

Dark Matter (and more) with DARWIN / XLZD

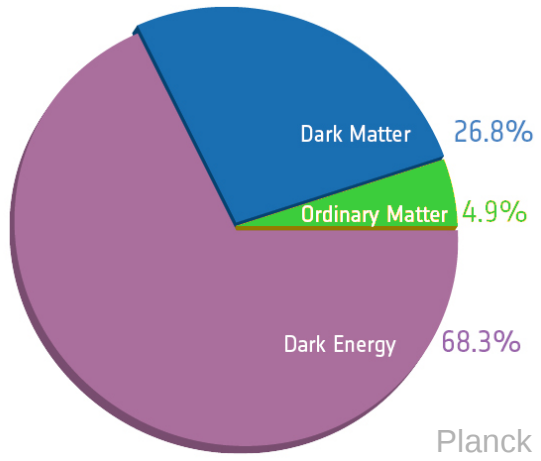
Marc Schumann University of Freiburg

Helmholtz MU Days, KIT 15.09.2023

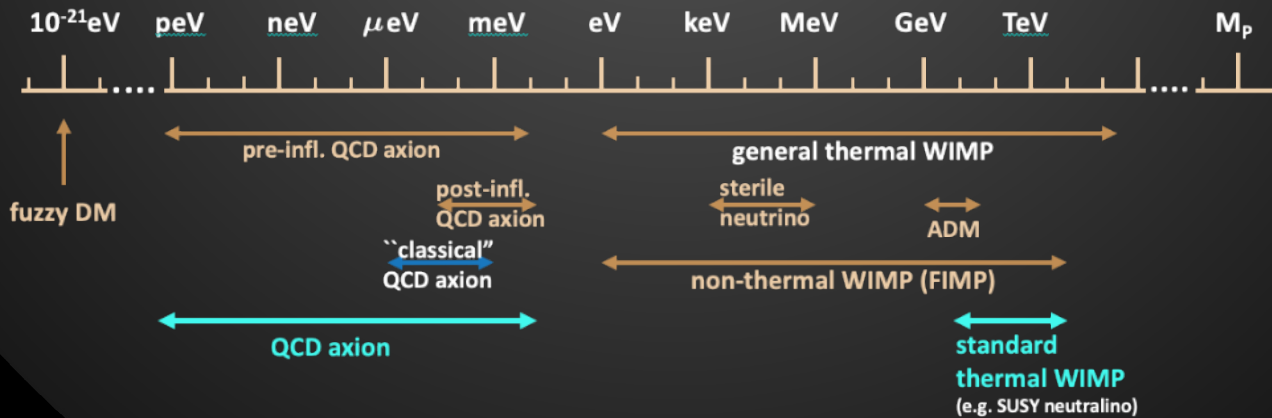
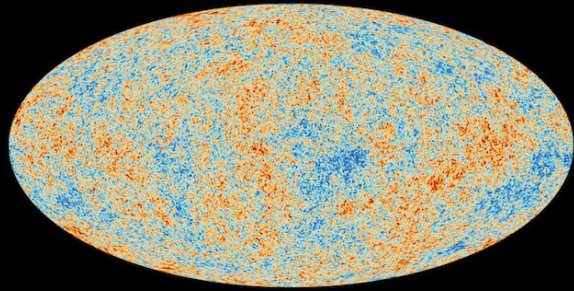
www.app.uni-freiburg.de

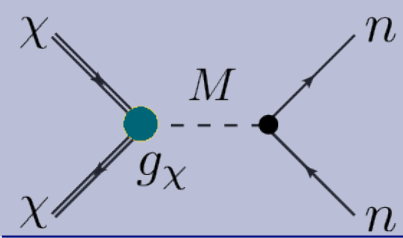


universität freiburg



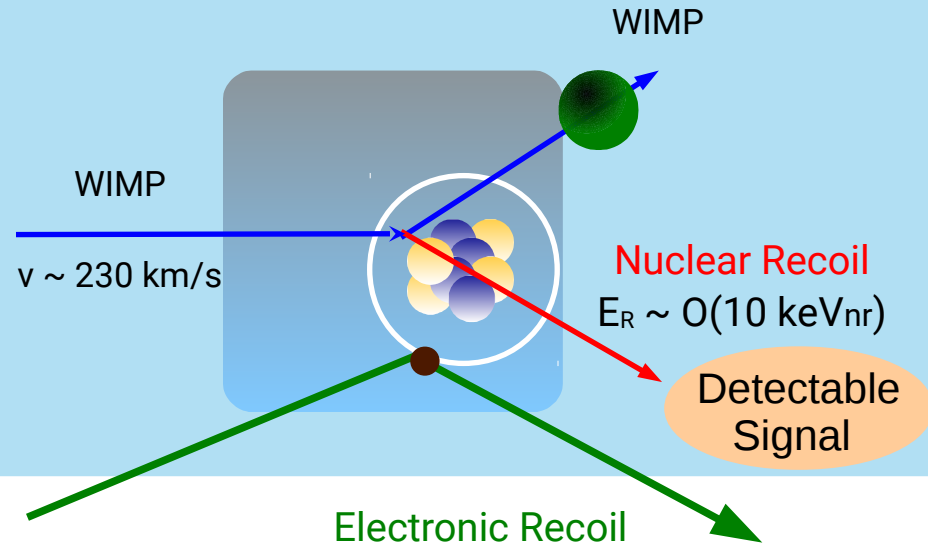
The indirect evidence for the existence of dark matter is a clear indication for physics beyond the Standard Model



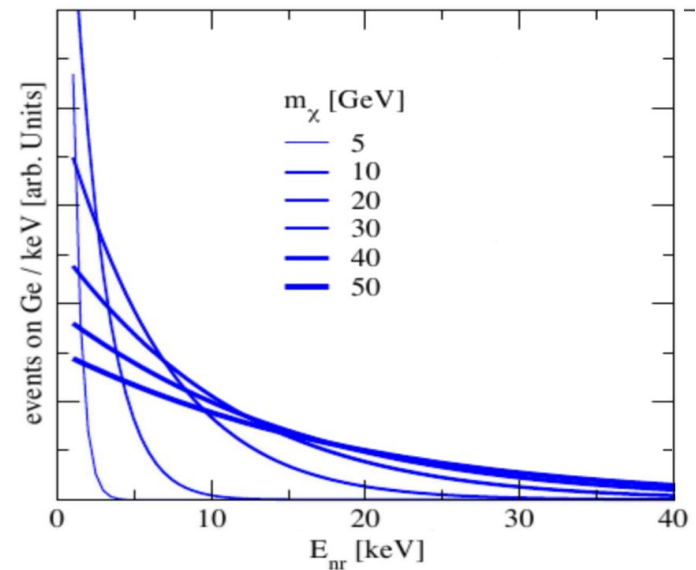
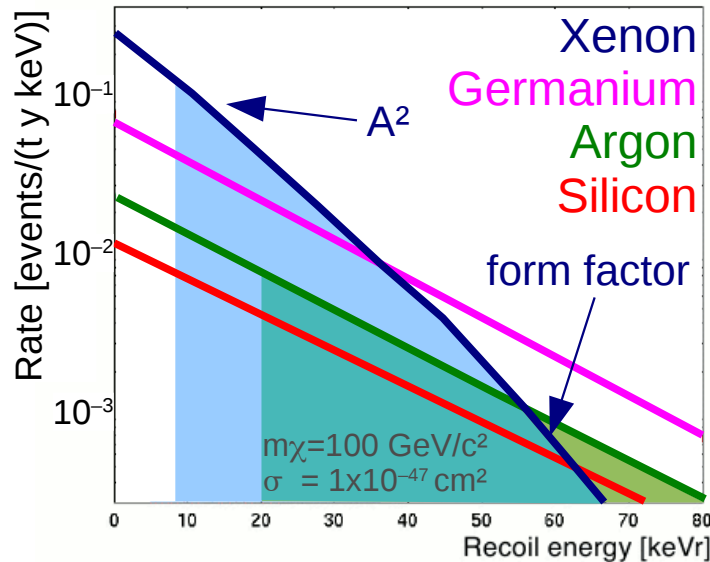


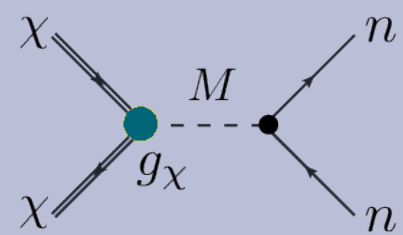
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
 → nuclear recoil



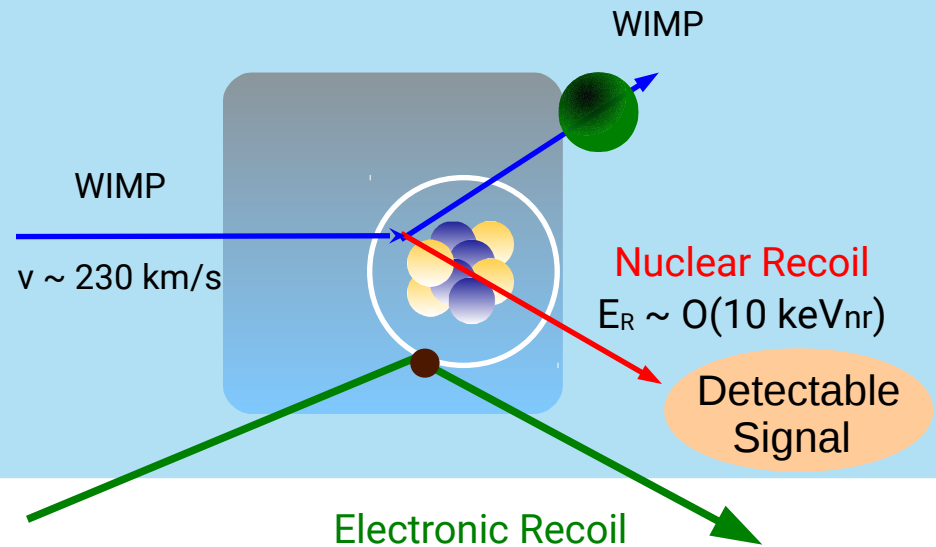
Recoil Spectra:



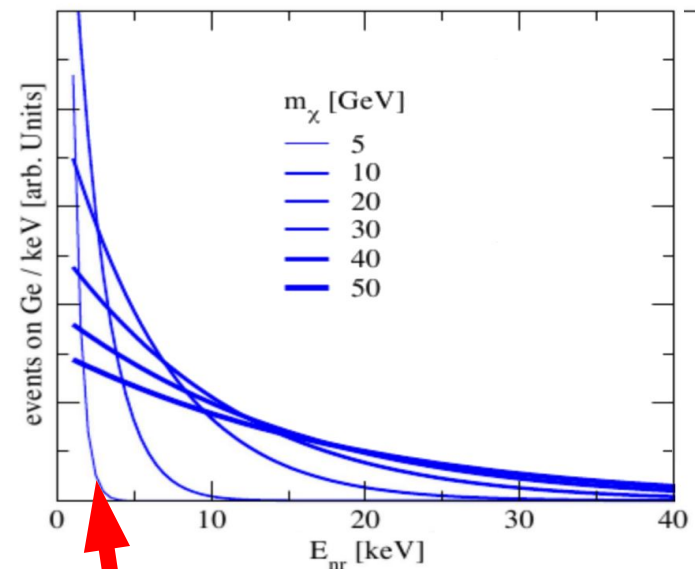
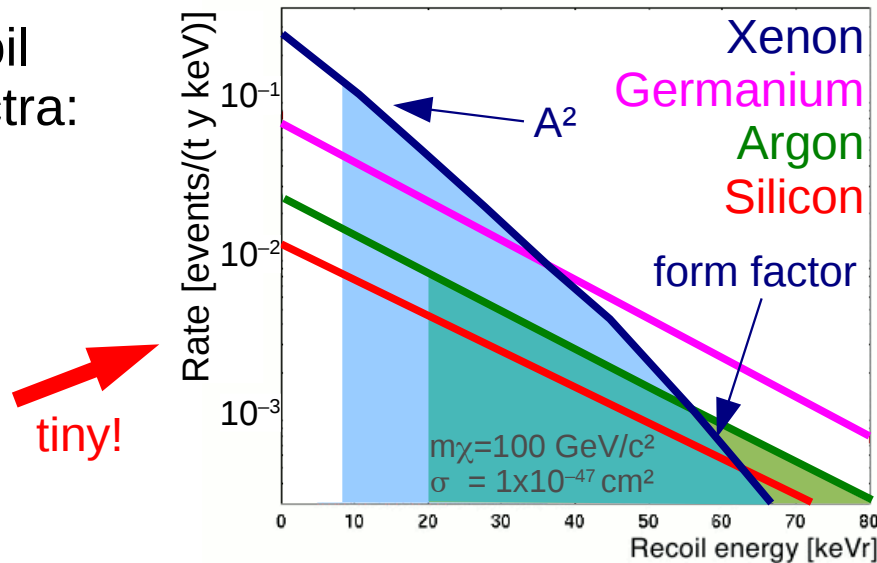


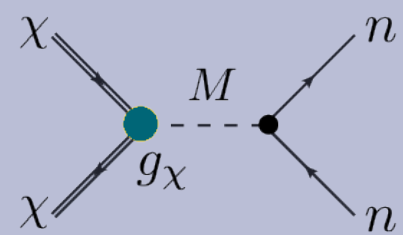
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
 → nuclear recoil



Recoil Spectra:

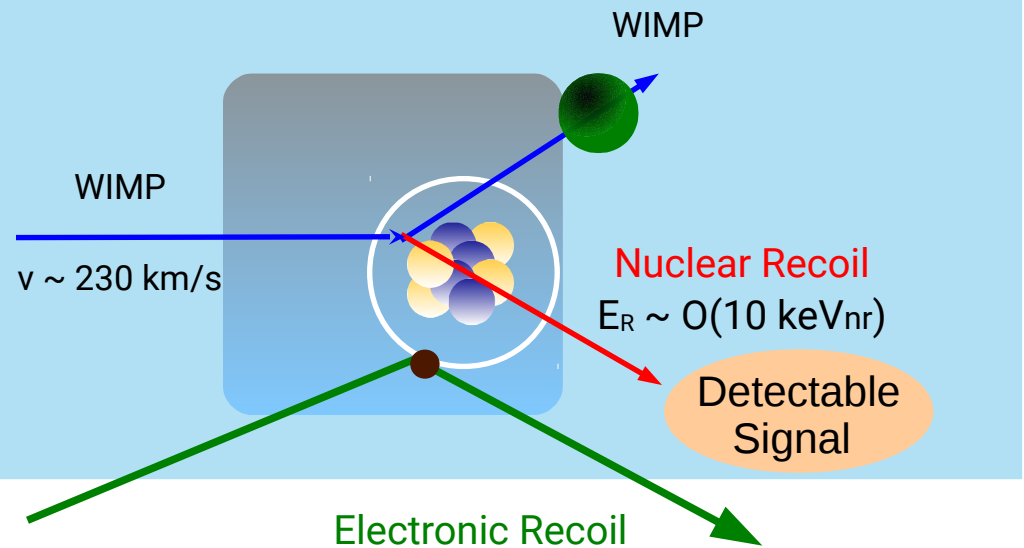




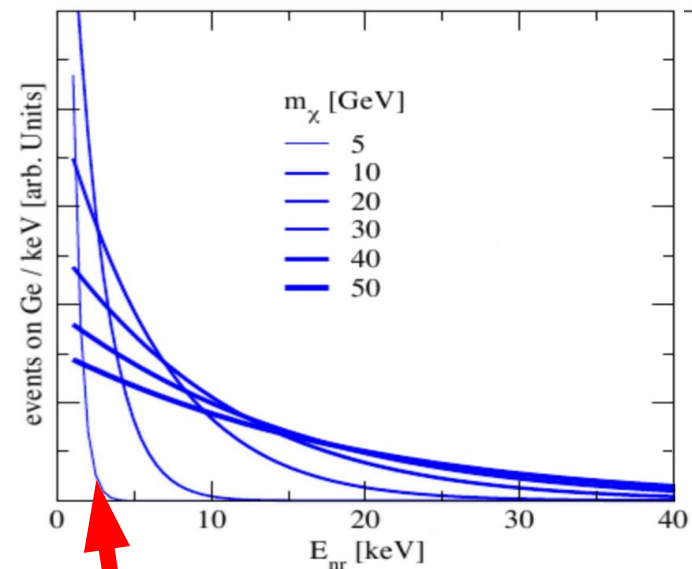
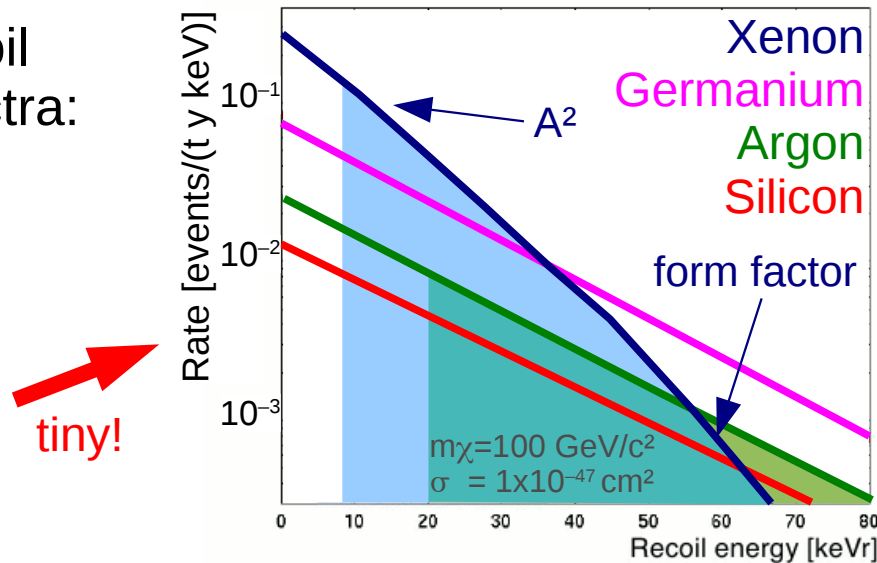
Direct WIMP Search

How to build a WIMP detector?

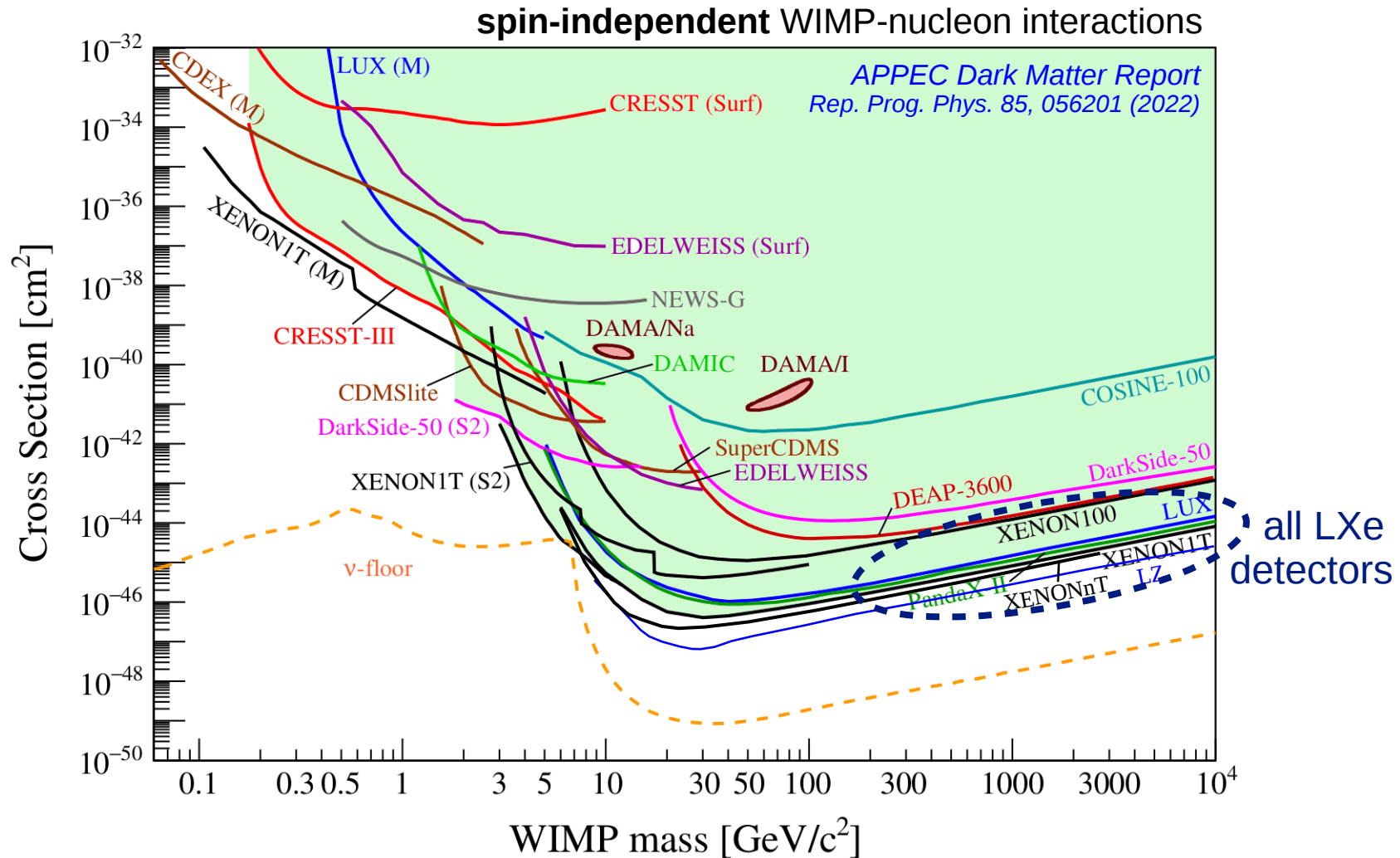
- large total mass, high A
- low energy threshold
- ultra low background
- good signal / background discrimination



Recoil Spectra:

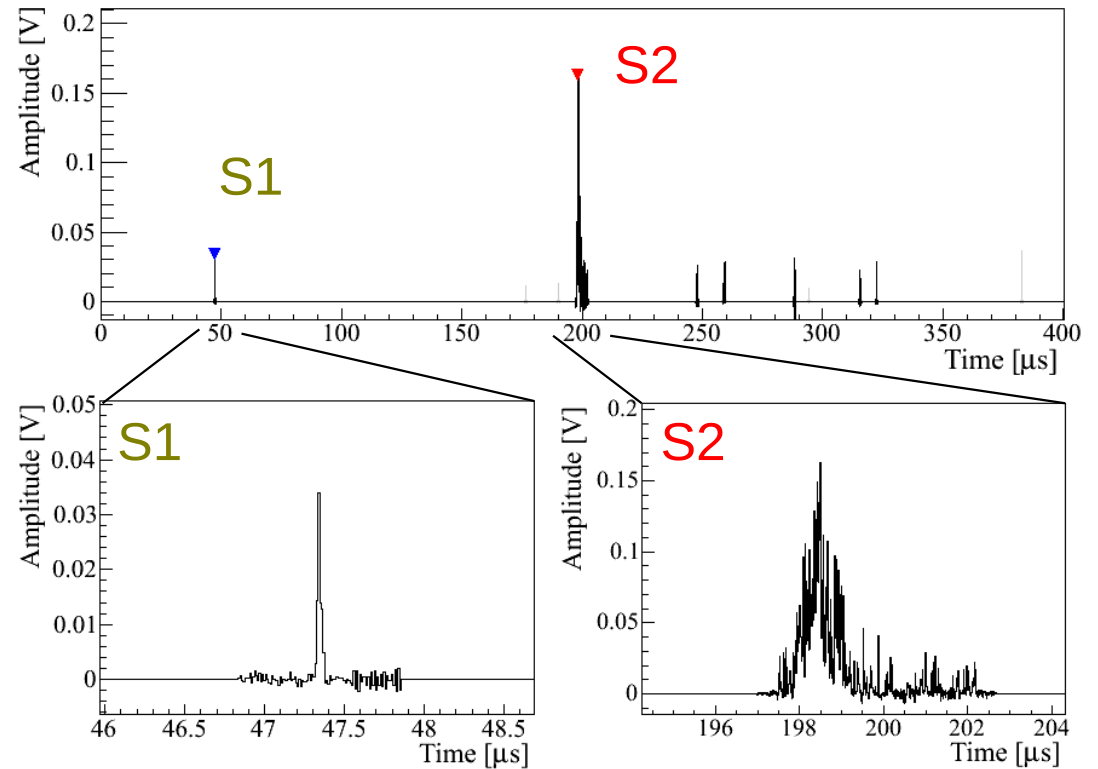
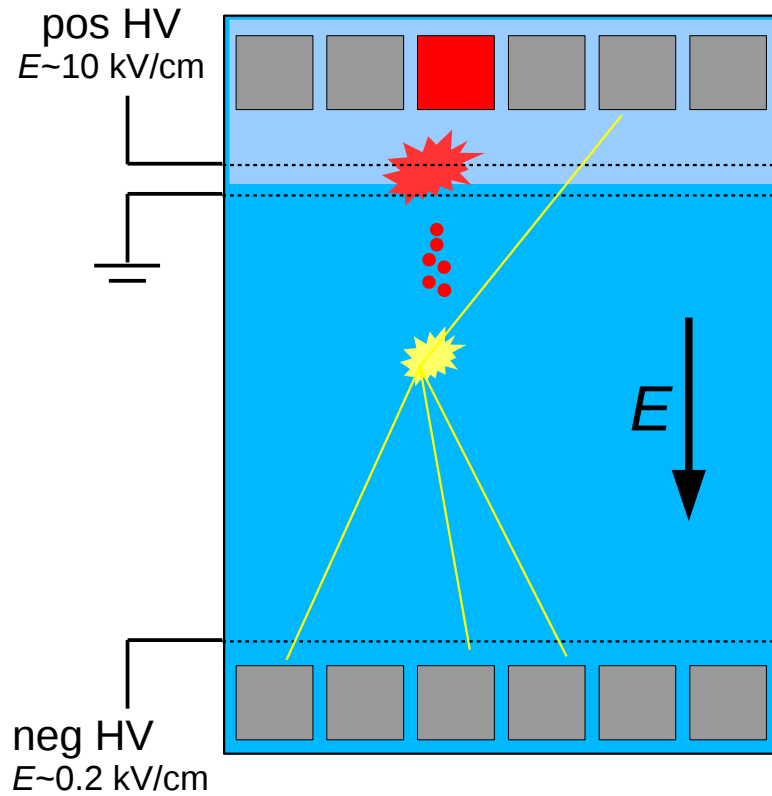


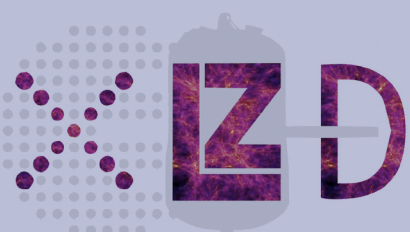
Current Status: WIMPs



Dual Phase TPC

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





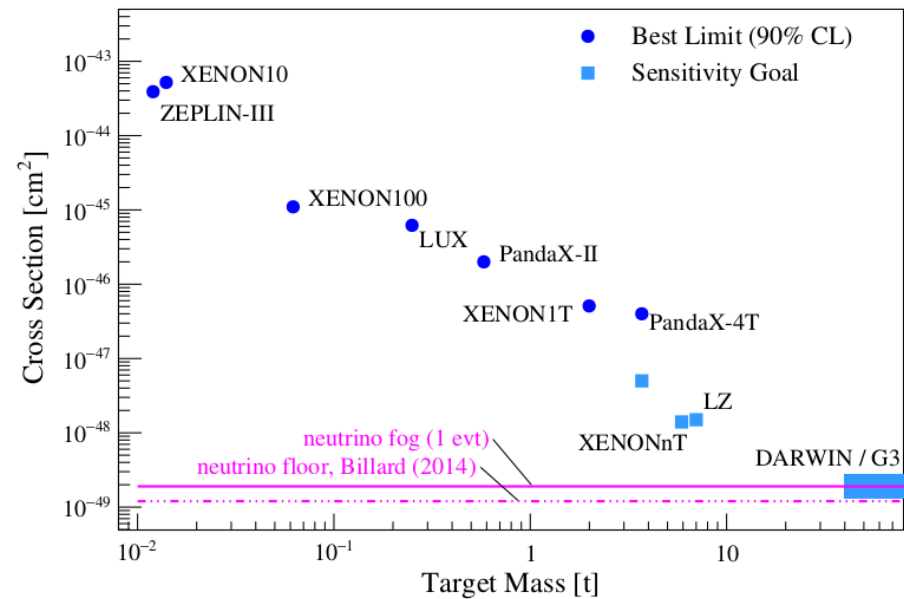
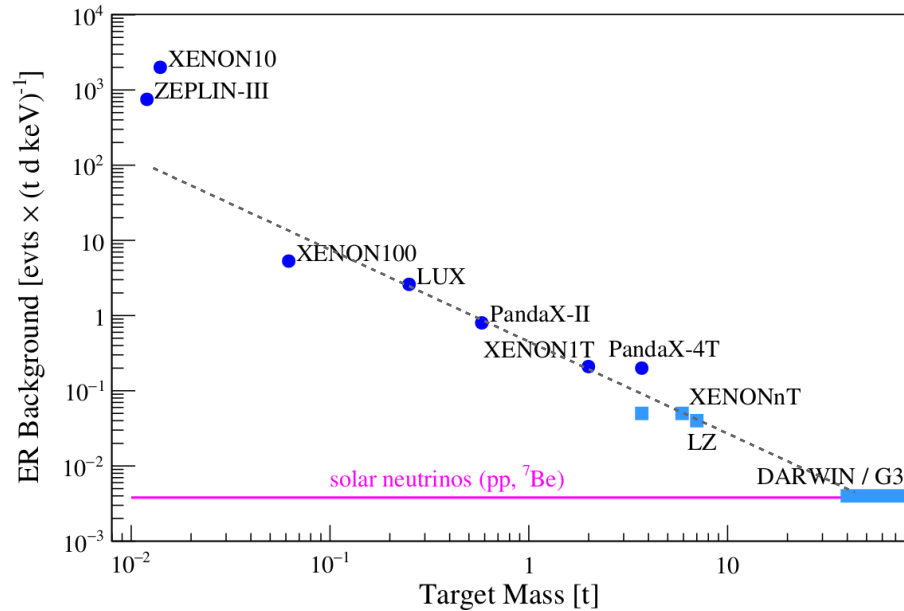
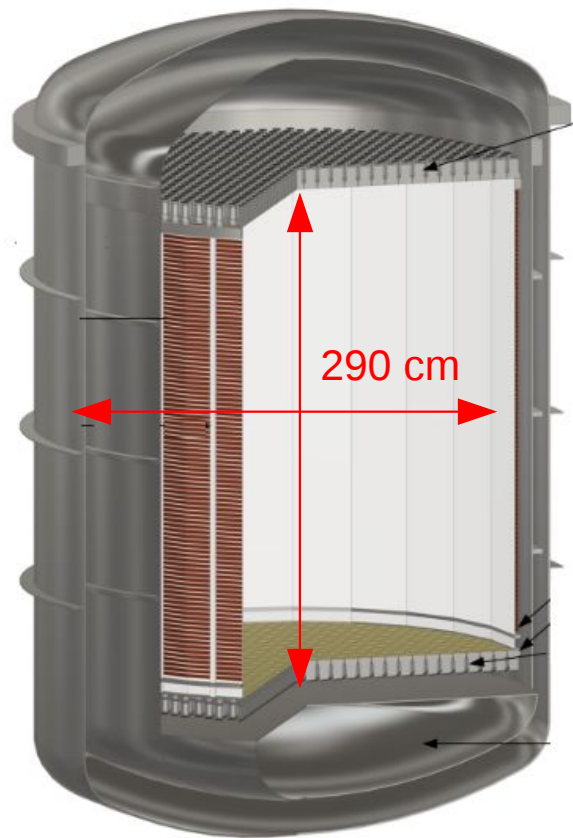
The ultimate LXe WIMP Detector

Background dominated by irreducible neutrinos

Baseline design

- ~73t total LXe mass
- ~60 t LXe TPC
- ~54 t fiducial mass

PRELIMINARY



XENON + LZ + DARWIN =

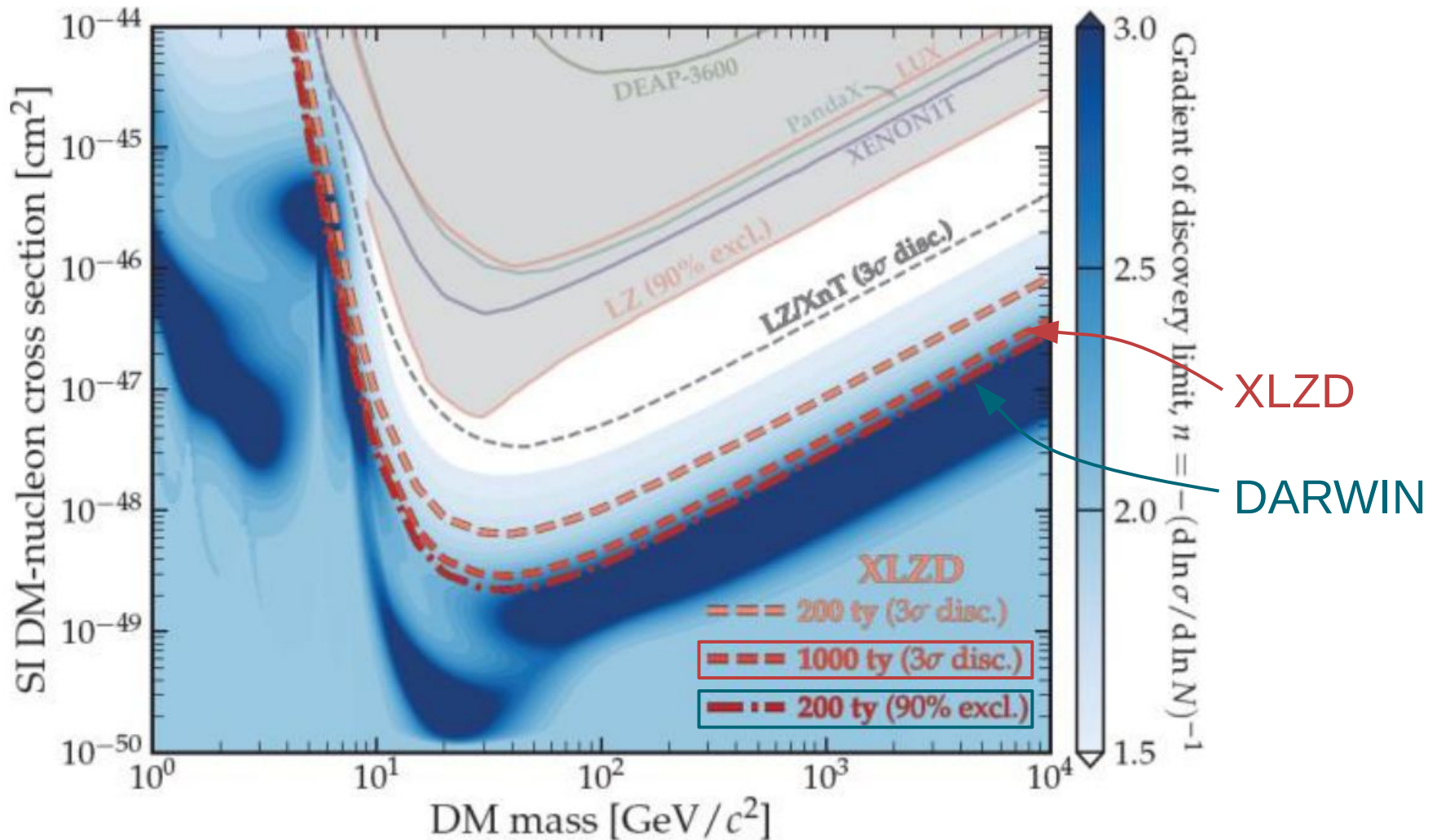
www.xlzd.org



- 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 ↔ XLZD: Science Reach



200 t \times y: probe entire mass range ≥ 10 GeV at 90% CL

DARWIN (40t)

1000 t \times y: probe entire mass range ≥ 10 GeV at 3 σ evidence

XLZD (60t+)
+lower bg for $0\nu\beta\beta$

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

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H. M. Araújo,⁹ S. Baek,¹⁰ D. Bajpai,¹¹ A. Bandyopadhyay,¹² L. Baudis,¹³ A. L. Baxter,¹ N. F. Bell,¹⁴
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...

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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. Panesar, *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)



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

Spin-Dependent WIMP Couplings

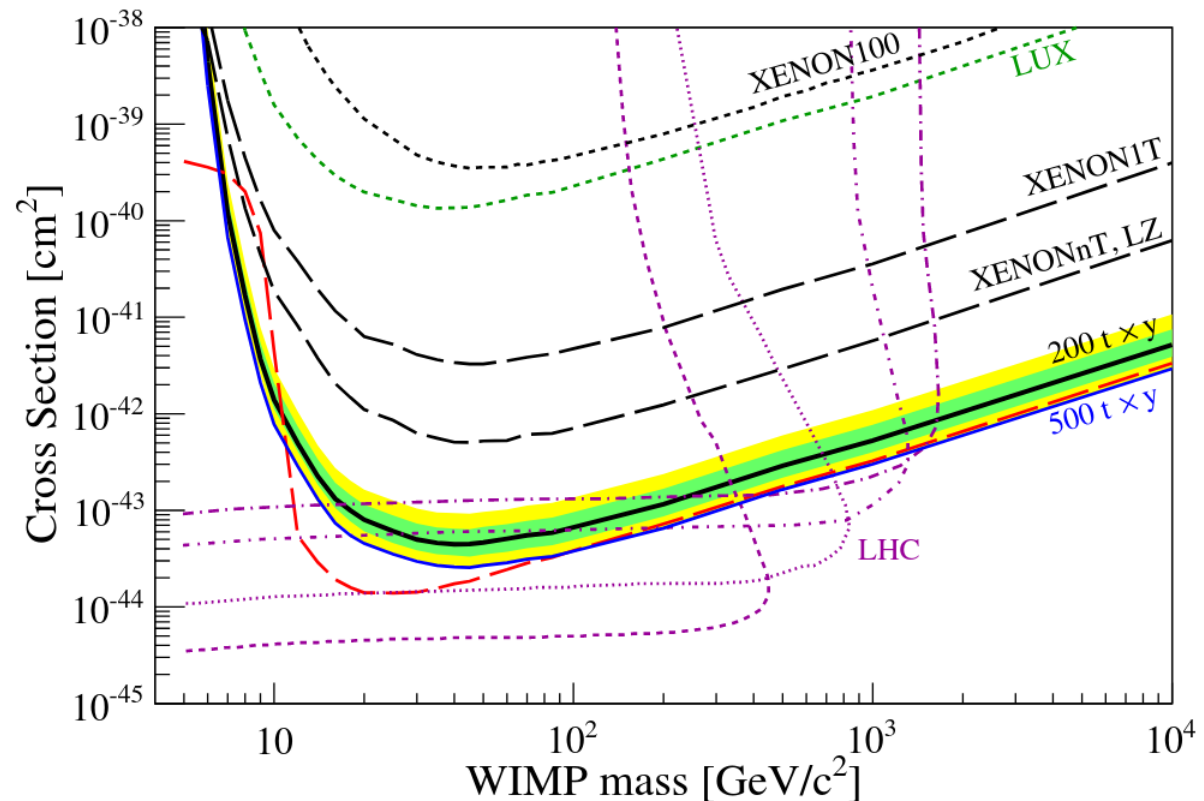
JCAP 10, 016 (2015)

- 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

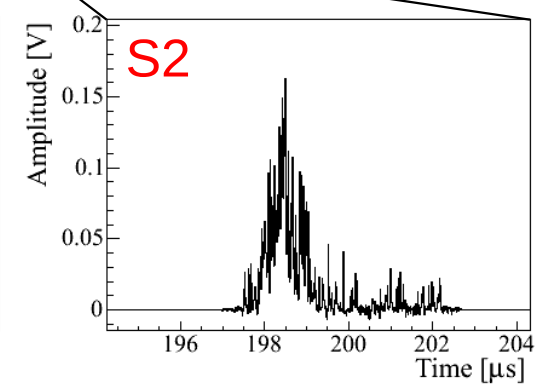
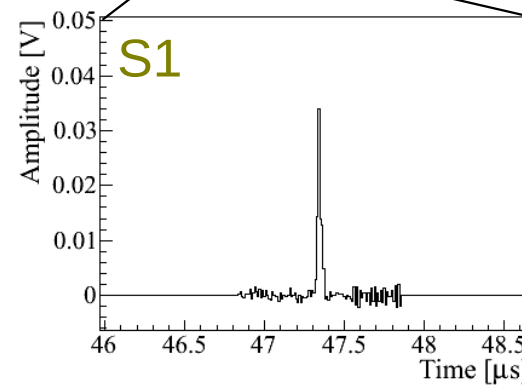
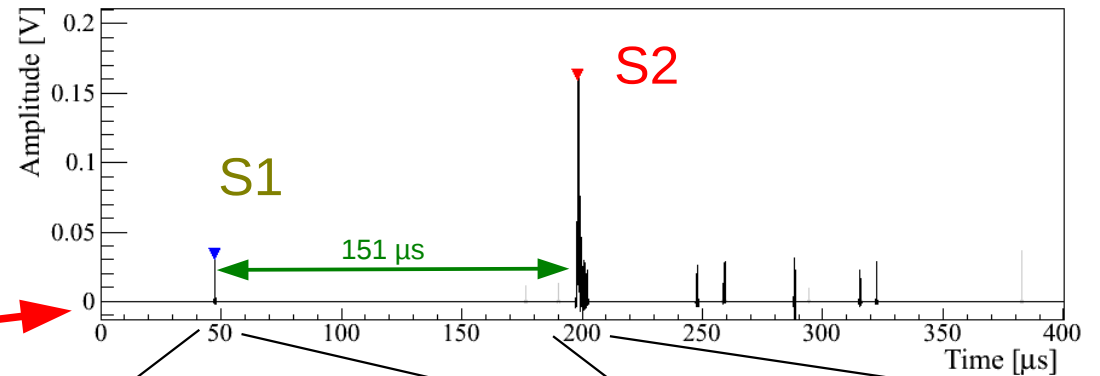
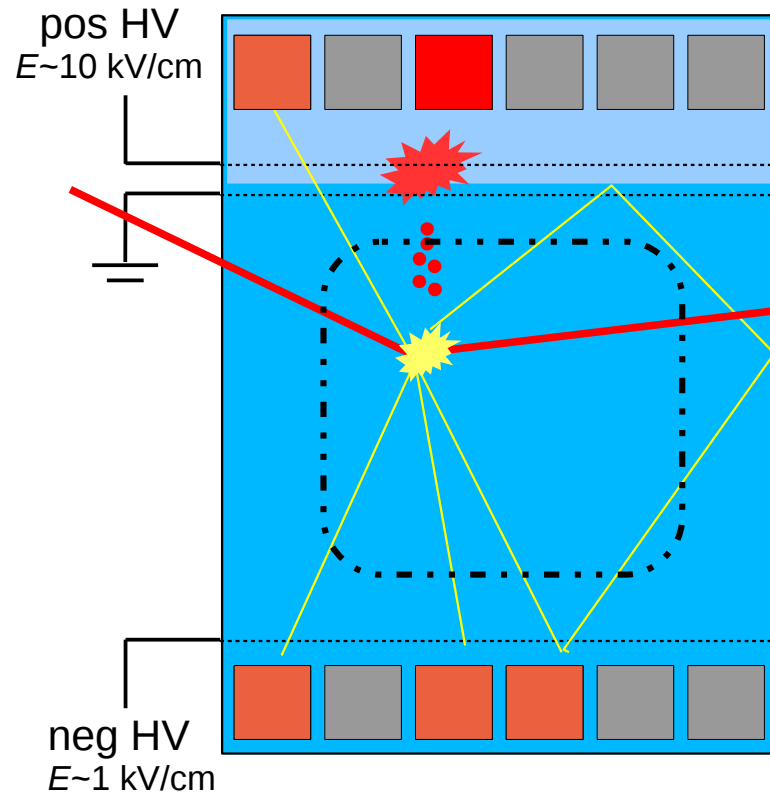
Isotope	Abundance	Spin	Unpaired Nucleon	Relative Strength
${}^7\text{Li}$	92.6%	3/2	proton	12.8
${}^{19}\text{F}$	100.0%	1/2	proton	100.0
${}^{23}\text{Na}$	100.0%	3/2	proton	1.3
${}^{29}\text{Si}$	4.7%	1/2	neutron	9.7
${}^{73}\text{Ge}$	7.7%	9/2	neutron	0.3
${}^{127}\text{I}$	100.0%	5/2	proton	0.3
${}^{131}\text{Xe}$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

WIMP-neutron scattering

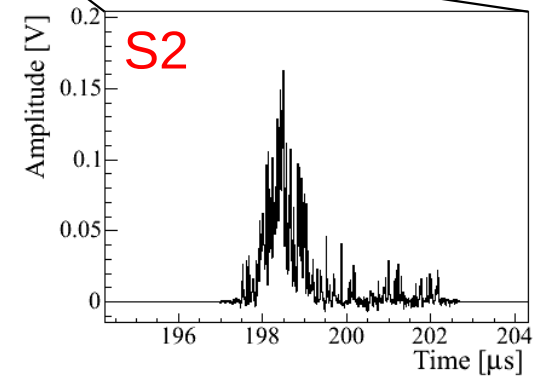
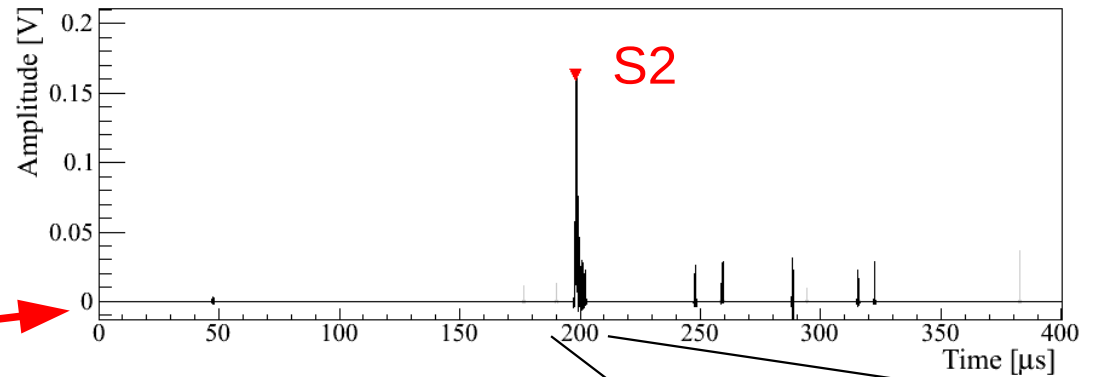
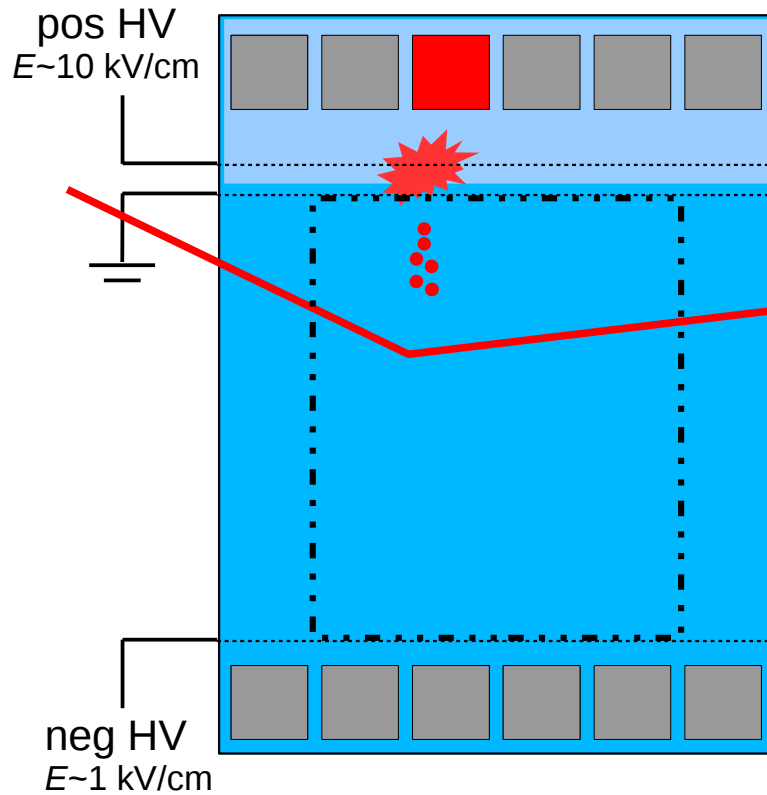
Interpretation of same WIMP search data



Standard Analysis

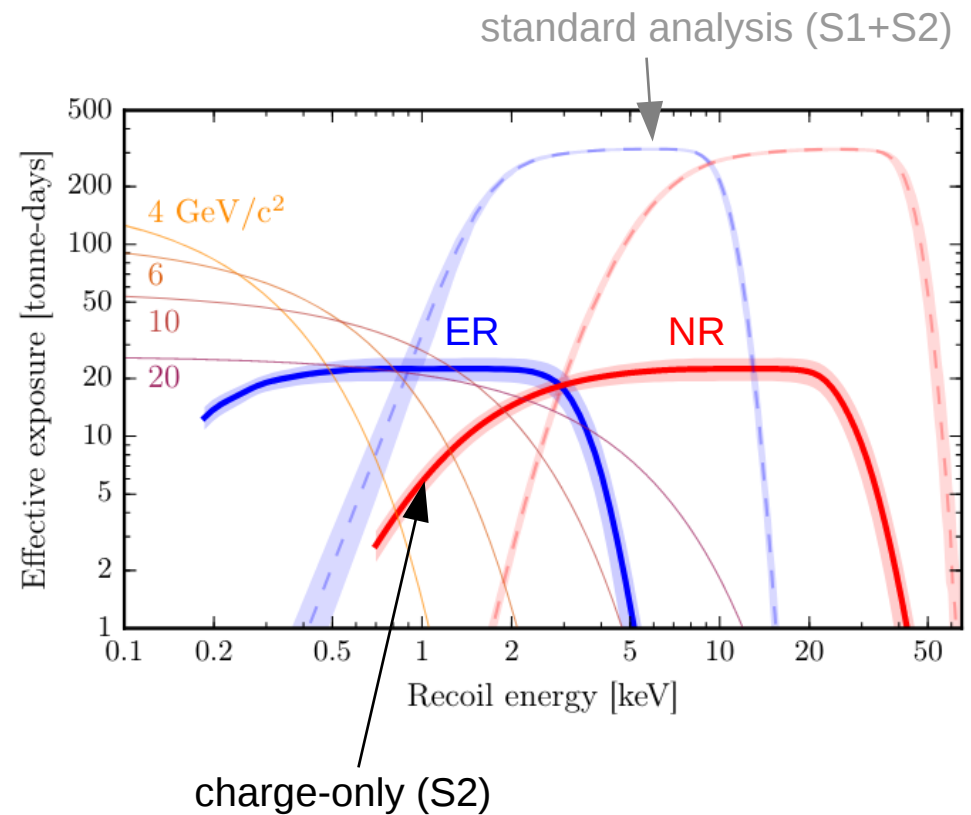
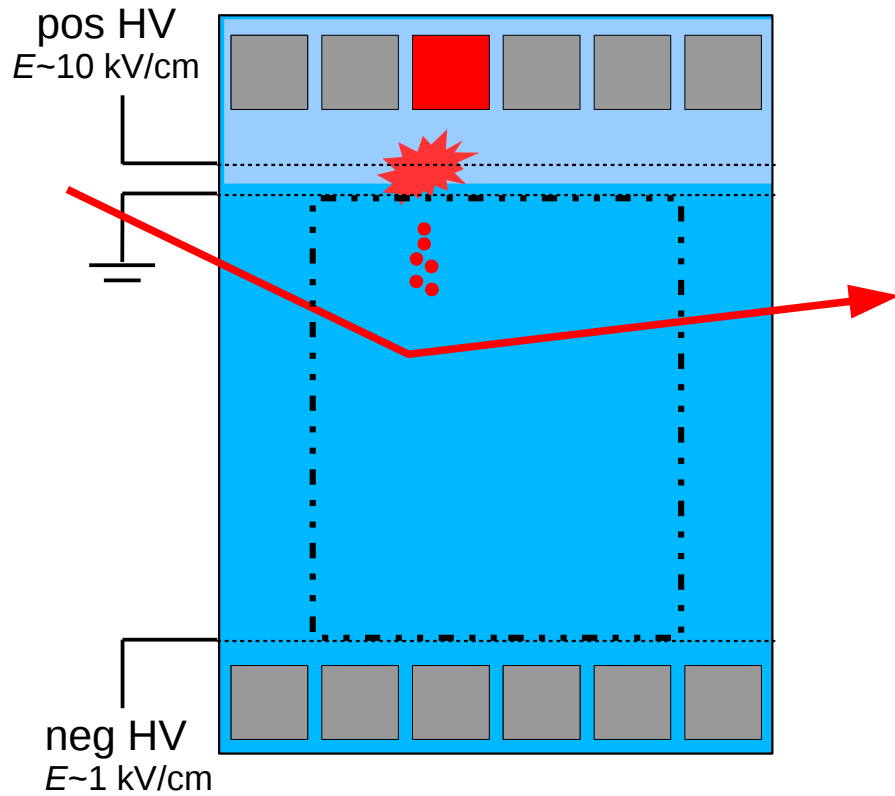


Charge-Only Analysis



Charge-Only Analysis

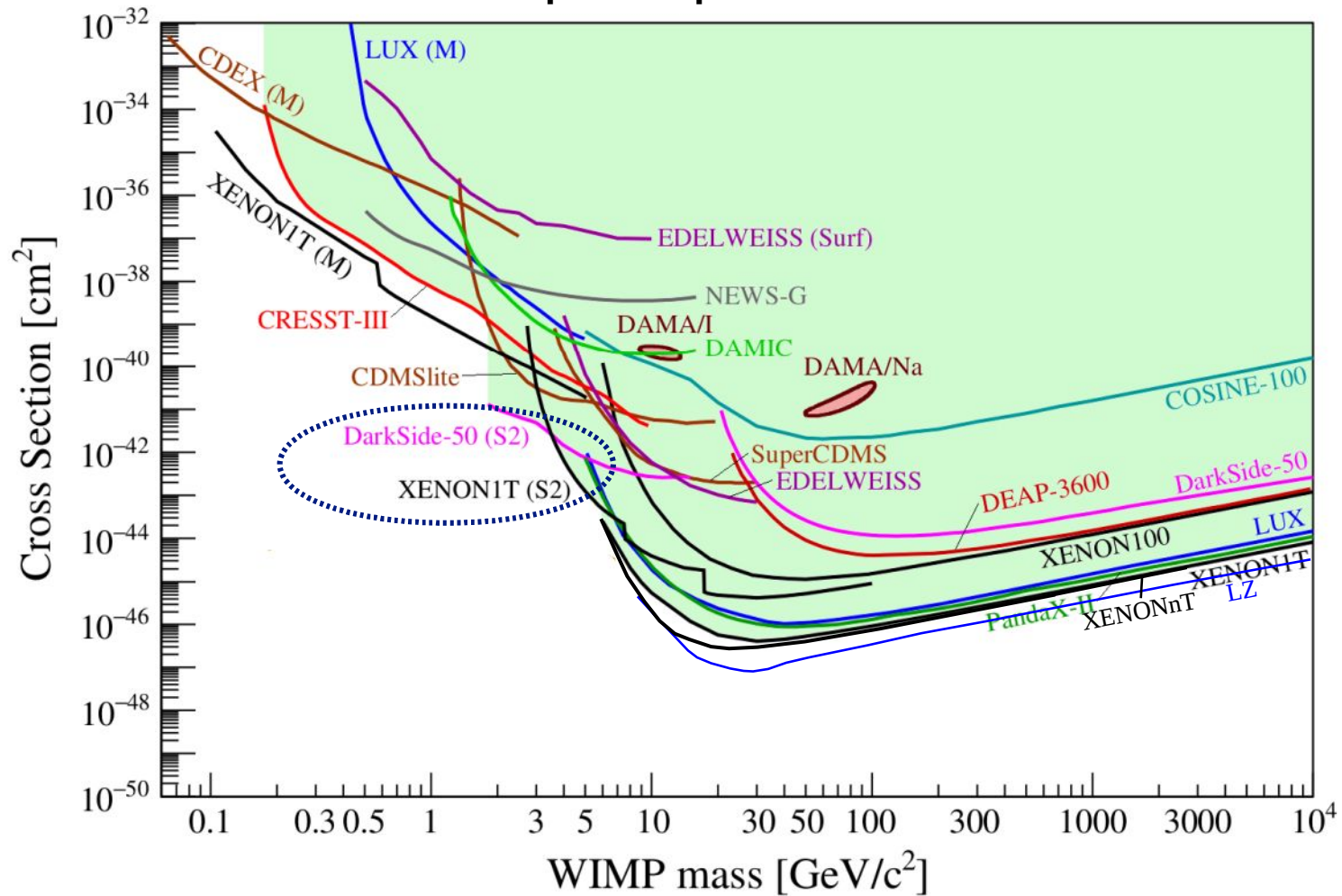
PRL 123, 251801 (2019)



Charge-Only Analysis

PRL 123, 251801 (2019)

spin-independent WIMP-nucleon interactions

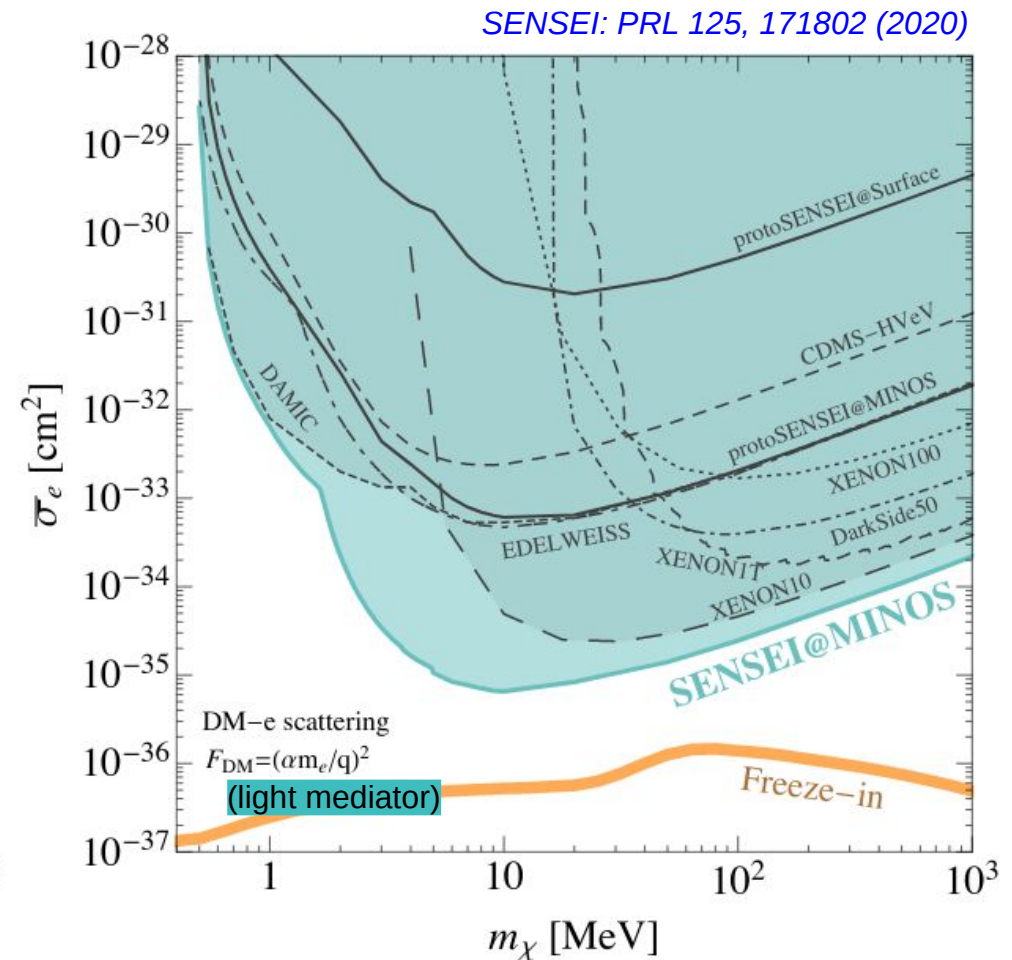
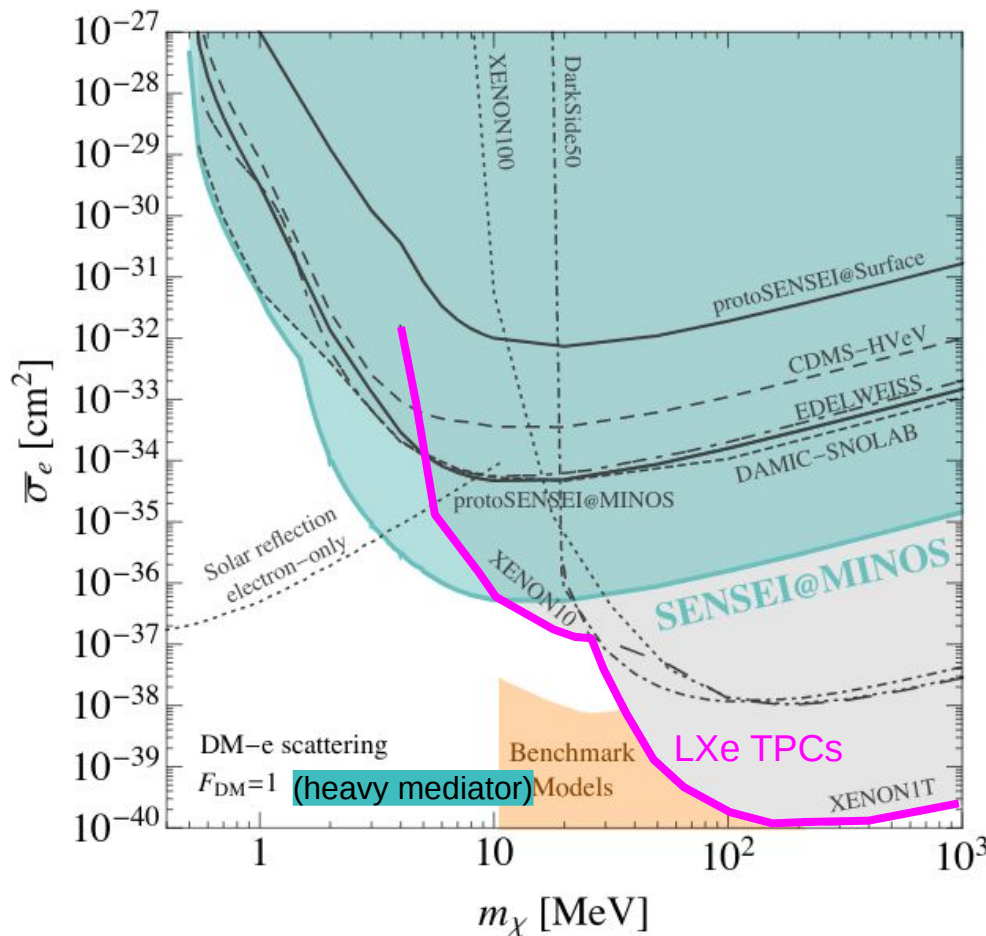
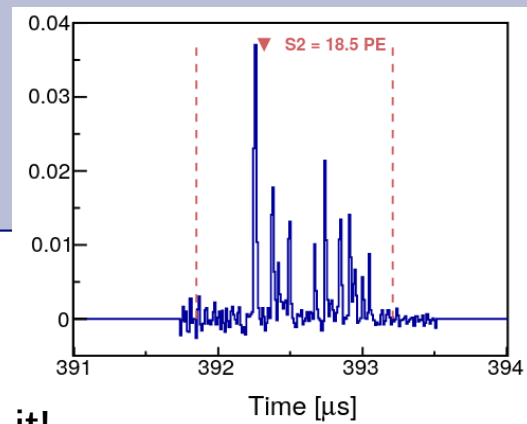


some results are missing...

WIMP- e^- Scattering

Very light DM scatters off electrons

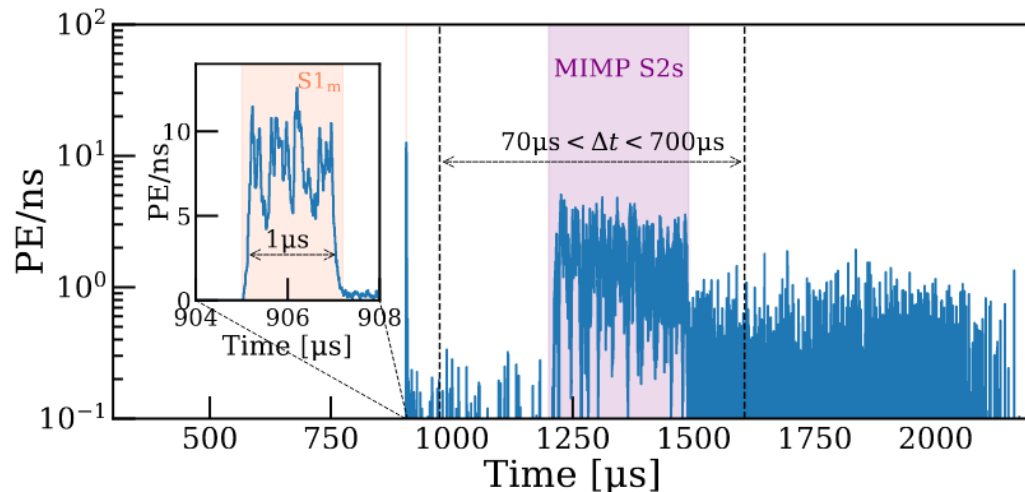
Detectors with single- e^- sensitivity required \rightarrow LXe TPCs have it!



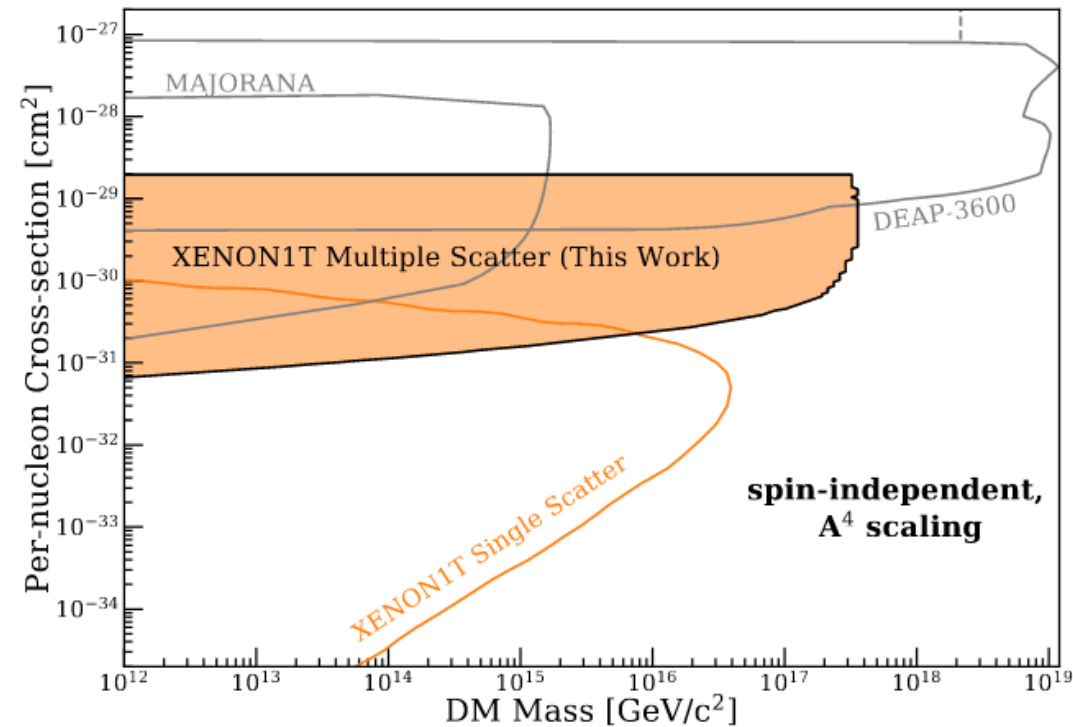
Planck-Scale Dark Matter

PRL 130, 261002 (2023)

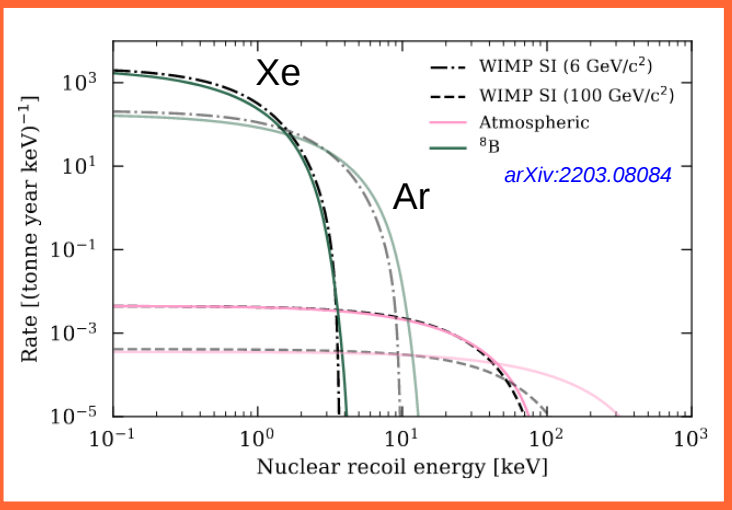
- Some production mechanisms predict DM near Planck mass $\sim 10^{19}$ GeV/c²
- Spin-independent cross section $\propto A^4$
- Expected flux: ~ 1 evt/(m² × yr) → flux limited
- Signal: multiple scattering → **Multiply-Interacting Massive Particle (MIMP)**



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

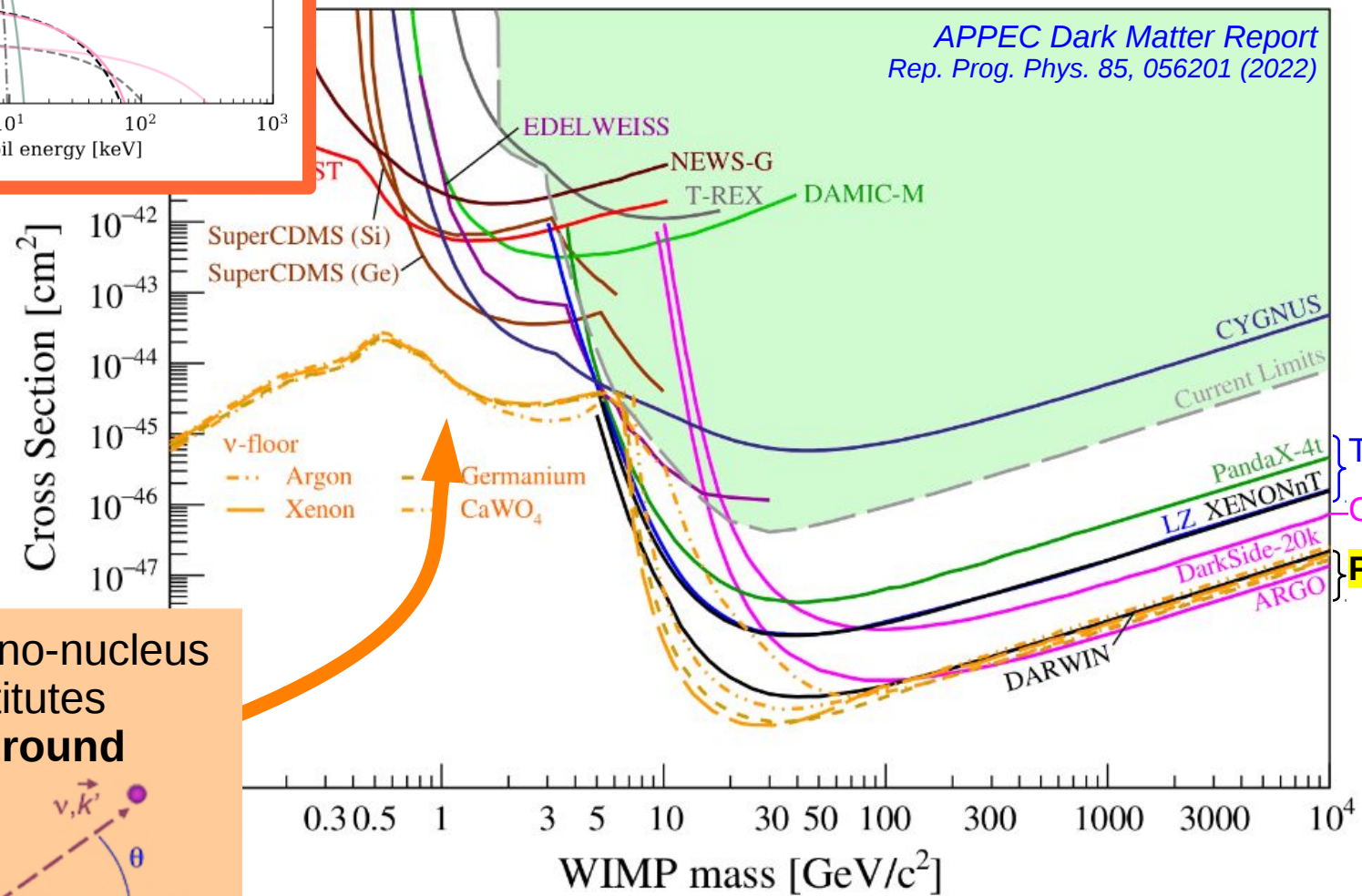


The Neutrino Floor

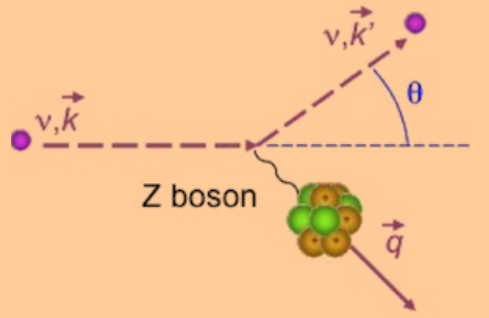


spin-independent WIMP-nucleon interactions

APPEC Dark Matter Report
Rep. Prog. Phys. 85, 056201 (2022)

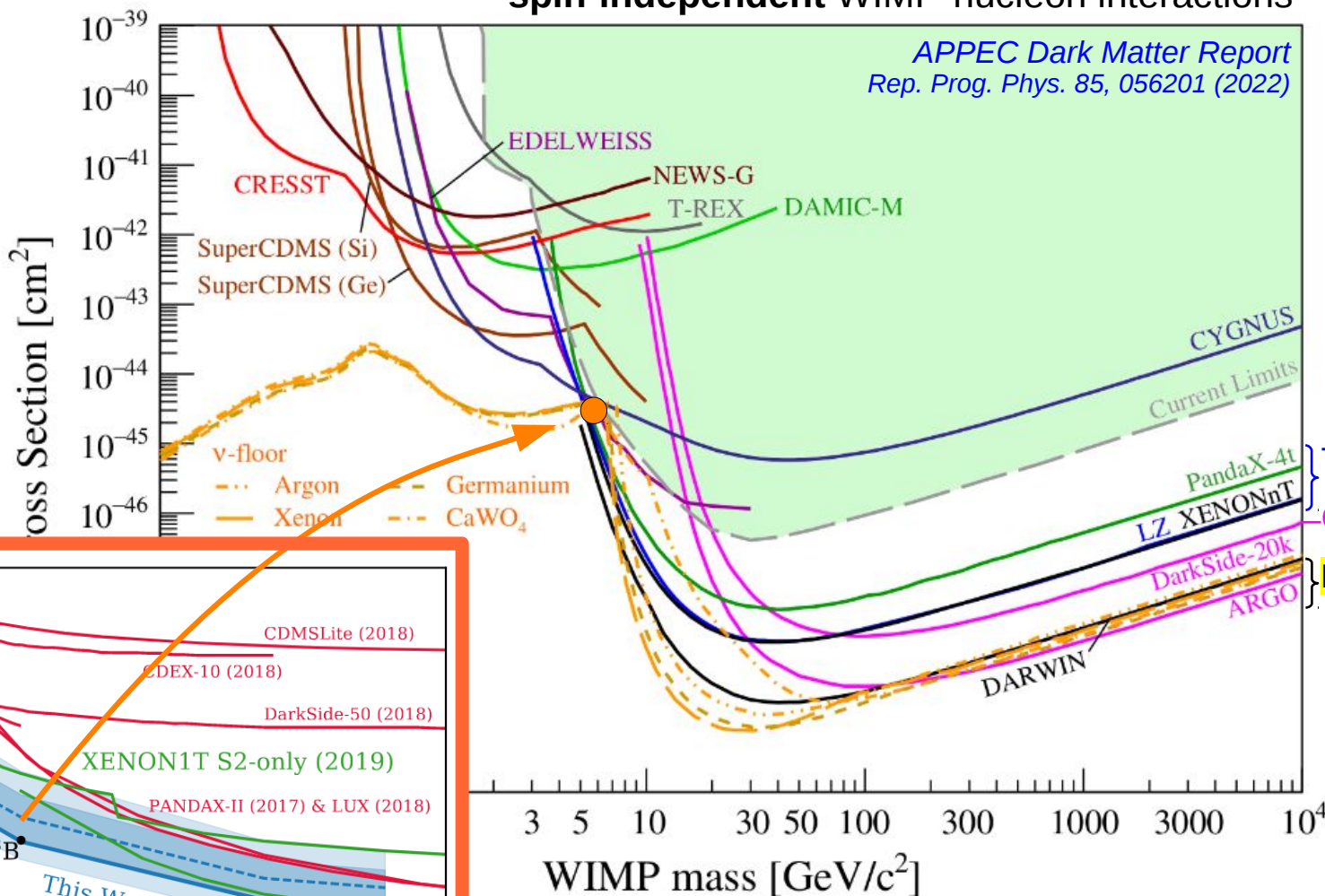


Coherent neutrino-nucleus scattering constitutes ultimate background

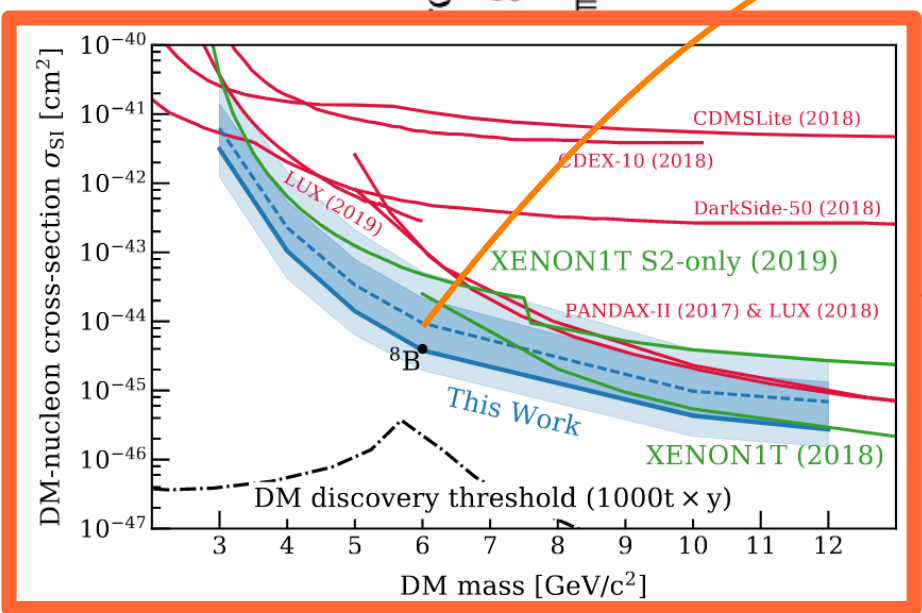


Almost there...

spin-independent WIMP-nucleon interactions



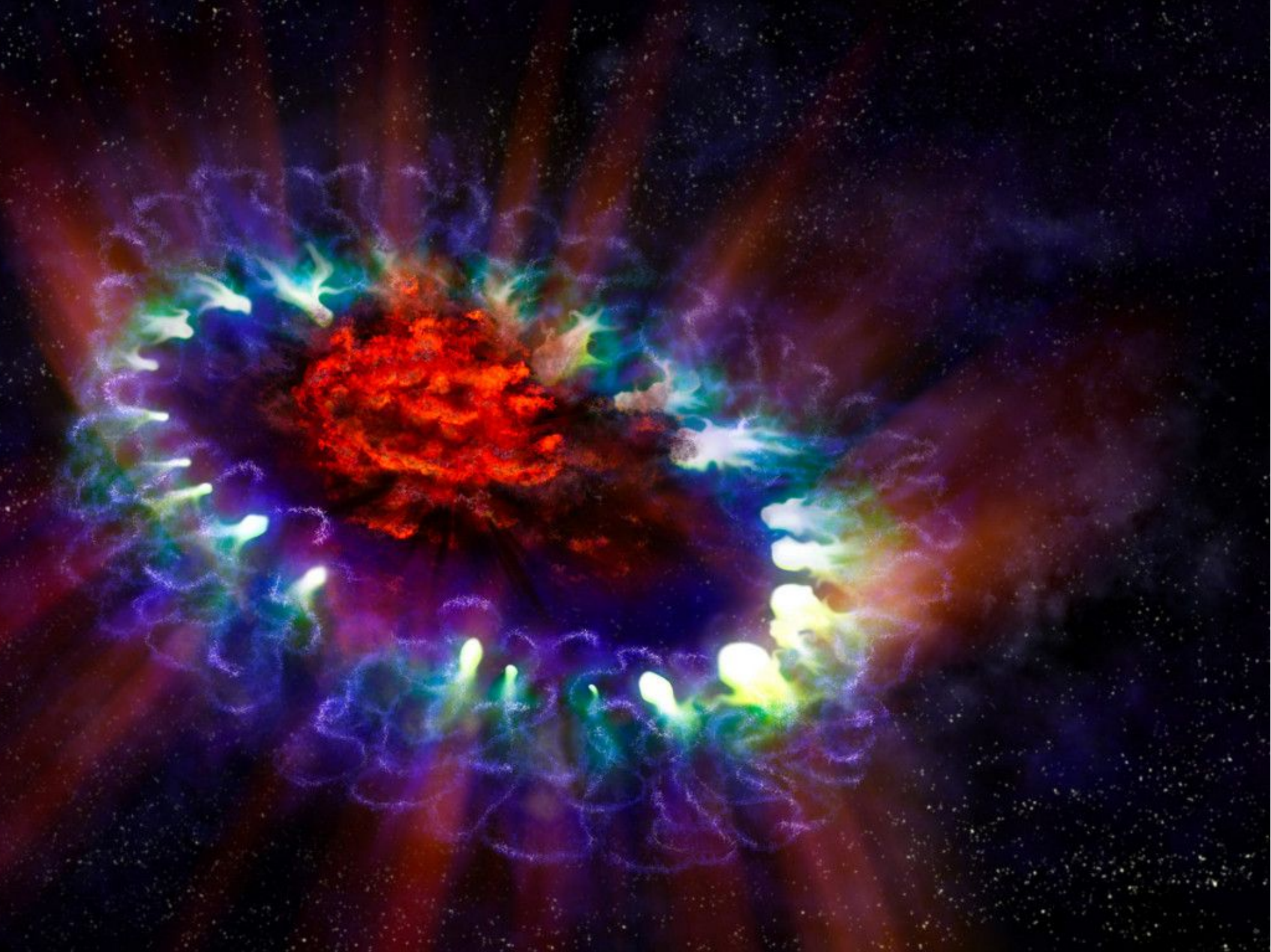
Taking data
Construction
Plan



XENON1T low-threshold search (S1+S2)

- 2.1 CNNS events (⁸B) expected
- no excess above background seen

Similar search by PandaX-4T [arXiv:2207.04883](https://arxiv.org/abs/2207.04883)

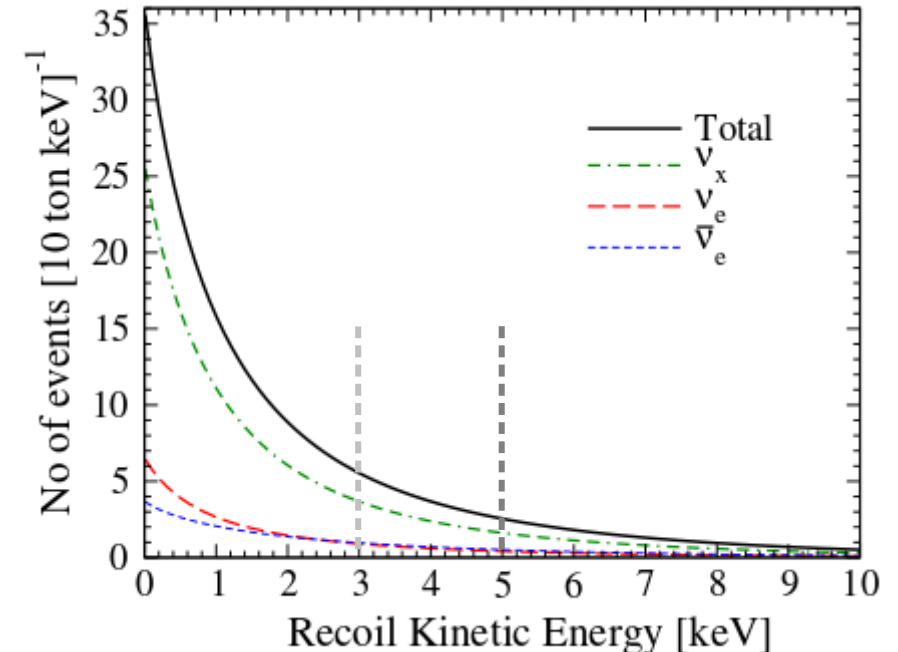
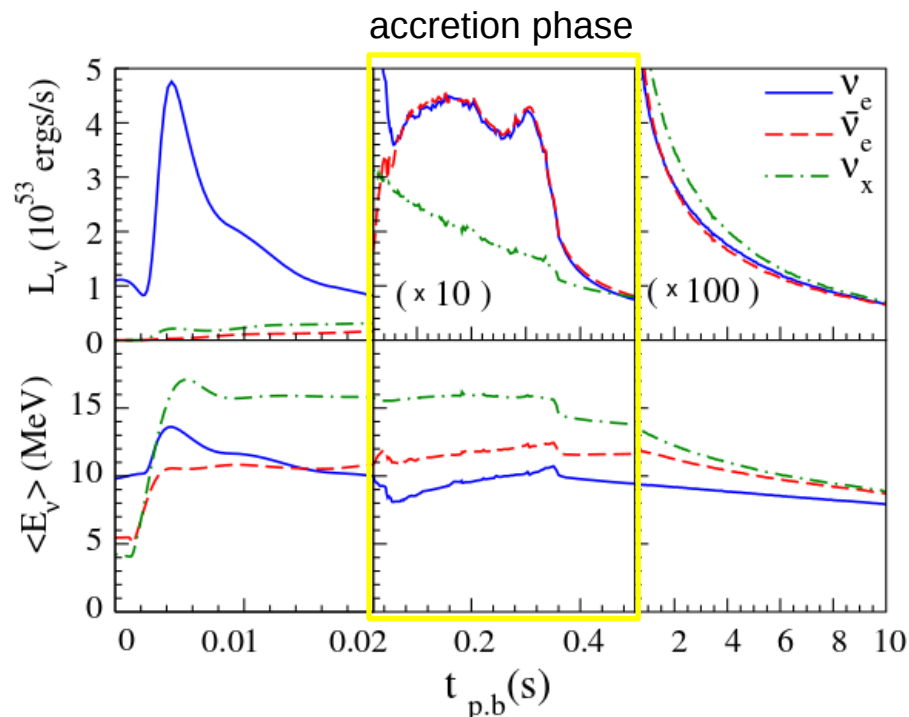


Supernova Neutrinos

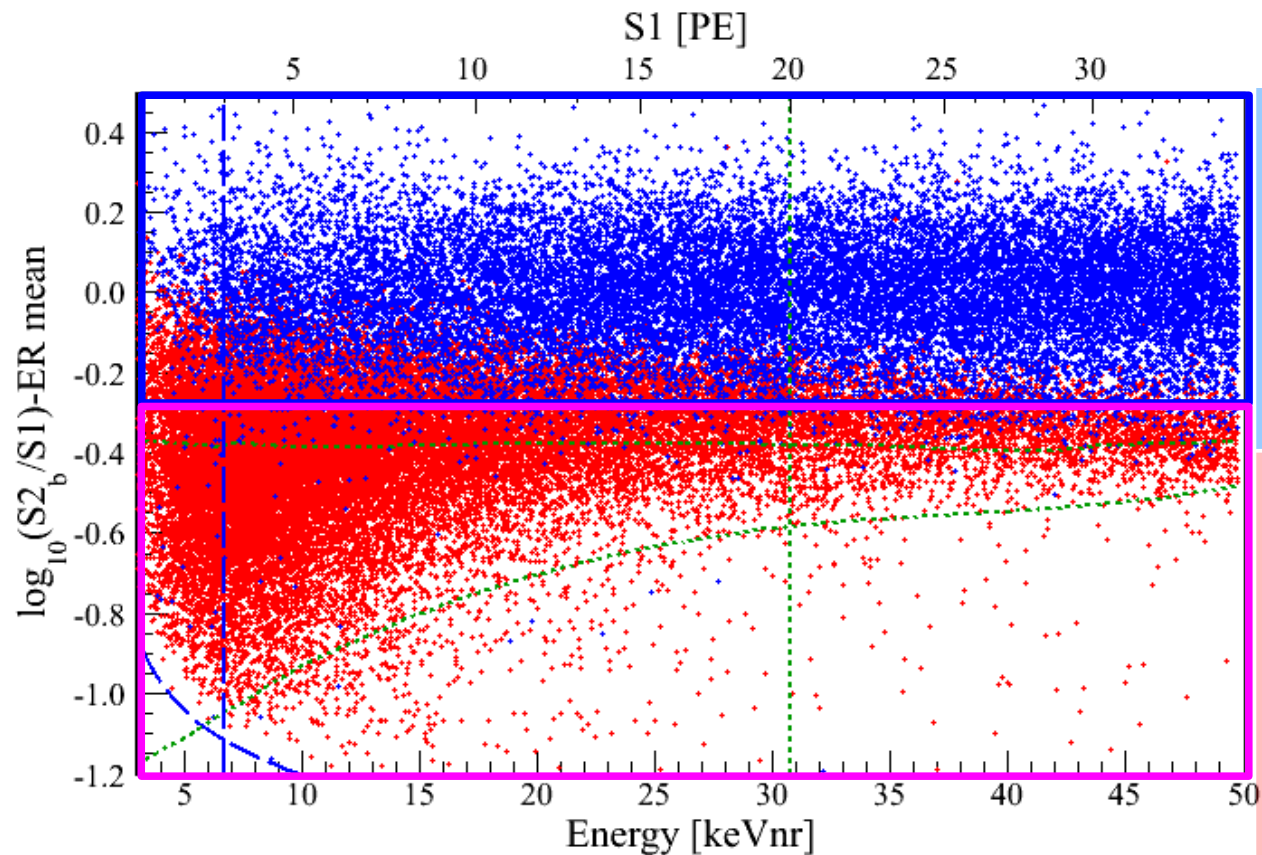
Chakraborty et al., PRD 89, 013011 (2014)

Lang et al., PRD 94, 103009 (2016)

- ν from supernovae could be detected via CNNS as well
- signal from accretion phase of a $\sim 18 M_{\text{sun}}$ supernova @ 10 kpc is visible in a **10t-LXe detector** (<DARWIN)
- signal: NRs plus precise time information
- challenge: threshold



Interactions in LXe Detectors



scattering off atomic electrons, excitations etc.

→ **electronic recoil**

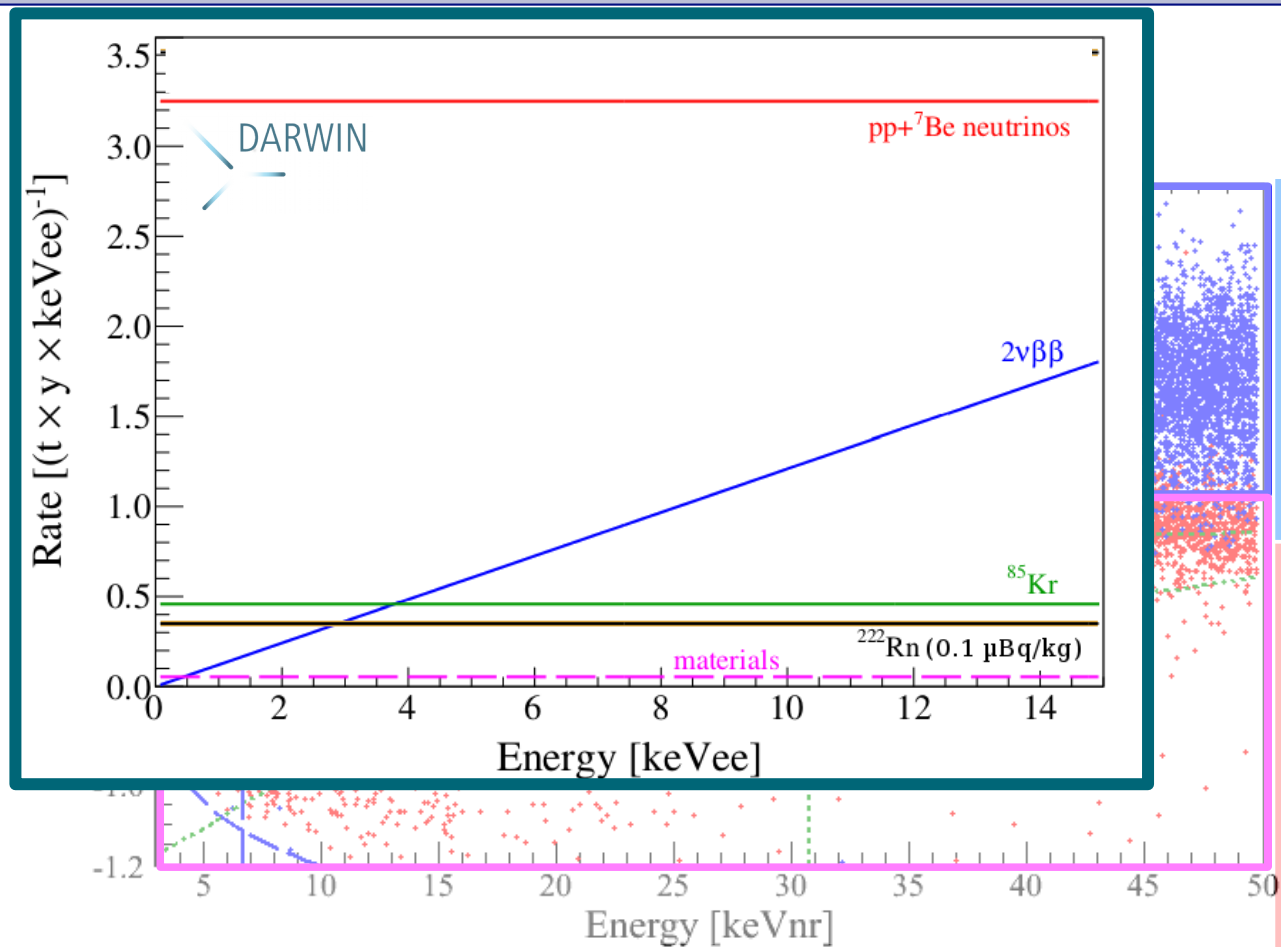
- rare processes detectable if ER background is low

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**

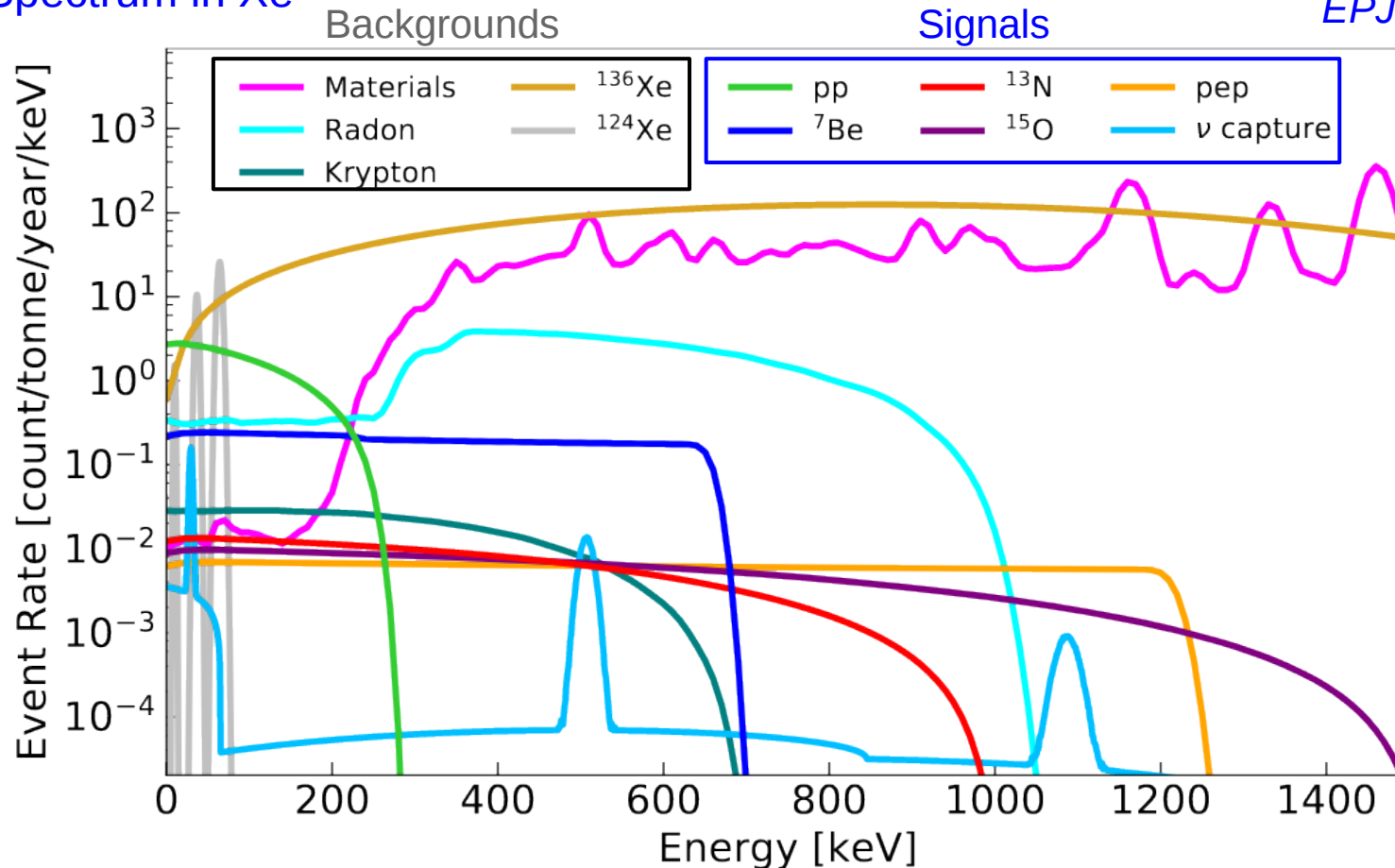
- Dark Matter
- CNNS
- Supernova Neutrinos

→ Many **science channels** are accessible

Solar Neutrinos

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

ER Spectrum in Xe

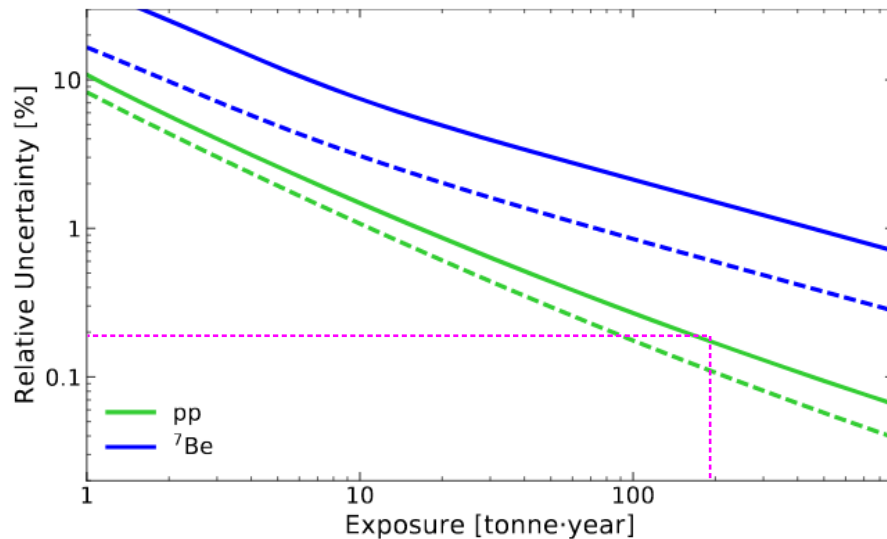
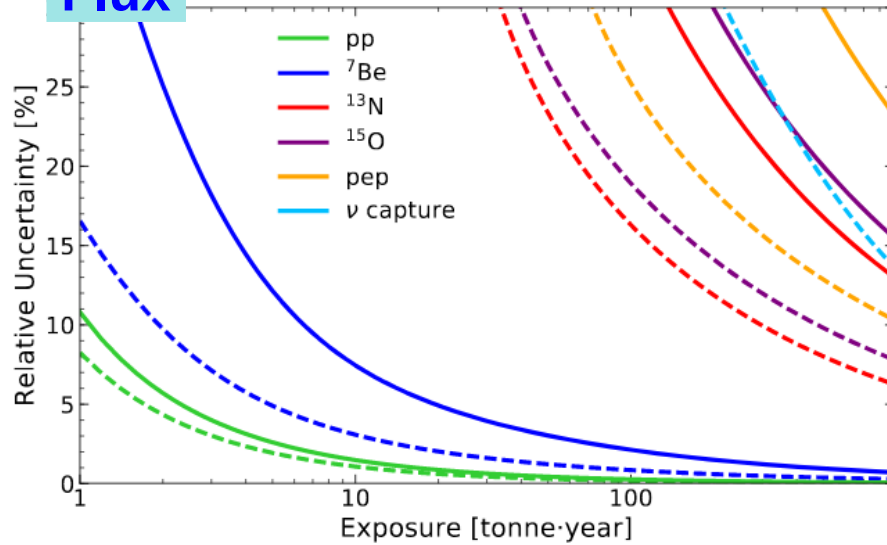


- DARWIN's low-E ER spectrum dominated by pp neutrinos (and $2\nu\text{ECEC}+2\nu\beta\beta$)
- distinct features in ν spectra allow extracting neutrino fluxes
→ full spectral fit of all components up to 3 MeV
(possibility to enhance sensitivity by more sophisticated analysis)

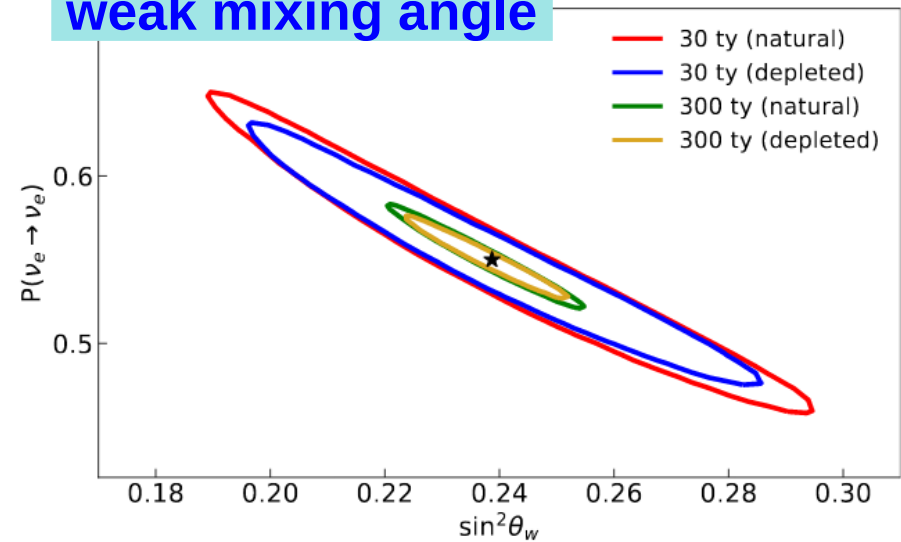
pp-Neutrinos in real time

EPJ C 80, 1133 (2020)

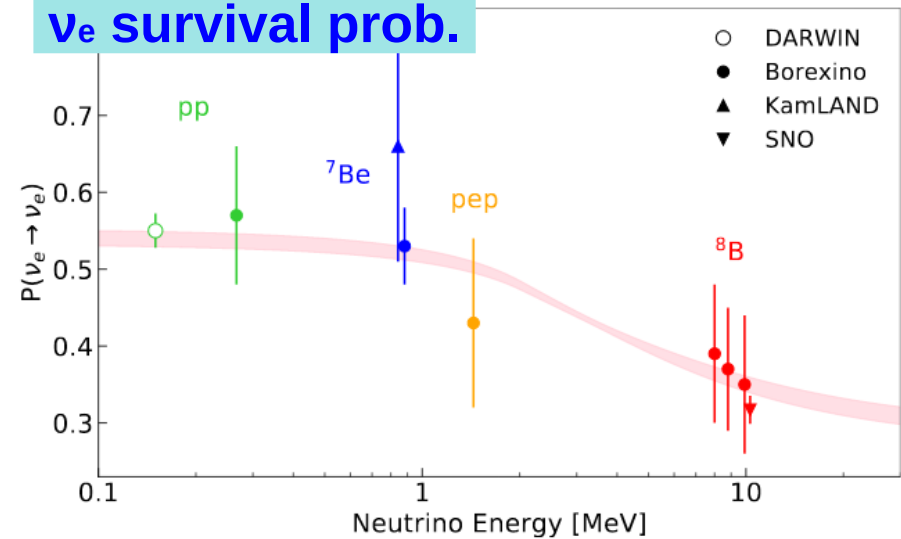
Flux



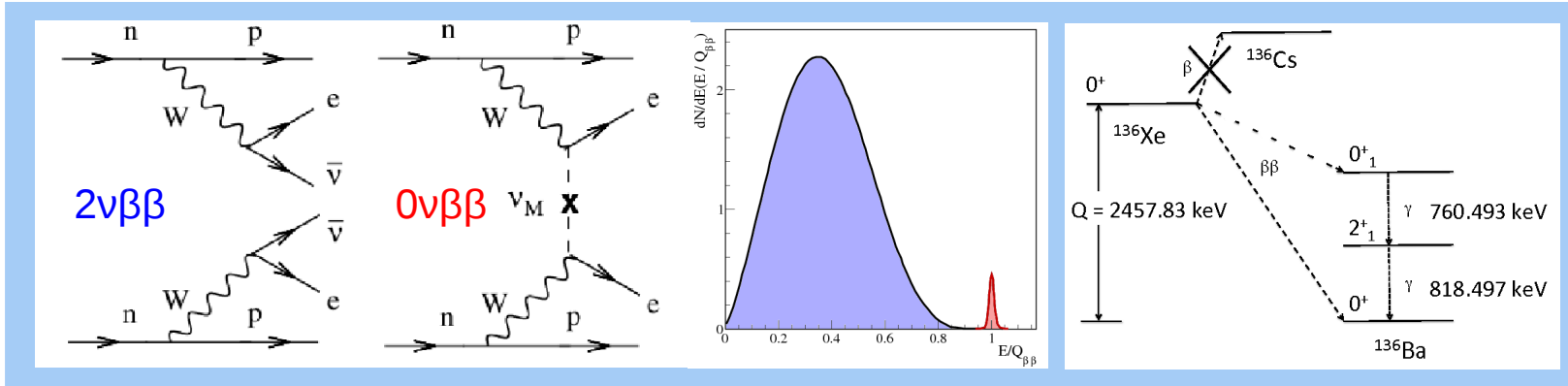
weak mixing angle



ν_e survival prob.



^{136}Xe : 0ν double-beta Decay

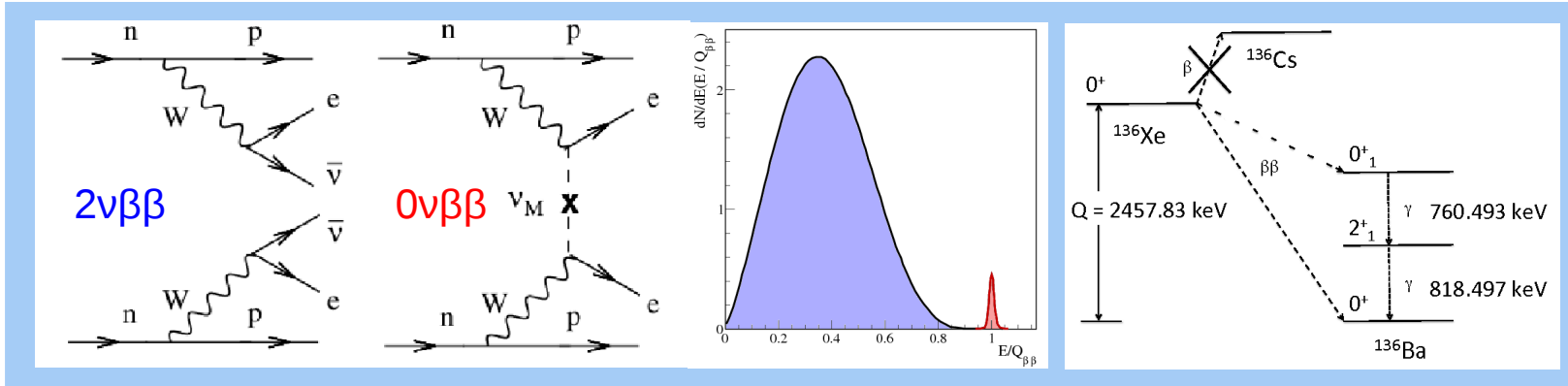


$\Delta L \neq 0$

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

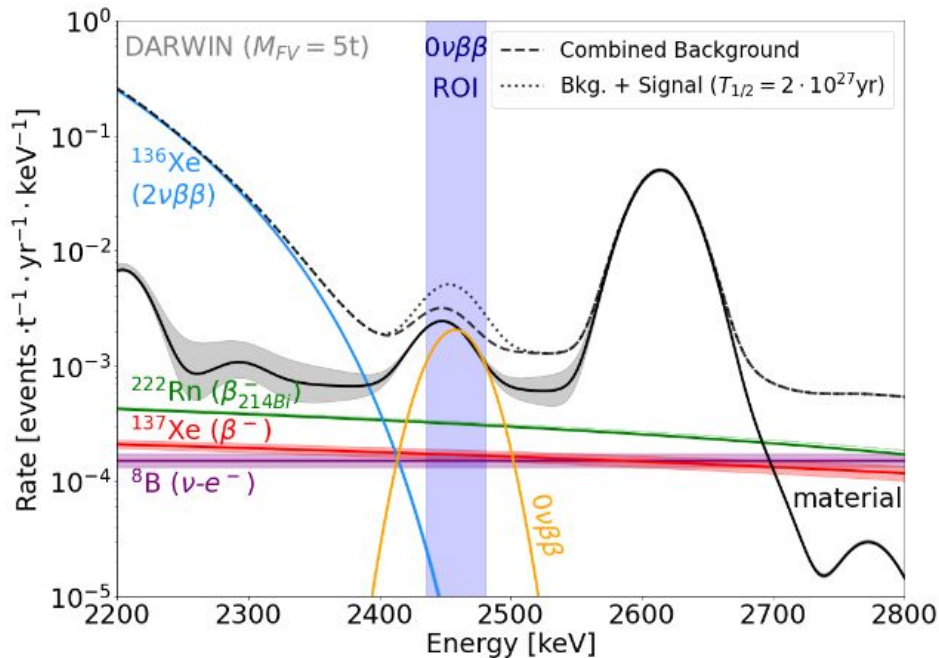
^{136}Xe : 0ν double-beta Decay

EPJ C 80, 808 (2020)



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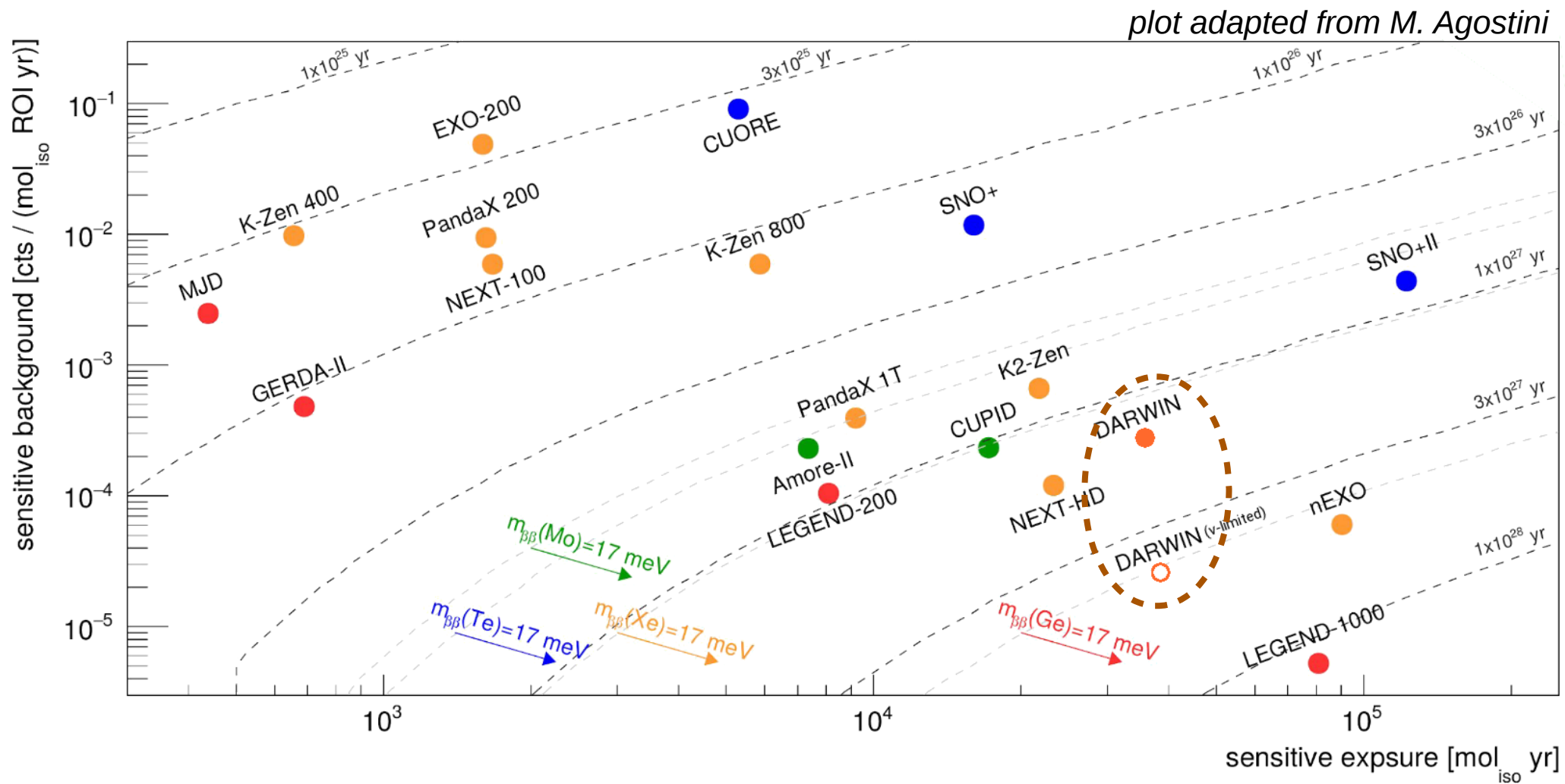
DARWIN Sensitivity

- 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



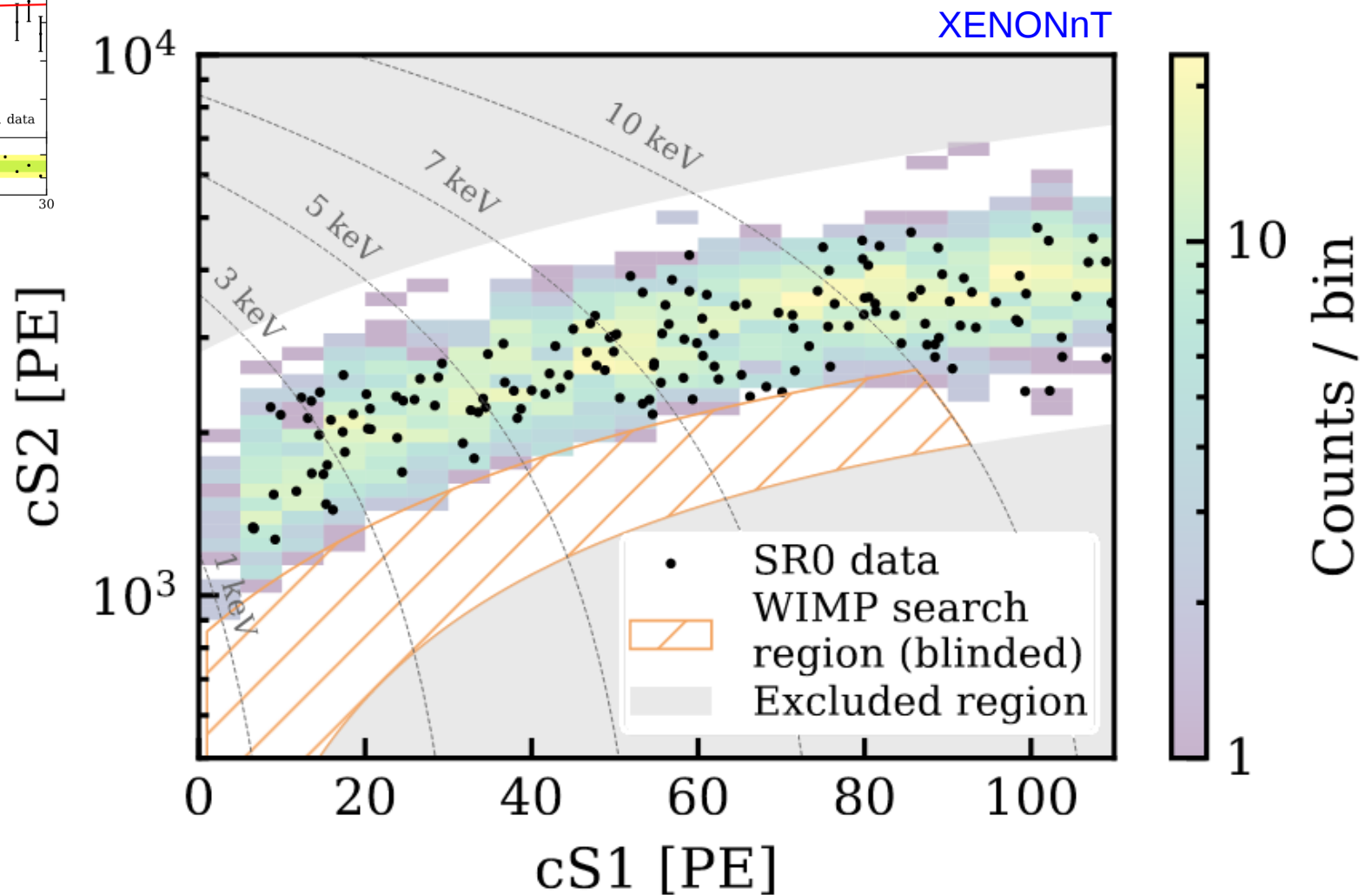
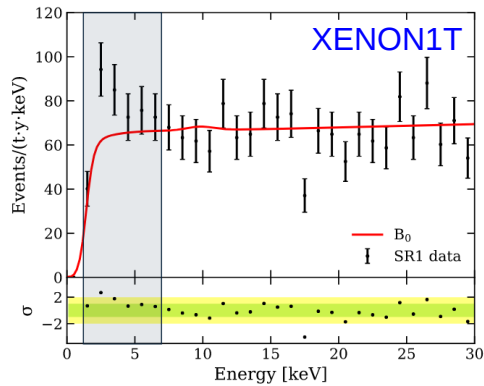
EPJ C 80, 808 (2020)



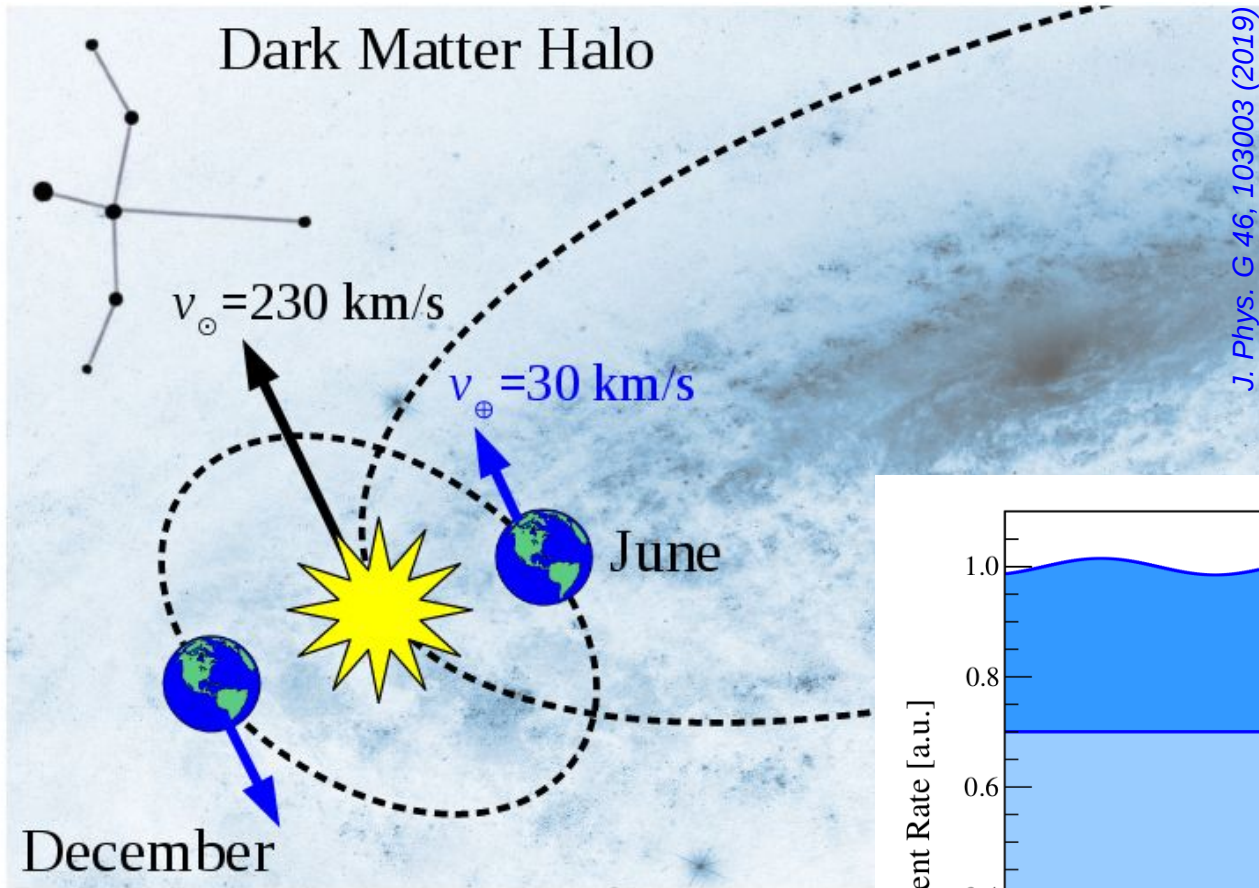
An updated study for XLZD is currently under preparation

Low-E Electronic Recoils

PRL 129, 161805 (2022)



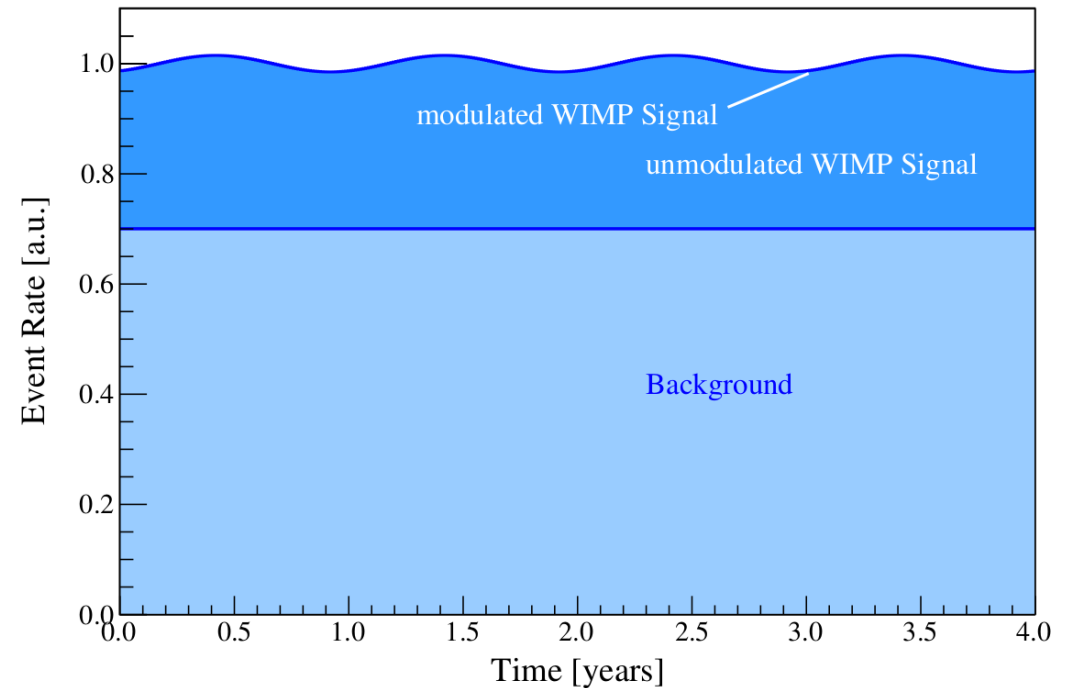
Annual Modulation Searches



Long-standing detection claim by DAMA/Libra:

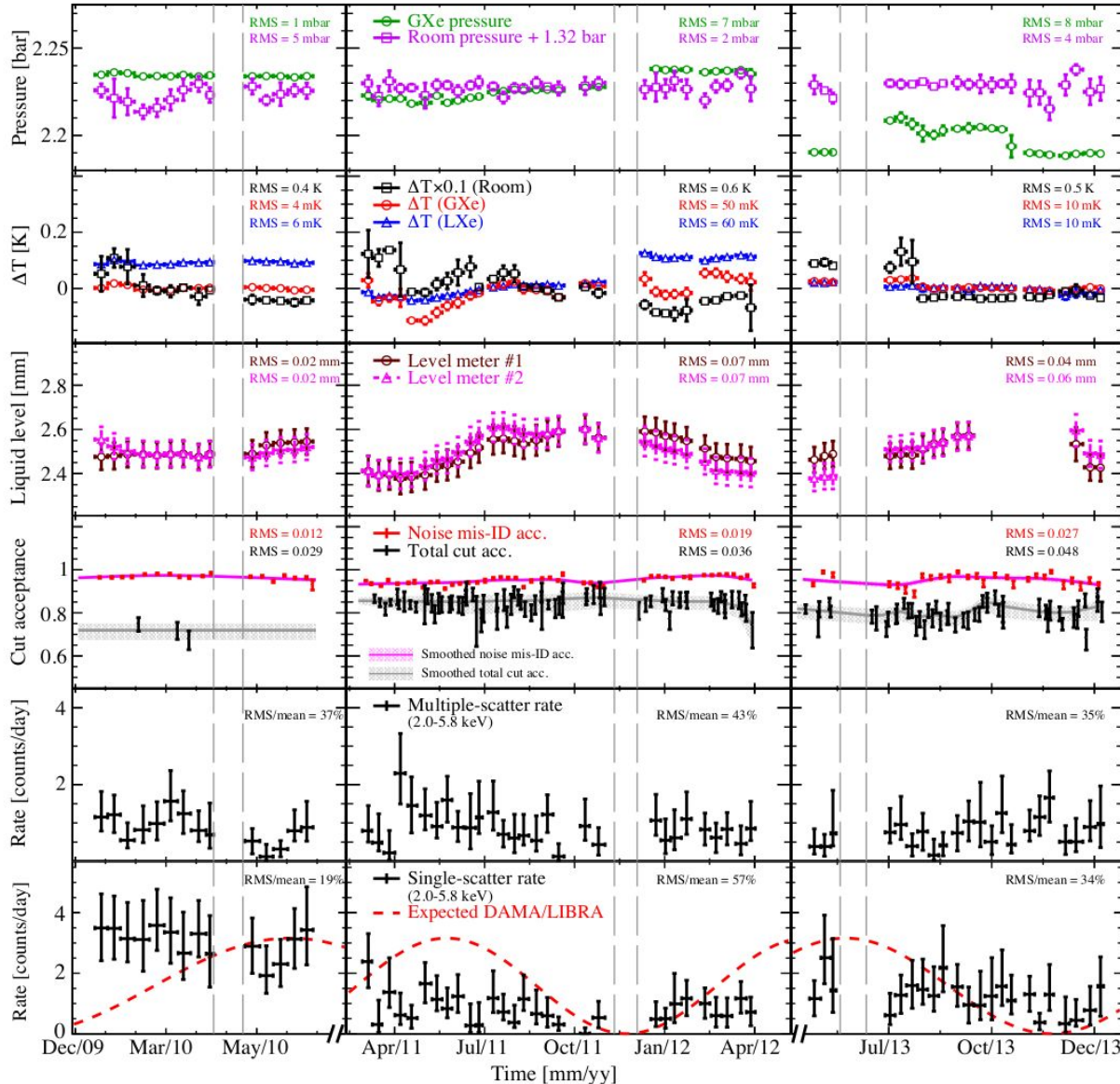
12.9σ

Nucl. Phys. At. Energy 19 (2018) 307



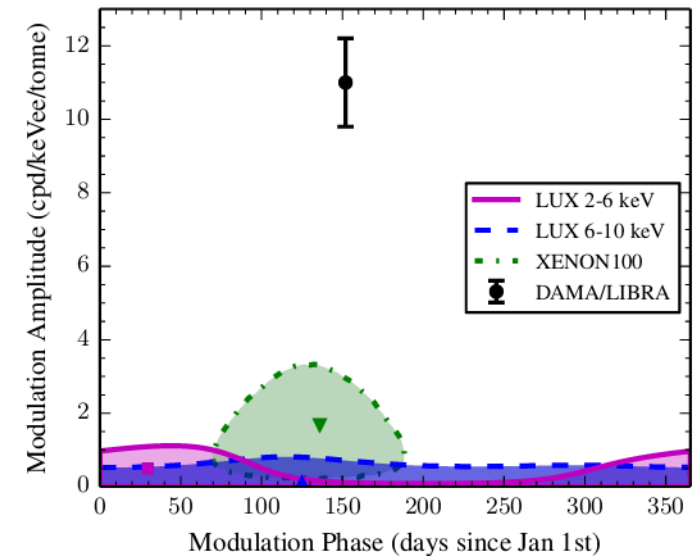
Annual Modulation Searches

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)

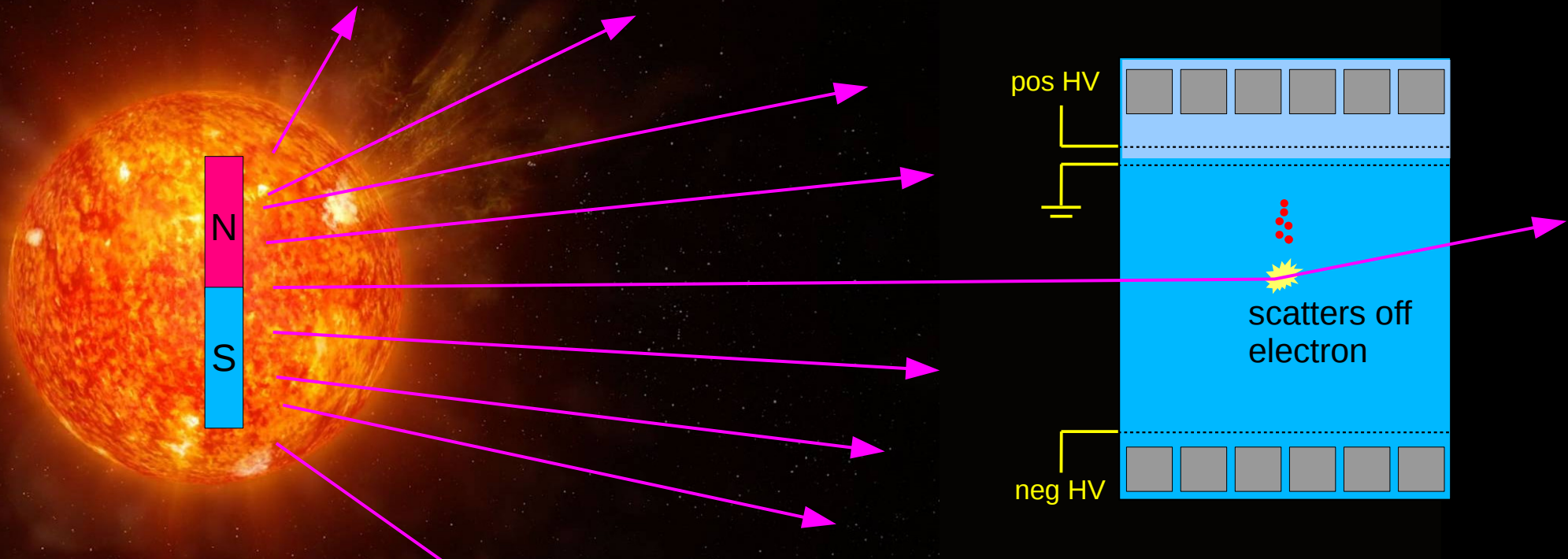
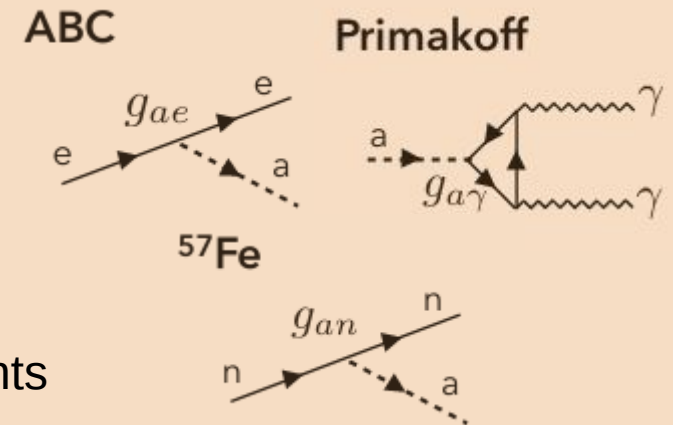


New Physics in ER Data I

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 $E_{\text{kin}} \sim \text{keV}$ 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

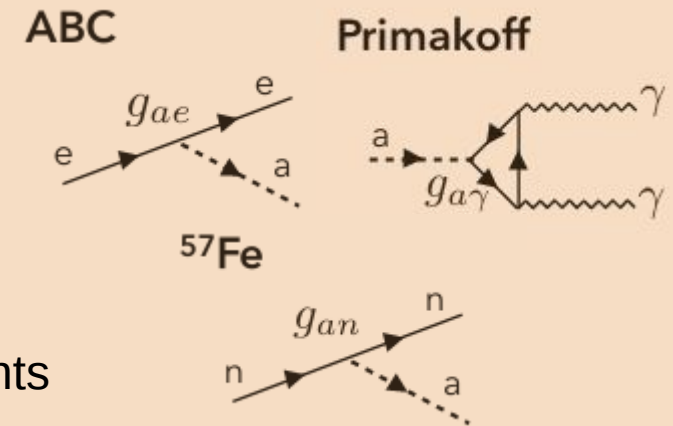


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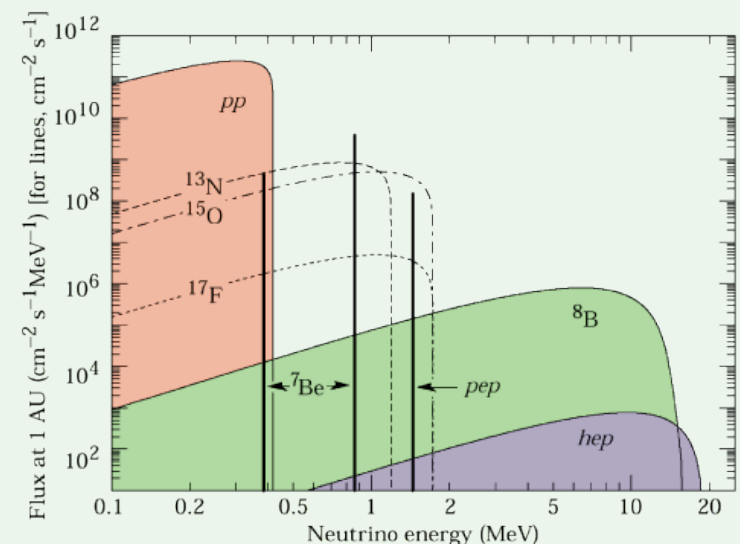
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Enhanced Neutrino Magnetic Moment

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



New Physics in ER Data II

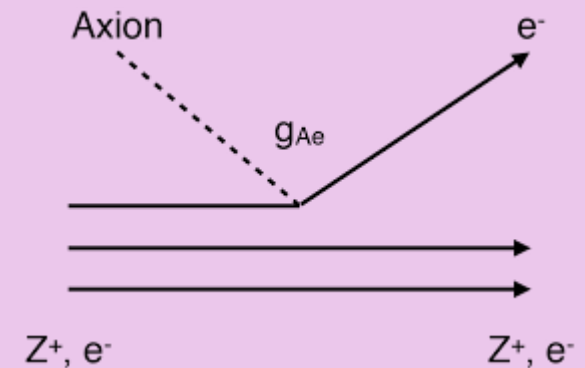
Many models predicts signatures from new physics in low-E ER data.

Some examples

Bosonic Dark Matter

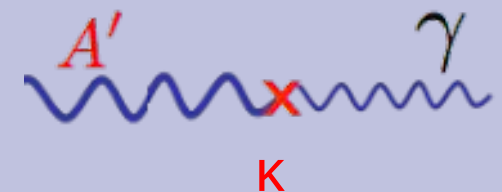
Axion-like Particles (ALPs, pseudoscalar DM)

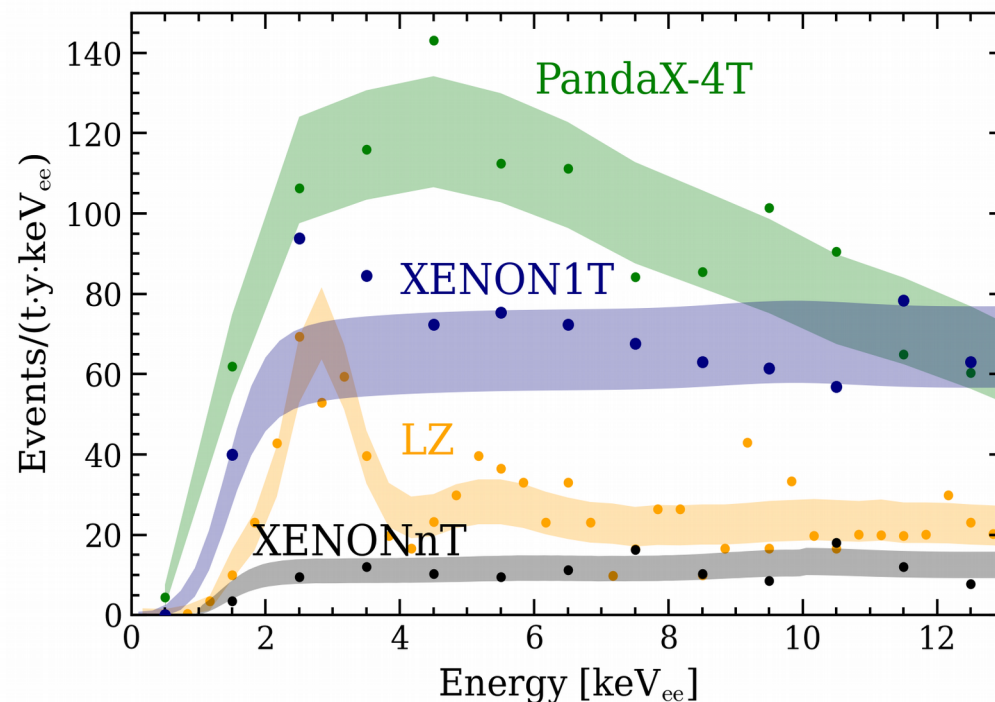
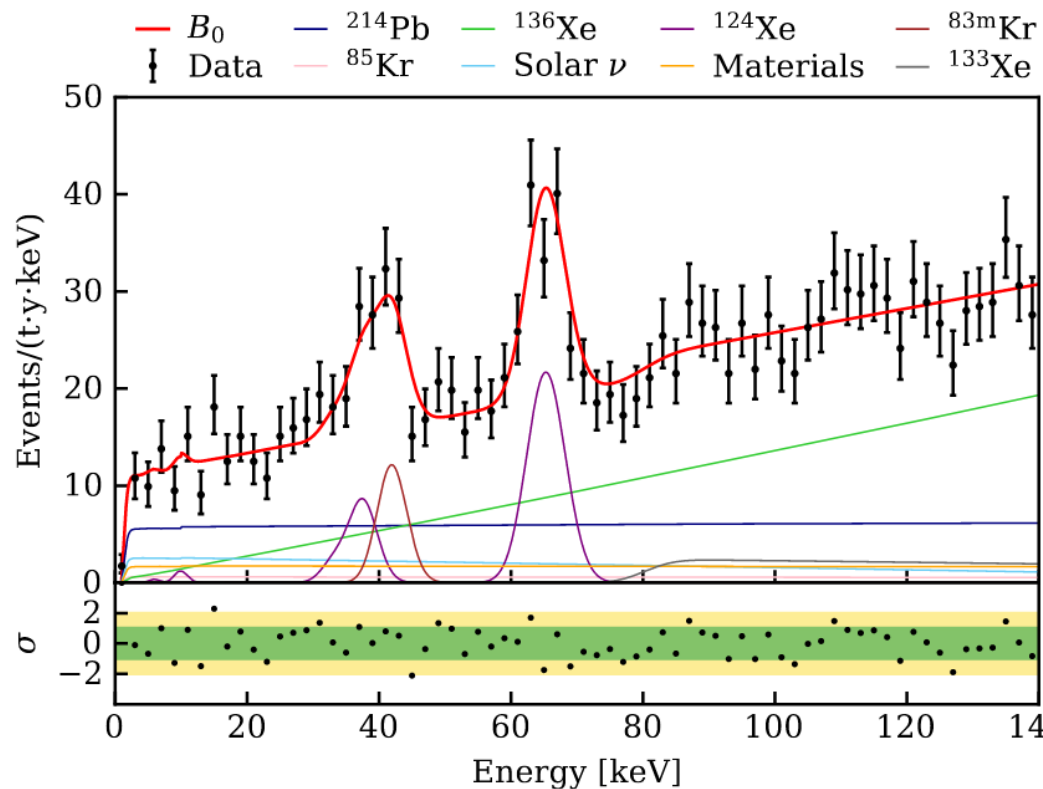
- Interaction with electrons via axio-electric effect
 - ALPs are absorbed by bound electrons
 - absorption rate depends on axion-electron coupling g_{ae}
- expect mono-energetic peak at unknown m_a
- assume all DM is made of non-relativistic ALPs



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

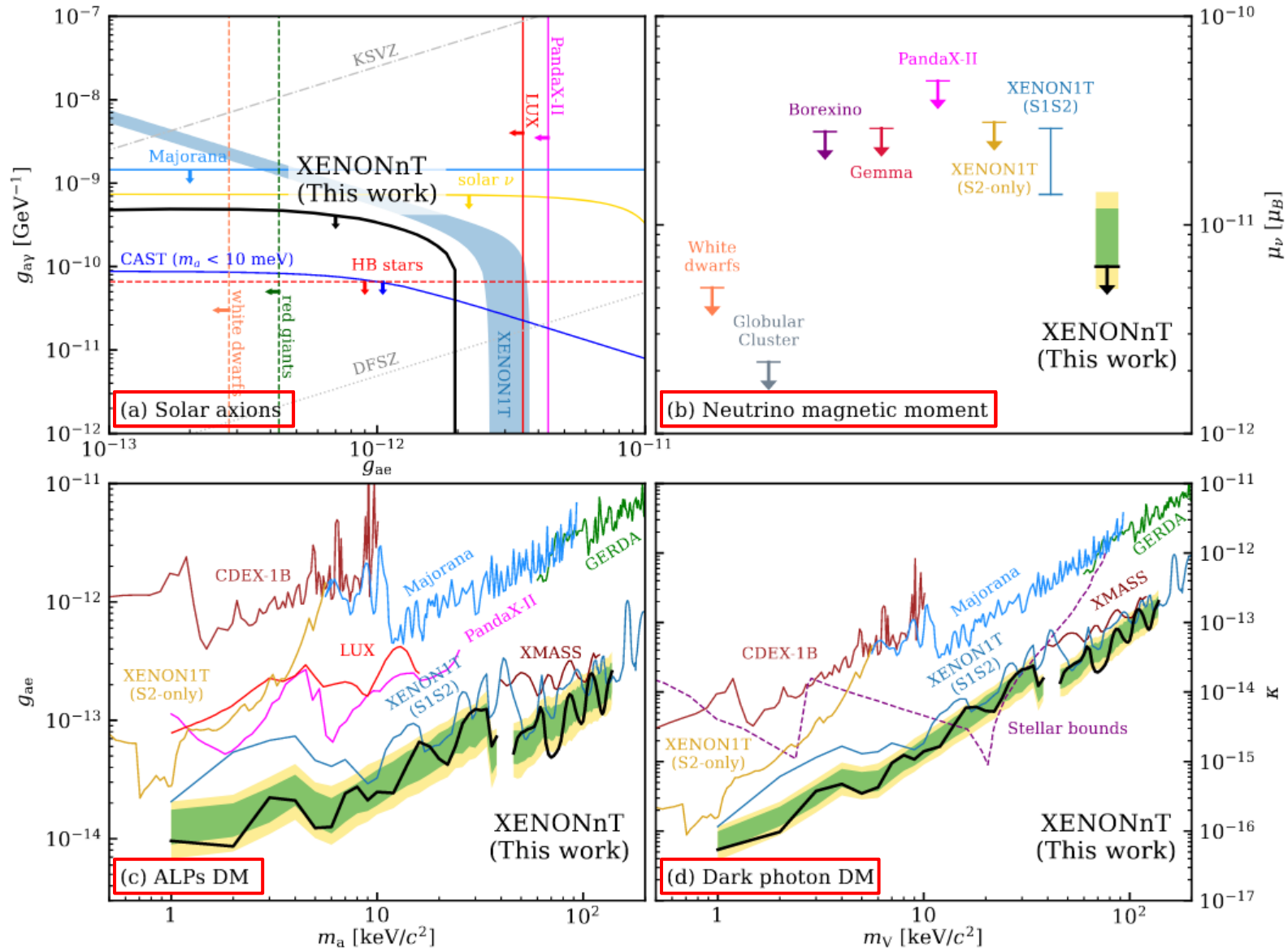




- **No excess above background observed**
→ XENON1T excess not from new physics
- For the first time, shape of low-E background spectrum dominated by **second order weak decays** ($0\nu\beta\beta$ of ^{136}Xe , $2\nu\text{ECEC}$ of ^{124}Xe)
- world-record **low ER background level**: (15.8 ± 1.3) evts/(t×yr×keV)

Limits on New Physics

PRL 129, 161805 (2022)



→ 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

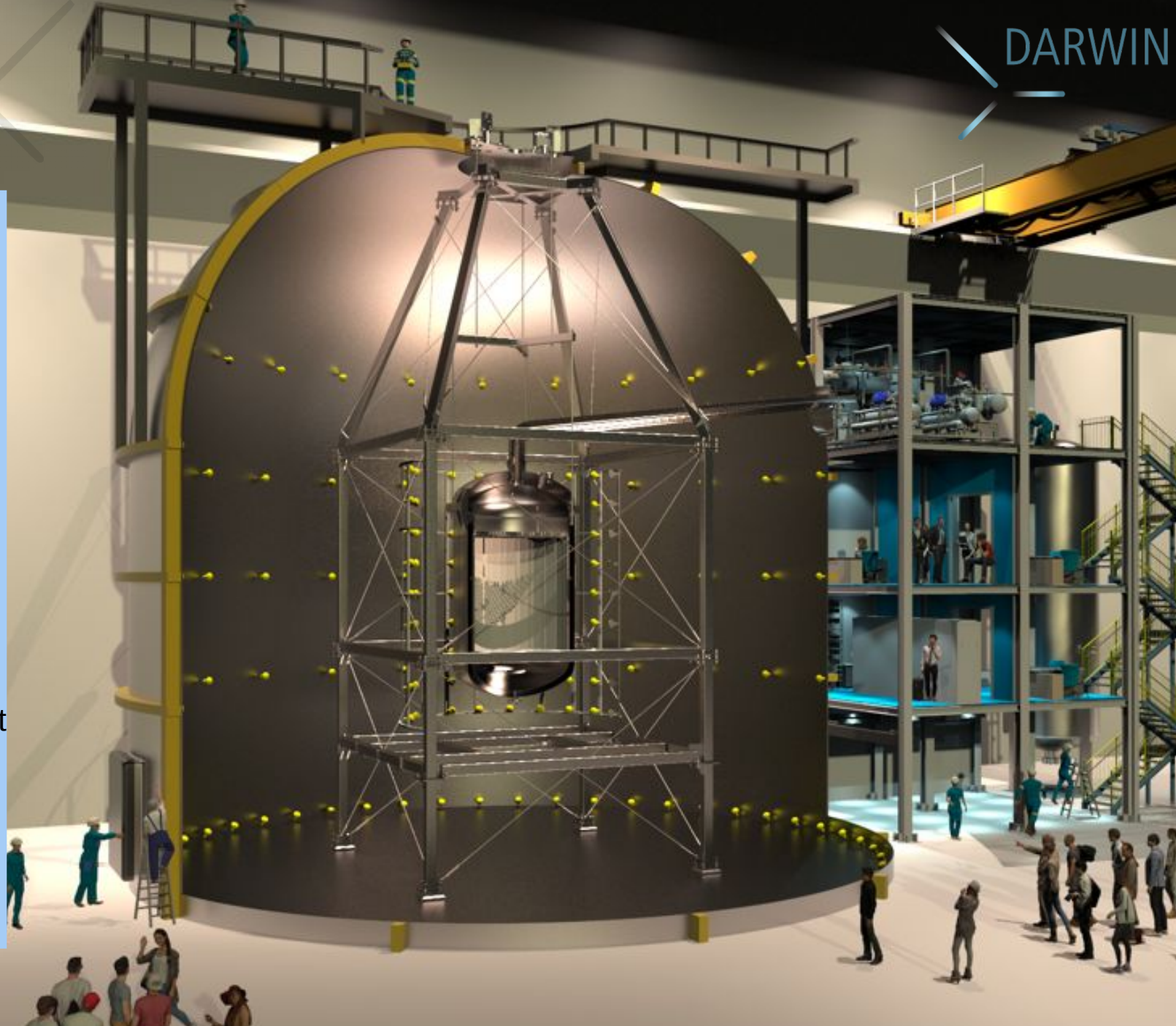
- CNNS
- supernova neutrinos
- solar neutrinos
- neutrino magn. moment

Rare nuclear decays

- $0\nu\beta\beta$ ^{136}Xe
- $0\nu / 2\nu\text{ECEC}$ ^{124}Xe

Solar Axions

... and even more!



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