Dark Matter Icebergs (~TeV scale particles)

Joel Bissell/Kalamazoo Gazette via AP

Hugh Lippincott, UCSB

TeVPA

August 26, 2024

Pinch hitter:
Matthew Szydagis,
UAlbany SUNY

Dark Matter in 2001

2001 Snowmass report - single 3 page section on dark matter and relic particles

Particle Astrophysics and Cosmology: Cosmic Laboratories for New Physics
(Summary of the Snowmass 2001 P4 Working Group)

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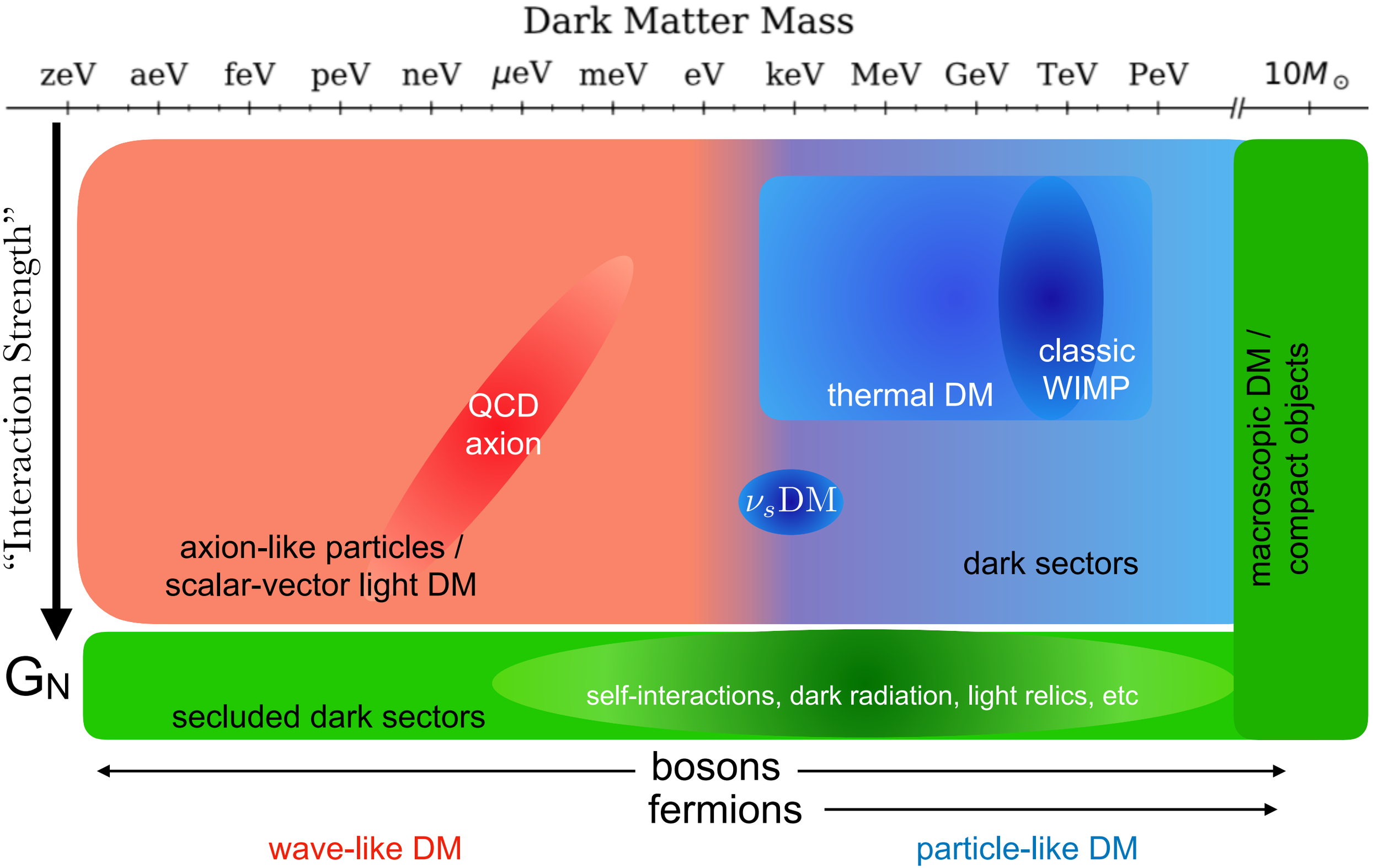
(Dated: October 30, 2018)

III. DARK MATTER AND RELIC PARTICLES

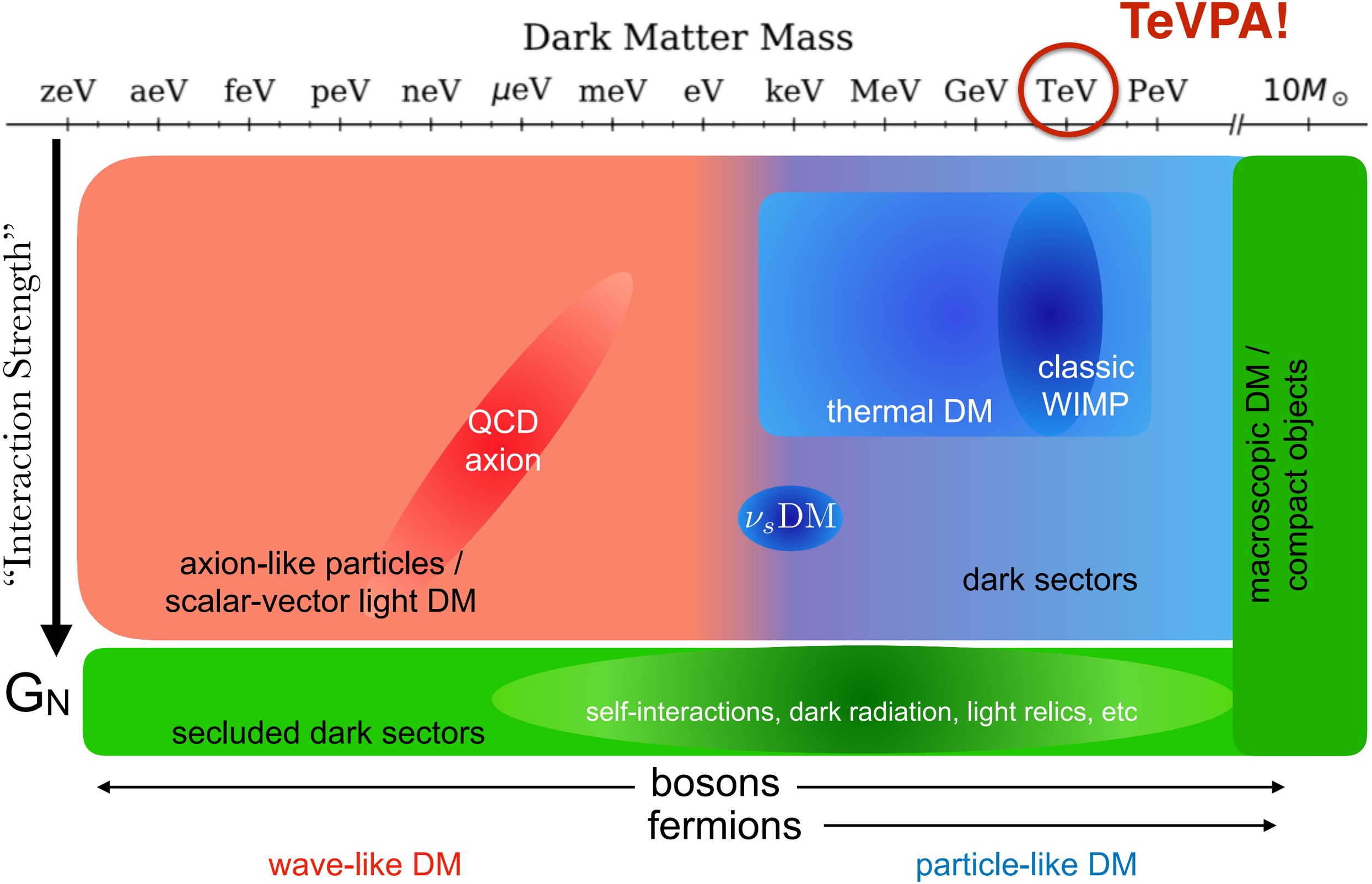
"Particle physics offers two different hypotheses for the dark matter—WIMPs and axions—either of which would constitute a major discovery of physics beyond the standard model."

Dark Matter Today



From A. Chou, Cosmic Frontier Plenary at Snowmass

Dark Matter Today



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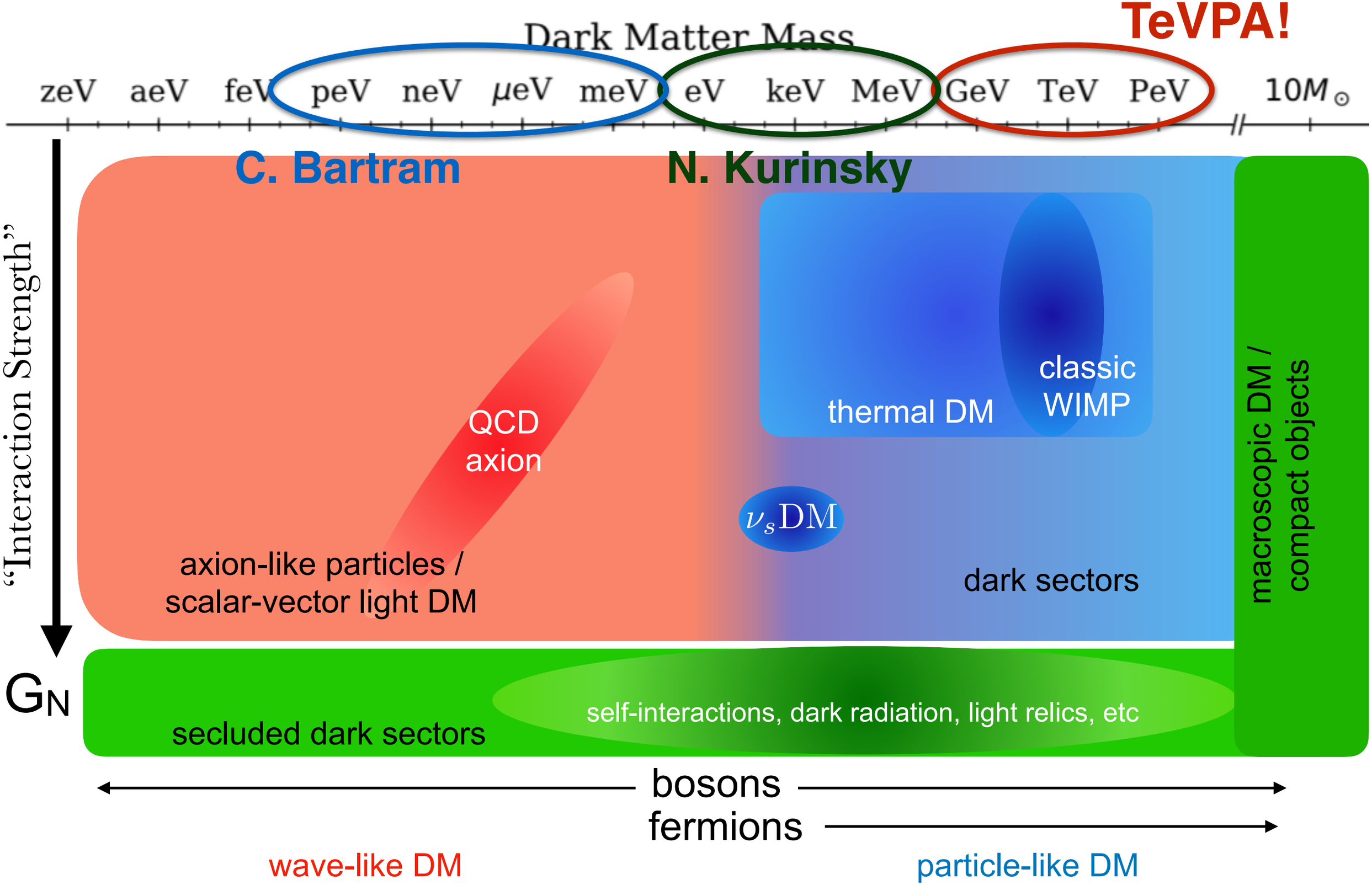
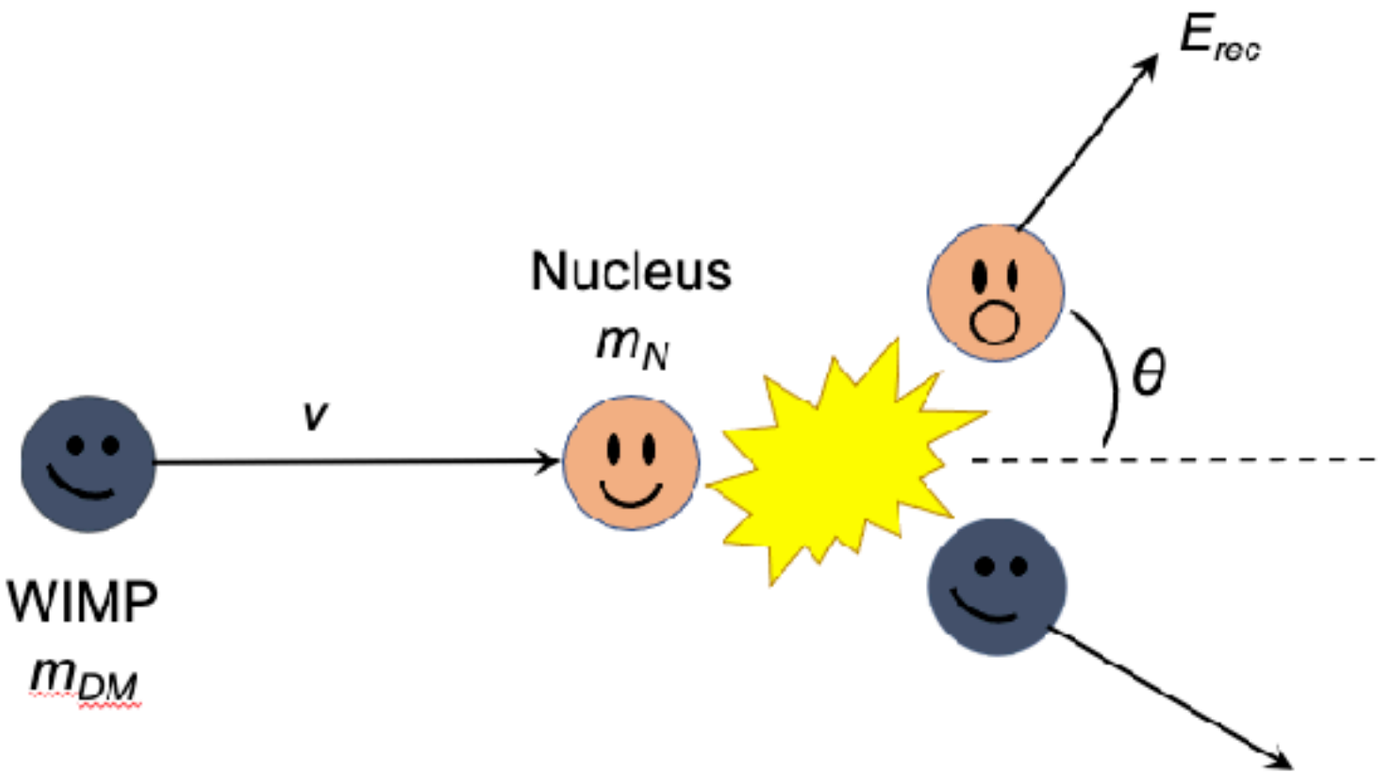


From A. Chou, Cosmic Frontier Plenary at Snowmass

“Direct Detection” of Dark Matter

Fill a detector with your favorite material and wait for WIMPs to scatter off it



A. Monte

Non-relativistic elastic scattering

$$\mu = \frac{m_{DM} m_N}{m_{DM} + m_N}$$

$$E_{rec} = \frac{\mu^2 v^2}{m_N}(1 - cos\theta)$$

m_{DM} = 100 GeV/c²
m_N = 131 GeV/c²
v = 220 km/s
E_{rec} = 3 keV

- Naturally sensitive to >GeV particles by kinematics and technology
- Great for WIMP hunting at the TeV scale

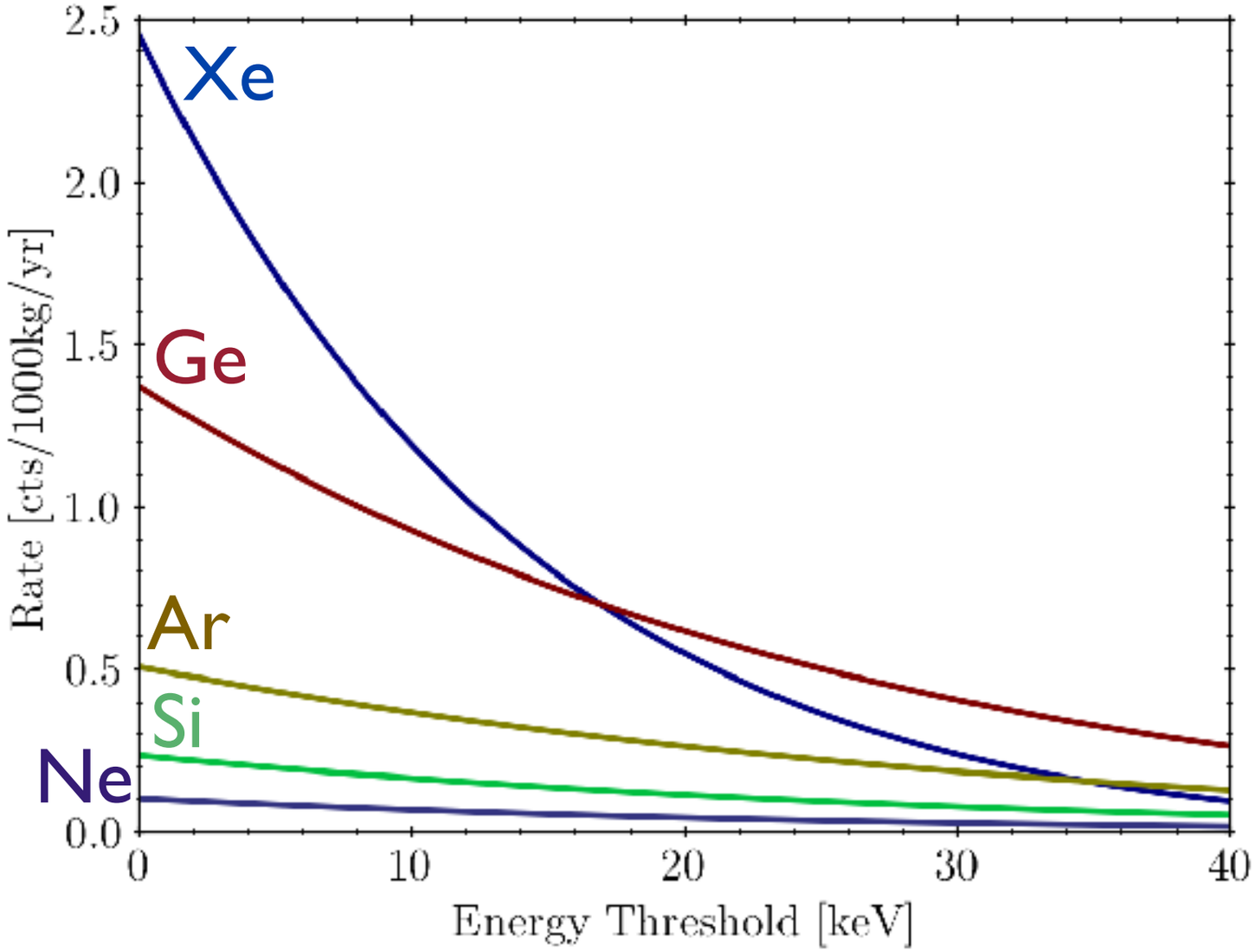
Direct Detection of Dark Matter

- Very rare process
  - Current best limits <10^{-47} cm^2
  - Path length in lead of ~10 million light years

- Luckily, there are lots of particles flying around (in theory)
  - Can look for a few counts in a detector per year

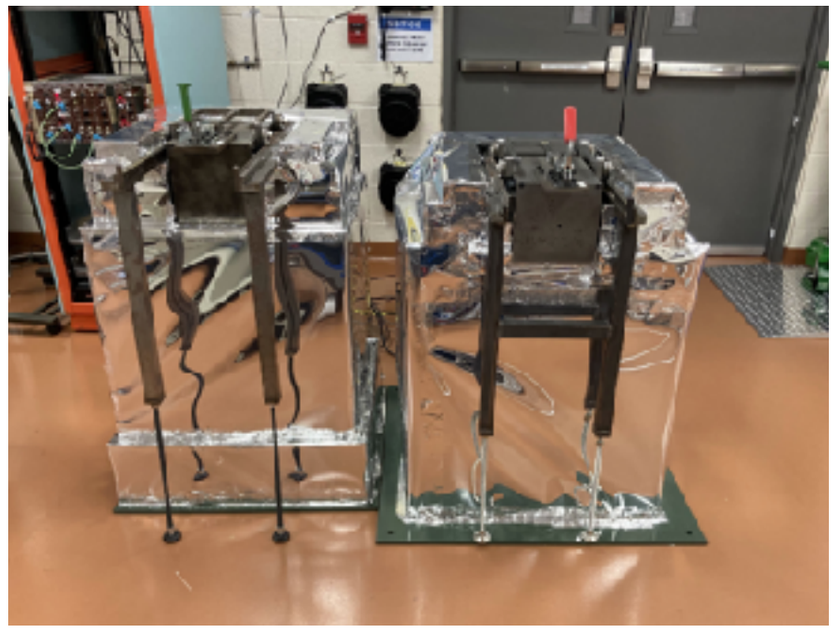
- Backgrounds, backgrounds, backgrounds
  - 10^{12} per tonne/year on surface

R(cts/tonne/yr) for 10^{-47} cm^2, 100 GeV

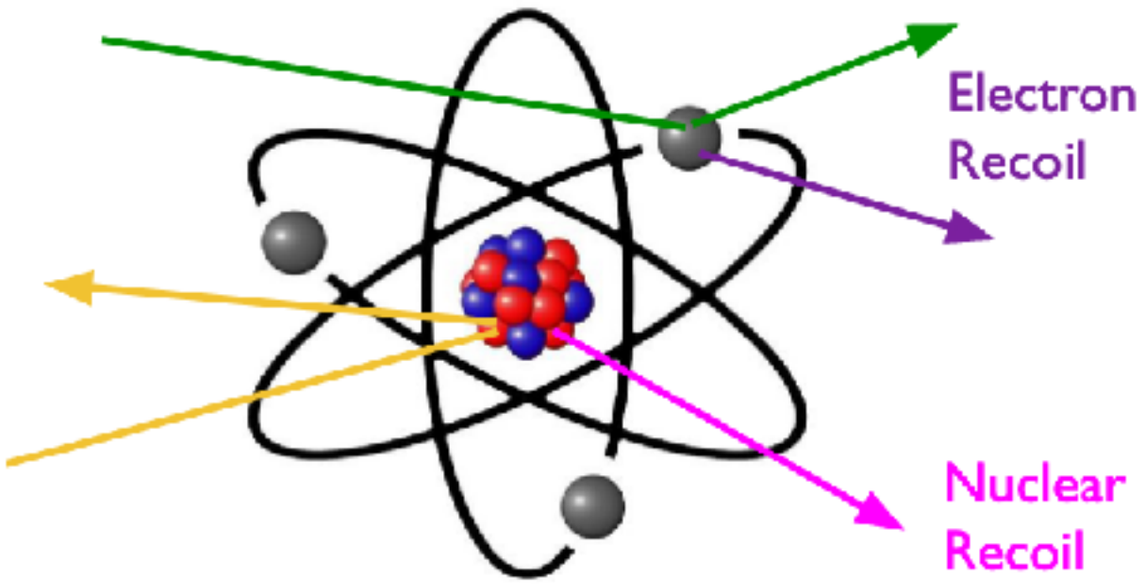


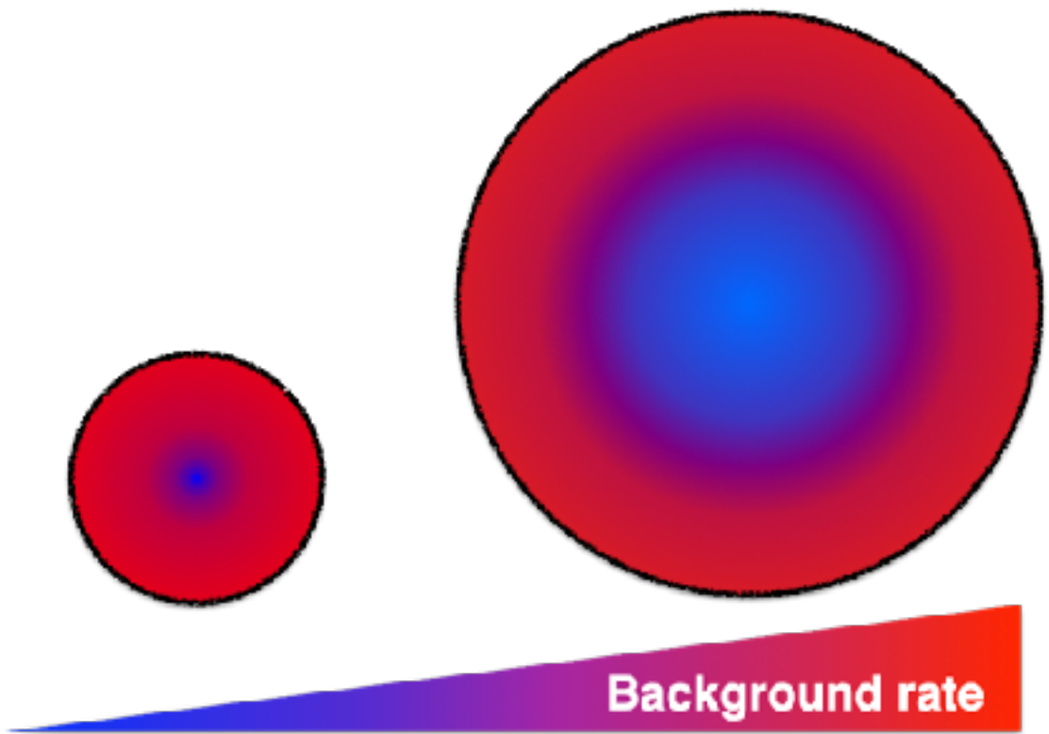
- Goal: Maximize sensitivity to DM while minimizing backgrounds

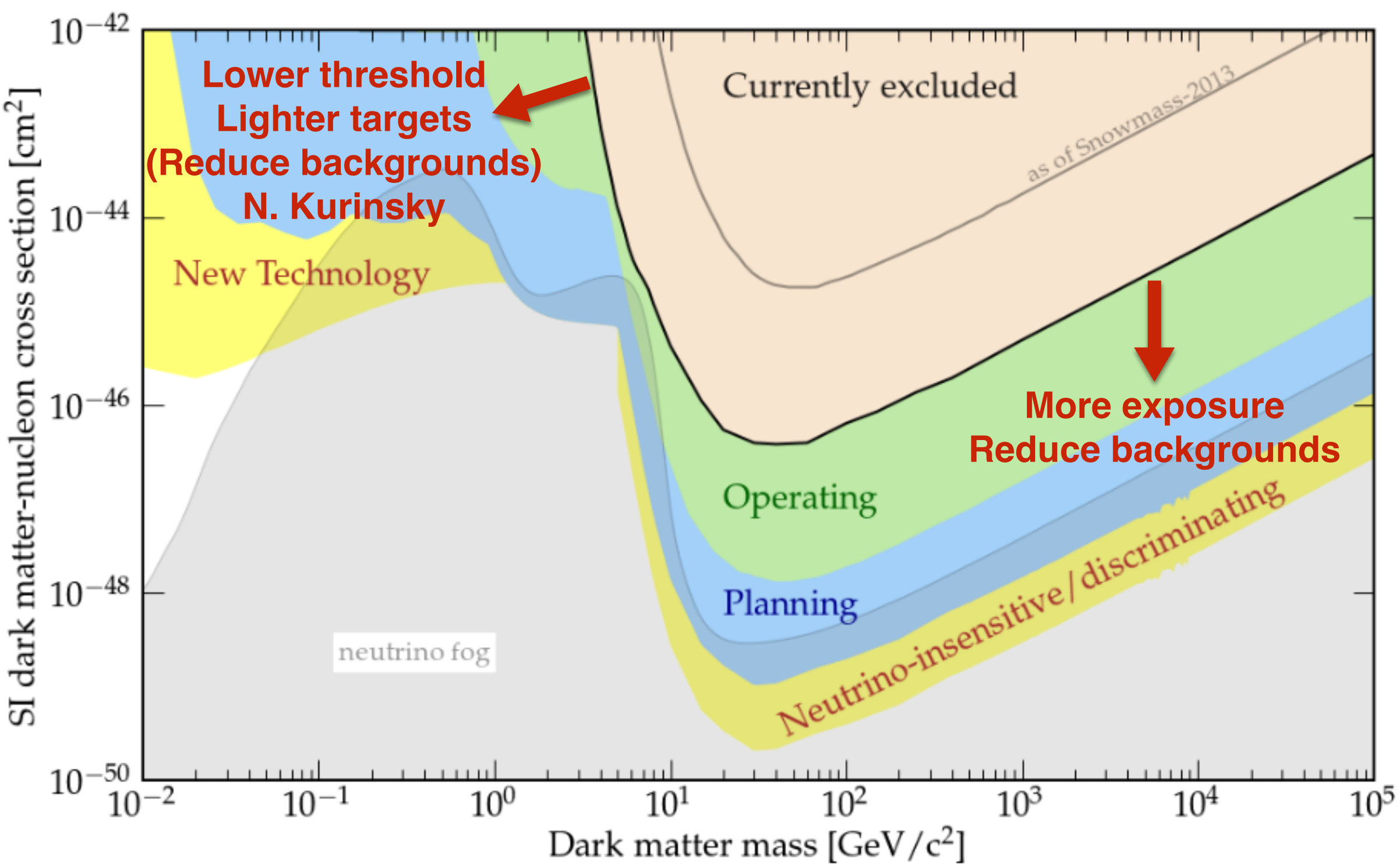
Direct Detection at ~1 TeV



- More sensitivity -> scale up target…
  - Now into multi-tonne scales
- …while reducing backgrounds
  - Radiopurity
  - Self shielding (size helps!)
  - Discrimination (nuclear recoils vs. electron recoils)
- Low thresholds important but not quite as vital
- Explore as many interactions as possible (e.g. SD/SI/EFT)

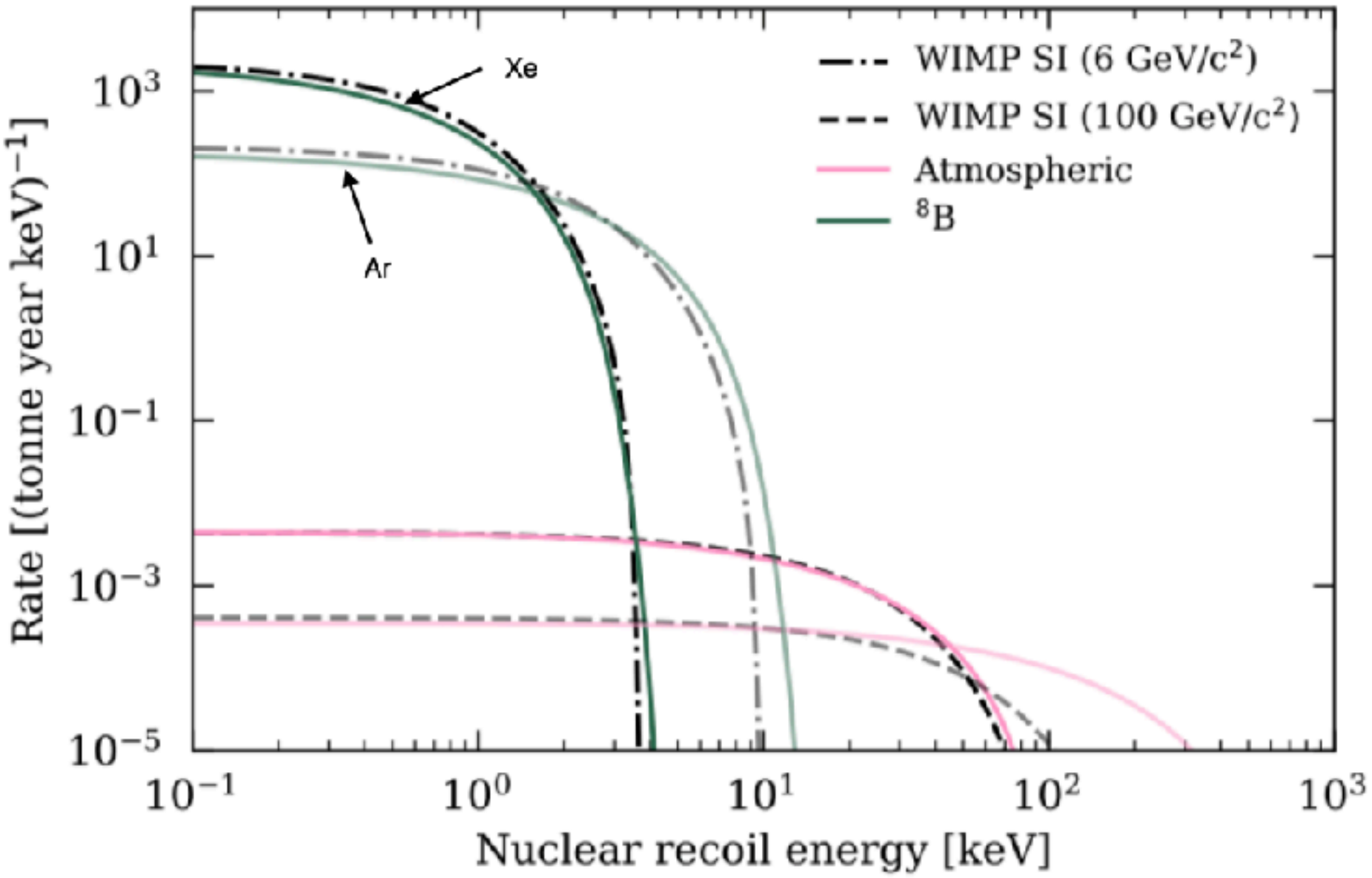






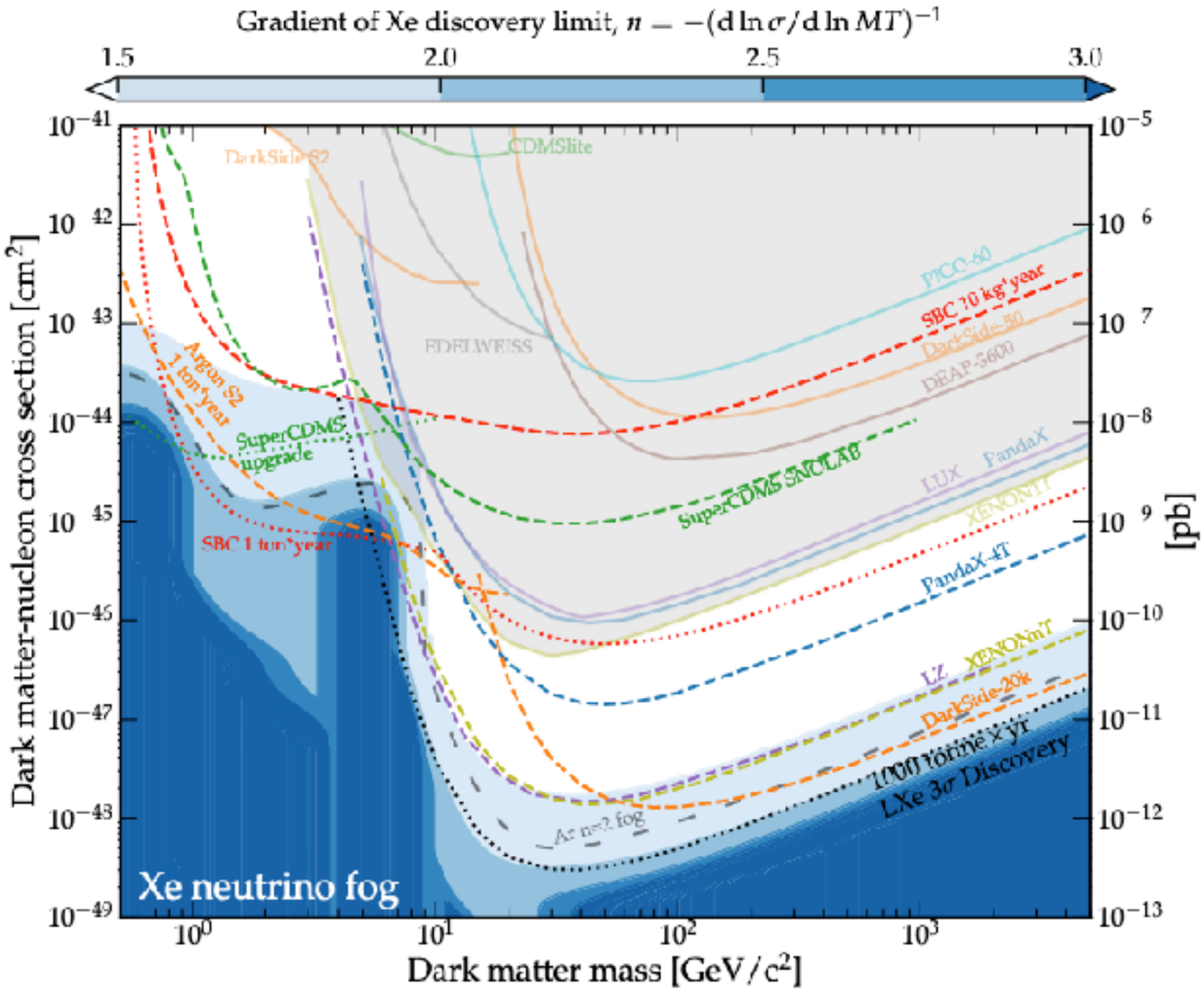
- Limited at low mass by detector threshold
- Limited at high mass by density
- Eventually limited by neutrinos

Neutrino Fog



- O'Hare (2109.03116) supported by Snowmass (2203.08084) define "neutrino fog"
- Rebranding of neutrino floor to better capture the actual effect
  - Index n - how fast one makes progress with respect to background
  - Increase in sensitivity by x10 requires 10^n more exposure

Neutrino Fog



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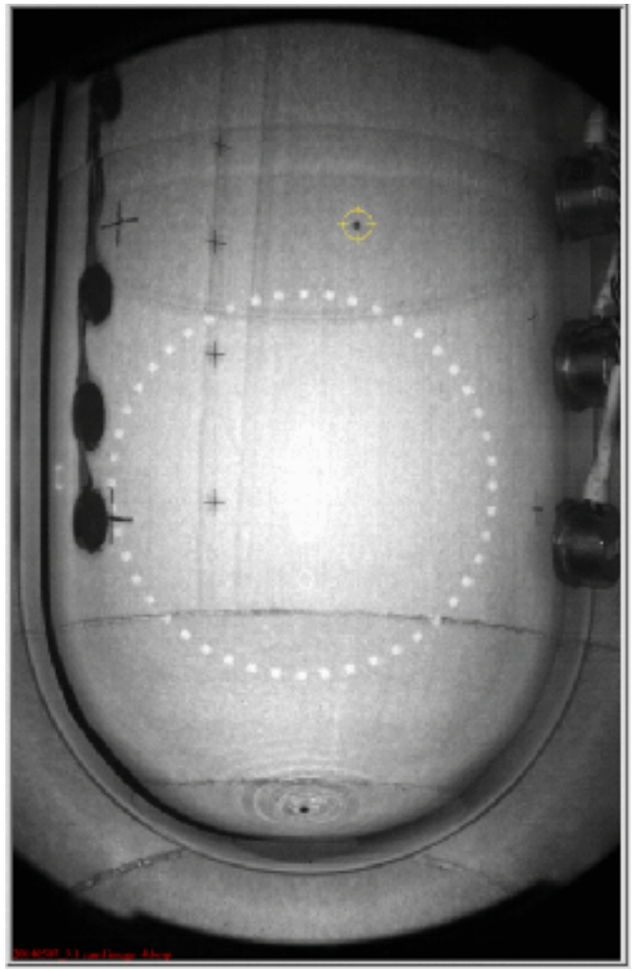
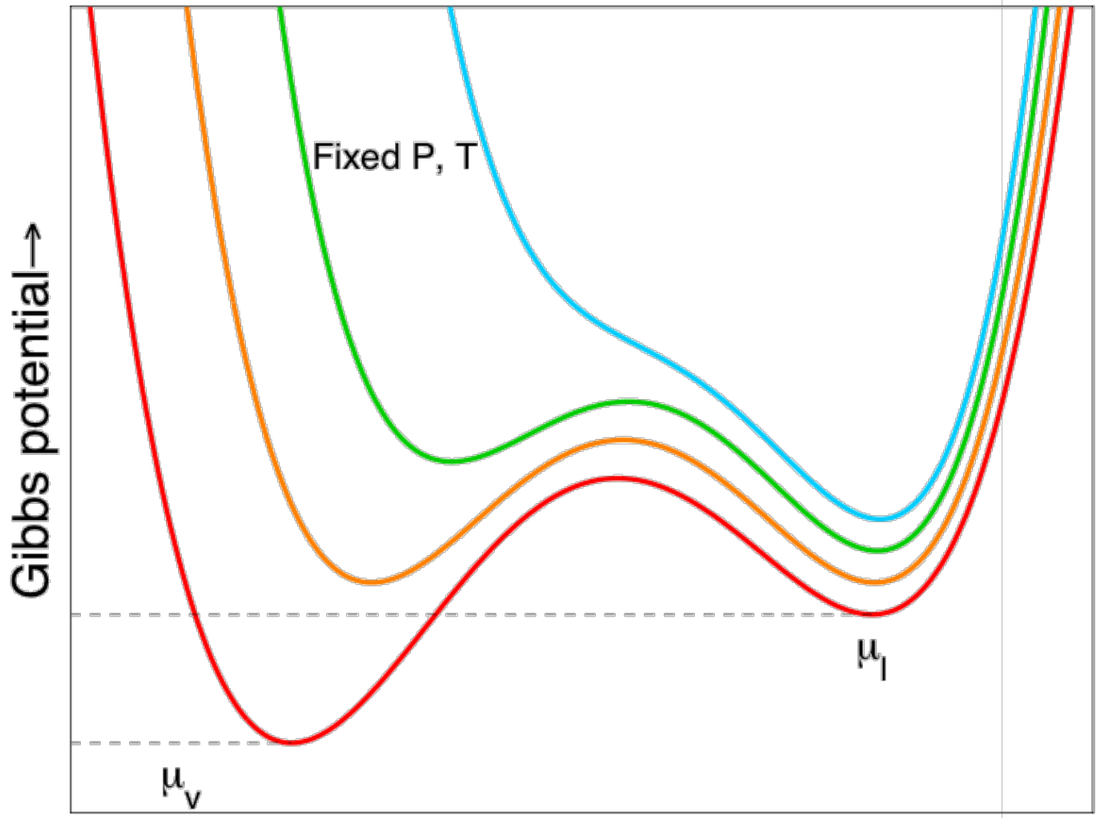
Direct Detection at ~TeV scale

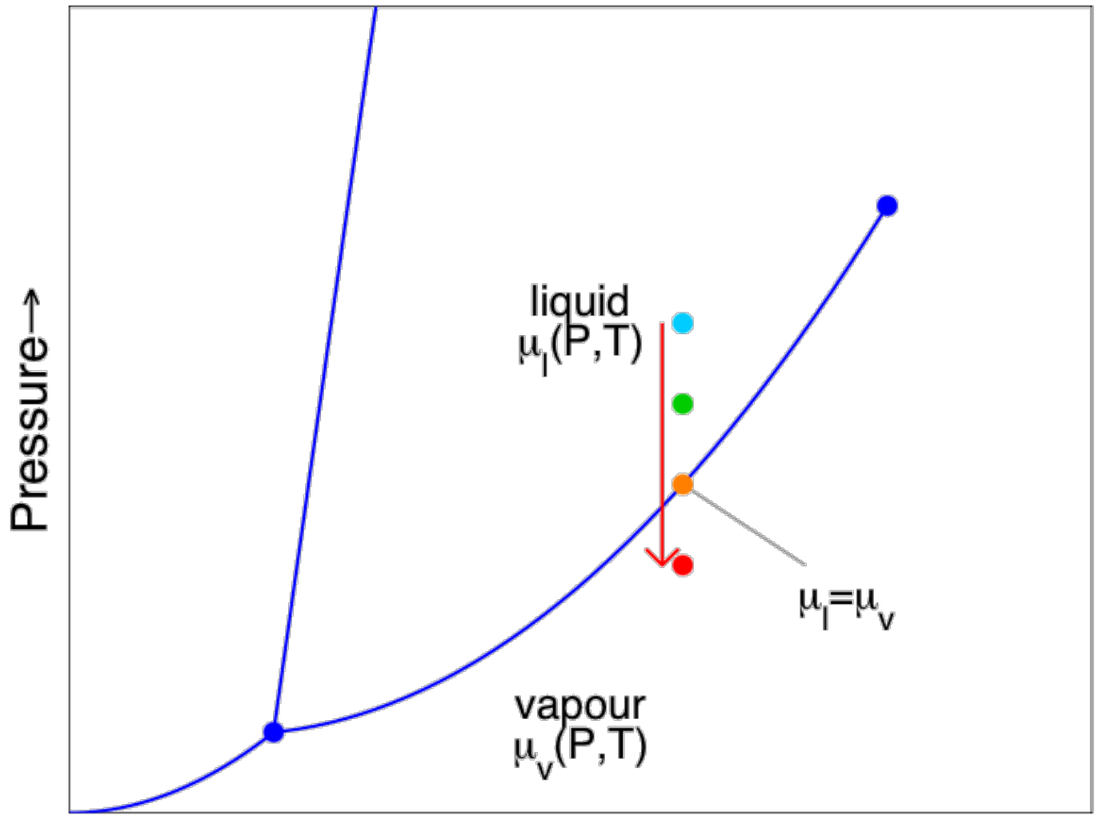
- Liquid Noble Detectors
  - Liquid Xenon (LZ, XENONnT, PandaX, XLZD)
  - Liquid Argon (DEAP, DarkSide, Argo)
- Bubble Chambers
  - PICO



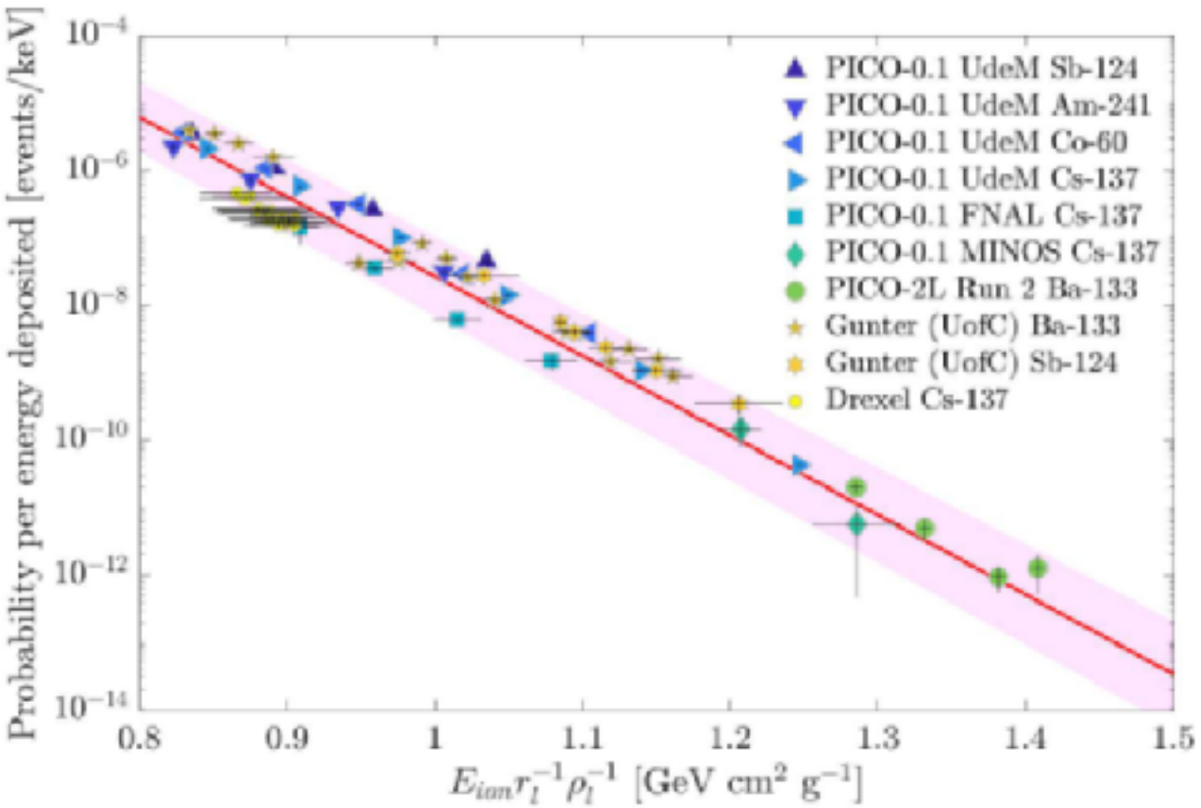
- Things they share
  - Liquids - scalable (get a bigger bucket)
  - Excellent 3D position reconstruction
    - Surfaces are the enemy
  - ER/NR discrimination

PICO Bubble Chambers

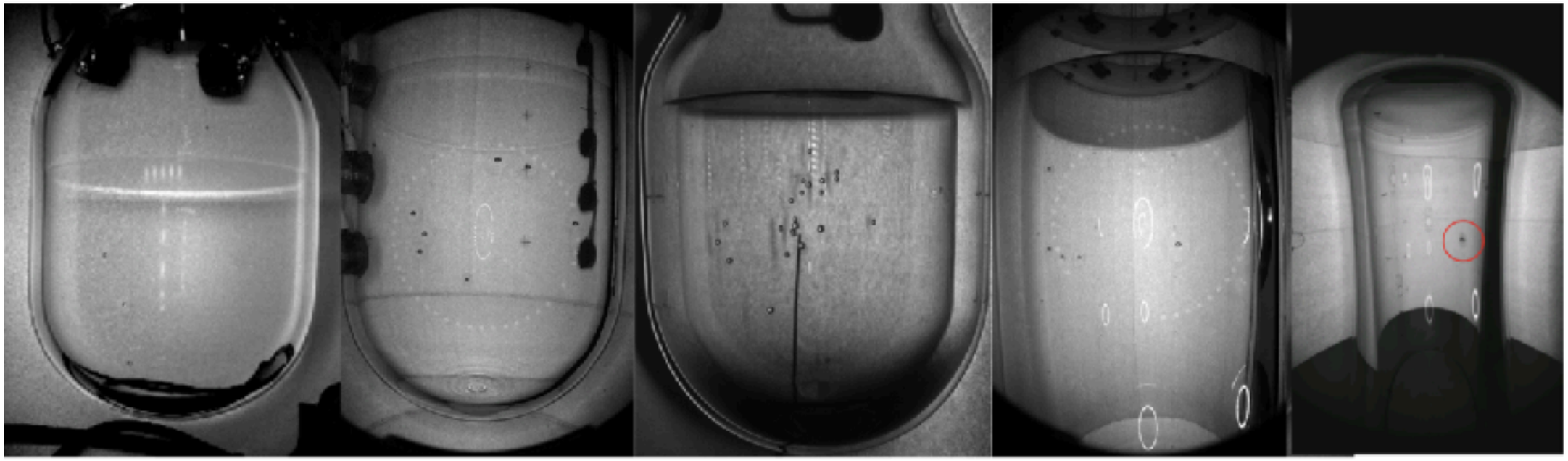




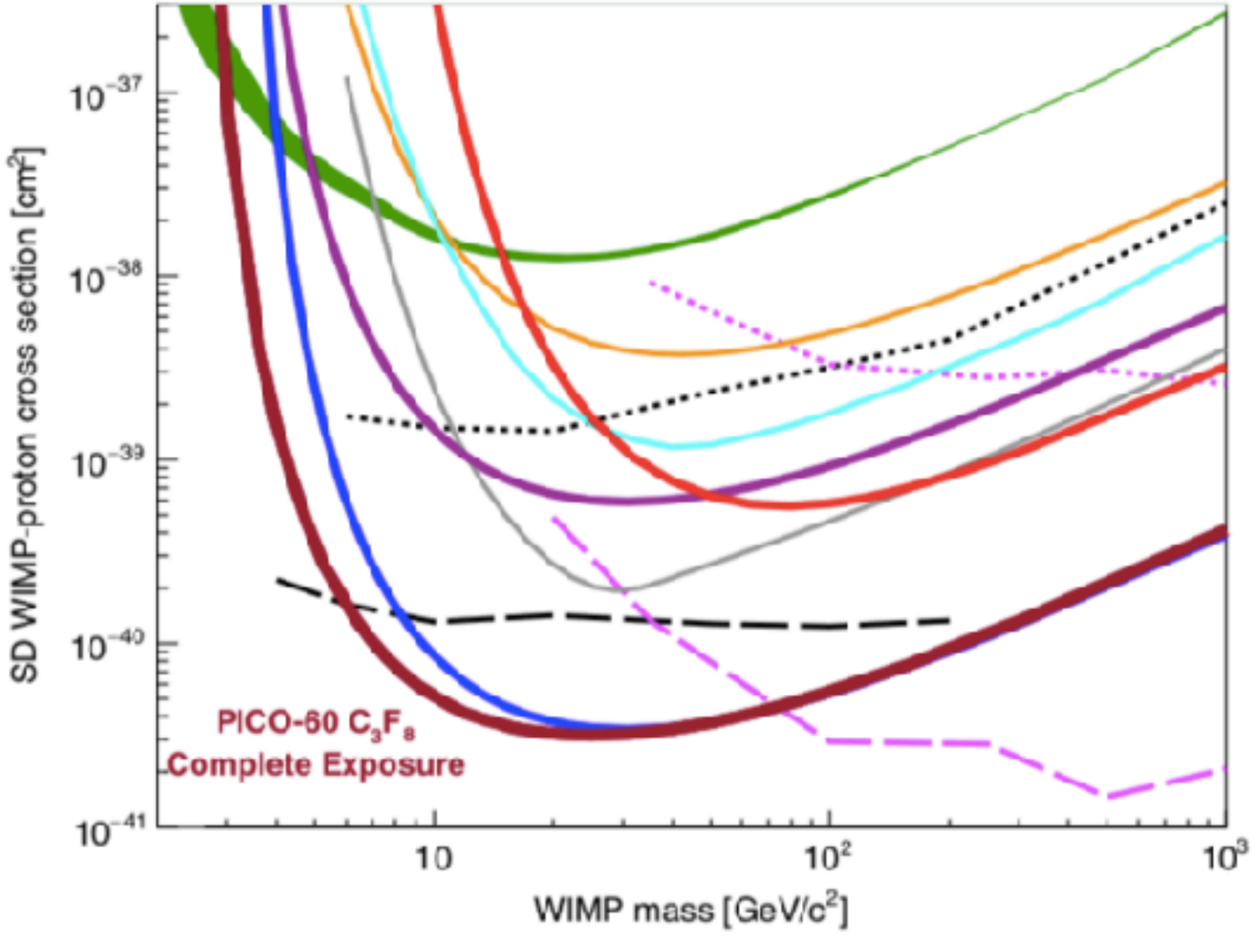
- Thermodynamics set sensitivity
- Need heat (energy) and density to make bubbles
  - ER do not cross density threshold
  - Acoustics provide further rejection
- Fluorine target with ~3 keV threshold



PICO Bubble Chambers

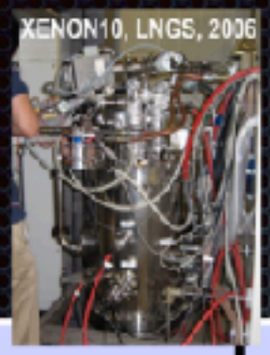


- Family of chambers with increasing size
  - PICO-60 - world's most sensitive SD proton result
  - PICO-40L - running now
  - PICO-500 under construction
- See O. Harris yesterday in parallel



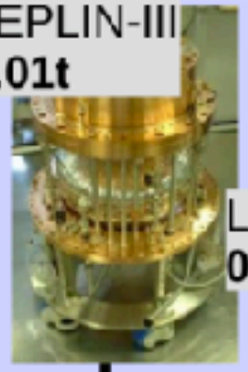
Genealogy of The Noble Target Field

(ZEPLIN I + II)

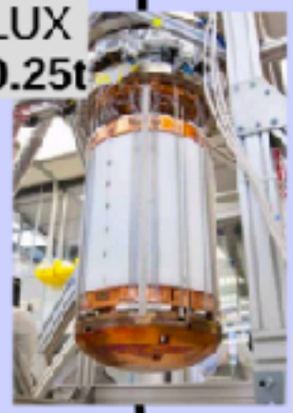


LXe

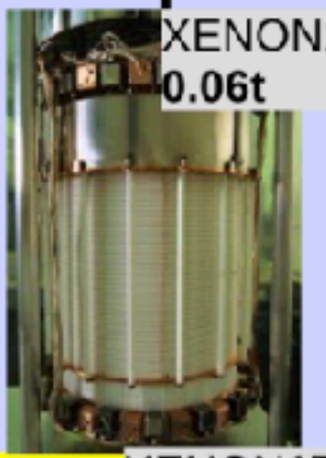
ZEPLIN-III
0.01t



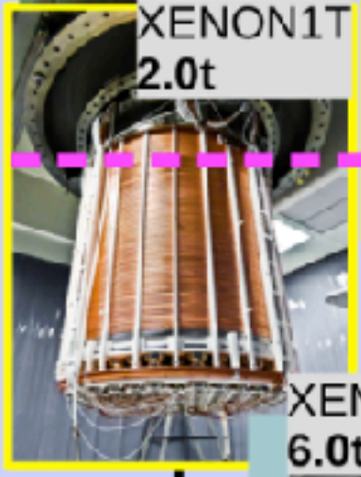
LUX
0.25t



XENON100
0.06t

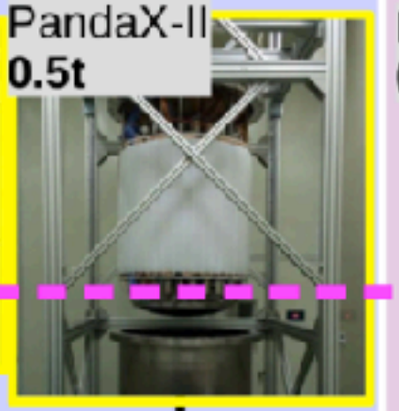


XENON1T
2.0t



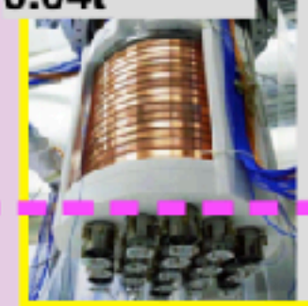
XMASS
0.8t

PandaX-II
0.5t



LAr

DarkSide-50
0.04t

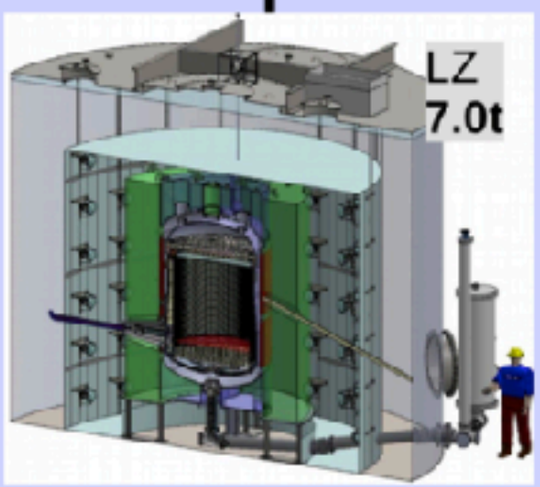


DEAP-3600
3.3t

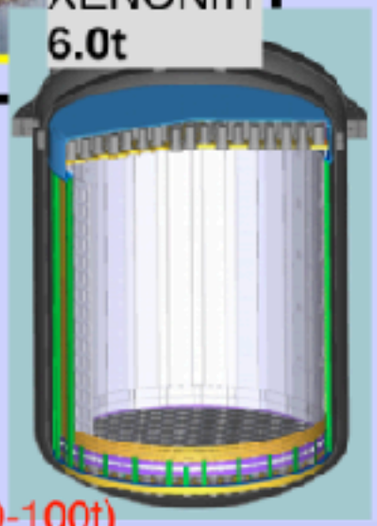
ArDM
0.8t

Ignore me

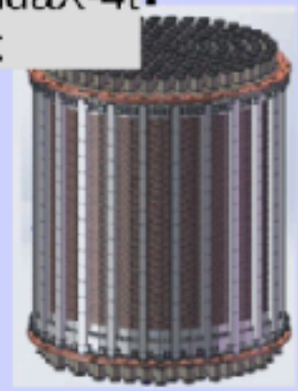
LZ
7.0t



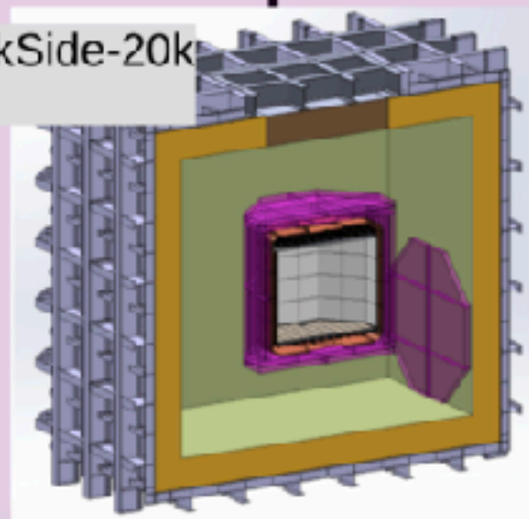
XENONnT
6.0t



PandaX-4t
4.0t



DarkSide-20k
30t



(followed by DARWIN 50-100t)

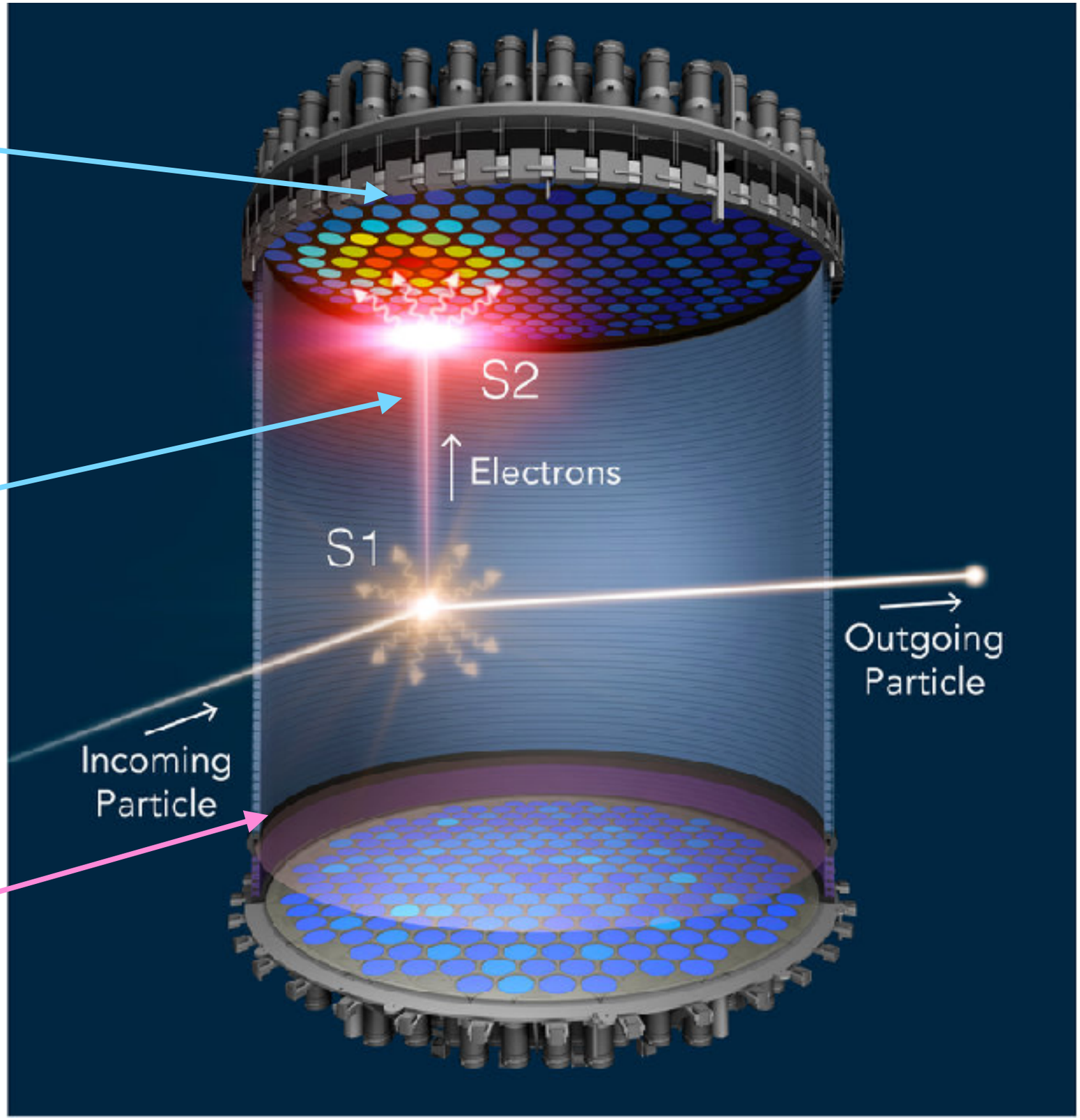
thanks to M. Schumann (Freiburg)

Liquid Noble TPCs

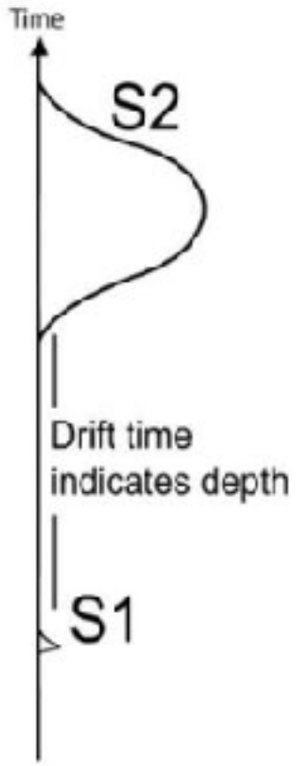
S2 light pattern gives x-y position
(~few mm resolution)

Drift time gives z position
(~0.5 mm resolution)

Cathode

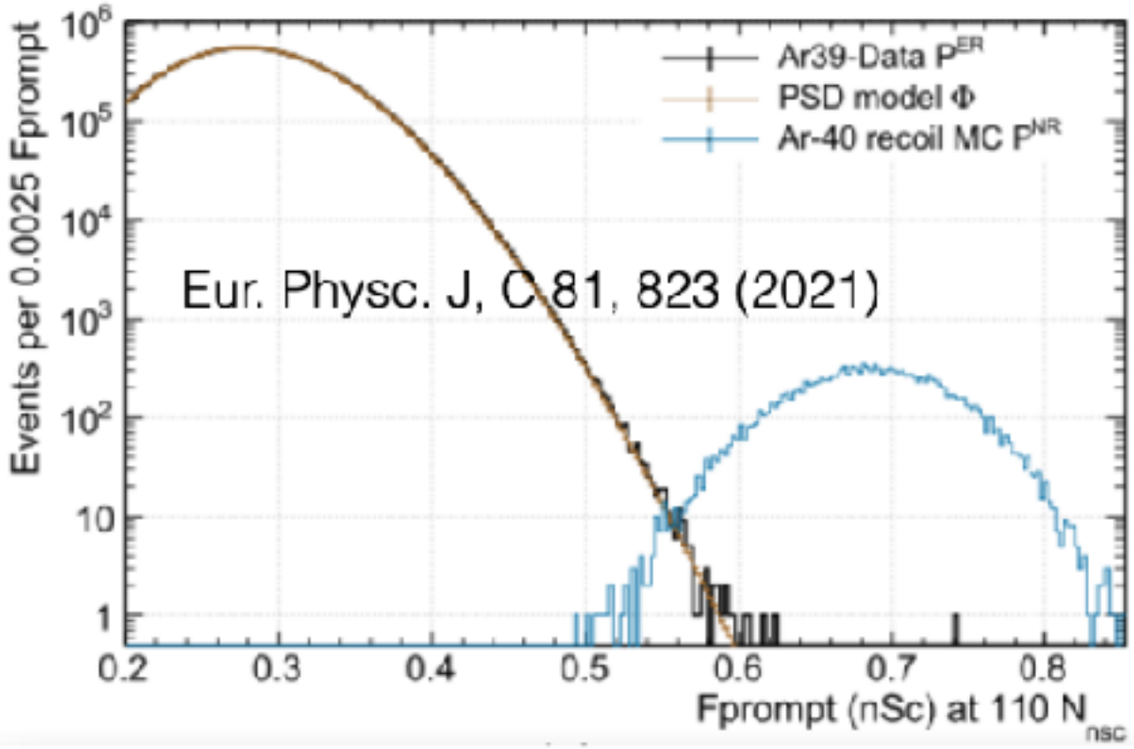


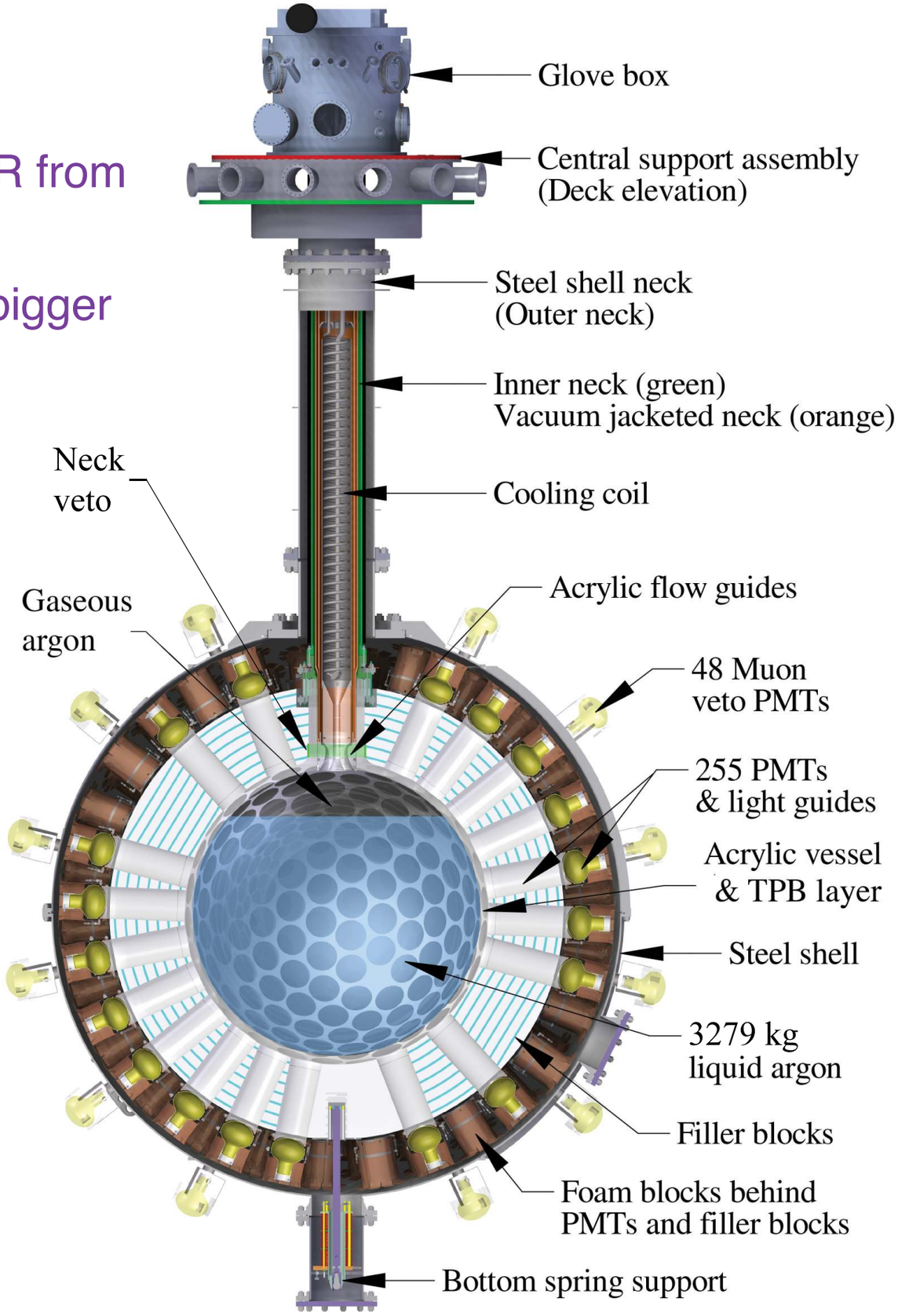
S1-S2 relative size gives event-type discrimination



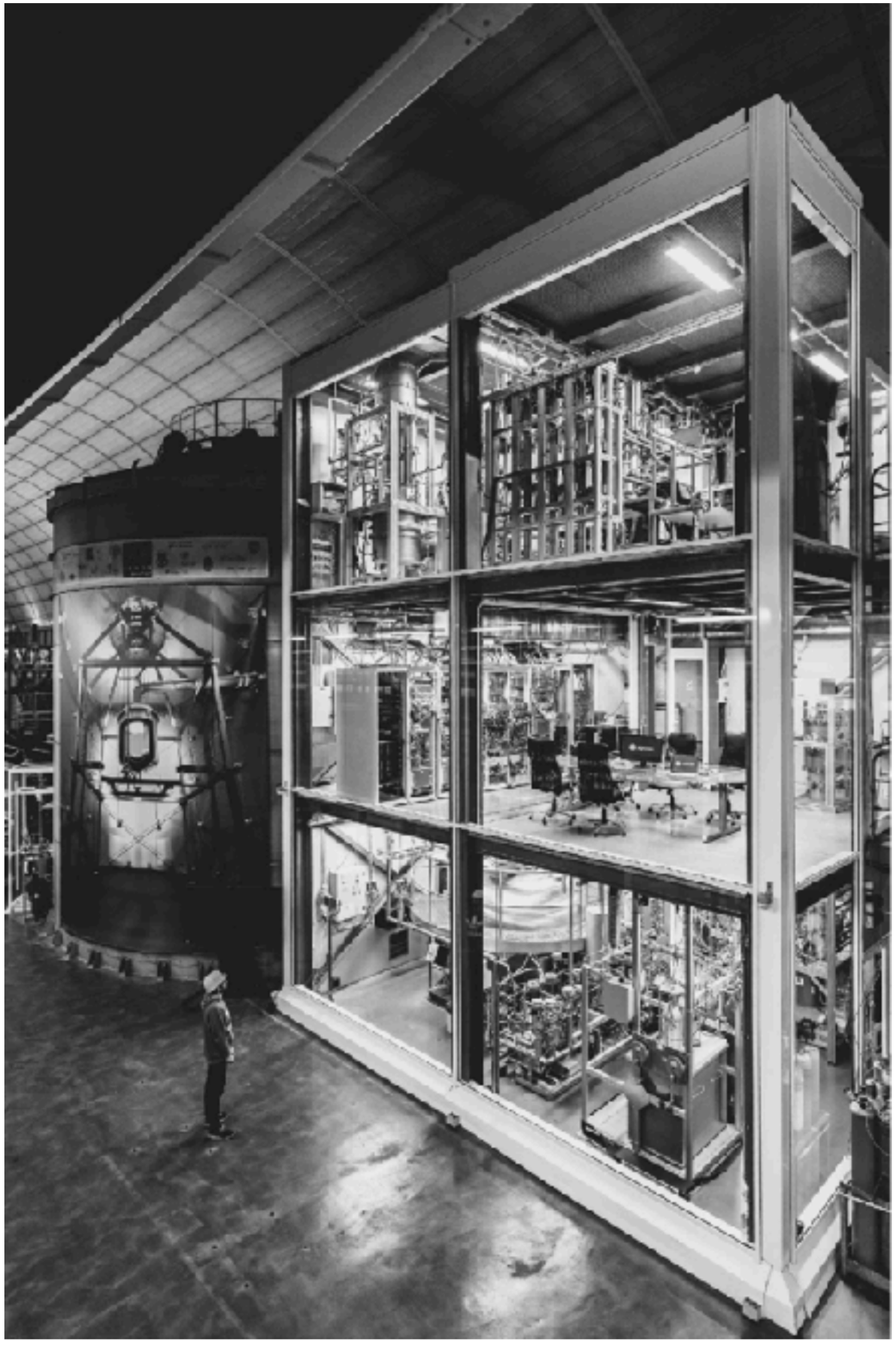
LAr Single Phase

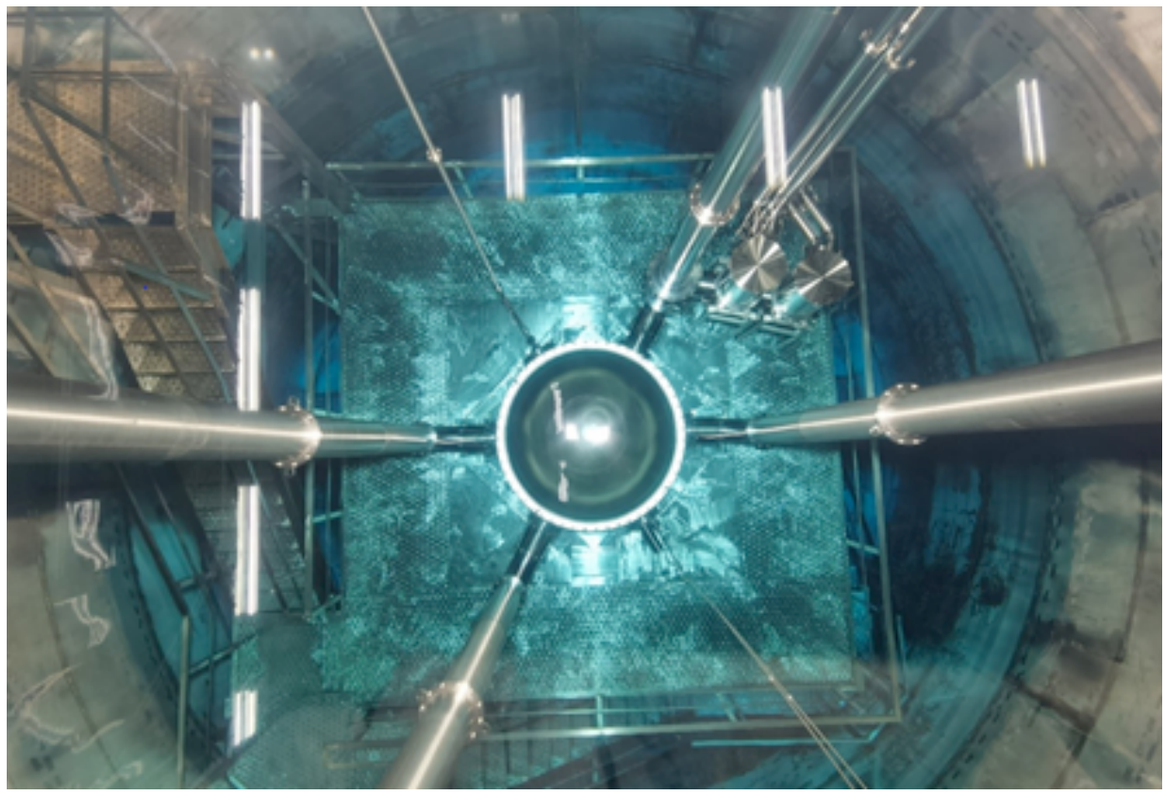
- Exquisite pulse shape discrimination (PSD) ER from NR using timing of light
- 3D reconstruction possible, easier as you go bigger

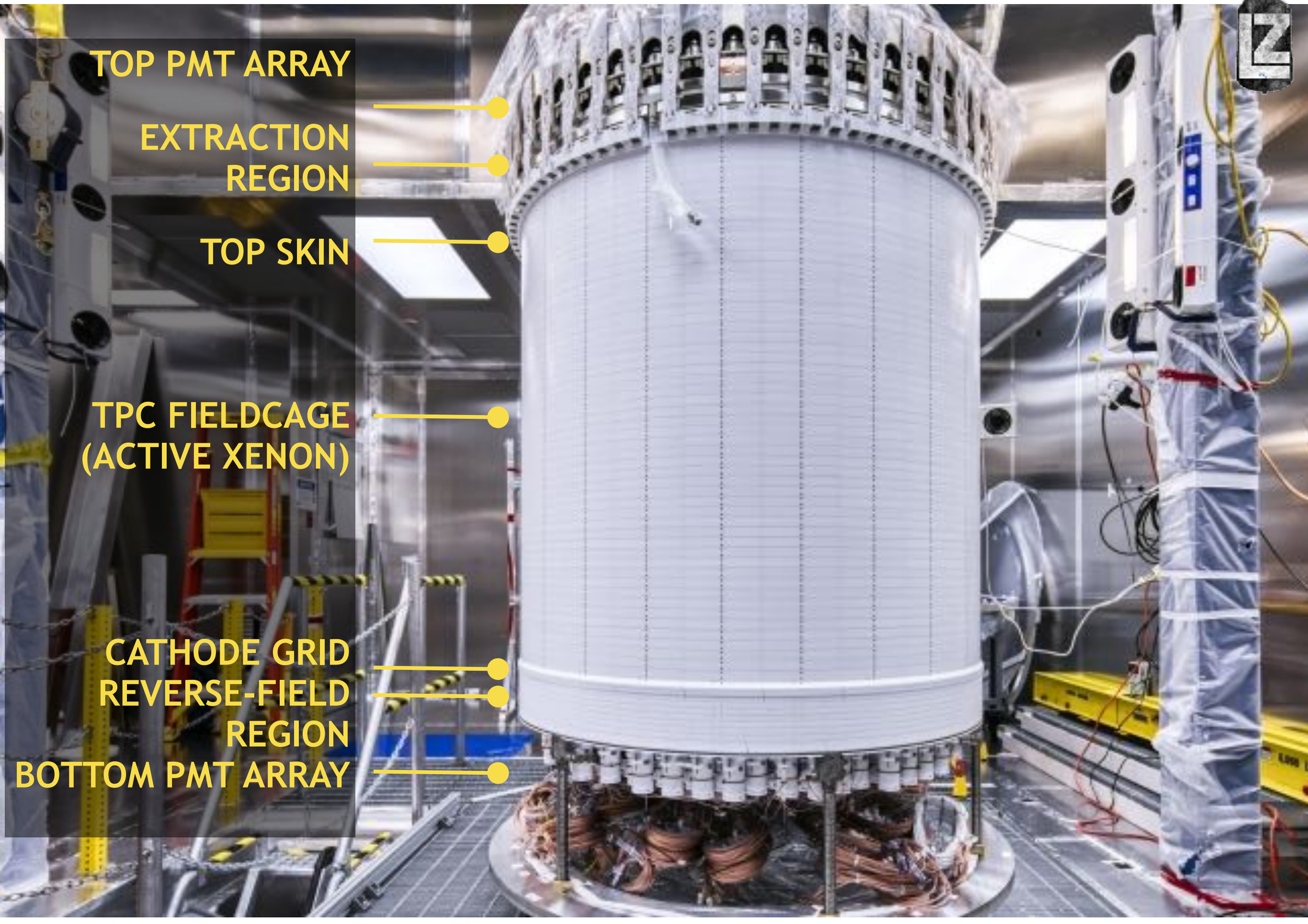


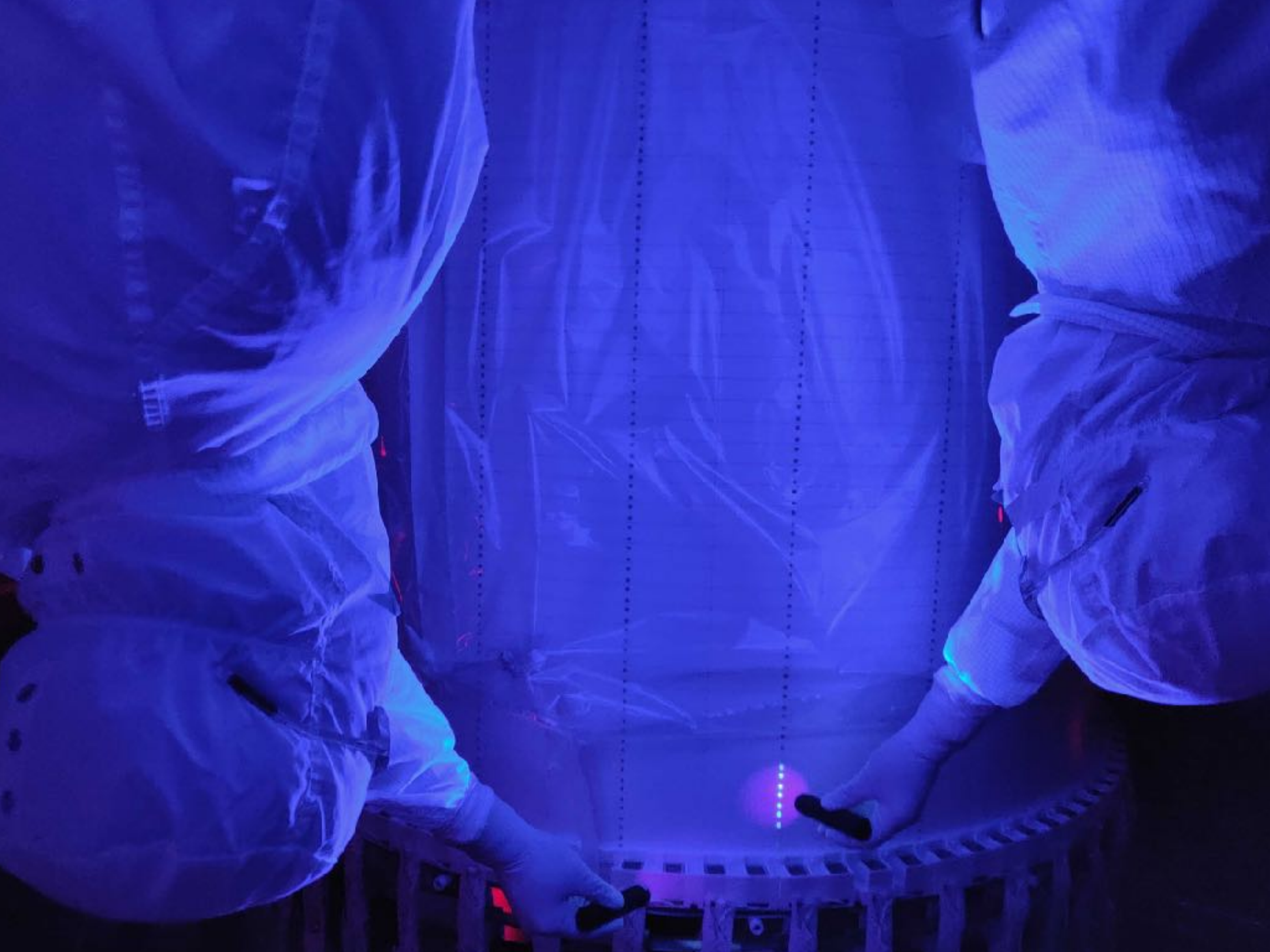


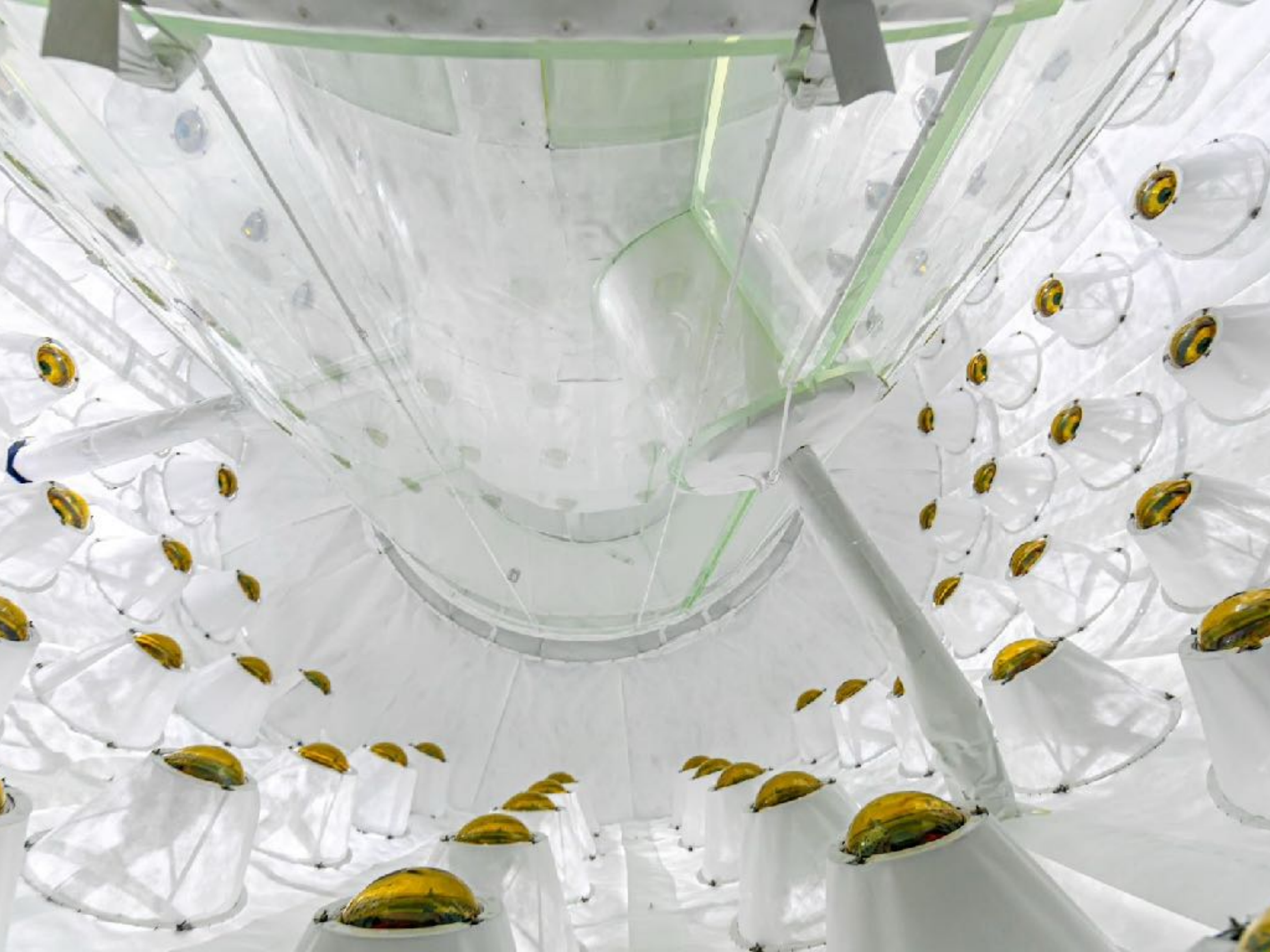
Liquid Noble TPCs





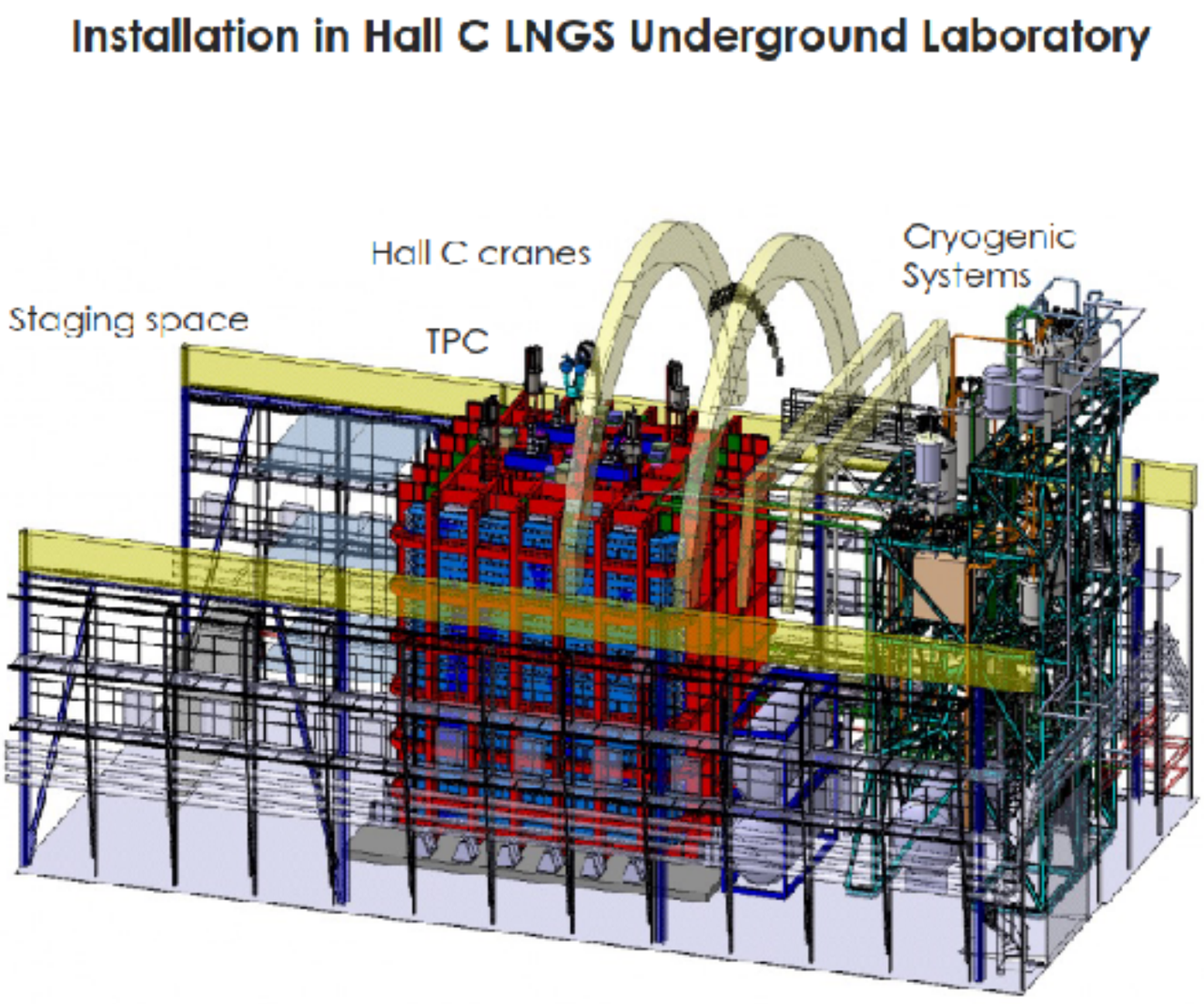

TOP PMT ARRAY
EXTRACTION REGION
TOP SKIN
TPC FIELDCAGE (ACTIVE XENON)
CATHODE GRID
REVERSE-FIELD REGION
BOTTOM PMT ARRAY





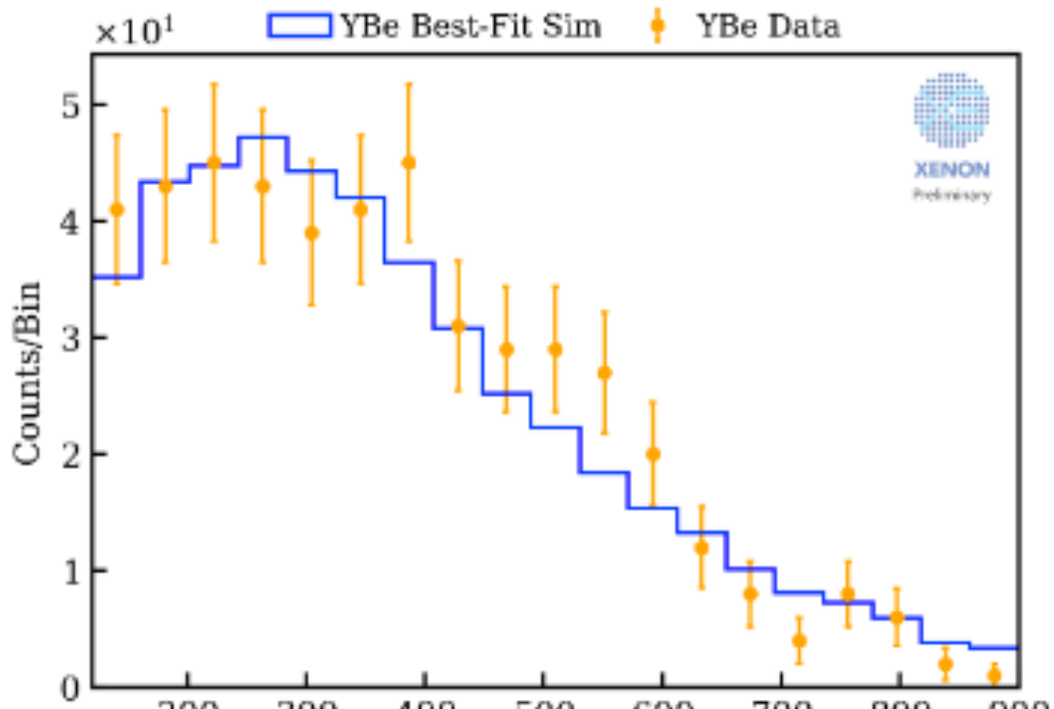
LAr Detectors

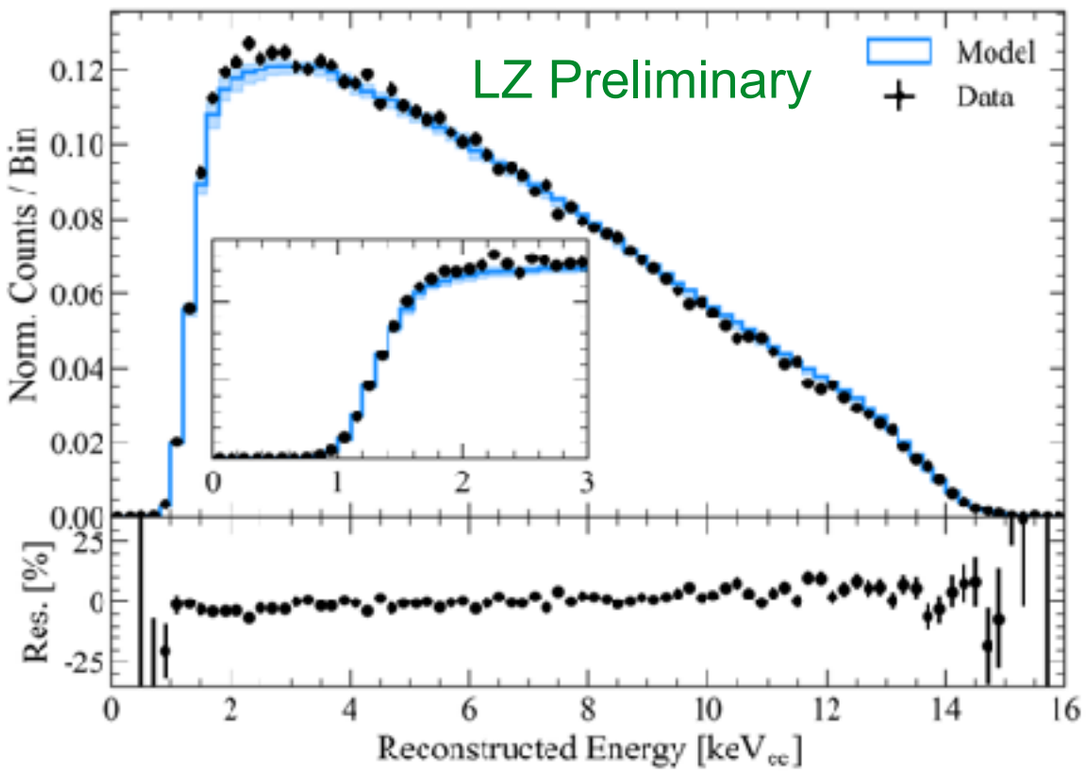
- DEAP-3600 upgrade nearly complete - goal to understand rare neck and dust backgrounds
- DarkSide-20k detector at LNGS under construction
  - 20 tonnes underground argon fiducial, ~700t total Ar
- Installation happening now!

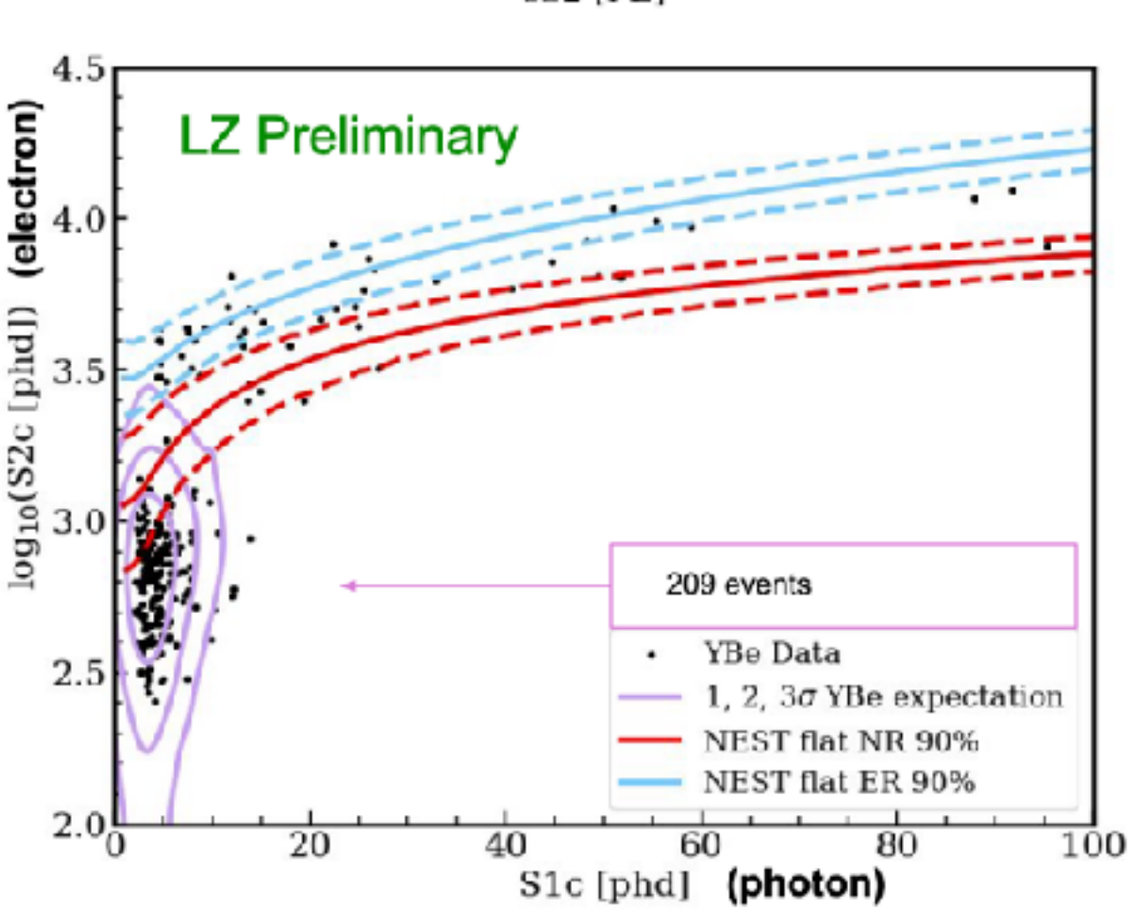


Recent developments

- Calibration is key - e.g.:
  - LZ - High stats of ER (background) distribution using dispersed tritium (CH_3T) - ~160k events!
  - LZ and XENON have now used YBe to calibrate low energy NR
- Allows for precise modeling in final analysis, enables discovery

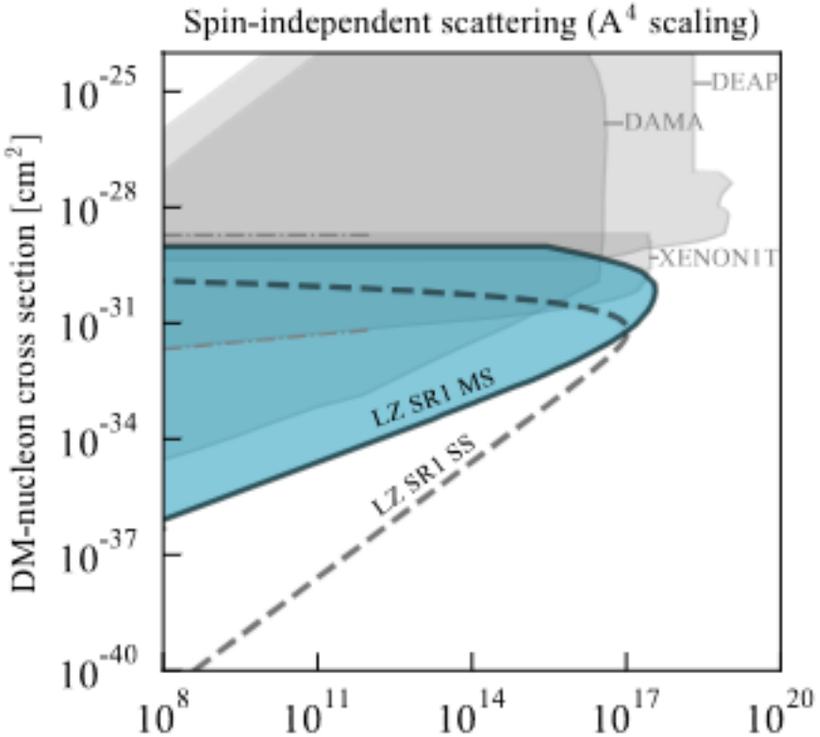


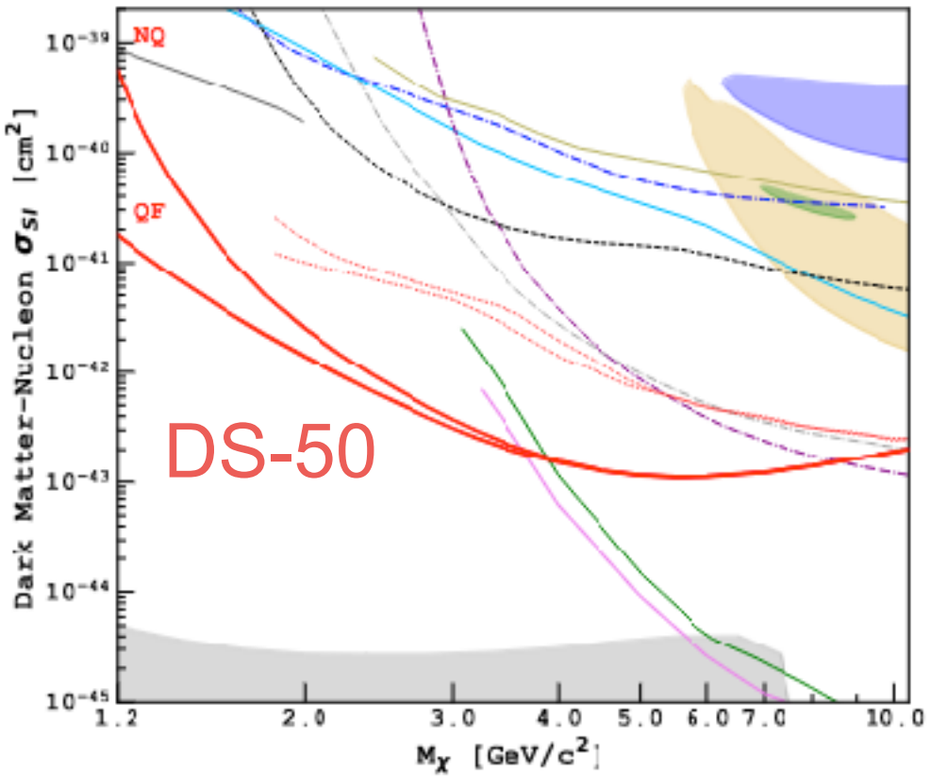




Recent developments

- Many rare event searches, e.g. (not complete):
  - ~Planck scale DM from DEAP, XENON, LZ
  - EFT and inelastic searches from PICO, XENON, LZ, DEAP
  - Electron recoil searches in XENON, LZ, PandaX
  - Low mass results from DarkSide
  - Lots of models in PandaX





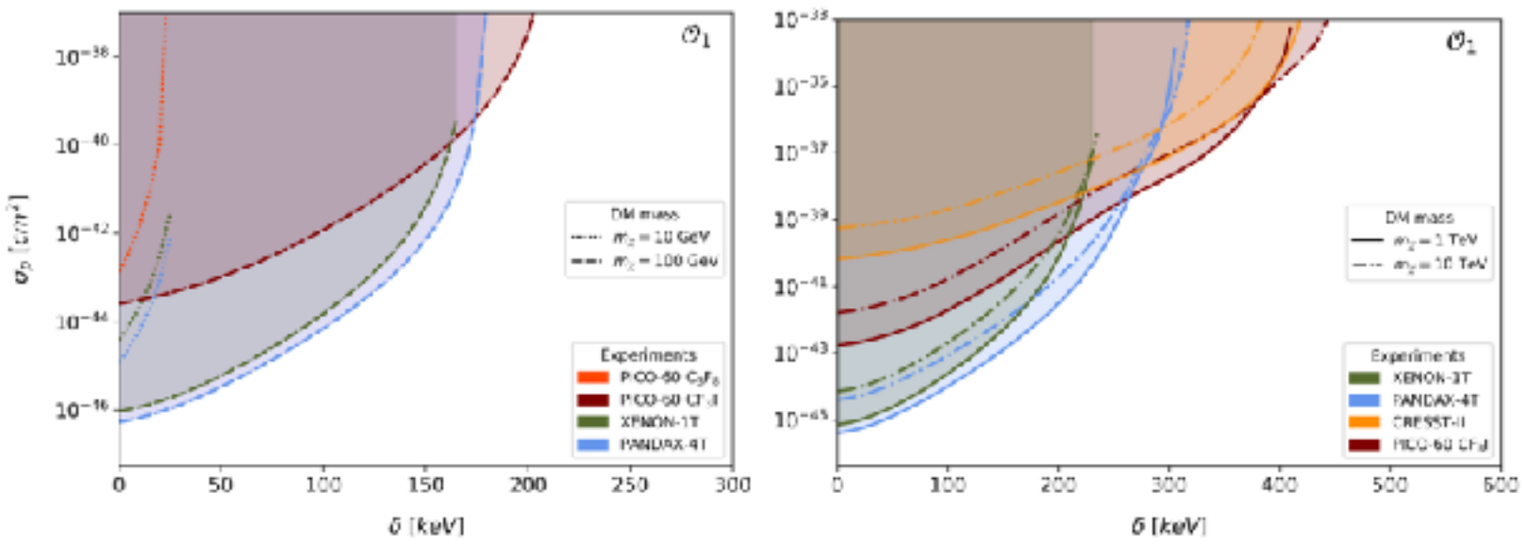
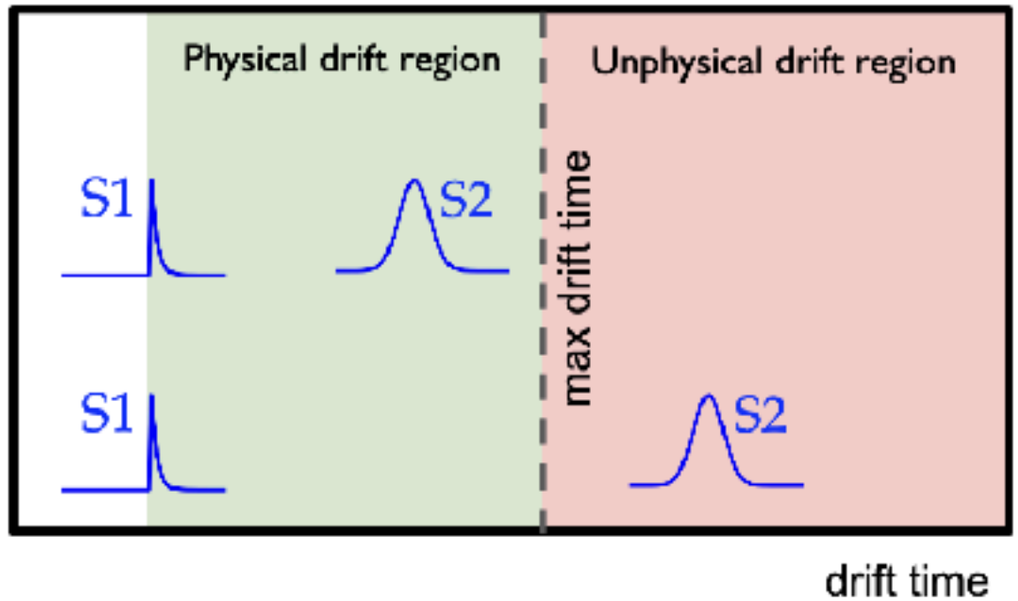
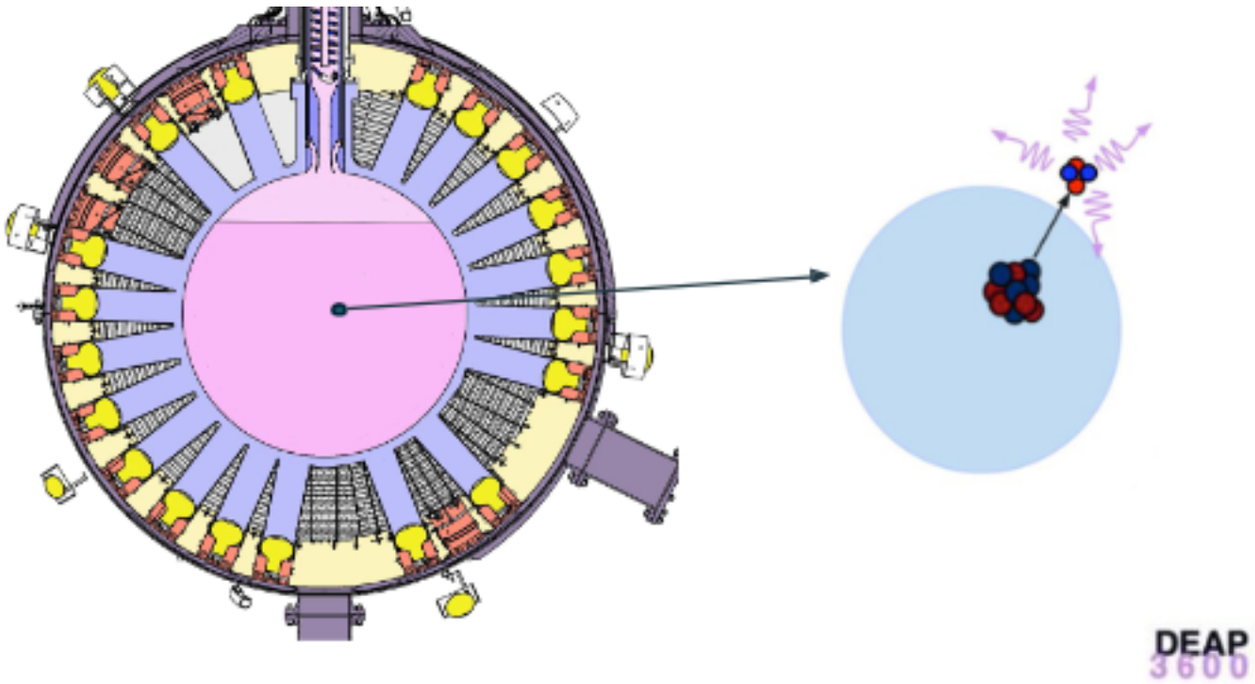


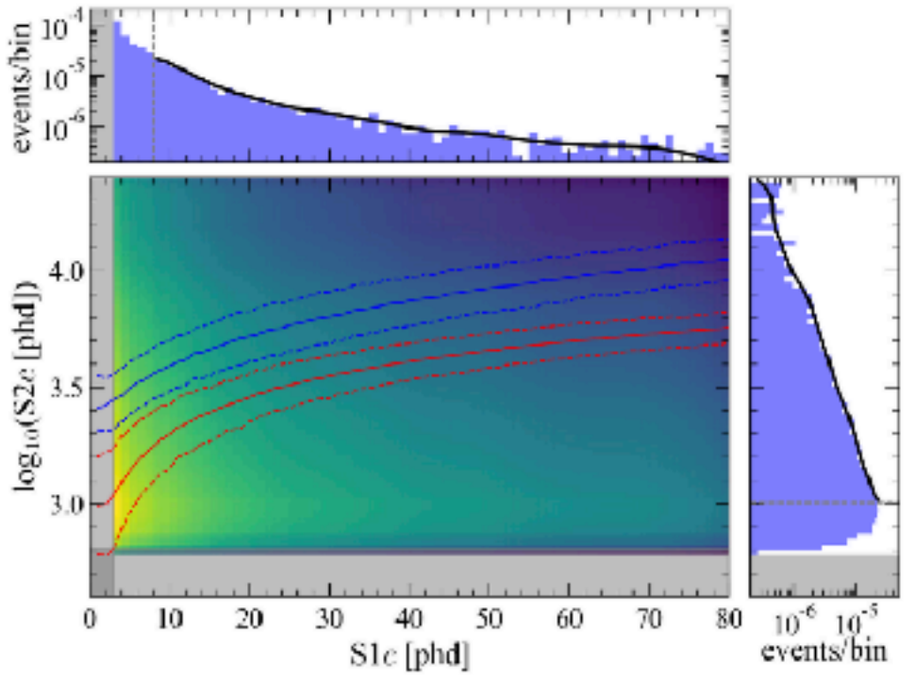
FIG. 1: Upper limits (90% C. L.) on DM-nucleon scattering cross sections as a function of the mass splitting for the effective operator $\mathcal{O}_1$ and DM masses of 10 GeV/c^2 and 100 GeV/c^2 (left), and 1 TeV/c^2 and 10 TeV/c^2 (right), from the analysis of the PICO-60 CF_3I and C_3F_8 experiments. Limits from XENON-1T [12], PANDAX-4T [11], and CRESST-II [16] are also shown.

Progress is hard!

- Each detector must grapple with a new set of backgrounds e.g.
  - Accidentals in LXe-TPCs
  - Dust and geometry in DEAP-3600
  - Neutrinos…?







We're into the fog!

- Two new papers that begin with "First measurement of Solar ^{8}B neutrinos…"

PandaX, 2407.10892
2.64 sigma

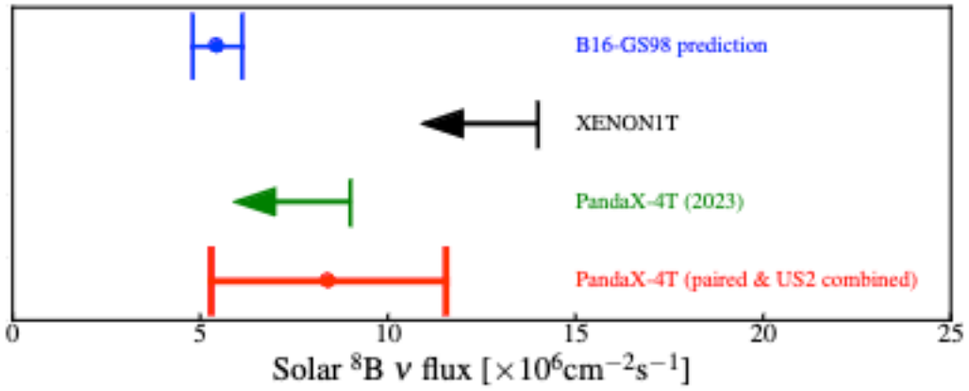


FIG. 6. The best-fit ^{8}B solar neutrino flux and 1σ uncertainty from this work (red), together with 90% C.L. regions of the PandaX-4T previous constraint [33] (green), XENON1T constraint [31] (black), and 1σ of the theoretical prediction from the standard solar model [45] (blue).

XENONnT, 2408.02877
2.73 sigma

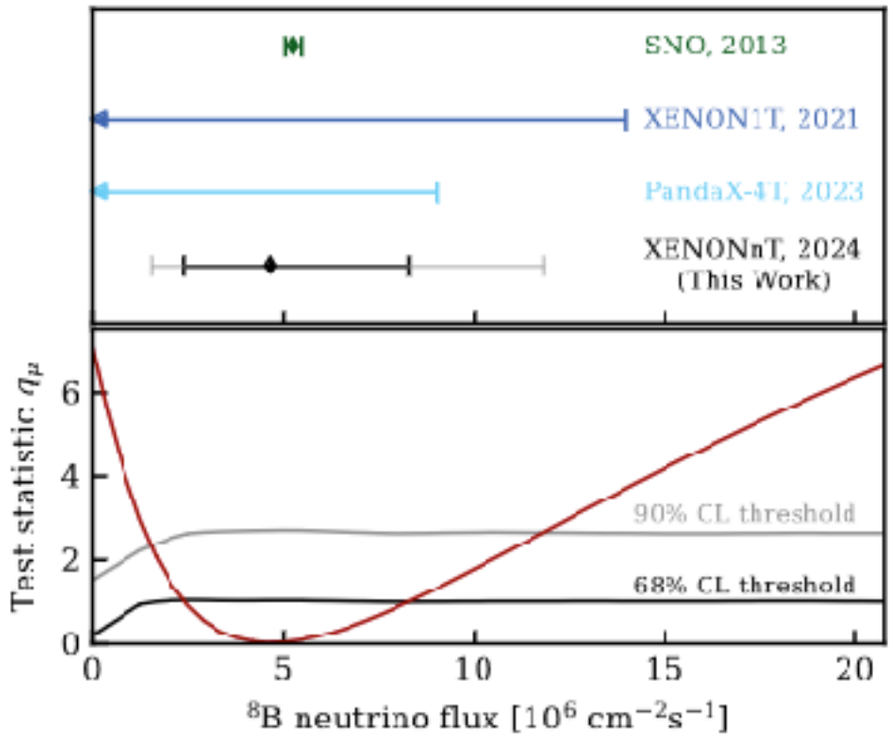
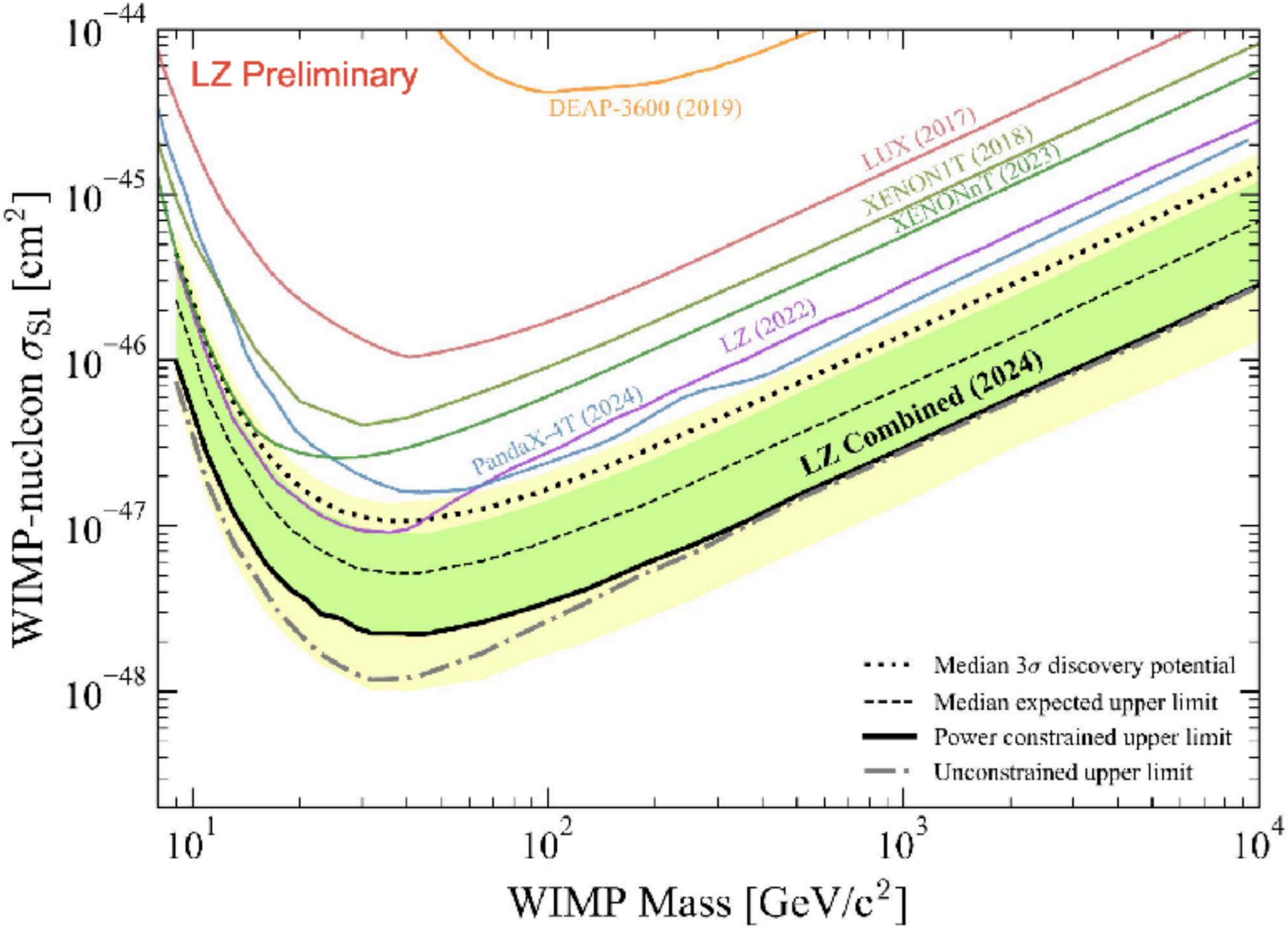


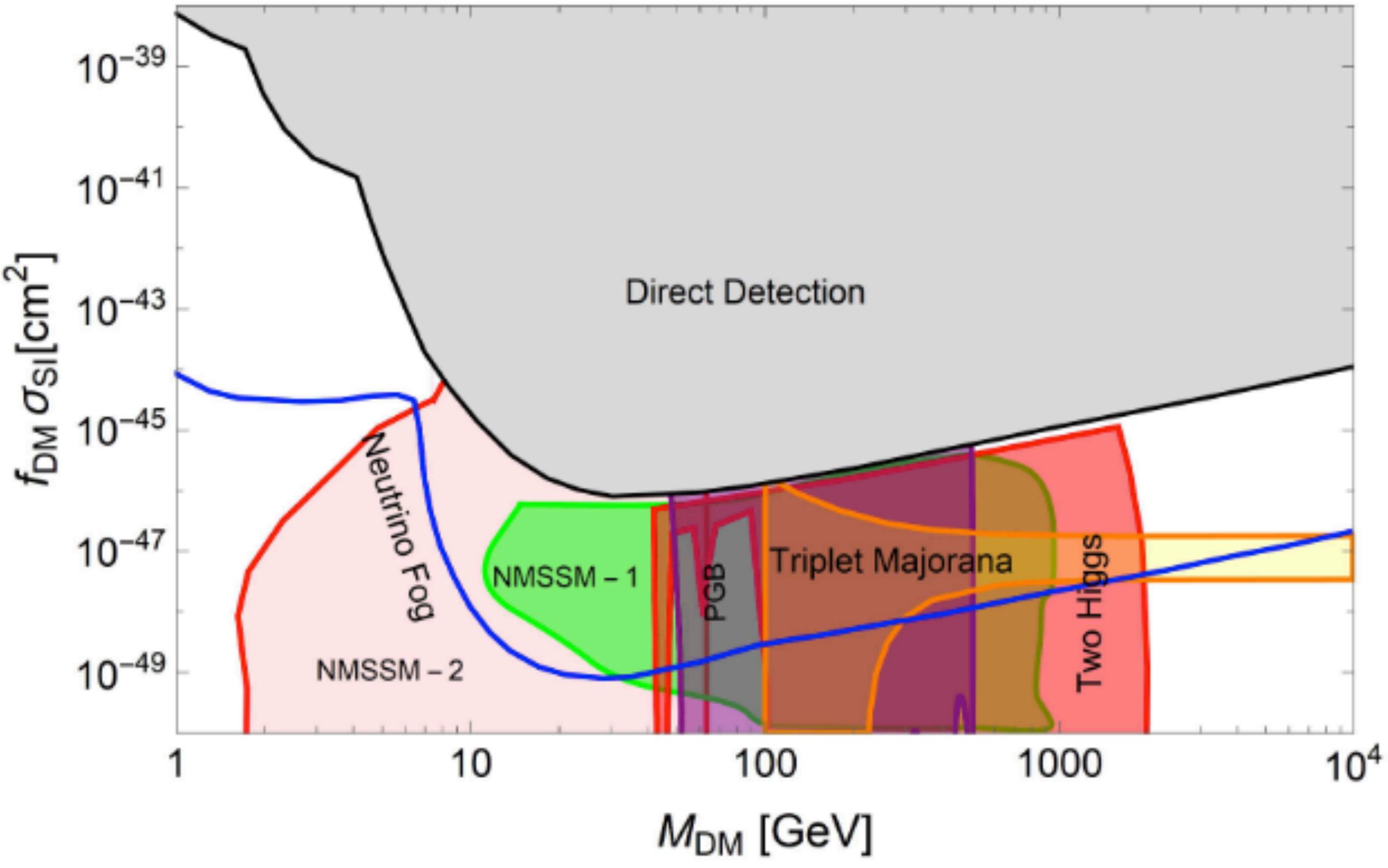
FIG. 3. Constraints on solar ^{8}B neutrino flux. Top: the 68% (90%) measurement of solar ^{8}B neutrino flux from this work is shown in black (gray). The 68% CL measurement from SNO [22], and 90% CL upper limits from XENON1T [6] and PandaX-4T [7] are also shown. Bottom: the solid red line shows the profile likelihood ratio test statistics q_μ as a function of solar ^{8}B neutrino flux. The constraints are derived with Feldman-Cousins construction at 68% (90%) CL, indicated by the black (gray) curve.

And still pushing WIMP sensitivity!



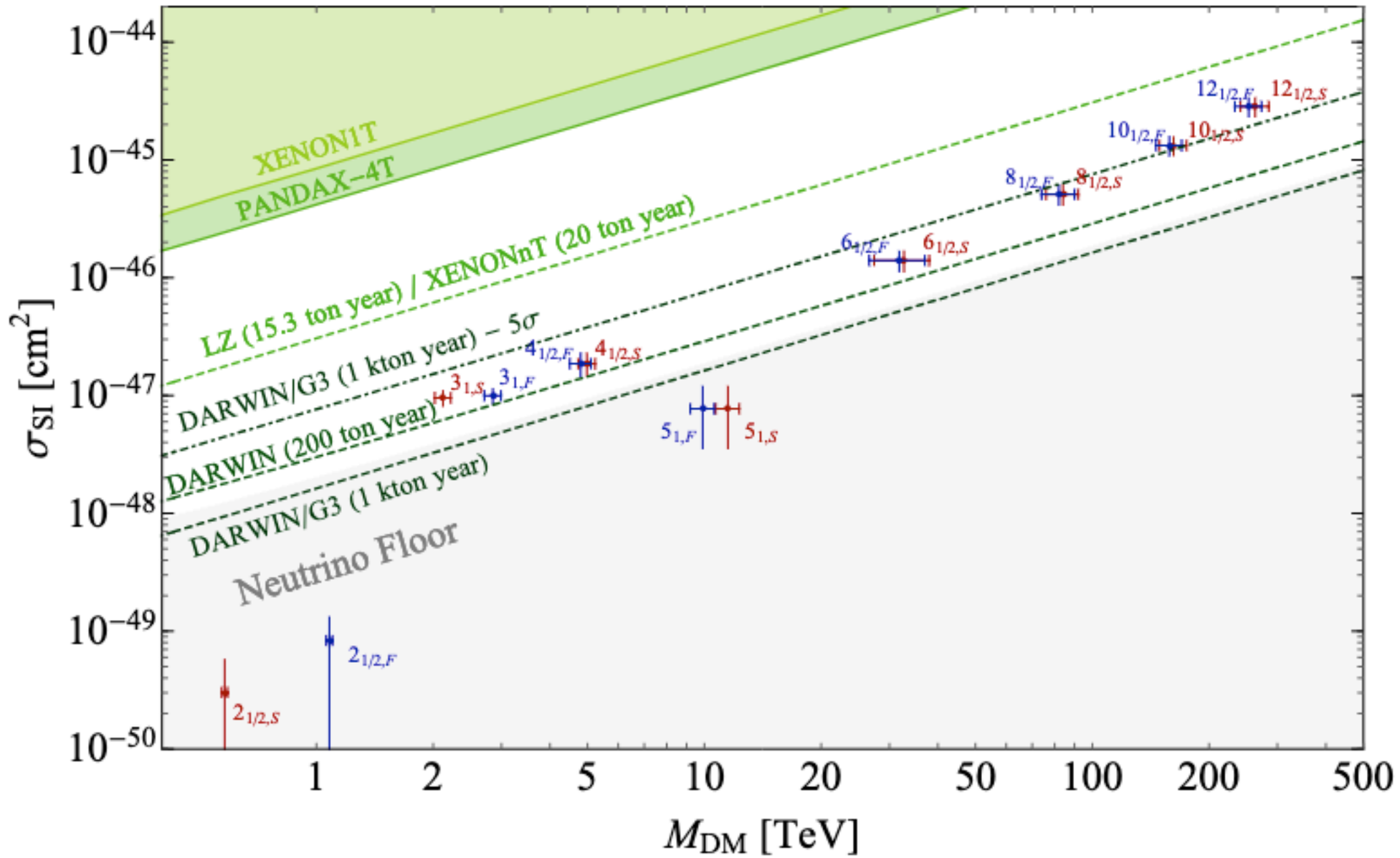
- New WIMP results from LZ (released at TeVPA!) and PandaX
  - See S. Haselschwardt from Monday and Q. Wang yesterday

What are we looking for? (Spin Independent)



CF Snowmass 2203.08084

What are we looking for? (Spin Independent)



From Bottaro et al, 2205.04486 - "The Last Complex WIMPs Still Standing"

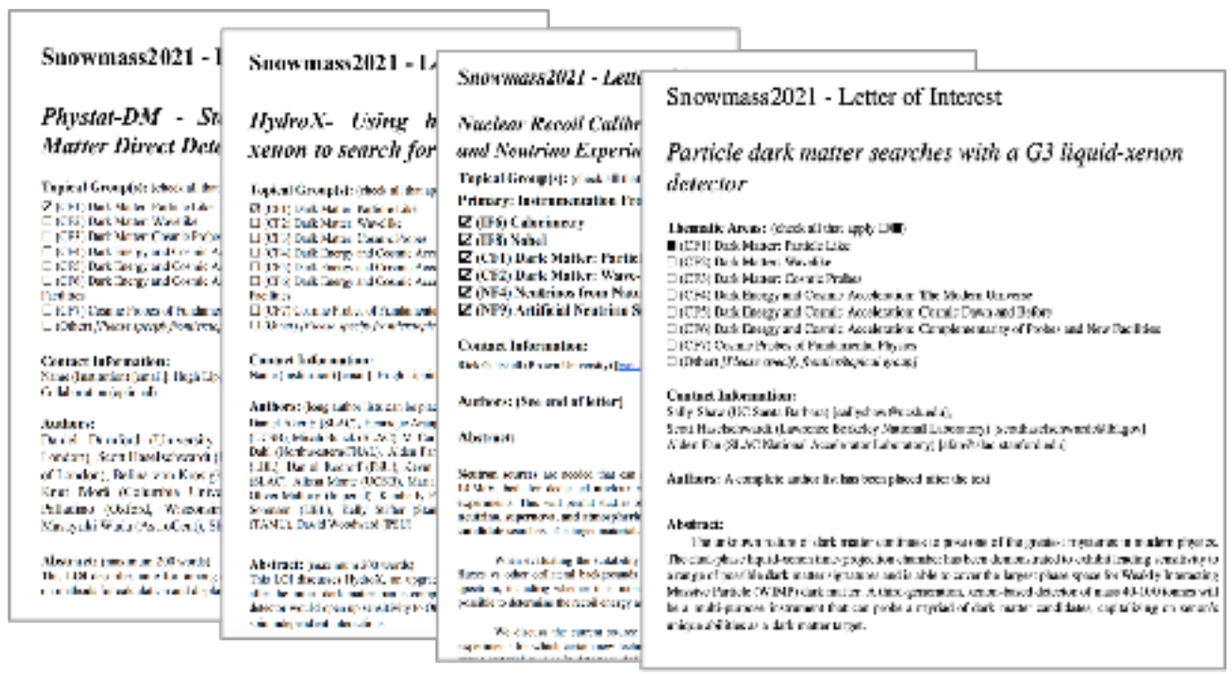
Pure electroweak WIMP candidates - tree-level Higgs process vanishes, so small cross sections

Snowmass and P5

- Today, dark matter is one of the biggest mysteries in particle physics

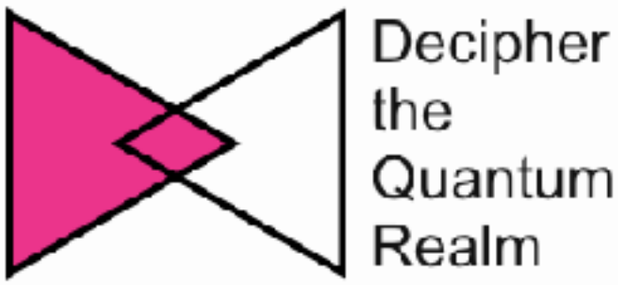
Illuminate the Invisible Universe

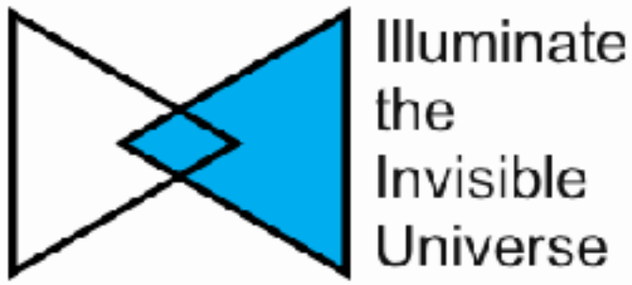
P5 Report December 2023



- Most commonly mentioned topic in Snowmass LOIs

P5 Report





- **Recommendation 2d:**
  - **An ultimate Generation 3 (G3) dark matter direct detection experiment reaching the neutrino fog, in coordination with international partners and preferably sited in the US (section 4.1).**

Figure 1 – Program and Timeline in Baseline Scenario (B)

Index: Operation Construction R&D, Research P: Primary S: Secondary

§ Possible acceleration/expansion for more favorable budget situations

Science Experiments	Timeline 2024–2034	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
		Science Drivers						
LHC			P	P		P	P	
LZ, XENONnT				P				
DarkSide-20k				P				
G3 Dark Matter §		S		P				

P5 Report

- **DOE response to P5 (M. Procario, DPF, May 2024)**

G3 Dark Matter

- From P5 Recommendation 2, Priority 4 out of 5 :
  - An **ultimate Generation 3 (G3) dark matter** direct detection experiment reaching the neutrino fog, in coordination with international partners and **preferably sited in the US.**
- DOE response and actions:
  - At the present time, based on the Snowmass Community Summer Study, there have been two proposals for G3 Dark Matter detectors : XLZD and ARGO
  - P5 recommended a **domestic site for the experiment in the higher funding scenario** and an international site in the lower funding scenario.
  - Start with site independent R&D as we understand the funding that will be available.
    - Engage with partners who are interested in hosting.
  - DOE will entertain proposals by U.S. groups for pre-project R&D.

XLZD Consortium

Leading Xenon Researchers unite to build next-generation Dark Matter Detector

SURF is distributing this press release on behalf of the DARWIN and LZ collaborations

July 20, 2021

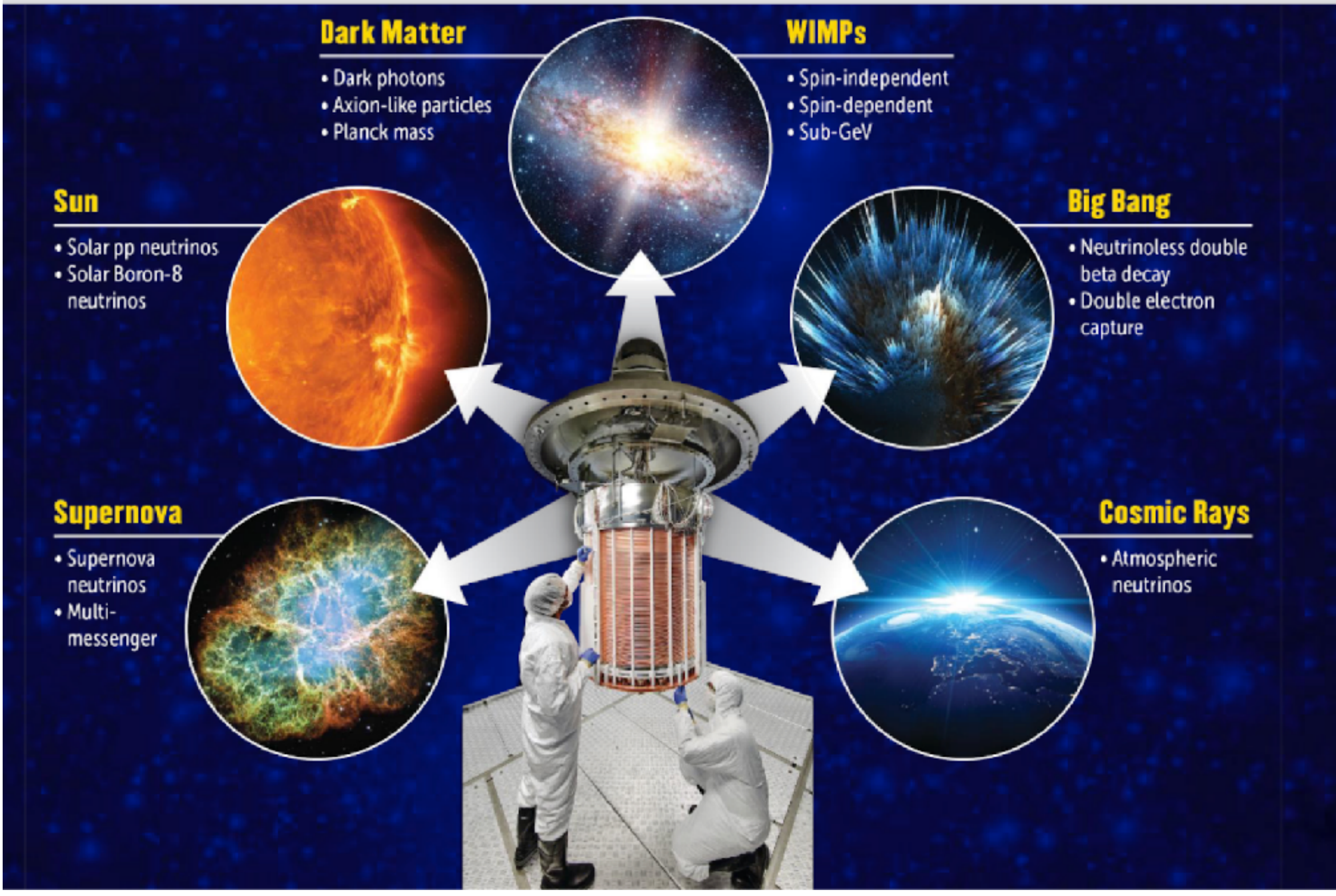
Several successful XLZD meetings already completed

White paper at 2203.02309

Official collaboration coming together

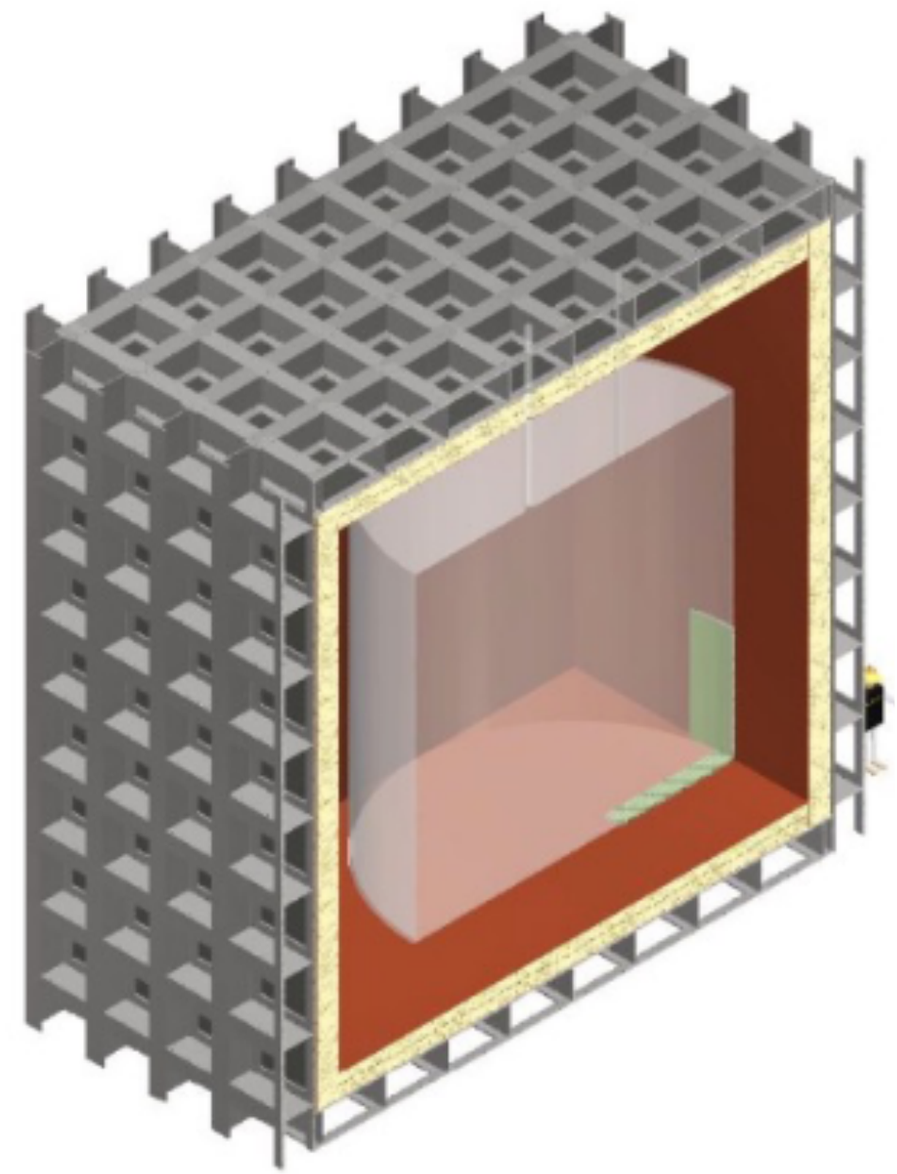
DARWIN/XENON + LUX ZEPLIN Summer Meeting 2022

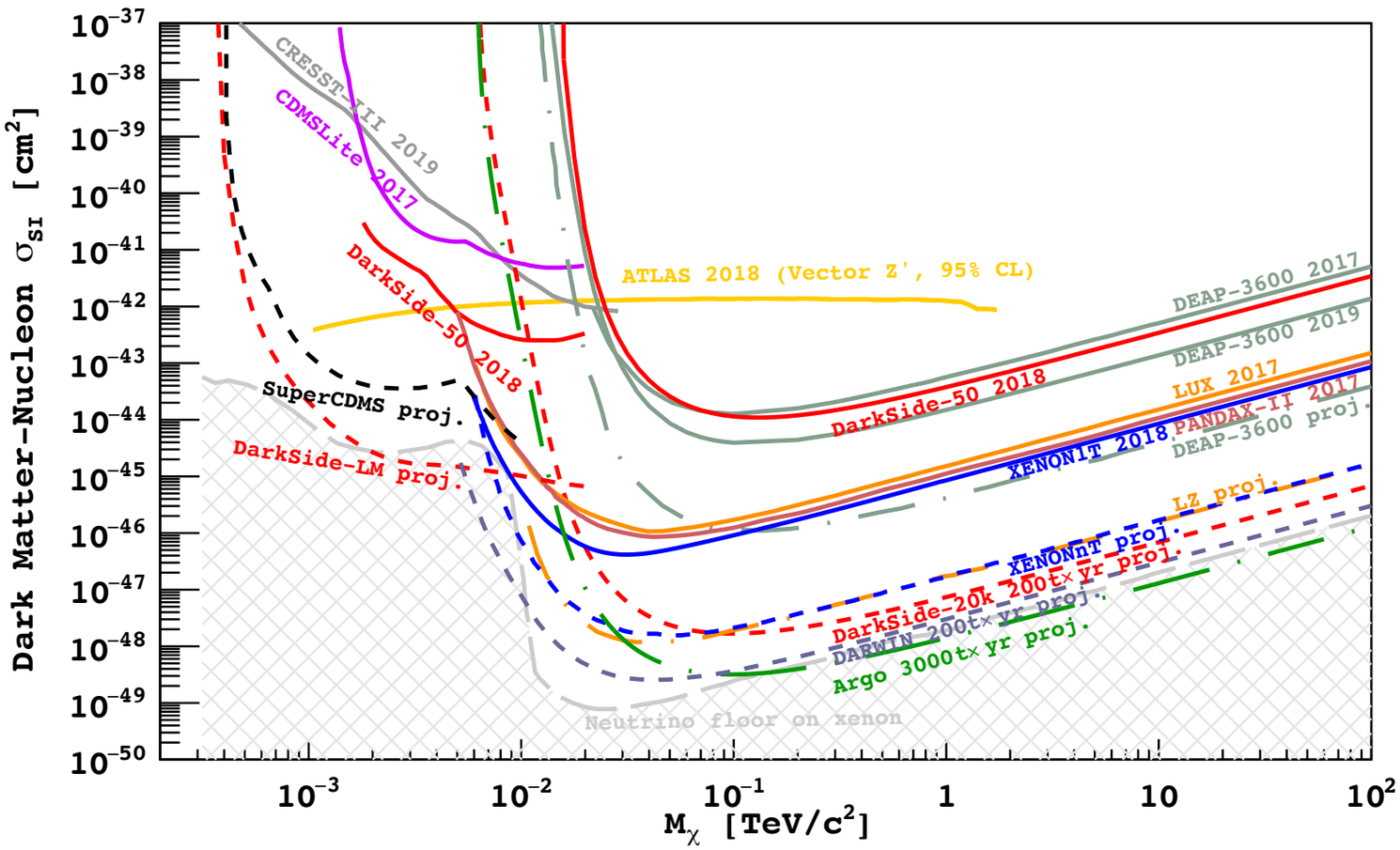
XLZD Consortium



ARGO

- ArDM, DS-50, DEAP-3600, and MiniCLEAN jointly formed the Global Argon Dark Matter Collaboration (GADMC)
- A 300-tonnes fiducial argon detector filled with underground argon
- 3000 tonne×year exposure to reach into the neutrino fog





Summary

2001 Snowmass report - single 3 page section on dark matter and relic particles

Particle Astrophysics and Cosmology: Cosmic Laboratories for New Physics
(Summary of the Snowmass 2001 P4 Working Group)

Daniel S. Akerib*
Department of Physics, Case Western Reserve University, Cleveland, OH 44106

Sean M. Carroll†
Department of Physics and Enrico Fermi Institute,
University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637

Marc Kamionkowski‡
California Institute of Technology, Mail Code 130-33, Pasadena, CA 91125

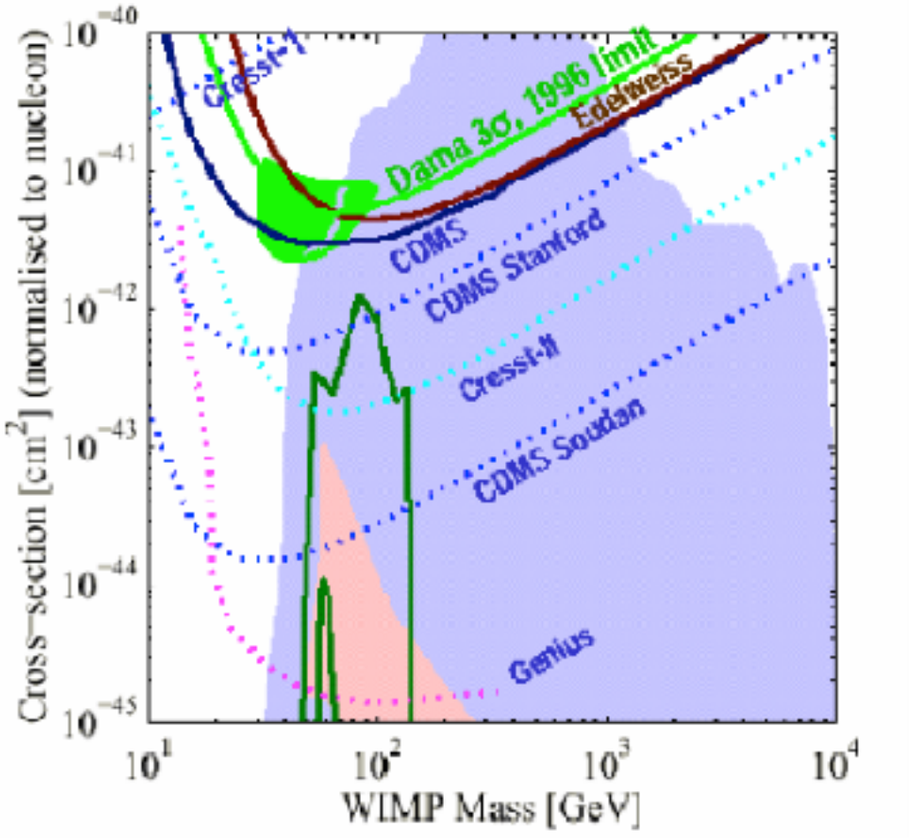
Steven Ritz§
NASA/Goddard Space Flight Center, Mail Code 661, Greenbelt, MD 20771

(Dated: October 30, 2018)

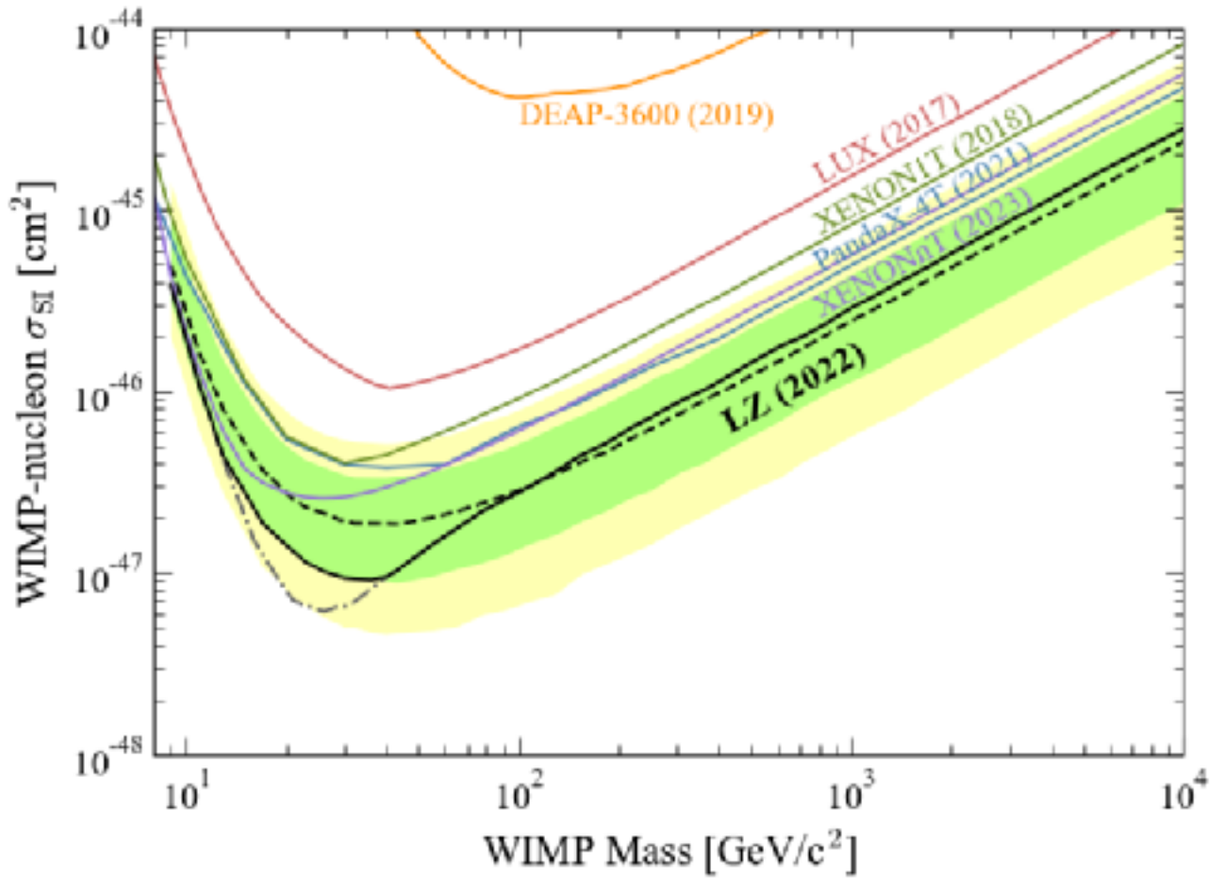
"Current searches are already exploring the parameter space of supersymmetric WIMPs [10-1000 GeV], with prospects for a factor of a hundred improvement in the coming years."

WIMPs

- CDMS PRL 84: 5699, (2000)
- Best limit at 3 x 10^{-42} cm^2



- LZ, TeVPA, S. Haselschwardt (2024)
- Best limit at 2.2 x 10^{-48} cm^2

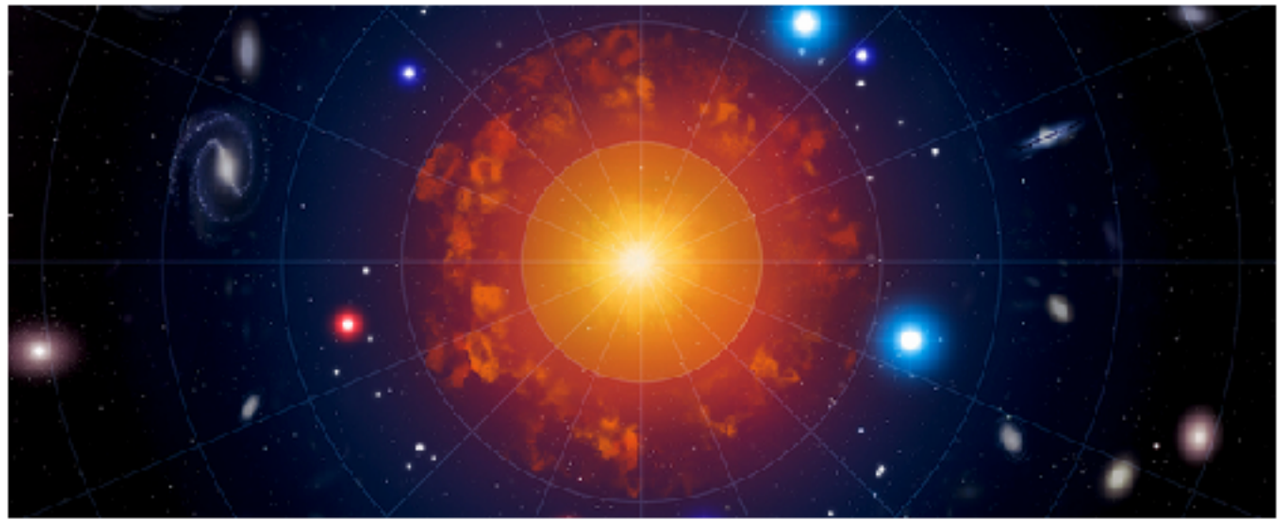


- Factor of >1,000,000 improvement in 24 years! Doubling every 1.2 years!
- Much faster than Moore's Law! A triumph of human ingenuity!
- No WIMPs :(

Losing the narrative?

Physicist Claims Universe Has No Dark Matter And Is 27 Billion Years Old

SPACE 18 March 2024 By MIKE MCRAE



(Mark Garlick/Science Photo Library/Getty Images)

Elon Musk ✓ 𝕏
@elonmusk

Subscribe ···

Possibly.

Dark matter is what seems most sketch to me.

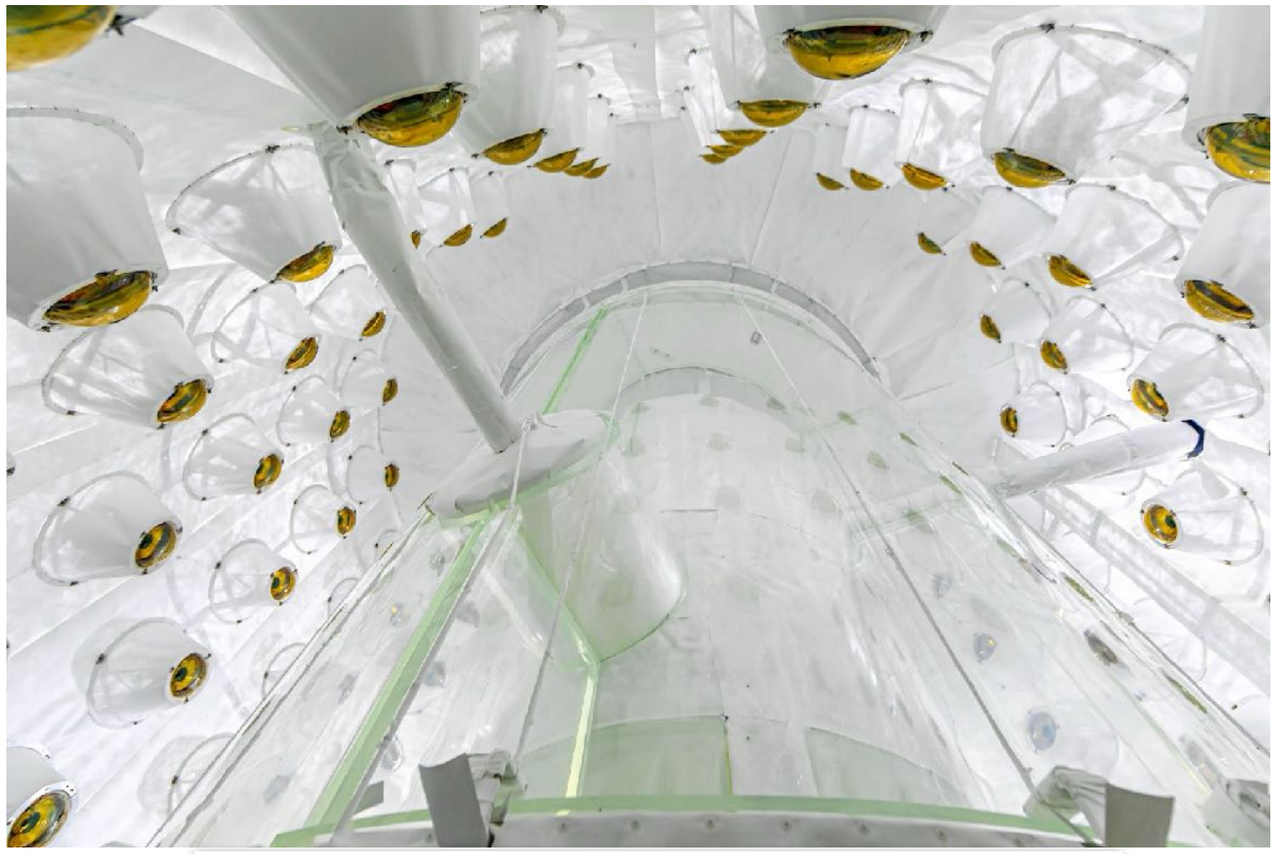
9:02 PM · Jul 16, 2023 · **2.8M** Views

Lights in the dark

- **DarkSide operating a prototype distillation column to isotopically separate ^{39}Ar from ^{40}Ar**

Lights in the dark

- **XENONnT at ~15 events/ tonne/year/keV**
- **LZ has zero candidate events in a 4.2 tonne-years of exposure**

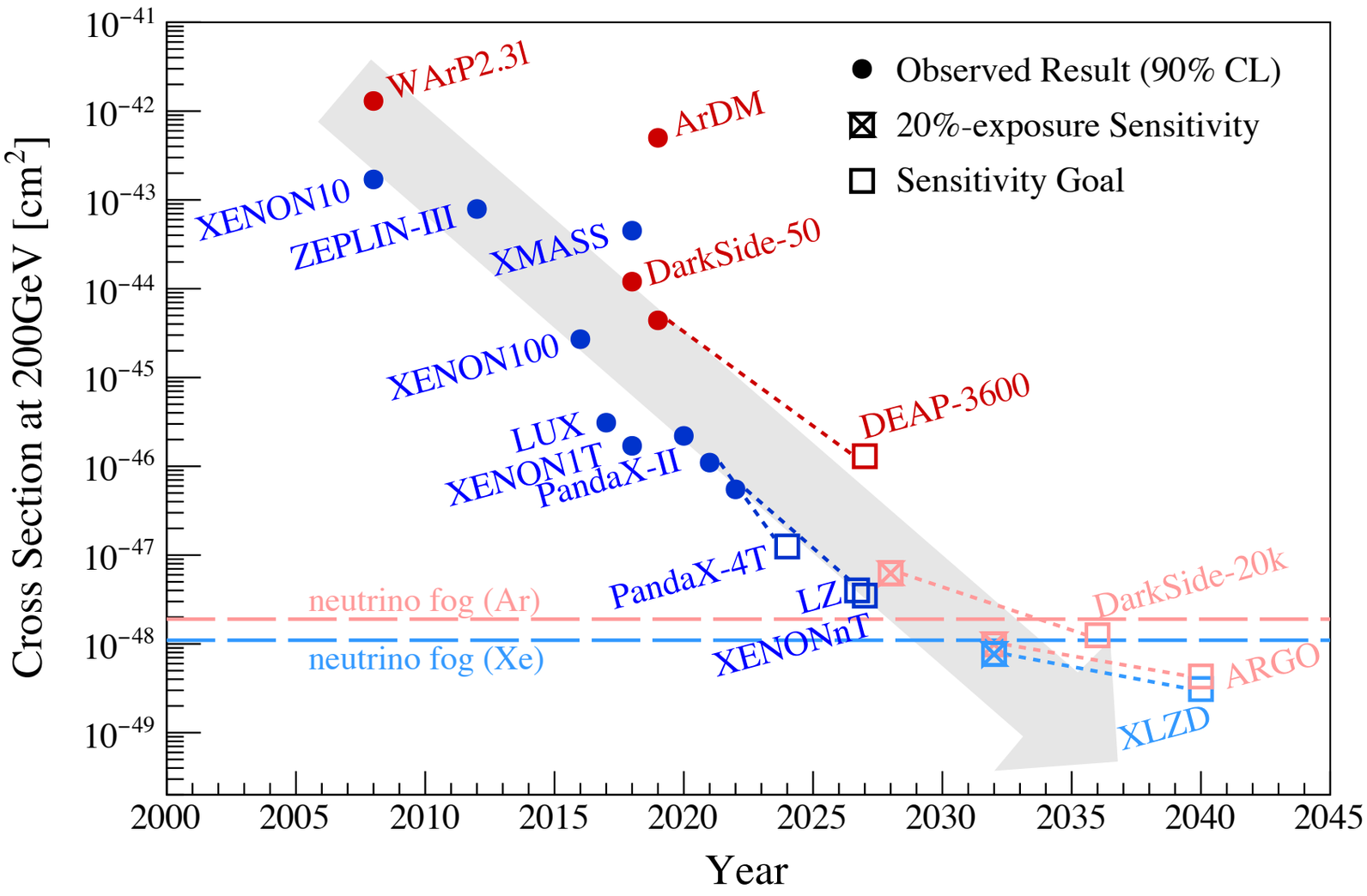


These numbers are incredible!

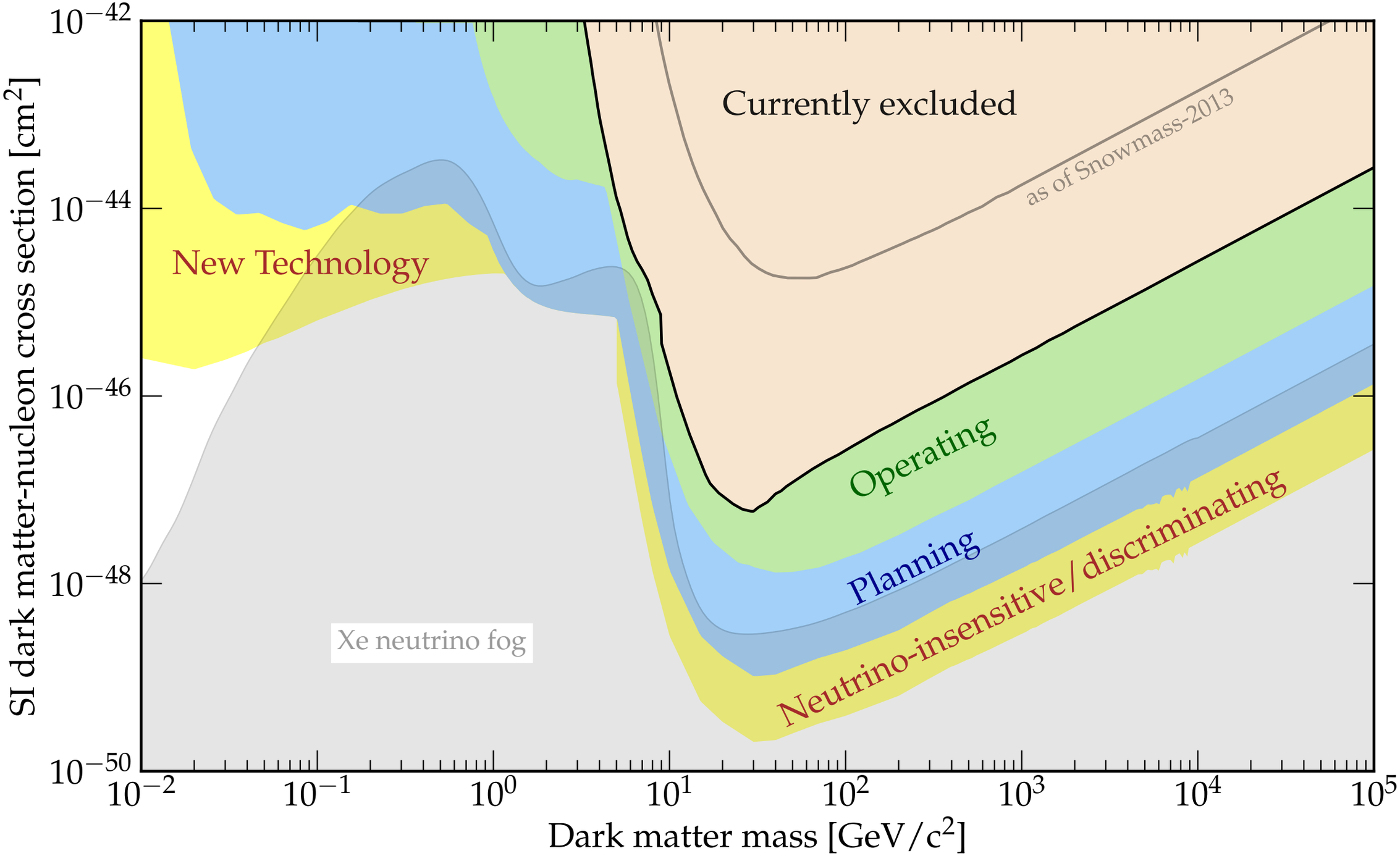
Suppression by a factor of a trillion!

Lights in the dark

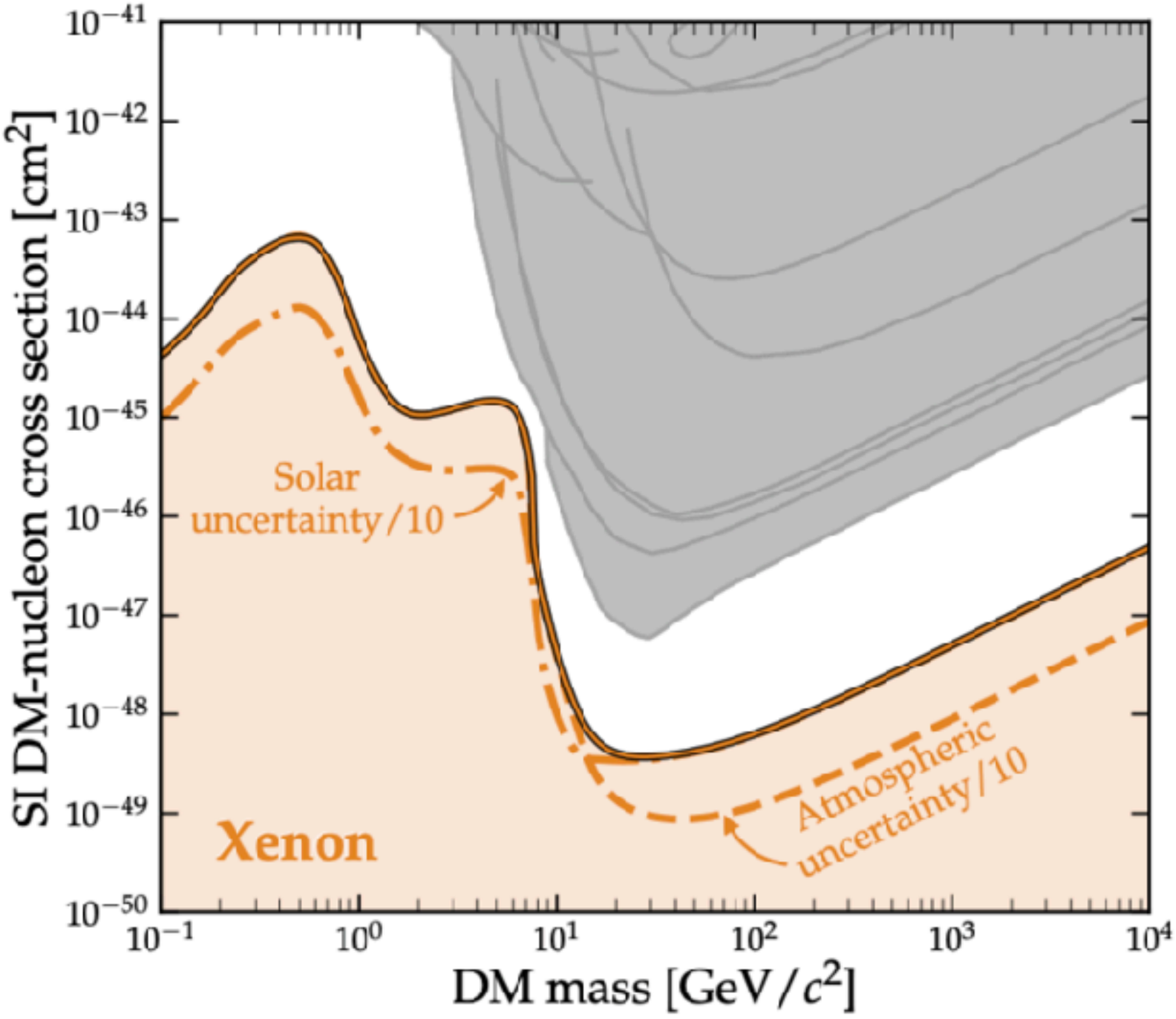
- Four multi-tonne detectors operating simultaneously, with more on the way!
- Demonstration of technological maturity
  - Building these detectors is hard!
  - Every time we build one, we find something we want to do better
- Ready for one more push




This is a problem worth solving!
I’m eager to see what’s next!

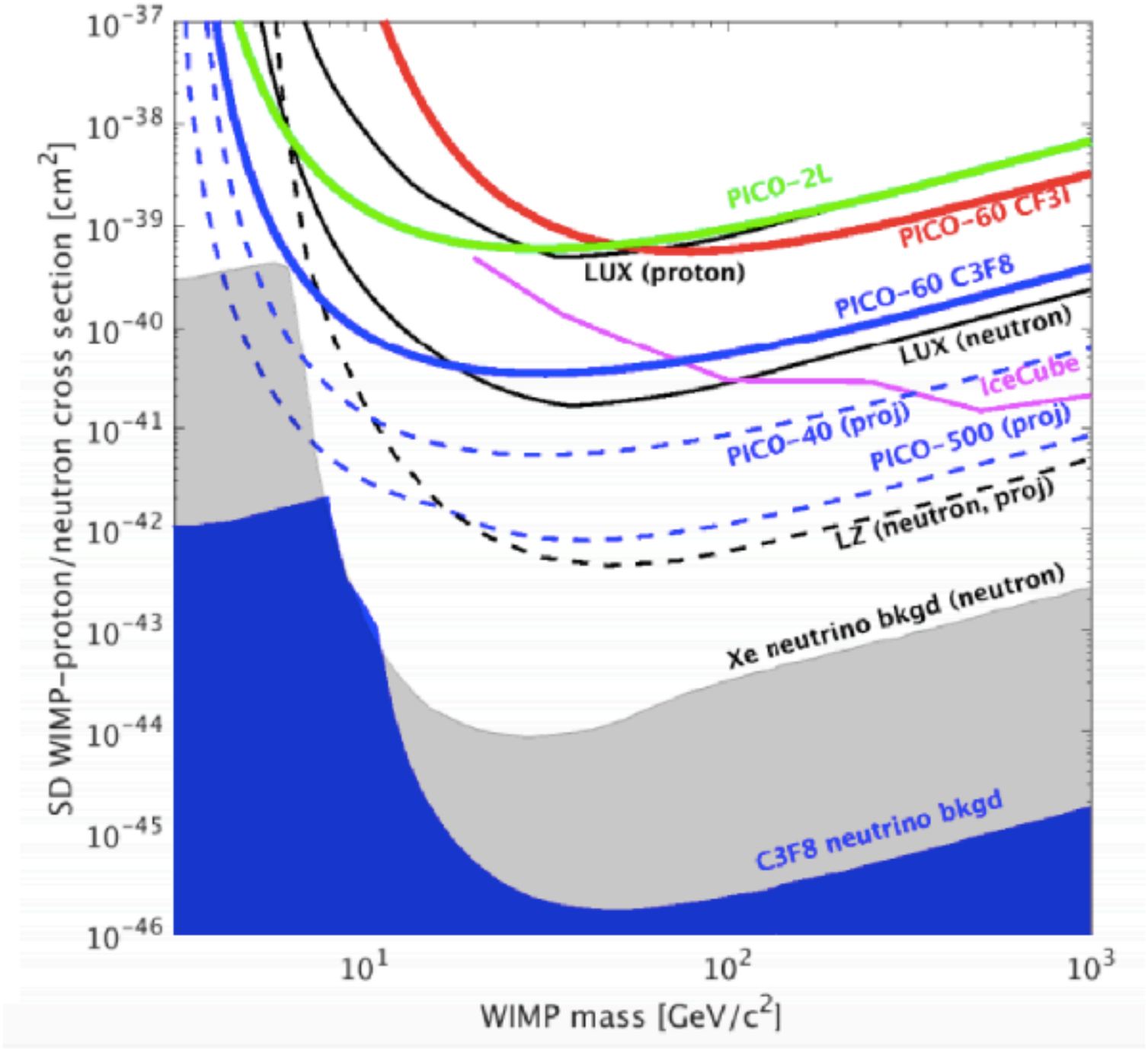

Currently excluded
as of Snowmass-2013
New Technology
Operating
Planning
Neutrino-insensitive/discriminating
Xe neutrino fog
SI dark matter-nucleon cross section [cm^2]
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Dark matter mass [GeV/c^2]

Neutrino Fog



- Future progress can be made with better measurements of the atmospheric neutrino flux

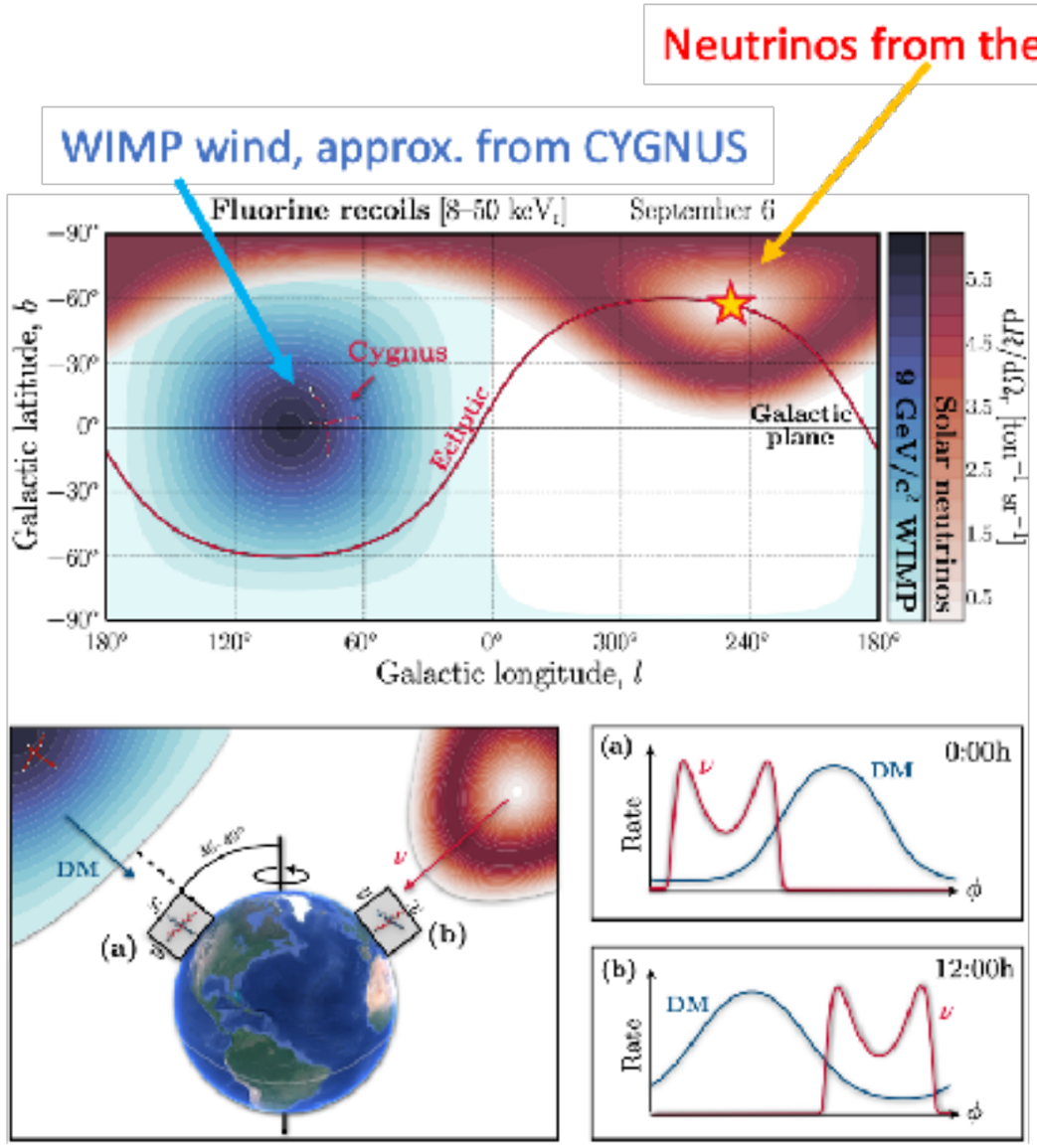
Neutrino Fog

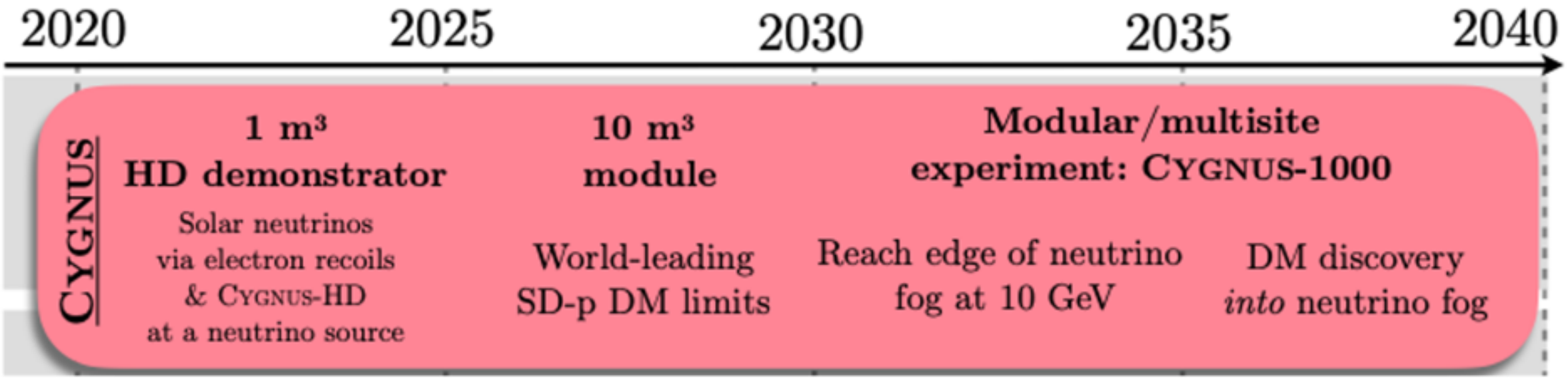


- Future progress can be made depending on target
  - Fluorine based SD detector can go deeper than xenon-based SD detector

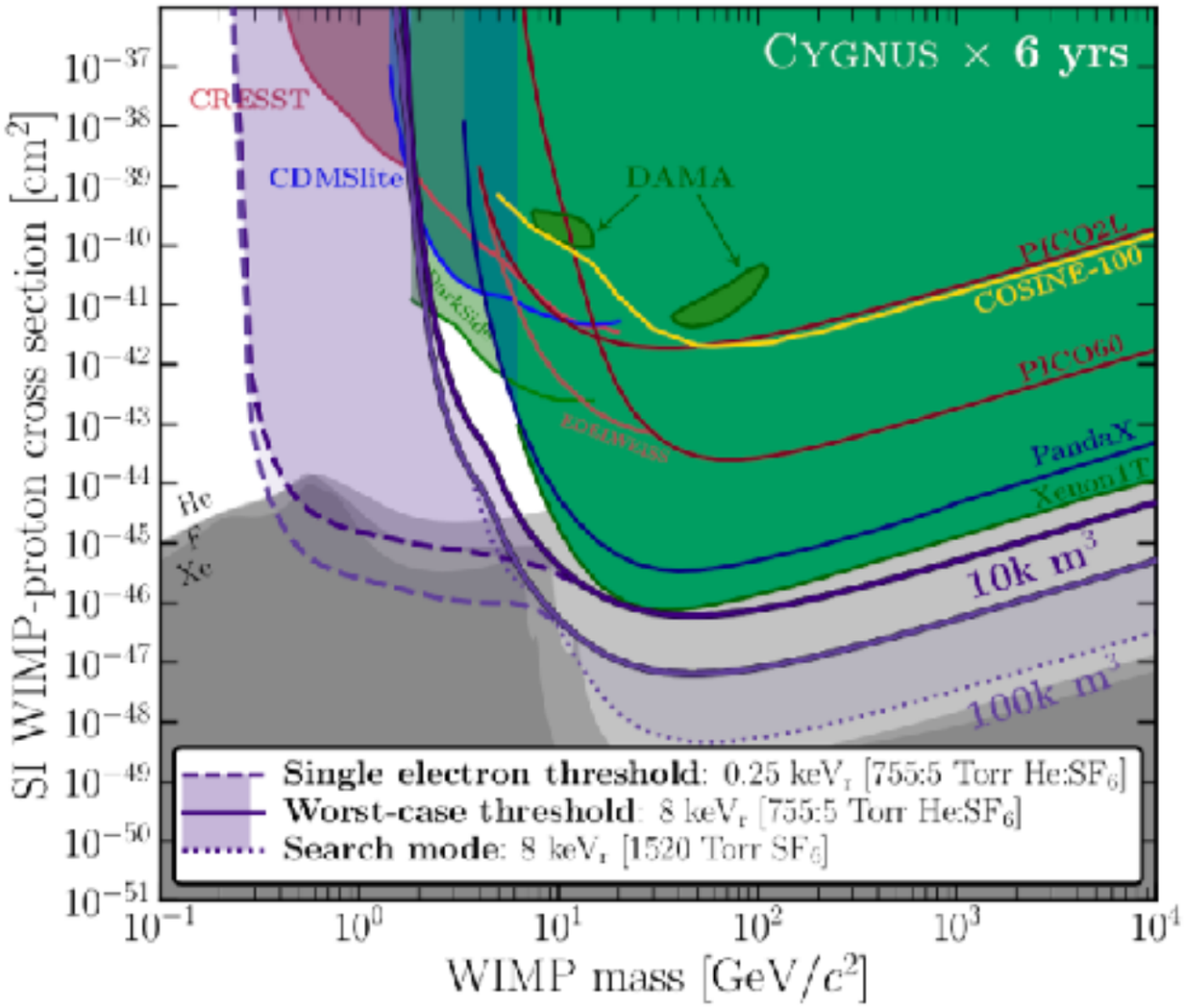
Directionality

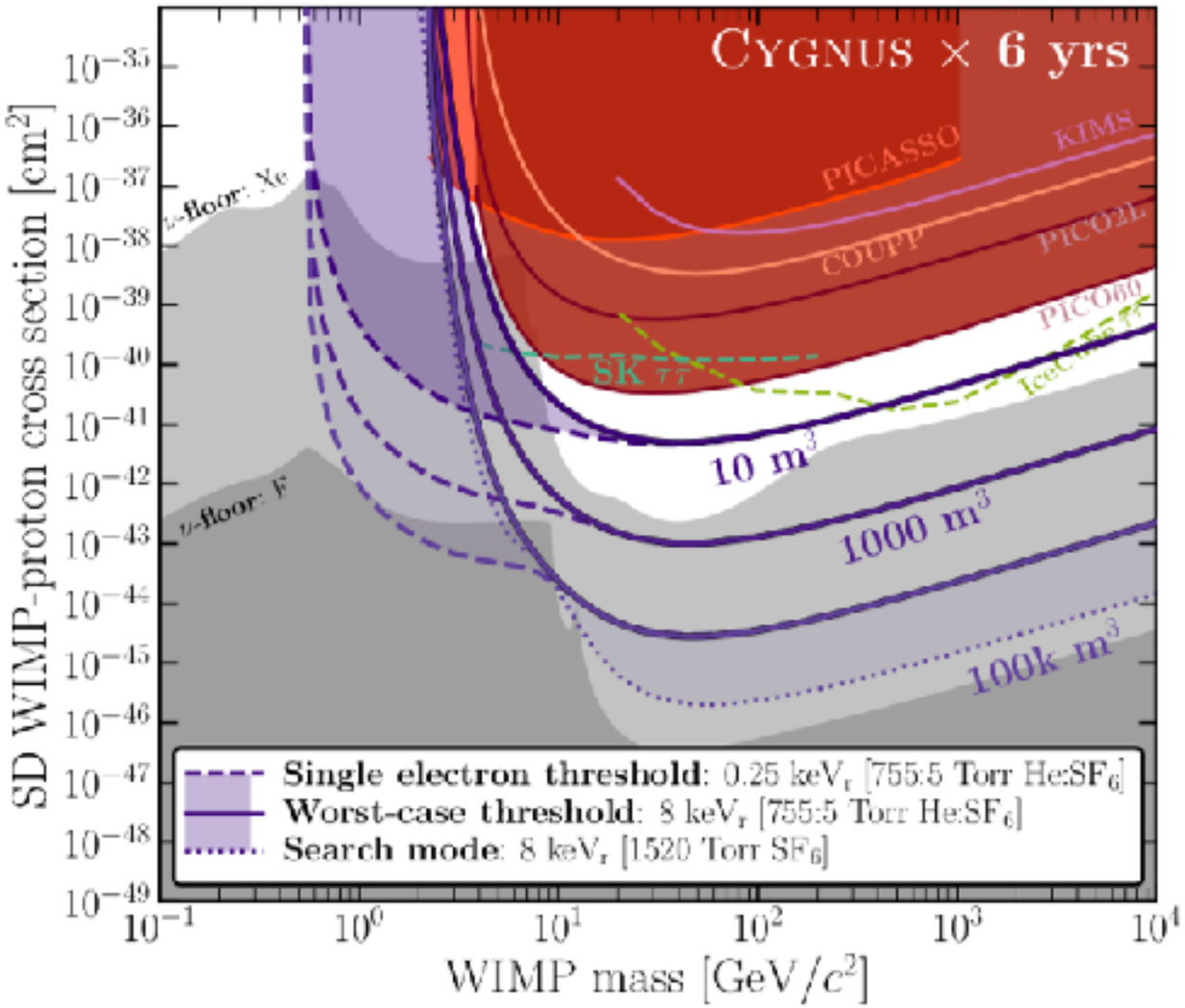
- Directionality can identify WIMP wind with only handful of events
  - Ideal case - 3D direction plus energy
  - Experimentally challenging
- Cygnus program doing R&D now to enable large scale directionality
  - Physics program for dark matter and neutrinos described in 2102.04596



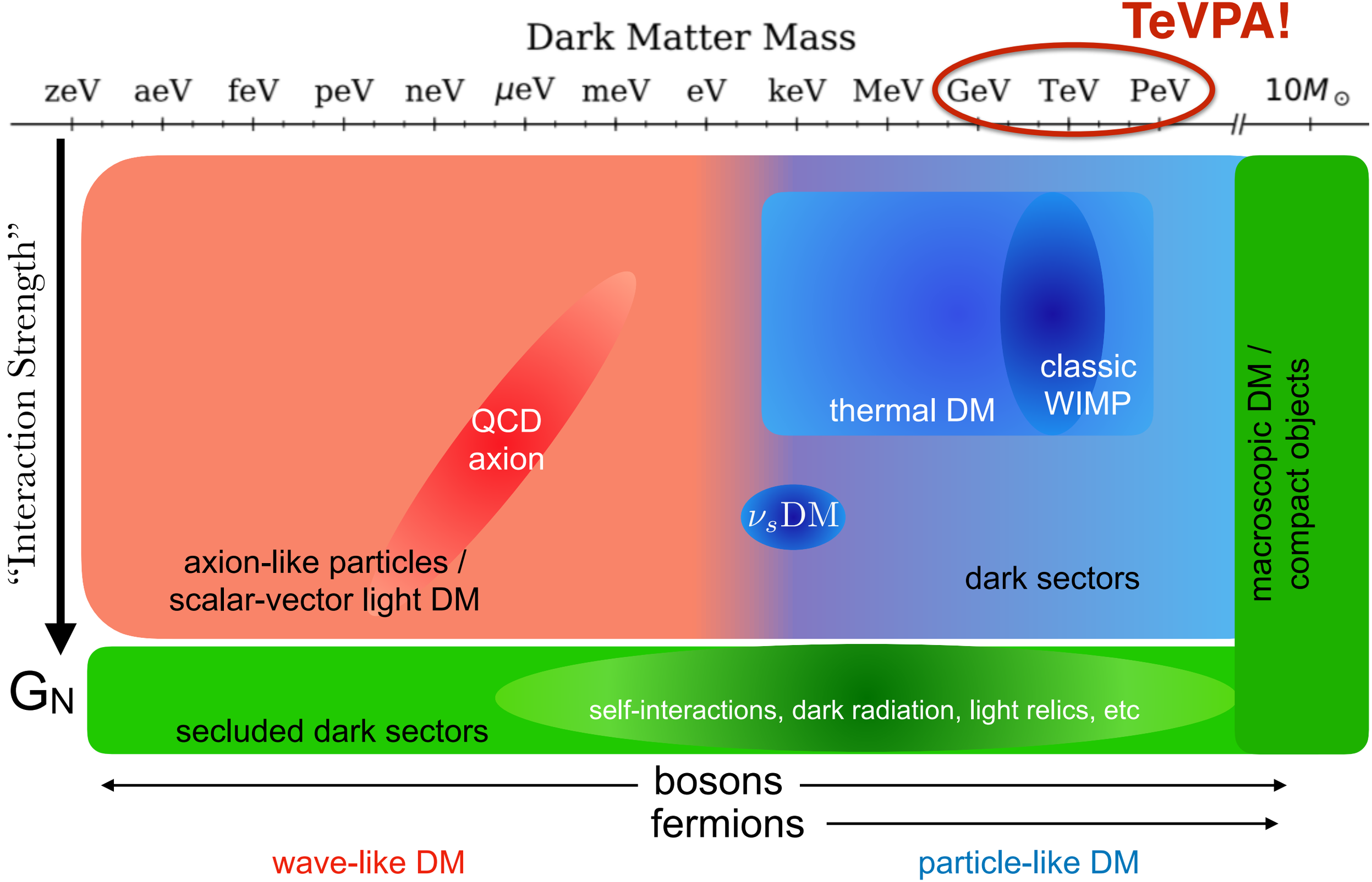


Directionality



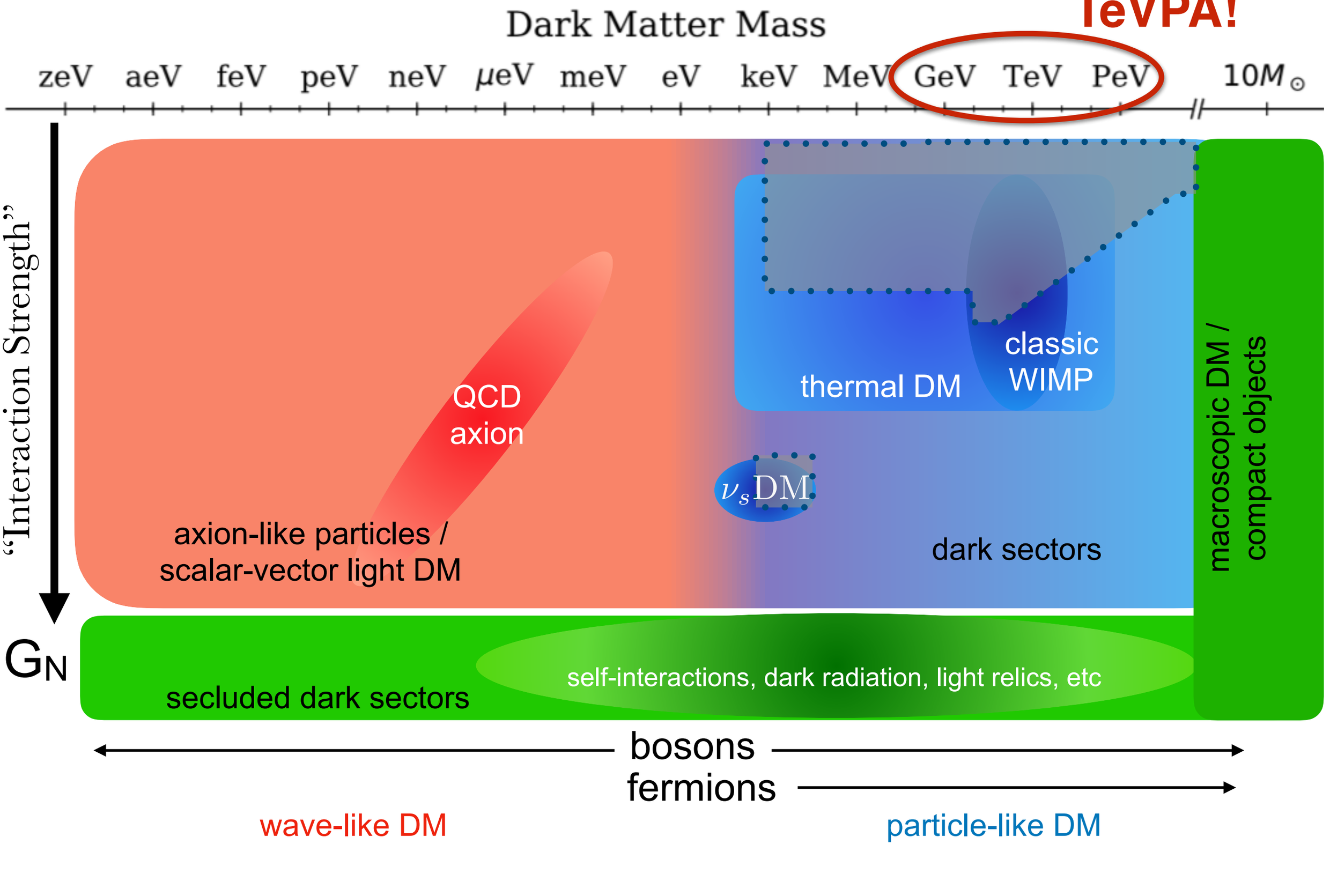


Dark Matter at ~TeV and beyond

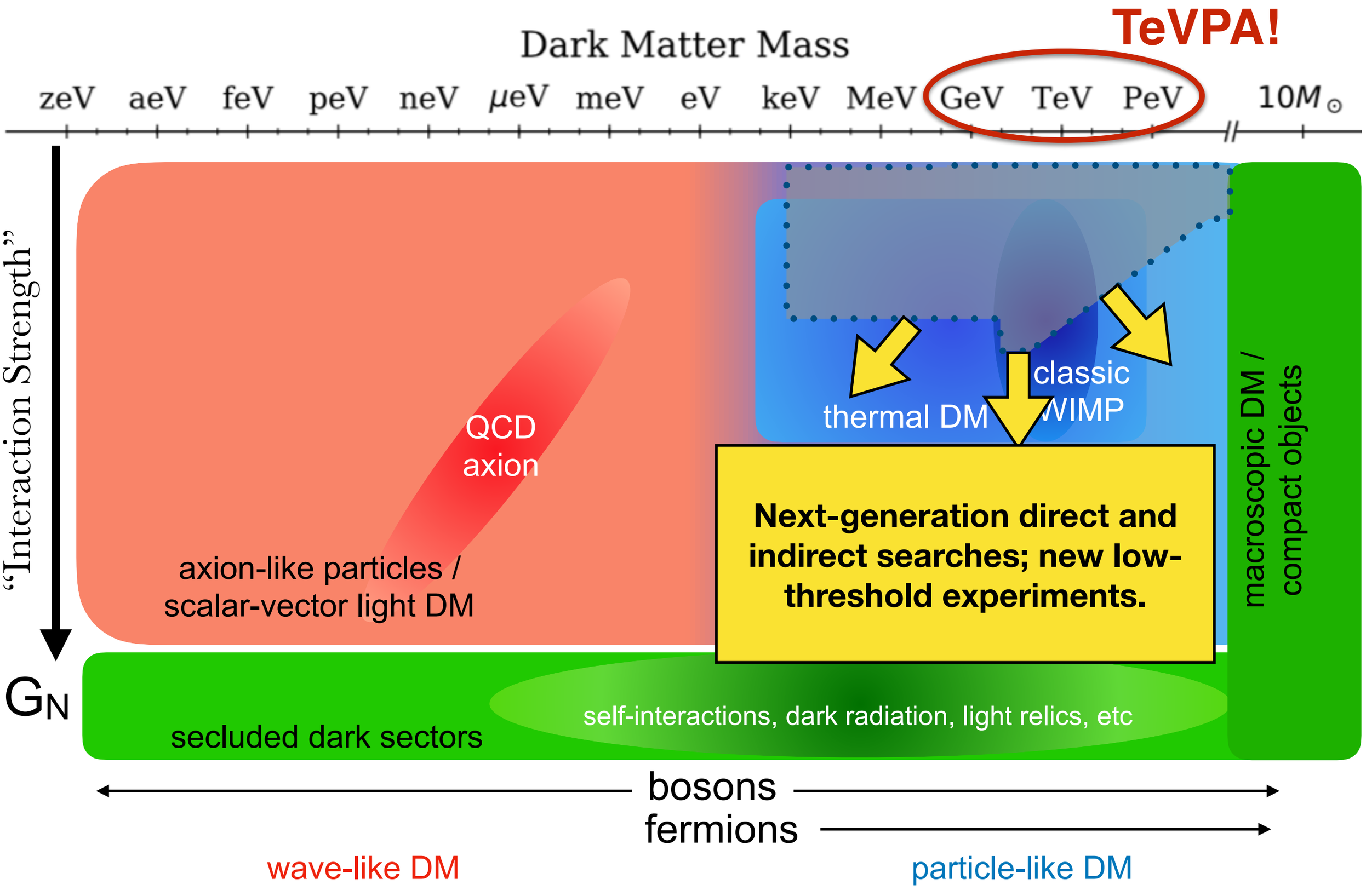


From A. Chou, Cosmic Frontier Plenary at Snowmass

Dark Matter at ~TeV and beyond

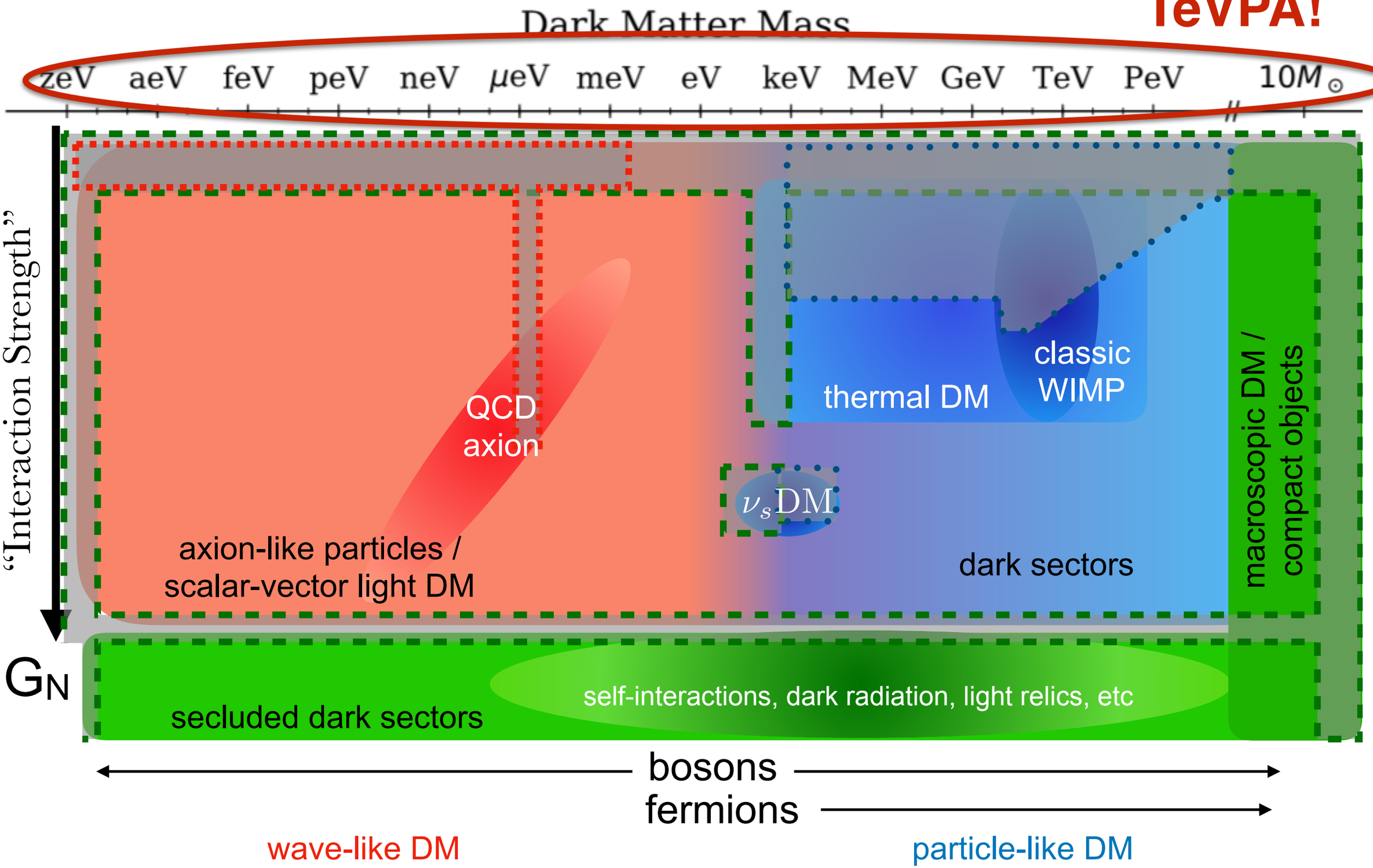


Dark Matter at ~TeV and beyond



Dark Matter at ~TeV and beyond

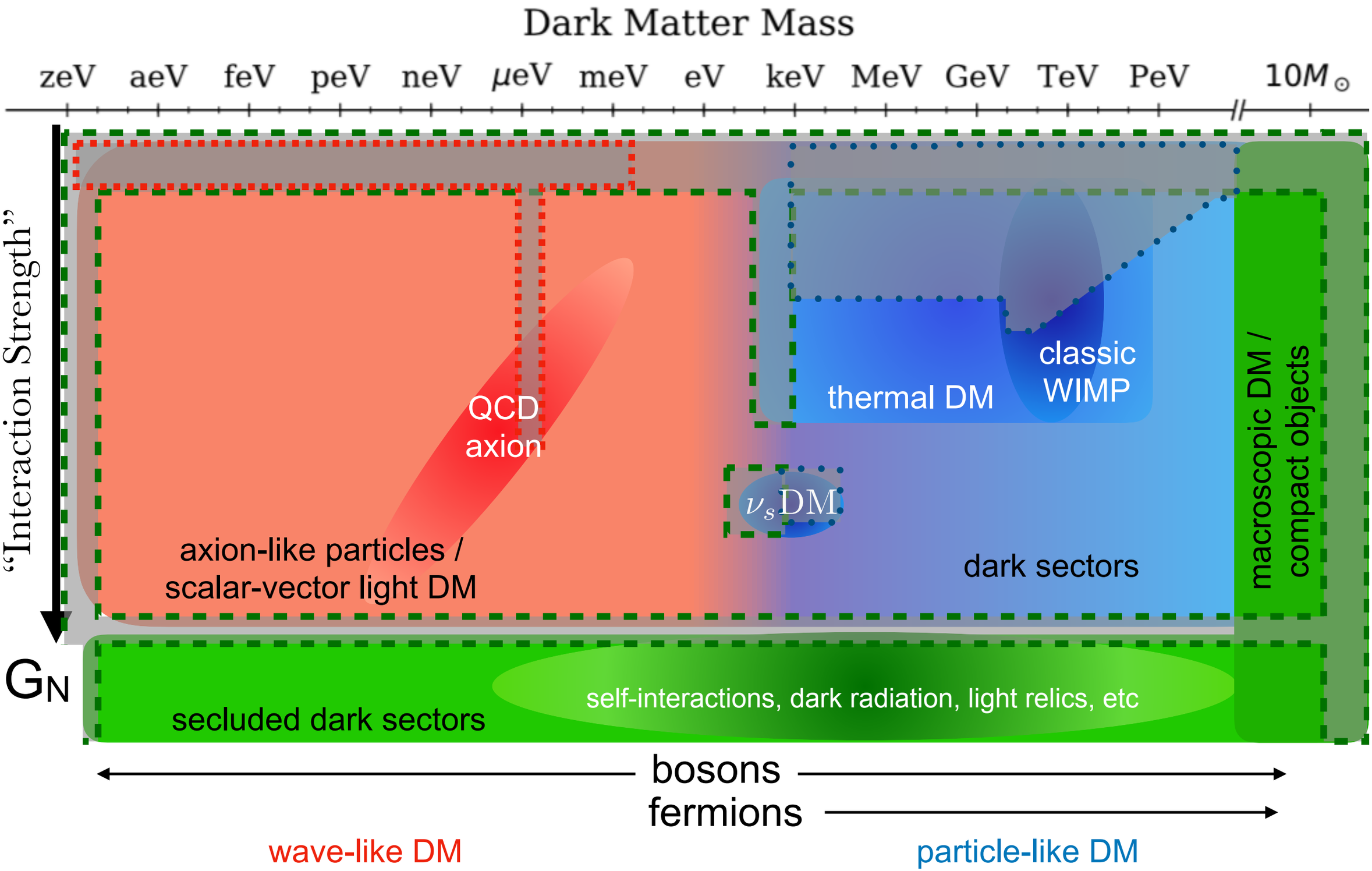
TeVPA!



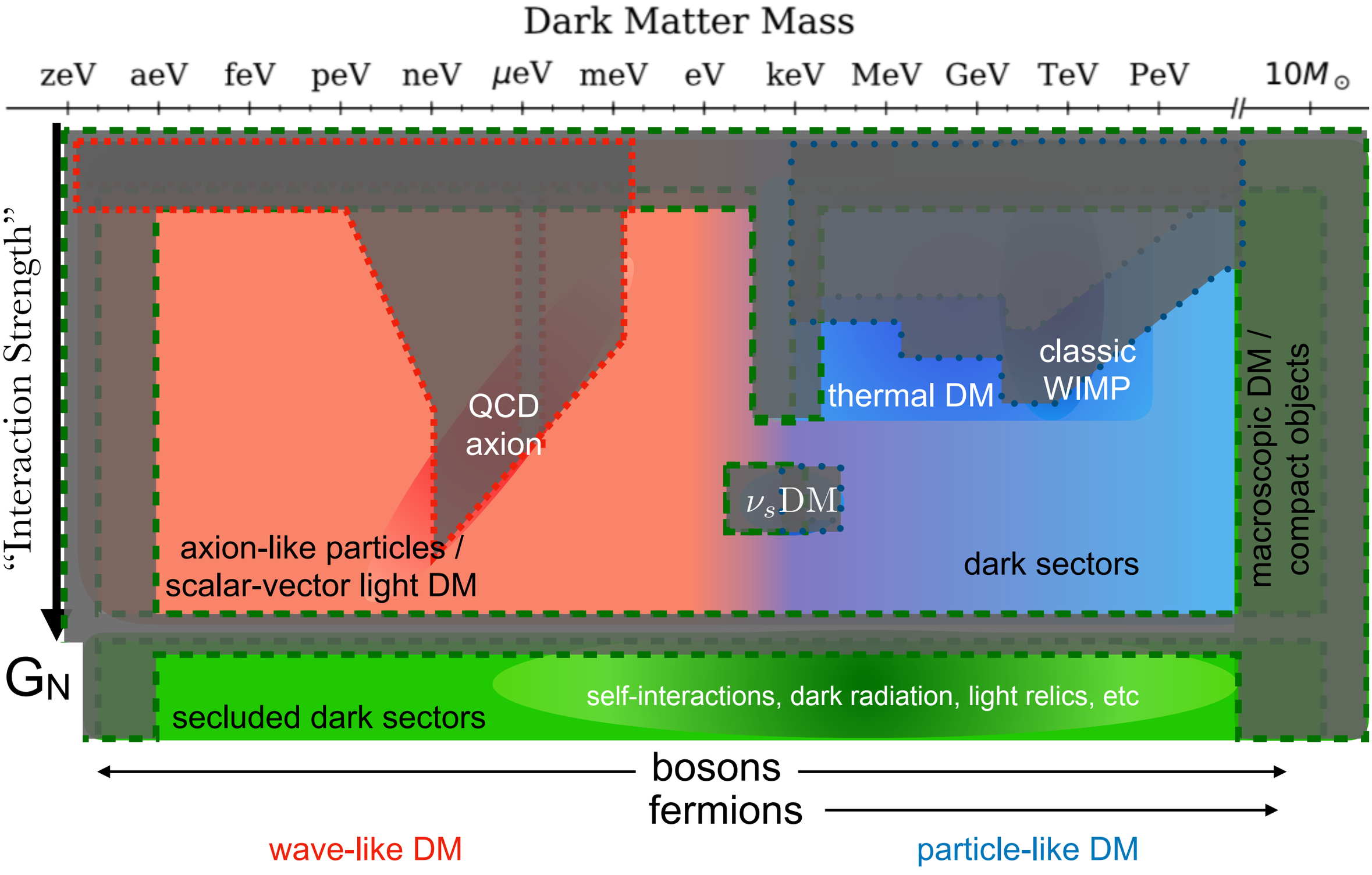
Dark Matter at TeV scales (and beyond)

- **Dark matter poses a profound and exciting challenge to our understanding of fundamental physics.**
- **Maximize the probability of discovery**
    - **Delve Deep:** Fully explore high-priority theoretical target regions (e.g., WIMPs and QCD axions).
    - **Search Wide:** Deploy new techniques and pathfinder experiments to access unexplored dark matter scenarios and lay the groundwork to go deep on future targets.
- **Dark Matter Crosses Boundaries:** Complementarity across frontiers including a vibrant theory program is critical for the discovery and characterization of dark matter and dark sectors.

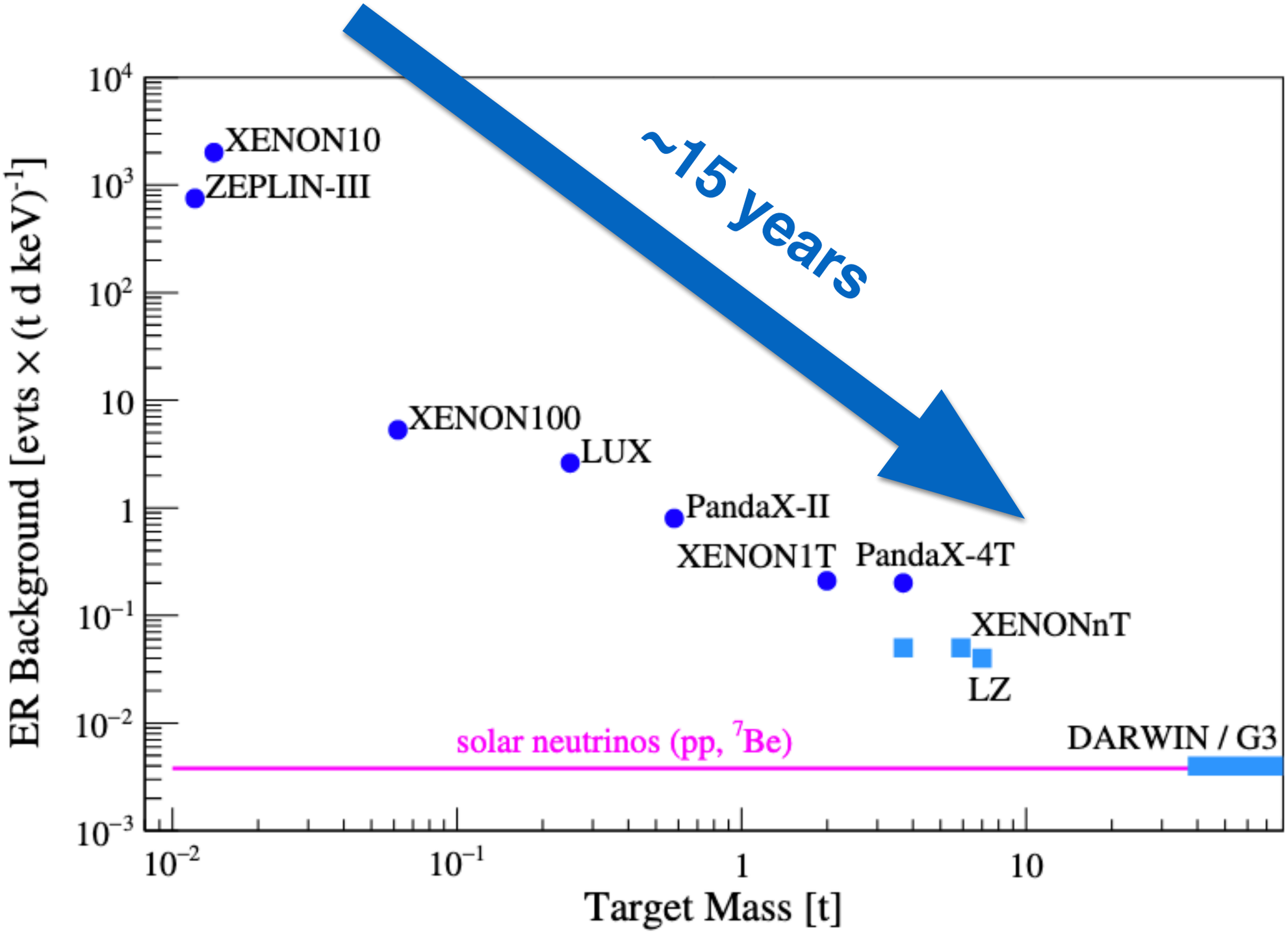
Current status



Plan for next decade

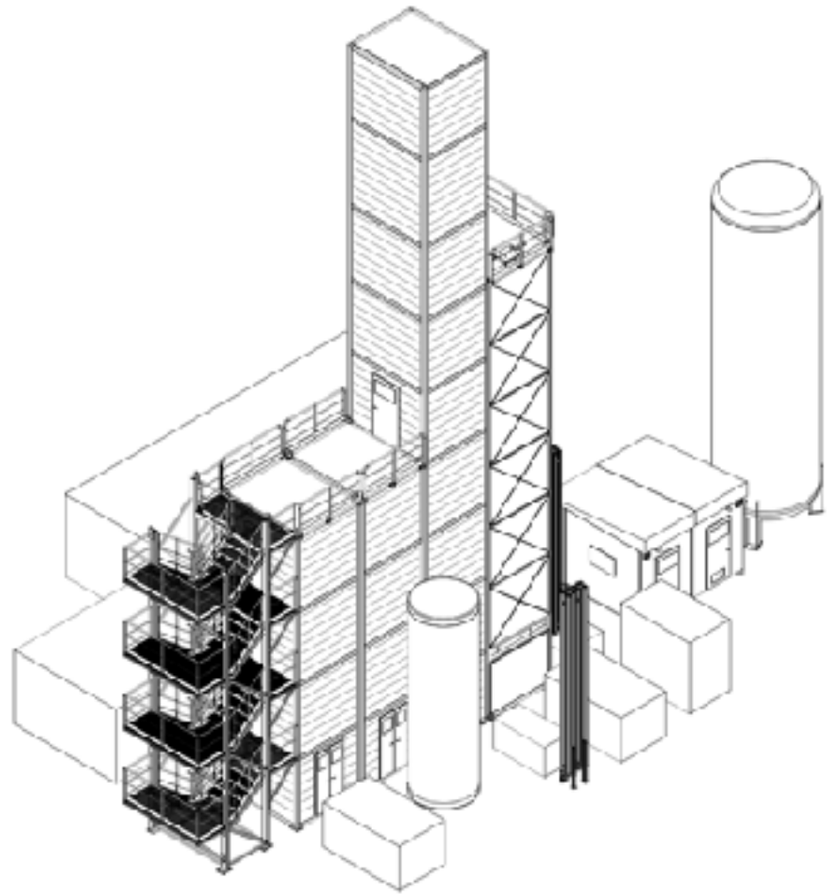


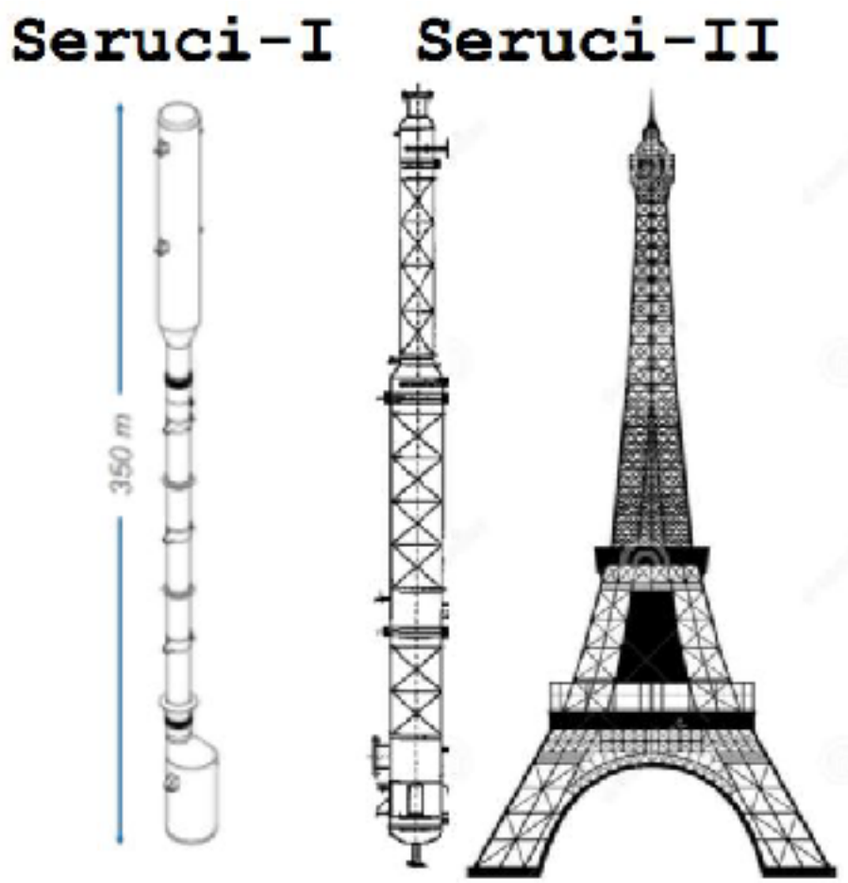
Liquid Xenon TPCs



URANIA

- Procurement of 50 tonnes of UAr from same Colorado source as for DS-50
- Extraction of 250 kg/day, with 99.9% purity
- UAr transported to Sardinia for final chemical purification at Aria



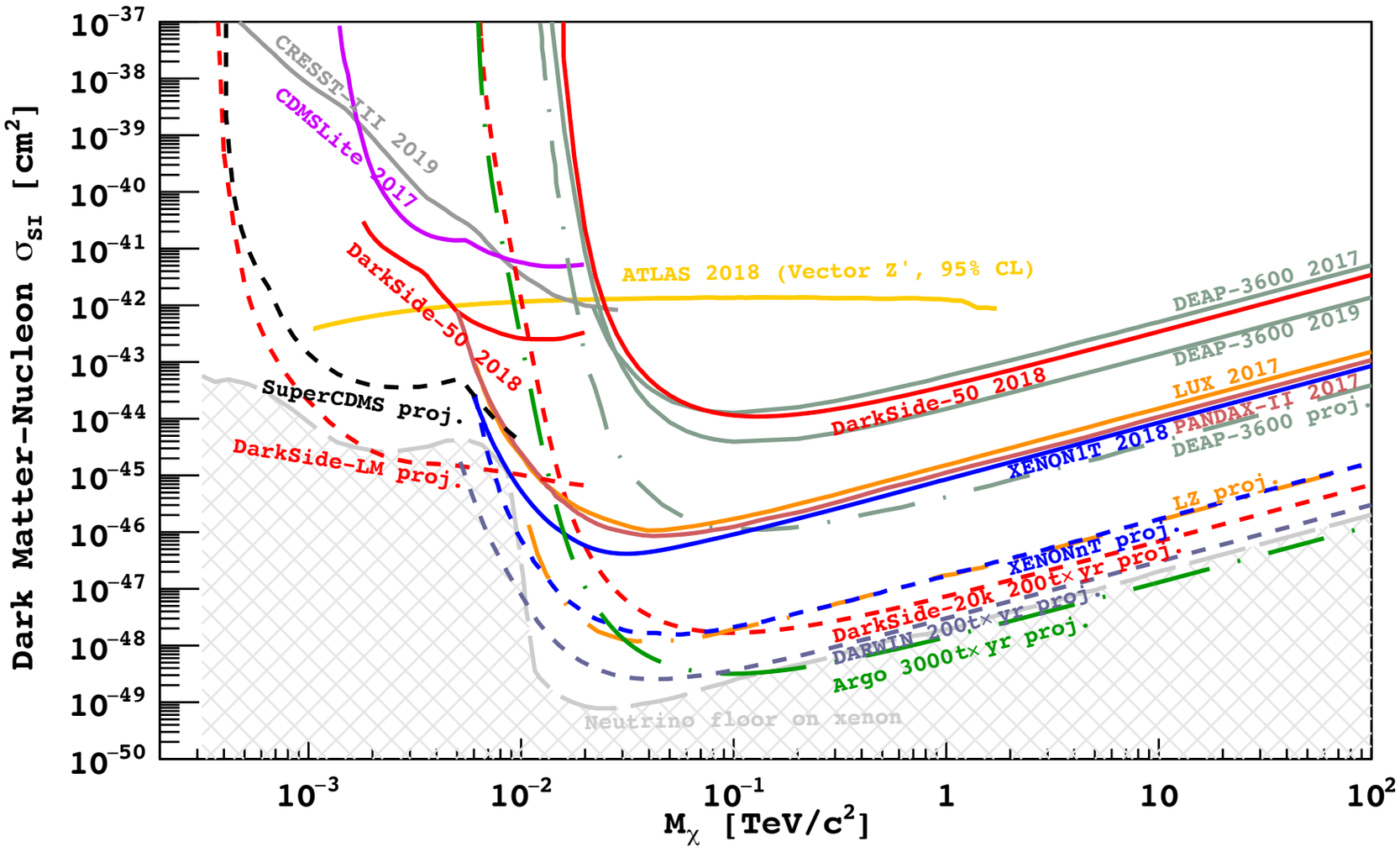


ARIA

- Big cryogenic distillation column in Seruci, Sardinia
- Final chemical purification of the UAr
- Can process O(1 tonne/day) with 10^3 reduction of all chemical impurities
- Ultimate goal is to isotopically separate ^{39}Ar from ^{40}Ar (at the rate of 10 kg/day in Seruci-I)

ARGO

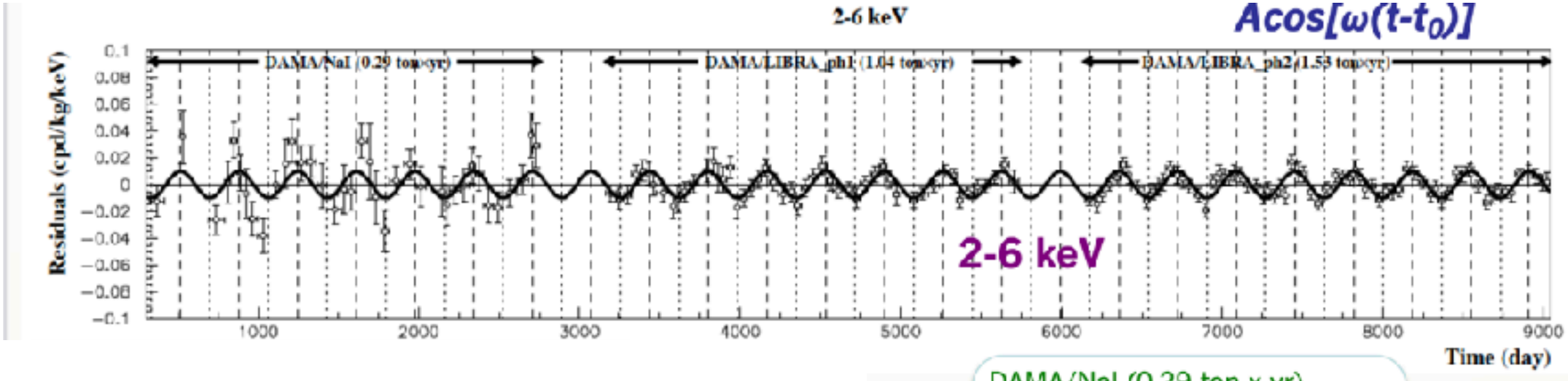
- ArDM, DS-50, DEAP-3600, and MiniCLEAN jointly formed the Global Argon Dark Matter Collaboration (GADMC)
- A 300-tonnes fiducial argon detector filled with underground argon
- 3000 tonne×year exposure to reach the neutrino floor



GADMC experiments cover the WIMP hypothesis from 1GeV/c² to several hundreds of TeV/c² masses in the search for spin-independent coupling.

Sodium Iodide

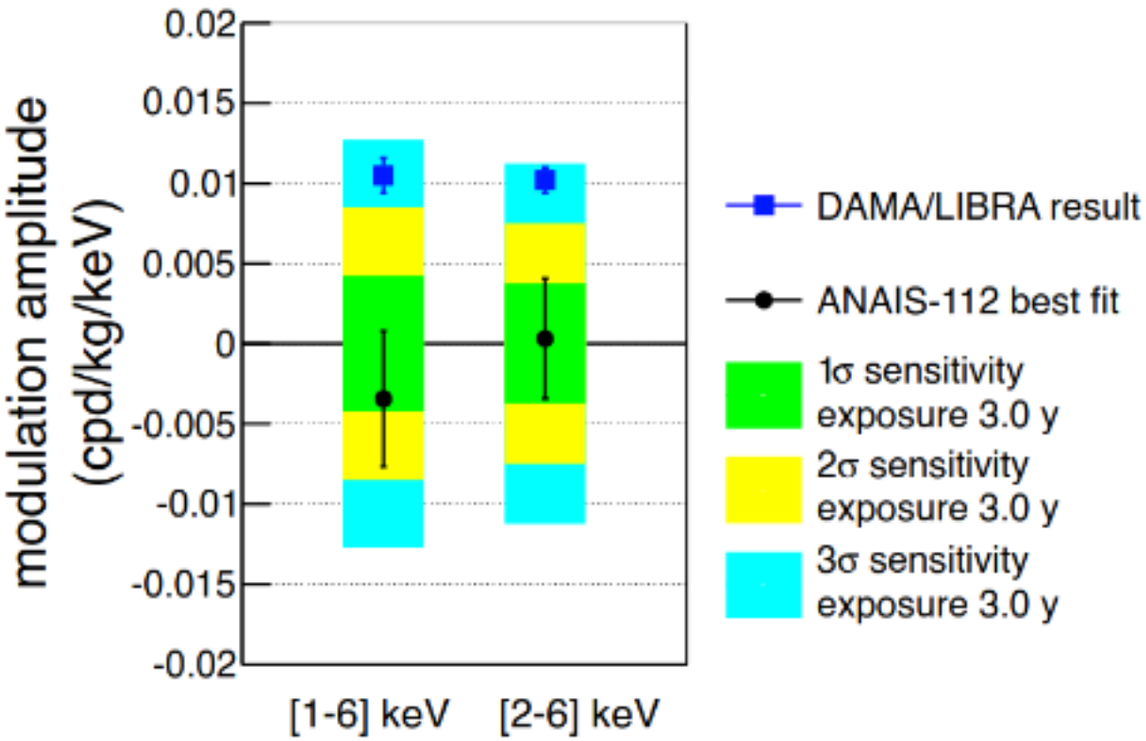
- **DAMA**

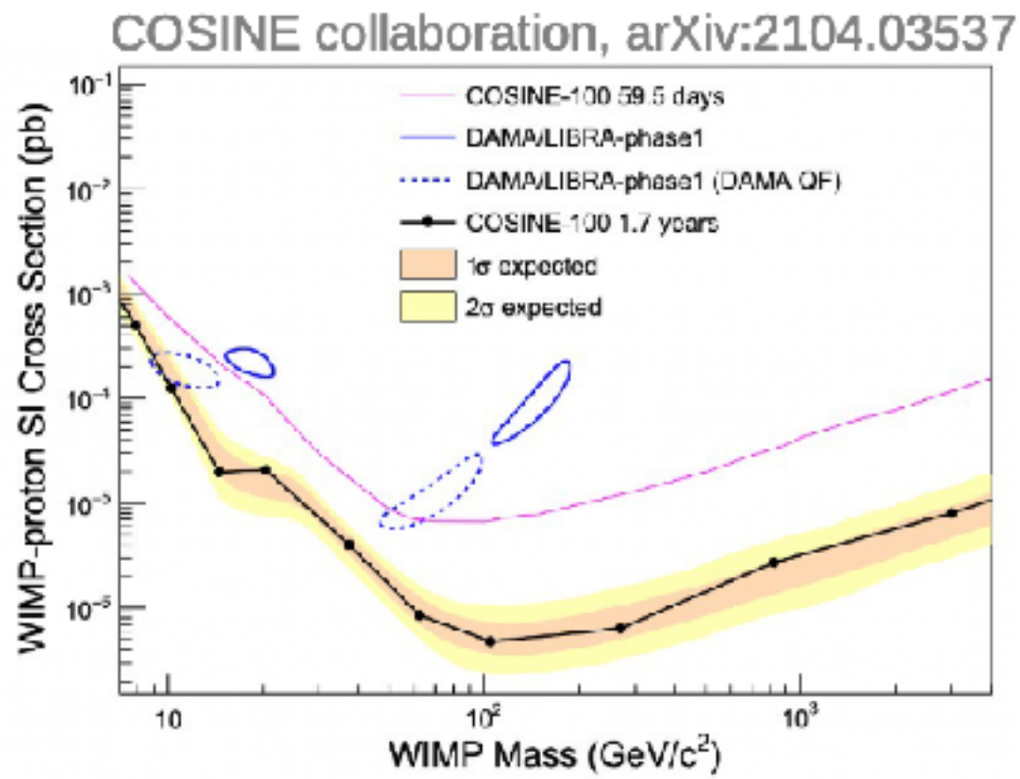


This is 24 years!!!

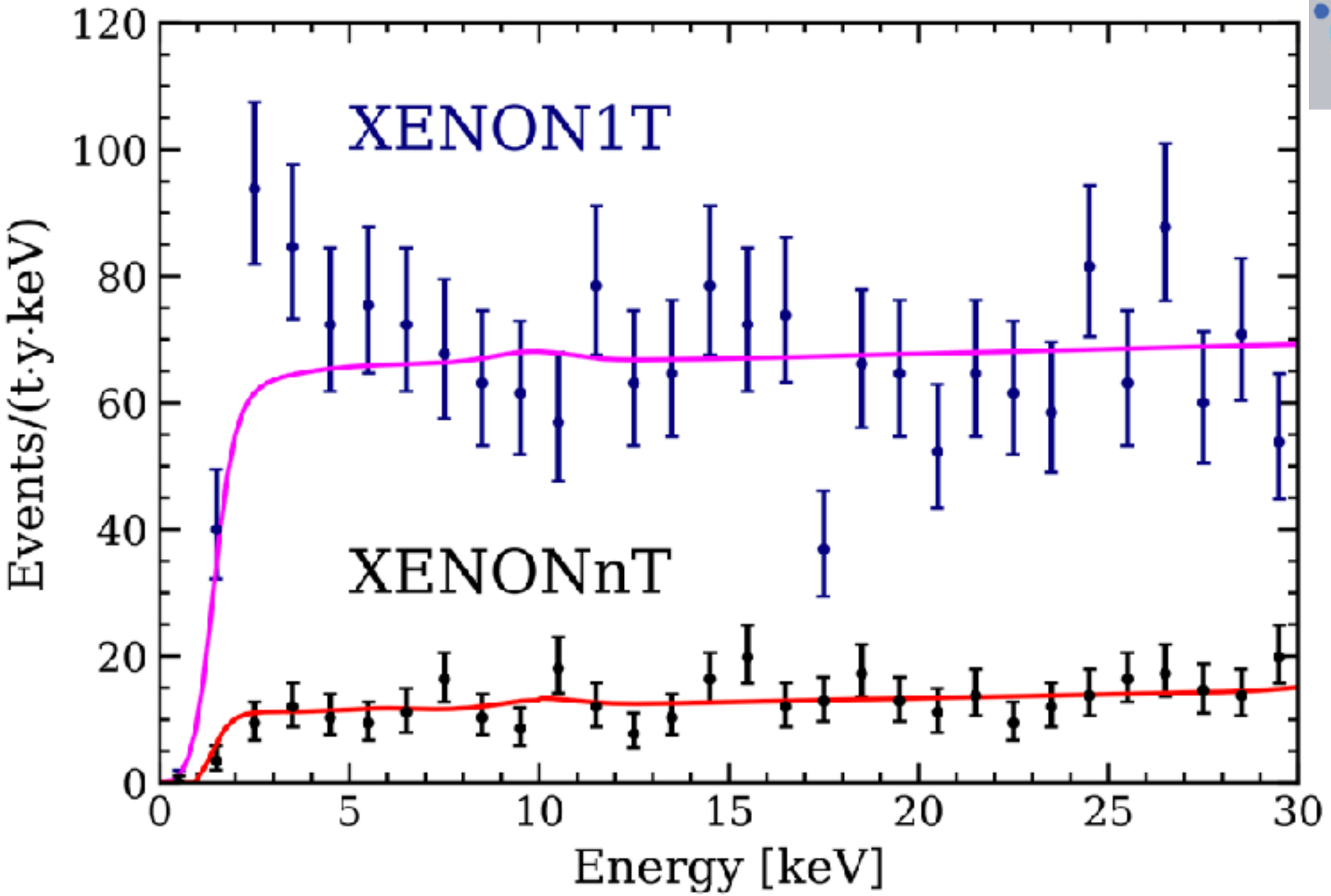
DAMA/NaI (0.29 ton x yr)
DAMA/LIBRA-ph1 (1.04 ton x yr)
DAMA/LIBRA-ph2 (1.53 ton x yr)
total exposure = 2.86 tonxyr

- **ANAIS, COSINE, SABRE, PICO-LON, DM-ICE**





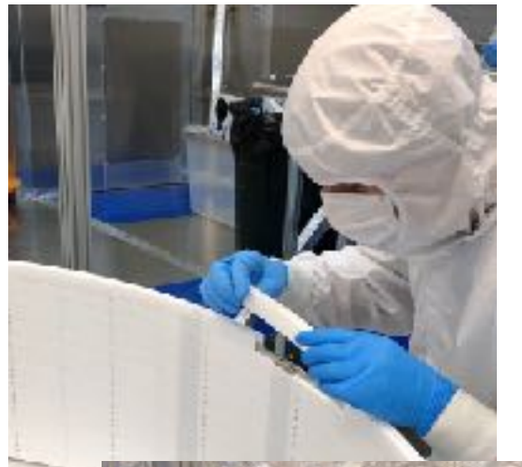
XENON1T Excess

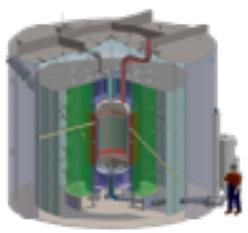


- Exquisite background control with expectation of further reductions
- New limits on ALPs, dark photons, axions, neutrino magnetic moment
  - Knut Mora at IDM2022 - 2207.11330

LZ

- LXe TPC, 7 tonnes active
- Located at SURF, SD, USA
- GdLS neutron veto
- Filled in Fall 2021
- All systems working well
- First results a month ago!
  - ~25 ER cts/keV/tonne/yr
  - See S. Eriksen tomorrow at 5:10



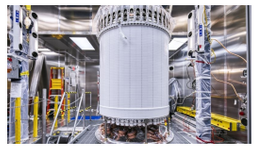


TDR and CD-3

2017

2018

PMT arrays arrive



TPC Complete

2019

Cryostat arrives

Grid weaving

TPC Underground

2020

Cryostat sealed

Electronics

OD Construction

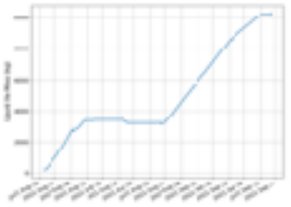
2021

OD filling

Cold Gas

Commissioning

Xe filling

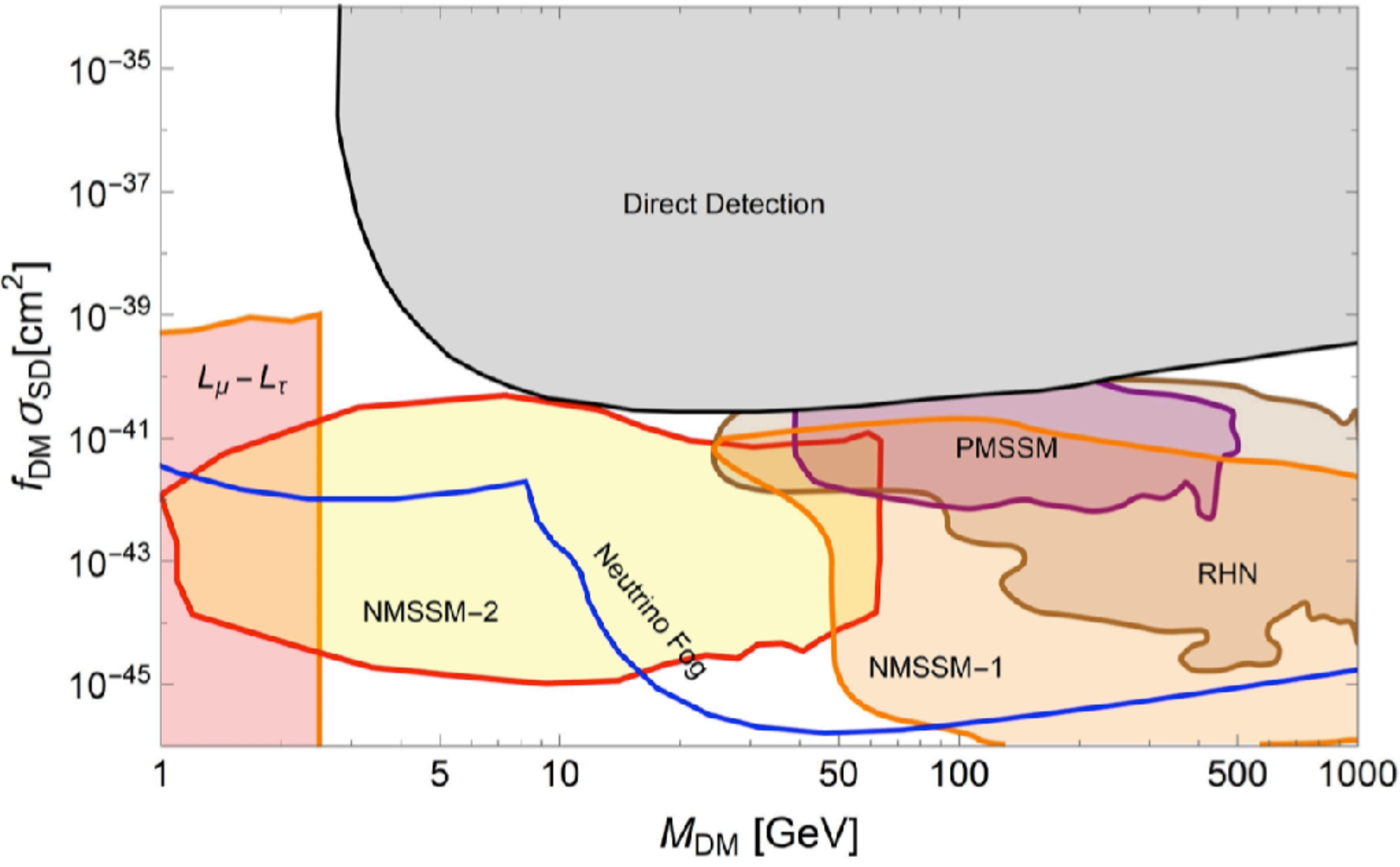


2022

SR1 starts

Science!

What are we looking for? (Spin Dependent)



CF Snowmass 2203.08084