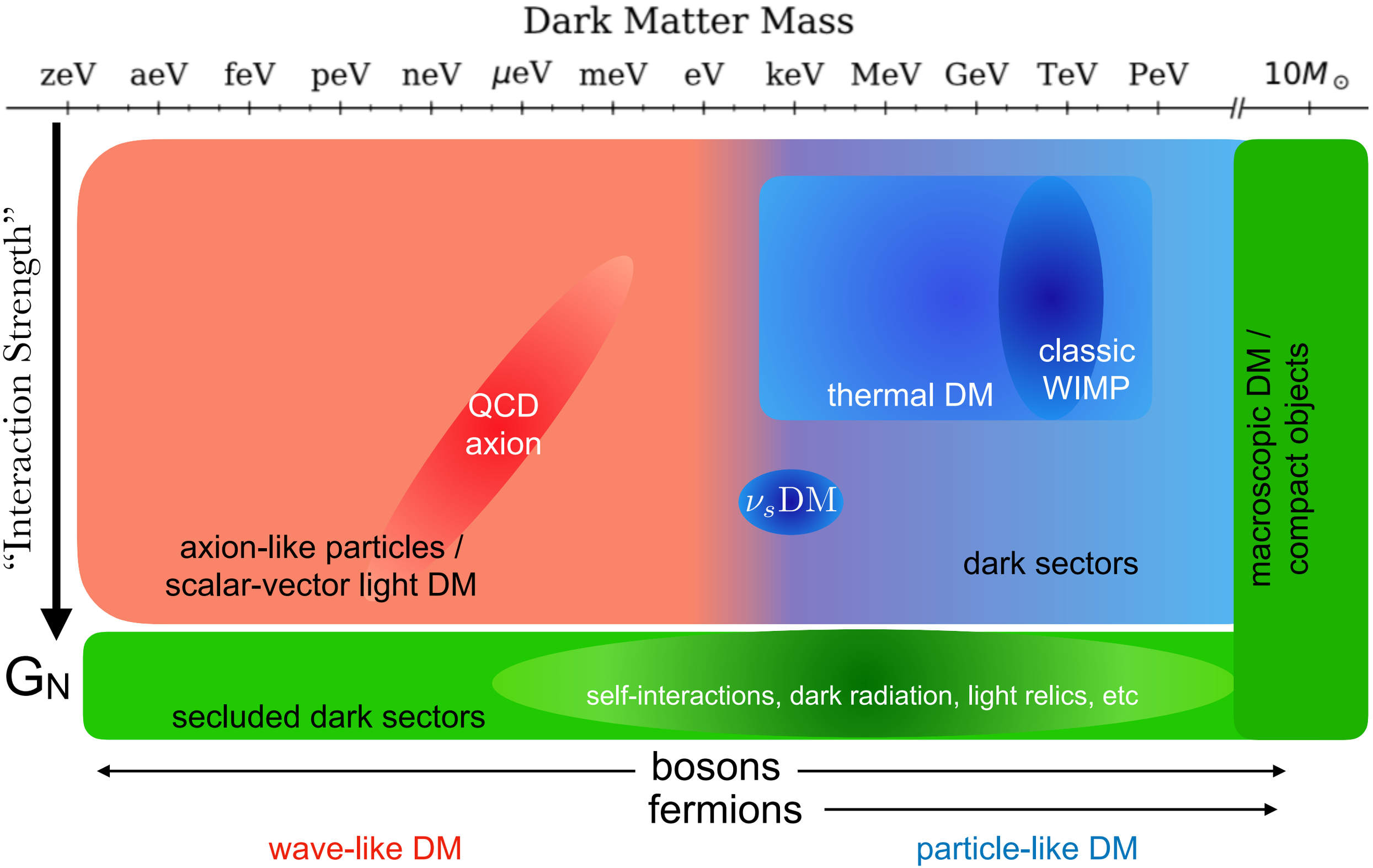
Direct Detection of Dark Matter (at ~TeV scales)

Hugh Lippincott, UCSB

TeVPA
August 10, 2022

The range of DM masses being studied by the community spans many orders of magnitude



From A. Chou, Cosmic Frontier Plenary at Snowmass

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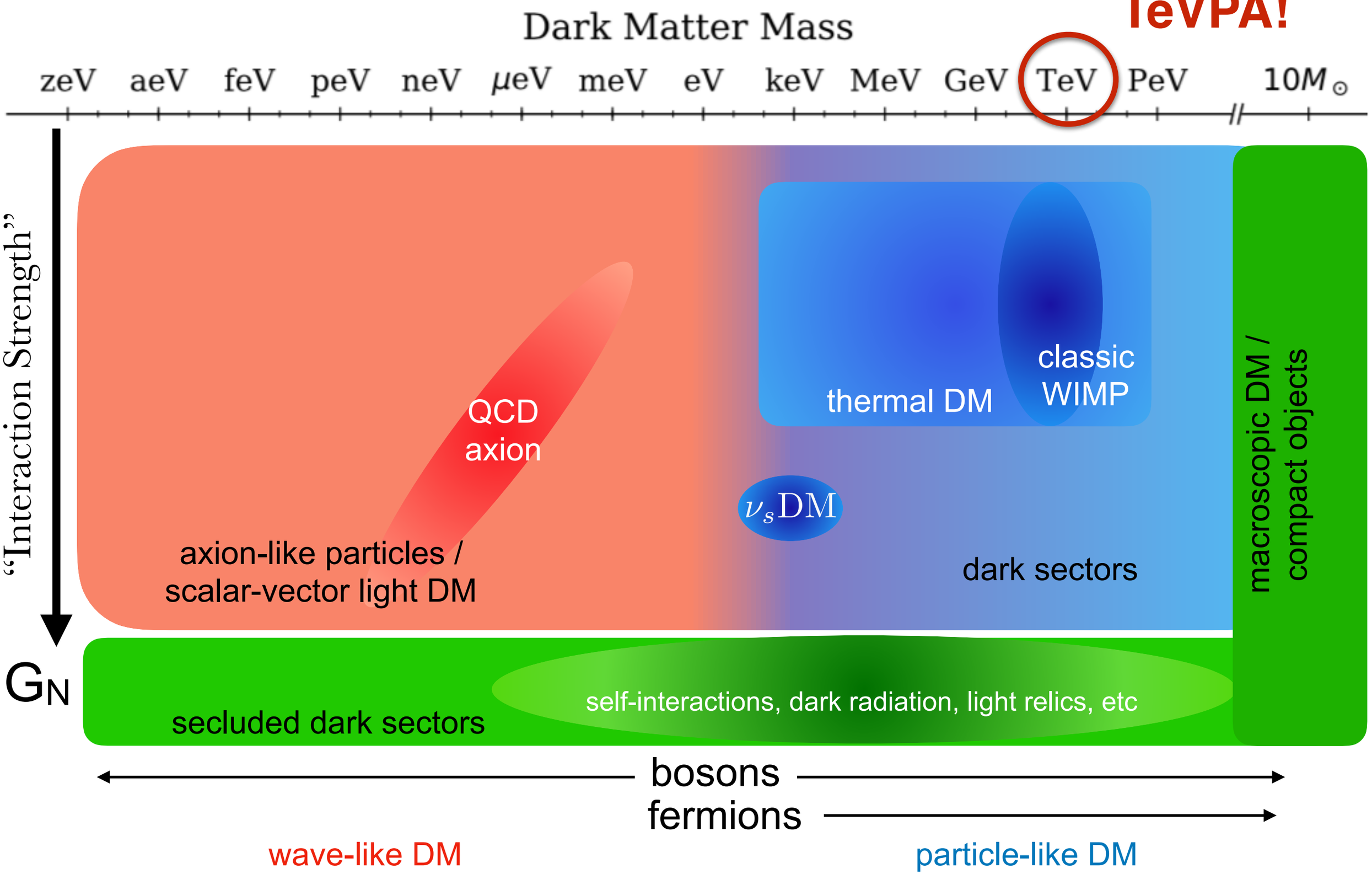

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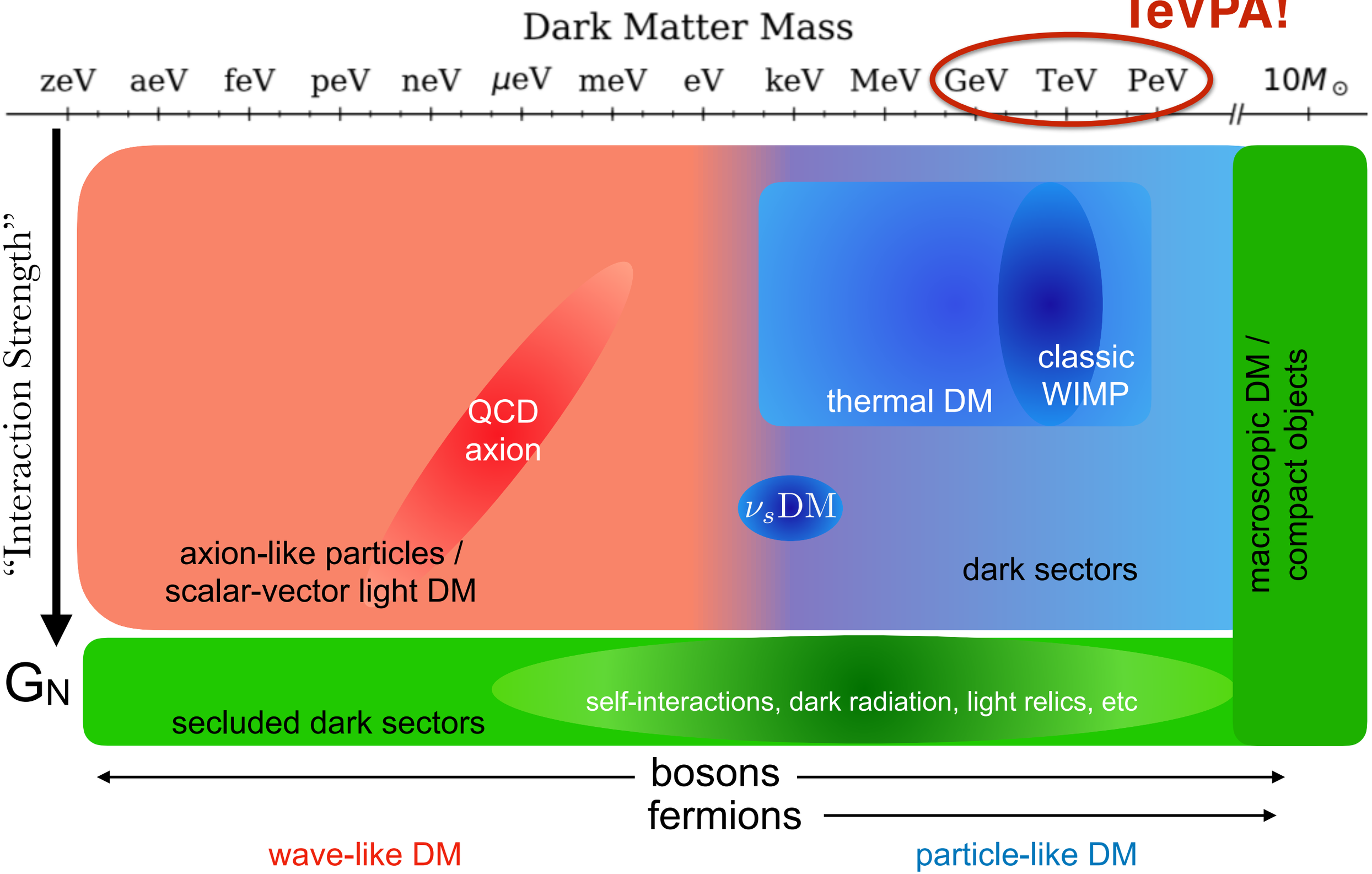
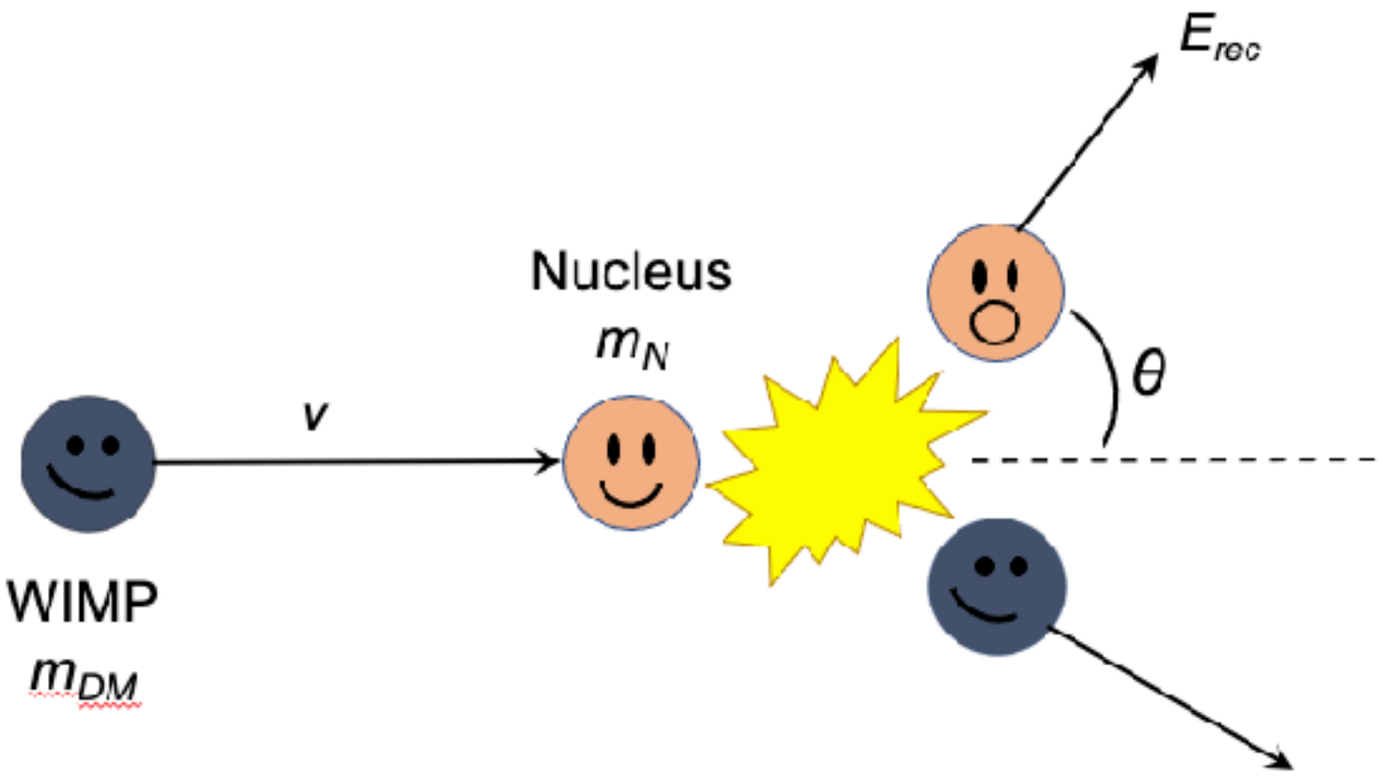


From A. Chou, Cosmic Frontier Plenary at Snowmass

“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

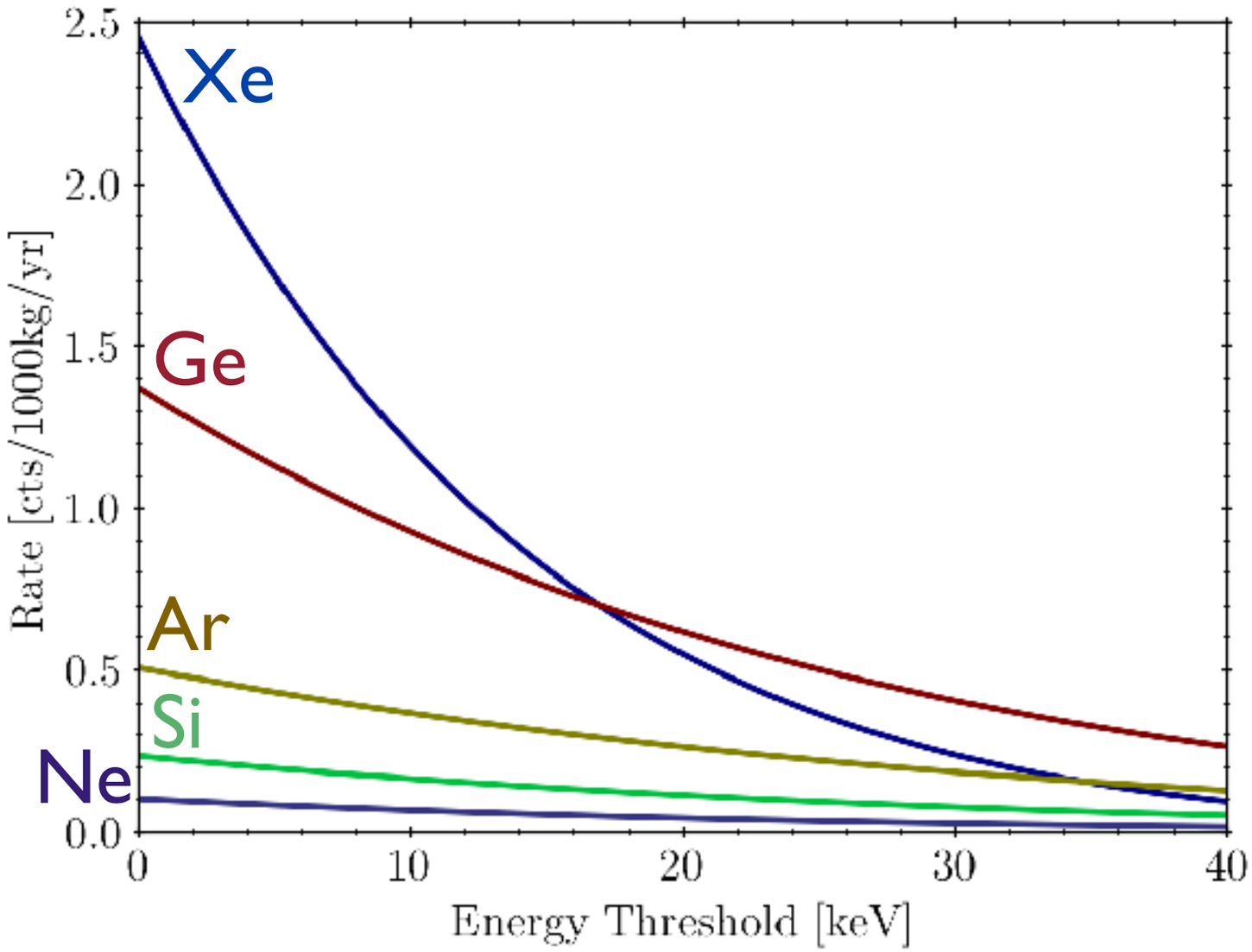
Direct Detection of Dark Matter

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

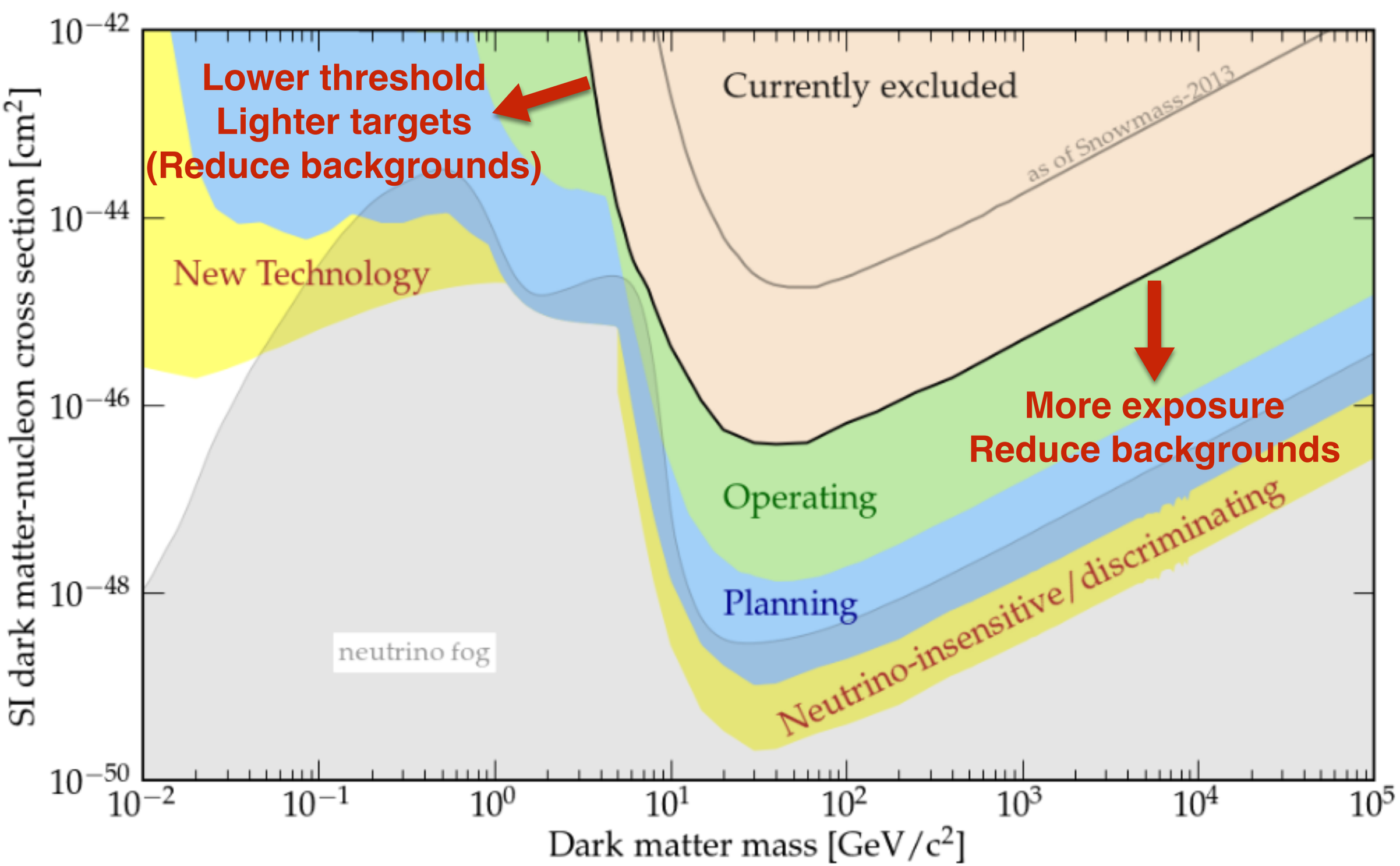
- Luckily, there are lots of particles flying around (in theory)
  - Can look for a few counts in a detector per year

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

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

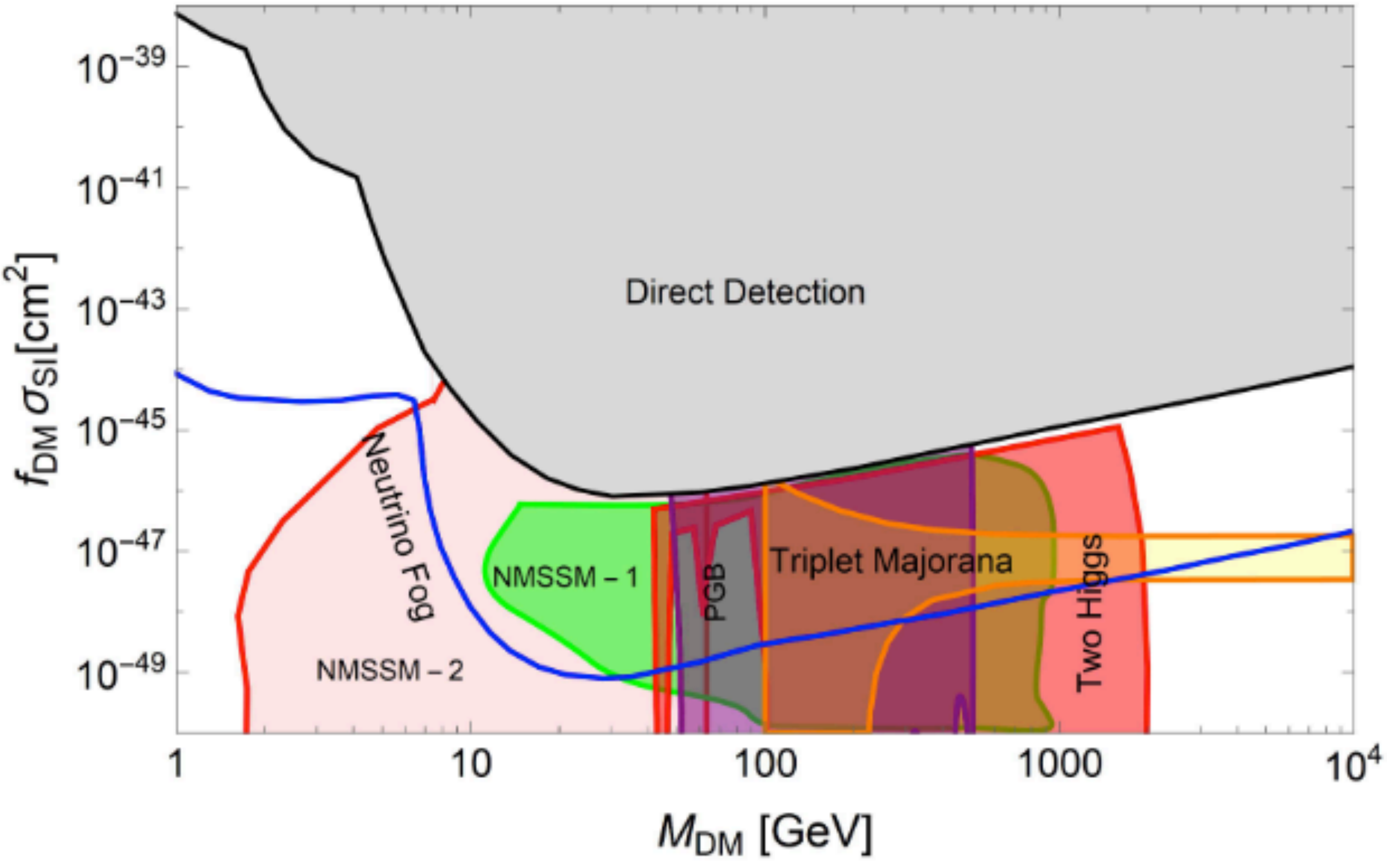


- Goal: Maximize sensitivity to DM while minimizing backgrounds



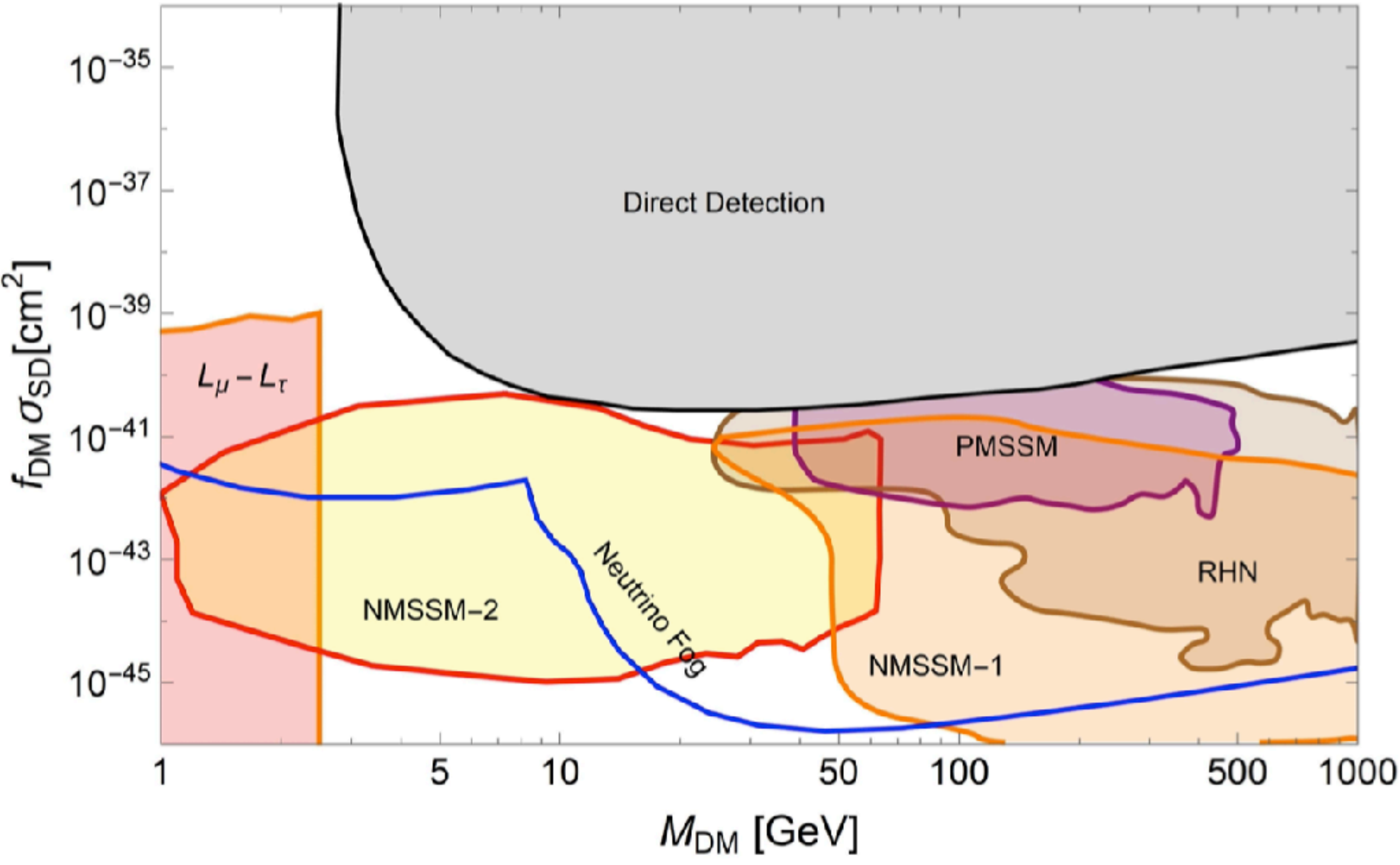
- Limited at low mass by detector threshold
- Limited at high mass by density
- Eventually limited by neutrinos

What are we looking for? (Spin Independent)



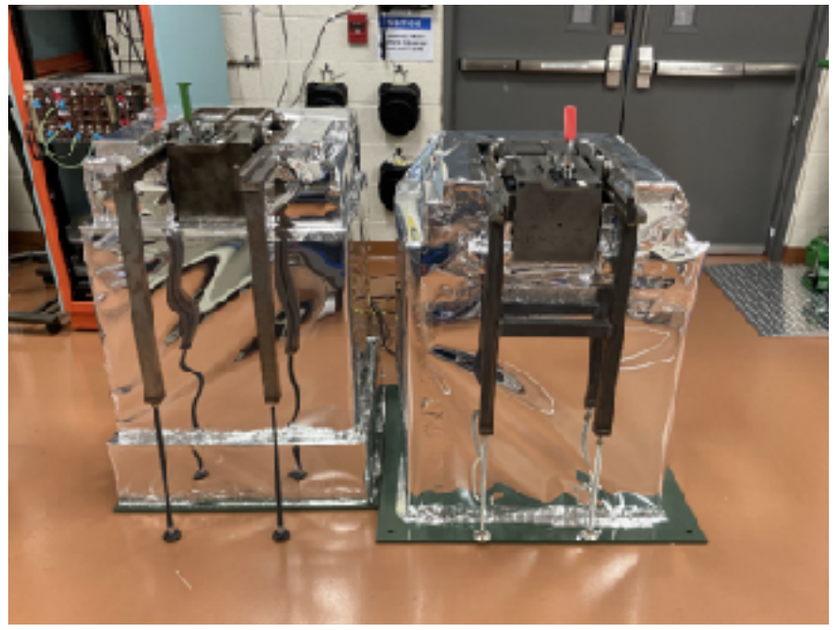
CF Snowmass 2203.08084

What are we looking for? (Spin Dependent)

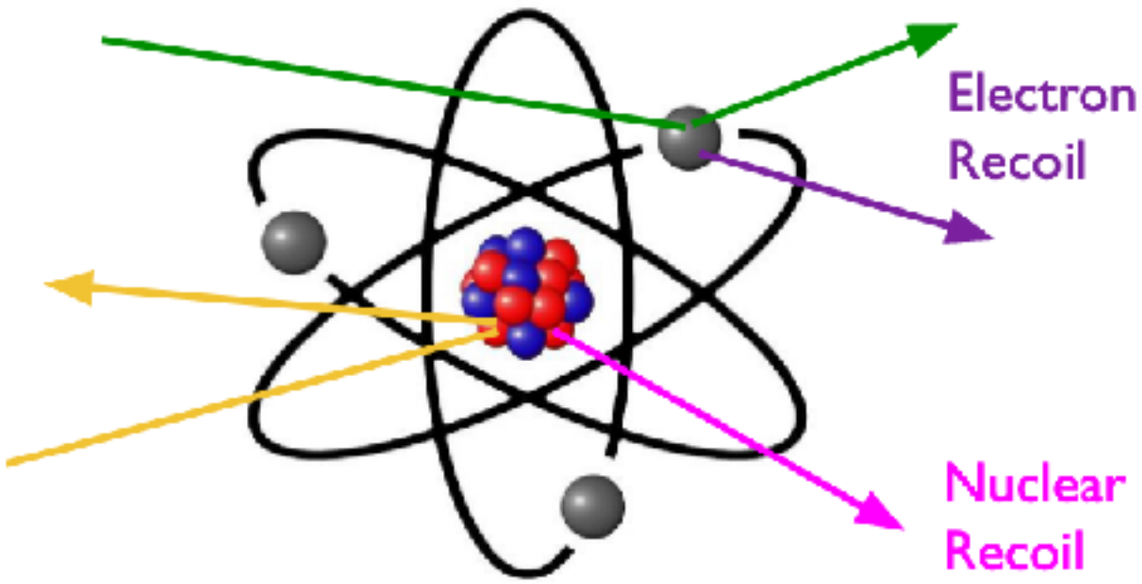


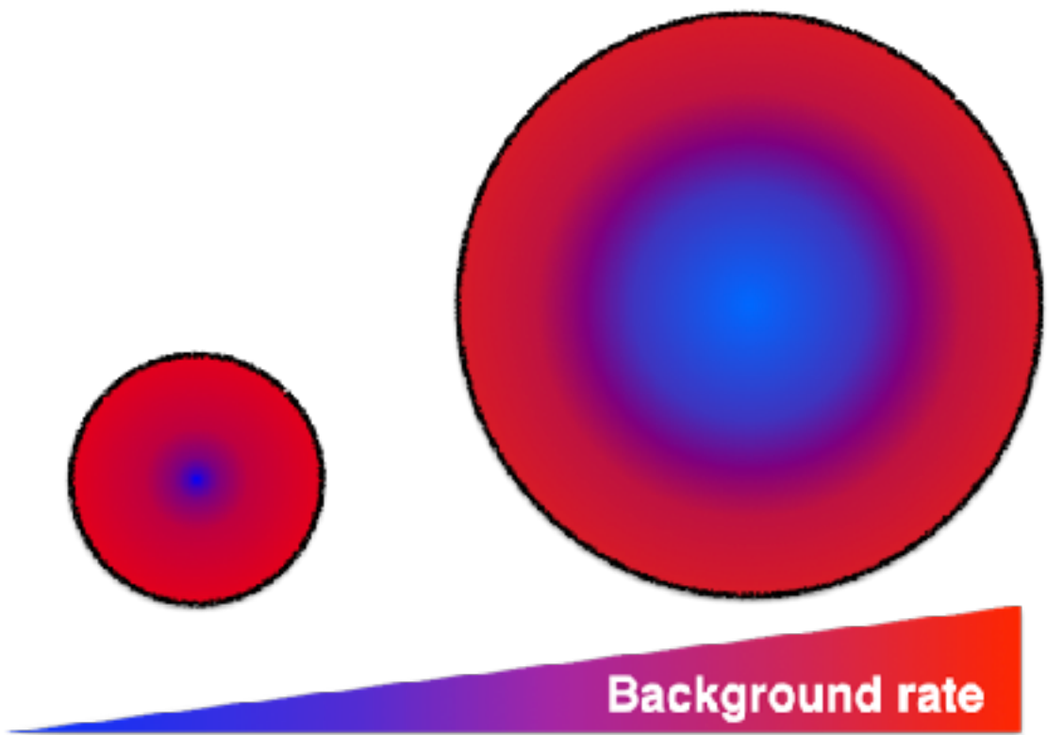
CF Snowmass 2203.08084

Direct Detection at ~1 TeV



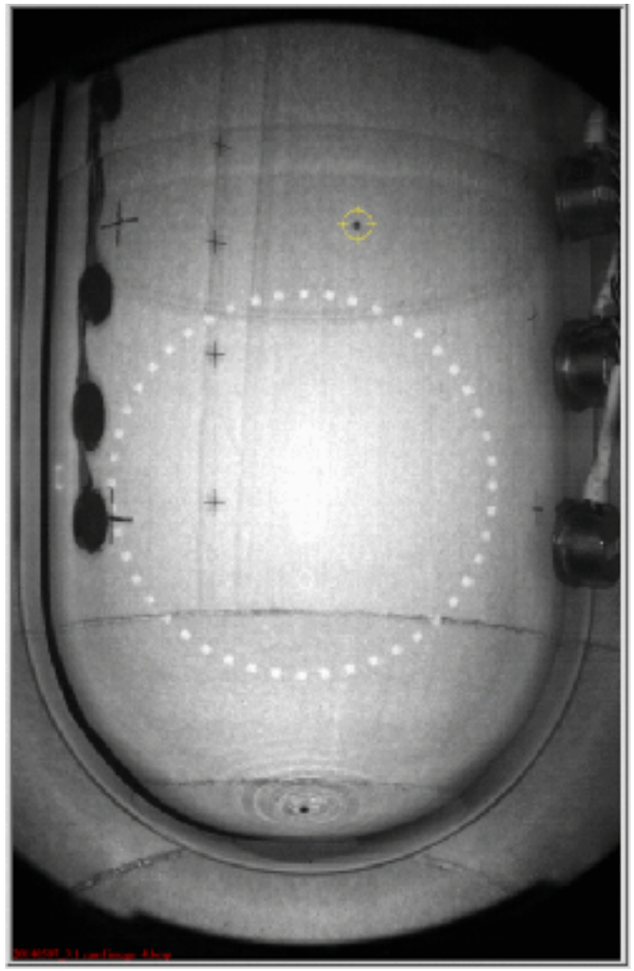
- More sensitivity -> scale up target…
  - Now into multi-tonne scales
- …while reducing backgrounds
  - Radiopurity
  - Self shielding (size helps!)
  - Discrimination (nuclear recoils vs. electron recoils)
- Low thresholds important but not quite as vital
- Explore as many interactions as possible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





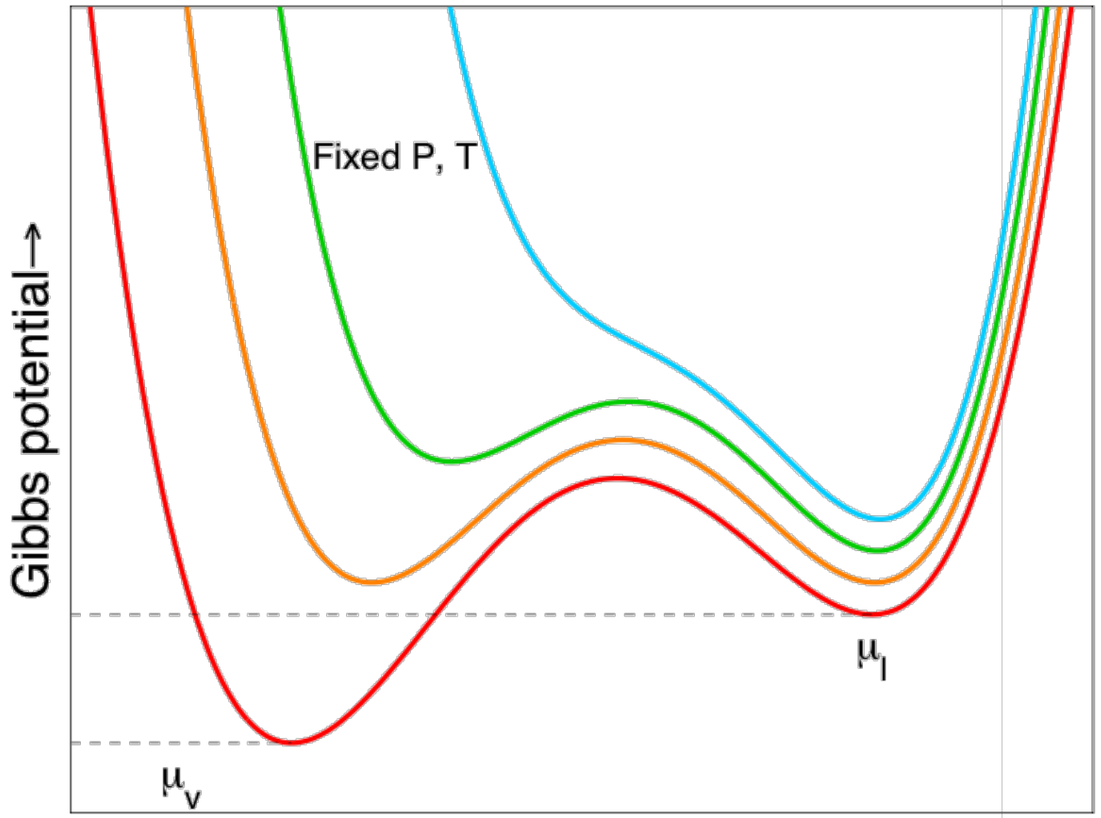
Direct Detection at ~TeV scale

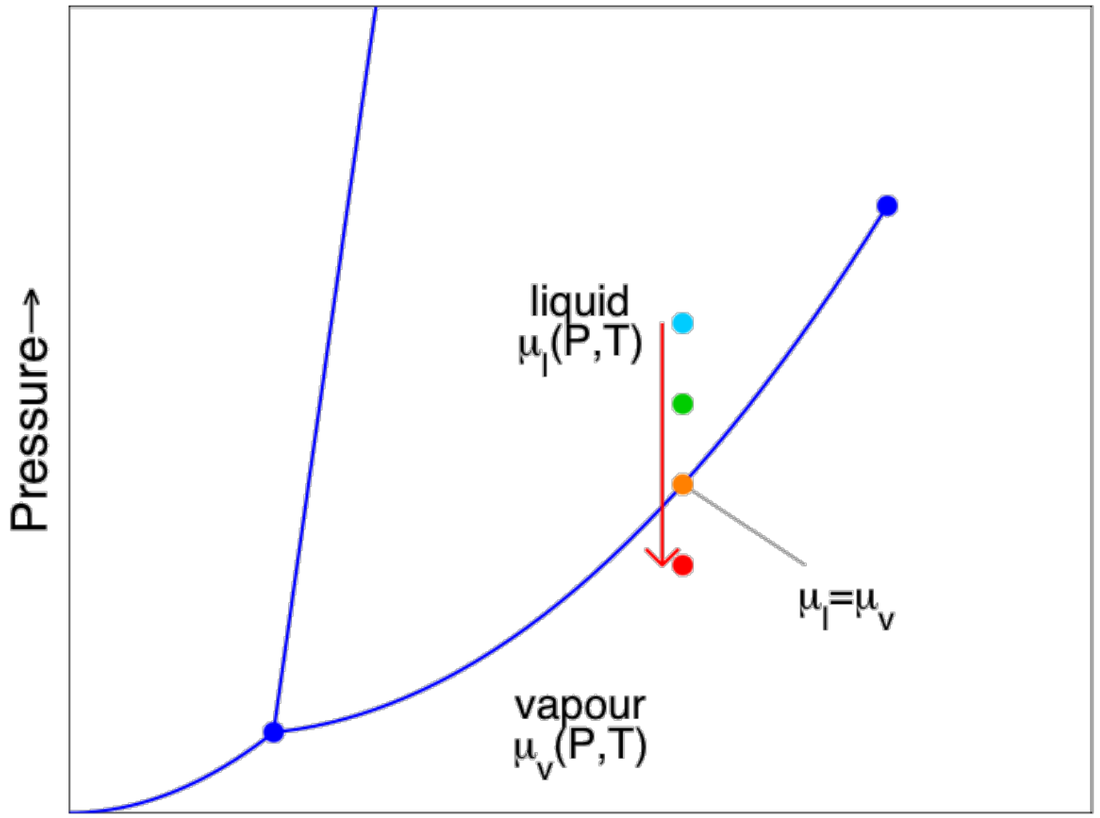
- Liquid Noble Detectors
  - Liquid Xenon (LZ, XENONnT, PandaX-4T)
  - Liquid Argon (DEAP, DarkSide, Argo)
- Bubble Chambers
  - PICO



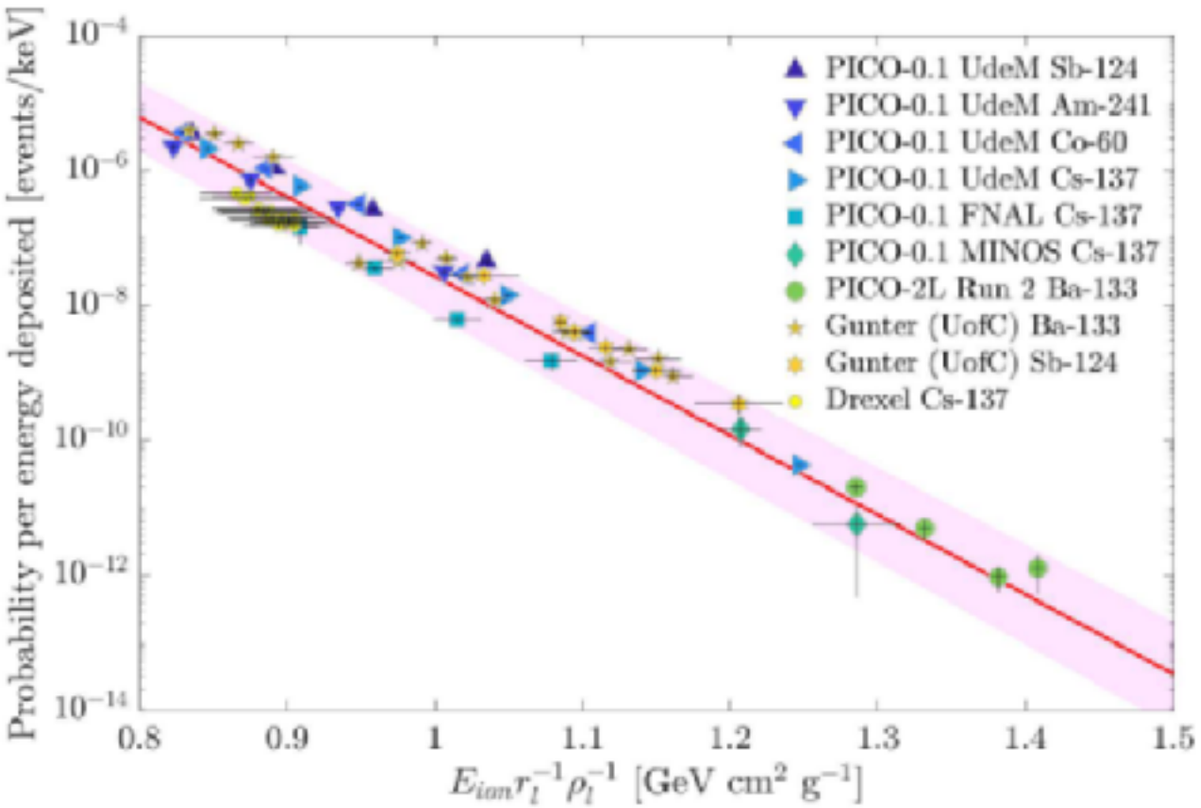
- Things they share
  - Liquids - scalable (get a bigger bucket)
  - Excellent 3D position reconstruction
    - Surfaces are the enemy
  - ER/NR discrimination

PICO Bubble Chambers

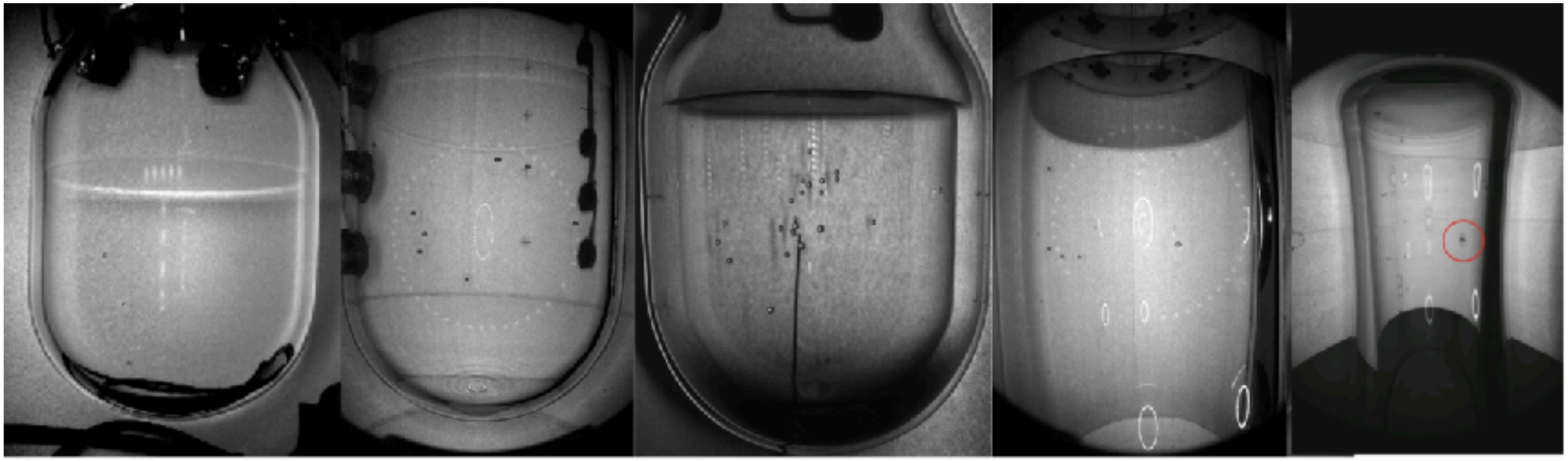




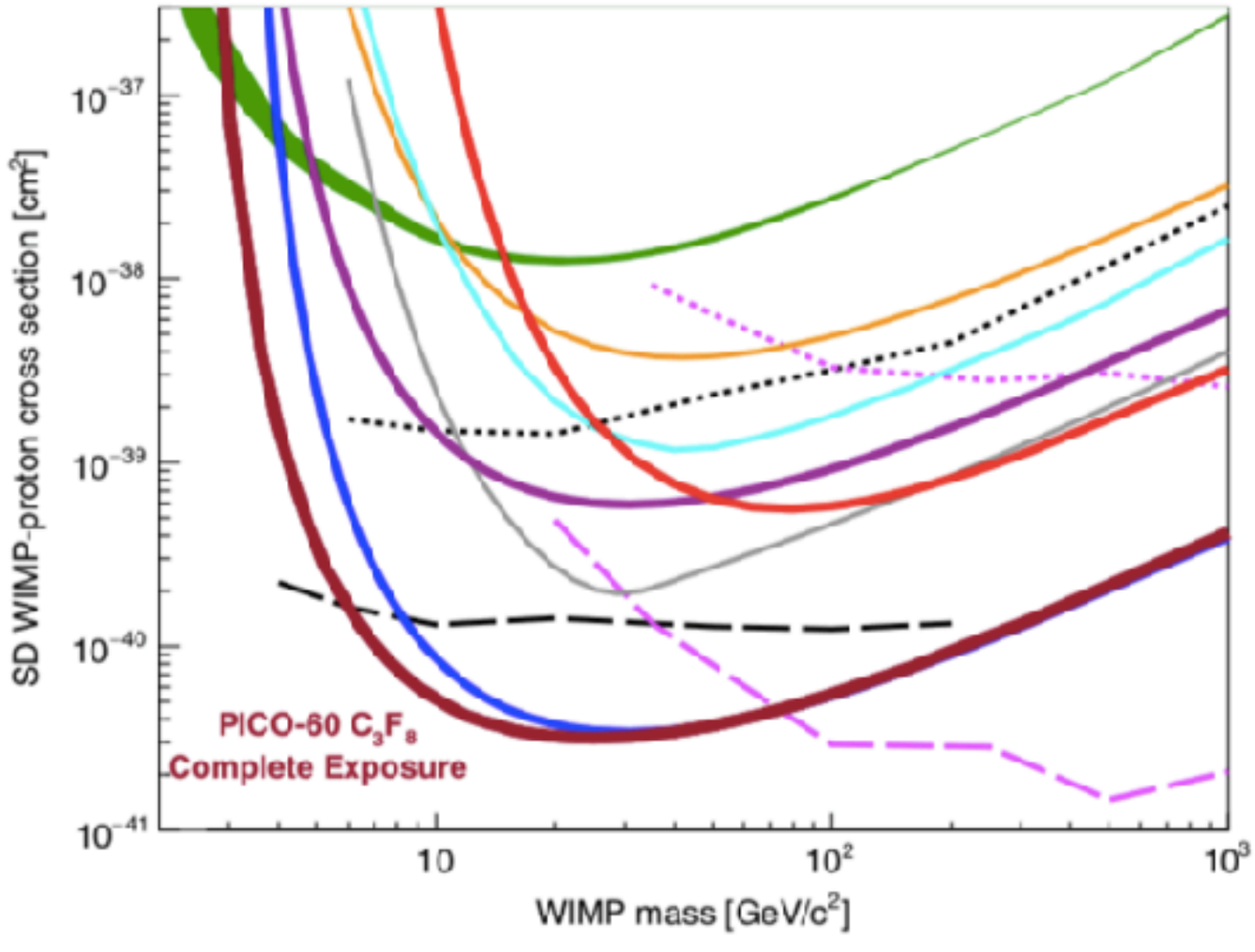
- Thermodynamics set sensitivity
- Need heat (energy) and density to make bubbles
  - ER do not cross density threshold
  - Acoustics provide further rejection
- Fluorine target with ~3 keV threshold



PICO Bubble Chambers

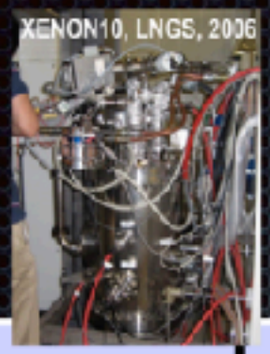


- Family of chambers with increasing size
  - PICO-60 - world's most sensitive SD proton result
  - PICO-40L - commissioning now
  - PICO-500 in design
- Several new results on various EFT interactions
- See G. Giroux today at 4:10



Genealogy of The Noble Target Field

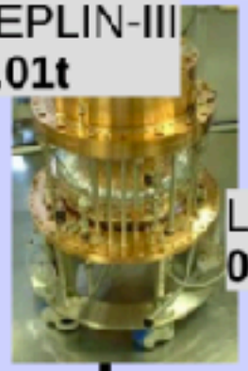
(ZEPLIN I + II)



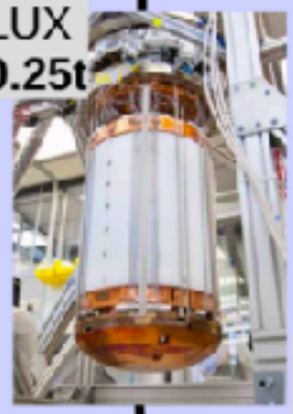
LXe

LAr

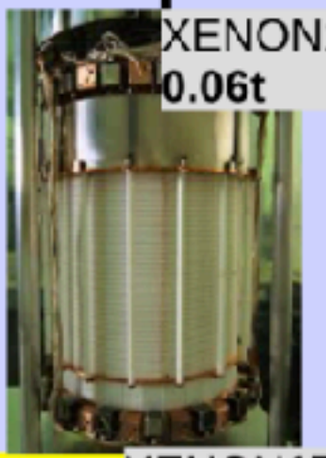
ZEPLIN-III
0.01t



LUX
0.25t



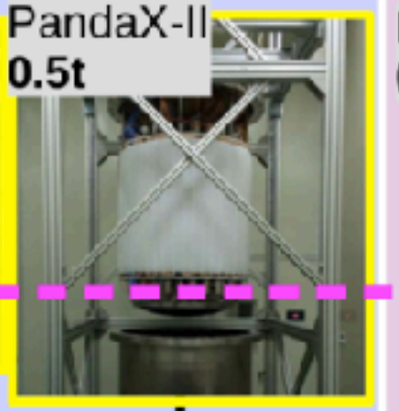
XENON100
0.06t



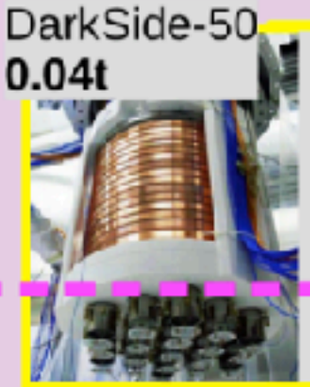
XENON1T
2.0t

XMASS
0.8t

PandaX-II
0.5t



DarkSide-50
0.04t

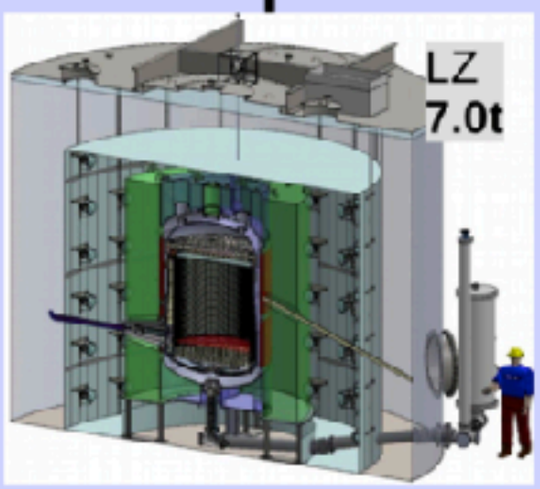


DEAP-3600
3.3t

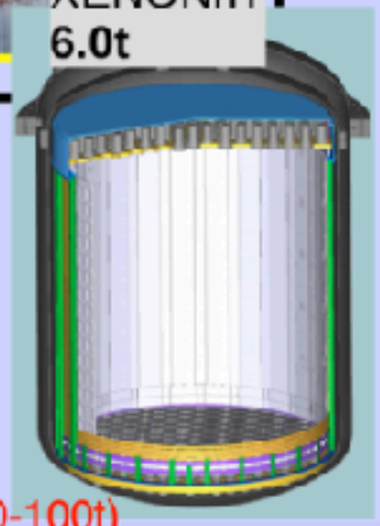
ArDM
0.8t

Ignore me

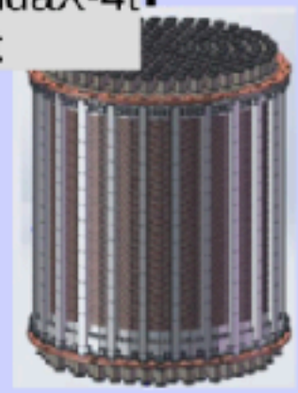
LZ
7.0t



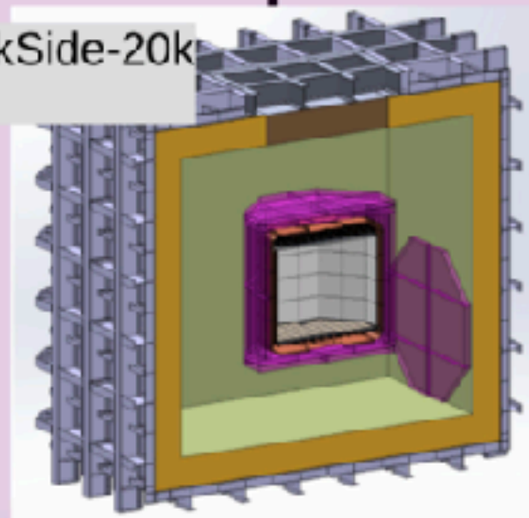
XENONnT
6.0t



PandaX-4t
4.0t



DarkSide-20k
30t



(followed by DARWIN 50-100t)

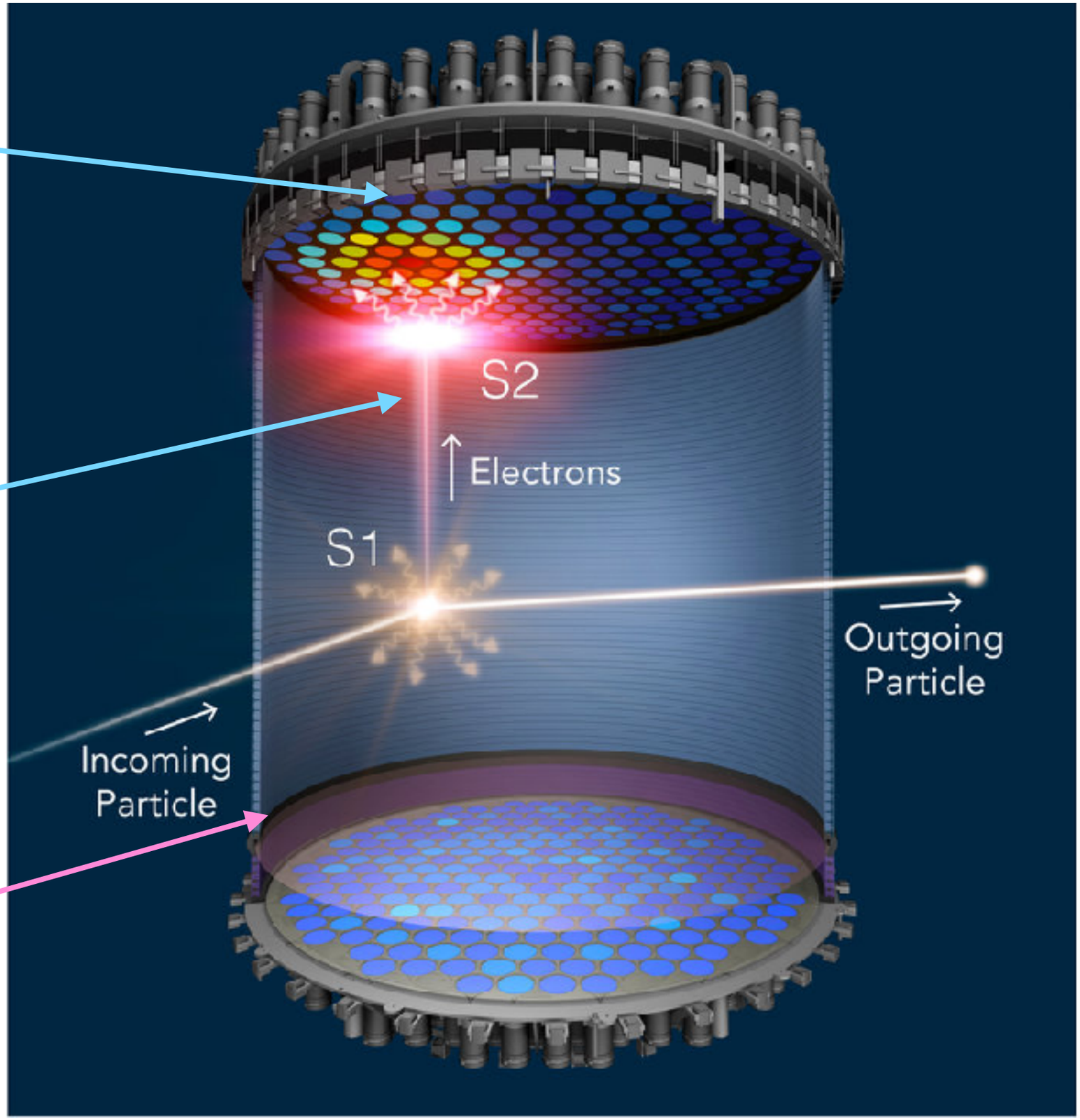
thanks to M. Schumann (Freiburg)

Liquid Noble TPCs

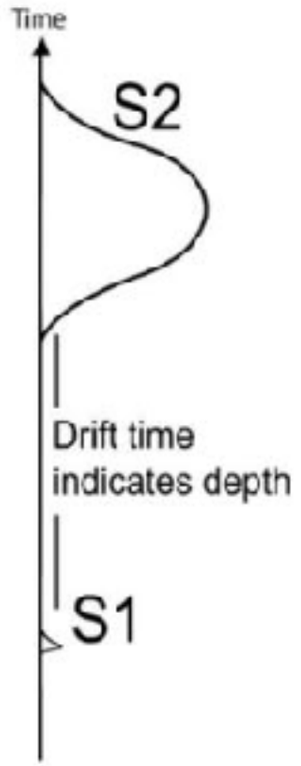
S2 light pattern gives x-y position
(~few mm resolution)

Drift time gives z position
(~0.5 mm resolution)

Cathode

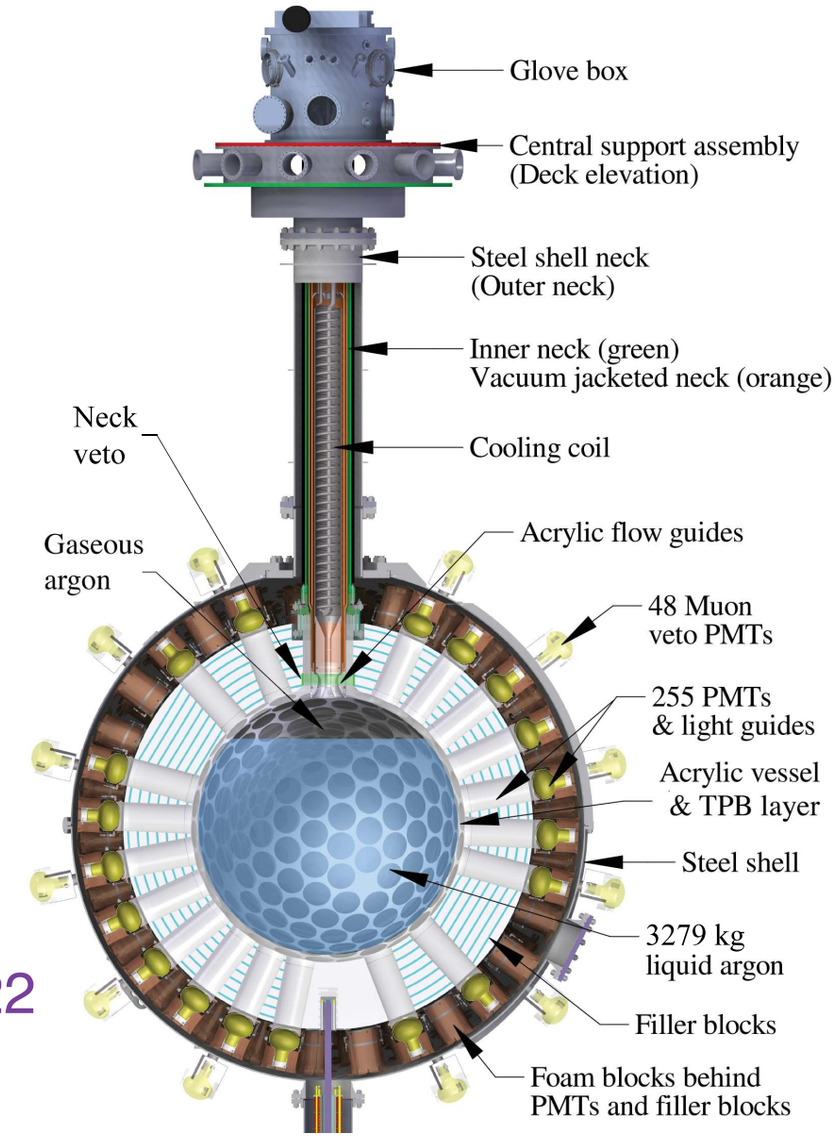


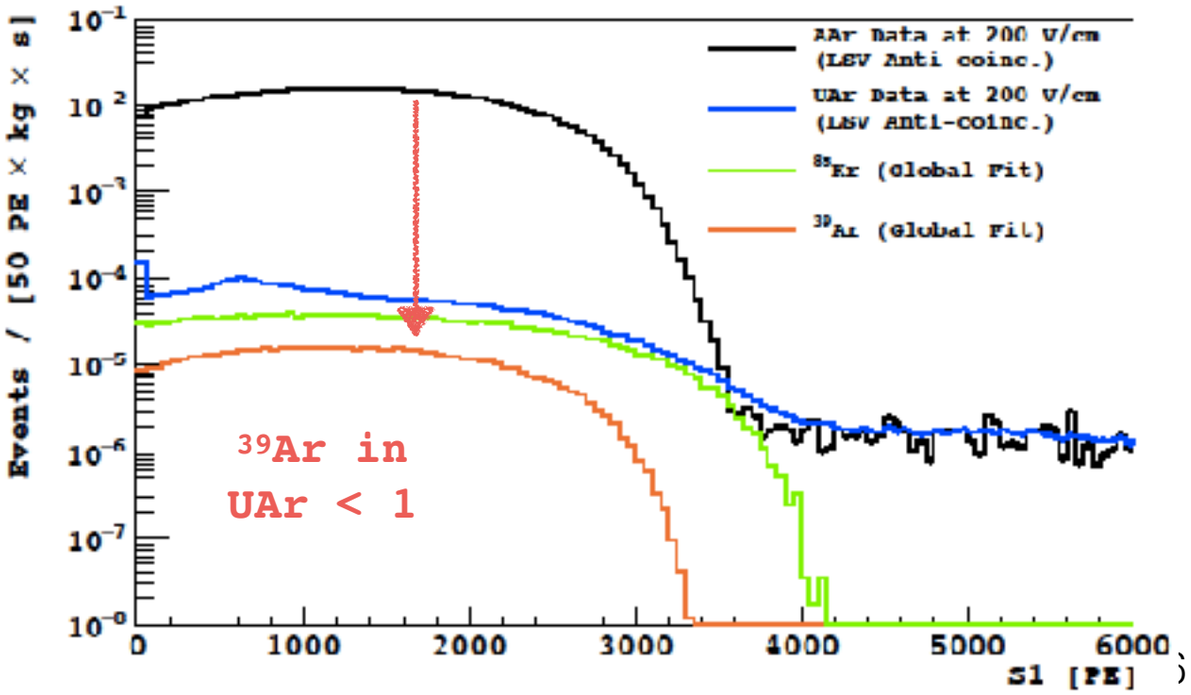
S1-S2 relative size gives event-type discrimination

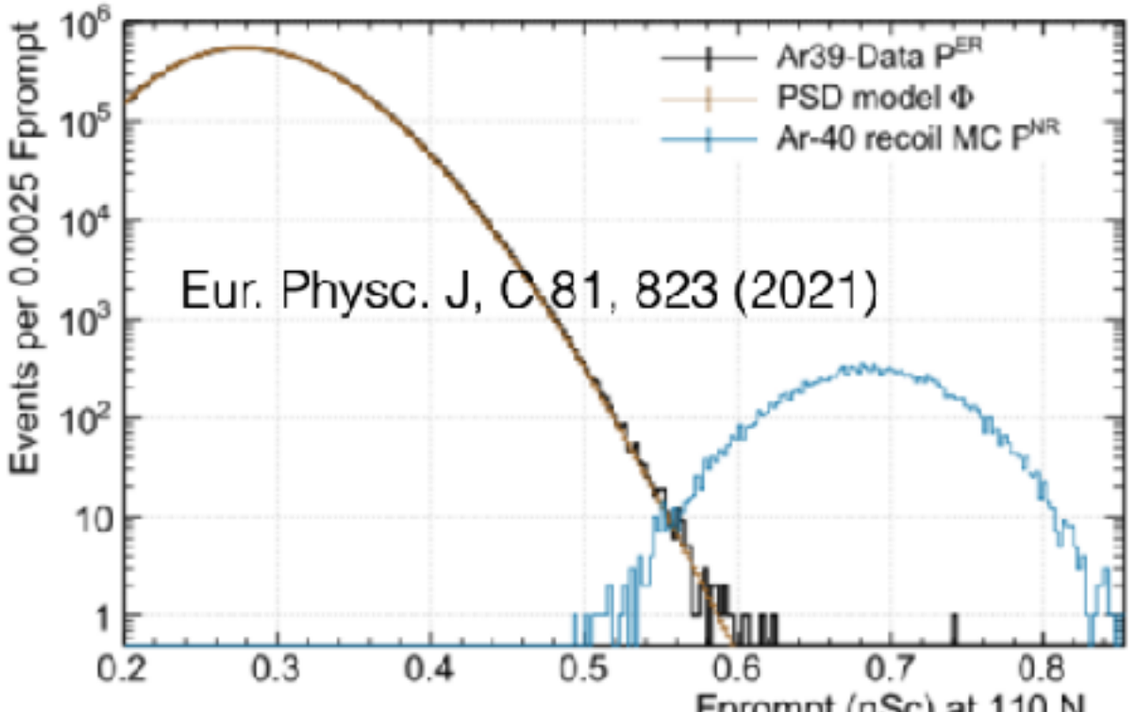


LAr Detectors

- LAr TPC (DarkSide) or single phase (DEAP)
  - Exquisite pulse shape discrimination (PSD) ER from NR using just light
- DarkSide-50
  - 150 kg underground argon (UAr) to mitigate ^{39}Ar
  - Recent low mass results at IDM from M. Kimura
- DEAP-3600 - See S. Viel, today at 2:20
  - World leading results on very high mass dark matter
  - Demonstration of PSD
  - Background from neck events, upgrade to complete in 2022
  - Data to resume in 2023, recover design senstivity by 2025

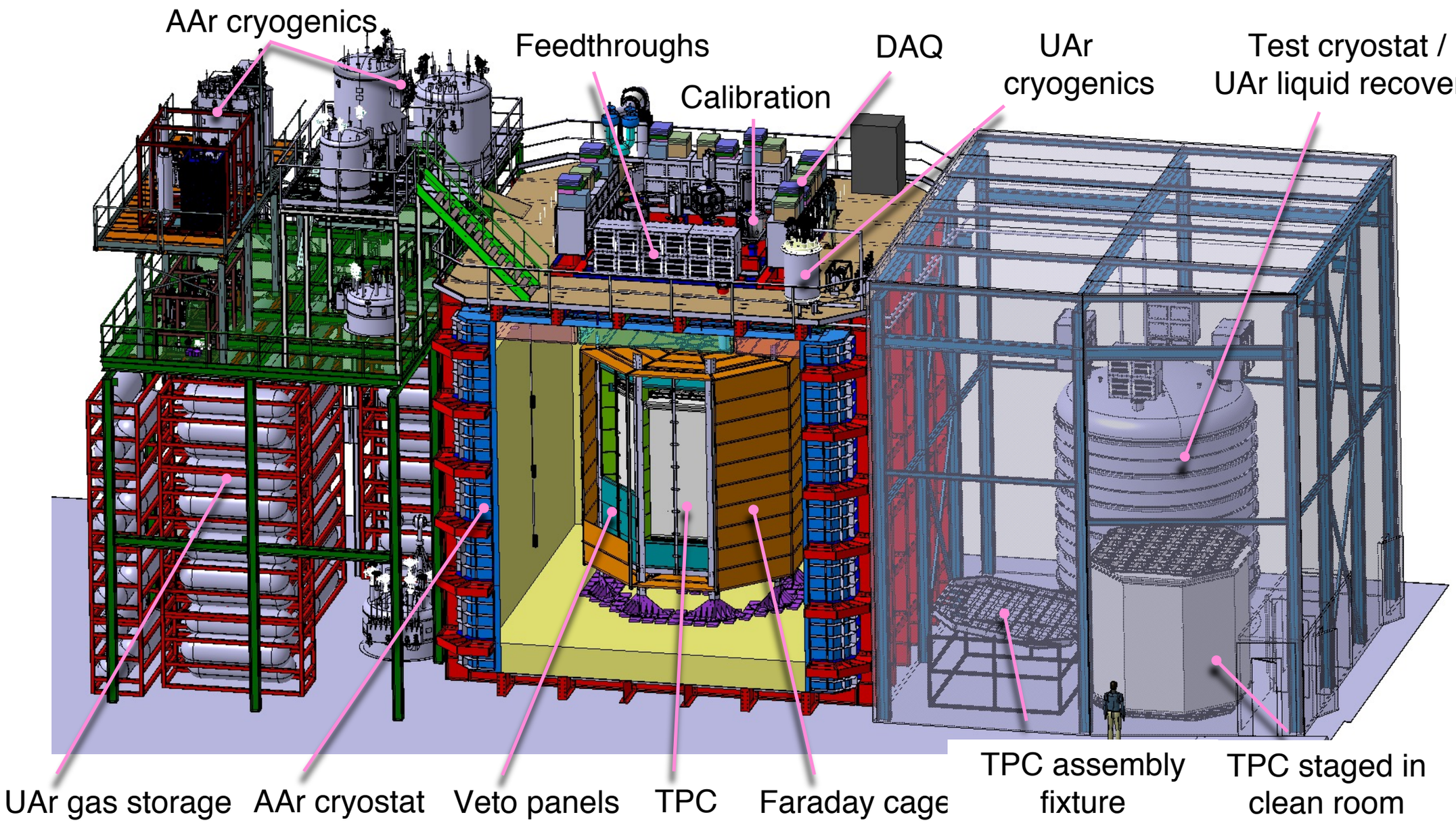






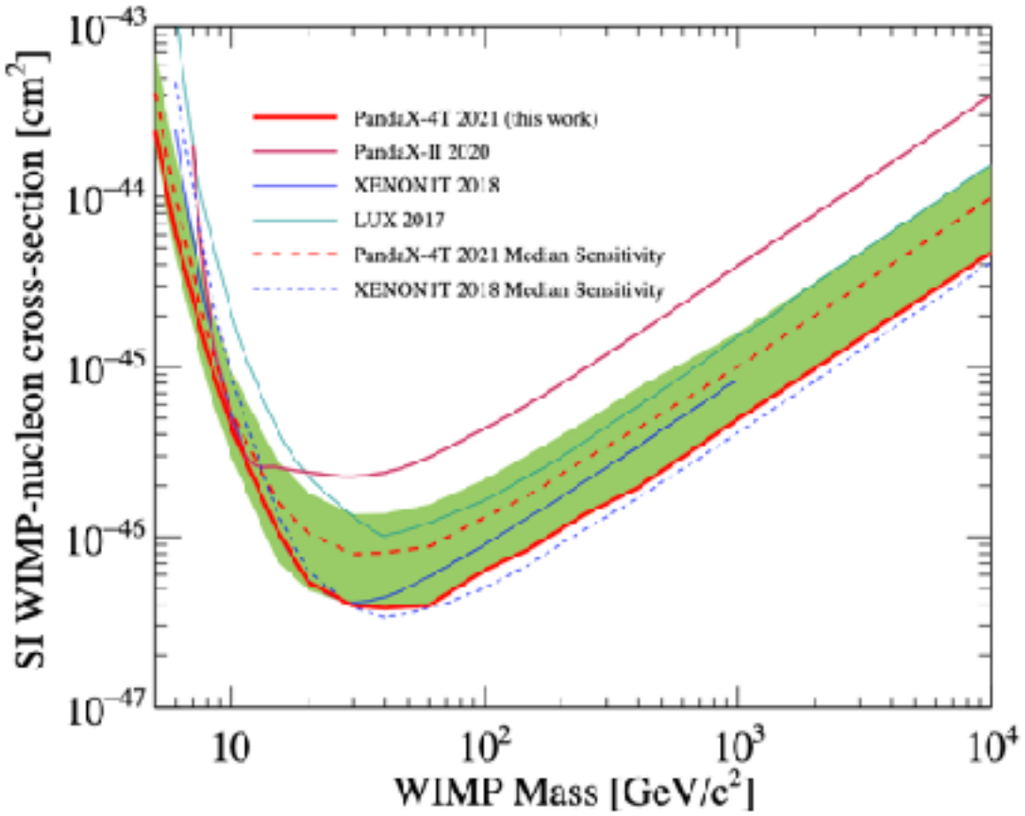
LAr Detectors

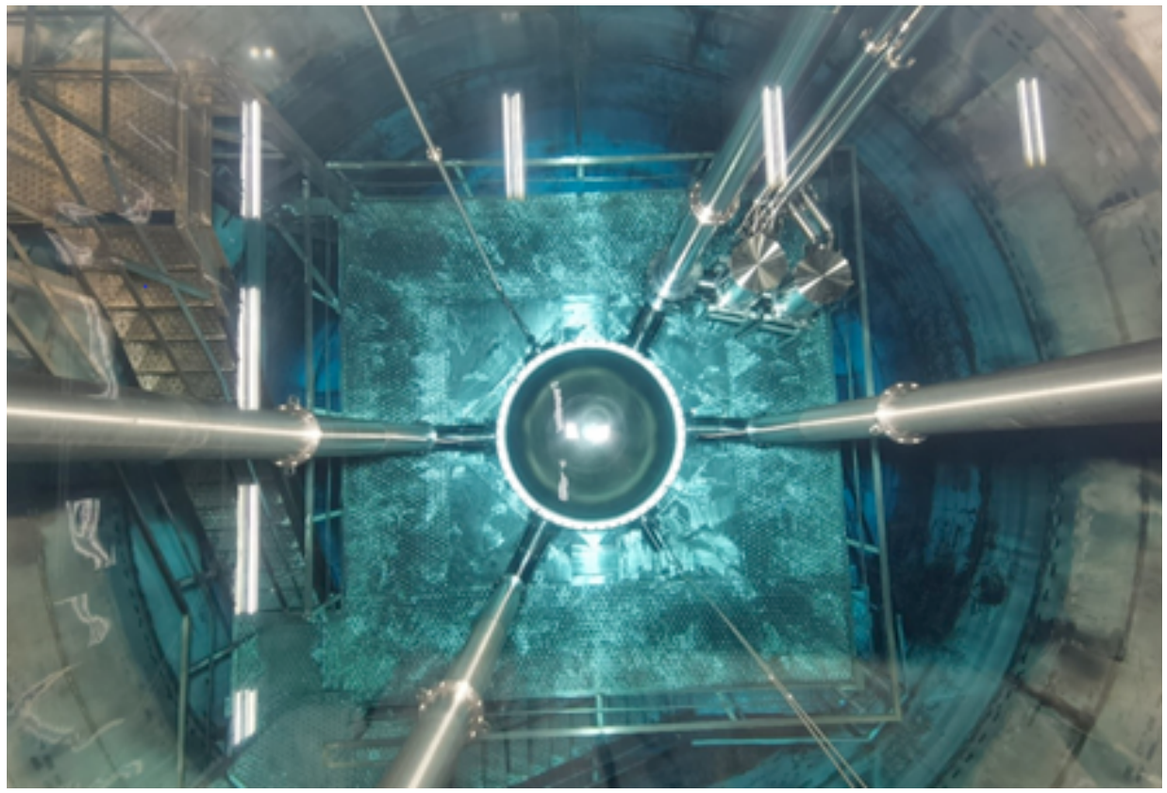
- Planned DarkSide-20k detector at LNGS
  - 20 tonnes underground argon fiducial, ~700t total Ar
- Significant R&D into cryogenics, SiPMs, neutron veto systems
- Installation of cryostat now begun in Hall C
- See talks from M. B. Walczak and Thomas Thorpe, today at 2:40



PandaX-4T

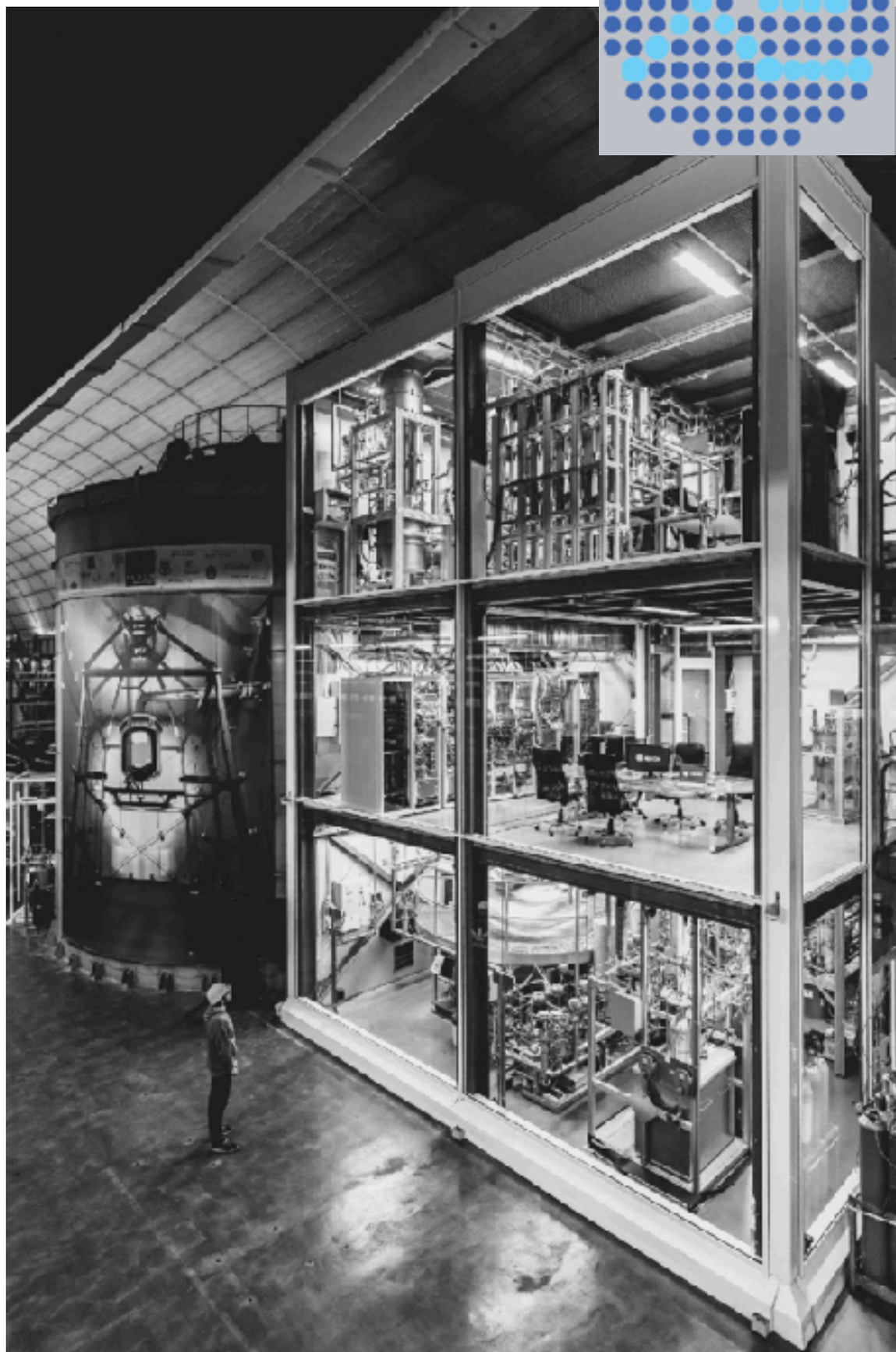
- LXe-TPC, 3.7 tonnes active
- Located in China's CJPL
- Commissioning run from November 2020 to April 2021
- World best limits last summer
- ~50 ER cts/keV/tonne/yr
  - Residual contamination from tritium being addressed by purification campaign



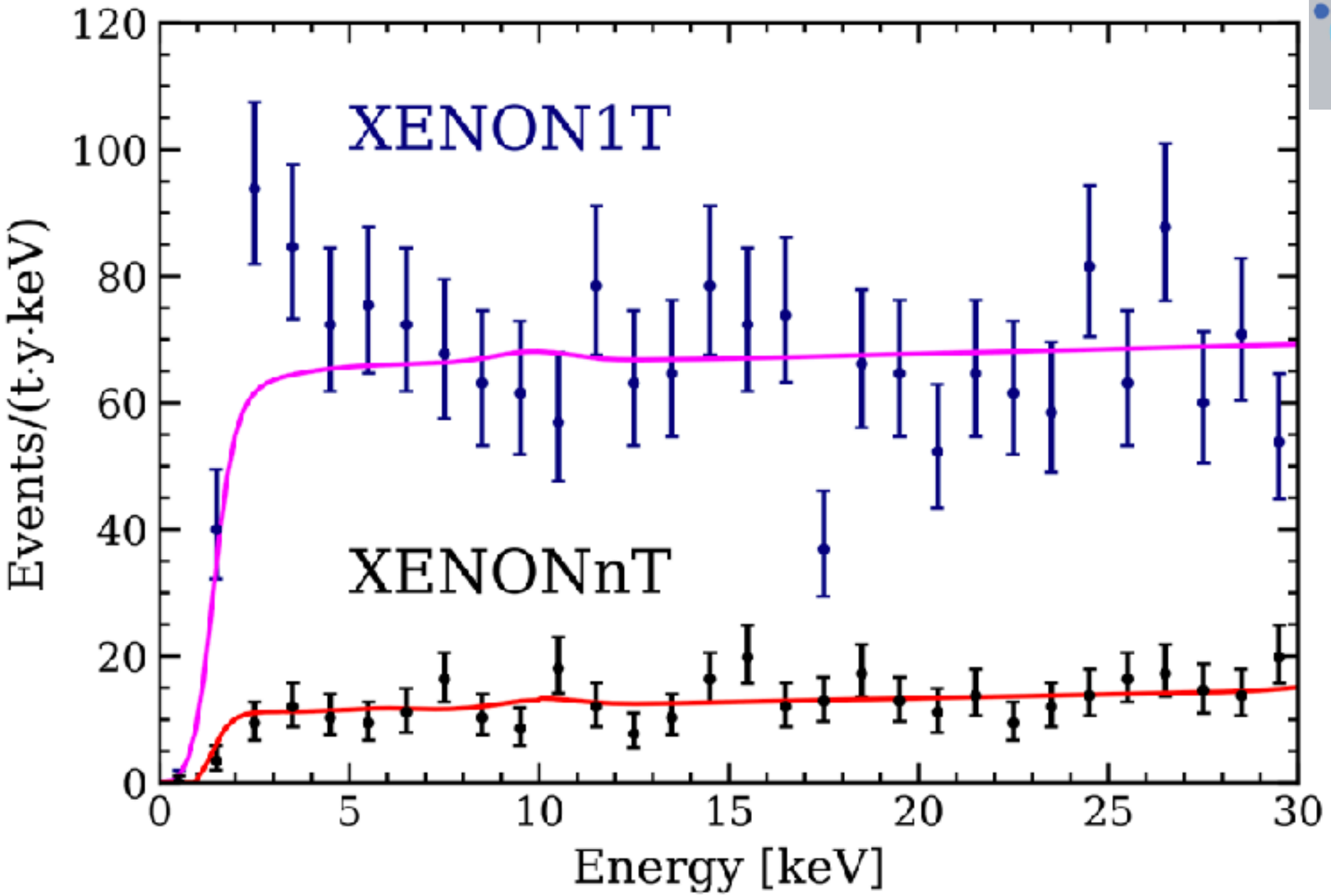


XENONnT

- LXe TPC, 5.9 active tonnes
- Located at Gran Sasso in Italy
- Liquid purification
  - Radon distillation working well
- Cathode voltage well below design
- Gd-loaded water neutron veto
- Science data from July-November 2021
- First results at IDM two weeks ago
  - ~16 ER cts/keV/tonne/year



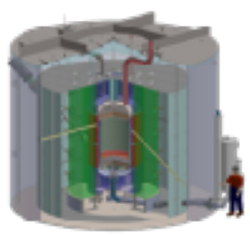
XENON1T Excess

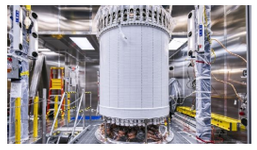


- Exquisite background control with expectation of further reductions
- New limits on ALPs, dark photons, axions, neutrino magnetic moment
  - Knut Mora at IDM - 2207.11330

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





2017 2018 2019 2020 2021 2022

TDR and CD-3

PMT arrays arrive

TPC Complete

Cryostat sealed

Electronics

OD filling

Commissioning

SR1 starts

Cryostat arrives

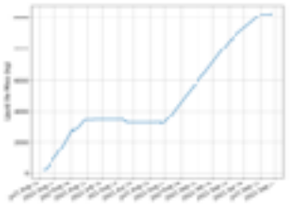
Grid weaving

TPC Underground

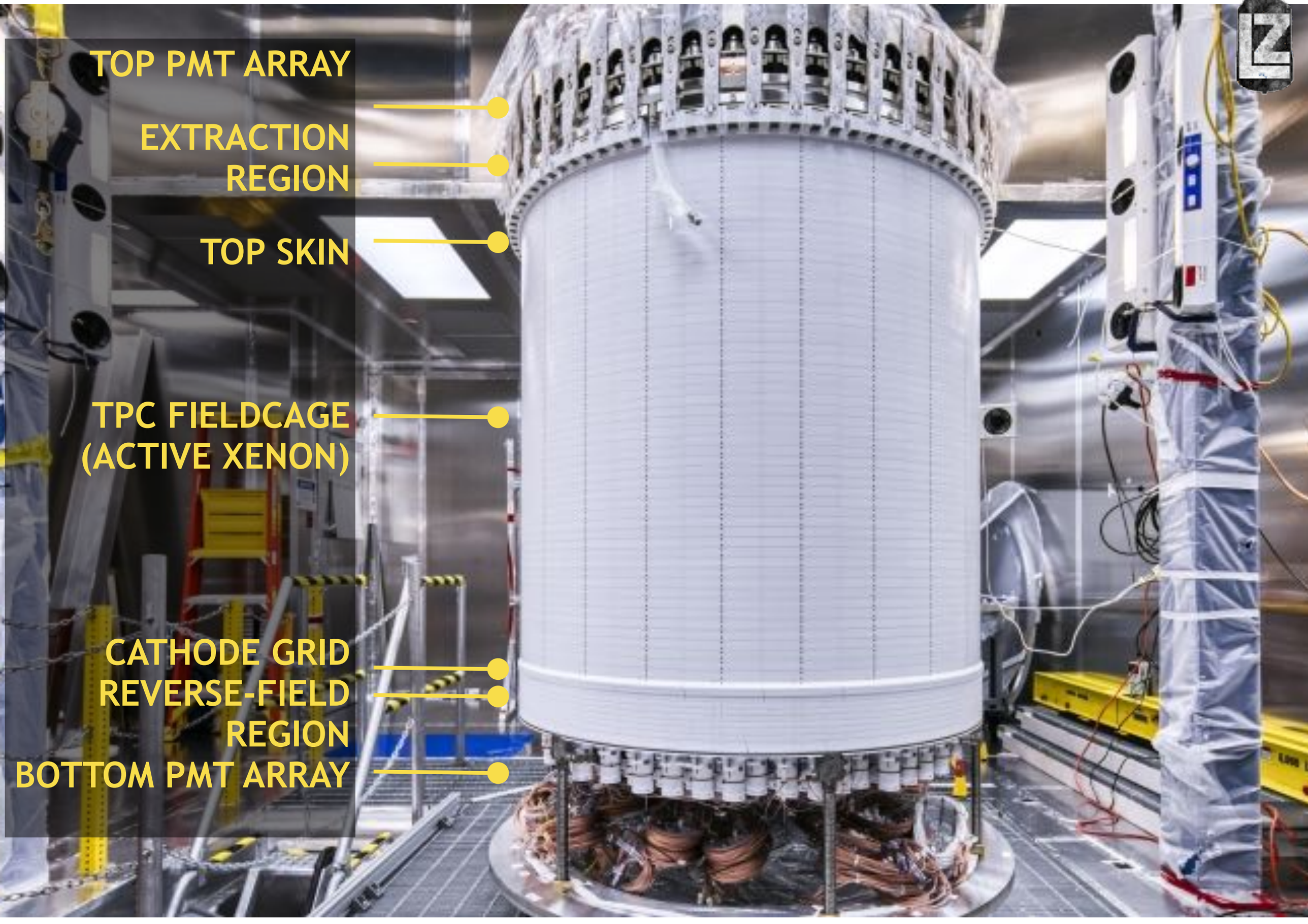
OD Construction

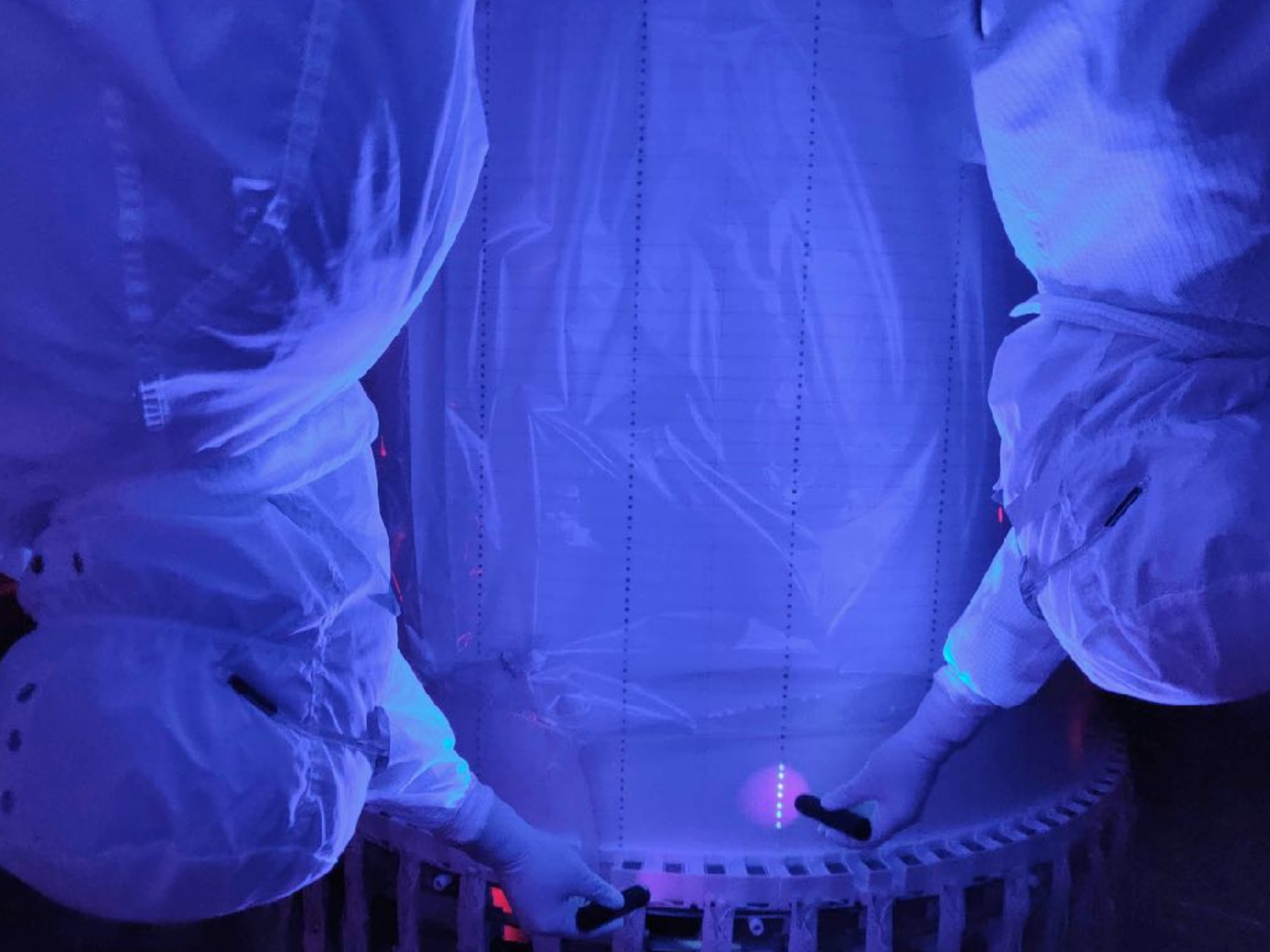
Cold Gas

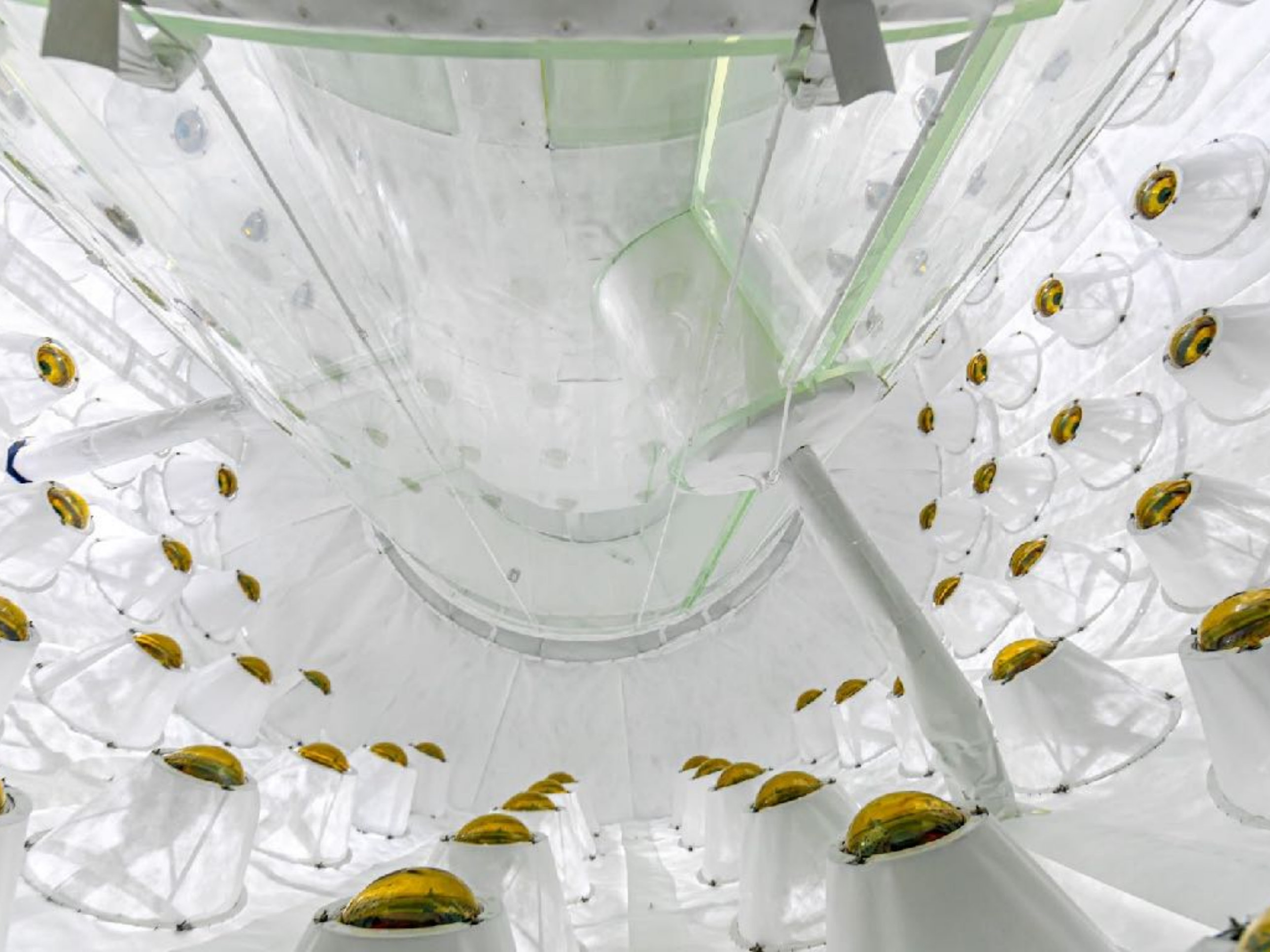
Xe filling



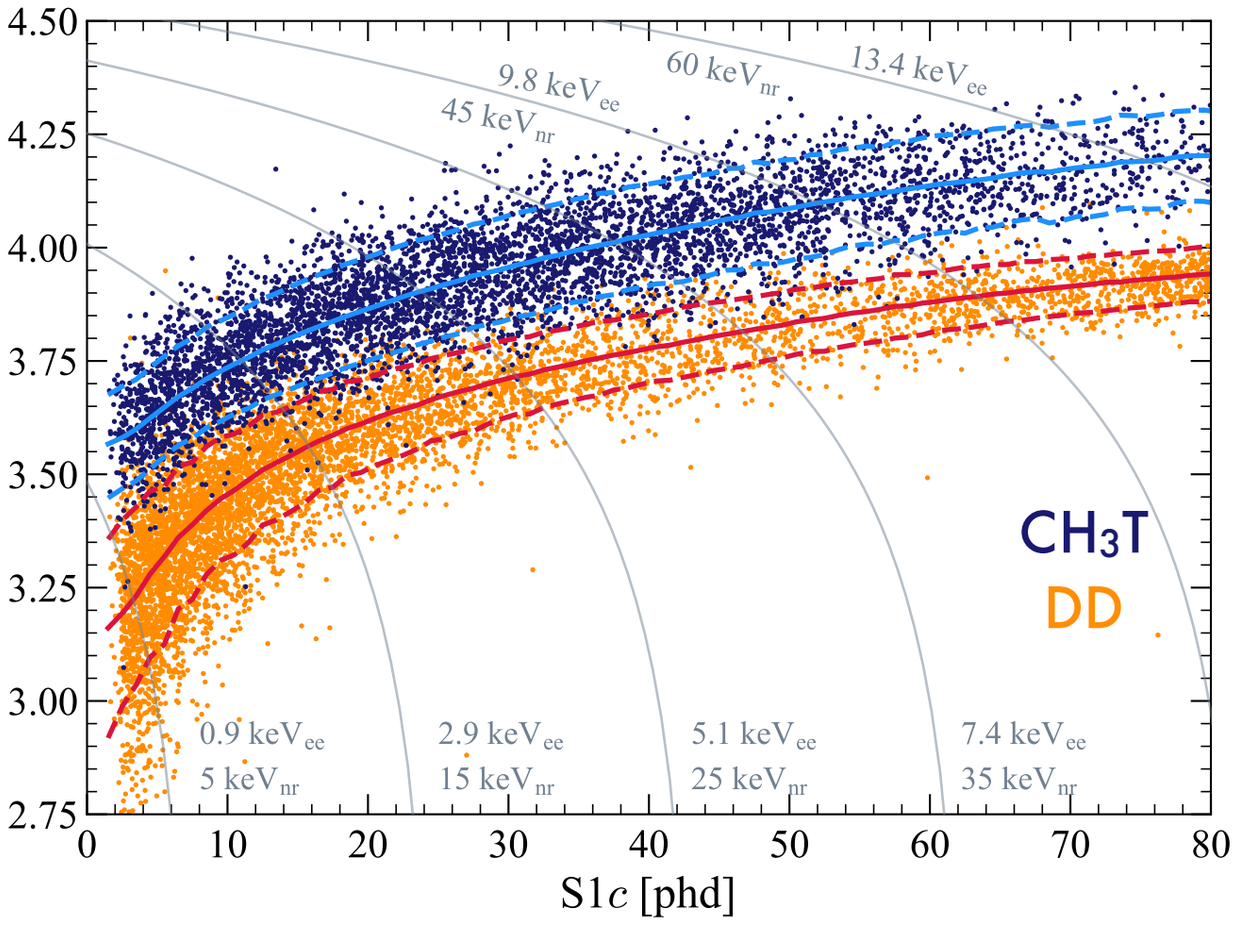
Science!

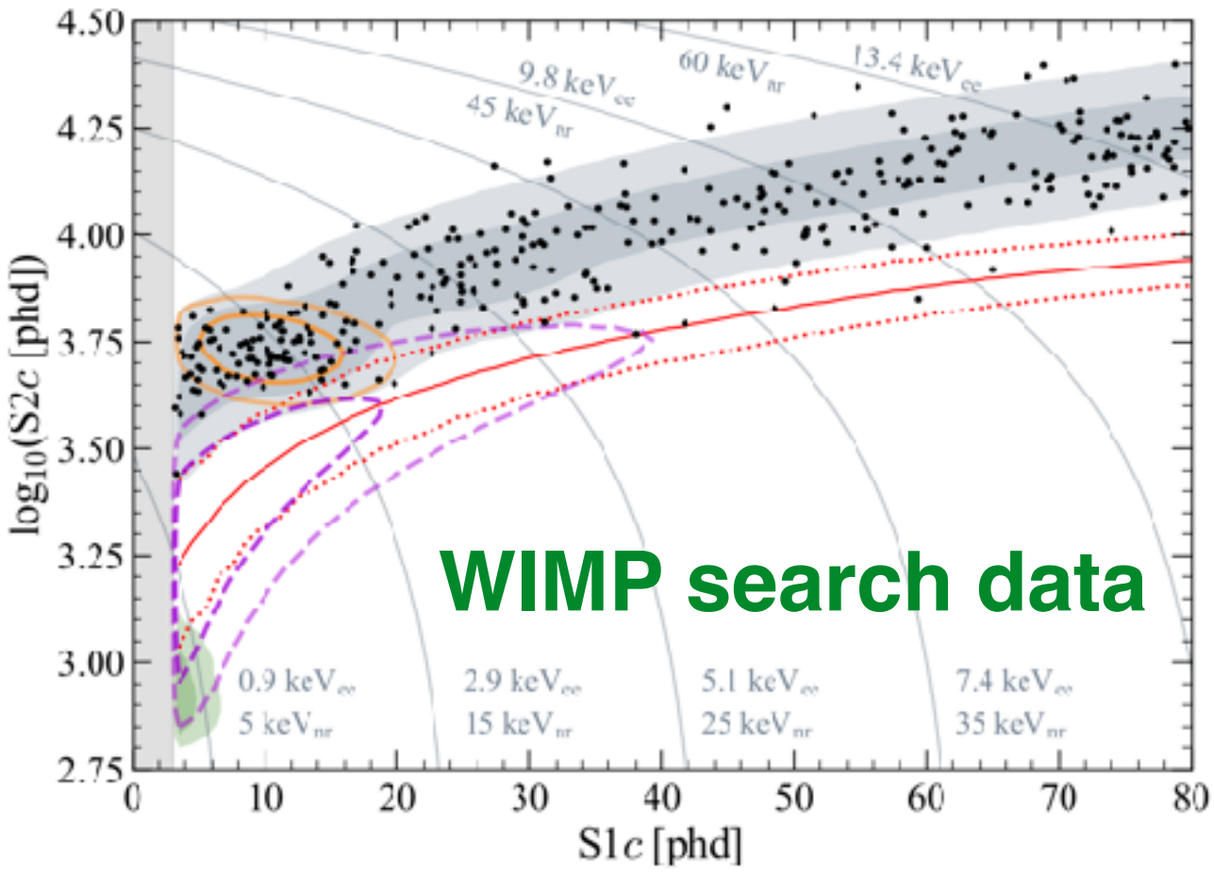

TOP PMT ARRAY
EXTRACTION REGION
TOP SKIN
TPC FIELDCAGE (ACTIVE XENON)
CATHODE GRID
REVERSE-FIELD REGION
BOTTOM PMT ARRAY





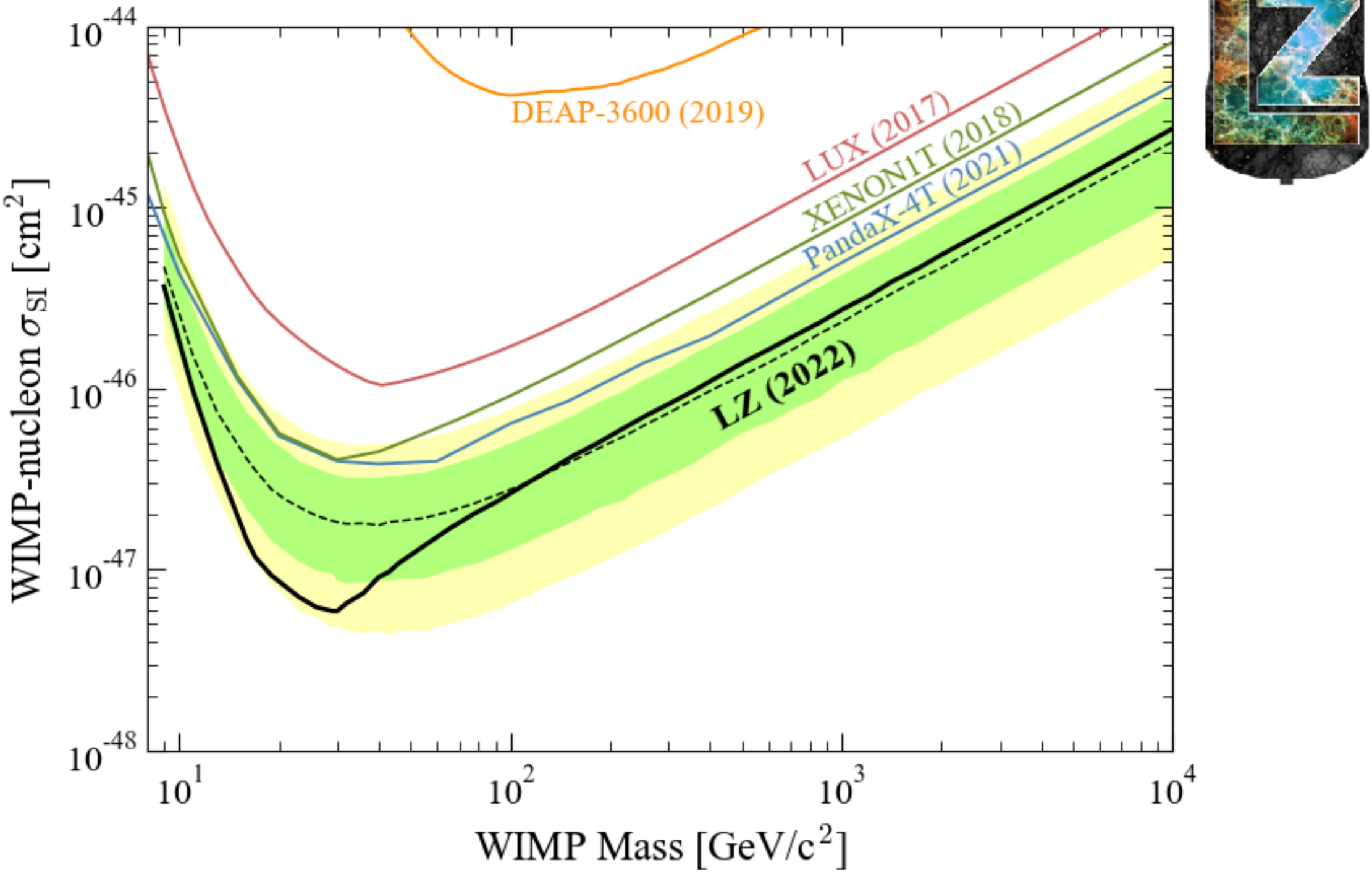
LZ





- Calibration for all LXe-TPCs is key
  - LZ - Full calibration of ER (background) distribution using dispersed tritium (CH_3T)
  - Neutrons directly calibrate proposed WIMP signal (DD)
- Allows for precise modeling in final analysis, enables discovery

LZ



- New limits, with a minimum at 6 x 10^{-48} cm^2 at 30 GeV
- See S. Eriksen, Thursday at 5:10 pm, and 2207.03764

XLZD Consortium

Successful joint XLZD meeting
June 27-29 at KIT
https://xlzd.org/
White paper (2203.02309)

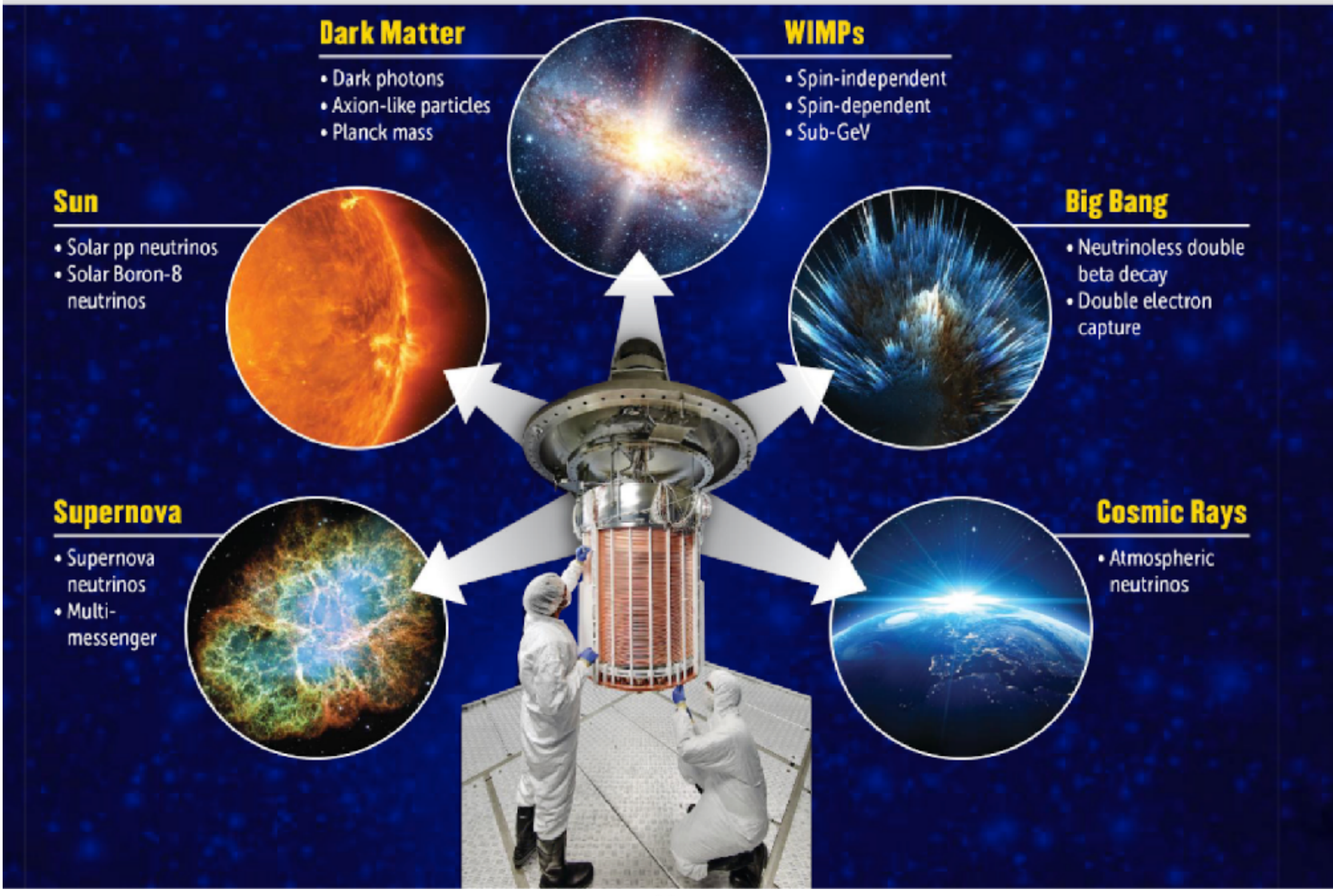
Leading Xenon Researchers unite to build next-generation Dark Matter Detector

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

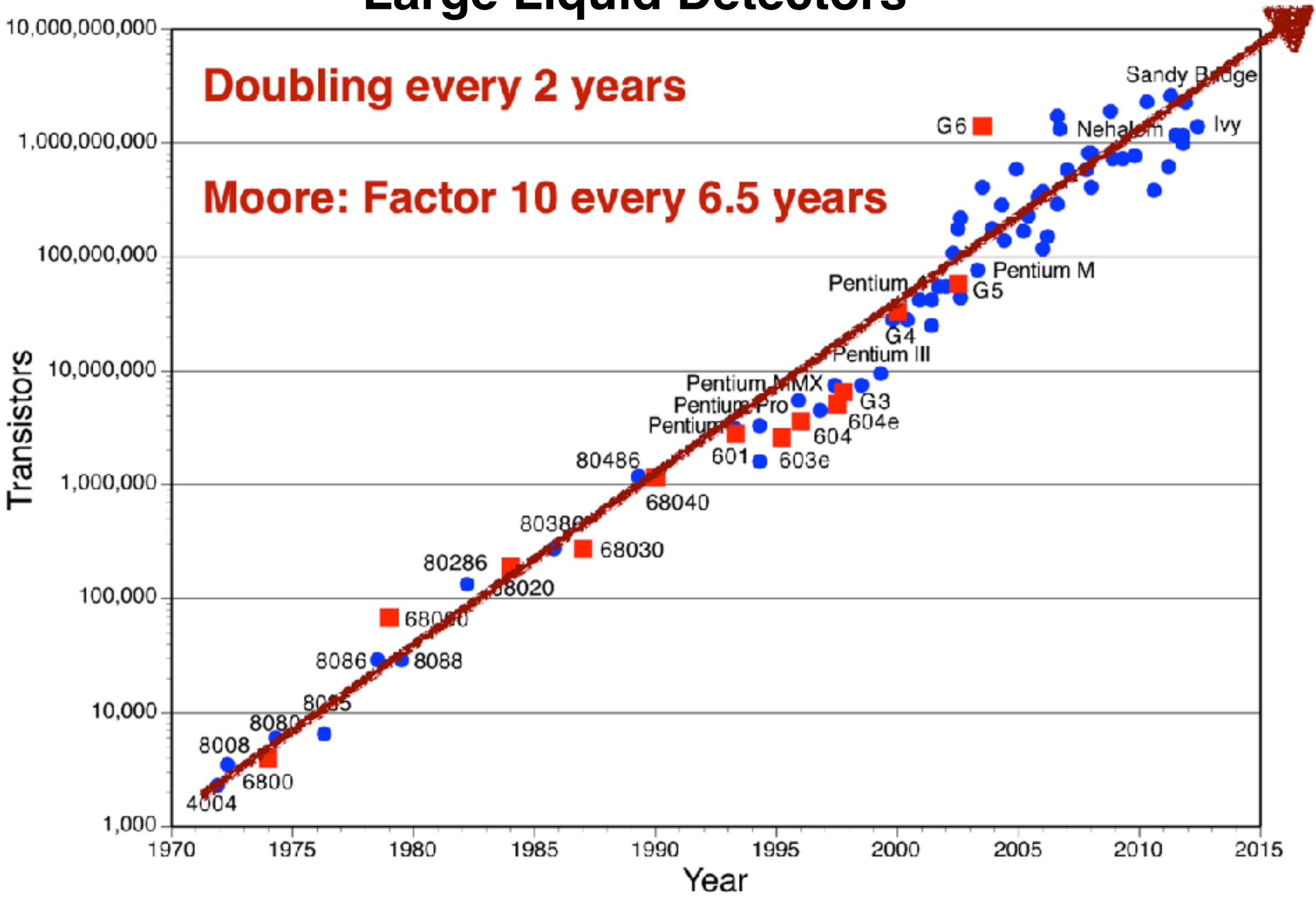
July 20, 2021

DARWIN/XENON + LUX ZEPLIN Summer Meeting 2022

XLZD Consortium

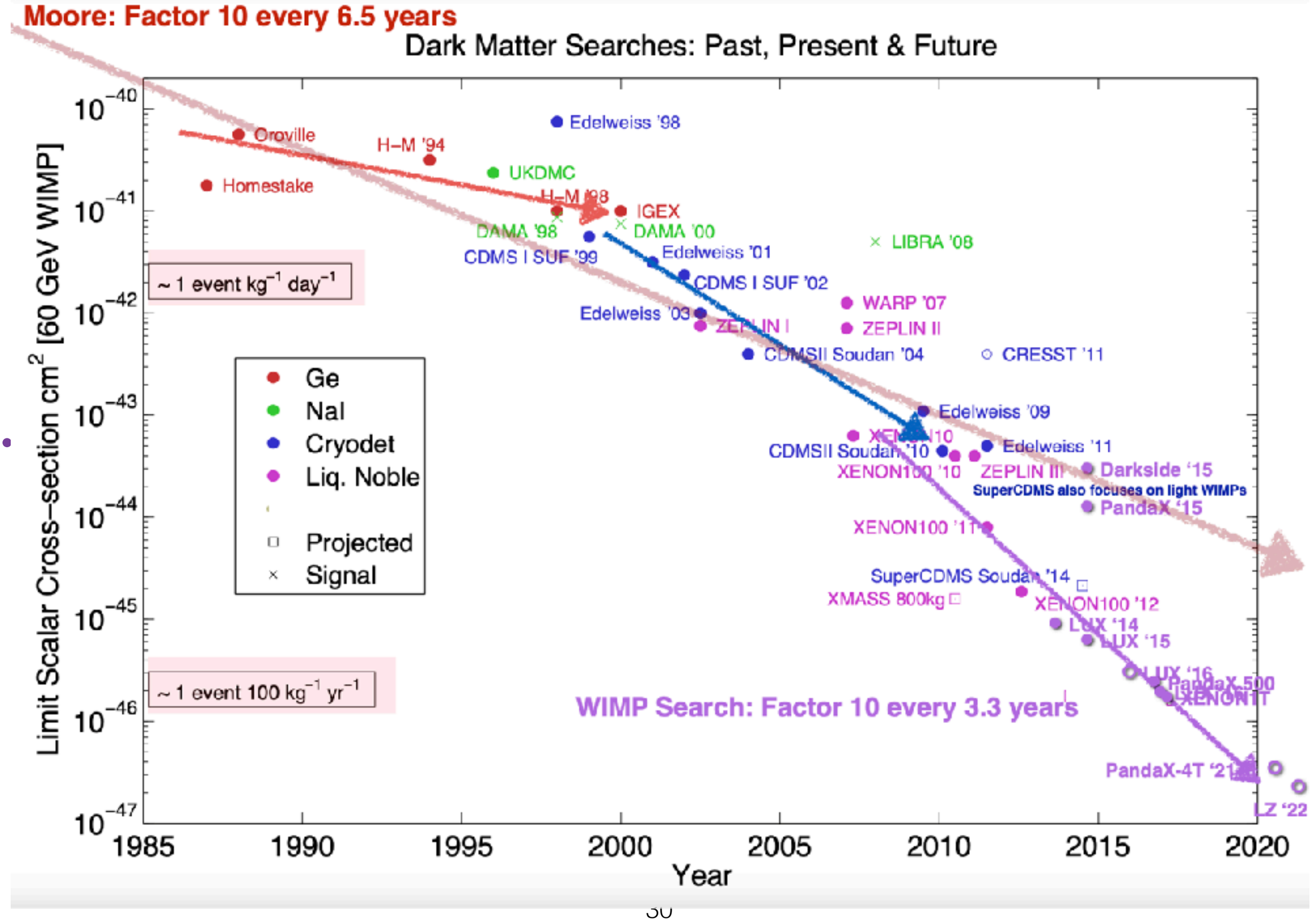


Large Liquid Detectors



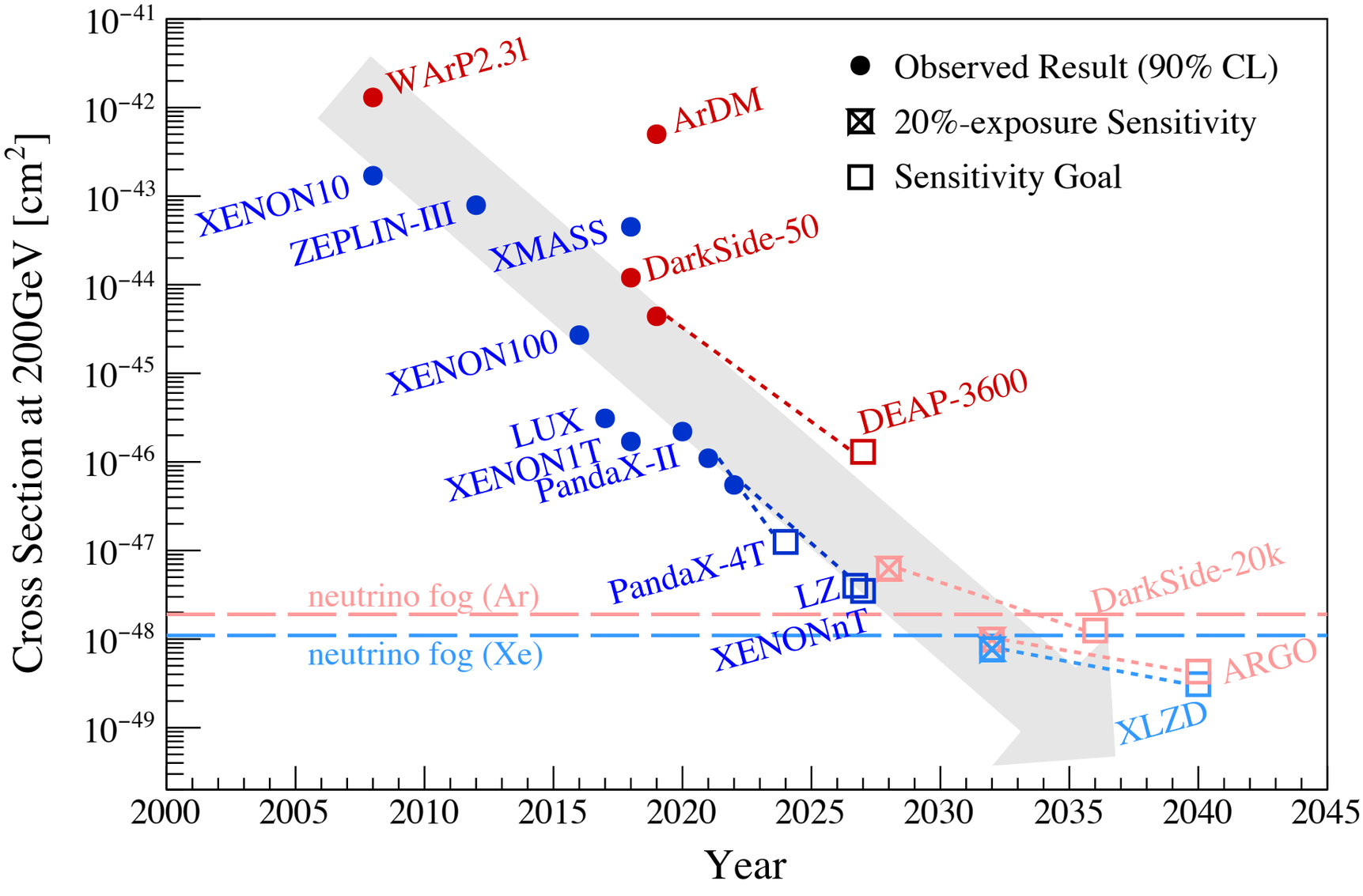
http://education.mrsec.wisc.edu/SlideShow/images/computer/Moores_Law.png

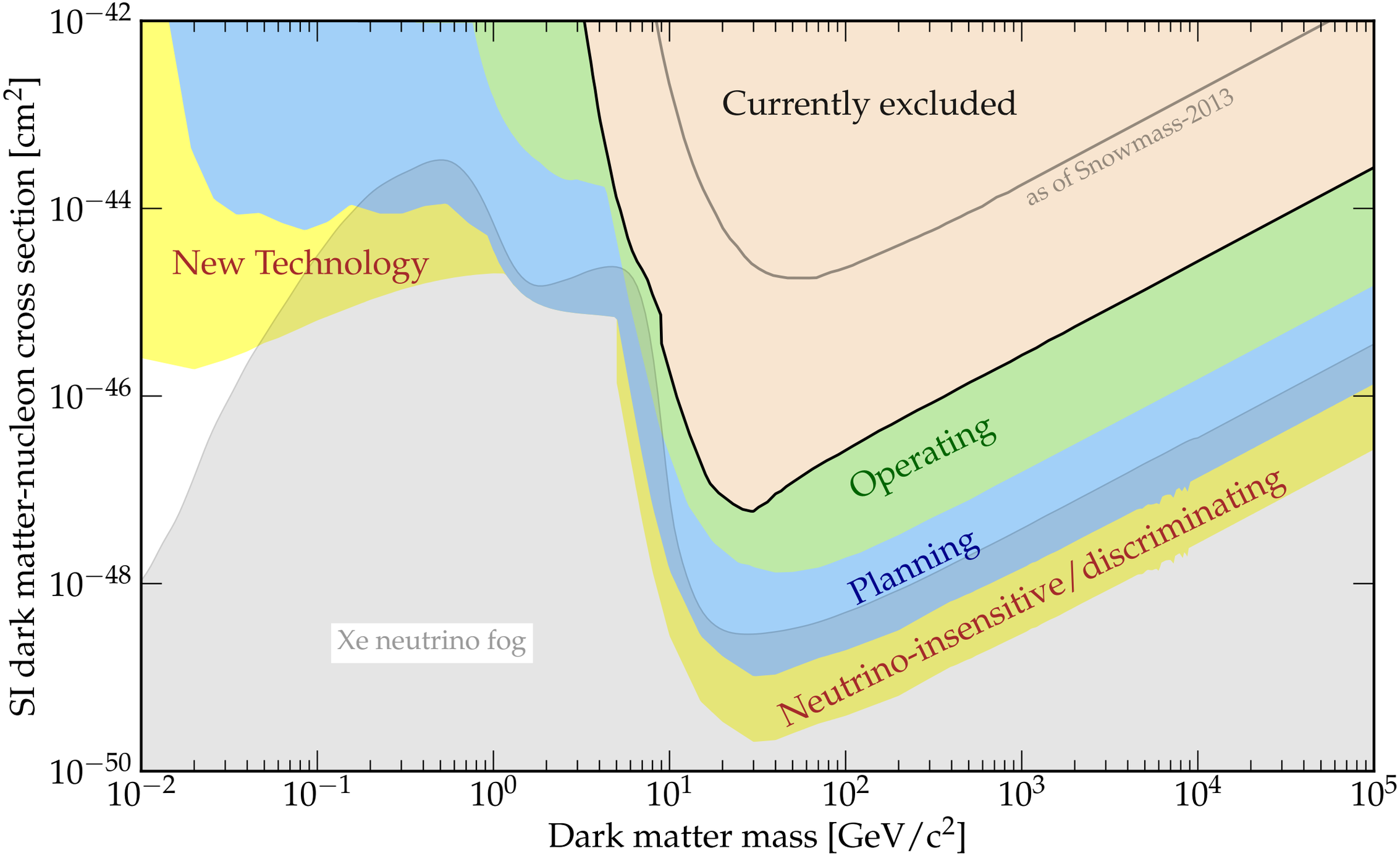
Large Liquid Detectors



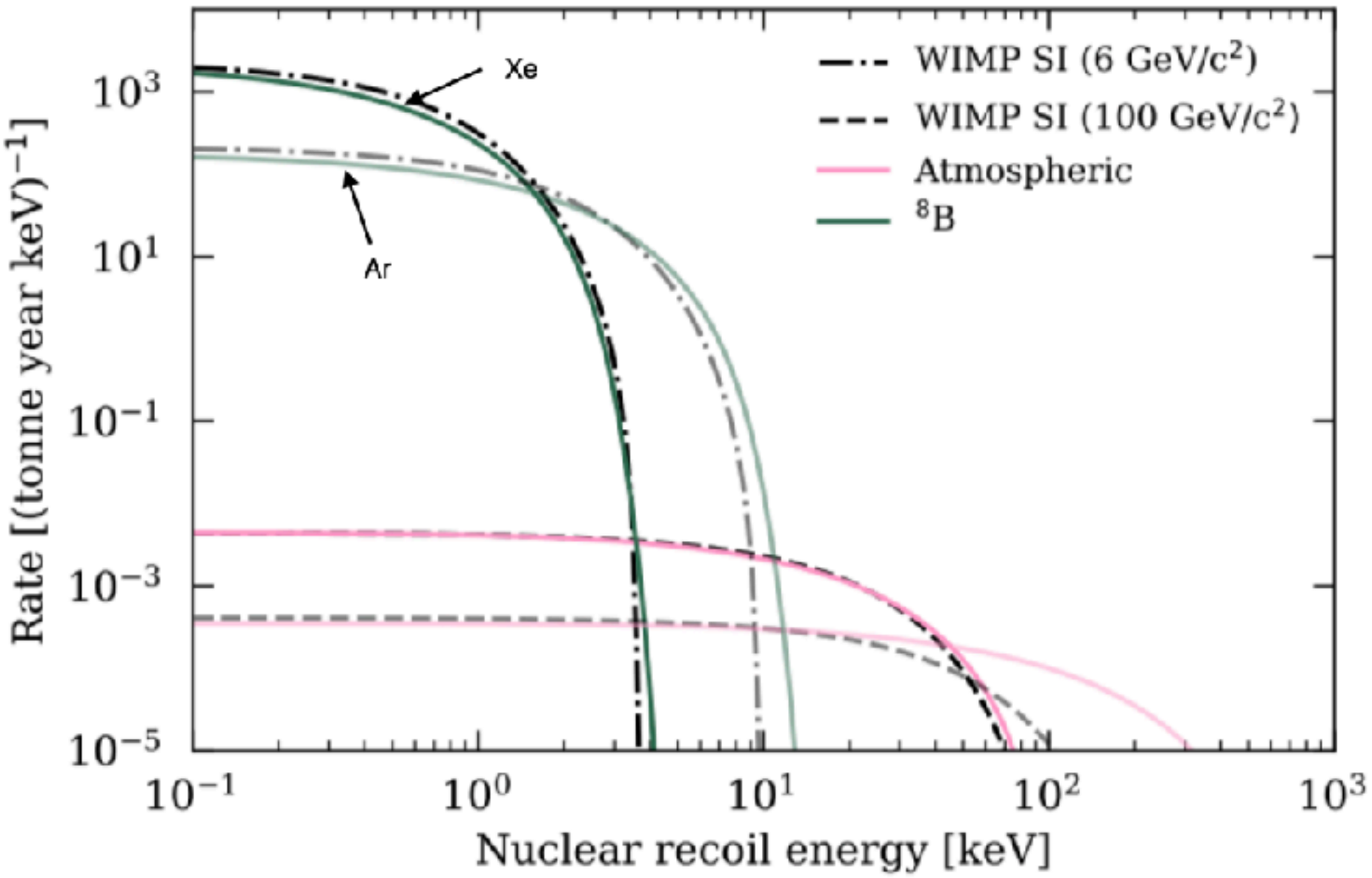
Large Liquid Detectors

- 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 fix next time
- Ready for one more push



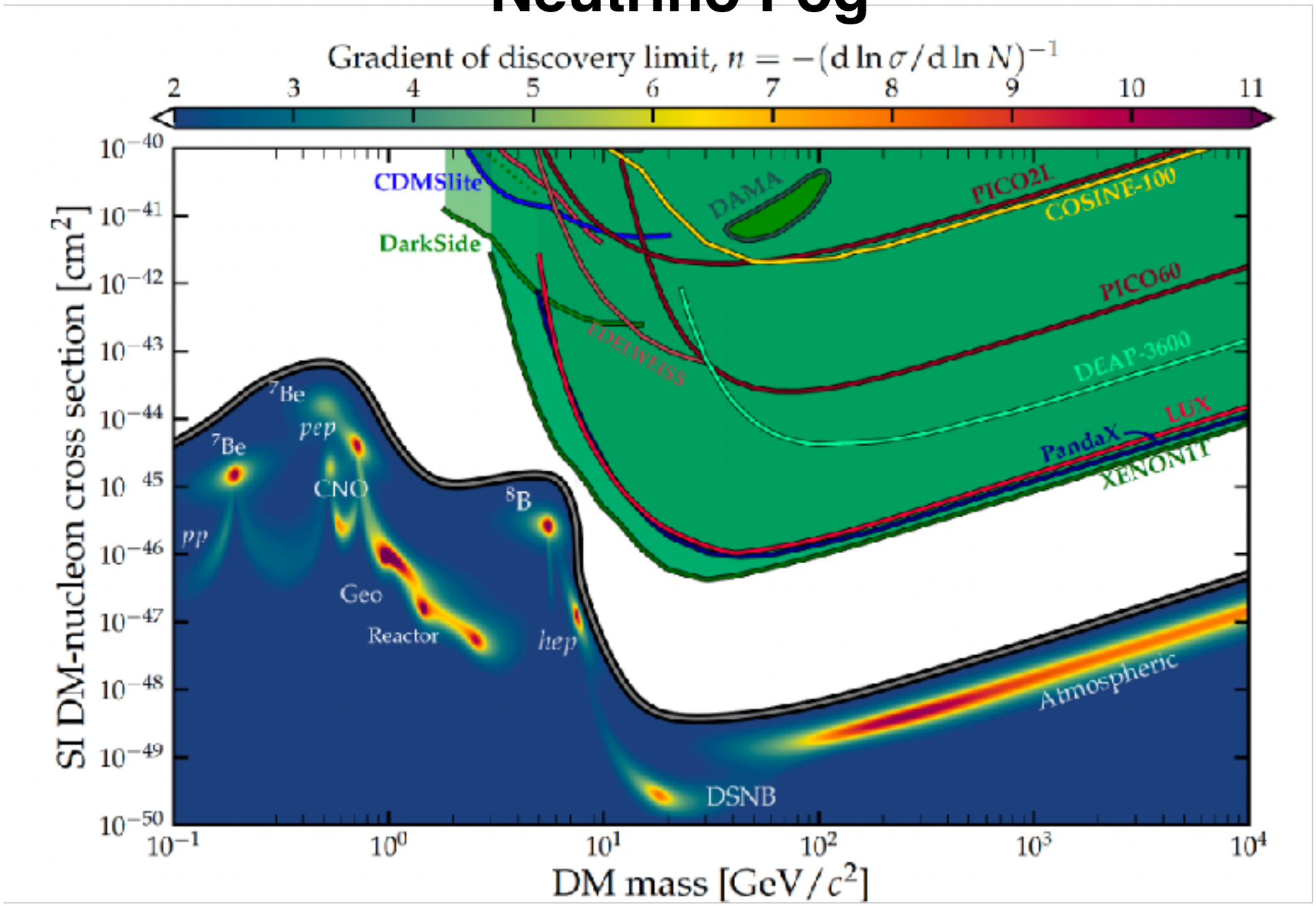

Currently excluded
as of Snowmass-2013
New Technology
Operating
Planning
Neutrino-insensitive/discriminating
Xe neutrino fog
SI dark matter-nucleon cross section [cm^2]
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Dark matter mass [GeV/c^2]

Neutrino Fog



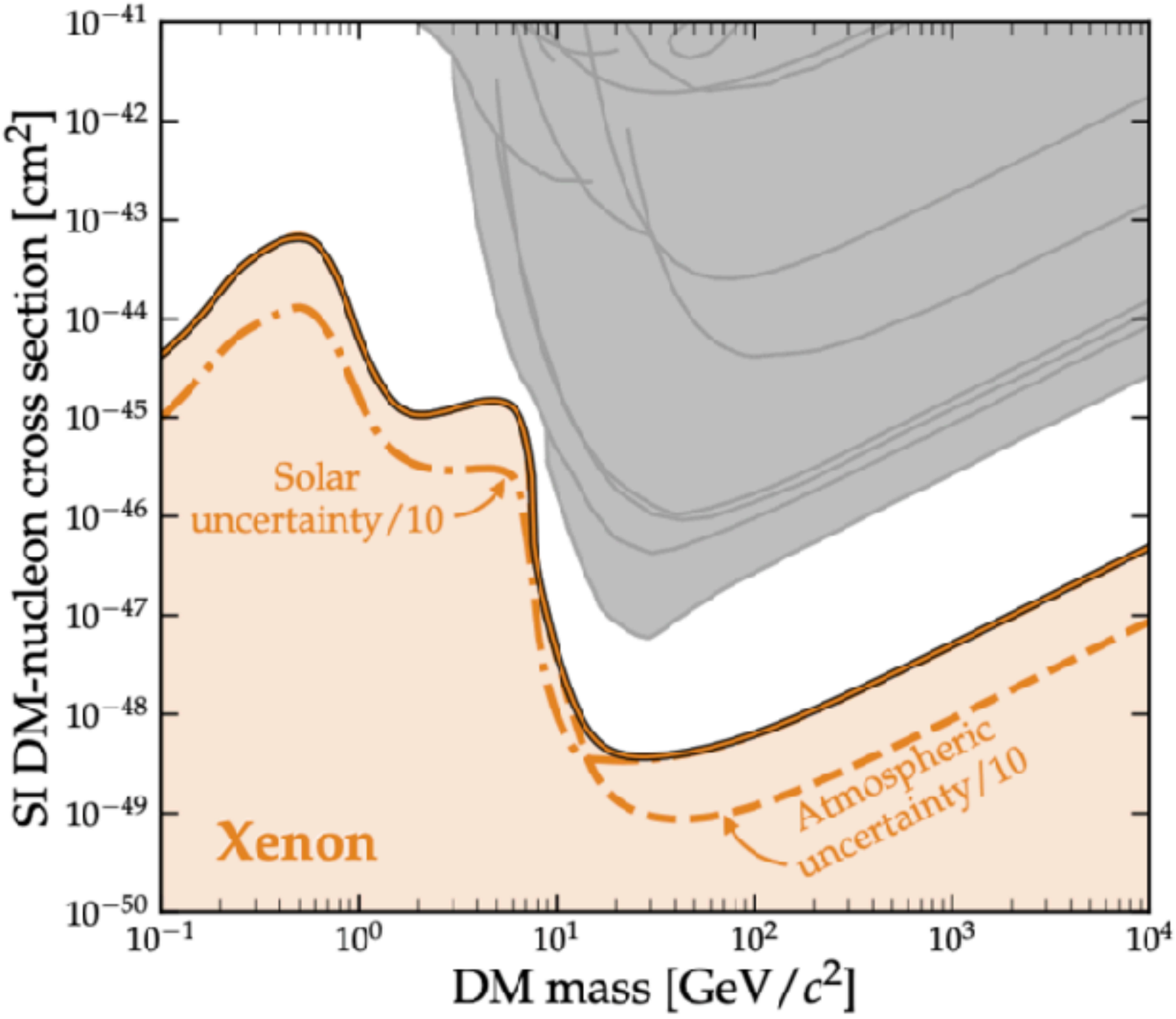
- "Neutrino fog" proposed by O'Hare (2109.03116) adopted by Snowmass (2203.08084)
  - Rebranding of neutrino floor to better capture the actual effect
- Index n - how fast one makes progress with respect to background
  - Increase in sensitivity by x10 requires 10^n more exposure

Neutrino Fog



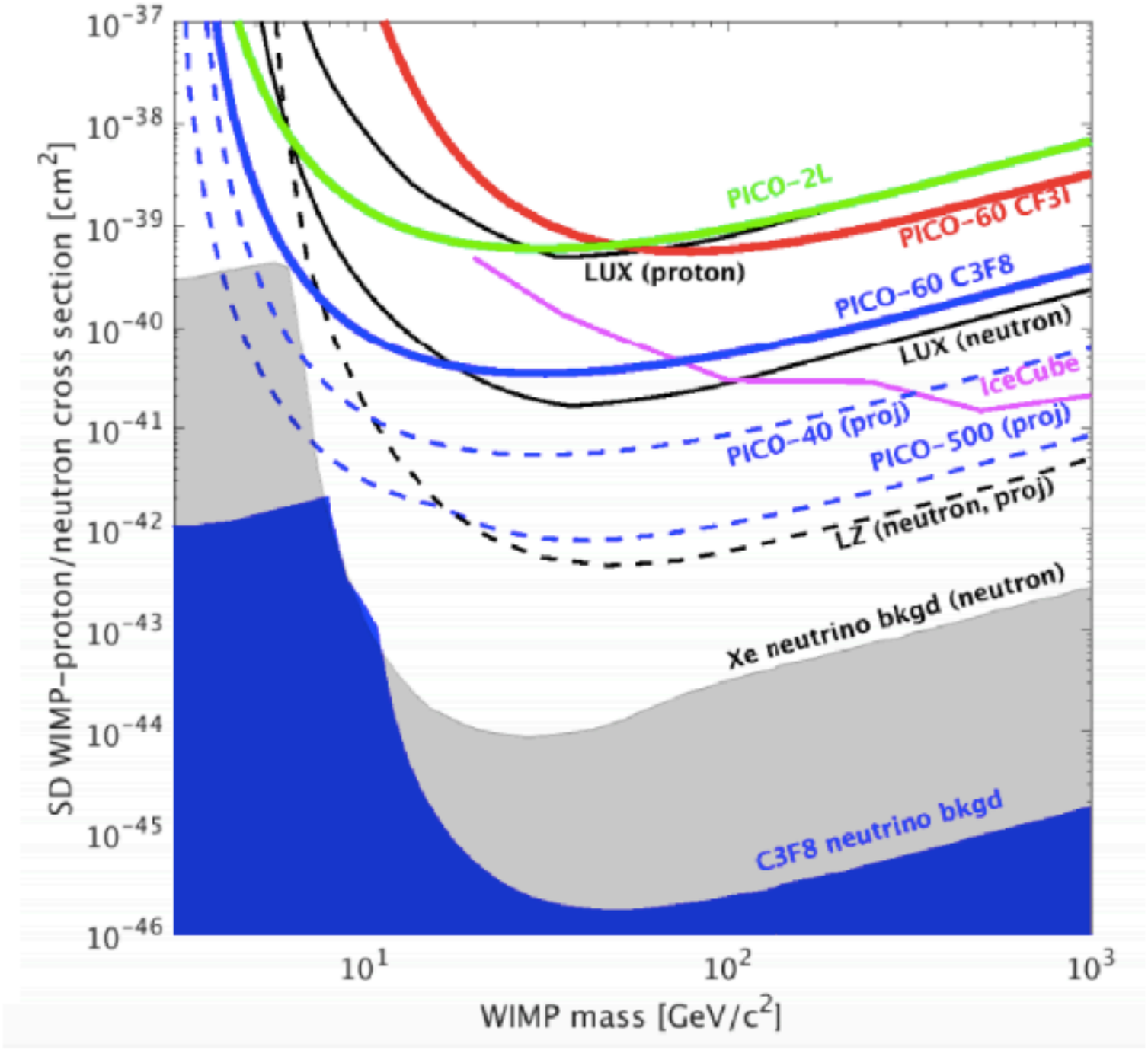
- O'Hare (2109.03116) supported by Snowmass (2203.08084) define "neutrino fog"
- Rebranding of neutrino floor to better capture the actual effect
  - Index n - how fast one makes progress with respect to background
  - Increase in sensitivity by x10 requires 10^n more exposure

Neutrino Fog



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

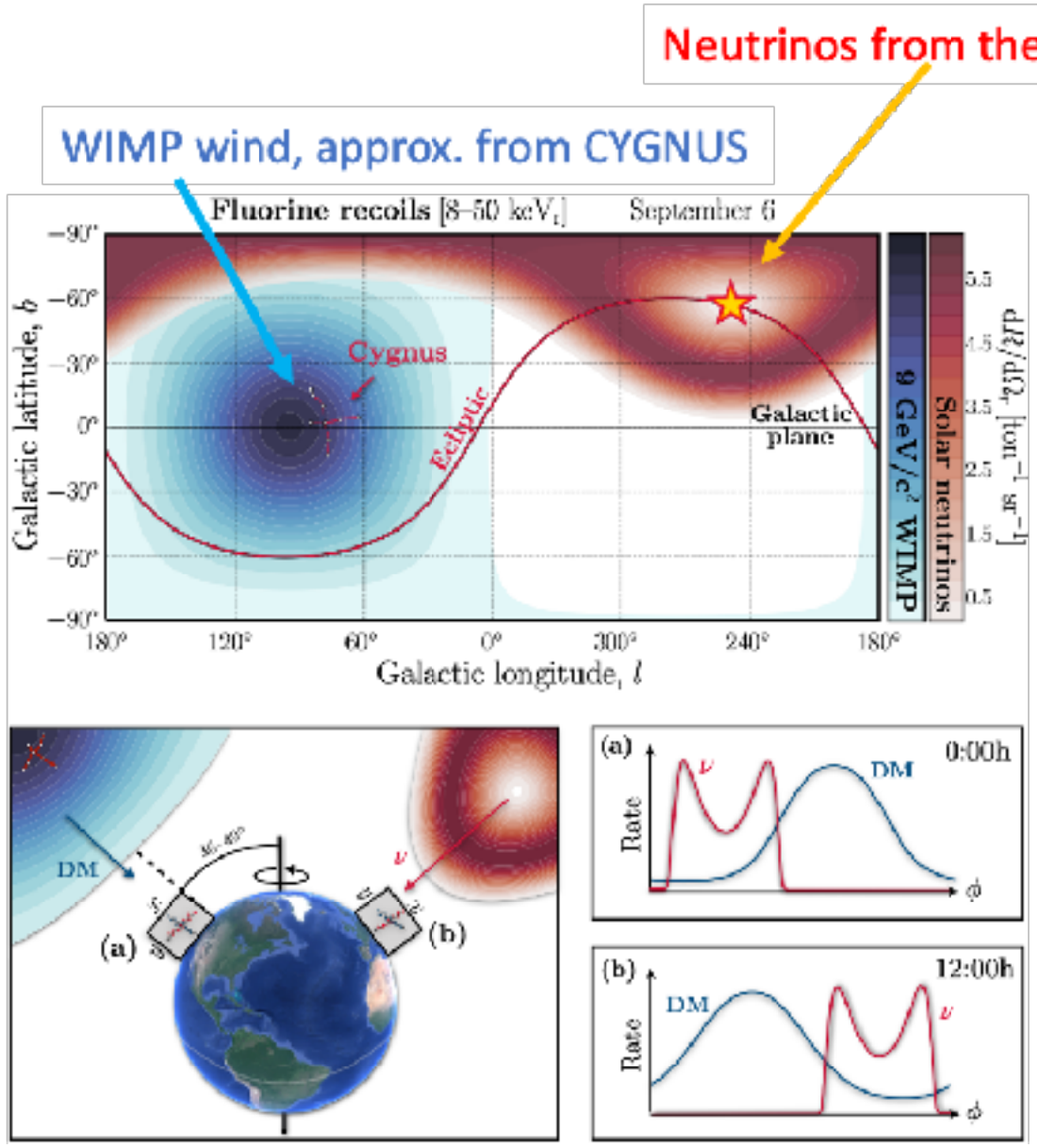
Neutrino Fog

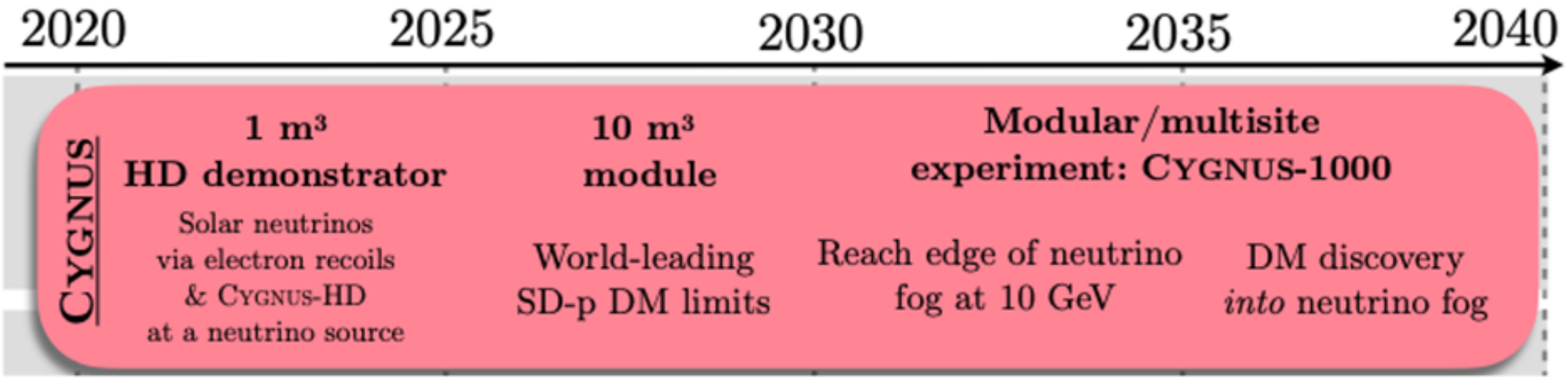


- Future progress can be made depending on target
  - Fluorine based SD detector can go deeper than xenon-based SD detector

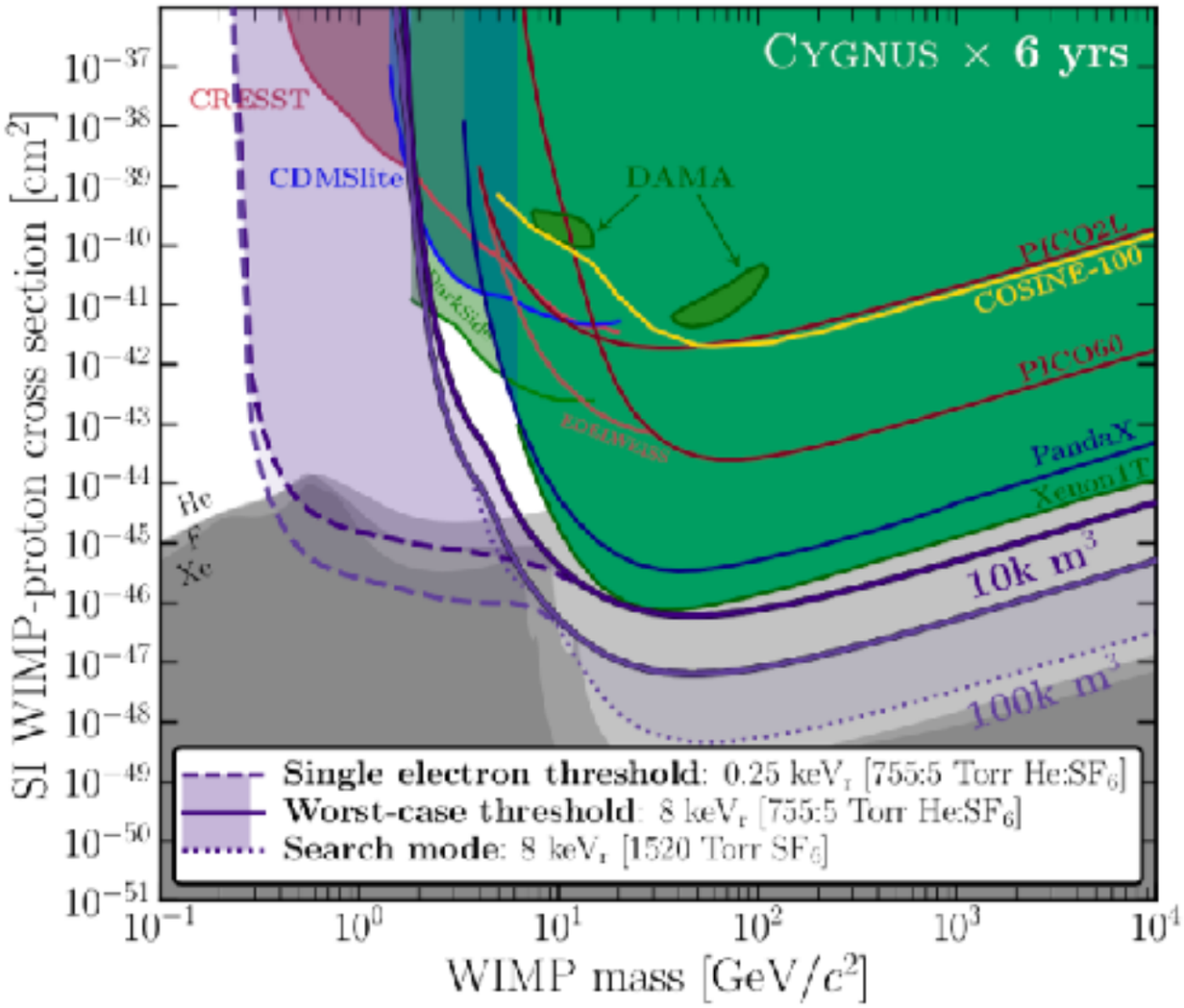
Directionality

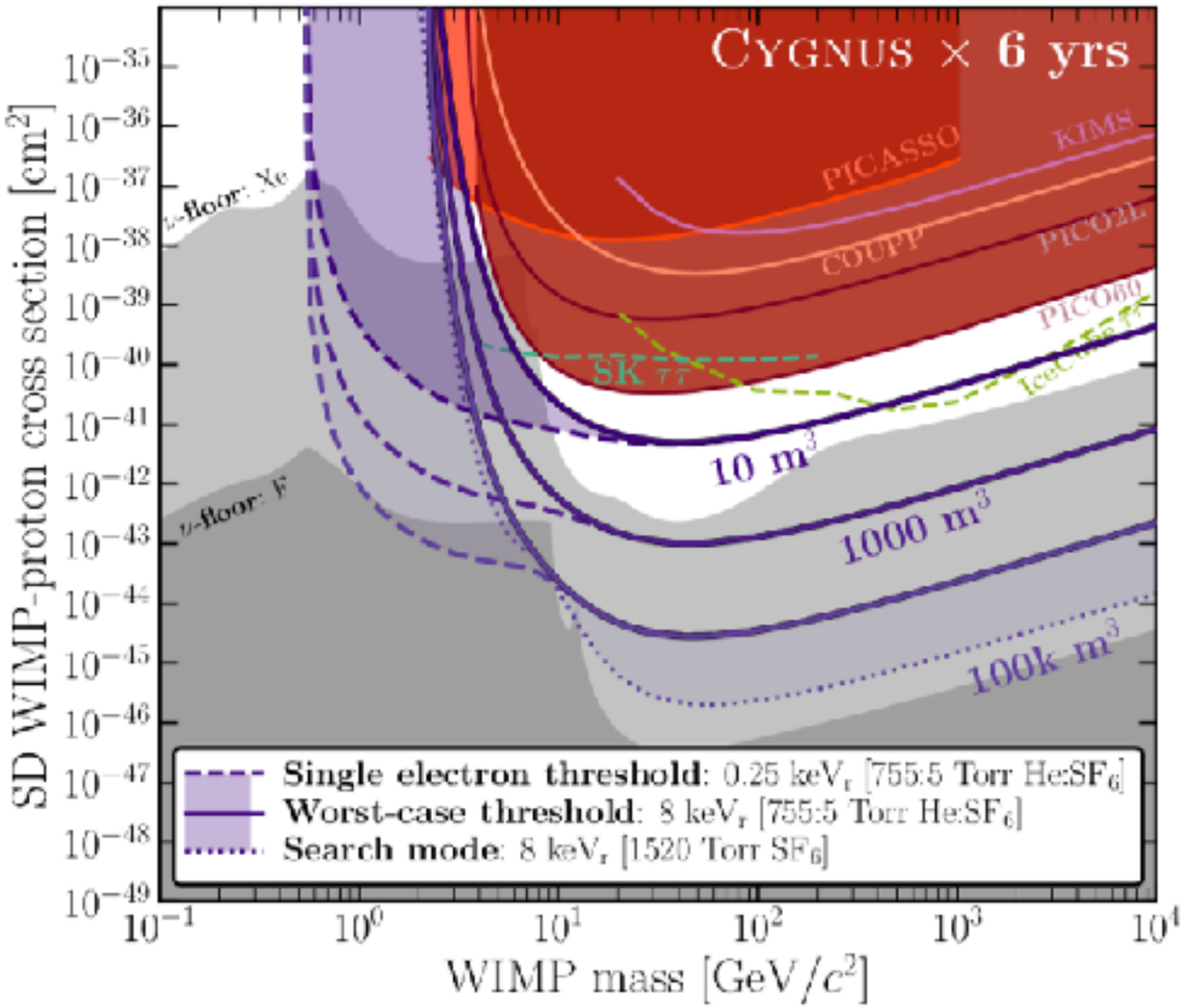
- Directionality can identify WIMP wind with only handful of events
  - Ideal case - 3D direction plus energy
  - Experimentally challenging
- Cygnus program doing R&D now to enable large scale directionality
  - Physics program for dark matter and neutrinos described in 2102.04596





Directionality





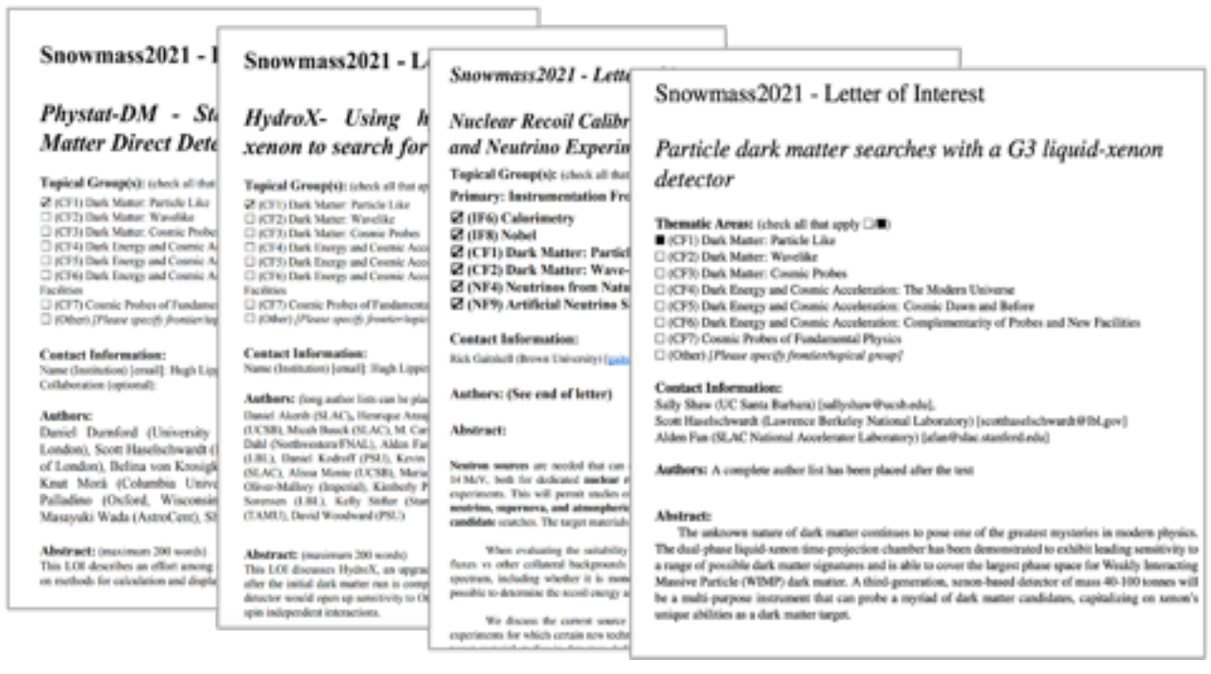
Dark Matter at TeV scales (and beyond)

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

P5:
dark matter
a top priority

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles.



Snowmass2021 - Letter of Interest

Particle dark matter searches with a G3 liquid-xenon detector

Thematic Areas: (check all that apply ☐■)
■ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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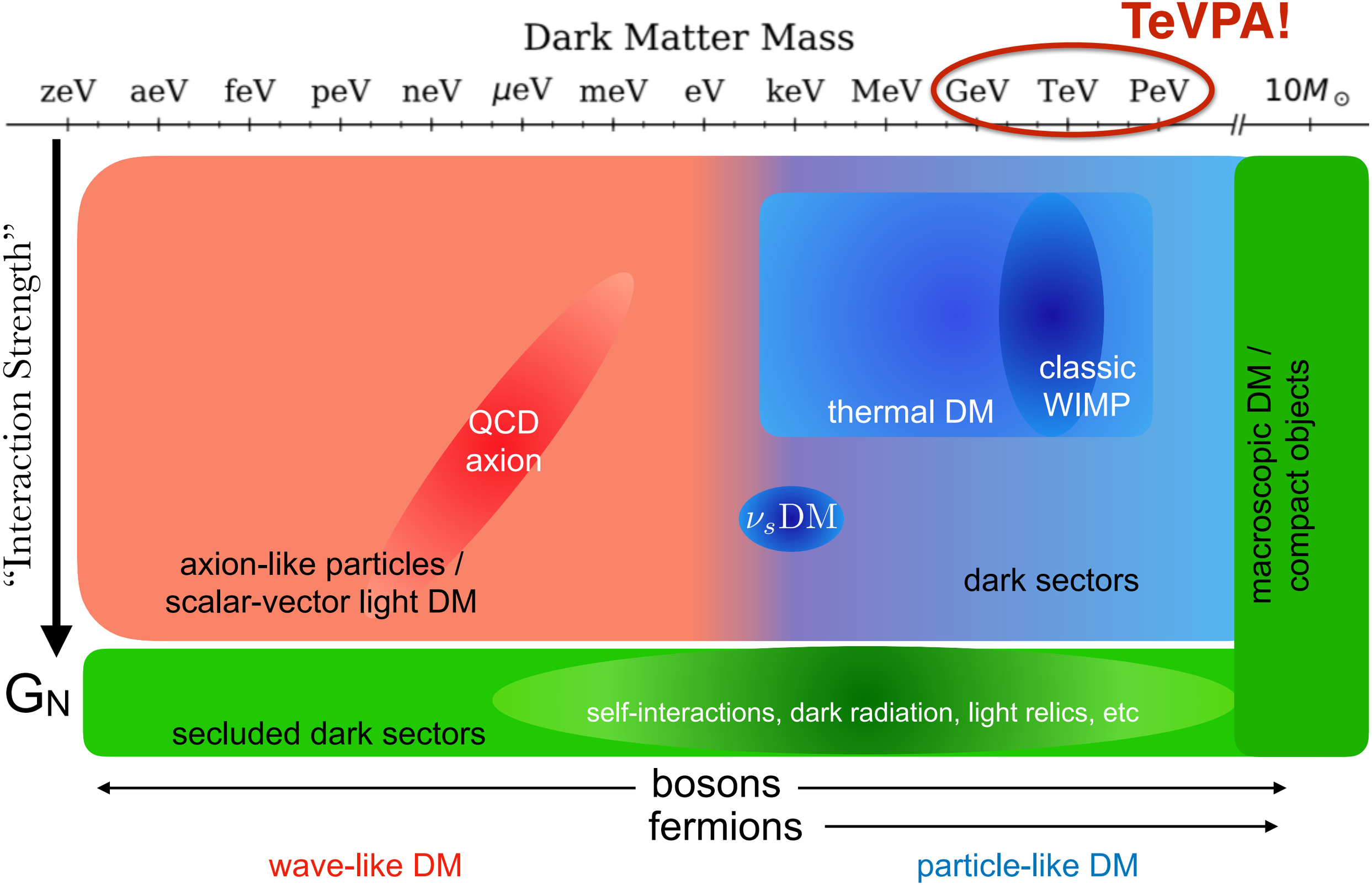
Alden Fan (SLAC National Accelerator Laboratory) [afan@slac.stanford.edu]

Authors: A complete author list has been placed after the text

Abstract:
The unknown nature of dark matter continues to pose one of the greatest mysteries in modern physics. The dual-phase liquid-xenon time-projection chamber has been demonstrated to exhibit leading sensitivity to a range of possible dark matter signatures and is able to cover the largest phase space for Weakly Interacting Massive Particle (WIMP) dark matter. A third-generation, xenon-based detector of mass 40-100 tonnes will be a multi-purpose instrument that can probe a myriad of dark matter candidates, capitalizing on xenon's unique abilities as a dark matter target.

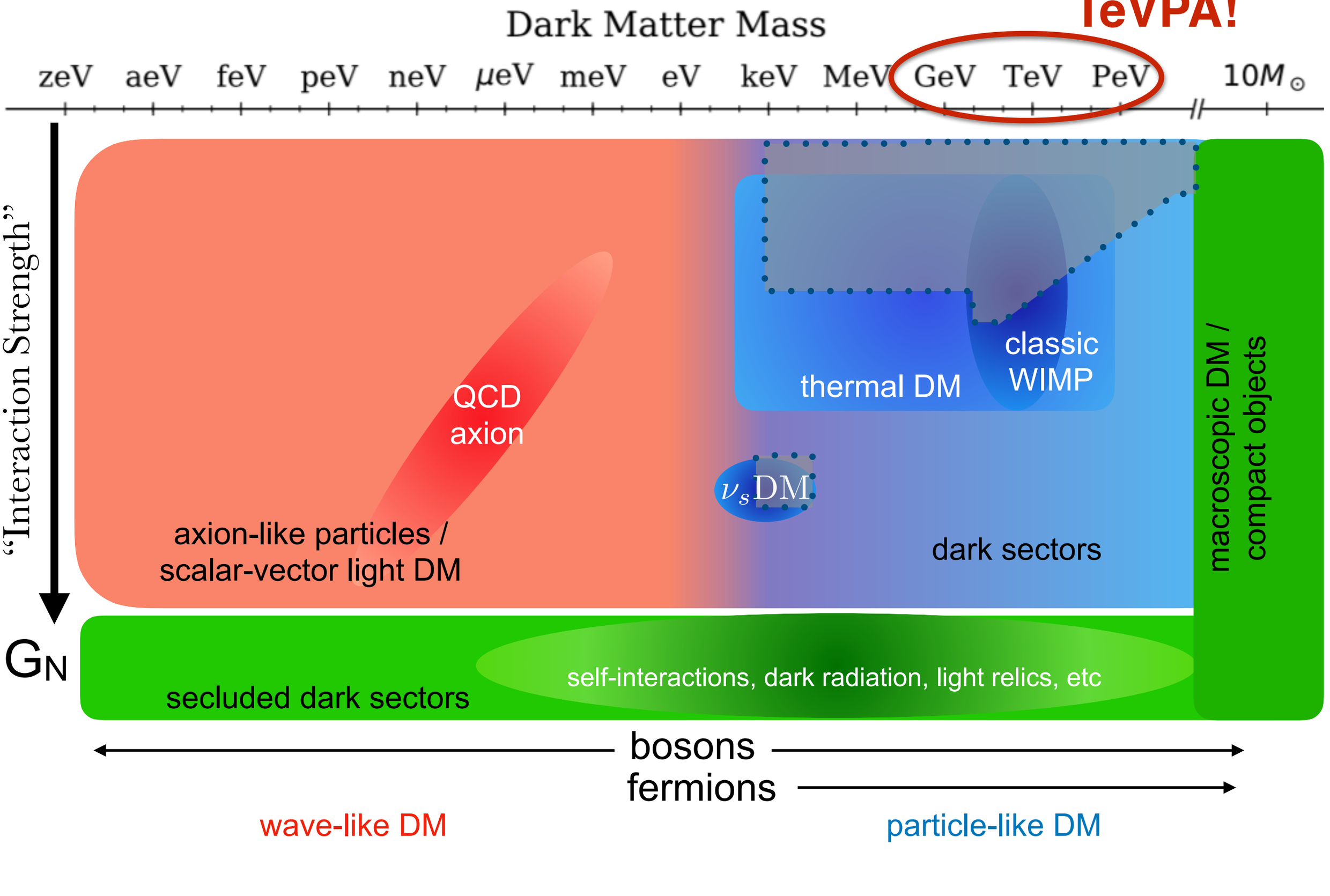
- **Most commonly mentioned topic in Snowmass LOIs**

Dark Matter at ~TeV and beyond

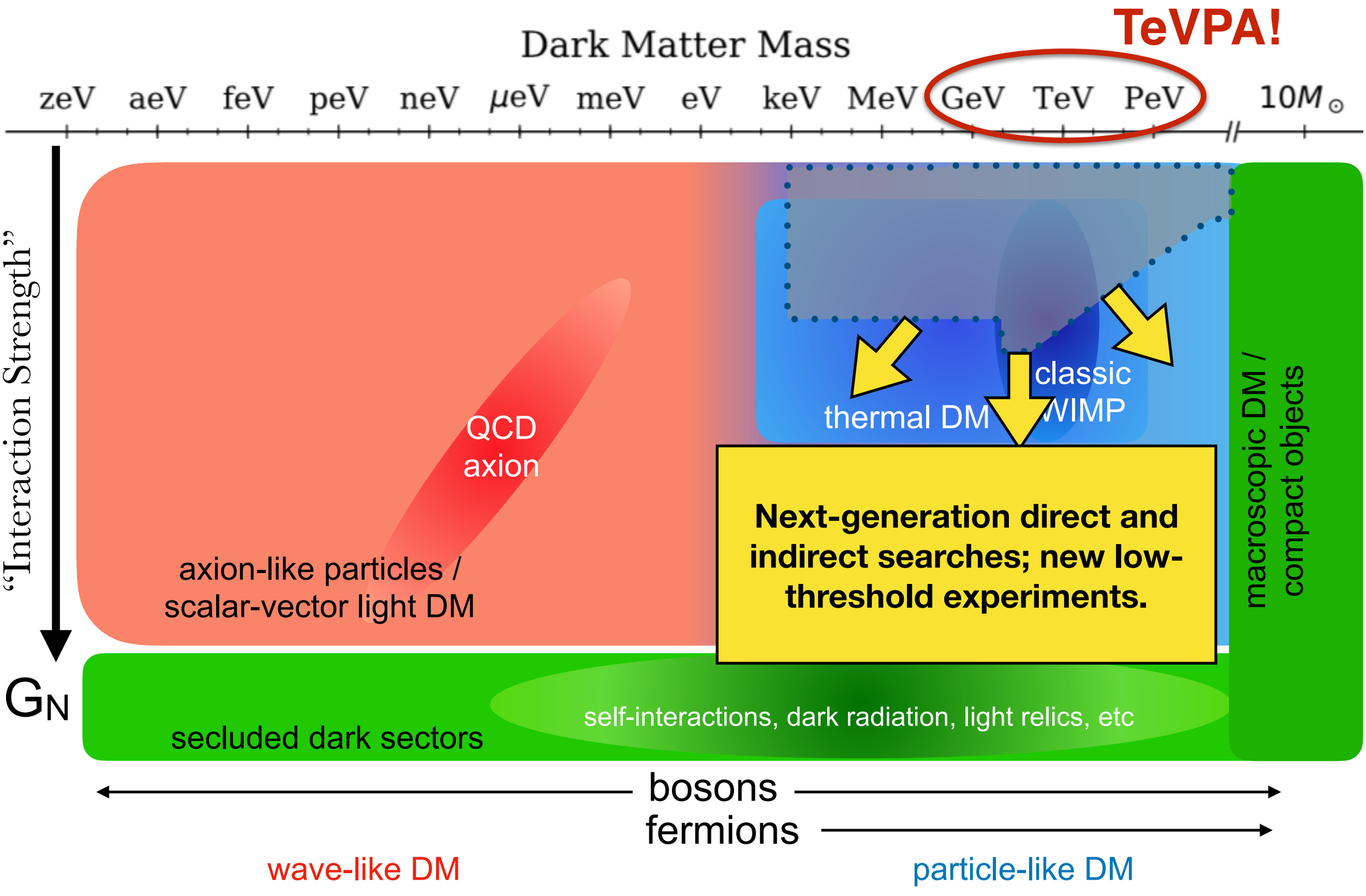


From A. Chou, Cosmic Frontier Plenary at Snowmass

Dark Matter at ~TeV and beyond

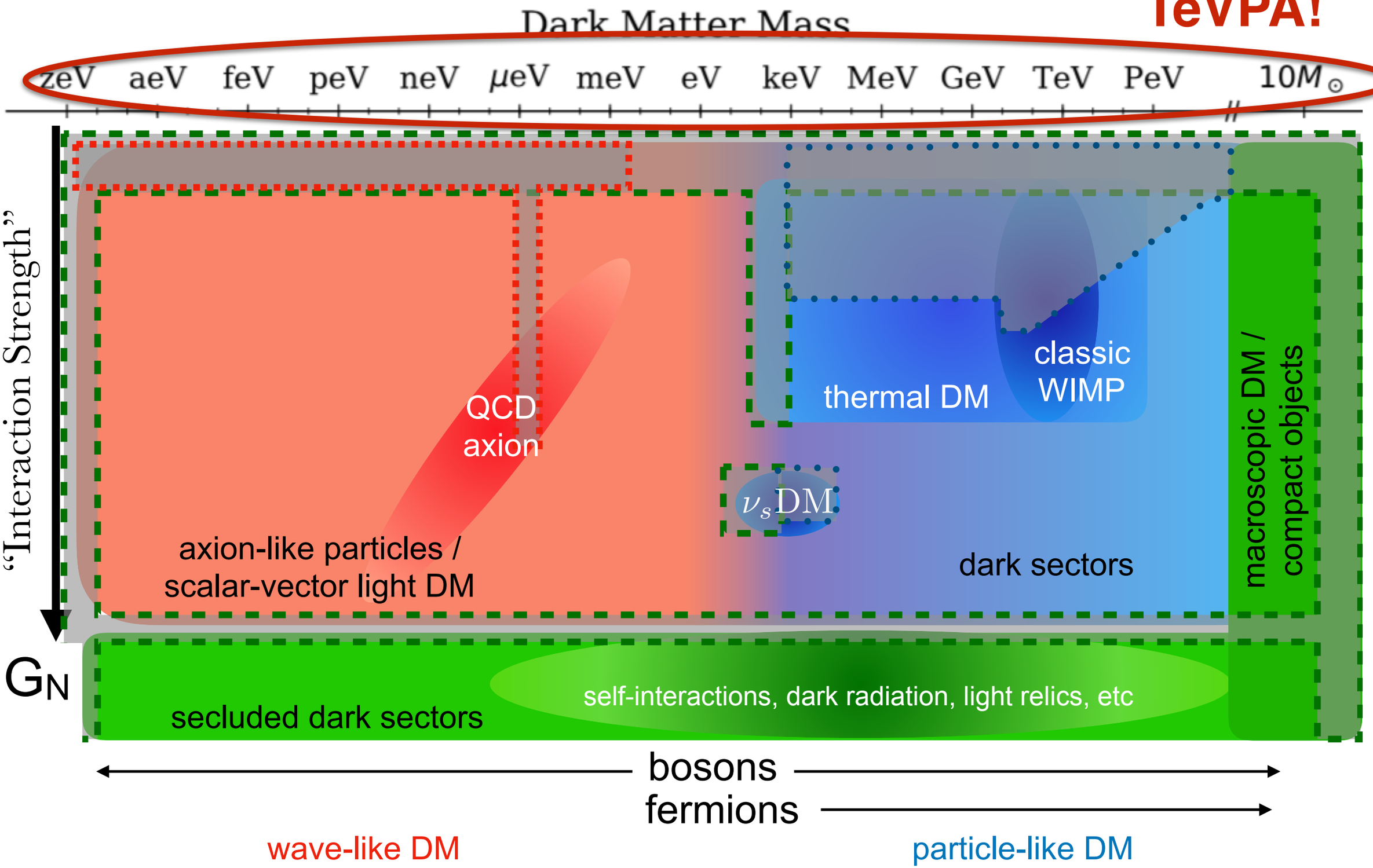


Dark Matter at ~TeV and beyond



Dark Matter at ~TeV and beyond

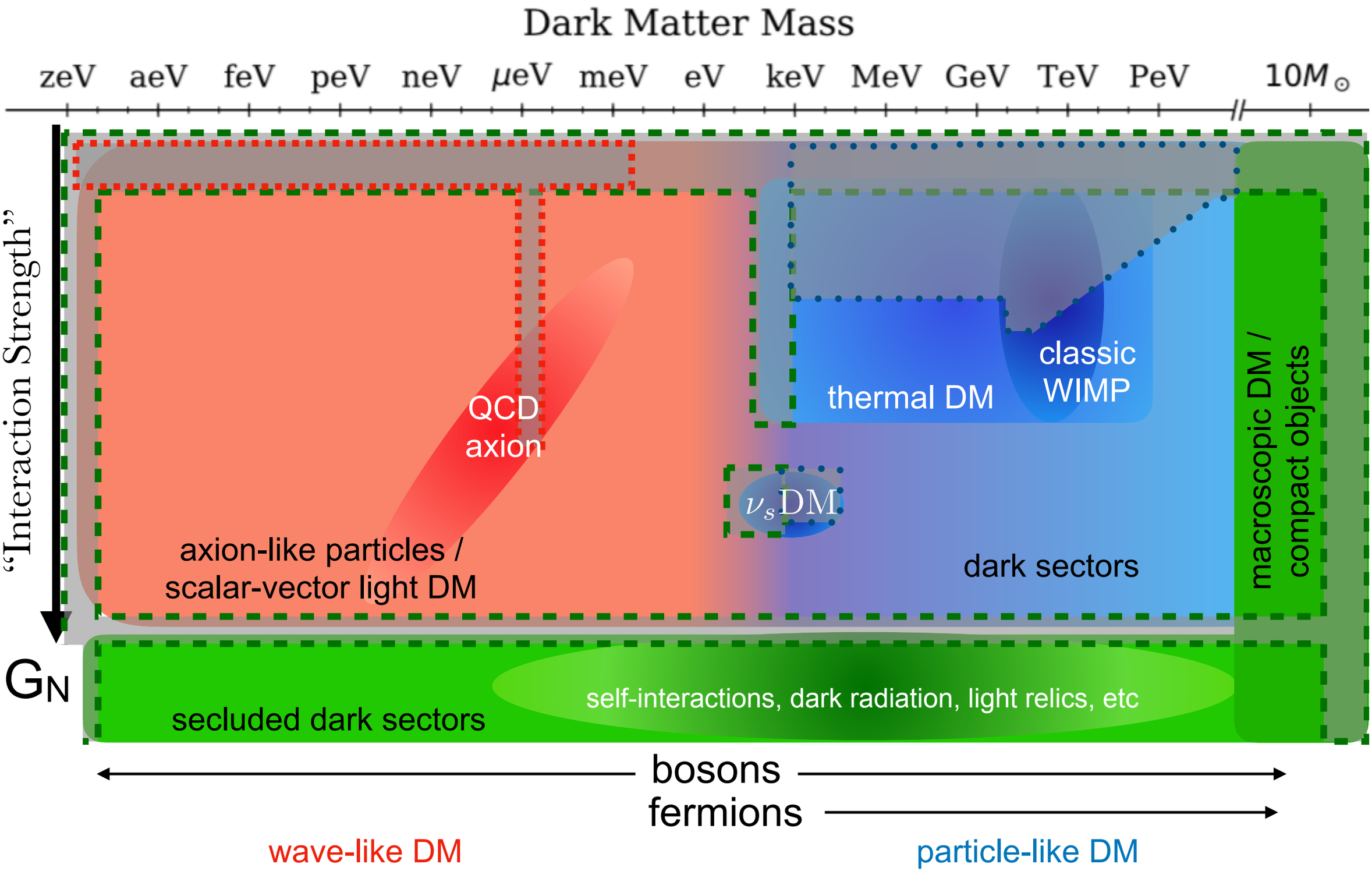
TeVPA!



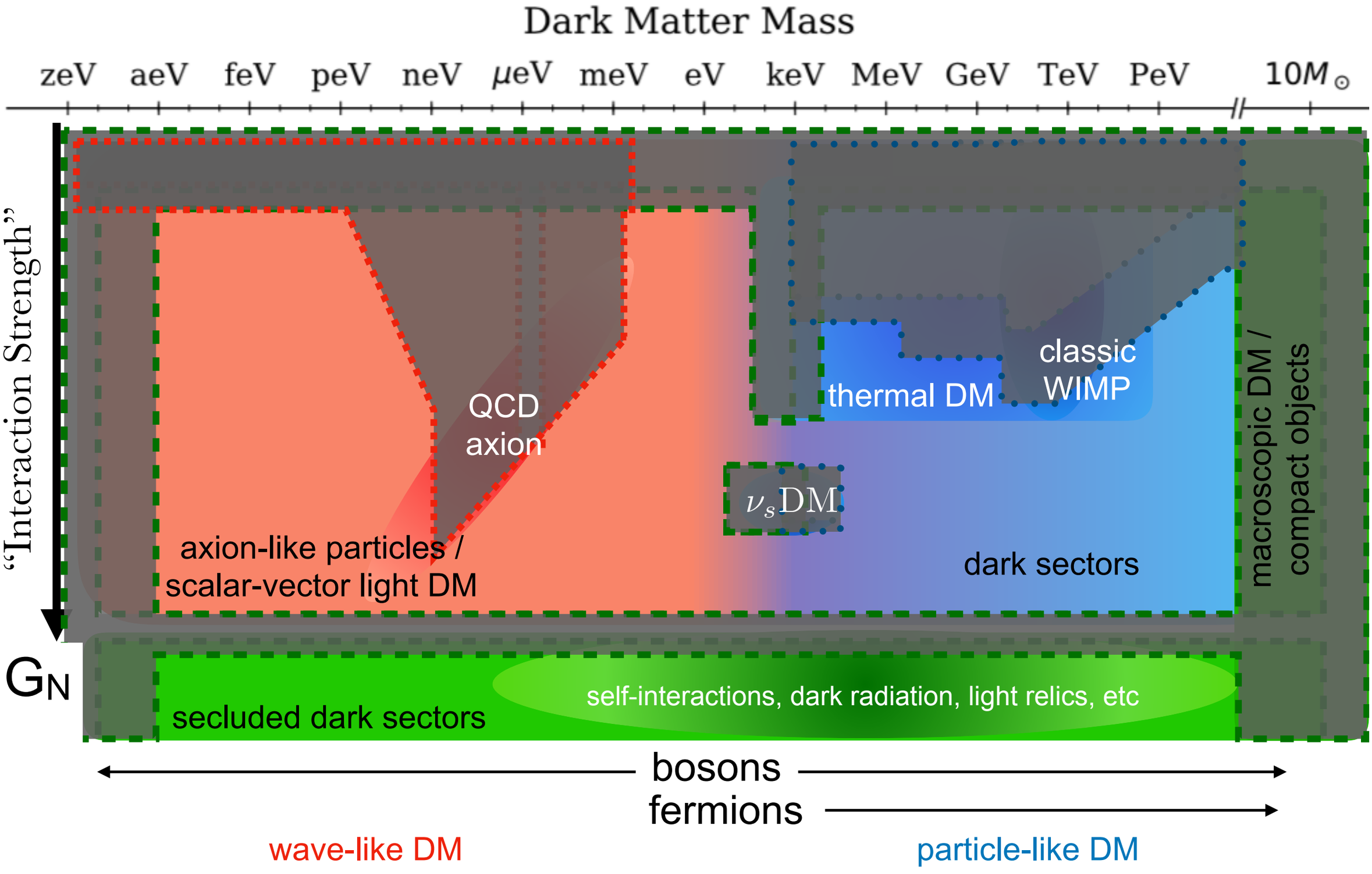
Dark Matter at TeV scales (and beyond)

- **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.

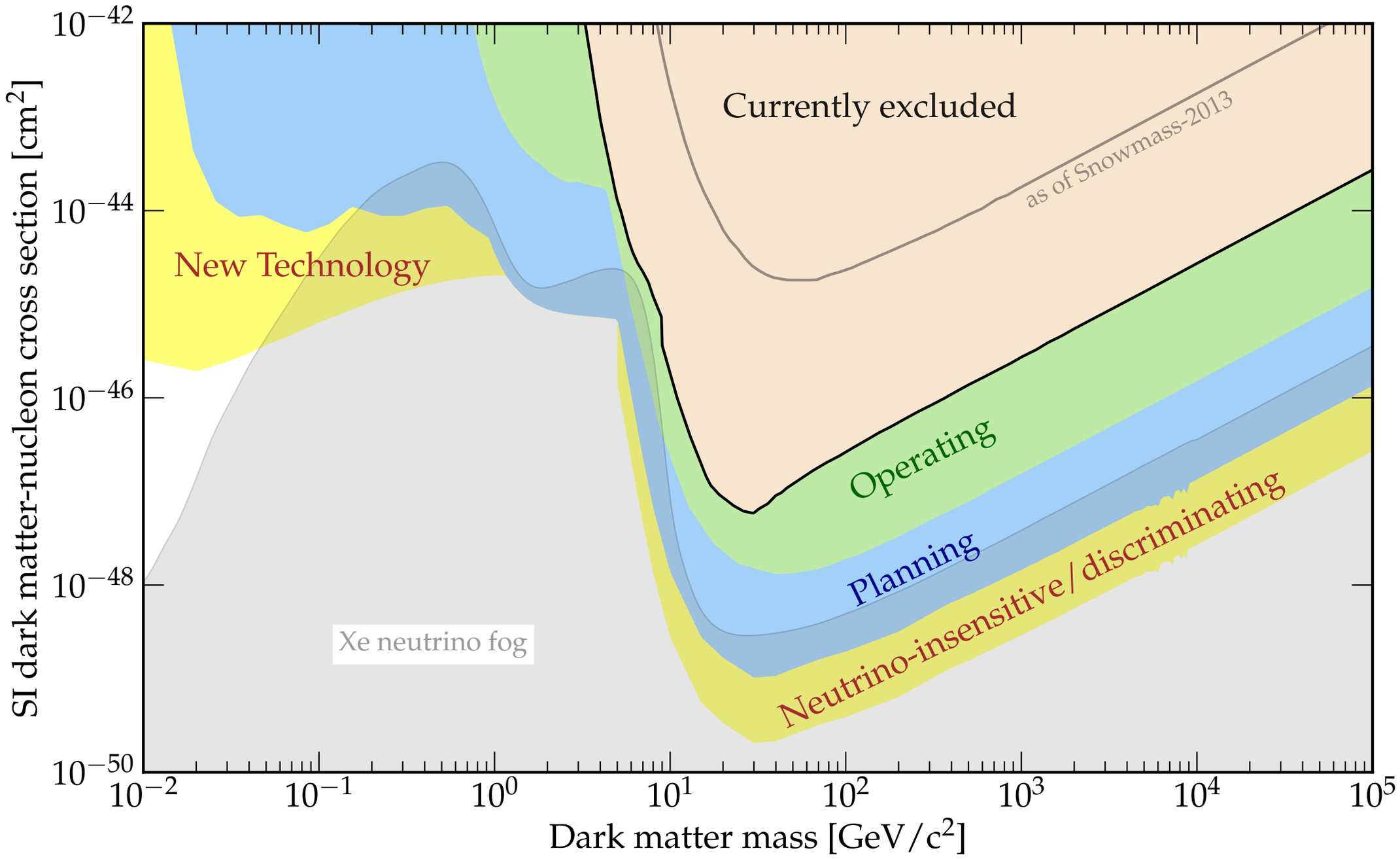
Current status



Plan for next decade



- **Direct detection at ~TeV scale has now entered the multi-tonne era (delve deep)!**
  - **LZ with new WIMP limits! (but no dark matter)**
  - **Lots of interesting talks here (and at IDM two weeks ago)**



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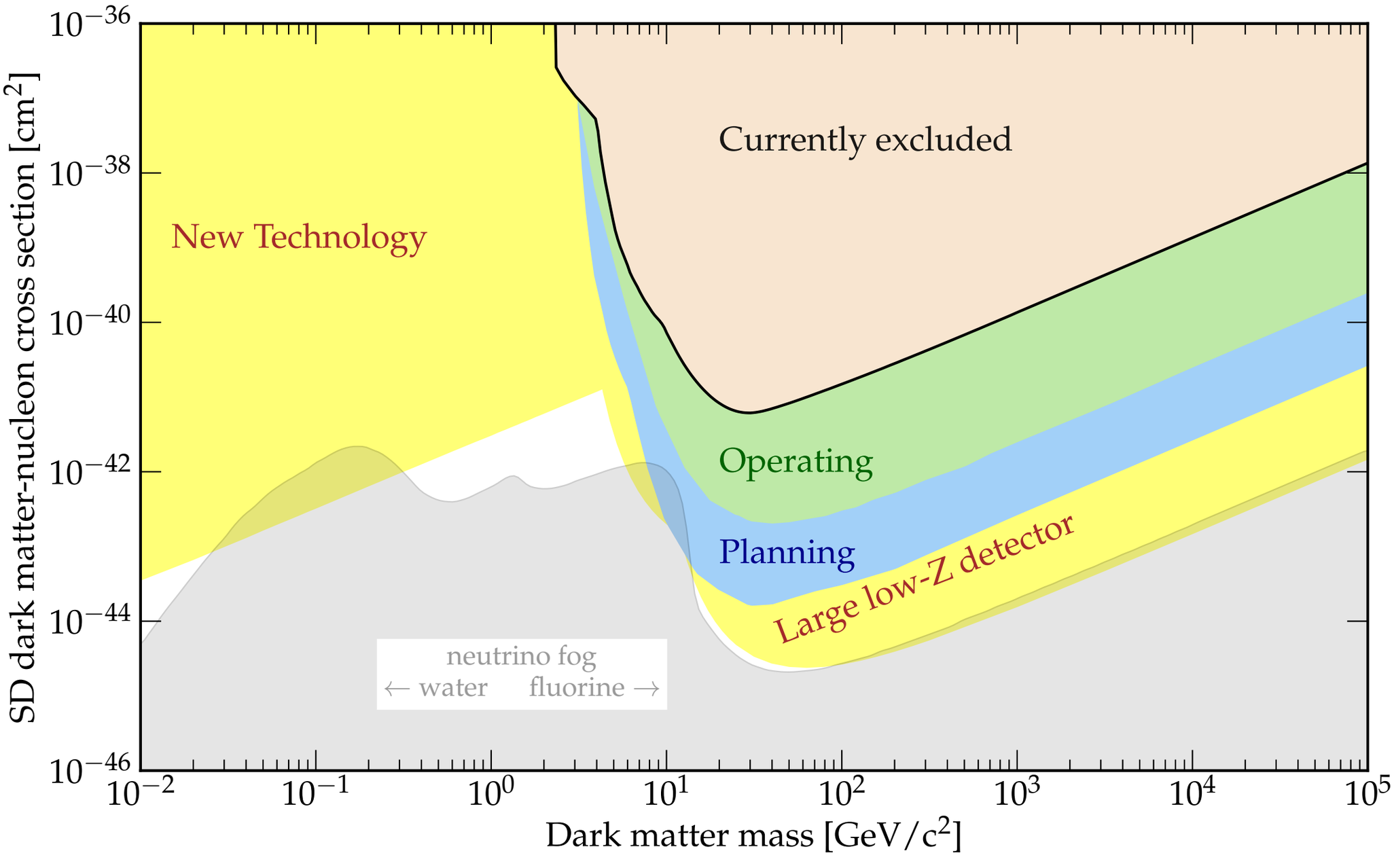
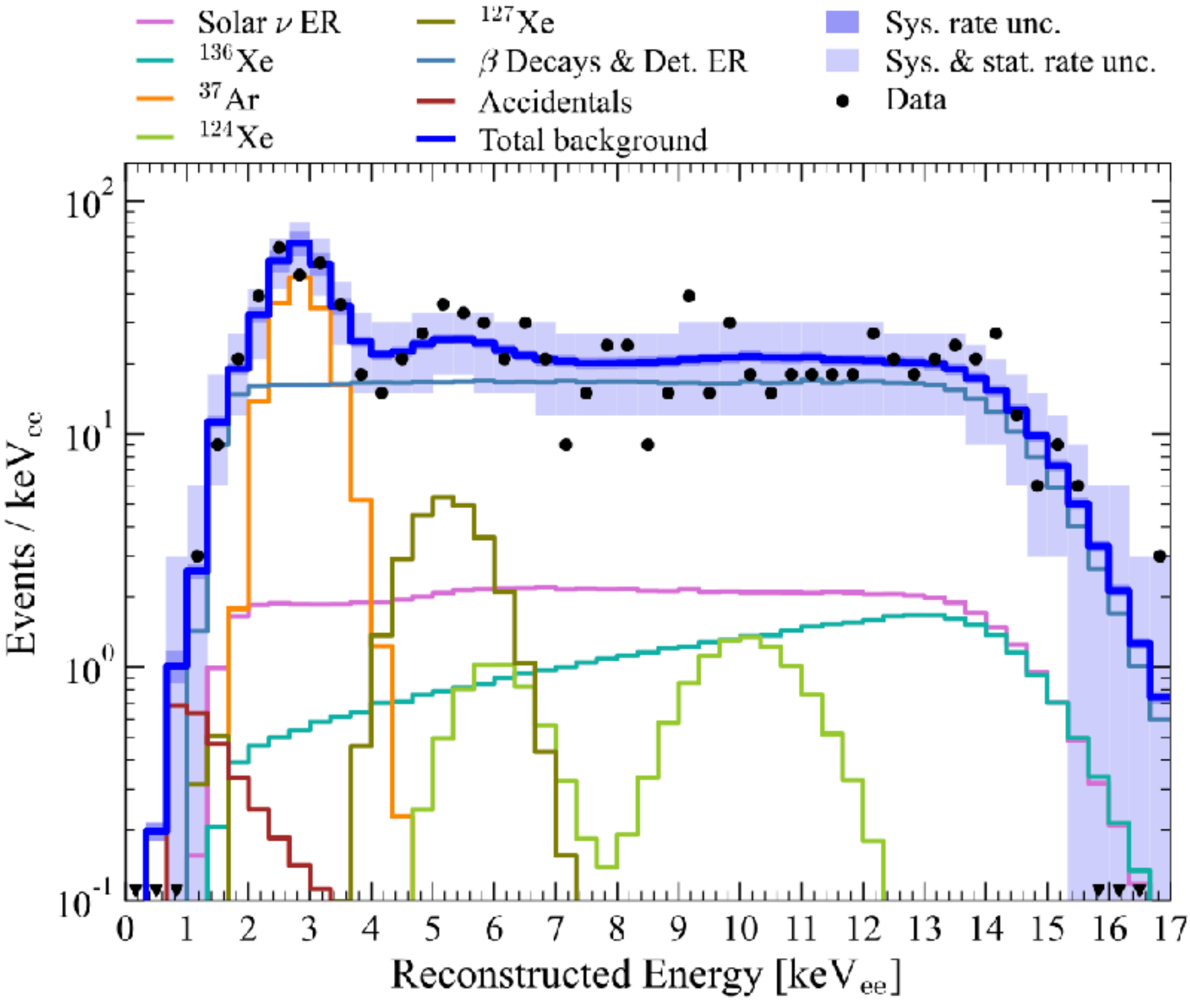
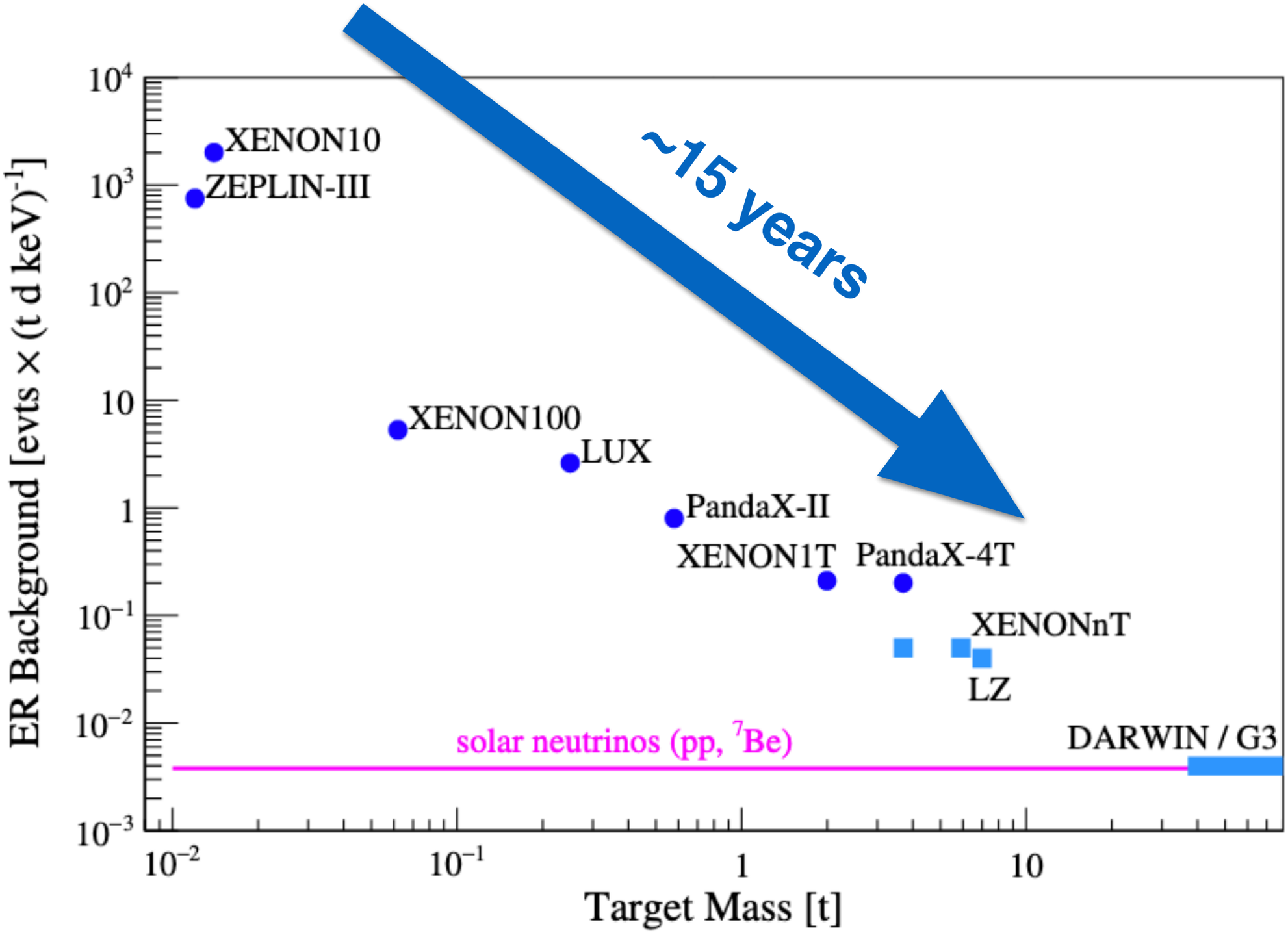


- **Backup**

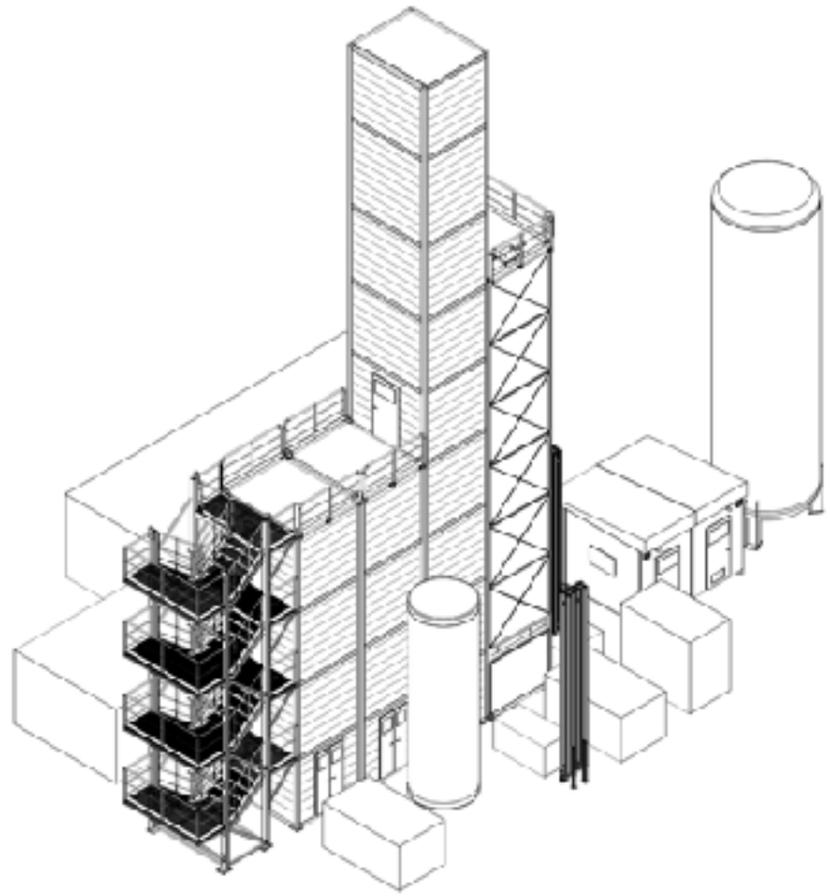

Solar ν ER
136Xe
37Ar
124Xe
127Xe
β Decays & Det. ER
Accidentals
Total background
Sys. rate unc.
Sys. & stat. rate unc.
Data
Events / keV_ee
Reconstructed Energy [keV_ee]

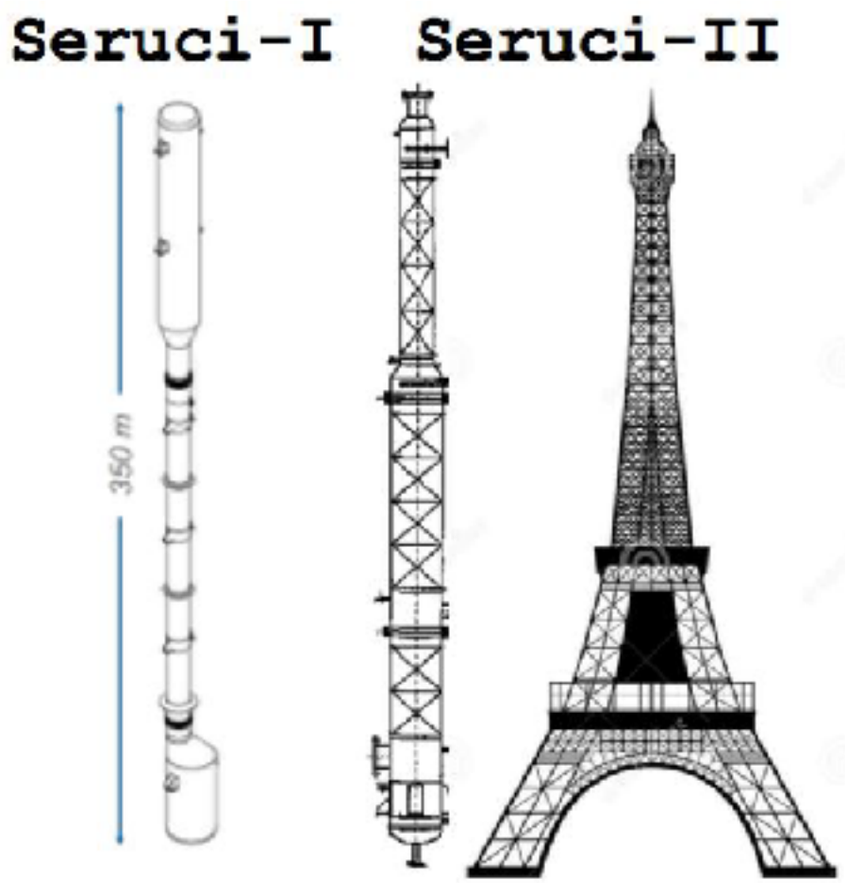
Liquid Xenon TPCs



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



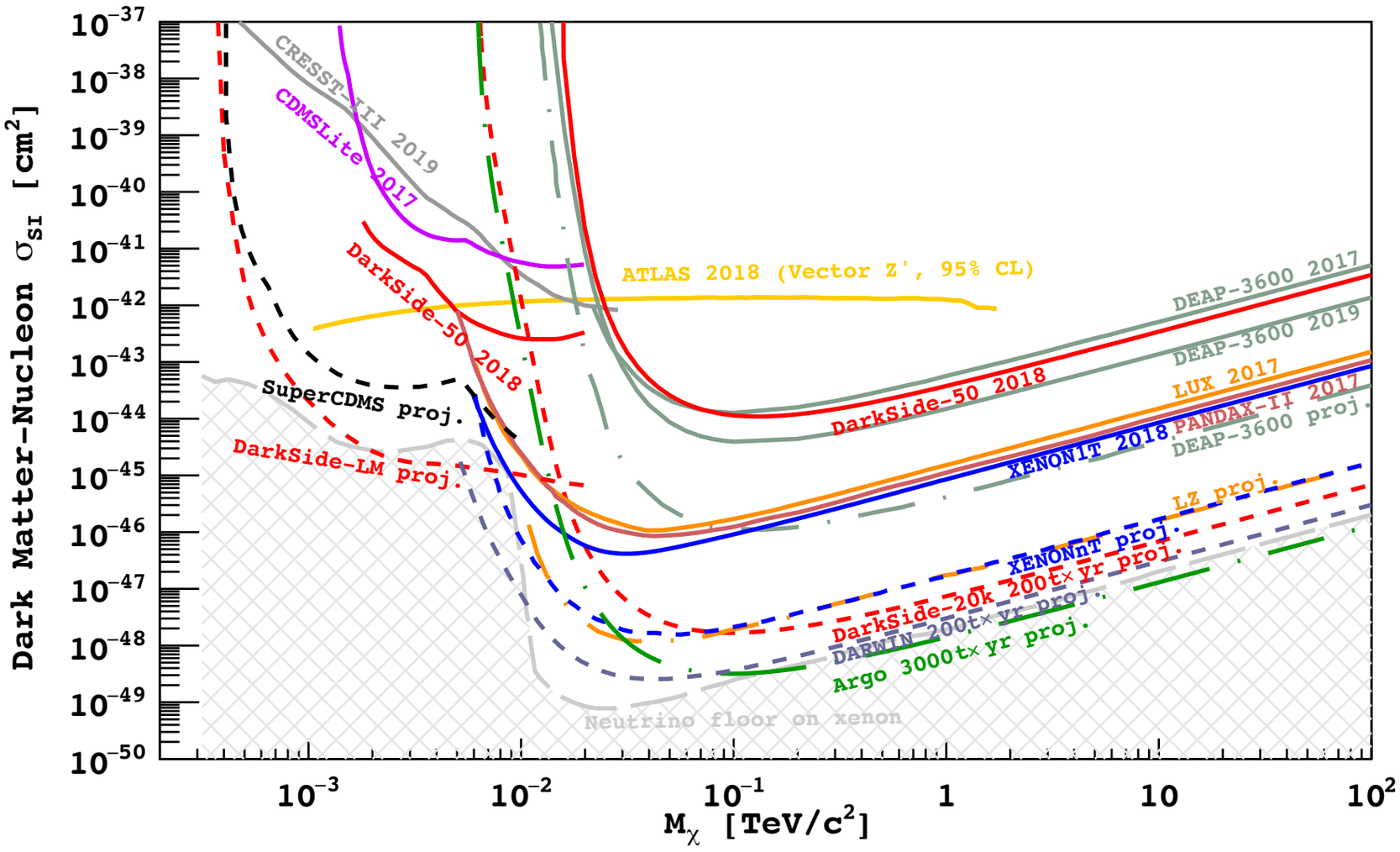


ARIA

- 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

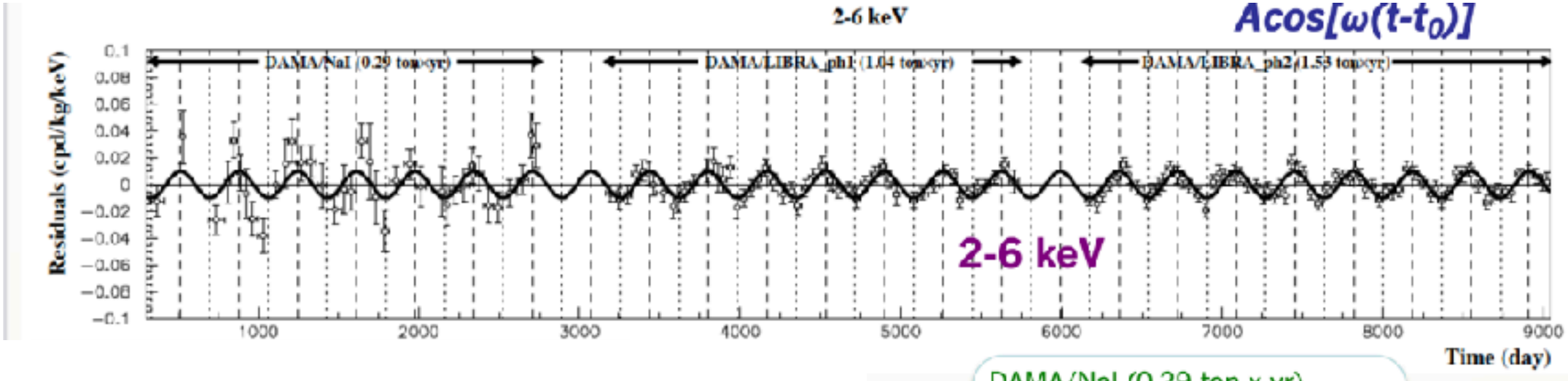
- ArDM, DS-50, DEAP-3600, and MiniCLEAN jointly formed the Global Argon Dark Matter Collaboration (GADMC)
- A 300-tonnes fiducial argon detector filled with underground argon
- 3000 tonne×year exposure to reach the neutrino floor



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**