Progress and Prospects in Dark Matter Direct Detection

Hugh Lippincott, UCSB

May 11-13, 2026 – PHENO

Dark Matter 25 years ago

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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Department of Physics and Enrico Fermi Institute,
University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637

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

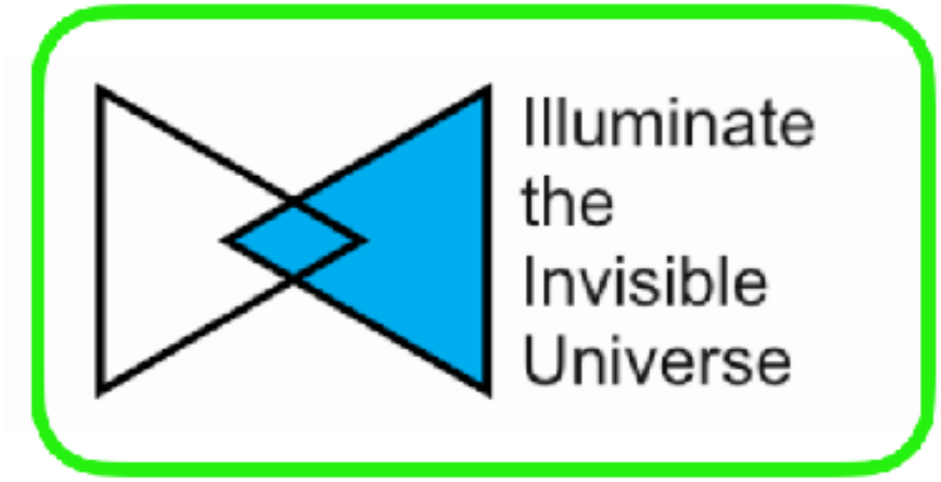
(Dated: October 30, 2018)

III. DARK MATTER AND RELIC PARTICLES

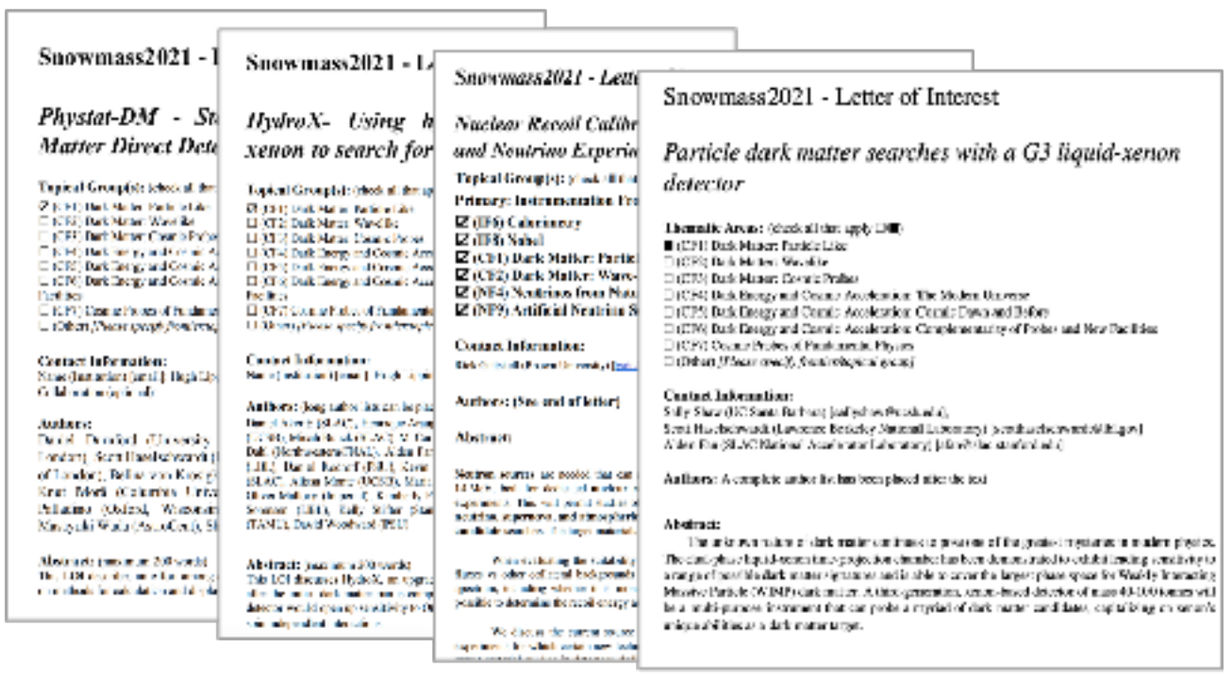
"Particle physics offers two different hypotheses for the dark matter—WIMPs and axions—either of which would constitute a major discovery of physics beyond the standard model."

Snowmass and P5

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



P5 Report December 2023



- Most commonly mentioned topic in Snowmass LOIs

Snowmass and P5

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

Report of the Topical Group on Wave Dark Matter for Snowmass 2021

Conveners: Joerg Jaeckel[1], Gray Rybka[2], and Lindley Winslow[3]

[1]Institut für Theoretische
[2]Department of Phys
[3]Laboratory for Nuclear Science,

Report of the Topical Group on Particle Dark Matter for Snowmass 2021

Conveners: Jodi Cooley[1,2], Tongyan Lin[3], W. Hugh Lippincott[4], Tracy R. Slatyer[5], Tien-Tien Yu[6],
Contributors: Daniel S. Akerib[7], Tsuguo Aramaki[8], Daniel Baxter[9], Torsten Bringmann[10], Ray Bunker[11], Daniel Carney[12], Susana Cebrián[13], Thomas Y. Chen[14], Priscilla Cushman[15], C.E. Dahl[16], Rouven Essig[17], Alden Fan[7], Richard Gaitskell[18], Cristano Galbiati[19], Graciela B. Gelmini[20], Graham K. Giovanetti[21], Guillaume Giroux[22], Luca Grandi[23], J. Patrick Harding[24], Scott Haselschwardt[12], Lauren Hsu[6], Shunsaku Horiuchi[25], Yonatan Kahn[26], Doojin Kim[27], Geon-Bo Kim[28], Scott Kravitz[12], V. A. Kudryavtsev[29], Noah Kurinsky[7], Rafael F. Lang[30], Rebecca K. Leane[7], Benjamin V. Lehmann[31], Cecilia Levy[32], Shengchao Li[30], Marfa[33], Gopolang Mohlabeng[34], M.E. Monzani[7,35,36], Alexander St. Nelson[5], Ciaran A. J. O'Hare[37], K.J. Palladino[40], Aditya Parikh[41], Jur Profumo[31,45], Nirmal Raj[46], Brandon M. Roach[44], Tarek Saab[47], Mari Shaw[6], Seodong Shin[44], Kuver Sinha[43], Kelly Stifter[9], Aritoki Suzu Volodymyr Takhistov[51,52], Yu-Dai Tsai[34], S. E. Vahsen[53], Edoardo Gensheng Wang[54], Shawn Westerdale[55], David A. Williams[31,

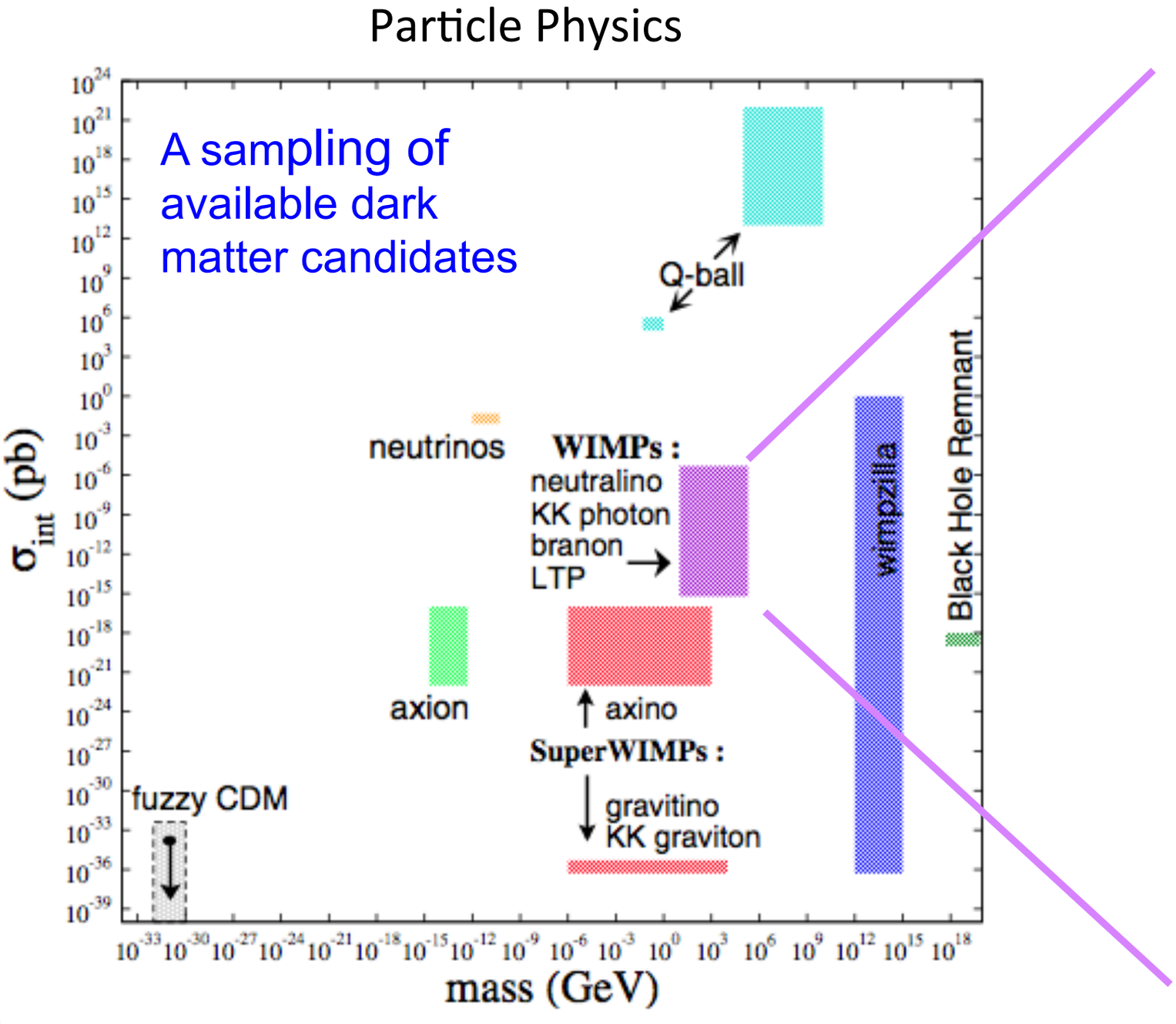
Cosmic Probes of Dark Matter

Conveners: Alex Drlica-Wagner, Chanda Prescod-Weinstein, Hai-Bo Yu

Contributors: Andrea Albert, Mustafa Amin, Arka Banerjee, Masha Baryakhtar, Keith Bechtol, Simeon Bird, Simon Birrer, Torsten Bringmann, Regina Caputo, Sukanya Chakrabarti, Thomas Y. Chen, Djuna Croon, Francis-Yan Cyr-Racine, William A. Dawson, Cora Dvorkin, Vera Gluscevic, Daniel Gilman, Daniel Grin, Renée Hložek, Rebecca K. Leane, Ting S. Li, Yao-Yuan Mao, Joel Meyers, Siddharth Mishra-Sharma, Julian B. Muñoz, Ferah Munshi, Ethan O. Nadler, Aditya Parikh, Kerstin Perez, Annika H. G. Peter, Stefano Profumo, Katelin Schutz, Neelima Sehgal, Joshua D. Simon, Kuver Sinha, Monica Valluri, Risa H. Wechsler

- Over 100 pages of dedicated Snowmass reports in CF
- High prominence in other frontiers
- Dedicated Complementarity report
- Can only give a sense here - impossible to summarize in 30 minutes!

Dark Matter



It's probably WIMPs, right?

Back to 2021

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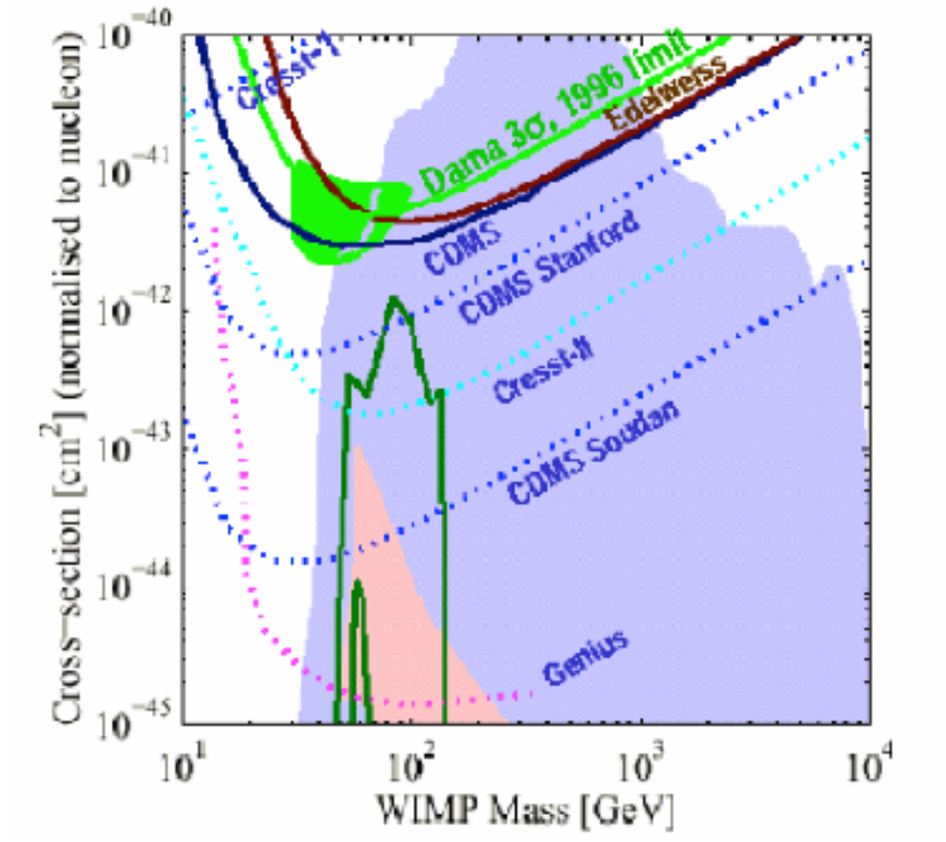
(Dated: October 30, 2018)

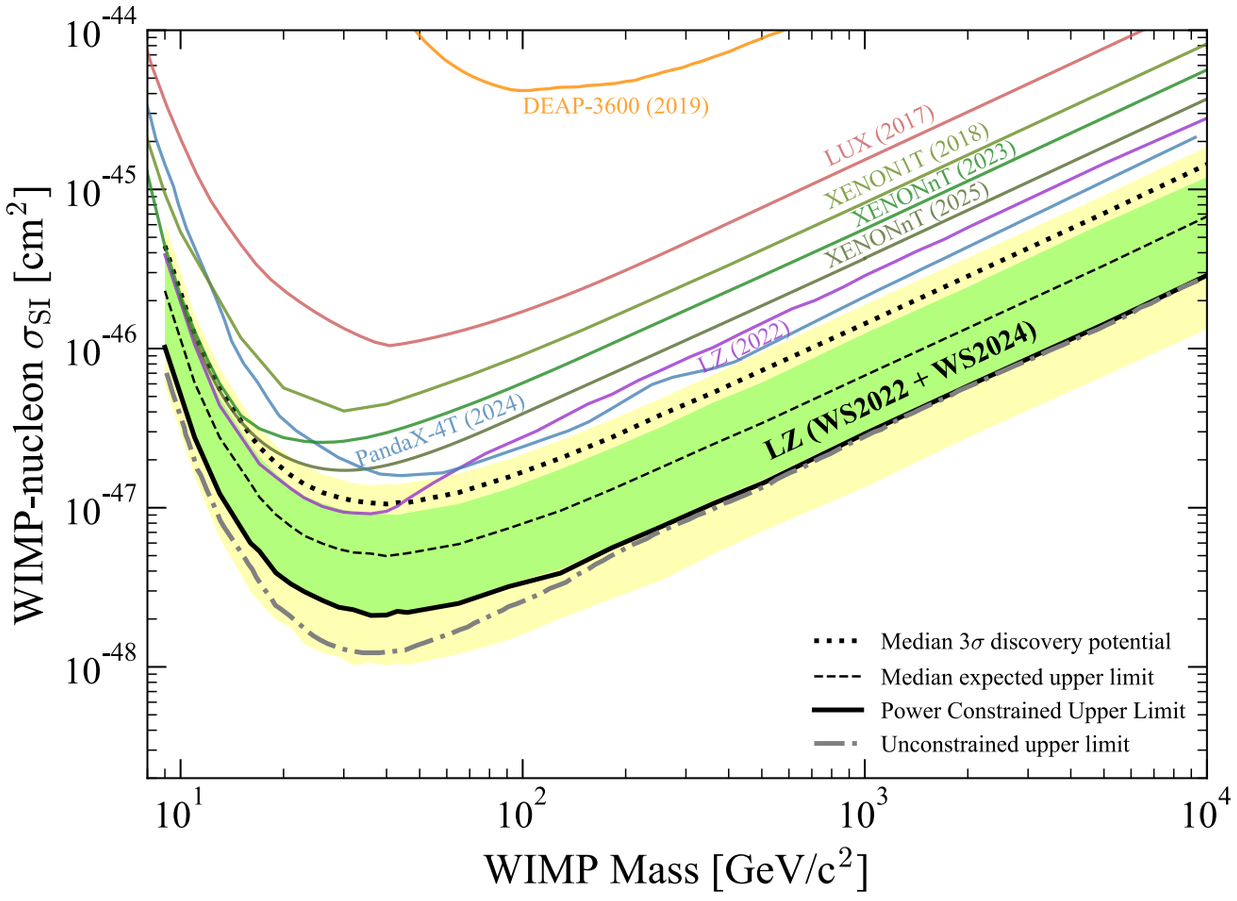
"Current searches are already exploring the parameter space of supersymmetric WIMPs [10-1000 GeV], with prospects for a factor of a hundred improvement in the coming years."

WIMPs

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

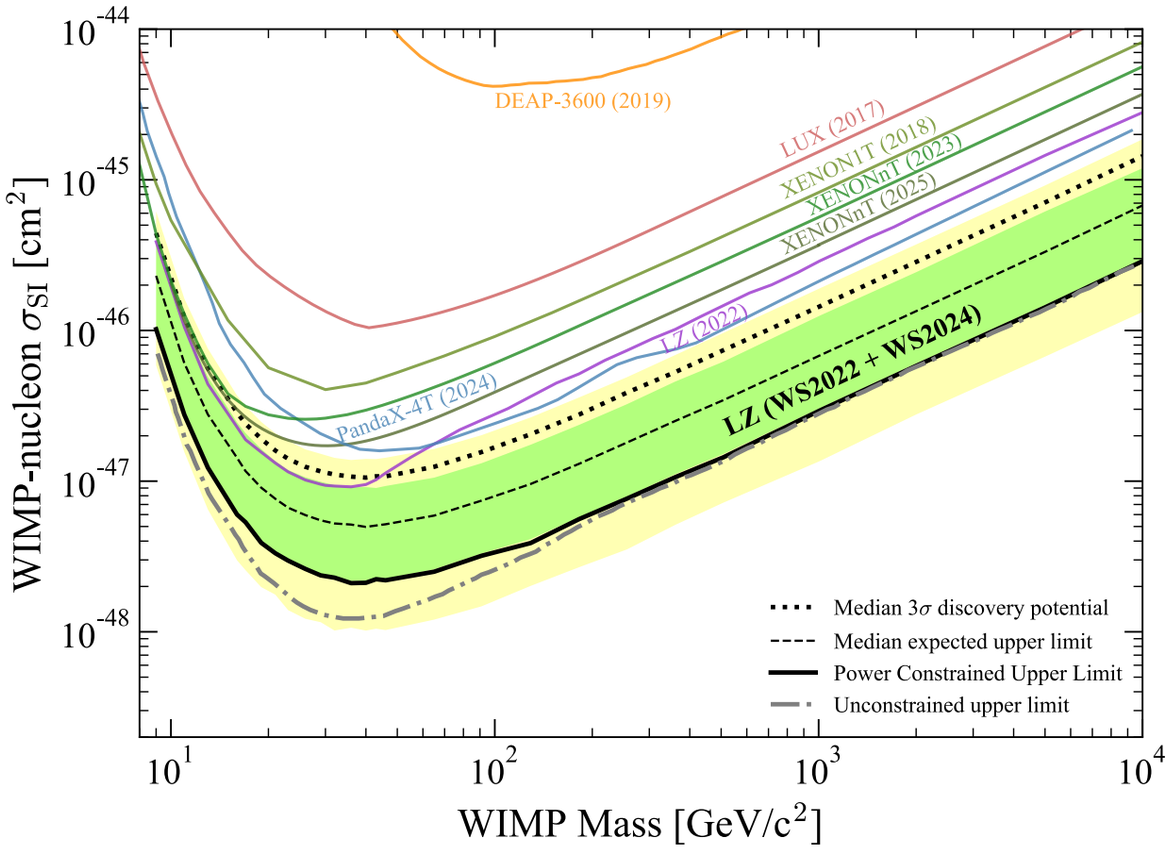


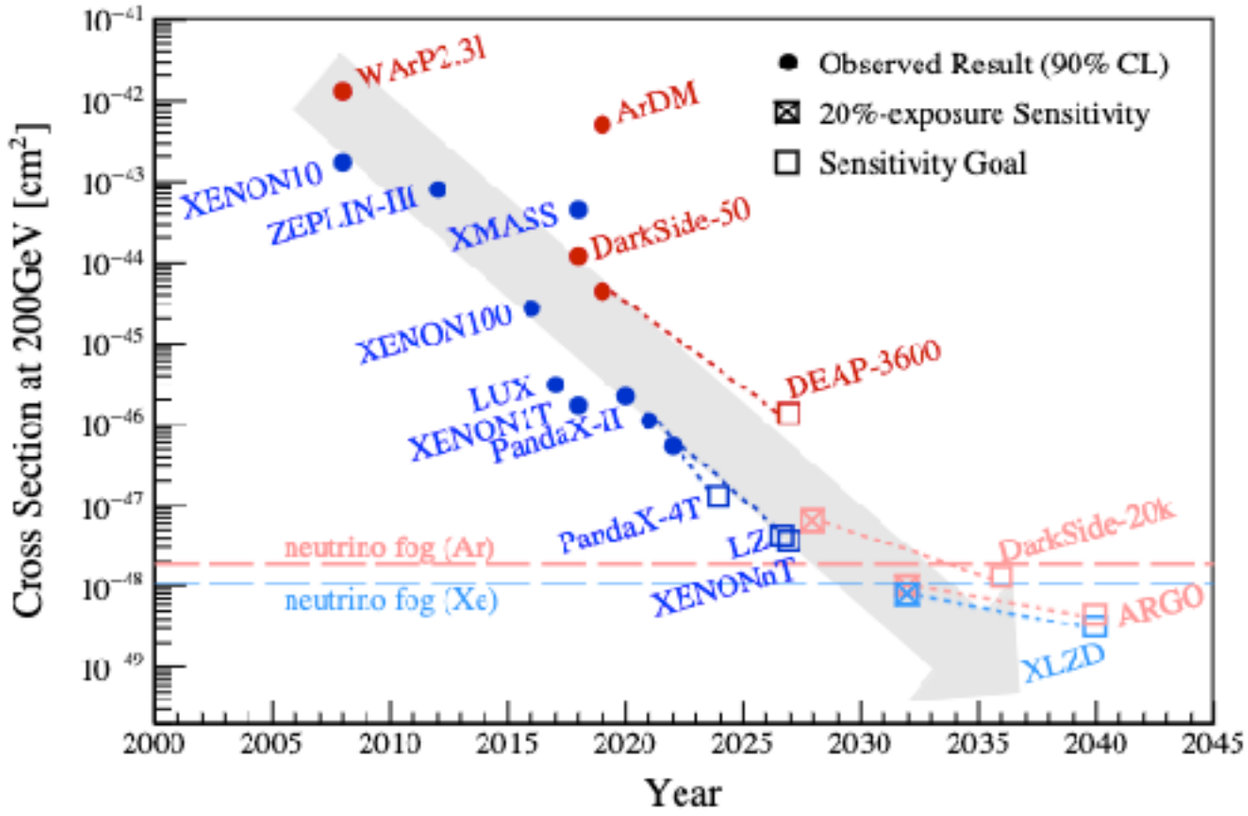
- LZ PRL 135: 011802, (2025)
- Best limit at 2.2 x 10^{-48} cm^2



- Factor of 1,360,000 improvement in 25 years! Doubling every 1.2 years!
- A triumph of human ingenuity!
- No WIMPs :(

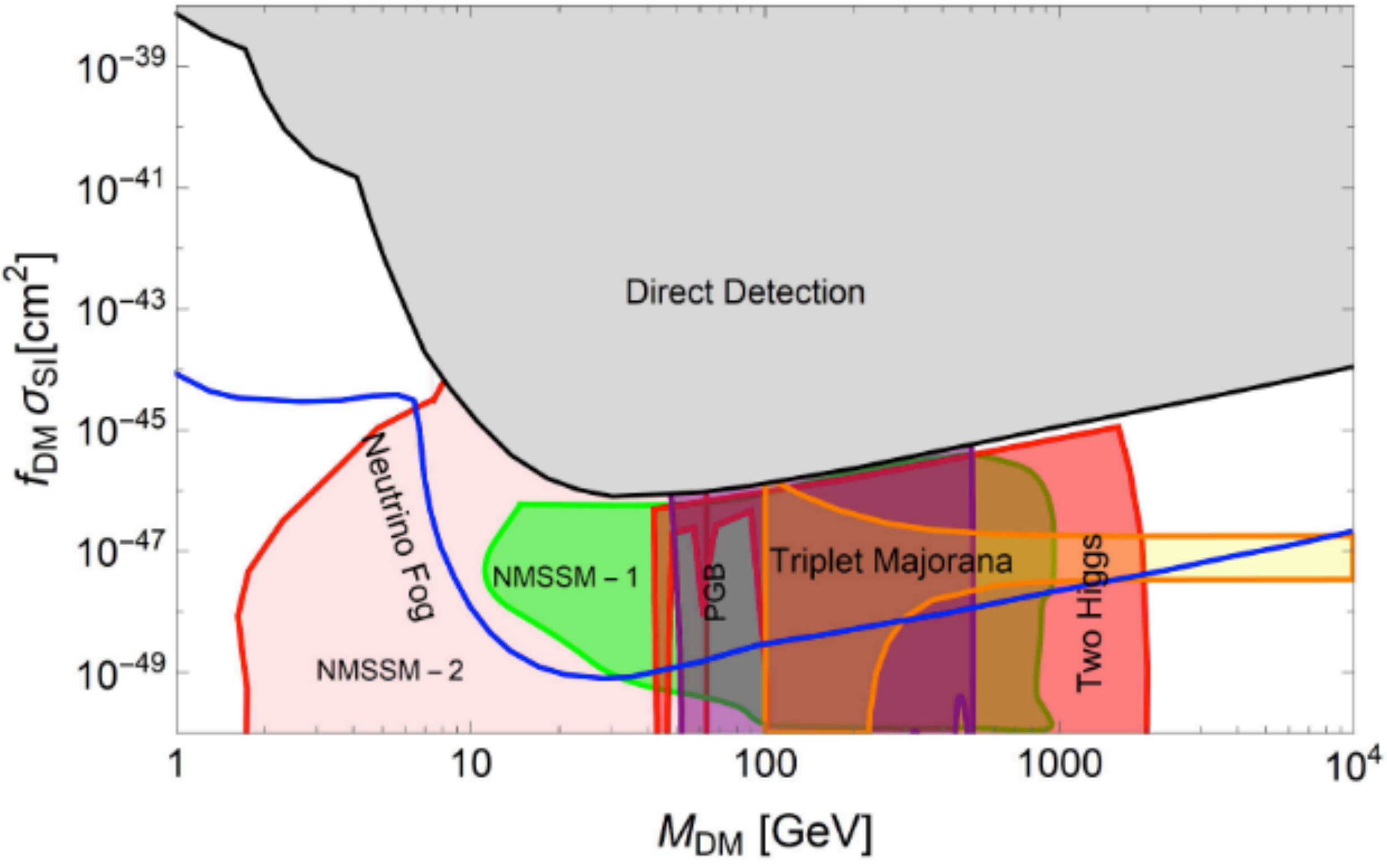
WIMPs





- Xenon experiments have been driving sensitivity to ~100 GeV “classic” WIMPs for the past 20 years
  - LZ, XENONnT, and PandaX-4T - multi tonne xenon experiments now operating
- Argon experiments offer very large targets with good background discrimination
  - DarkSide-20k under construction

What are we looking for?



CF Snowmass 2203.08084

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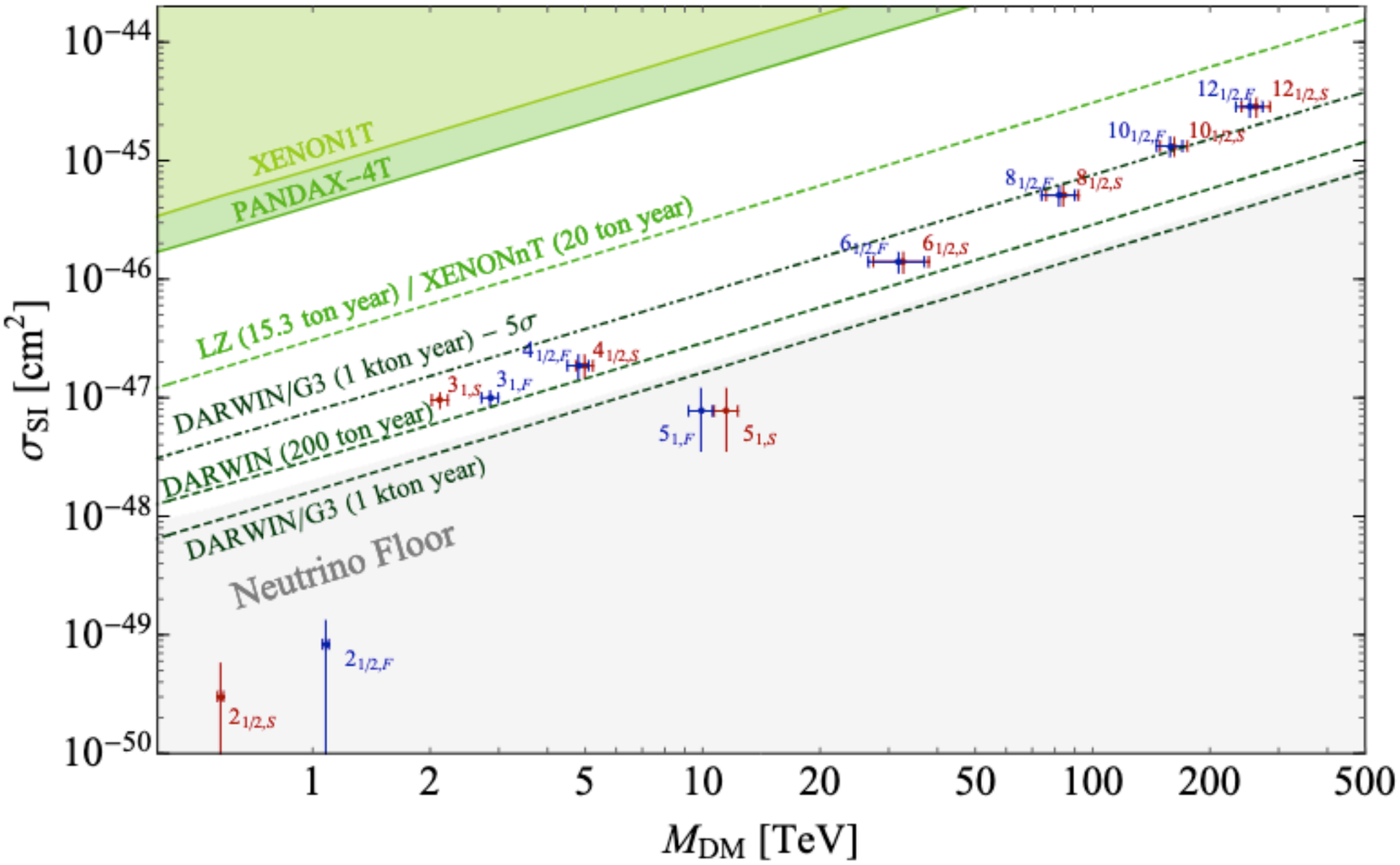
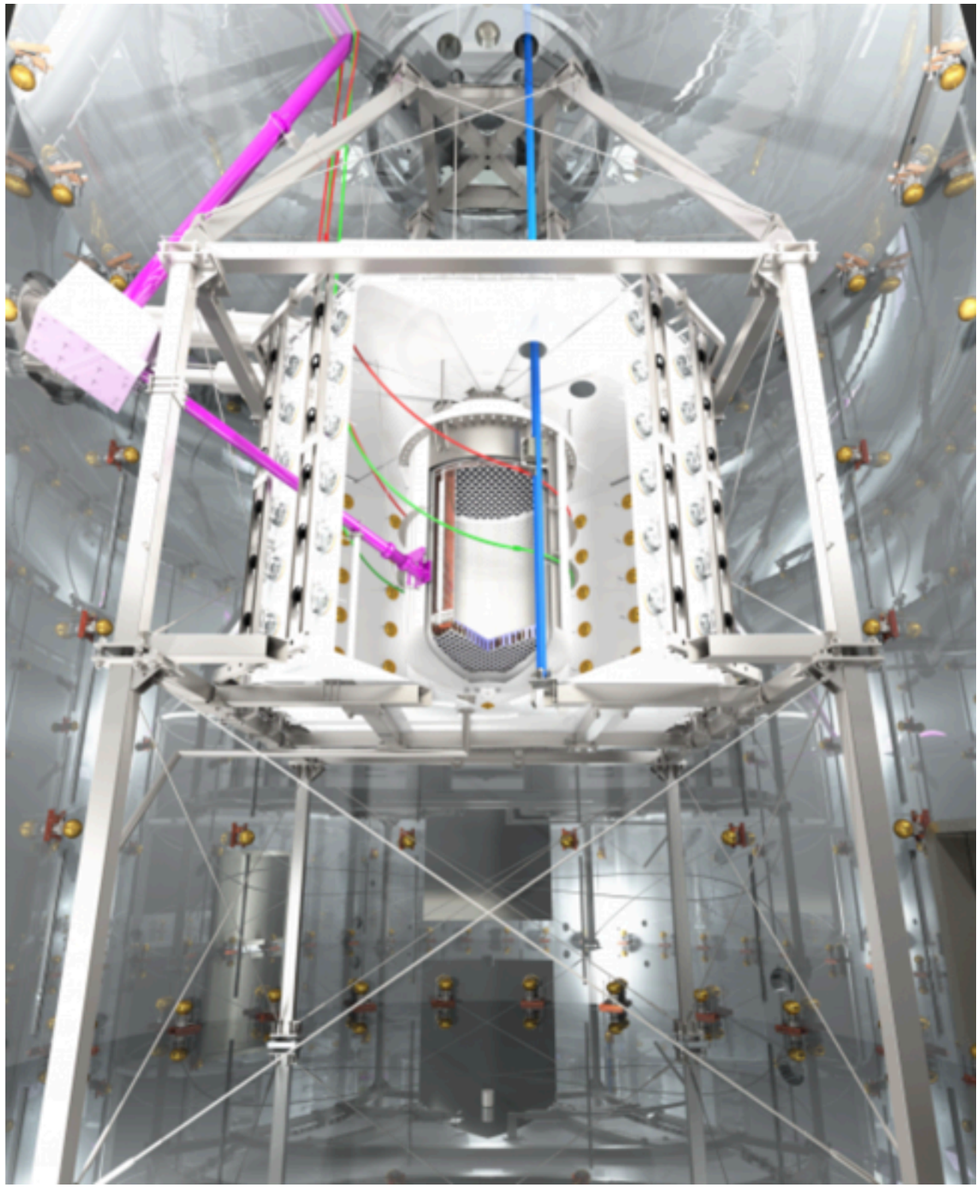


From Bottaro et al, 2205.04486 - Electroweak WIMP candidates - tree-level Higgs process vanishes -> small cross sections

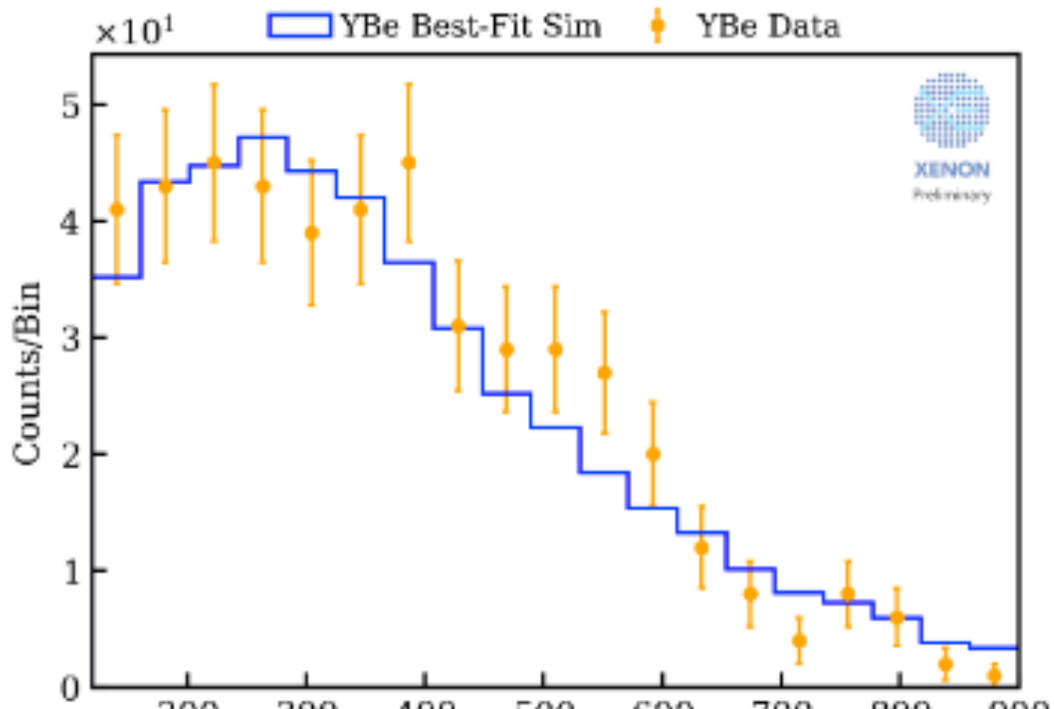
WIMPs

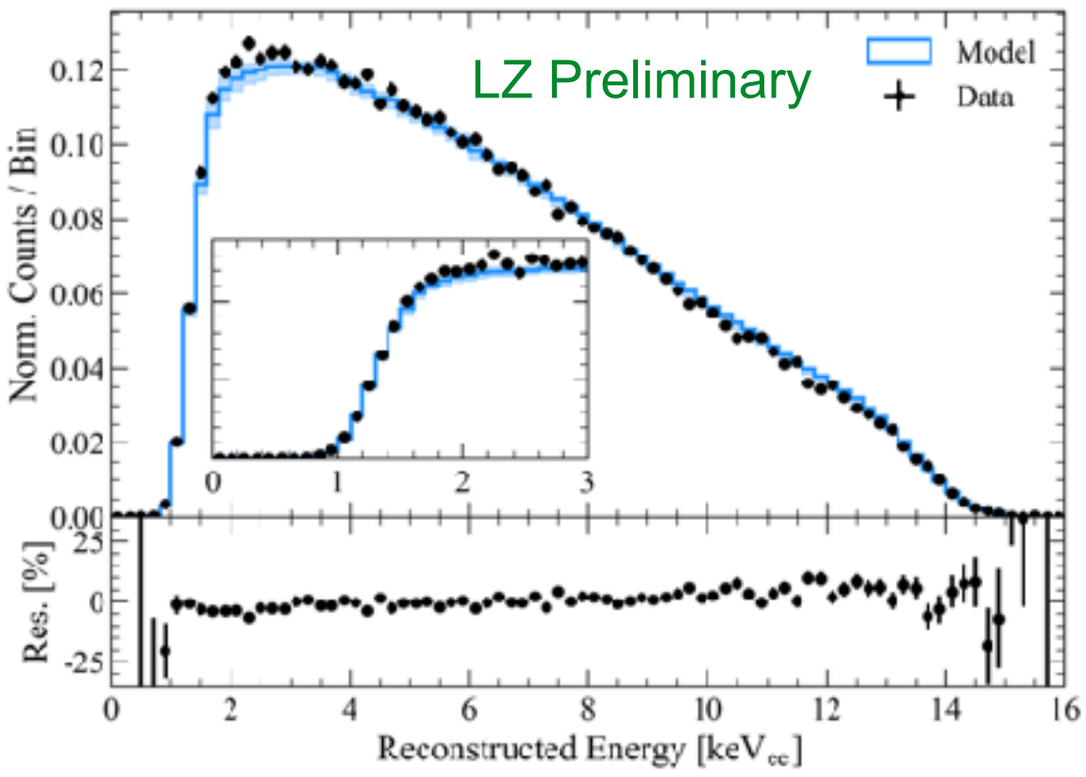
WIMPs

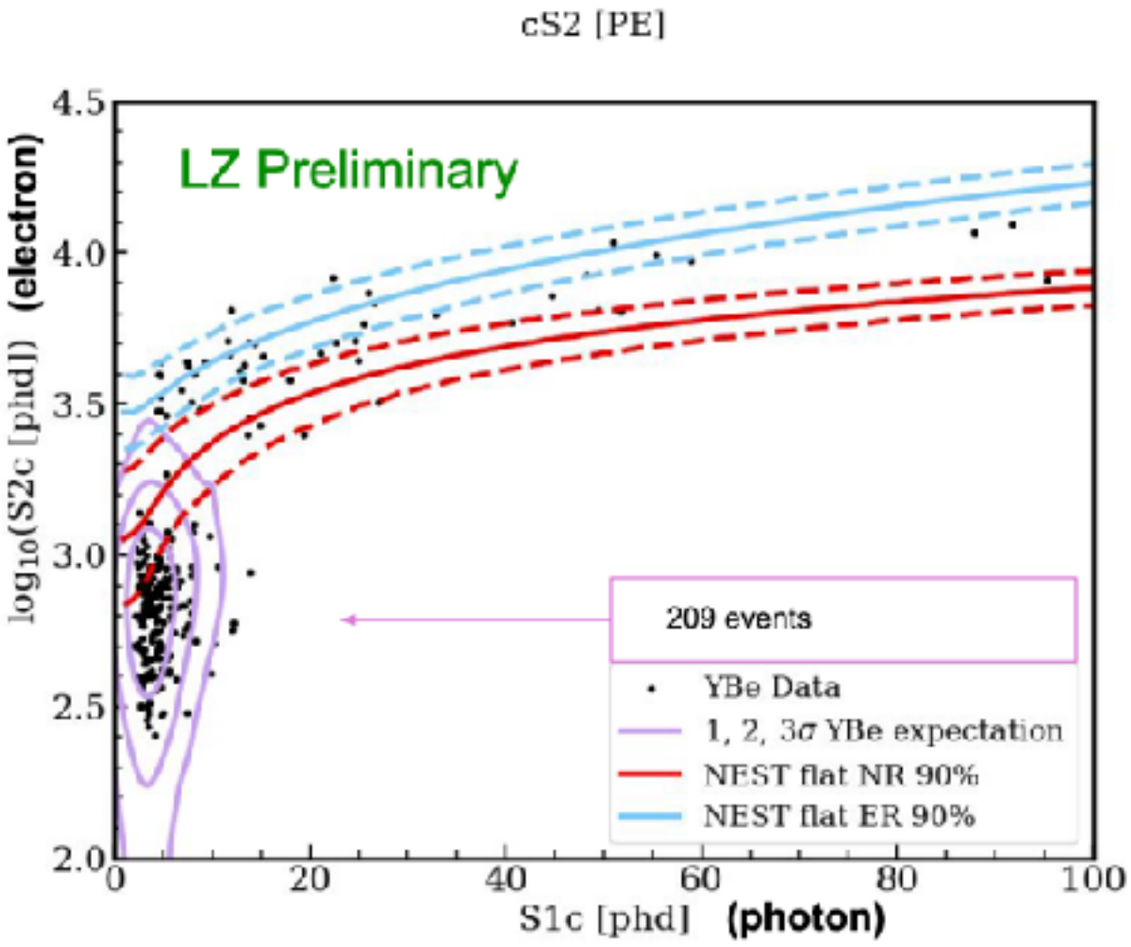


Some recent developments

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

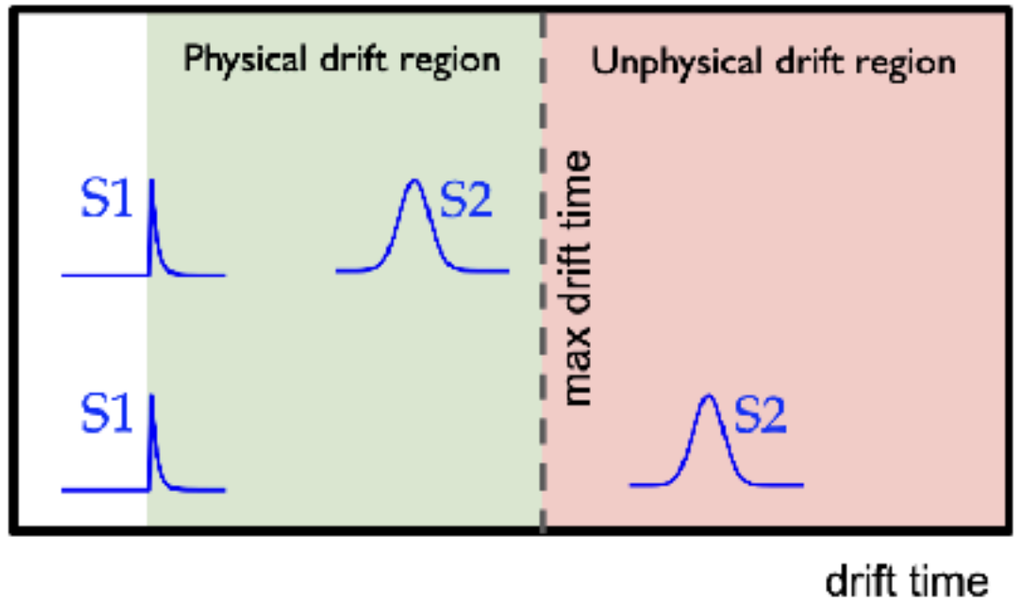


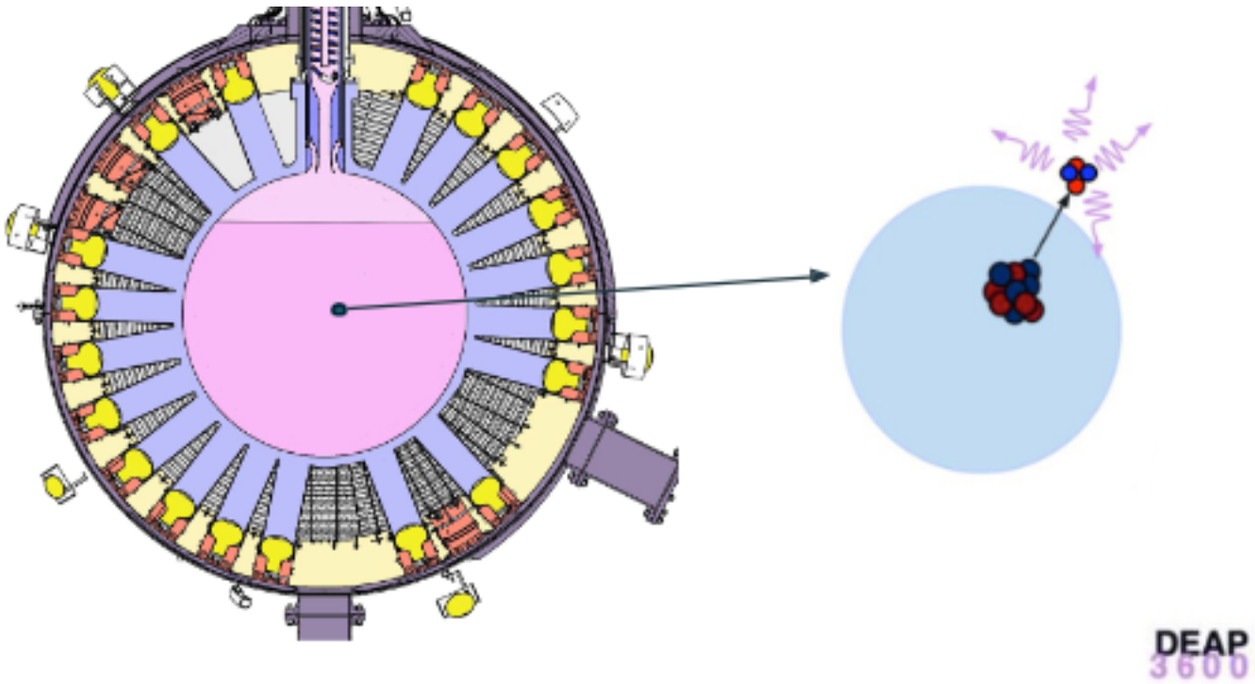


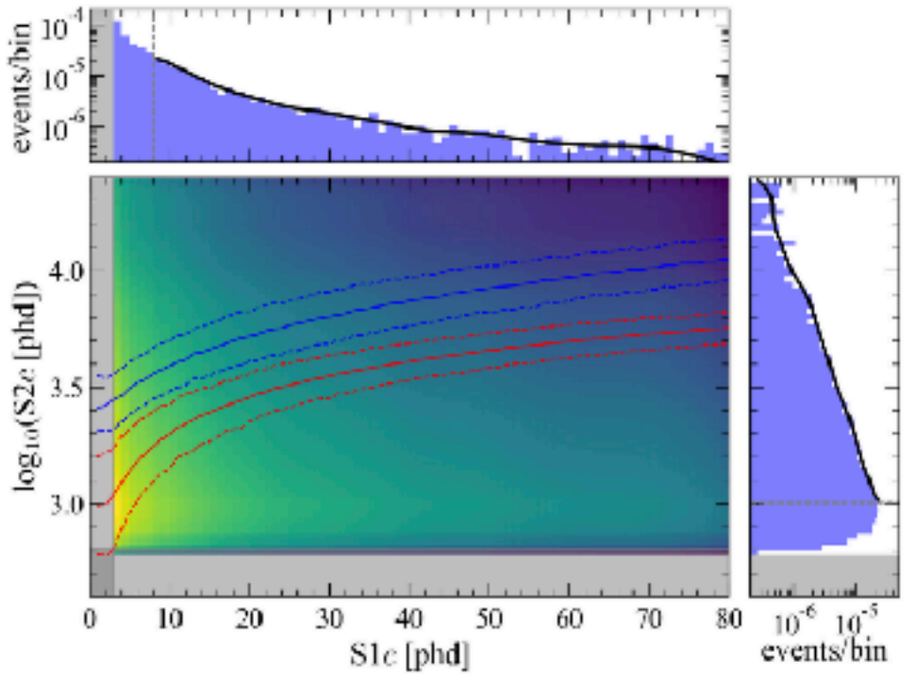


Progress is hard!

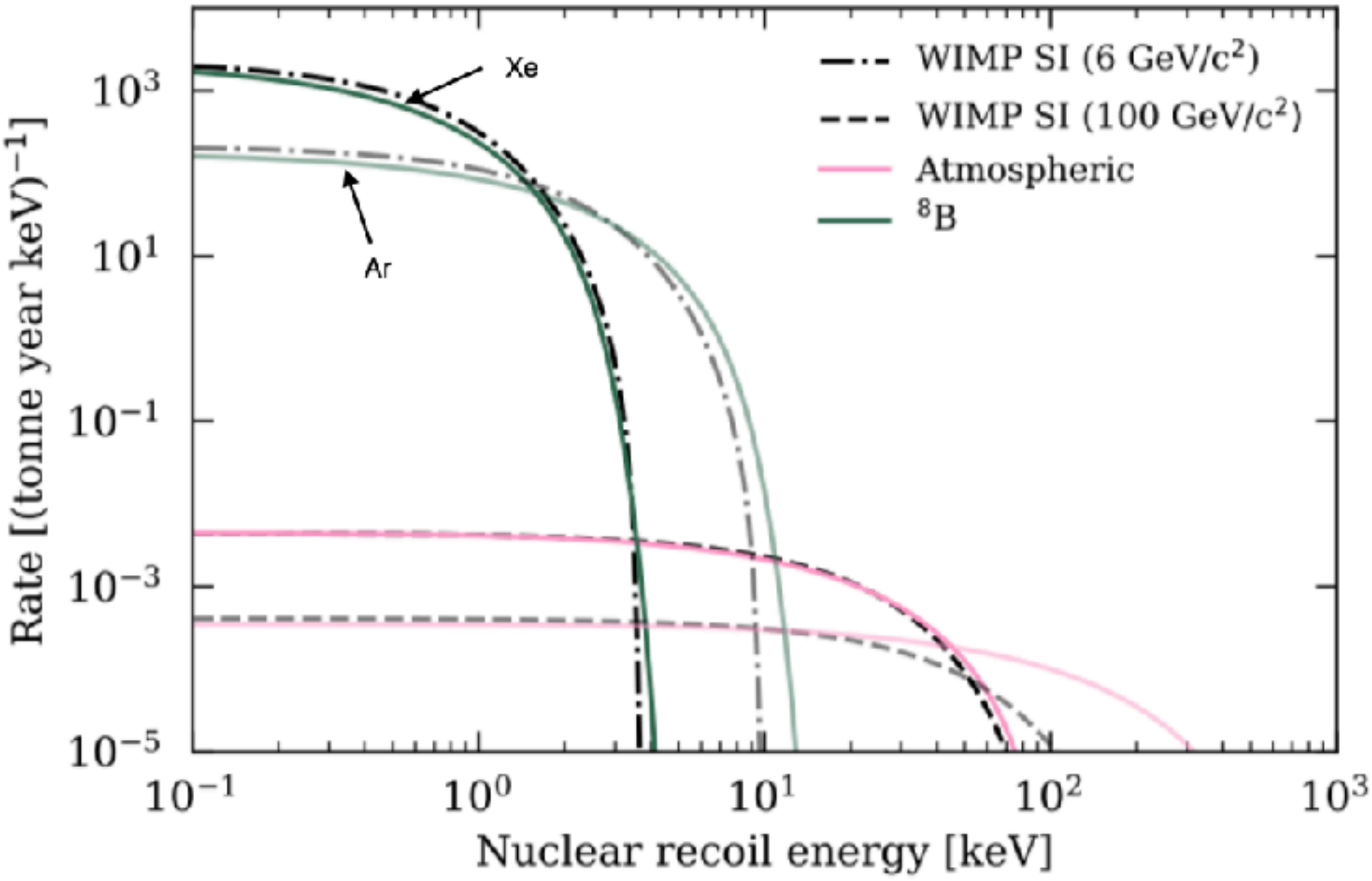
- Each detector must grapple with a new set of backgrounds e.g.
  - Accidentals in LXe-TPCs
  - Dust and geometry in DEAP-3600
  - Neutrinos…?







Neutrino Fog

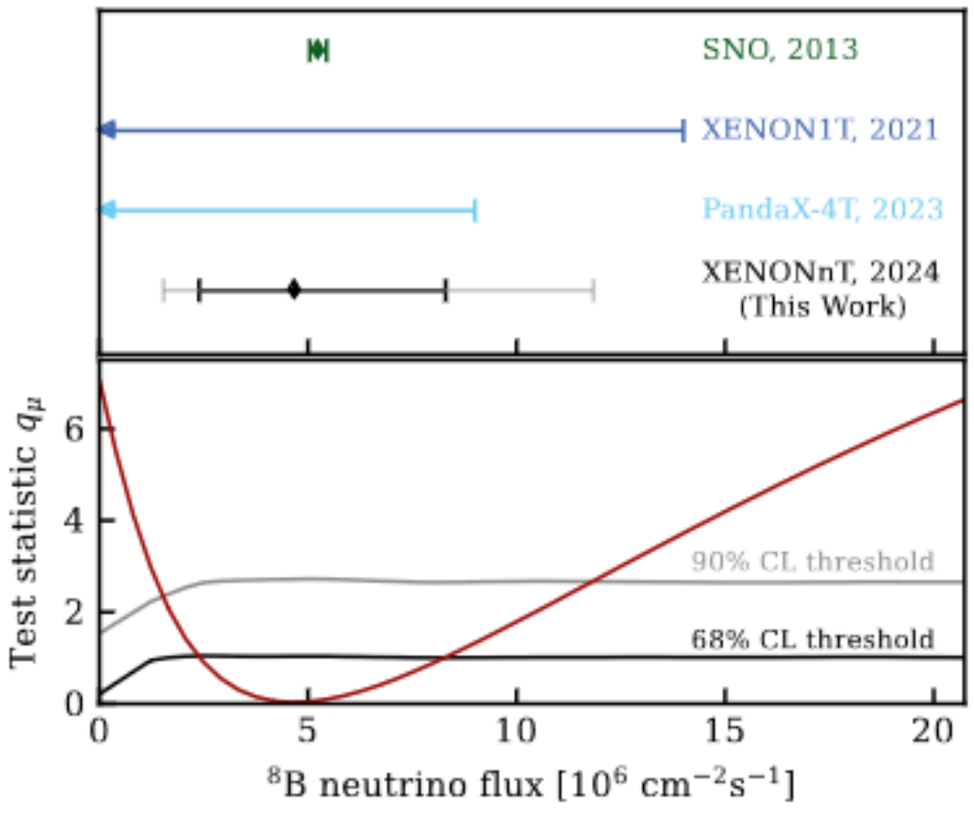


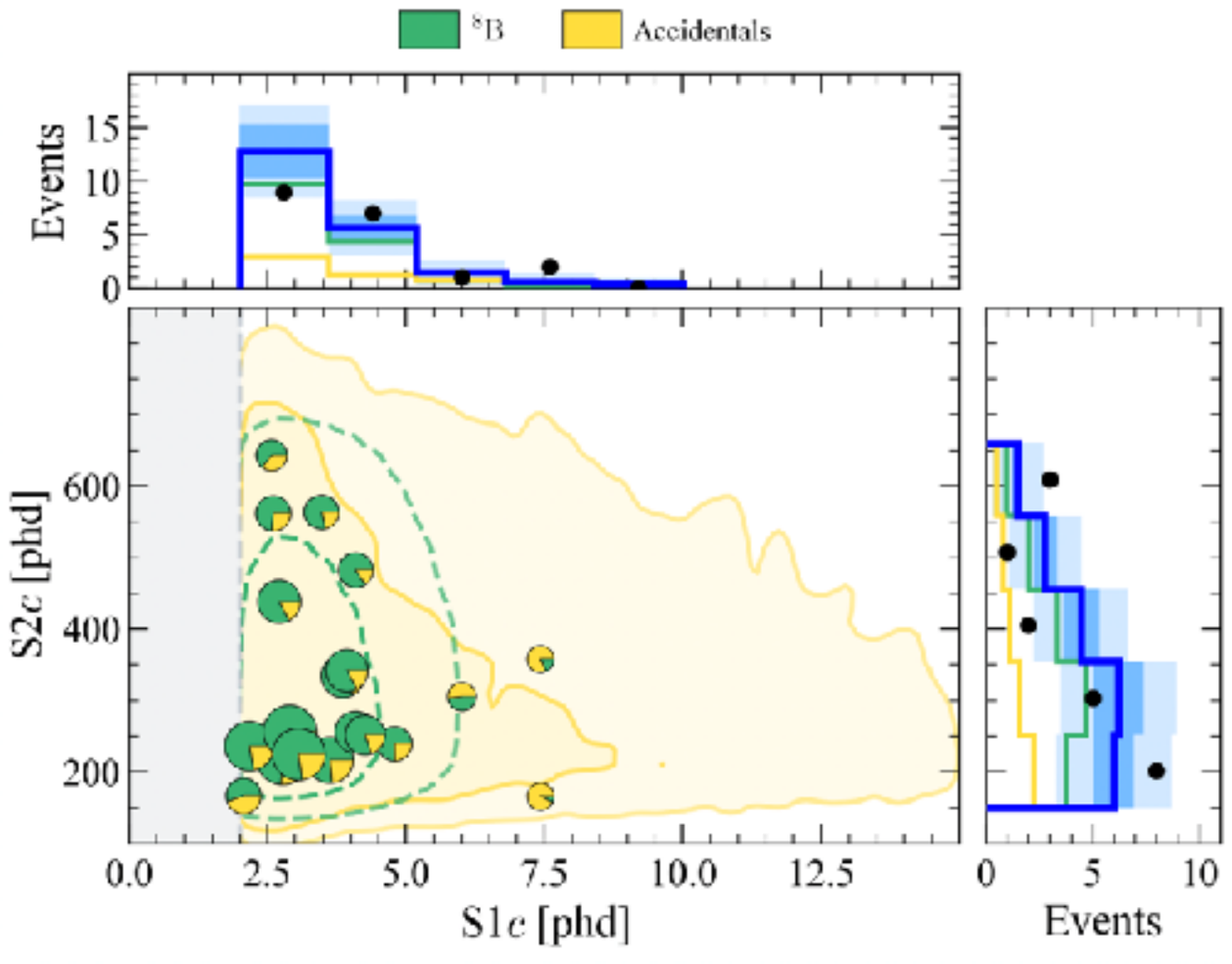
- ^{8}B solar neutrinos have a measured flux (SNO, SuperK, etc)
- Interact coherently with nuclei like DM - coherent neutrino nucleus scattering
  - First observed in 2017 by COHERENT collaboration at Spallation Neutron Source at Oak Ridge

We're into the fog!

- The three xenon experiments are seeing clear evidence for solar ^{8}B neutrinos
- PandaX (2407.10892) and XENONnT (2408.02877) reported in 2024 with ~2.7 sigma
- LZ reported in December with 4.5 sigma (see J. Genovesi, today at 4:30)

Components	Expectation	Background-Only Fit
Spin-Independent DM	-	-
^{8}B CEνNS	$20.6^{+8.9}_{-6.8}$	$15.0^{+2.9}_{-2.5}$
Accidental coincidences	6.6 ± 0.3	6.5 ± 0.3
Detector neutrons	$0.04^{+0.25}_{-0.04}$	$0.1^{+0.2}_{-0.1}$
Total	$27.2^{+9.2}_{-6.7}$	$21.6^{+4.7}_{-3.8}$





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  (2408[illegible]
  ~2.7 s[illegible]
- LZ re[illegible]
  sigma (see J. Genovesi, XXX)

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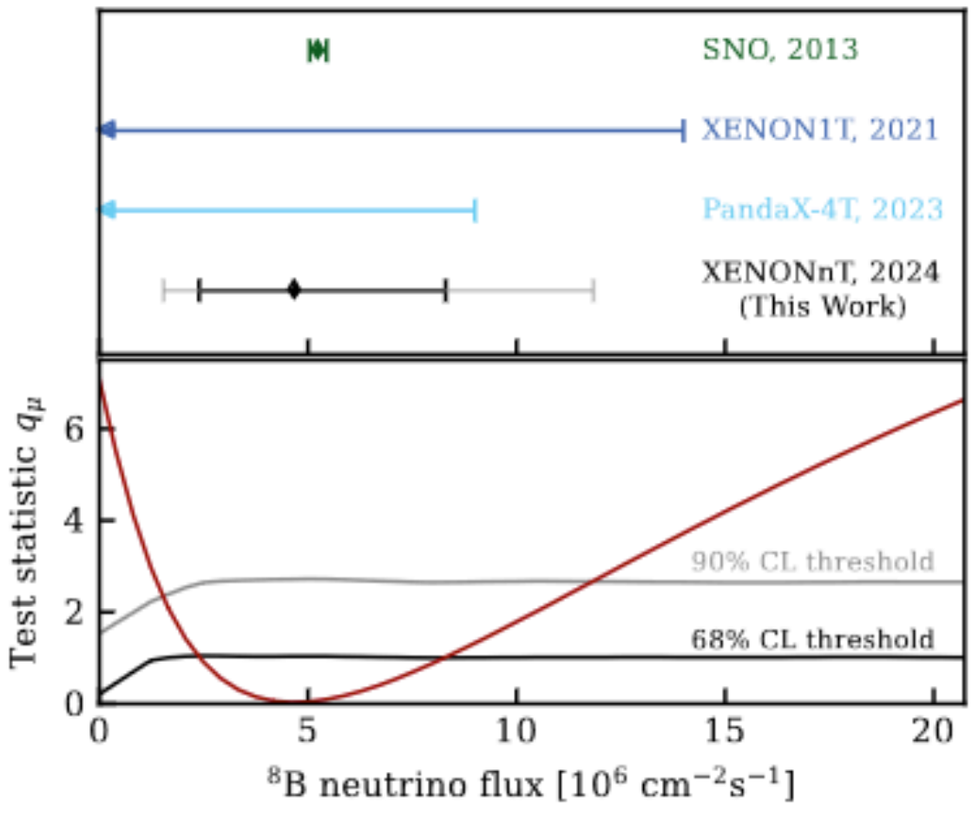
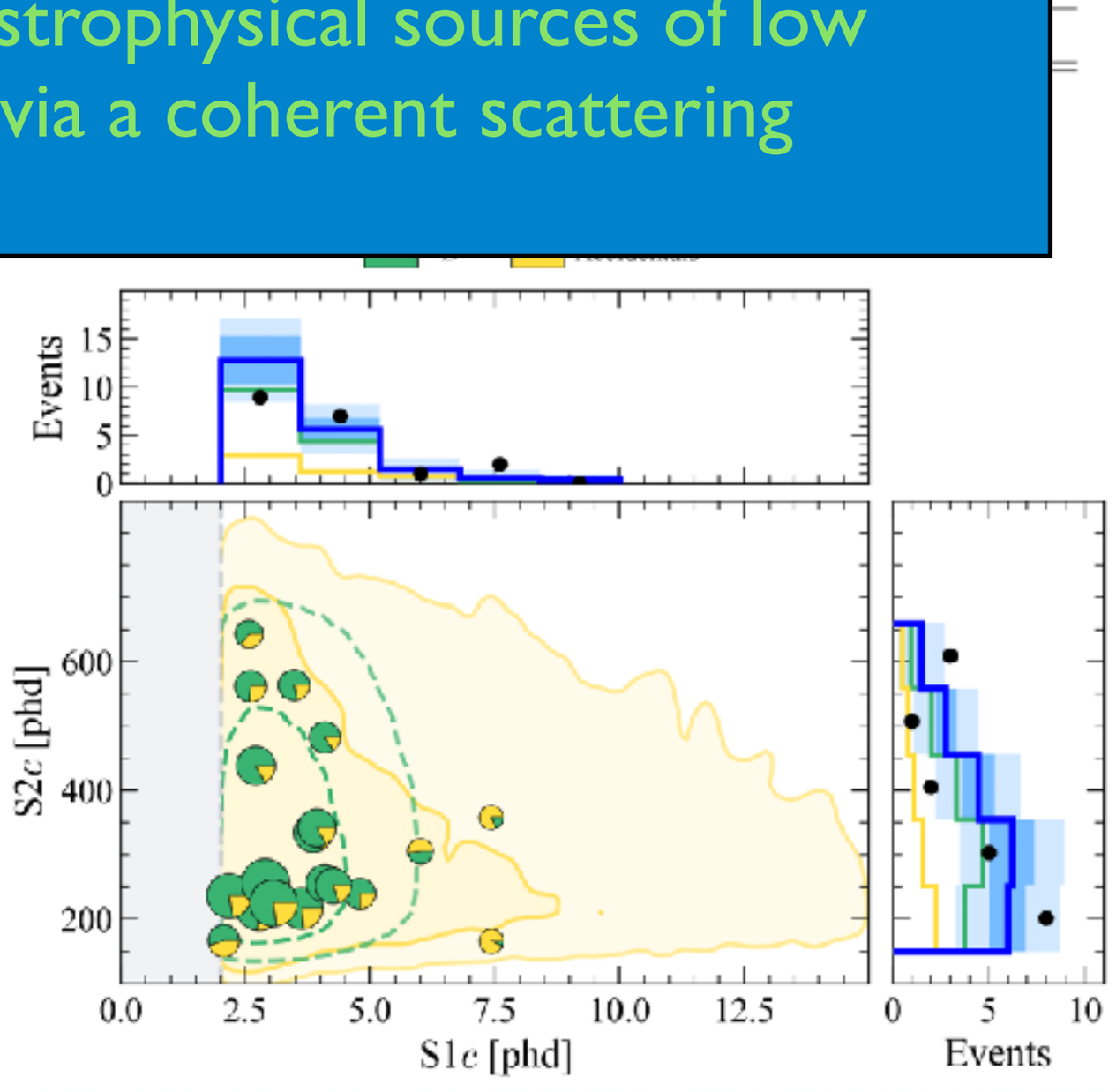
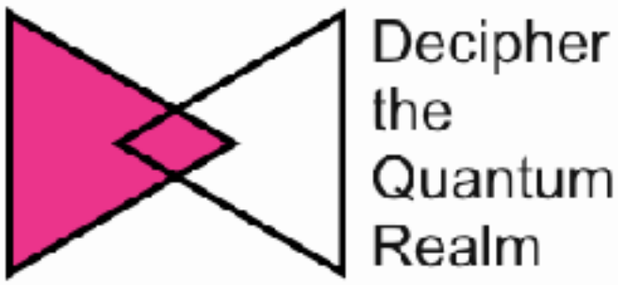
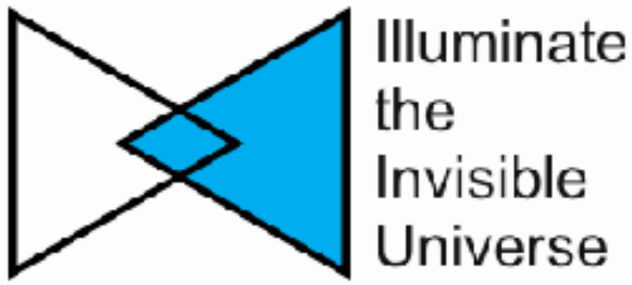
- Clear observation of astrophysical sources of low energy nuclear recoils via a coherent scattering process!





P5 Report





- **Recommendation 2d:**
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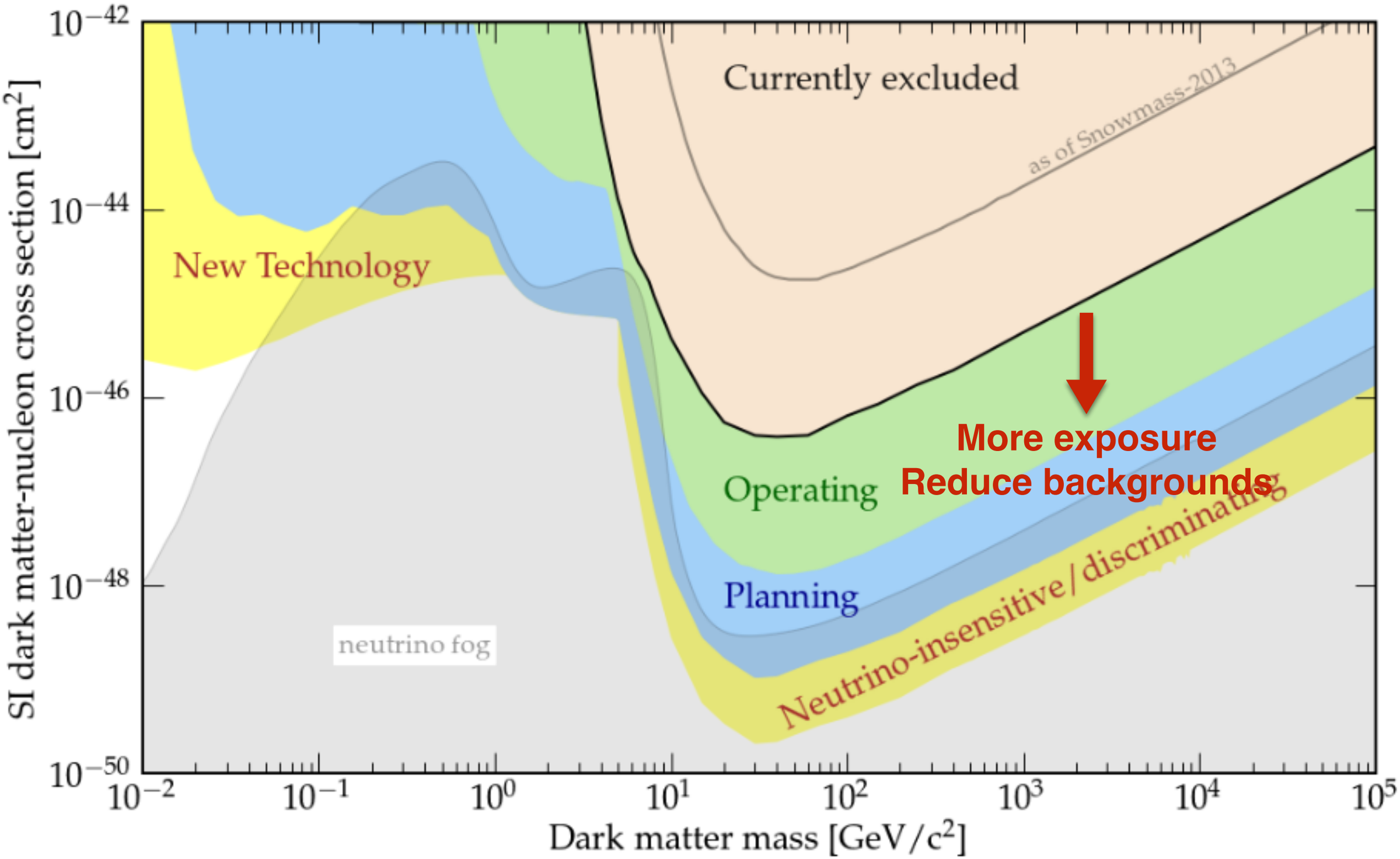
Figure 1 – Program and Timeline in Baseline Scenario (B)

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

§ Possible acceleration/expansion for more favorable budget situations

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

How to make progress



XLZD Collaboration

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

Dark Matter

- Dark photons
- Axion-like particles
- Planck mass

WIMPs

- Spin-independent
- Spin-dependent
- Sub-GeV

Sun

- Solar pp neutrinos
- Solar Boron-8 neutrinos

Big Bang

- Neutrinoless double beta decay
- Double electron capture

Supernova

- Supernova neutrinos
- Multi-messenger

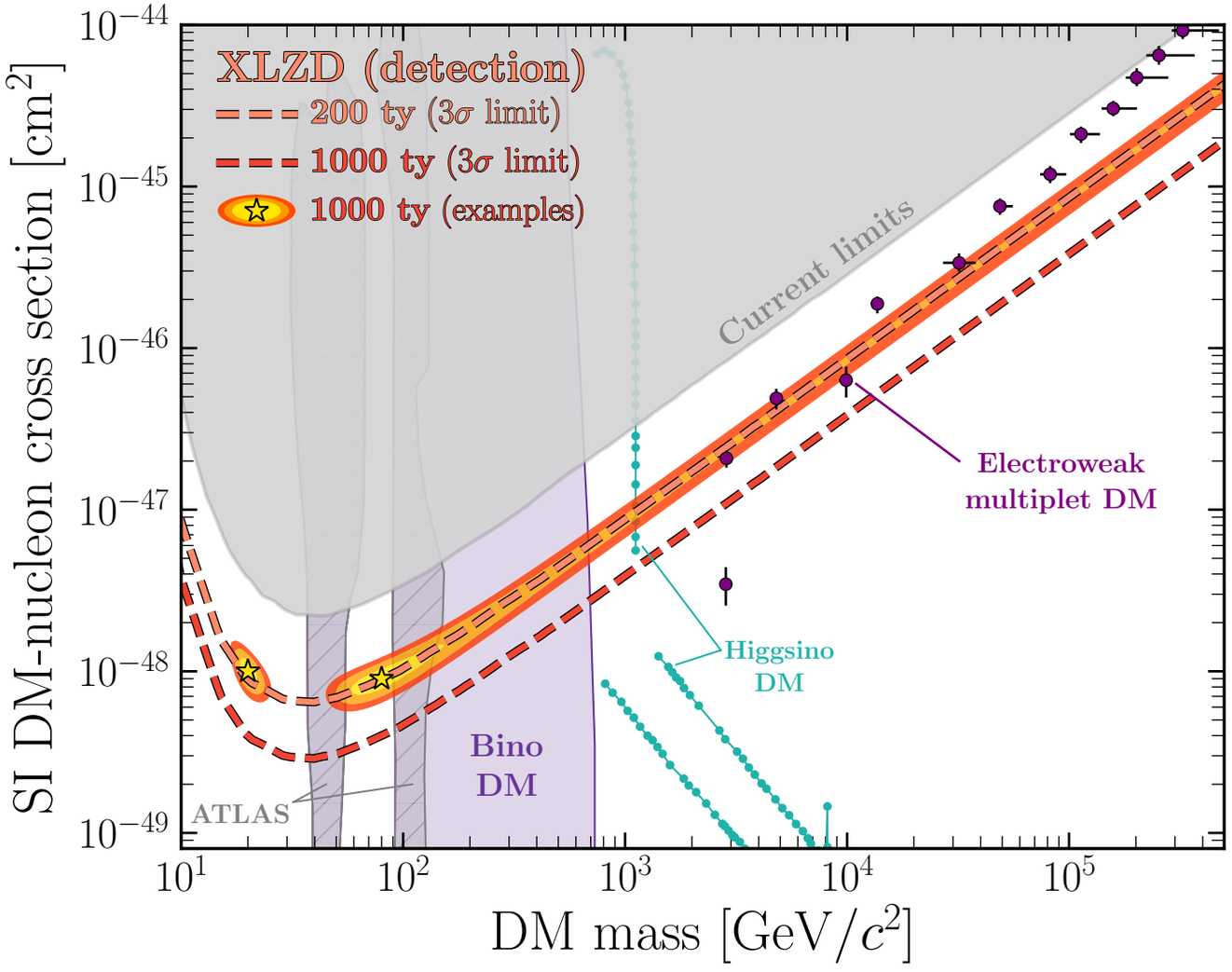
Cosmic Rays

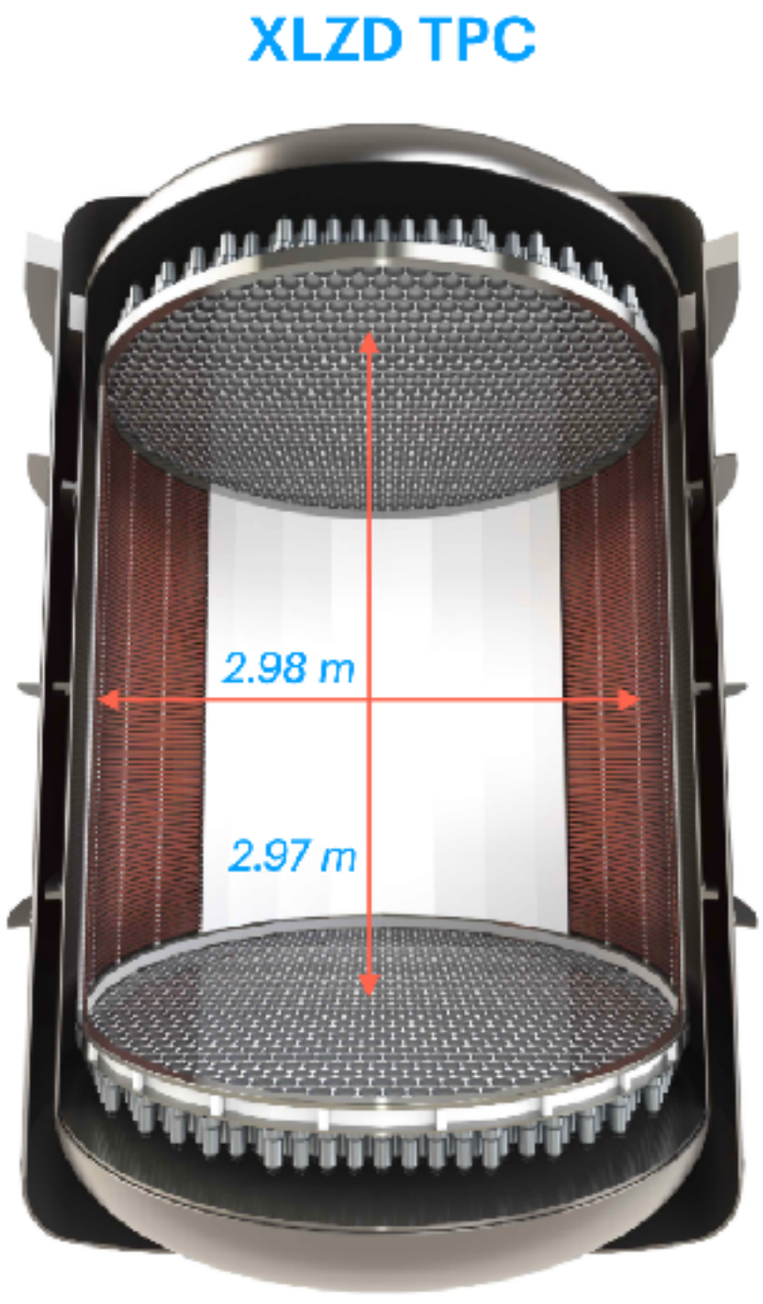
- Atmospheric neutrinos

Courtesy R. Lang

XLZD Collaboration

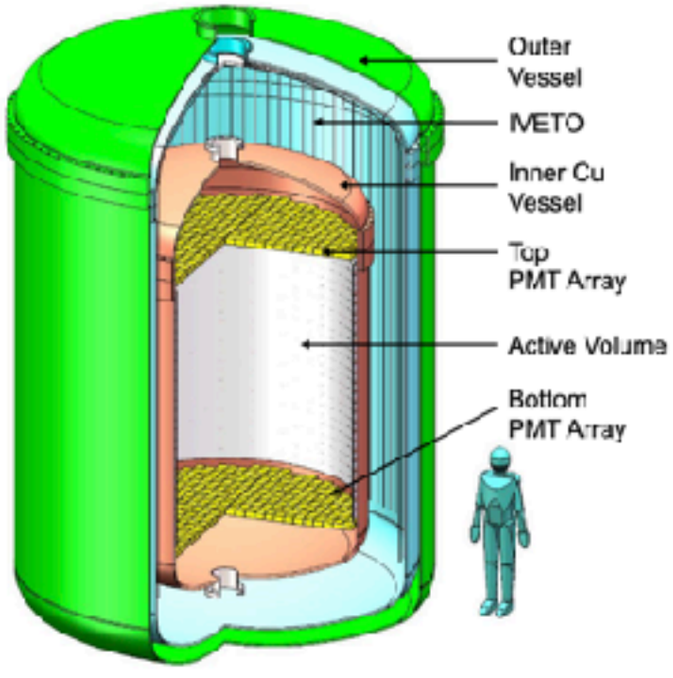
- 60-80 tonne LXe-TPC, 3 m x 3 m (x2 scale up from LZ/XnT)
- Neutron and muon vetoes
- Site - several options (LNGS, Boulby, SURF, SNOLAB)
- Physics case: 2203.02309
- Design book: 2410.17137

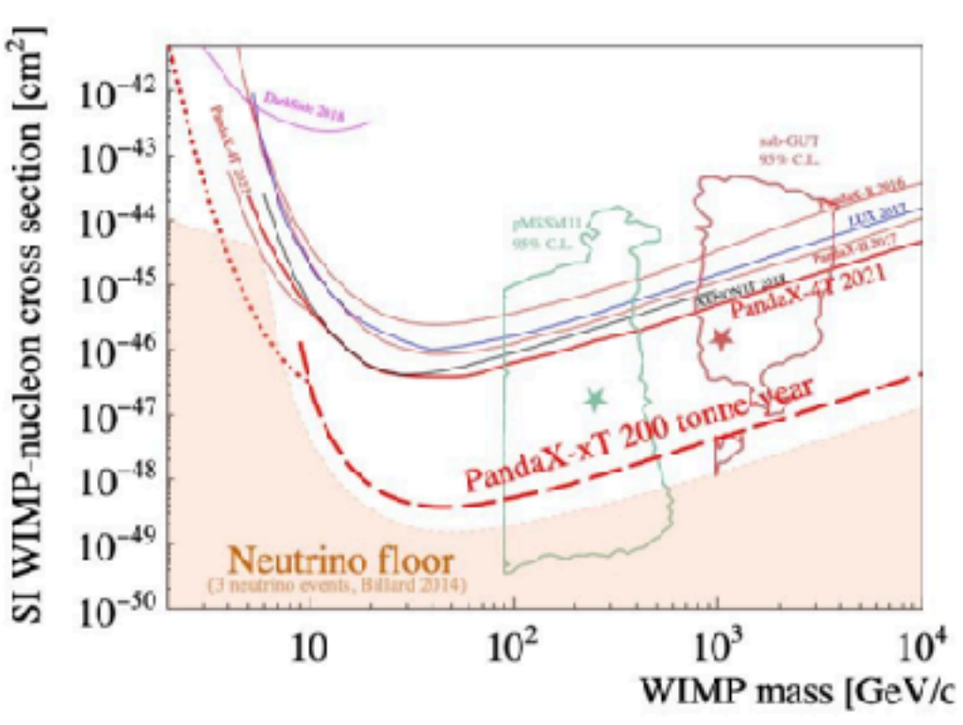


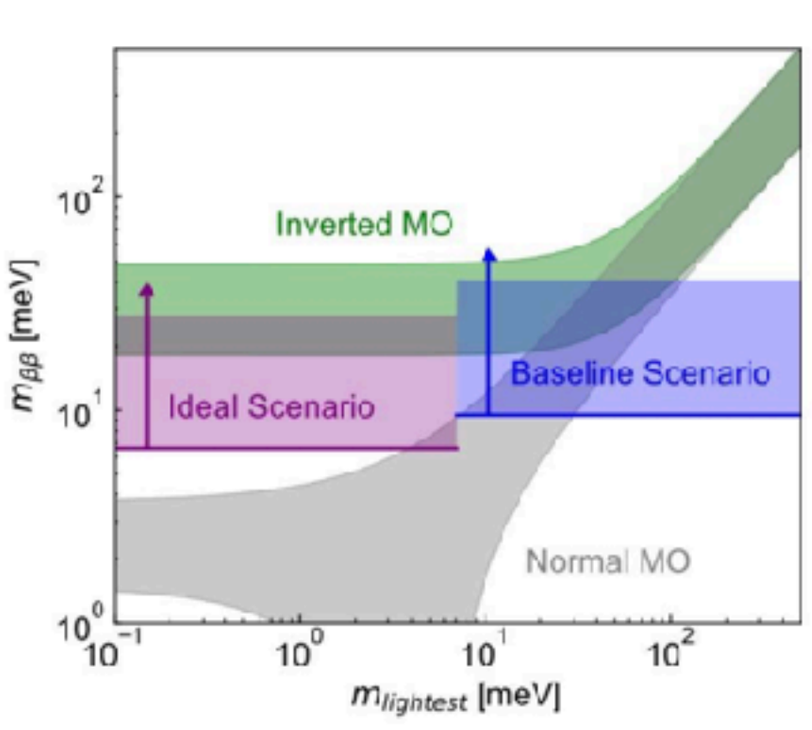


PandaX-xT

- Planned 40t LXe detector - similar science goals as XLZD
- 20 tonne intermediate scale
  - Infrastructure planned to complete in second half of 2026
  - Commissioning in 2027
  - First physics data starting in 2028!







arXiv:2402.03596, **SCPMA** 68, 221011 (2025)

16

GADMC Collaboration - ARGO

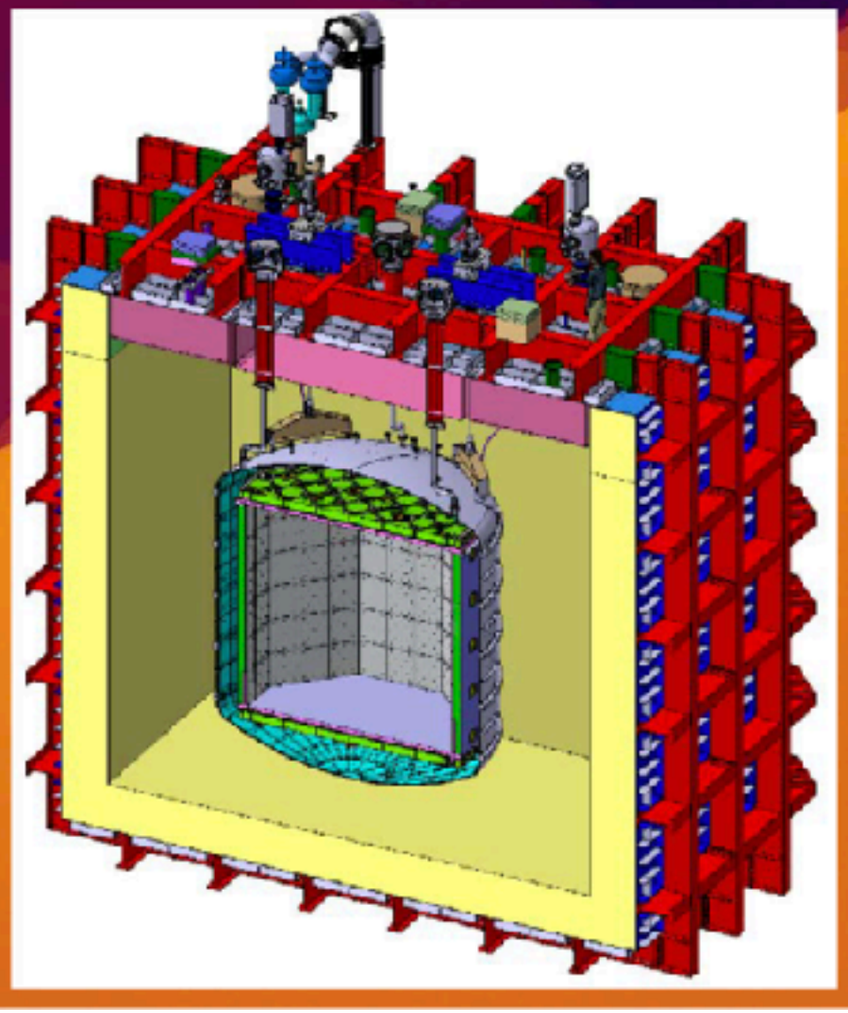
Since 2017

The Global Argon Dark Matter Collaboration (GADMC)

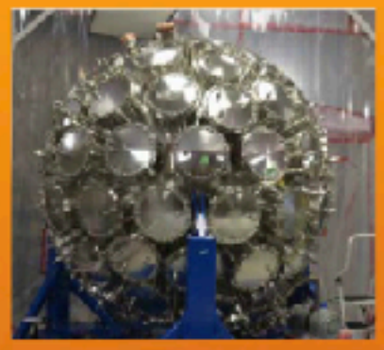
GADMC unified in a single Collaboration more than 400 scientists interested in DM searches with argon to explore heavy (and light) dark matter to the neutrino floor and beyond

DEAP-3600

DarkSide-50



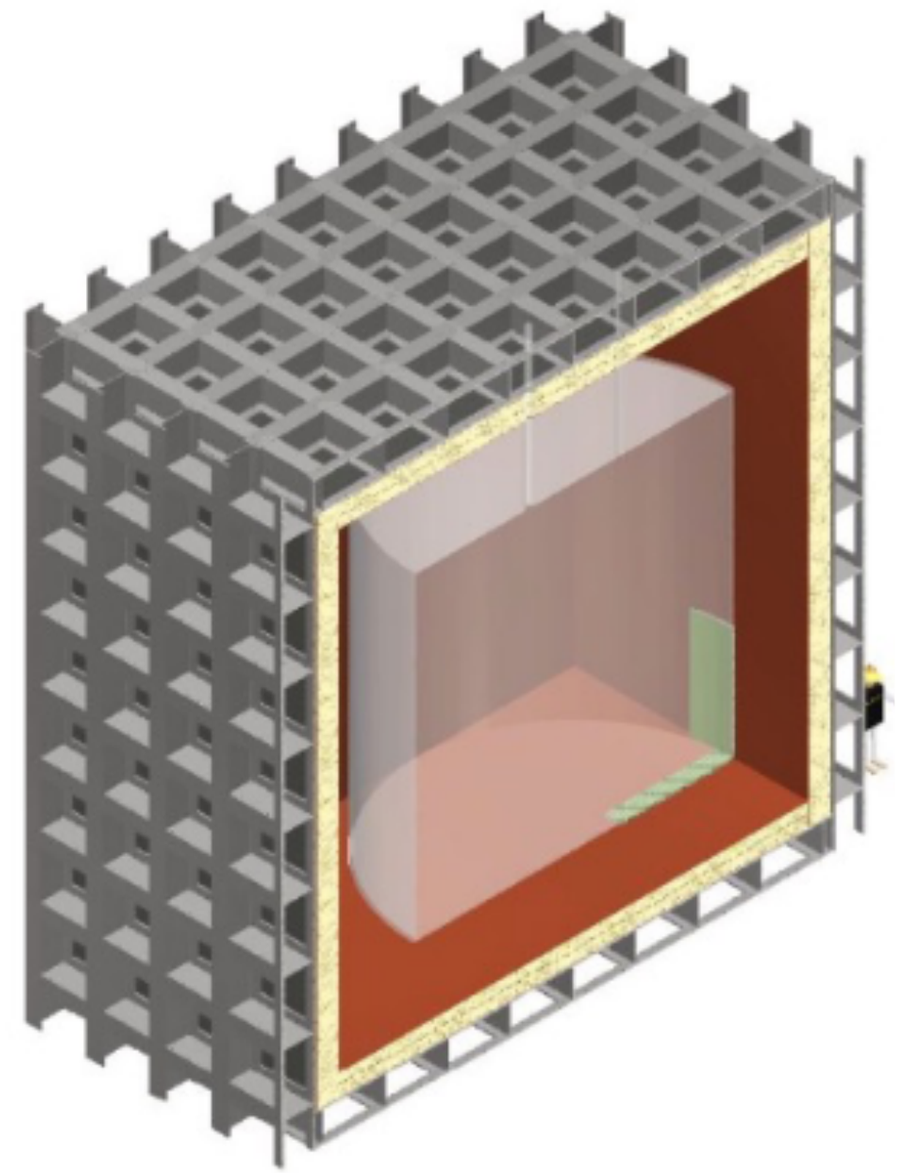
MiniCLEAN

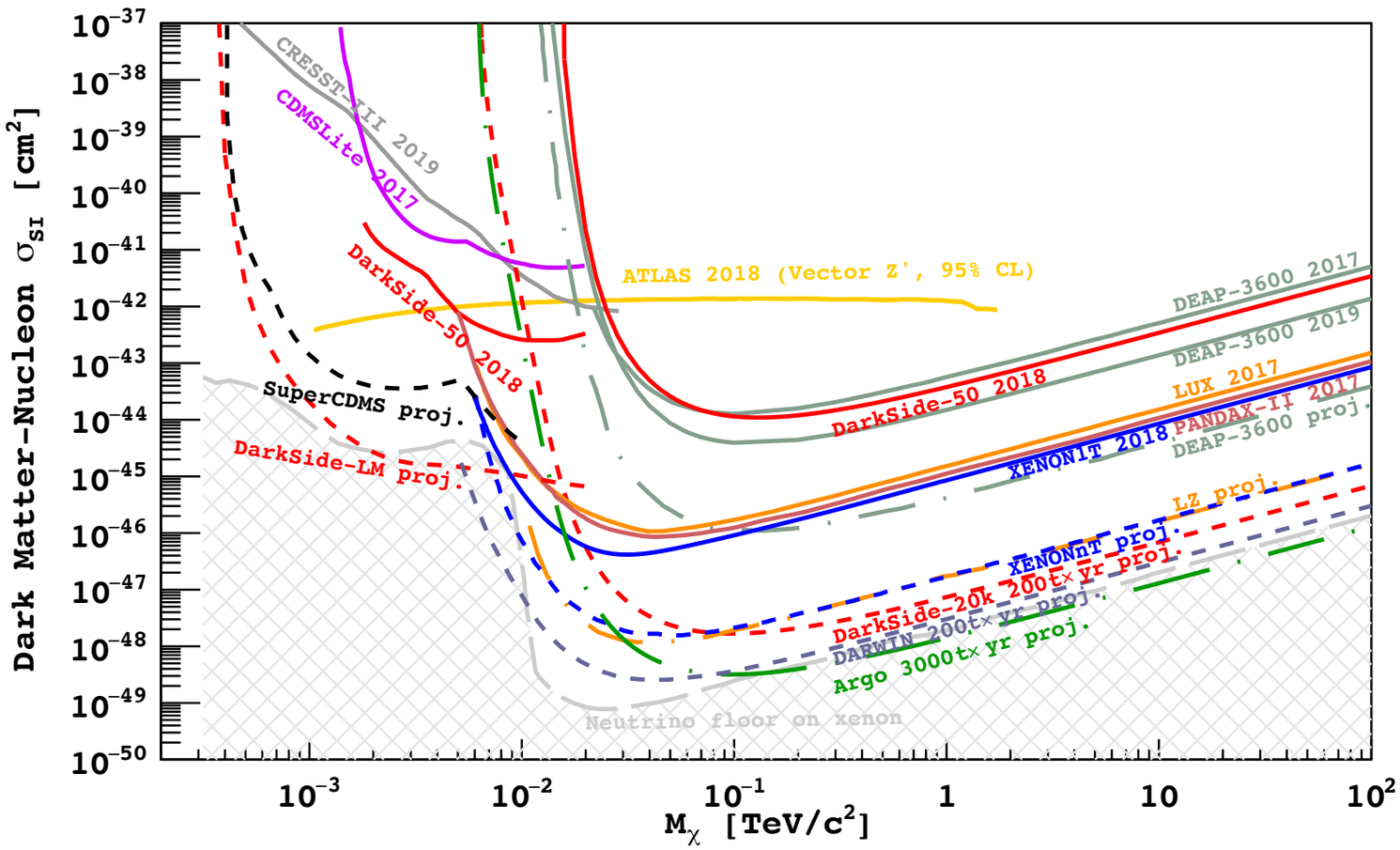


ARDM

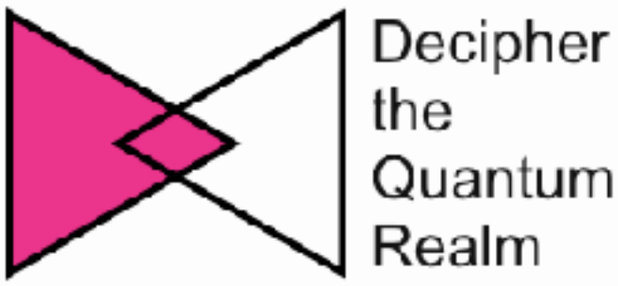
ARGO

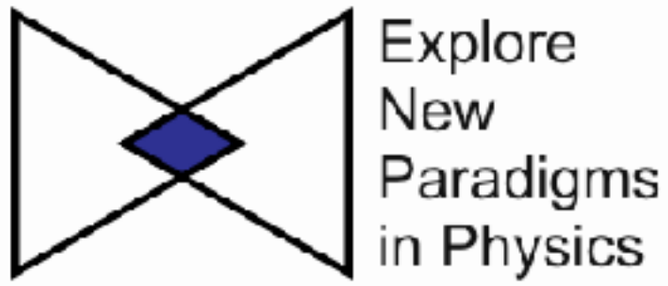
- ArDM, DS-50, DEAP-3600, and MiniCLEAN jointly formed the Global Argon Dark Matter Collaboration (GADMC)
- A 300-tonnes fiducial argon detector filled with underground argon
- 3000 tonne×year exposure to reach into the neutrino fog





P5 Report

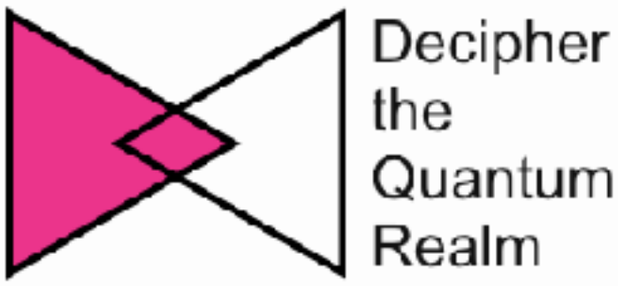


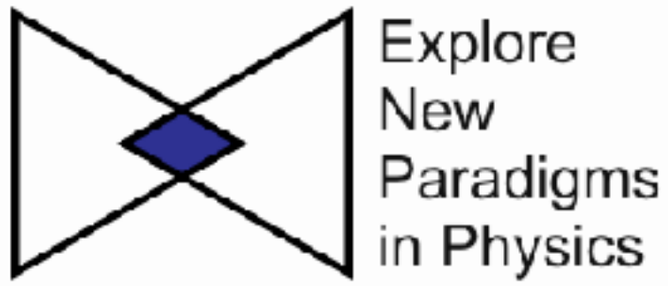


- **Recommendation 1 - continued support for, including construction, operation, and research**
  - **DarkSide-20k, LZ, SuperCDMS, and XENONnT**

- **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).**
  - **With favorable budget scenario**
    - **Do two G3 experiments**
  - **Less favorable budget scenario**
    - **Reduced participation in offshore G3**

P5 Report





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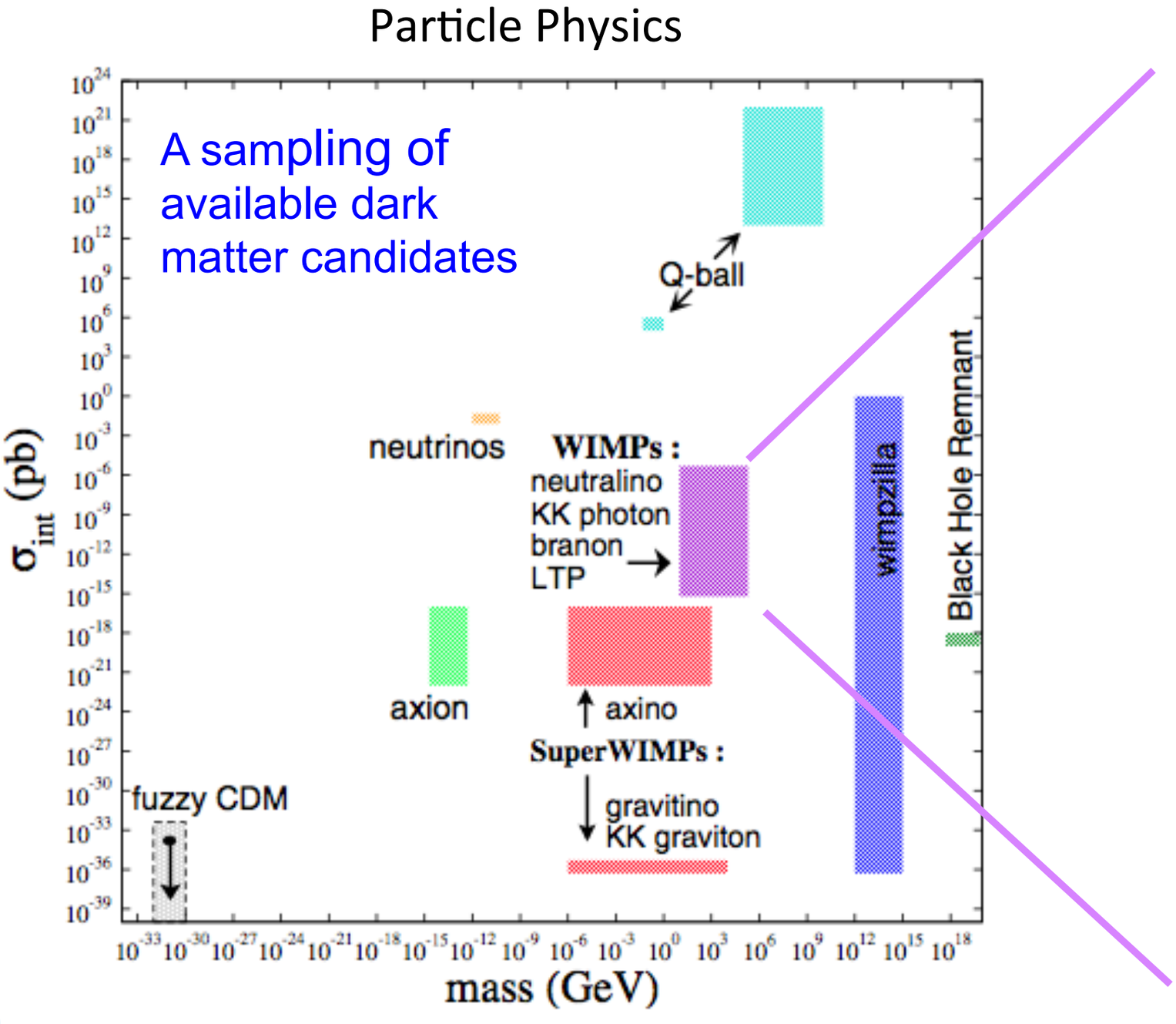
    - **Reduced participation in offshore G3**

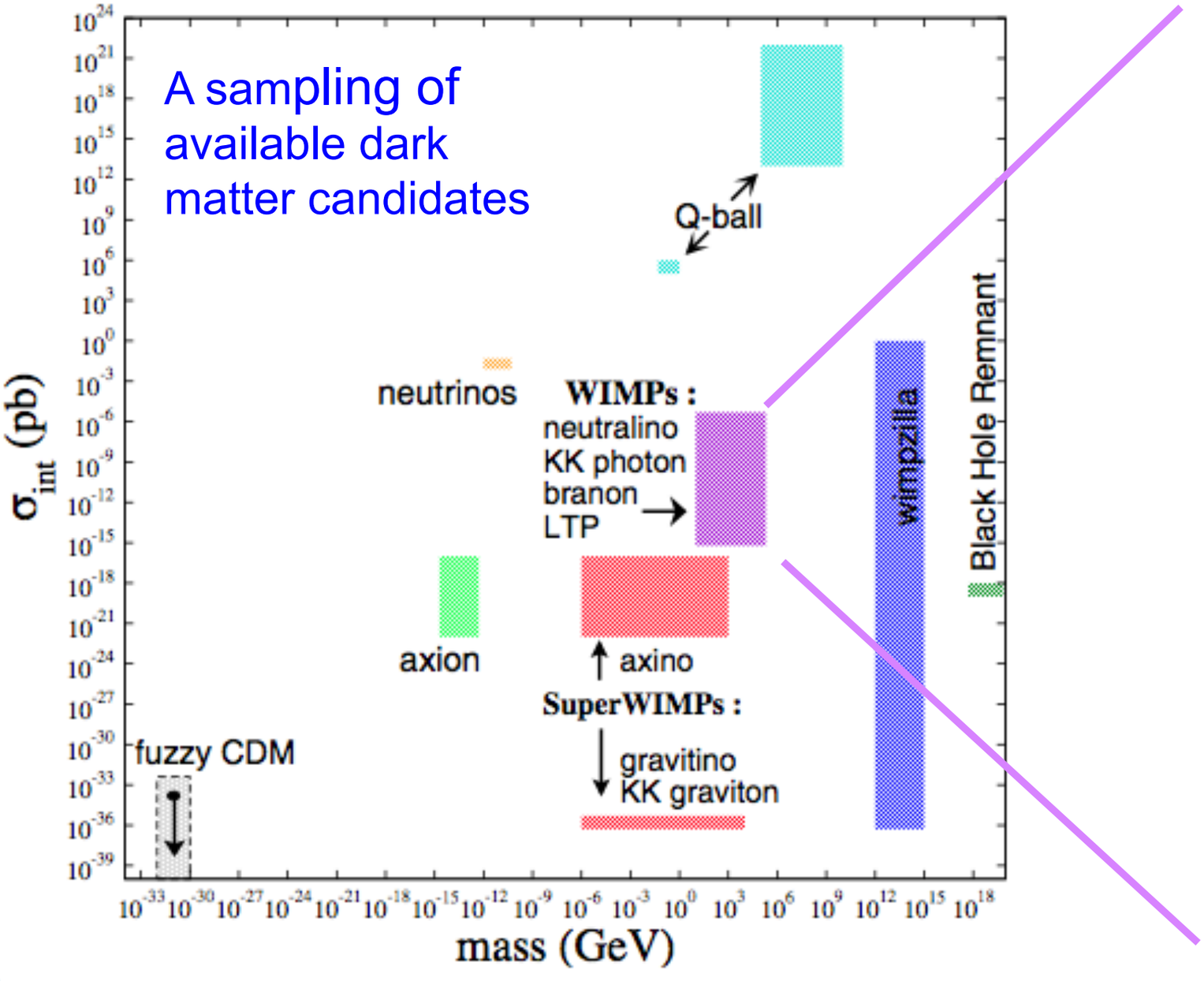
Dark Matter



It's probably WIMPs, right?

Dark Matter

Particle Physics



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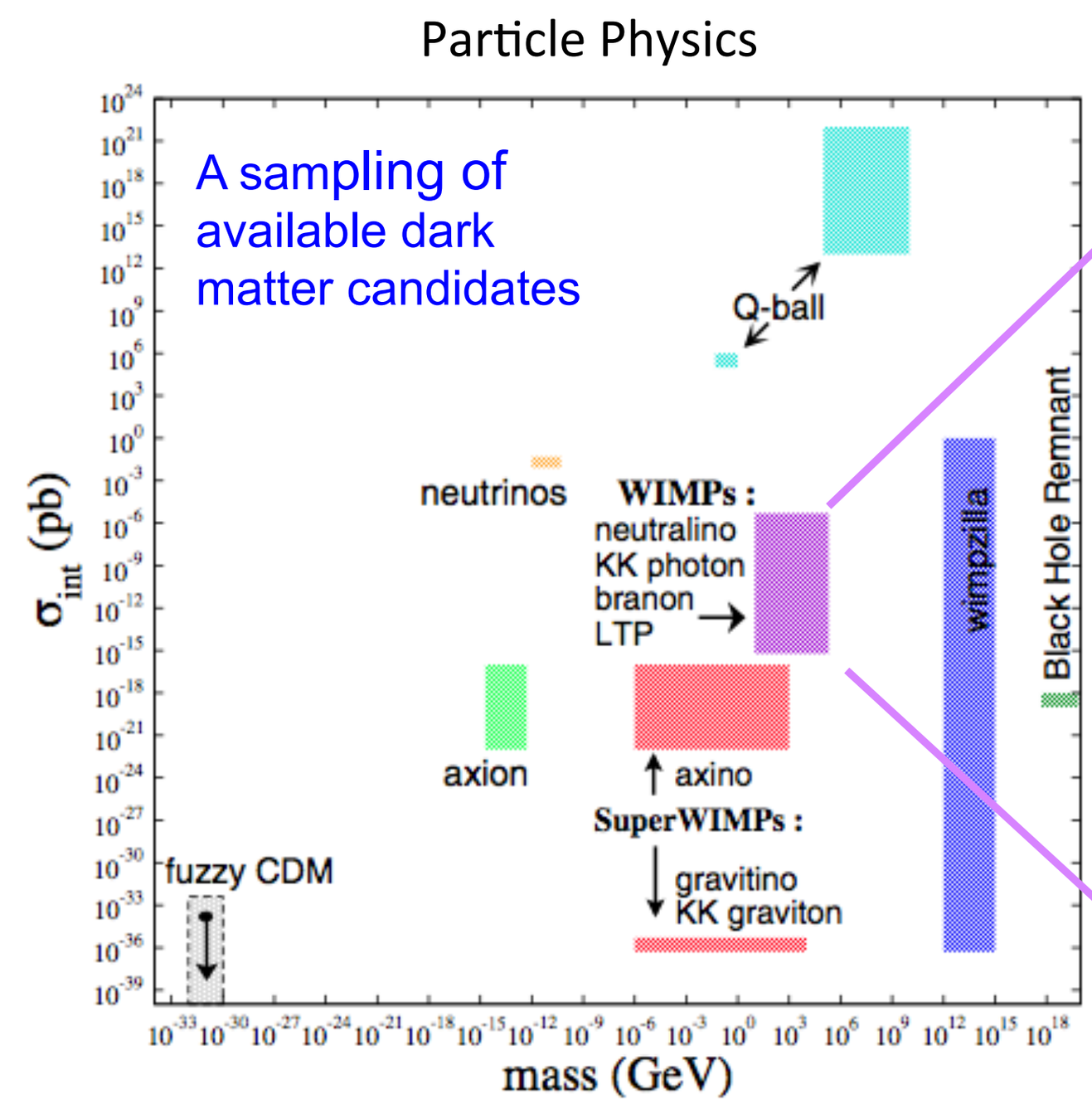
Dark Matter



It's definitely an axion

See P. Agrawal, Wed at 11

Axions 25 years ago

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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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

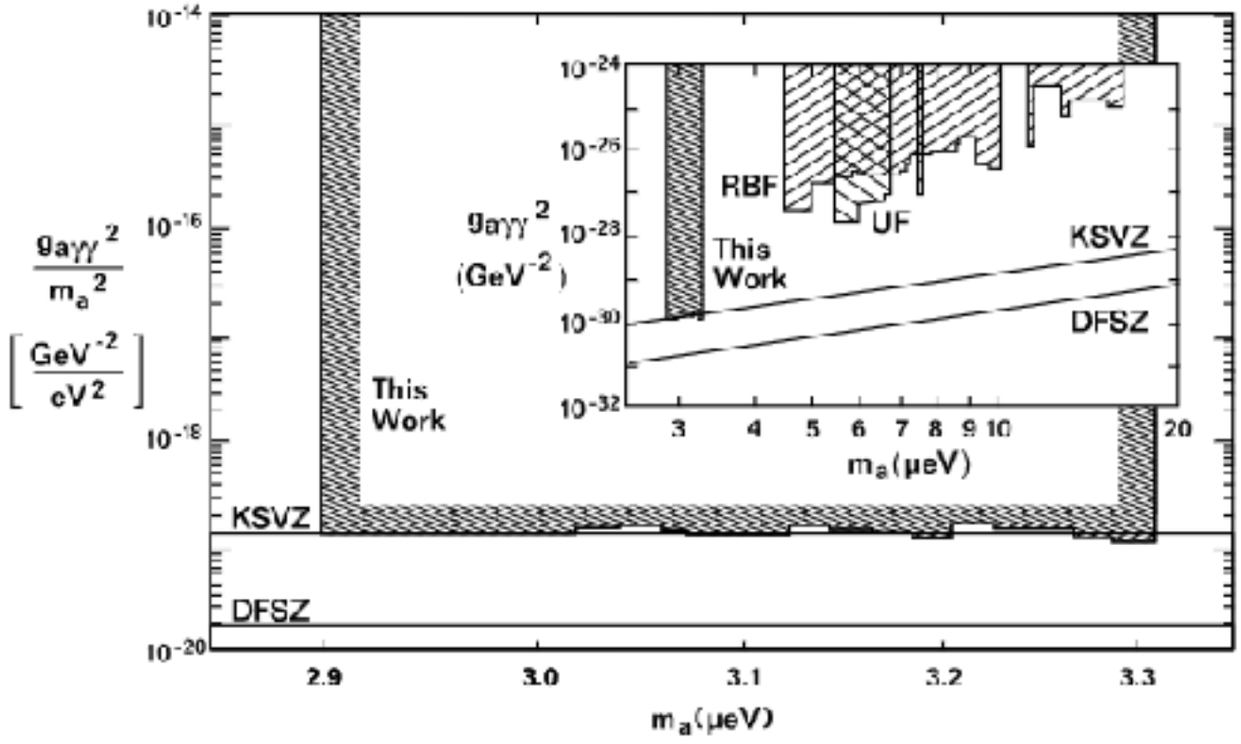
(Dated: October 30, 2018)

"The two decades of axion mass range that have not yet been ruled out by experiments or astrophysical observations are precisely in the range that could explain the dark matter…

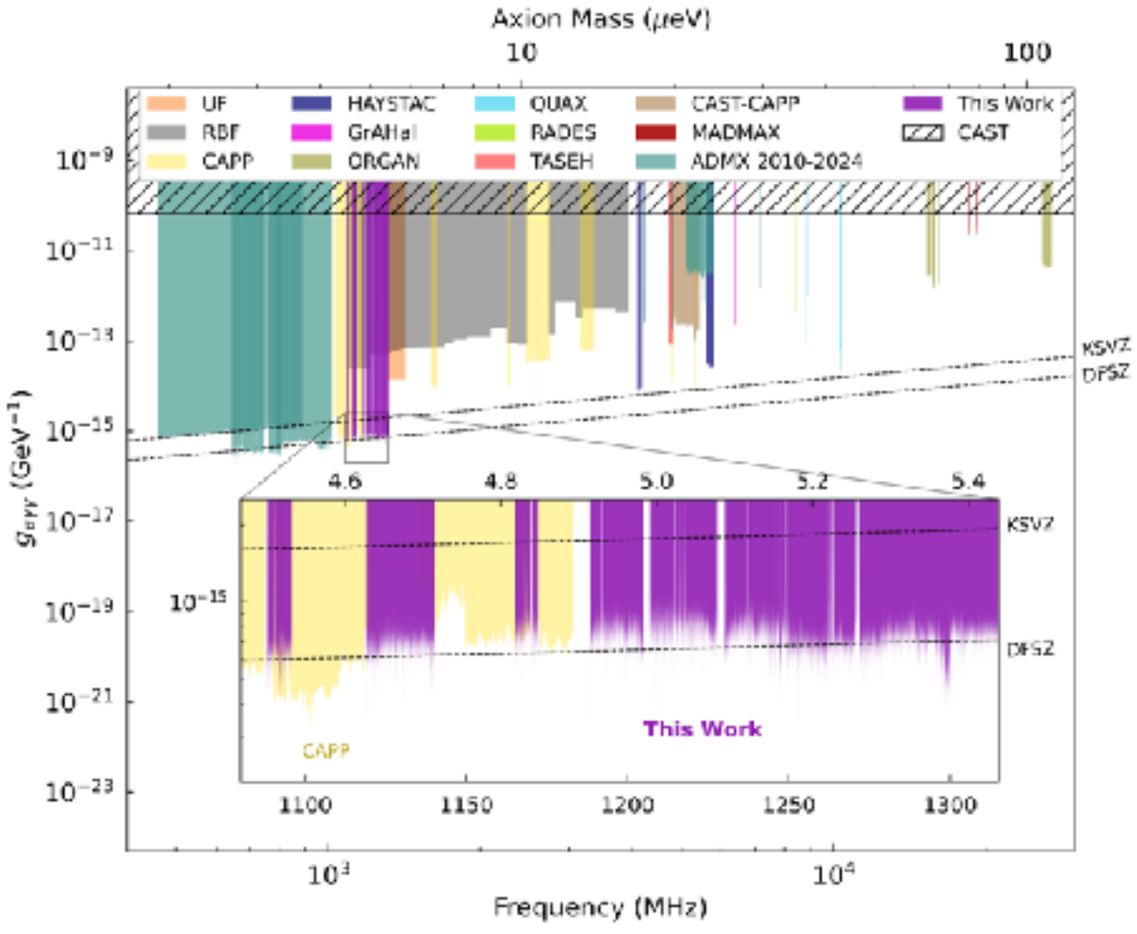
It is reasonable to expect that in less than a decade, axions as dark matter could be detected or definitively ruled out."

Axions

- ADMX, PRD 64: 092003 (2001)
- Touching the KSVZ line at 3e-6 eV



- ADMX, PRL 127:261803 (2021) and 135:191001 (2025)
- To DFSZ line from 2.5 to 5.4e-6 eV

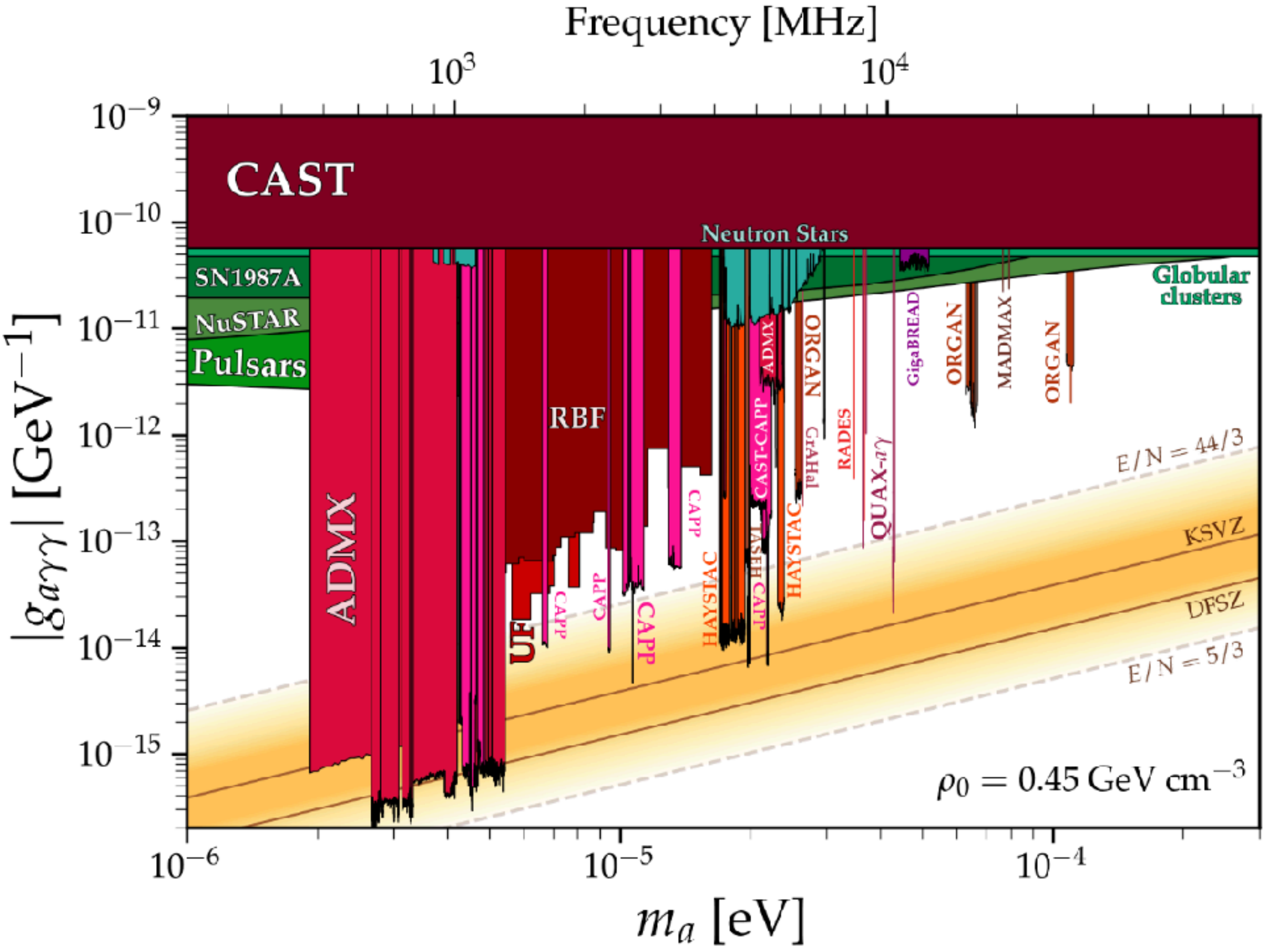


- Order of magnitude improvement in both coupling and mass
- We did not discover or rule out axion dark matter, sadly
- Many more resources moving into axion physics

Axions from the bottom up

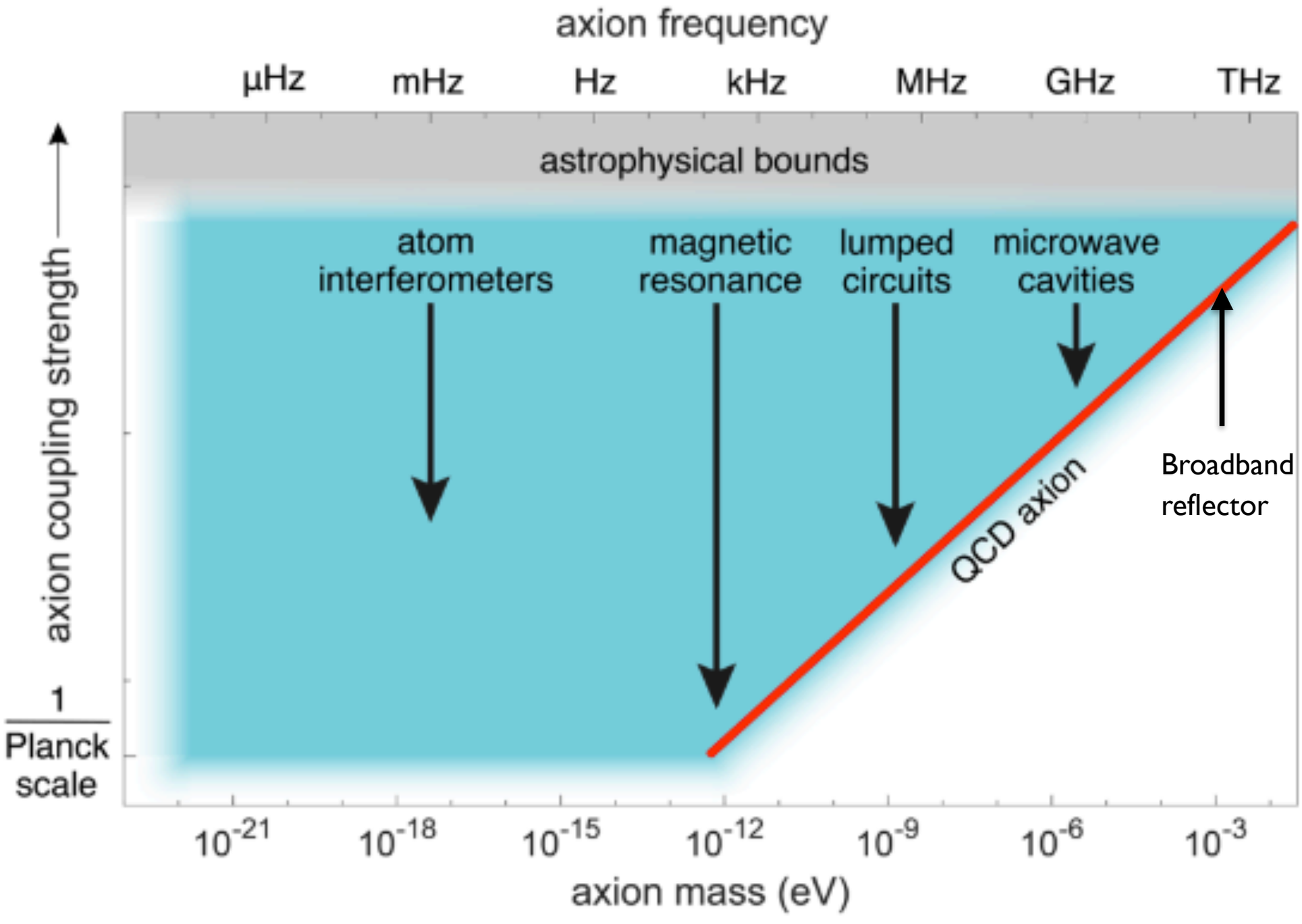
"The *two decades of axion mass range that have not yet been ruled out* by experiments or astrophysical observations are precisely in the range that could explain the dark matter… - Snowmass 2001

Recent theoretical advances have significantly expanded the phenomenology of the QCD axion, resulting in the realization that *QCD axion dark matter can exist over wide range of masses from 100 Hz to 1 THz* (roughly 10^{-12} eV to 10^{-3} eV). - DMNI Report, 2018

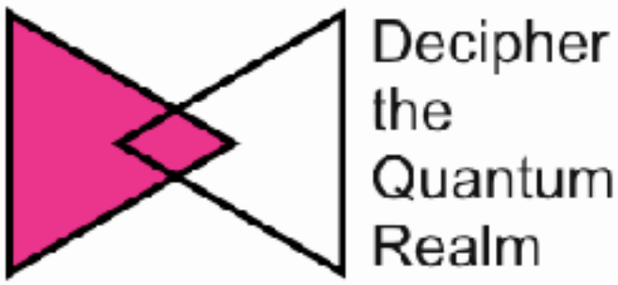


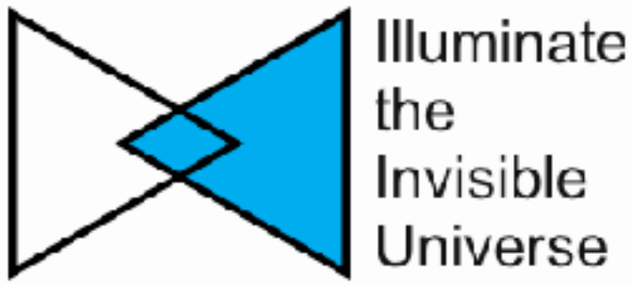
from https://cajohare.github.io/AxionLimits/

Axions from the bottom up



P5 Report

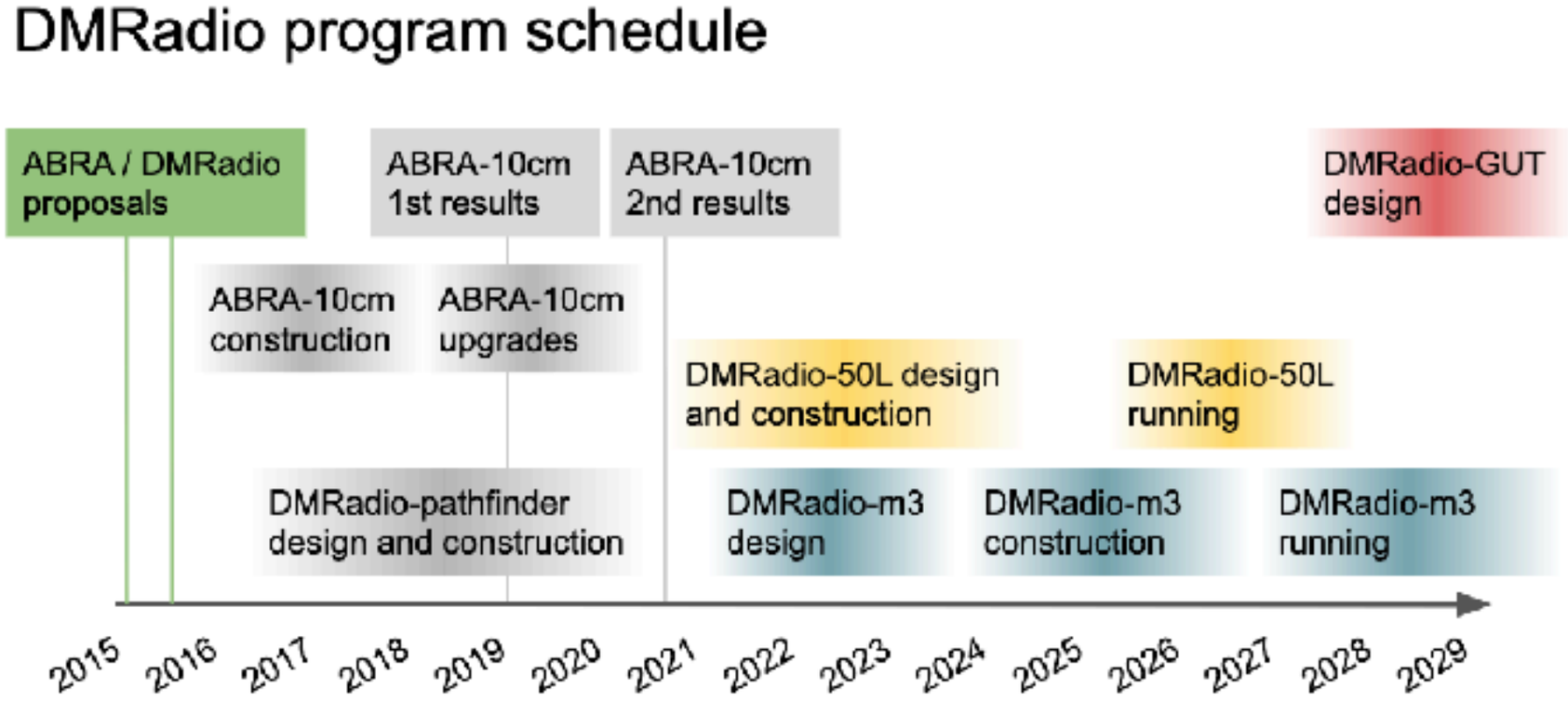




- **Recommendation 3a:**
  - **Implement a new small-project portfolio at DOE, Advancing Science and Technology through Agile Experiments (ASTAE)…The program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP.**
- **Recommendation 4d:**
  - **Invest R&D in instrumentation to develop innovative scientific tools**

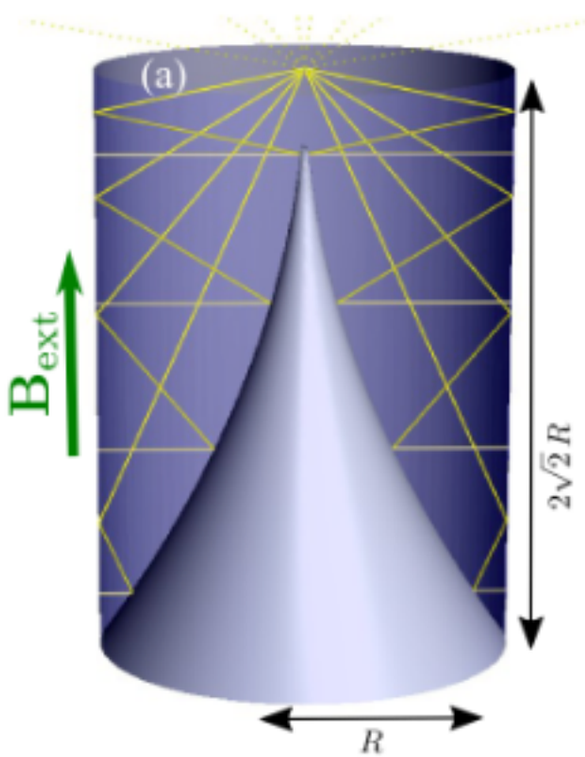
Broadening the mass reach

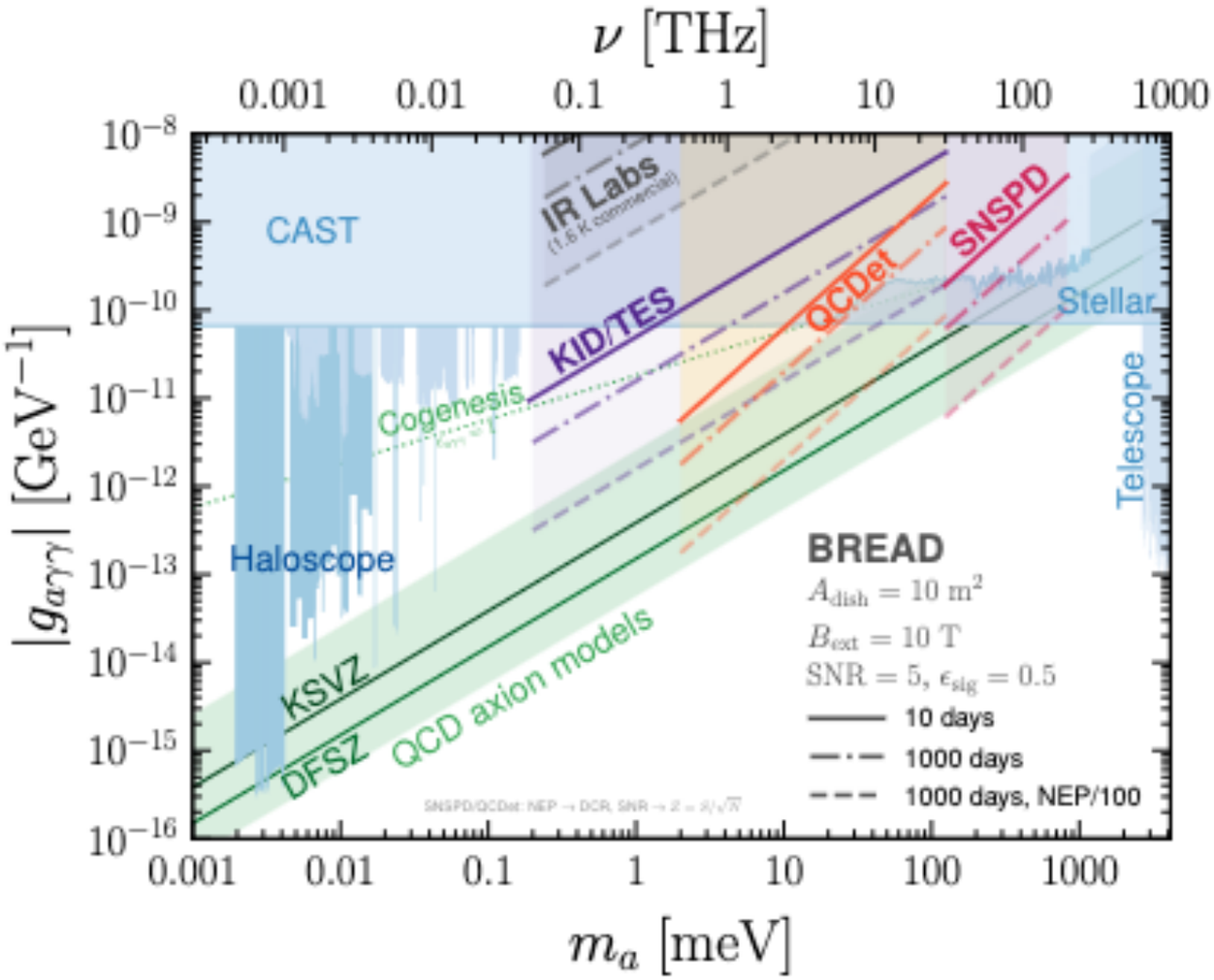
- **ADMX-EFR, HAYSTAC going to higher frequencies in cavity searches (axion converts to a photon in a cavity)**
- **DMRadio looks to push below 1 ueV with lumped elements (axions convert into an effective current measured by a resonator)**
- **CASPEr pushing even lower with precision NMR (axions interact with nuclear spin creating precession)**



Broadening the mass reach

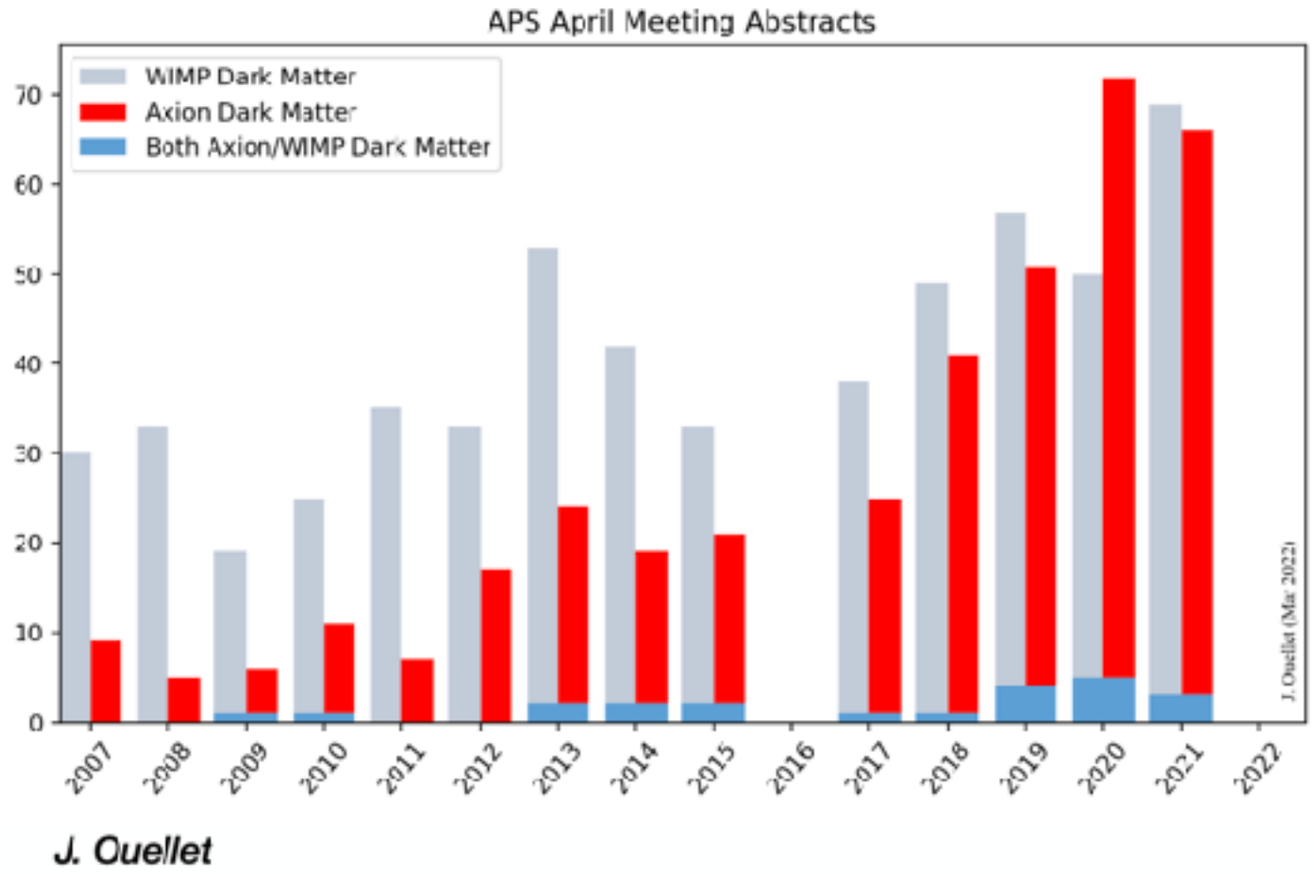
- **BREAD, LAMPOST look for conversion into photons at surfaces, count photons**
  - **Amplified by area/dielectric stack/disorder instead of cavity**





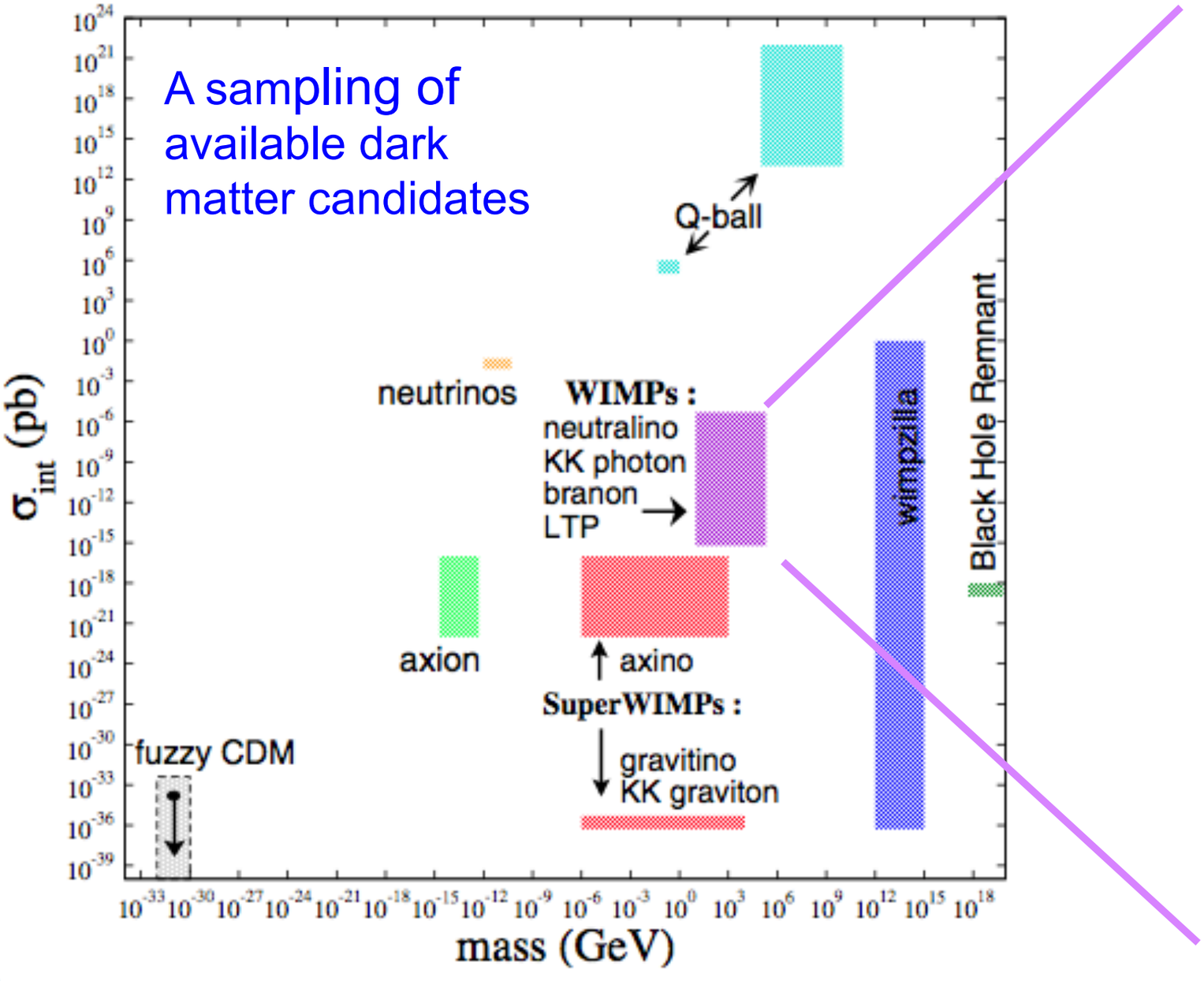
Broadening the mass reach

- **Axion field driven by developments in quantum sensing/quantum information/ low temperature physics**
  - **Ultra low dark rate photon sensors**
  - **Beating down the standard quantum limit with squeezing**
  - **Advanced magnet technology**
  - **Many more…including some interesting ideas tomorrow afternoon in the 2 pm session (e.g. more NMR, quantum semiconductors)**



Dark Matter

Particle Physics



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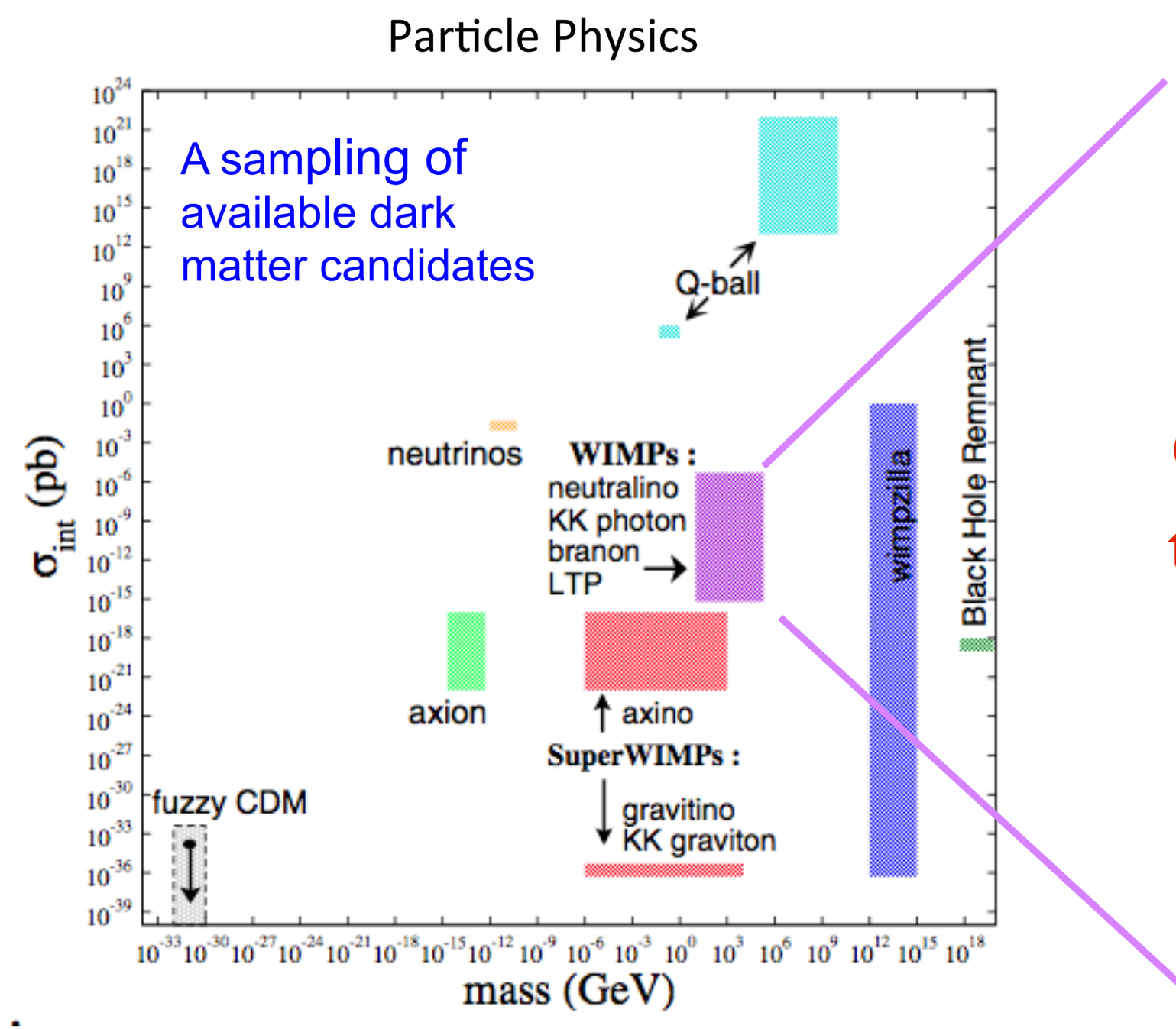
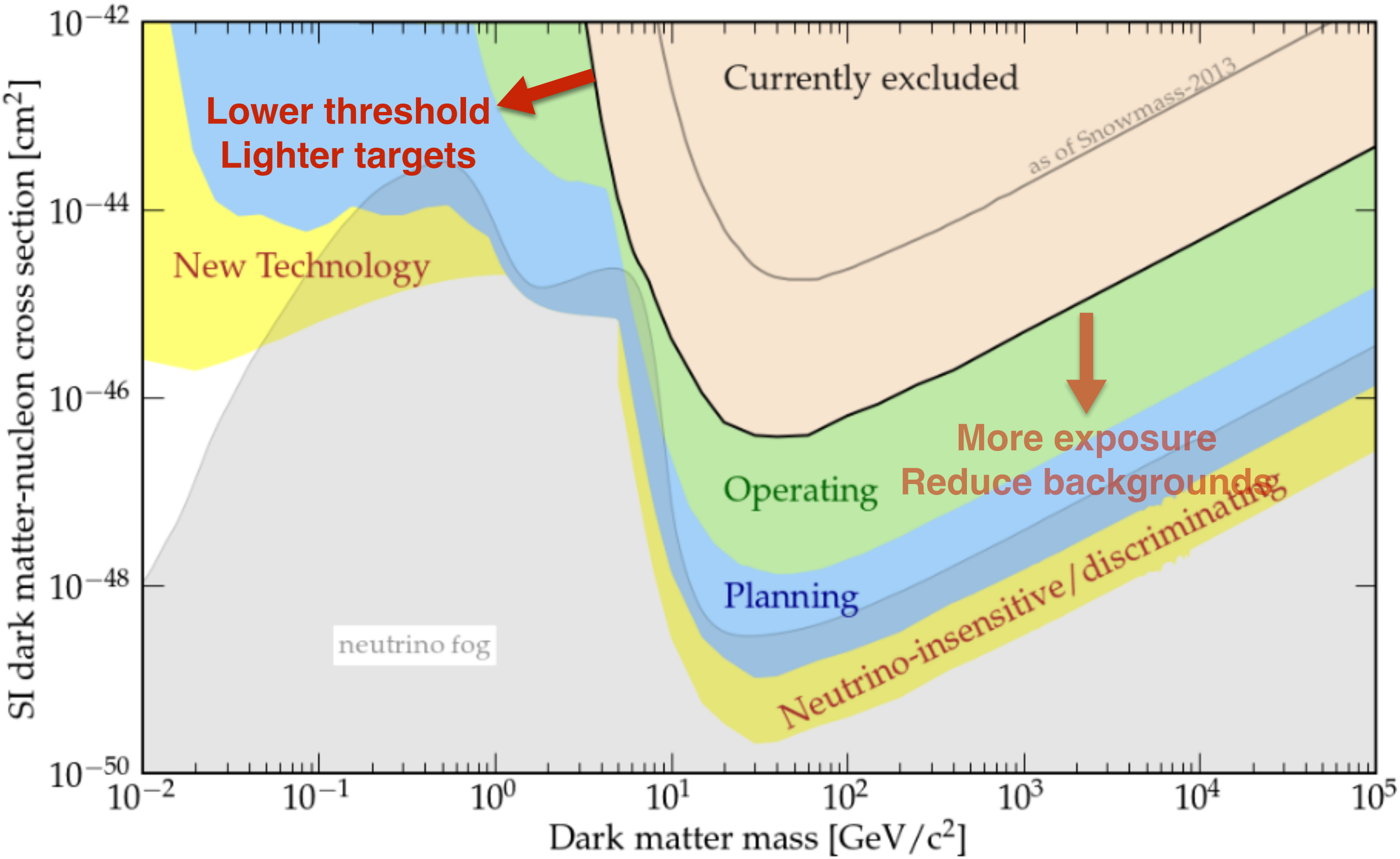
Dark Matter



Or at least a thermal relic

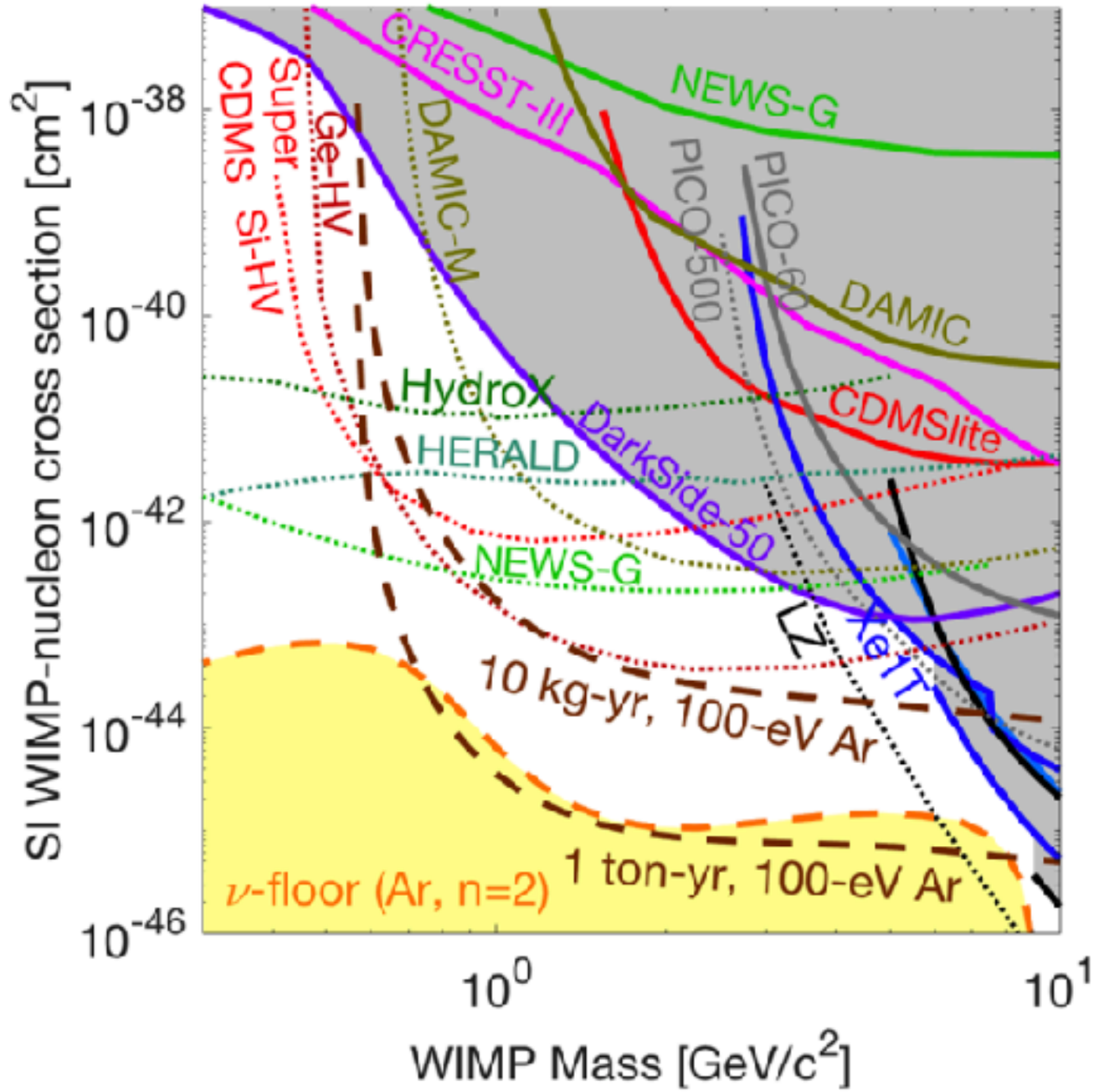
Prediction is strongly correlated with discovery prospects.

How to make progress



Broadening the mass reach

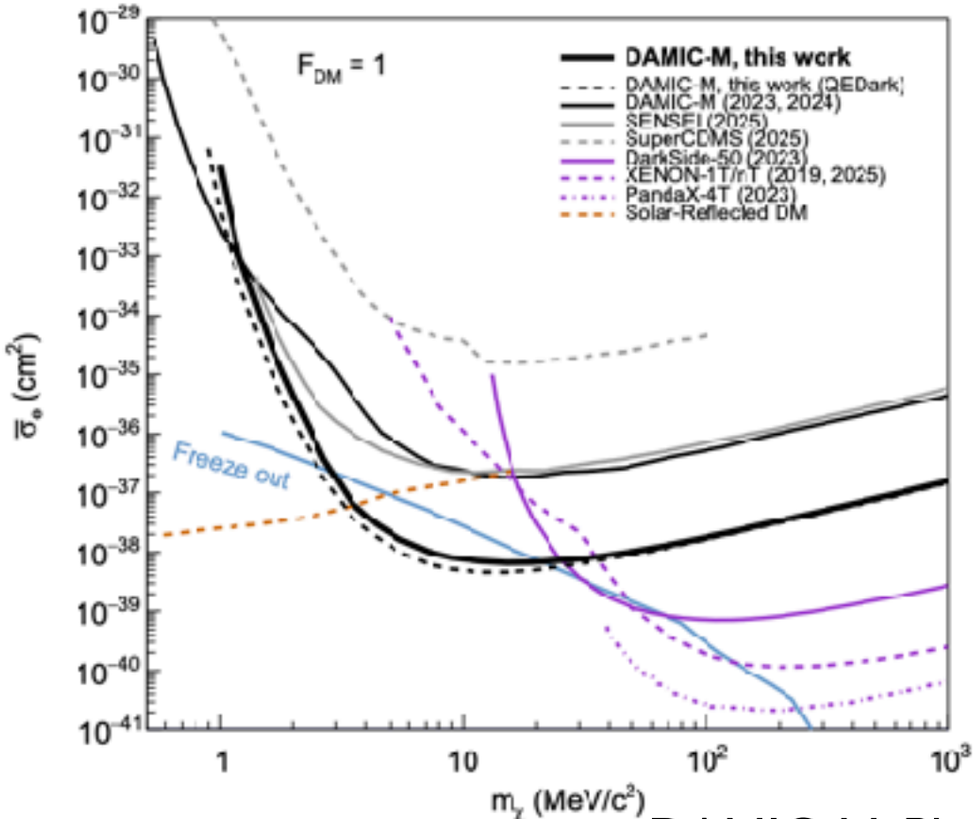
- **Exploring the <10 GeV range**
  - **SuperCDMS-SNOLAB UG now operating**
  - **Scintillating Bubble Chamber (SBC) project took first argon bubble data at FNAL in last few months**
  - **HydroX - hydrogen doped in liquid xenon**
  - **…**

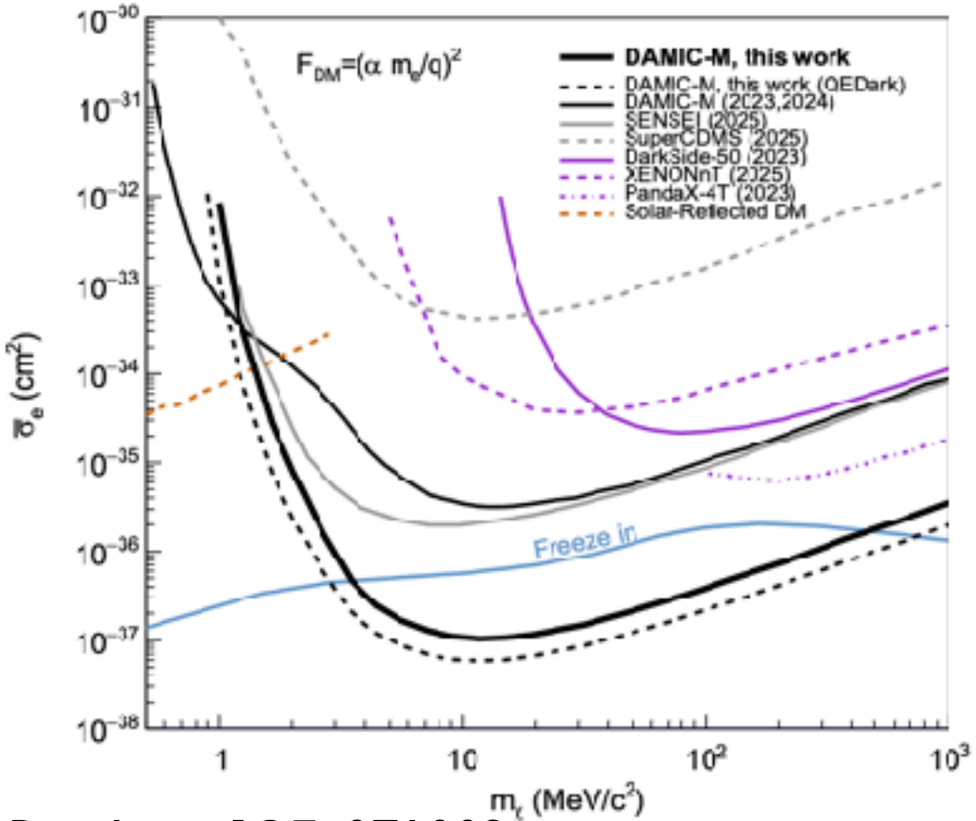


← SBC at Fermilab

Broadening the mass reach

- **Down to the MeV region**
  - **Superconducting devices - SuperCDMS HVeV, TESSERACT, CRESST, EDELWEISS, Quantum sensing R&D, qbits…**
  - **CCDs - DAMIC/SENSEI/OSCURA, …**
  - **Scintillators - TESSERACT, organic crystals**
  - **Annual modulation at atomic scale (eg. crystals, graphene)**
  - **See talks this afternoon in the 4 pm session**

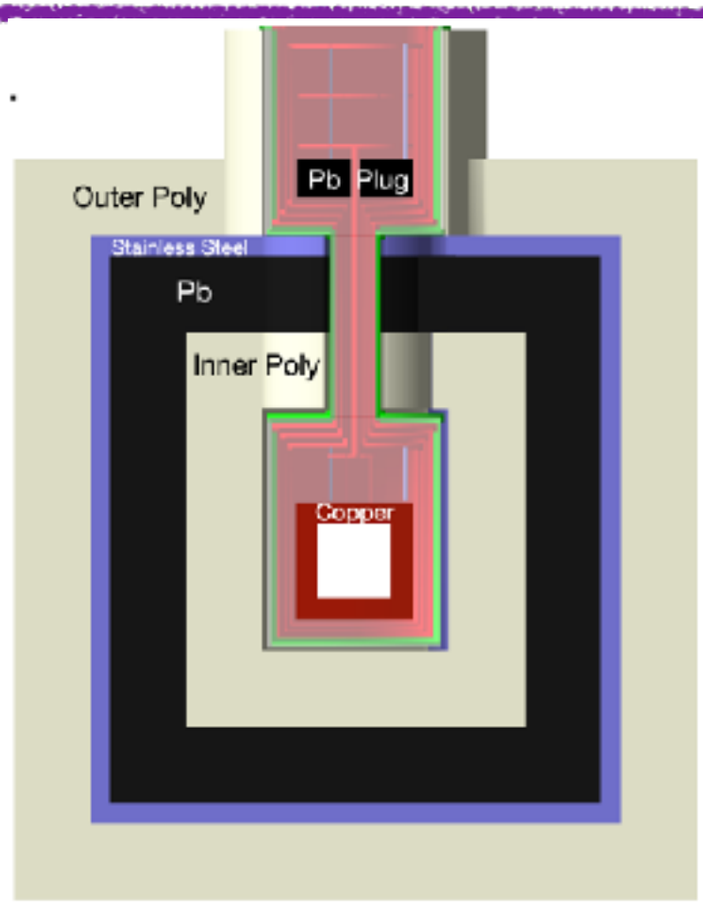


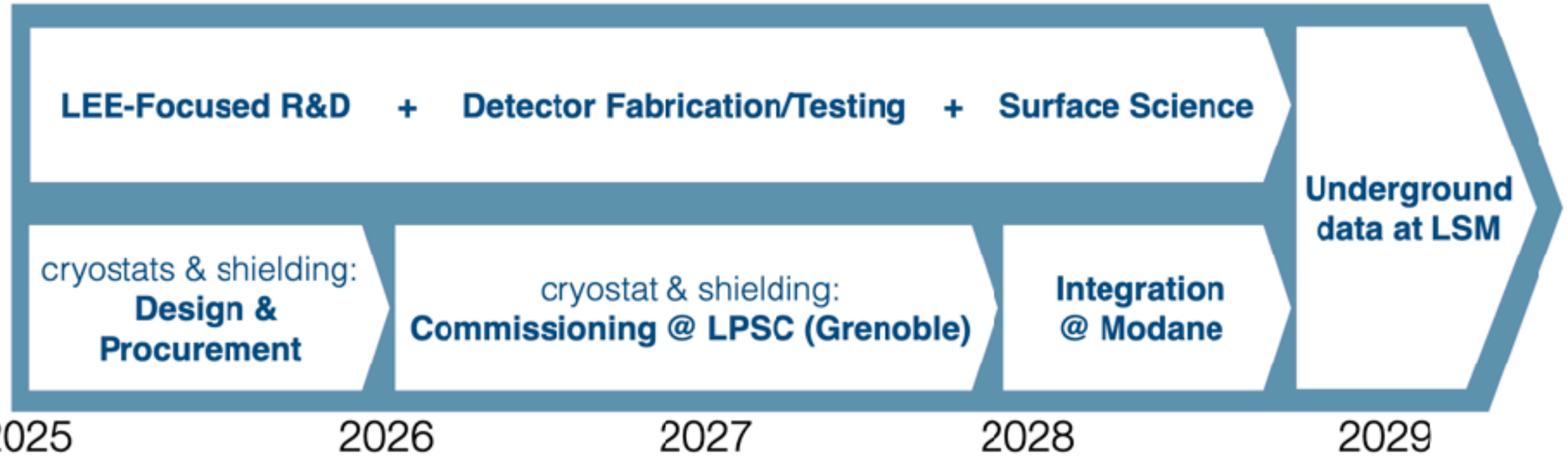


DAMIC-M, Phys. Rev. Lett. **135**, 071002

Broadening the mass reach (with noble gases)

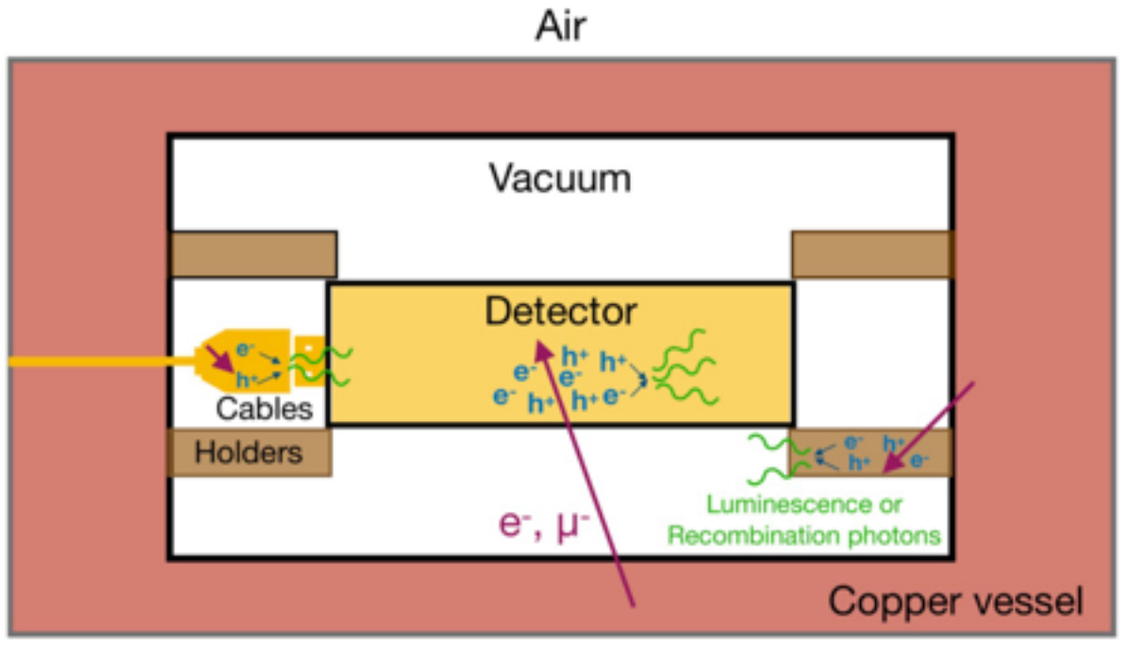
- **Down to the MeV region - TESSERACT Project**
  - **Approved to proceed (Dark Matter New Initiatives)**
  - **Two low background, shielded cryostats at Modane Laboratory in France**
  - **Targets can be swapped between technologies**

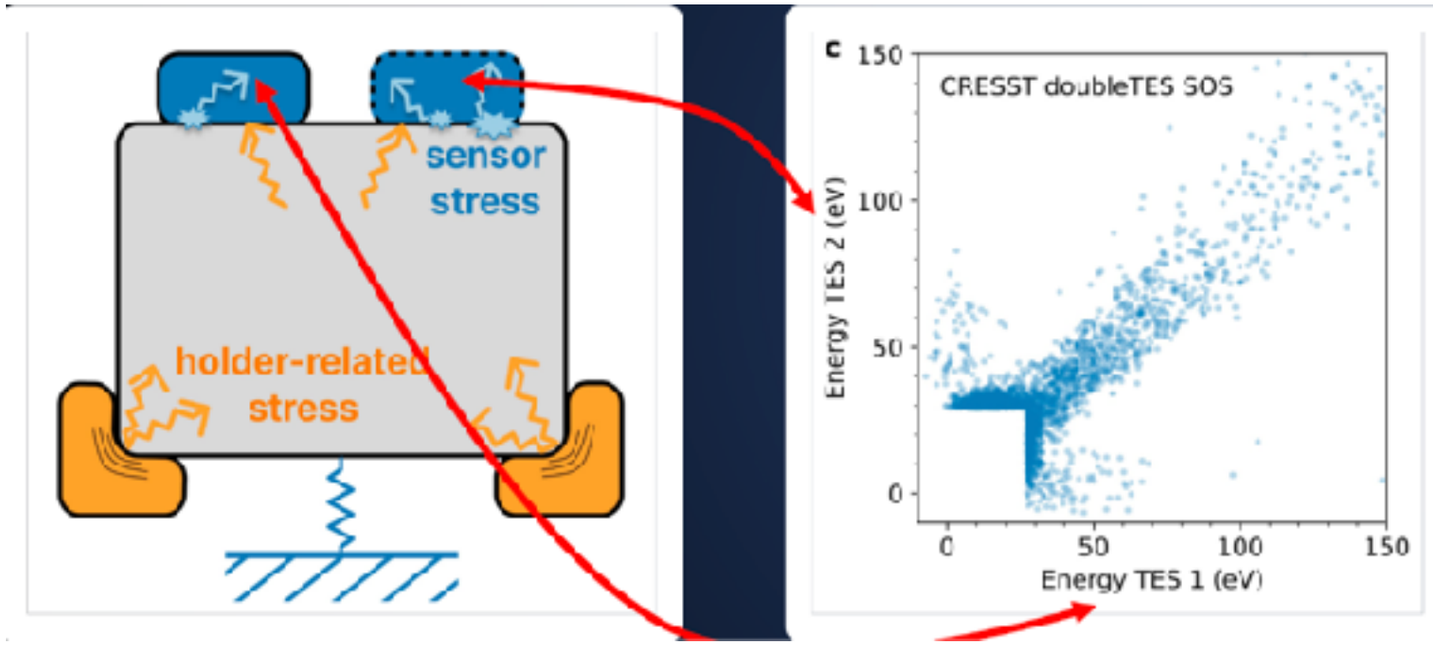




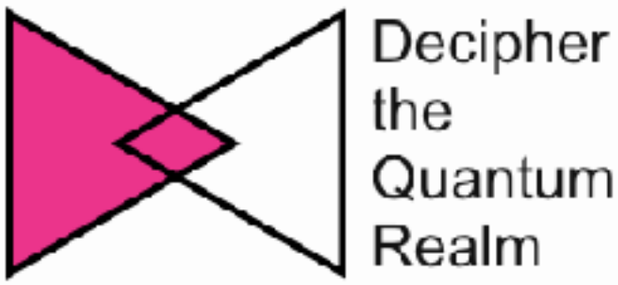
The low energy excess

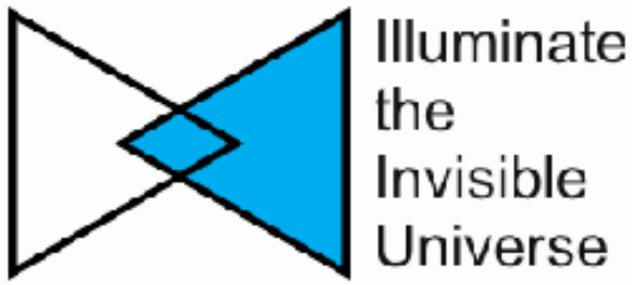
- **Low threshold detectors observe a rising spectrum in phonon and charge channels**
- **Phonon excess above and below the ionization threshold**
  - **Some caused by stresses of various kinds, evidence for decay over time**
- **Charge excess partly photo-induced (luminescence/Cerenkov/IR)**
- **Huge area of study**
  - **Annual EXCESS conference**
- **Recent review in 2503.08859**





P5 Report





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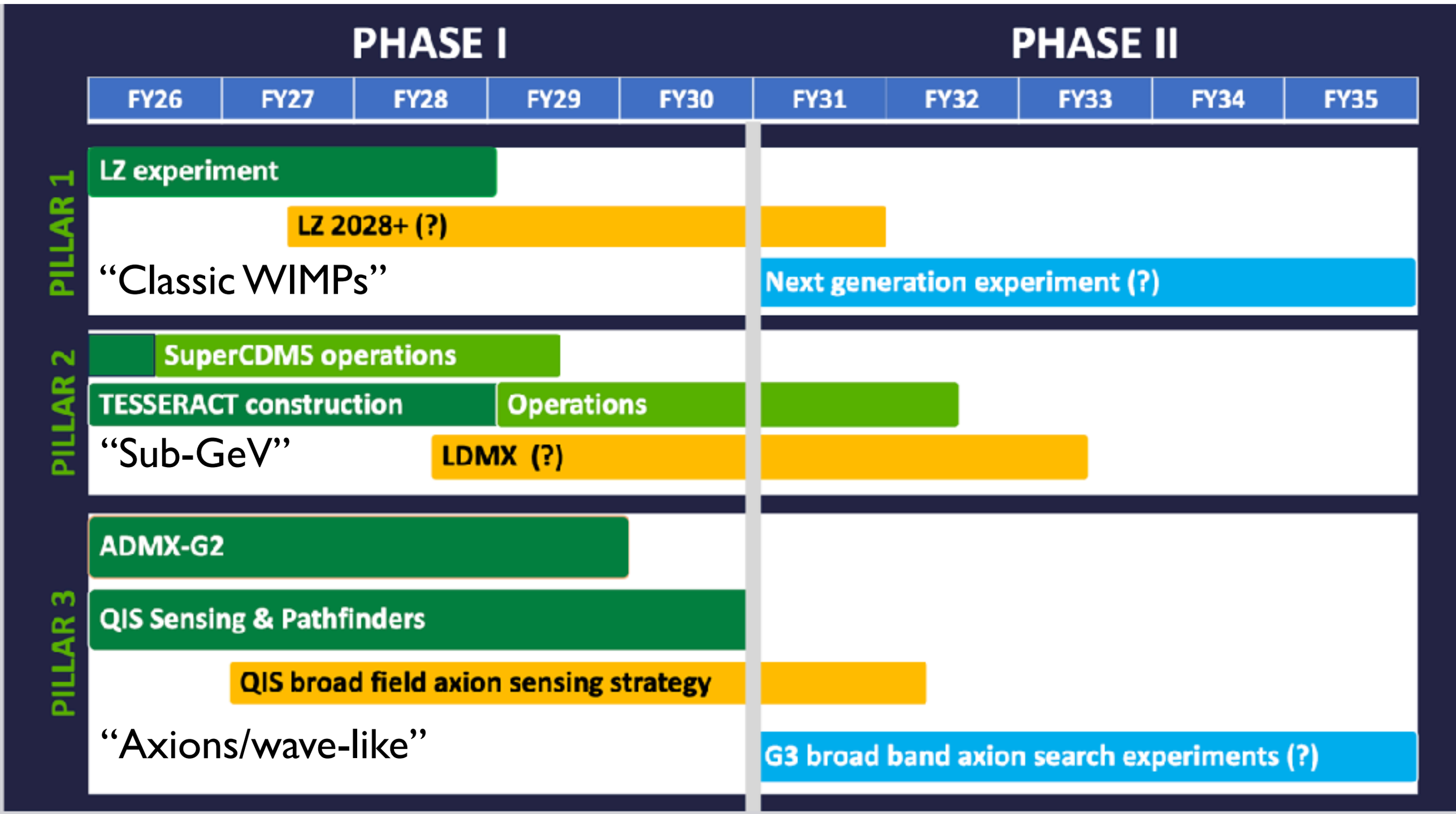
- **Less favorable budget scenario** ← Unfortunately…We are here

P5 Report



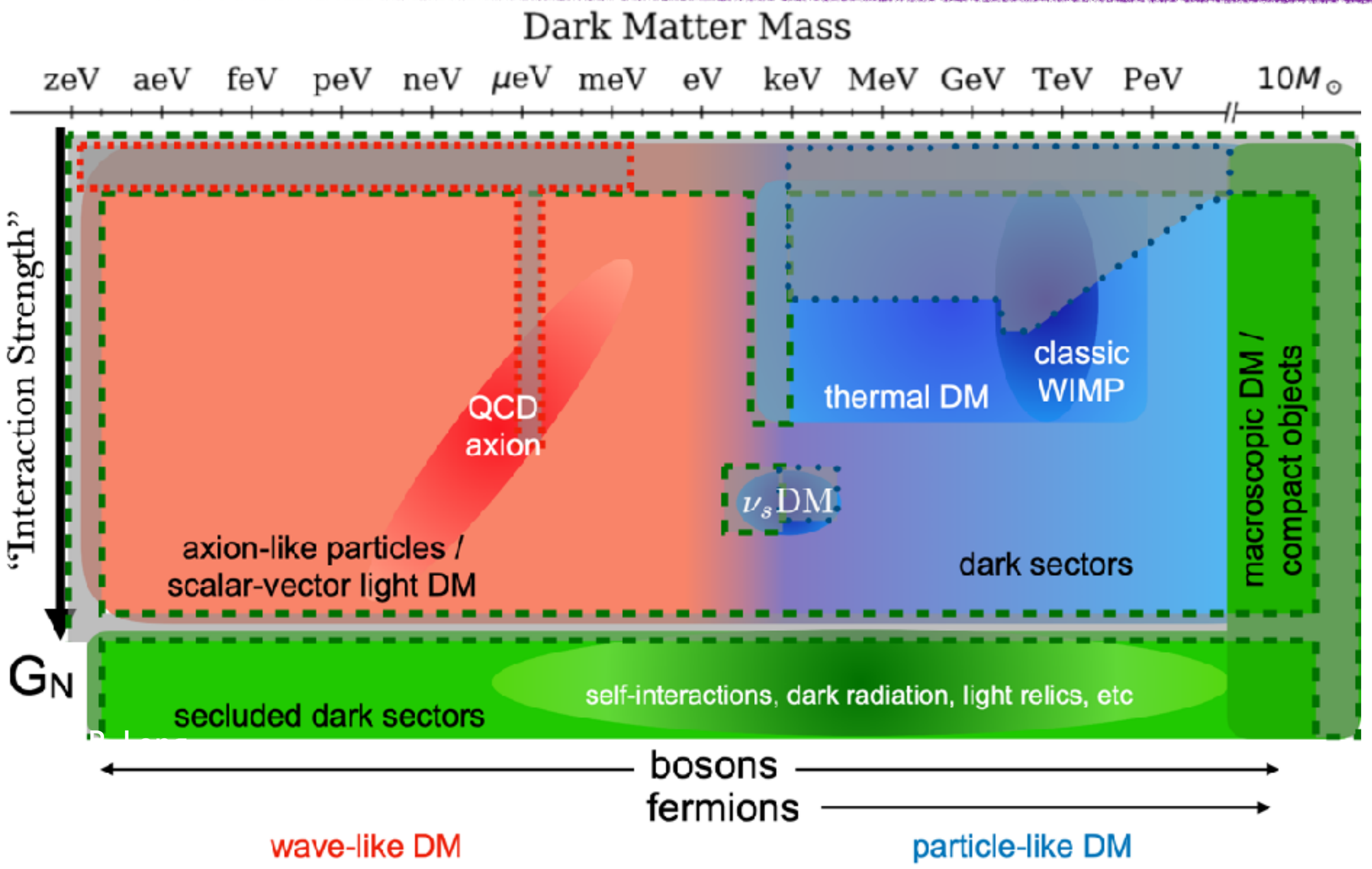
From M. Bautista, DOE, at DPF Community Meeting, December 2025

Dark Matter

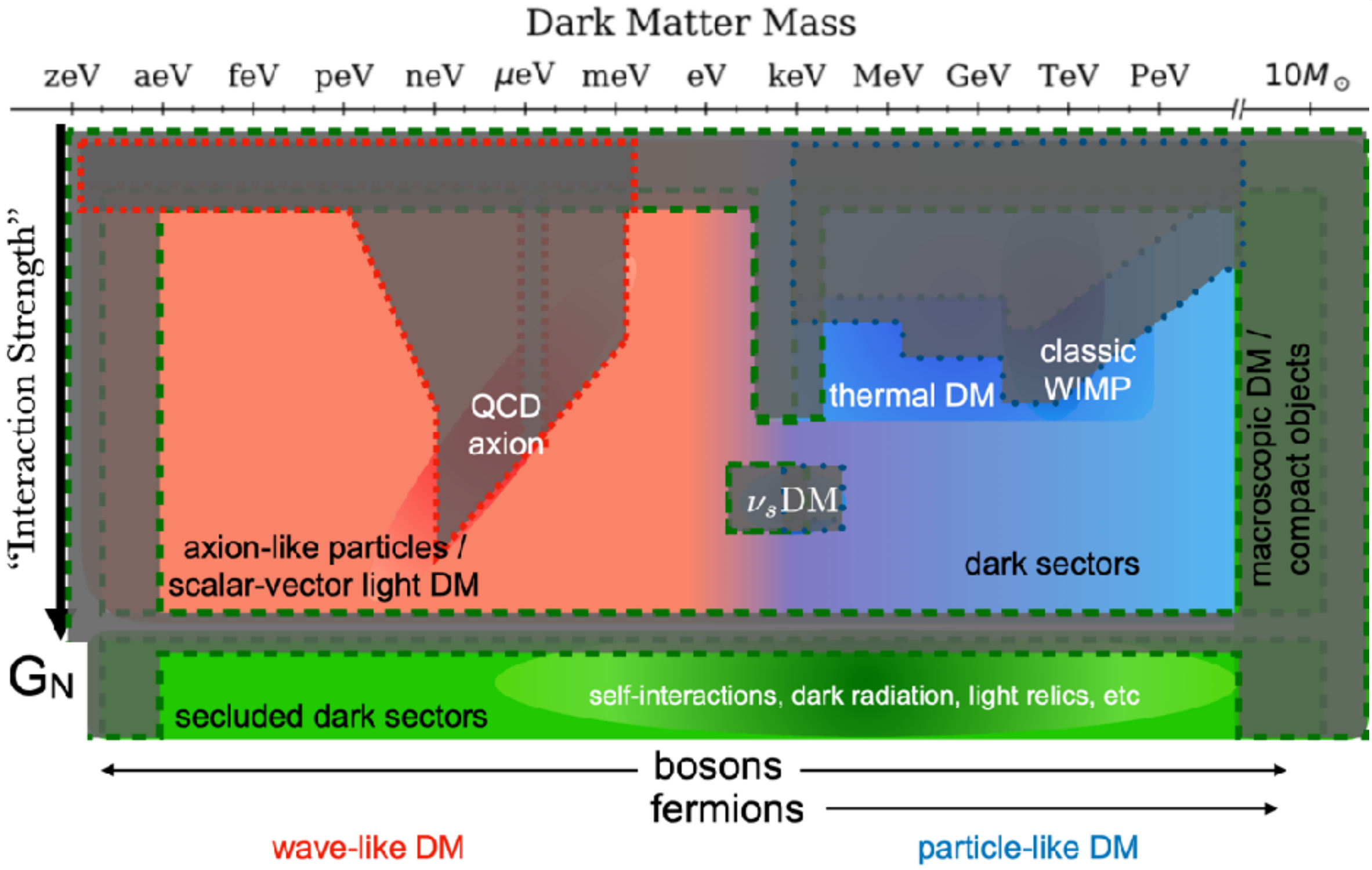
In 2001, dark matter was either a WIMP or an axion and we were going to rule out the relevant region of axion parameter space in a few years

Now, we make summary dark matter plots that look like…

Dark Matter Today



Dark Matter Today

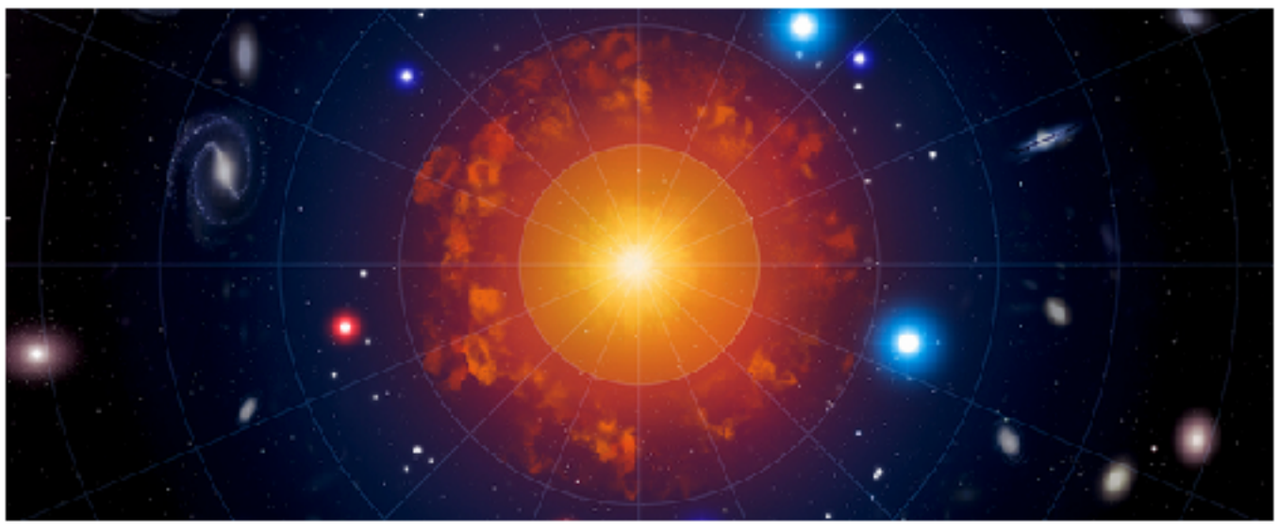


Glass Half Empty?

- It sometimes feels like we know less now than we did before
  - What was “axions or WIMPs” is now 50 orders of magnitude
- The odds of any one experiment finding something are pretty low

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 
@elonmusk

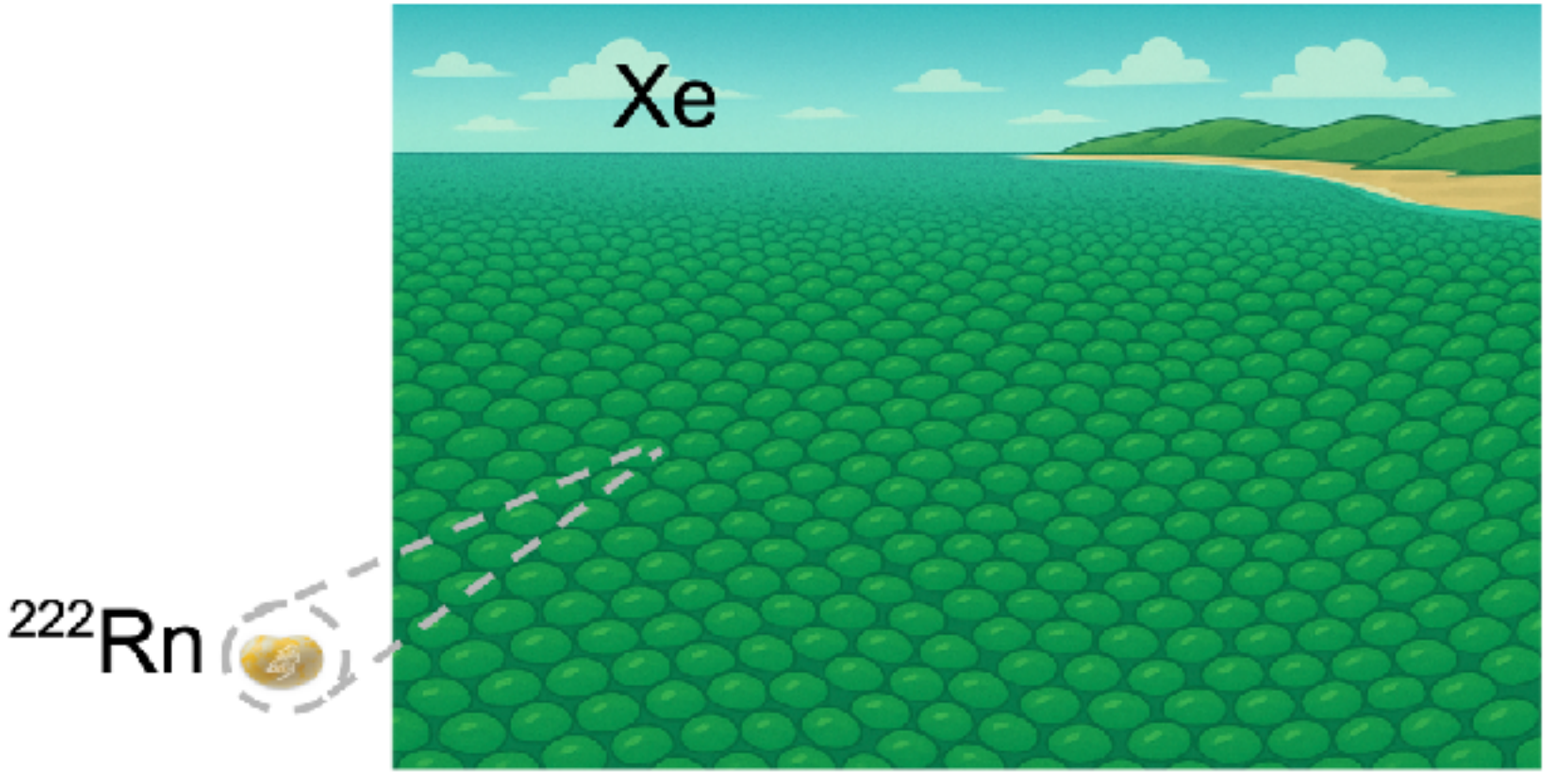
Possibly.

Dark matter is what seems most sketch to me.

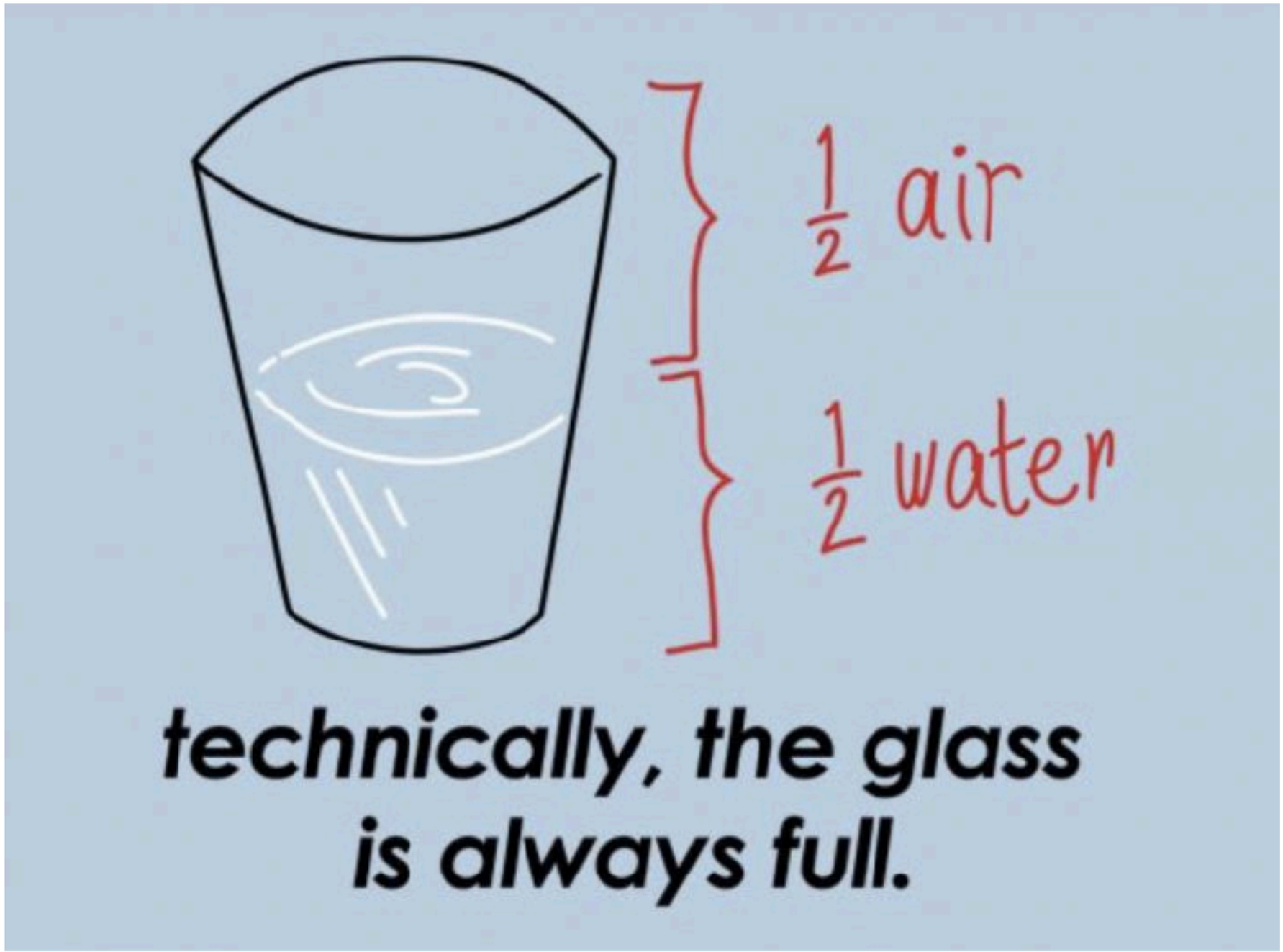
9:02 PM · Jul 16, 2023 · **2.8M** Views

Glass Half Full?

- A factor of over a million improvement in sensitivity in 25 years
  - LZ's biggest background is Pb214 from radon decay, at 2 atoms/kg Xe
  - Equivalent to 1 jelly bean in all the world's oceans!
- Explosion of ideas to search wide and delve deep!
- These are opportunities!

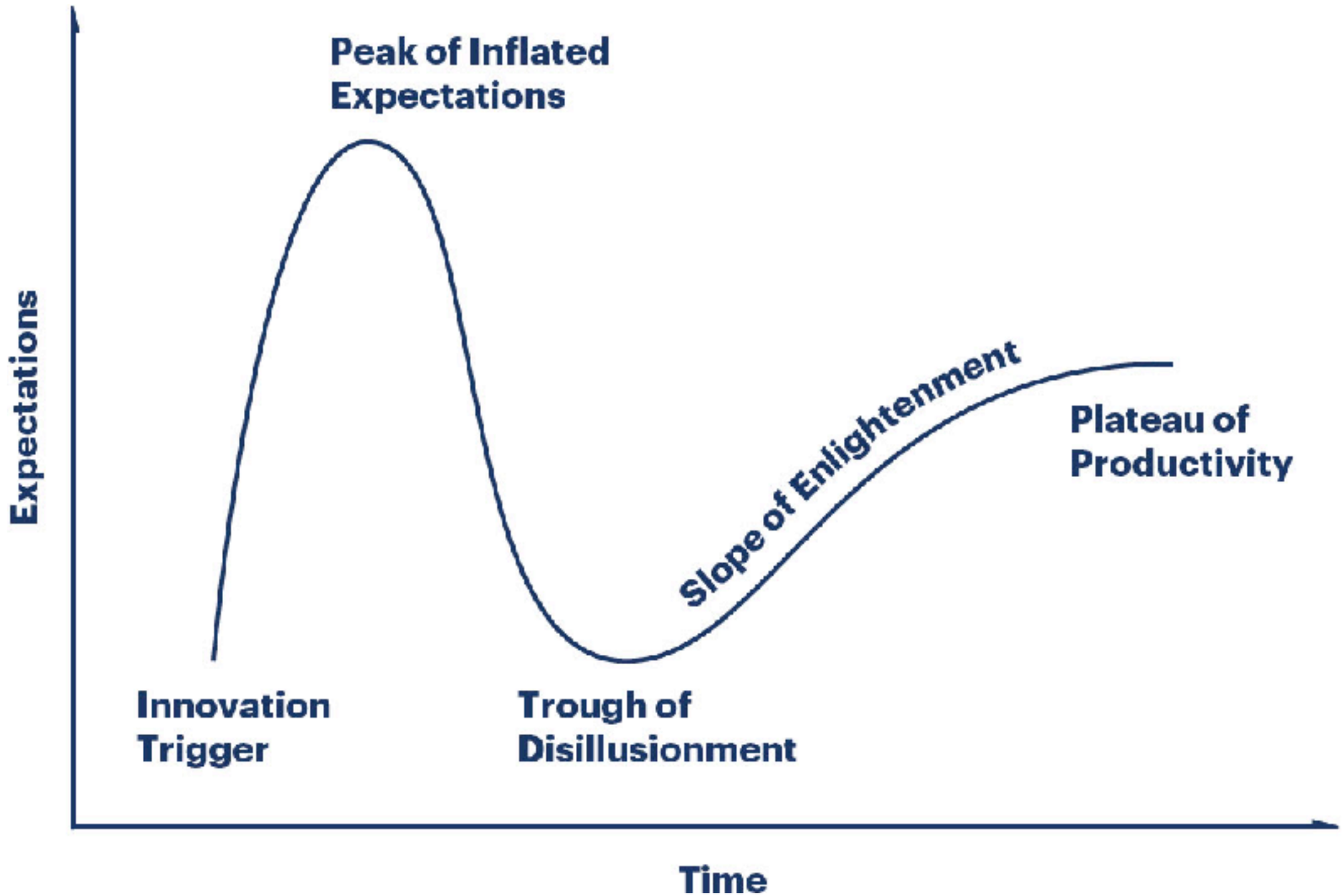


Glass is simply full



STEAMfest at Woodlawn School, NC

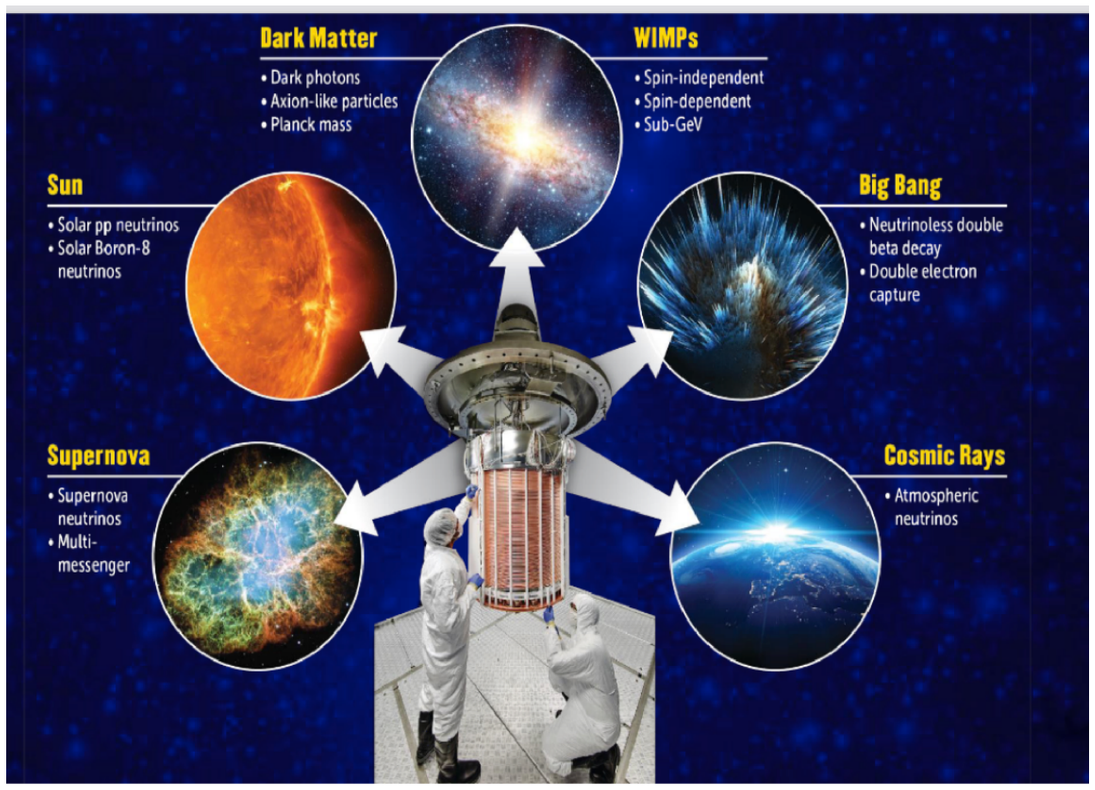
Dark Matter Hype Cycle?

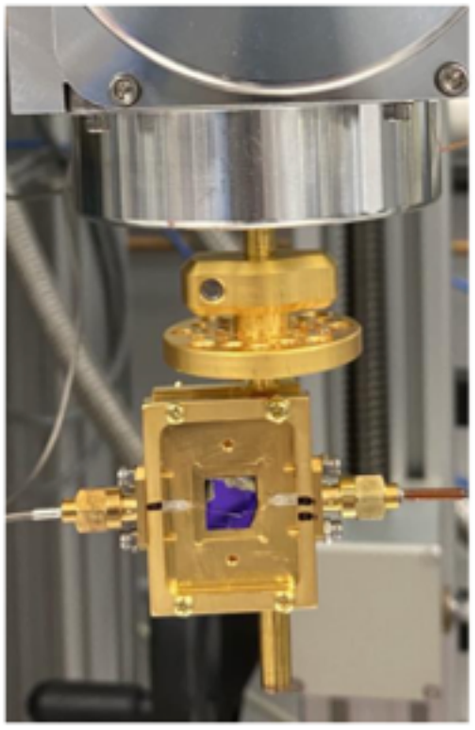


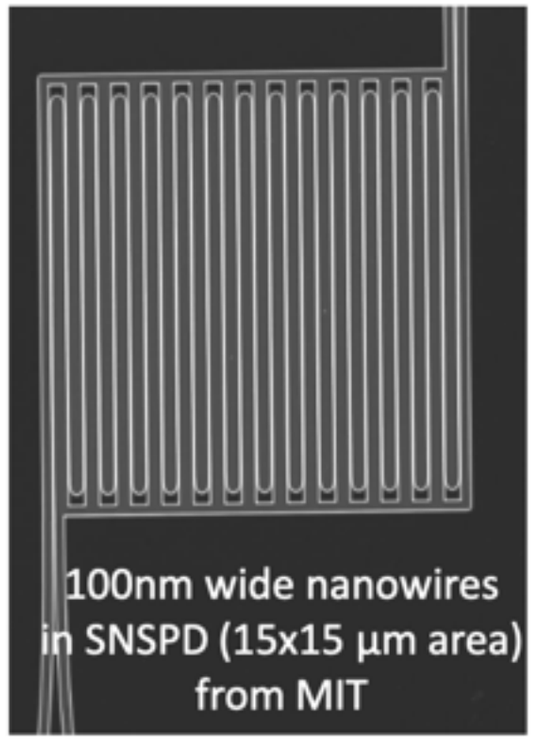
Gartner Hype Cycle h/t Eric Hudson, UCLA, on quantum computing

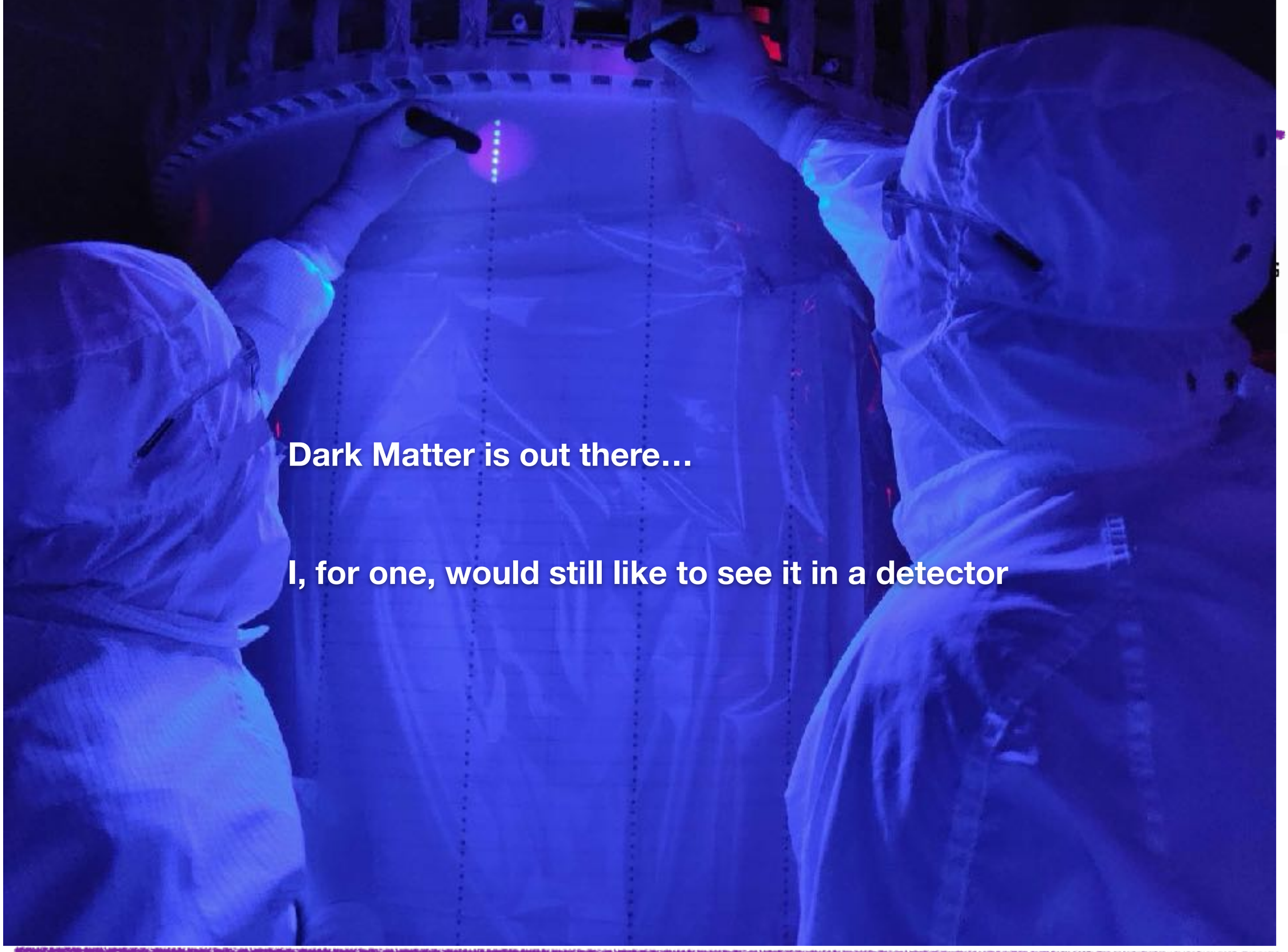
Glass is simply full

- The mystery has not gone away - Dark matter is still a fascinating mystery
- My opinion:
  - Large experiments (both in people and budget) need to do more than one thing
  - Smaller efforts are driving and driven by technical development and instrumentation
    - Great training! AI-compatible! Quantum-compatible!
- Support what we can given the environment, try not to fragment the community





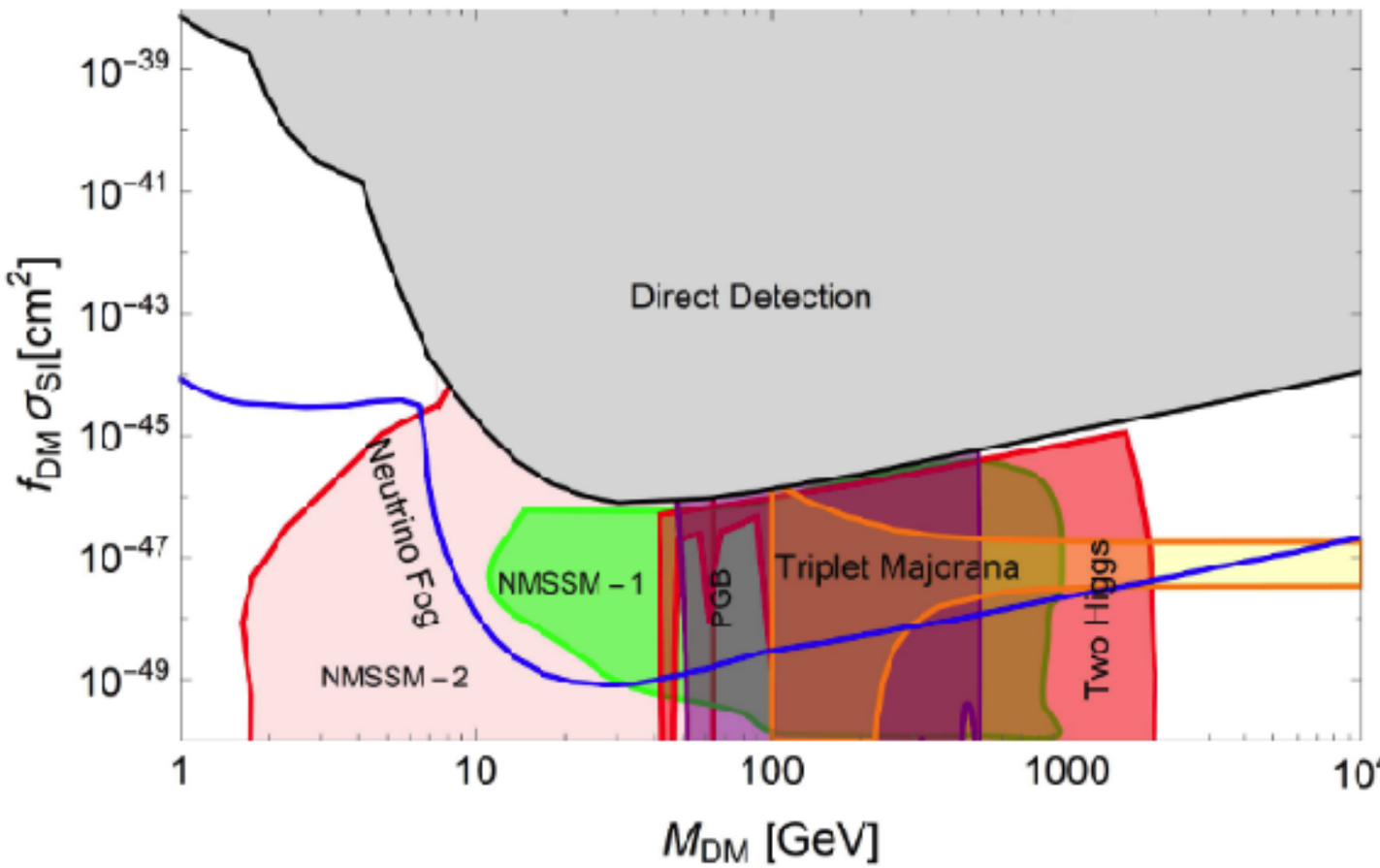



Dark Matter is out there…
I, for one, would still like to see it in a detector

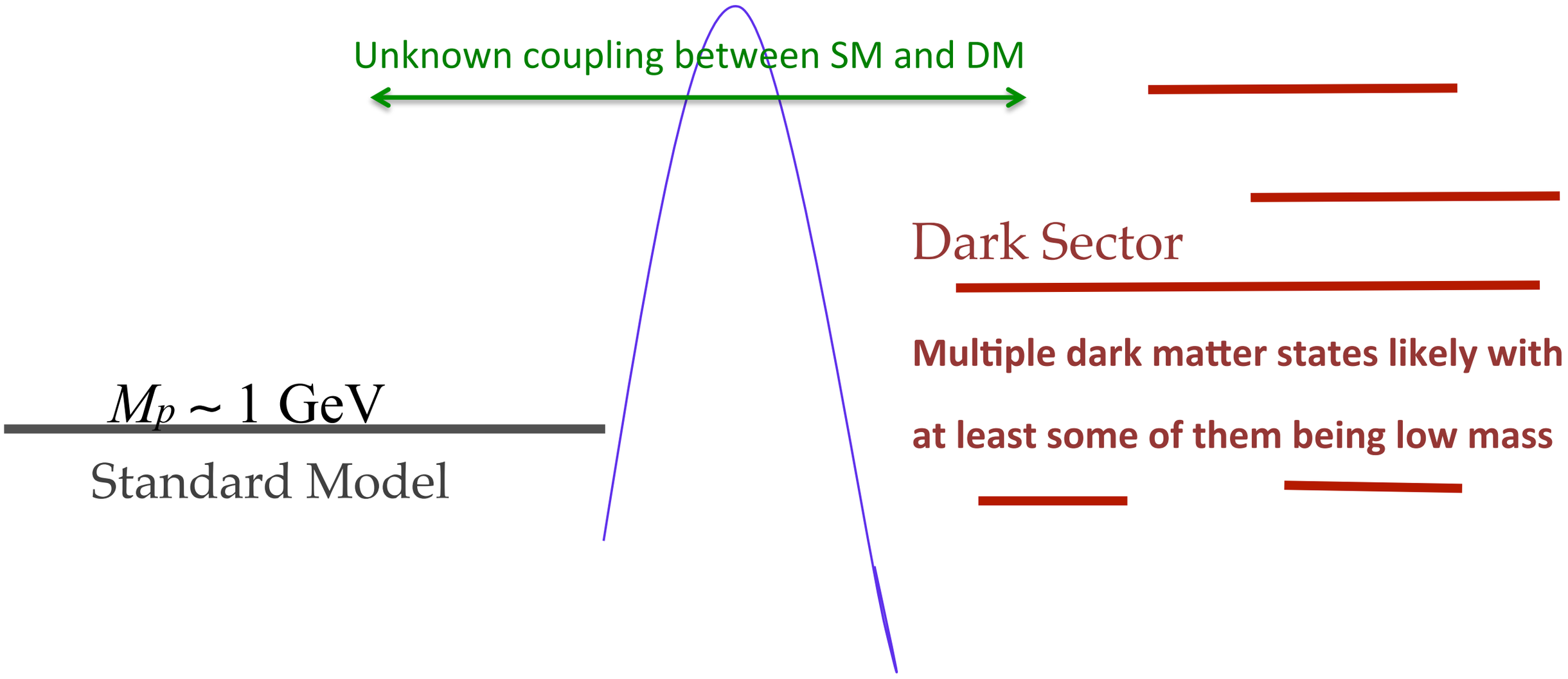
Dark Matter

- One of the best motivated candidates is a "WIMPy" thermal relic
  - ✦ MeV - 100 TeV scale particle (cosmological bounds)
  - ✦ Weak scale interactions leads to correct density today

- e.g. SUSY models, twin Higgs, Triplet Majorana, Hidden Sector
- Recent summary in Snowmass CF1-WP1 - 2203.08084
  - ✦ Many other references therein
- Now probing some of the most interesting models from 20 years ago



WIMP crisis?

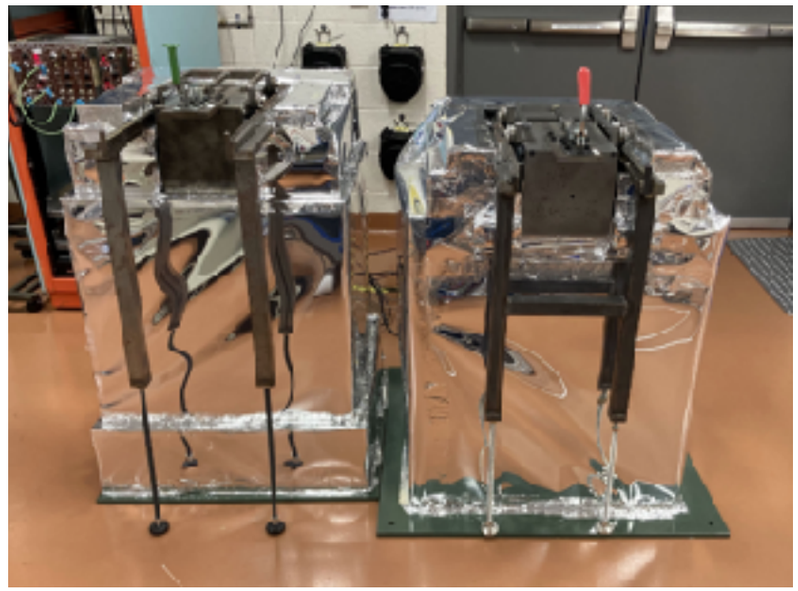

Unknown coupling between SM and DM
Dark Sector
Multiple dark matter states likely with
at least some of them being low mass
$M_p \sim 1$ GeV
Standard Model

Background Sources and Mitigation

Many sources of BG

Many methods for BG mitigation

- Detector materials
  - ✦Nothing went into the detector without screening
  - ✦Radio-assay campaign with 13 HPGe detectors, ICPMS, neutron activation analysis, and radon emanation
    - For example, cryostat made of most radiopure titanium in the world (Astropart. Phys. 96, 1 2017)
- Rn daughters and dust on surfaces
  - ✦TPC assembly in Rn-reduced cleanroom
  - ✦Dust <500 ng/cm^2 on all LXe wetted surfaces
  - ✦Rn-daughter plate-out on TPC walls <0.5 mBq/m^2
- Xenon contaminants
  - ✦Charcoal chromatography at SLAC
  - ✦Continuous purification underground



Eur. Phys. J. C, 80: 1044 (2020)