Direct Detection “Overview”

Hugh Lippincott, UCSB

March 5, 2024 – The Future of High Energy Physics

Dark Matter

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)

III. DARK MATTER AND RELIC PARTICLES

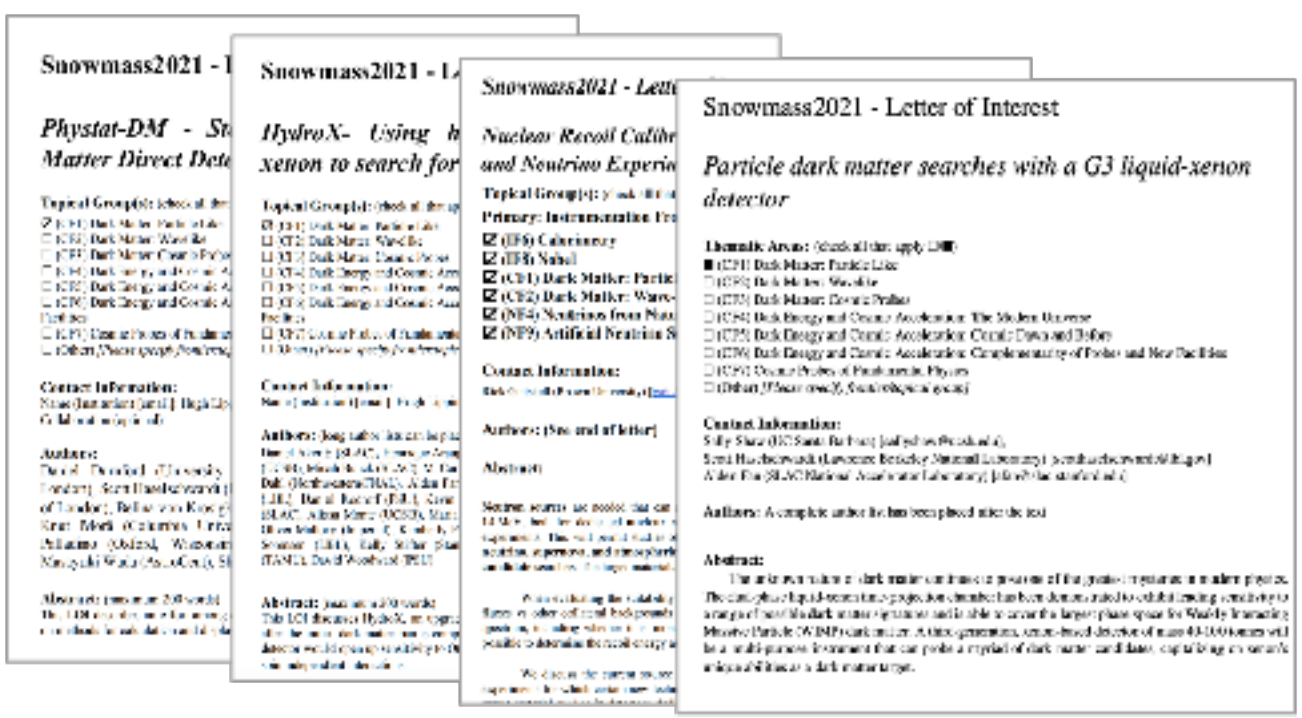
Since the mystery of dark matter first appeared in the thirties due to observations of galaxy clusters by Zwicky, the evidence has steadily mounted and today strongly suggests the possibility of a solution rooted in new fundamental particle physics [2]. Dark matter refers to matter that is inferred only through its gravitational effects, and which neither emits nor absorbs electromagnetic radiation. These effects are observed on a wide range of distance scales—from individual galaxies to superclusters to mass flows on the largest observable scales. Direct observation of dark matter and the determination of its nature is one of the most important challenges to be met in cosmology today. Moreover, it is likely that this determination will yield new information in particle physics, since there is strong evidence that the dark matter is not composed of baryons, but rather is in some exotic form.

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

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], Marloff[33], Gopolang Mohlabeng[34], M.F. Morzani[7,35,36], Alexander St. Nelson[5], Ciaran A. J. O'Hare[39], K.J. Palladino[40], Aditya Parikh[41], Jung Profumo[31,45], Nirmal Raj[46], Brandon M. Roach[44], Tarek Saab[47], Mari Shaw[4], Seodong Shin[49], Kuver Sinha[50], 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 20 minutes!

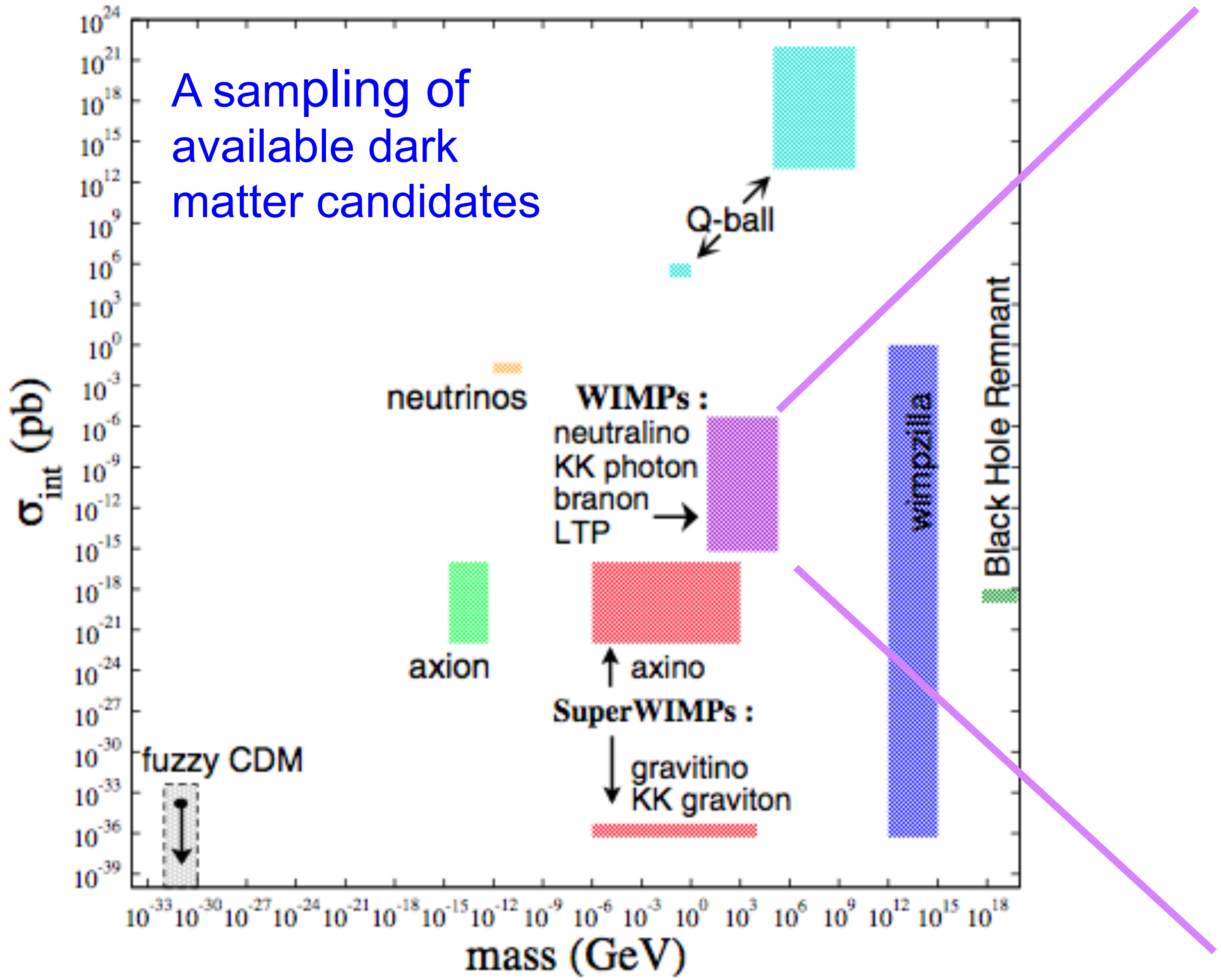
Dark Matter

2001 - 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.

2022 - Well-studied theoretical models provide a compelling scientific case to make broad and rapid inroads into unexplored dark matter parameter space via a *search wide, delve deep* strategy. With new experiments that will come online in this decade, the HEP community will search wide to efficiently probe broad, logarithmic ranges of parameter space…Concurrently the community will delve deep to comprehensively explore the high priority science targets of WIMPs and the QCD axion.

Dark Matter

Particle Physics



It's probably WIMPs, right?

WIMPs

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

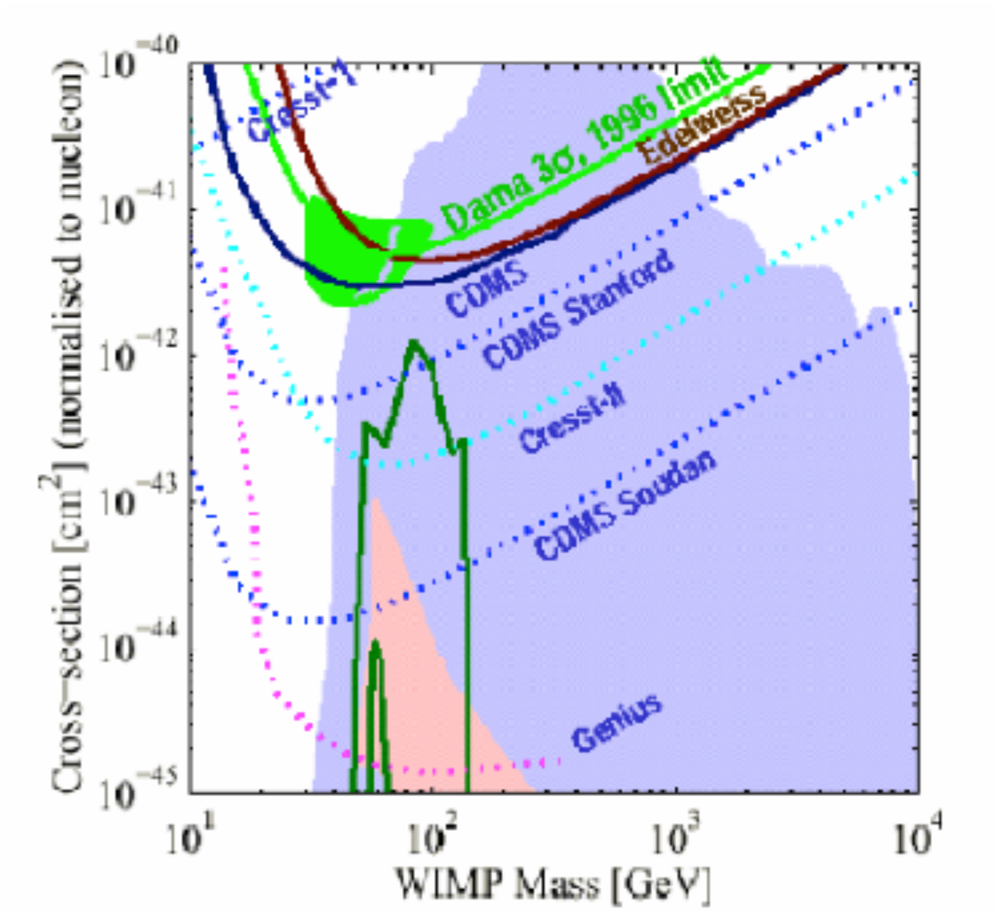
(Dated: October 30, 2018)

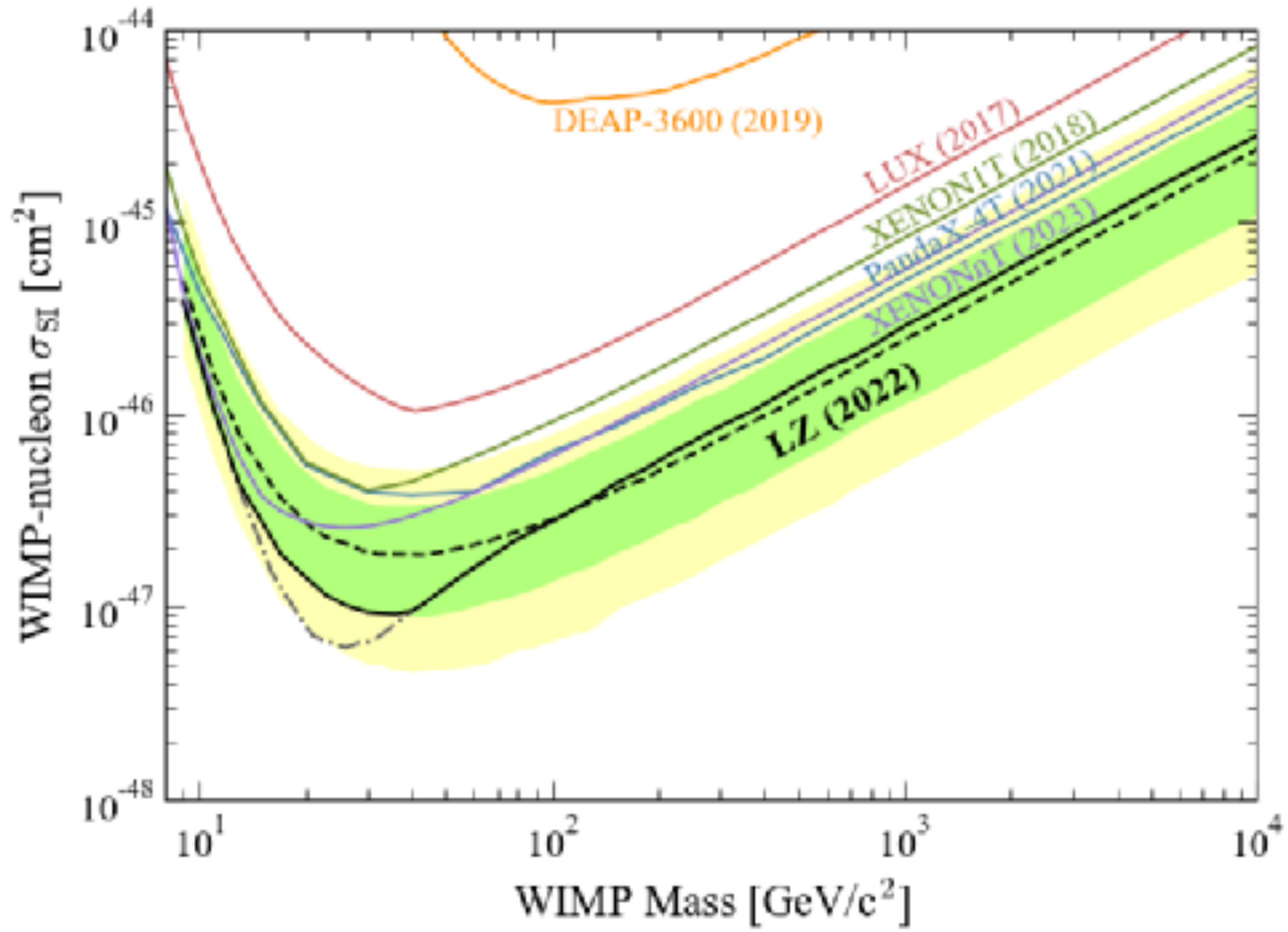
"Current searches are already exploring the parameter space of supersymmetric WIMPs [10-1000 GeV], with prospects for a factor of a hundred improvement in the coming years."

WIMPs

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

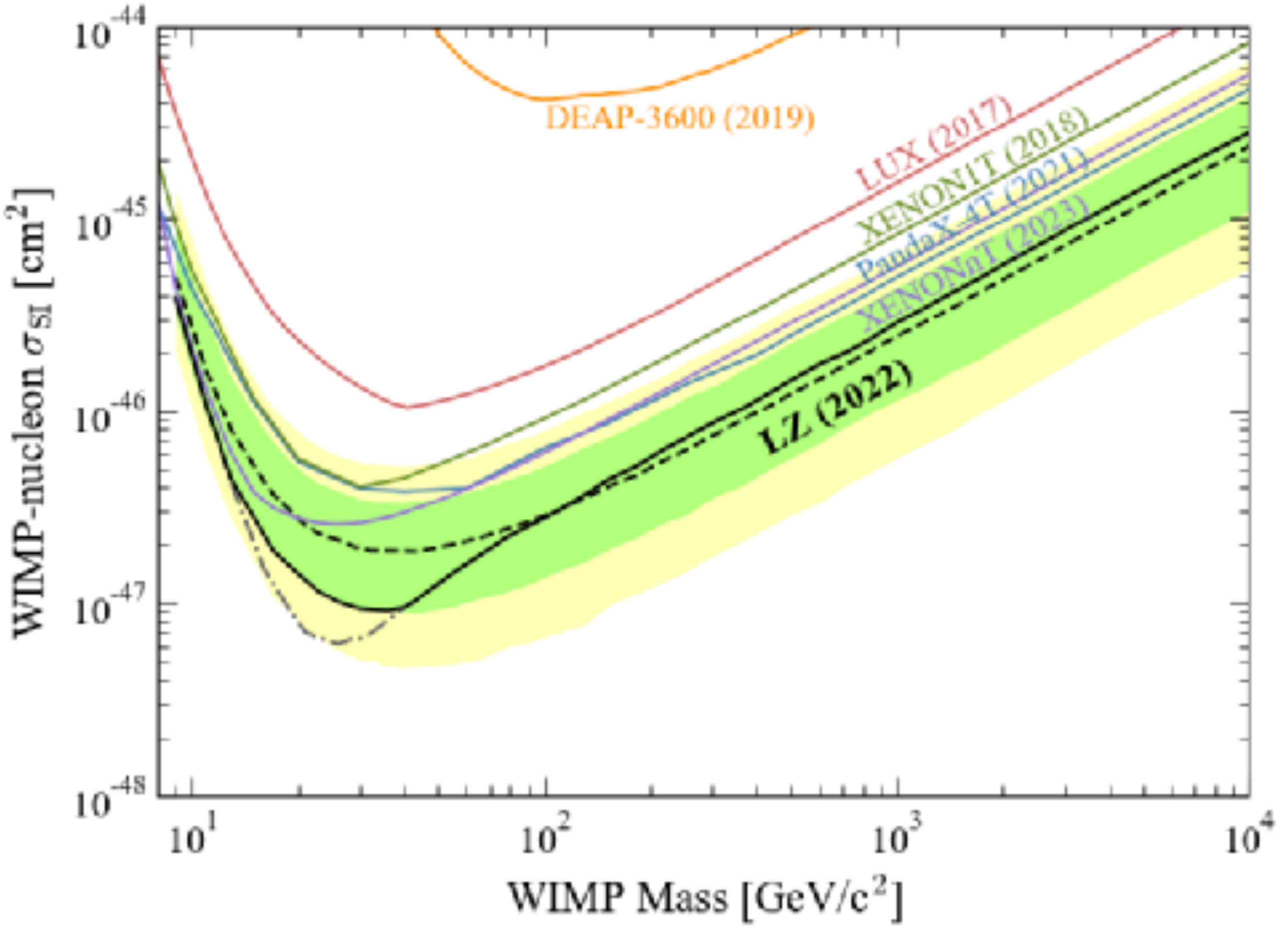
- LZ PRL 131: 041002, (2023)
- Best limit at 9.2×10^{-48} cm^2

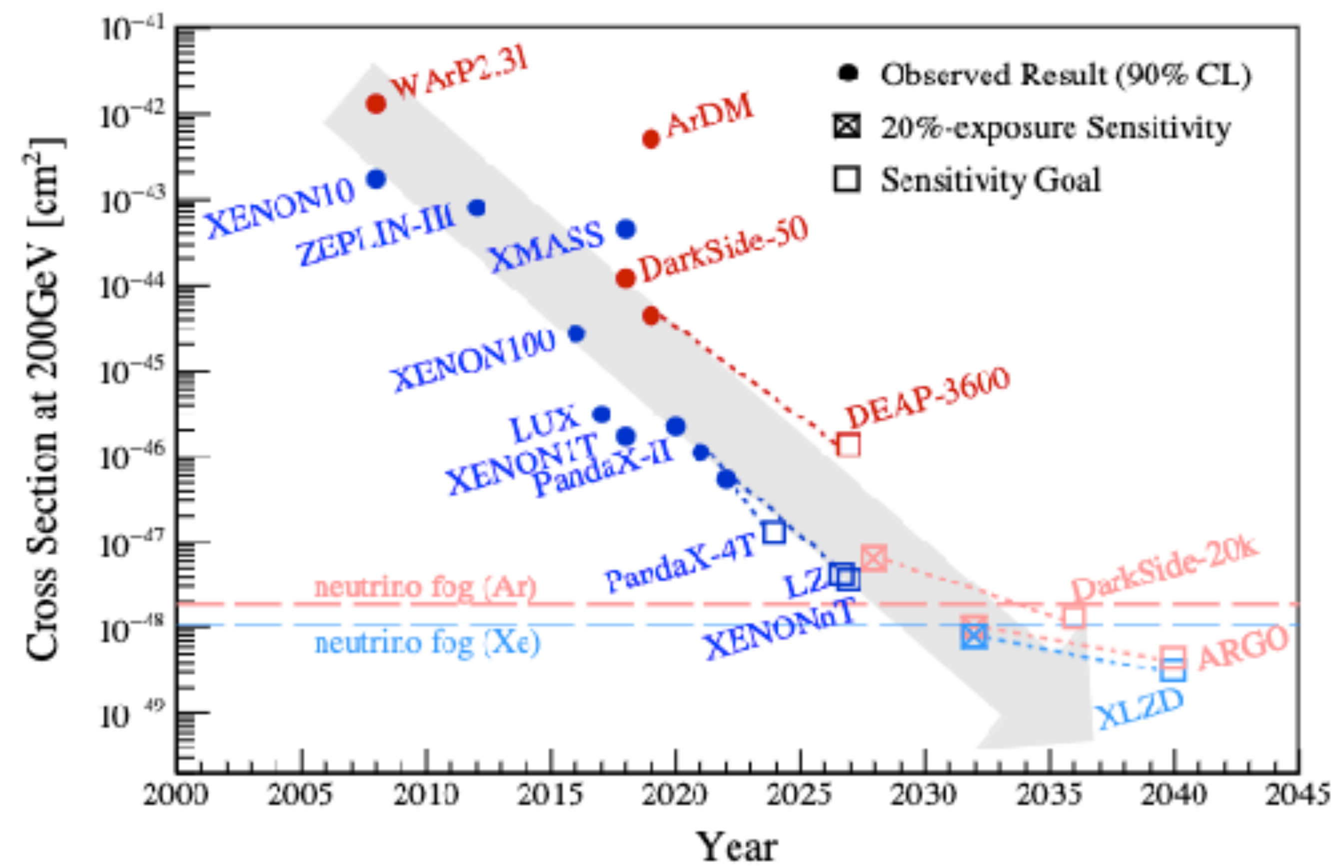




- Factor of 320,000 improvement in 23 years! Doubling every 1.25 years!
- A triumph of human ingenuity!
- No WIMPs :(

WIMPs

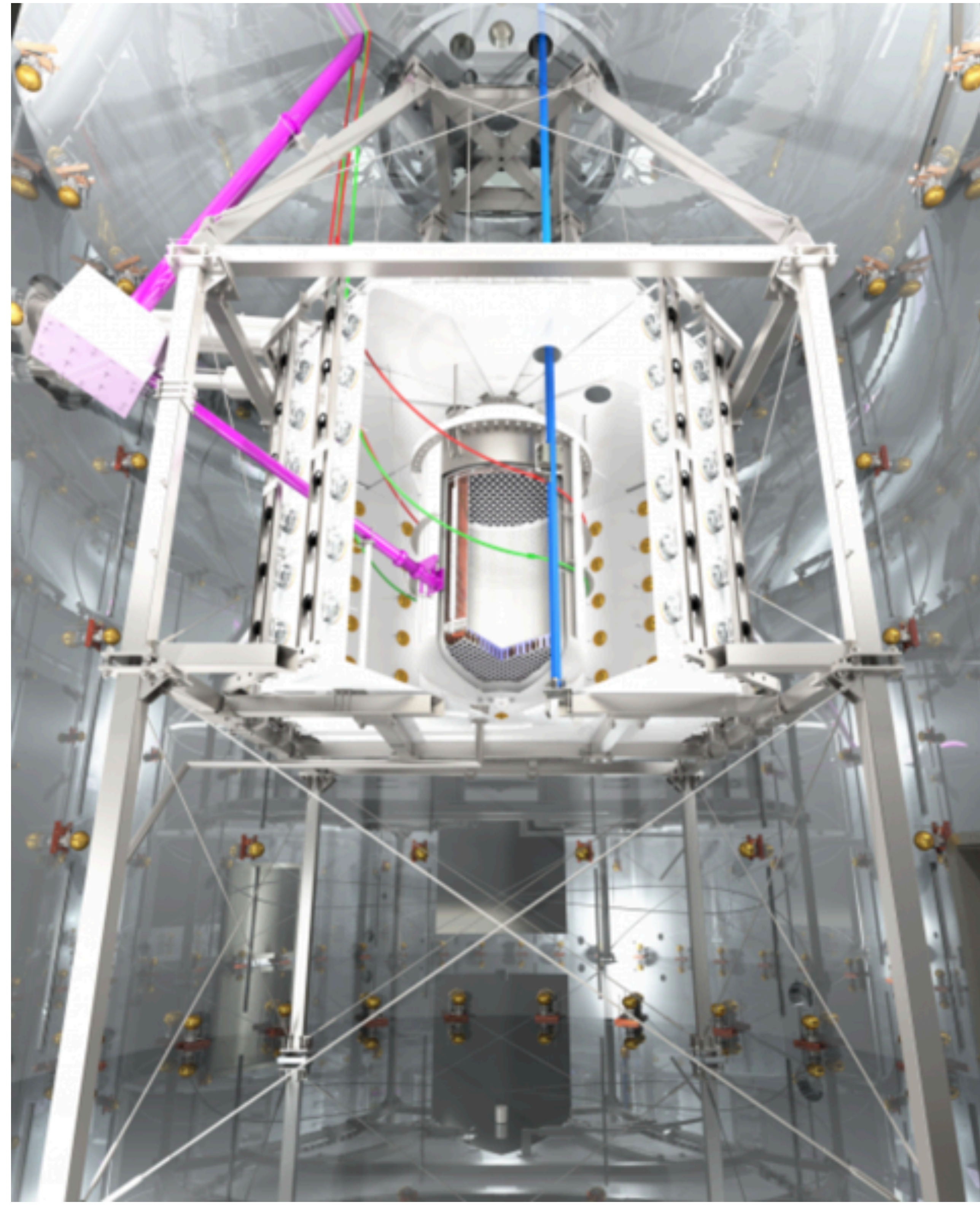




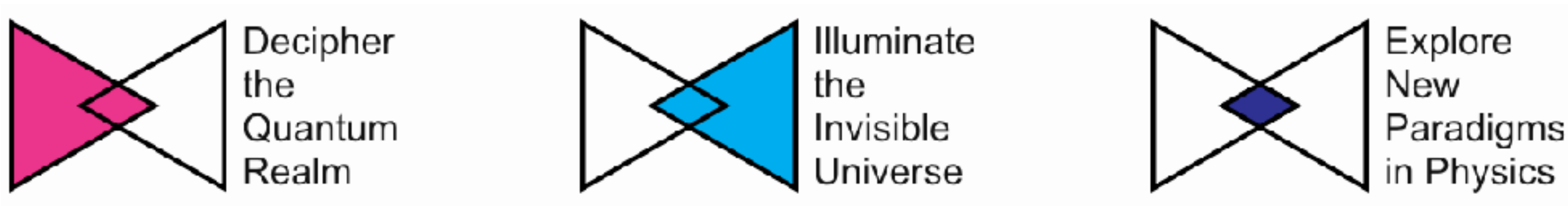
- Xenon experiments have been driving sensitivity to ~100 GeV "classic" WIMPs for the past 15 years
  - LZ, XENONnT, and PandaX-4T - multi tonne xenon experiments now operating
- Argon experiments offer very large targets with good background discrimination
  - DarkSide-20k under construction

WIMPs

WIMPs

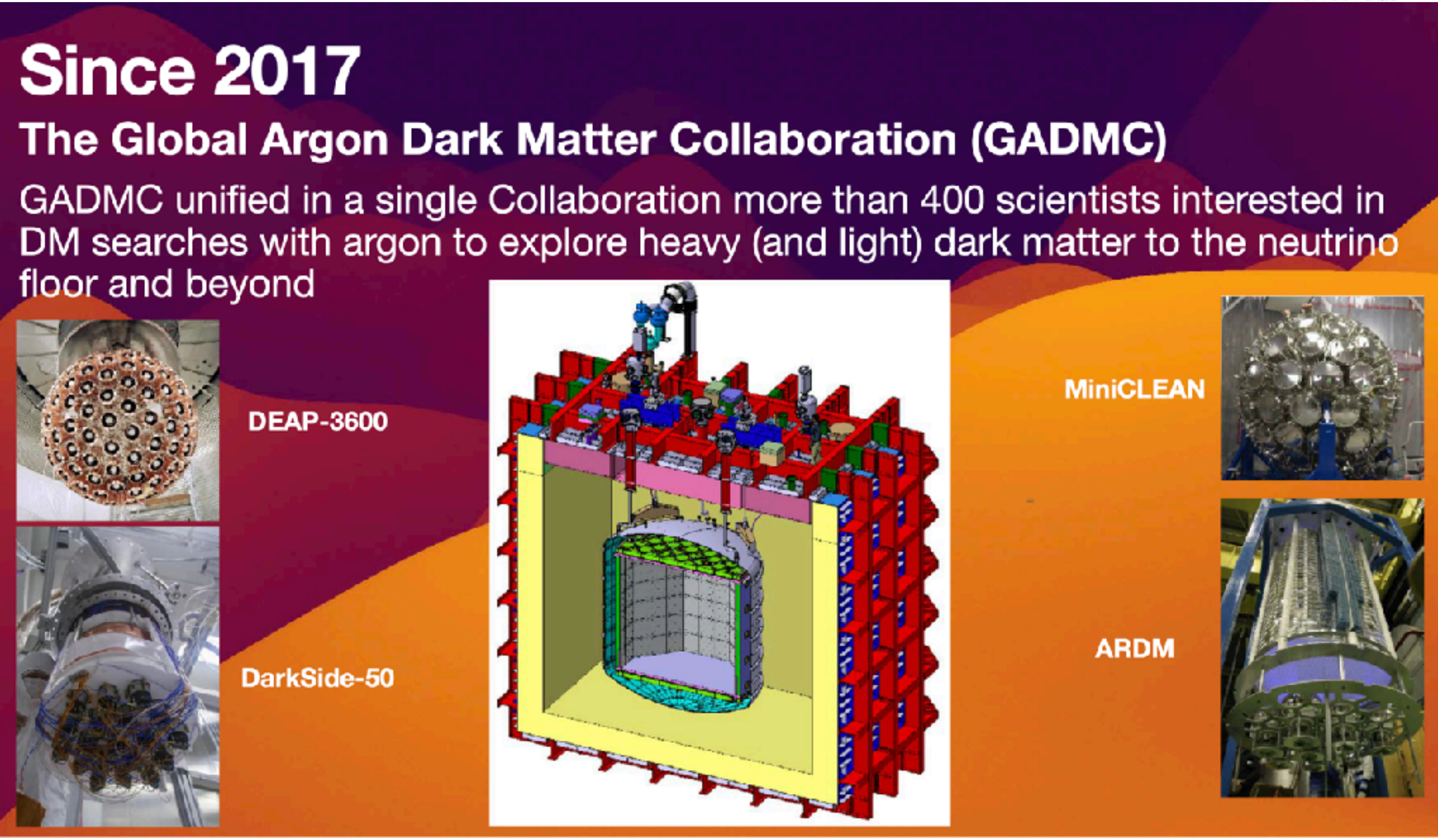


P5 Report



- **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**

GADMC Collaboration



XLZD Consortium

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

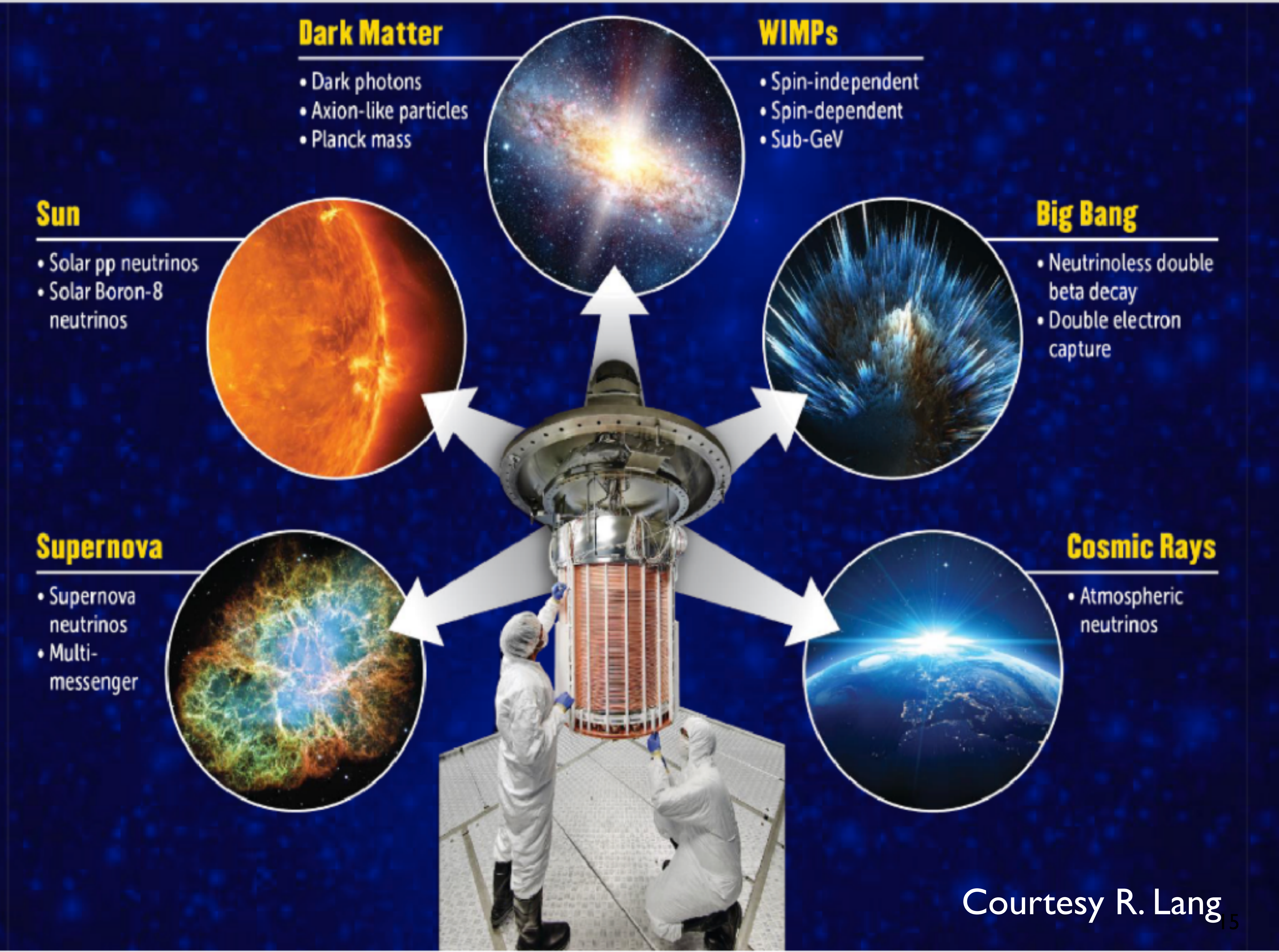
SURF is distributing this press release on behalf of the DARWIN and LZ collaborations

July 20, 2021

Several successful meetings

https://xlzd.org/

White paper (2203.02309)



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

P5 Report

Decipher the Quantum Realm

Illuminate the Invisible Universe

Explore New Paradigms in Physics

- **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)

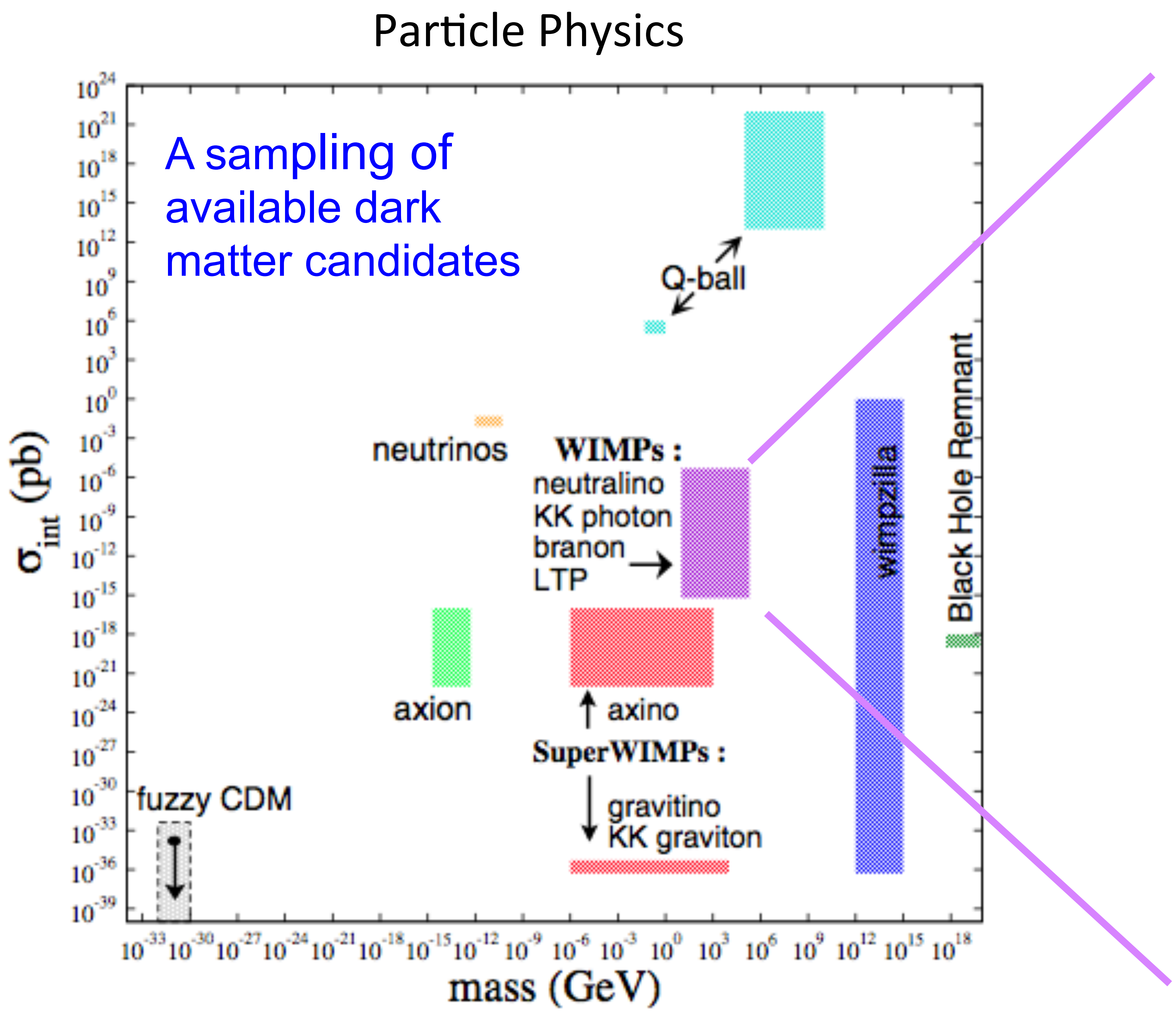
Index: Operation Construction R&D, Research P: Primary S: Secondary

§ 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
LHC		P	P		P	P	
LZ, XENONnT			P				
DarkSide-20k			P				
G3 Dark Matter §	S		P				

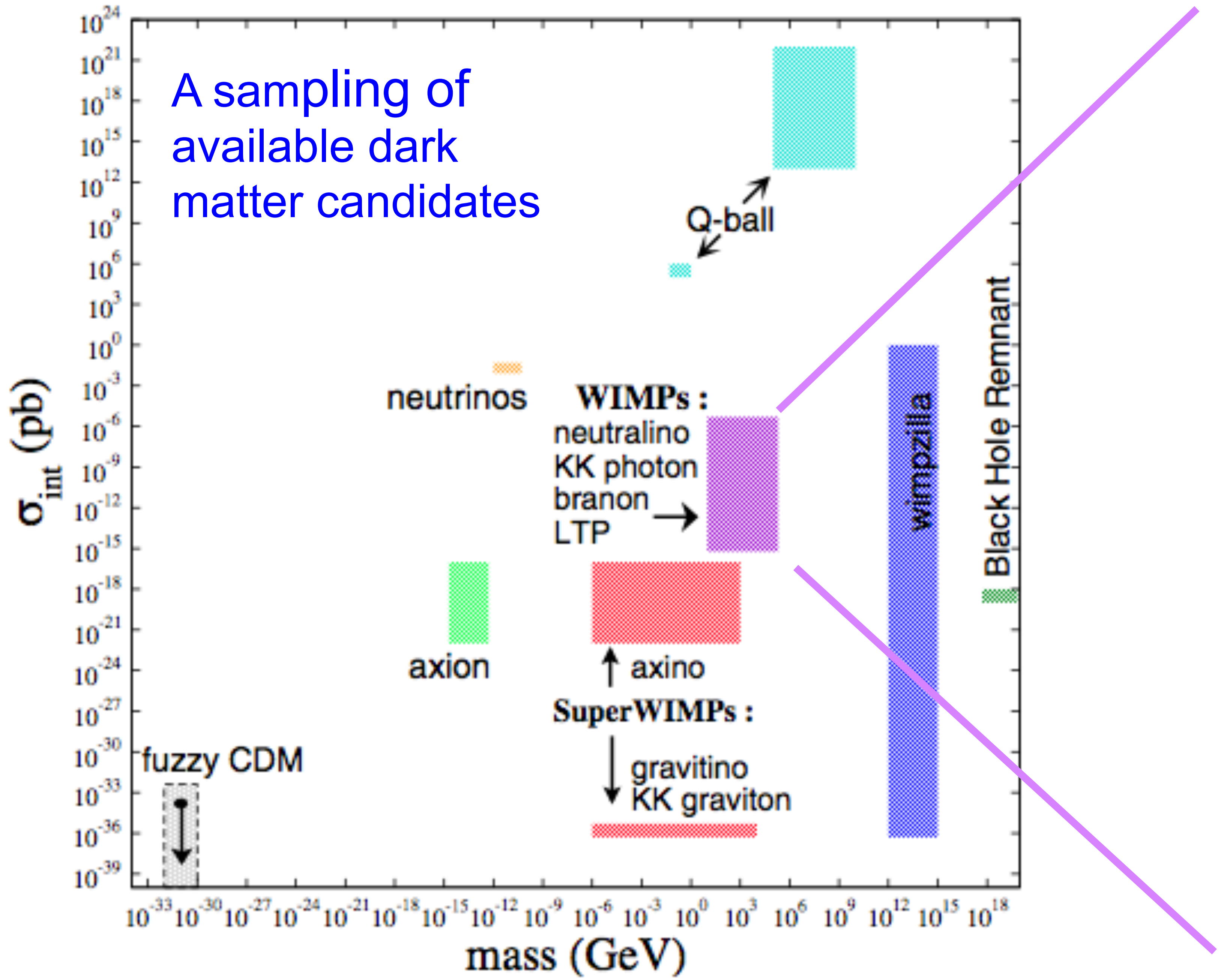
Dark Matter



It's probably WIMPs, right?

Dark Matter

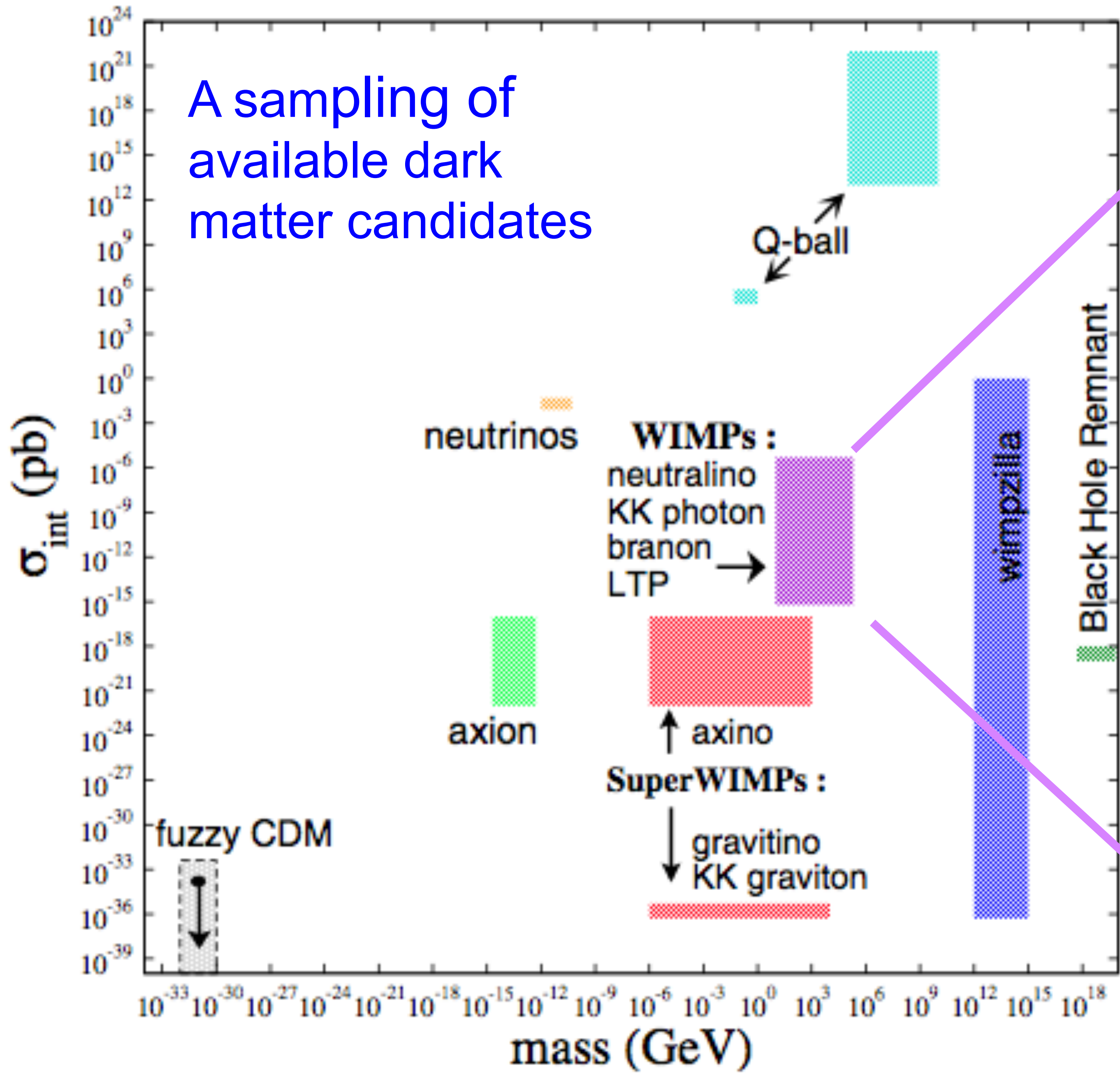
Particle Physics



~~It's probably WIMPs, right?~~

Dark Matter

Particle Physics



It's definitely an axion

Axions

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

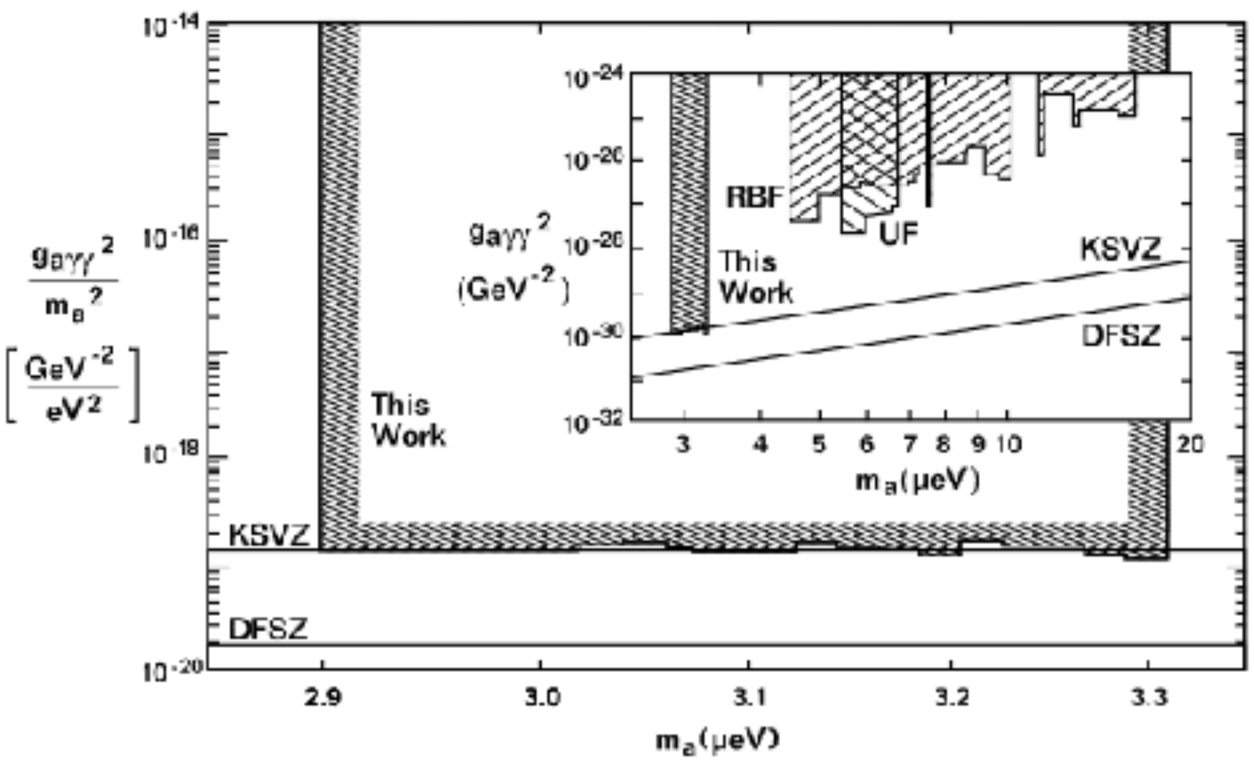
(Dated: October 30, 2018)

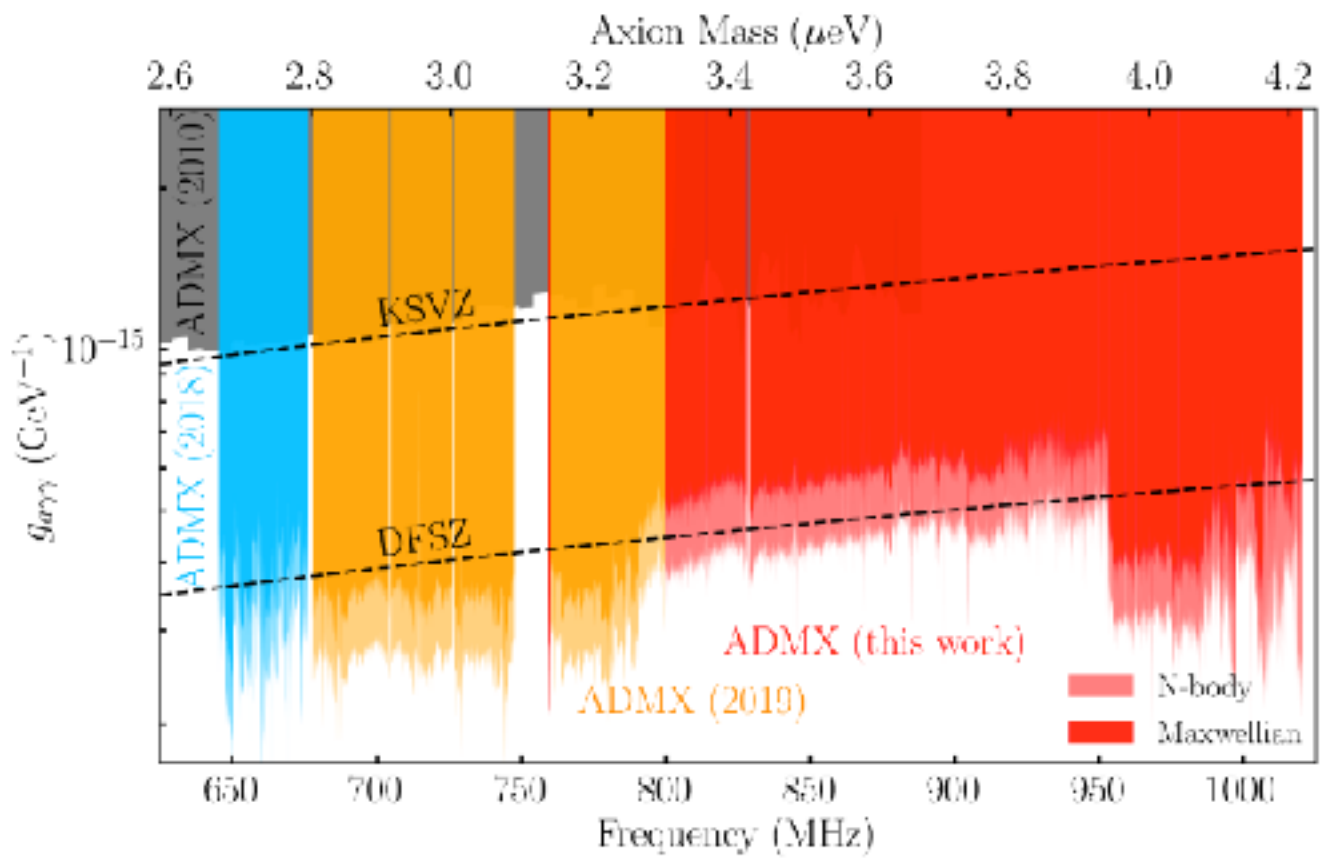
"The two decades of axion mass range that have not yet been ruled out by experiments or astrophysical observations are precisely in the range that could explain the dark matter…

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

Axions

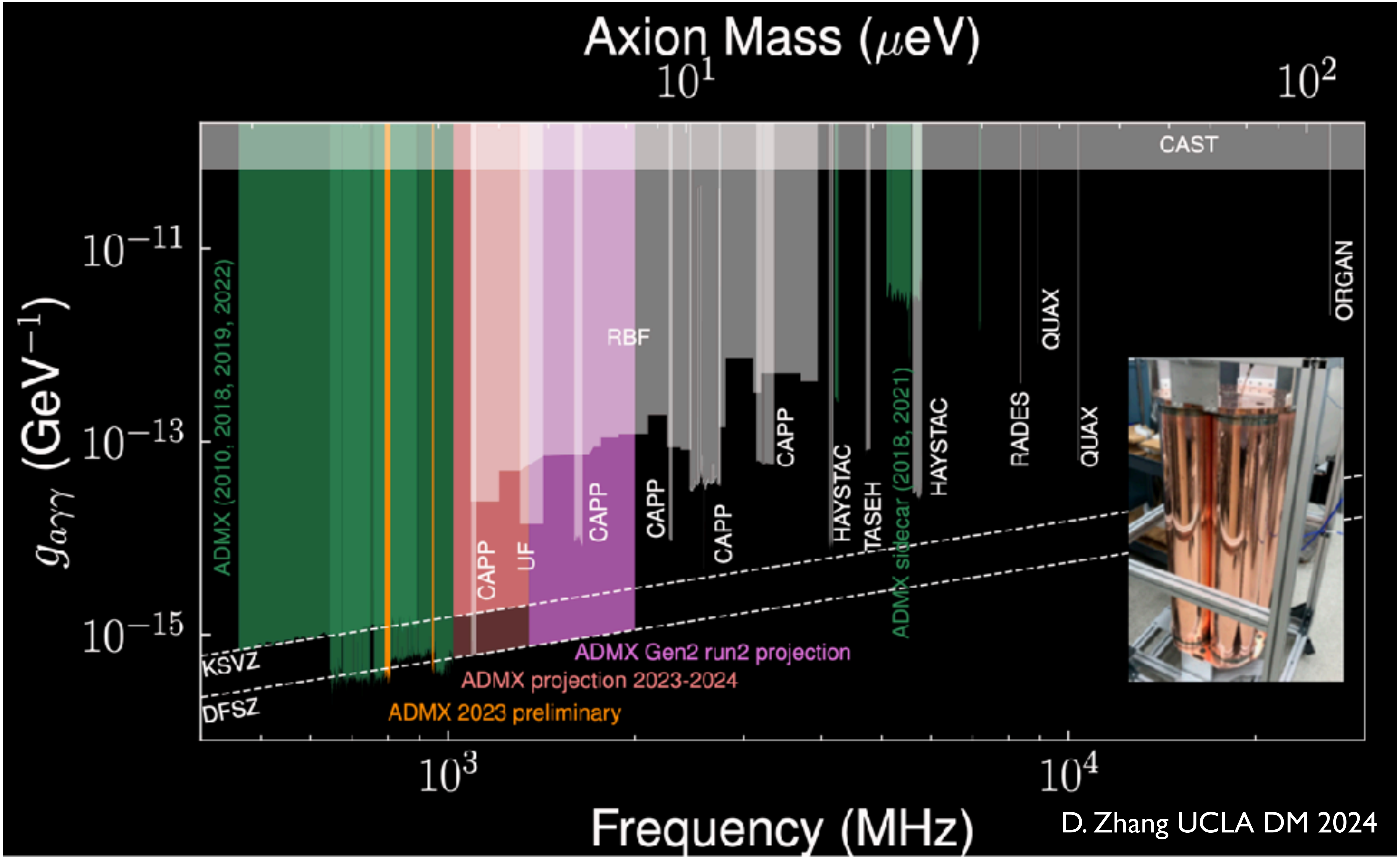
- ADMX, PRD 64: 092003 (2001)
- Touching the KSVZ line at 3e-6 eV
- ADMX, PRL 127:261803 (2021)
- To DFSZ line from 2.5 to 4.2e-6 eV





- Close to order of magnitude improvement in both coupling and mass
- We did not discover or rule out axion dark matter, sadly
- Many more resources now starting to move into axion physics
- Panofsky Prize in 2024 for David Tanner and Leslie Rosenberg!

Dark Matter



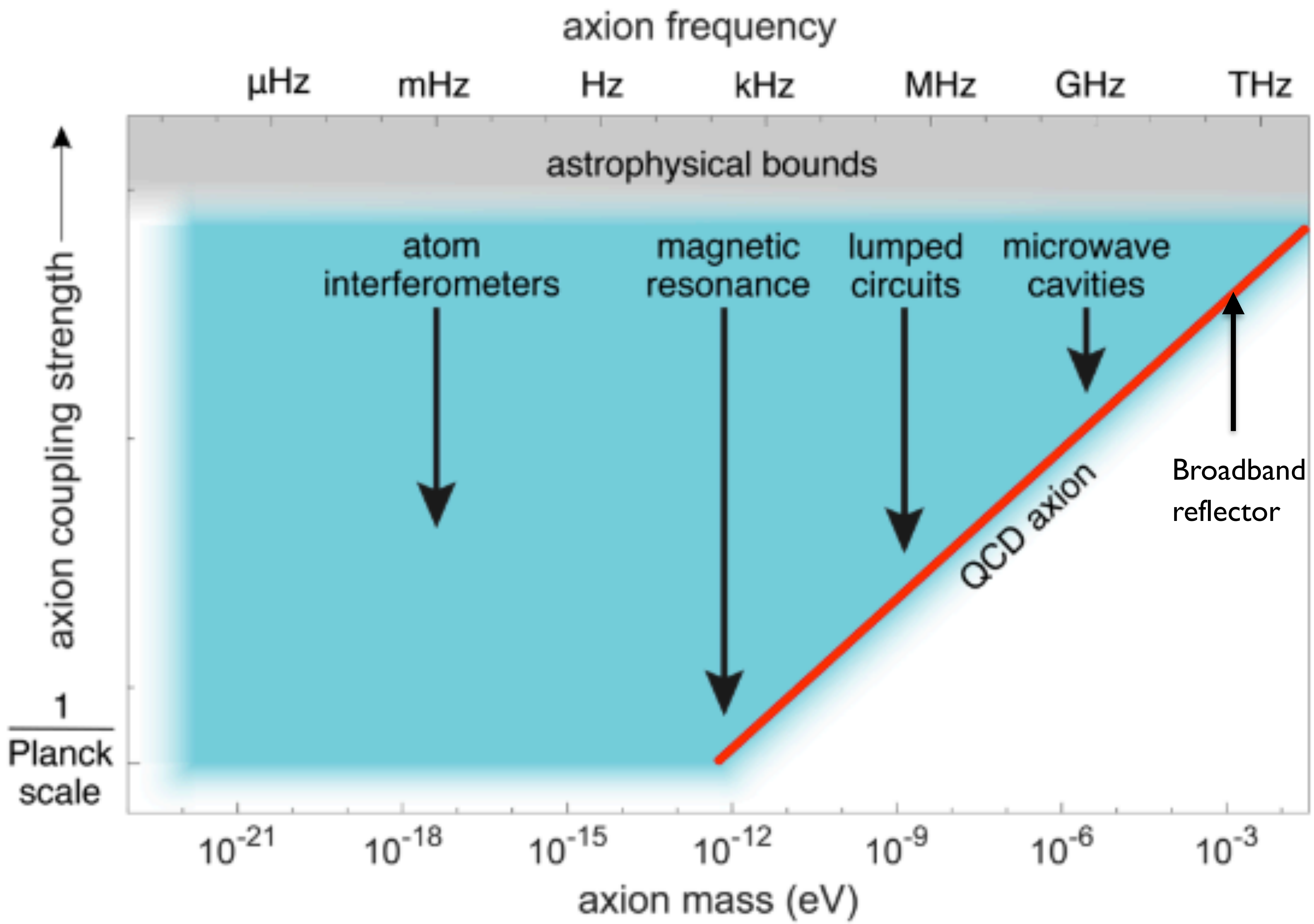
Axion Mass (μeV)
10^1
10^2
CAST
10^{-11}
10^{-13}
10^{-15}
$g_{a\gamma\gamma}$ (GeV^{-1})
ADMX (2010, 2018, 2019, 2022)
RBF
CAPP
UF
CAPP
CAPP
CAPP
CAPP
HAYSTAC
TASEH
ADMX sidecar (2018, 2021)
HAYSTAC
RADES
QUAX
QUAX
ORGAN
KSVZ
DFSZ
ADMX Gen2 run2 projection
ADMX projection 2023-2024
ADMX 2023 preliminary
10^3
10^4
Frequency (MHz)
D. Zhang UCLA DM 2024

Axions from the bottom up

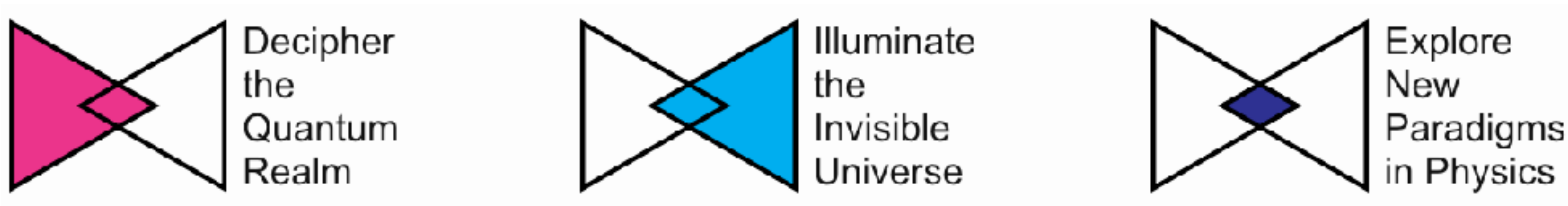
“The *two decades of axion mass range that have not yet been ruled out* by experiments or astrophysical observations are precisely in the range that could explain the dark matter…   - Snowmass 2001

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

Axions from the bottom up



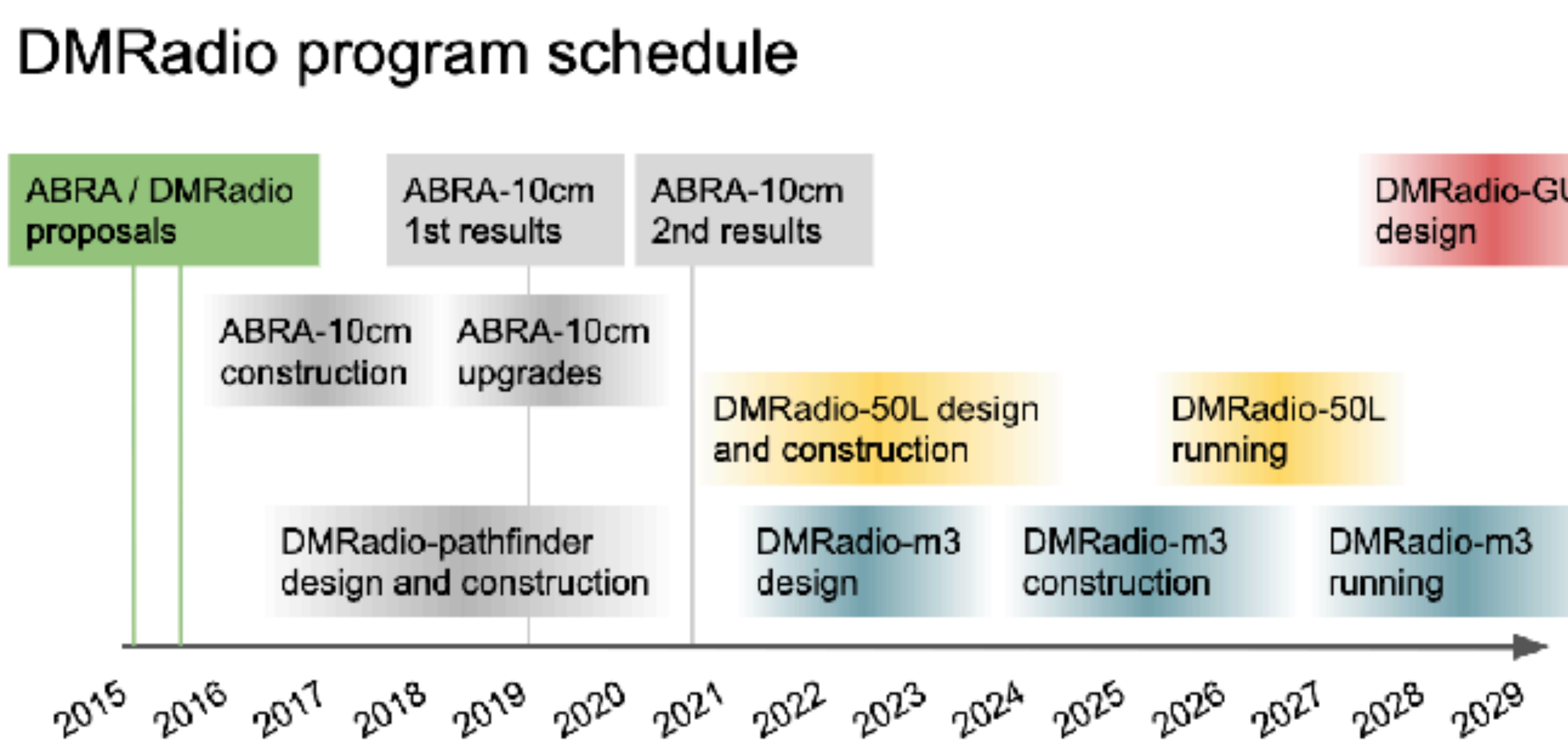
P5 Report



- **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

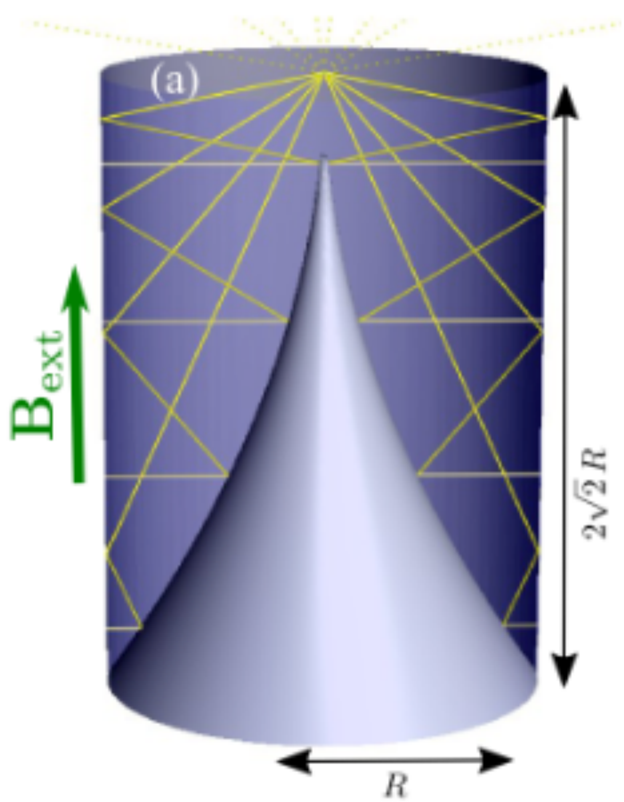
- **ADMX-EFR*, HAYSTAC going to higher frequencies in cavity searches (axion converts to a photon in a cavity)**
- **DMRadio* looks to push below 1 ueV with lumped elements (axions convert into an effective current measured by a resonator)**
- **CASPEr pushing even lower with precision NMR (axions interact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

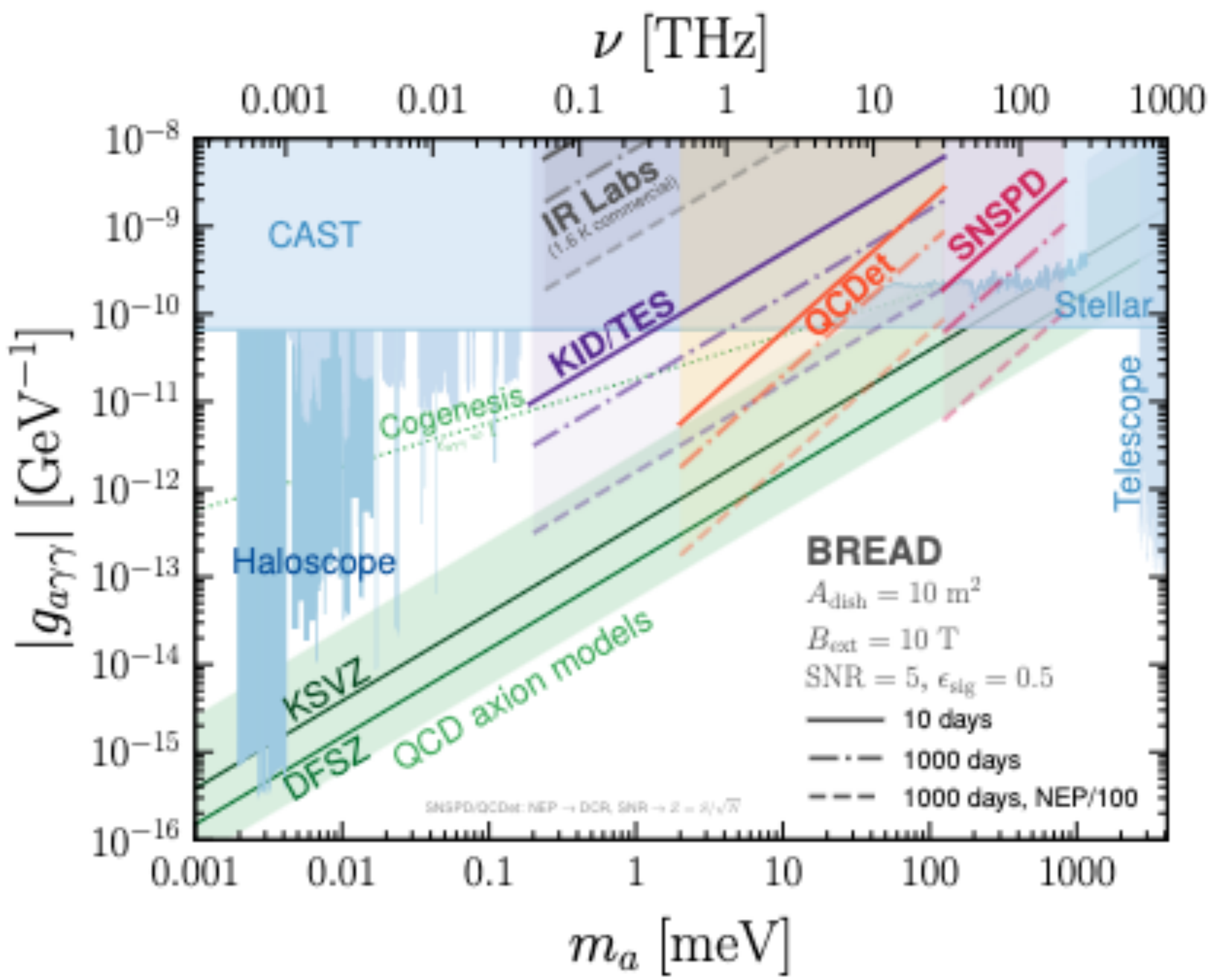


*DMNI Project

Broadening the mass reach

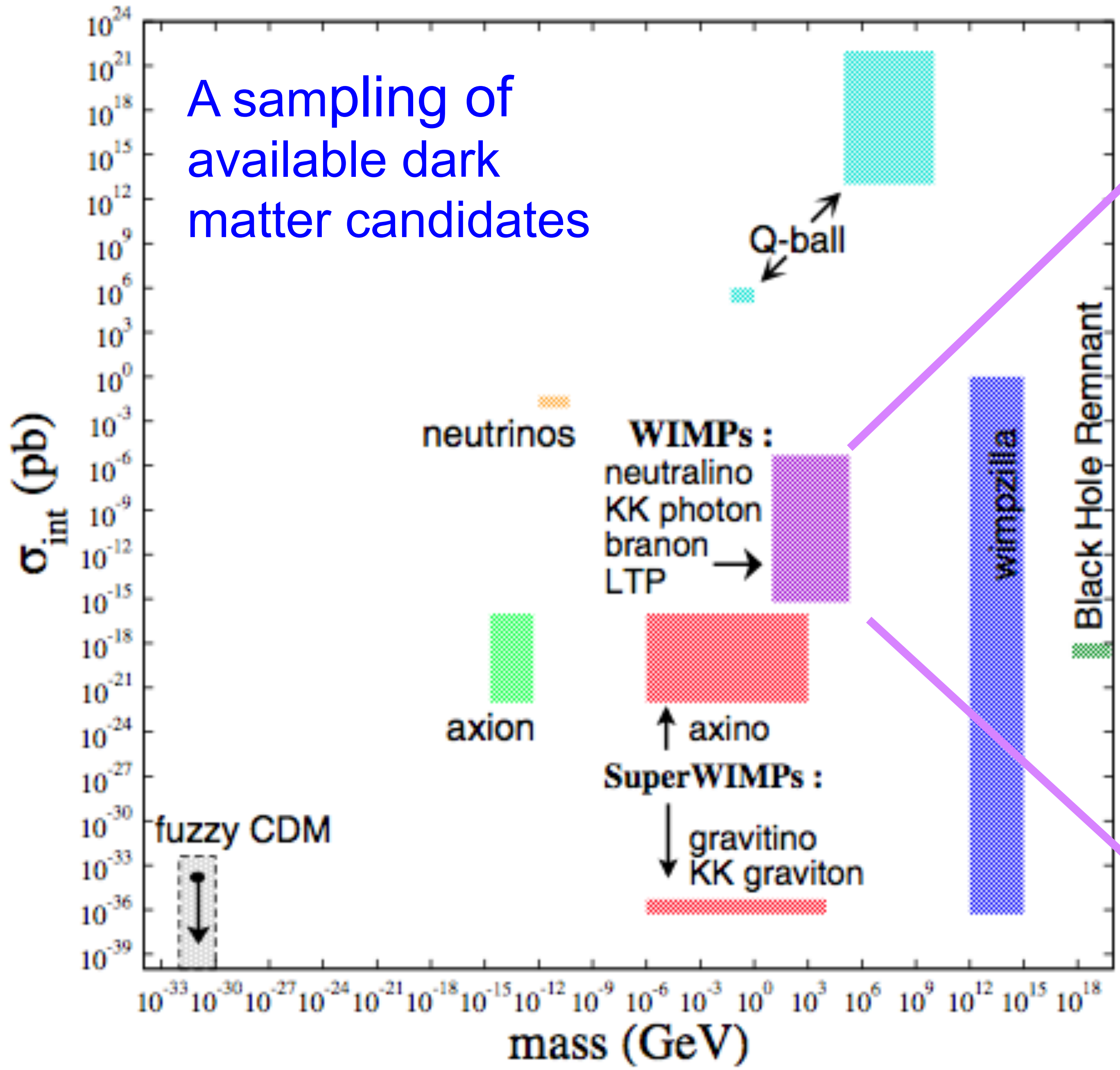
- **BREAD, LAMPOST look for conversion into photons at surfaces, count photons**
  - **Amplified by dielectric stack**





Dark Matter

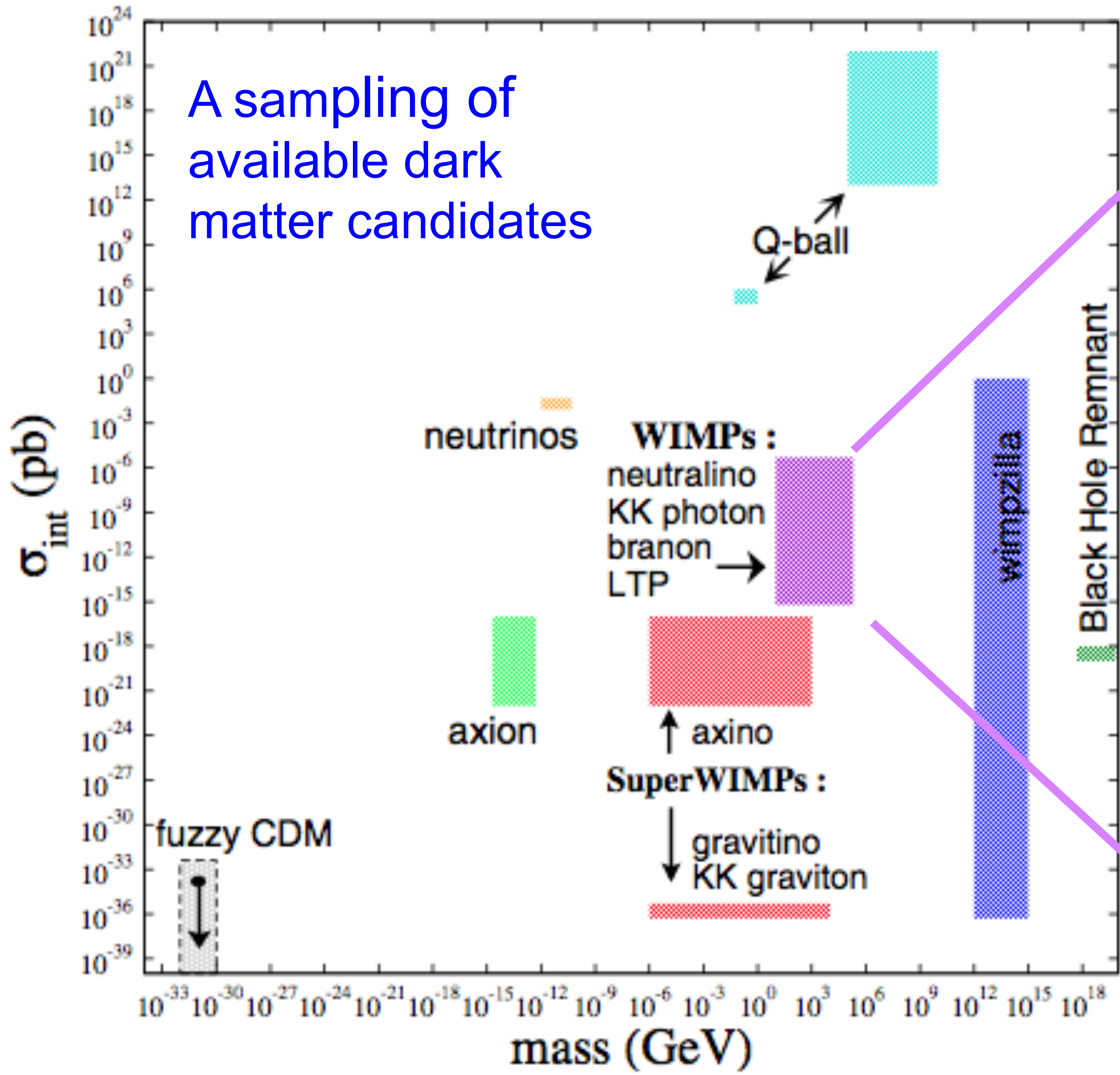
Particle Physics



~~It's probably WIMPs, right?~~

Dark Matter

Particle Physics

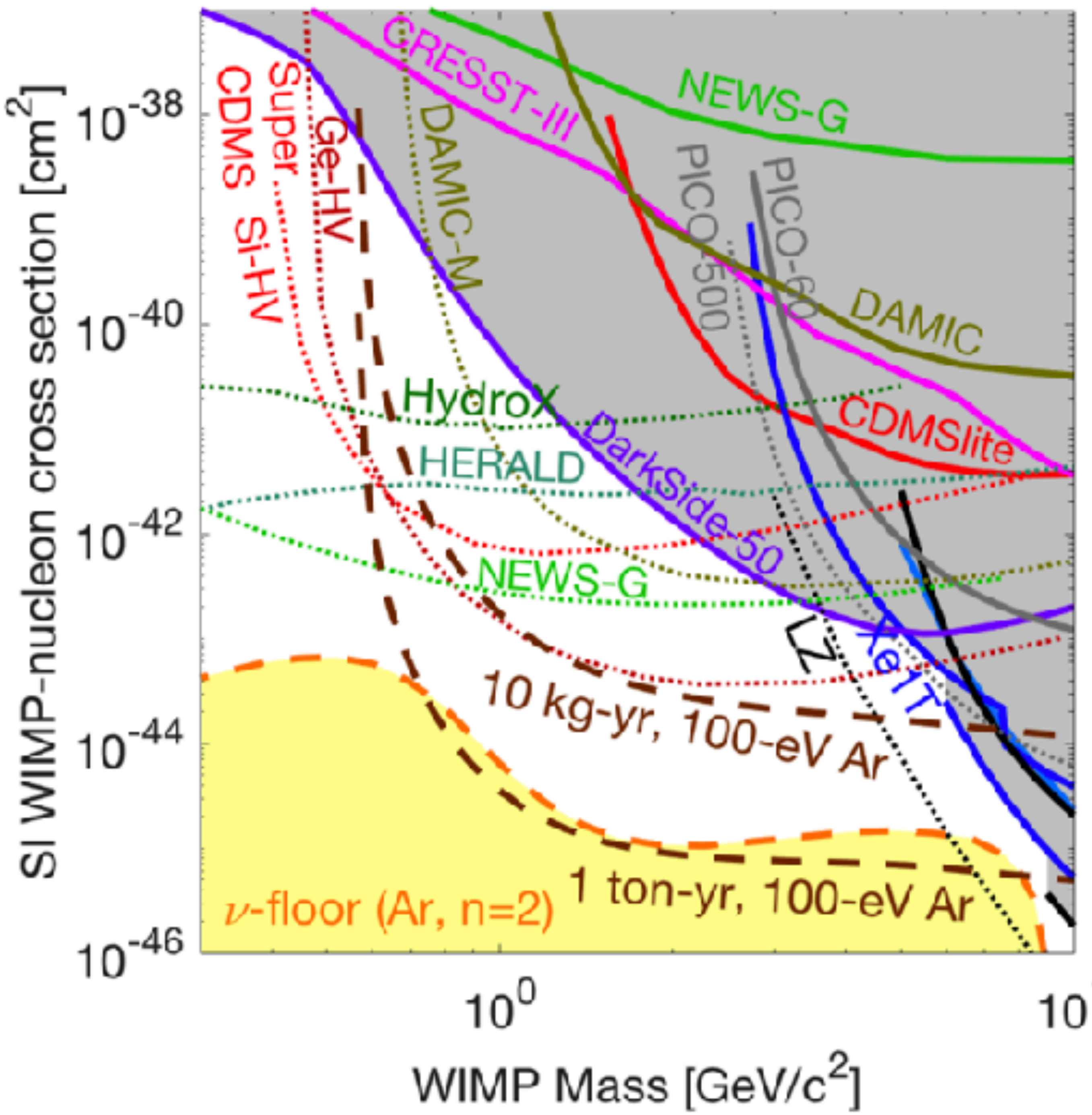


Or at least a thermal relic

Prediction is strongly correlated with discovery prospects.

Broadening the mass reach

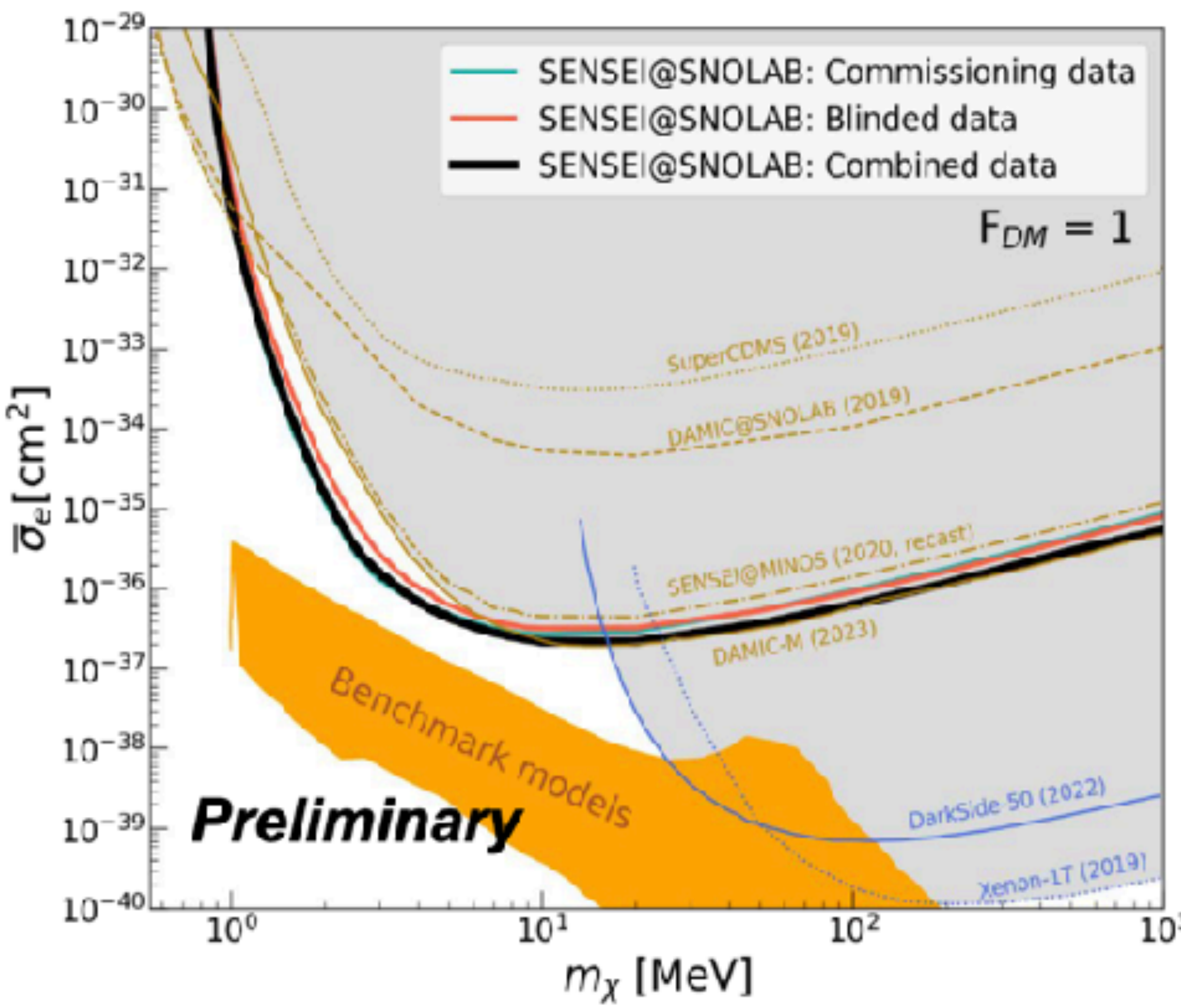
- **Exploring the <10 GeV range**
  - **SuperCDMS-SNOLAB UG tower testing underway**
  - **Scintillating Bubble Chamber (SBC) project operating this summer at FNAL**
  - **HydroX - hydrogen doped in liquid xenon**
  - **...**

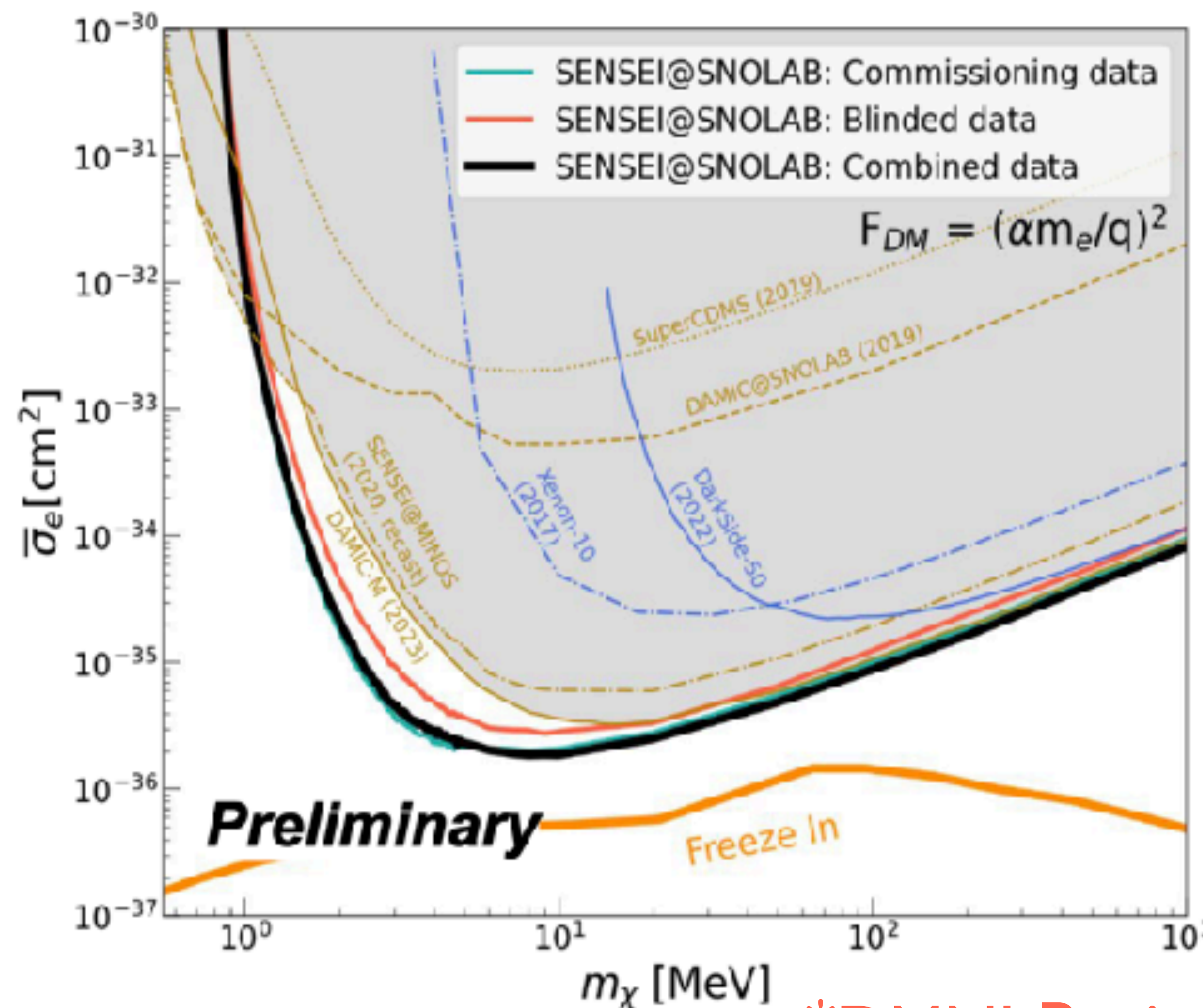


SBC at Fermilab

Broadening the mass reach

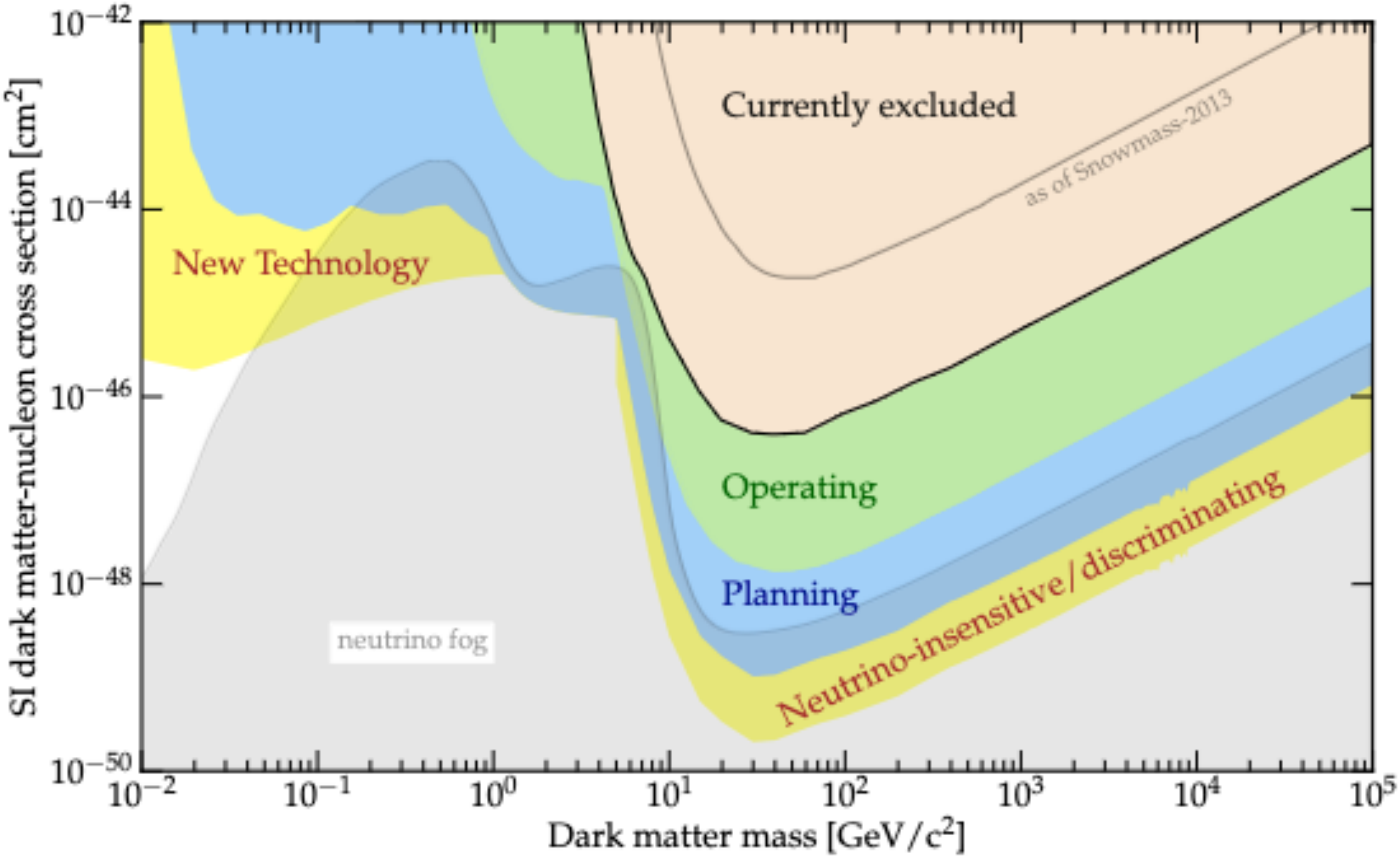
- **Down to the MeV region**
  - **Superconducting devices - SuperCDMS HVeV, TESSERACT*, CRESST, EDELWEISS,…**
  - **CCDs - DAMIC/SENSEI/OSCURA*, …**
  - **Scintillators - TESSERACT*, organic crystals, …**



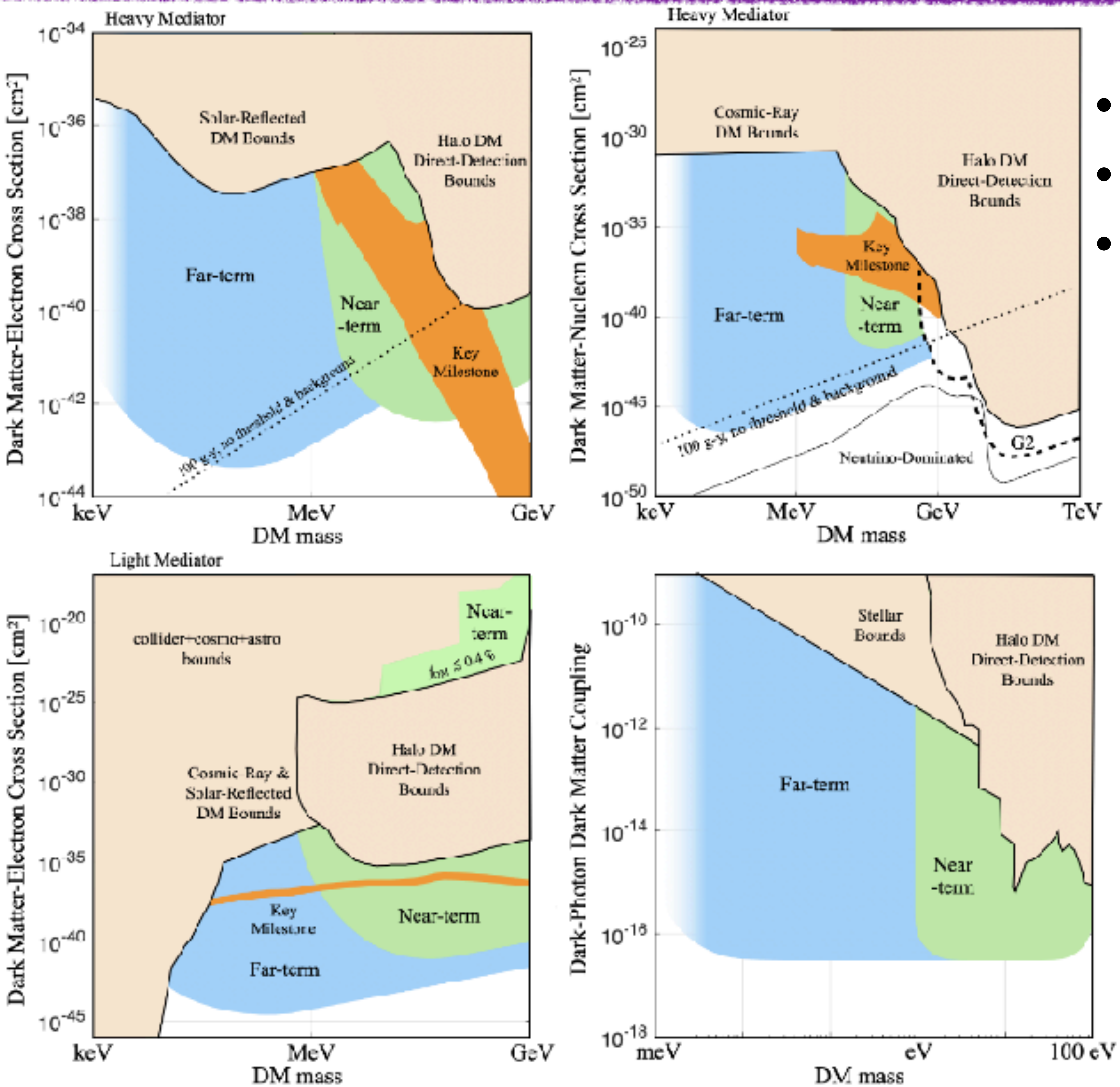


*DMNI Project

Broadening the mass reach



Broadening the mass reach



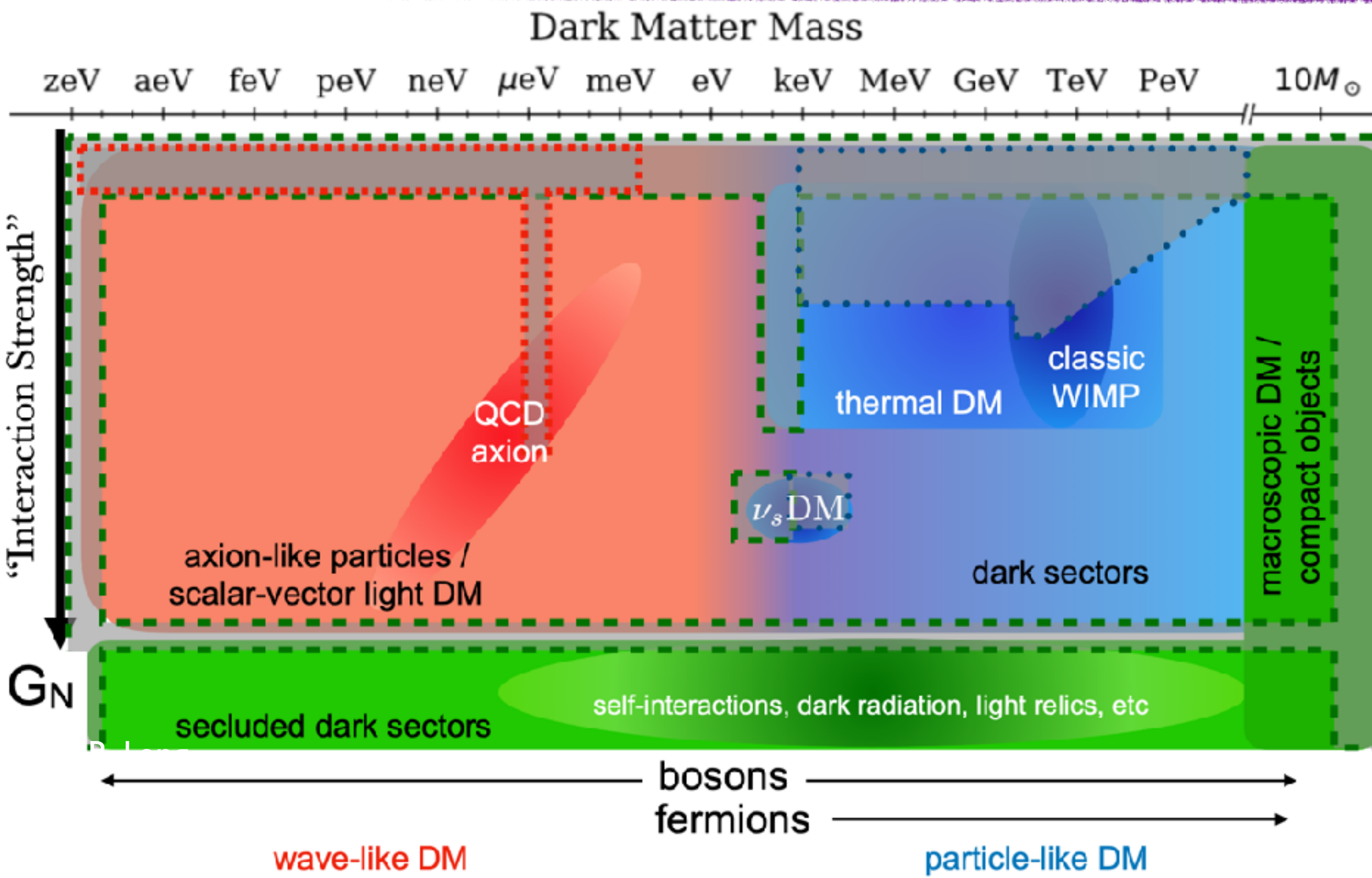
- **Near term - ~5 years**
- **Far term > 5 years**
- **Key milestone - benchmark models from DMNI report**

Dark Matter

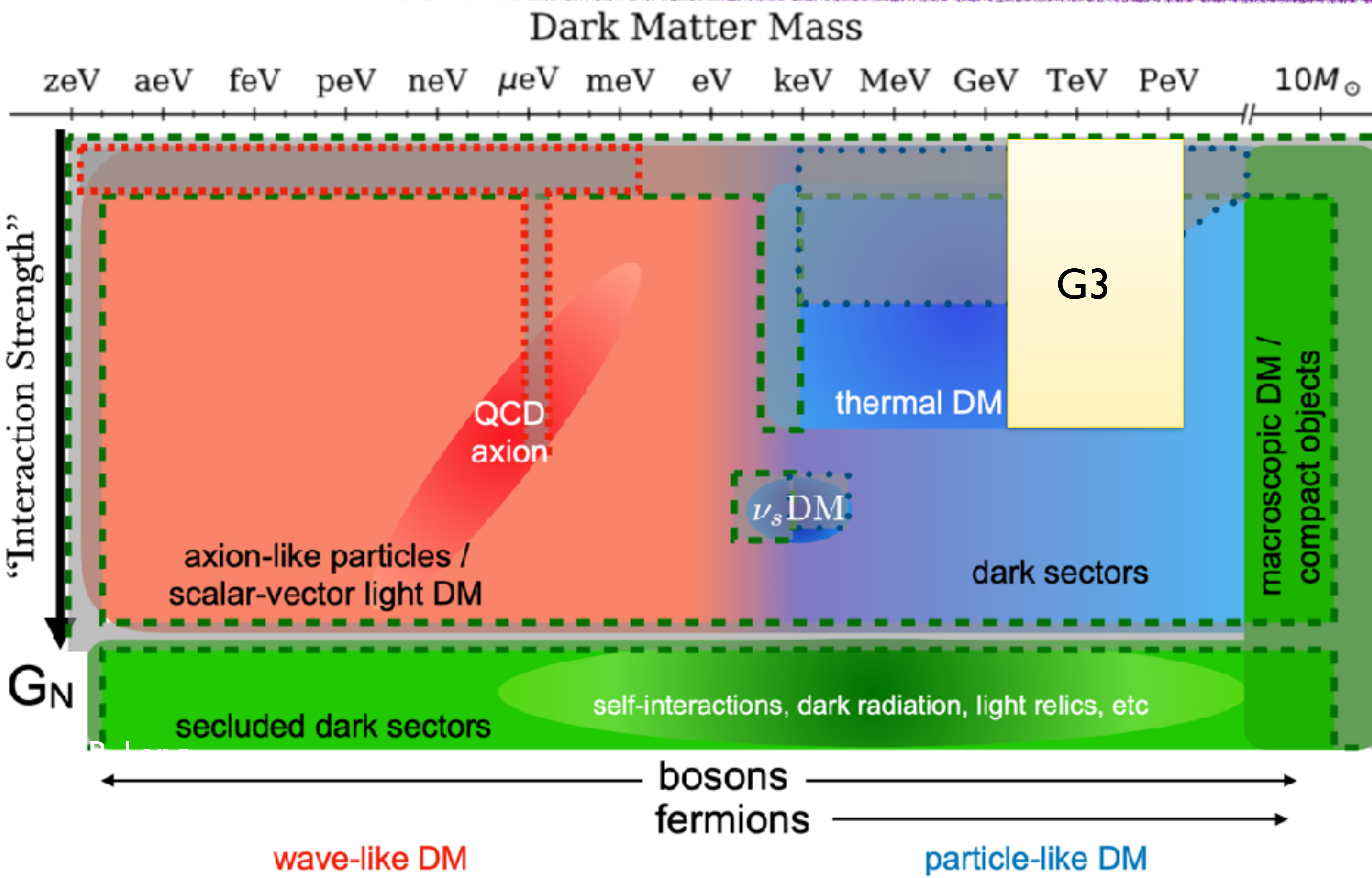
2001 - Particle physics offers two different hypotheses for the dark matter—WIMPs and axions—either of which would constitute a major discovery of physics beyond the standard model.

2022 - Well-studied theoretical models provide a compelling scientific case to make broad and rapid inroads into unexplored dark matter parameter space via a ***search wide, delve deep*** strategy. With new experiments that will come online in this decade, the HEP community will search wide to efficiently probe broad, logarithmic ranges of parameter space…Concurrently the community will delve deep to comprehensively explore the high priority science targets of WIMPs and the QCD axion.

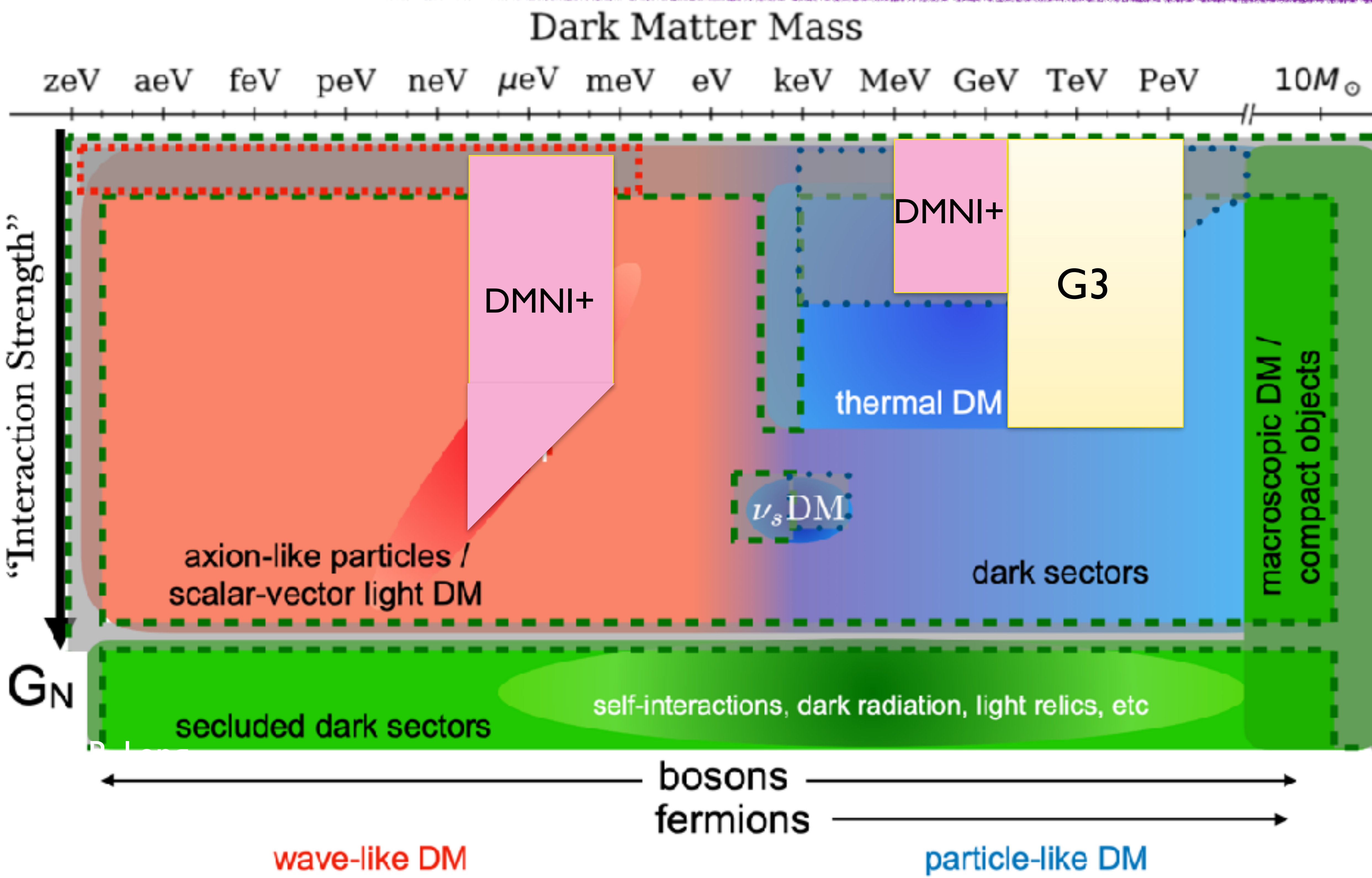
Snowmass and P5



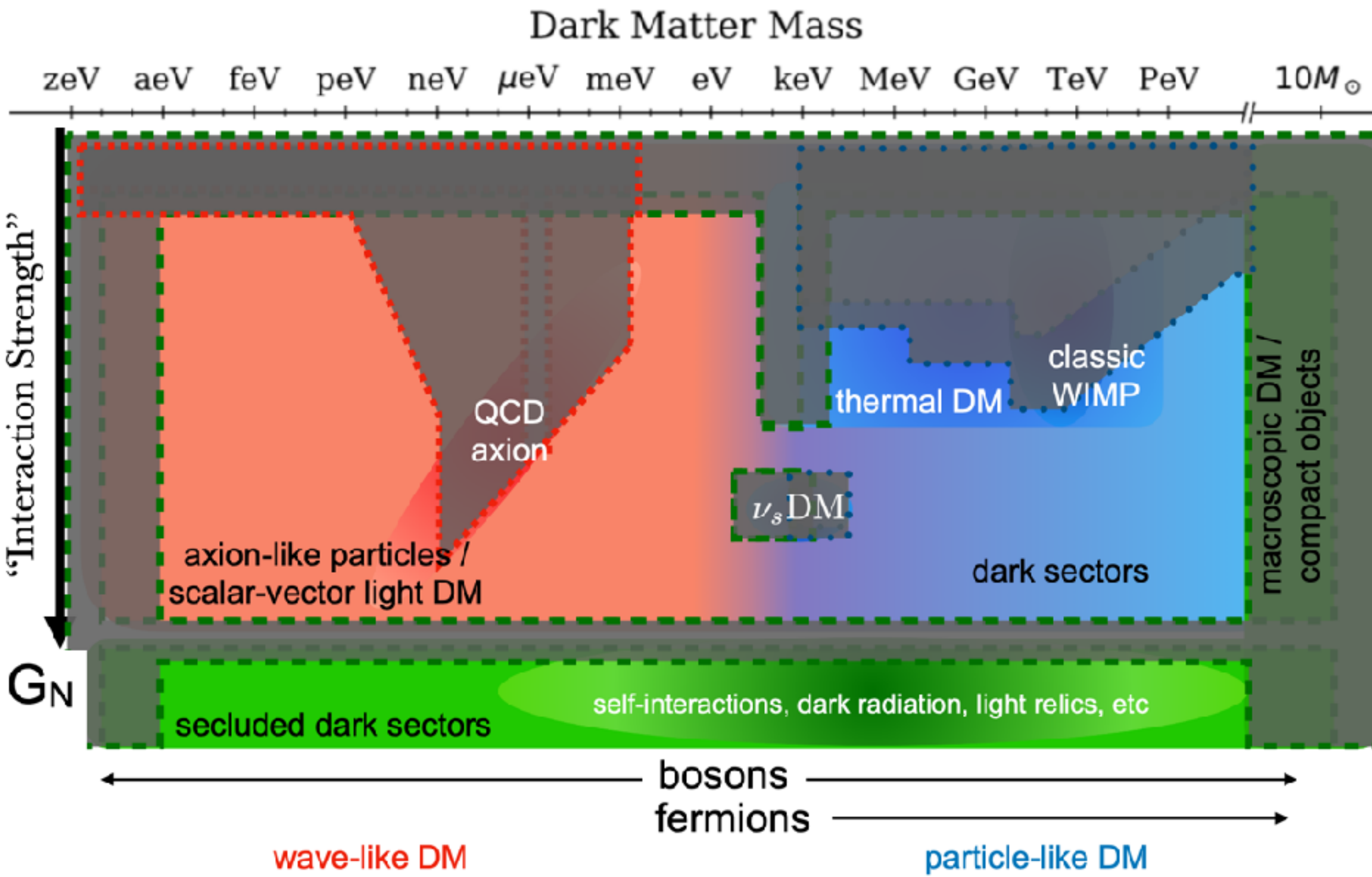
Snowmass and P5



Snowmass and P5



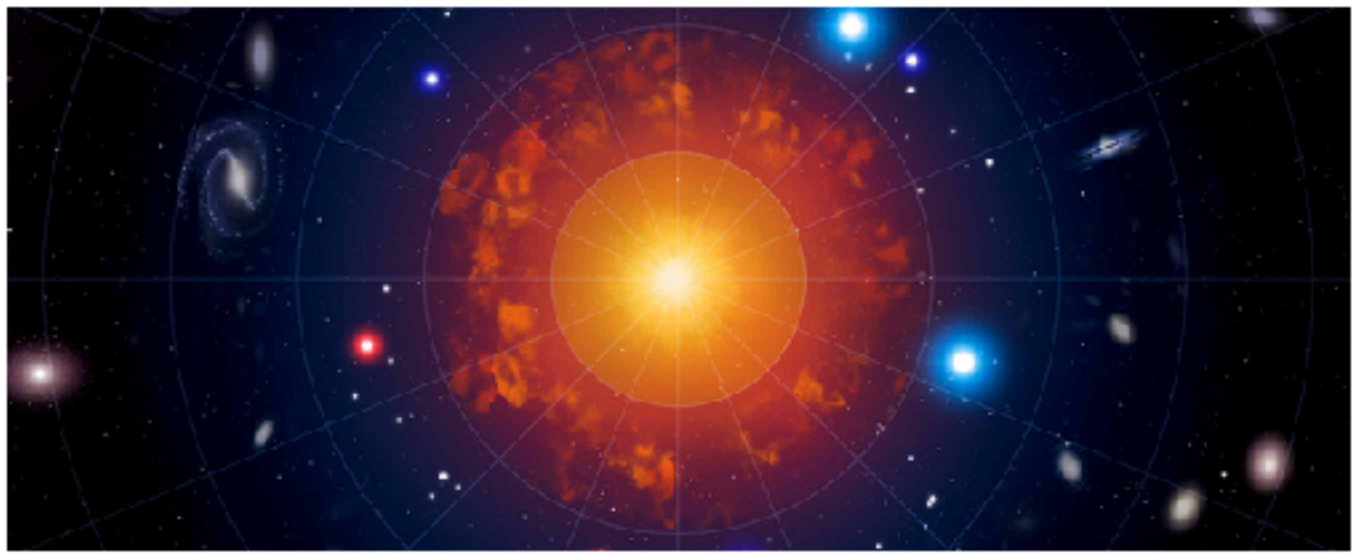
Snowmass and P5



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 @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

- **XENONnT recorded ~15 events/tonne/year/keV in their first result**

- **LZ had zero candidate events in a tonne-year of exposure**

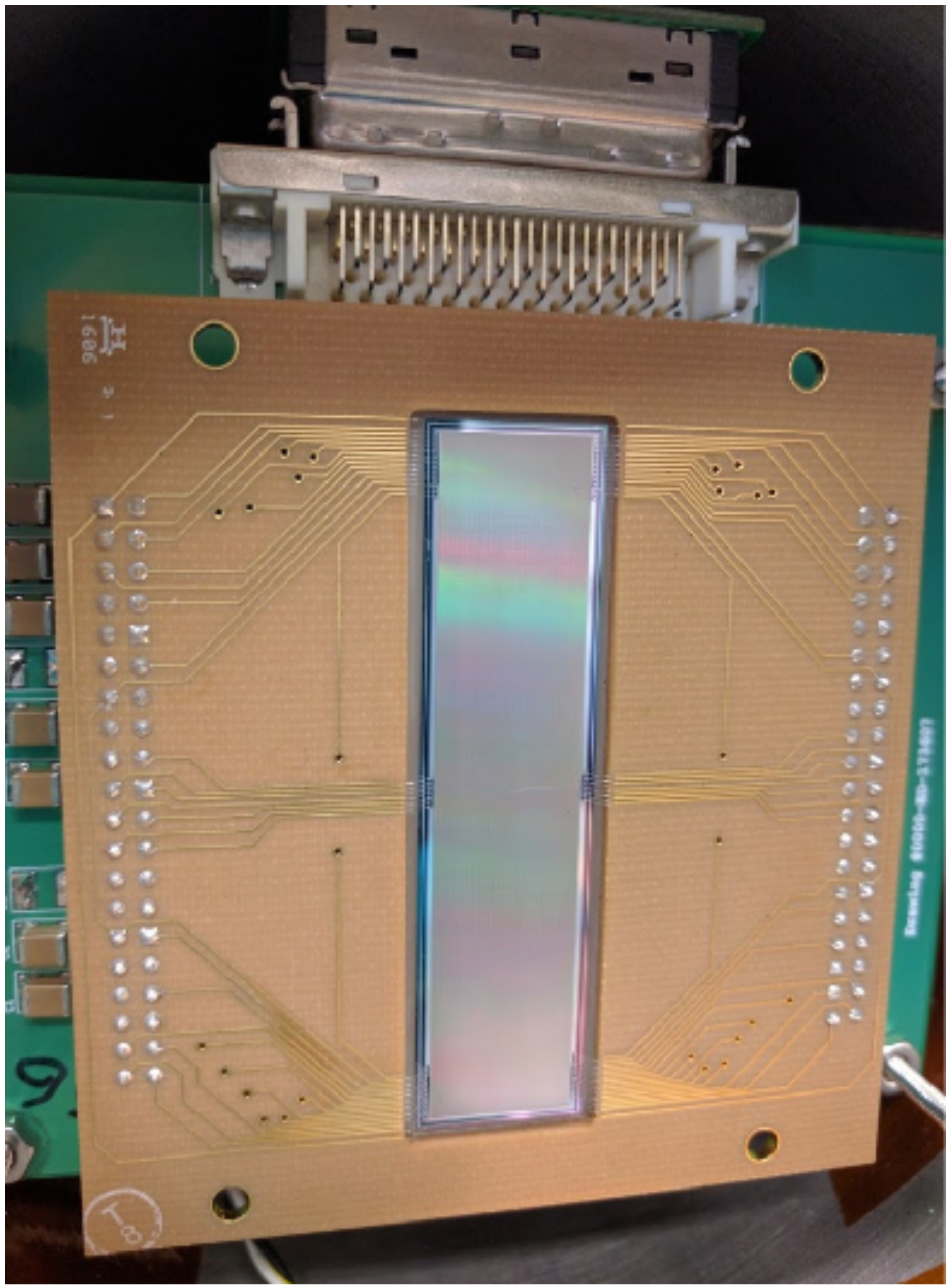
These numbers are incredible!

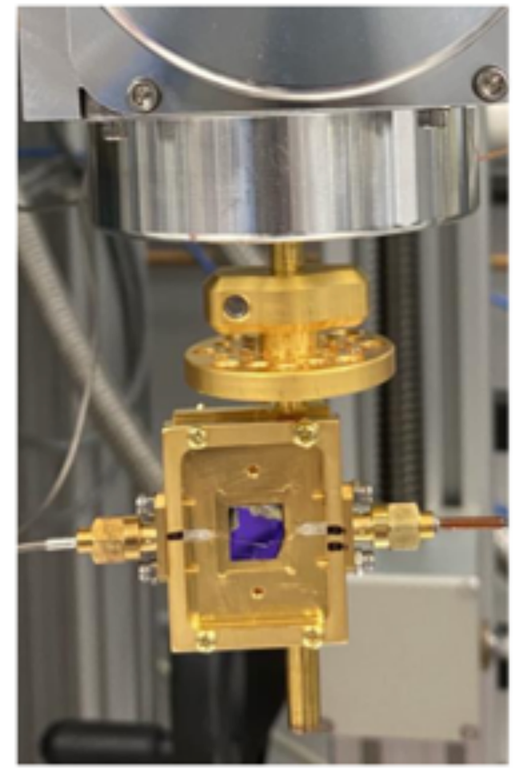
Suppression by a factor of a trillion!

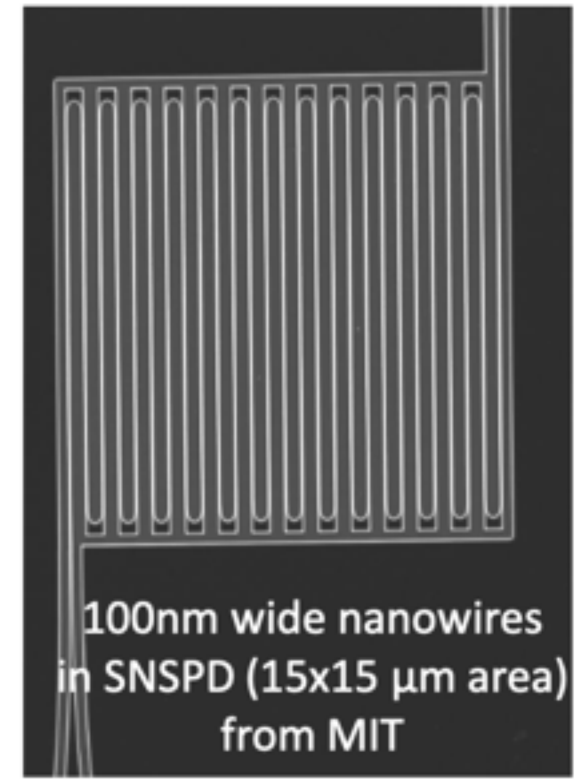
Lights in the dark

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

Lights in the dark

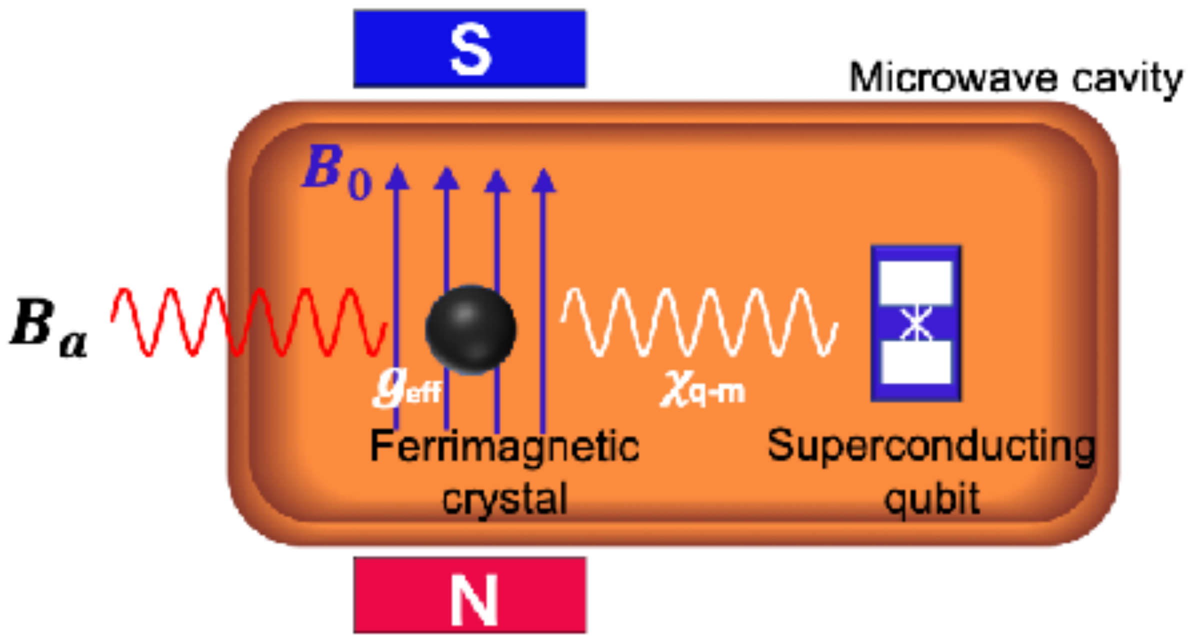


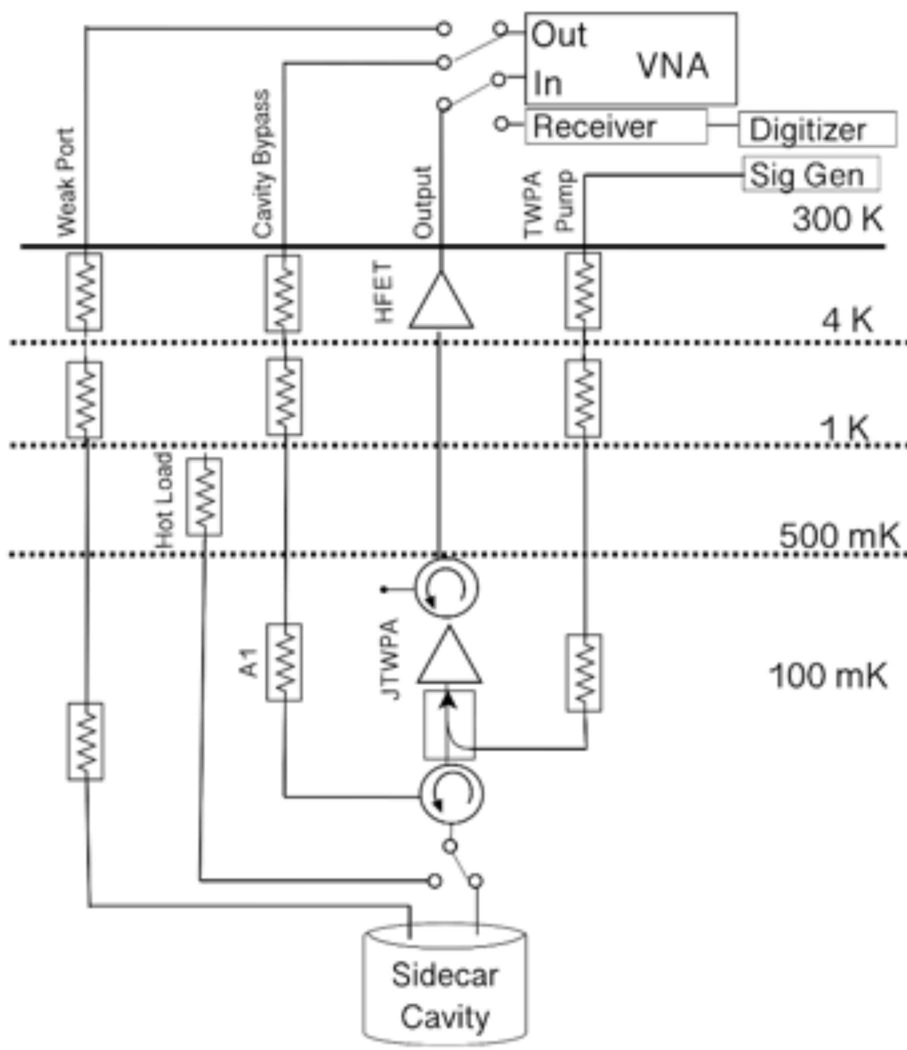




- **Ultra low noise sensors**
- **Skipper CCDs dark rate at 6e-4 e-/pixel/day, with exquisite single electron resolution**
- **SNSPDs reaching < 1e-5 dark counts per second**

Lights in the dark



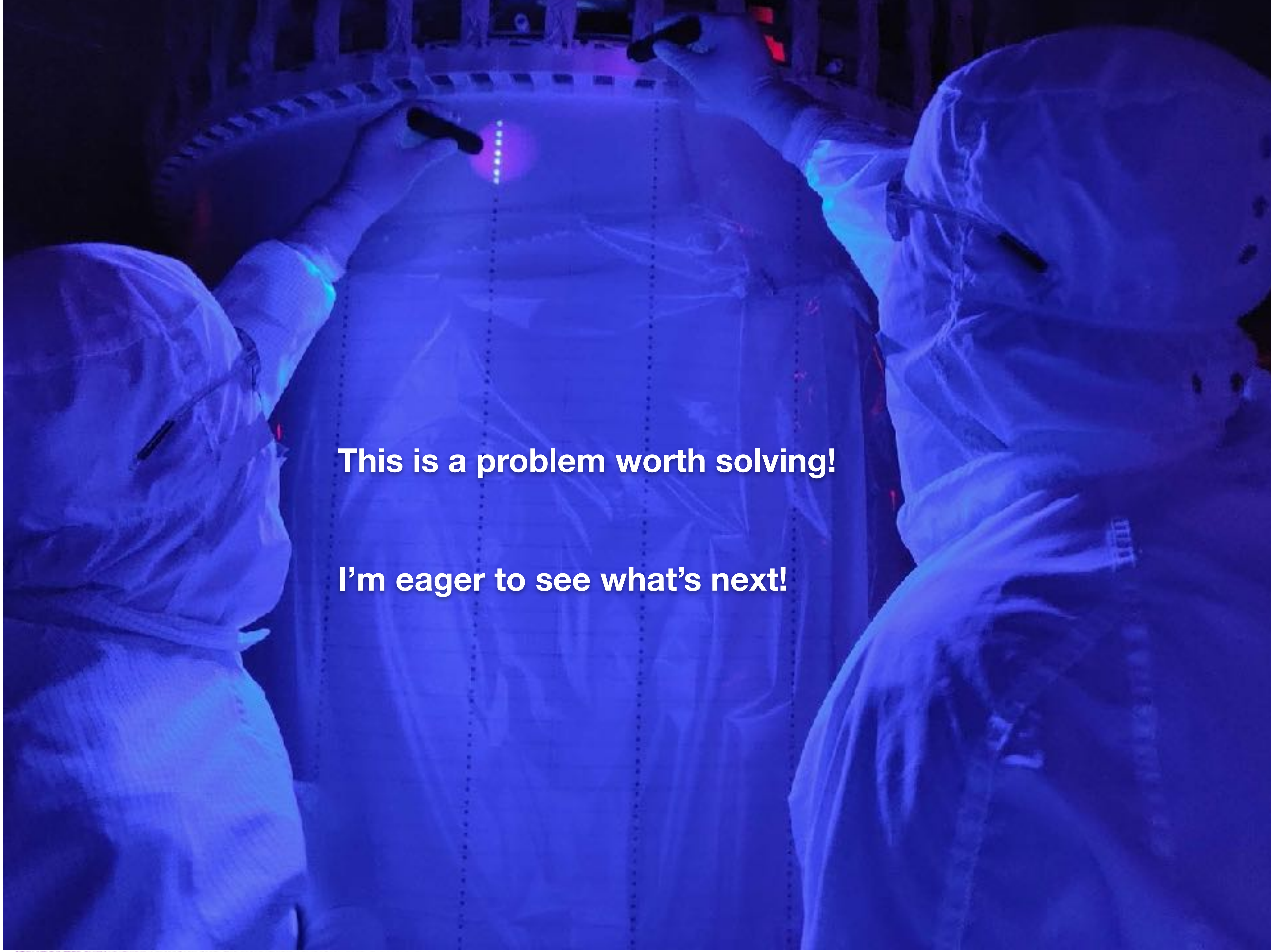


- **Quantum non-demolition techniques to push below standard quantum noise limit**
- **10^{-21} - 10^{-22} W/Hz$^{1/2}$**

Lights in the dark

Opportunities and Challenges

- **Dark Matter is a central problem in high energy physics**
- **After 30 years of experimental progress, the theory priors have weakened**
  - **What was WIMPs and two decades of axion mass is now 30+ orders of magnitude in mass**
- **An explosion of ideas and techniques, drawing from atomic physics, quantum sensing, etc - we are inventing new lamps, and making the existing ones brighter**
- **There is risk that direct detection could become completely fragmented into many small efforts**
  - **Why do this one over another one? Why do any of them at all?**
- **Need to think carefully about how to prioritize and manage all this activity?**
  - **G3 recommended by P5 - classic DOE project**
  - **ASTAE and other sources - how to light the brightest lamps?**



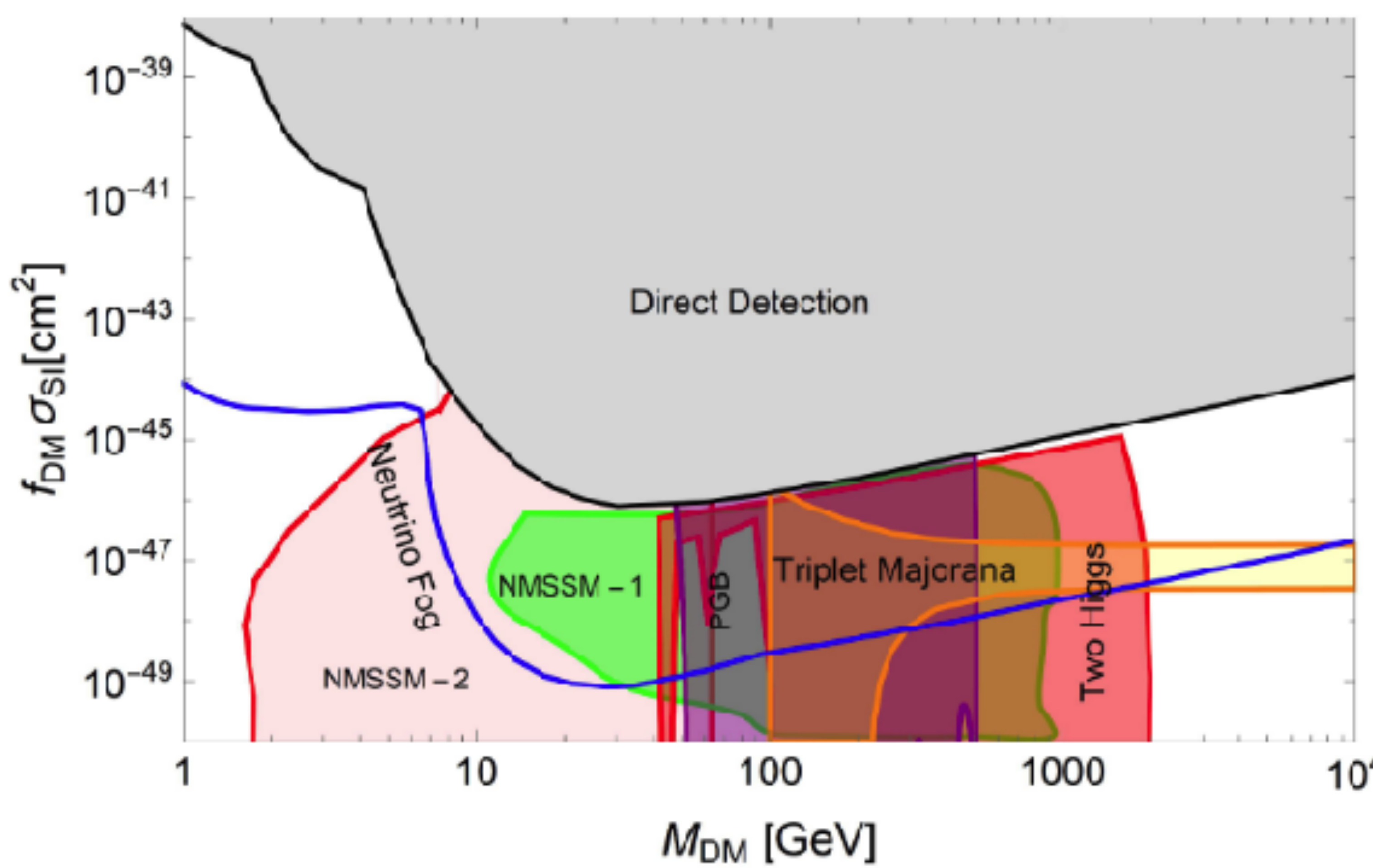
This is a problem worth solving!

I’m eager to see what’s next!

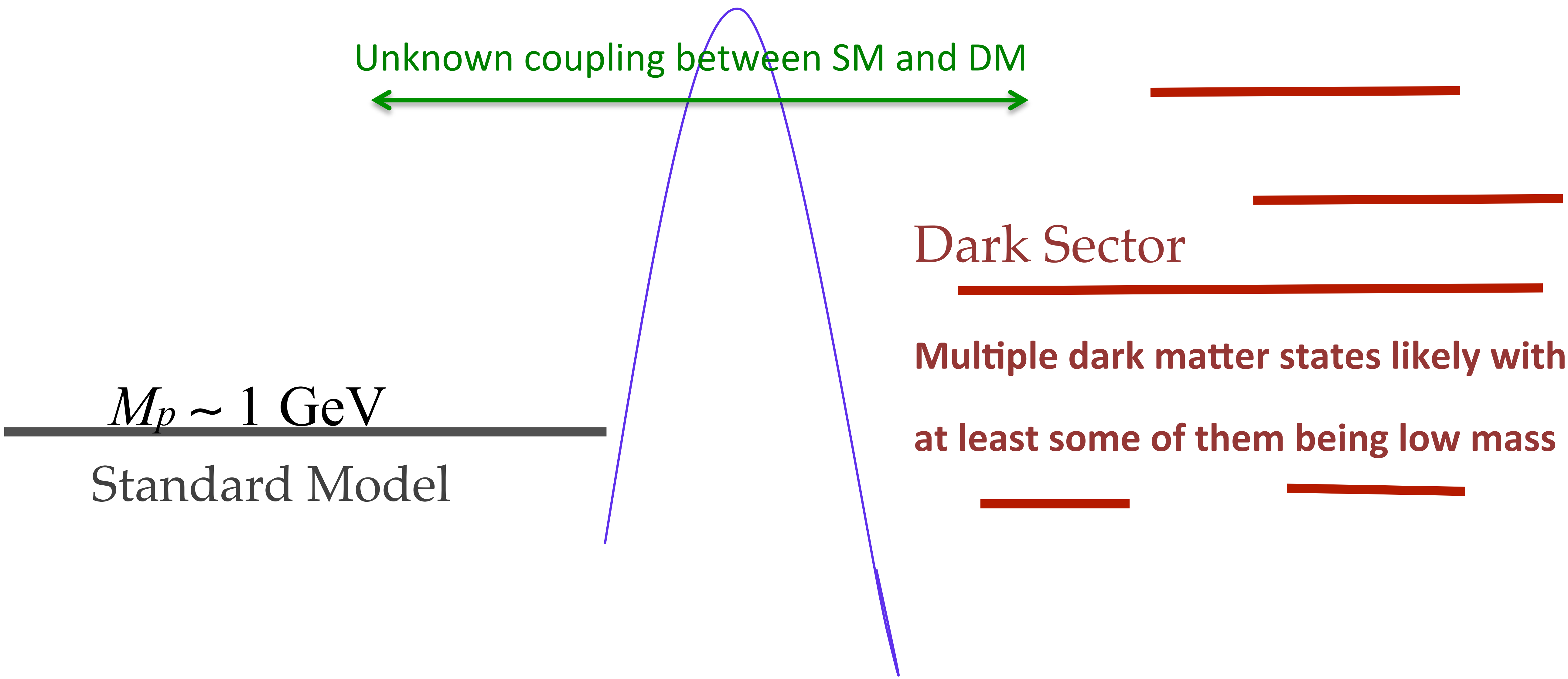
Dark Matter

- 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?



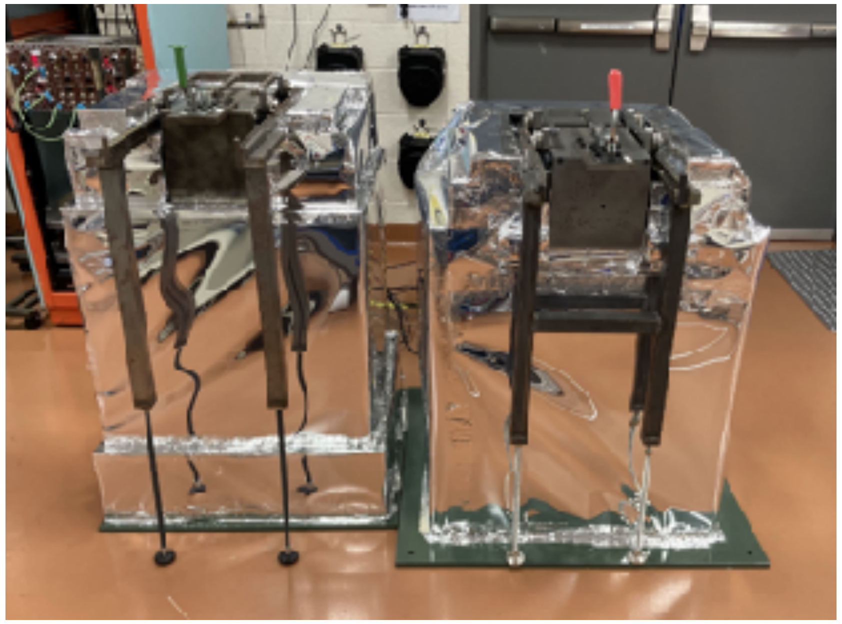
Unknown coupling between SM and DM
Dark Sector
Multiple dark matter states likely with at least some of them being low mass
$M_p \sim 1$ GeV
Standard Model

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)