



# Dark Matter Searches with XENON: Recent Results, Future Prospects

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Vienna Central European Seminar 2022, 25.11.2022

[www.app.uni-freiburg.de](http://www.app.uni-freiburg.de)

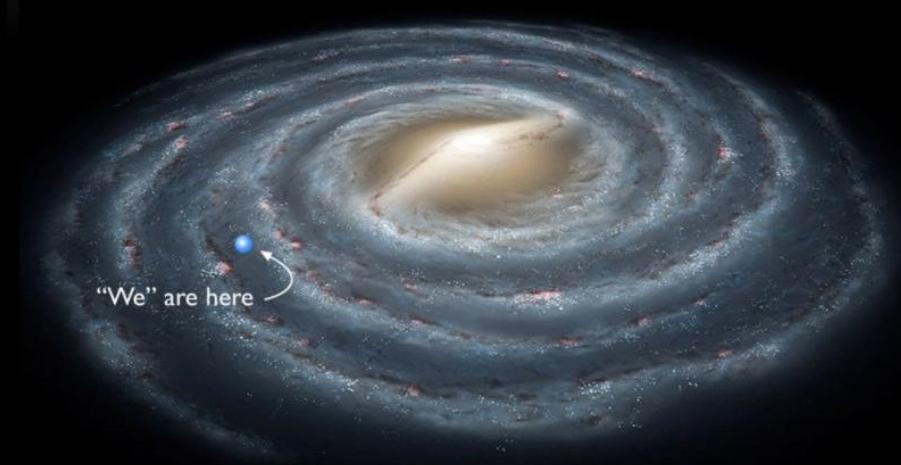
Bundesministerium  
für Bildung  
und Forschung



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UNI  
**FREIBURG**





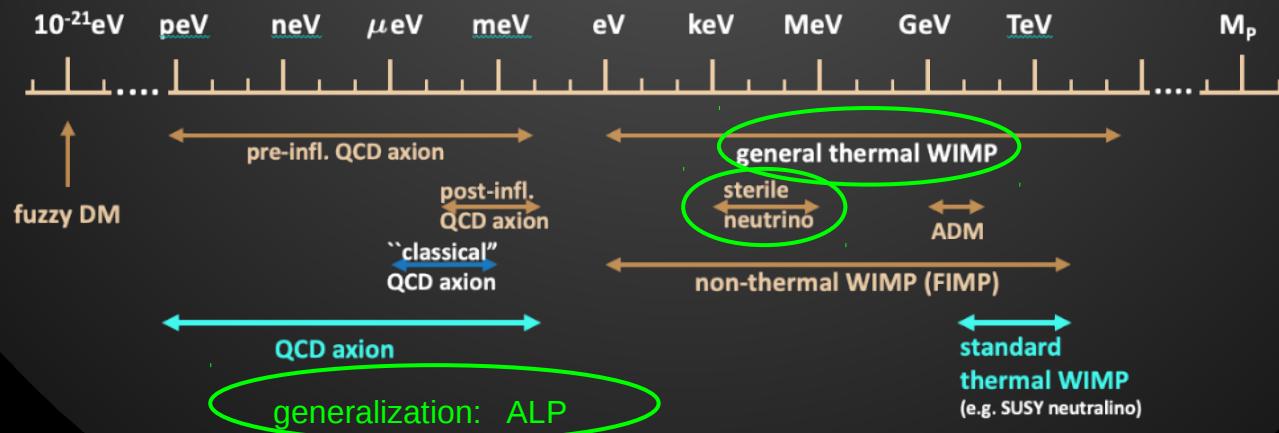
"We" are here

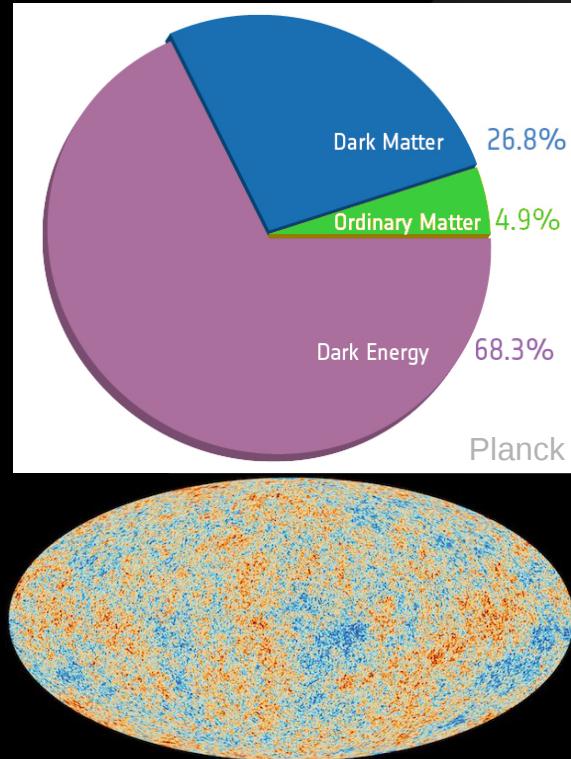
...moving through the Dark Matter Halo



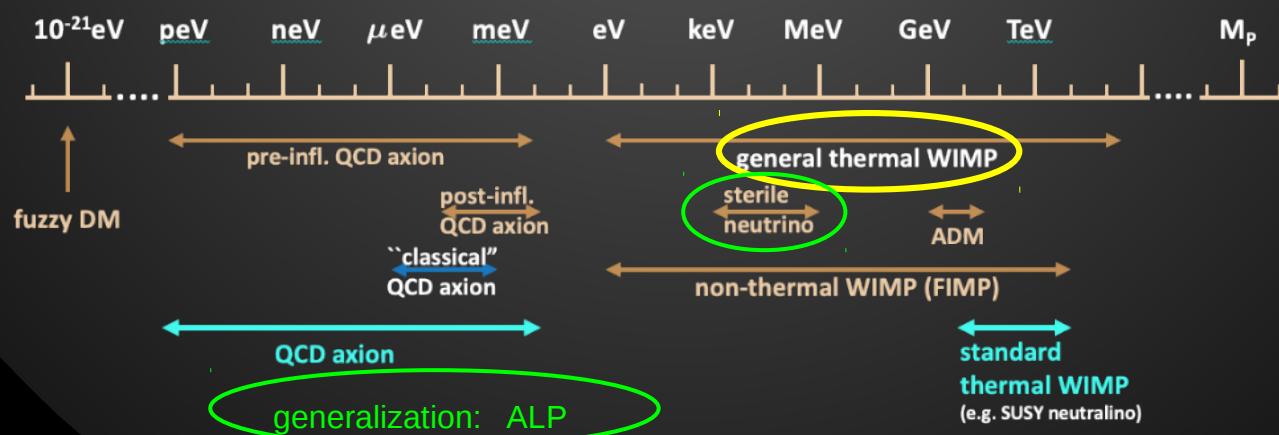
...moving through the Dark Matter Halo

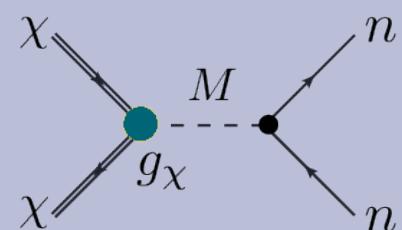
made of ???





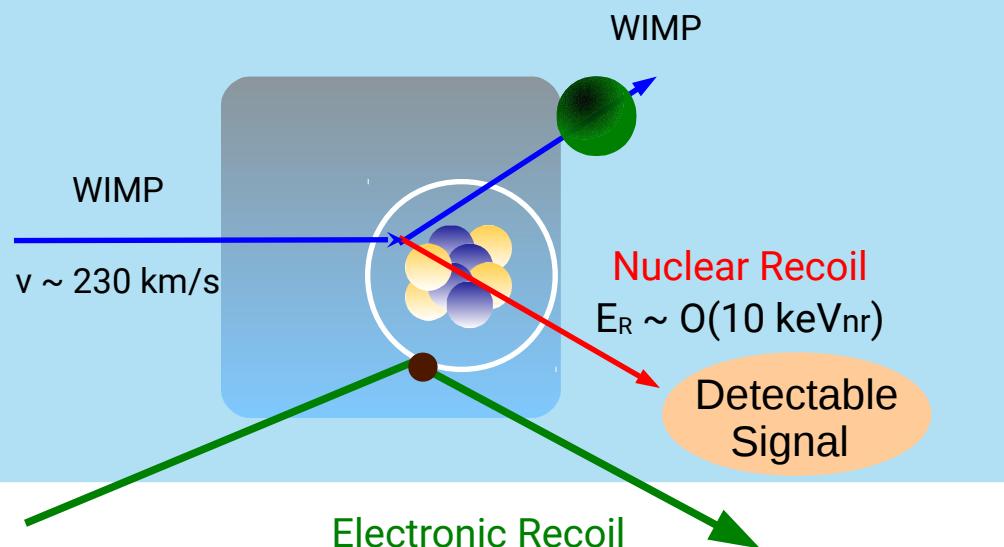
The indirect evidence for the existence of dark matter is a clear indication for physics beyond the Standard Model



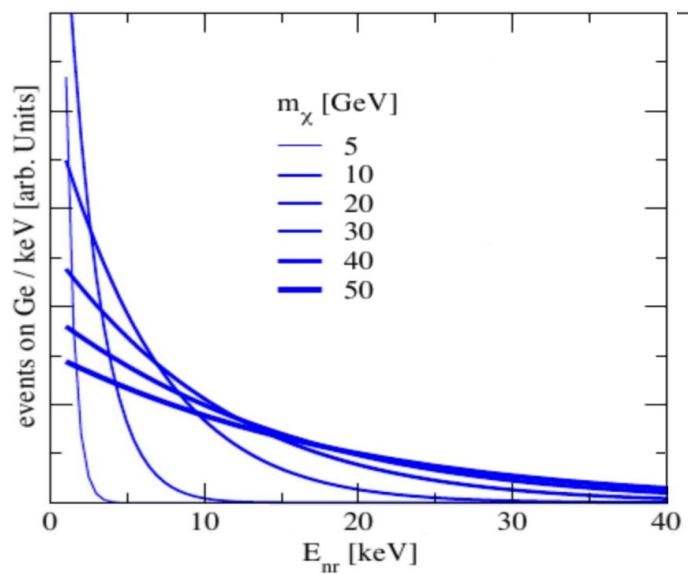
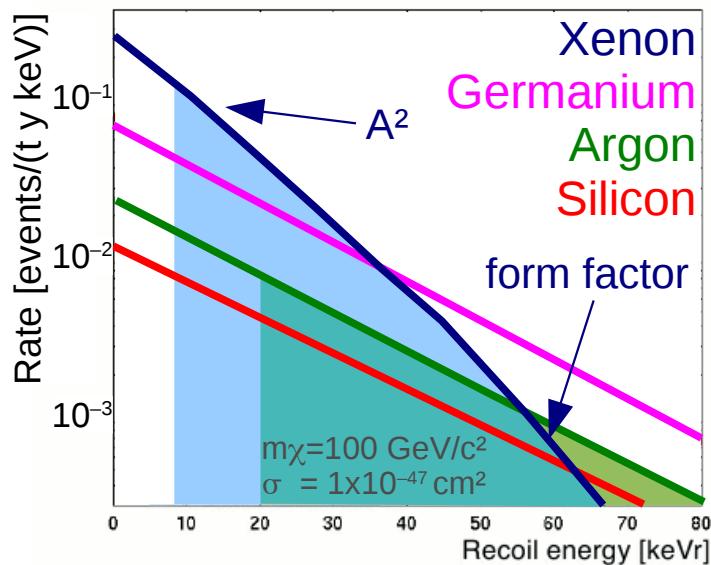


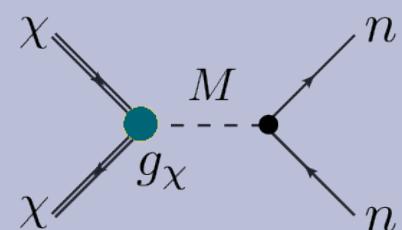
# Direct WIMP Search

Elastic Scattering of  
WIMPs off target nuclei  
→ nuclear recoil



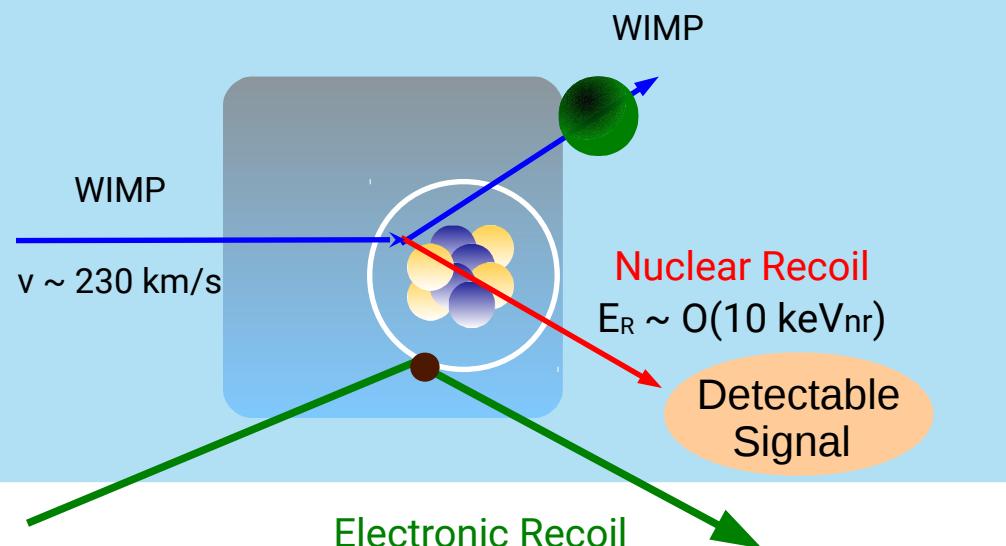
Recoil  
Spectra:



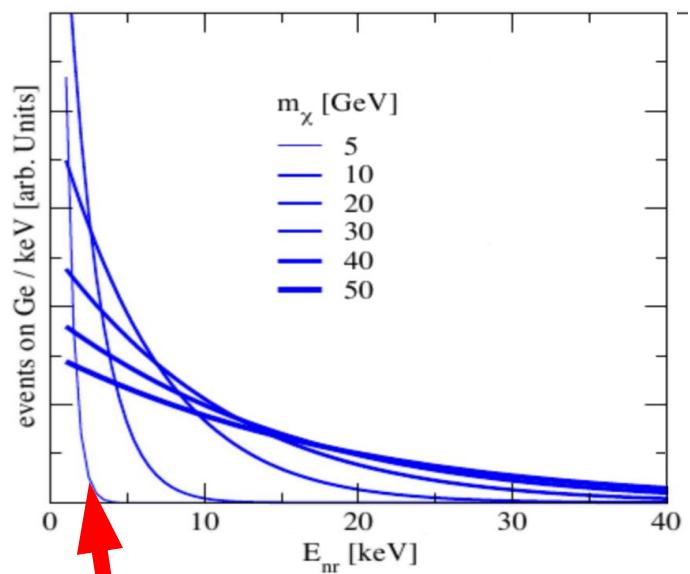
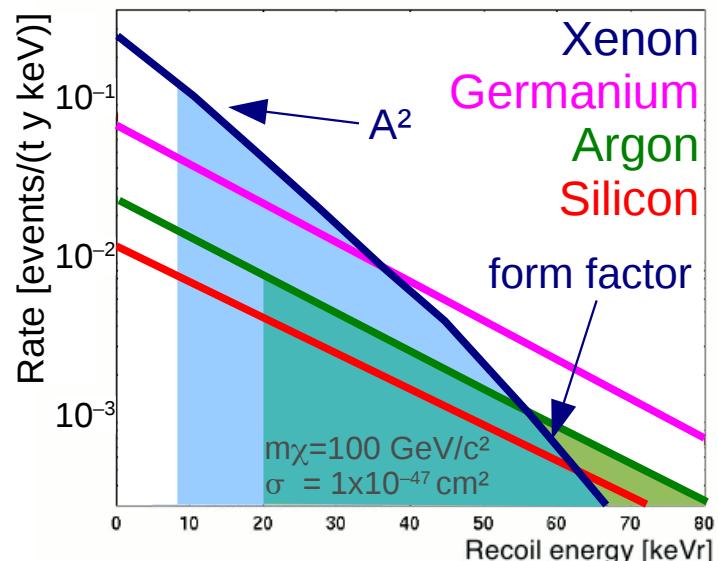


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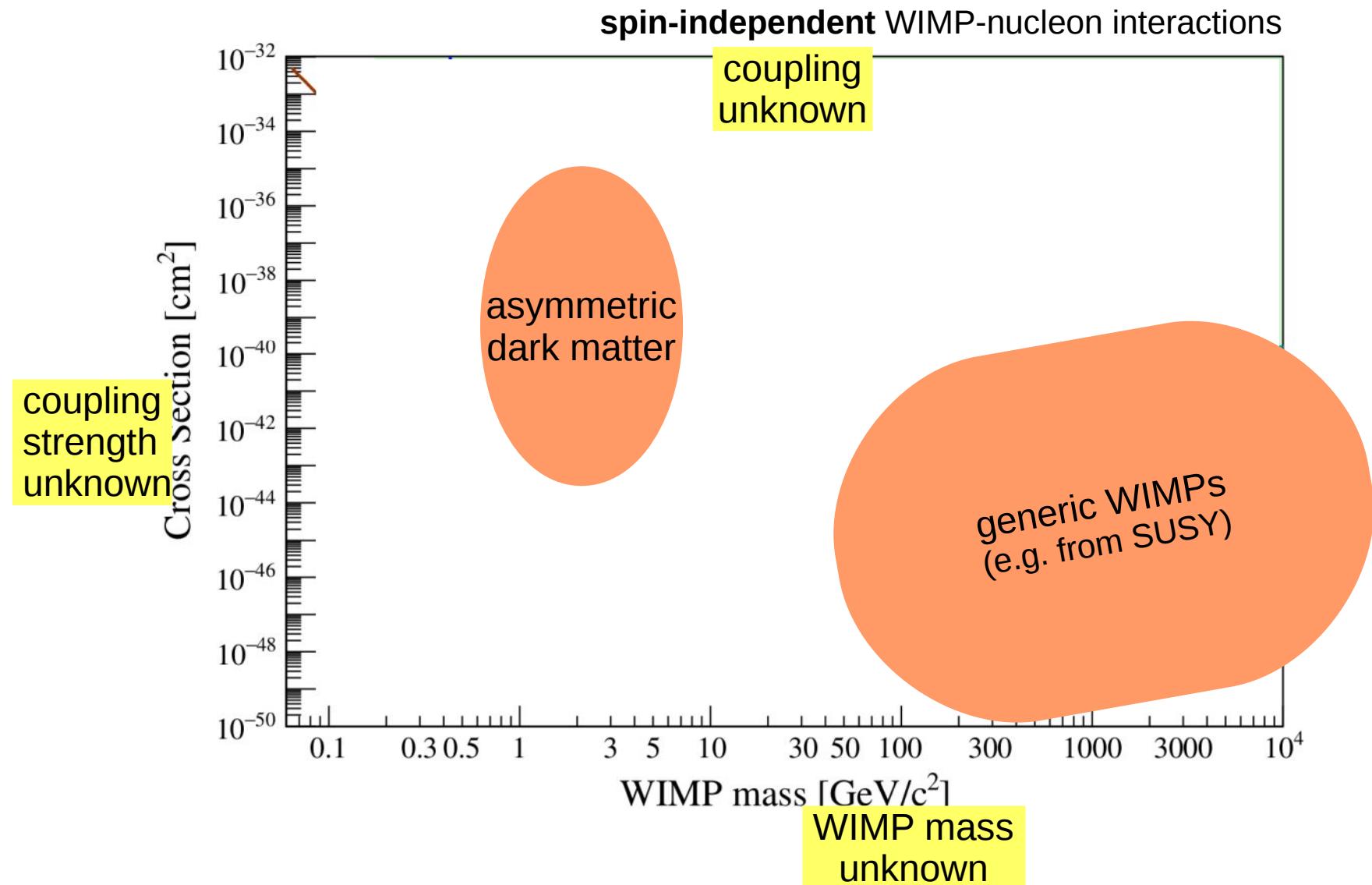
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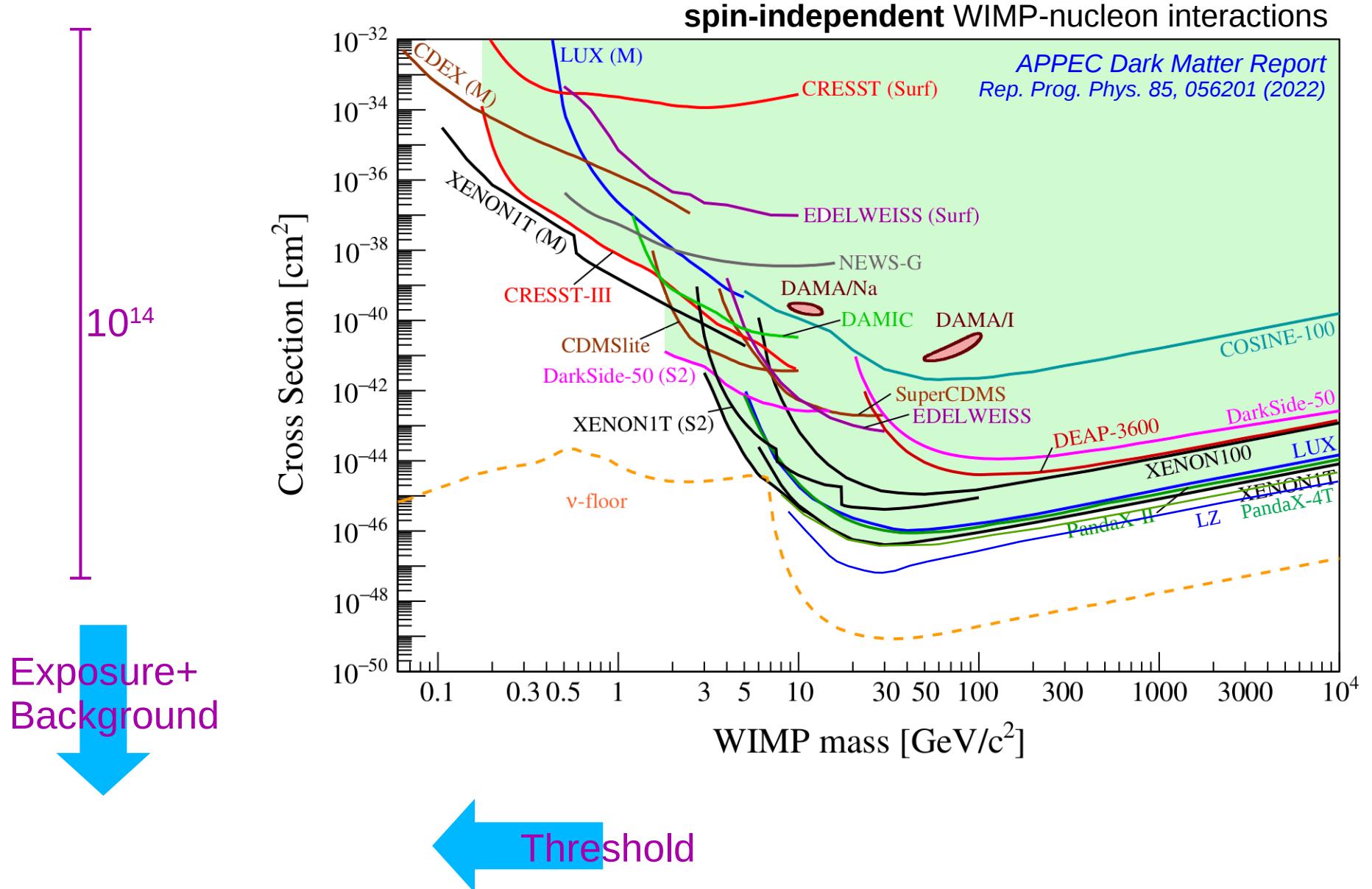
Recoil Spectra:



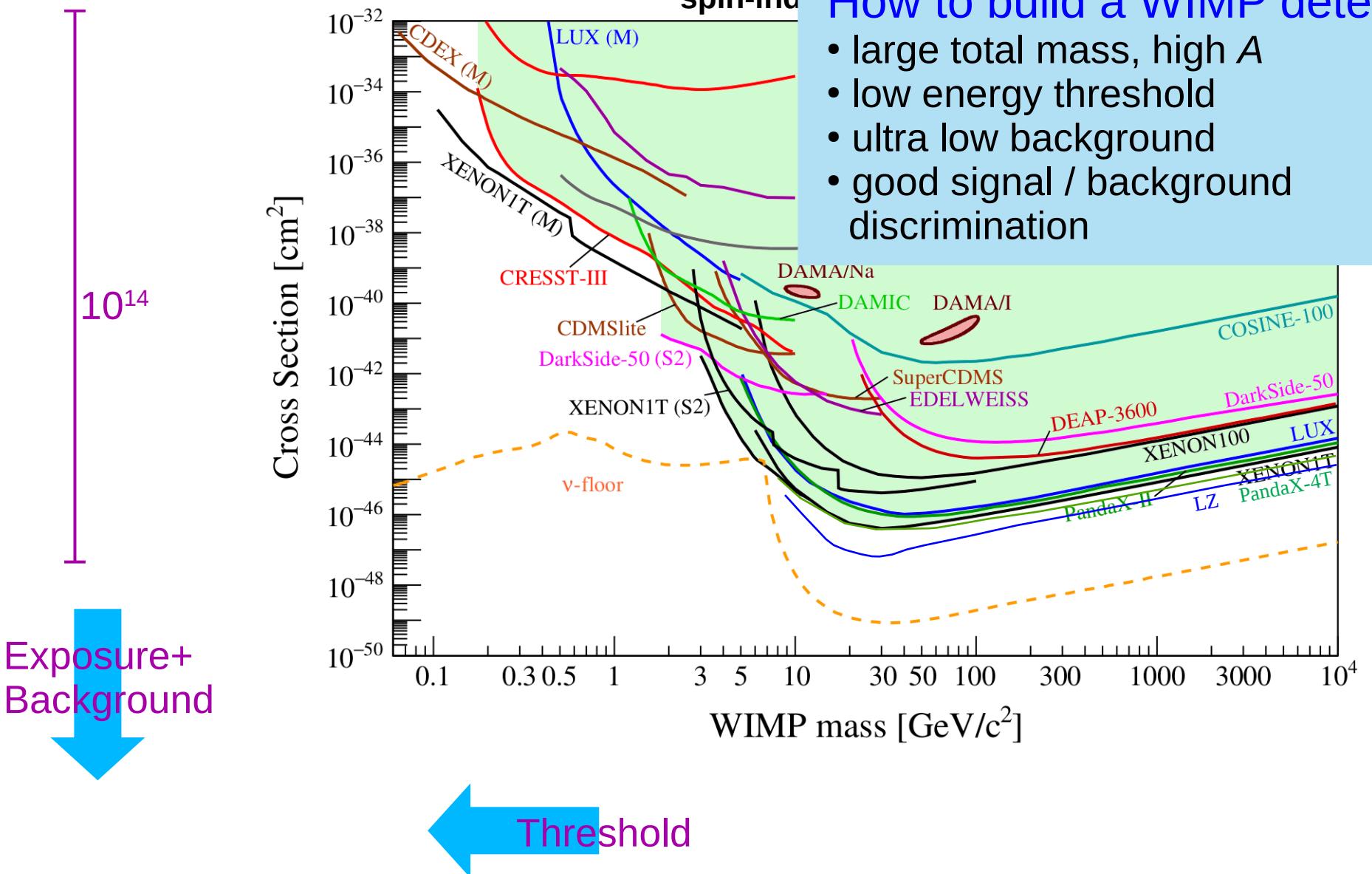
# The WIMP Parameter Space



# Current Status

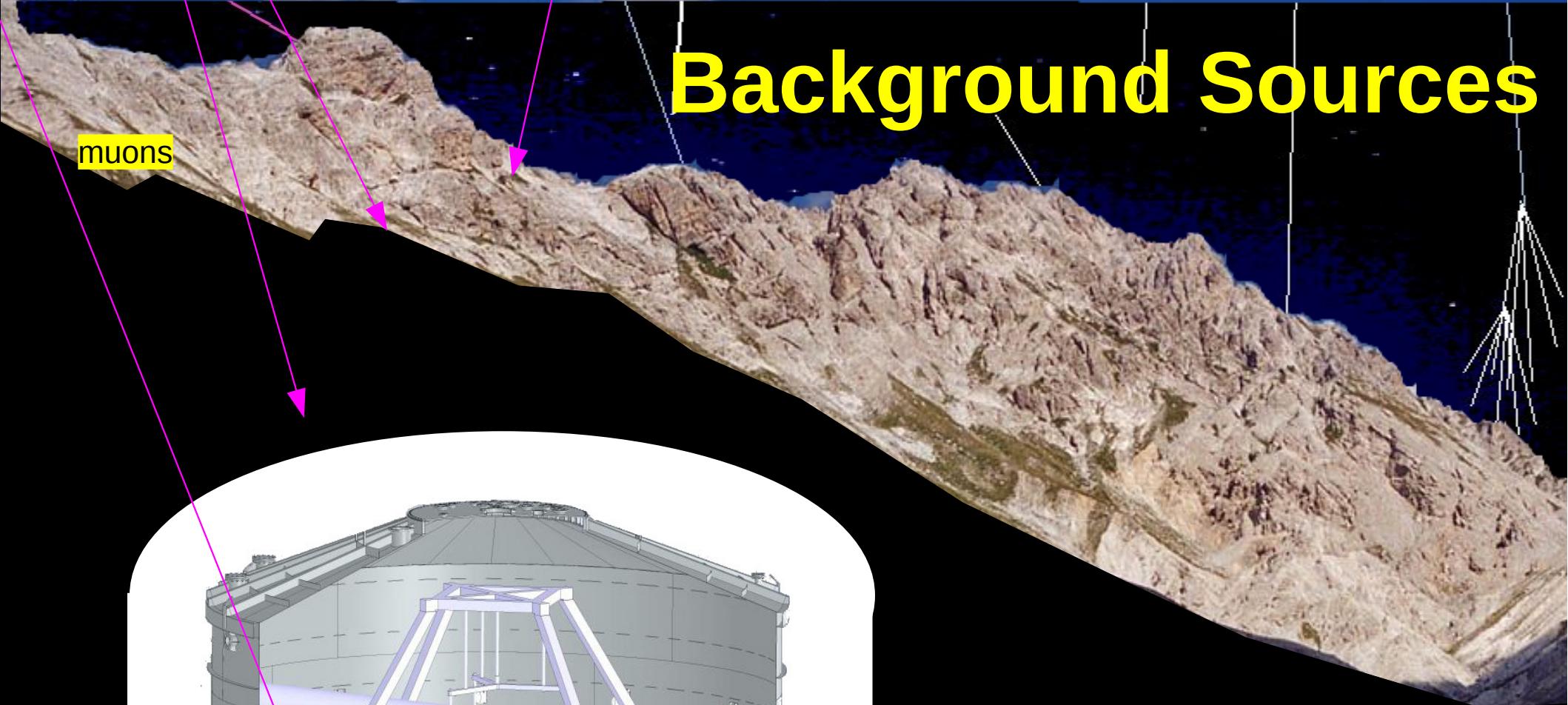
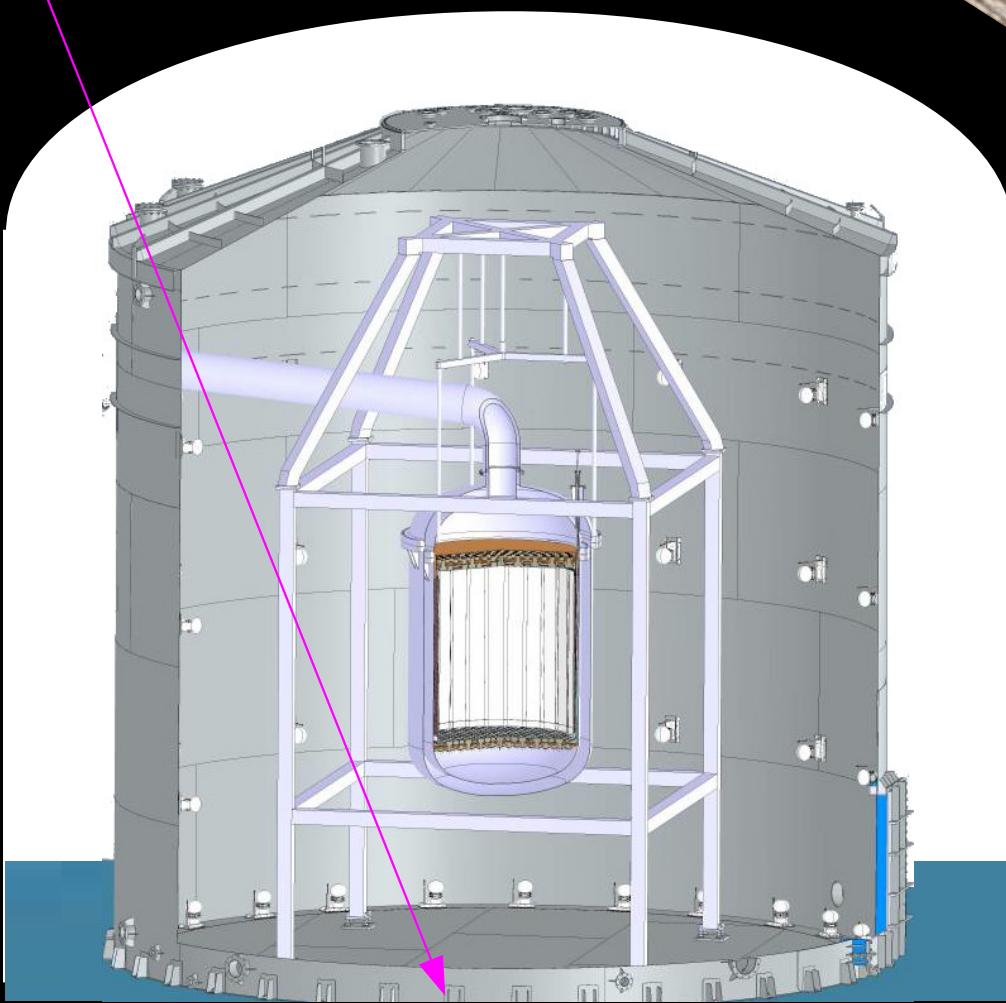


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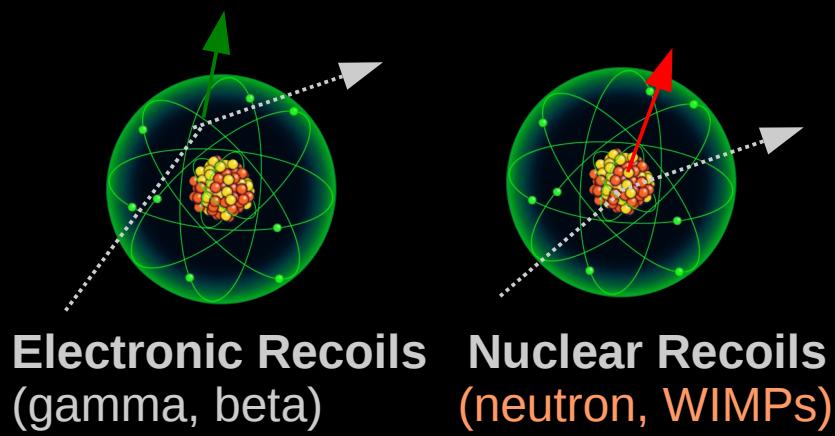
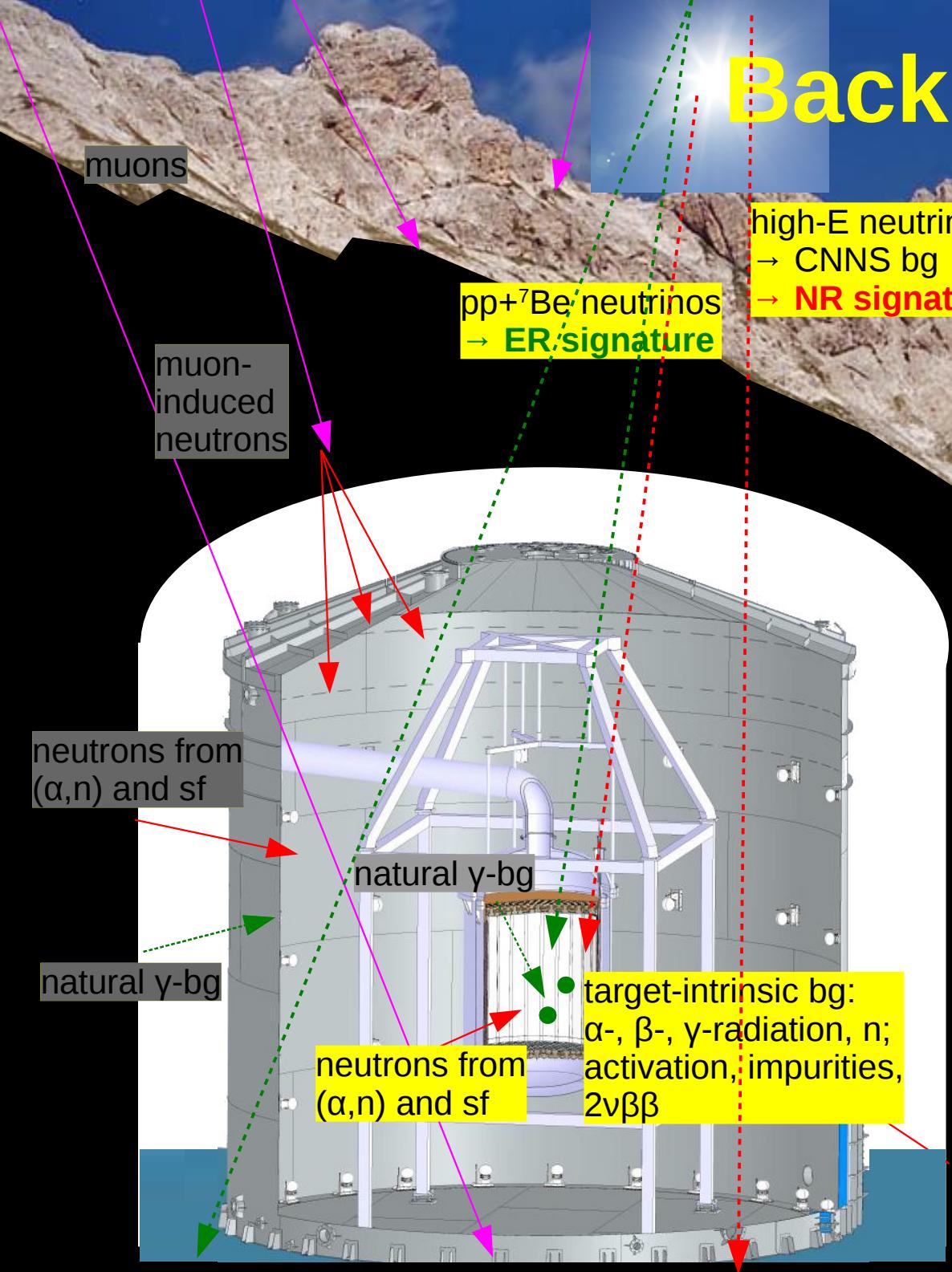
# Background Sources

muons



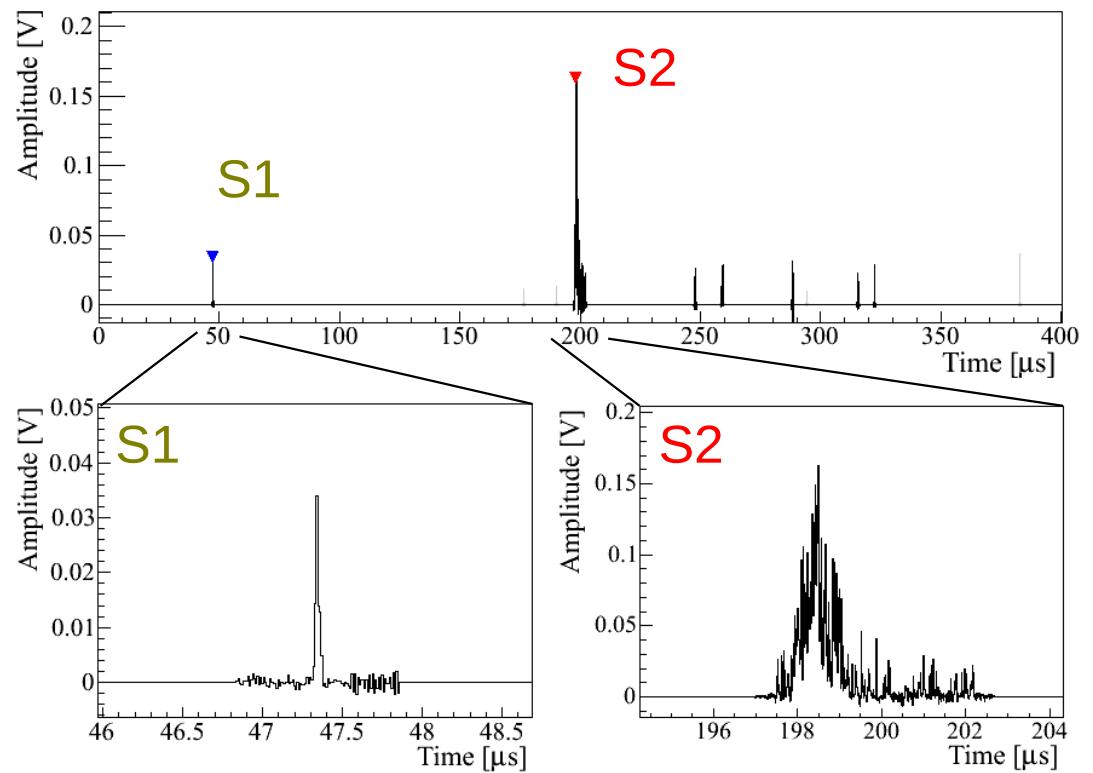
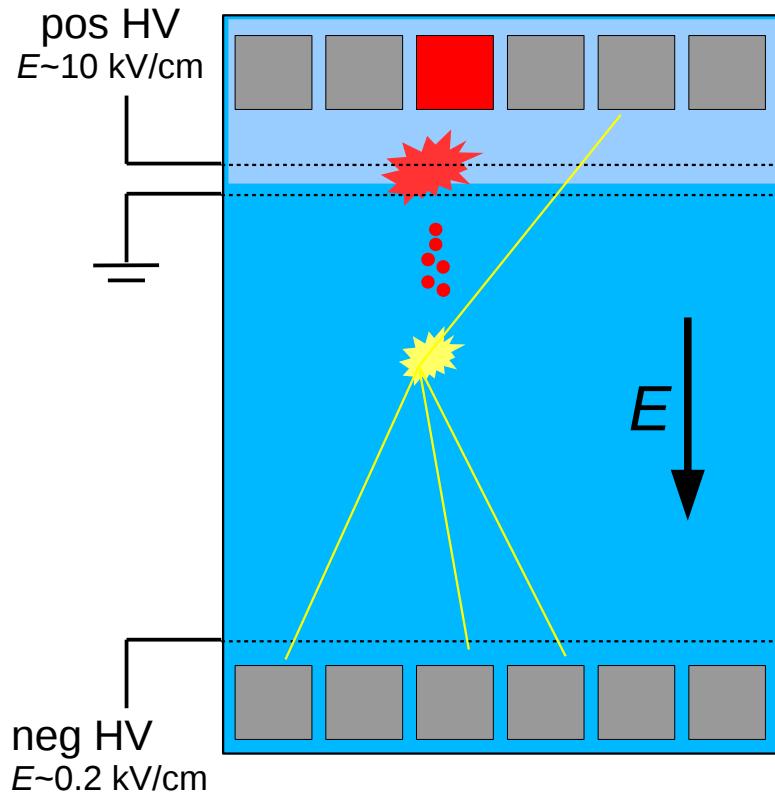
# Background Sources

(for ton-scale detectors)



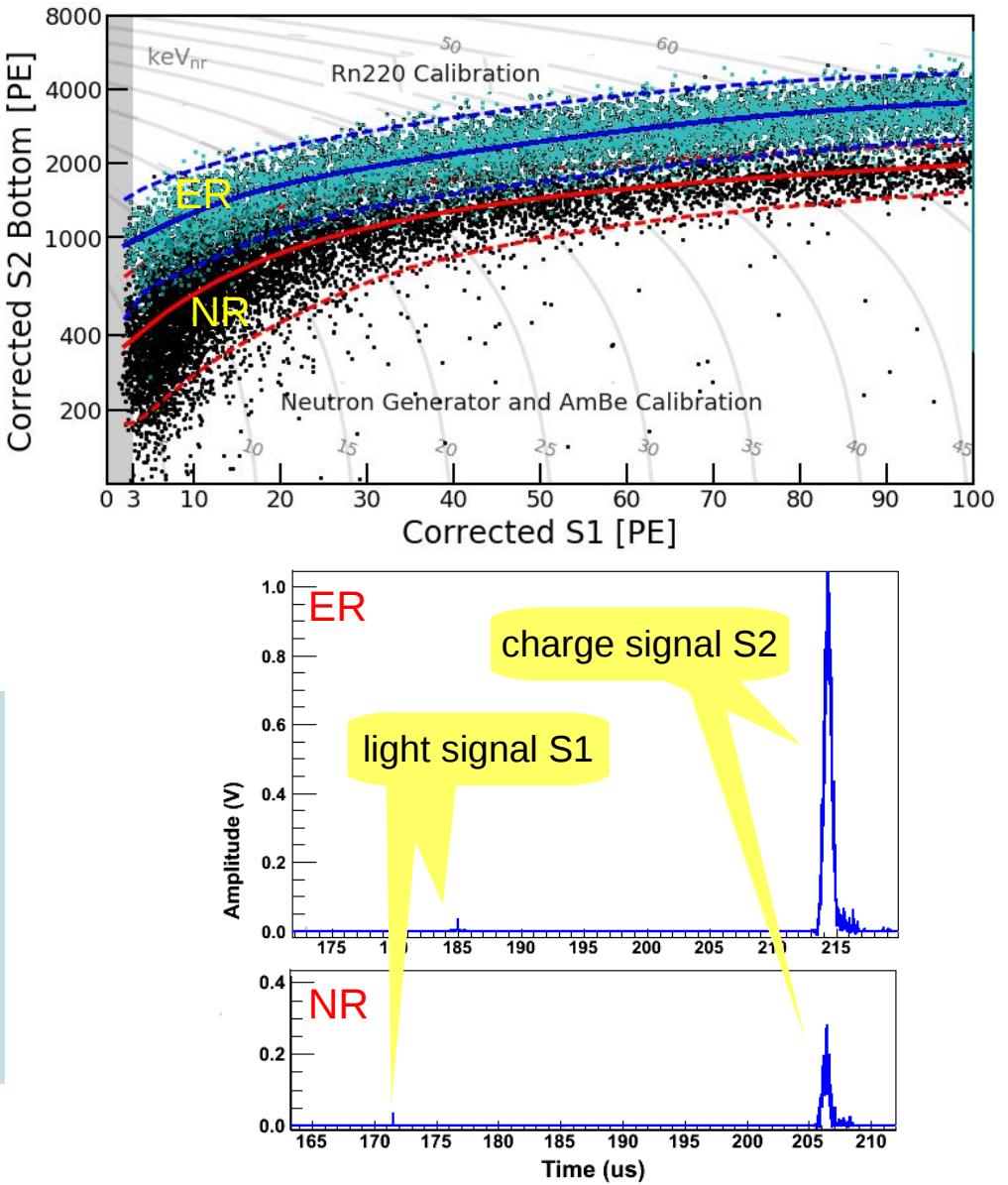
# Dual Phase TPC

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



# LXe TPC Features

- 3dim vertex reconstruction  
→ **fiducialization**
- multi-scatter rejection
- energy measurement ( $S_1 + S_2$ )
- **Charge-Light-Ratio ( $S_2/S_1$ ):**  
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



# (Still) State of the Art: Selected Results from **XENON1T @ LNGS**



EPJ C 77, 991 (2017)



*EPJ C 77, 991 (2017)*



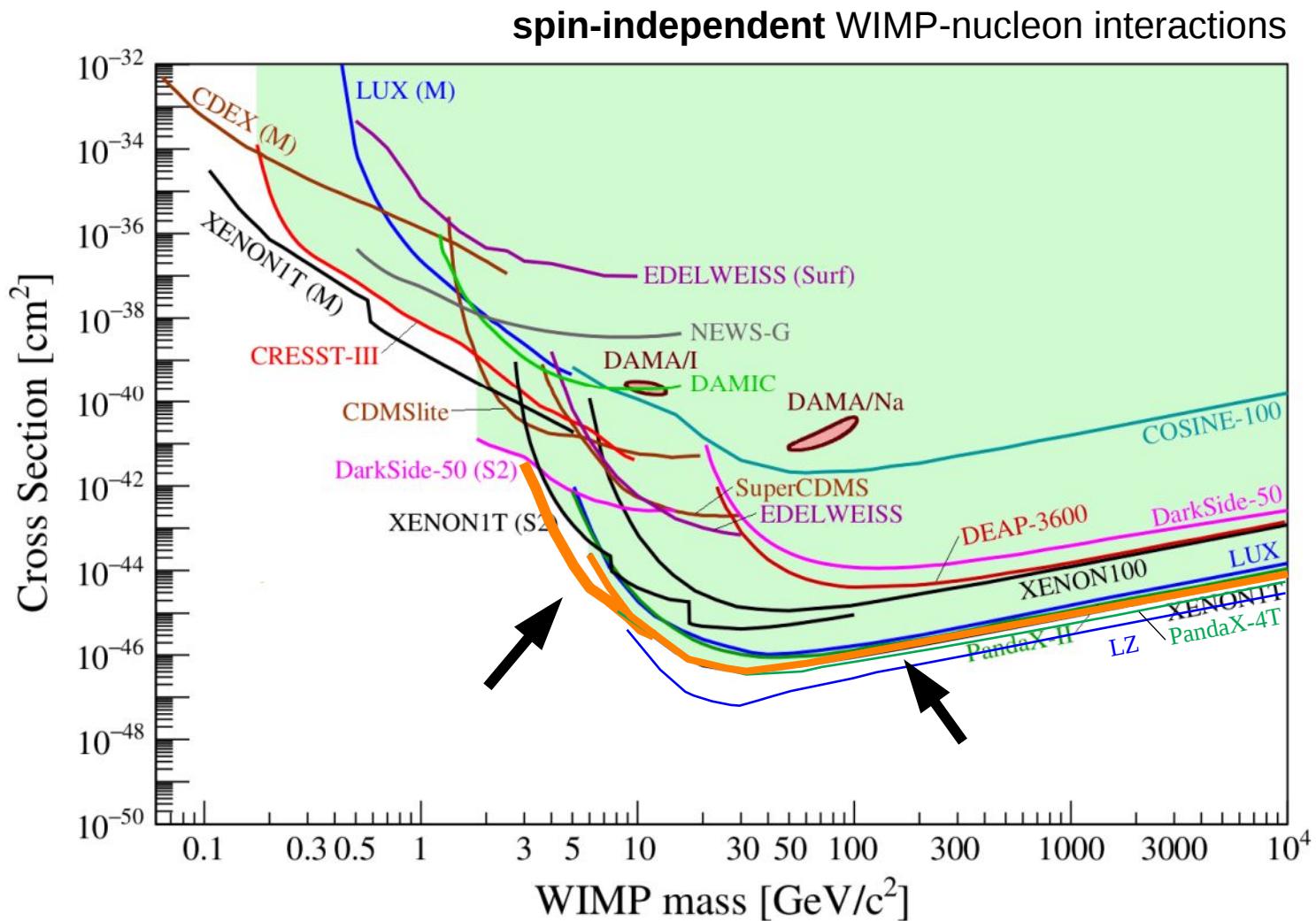
cylinder: 96 cm  
active LXe target: 2.0t (3.2t total)  
248 PMTs

# 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*



# XENON1T Results



Spin independent S1+S2  
*PRL 121, 111302 (2018)*  
*PRL 126, 091301 (2021)*

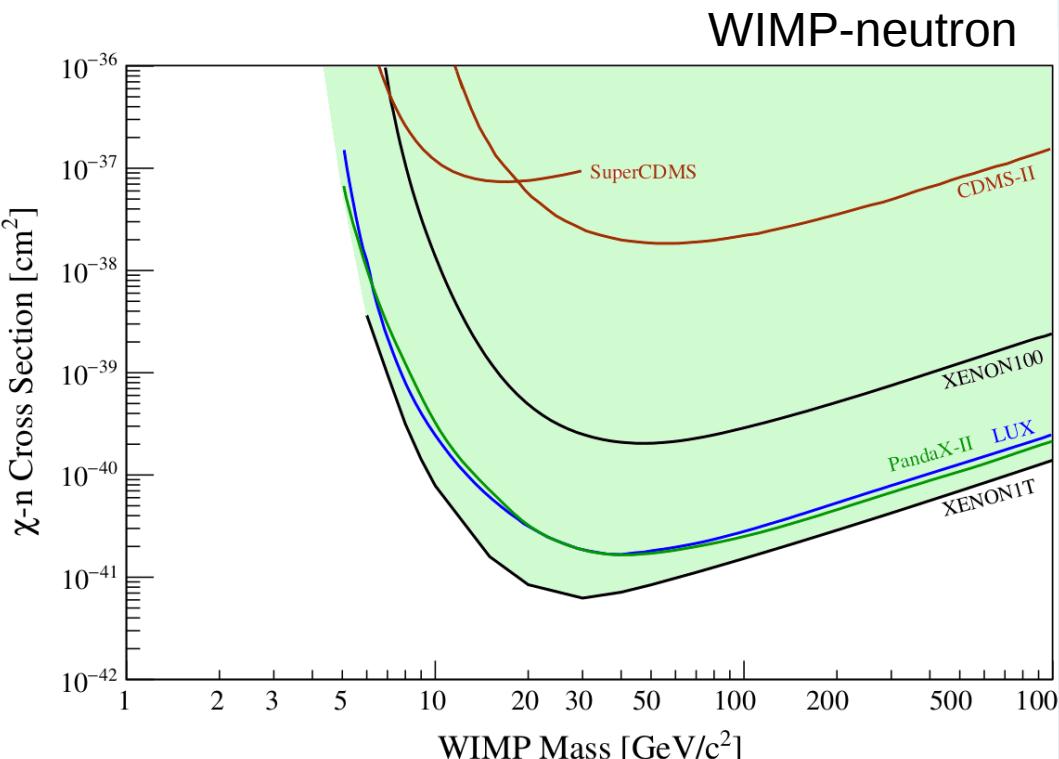
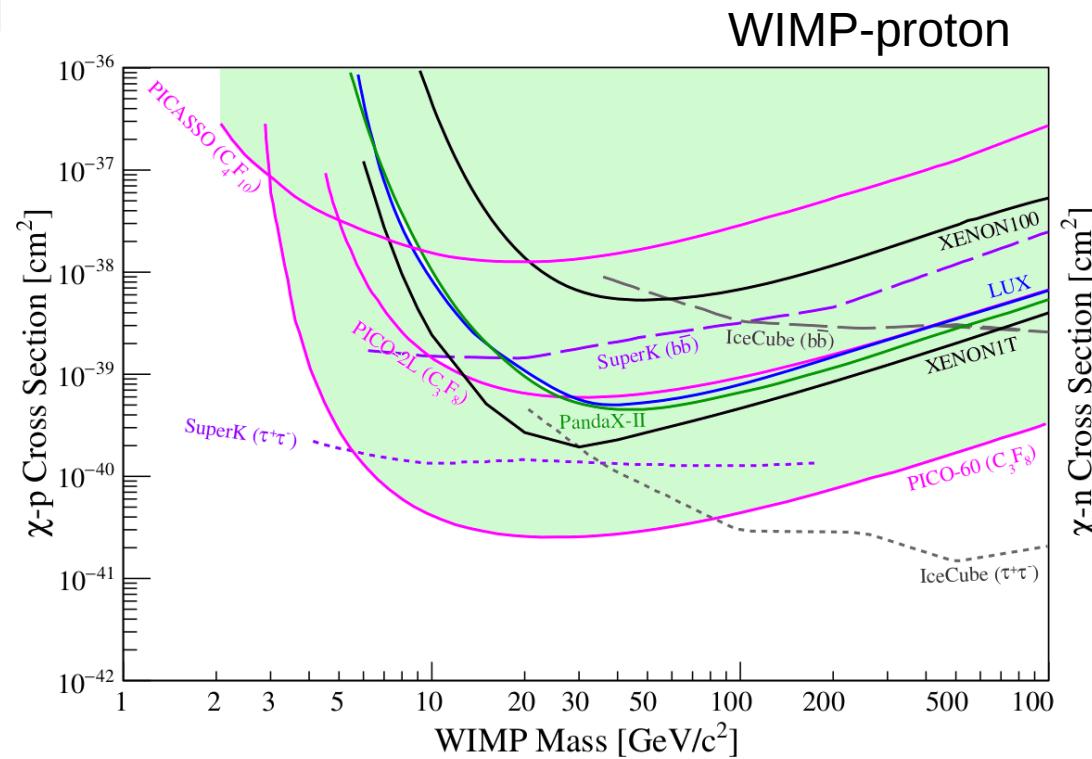
Spin-dependent S1+S2  
*PRL 122, 141301 (2019)*

# Spin-Dependent Couplings

*PRL 122, 141301 (2019)*

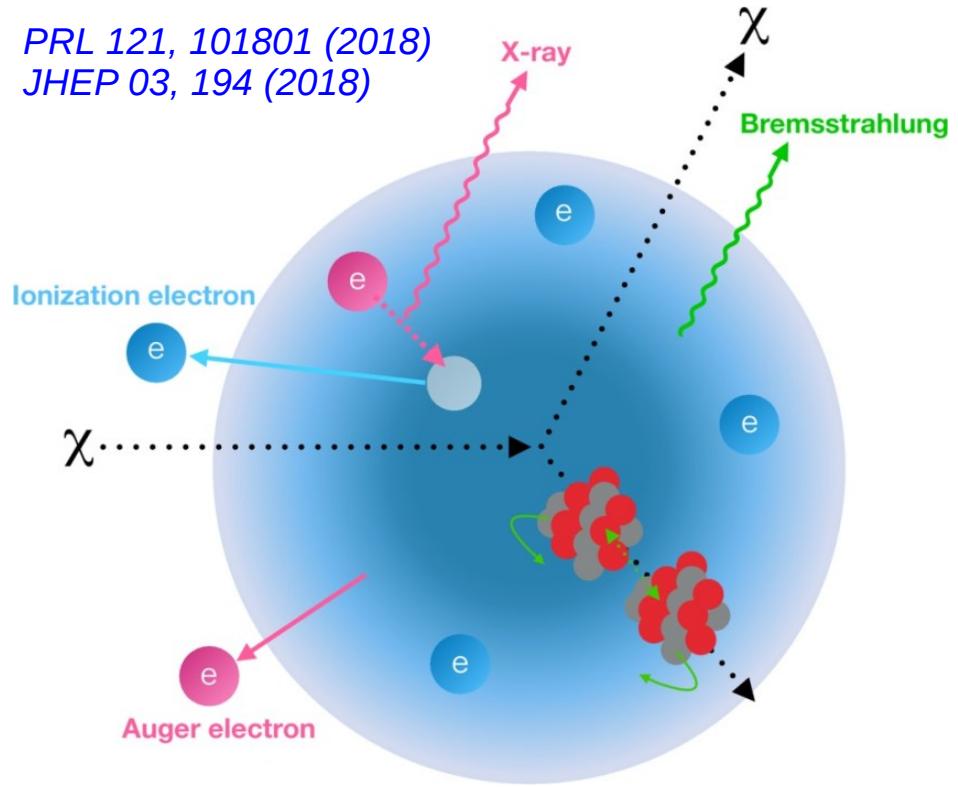
- coupling of WIMP to unpaired nucleon spins  
→ Xenon very favoured target
- traditionally separated in proton-only and neutron-only
- same parameter space explored by indirect and collider searches**

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

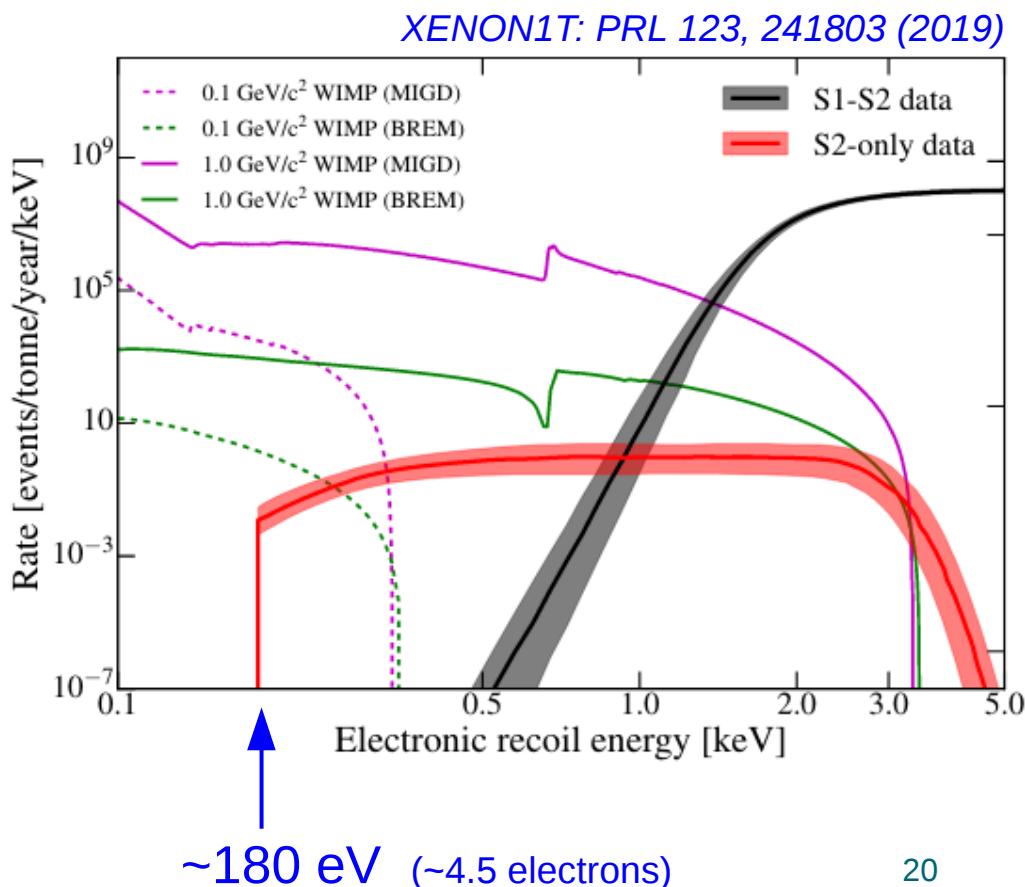
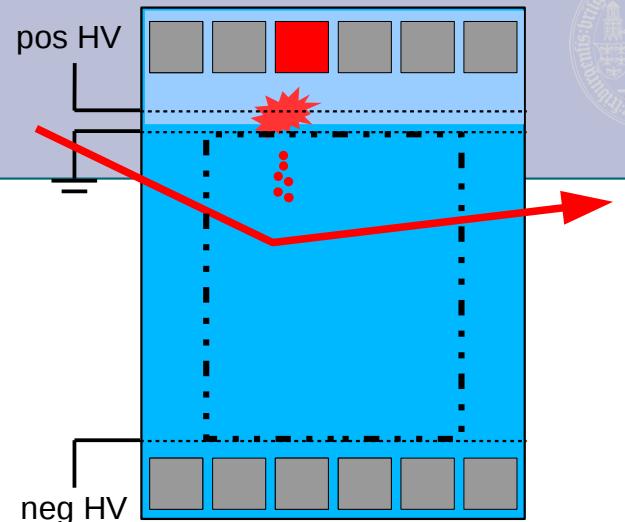


# S2-only+Migdal Effect

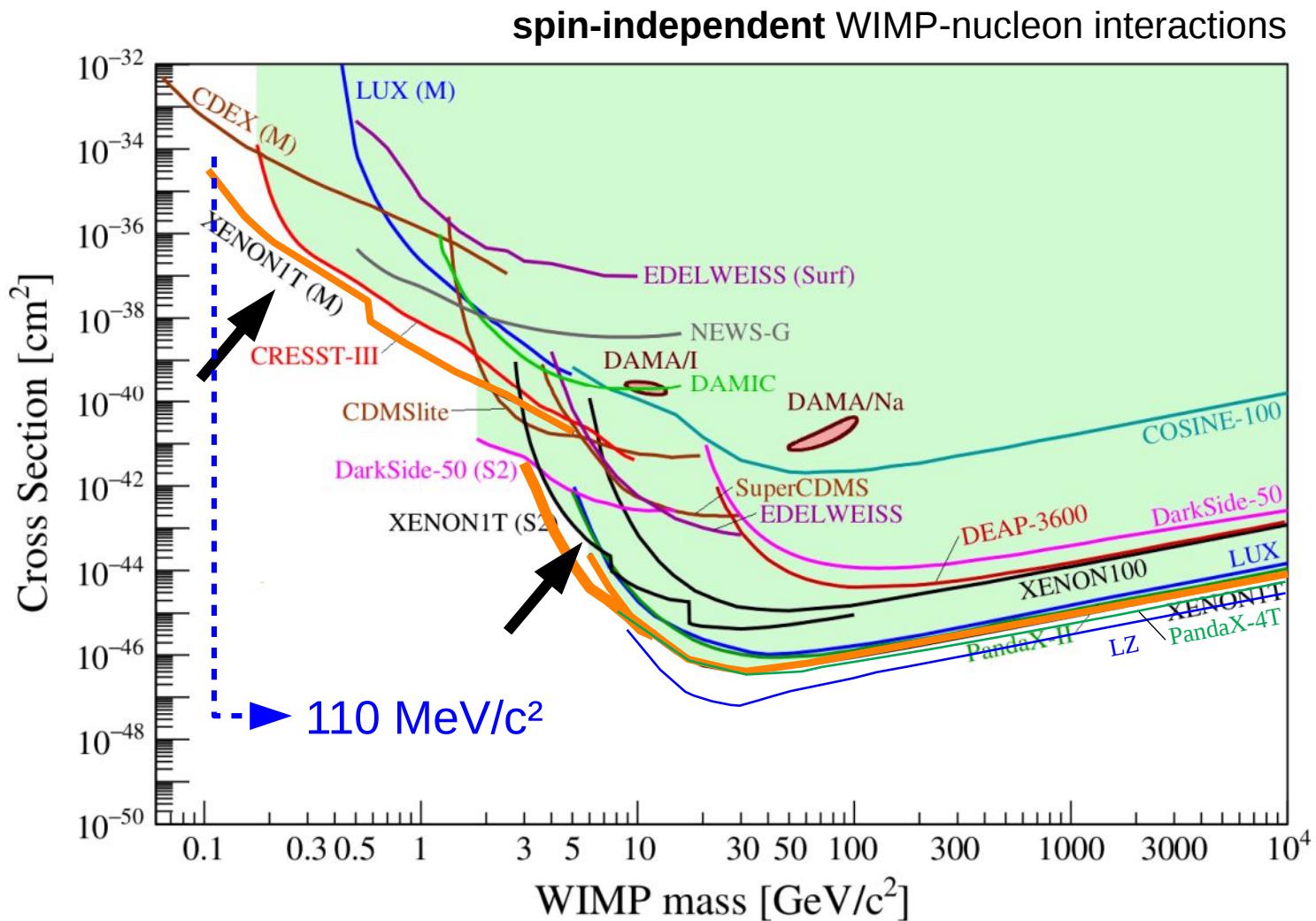
PRL 121, 101801 (2018)  
 JHEP 03, 194 (2018)



- use only charge signals (S2) and exploit expected effects after nuclear recoil  
 $\rightarrow$  very low threshold
- caveat: effect not yet observed in calibration



# XENON1T Results



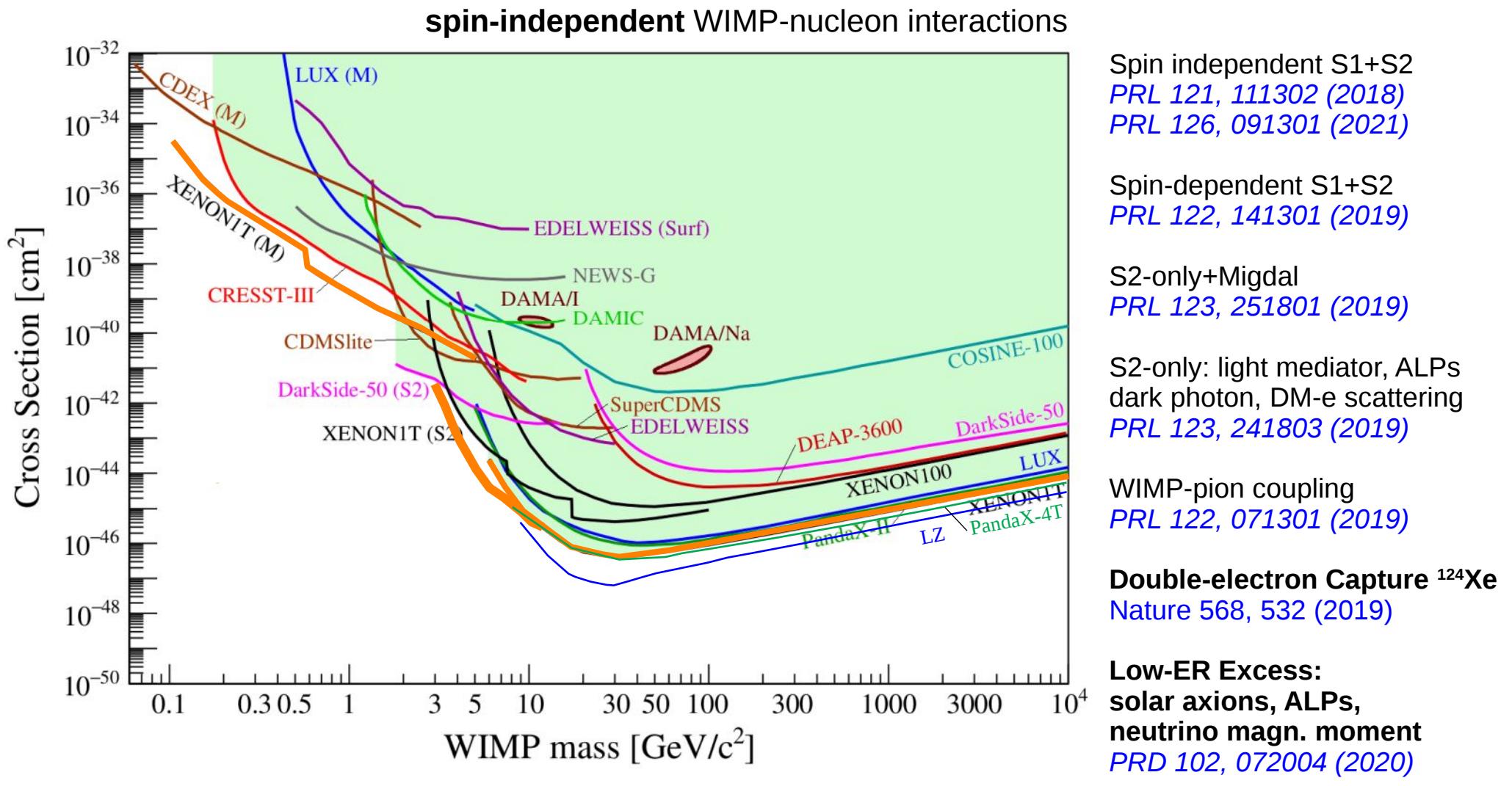
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Spin-dependent S1+S2  
*PRL 122, 141301 (2019)*

S2-only+Migdal  
*PRL 123, 251801 (2019)*

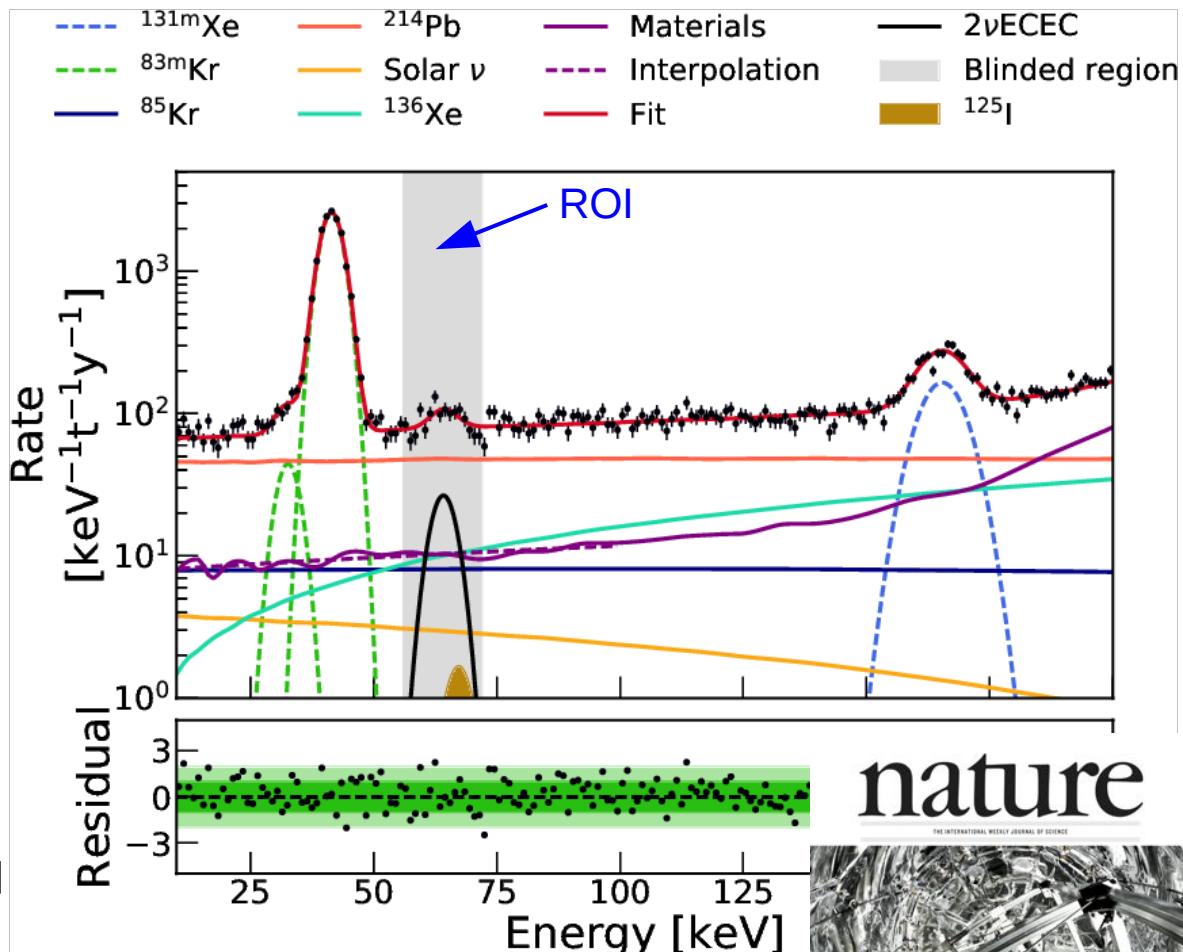
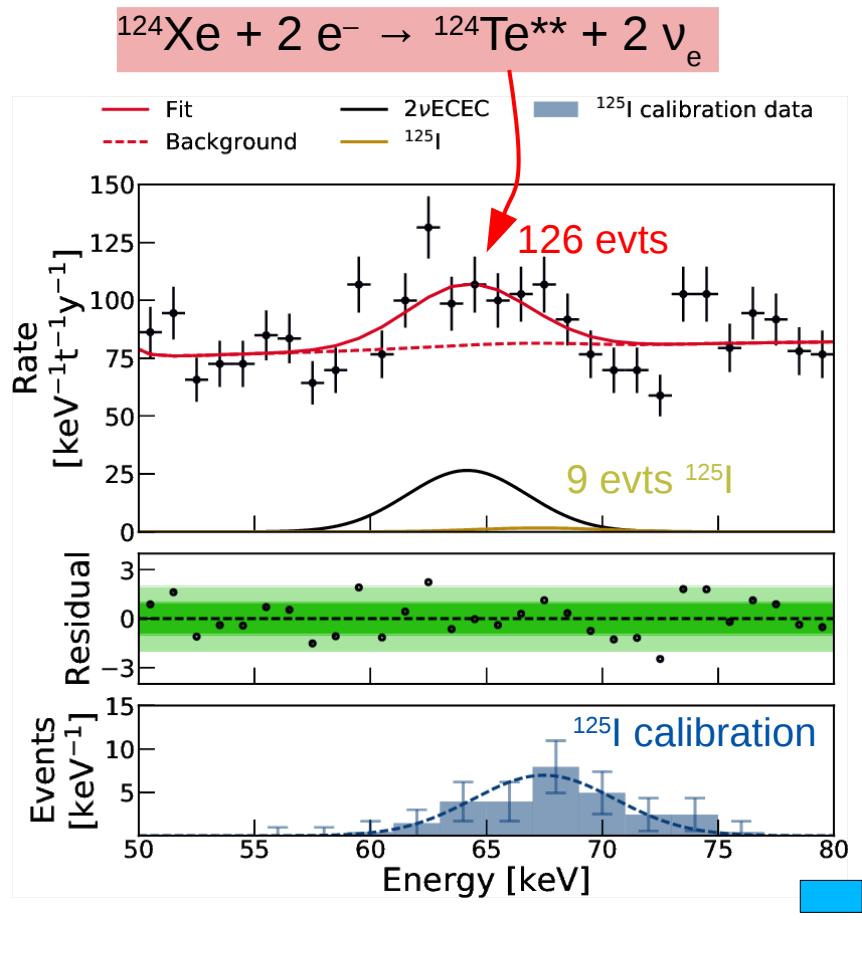
S2-only: light mediators, ALPs  
dark photon, DM-e scattering  
*PRL 123, 241803 (2019)*

# XENON1T Results



# Double-Electron Capture of $^{124}\text{Xe}$

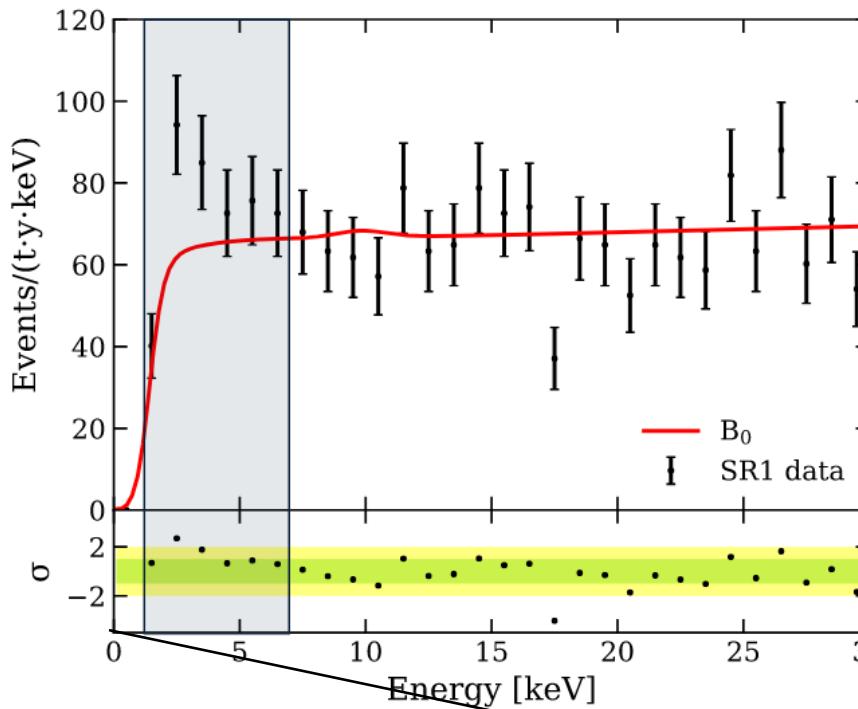
Nature 568, 532 (2019)



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

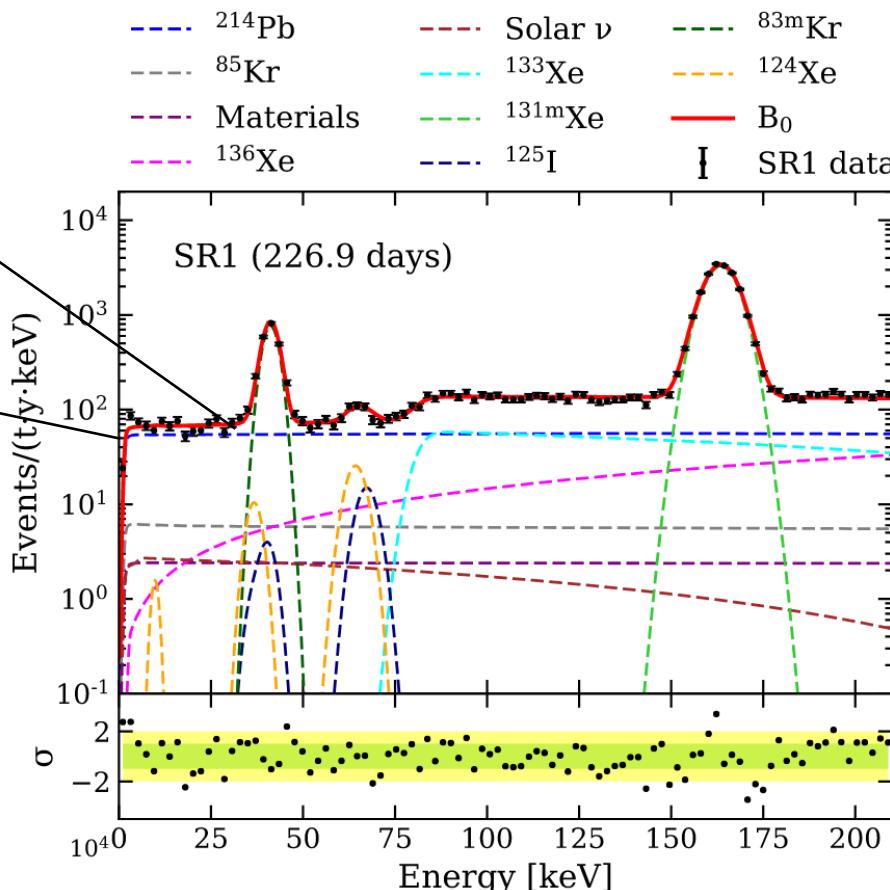
# Low-ER Excess

PRD 102, 072004 (2020)



Needs to be checked  
by instruments with  
reduced background!

- **excess in electronic recoils (1-7 keV range)**  
285 evts observed vs  $232 \pm 15$  expected  
→ **(naive)  $3.3\sigma$  fluctuation**
- New physics (solar axions, ALPs, magnetic moment of neutrino, etc.) or old background ( ${}^3\text{H}$ )?





# Running now: XENONnT



- target mass **5.9t**  
→ new, larger TPC
- lower background  
→ lightweight TPC design



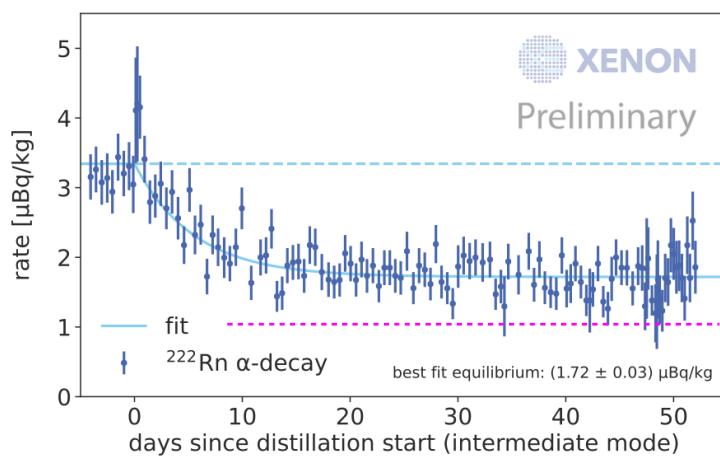
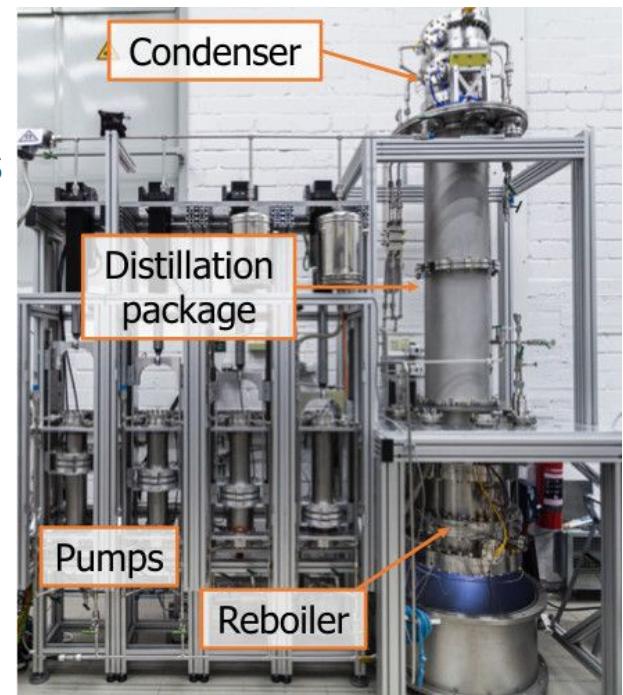
# XENONnT

- target mass **5.9t**  
→ new, larger TPC
- lower background  
→ **lightweight TPC design**
  - Rn reduced by factor 6  
→ **online Rn-removal**
  - neutrons below neutrinos  
→ **neutron veto**
  - avoid  $^3\text{H}$  contamination  
→ **cleaning, materials**

Radon dominates ER background of current detectors

## Active on-line Rn removal via cryogenic distillation

Demonstrated factor >27 on XENON100  
*EPJ C 77, 358 (2017)*



1  $\mu\text{Bq}/\text{kg}$  reached in LXe distillation mode

- target mass **5.9t**  
→ new, larger TPC



- lower background  
→ **lightweight TPC design**

Rn reduced by factor 6  
→ **online Rn-removal**

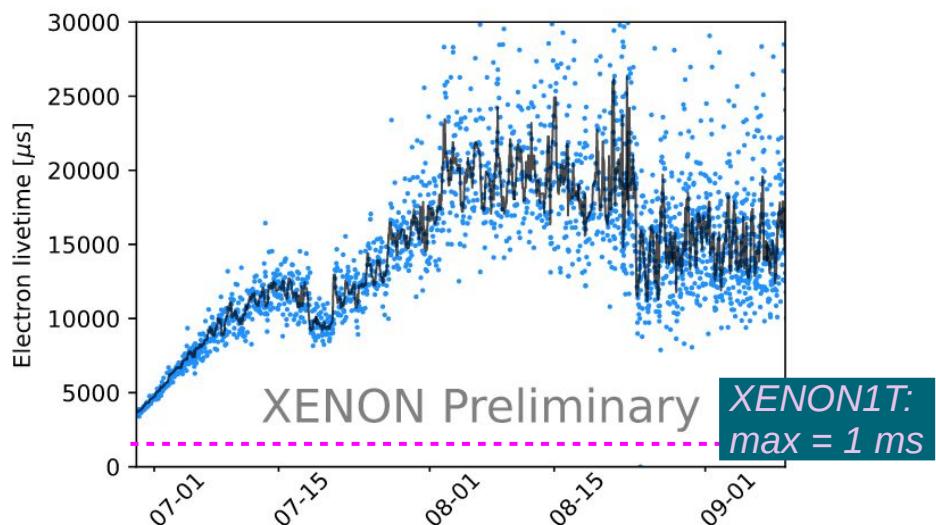
neutrons below neutrinos  
→ **neutron veto**

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

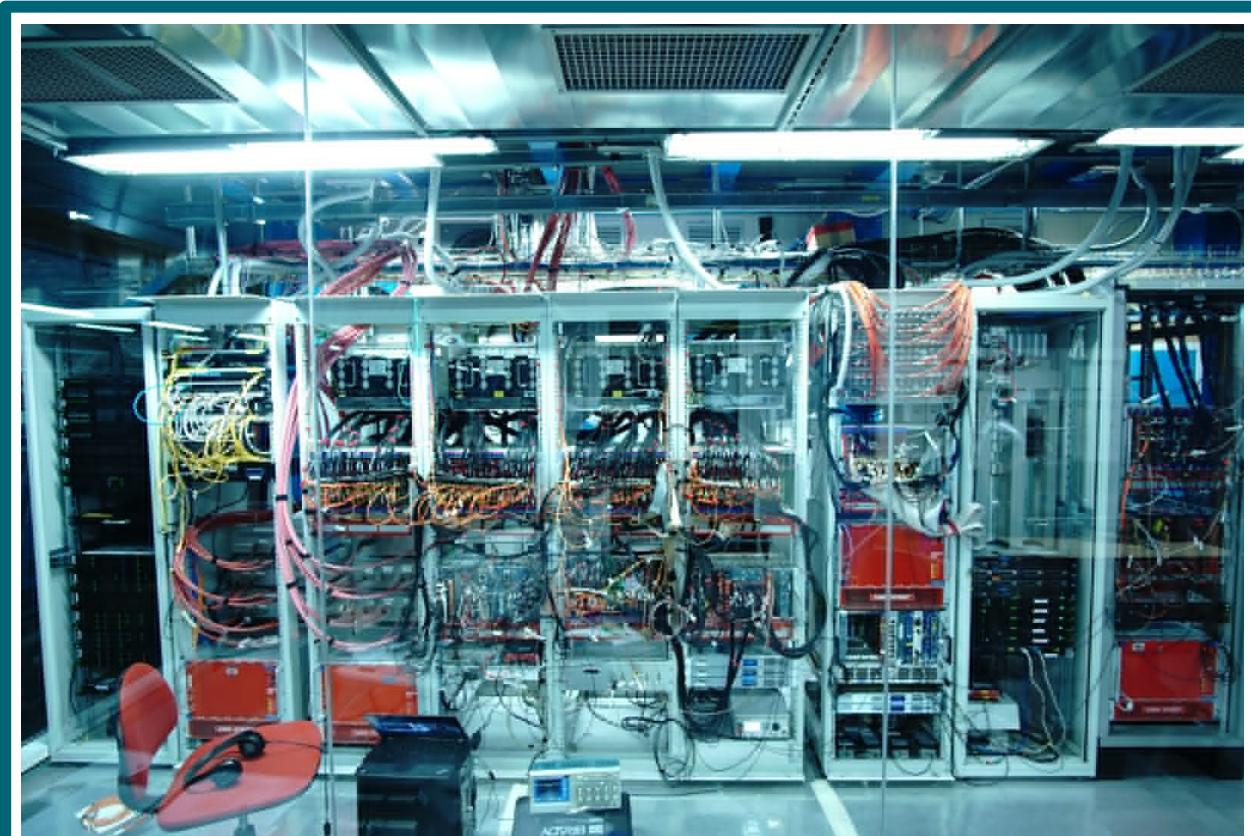
### Continuous Purification of liquid Xenon



- remove electronegative impurities ( $\rightarrow \text{O}_2$ ) by absorption in cryogenic filters
- flux goal:  $\sim 2 \text{ LPM}$  ( $\cong 1000 \text{ slpm}$ )



- target mass **5.9t**  
→ 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
  - \* DAQ
  - \* storage (Restox-II),
  - \* gas purification (Rn-free pumps),
  - \* computing etc.



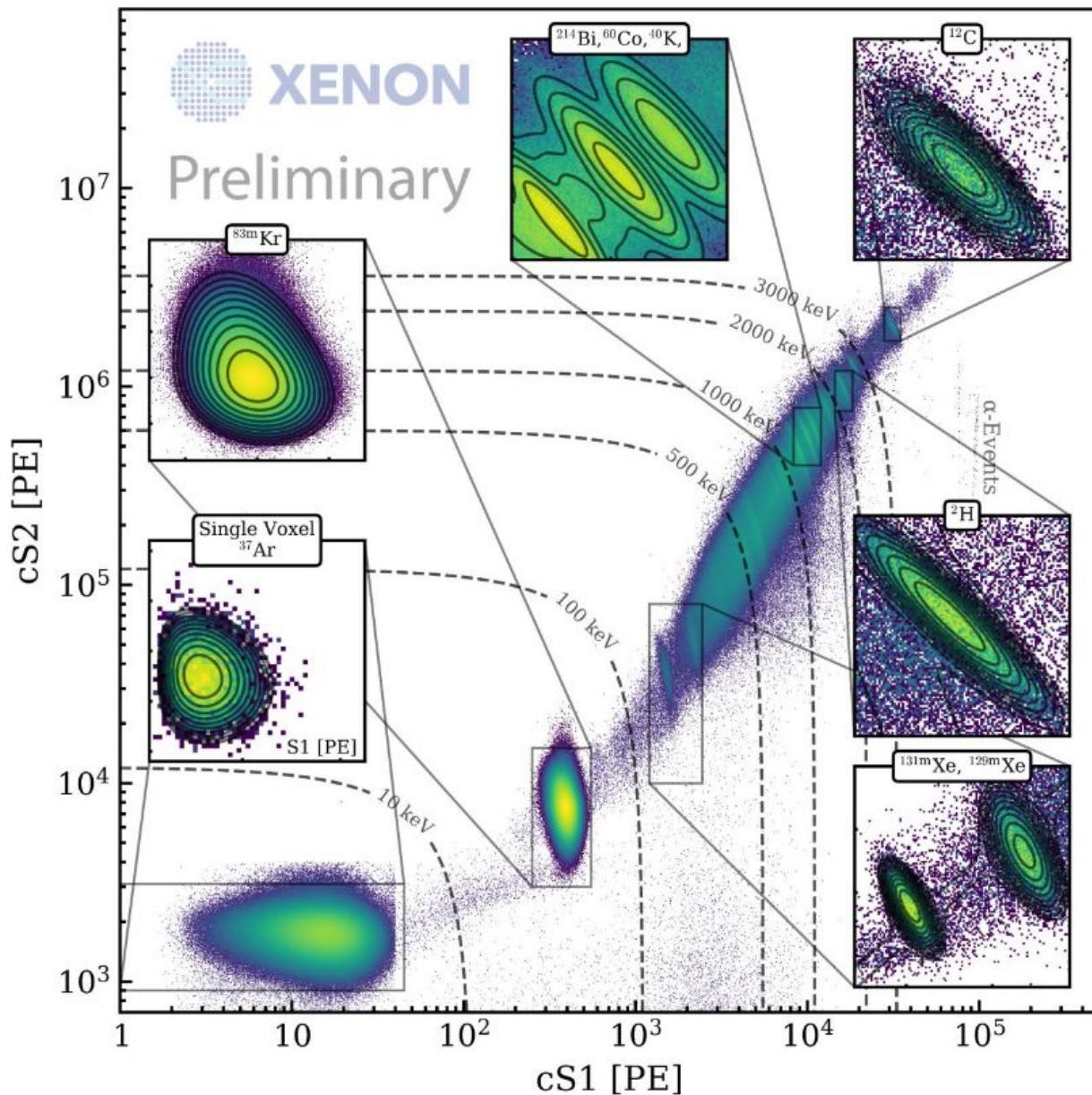
## Triggerless DAQ System

concept: JINST 14, P07016 (2019)

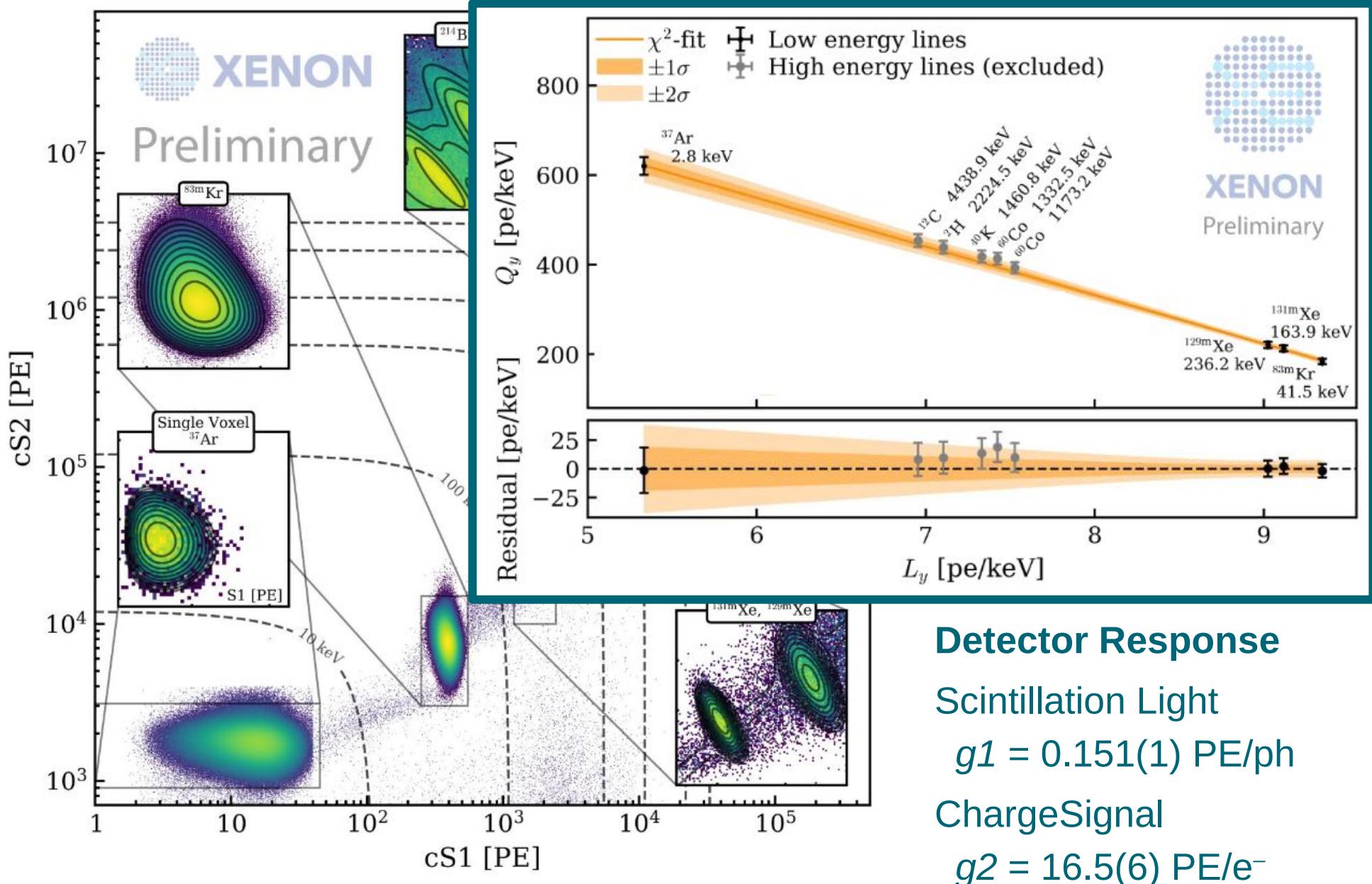
- continuous, asynchronous readout of ~750 channels (0.1 PE threshold)
- on-line processing
- low-gain channels for  $0\nu\beta\beta$

XENONnT is currently taking data at LNGS

# Calibration & Characterization

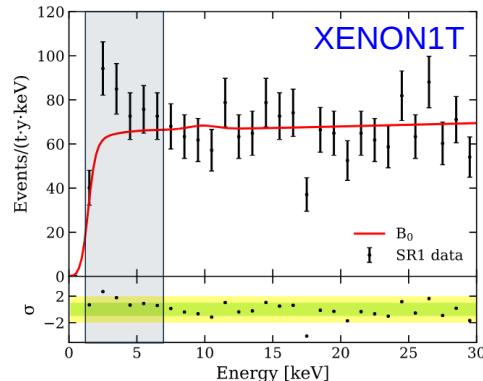


# Calibration & Characterization



# Low-E Electronic Recoils

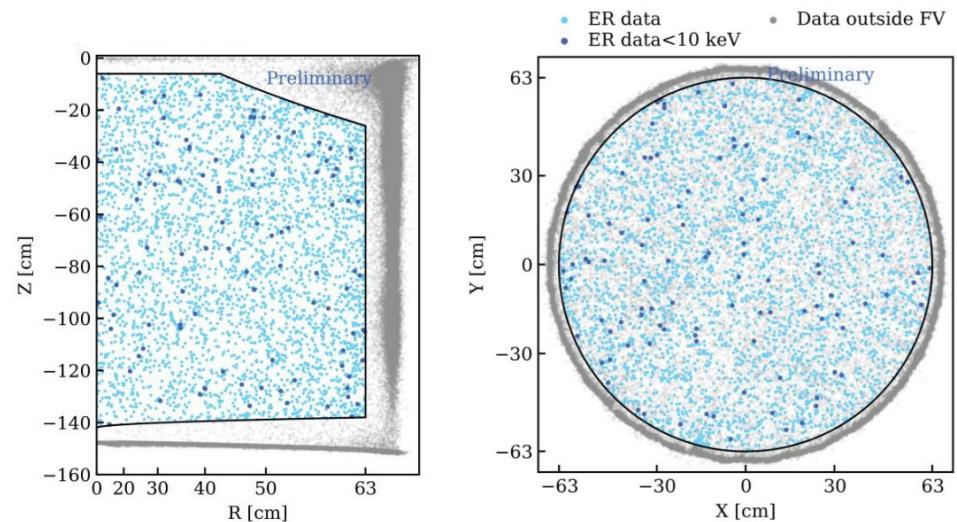
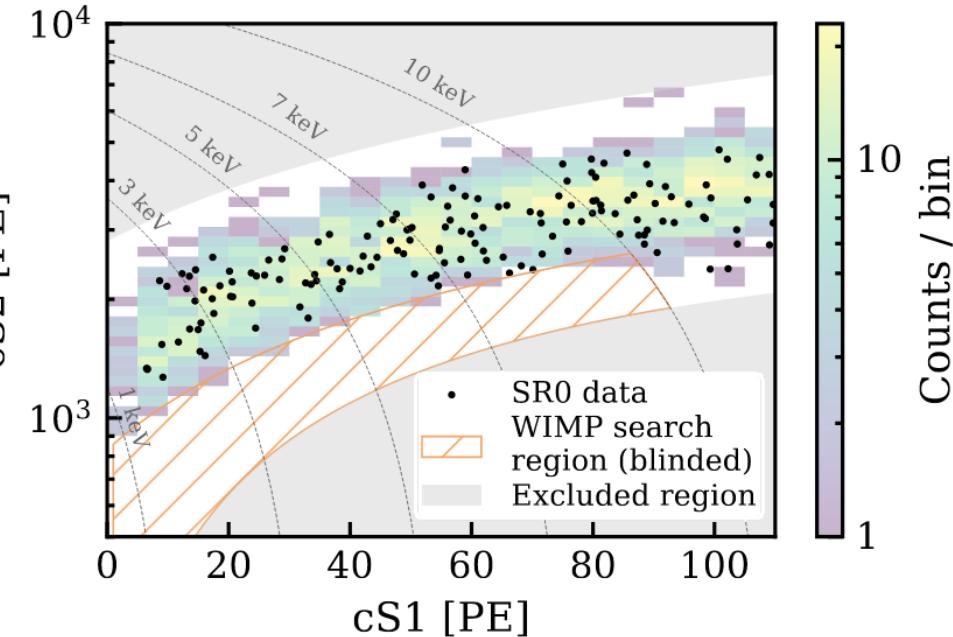
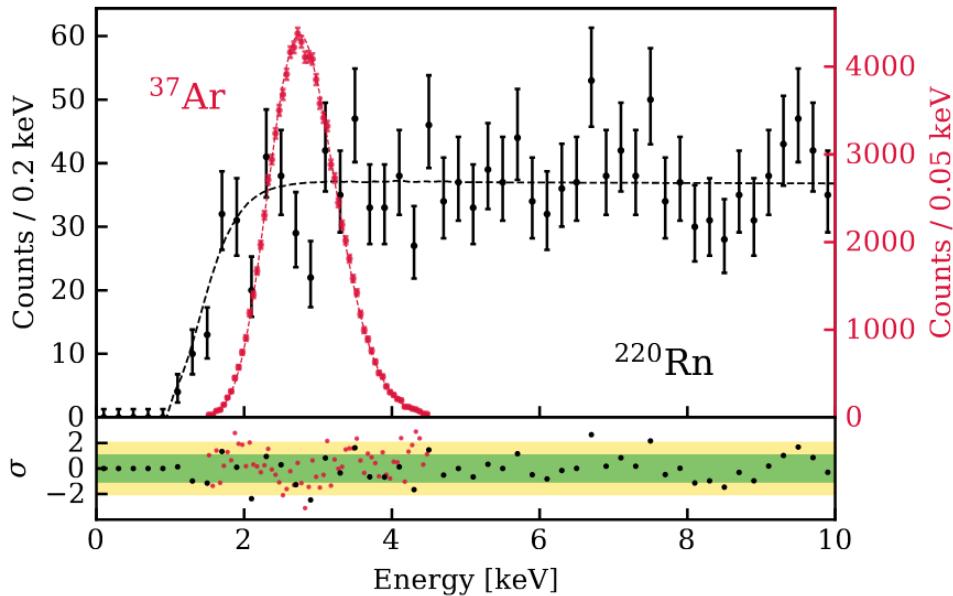
PRL 129, 161805 (2022)



Focus on  
ERs <10 keV  
to investigate  
low-E excess from  
XENON1T

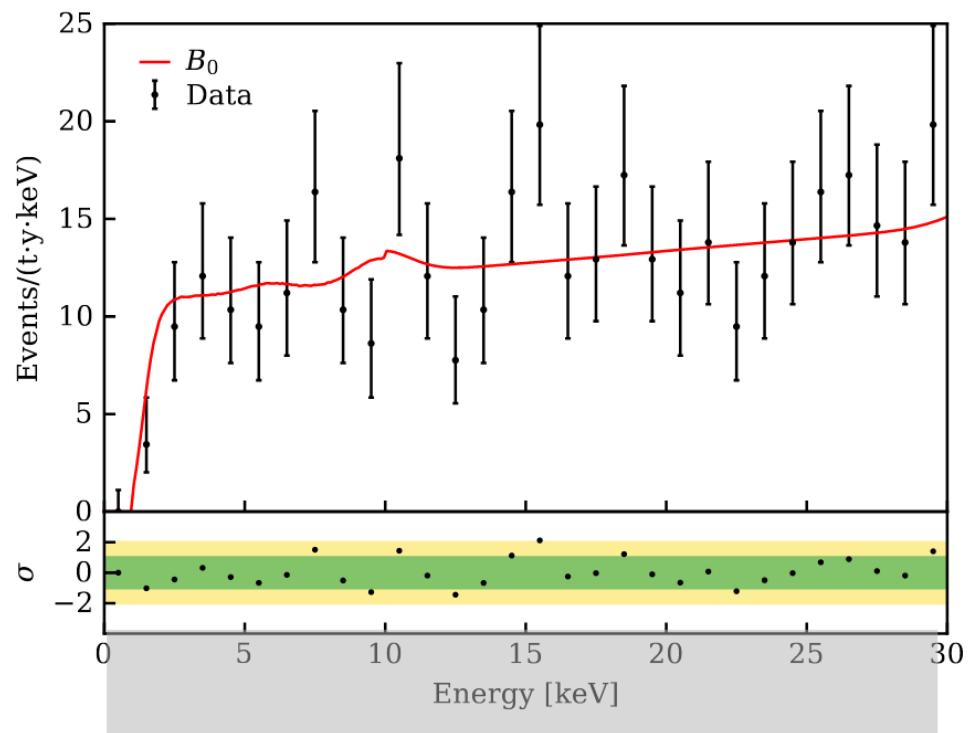
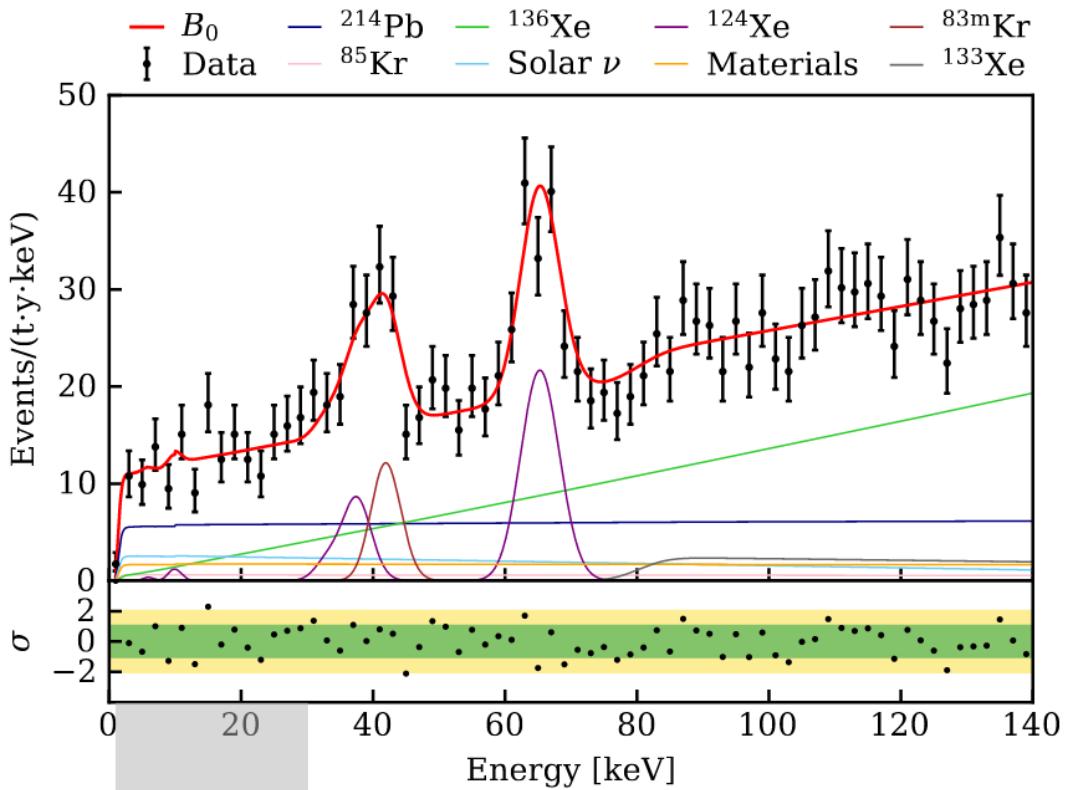
**Blind analysis!**

XENONnT Calibration data



# Low-E Electronic Recoils

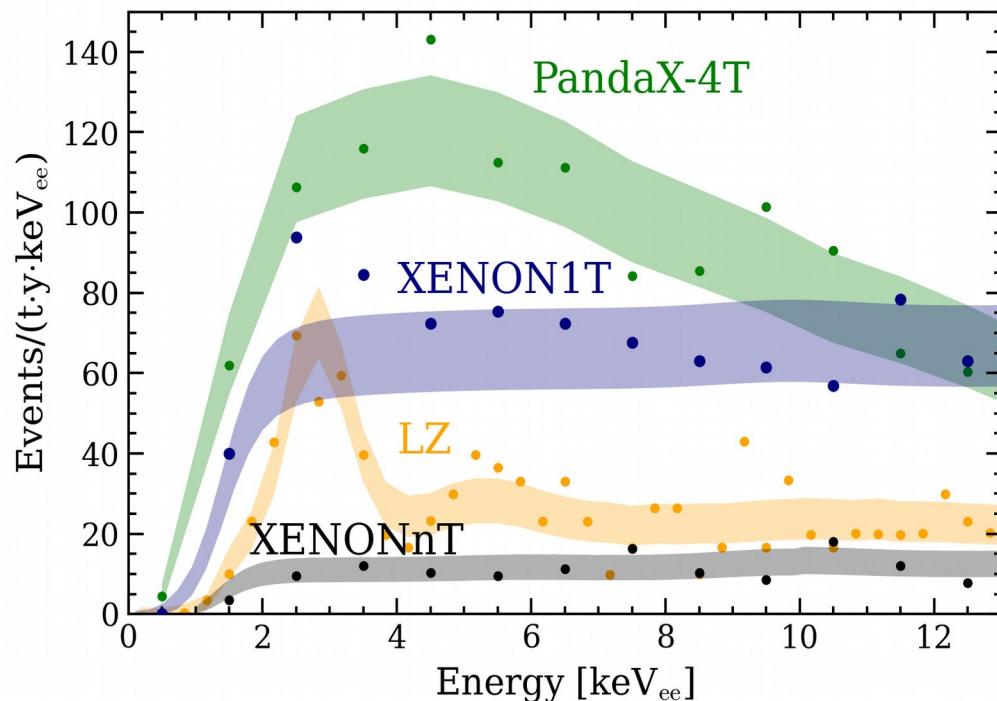
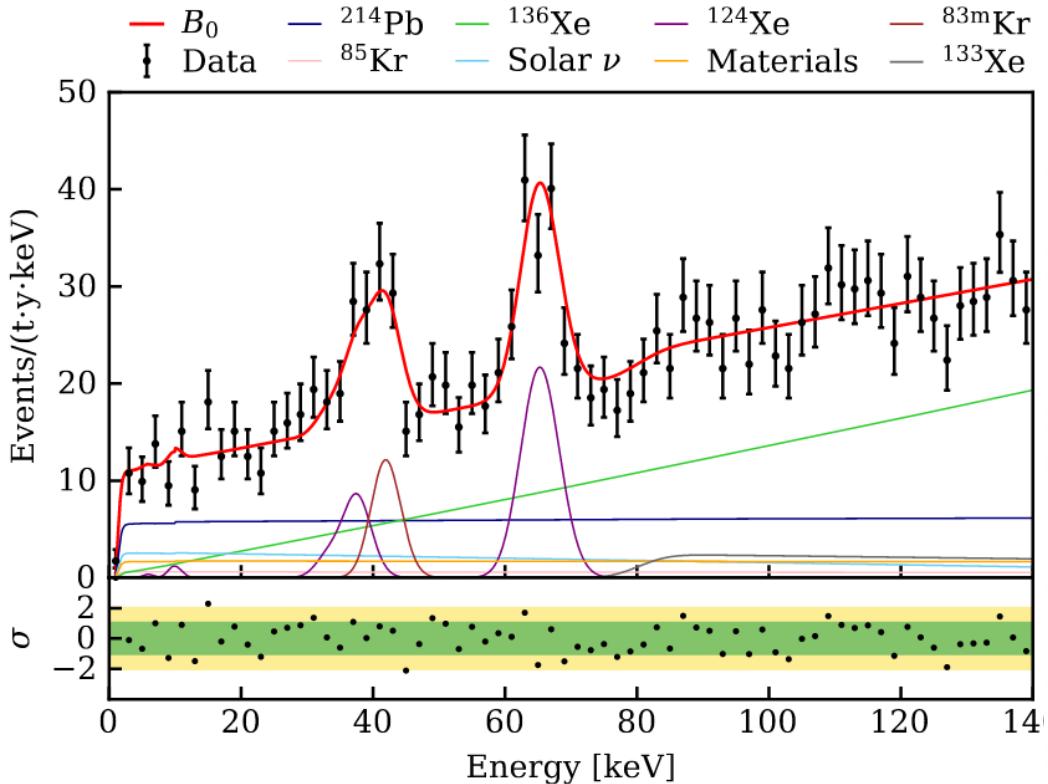
PRL 129, 161805 (2022)



- No excess above background observed  
→ XENON1T excess not from new physics
- For the first time, shape of low-E background spectrum dominated by **second order weak decays** ( $0\nu\beta\beta$  of  $^{136}\text{Xe}$ ,  $2\nu\text{ECEC}$  of  $^{124}\text{Xe}$ )

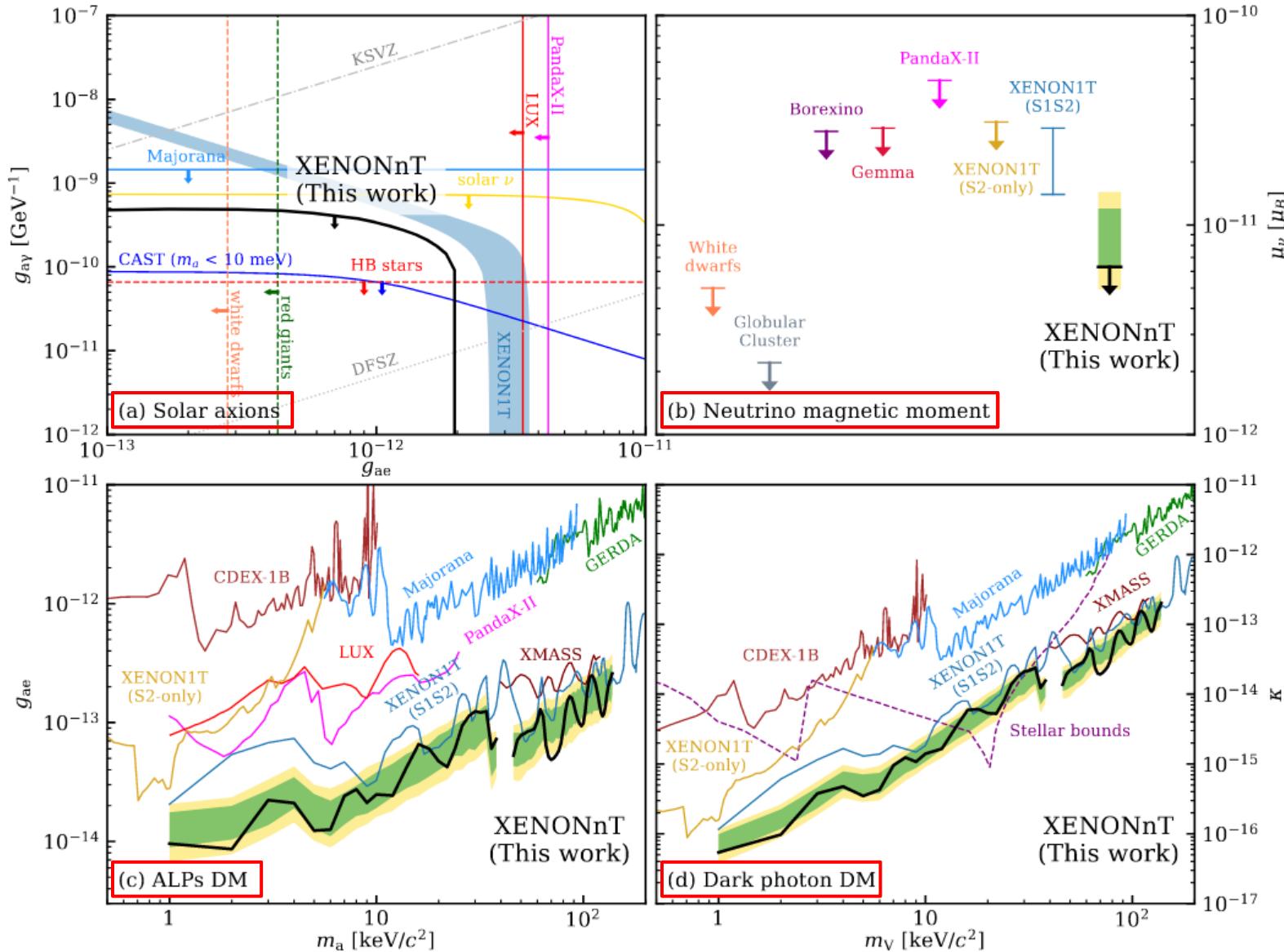
# Low-E Electronic Recoils

PRL 129, 161805 (2022)



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- world-record **low ER background** level:  $(15.8 \pm 1.3) \text{ evts/(txyrxkeV)}$

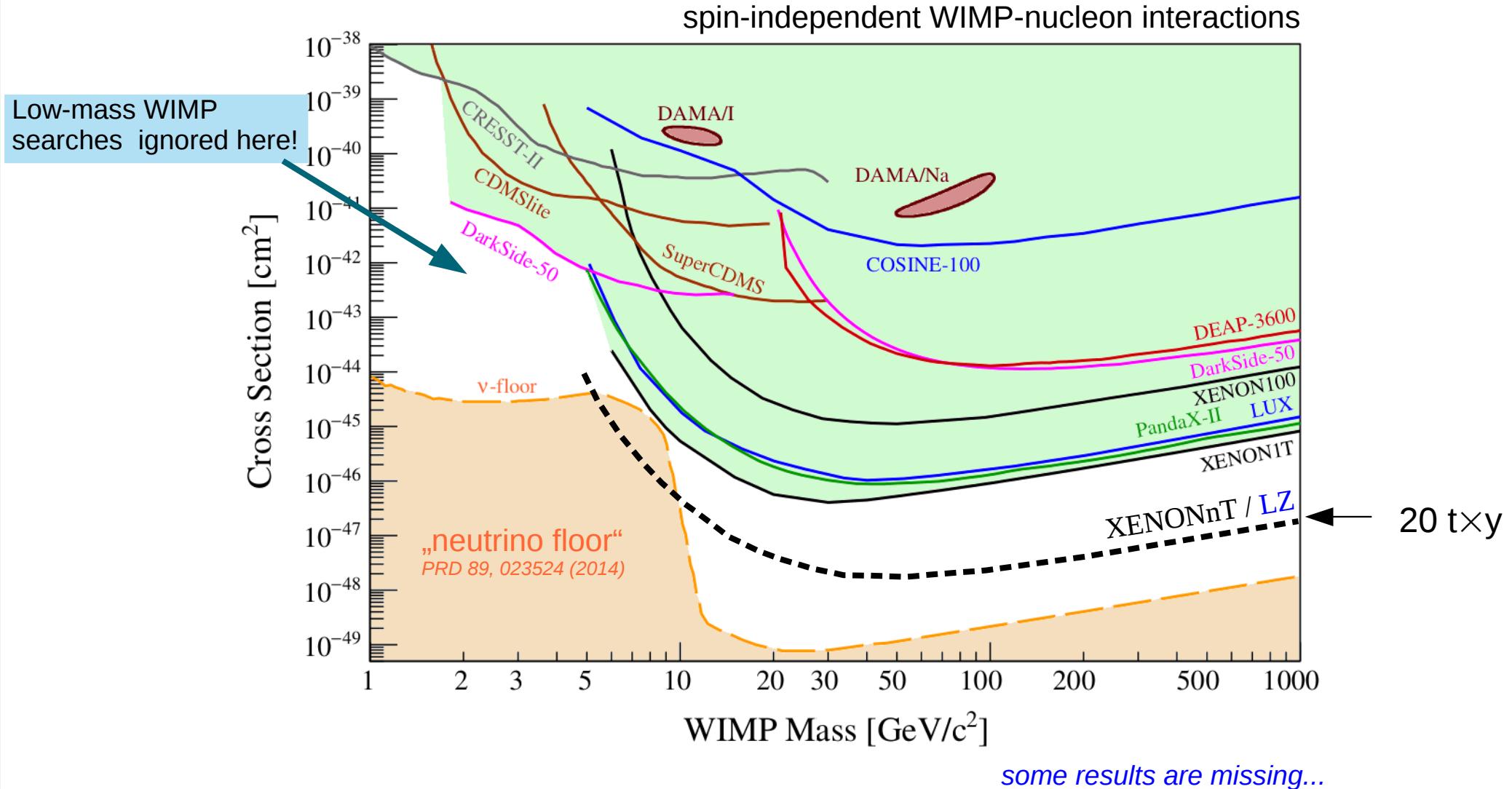
# Limits on New Physics

*PRL 129, 161805 (2022)*


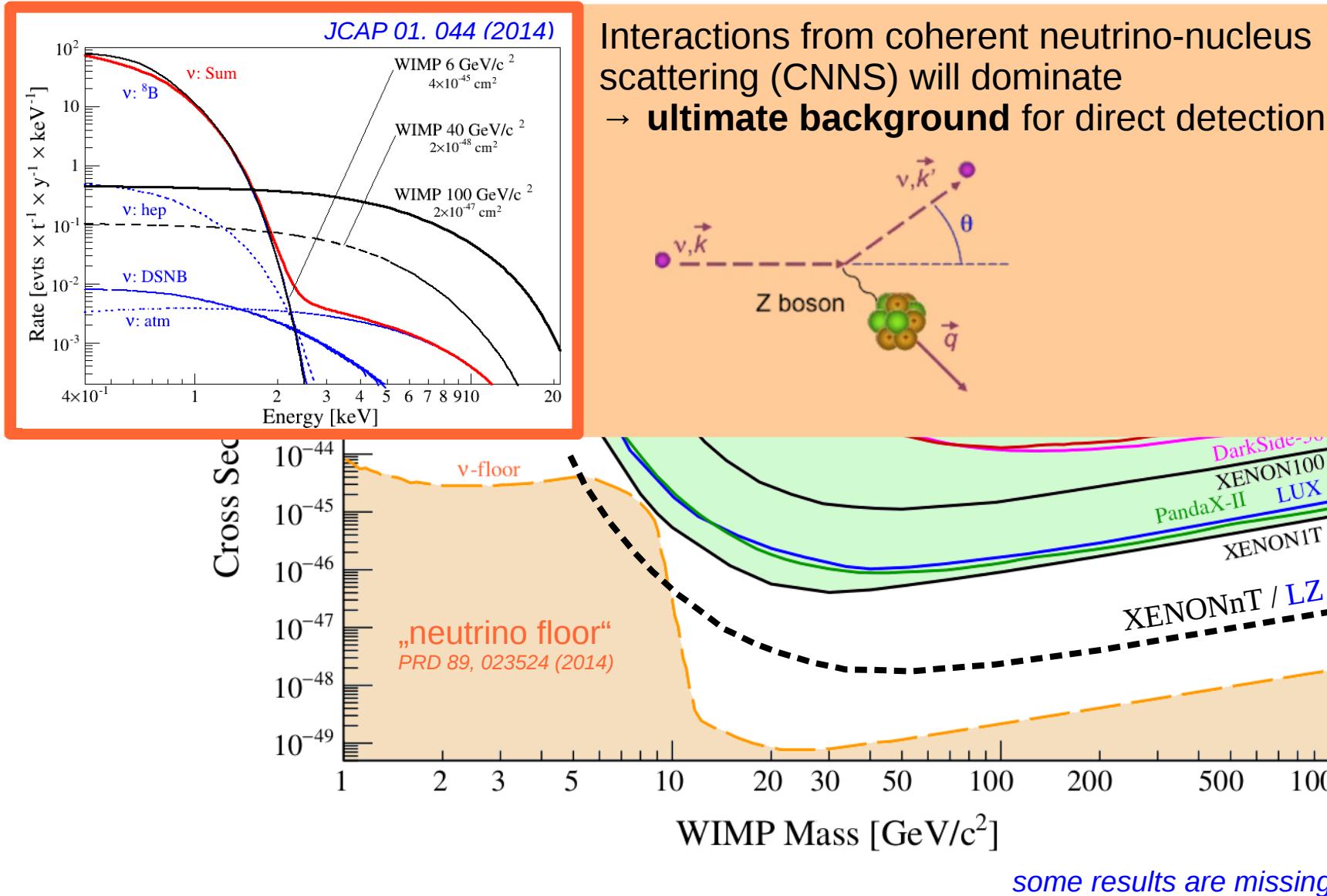
→ new leading results for several new physics channels

# XENONnT WIMP Sensitivity

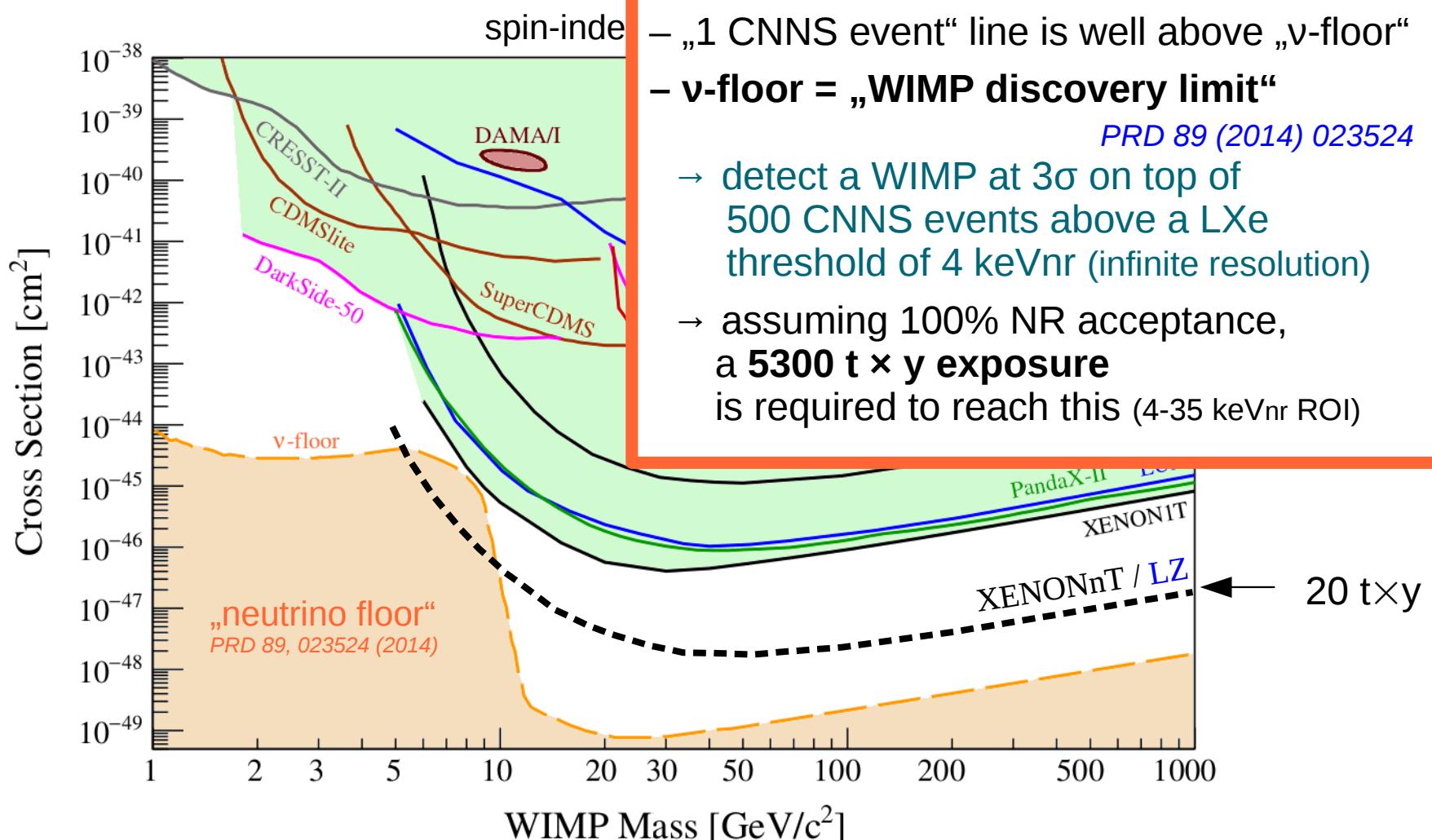
JCAP 11, 031 (2020)



# The ultimate Limit



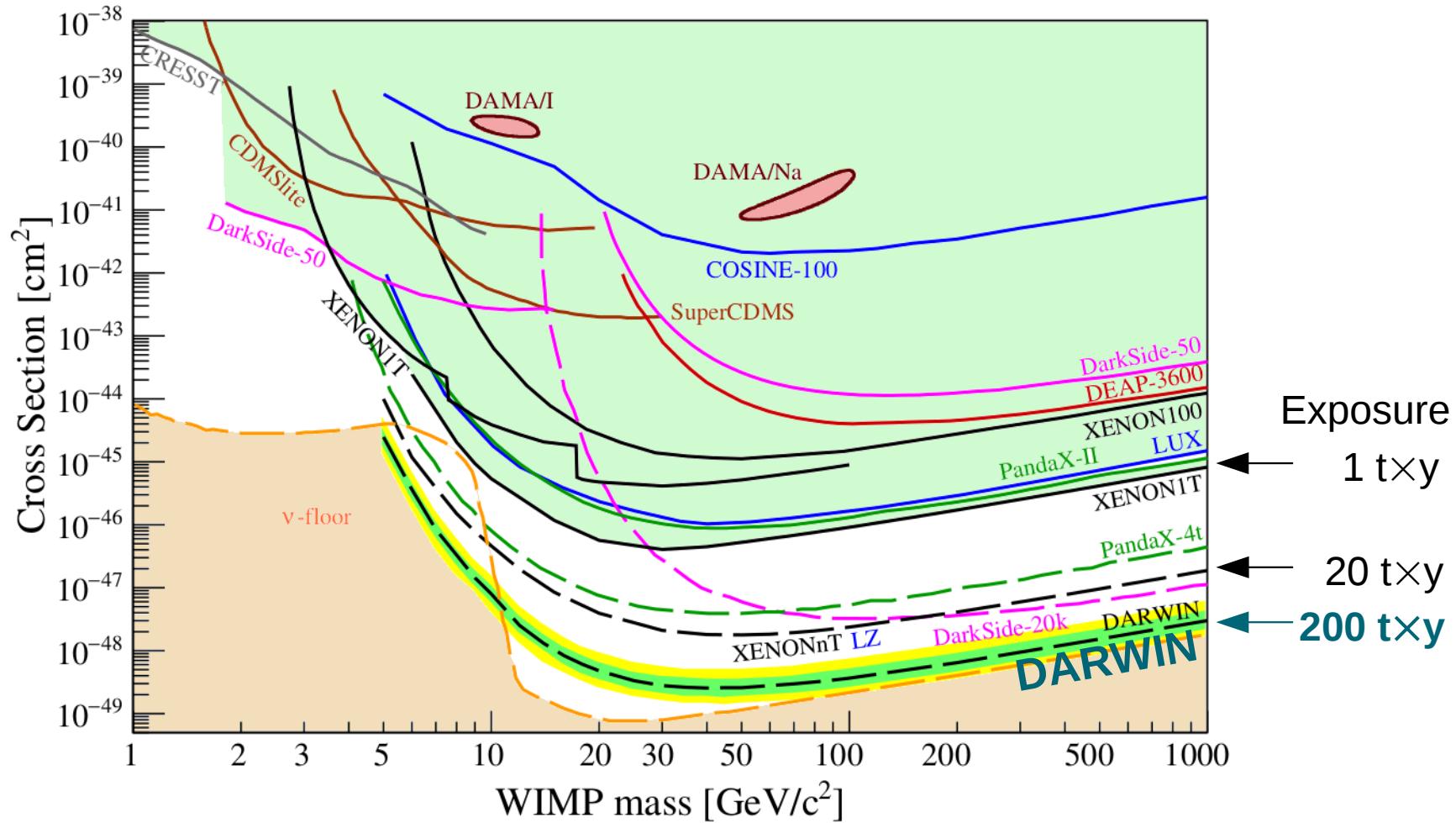
# The ultimate Limit



# DARWIN: The ultimate LXe WIMP Detector

DARWIN

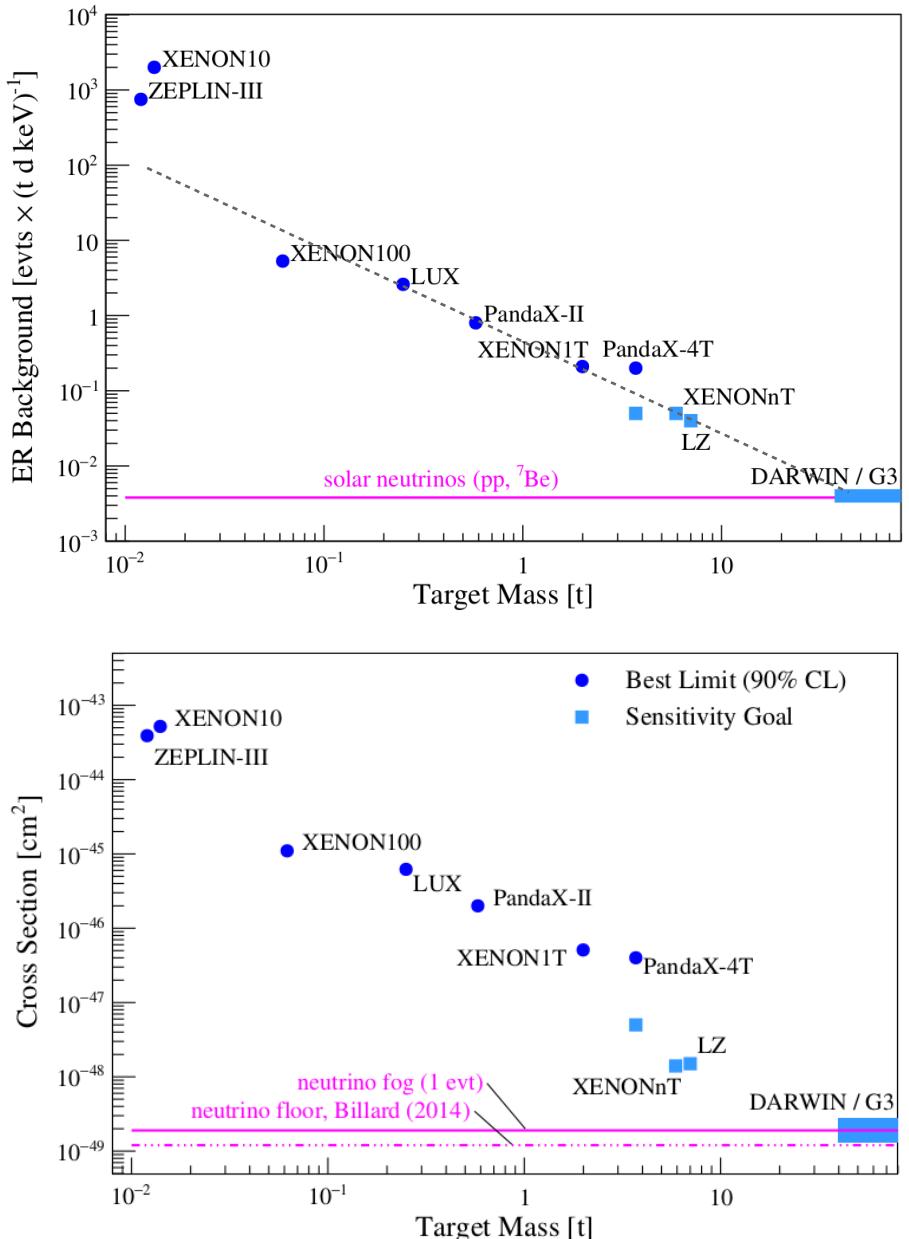
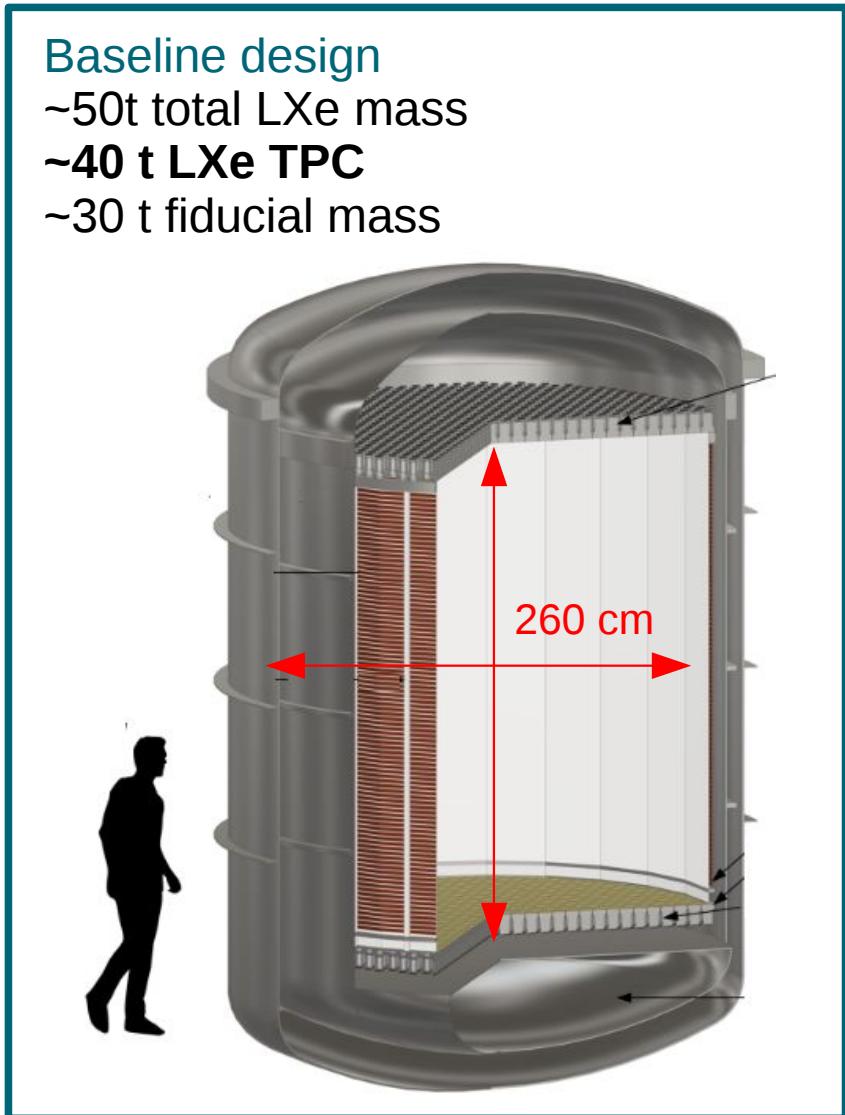
[darwin-observatory.org](http://darwin-observatory.org)  
 JCAP 11, 017 (2016)



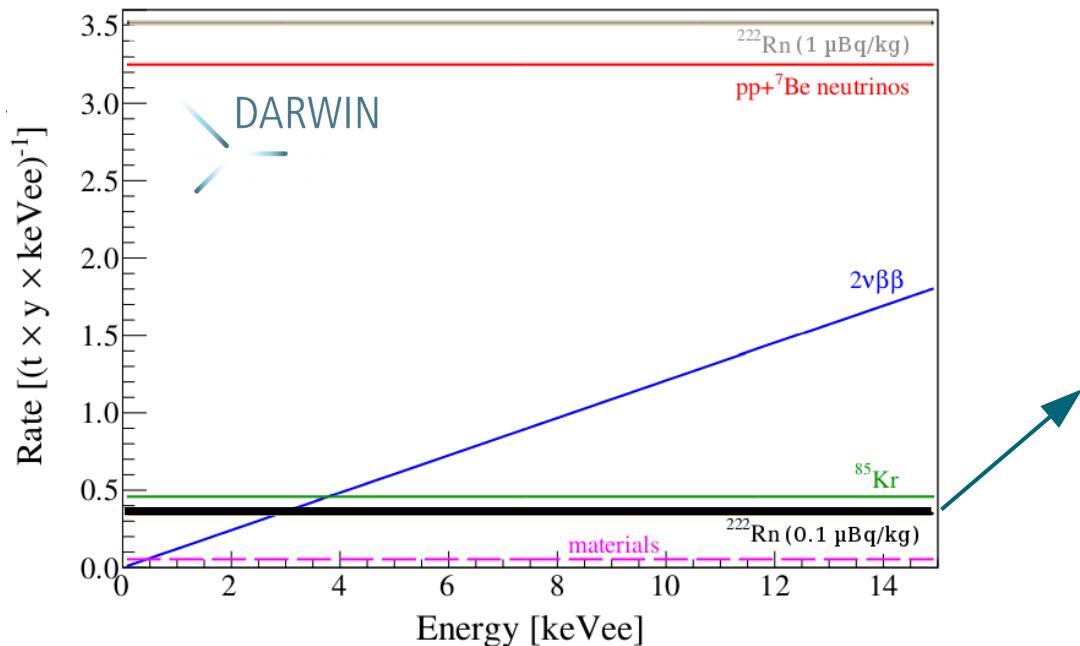
# DARWIN: The ultimate LXe WIMP Detector

[darwin-observatory.org](http://darwin-observatory.org) JCAP 11, 017 (2016)

Background dominated by irreducible neutrinos



# DARWIN: Radon Background



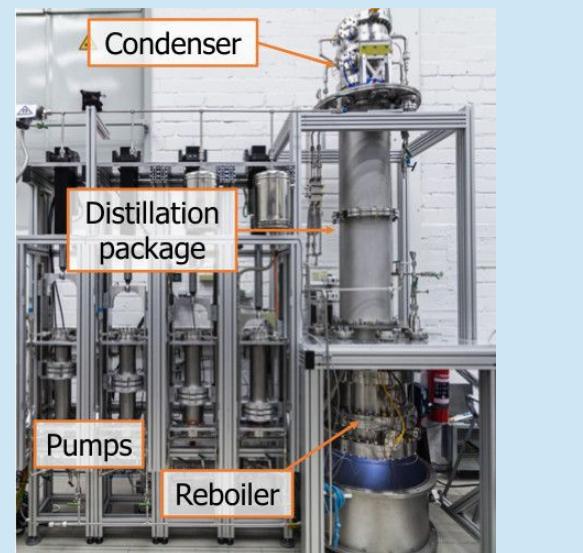
DARWIN goal:  
ER background dominated  
by solar neutrinos

**$^{222}\text{Rn}$  emanated from all  
detector surfaces.**  
Need concentration  
factor  $\sim 50$  below XENON1T  
factor  $\sim 10$  below XENONnT

→ **main background challenge**

## Strategy DARWIN

- active Rn removal via cryogenic distillation
  - column developed for XENONnT is R&D for DARWIN
- avoid Rn emanation by
  - optimal material production
  - material selection
  - surface treatment
  - optimized detector design



# Size challenge: PANCAKE Detector Platform



DARWIN LXe test platform 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



# Size challenge: PANCAKE Detector Platform



DARWIN LXe test platform in Freiburg:

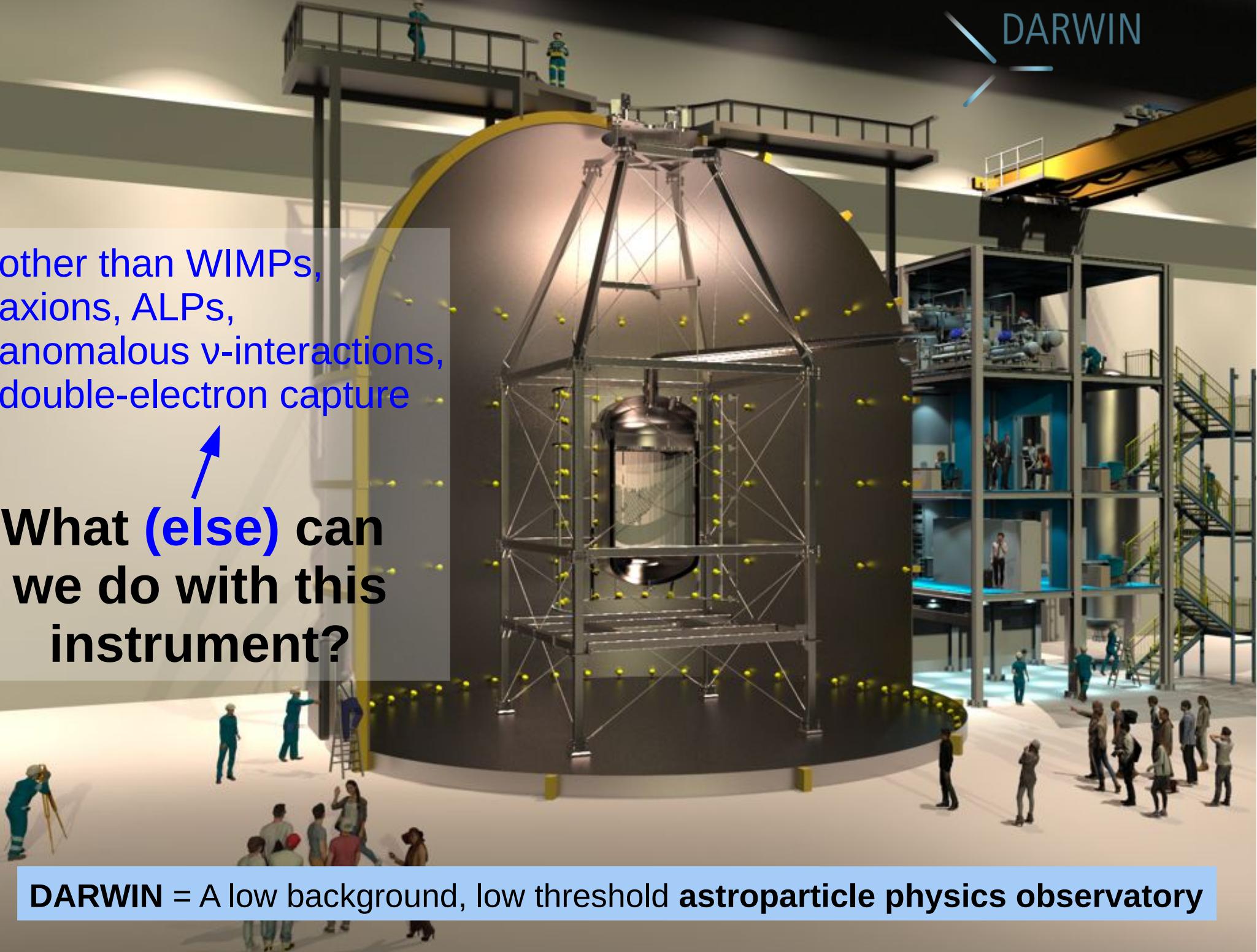
- 2.7 m inner diameter
- up to ~15 cm height (~5 cm LXe)
- ~400 kg Xe gas
- test horizontal components, real-scale electrodes etc.



DARWIN

other than WIMPs,  
axions, ALPs,  
anomalous  $\nu$ -interactions,  
double-electron capture

What (else) can  
we do with this  
instrument?



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

# LXe Whitepaper

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## A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

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~600 authors  
from DARWIN,  
XENON, LZ  
+ theory

~100 institutions

The nature of dark matter and properties of neutrinos are most pressing issues in contemporary particle physics. The dual-phase xenon time-projection chamber is the leading technology to cover the available parameter space for Weakly Interacting Massive Particles (WIMPs) while featuring extensive sensitivity to many alternative dark matter candidates as well. The same detectors can study neutrinos through a variety of astrophysical sources and through neutrinoless double-beta decay. A next-generation xenon-based detector will therefore be a true multi-purpose machine to significantly advance particle physics, astrophysics, nuclear physics, and cosmology. This review article presents the science cases for such a detector.

Keywords: Dark Matter, Neutrinoless Double-Beta Decay, Neutrinos, Supernova, Direct Detection, Astroparticle Physics, Xenon

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Covers (probably) all science channels you can think of...

# XENON + LZ + DARWIN = XLZD

[www.xlzd.org](http://www.xlzd.org)



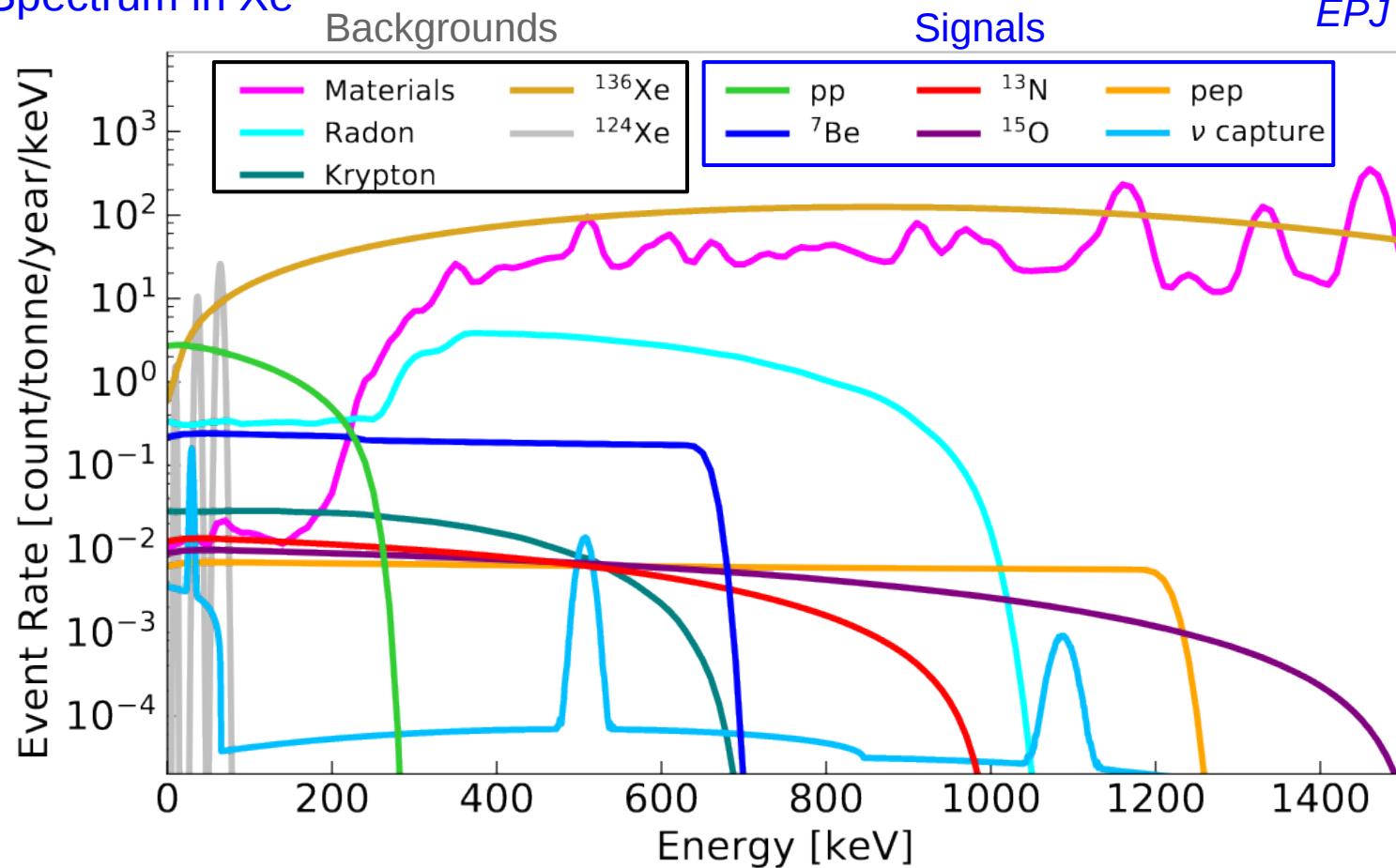
- Future merger of DARWIN / XENON + LZ collaborations to build and operate the next-generation liquid xenon observatory
  - new, stronger collaboration
  - will come once XENONnT and LZ are in routine operation
- Now: paving the way with XLZD Consortium
  - MoU 2021: 104 group leaders from 16 countries
  - joint whitepaper on science published
  - first joint workshops



# Solar Neutrinos

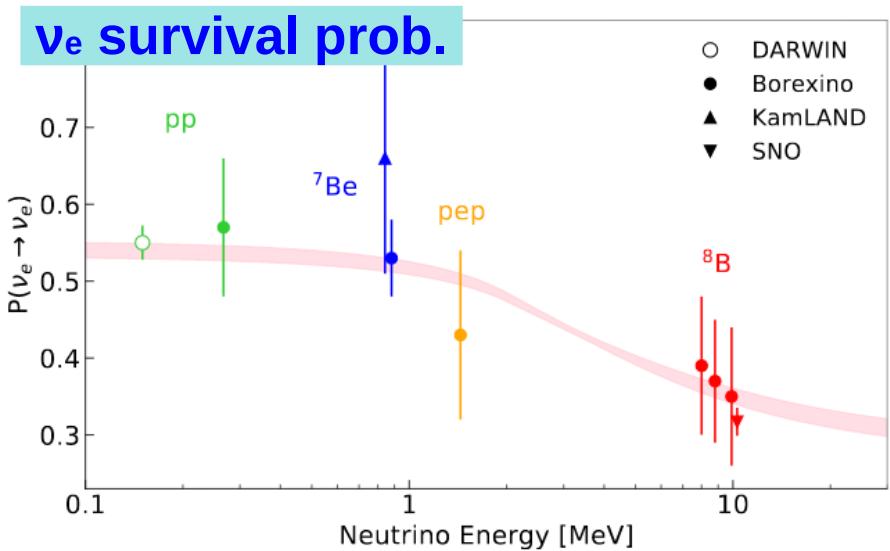
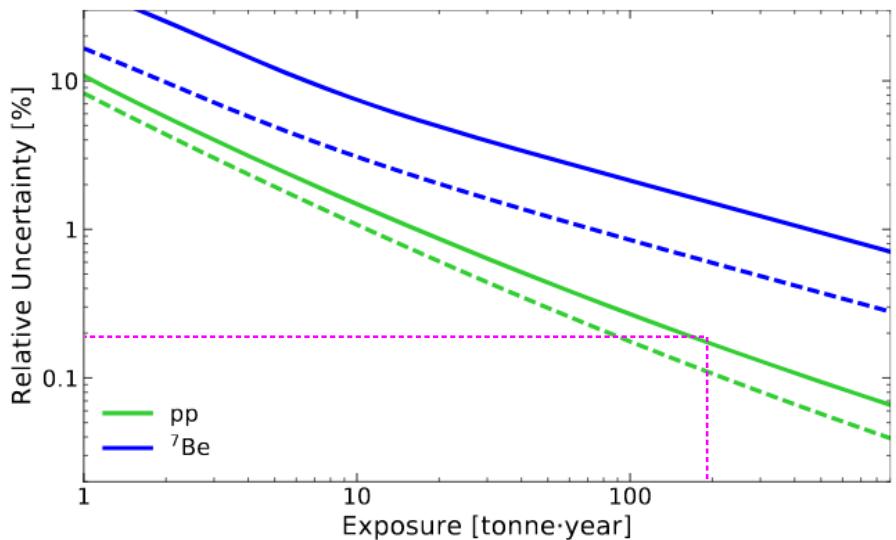
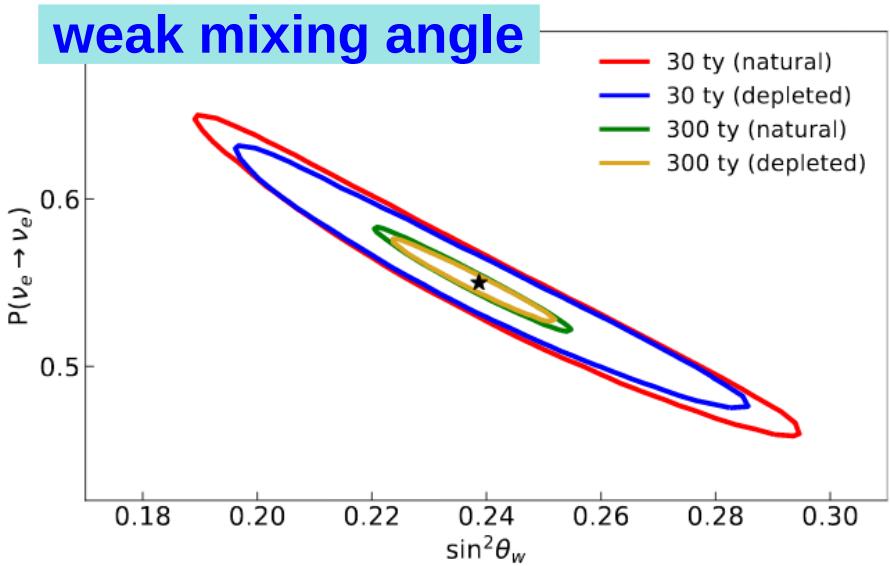
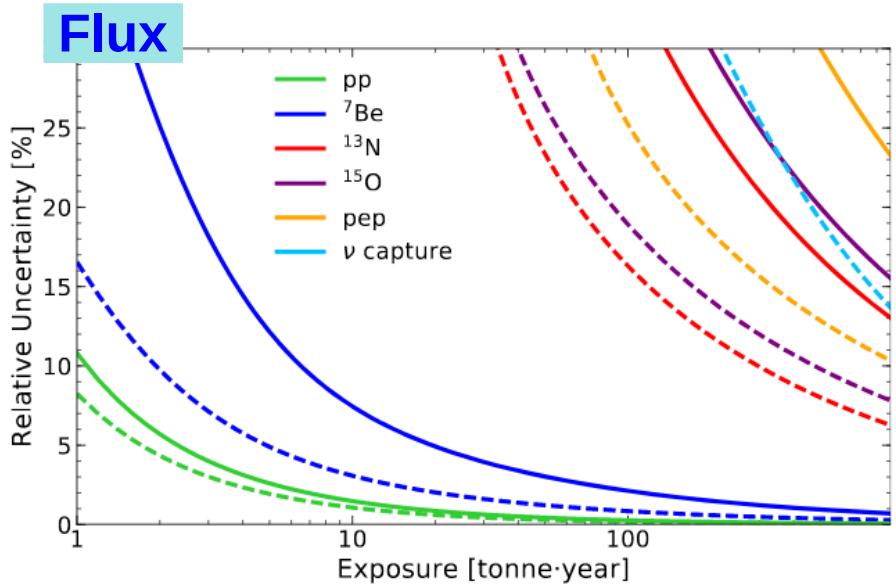
ER Spectrum in Xe

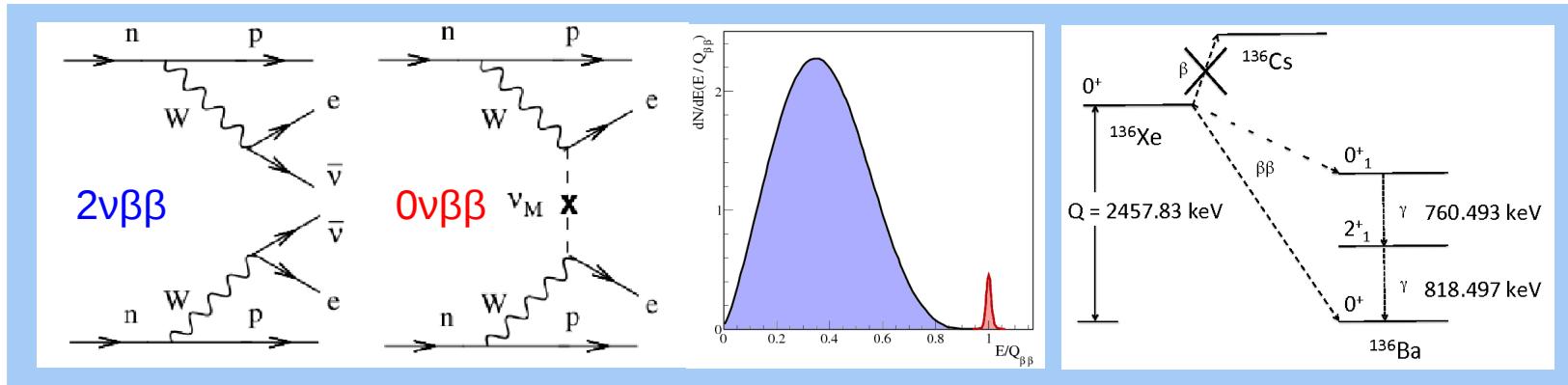
JCAP 01, 044 (2014)  
 EPJ C 80, 1133 (2020)



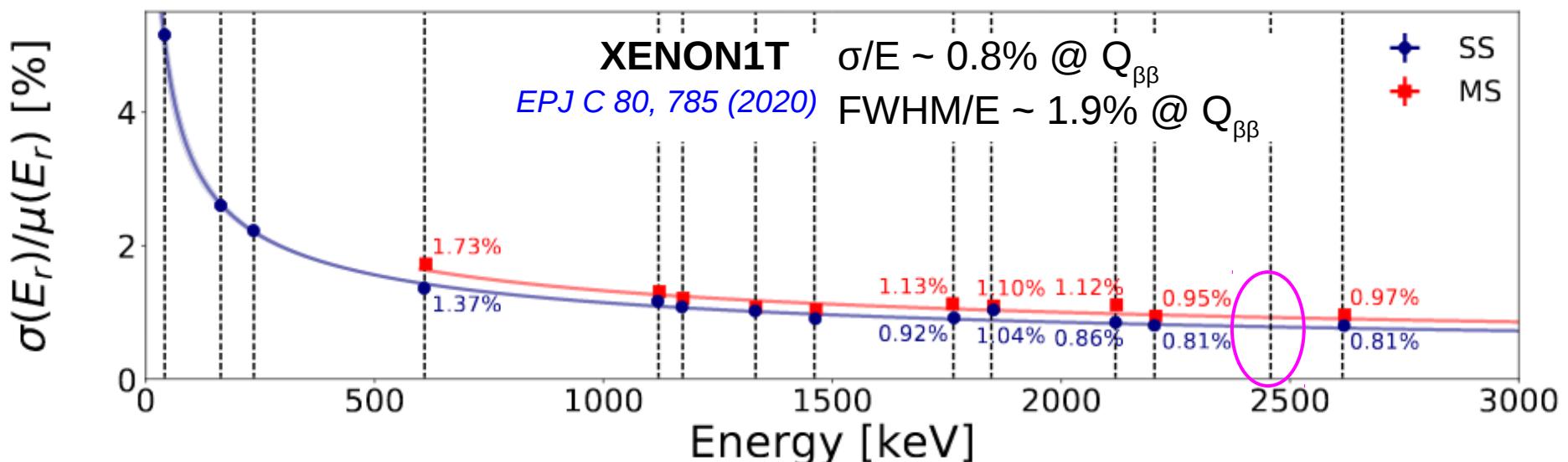
- DARWIN's low-E ER spectrum dominated by pp neutrinos (and  $2\nu\text{ECEC}+2\nu\beta\beta$ )
- distinct features in  $\nu$  spectra allow extracting neutrino fluxes  
 → full spectral fit of all components up to 3 MeV  
 (possibility to enhance sensitivity by more sophisticated analysis)

# pp-Neutrinos in real time

*EPJ C 80, 1133 (2020)*



 $\Delta L \neq 0$ 

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

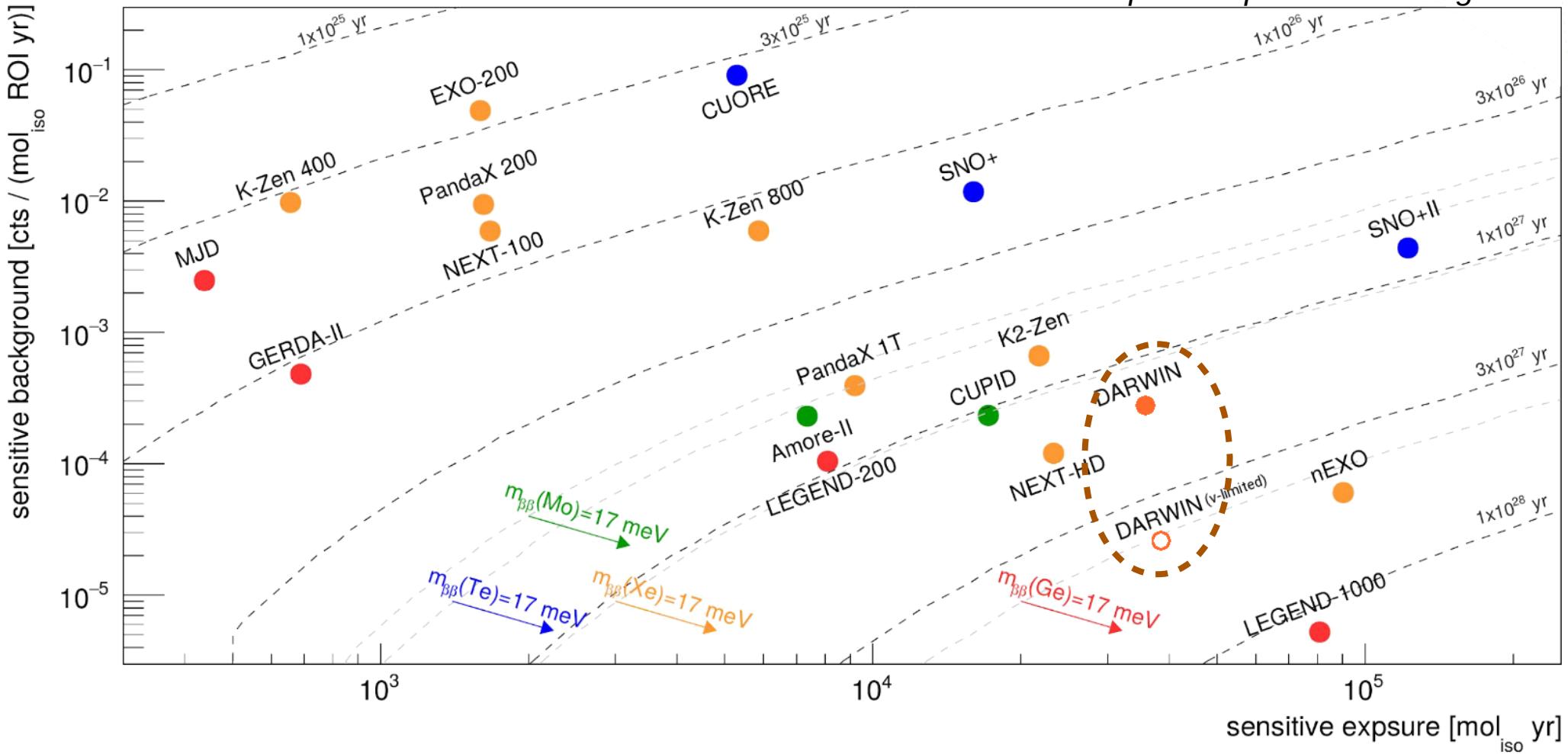


# $^{136}\text{Xe}$ : 0 $\nu$ double-beta Decay

EPJ C 80, 808 (2020)



plot adapted from M. Agostini



half-life sensitivity:  $2.4 \times 10^{27}$  y

# Exciting times ahead of us



DARWIN

a low-background  
low-threshold observatory  
for astroparticle physics

