

# Diary of a WIMP(y) Kid

*A Talk in Cartoons (mostly not mine)*

Kimberly Palladino  
PATRAS

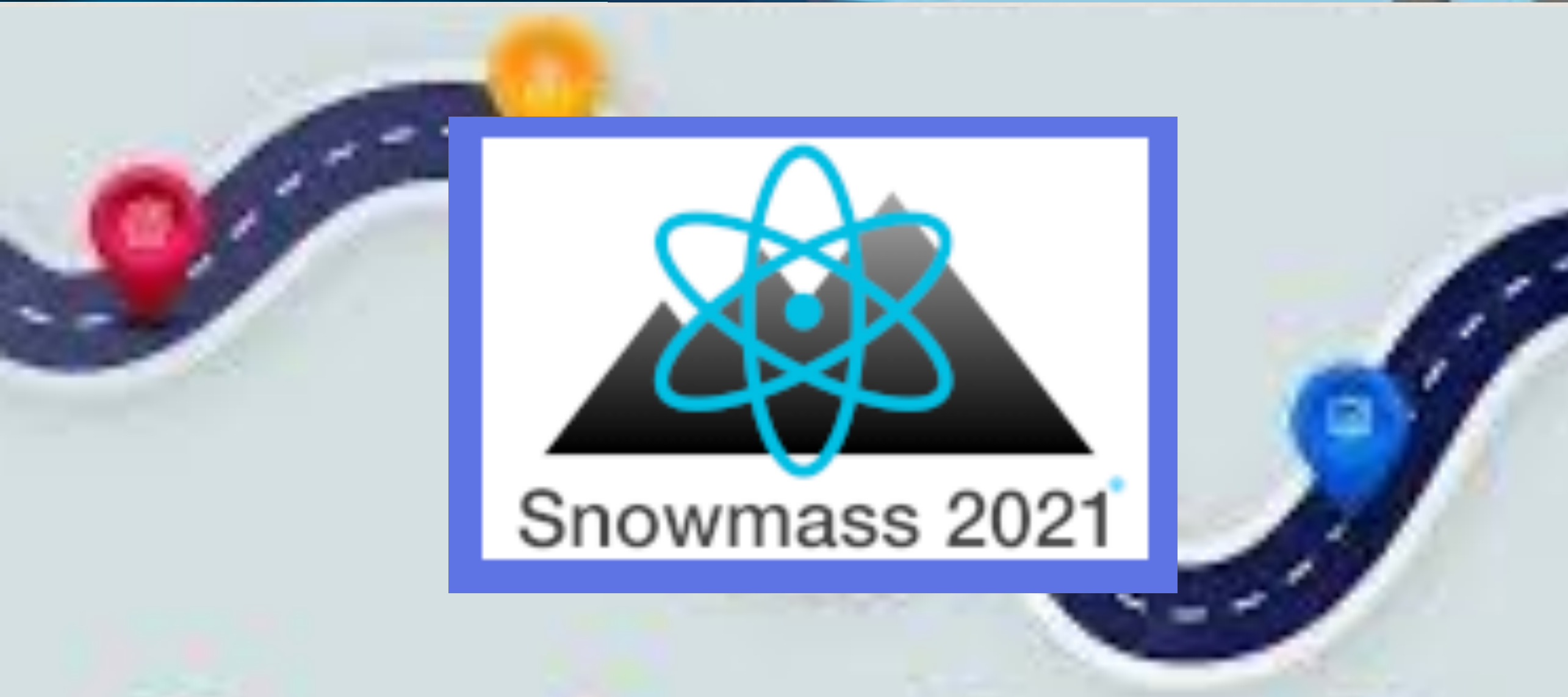
8 August 2022



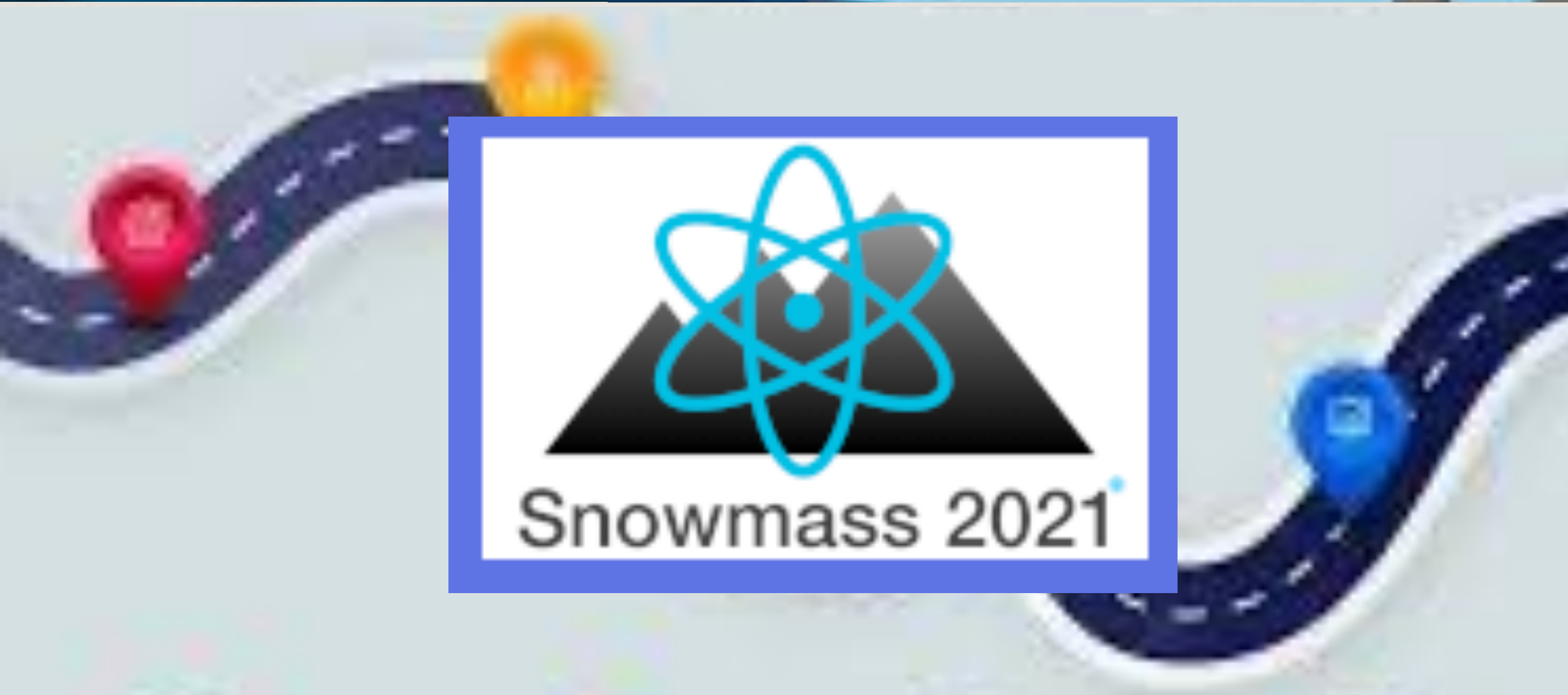
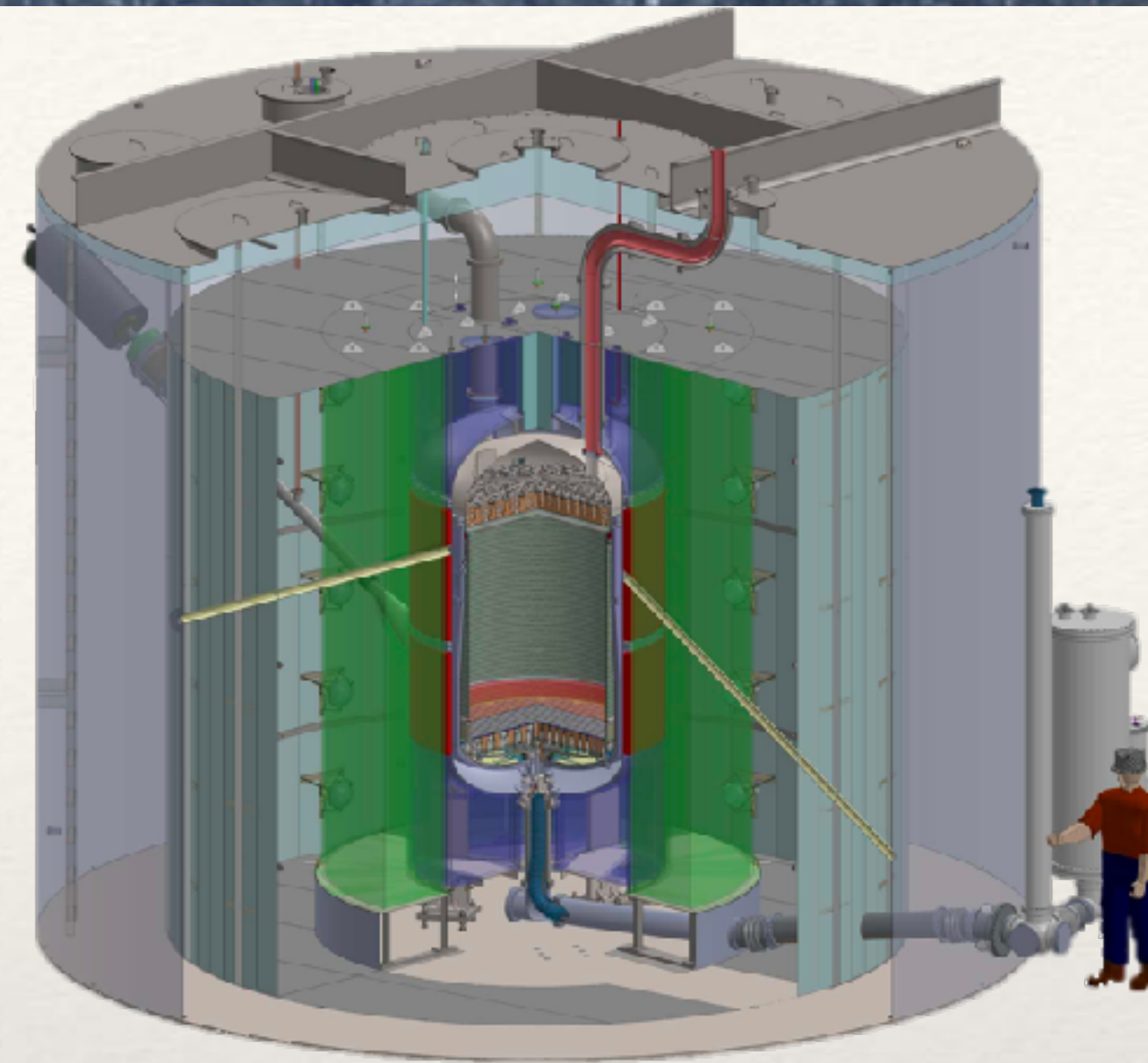
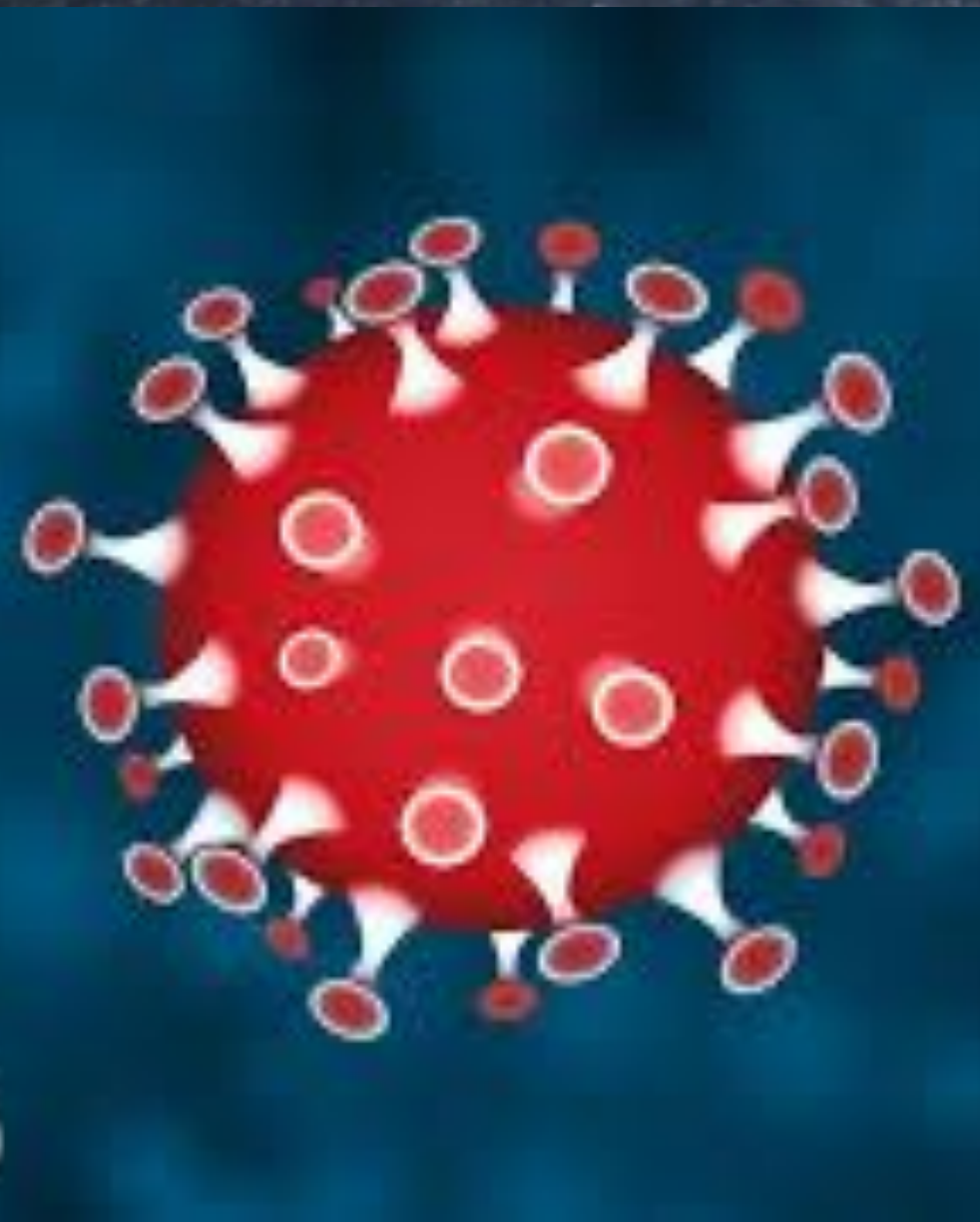
# This point in time...



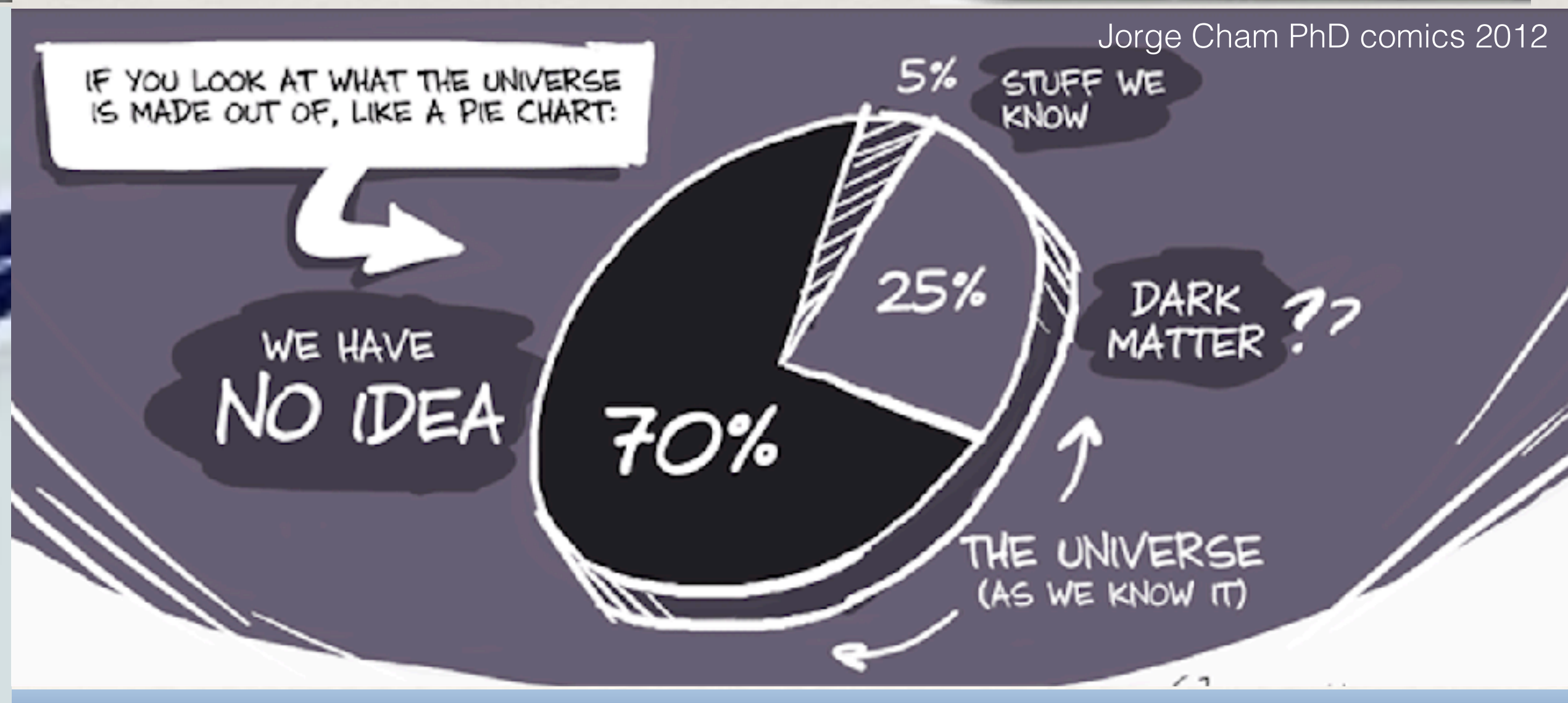
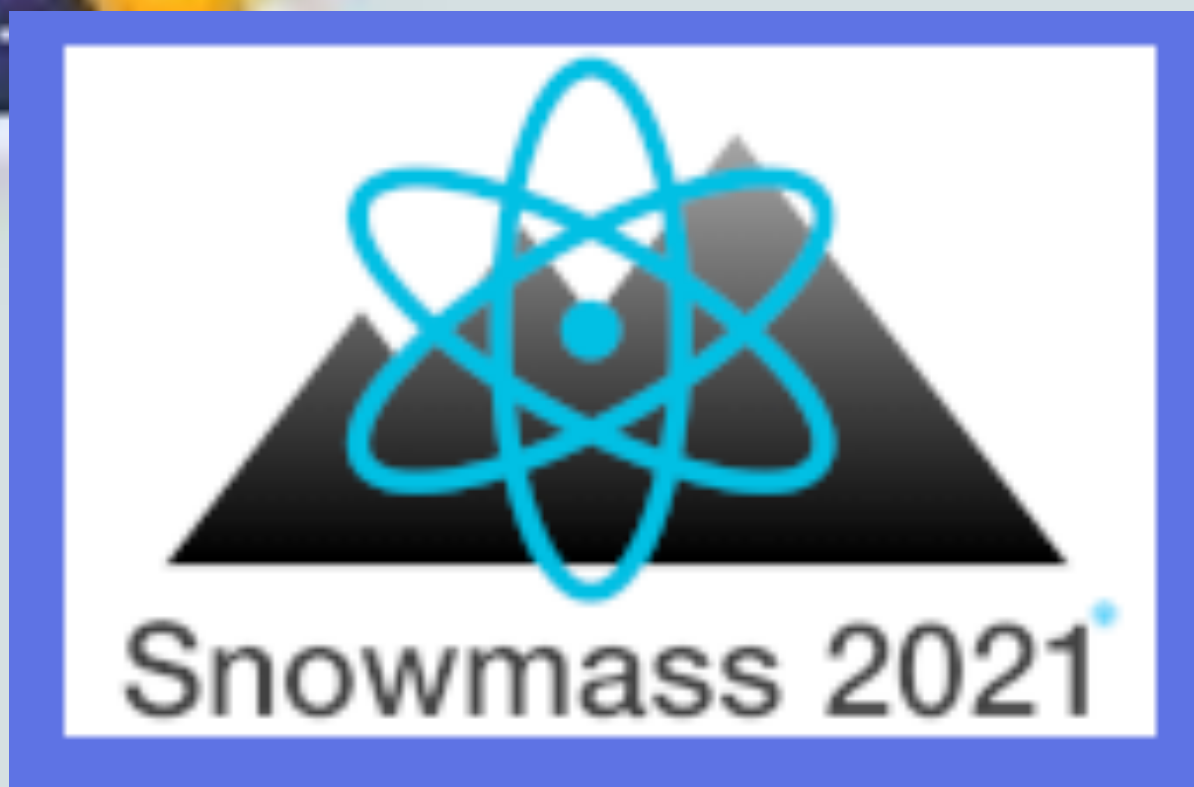
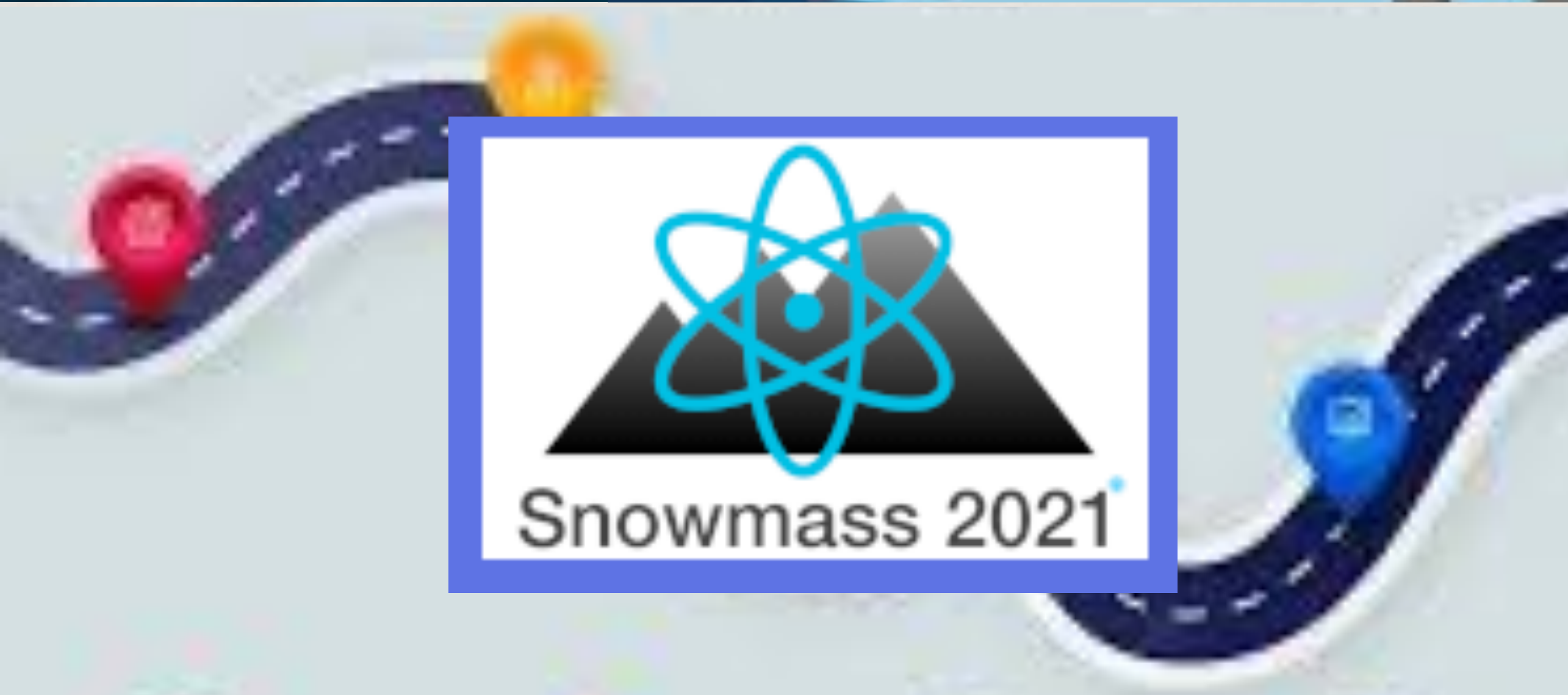
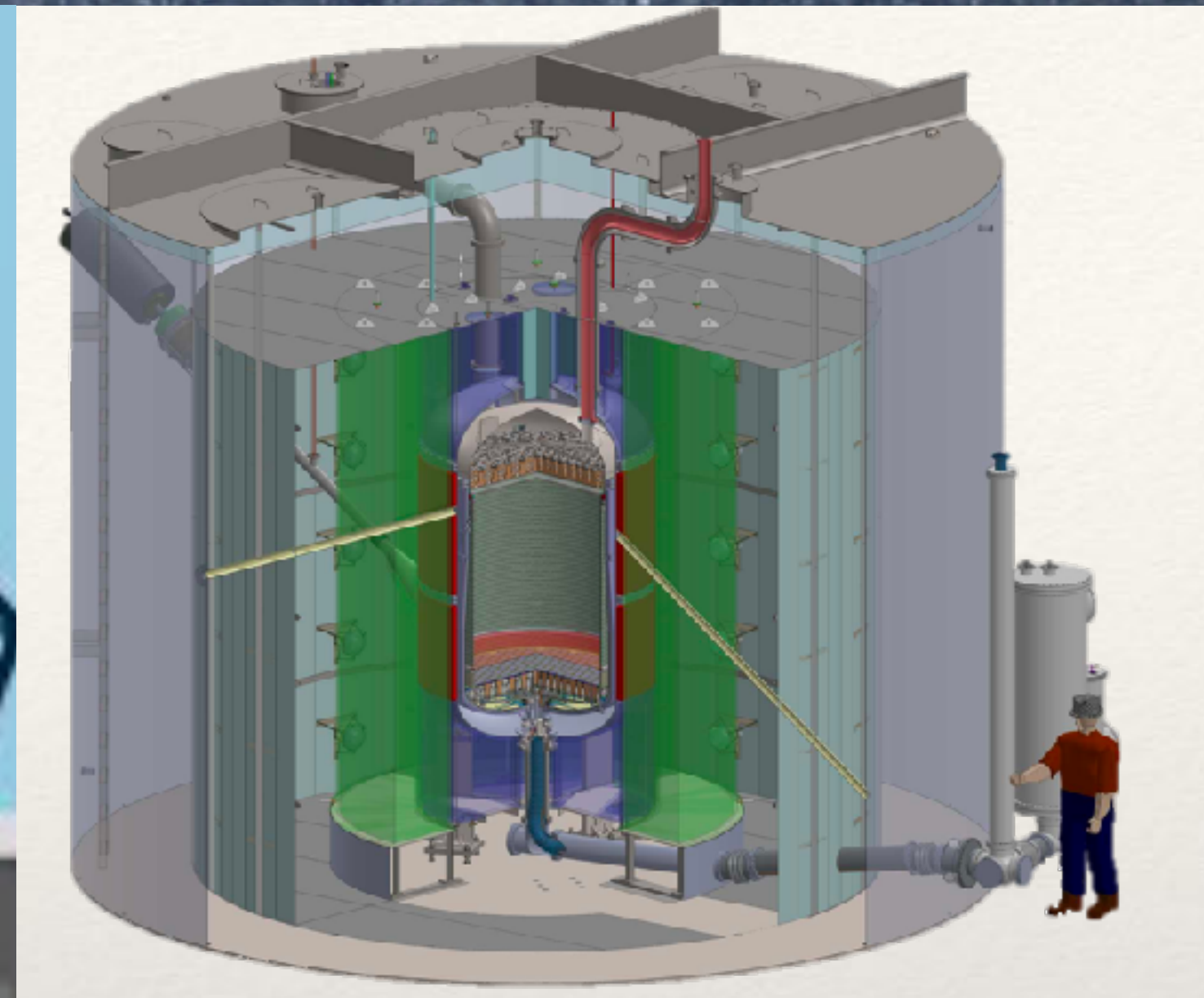
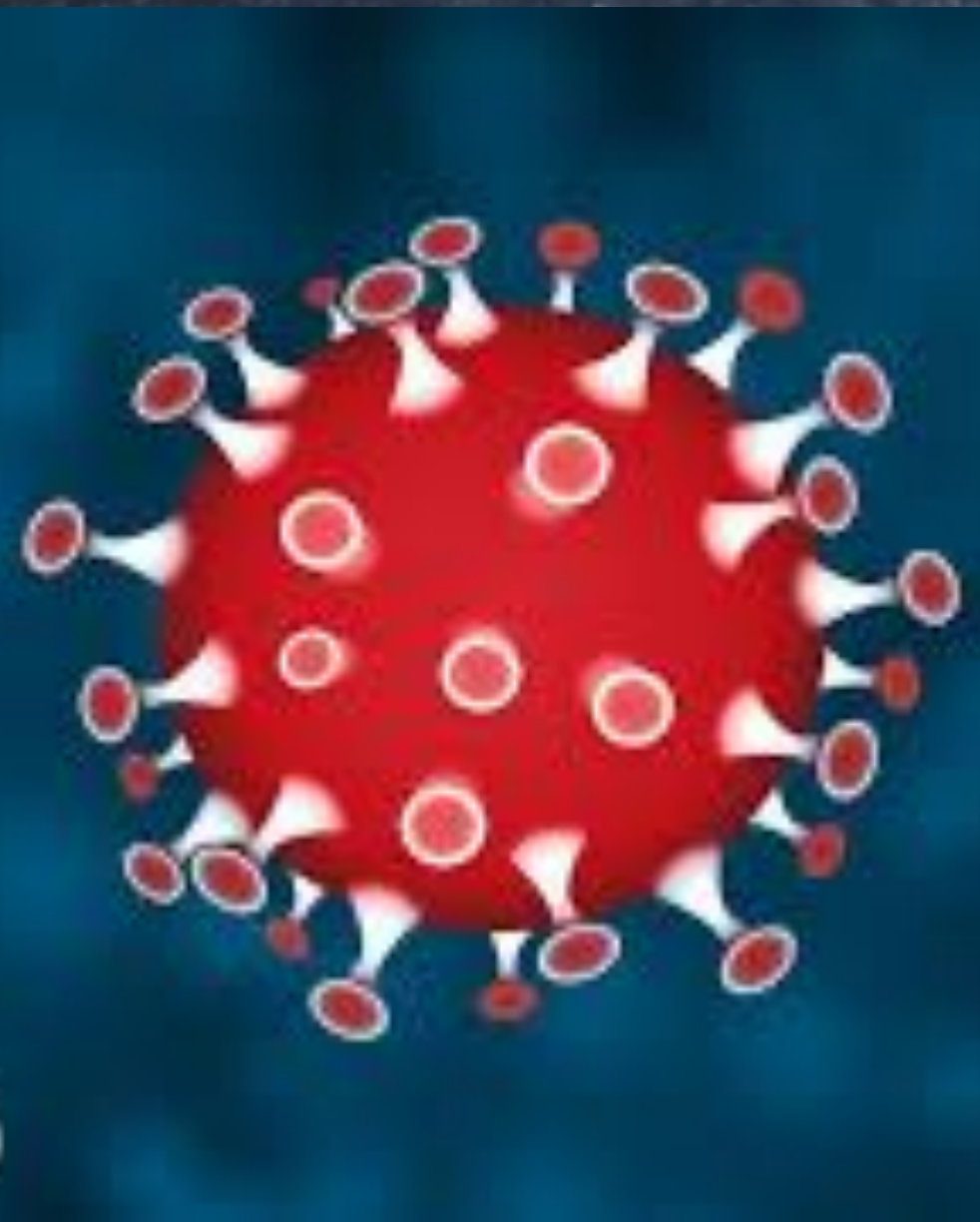
# This point in time...



# This point in time...



# This point in time...



# Where are we, and where are we going?

## Reports, Reviews, and Roadmaps

### European Astroparticle Physics Strategy 2017-2026

#### Direct Detection of Dark Matter – APPEC Committee Report \*

##### Committee Members:

Julien Billard,<sup>1</sup> Mark Boulay,<sup>2</sup> Susana Cebrián,<sup>3</sup> Laura Covi,<sup>4</sup>  
Giuliana Fiorillo,<sup>5</sup> Anne Green,<sup>6</sup> Joachim Kopp,<sup>7</sup> Béla Majorovits,<sup>8</sup>  
Kimberly Palladino,<sup>9,12</sup> Federica Petricca,<sup>8</sup> Leszek Roszkowski (chair),<sup>10</sup> Marc Schumann<sup>11</sup>

[arXiv:2104.07634](https://arxiv.org/abs/2104.07634)



#### DPF Community Planning Exercise

- D. S. Akerib, P. B. Cushman, C. E. Dahl, R. Ebadi, A. Fan, R. J. Gaitskell, et al. "Dark Matter Direct Detection to the Neutrino Fog", [arXiv:2203.08084](https://arxiv.org/abs/2203.08084) [hep-ex] [\(pdf\)](#).
- Rouven Essig, Graham K. Giovanetti, Noah Kurinsky, Dan McKinsey, Karthik Ramanathan, Kelly Stifter, Tien-Tien Yu. "The landscape of low-threshold dark matter direct detection in the next decade", [arXiv:2203.08297](https://arxiv.org/abs/2203.08297) [hep-ph] [\(pdf\)](#).
- D. Antypas, A. Banerjee, C. Bartram, M. Baryakhtar, J. Betz, et al. "New Horizons: Scalar and Vector Ultralight Dark Matter", [arXiv:2203.14915](https://arxiv.org/abs/2203.14915) [hep-ex] [\(pdf\)](#). (also under RF03, TF09, IF01)
- Rebecca K. Leane, Seodong Shin, Liang Yang, Govinda Adhikari, et al. "Puzzling Excesses in Dark Matter Searches and How to Resolve Them", [arXiv:2203.06859](https://arxiv.org/abs/2203.06859) [hep-ph] [\(pdf\)](#). (also under TF09)

<https://snowmass21.org/submissions/cf>

# View from altitude

- **WIMP/high mass particle dark matter is a viable, motivated dark matter model.**



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- **New detectors and technologies are coming to probe lower mass particle DM.**
  - **When proven, they should also be used until neutrino events are seen.**

# View from altitude

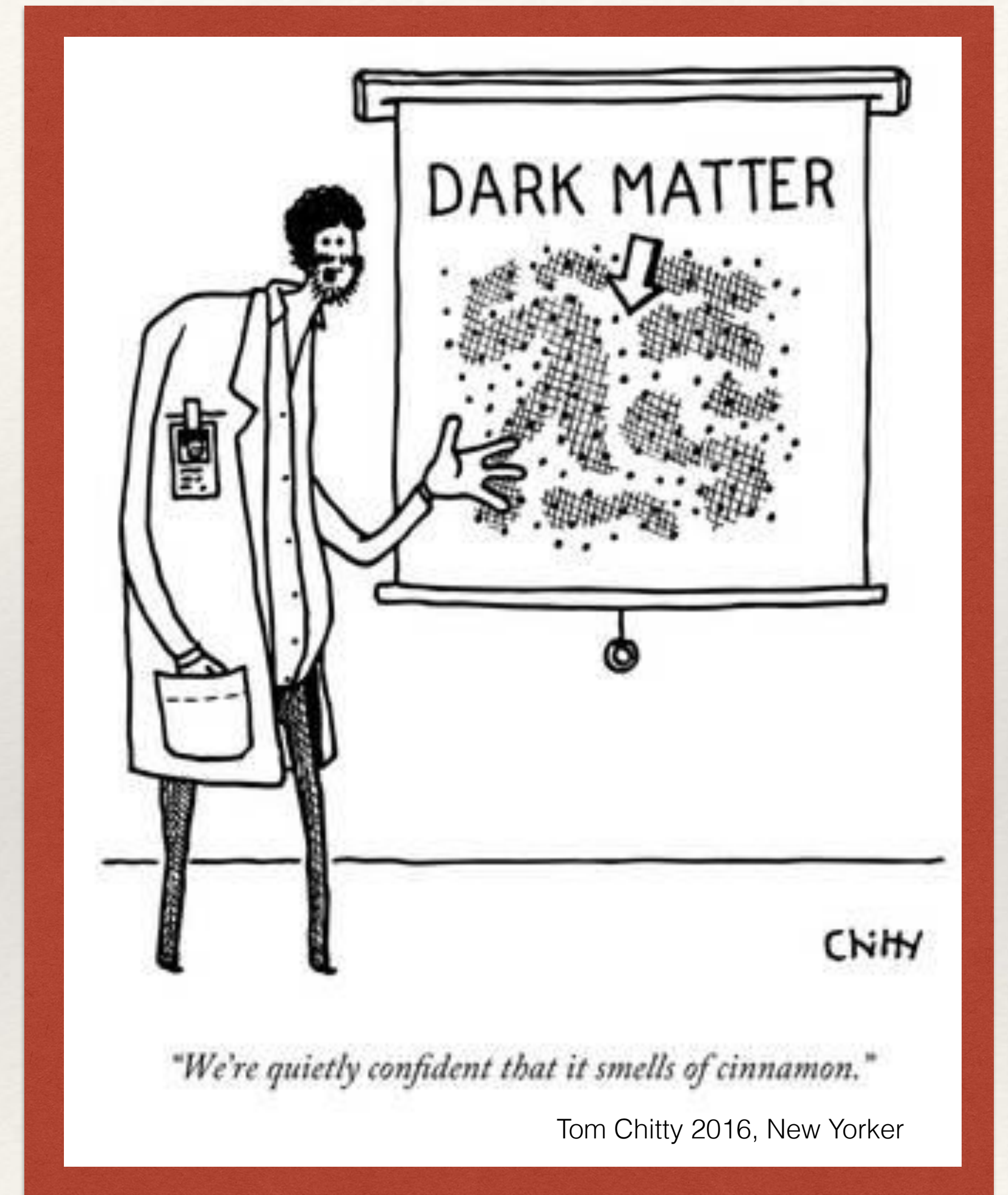
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- **We should be prepared for discovery at any moment, and have multiple technologies ready for confirmation.**
- **WIMP searches fit into a wider ecosystem of dark matter searches, all are important.**

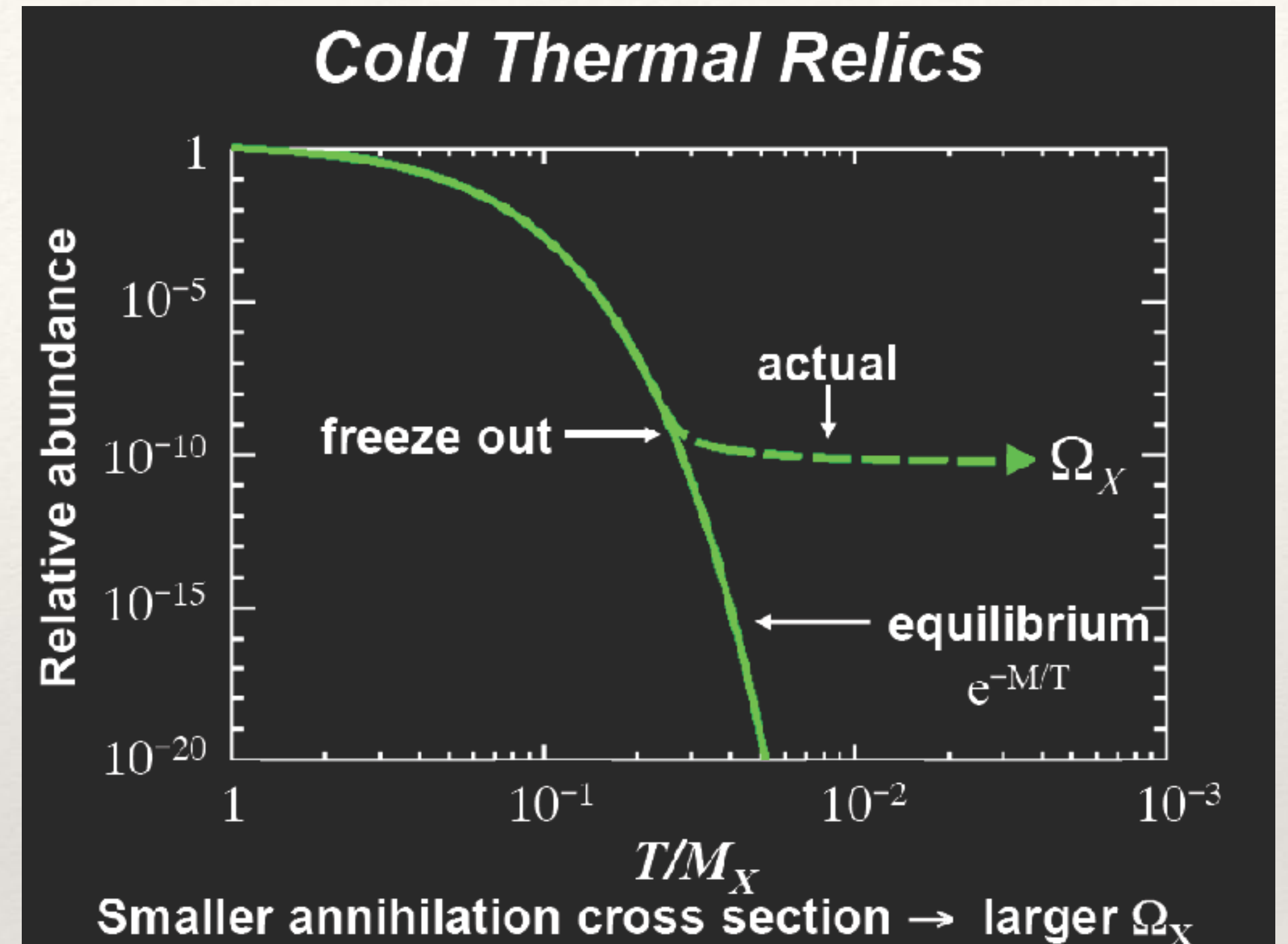
# Outline

- Particle Dark Matter Models
  - Where are we in the WIMP paradigm?
- Direct Searches for Particle Dark Matter
  - High Mass: Liquid Nobles
  - Lower Mass: Multiple Technologies
- Expectations for the Future
  - Direct Detection plans
  - Meshing with other searches



# Old Slide of the WIMP Miracle

Particles with masses of  $\sim 100$  GeV and interactions at the weak scale would give current dark matter density of  $.3 \text{ GeV}/\text{cm}^3$



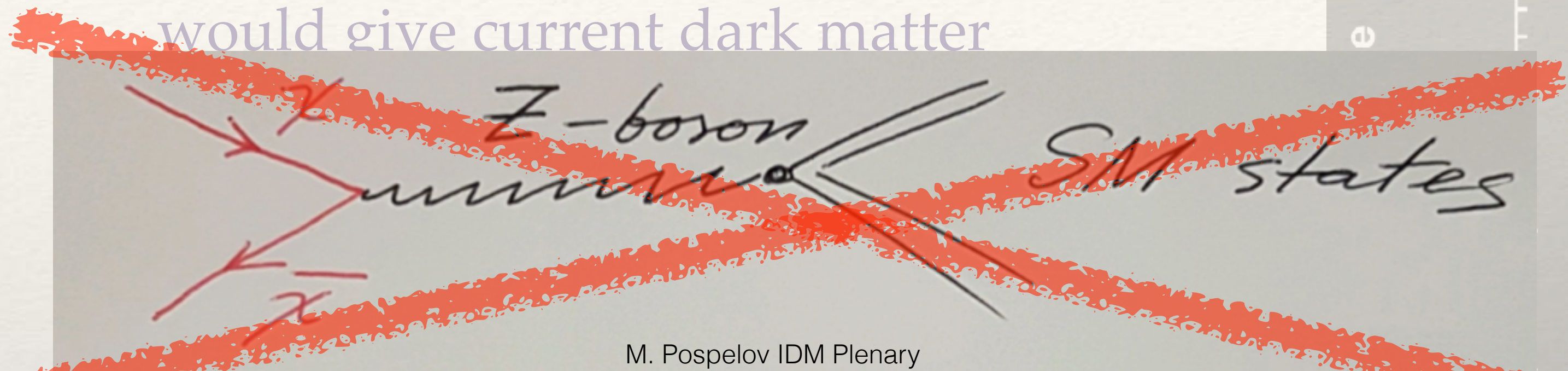
WIMPs fit naturally with SuSY:  
lightest neutralino, the LSP

# But I was asked ...

Particles with masses of  $\sim 100$  GeV

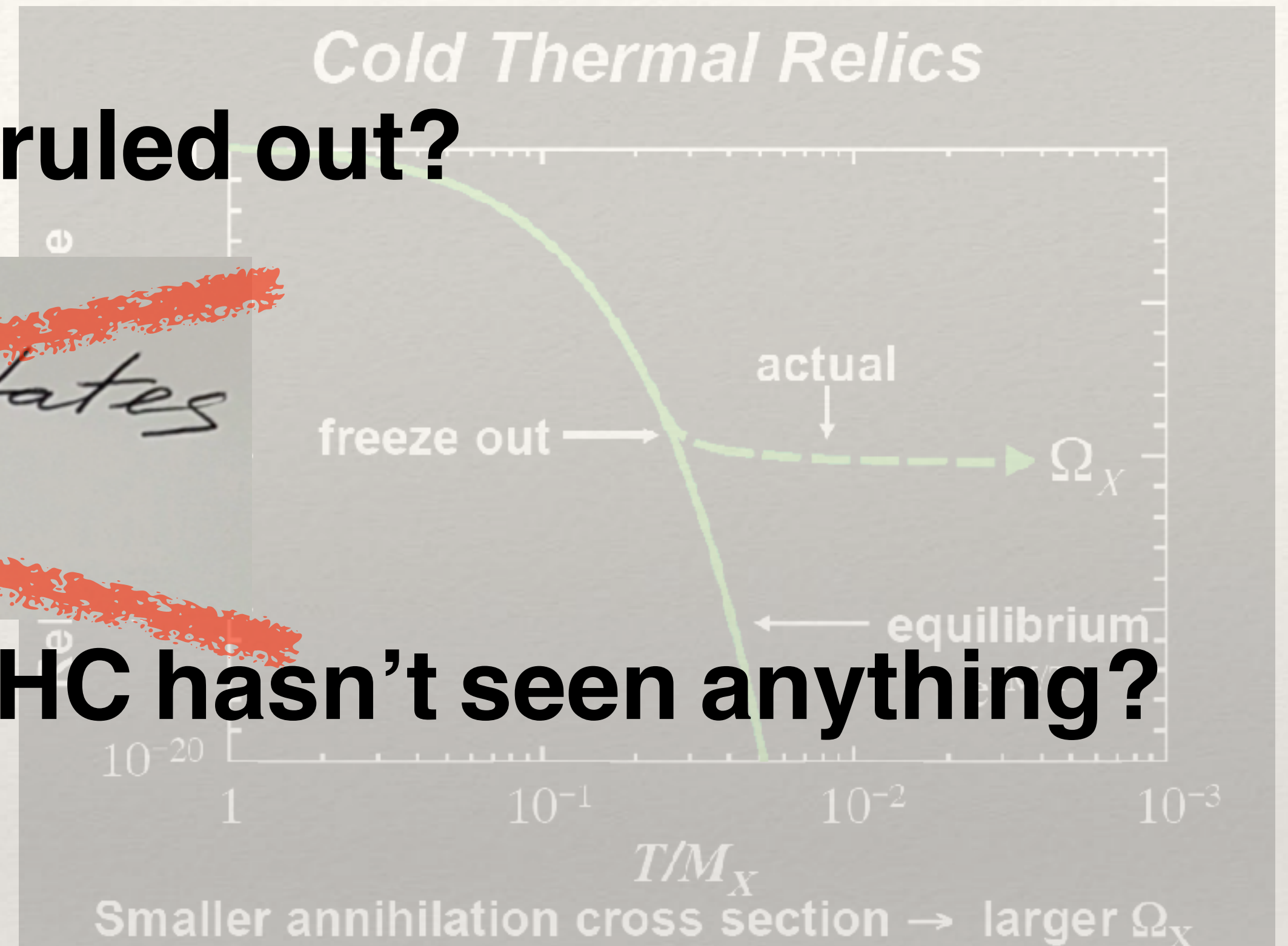
- **Hasn't a 'true' WIMP already been ruled out?**

would give current dark matter



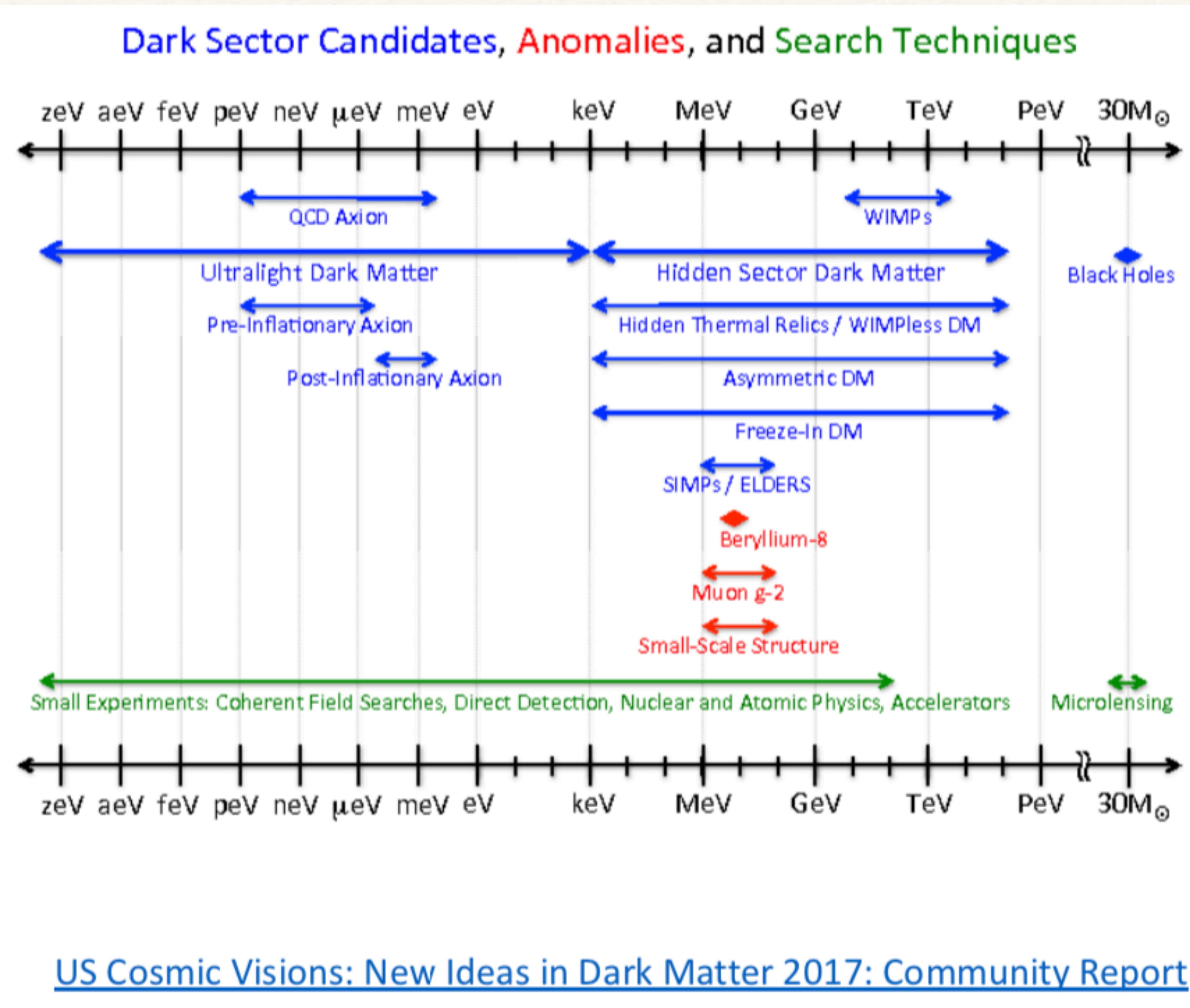
M. Pospelov IDM Plenary

- **Isn't SUSY discredited since the LHC hasn't seen anything?**

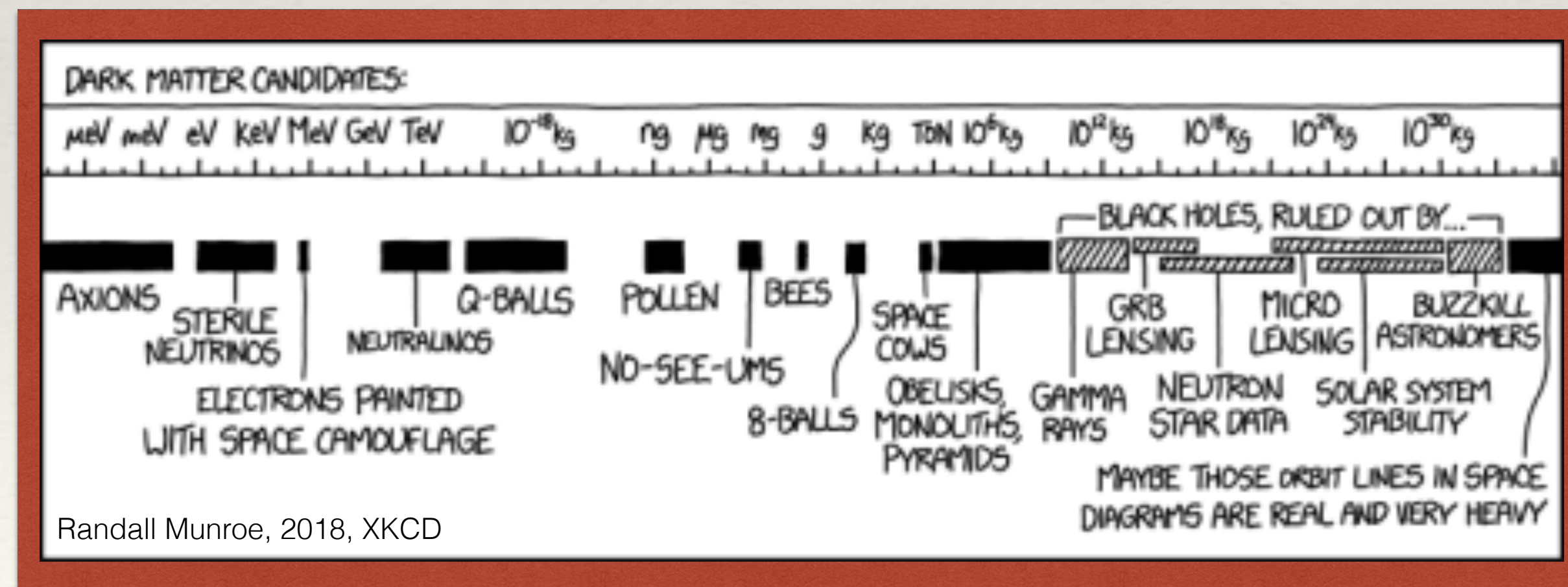


WIMPs fit naturally with SuSY:  
lightest neutralino, the LSP

# An more recent discussion of models

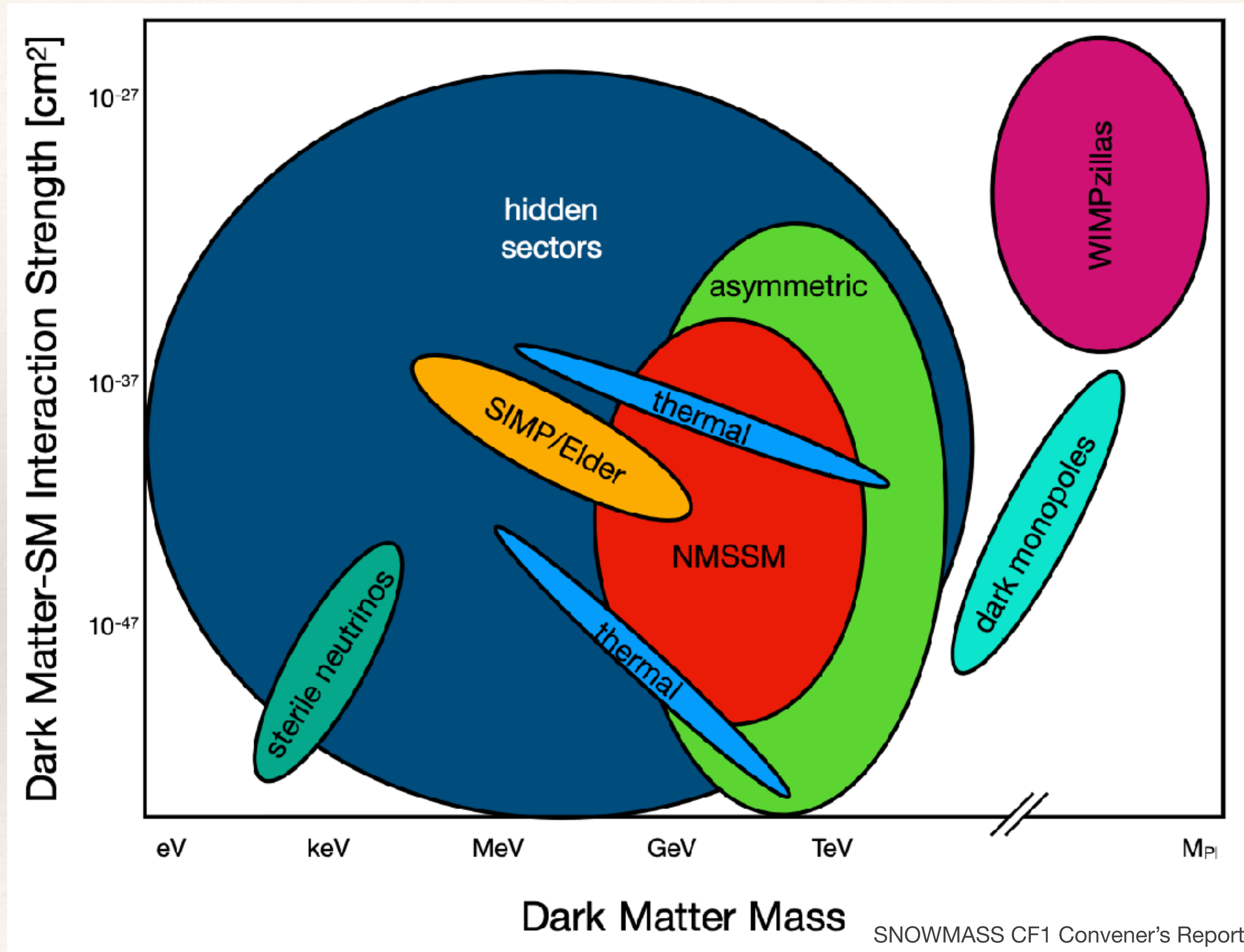


- Canonical Dark matter is:
  - non-relativistic
  - electrically neutral
  - limited self-interactions
  - density of DM  $\sim 0.3 \text{ GeV}/\text{cm}^3$
- Some theories push these boundaries
- Can dark matter candidates fit with other theories or open problems?

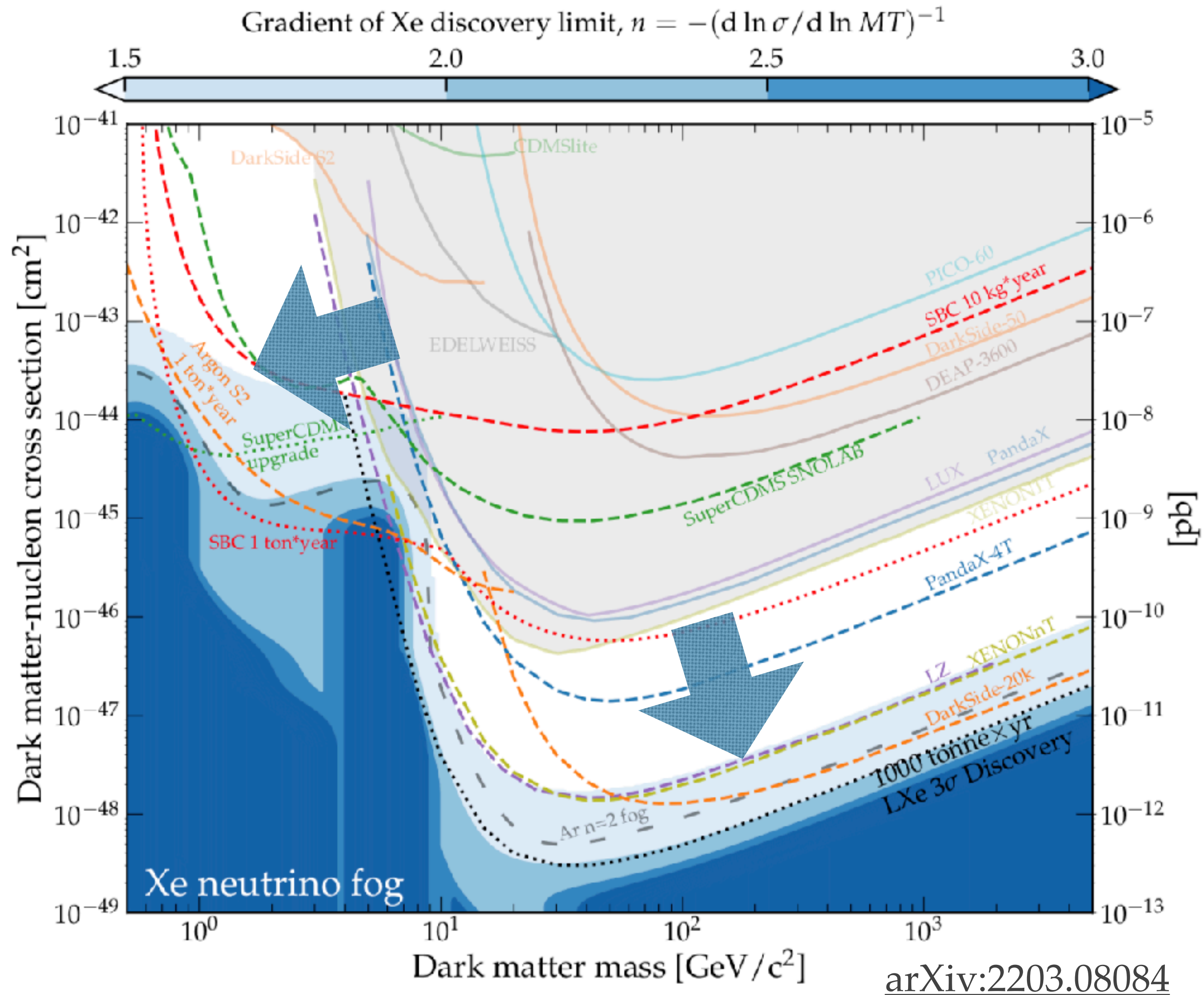




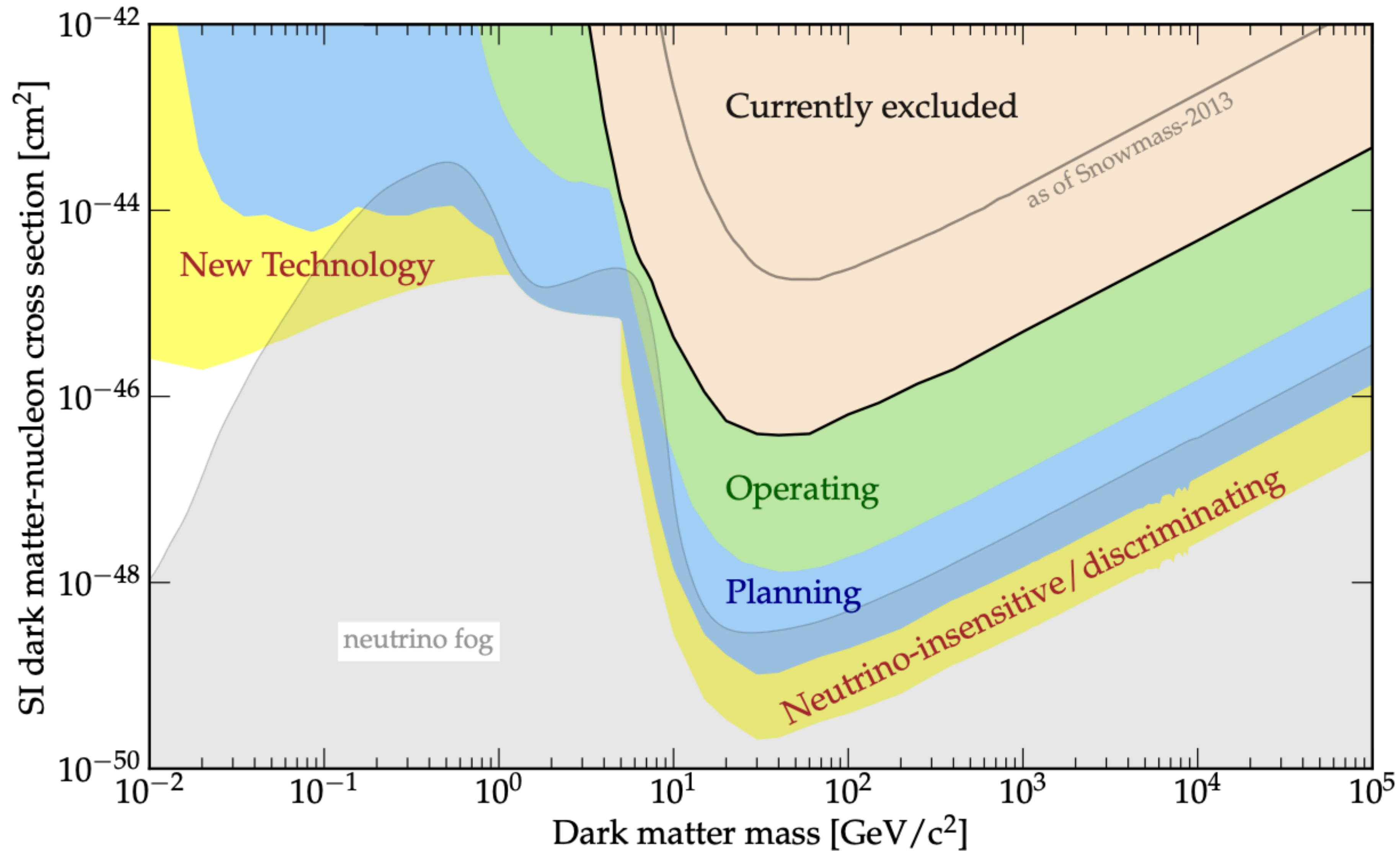
# An updated cartoon



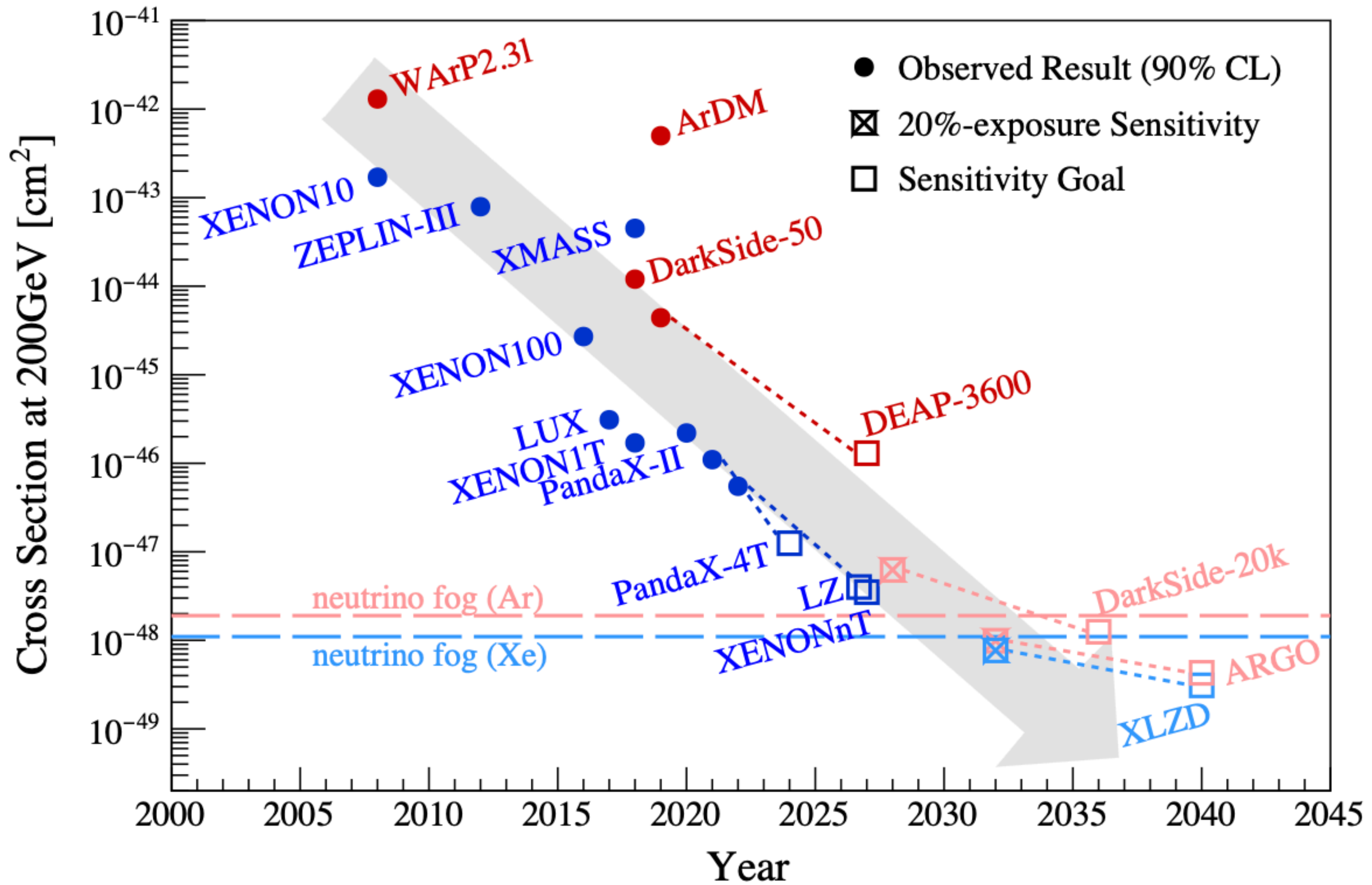
# SI Direct DM status



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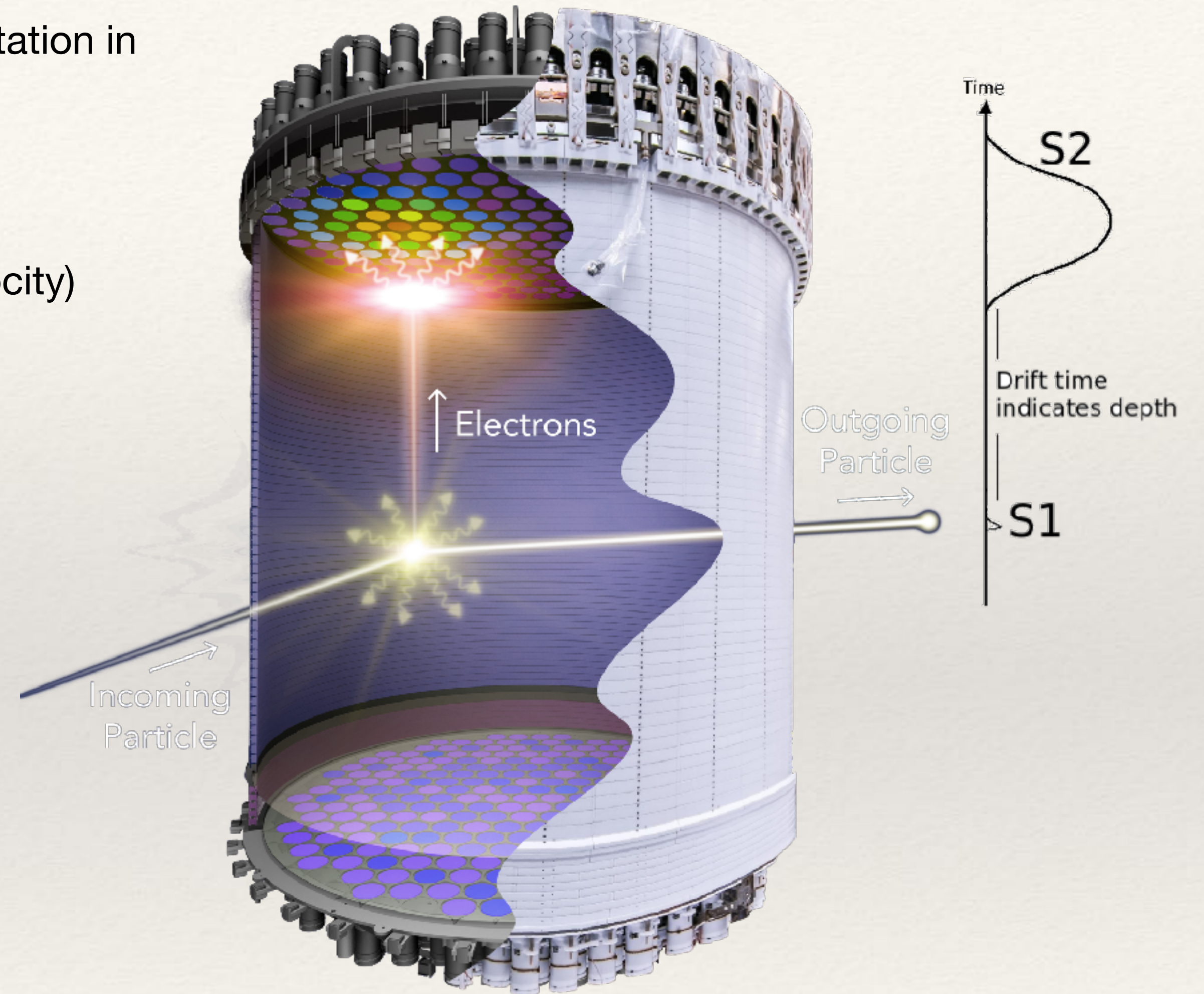
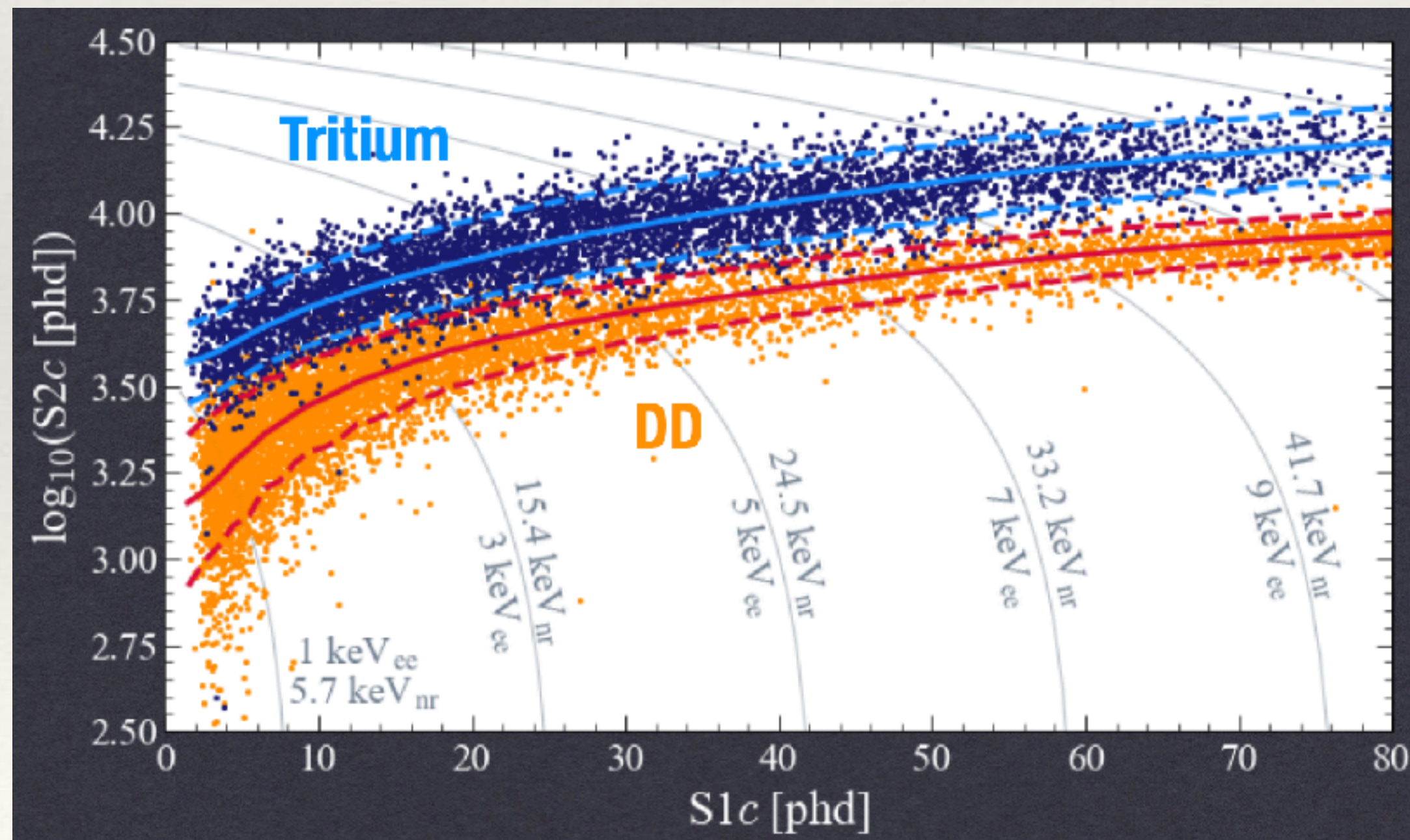
# DM as Moore's Law



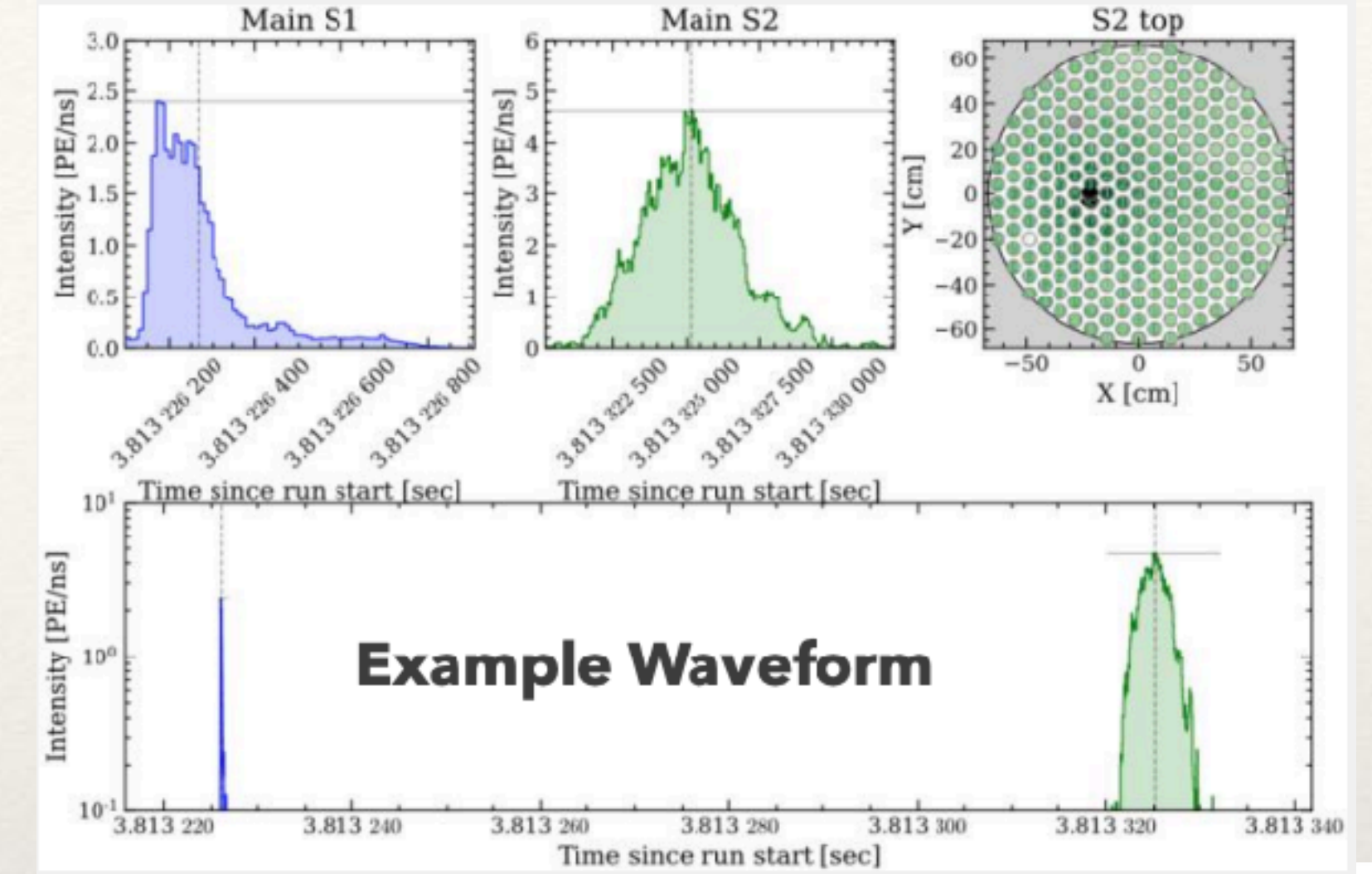
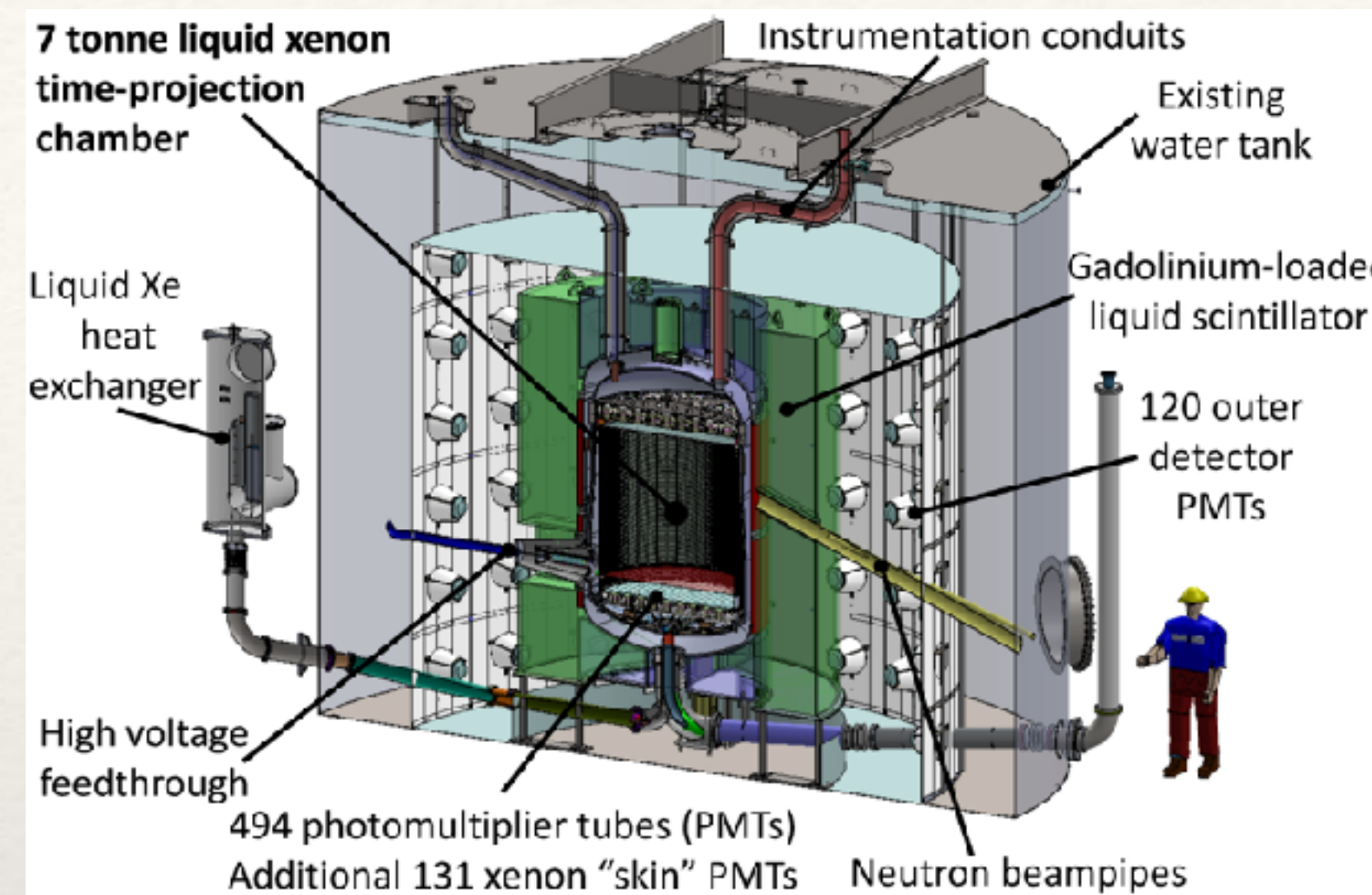
Shengchao Li, SNOWMASS CF1 Convener's Report

# Liquid Noble TPCs

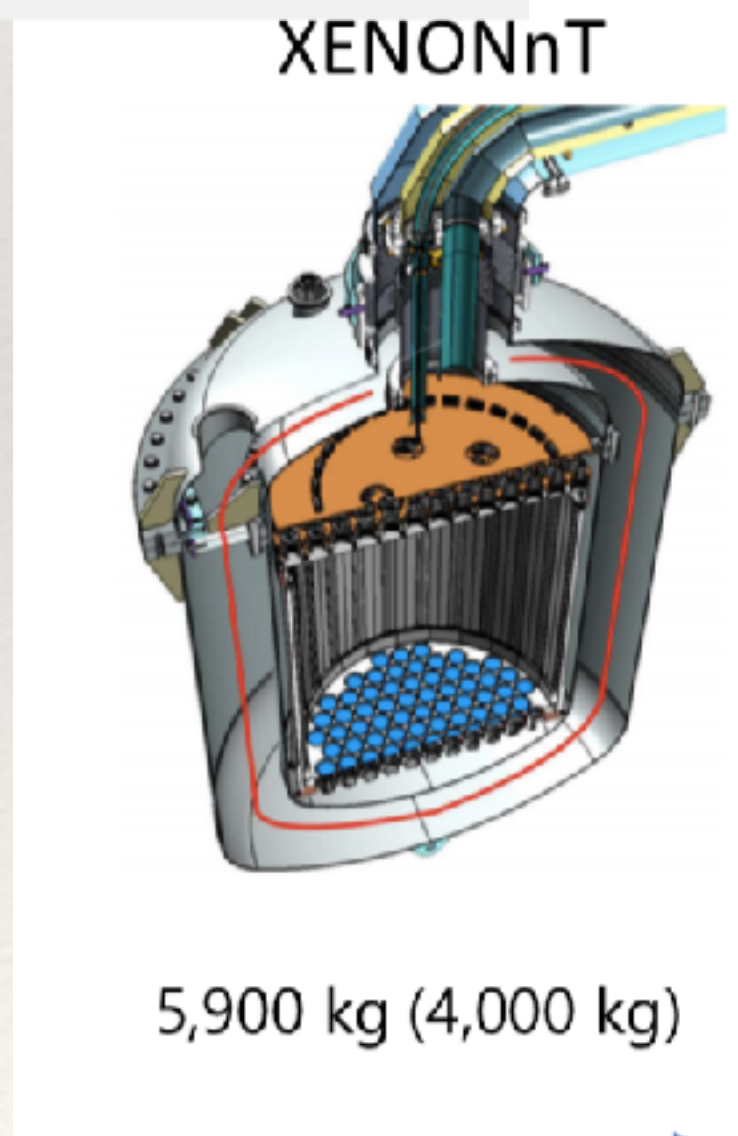
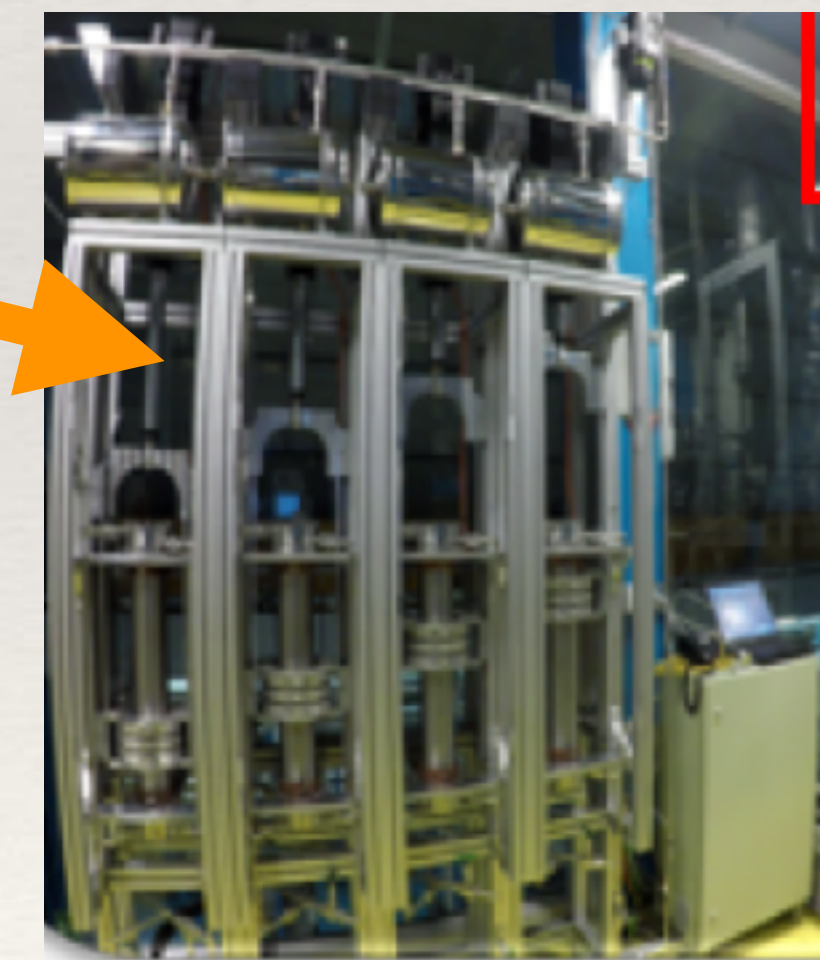
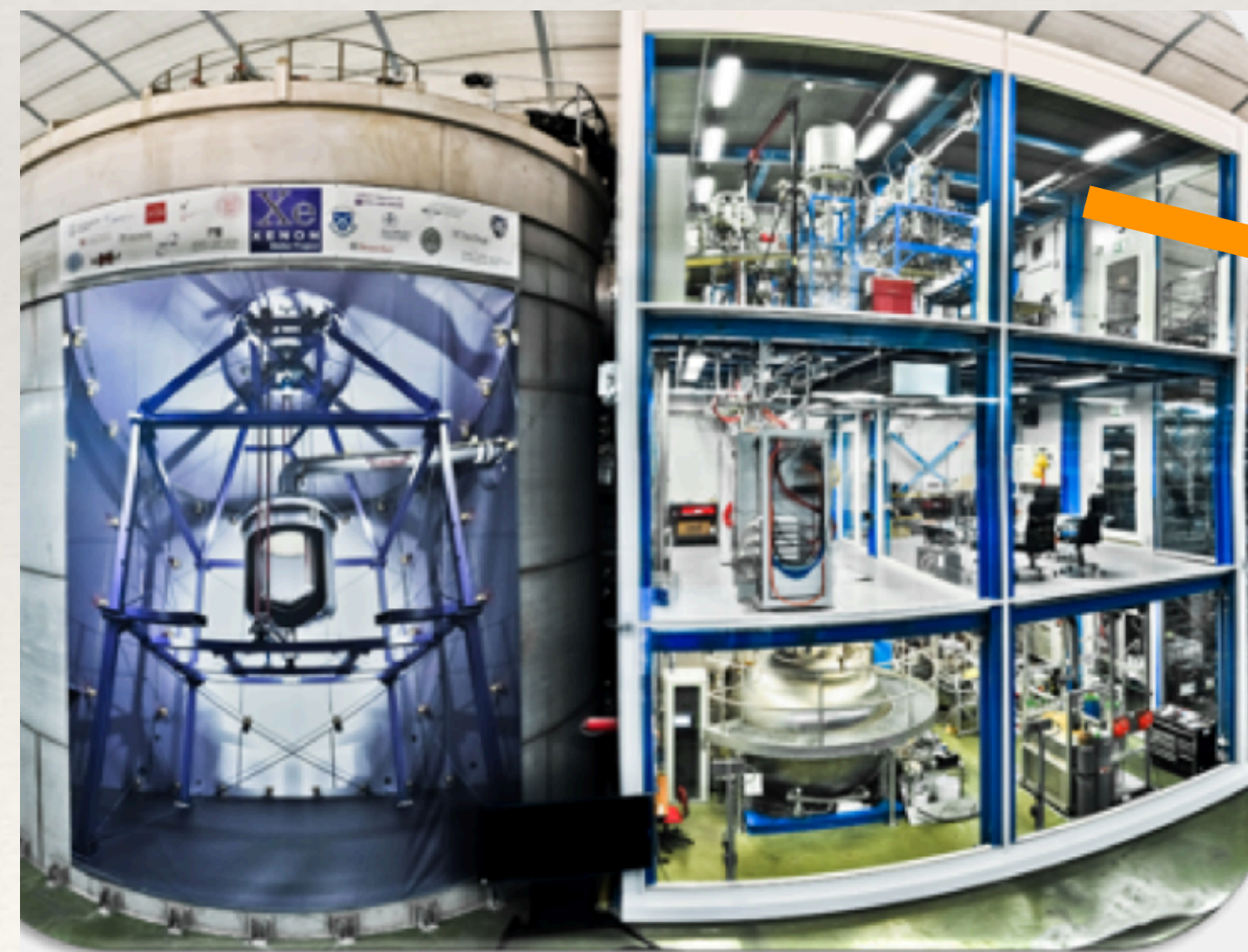
- Self-shielding, large fiducial masses
- Primary Scintillation (S1) with some recombination and de-excitation in the liquid
- Ions drift in TPC electric field
- Amplification region in gas creates proportional light (S2)
- S2/S1 provides particle ID and discrimination
- Events are hundreds of microseconds (set by electron drift velocity)
- Strong position reconstruction
- Argon can use timing of S1 light for pulse shape discrimination



# LZ and XENONnT

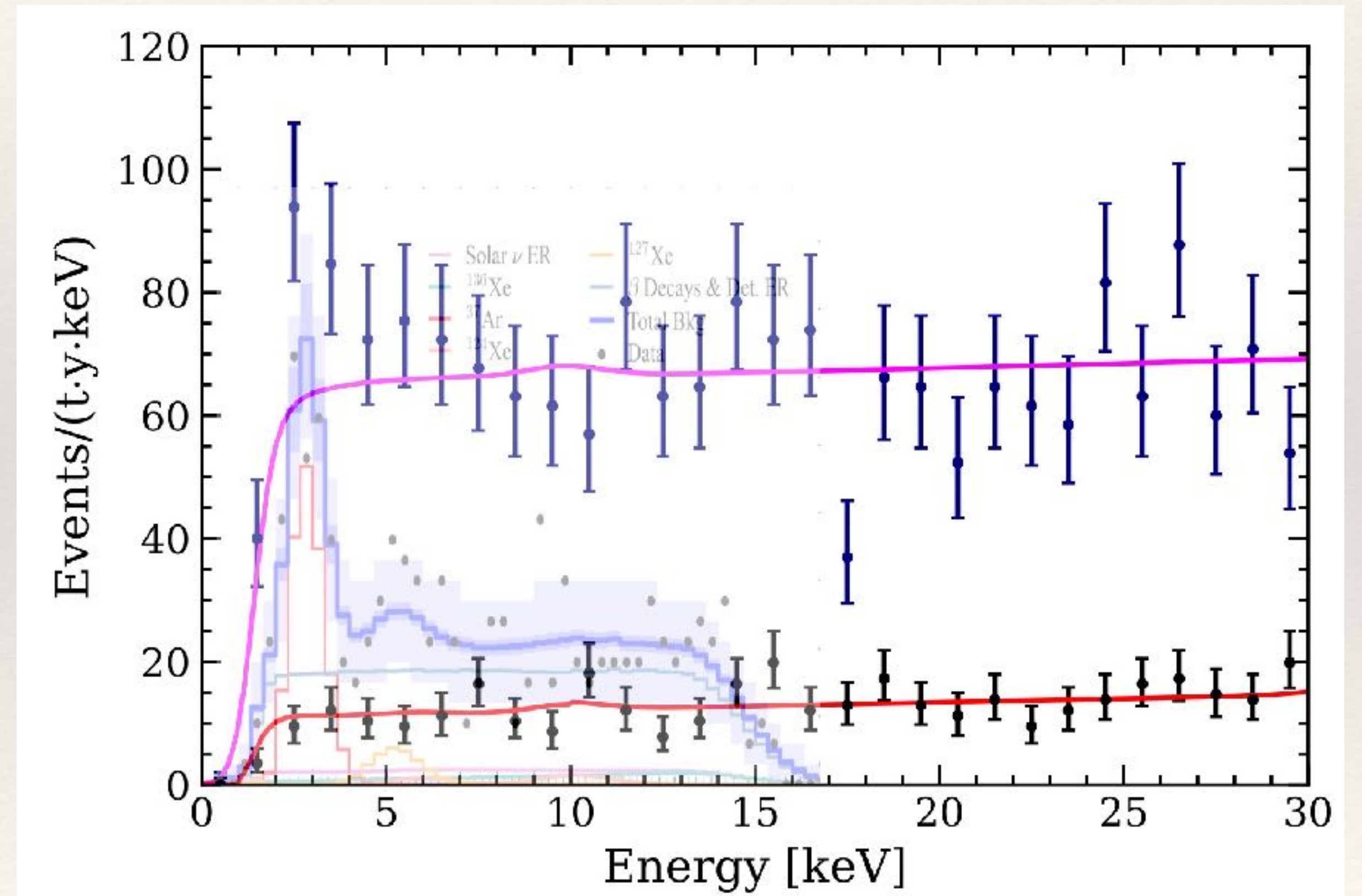
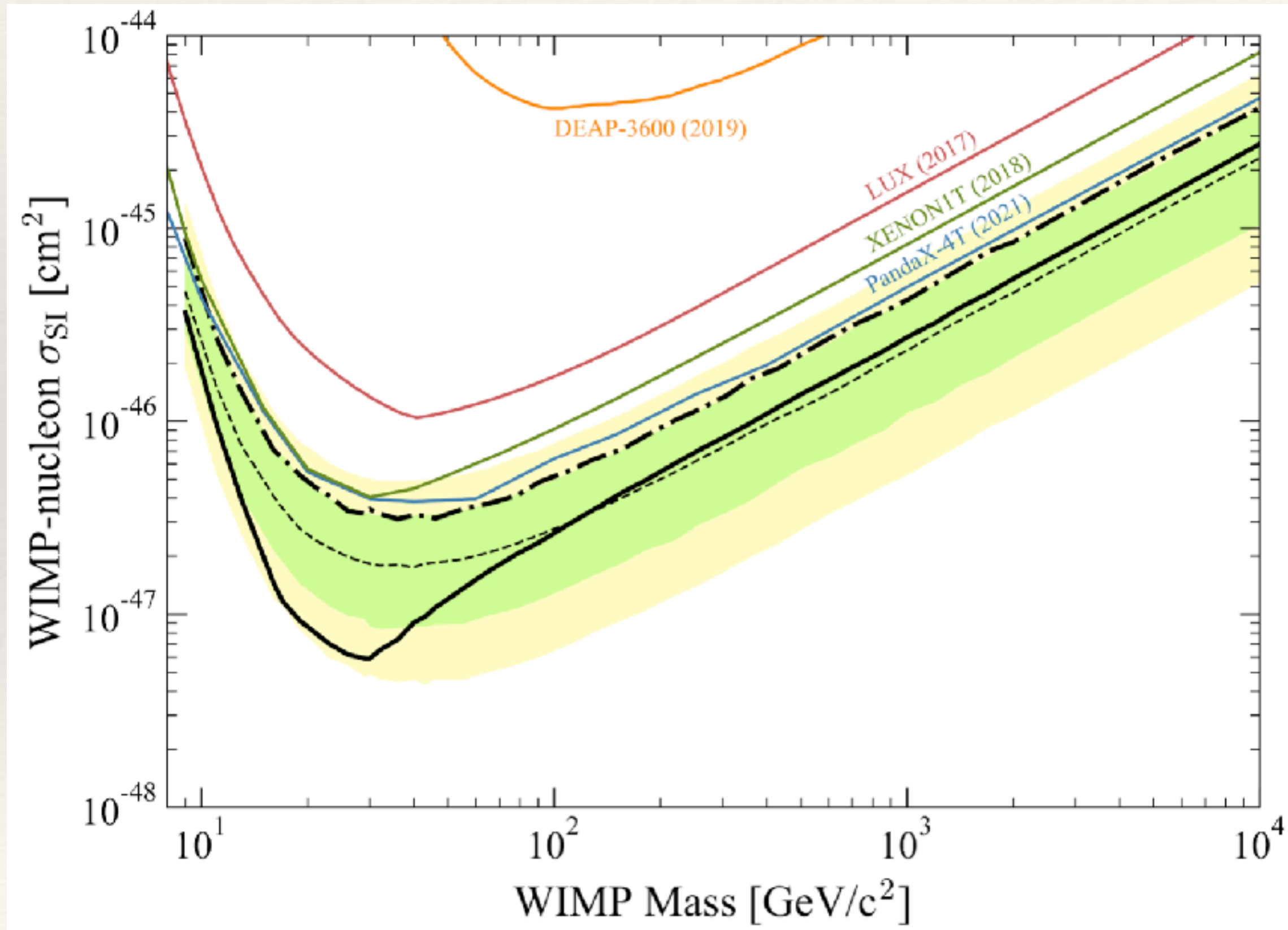


- 2 very sensitive detectors with new results
  - Talks Tuesday and Wednesday

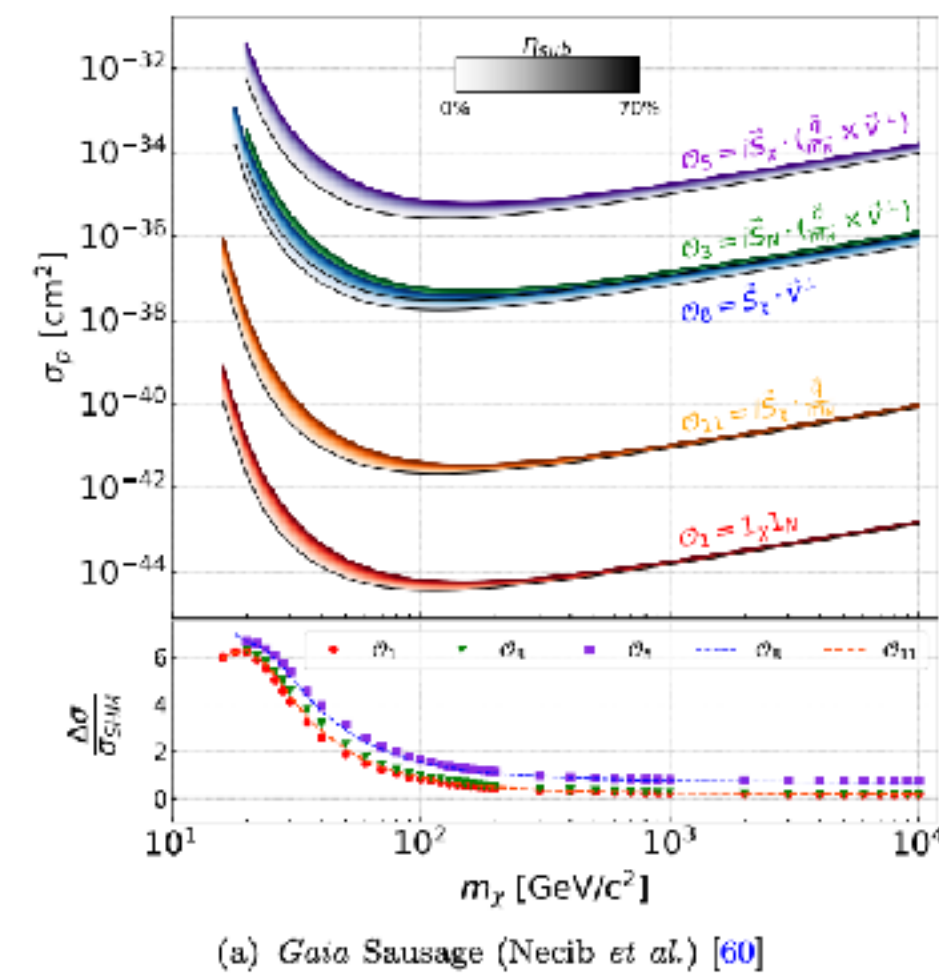
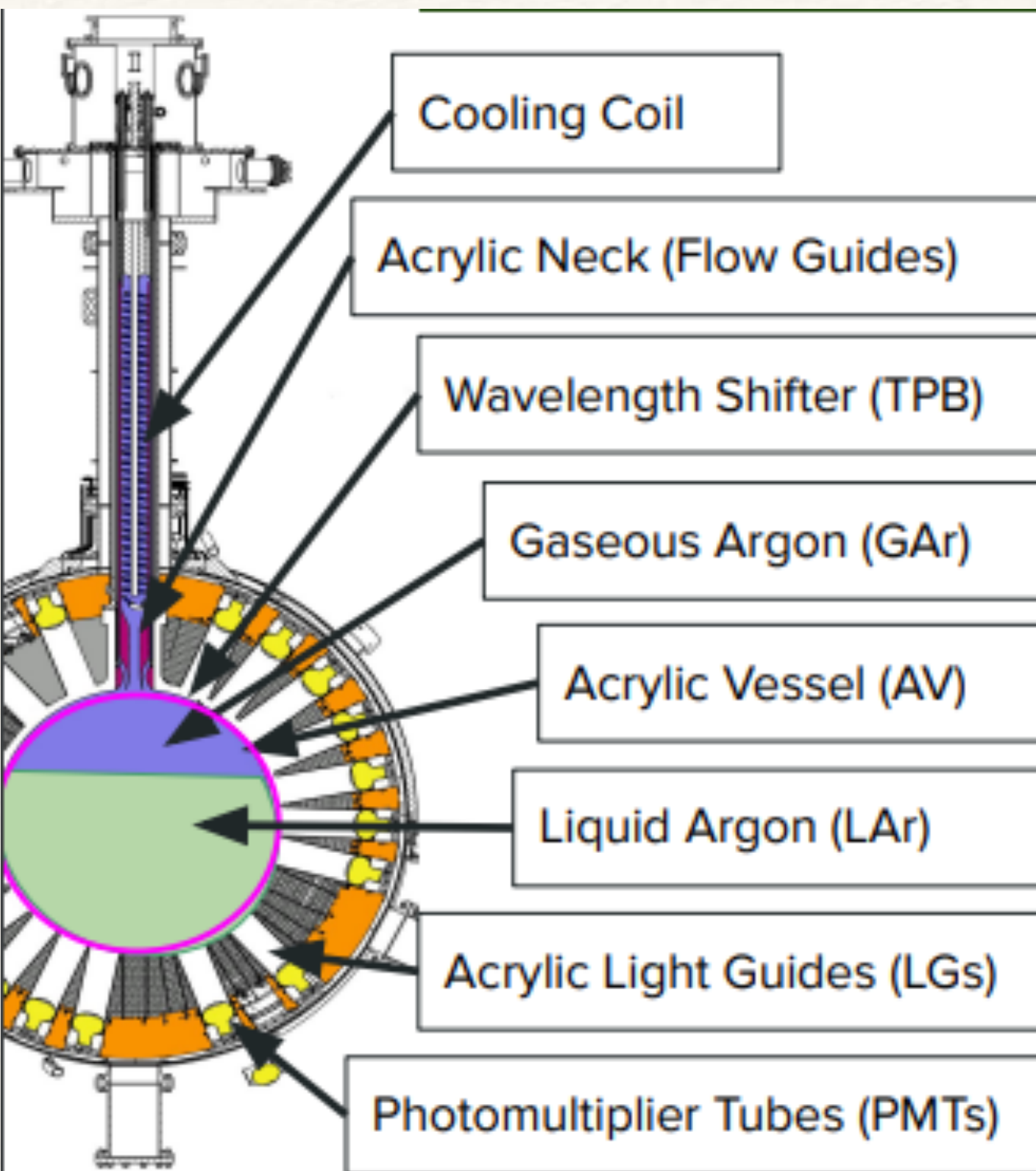


# LXe Results

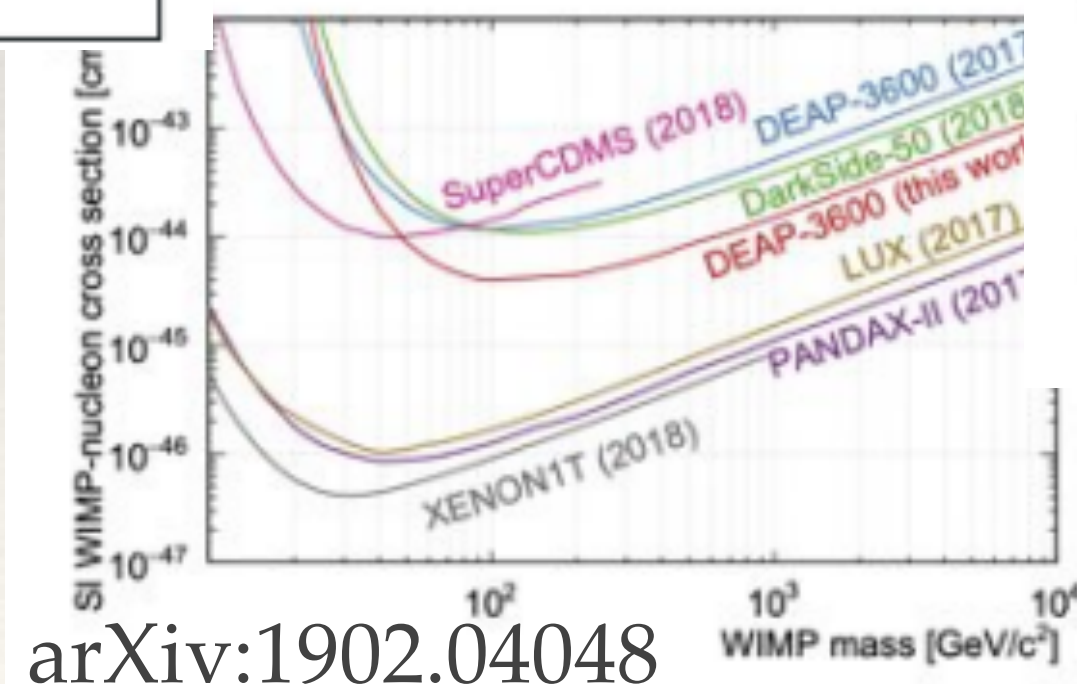
- LZ leading Limits from an initial run
- XENONnT lowest backgrounds, which are electronic recoils, rules out past excess from XENON1T
- Electronic recoils give sensitivity to solar axions, ALPs, Dark Photons, and the neutrino magnetic moment



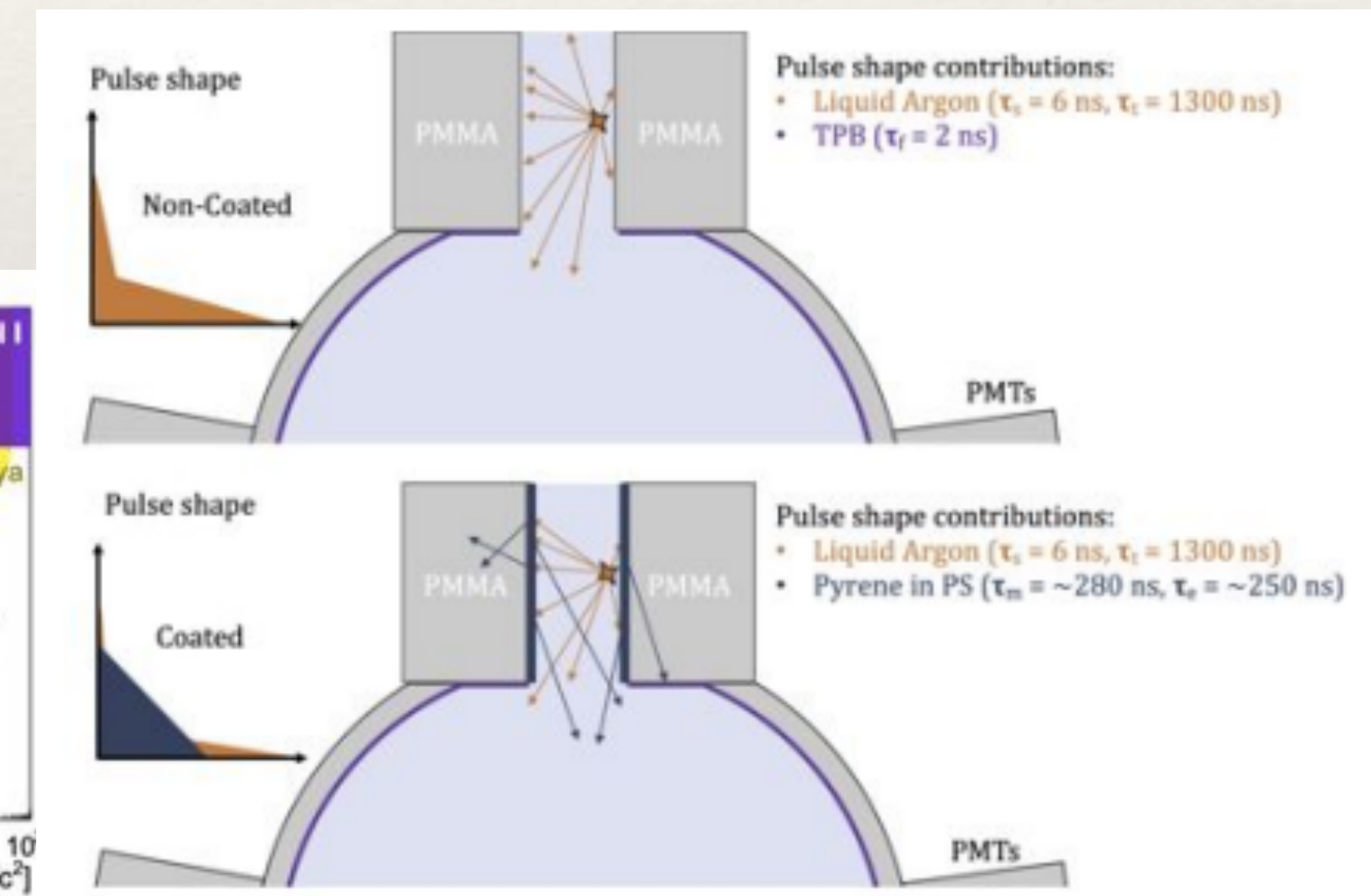
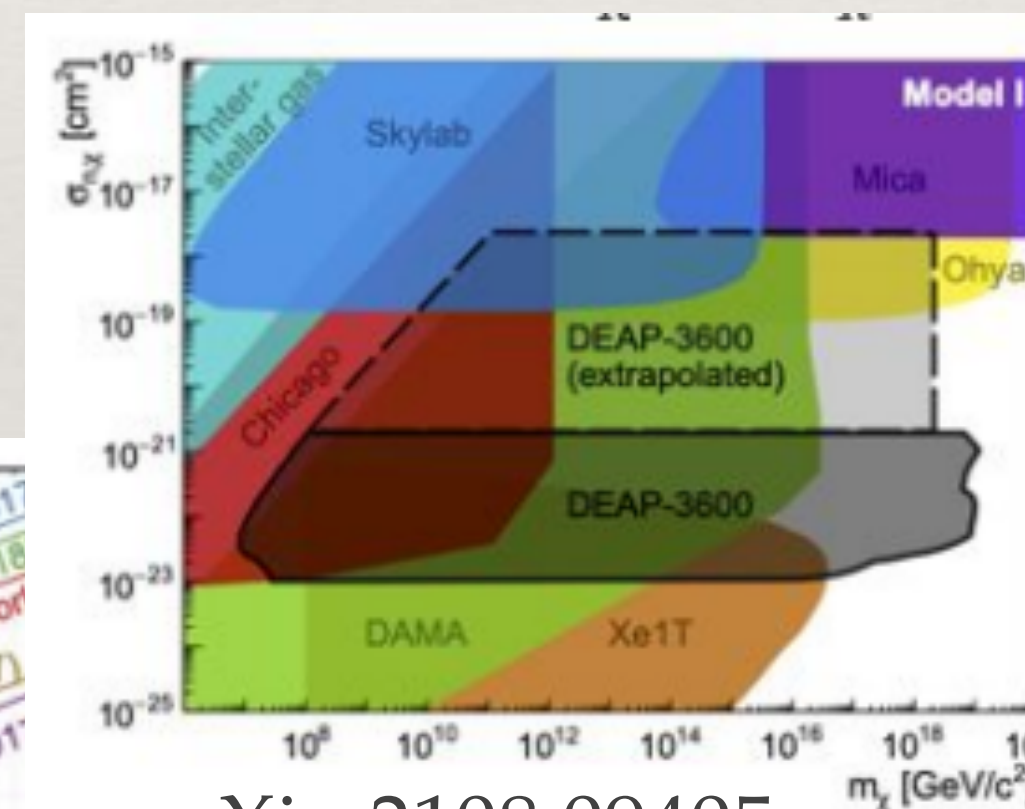
# DEAP-3600



[arXiv:2005.14667](https://arxiv.org/abs/2005.14667)



- Single phase Liquid Argon (3.3 t)
- Operating since 2016 at SNOLAB in Canada
- Results:
  - SI and EFT framework limits from 231 live days
  - Planck-scale DM Multi-scatter limits from 813 live-days
- Hardware upgrades coming:
  - Fill to neck
  - tag neck alphas
  - filter dust



- WLS characterization published in [JINST](#)
- Technical paper on slow WLS coating for background rejection in LAr submitted to [NIMA](#)

[Mielnichuk LLWI](#)



# DarkSide 50 + 20K

- ~50 t liquid argon time projection chamber
- Under construction at LNGS in Italy
- Innovations in photosensors, underground argon production (reduced Ar-39 background)

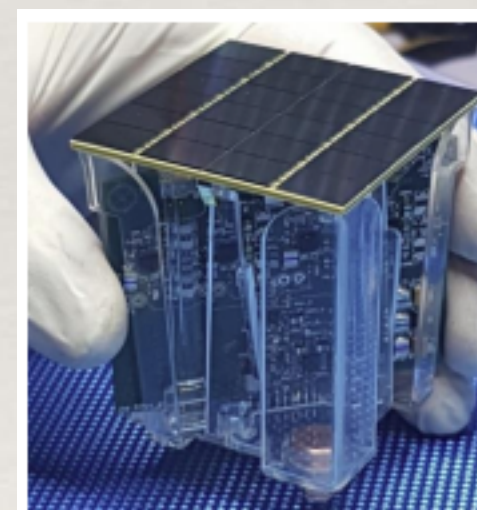
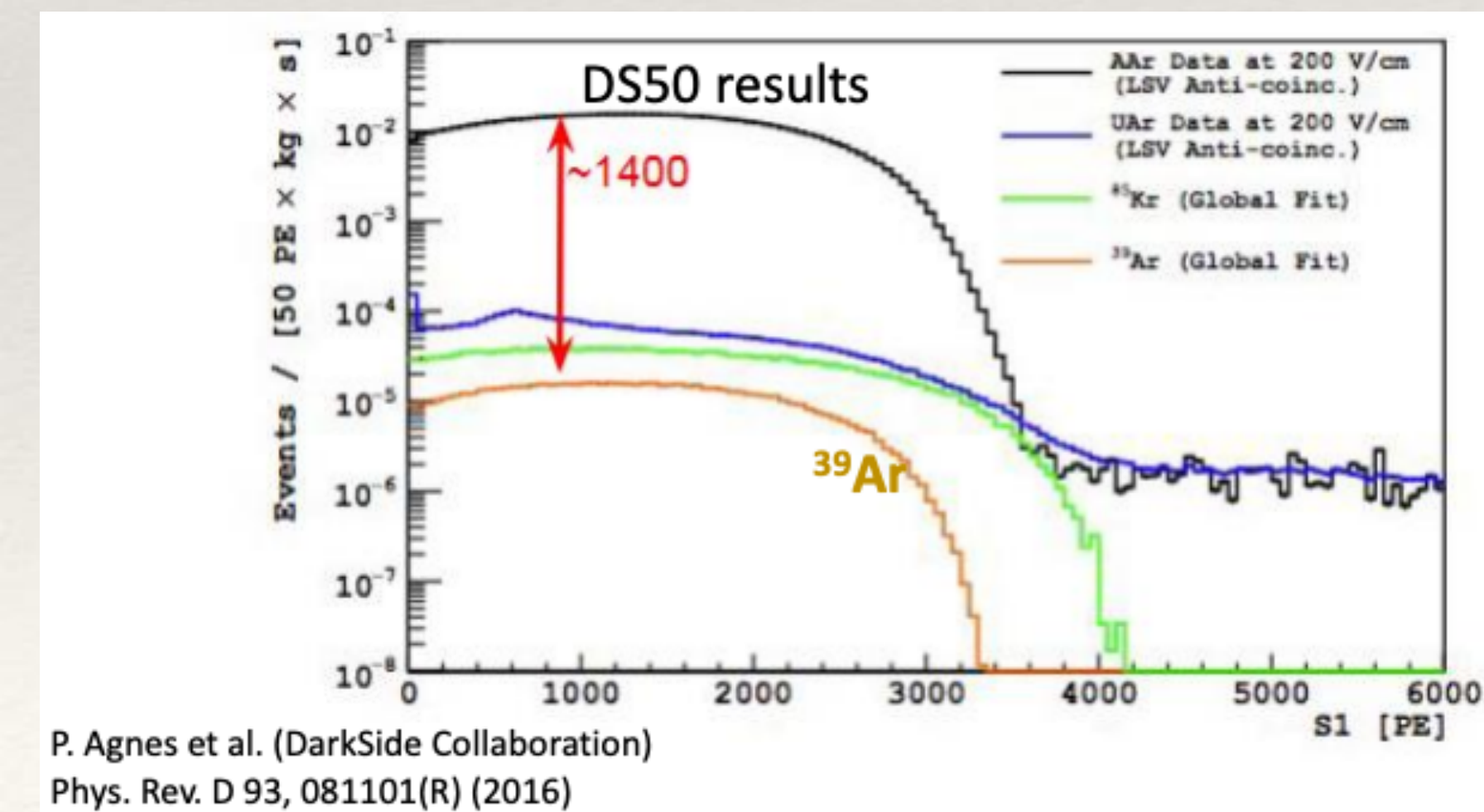
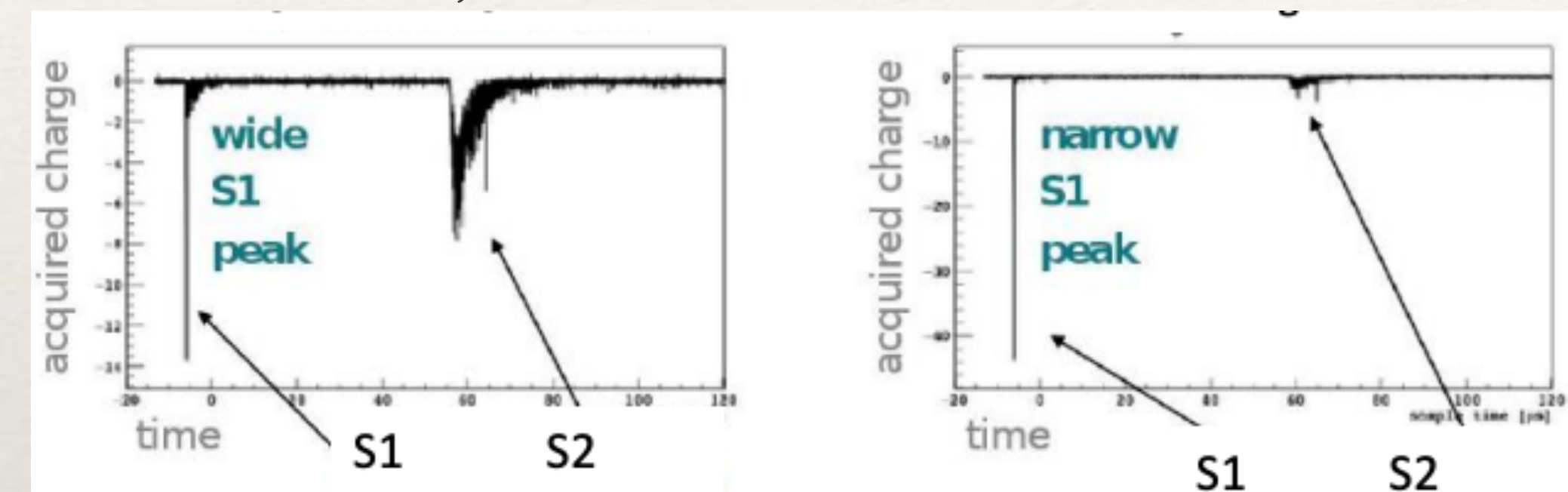
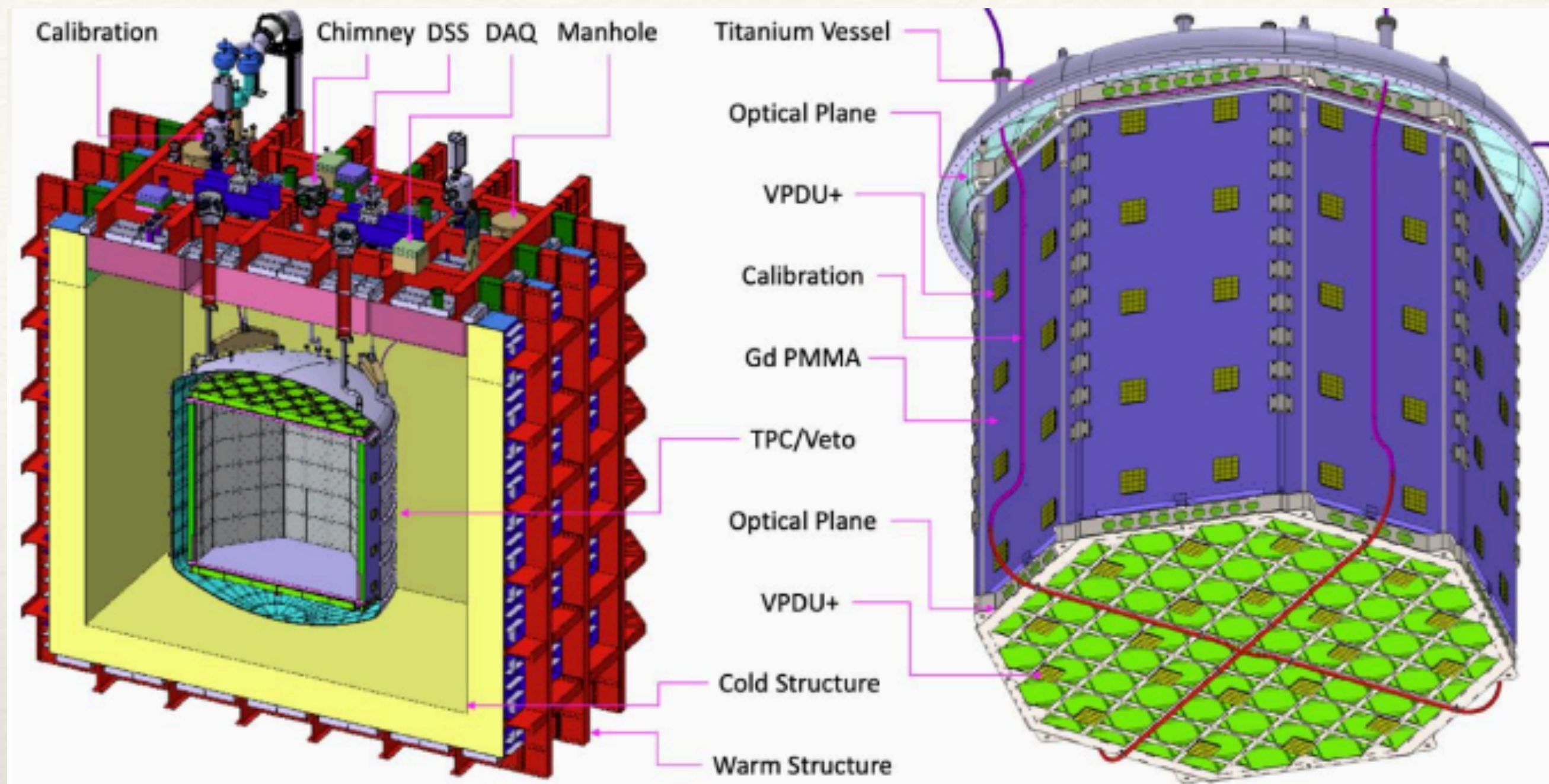
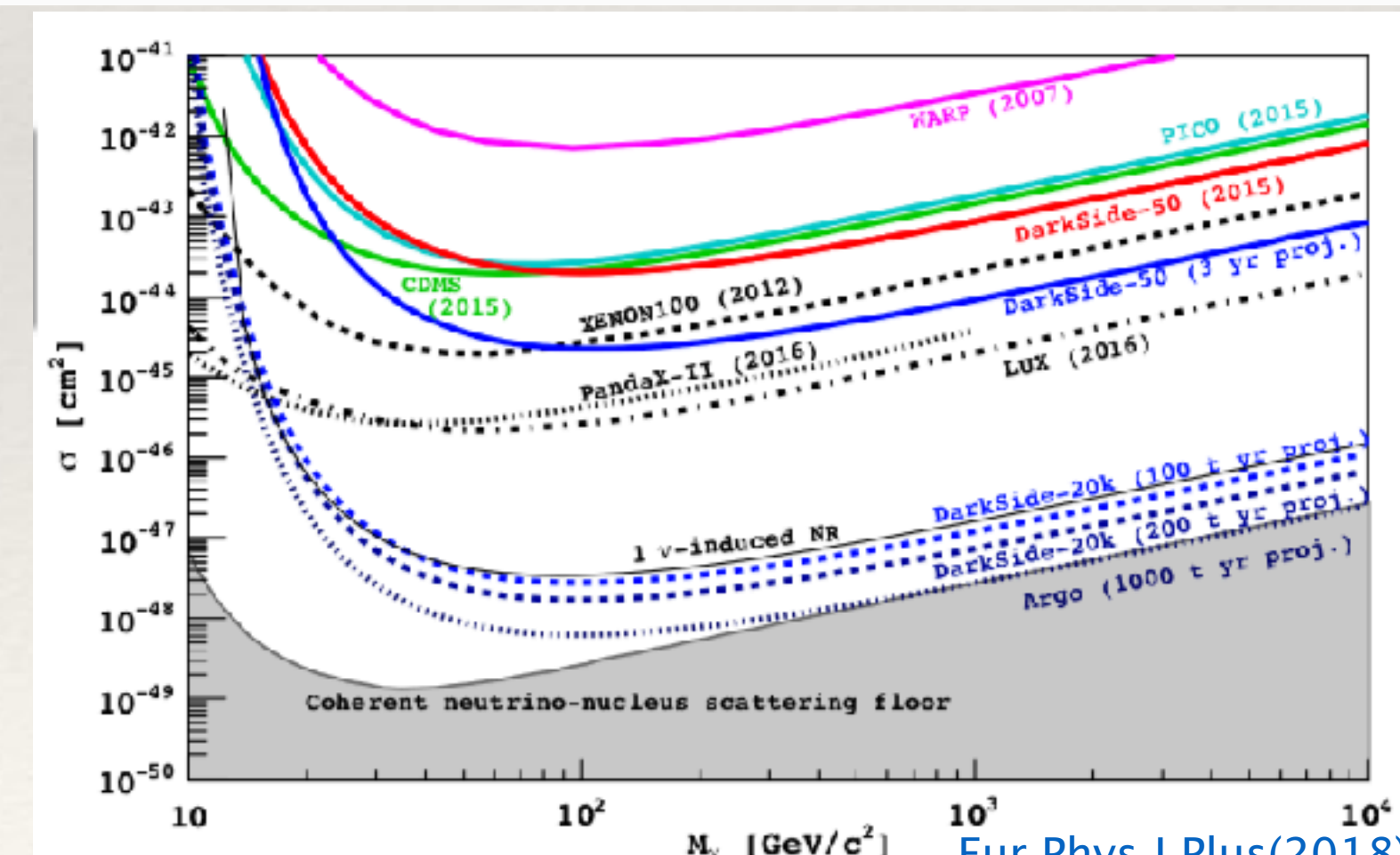
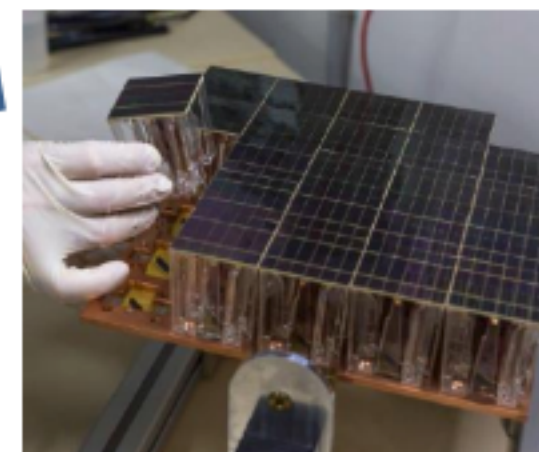


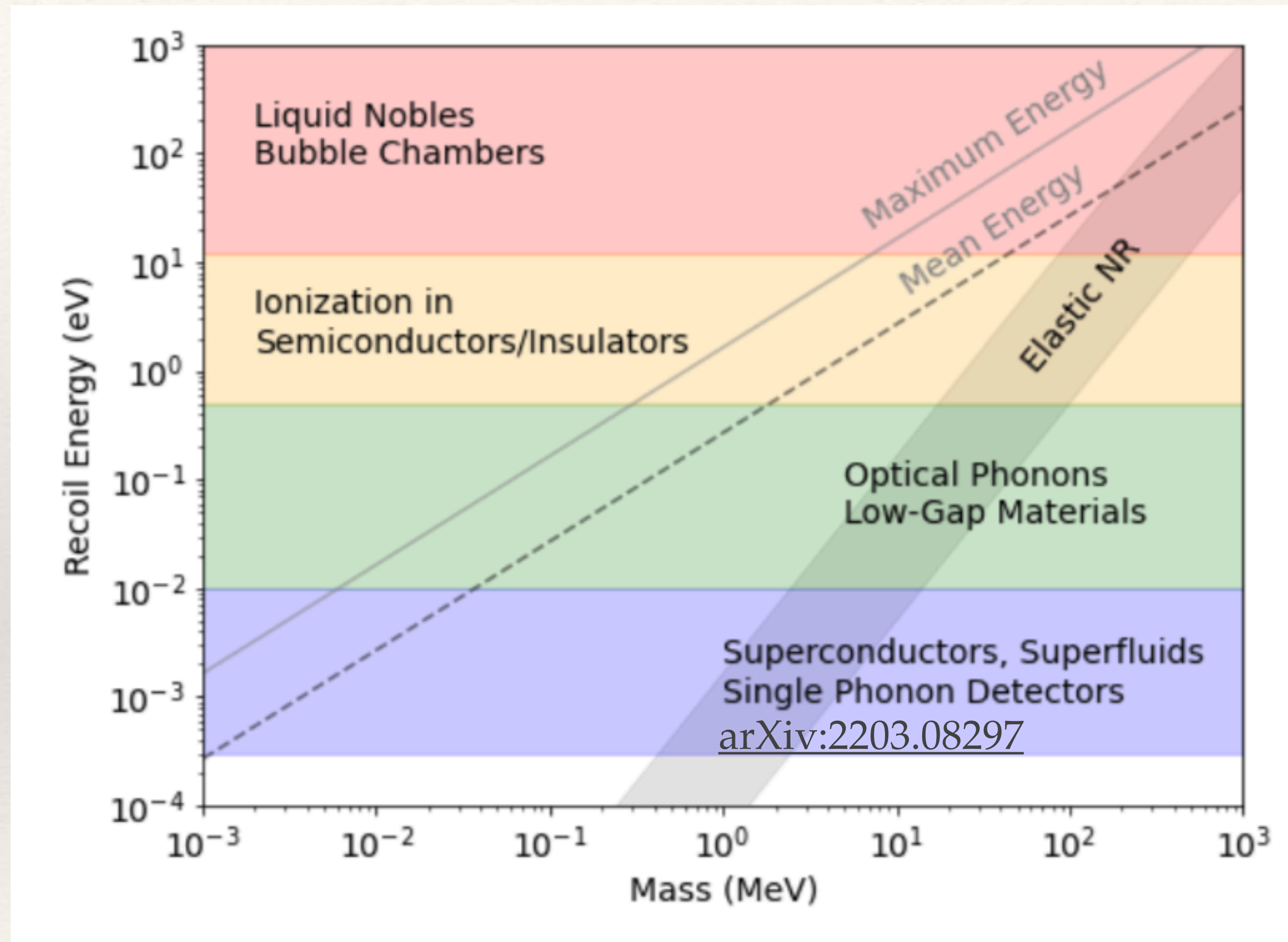
Photo Detector Module (PDM)  
matrix of 24 SiPMs,  
(5 x 5 cm<sup>2</sup>)

Prototype of the  
Photo Detector Unit  
(PDU)



Eur.Phys.J.Plus(2018)133:131

# What technology makes sense?



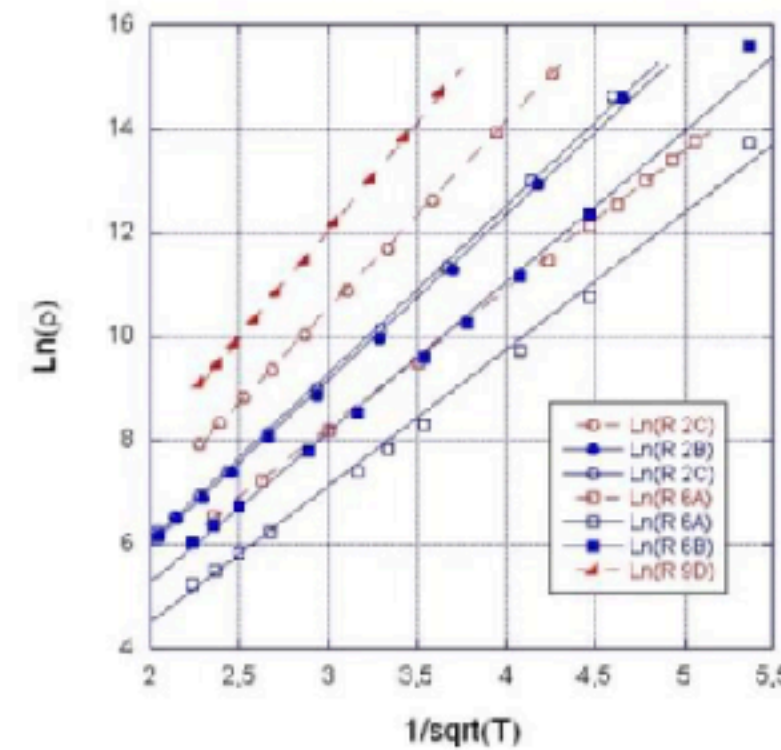
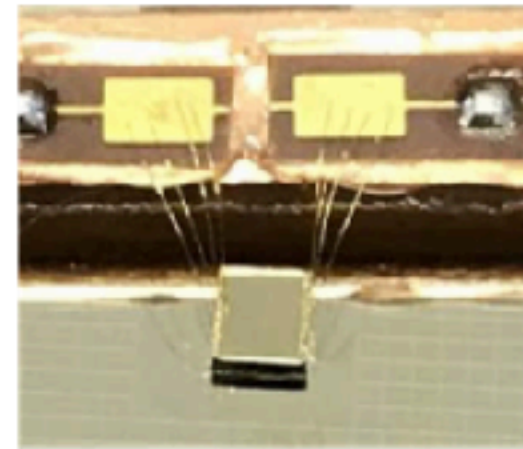
# Technologies for Low Mass Searches

## Sensor types:

### EDELWEISS

#### Neutron-transmutation-doped (NTD) sensors

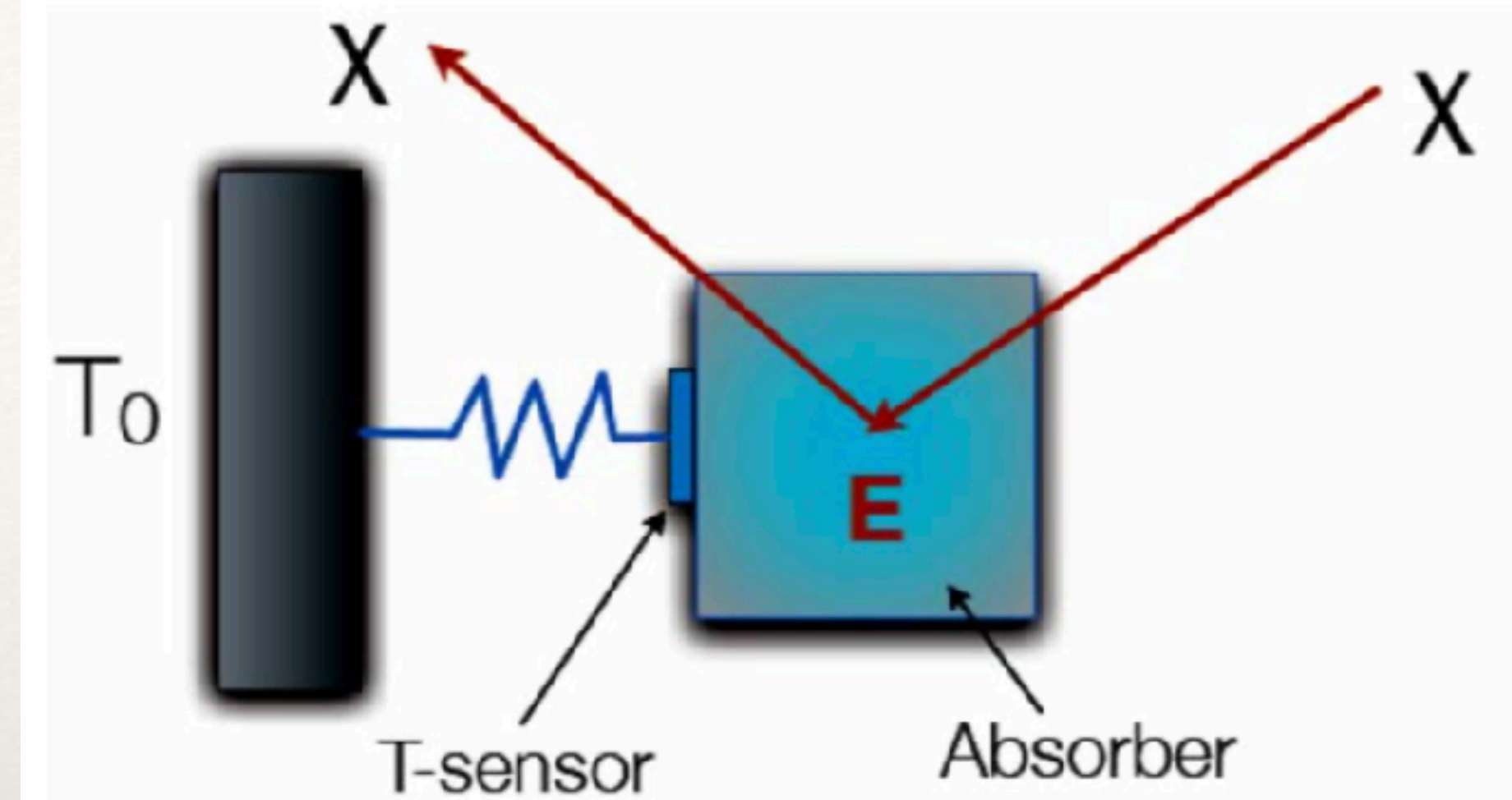
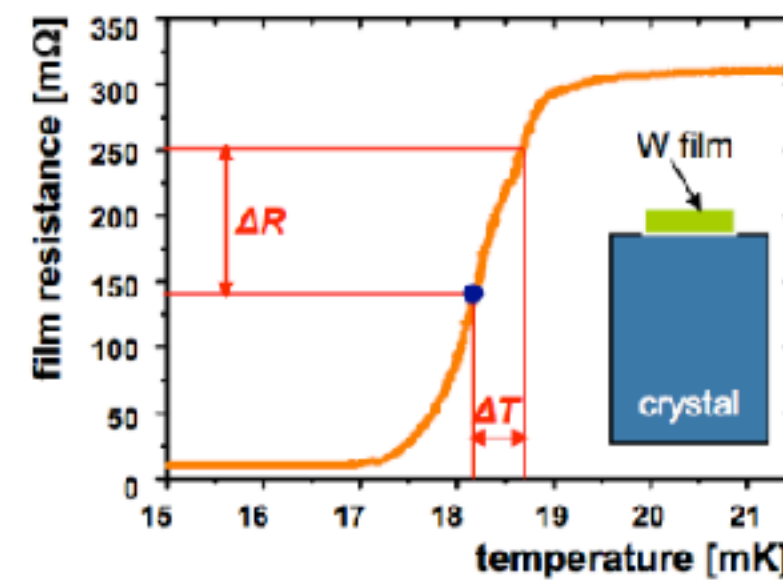
- Ge wafers with strong T-R dependence
- High linearity
- Sensitive to thermal phonons



### CRESST, SuperCDMS, COSINUS, EDELWEISS <sup>NEW</sup>

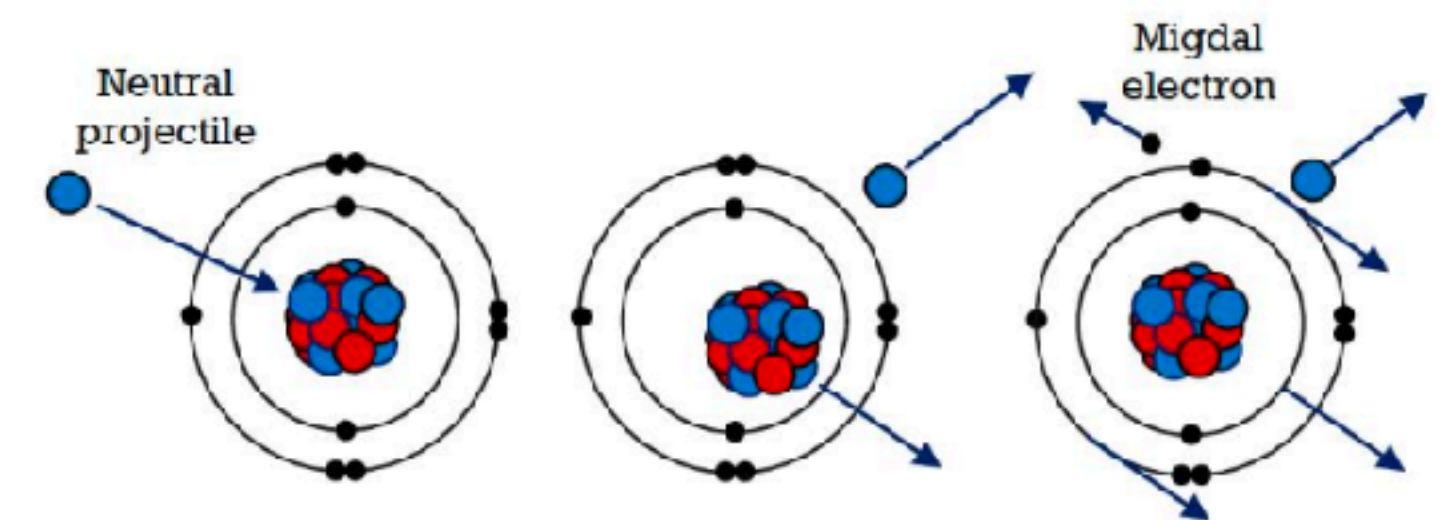
#### Transition-Edge-Sensor (TES)

- Thin-film deposited on crystals
- Strong R-T dependence at superconducting transition
- Sensitive to athermal phonons

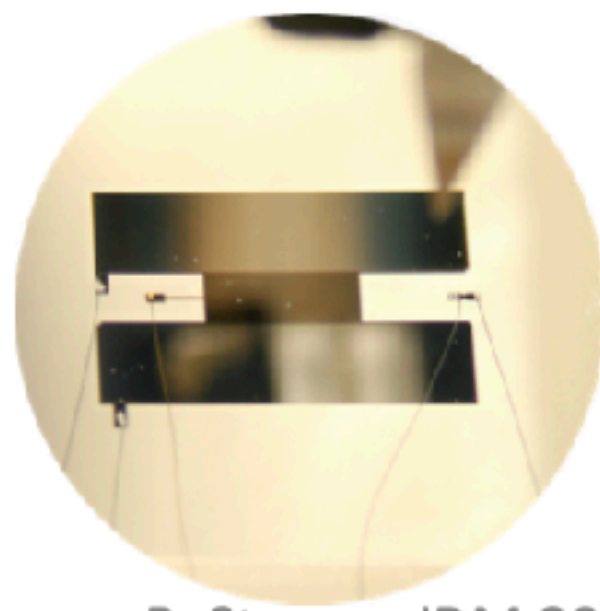


R. Strauss IDM plenary

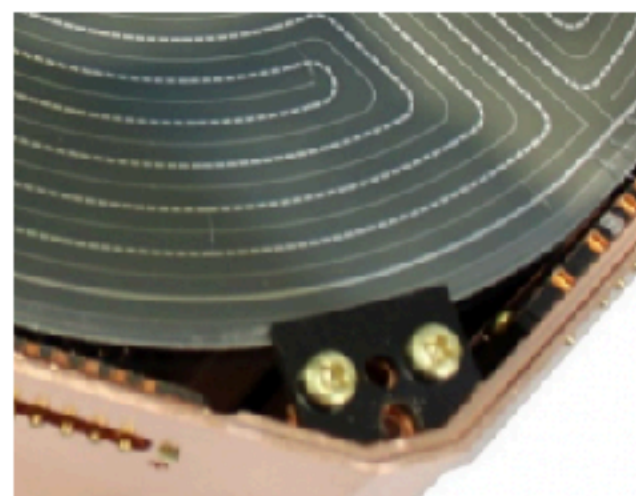
**But also!**



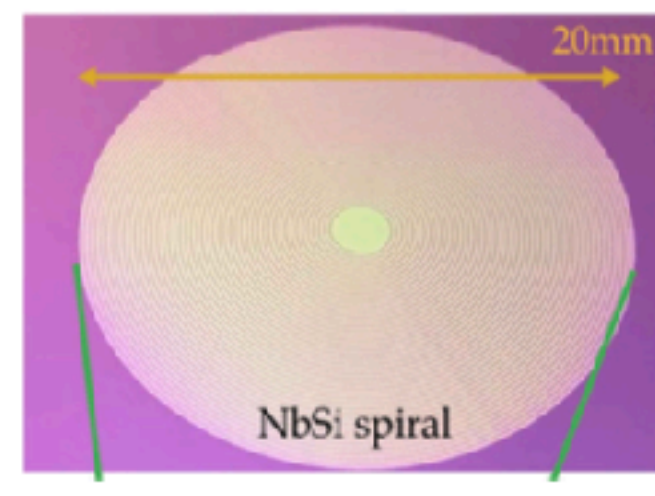
Migdal event topology involves a nuclear recoil and electron recoil originating from the same vertex.



CRESST



SuperCDMS

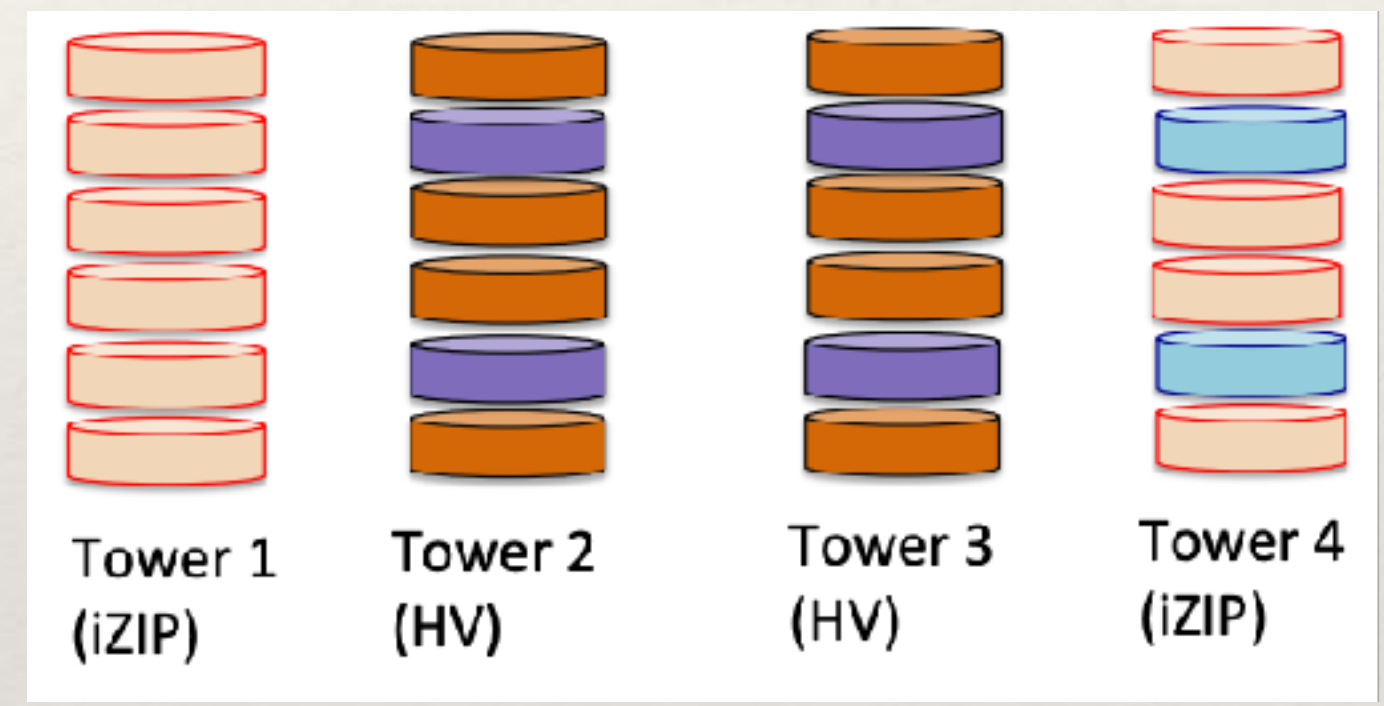
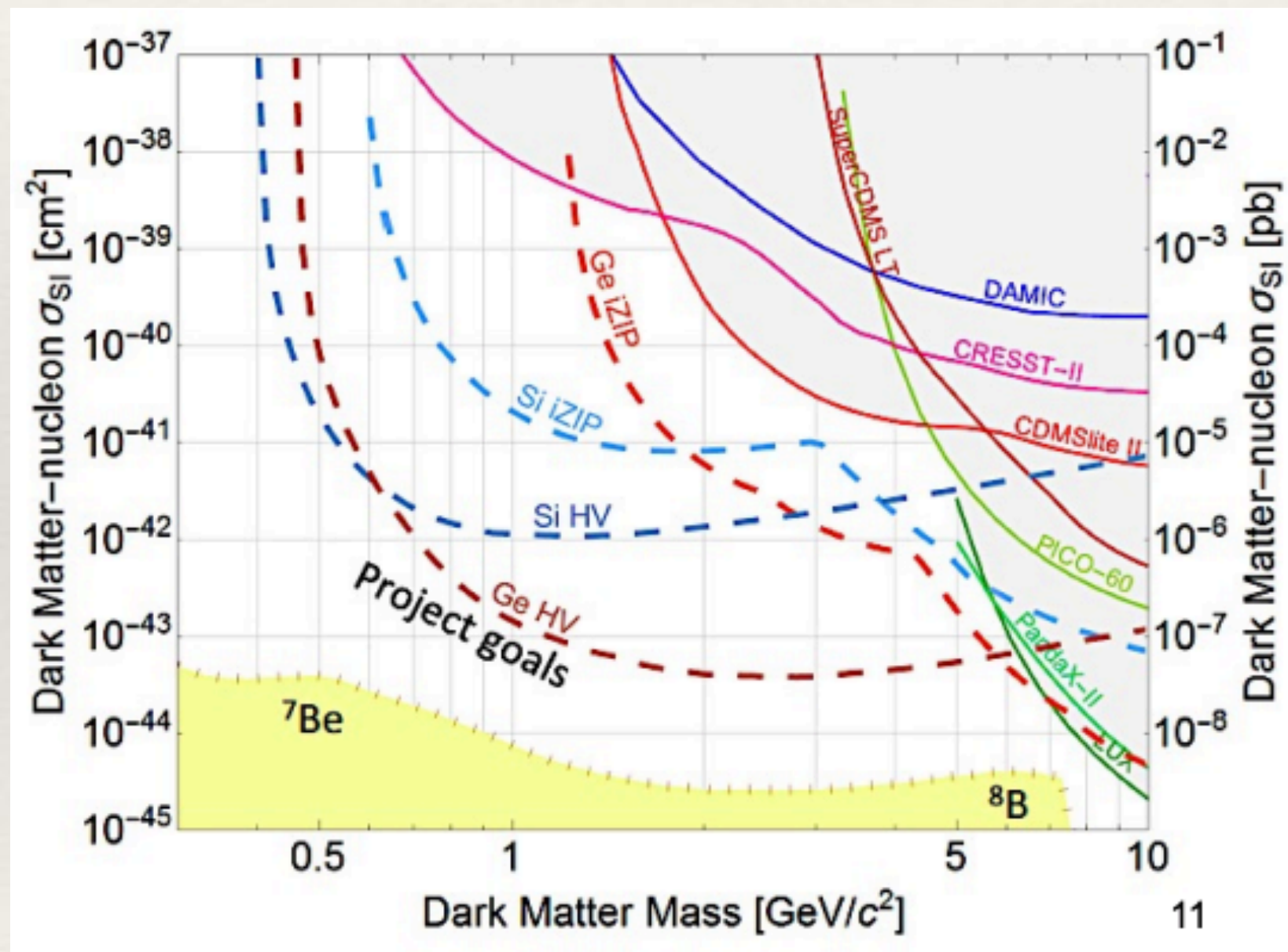
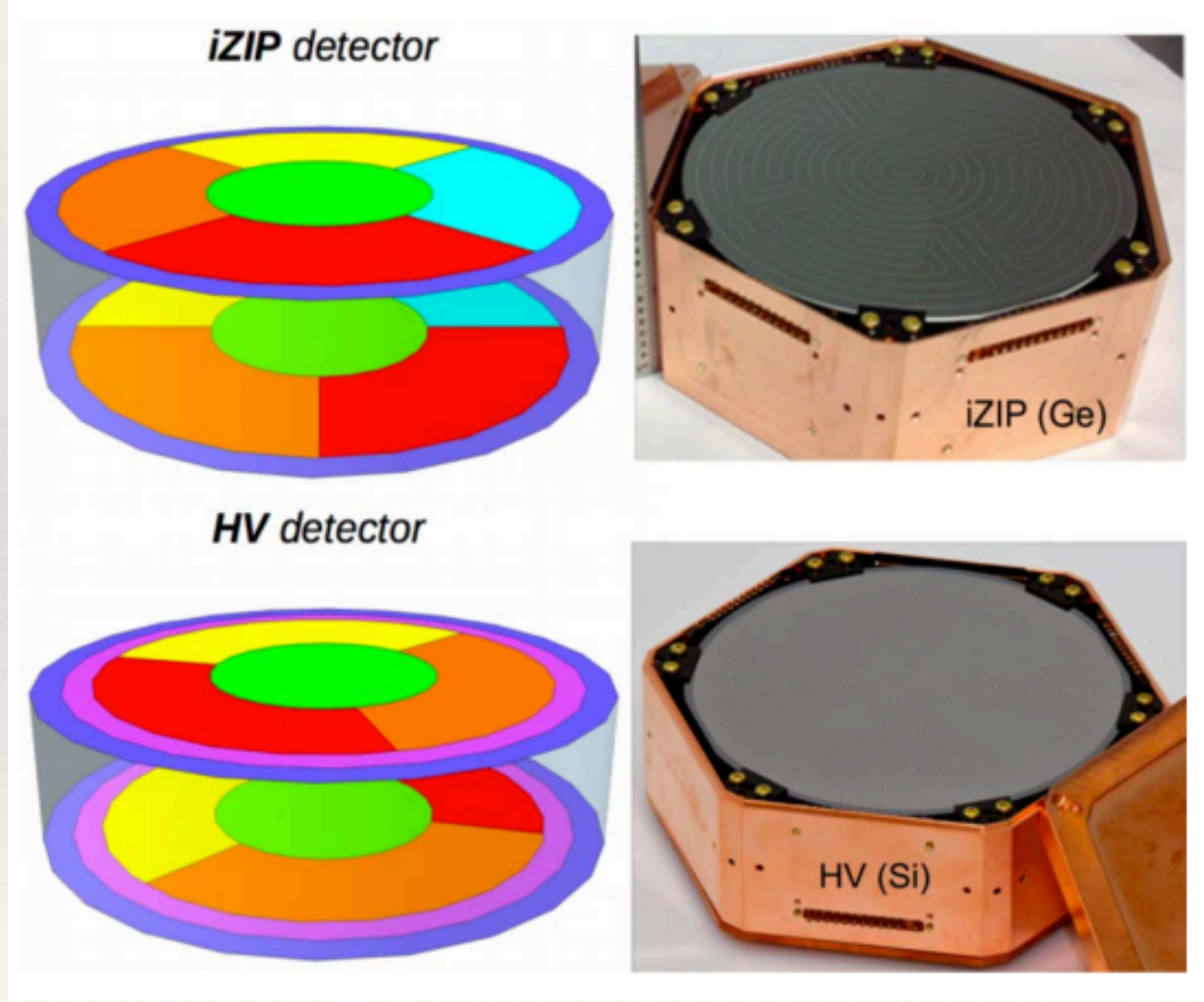


EDELWEISS

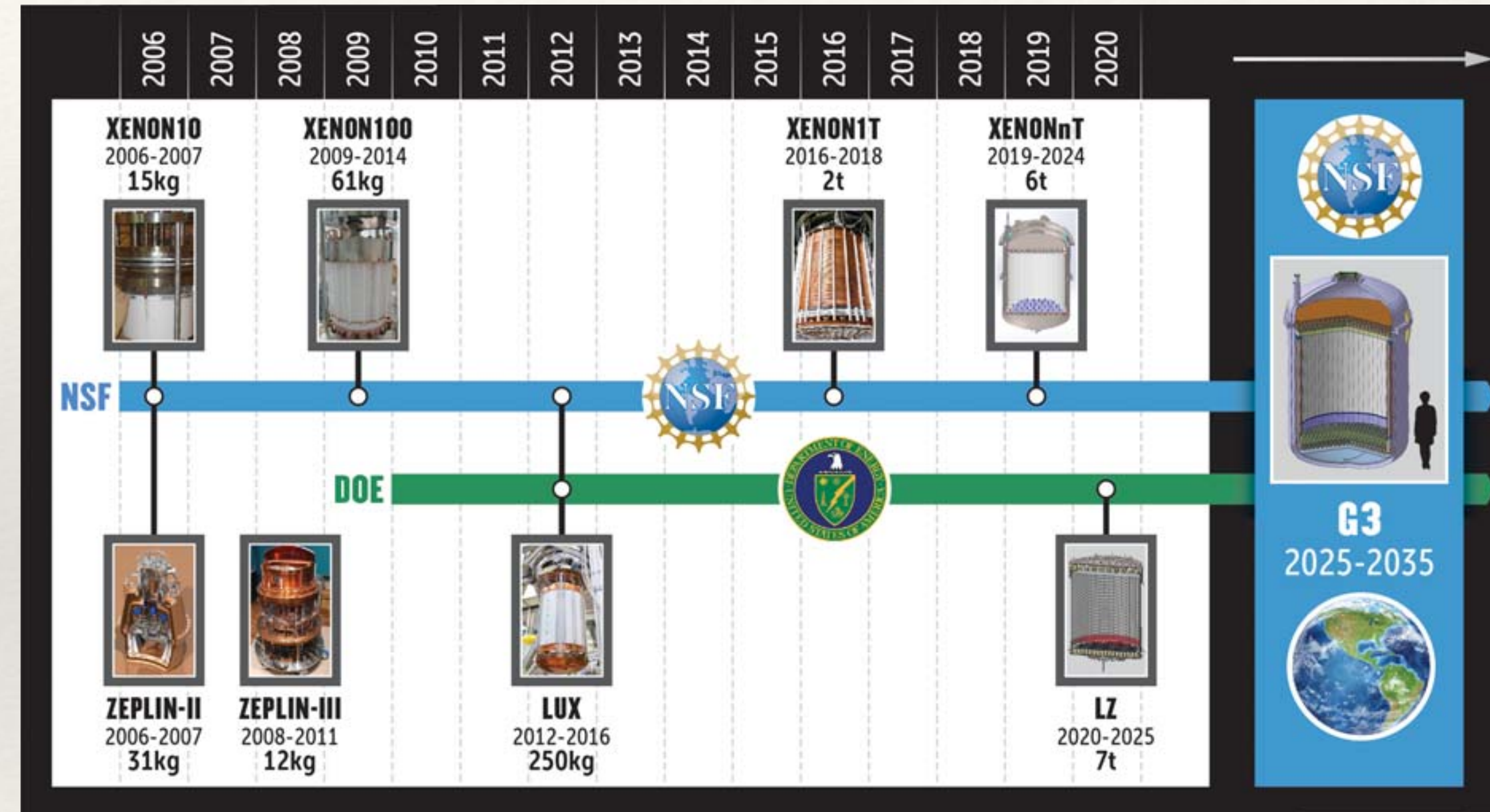
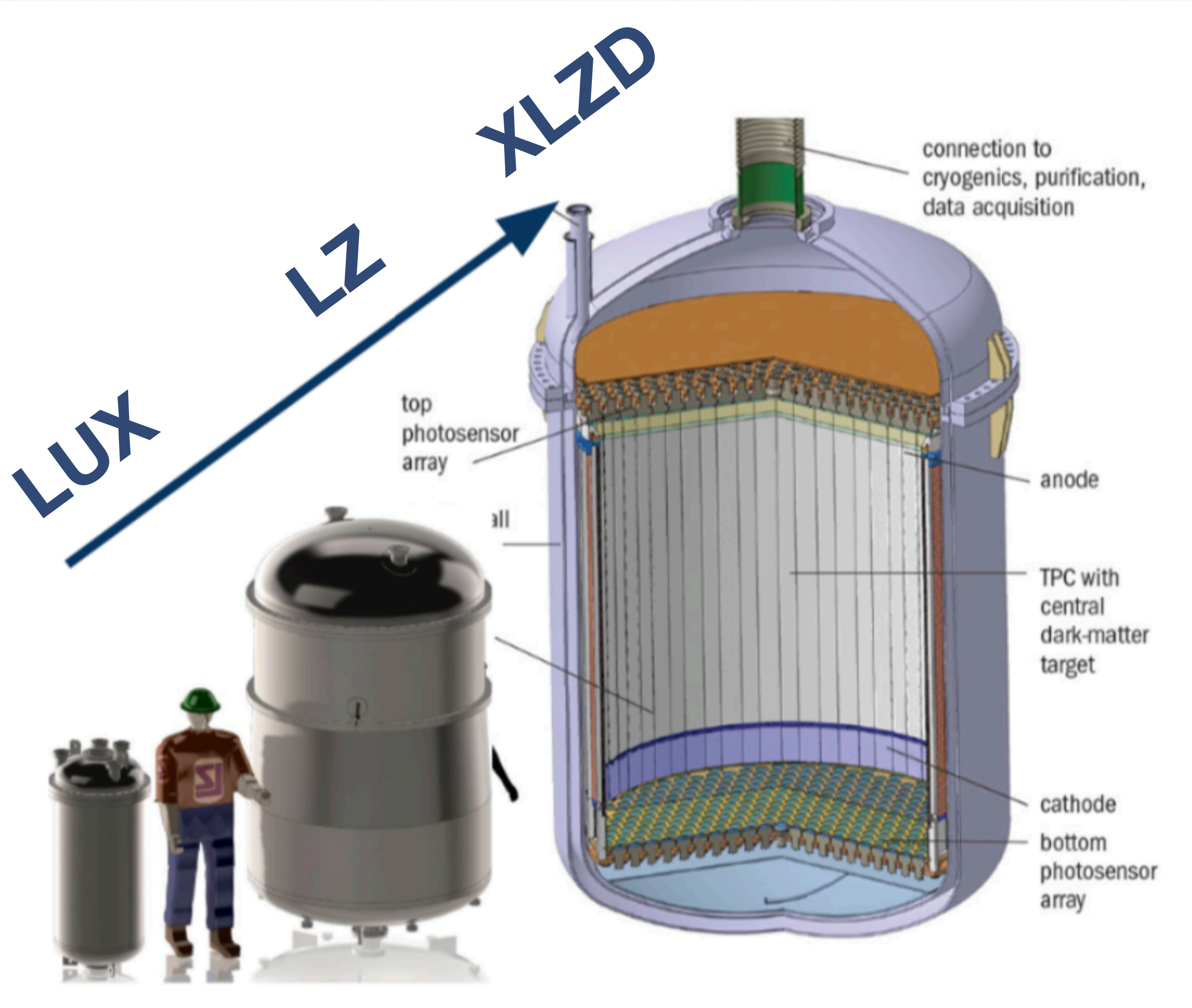
# SuperCDMS SNOLAB

- Cryogenic thermal phonon technology
  - iZIP (phonon and ionization) and HV sensors
  - Ge (1.4 kg) and Si (0.6 kg)
- Under construction at SNOLAB
- Operations beginning Fall 2023

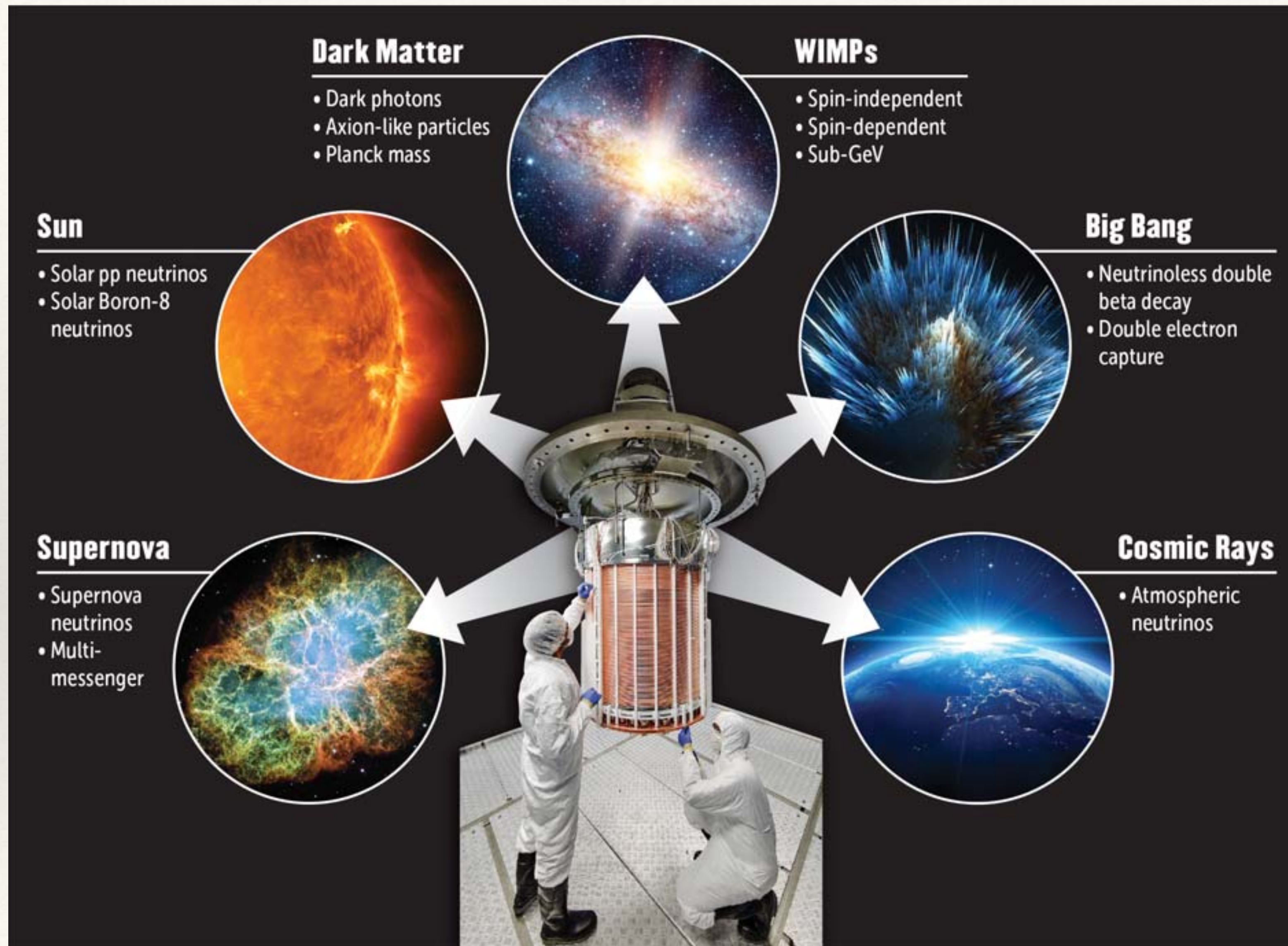
	Germanium	Silicon
HV	Lowest threshold for low mass DM Larger exposure, no $^{32}\text{Si}$ bkgd	Lowest threshold for low mass DM Sensitive to lowest DM masses
iZIP	Nuclear Recoil Discrimination Understand Ge Backgrounds	Nuclear Recoil Discrimination Understand Si Backgrounds



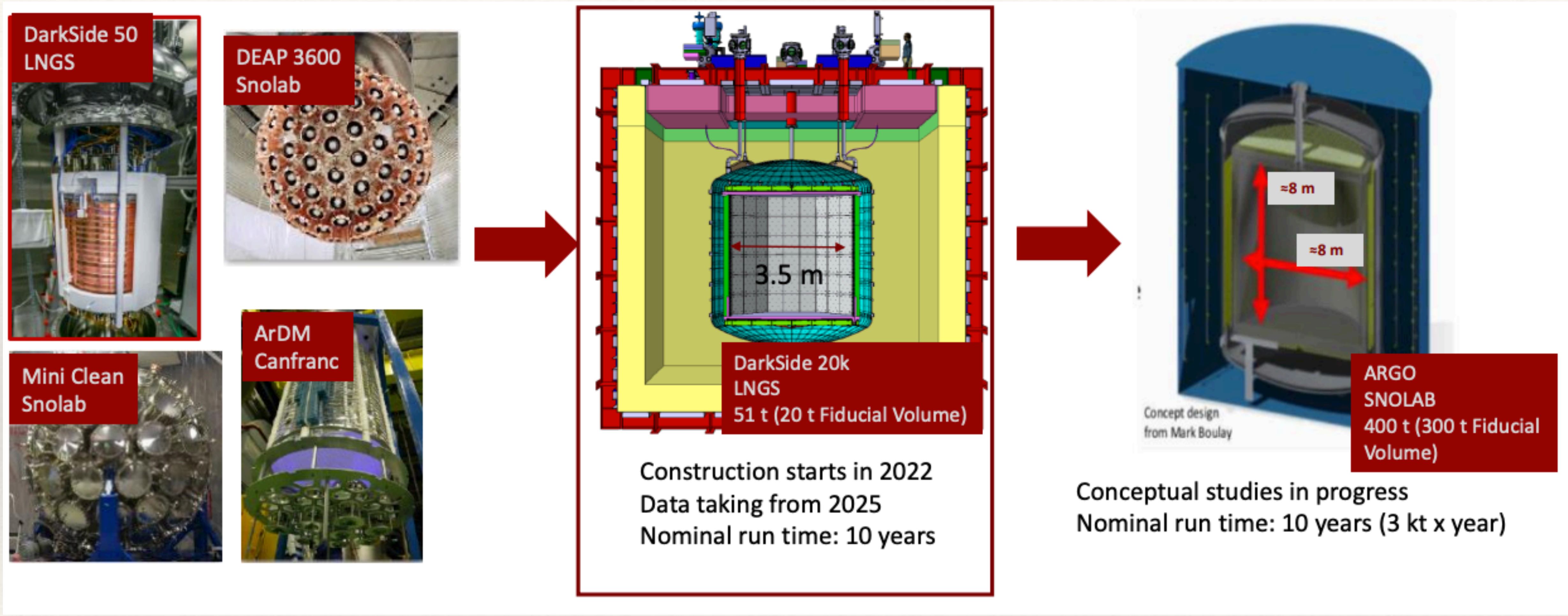
# Get to the Neutrino Fog: Xe



# What else can be done with a big detector?



# GADM programme



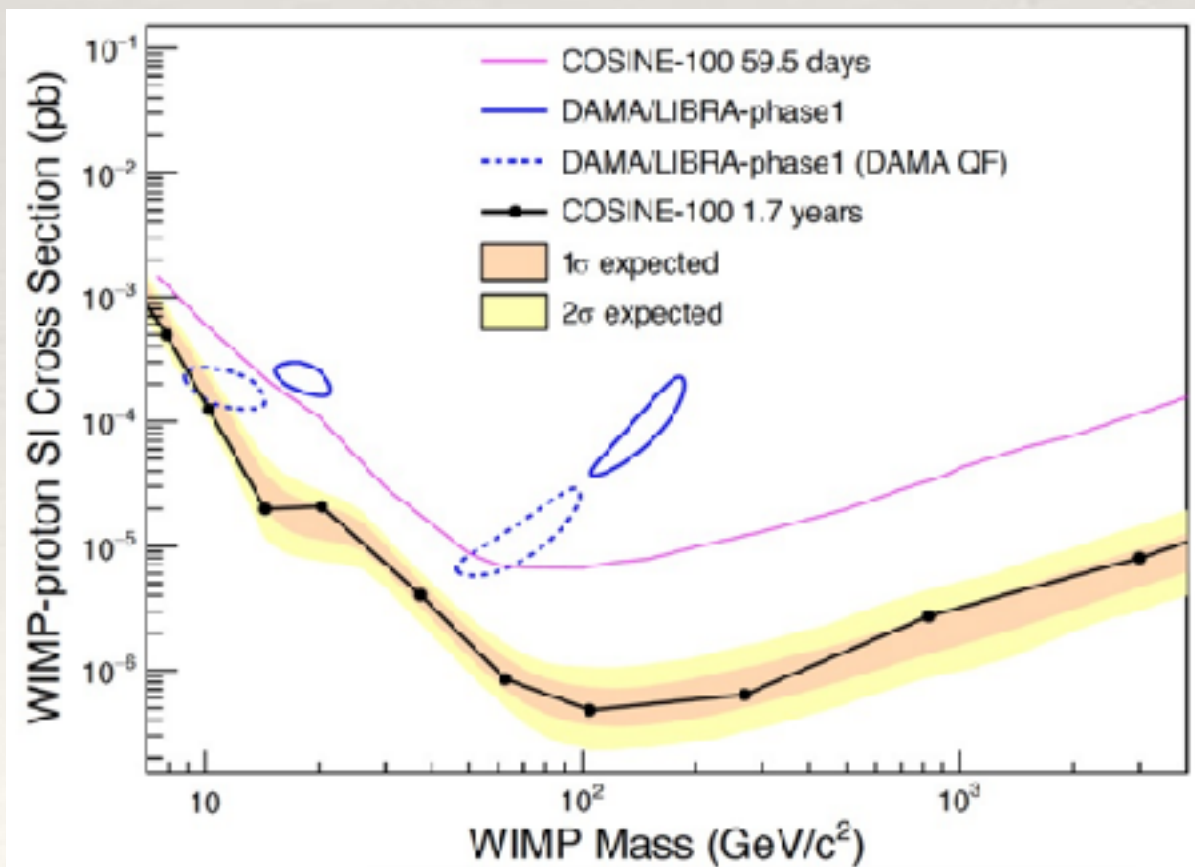
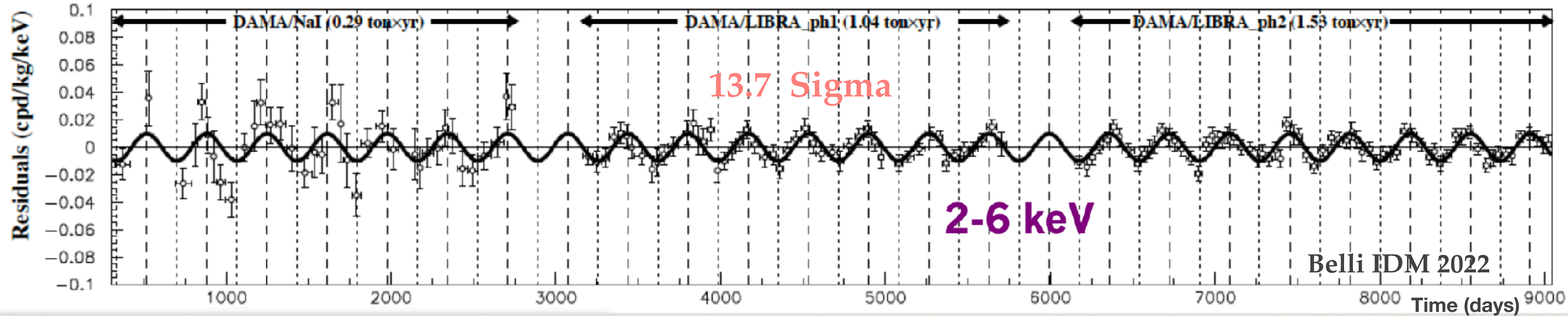
Testera LeptonPhoton21

# Resolve the DAMA/LIBRA Signal

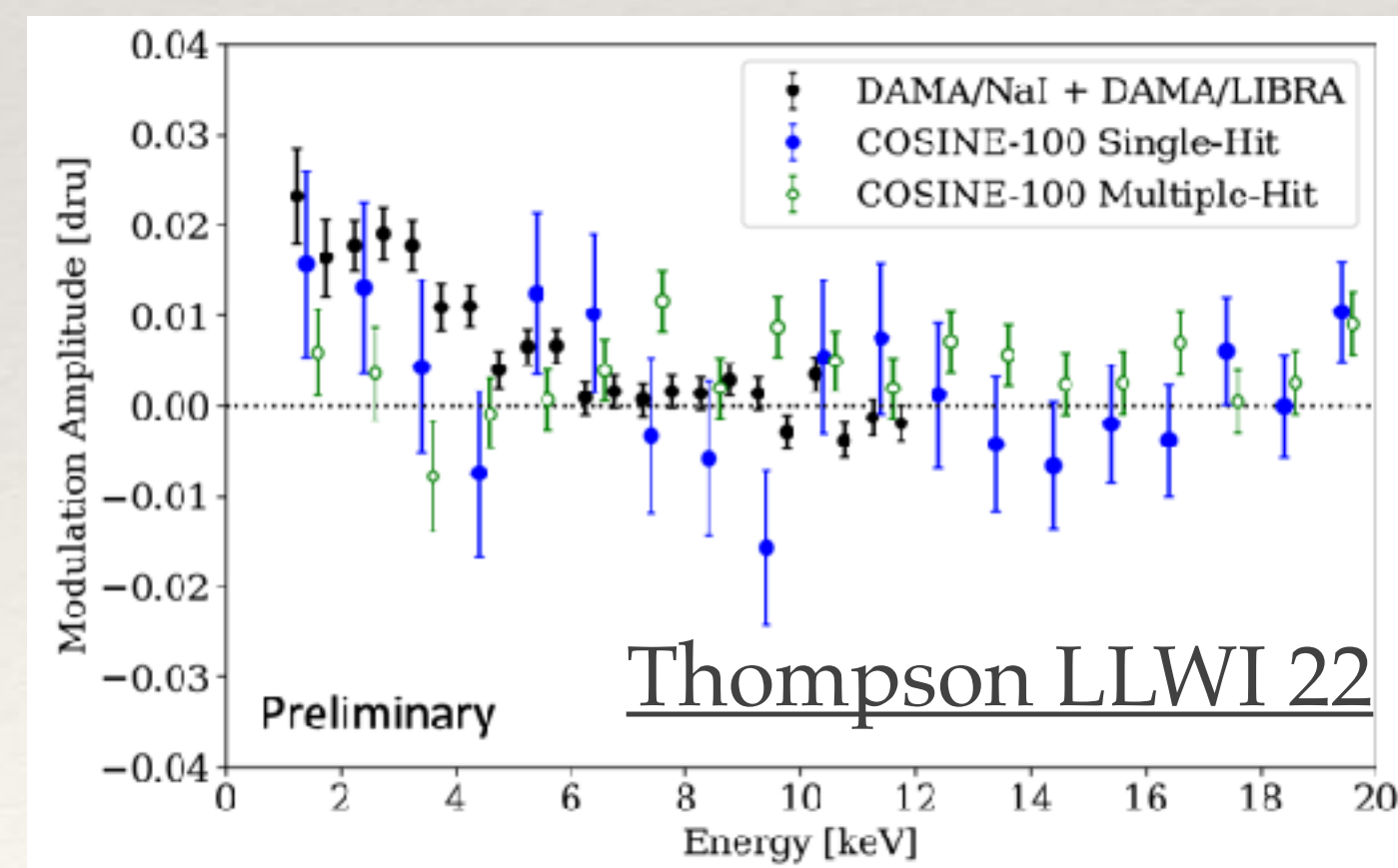
DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.86 ton × yr)

2-6 keV

$$A \cos[\omega(t-t_0)]$$



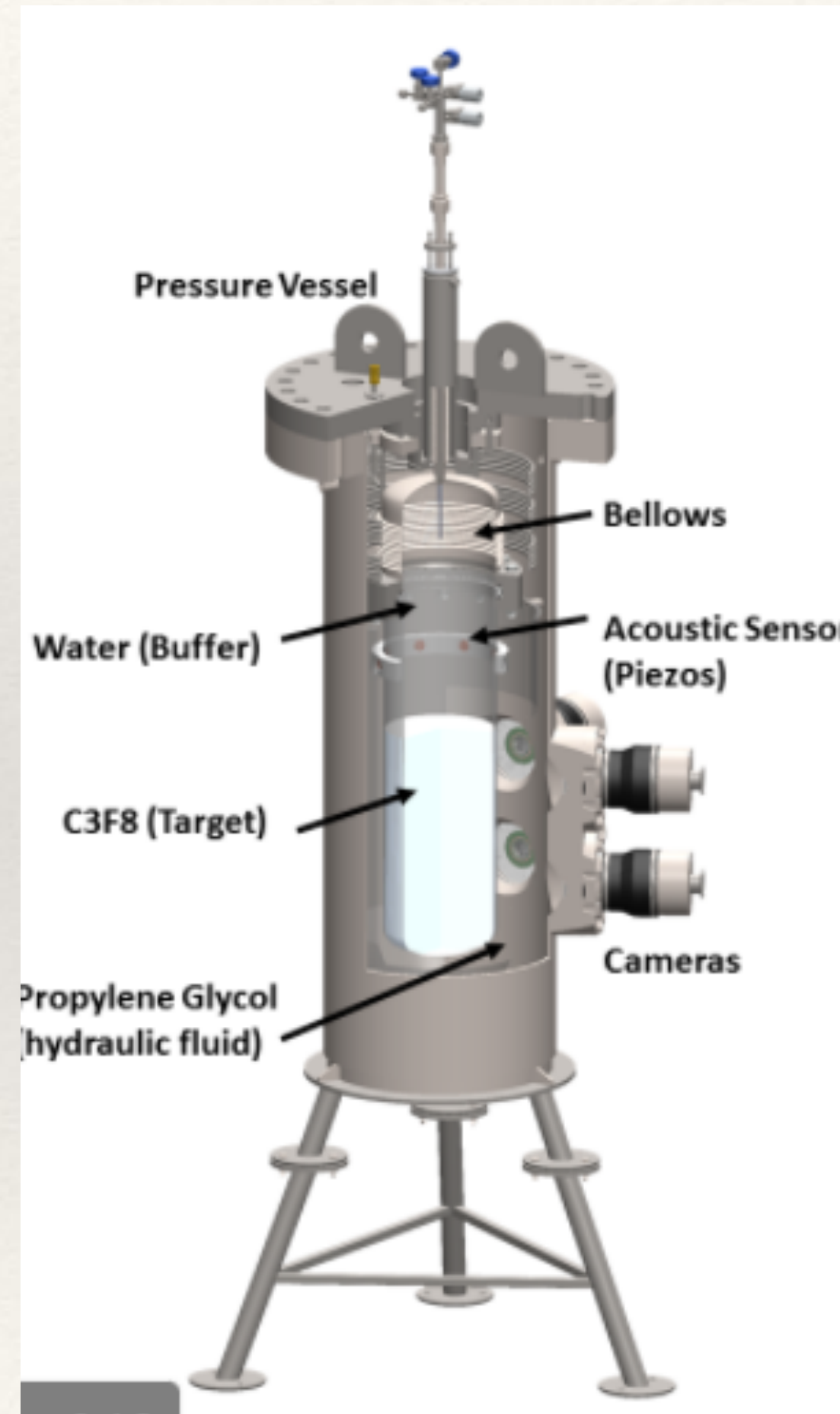
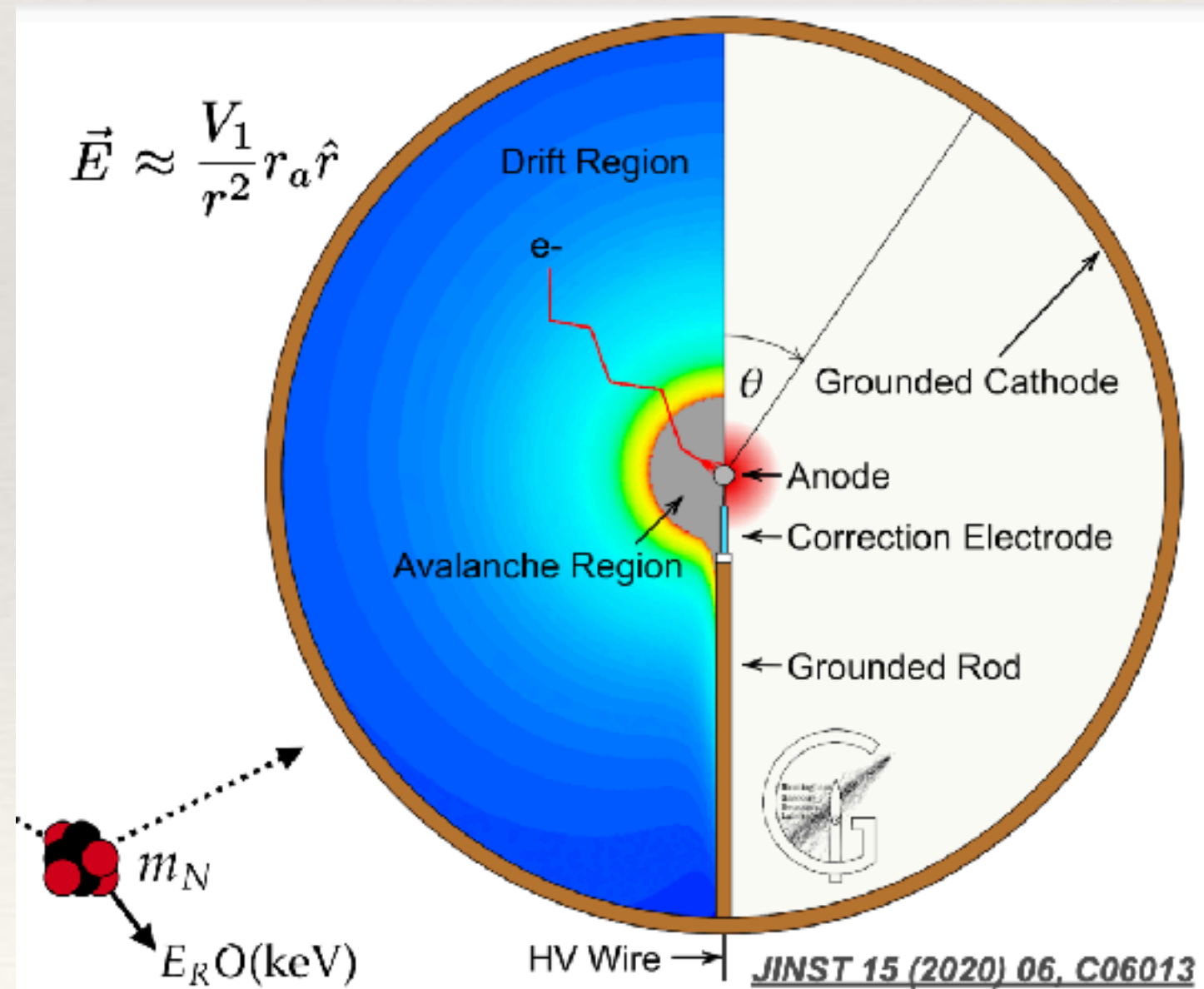
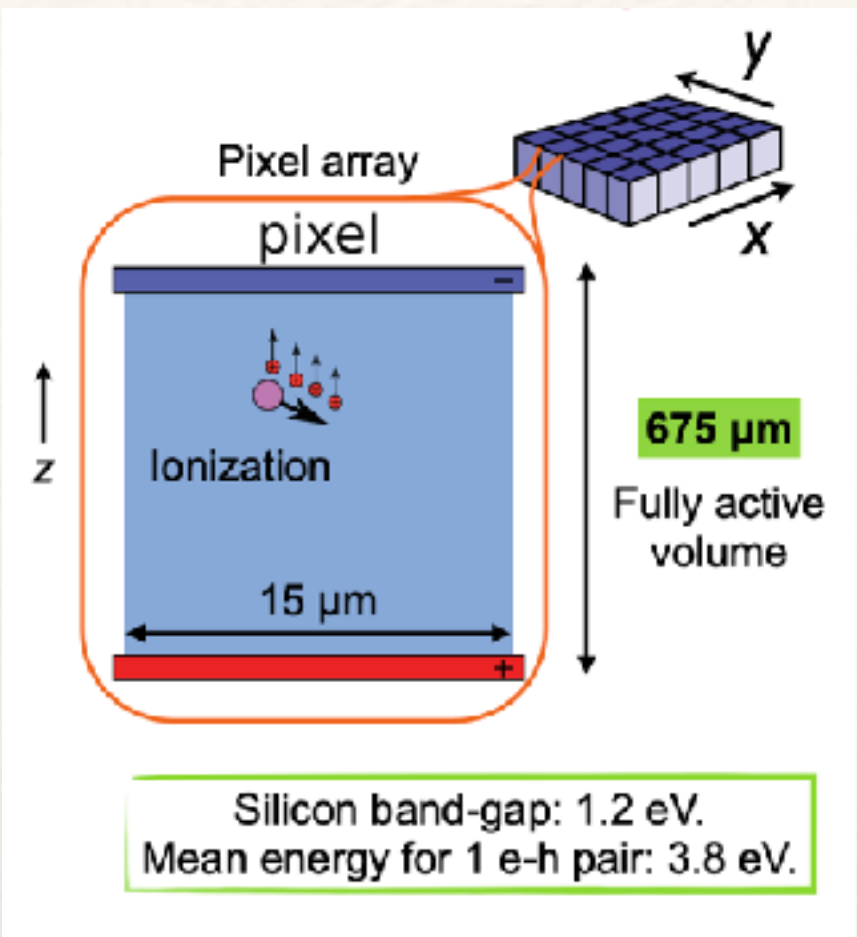
SciAdv 7 46 '21



Multiple NaI detectors investigating  
ANAIS, COSINE  
SABRE, COSINUS

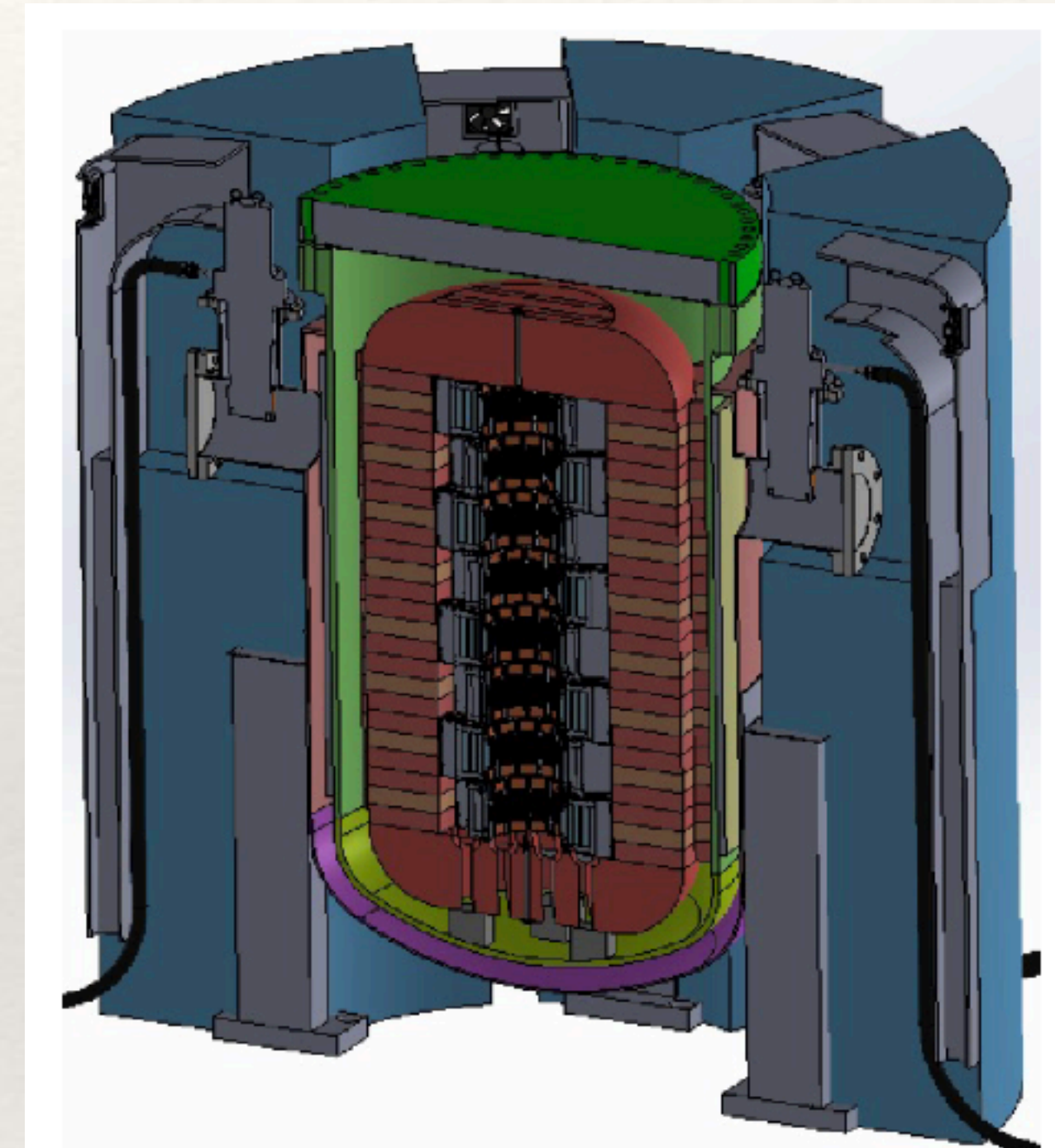


# Use new technologies for lower masses



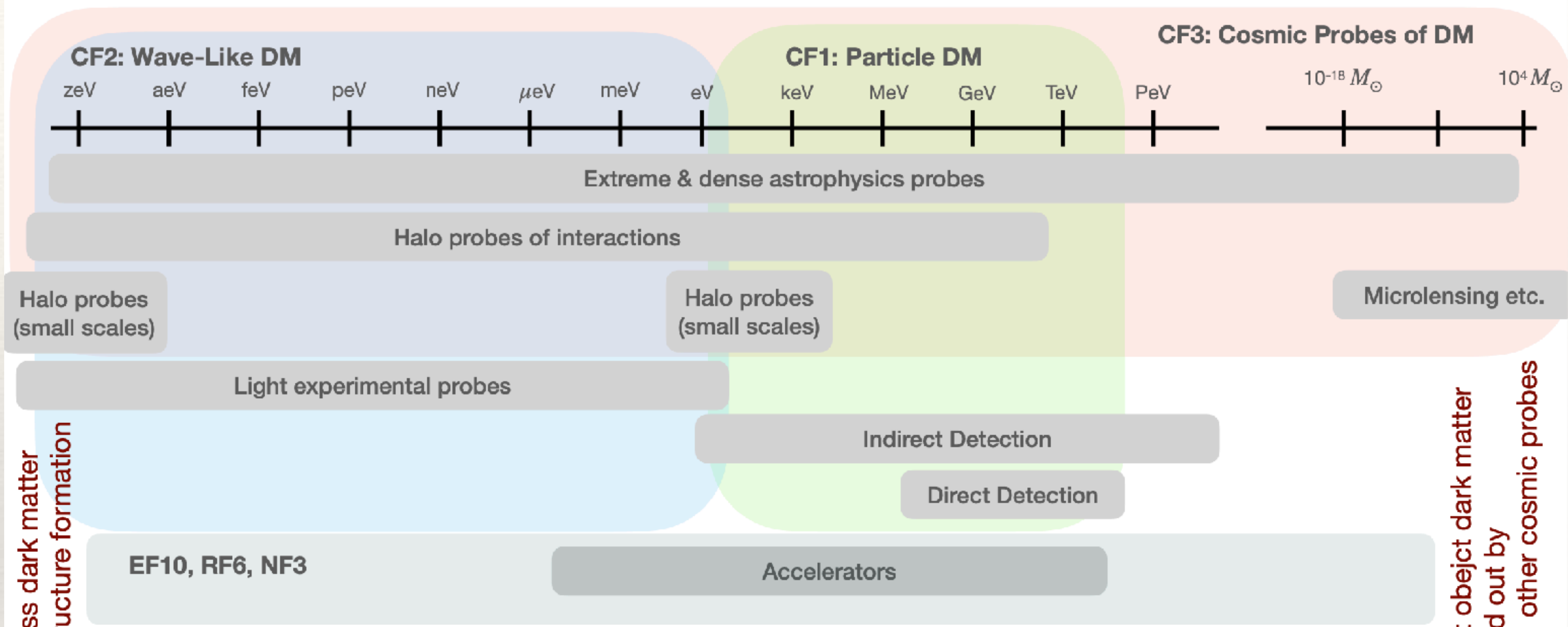
- NEWS-G
- PICO
- SENSEI & other Si
- SBC
- TESSERACT
- QUEST-DMC

## OSCURA



Full payload 100 SMs:  
10 kg!

# Complementarity

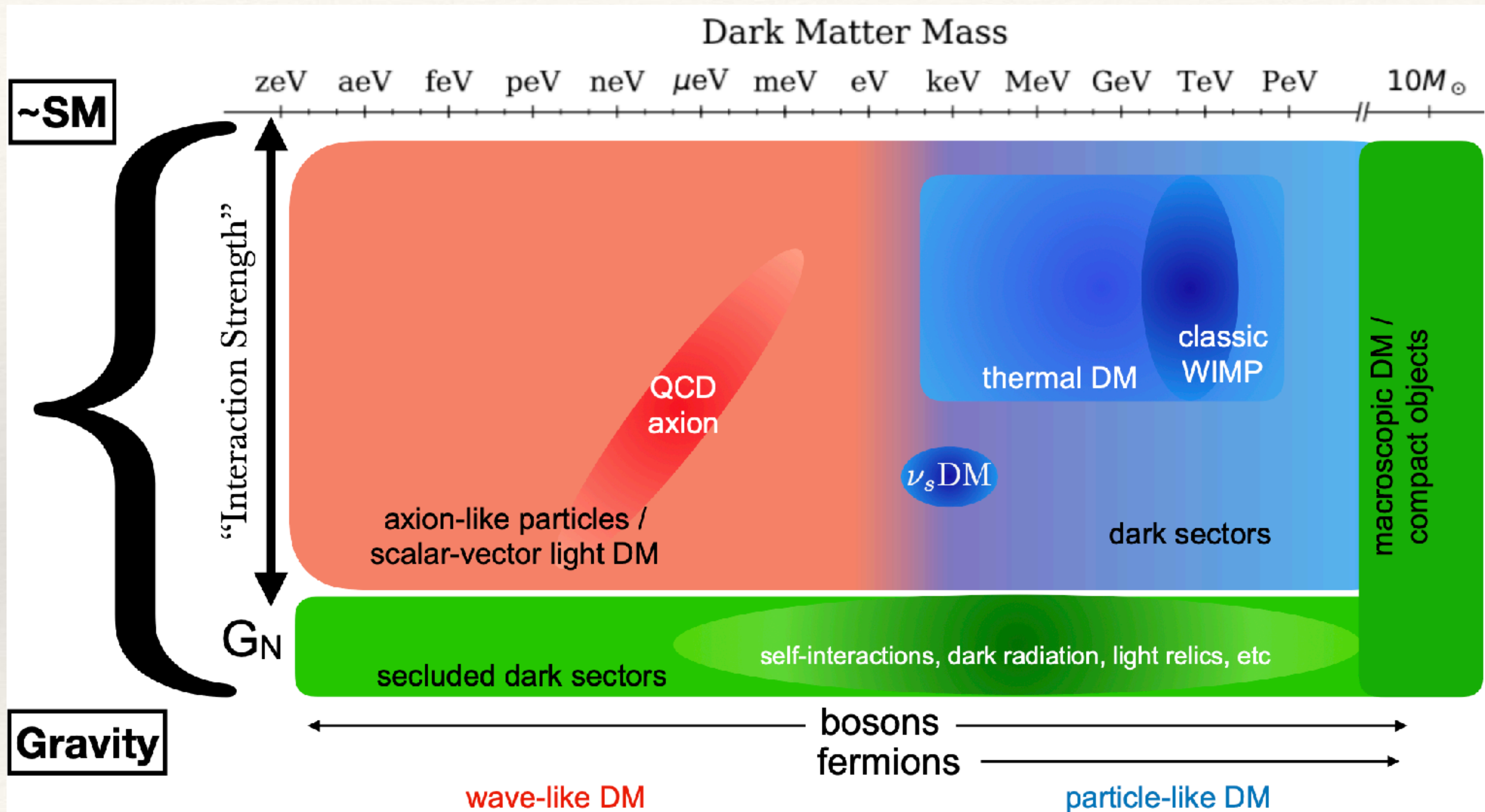


Very low mass dark matter suppresses structure formation

~90 orders of magnitude for the possible dark matter mass:  
 $10^{-22}$  eV to  $10^{68}$  eV  
*Bounded by astrophysical constraints.*

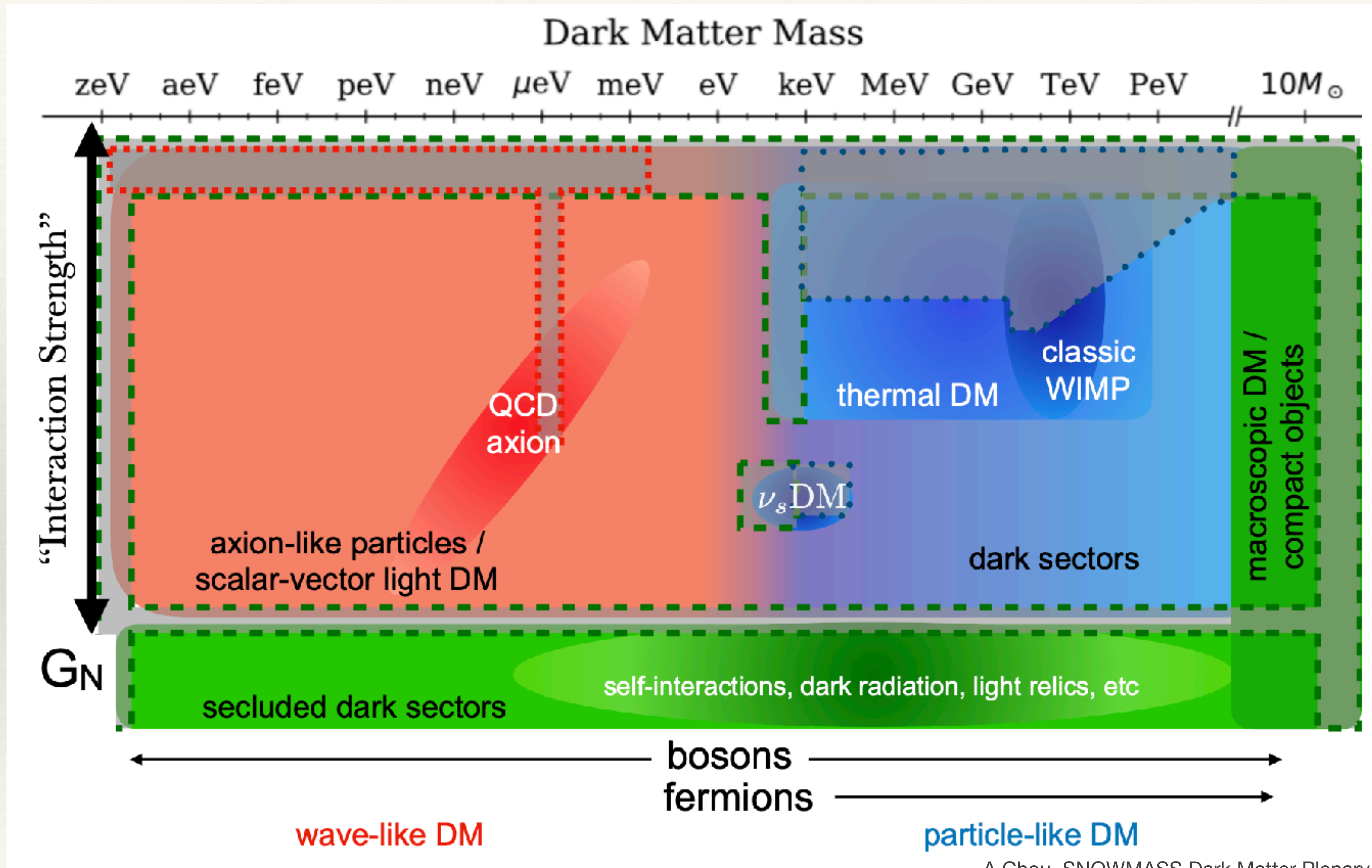
Massive compact object dark matter is ruled out by microlensing, CMB, other cosmic probes

# A Unified Vision coming from SNOWMASS



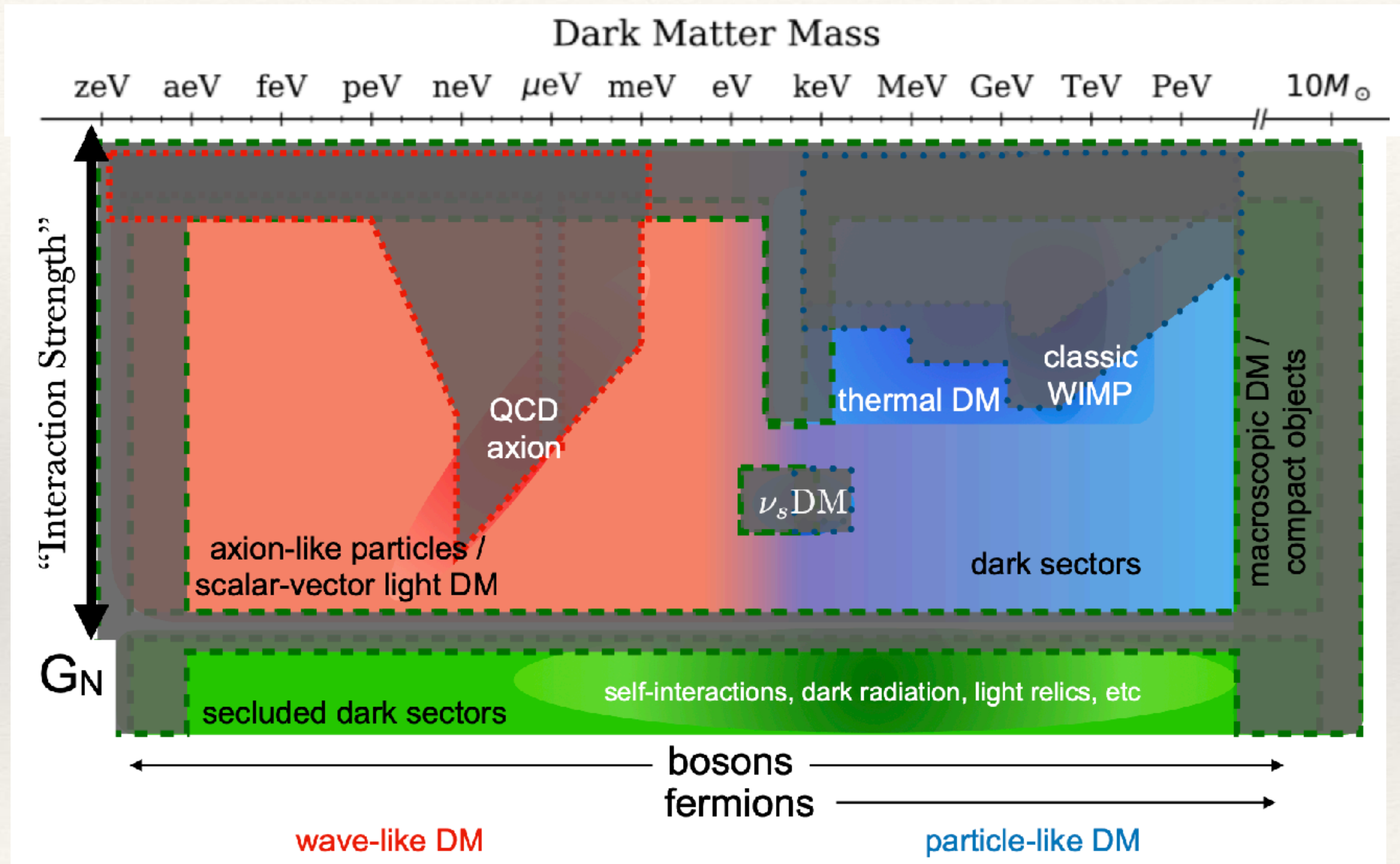
A Chou, SNOWMASS Dark Matter Plenary

# Our Current Status



A Chou, SNOWMASS Dark Matter Plenary

# If we Delve Deep, Search Wide



A Chou, SNOWMASS Dark Matter Plenary

# Launching into the future

- **WIMP/high mass particle dark matter is a viable, motivated dark matter model.**
- **There are wider models of particle DM that cover broader mass and interaction strength parameter space that are also well motivated.**
- **We have trusty liquid noble technologies that should be used to look for dark matter until we see many neutrino-induced nuclear recoils.**
  - **They can do other DM/BSM searches, neutrino physics, & neutrino astronomy**
- **New detectors and technologies are coming to probe lower mass particle DM.**
  - **When proven, they should also be used until neutrino events are seen.**
- **We should be prepared for discovery at any moment, and have multiple technologies ready for confirmation.**
- **WIMP searches fit into a wider ecosystem of dark matter searches, all are important.**

# **Delve Deep, Search Wide**

# In Memoriam



Noel Palladino

My Uncle who said, upon my leaving neutrino astronomy for Direct DM,  
“So you’re going from searching for the almost impossible to the actually impossible?”

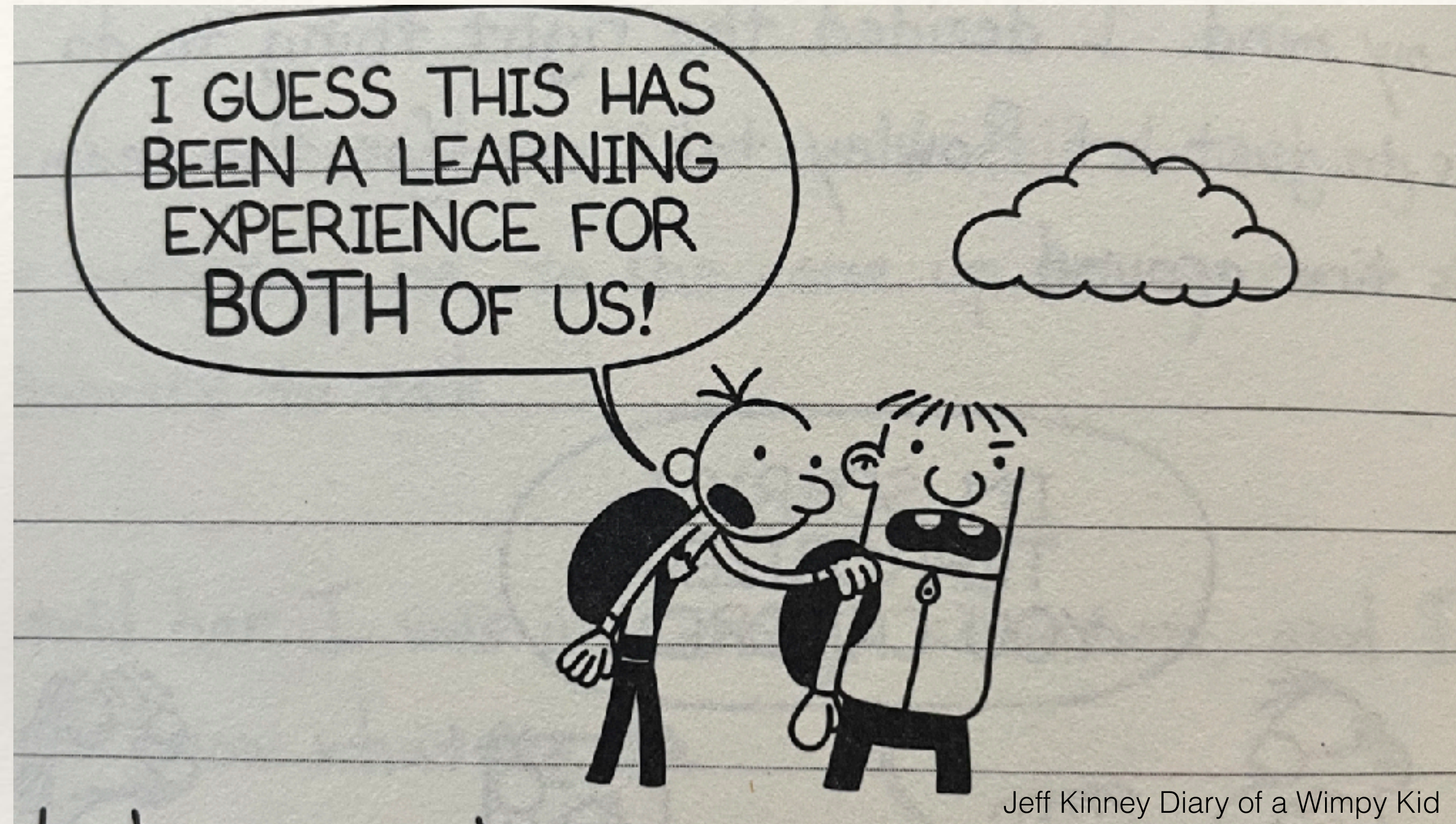


Andrew Hime

Spokesperson for MiniCLEAN  
(my first DM experiment)  
Single Phase liquid Ar/Ne  
goal of DM and neutrino physics



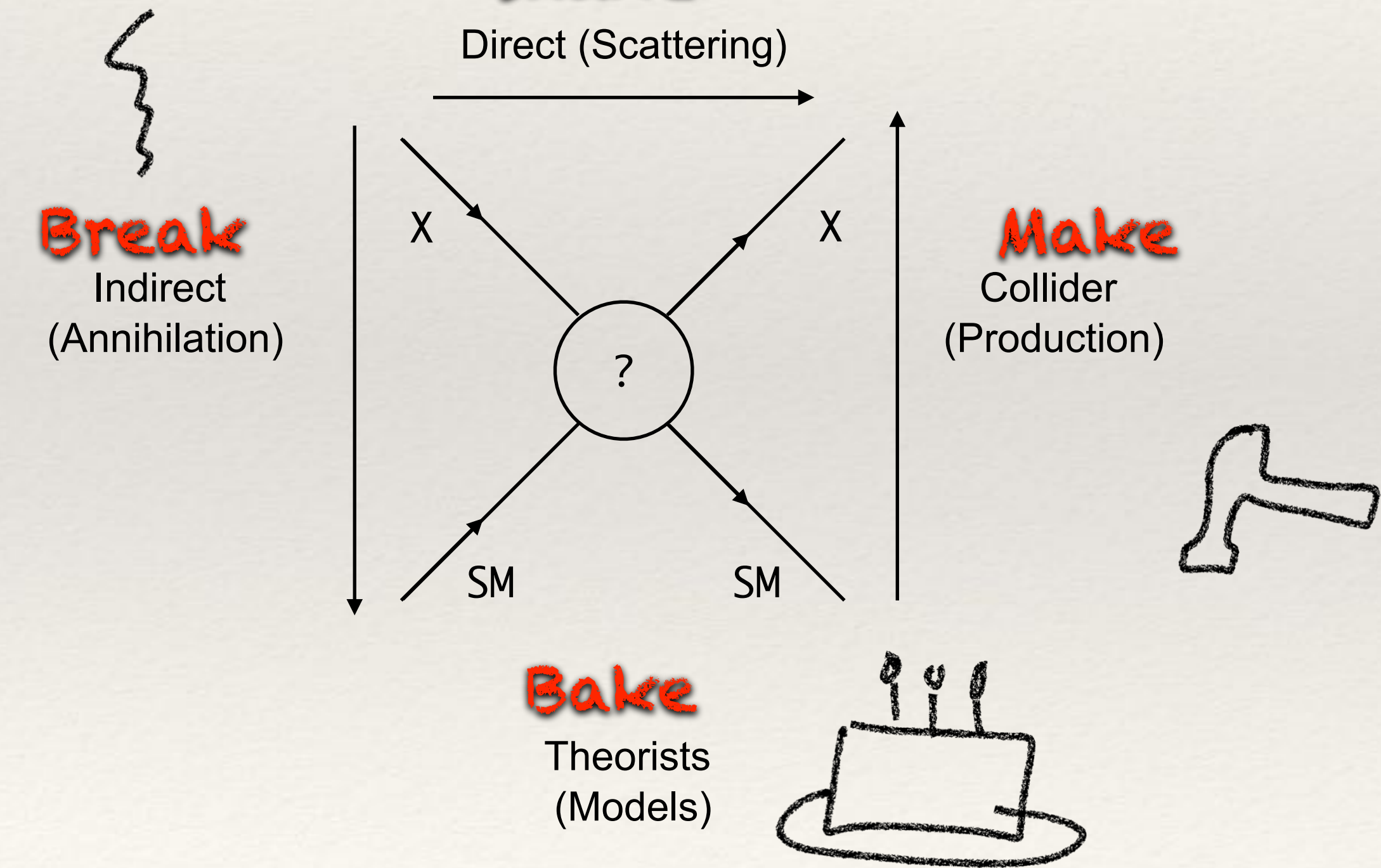
# Backup Slides



# More Cartoons



Anthropomorphic WIMP  
from Symmetry magazine



# Experiments Currently running

Name	Technology	Target	Active Mass	Experiment Location	Start Ops	End Ops
<b>Currently Running or Under Construction</b>						
LZ	TPC	LXe	7,000 kg	SURF	2021	2026
PandaX-4T	TPC	LXe	4,000 kg	CJPL	2021	2025
XENONnT	TPC	LXe	7,000 kg	LGNS	2021	2025
DEAP-3600	Scintillator	LAr	3,300 kg	SNOLAB	2016	202X
Darkside-20k	TPC	LAr	50 t	LNGS	2025	2030
DAMA/LIBRA	Scintillator	NaI	250 kg	LNGS	2003	
ANAIS-112	Scintillator	NaI	112 kg	Canfranc	2017	2022
SABRE PoP	Scintillator	NaI	5 kg	LNGS	2021	2022
COSINE-200	Scintillator	NaI	200 kg	YangYang	2022	2025
CDEX-10	Ionization (77K)	Ge	10 kg	CJPL	2016	
EDELWEISS III (High Field)	Cryo Ionization / HV	Ge	33 g	LSM	2019	
SuperCDMS CUTE	Cryo Ionization / HV	Ge/Si	5 kg/1 kg	SNOLAB	2020	2022
SuperCDMS SNOLAB	Cryo Ionization / HV	Ge/Si	11 kg/3 kg	SNOLAB	2023	2028
CRESST-III (HW Tests)	Bolometer Scintillation	CaWO4		LNGS	2020	
PICO-40	Bubble Chamber	C3F8	35 kg	SNOLAB	2020	
NEWS-G	Gas Drift	CH4		SNOLAB	2020	2025

# Experiments Currently running, cont'd

Name	Technology	Target	Active Mass	Experiment Location	Start Ops	End Ops
<b>Currently Running or Under Construction</b>						
DAMIC-M prototype	CCD Skipper	Si	18 g	LSM	2022	2023
DAMIC-M	CCD Skipper	Si	1 kg	LSM	2024	2025
SENSEI	CCD Skipper	Si	2 g	Fermilab	2019	2020
SENSEI	CCD Skipper	Si	100 g	SNOLAB	2021	2023

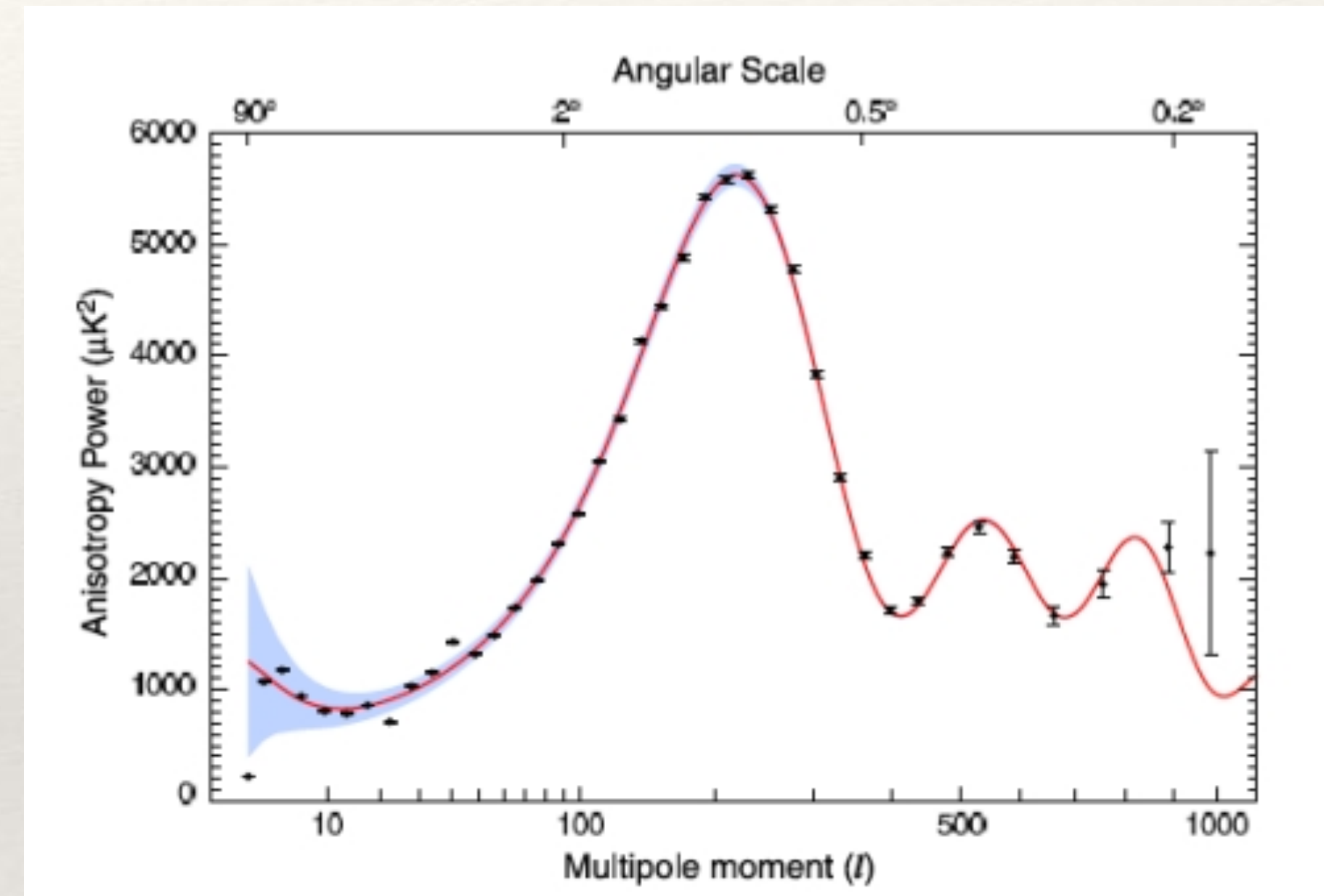
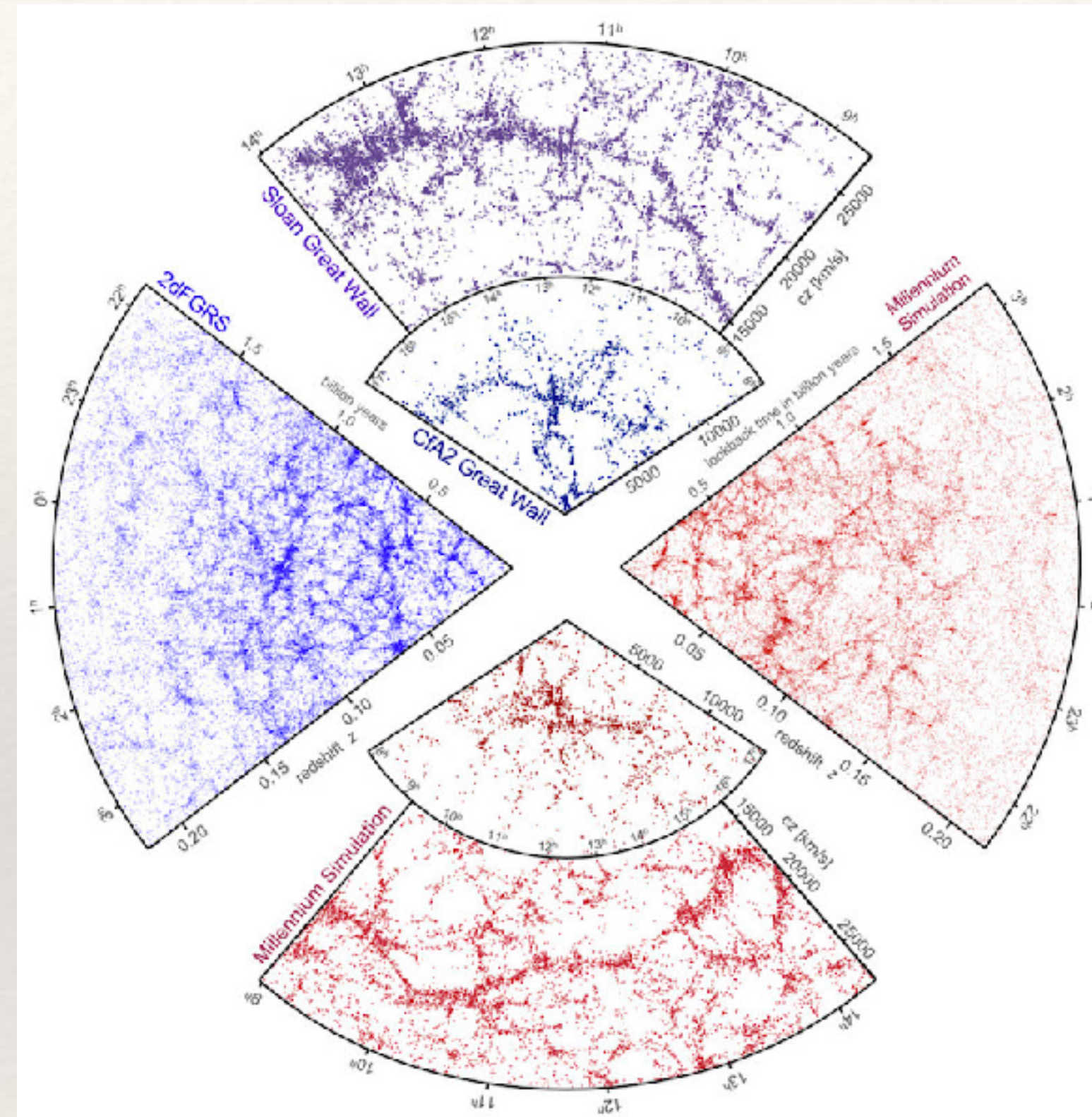
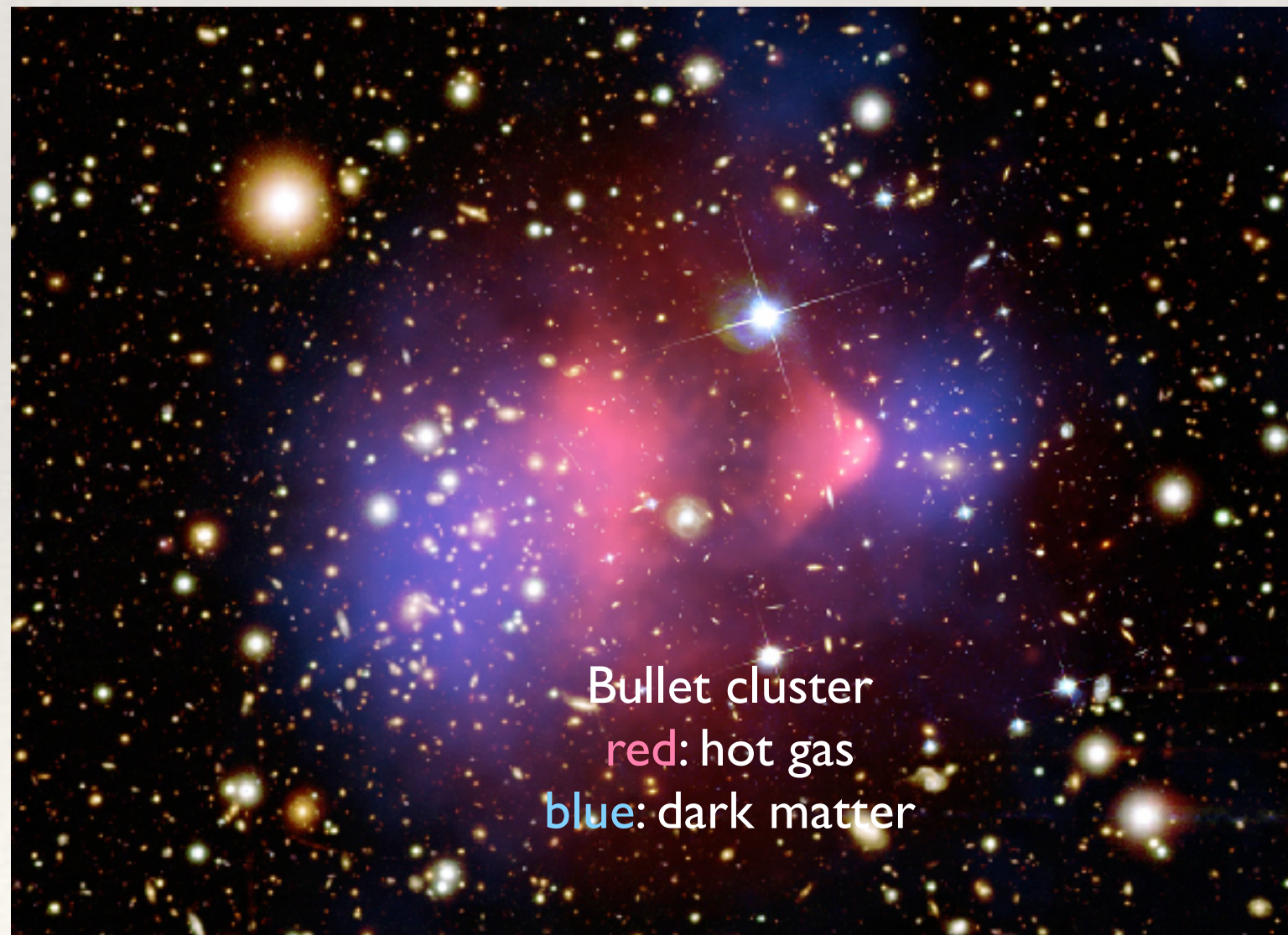
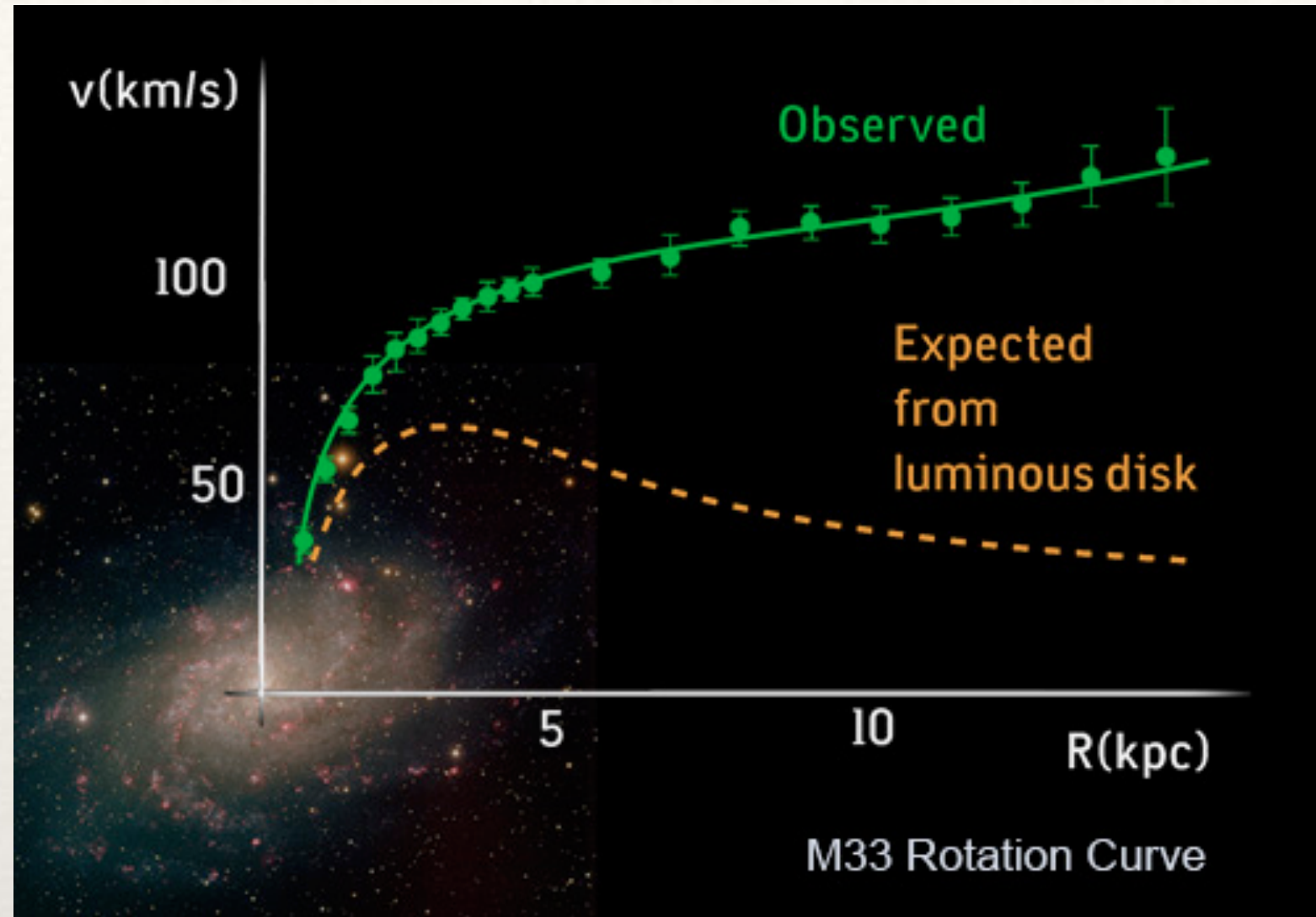
# Planned Experiments

Name	Technology	Target	Active Mass	Experiment Location	Start Ops	End Ops
<b>Planned</b>						
SABRE (North)	Scintillator	NaI	50 kg	LNGS	2022	2027
SABRE (South)	Scintillator	NaI	50 kg	SUPL	2022	2027
COSINE-200 South Pole	Scintillator	NaI	200 kg	South Pole	2023	
COSINUS	Bolometer Scintillator	NaI		LNGS	2023	
Darwin / XLZD (US LXe G3)	TPC	LXe	50,000 kg	undetermined	2028	2033
ARGO	TPC or Scin- tillator	LAr	300 t	SNOLAB	2030	2035
CDEX-100 / 1T	Ionization (77K)	Ge	100-1000 kg	CJPL	202X	
PICO-500	Bubble Chamber	C3F8	430 kg	SNOLAB	2021	

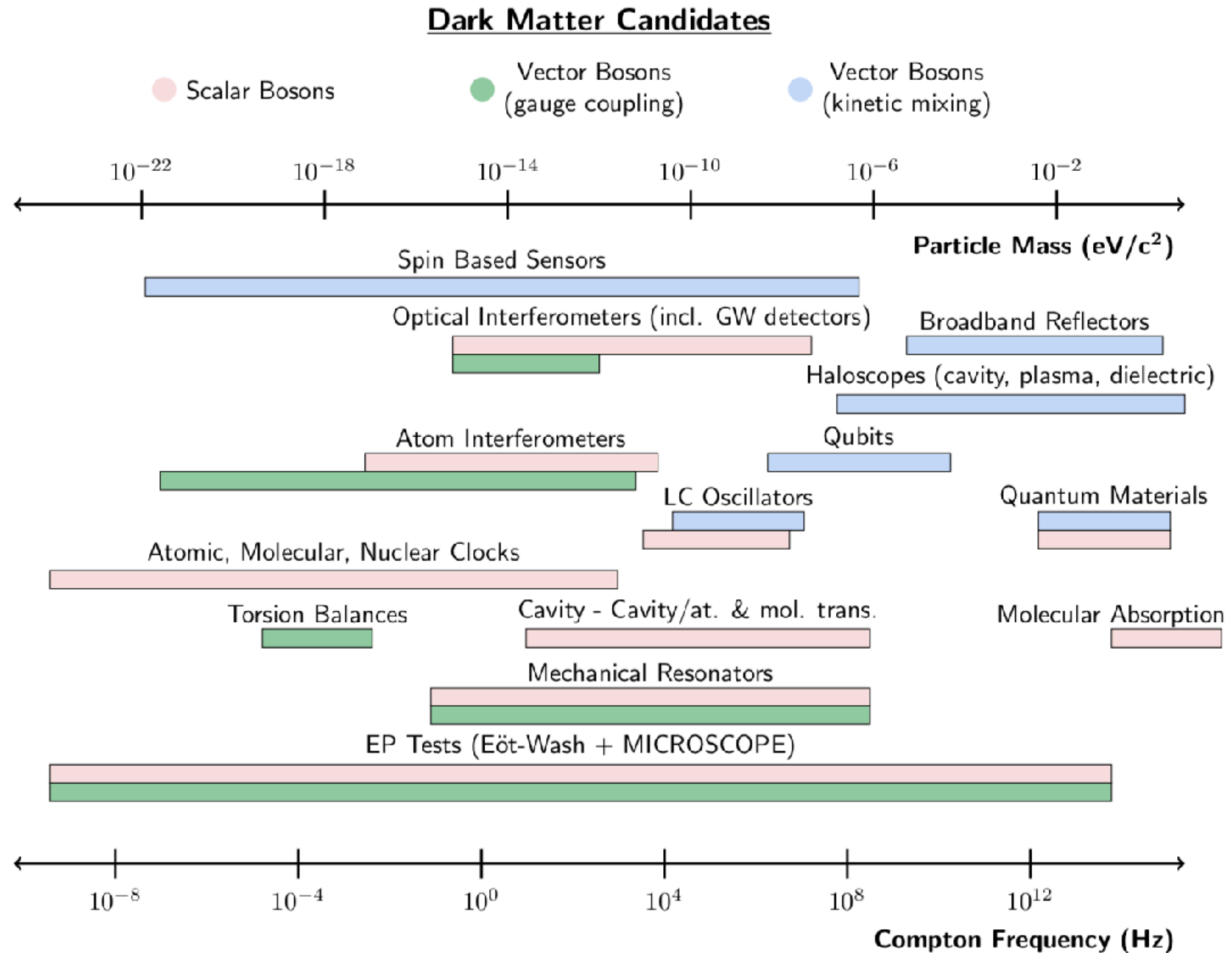
# Potential Future Experiments

Name	Technology	Target	Active Mass	Experiment Location	Start Ops	End Ops
<b>Concept or R&amp;D</b>						
Oscura	CCD Skipper	Si	10 kg Si	SNOLAB	2025	2028
SBC	Bubble Chamber	LAr	1 t	SNOLAB	2028	
SNOWBALL	Supercooled Liquid H <sub>2</sub> O					
DarkSide-LowMass	TPC	LAr	1.5 t			
ALETHEIA	TPC	He		China Inst. At. Energy		
TESSERACT	Cryo TES	LHe, SiO <sub>2</sub> , Al <sub>2</sub> O <sub>3</sub> , GaAs		undetermined	2026	
CYGNO	Gas Directional	He + CF <sub>4</sub>	0.5 - 1 kg	LNGS	2024	
CYGNUS	Gas Directional	He + SF <sub>6</sub> /CF <sub>4</sub>		Multiple sites		
Windchime	Accelerometer array			Multiple sites	2	

# Evidence for Dark Matter



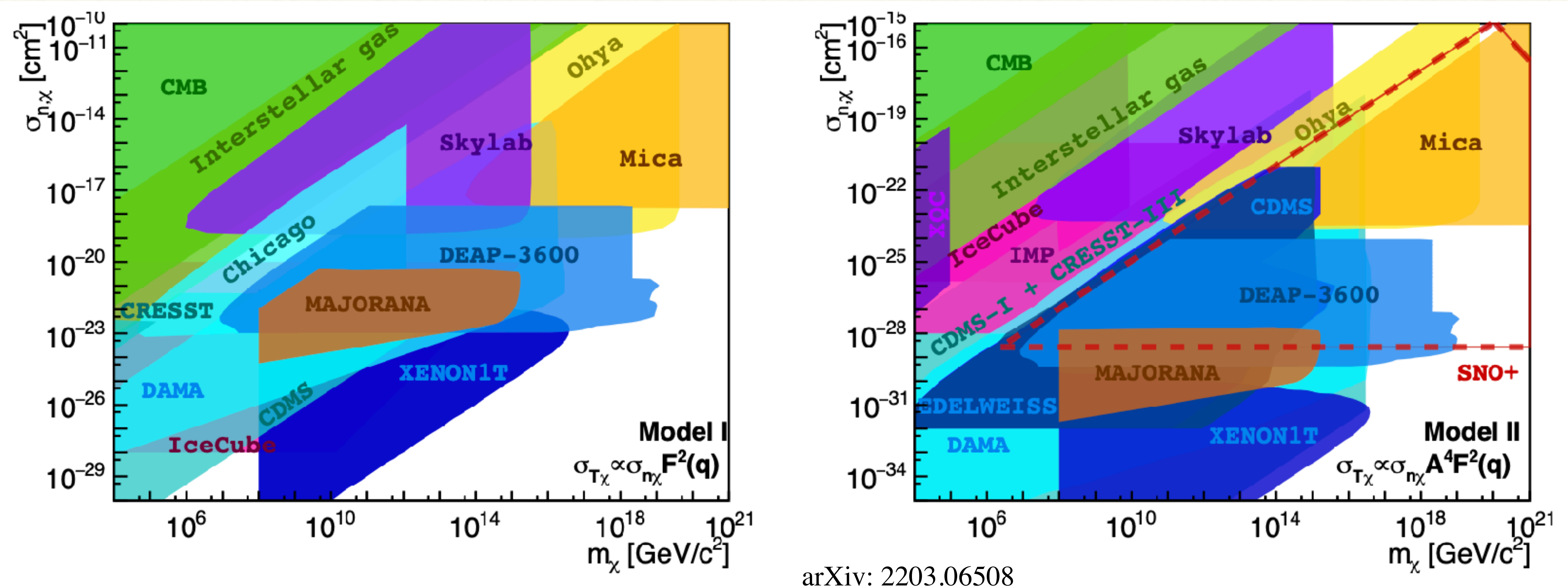
# Wavelike Dark Matter



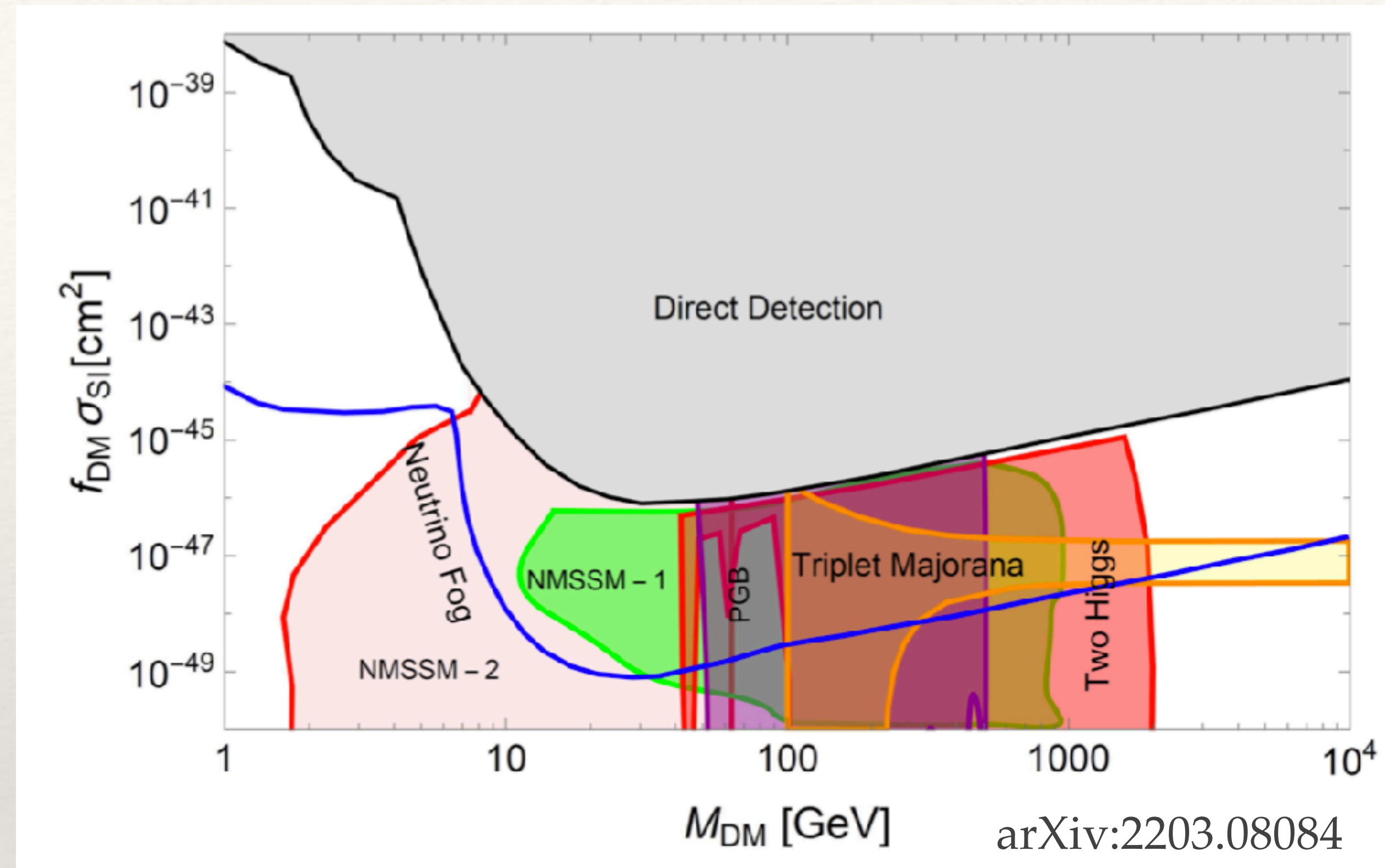
[arXiv:2203.14915](https://arxiv.org/abs/2203.14915)



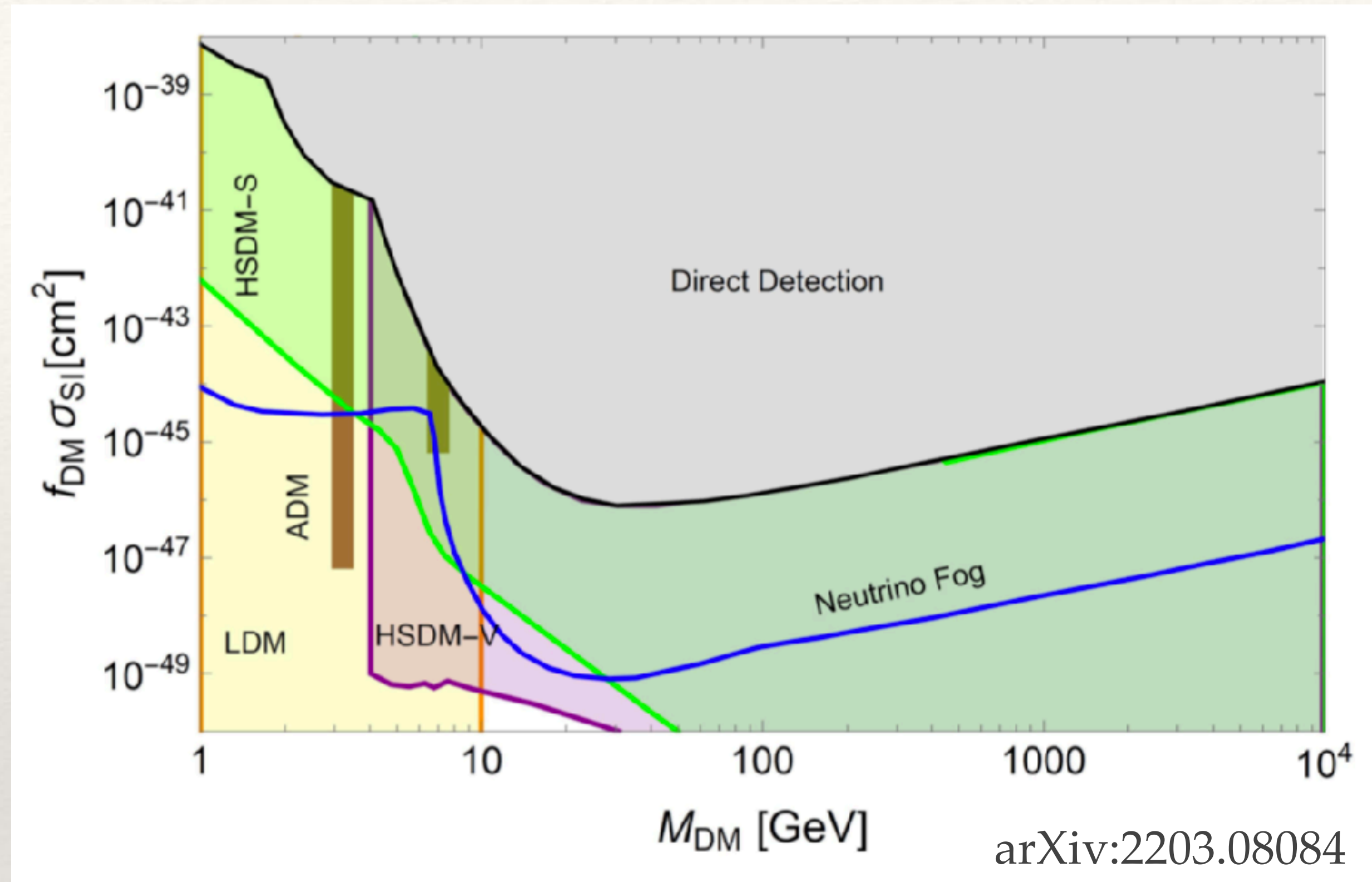
# Ultraheavy dark matter

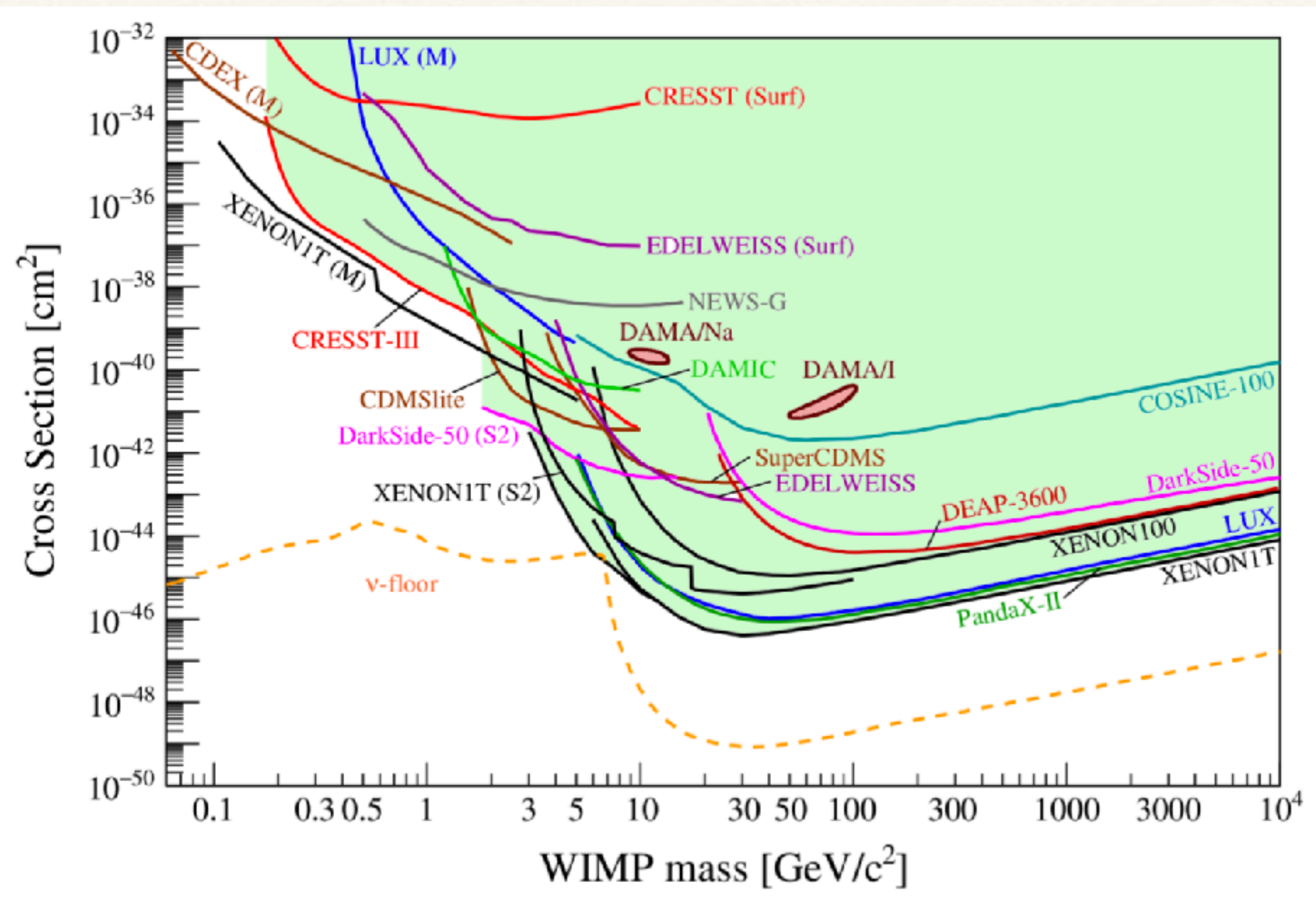


# A Modern WIMP view

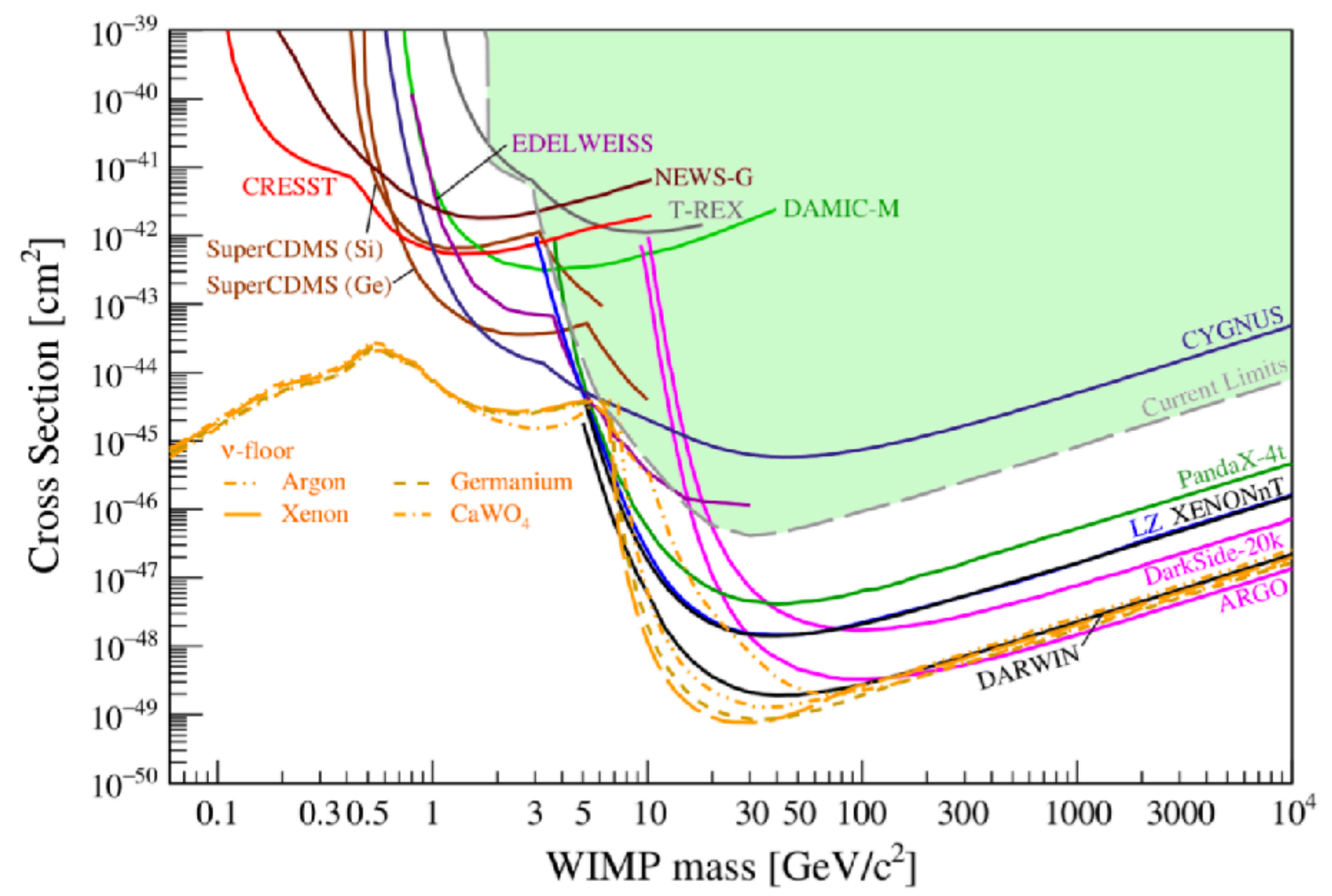


# High Mass Particle DM Beyond the WIMP





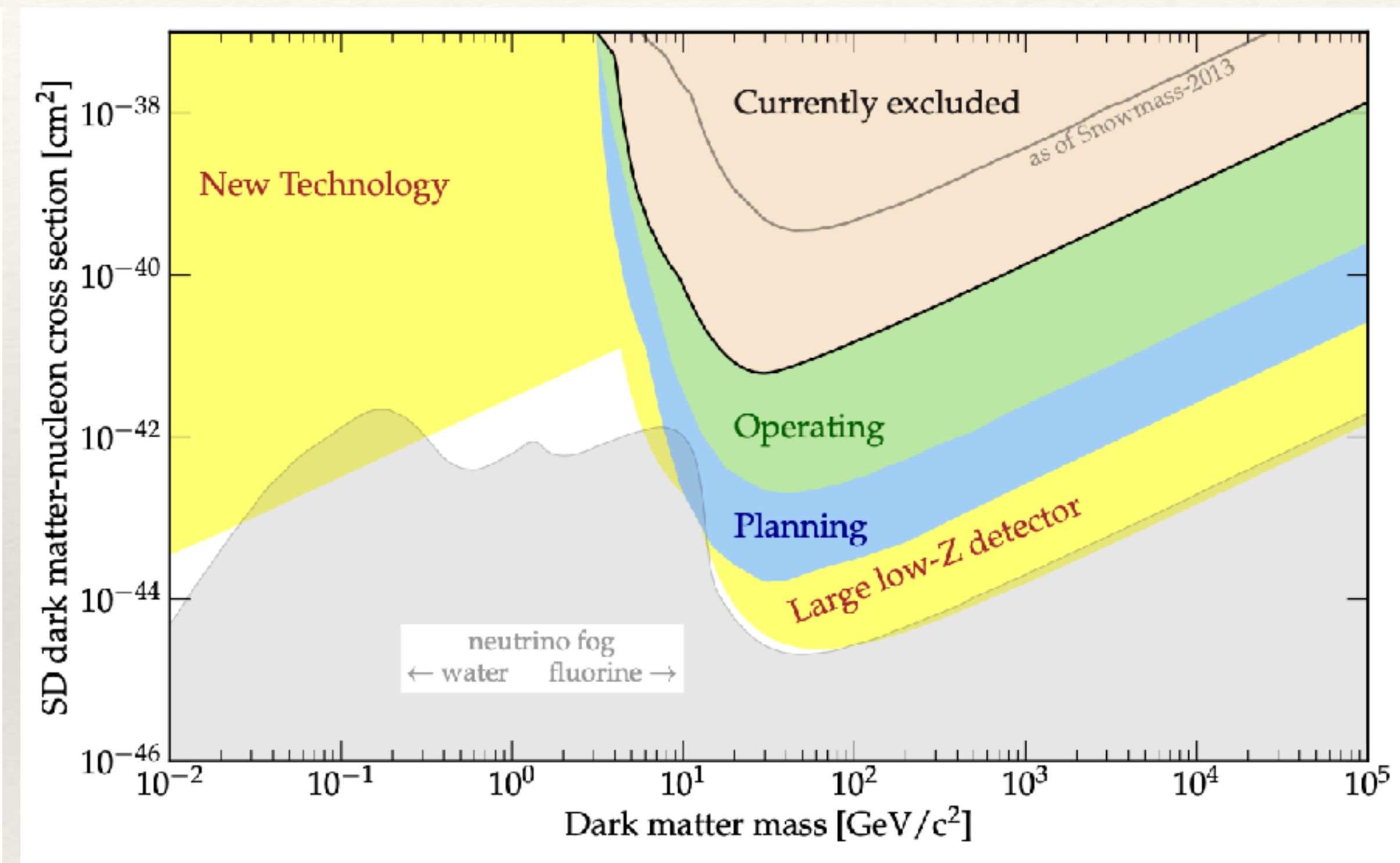
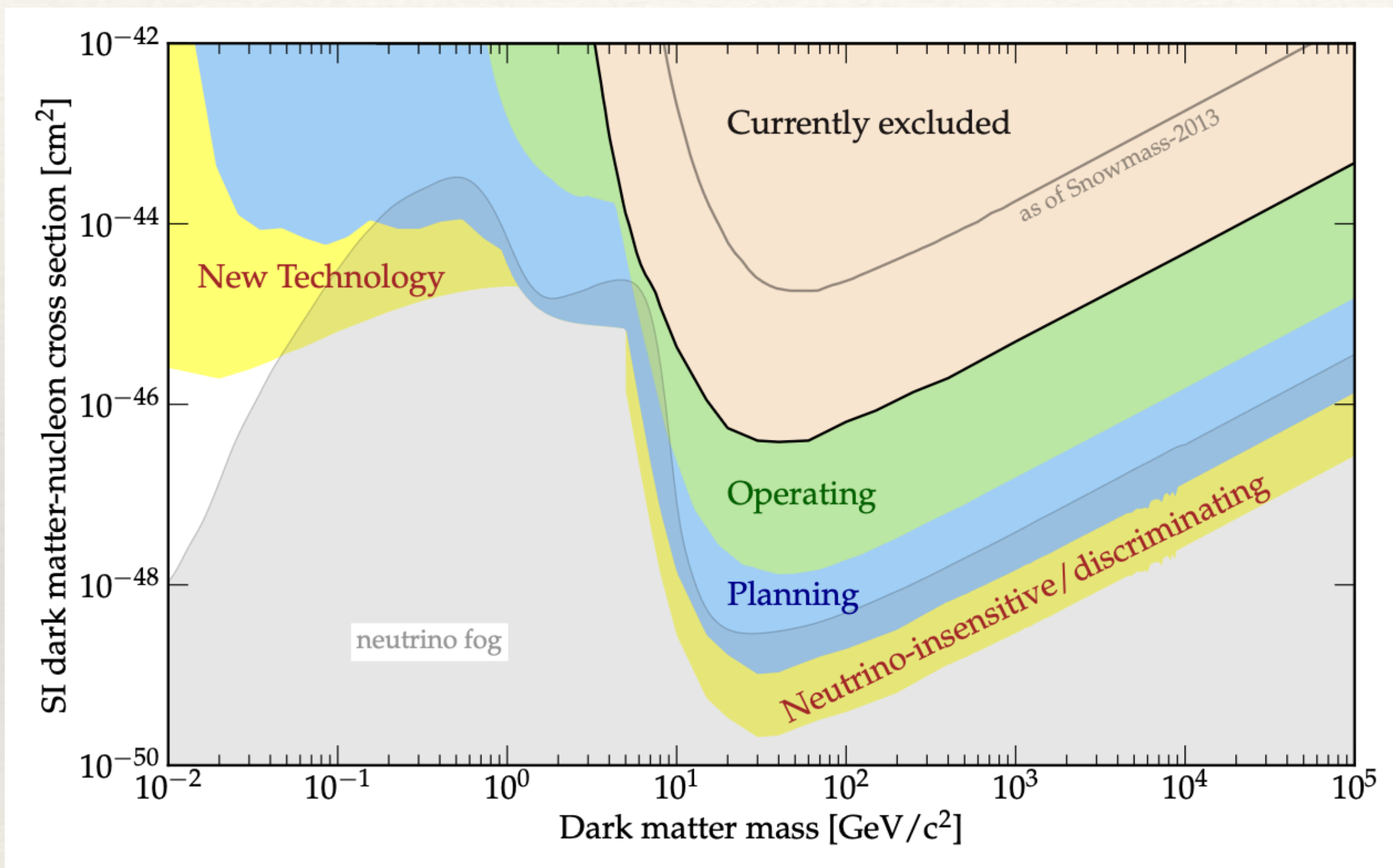
Limits!



Projections!

[arXiv:2104.07634](https://arxiv.org/abs/2104.07634)

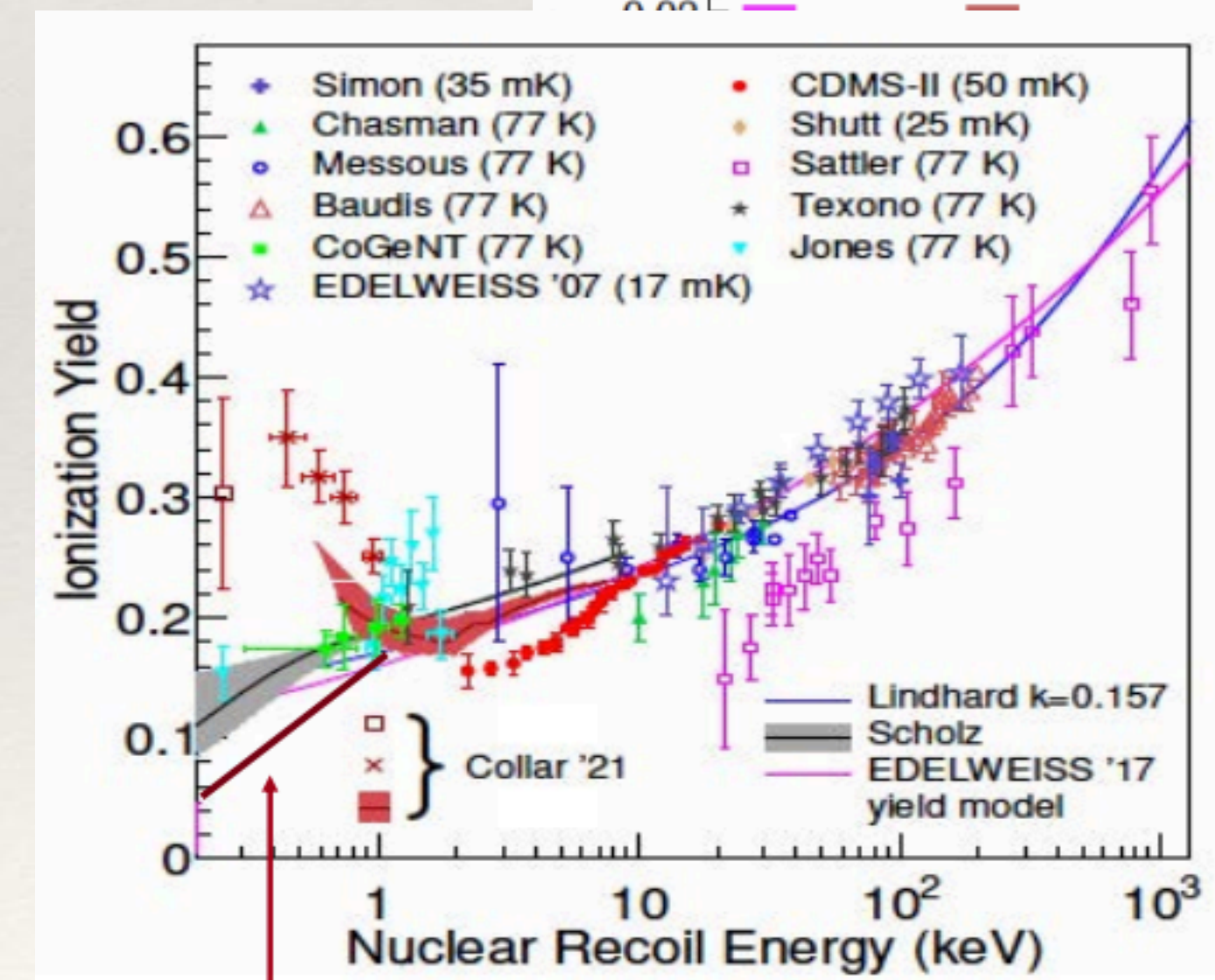
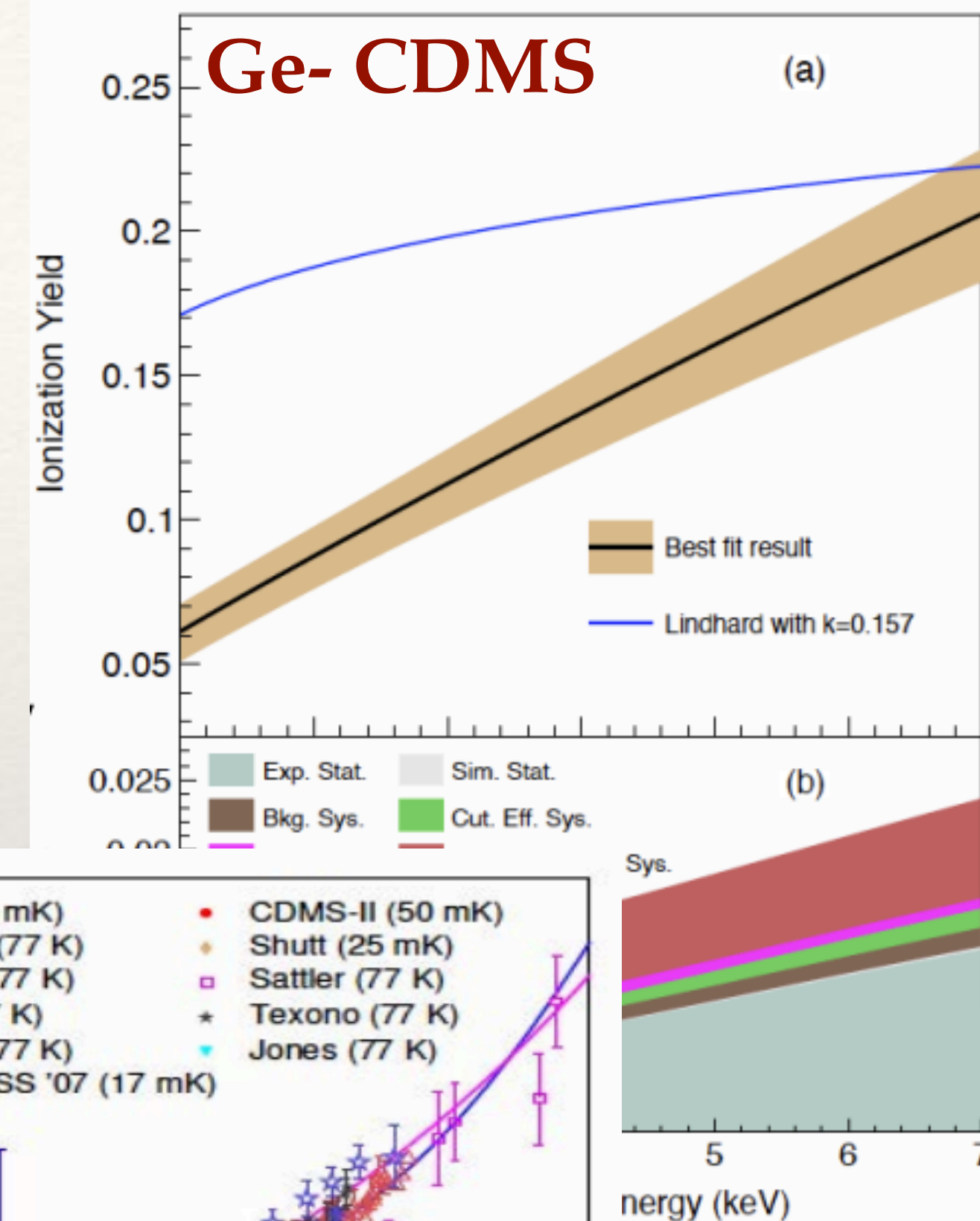
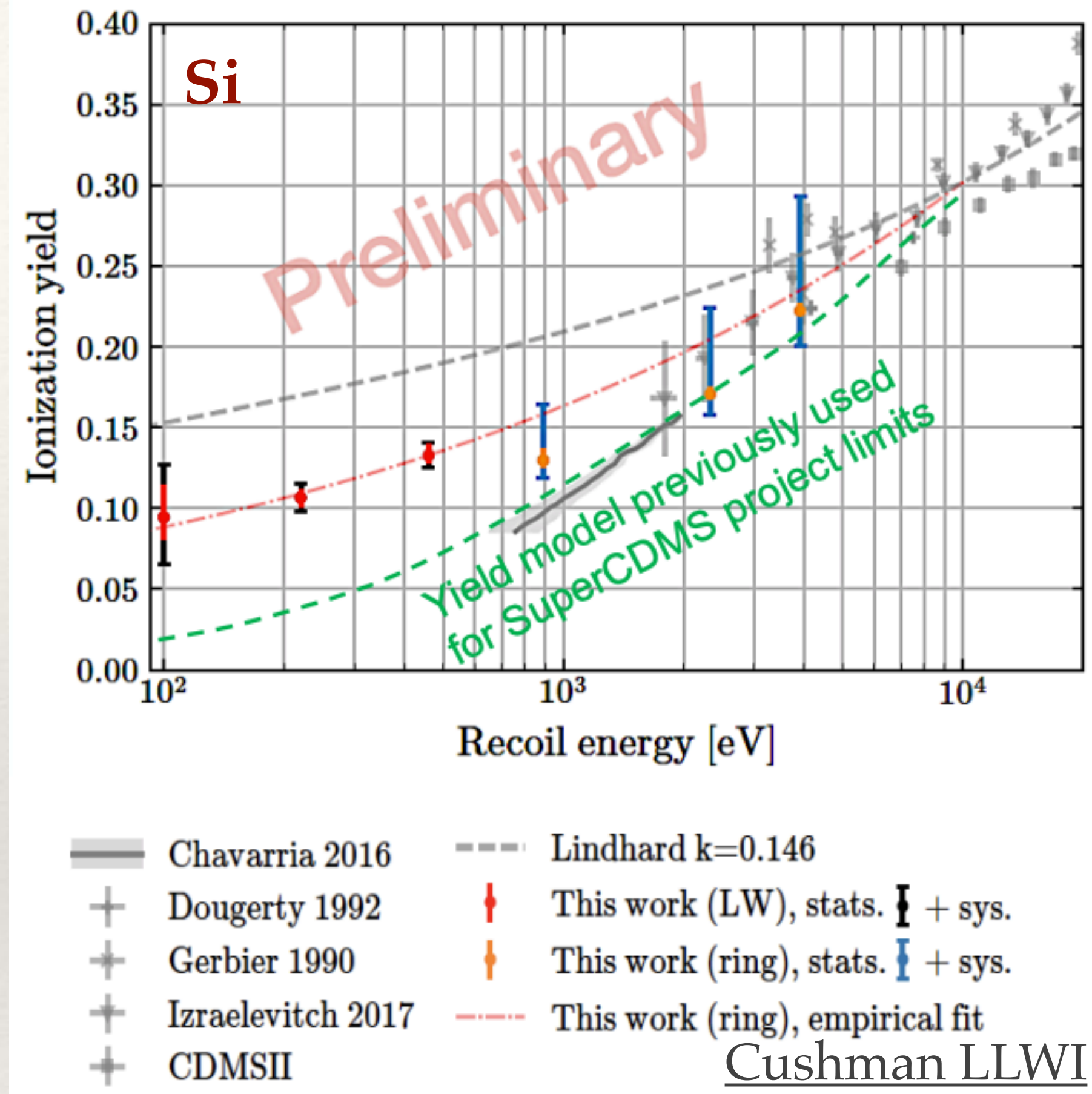
# Direct Detection Sensitivities



arXiv:2203.08084

# SuperCDMS Calibrations

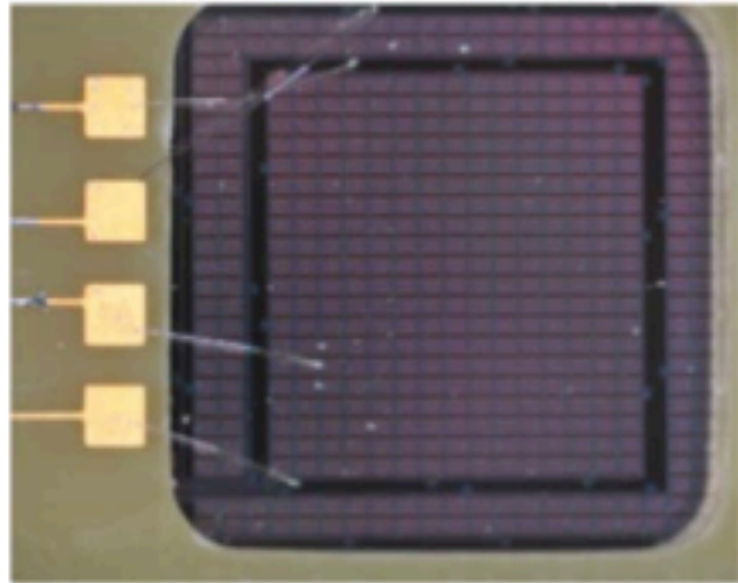
- Calibrating low energy nuclear recoils is difficult
- Discrepancies in the field
- Definitely divergent from Lindhard theory
- Projections for Si more conservative than preliminary measurements



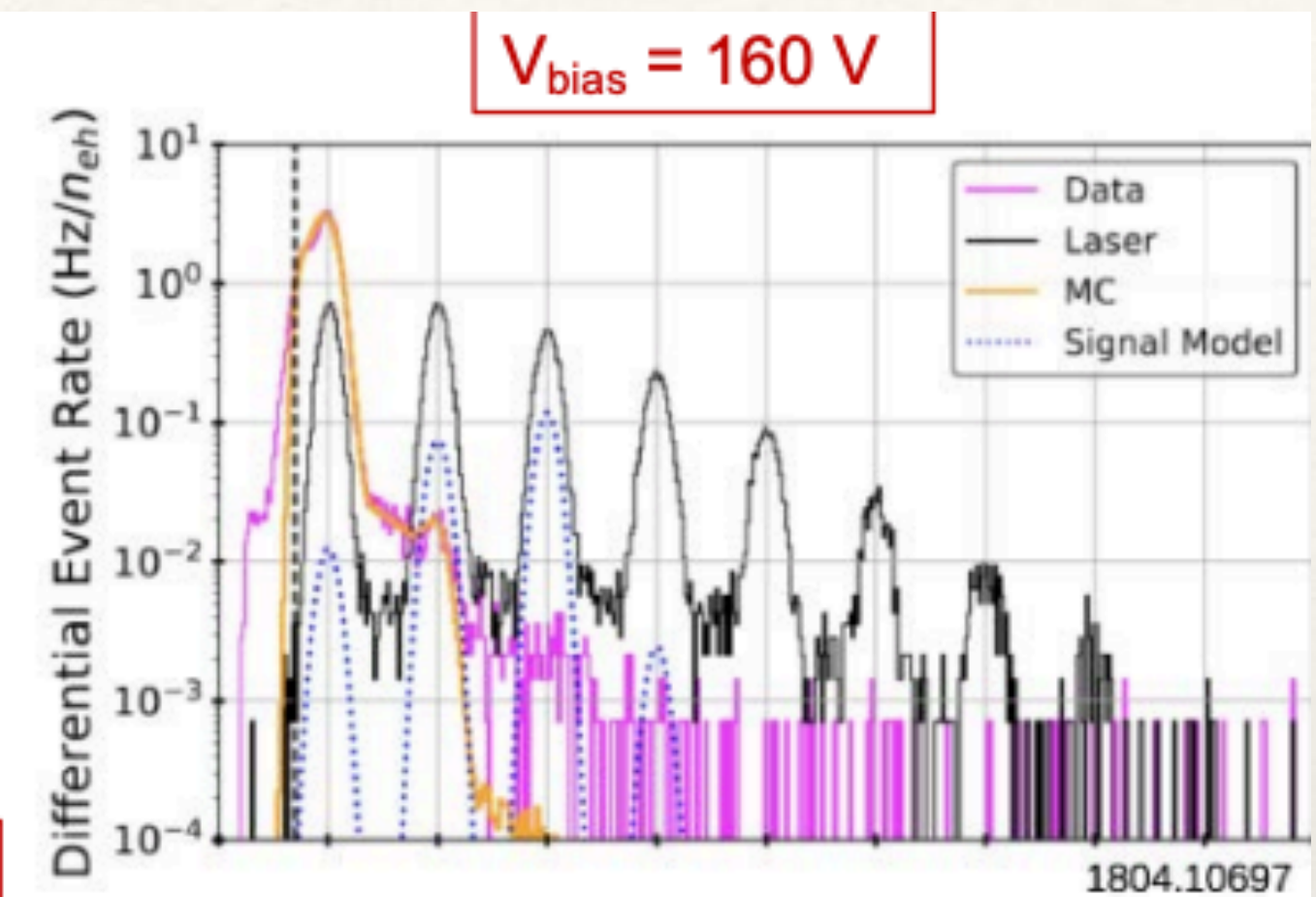
# SuperCDMS: Science with new prototypes

## HVeV (Si or Ge, 1 x 1 cm<sup>2</sup> x 4 mm). 2 equal area QET sensors

R. Agnese *et al.* Phys. Rev. Lett. **121**, 051301 (2018)

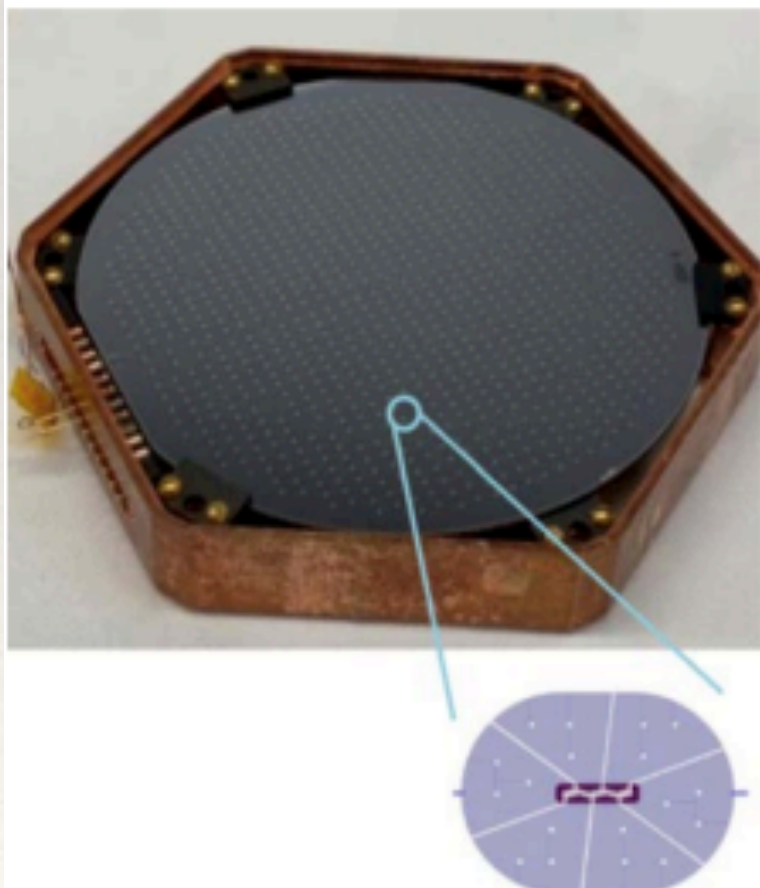


- Study charge transport in Si and Ge, minimize charge leakage
- Improve phonon resolution, study single e-h devices
- Physics runs in NEXUS (FNAL) and CUTE ongoing
- Used in the TUNL ionization yield measurements.

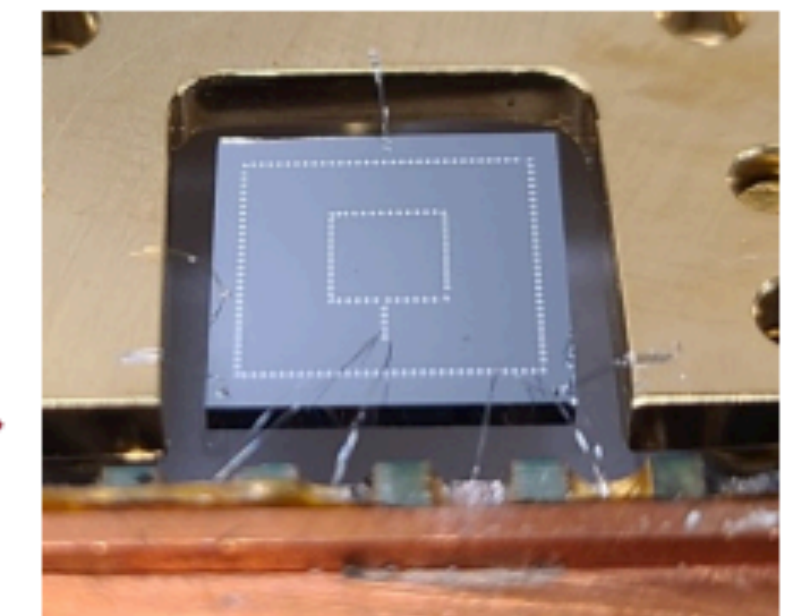


A mosaic of these on 2 SuperCDMS towers can get us to the  $\nu$ -fog in 0.5 – 5 GeV range

## 0V, CPD (cryogenic photon detector) 1 mm thick (45.6 cm<sup>2</sup>) Si wafer with CDMS phonon readout



- Study phonon resolution and test facility noise performance  
*especially “environmental” sub-keV phonon-only backgrounds*
- Phonon resolution in the  $\sigma_{pt} \sim 1$  eV range now.
- New prototype (with new hanging support) may have  $\sigma_{pt} \sim 50 - 100$  meV



A mosaic of the current CPDs on 2 SuperCDMS towers can get us to DM masses of 100 MeV now and down to 50 MeV if the new prototype has sub-eV resolution

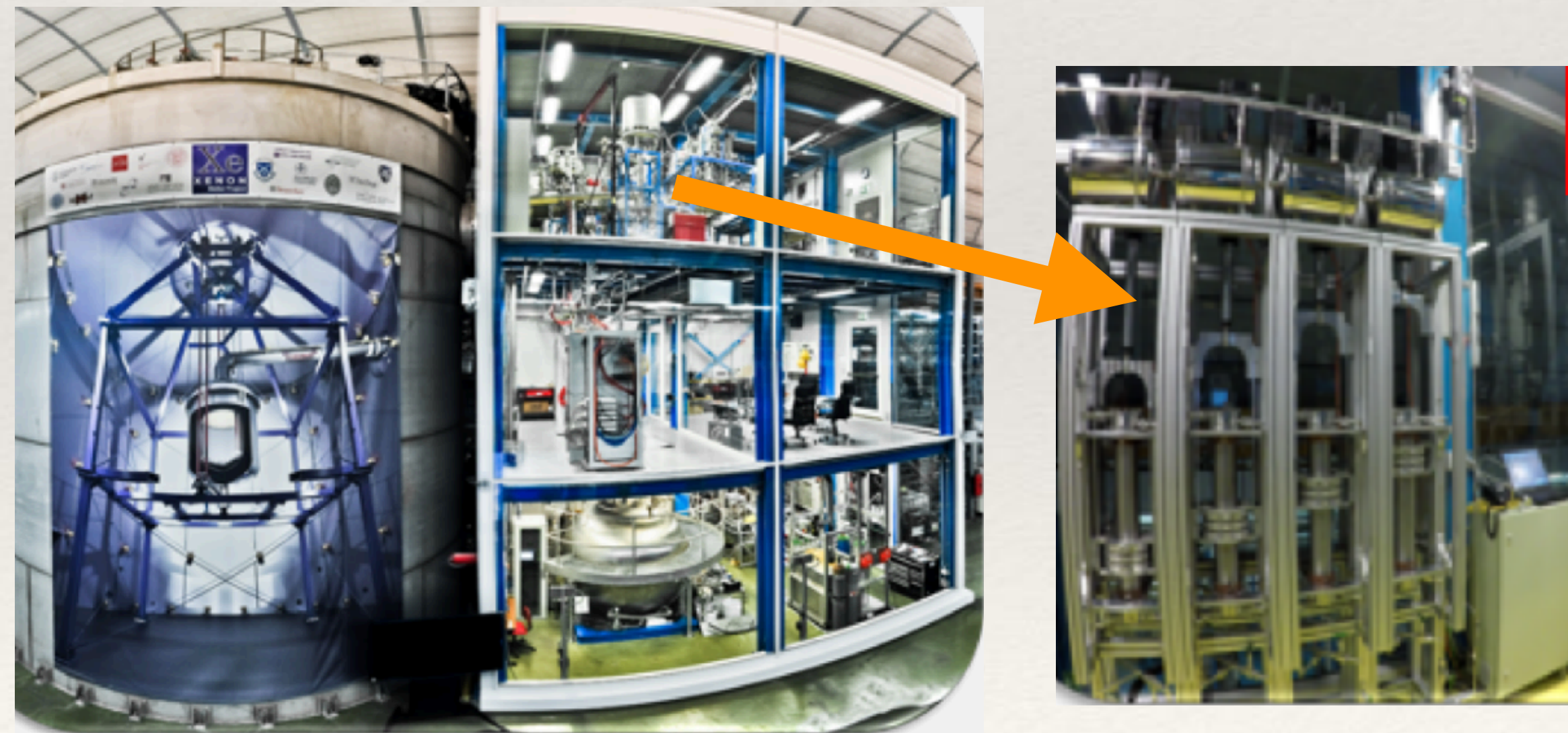
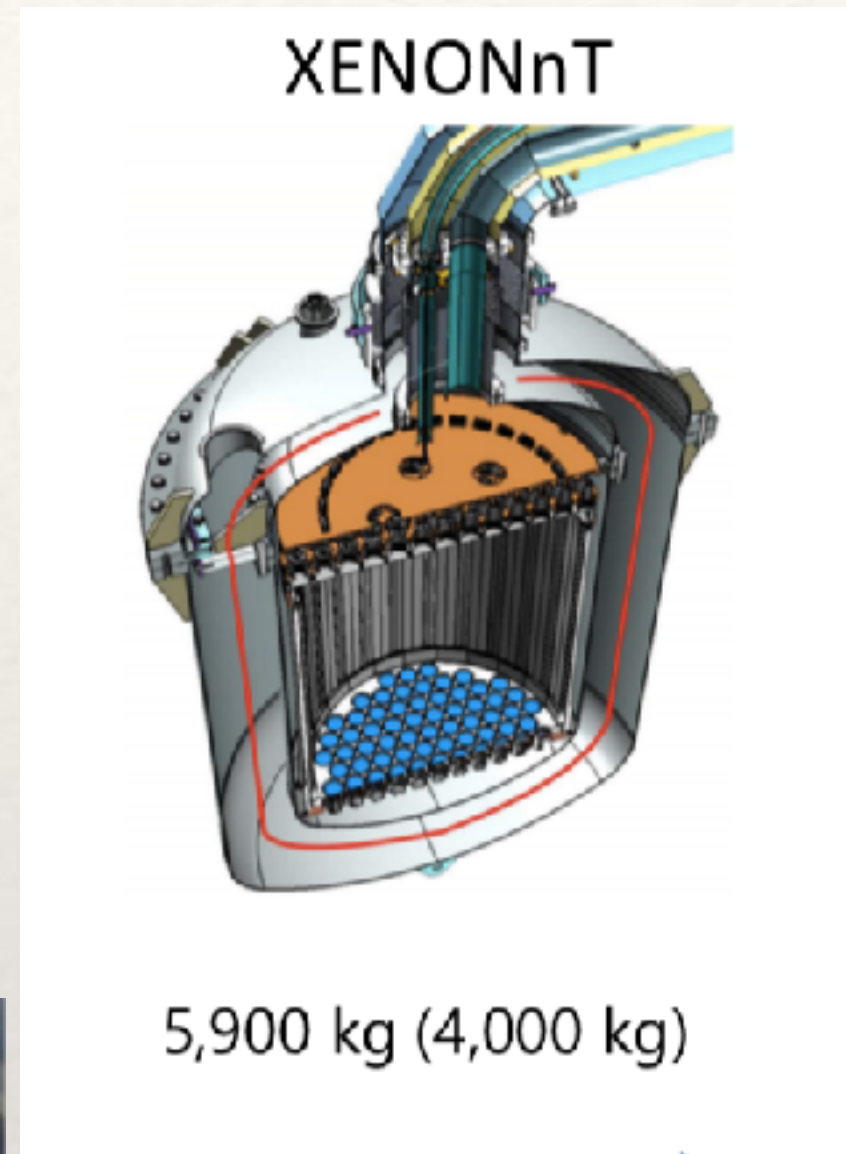
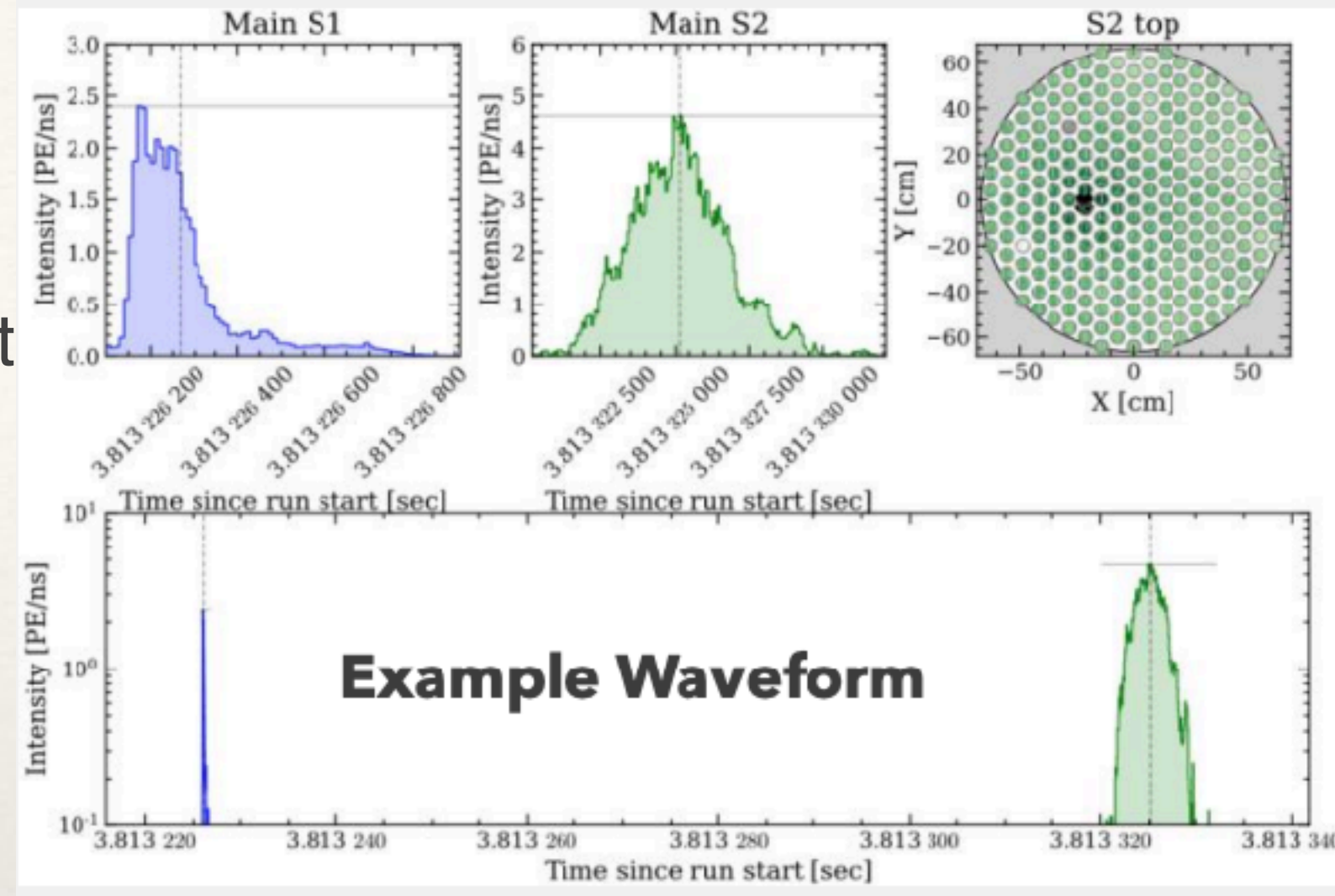
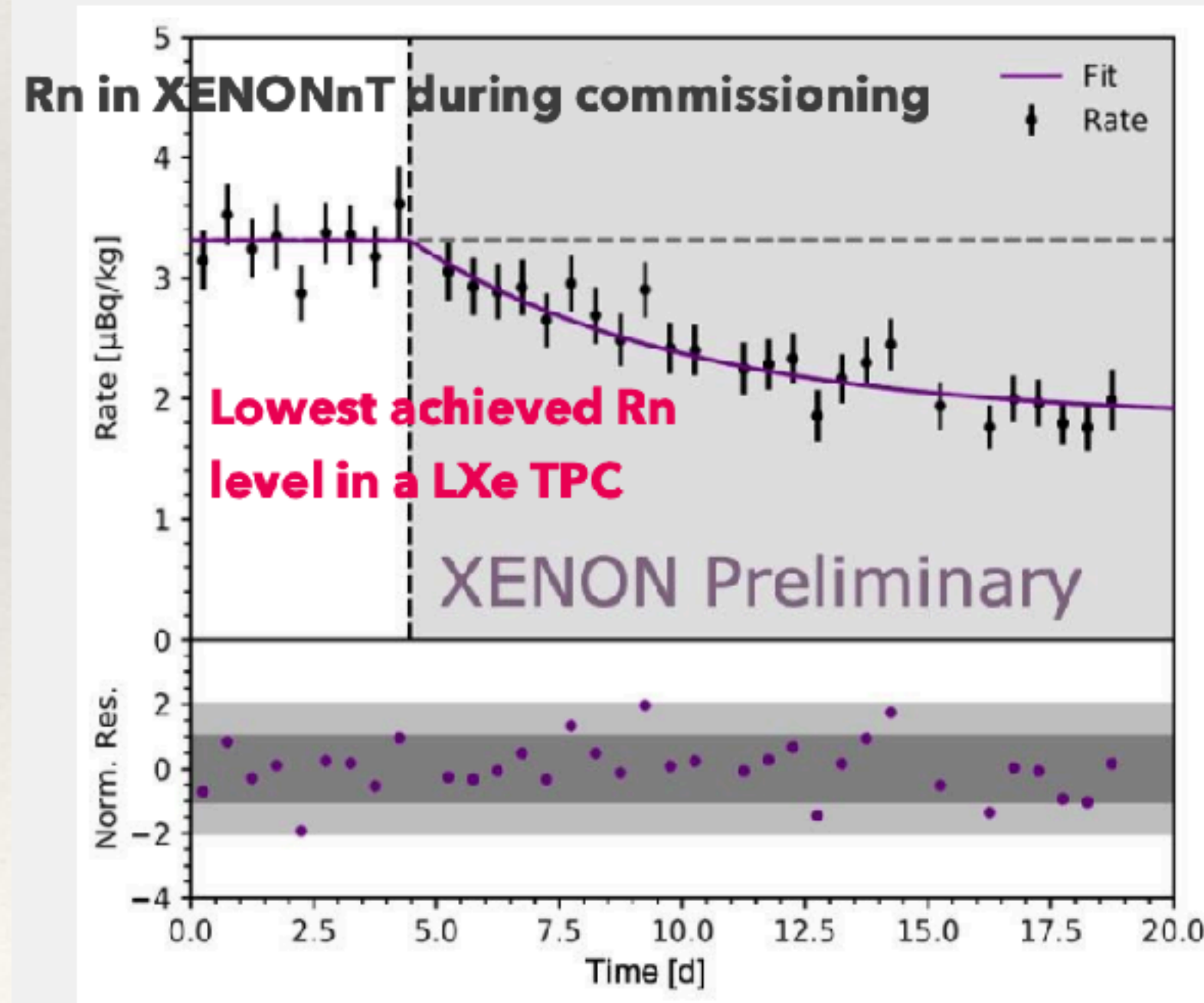
14

Cushman LLWI

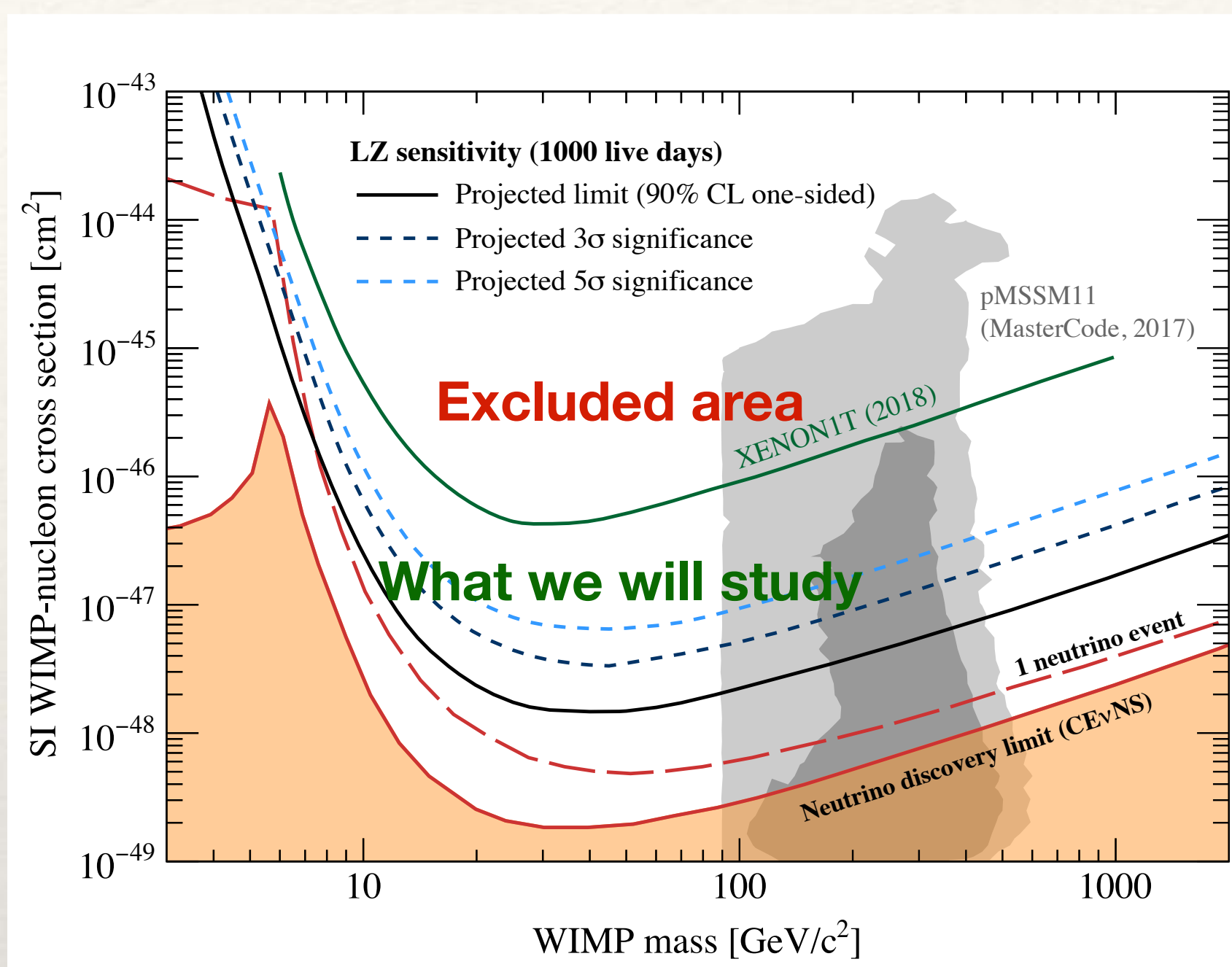
# XENONnT

- 5.9 t liquid xenon TPC
- Operating at LNGS in Italy since Sept '21
- Radon/krypton reduction with cryogenic dist and custom pump
- Drift field is a little low

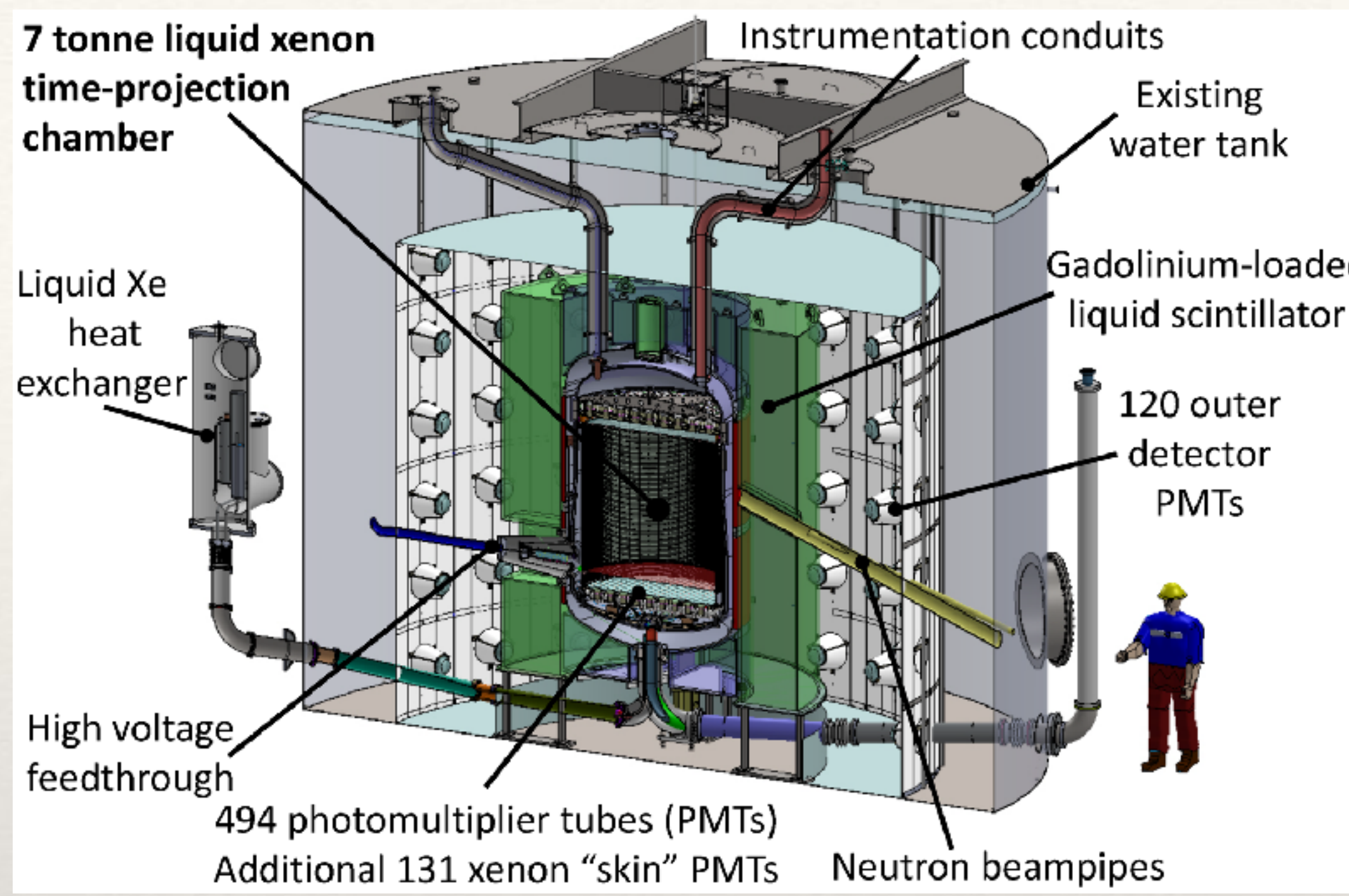
## Pienaar TAUP 21



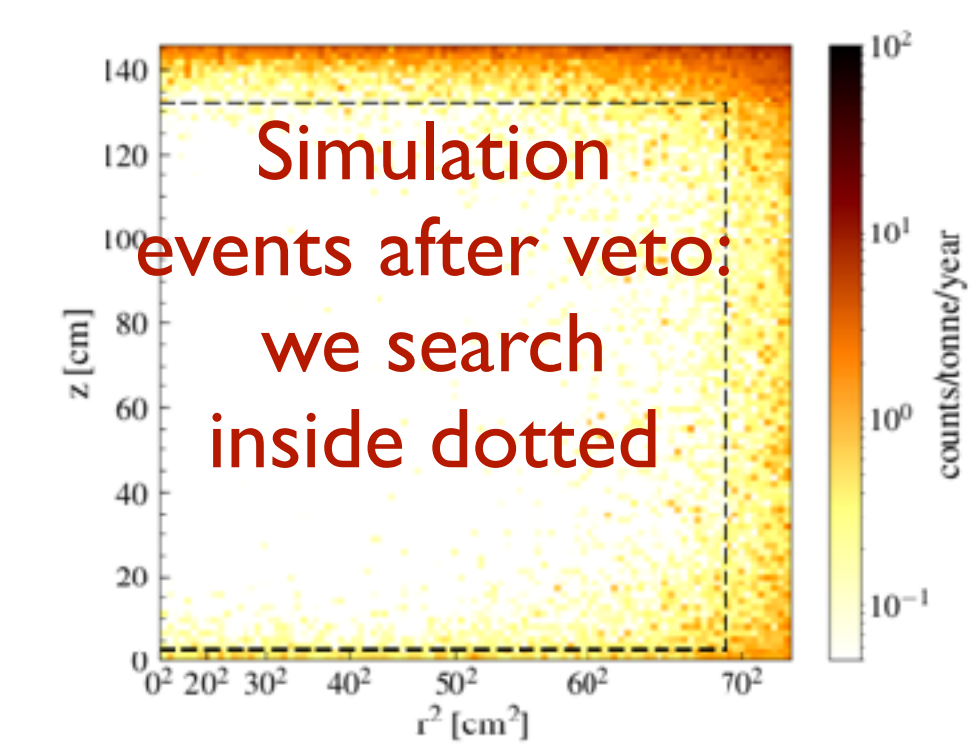
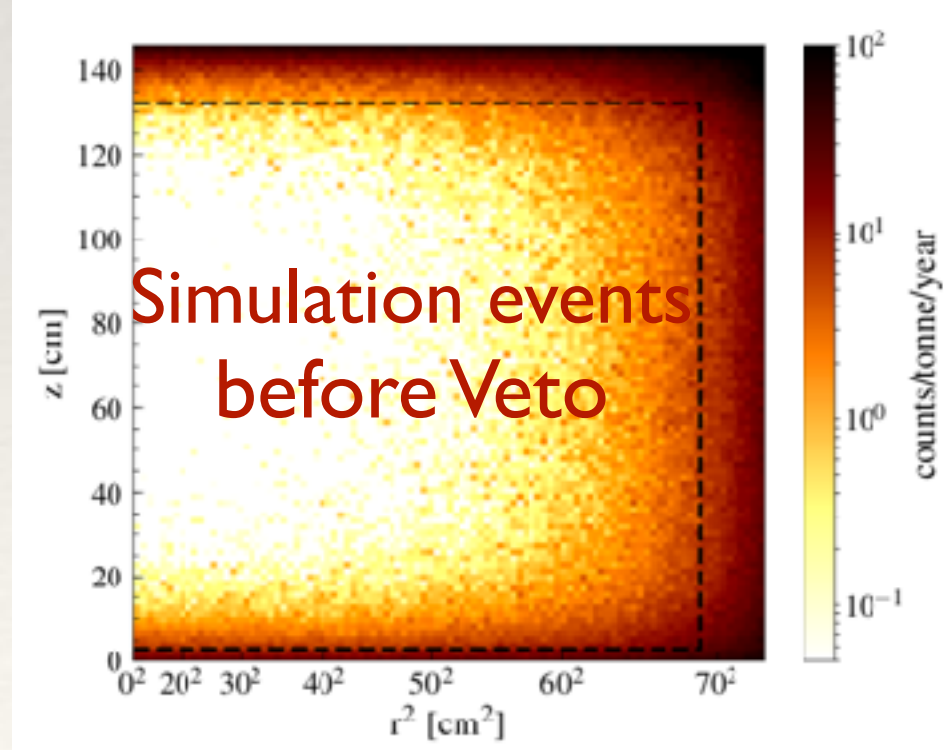




arXiv:1802.06039



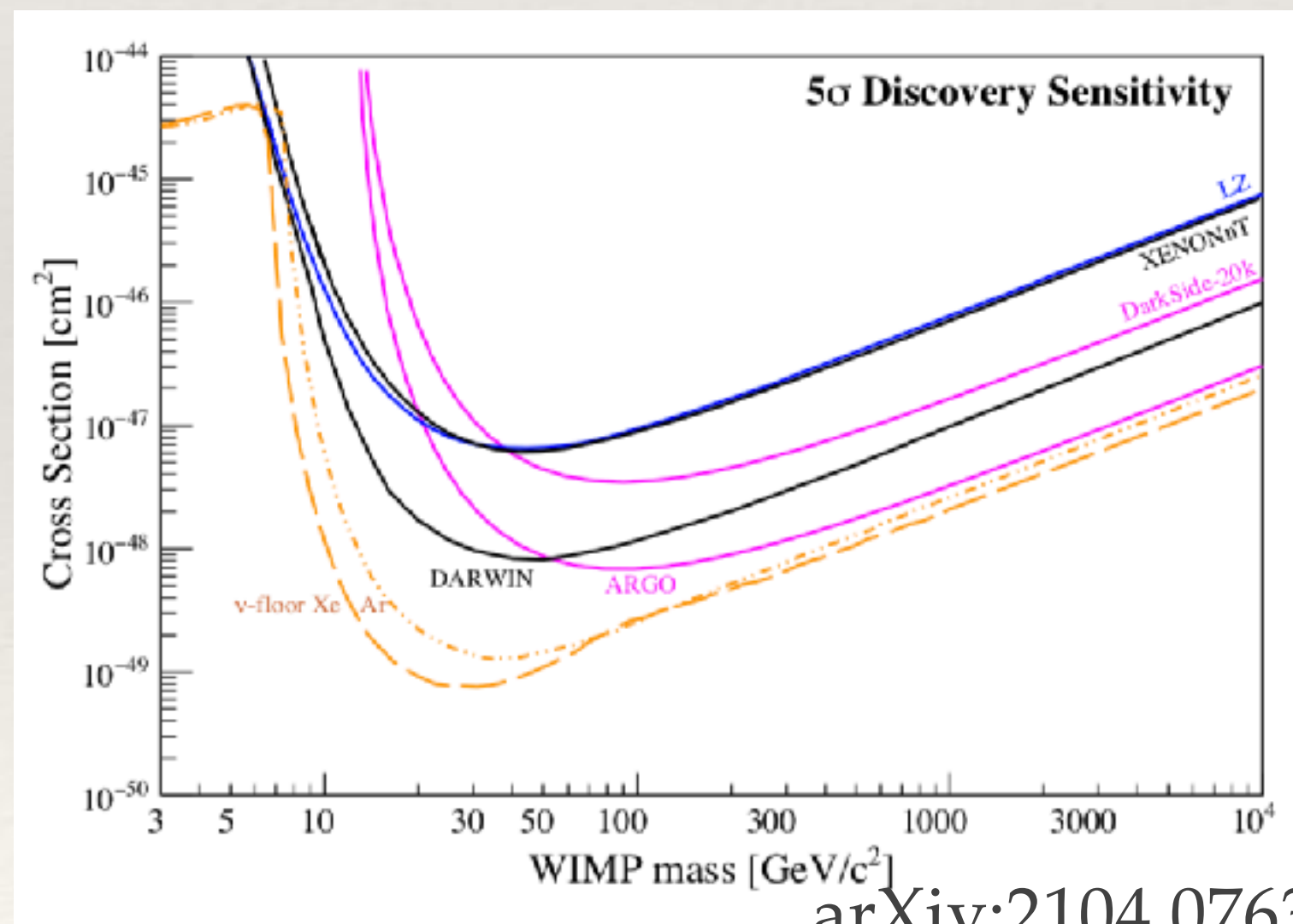
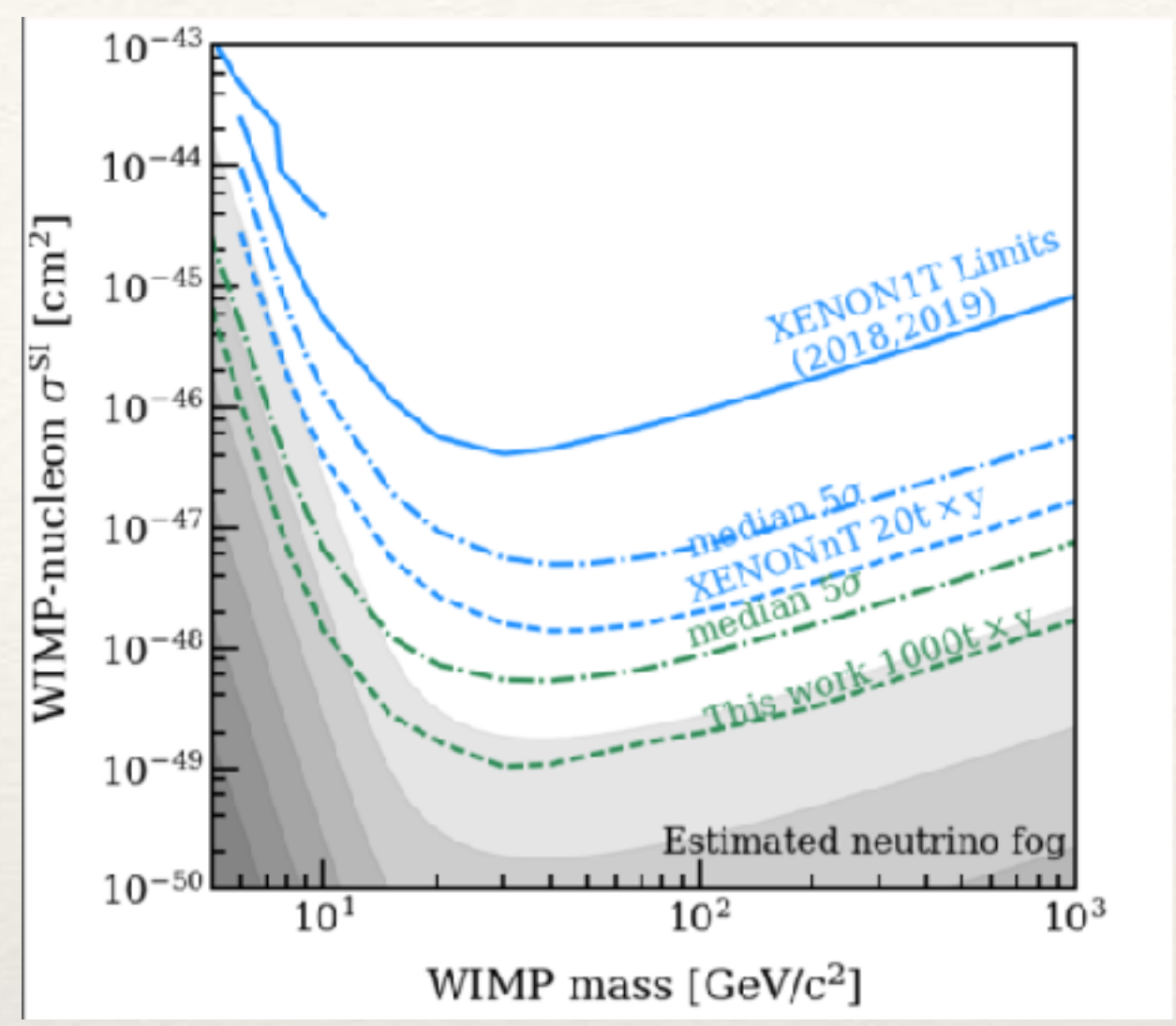
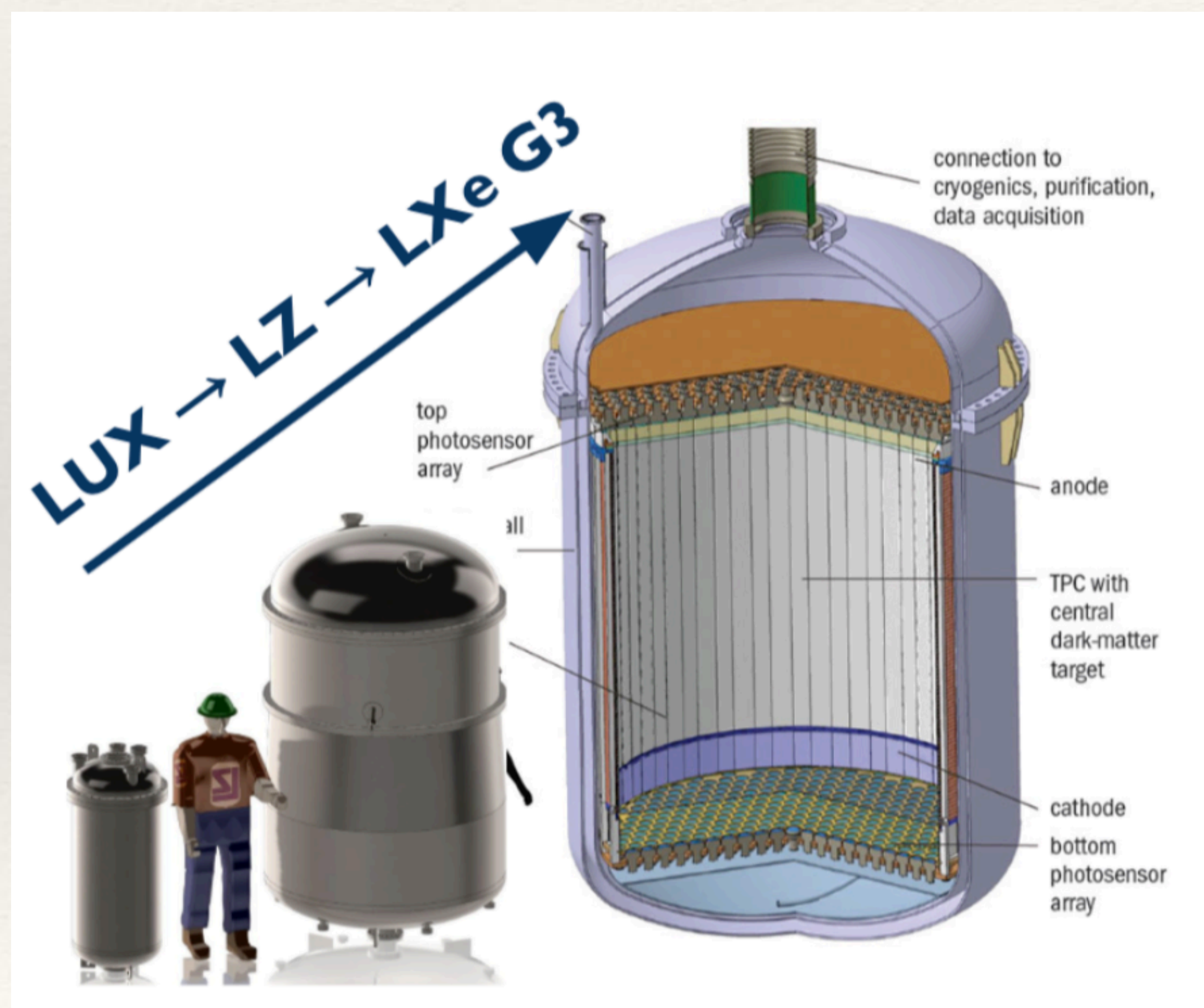
- 10 t liquid xenon
- Operating at SURF in South Dakota USA
- Planned for 1000 live days over ~5 years



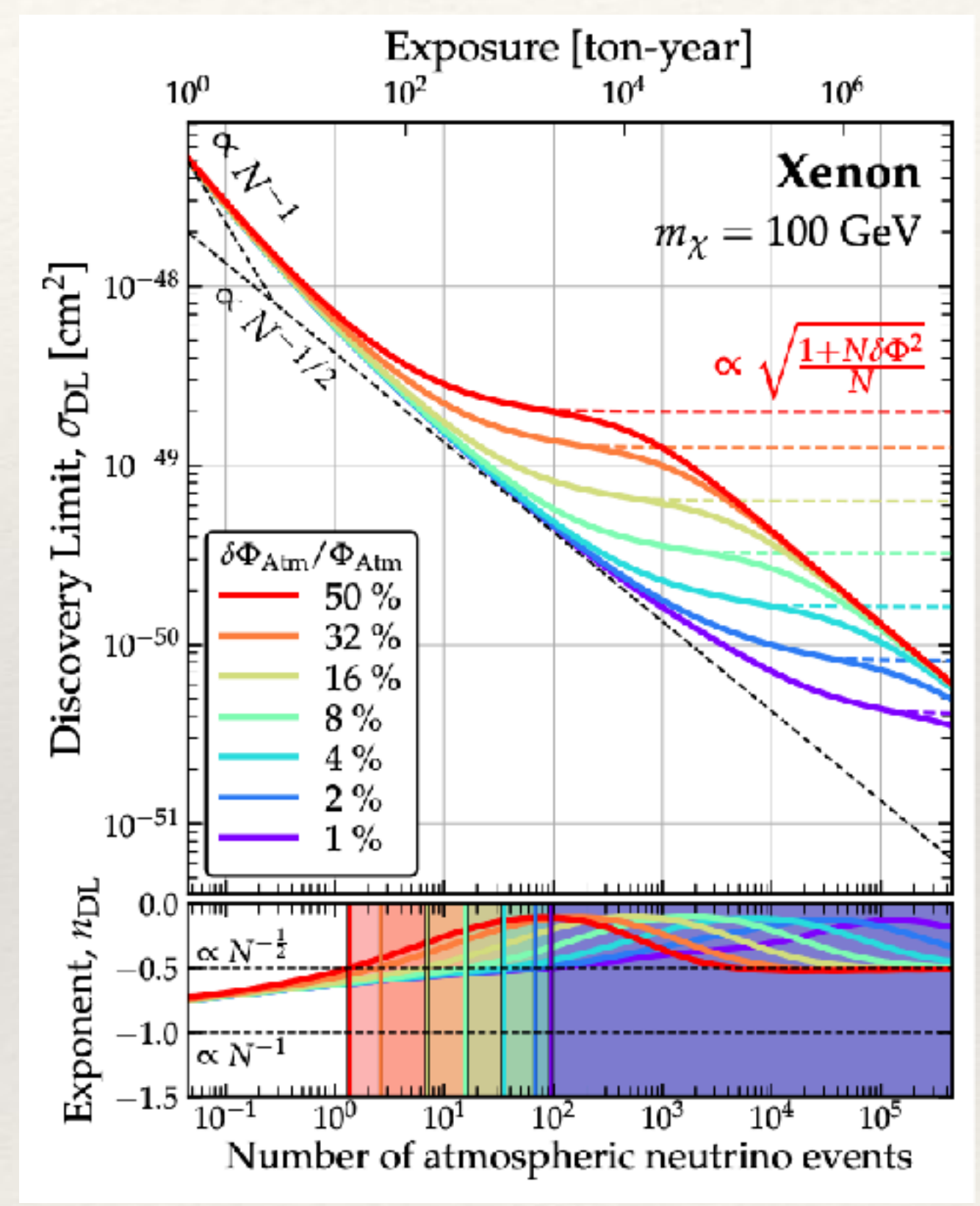
- Many talks in parallels this afternoon and tomorrow

# Next Generation Liquid Xenon

- 50–100 t liquid xenon TPC
- Combination of XENONnT/DARWIN and LZ collaborations
- Location TBD
- Joint workshop last spring, meeting this summer

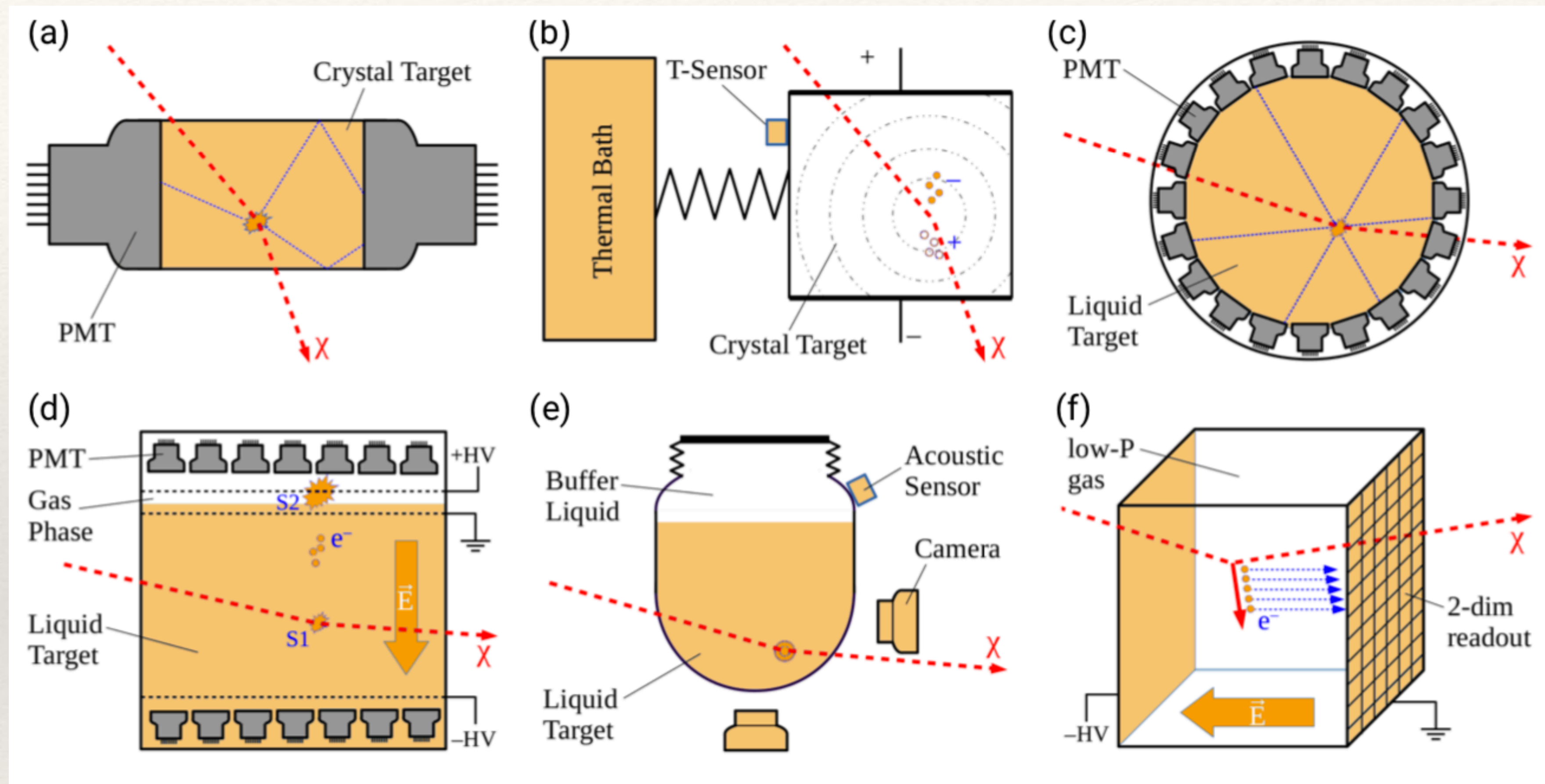


arXiv:2203.02309

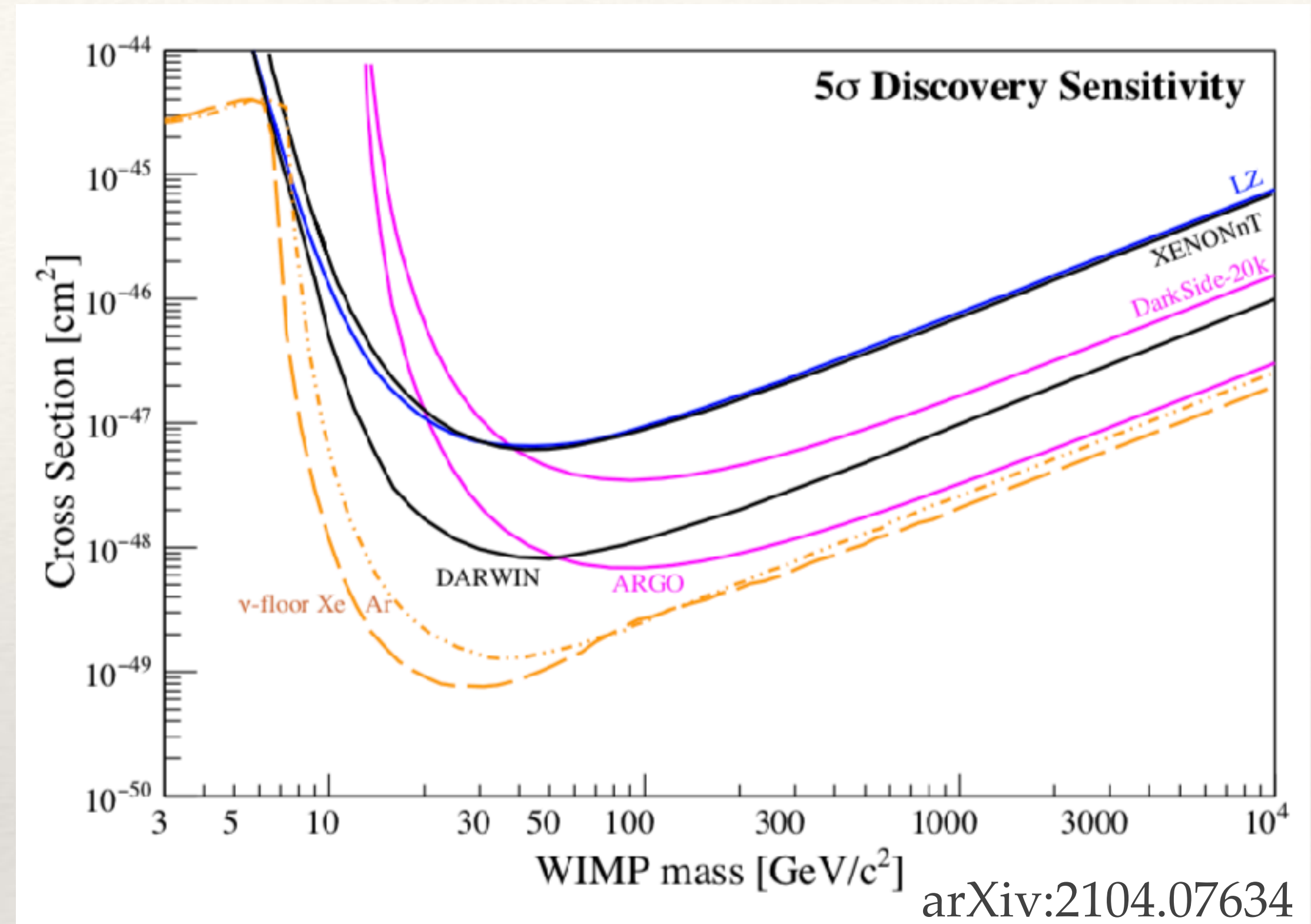


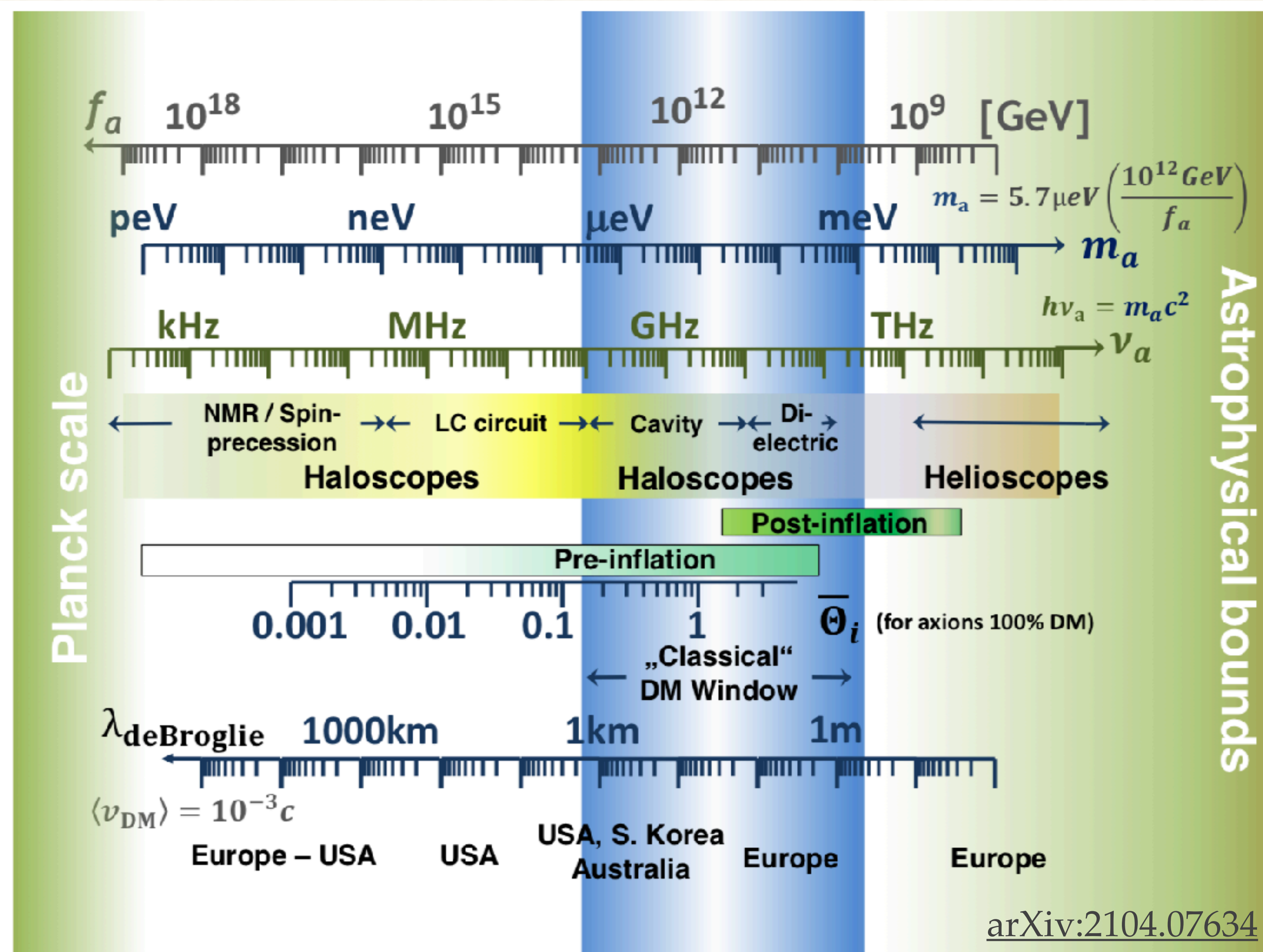
arXiv:2104.07634

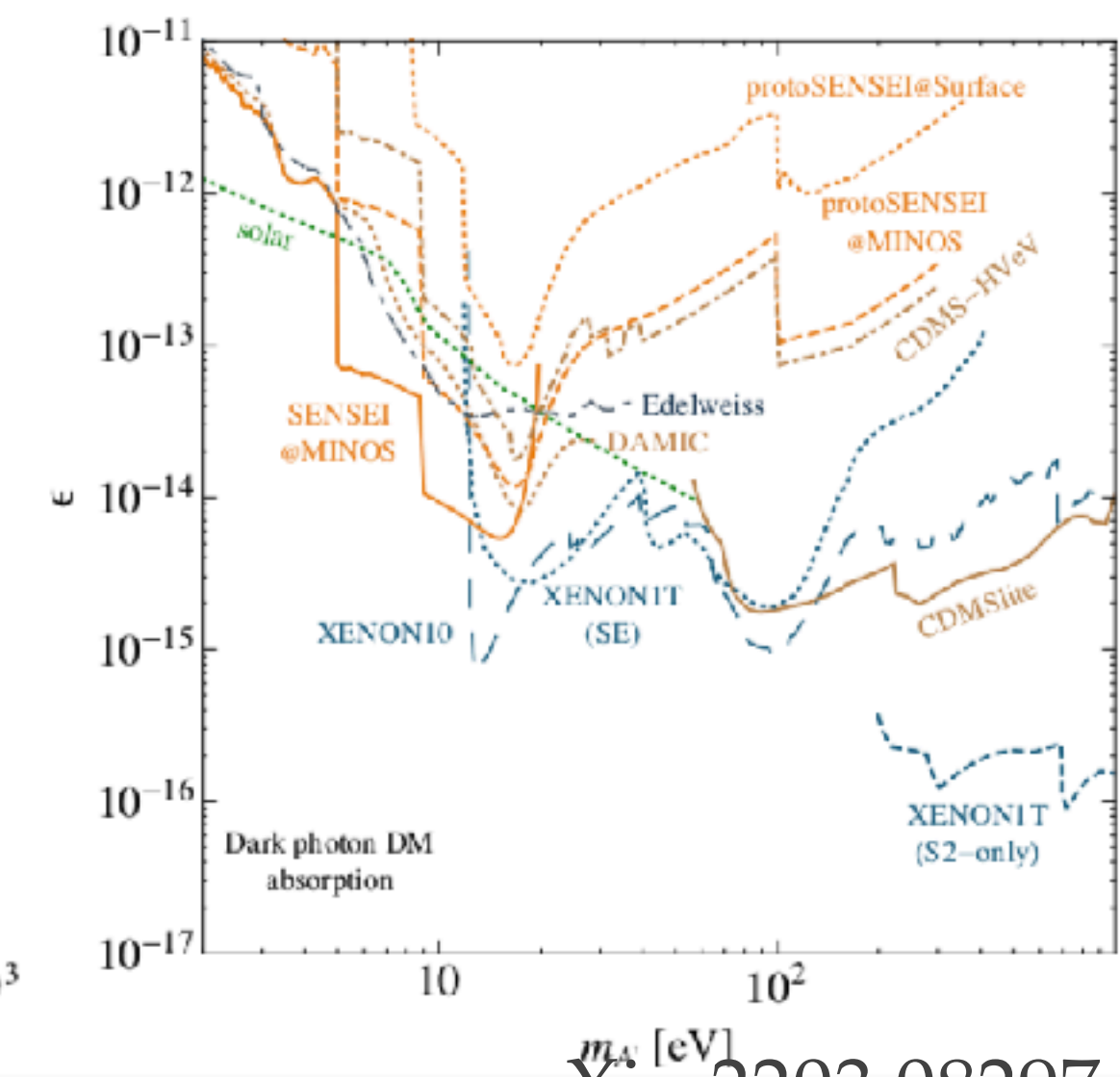
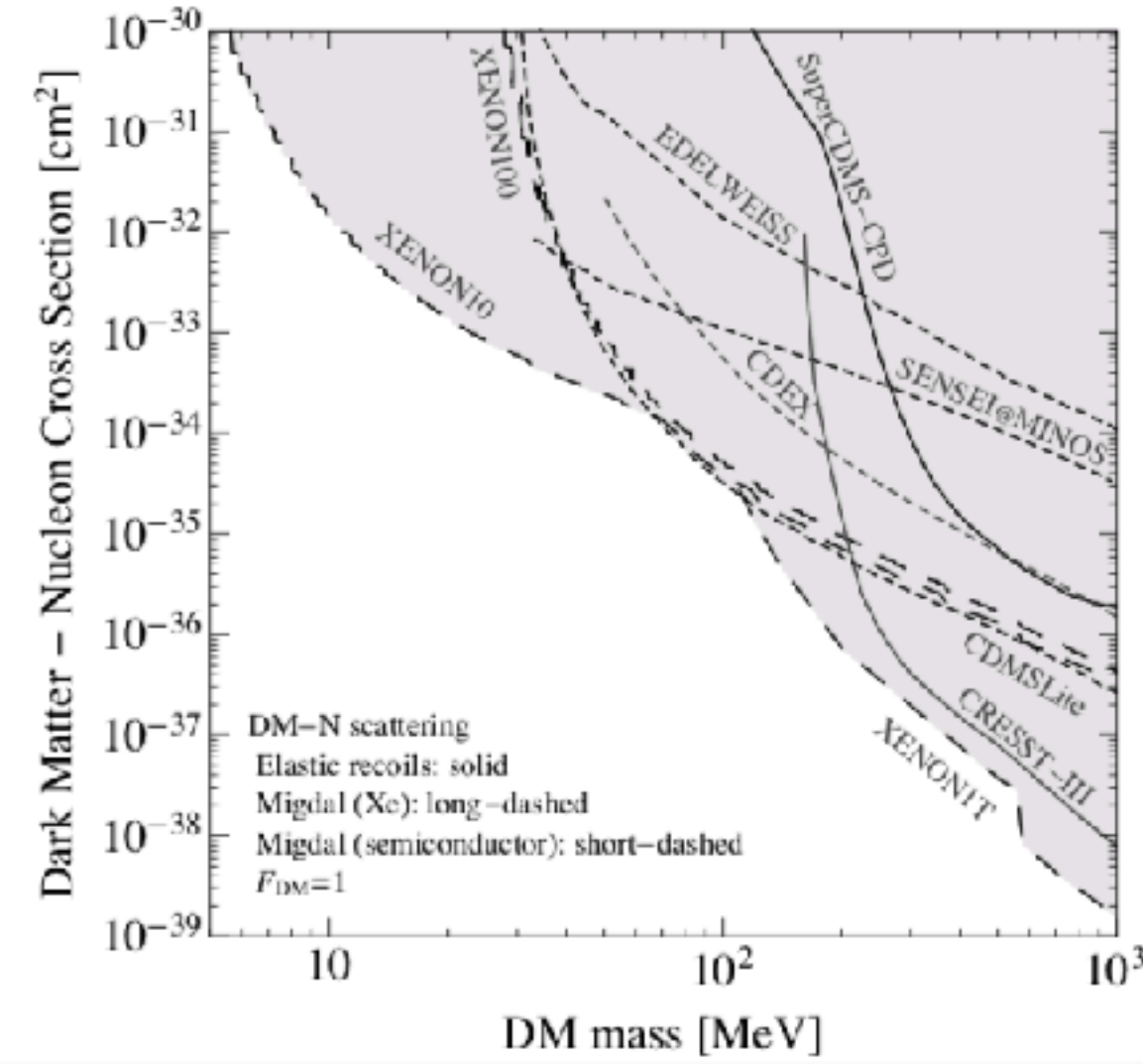
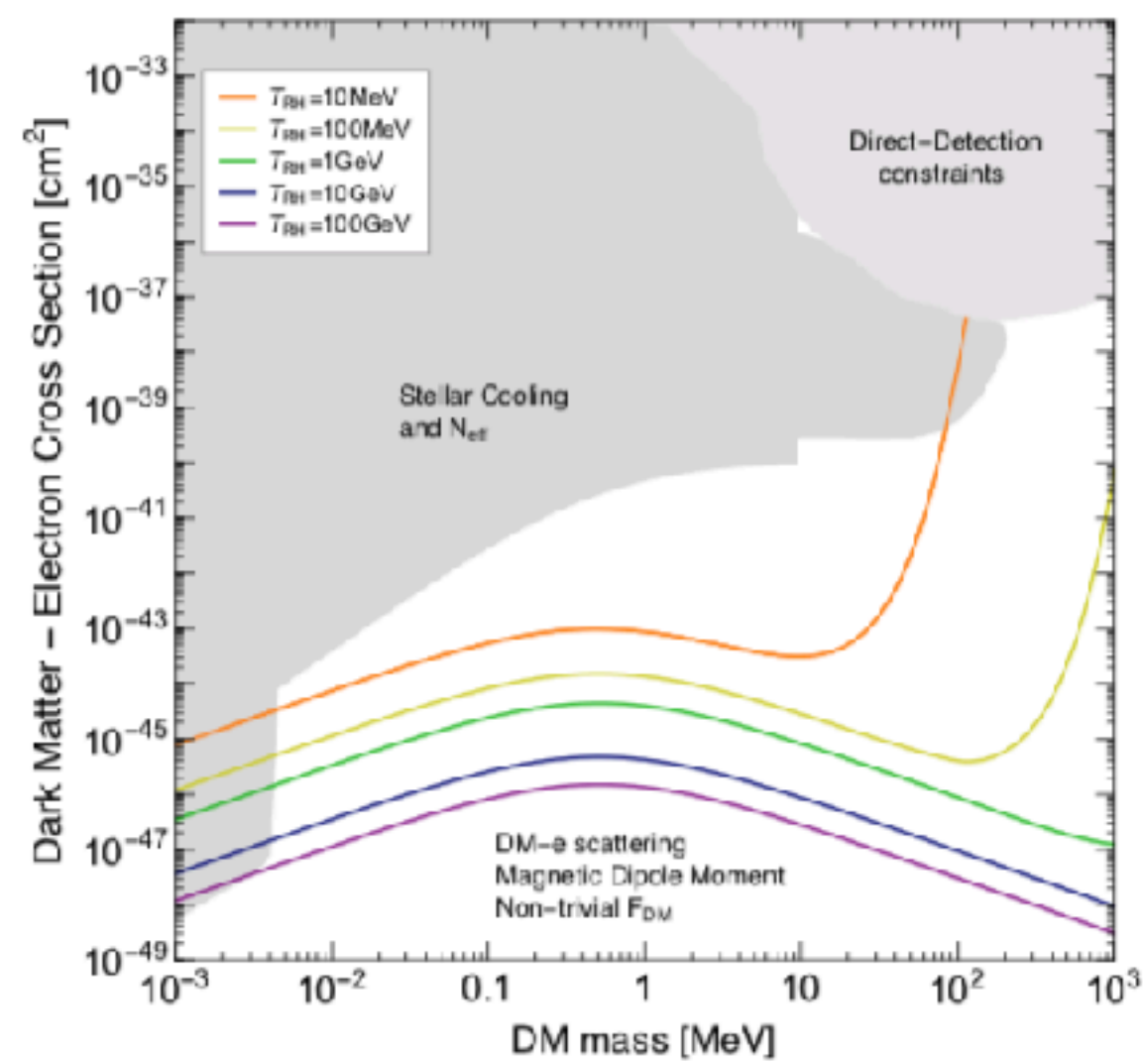
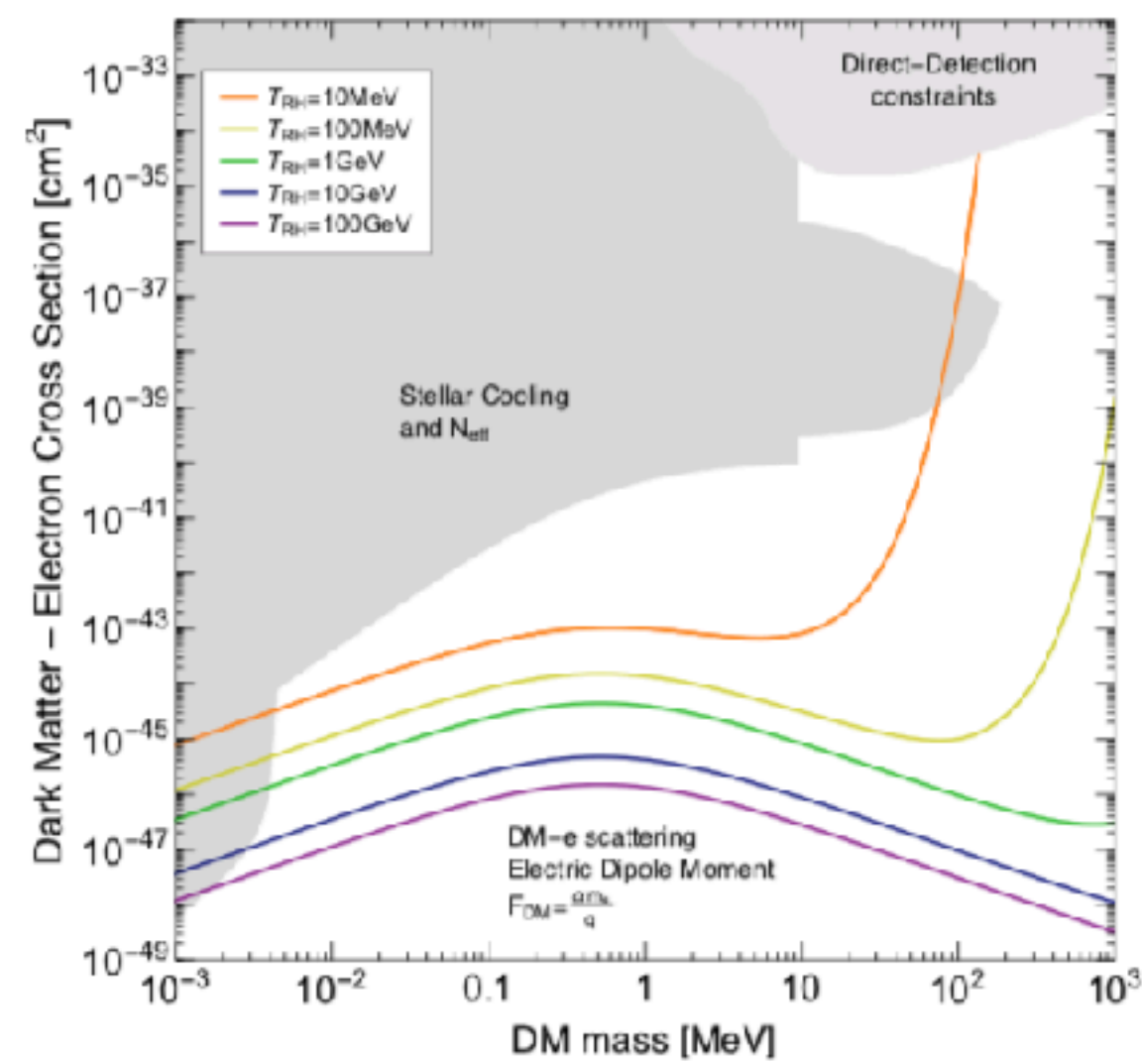
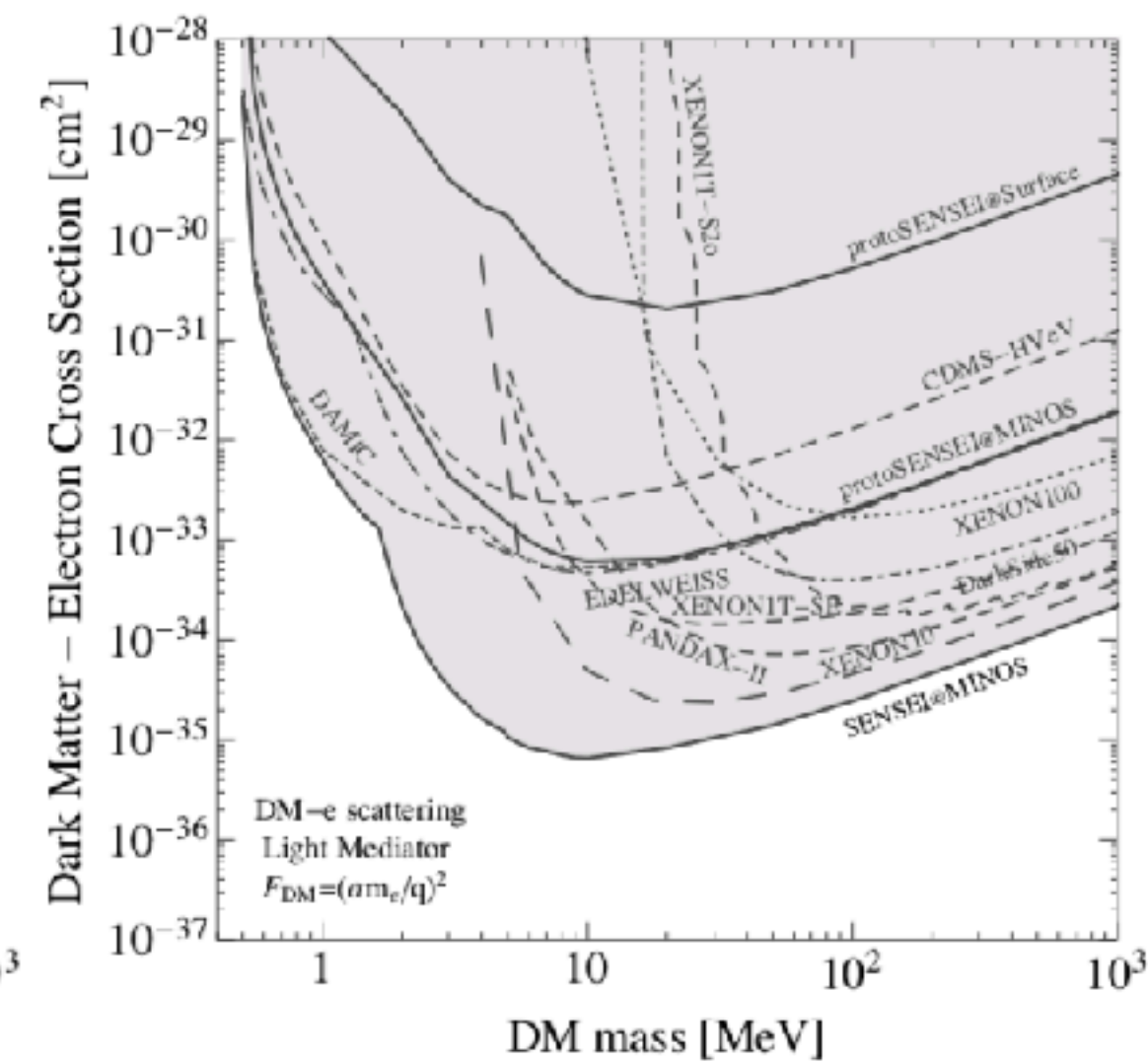
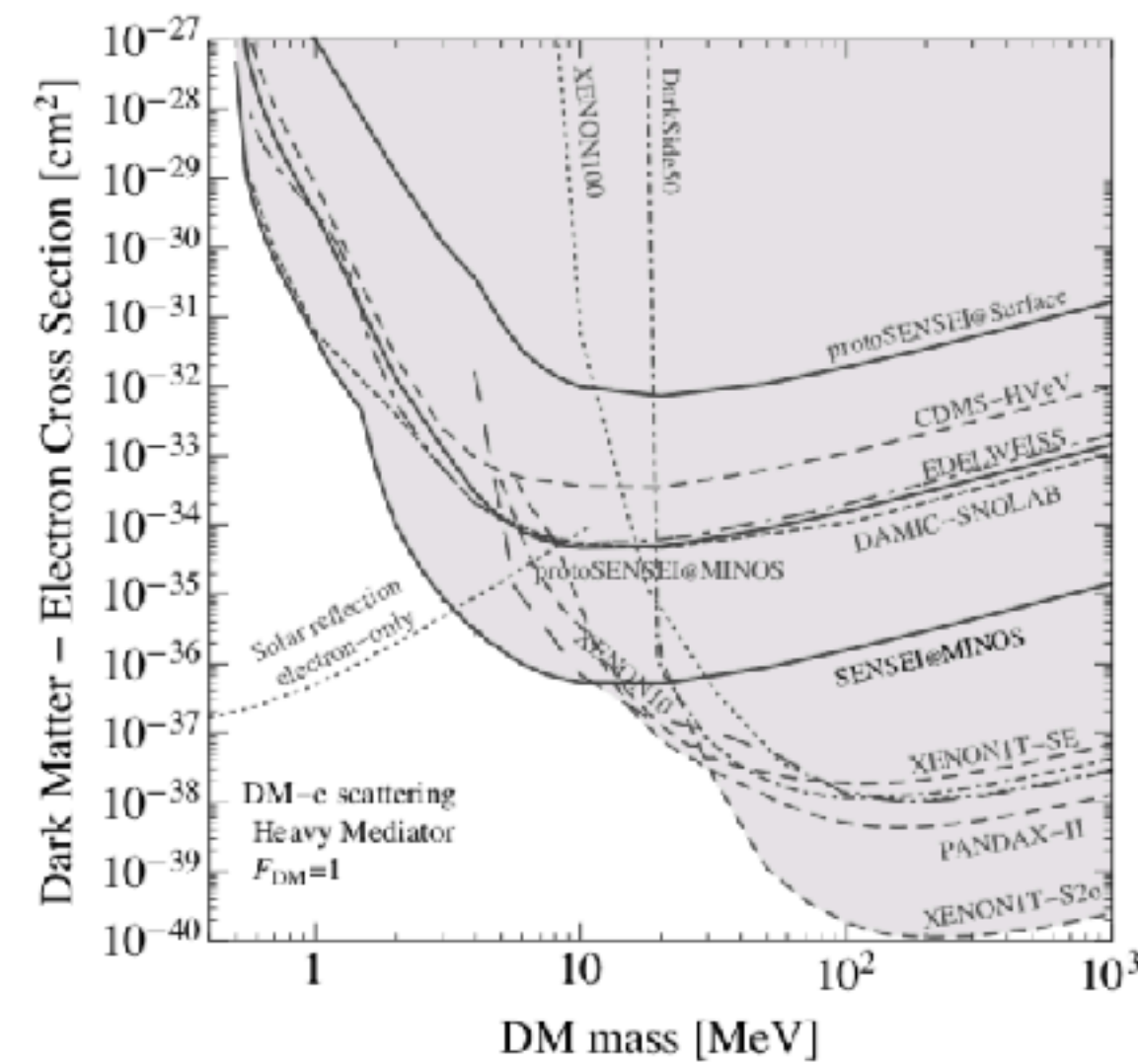
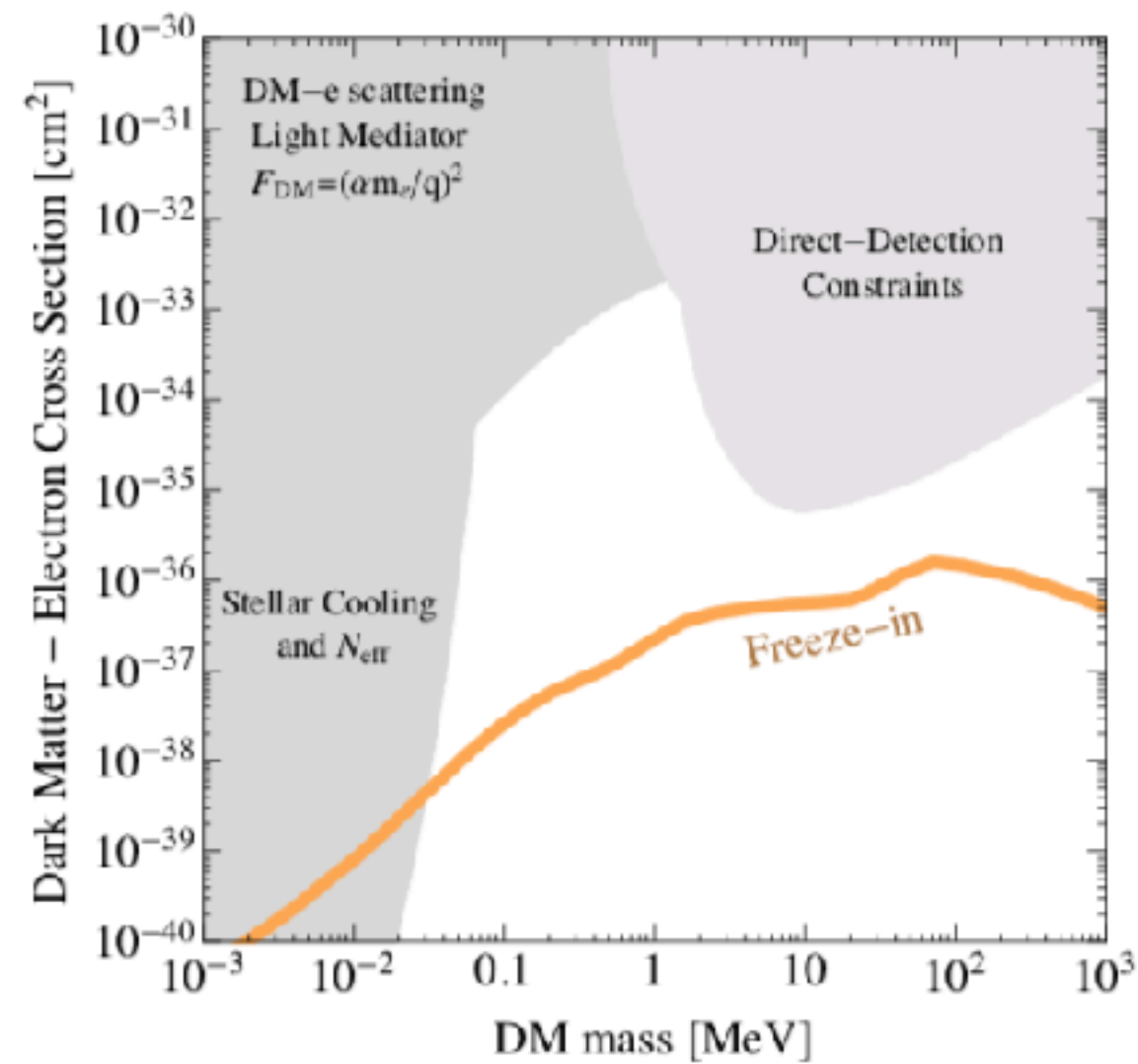
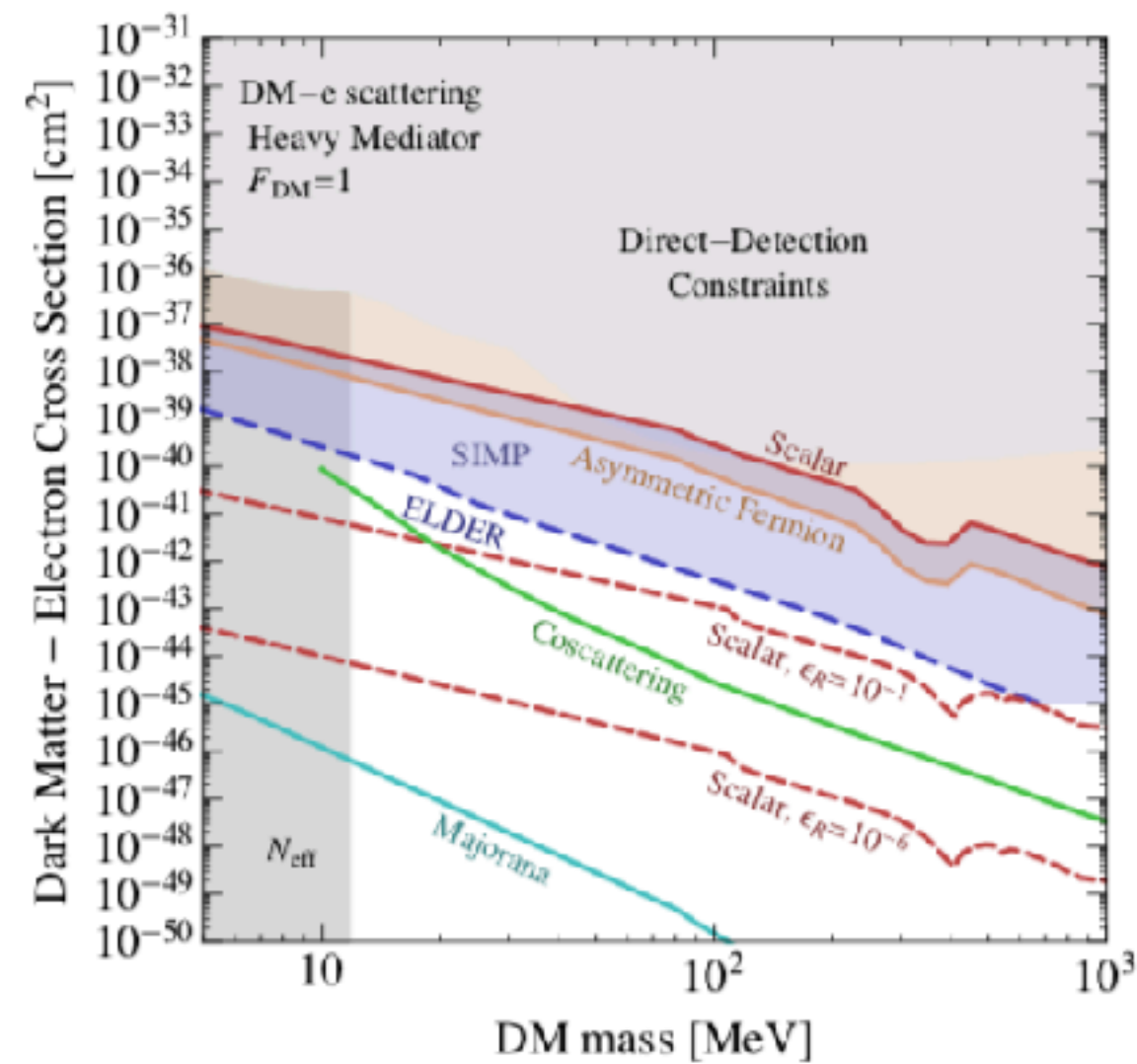
- 
- **April Showers Bring May Flowers:**
  - **Good things are coming**
  - **Strong chances for Discovery**
  - **Headlining experiments and small tests**
  - **Many more DM candidates and experimental techniques to explore than we considered a decade ago**



[arXiv:2104.07634](https://arxiv.org/abs/2104.07634)

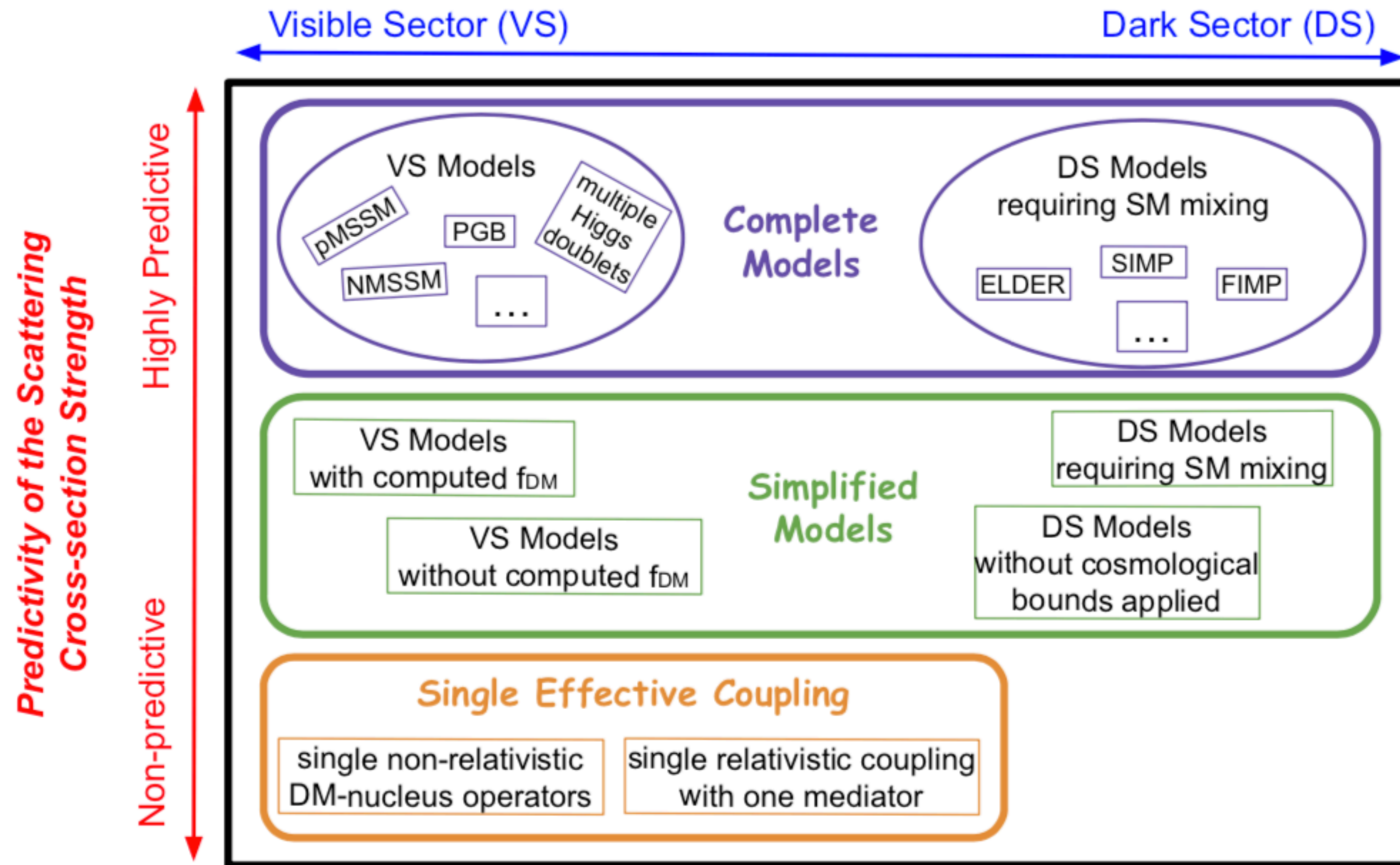






$m_\chi$  [eV]  
arXiv:2203.08297

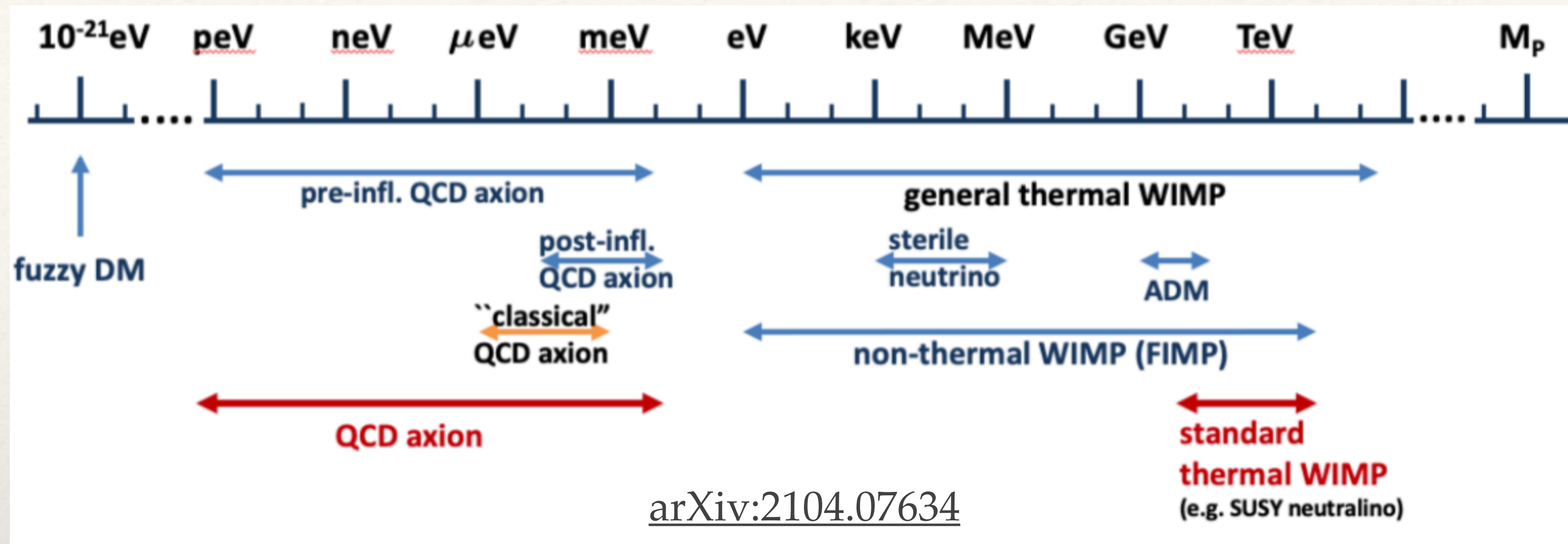
## Type of Dark Matter Model

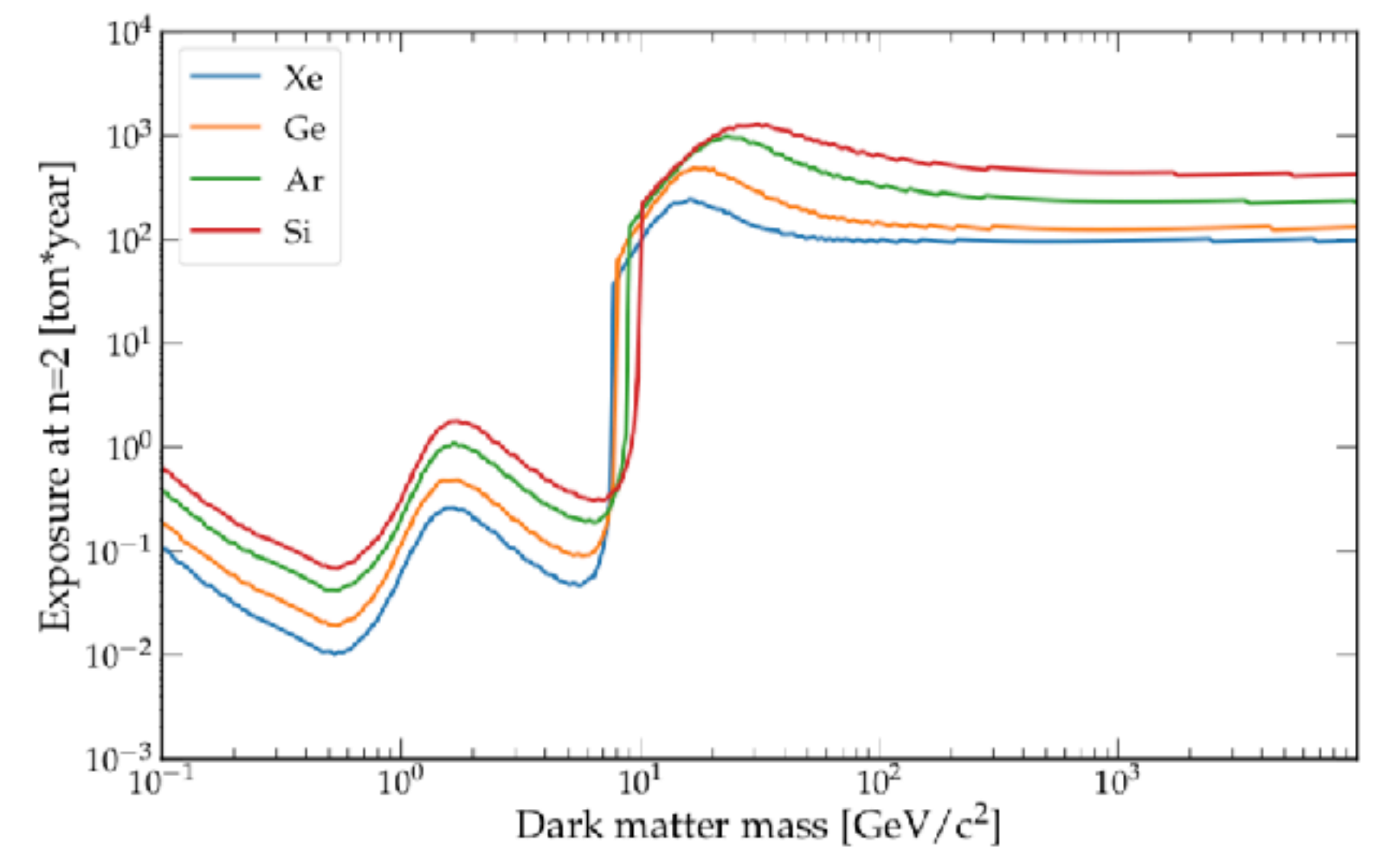
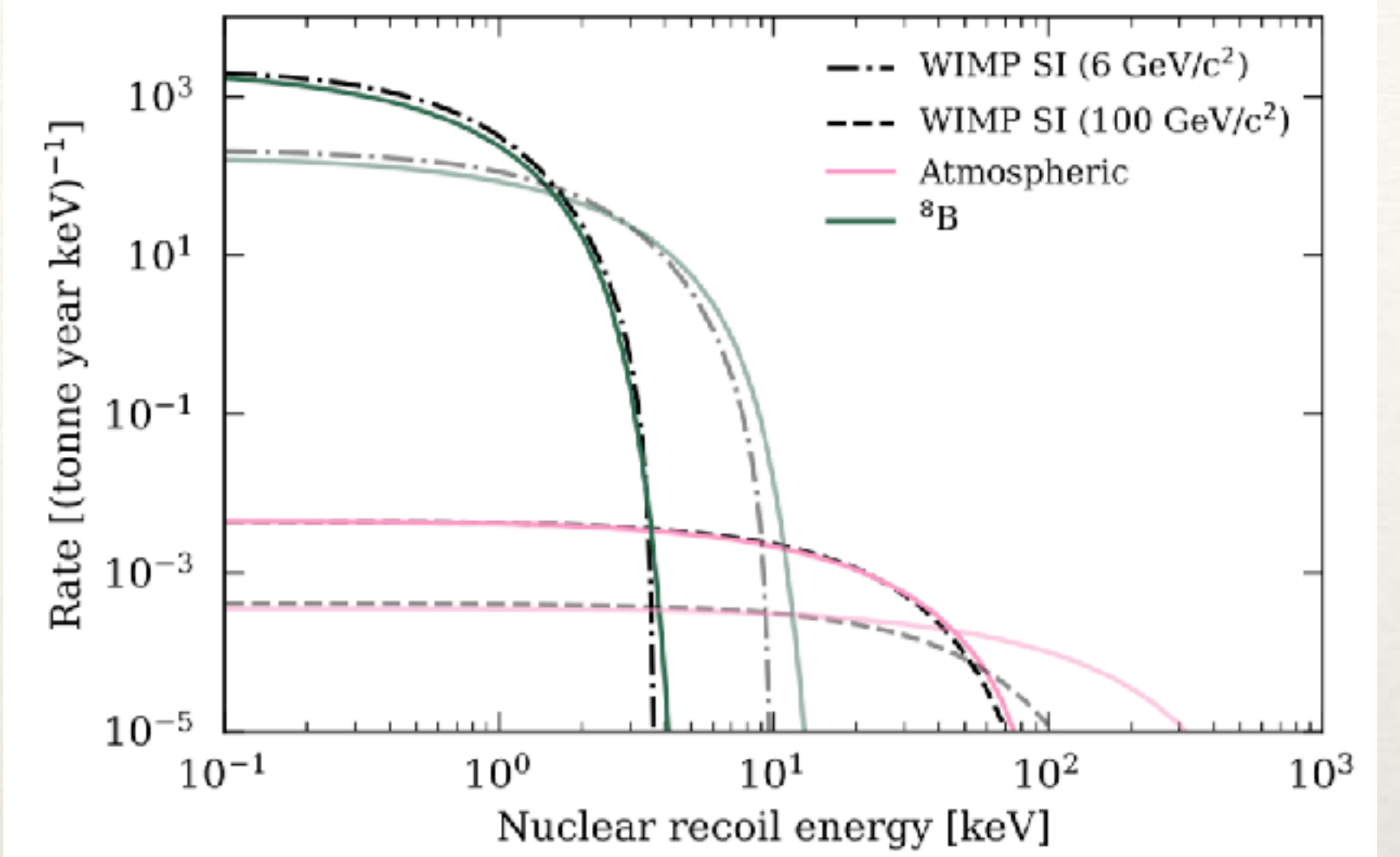


arXiv:2203.08084



# The Main Options





arXiv:2203.08084