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The XENON Dark Matter Project: Recent Results and Future Plans

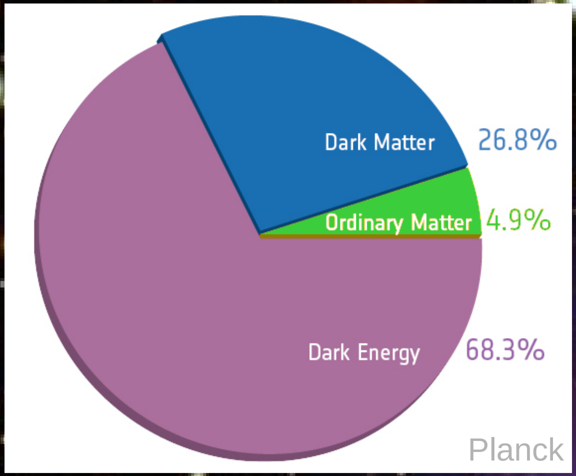
Marc Schumann *University of Freiburg*

DESY Particle and Astroparticle Physics Colloquium, 30.06.2020

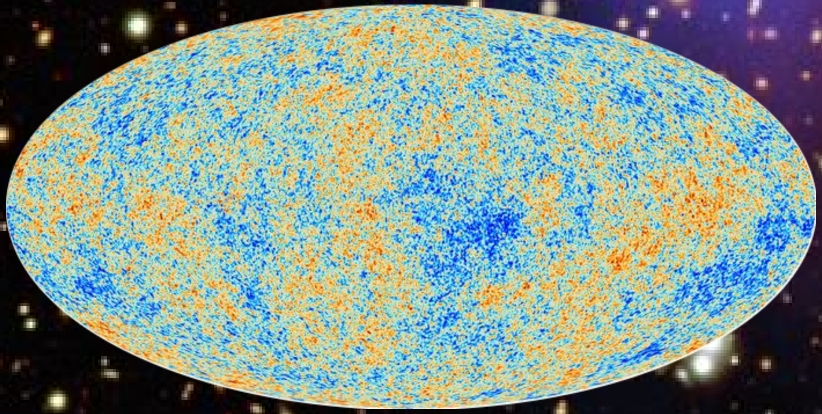
`www.app.uni-freiburg.de`

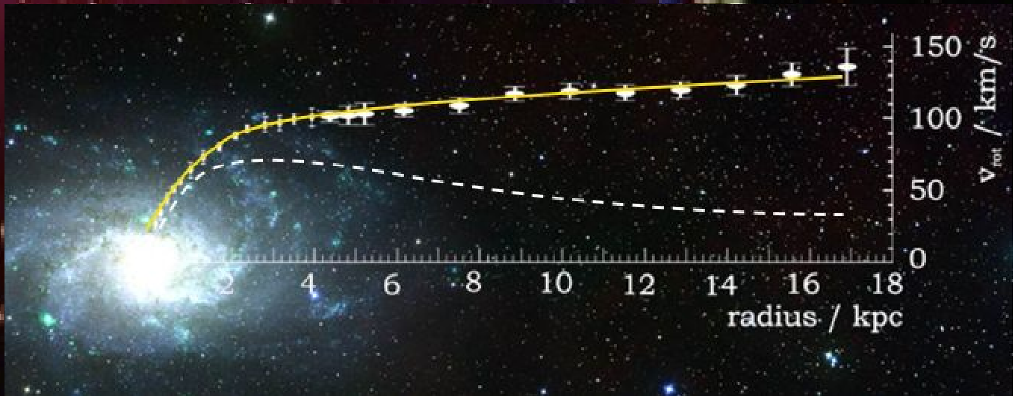
UNI
FREIBURG

Dark Matter: (indirect) **Evidence**



The indirect evidence for the existence of dark matter is a clear indication for physics beyond the Standard Model





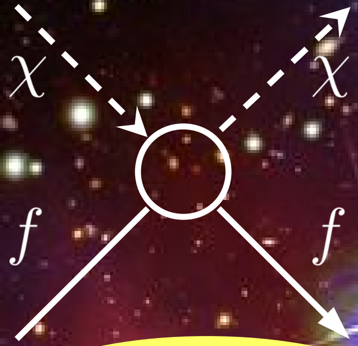
THE DM CANDIDATES ZOO

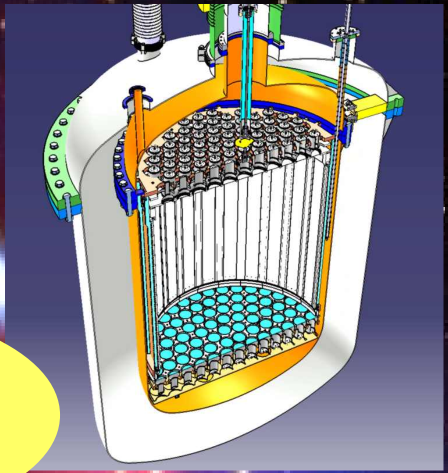
WIMPs

= weakly interacting massive particles

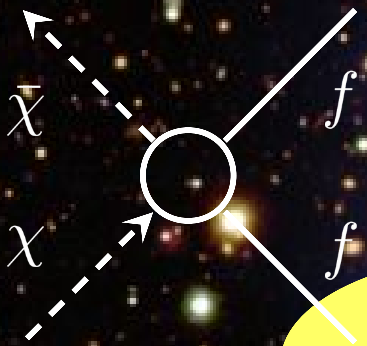
stolen from G. Bertone

Dark Matter WIMP Search

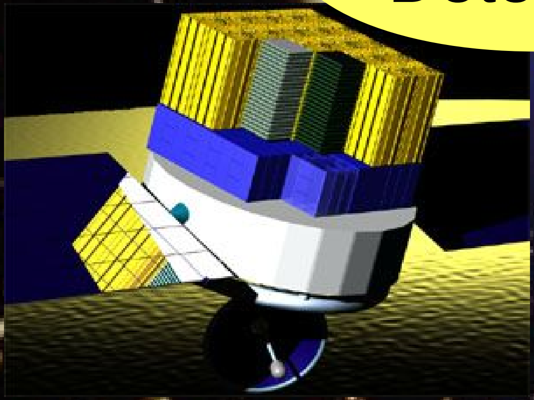




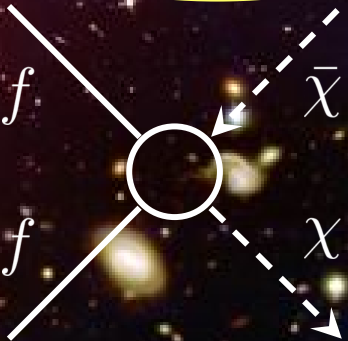
Direct Detection

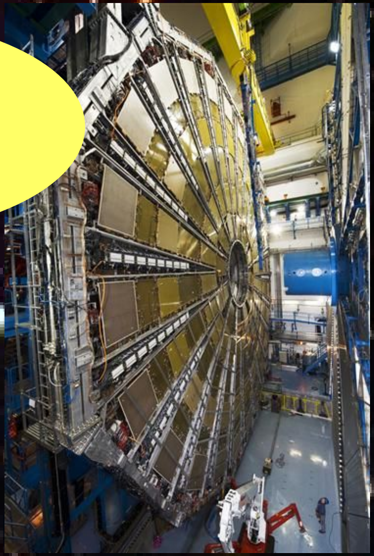


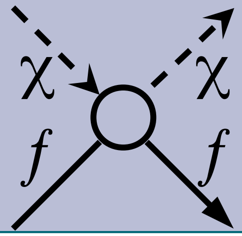
Indirect Detection



Production @Collider



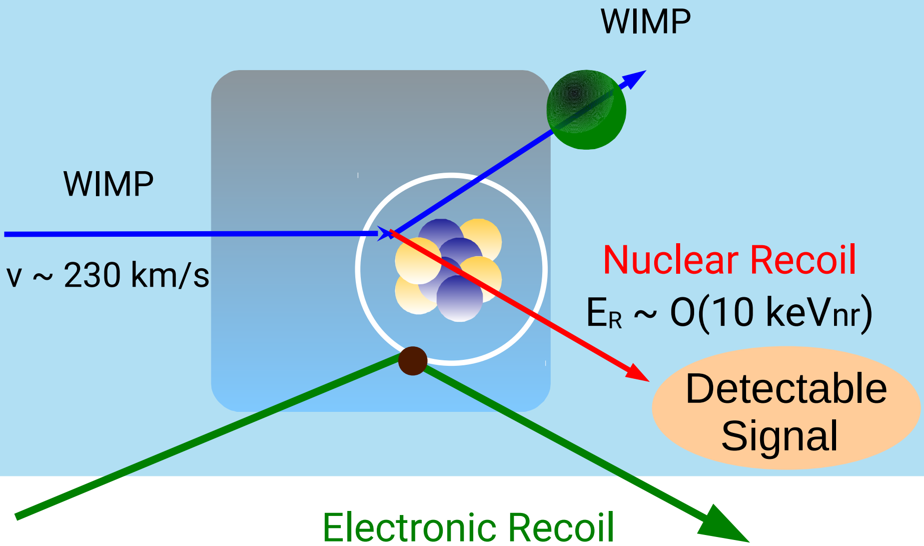




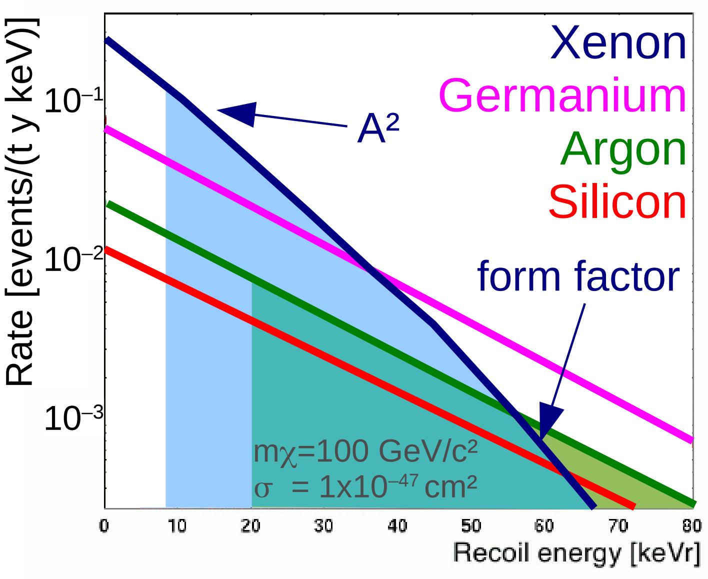
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei

→ nuclear recoil

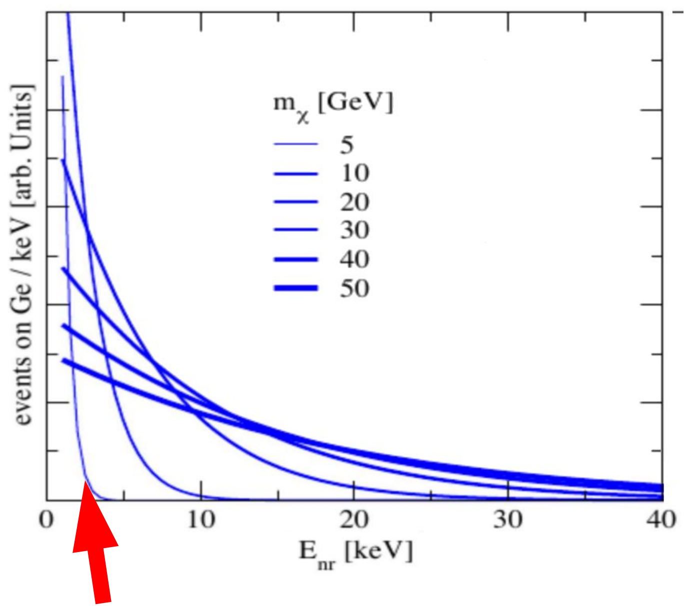


Recoil Spectra:



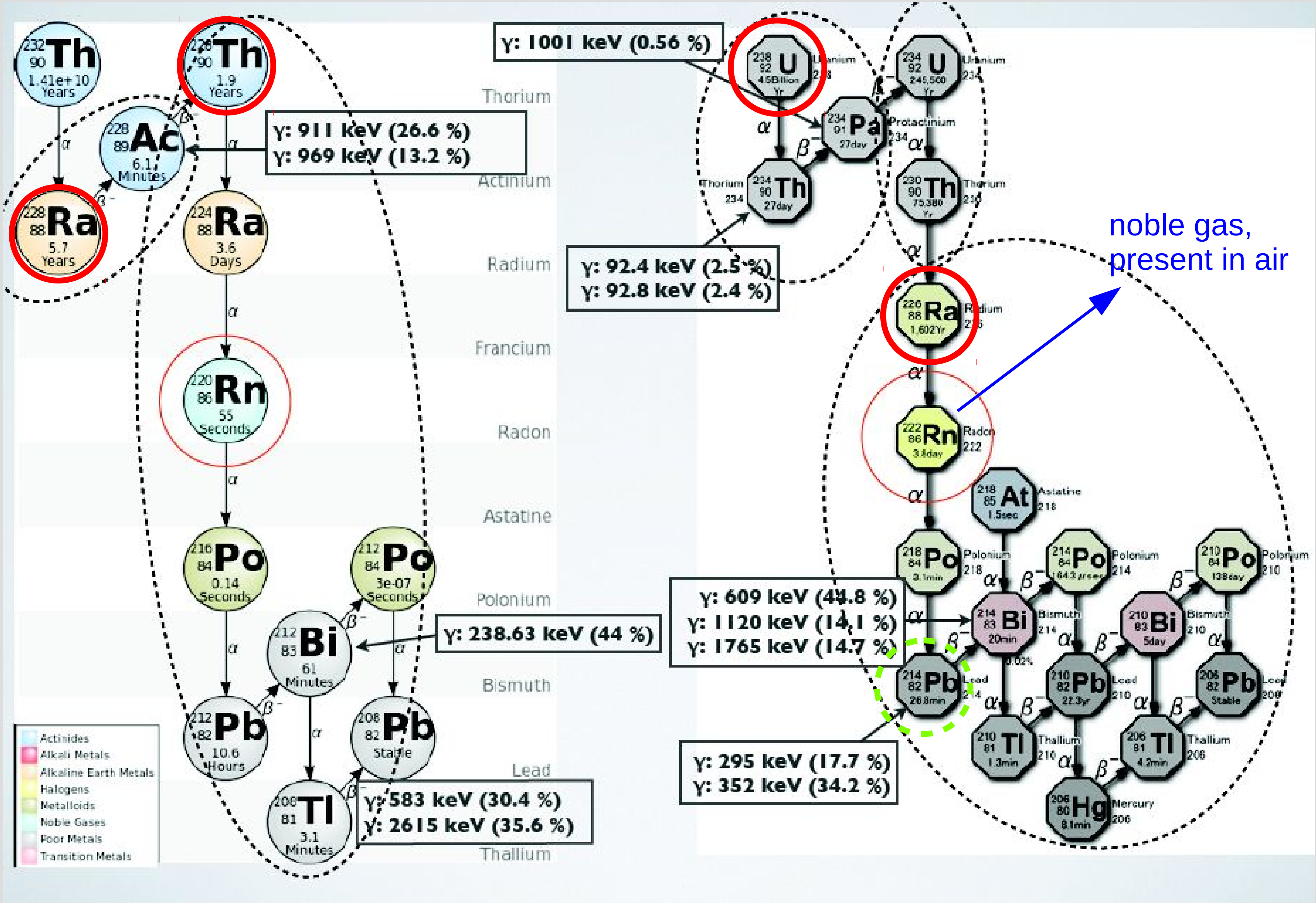
tiny!

tiny!



low mass → low threshold

The U and Th Chains



γ: 1001 keV (0.56 %)

γ: 911 keV (26.6 %)
γ: 969 keV (13.2 %)

γ: 92.4 keV (2.5 %)
γ: 92.8 keV (2.4 %)

noble gas, present in air

γ: 609 keV (44.8 %)
γ: 1120 keV (14.1 %)
γ: 1765 keV (14.7 %)

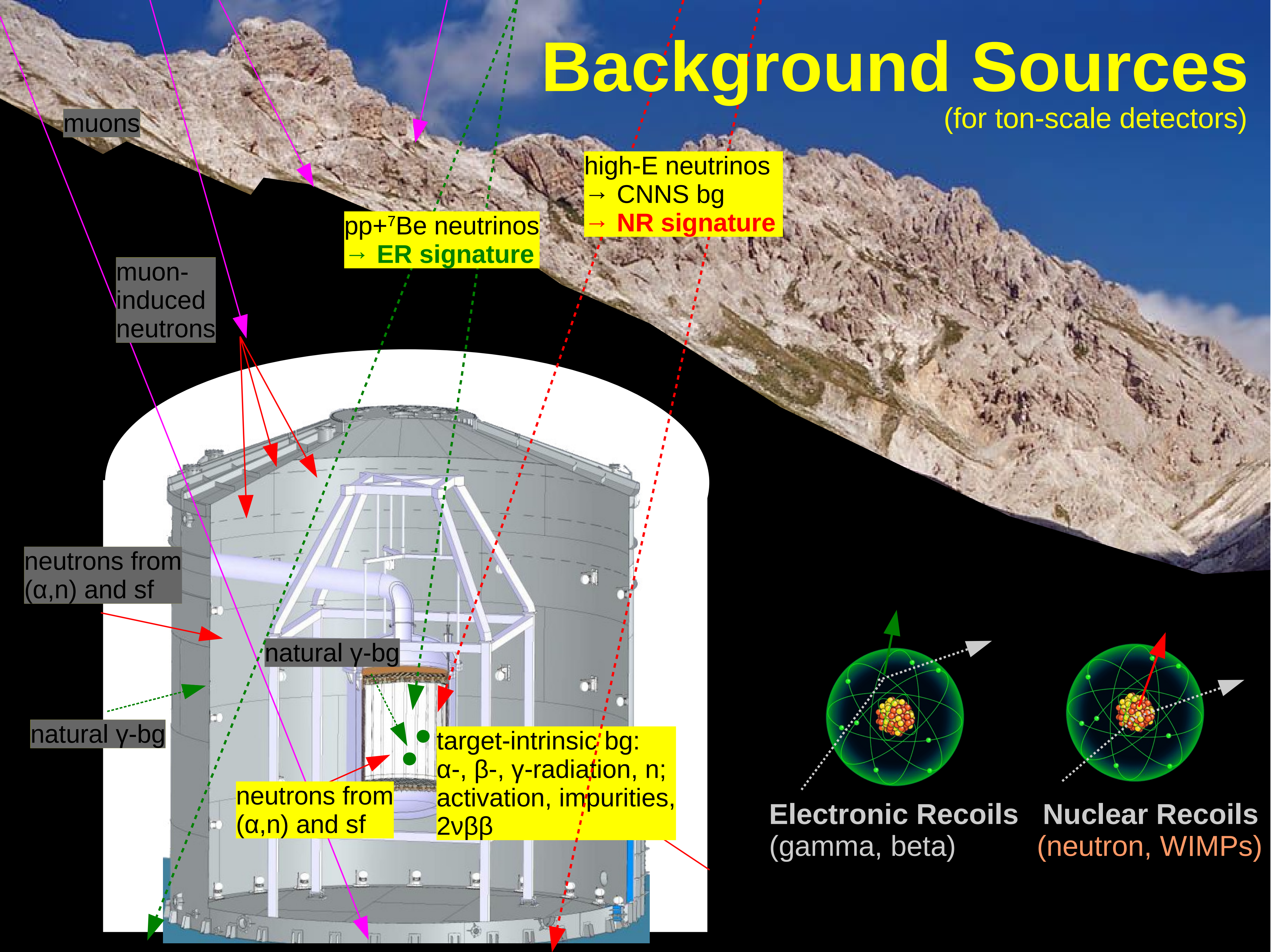
γ: 238.63 keV (44 %)

γ: 295 keV (17.7 %)
γ: 352 keV (34.2 %)

γ: 583 keV (30.4 %)
γ: 2615 keV (35.6 %)

Background Sources

(for ton-scale detectors)



muons

muon-induced neutrons

pp+^{7}Be neutrinos
→ **ER signature**

high-E neutrinos
→ CNNS bg
→ **NR signature**

neutrons from (α,n) and sf

natural γ-bg

natural γ-bg

neutrons from (α,n) and sf

target-intrinsic bg:
α-, β-, γ-radiation, n;
activation, impurities,
2νββ

Electronic Recoils
(gamma, beta)

Nuclear Recoils
(neutron, WIMPs)

Background Suppression

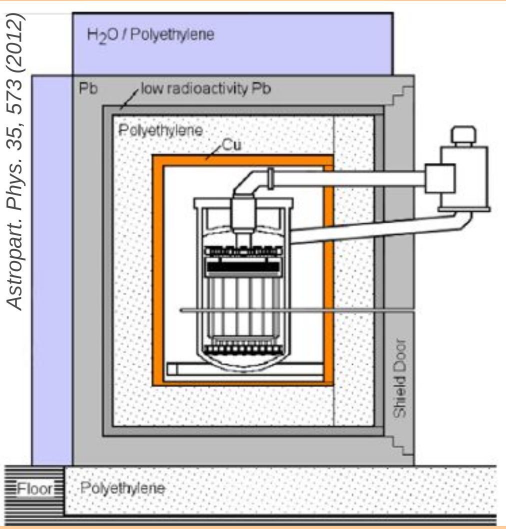
A Avoid Backgrounds

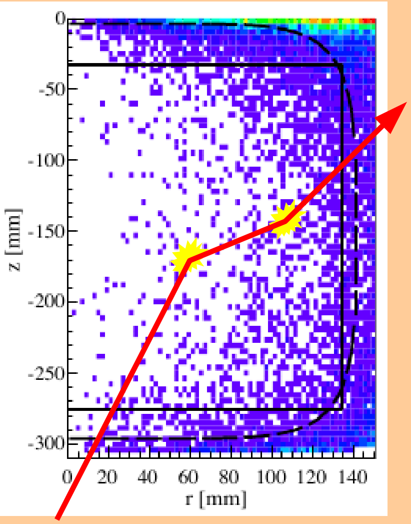
Use of radiopure materials

Shielding

deep underground location
large shield (Pb, water, poly)
active veto (μ, γ coincidence)

self shielding → fiducialization


Astropart. Phys. 35, 573 (2012)



B Use knowledge about expected WIMP signal

WIMPs interact only once

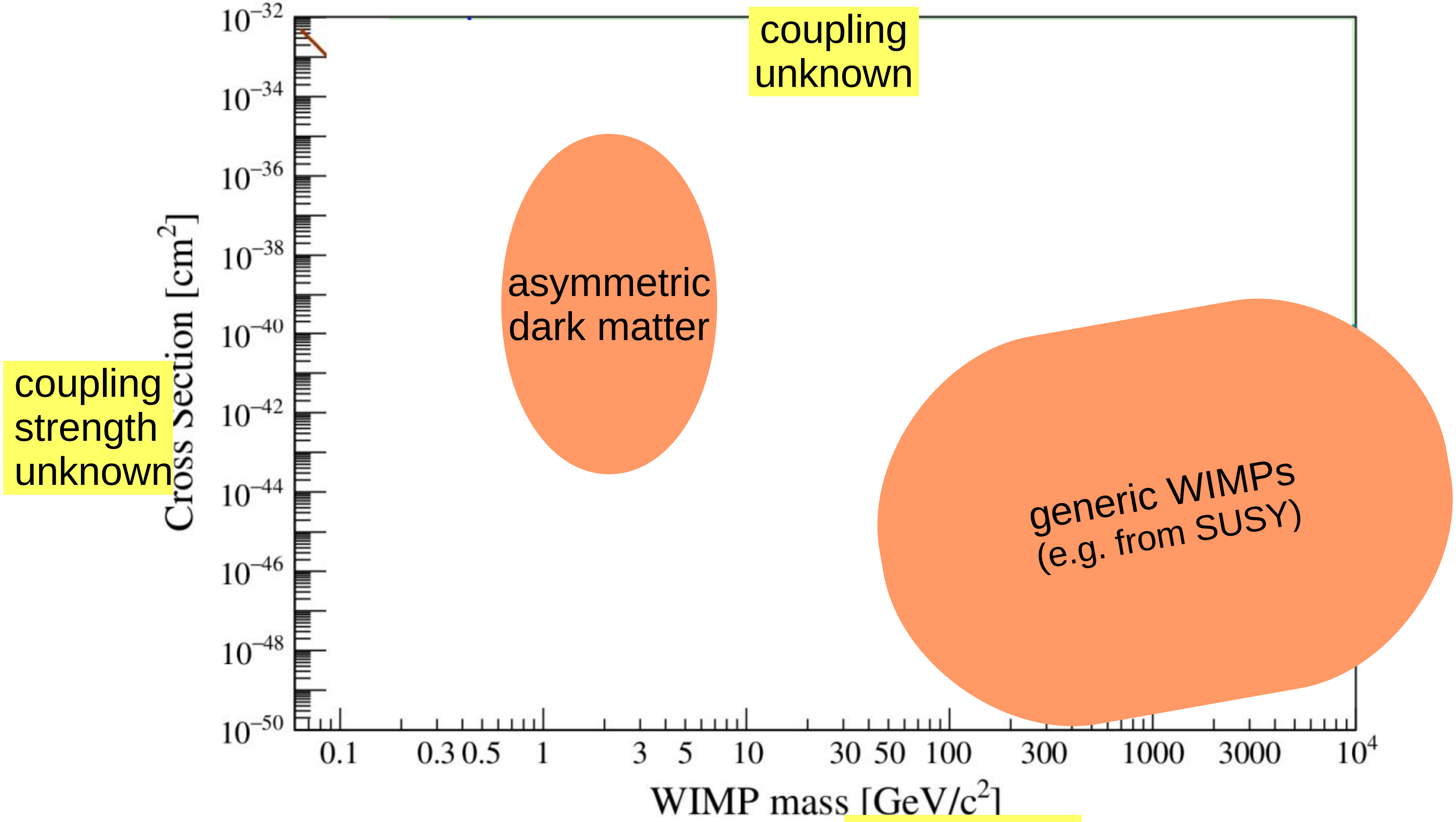
→ single scatter selection
require some position resolution

WIMPs interact with target nuclei

→ nuclear recoils
exploit different d*E*/dx from
signal and background

The WIMP Parameter Space

spin-independent WIMP-nucleon interactions



WIMP mass unknown

The XENON Collaboration

www.xenon1t.org

Xe XENON Dark Matter Project

Columbia RPI Nikhef Muenster KIT Stockholm Mainz MPIK, Heidelberg Freiburg

Chicago

UCSD

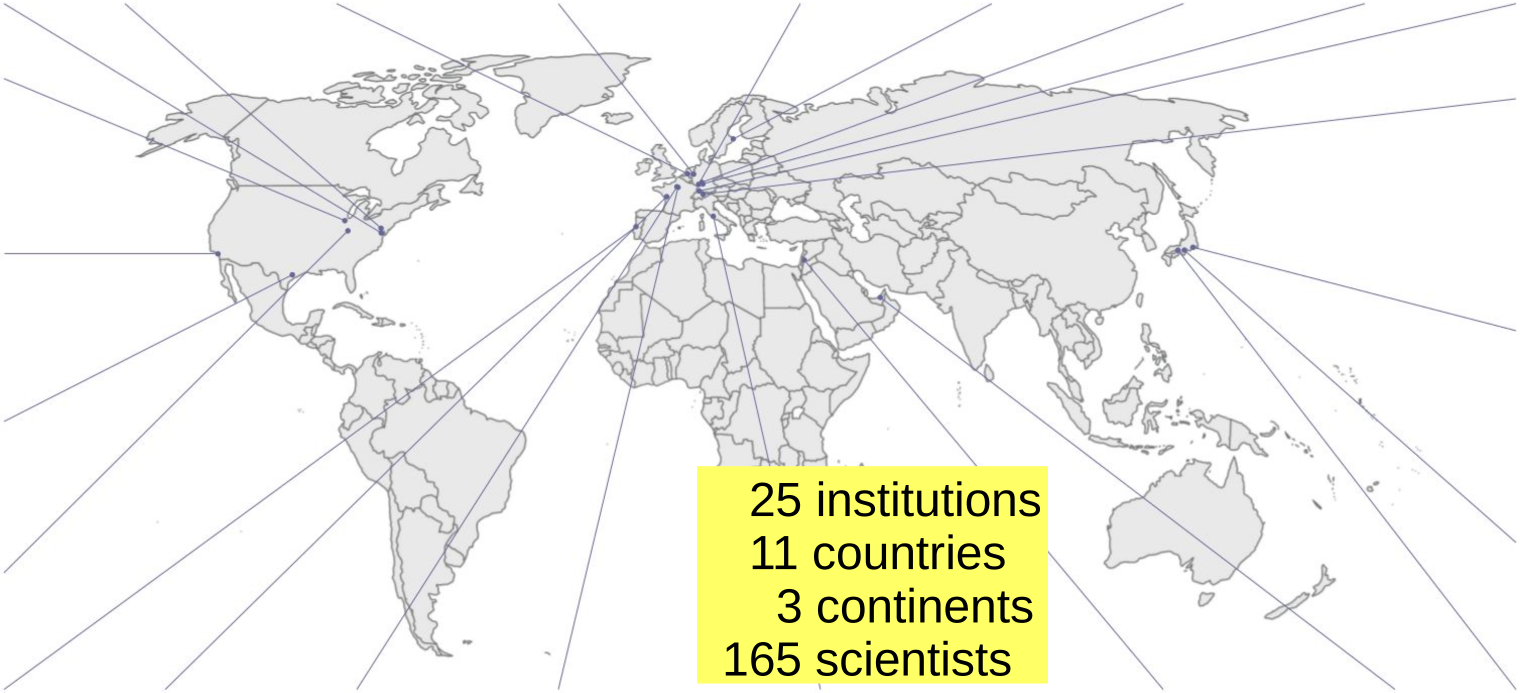
Rice

Purdue

Zurich

Tokyo

Nagoya

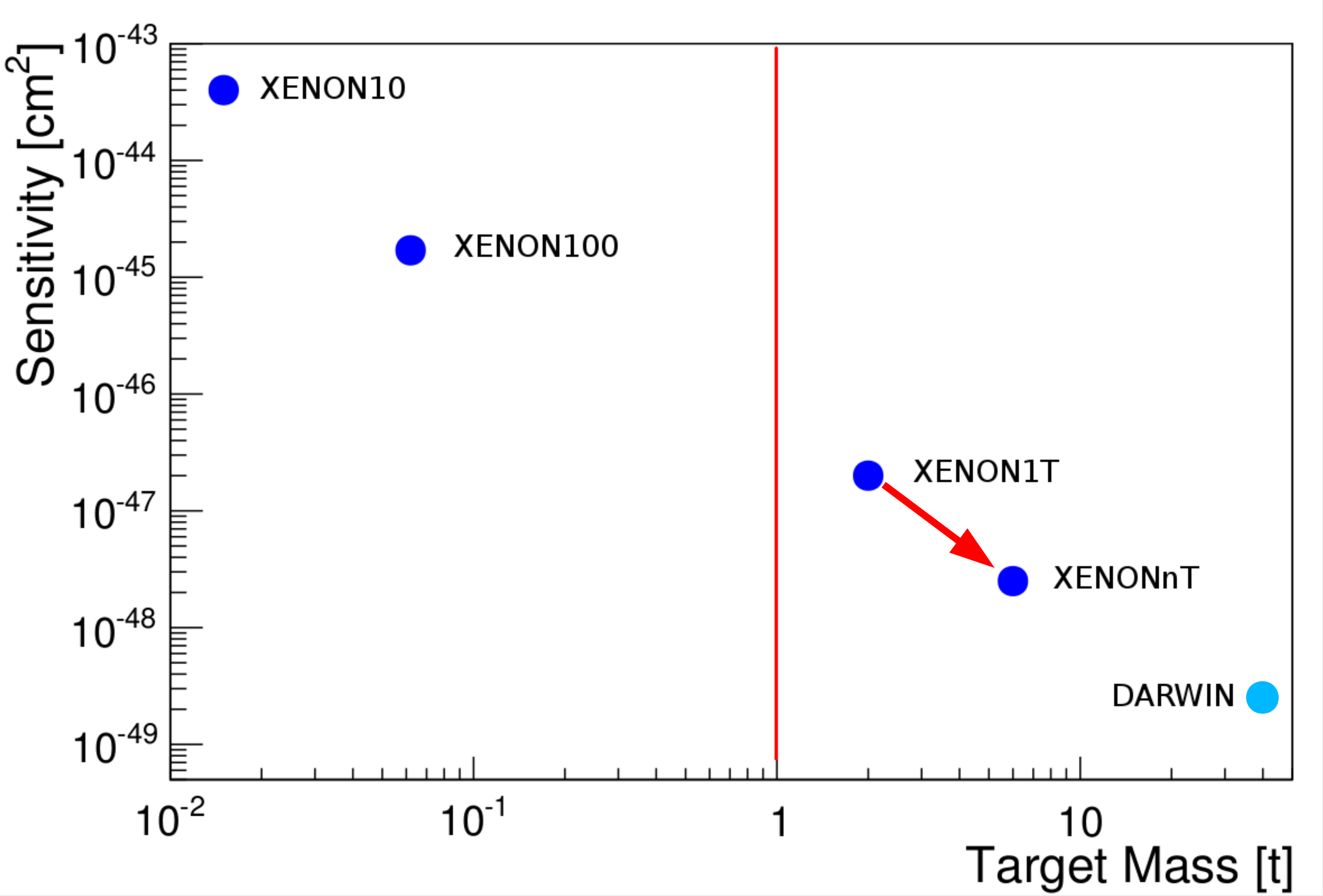


25 institutions
11 countries
3 continents
165 scientists

Coimbra Subatech LPNHE LAL Bologna LNGS Torino Napoli Weizmann NYUAD Kobe

XENON Technical Meeting, May 12-14, 2020

XENON Instruments

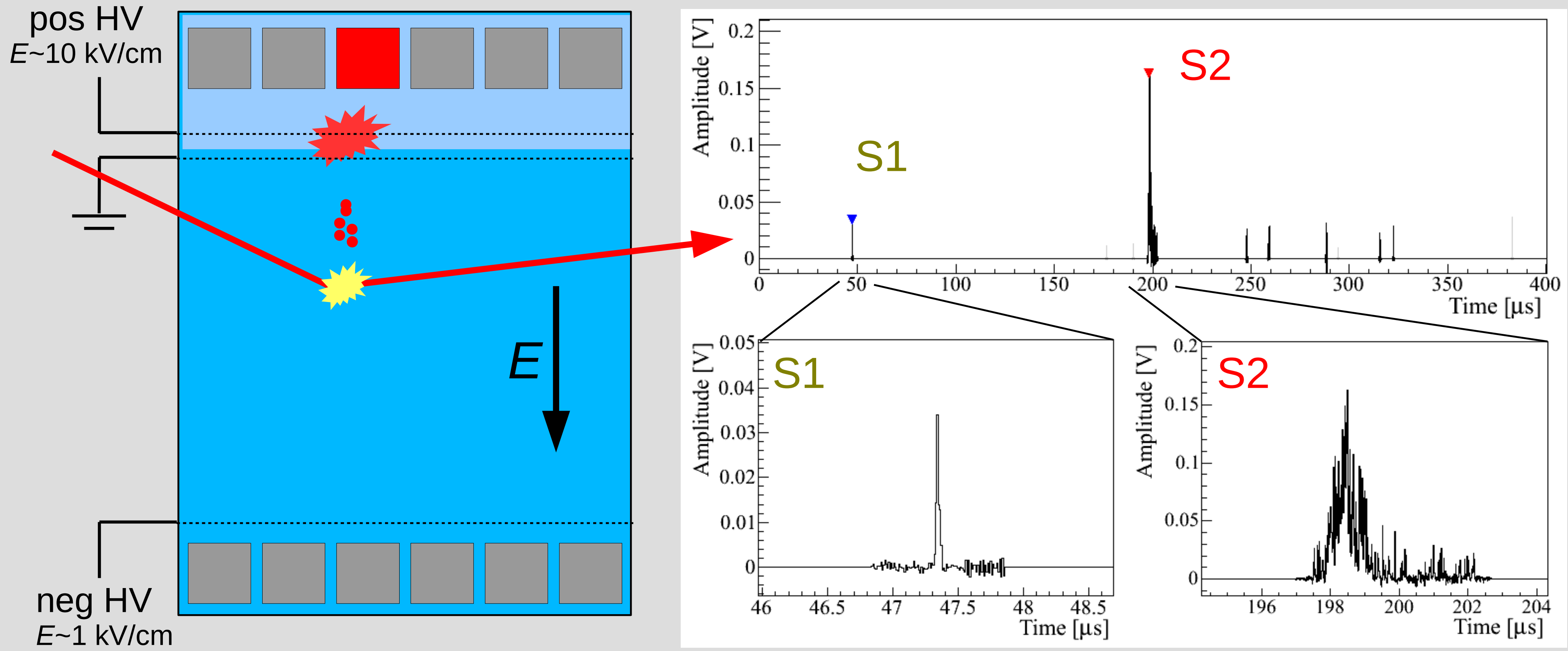


The XENON collaboration develops and operates
dark matter detectors of increasing size and sensitivity

Dual Phase TPC

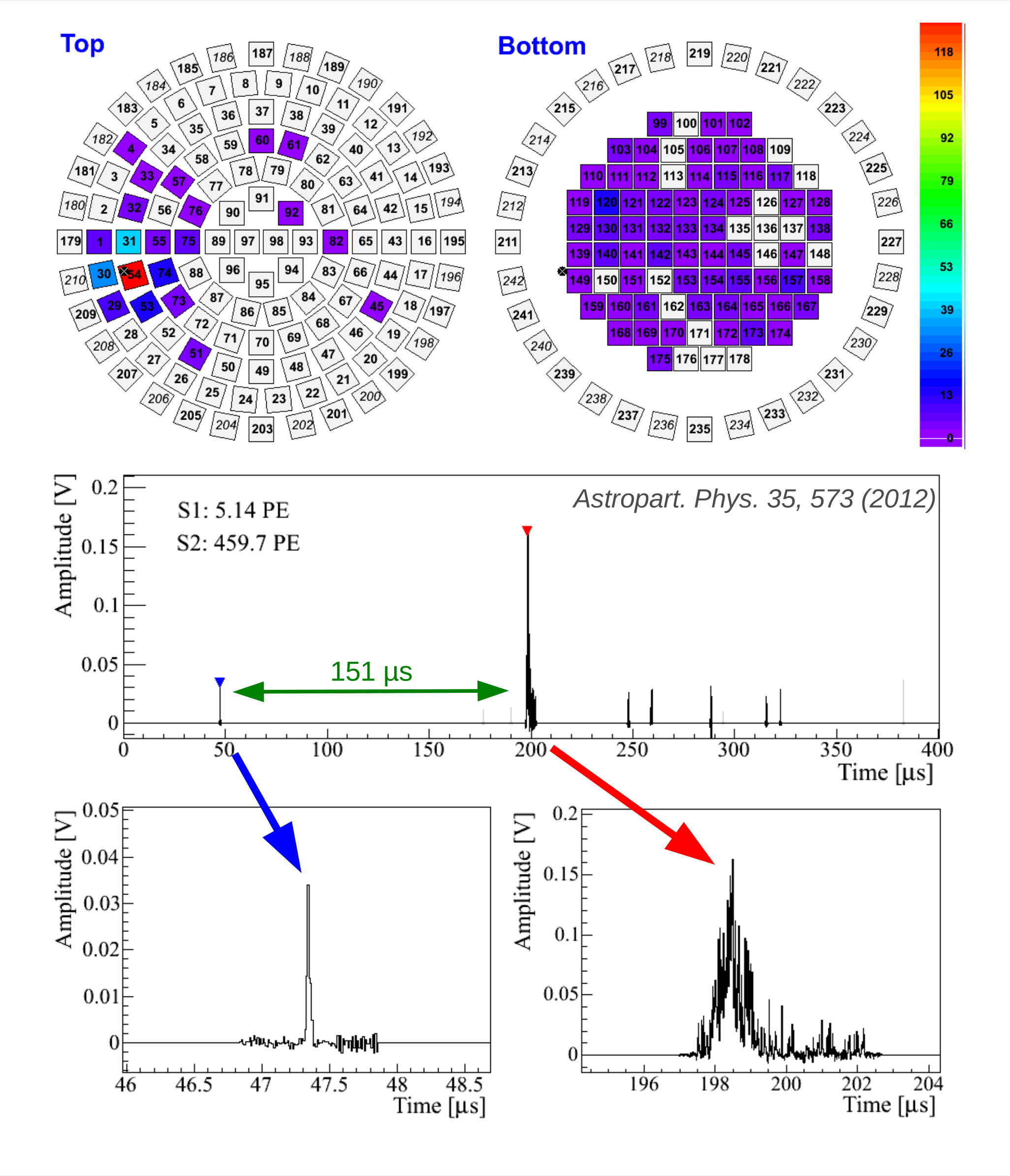
Dolgoshein, Lebedenko, Rodionov, JETP Lett. 11, 513 (1970)

TPC = time projection chamber



Background Rejection

- 3dim vertex reconstruction
  → **fiducialization**
- multi-scatter rejection
- energy measurement



Astropart. Phys. 35, 573 (2012)

Figures: XENON100

TPC Features

- 3dim vertex reconstruction
  → **fiducialization**

- multi-scatter rejection

- energy measurement

- **Charge-Light-Ratio (S2/S1):**
  Particle ID

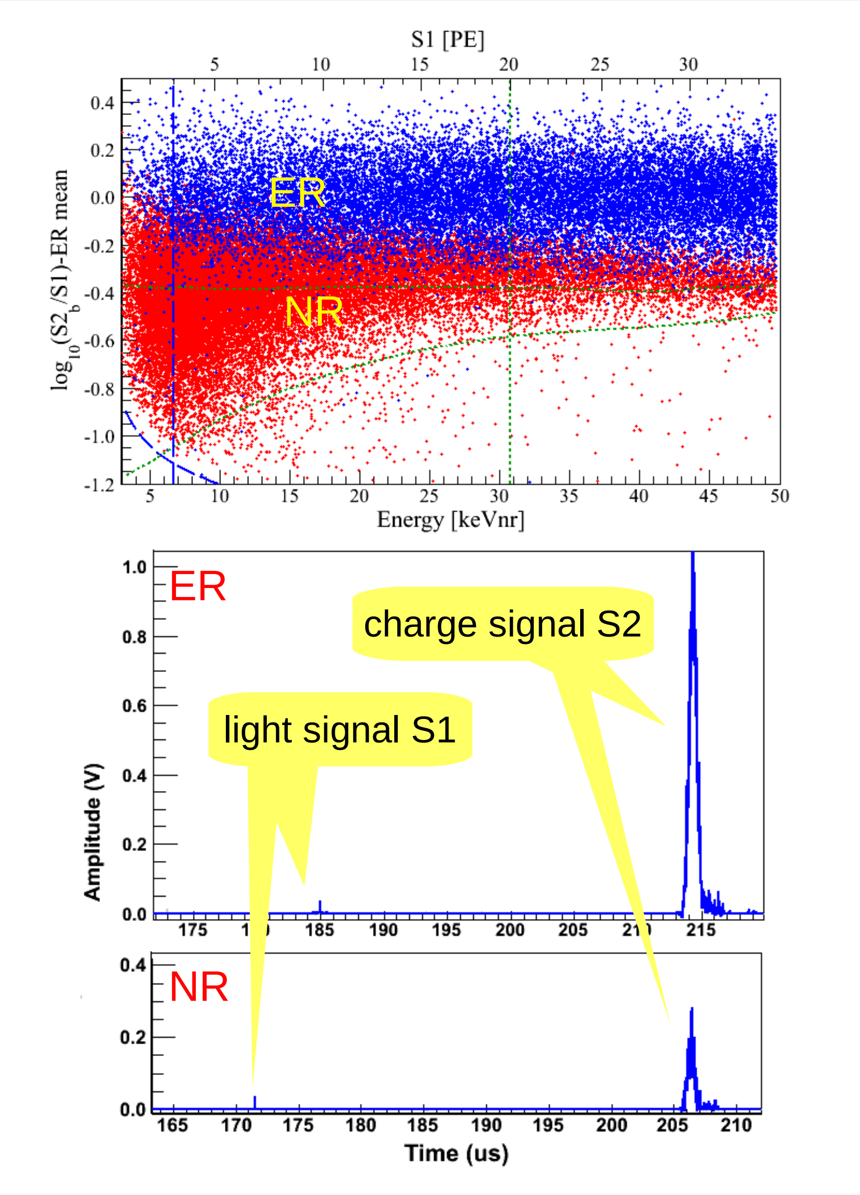
→ ER background rejection (WIMP search)

→ selection of ER channels

- very low background

- low threshold
  (light: ~2-3 PE, charge: few electrons)

- large target mass → high exposure

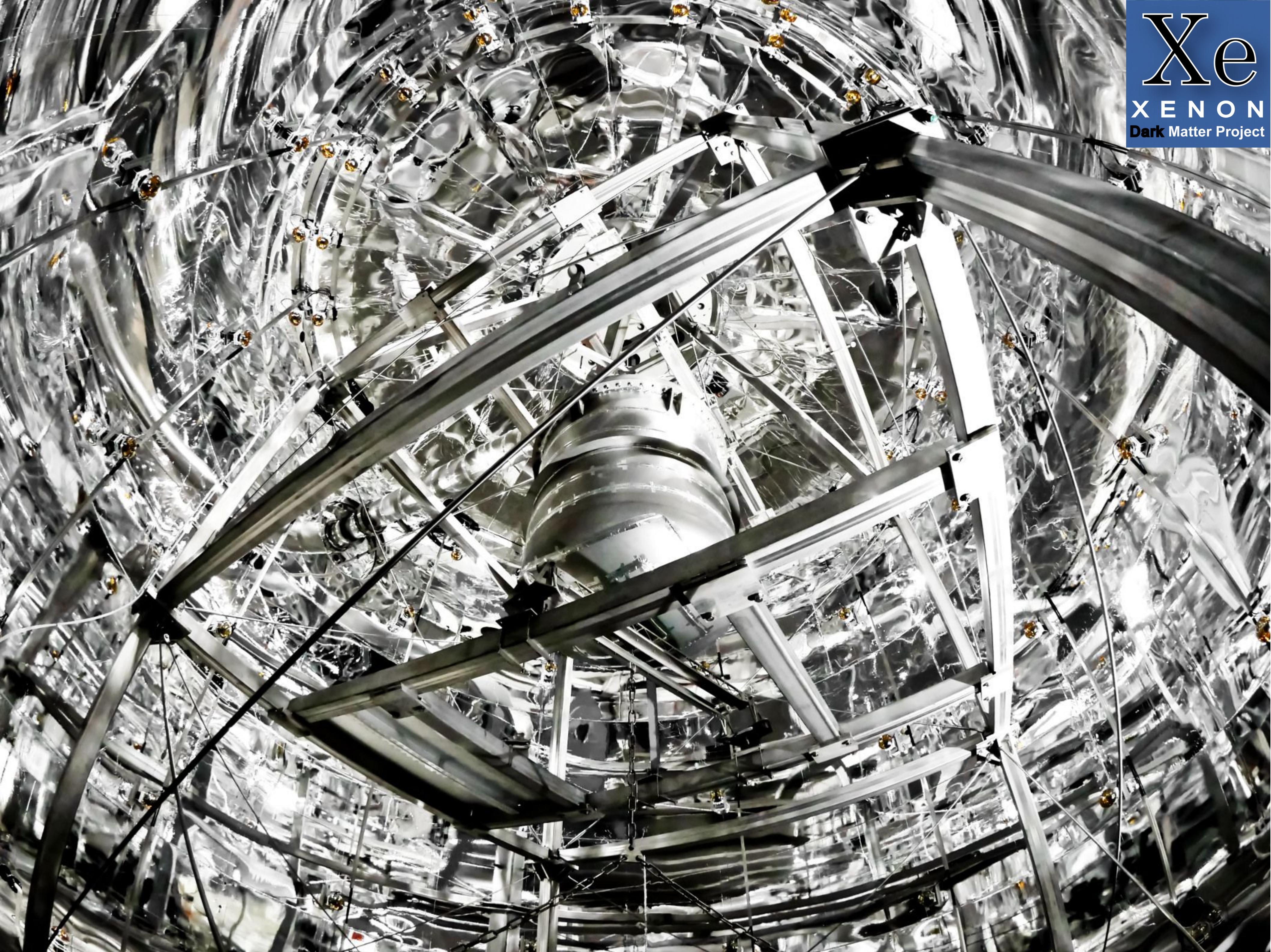


Figures: XENON100

XENON1T @ LNGS

Xe XENON Dark Matter Project

EPJ C 77, 991 (2017)



Xe
XENON
Dark Matter Project

EPJ C 77, 991 (2017)

largest LXe TPC ever built

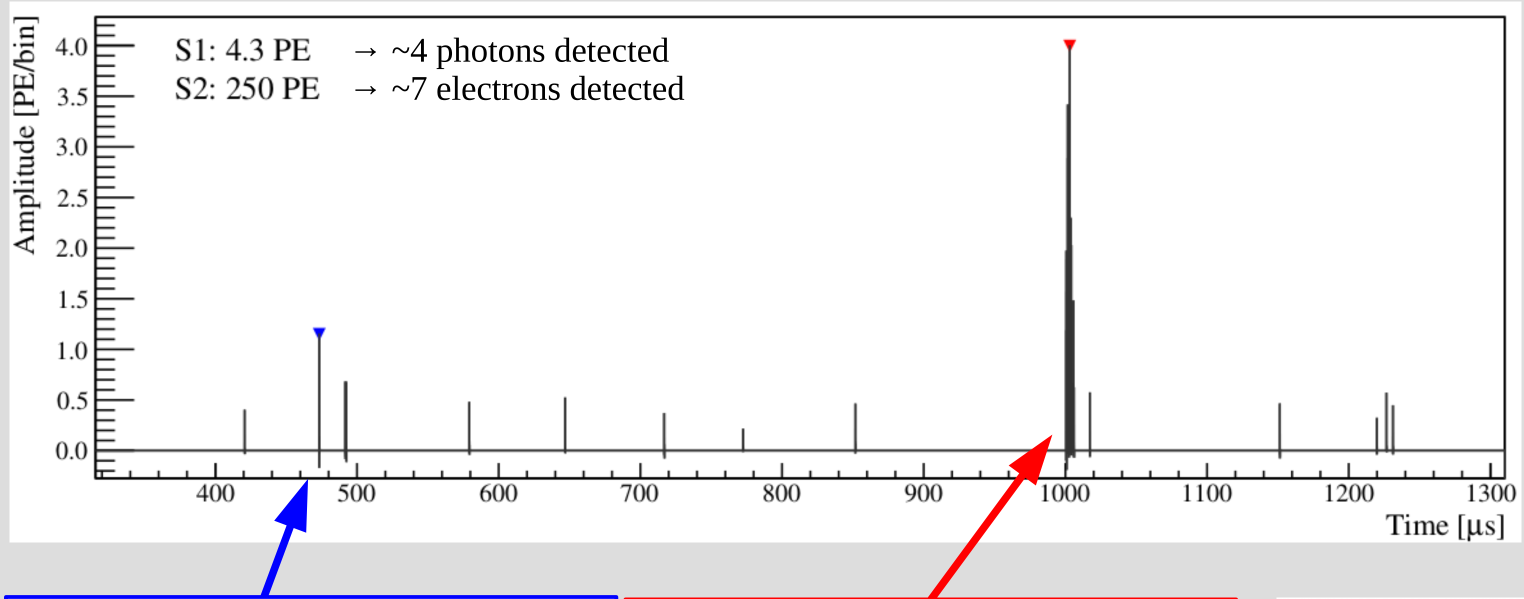
- **cylinder: 96 cm**
- **active LXe target: 2.0t** (3.2t total)
- **248 PMTs**

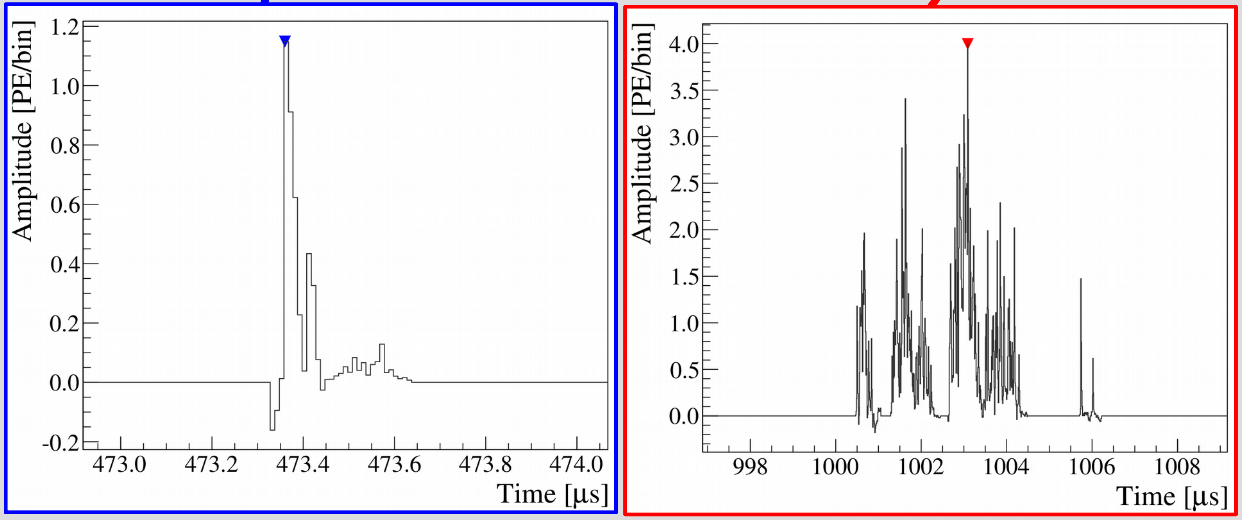
Selected Results from XENON1T

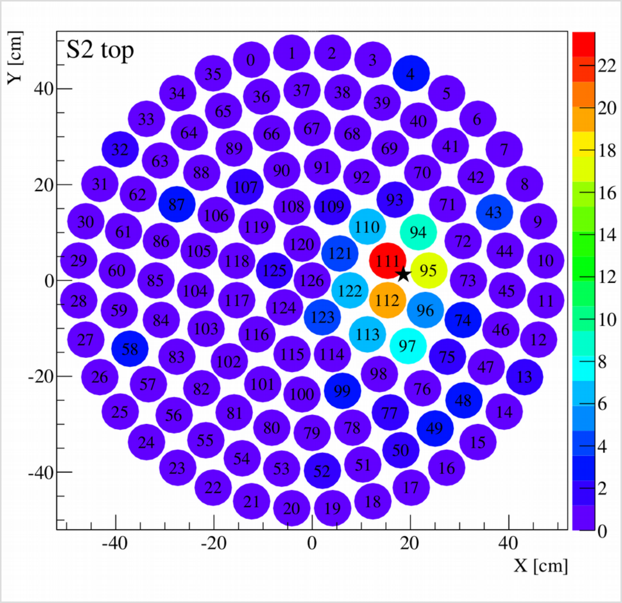
WIMPs

How would dark matter look?

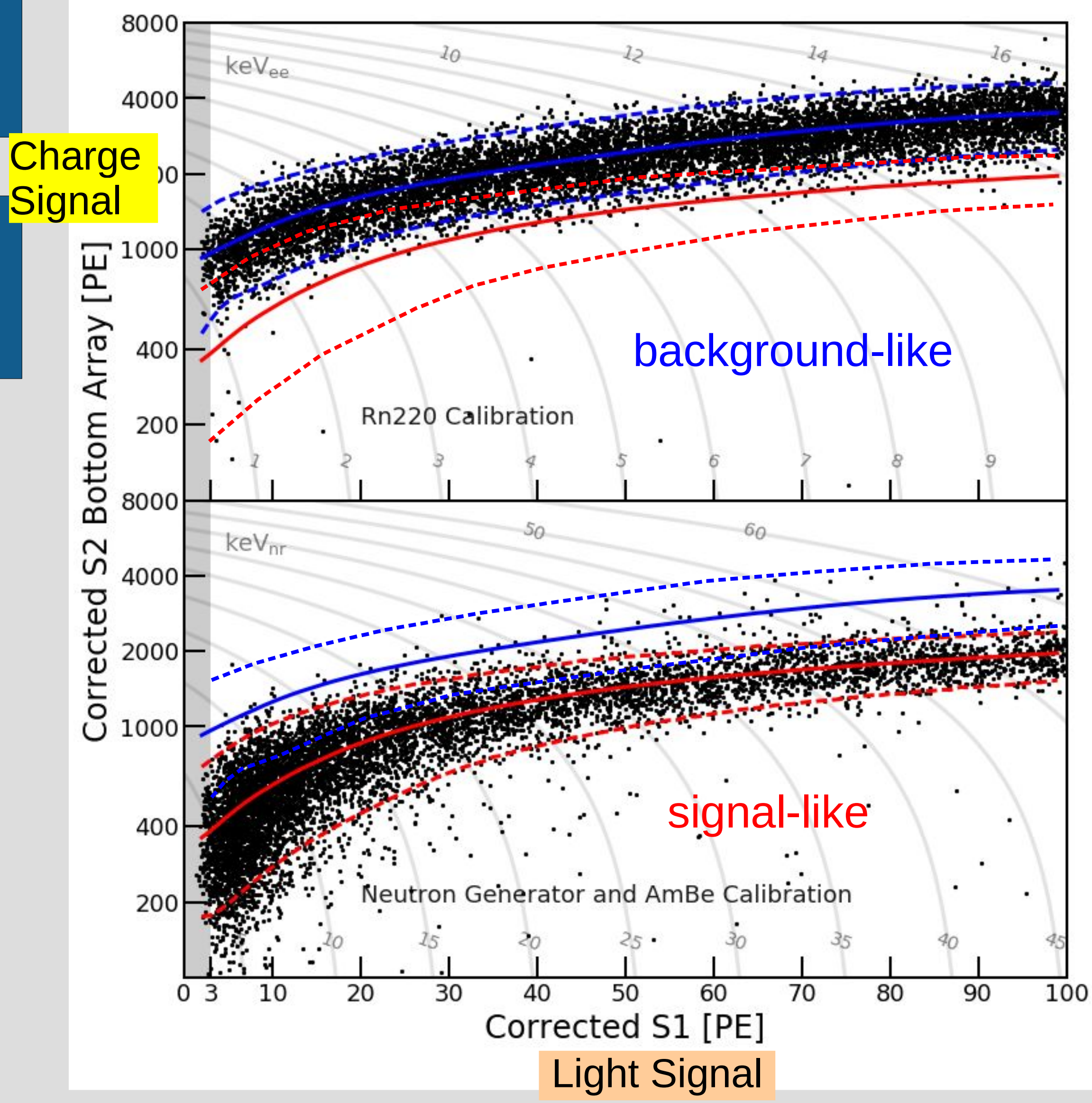
… but it's a low-E neutron interaction from calibration!

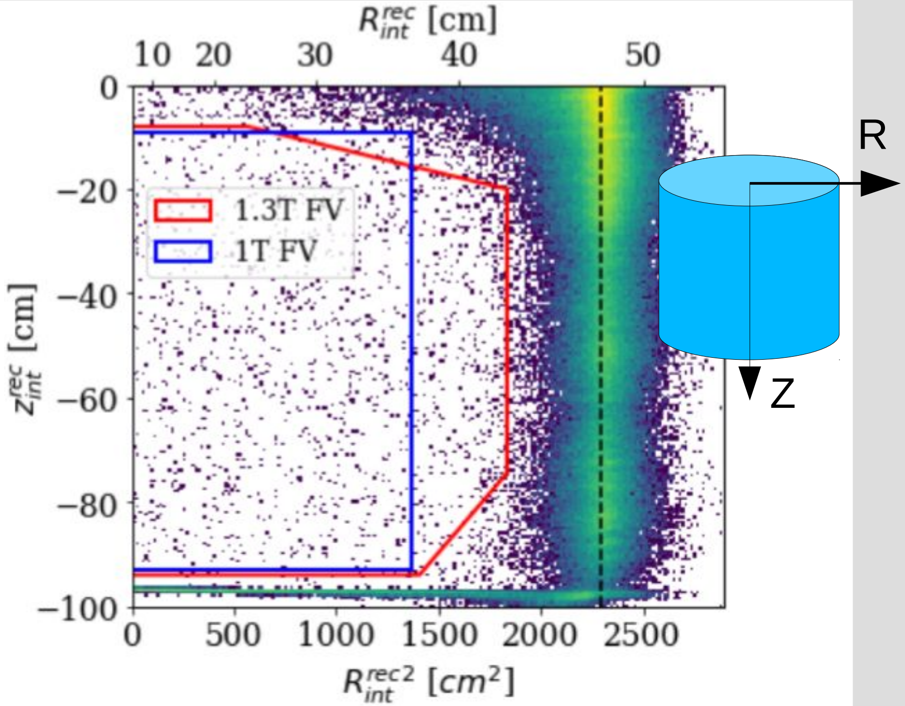






Calibration and Analysis



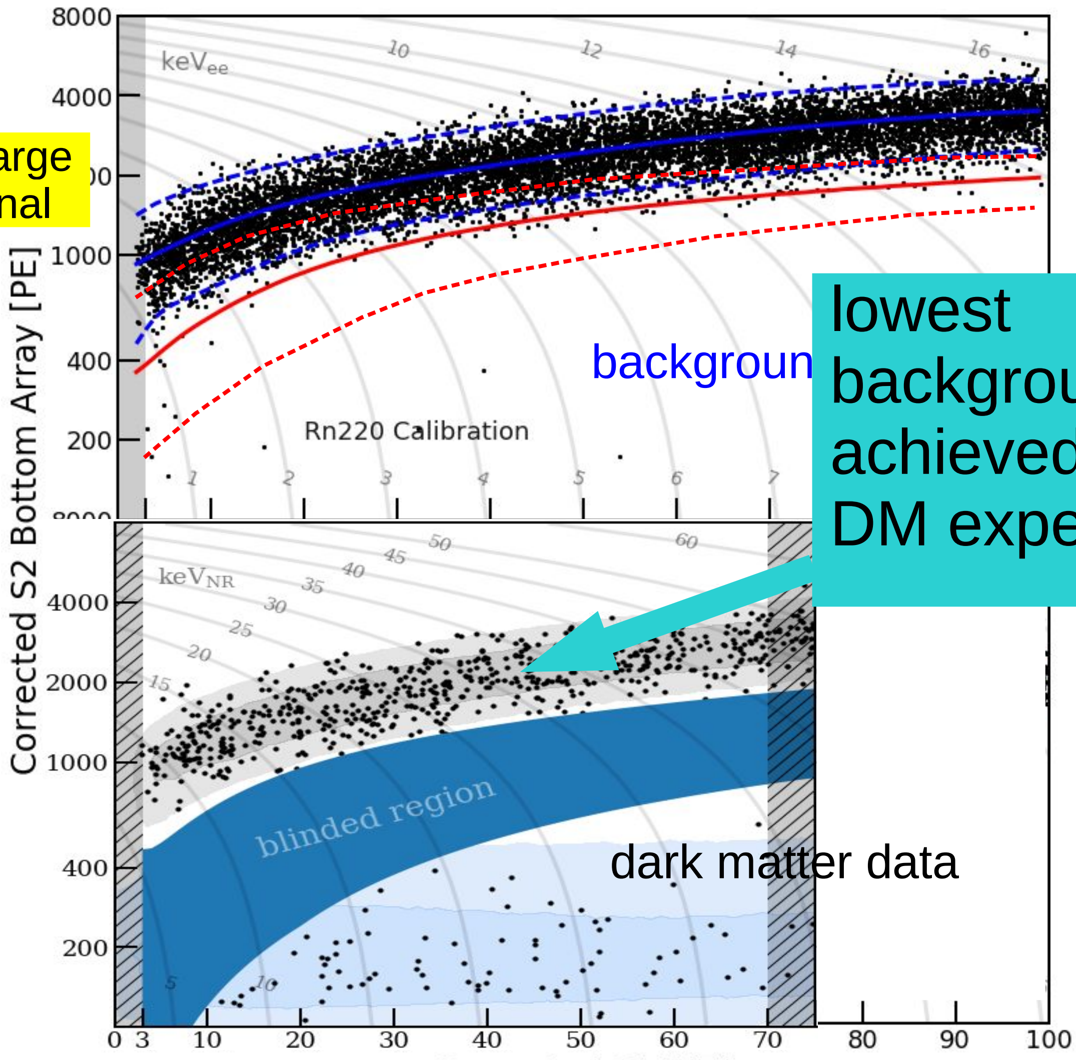


Used to construct background and signal models.

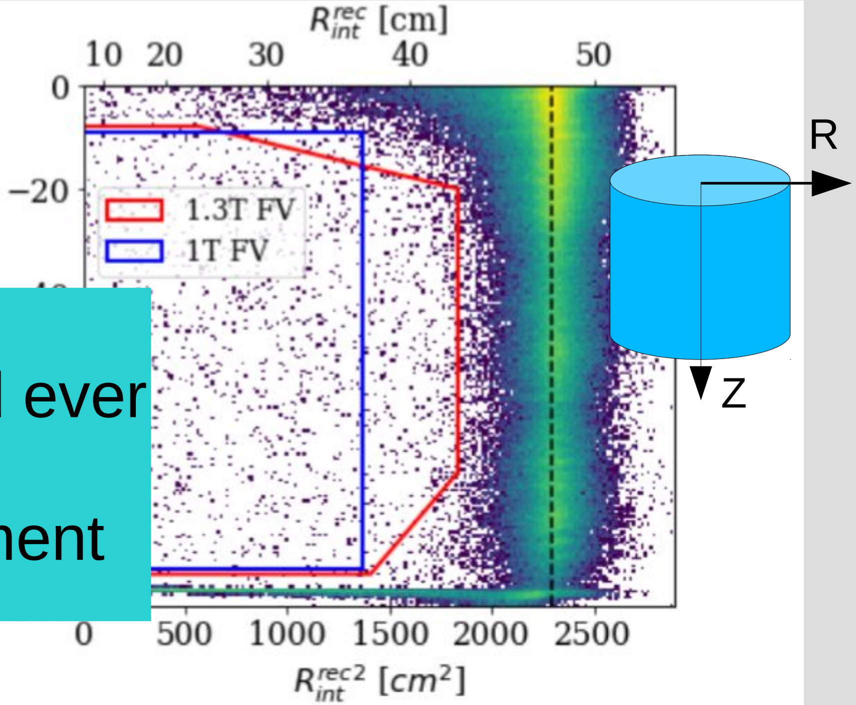
use **central 1.3 t** LXe for analysis

Exposure: 1.3 t × 278.8 d = 1.0 t×y
→ **largest low-bg exposure ever**

Blind WIMP Search



lowest background ever achieved in DM experiment



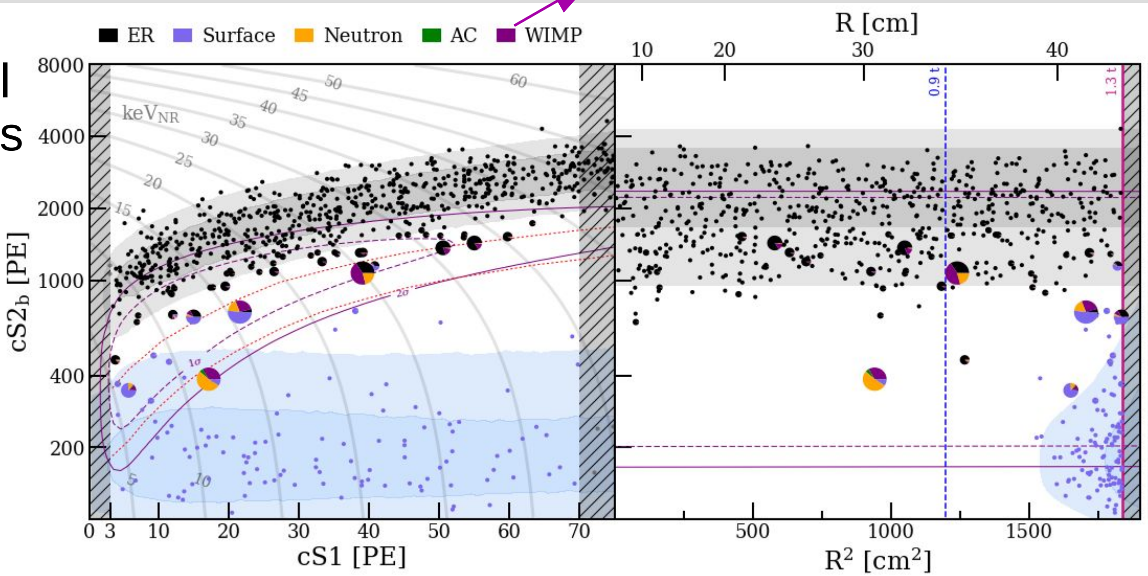
Used to construct background and signal models.

use **central 1.3 t** LXe for analysis

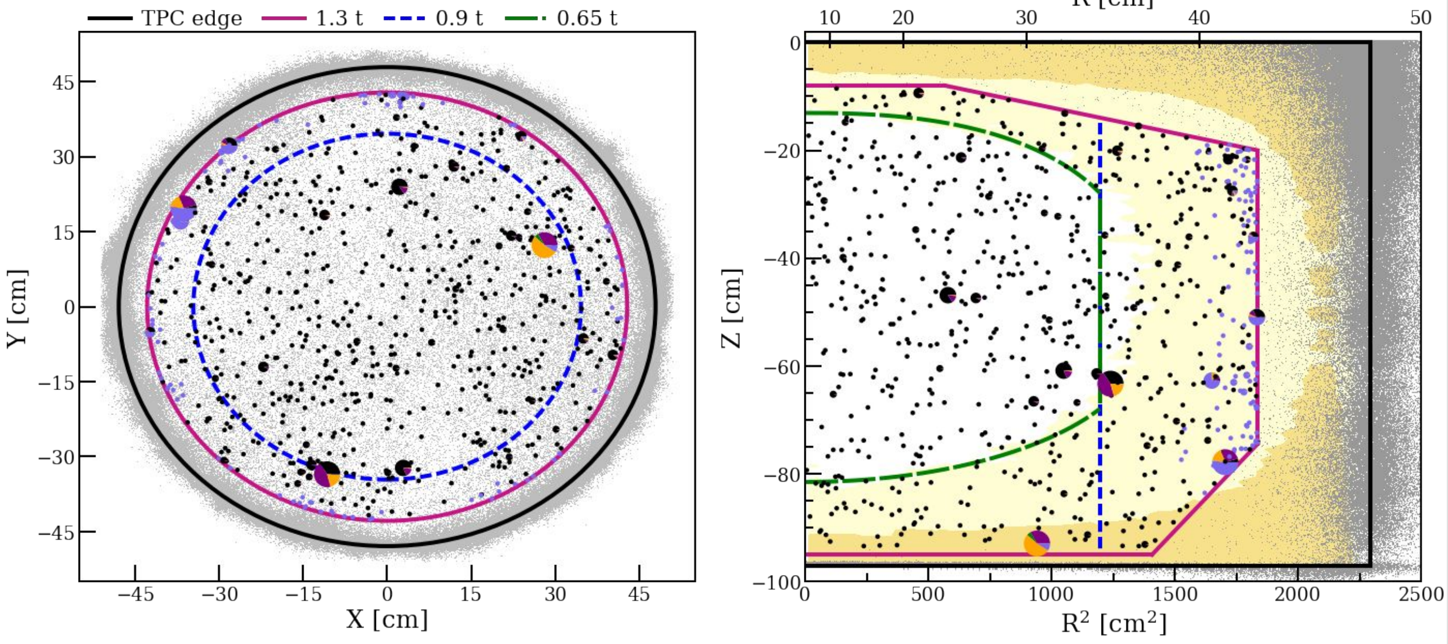
Blind analysis
= region of interest inaccessible during analysis to avoid human bias

Unblinding

multi-dimensional likelihood analysis



200 GeV/c²

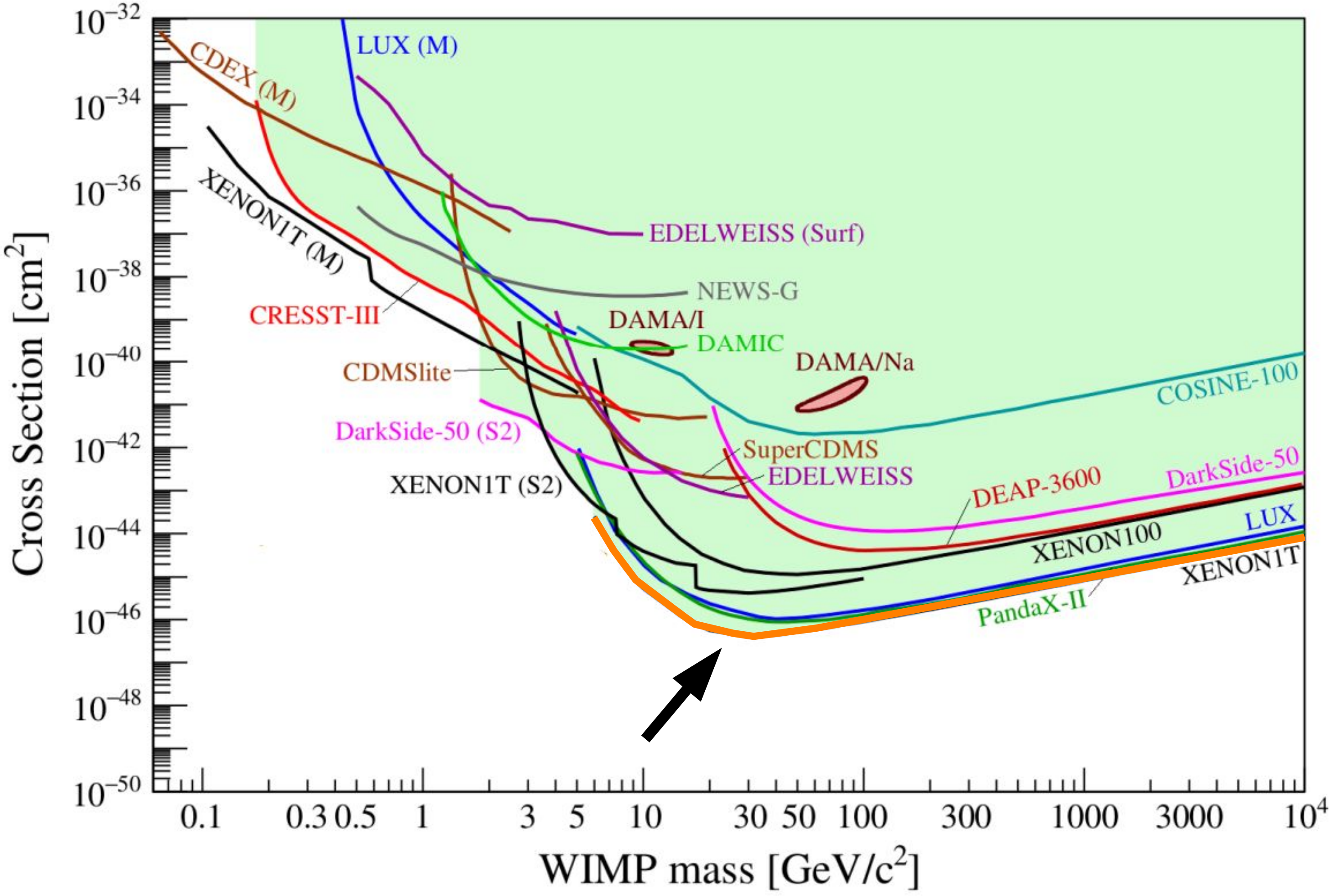


→ no statistically significant excess observed

No Signal → Exclusion Limit

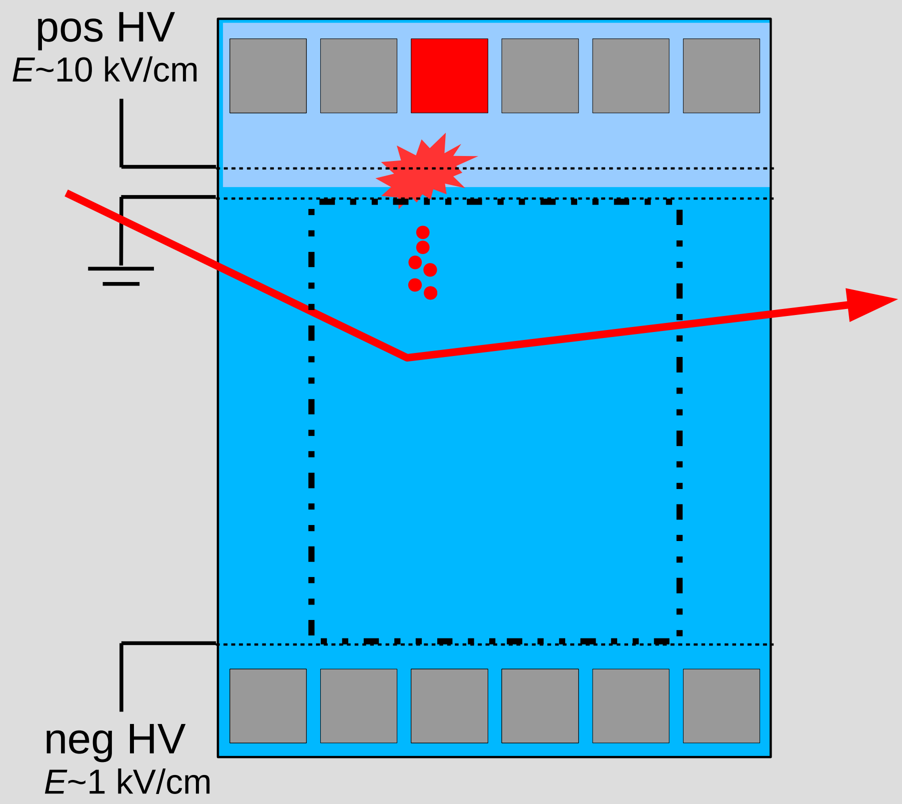
PRL 121, 111302 (2018)

spin-independent WIMP-nucleon interactions

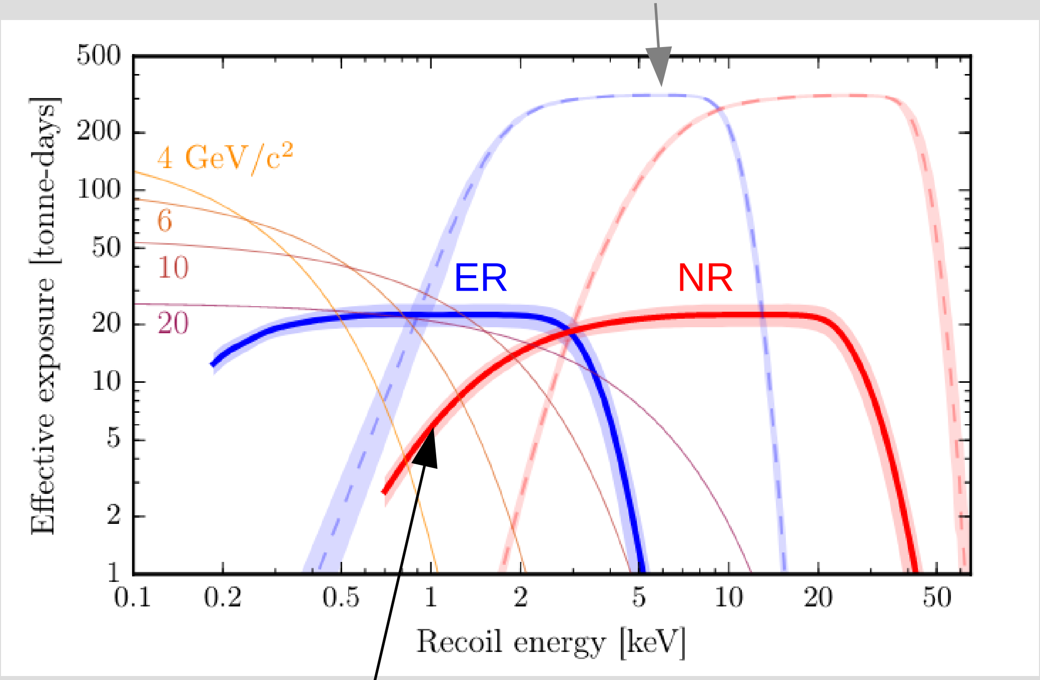


some results are missing...

Charge-Only Analysis



standard analysis (S1+S2)

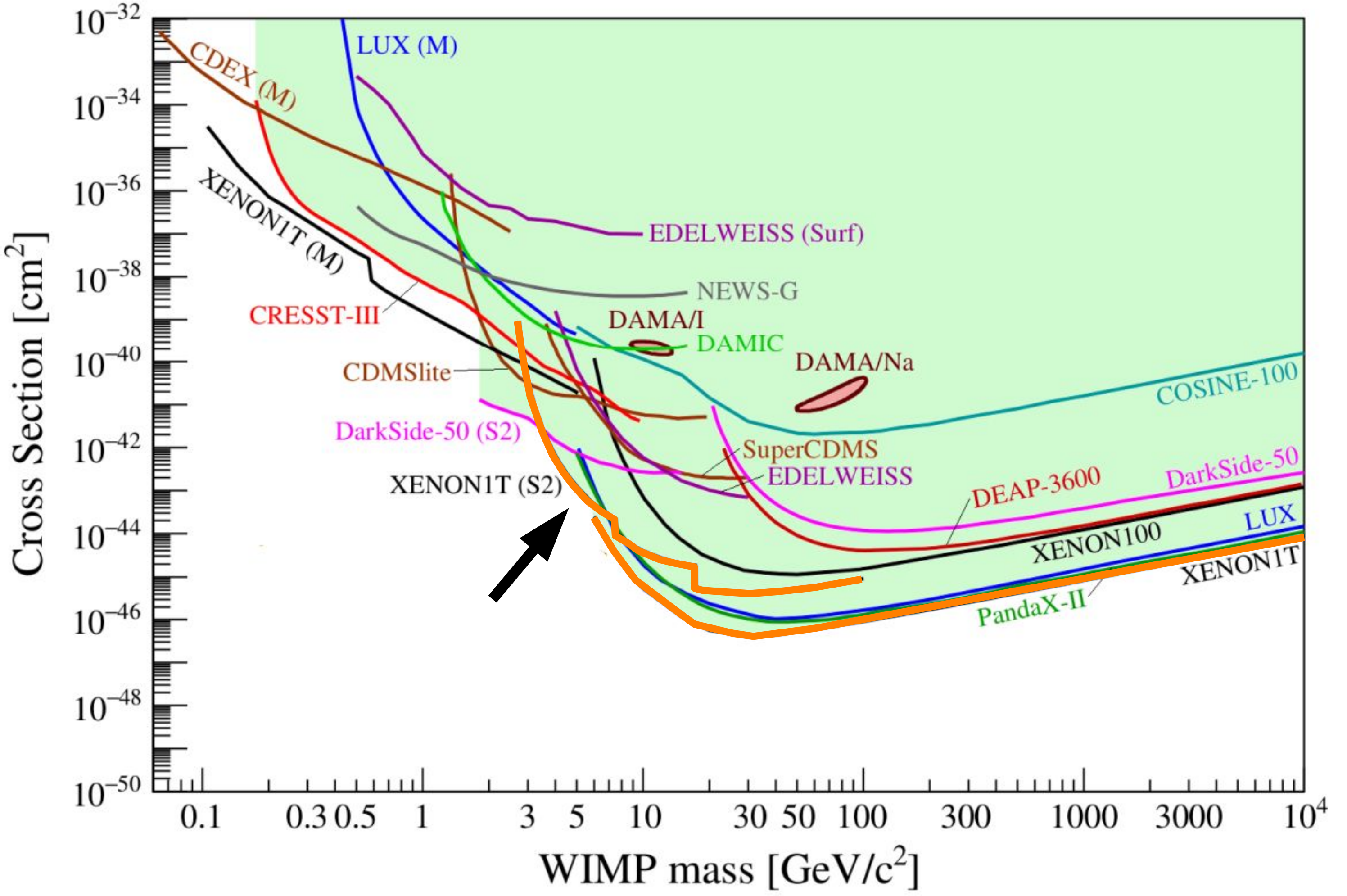


charge-only (S2)

Charge-Only Analysis

PRL 123, 251801 (2019)

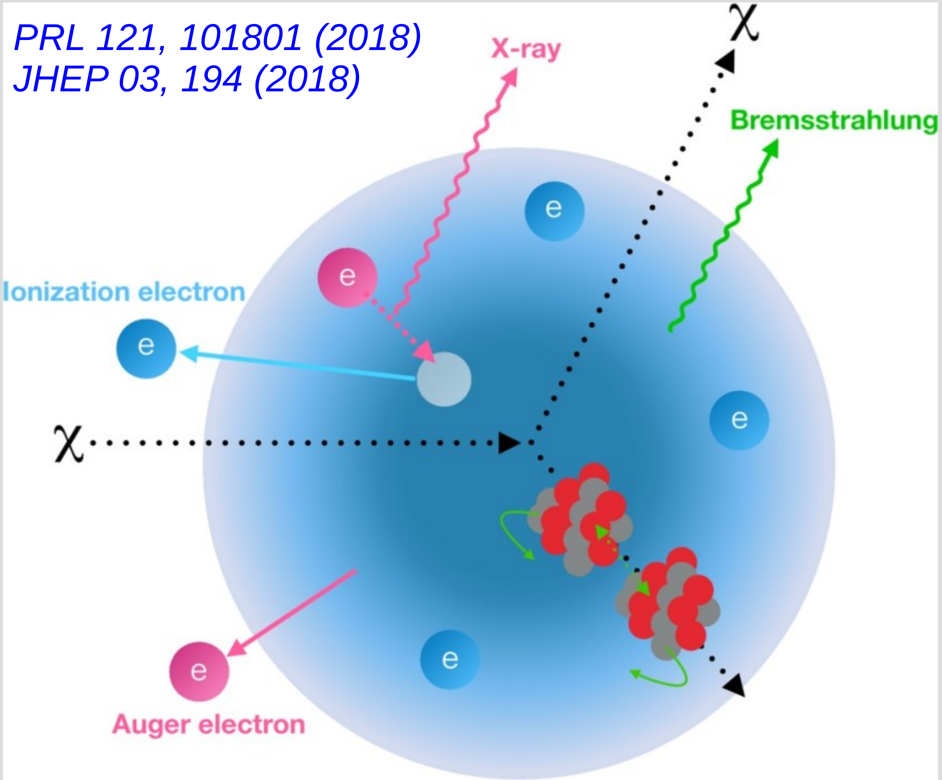
spin-independent WIMP-nucleon interactions

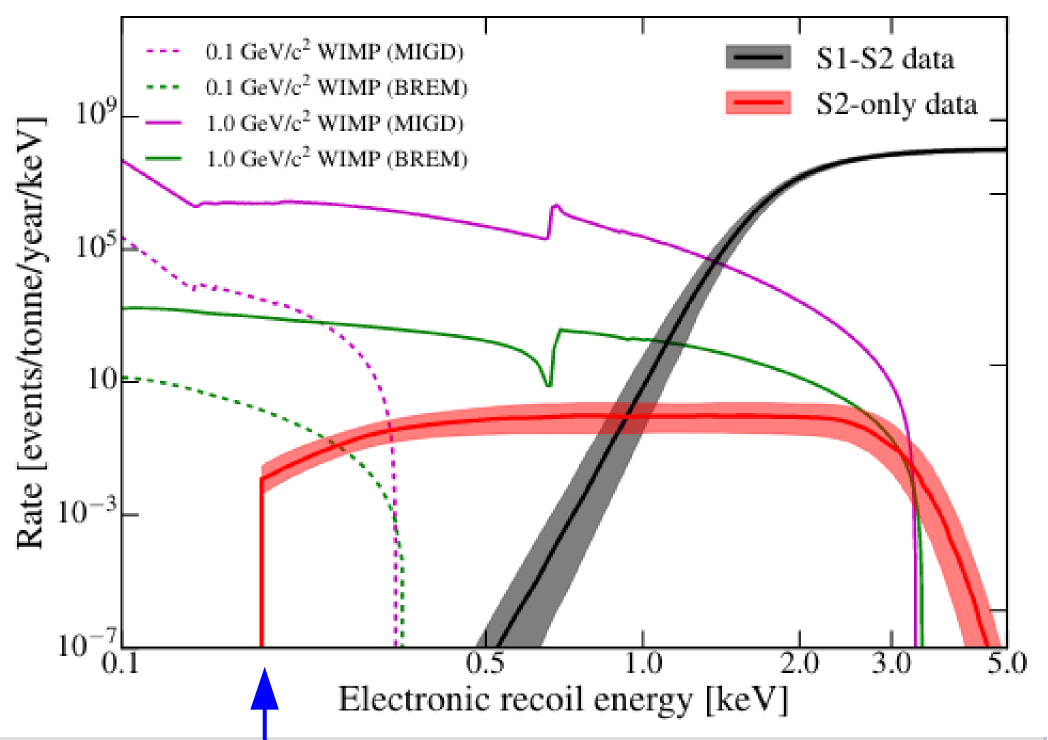


some results are missing...

Migdal Effect, Bremsstrahlung

PRL 123, 241803 (2019)





~180 eV (~4.5 electrons)

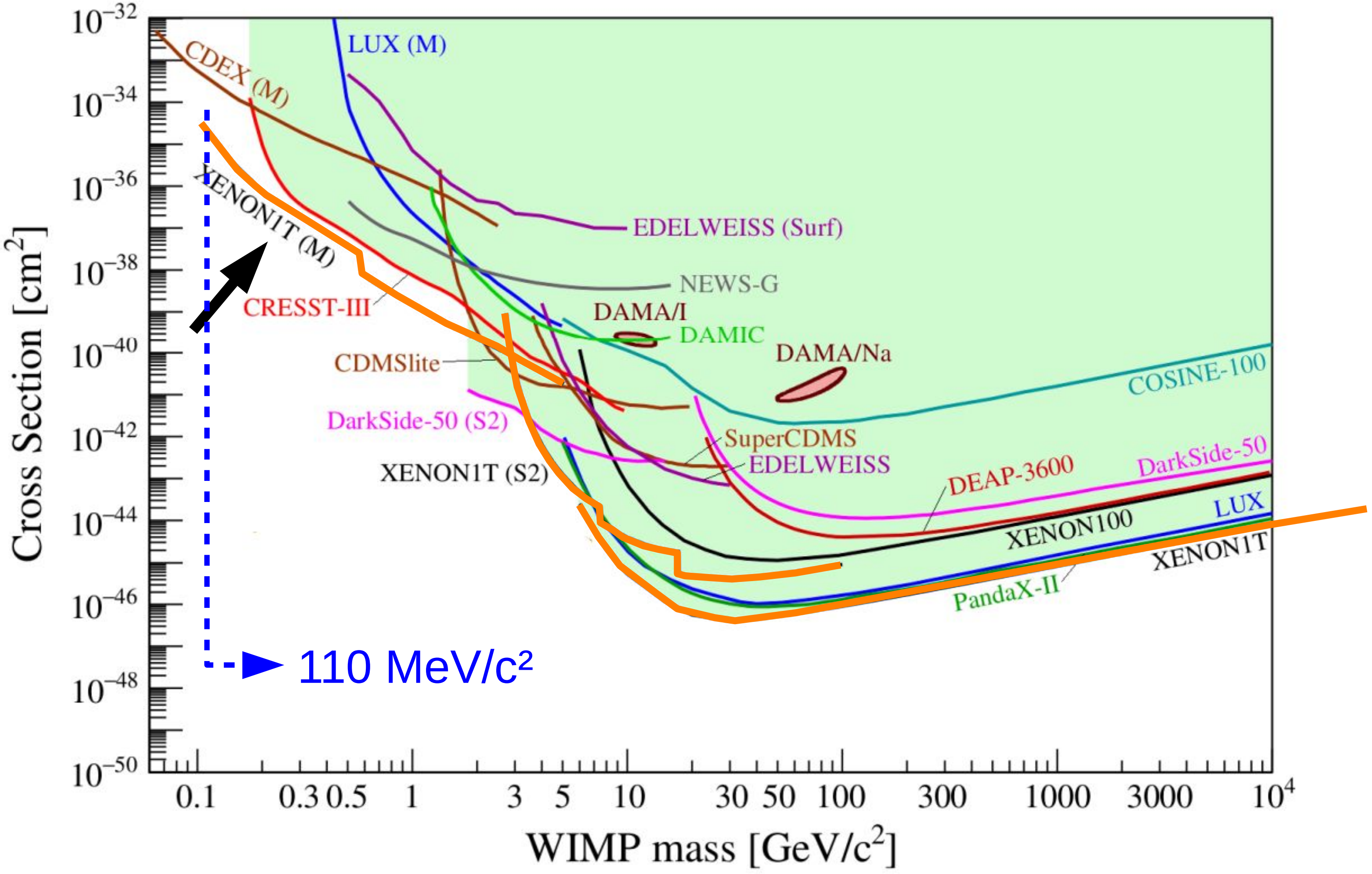
– exploit expected effects after nuclear recoil
→ very low threshold

– caveat: effect not yet observed in calibration

Migdal Analysis

PRL 123, 251801 (2019)

spin-independent WIMP-nucleon interactions



some results are missing...

Selected Results from XENON1T

Low-energy electronic recoils

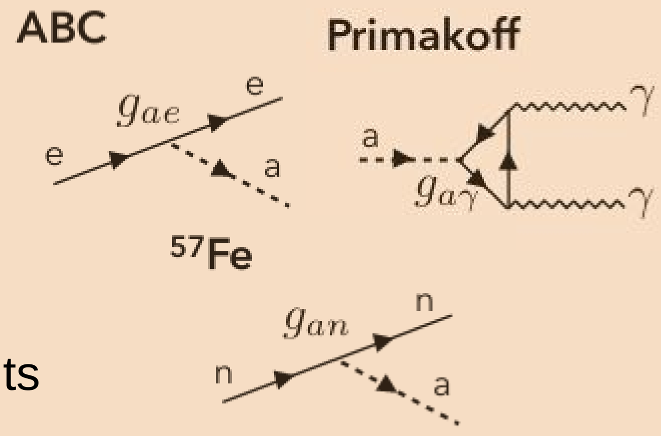
arXiv:2006.09721

New Physics in ER Data

Many models predicts signatures from new physics in low-E ER data.
Our selection:

Solar Axions

- axions: solve strong CP problem and CDM candidate
- if axions exists, production in Sun with E_{kin} ~ keV via
  - **ABC**: atomic recombination/deexcitation, Bremsstr., Compton i/a
  - **Primakoff** $\gamma \rightarrow a$ conversion
  - **^{57}Fe**: 14.4 keV M1 nuclear transition
- normalization of spectra depends on axion coupling constants

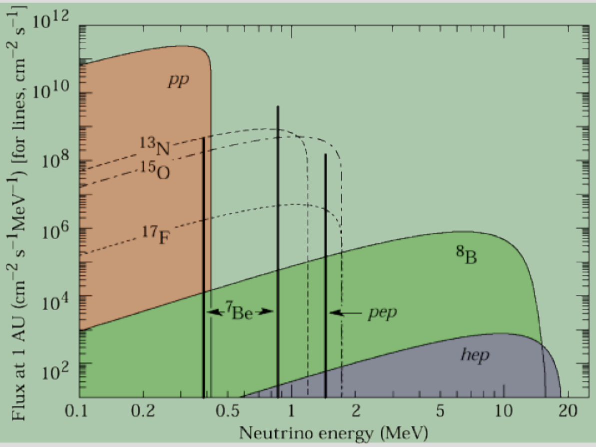


Axion-like Particle (Bosonic ALPs)

- assume all DM is made of non-relativistic ALPs
- expect mono-energetic peak at unknown m_a

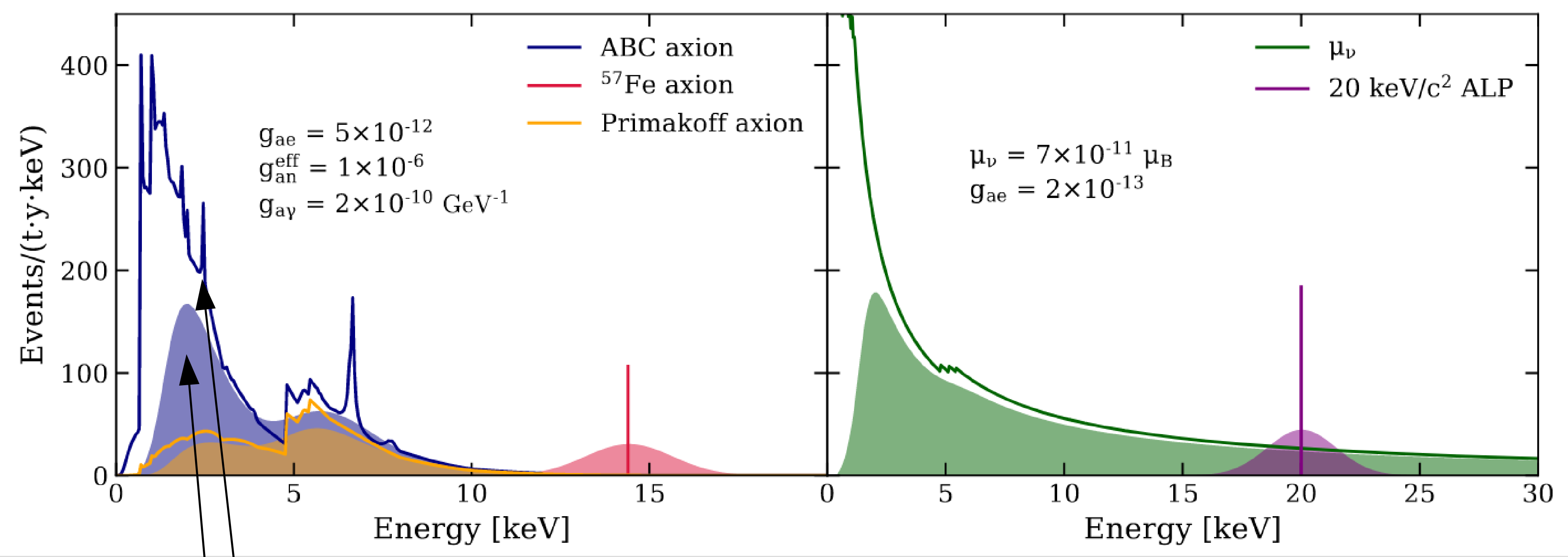
Enhanced Neutrino Magnetic Moment

- expect $\mu_\nu \sim 10^{-20}\ \mu_B$ for massive neutrinos
- BSM physics could enhance μ_ν;
  if $\mu_\nu > 10^{-15}\ \mu_B$ → neutrino is Majorana
- current limit $\mu_\nu < 3\times10^{-11}\ \mu_B$ *Borexino PRD 96, 091103 (2017)*
- i/a cross-section increases with μ_ν^2/E_ν



Detection

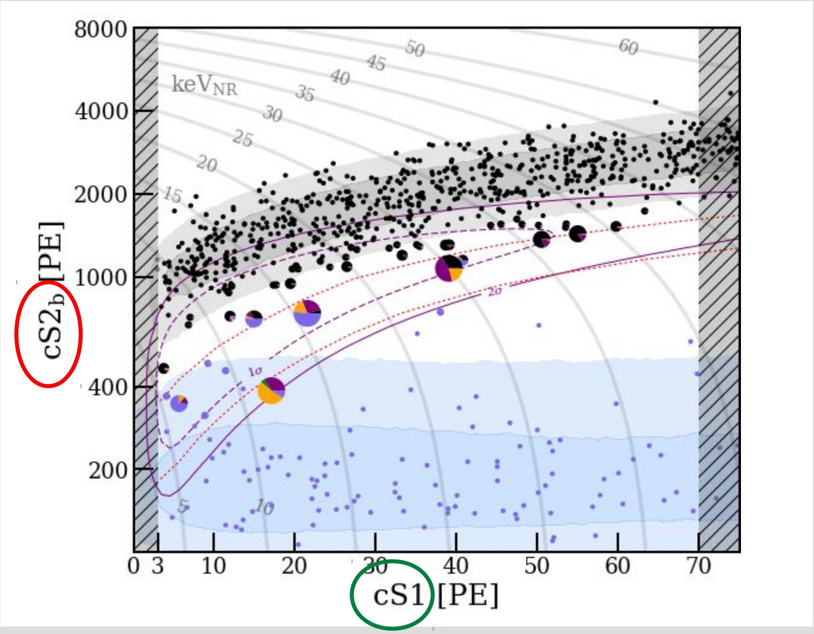
- neutrinos: elastic νe-scattering
- axions/ALPs: **axio-electric effect** ⟶ $\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2}\left(1 - \frac{\beta^{2/3}}{3}\right)$
- detector effects need to be considered: *E*-resolution, detection efficiency



Production ⊗ Detection

Production ⊗ Detection ⊗ Reconstruction

ER Data: Calibration

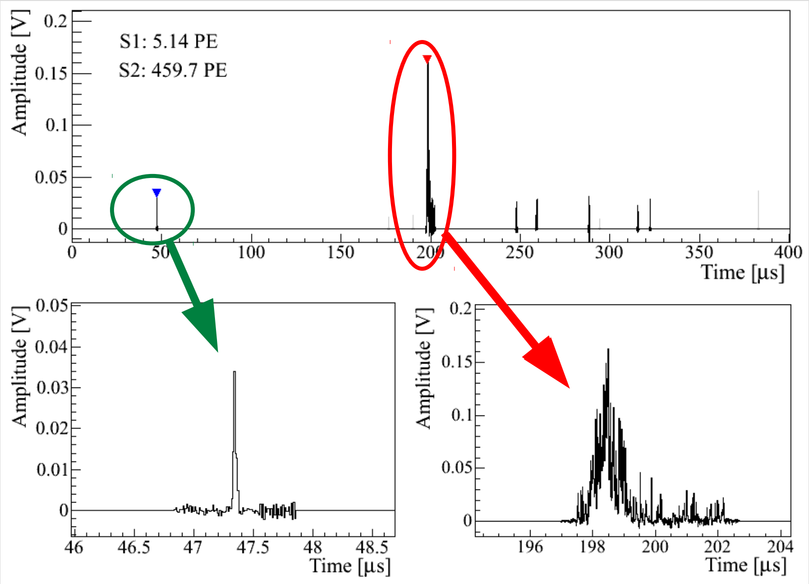


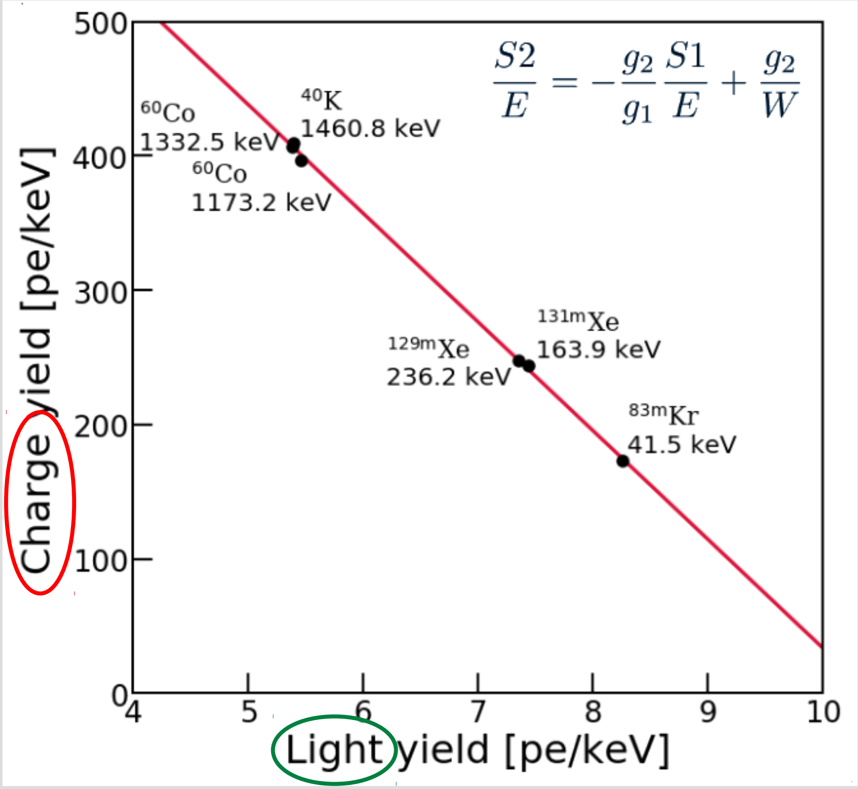
$$E = W(n_{ph} + n_e)$$

$$= W\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$

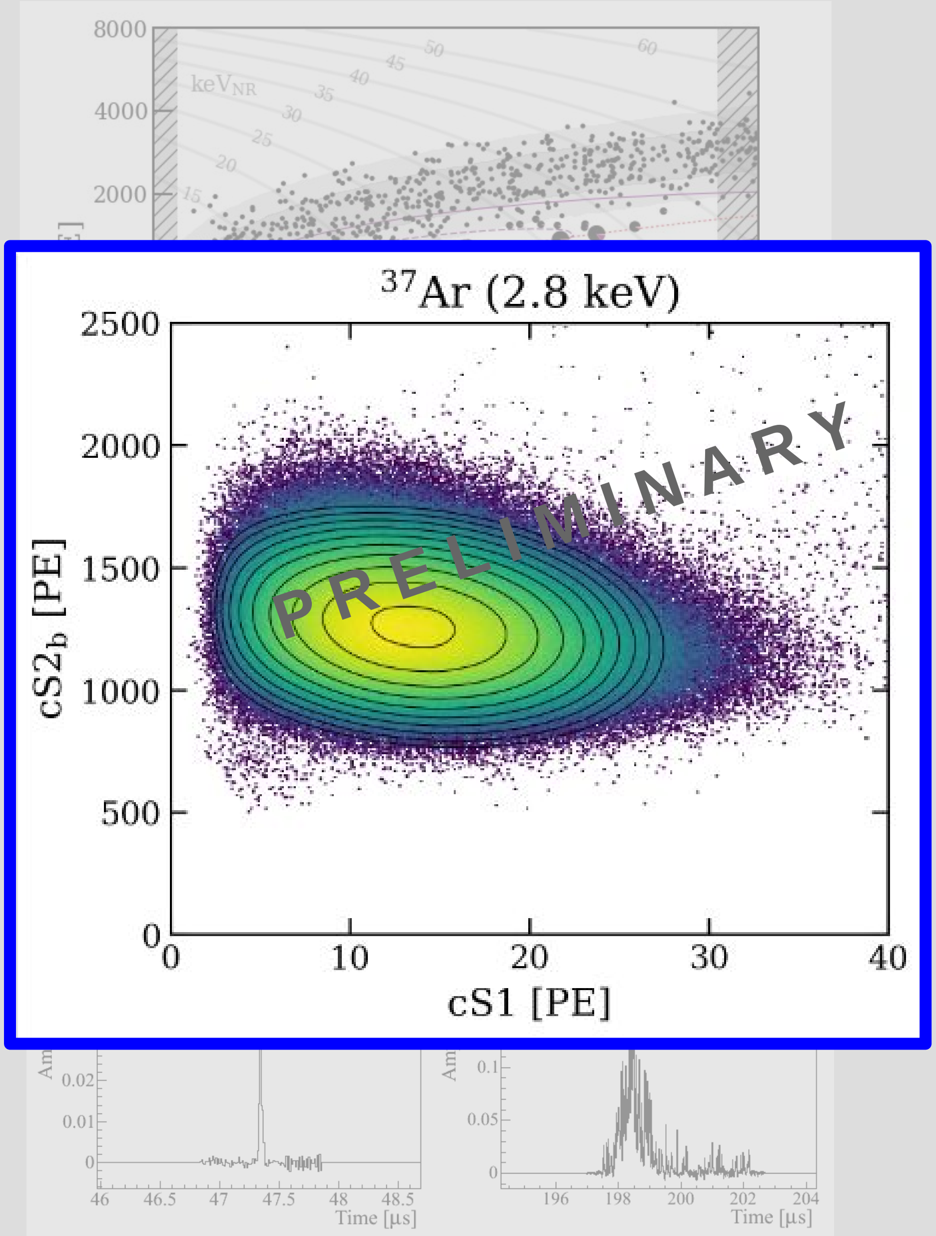
W=13.7 eV/q

Detector specific constants from calibration





ER Data: Calibration



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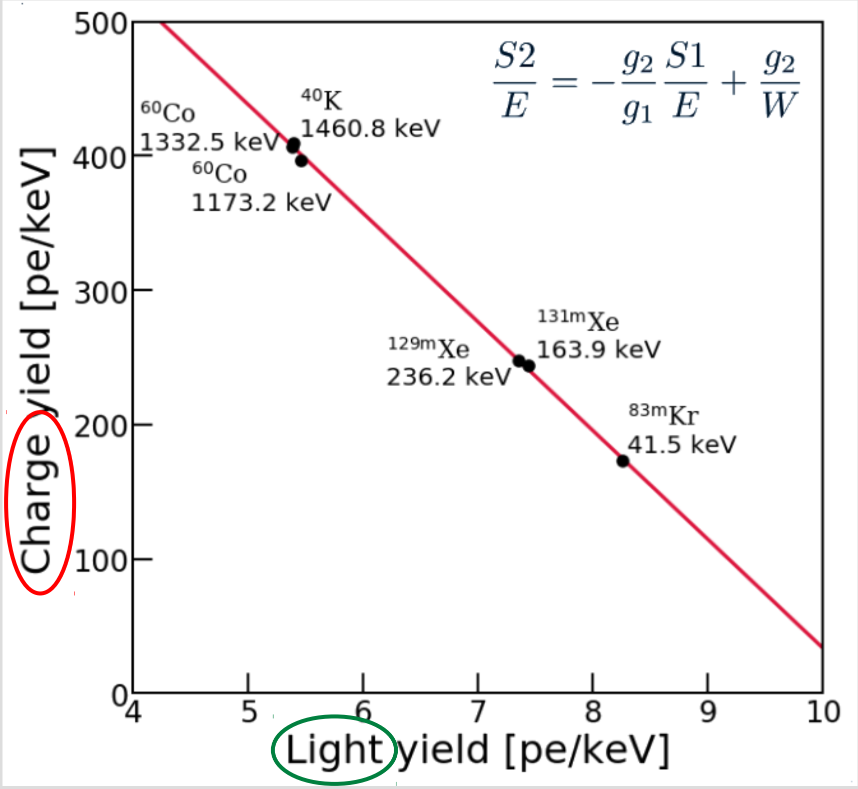
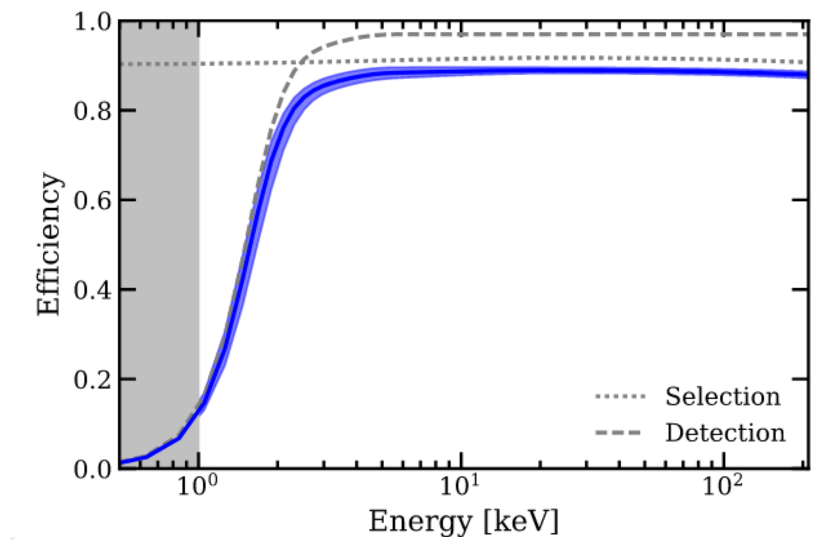
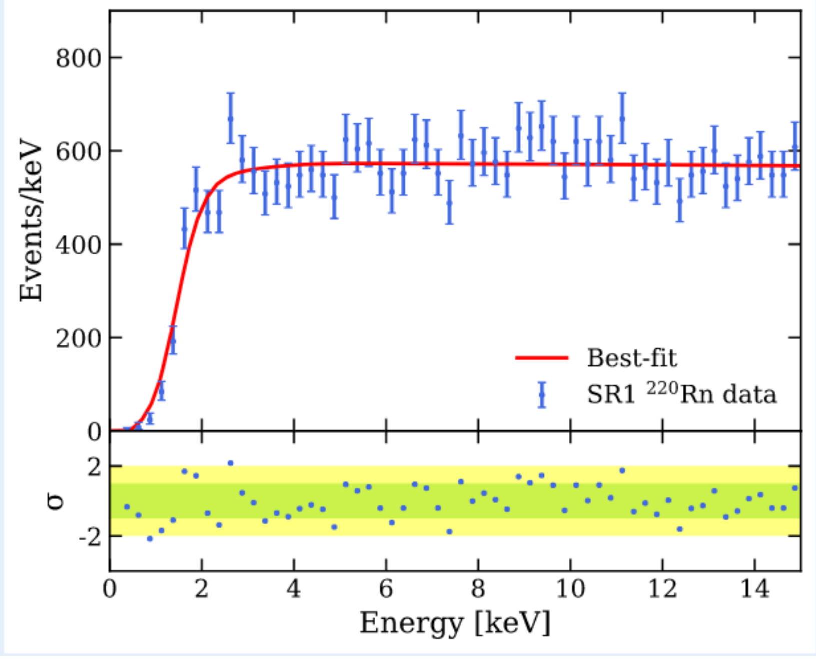
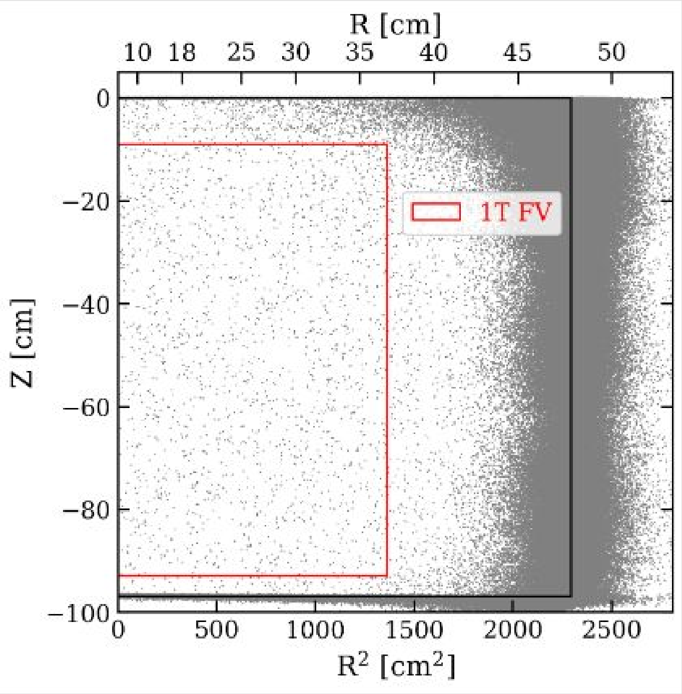


Data Selection and Threshold

- SR1: 226.9 live days
- standard data quality cuts
- single scatter events
- energy range: 1-210 keVee
- inside cylindrical 1.042 t fiducial volume
- **threshold** dominated by 3x PMT requirement
  → from data and waveform simulation,
  tested with Rn220 calibration data

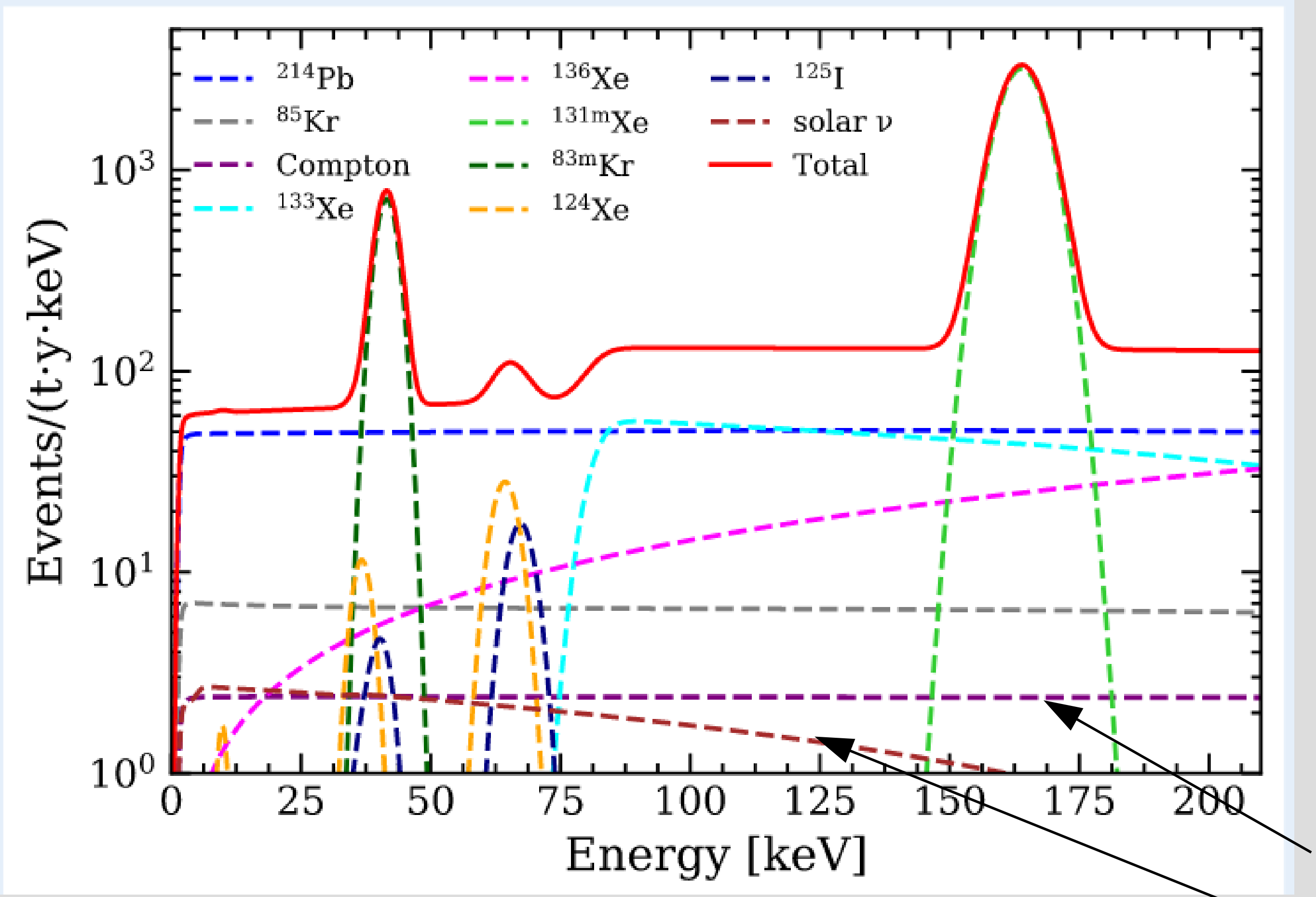






Background Model

10 components



LXe intrinsic:

^{214}Pb (from 222Rn)

^{85}Kr

^{83m}Kr (from calibration)

^{136}Xe (2νββ)

^{124}Xe (2νDEC)

→ *today's signal is tomorrow's background*

From neutron-activation:

^{131m}Xe (IC)

^{133}Xe (β+81 keV γ)

^{125}I (EC)

→ *divide data in two periods: close/far from n-calibration*

Detector materials

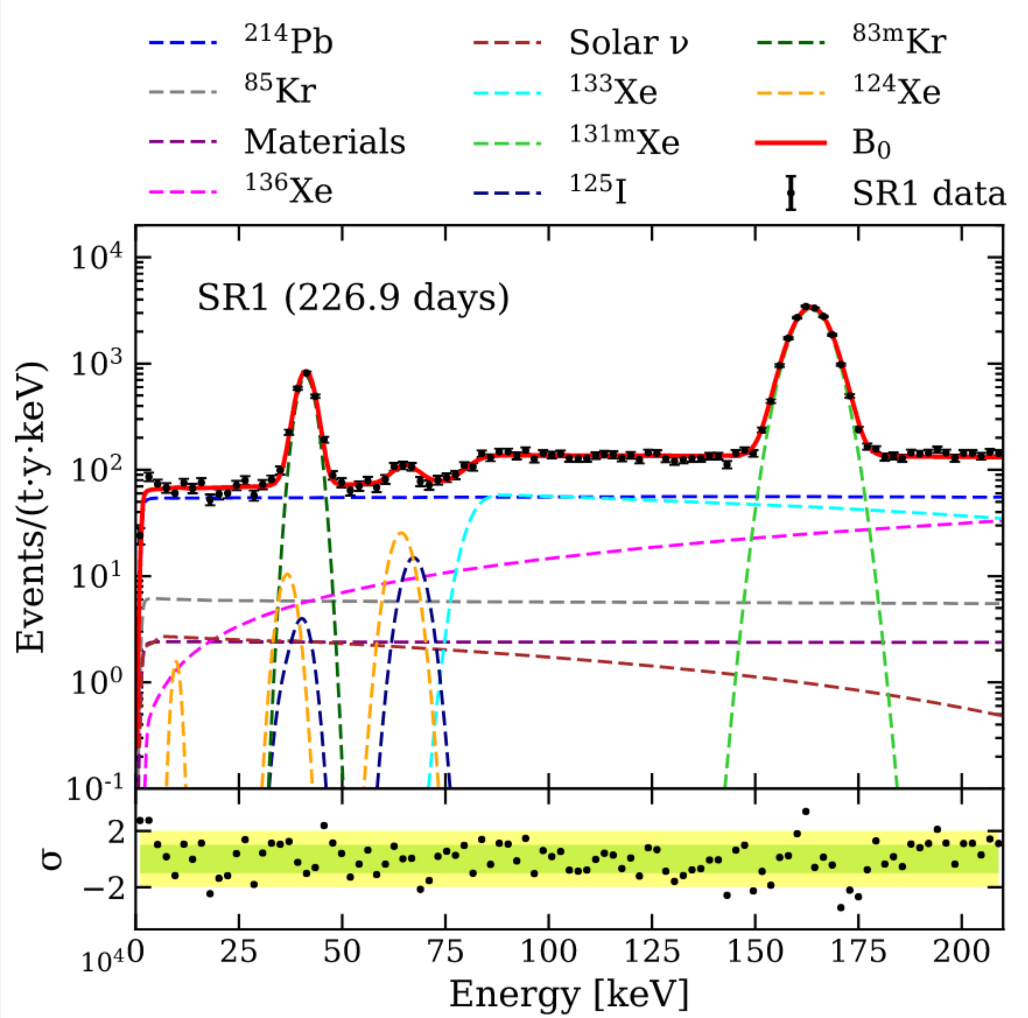
Solar neutrinos

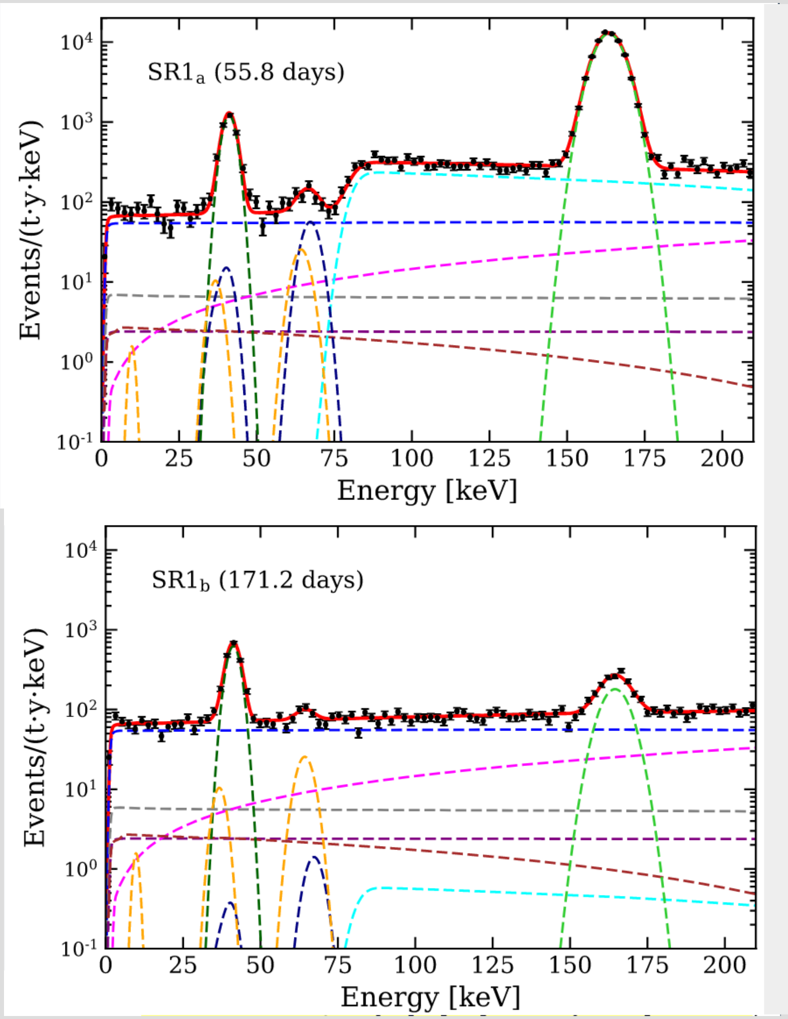
Background Fit

- unbinned profile likelihood fit to data
- combined fit of data close/far to neutron calibration

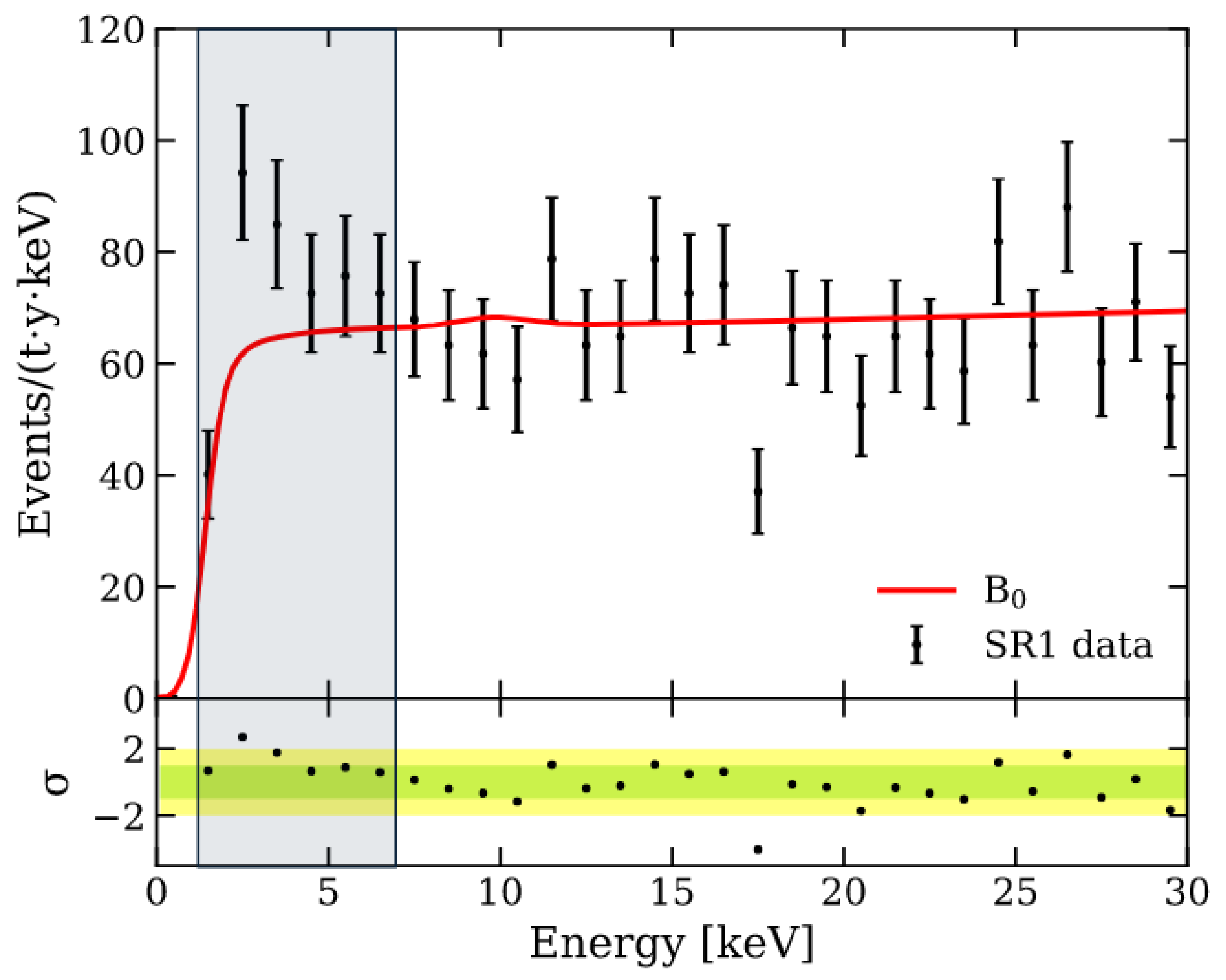
(76 ± 2) evts/(t y keV) in 1-30 keV

→ world record background level!





Excess of Events



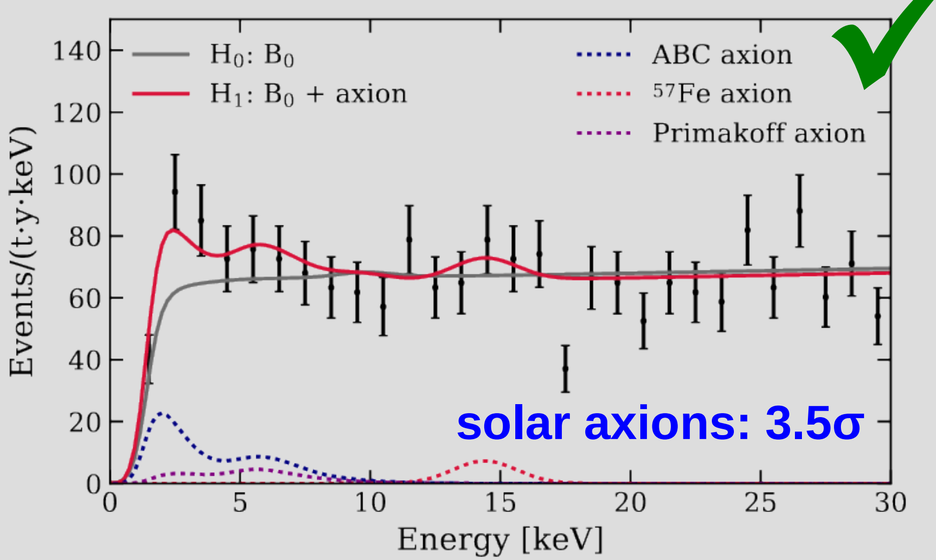
- **excess in 1-7 keV range**
  285 evts observed vs
  232 ± 15 expected
  → **(naive) 3.3σ fluctuation**

- events uniformly distributed
  – in space
  – in time (but low stats)

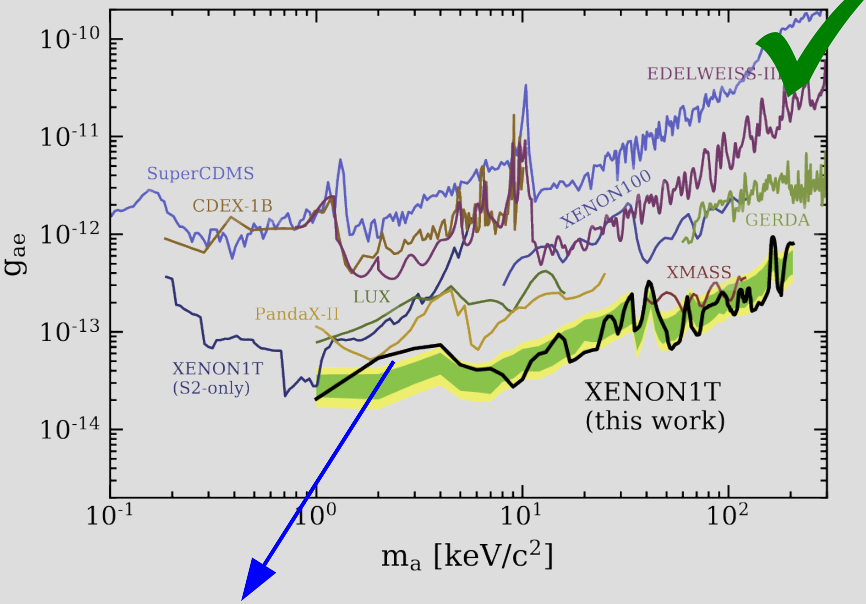
- far away from typical WIMP artefact backgrounds
  – accidental coincidences
  – surface background

What causes it????

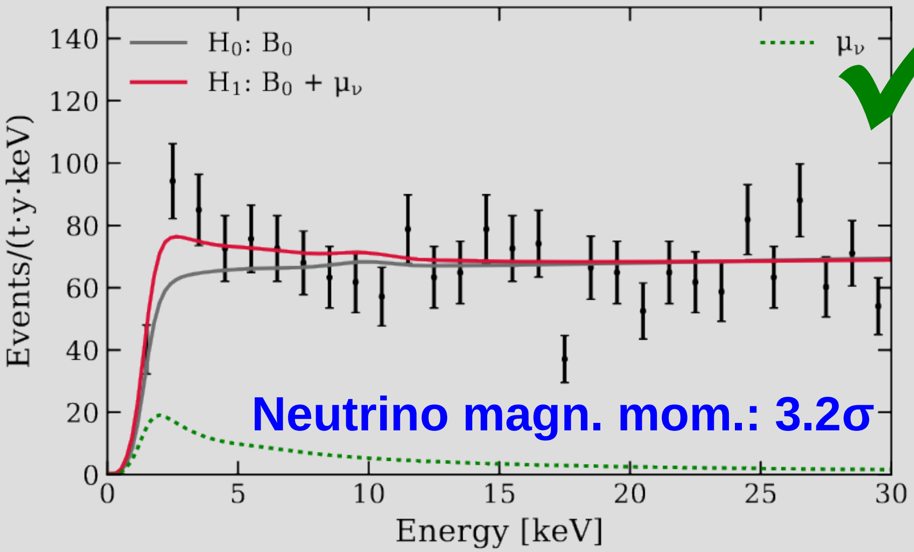
BSM Signal Models?



solar axions: 3.5σ



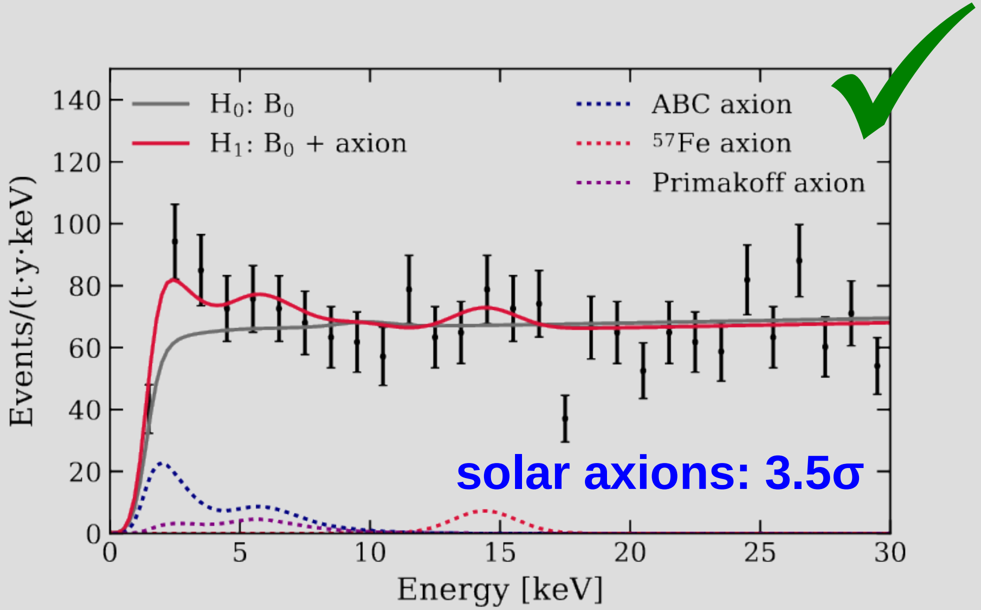
Bosonic ALPs
3.0σ global (4.0σ local)
@ m_a=2.3±0.2 keV



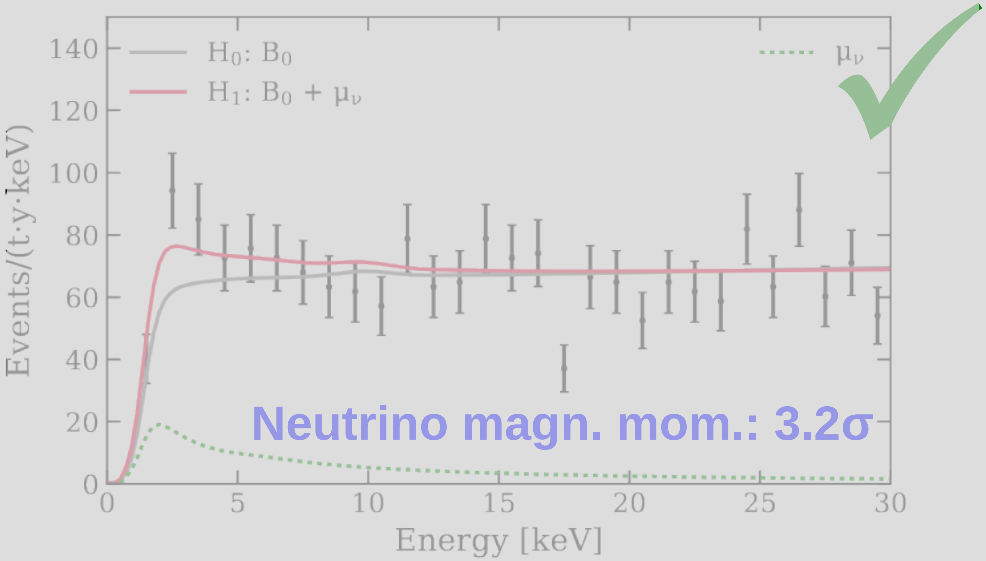
Neutrino magn. mom.: 3.2σ

… and many others since we made our result public.

BSM Signal Models?

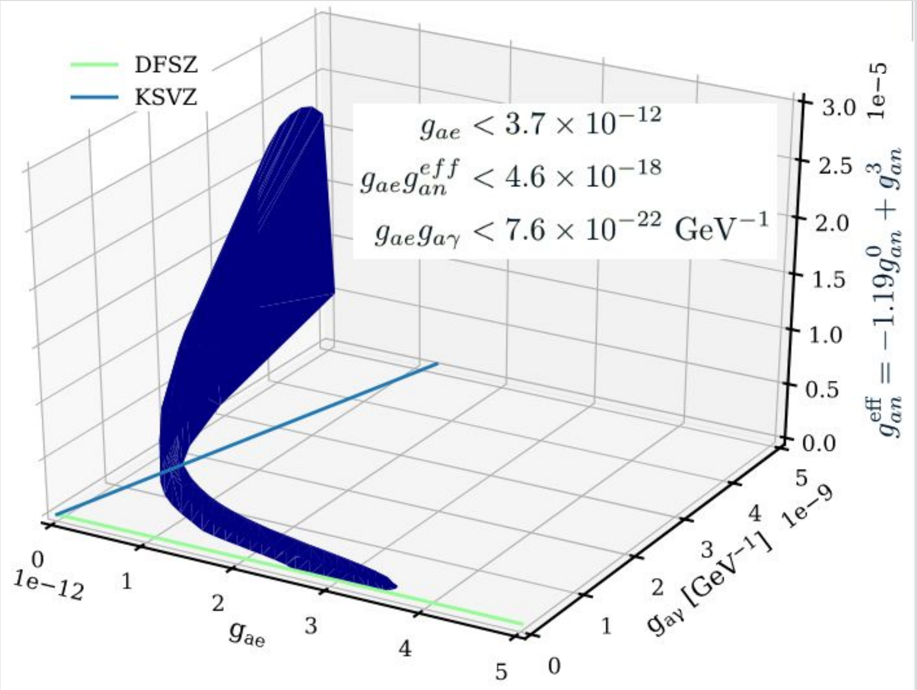


solar axions: 3.5σ



Neutrino magn. mom.: 3.2σ

Assume (not claim!) that the entire excess is caused by solar axions

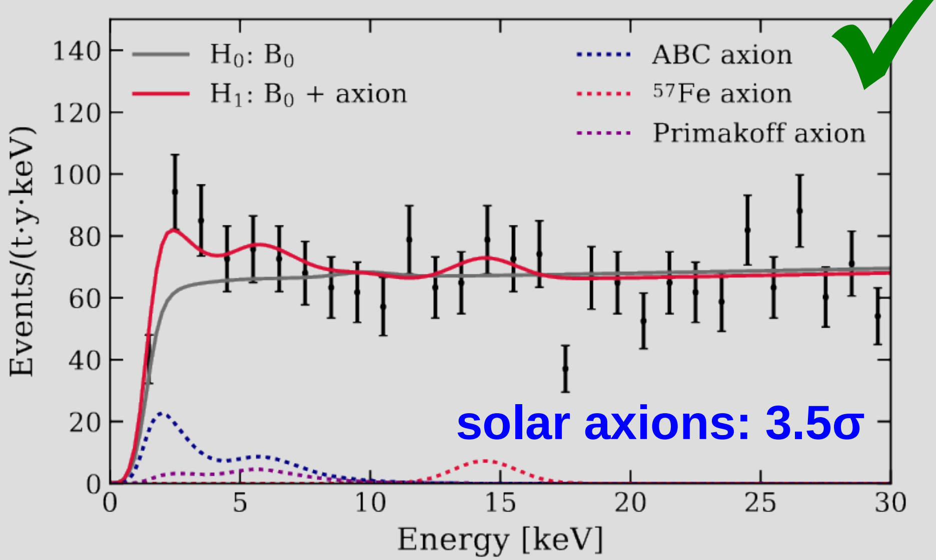


3d 90% CL volume excludes one of:

$g_{ae} = 0$

$g_{a\gamma} = g_{an}^{eff} = 0$

BSM Signal Models?



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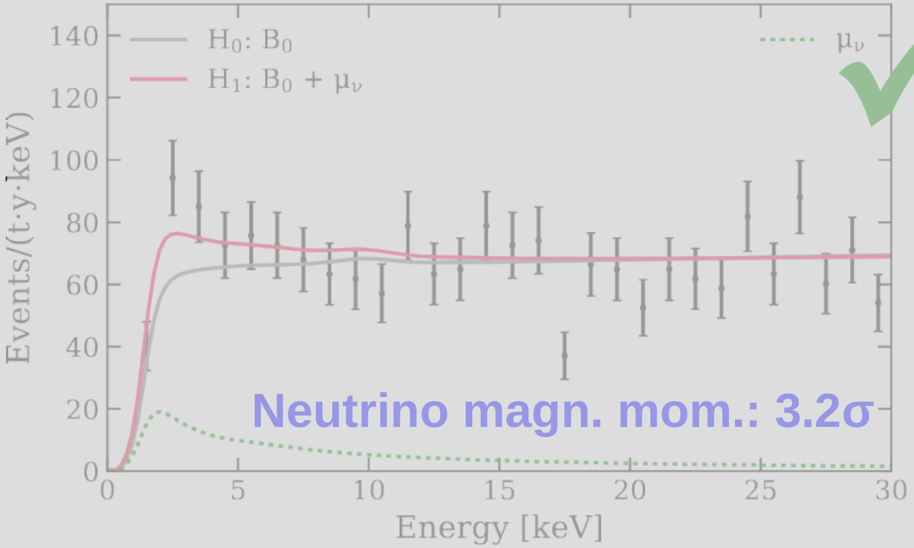
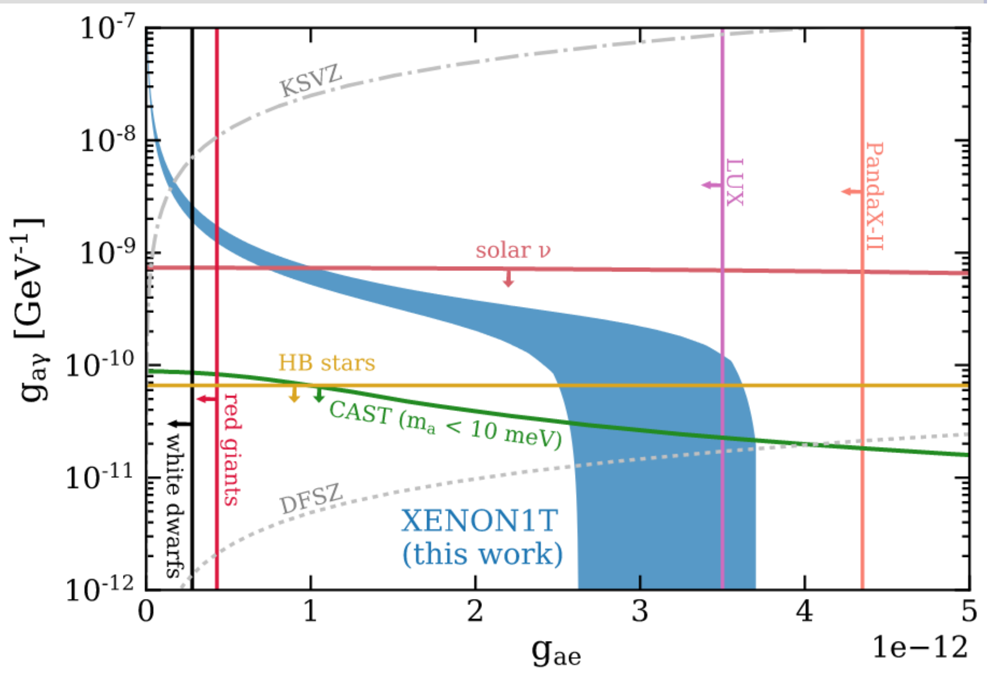


Neutrino magn. mom.: 3.2σ

<u>Assume (not claim!)</u> that the entire excess is caused by solar axions

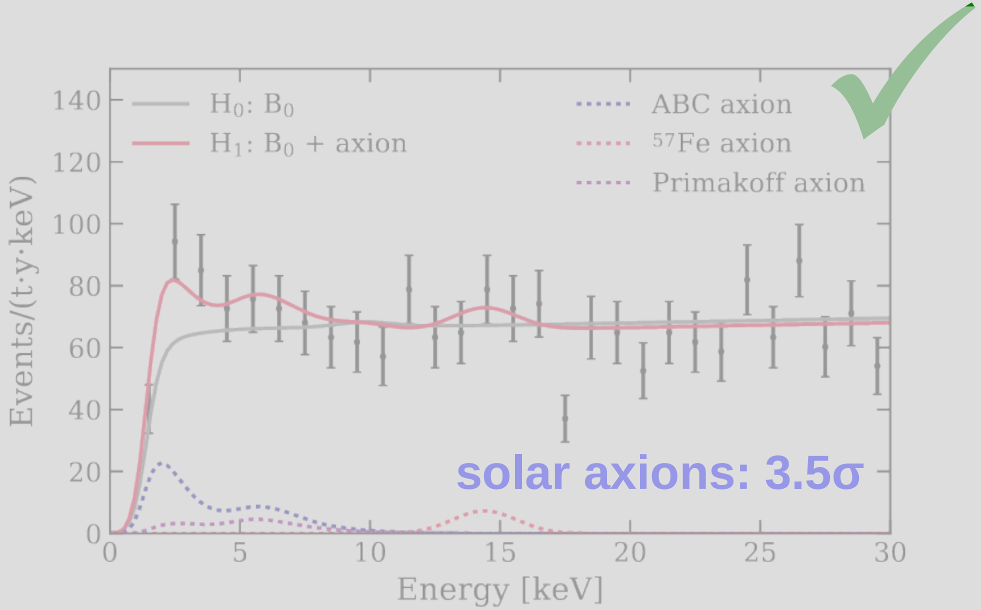


- projection onto $g_{a\gamma}$ vs. g_{ae} plane
- in conflict with astrophysical contraints

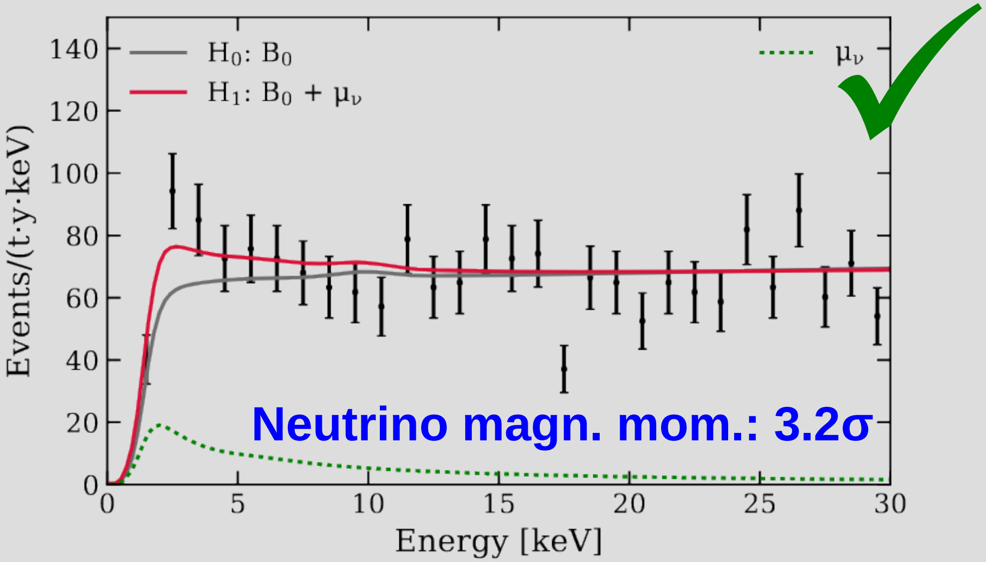
  arXiv:2003.01100
- new: considering **inverse Primakoff effect** for detection weakens tension

  arXiv 2006.14598

Neutrino Magnetic Moment?



solar axions: 3.5σ



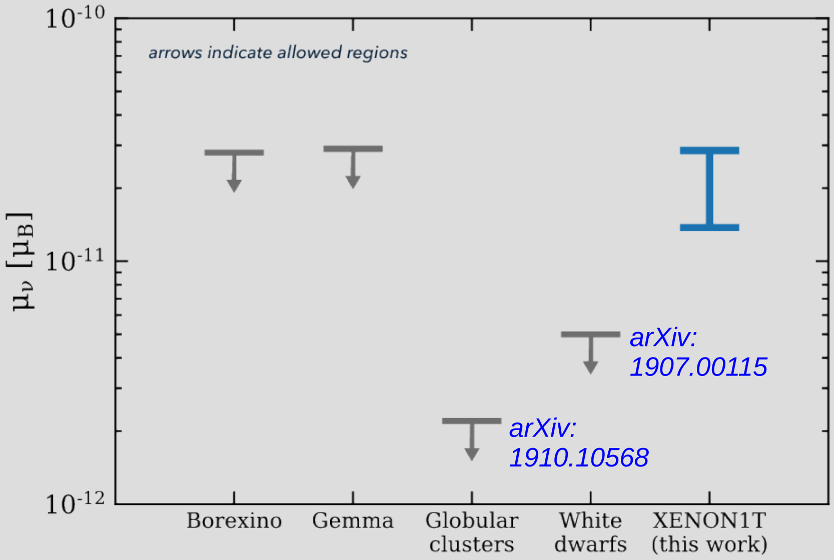
Neutrino magn. mom.: 3.2σ

<u>Assume (not claim!)</u> that the entire excess is caused by an enhanced μ_ν

$$\mu_\nu = [1.4, 2.9] \times 10^{-11}\ \mu_B$$

(90% CL interval)

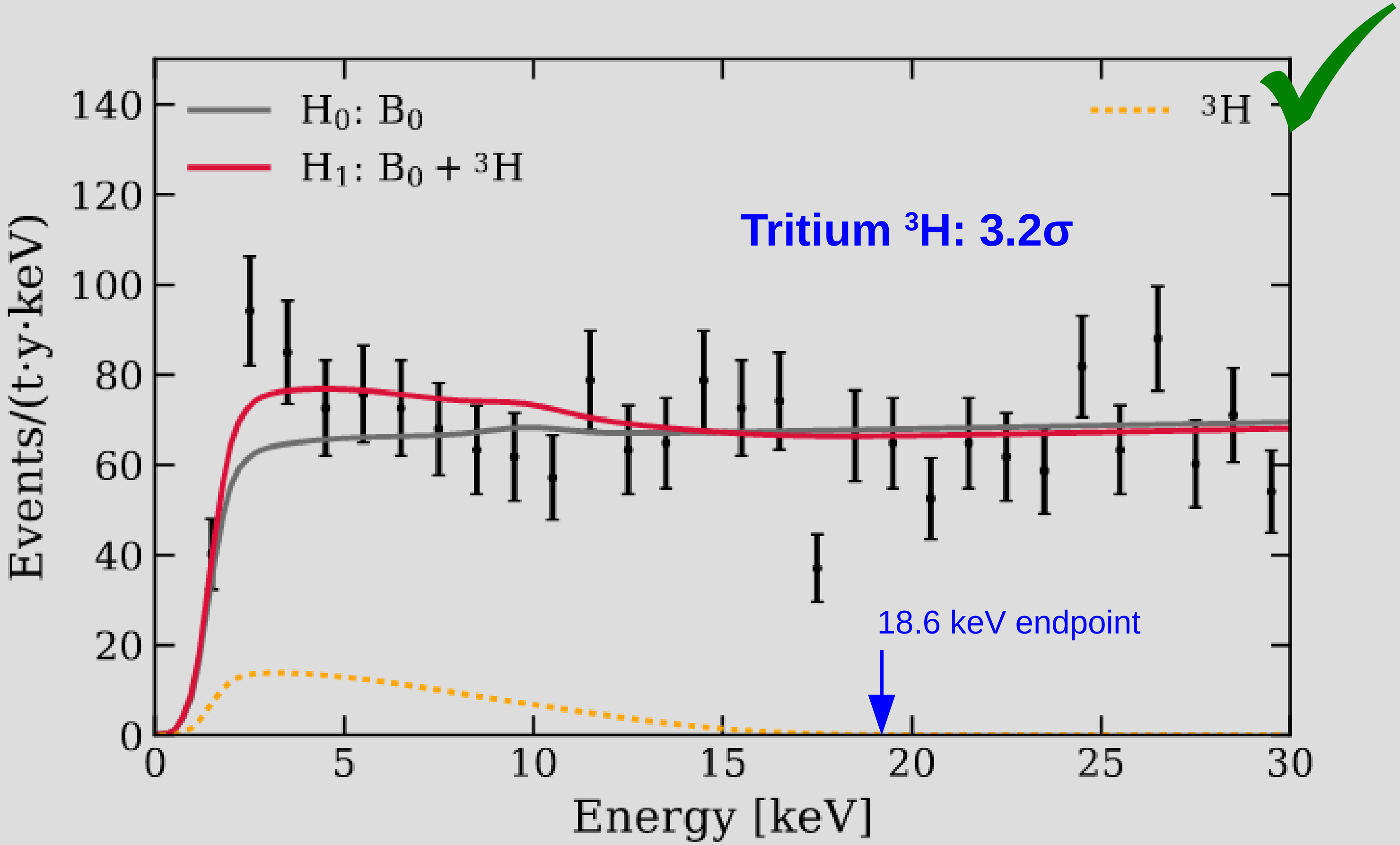
- compatible with experiments
- tension with astrophysical constraints



arXiv: 1907.00115

arXiv: 1910.10568

Tritium: A new background?

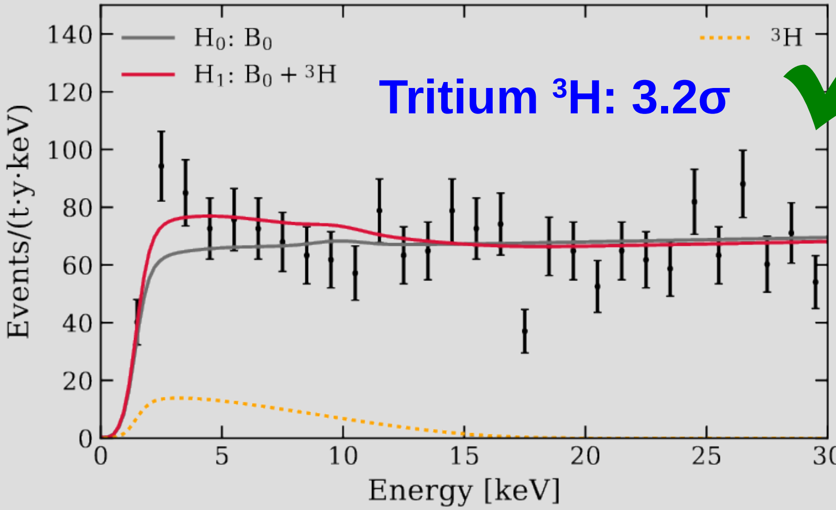


Tritium ^{3}H: 3.2σ

18.6 keV endpoint

- **cosmogenic production** by Xe-spallation or present in H_2O (outgassing from walls)
  → ONLY above-ground activation relevant!
- half-life = 12.3 y → ~constant in our dataset
- ^{3}H:Xe concentration from fit: (6 ± 2) × 10^{-25} mol/mol → <3 ^{3}H atoms per kg of Xe

Tritium: A new background?



Tritium ${}^3H$: 3.2σ ✓

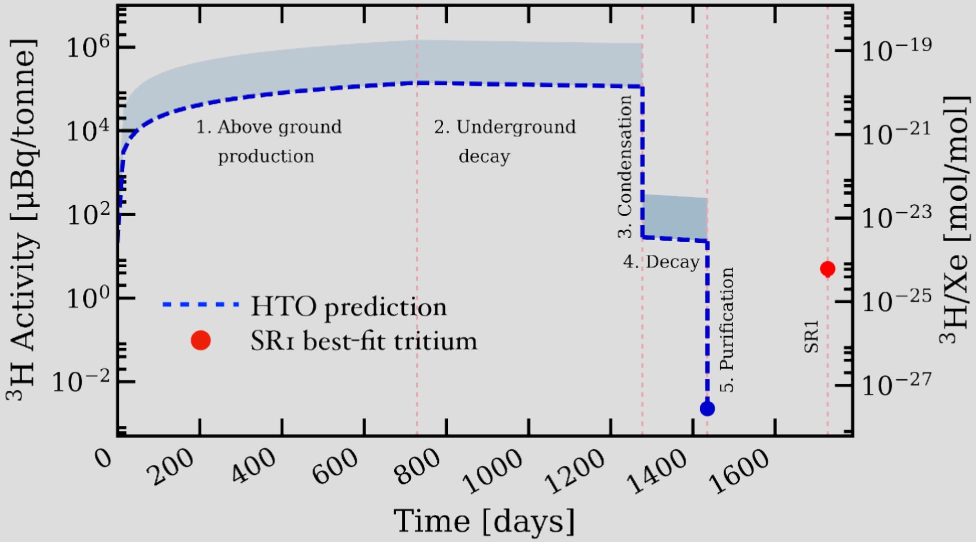
Many unknowns about ${}^3H$ in LXe

- Radiochemistry? Formation of molecules?
- Diffusion of tritiated molecules?
- Desorption? Emanation?
- No direct measurent for H_2 nor HT

At this point, we can neither confirm nor exclude the presence of tritium!

${}^3H$ from spallation of Xe

- expect 32 ${}^3H$-atoms/kg/day
- ${}^3H$ is reactive → forms HTO in Xe gas
- HTO is effectively removed from Xe
- expected activity 100x lower than from excess



Emanation of gases containing ${}^3H$ into LXe

- HTO from initial H_2O contamination
  → unlikely: required concentration spoils purity
- Tritiated hydrogen HT?
  → no direct measurement but could explain excess if 100x more H_2 than other molecules

Excess Summary

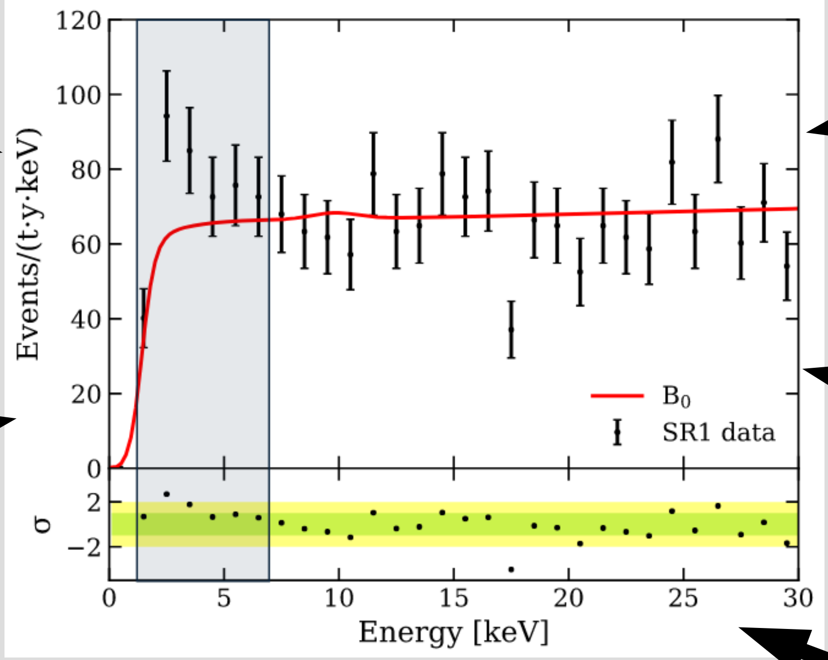
arXiv:2006.09721

We see an excess of low-E ER events above our known backgrounds.

Tritium ^{3}H ✓

Neutrino μ_ν ✓

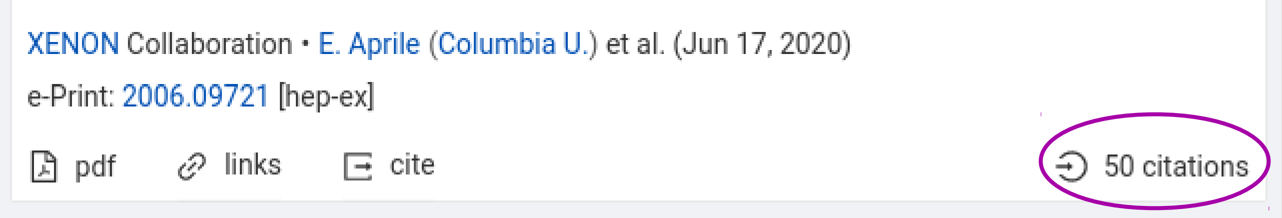
Artefacts ✗



Solar Axions ✓

Bosonic ALPs ✓

and many others... ✓



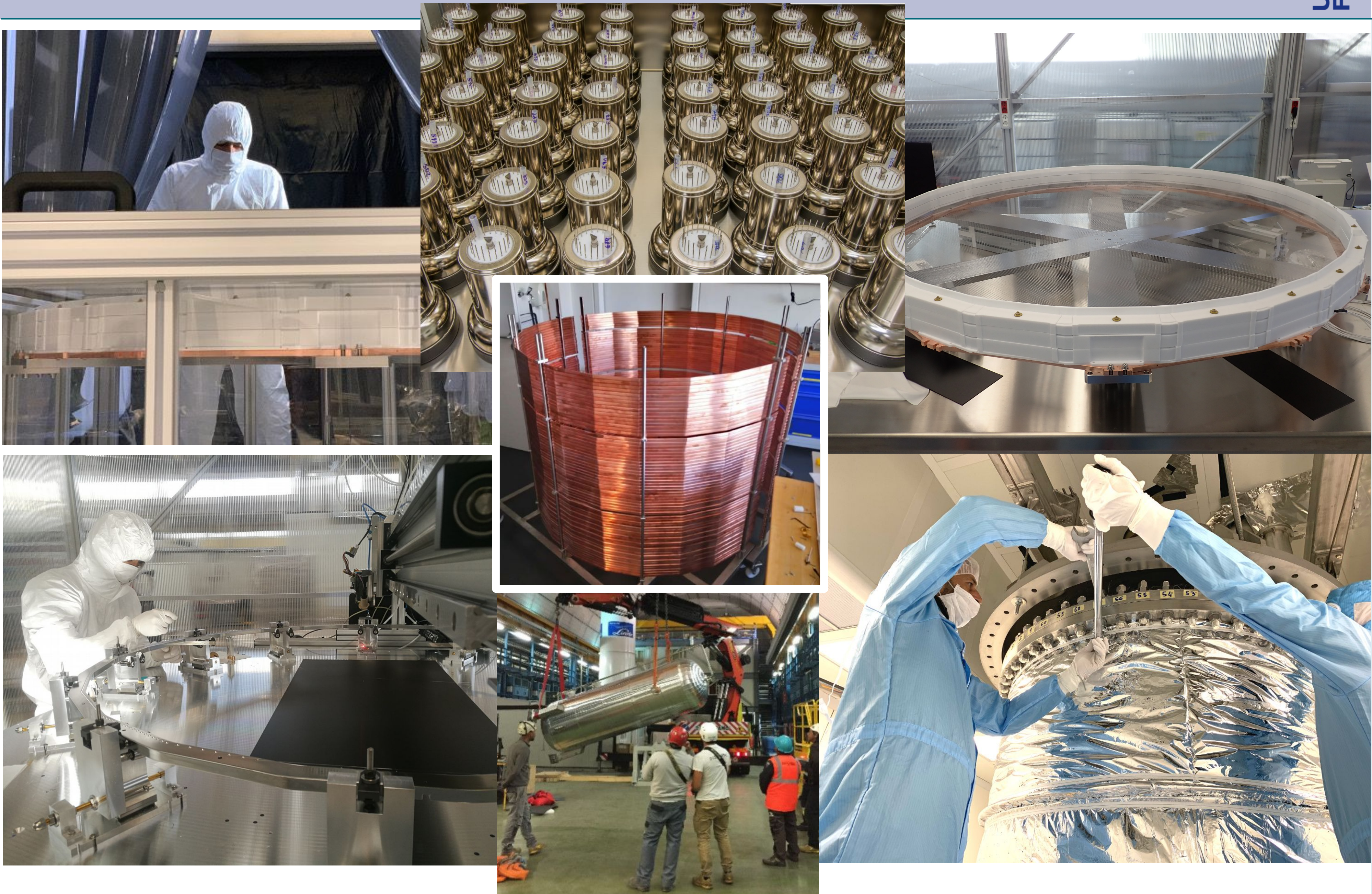
Observation of Excess Electronic Recoil Events in XENON1T

#1

XENON Collaboration • E. Aprile (Columbia U.) et al. (Jun 17, 2020)

e-Print: 2006.09721 [hep-ex]

XENONnT: The new instrument

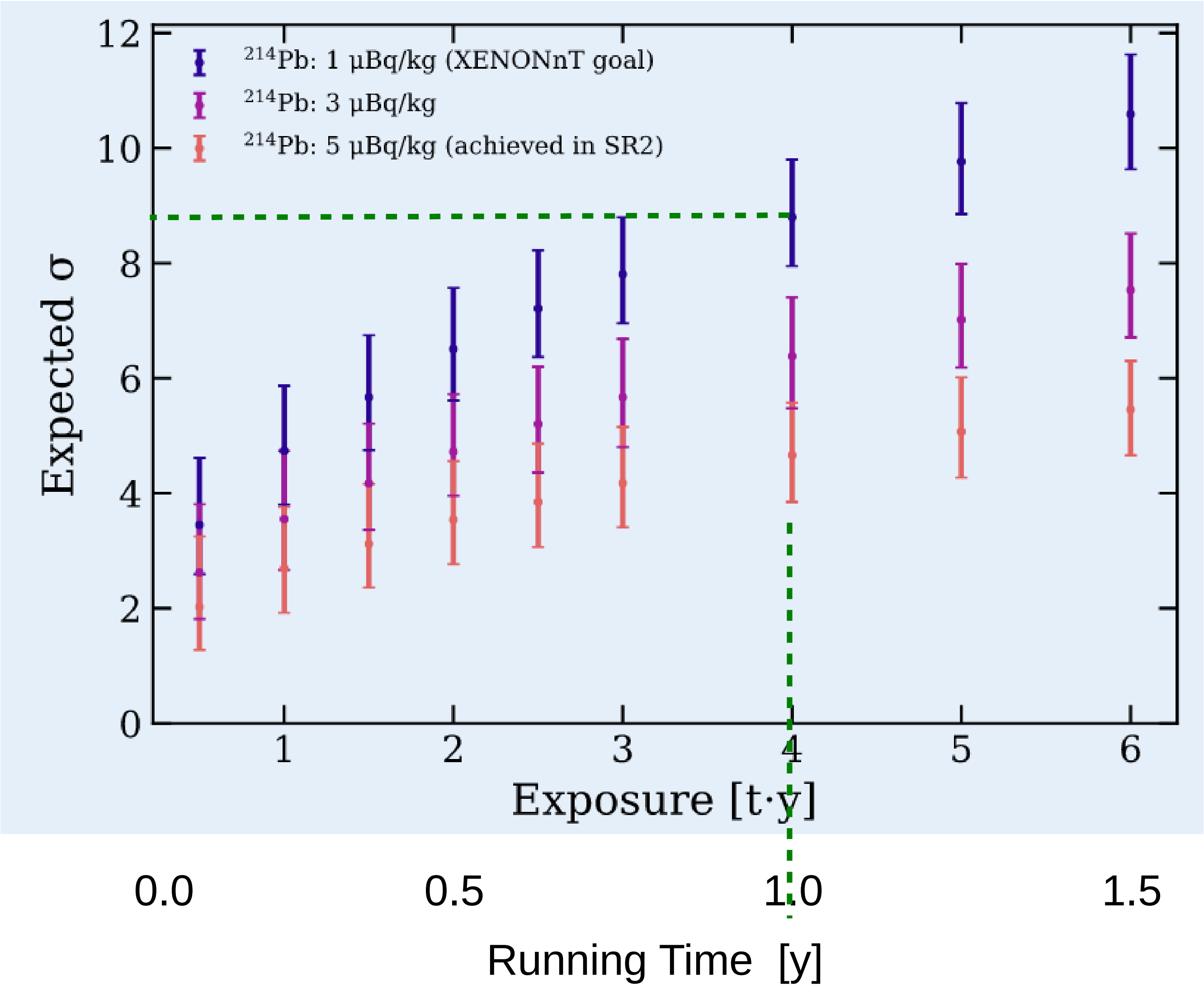


XENONnT

- – target mass ×3
- – background ×0.16
  → online Rn-removal
- – liquid Xe purification

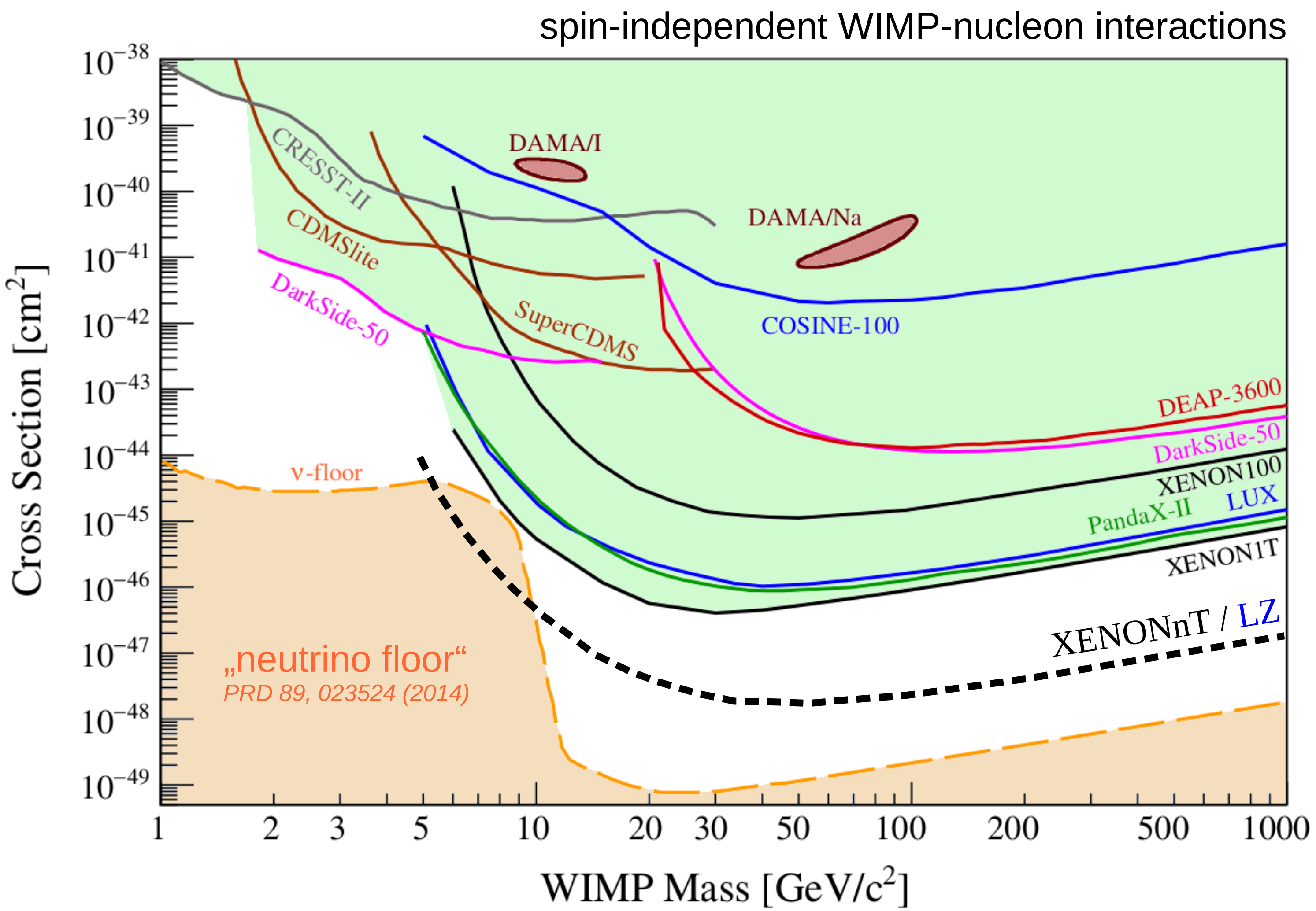
XENONnT: Axions vs. Tritium

- assume excess persists and is from solar axions
- **How much data is needed to distinguish it from ³H?**
- exploit differences in spectral shape
- sensitivity depends on background level



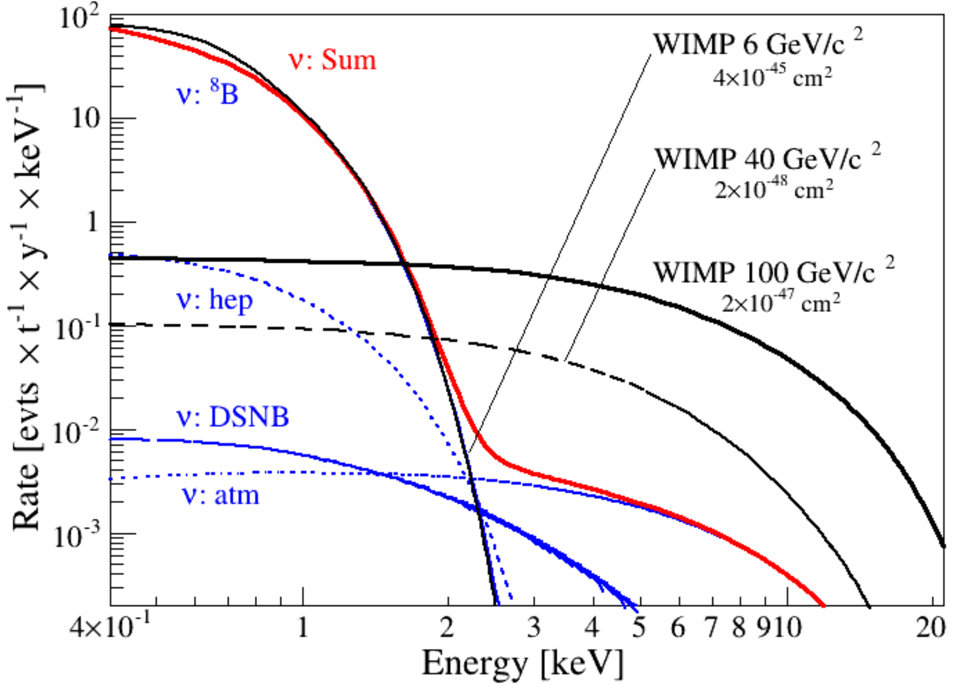
assume 4t FV and no calibration

XENONnT Sensitivity Goal

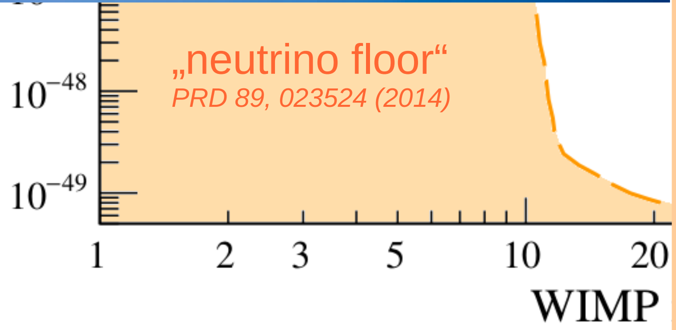


some results are missing...

The ultimate Limit



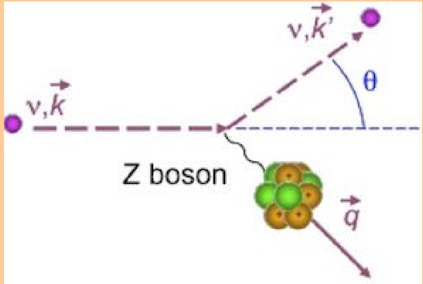
JCAP 01, 044 (2014)



„neutrino floor“

PRD 89, 023524 (2014)

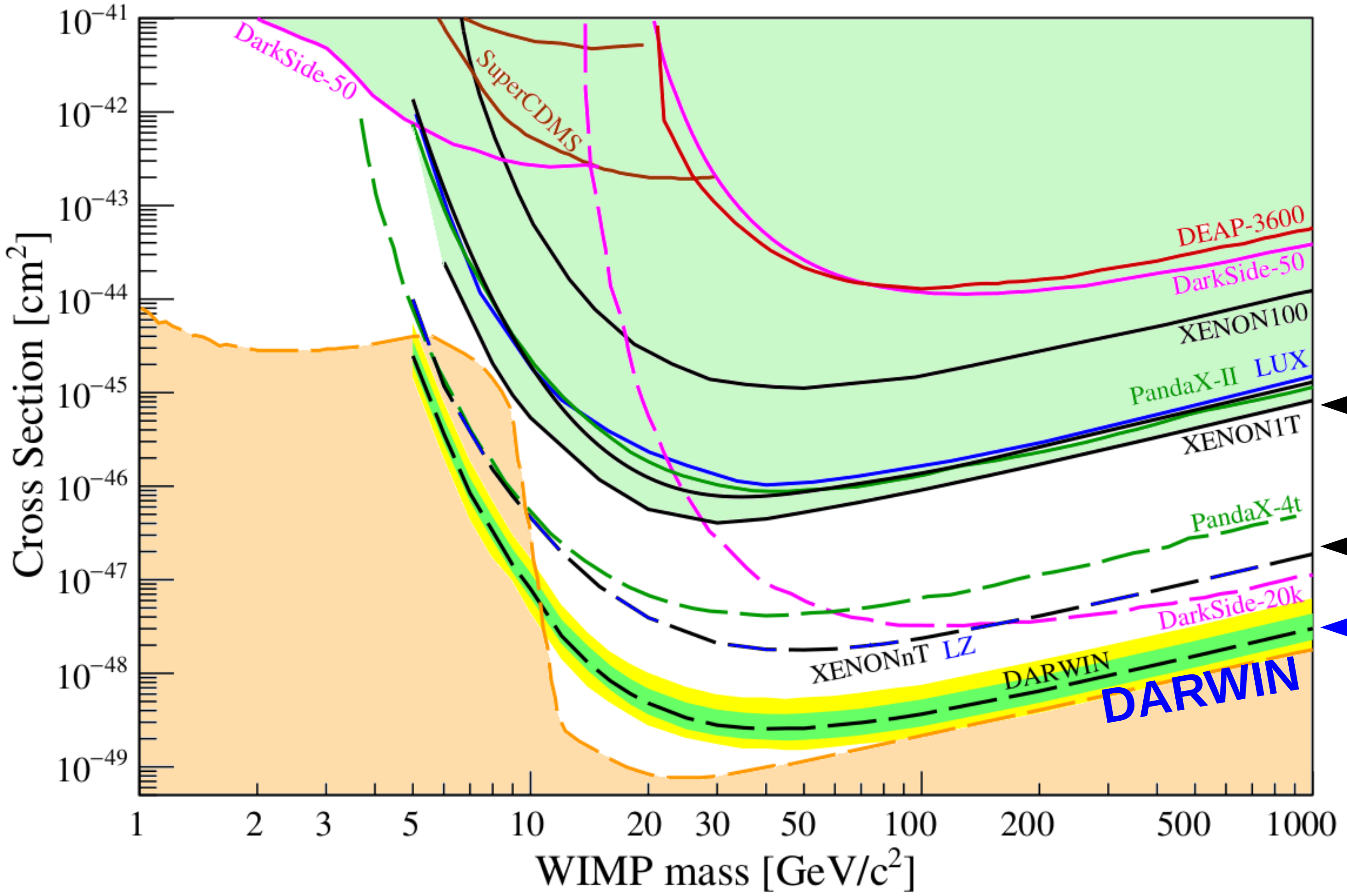
Interactions from coherent neutrino-nucleus scattering (CNNS) will dominate
→ **ultimate background** for direct detection



DARWIN The **ultimate** WIMP Detector

LXe-based

darwin-observatory.org



Exposure

1 t×y

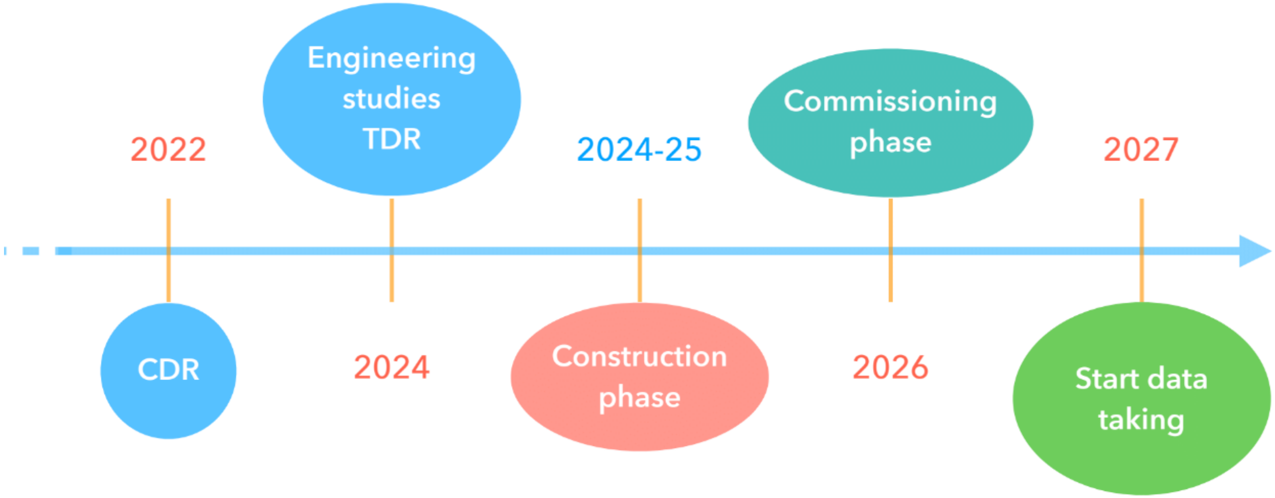
20 t×y

200 t×y

DARWIN

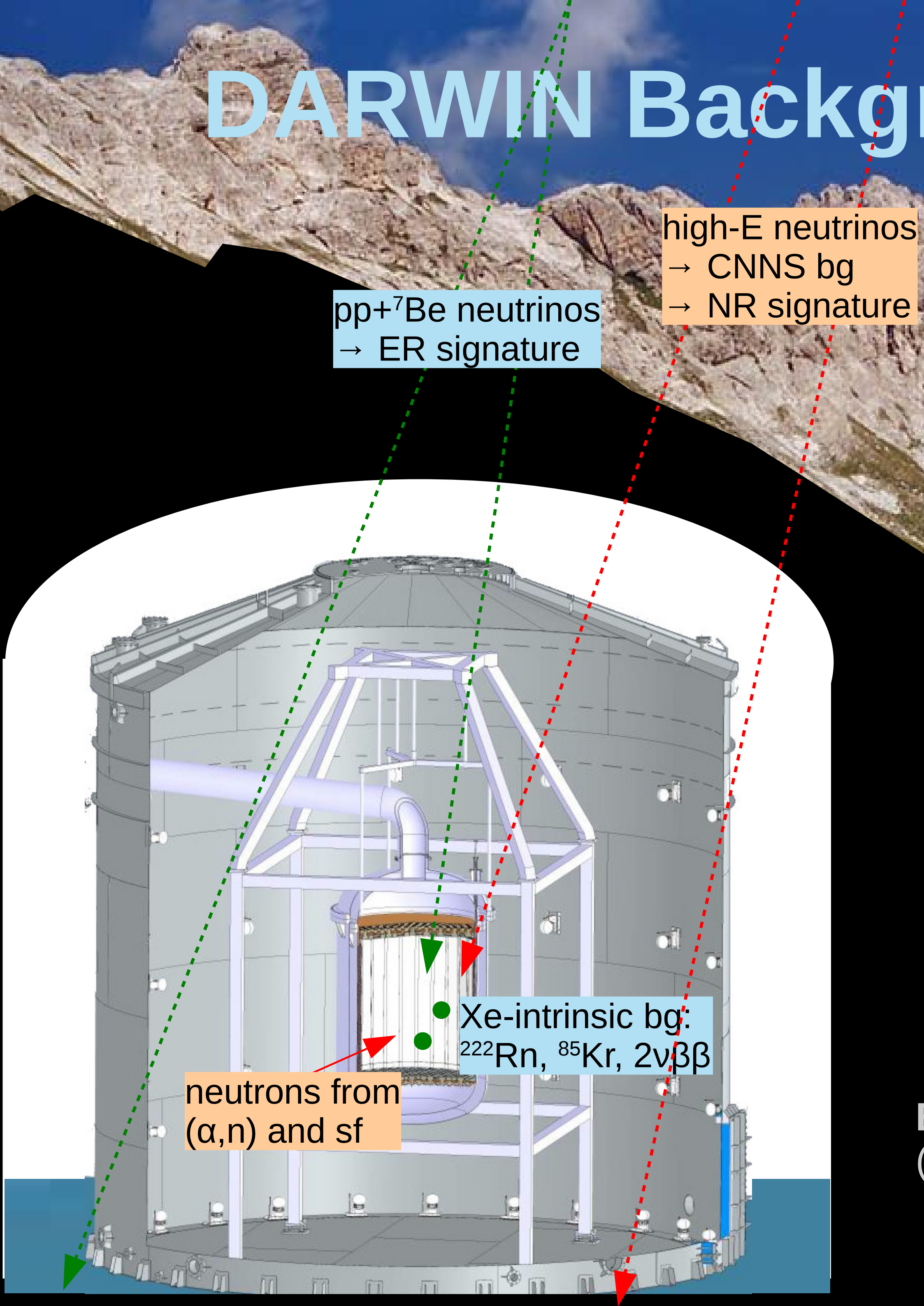
www.darwin-observatory.org

- aim at sensitivity of a few 10^{-49} cm^2, limited by **irreducible ν-backgrounds**
- international collaboration, 30 groups, ~160 scientists
  → continuously growing
- endorsed by several national and international agencies
- preparing CDR for LNGS
- Timescale: start after XENONnT



2022
CDR
Engineering studies TDR
2024
2024-25
Construction phase
Commissioning phase
2026
2027
Start data taking

DARWIN Backgrounds



pp+^{7}Be neutrinos
→ ER signature

high-E neutrinos
→ CNNS bg
→ NR signature

Xe-intrinsic bg:
^{222}Rn, ^{85}Kr, $2\nu\beta\beta$

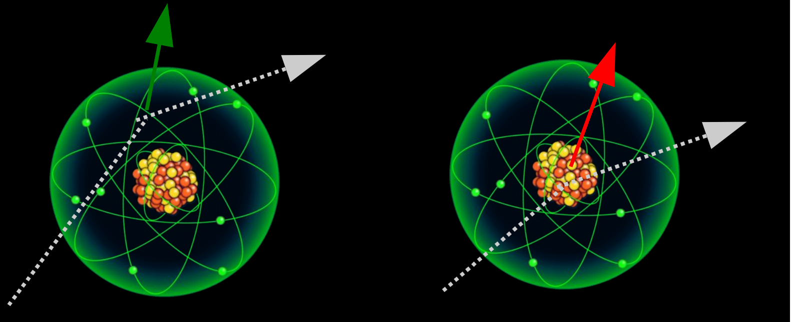
neutrons from
(α,n) and sf

Remaining background sources:

- Neutrinos (→ ERs and NRs)
- Detector materials (→ n)
- Xe-intrinsic isotopes (→ e^-)

(assume 100% effective shield against μ-induced background)

JCAP 10, 016 (2015)



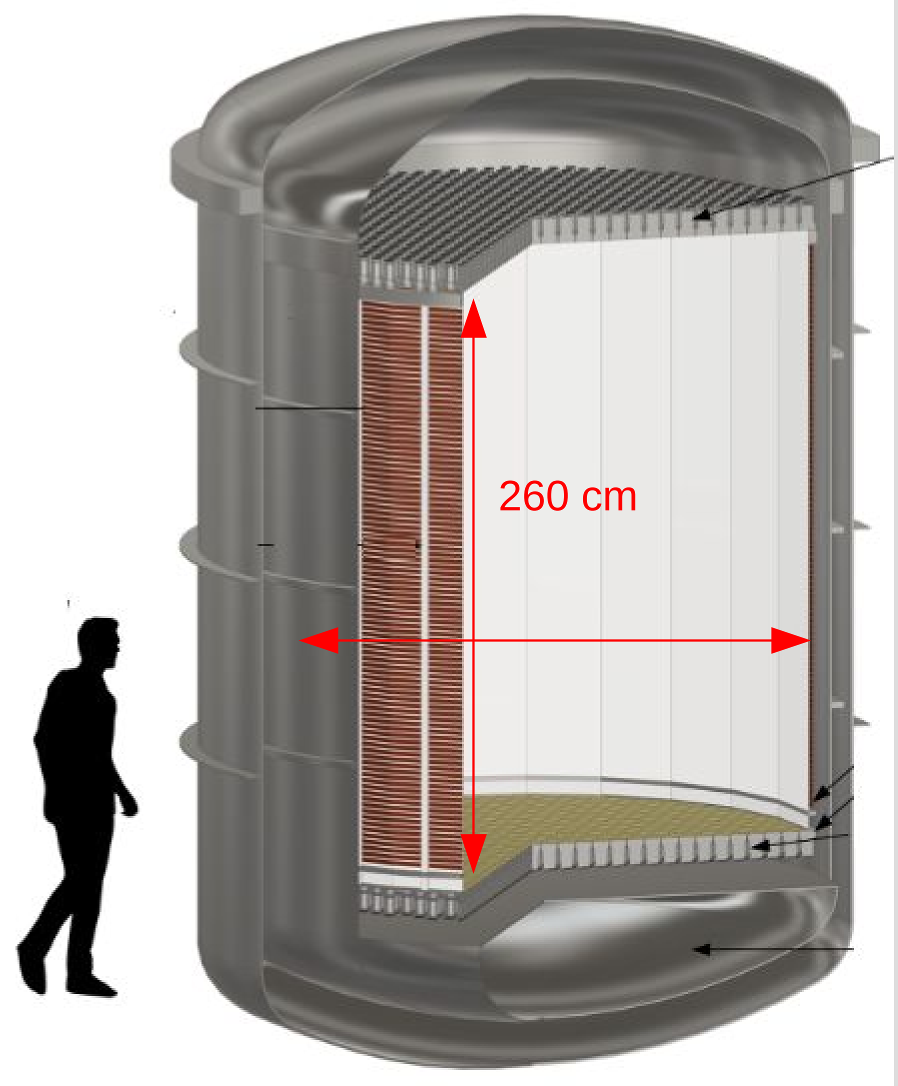
Electronic Recoils
(gamma, beta)

Nuclear Recoils
(neutron, WIMPs)
→ only single scatters


PROJETMAN - ccm
matr 003-87
PORTATA t. 5

DARWIN The ultimate WIMP Detector

JCAP 11, 017 (2016)



Challenges

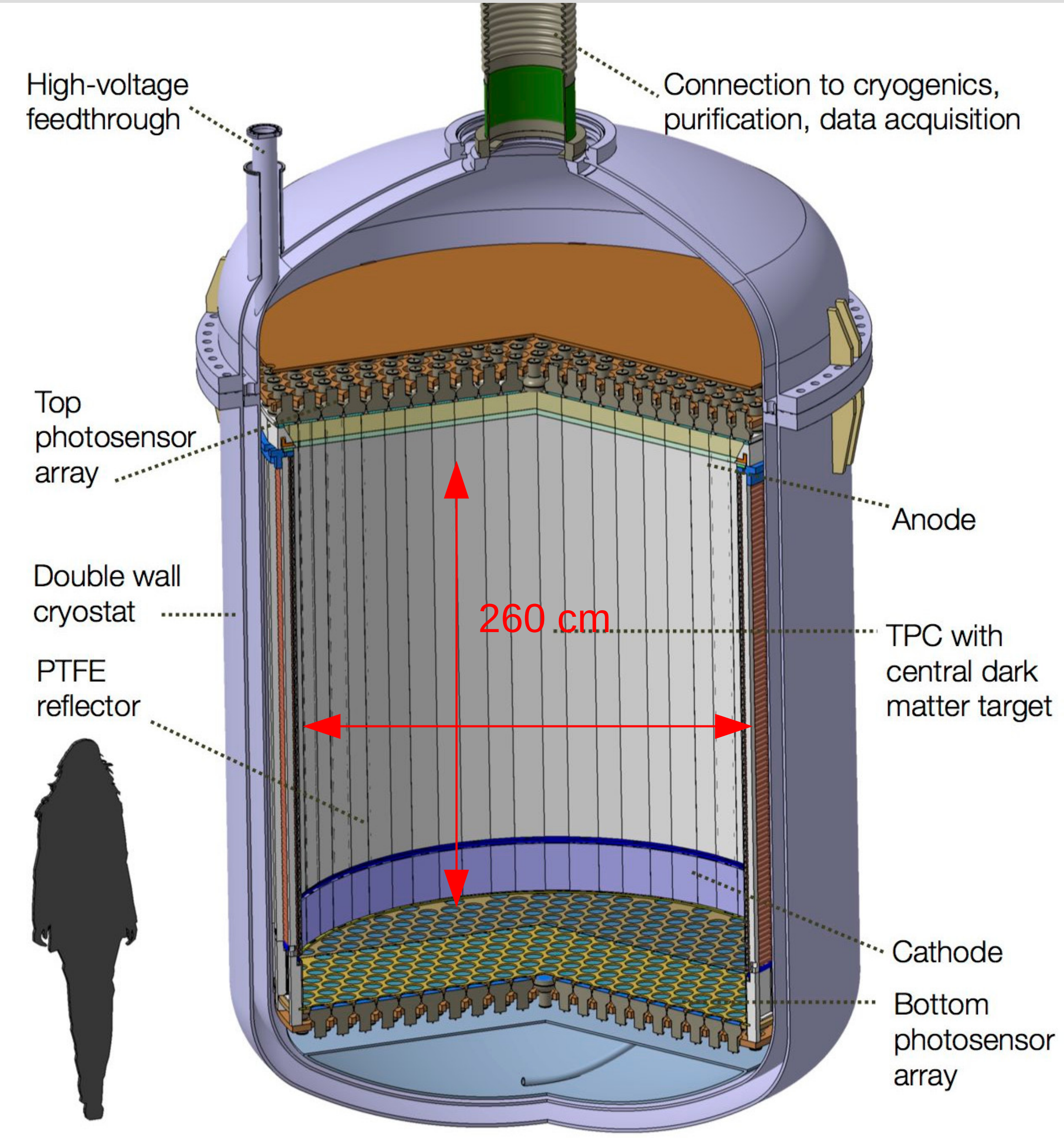
- **Size**
  - → electron drift (HV)
  - → diameter (TPC electrodes)
  - → mass (LXe purification)
  - → dimensions (radioactivity)
  - → detector response (calibration, corrections)
- **Backgrounds**
  - → ^{222}Rn: factor 100 required
  - → (α,n) neutrons (from PTFE)
- **Photosensors**
  - → high light yield (QE)
  - → low radioactivity
  - → long-term stability
- etc etc

DARWIN The *ultimate* WIMP Detector

JCAP 11, 017 (2016)

- R&D within XENON collaboration ++
- **two ERC projects**
  - ***ULTIMATE*** (Freiburg)
  - *Xenoscope* (Zürich)

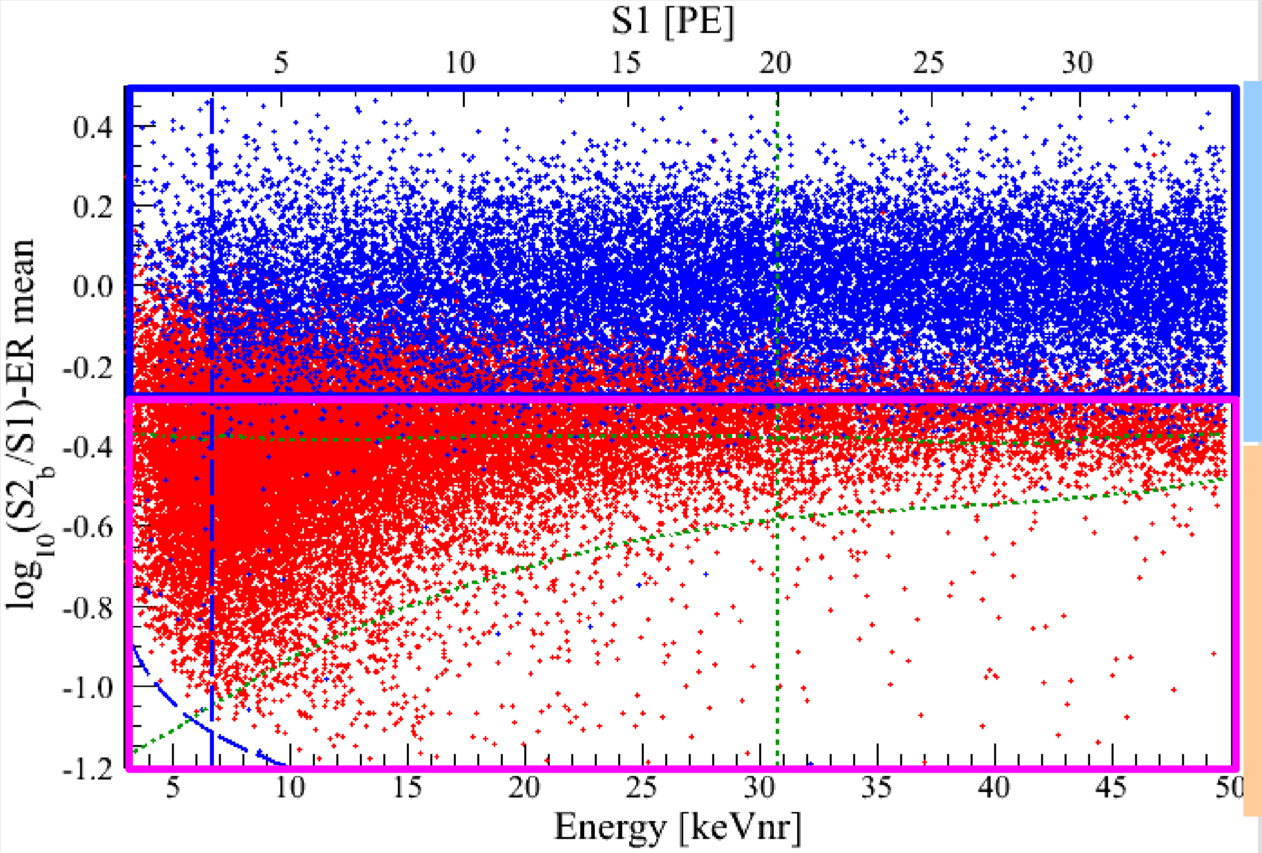
DARWIN The ultimate WIMP Detector



other than WIMPs

What (else) can we do with these instruments?

Interactions in LXe Detectors



scattering off atomic electrons, excitations etc.
→ electronic recoil

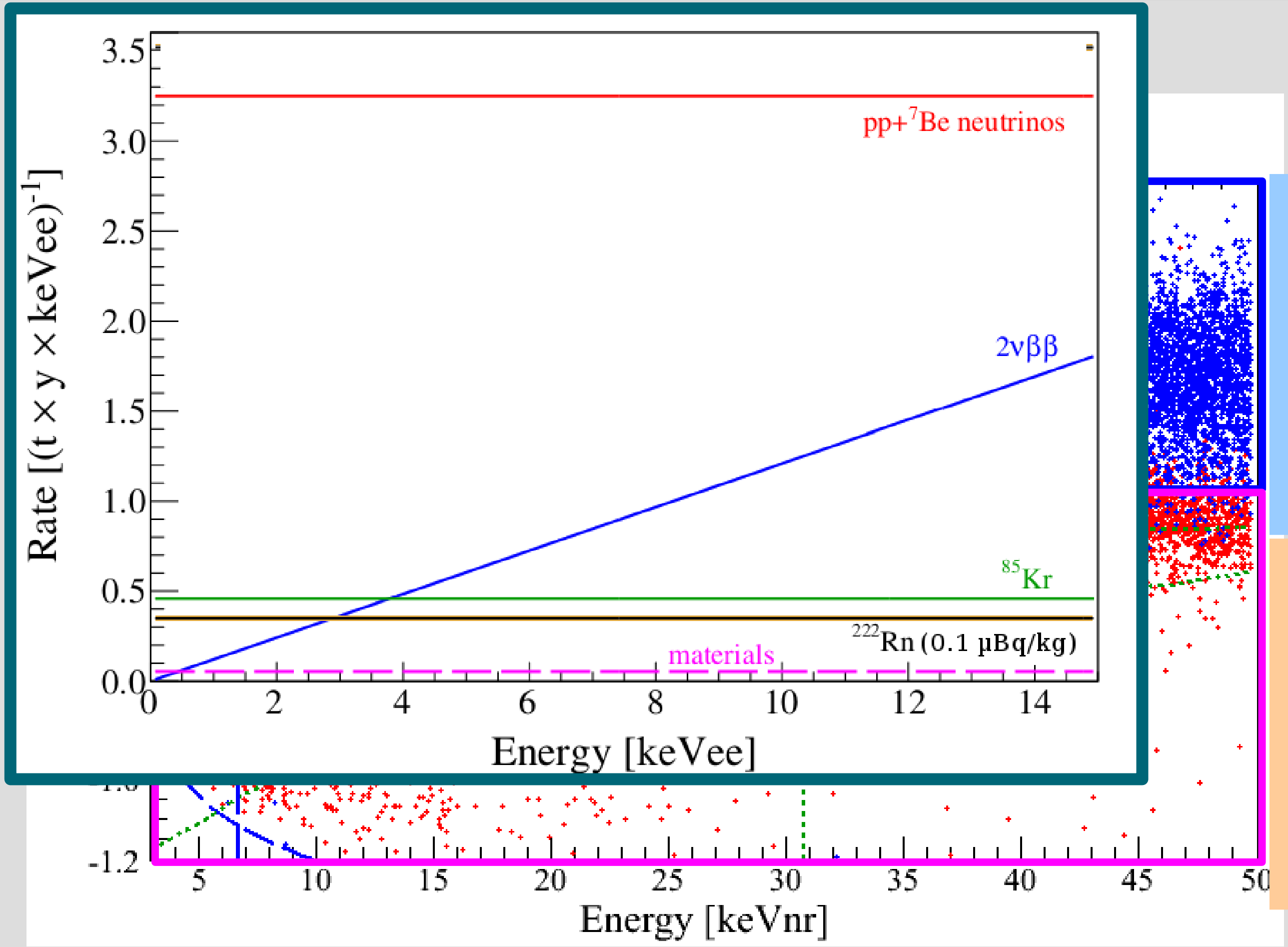
→ axions/ ALPs

- rare processes detectable if ER background is low

coherent scattering off xenon nucleus
→ nuclear recoil

- Dark Matter
- CNNS

Interactions in LXe Detectors



scattering off atomic electrons, excitations etc.
→ electronic recoil

→ axions/ ALPs

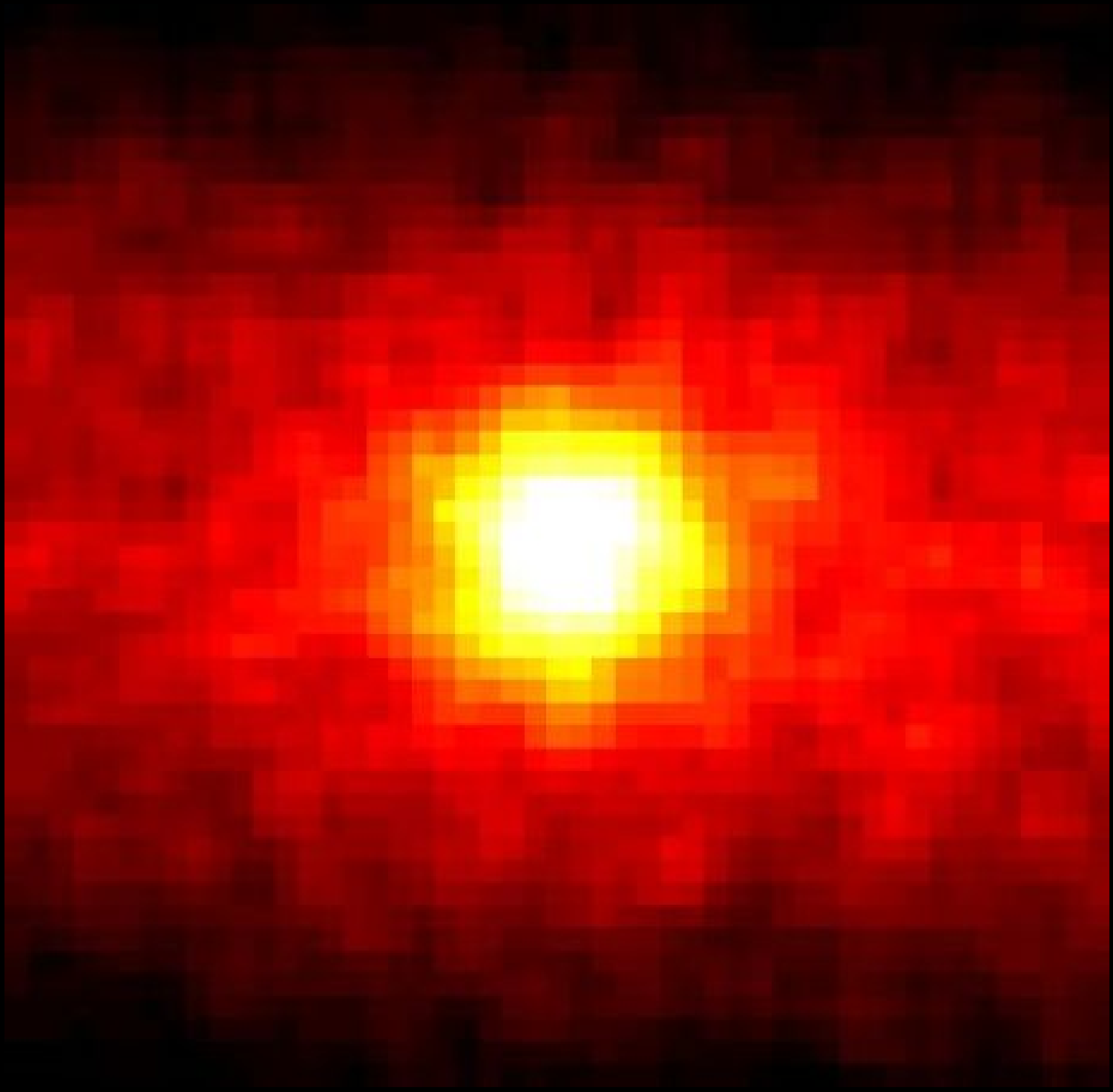
- rare processes detectable since ER background **is low**

coherent scattering off xenon nucleus
→ nuclear recoil

- Dark Matter
- CNNS

→ Many **science channels** are accessible

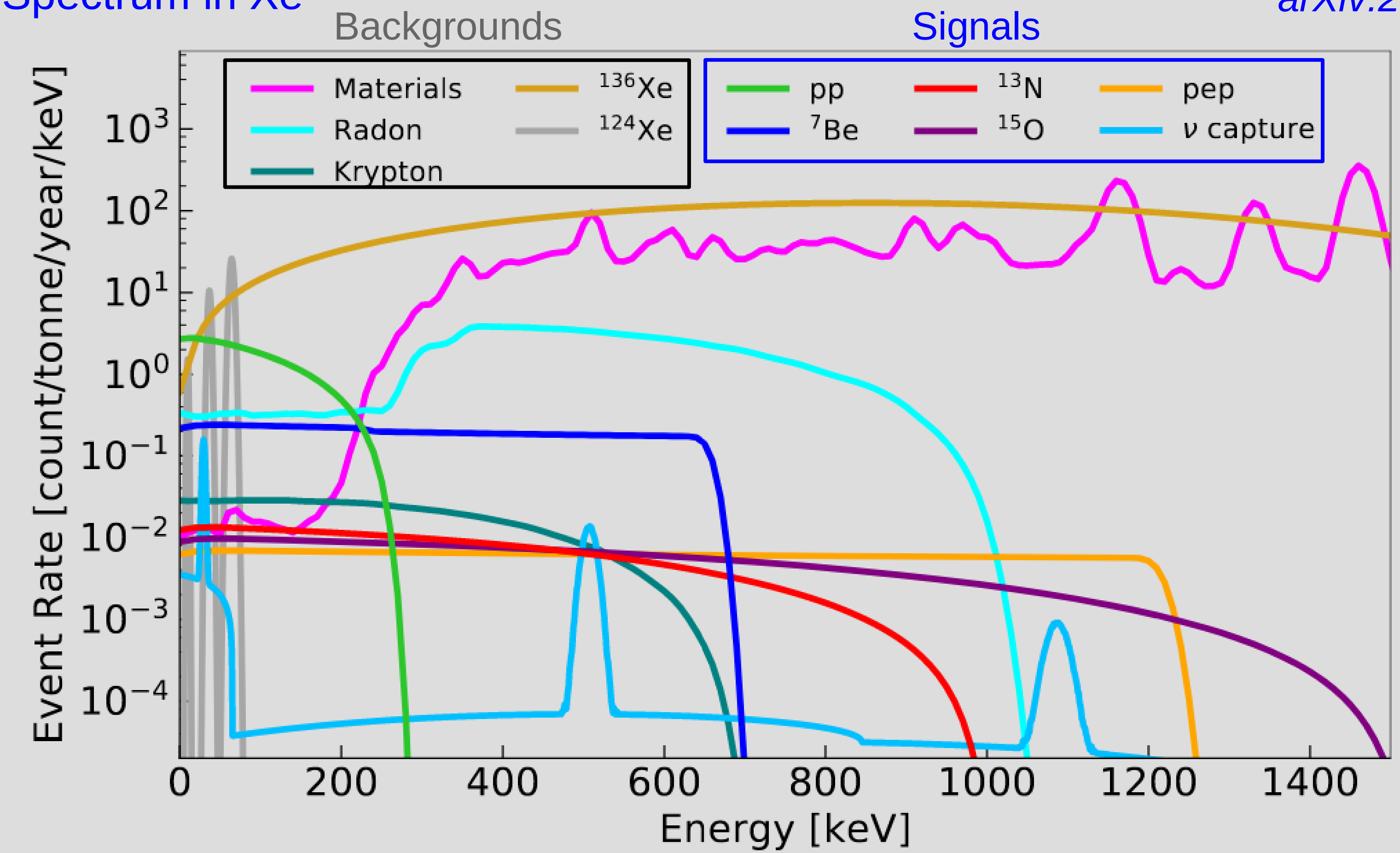
DARWIN = A low background, low threshold **astroparticle physics observatory**



Solar Neutrinos

JCAP 01, 044 (2014)
arXiv:2006.03114

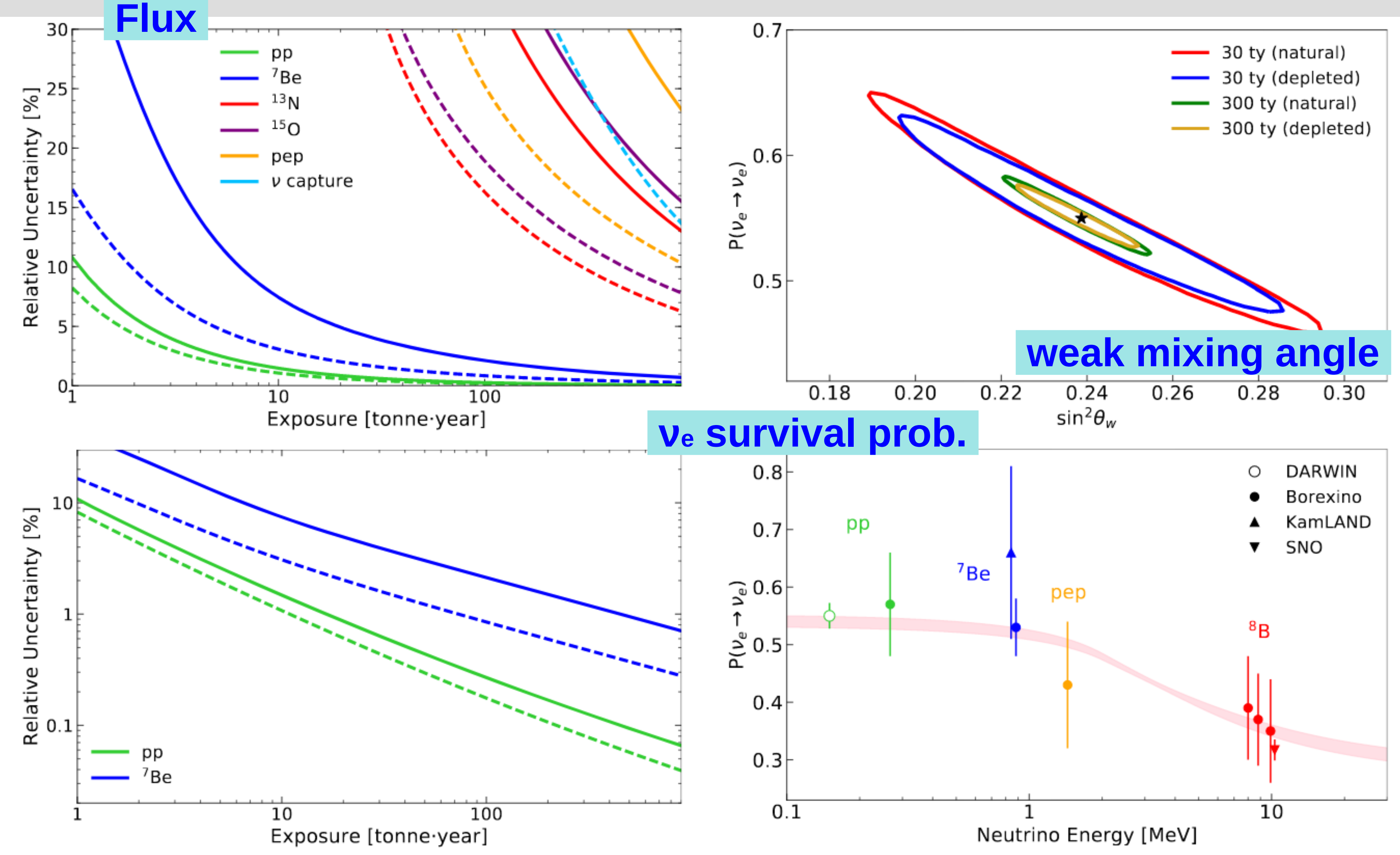
ER Spectrum in Xe



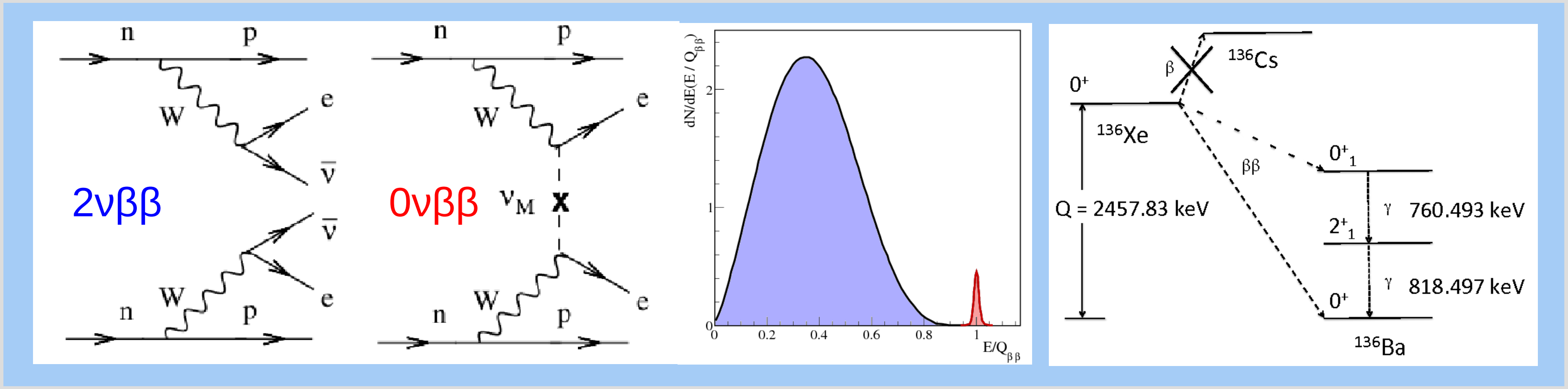
- DARWIN's ER spectrum will be dominated by pp neutrinos (and 2νDEC+2νββ)
- distinct features in ν spectra allow extracting neutrino fluxes
  → full spectral fit of all components up to 3 MeV

Solar Neutrinos

JCAP 01, 044 (2014)
arXiv:2006.03114

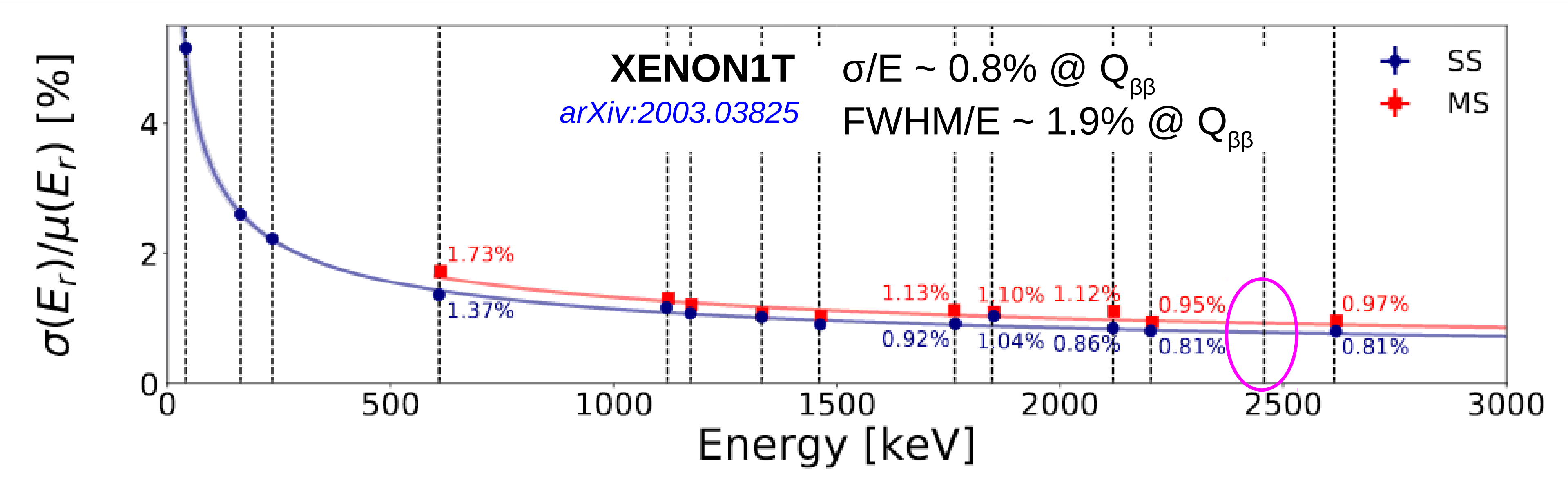


^{136}Xe: 0ν double-beta Decay

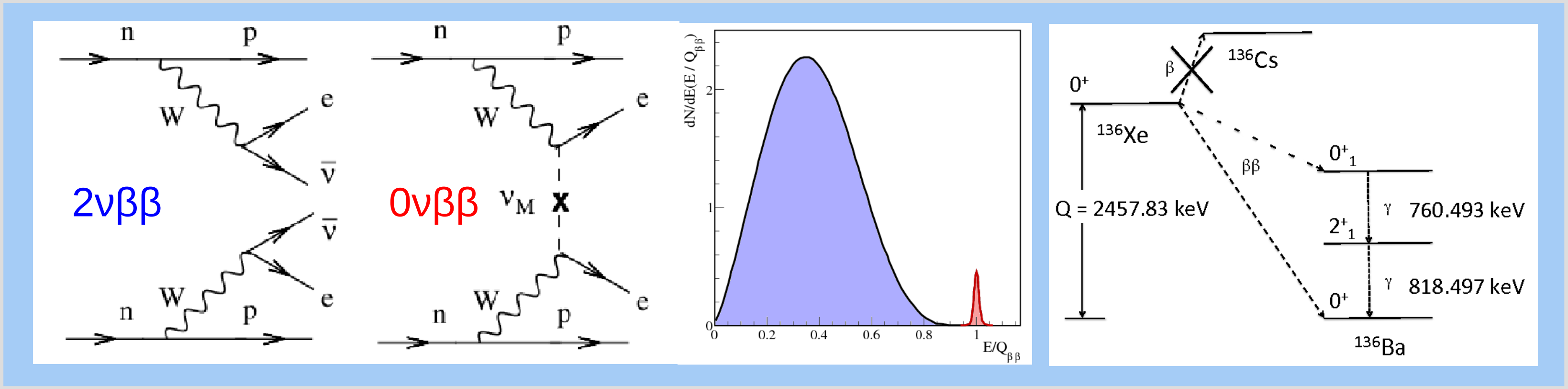


ΔL ≠ 0

- 0νββ candidate with $Q_{\beta\beta}$=2.46 MeV
- 40t DARWIN LXe target contains 3.5t of ^{136}Xe **without any enrichment**!



^{136}Xe: 0ν double-beta Decay



$\Delta L \neq 0$

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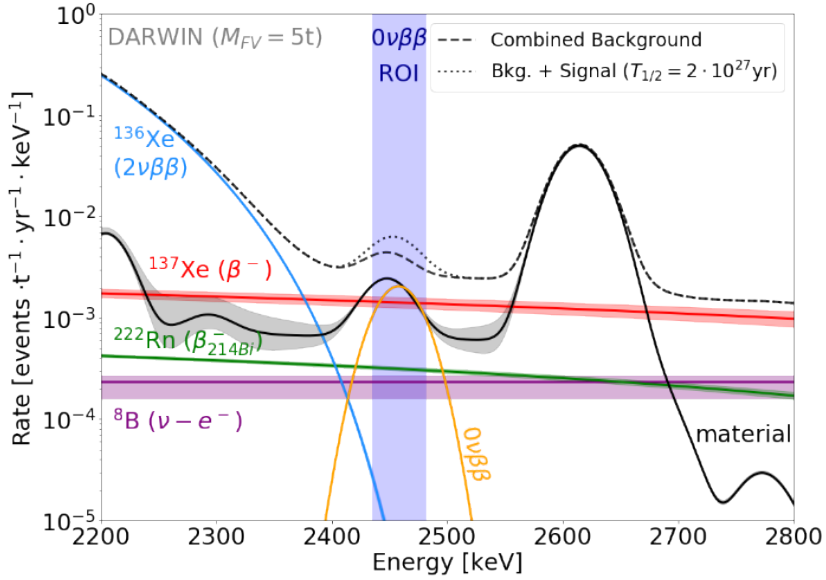

DARWIN Sensitivity

- optimize sensitivity by fiducialization
- important background from decays of neutron-activated ^{137}Xe
  → assume LNGS depth
- **half-life sensitivity: 2.4 × 10^{27} y**

XENON & DARWIN: Exciting Times

Xe
XENON
Dark Matter Project

DARWIN

a low-background
low-threshold observatory
for astroparticle physics

WIMPs

axions/ALPs

solar neutrinos

0νββ, 0νDEC

SN neutrinos

CNNS

+more rare processes