Dark Matter (and more) with XENON detectors

Marc Schumann *University of Freiburg*

GRK 2149 Colloquium, 15.01.2021

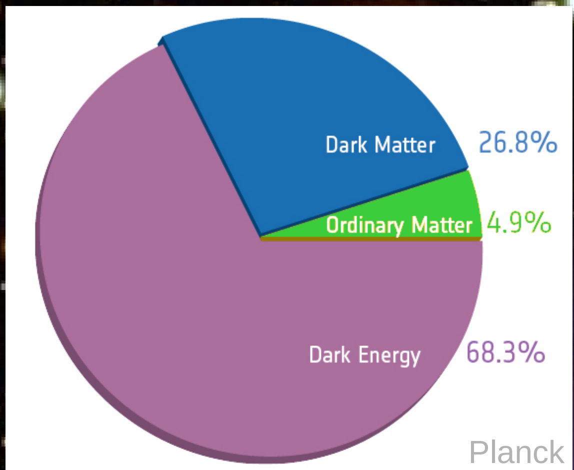
www.app.uni-freiburg.de

Bundesministerium für Bildung und Forschung

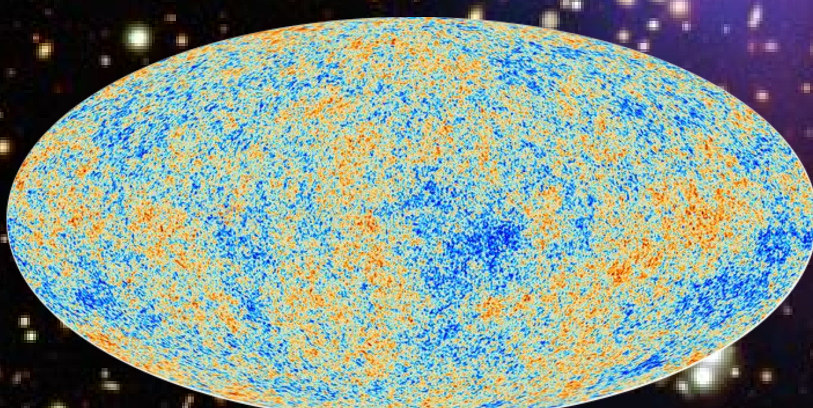
erc

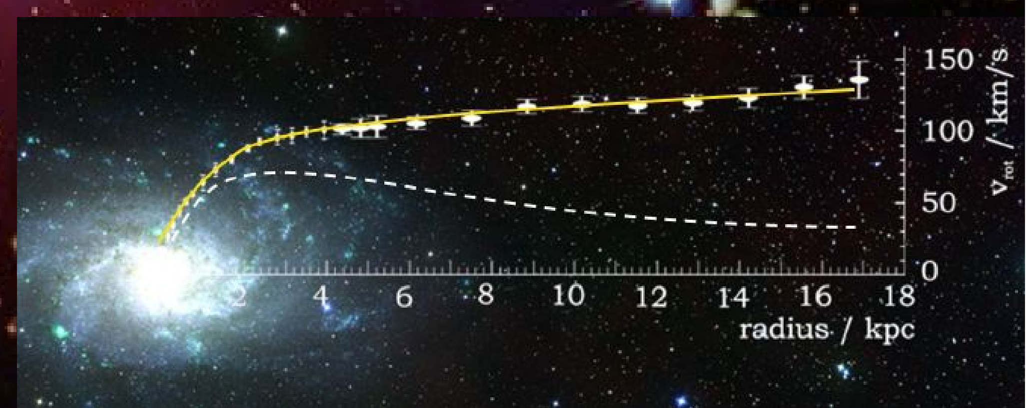
UNI FREIBURG

Dark Matter: (indirect) **Evidence**



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





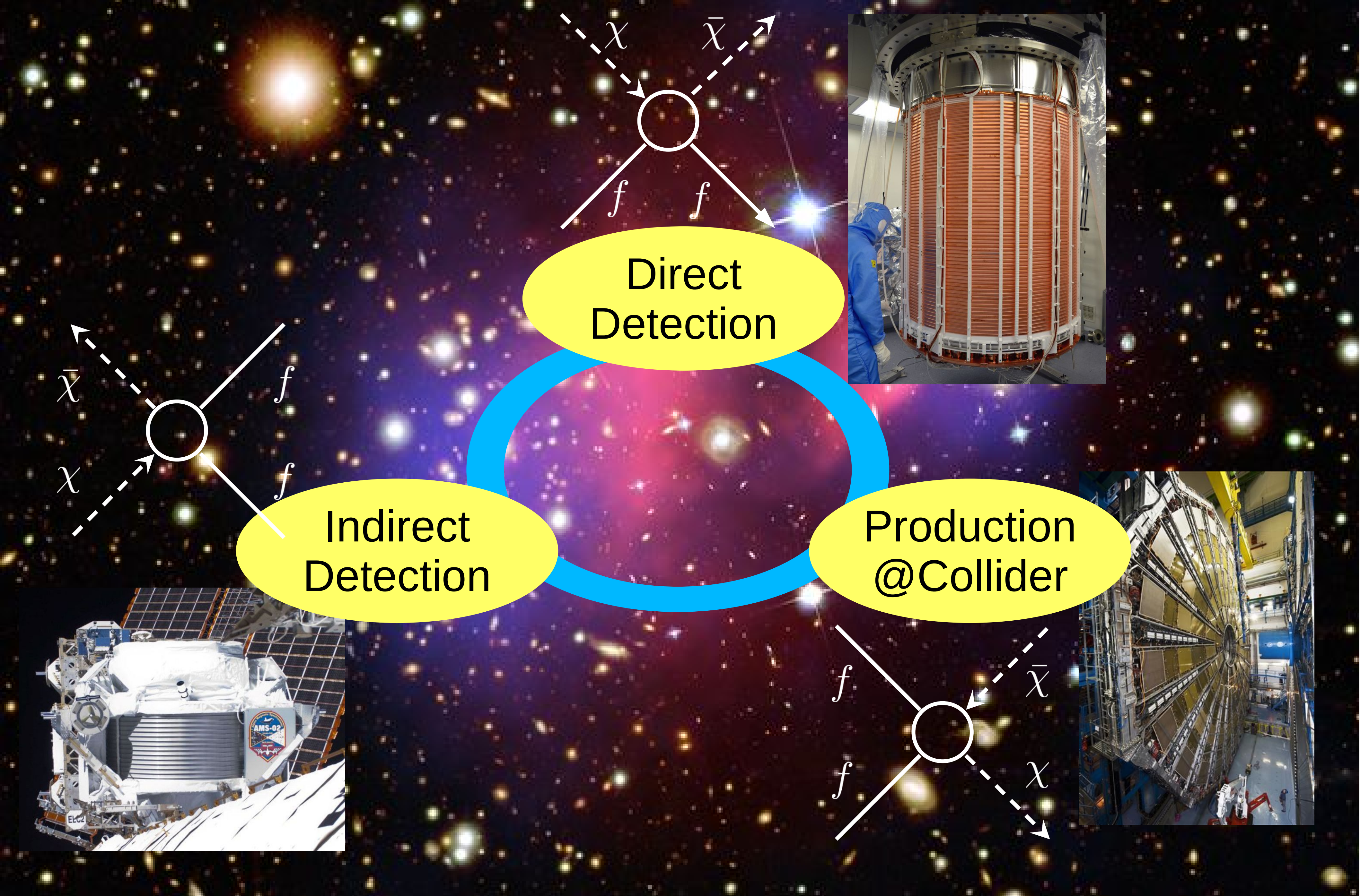
The DM candidates Zoo

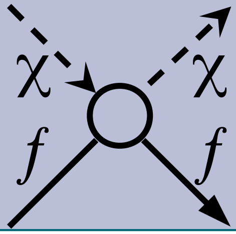
WIMPs
= weakly interacting massive particles

Axions

stolen from G. Bertone

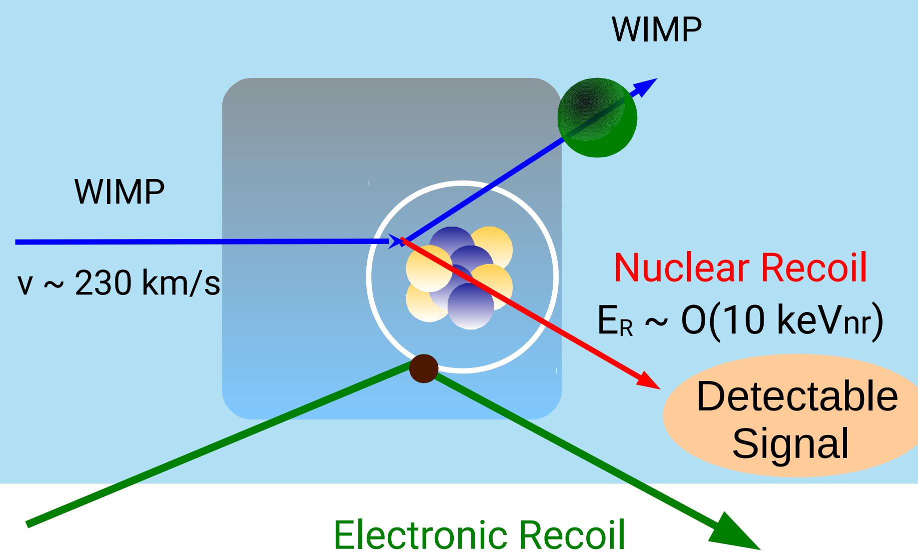
Dark Matter WIMP Search



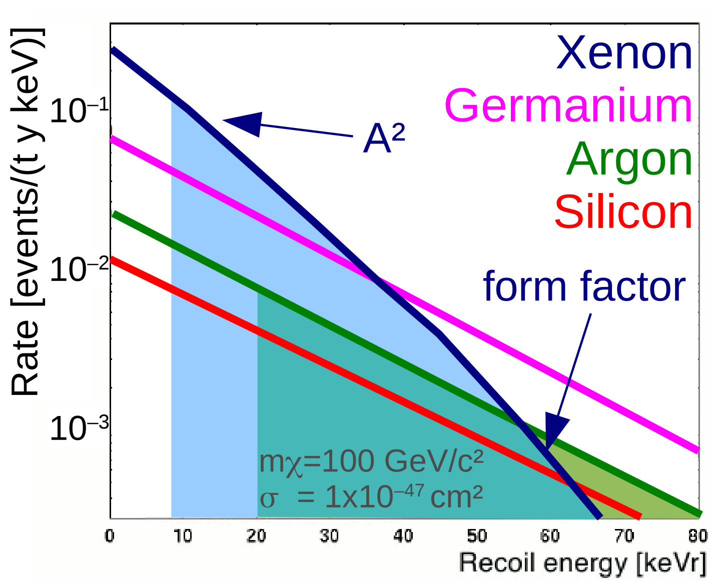


Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
→ nuclear recoil

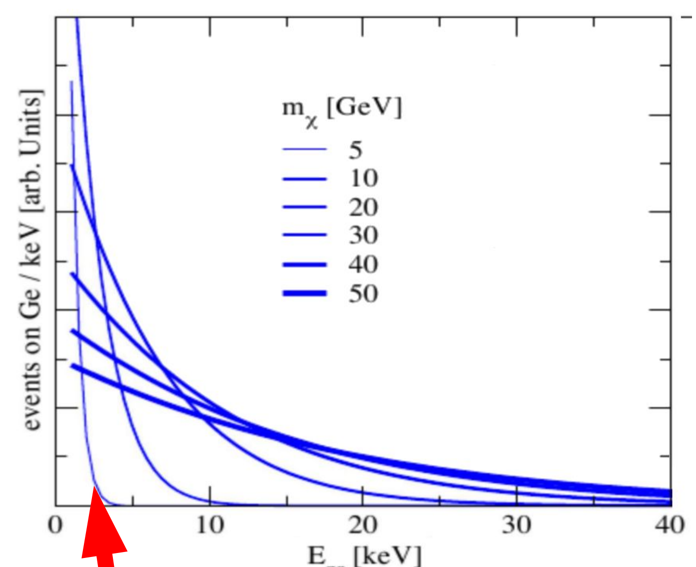


Recoil Spectra:



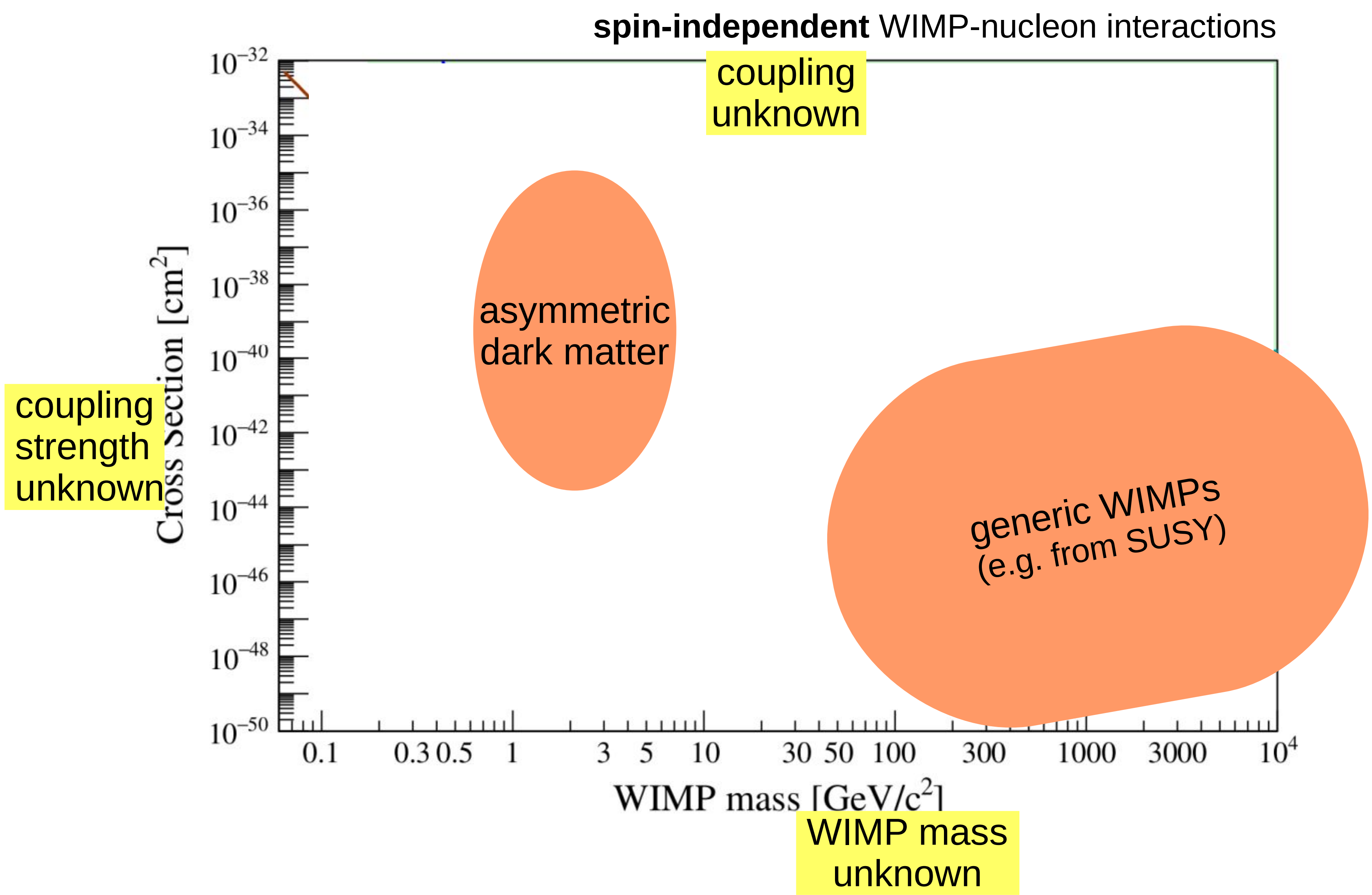
tiny!

tiny!



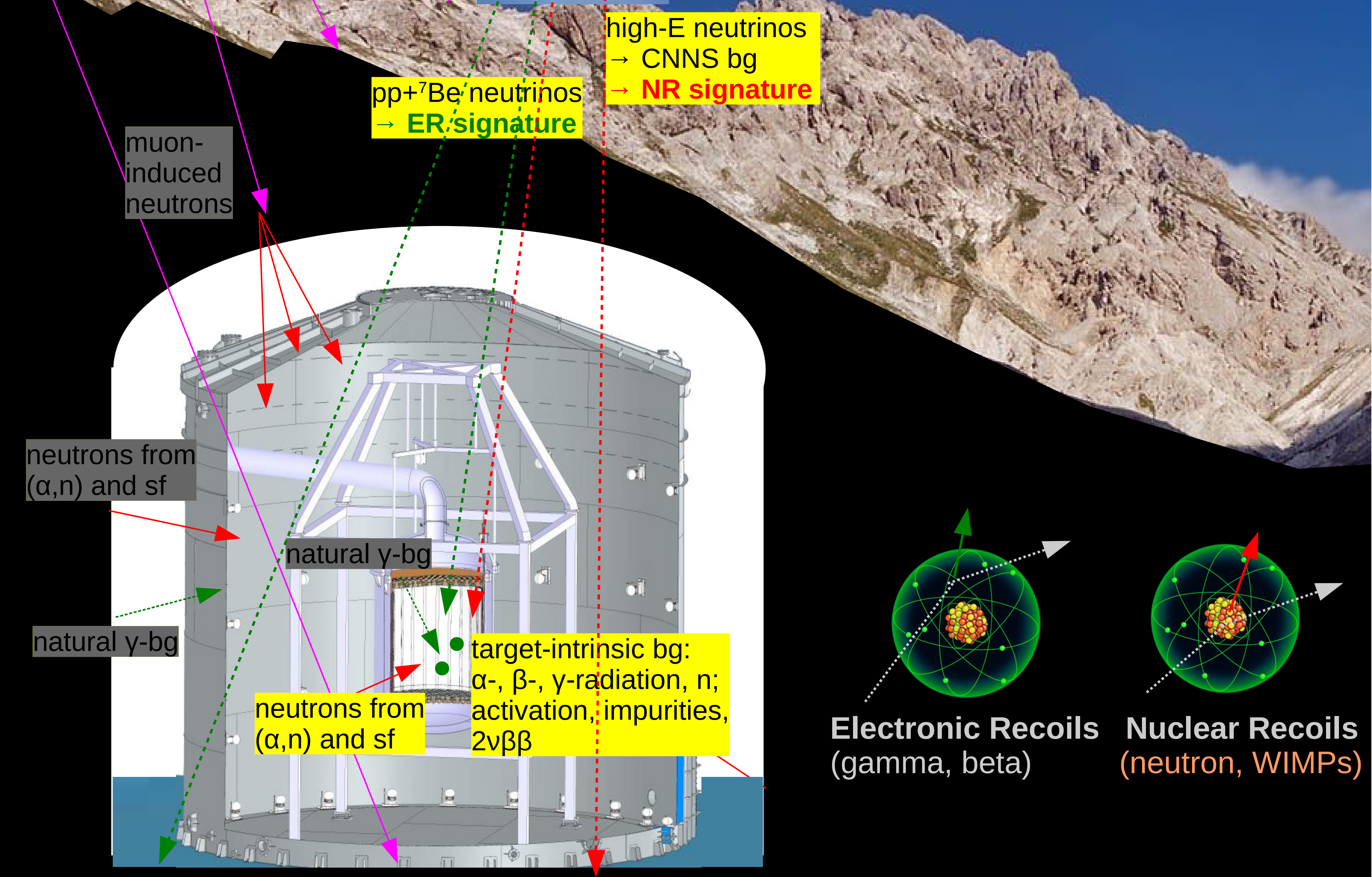
low mass → low threshold

The WIMP Parameter Space



Background Sources

(for ton-scale detectors)



Background Suppression

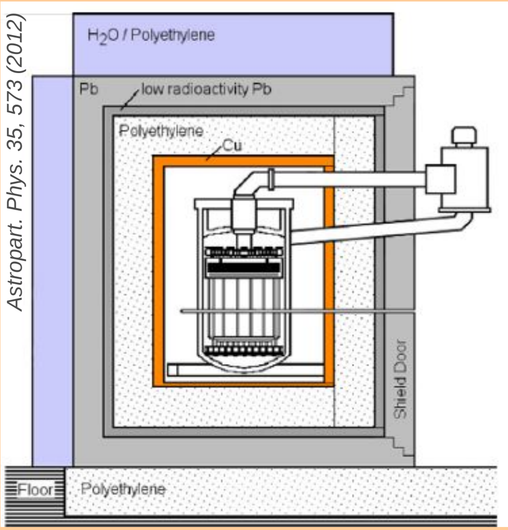
A Avoid Backgrounds

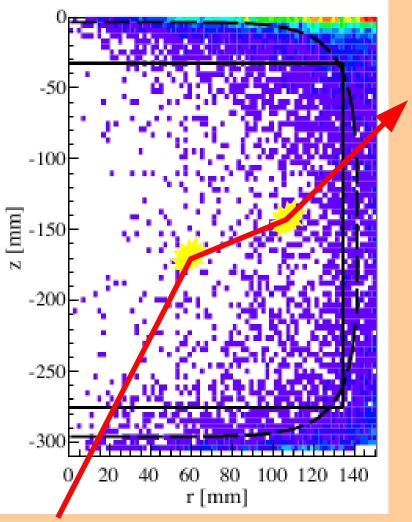
Use of radiopure materials

Shielding

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

self shielding → fiducialization





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*/d*x* from
signal and background

The XENON Collaboration

www.xenon1t.org

Columbia | KIT | Nikhef | Muenster | Stockholm | Mainz | MPIK, Heidelberg | Freiburg | Zurich | Tsinghua

Chicago

UCSD

Rice

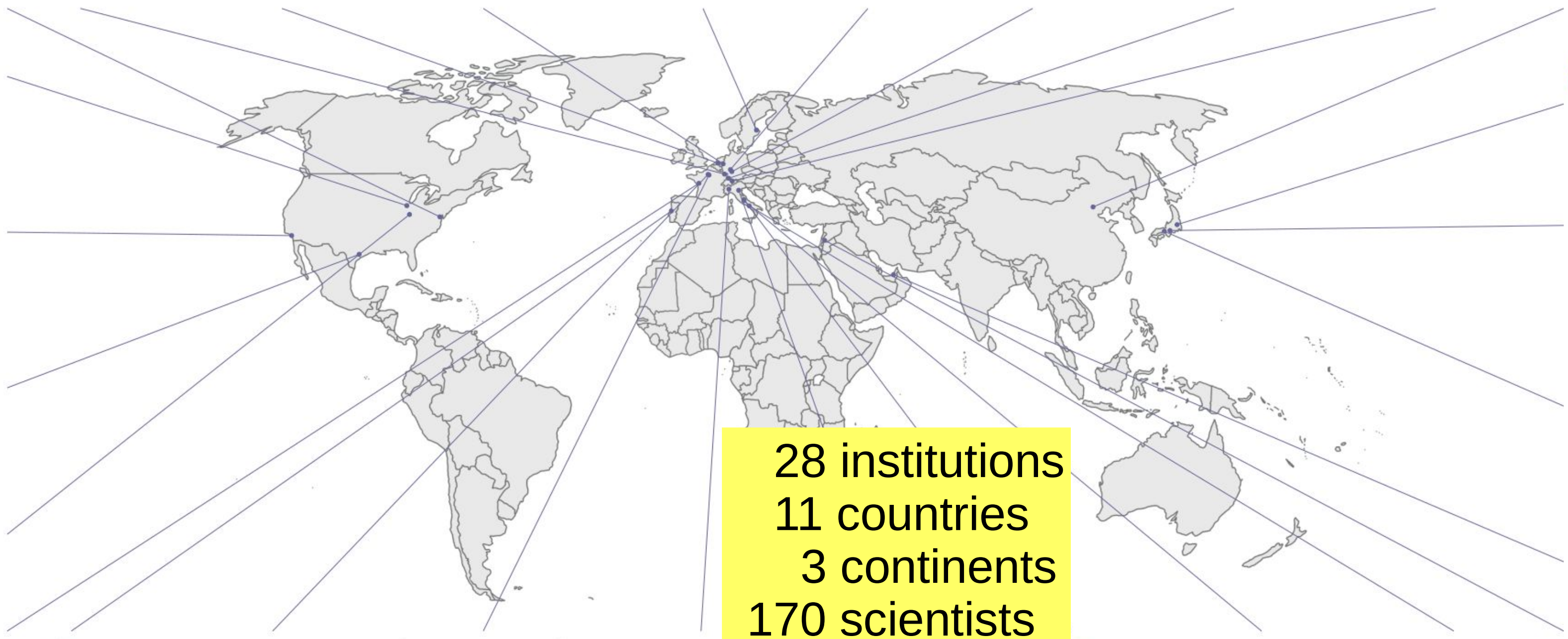
Purdue

Tokyo

Nagoya

Kobe

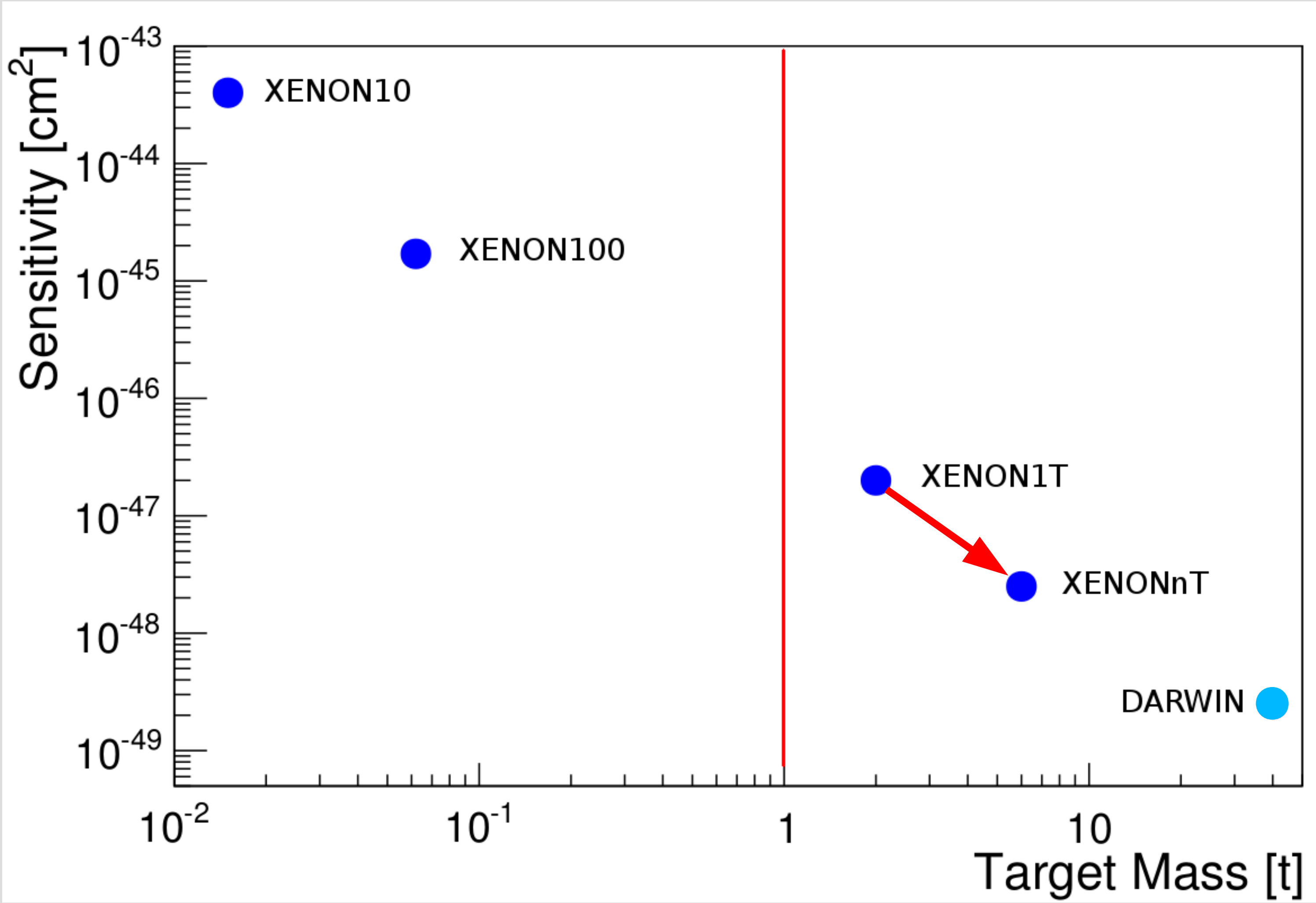
NYUAD



28 institutions
11 countries
3 continents
170 scientists

Subatech | Coimbra | LPNHE | IJCLab | Torino | Bologna | L'Aquila | LNGS | Napoli | Weizmann

XENON Instruments

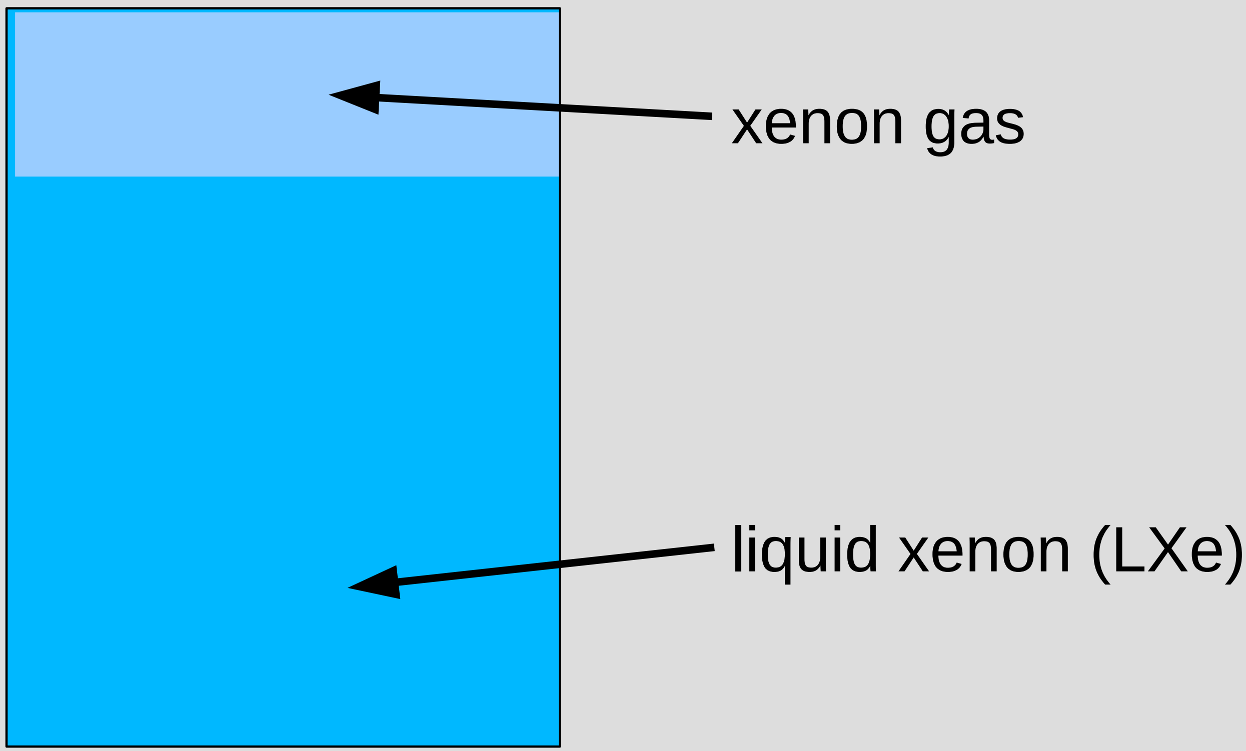


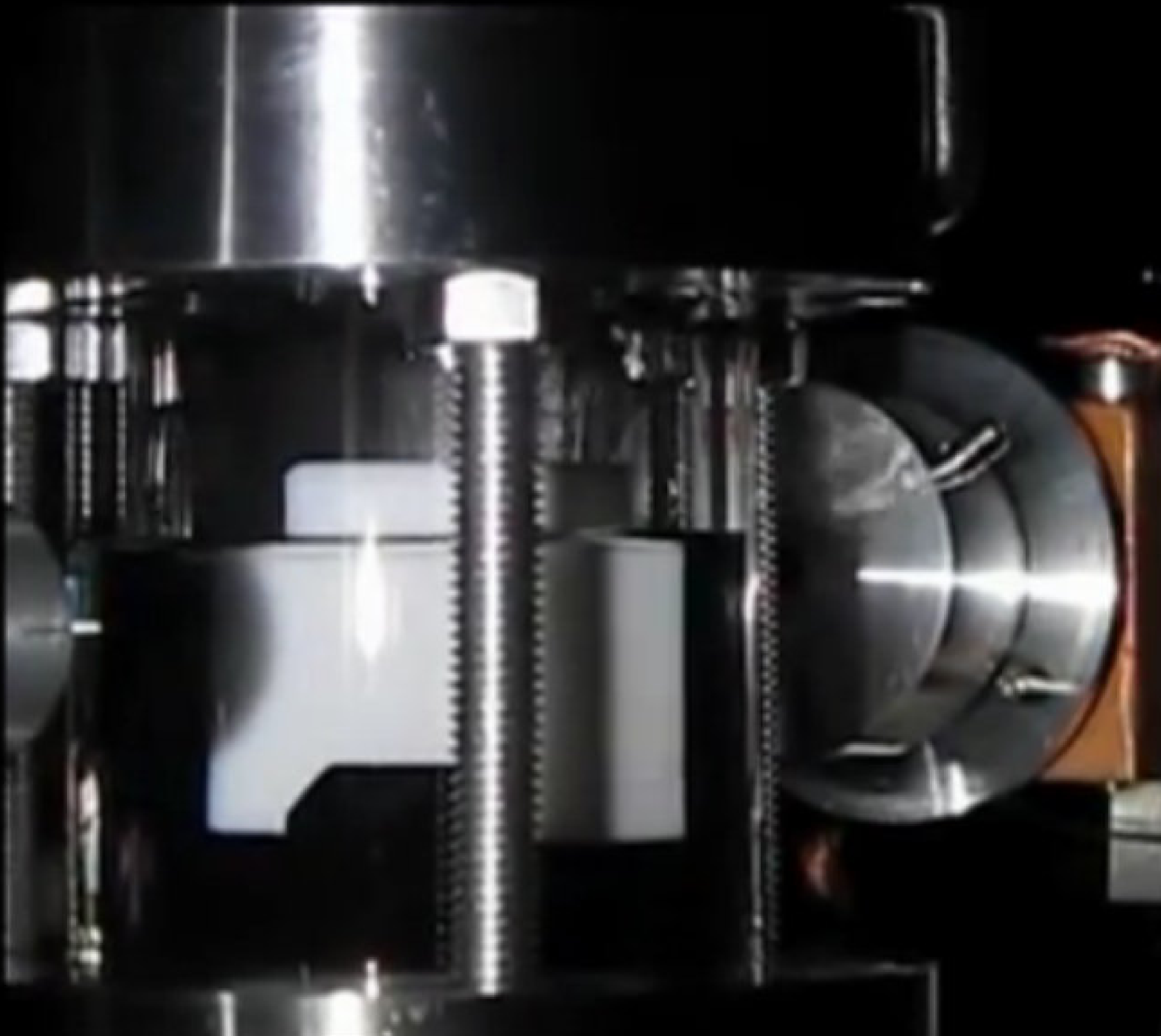
The XENON collaboration develops and operates
dark matter detectors of increasing size and sensitivity

Dual Phase TPC

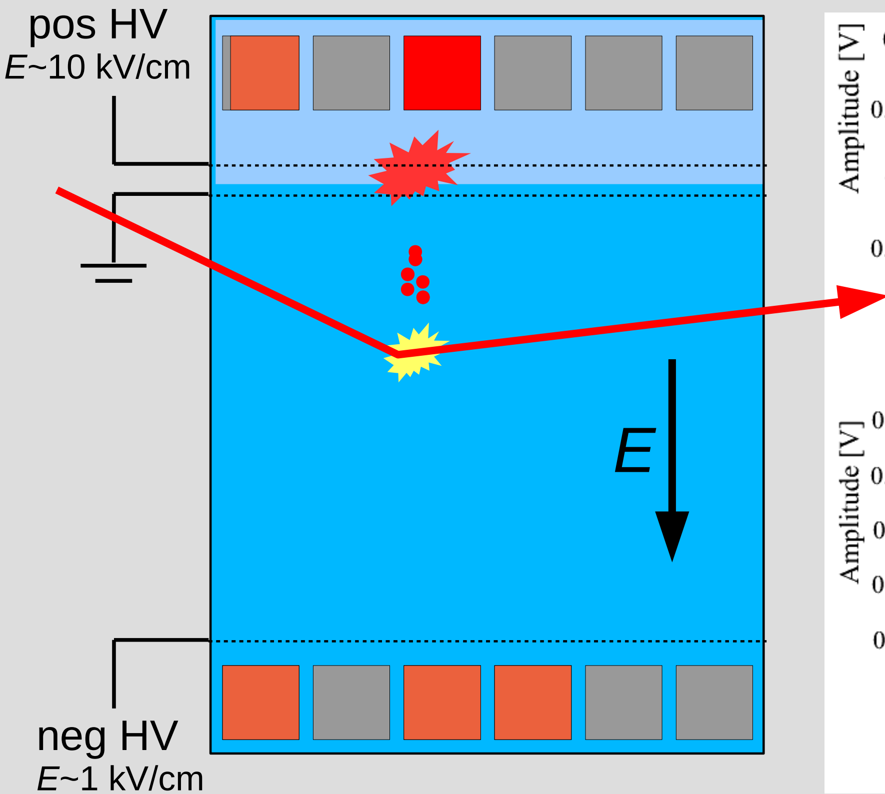
Dolgoshein, Lebedenko, Rodionov, JETP Lett. 11, 513 (1970)

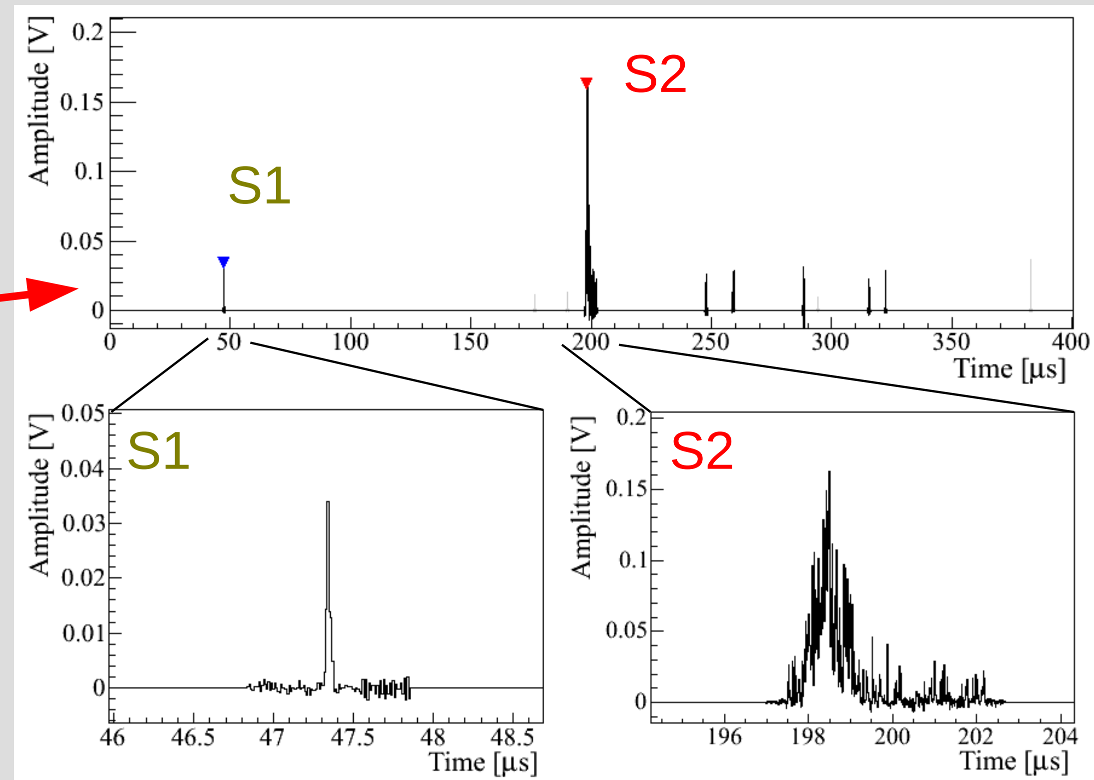
TPC = time projection chamber

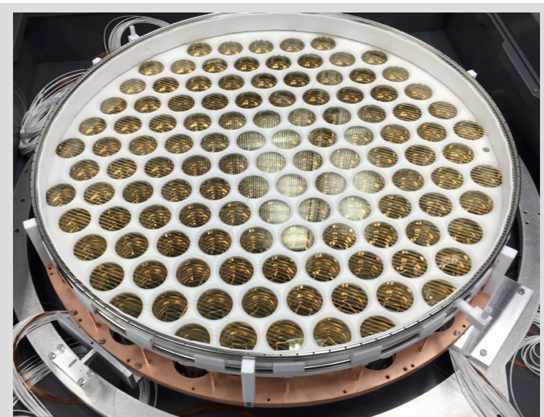




Dual Phase TPC





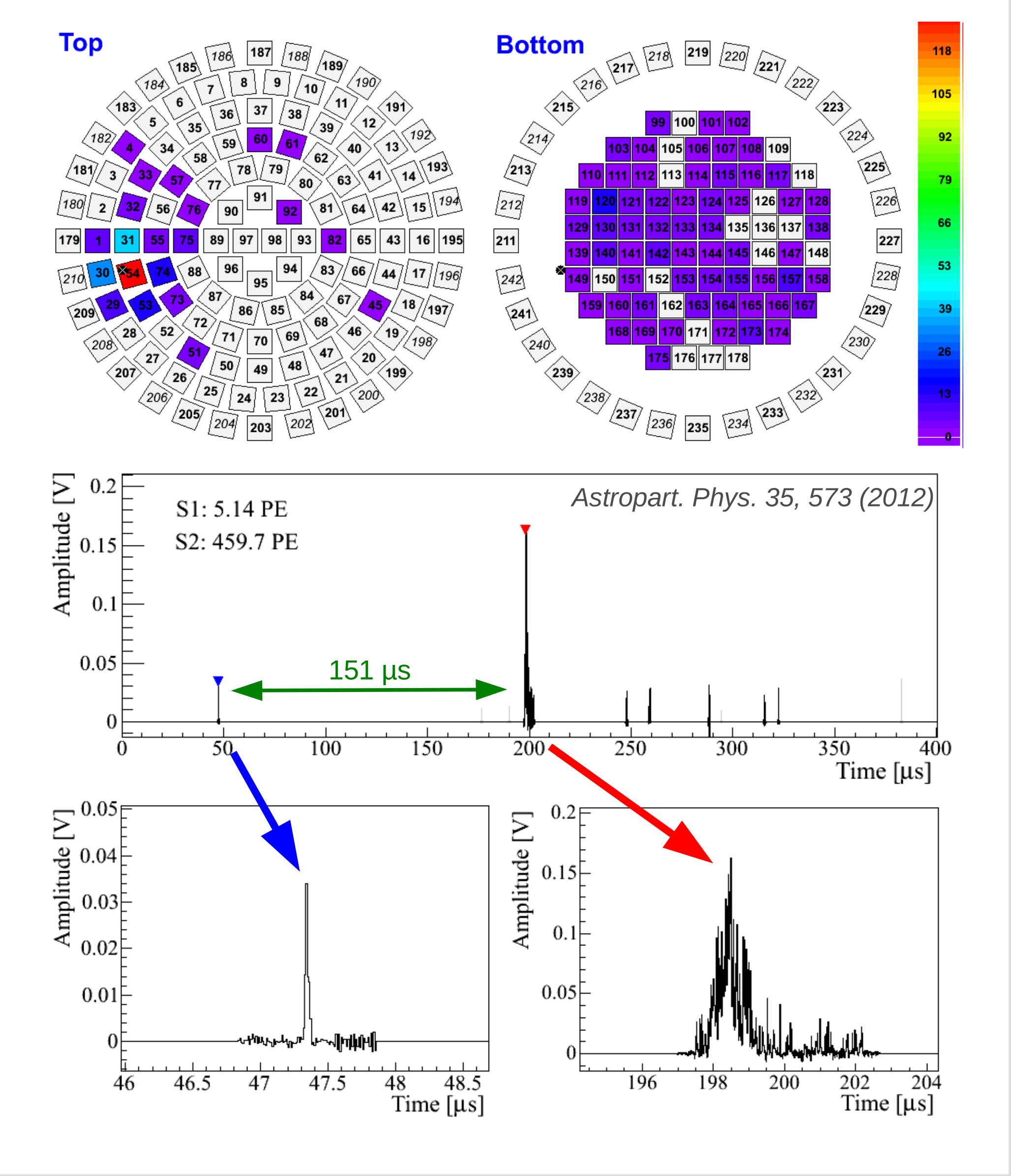


Background Rejection

– 3dim vertex reconstruction
→ **fiducialization**

– multi-scatter rejection

– energy measurement (S1+S2)



Figures: XENON100

LXe TPC Features

– 3dim vertex reconstruction
→ **fiducialization**

– multi-scatter rejection

– energy measurement (S1+S2)

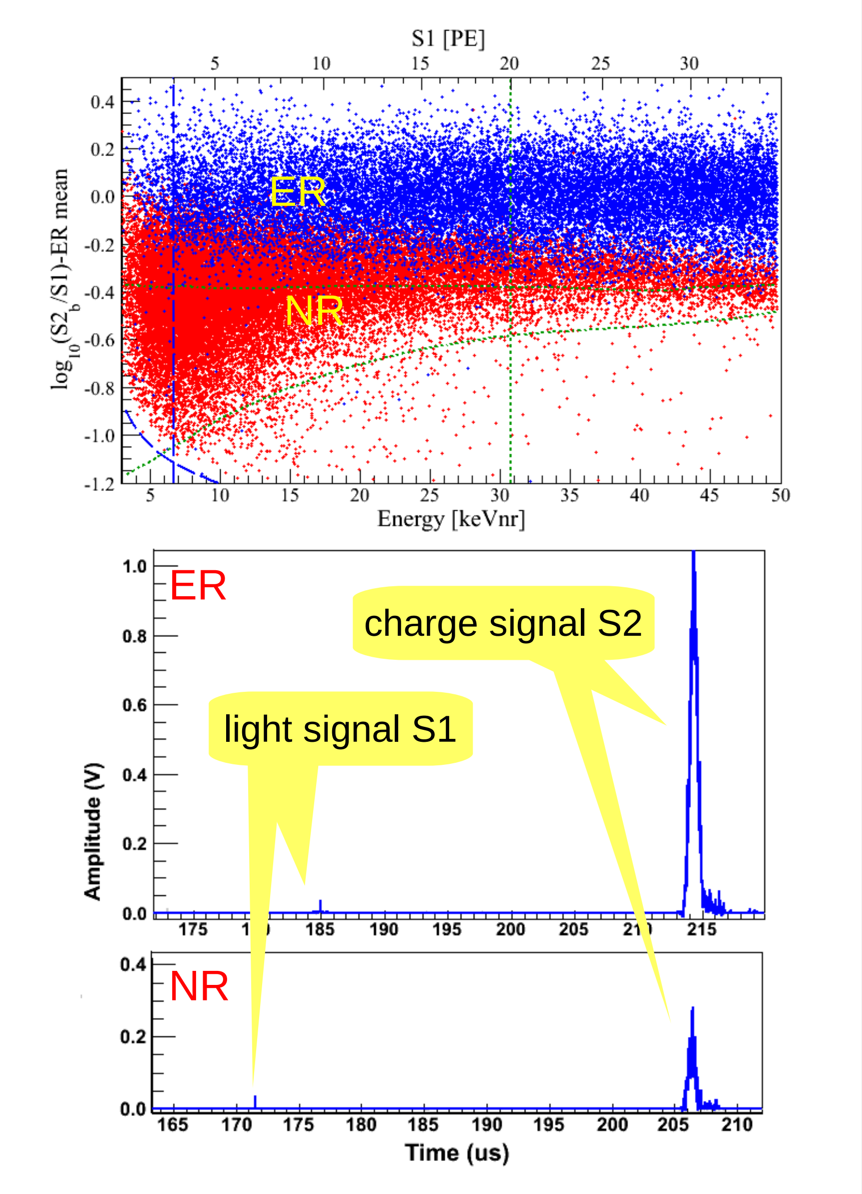
– **Charge-Light-Ratio (S2/S1):**
Particle ID

→ ER background rejection (WIMP search)
→ selection of ER channels

– very low background

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

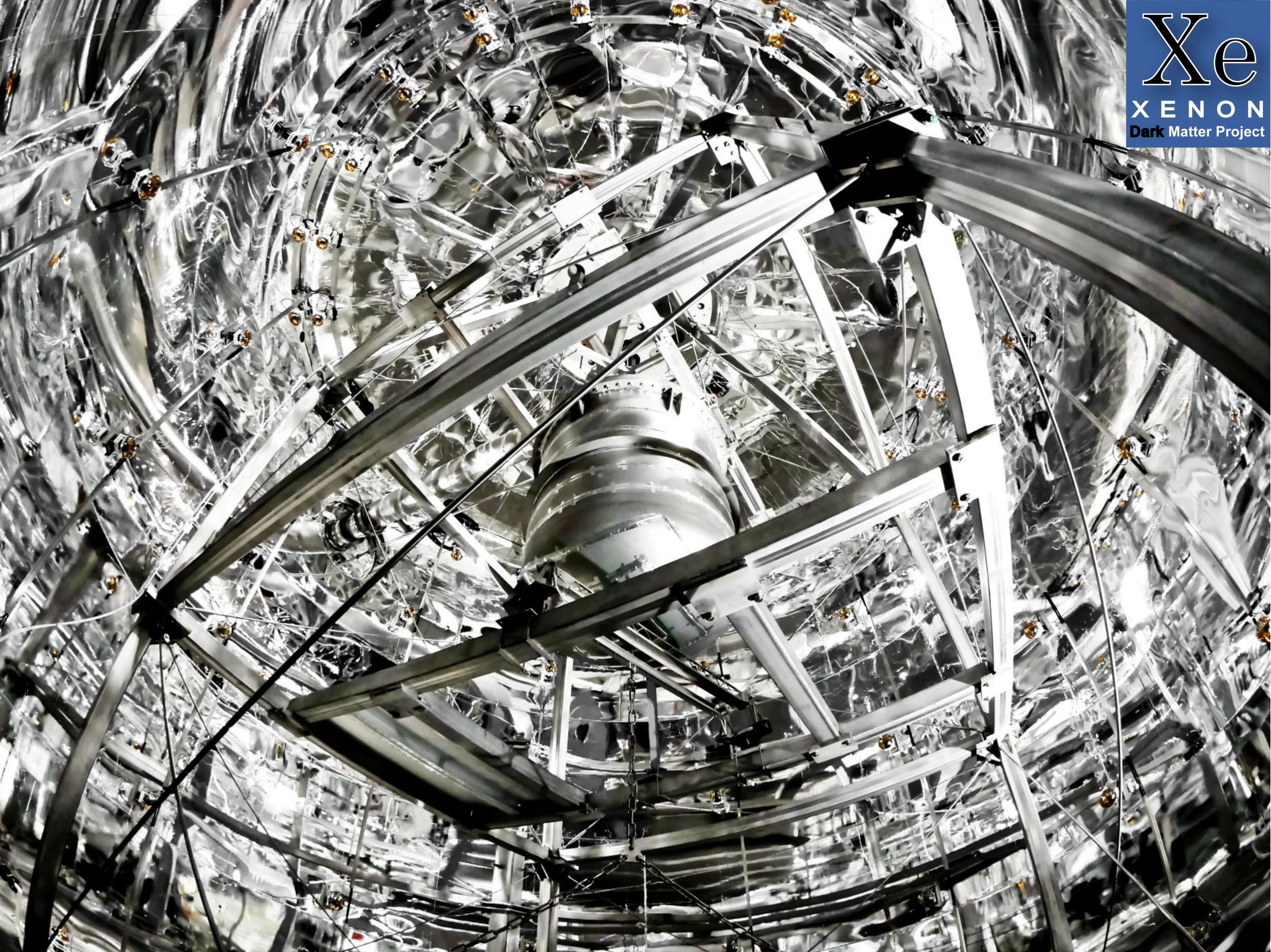
– large target mass → high exposure



Figures: XENON100

State of the Art: Selected Results from XENON1T @ LNGS

EPJ C 77, 991 (2017)


Xe
XENON
Dark Matter Project

XENON Dark Matter Project

EPJ C 77, 991 (2017)

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


Selected Results from
XENON1T
WIMP Dark Matter

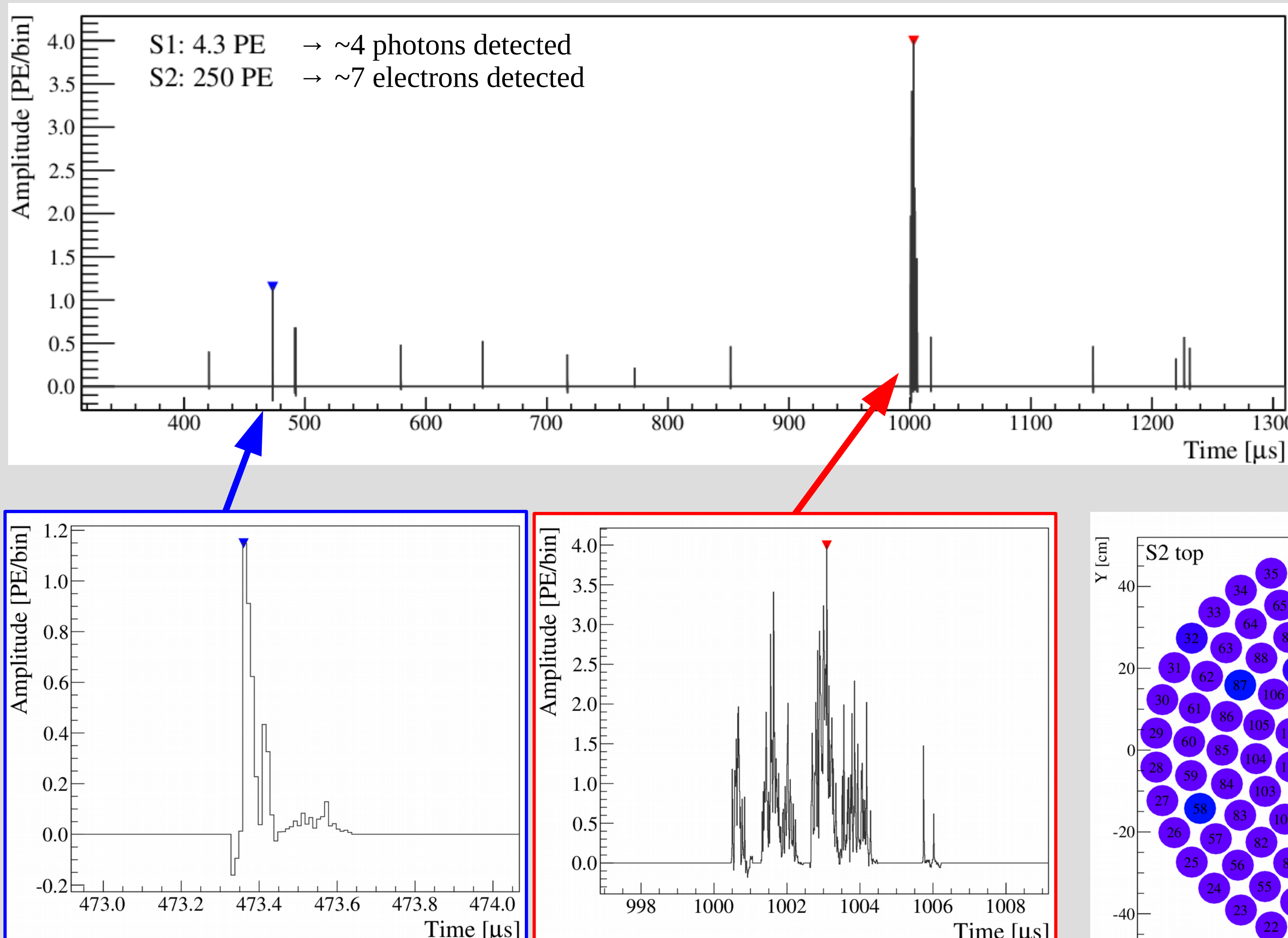
General Search Strategy

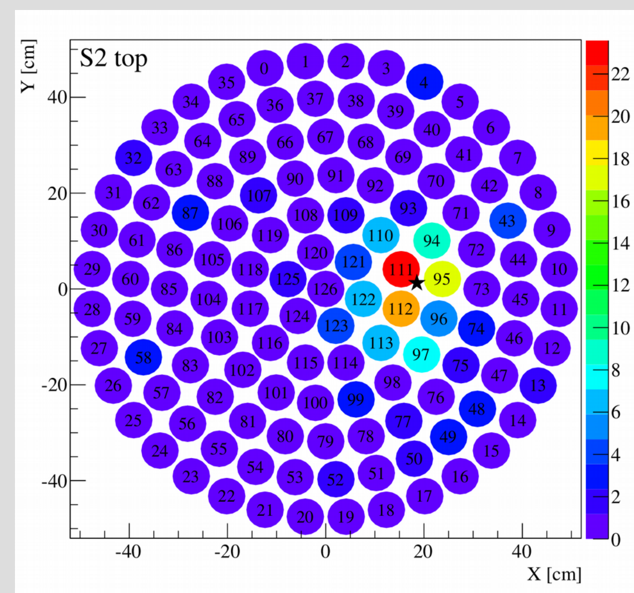
1. **reduce background**
   → *pick optimal region of interest (ROI)*
2. know your **expected signal**
3. know your **backgrounds**
   → *requires lots of detector calibration*
4. perform a **„blind“ search** to avoid bias
   → *ROI not accessible*
5. **Unblind**
   → *check if there is an excess of signals above the background expectation in the ROI*

Looks like Dark Matter?

XENON Dark Matter Project

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

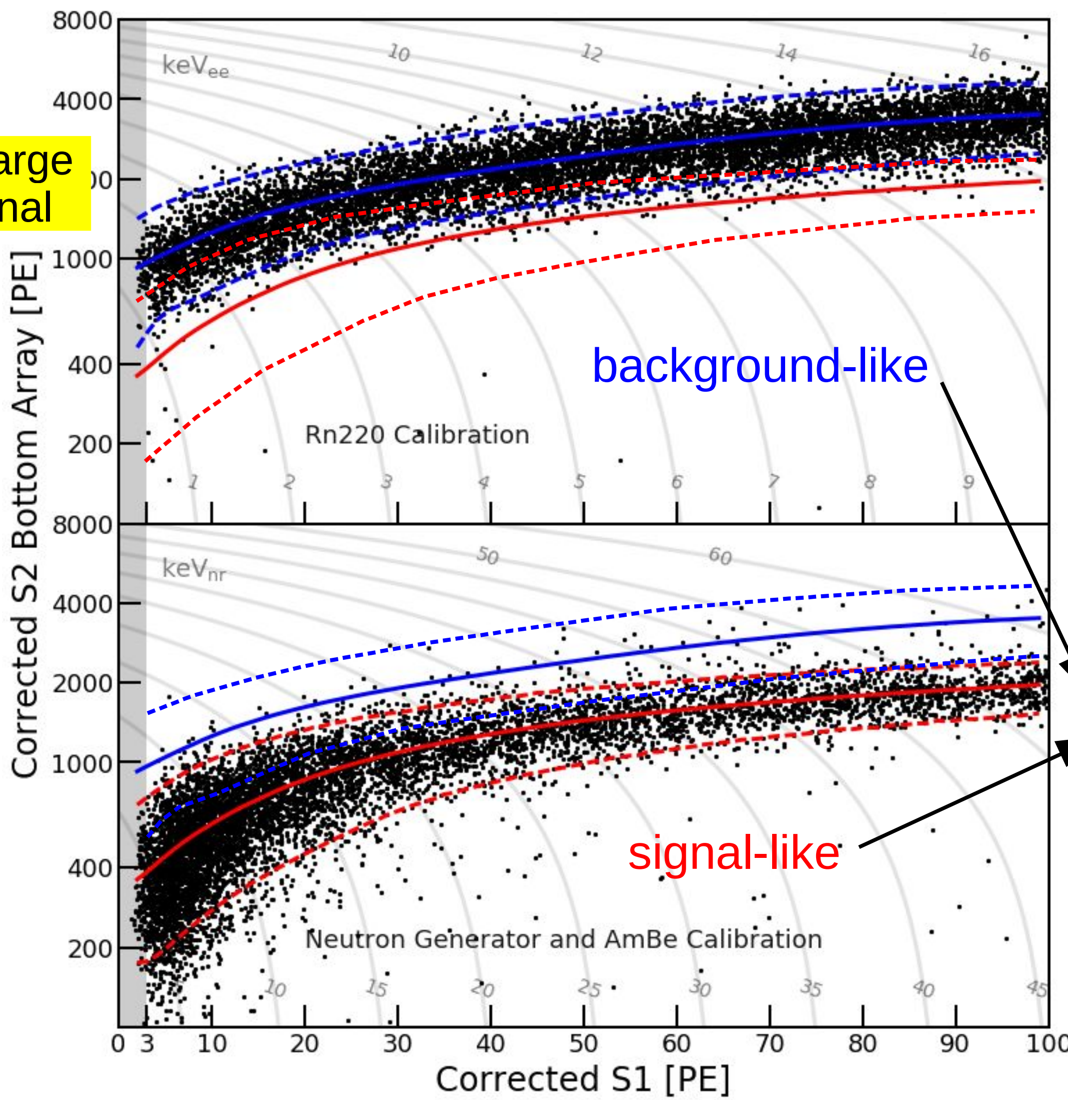




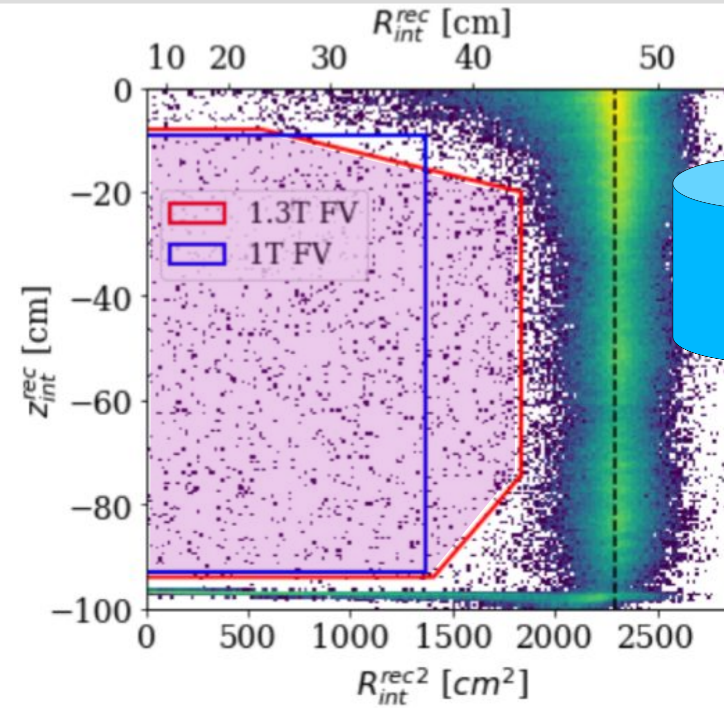
Calibration and Analysis

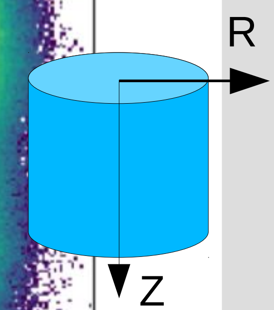
XENON Dark Matter Project

Charge Signal



Light Signal



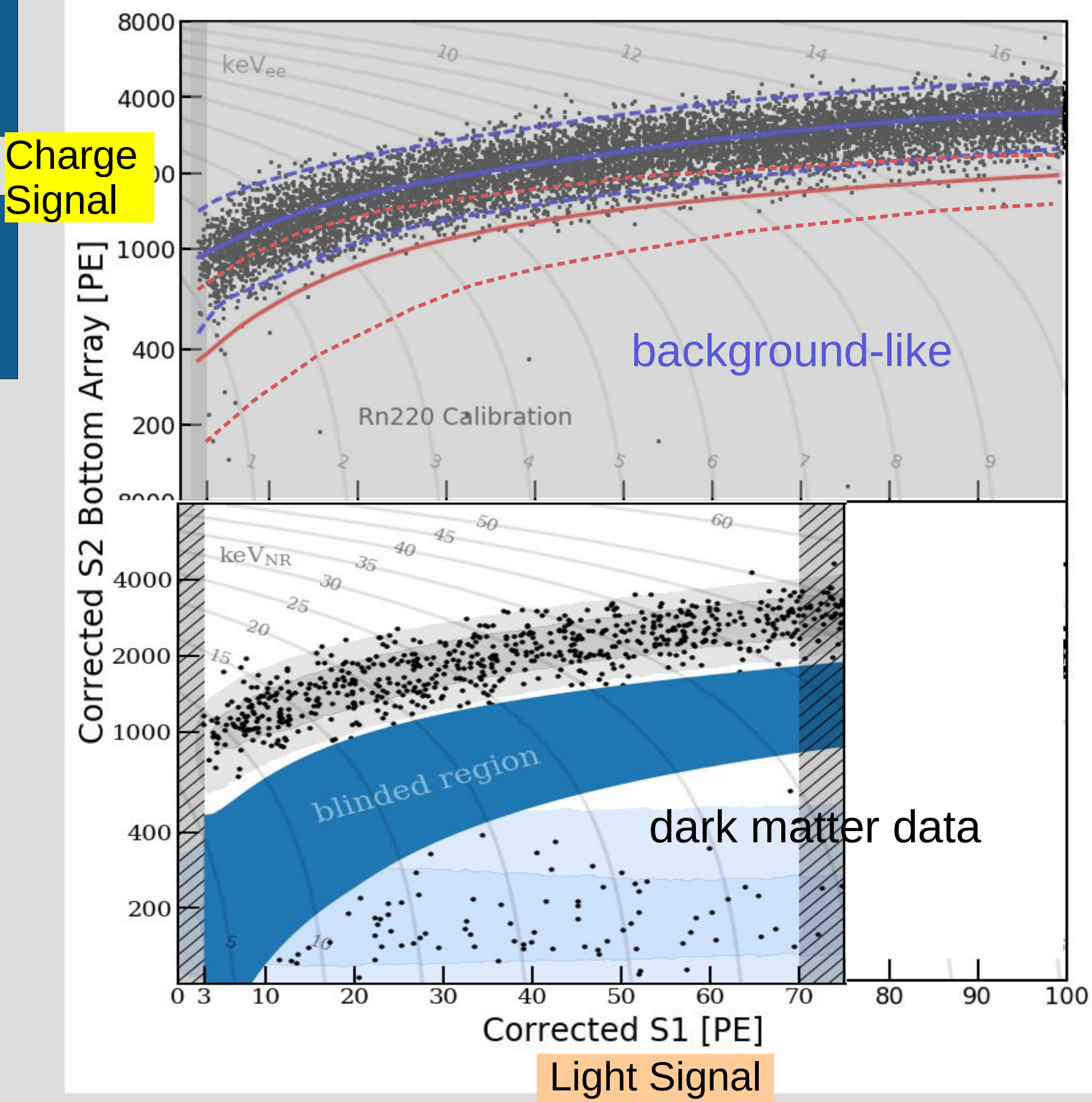


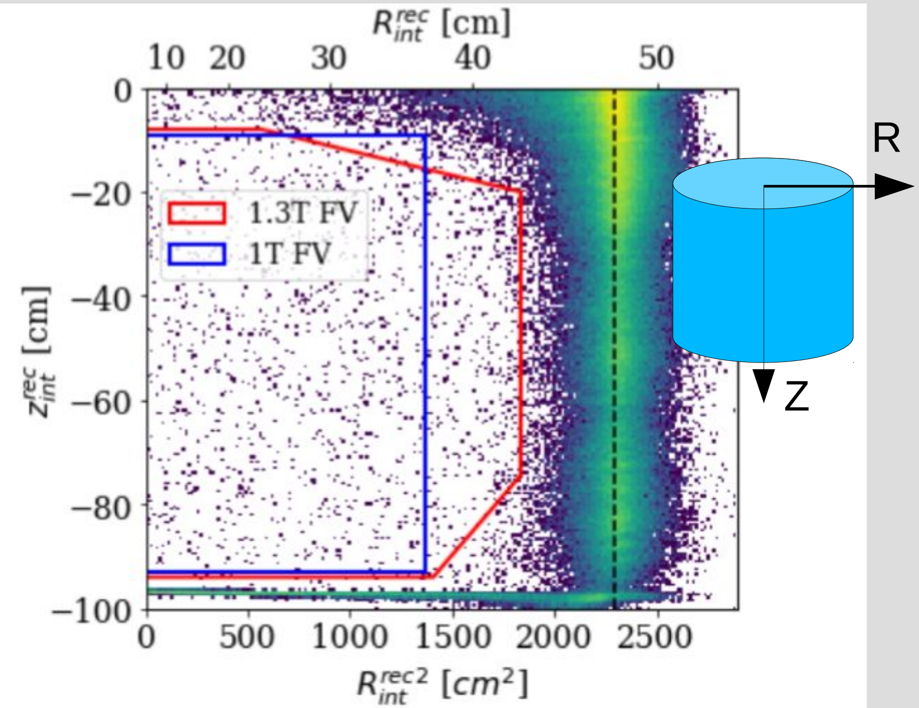
Used to construct background and signal models.

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



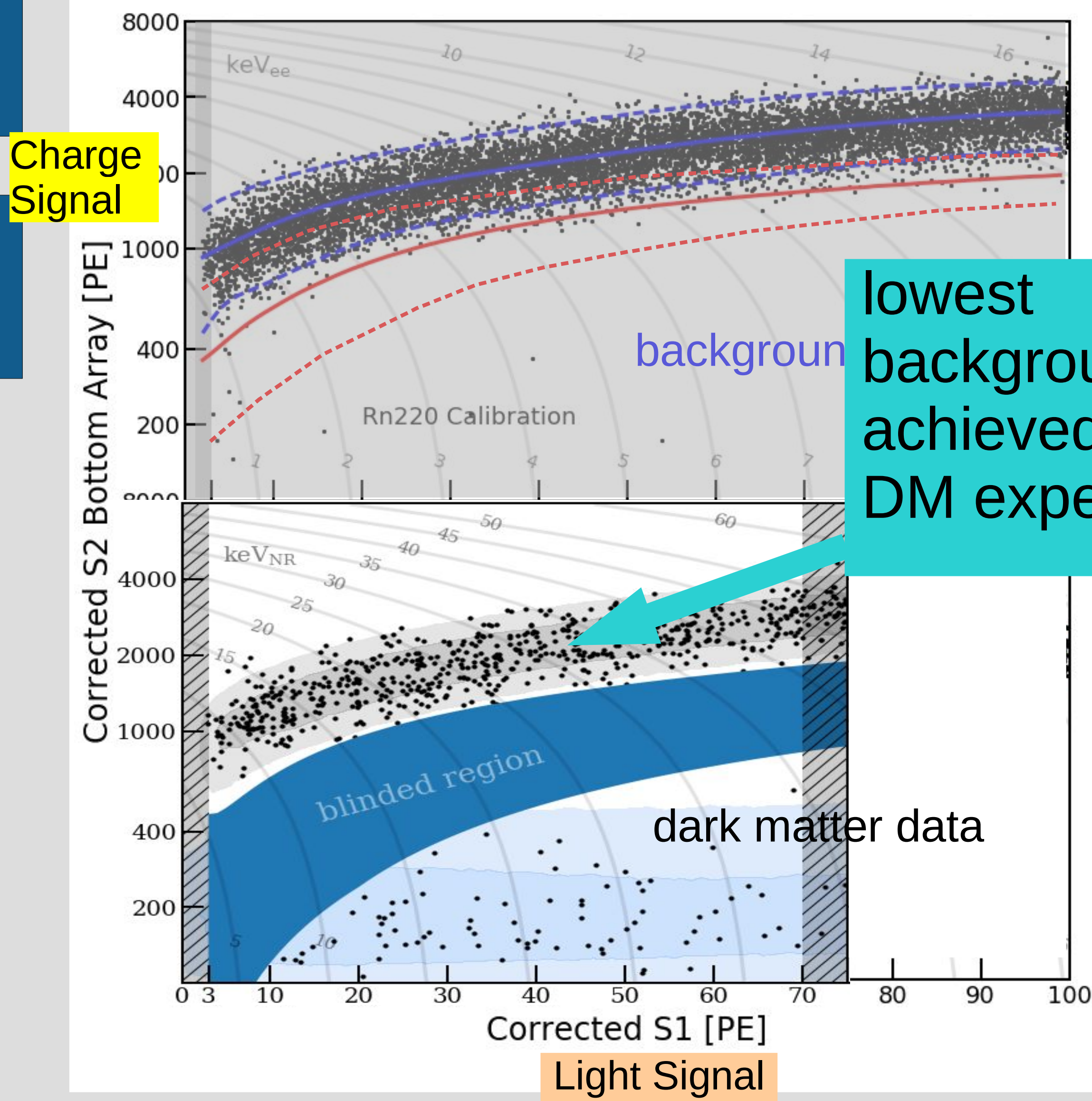


Used to construct background and signal models.

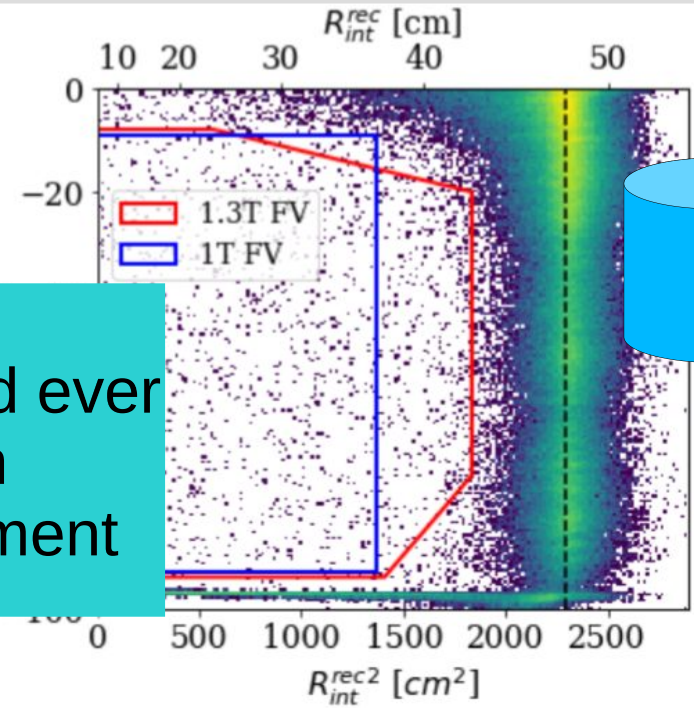
use **central 1.3 t** LXe for analysis

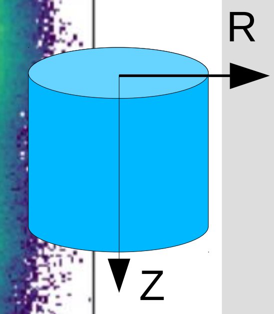
Blind analysis
= region of interest inaccessible during analysis to avoid human bias

Blind WIMP Search



lowest background ever achieved in DM experiment





Used to construct background and signal models.

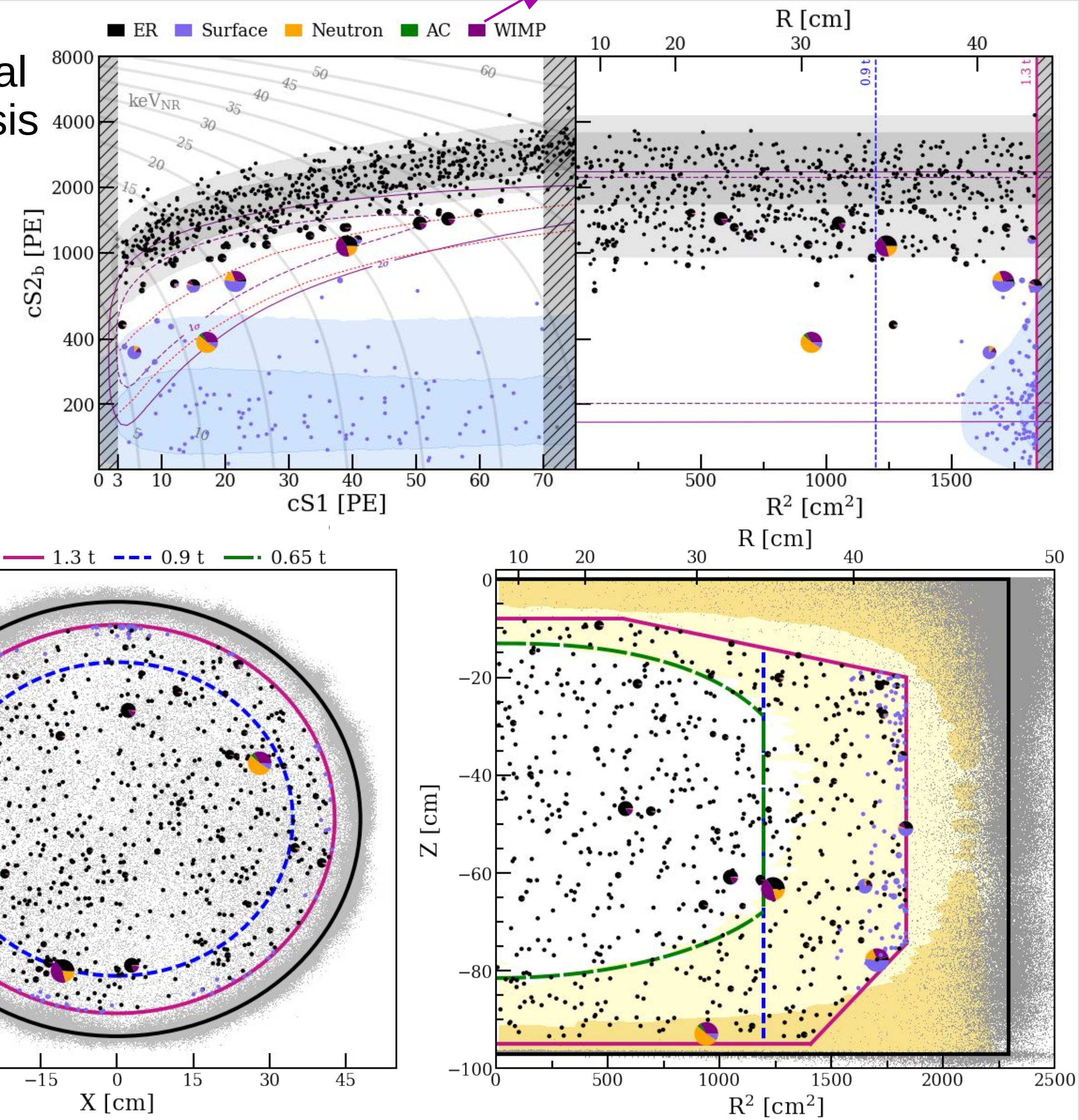
use **central 1.3 t** LXe for analysis

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

Unblinding

200 GeV/c²

multi-dimensional likelihood analysis

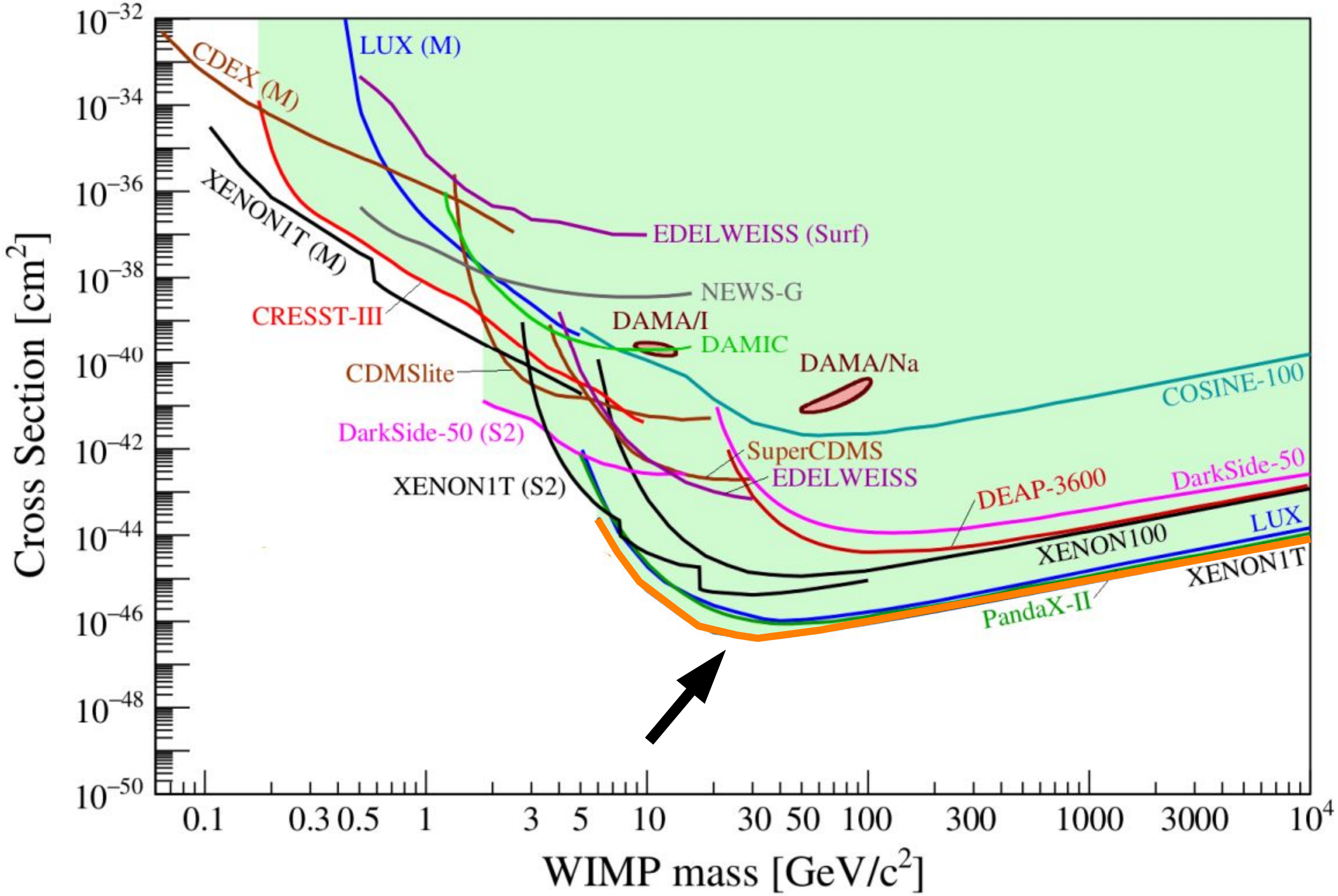


→ no statistically significant excess observed

No Signal → Exclusion Limit

PRL 121, 111302 (2018)

spin-independent WIMP-nucleon interactions



some results are missing...

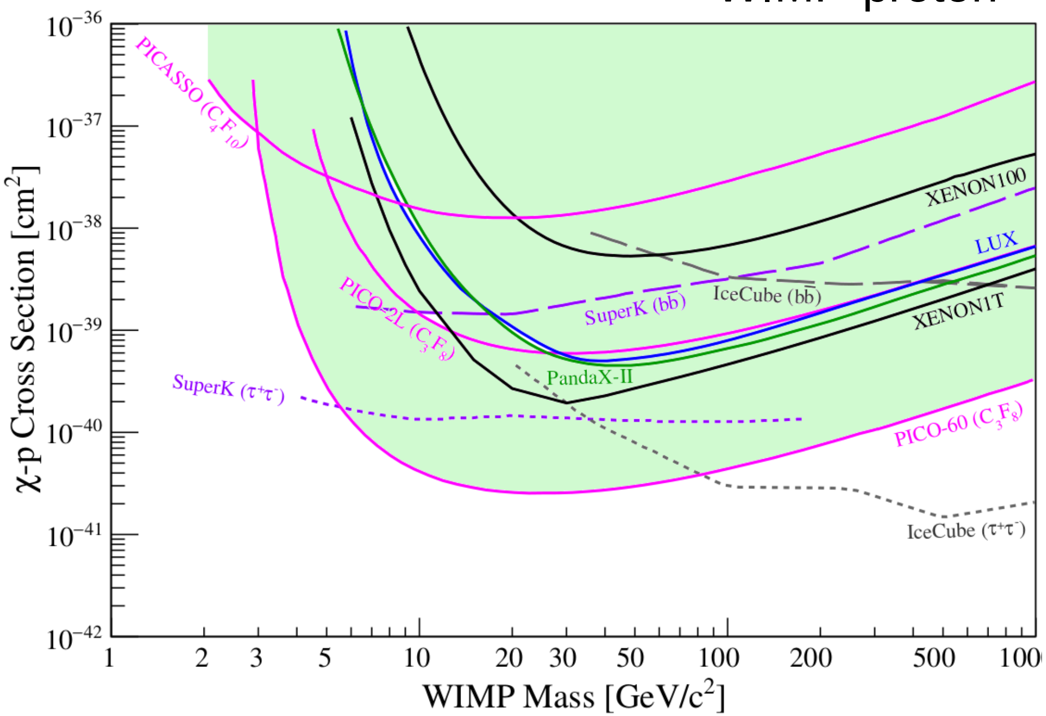
Spin-Dependent Couplings

PRL 122, 141301 (2019)

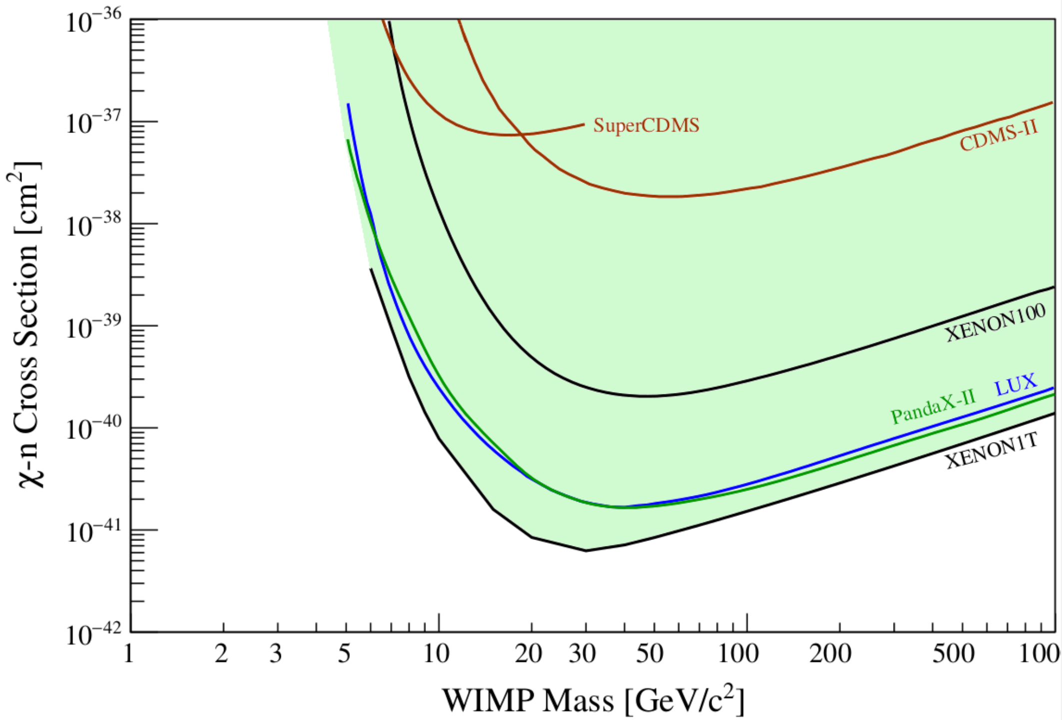
- coupling of WIMP to unpaired nucleon spins
- traditionally separated in proton-only and neutron-only
- same parameter space explored by indirect and collider searches

Isotope	Abundance	Spin	Unpaired Nucleon	Relative Strength
^{7}Li	92.6%	3/2	proton	12.8
^{19}F	100.0%	1/2	proton	100.0
^{23}Na	100.0%	3/2	proton	1.3
^{29}Si	4.7%	1/2	neutron	9.7
^{73}Ge	7.7%	9/2	neutron	0.3
^{127}I	100.0%	5/2	proton	0.3
^{131}Xe	21.3%	3/2	neutron	1.7

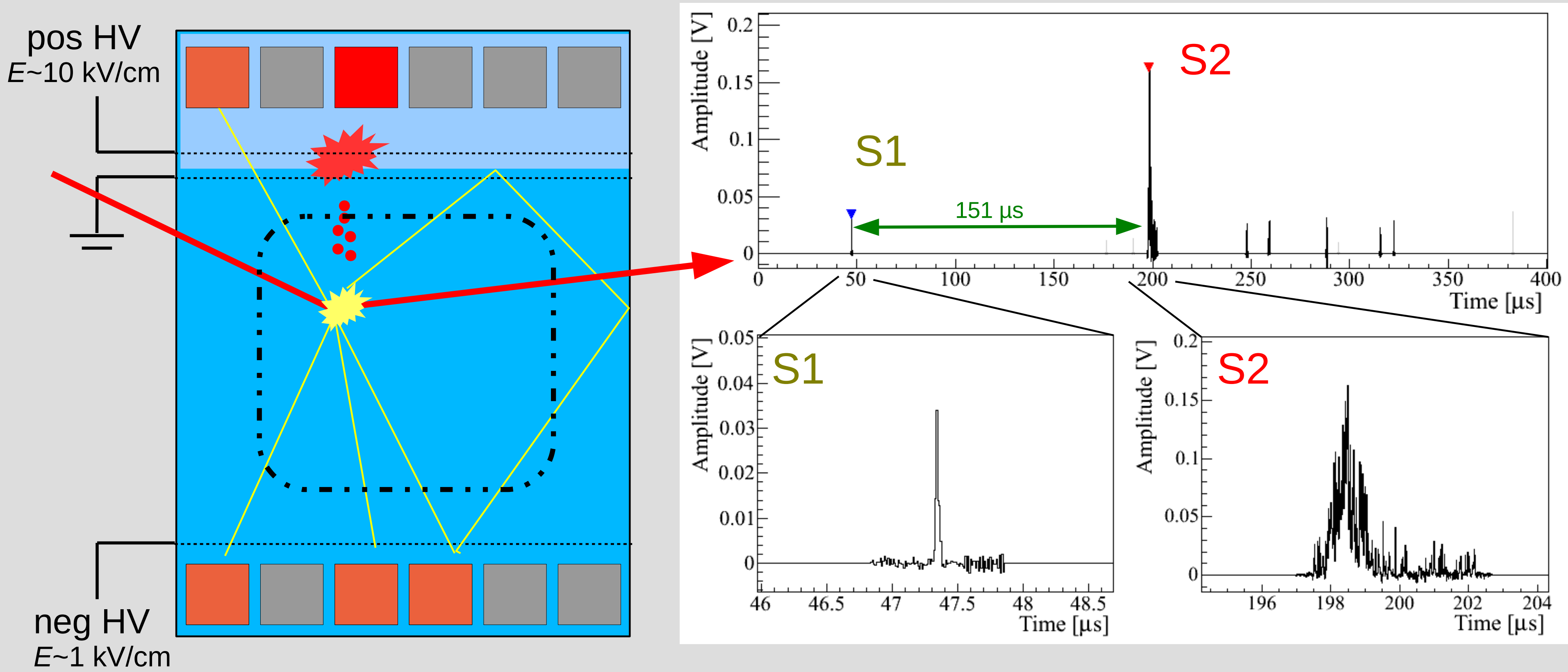
WIMP-proton



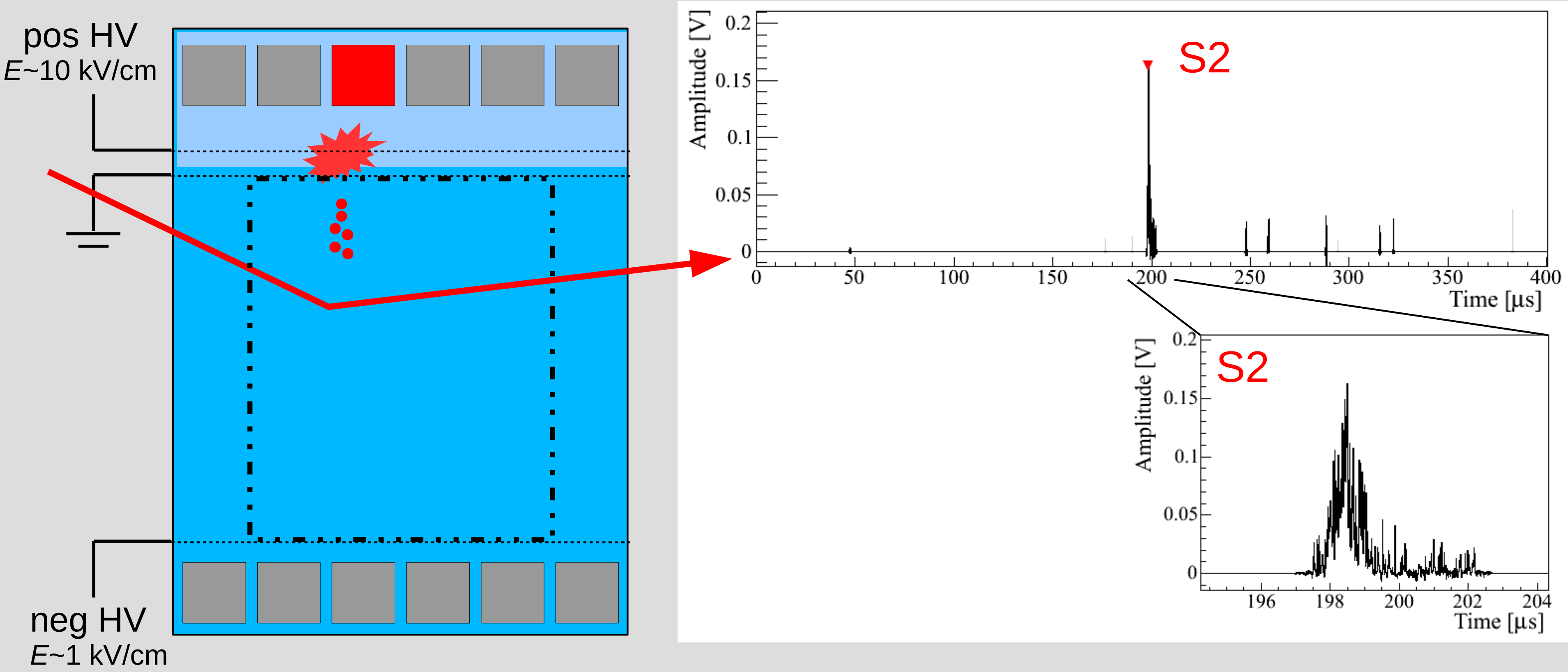
WIMP-neutron



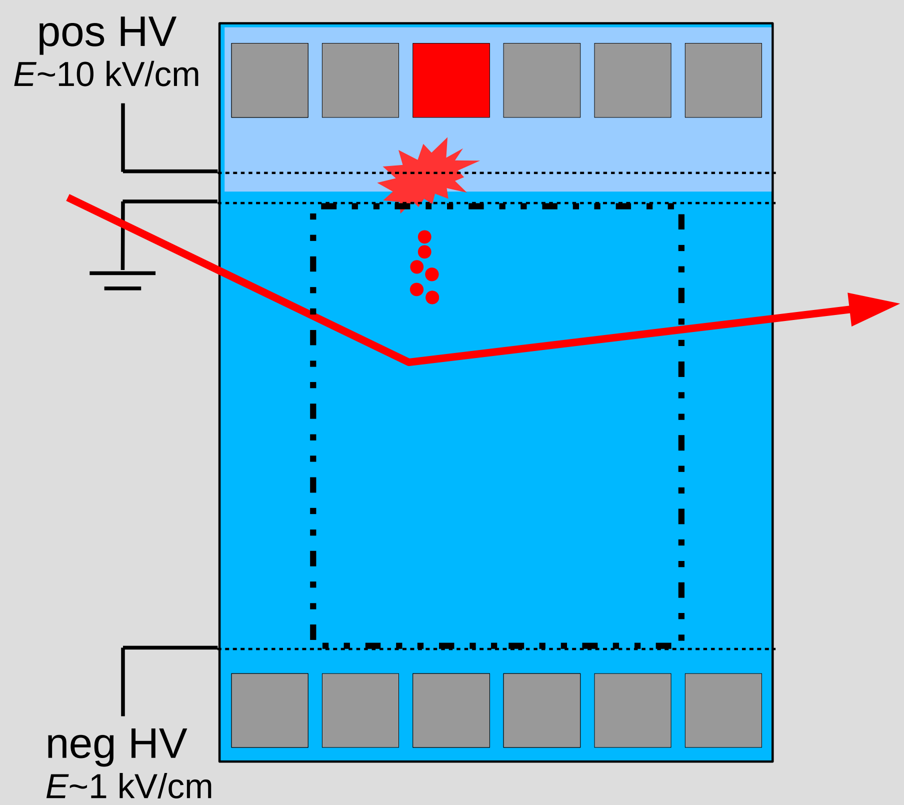
Standard Analysis

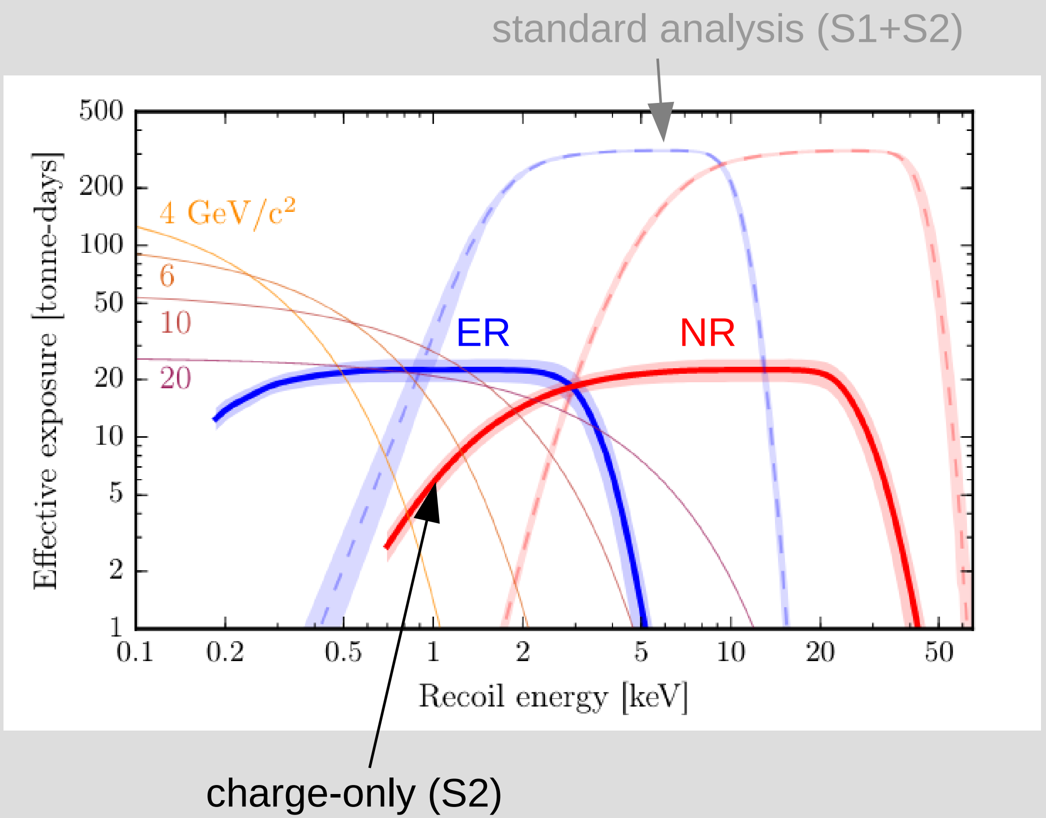


Charge-Only Analysis



Charge-Only Analysis

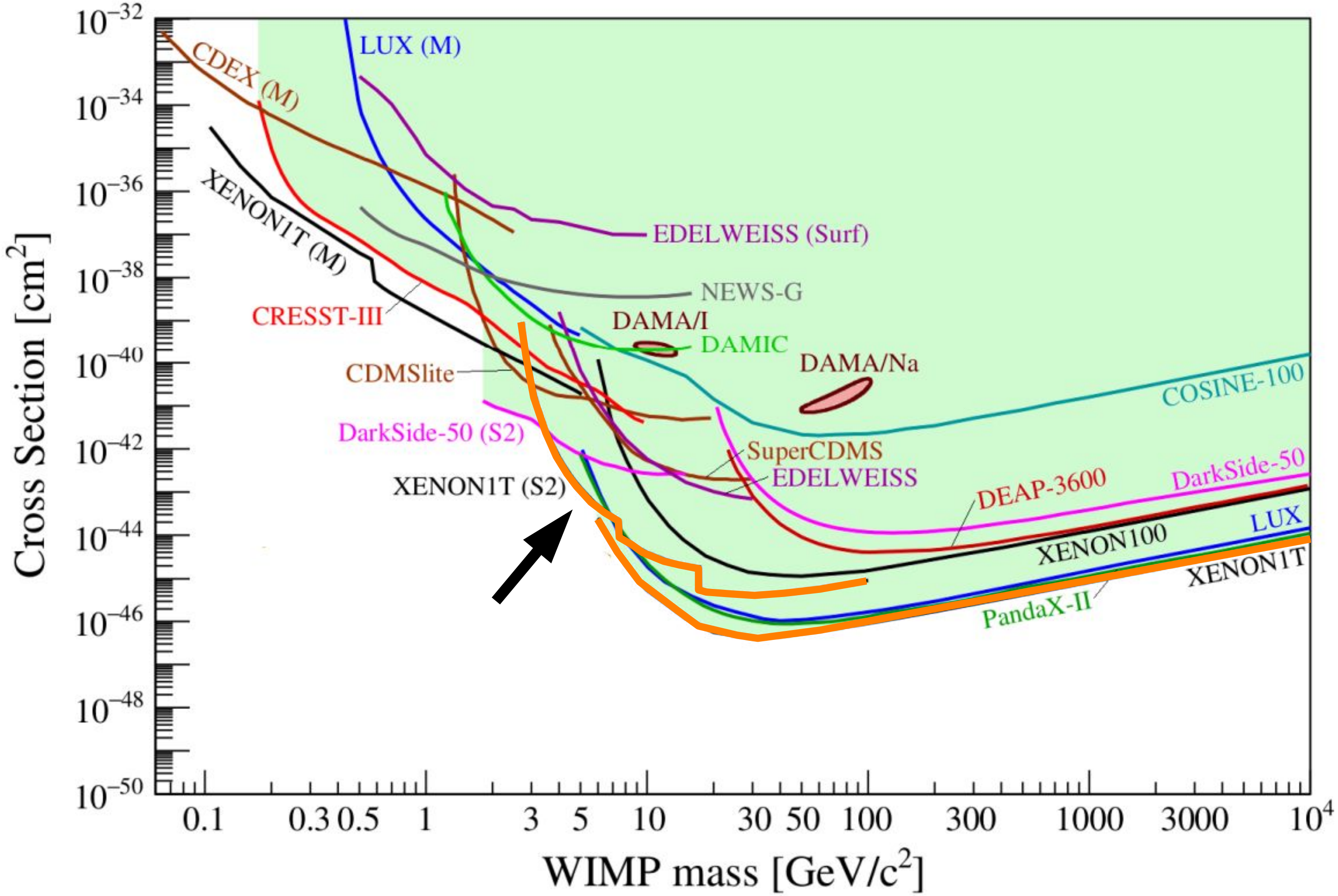




Charge-Only Analysis

PRL 123, 251801 (2019)

spin-independent WIMP-nucleon interactions

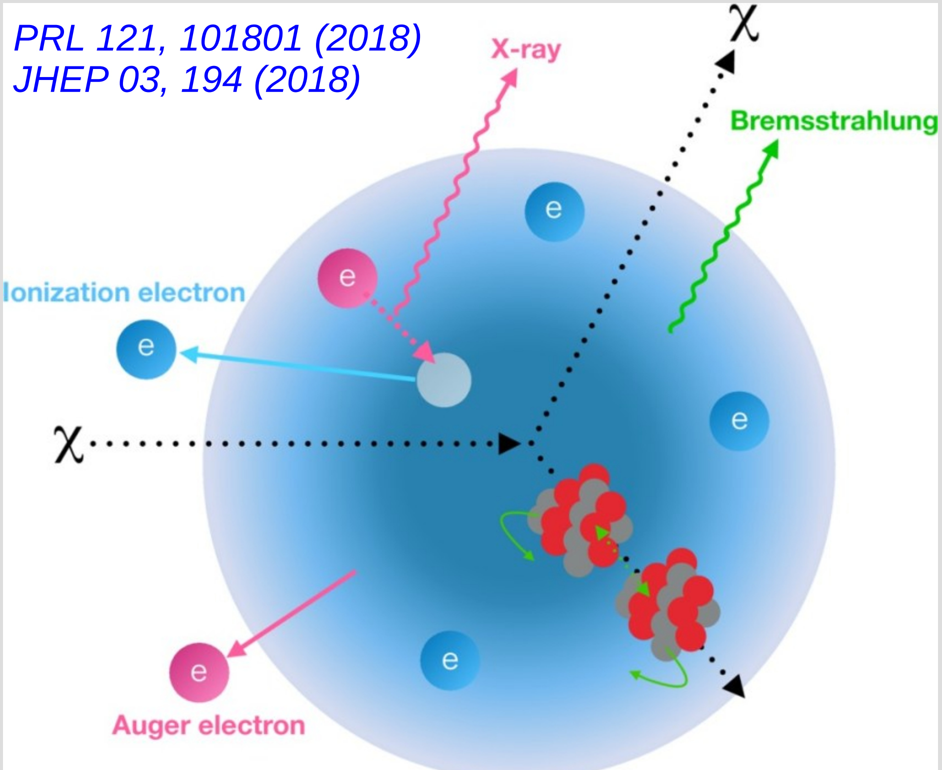


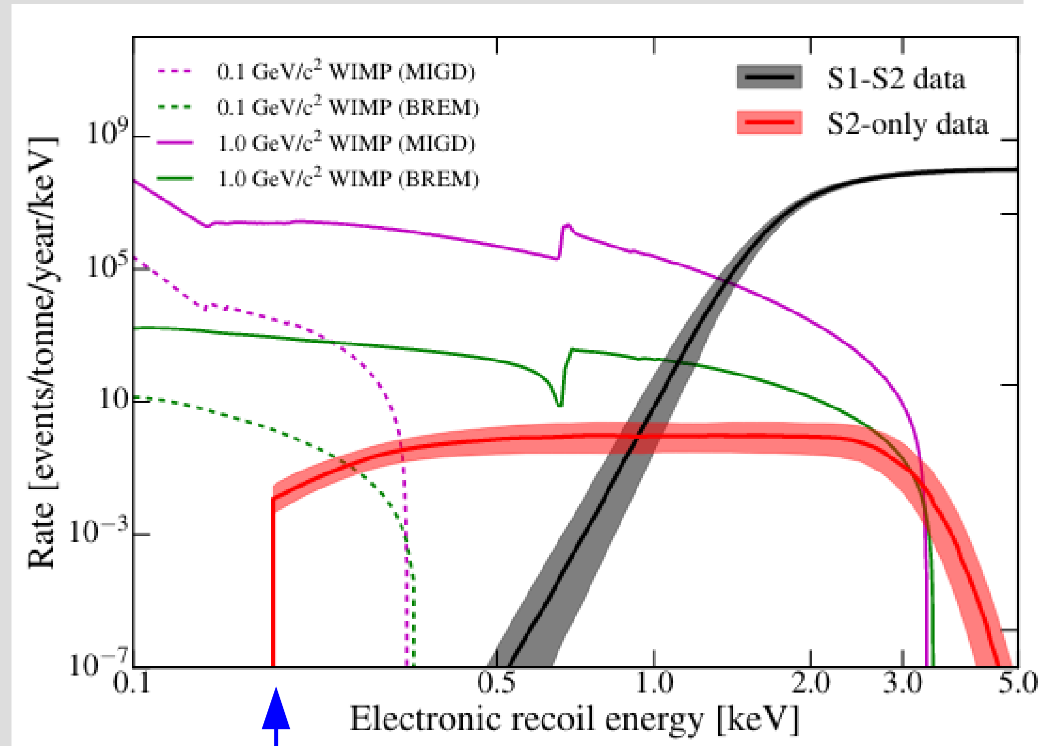
some results are missing...

Migdal Effect, Bremsstrahlung

PRL 123, 241803 (2019)

PRL 121, 101801 (2018)
JHEP 03, 194 (2018)





– exploit expected „relaxation" effects after NR
→ very low threshold

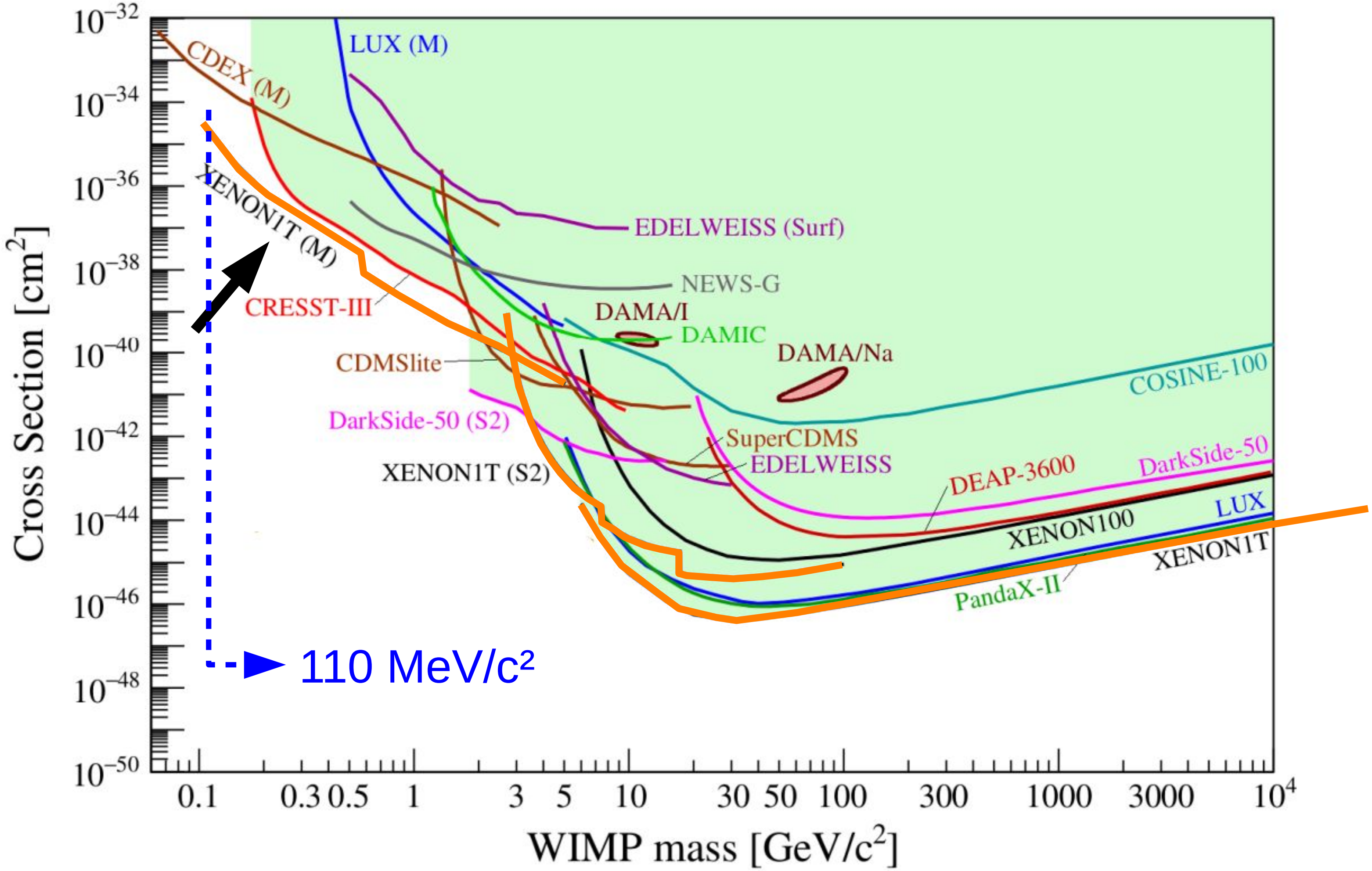
– caveat: effect not yet observed in calibration

~180 eV (~4.5 electrons)

Migdal Analysis

PRL 123, 251801 (2019)

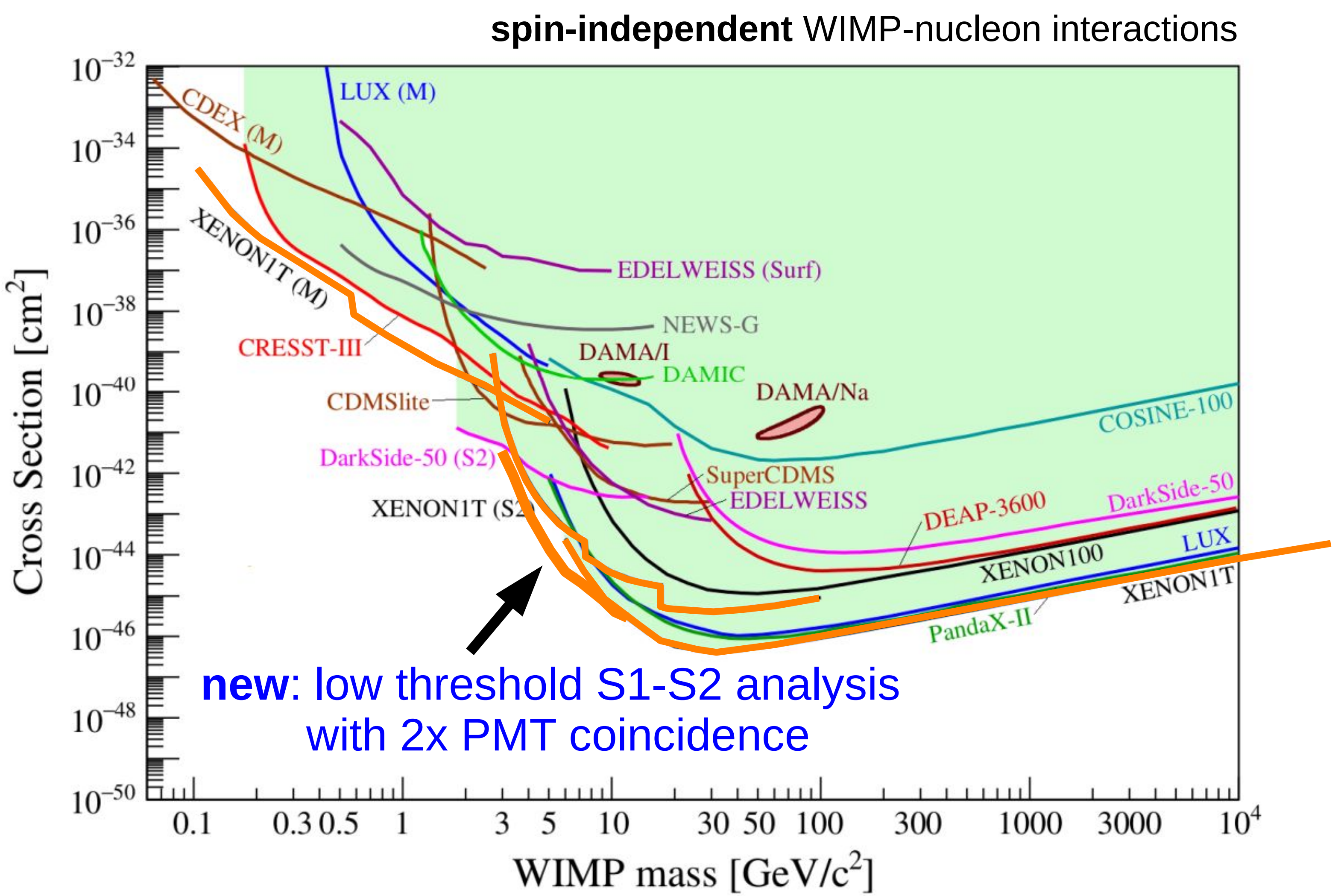
spin-independent WIMP-nucleon interactions



some results are missing...

New: Low-threshold S1-S2

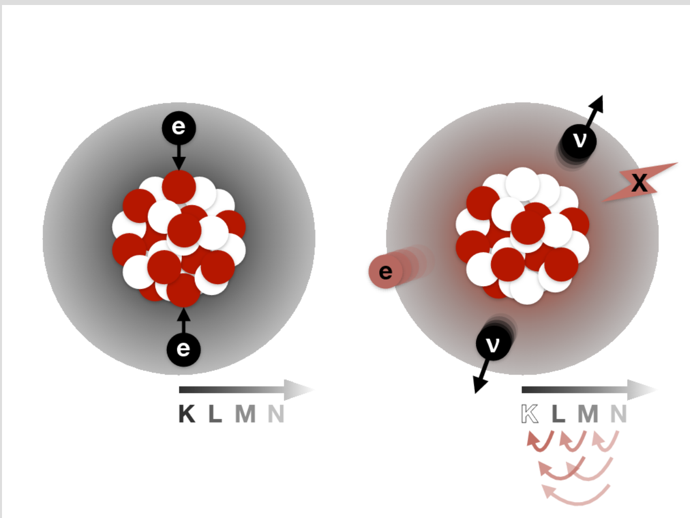
arXiv:2012.02846



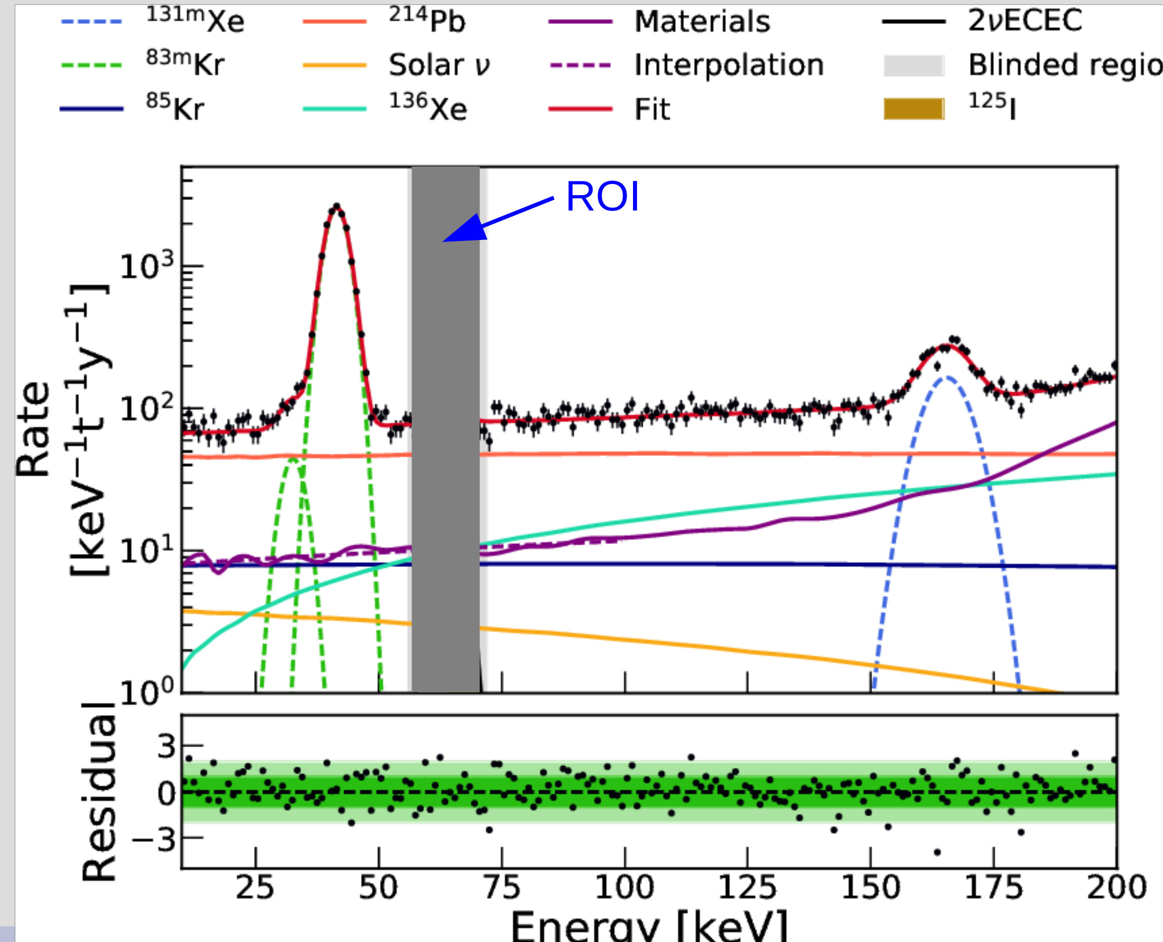
some results are missing...


nature
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
CAUGHT IN THE ACT
Dark-matter detector captures elusive nuclear decay in xenon PAGES 402 & 532
TRANSITIONAL INSIGHTS
The world's largest study of transgender people
IN THE DARK
How high-rise living deprives urban centres of natural light
SPEECH SYNTHESIZER
Implant gives voice to brain signals that control movement
NATURE.COM

Double-Electron Capture of ^{124}Xe



- weak 2nd order decay with very long half life $T_{1/2}$
- already observed for ^{78}Kr, ^{130}Ba



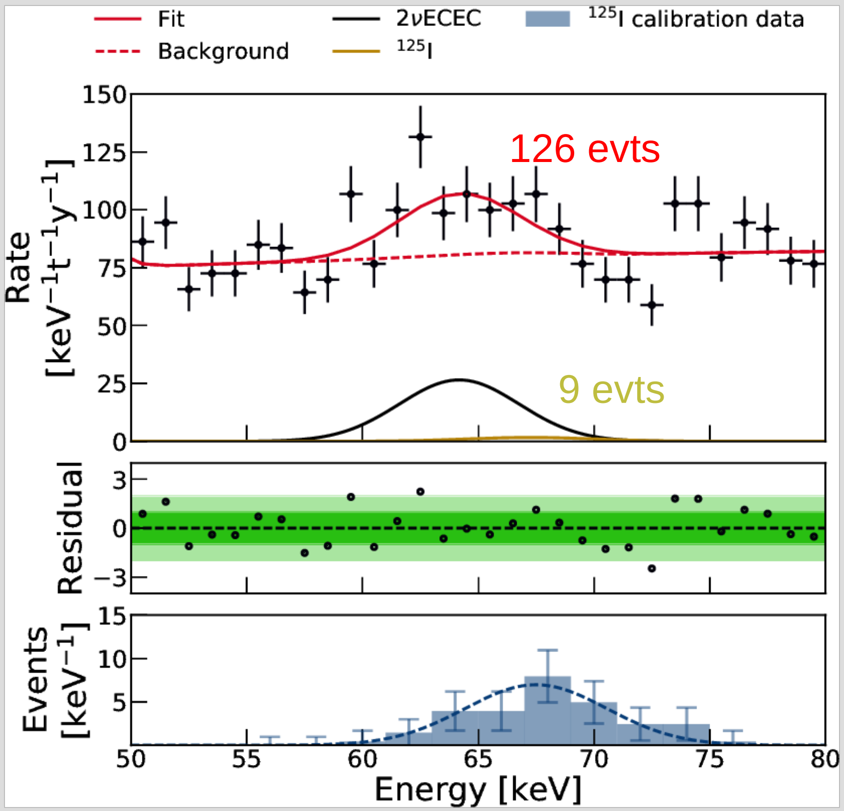
- $^{124}Xe + 2\,e^{-} \rightarrow {}^{124}Te^{**} + 2\,\nu_e$

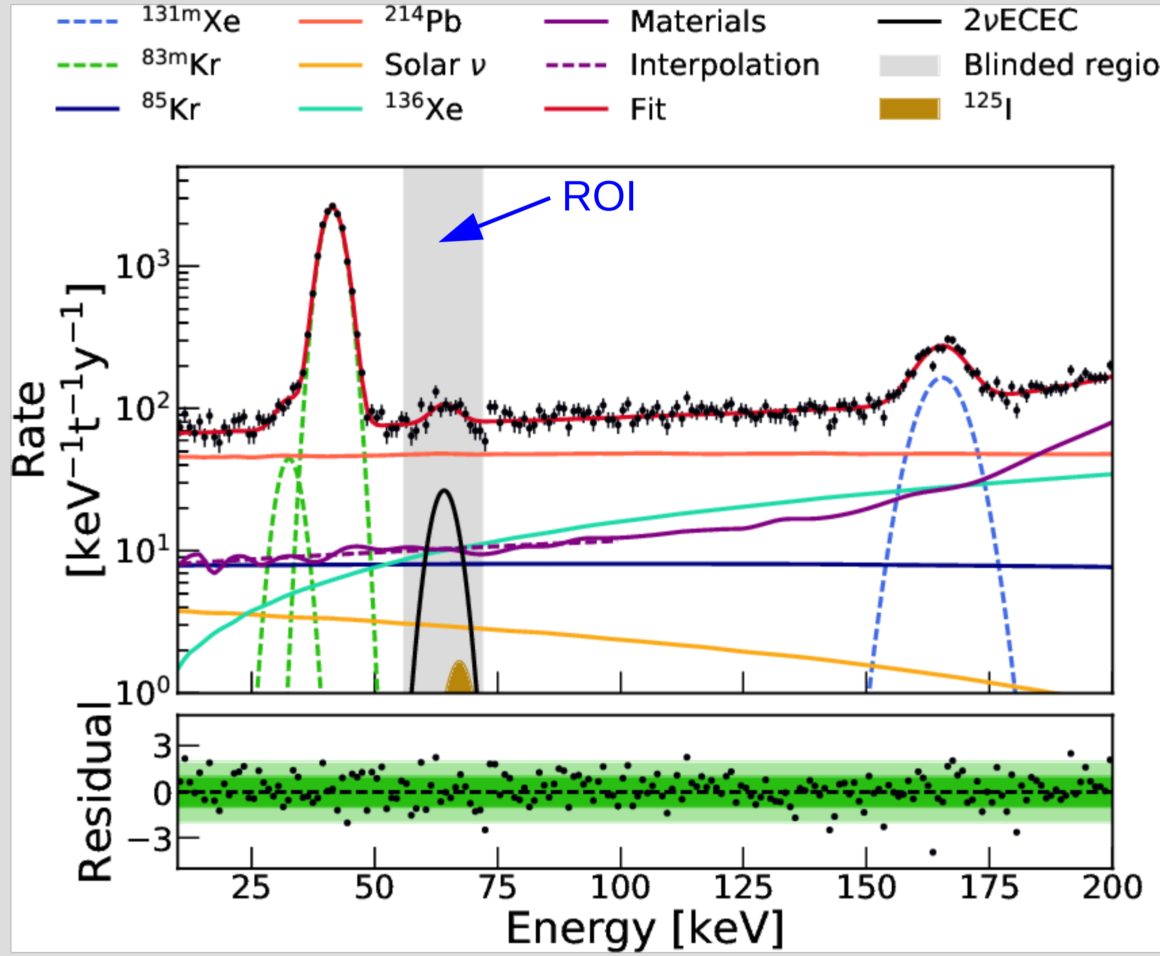
monoenergetic line at 64.33 keV

^{nat}Xe contains ~1 kg ^{124}Xe per ton

Double-Electron Capture of ^{124}Xe

Nature 568, 532 (2019)



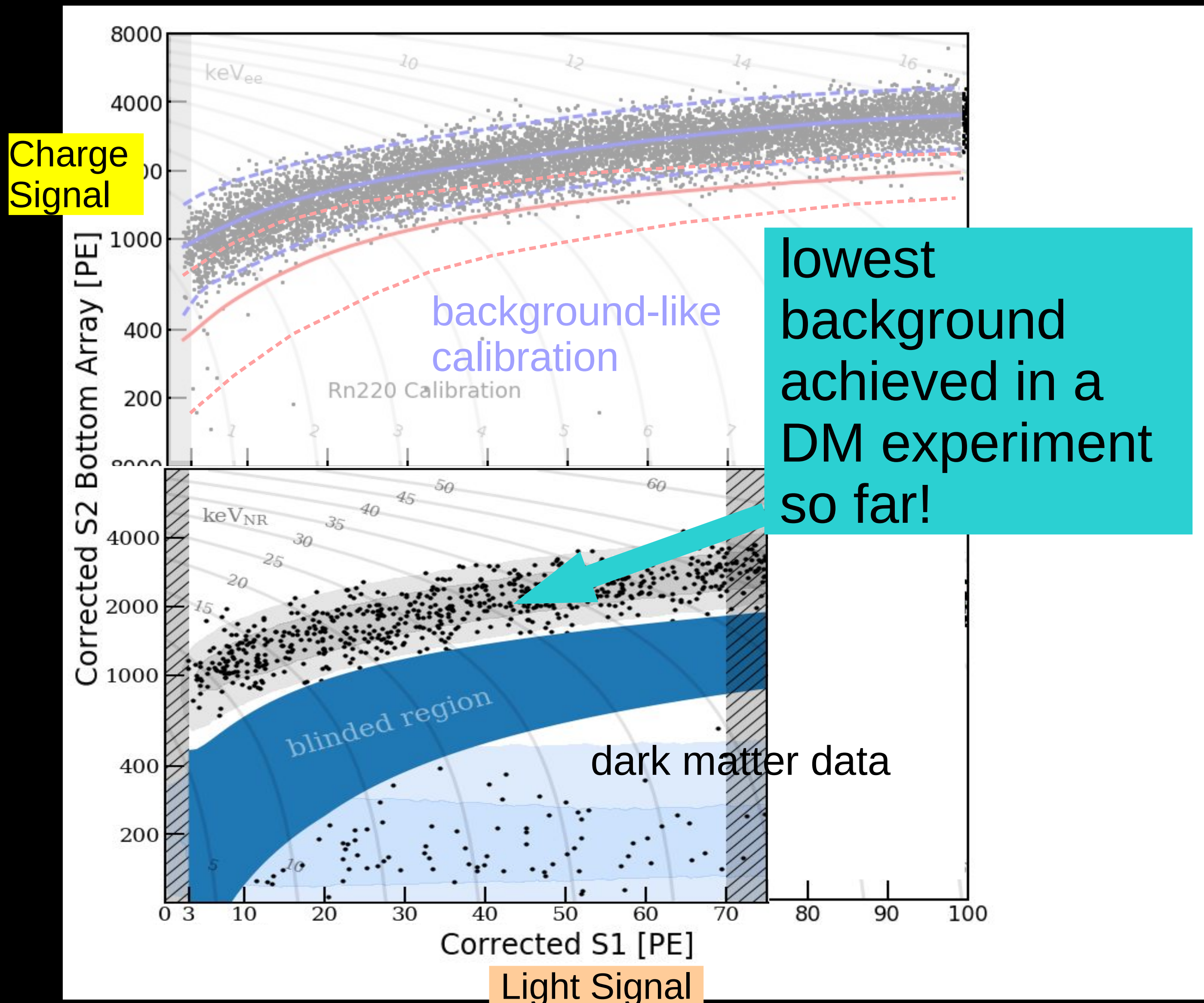


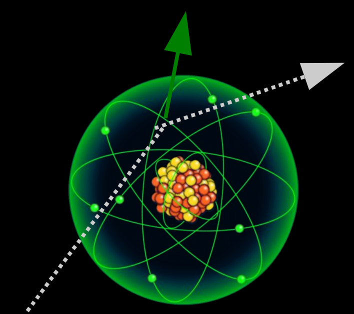
- 126 events above background in 1.5 t Xenon
- $T^{2\nu ECEC}_{1/2} = (1.8 \pm 0.5_{stat} \pm 0.1_{sys}) \times 10^{22}$ y
- **Longest half-life ever directly measured!**

WWU MÜNSTER

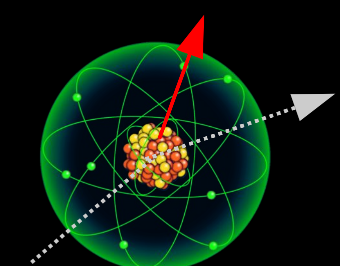
Electronic Recoil Search

PRD 102, 072004 (2020)





Electronic Recoil
(gamma, beta, **??**)



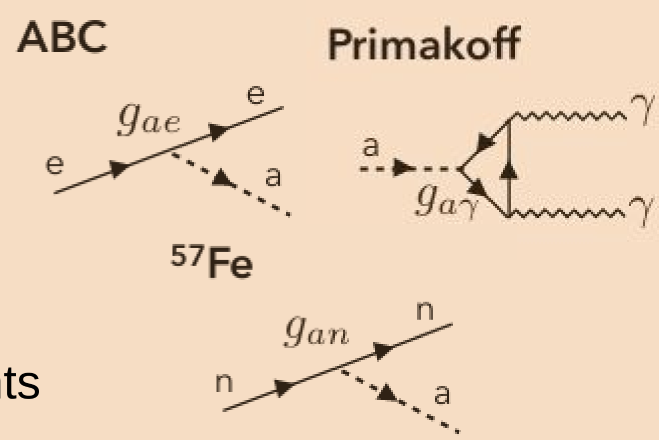
Nuclear Recoil
(neutron, WIMP)

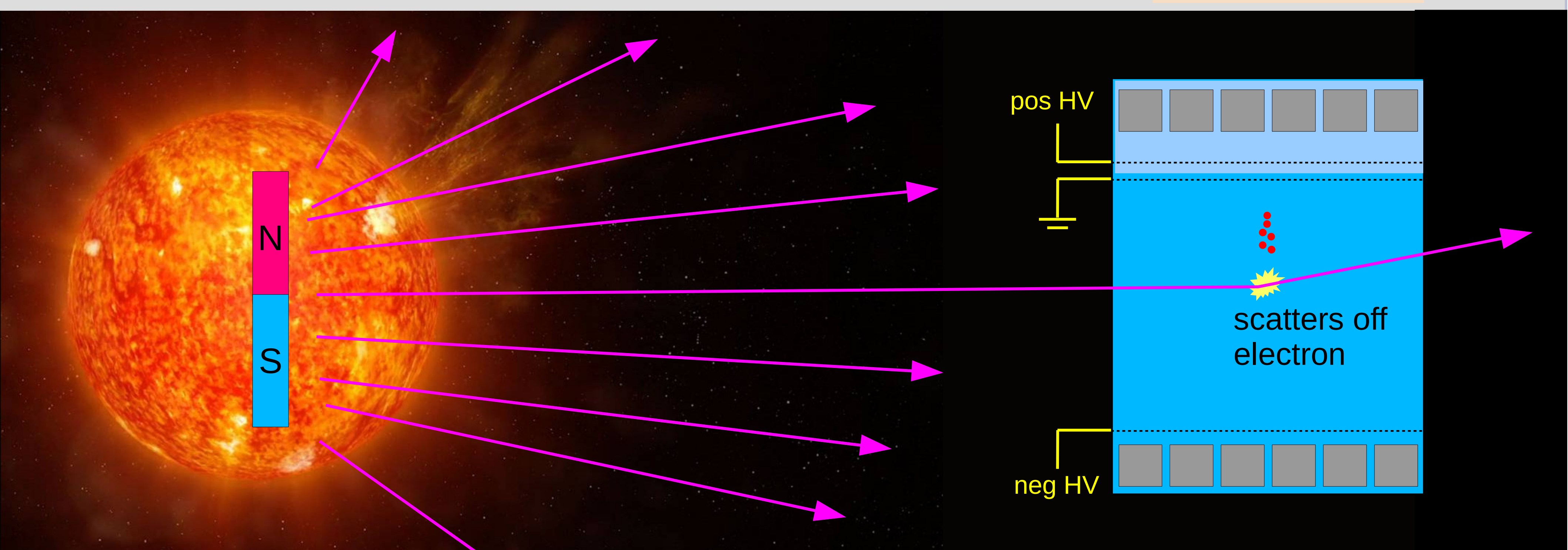
New Physics in ER Data

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** γ→a conversion
  - **^{57}Fe**: 14.4 keV M1 nuclear transition
- normalization of spectra depends on axion coupling constants



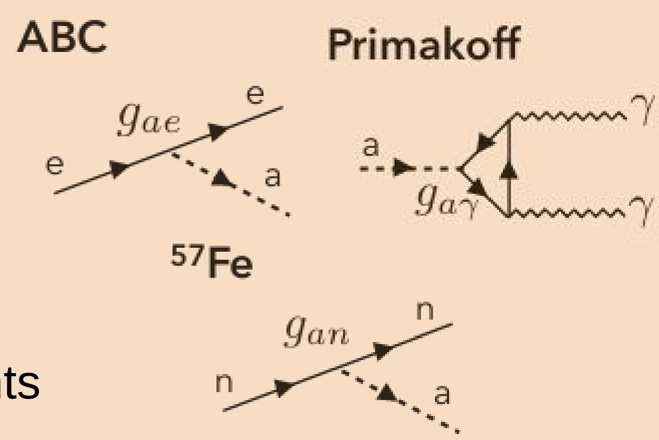


New Physics in ER Data

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

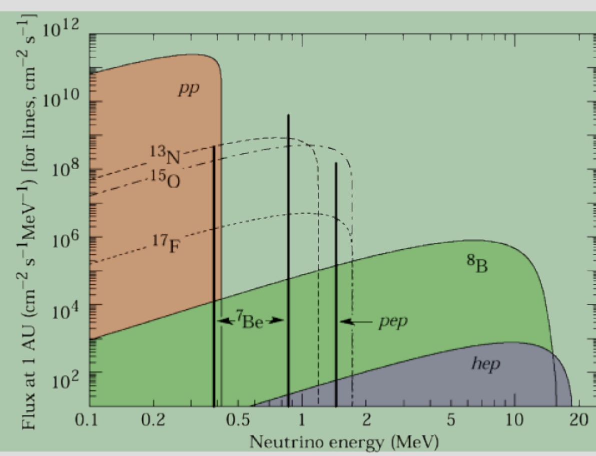


Axion-like Particle (Bosonic ALPs)

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

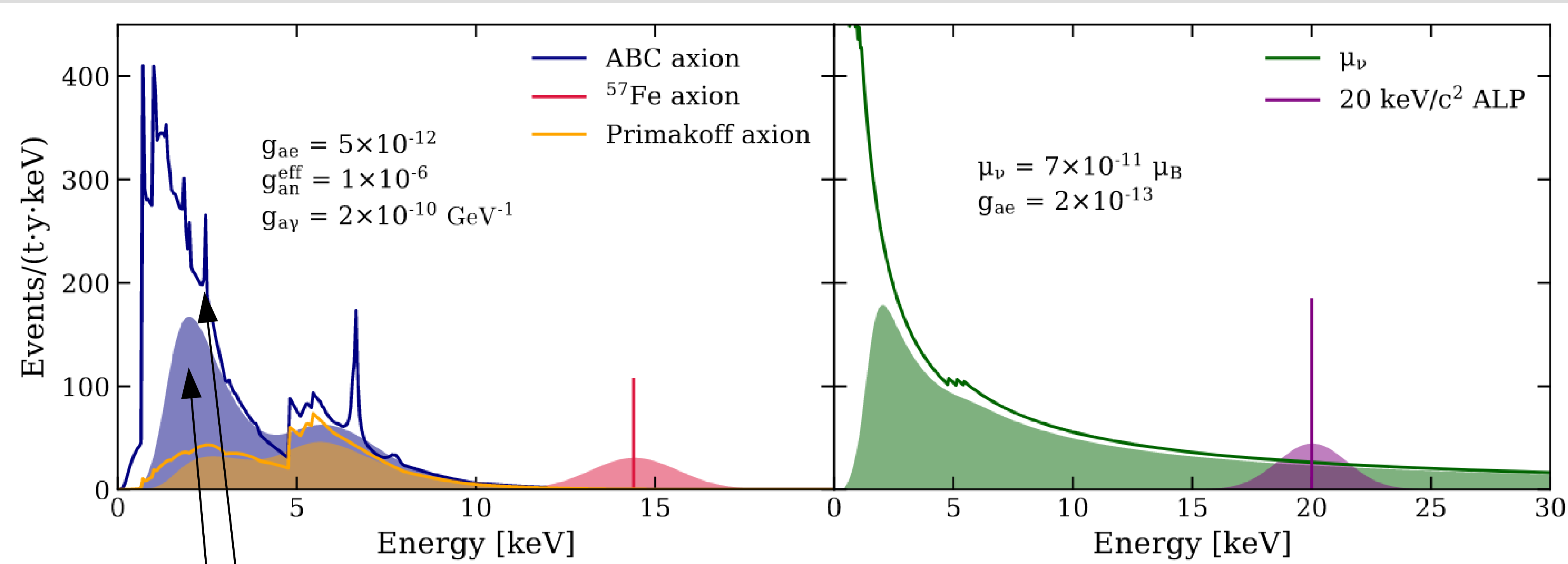
Enhanced Neutrino Magnetic Moment

- expect $\mu_\nu \sim 10^{-20}\ \mu_B$ for massive neutrinos
- BSM physics could enhance μ_ν;
  if $\mu_\nu > 10^{-15}\ \mu_B \rightarrow$ 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

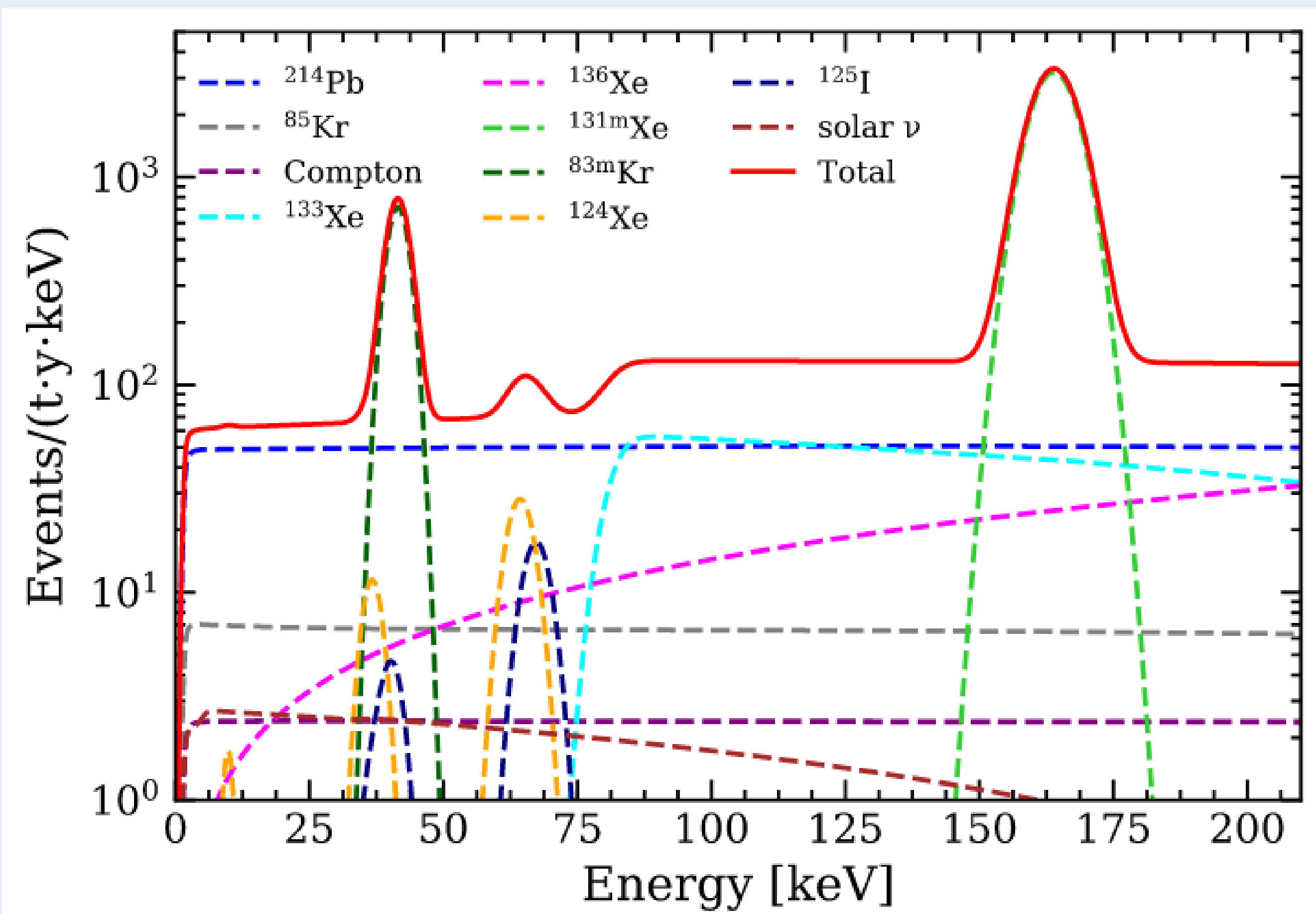


Production ⊗ Detection

Production ⊗ Detection ⊗ Reconstruction

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*

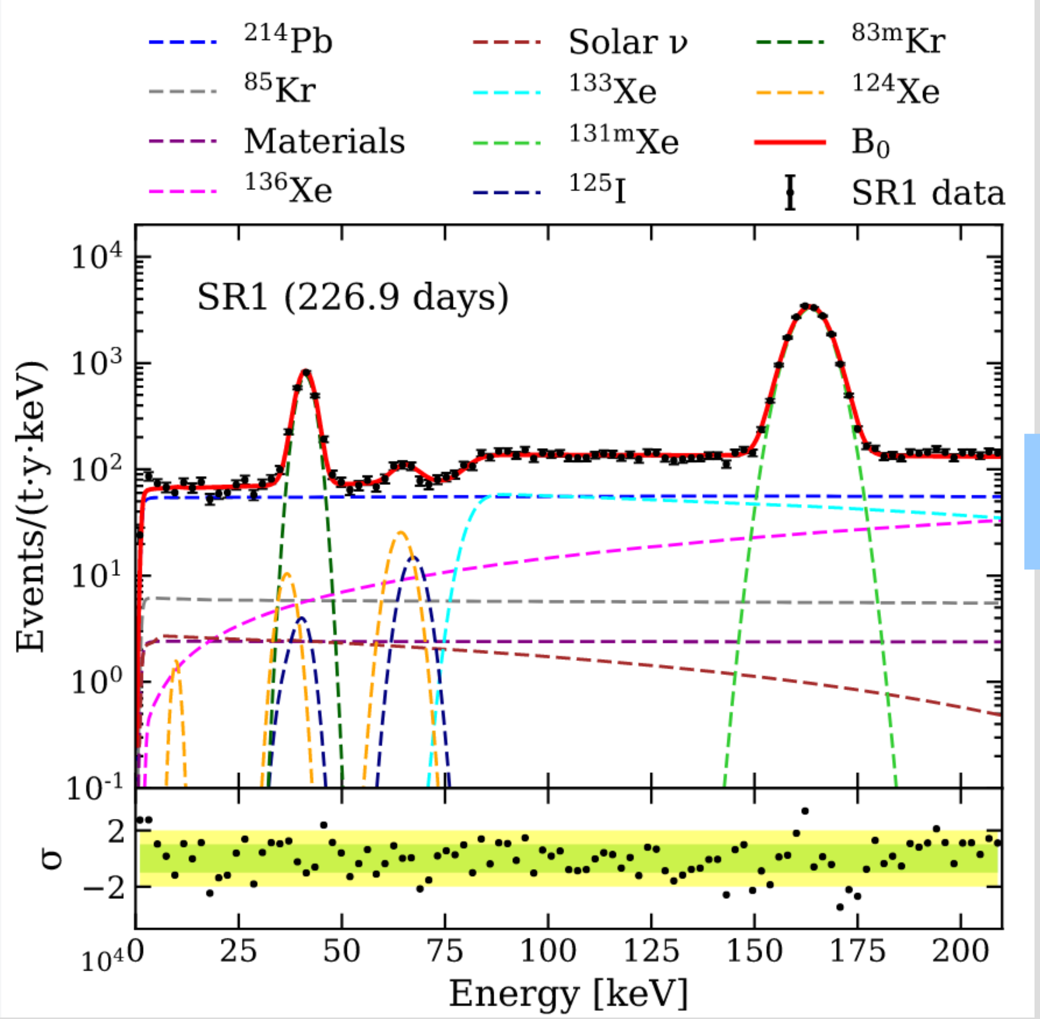
From neutron-activation:
^{131m}Xe (IC)
^{133}Xe (β+81 keV γ)
^{125}I (EC)
→ *divide data in two periods: close/far from n-calibration*

Detector materials

Solar neutrinos

Background Fit

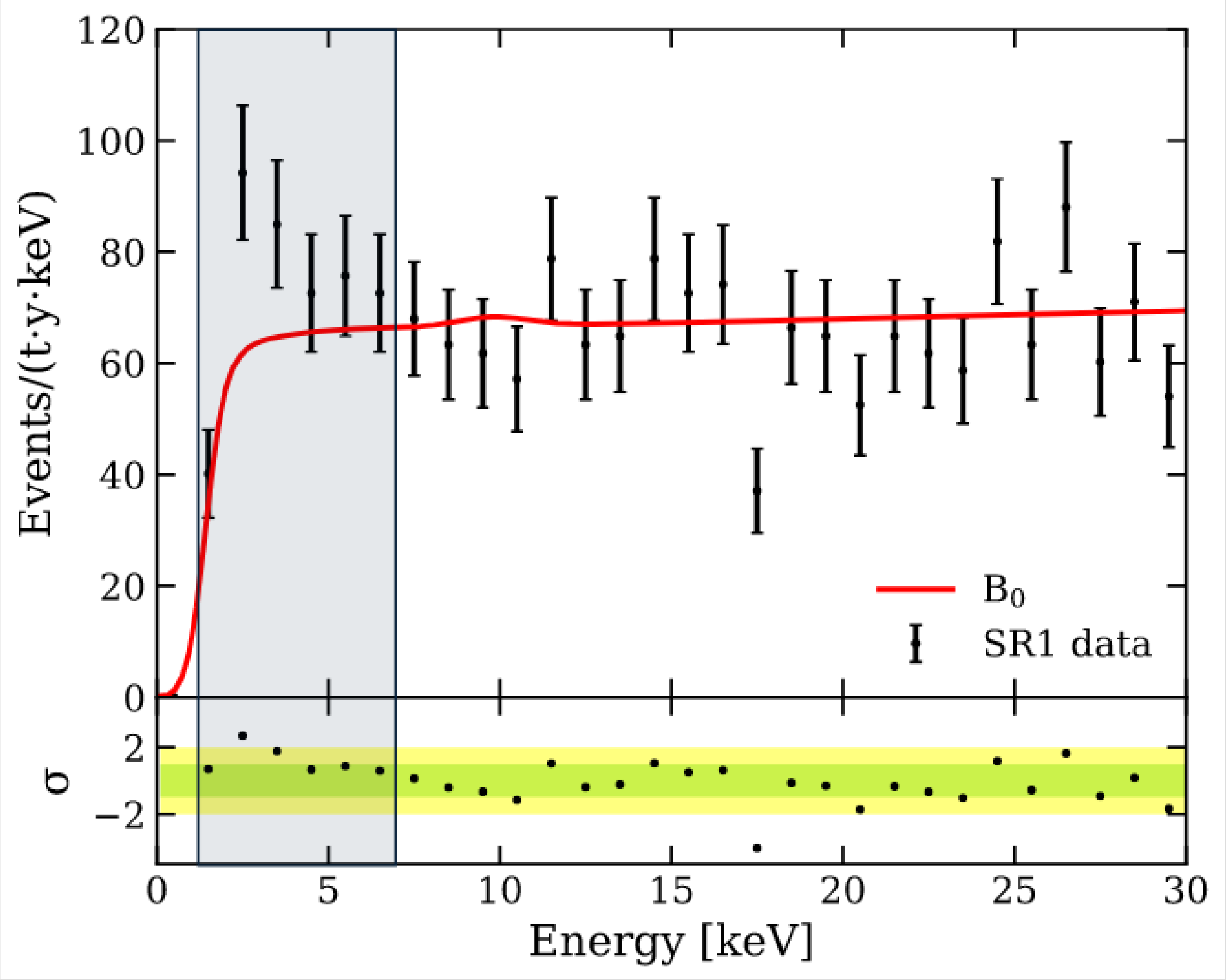
– unbinned profile likelihood fit to data
– combined fit of data close/far to neutron calibration



(76 ± 2) evts/(t y keV) in 1-30 keV

→ world record background level!

Excess of Events



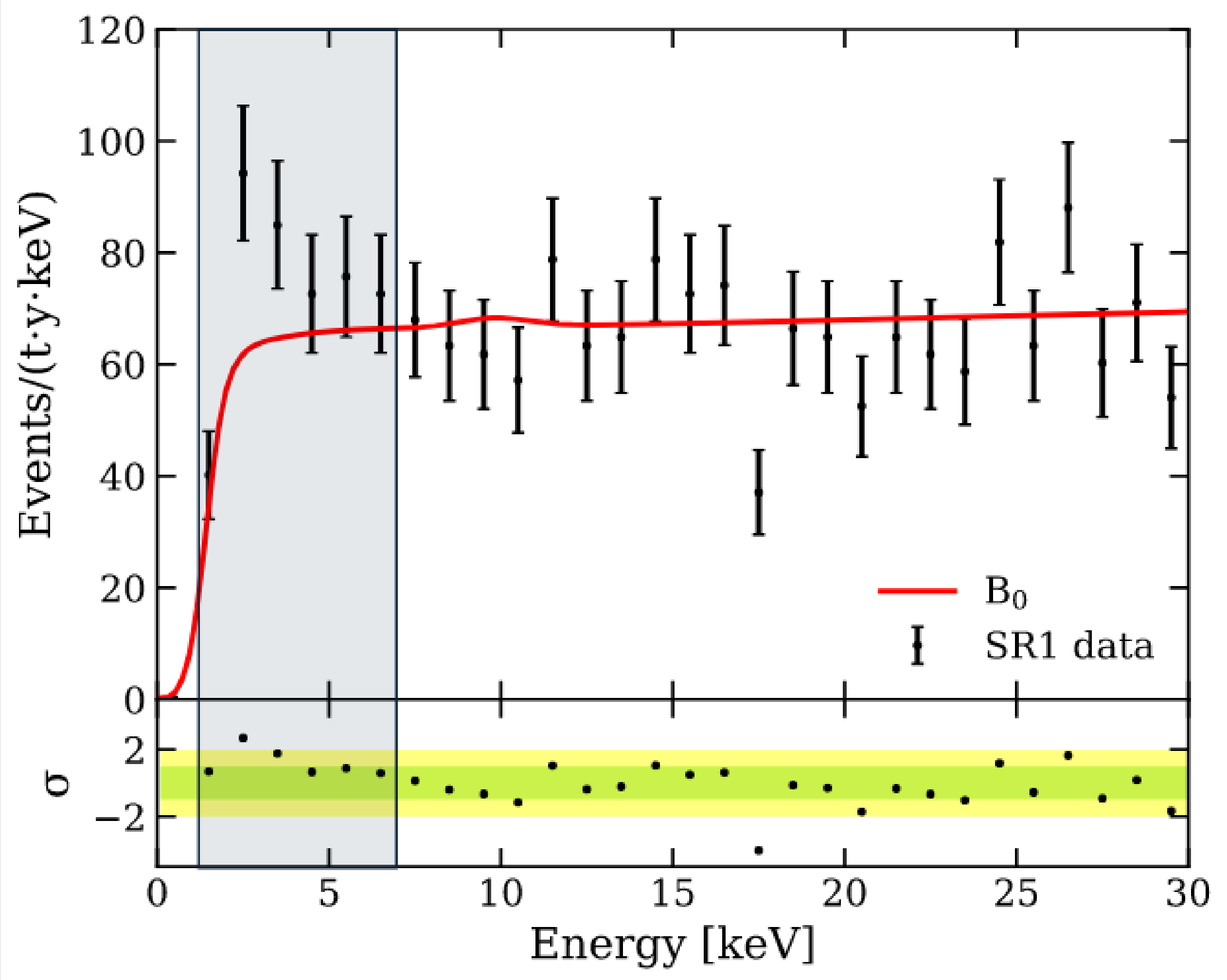
- **excess in 1-7 keV range**
  285 evts observed vs
  232 ± 15 expected
  → **(naive) 3.3σ fluctuation**

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

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

- energy threshold well understood

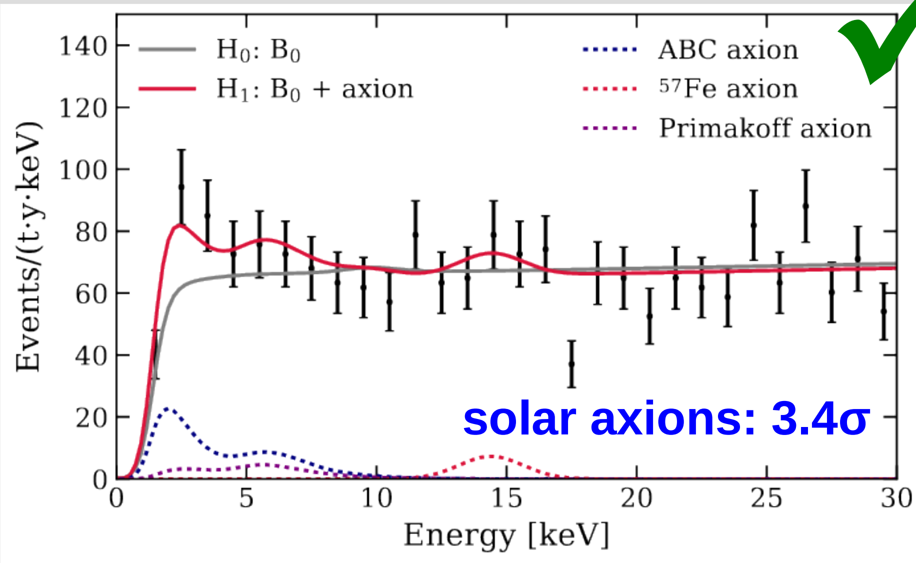
Excess of Events

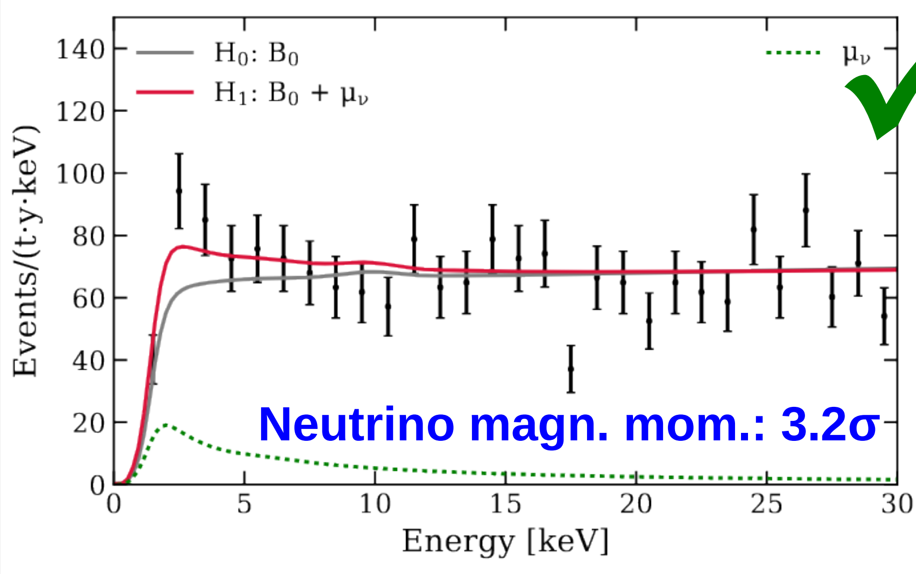


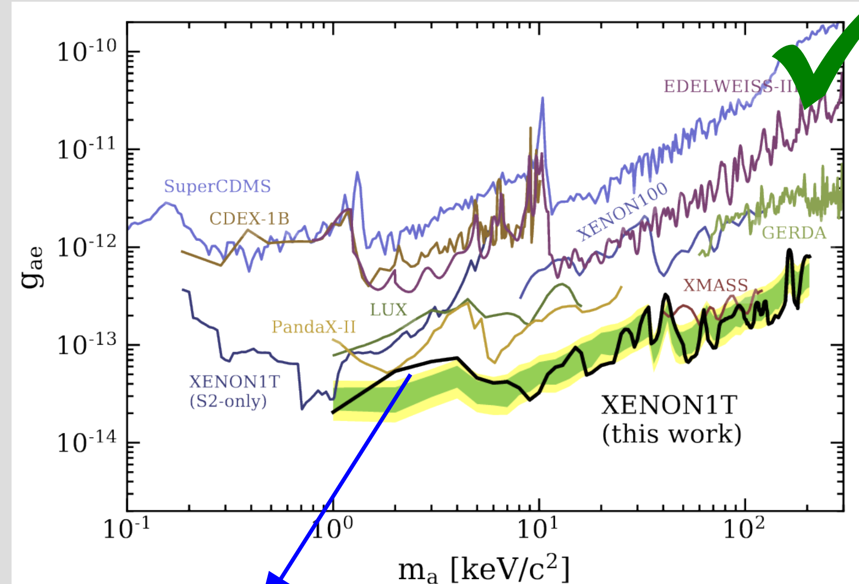
- **excess in 1-7 keV range**
  285 evts observed vs
  232 ± 15 expected
  → **(naive) 3.3σ fluctuation**
- events uniformly distributed
  – in space
  – in time (but low stats)
- far away from typical WIMP artefact backgrounds
  – accidental coincidences
  – surface background
- energy threshold well understood

What causes it????

BSM Signal Models?





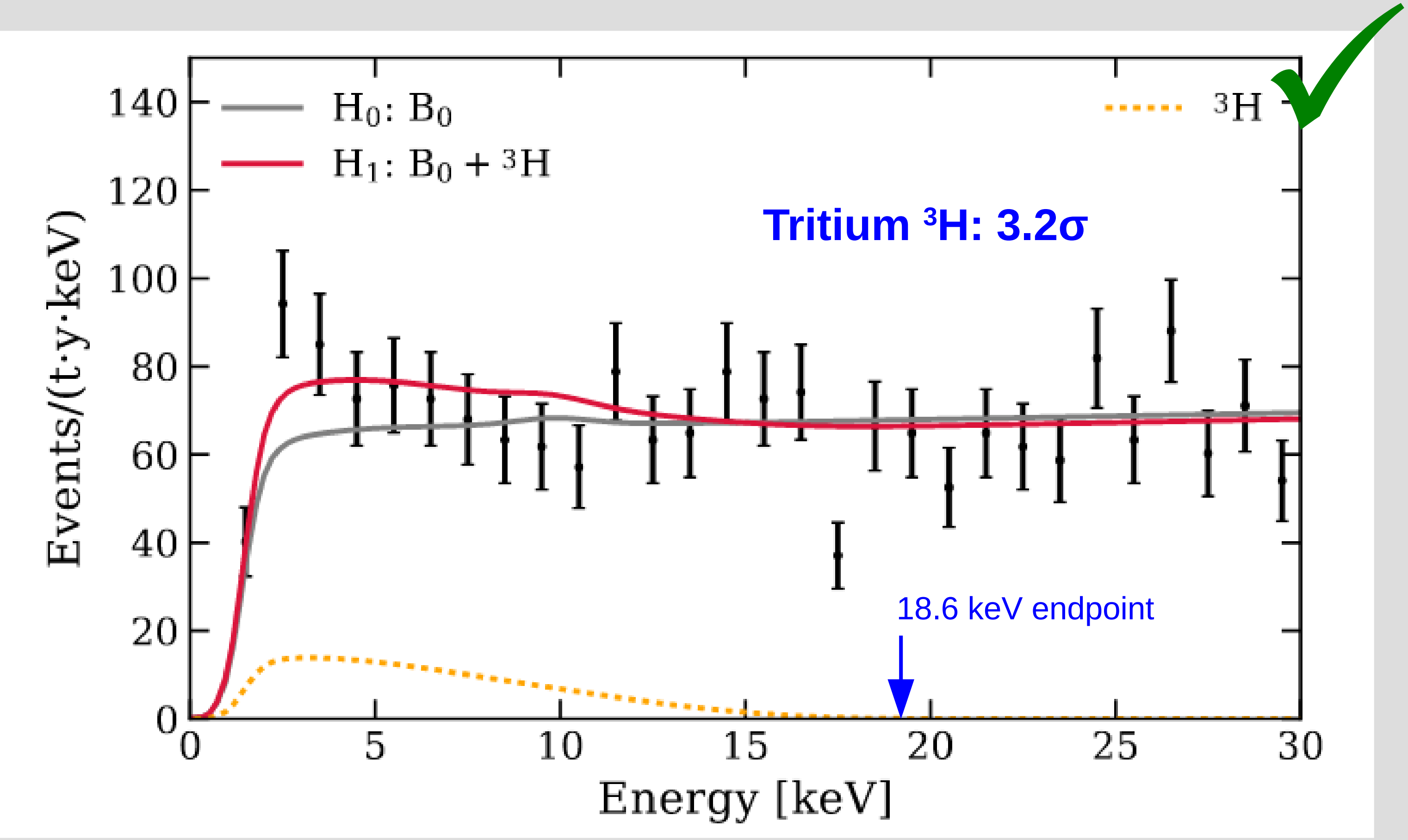


Bosonic ALPs
3.0σ global (4.0σ local)
@ m_a=2.3±0.2 keV

… and many others since we made our result public.

BUT...

Tritium: A new background?



- **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 from fit: <3 ^{3}H atoms per kg of Xe
- **we can neither confirm nor exclude the Tritium hypothesis at this point**

Excess Summary

PRD 102, 072004 (2020)

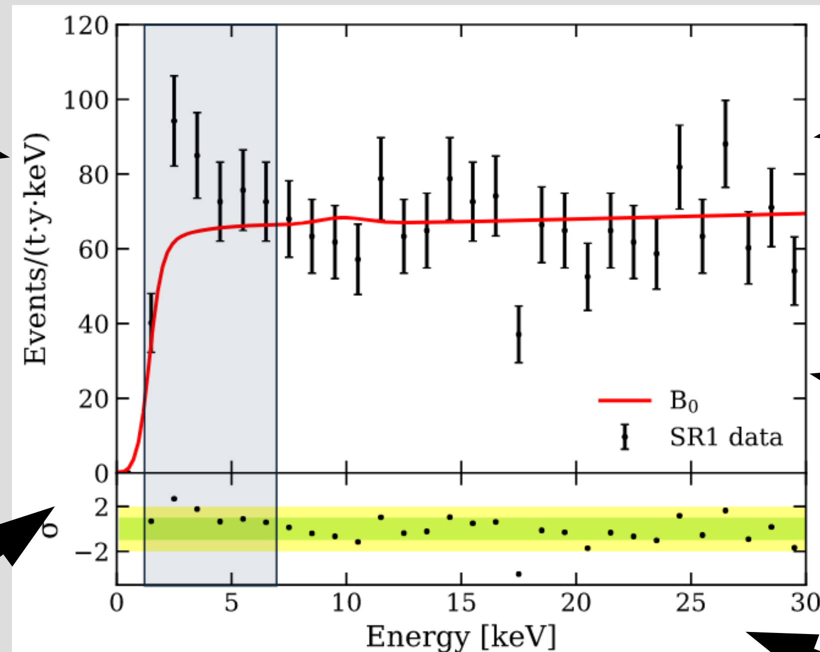
We see an excess of low-E ER events above our known backgrounds.

Tritium ^3H ✓

Argon ^{37}Ar ✗
peak @ 2.8 keV

Neutrino μ_ν ✓

Artefacts ✗



Solar Axions ✓

Bosonic ALPs ✓

and many others... ✓

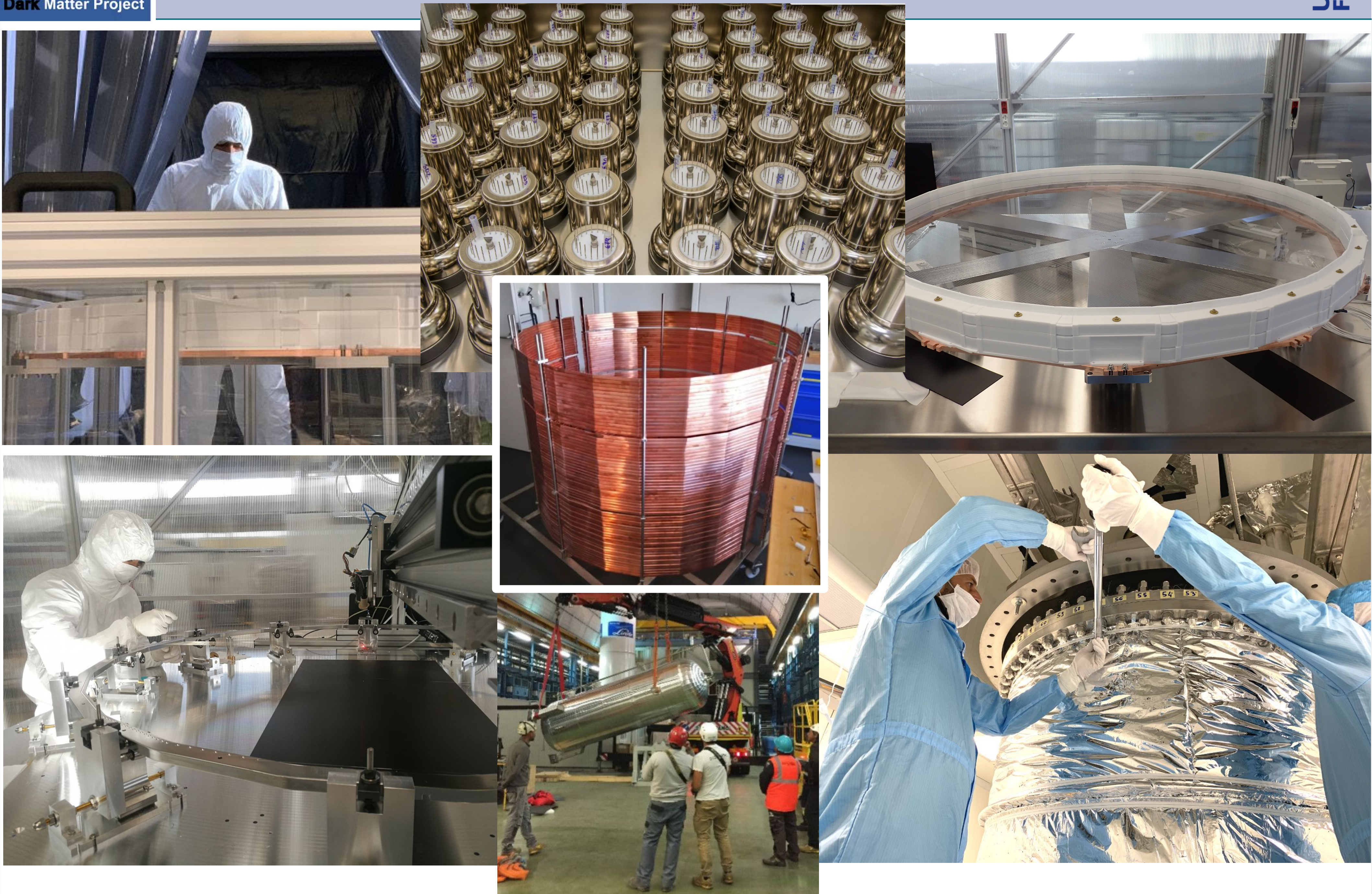
Excess electronic recoil events in XENON1T #1

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

Published in: *Phys.Rev.D* 102 (2020) 7, 072004 • e-Print: 2006.09721 [hep-ex]

pdf links DOI cite ~~152~~ 185 citations

XENONnT: The new instrument



XENONnT

- **target mass ×3**
  → new, larger TPC

- **lower background**
  → lightweight TPC design

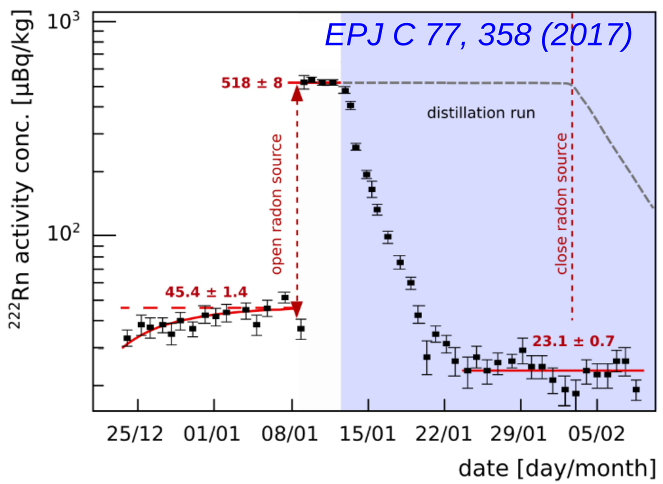
XENONnT

- **target mass ×3**
  → new, larger TPC
- **lower background**
  → lightweight TPC design

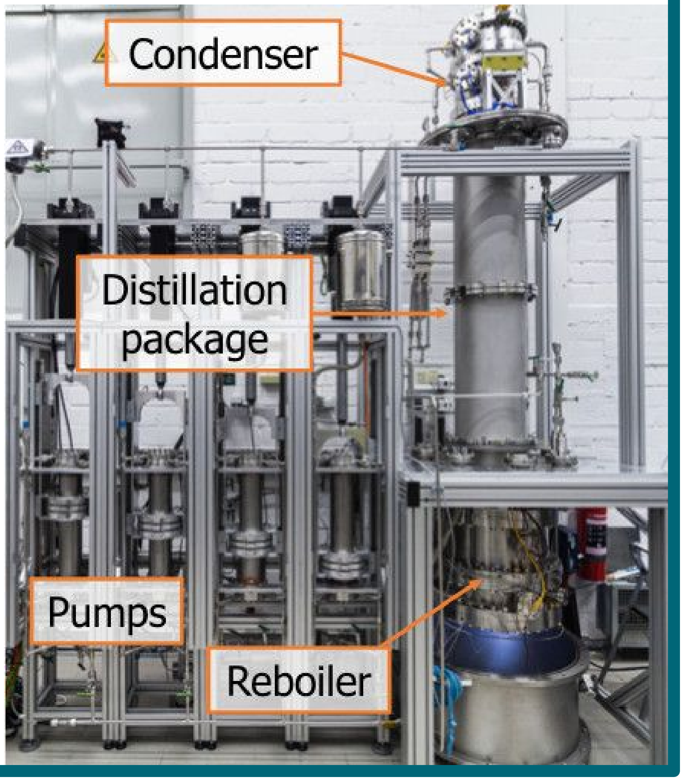
  Rn reduced by factor 6
  → online Rn-removal

Active on-line Rn removal via cryogenic distillation

Demonstrated factor >27 on XENON100



XENONnT column
- design flow 200 slpm
- reduction of Rn from TPC/cryostat by factor (>)2
- reduction of Rn from cryosystem/ cables by factor (>)2



WWU MÜNSTER

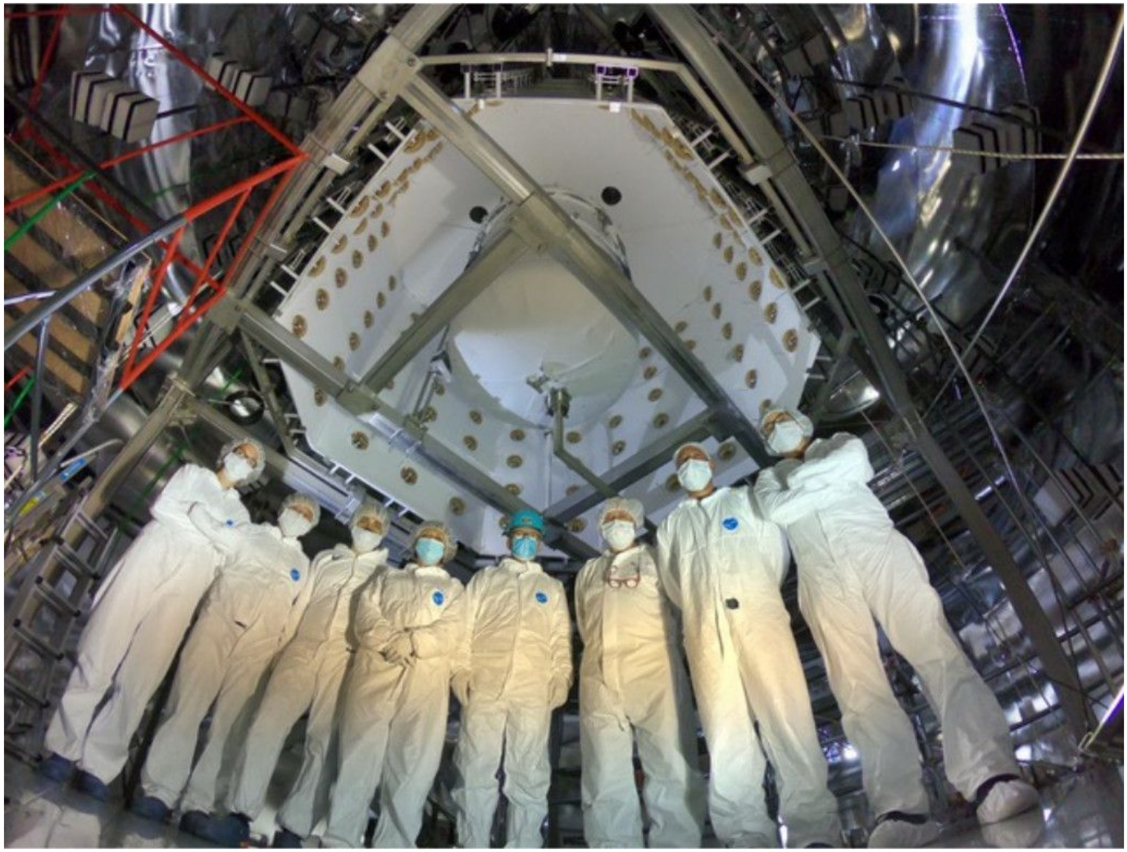
XENONnT

– **target mass ×3**
→ new, larger TPC

– **lower background**
→ lightweight TPC design

Rn reduced by factor 6
→ online Rn-removal

neutrons below neutrinos
→ neutron veto



Gd-loaded Water Cherenkov Detector

– neutron moderation in water, capture on Gd
– 0.2% Gd-loaded water (technology from EGADS-SK)
– 120 PMTs around cryostat for light detection
– goal: 85% neutron tagging efficiency (x10 PMT coincidence)
– background goal: **0.3 neutrons** in ROI, 20 t×y exposure

XENONnT

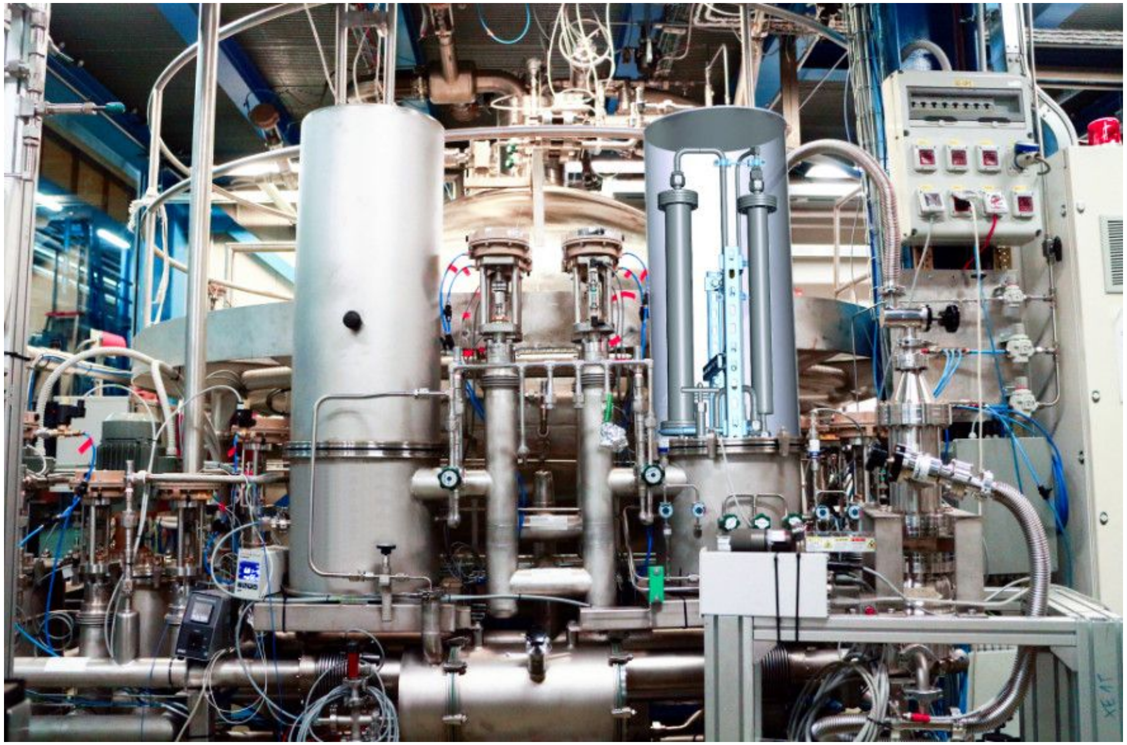
– **target mass ×3**
→ new, larger TPC

– **lower background**
→ lightweight TPC design

Rn reduced by factor 6
→ online Rn-removal

neutrons below neutrinos
→ neutron veto

– **higher Xe purity**
(=smaller corrections)
→ liquid Xe purification



Continuous Purification of liquid Xenon

– remove electronegative impurities (→O_2) by absorption in cryogenic filters
– flux goal: ~2 LPM (≙1000 slpm)
– aim for electron lifetime ≫1 ms in very short time
– challenge: low Rn budget (filter dependent)

XENONnT

– **target mass ×3**
→ new, larger TPC

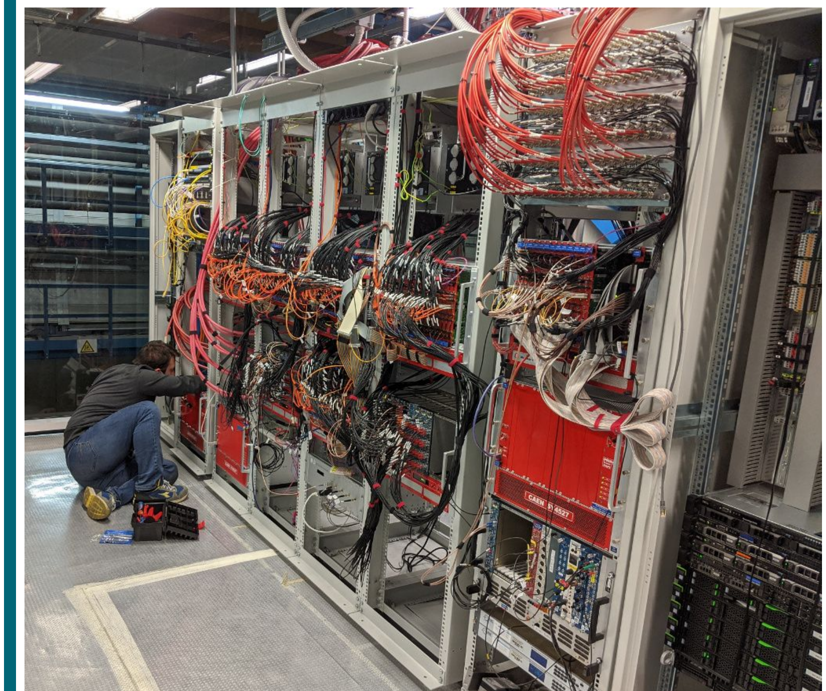
– **lower background**
→ lightweight TPC design

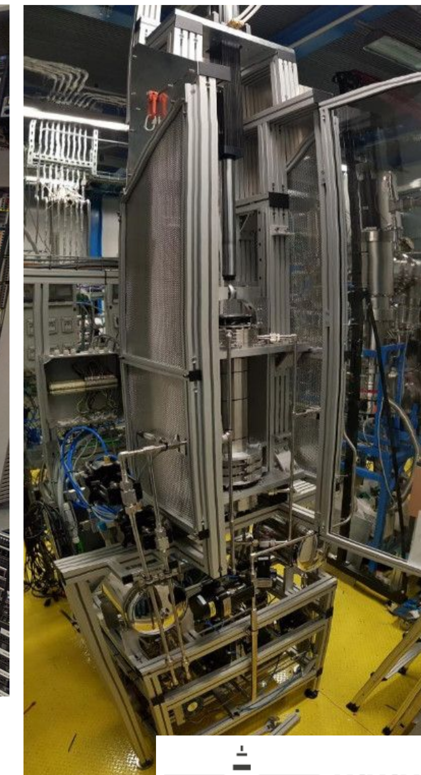
Rn reduced by factor 6
→ online Rn-removal

neutrons below neutrinos
→ neutron veto

– **higher Xe purity**
(=smaller corrections)
→ liquid Xe purification

– **additional upgrades**
* storage (Restox-II),
* gas purification (Rn-free pumps),
* DAQ (new design, new processing, low gain channels for $0\nu\beta\beta$),
* computing etc.

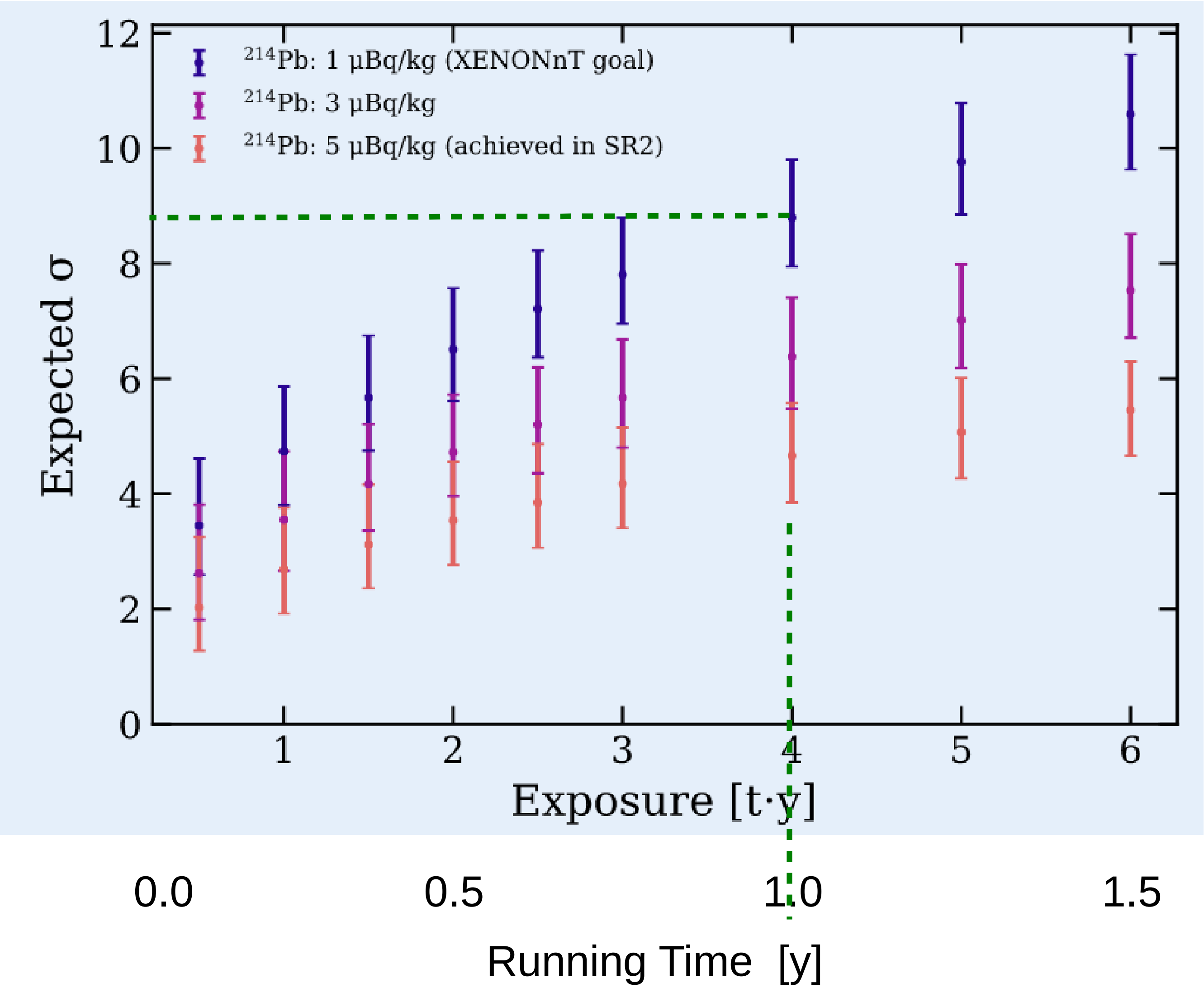




XENONnT is currently under commissioning at LNGS.

XENONnT: Axions vs. Tritium

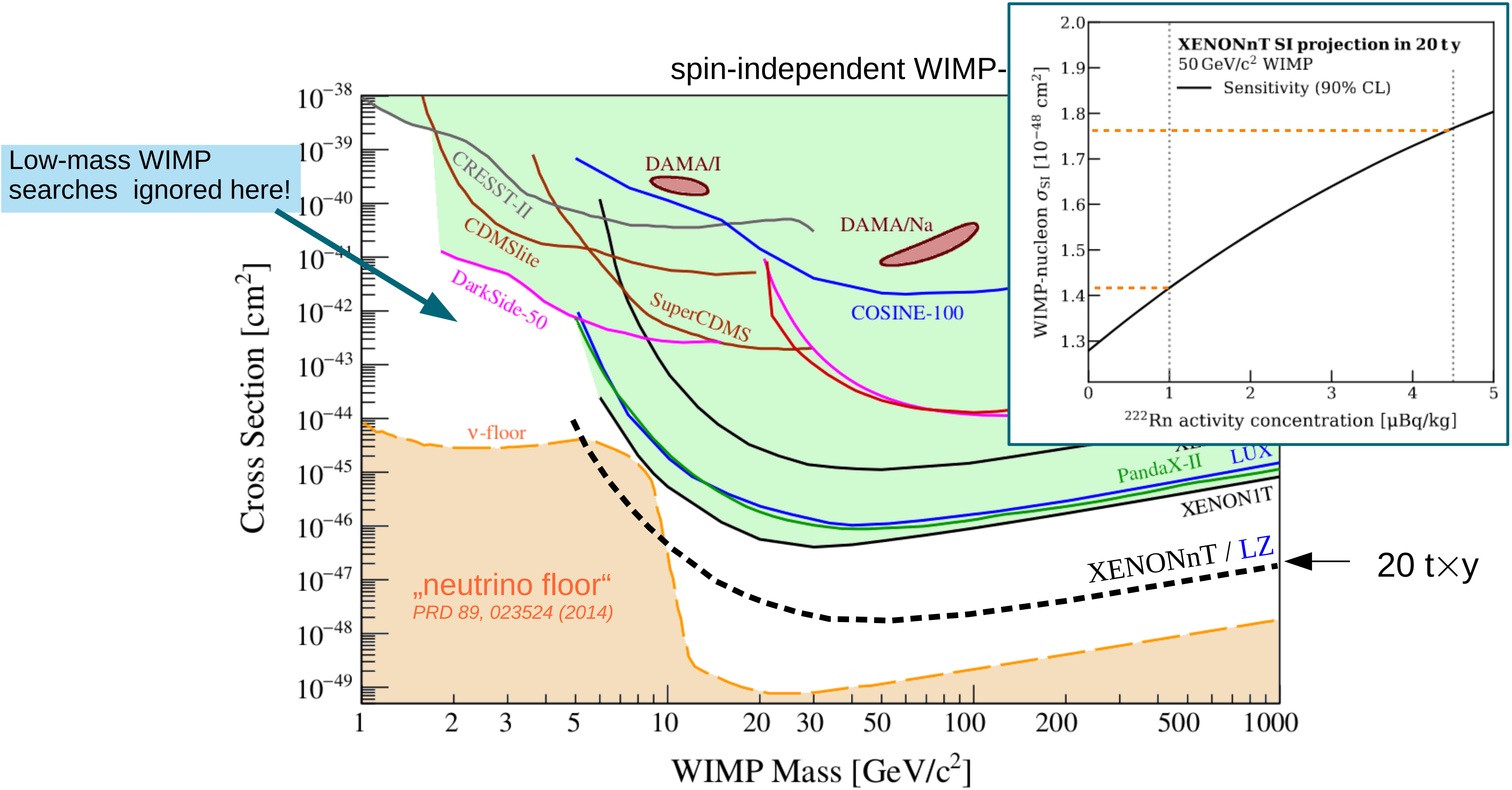
- assume excess persists and is from solar axions
- **How much data is needed to distinguish it from ³H?**
- exploit differences in spectral shape
- sensitivity depends on background level



assume 4t FV and no calibration

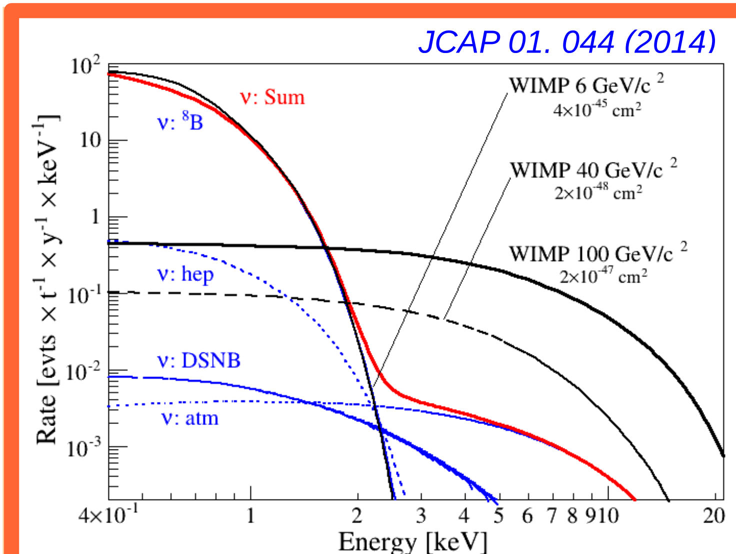
XENONnT WIMP Sensitivity

JCAP 11, 031 (2020)

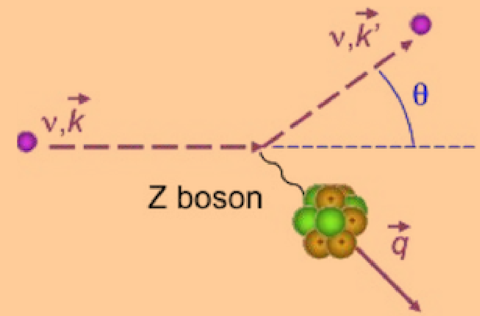


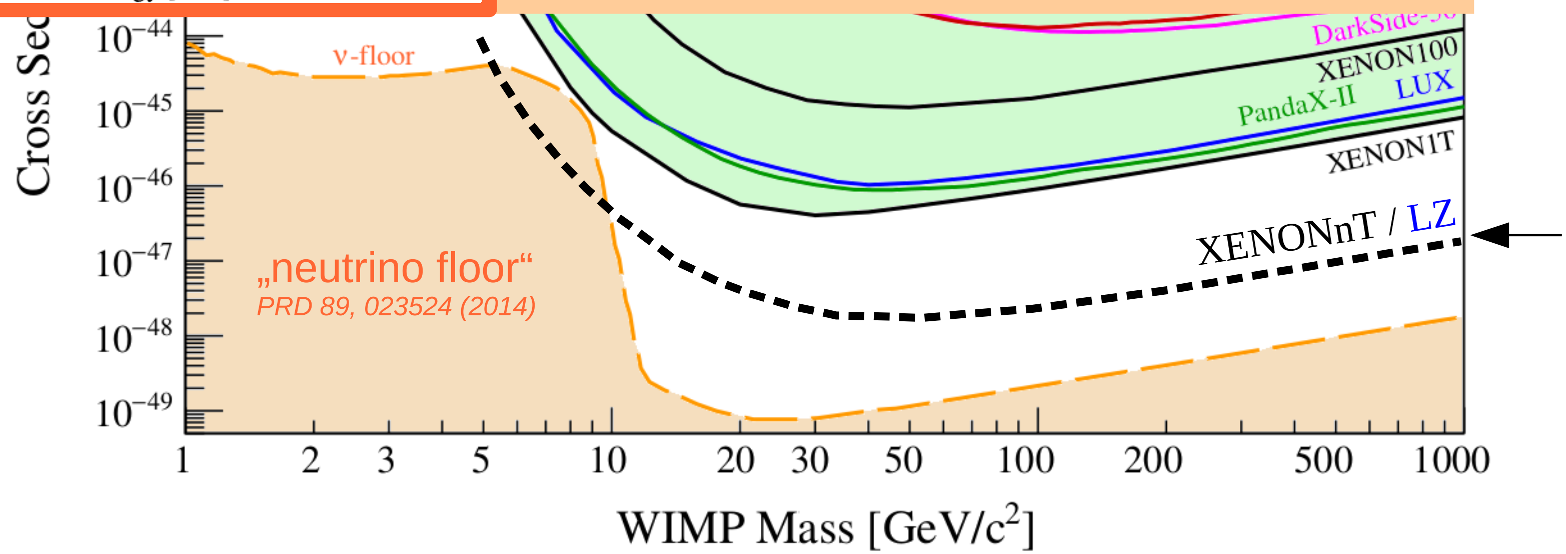
some results are missing...

The ultimate Limit



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

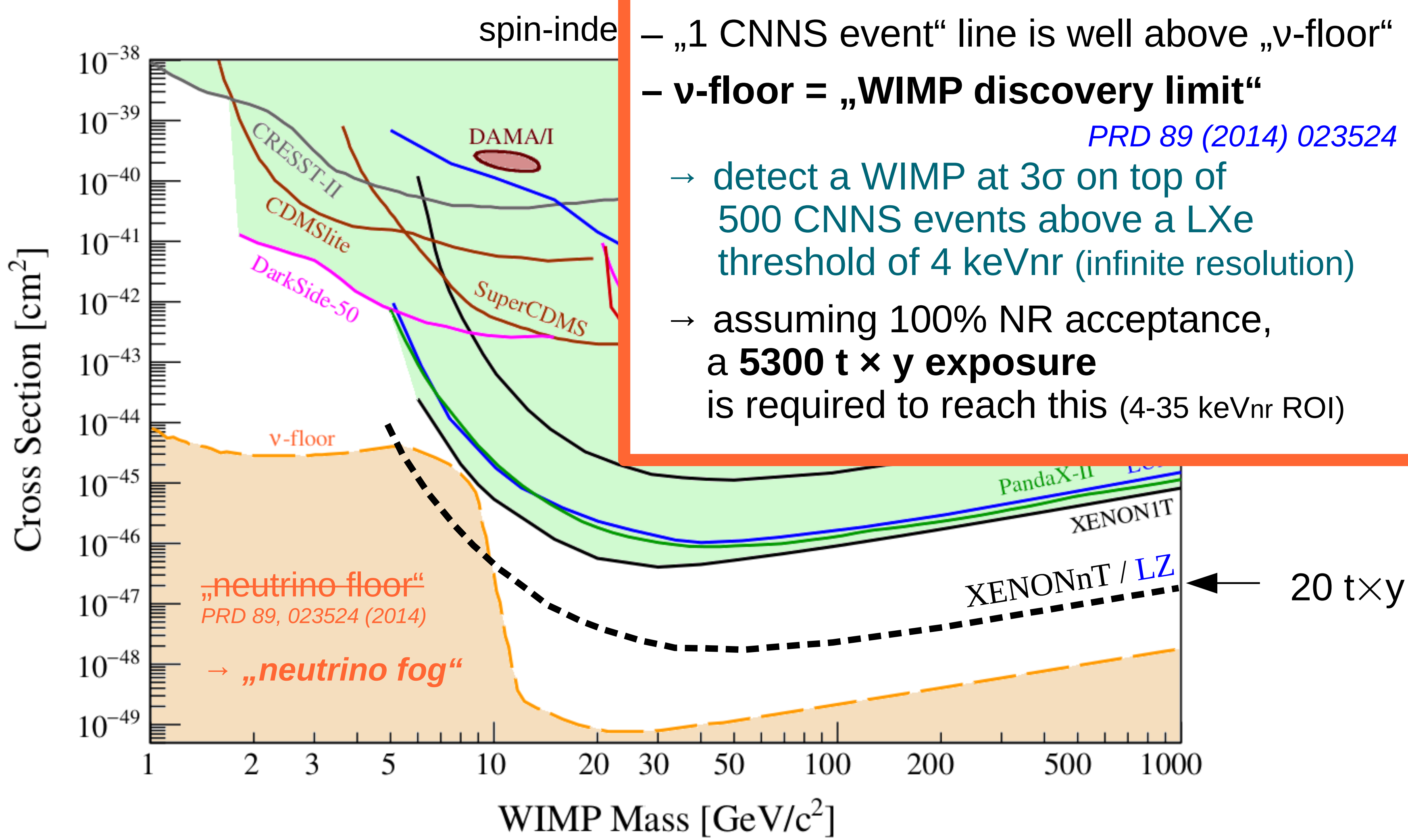




20 t×y

some results are missing...

The ultimate Limit



Be aware of the **definition**

– „1 CNNS event“ line is well above „ν-floor“

– ν-floor = „WIMP discovery limit“

PRD 89 (2014) 023524

→ detect a WIMP at 3σ on top of 500 CNNS events above a LXe threshold of 4 keVnr (infinite resolution)

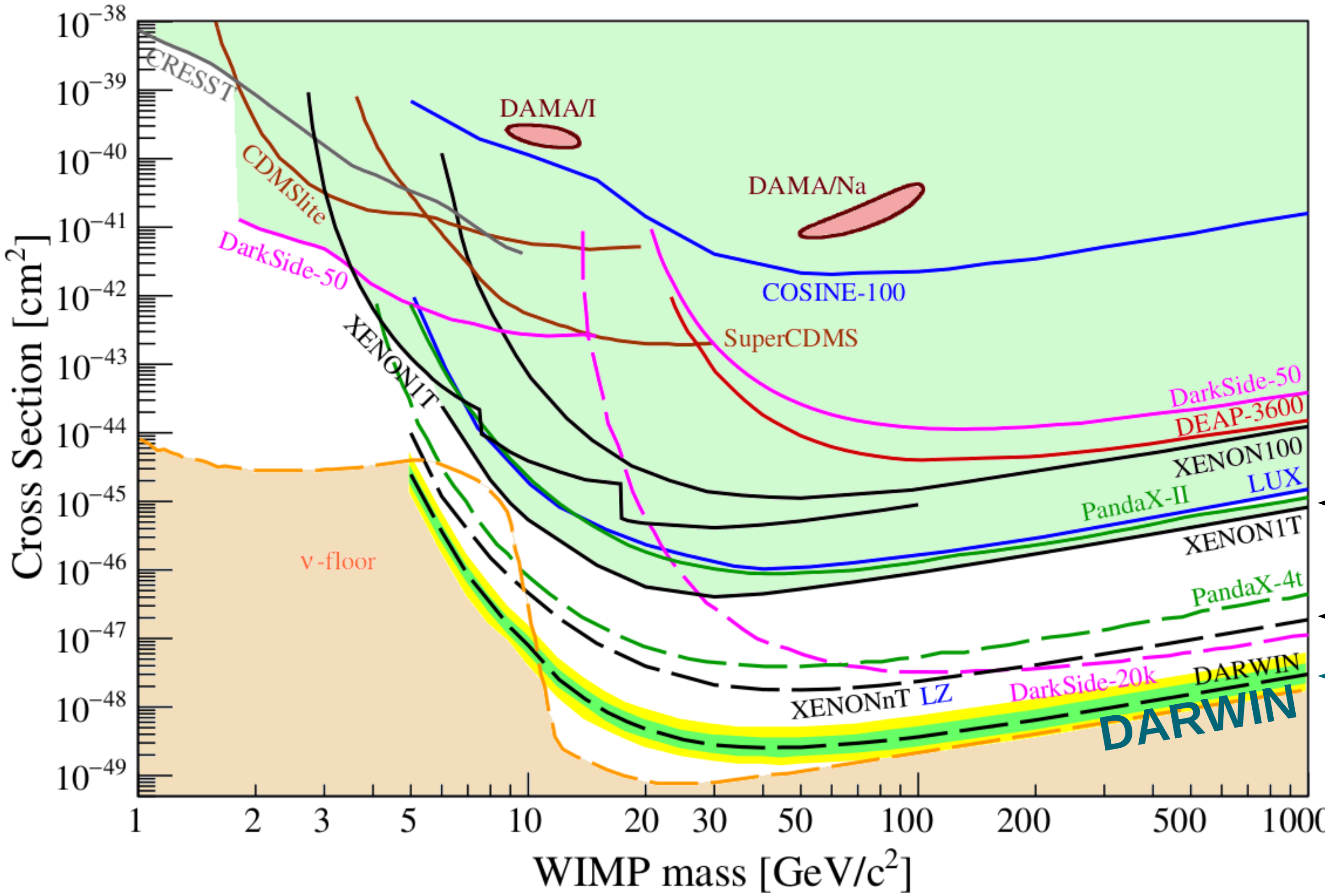
→ assuming 100% NR acceptance, a **5300 t × y exposure** is required to reach this (4-35 keVnr ROI)

some results are missing...

DARWIN: The ultimate WIMP Detector

LXe-based

darwin-observatory.org



Exposure

1 t×y

20 t×y

200 t×y

DARWIN: The ultimate WIMP Detector

LXe-based

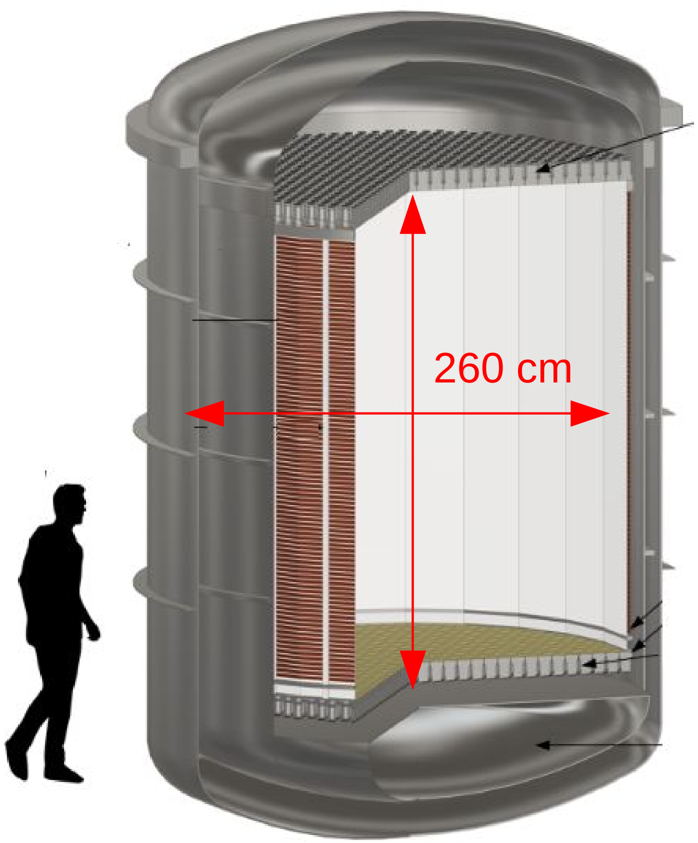
darwin-observatory.org

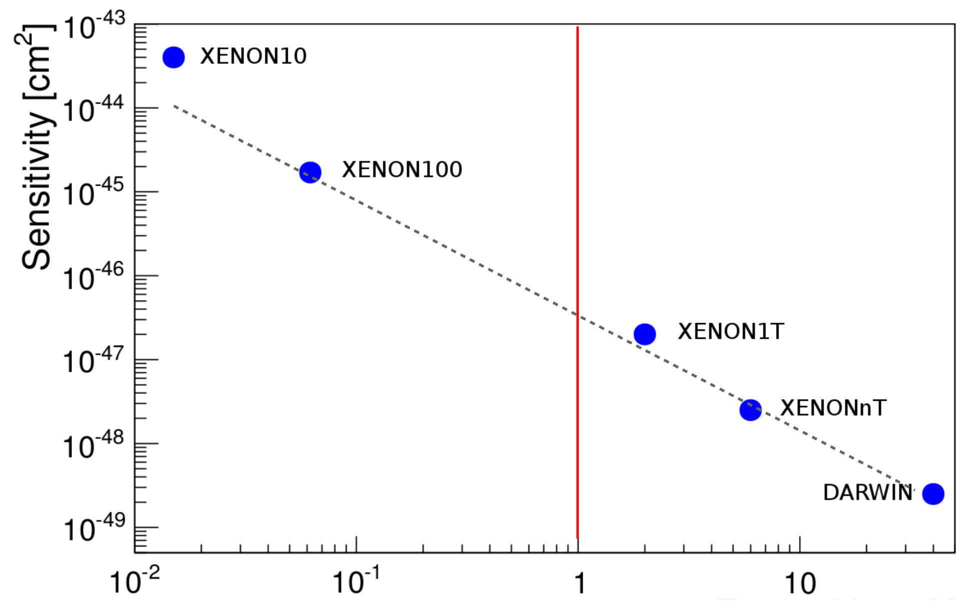
Baseline scenario

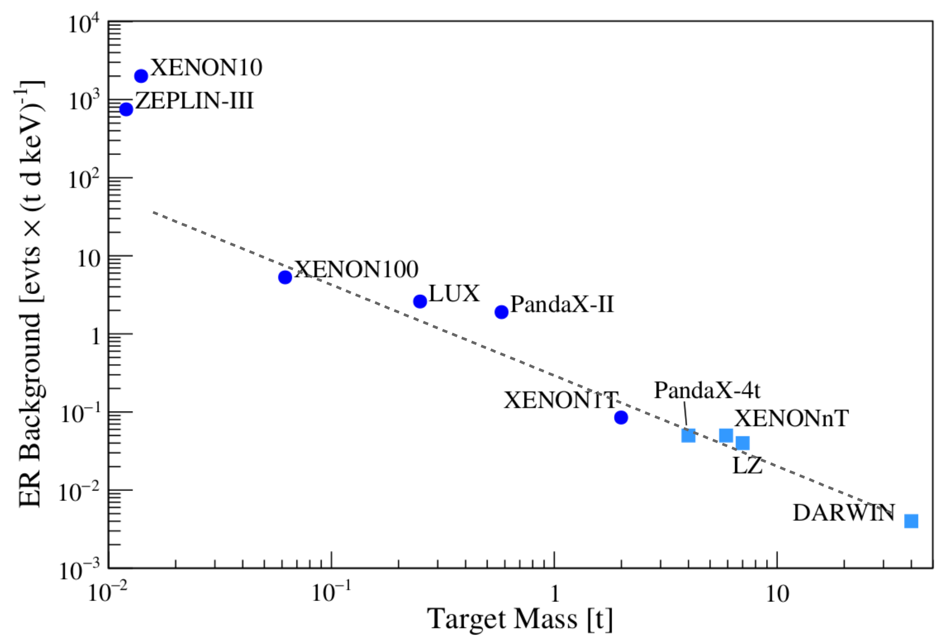
~50t total LXe mass

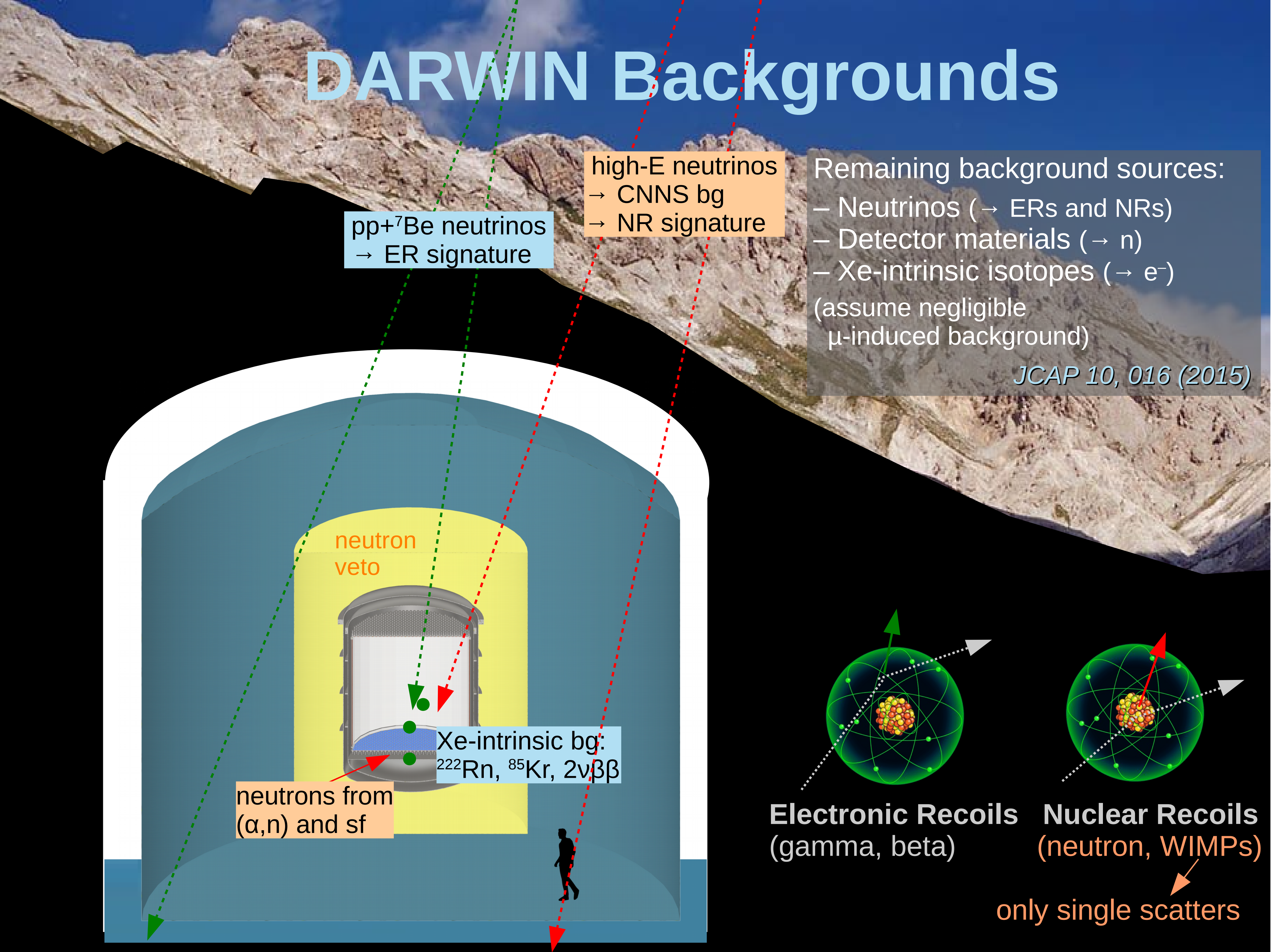
~40 t LXe TPC

~30 t fiducial mass

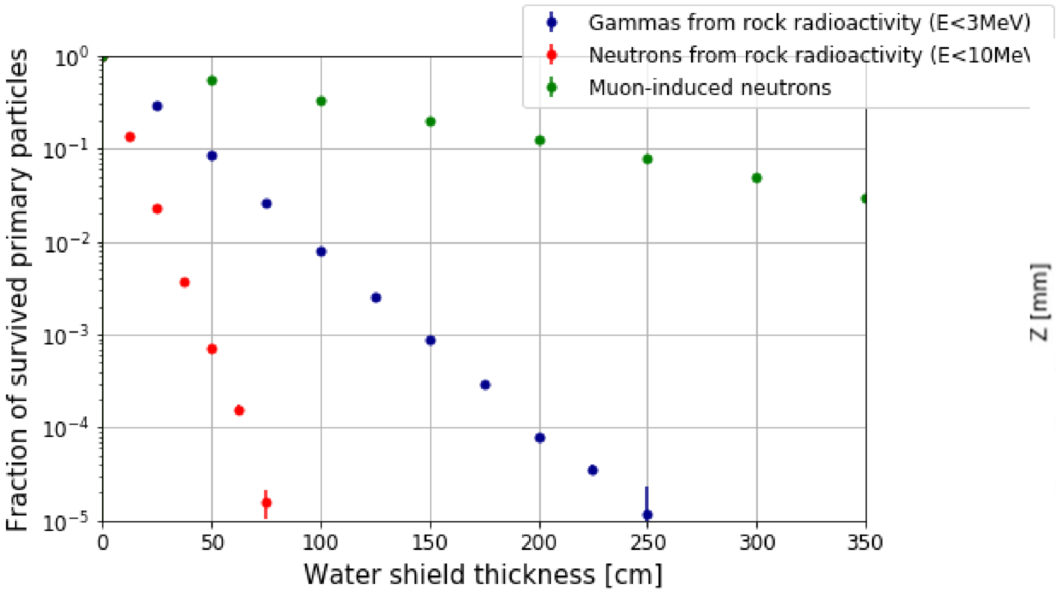


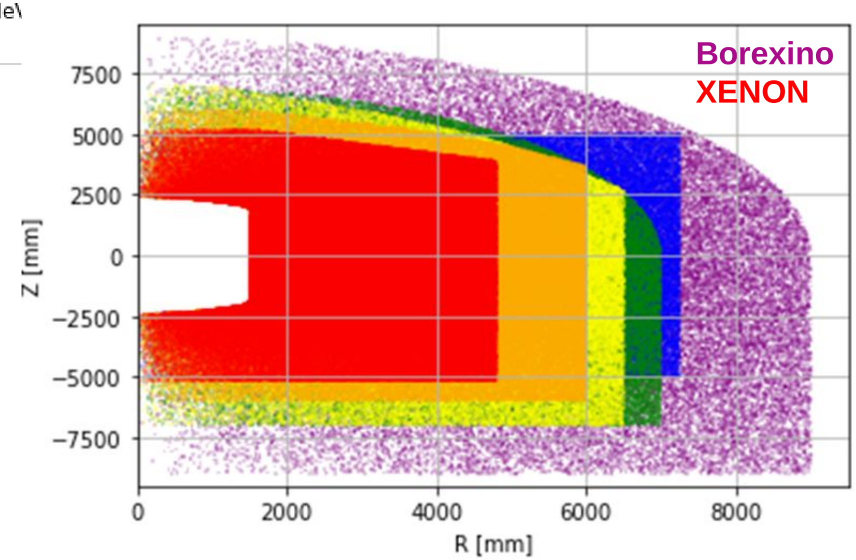





DARWIN Backgrounds
high-E neutrinos
→ CNNS bg
→ NR signature
pp+⁷Be neutrinos
→ ER signature
Remaining background sources:
– Neutrinos (→ ERs and NRs)
– Detector materials (→ n)
– Xe-intrinsic isotopes (→ e⁻)
(assume negligible
μ-induced background)
JCAP 10, 016 (2015)
neutron
veto
Xe-intrinsic bg:
²²²Rn, ⁸⁵Kr, 2νββ
neutrons from
(α,n) and sf
Electronic Recoils
(gamma, beta)
Nuclear Recoils
(neutron, WIMPs)
only single scatters

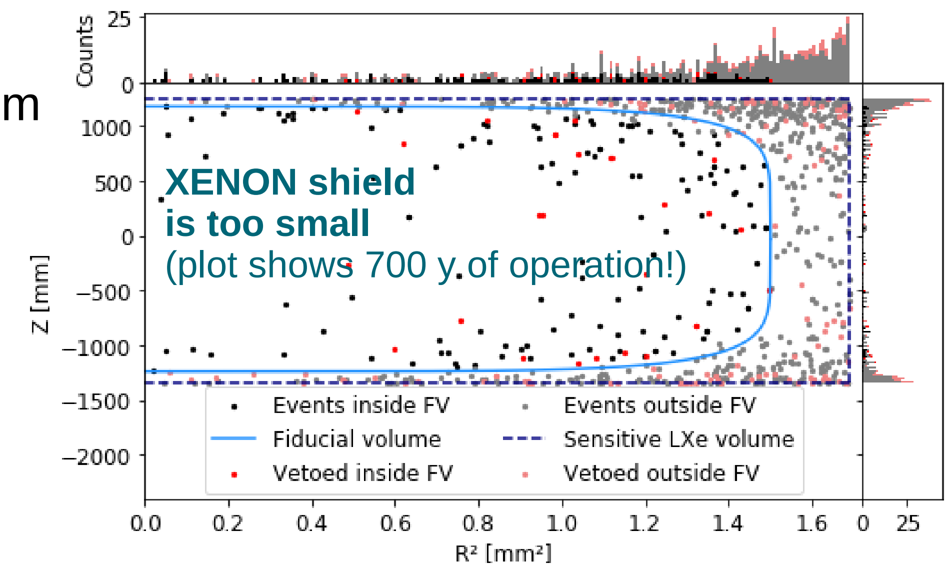
Water Shield @ LNGS ✓



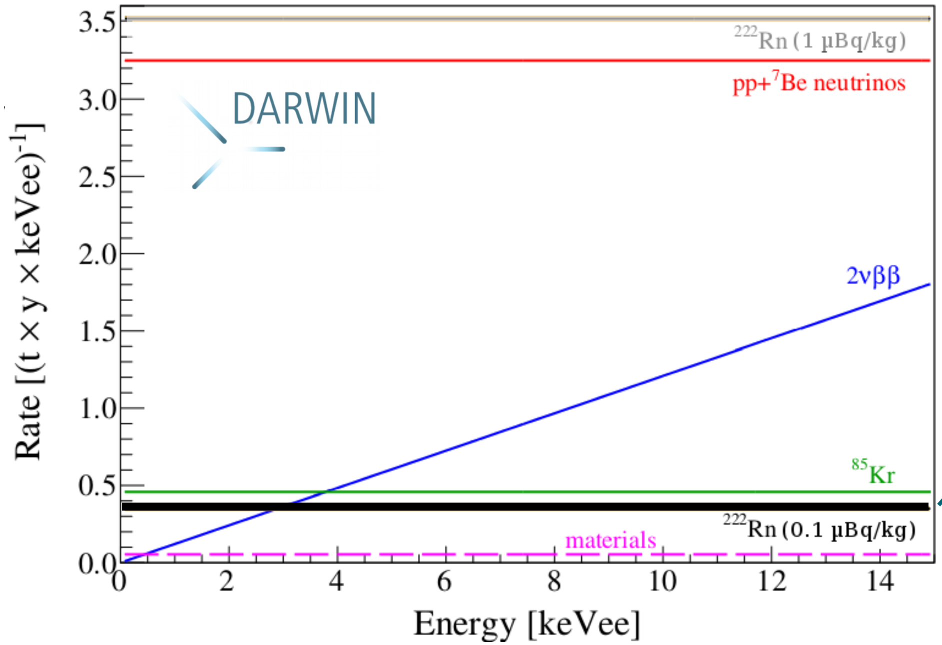


Full MC Simulation for 3600 mwe

- external γ, n background irrelevant after >2.5m
- critical: μ-induced neutrons of high energy
- studied several water shield geometries between XENON and Borexino tank
- **12m tank: ~0.4 n/(200 t×y)**
  Borexino: <0.05 n/(200 t×y)
- Gd-loaded water further reduces numbers



LXe: Radon Background



DARWIN goal:
ER background dominated by solar neutrinos

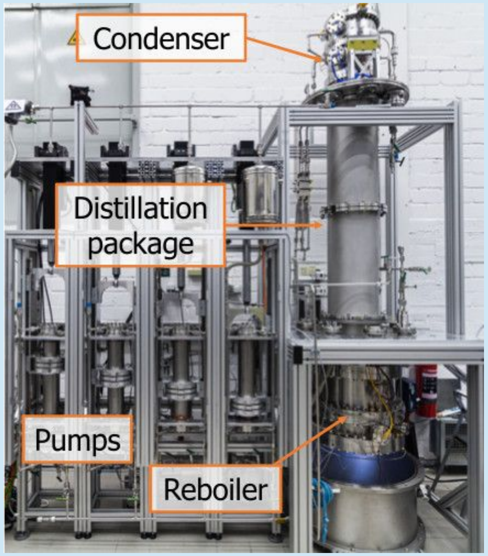
^{222}Rn concentration
factor ~50 below XENON1T
^{222}Rn atoms in target
factor ~2.5 below XENON1T

→ **main background challenge**

Strategy DARWIN

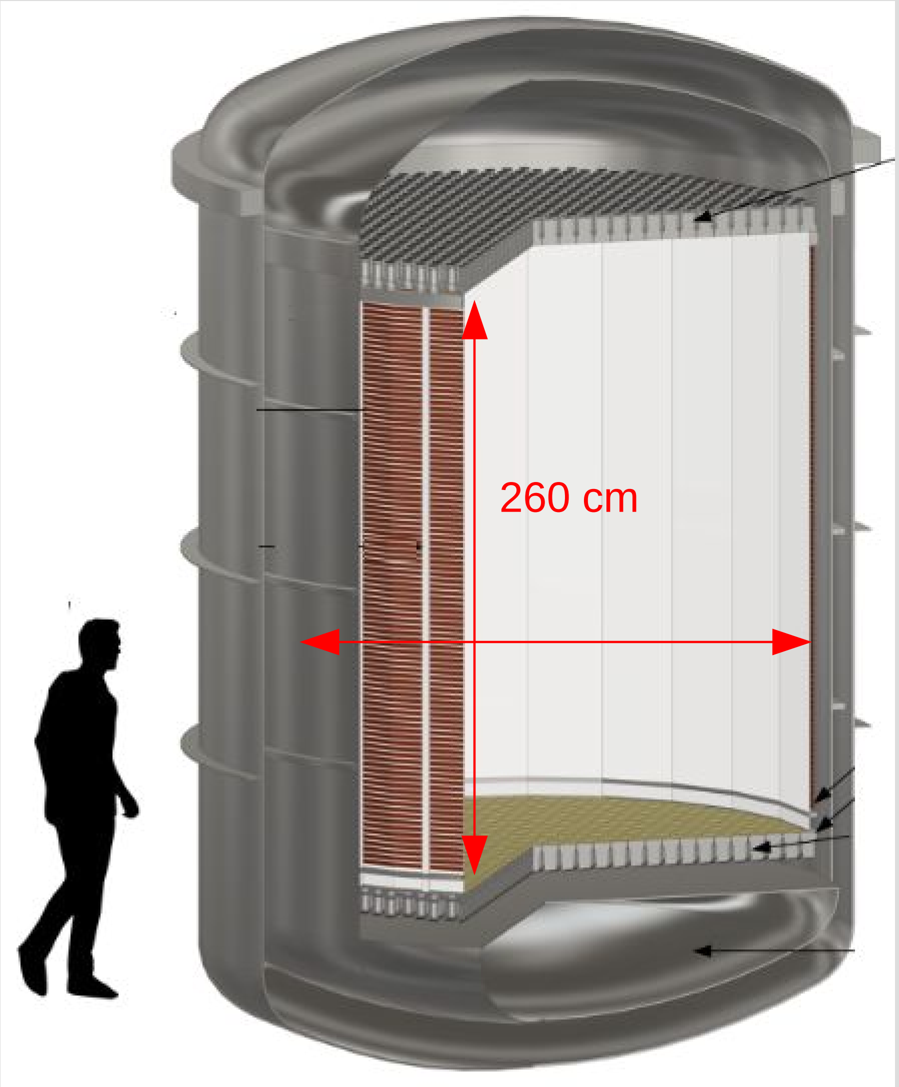
– avoid Rn emanation by
→ optimal material production
→ material selection
→ surface treatment
→ optimized detector design

– **active Rn removal via cryogenic distillation**
→ column developed for XENONnT is R&D for DARWIN



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

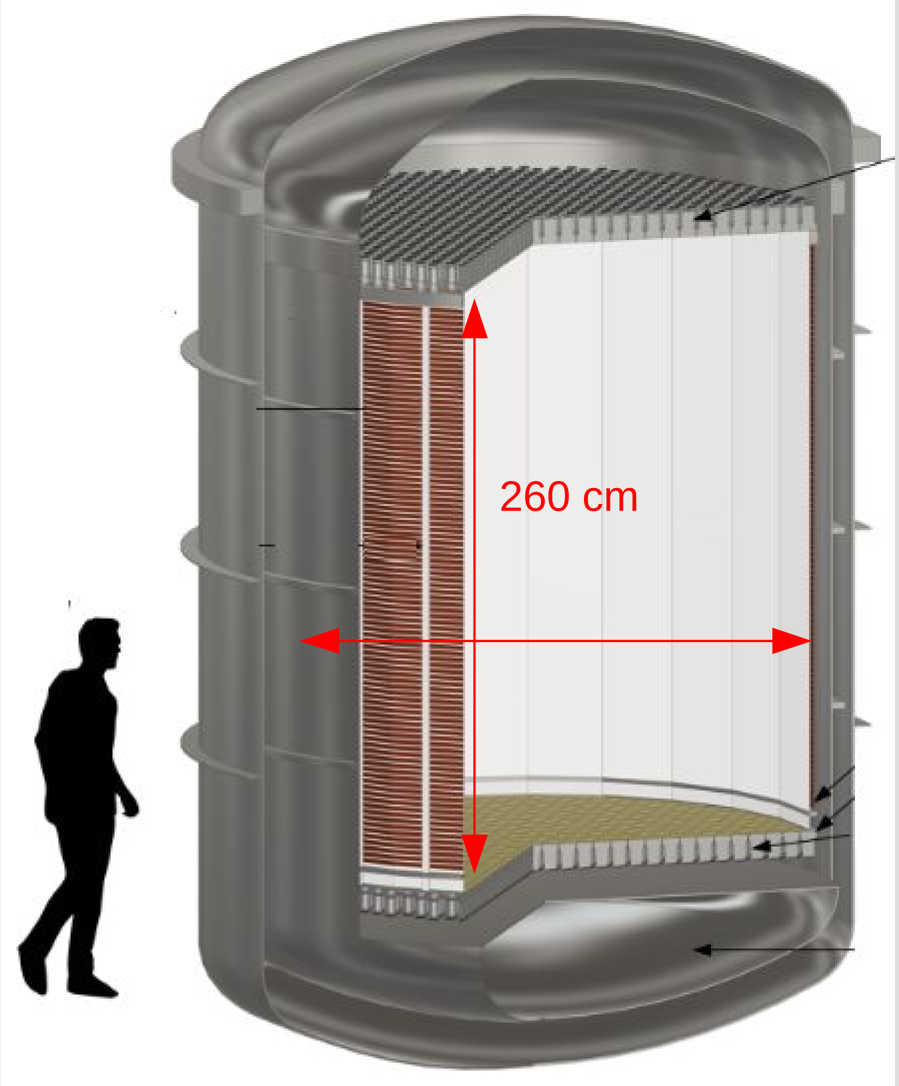
– R&D within XENON collaboration
– **two ERC projects**
ULTIMATE (Freiburg)
Xenoscope (Zürich)

DARWIN LXe Testplatform in **Freiburg**:
– 2.7 m inner diameter
– up to ~15 cm height (~5 cm LXe)
→ ~400 kg Xe gas
→ test horizontal components, real-scale electrodes etc.

DFG
Deutsche Forschungsgemeinschaft

UNI FREIBURG

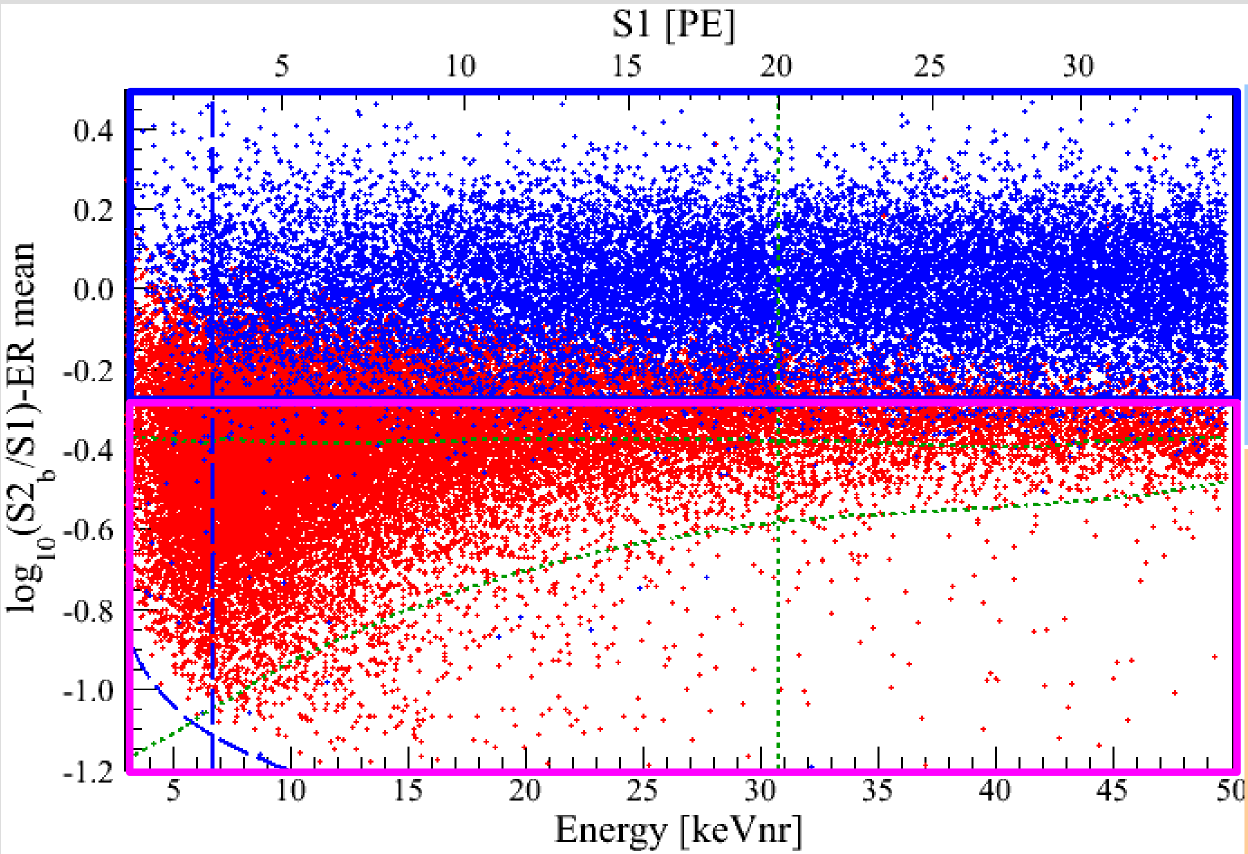
DARWIN The ultimate WIMP Detector



other than WIMPs,
axions, ALPs,
anomalous ν-interactions,
double-electron capture

What (else) can we do with this instrument?

Interactions in LXe Detectors



scattering off atomic electrons, excitations etc.
→ electronic recoil

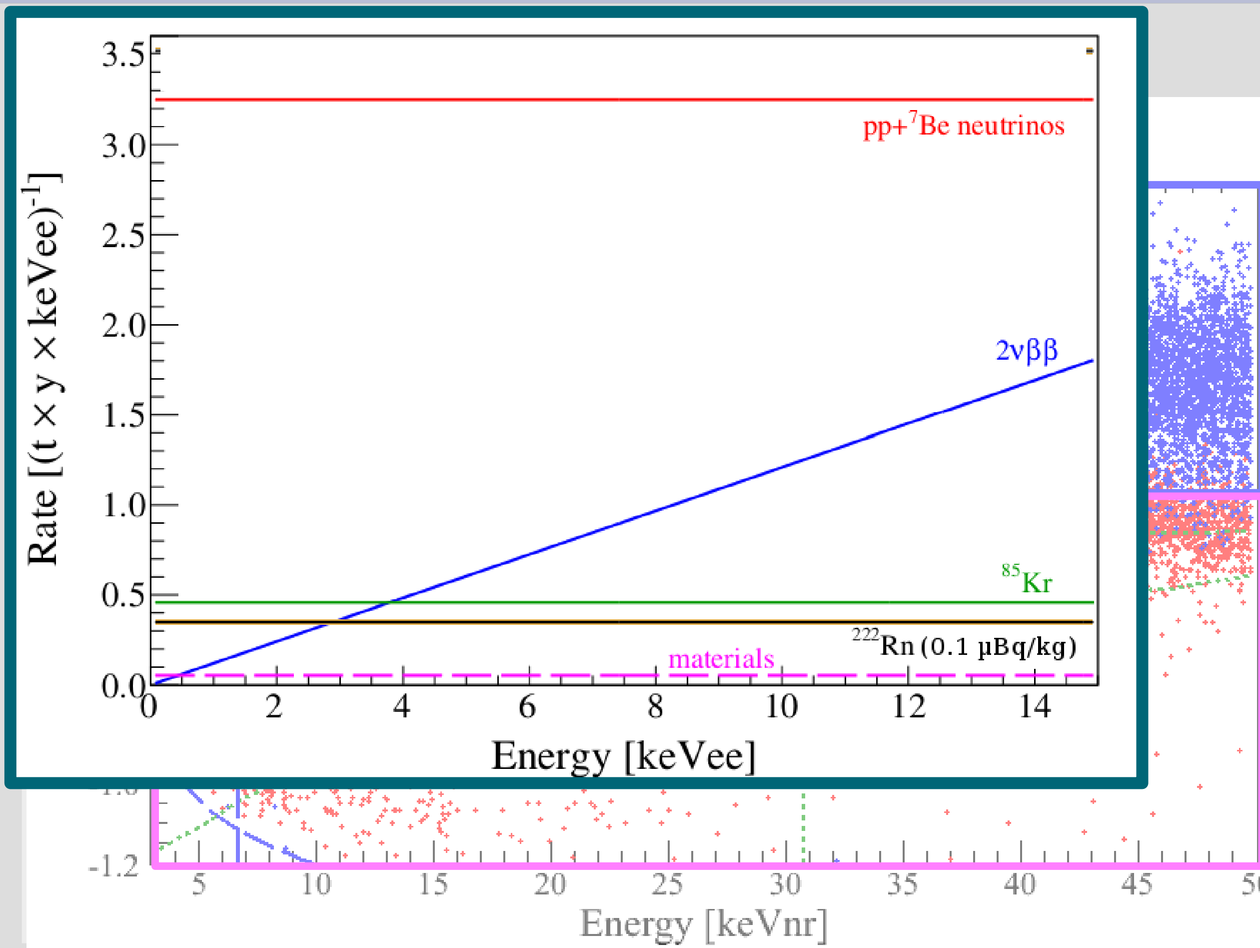
→ axions/ ALPs

- rare processes detectable if ER background is low

coherent scattering off xenon nucleus
→ nuclear recoil

- Dark Matter
- **CNNS**
- **Supernova Neutrinos**

Interactions in LXe Detectors



scattering off atomic electrons, excitations etc.
→ electronic recoil

→ axions/ ALPs

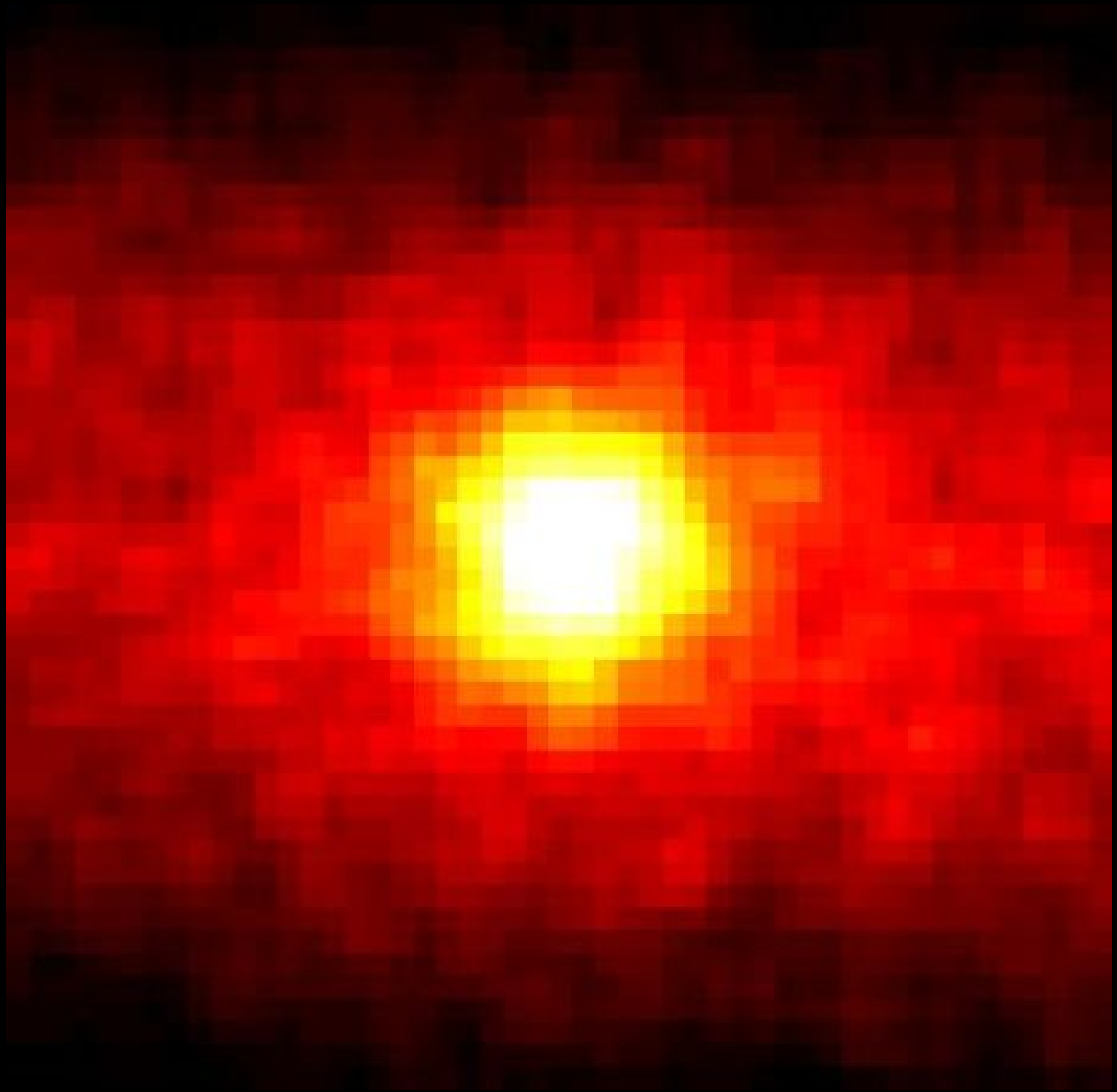
- rare processes detectable since ER background **is low**

coherent scattering off xenon nucleus
→ nuclear recoil

- Dark Matter
- CNNS
- Supernova Neutrinos

→ Many **science channels** are accessible

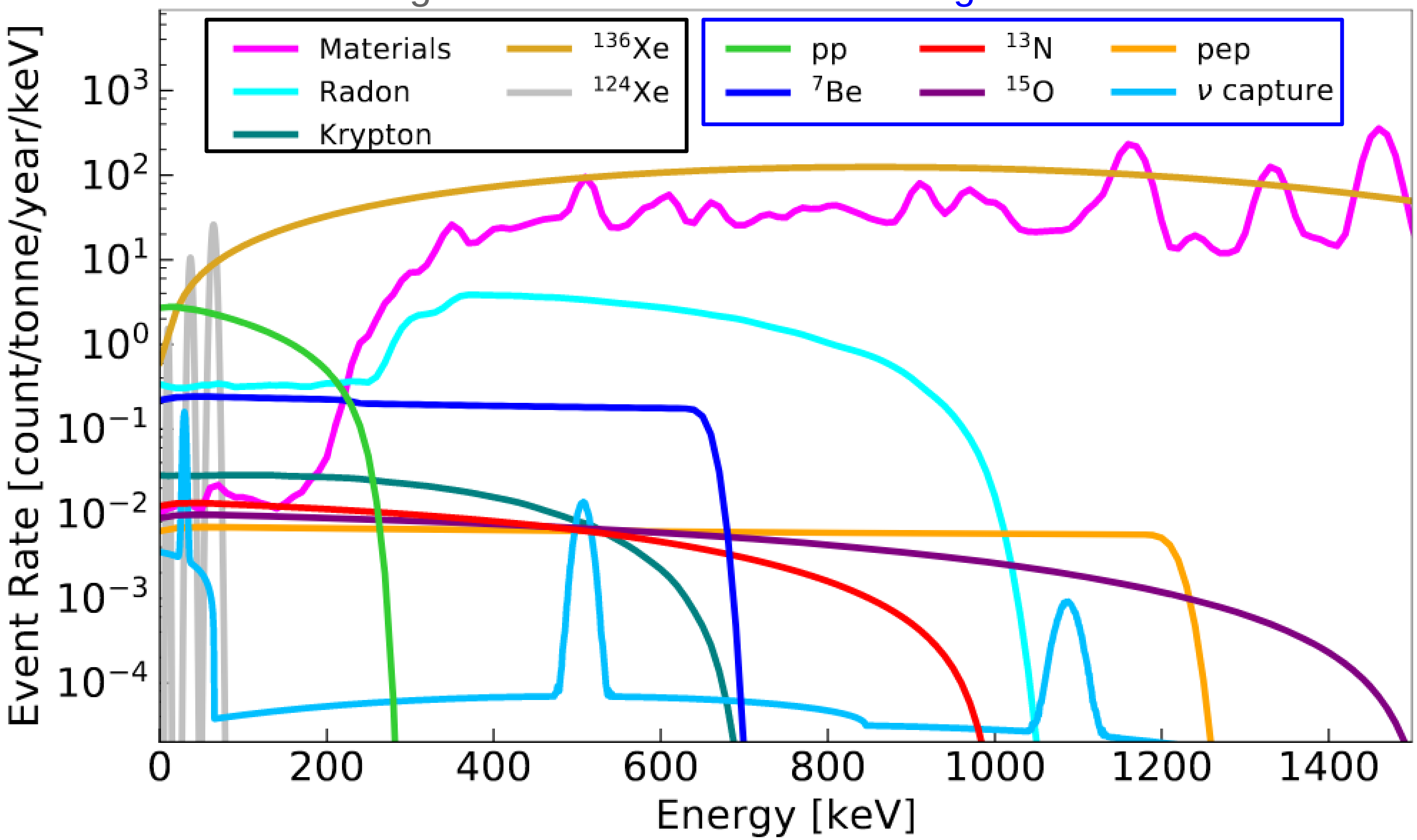
DARWIN = A low background, low threshold **astroparticle physics observatory**



Solar Neutrinos

ER Spectrum in Xe

JCAP 01, 044 (2014)
EPJ C 80, 1133 (2020)



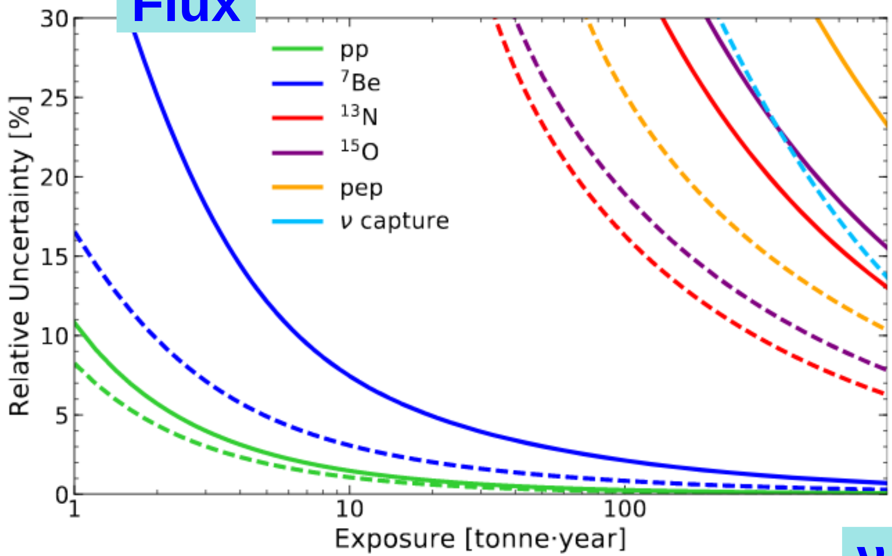
- DARWIN‘s ER spectrum will be dominated by pp neutrinos (and 2νDEC+2νββ)
- distinct features in ν spectra allow extracting neutrino fluxes
  → full spectral fit of all components up to 3 MeV
  (possibility to enhance sensitivity by more sophisticated analysis)

Solar Neutrinos

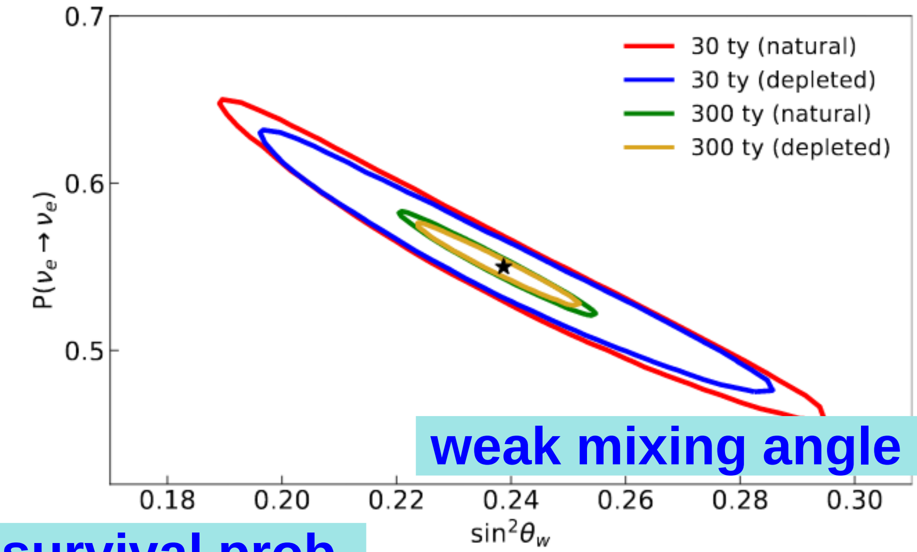
DARWIN

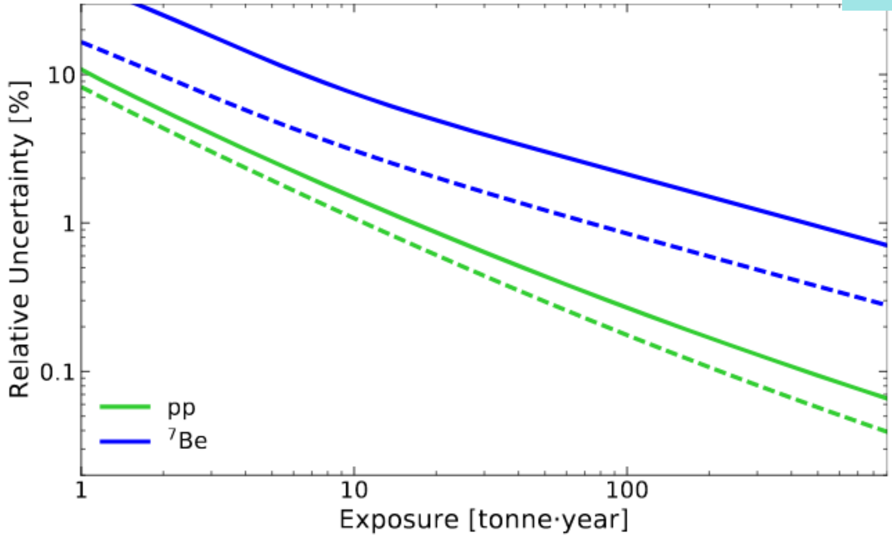
UNI FREIBURG

Flux

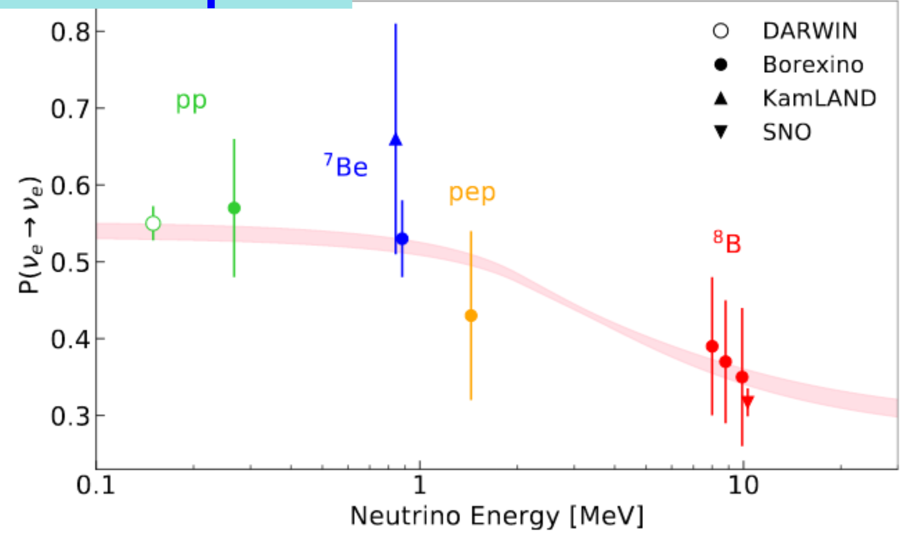


weak mixing angle

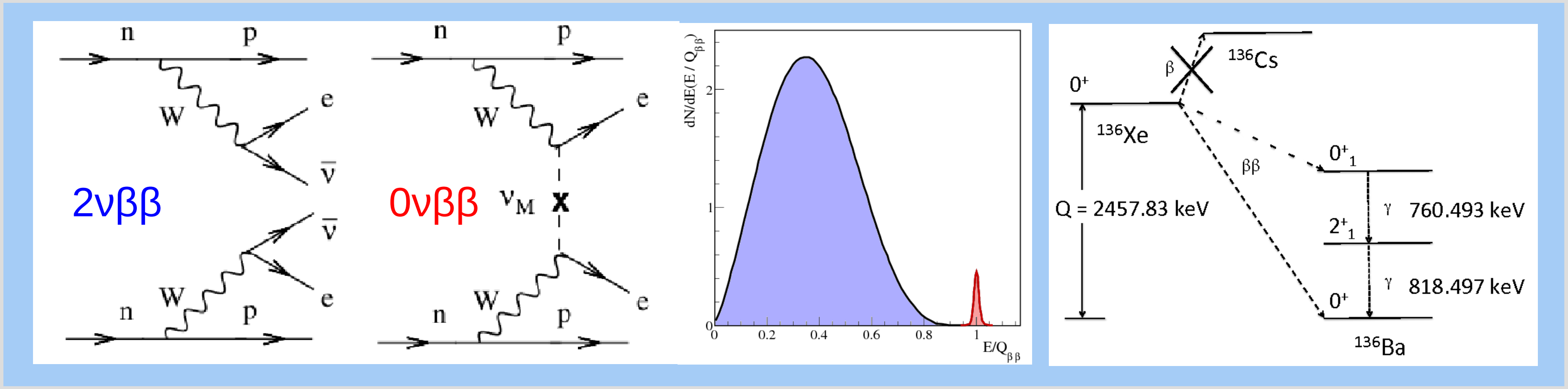




ν_e survival prob.

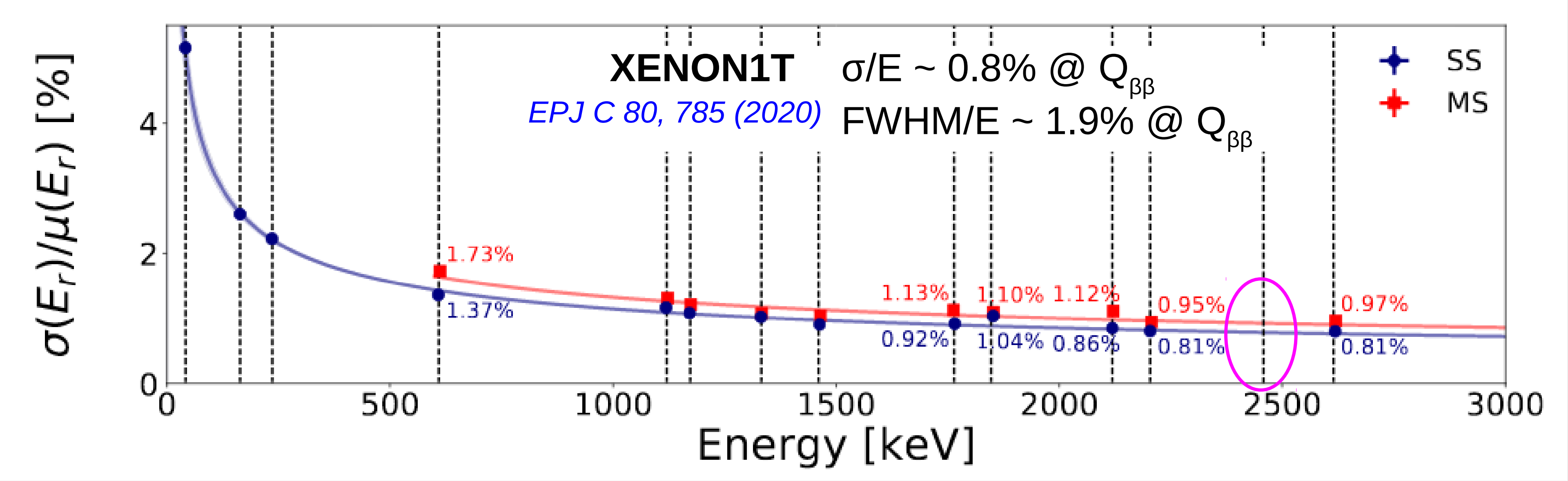


^{136}Xe: 0ν double-beta Decay



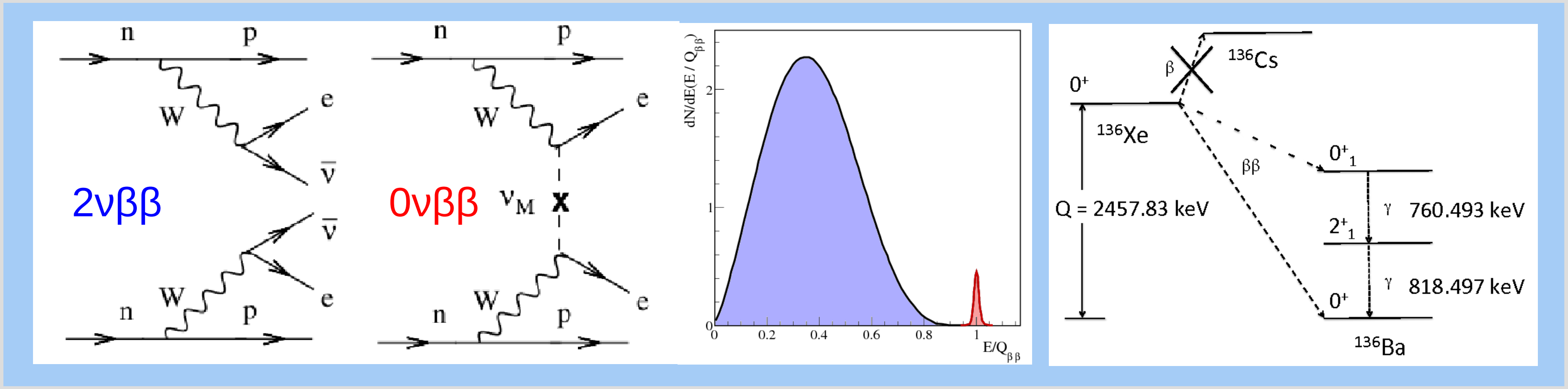
ΔL ≠ 0

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



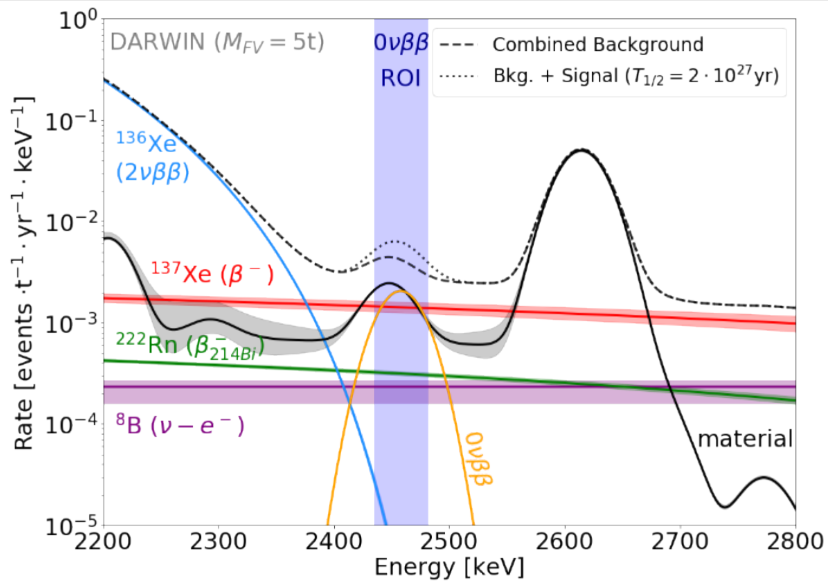
^{136}Xe: 0ν double-beta Decay

EPJ C 80, 808 (2020)



ΔL ≠ 0

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



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**

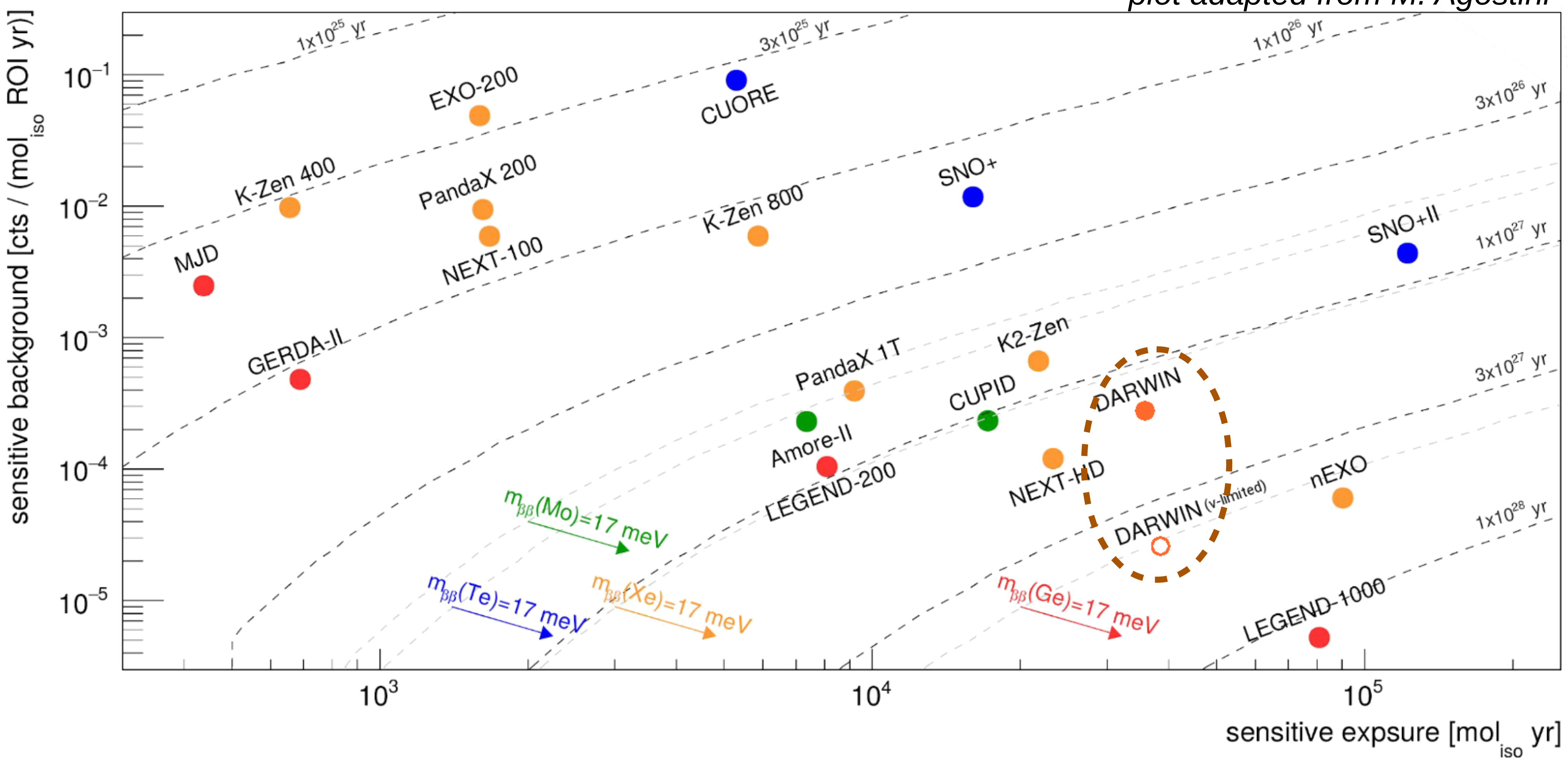
^{136}Xe: 0ν double-beta Decay

DARWIN

UNI FREIBURG

EPJ C 80, 808 (2020)

plot adapted from M. Agostini



XENON & DARWIN: Exciting Times

XENON Dark Matter Project

DARWIN

a low-background
low-threshold observatory
for astroparticle physics