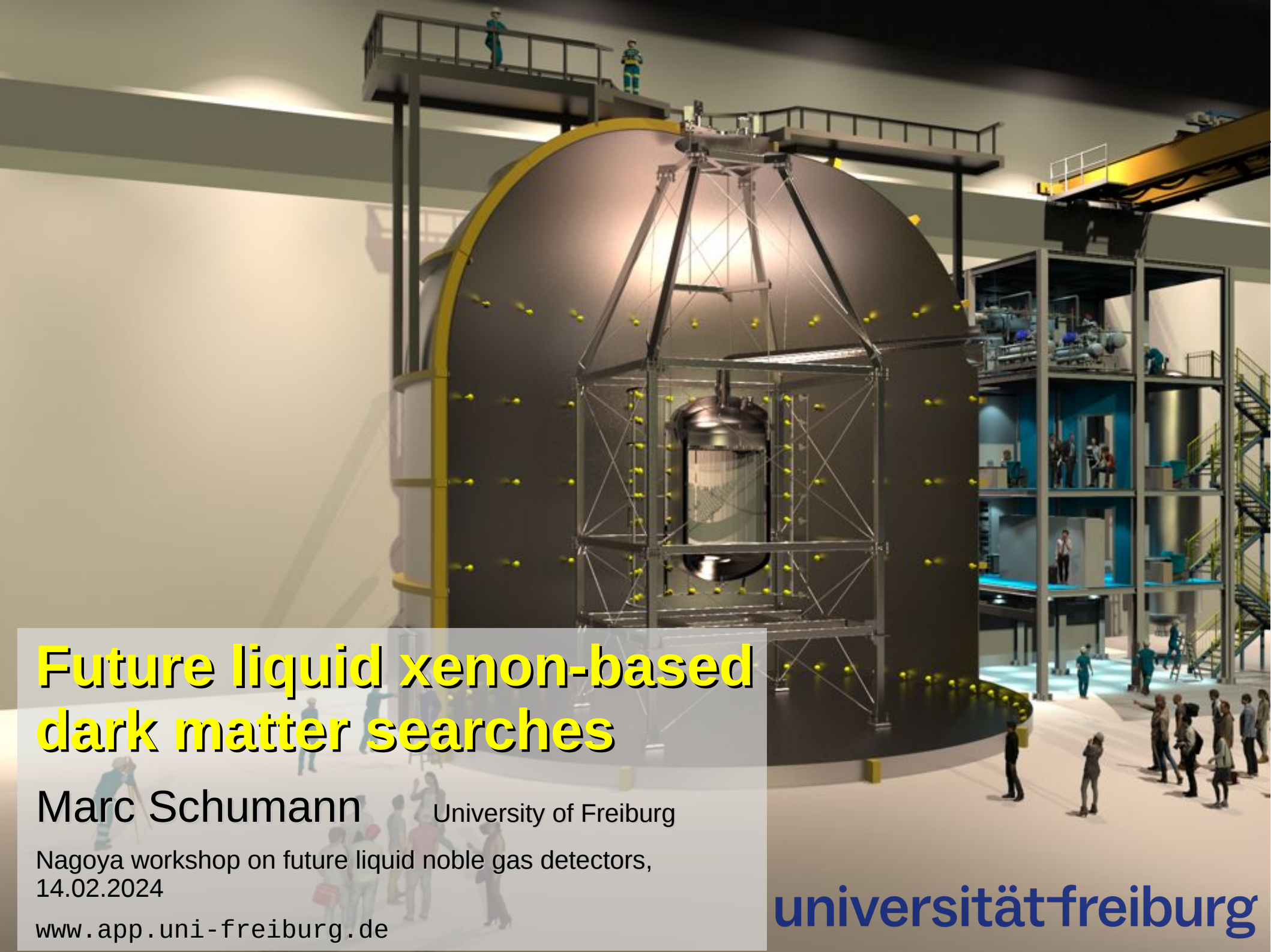


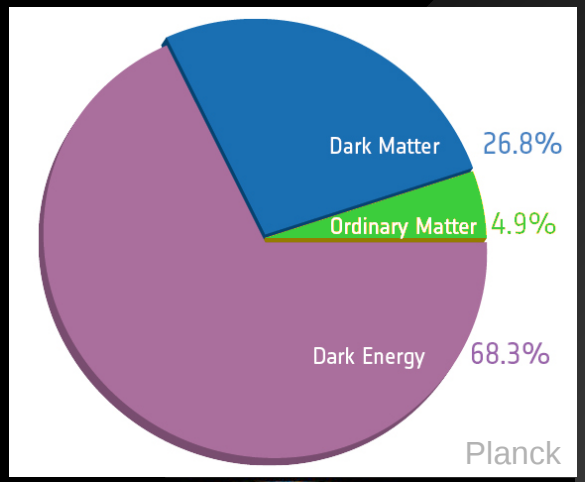
Future liquid xenon-based dark matter searches

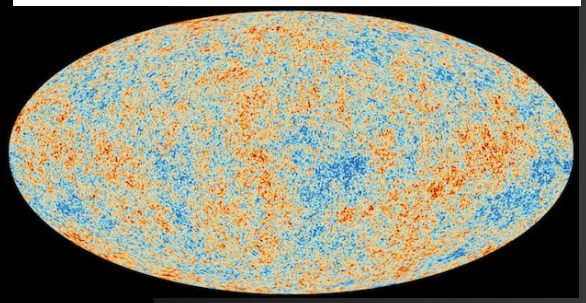
Marc Schumann University of Freiburg

Nagoya workshop on future liquid noble gas detectors, 14.02.2024

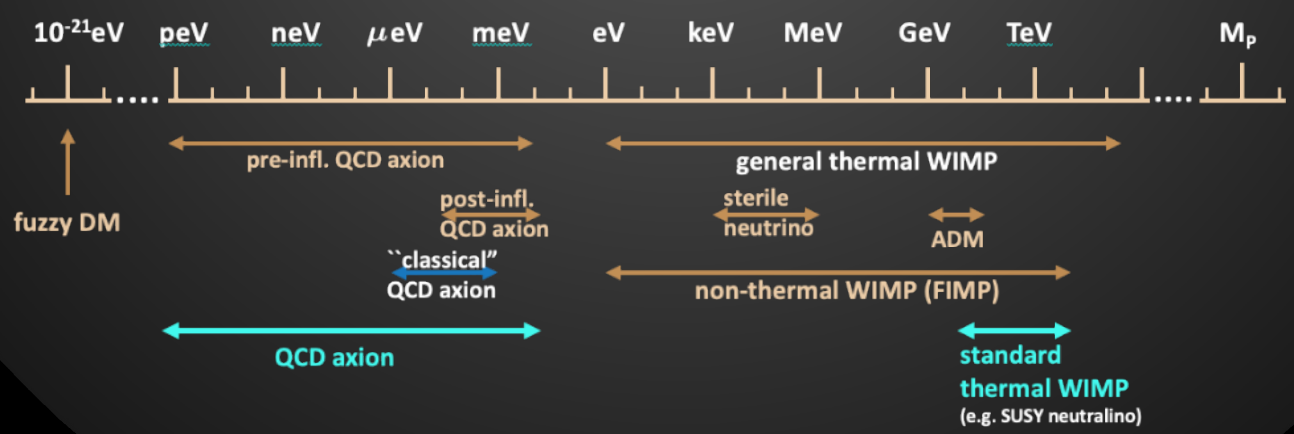
www.app.uni-freiburg.de

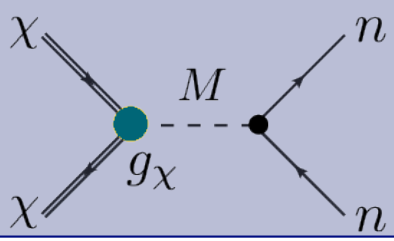
universität freiburg





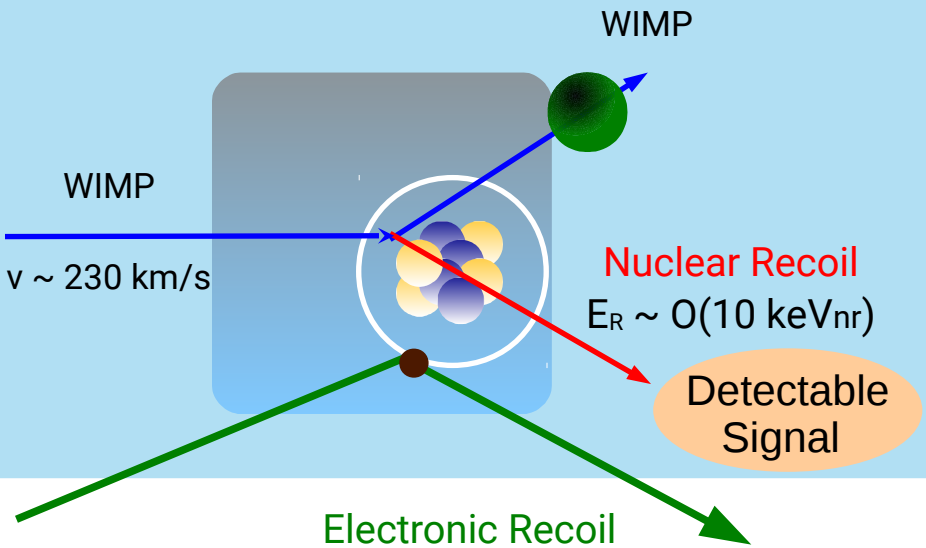
The indirect evidence for the existence of dark matter is a clear indication for physics beyond the Standard Model



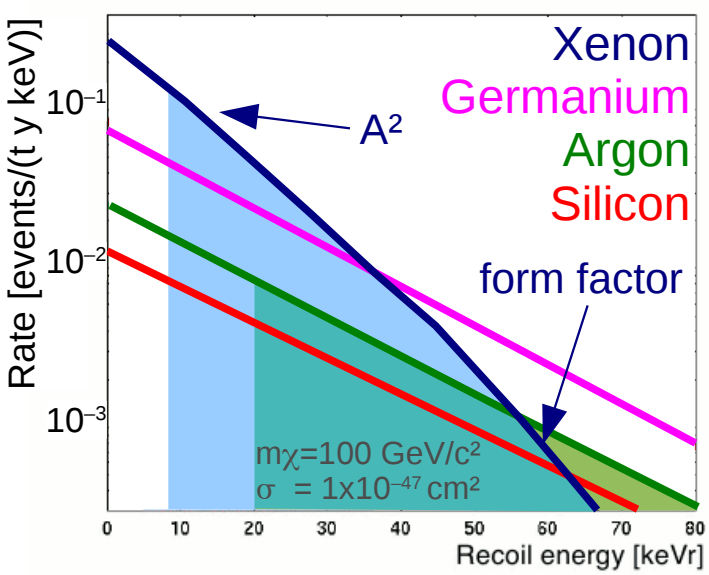


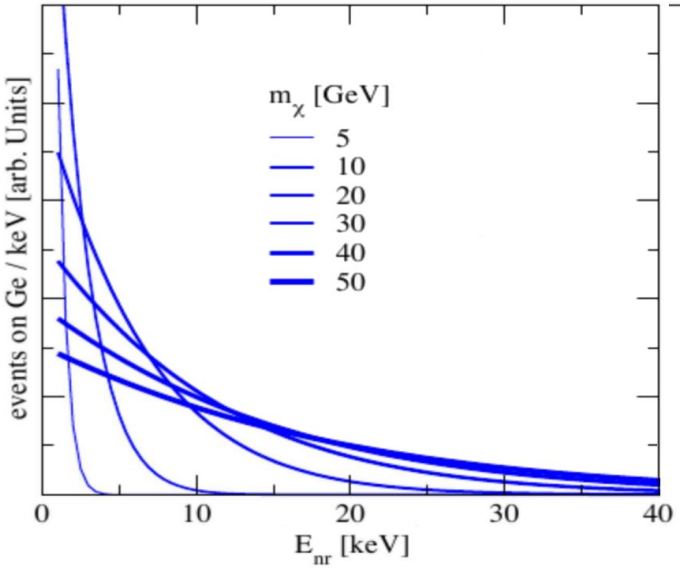
Direct WIMP Search

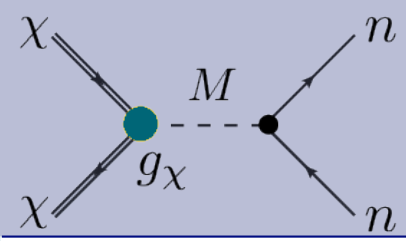
Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



Recoil Spectra:







Direct WIMP Search

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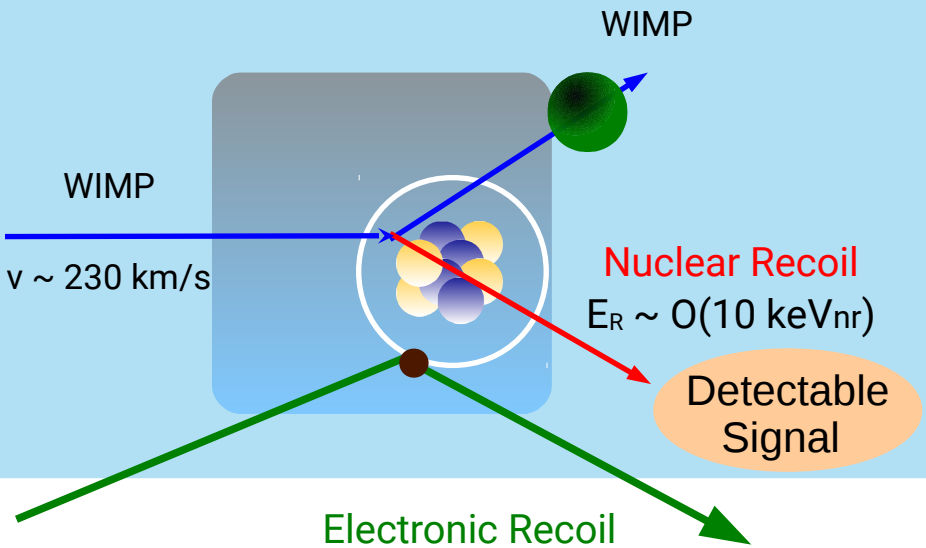
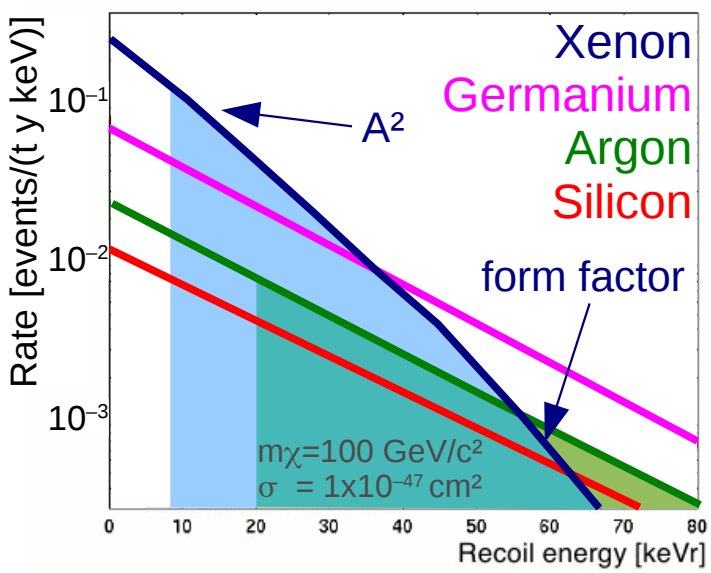
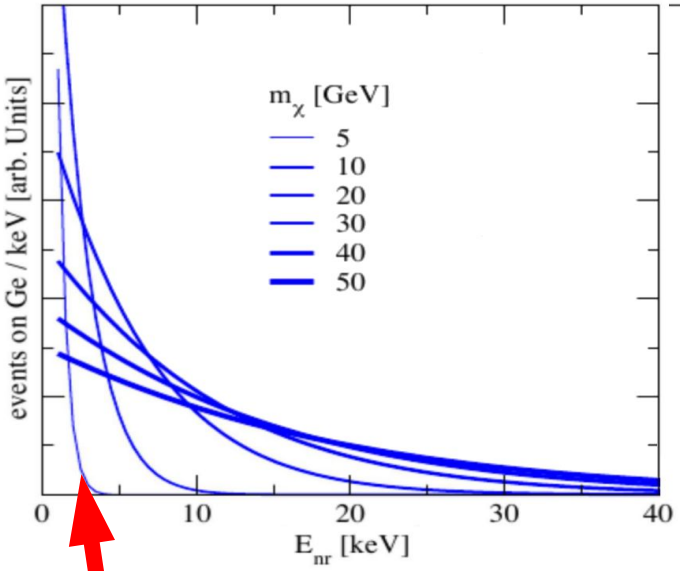


Recoil Spectra:

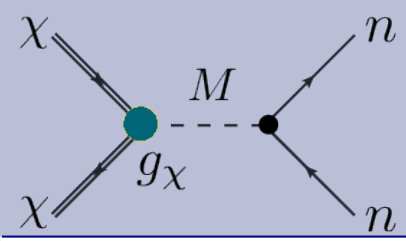


tiny!



tiny!

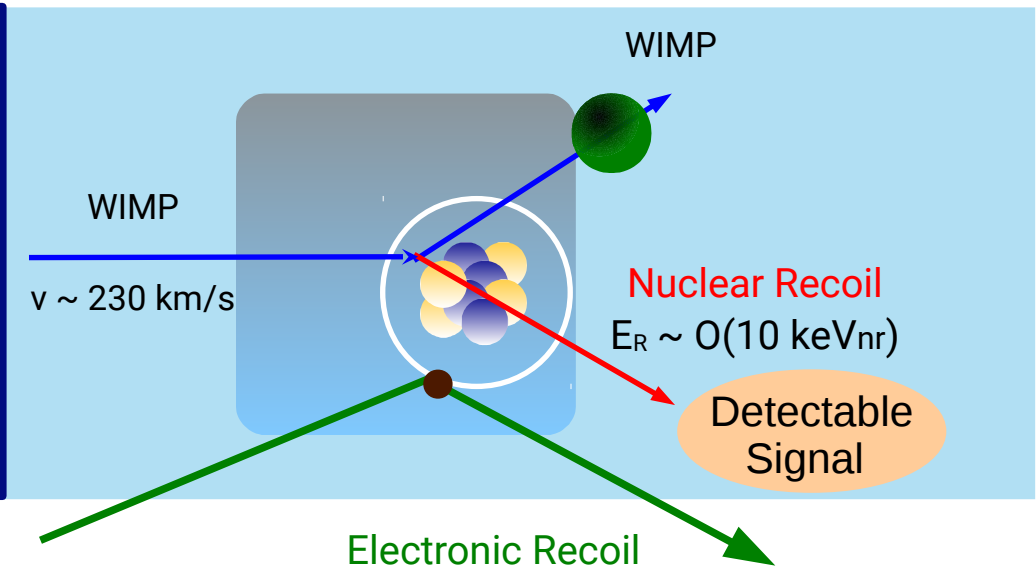
low mass → low threshold



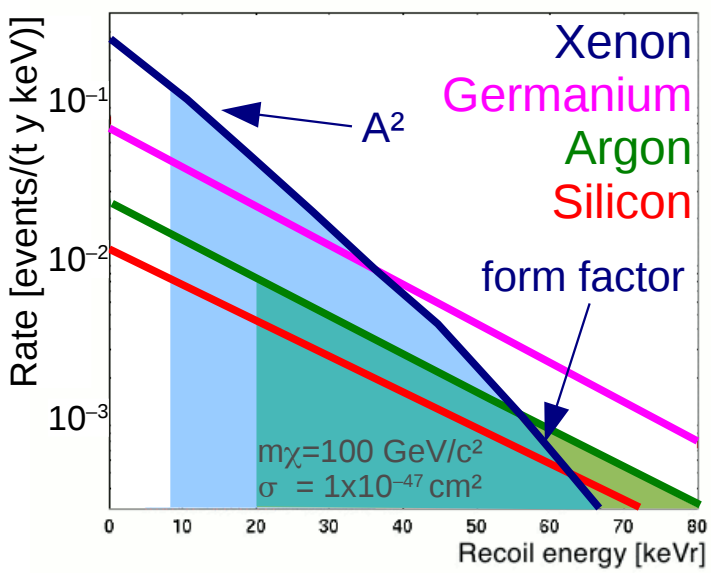
Direct WIMP Search

How to build a WIMP detector?

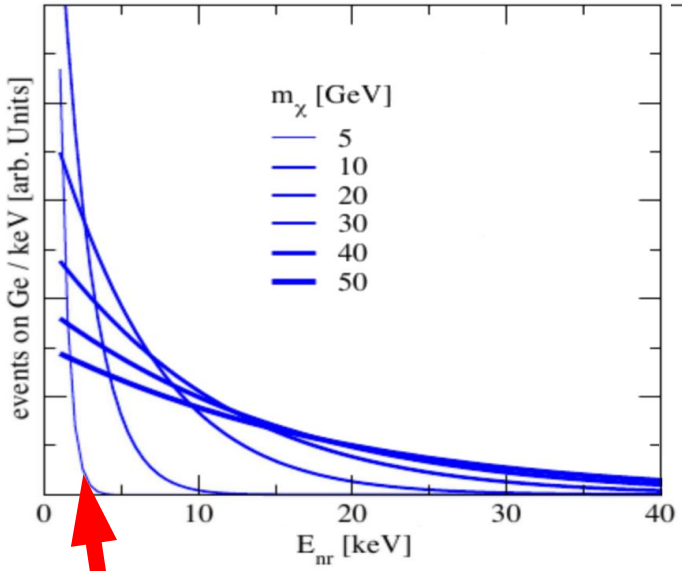
- large total mass, high *A*
- low energy threshold
- ultra low background
- good signal / background discrimination



Recoil Spectra:



tiny!

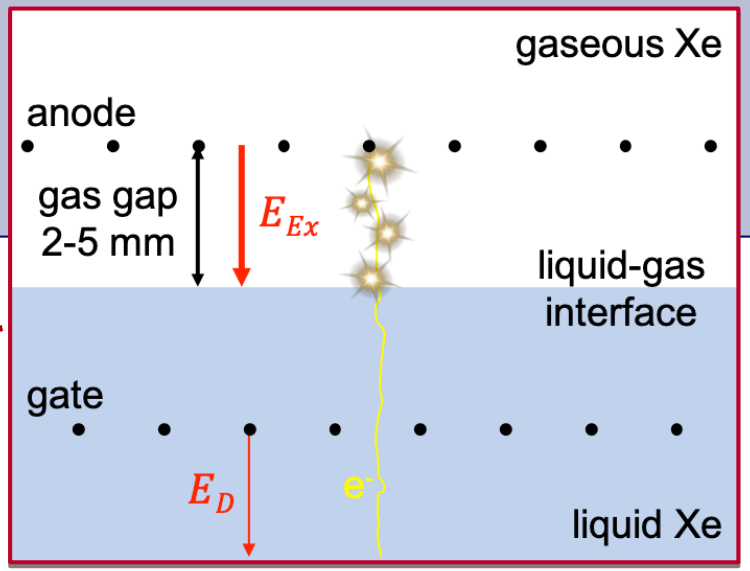


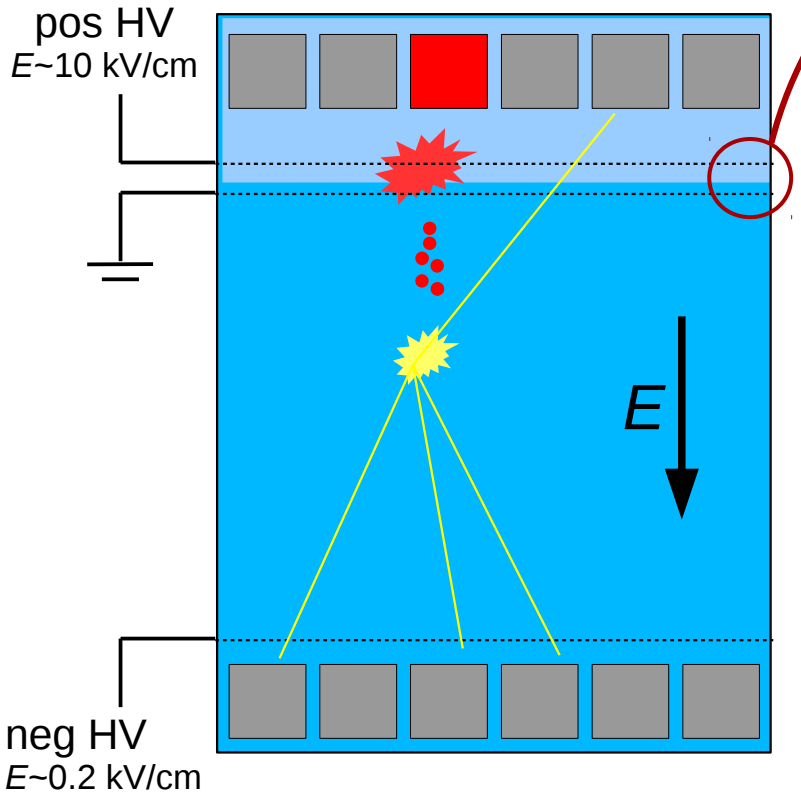
tiny!

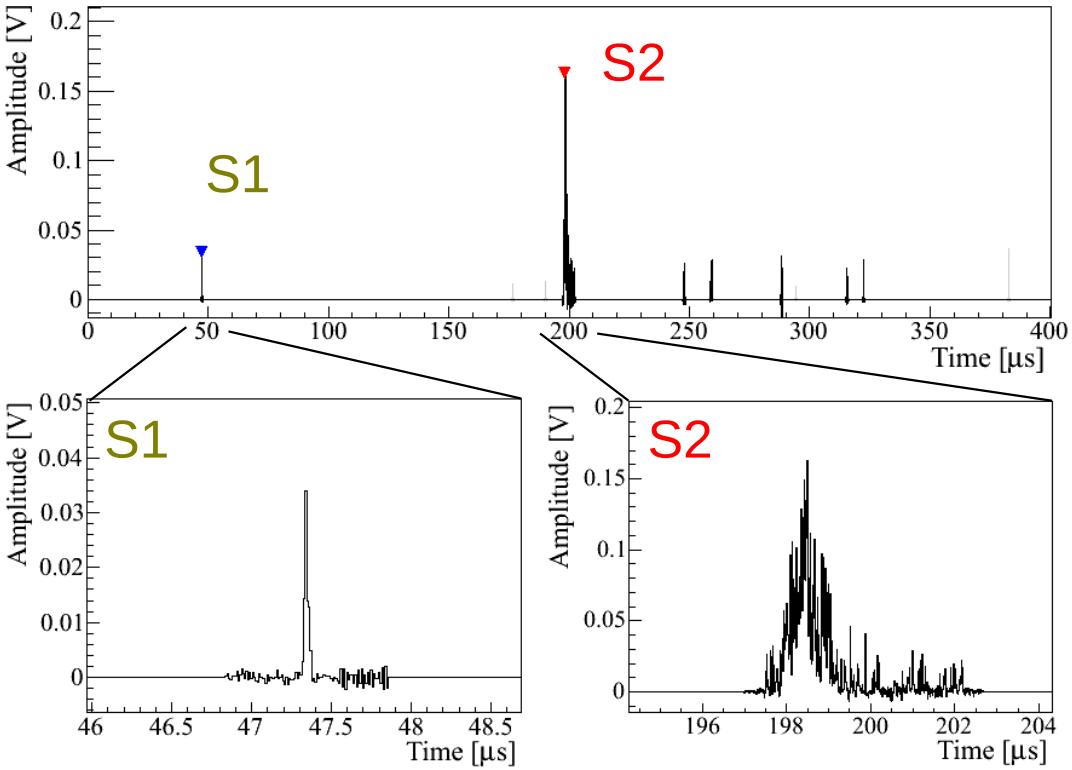
low mass → low threshold

Dual Phase TPC

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

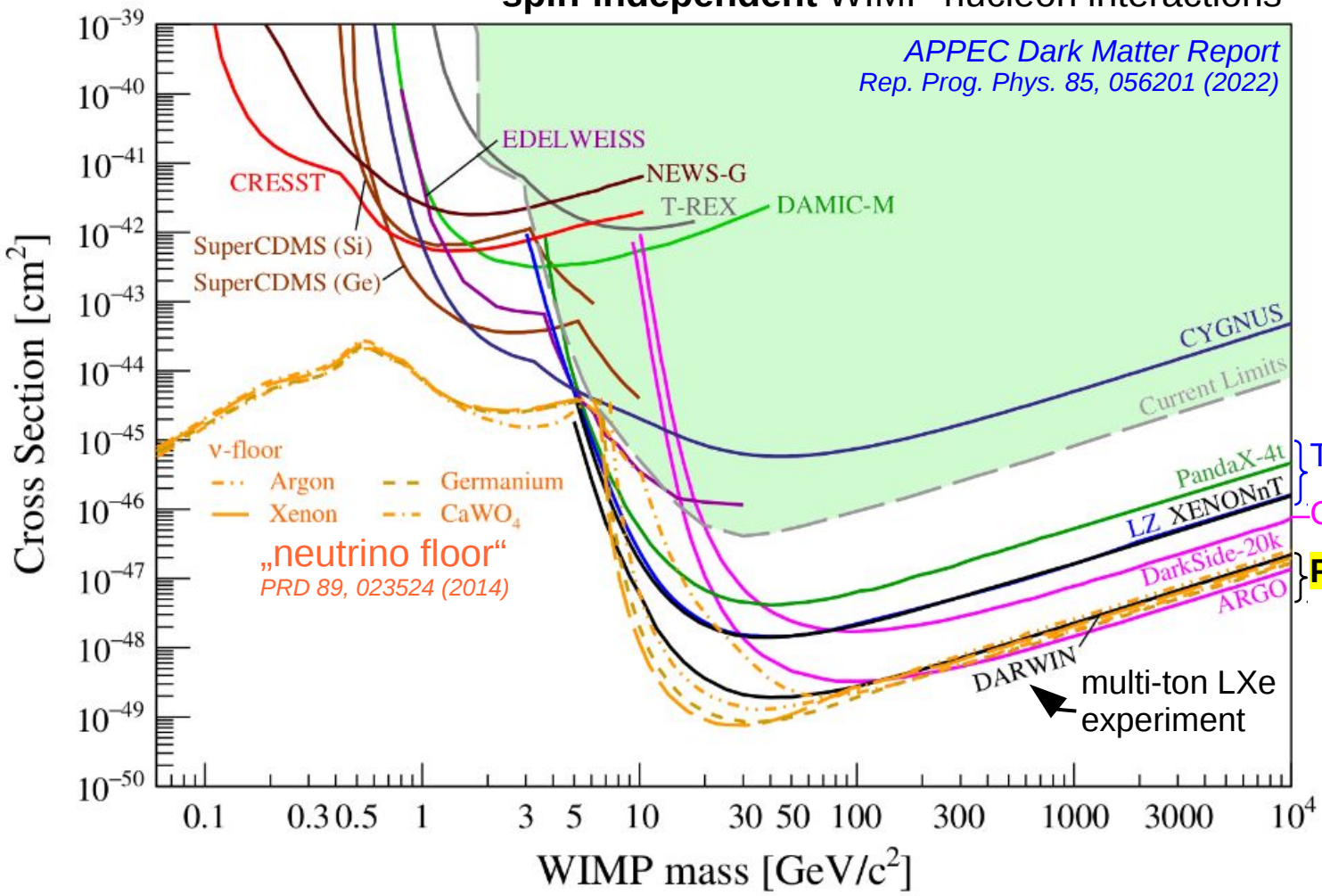






The WIMP Parameter Space

spin-independent WIMP-nucleon interactions



10^{10}

Taking data

Construction

Plan

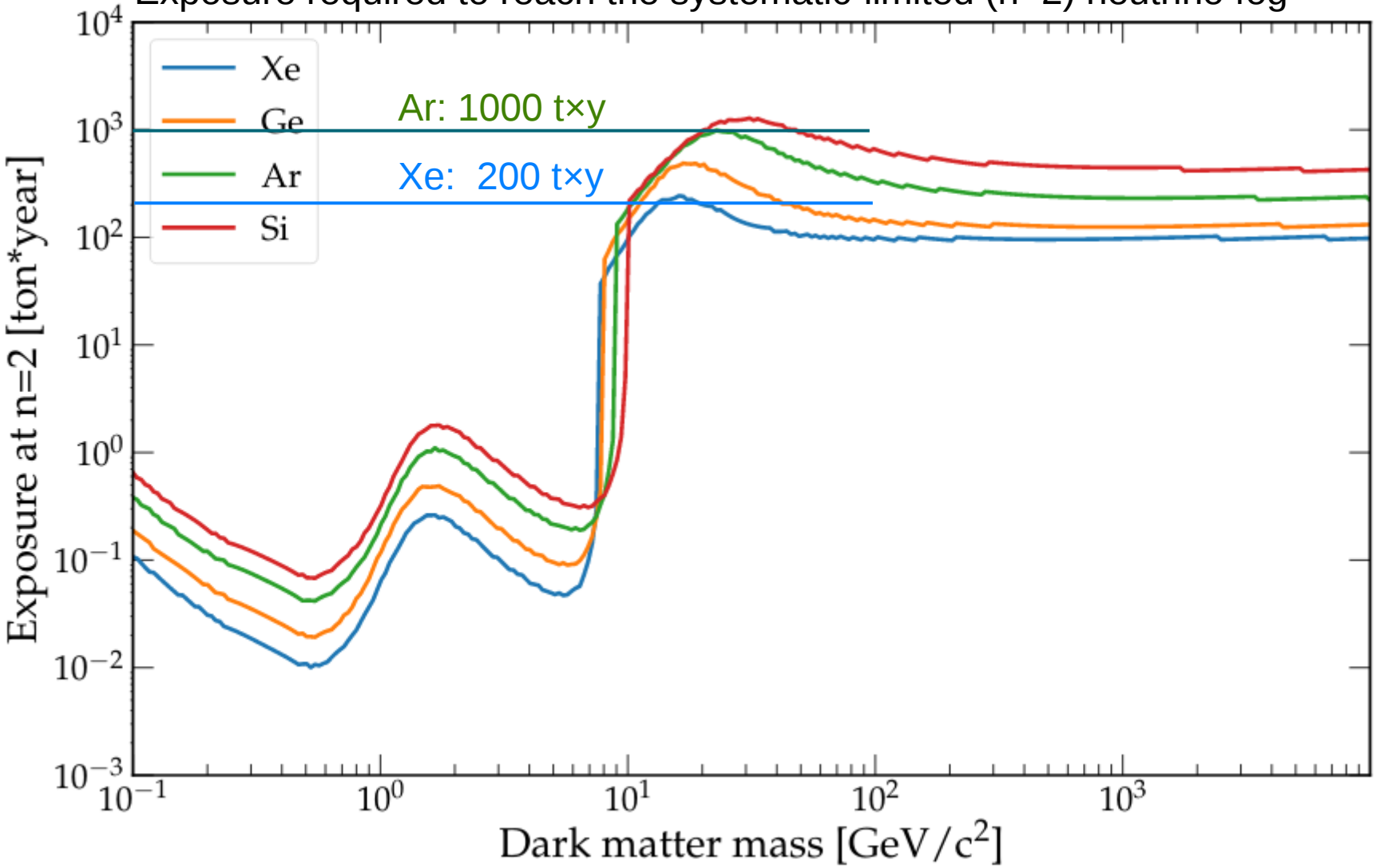
Exposure+
Background

Threshold

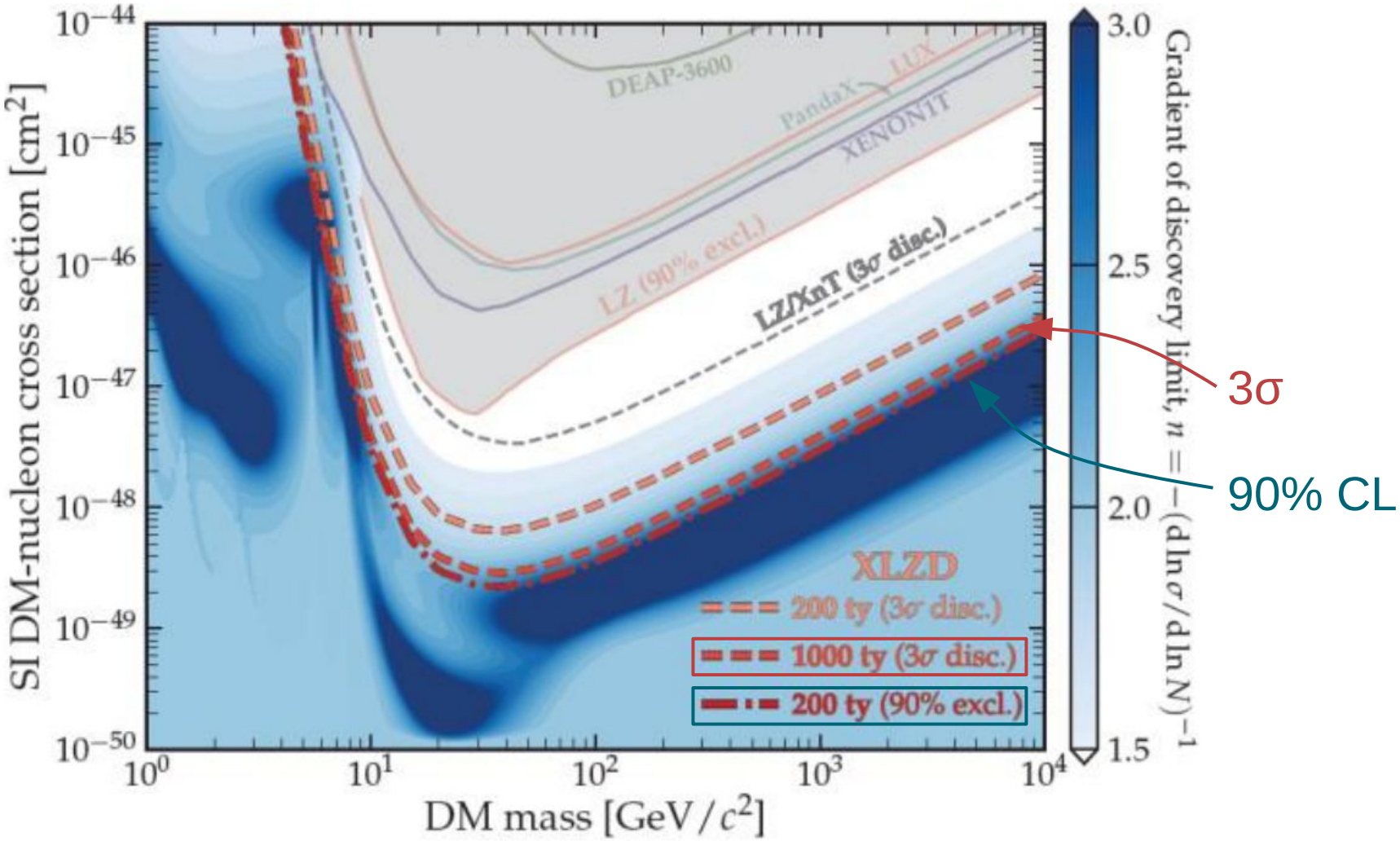
Reaching the neutrino fog

arXiv:2203.08084

Exposure required to reach the systematic-limited (n=2) neutrino fog



Exclusion vs. Detection

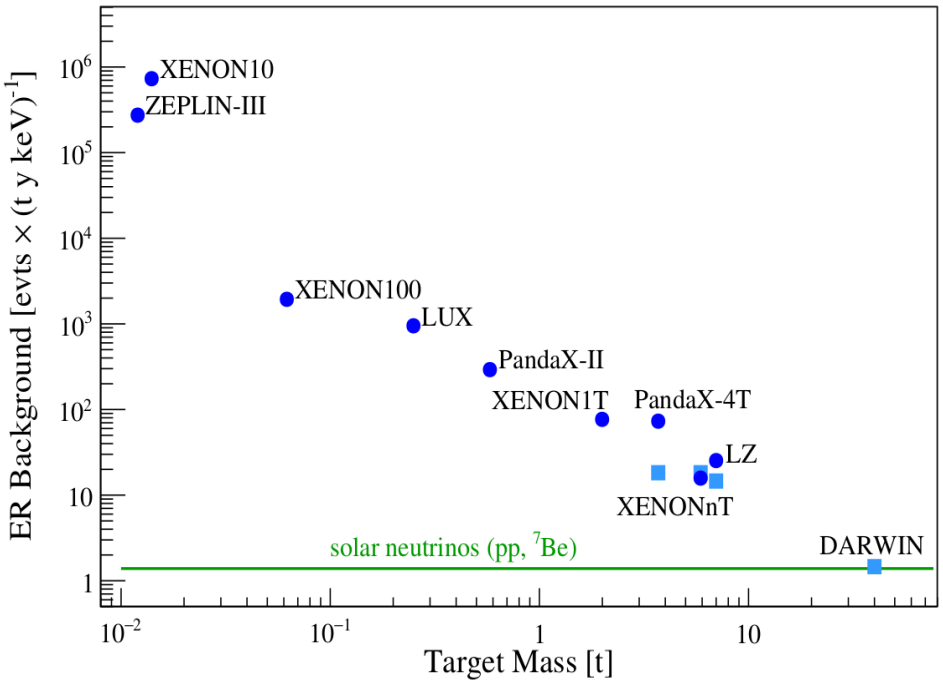


200 t×y: probe entire mass range ≥10 GeV at 90% CL

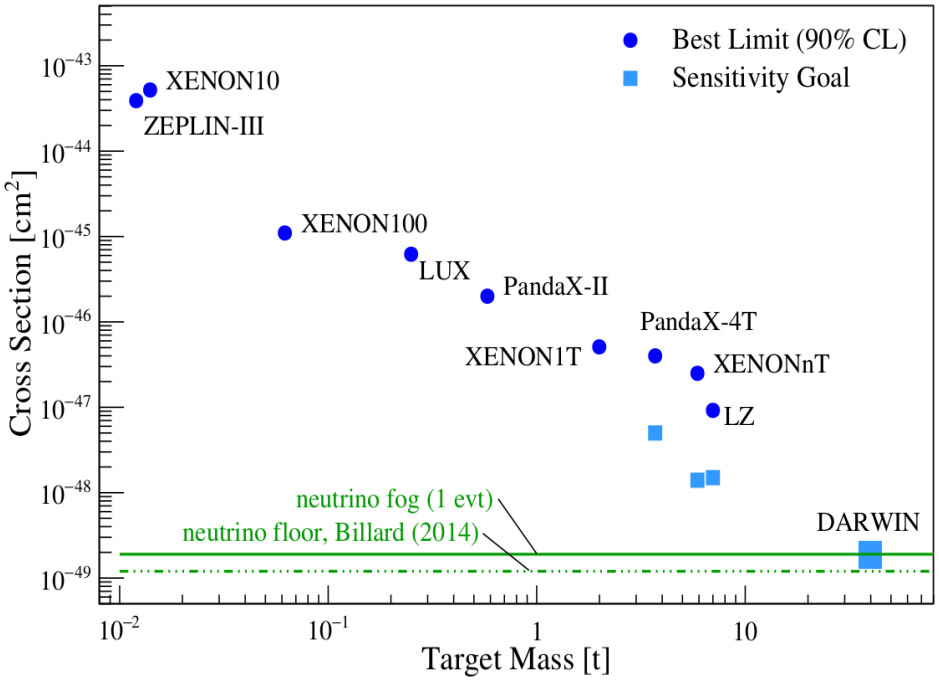
1000 t×y: probe entire mass range ≥10 GeV at 3σ evidence

Background Requirements

Electronic Recoils (ER)



Nuclear Recoils (NR)

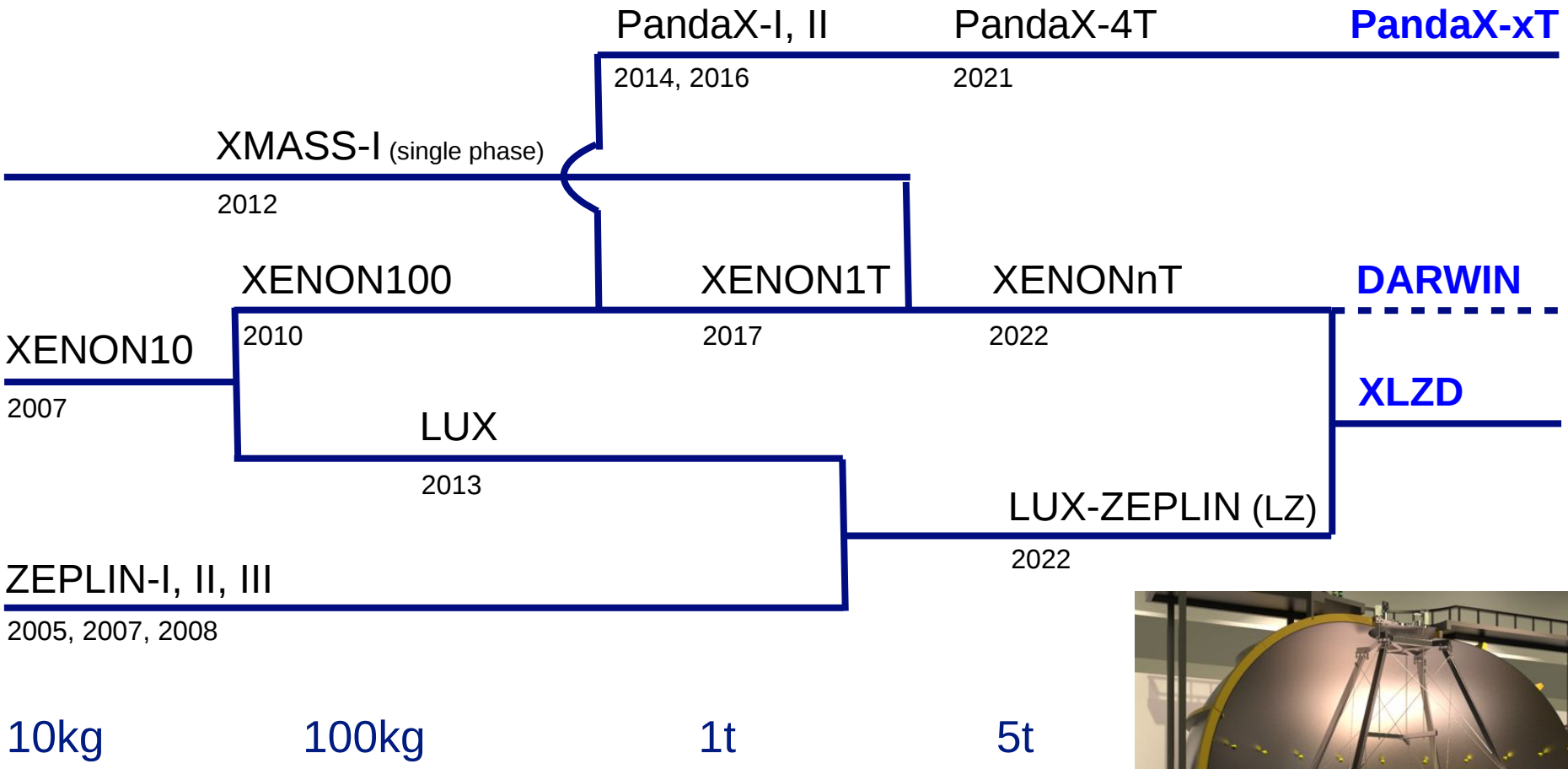


Backgrounds must be dominated by irreducible neutrinos

ER: pp, ^{7}Be

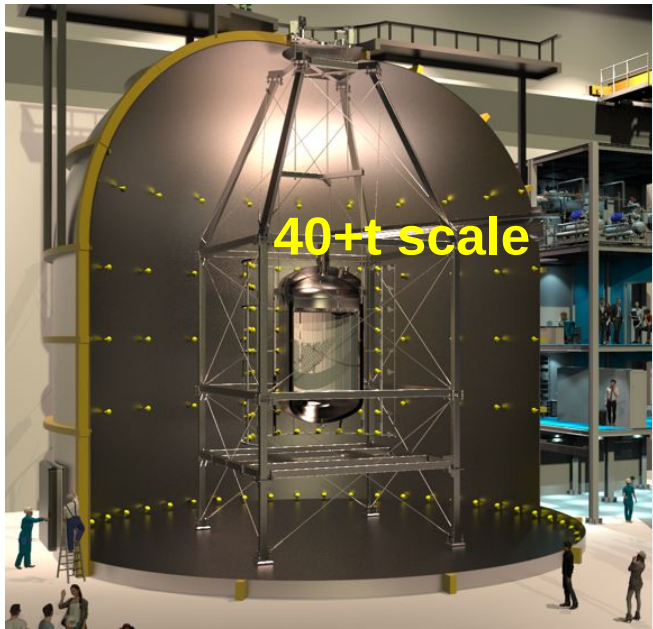
NR: ^{8}B, atmospheric

The LXe Family Tree



13 very successful LXe dark matter detectors in ~20 years!

Note: timelines are only indicative,
years indicate publication of first science results



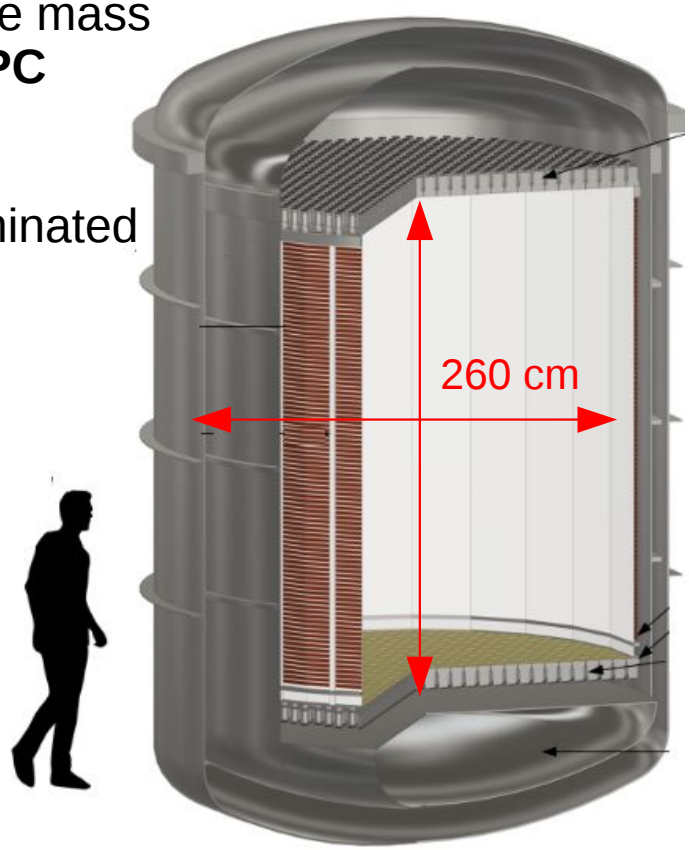
General Features of current Designs

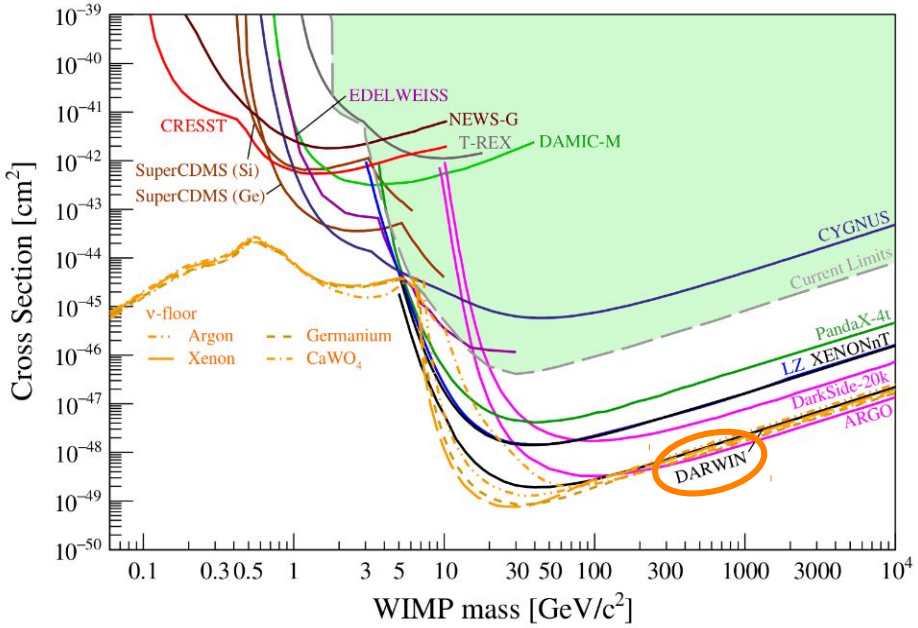
- dual-phase TPC
  → rely on experience from smaller „demonstrators“
- Target mass and background level aimed at neutrino floor
- Cylindrical target, light readout on top and bottom
- PMTs as light sensors
- Drift field >100 V/cm (ideal: 250-290 V/cm)
  LUX: PRD 102, 112002 (2020)
  → 30-100 kV on cathode for 3 m drift
- Staged approach in line with Xe procurement
- Neutron veto

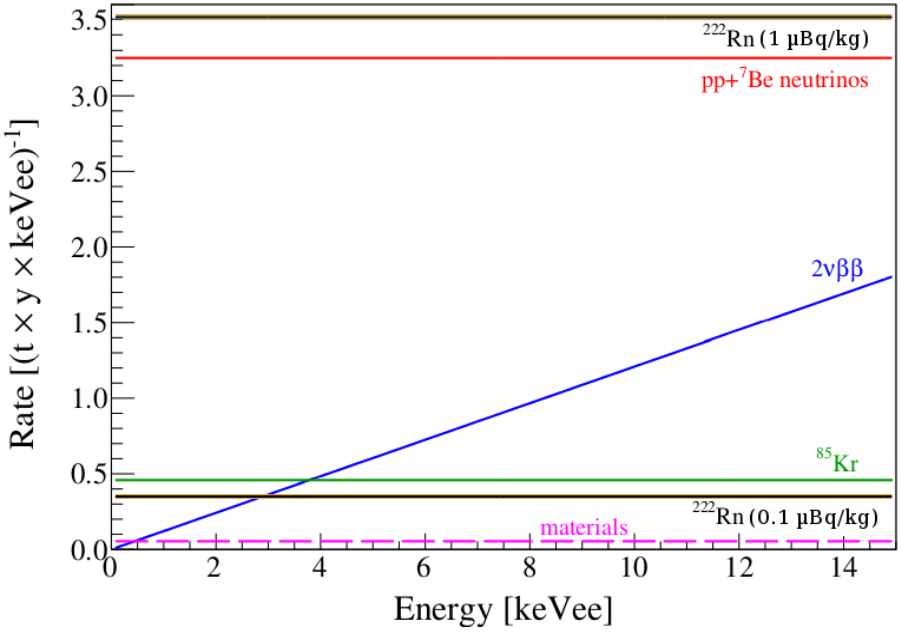
DARWIN Dark matter WImp search with liquid xenoN

Baseline design
~50t total LXe mass
40 t LXe TPC
~32 t fiducial

neutrino-dominated background





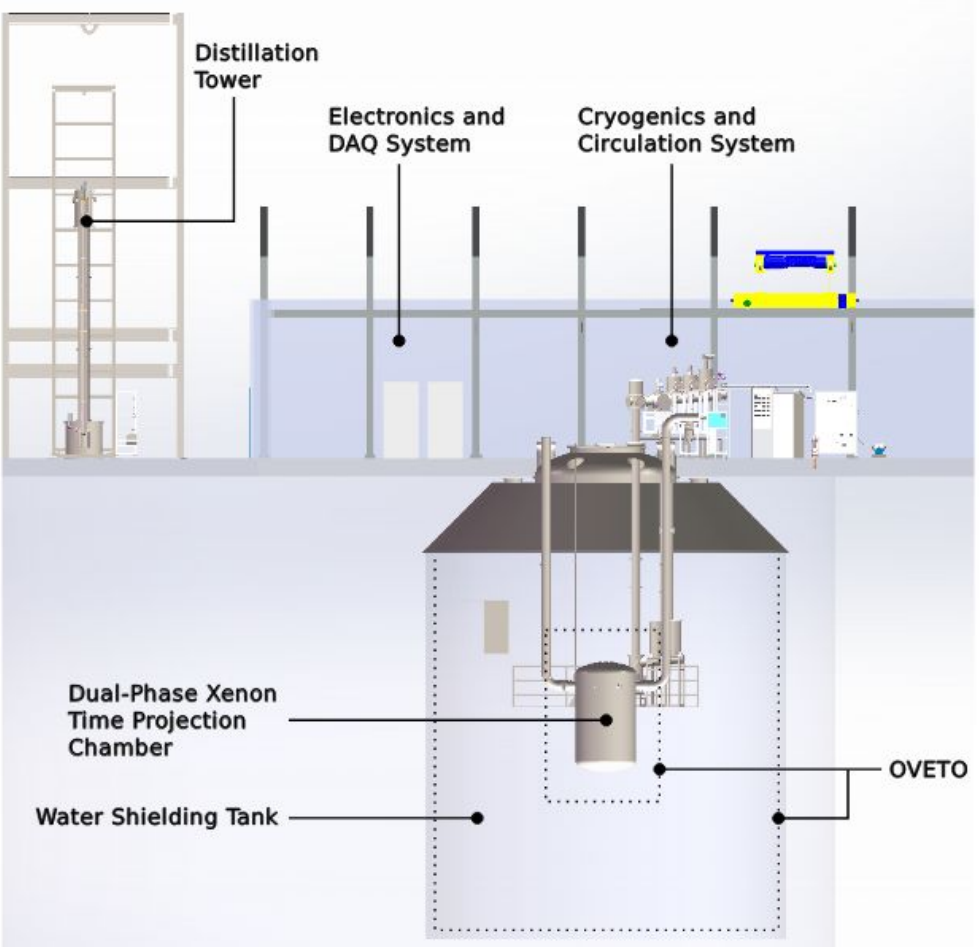


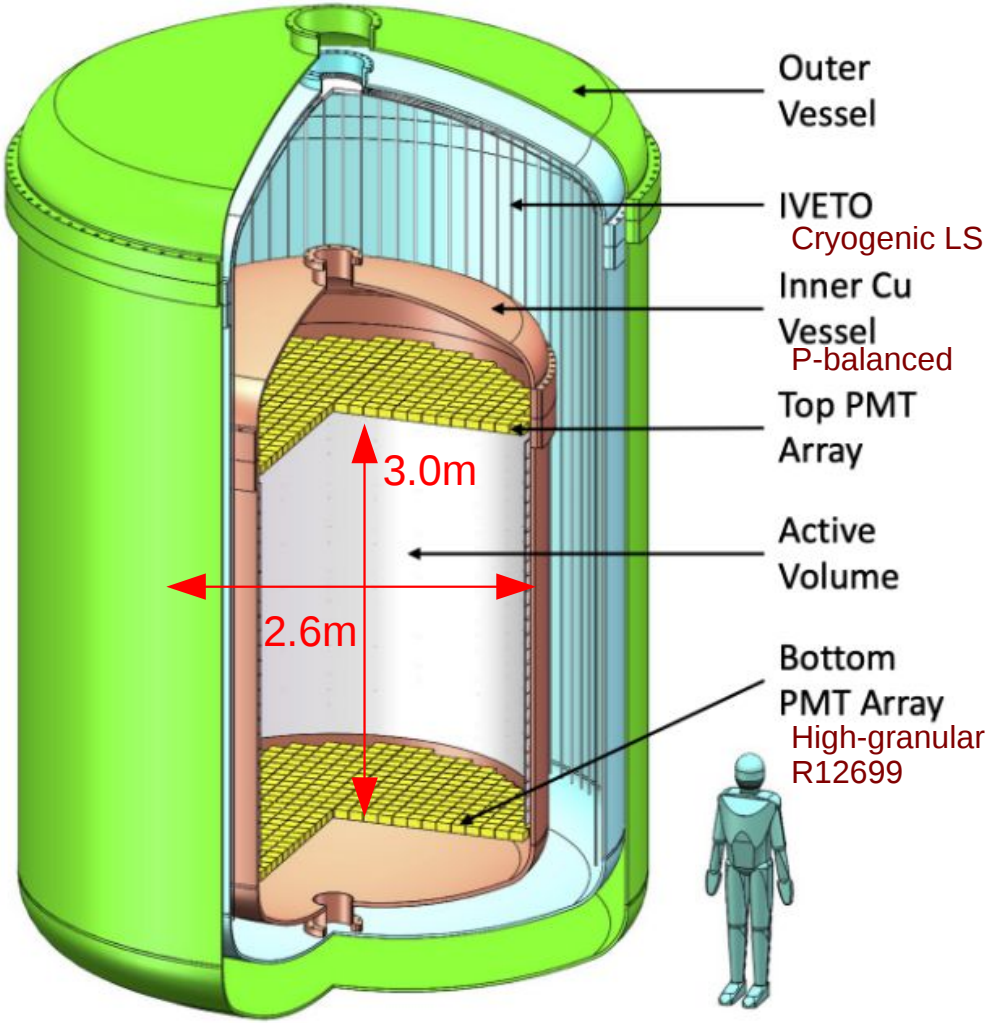
Neutrinos: JCAP 01, 044 (2014)
WIMP/BG: JCAP 100, 016 (2015)
Concept: JCAP 11, 017 (2016)
Solar ν: EPJ C 80, 1133 (2020)
0νββ: EPJ C 80, 808 (2020)
Light MC: JINST 17, P07018 (2022)
Cosmogenics: EPJ C 84, 88 (2024)

PandaX-xT

arXiv:2402.03596

Proposal to upgrade PandaX-4T at CJPL





43t LXe in target, 34.2t fiducial

XENON + LZ + DARWIN =

www.xlzd.org

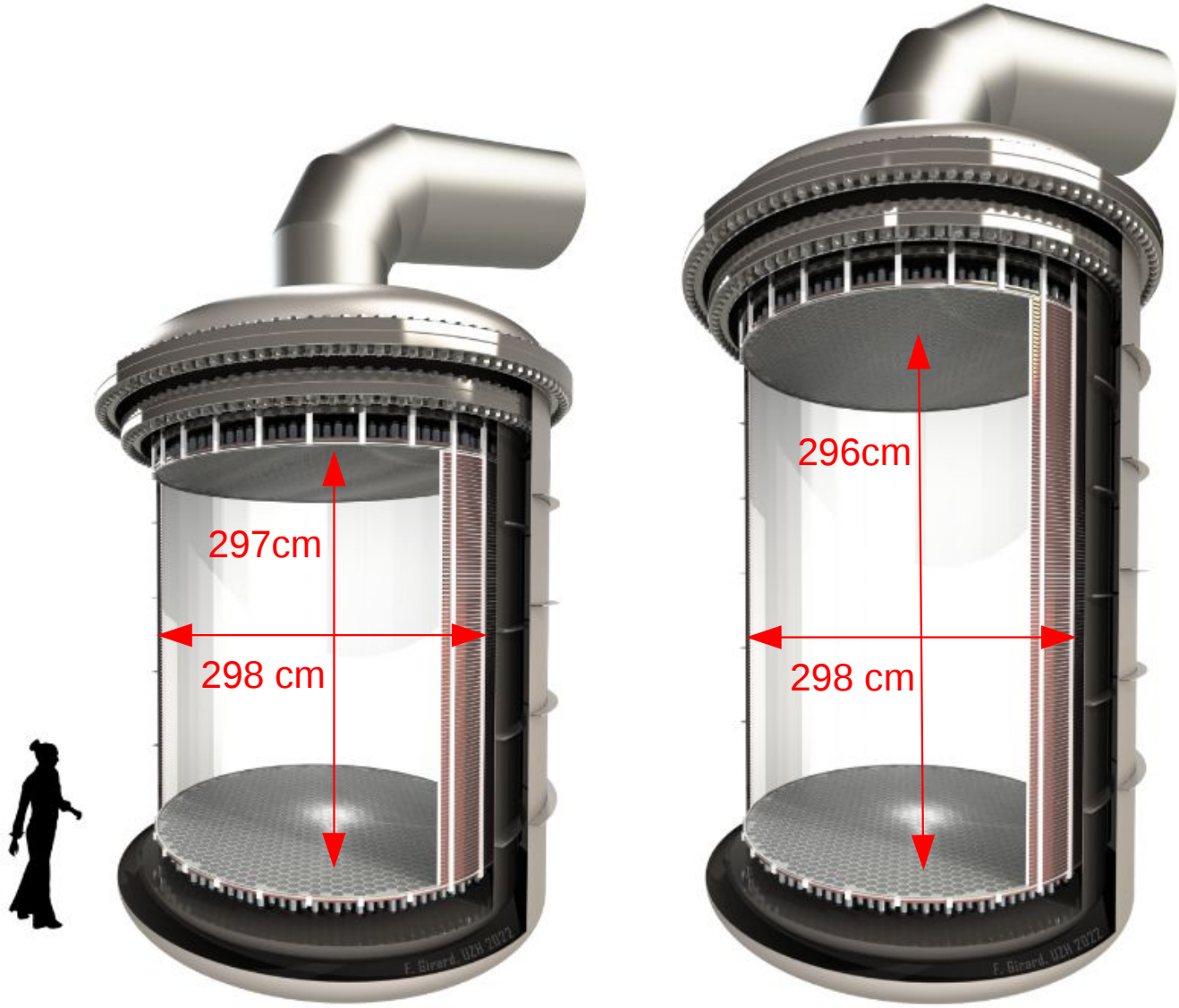
- Preparation of merger of DARWIN / XENON + LZ collaborations to build and operate the next-generation LXe observatory
  - → new, stronger collaboration
  - → P5 recommendations for G3 detector positive (US)
- Currently: paving the way with XLZD Consortium
  - → MoU 2021: 104 group leaders from 16 countries
  - → joint whitepaper, workshops (2022 KIT, 2023 UCLA, 2024 RAL)
  - → common WGs, regular SteCo meetings
  - → preparing documents (detector, siting, etc)
- Preparing to form full collaboration

XLZD Strategy

Low-background
dual-phase LXe TPC
with **nominal 60t target**
(54t fiducial mass)

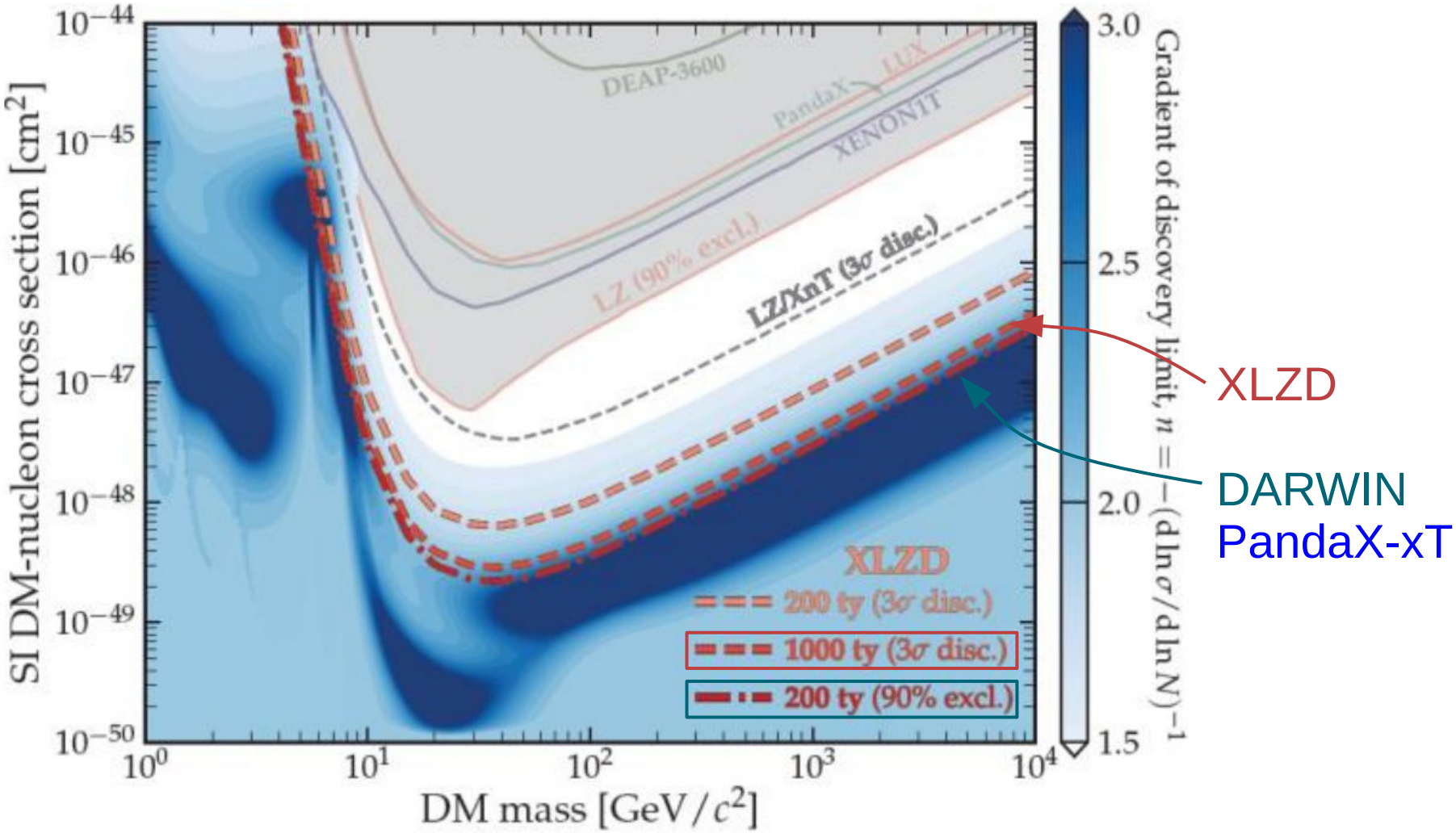
System can be readily
upgraded to 80t target
if LXe market allows
for faster acquisition rate

Siting decision currently
being prepared.
Five labs expressed interest:
Boulby, Kamioka,
LNGS, SNOLab, SURF



60t LXe target → 80t LXe target

DARWIN/PandaX ↔ XLZD: Science Reach



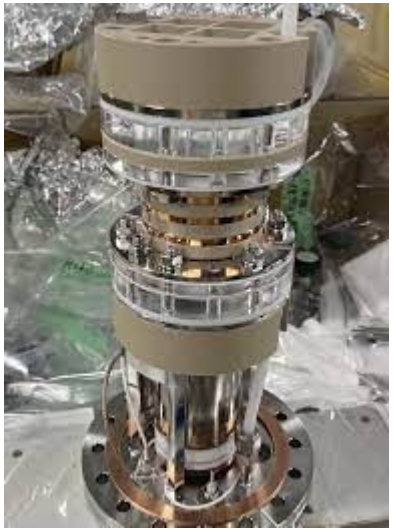
200 t×y: probe masses ≥10 GeV at 90% CL — DARWIN, PandaX (40t)

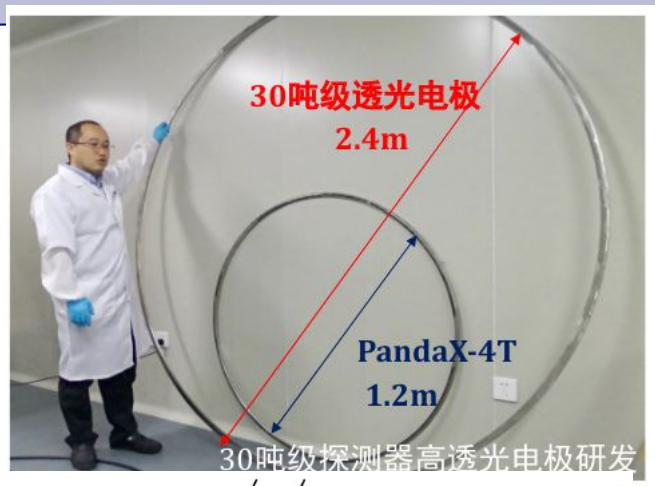
1000 t×y: probe masses ≥10 GeV at 3σ evidence — XLZD (60t-80t)

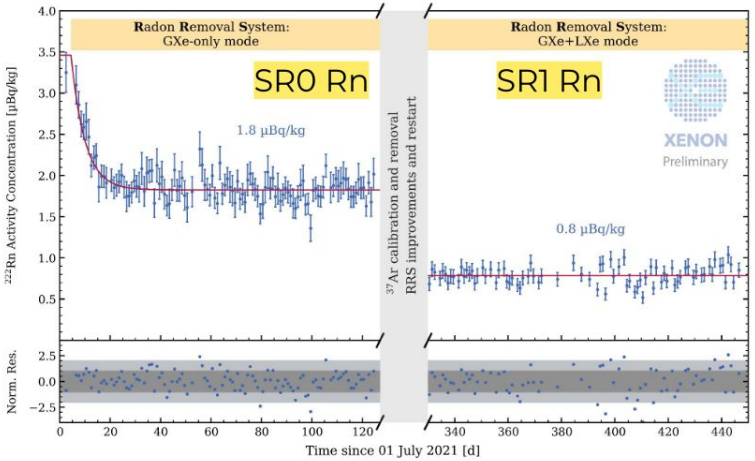
+lower bg for 0νββ

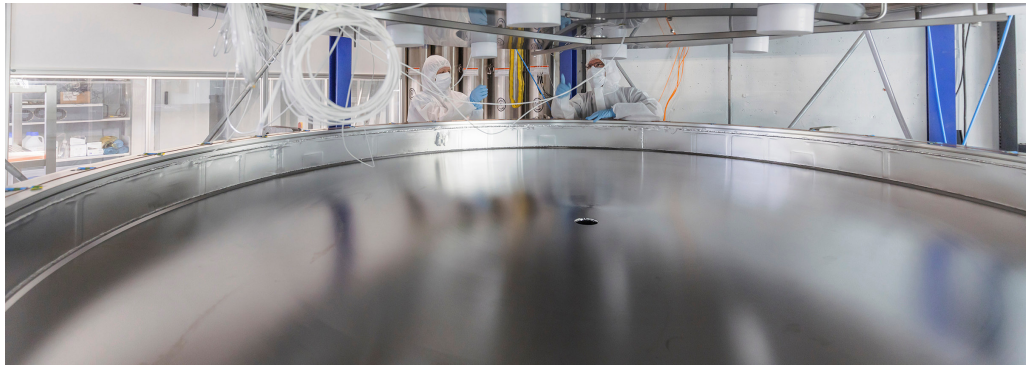
Common Challenges

- Sufficiently high drift field
- Dual-phase S2 electrodes
- Backgrounds
  - Rn emanation
  - neutrons (materials, veto)
  - avoid contaminations
  - accidental coincidences
- Size
  - mass (→ background) vs. stability
  - Thermal contraction
- Photosensors
  - background
  - low DC rate
- **Xenon procurement**
- ...









What can we do with such an amazing Instrument?

nb: I often show results from smaller LXe detectors for illustration. In general, all channels explored by smaller detectors can also be studied with larger instruments.
And I have easier access to XENON results...

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]

...

[97] *Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, 48149 Münster, Germany*
[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 ences, 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

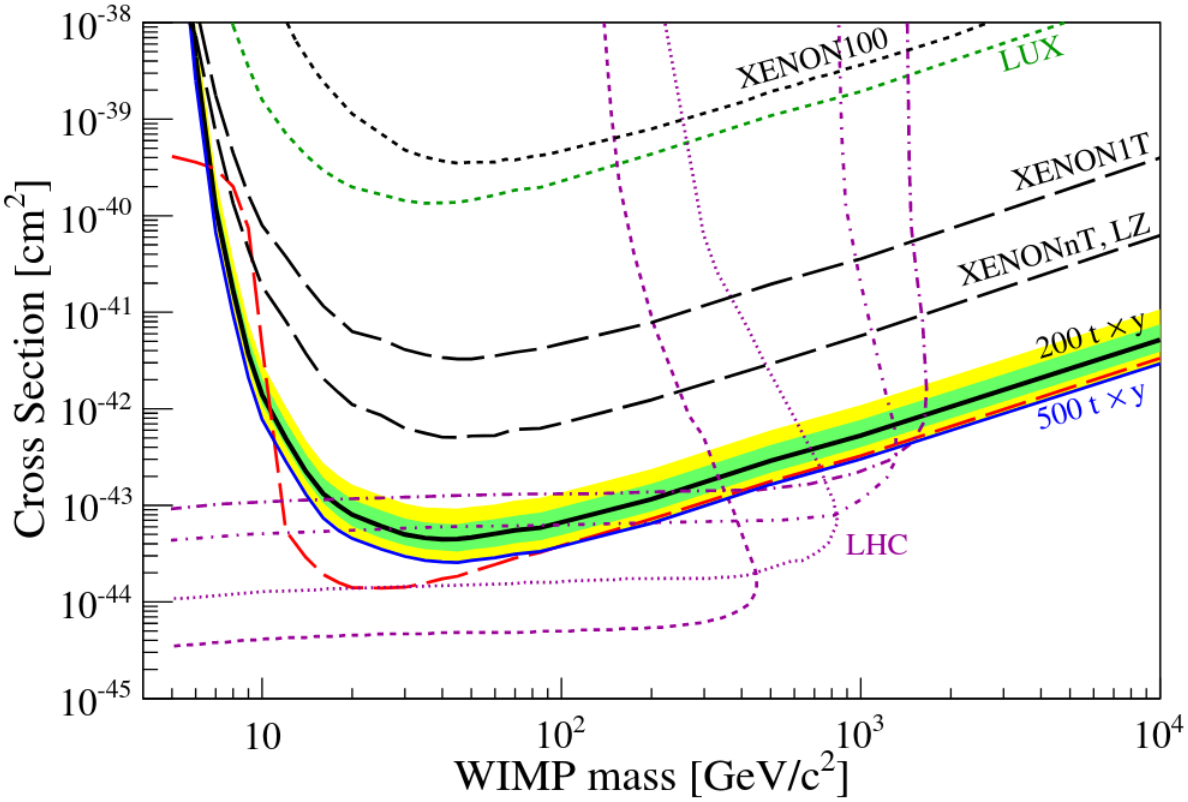
JCAP 10, 016 (2015)

- 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

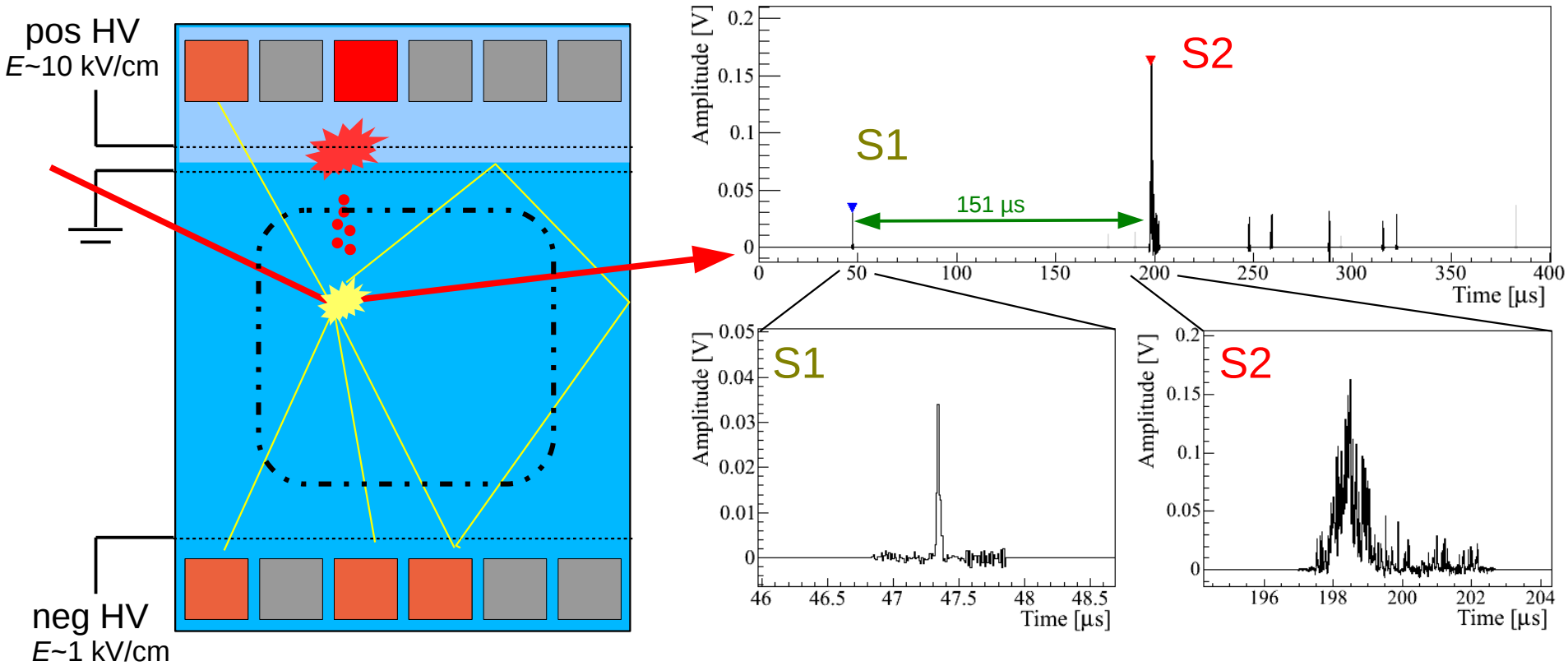
Isotope	Abundance	Spin	Unpaired Nucleon	Relative Strength
^{7}Li	92.6%	3/2	proton	12.8
^{19}F	100.0%	1/2	proton	100.0
^{23}Na	100.0%	3/2	proton	1.3
^{29}Si	4.7%	1/2	neutron	9.7
^{73}Ge	7.7%	9/2	neutron	0.3
^{127}I	100.0%	5/2	proton	0.3
^{131}Xe	21.3%	3/2	neutron	1.7

WIMP-neutron scattering

Interpretation of same WIMP search data

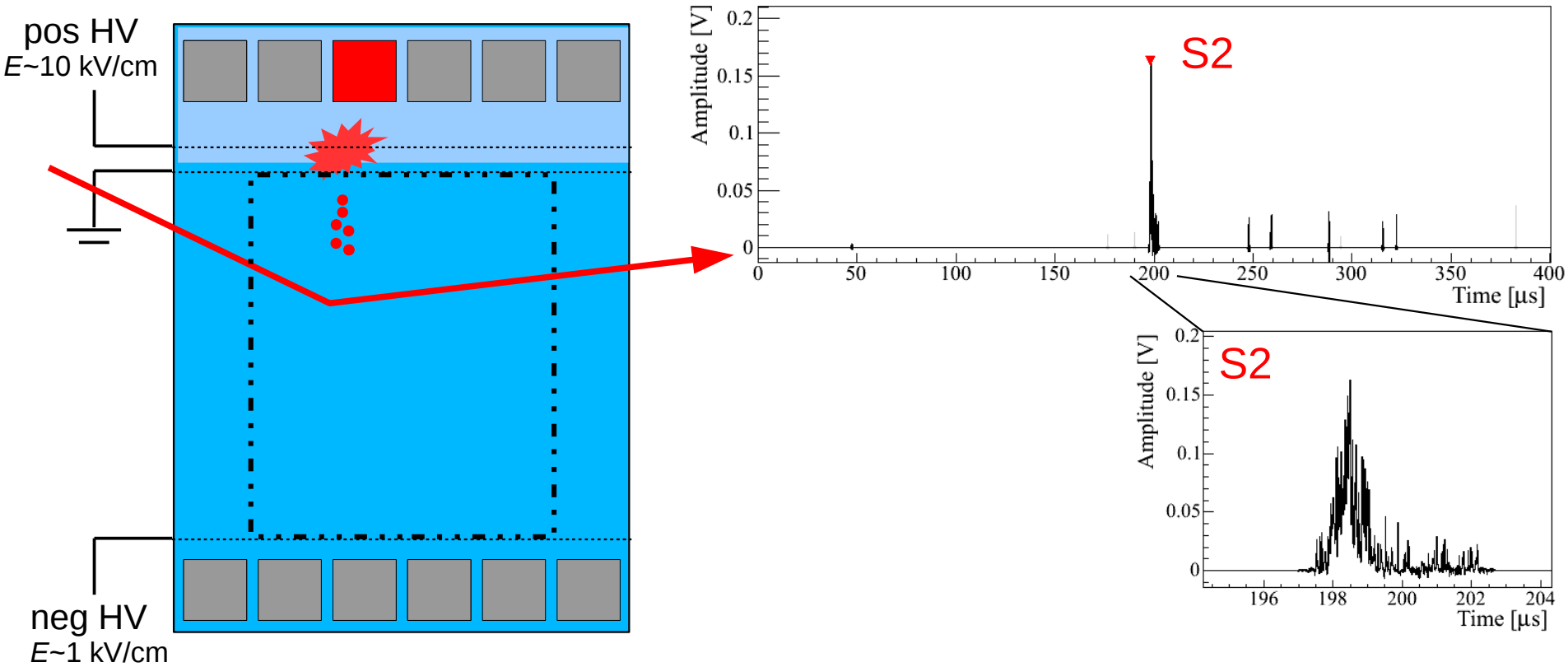


Standard Analysis



Charge-Only Analysis

PRL 107, 051301 (2011)

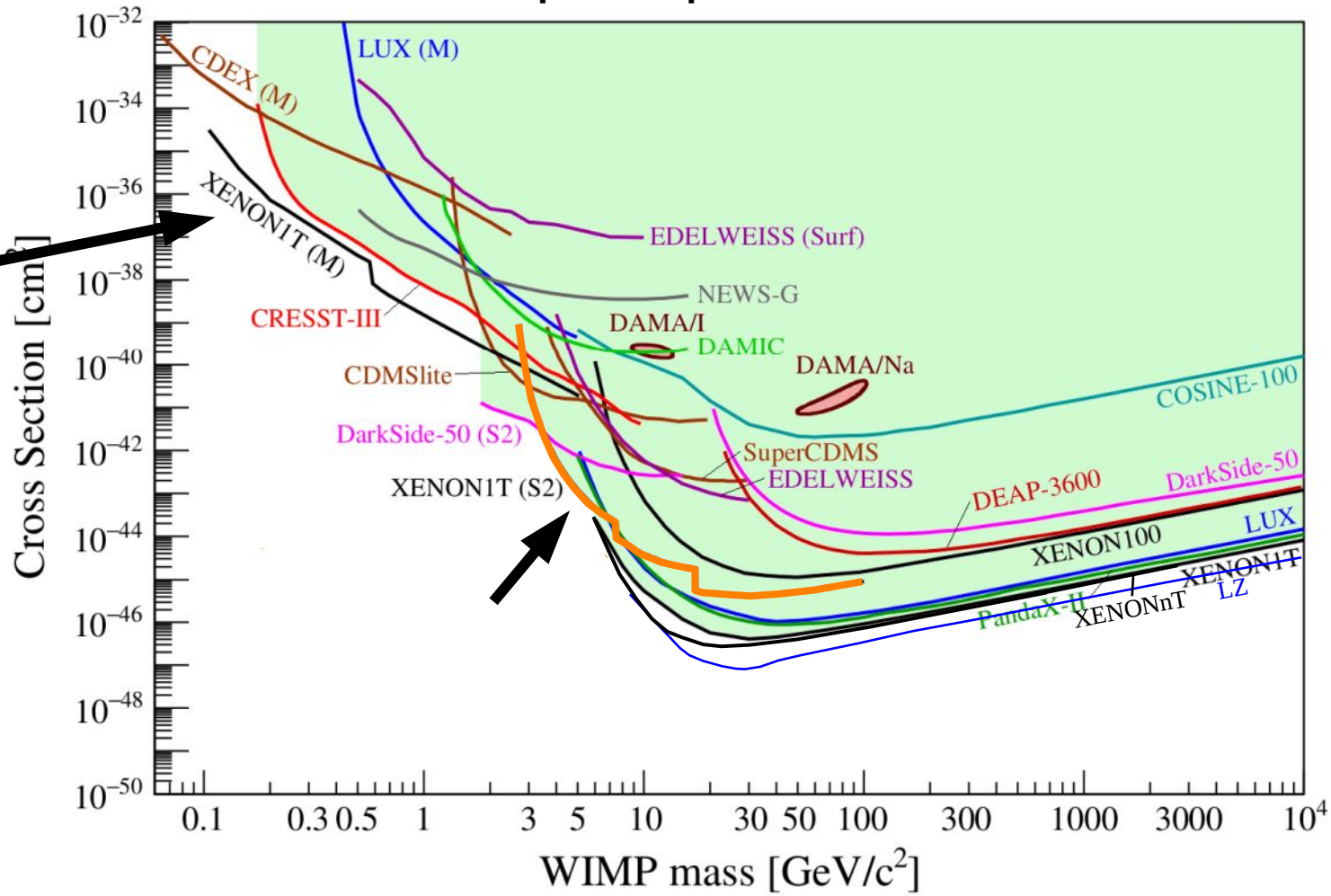


Charge-Only Analysis

PRL 123, 251801 (2019)

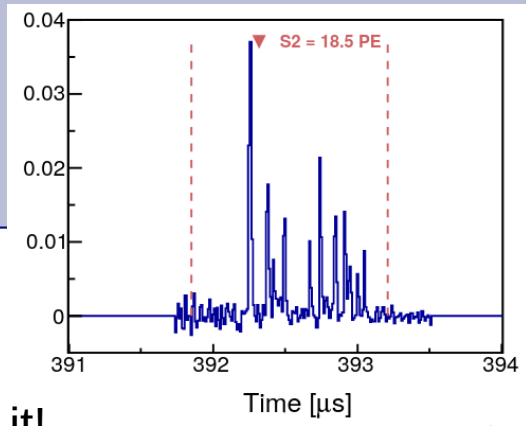
spin-independent WIMP-nucleon interactions

with Migdal effect



some results are missing...

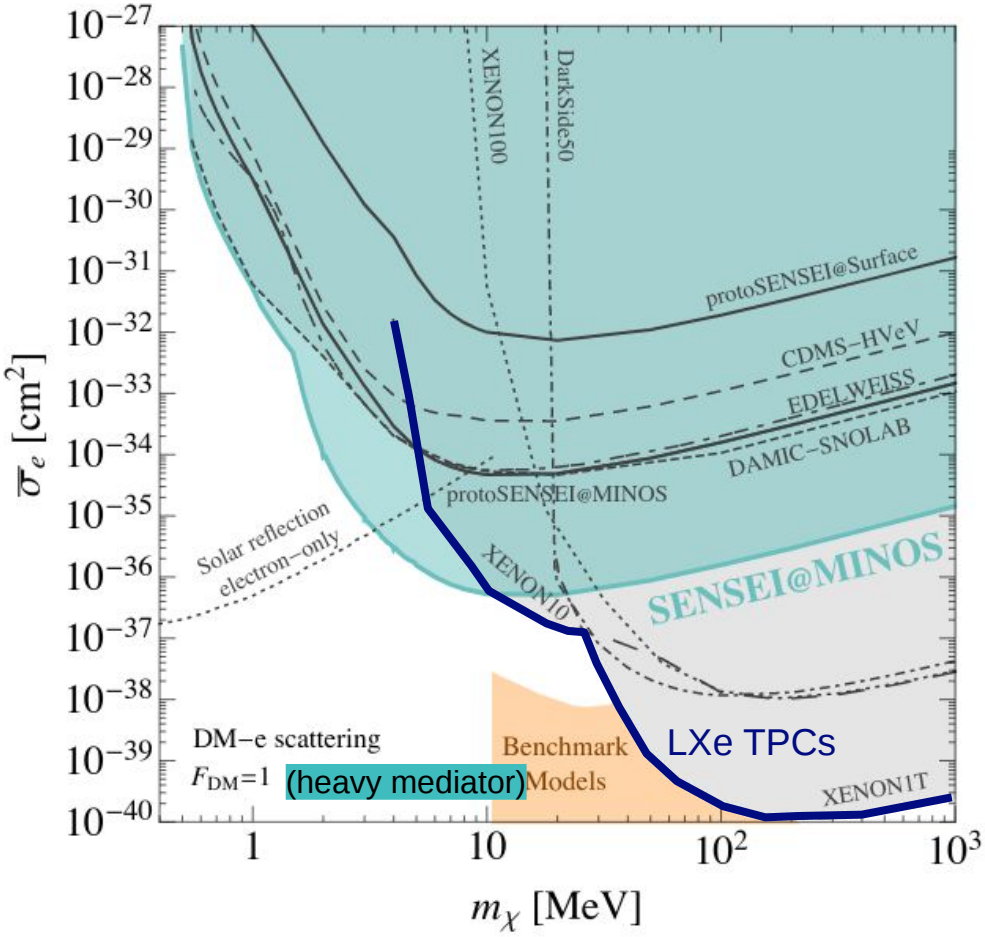
WIMP-e⁻ Scattering

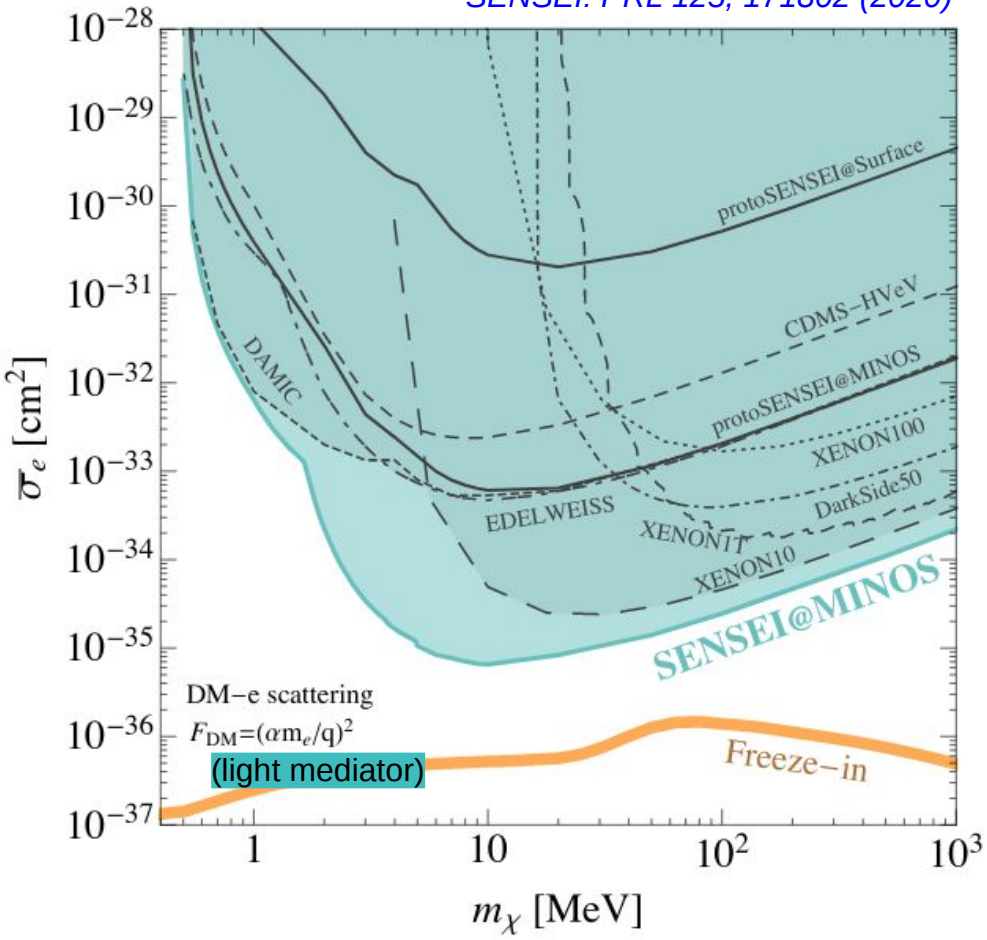


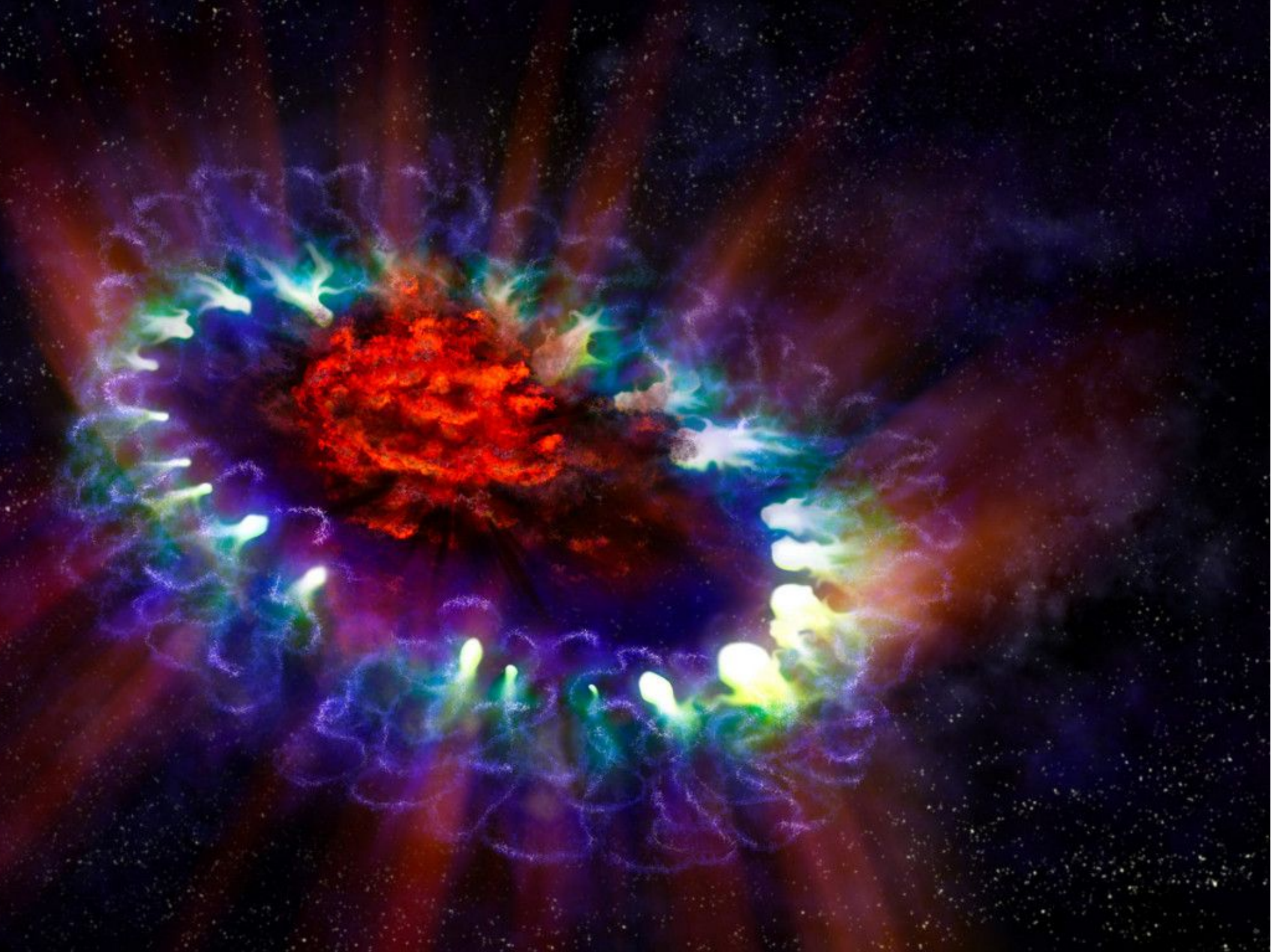
Very light DM scatters off electrons

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

SENSEI: PRL 125, 171802 (2020)



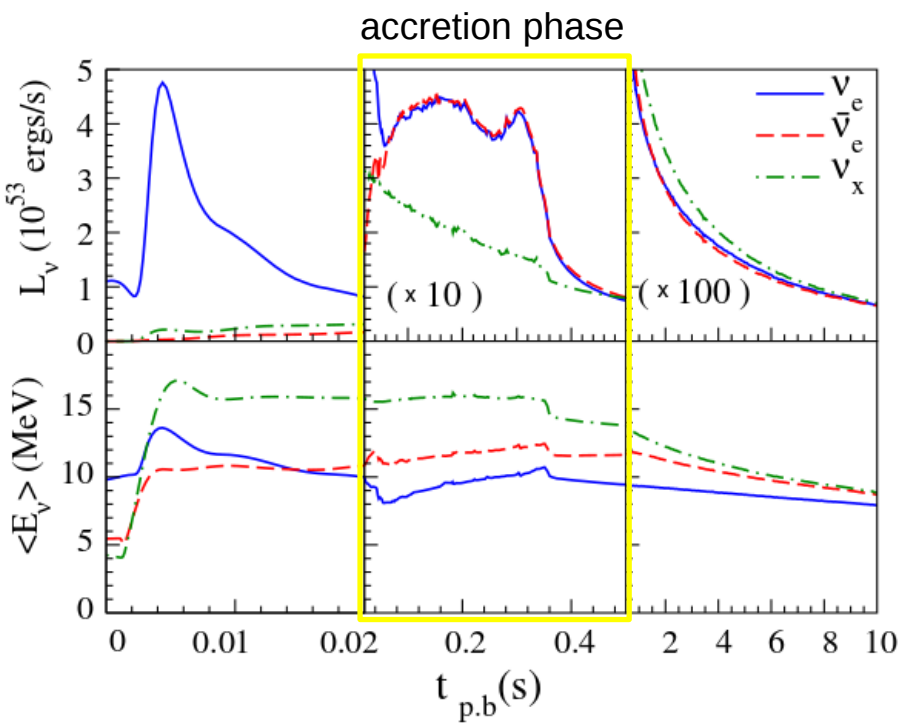


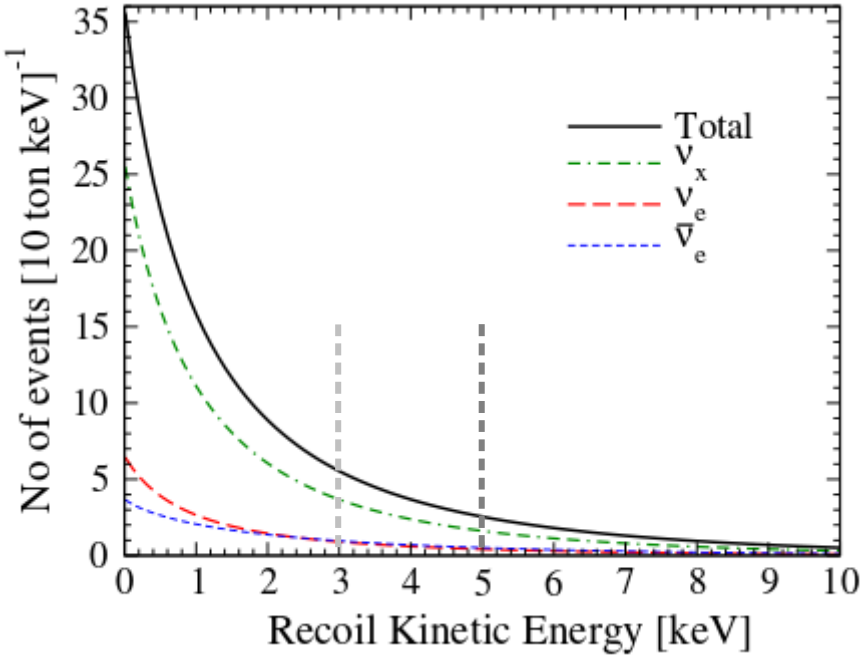


Supernova Neutrinos

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 (<future dets)
- signal: NRs plus precise time information
- challenge: theshold

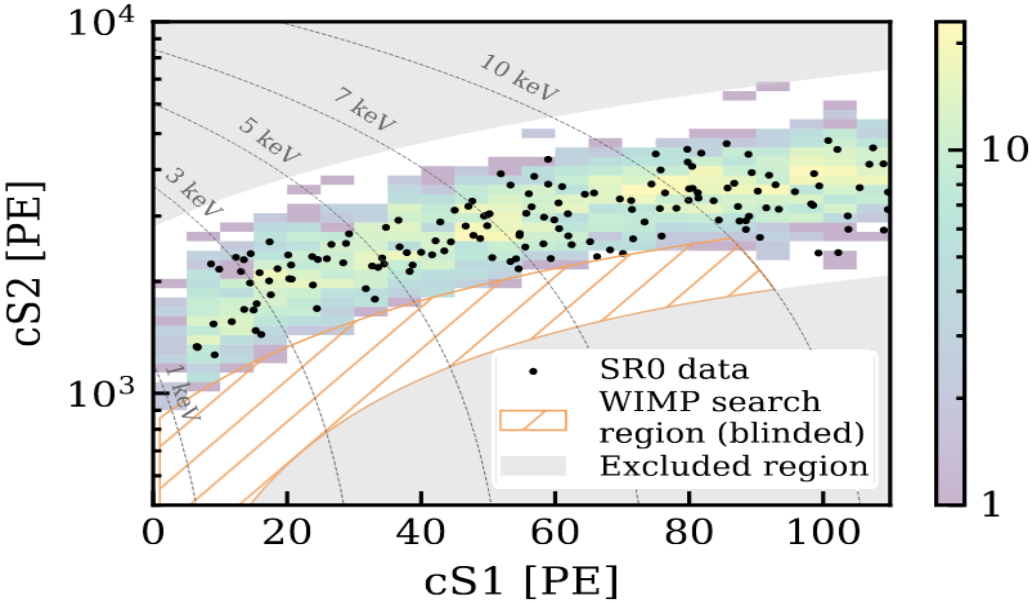


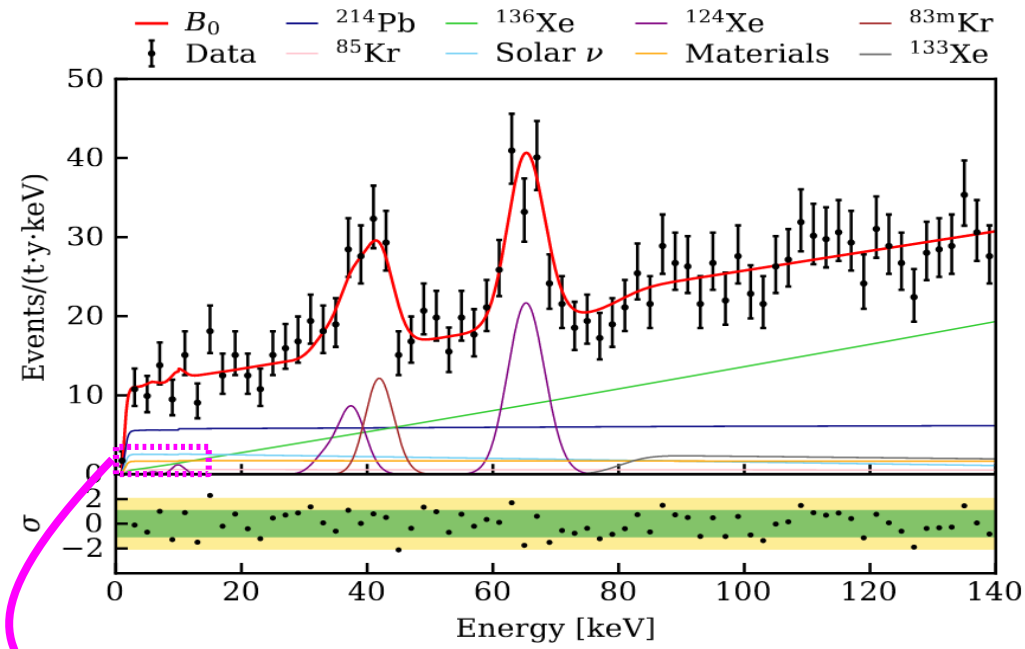


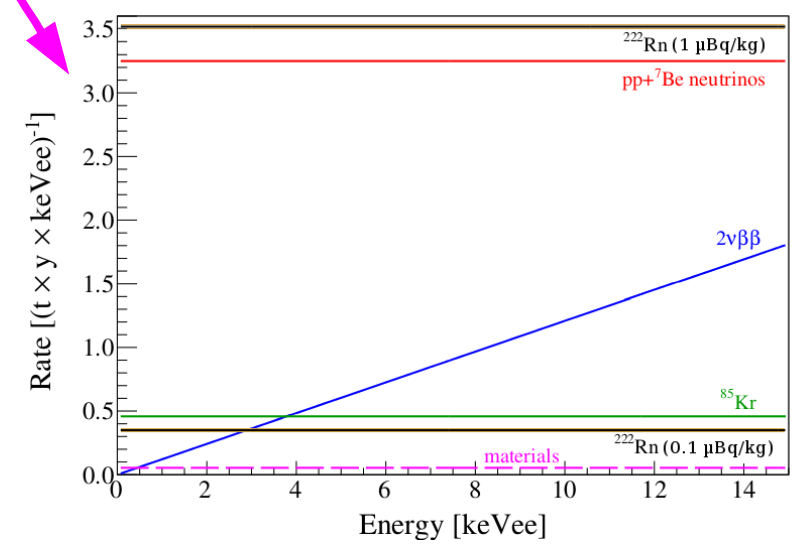
Low-E Electronic Recoils

PRL 129, 161805 (2022)

Current Status





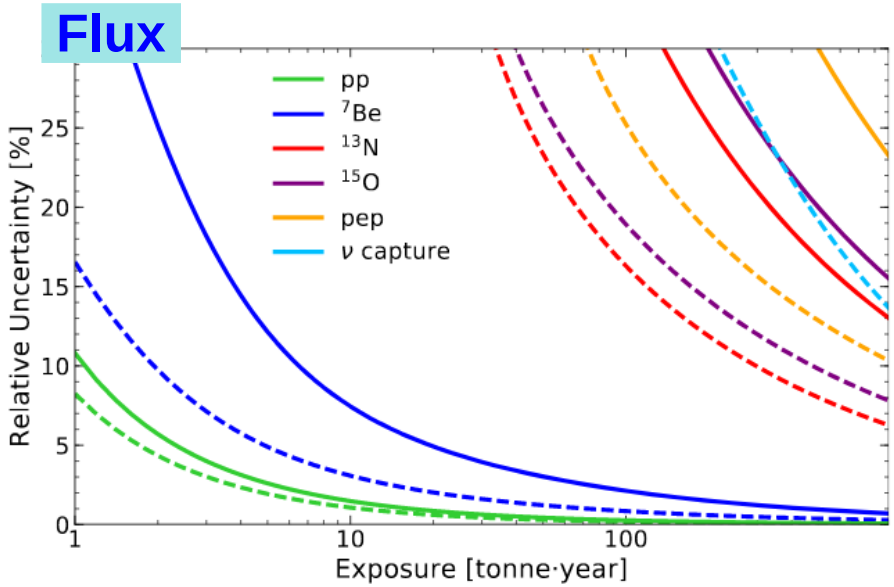


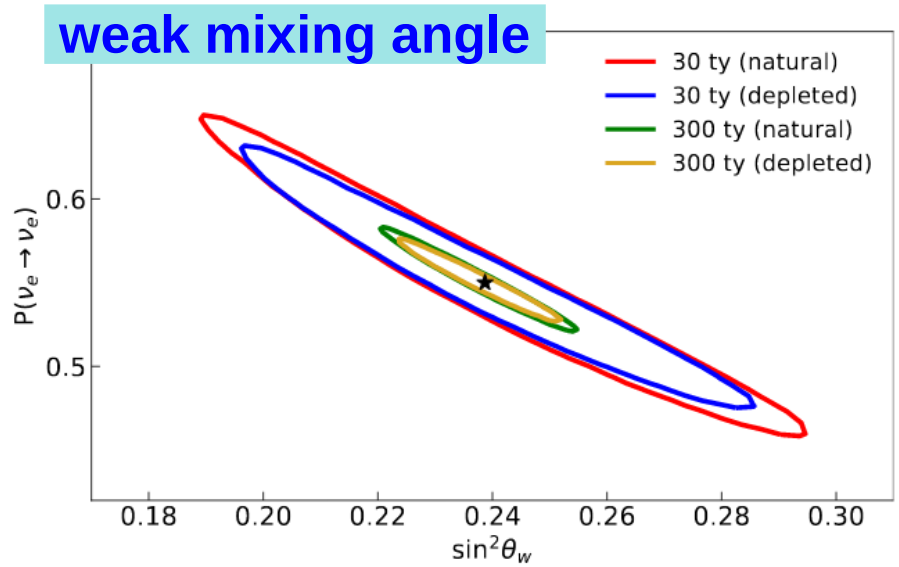
Future Goal

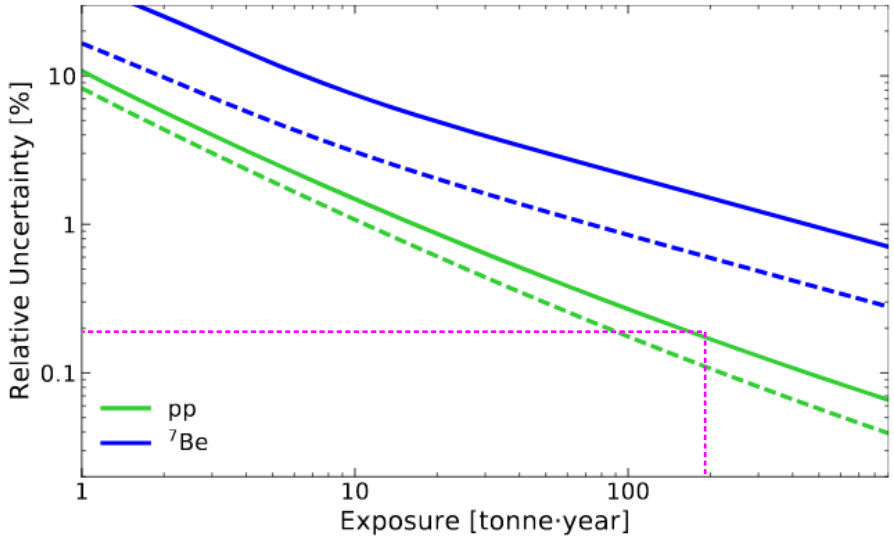
→ rare processes get detectable since ER backgrounds are low!

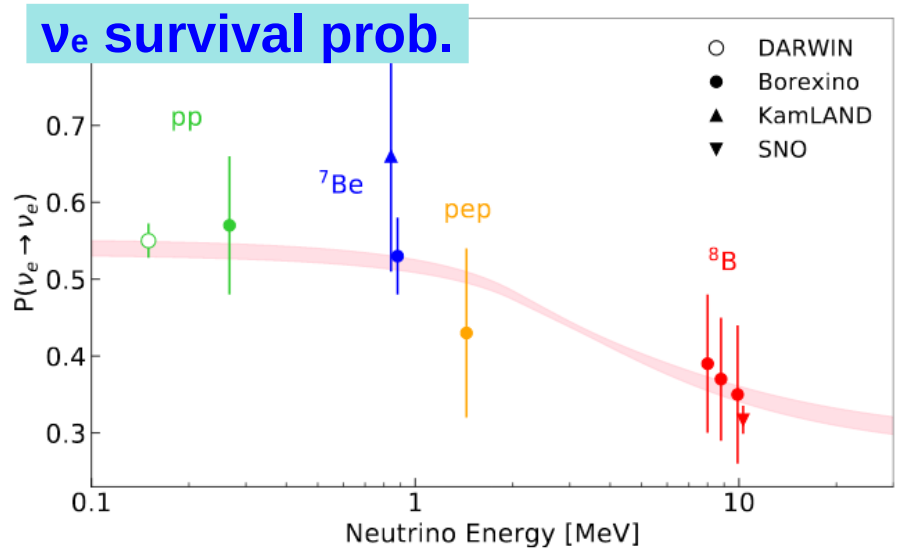
pp-Neutrinos in real time

EPJ C 80, 1133 (2020)



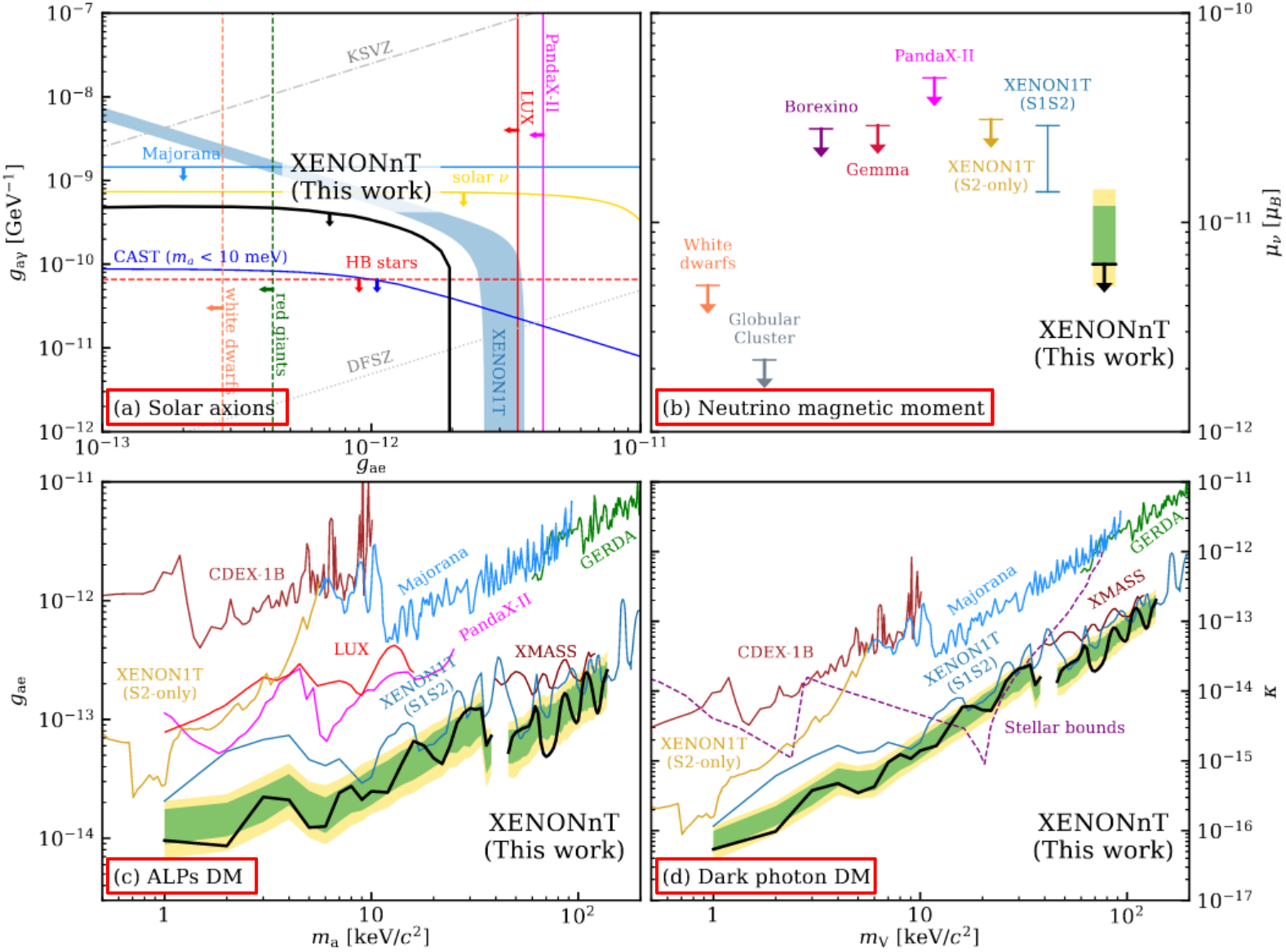






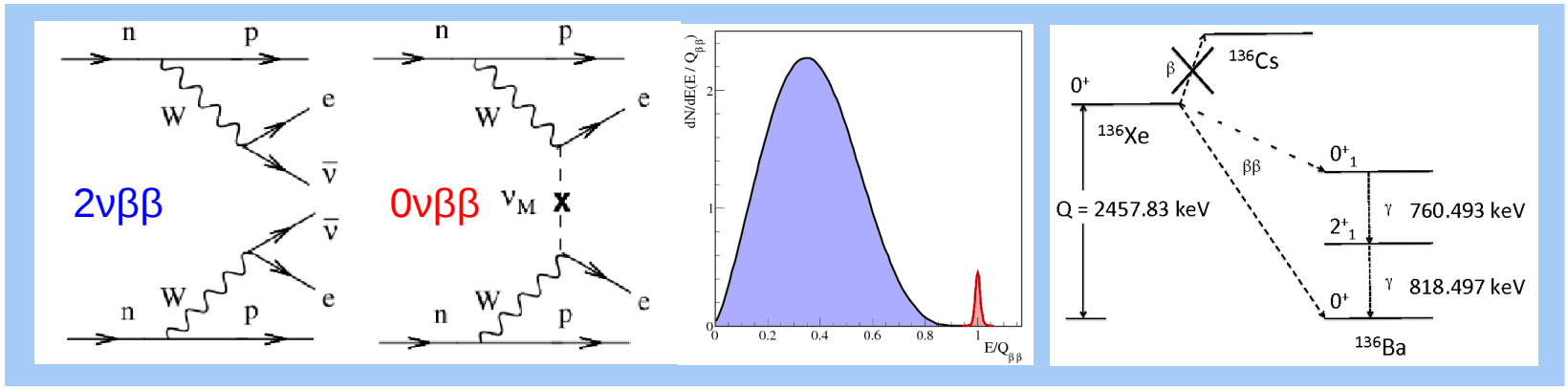
Limits on New Physics

PRL 129, 161805 (2022)



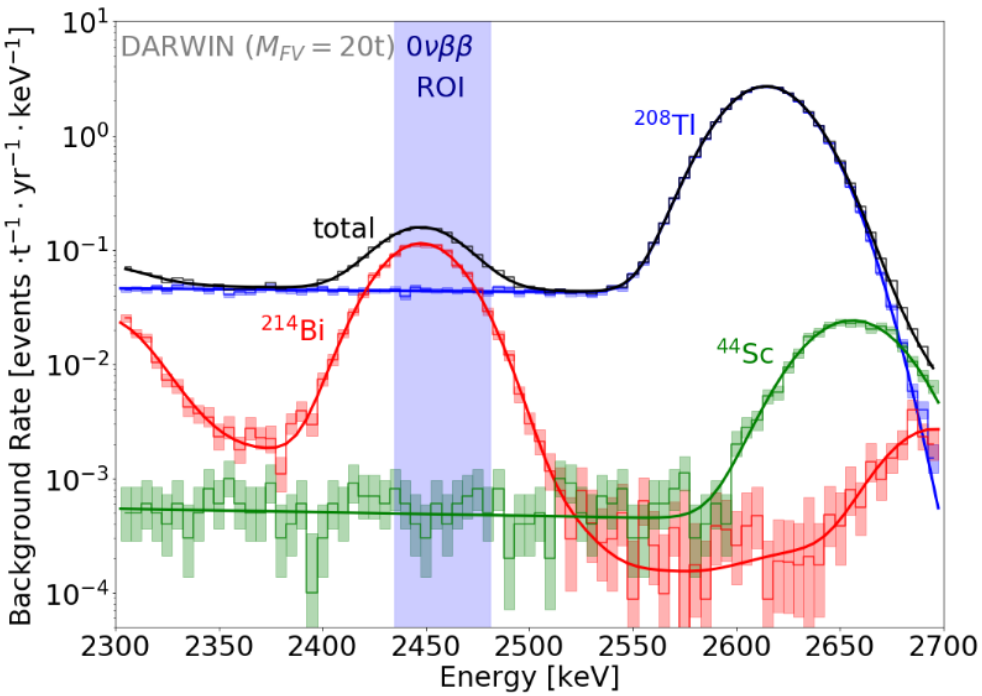
^{136}Xe: 0ν double-beta Decay

EPJ C 80, 808 (2020)



ΔL ≠ 0

- 0νββ candidate with $Q_{\beta\beta}$=2.46 MeV



DARWIN Sensitivity

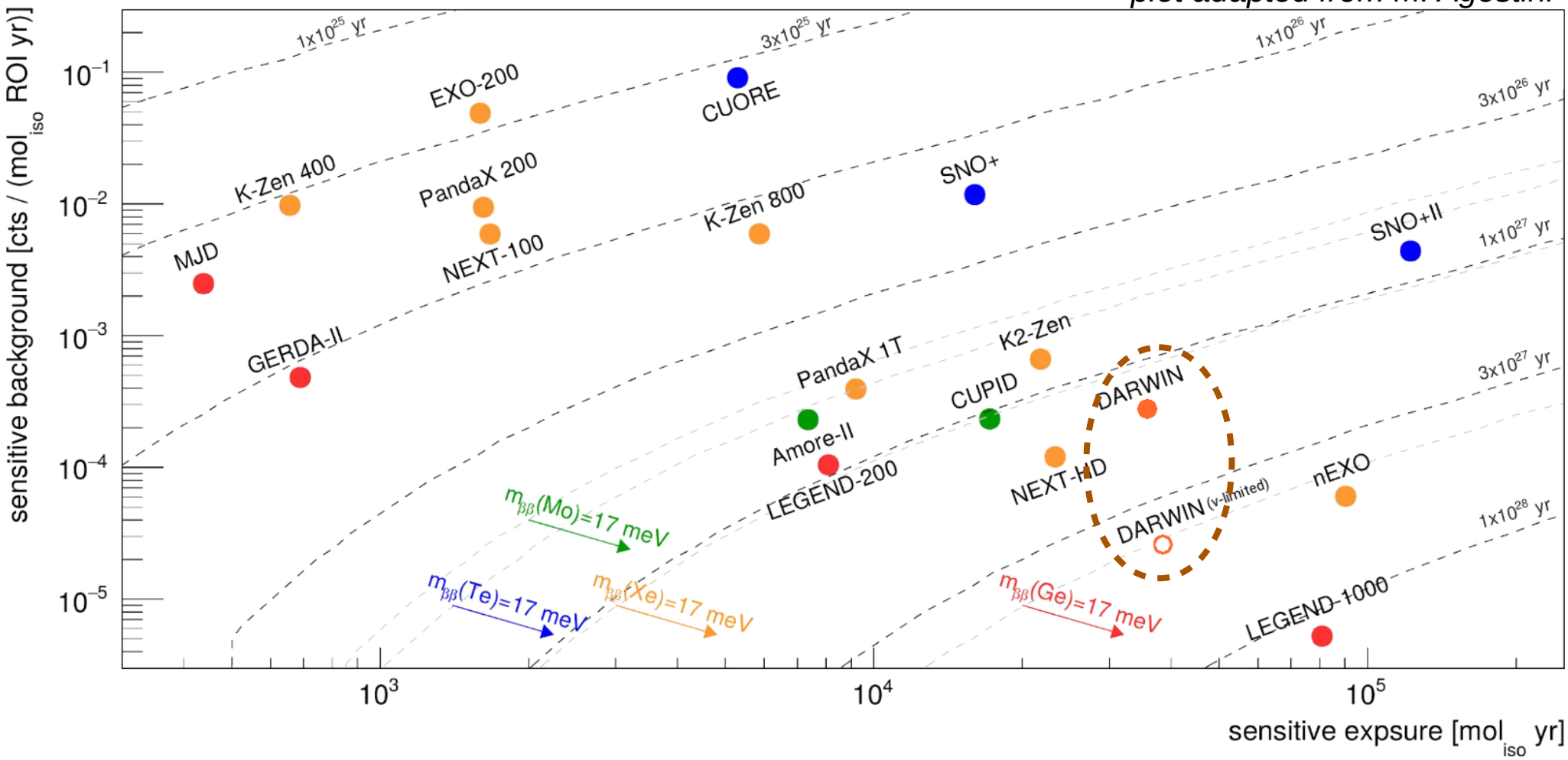
- optimize sensitivity by fiducialization
- background from decays of neutron-activated ^{137}Xe irrelevant at LNGS depth
- **half-life sensitivity: 3 × 10^{27} y**

  (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

An exciting future ahead of us

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
- $0\nu bb$ ^{136}Xe
- 0ν / $2\nu ECEC$ ^{124}Xe

Solar Axions

… and even more:
J. Phys. G 50, 013001 (2023)