Searching Deep and Wide

Where Direct Dark Matter Searches Are Going

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UGAP
5 March 2024

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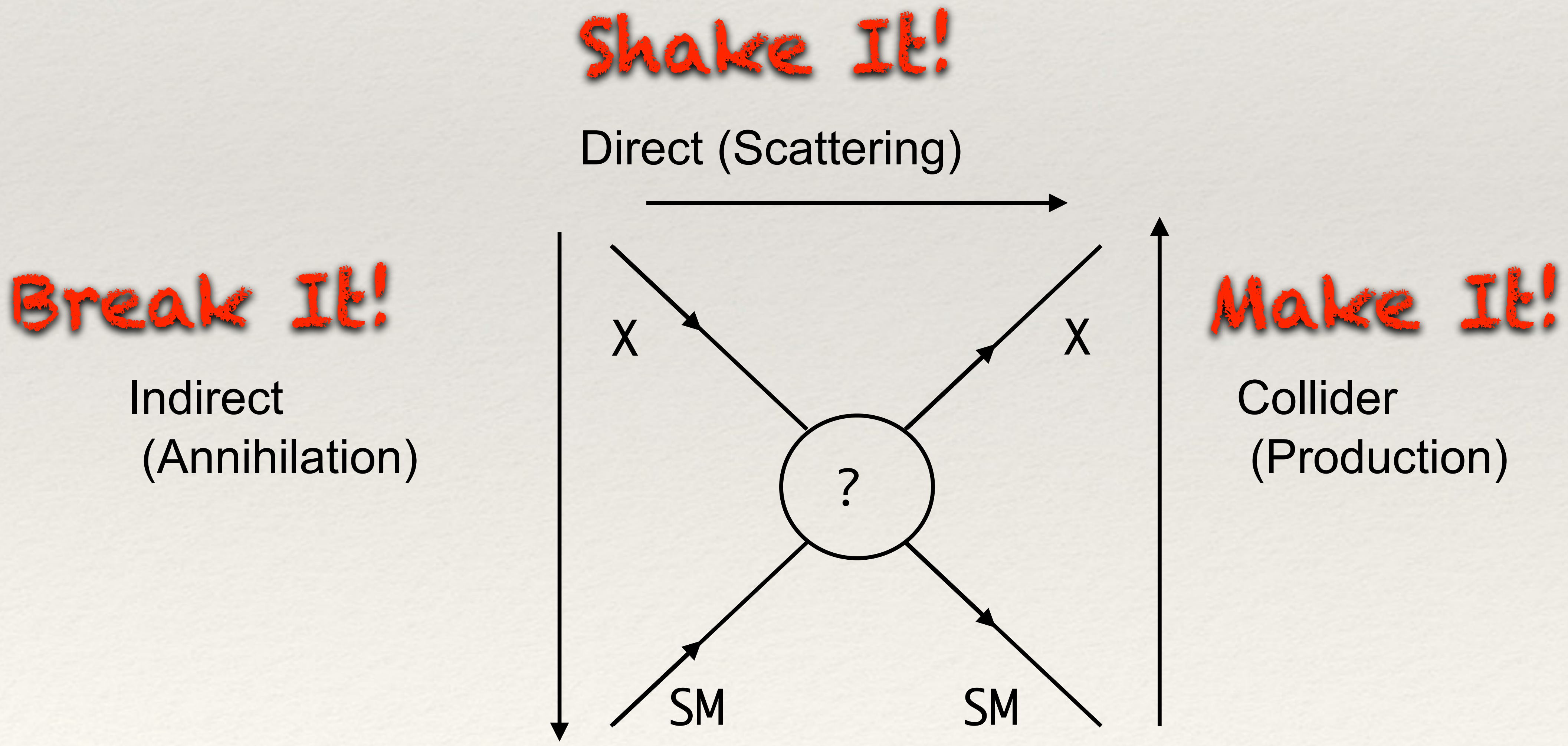
Outline

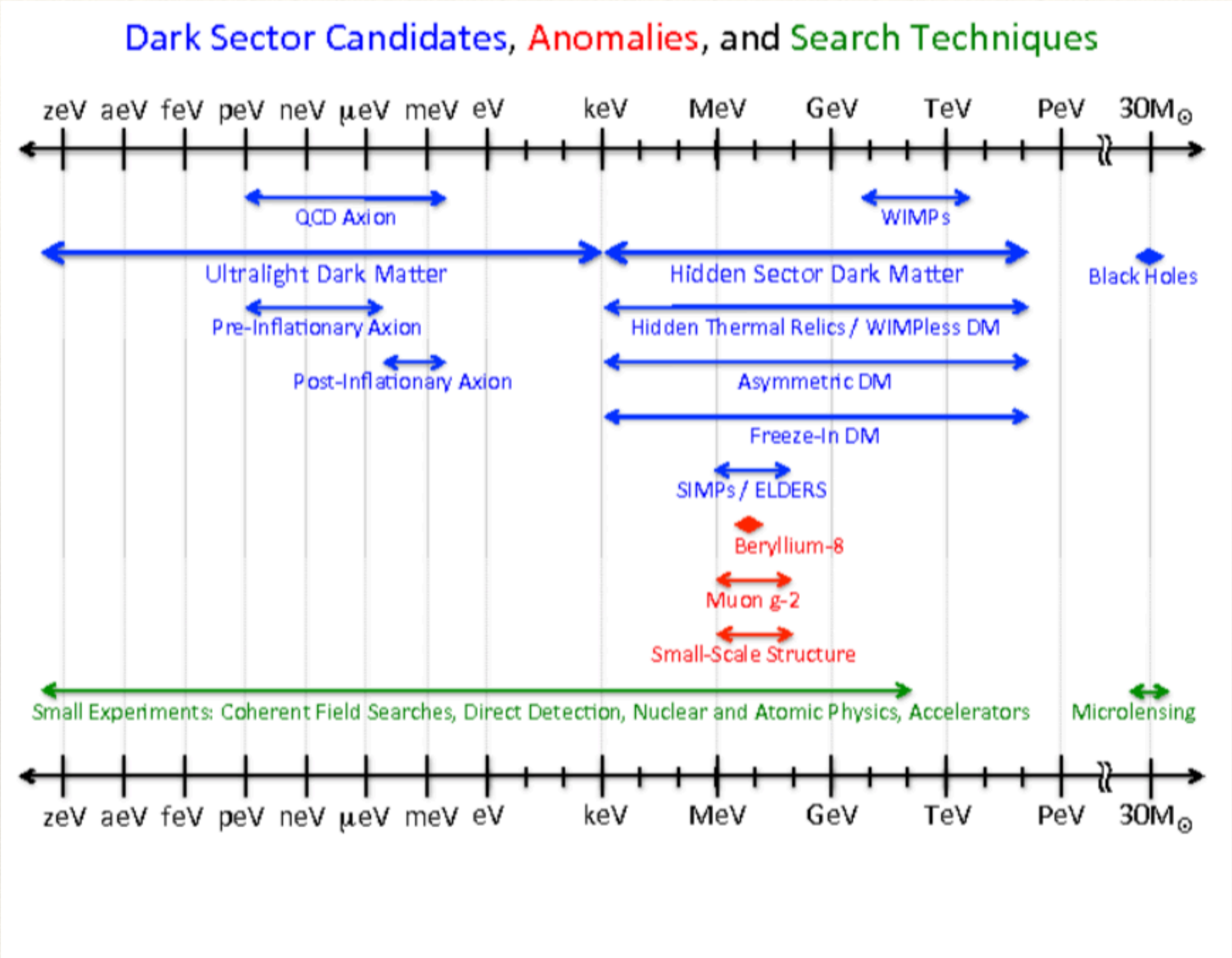
- Broader Models for Particle Dark Matter
- Current and Future Searches
  - >10 GeV/c² Dark Matter
  - 1-10 GeV/c² Dark Matter
  - <1 GeV/c² Dark Matter
- Context and Conclusions



"We're quietly confident that it smells of cinnamon."

Tom Chitty 2016, New Yorker

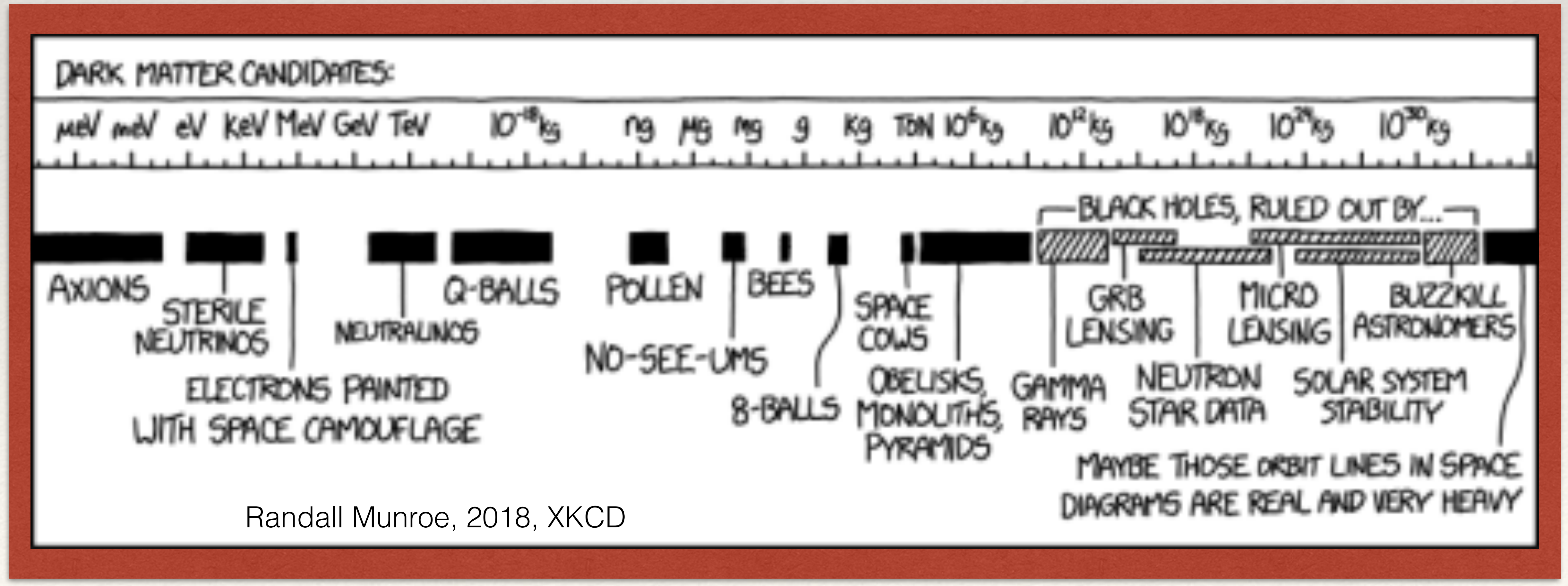
Models



US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report

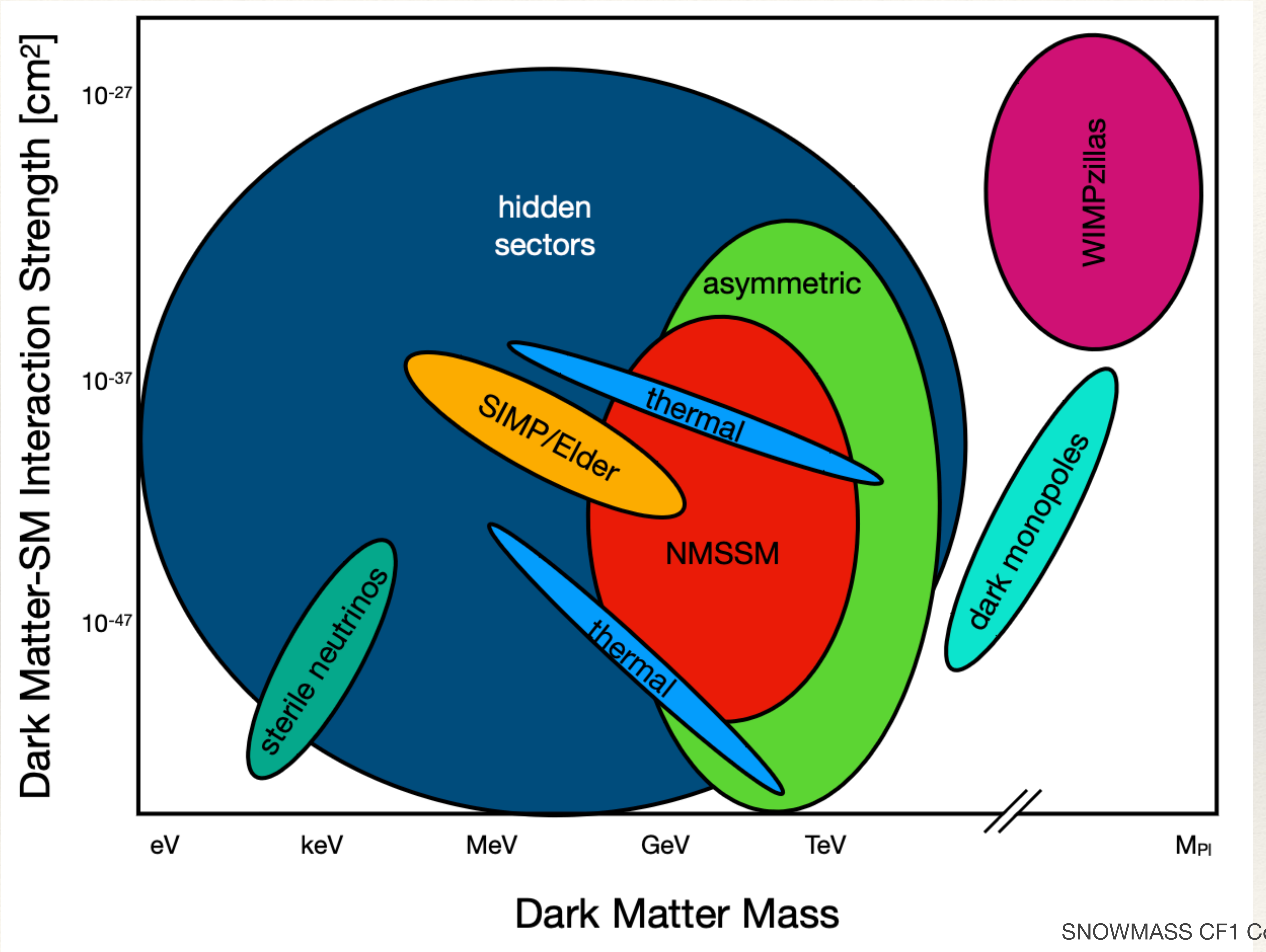
- Canonical Dark matter is:
  - non-relativistic
  - electrically neutral
  - limited self-interactions
  - density of DM ~0.3-0.45 GeV/cm^3

  - Some theories push these boundaries
  - Can dark matter candidates fit with other theories or open problems?



Randall Munroe, 2018, XKCD

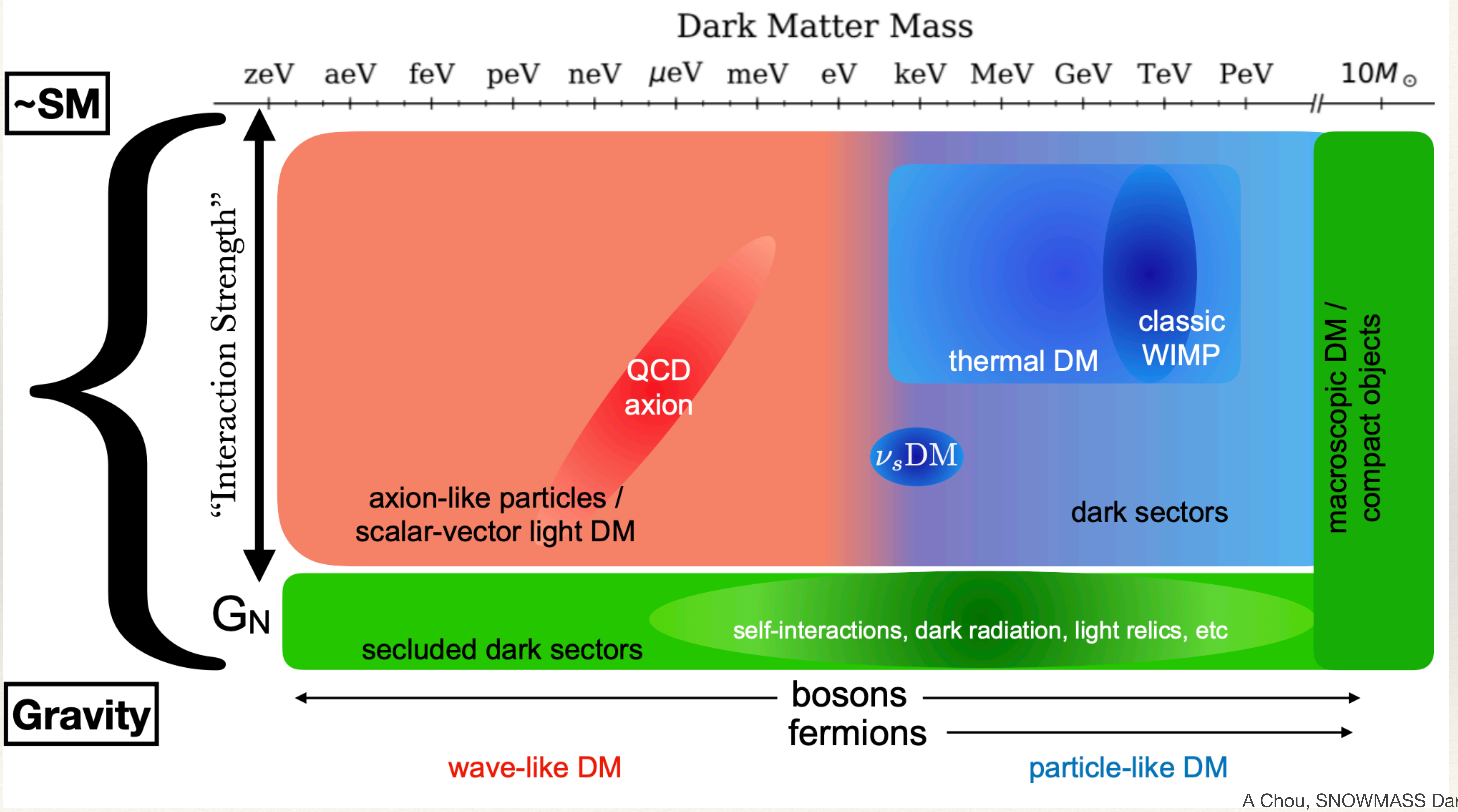
An updated cartoon for particle dark matter



SNOWMASS CF1 Convener's Report

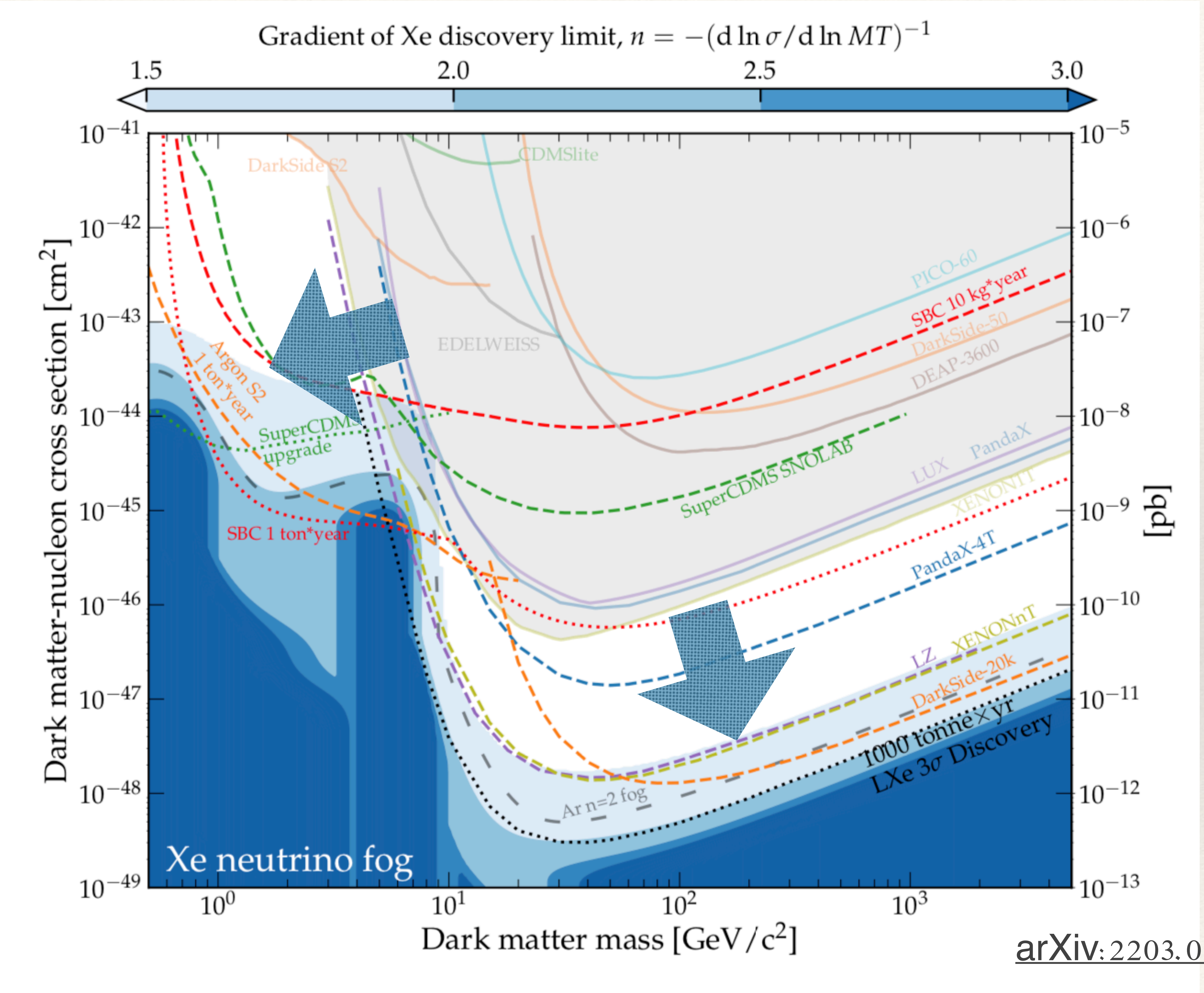
"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."

A Unified Vision coming from SNOWMASS



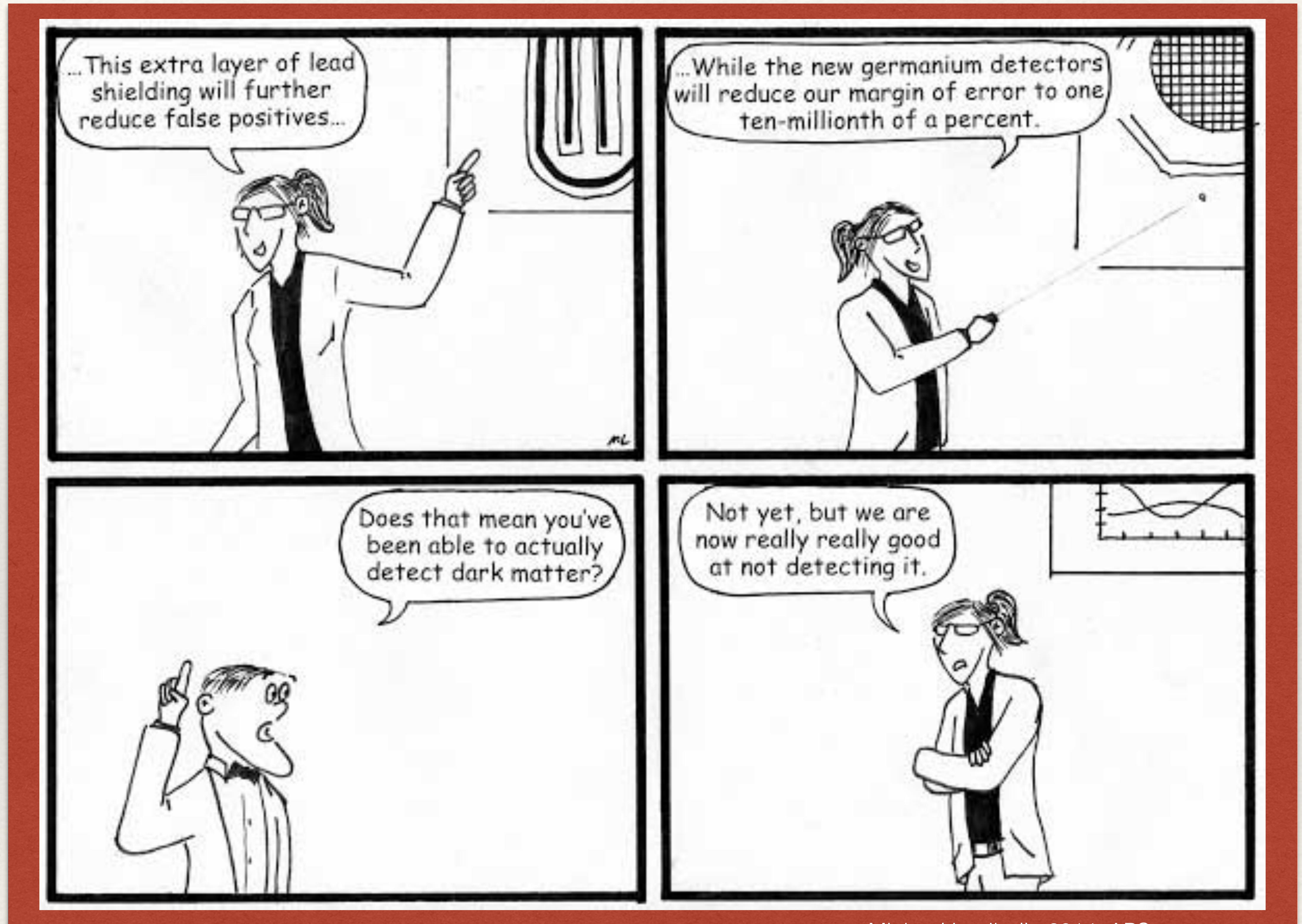
A Chou, SNOWMASS Dark Matter Plenary

Spin Independent Direct DM status



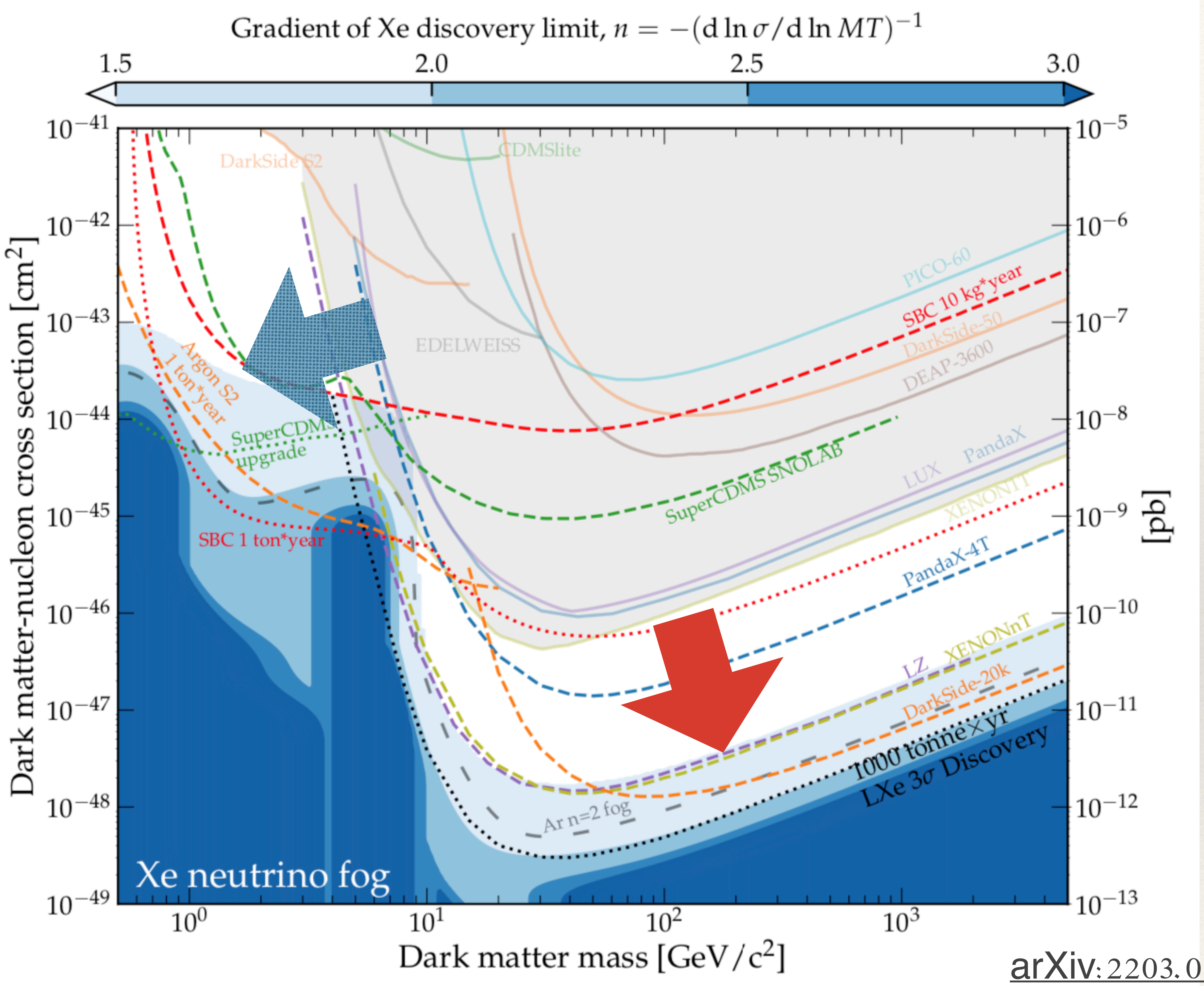
arXiv: 2203.08084

Focus on spin-independent DM-nuclear scattering



Michael Lucibella 2014, APS.org

Spin Independent Direct DM status



arXiv: 2203.08084

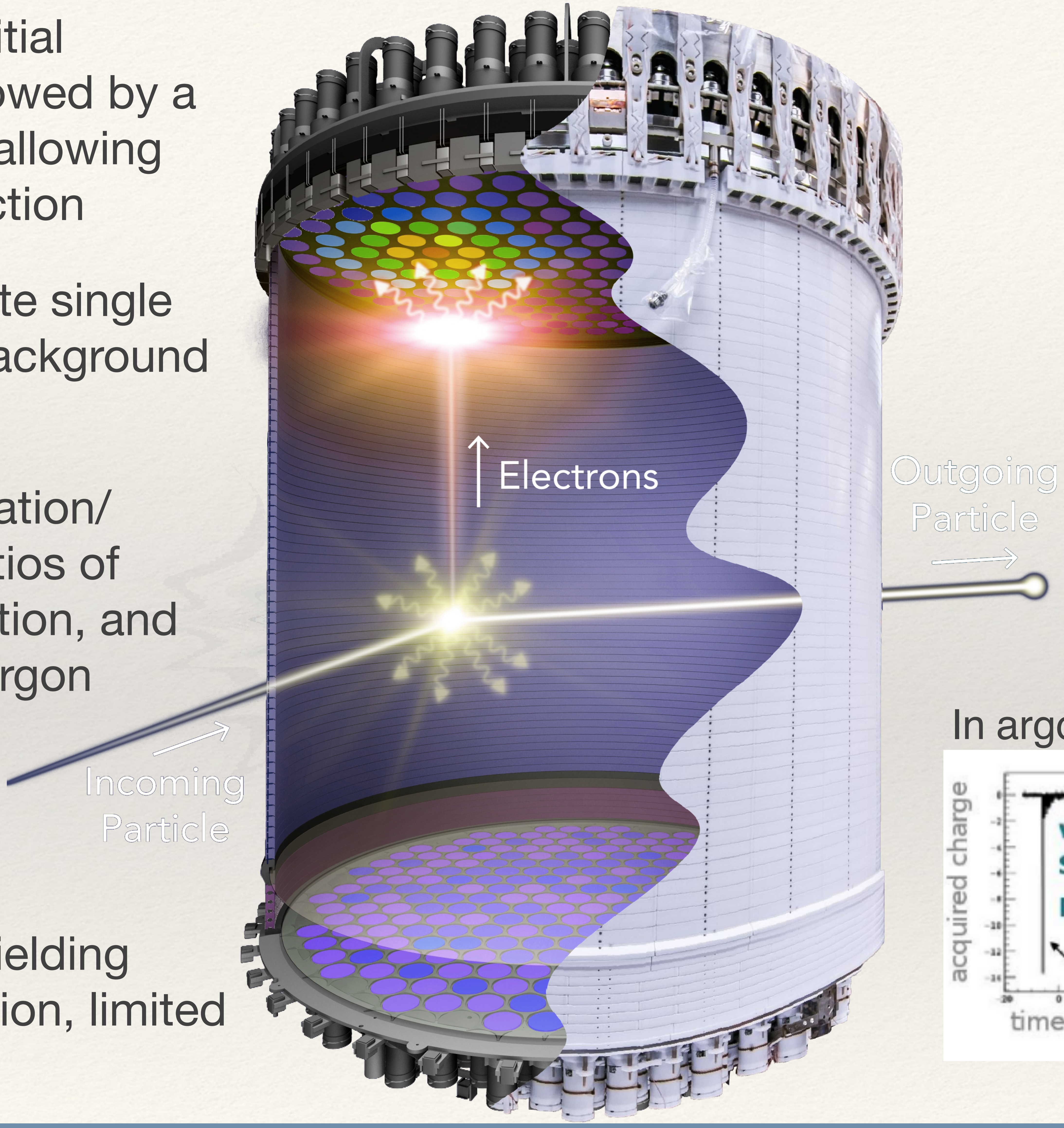
Focus on spin-independent DM-nuclear scattering

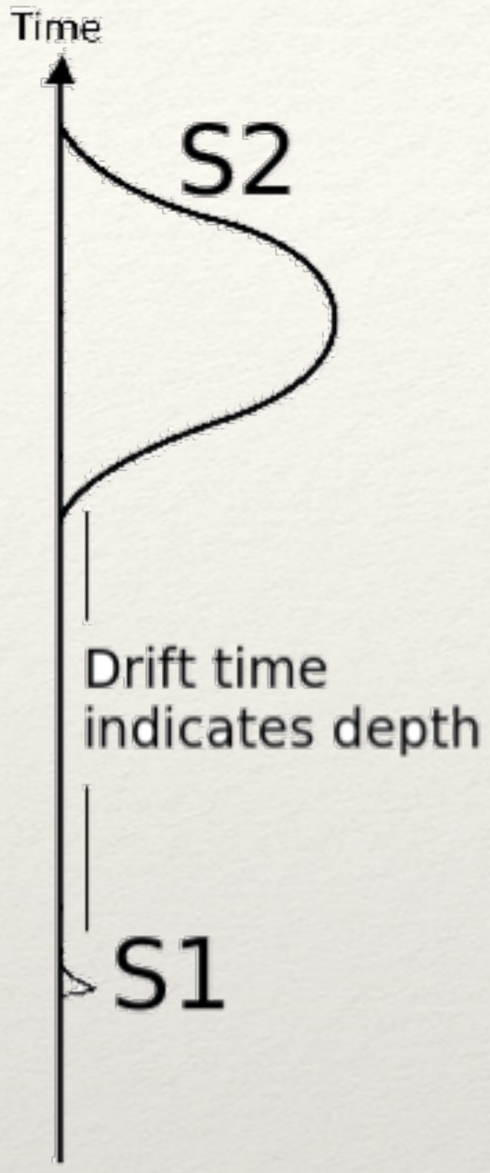
Michael Lucibella 2014, APS.org

For DM masses > 10 GeV/c^2,
liquid noble detectors are the right technology,
and future experiments can get to the neutrino fog.

Liquid Noble Time Projection Chambers

- Interactions give an initial scintillation signal followed by a signal from ionization allowing for position reconstruction
- Good ability to separate single scatter signals from background multiple scatters
- Background discrimination/ particle ID given by ratios of scintillation and ionization, and scintillation timing in argon



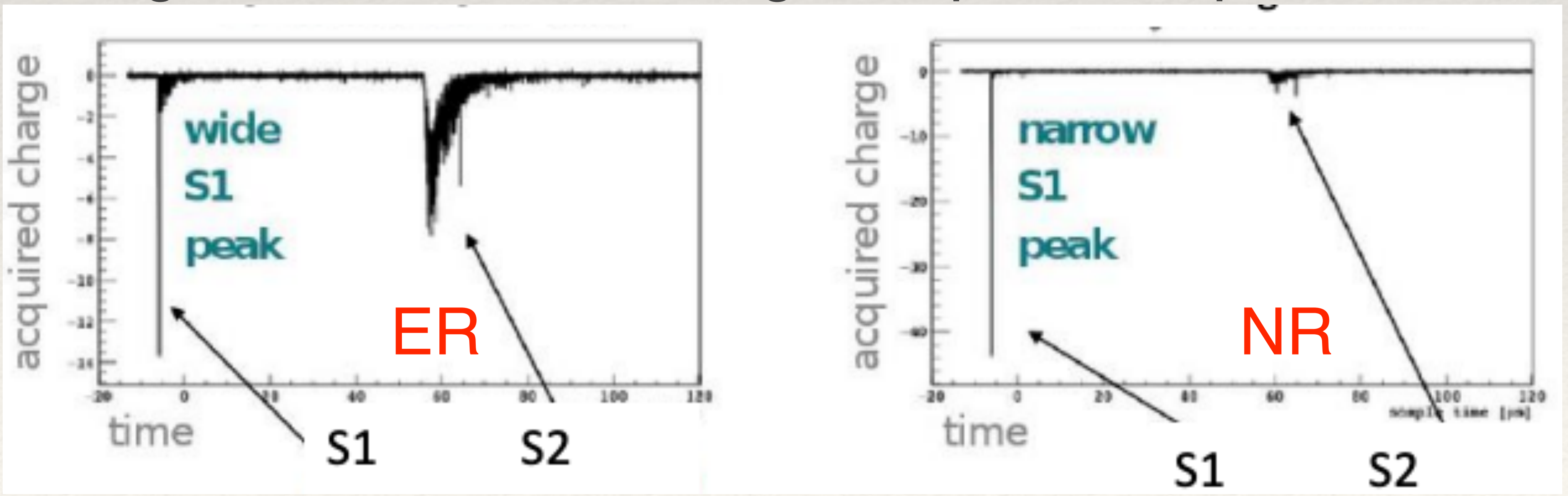


- Other benefits: self shielding against external radiation, limited radioactivity in targets

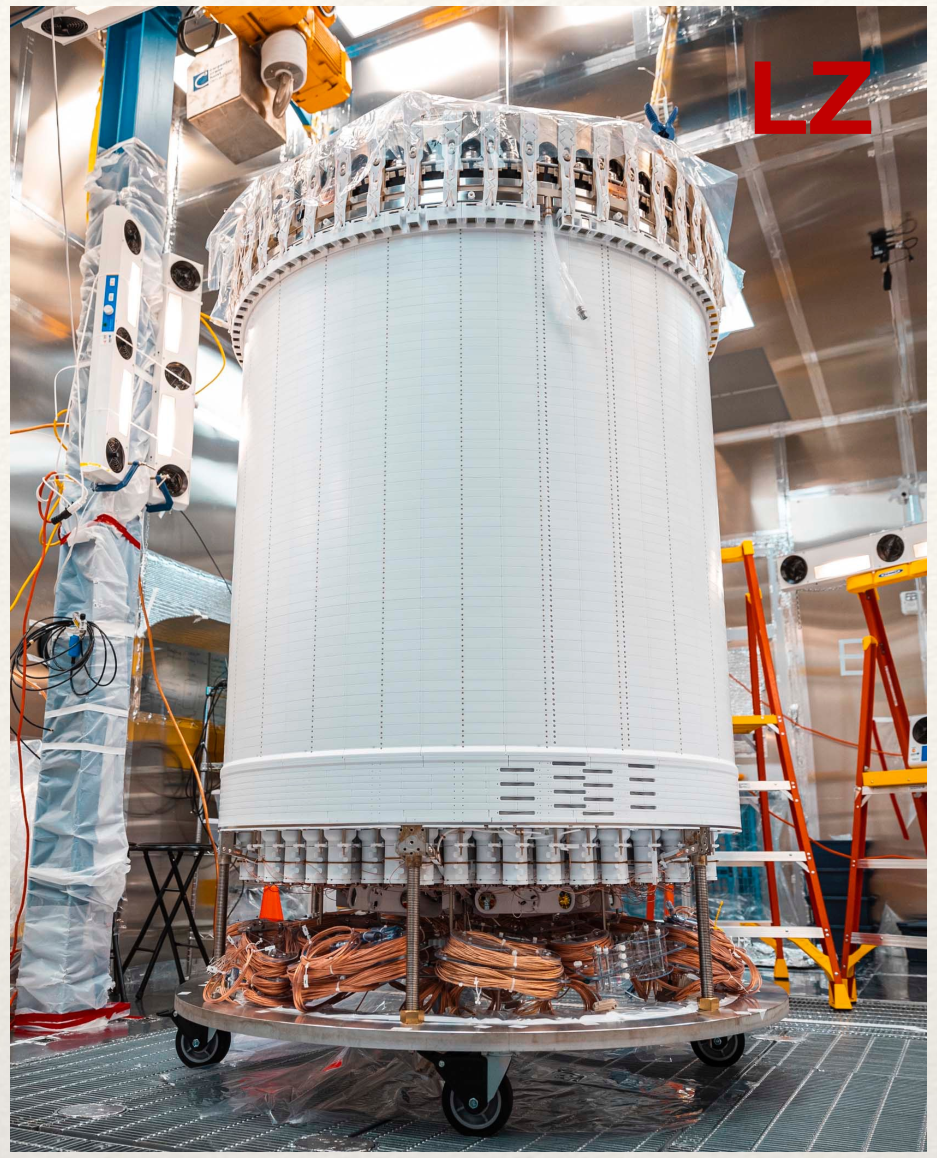
Large detectors with sensitivity over many orders of magnitude of DM mass.

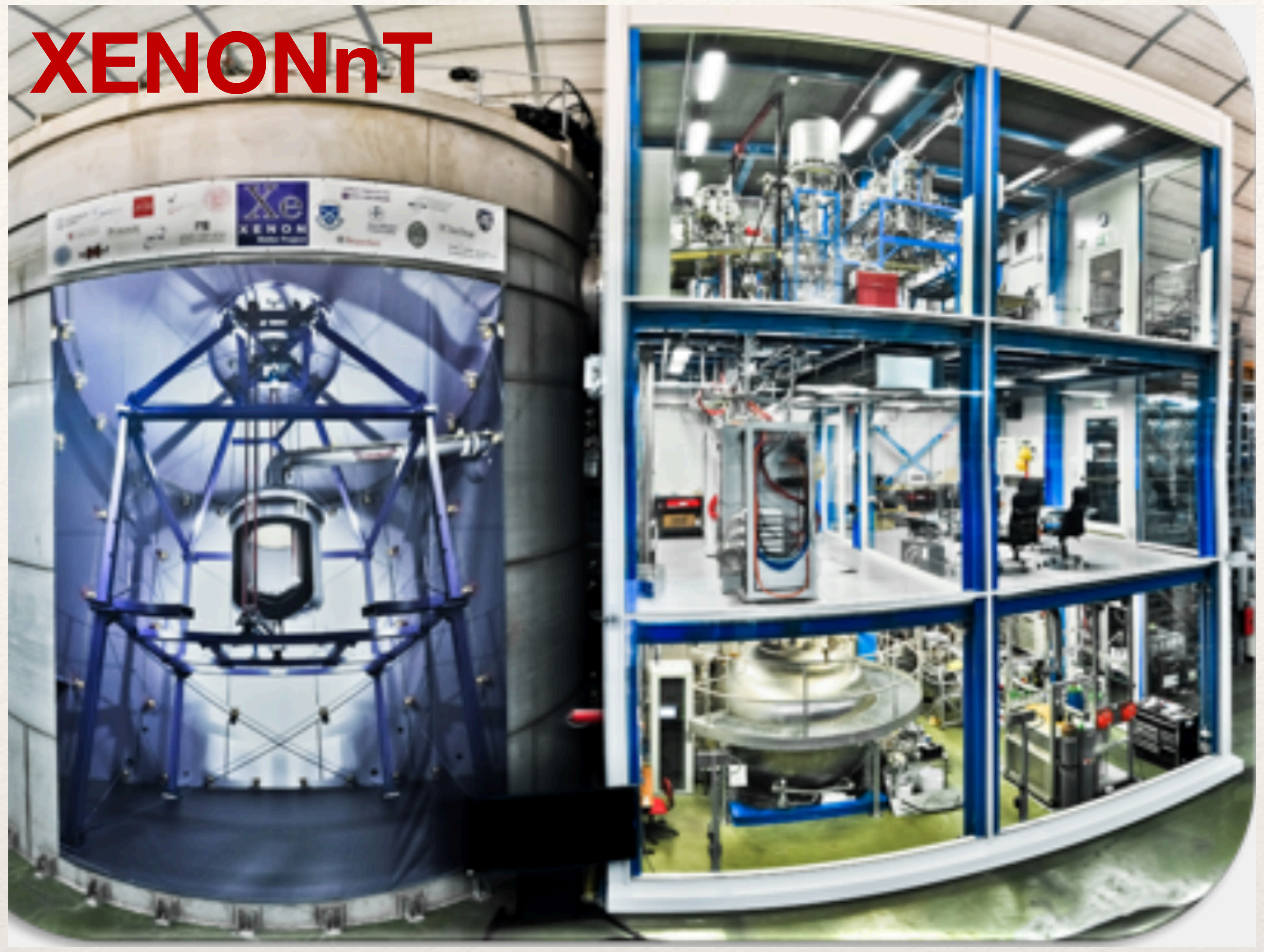
Physics beyond WIMP searches also.

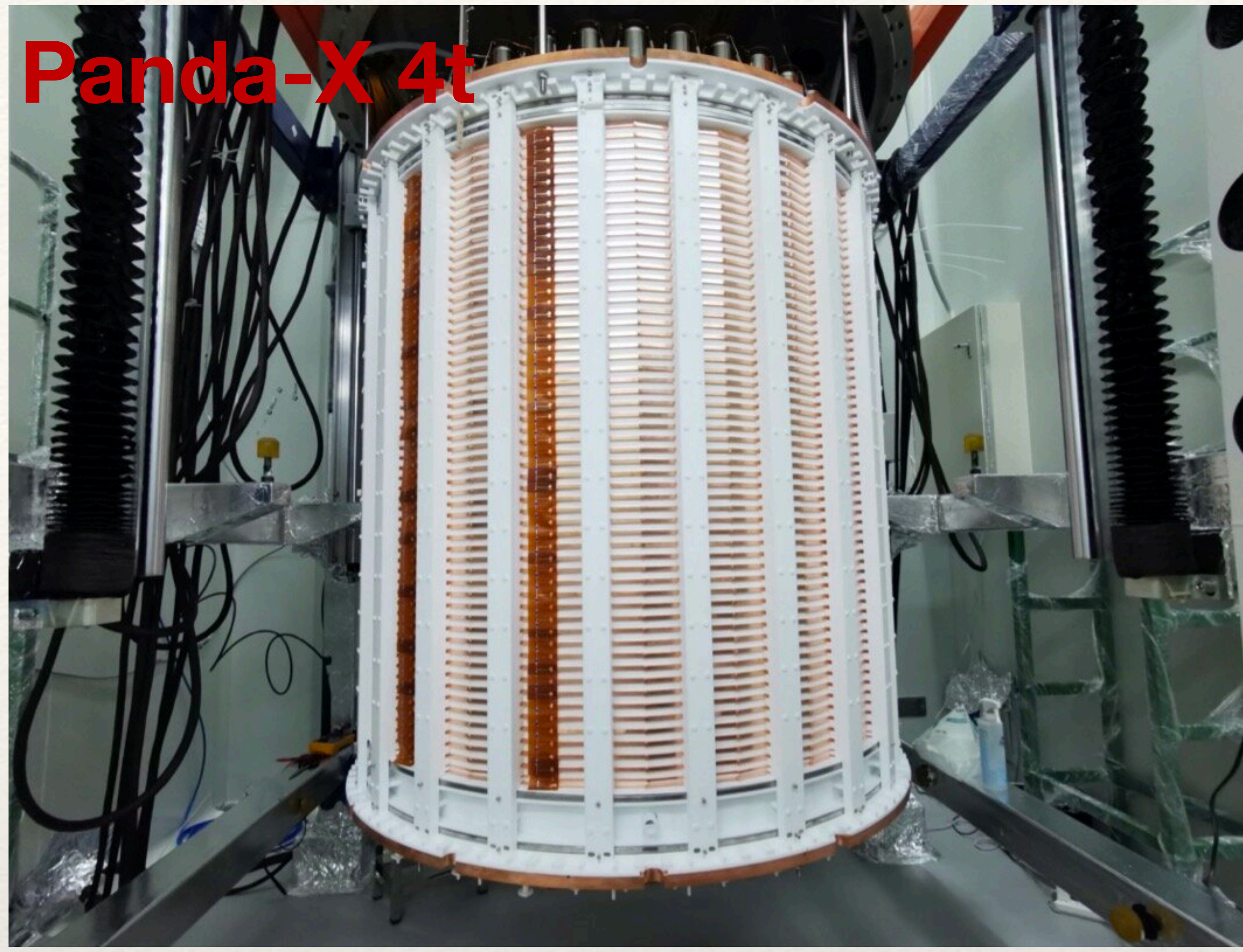
In argon, scintillation timing also provides particle ID

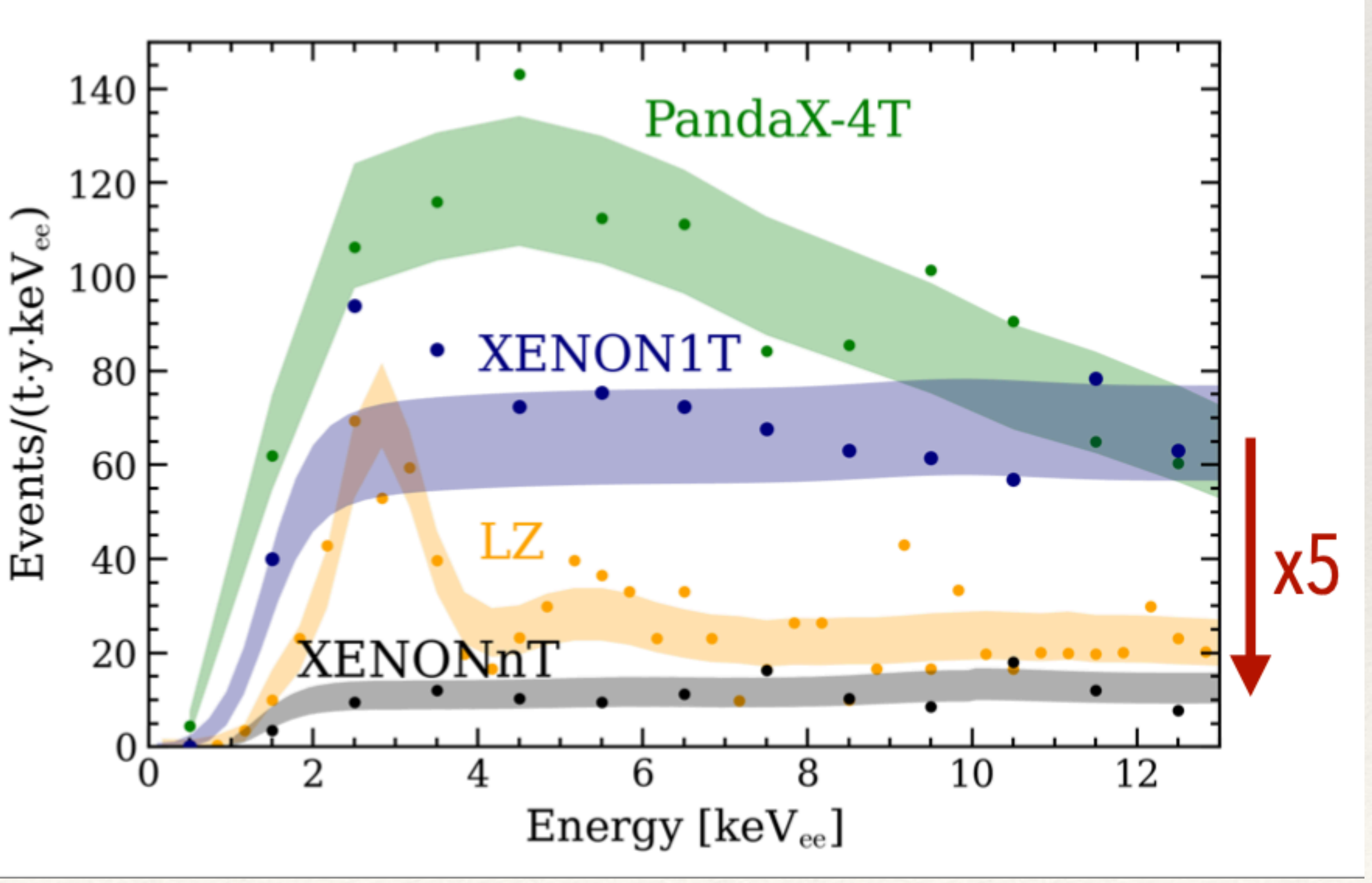


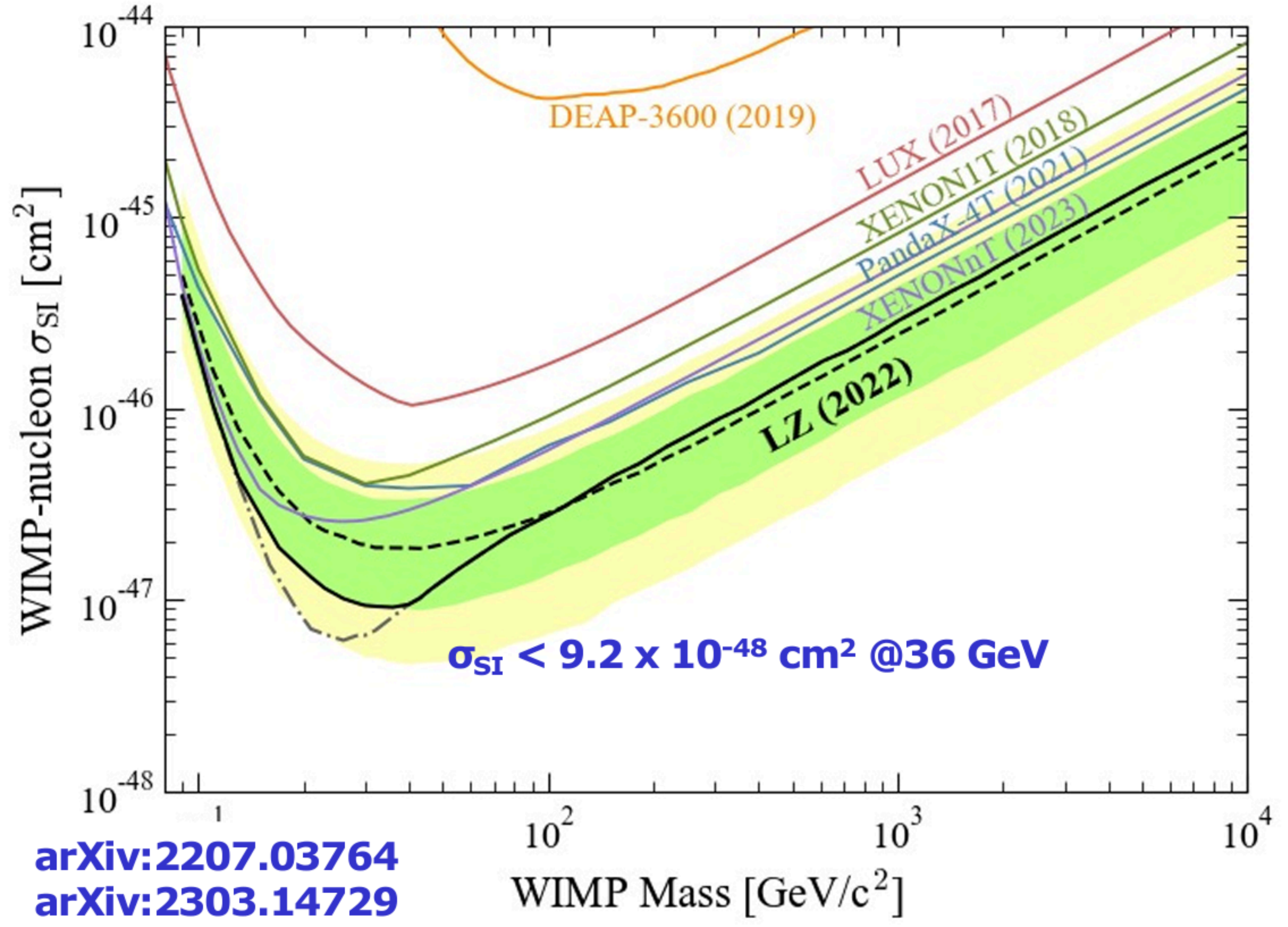
Running Xenon Experiments





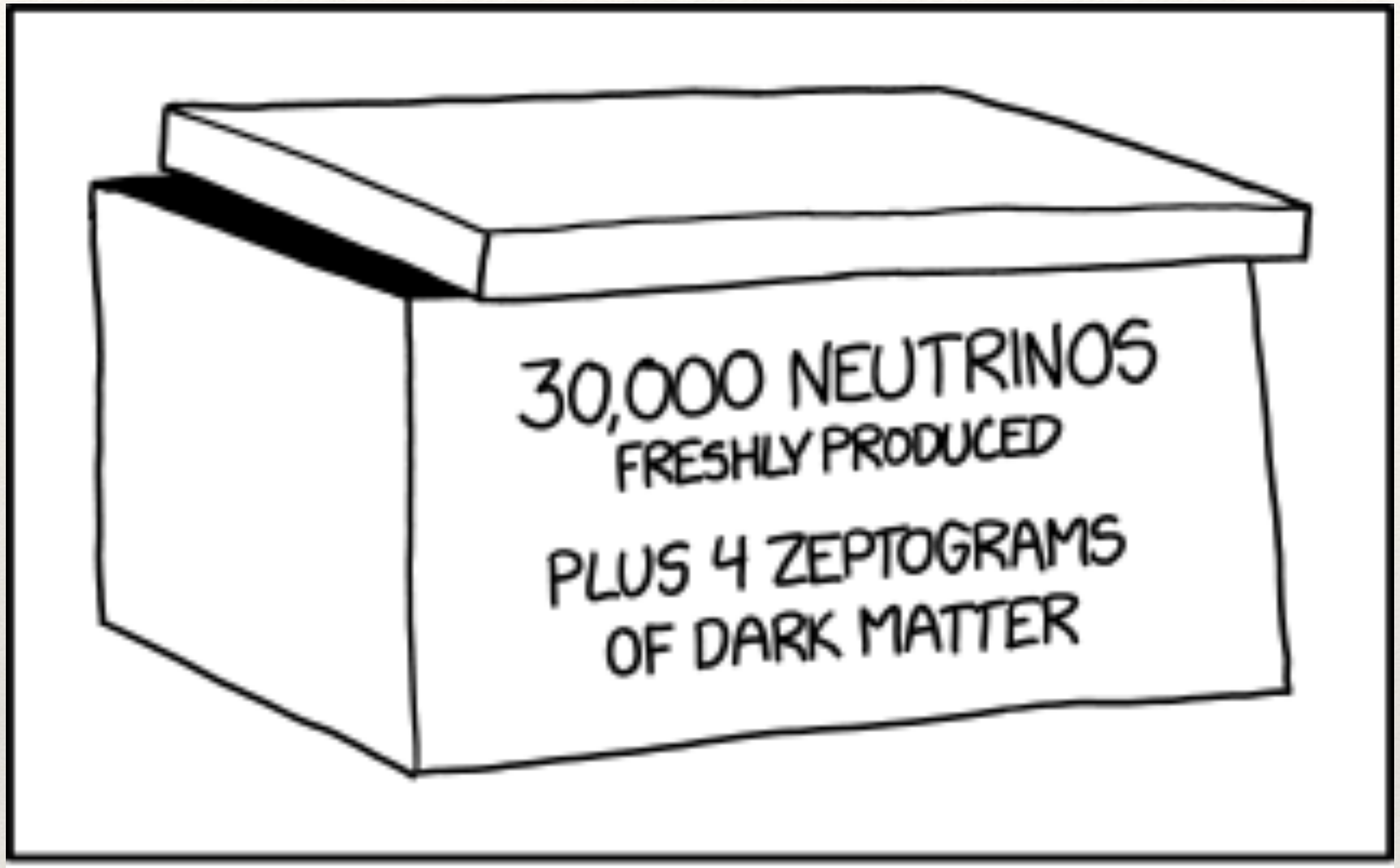






- 3 running experiments that will continue ~5 years
- Continuing their understanding of xenon microphysics
- Science also with electronic recoils, effective field theory models, MIMPs, 0vbb and double electron capture, solar neutrinos, ….

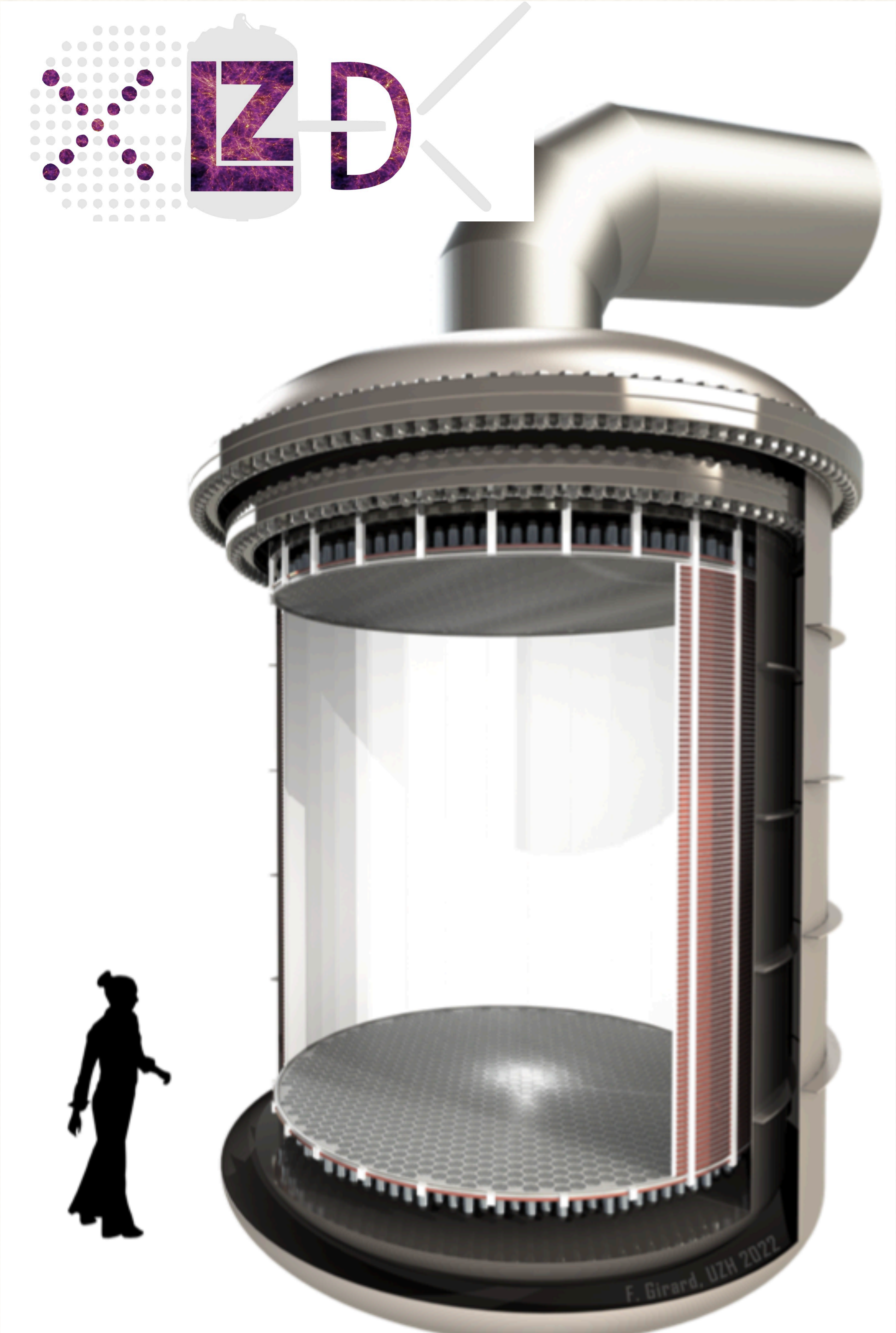
The Future



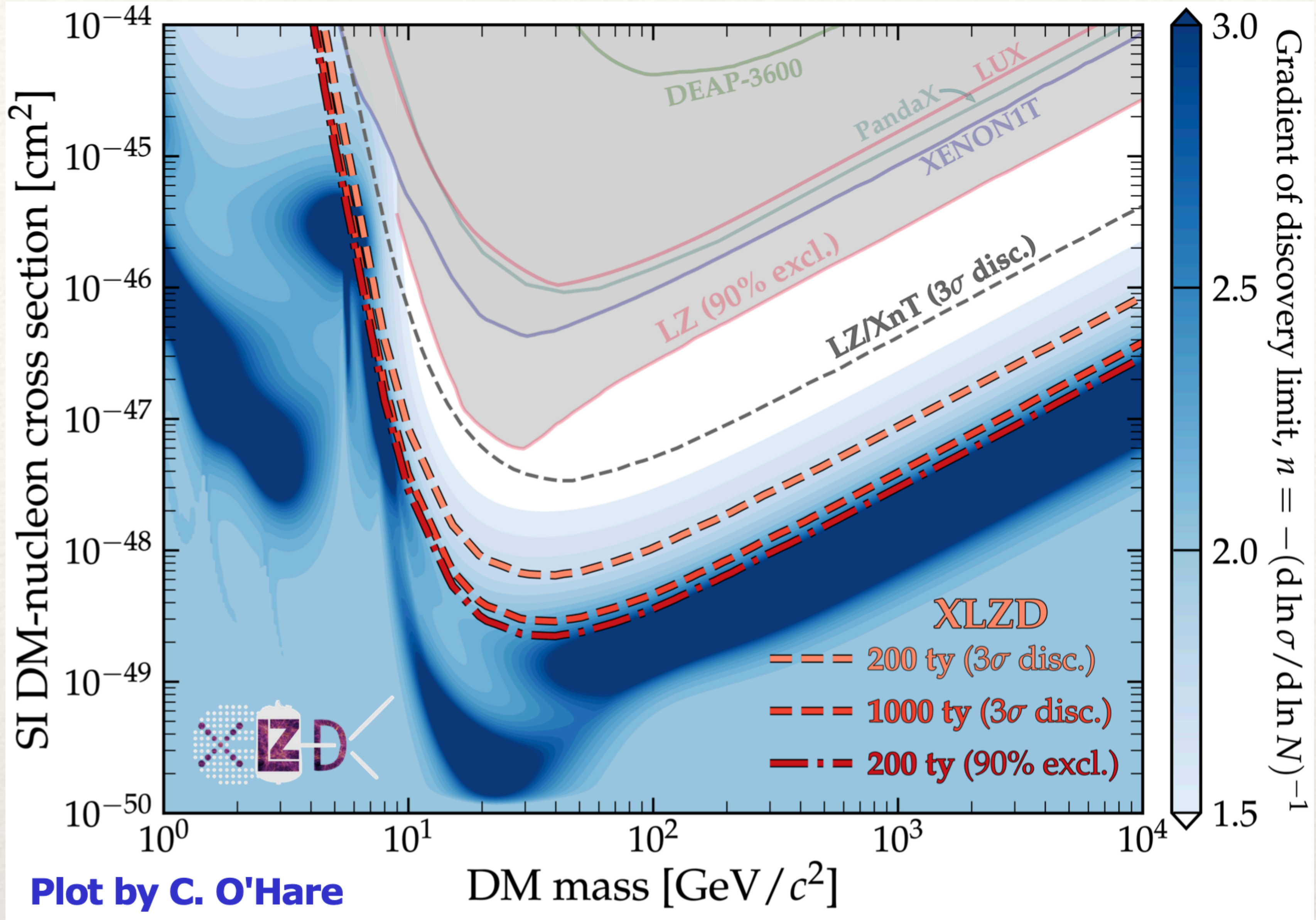
COSMOLOGISTS ARE EASY TO SHOP FOR BECAUSE YOU CAN JUST GET THEM A BOX.

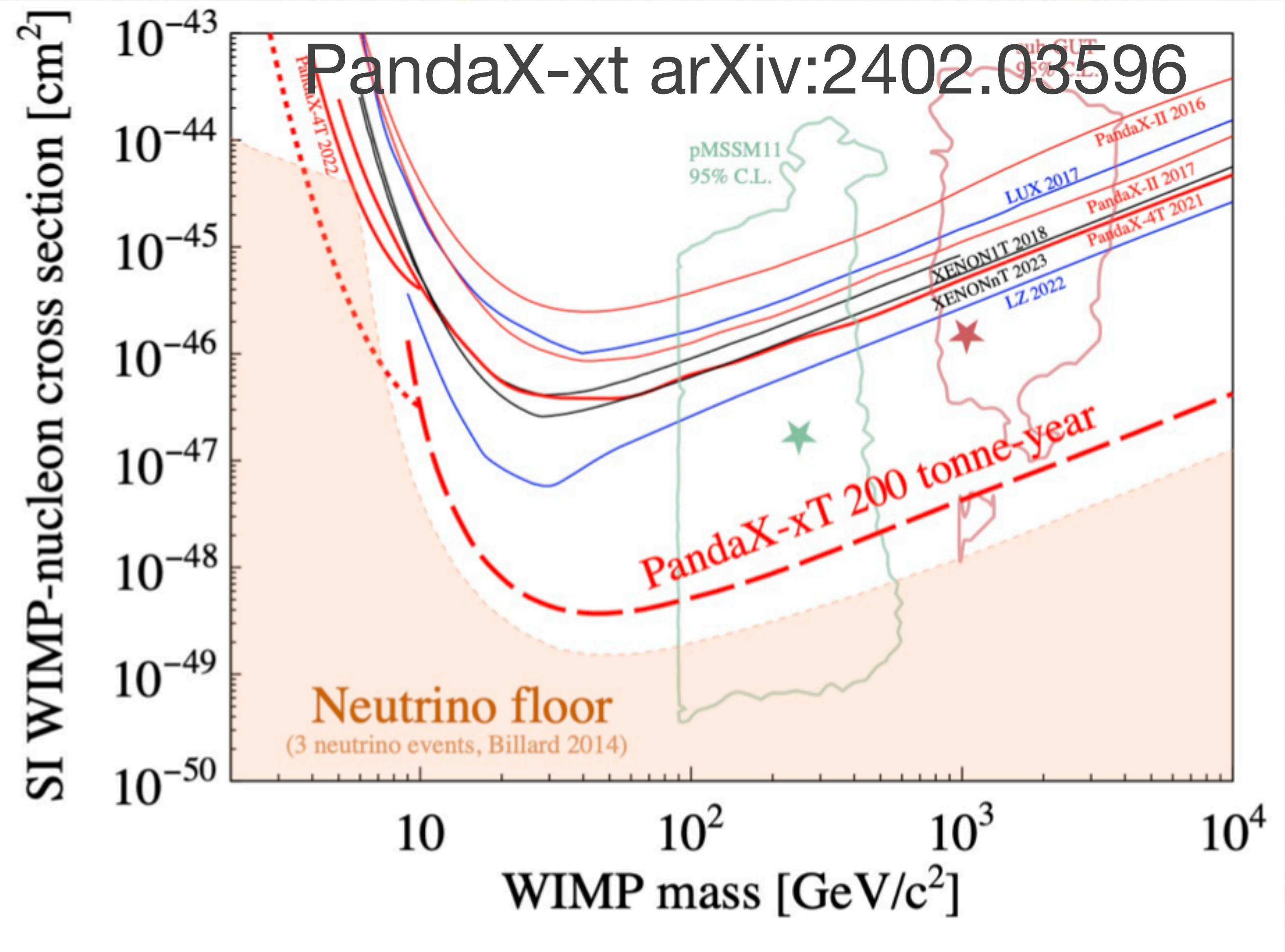
But particle astrophysicists want DETECTORS to find Dark Matter

Future Xenon Experiments

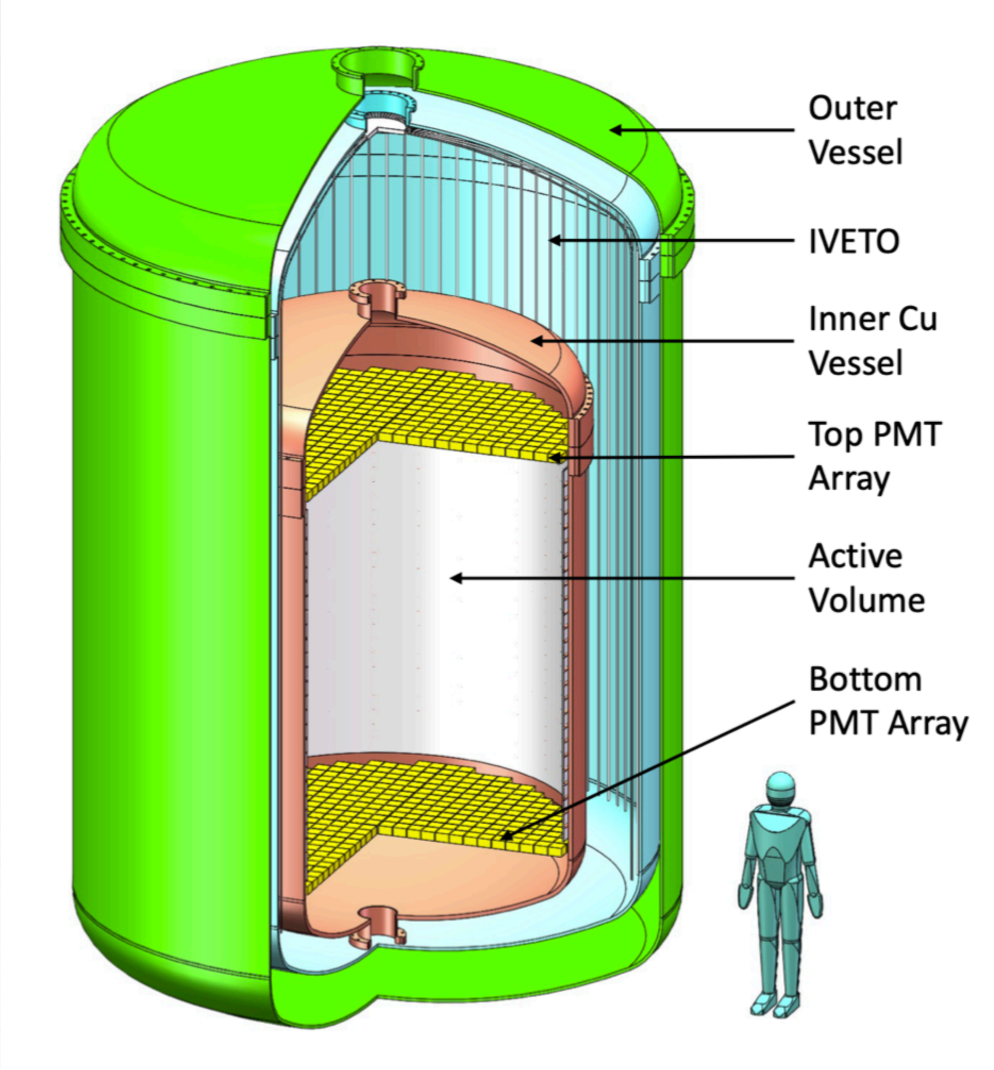


60t fiducial for baseline



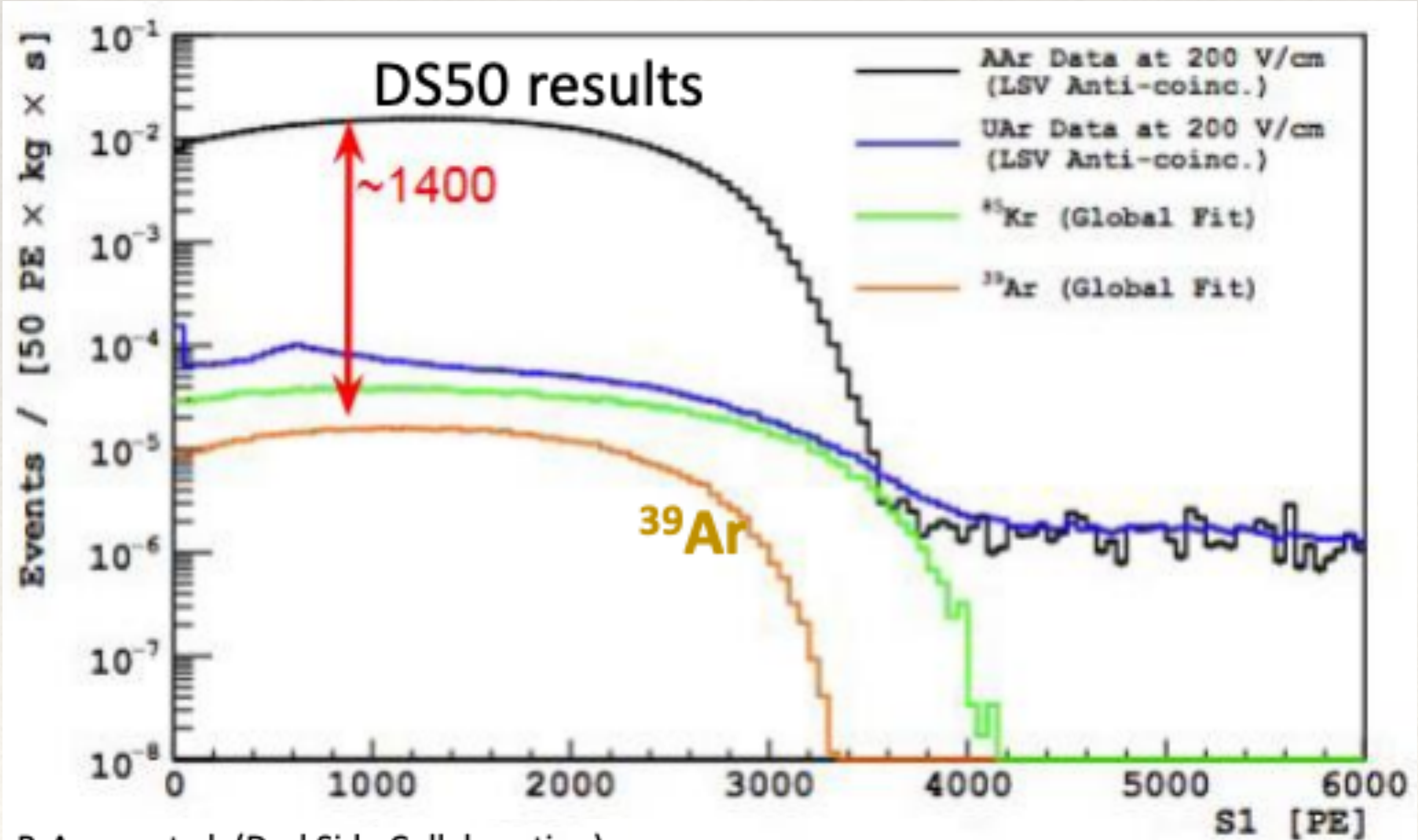


- XLZD: XENON, LZ (LUX-ZEPLIN), DARWIN
  - 60t fiducial baseline detector, with early science with initial xenon, starting ~2032
- PandaX-xt
  - staged growth of PandaX-4t to 43t fiducial, most infrastructure in place

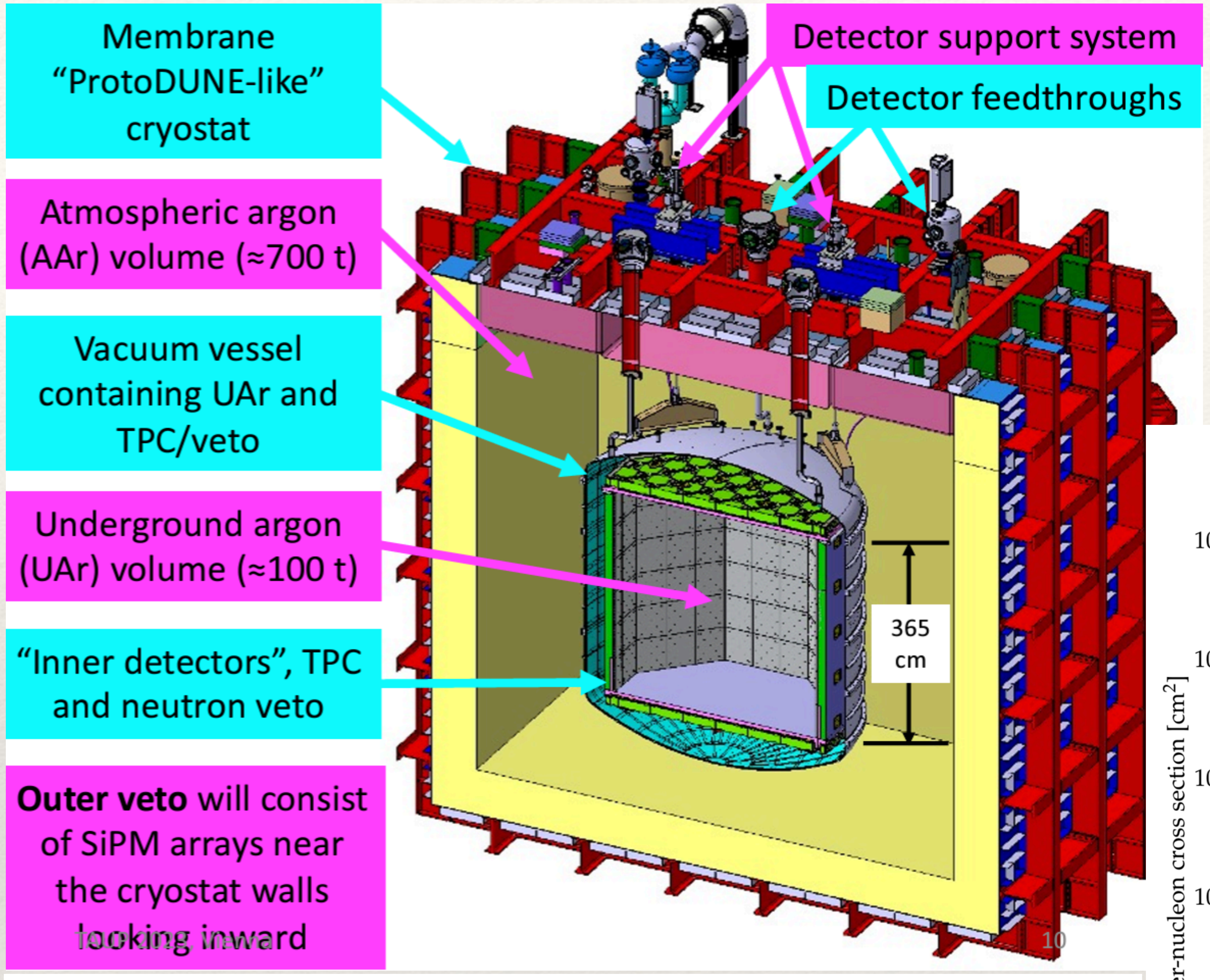


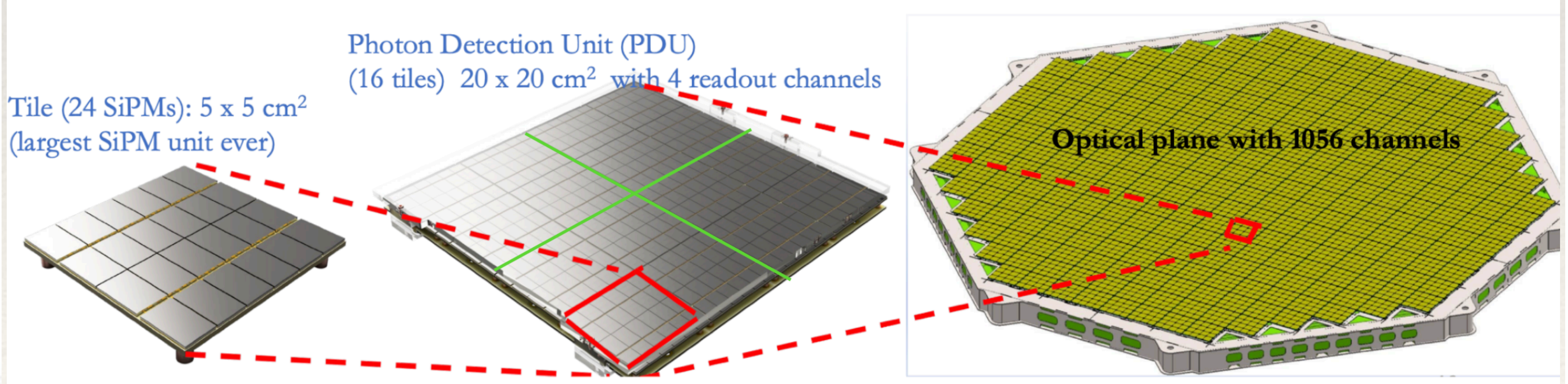
Argon Experiments

- Single phase DEAP-3600 undergoing hardware upgrades
- DarkSide-20k under construction at LNGS, data taking expected to start in 2026
  - Technology advances in SiPMs, Gd-loaded acrylic, Ar distillation



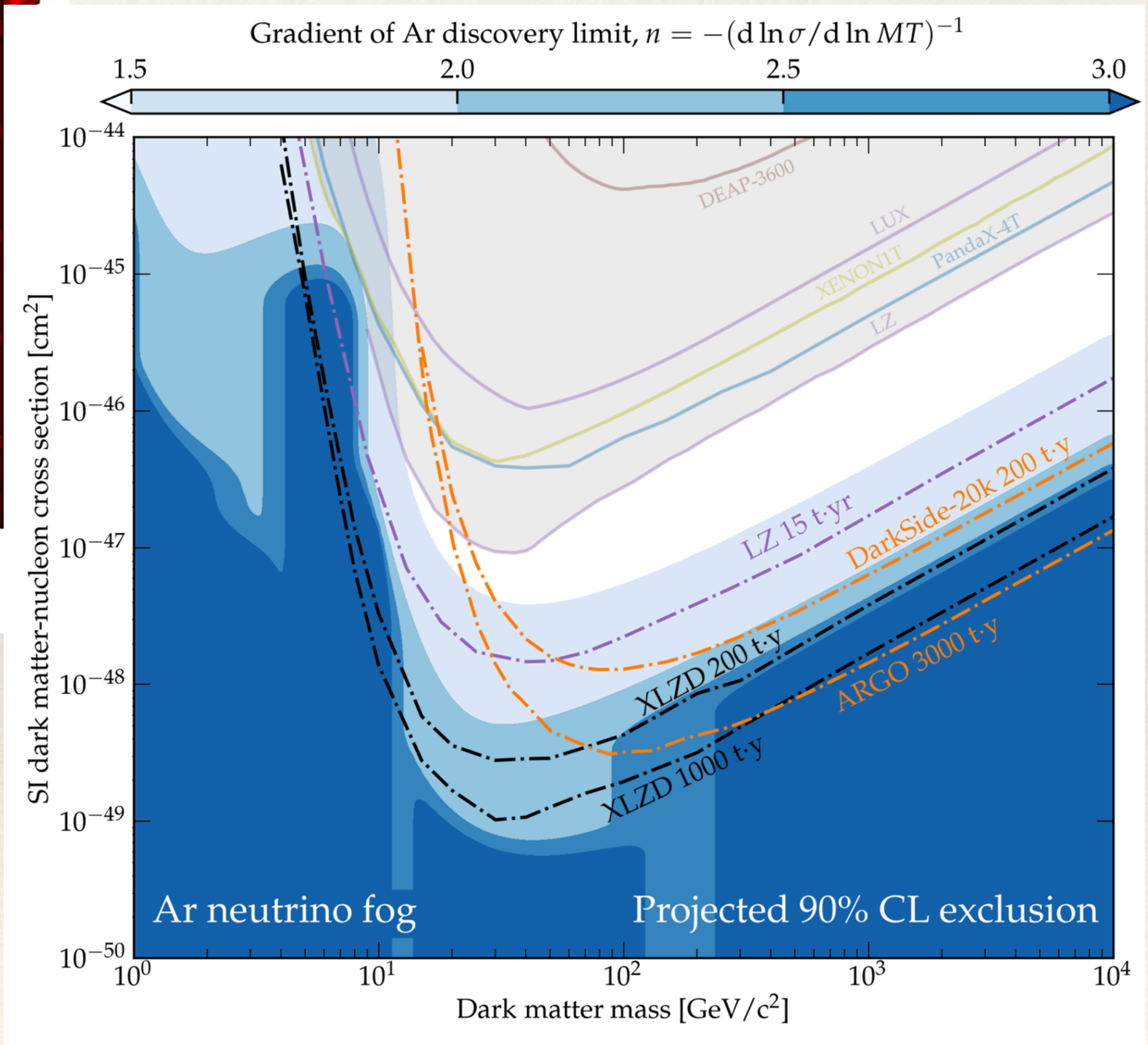
P. Agnes et al. (DarkSide Collaboration)
Phys. Rev. D 93, 081101(R) (2016)





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

- Future ARGO detector to get to neutrino fog, 300t fiducial, 2035?
  - UAr in demand by other projects too (LEGEND, DUNE, COHERENT)

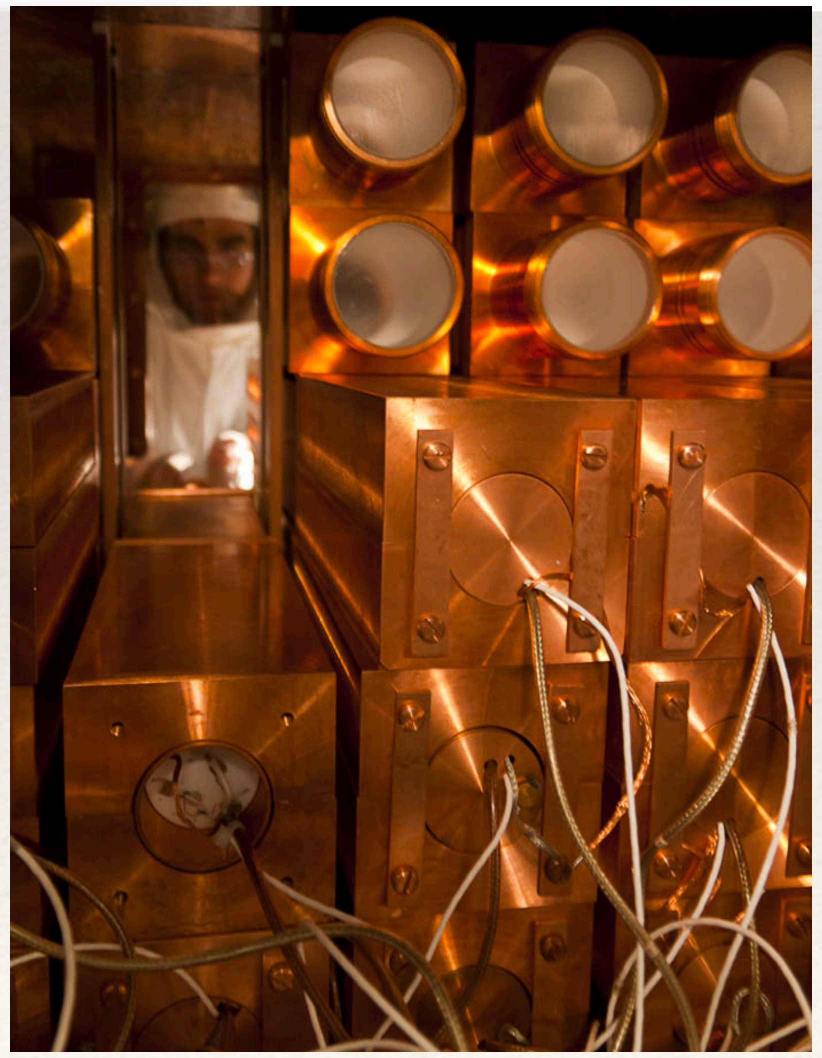


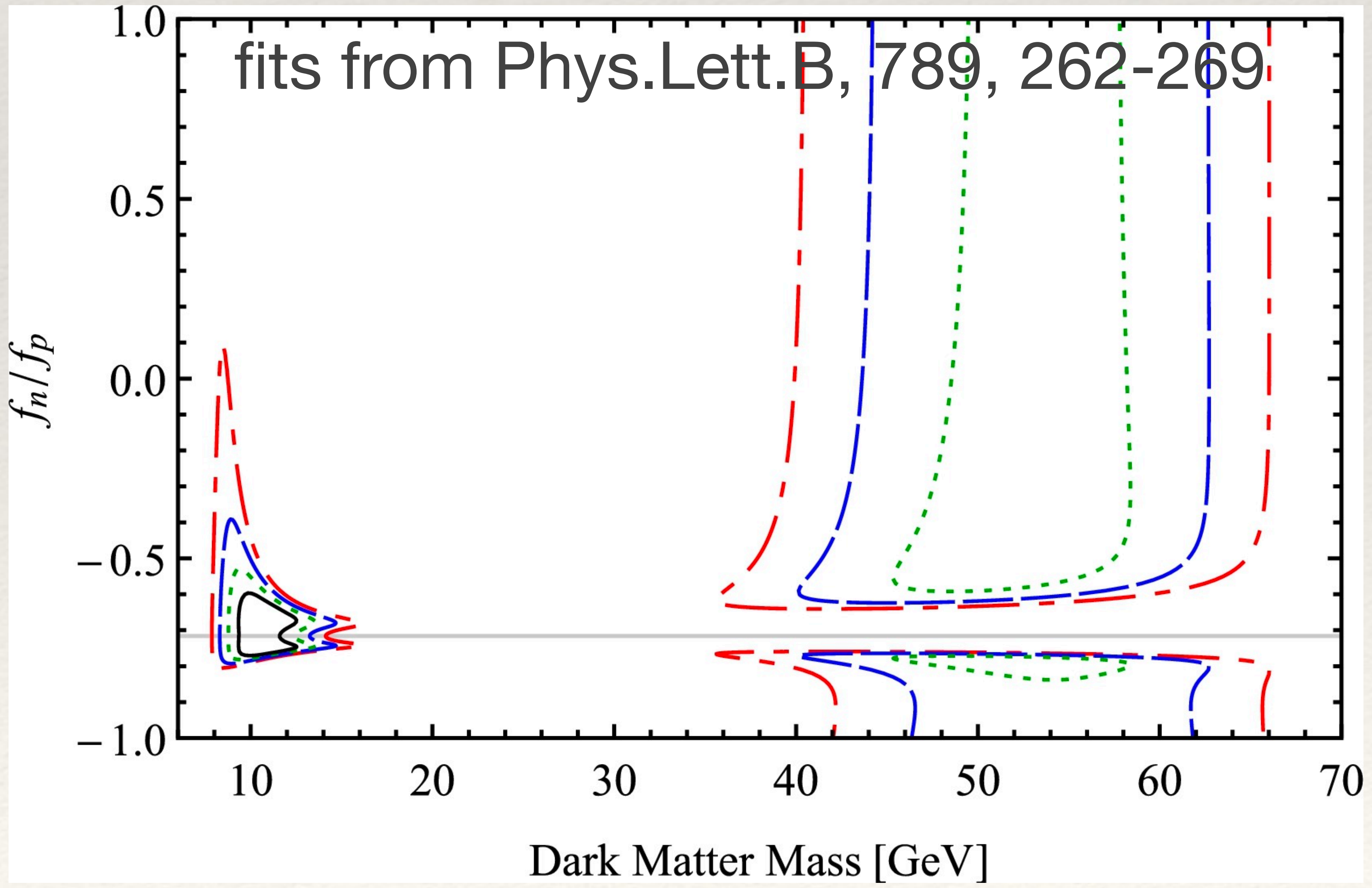
We will have definitive refutation (or confirmation) of the DAMA/LIBRA signal in NaI soon.

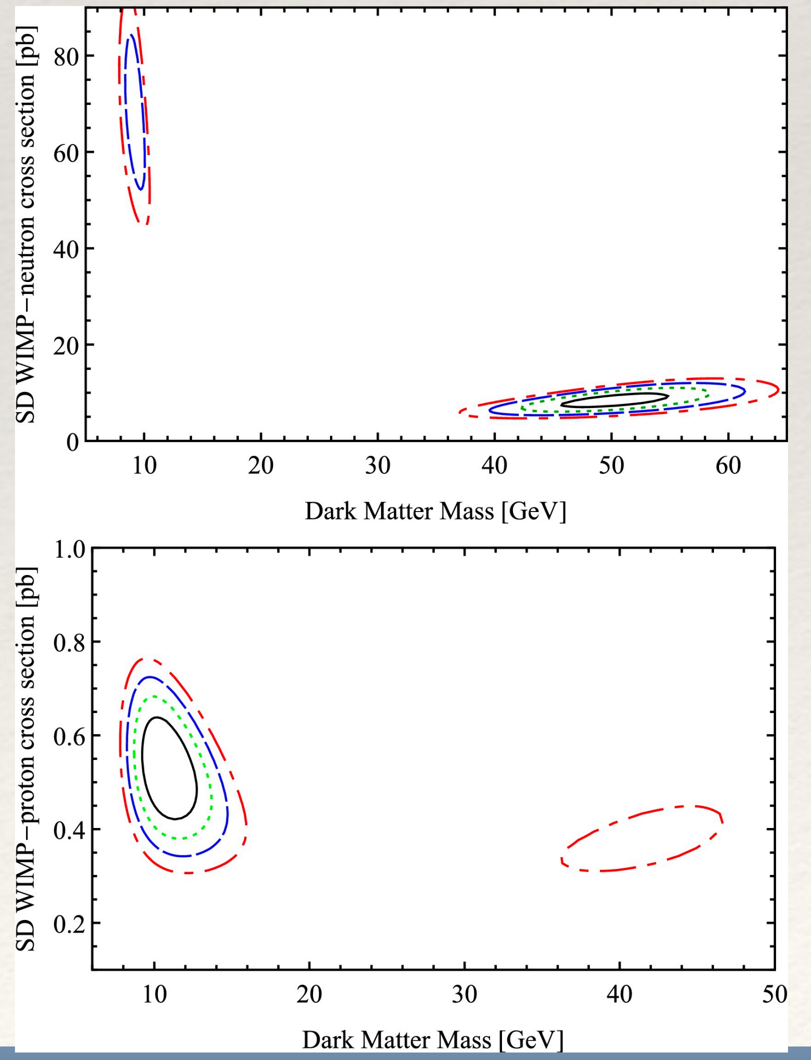
NaI crystals: DAMA/LIBRA signal

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

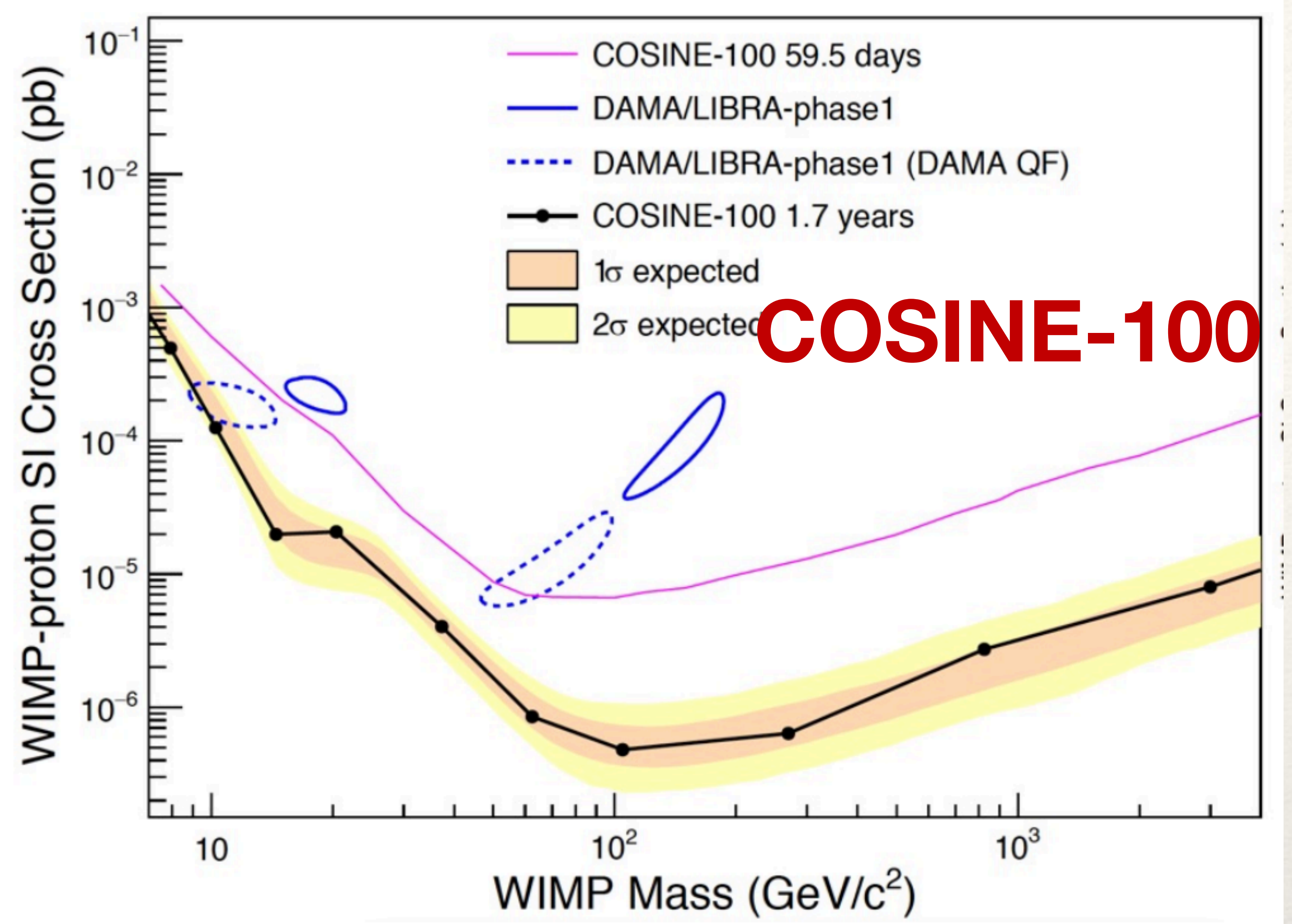
- Annual Modulation seen at $>13\sigma$
- Not SI isospin-conserving
- Isospin-violating SI at ~10 GeV/c^2,
  - or SD at 10 or 45 GeV/c^2
- Also studied with updated quenching

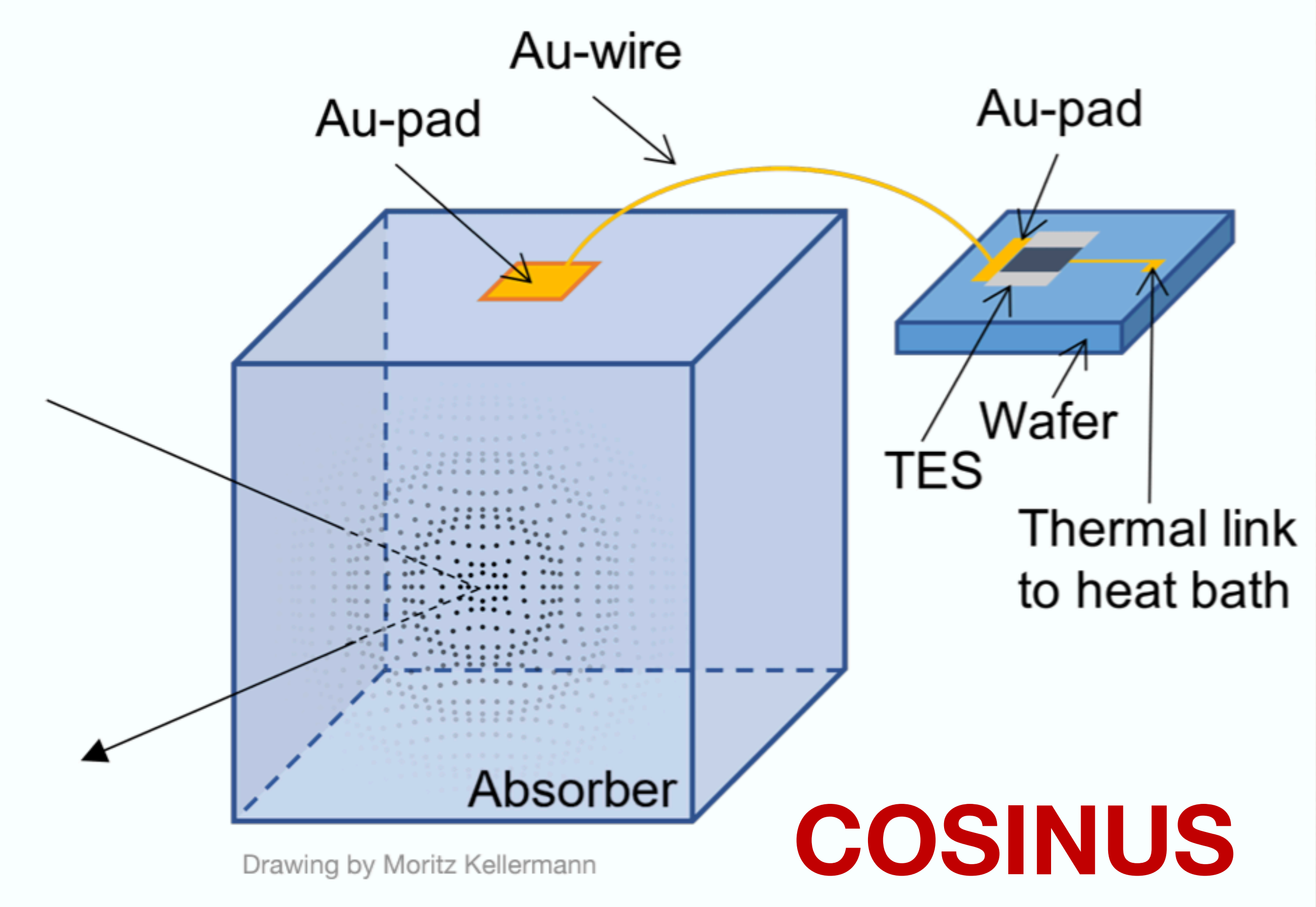






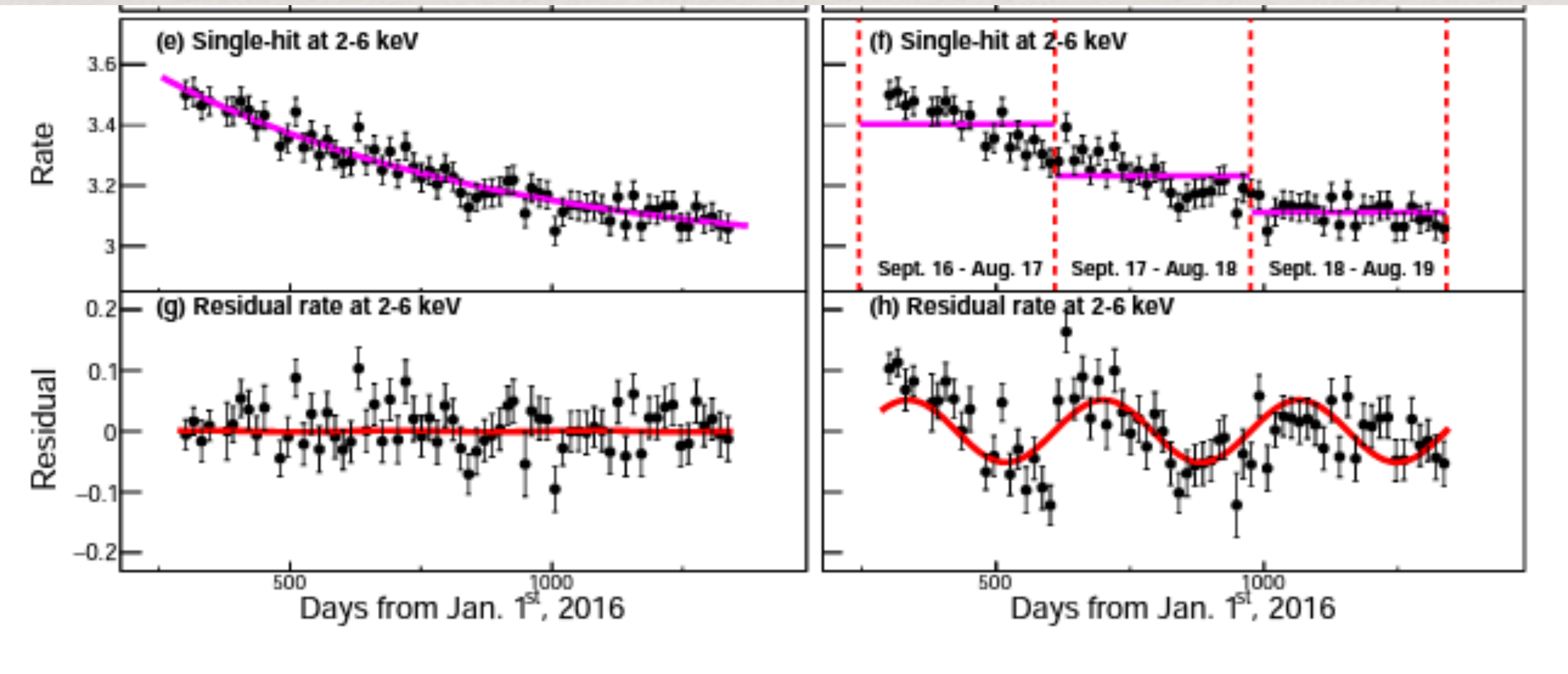
NaI tests: ongoing and future

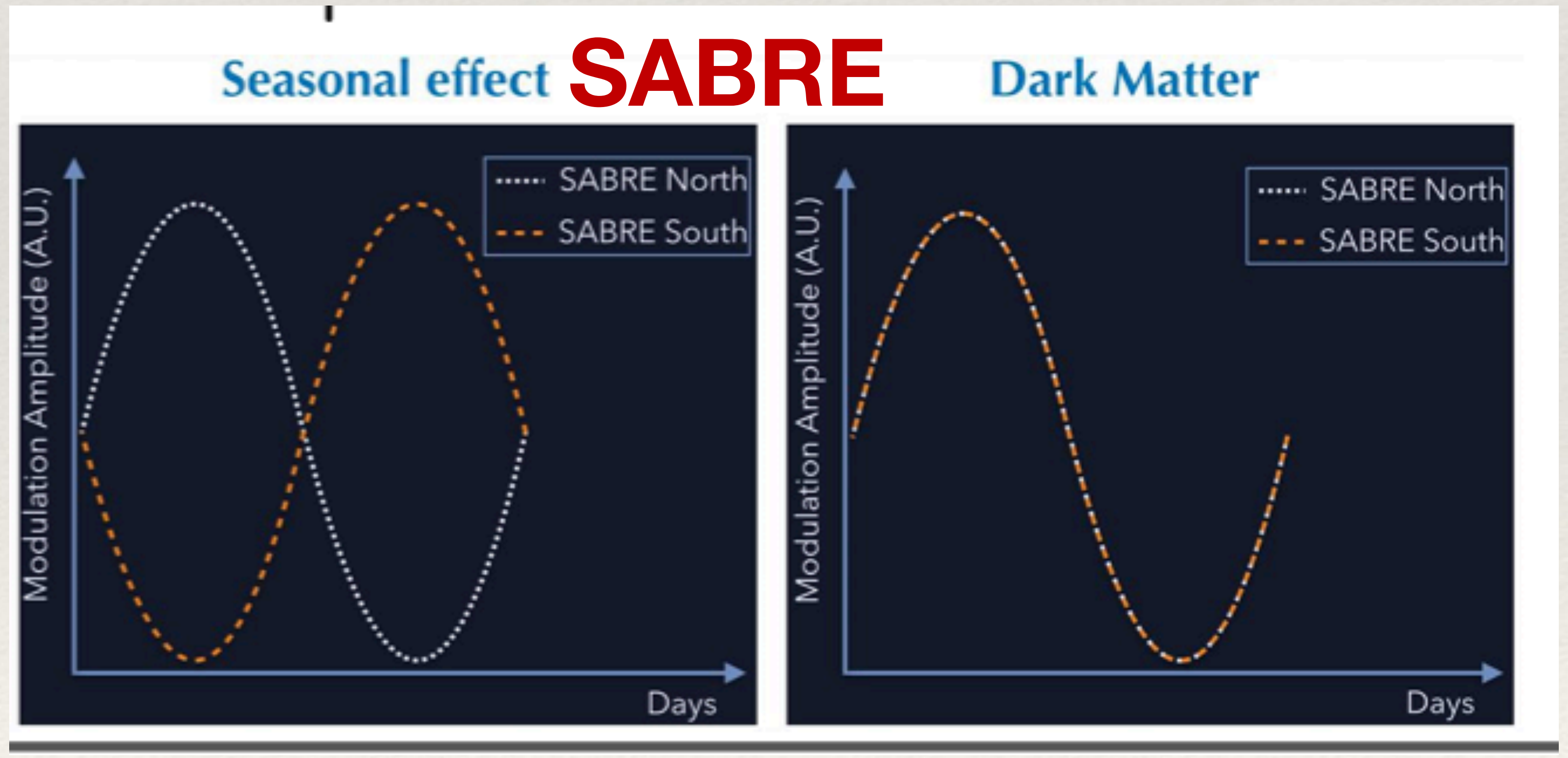


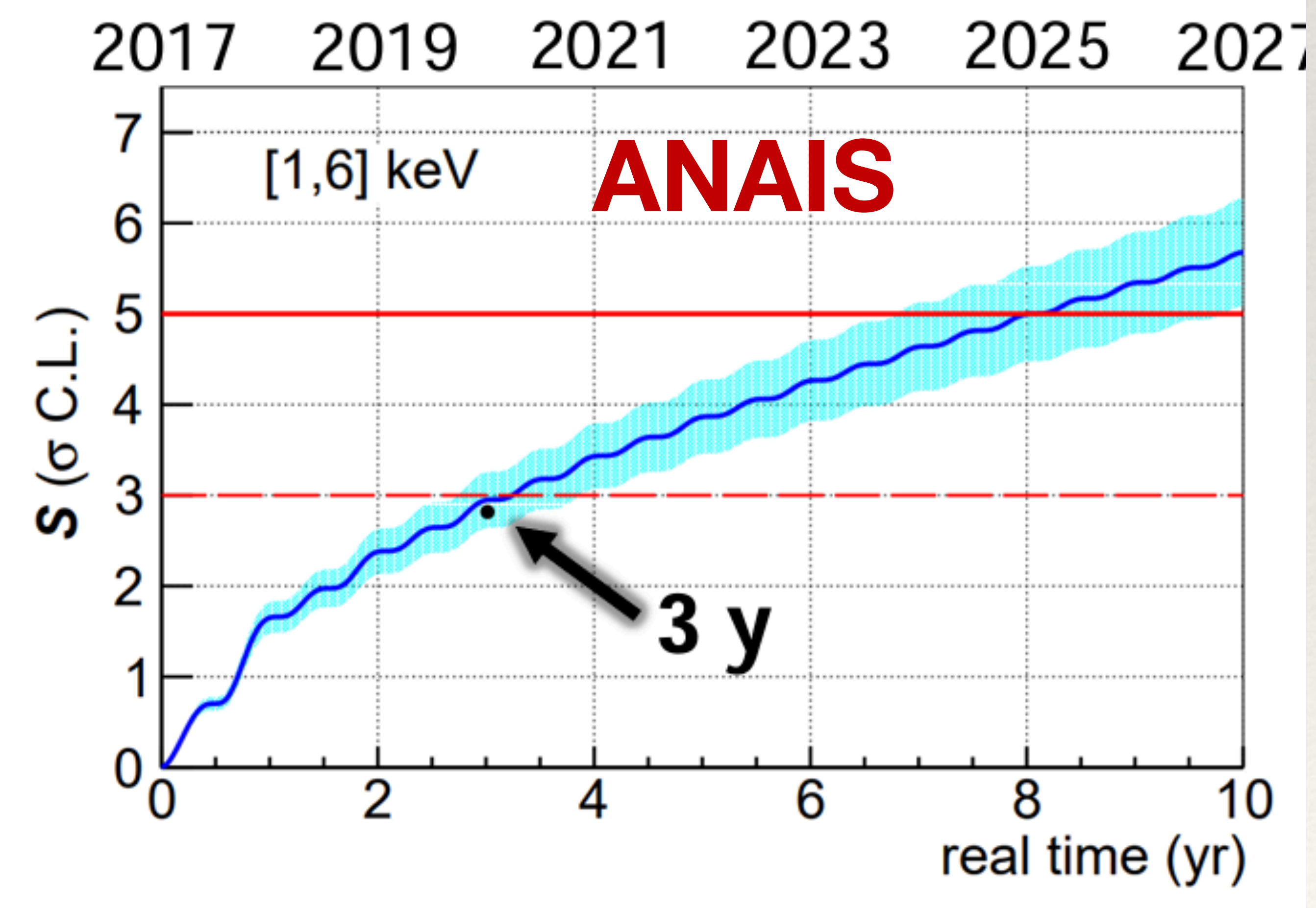


- Multiple NaI detectors - we'd like to know the cause of the modulation, not just rule out DM.
- ANAIS-112, running, could be on track for 5 σ rejection of DAMA by 2025.
- COSINE saw that how calibrations are handled can induce a modulation of residuals, Moved lab in 2023.
- COSINUS cryogenic search with discrimination, starting this year.
- SABRE: low bkgd crystals, with Northern and Southern sites, also starting this year.

SciAdv 7 46 '21



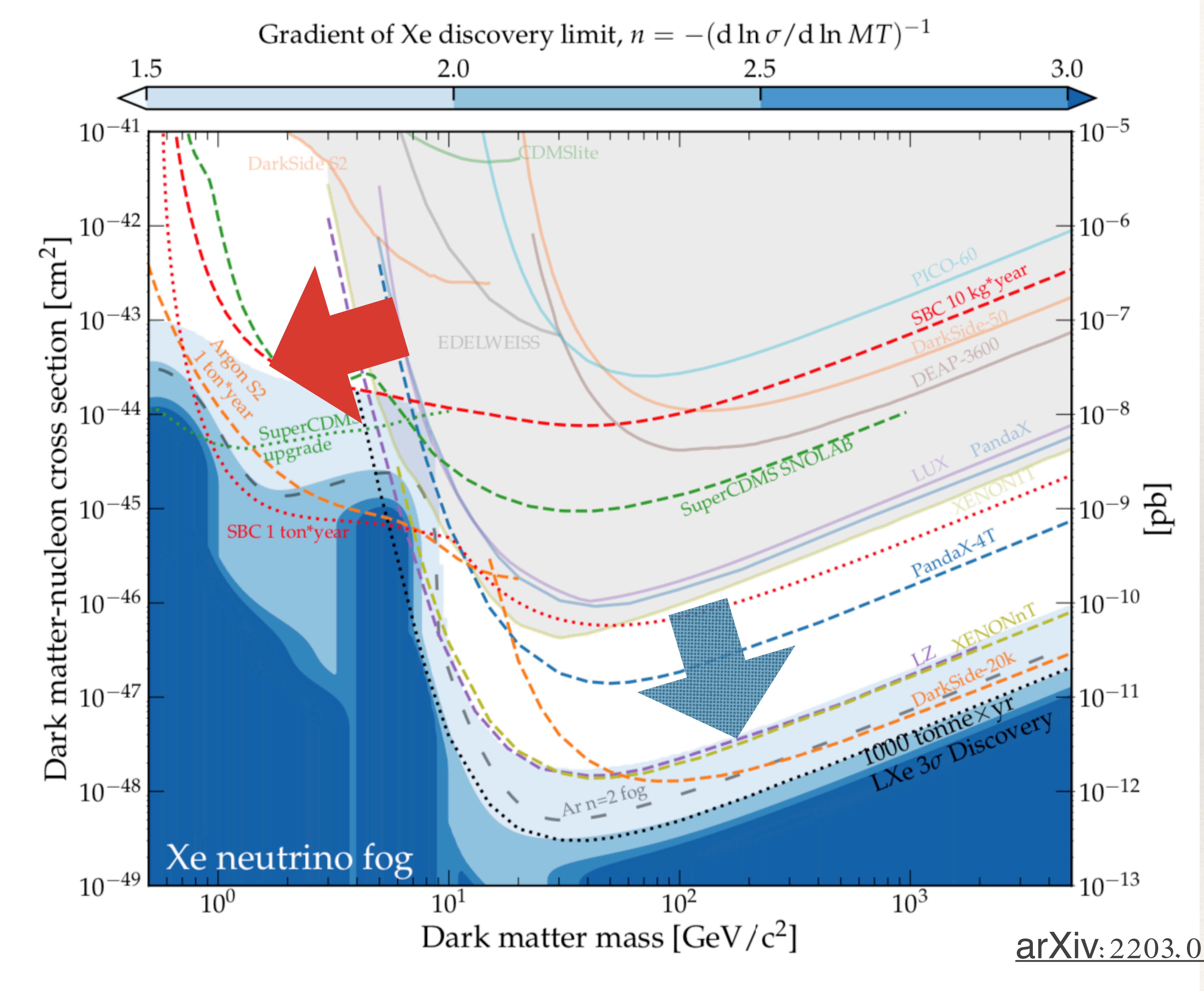




Is it just an analysis artifact? arXiv:2208.05158

For DM masses 1-10 GeV/c^2,
there is a lot of activity!
Timing may be more important than technology.

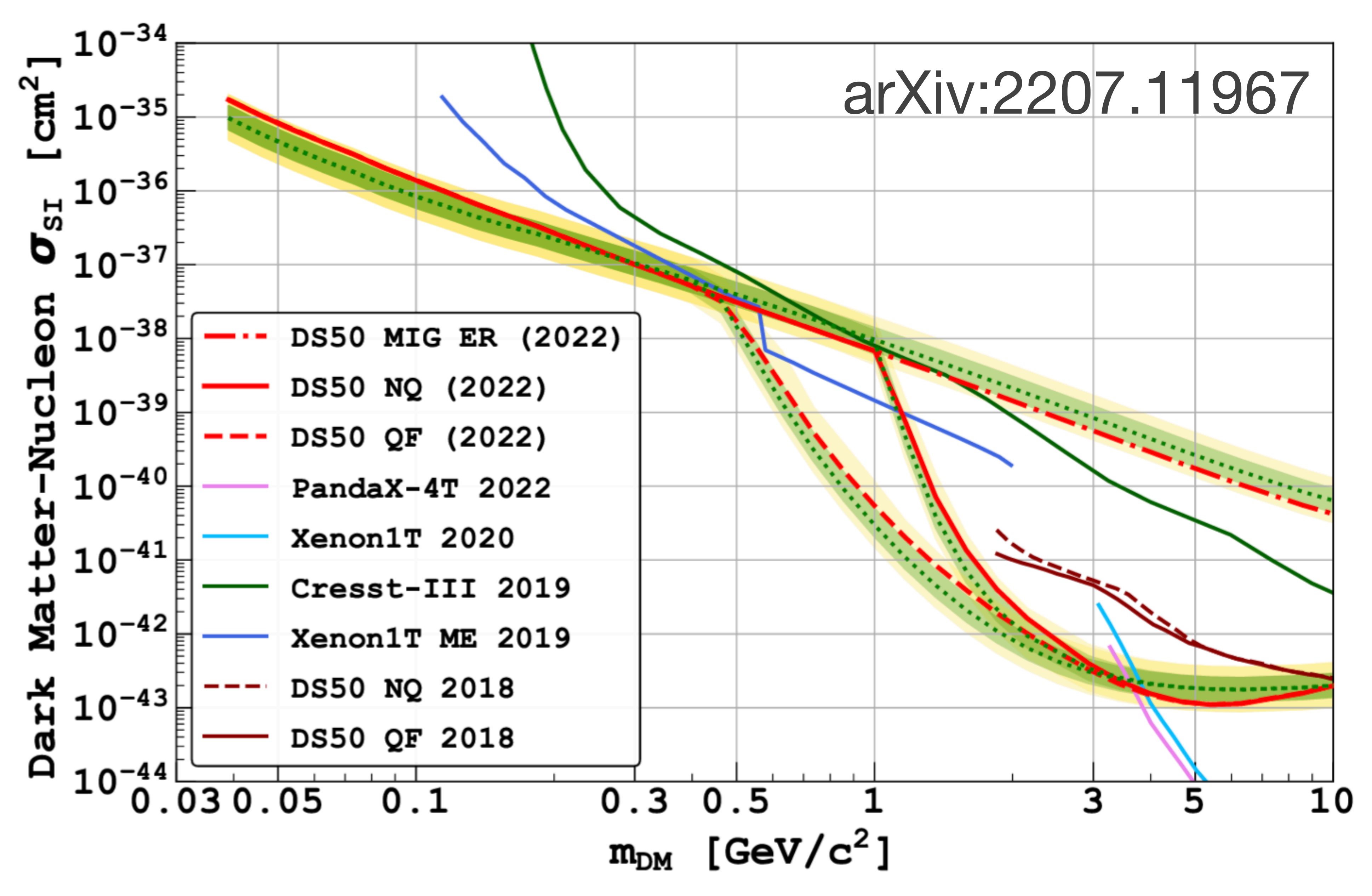
Going to Lower Masses



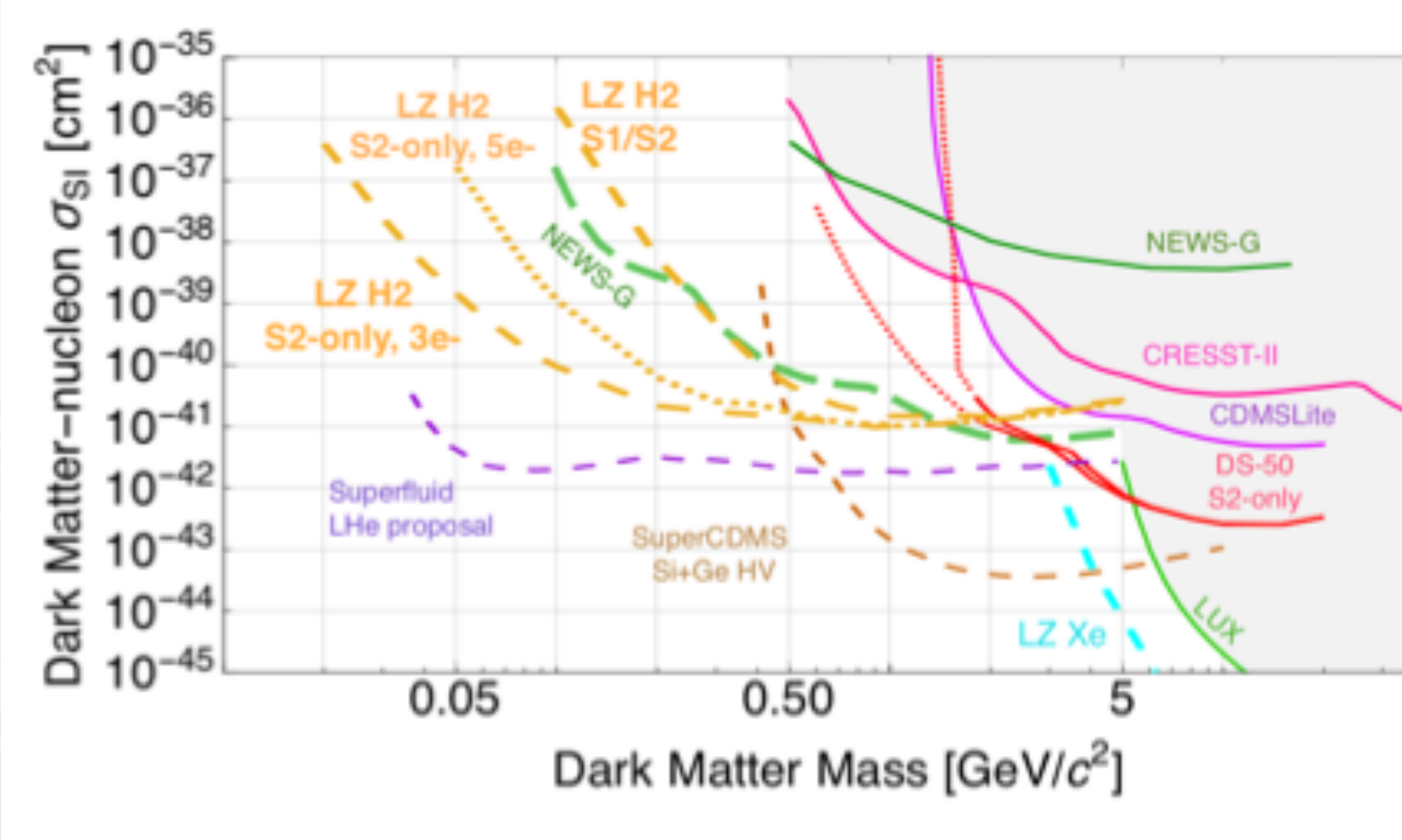
arXiv: 2203.08084

- Lower mass region can be reached by multiple technologies, ones with long histories in the search for dark matter, as well as new.
- Generally smaller target masses (both in total mass, as well as atomic masses), and interest in spin-dependent models too.

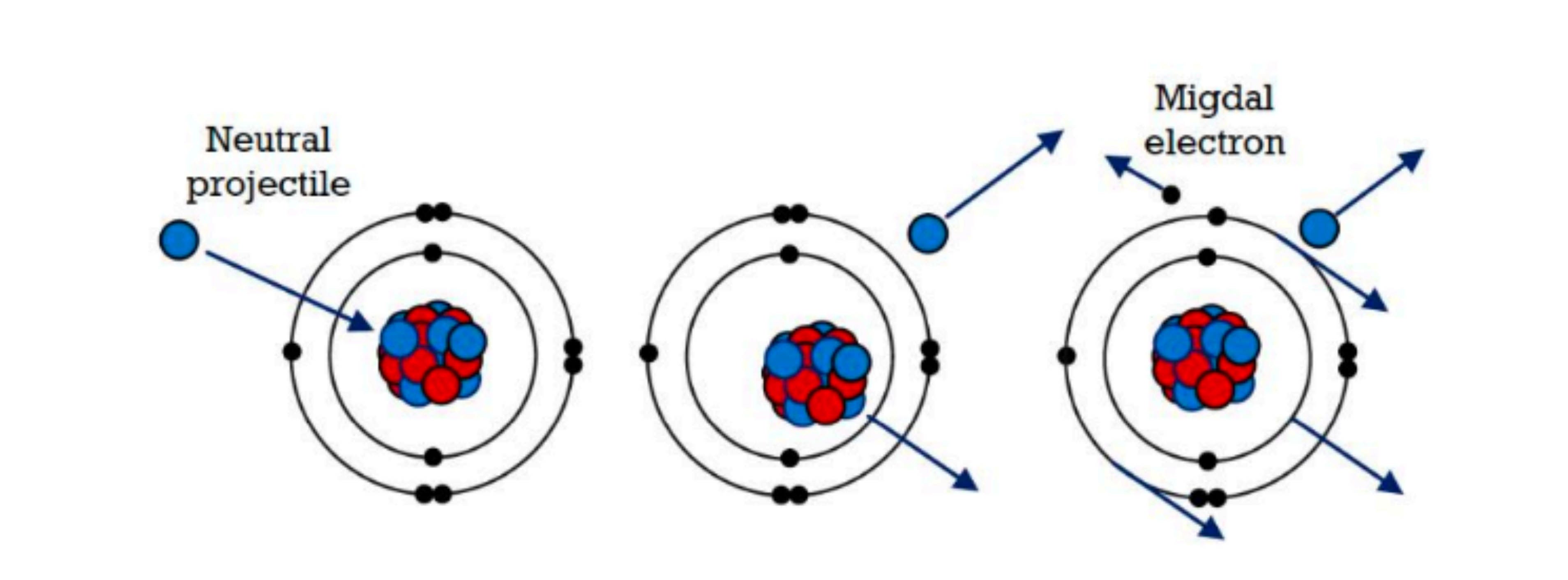
Once more, from the nobles…



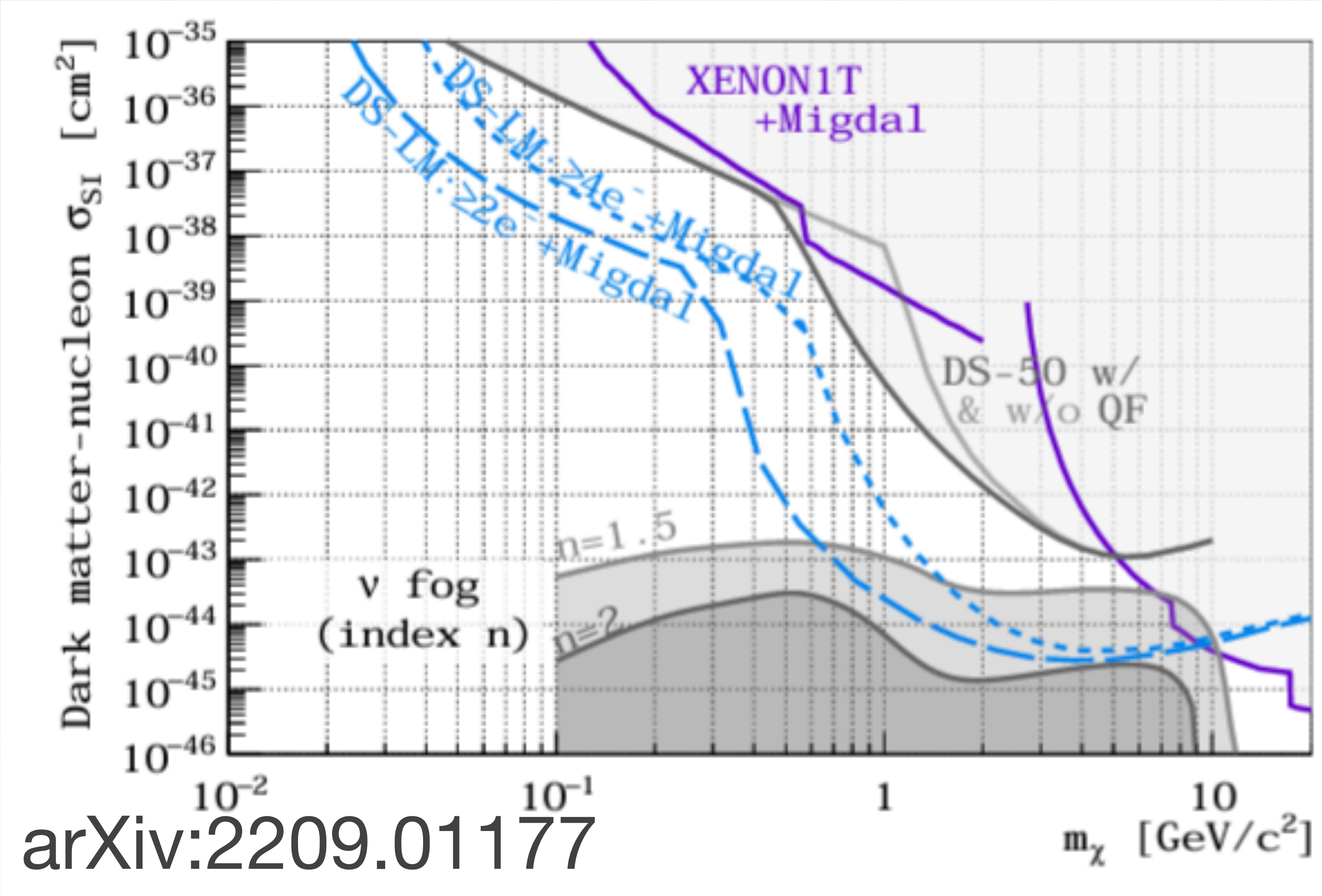
- Future: S2-only searches from current detectors (with Migdal?)
- HydroX
  - Proposed doping of LXe detector with H
- DarkSide-LowMass
  - Proposed 1T detector to get to neutrino fog in 1t-yr exposure



- Leading limits are from DarkSide-50 with a low threshold enabled by ionization only signals (no background discrimination)
- These signals may be enhanced by the Migdal effect, but **this needs to be confirmed**!
- Microphysics uncertainties too



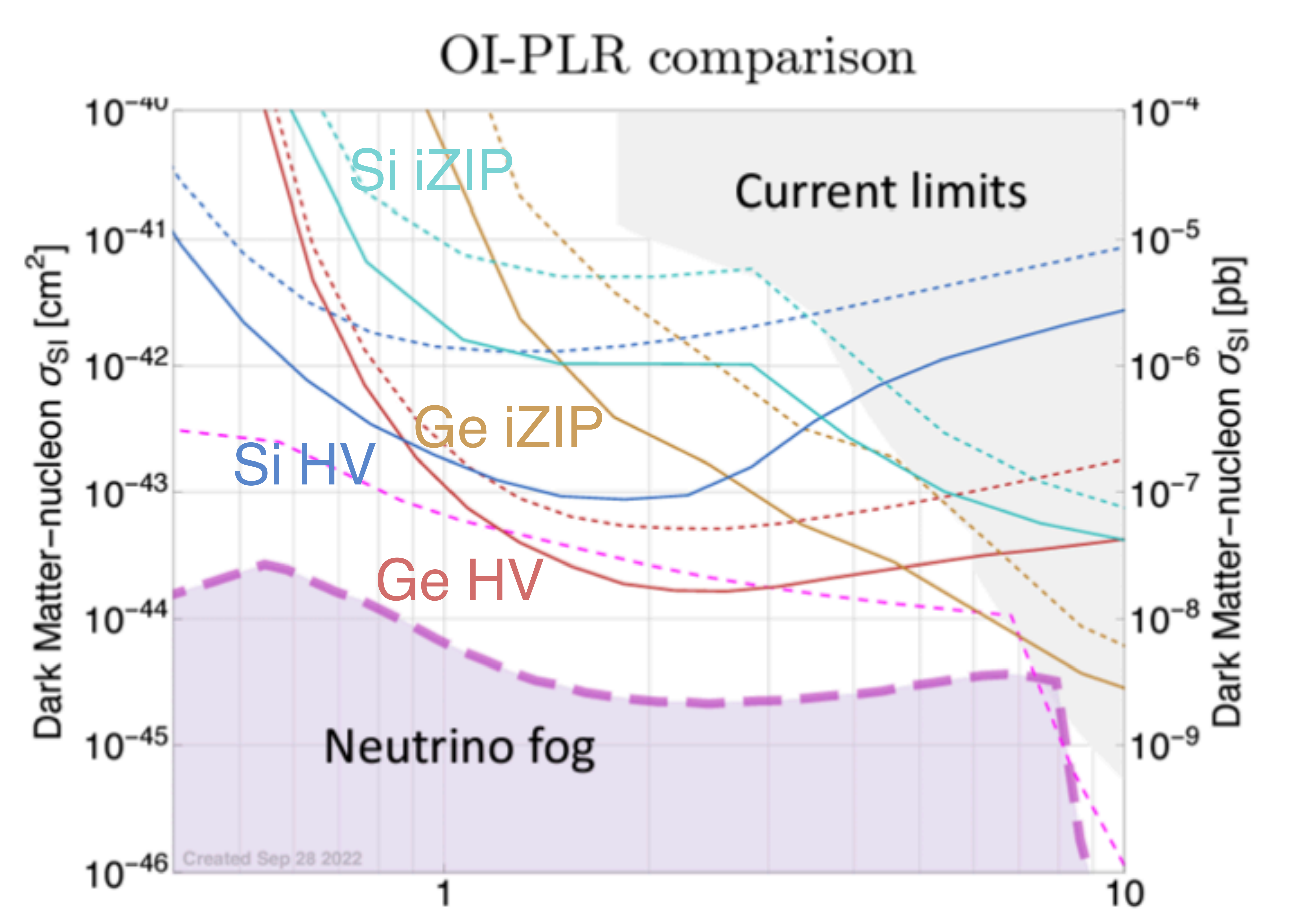
Migdal event topology involves a nuclear recoil and electron recoil originating from the same vertex.



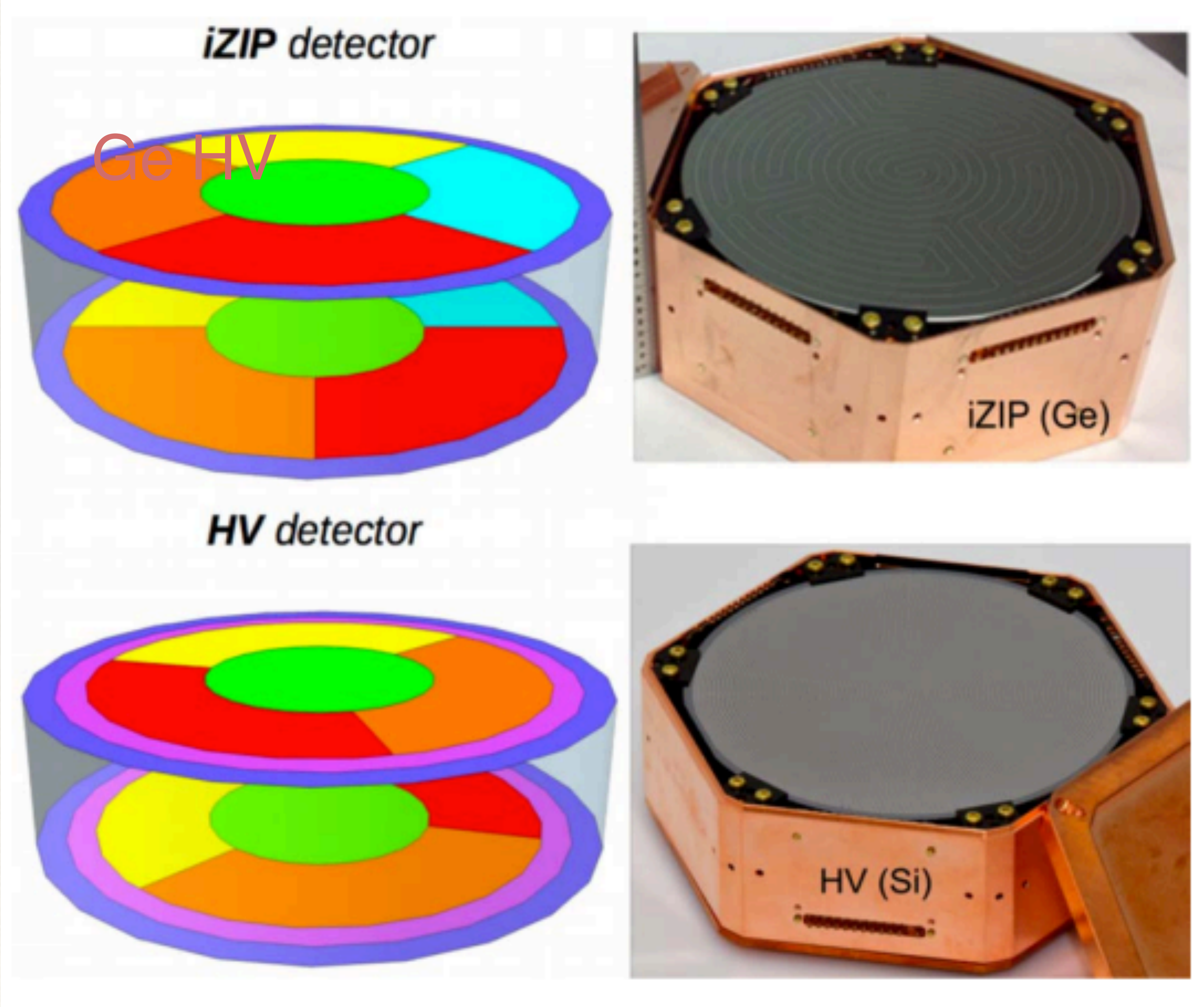
SuperCDMS

- Under construction at SNOLAB
- 4 towers: 1 Ge iZIP, 1 Ge & Si iZIP, 2 Ge &Si HV
- Programme, including new detectors and upgrades discussed at arXiv:2203.08463

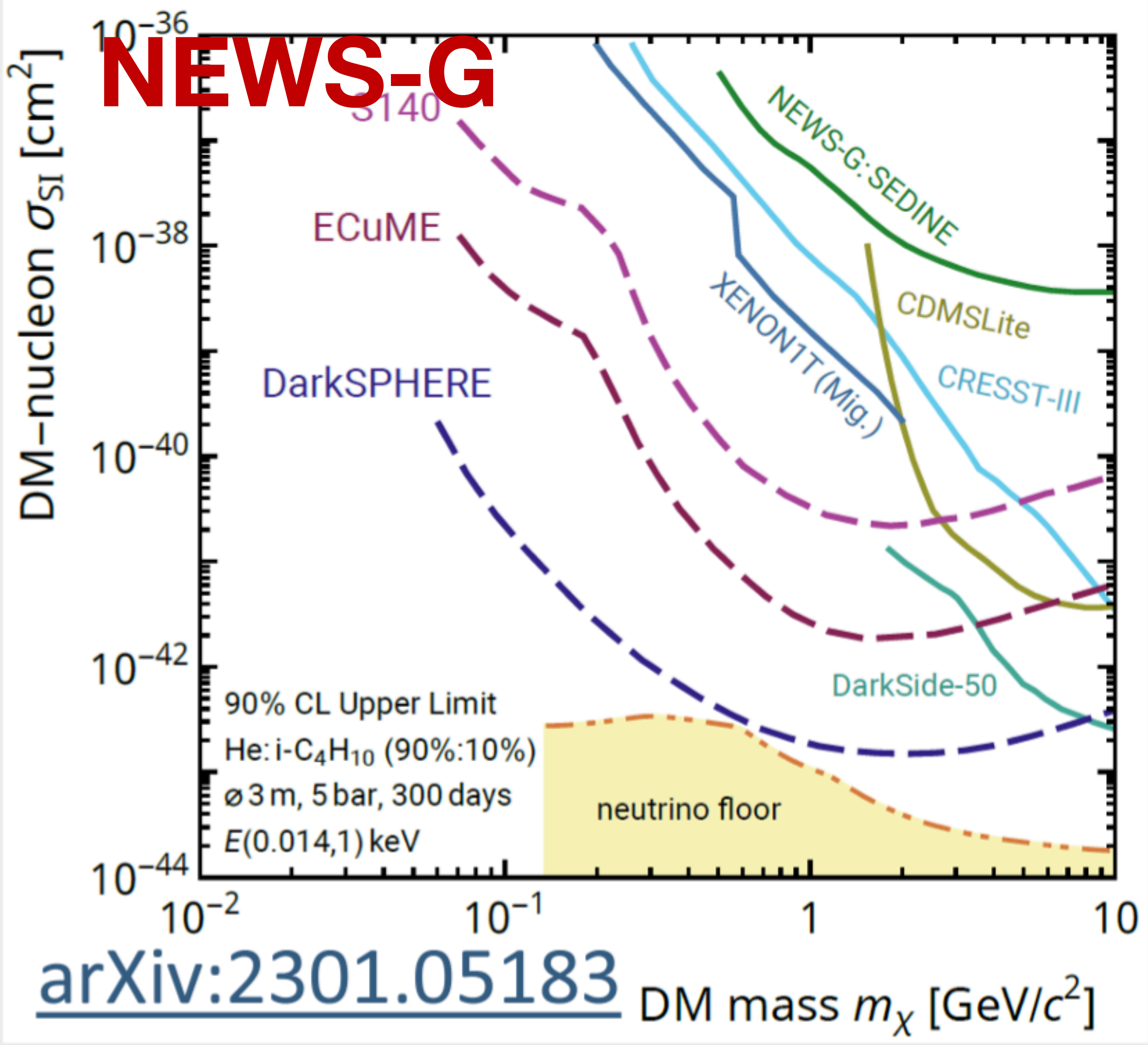
	Germanium	Silicon
HV	Lowest threshold for low mass DM Larger exposure, no ^{32}Si bkgd	Lowest threshold for low mass DM Sensitive to lowest DM masses
iZIP	Nuclear Recoil Discrimination Understand Ge Backgrounds	Nuclear Recoil Discrimination Understand Si Backgrounds



arXiv:2203.08463

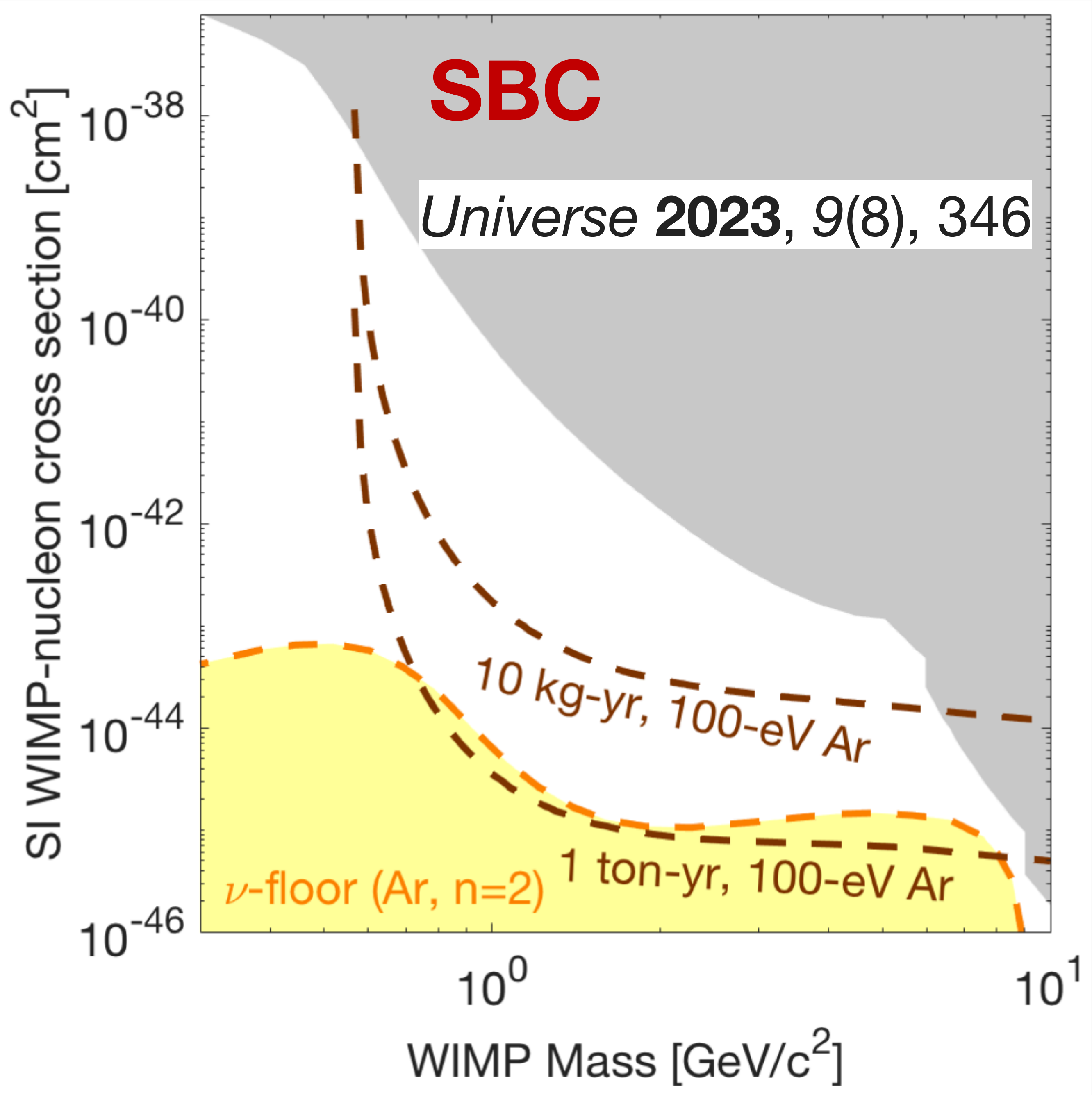


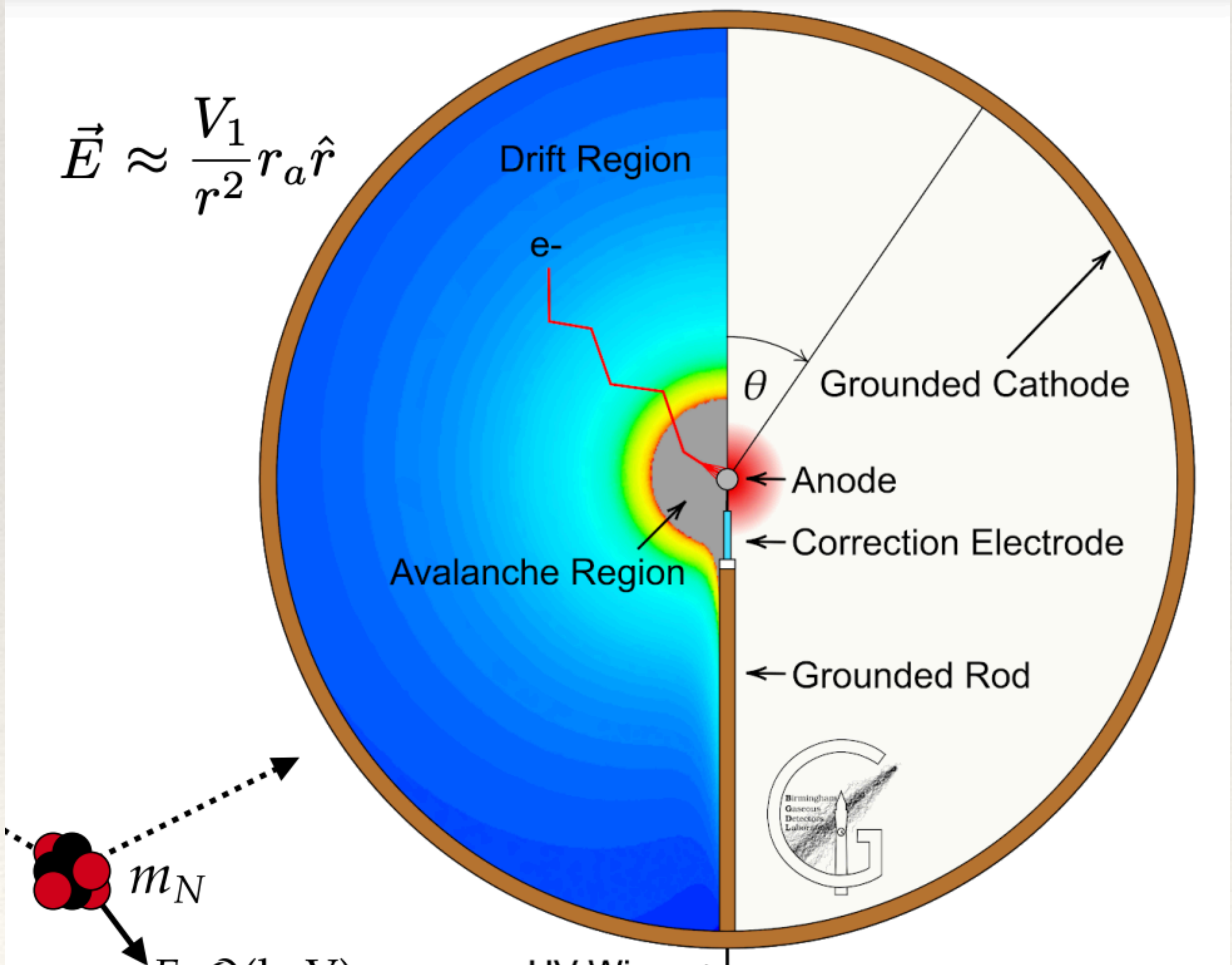
Technologies new and old



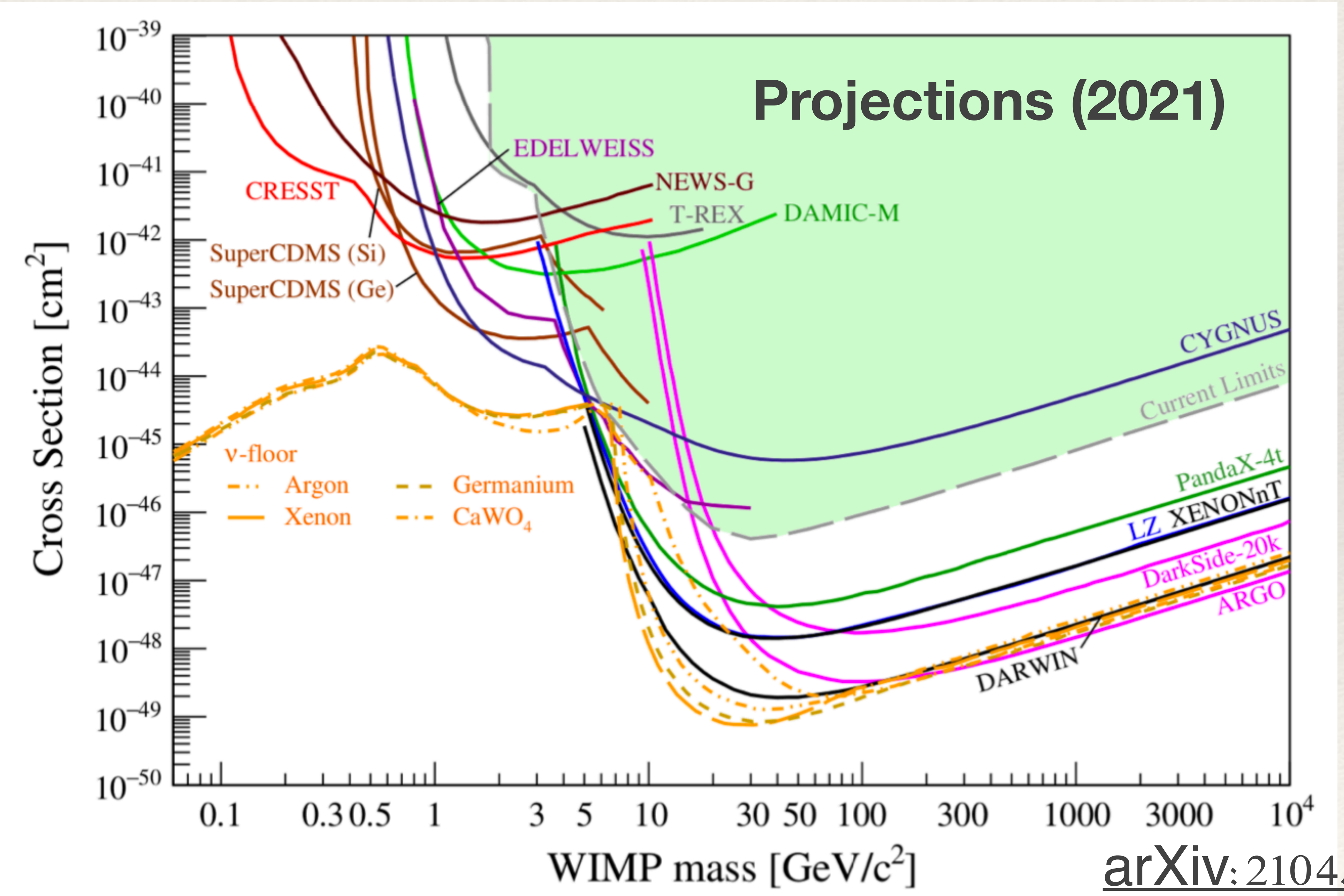
arXiv:2301.05183

- Signals from nuclear recoils
- Semiconductor targets: Si, Ge
- Scintillating bolometers $CaWO_4$
- Spherical Proportional Counter
- Scintillating Bubble Chamber (LAr)

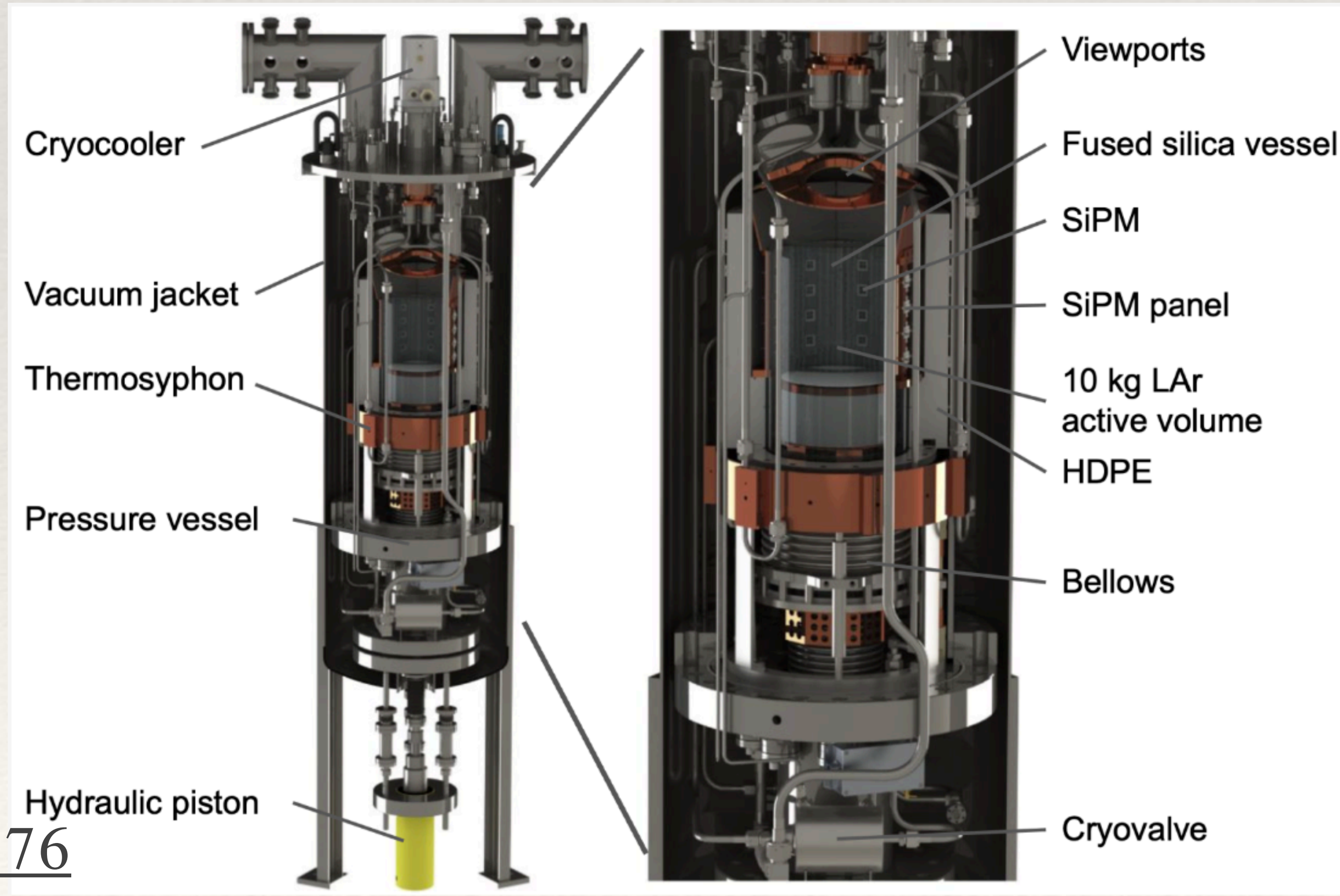




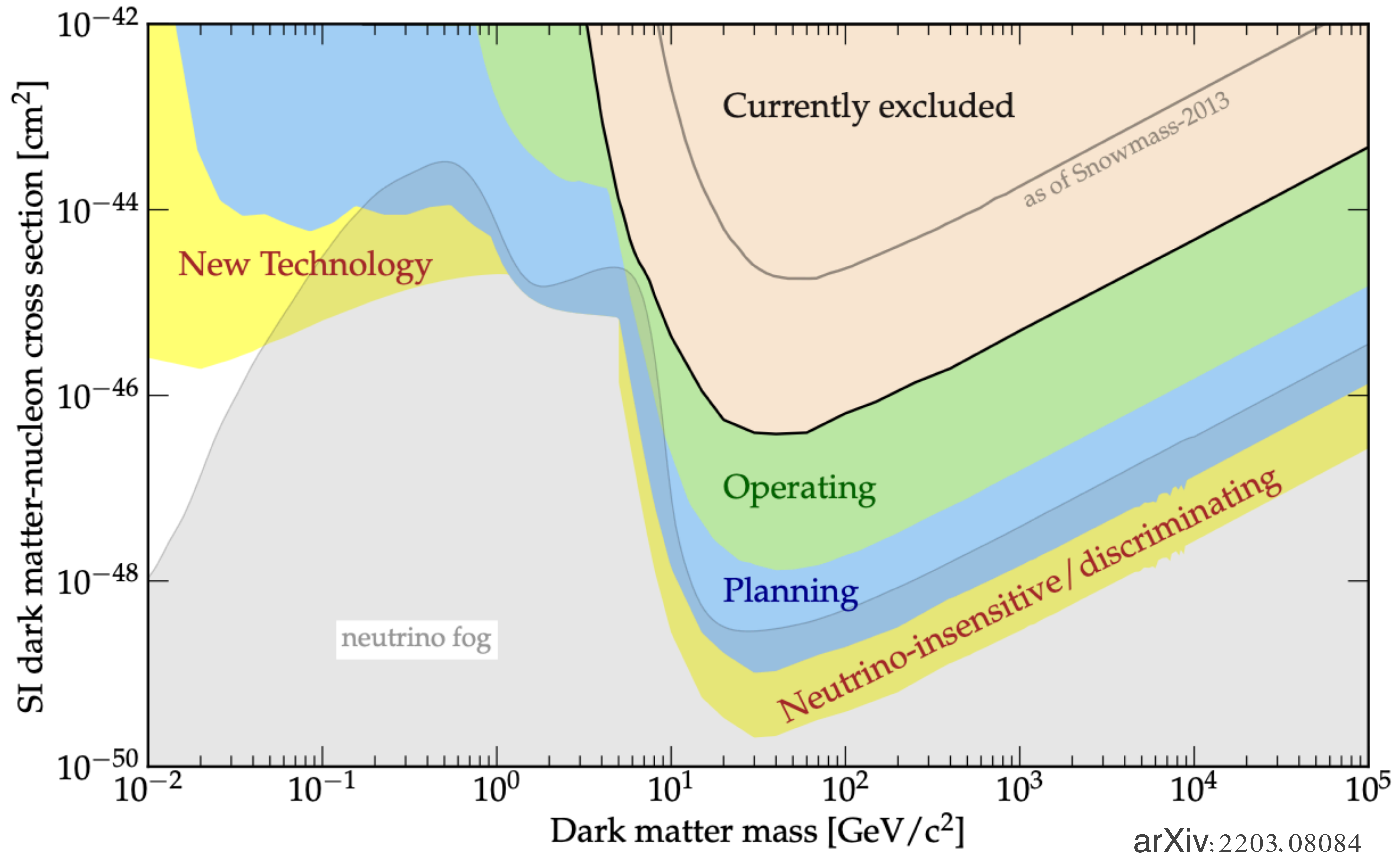
JINST 15 (2020) 06, C06013



arXiv: 2104.076



Going into the neutrino fog



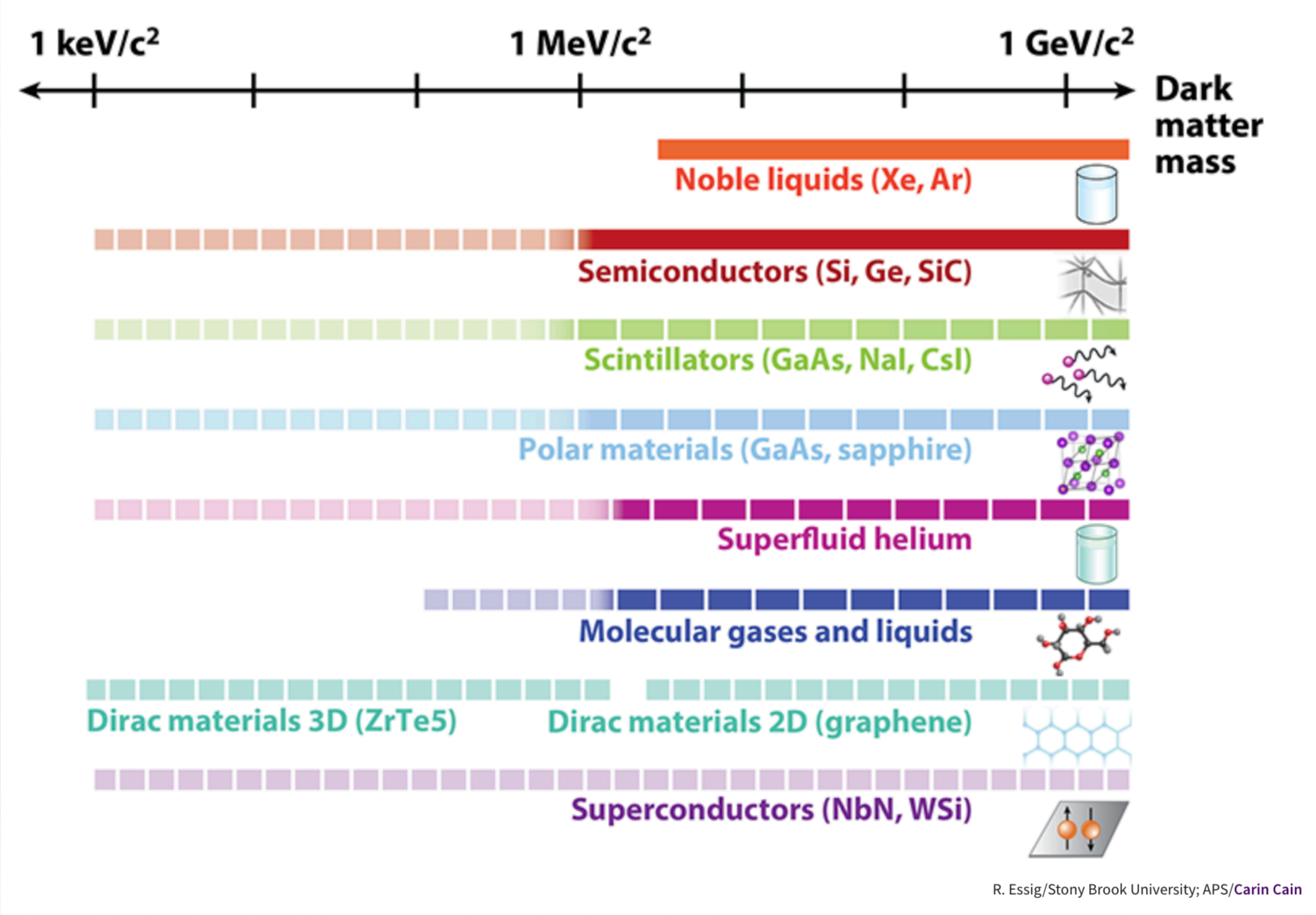
arXiv: 2203.08084

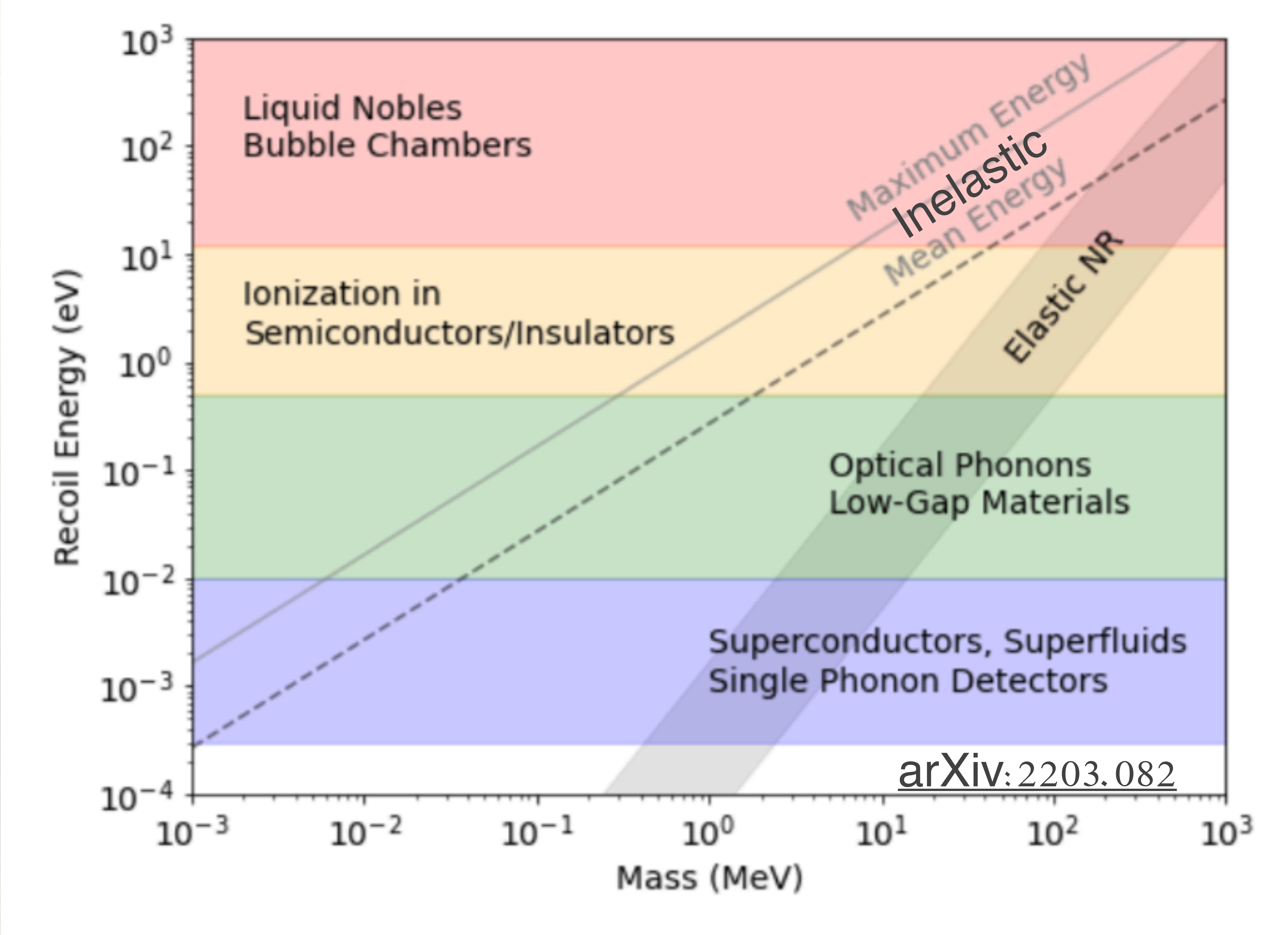
Directional detection offers the best current approach to explore into the neutrino fog

Sandbox Studio, Chicago with Corinne Mucha

For DM masses <1 GeV/c^2,
gram scale detectors can produce leading results.
Lots of new ideas, many exploiting quantum technologies.
There are many unknowns.

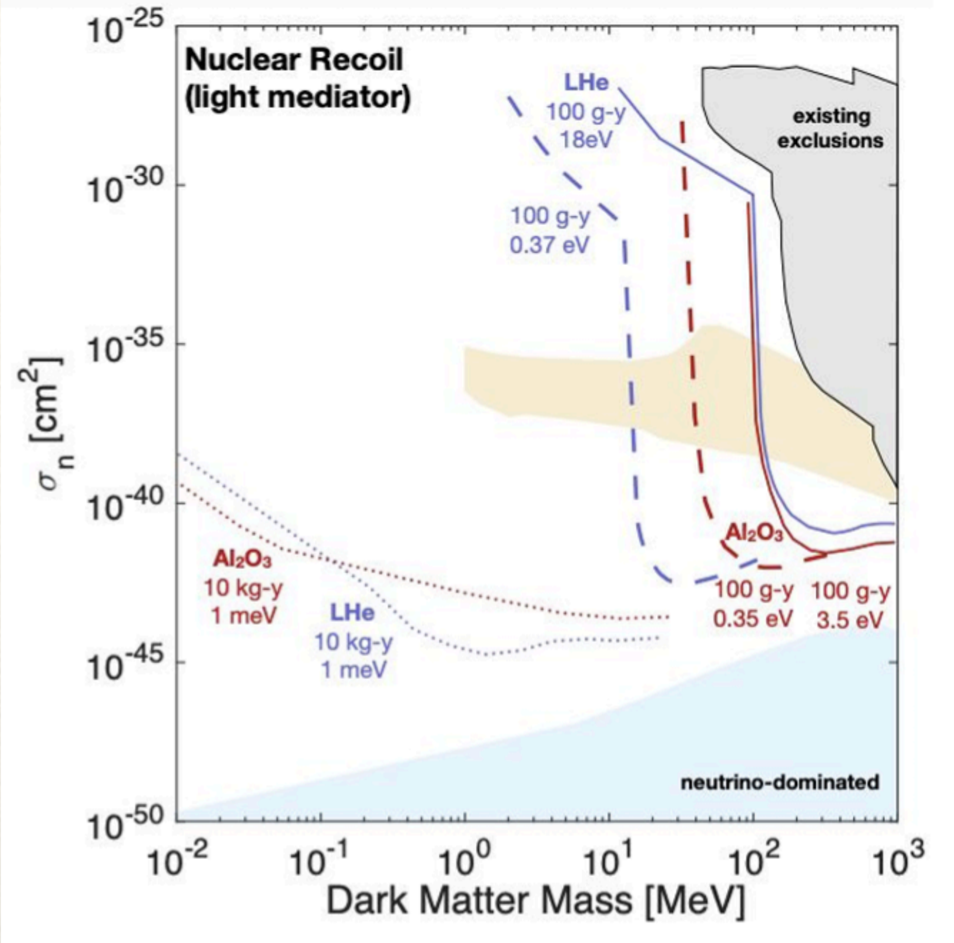
Below a GeV: technologies

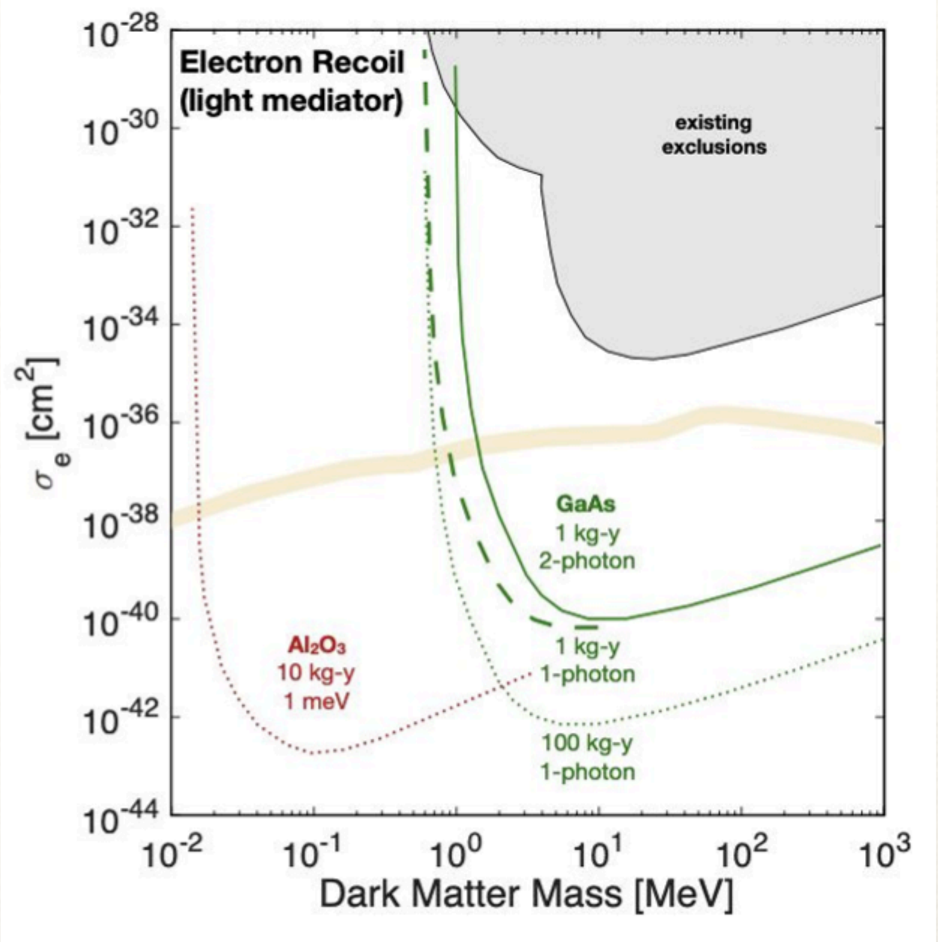


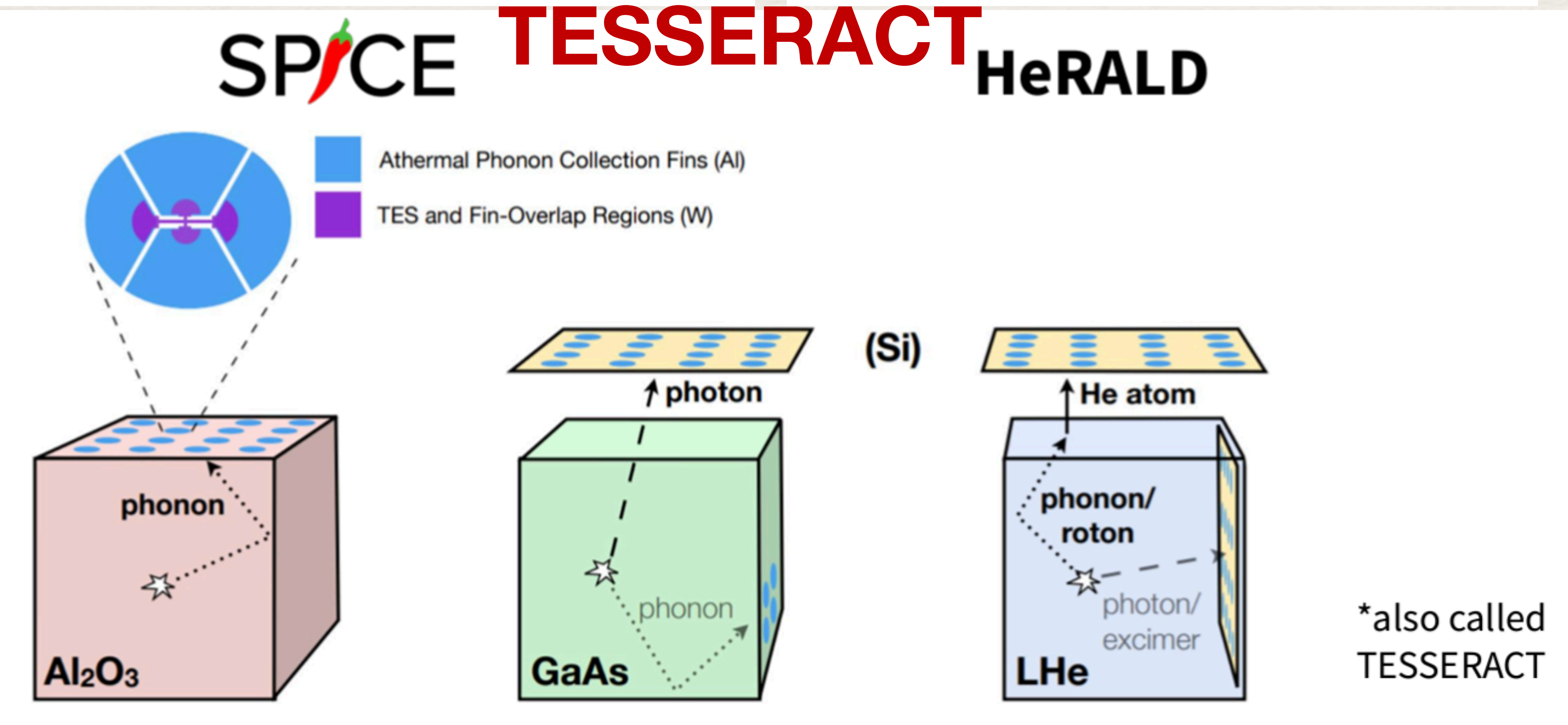


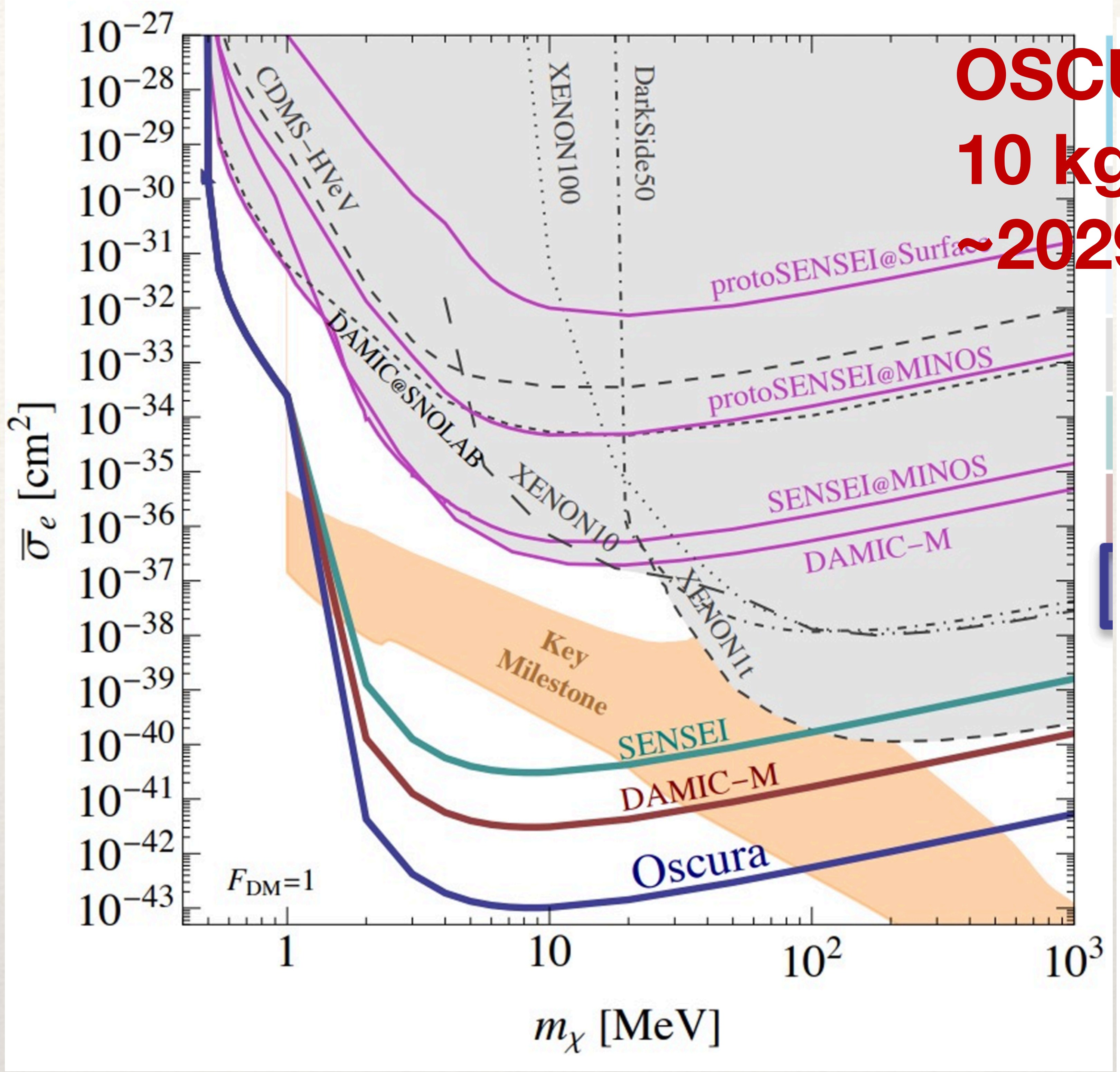
DM–electron scattering and absorption now of interest

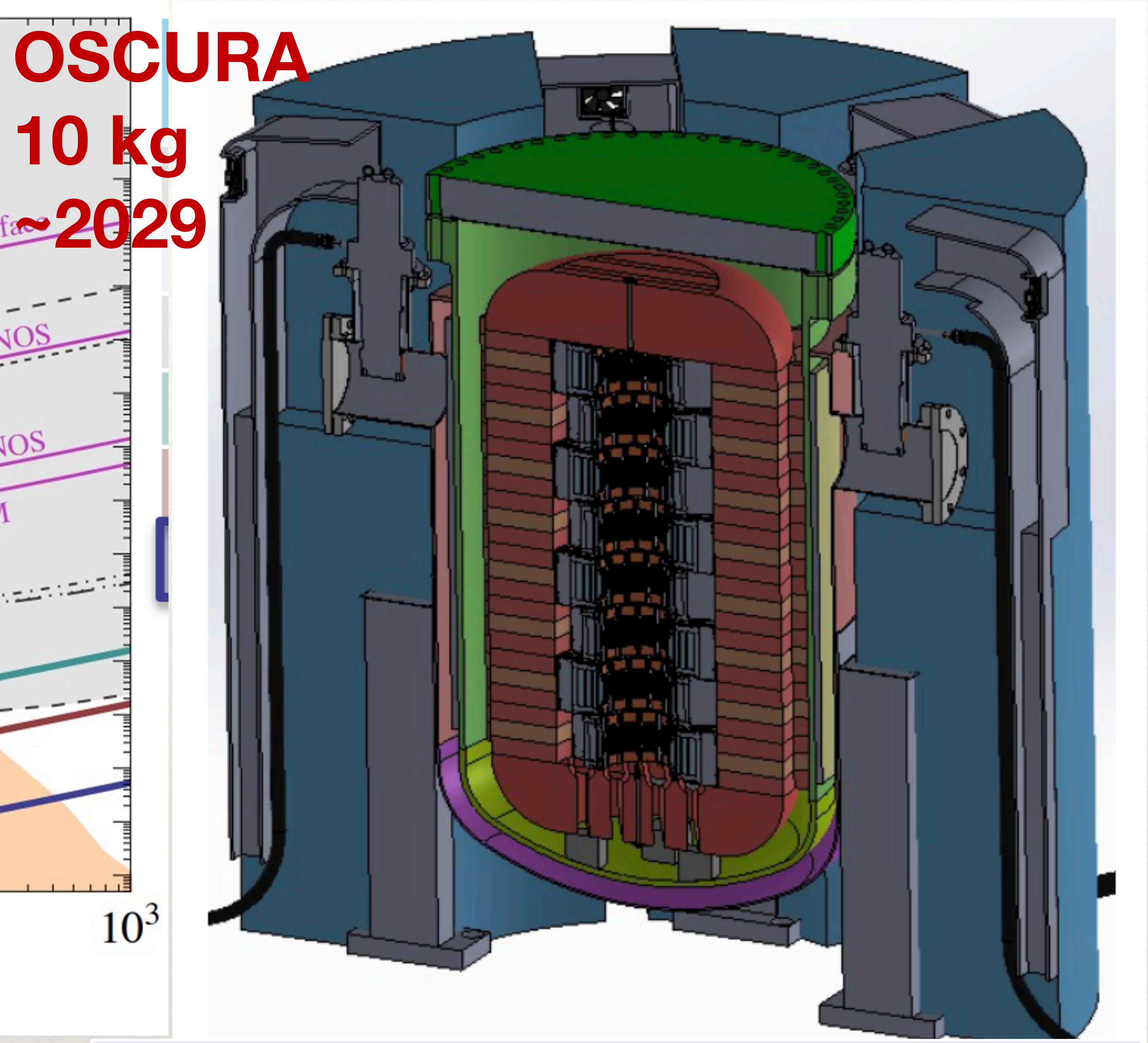
Funded in the US BRN

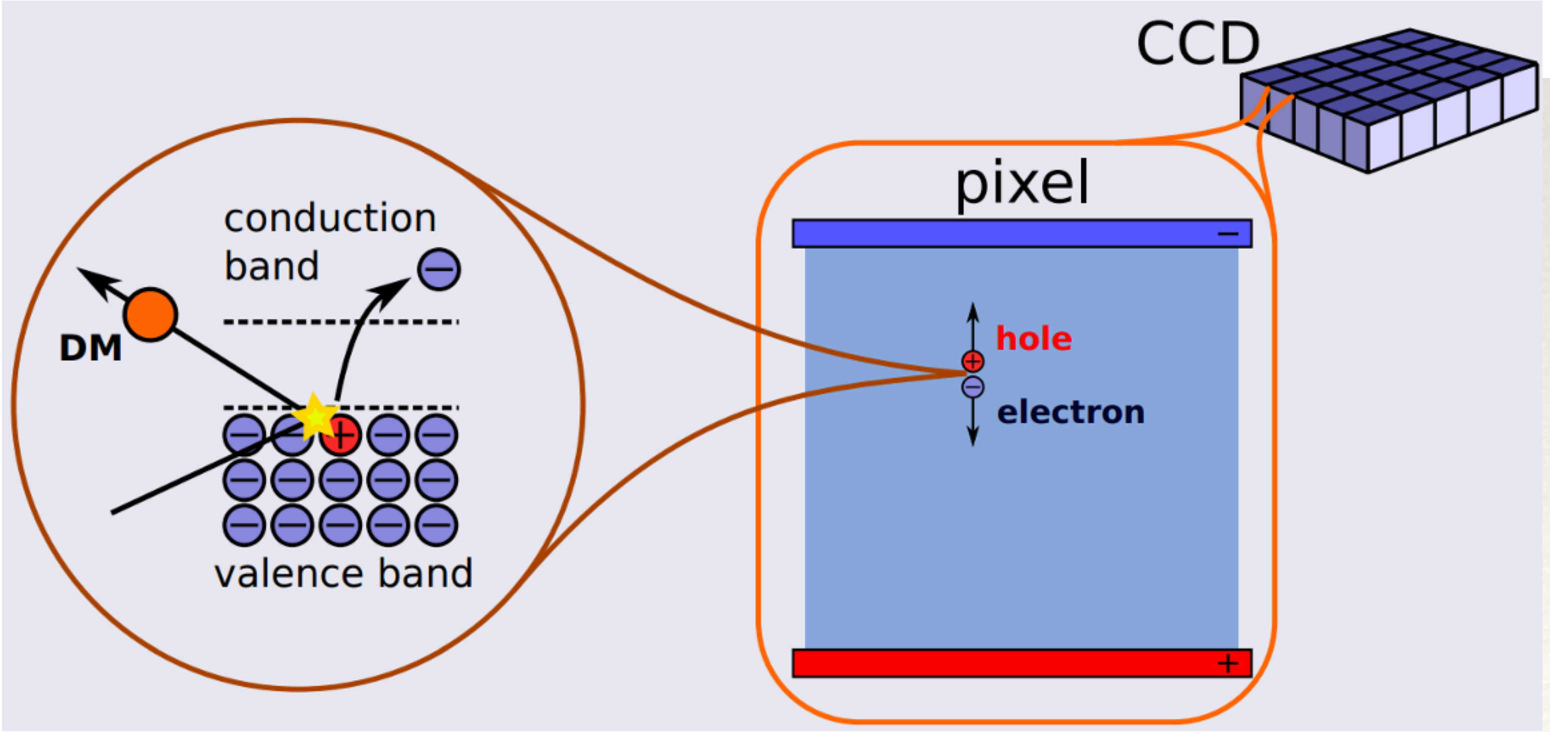








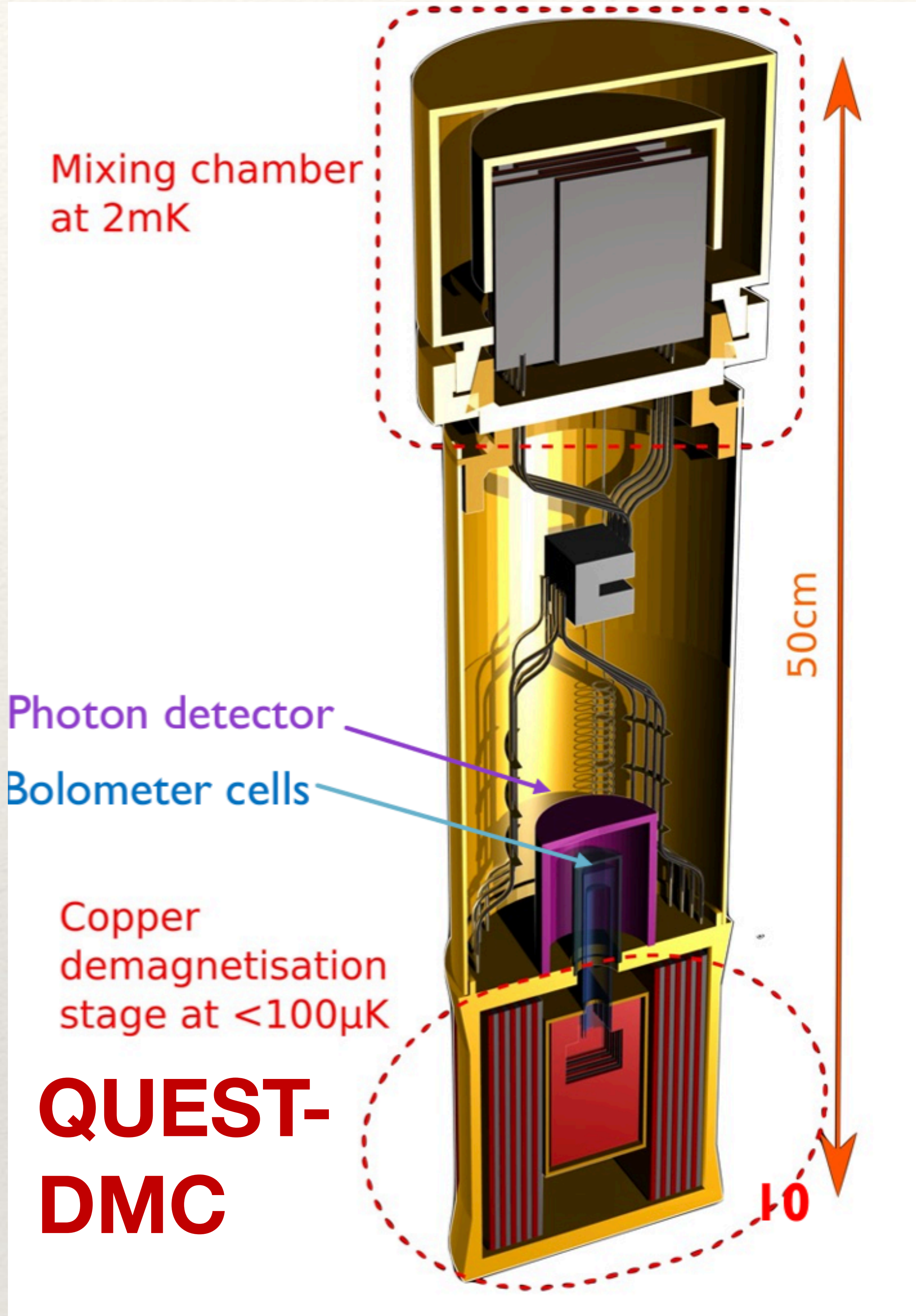


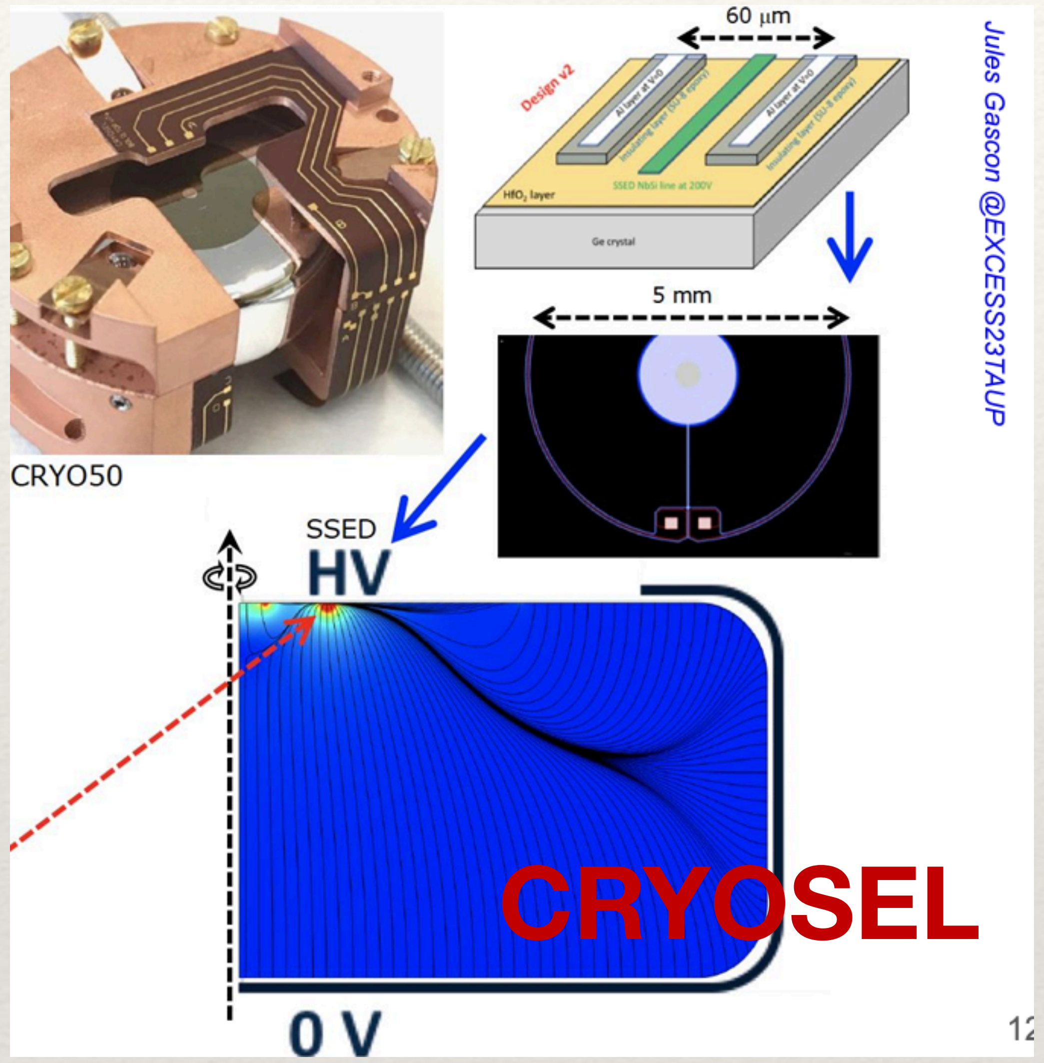


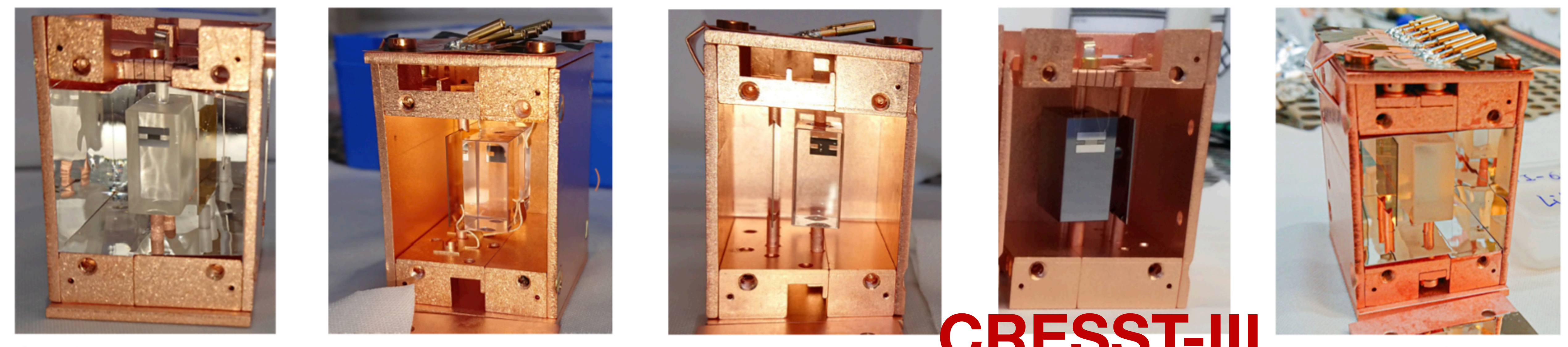
- Athermal phonons, scintillating crystals, superfluid helium, skipper CCDs
- Updates from TAUP 2023

So many new detectors…

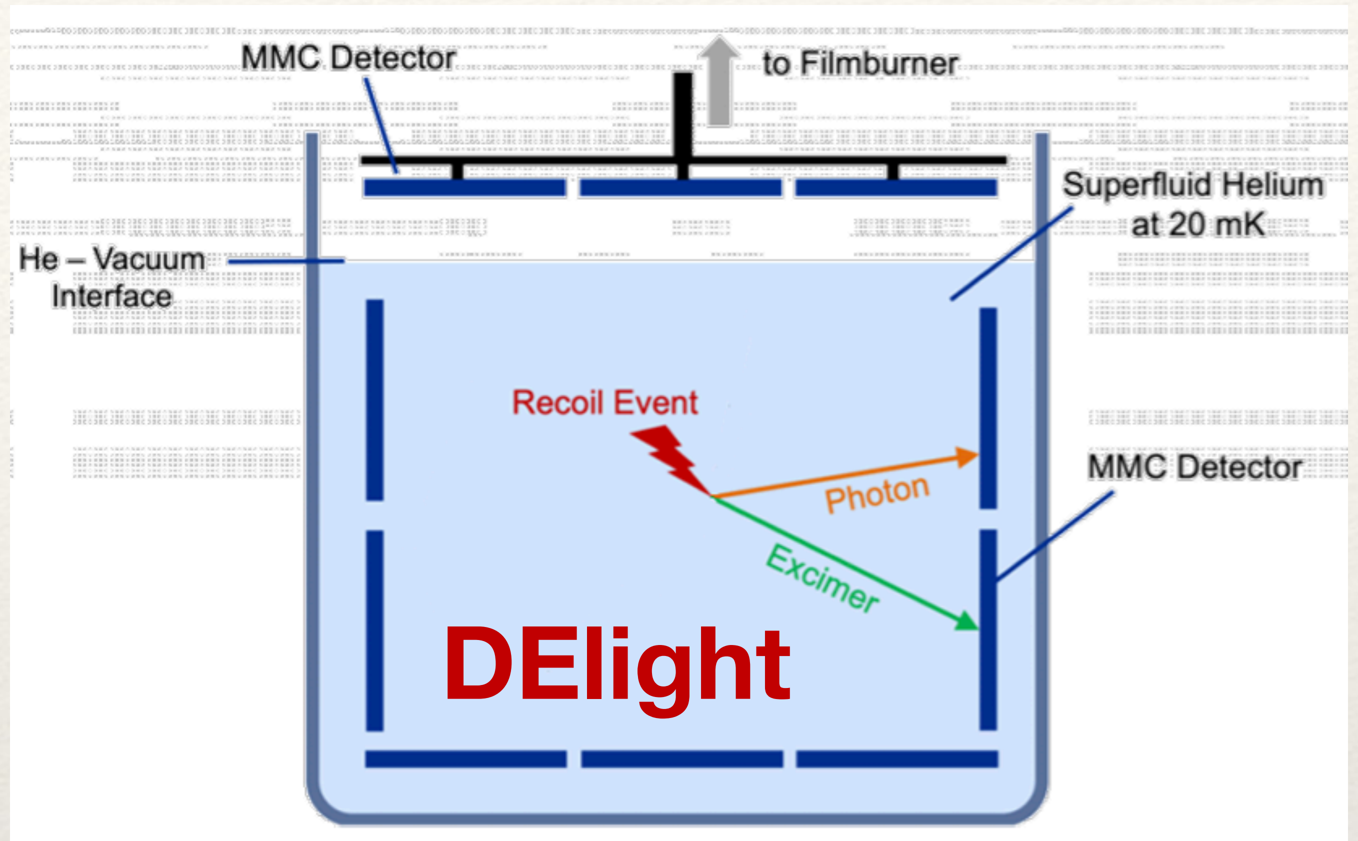
so many ~~hot~~ cold technologies: SNSPDs, TESs, KIDs, MMCs, superfluid He, superconducting QUBITs …

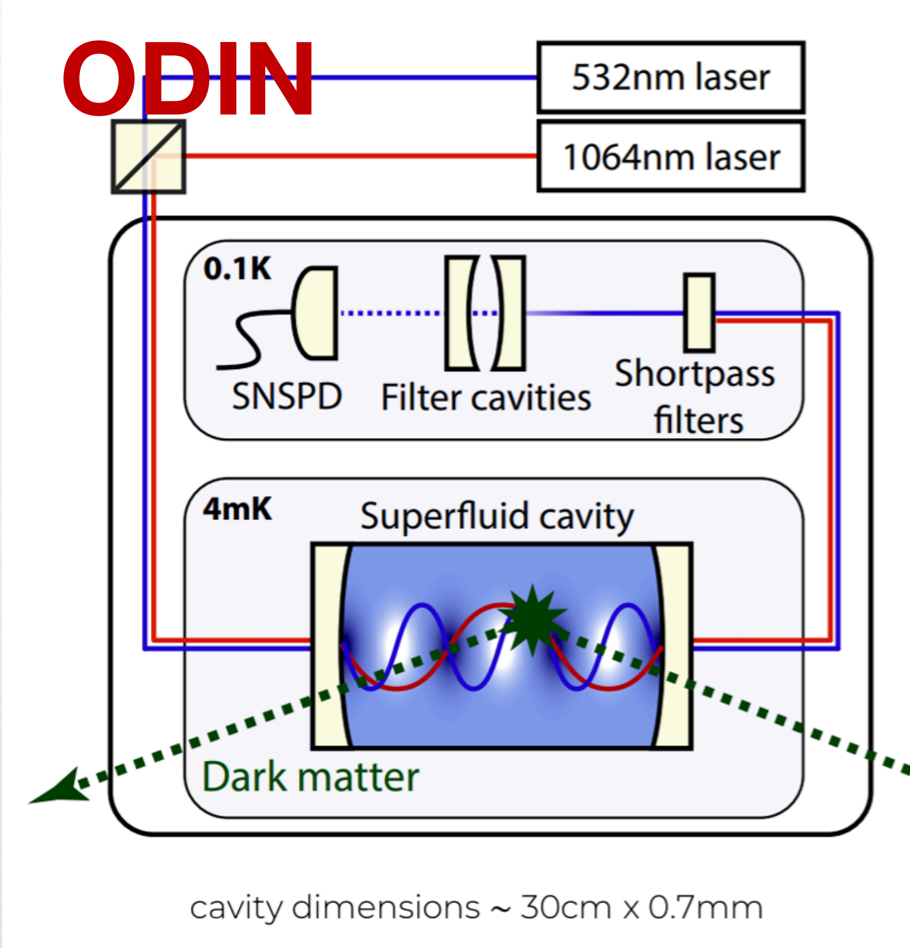


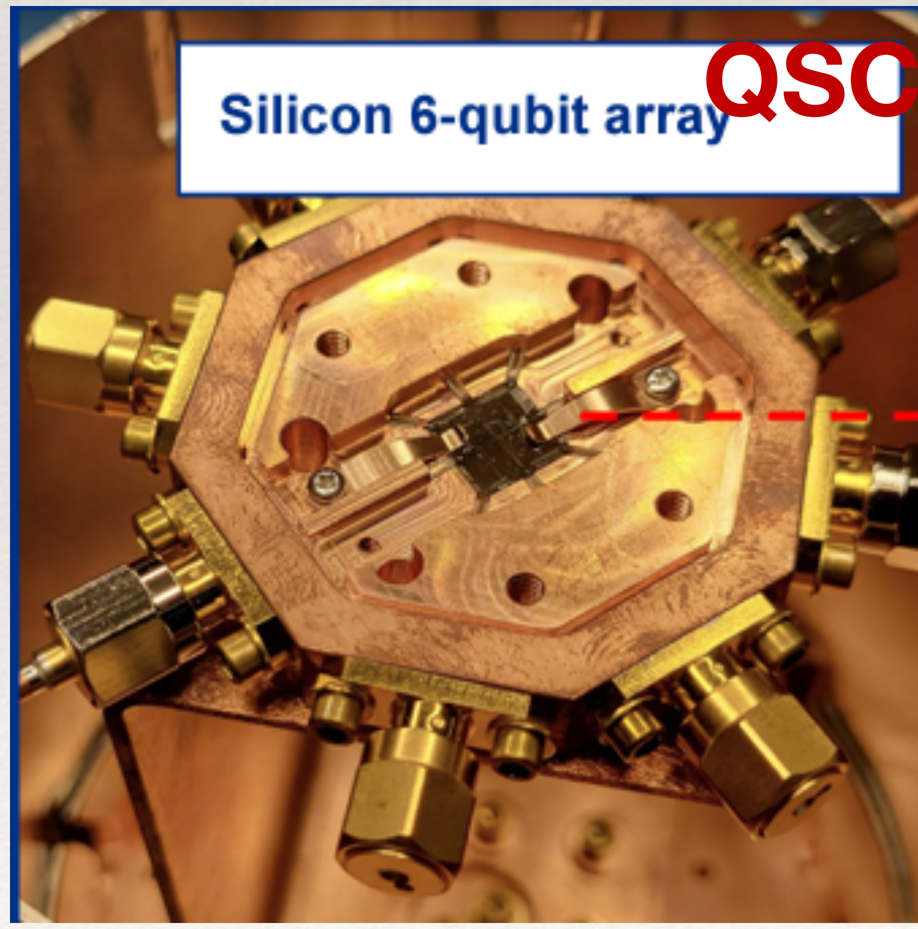




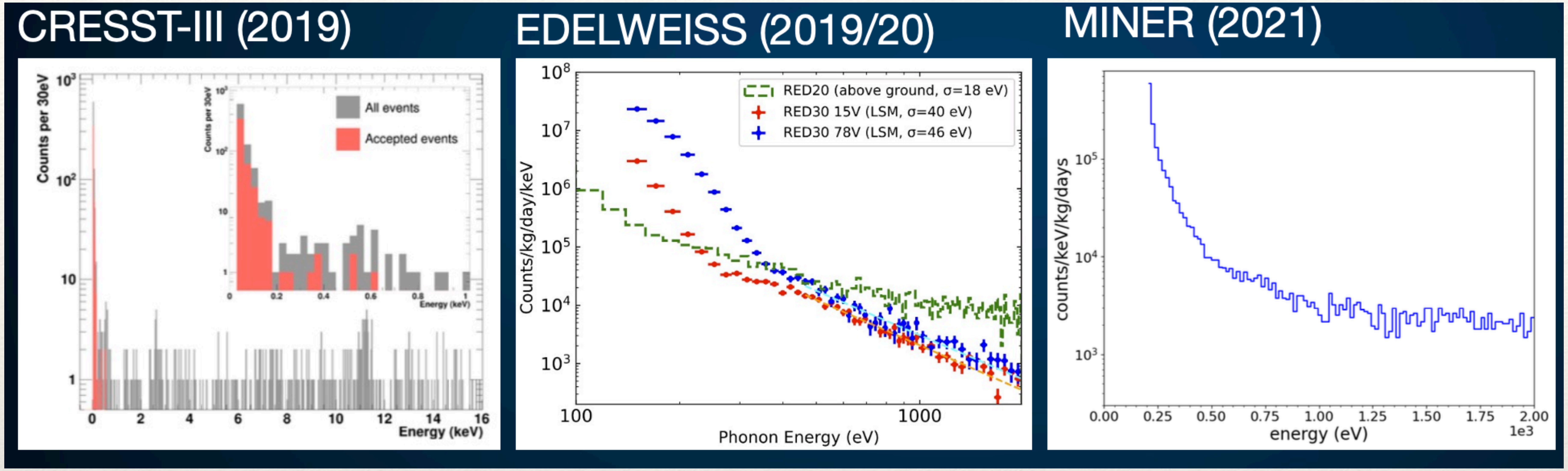
$CaWO_4$ grown at TUM | Commercially grown $CaWO_4$ | Al_2O_3 | Si | $LiAlO_2$

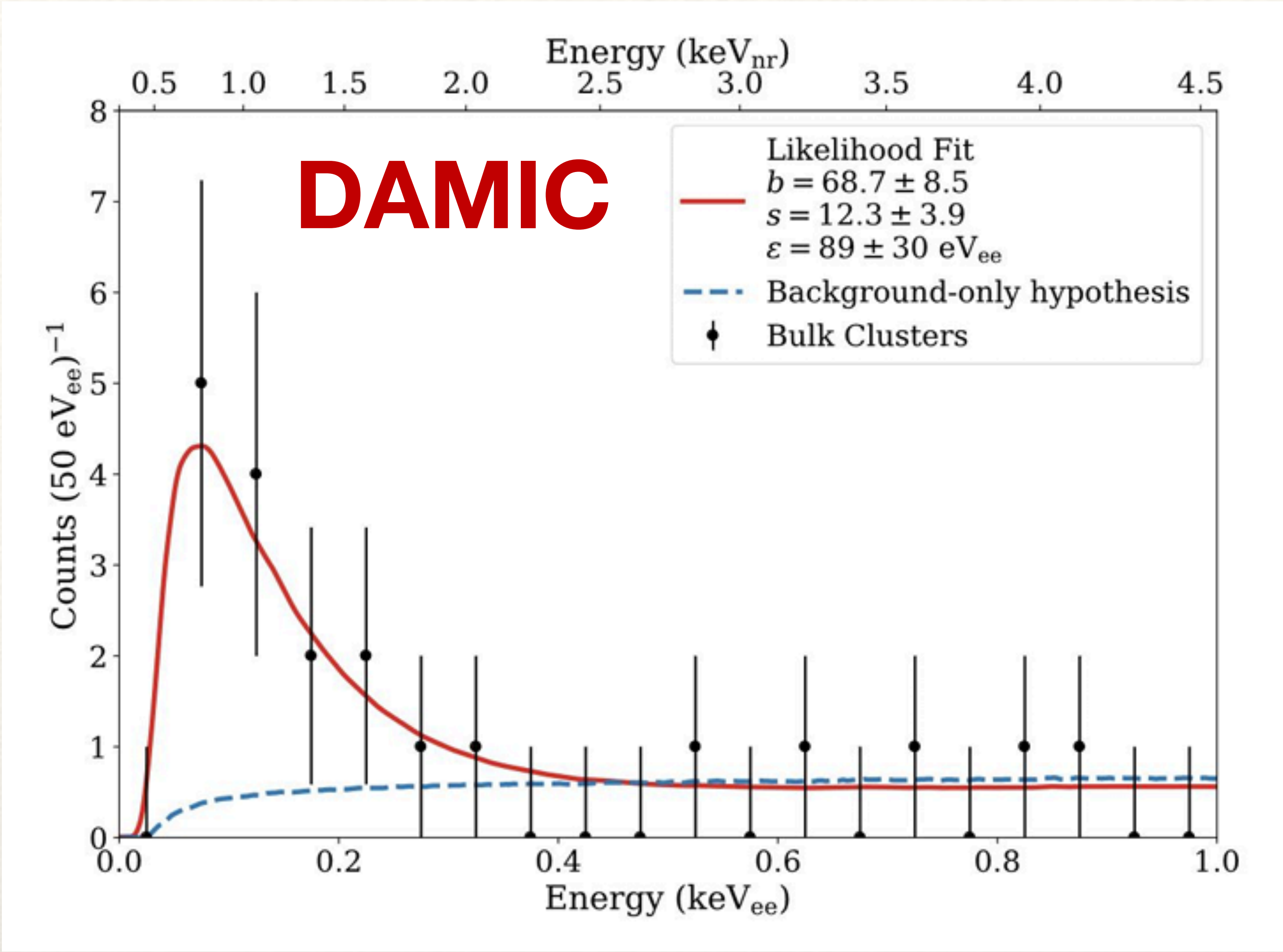






Low energy EXCESS





Reindl, UCLA Dark Matter 2023, Baxter, TAUP 2023

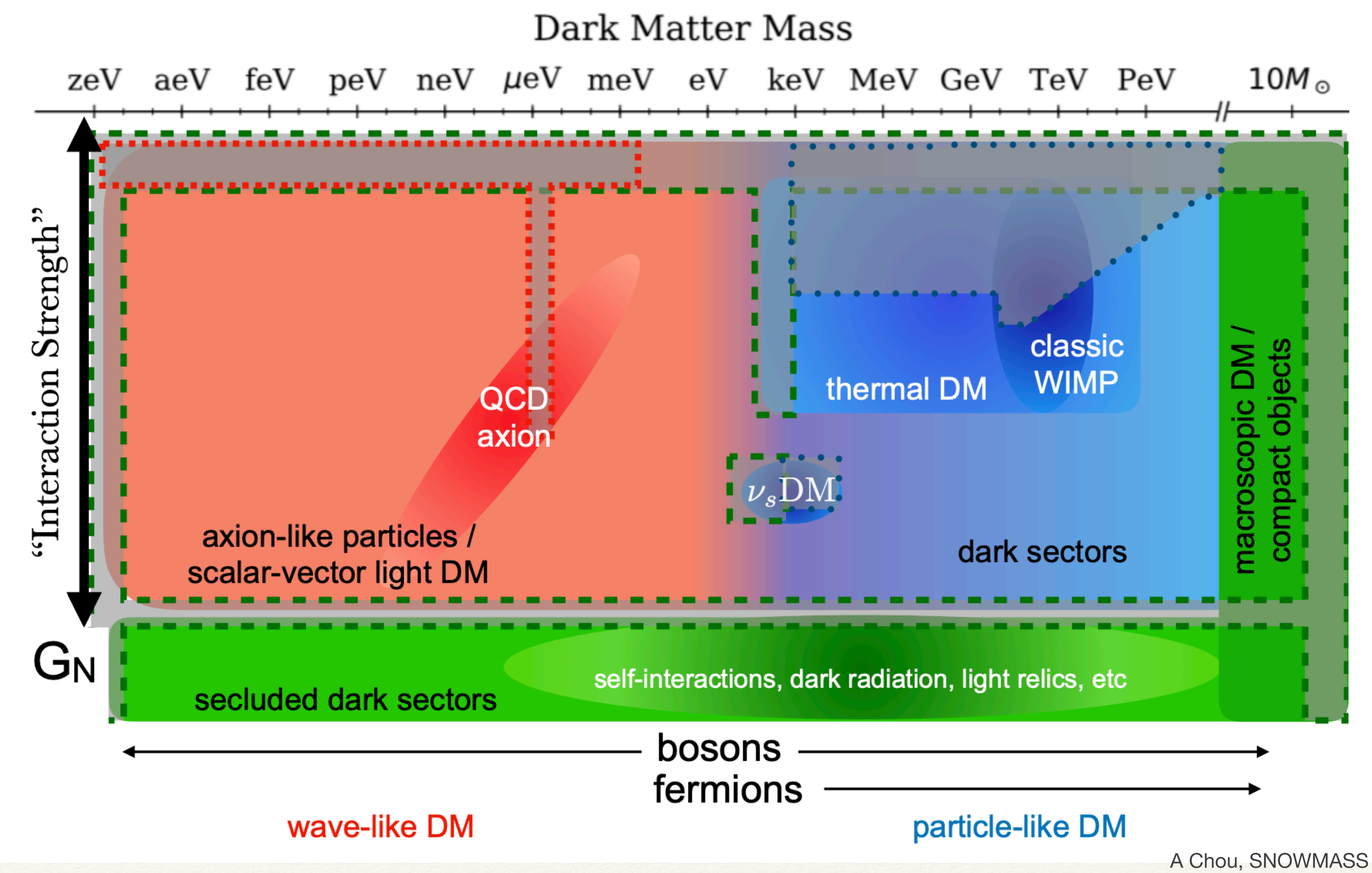
- Excesses in **cryo-detectors** (non-ionizing, decaying, …) have possibly one common origin! Hot suspect: interface and bulk stress. Currently focused research topic, transferable impact expected (qubits, …).
- Excesses in **CCDs** (single electron production) can be explained by dark current and detector effects, but further reduction is required or future experiments (e.g. OSCURA).
- The **DAMIC excess** remains a riddle.

Multiple experiments see rising signals near t

EXCESS initiative: SciPost Phys. Proc. 9, 001 (2022)

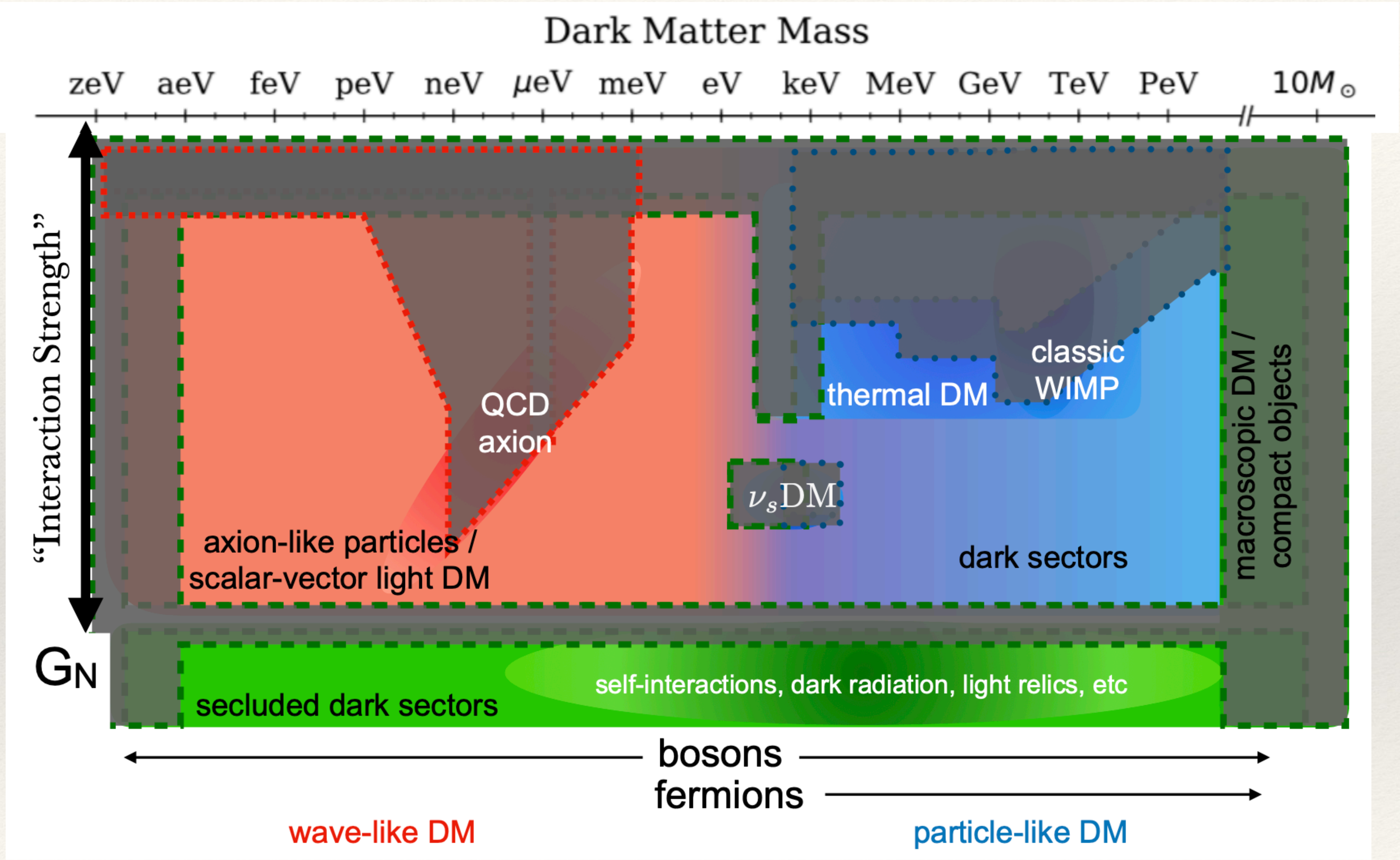
- Not Dark Matter
- Not the same backgrounds
- Can it be mitigated?

Our Current Status



A Chou, SNOWMASS Dark Matter Plenary

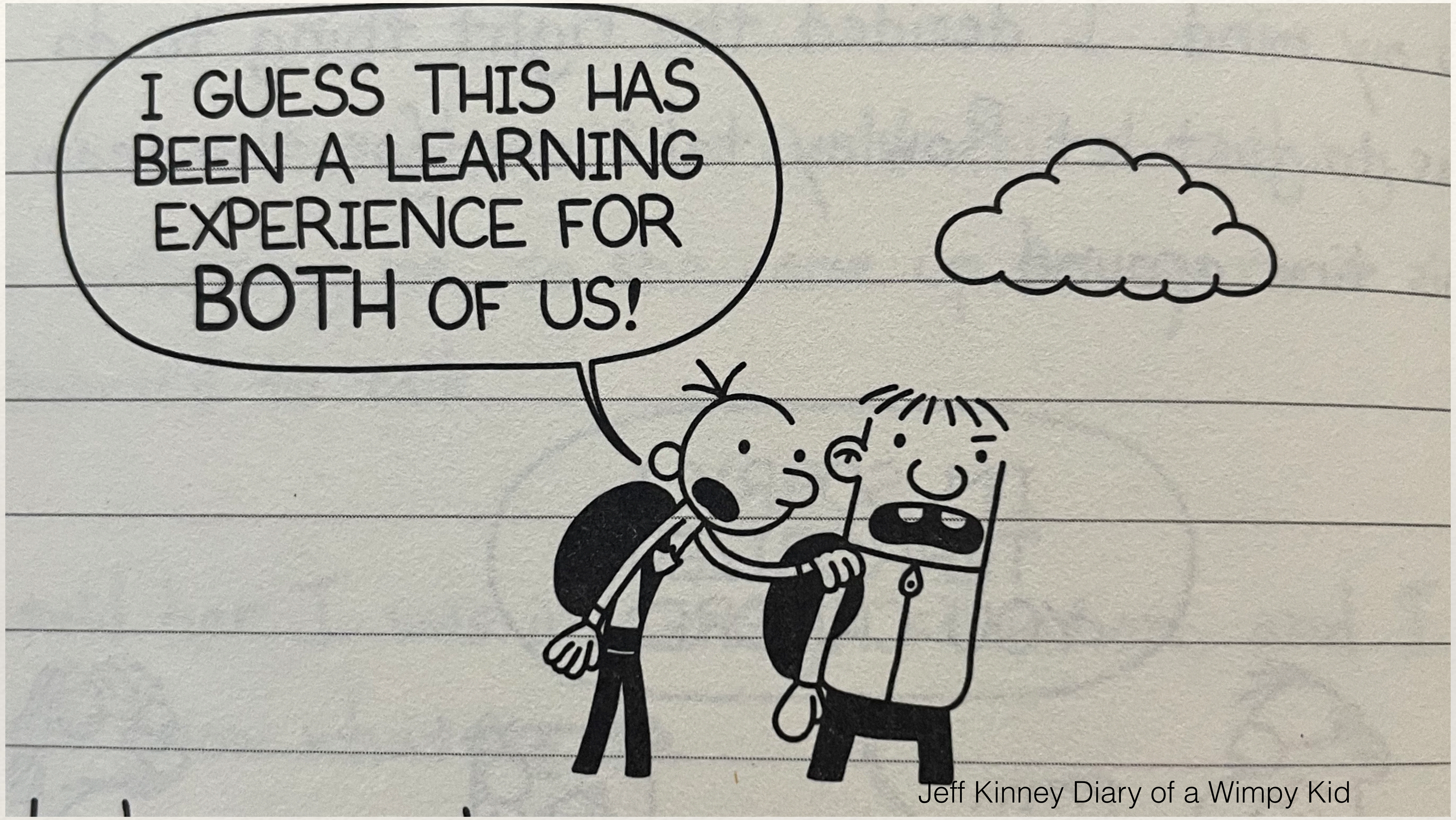
If we Search Deep and Wide, in 20 years



A Chou, SNOWMASS Dark Matter Plenary

This must all be taken in conjunction with axion/wavelike DM searches, collider searches, and astrophysical evidence.

I hope there is a dark sector with many interesting new particles, which solve current mysteries and open new ones.

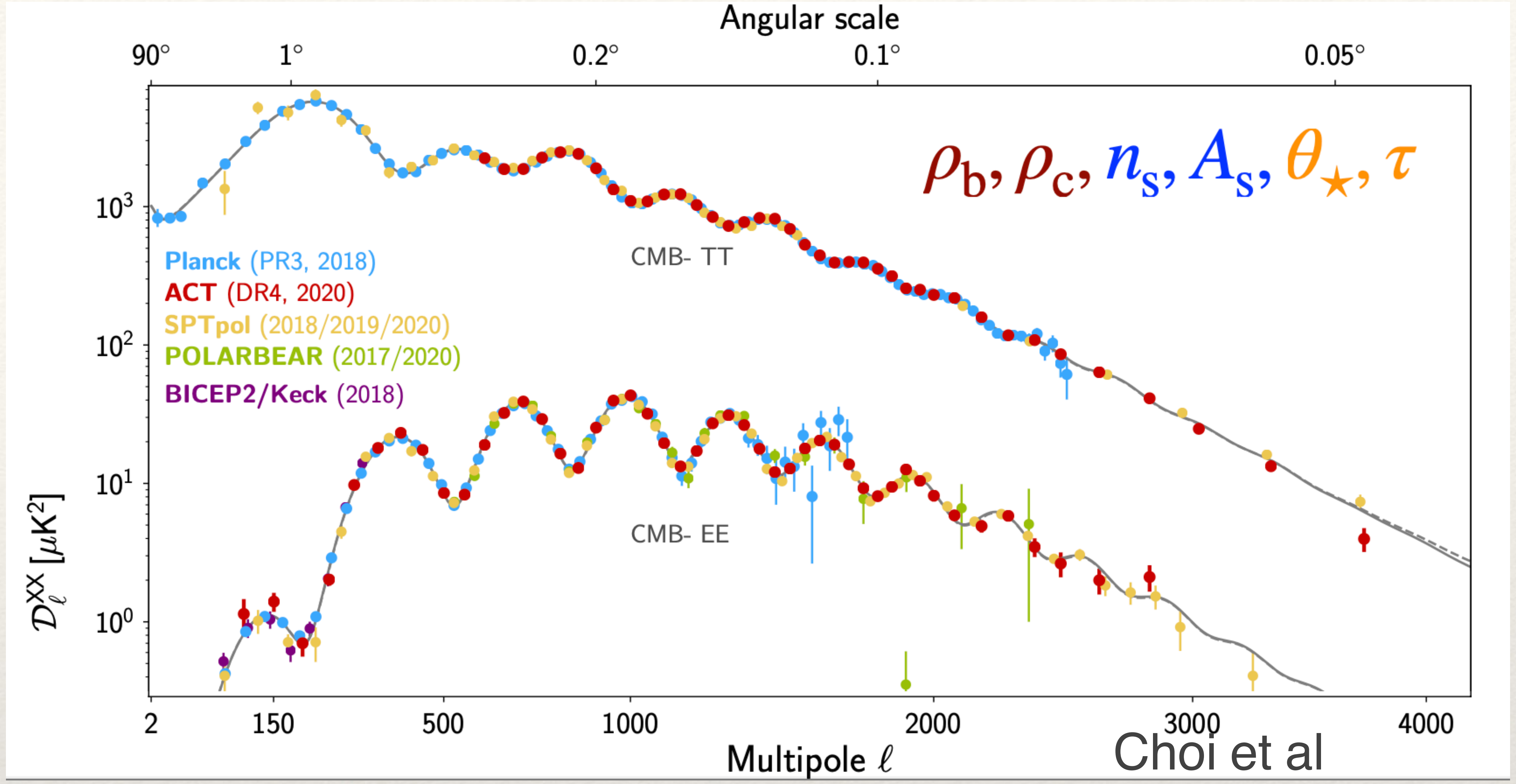


Jeff Kinney Diary of a Wimpy Kid

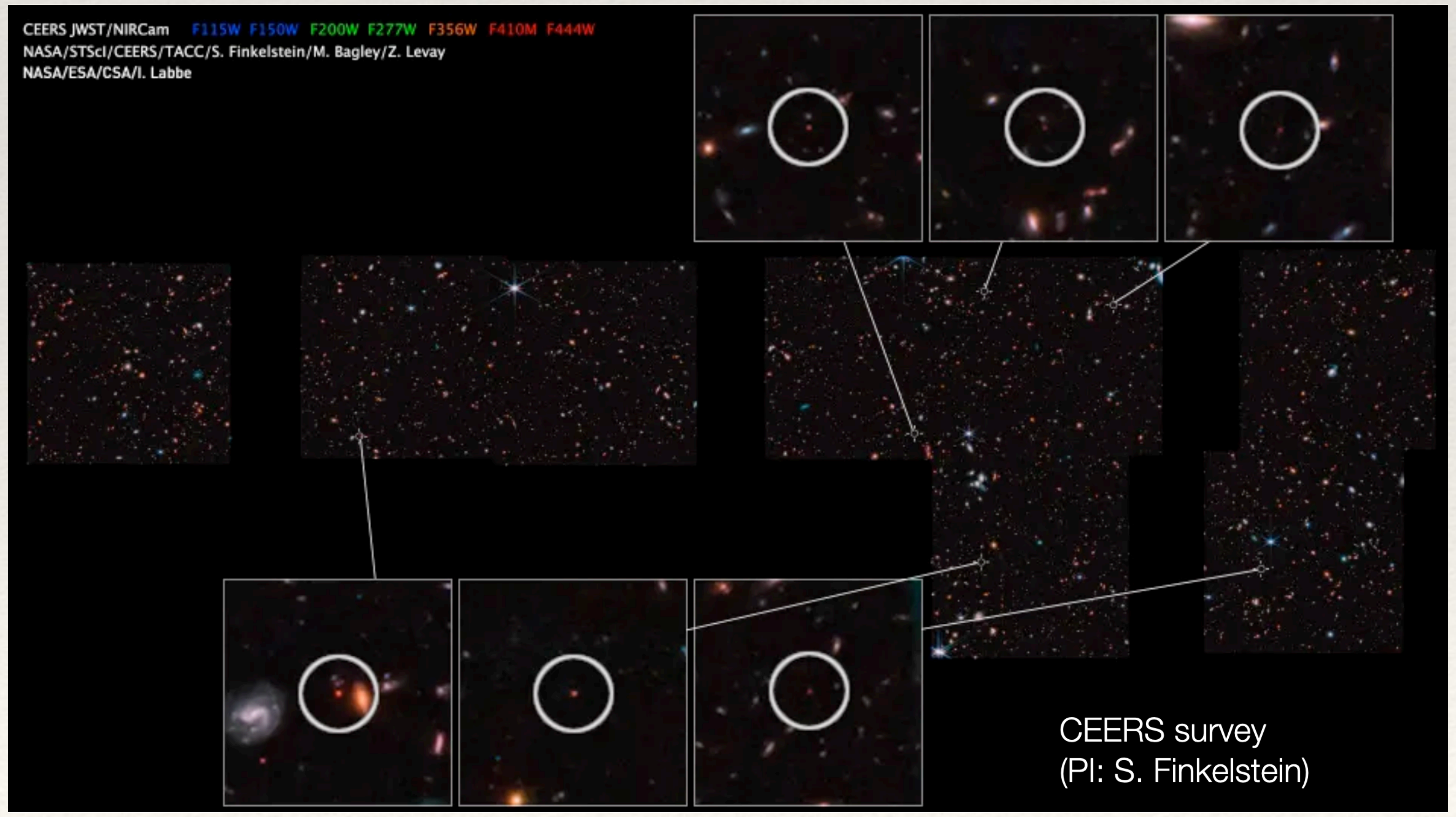
Astronomy and Cosmology

- Our cosmological models work really well

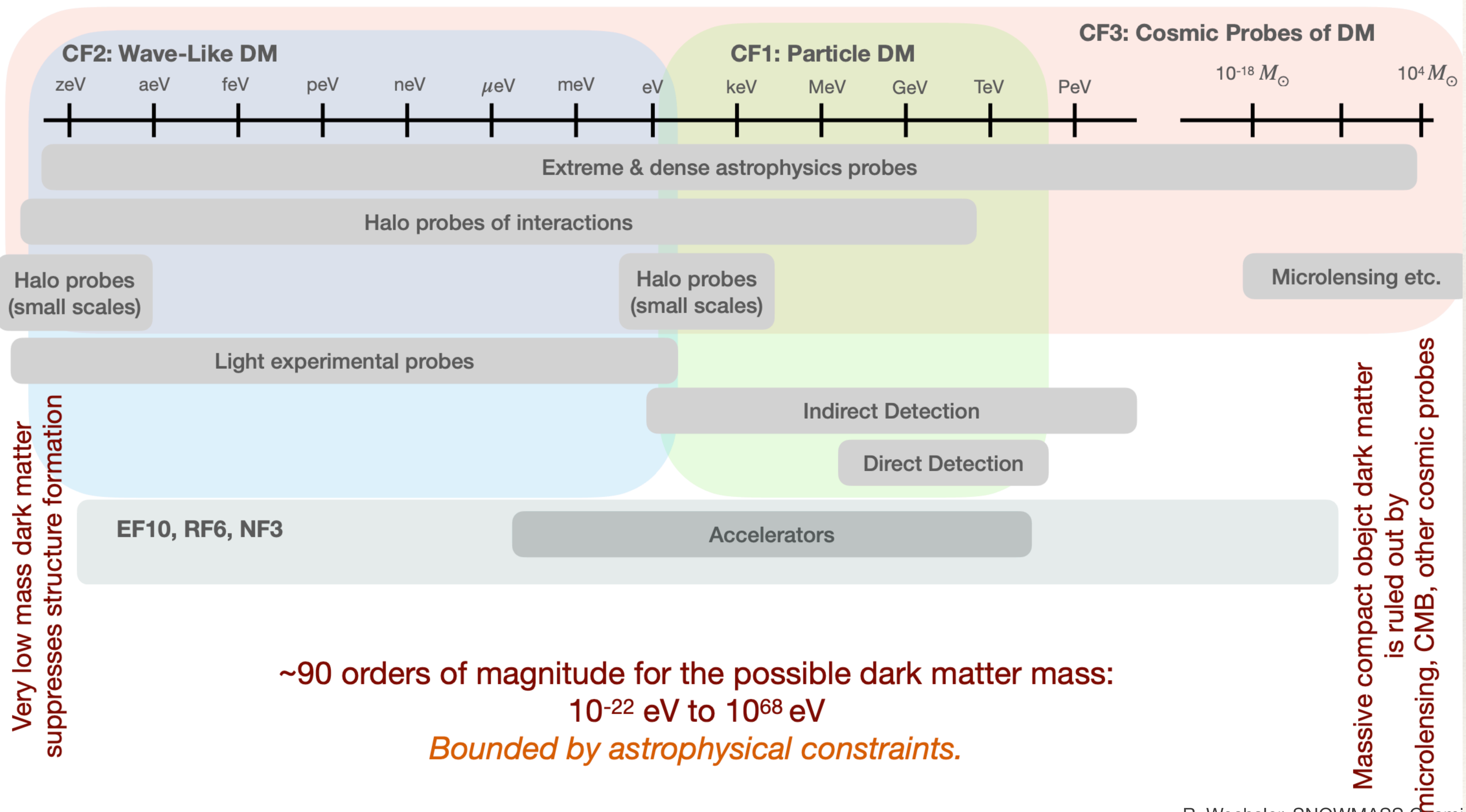
- But…
  - many big young galaxies seen by the James Webb Space telescope
  - different measured values for the Hubble constant
  - Black Holes are surprising us too, could they be dark matter?



Choi et al

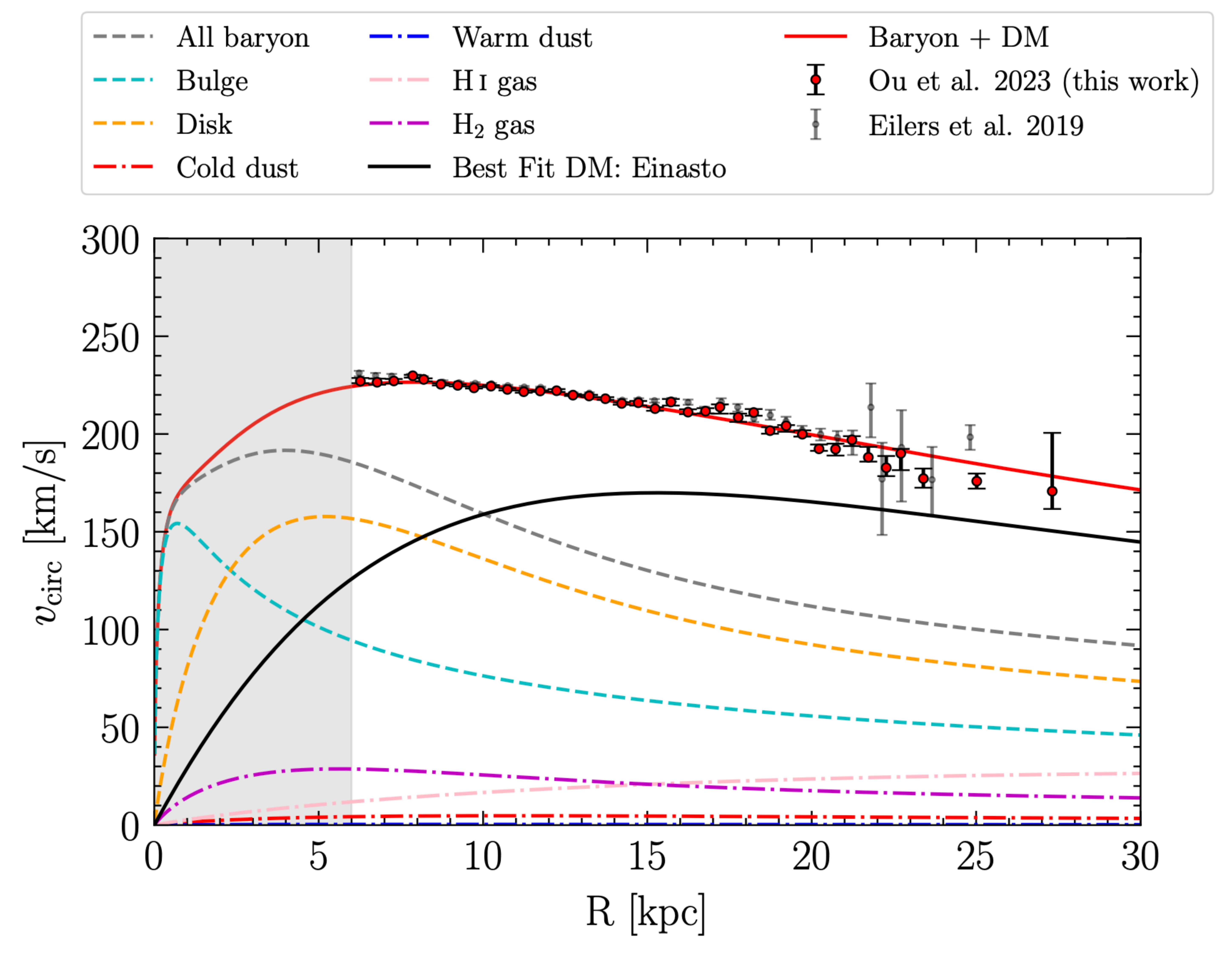


Complementarity



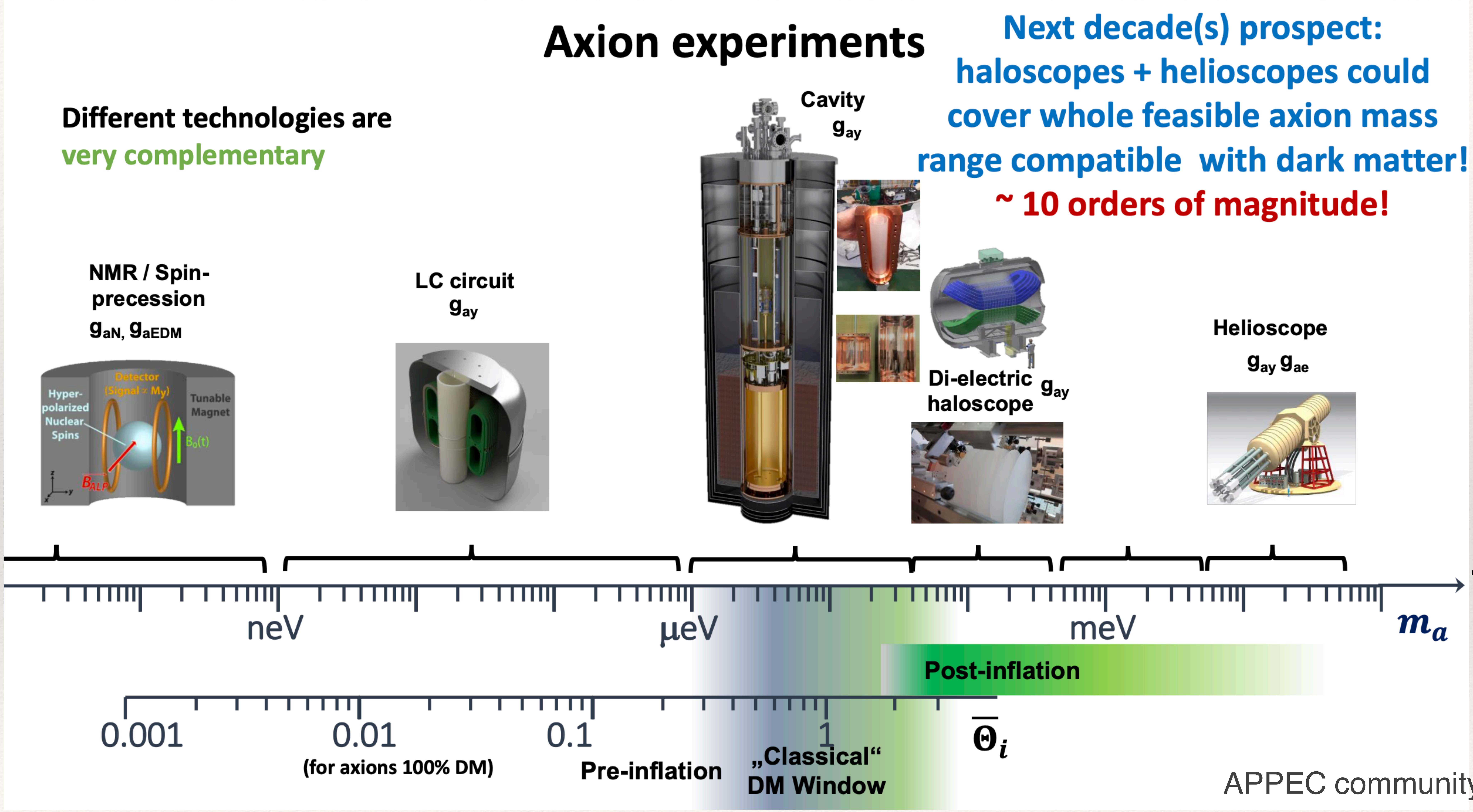
R. Wechsler, SNOWMASS Cosmic Probe Plenary

Milky Way Galactic Rotation Curve



- Updated with Gaia, 2MASS and WISE
- Galaxy model: best fit cored Einasto
- arXiv:2303.12838

Axions and Bosonic Dark Matter

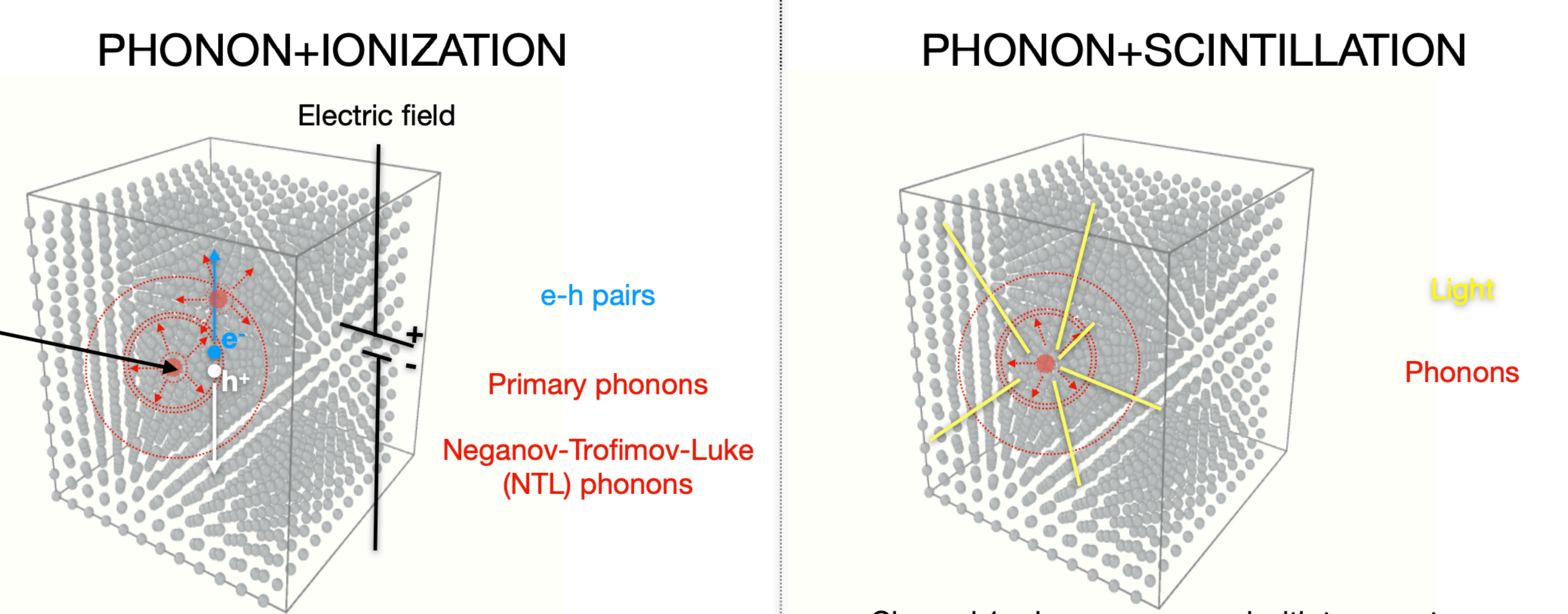


Many ways to get axions in theories

Many ways to look for axions in experiments

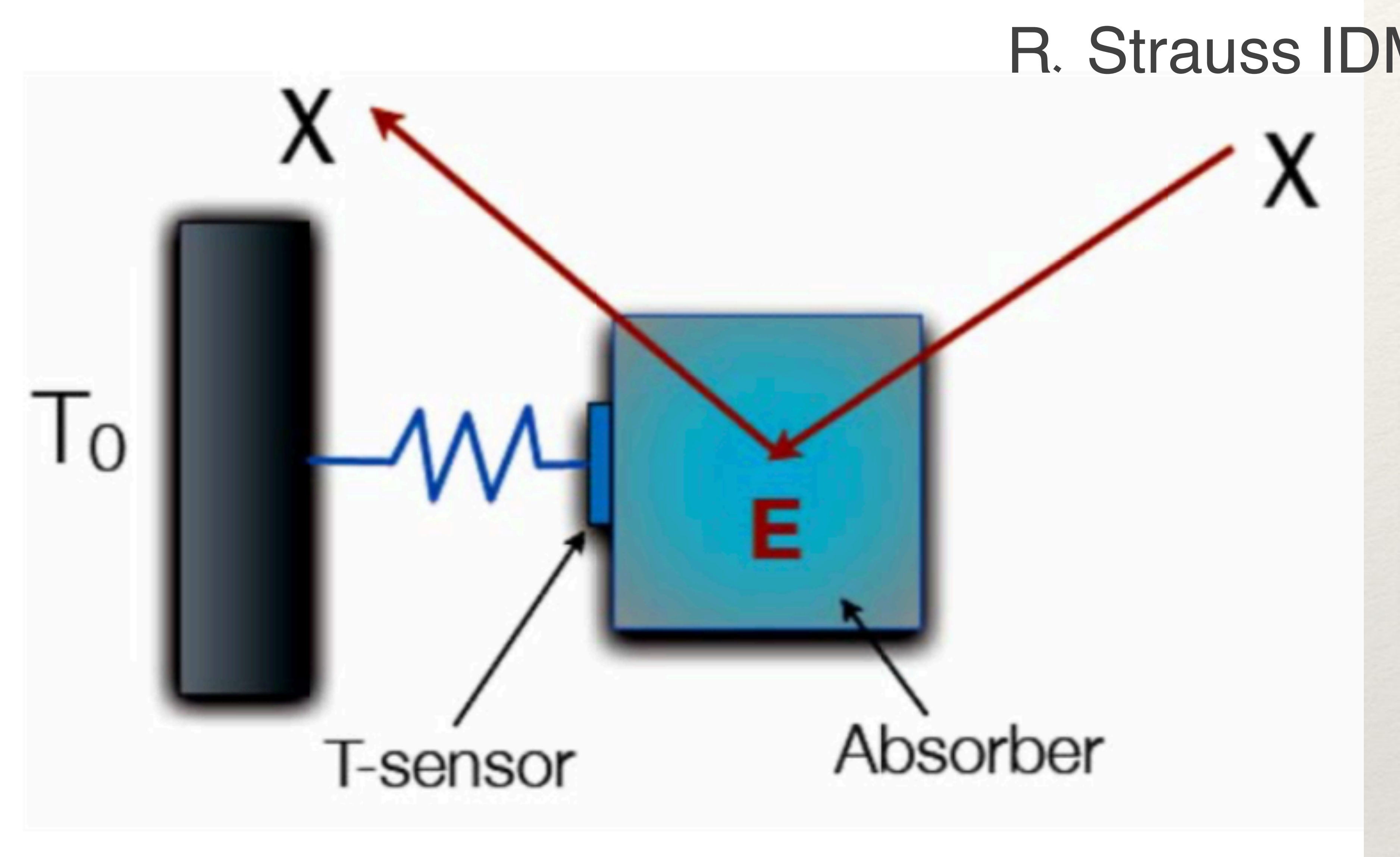
APPEC community discussion slides

Technologies for Low Mass Searches



- Channel 1: phonon measured with temperature sensor -> Enhanced
- Channel 2: charge measured with electrodes placed on both surfaces

- Channel 1: phonon measured with temperature sensor
- Channel 2: light collected by another absorber (wafer or beaker shaped) and measured with a temperature sensor



Zema talk

SuperCDMS, CRESST, EDELWEISS
COSINUS, TESSERACT

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

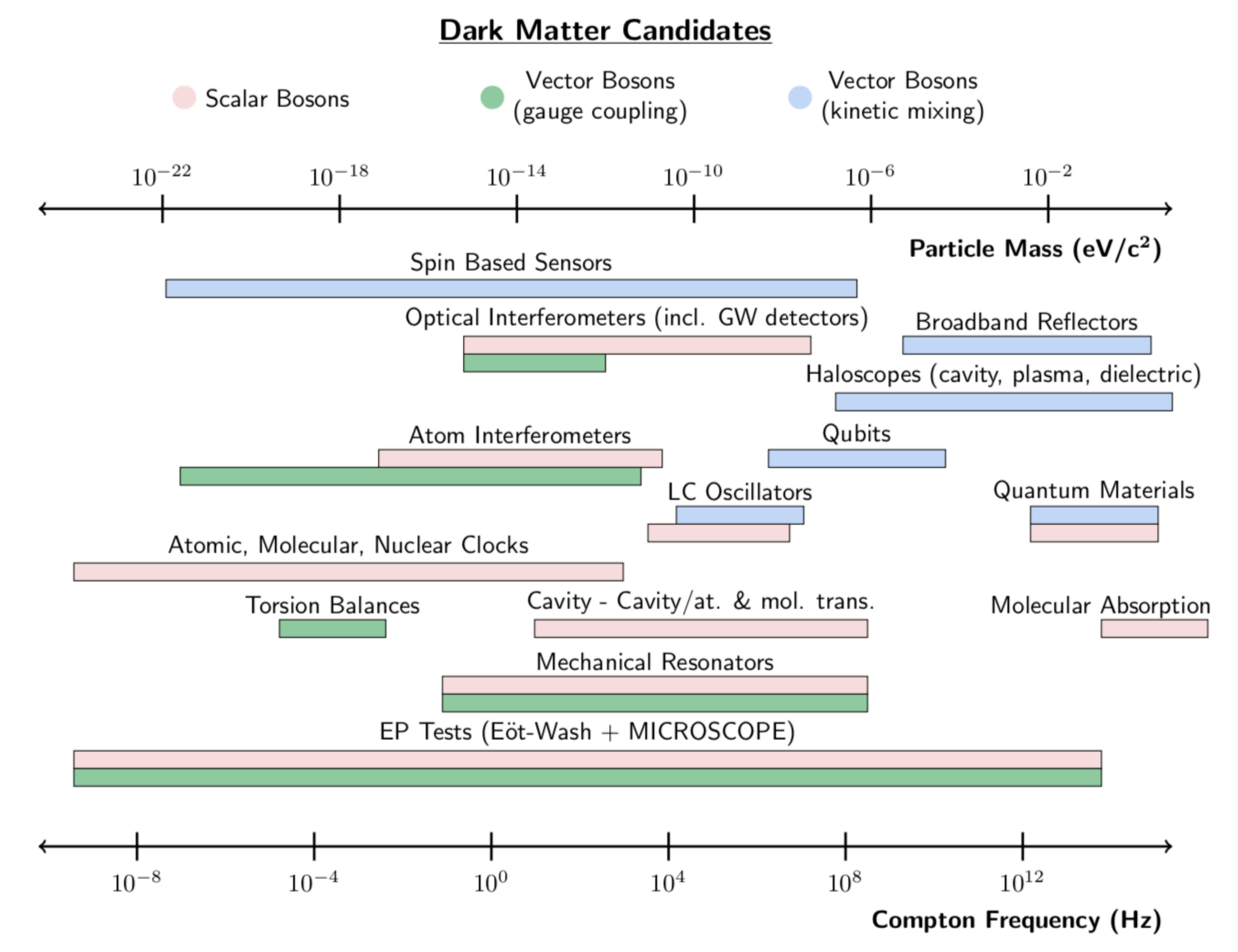
Planned Experiments

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 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

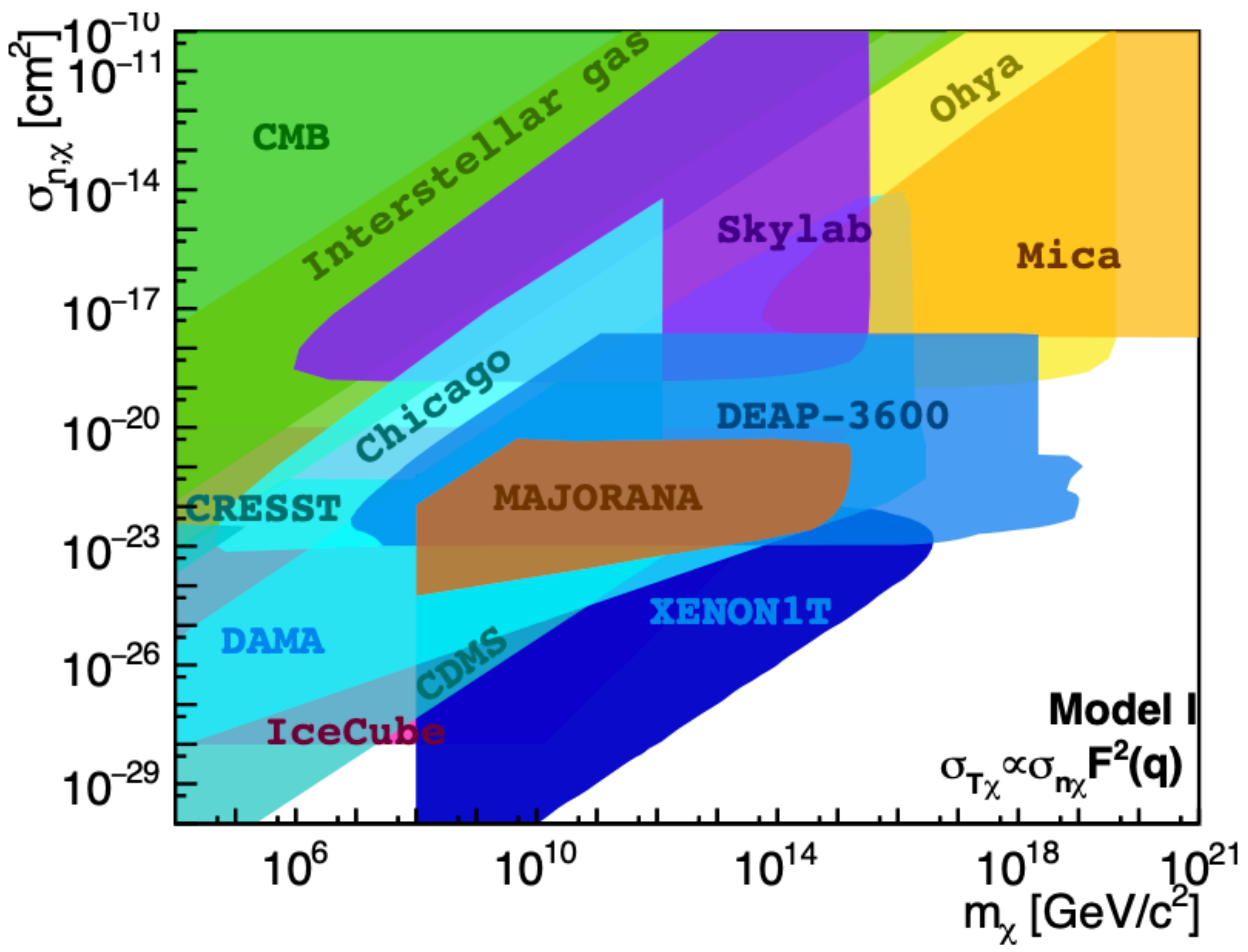
Name	Technology	Target	Active Mass	Experiment Location	Start Ops	End Ops
Concept or R&D						
Oscura	CCD Skipper	Si	10 kg Si	SNOLAB	2025	2028
SBC	Bubble Chamber	LAr	1 t	SNOLAB	2028	
SNOWBALL	Supercooled Liquid H2O					
DarkSide-LowMass	TPC	LAr	1.5 t			
ALETHEIA	TPC	He		China Inst. At. Energy		
TESSERACT	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	

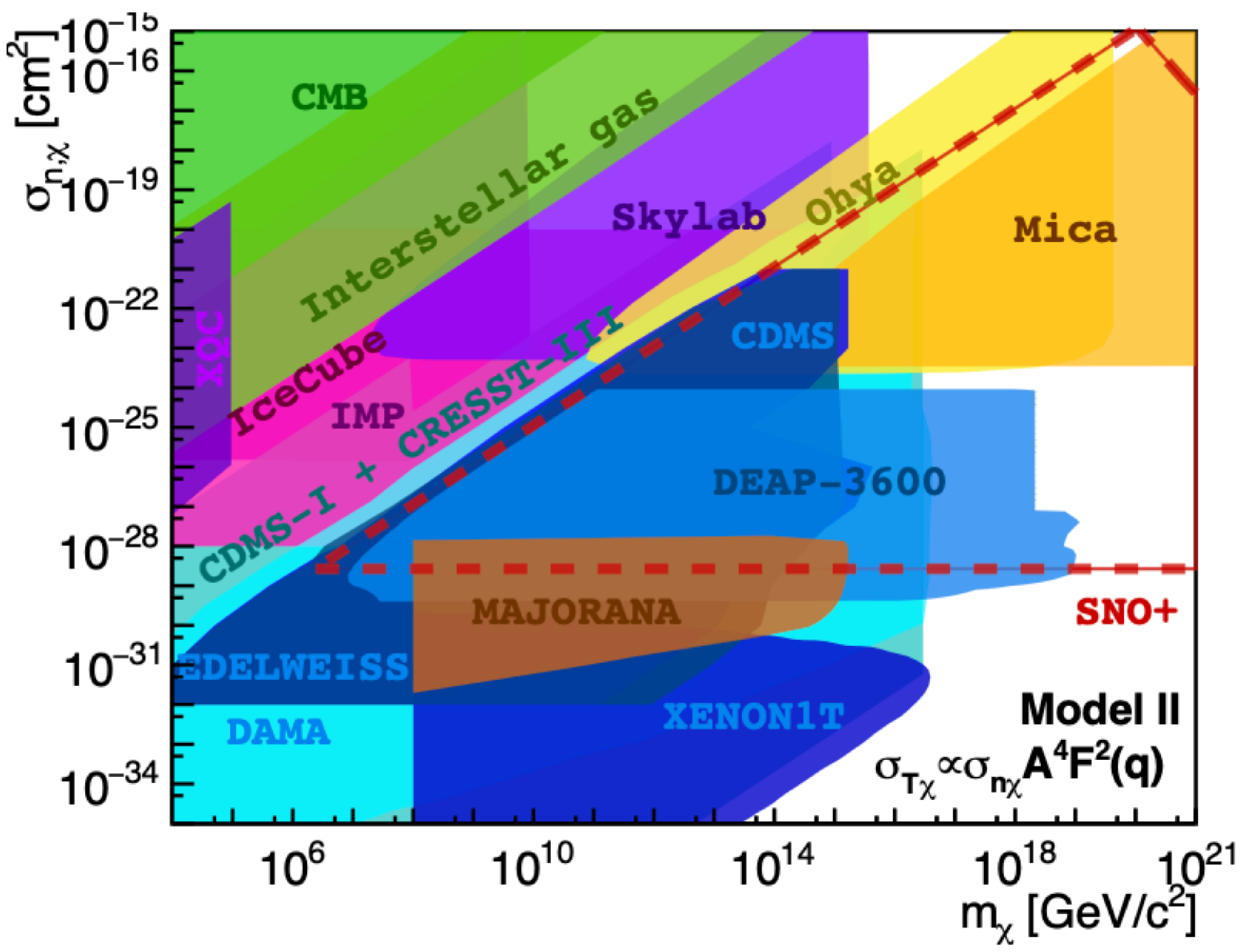
Wavelike Dark Matter



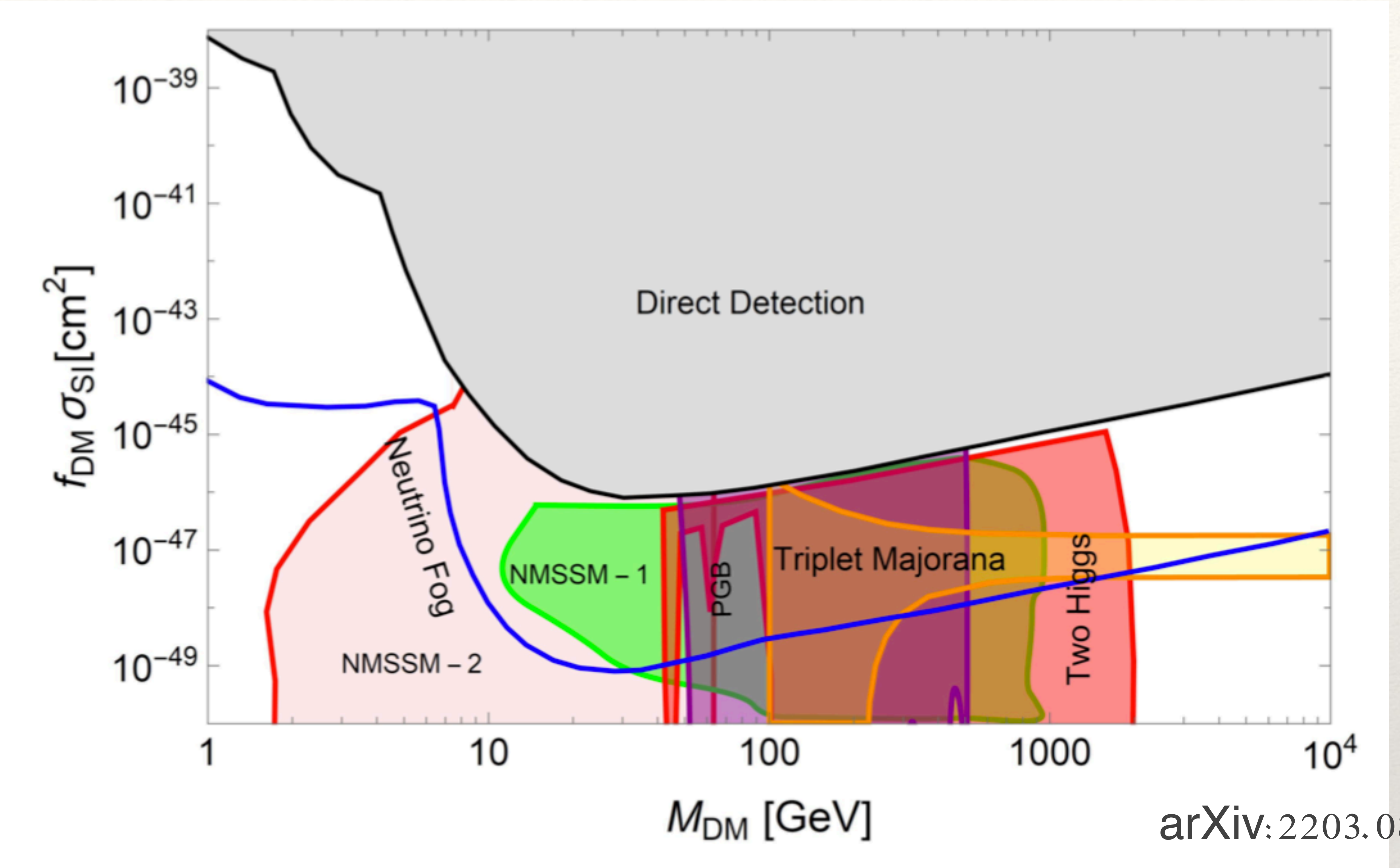
arXiv:220

Ultraheavy dark matter



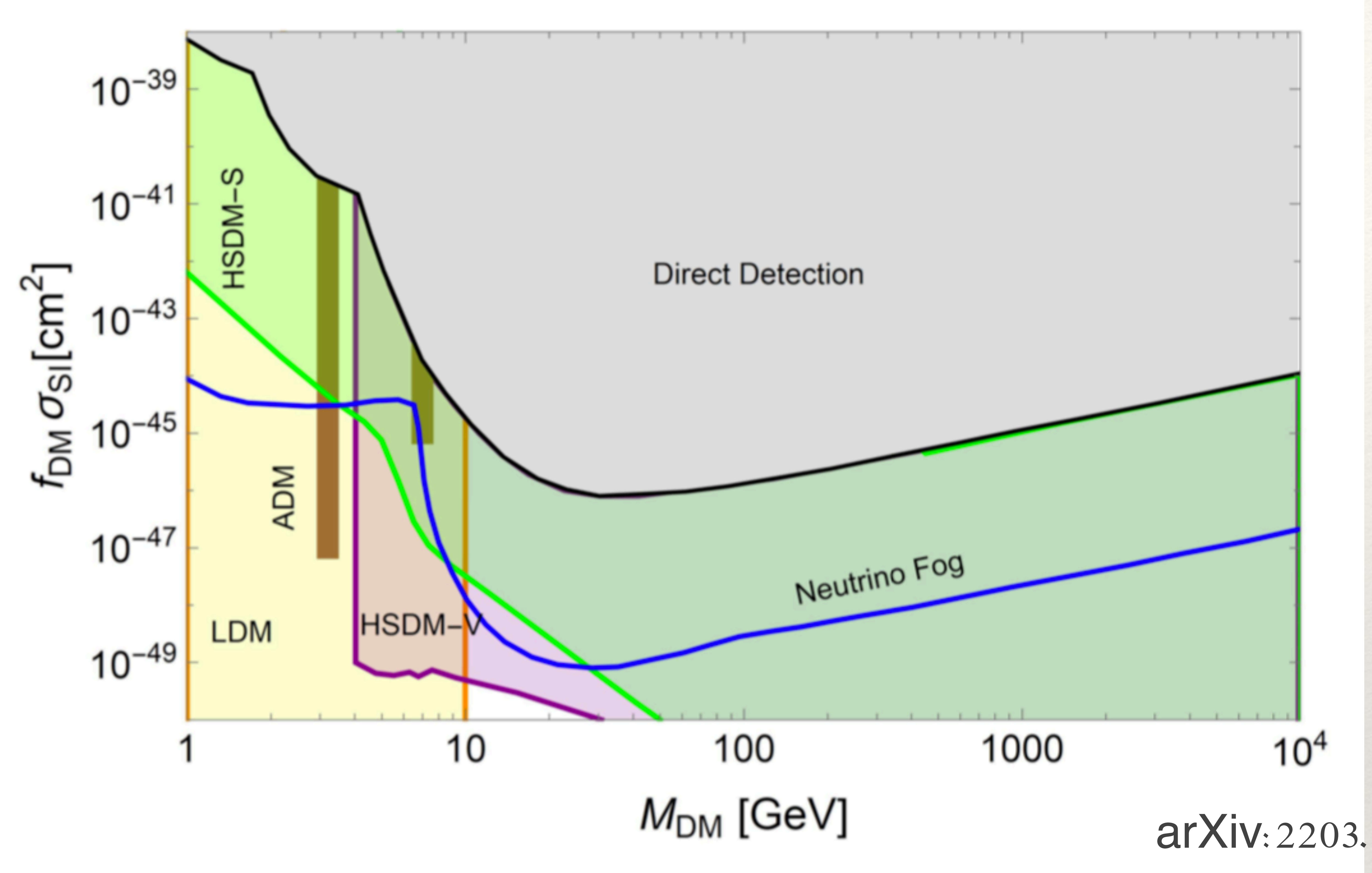


A Modern WIMP view

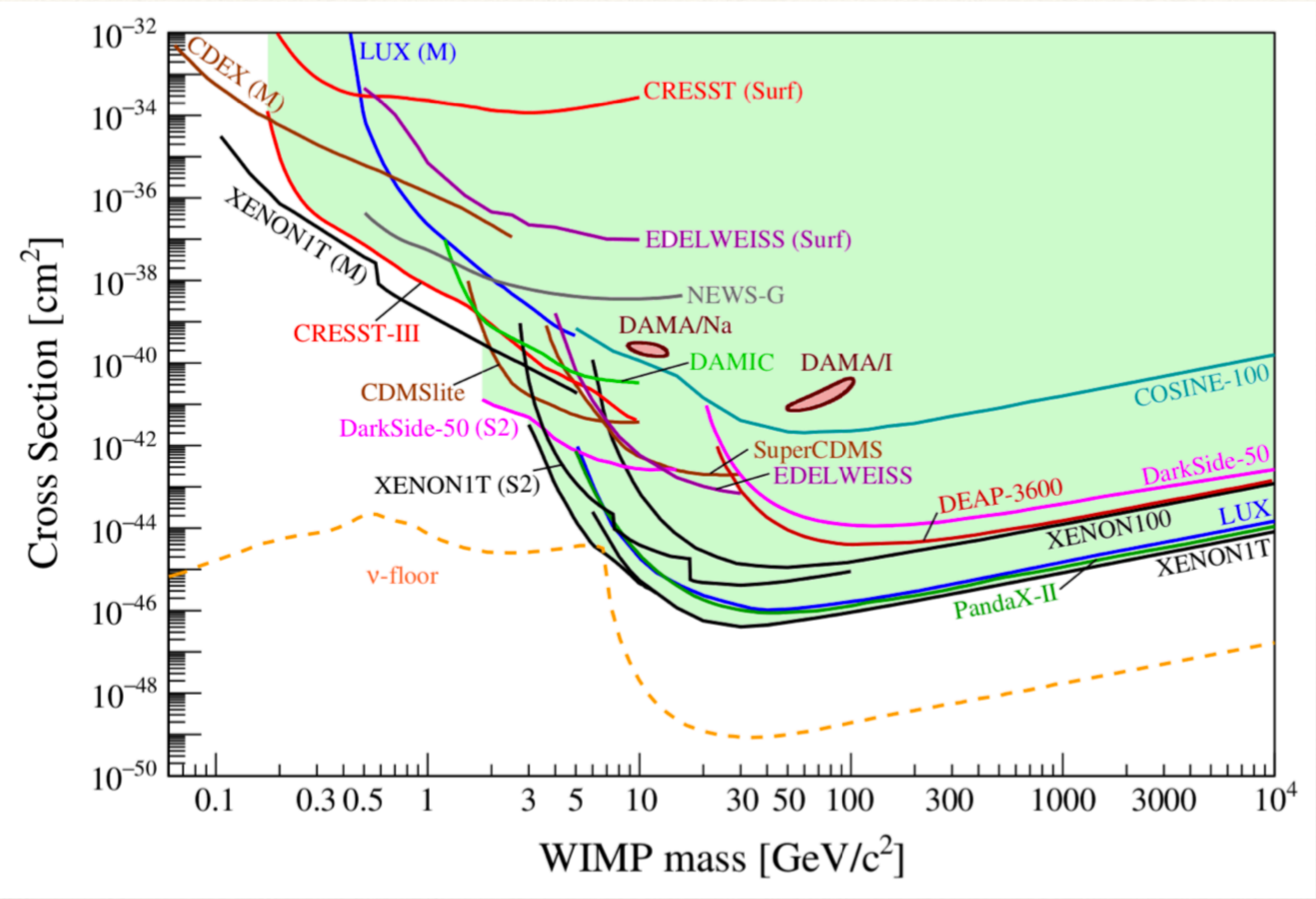


arXiv: 2203.08084

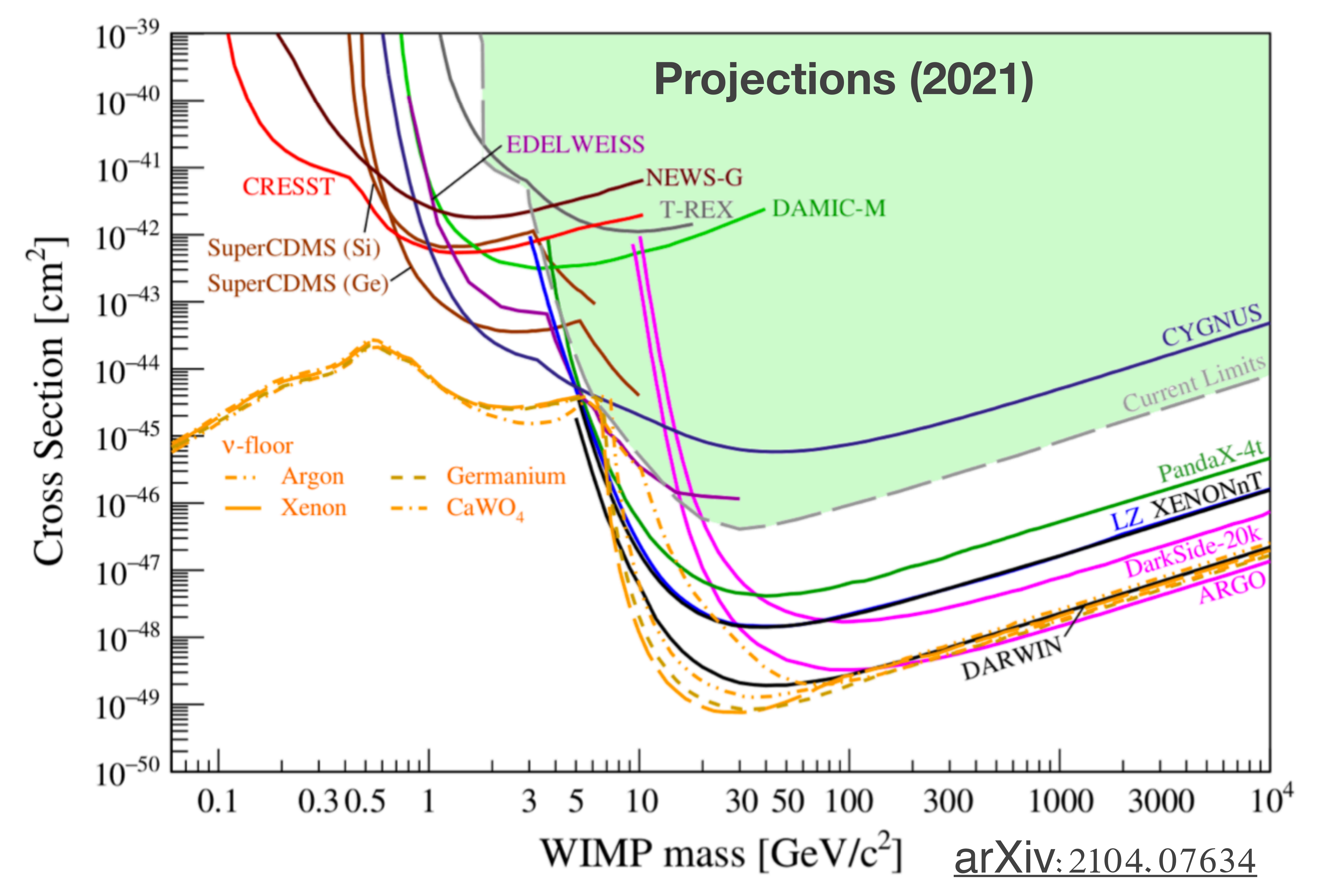
High Mass Particle DM Beyond the WIMP



arXiv: 2203.08084



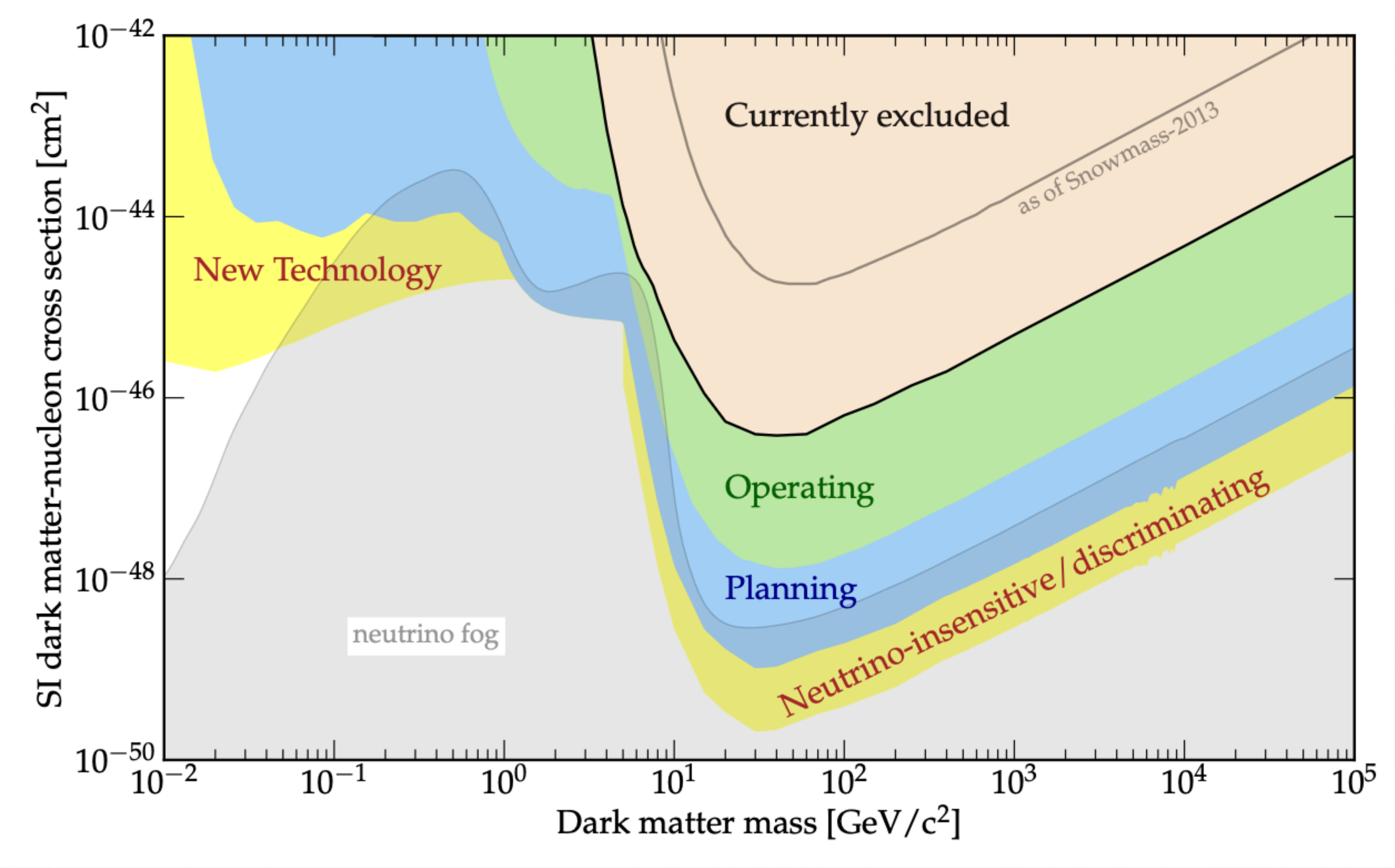
Cross Section [cm^2]
WIMP mass [GeV/c^2]
LUX (M)
CDEX (M)
CRESST (Surf)
XENON1T (M)
EDELWEISS (Surf)
NEWS-G
CRESST-III
DAMA/Na
DAMIC
DAMA/I
CDMSlite
COSINE-100
DarkSide-50 (S2)
SuperCDMS
EDELWEISS
XENON1T (S2)
DEAP-3600
DarkSide-50
XENON100
LUX
XENON1T
PandaX-II
ν-floor

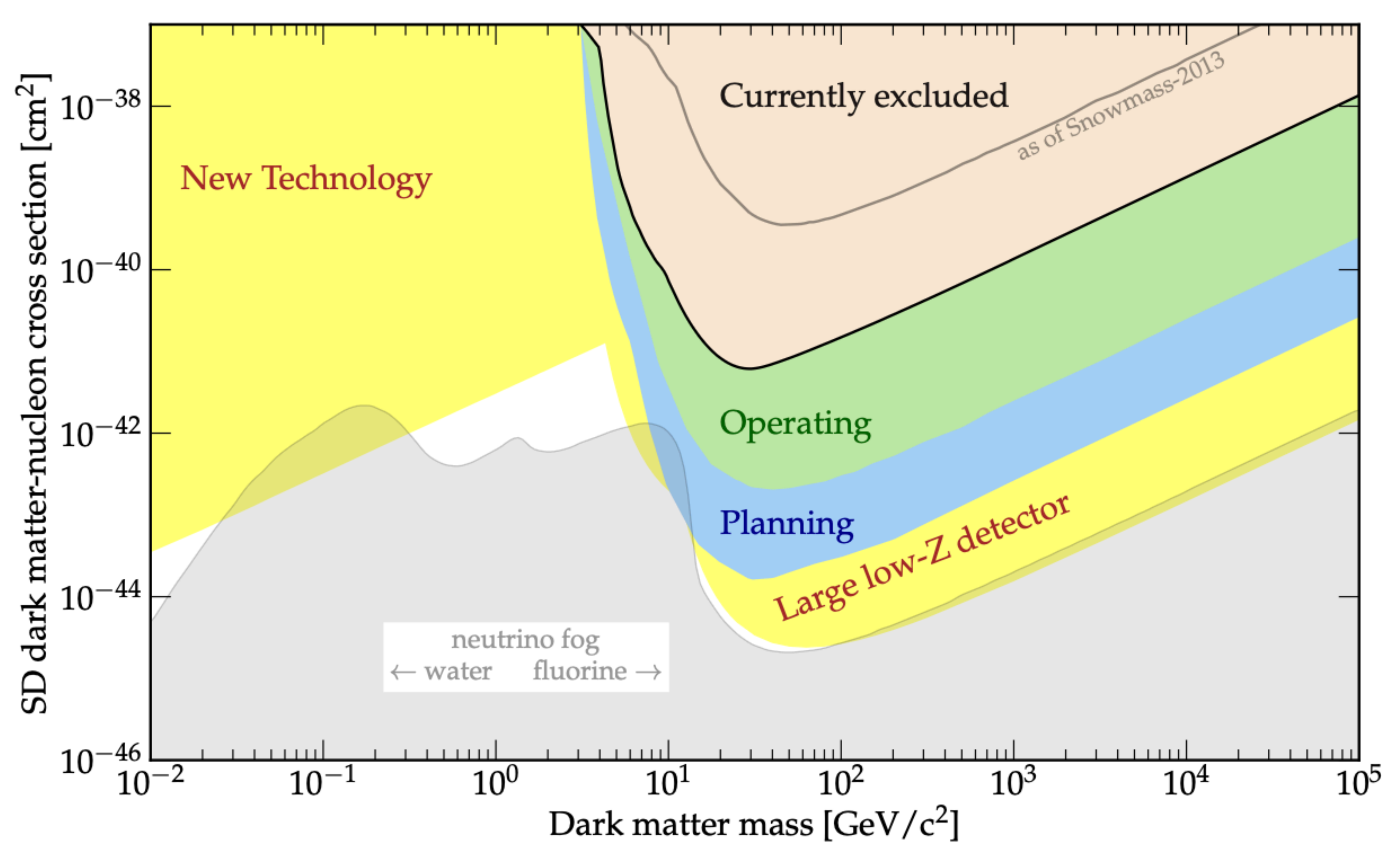


Projections (2021)
Cross Section [cm^2]
WIMP mass [GeV/c^2]
EDELWEISS
NEWS-G
CRESST
T-REX
DAMIC-M
SuperCDMS (Si)
SuperCDMS (Ge)
CYGNUS
Current Limits
ν-floor
Argon
Xenon
Germanium
CaWO$_4$
PandaX-4t
LZ XENONnT
DarkSide-20k
ARGO
DARWIN
arXiv: 2104.07634

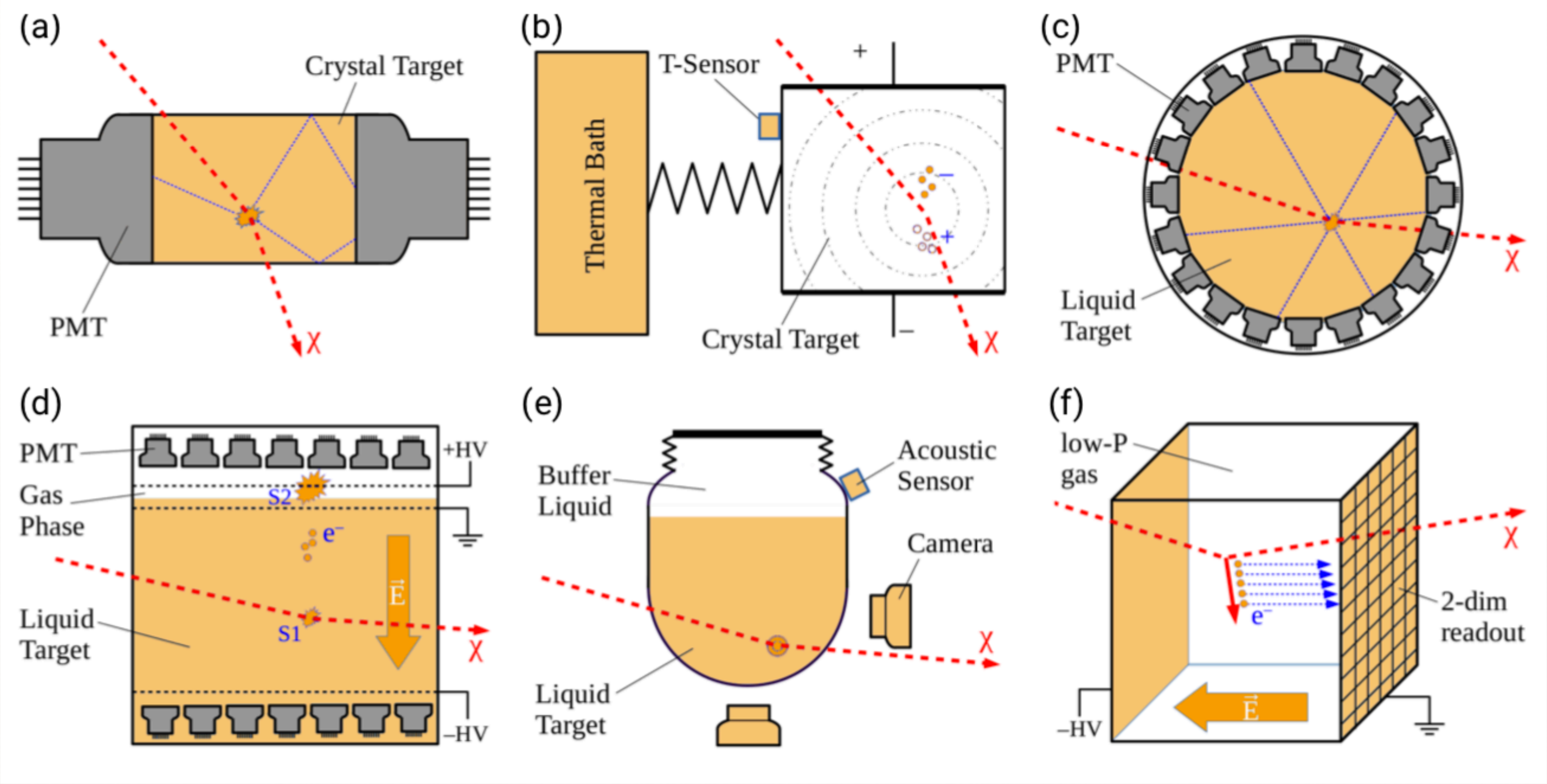
Limits

Direct Detection Sensitivities





arXiv: 2203.080



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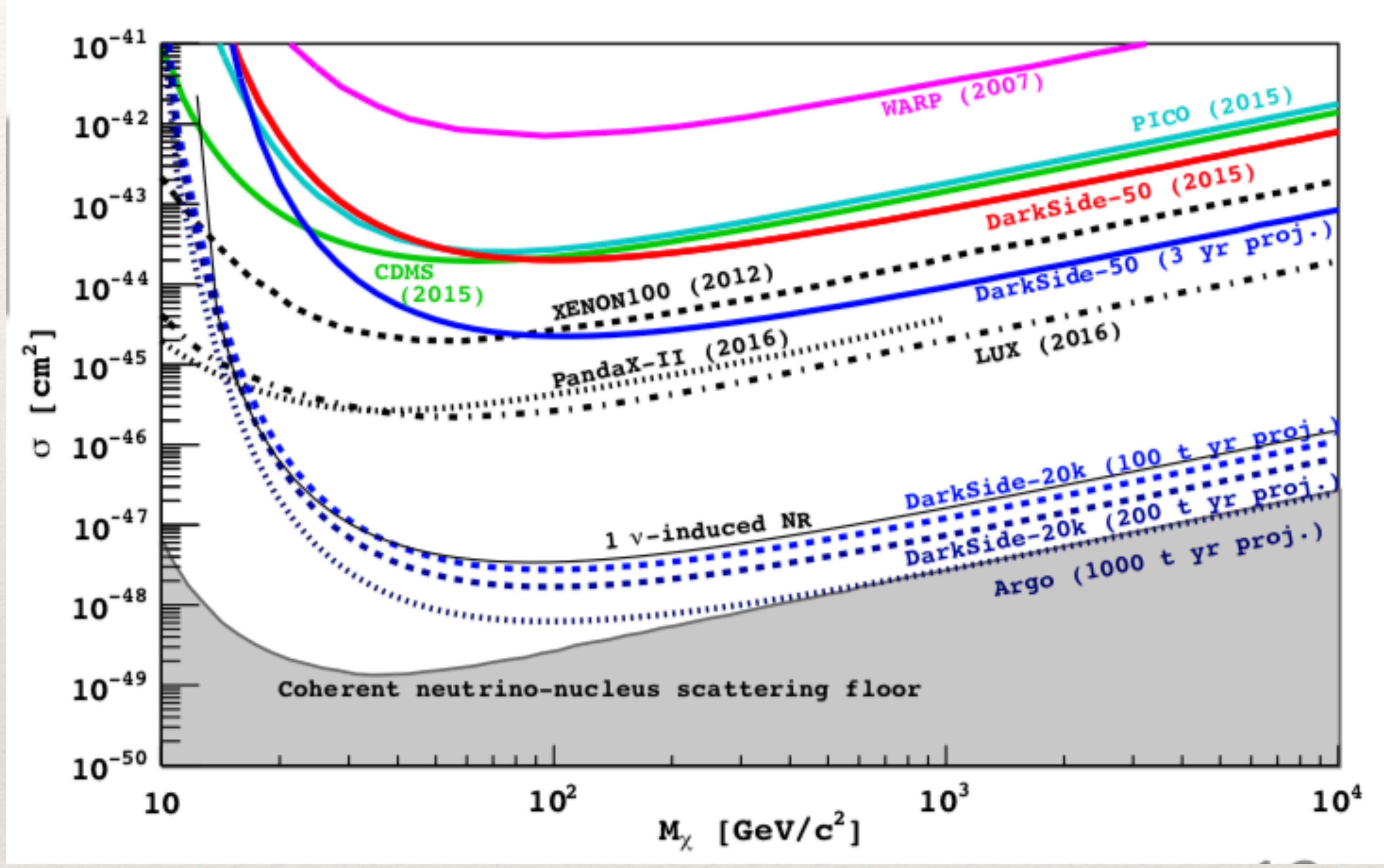
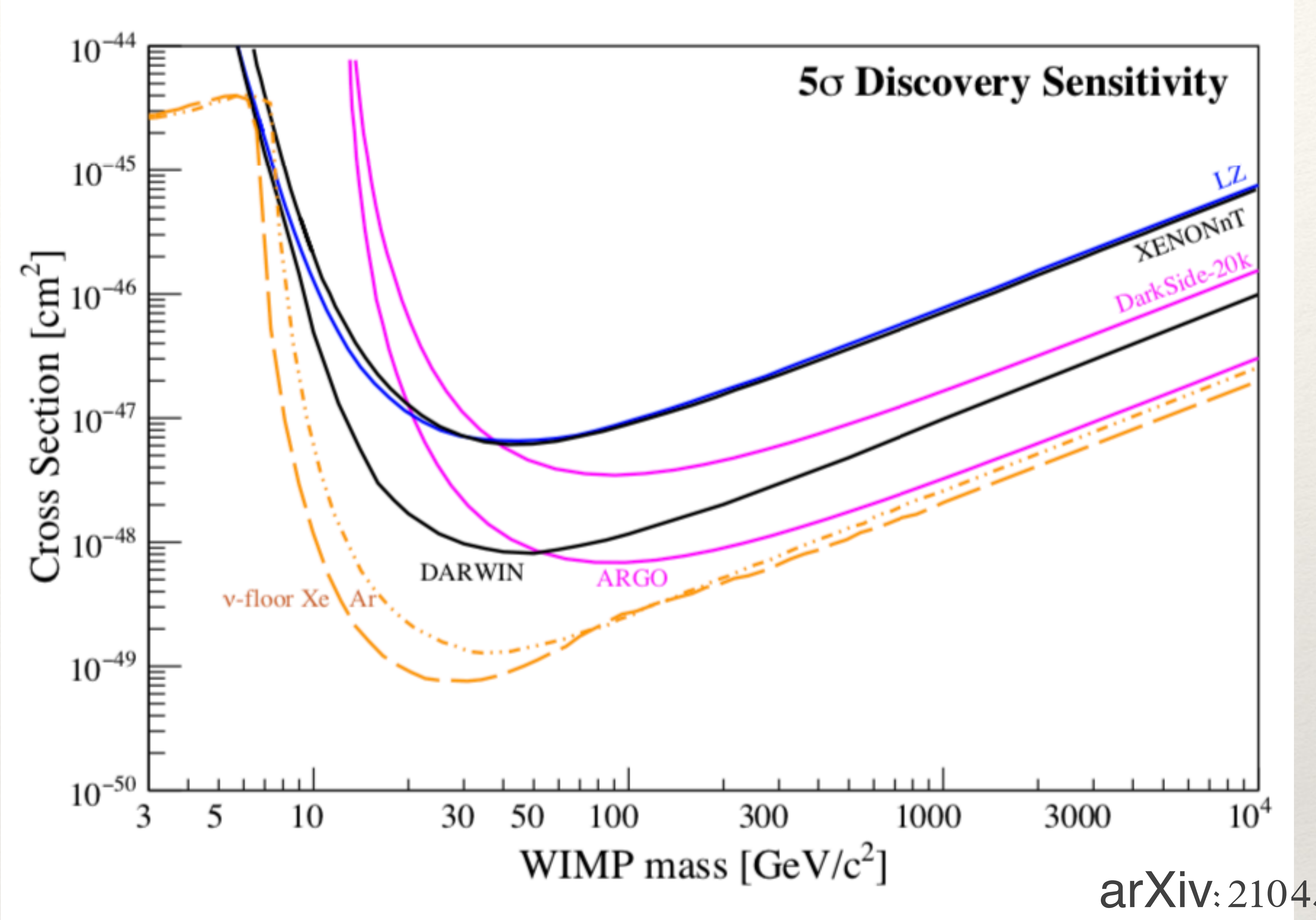
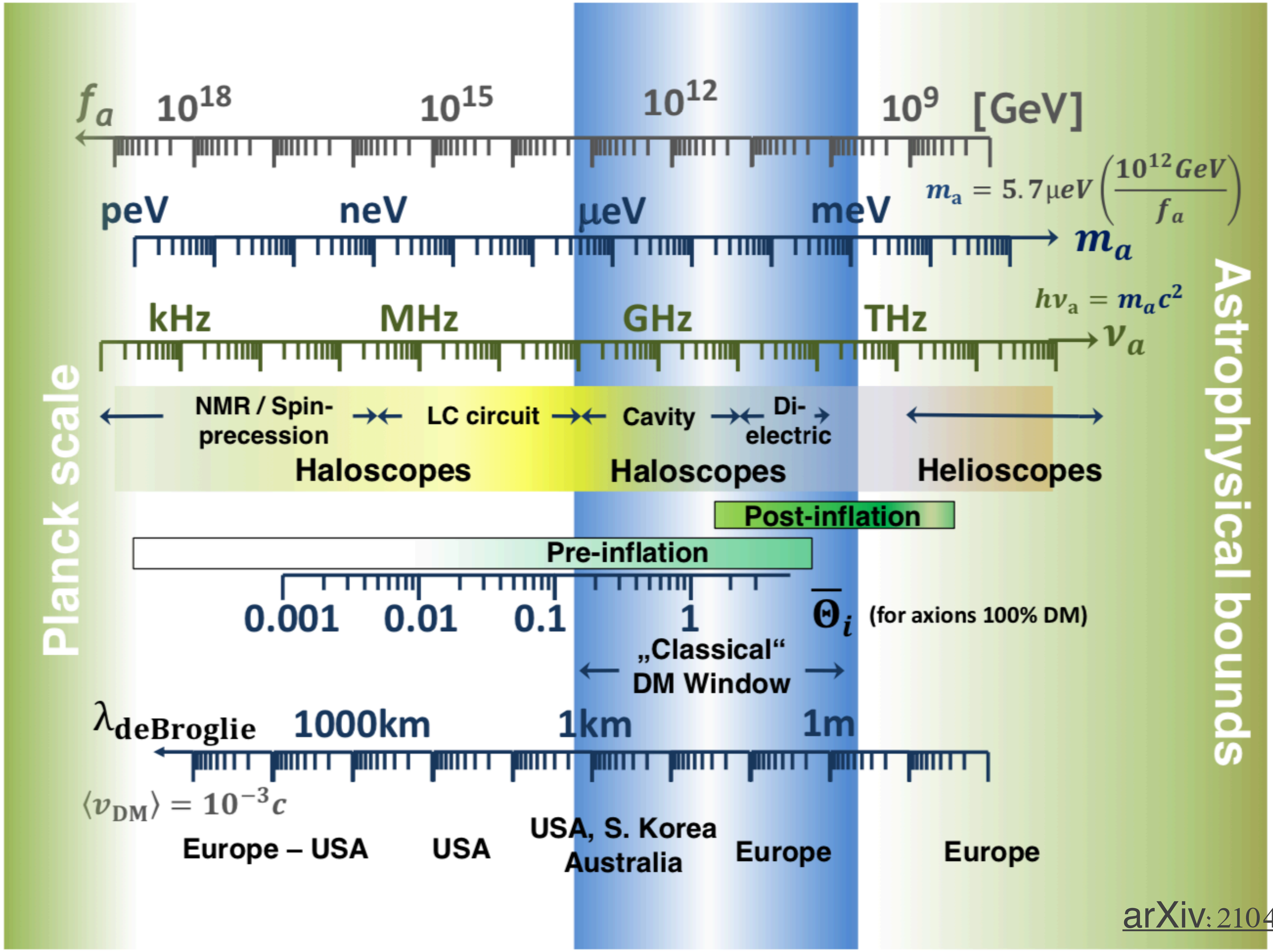


Eur.Phys.J.Plus(2018)133:131



arXiv: 2104.07



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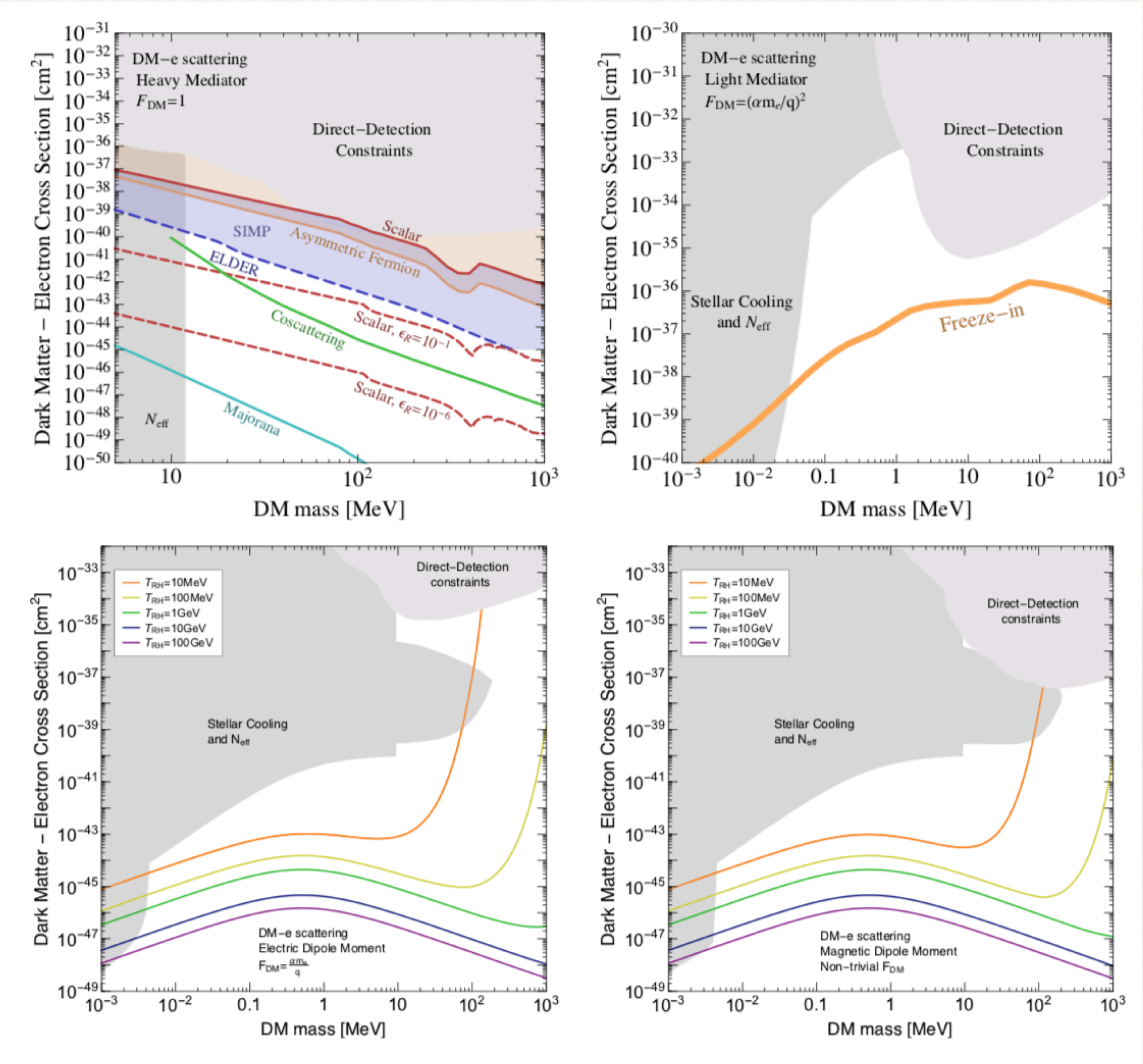
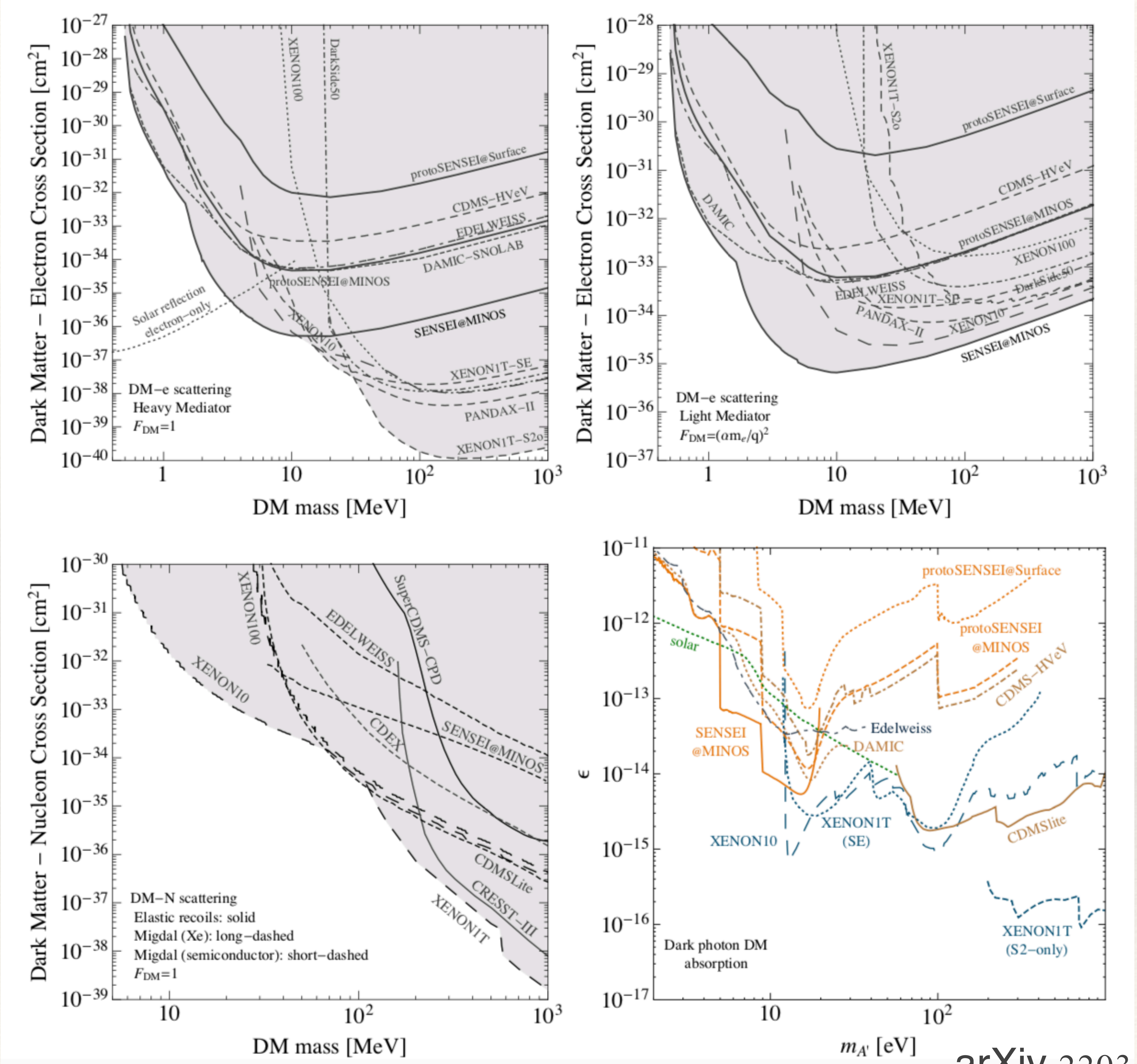
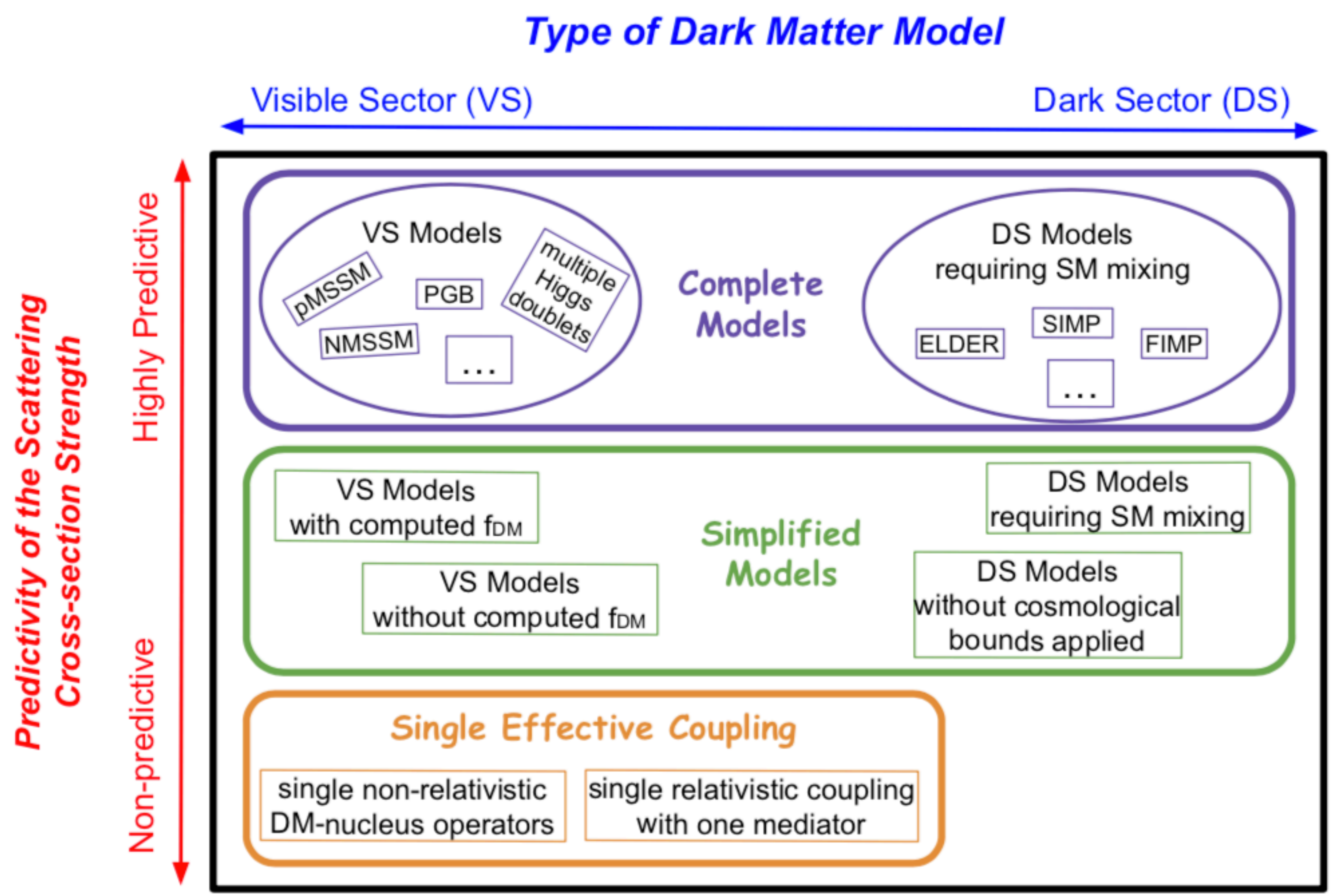




arXiv: 2203.08



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