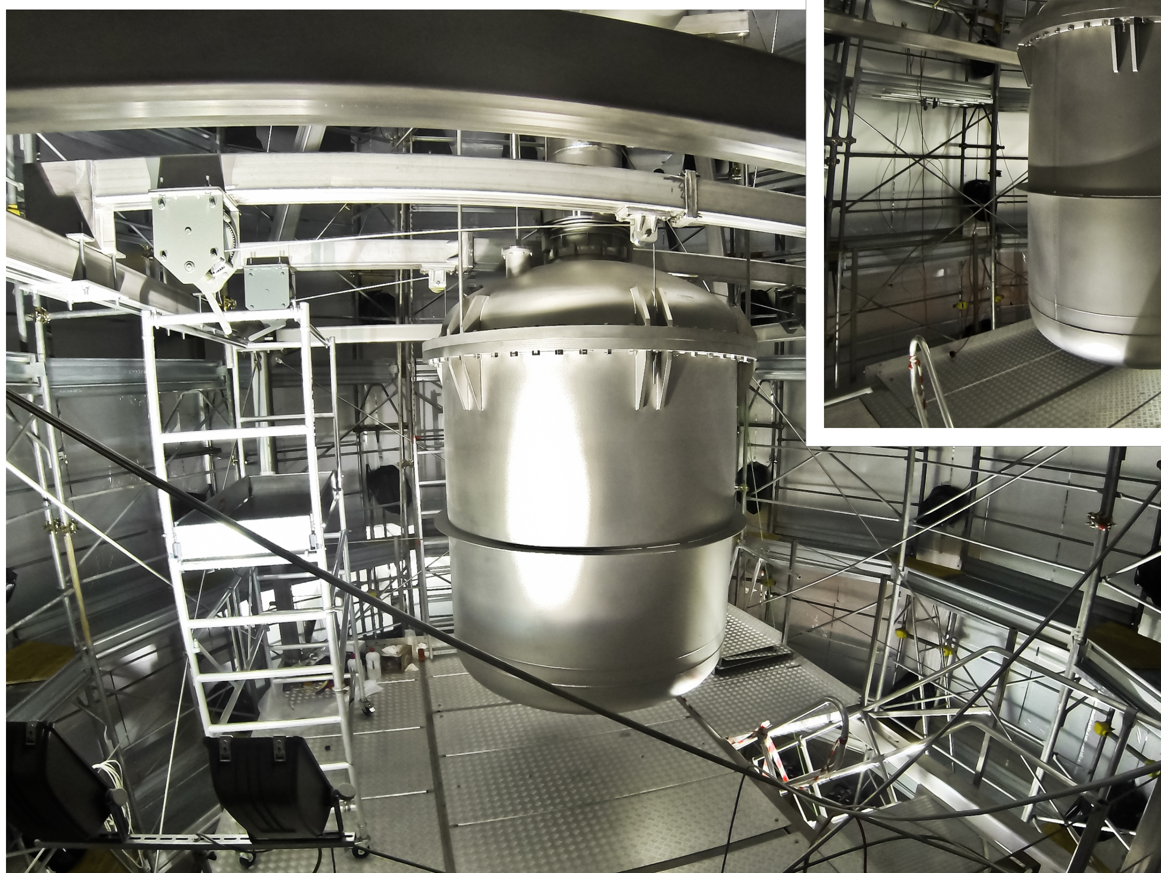
– Installation –

Installation of the outer vessel was finished in February 2015!

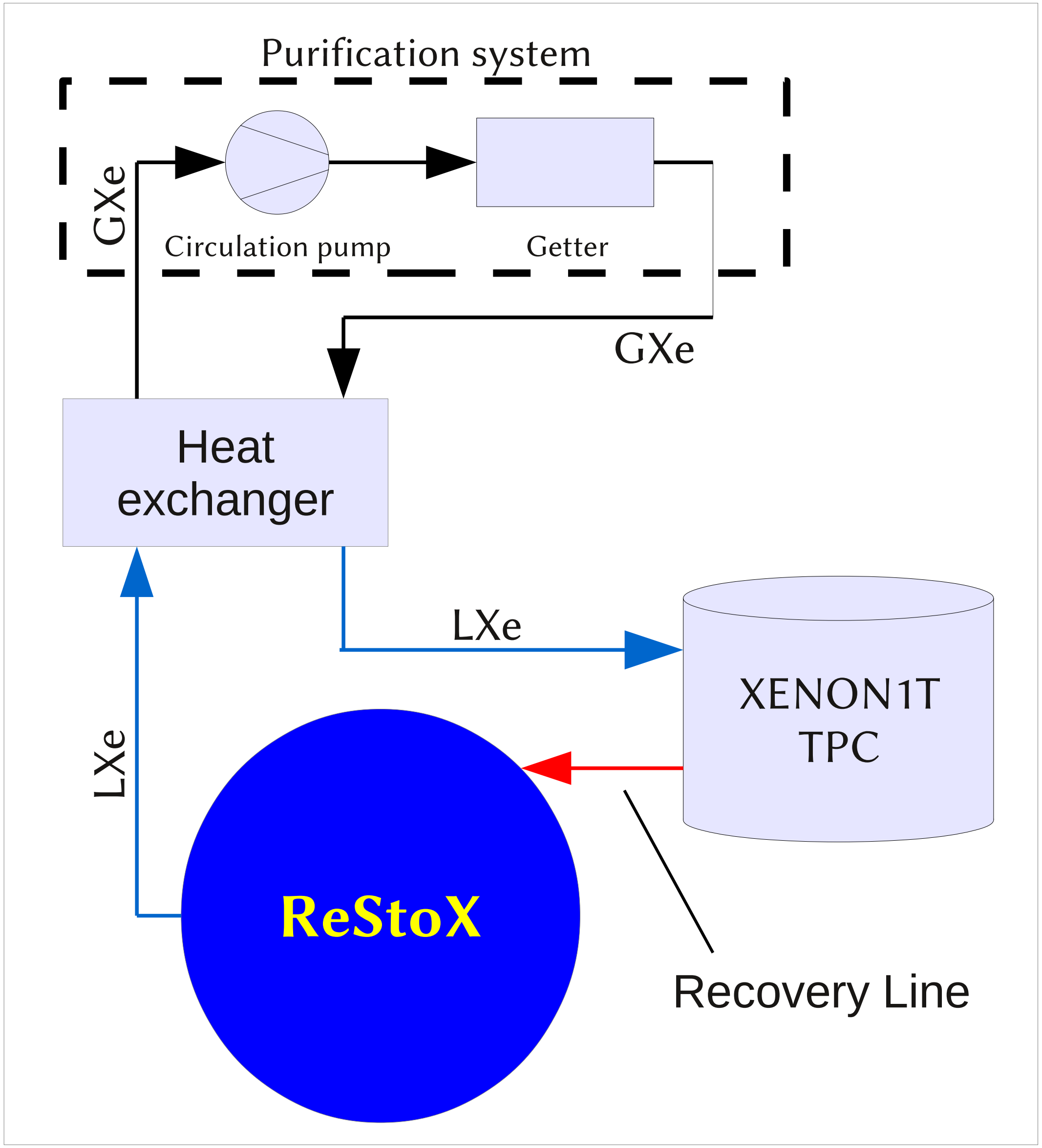
→ Ongoing vacuum tests before the TPC is mounted

→ TPC design fixed

→ Construction started



XENON1T: Xenon Cycle



Xenon cycle via:

- ReStoX
- Purification system
- XENON1T TPC

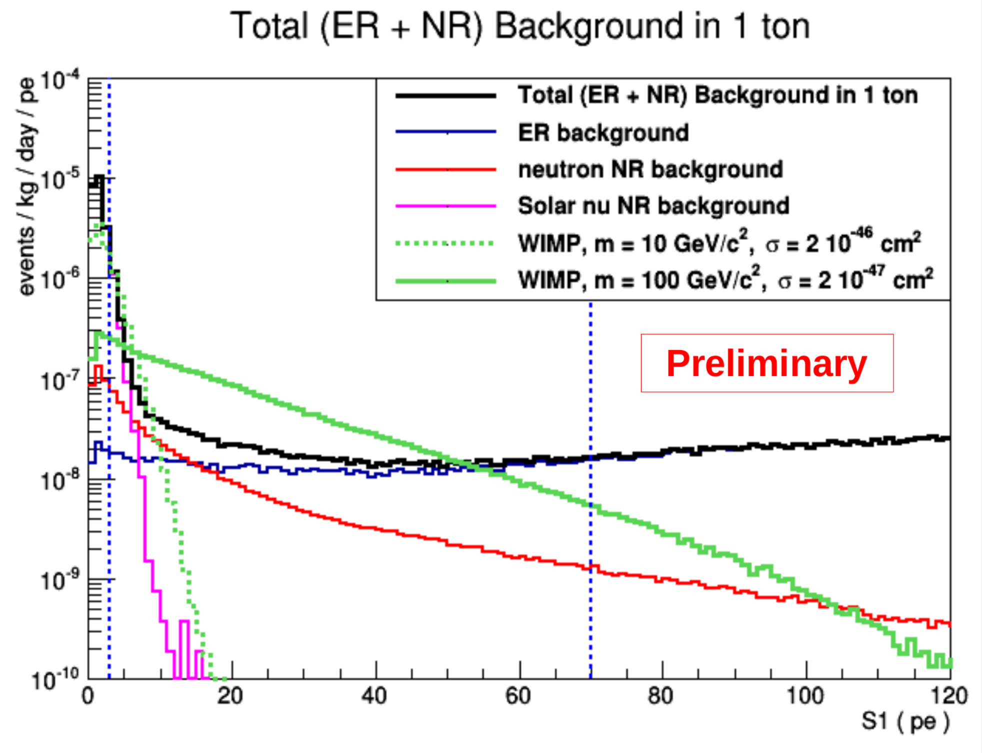
Heat exchanger measure the xenon flow

Xenon is cleaned with purification system

XENON1T: Background Estimations

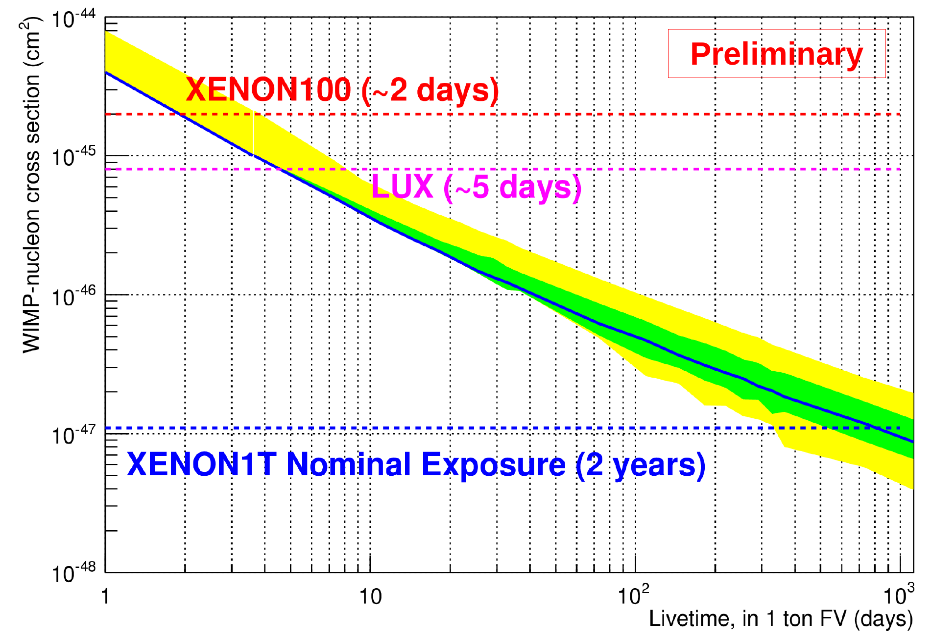
Background calculated from MC simulations

- Full simulation of the XENON1T TPC
- Fiducial volume: 1t
- Electronic recoil rejection: 99.75%
- Background expectation in 4 – 70 pe window:
  0.67 events/ton/year



Solar neutrinos:	
- Electronic recoil:	0.08
- Nuclear recoil (coherent):	0.55
$2\nu2\beta$ (^{136}Xe):	0.02
ER Materials:	0.05
NR Materials:	0.24
Intrinsic (Xenon contamination):	0.15

Expected events in XENON1T



Expected sensitivity (90% C.L.) for 50 GeV WIMP(PL)

XENONnT: Upgrade

Aim:

⟶ Increase amount of xenon to ~7 tons

⟶ Sensitivity goal: a few 10^{-48} cm^2 @20ton-years

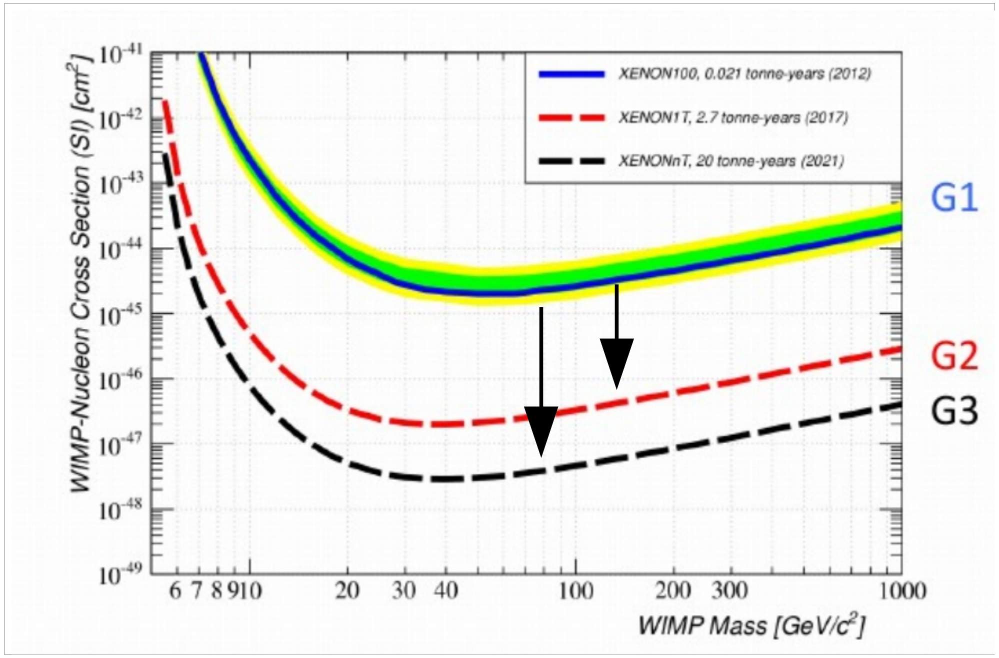
⟶ Start directly after XENON1T (~2018)

How to achieve:

⟶ Replace: TPC + Inner vessel

⟶ Remain unchanged: Cryostat, water tank
ReStoX

⟶ Advantage:
Low cost & faster update



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 source/MC matching results
- Develop and test alternative analysis methods, e.g. Bayesian approach
- Krypton removal technique tested for XENON1T
- Calibration with YBe source
- Further analysis topics are under investigation

Stay tuned!!!

XENON1T

→ XENON1T is under construction!

- Suppress background by a factor 100
- Increase detection probability by a larger amount of xenon
- Active muon veto
- Sensitive to $2 \times 10^{-47} cm^2$
- First data in 2015

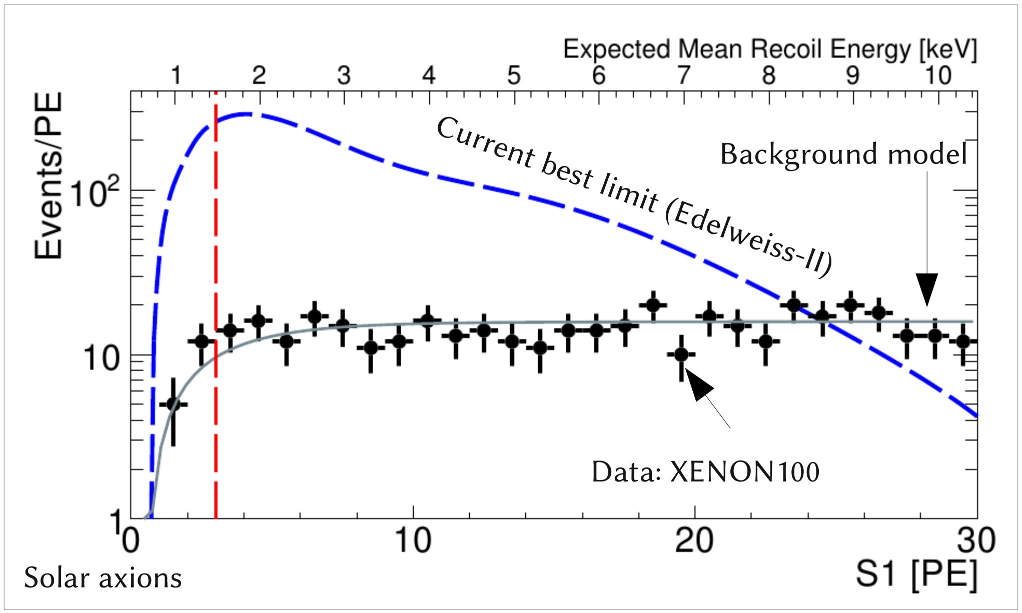
The next level XENON - TPC for Dark Matter detection is coming!

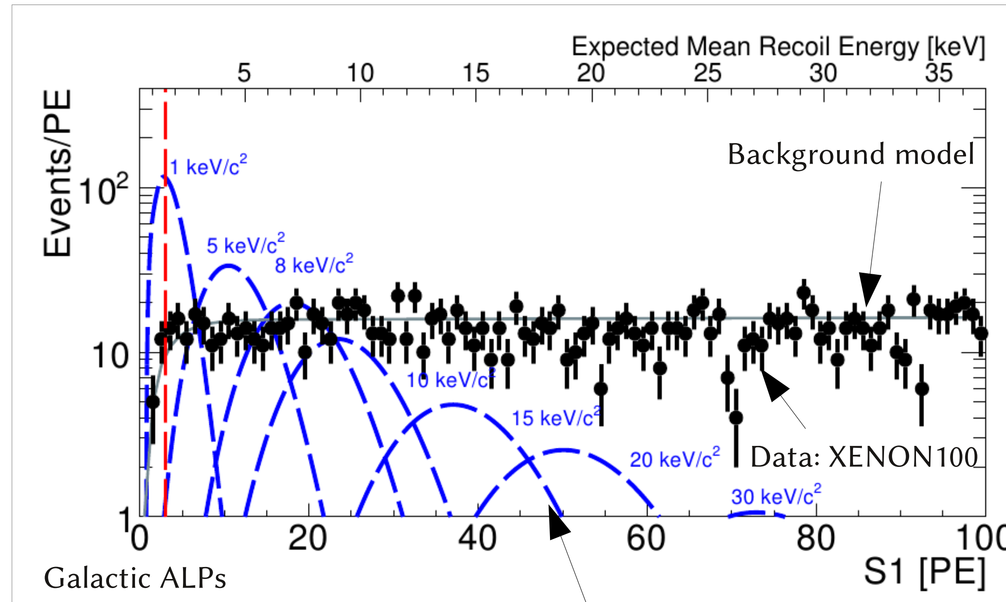
XENONnT

→ Future upgrade for XENON1T
→ Sensitive to a few $10^{-48} cm^2$

Backup: Axion Dark Matter

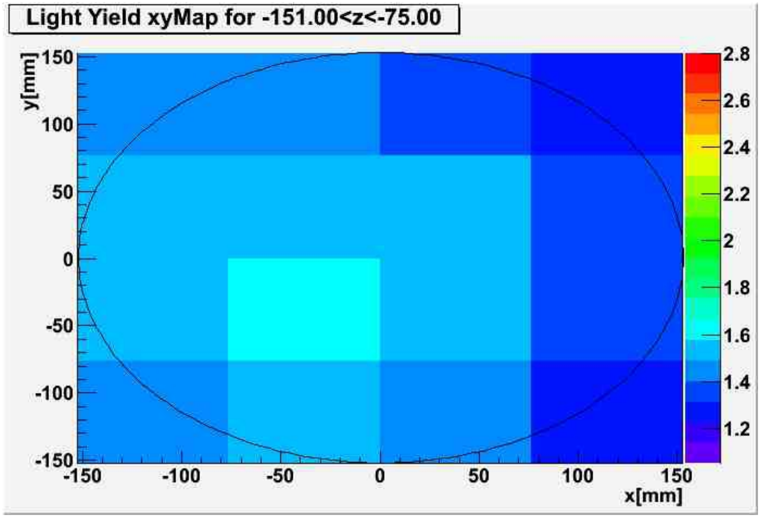
Event distributions: Solar axions & galactic ALPs



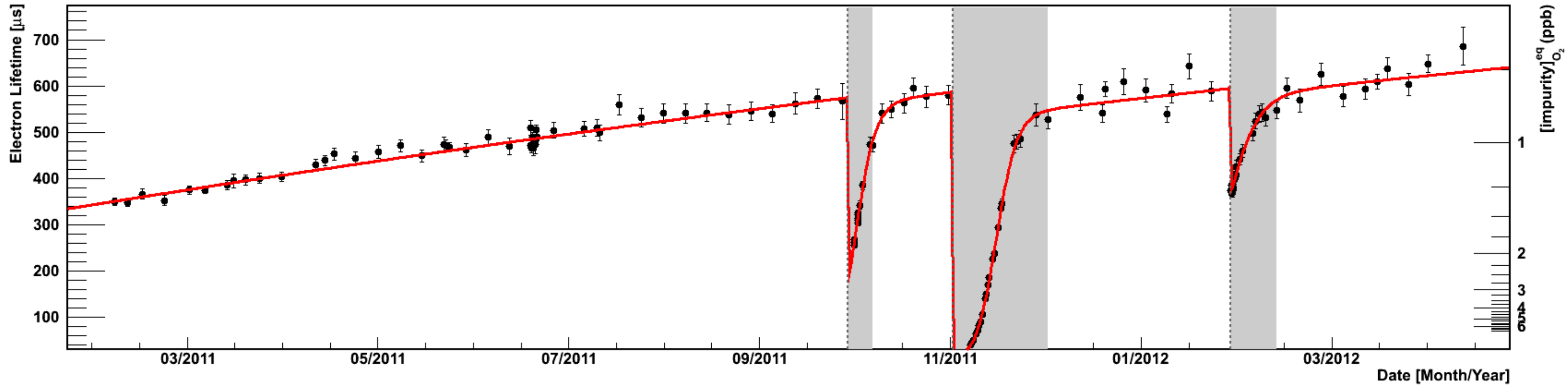


Expected signal of various ALP masses for $g_{Ae} = 4 \times 10^{-12}$

Backup: Correction



Example: Light yield map from 225 days of data ^{137}Cs



Electron life time of 225 days of data

Poisson distributed control measurements:

$$\mathcal{L}_2 = \prod_j^k Poiss(m_s^j|\epsilon_s^j M_s)$$

$$\mathcal{L}_2 = \prod_j^k Poiss(m_b^j|\epsilon_b^j M_b)$$

Backup: Profile Likelihood

Full Likelihood function[1)] for m_χ and σ_χ

$$\mathscr{L} = \mathscr{L}_1(\sigma, N_b, \epsilon_s, \epsilon_b, \mathcal{L}_{\rm eff}, v_{\rm esc}; m_\chi) \times \mathscr{L}_2(\epsilon_s) \times \mathscr{L}_3(\epsilon_b) \times \mathscr{L}_4(\mathcal{L}_{\rm eff})$$

XENON100 measurement   Additional uncertainties

Detailed view:

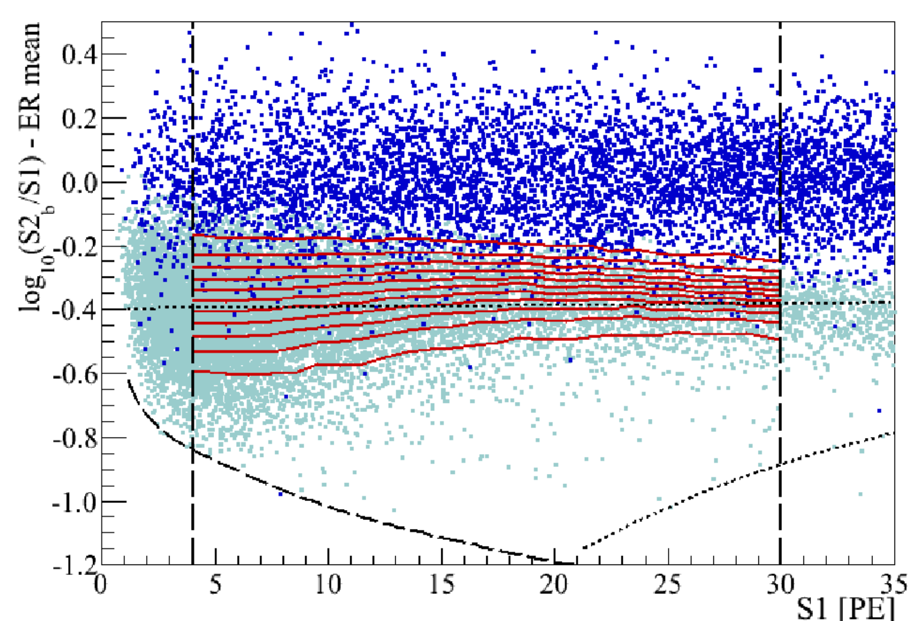
$$\mathcal{L}_1 = \prod_j^k Poiss(n^j|\epsilon_s^j N_s + \epsilon_b^j N_b) \times \prod_{i=1}^{n^j} \frac{\epsilon_s^j N_s f_s(S1_i) +_b^j N_b f_b(S1_i)}{\epsilon_s^j N_s +_b^j N_b}$$

- ϵ_b, ϵ_s – Probabilities to find an event
- N_b, N_s – Expected number signal/background events
- f_s – Normalized WIMP spectrum
- f_b – ER background spectrum (Observation + MonteCarlo)

Likelihood function over k-bands with n^j entries each

Single nuisance parameter t (normal distributed) to take uncertainty into account:

$$\mathcal{L}(L_{\rm eff}))_4 = e^{\frac{-(t-t_{\rm obs})^2}{2}}$$



Background with (k = 12) bands based on NR data

Backup: Water Cherenkov Muon Veto

– Status of the water tank –

- Water Tank construction finished
- Support building already constructed
- Increase reflectivity and wavelength shifting
    - Wavelength of interest: $\lambda < 380$nm
    - Foil inside the water tank
    - Cladding finished
- PMT installation finished
- Calibration of the PMTs in the Muon veto:
    - Diffuse light source → four diffuser balls
    - Diffuser ball tests finished

global

- Each single PMT is calibrated by a fibre

individual