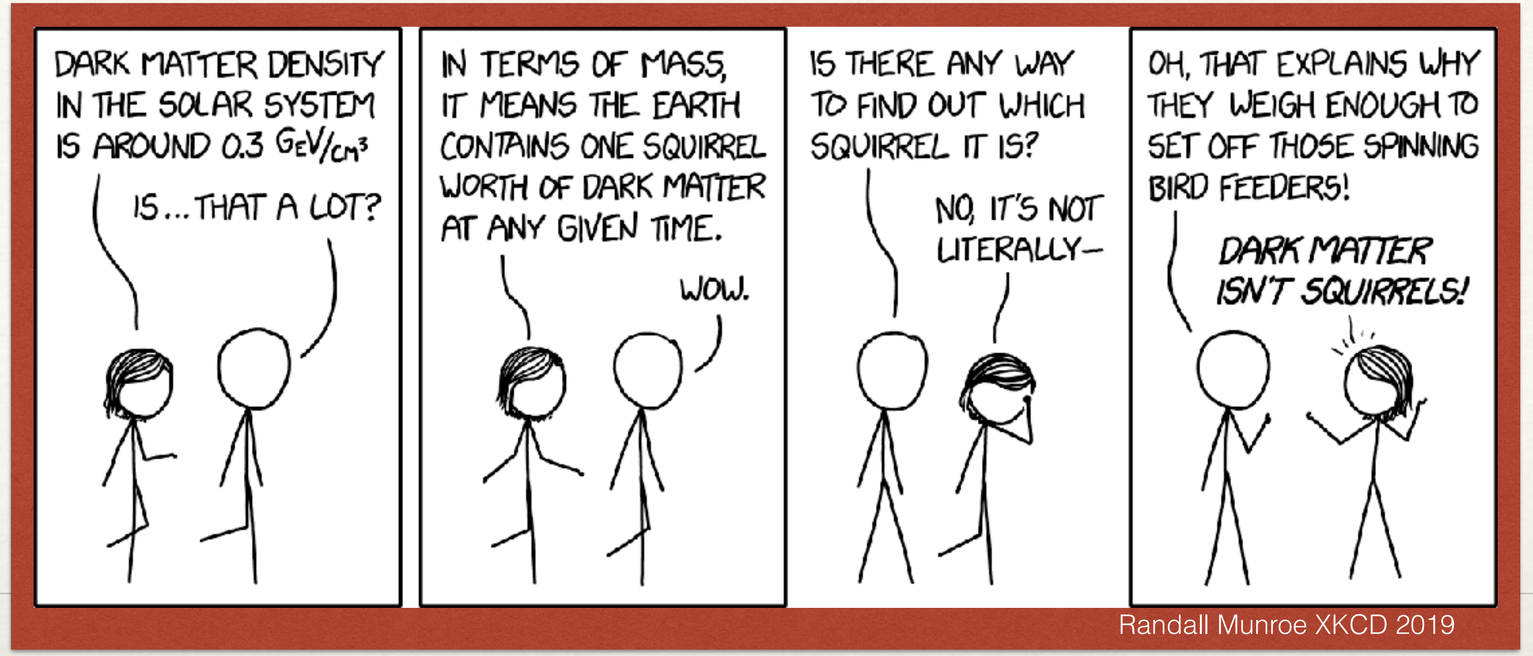


Randall Munroe XKCD 2019

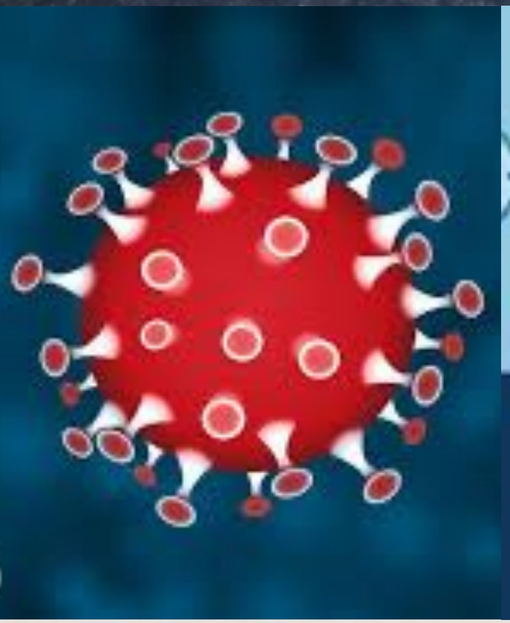
Diary of a WIMP(y) Kid

A Talk in Cartoons (mostly not mine)

Kimberly Palladino
RICAP
9 September 2022

UNIVERSITY OF OXFORD

This point in time…



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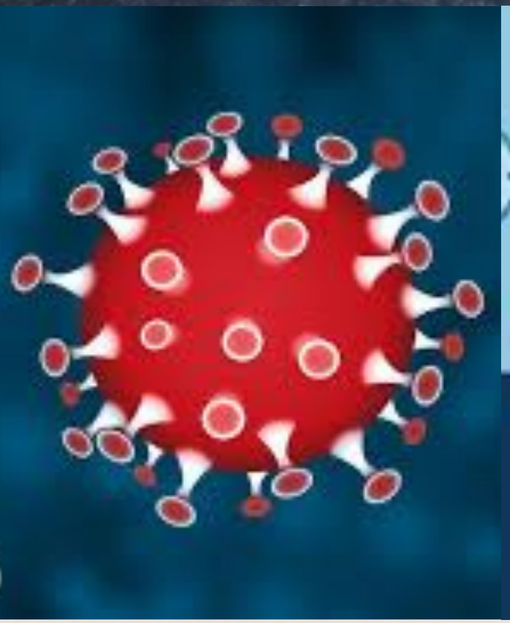

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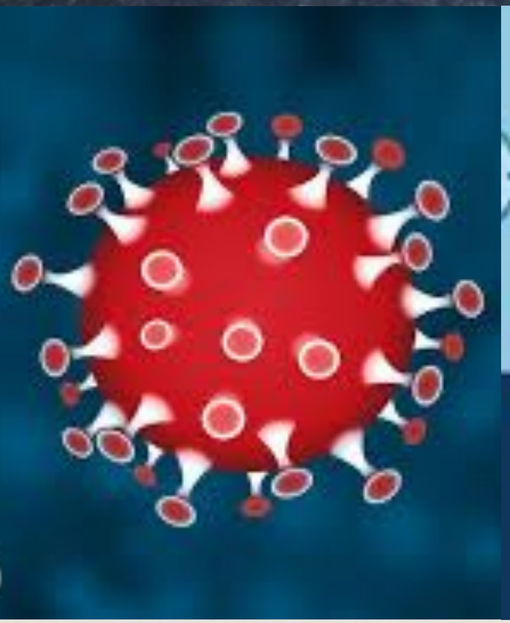

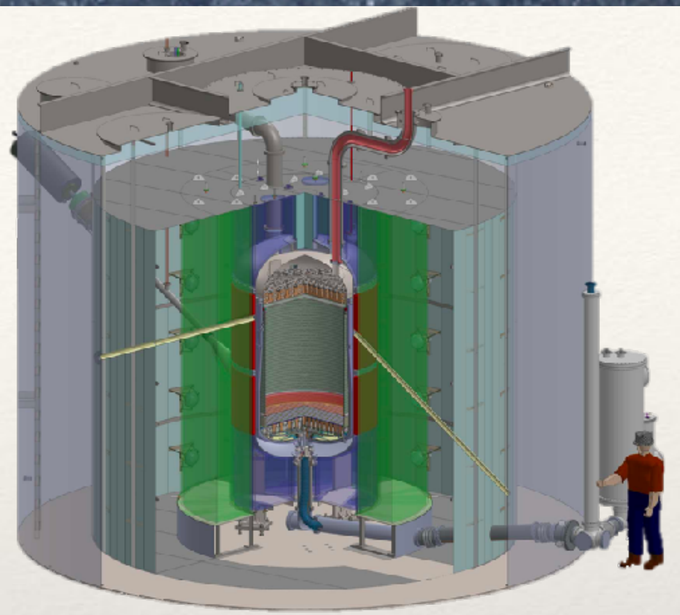

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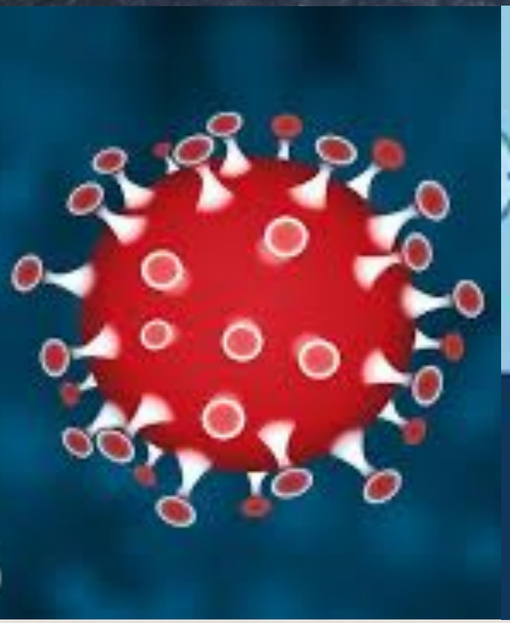
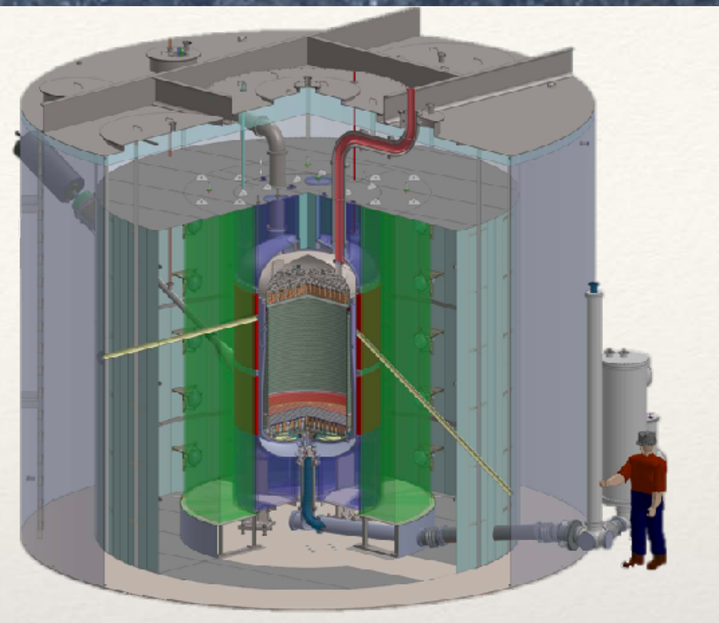
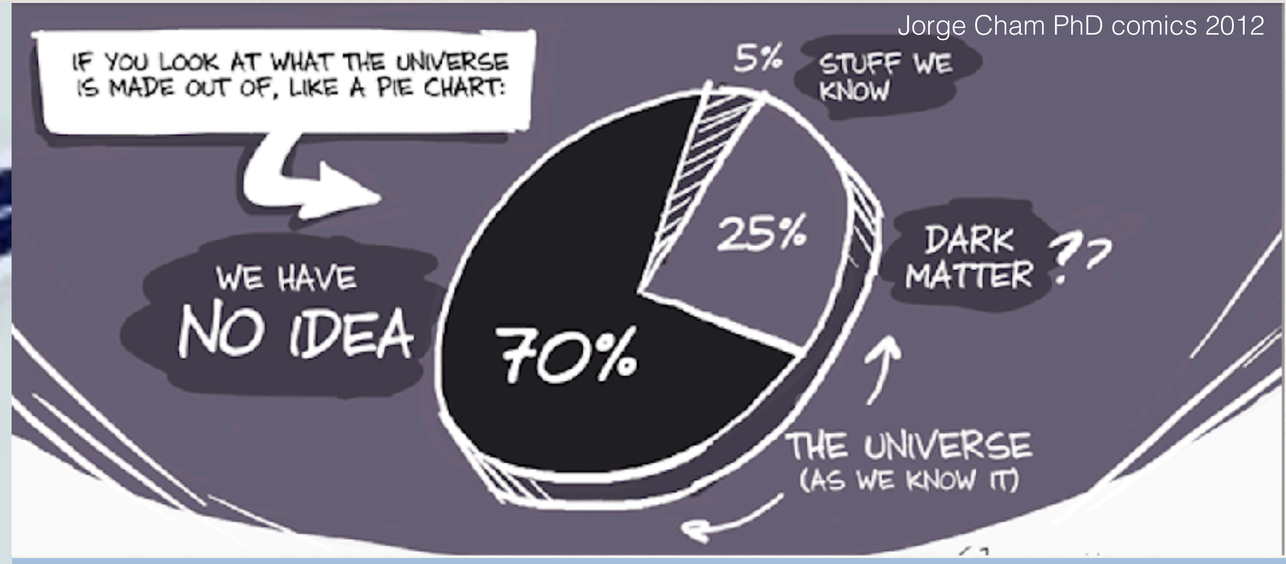


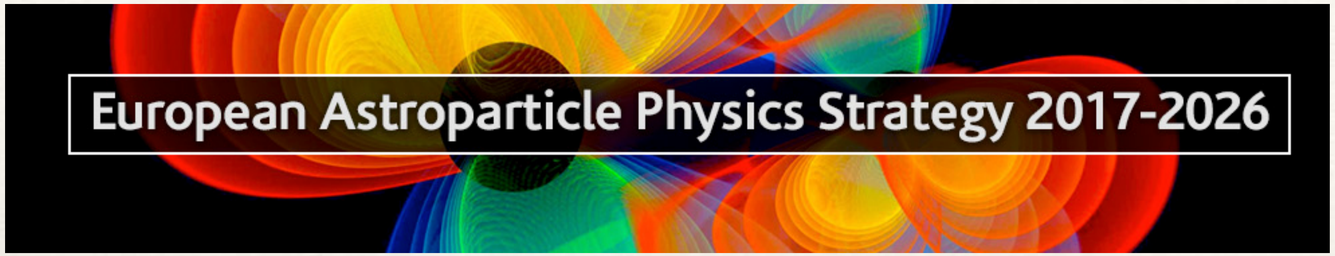




Jorge Cham PhD comics 2012

Where are we, and where are we going?

Reports, Reviews, and Roadmaps



Direct Detection of Dark Matter – APPEC Committee Report *

Committee Members:

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

arXiv:2104.07634

Snowmass 2021

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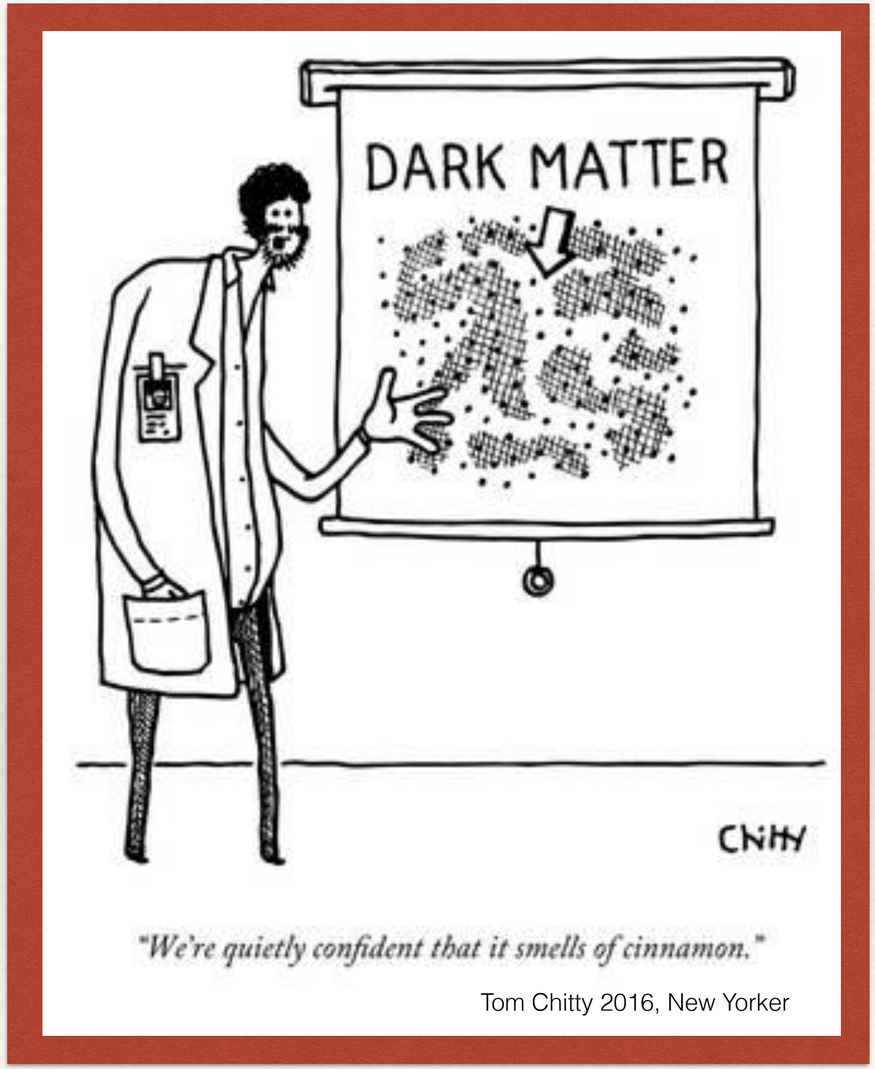
- **We should be prepared for discovery at any moment, and have multiple technologies ready for confirmation.**
- **WIMP searches fit into a wider ecosystem of dark matter searches, all are important.**

Outline

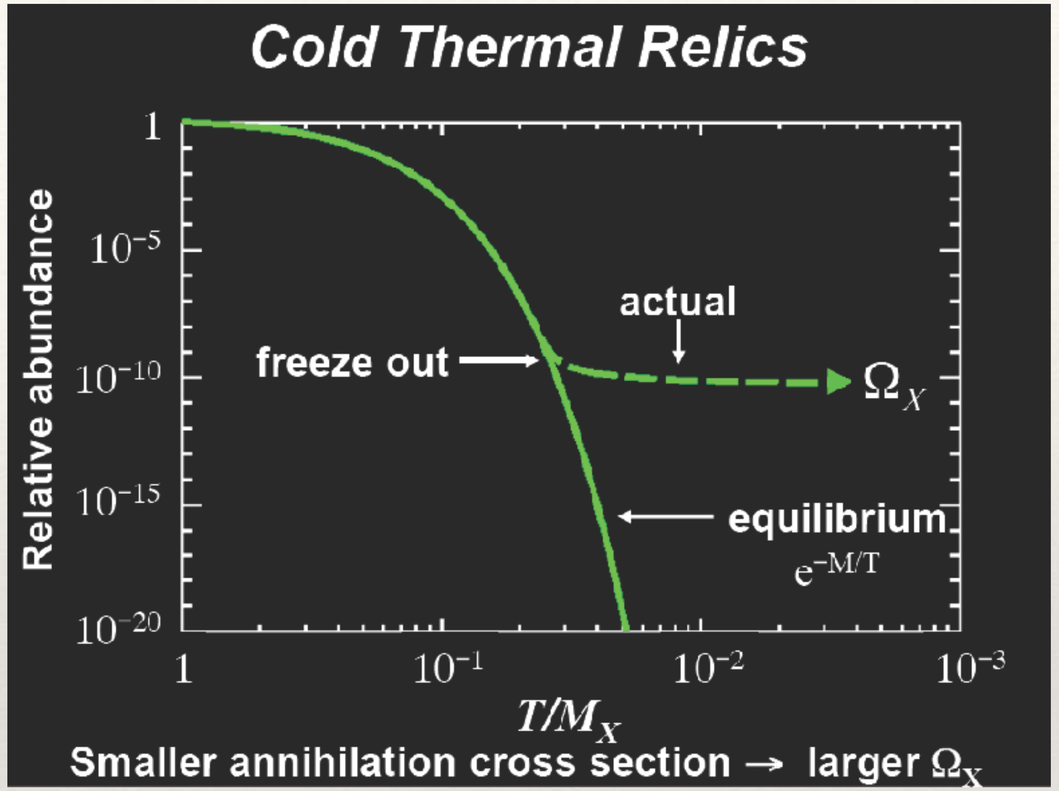
- Particle Dark Matter Models
  - Where are we in the WIMP paradigm?
- Direct Searches for Particle Dark Matter
  - High Mass: Liquid Nobles
  - Lower Mass: Multiple Technologies
- Expectations for the Future
  - Direct Detection plans
  - Meshing with other searches

And things presented here!



Old Slide of the WIMP Miracle

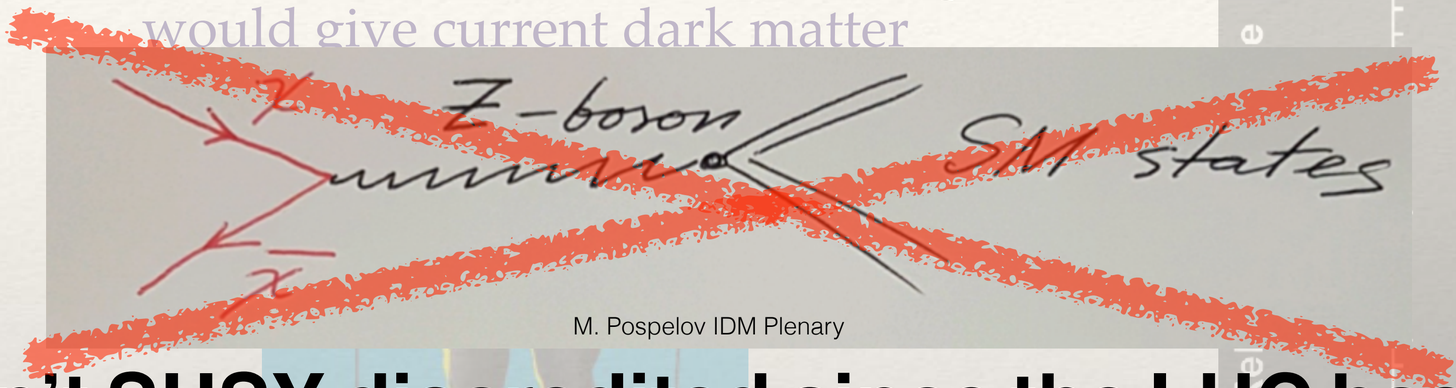
Particles with masses of ~100 GeV and interactions at the weak scale would give current dark matter density of .3 GeV/cm^3



WIMPs fit naturally with SuSY: lightest neutralino, the LSP

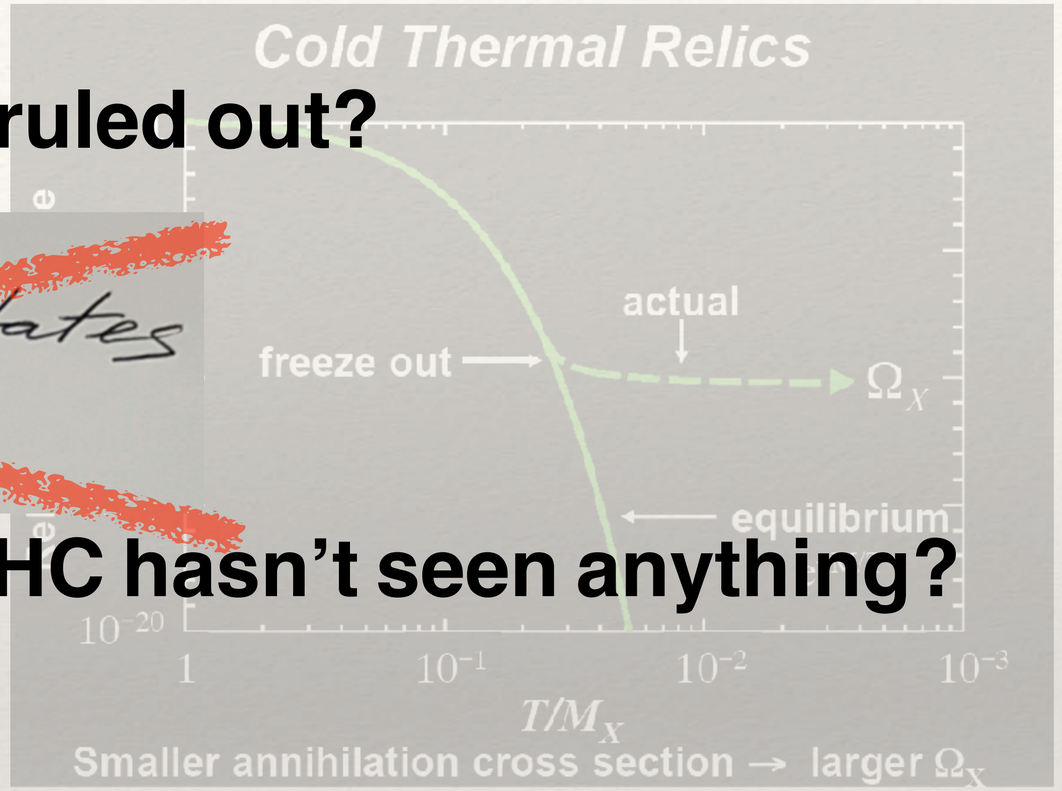
But I was asked …

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



M. Pospelov IDM Plenary

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



WIMPs fit naturally with SuSY:
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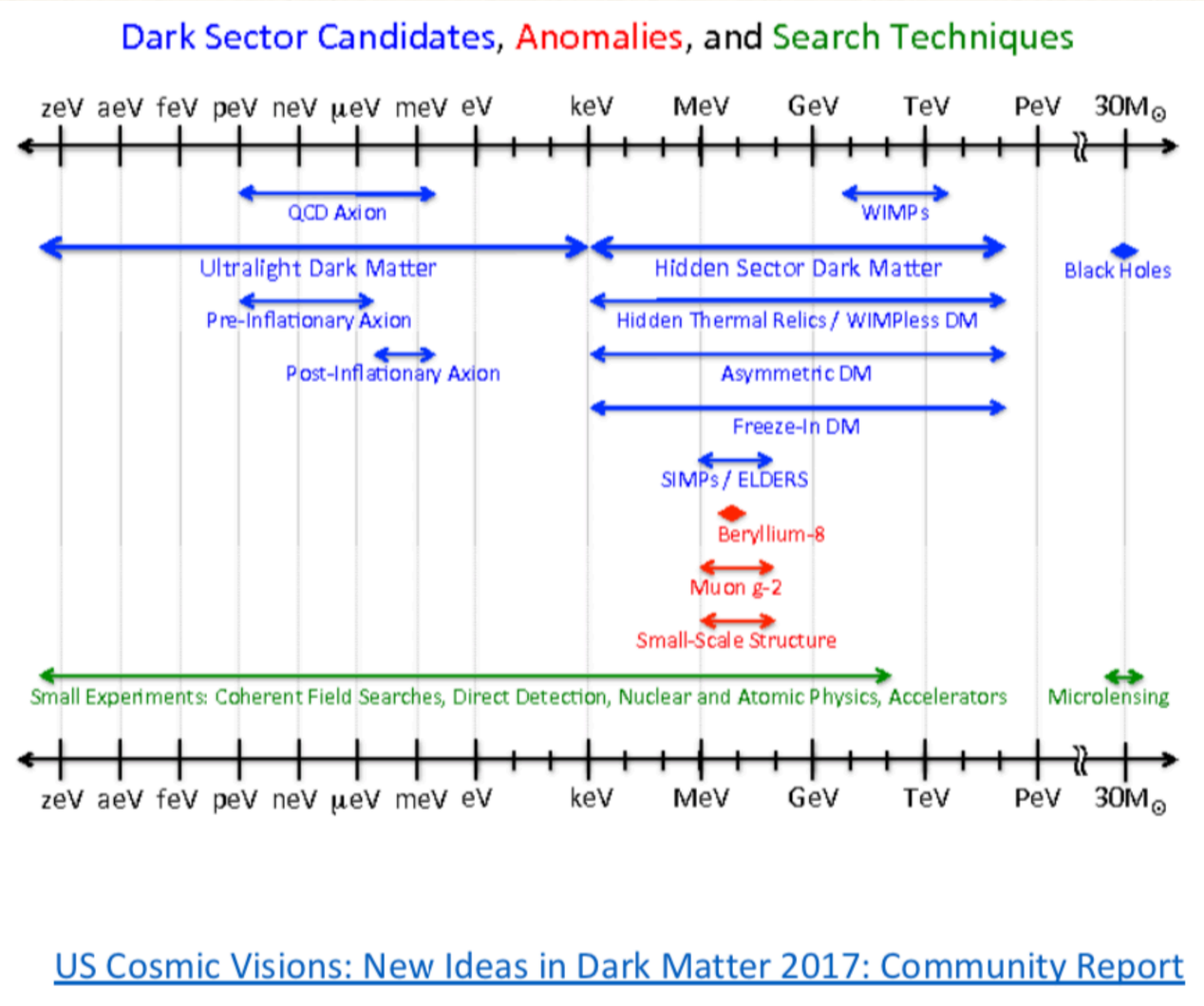
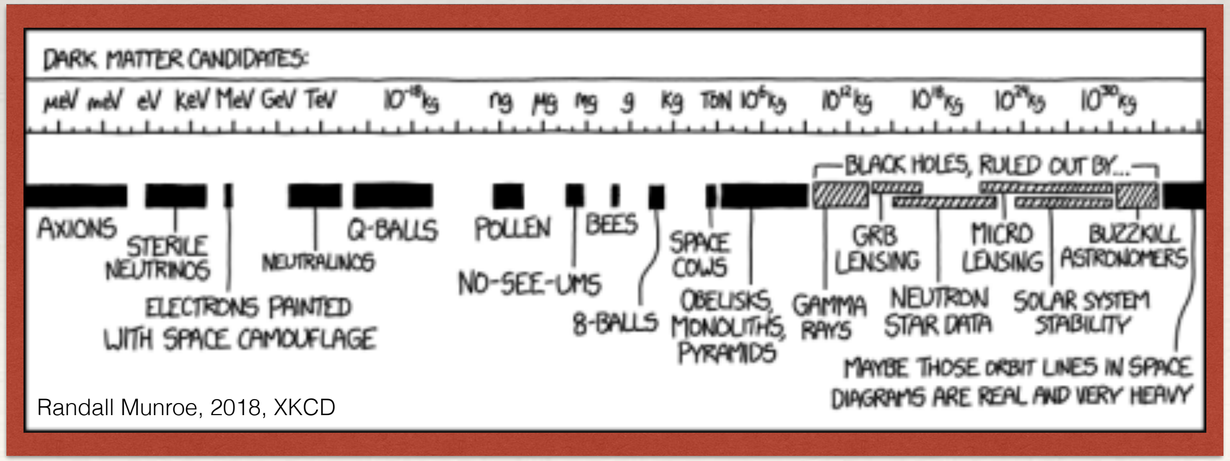
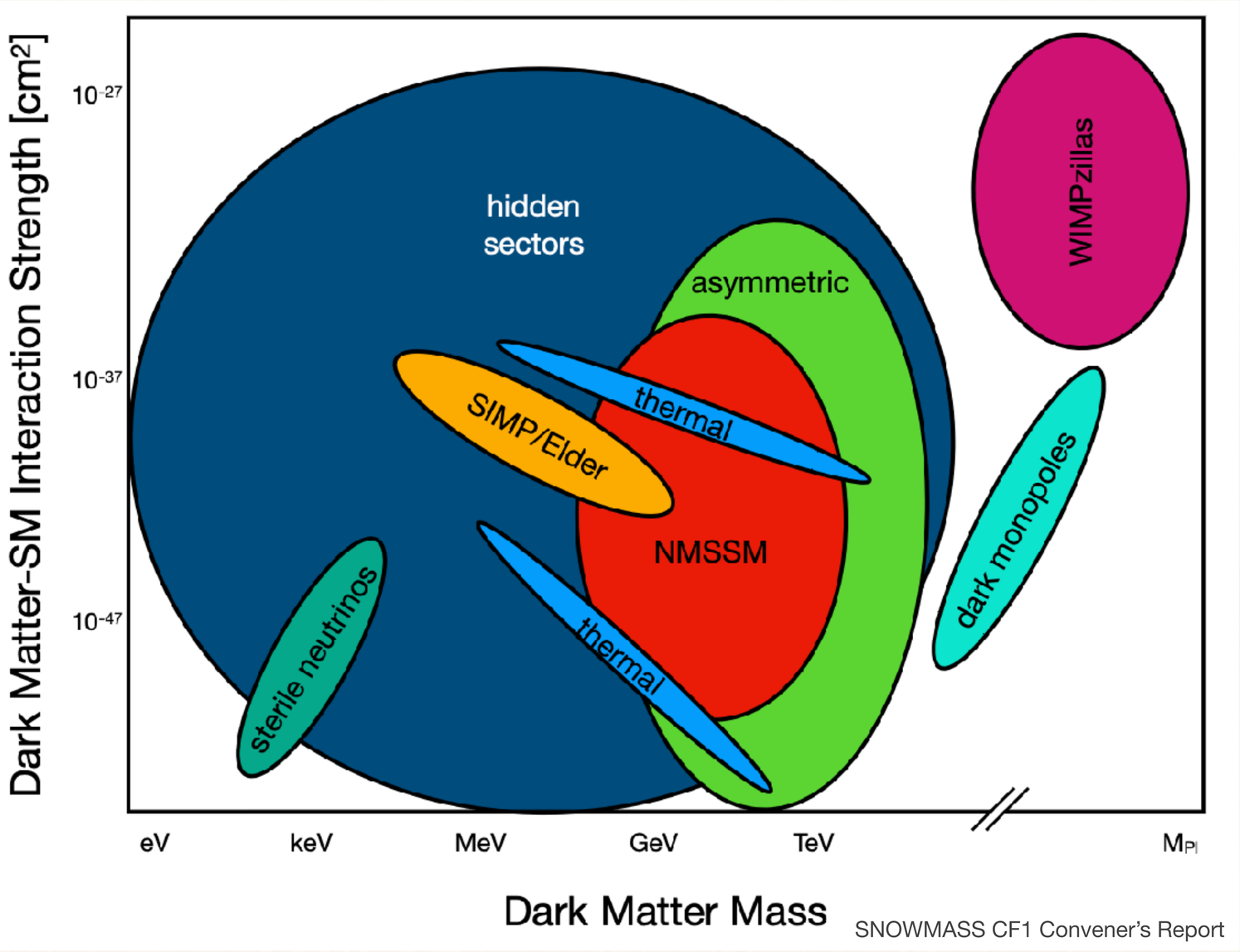
A more recent discussion of models



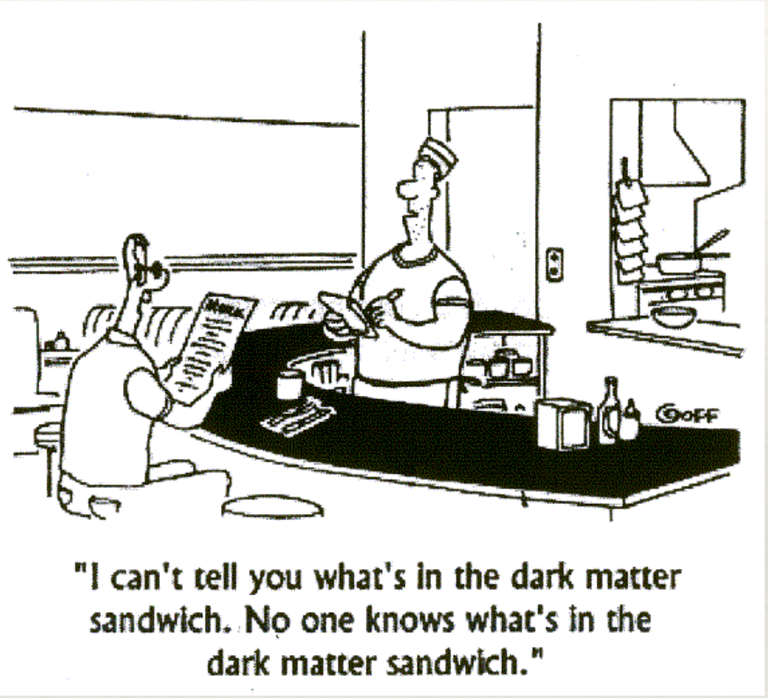
- Canonical Dark matter is:
  - non-relativistic
  - electrically neutral
  - limited self-interactions
  - density of DM ~ 0.3 GeV/cm^3
  - Some theories push these boundaries
  - Can dark matter candidates fit with other theories or open problems?



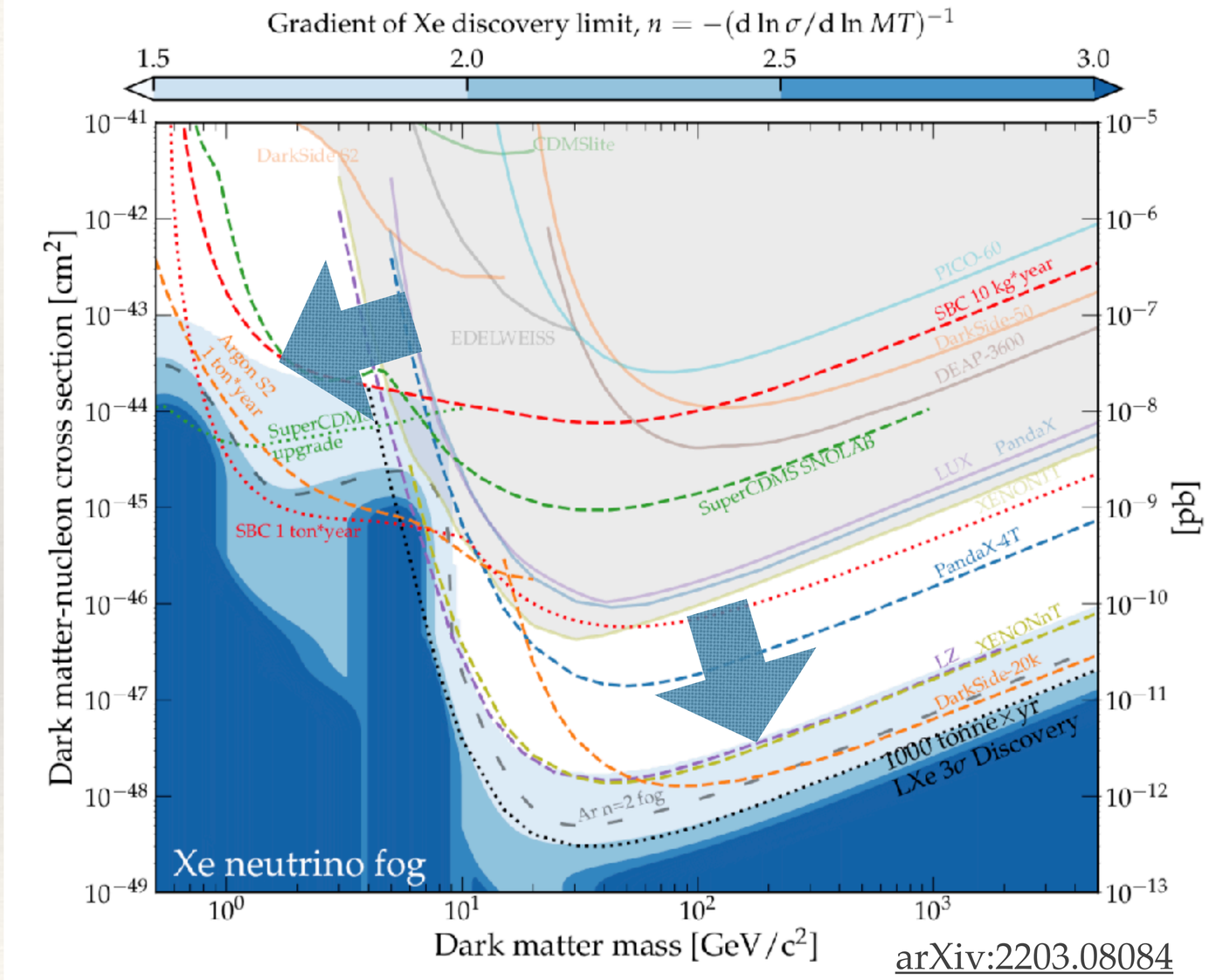
An updated cartoon for particle dark matter



SNOWMASS CF1 Convener's Report



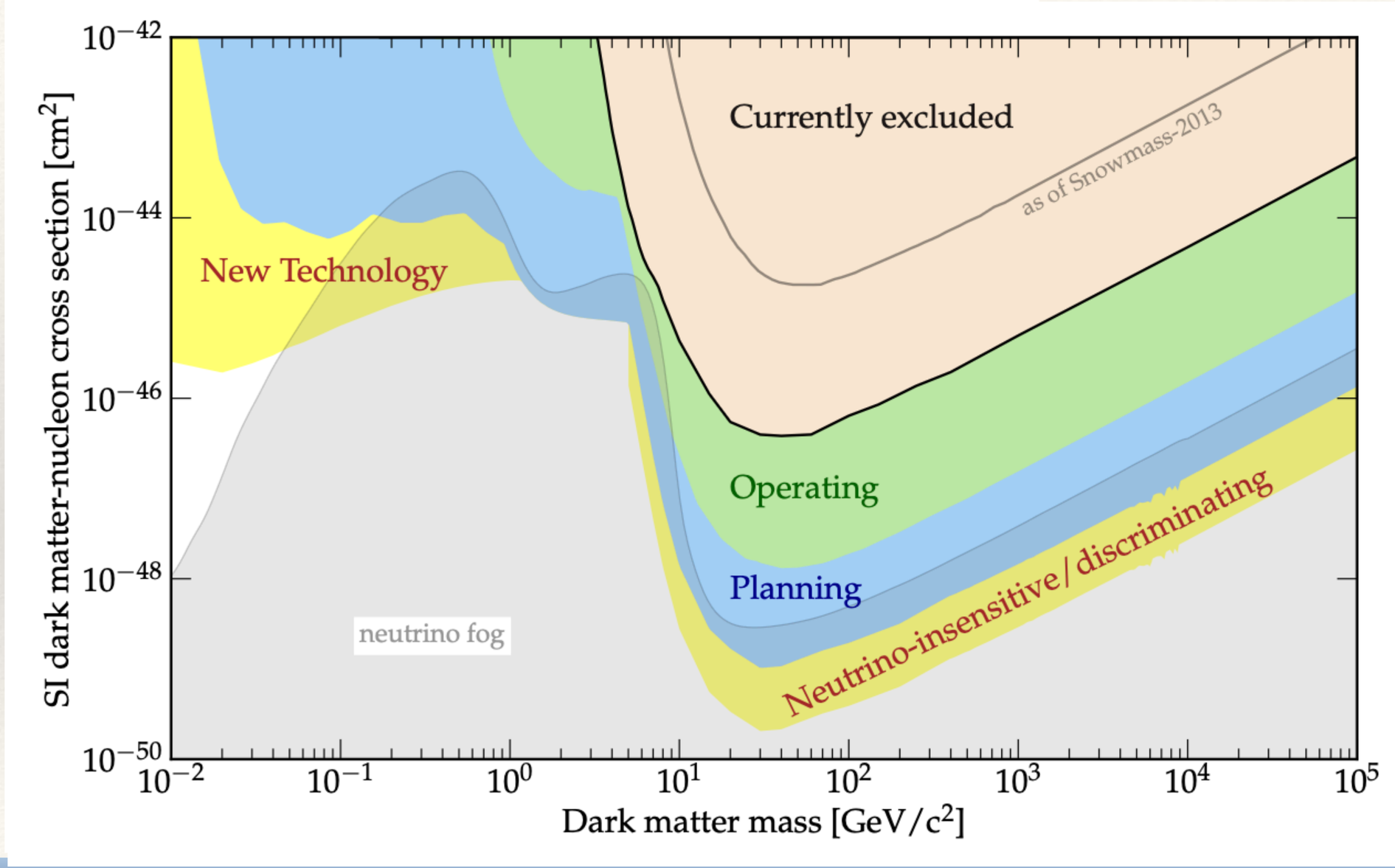
SI Direct DM status



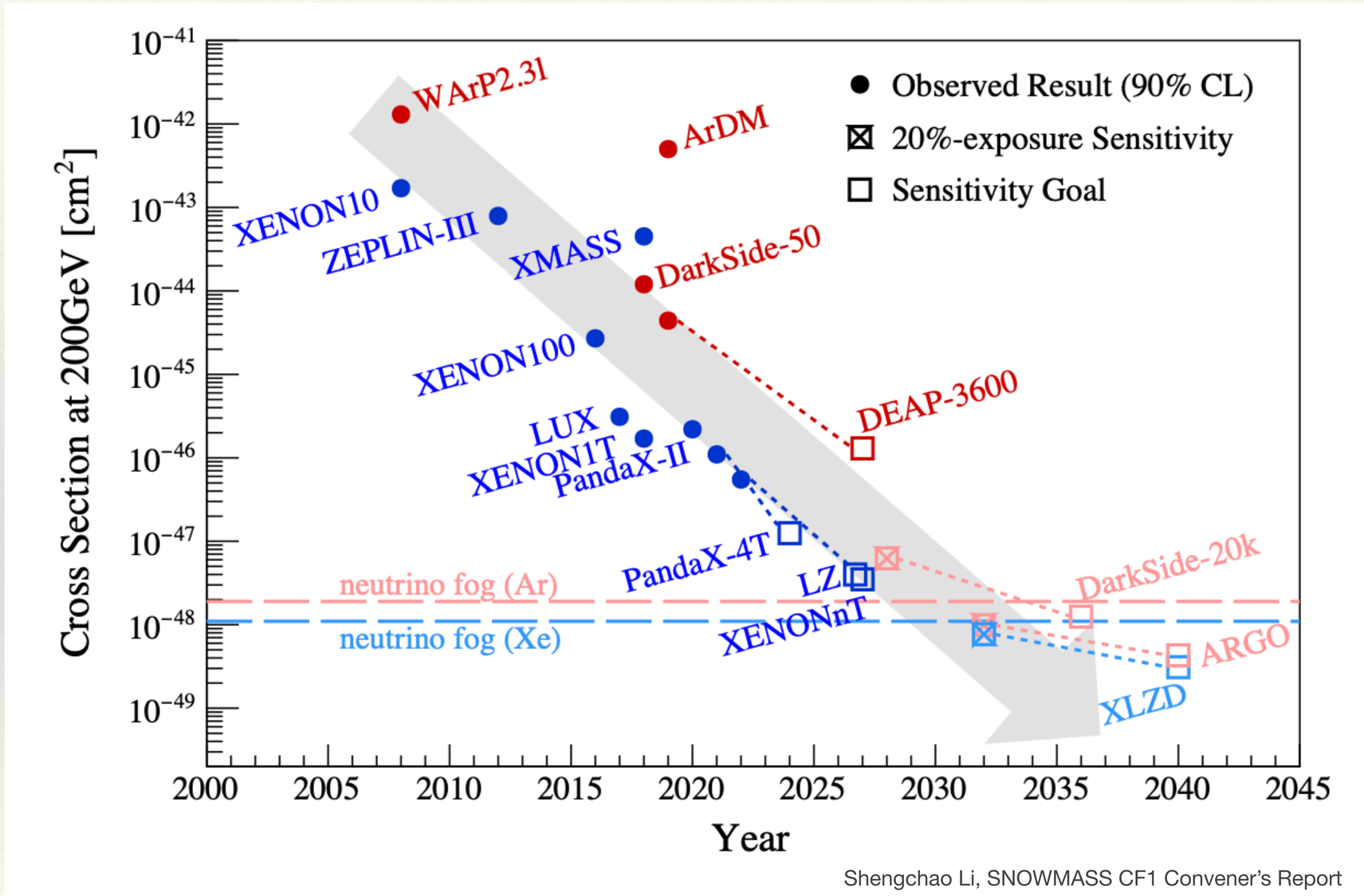
arXiv:2203.08084

Michael Lucibella 2014, APS.org

SI Direct DM status



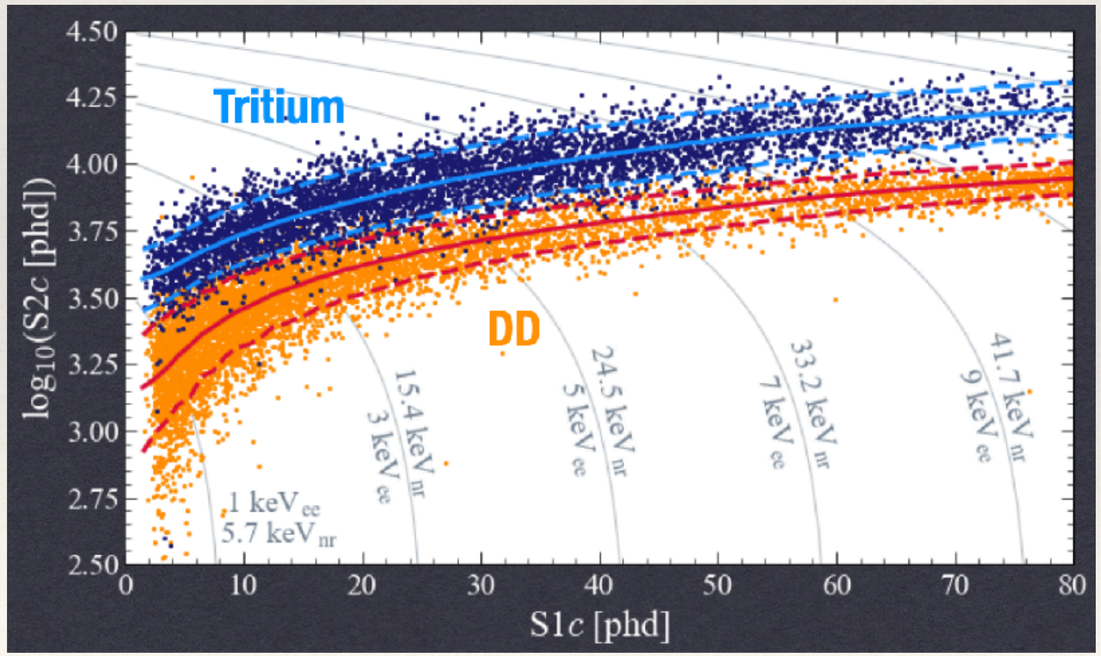
DM as Moore's Law

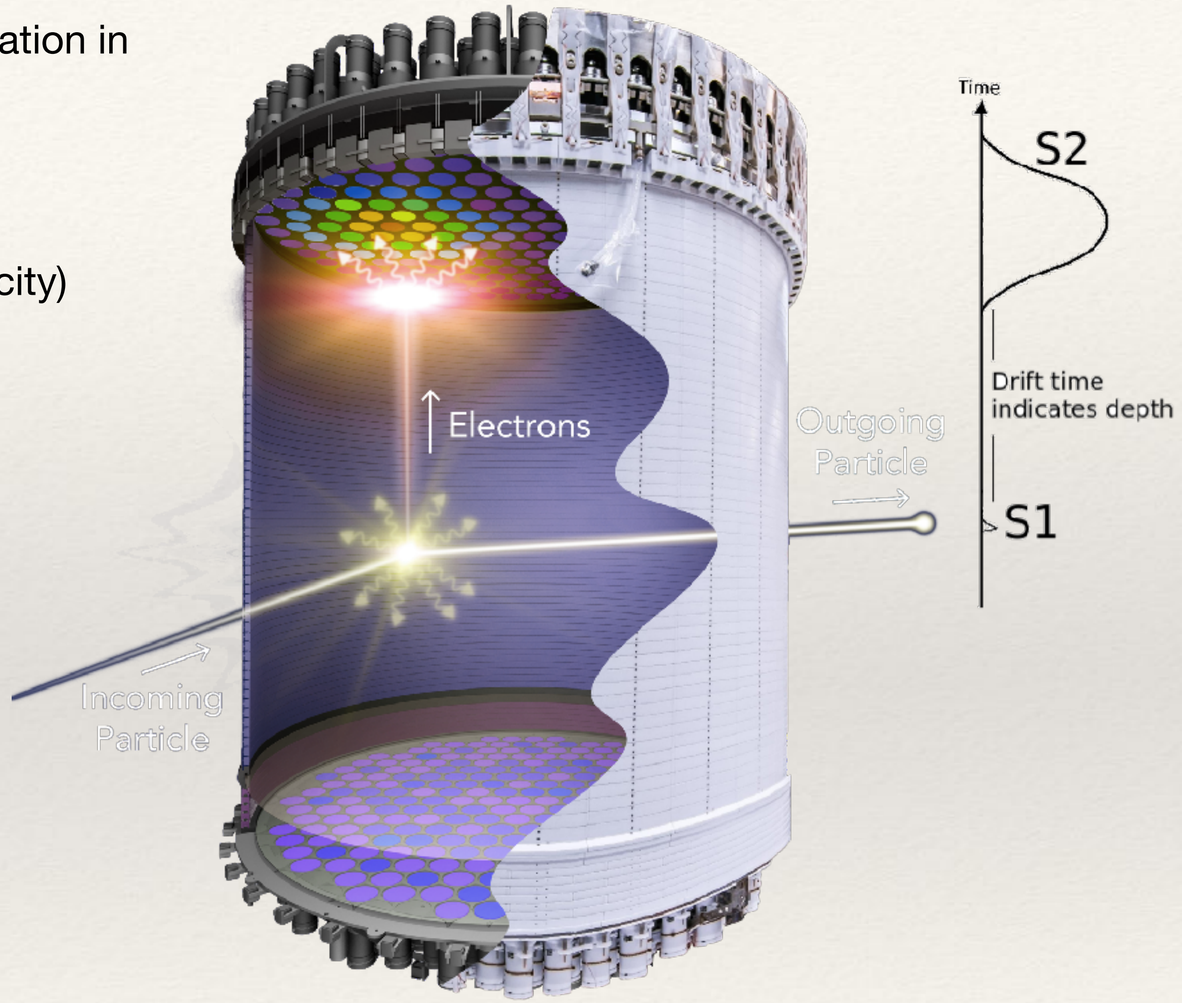


Shengchao Li, SNOWMASS CF1 Convener's Report

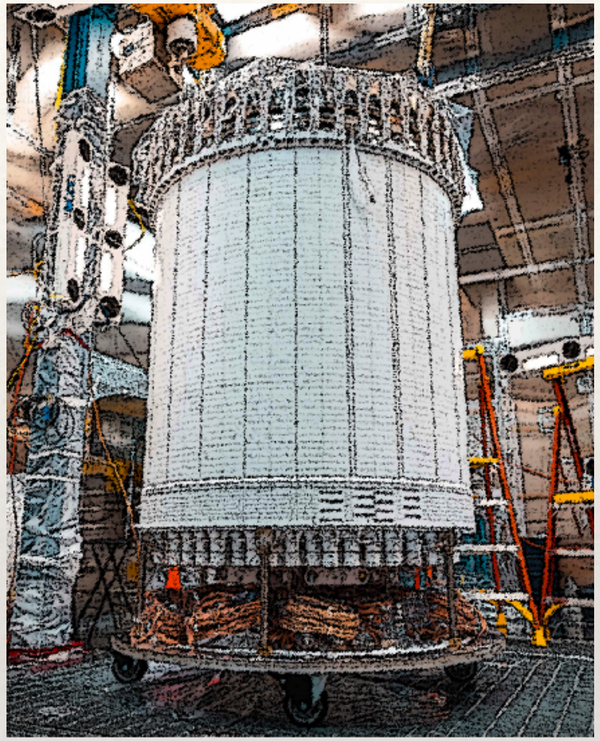
Liquid Noble TPCs

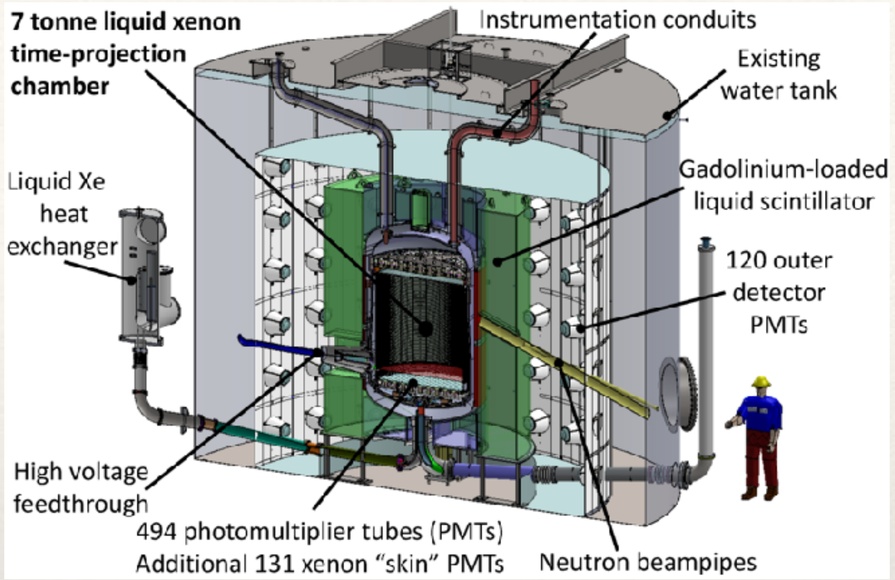
- Self-shielding, large fiducial masses
- Primary Scintillation (S1) with some recombination and de-excitation in the liquid
- Ions drift in TPC electric field
- Amplification region in gas creates proportional light (S2)
- S2/S1 provides particle ID and discrimination
- Events are hundreds of microseconds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

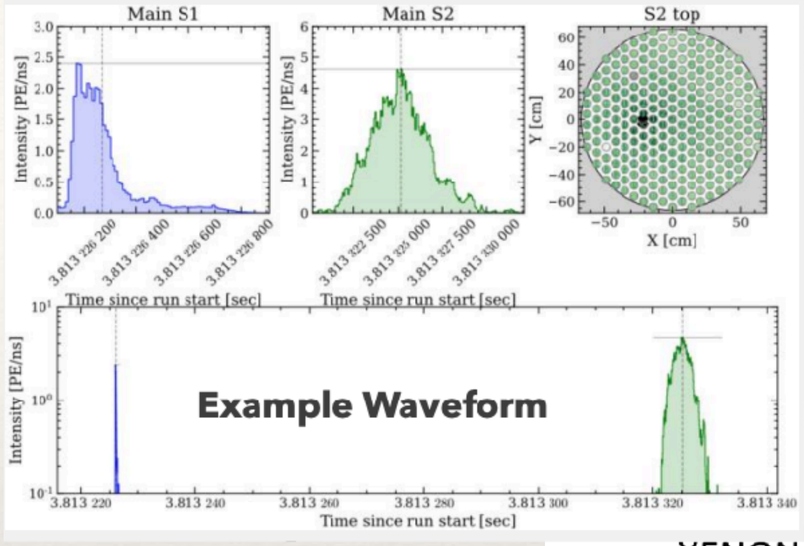


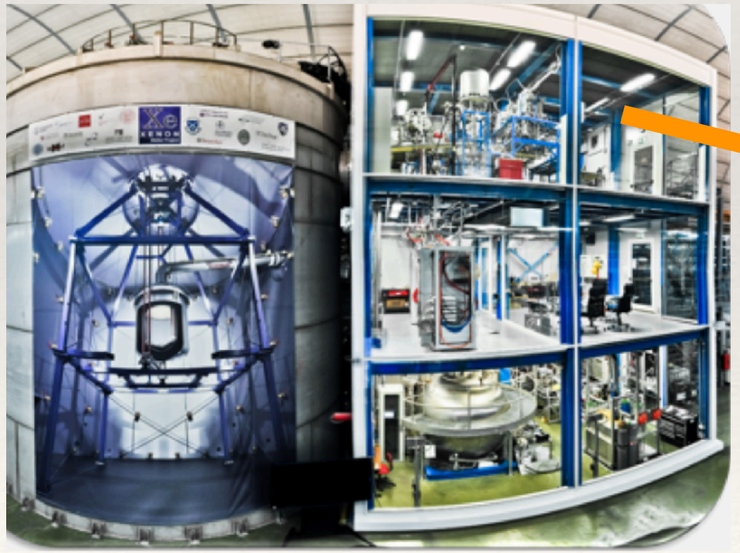


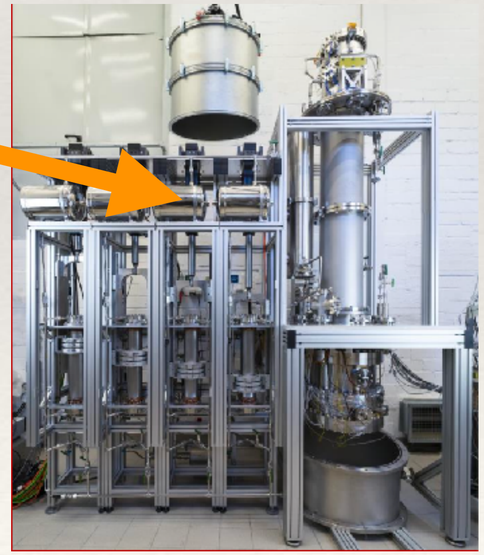
LZ and XENONnT

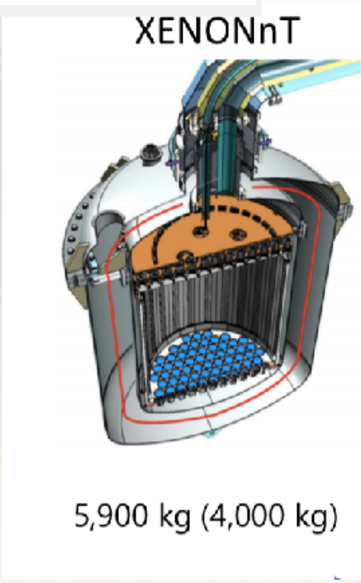








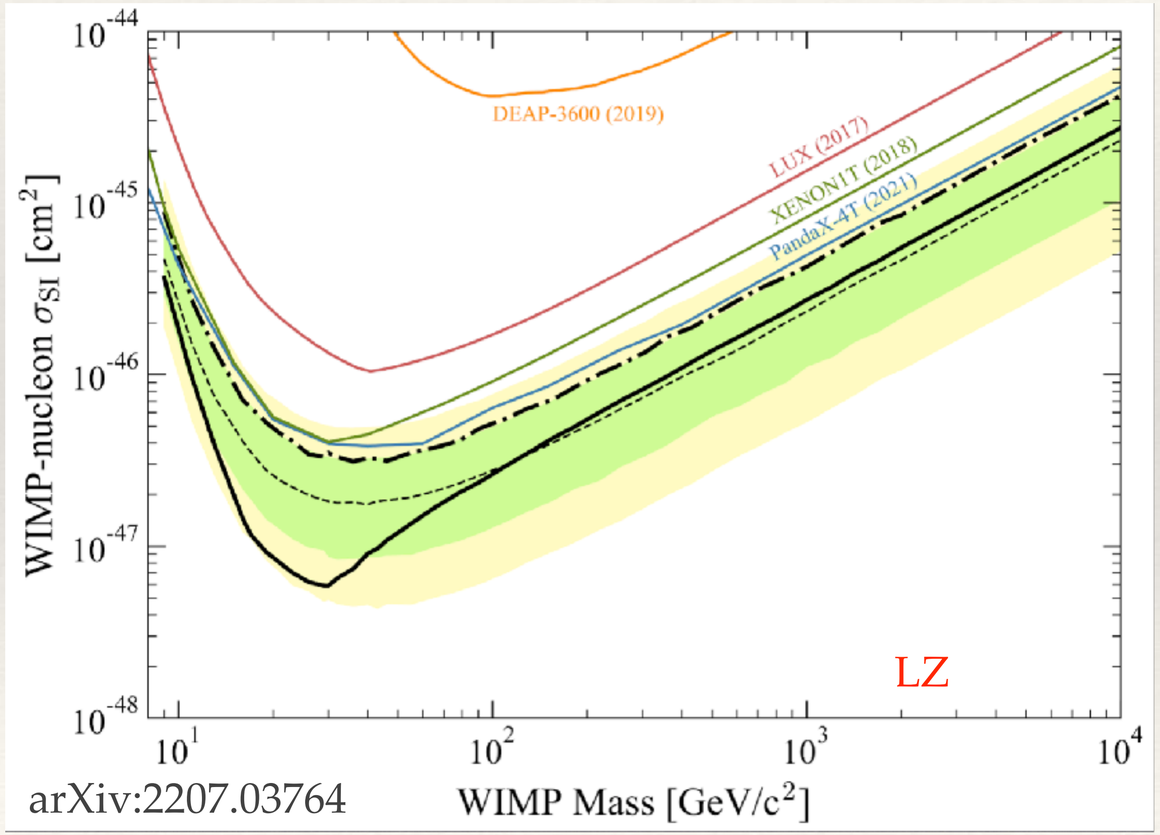


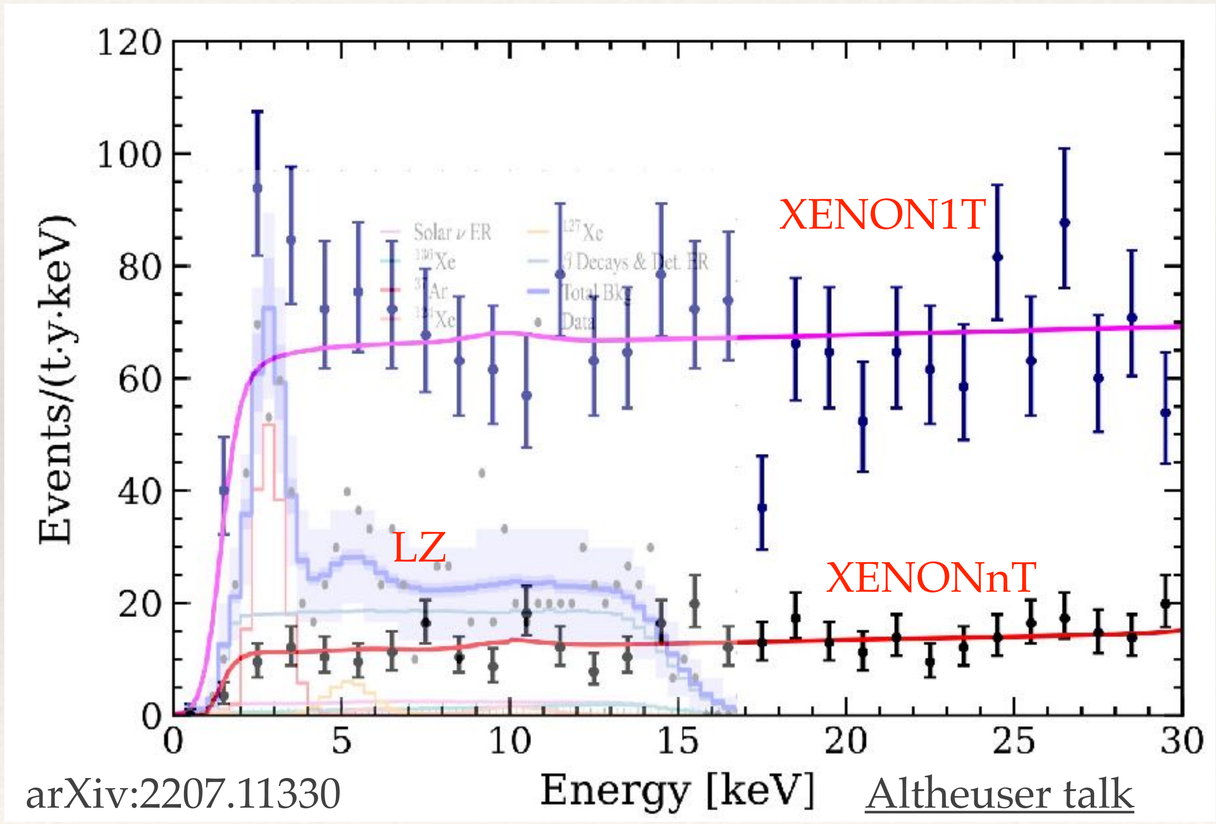


- 2 very sensitive detectors with new results
  - Talks Tuesday and Wednesday

LXe Results

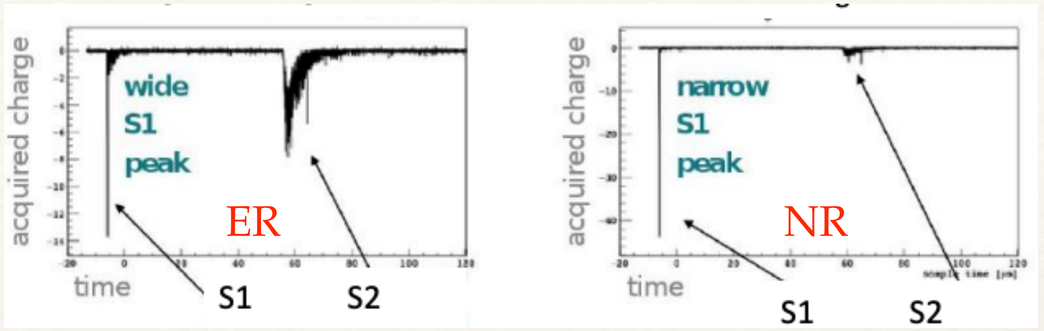
- LZ leading Limits from an initial run
- XENONnT lowest backgrounds, which are electronic recoils, rules out past excess from XENON1T
- Electronic recoils give sensitivity to solar axions, ALPs, Dark Photons, and the neutrino magnetic moment

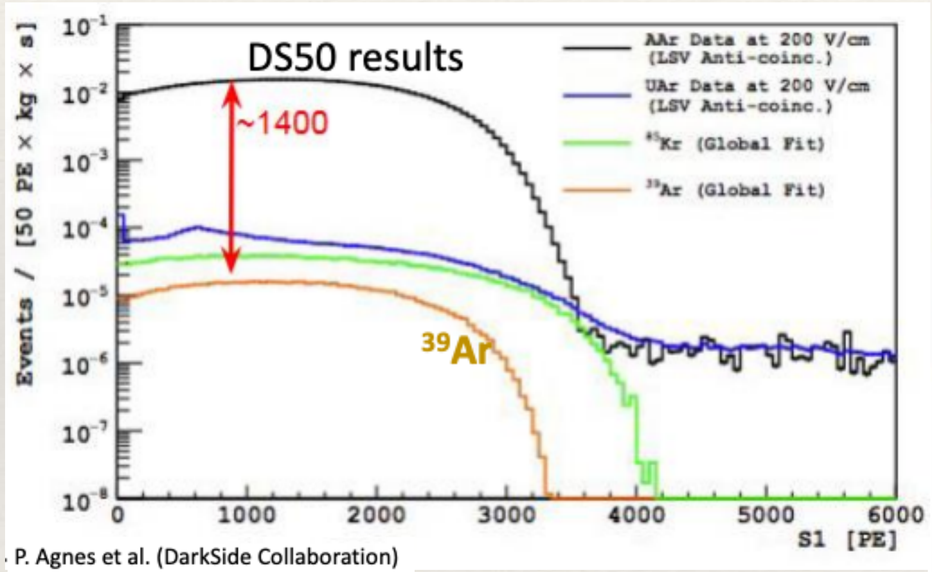




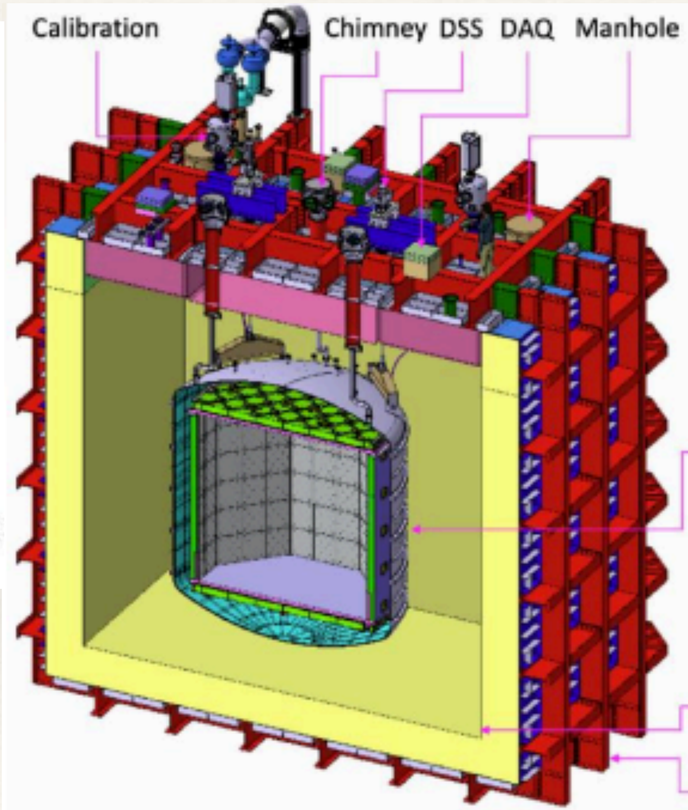
DarkSide 50 + 20K

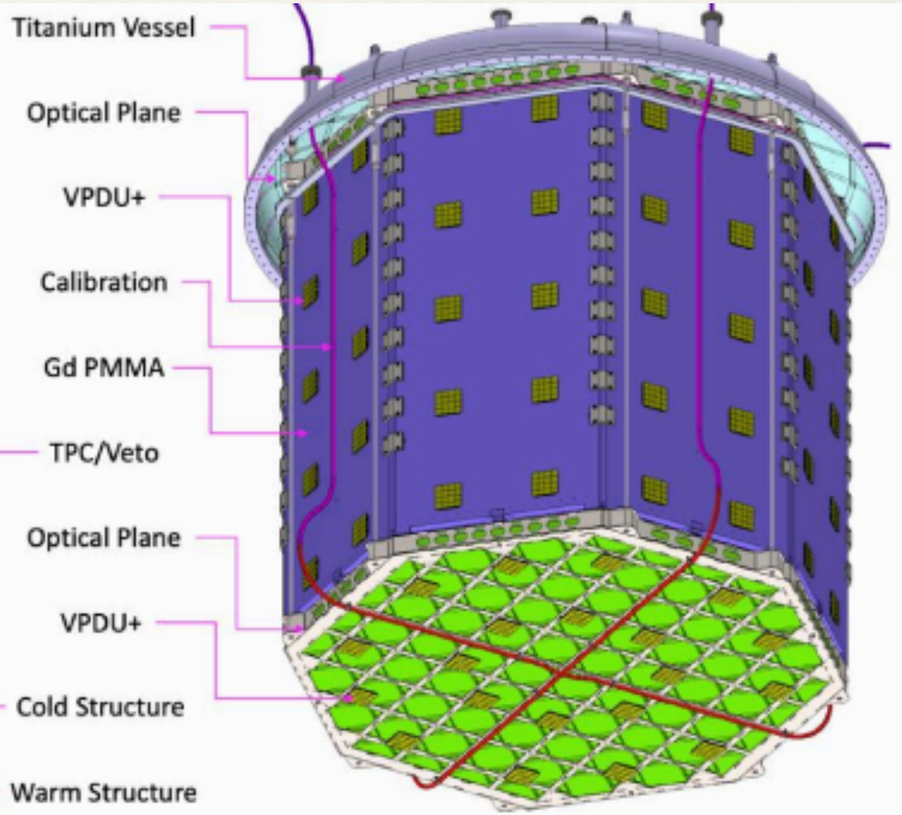
- ~50 t liquid argon time projection chamber
- Under construction at LNGS in Italy
- Innovations in photosensors, underground argon production (reduced Ar-39 background),





P. Agnes et al. (DarkSide Collaboration)
Phys. Rev. D 93, 081101(R) (2016)





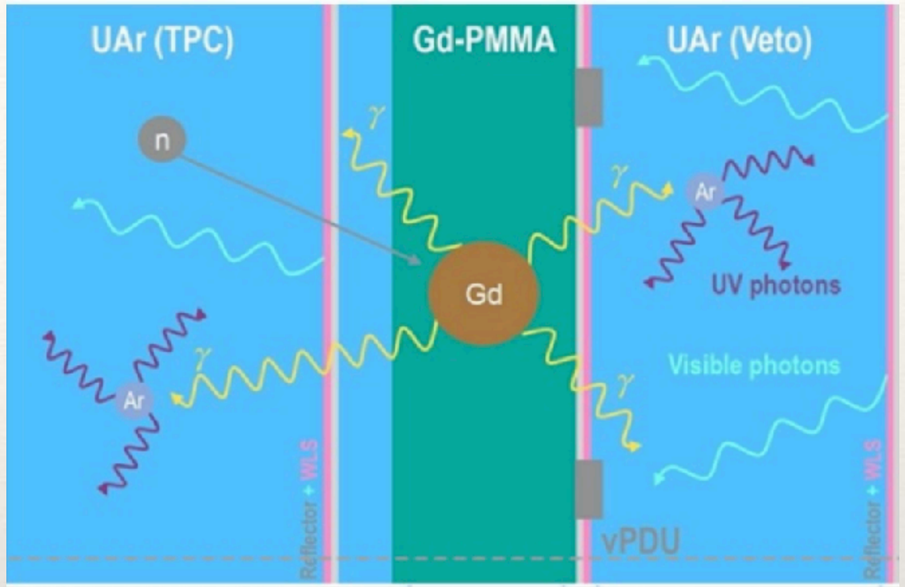
DarkSide Technologies

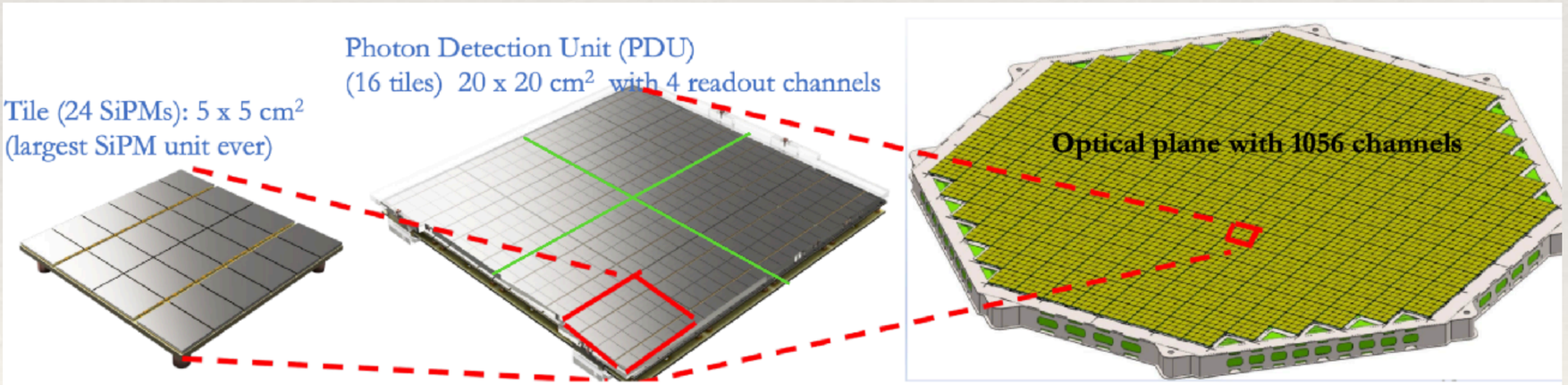
Gadolinium loaded acrylic TPC wall for neutron veto

SiPM, fabrication underway

Agnese talk

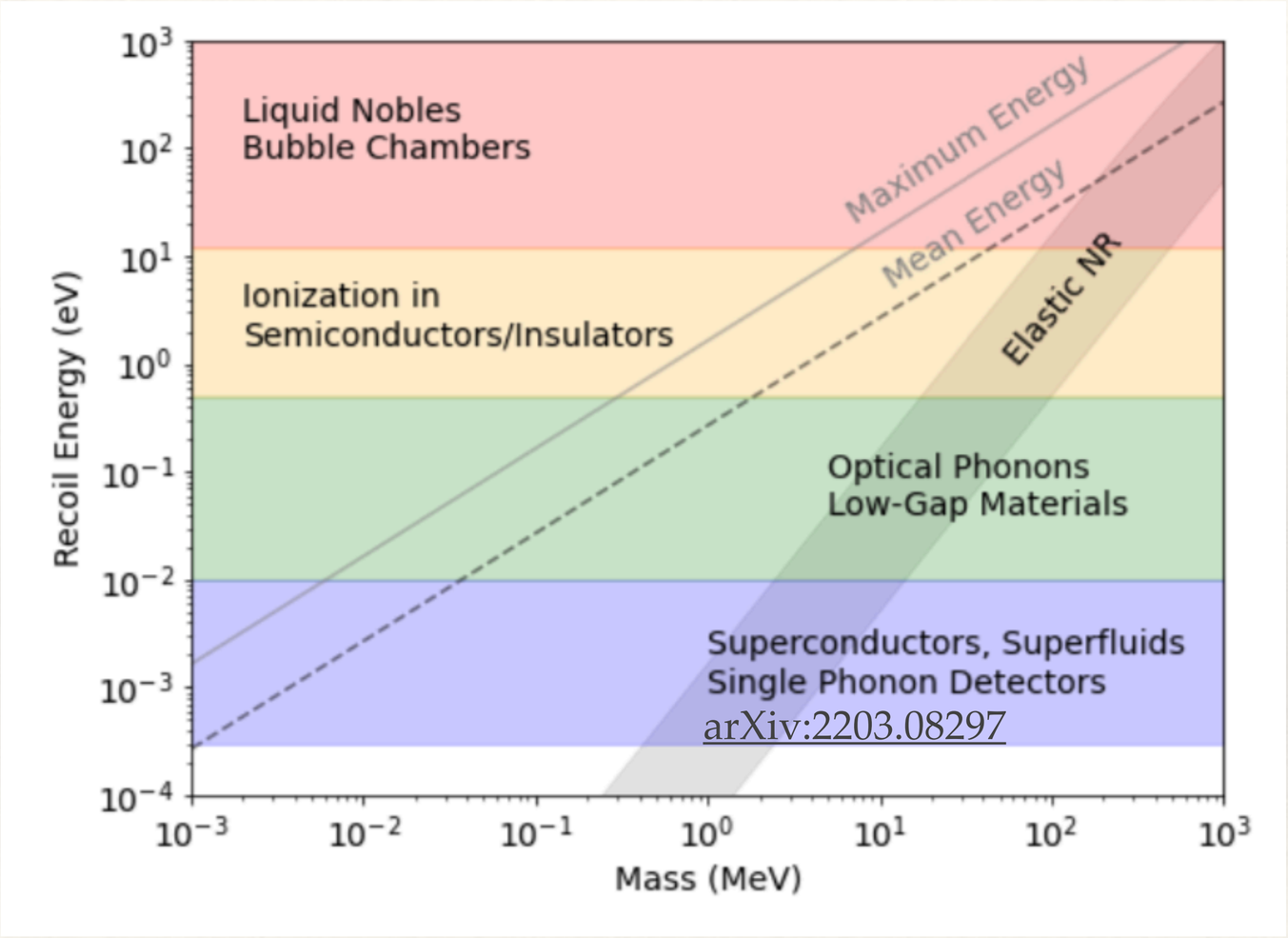
$Gd(MAA)_3$ doped acrylic sheet (5 cm thick)



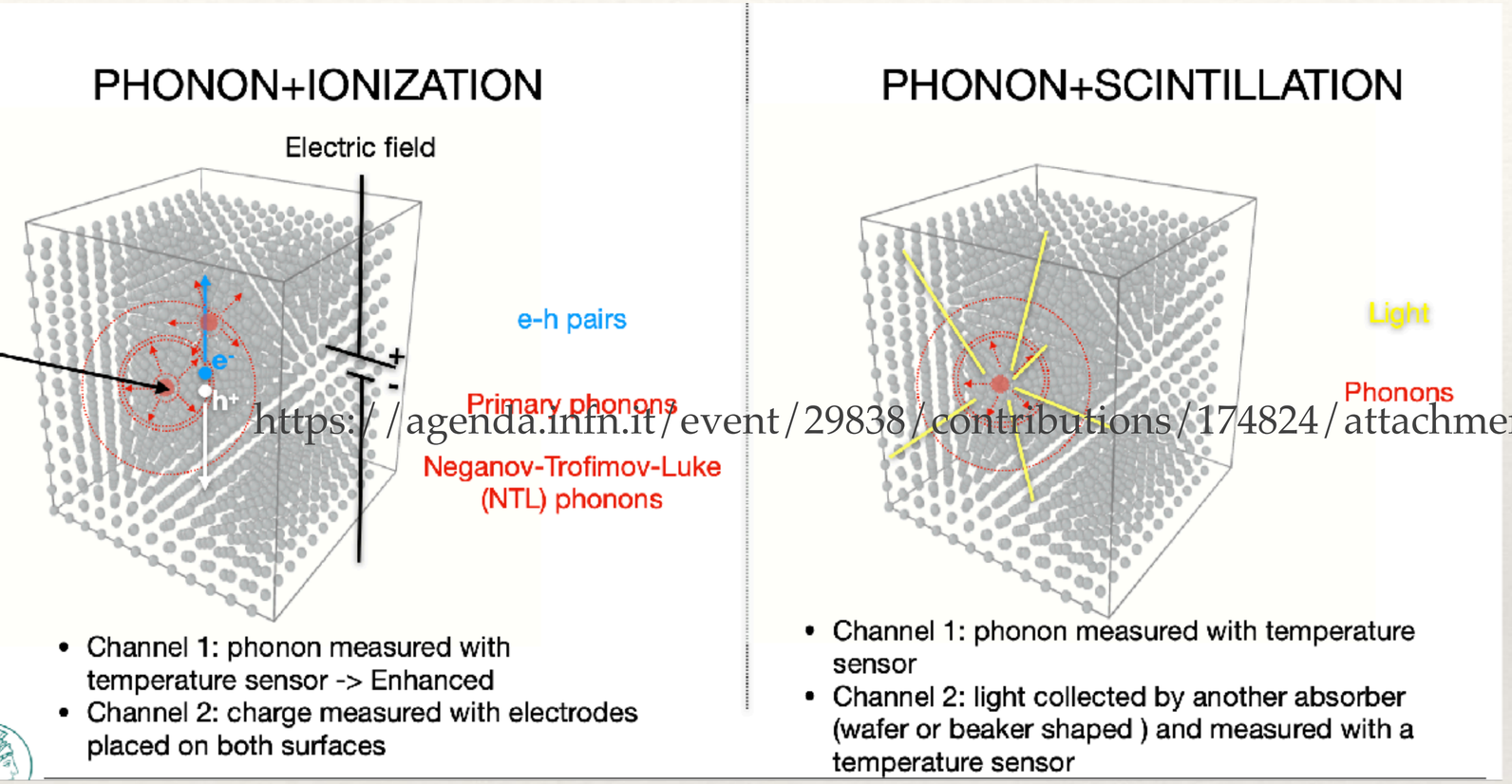


2 optical planes for the TPC
+ 480 channels to instrument the UAr veto

What technology makes sense?

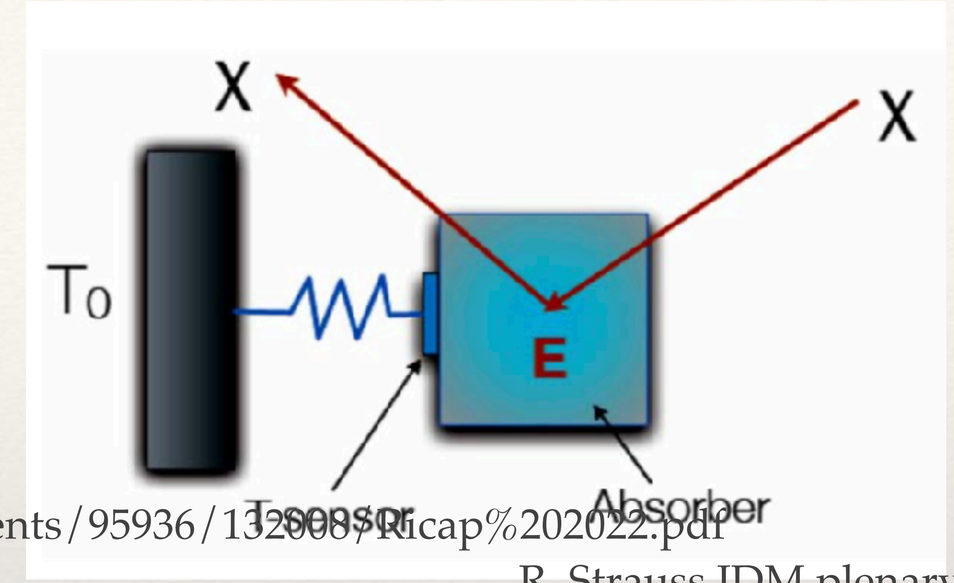


Technologies for Low Mass Searches



SuperCDMS, CRESST, EDELWEISS
COSINUS, TESSERACT

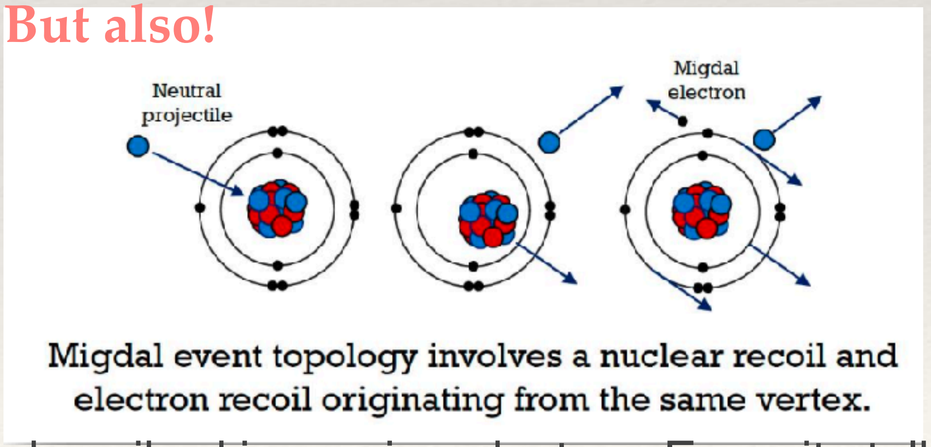
Zema talk



https://agenda.infn.it/event/29838/contributions/174824/attachments/95936/132008/Ricap%202022.pdf

R. Strauss IDM plenary

But also!

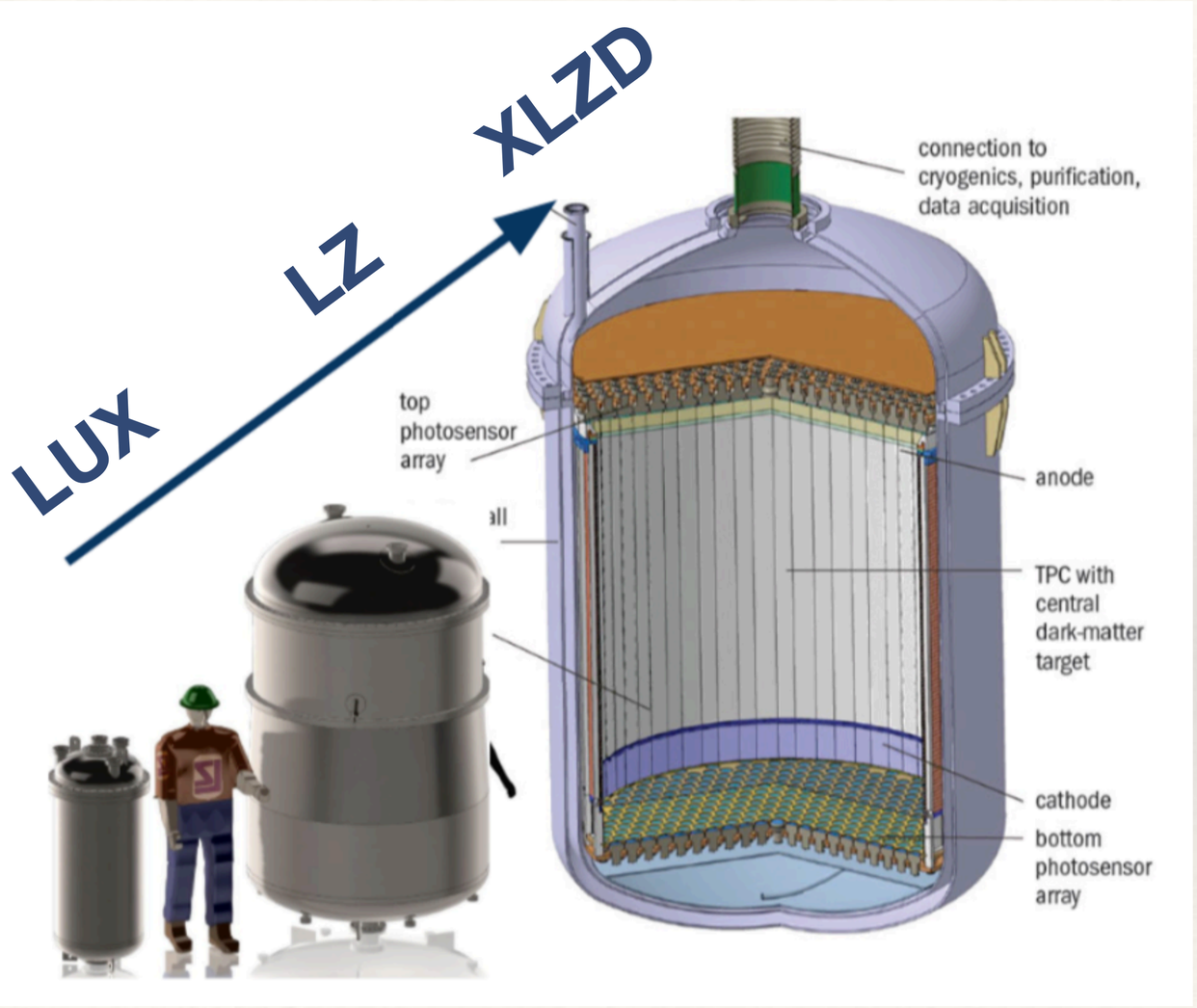


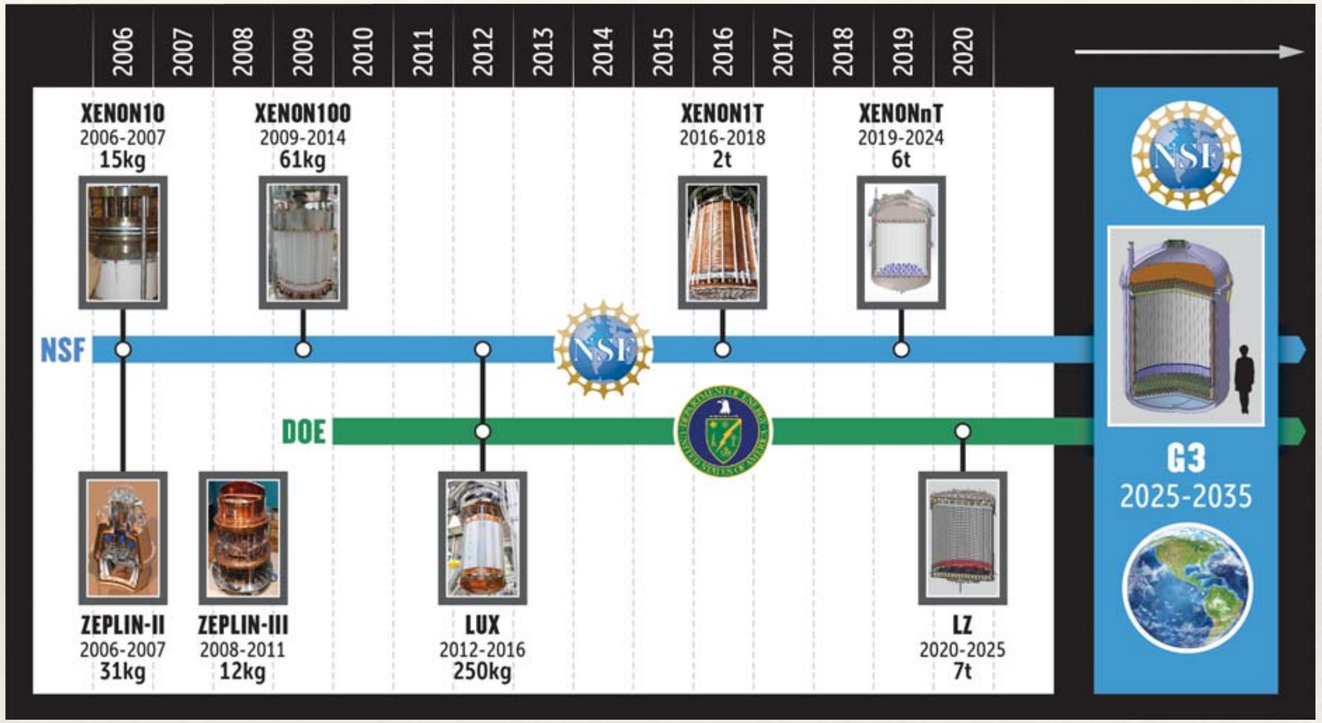
Also described in semiconductors: Esposito talk

The Future

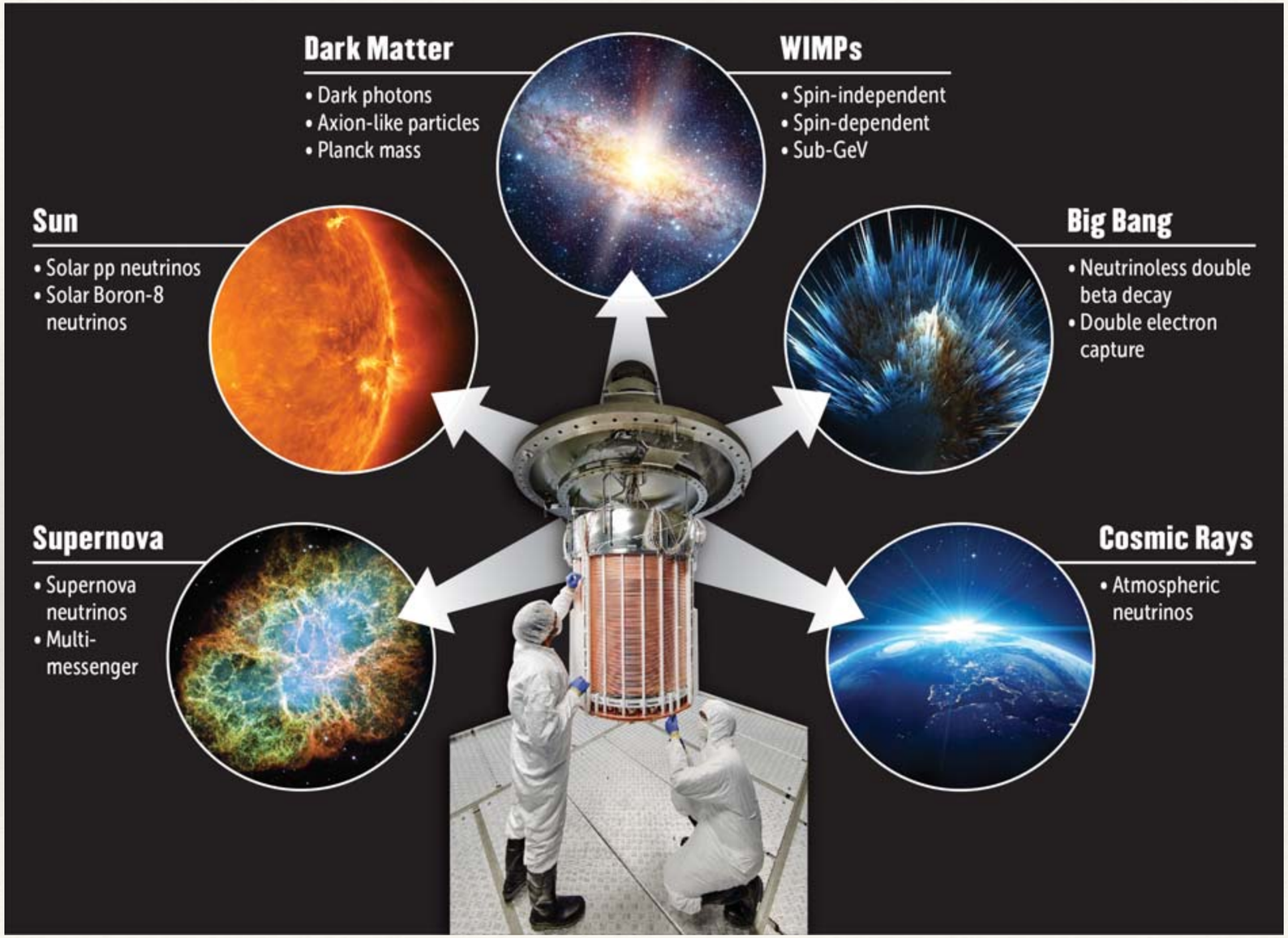
But particle astrophysicists want DETECTORS to find Dark Matter

Get to the Neutrino Fog: Xe

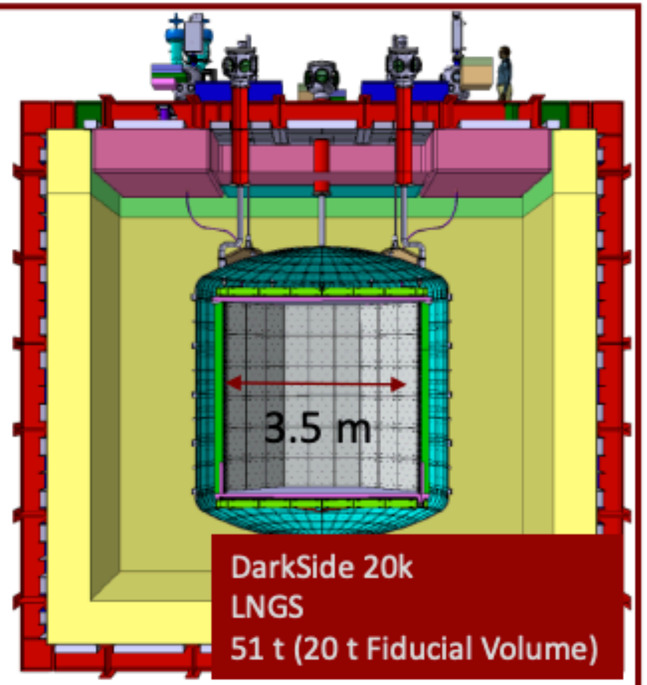




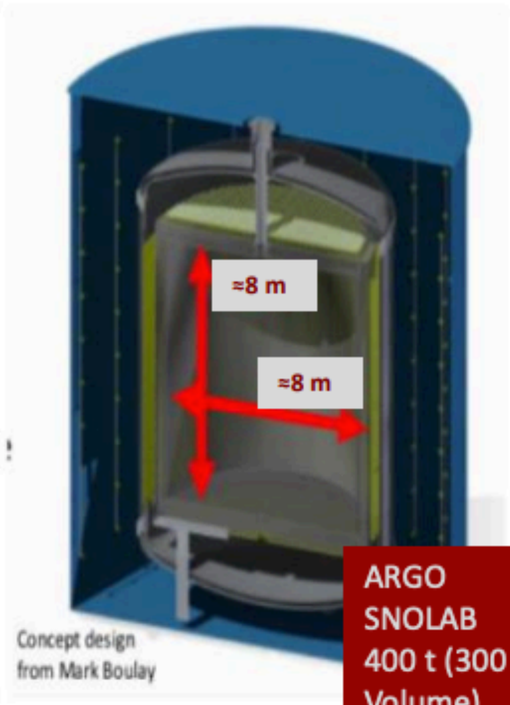
What else can be done with a big detector?



GADM programme



Construction starts in 2022
Data taking from 2025
Nominal run time: 10 years

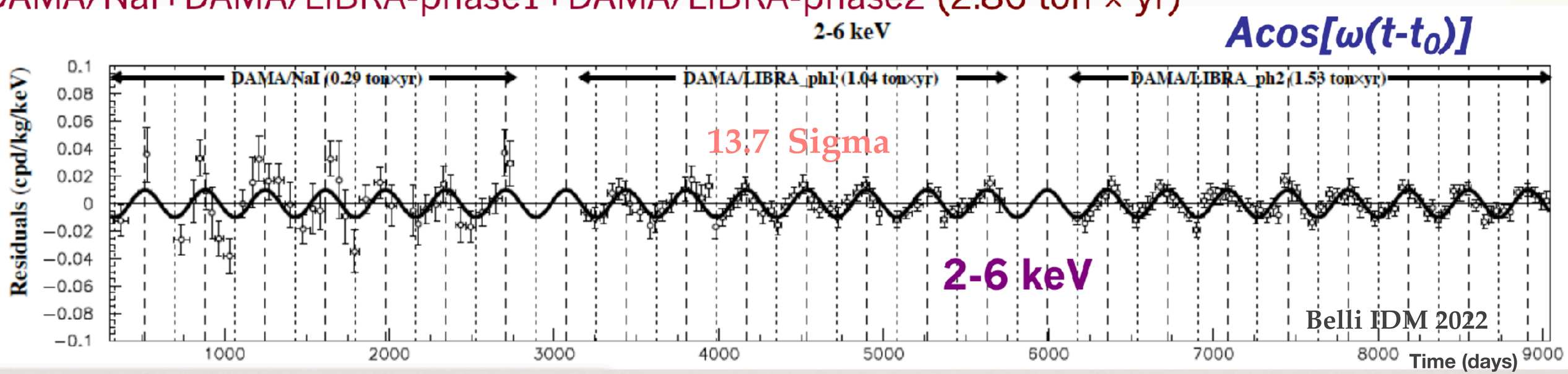


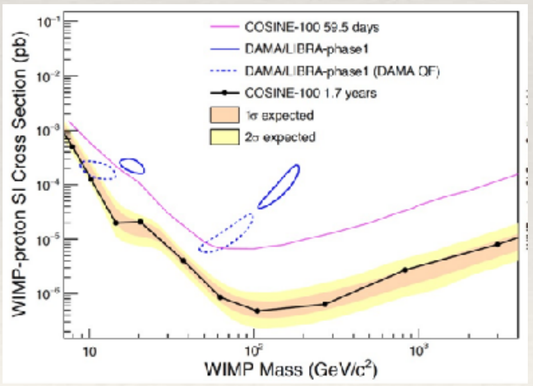
Conceptual studies in progress
Nominal run time: 10 years (3 kt x year)

Testera LeptonPhoton21

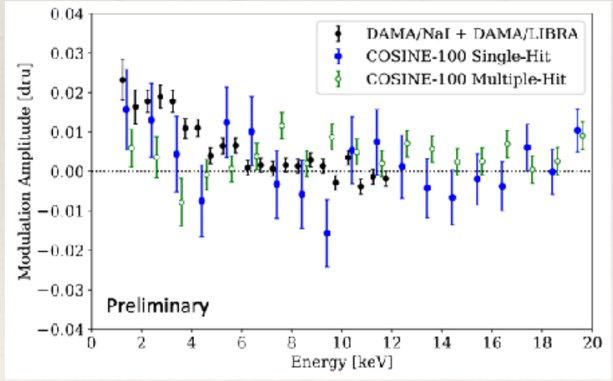
Resolve the DAMA/LIBRA Signal

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





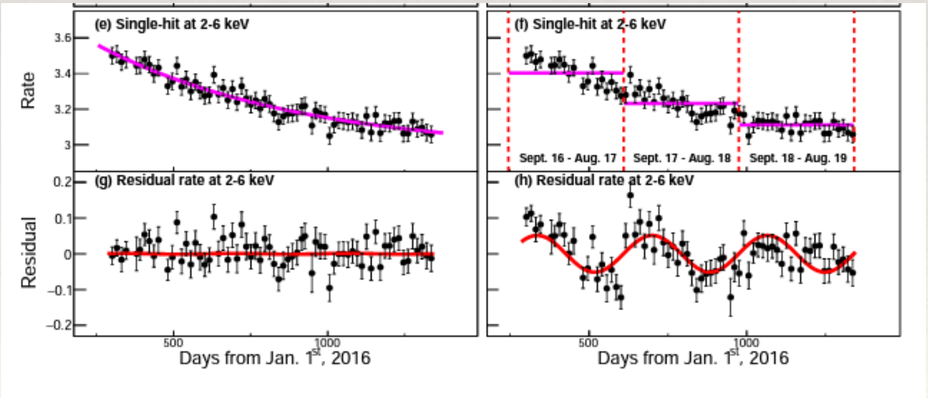
SciAdv 7 46 '21



Thompson LLWI 22

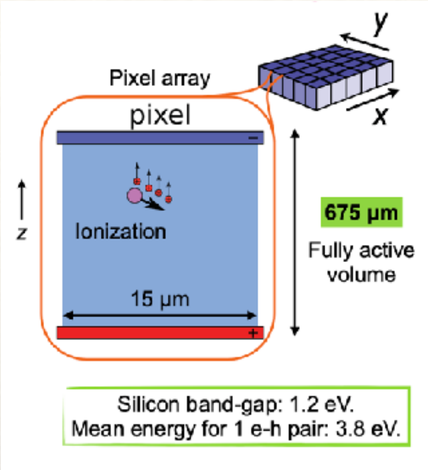
Multiple NaI detectors investigating
ANAIS, COSINE
SABRE, COSINUS

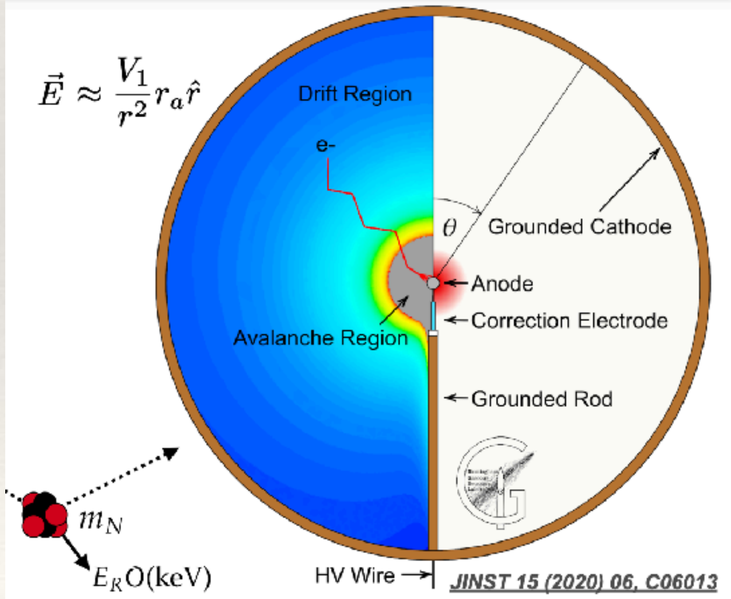
Zema talk

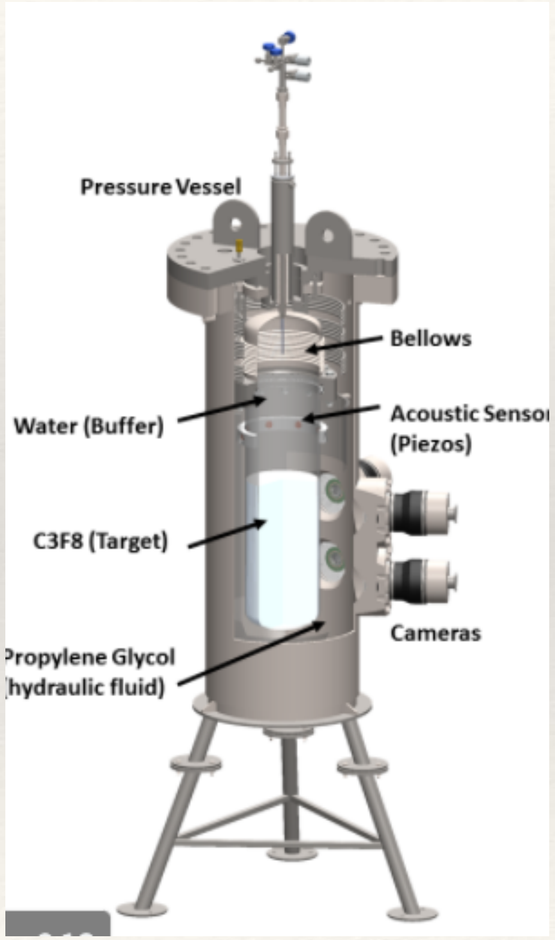


Is it just an analysis artifact? arXiv:2208.05158

Use new technologies for lower masses

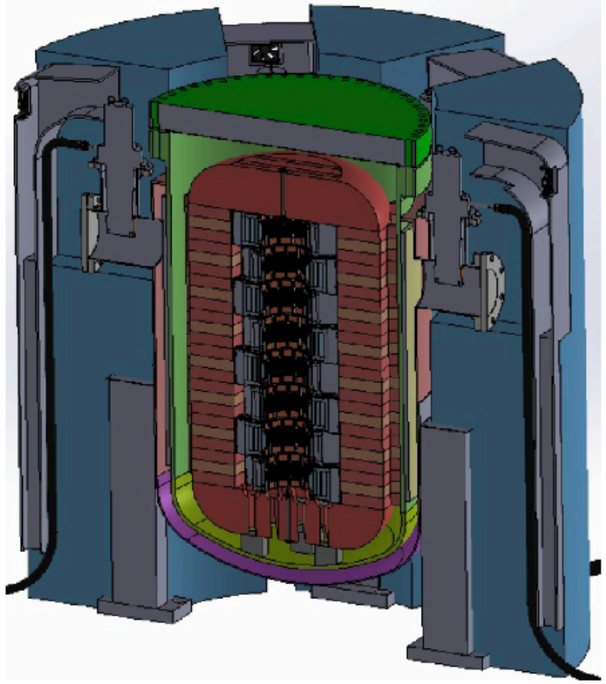






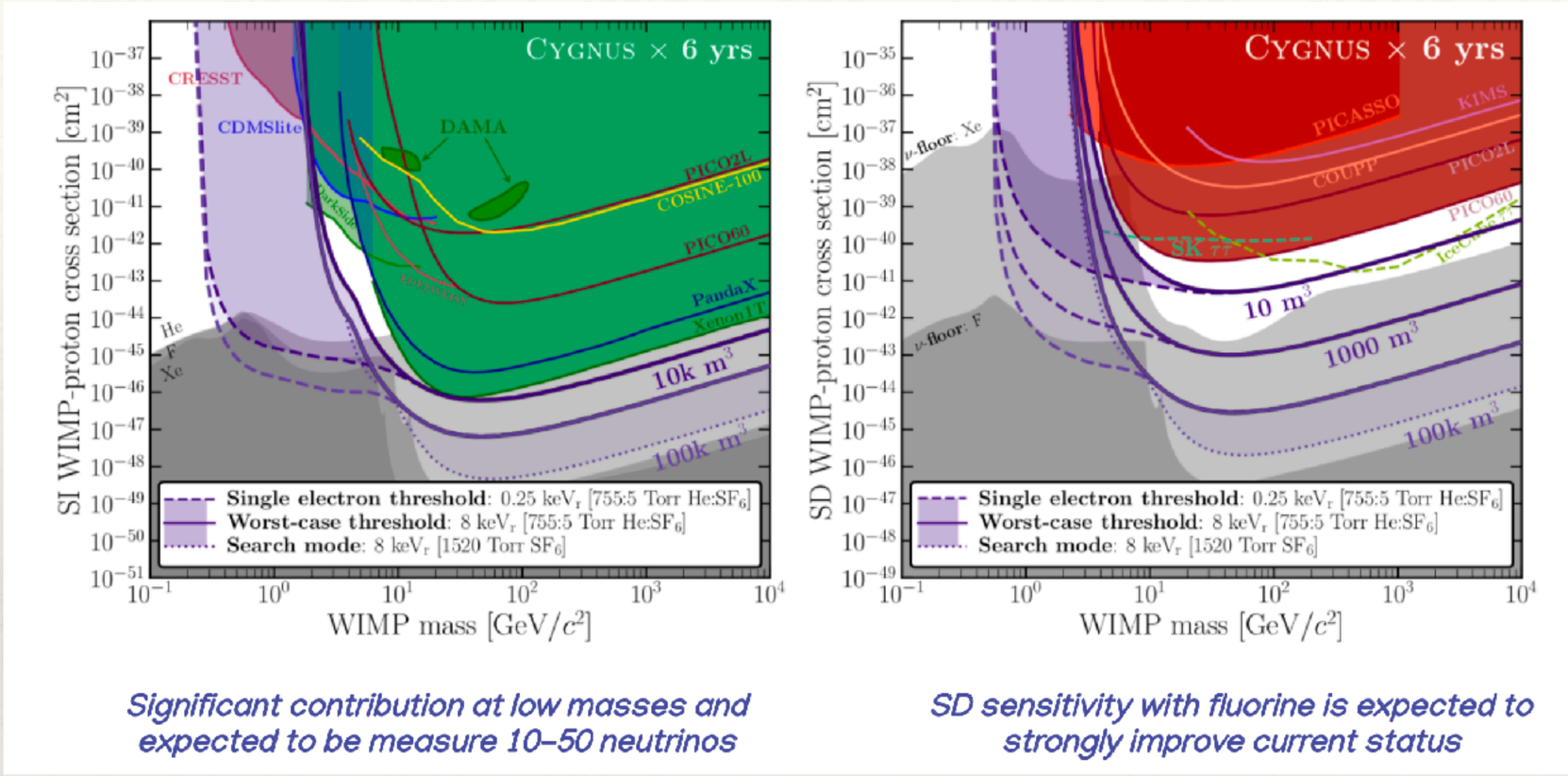
- NEWS-G
- PICO
- SENSEI & other Si
- SBC
- TESSERACT
- QUEST-DMC

OSCURA



Full payload 100 SMs:
10 kg!

Directional Detection



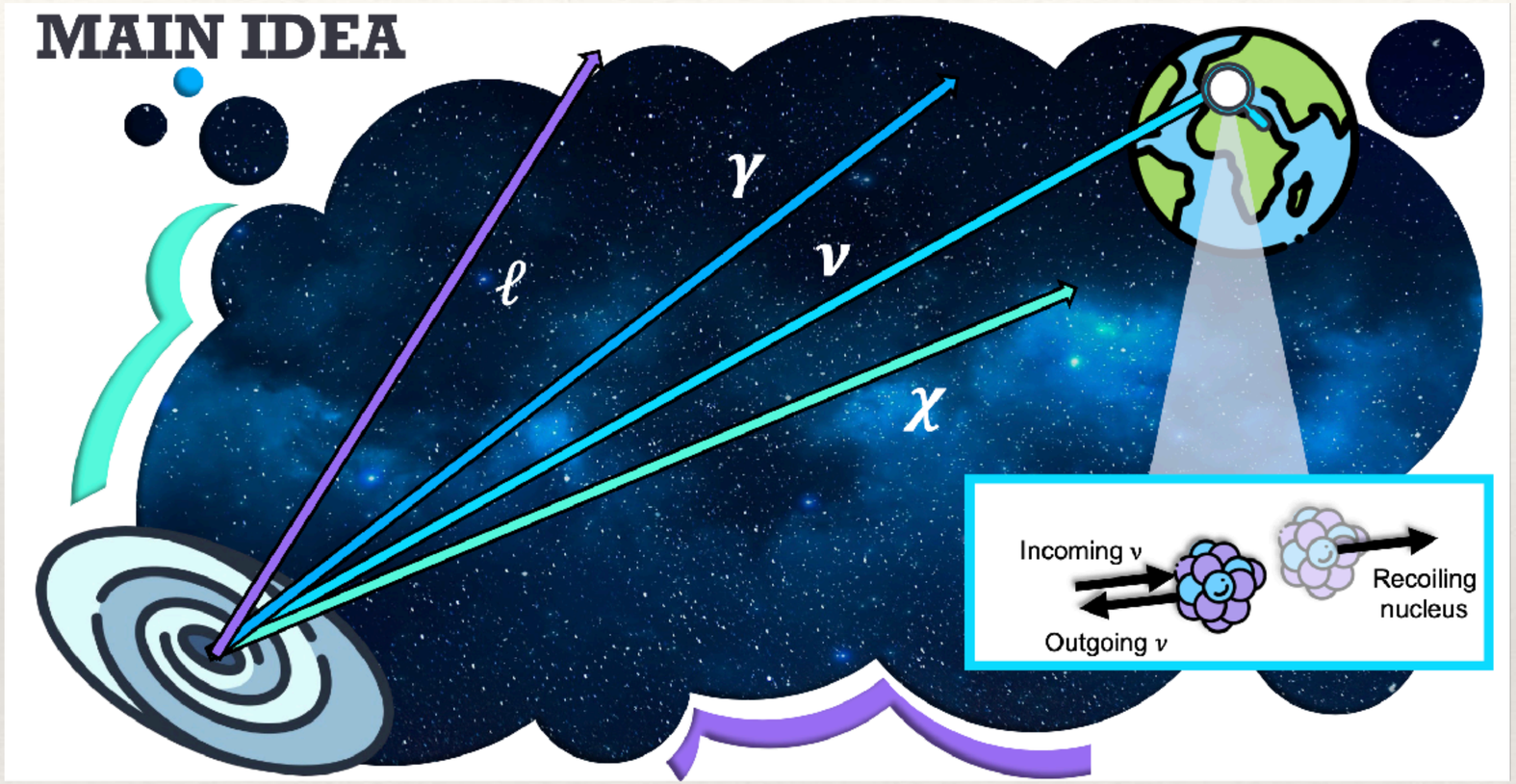
Significant contribution at low masses and expected to be measure 10–50 neutrinos

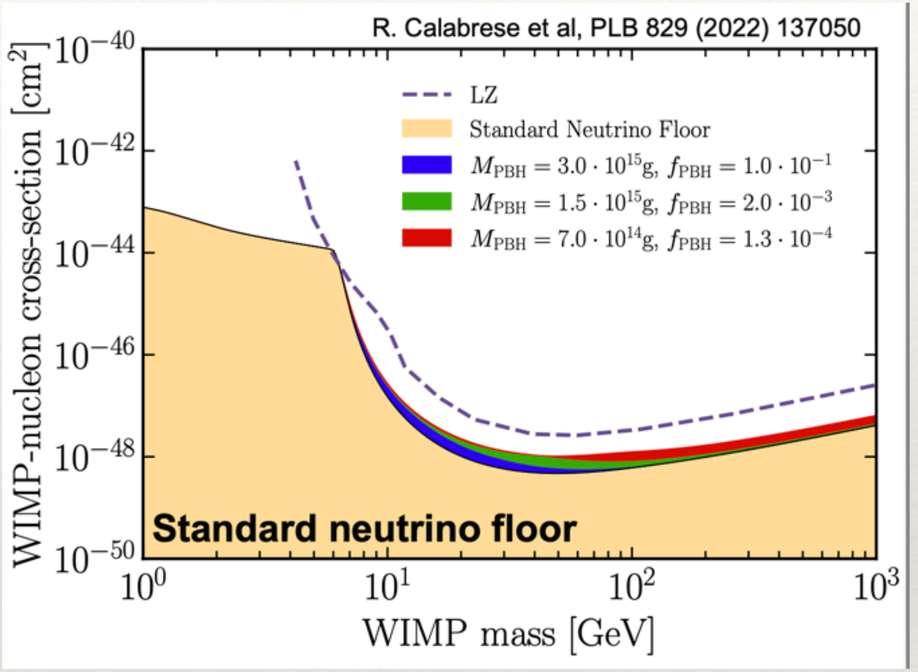
SD sensitivity with fluorine is expected to strongly improve current status

Dho talk

- Solid and gaseous directional detectors
- Can probe under the neutrino fog, first place to look is at low mass

Neutrinos from Primordial Black Holes

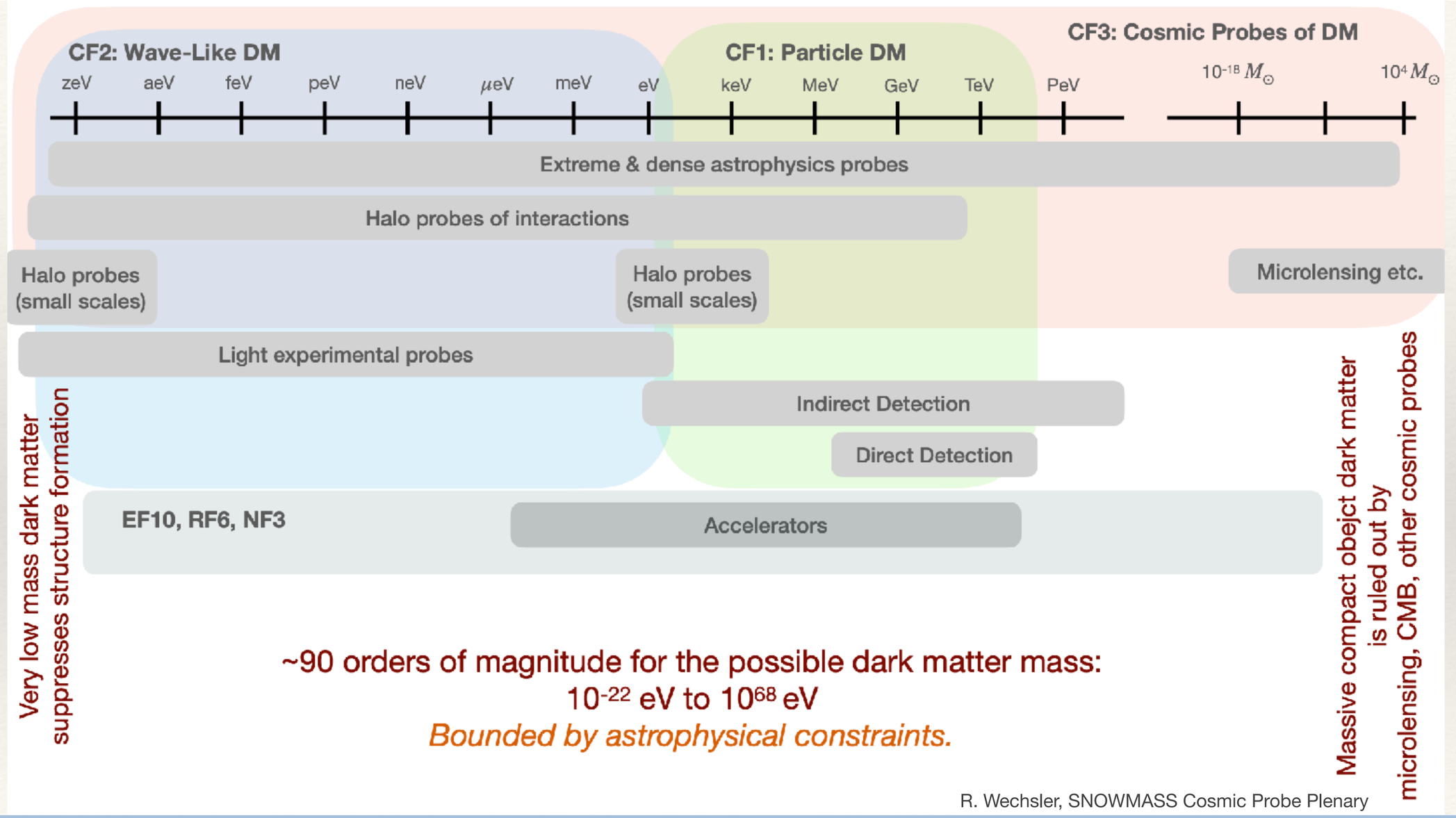




- PBH evaporation neutrinos could be seen in direct detectors

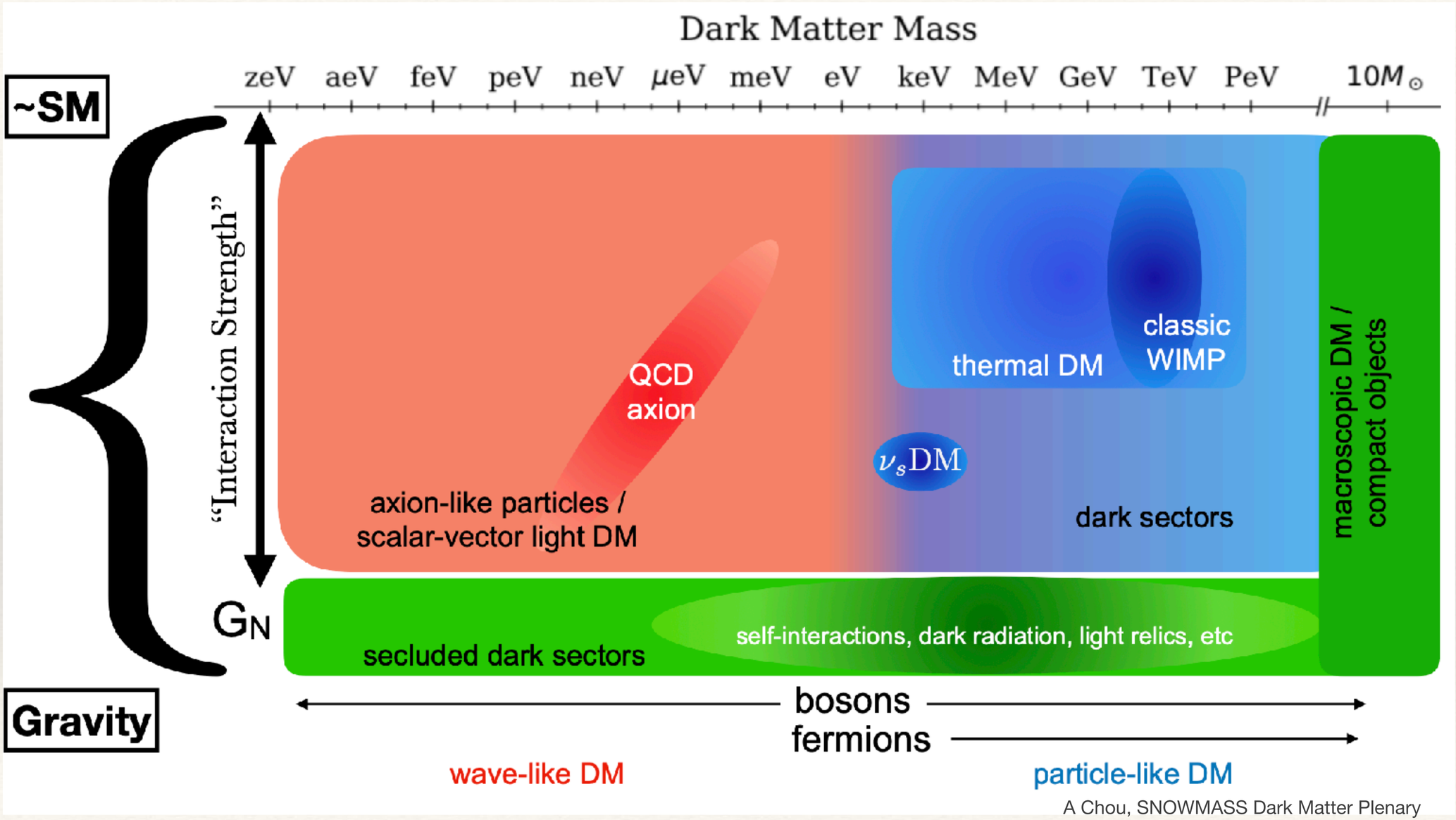
R. Calabrese talk

Complementarity



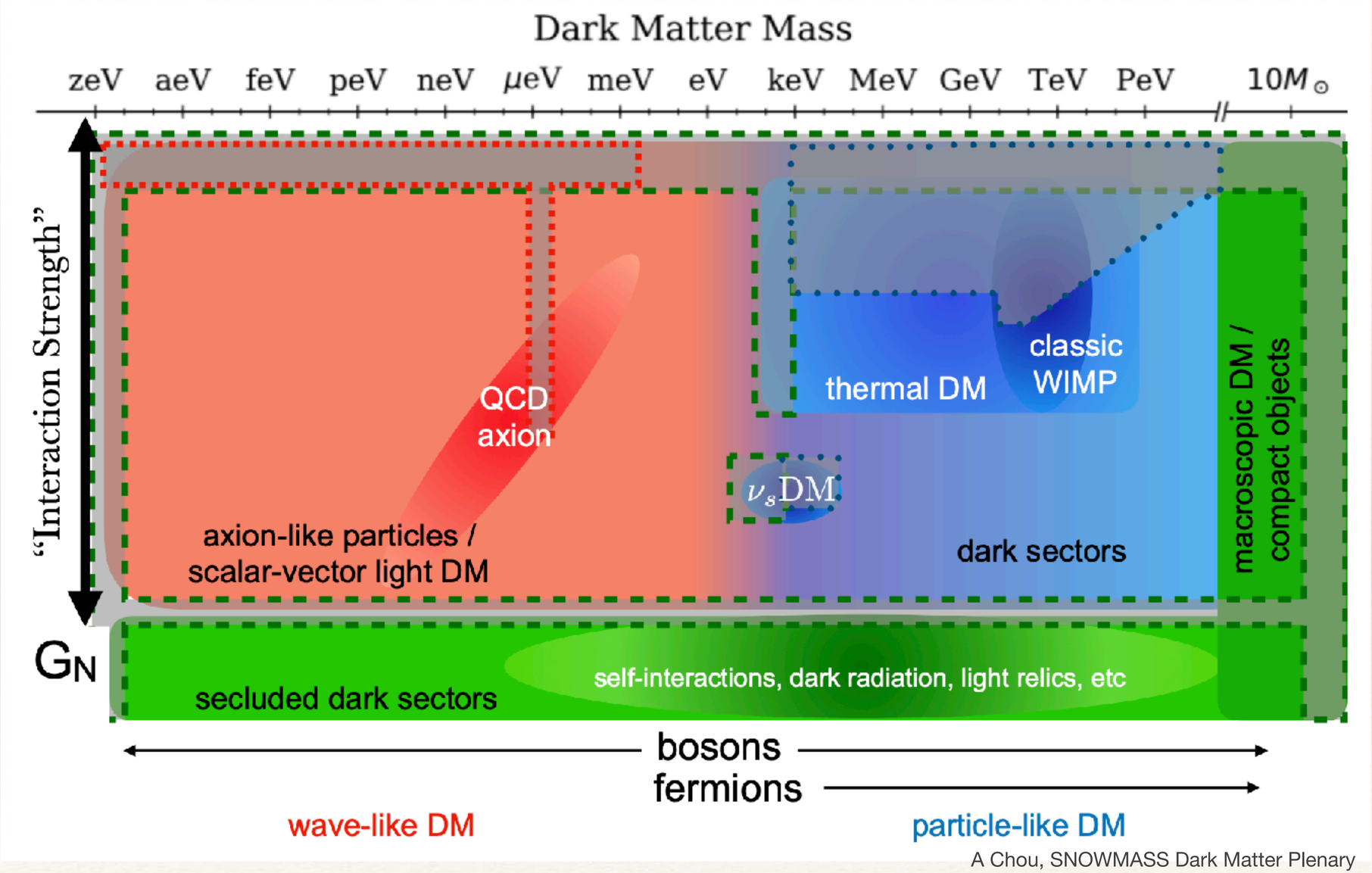
R. Wechsler, SNOWMASS Cosmic Probe Plenary

A Unified Vision coming from SNOWMASS



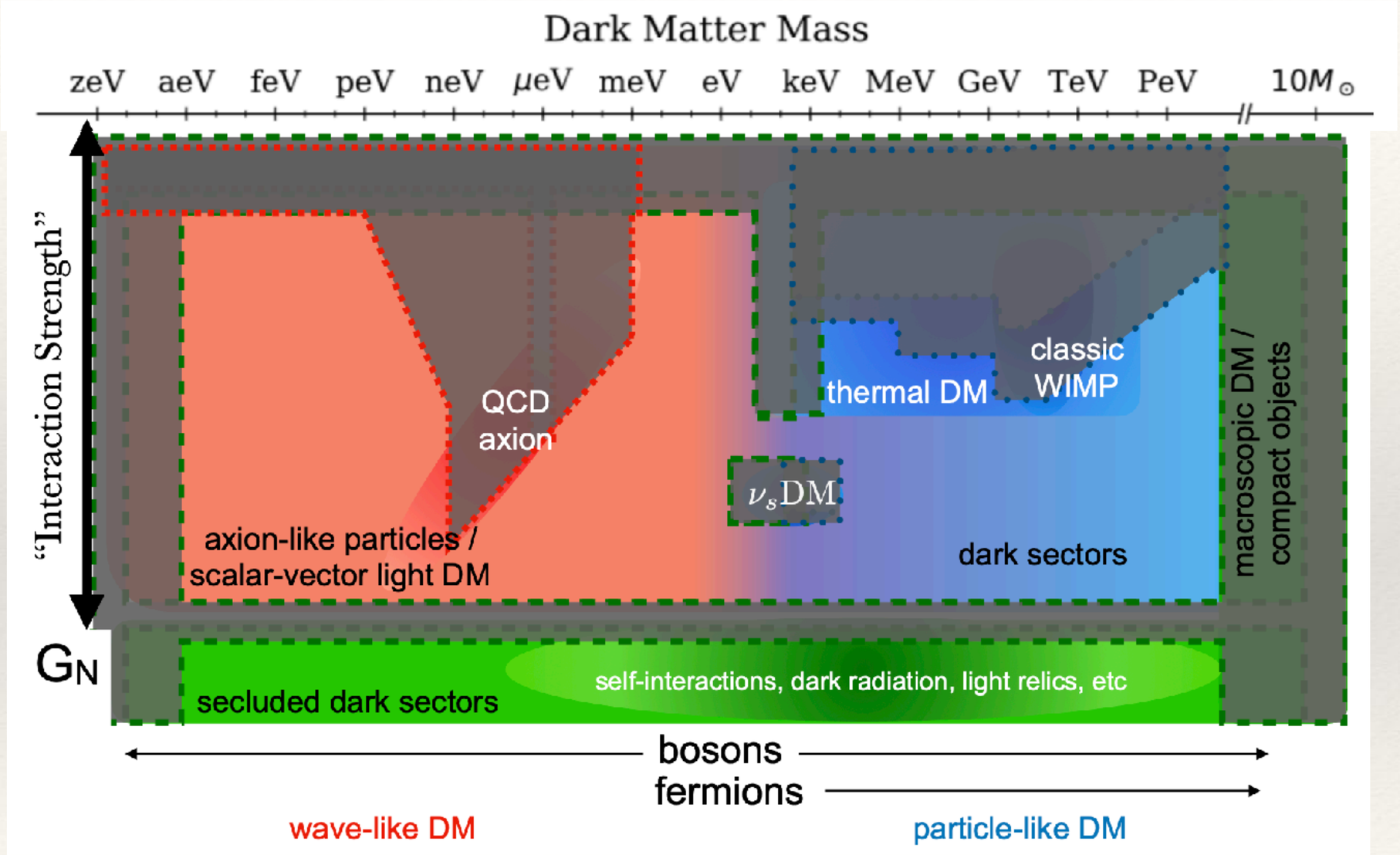
A Chou, SNOWMASS Dark Matter Plenary

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

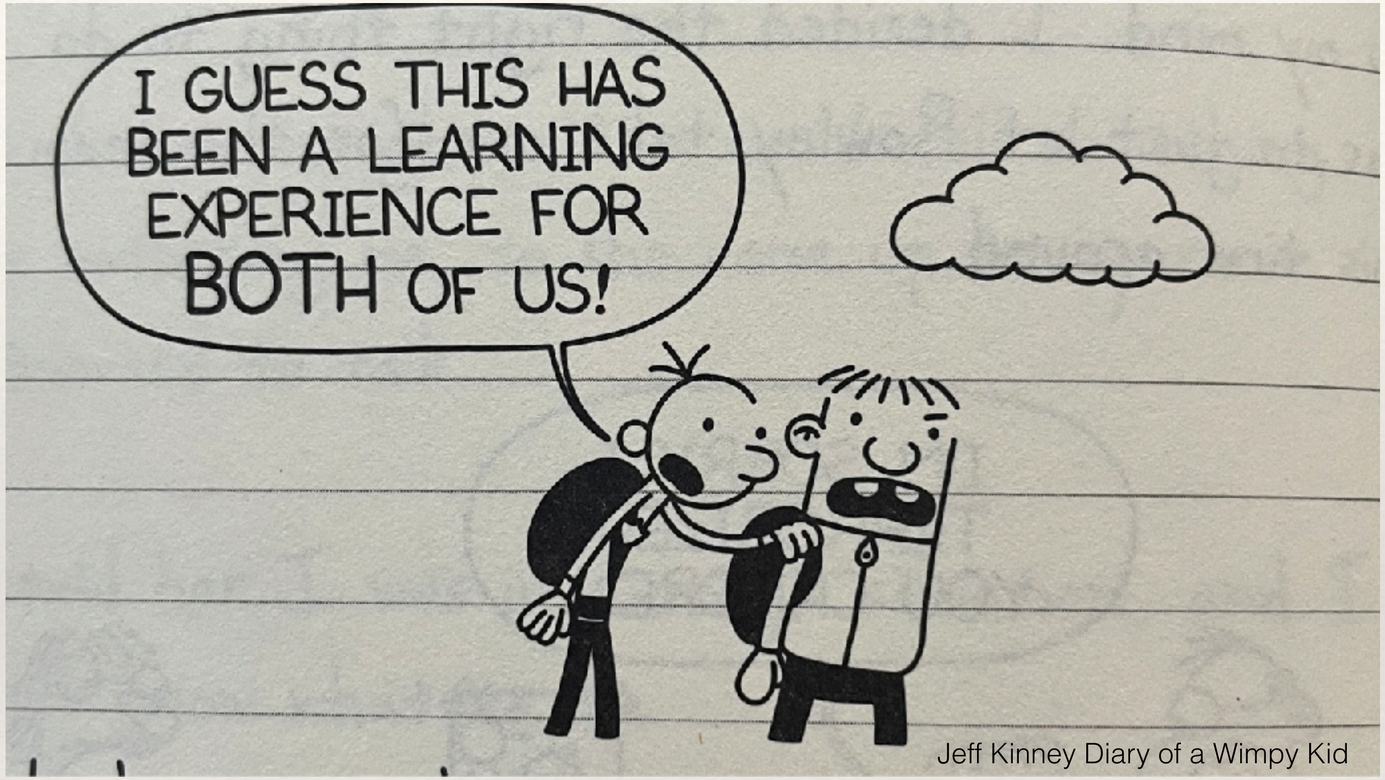
In Memoriam

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

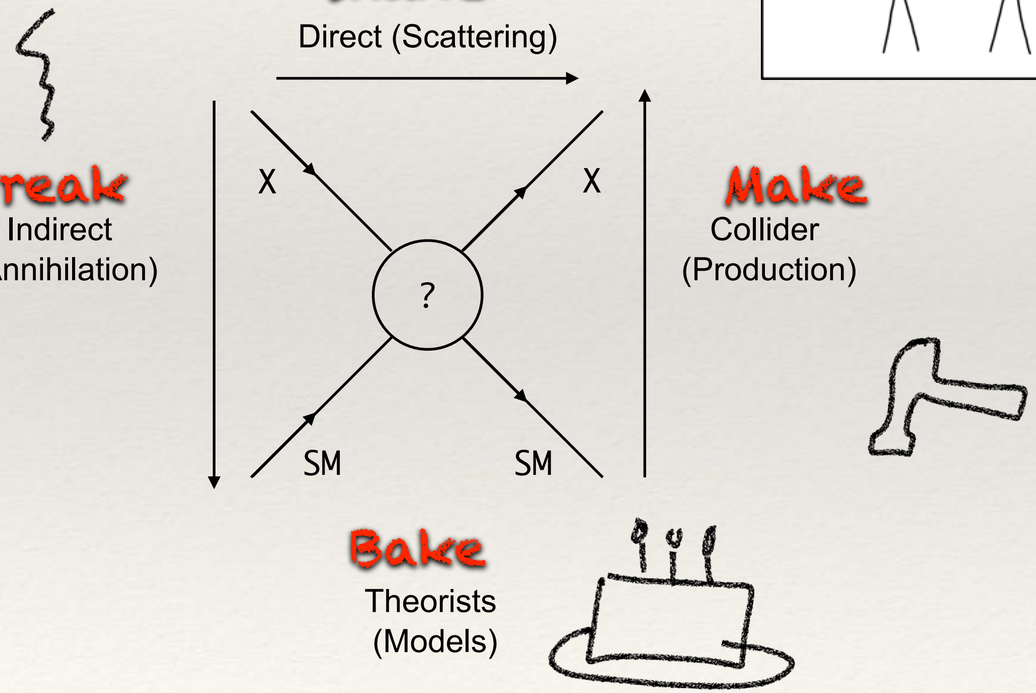
Spokesperson for MiniCLEAN
(my first DM experiment)
Single Phase liquid Ar/Ne
goal of DM and neutrino physics

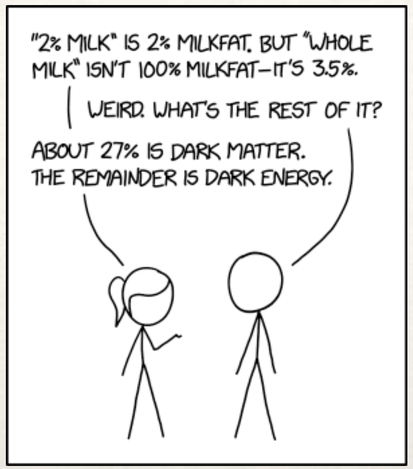


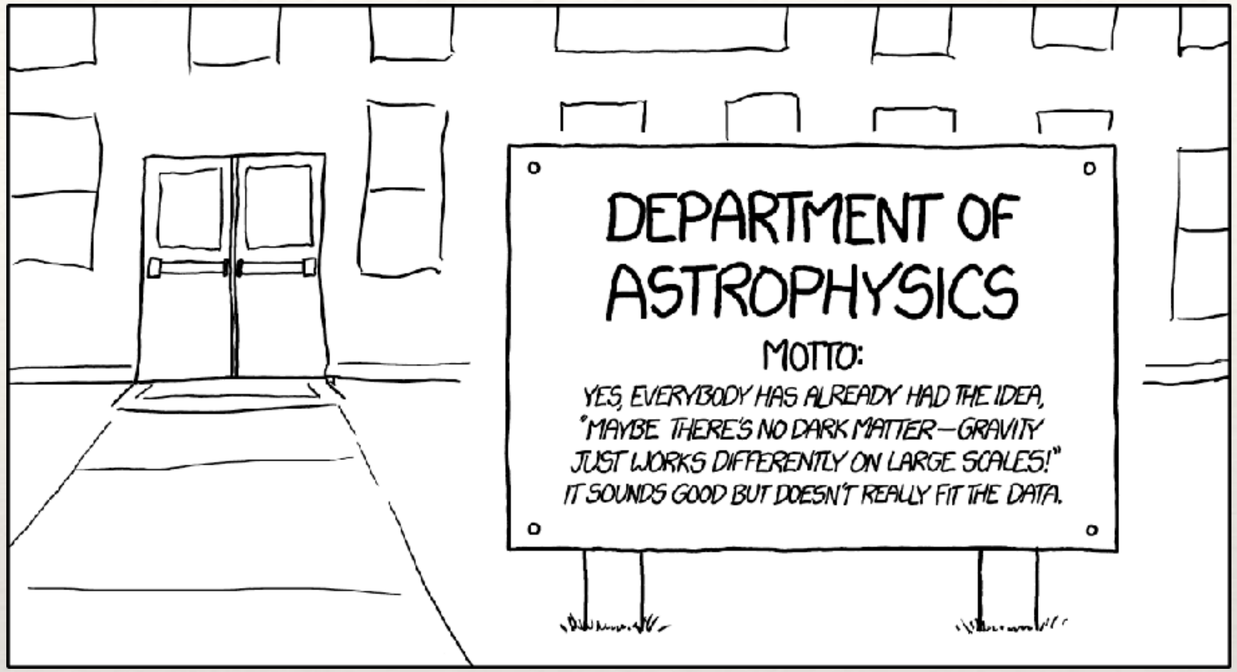
Jeff Kinney Diary of a Wimpy Kid

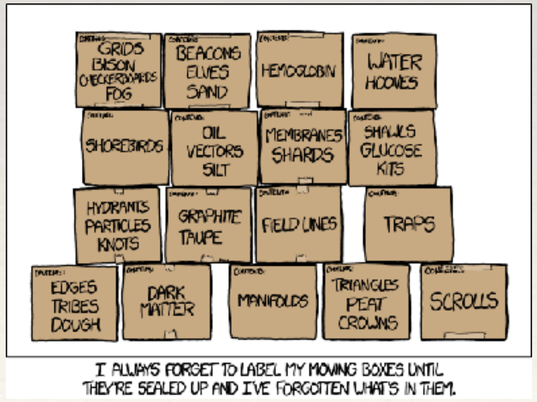
More Cartoons

Anthropomorphic WIMP
from Symmetry magazine

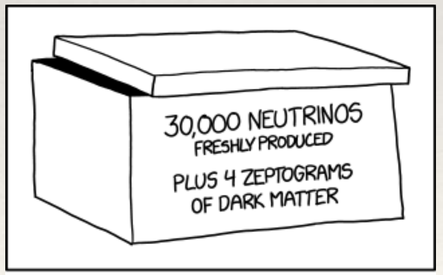






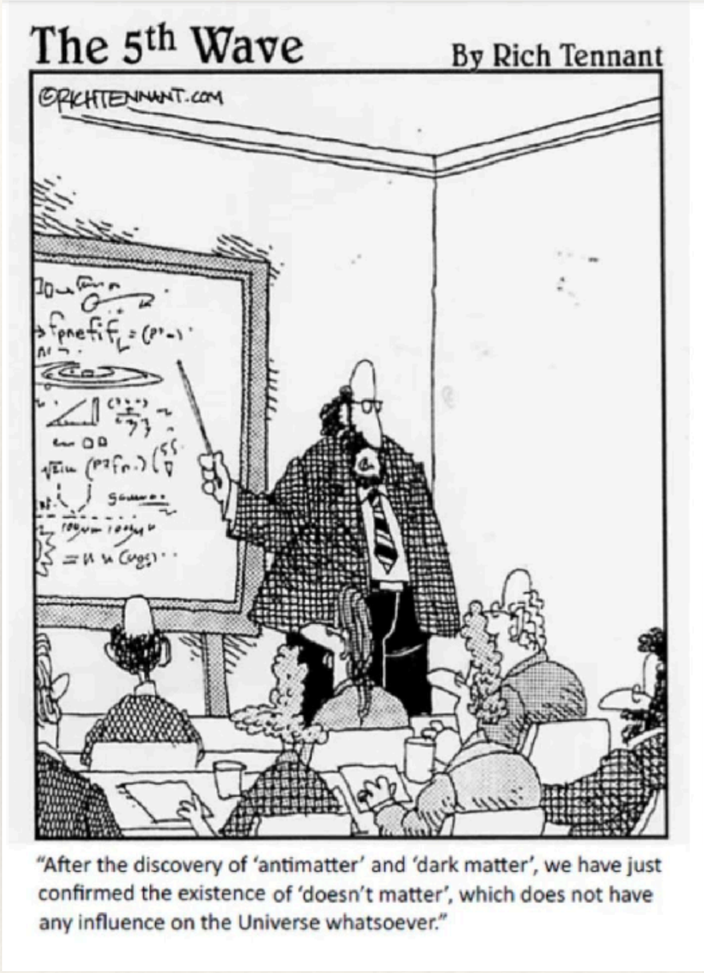


I ALWAYS FORGET TO LABEL MY MOVING BOXES UNTIL THEY'RE SEALED UP AND I'VE FORGOTTEN WHAT'S IN THEM.

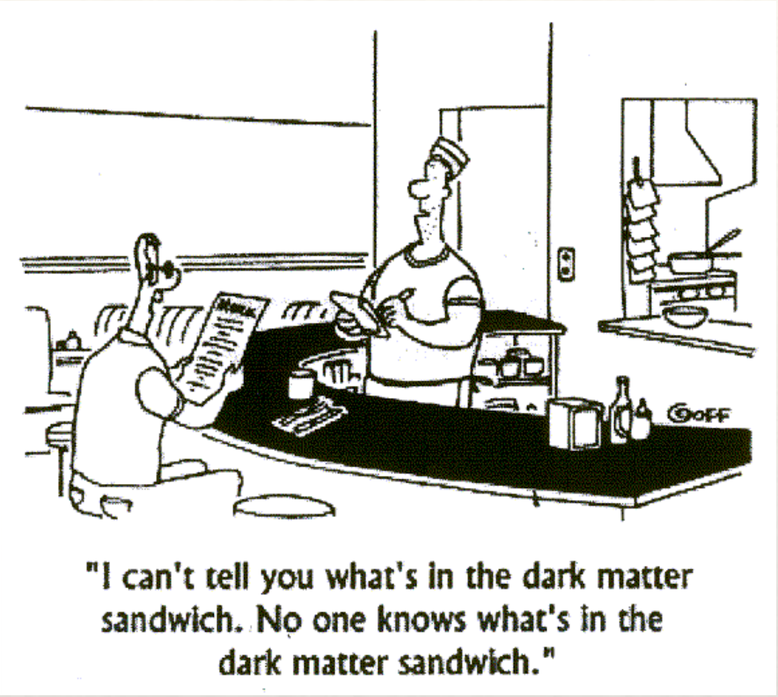


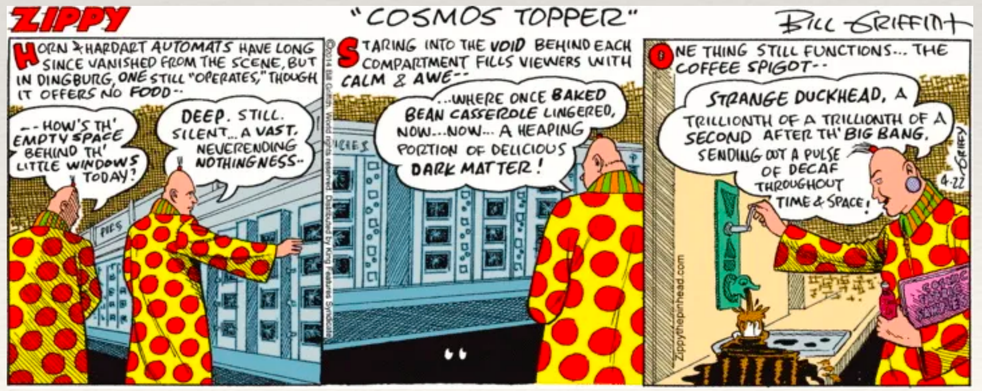
COSMOLOGISTS ARE EASY TO SHOP FOR BECAUSE YOU CAN JUST GET THEM A BOX.

More Cartoons

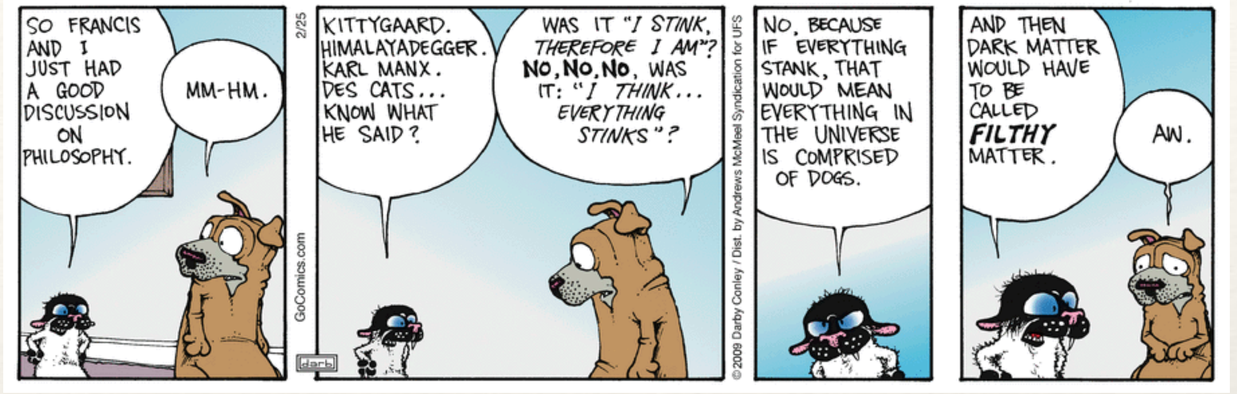


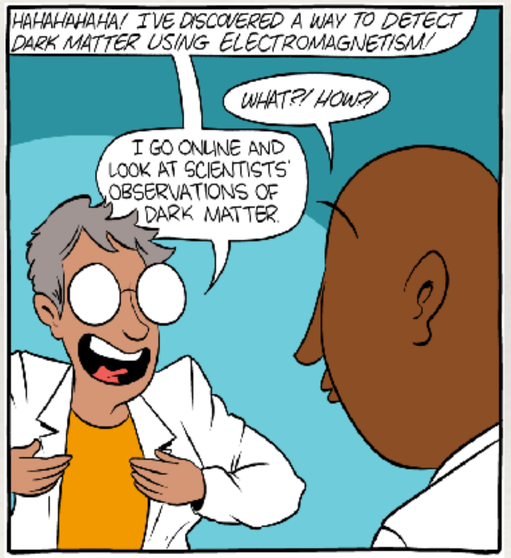
"After the discovery of 'antimatter' and 'dark matter', we have just confirmed the existence of 'doesn't matter', which does not have any influence on the Universe whatsoever."





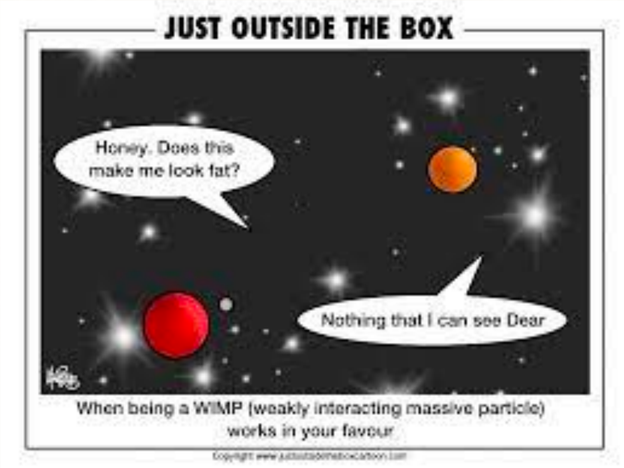
More Cartoons

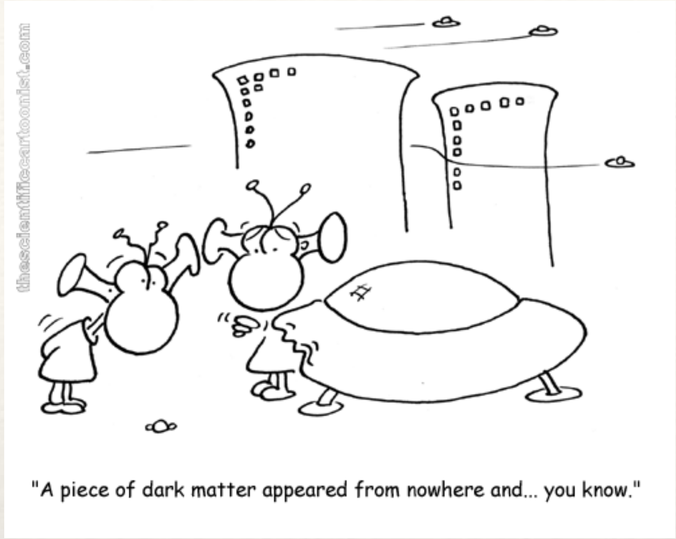




So far, the Nobel Committee has not returned my calls.

More Cartoons





Experiments Currently running

Name	Technology	Target	Active Mass	Experiment Location	Start Ops	End Ops
Currently Running or Under Construction						
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

Experments Currently running, cont'd

Name	Technology	Target	Active Mass	Experiment Location	Start Ops	End Ops
Currently Running or Under Construction						
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

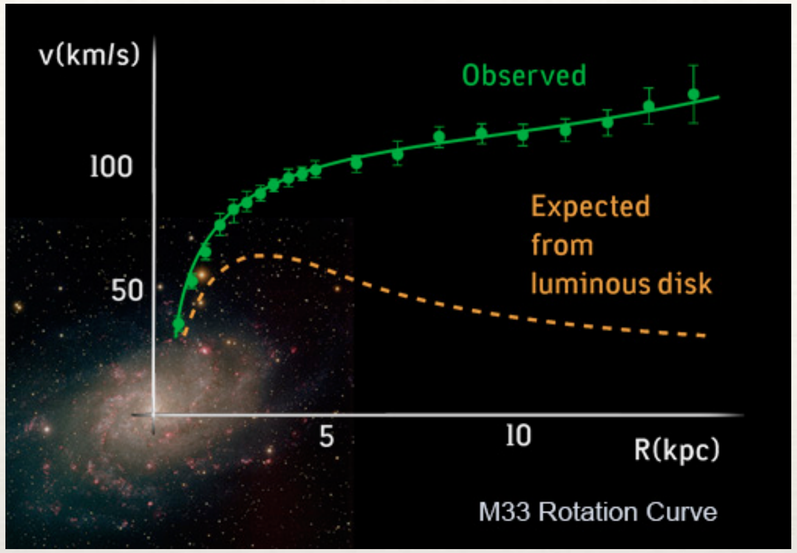
Planned Experiments

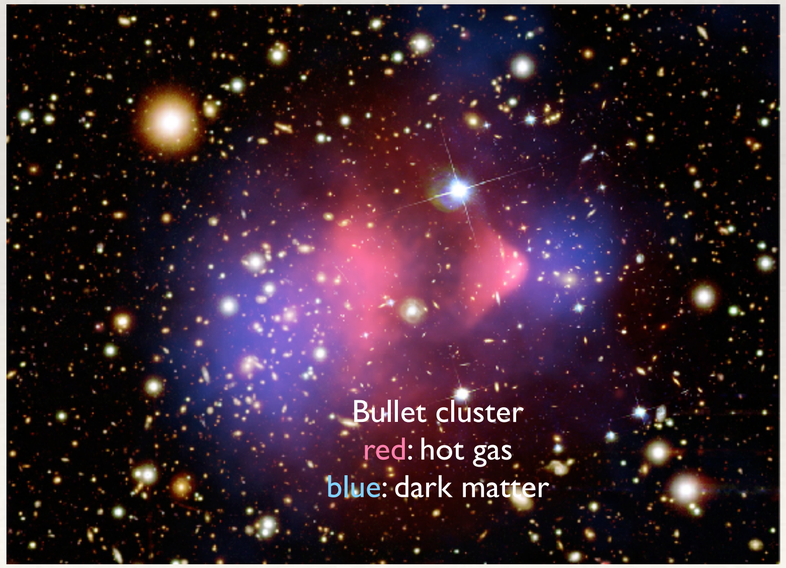
Name	Technology	Target	Active Mass	Experiment Location	Start Ops	End Ops
Planned						
SABRE (North)	Scintillator	NaI	50 kg	LNGS	2022	2027
SABRE (South)	Scintillator	NaI	50 kg	SUPL	2022	2027
COSINE-200 South Pole	Scintillator	NaI	200 kg	South Pole	2023	
COSINUS	Bolometer Scintillator	NaI		LNGS	2023	
Darwin / XLZD (US LXe G3)	TPC	LXe	50,000 kg	undetermined	2028	2033
ARGO	TPC or Scintillator	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	

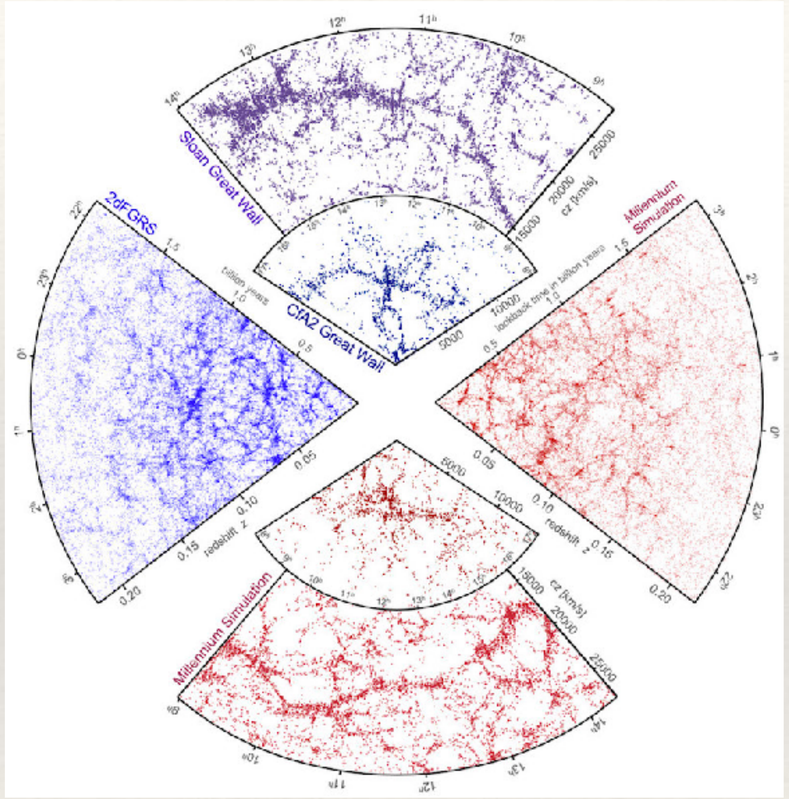
Potential Future Experiments

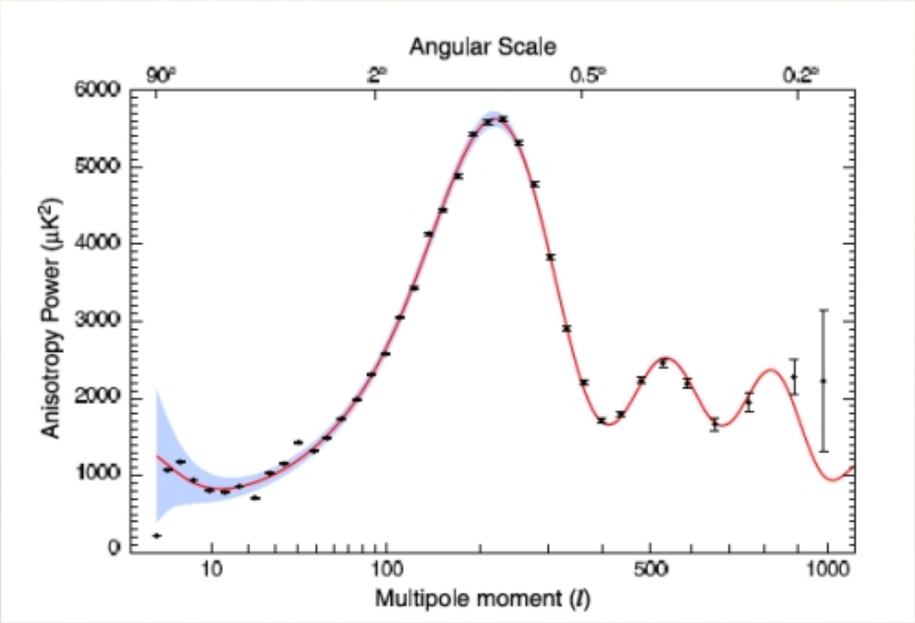
Name	Technology	Target	Active Mass	Experiment Location	Start Ops	End Ops
Concept or R&D						
Oscura	CCD Skipper	Si	10 kg Si	SNOLAB	2025	2028
SBC	Bubble Chamber	LAr	1 t	SNOLAB	2028	
SNOWBALL	Supercooled Liquid H2O					
DarkSide-LowMass	TPC	LAr	1.5 t			
ALETHEIA	TPC	He		China Inst. At. Energy		
TESSERACT	Cryo TES	LHe, SiO_2, Al_2O_3, GaAs		undetermined	2026	
CYGNO	Gas Directional	He + CF_4	0.5 - 1 kg	LNGS	2024	
CYGNUS	Gas Directional	He + SF_6/CF_4		Multiple sites		
Windchime	Accelerometer array			Multiple sites	2	

Evidence for Dark Matter

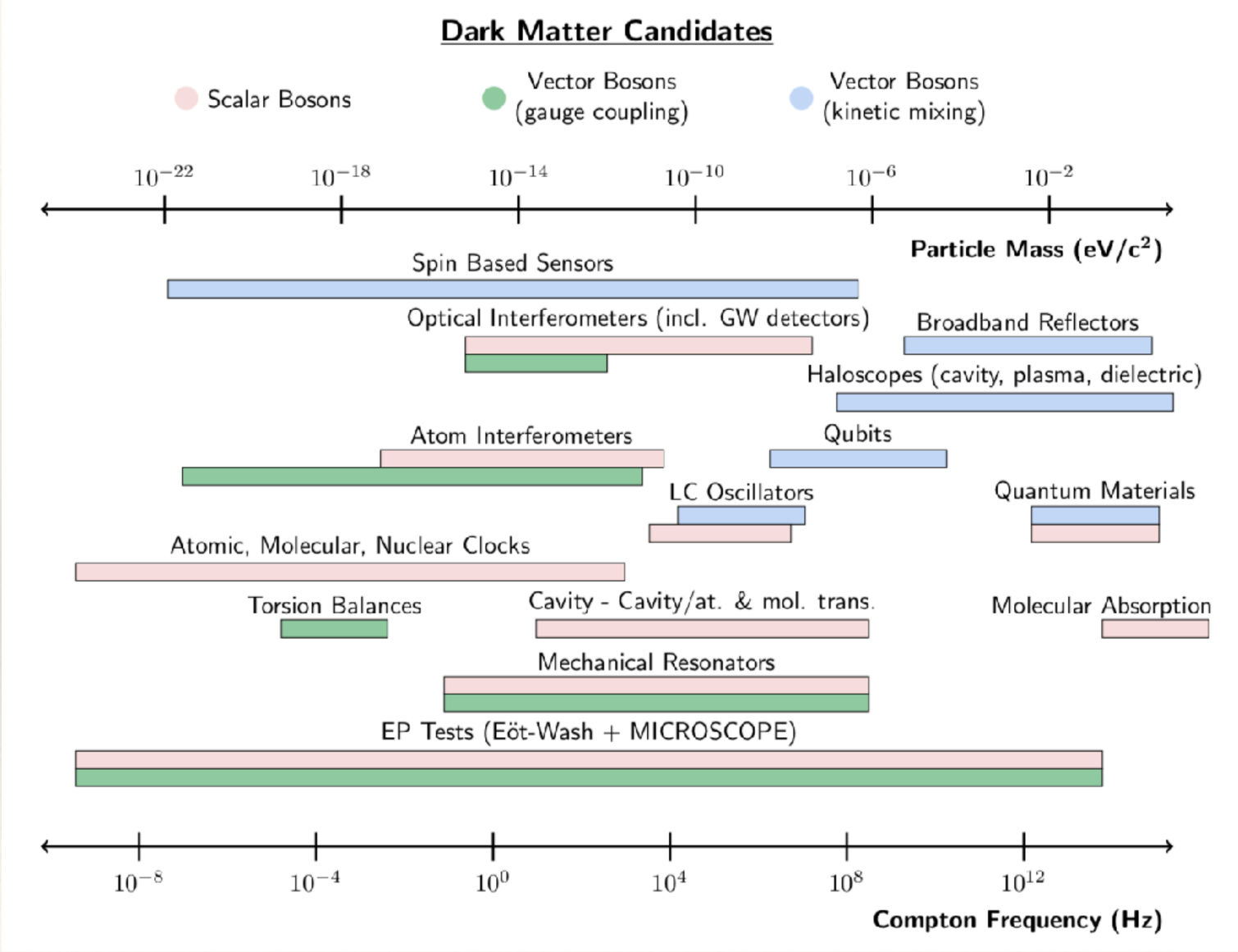






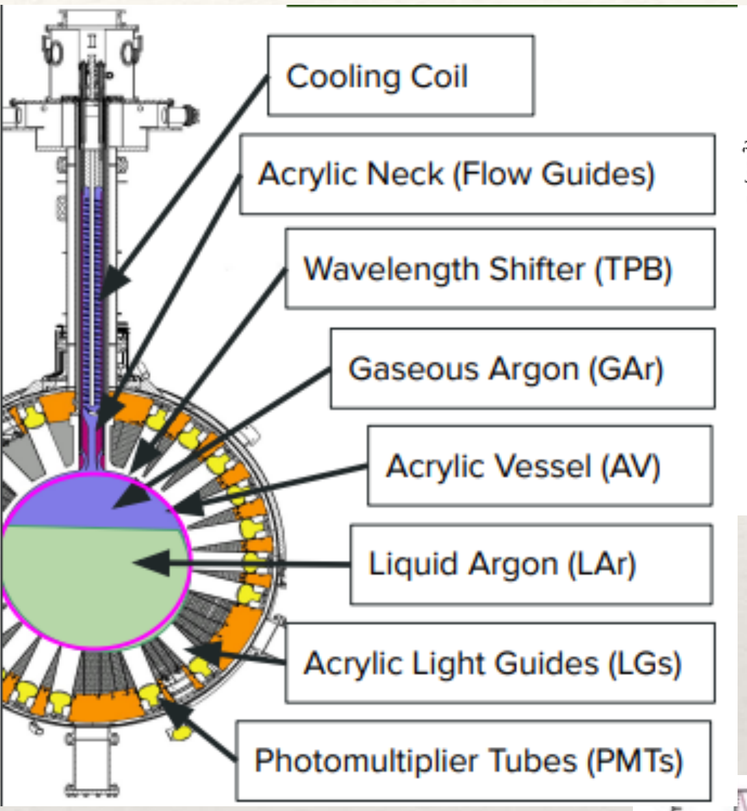


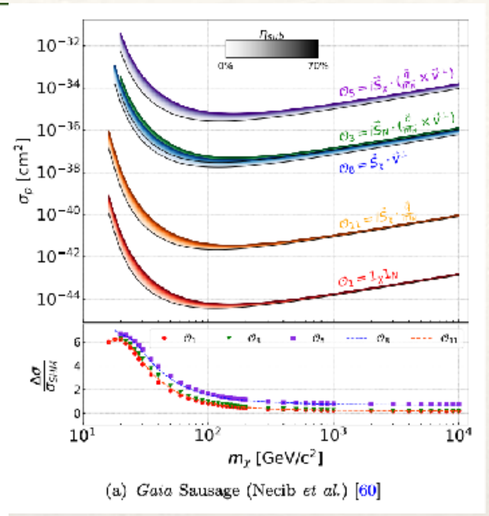
Wavelike Dark Matter



arXiv:2203.14915

DEAP-3600

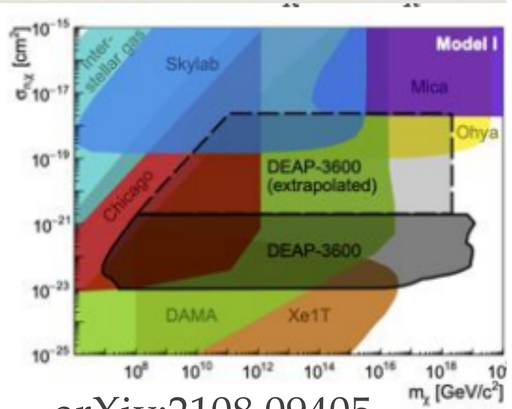




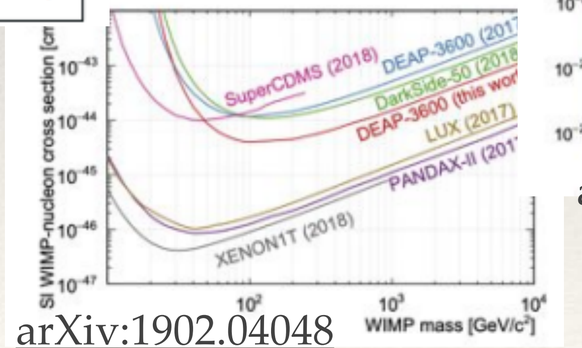
(a) *Gaia* Sausage (Necib *et al.*) [60]

- 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

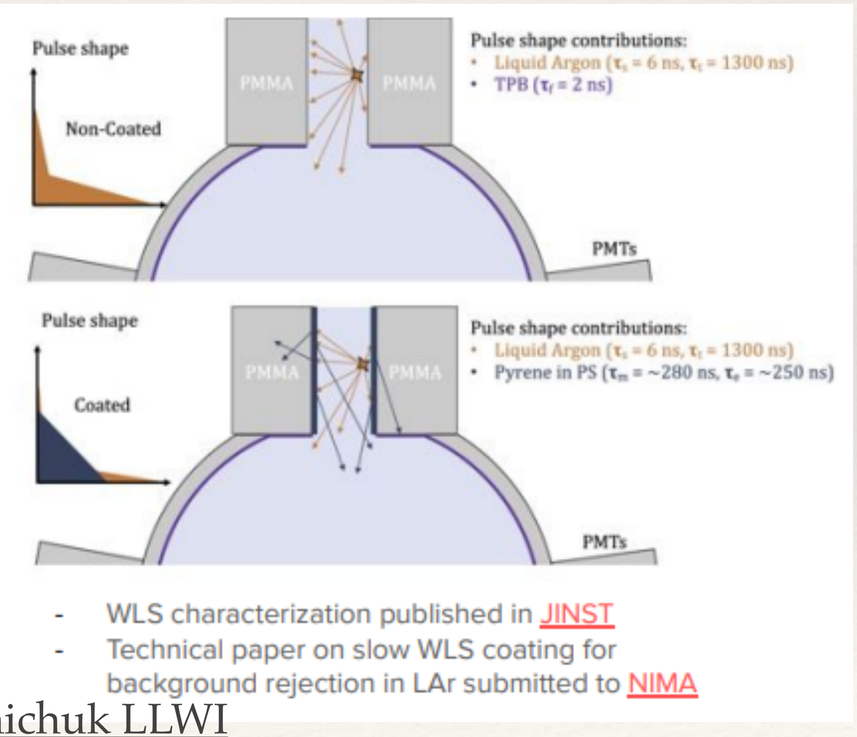
arXiv:2005.14667



arXiv:2108.09405



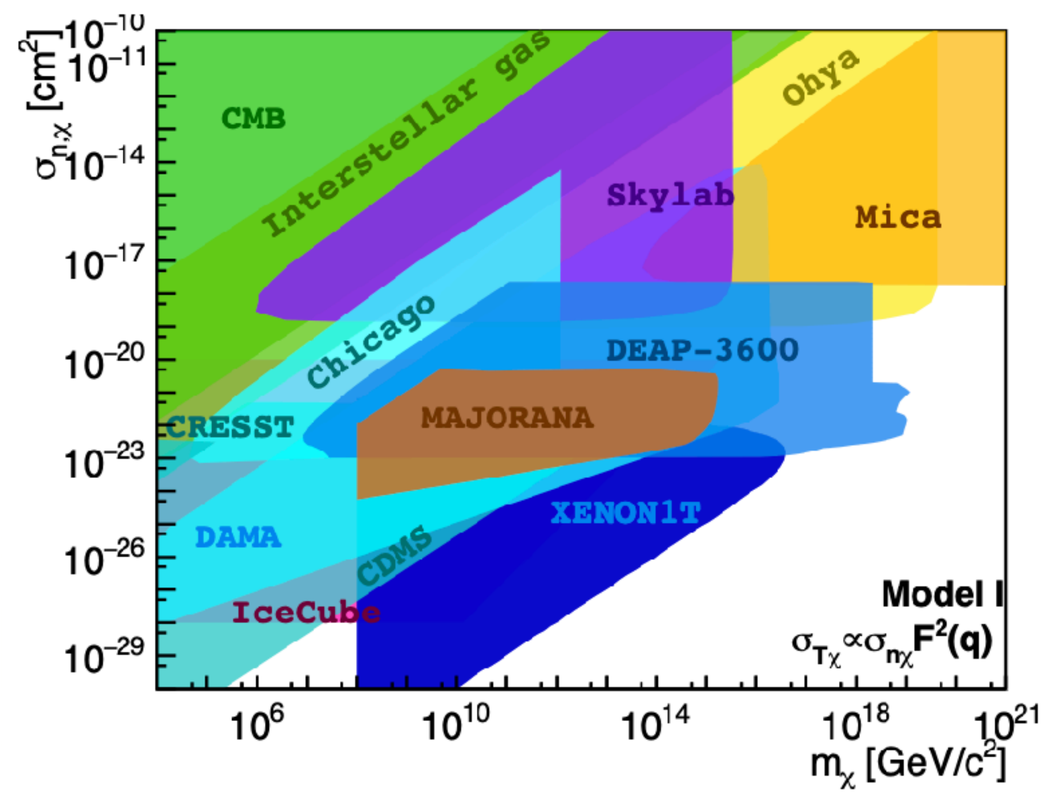
arXiv:1902.04048

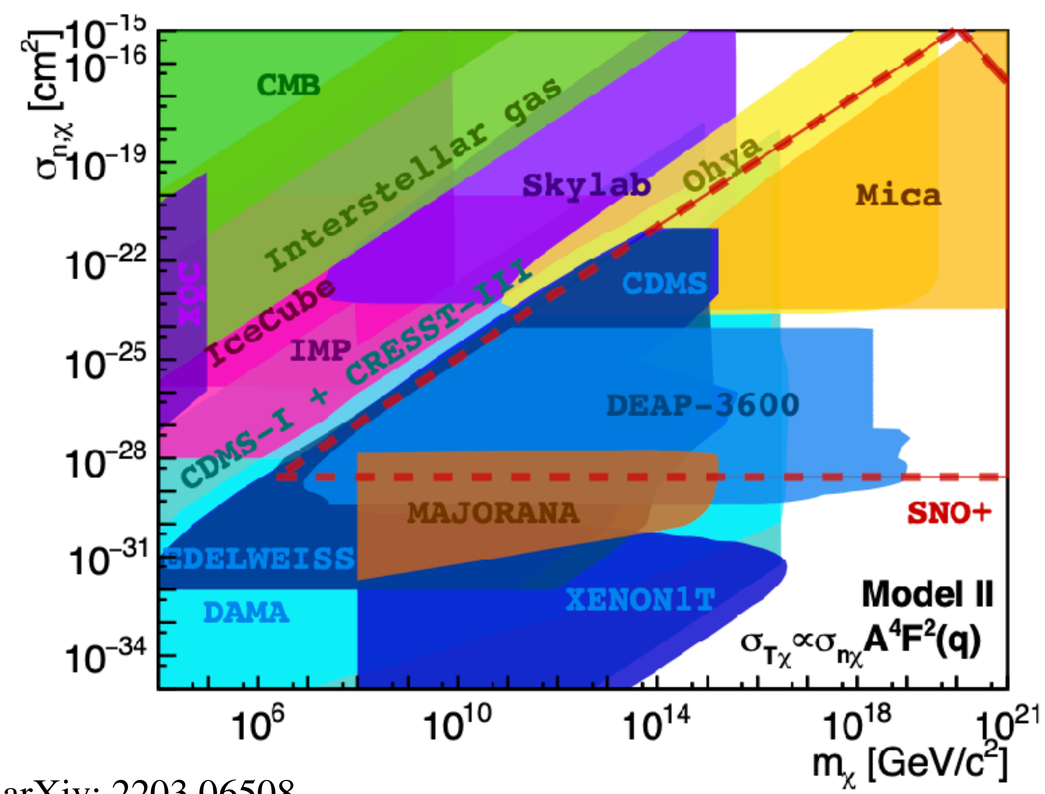


- WLS characterization published in JINST
- Technical paper on slow WLS coating for background rejection in LAr submitted to NIMA

Mielnichuk LLWI

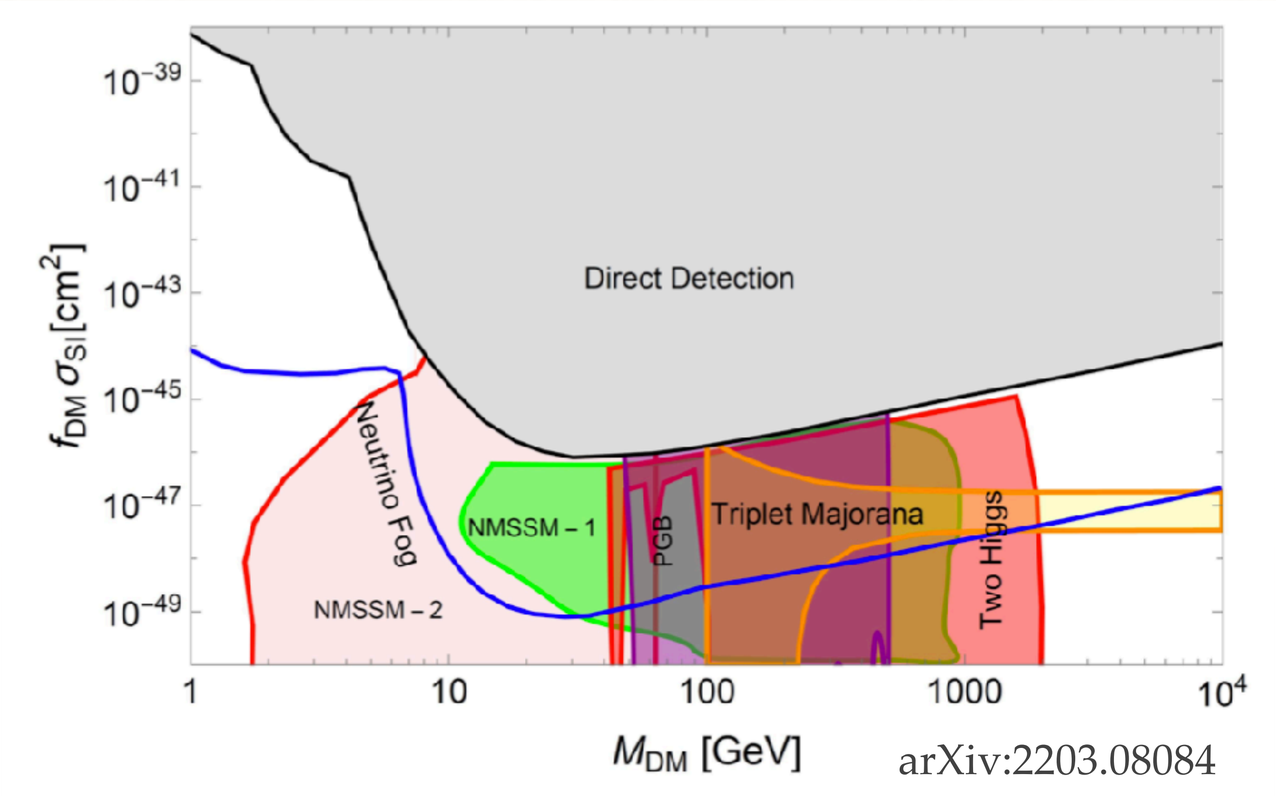
Ultraheavy dark matter





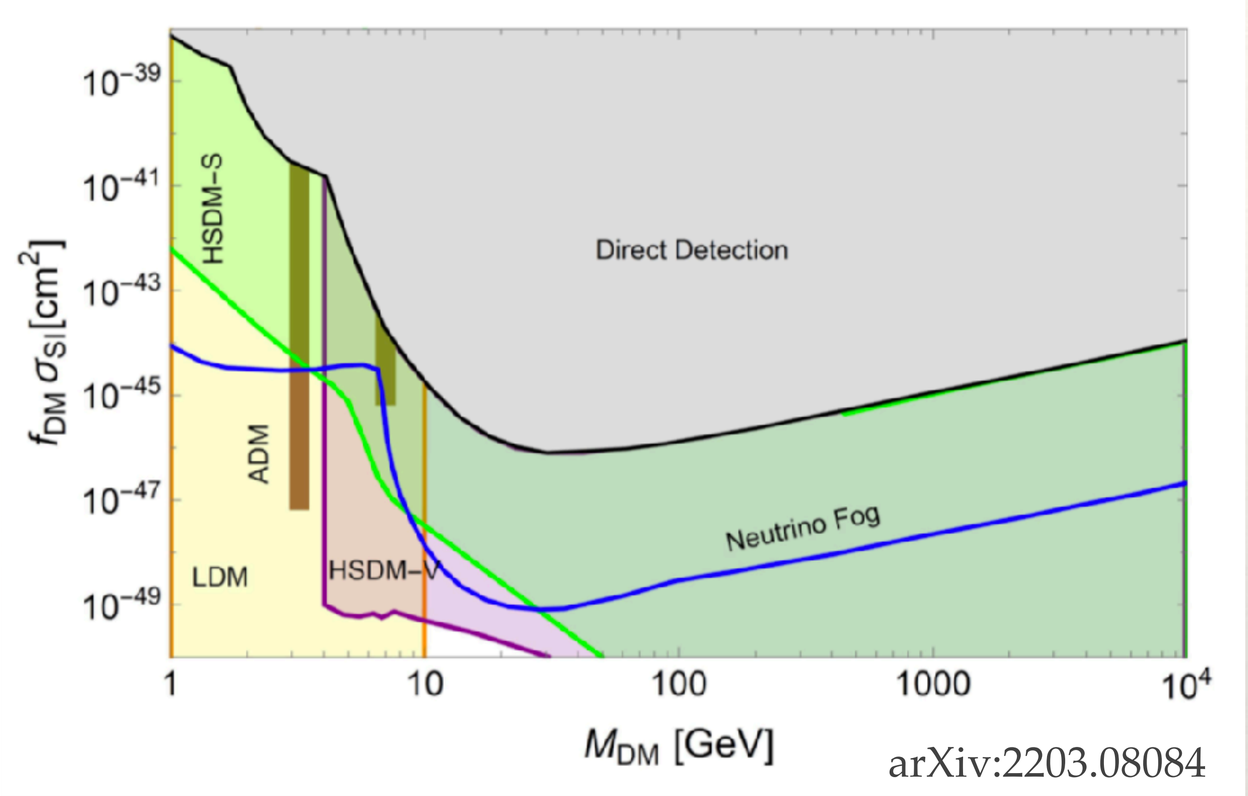
arXiv: 2203.06508

A Modern WIMP view

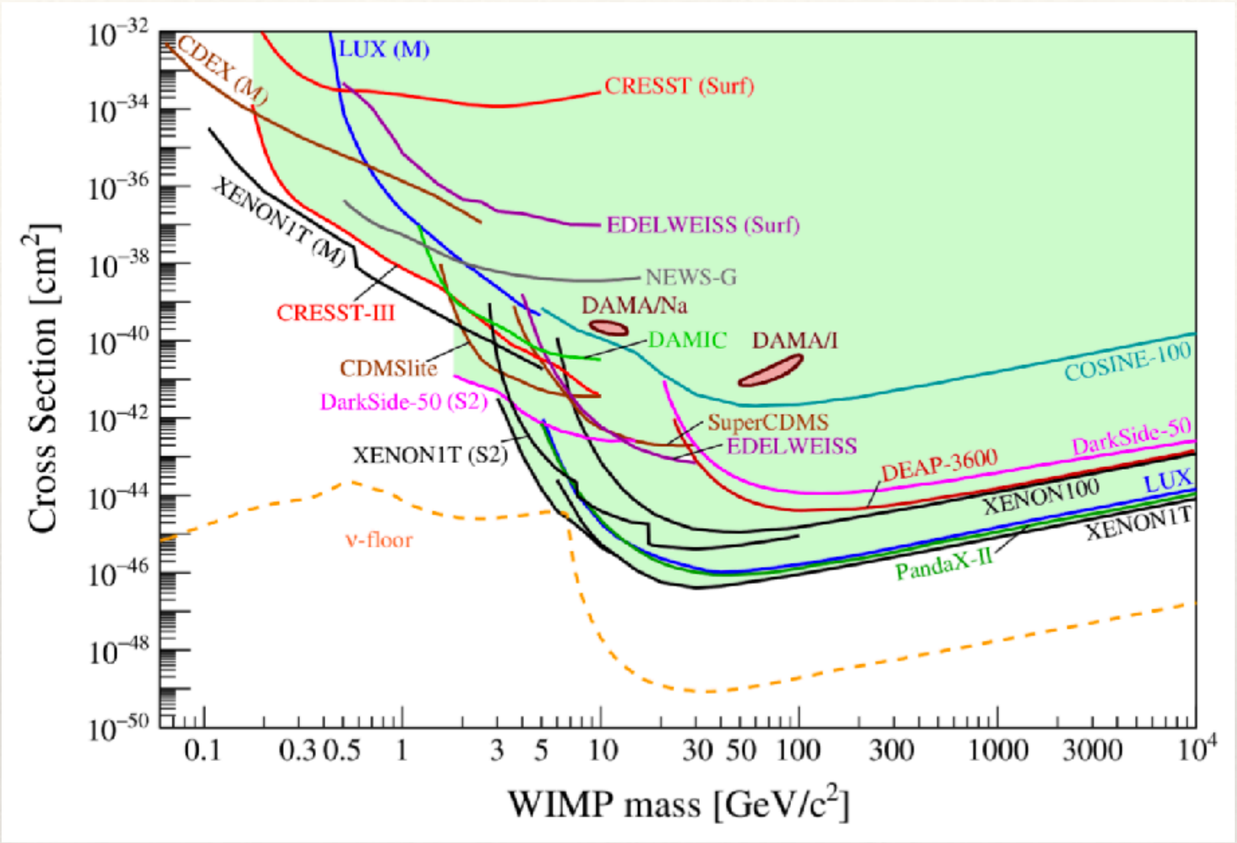


arXiv:2203.08084

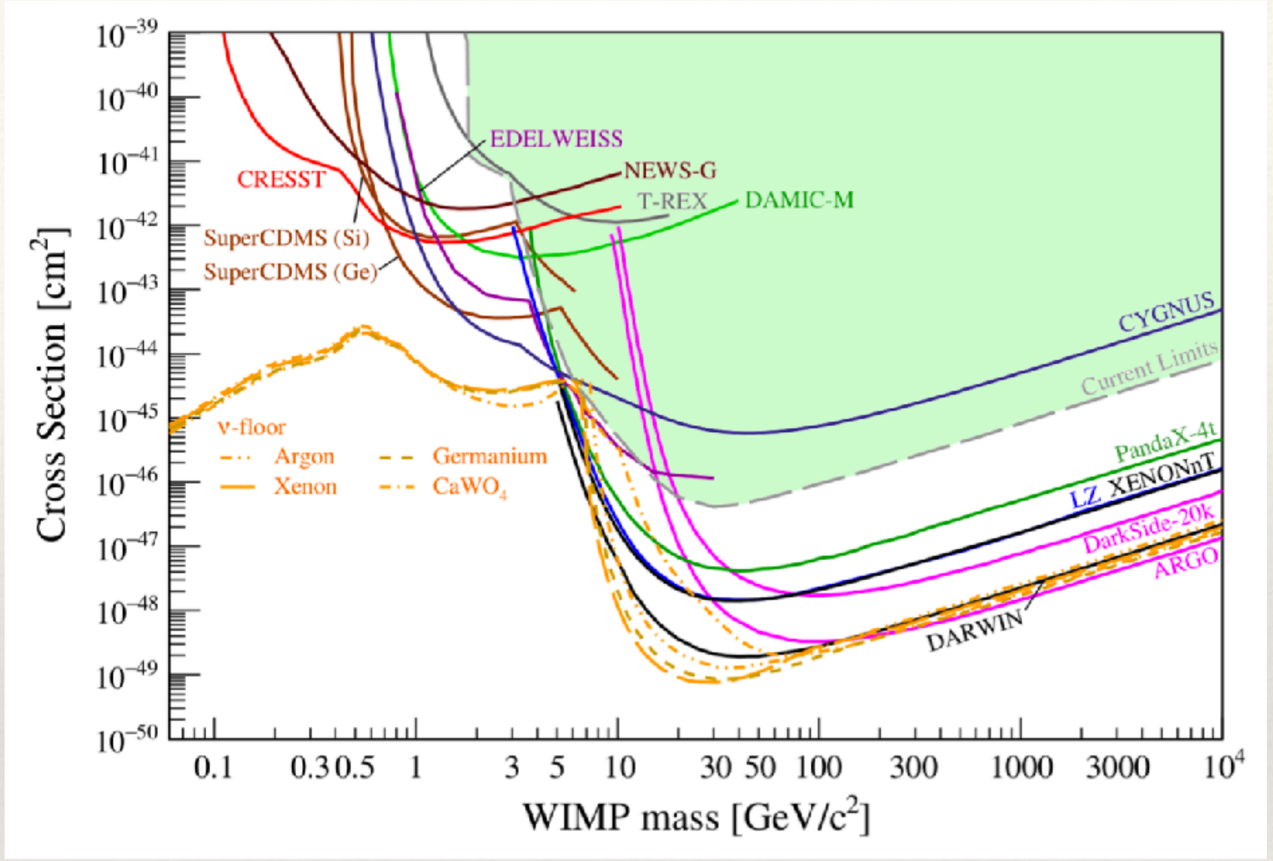
High Mass Particle DM Beyond the WIMP



arXiv:2203.08084



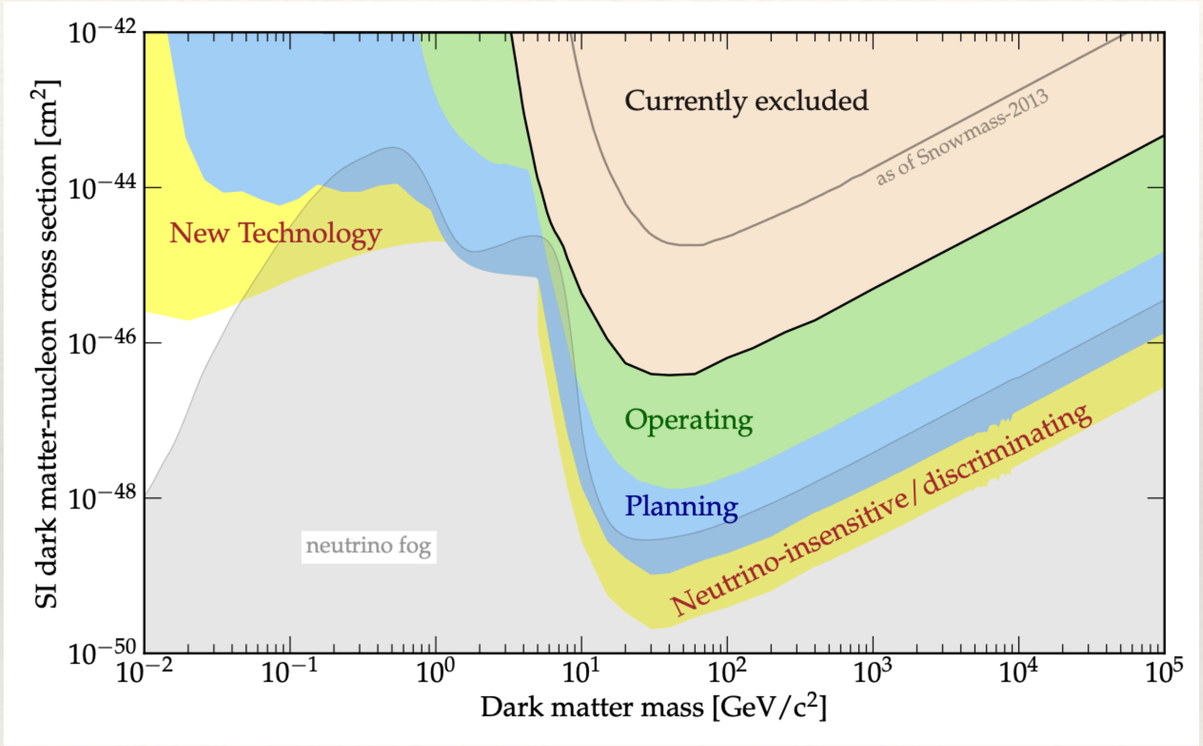
Limits!

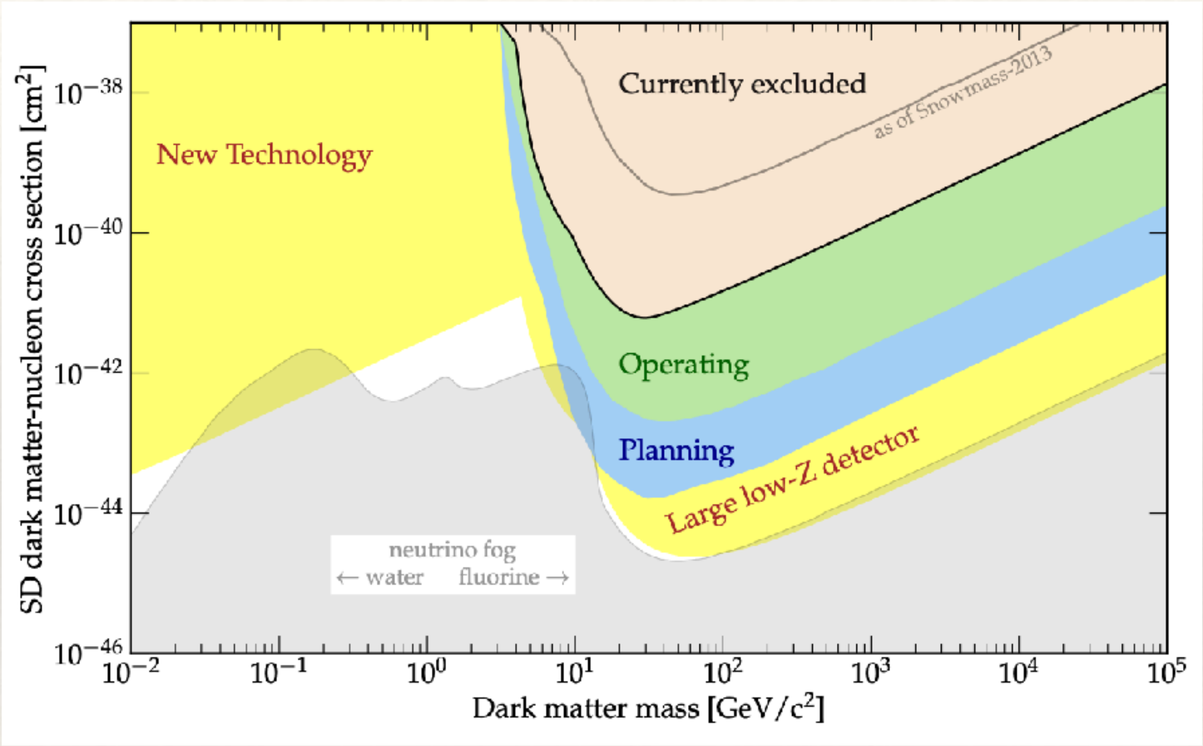


Projections!

arXiv:2104.07634

Direct Detection Sensitivities

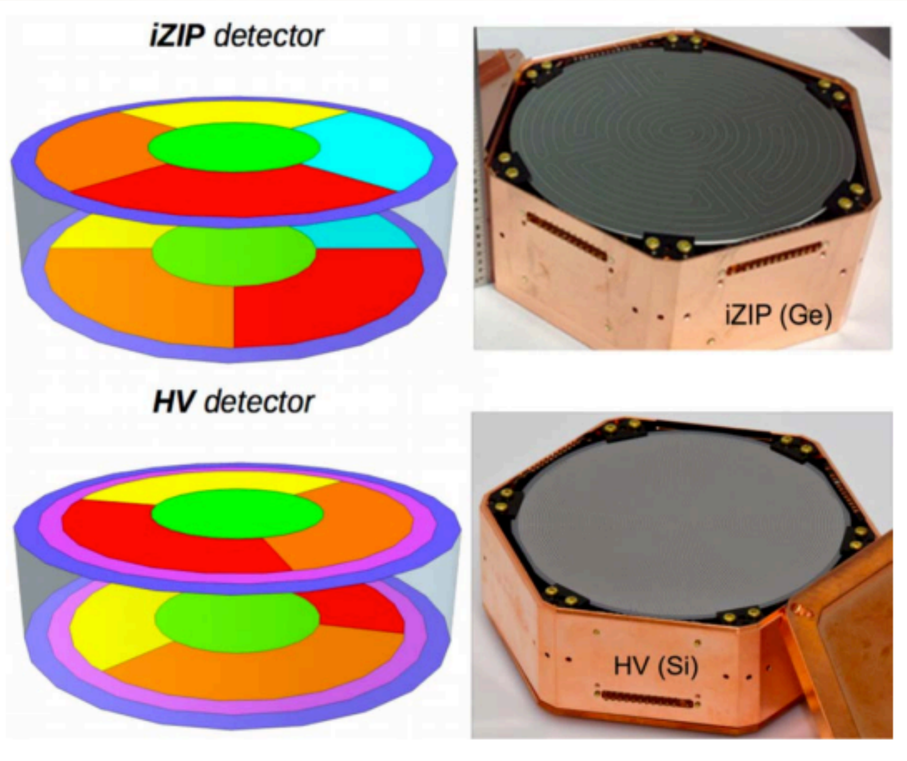




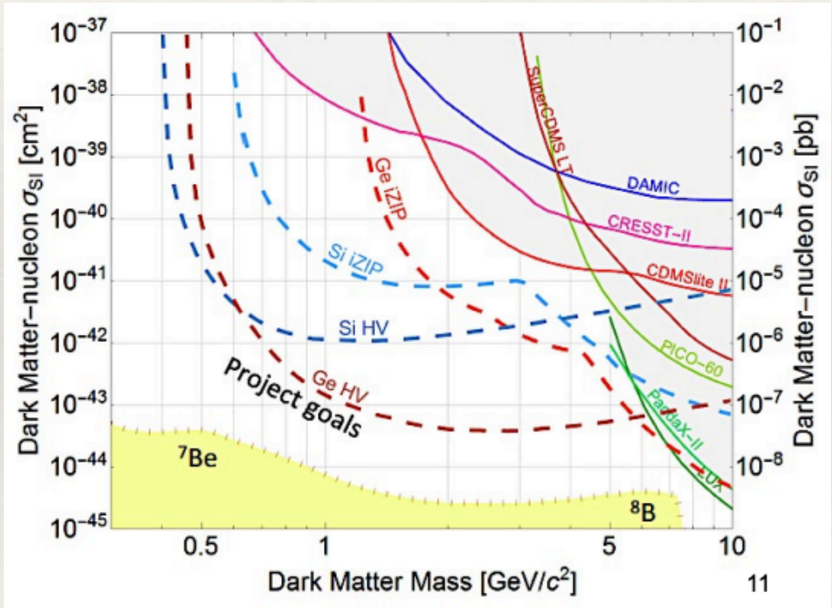
arXiv:2203.08084

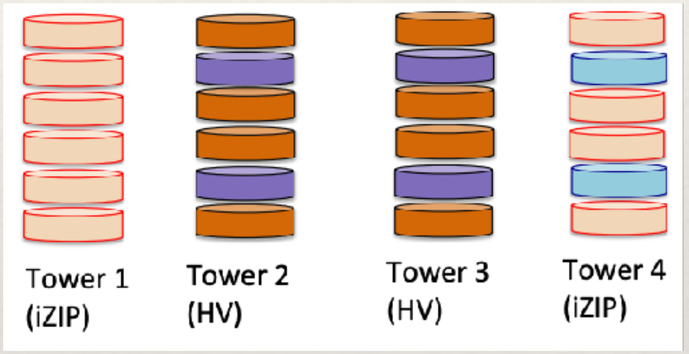
SuperCDMS SNOLAB

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



	Germanium	Silicon
HV	Lowest threshold for low mass DM Larger exposure, no ^{32}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





SUPER CDMS
Cryogenic Dark Matter Search

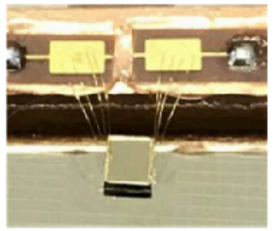
Technologies for Low Mass Searches

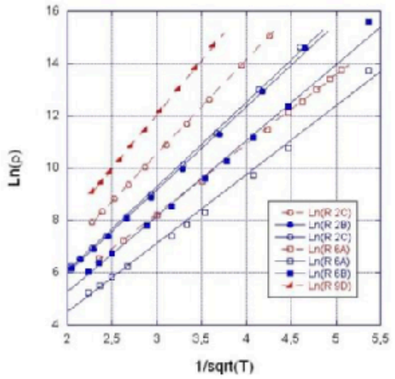
Sensor types:

EDELWEISS

Neutron-transmutation-doped (NTD) sensors

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

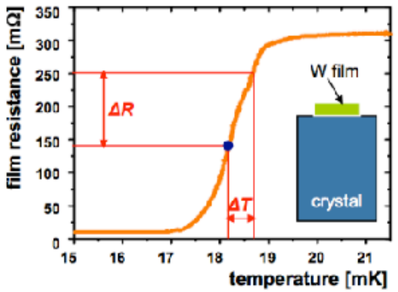




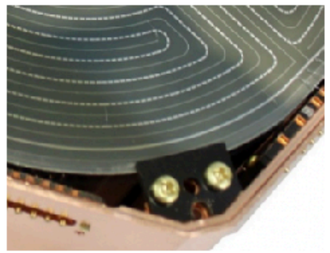
CRESST, SuperCDMS, COSINUS, EDELWEISS NEW

Transition-Edge-Sensor (TES)

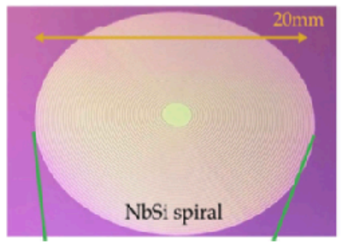
- Thin-film deposited on crystals
- Strong R-T dependence at superconducting transition
- Sensitive to athermal phonons



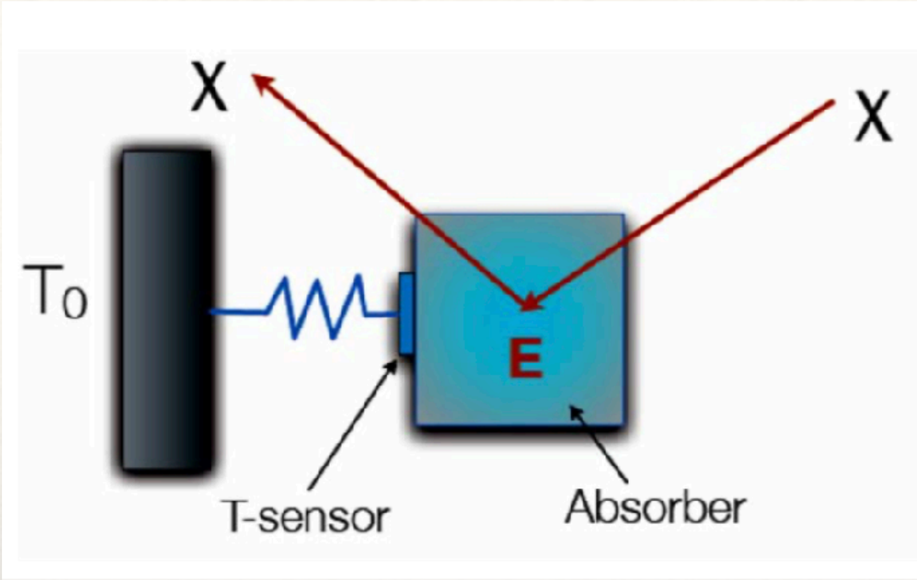
CRESST



SuperCDMS

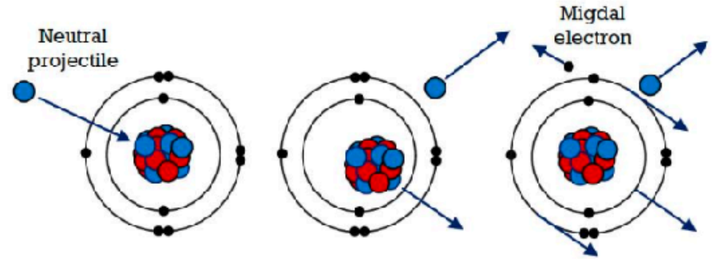


EDELWEISS



R. Strauss IDM plenary

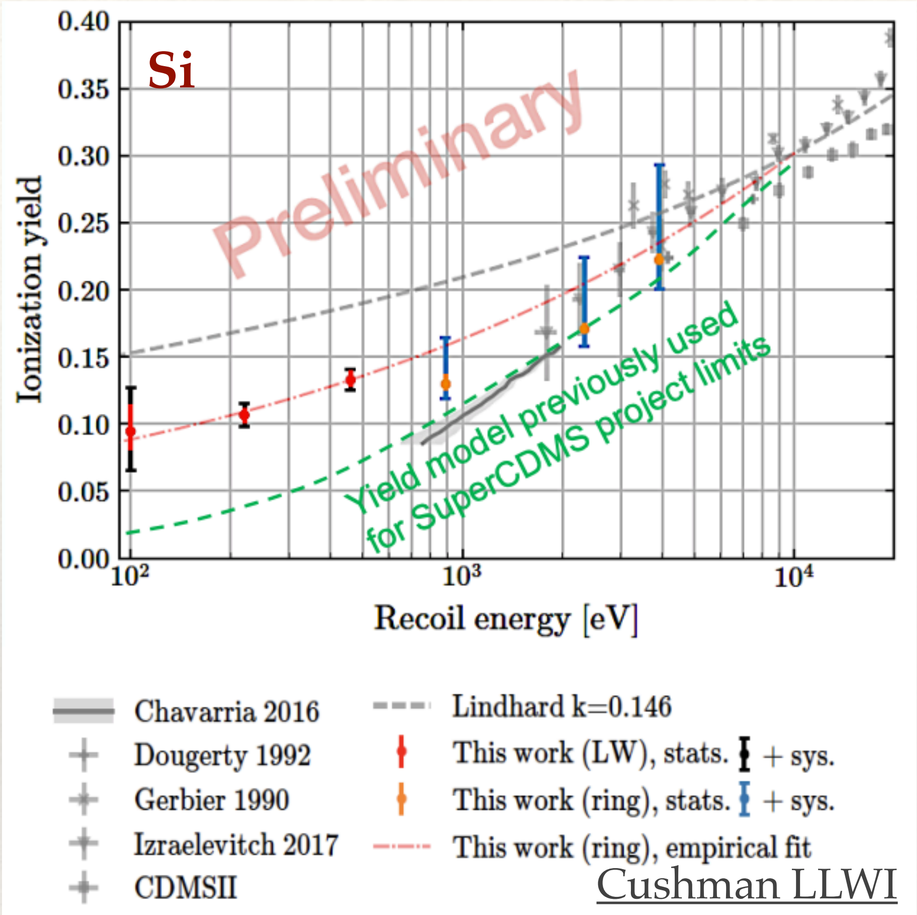
But also!

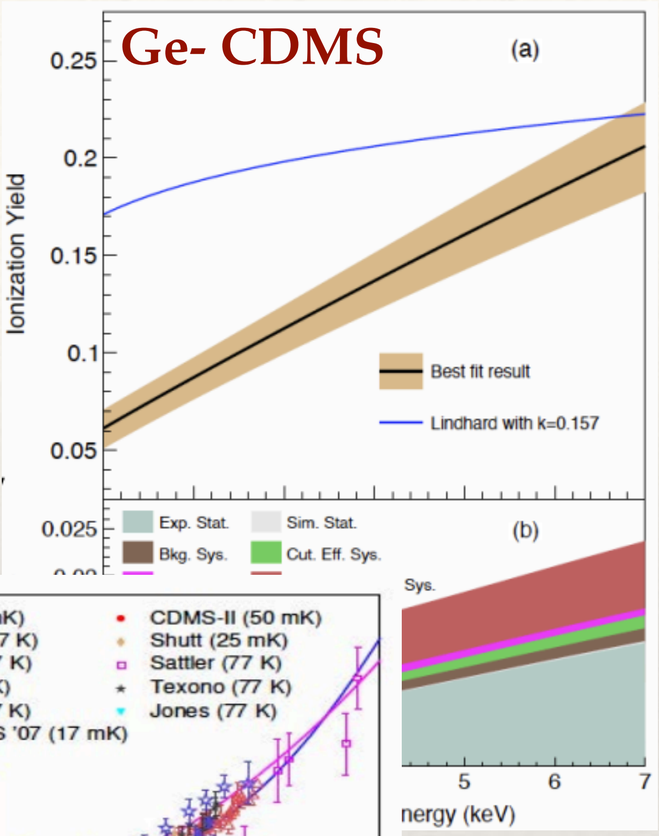


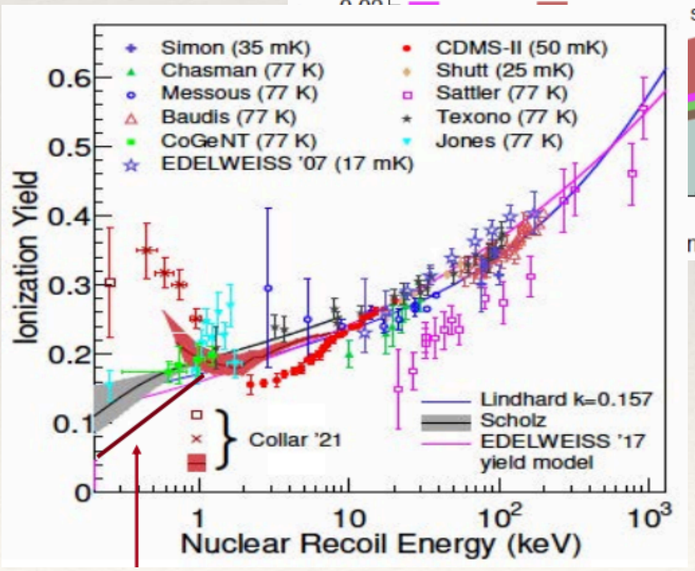
Migdal event topology involves a nuclear recoil and electron recoil originating from the same vertex.

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

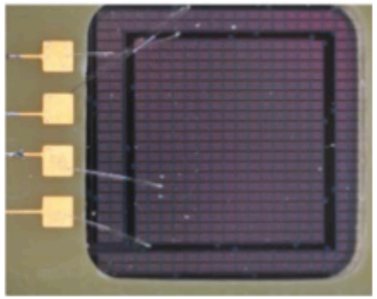






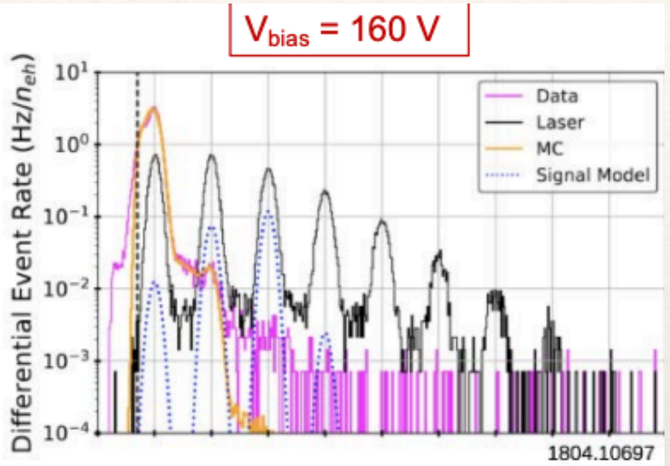
SuperCDMS: Science with new prototypes

HVeV (Si or Ge, 1 x 1 cm^2 x 4 mm). 2 equal area QET sensors



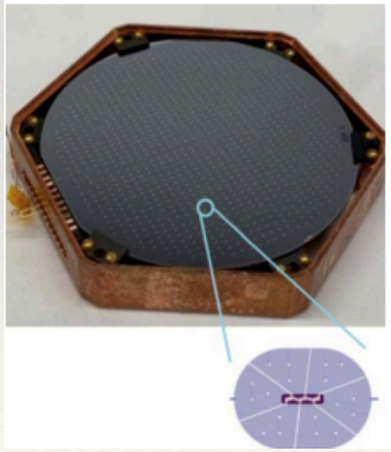
R. Agnese *et al.* Phys. Rev. Lett. **121**, 051301 (2018)

- 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.

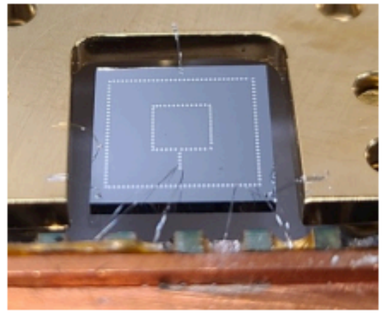


A mosaic of these on 2 SuperCDMS towers can get us to the ν-fog in 0.5 – 5 GeV range

0V, CPD (cryogenic photon detector) 1 mm thick (45.6 cm^2) 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 σ_{pt} ~ 1 eV range now.
- New prototype (with new hanging support) may have σ_{pt} ~ 50 - 100 meV



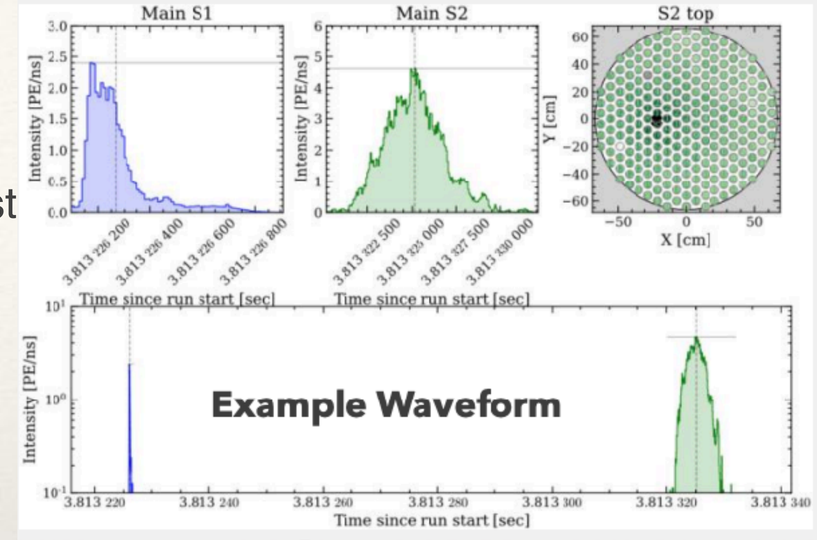
A mosaic of the current CPDs on 2 SuperCDMS towers can get us to DM masses of 100 MeV now and down to 50 MeV if the new prototype has sub-eV resolution

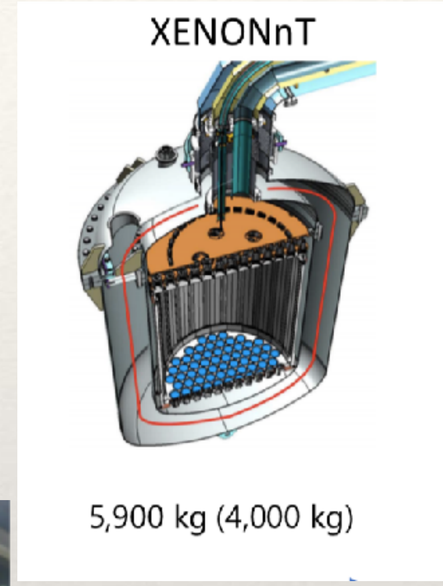
14

Cushman LLWI

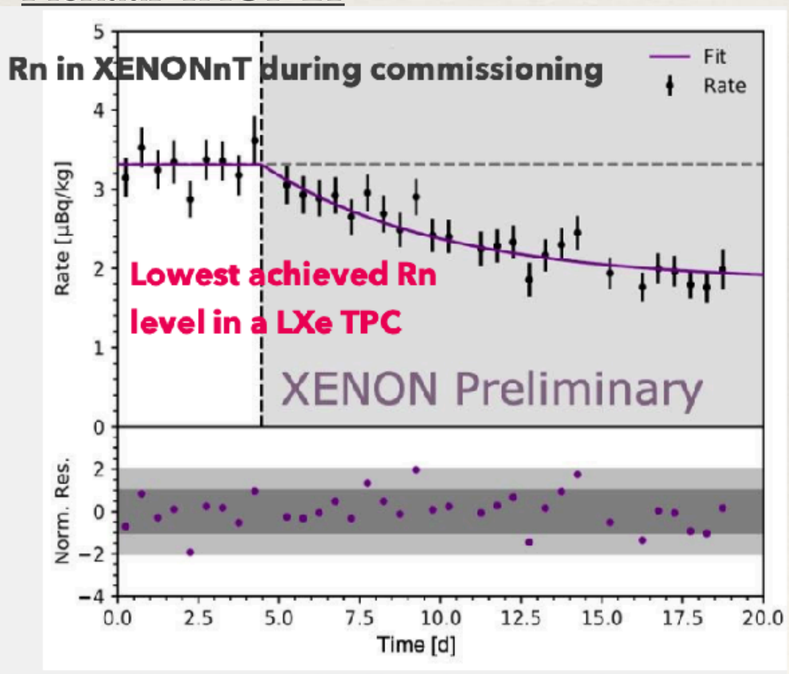
XENONnT

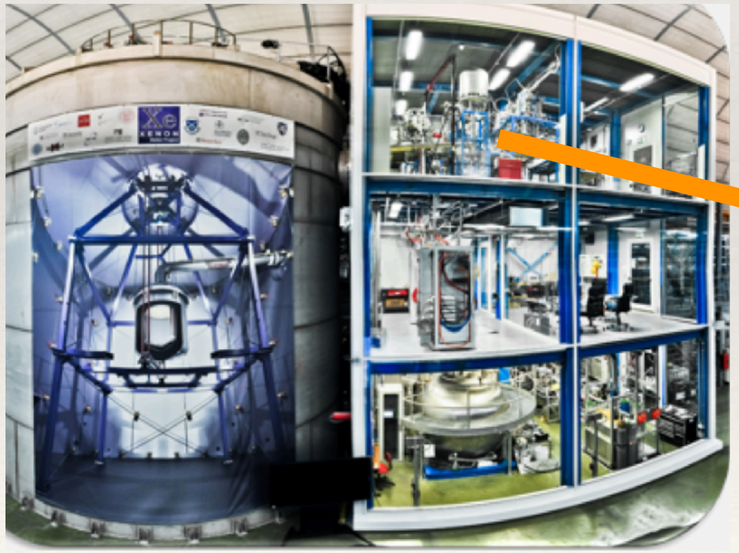
- 5.9 t liquid xenon TPC
- Operating at LNGS in Italy since Sept ’21
- Radon/krypton reduction with cryogenic dist and custom pump
- Drift field is a little low

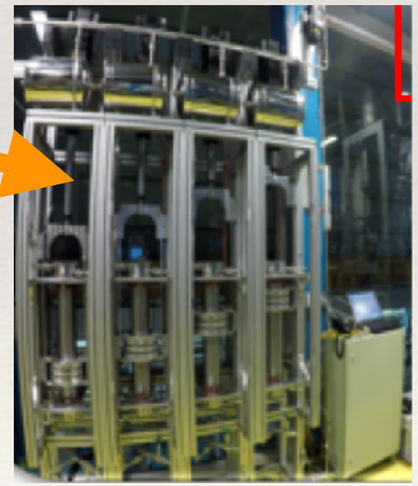




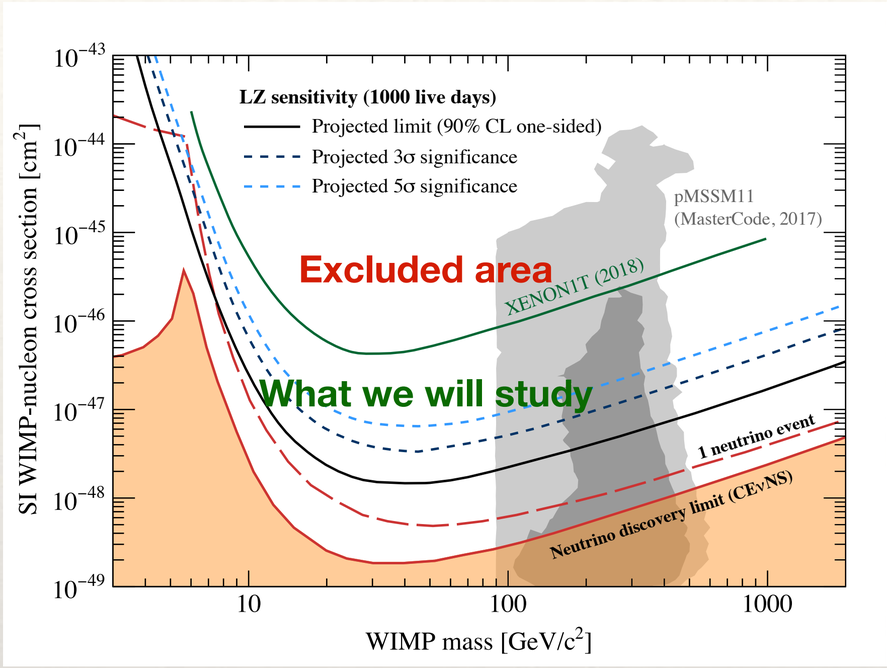
Pienaar TAUP 21



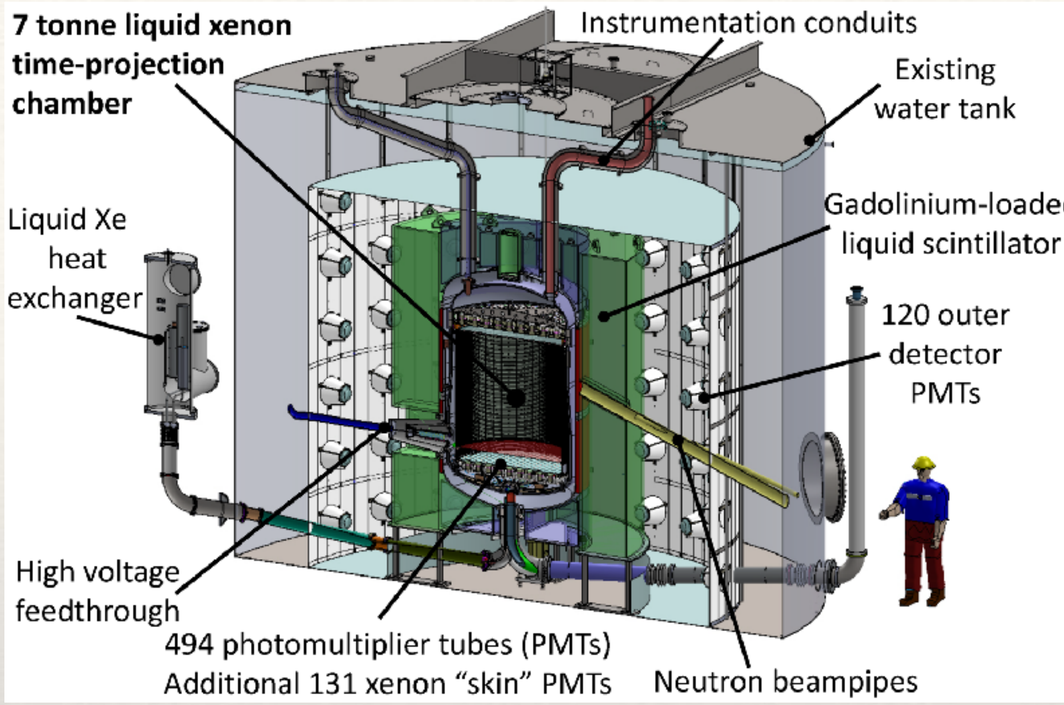




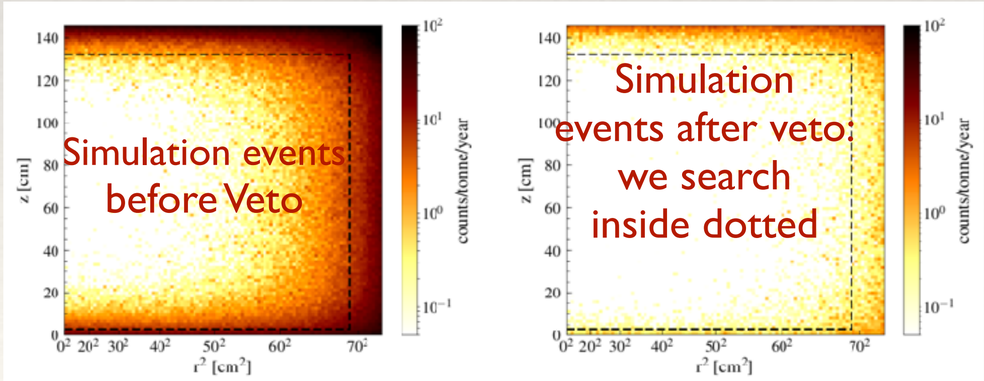
LZ



arXiv:1802.06039



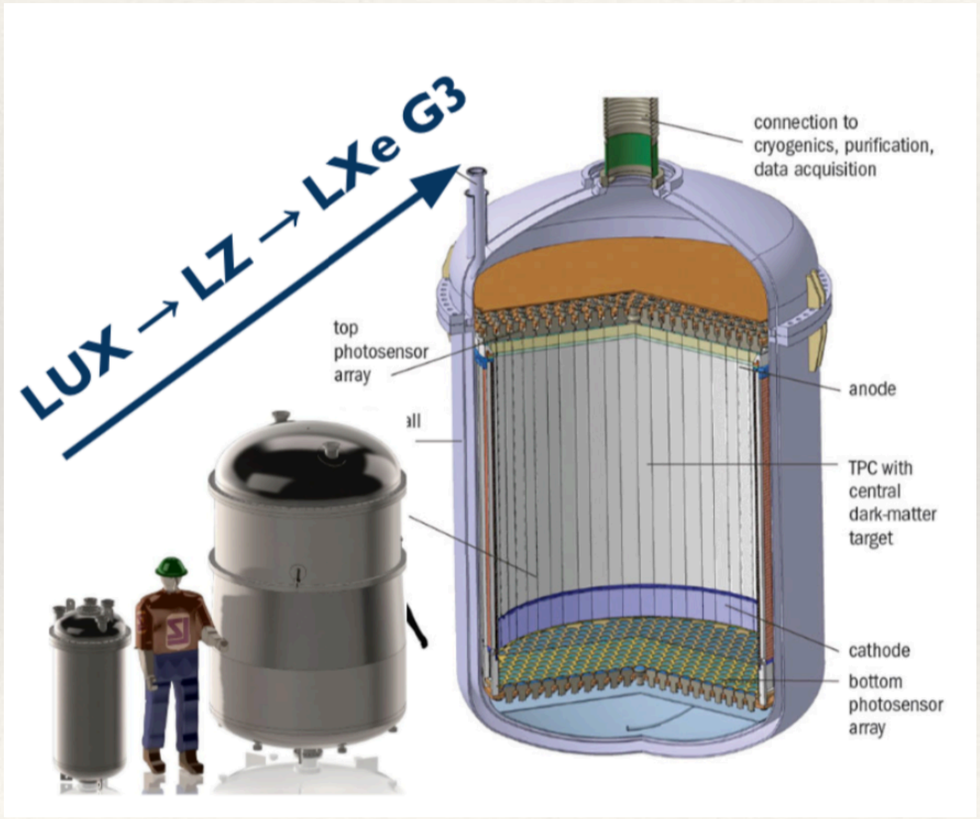
- 10 t liquid xenon
- Operating at SURF in South Dakota USA
- Planned for 1000 live days over ~5 years

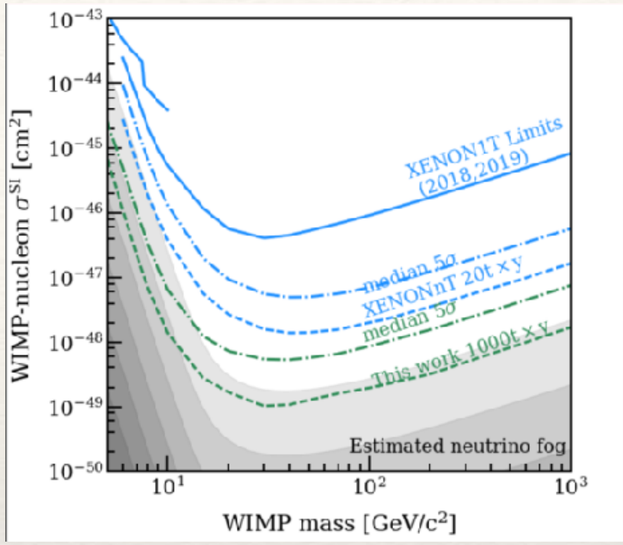


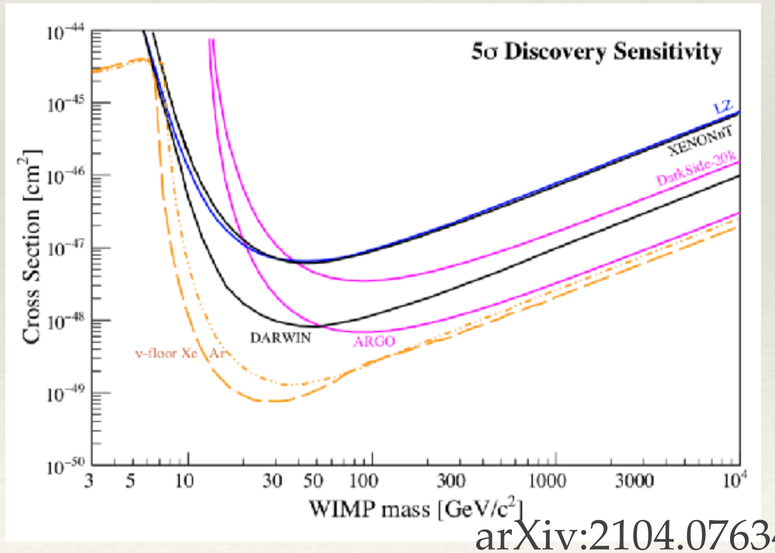
- Many talks in parallels this afternoon and tomorrow

Next Generation Liquid Xenon

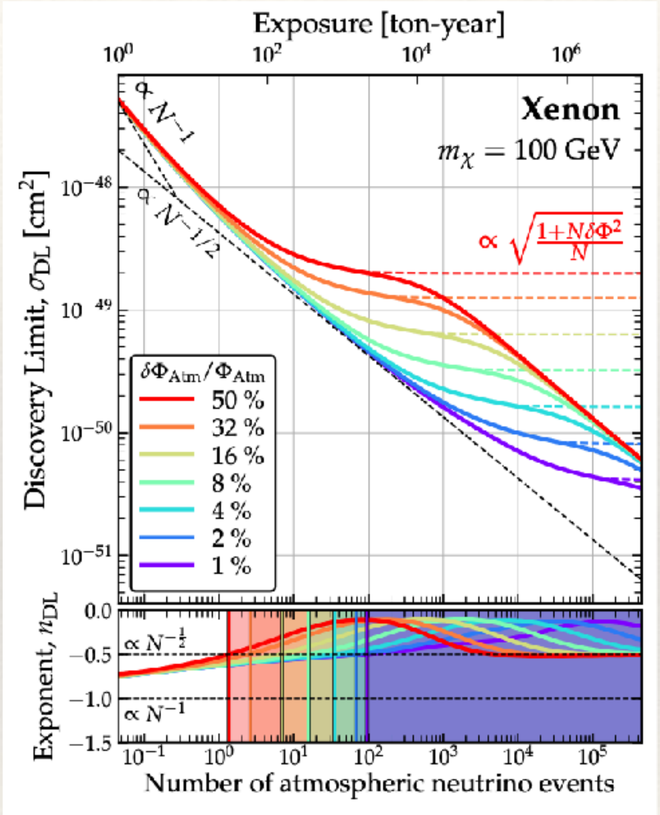
- 50–100 t liquid xenon TPC
- Combination of XENONnT/DARWIN and LZ collaborations
- Location TBD
- Joint workshop last spring, meeting this summer







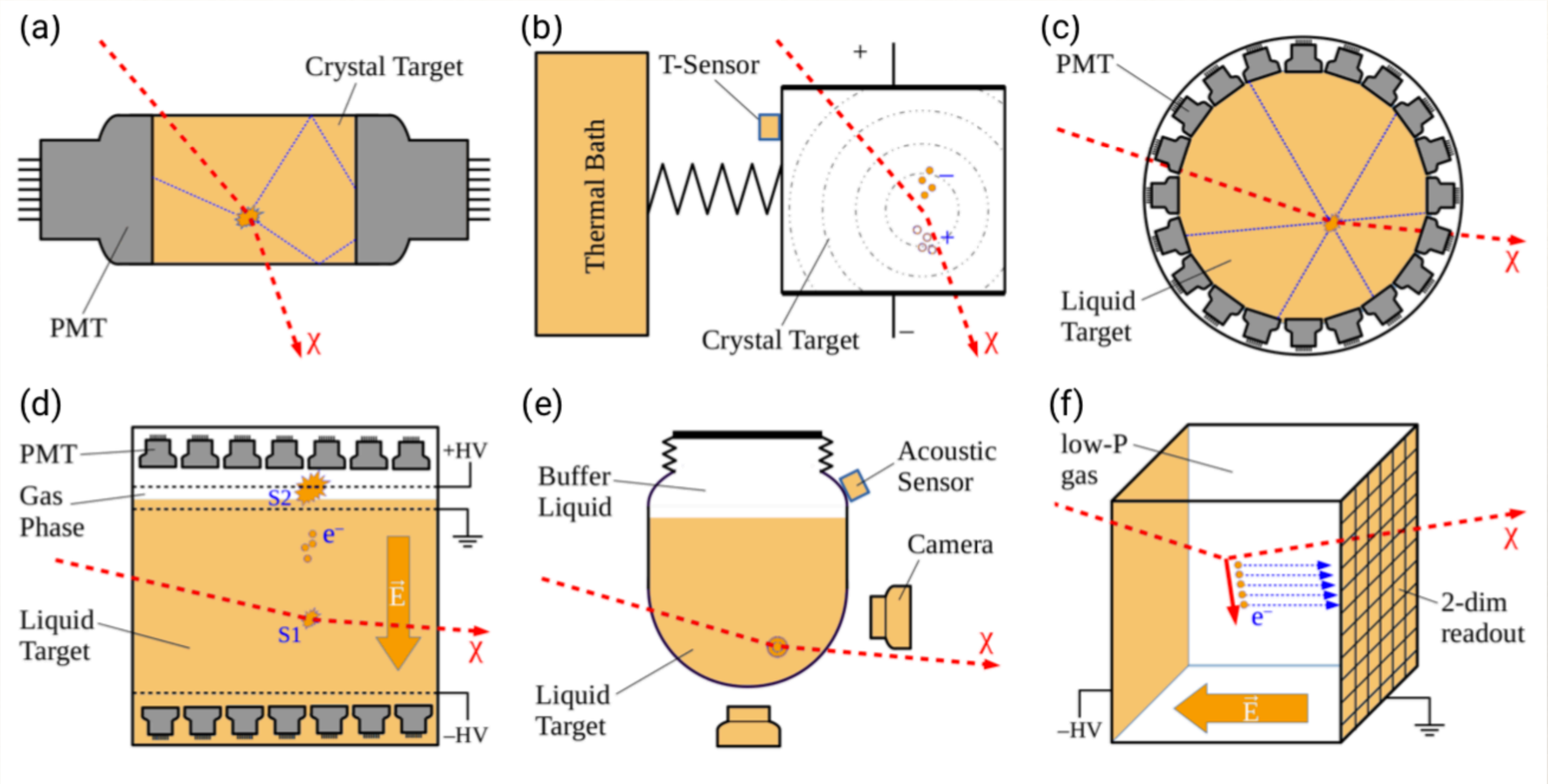
arXiv:2203.02309



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**



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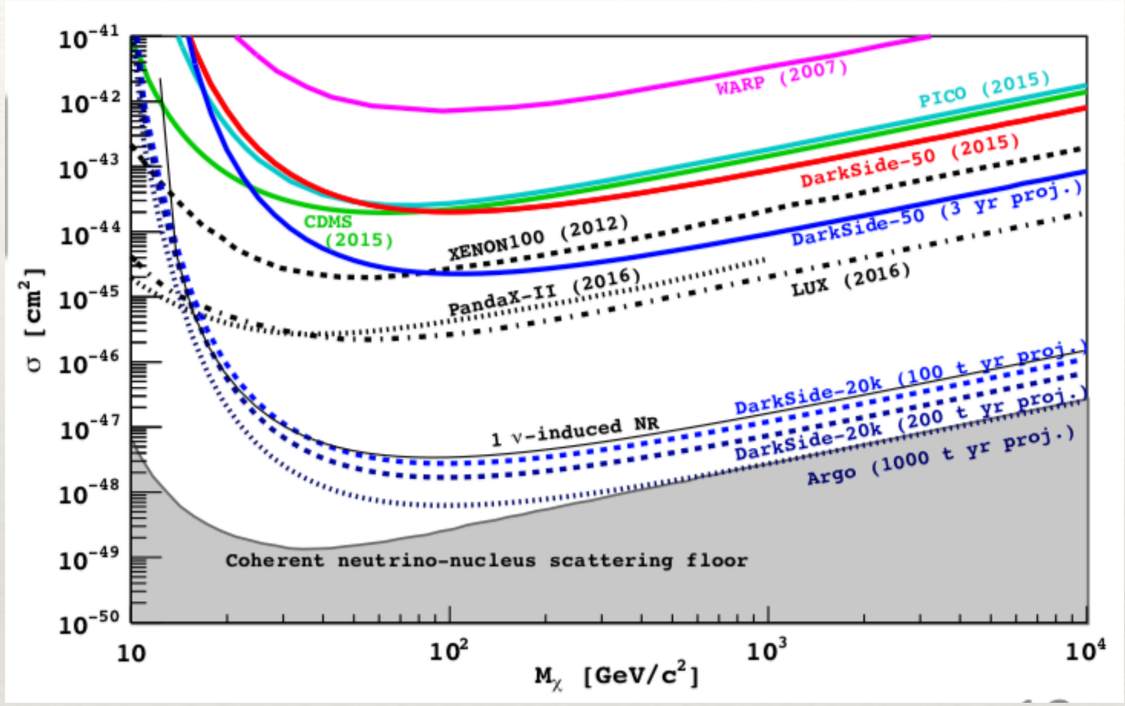
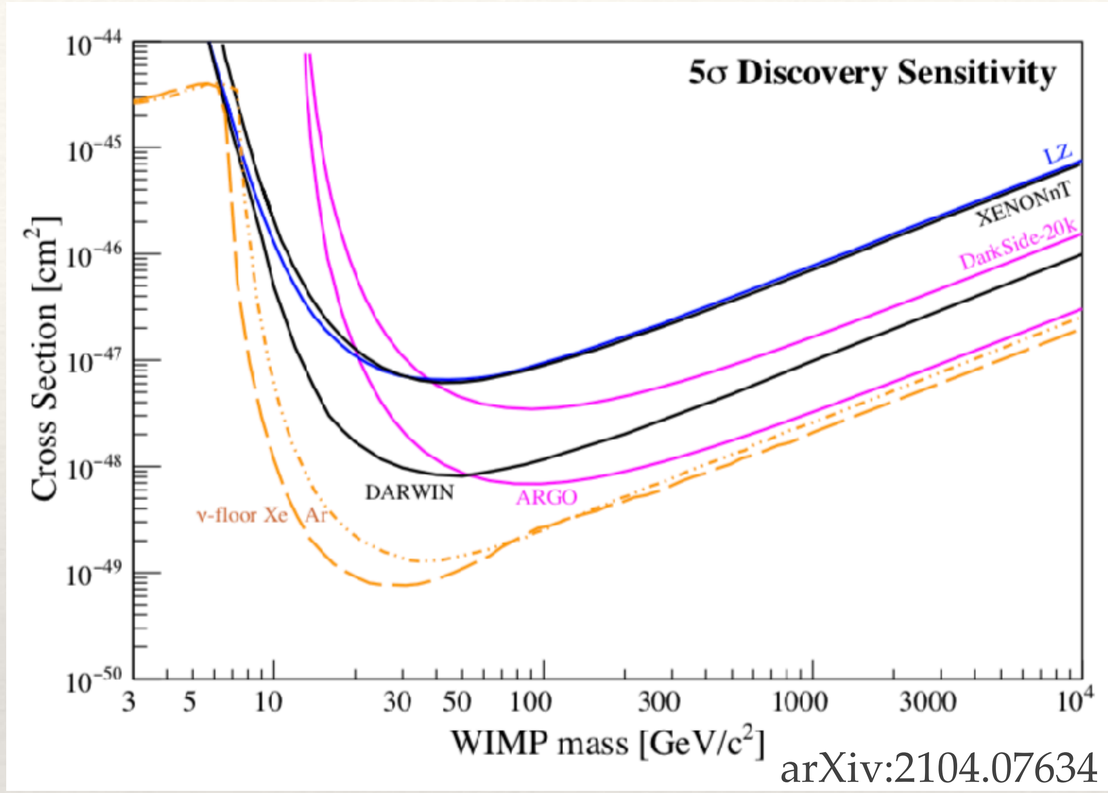


Eur.Phys.J.Plus(2018)133:131



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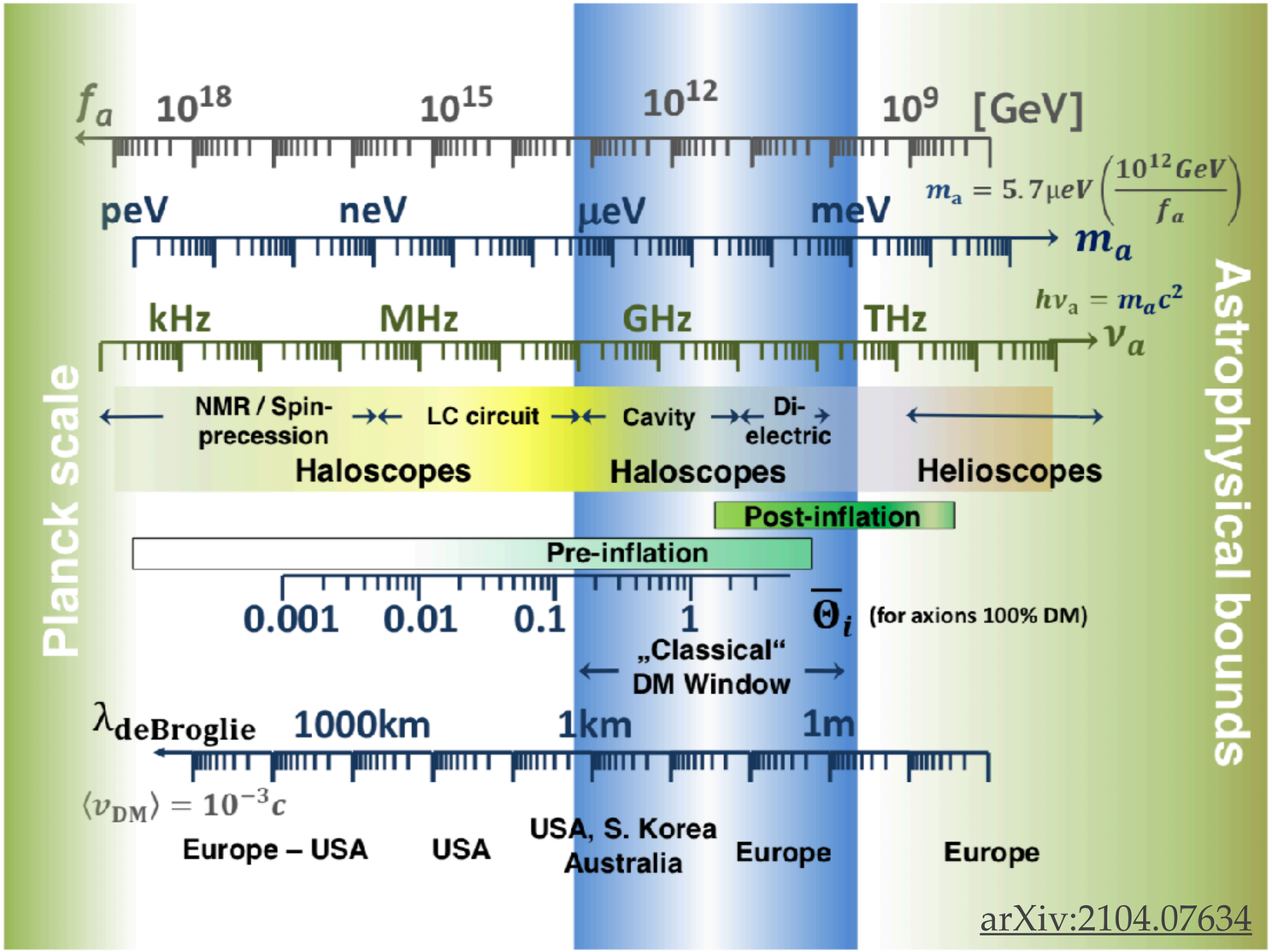
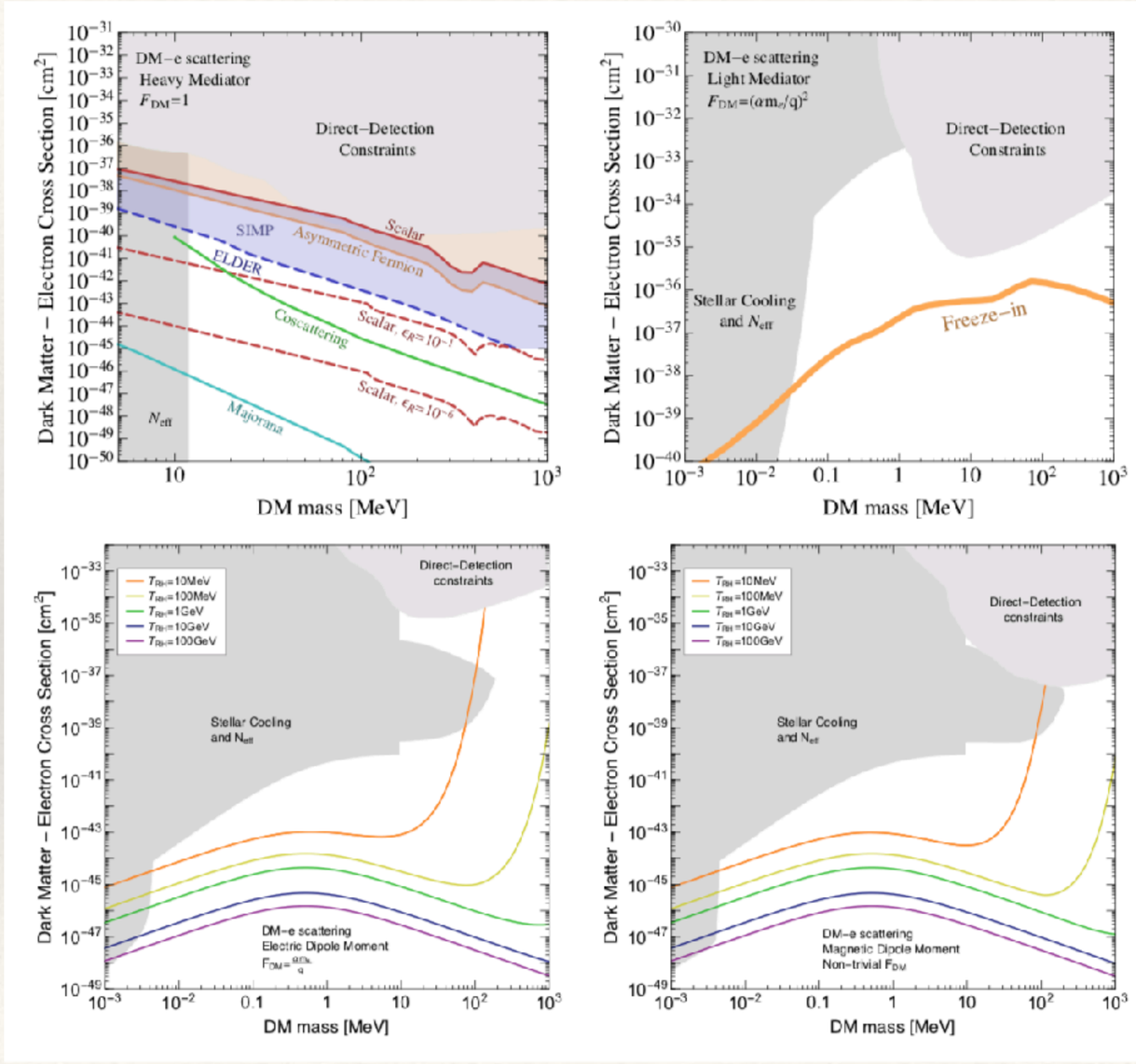
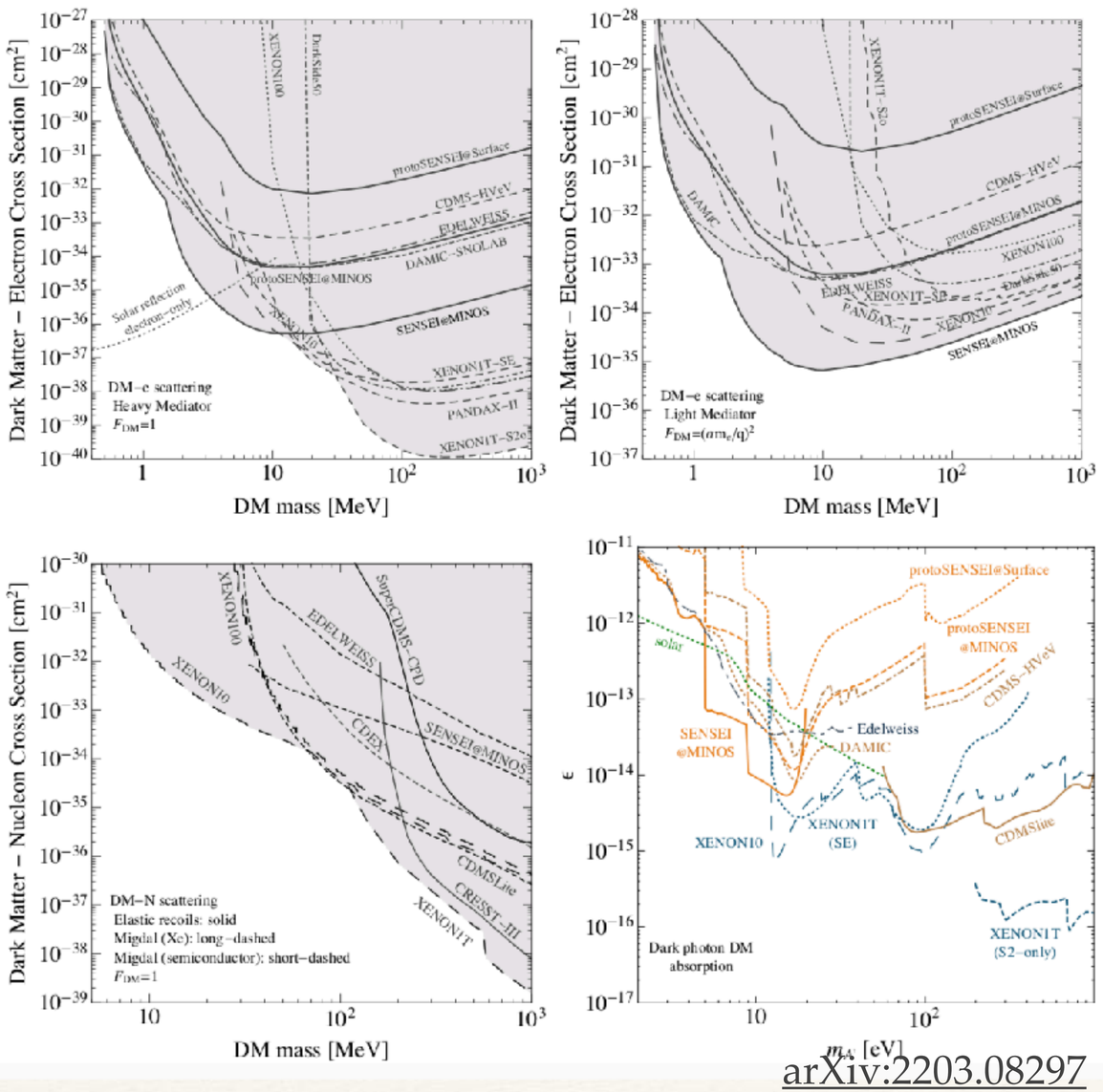
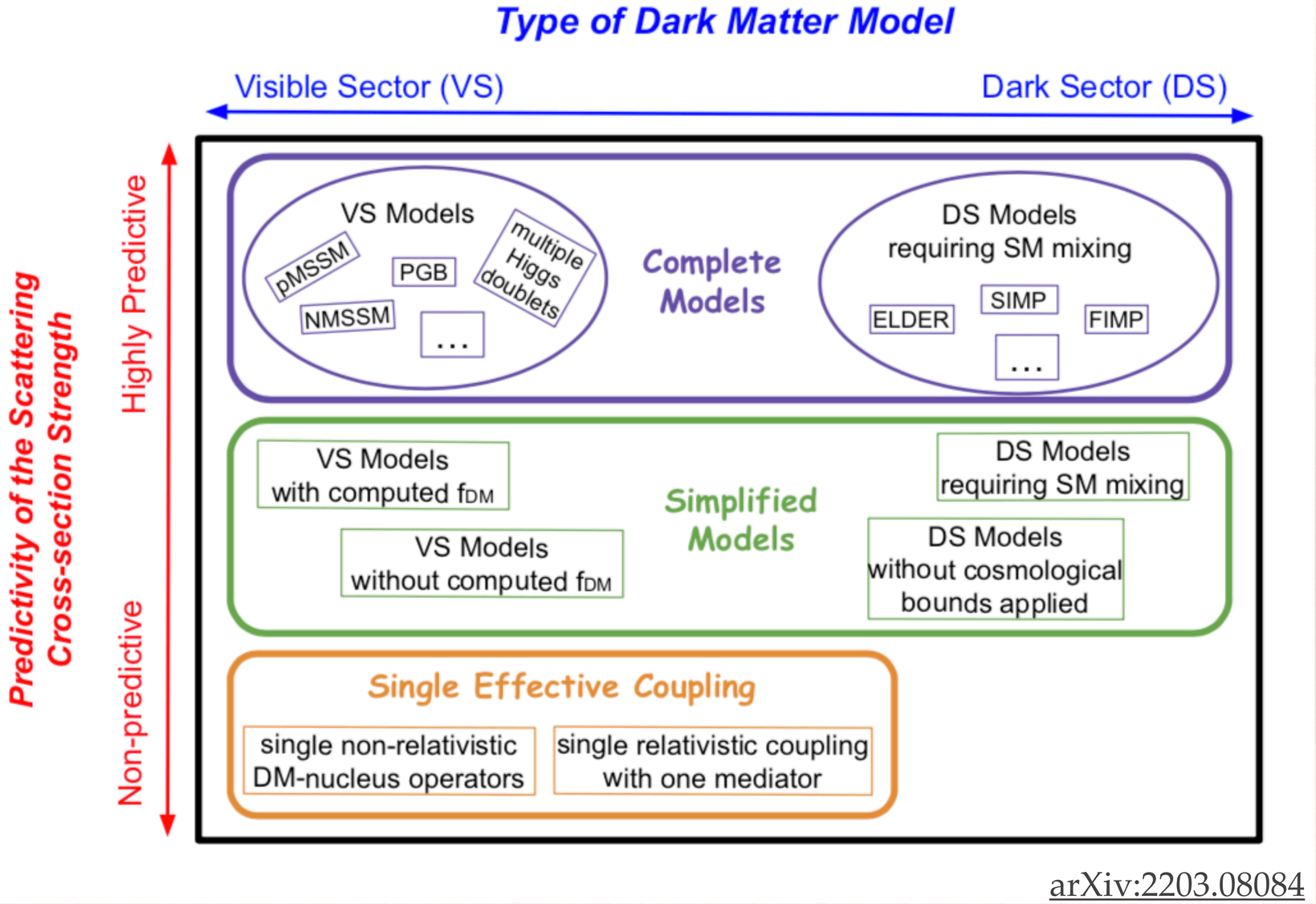

f_a 10^{18} 10^{15} 10^{12} 10^{9} [GeV]
$m_a = 5.7\mu eV\left(\frac{10^{12}GeV}{f_a}\right)$
peV neV μeV meV
m_a
$h\nu_a = m_a c^2$
kHz MHz GHz THz
ν_a
Planck scale
Astrophysical bounds
NMR / Spin-precession
LC circuit
Cavity
Di-electric
Haloscopes
Haloscopes
Helioscopes
Post-inflation
Pre-inflation
0.001 0.01 0.1 1
$\overline{\Theta}_i$
(for axions 100% DM)
„Classical“ DM Window
$\lambda_{deBroglie}$ 1000km 1km 1m
$\langle v_{DM} \rangle = 10^{-3}c$
Europe – USA
USA
USA, S. Korea Australia
Europe
Europe
arXiv:2104.07634



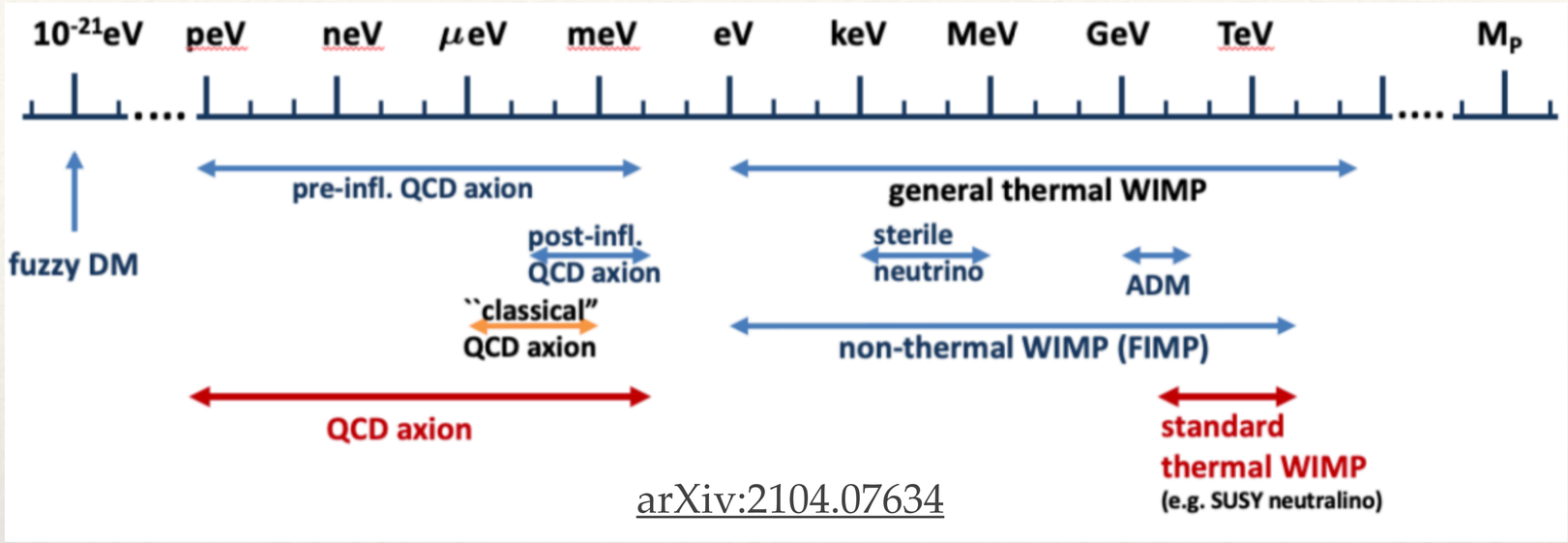


arXiv:2203.08297



arXiv:2203.08084

The Main Options



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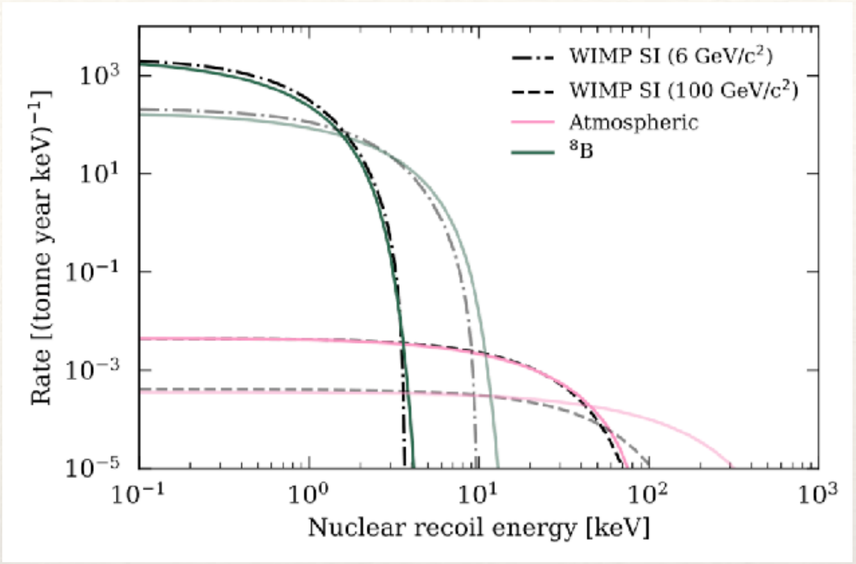

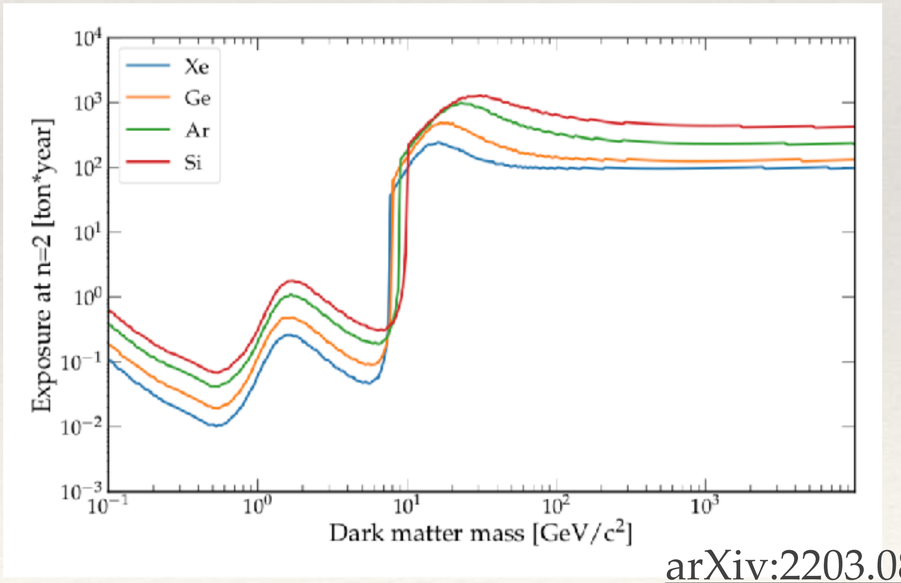

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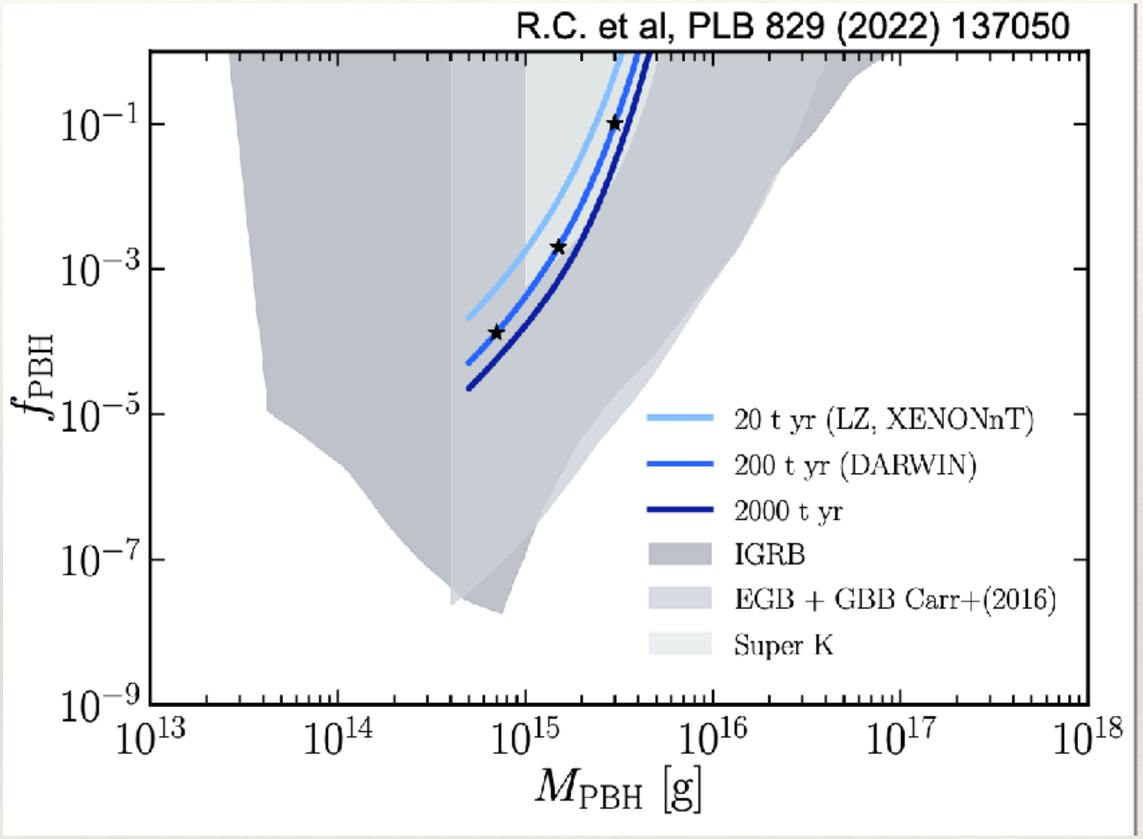
R.C. et al, PLB 829 (2022) 137050
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
$f_{\rm PBH}$
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
$M_{\rm PBH}$ [g]
20 t yr (LZ, XENONnT)
200 t yr (DARWIN)
2000 t yr
IGRB
EGB + GBB Carr+(2016)
Super K