

# Direct Detection "Overview" Hugh Lippincott, UCSB



March 5, 2024 – The Future of High Energy Physics

#### 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<sup>\*</sup> Department of Physics, Case Western Reserve University, Cleveland, OH 44106

Sean M. Carroll<sup>†</sup> Department of Physics and Enrico Fermi Institute, University of Chicago, 5640 South Ellis Avenue, Chicago, 1L 60637

Marc Kamionkowski<sup>4</sup> California Institute of Technology, Mail Code 130-33, Pasadena, CA 91125

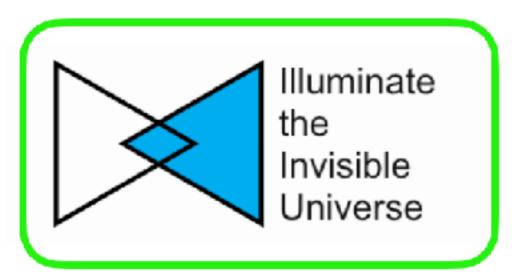
Steven Ritz<sup>§</sup> NASA/Goddard Space Flight Center, Mail Code 661, Greenbelt, MD 20771 (Dated: October 30, 2018)

#### 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



#### P5 Report December 2023

Physiat-DM       Snowmass2021 - Letter of Interest         Physiat-DM       Snowmass2021 - Letter of Interest         Physiat-DM       Snowmass2021 - Letter of Interest         Physiatro Direct Date       Snowmass2021 - Letter of Interest         Taylor Group (c) block at the Physiatro Date Works       Snowmass2021 - Letter of Interest         Physiatro Date Works       Data Dependence of the Data Dependence of the Data Dependence of the Data Dependence of the Data Dependence of the Data Dependence of the Data Dependence of the Data Dependence of the Data Dependence of the Data Dependence of the Data Dependence of the Data Dependence of the Data Depe	Physiai-DM       St       Hydro X-       Using b         Matter Direct Date       Xenon to search for         Tagical Group (c) televantic       Topical Group	
Matter Direct Deta       Neuron to Search for         Tapied Group(is tests in the spectral for       Search for         Cisit for the method of the spectral for       Tapied Group(is tests in the spectral for         Cisit for the method of the spectral for       Tapied Group(is tests in the spectral for         Cisit for the method of the spectral for       Tapied Group(is tests in the spectral for         Cisit for the spectral for       Tapied Group(is tests in the spectral for         Cisit for the spectral for       Tapied Group(is tests in the spectral for         Cisit for the spectral for       Tapied Group(is tests in the spectral for         Cisit for the spectral for       Tapied Group(is tests in the spectral for         Cisit for the spectral for       Tapied Group(is tests in the spectral for         Cisit for the spectral for       Tapied Group(is tests in the spectral for         Cisit for the spectral for the spectra for the spectral for the spectral for the spectral f	Matter Direct Deta       Network County in Sectors in Secto	t
Topical Group(is) idea of iter and the control of a	Topical Group(d): belock at the 2 (Fig) (add base Workshill With Charles (See See See See See See See See See Se	
Control         Control <t< td=""><td>Uniped Complete Second and product second second</td><td>h a G3 liquid-xenon</td></t<>	Uniped Complete Second and product second	h a G3 liquid-xenon
2 (FF) that basis where the field of the part basis b	2 (1) Fig. 1 met ware van in the GES (1) Fig. 1 met ware van in the S	_
[153] Out Maner Cover Derion       [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion         [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion         [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion         [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion         [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion         [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion         [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion         [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion         [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion         [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion         [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion         [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion         [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion       [157] Duk Maner Cover Derion         [157] Duk Maner Cover Derion       [156] Du	First Dark Maner Waw Ra       E (77): Dark Maner Court Protocol       E (77): Dark Man	
[15] [15] Dark Marser Cheer Prive       [15] Dark Marser Cheer Prive         [15] [15] Dark Marser Device (15) Dark Deep end Construction       [15] Dark Marser Device (15) Dark Determines         [15] [15] Dark Marser Device (15) Dark Device (1	[CF0] Dark Marser Chorn FANNE       [CF1] Dark Marser Chorn FANNE         [CF0] Dark Marser Chorn FANNE       [CF1] Dark Marser Chorn FANNE         [CF0] Dark Marser Group and Control       [CF1] Dark Marser Chorn FANNE         [CF0] Dark Marser Group And Control       [CF1] Dark Marser Chorn FANNE         [CF0] Dark Marser Group And Control       [CF1] Dark Marser Chorn FANNE         [CF1] Dark Marser Group And Control       [CF1] Dark Marser Chorn FANNE         [CF1] Dark Marser Chorn FANNE       [CF1] Dark Marser Chorn FANNE         [CF1] Dark Marser Chorn FANNE       [CF1] Dark Marser Chorn FANNE         [CF1] Dark Marser Chorn FANNE       [CF1] Dark Marser Chorn FANNE         [CF1] Dark Marser Chorn FANNE       [CF1] Dark Marser Chorn FANNE         [CF1] Dark Marser Chorn FANNE       [CF1] Dark Marser Chorn FANNE         [CF1] Dark Marser Chorn FANNE       [CF1] Dark Marser Chorn FANNE         [CF1] Dark Marser Chorn FANNE       [CF1] Dark Marser Chorn FANNE         [CF1] Chorn FANNE       [CF1] Dark Marser Chorn FANNE         [CF2] Chorn FANNE       [CF1] Dark Marser Chorn FANNE	
<ul> <li>Construction of the family and construction of the family o</li></ul>	<ul> <li>Differ functions of statistics from the second states of states</li></ul>	
<ul> <li>In (19) Detailing and Control (1)</li> <li>In (19) Detail dense of the mark the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and Control (1)</li> <li>In (19) Detail dense of the large and the large and</li></ul>	<ul> <li>Cherge and Contack A. L. (19) Data Large and Contack A. D. (19) Data Large and Da</li></ul>	
The field of	<ul> <li>The first of the second rest of the se</li></ul>	
<ul> <li>E.P.P.) Connect Process of Findance         <ul> <li>D.P.T. Science Procession</li> <li>D.P.T. Science Processing Procession<td><ul> <li>□ (3) (1) Constructions of Finderse 10 (3) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1</li></ul></td><td>in other</td></li></ul></li></ul>	<ul> <li>□ (3) (1) Constructions of Finderse 10 (3) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1</li></ul>	in other
Contact Information: Num (Junced Linear Josef)       Contact Information: Num (Junce	Contact Information: Num (an except part) [ htgh 1];       Contact Information: Num (an except part) [ htgh 1];       Contact Information: Num (an except part) [ htgh 1];         Autors: David Contact Information (and the set (and the set (b)	
Contact Information:         Control Information:         Each installable control in	Contact Information: Name (unamber (part))     Context Infor	ity of Prohes and New Pacificies
Name (Instructor (perc))     Name (Instructo	Name (Instructor (Inst))     Name (Instructor (Inst))     Name (Instructor (Inst))     Name (Instructor (Inst))     Constructor (Inst)       Challense (Constructor (Inst))     Anthores (Constructor (Inst))     Anthores (See and of letter)     Anthores (See and of letter)       David (Instructor (Inst))     Anthores (Constructor (Inst))     Anthores (See and of letter)     Anthores (See and of letter)       David (Instructor (Inst))     Anthores (Constructor (Inst))     Anthores (See and of letter)       David (Instructor (Inst))     Anthores (Inst)     Anthores (Inst)       Construct (Inst)     Anthores (Inst)     Anthores (Inst)	
G Minut wight all       Anthons: (See and of letter)         G Minut wight all       Anthons: (See and of letter)         Guider:       Devided (University)         Devided (University)       Endow (SAC), here, scalar         Divide (SacoCore)       Endow (SAC), here, scalar         Divide (SacoCore)       Endow (SAC), here, scalar         Divide (SacoCore)       Endow (SacoCore)         Anthone (SacoCore)       Endow (SacoCore)         Anthone (SacoCore)       Endow (SacoCore)         Divide (SacoCore)       Endow (SacoCore)	G. Minut within a depinent       Anthony: (See and of letter)         Authors:       Devide The effect of 10 AC, here an	
Authors:         Authors: (See and affeiter)         Cutotics:         Cutotics: (See and affeiter)         Cutotics: (See and affeiter)           Dord Portfol (Unservity)         Derd here (SAC, here are free affeiter)         Authors: (See and affeiter)         See (Hasher)	Authors:     Authors: (See and of lefter)     Connectance       Authors:     Devide To under (DAC), hence and an interval (DAC), hence and hence and the interval (DAC), hence and hence and the interval (DAC), hence and henc	
Audamest       David Demind of Charles J       David Demind of Charles	Austame       Tandor (Charles)       Tandor (	
Devid     Devided	Devide     Devided     Construct     Construct<	and the second different
Control Score (Linear Contents Control Contrelectuation Control Control Control Control Control	Invitery, Seer Hassissiener Rody, Seer Hassissiener Rody, Seere Rody, Seere States Phase, Contract Rody, Seere Rody, Seer	
<ul> <li>Antiberg Relation Ros (F)</li> <li>Kart Meric (Catamba Urage (Catamba Urage (Catamba Urage)), tain Status (Oction, Value (Catamba Urage)),</li></ul>	<ul> <li>Anthony, Reine Verifie (Controls, Marcolle and Control (Controls), Marcolle and Control (Control), Marcolle and Control (Control</li></ul>	
Kran Meri Columba Urizi     Columo Urizi     Columba Urizi     Columba Urizi     Columba Urizi	Kran Moril Columbia Unity         Basis Columbia Unity         Basis Columbia Unity         Basis Columbia Unity         Basis Columbia Unity         Abstract         Abstract         Abstract         Columbia Columbia Unity         Abstract         Columbia Unity         Columbia Unity	
Printing (Veloc), velocity     Sense (10, 04), 040, 040, 040, 040, 040, 040, 04	Humanian (Markaya Karakara)     Souther (Markaya Karakara	
<ul> <li>Kins yeak Wata (*s. 100 er), 51</li> <li>HAND, Deel Woots (s. 100)</li> <li>Abstract: (woots of 20 work)</li> <li>Abstract: (woots</li></ul>	Kinstychi Wala (Astrochen), Si         MARTE Dari Woorkeid (PCD)         Anterest         Anterest           Abstracti (montaria 200 world)         Abstracti (montaria 200 world)         Manterest (montaria 200 world)         The rich world world)         The rich world world (Martin 200 world)         The rich world world)         The rich world)	
Abstracts (mean as 20 work) The 101 reputsion with a mean weak as a set of the set of th	Abstracts (mean and for which is a straight of the straight of	
The LDH double of the second secon	The LEM was shown and the mean of the second the second to the second	
In the formation of the set of	a michail, far add dat a mal digta die eine einer weigen einer einer einer weigen einer	
Assess wells group subjects points between the cost entry a loss of the subsection o	Jacob web (parage a set bigge of parallel point in the resil energy is the a multiparates for amount that can poole a regrited of dark of	
sin almost de de se		
	We does not carried and a state matter target.	



• 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<sup>1</sup>, Gray Rybka<sup>2</sup>, and Lindley Winslow<sup>3</sup>

<sup>1</sup>Institut für Theoretische <sup>2</sup>Department of Phys <sup>1</sup>Laboratory for Nuclear Science,

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

Conveners: Jodi Cooley<sup>1,2</sup>, Tongyan Lin<sup>3</sup>, W. Hugh Lippincott<sup>4</sup>, Tracy R. Slatyer<sup>5</sup>, Tien-Tien Yu<sup>6</sup>,
Contributors: Daniel S. Akerib<sup>7</sup>, Tsuguo Aramaki<sup>8</sup>, Daniel Baxter<sup>5</sup>, Torsten Bringmann<sup>10</sup>, Ray Bunker<sup>11</sup>, Daniel Carney<sup>12</sup>, Susana Cebrián<sup>13</sup>, Thomas Y. Chen<sup>14</sup>, Priscilla Cushman<sup>15</sup>, C.E. Dahl<sup>19</sup>, Rouven Essig<sup>17</sup>, Alden Fan<sup>7</sup>, Richard Gaitskell<sup>18</sup>, Cristano Galbiati<sup>19</sup>, Graciela B. Gelmini<sup>20</sup>, Graham K. Giovanetti<sup>21</sup>, Guillaume Giroux<sup>22</sup>, Luca Grandi<sup>23</sup>, J. Patrick Harding<sup>24</sup>, Scott Haselschwardt<sup>12</sup>, Lauren Hsu<sup>6</sup>, Shunsaku Horiuchi<sup>26</sup>, Yonatan Kahn<sup>26</sup>, Doojin Kim<sup>27</sup>, Geon-Bo Kim<sup>28</sup>, Scott Kravitz<sup>12</sup>, V. A. Kudryavtsev<sup>20</sup>, Noah Kurinsky<sup>7</sup>, Rafael F. Lang<sup>30</sup>, Rebecca

 K. Leane<sup>7</sup>, Benjamin V. Lehmann<sup>31</sup>, Cecilia Levy<sup>32</sup>, Shengchao Li<sup>30</sup>, Martoff<sup>331</sup>, Gopolang Mohlabeng<sup>34</sup>, M.E. Monzani<sup>7,35,36</sup>, Alexander St. Nelson<sup>5</sup>, Ciaran A. J. O'Hare<sup>39</sup>, K.J. Palladino<sup>40</sup>, Aditya Parikh<sup>41</sup>, Jon Profumo<sup>31,45</sup>, Nirmal Raj<sup>46</sup>, Brandon M. Roach<sup>44</sup>, Tarek Saab<sup>47</sup>, Mari Shaw<sup>4</sup>, Seodong Shin<sup>49</sup>, Kuver Sinha<sup>50</sup>, Kelly Stifter<sup>9</sup>, Aritoki Suzu Volodymyr Takhistov<sup>51,52</sup>, Yu-Dai Tsai<sup>34</sup>, S. E. Vahsen<sup>53</sup>, Edoardo<sup>4</sup> Gensheng Wang<sup>54</sup>, Shawn Westerdale<sup>55</sup>, David A. Williams<sup>31,4</sup>

#### **Cosmic Probes of Dark Matter**

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

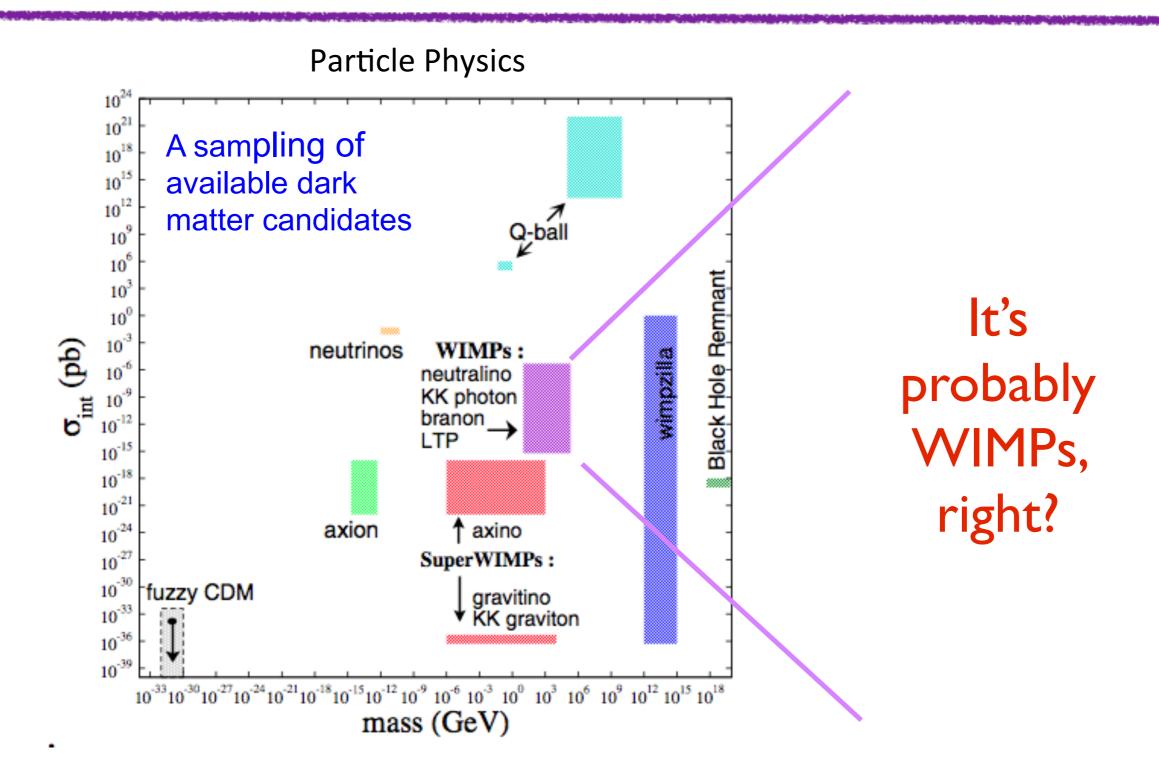
- Over 100 pages of dedicated Snowmass reports in CF
- High prominence in other frontiers
- Dedicated Complementarity report
- Can only give a sense here impossible to summarize in 20 minutes!

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 Sahgal, Joshua D. Simon, Kuver Sinha, Monica Valluri, Risa H. Wechsler

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.



#### 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<sup>\*</sup> Department of Physics, Case Western Reserve University, Cleveland, OH 44105

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

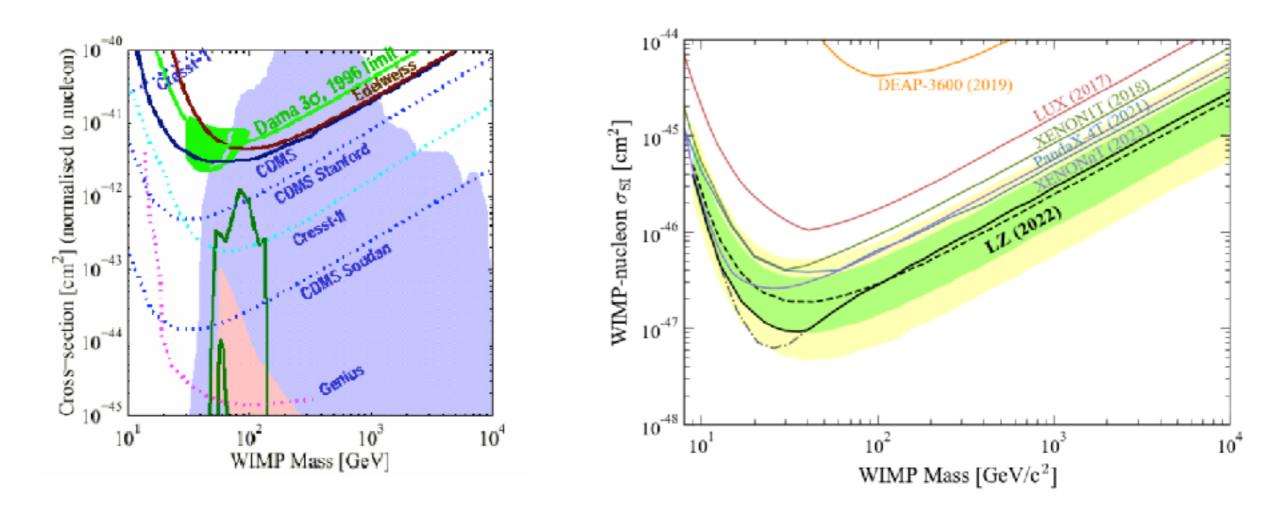
Marc Kamionkowski<sup>‡</sup> California Institute of Technology, Mail Code 130-33, Pasadena, CA 91125

Steven Ritz<sup>§</sup> NASA/Goddard Space Flight Center, Mail Code 661, Greenbelt, MD 20771 (Dated: October 30, 2018)

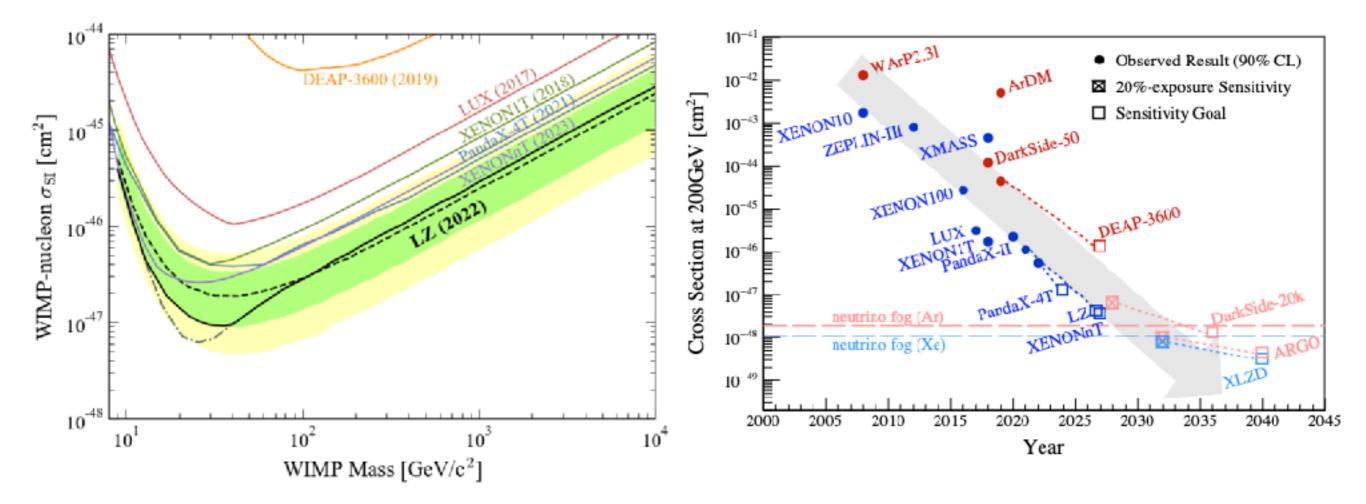
"Current searches are already exploring the parameter space of supersymmetric WIMPs [10-1000 GeV], with prospects for a factor of a hundred improvement in the coming years."

- CDMS PRL 84: 5699, (2000)
- Best limit at 3 x 10<sup>-42</sup> cm<sup>2</sup>

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



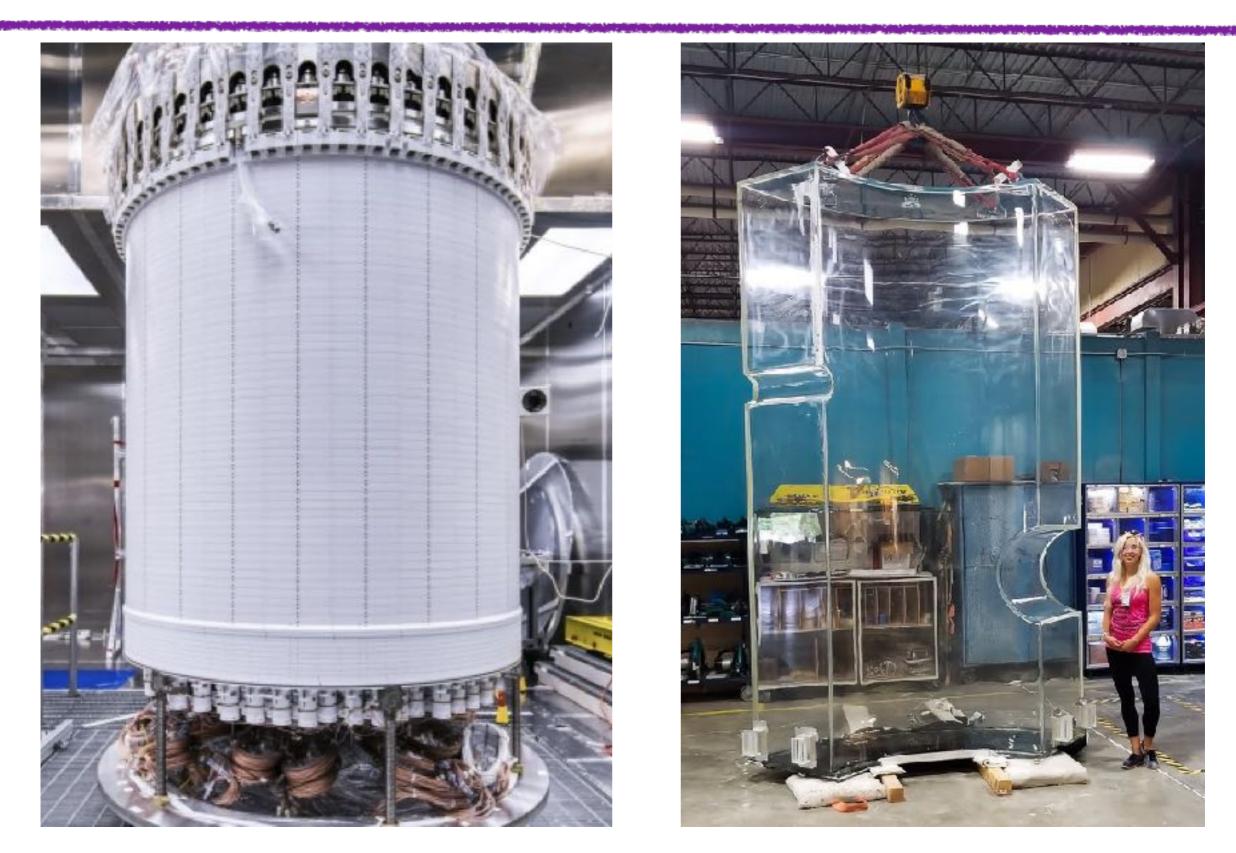
- Factor of 320,000 improvement in 23 years! Doubling every 1.25 years!
- A triumph of human ingenuity!
- No WIMPs :(

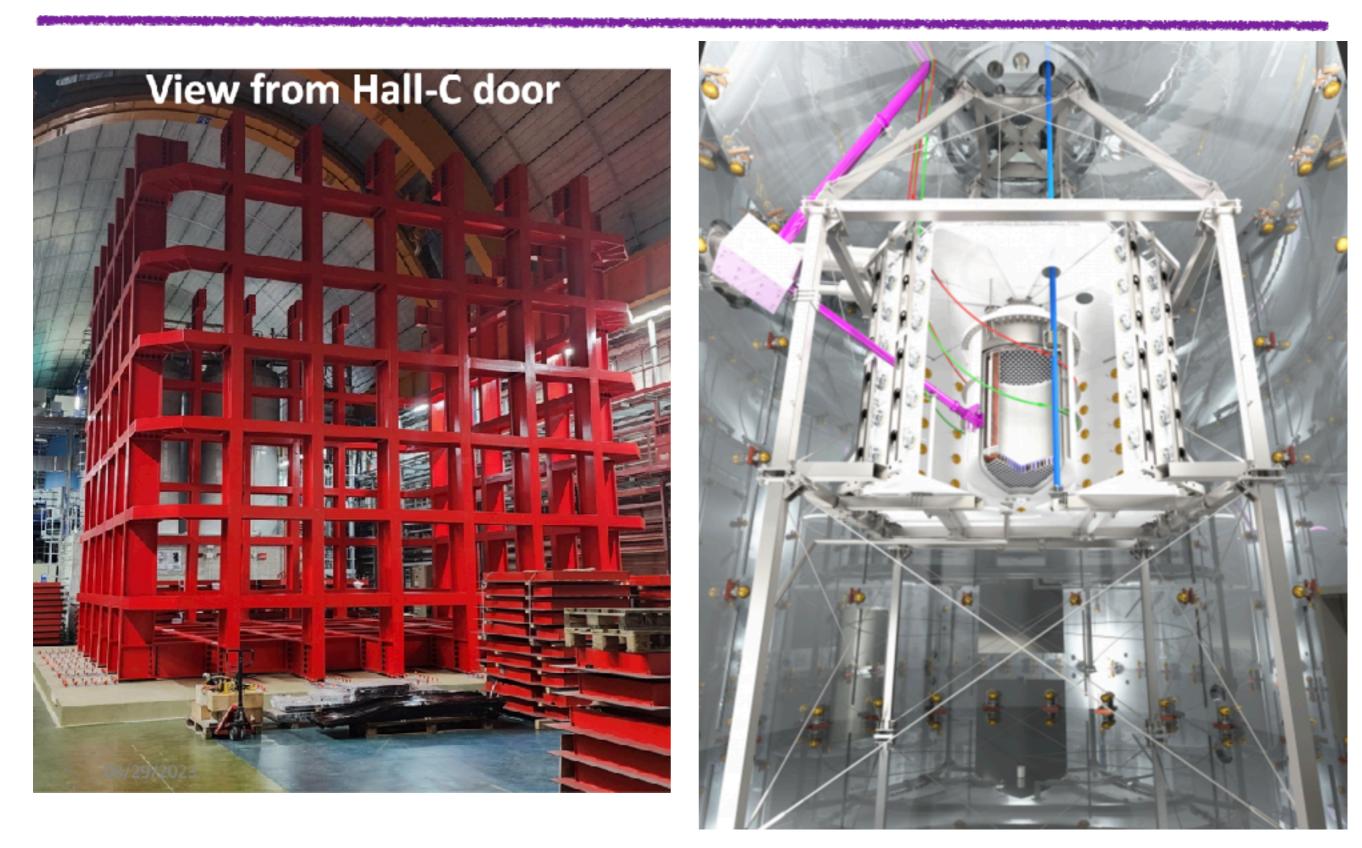


 Xenon experiments have been driving sensitivity to ~100 GeV "classic" WIMPs for the past 15 years

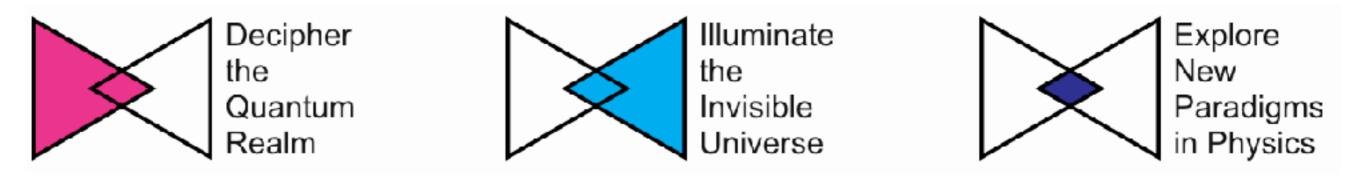
LZ, XENONnT, and PandaX-4T - multi tonne xenon experiments now operating
Argon experiments offer very large targets with good background discrimination

DarkSide-20k under construction





# P5 Report



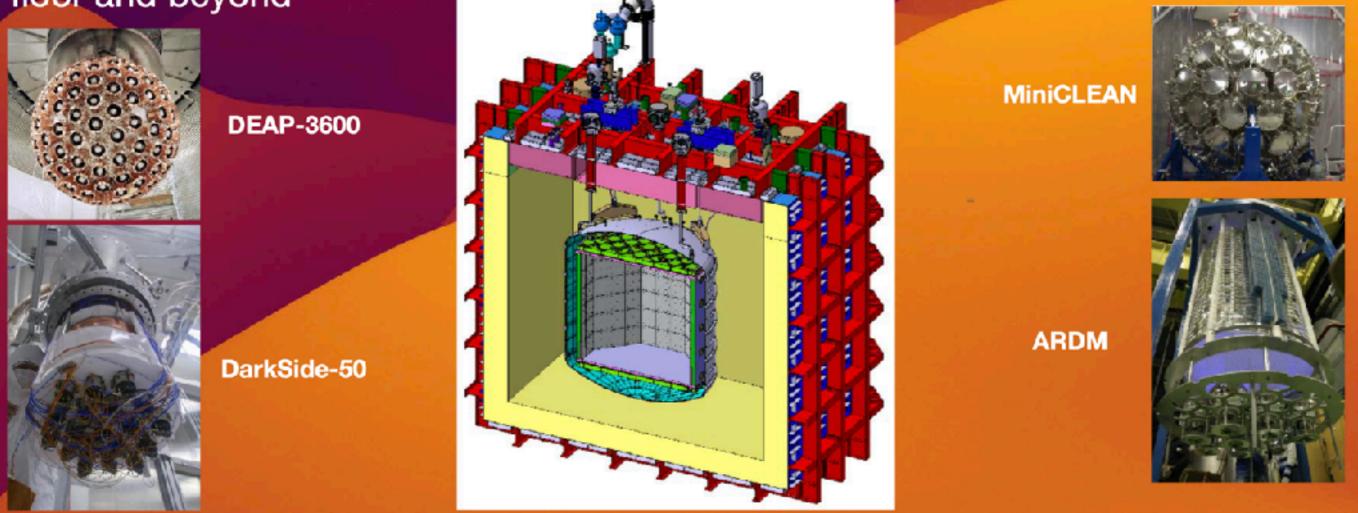
- Recommendation 1 continued support for, including construction, operation, and research
  - DarkSide-20k, LZ, SuperCDMS, and XENONnT
- Recommendation 2d:
  - An ultimate Generation 3 (G3) dark matter direct detection experiment reaching the neutrino fog, in coordination with international partners 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

# **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



#### **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

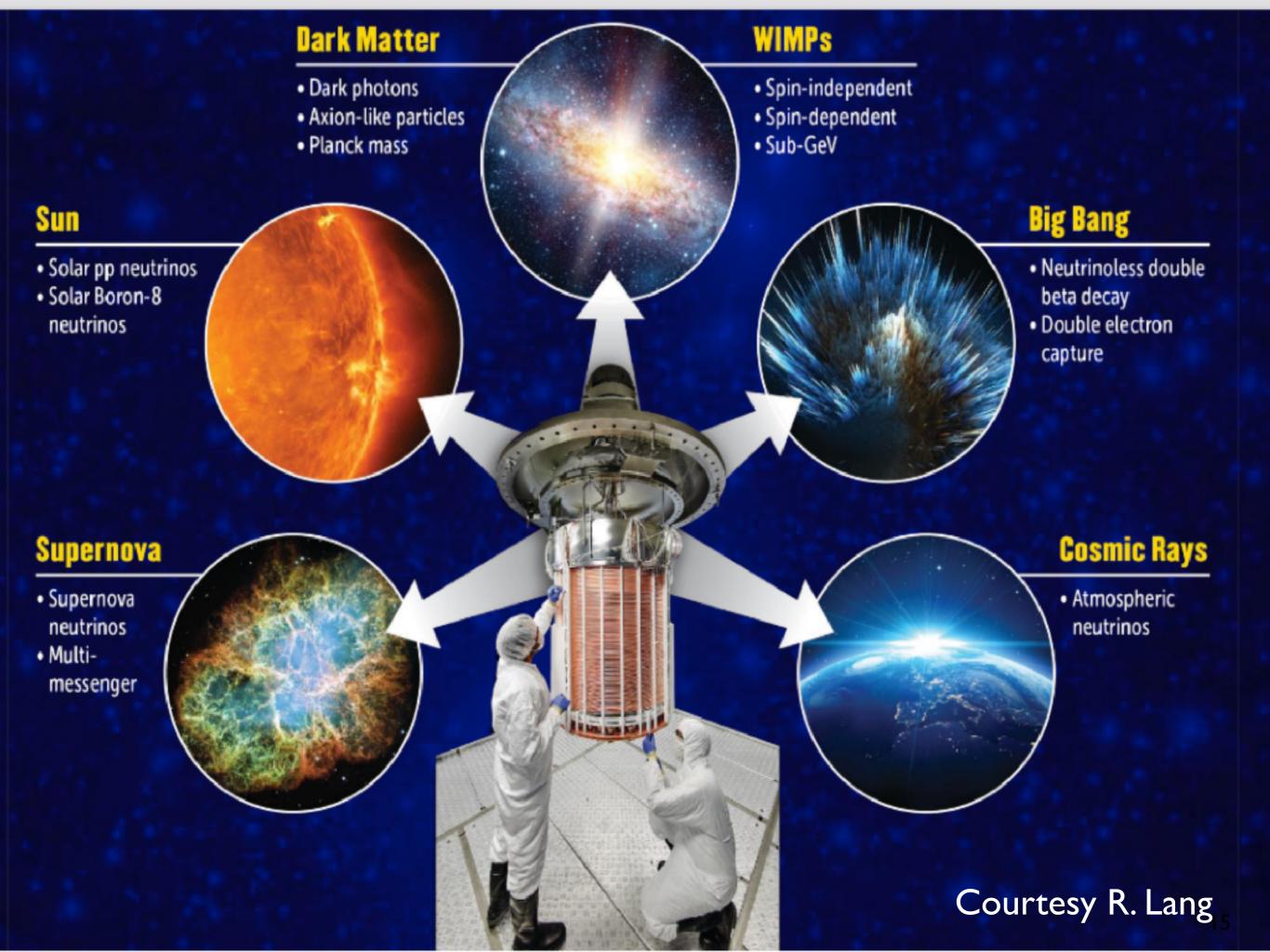
July 20, 2021

Several successful meetings https://xlzd.org/ White paper (2203.02309)

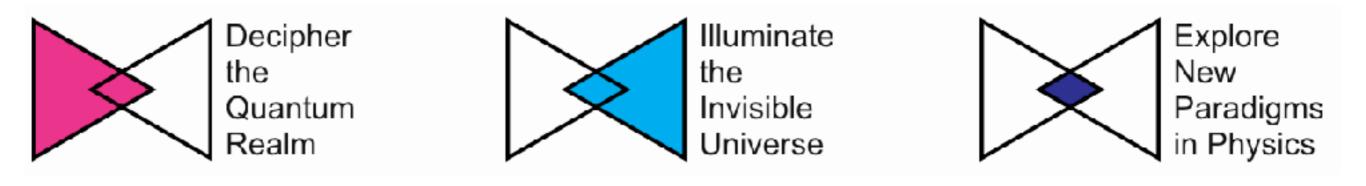


DARWIN/XENON + LUX ZEPLIN Summer Meeting 2022





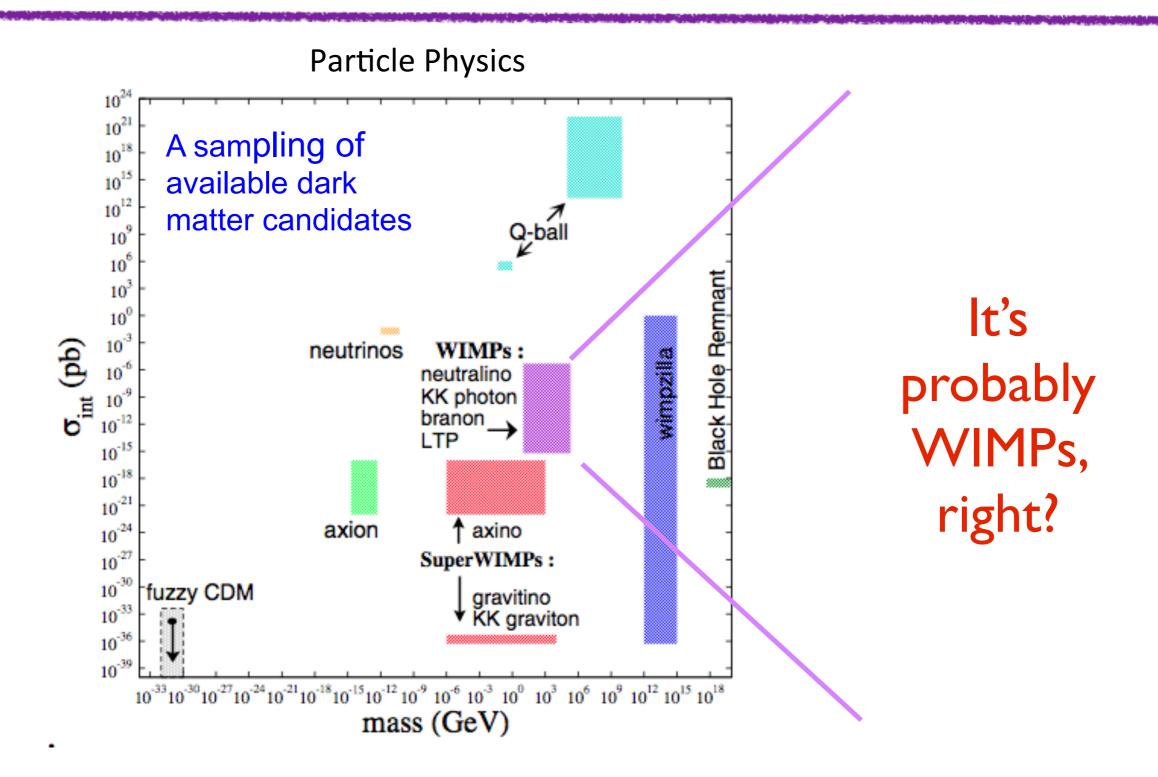
# P5 Report

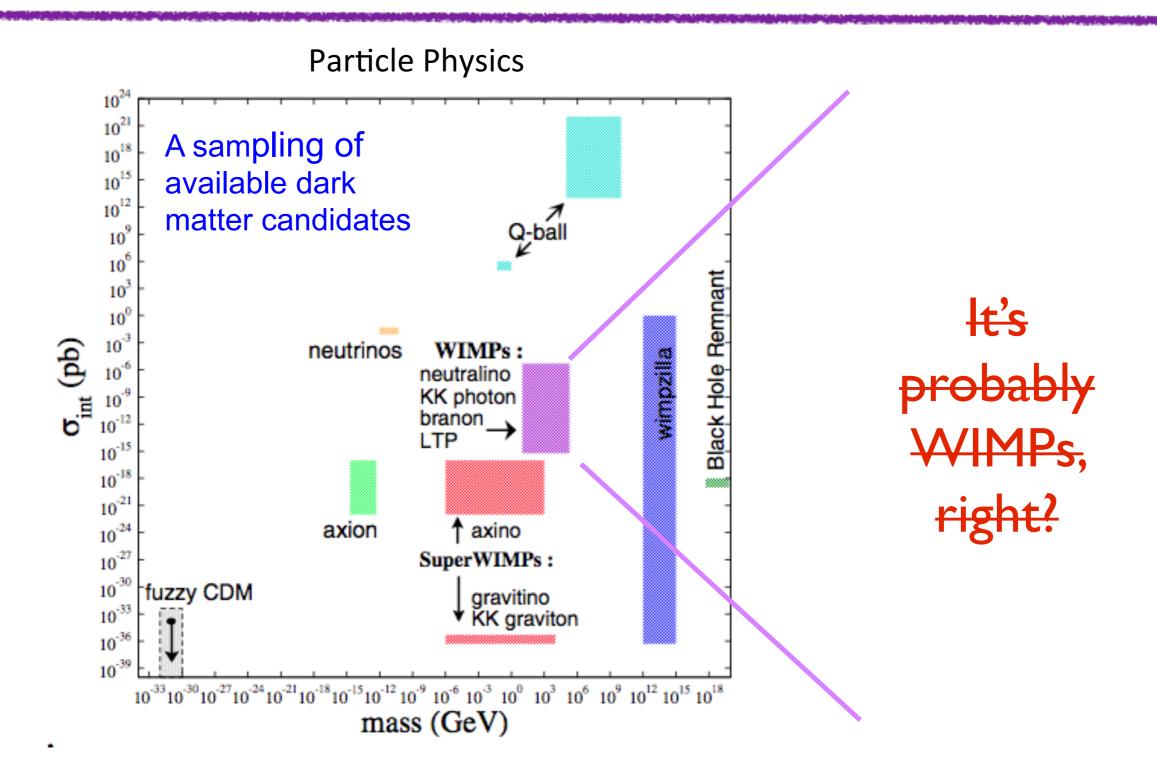


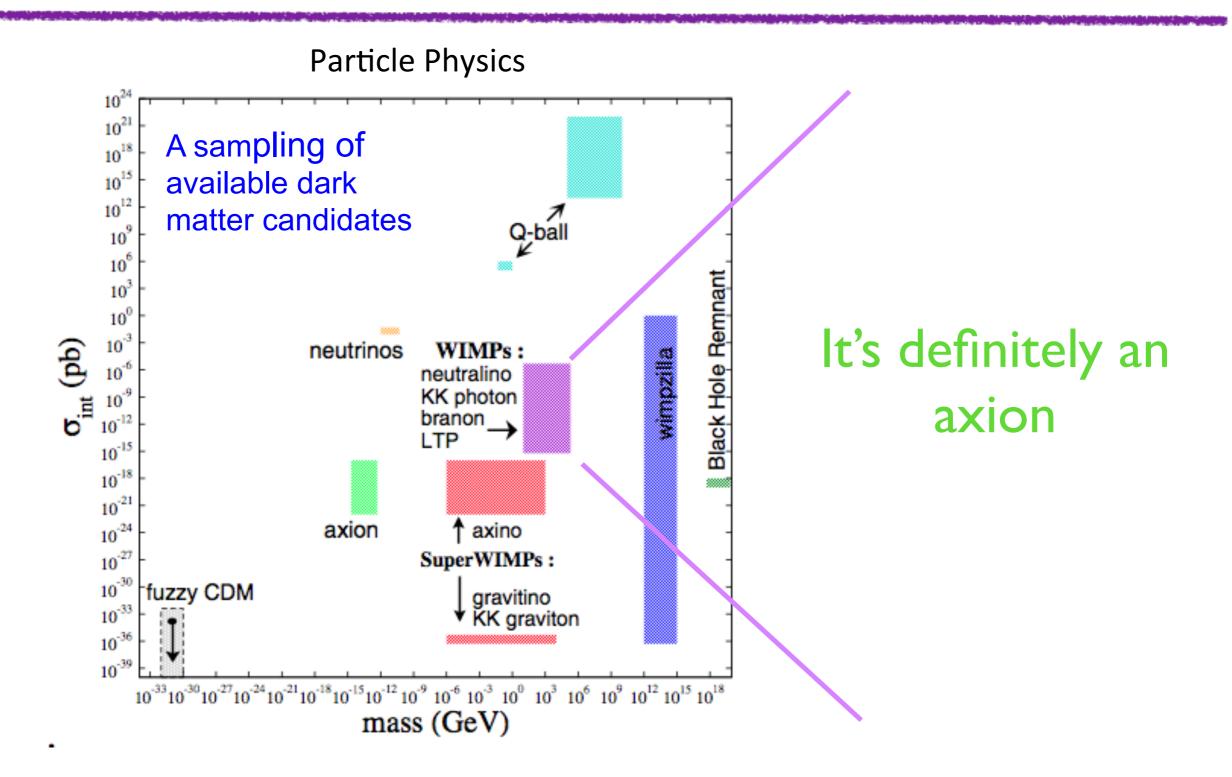
- Recommendation 2d:
  - An ultimate Generation 3 (G3) dark matter direct detection experiment reaching the neutrino fog, in coordination with international partners and preferably sited in the US (section 4.1).

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 Veutrinos Astronomy Astrophysic Cosmic Direct Imprints Dark Matter Higgs Boson Science Experiments Timeline 2024 2034 Science Drivers Ρ LHC Р Ρ Р LZ, XENONnT P Ρ DarkSide-20k G3 Dark Matter § S Р







#### 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<sup>\*</sup> Department of Physics, Case Western Reserve University, Cleveland, OH 44105

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

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

Steven Ritz<sup>3</sup> NASA/Goddard Space Flight Center, Mail Code 661, Greenbelt, MD 20771 (Dated: October 30, 2018)

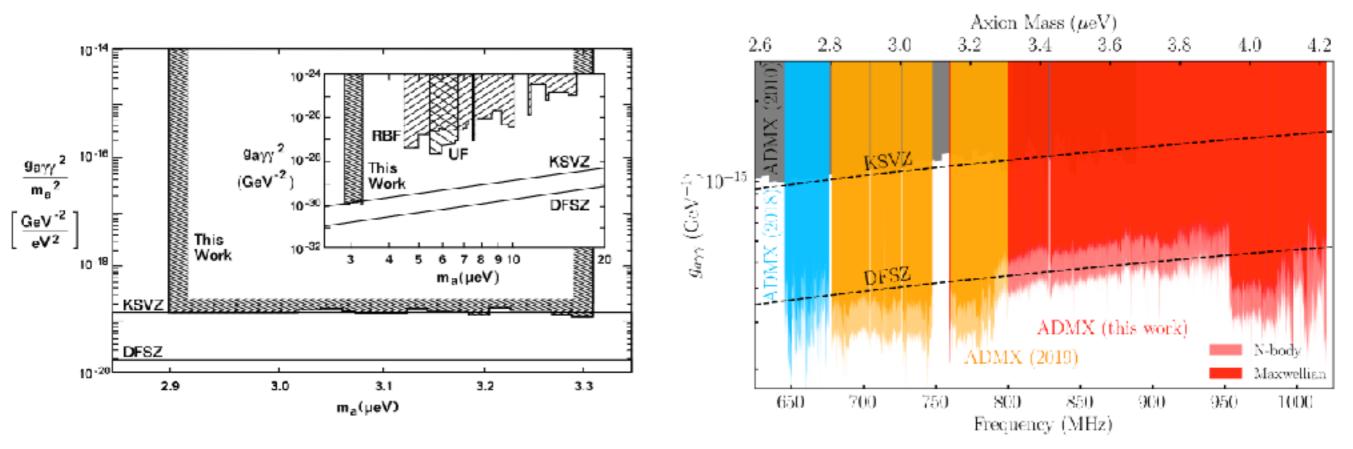
"The two decades of axion mass range that have not yet been ruled out by experiments or astrophysical observations are precisely in the range that could explain the dark matter...

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

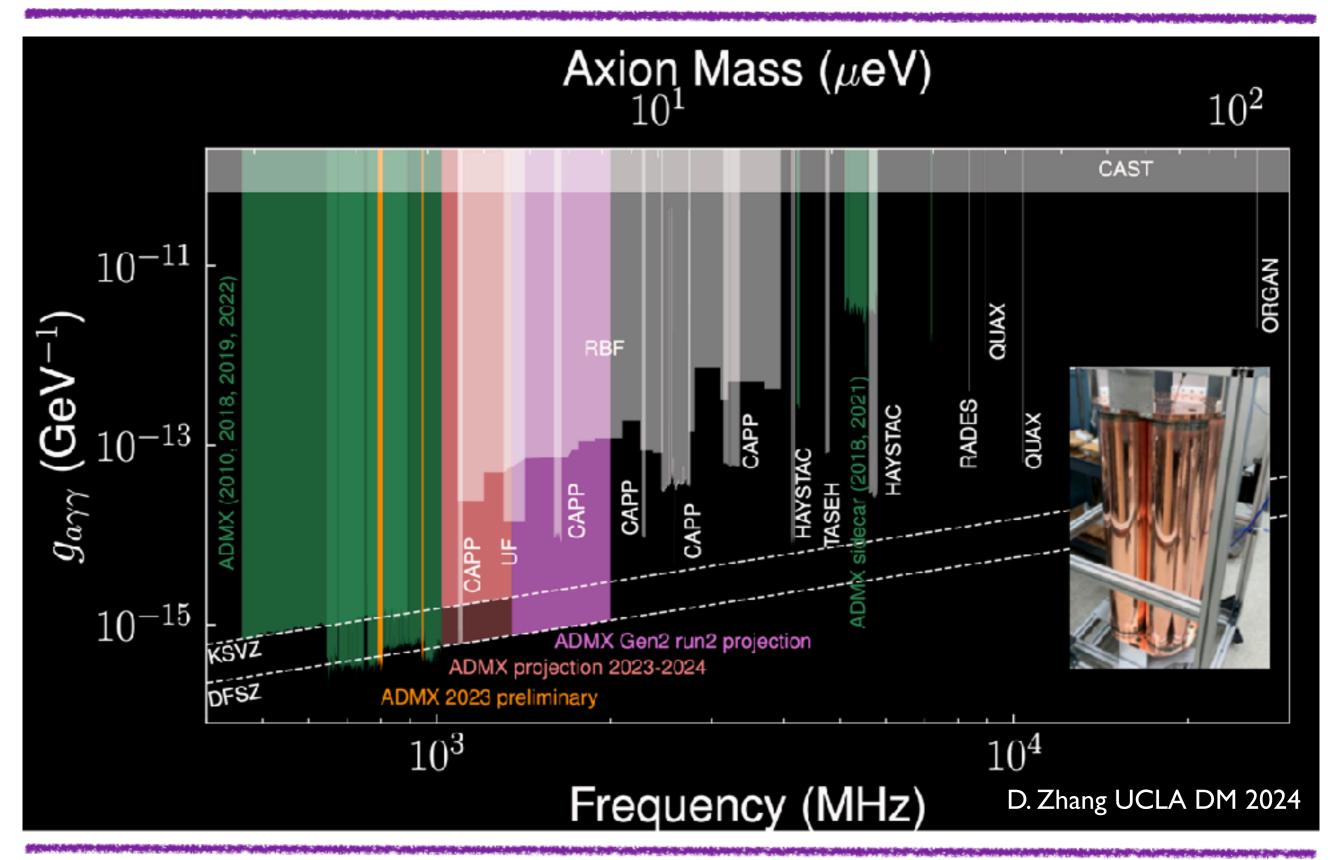
### Axions

- 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!



Hugh Lippincott, UCSB

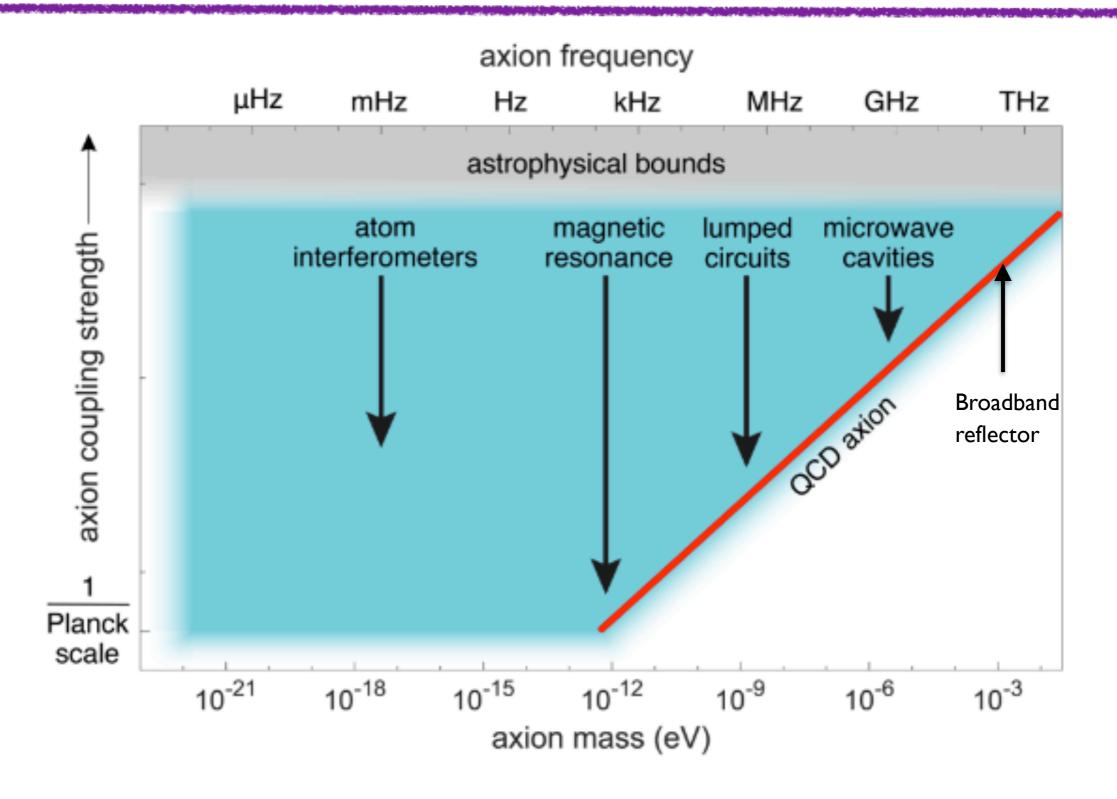
### Axions from the bottom up

"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

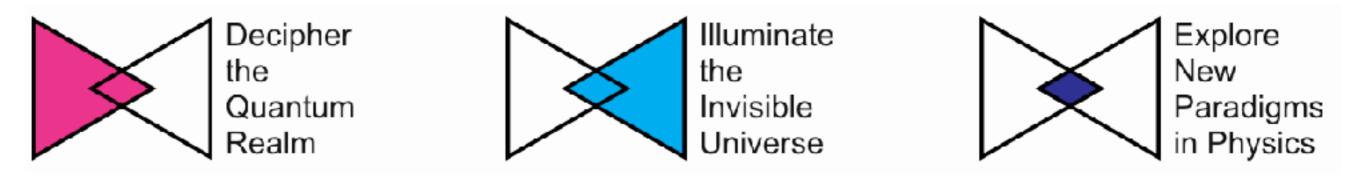
Recent theoretical advances have significantly expanded the phenomenology of the QCD axion, resulting in the realization that QCD axion dark matter can exist over wide range of masses from 100 Hz to 1 THz (roughly 10<sup>-12</sup> eV to 10<sup>-3</sup>

eV). - DMNI Report, 2018

### Axions from the bottom up



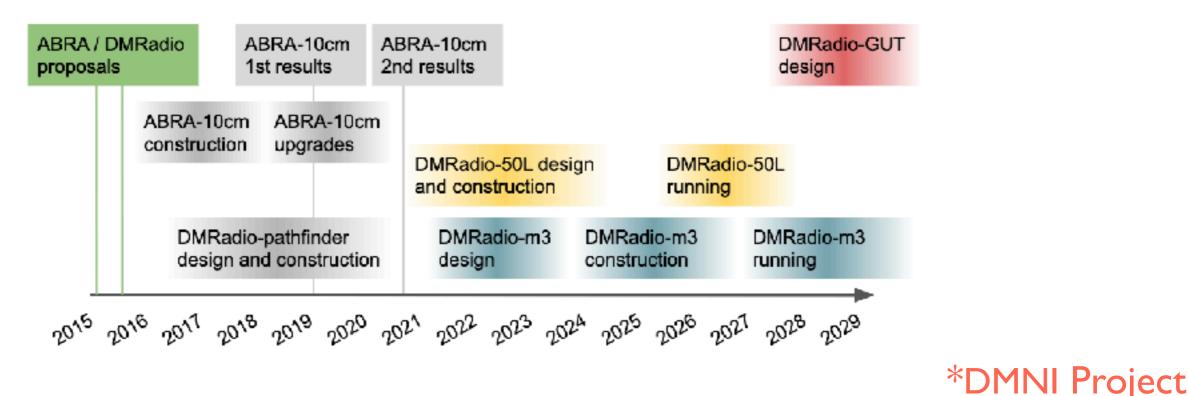
# P5 Report



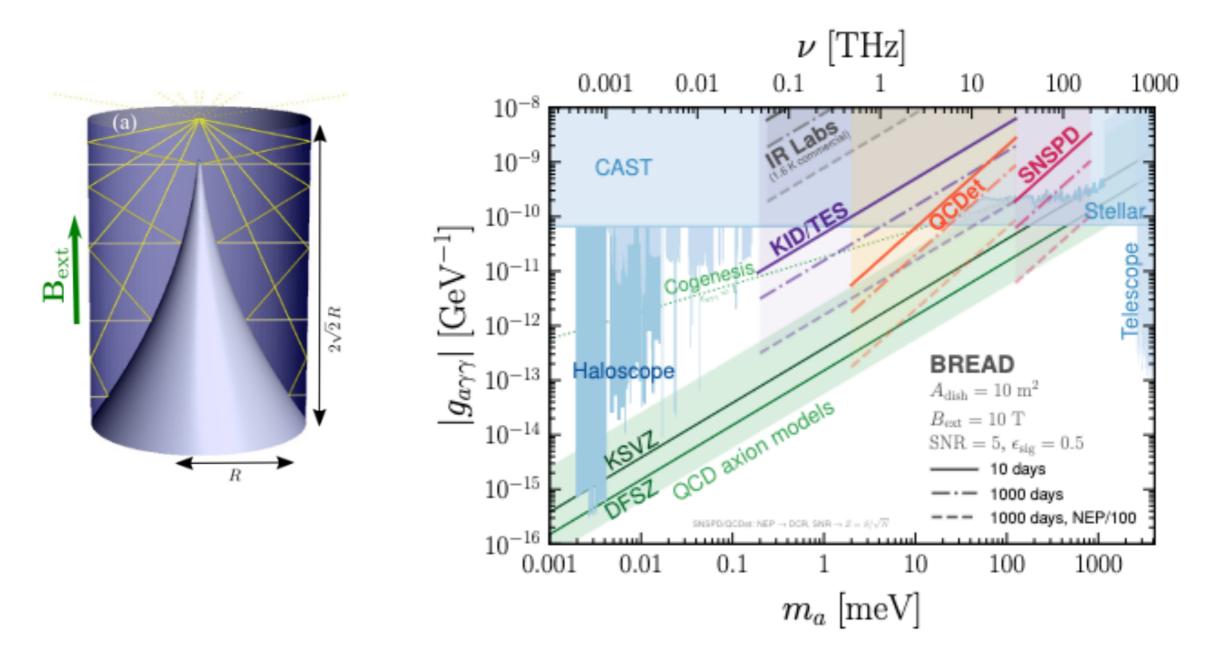
- Recommendation 3a:
  - Implement a new small-project portfolio at DOE, Advancing Science and Technology through Agile Experiments (ASTAE)...The program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP.
- Recommendation 4d:
  - Invest R&D in instrumentation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

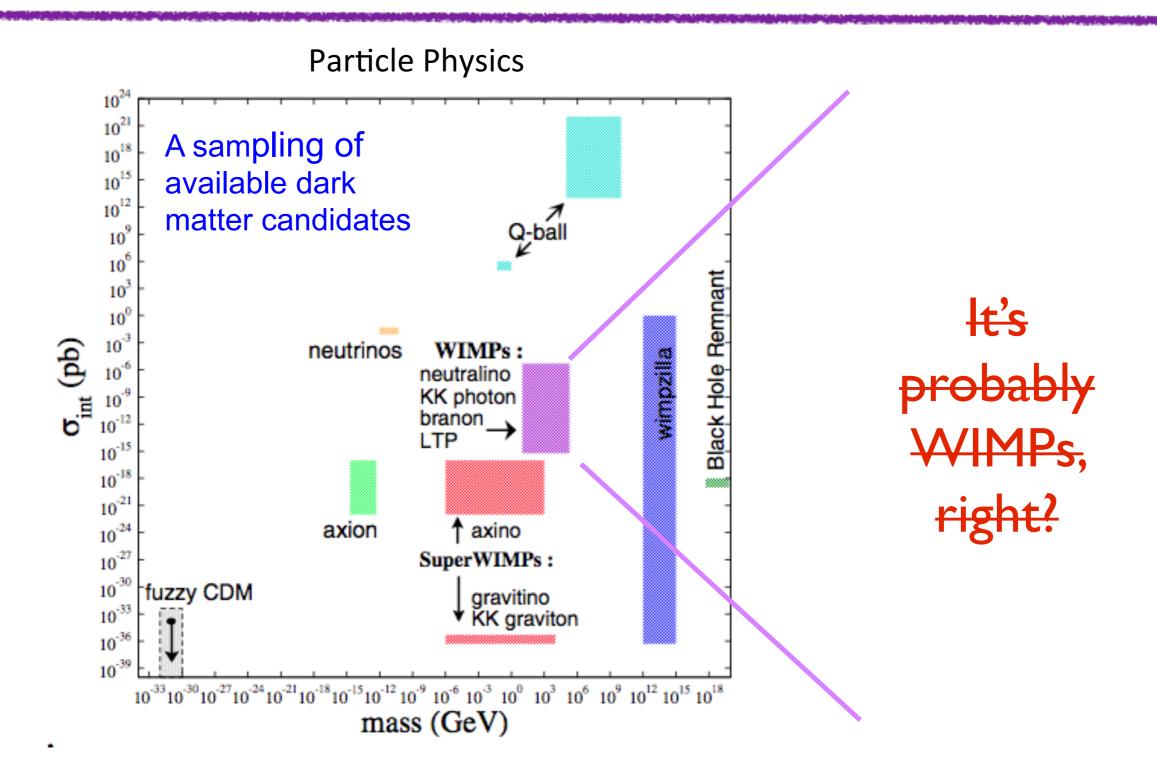
- ADMX-EFR\*, HAYSTAC going to higher frequencies in cavity searches (axion converts to a photon in a cavity)
- DMRadio\* looks to push below 1 ueV with lumped elements (axions convert into an effective current measured by a resonator)
- CASPEr pushing even lower with precision NMR (axions interact with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

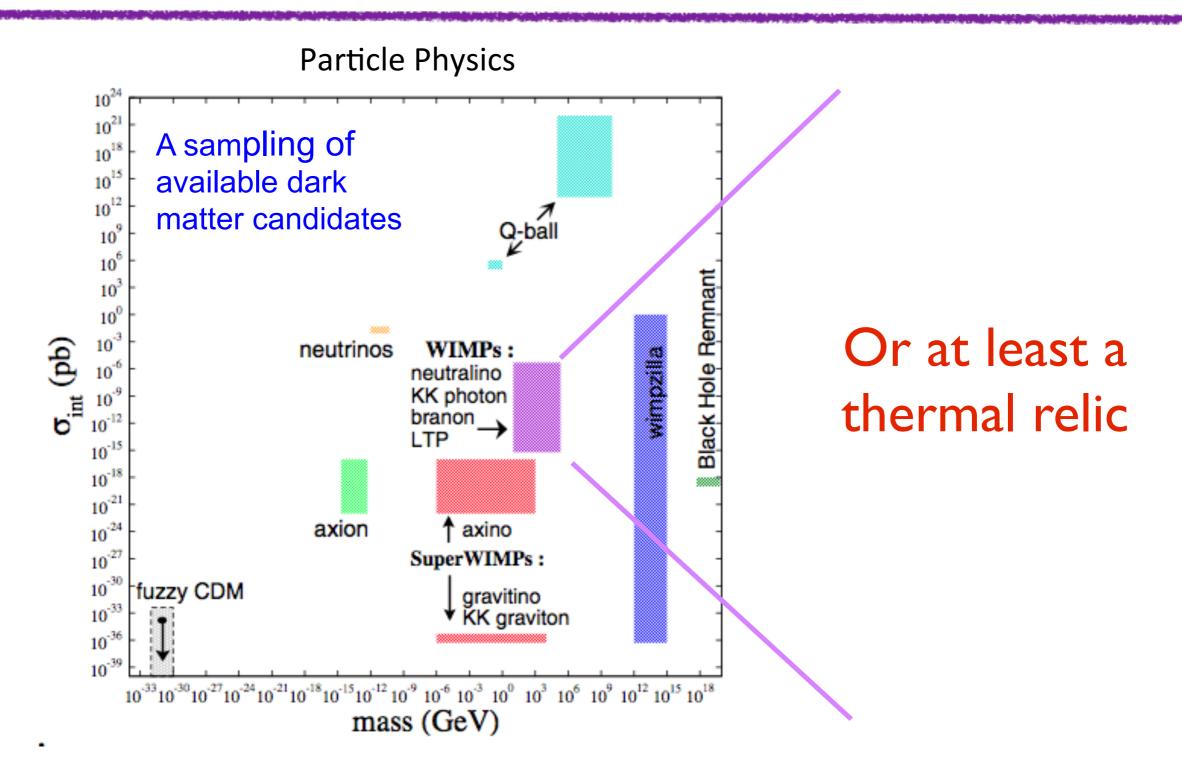
#### DMRadio program schedule



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

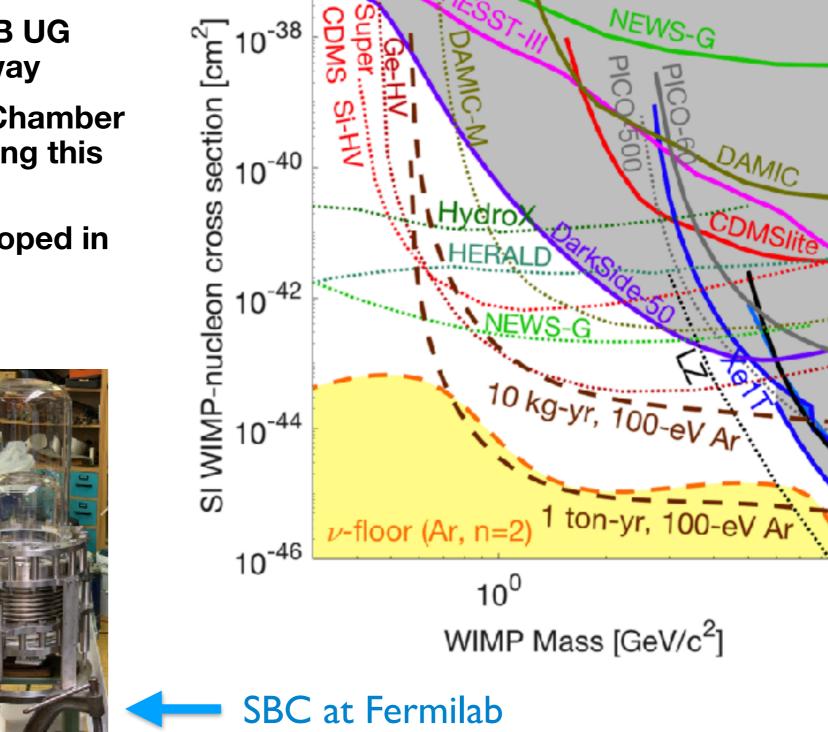




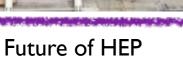


#### Prediction is strongly correlated with discovery prospects.

- 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

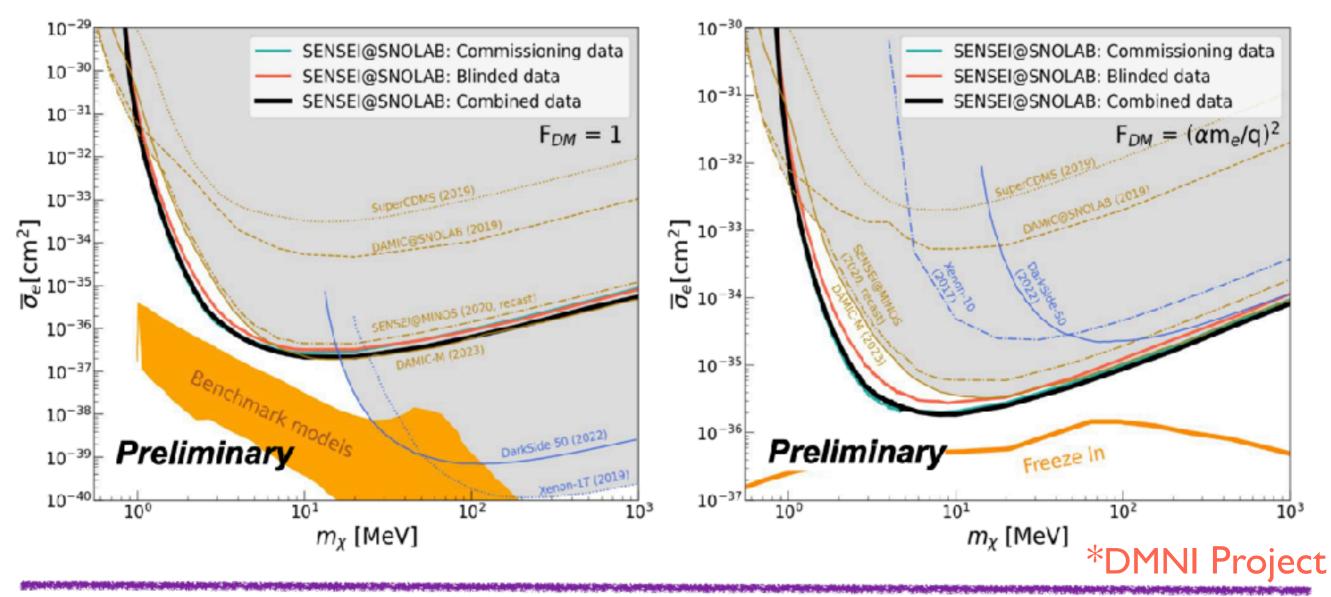


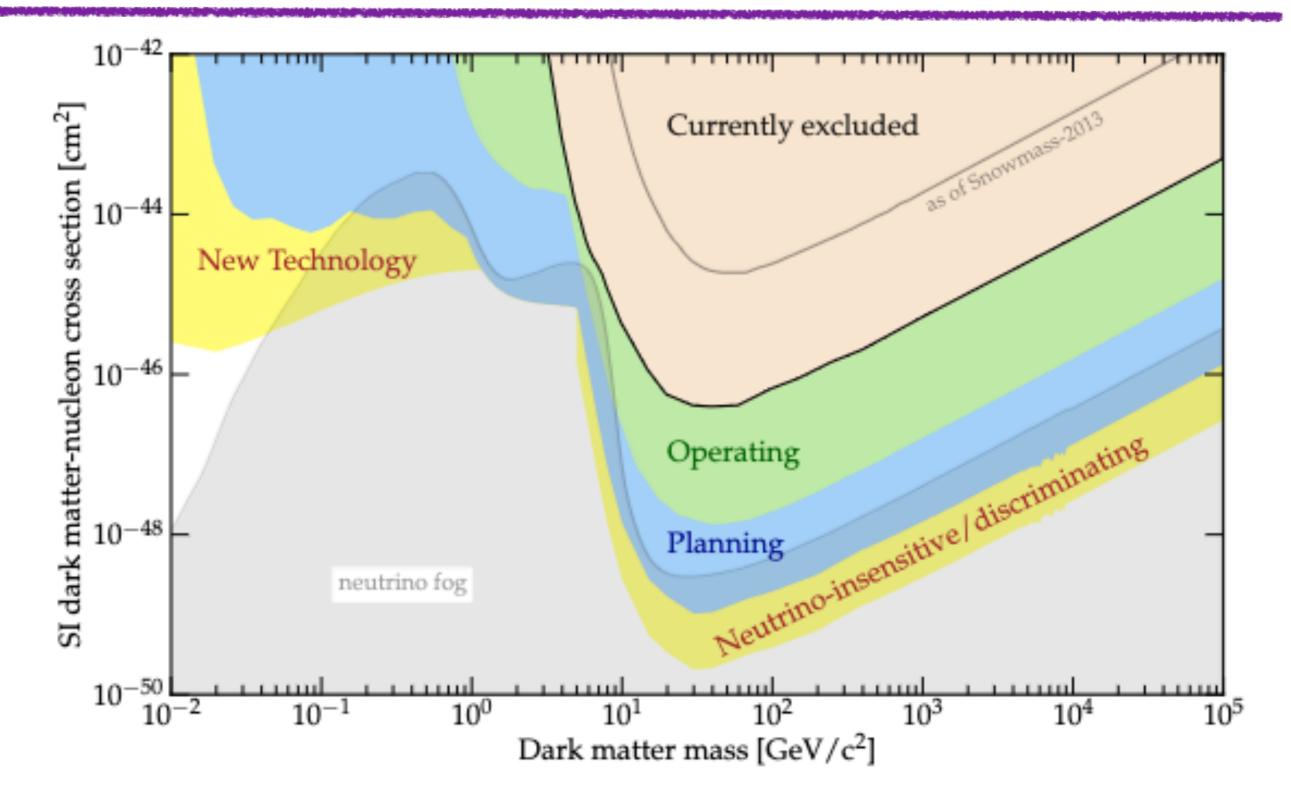


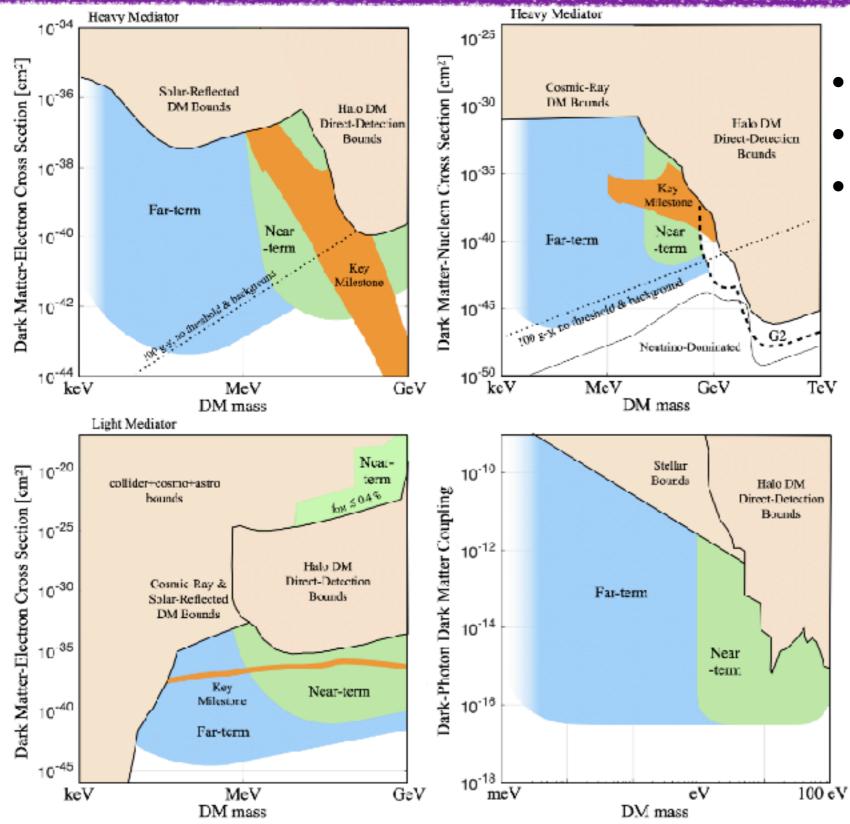


 $10^{1}$ 

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





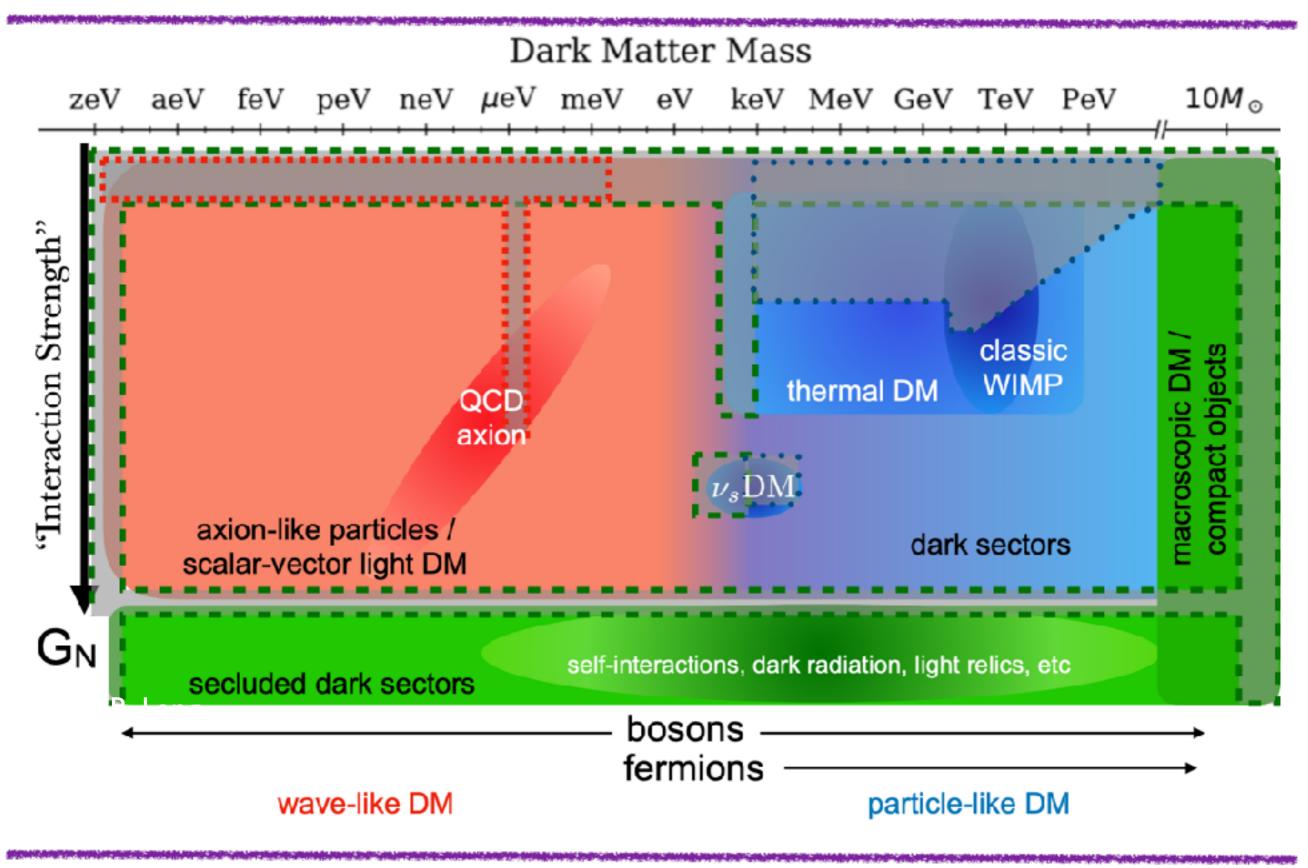


- Near term ~5 years
- Far term > 5 years
- Key milestone benchmark models
   from <u>DMNI report</u>

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.

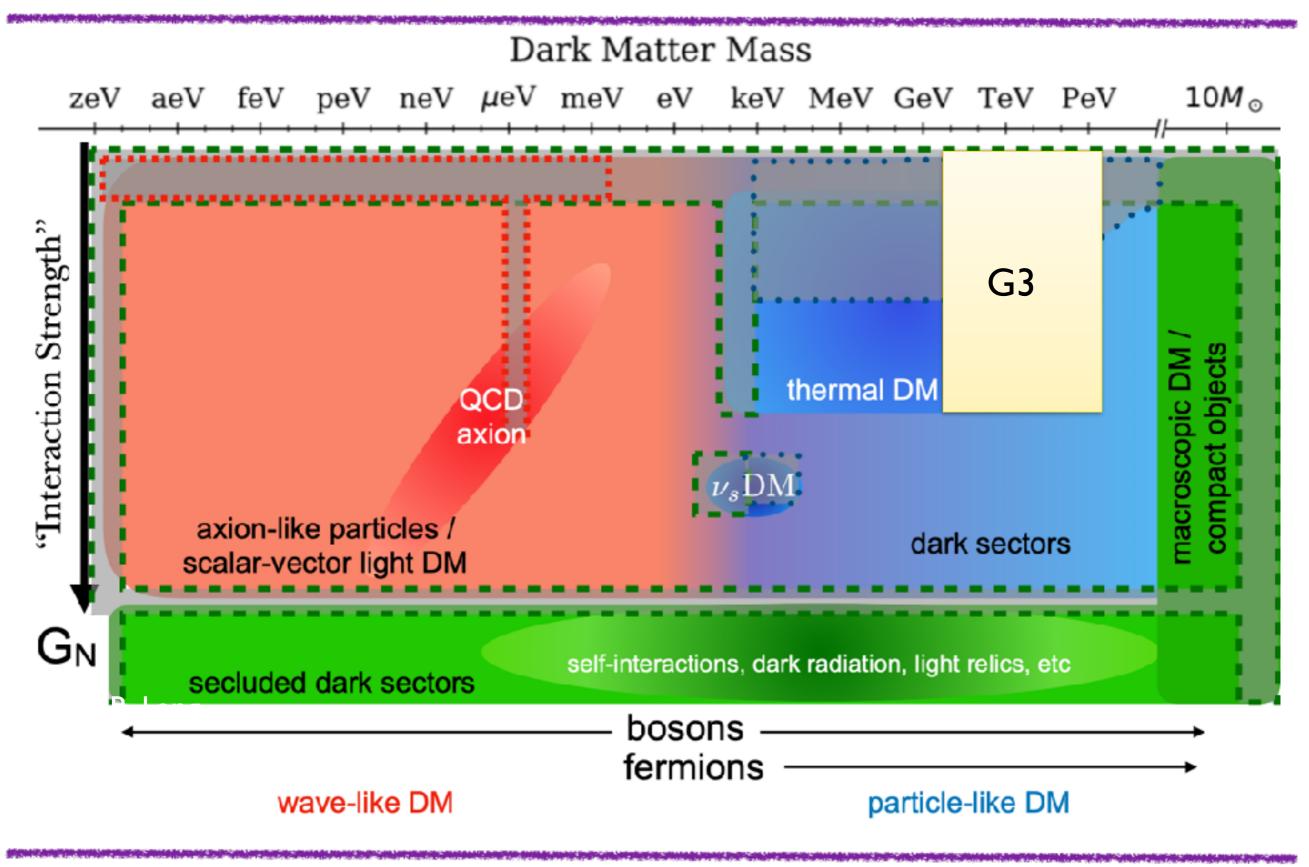
2022 - Well-studied theoretical models provide a compelling scientific case to make broad and rapid inroads into unexplored dark matter parameter space via a **search wide, delve deep** strategy. With new experiments that will come online in this decade, the HEP community will search wide to efficiently 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



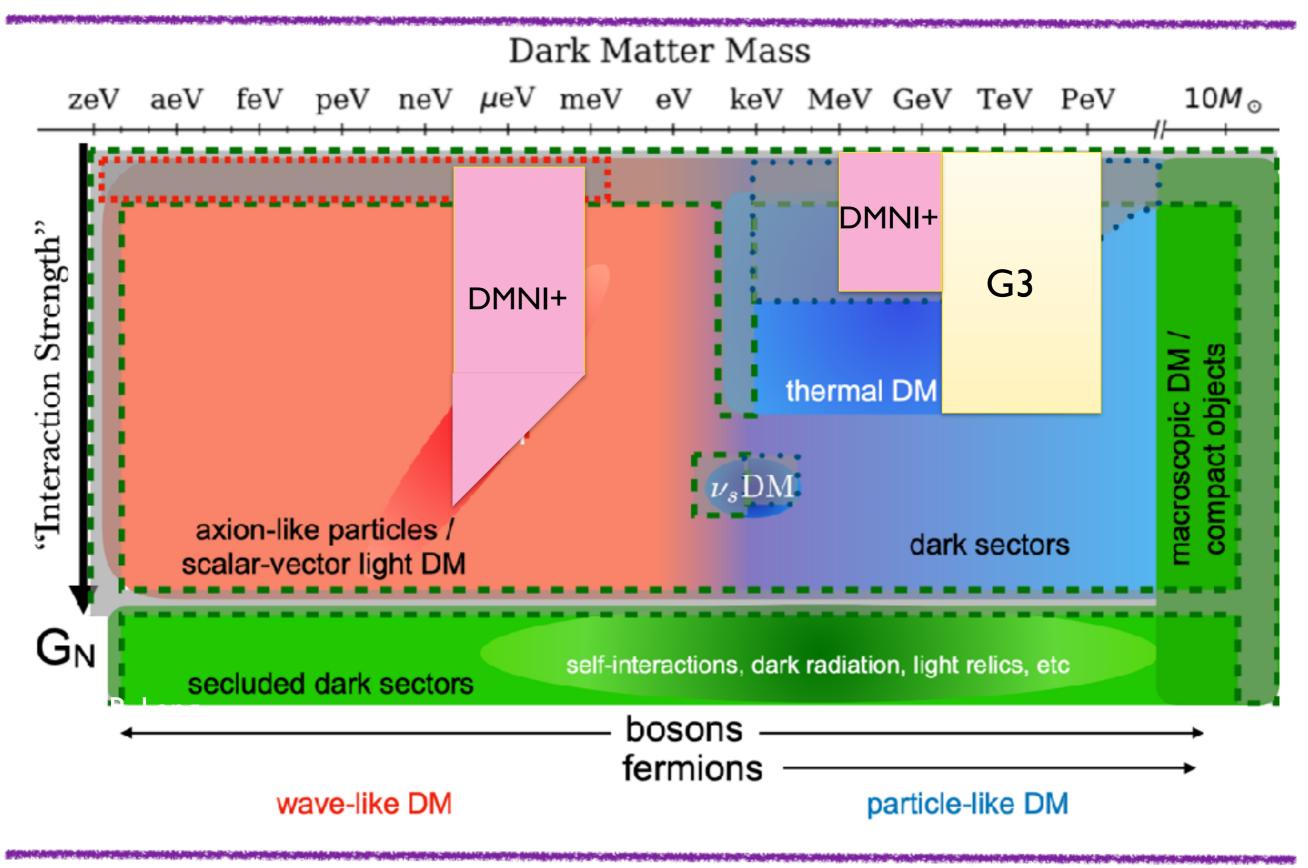
Hugh Lippincott, UCSB

### Snowmass and P5



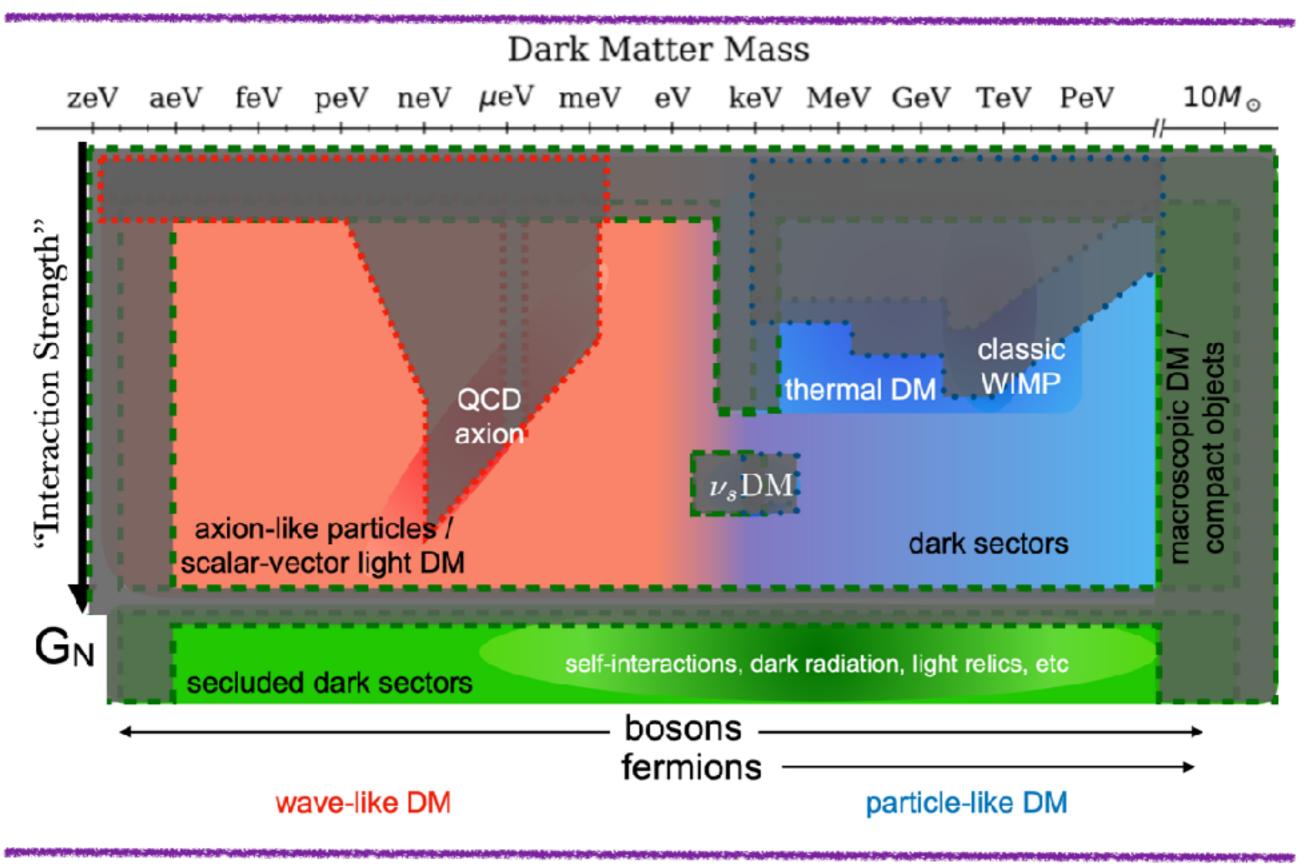
Hugh Lippincott, UCSB

## Snowmass and P5



Hugh Lippincott, UCSB

## Snowmass and P5



Hugh Lippincott, UCSB

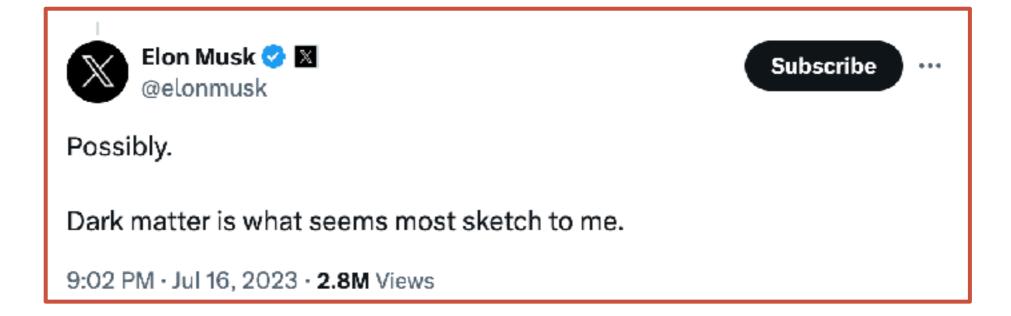
## Losing the narrative?

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

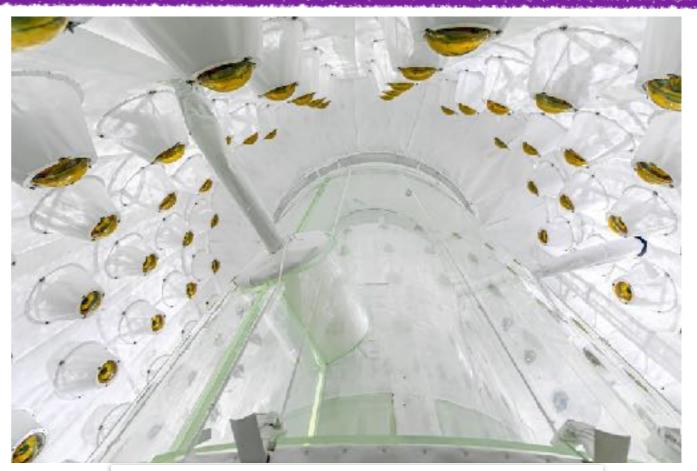
SPACE 18 March 2024 By MIKE MCRAE

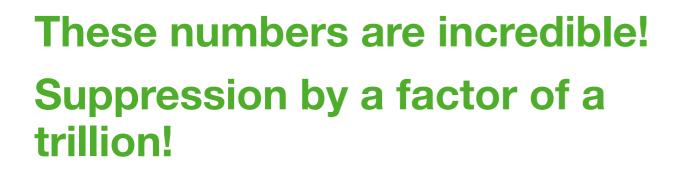


(Mark Garlick/Science Photo Library/Getty Images)



- XENONnT recorded ~15 events/tonne/year/keV in their first result
- LZ had zero candidate events in a tonne-year of exposure



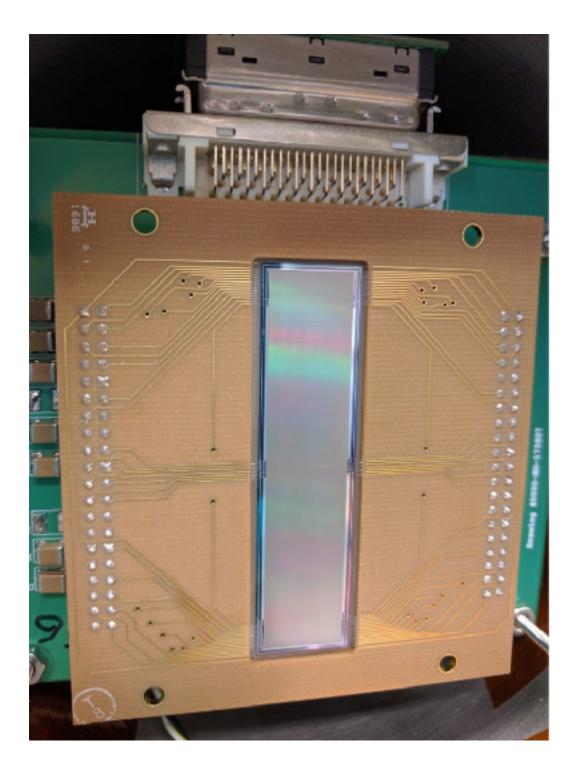


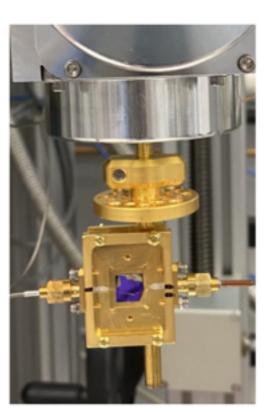


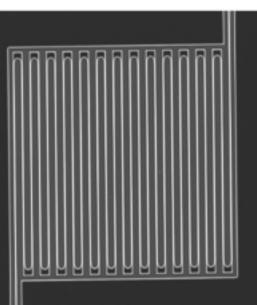
 DarkSide operating a prototype distillation column to isotopically separate <sup>39</sup>Ar from <sup>40</sup>Ar





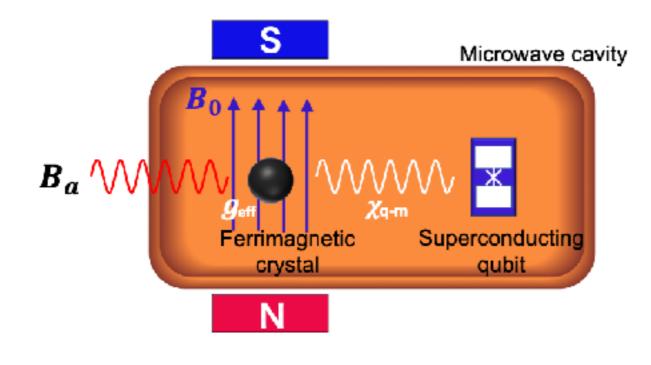


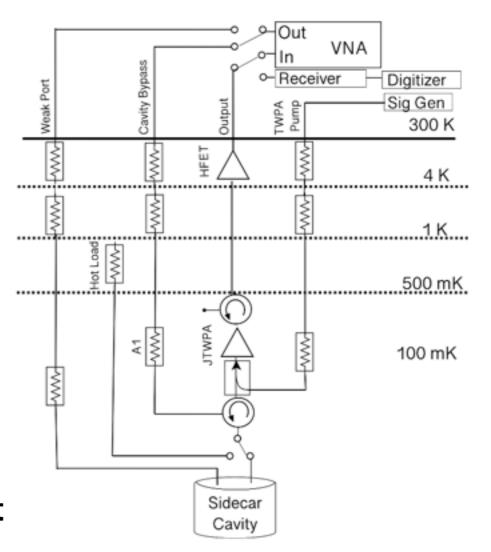




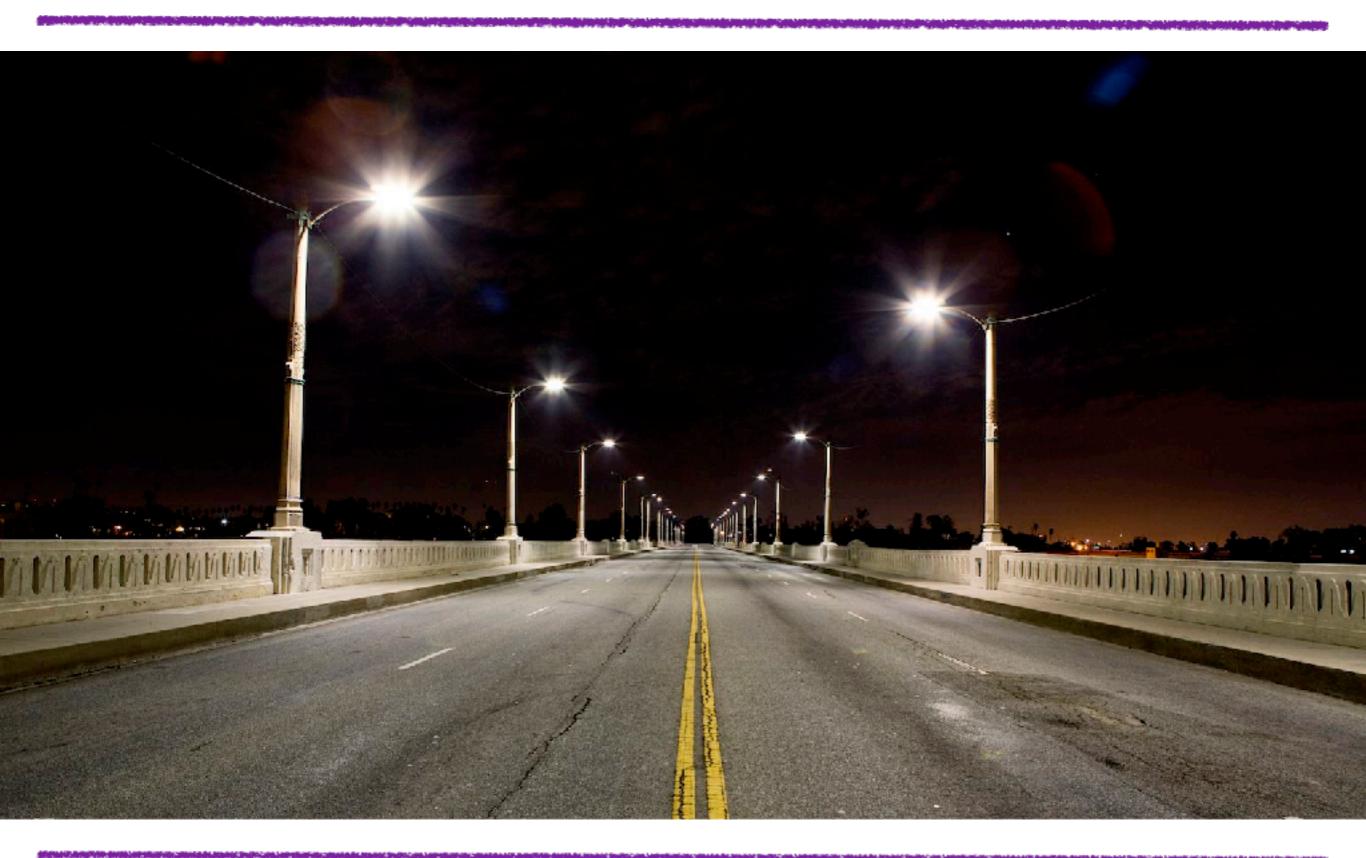
100nm wide nanowires in SNSPD (15x15 μm area) from MIT

- 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

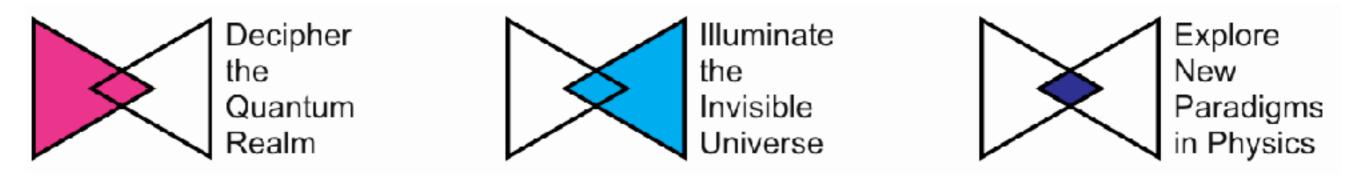




- Quantum non-demolition techniques to push below standard quantum noise limit
- 10-21 10-22 W/Hz<sup>1/2</sup>



# **Opportunities and Challenges**



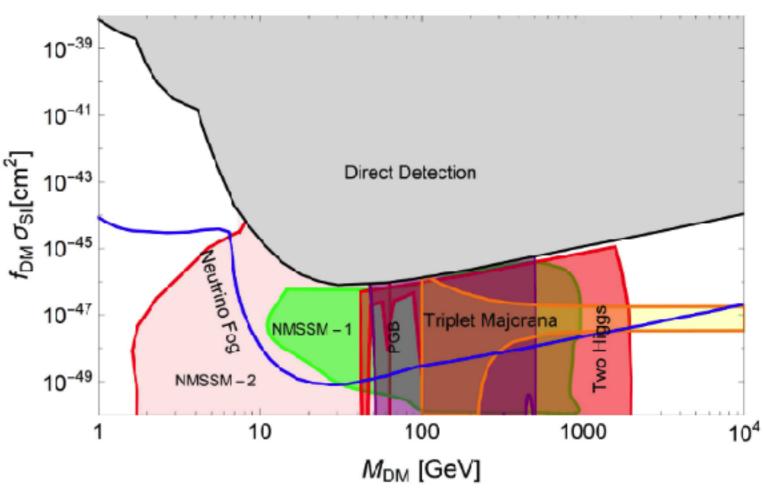
- Dark Matter is a central problem in high energy physics
- After 30 years of experimental progress, the theory priors have weakened
  - What was WIMPs and two decades of axion mass is now 30+ orders of magnitude in mass
- An explosion of ideas and techniques, drawing from atomic physics, quantum sensing, 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!

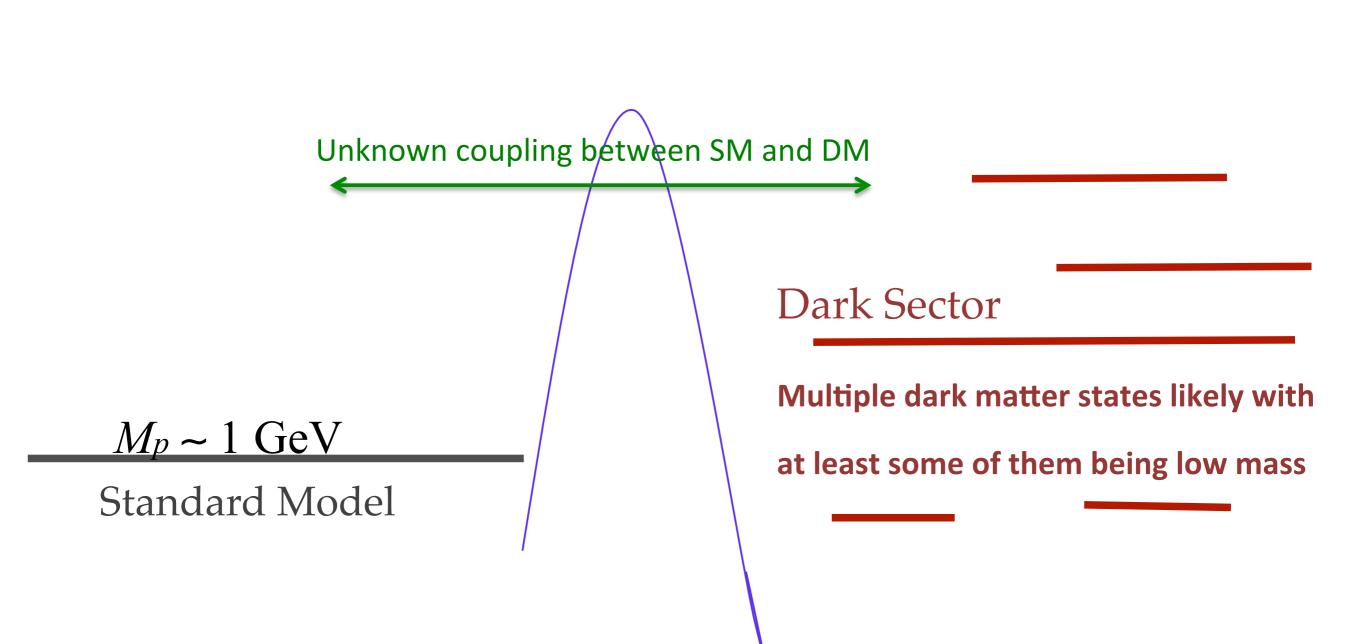
#### I'm eager to see what's next!

## 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
  - CFI-WPI 2203.08084
    - Many other references
       therein
  - Now probing some of the most interesting models from 20 years ago



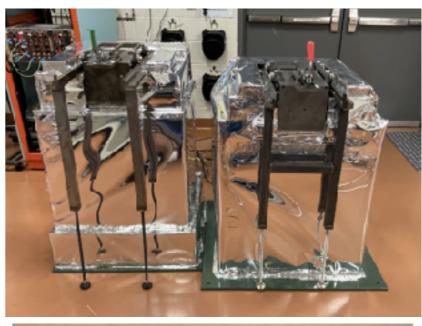
## WIMP crisis?



# **Background Sources and Mitigation**

- Detector materials
  - Many methods for BG mitigation
    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 (<u>Astropart. Phys. 96, 1 2017</u>)
- Rn daughters and dust on surfaces
   TPC assembly in Rn-reduced cleanroom
   Dust <500 ng/cm<sup>2</sup> on all LXe wetted surfaces
   Rn-daughter plate-out on TPC walls <0.5 mBq/m<sup>2</sup>
- Xenon contaminants
  - Charcoal chromatography at SLAC
  - Continuous purification underground

#### Many sources of BG





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