RICAP-14
Roma International Conference on Astroparticle Physics

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INSTITUT DE FÍSICA CORPUSCULAR

UNIVERSITY of COIMBRA

XENON Dark Matter Project

Direct Dark Matter Search with XENON100

Sonja Orrigo

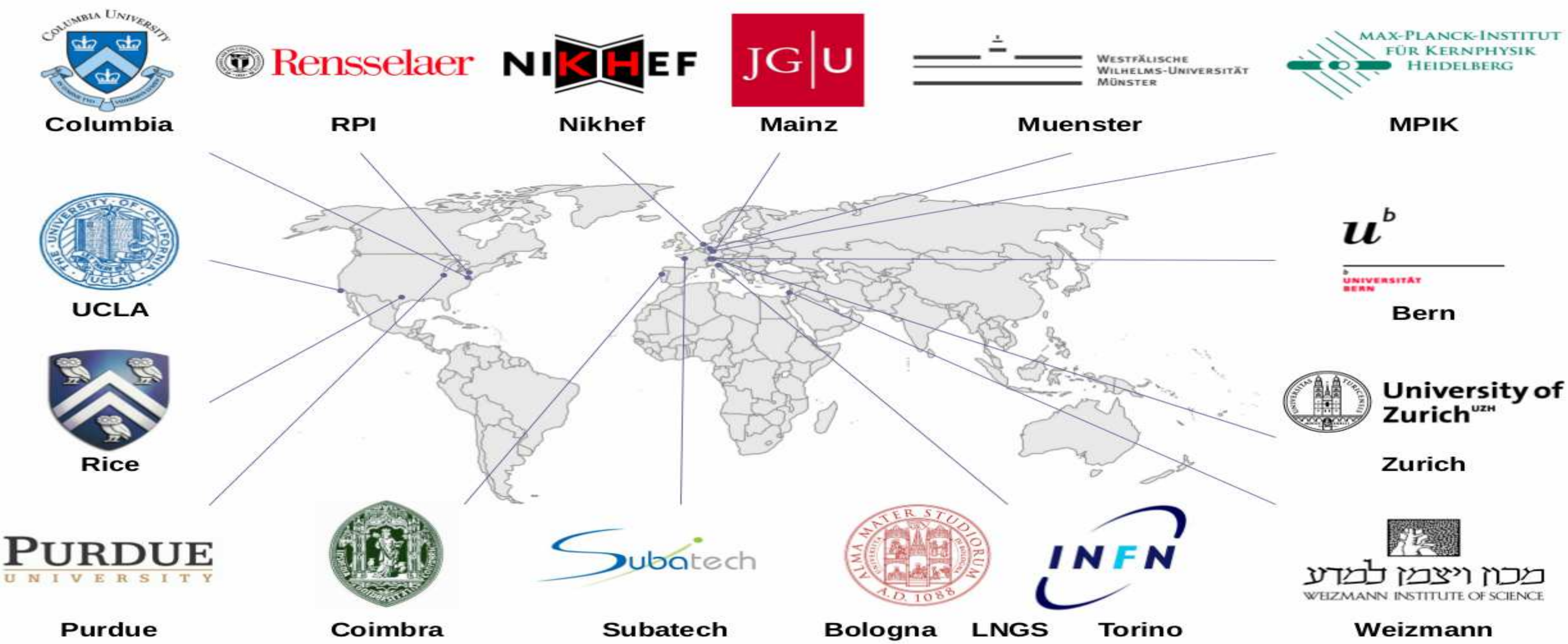
On Behalf of the XENON Collaboration

The XENON Collaboration

~ 110 scientists

from 16

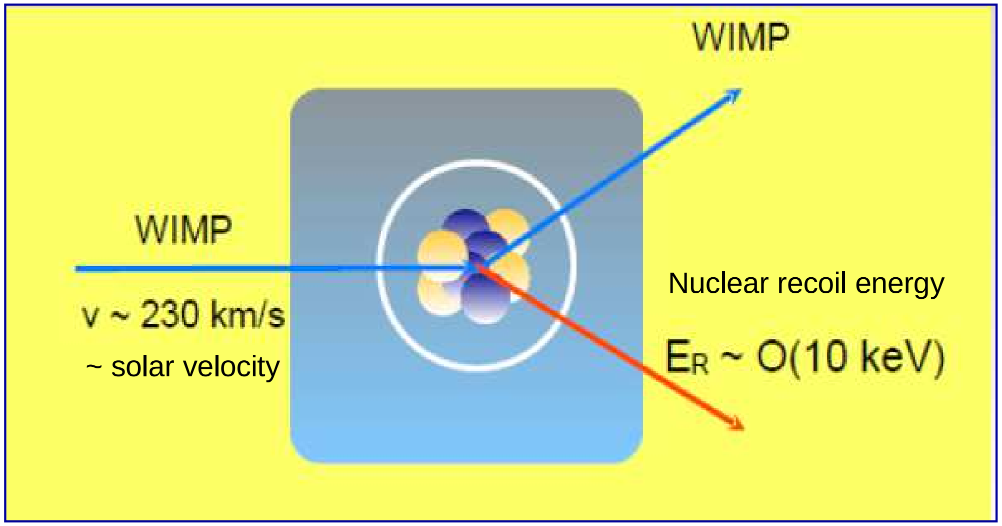
institutions



Direct Dark Matter Search

Elastic scattering WIMPs - target nuclei (Xe)

→ **low energy** nuclear recoils with **low rate**



Detector requirements

✓ Low rate signal → Ultra low background

✓ Low energy signal → Low energy threshold

✓ Small cross section → High target mass

Interaction

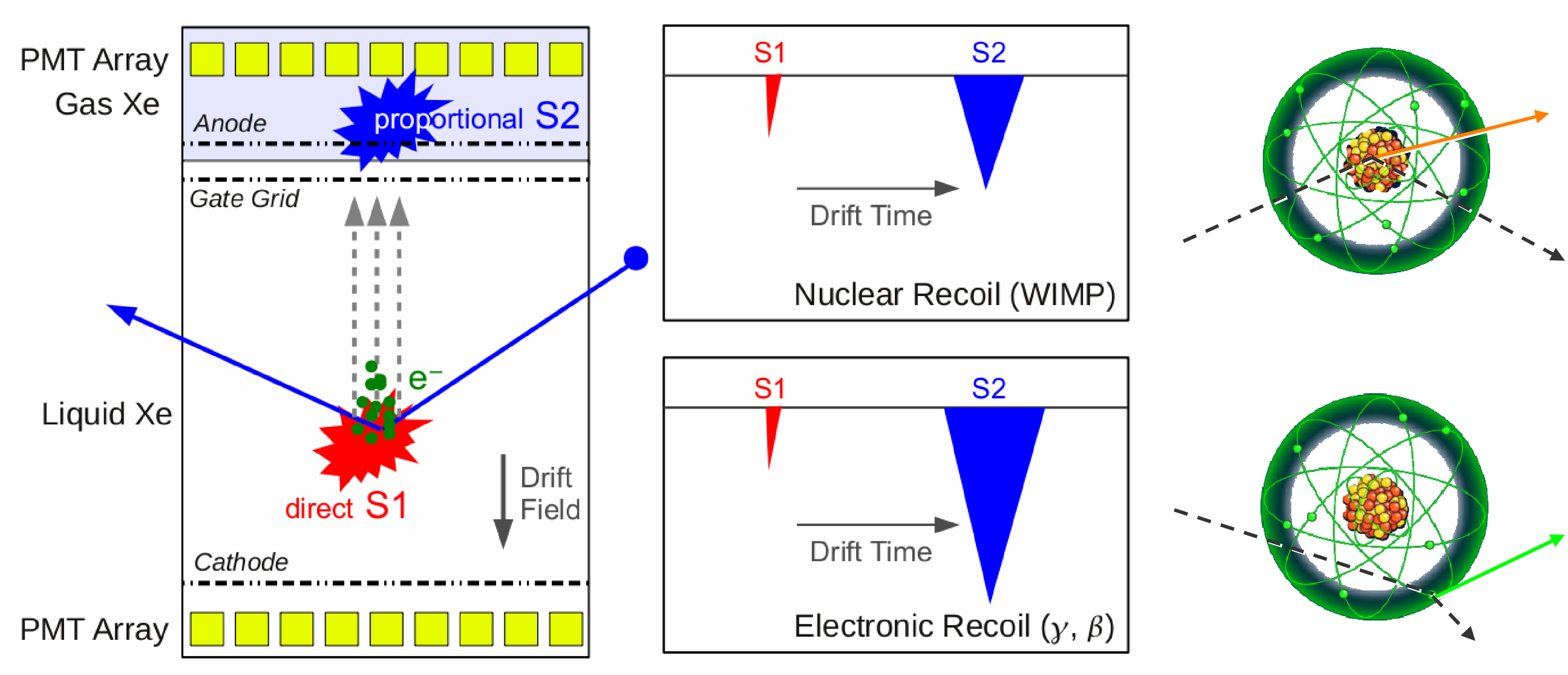
✓ **Spin Independent (SI)**

Possible with all nuclei

✓ **Spin Dependent (SD)**

Only possible with odd mass nuclei (^{129}Xe, ^{131}Xe) if the WIMP carries spin

Principle of two-phase TPC



✓ **Prompt scintillation signal (S1)**

Charges are extracted to GXe

✓ **Proportional scintillation signal (S2)**

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

Electron recombination is stronger for NR

→ $(S2/S1)_{WIMP} < (S2/S1)_{\gamma,\beta}$

→ ER - NR discrimination

ER = electronic recoil, NR = nuclear recoil

The phased XENON program

Past: 2005 - 2007

XENON10

15 cm drift TPC - 25 kg

σ_{SI} < 8.8 x 10^{-44} cm^2 (2007)

Present: 2008 - 2015

XENON100

30 cm drift TCP - 161 kg

σ_{SI} < 7.0 x 10^{-45} cm^2 (2011)

σ_{SI} < 2.0 x 10^{-45} cm^2 (2012)

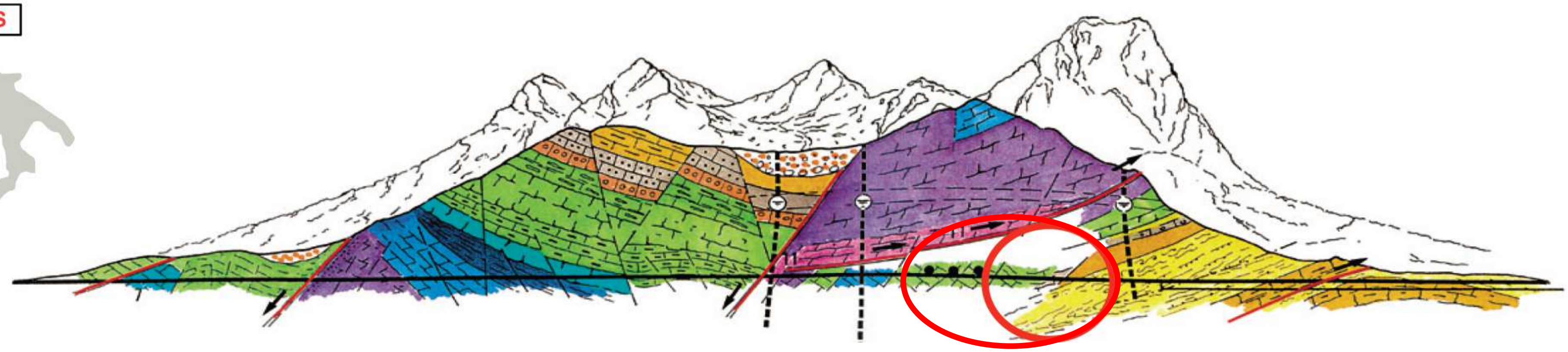
Future: 2012 – 2017 / 2022

XENON1T / nT

100 cm drift – 3300 / 7000 kg

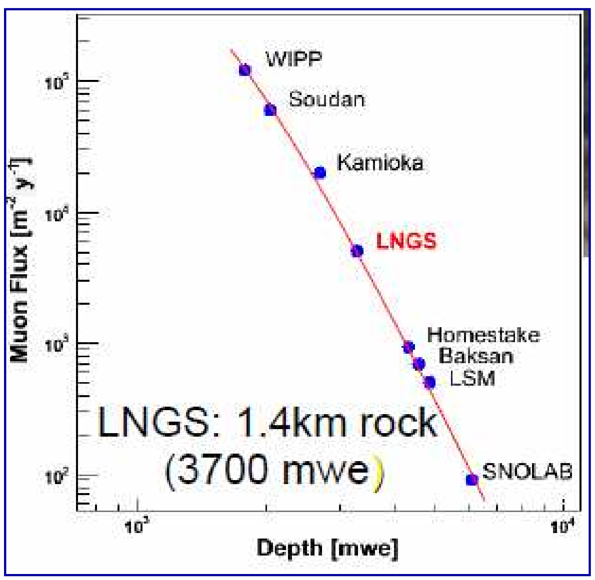
***proj.:* σ_{SI} ~ 2 x $10^{-47/48}$ cm^2**

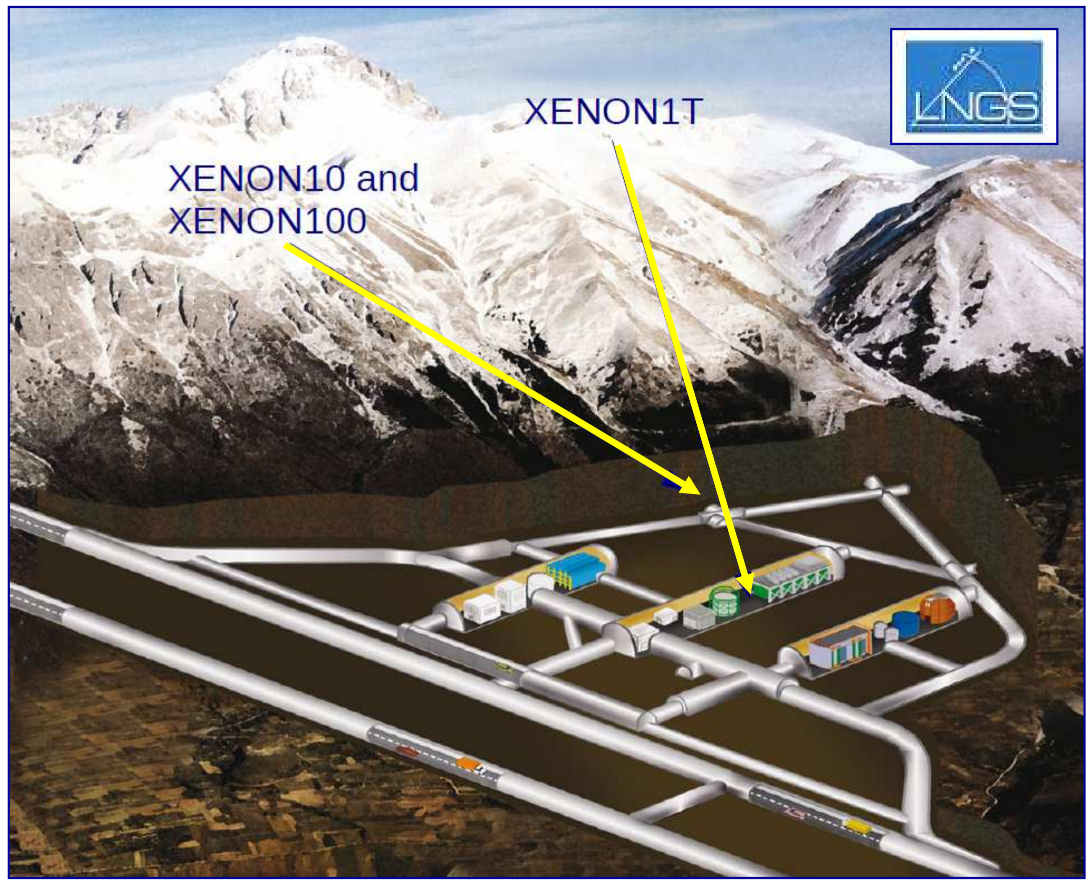
Location of the XENON Experiments



Laboratori Nazionali del Gran Sasso, Italy

1.4 km of rock → 3600 m.w.e. shielding from cosmic rays → factor 10^6 reduction of muon flux





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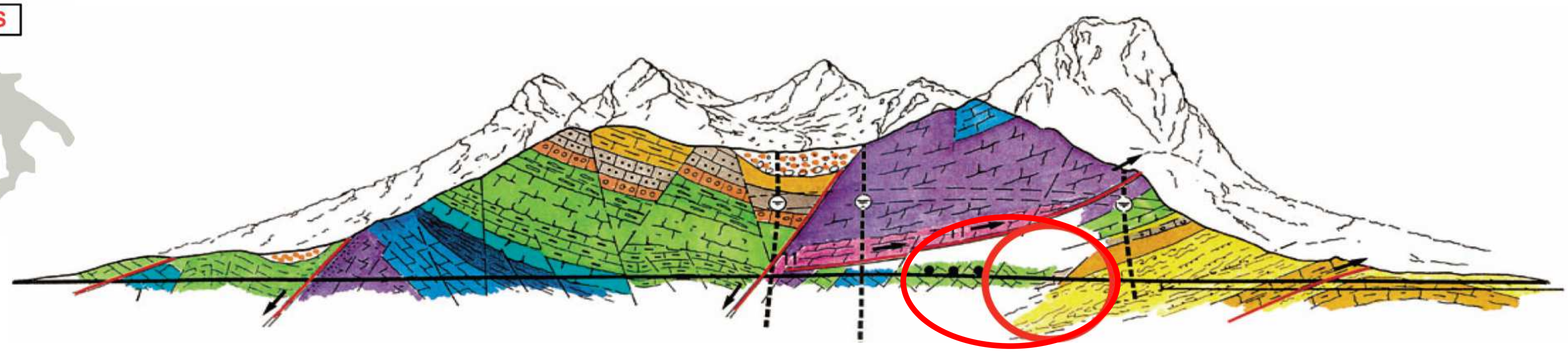

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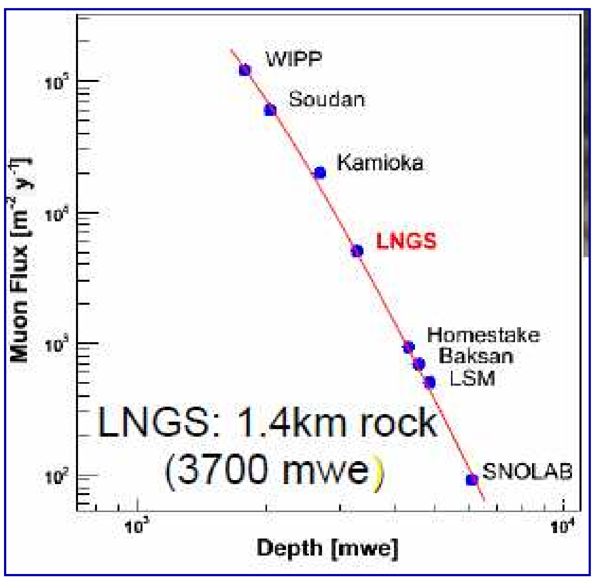
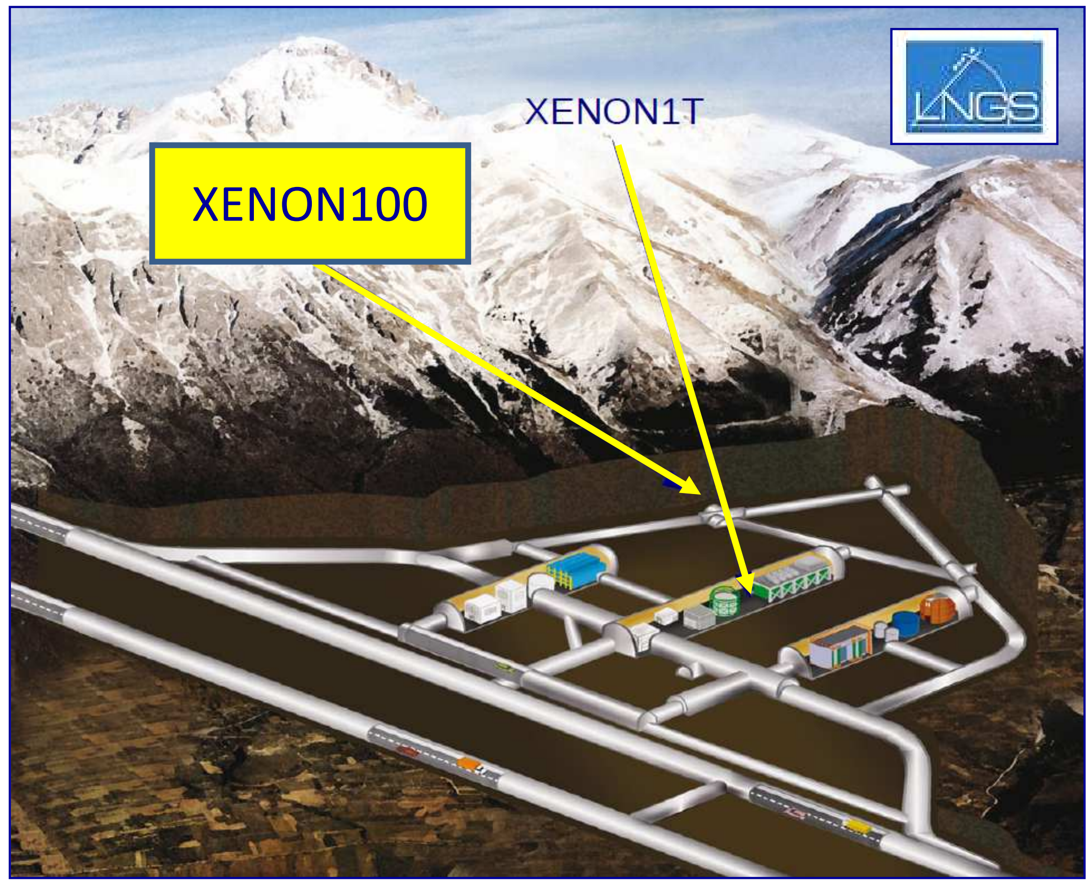


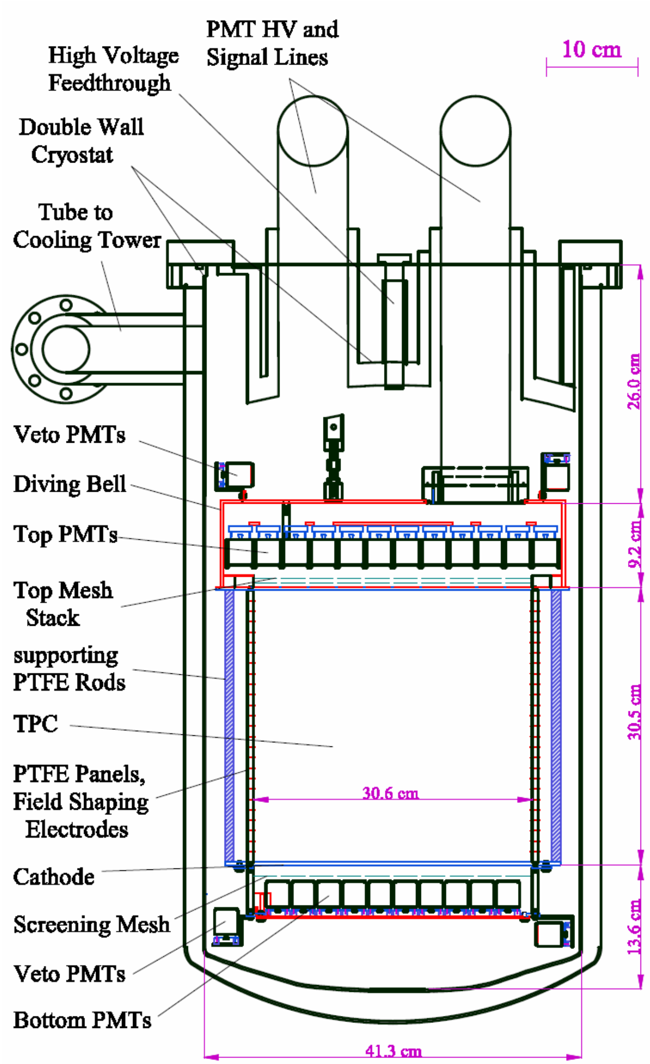


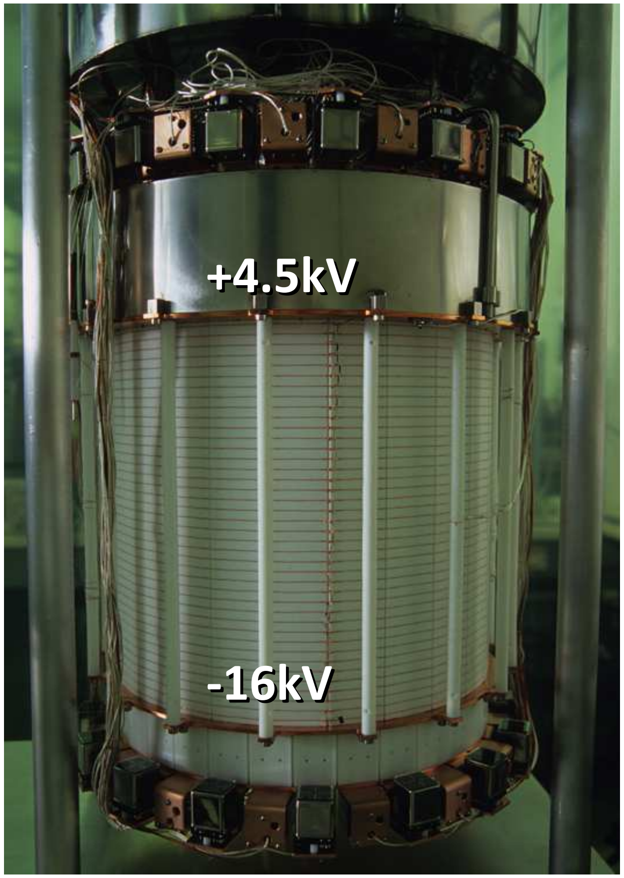
The XENON100 detector

- **161 kg LXe total mass**
  - ✓ Factor 10 more than XENON10
  - ✓ 62 kg sensitive volume
  - ✓ 99 kg active veto
  - ✓ 30 cm drift length x 30 cm diameter
- **Electric fields**
  - ✓ Drift = 0.53 kV/cm
  - ✓ Extraction = 12 kV/cm
  - ✓ 100% electron extraction to GXe
- **PTFE structure** (12 kg)
  Good UV reflector and insulator
- **Extremely low background**
  - ✓ Factor 100 lower than XENON10
  - ✓ Material screening and selection
  - ✓ Detector design
  - ✓ Active/passive shielding

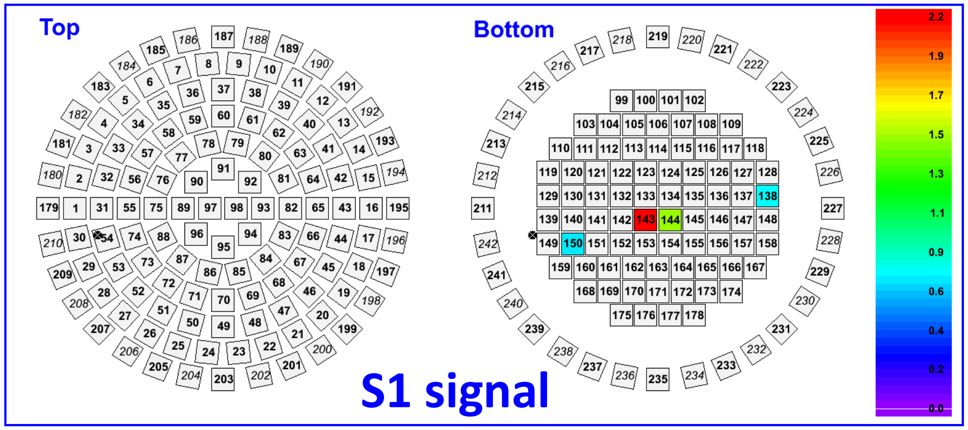
E. Aprile et al. (XENON100), Astroparticle Physics 35, 573 (2012)

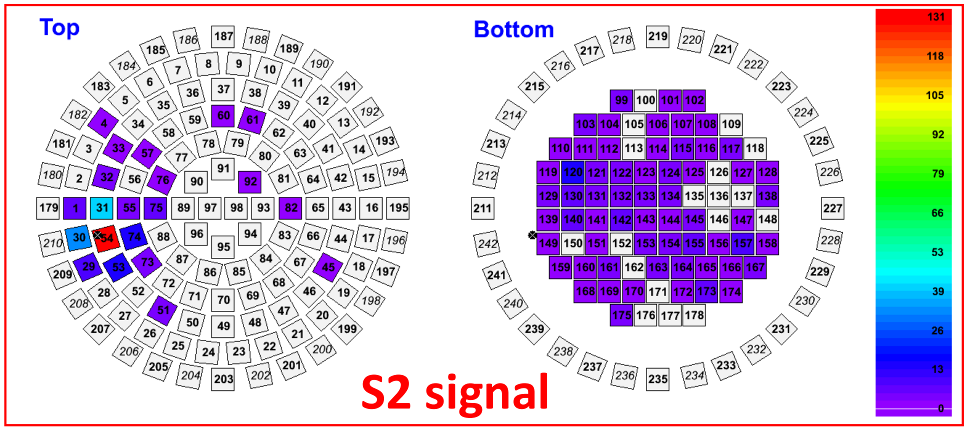
- **Cryostat**
  - ✓ Double-walled (1.5 mm thick) low radioactivity stainless steel (tot. 70 kg)

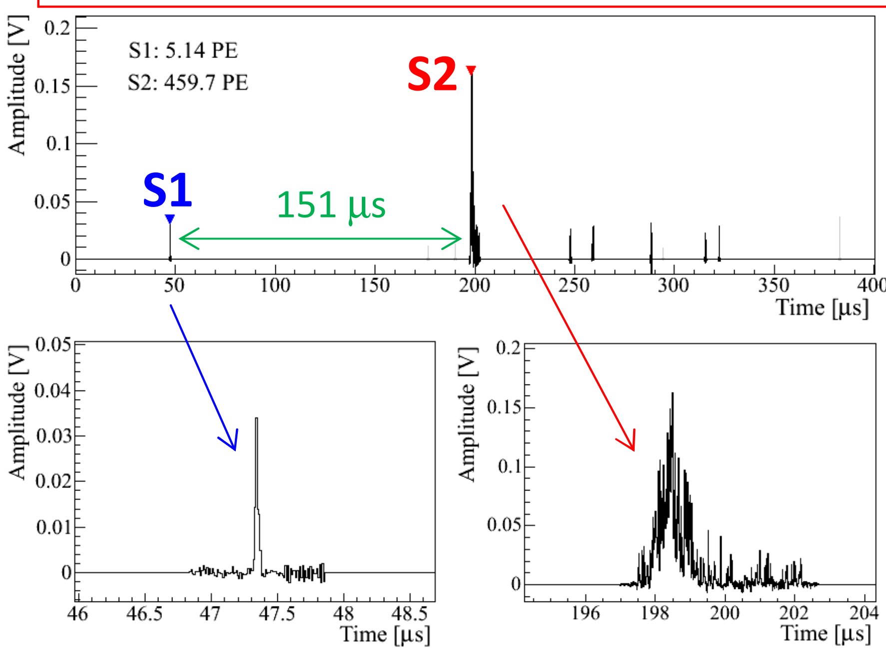


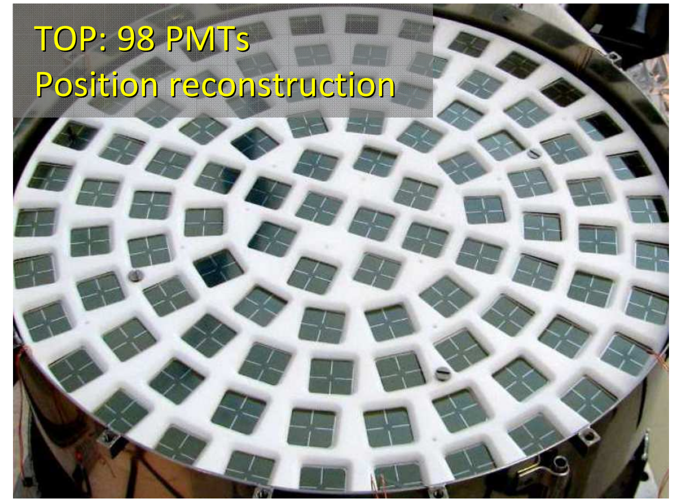


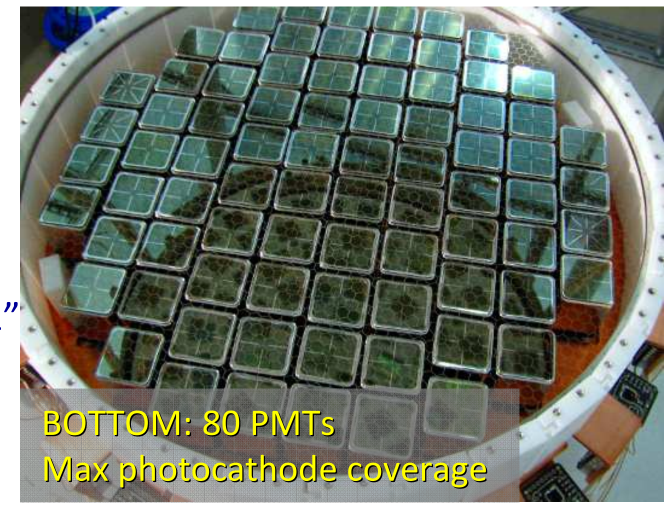
The XENON100 PMTs

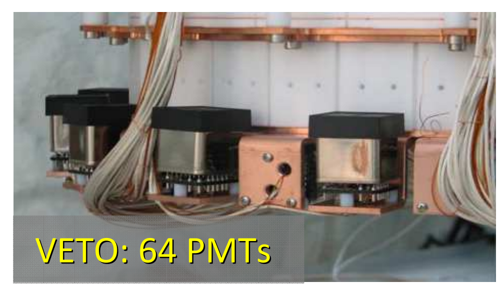












- **PMTs: 242 low intrinsic radioactivity** (<10 mBq/PMT)

  Hamamatsu R8520-06-Al 1”x1”

  ✓ QE > 30% @178nm

- **3D event localization**

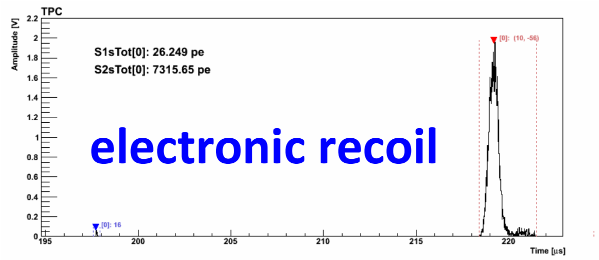
  X,Y res. 3 mm

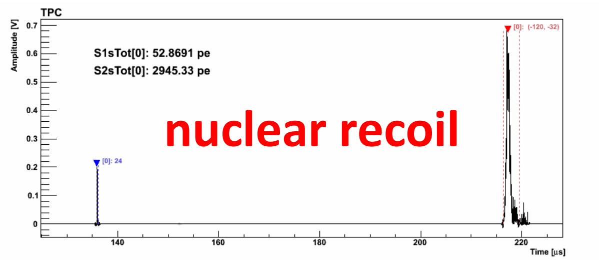
  Z res. 0.3 mm, sep. 3 mm

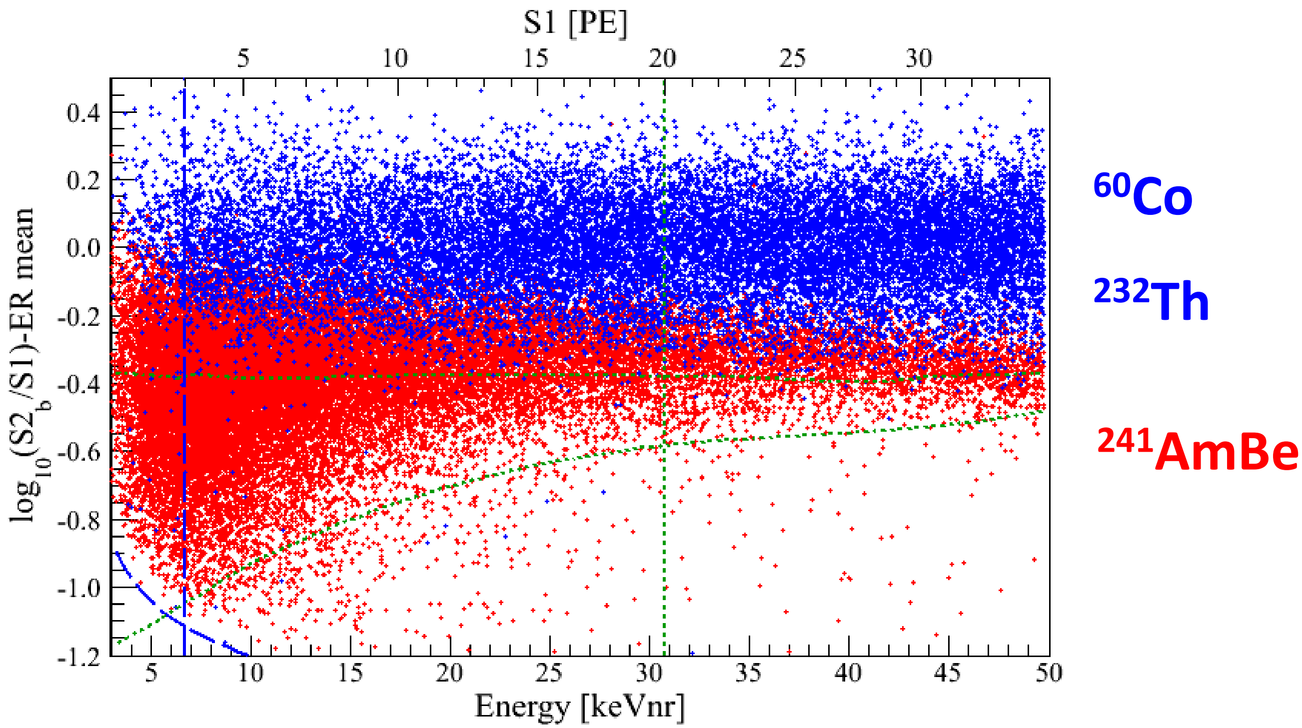
- **Active Veto** for BG reduction

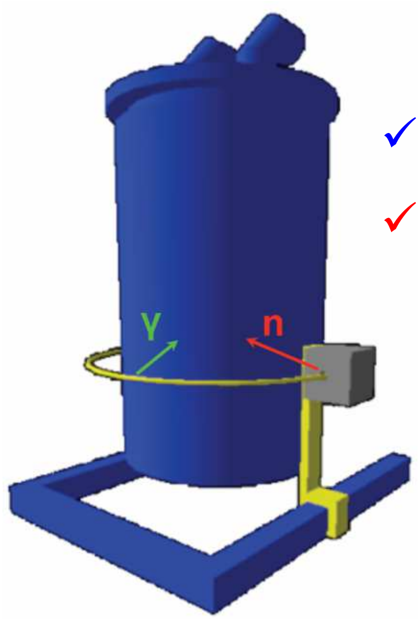
E. Aprile et al. (XENON100), Astroparticle Physics 35, 573 (2012)

ER / NR discrimination and calibrations







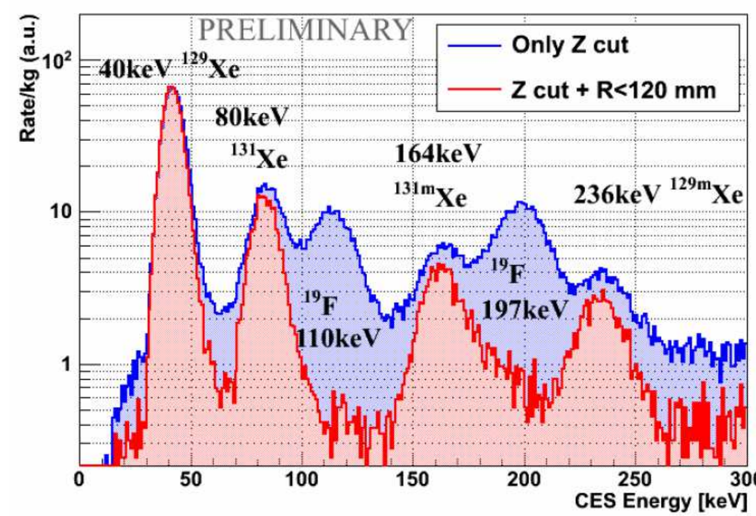


- ✓ **ER band** calibrated with **^{60}Co & ^{232}Th** sources
- ✓ **NR band** calibrated with **^{241}AmBe** source

$$(S2/S1)_{NR} < (S2/S1)_{ER}$$

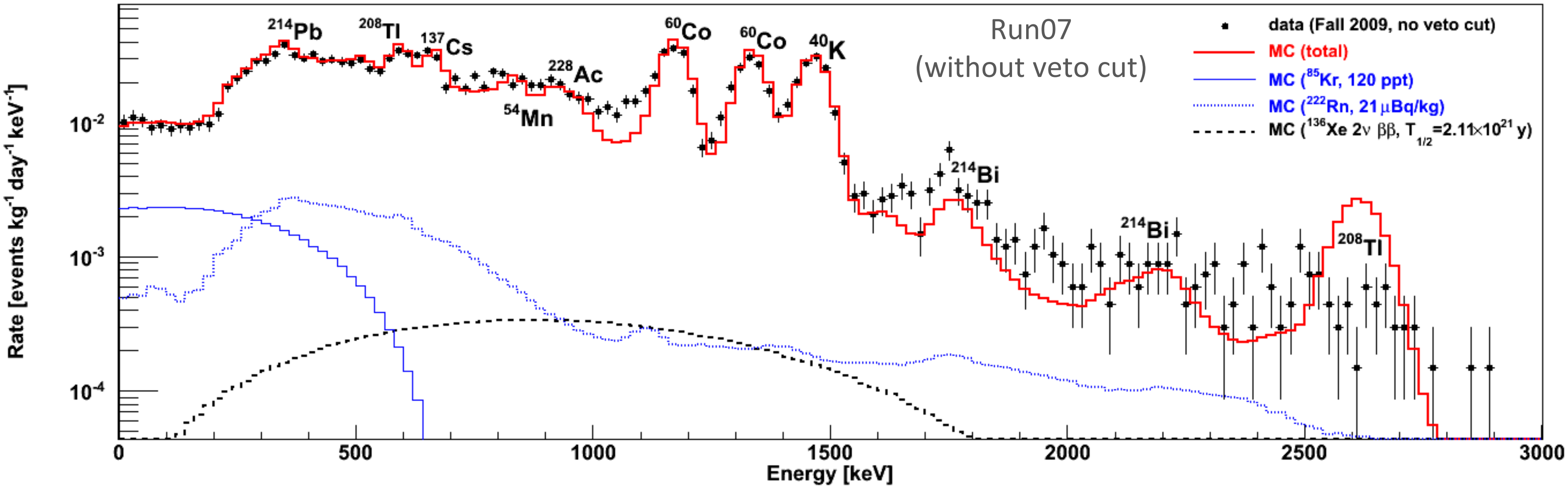
E. Aprile et al. (XENON100), Astroparticle Physics 54, 11 (2014)

ER lines during neutron calibration



Electromagnetic background in XENON100

E. Aprile et al. (XENON100), Phys. Rev. D 83, 082001 (2011)



- **ER background: excellent agreement between MC simulations and measured data in the full energy range**
  - ✓ Activity taken from screening measurements only
  - ✓ No MC rate tuning!
- **Measured single scatter rate below 100keV**

✓Before LXe veto cut: ~ 10^{-2} evts/kg/keV/day

✓After LXe veto cut: **5 x 10^{-3} evts/kg/keV/day**

→ Factor 100 lower BG than XENON10 with factor 10 more mass

Blind data analysis

Blind analysis (data is blinded between 2 - 100 PE)

✓ The analysis (data quality and topology selection) is defined on calibration data (^{241}AmBe, ^{232}Th , ^{60}Co, BG outside ROI)

Detector stability

✓ Selection of periods with stable HV, low Rn level, stable thermodynamics of the detector (P, T, …)

(1)

Selection of physical interactions

✓ Reject noise, stability of PMTs, S1 seen by at least 2 PMTs

Selection of single scatters (WIMPs make a single interaction)

✓ Only one S2 peak, only one S1 peak, active veto cut

Consistency Cuts

✓ S1 and S2 PMT hit patterns and S2 pulse width consistent with a single interaction vertex at the reconstructed position

Fiducialization

✓ 34 kg elliptic volume

(2)

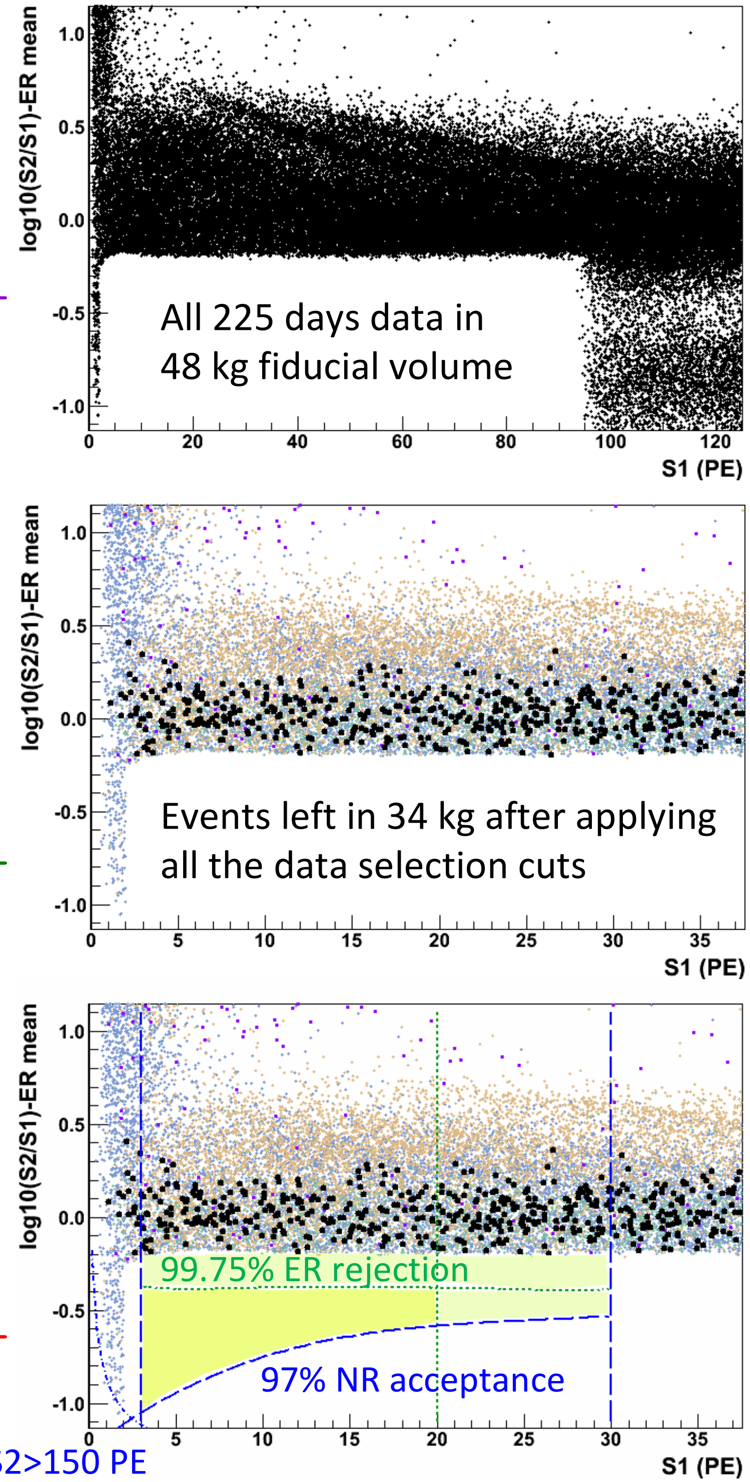
Definition of WIMP search region (ROI)

✓ (3<S1<20 or 30) PE, 97% NR acceptance, 99.75% ER rejection

✓ Trigger threshold S2 > 150 PE is irrelevant for this analysis

(3)

E. Aprile et al. (XENON100), Astroparticle Physics 54, 11 (2014)



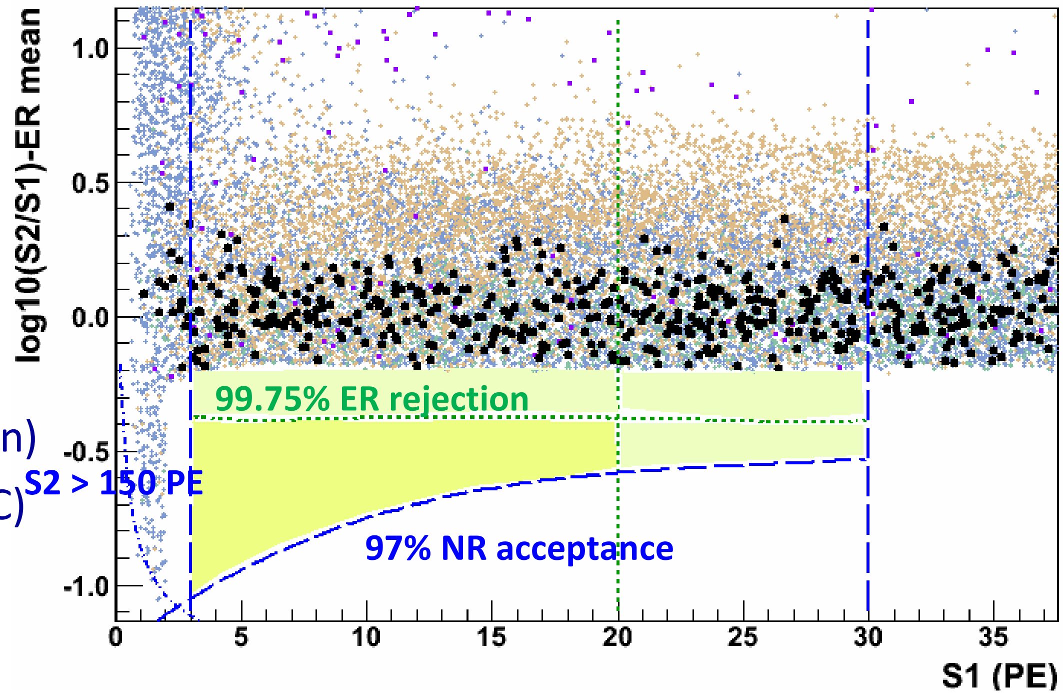
Unblinding 225 days of XENON100 data

- **XENON100 Run10**
  - ✓ 224.6 live days of data
  - ✓ 34 kg fiducial volume
  - ✓ Data blinded in WIMP ROI

- **Background expectation**

(1.0 ± 0.2) event in 224.6 days

- ✓Expected **ER** leakages = **0.79 ± 0.16** (by calibration)
- ✓ **NR** background prediction = $\mathbf{0.17^{+0.12}_{-0.07}}$ (by MC)
- ✓ Verified on the high energy sideband



E. Aprile et al. (XENON100), Phys. Rev. Lett. 109, 181301 (2012)

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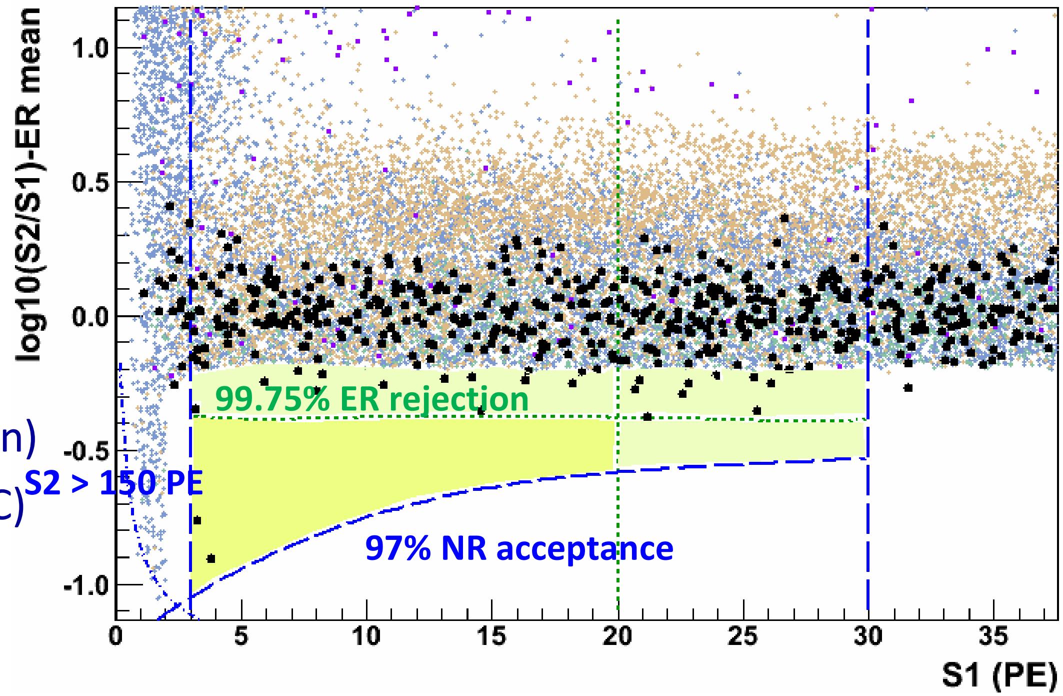
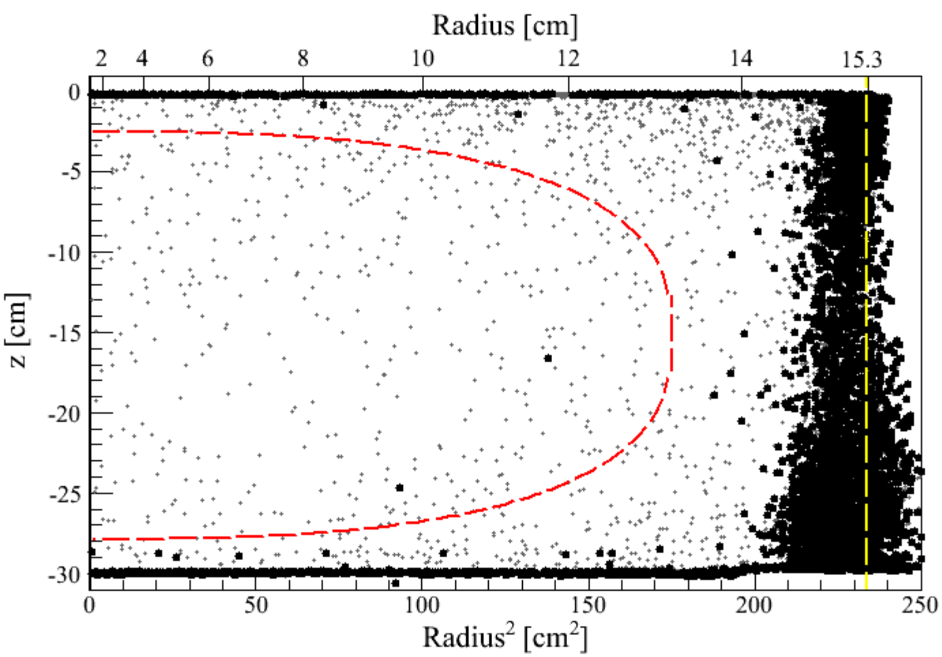




- **After unblinding: 2 WIMP-like candidates** inside the predefined ROI & 34 kg fiducial volume @ 3.3 and 3.8 PE

  (1) 26.4% Poisson probability that background oscillated to 2 events

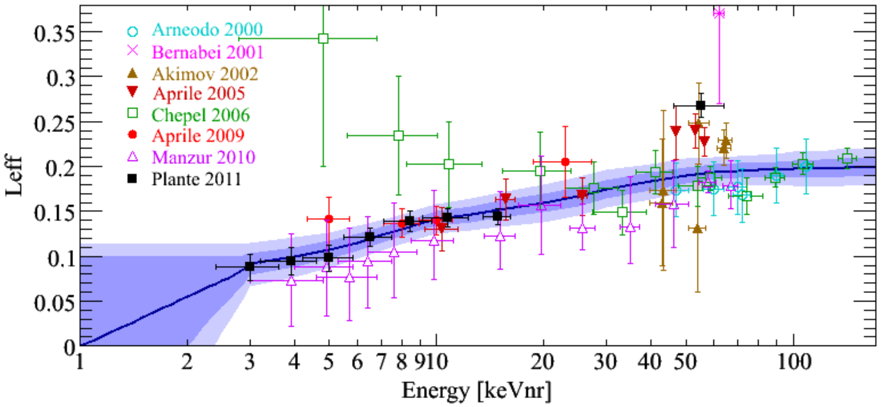
  (2) Profile Likelihood analysis does not reject the background only hypothesis

  → **No evidence of dark matter in the data**

  → Calculate upper limit

E. Aprile et al. (XENON100), Phys. Rev. Lett. 109, 181301 (2012)

Spin-Independent Results



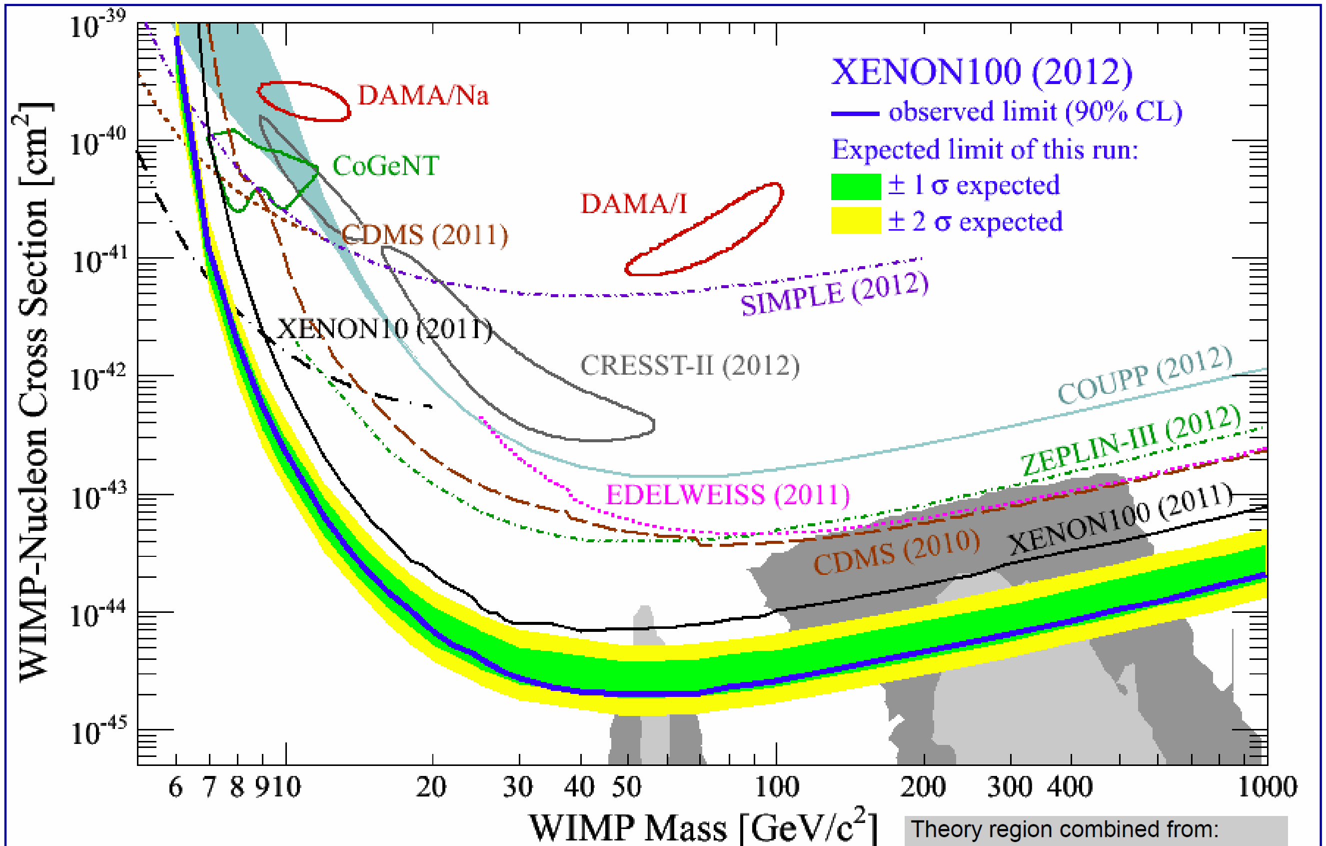
- ✓ L_{eff} global fit of available data, including new data (G. Plante et al., Phys. Rev. C 84, 045805 (2011))
- ✓ Blue band represents uncertainties
- ✓ Logarithmic extrapolation below 3 keV_{nr} to L_{eff} = 0 at 1 keV_{nr} (including large uncertainty)

v_0 = 220 km/s v_{esc} = 544 km/s ρ_0 = 0.3 GeV/cm^3

- **The limit on SI WIMP-nucleon elastic scattering cross section** is extracted by **Likelihood analysis**
- XENON100 established for years the **World's most sensitive limit** over a large WIMP mass range

  $\sigma < 2.0 \times 10^{-45}$ cm^2

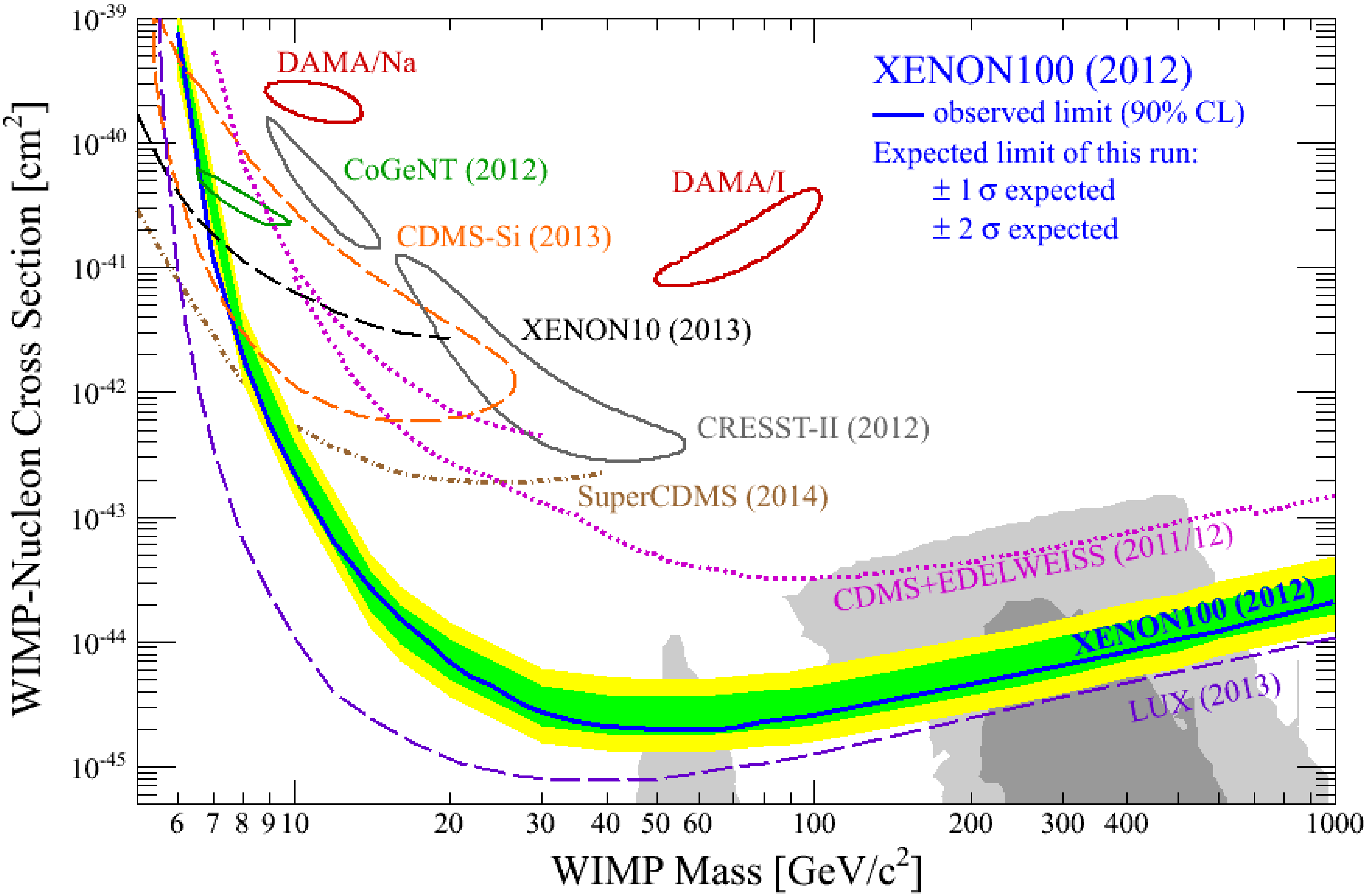
  for a 55 GeV/c^2 WIMP at 90% c.l.
- **It excludes** signal indications from other DM experiments



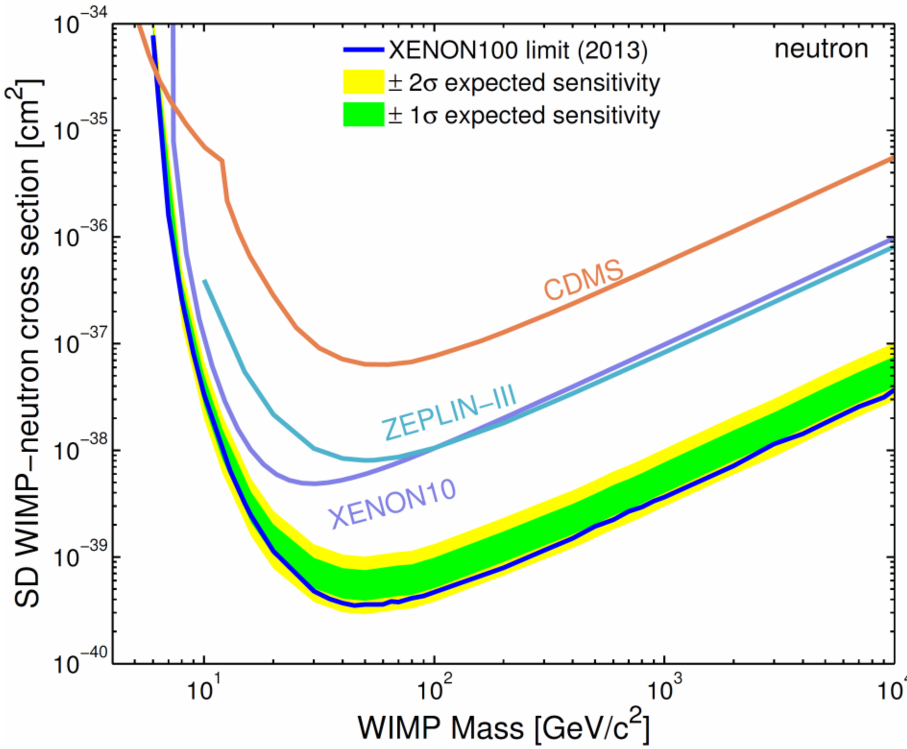
Theory region combined from:
Strege et al., JCAP 1203, 030(2012)
Fowlie et al., arXiv:1206.0264
Buchmueller et al., arXiv:1112.3564

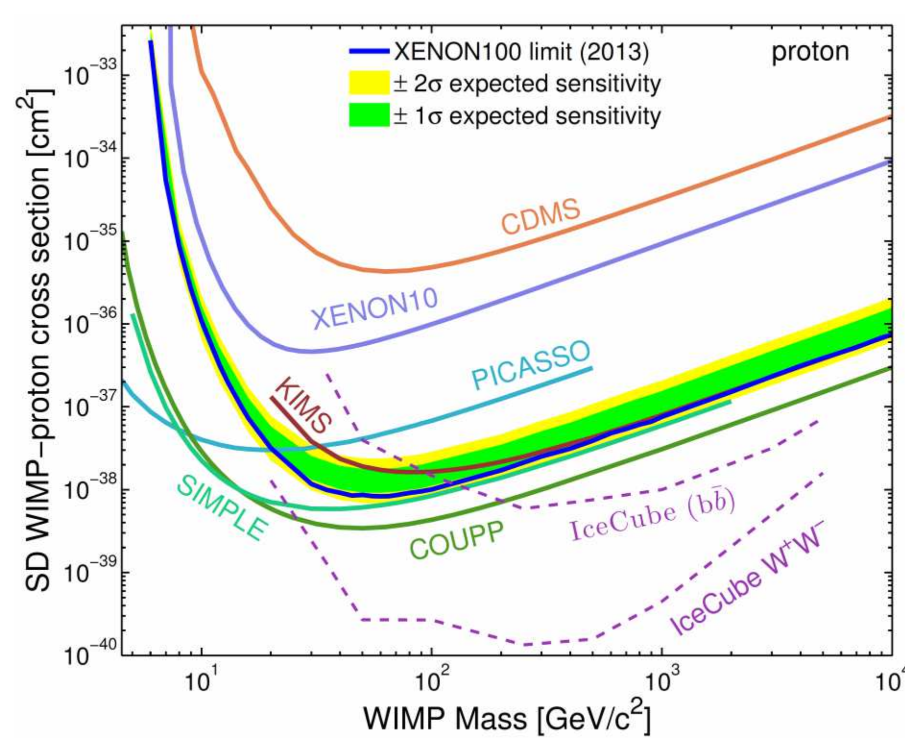
E. Aprile et al. (XENON100), Phys. Rev. Lett. 109, 181301 (2012)

Summary Spin-Independent Results (2014)



Spin-Dependent Results





- **Isotopes with a non-zero nuclear spin: 26.2% of ^{129}Xe ($J^{\pi} = 1/2^{+}$) and 21.8% of ^{131}Xe ($J^{\pi} = 3/2^{+}$)**
- **Set limit on pure WIMP-neutron and pure WIMP-proton cross sections**

✓ Same data and event selection as the SI search: 224.6 live days x 34 kg of exposure

✓ Nuclear model used: *Menendez et al.*, Phys. Rev. D86, 103511 (2012)

(1) Most sensitive limit on pure neutron coupling above 6 GeV/c^2

$\sigma_n < 3.5 \times 10^{-40}$ cm^2 for a 45 GeV/c^2 WIMP at 90% c.l.

(2) Competitive limit on pure proton coupling

weaker sensitivity because ^{129}Xe & ^{131}Xe have an unpaired neutron but even number of protons

E. Aprile et al. (XENON100), Phys. Rev. Lett. 111, 021301 (2013)

Control of systematics: NR response

- **Verification of the Nuclear Recoil energy scale**

✓ XENON100 NR energy scale includes all the measurements of direct neutron scattering experiments

- **Monte Carlo simulation of AmBe neutron source**

✓ Source strength measurement (PTB, Germany): **(160 ± 4) n/s**

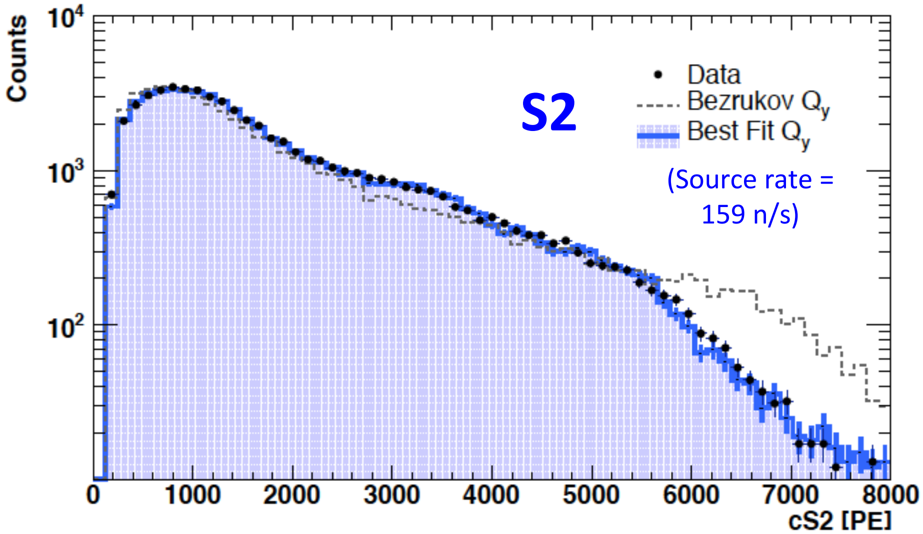
✓ Input AmBe spectrum (ISO 8529-1 standard). Analysis robust against variations of this spectrum

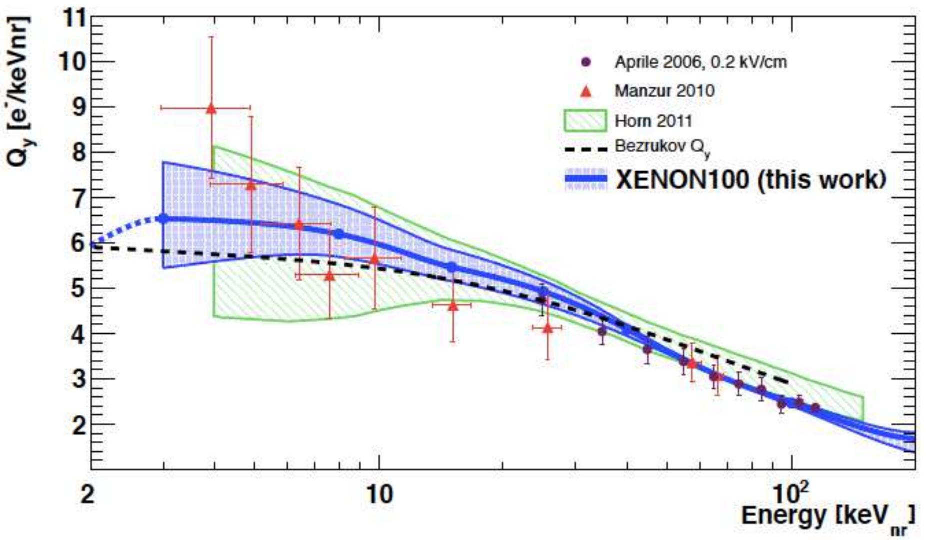
✓ Complete MC description of the detector including detector shield (water, lead, polyethylene, copper)

✓Simulation of both **scintillation (S1)** and **ionization (S2)** signals

✓**E_{dep} is converted to S1 and S2** using L_{eff} and Q_y including thresholds, resolutions and acceptances from data

Step 1: using L_{eff} from direct measurements → reproduce S2 spectrum → obtain optimum Q_y

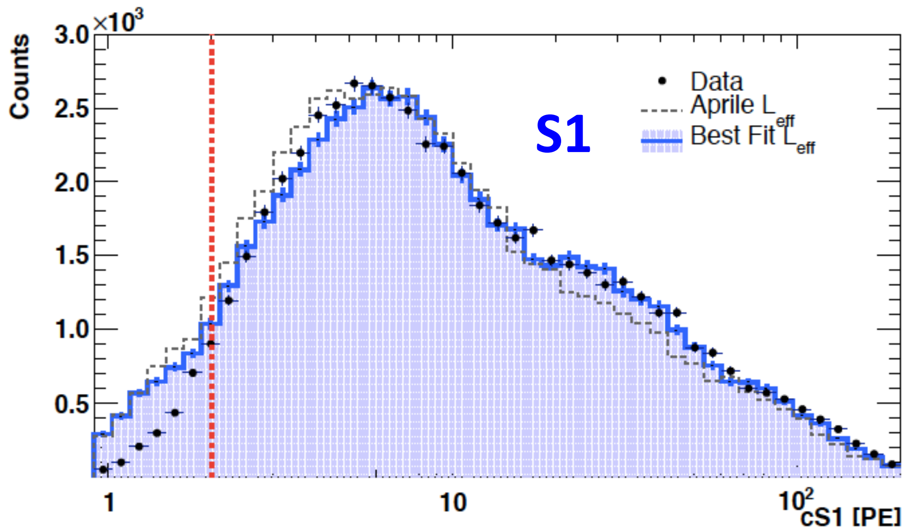


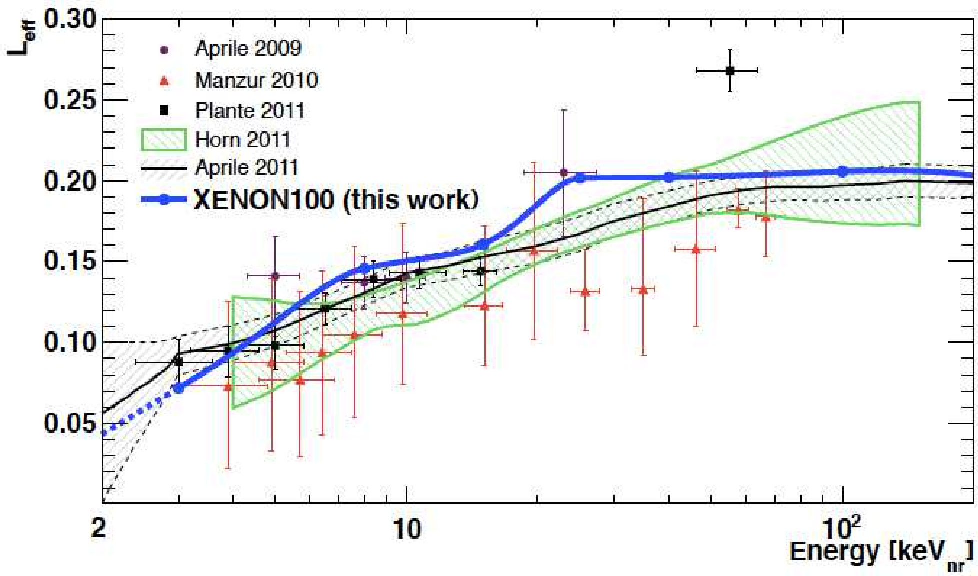


E. Aprile et al. (XENON100), Phys. Rev. D 88, 012006 (2013)

Control of systematics: NR response

Step 2: using the obtained Q_y → reproduce S1 spectrum → obtain a new L_{eff}





- **Excellent agreement over the whole spectrum down to 2 PE (~ 5 keV_{nr})**
- ✓ Poor agreement below 2 PE due to larger uncertainties on efficiencies
- **L_{eff} from best fit matches perfectly to the previous measurements**
- ✓ Consistency strengthens the reliability of analysis

  → **Results of XENON100 remain unchanged using this L_{eff}**

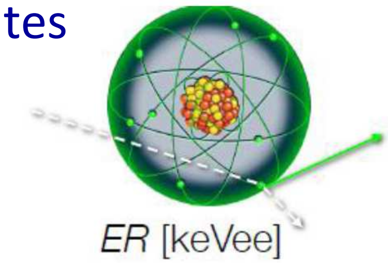
  → **Excellent understanding of the detector response to NRs at % level**

E. Aprile et al. (XENON100), Phys. Rev. D 88, 012006 (2013)

Axion searches in XENON100

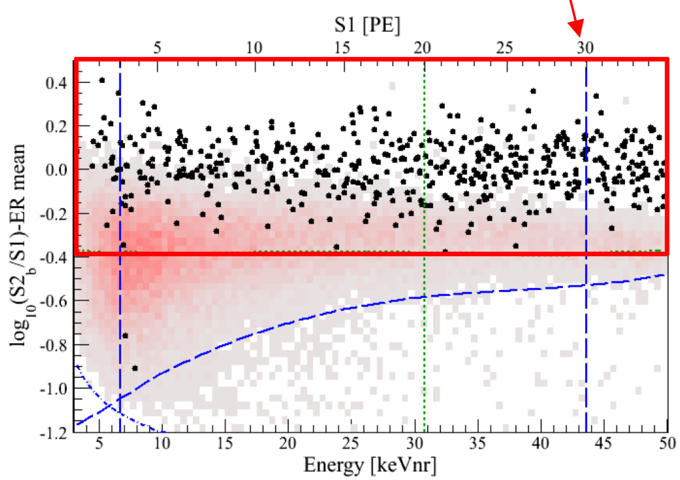
✓ QCD axions and axionlike particles ALPs are light cold DM candidates

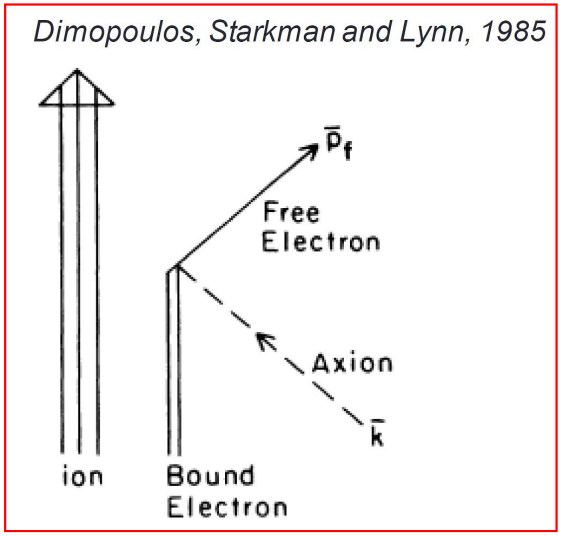
✓ They can couple to photons ($g_{A\gamma}$), electrons (g_{Ae}) and nuclei (g_{AN})



✓ The g_{Ae} coupling can be tested through the **axio-electric effect**: an axion ionize a Xe atom (as a photoelectric process but with an axion absorbed instead of a photon)

✓ Different energy scale: **ER scale**

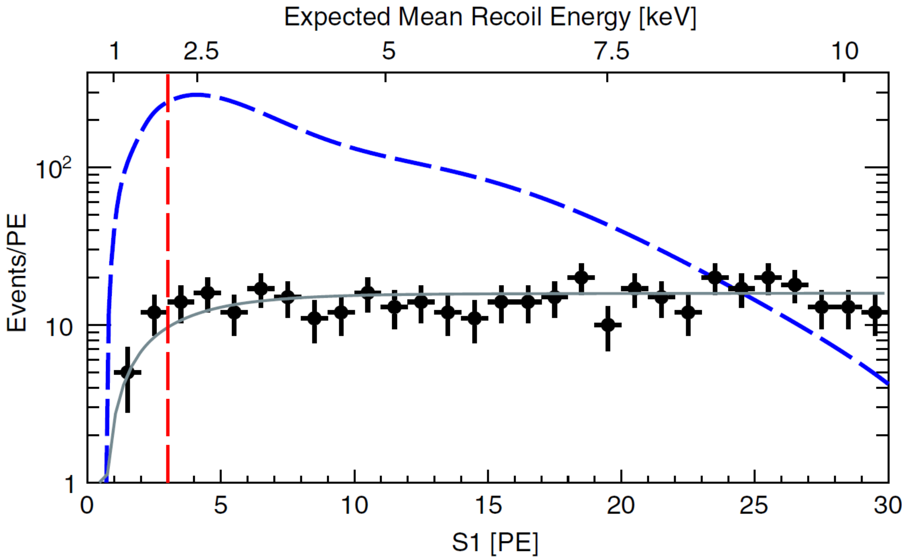




- **Solar axions:** Sun postulated to be a source of axions
- **Galactic axionlike particles:** ALPs in the keV range are potential DM candidates

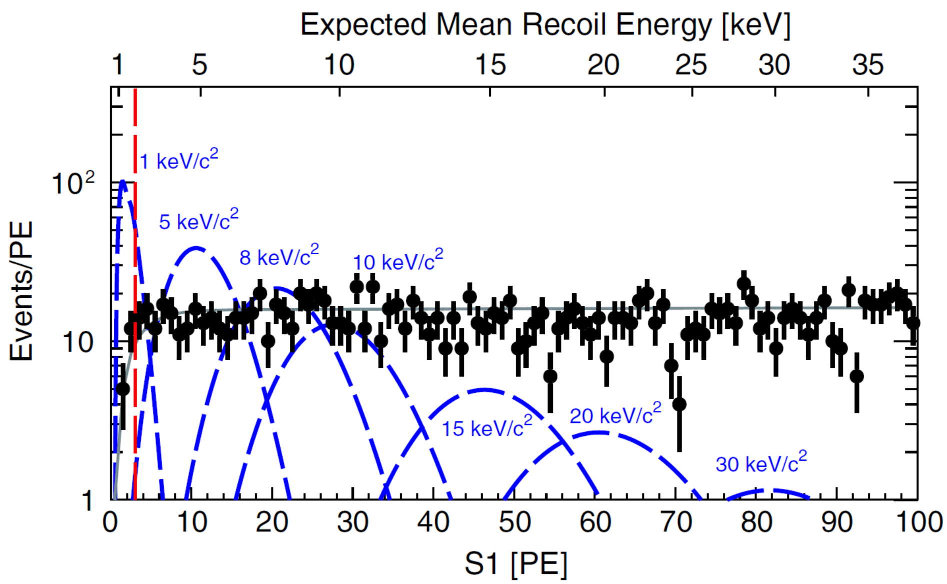
Axion Searches Results from XENON100

Solar axions (3-30 PE)



- ✓ Blue: expected signal for solar axions with $m_A < 1$ keV/c^2 for previously existing upper limit (EDELWEISS-II)
- ✓ Continuum spectrum

Galactic ALPs (3-100 PE)



- ✓ Expected event distribution for galactic ALPs with $g_{Ae} = 4 \times 10^{-12}$
- ✓ Monoenergetic signal is given by the energy resolution of the detector at the relevant S1

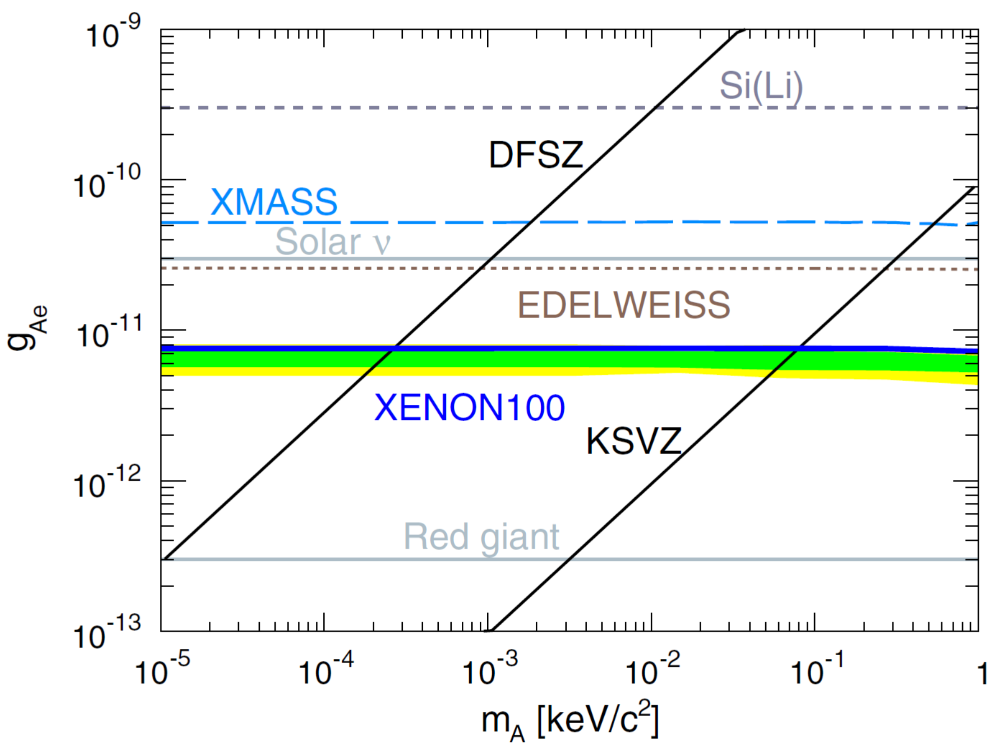
In both cases, the data is compatible with the background only hypothesis

E. Aprile et al. (XENON100), Phys. Rev. D 90, 062009 (2014)

First Axion Results from XENON100

- ✓ New leading limits on solar axions and ALPs
- ✓ First axion result from dual-phase TPC
- ✓ The very low background and threshold of XENON100 are crucial for these analyses

Solar axions

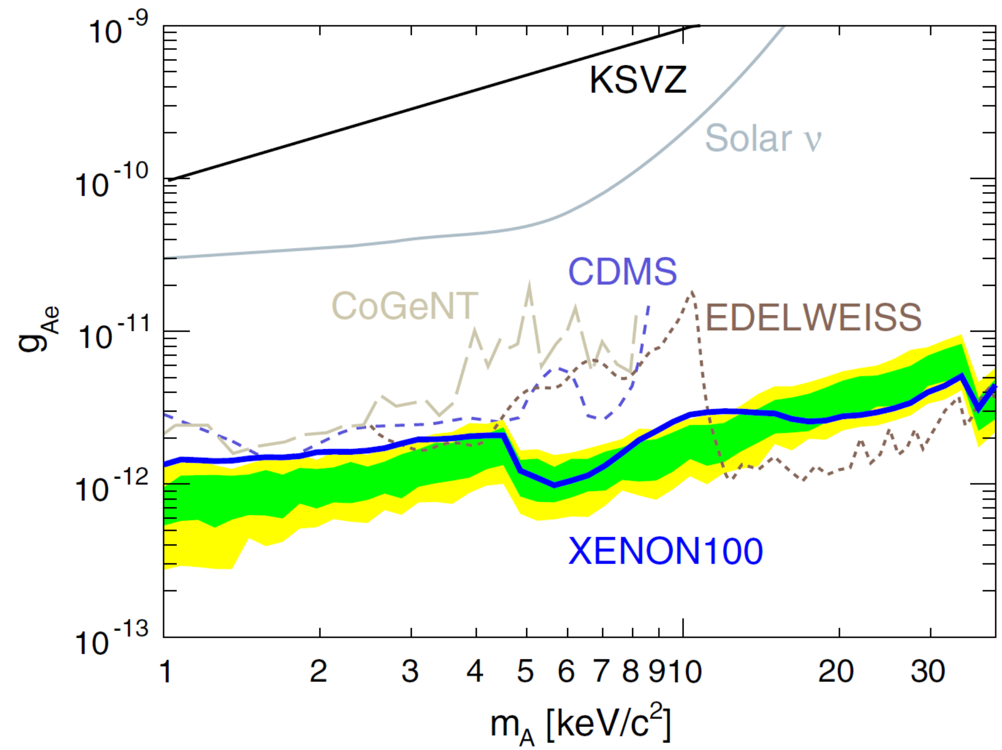


g_{Ae} < 7.7 x 10^{-12} at 90% c.l.

m_A < 0.3 eV (DFSZ model)

m_A < 800 eV (KSVZ model)

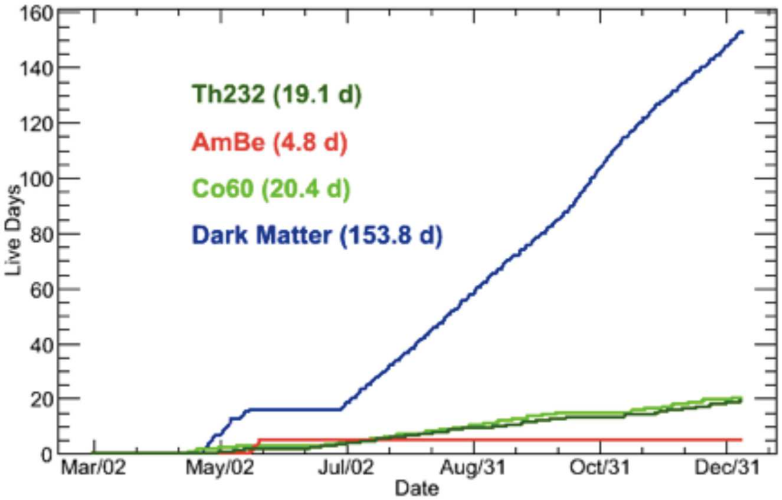
Galactic ALPs



g_{Ae} < 1 x 10^{-12} at 90% c.l.

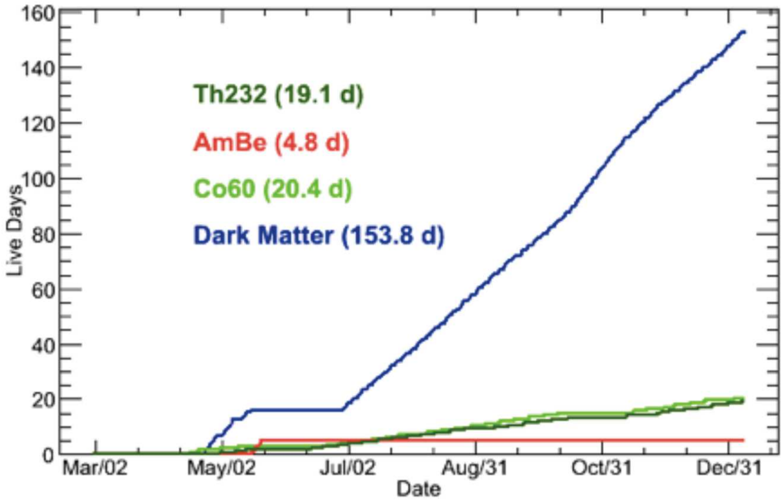
for masses 5-10 keV/c^2

E. Aprile et al. (XENON100), Phys. Rev. D 90, 062009 (2014)



XENON100: future goals

- **Ongoing physics analyses**
  - ✓ Search for annual modulation in low-energy ER
  - ✓ Light dark matter (using an S2-only analysis)
  - ✓ 154 days of new DM data in 2013 (blinded) under analysis
  - ✓ Investigation of sensitivity to < 7 GeV WIMPs with ^{88}YBe calibration
- **Improving detector characterization and demonstrations for XENON1T**
  - ✓ Response to single electrons:
    E. Aprile et al. (XENON100), J. Phys G: Nucl. Part. Phys. 41, 035201 (2014)
  - ✓ Performed a new AmBe calibration for NR and more calibrations (^{83}Kr, …) planned
  - ✓ Further reduction of Kr: now at **0.95 ppt**
  - ✓ All this will be important also for XENON1T



XENON100: future goals

Ongoing physics analyses

✓ Search for annual modulation in low-energy ER

✓ Light dark matter (using an S2-only analysis)

✓ 154 days of new DM data in 2013 (blinded) under analysis

✓ Investigation of sensitivity to < 7 GeV WIMPs with ^{88}YBe calibration

Improving detector characterization and demonstrations for XENON1T

✓ Response to single electrons:

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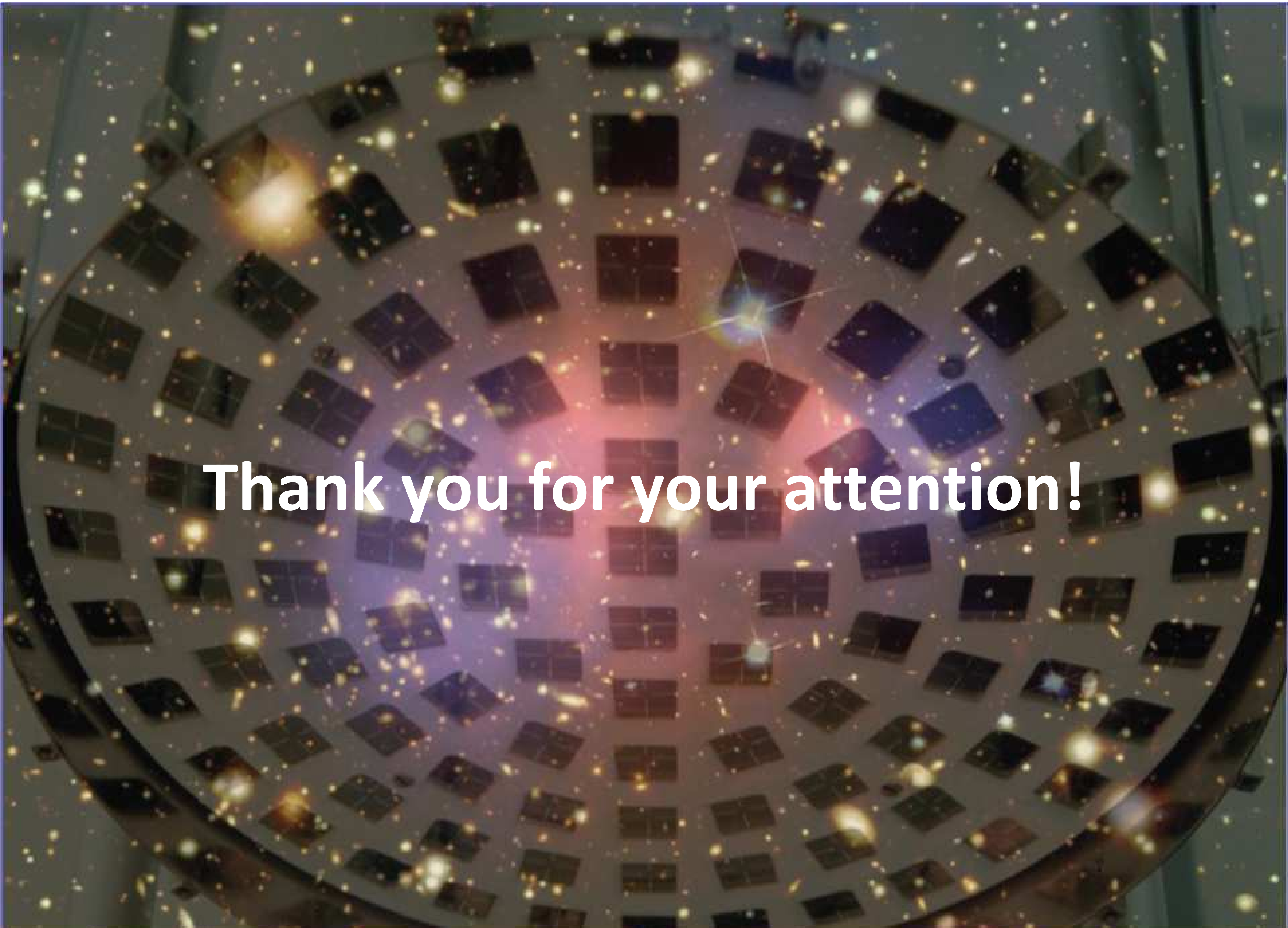
✓ Performed a new AmBe

more calibrations (^{83}Kr, …)

✓ Further reduction of Kr:

✓ All this will be important

XENON1T: see the talk by A. Rizzo



Thank you for your attention!