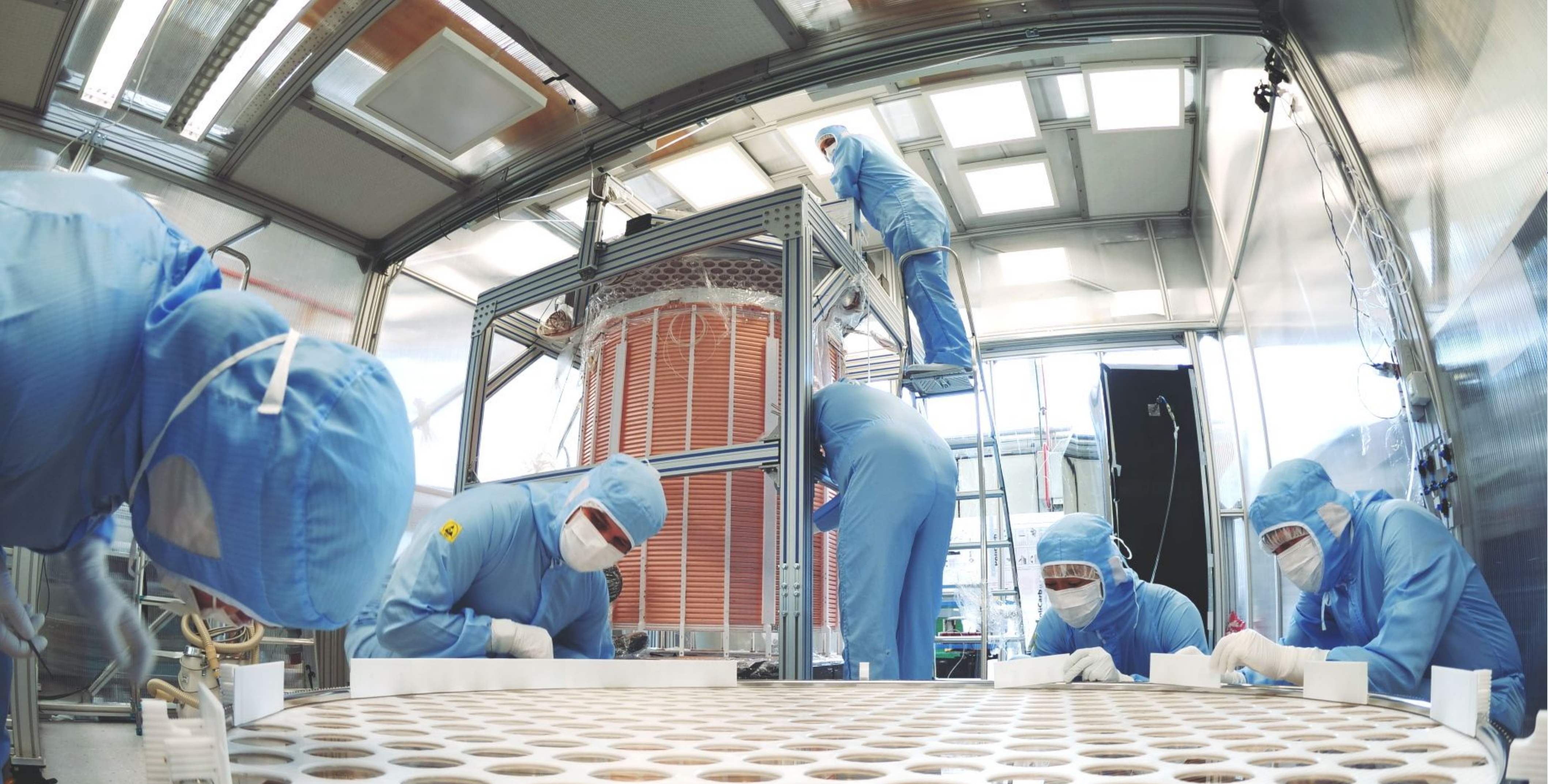


Dark Matter (and more) with DARWIN / XLZD

Marc Schumann University of Freiburg

Helmholtz MU Days, KIT 15.09.2023

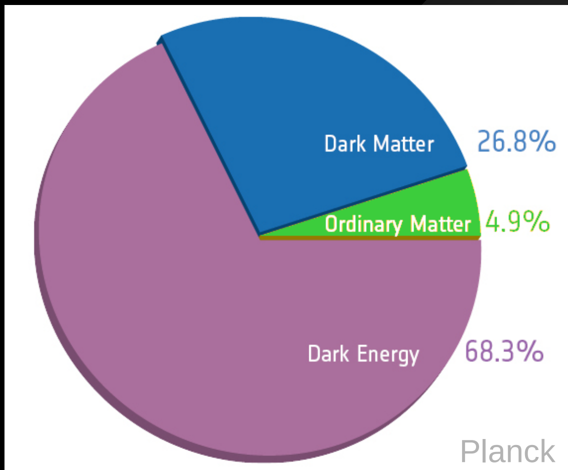
www.app.uni-freiburg.de

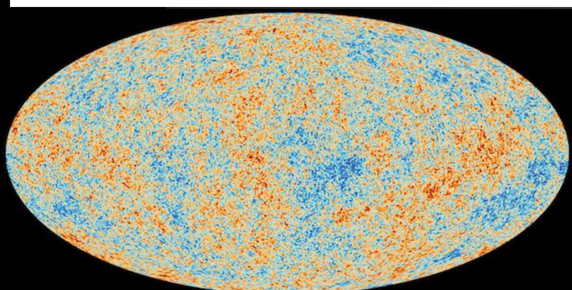
Bundesministerium für Bildung und Forschung

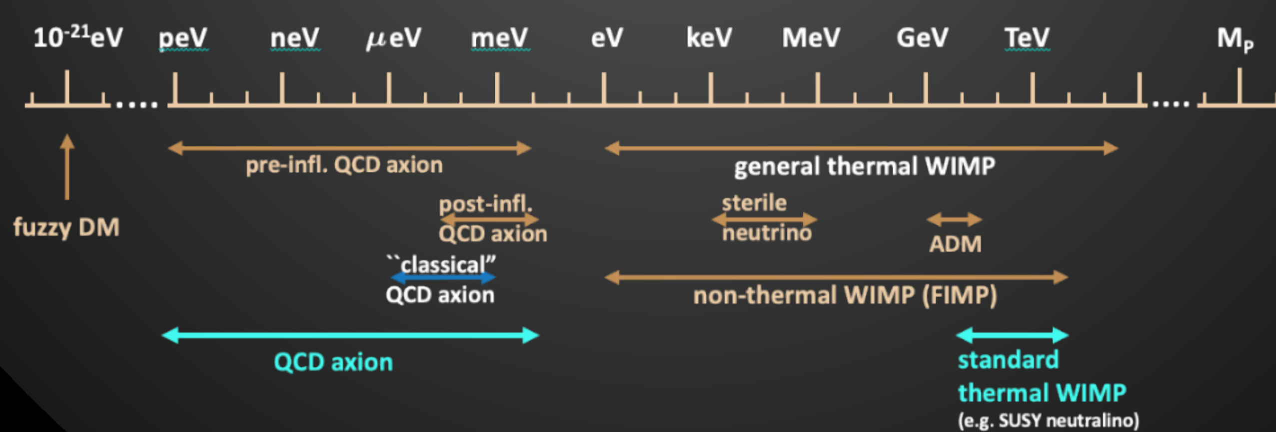
erc

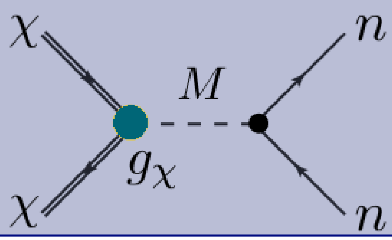
universität freiburg

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



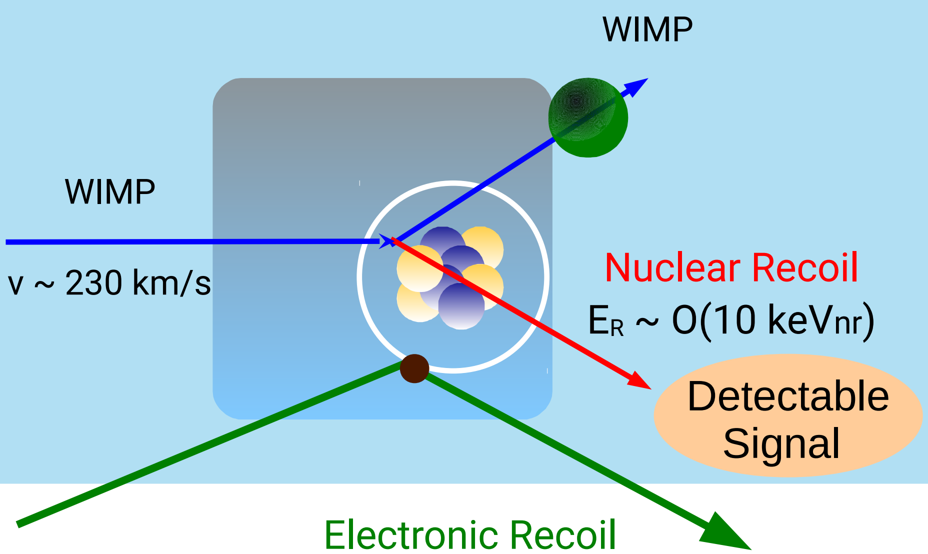




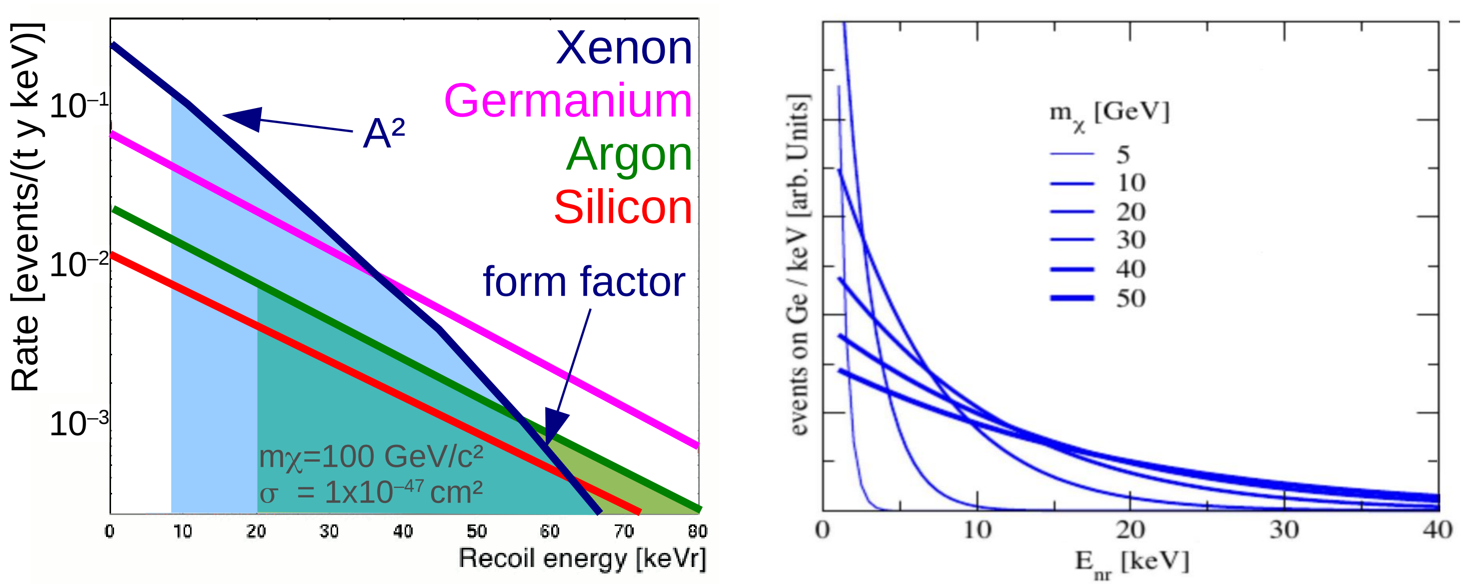


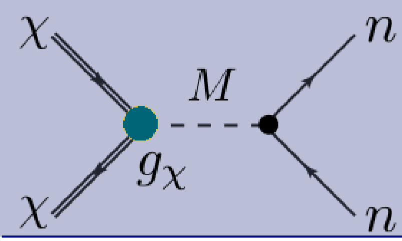
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



Recoil Spectra:





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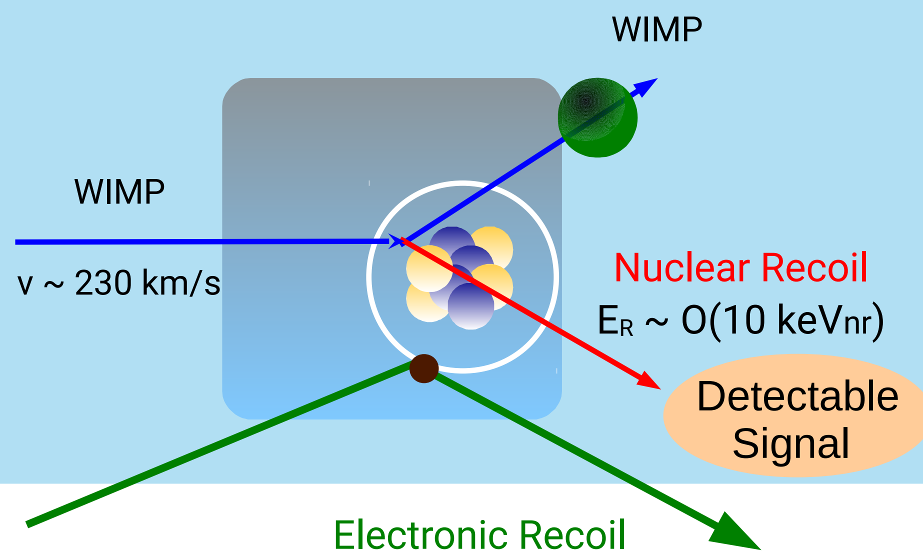
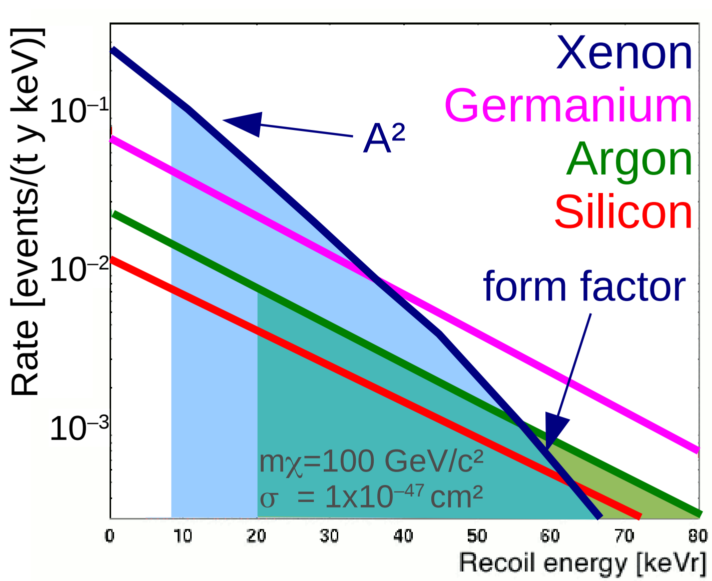
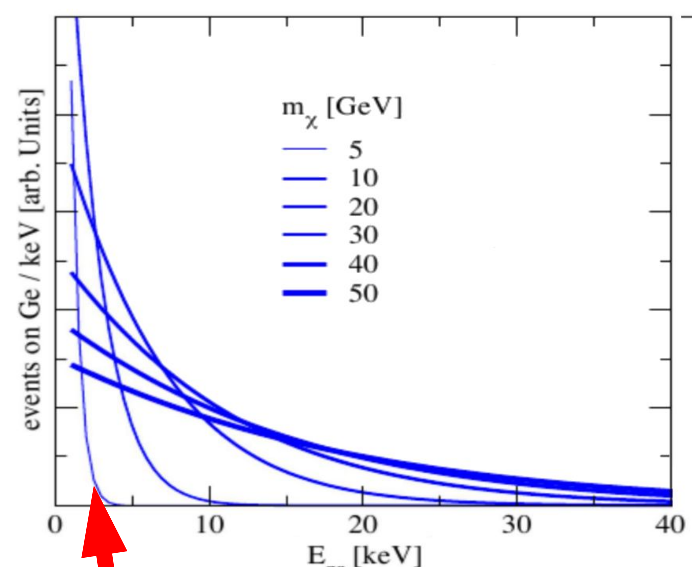


Recoil Spectra:

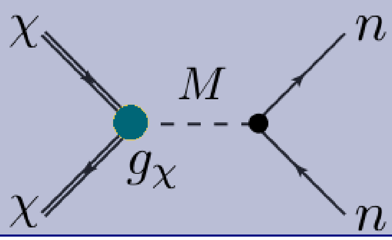


tiny!

tiny!



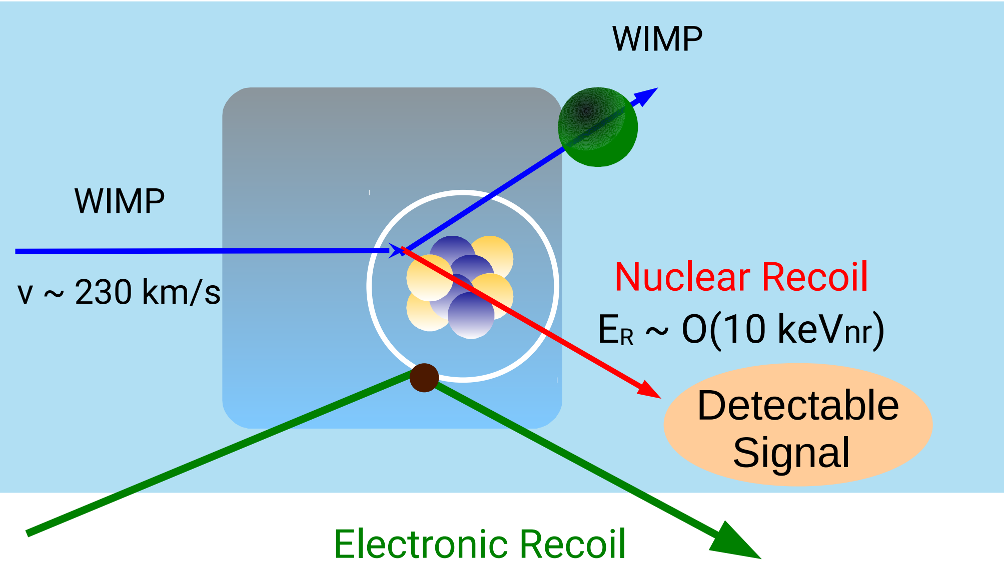
low mass → low threshold



Direct WIMP Search

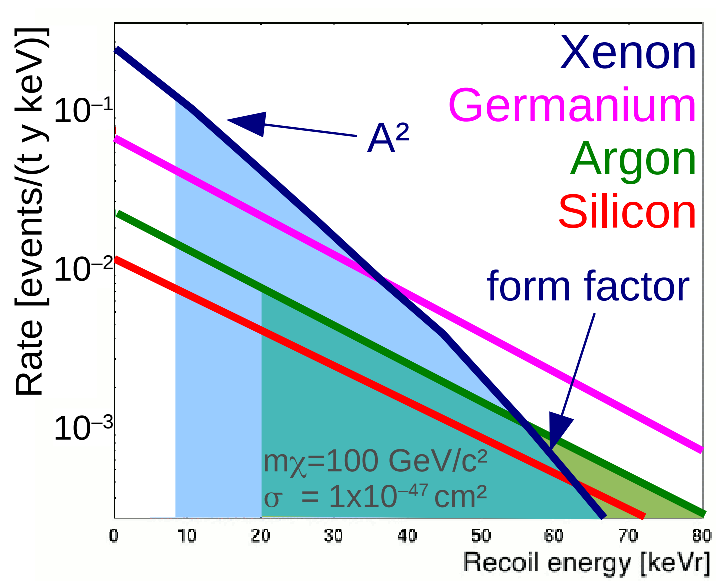
How to build a WIMP detector?

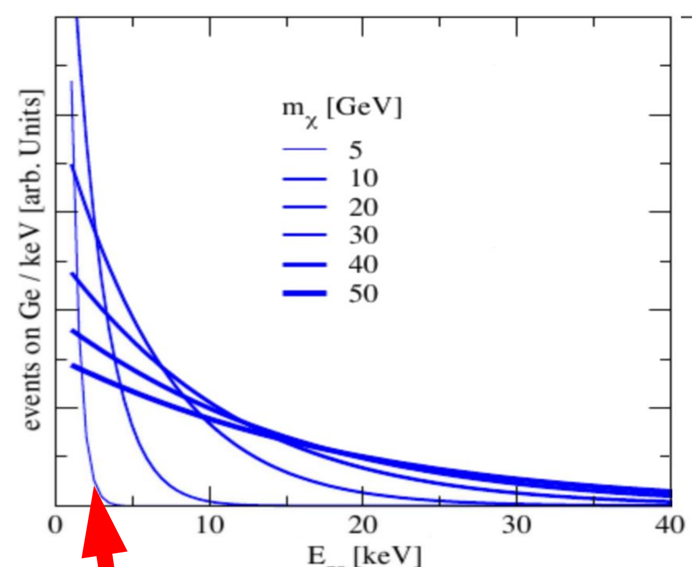
- large total mass, high *A*
- low energy threshold
- ultra low background
- good signal / background discrimination



Recoil Spectra:

tiny!

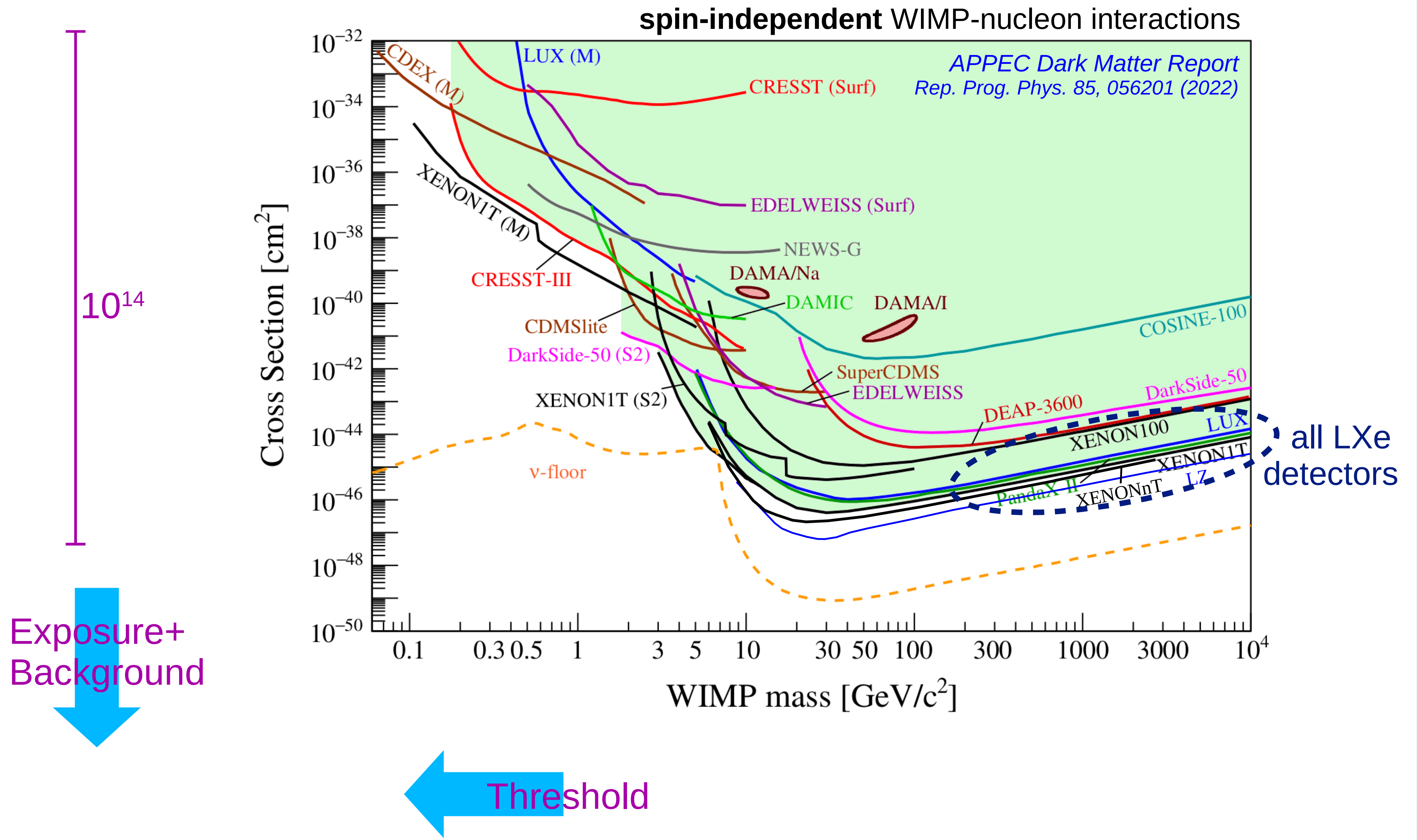




tiny!

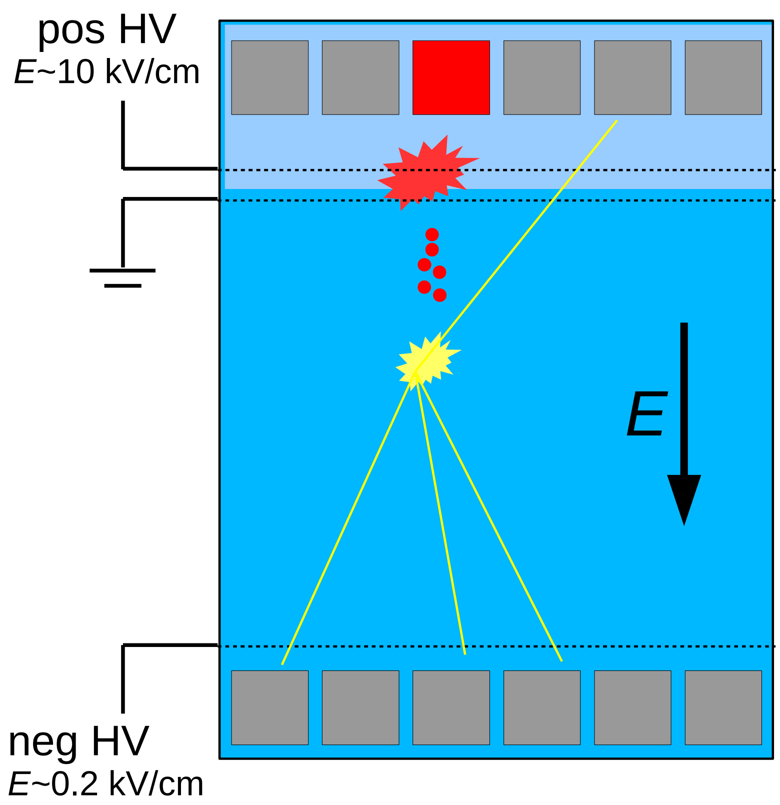
low mass → low threshold

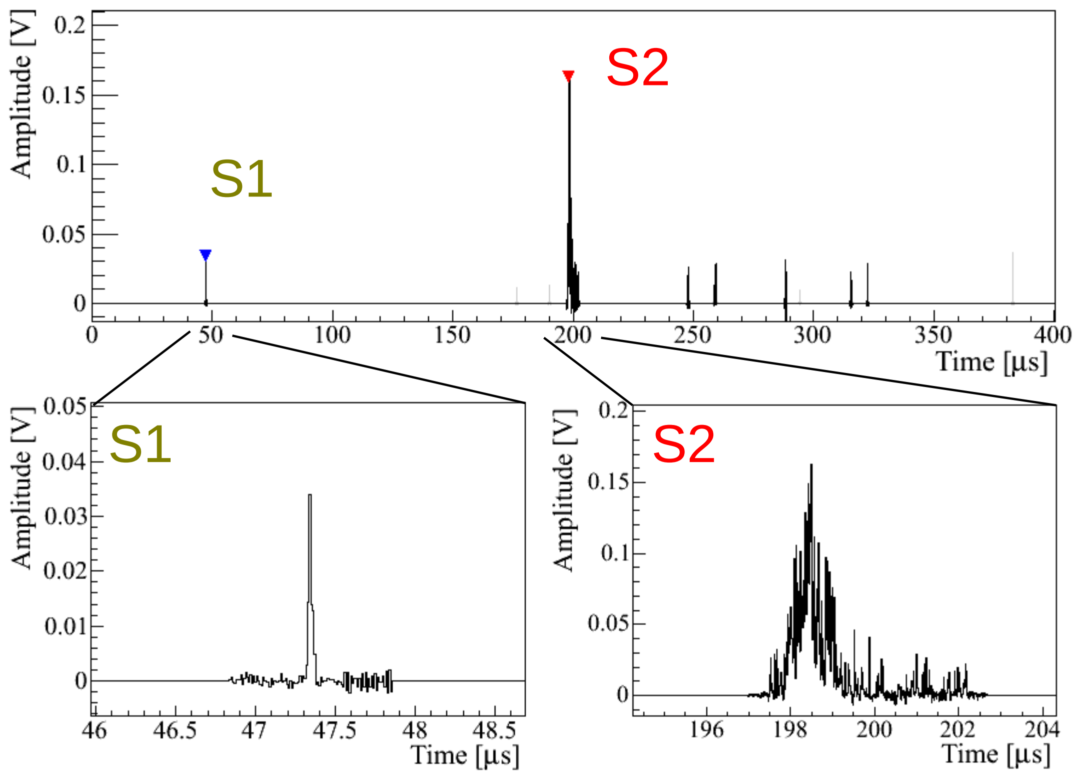
Current Status: WIMPs



Dual Phase TPC

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



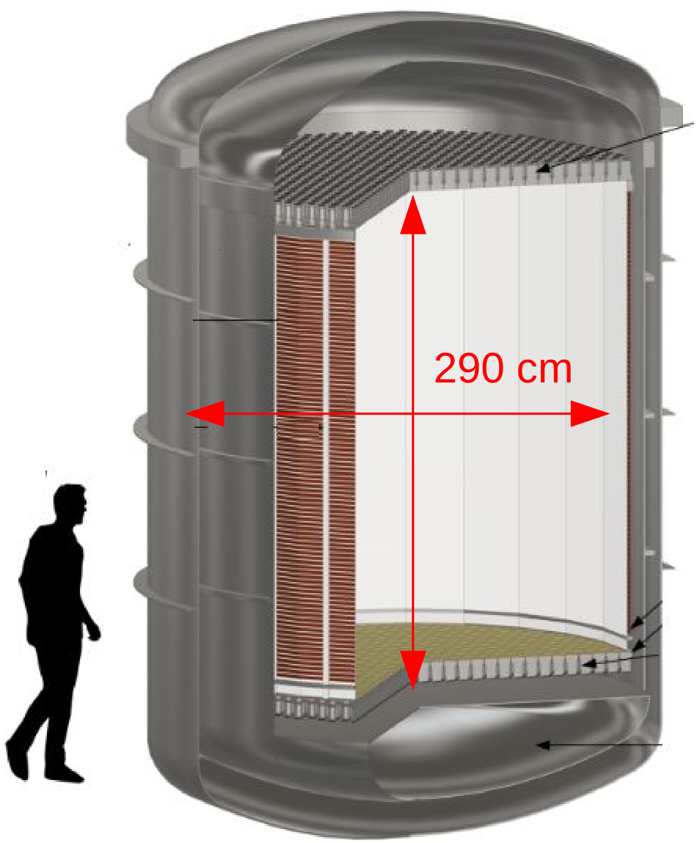


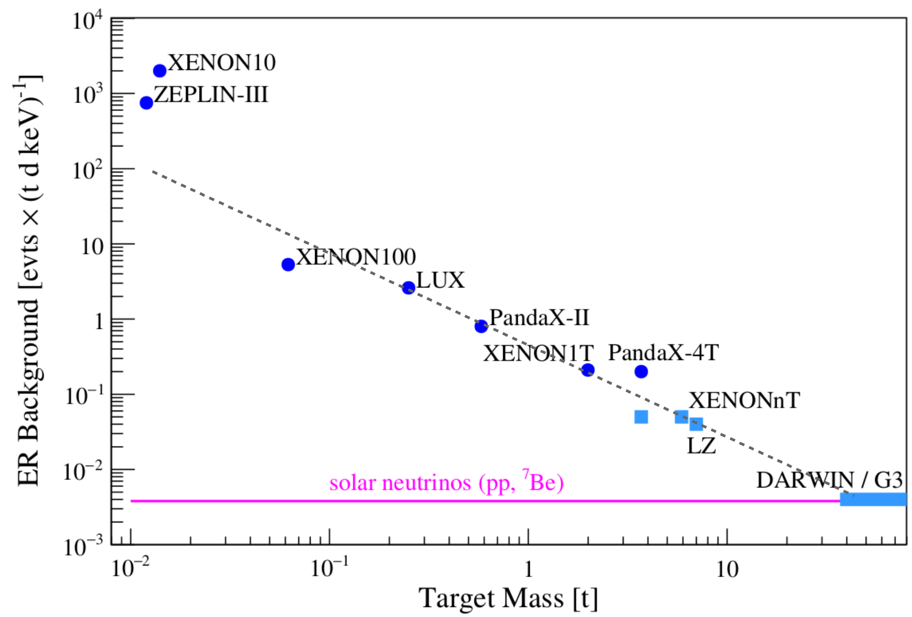
The ultimate LXe WIMP Detector

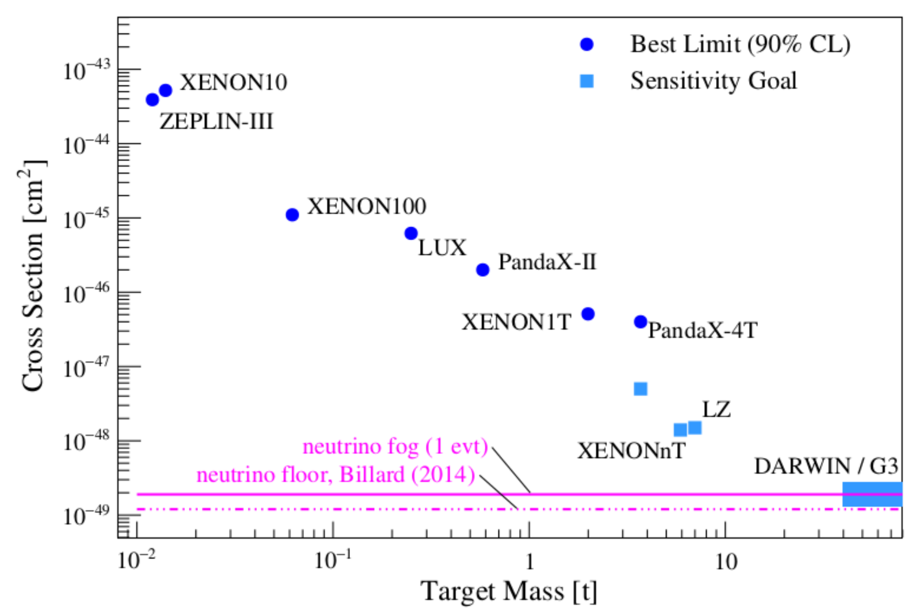
→ Background dominated by **irreducible neutrinos**

Baseline design
~73t total LXe mass
~60 t LXe TPC
~54 t fiducial mass

PRELIMINARY







XENON + LZ + DARWIN =

www.xlzd.org

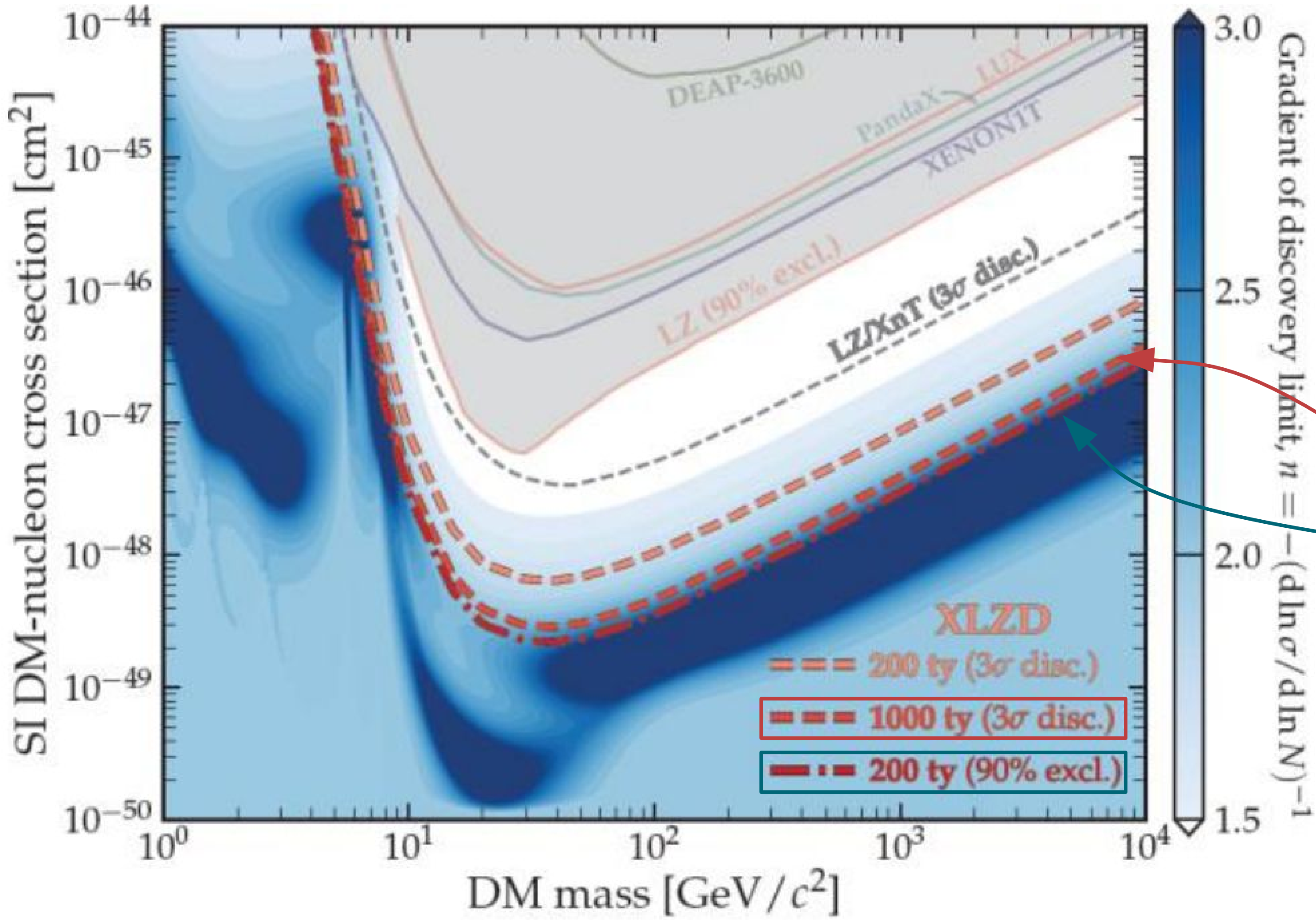
- Future merger of DARWIN / XENON + LZ collaborations to build and operate the next-generation LXe observatory
  → new, stronger collaboration
  → depends on P5 recommendations (US)

- Now: paving the way with XLZD Consortium
  → MoU 2021: 104 group leaders from 16 countries
  → joint whitepaper on science published
  → joint workshops (2022 KIT, 2023 UCLA)
  → common WGs, regular SteCo meetings
  → preparing documents (detector, siting, etc)

DARWIN

XENON

DARWIN ↔ XLZD: Science Reach



200 t×y: probe entire mass range ≥10 GeV at 90% CL — DARWIN (40t)

1000 t×y: probe entire mass range ≥10 GeV at 3σ evidence — XLZD (60t+)
+lower bg for 0νββ

What can we do with such an amazing Instrument?

nb: I often show results from „smaller“ LXe detectors for illustration. In general, all channels that can be explored with smaller detectors can also be studied with larger instruments.

LXe Whitepaper

J. Phys. G 50, 013001 (2023)

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

D. S. Akerib,[2,3] D. Yu. Akimov,[4] J. Akshat,[1] M. Alfonsi,[5] S. J. Andaloro,[6] E. Angelino,[7] J. Angevaare,[8] H. M. Araújo,[9] S. Baek,[10] D. Bajpai,[11] A. Bandyopadhyay,[12] L. Baudis,[13] A. L. Baxter,[1] N. F. Bell,[14] P. Bhattacharjee,[15] F. Bishara,[16] C. Blanco,[17] C. Boehm,[18] P. D. Bolton,[19] A. I. Bolozdynya,[4] B. Boxer,[20]

...

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[98] *Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA*
[99] *School of Physics, Beihang University, Beijing, 100083, P.R.China*
[100] *Technische Universität Dresden, 01069 Dresden, Germany*

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

[1075] A. Giuliani, J. J. Gomez Cadenas, S. Pascoli, E. Previtali, R. Saakyan, K. Schäffner, and S. Schönert (APPEC Committee) (2019), 1910.04688.
[1076] T. Panesor, *A Review of UK Astroparticle Physics Research* (2015).
[1077] N. Tyurin, *PARTICLE PHYSICS IN RUSSIA* (2012).
[1078] T. Nakada et al., *The European Strategy for Particle Physics Update 2013* (2013).
[1079] C. Bai et al., *Neutrinoless Double Beta Decay: A Study of Strategic Development by Chinese Academy of Sciences, in Chinese* (2020).

~600 authors from DARWIN, XENON, LZ + theory

~100 institutions

>1000 references

LXe Whitepaper

J. Phys. G 50, 013001 (2023)

CONTENTS

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

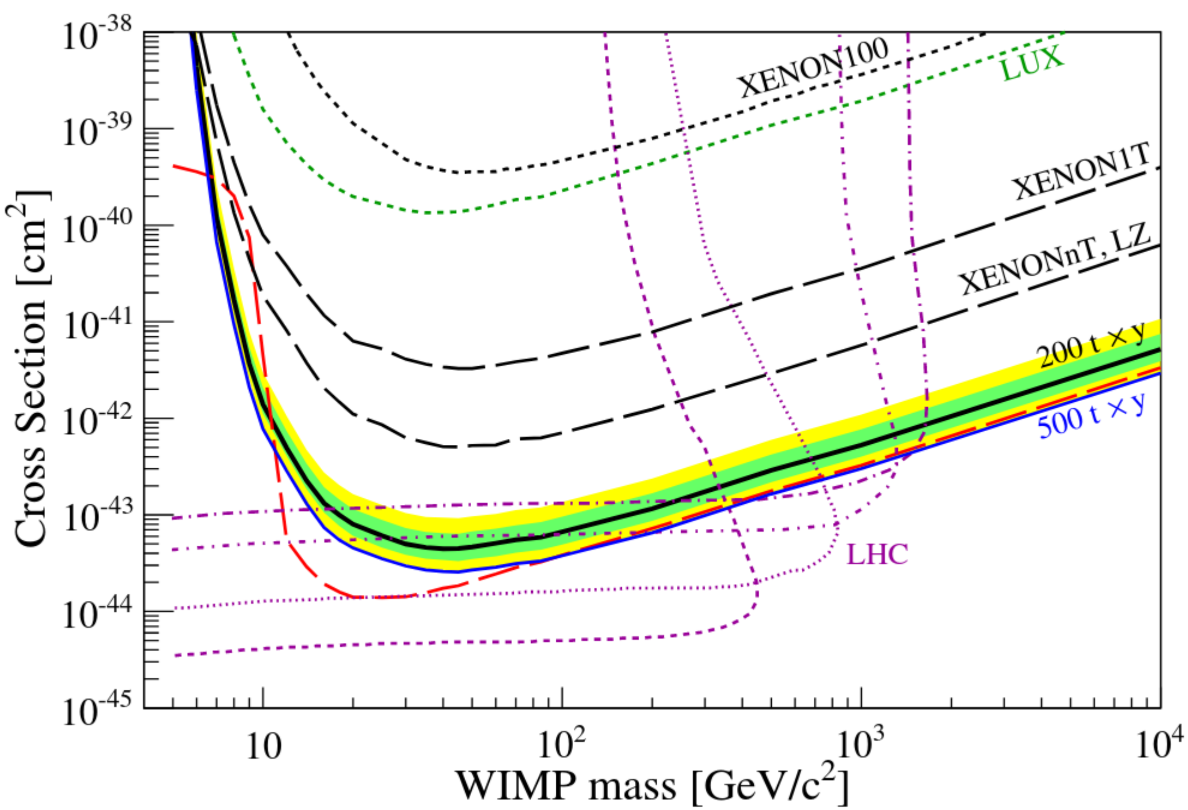
Spin-Dependent WIMP Couplings

JCAP 10, 016 (2015)

- 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

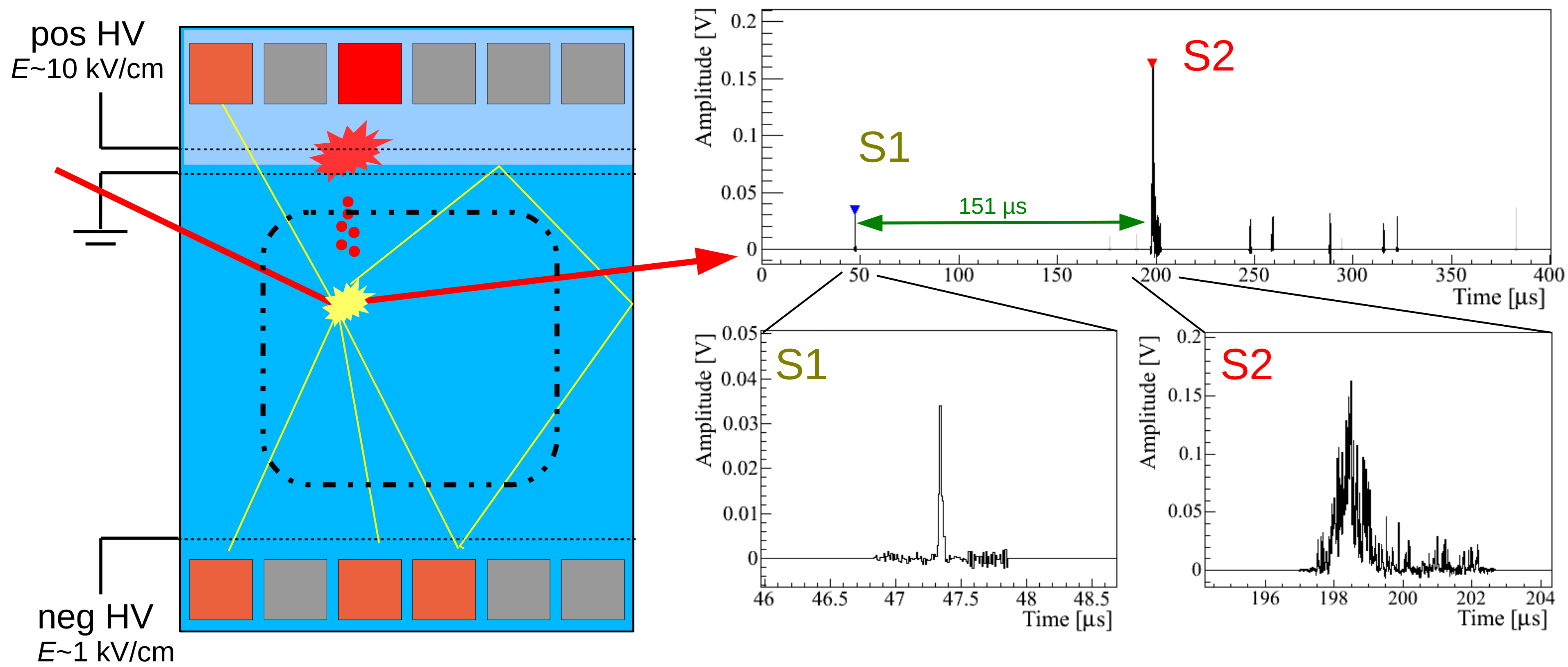
Isotope	Abundance	Spin	Unpaired Nucleon	Relative Strength
^{7}Li	92.6%	3/2	proton	12.8
^{19}F	100.0%	1/2	proton	100.0
^{23}Na	100.0%	3/2	proton	1.3
^{29}Si	4.7%	1/2	neutron	9.7
^{73}Ge	7.7%	9/2	neutron	0.3
^{127}I	100.0%	5/2	proton	0.3
^{131}Xe	21.3%	3/2	neutron	1.7

WIMP-neutron scattering

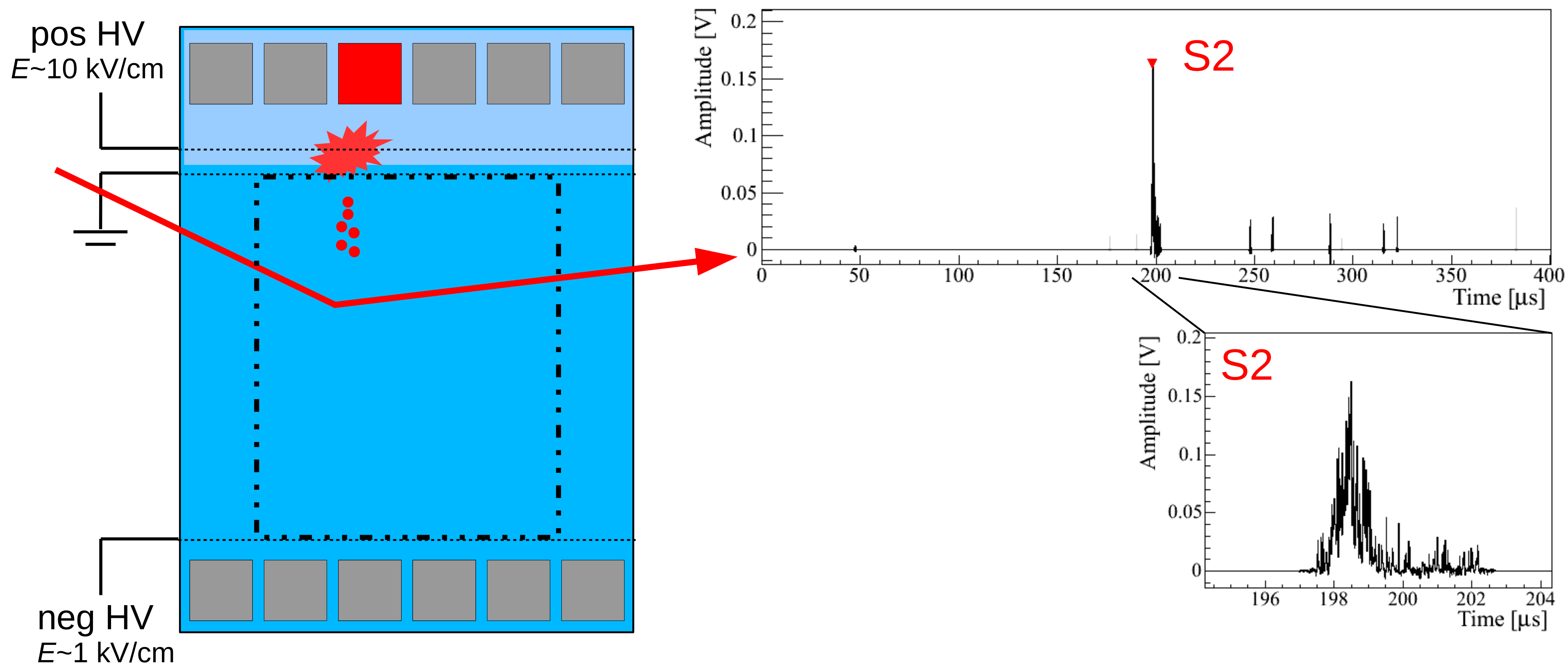


Interpretation of same WIMP search data

Standard Analysis

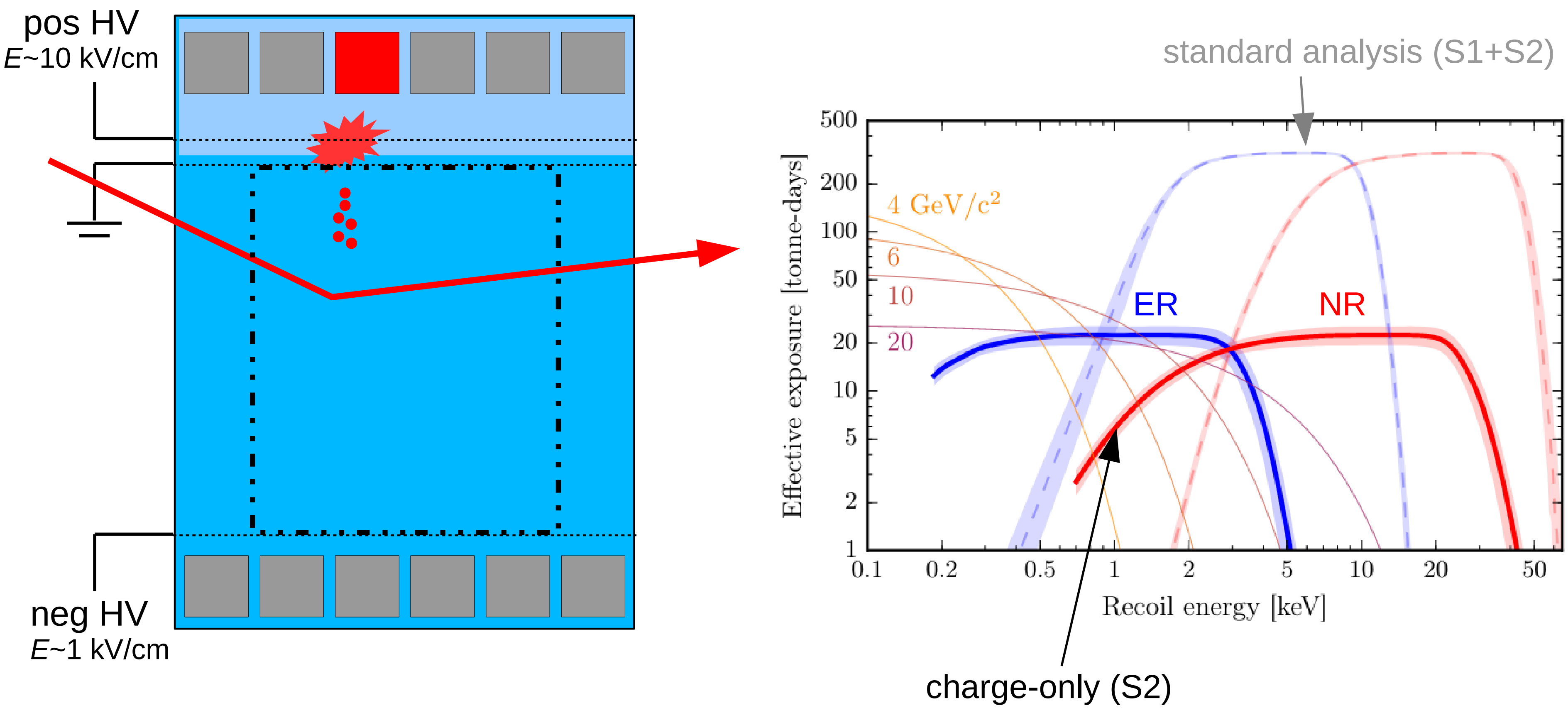


Charge-Only Analysis



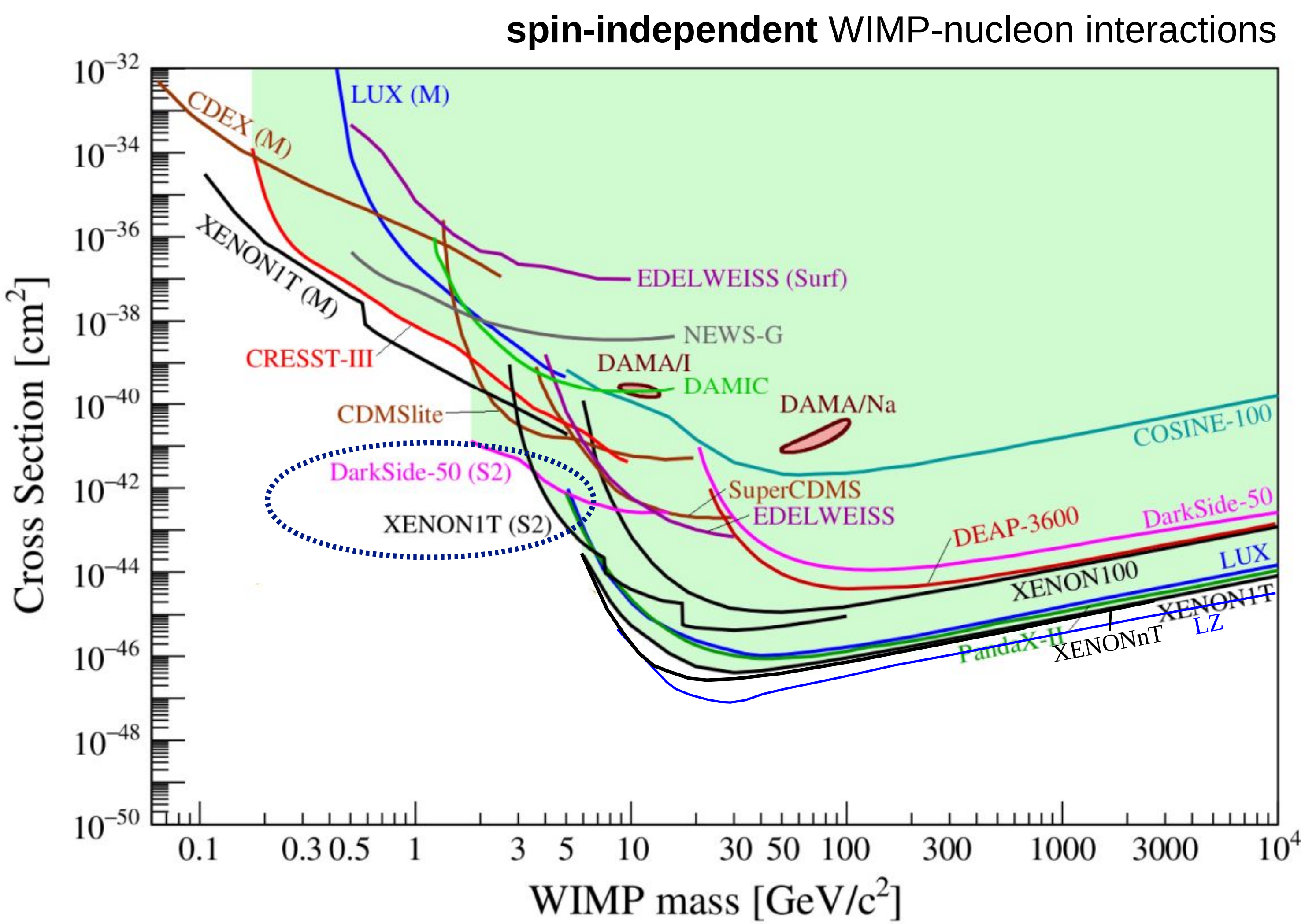
Charge-Only Analysis

PRL 123, 251801 (2019)



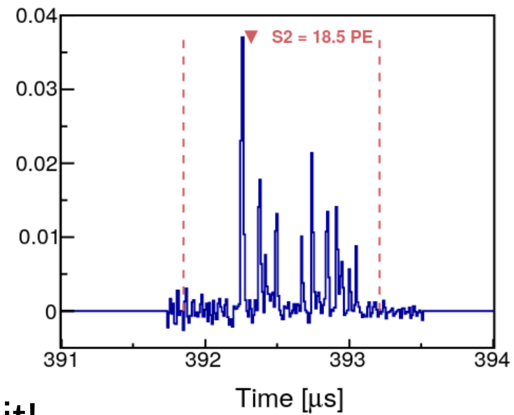
Charge-Only Analysis

PRL 123, 251801 (2019)



some results are missing...

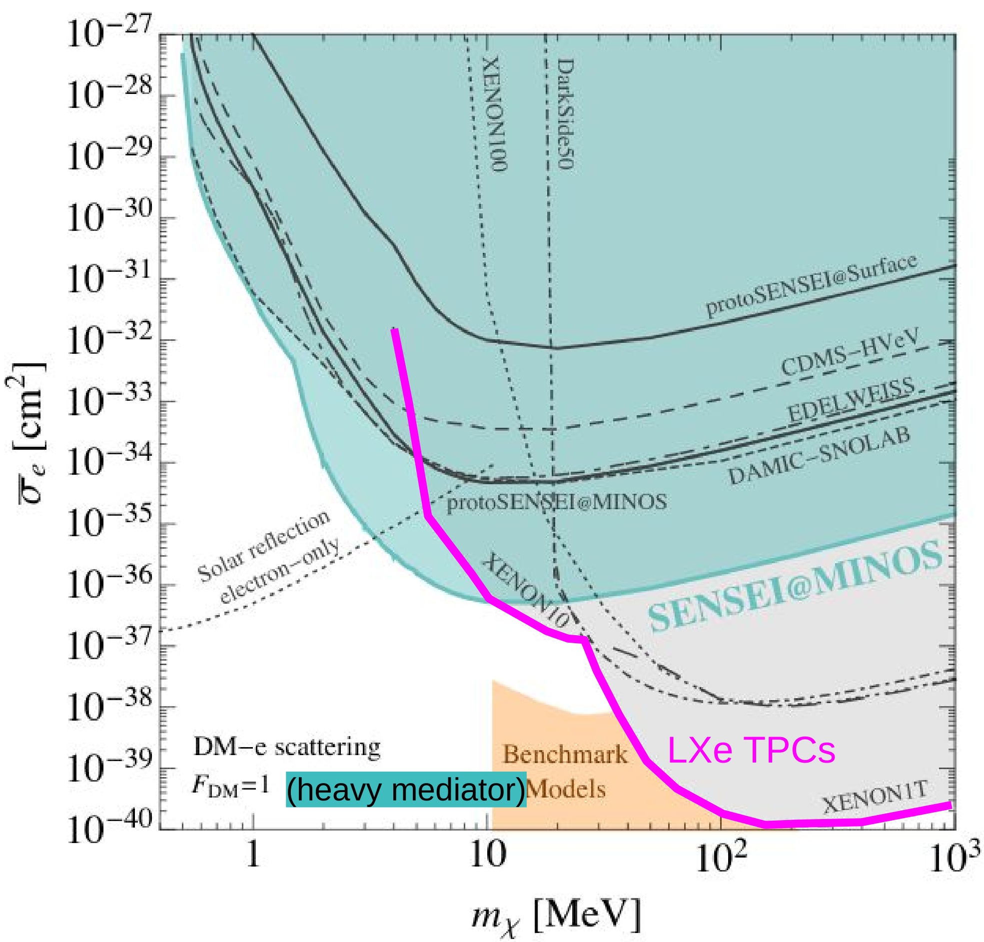
WIMP-e⁻ Scattering

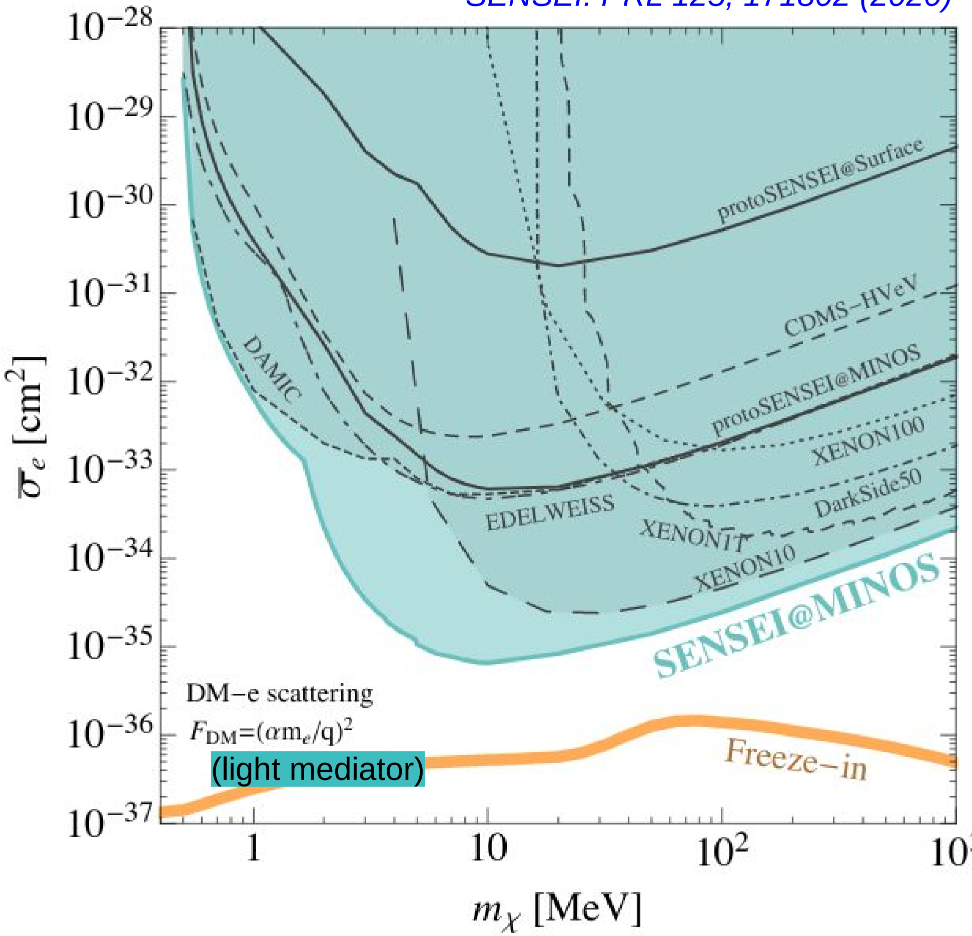


Very light DM scatters off electrons

Detectors with single-e⁻ sensitivity required → LXe TPCs have it!

SENSEI: PRL 125, 171802 (2020)

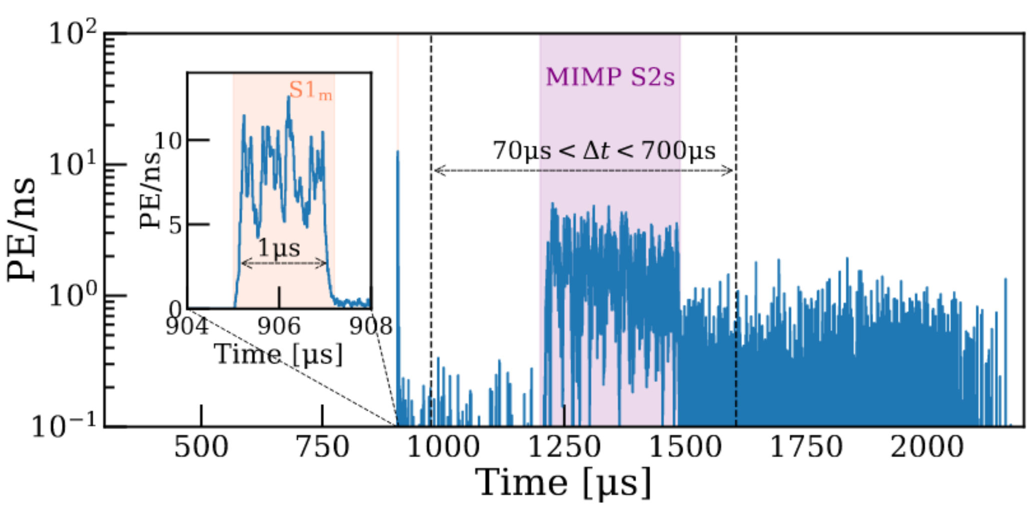




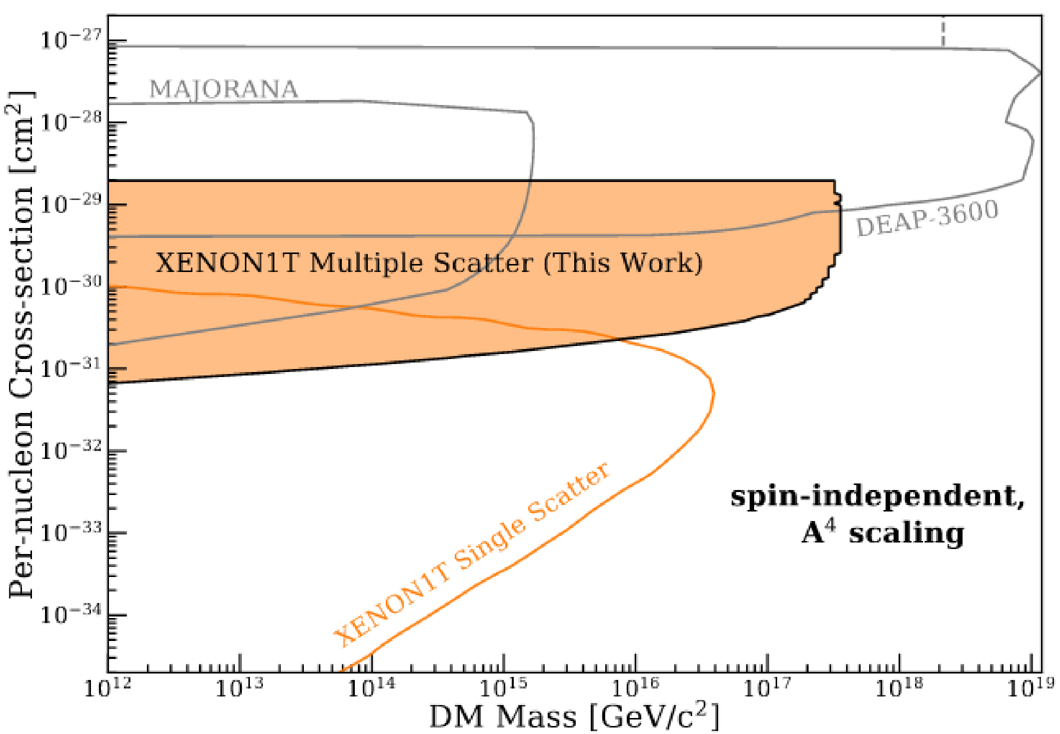
Planck-Scale Dark Matter

PRL 130, 261002 (2023)

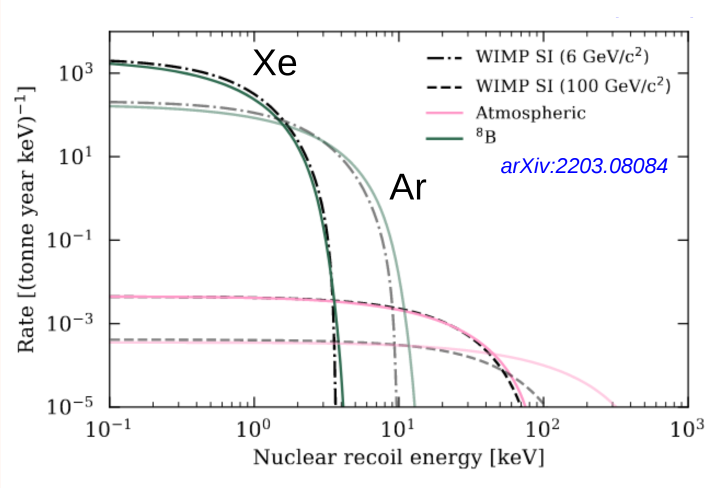
- Some production mechanisms predict DM near Planck mass ~10^{19} GeV/c²
- Spin-independent cross section $\propto A^4$
- Expected flux: ~1 evt/(m² × yr) → flux limited
- Signal: multiple scattering → **Multiply-Interacting Massive Particle** (MIMP)



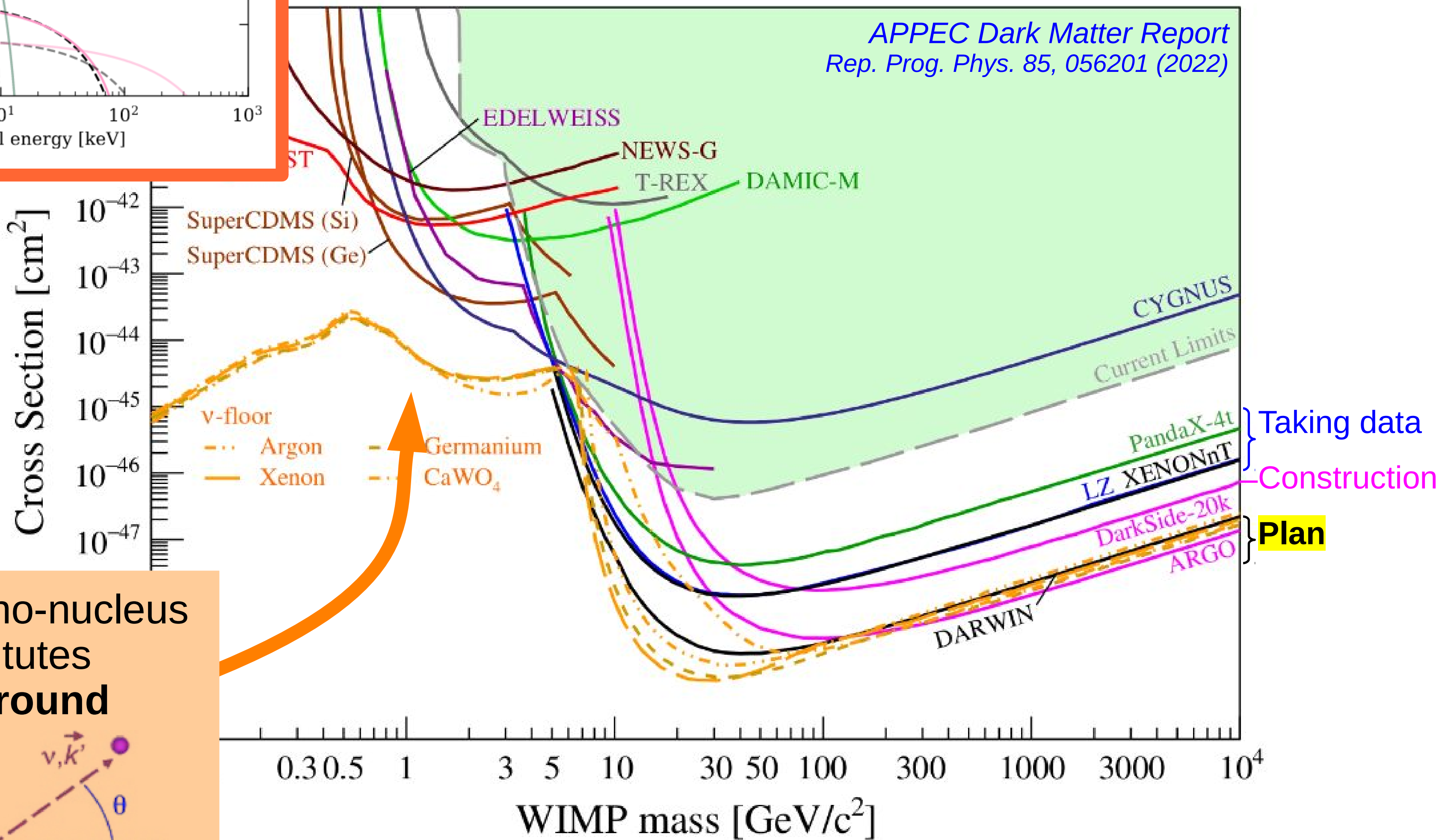
Simulated MIMP waveform for $\sigma_{SI}=10^{-29}$ cm²
→ 500 NRs/m



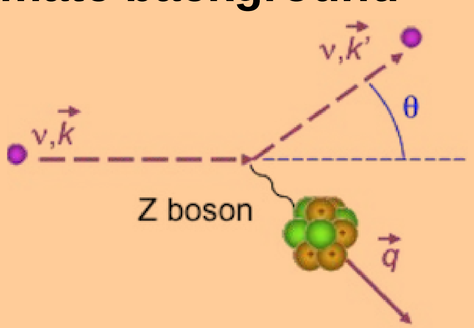
The Neutrino Floor



spin-independent WIMP-nucleon interactions



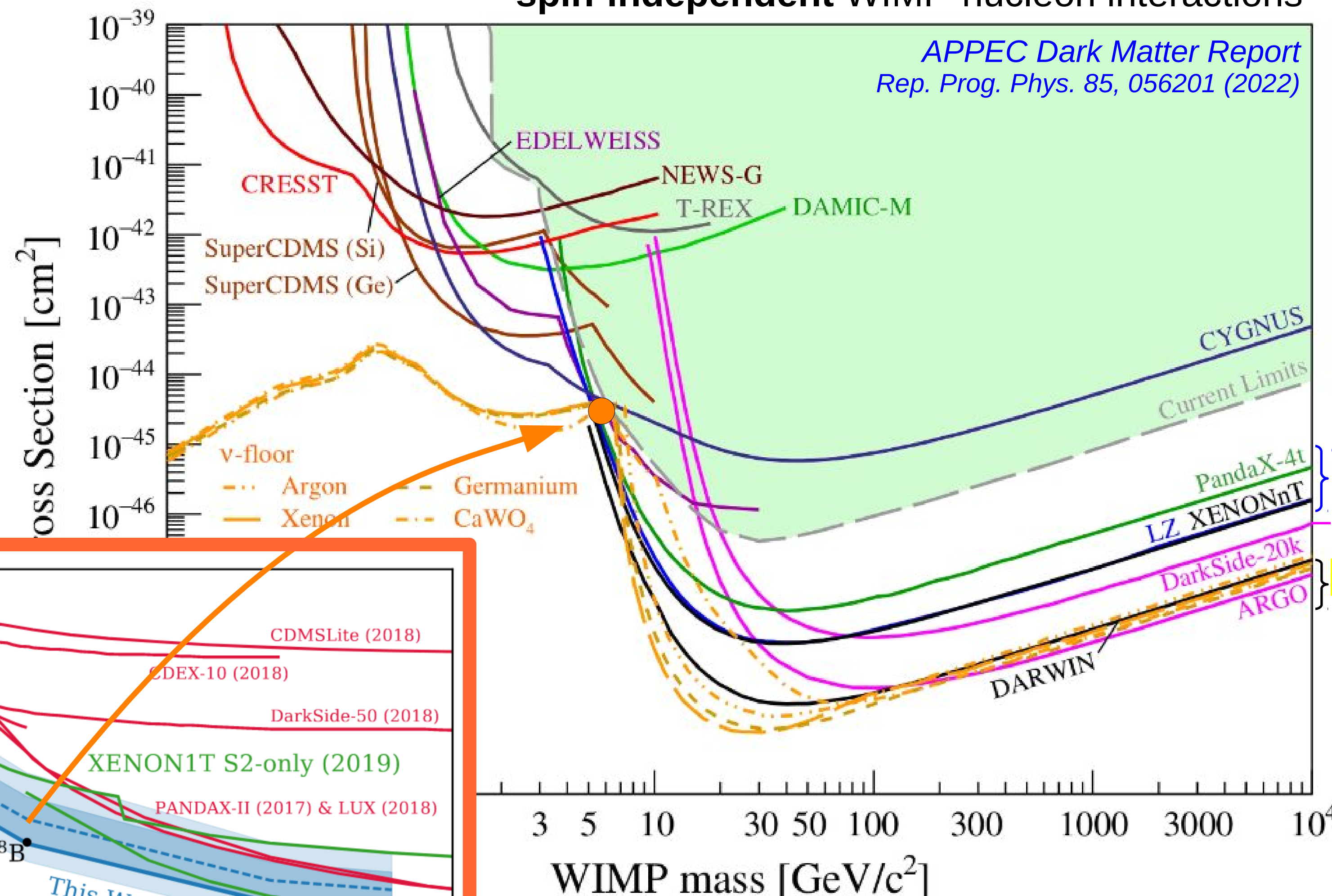
Coherent neutrino-nucleus scattering constitutes **ultimate background**

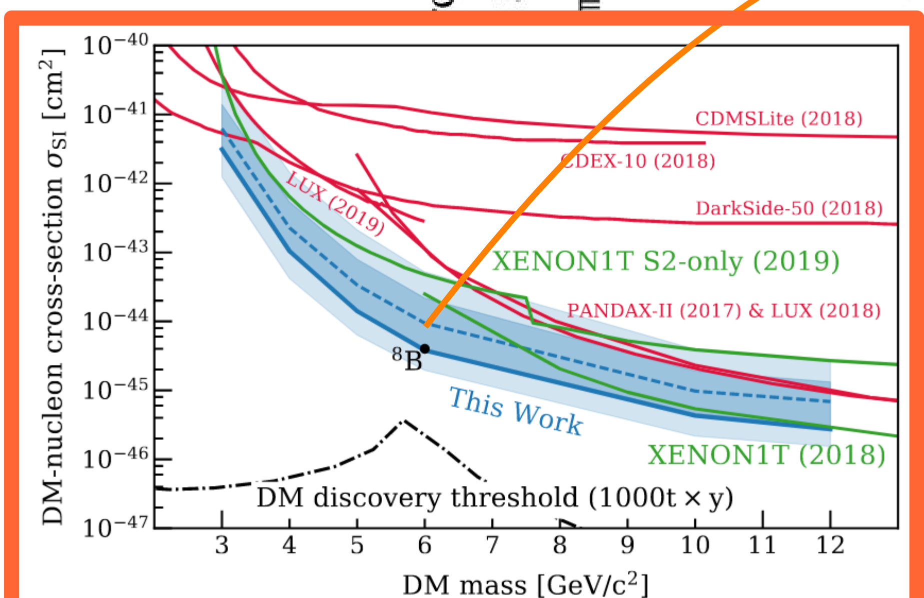


Almost there...

PRL 126, 091301 (2021)

spin-independent WIMP-nucleon interactions



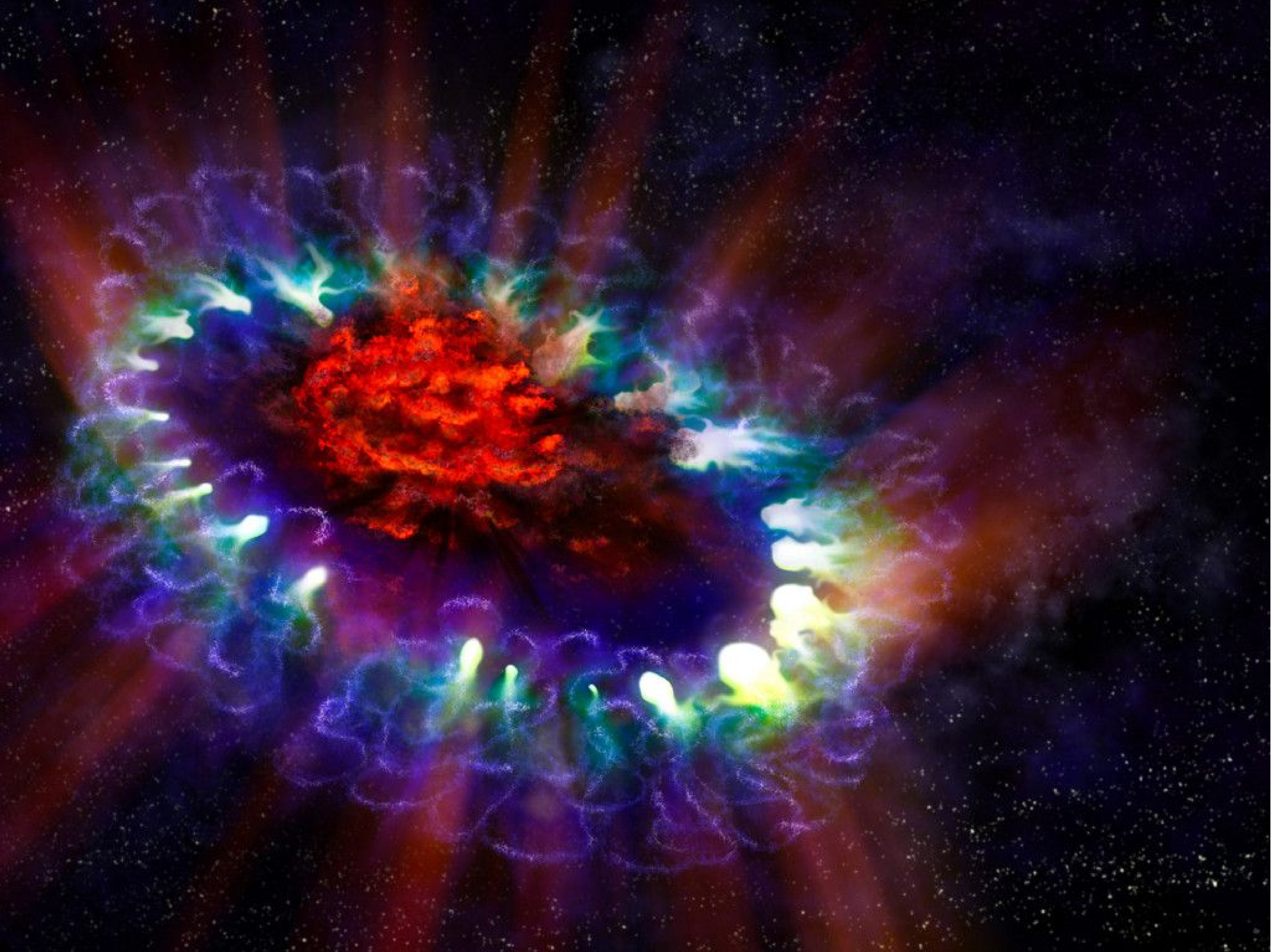


XENON1T low-threshold search (S1+S2)

→ 2.1 CNNS events (^{8}B) expected

→ no excess above background seen

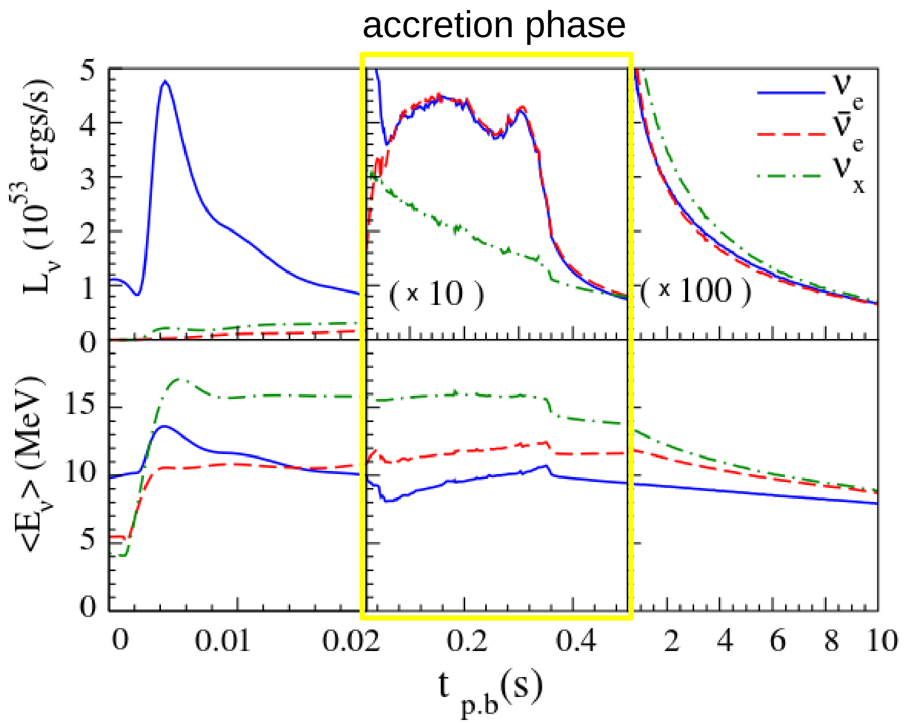
Similar search by PandaX-4T *arXiv:2207.04883*

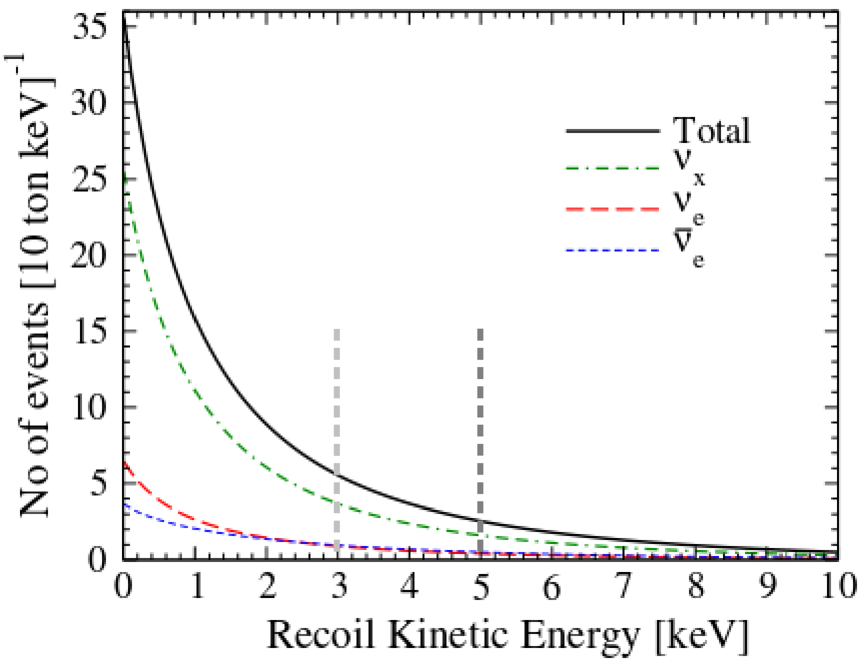


Supernova Neutrinos

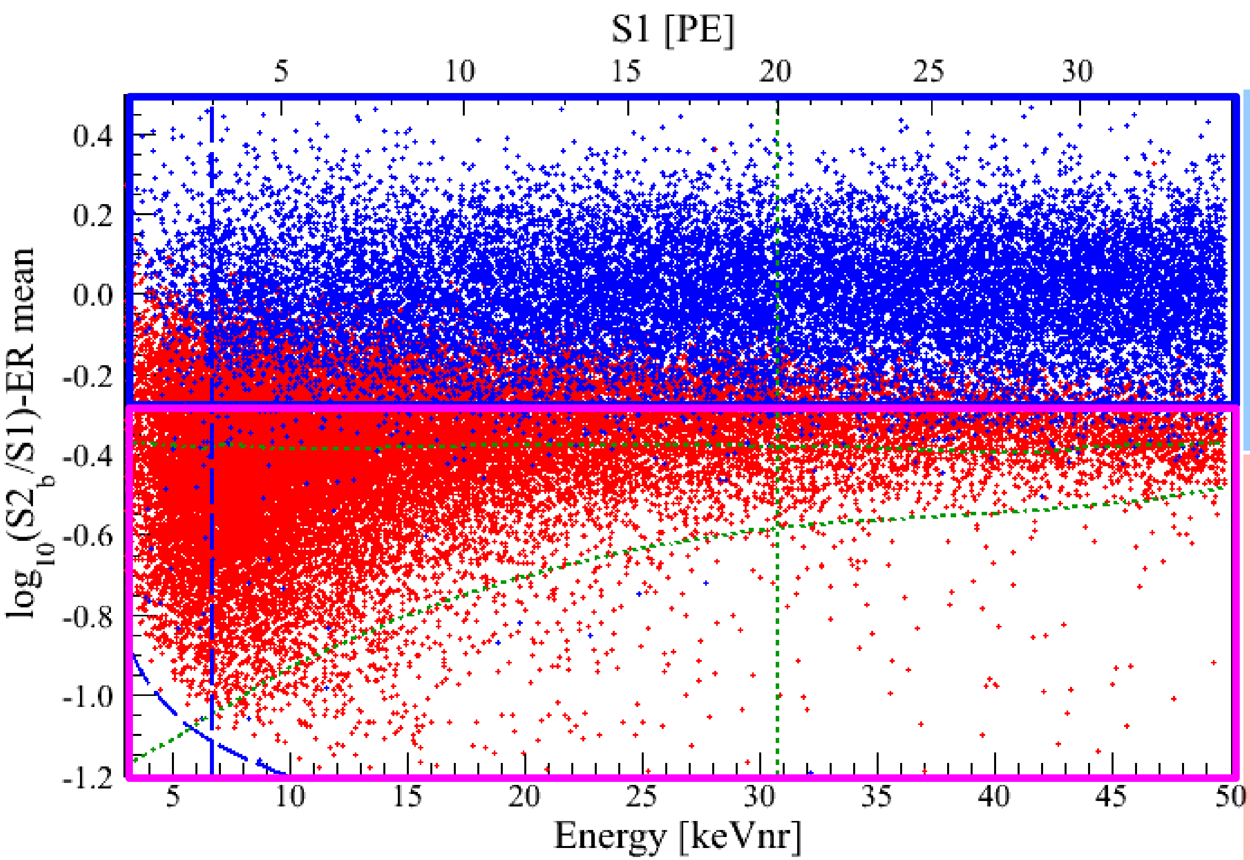
Chakraborty et al., PRD 89, 013011 (2014)
Lang et al., PRD 94, 103009 (2016)

- ν from supernovae could be detected via CNNS as well
- signal fom accretion phase of a ~18 Msun supernova @ 10 kpc is visible in a 10t-LXe detector (<DARWIN)
- signal: NRs plus precise time information
- challenge: theshold





Interactions in LXe Detectors



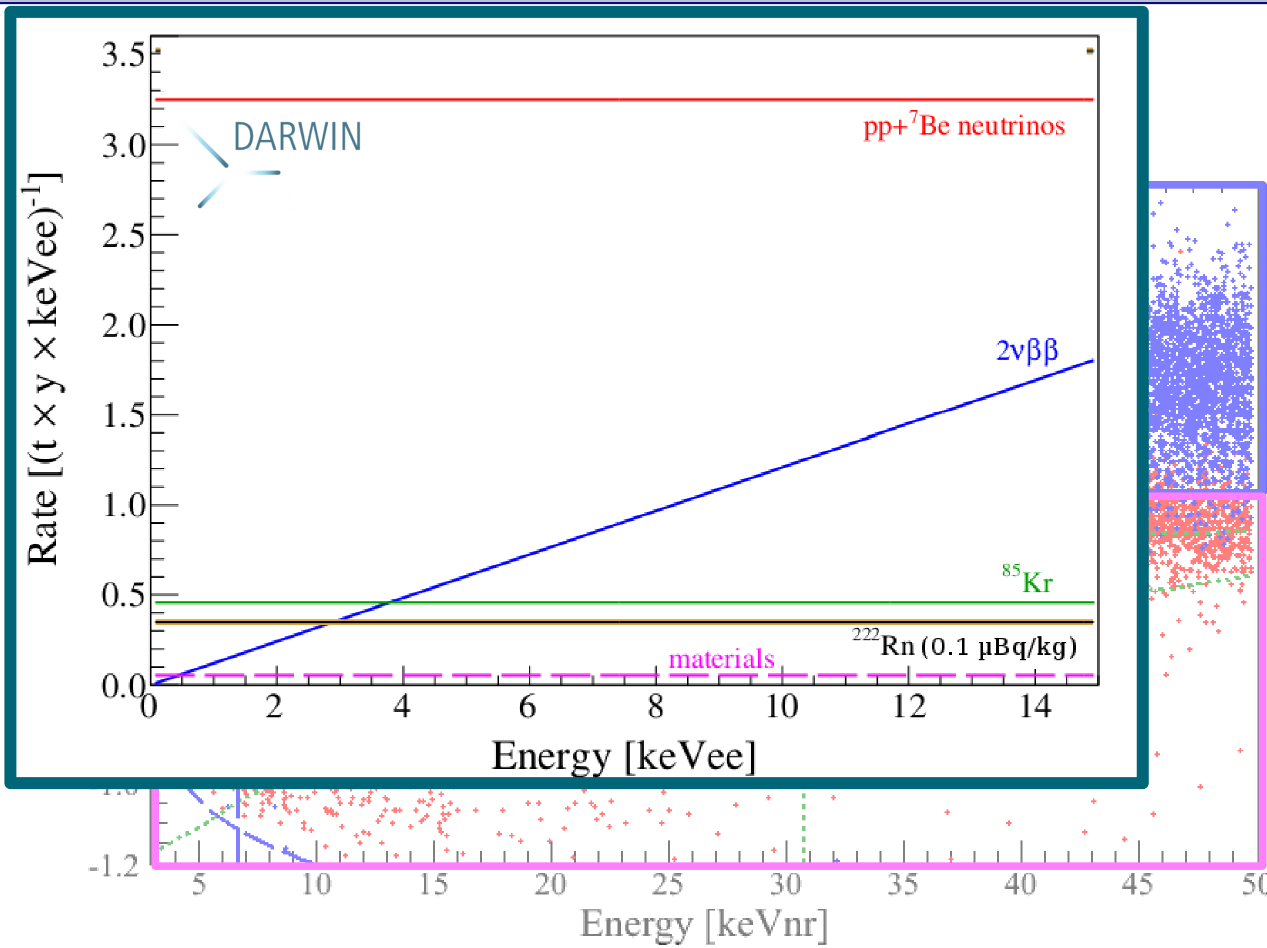
scattering off atomic electrons, excitations etc.
→ electronic recoil

- 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

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

coherent scattering off xenon nucleus
→ nuclear recoil

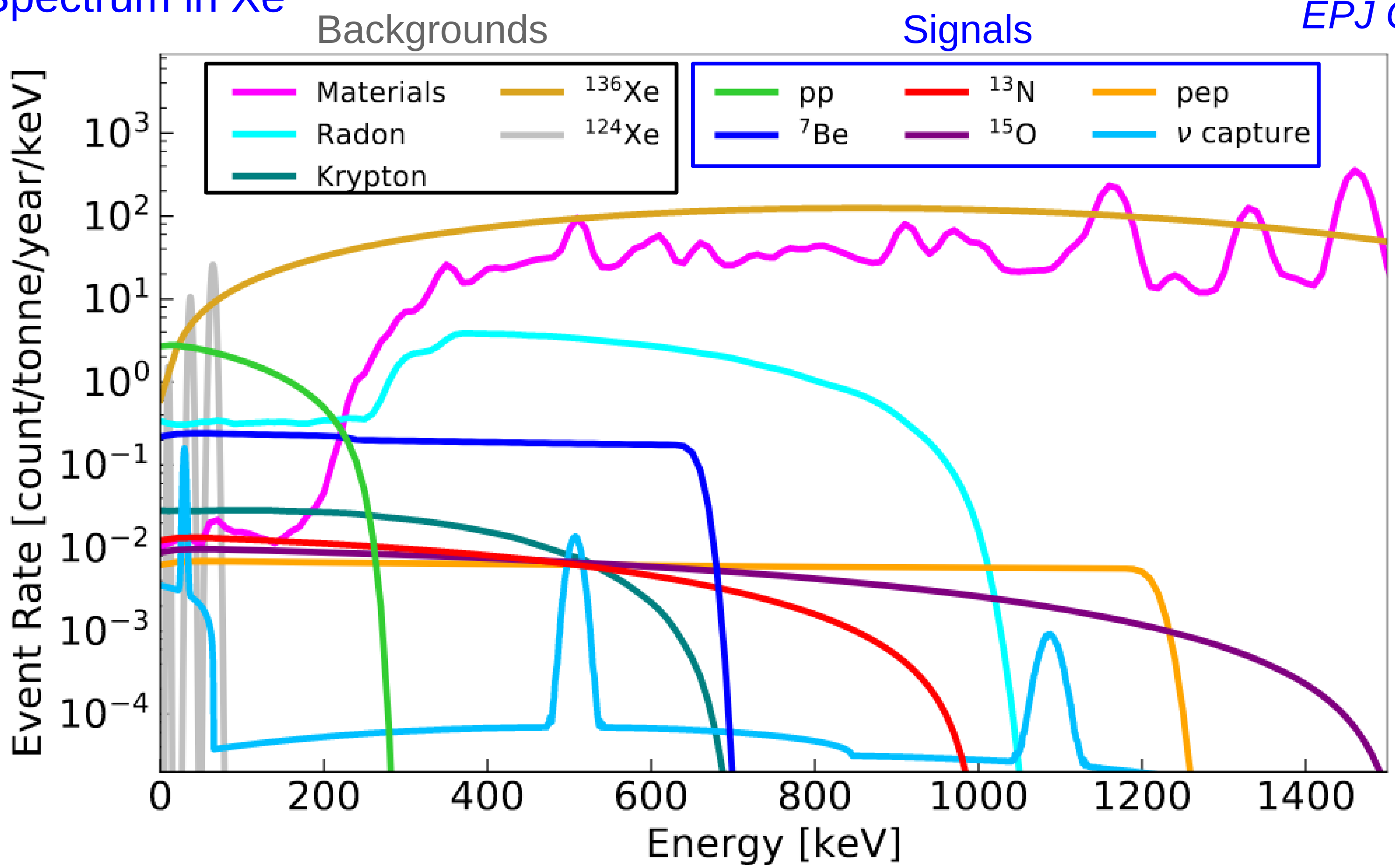
- Dark Matter
- CNNS
- Supernova Neutrinos

→ Many **science channels** are accessible

Solar Neutrinos

ER Spectrum in Xe

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

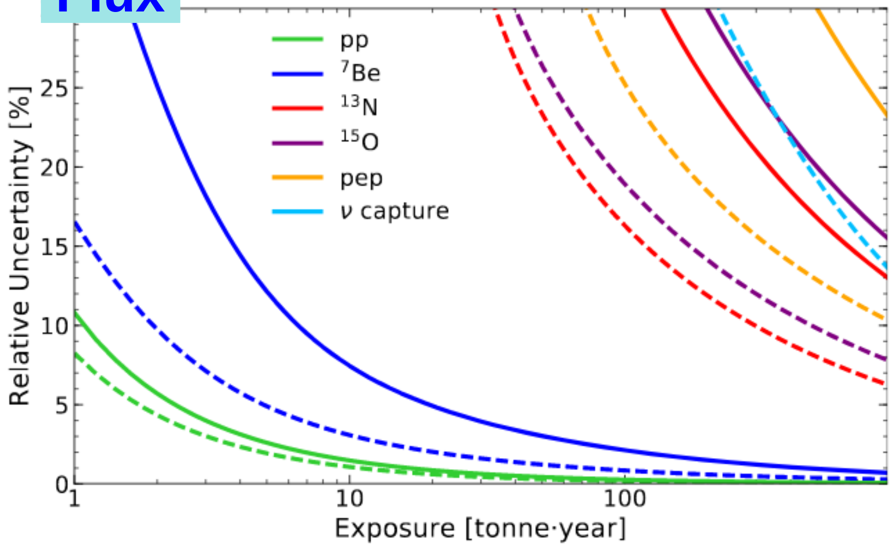


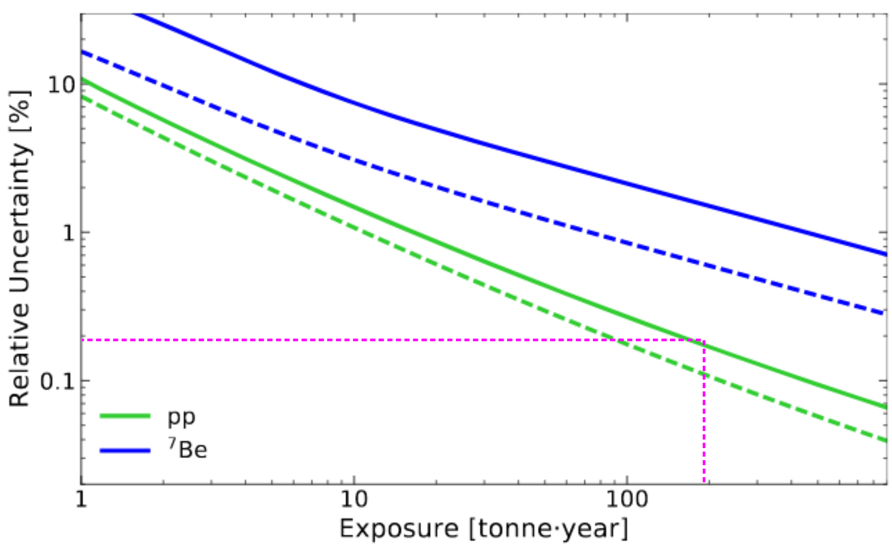
- DARWIN‘s low-E ER spectrum dominated by pp neutrinos (and 2νECEC+2νββ)
- distinct features in ν spectra allow extracting neutrino fluxes
  → full spectral fit of all components up to 3 MeV
  (possibility to enhance sensitivity by more sophisticated analysis)

pp-Neutrinos in real time

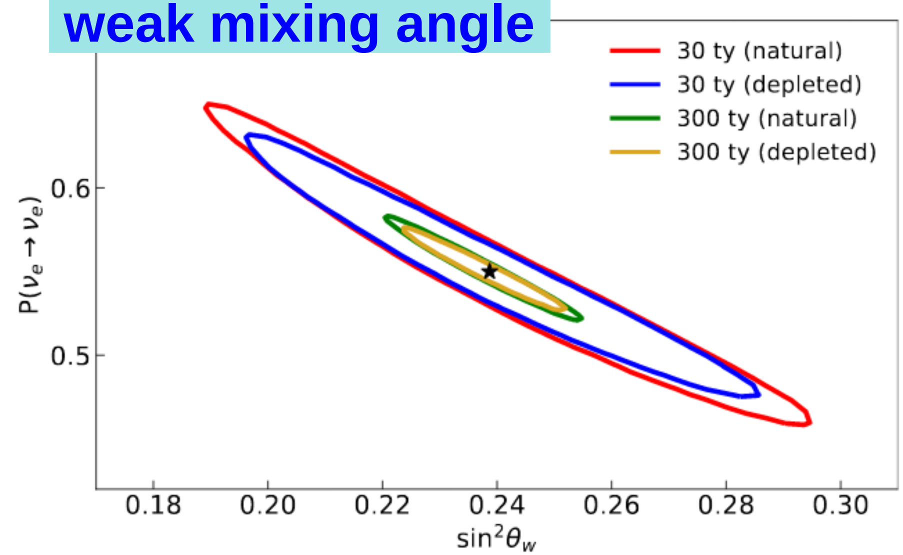
EPJ C 80, 1133 (2020)

Flux

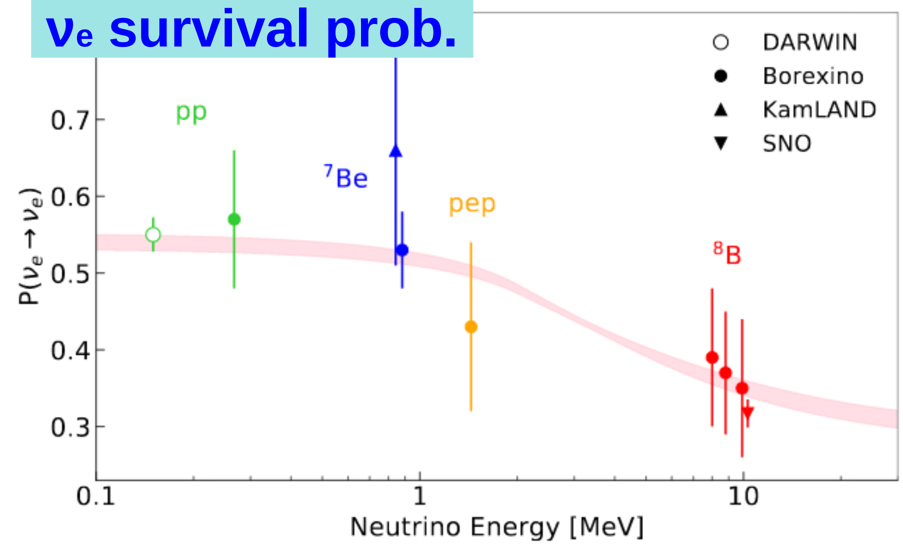




weak mixing angle

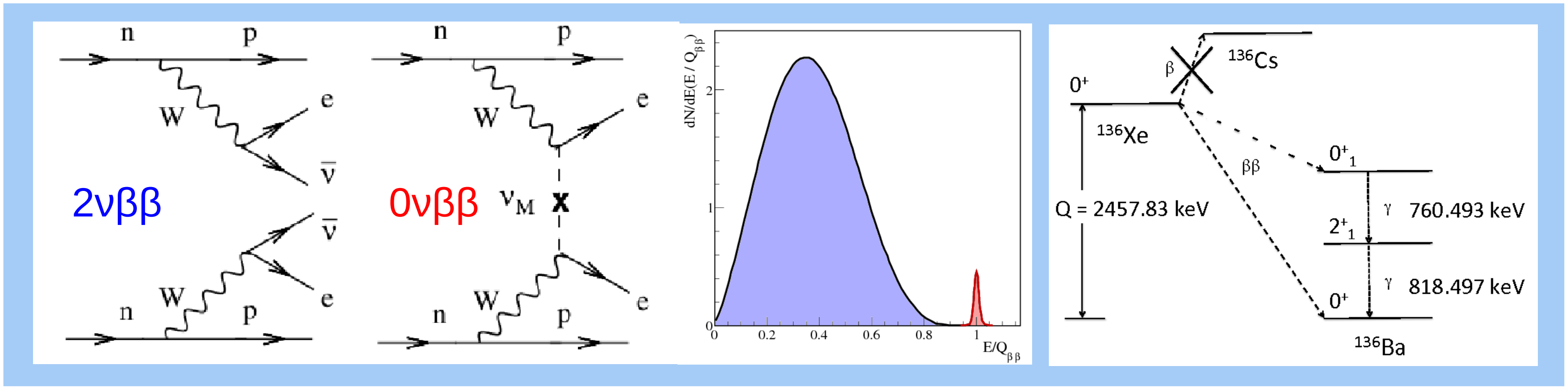


ν_e survival prob.



^{136}Xe: 0ν double-beta Decay

DARWIN

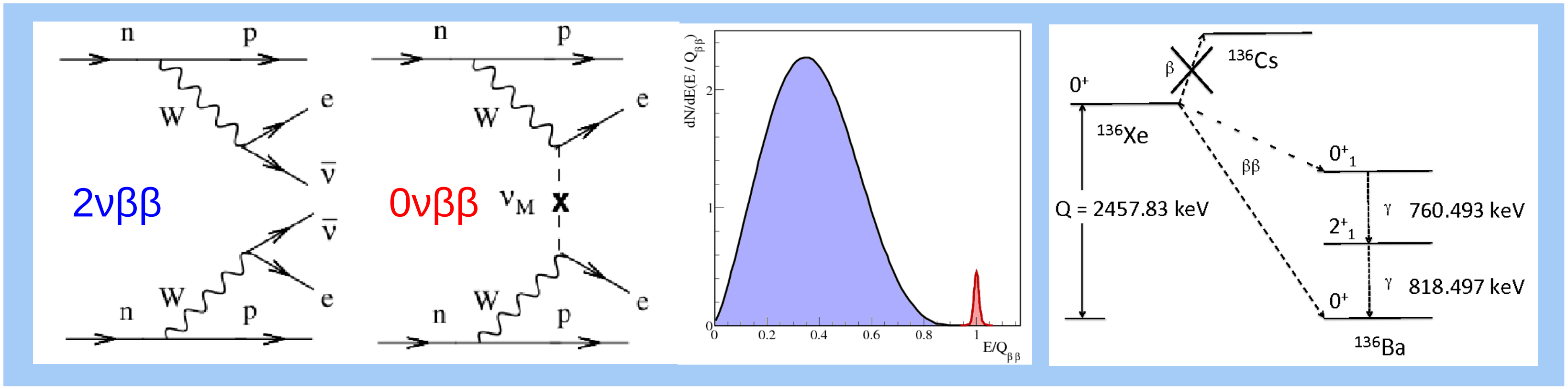


ΔL ≠ 0

- 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

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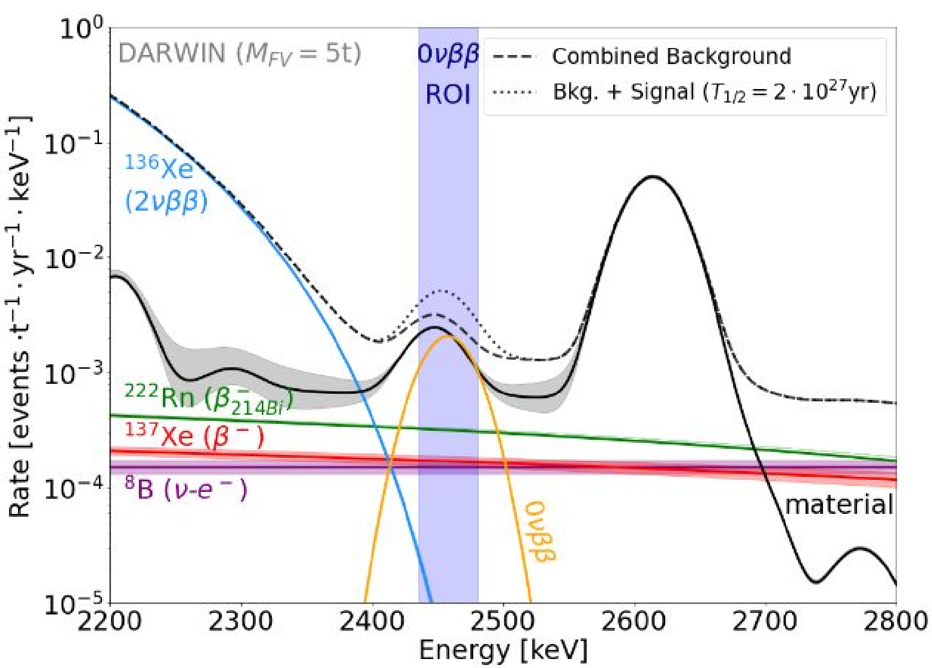


DARWIN Sensitivity

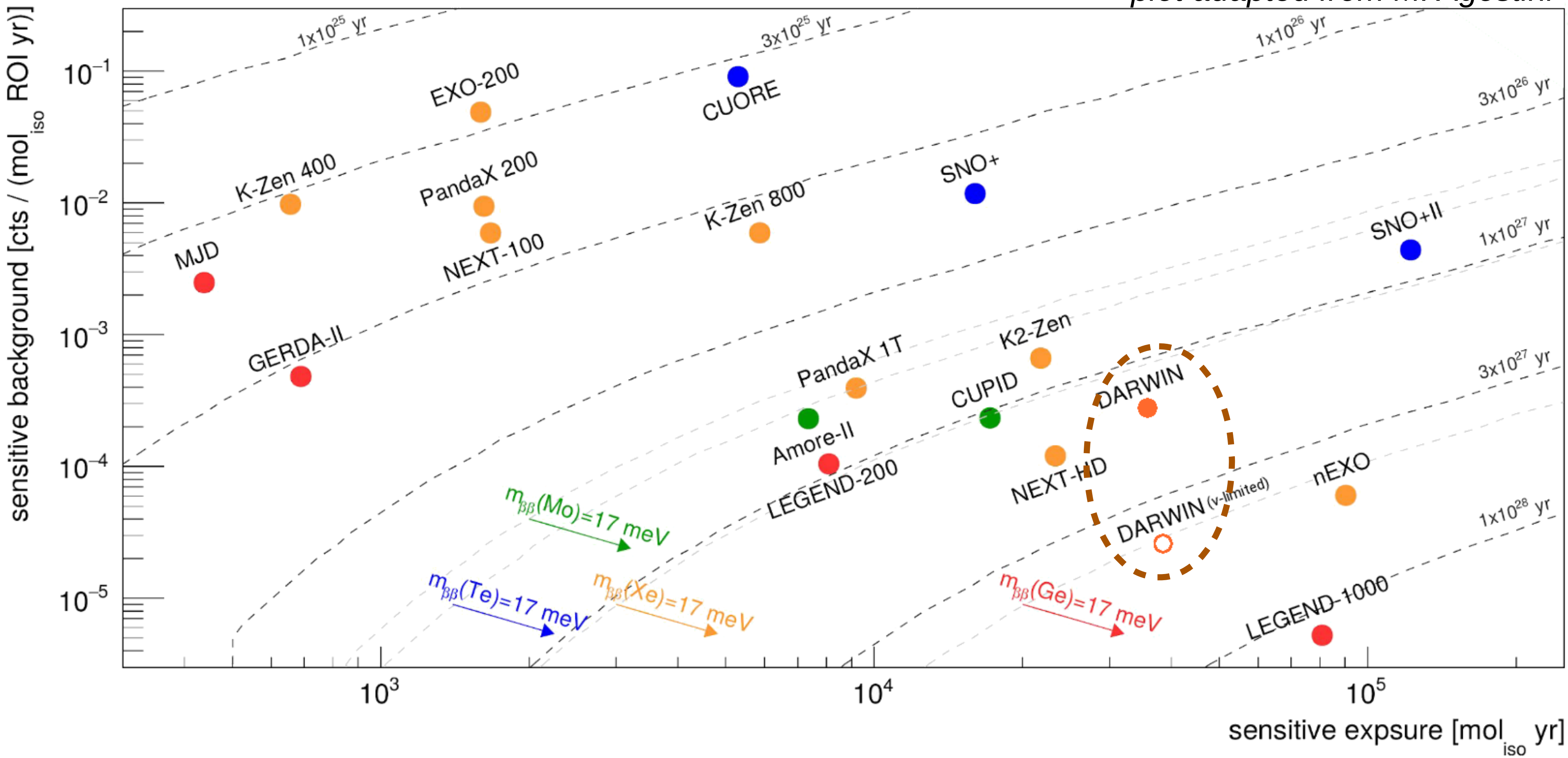
- optimize sensitivity by fiducialization
- background from decays of neutron-activated ^{137}Xe irrelevant at LNGS depth
- **half-life sensitivity: 3.0 × 10^{27} y**

(5t fiducial volume, 10y operation)

^{136}Xe: 0ν double-beta Decay

EPJ C 80, 808 (2020)

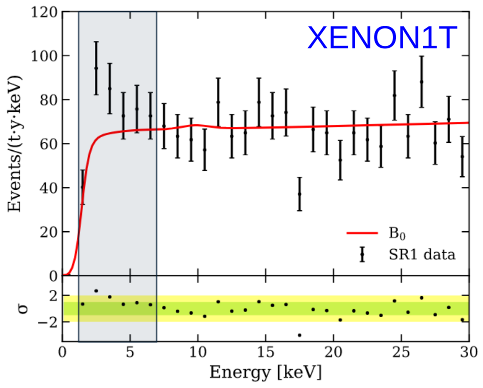
plot adapted from M. Agostini

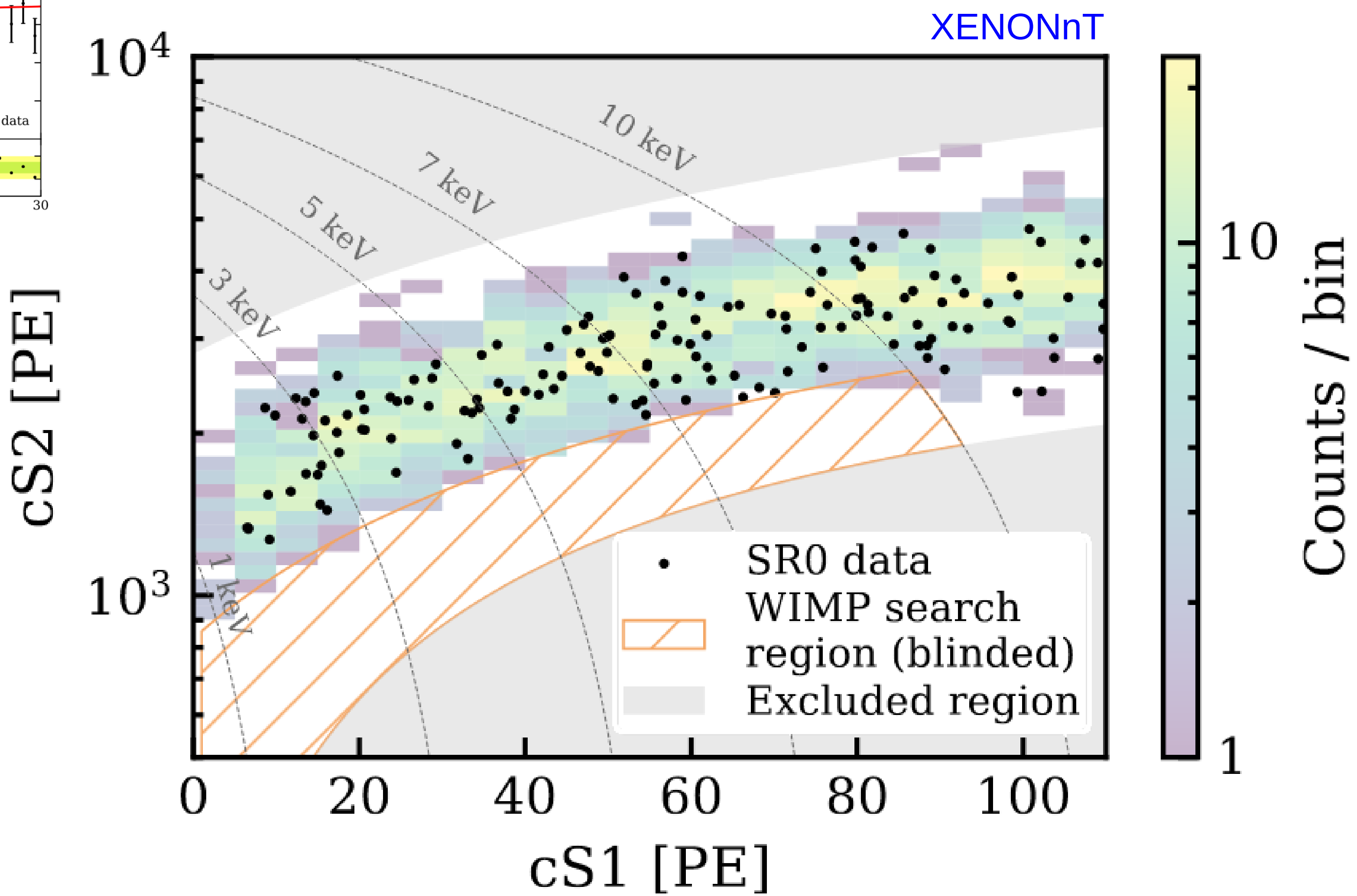


An updated study for XLZD is currently under preparation

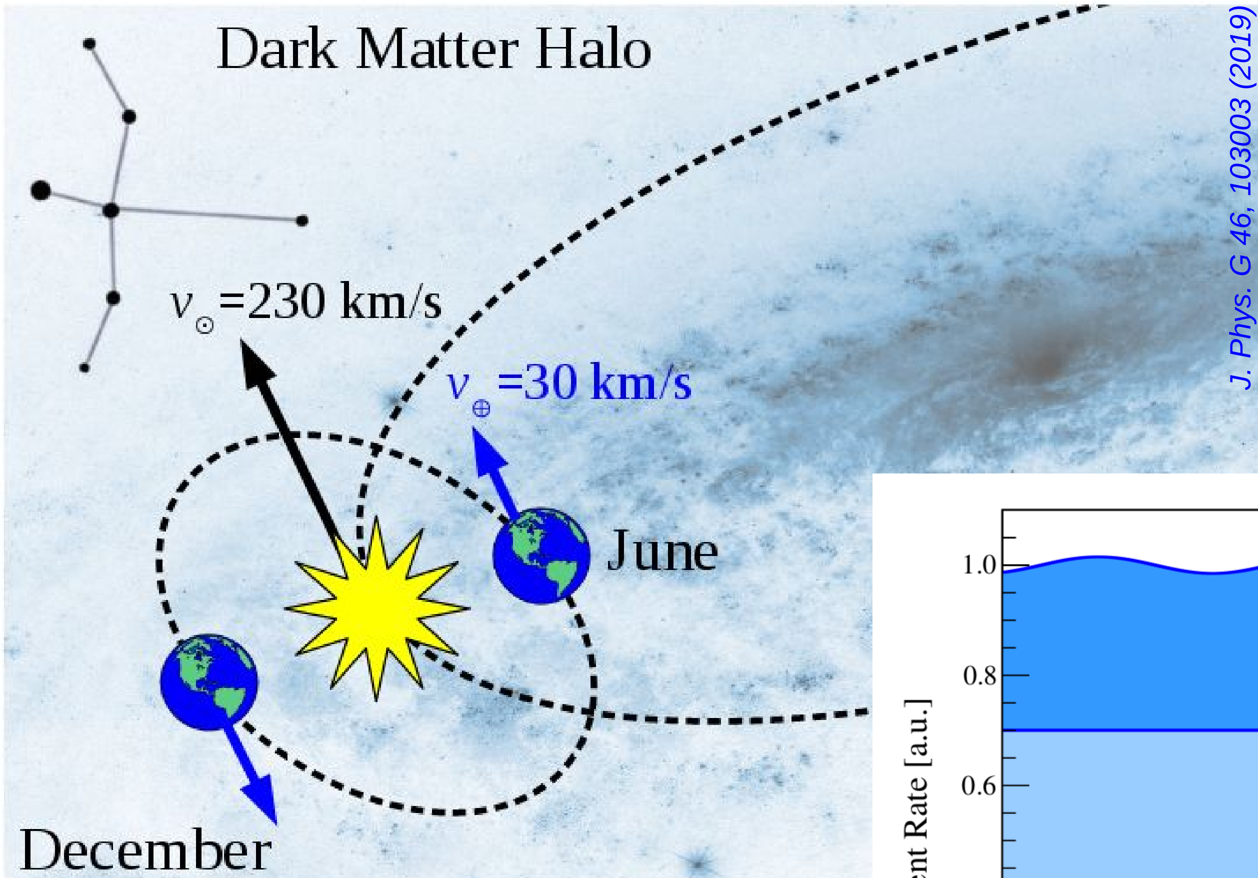
Low-E Electronic Recoils

PRL 129, 161805 (2022)



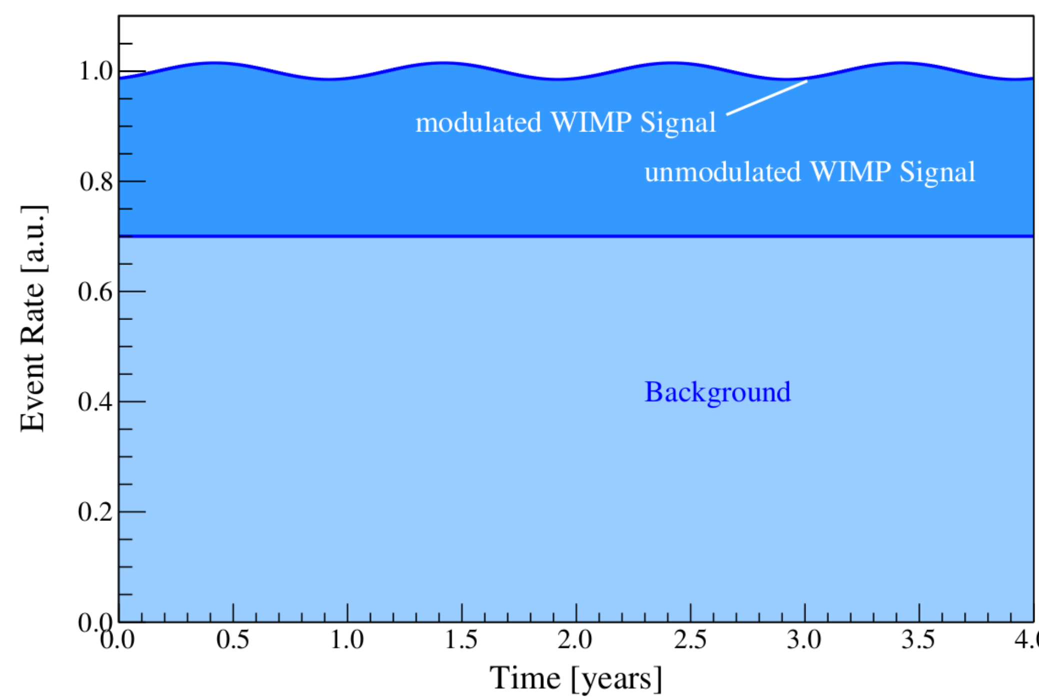


Annual Modulation Searches



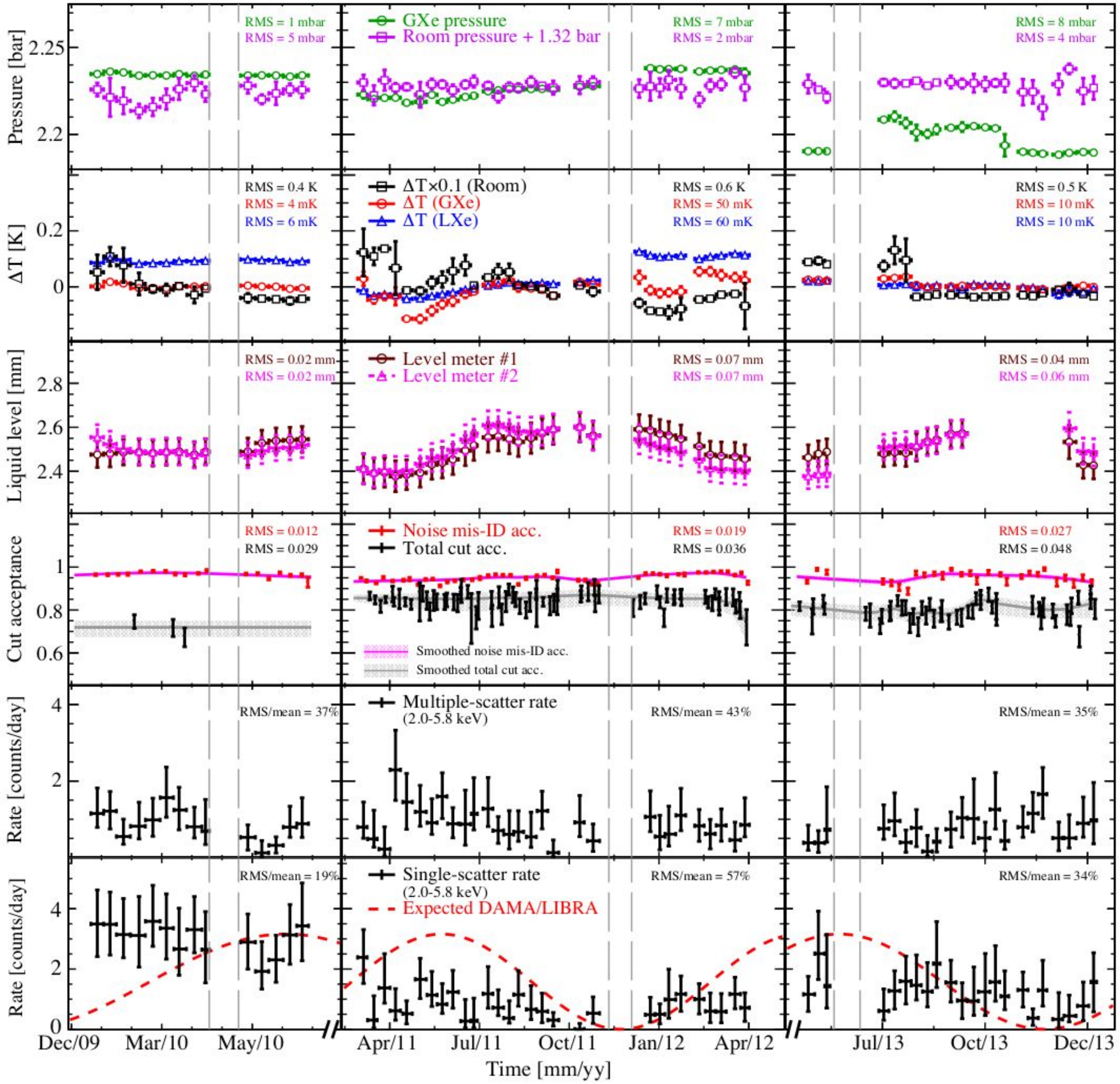
J. Phys. G 46, 103003 (2019)

Long-standing detection claim by DAMA/Libra:
12.9 σ
Nucl. Phys. At. Energy 19 (2018) 307



Annual Modulation Searches

XENON100: PRL 118, 101101 (2017)

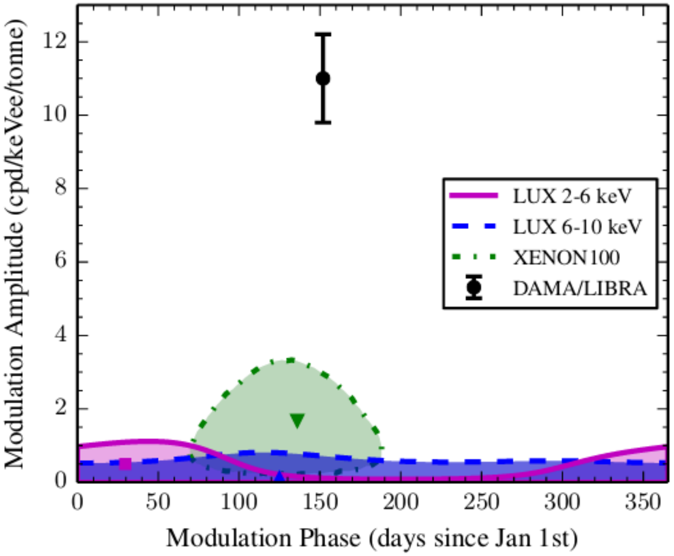


– dark matter–electron scattering

– **2-phase LXe TPCs** operated stably over long periods
  XENON100: 4 years
  LUX: 2 years

– challenges DAMA/LIBRA
  XENON100: **5.7σ**
  LUX: **9.2σ**

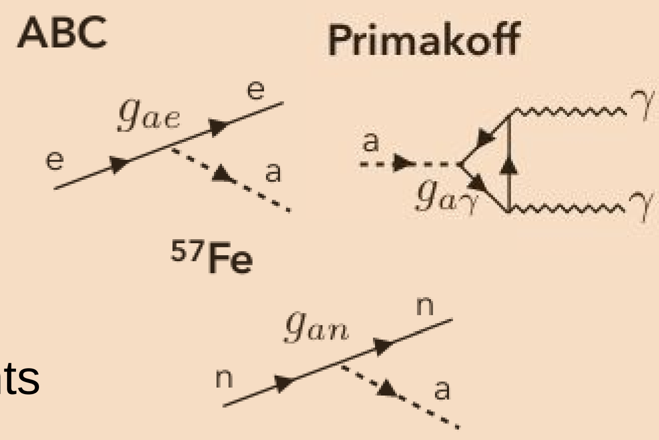
LUX: PRD 98, 062005 (2018)

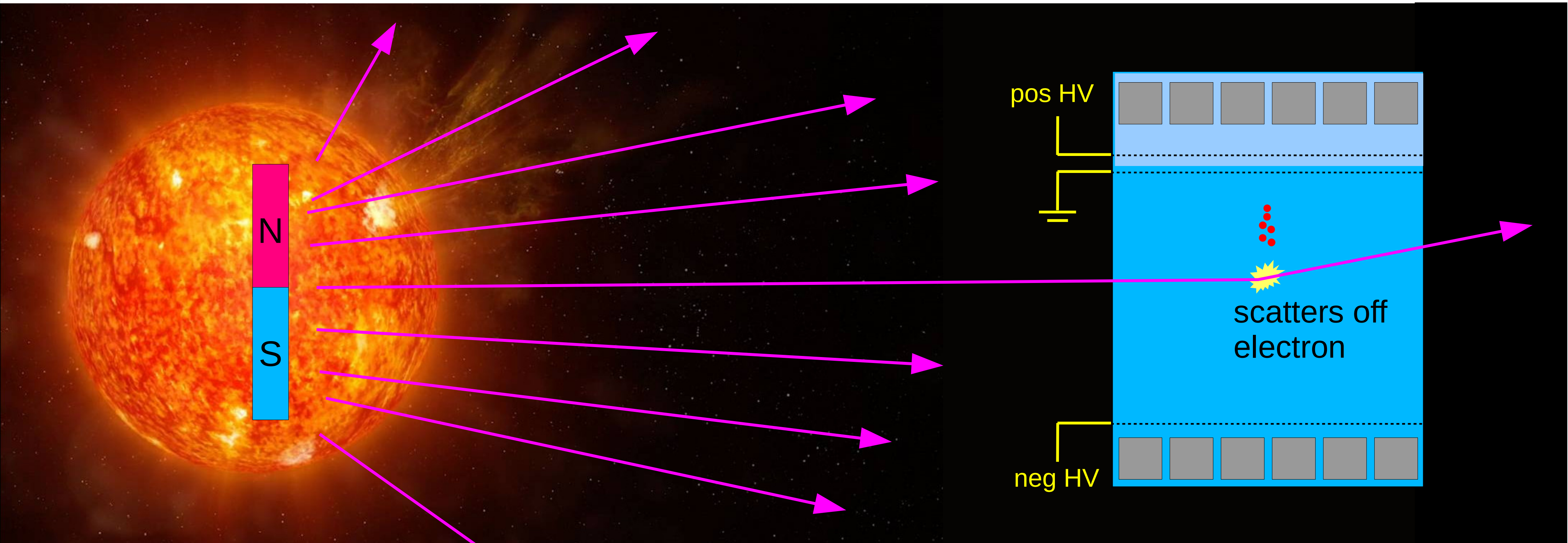


New Physics in ER Data I

Many models predicts signatures from new physics in low-E ER data.
Some examples

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





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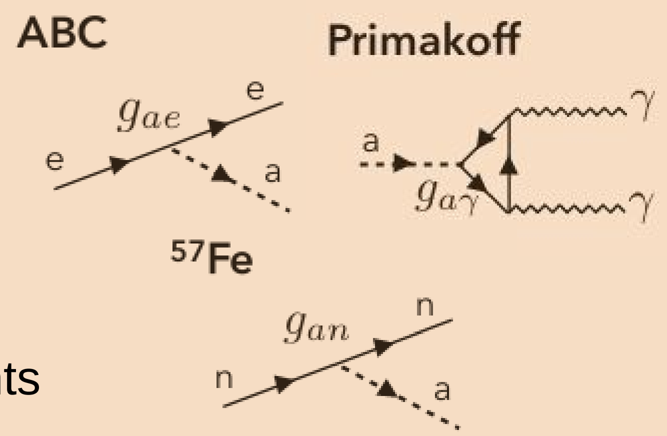
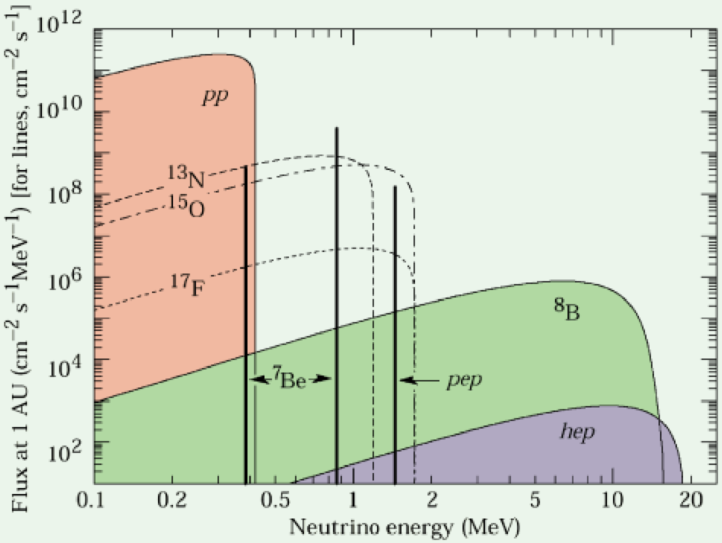


Enhanced Neutrino Magnetic Moment

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



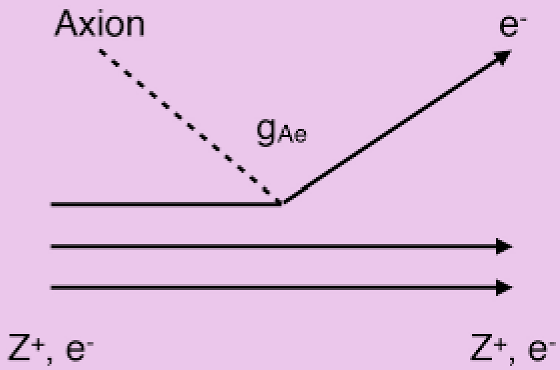
New Physics in ER Data II

Many models predicts signatures from new physics in low-E ER data.
Some examples

Bosonic Dark Matter

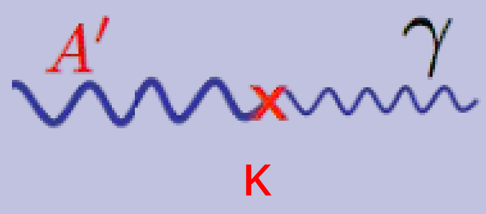
Axion-like Particles (ALPs, pseudoscalar DM)

- Interaction with electrons via axio-electric effect
  → ALPs are absorbed by bound electrons
  → absorption rate depends on axion-electron coupling g_{ae}
- expect mono-energetic peak at unknown m_a
- assume all DM is made of non-relativistic ALPs



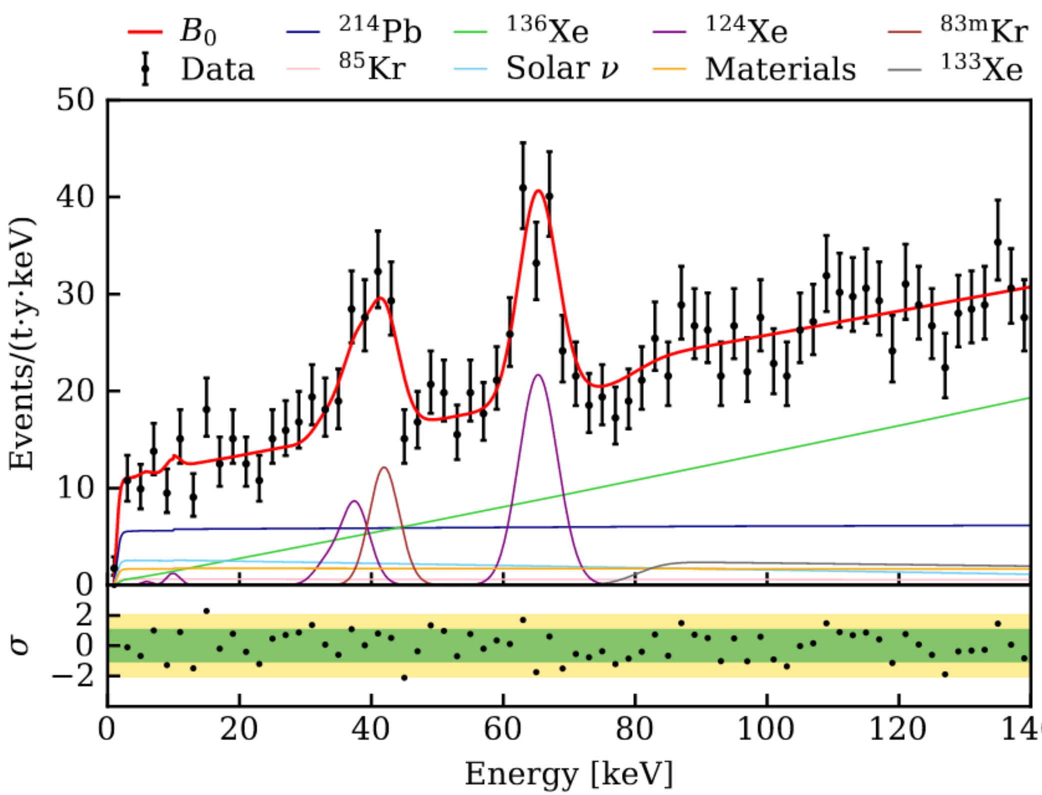
Dark Photons (vector-boson DM)

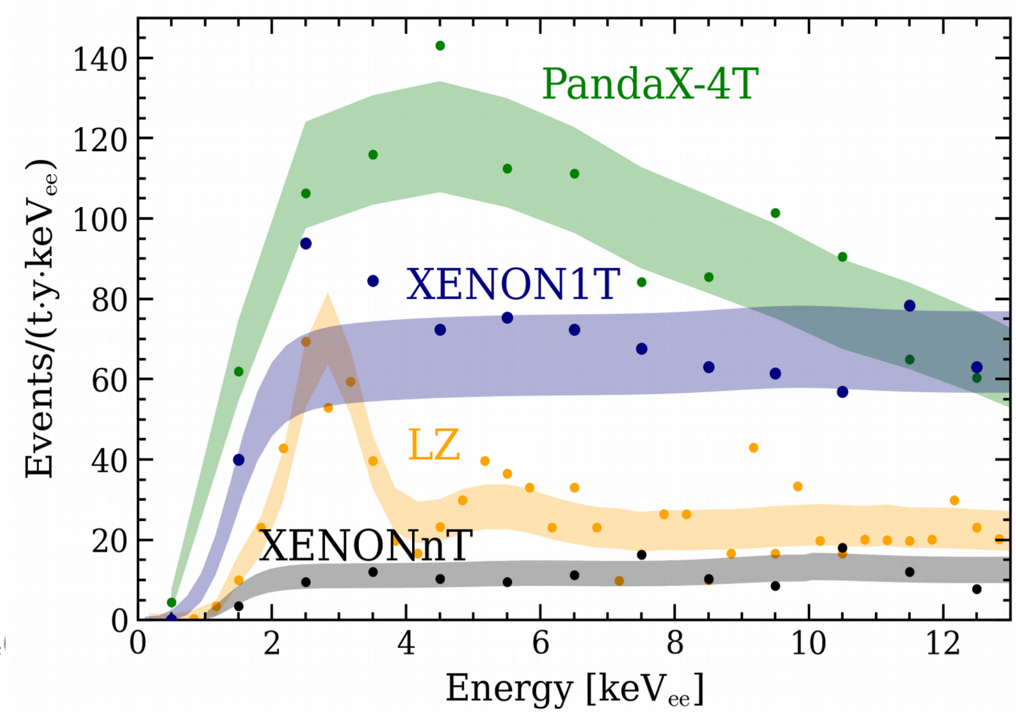
- Massive, non-relativistic dark photons ionize Xe atoms
  → signal strength given by kinetic mixing κ between dark photon and photon
- expect mono-energetic peak at unknown $m_{A'}$
- assume all DM is made of non-relativistic dark photons



XENONnT: 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** (0νββ of ^{136}Xe, 2νECEC of ^{124}Xe)
- world-record **low ER background** level: (15.8±1.3) evts/(t×yr×keV)

Limits on New Physics

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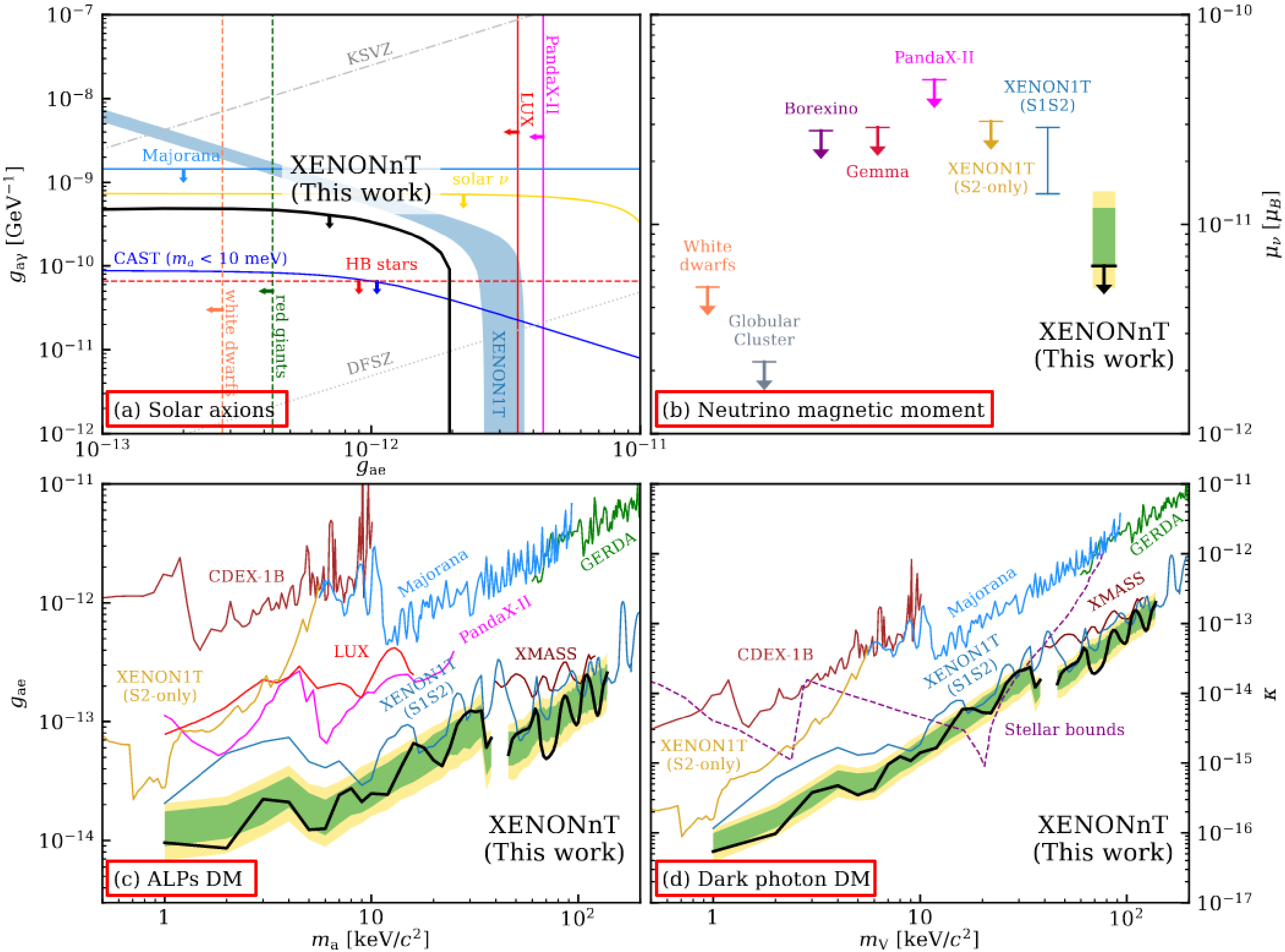
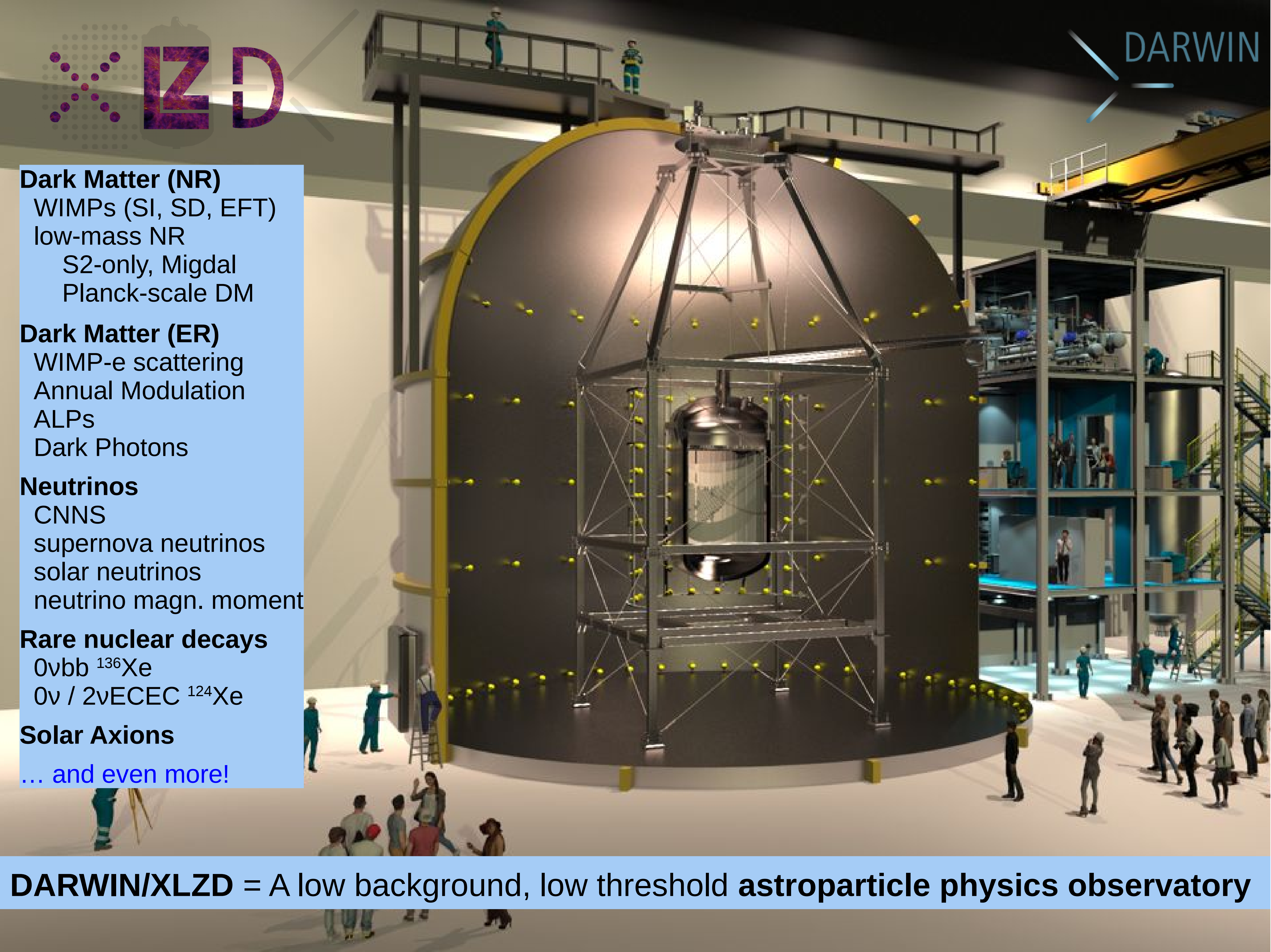


→ **new leading results for several new physics channels**



Dark Matter (NR)
- WIMPs (SI, SD, EFT)
- low-mass NR
  - S2-only, Migdal
  - Planck-scale DM

Dark Matter (ER)
- WIMP-e scattering
- Annual Modulation
- ALPs
- Dark Photons

Neutrinos
- CNNS
- supernova neutrinos
- solar neutrinos
- neutrino magn. moment

Rare nuclear decays
- 0νbb ^{136}Xe
- 0ν / 2νECEC ^{124}Xe

Solar Axions

… and even more!

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