



# Direct Dark Matter Experiments: Light Mass Particle Searches



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Light Dark World  
18 September 2025





# Outline

- Techniques, status and projections:
  - 1-10 GeV/c<sup>2</sup> Dark Matter
    - NaI targets
    - Other targets
  - <1 GeV/c<sup>2</sup> Dark Matter
    - Quantum technologies
    - Low Energy Excess

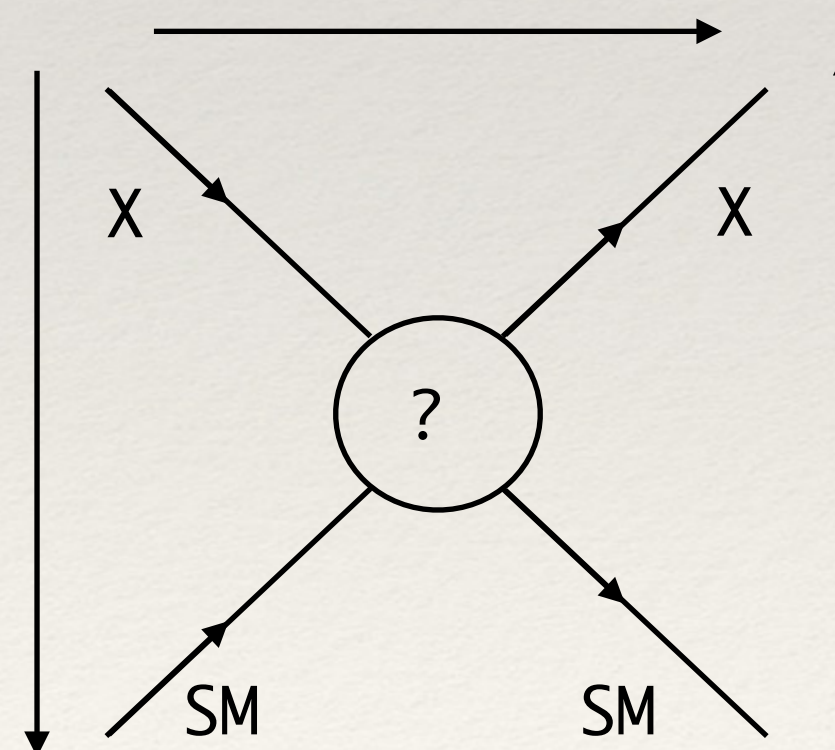
Not covering MeV ALP,  
millicharge, solar axions,  
that these detectors can see

**Break It!**

Indirect  
(Annihilation)

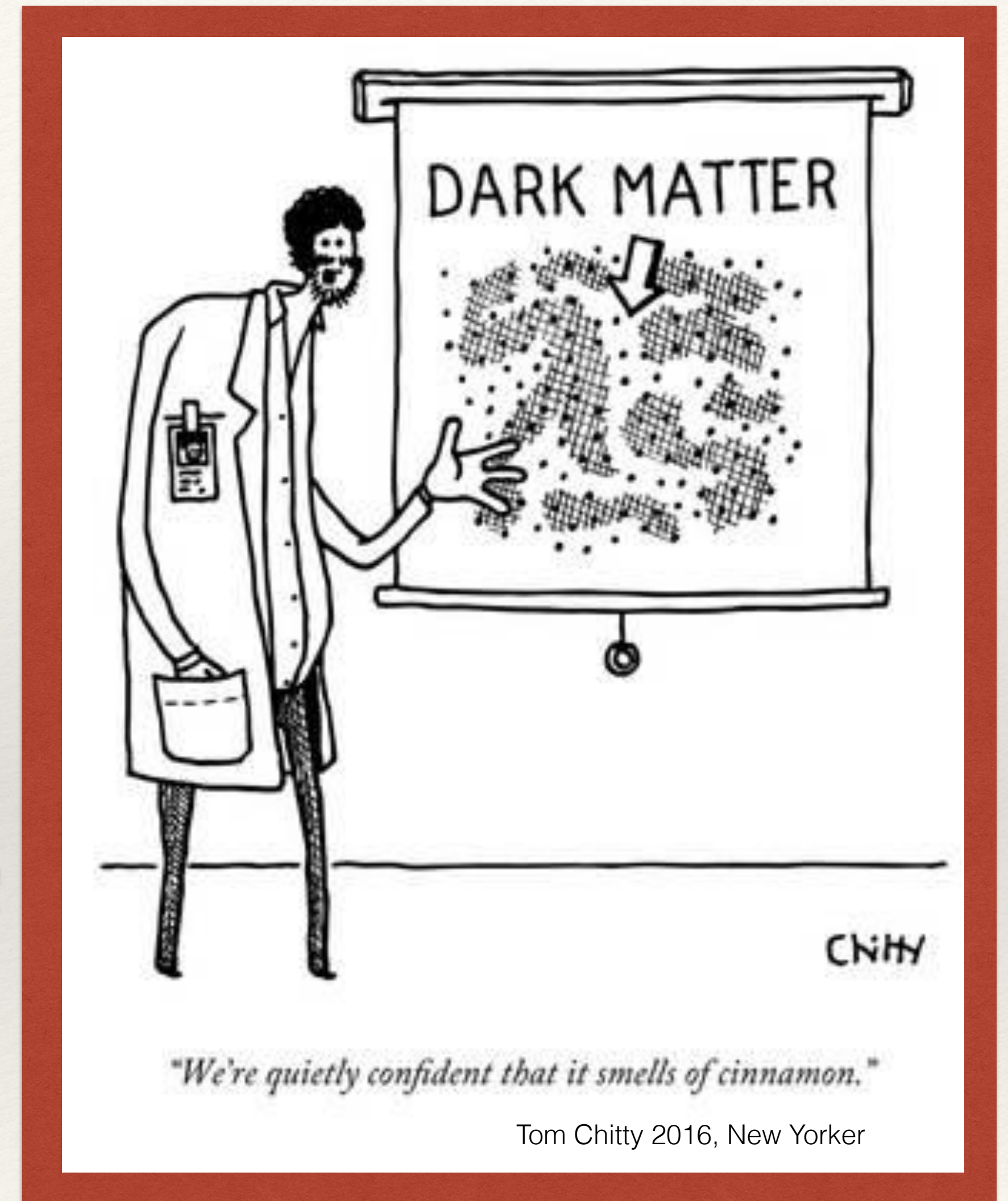
**Shake It!**

Direct (Scattering)



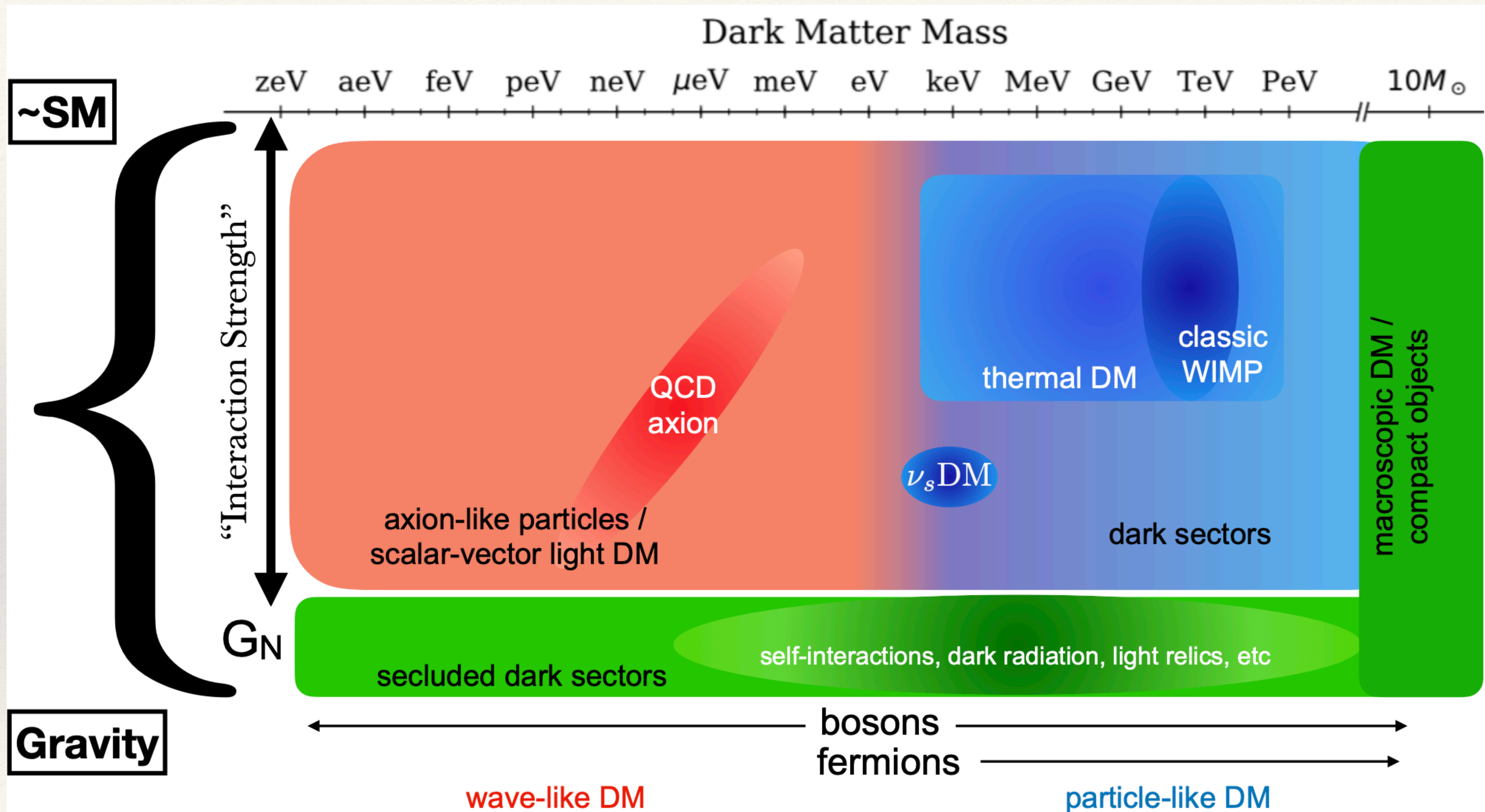
**Make It!**

Collider  
(Production)





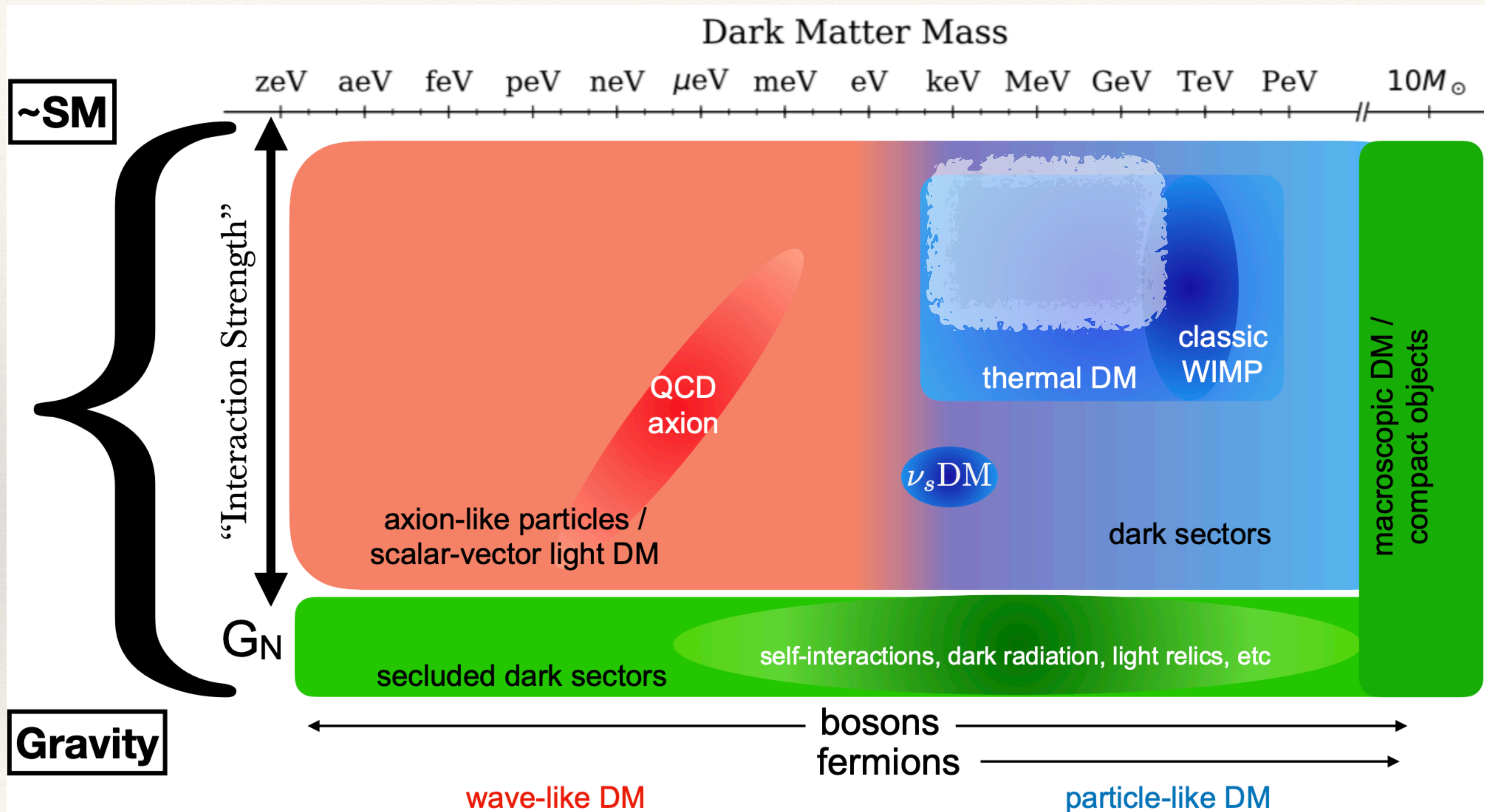
# A Unified Vision coming from SNOWMASS



A Chou, SNOWMASS Dark Matter Plenary



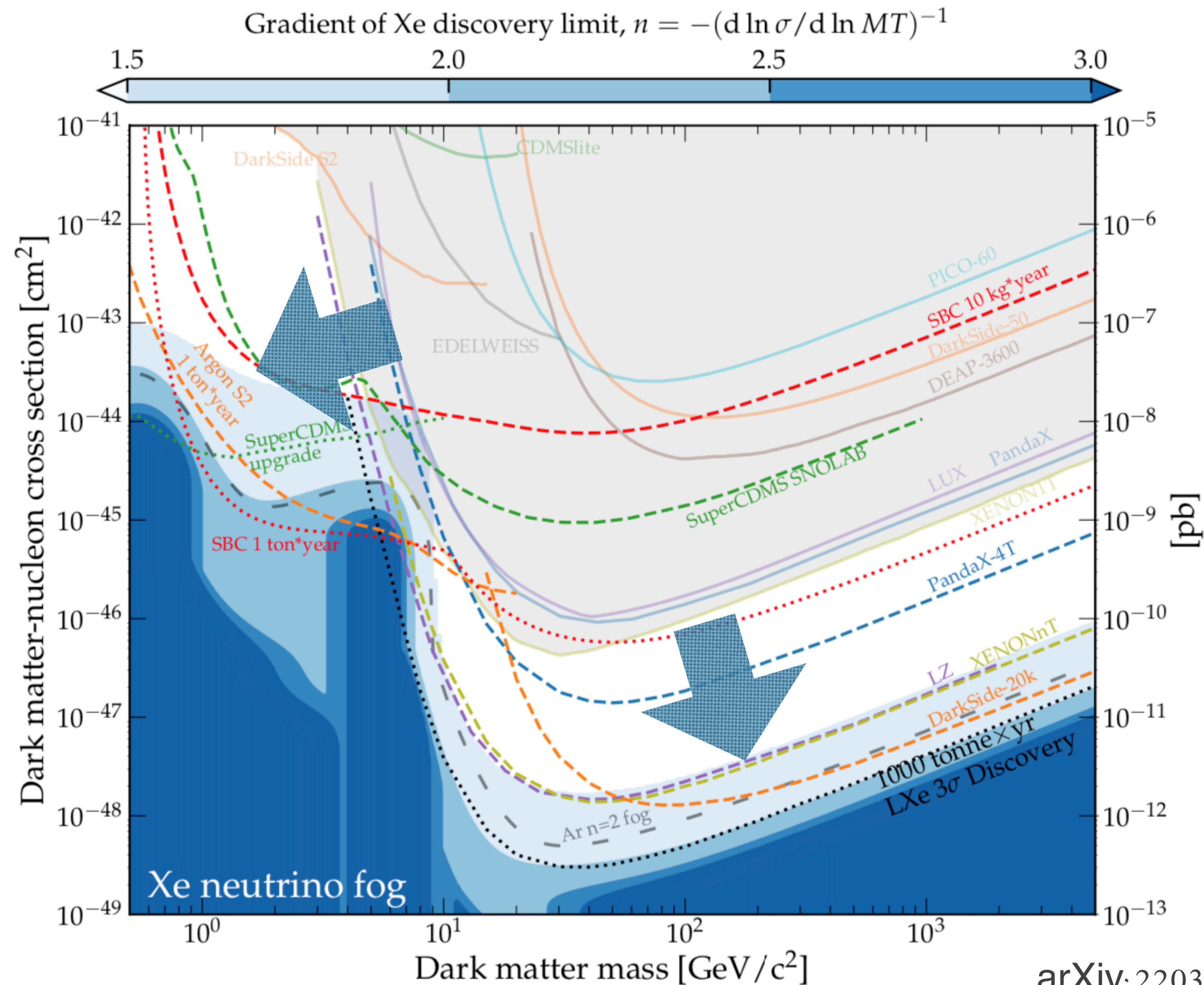
# A Unified Vision coming from SNOWMASS



A Chou, SNOWMASS Dark Matter Plenary



# Spin Independent Direct DM status



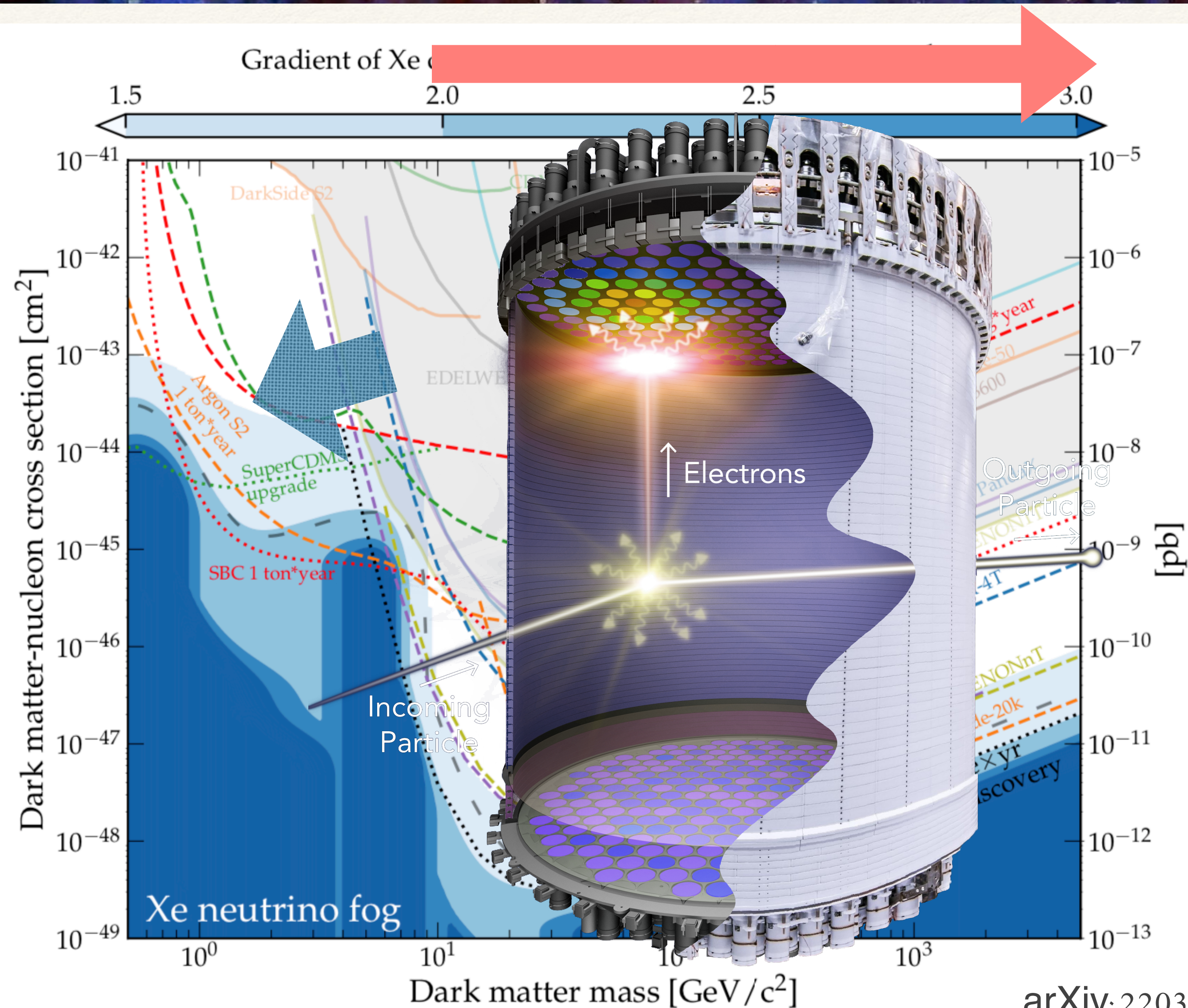
Focus on spin-independent DM-nuclear scattering



Michael Lucibella 2014, APS.org



# Spin Independent Direct DM status



[arXiv:2203.08084](https://arxiv.org/abs/2203.08084)

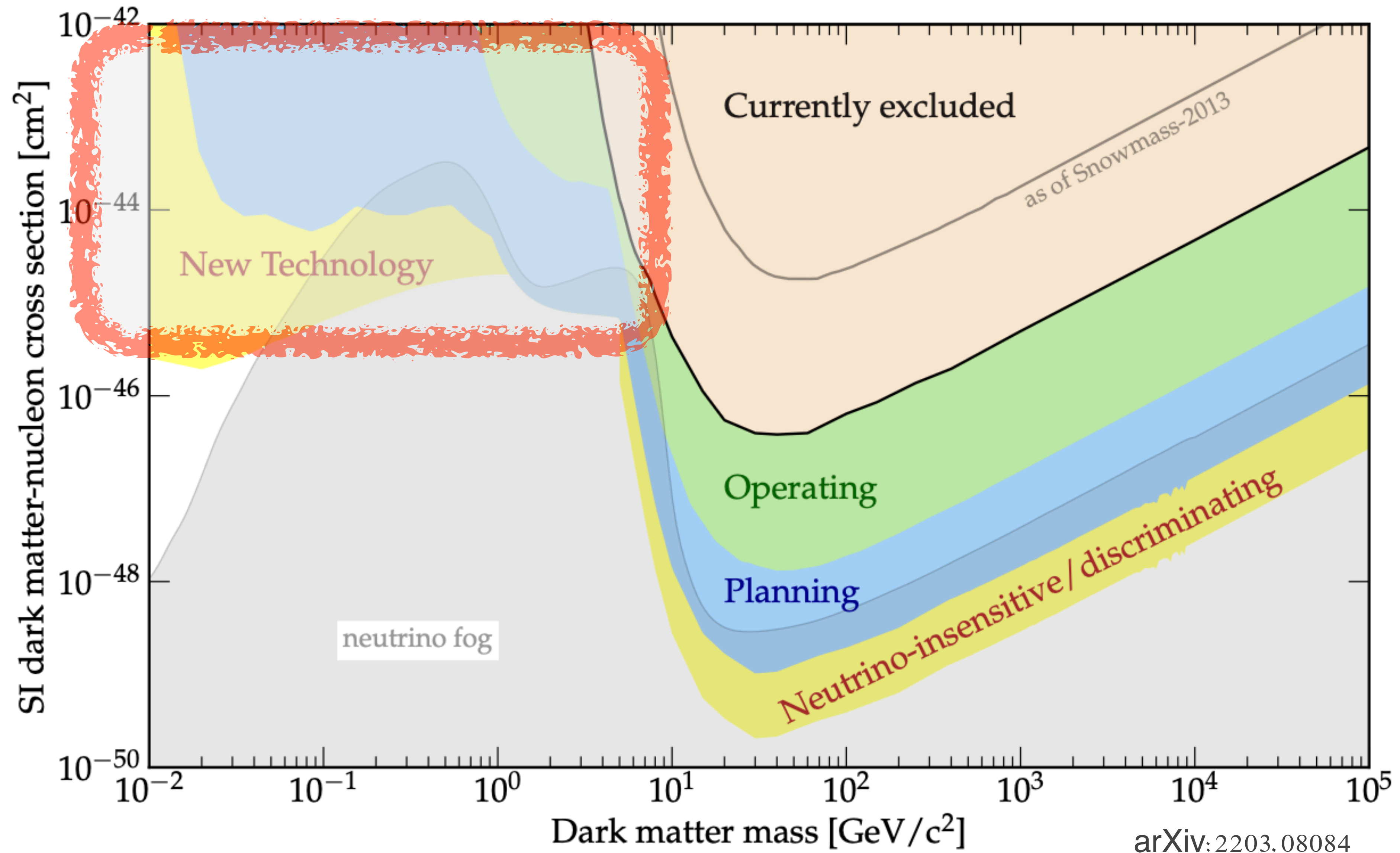
Liquid Noble TPC technology dominates  $> 10 \text{ GeV}$



Michael Lucibella 2014, APS.org

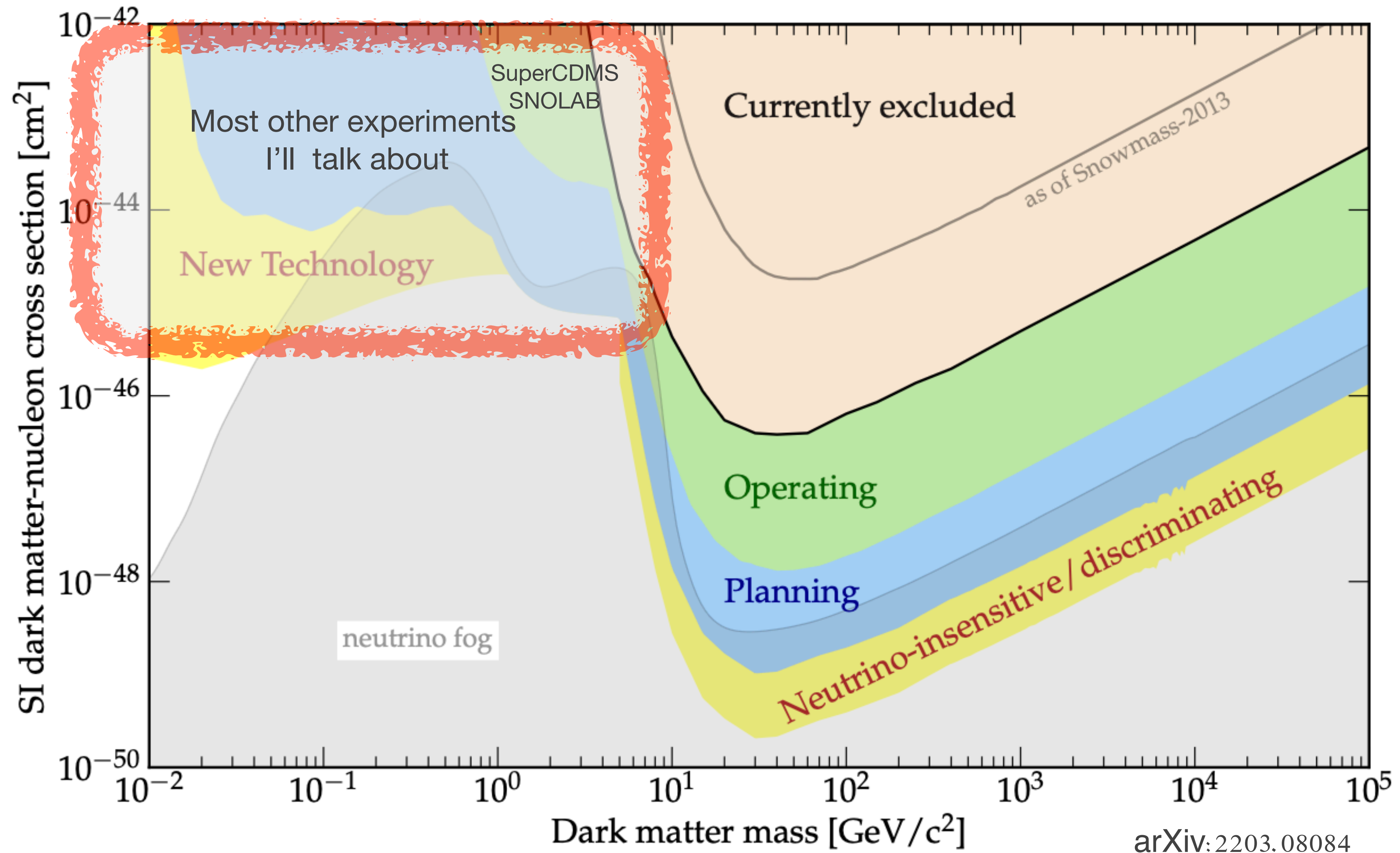


# Going to the neutrino fog





# Going to the neutrino fog





# Detecting light particle dark matter?

- Looking for interactions with target nuclei or electrons
- For lower masses it's all about
  - Lowering backgrounds: radioactivity and **detector effects**
  - Lowering the energy threshold: many detectors essentially looking at single quanta
- Want: Position reconstruction and a low background area
- No Particle ID available!
- Calibrations of energy & position corrections
- Interpretations beyond Spin-Independent DM-nucleon







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

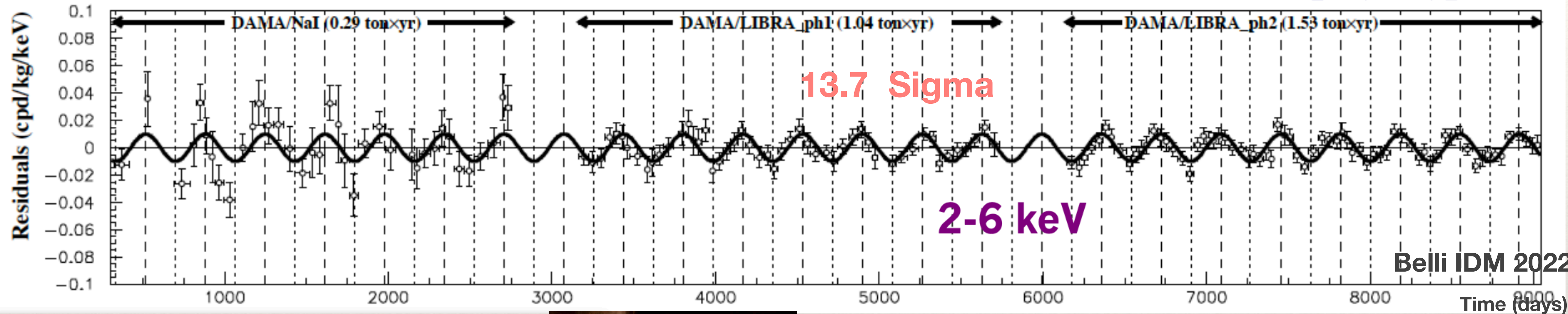


# NaI crystals: DAMA/LIBRA signal

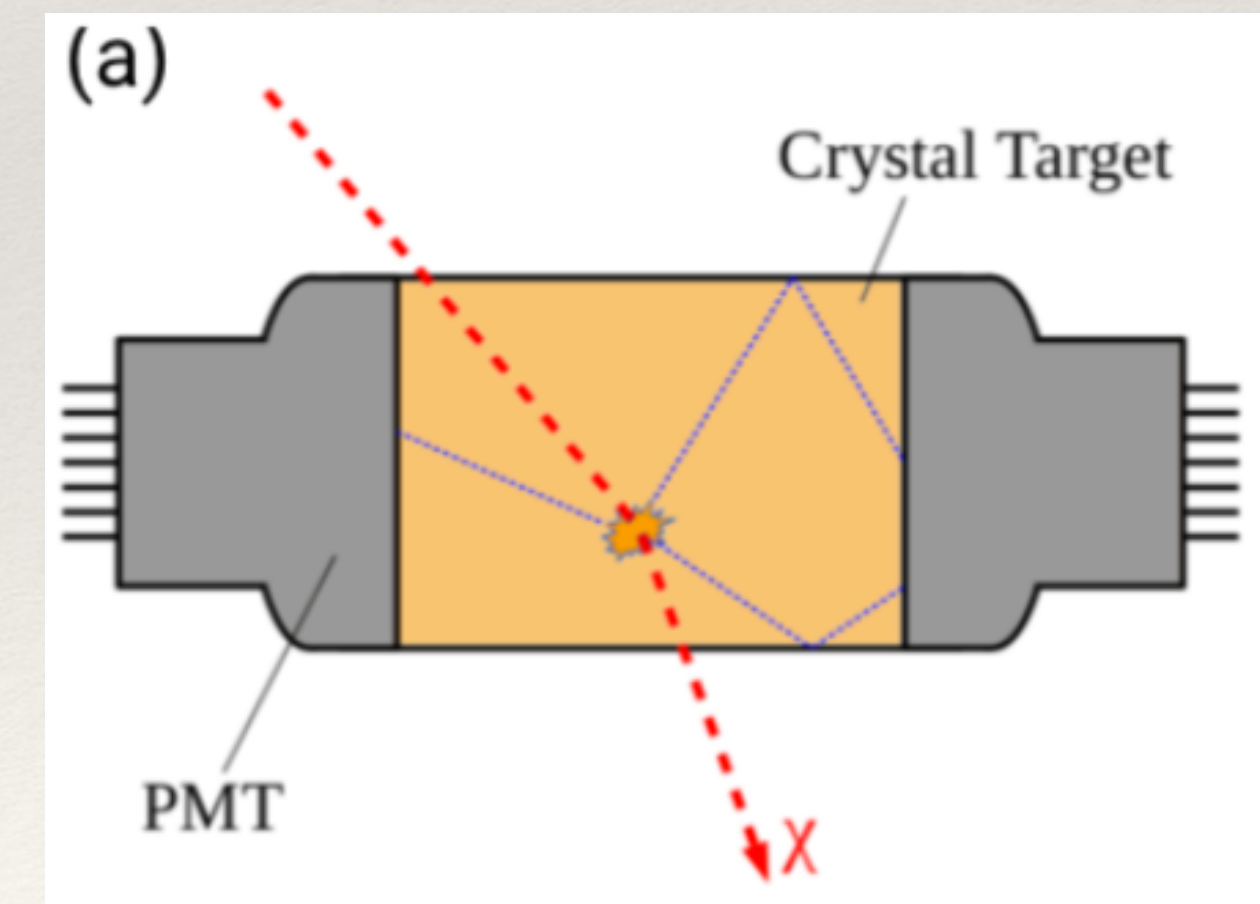
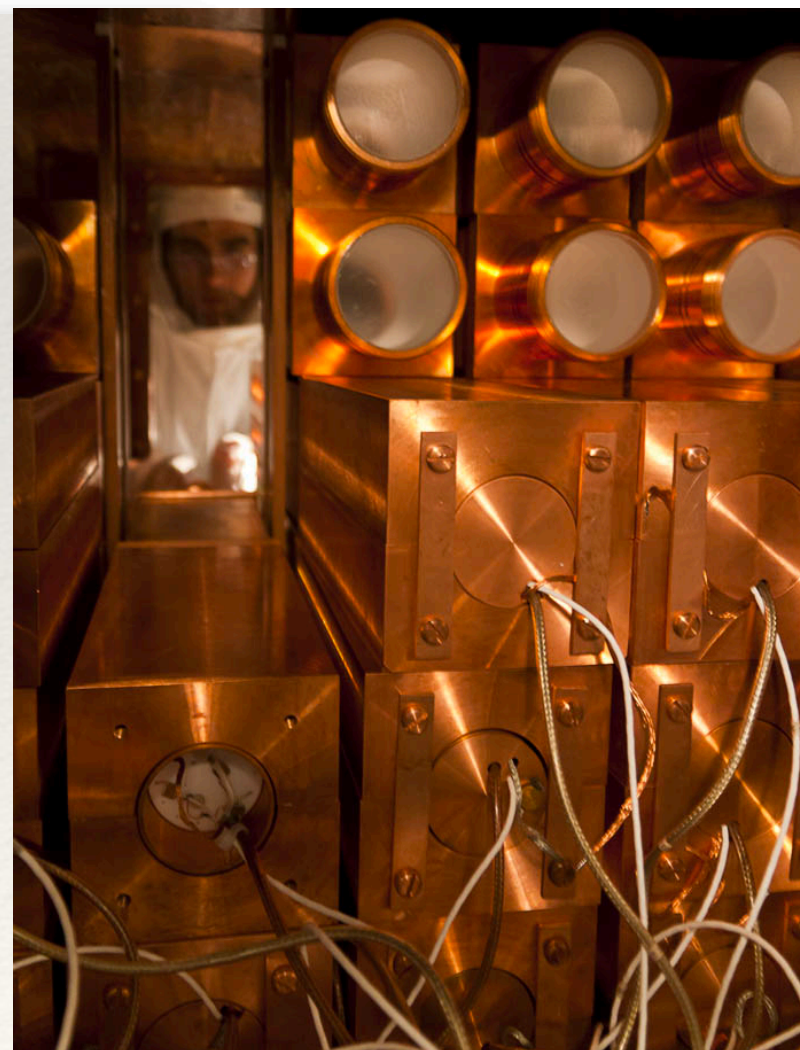
DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.86 ton × yr)

2-6 keV

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

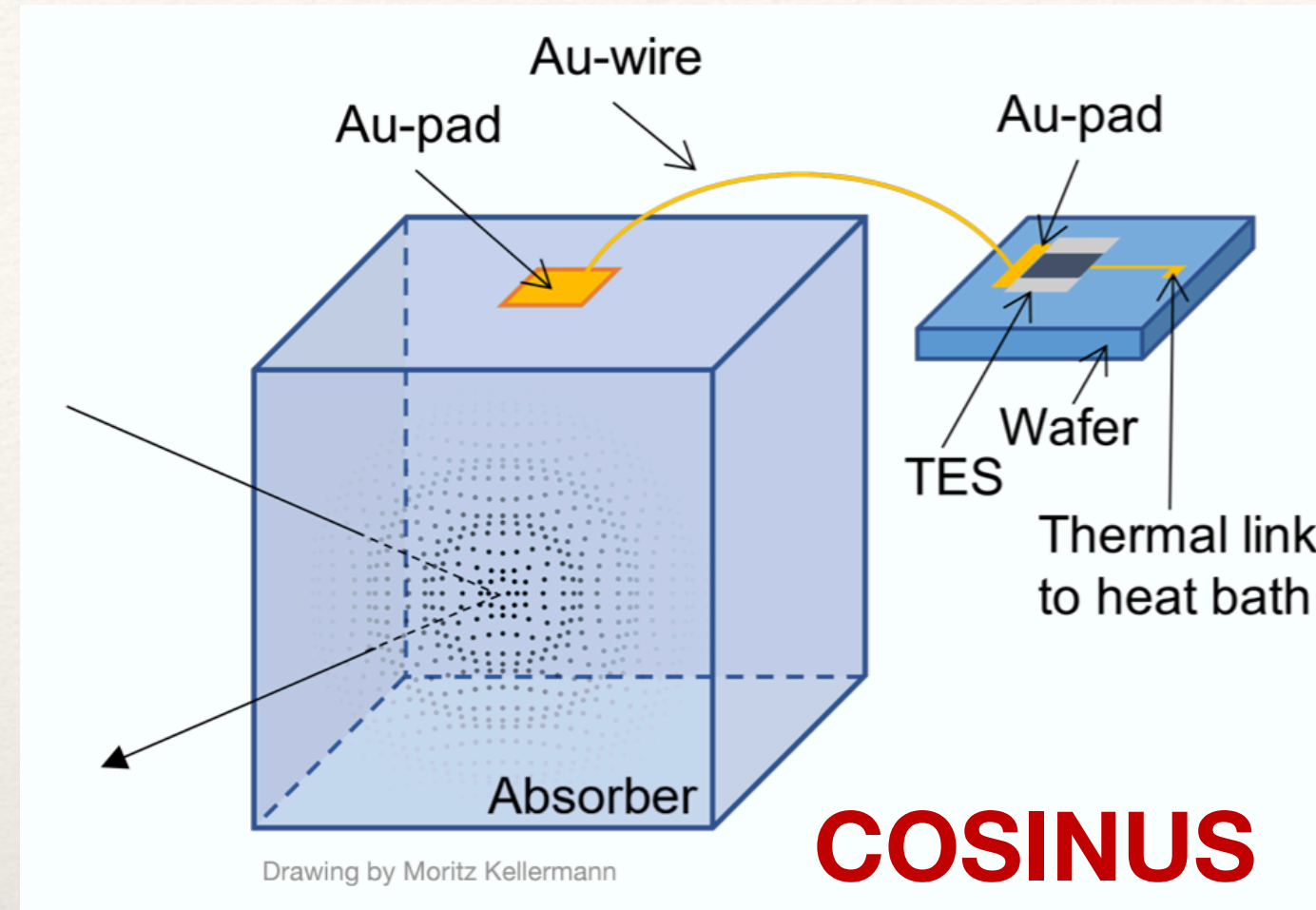
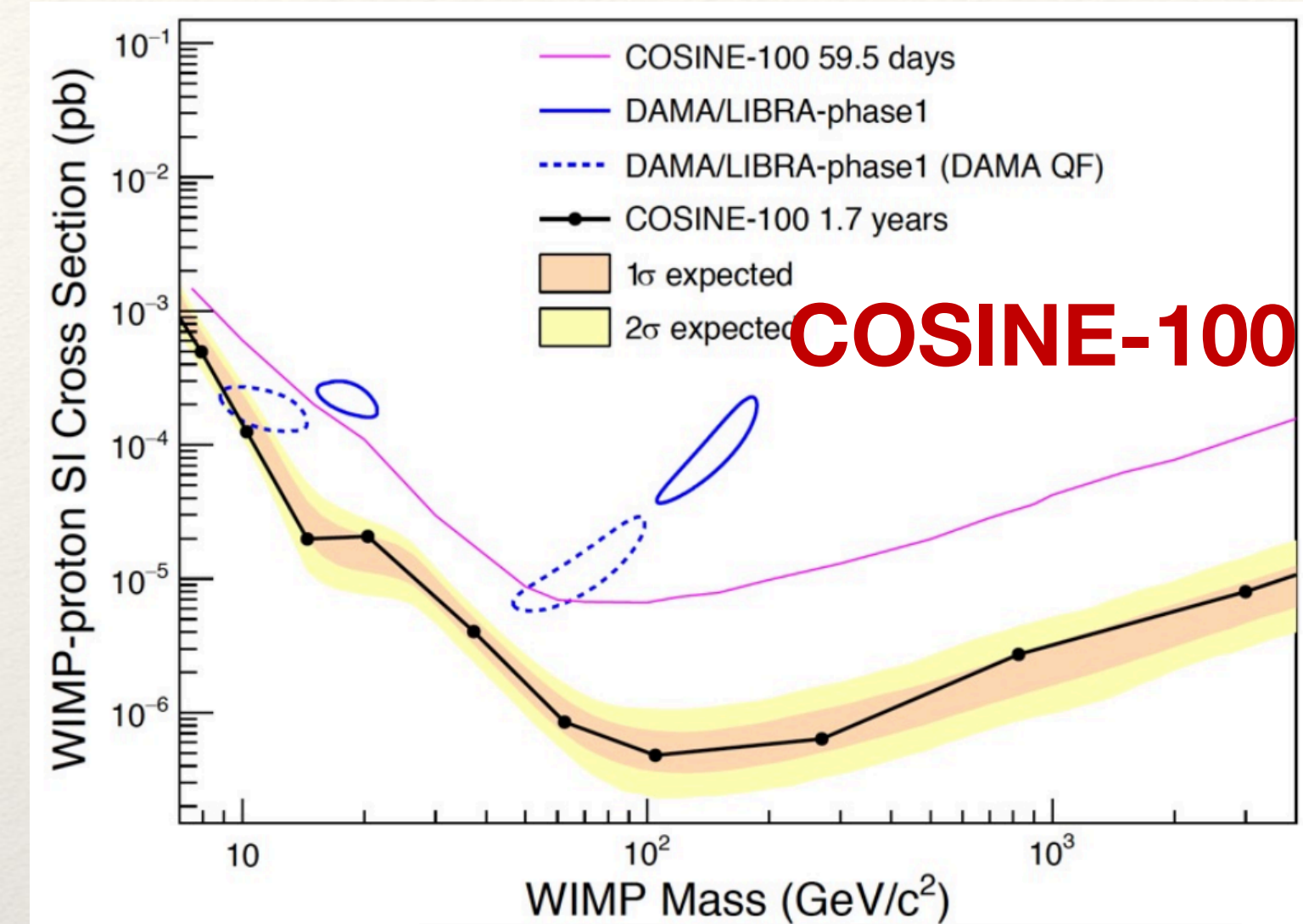


- Annual Modulation seen at  $>13\sigma$
- Not SI isospin-conserving
- Isospin-violating SI at  $\sim 10 \text{ GeV}/c^2$ ,
  - or SD at 10 or 45  $\text{GeV}/c^2$
  - key reason to think about low mass
- Also studied with updated quenching



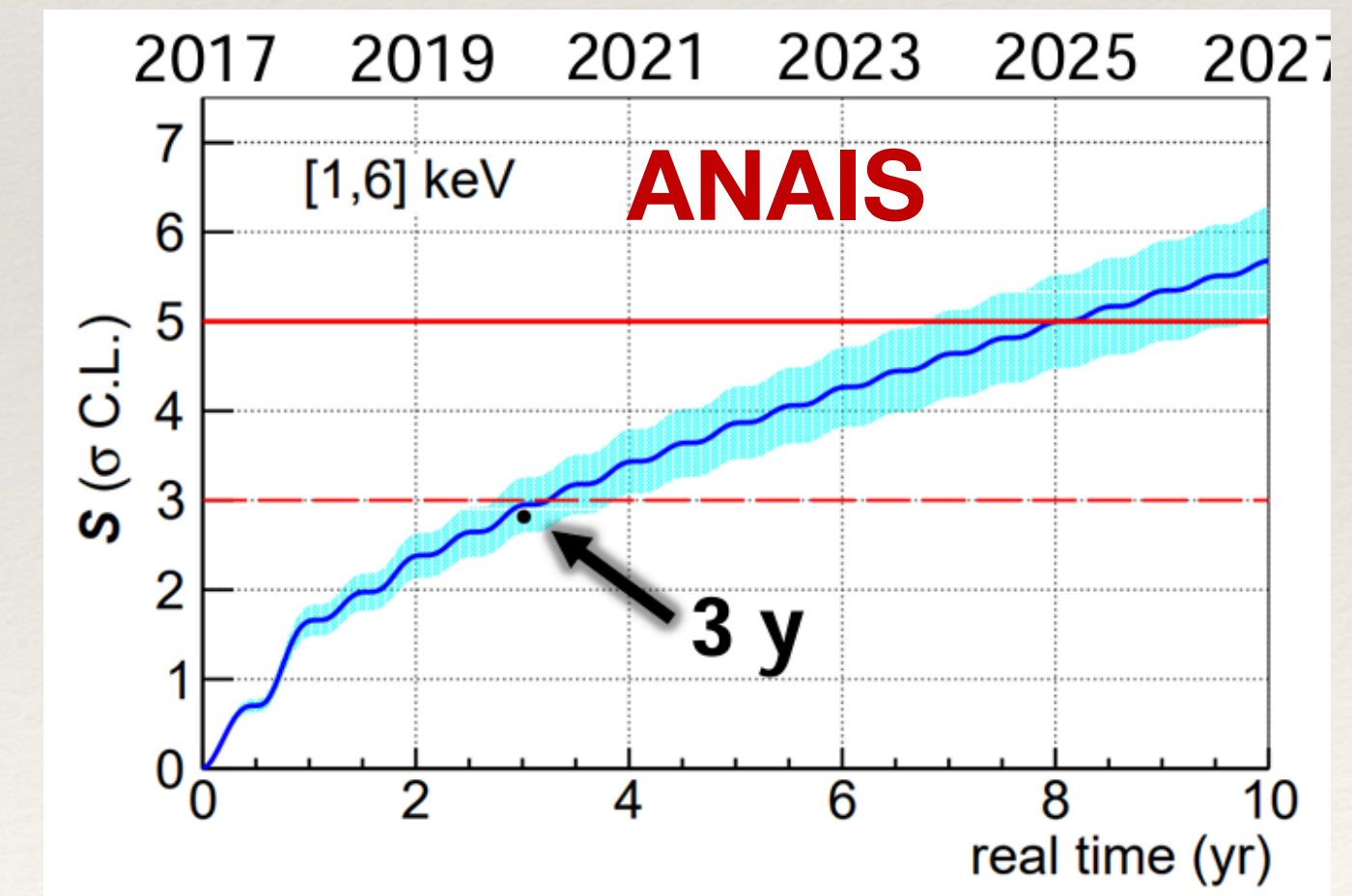
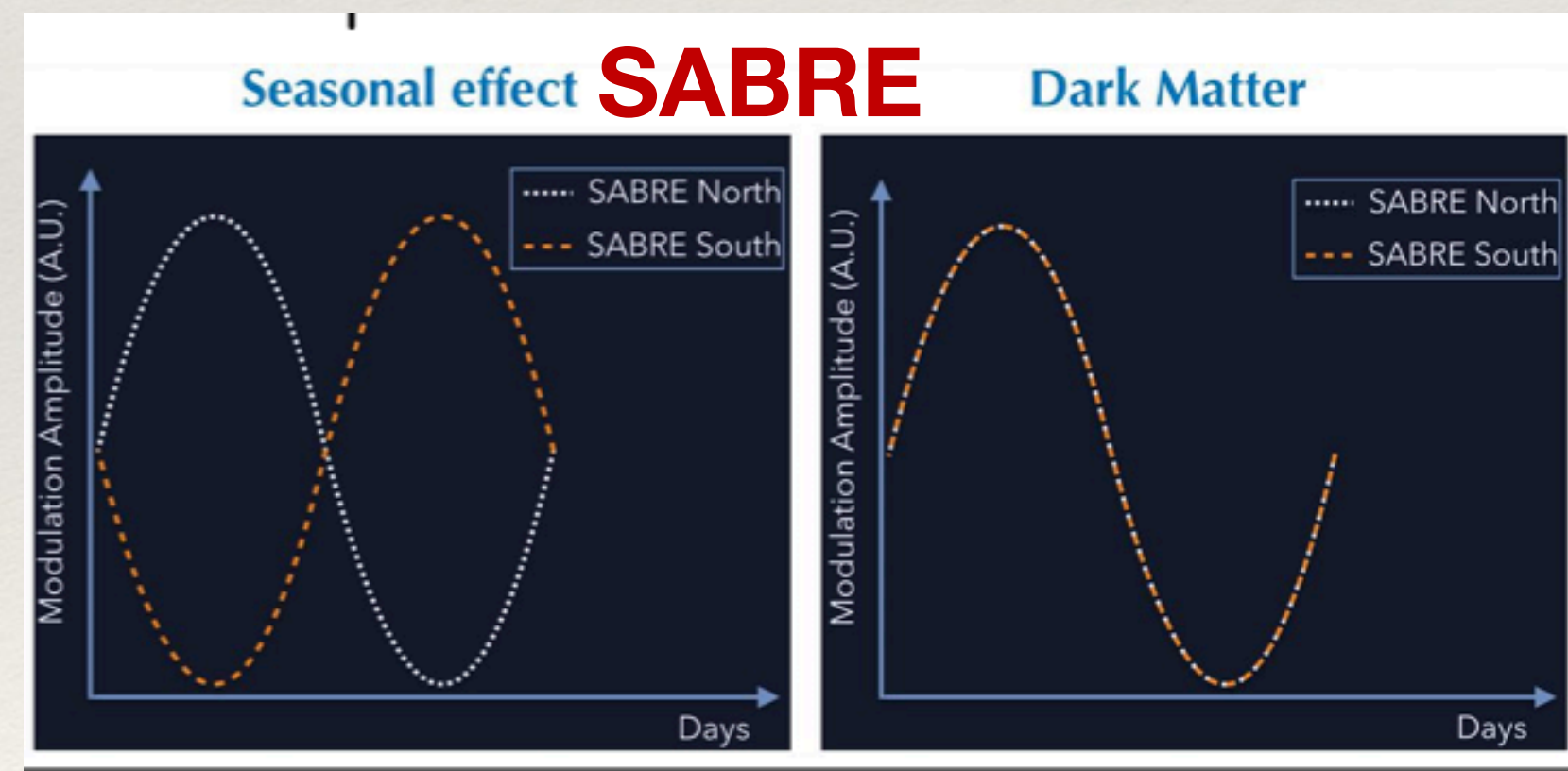
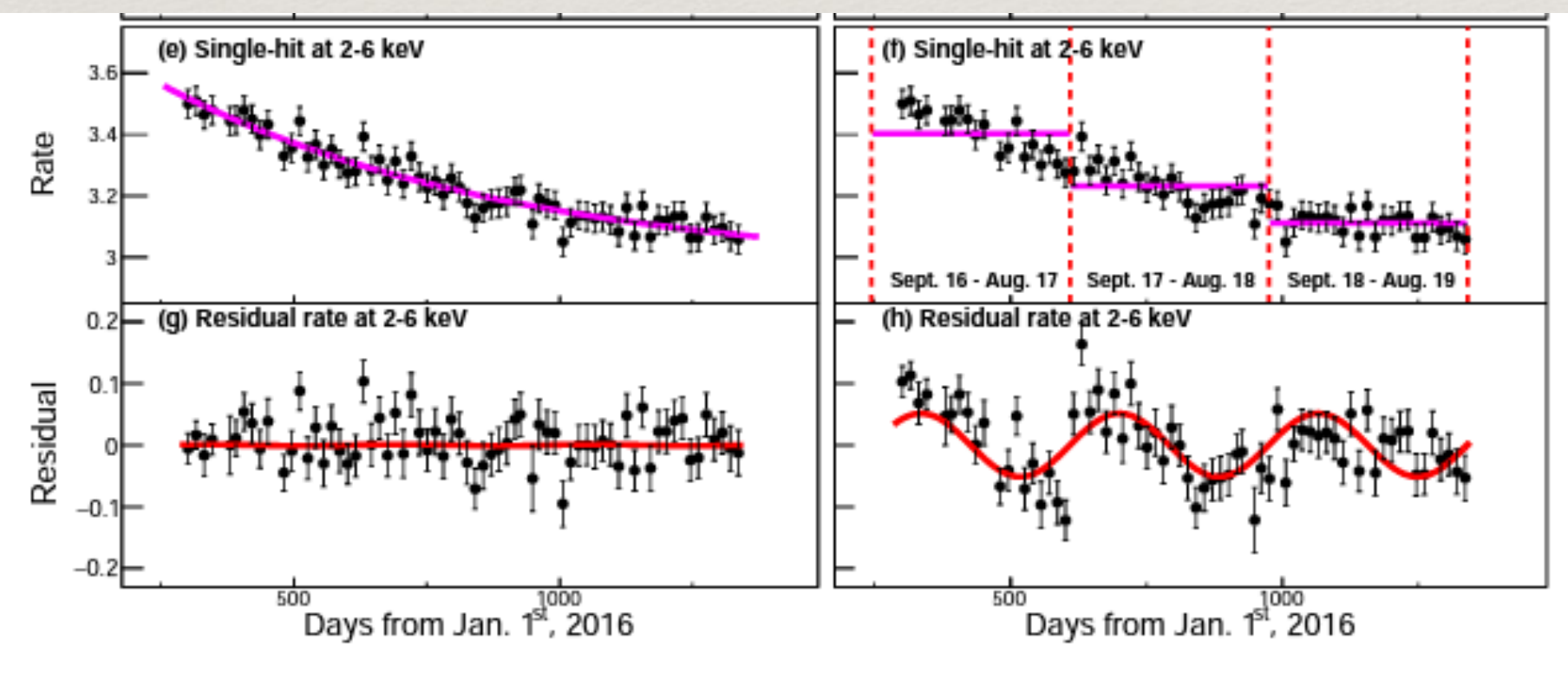


# Nal tests: ongoing and future



- 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  $\sigma$  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



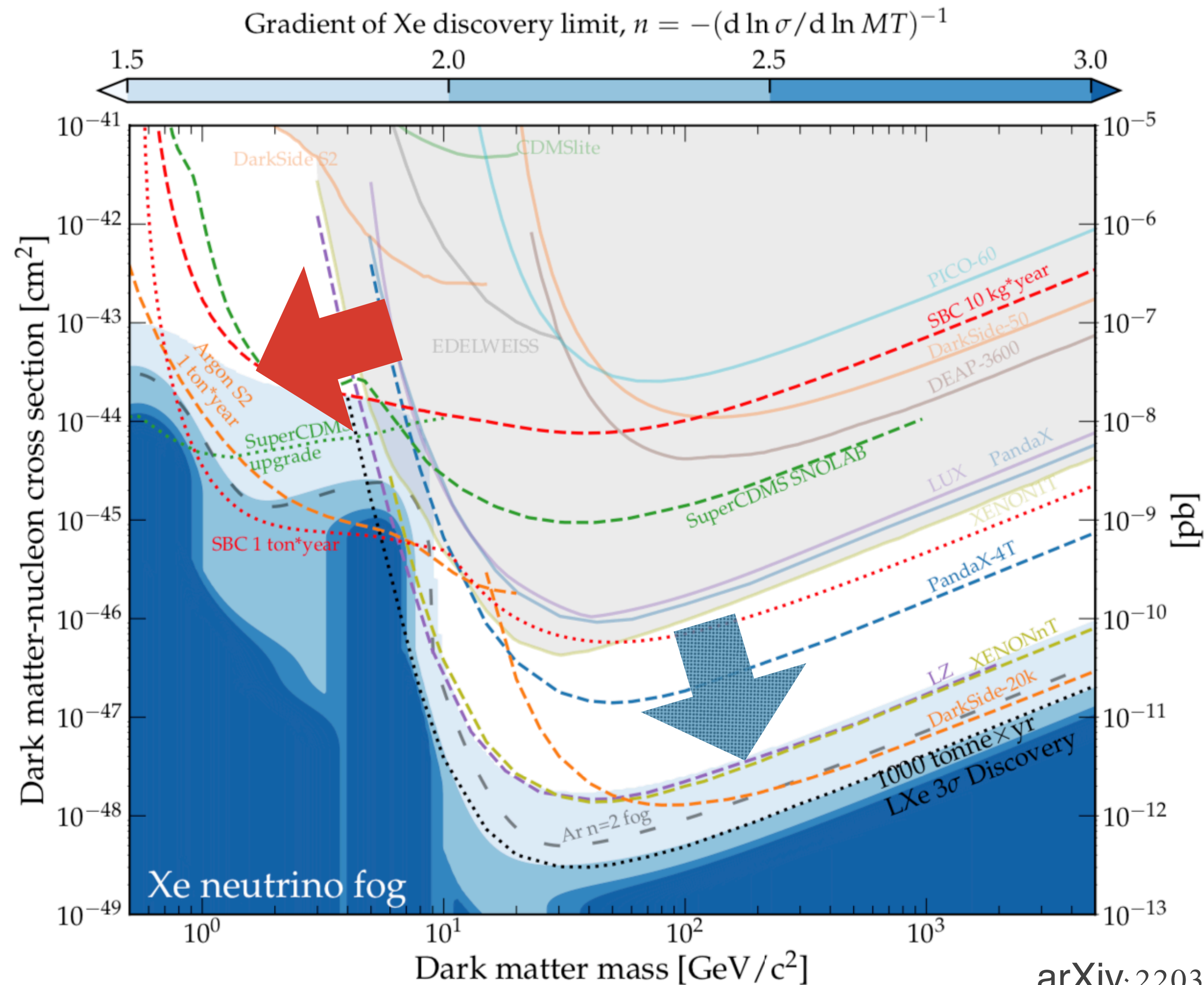


For DM masses 1-10  $\text{GeV}/c^2$ ,  
there is a lot of activity!

Timing may be more important than technology in  
covering the available parameter space.



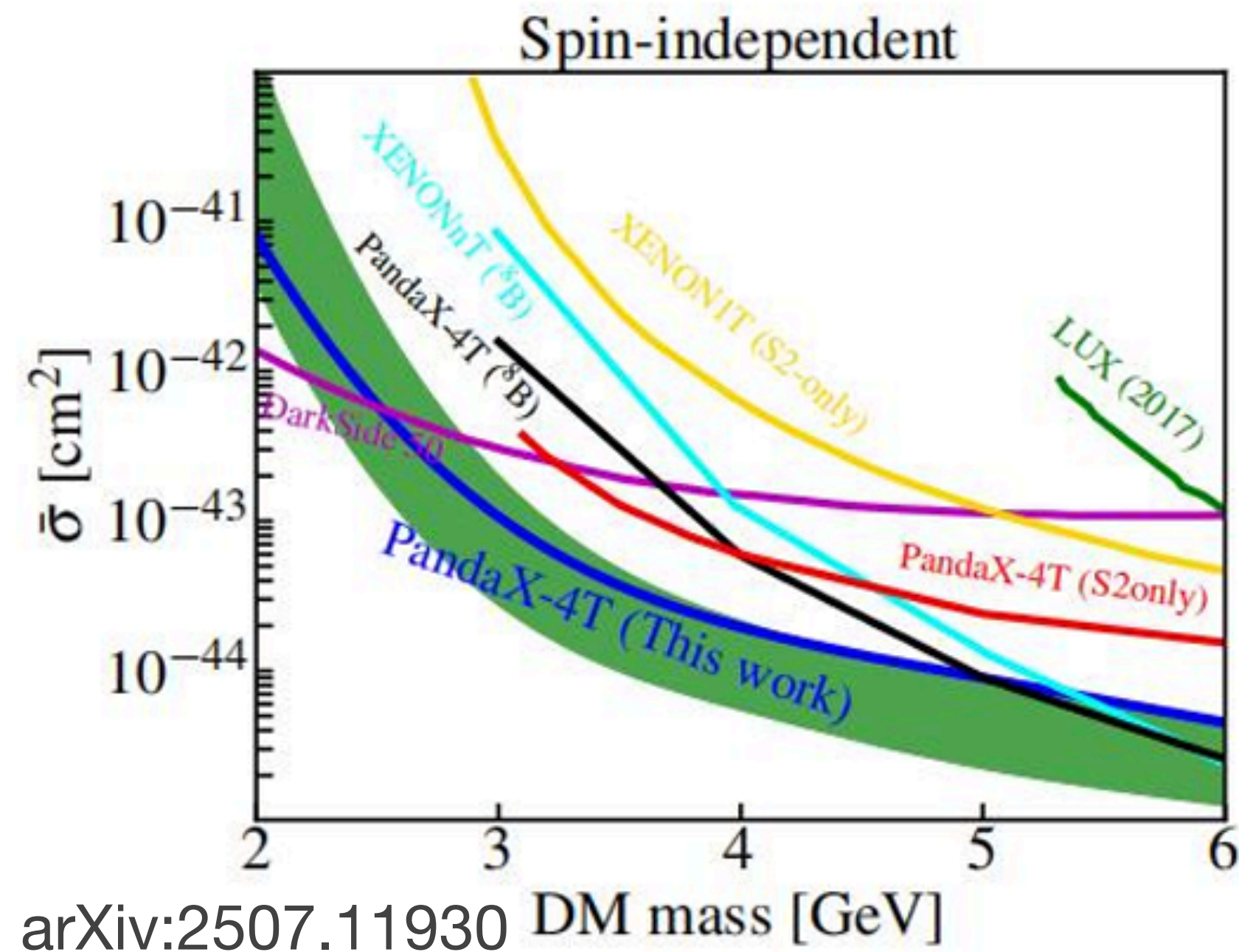
# Going to Lower Masses



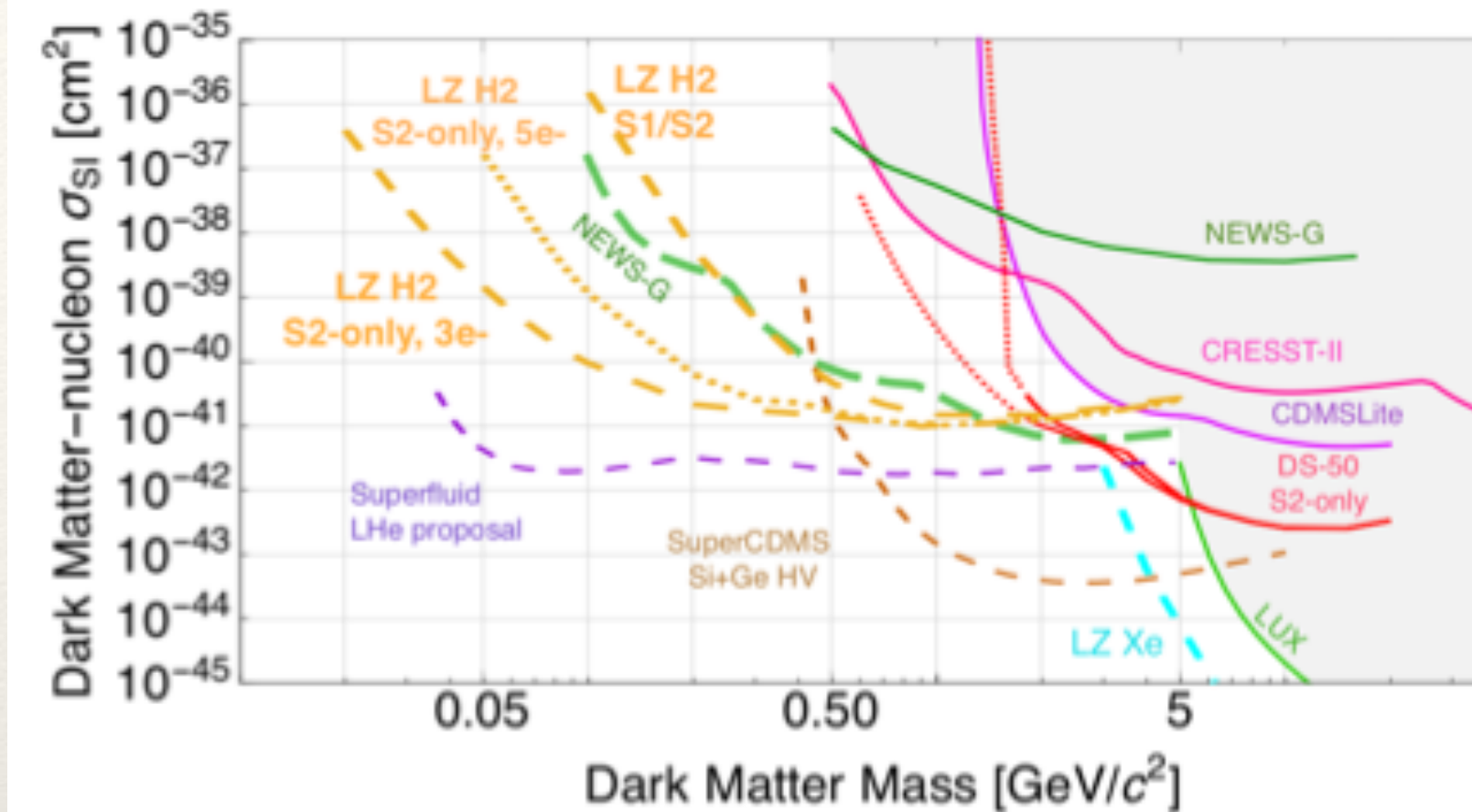
- Lower mass region can be reached by multiple technologies, ones with long histories in the search for dark matter, as well as new.
- Generally smaller target masses (both in total mass, as well as atomic masses), and interest in spin-dependent models too.



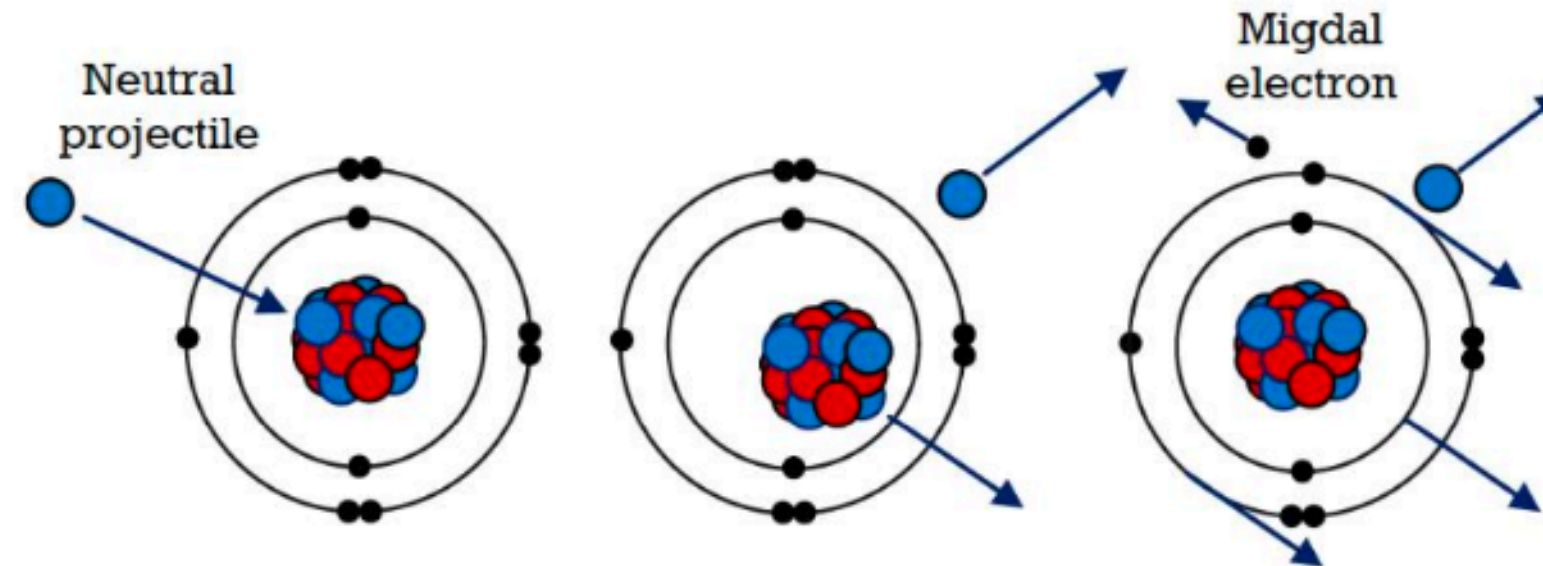
# Once more, from the nobles...



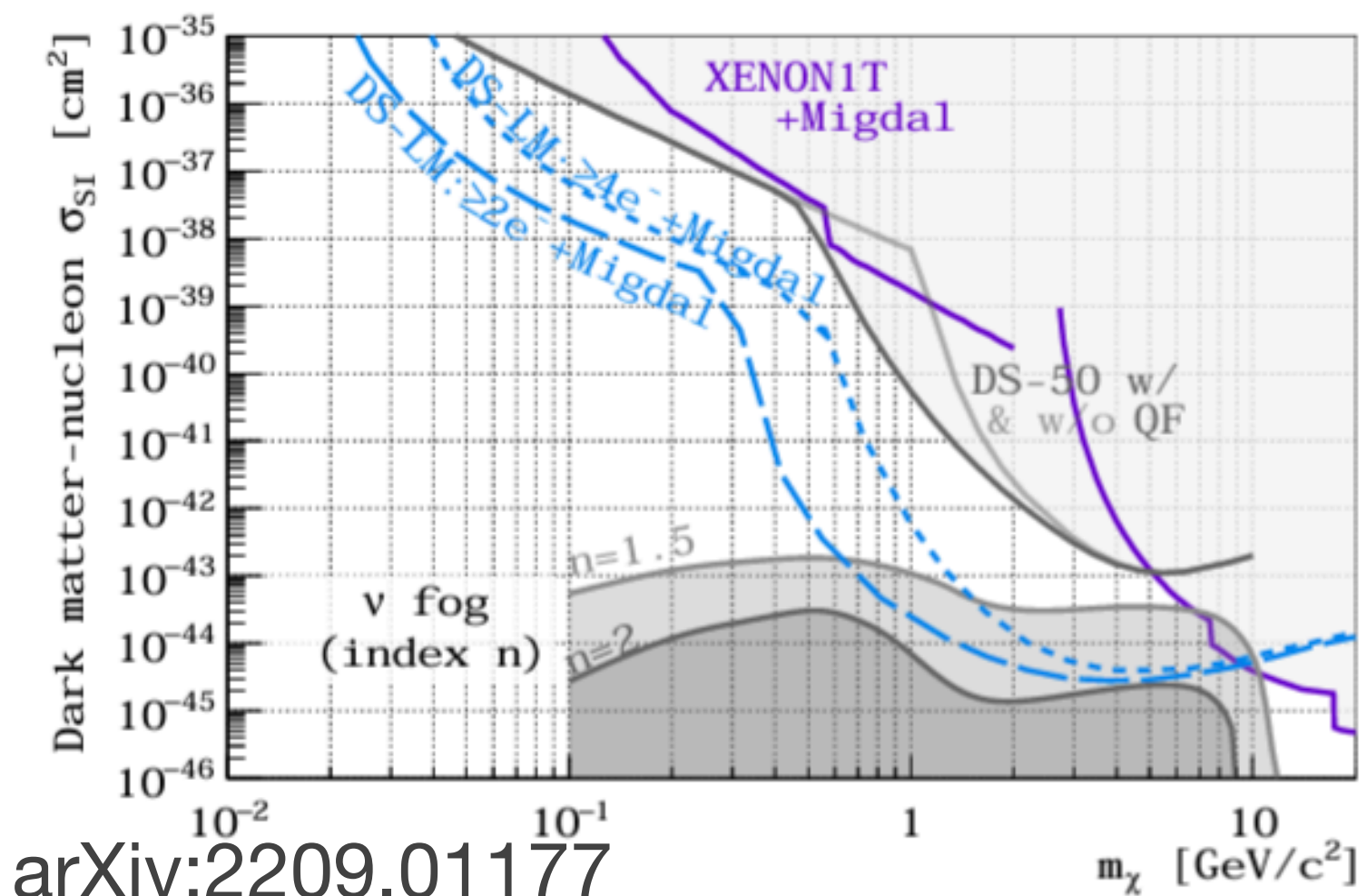
- Future: S2-only searches from current detectors (with Migdal?)
- HydroX
  - Proposed doping of LXe detector with H
- DarkSide-LowMass
  - Proposed 1T detector to get to neutrino fog in 1t-yr exposure



- Leading limits are from PandaX-4t 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



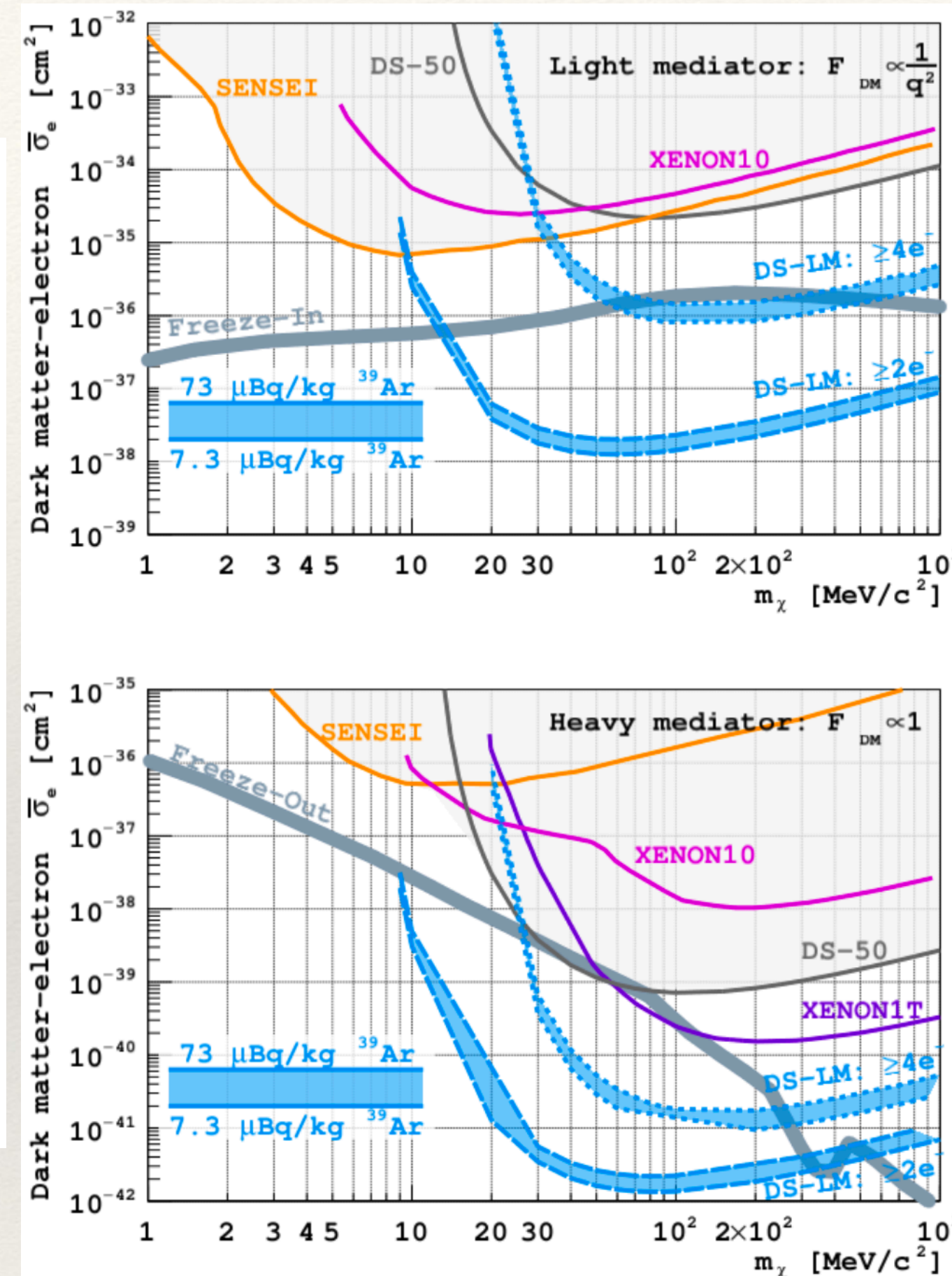
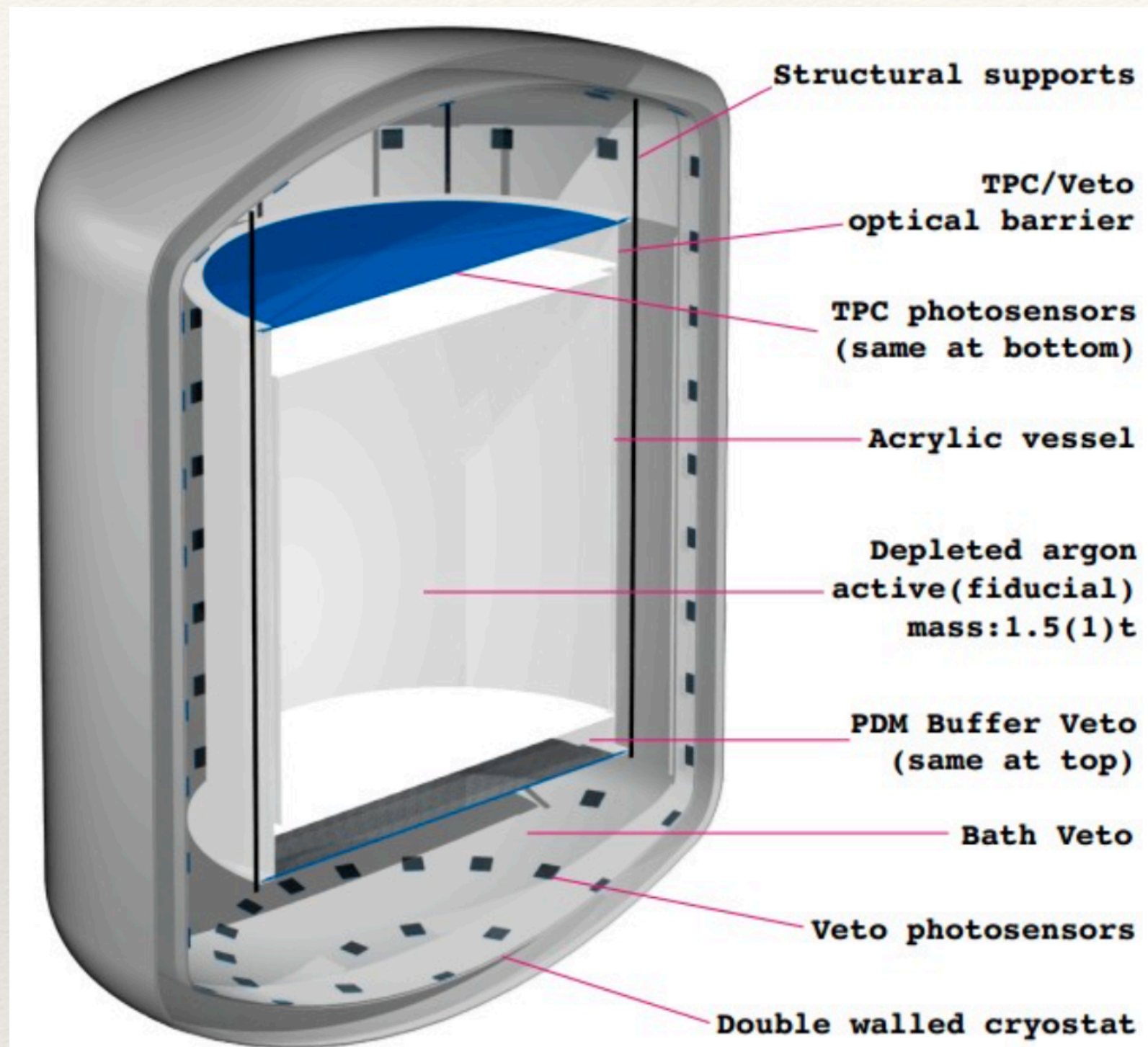
Migdal event topology involves a nuclear recoil and electron recoil originating from the same vertex.



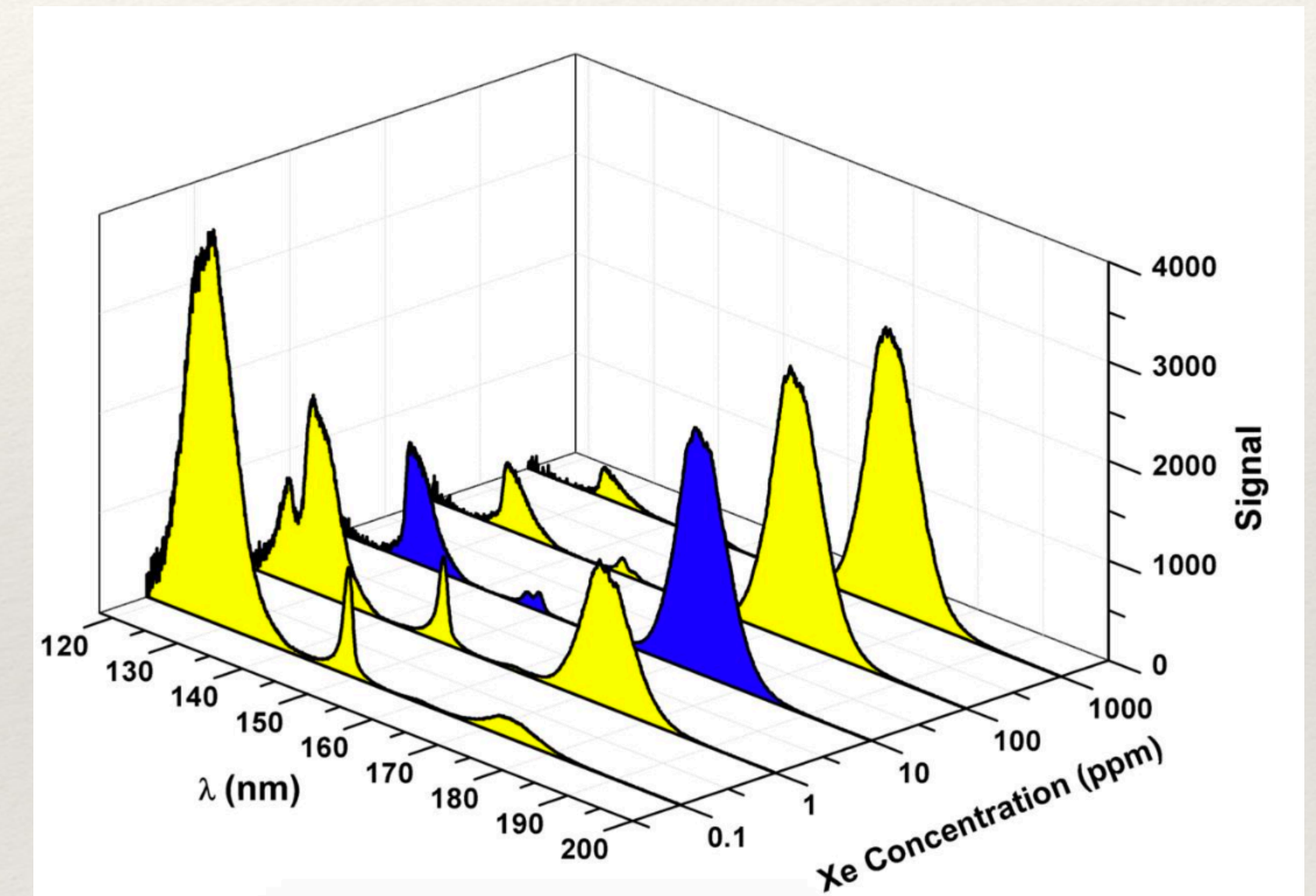


# Proposed: Low Mass Liquid Nobles

DarkSide-Low-Mass  
Westerdale UCLA DM 2025



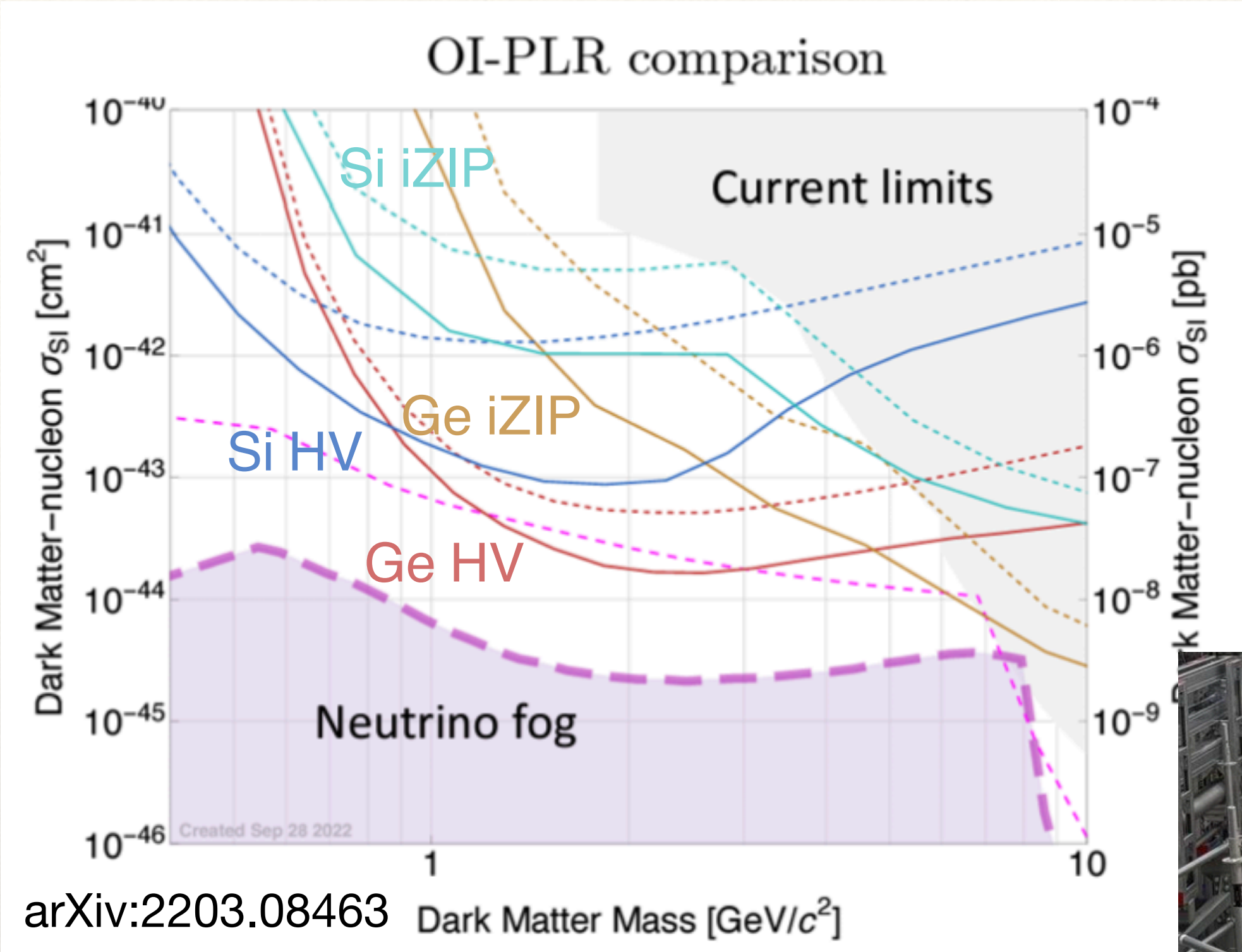
CHILLAX: Xe doped (low %) Ar  
–best of both targets?



Spectra of scintillation light emission in liquid argon-xenon mixtures  
*A. Neumeier et al., Europhys. Lett. 109 12001 (2015)*

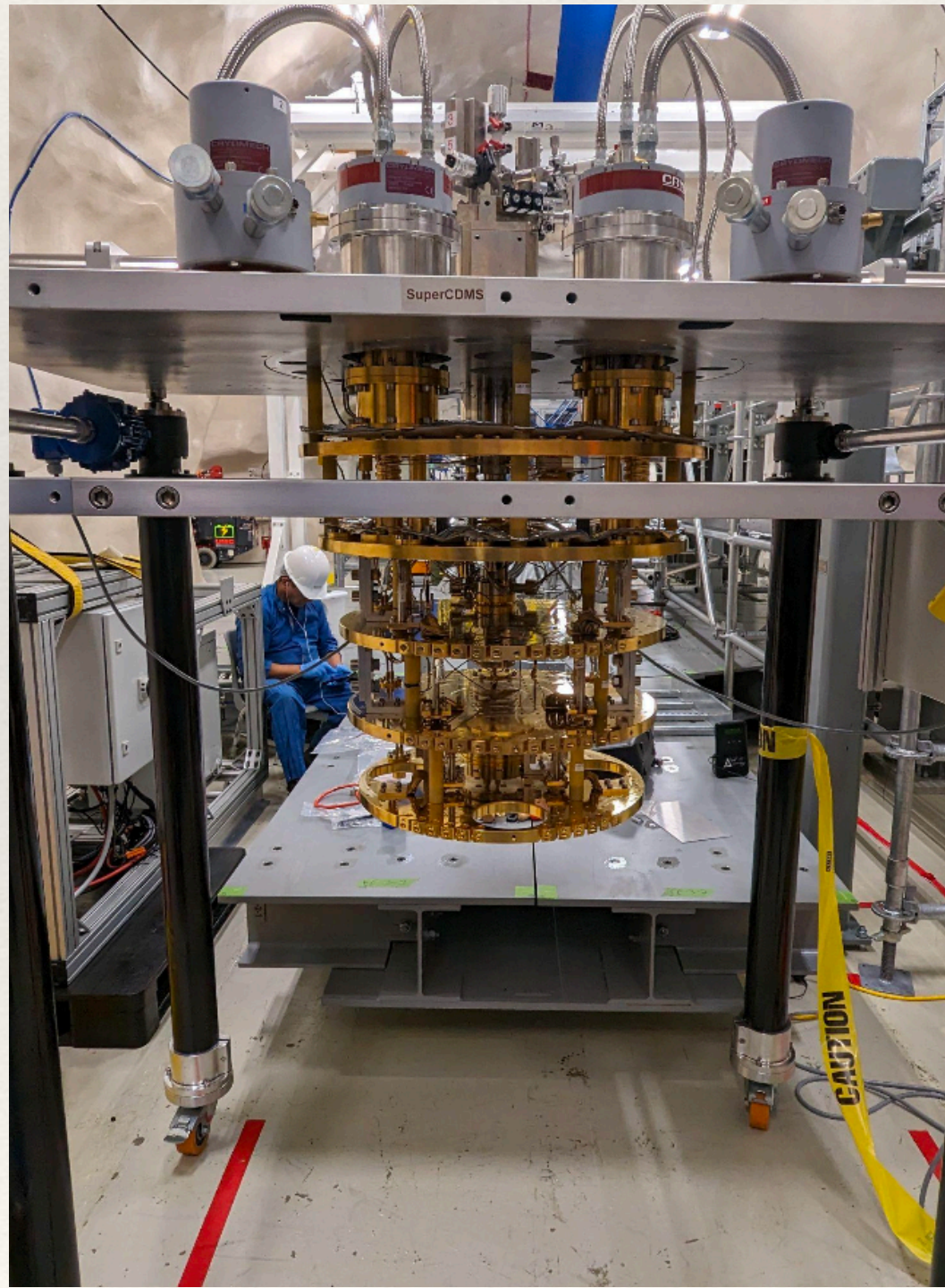
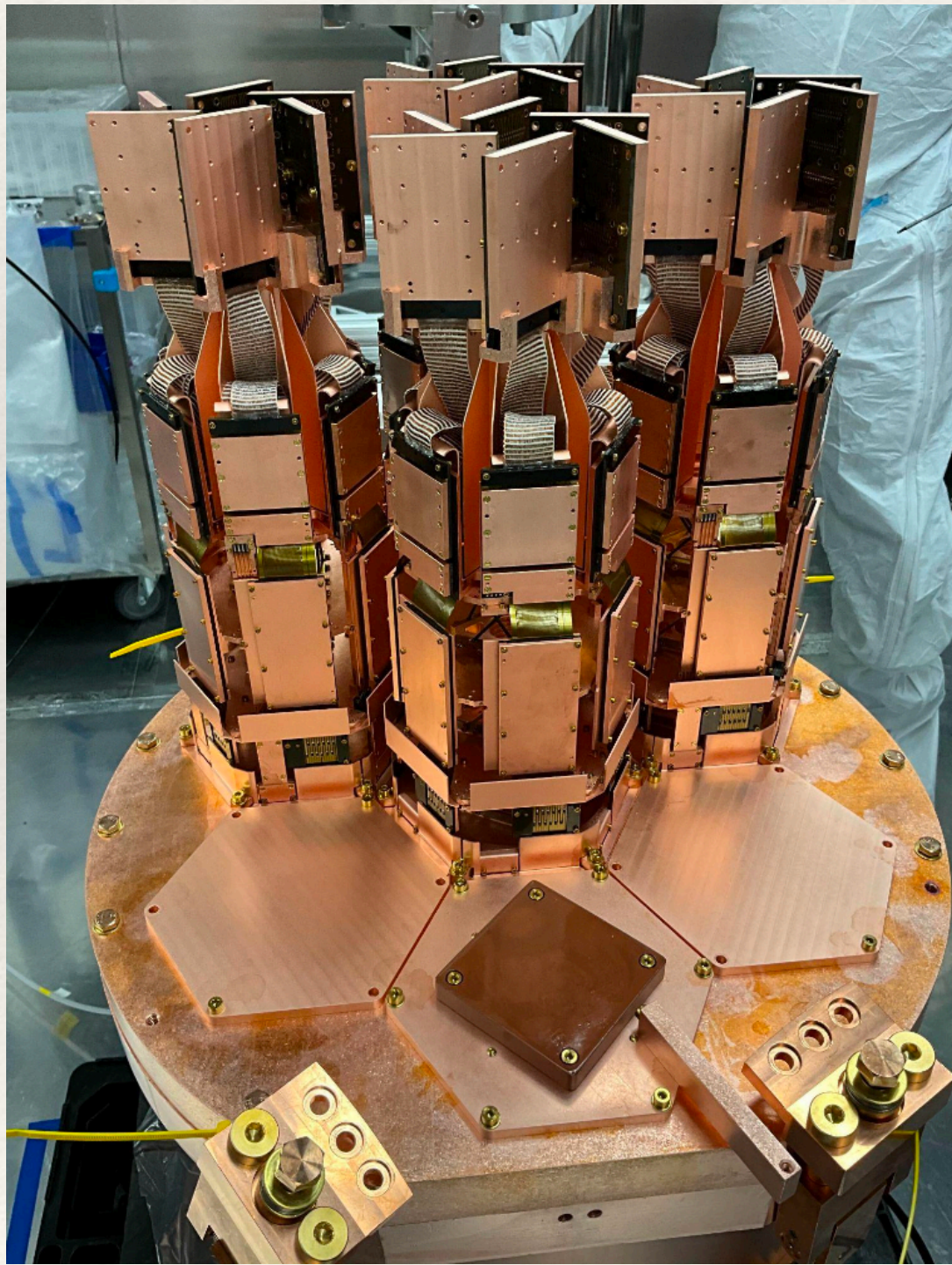


# SuperCDMS



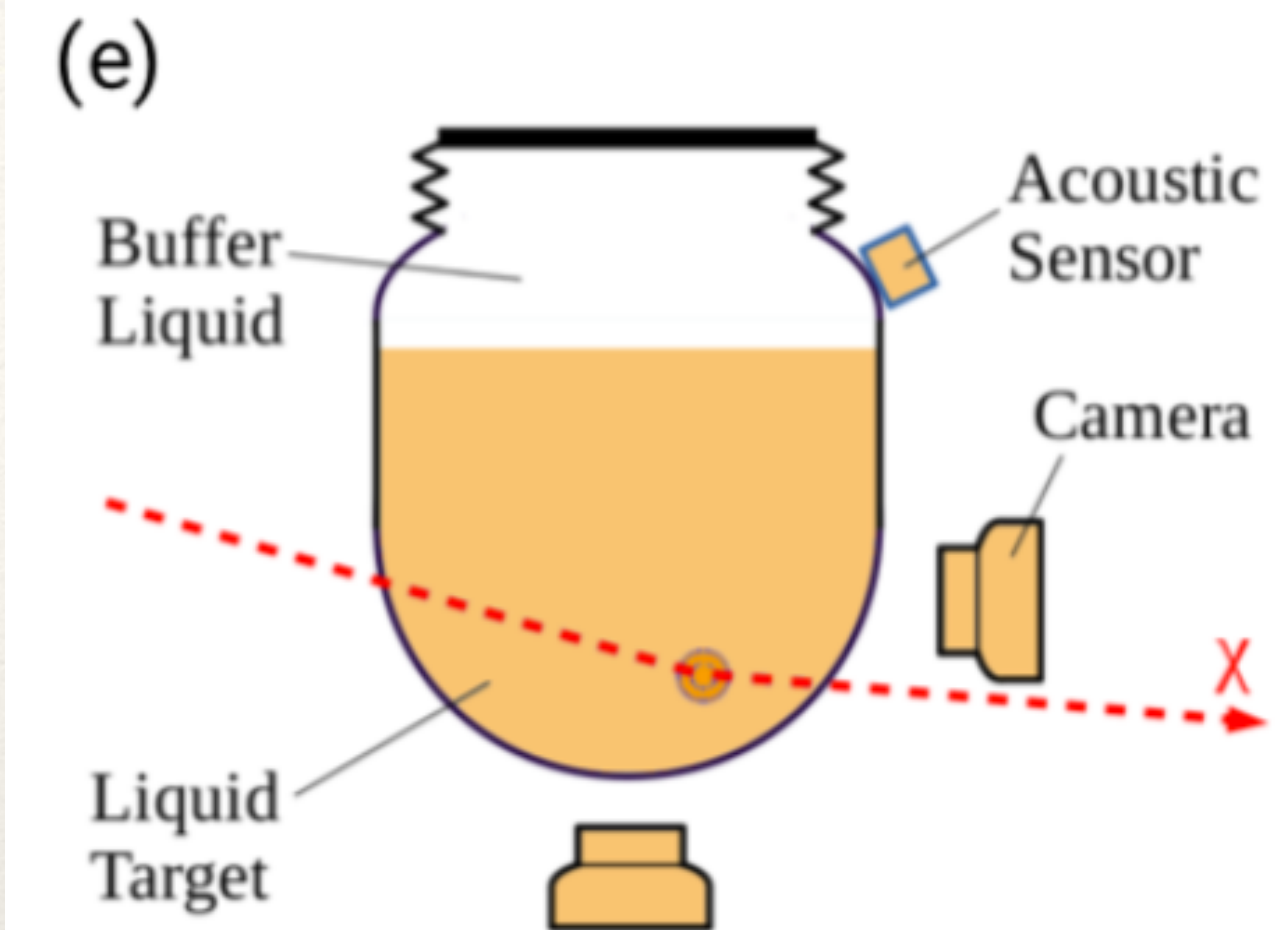
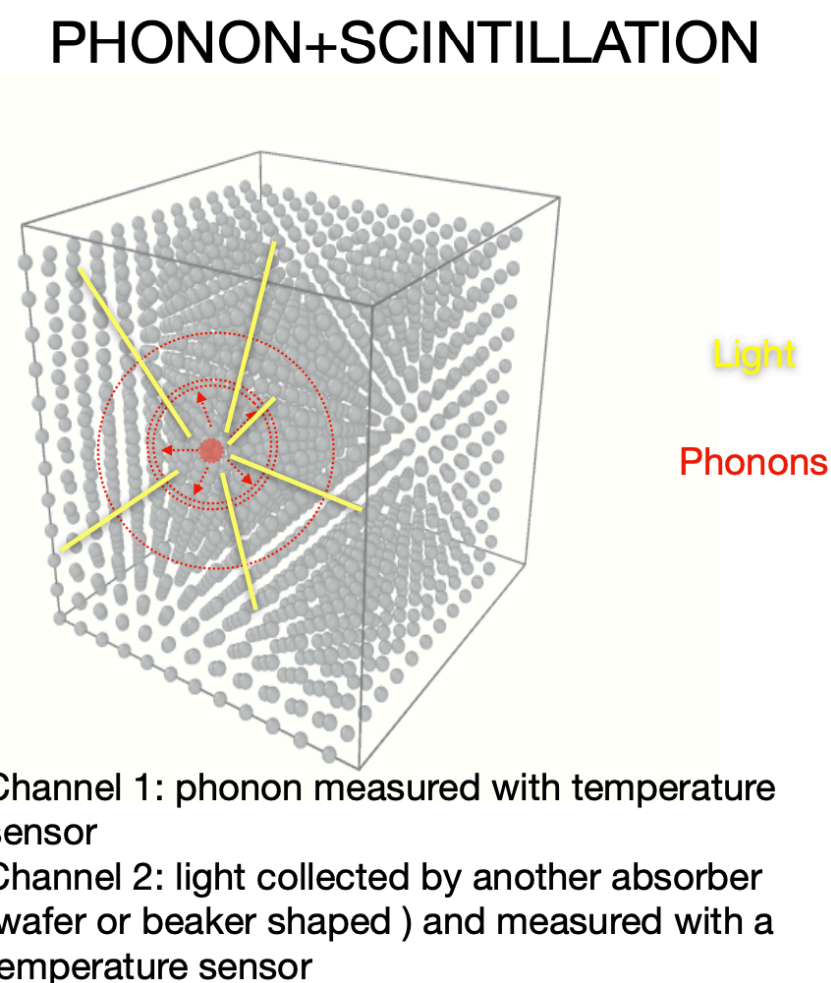
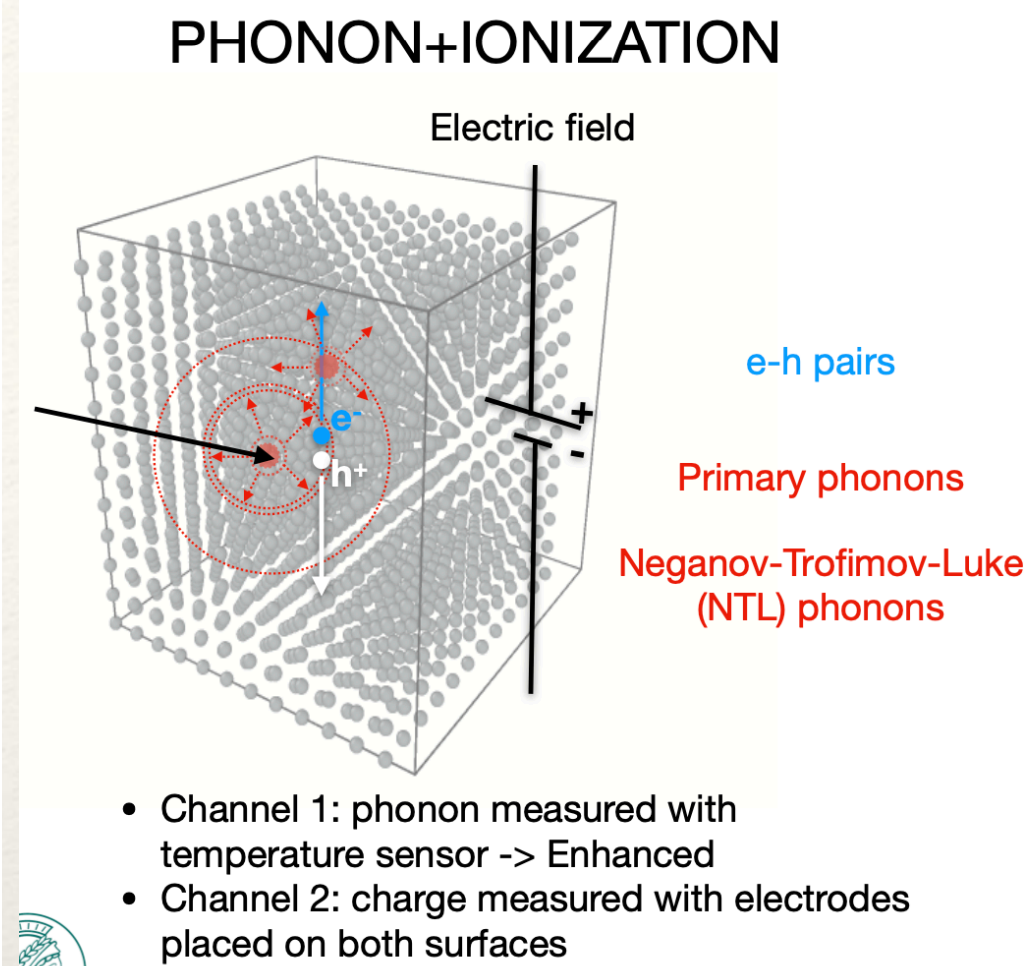
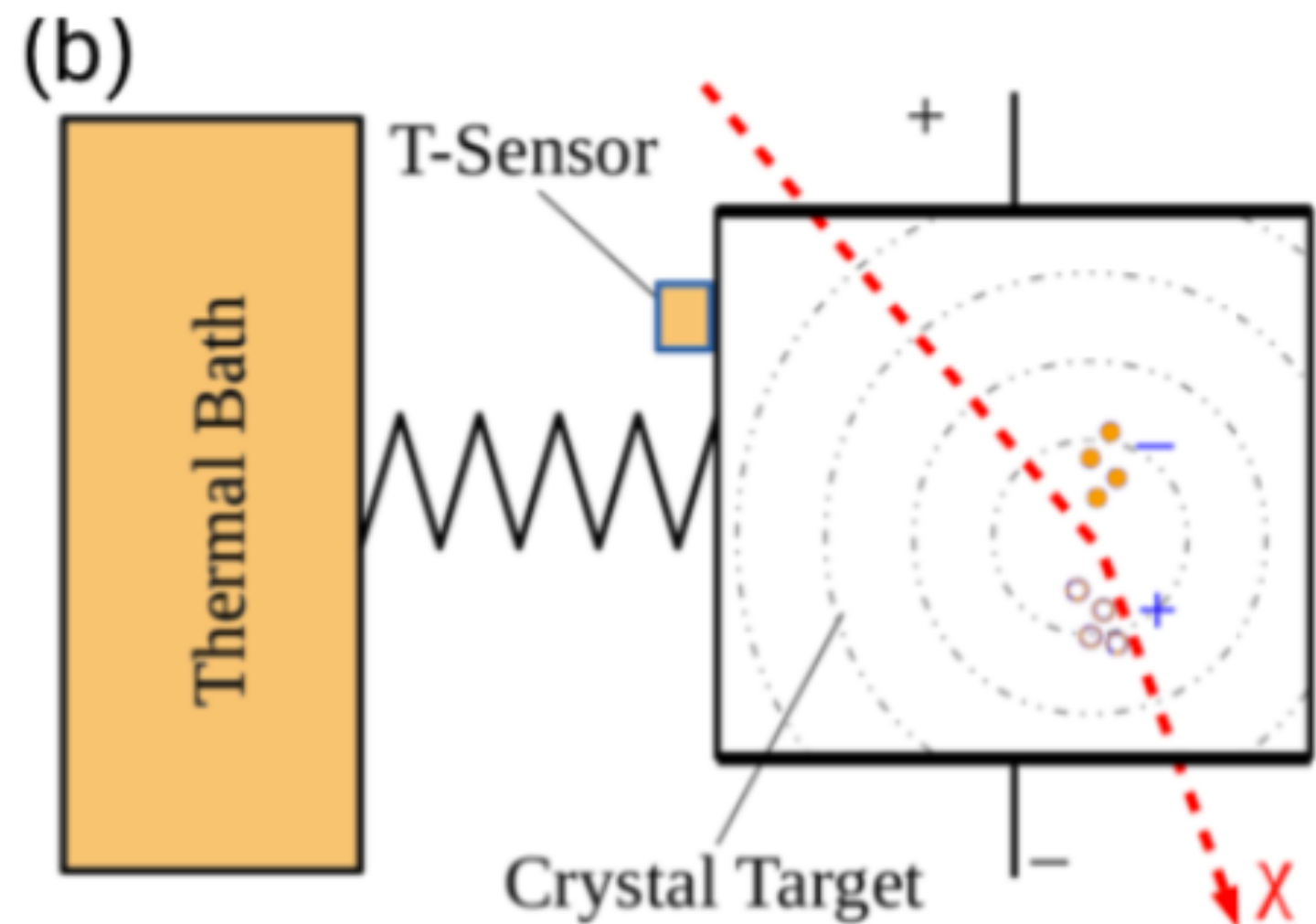
	Germanium	Silicon
<b>HV</b>	Lowest threshold for low mass DM Larger exposure, no $^{32}\text{Si}$ bkgd	Lowest threshold for low mass DM Sensitive to lowest DM masses
<b>iZIP</b>	Nuclear Recoil Discrimination Understand Ge Backgrounds	Nuclear Recoil Discrimination Understand Si Backgrounds

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



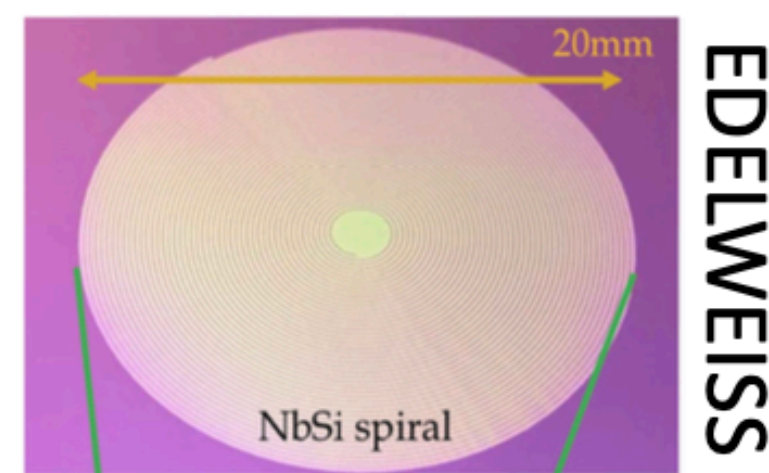
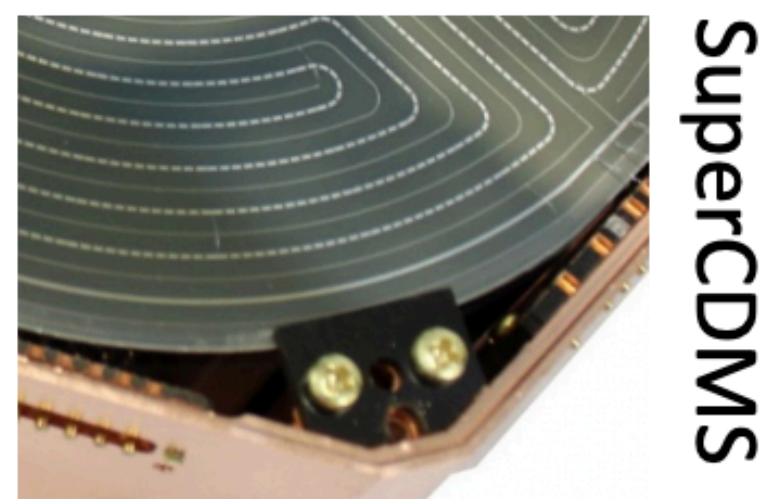
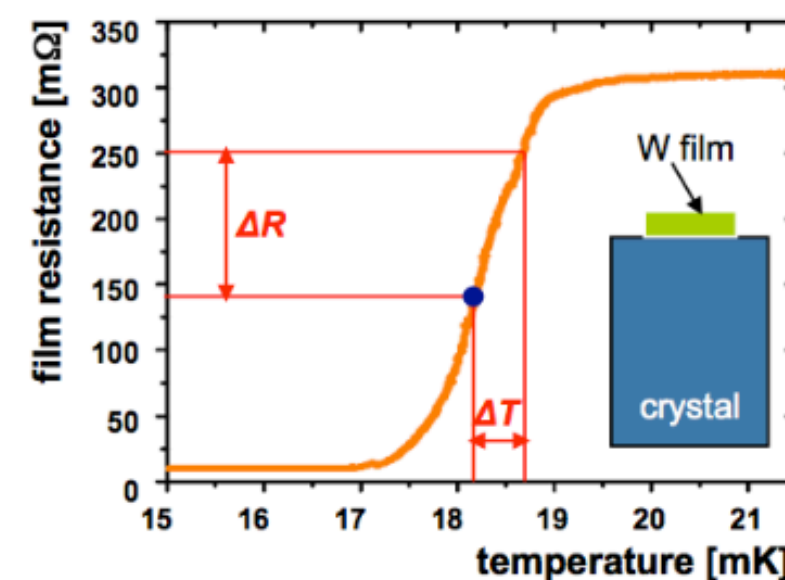


# Low Mass Dark Matter Search technologies



## CRESST, SuperCDMS, COSINUS, EDELWEISS<sup>NEW</sup> Transition-Edge-Sensor (TES)

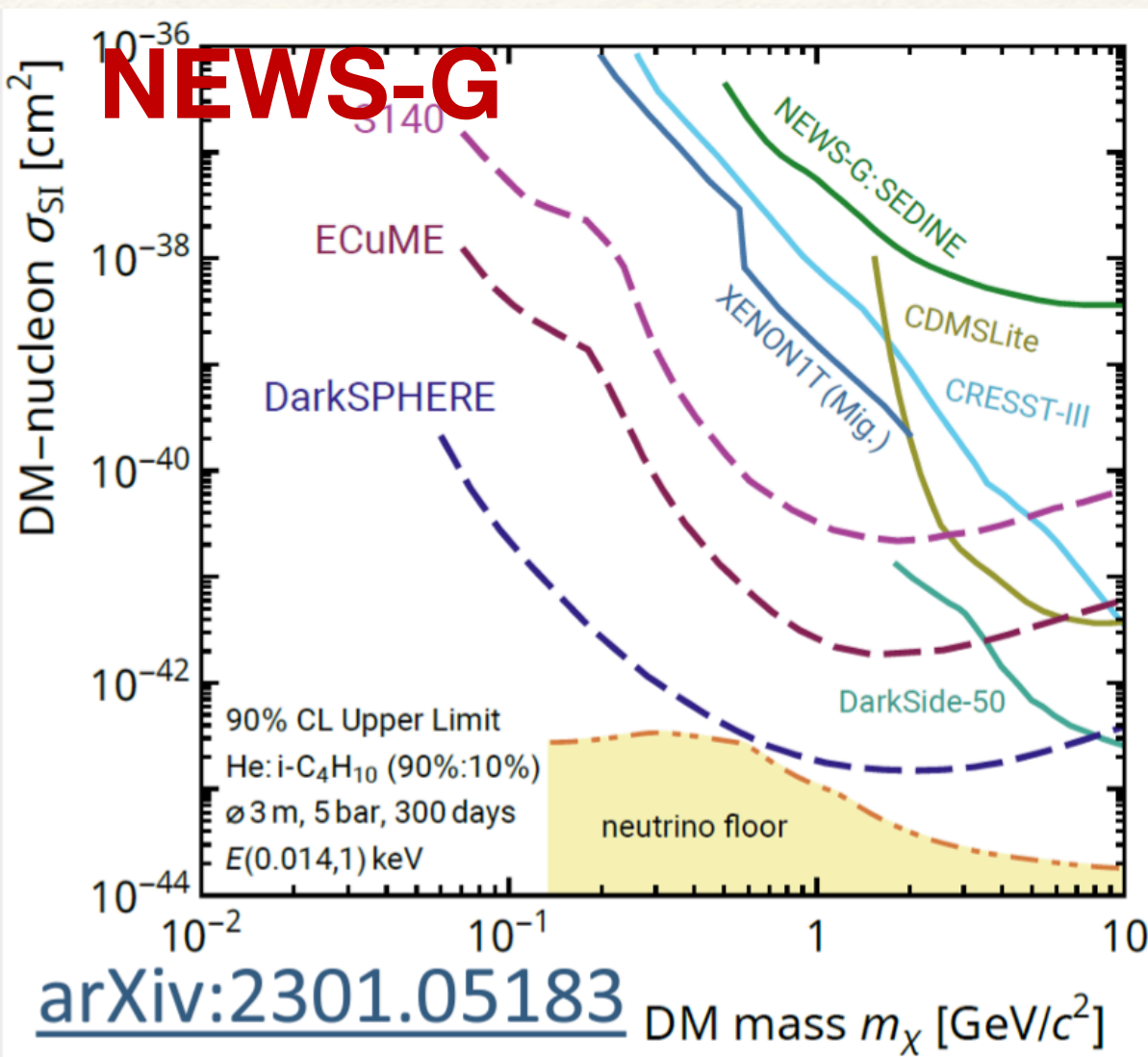
- Thin-film deposited on crystals
- Strong R-T dependence at superconducting transition
- Sensitive to athermal phonons



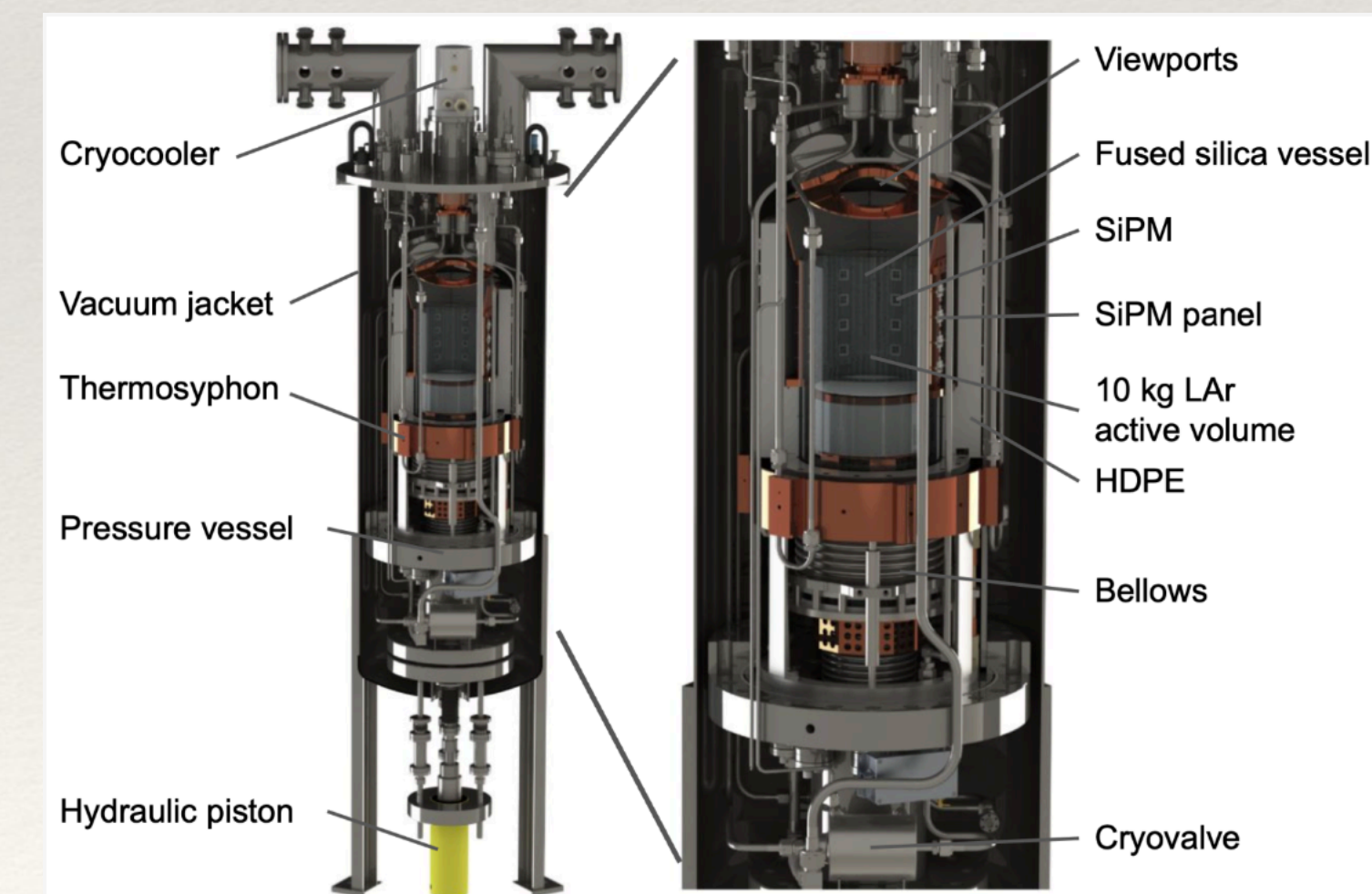
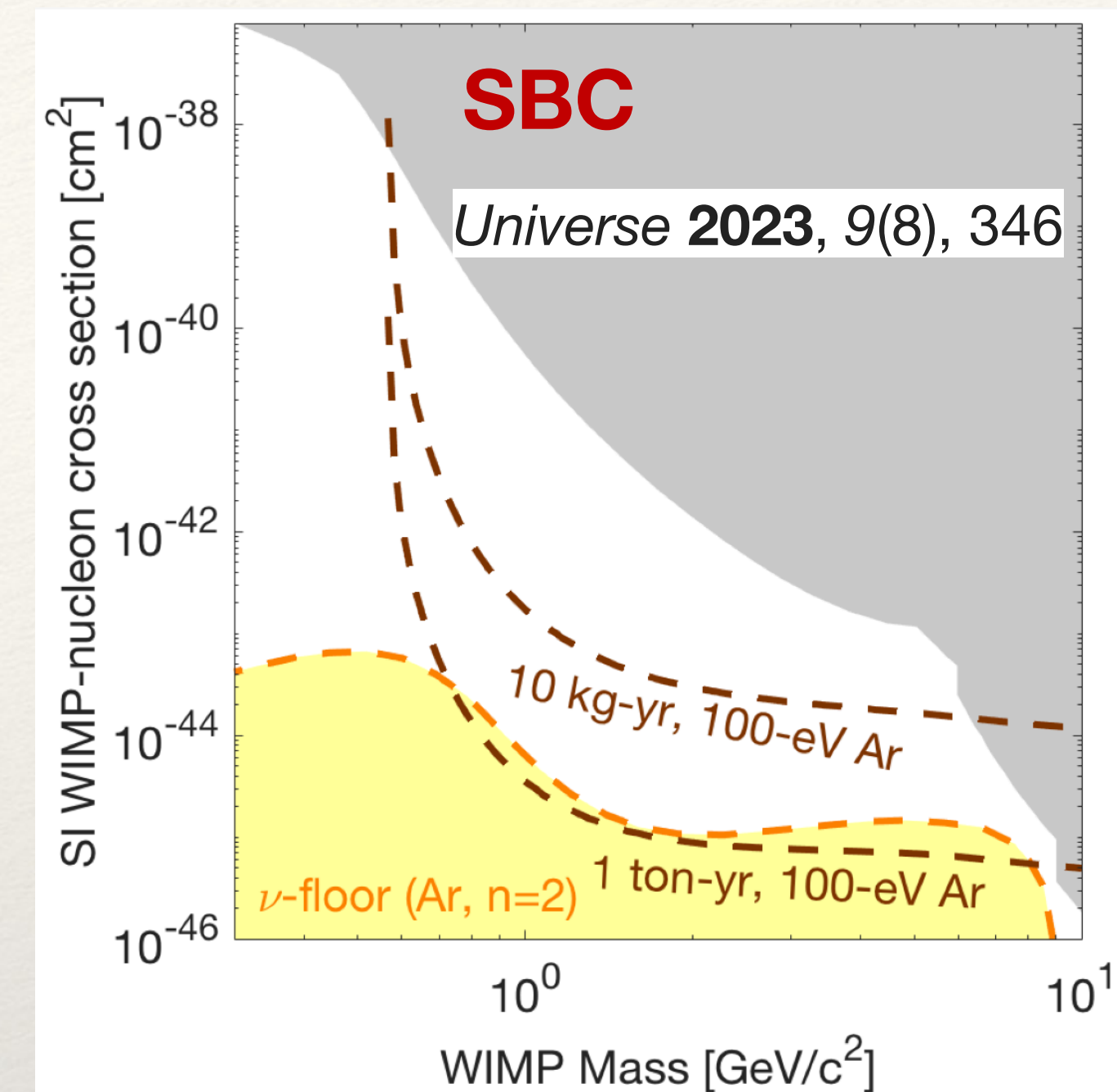
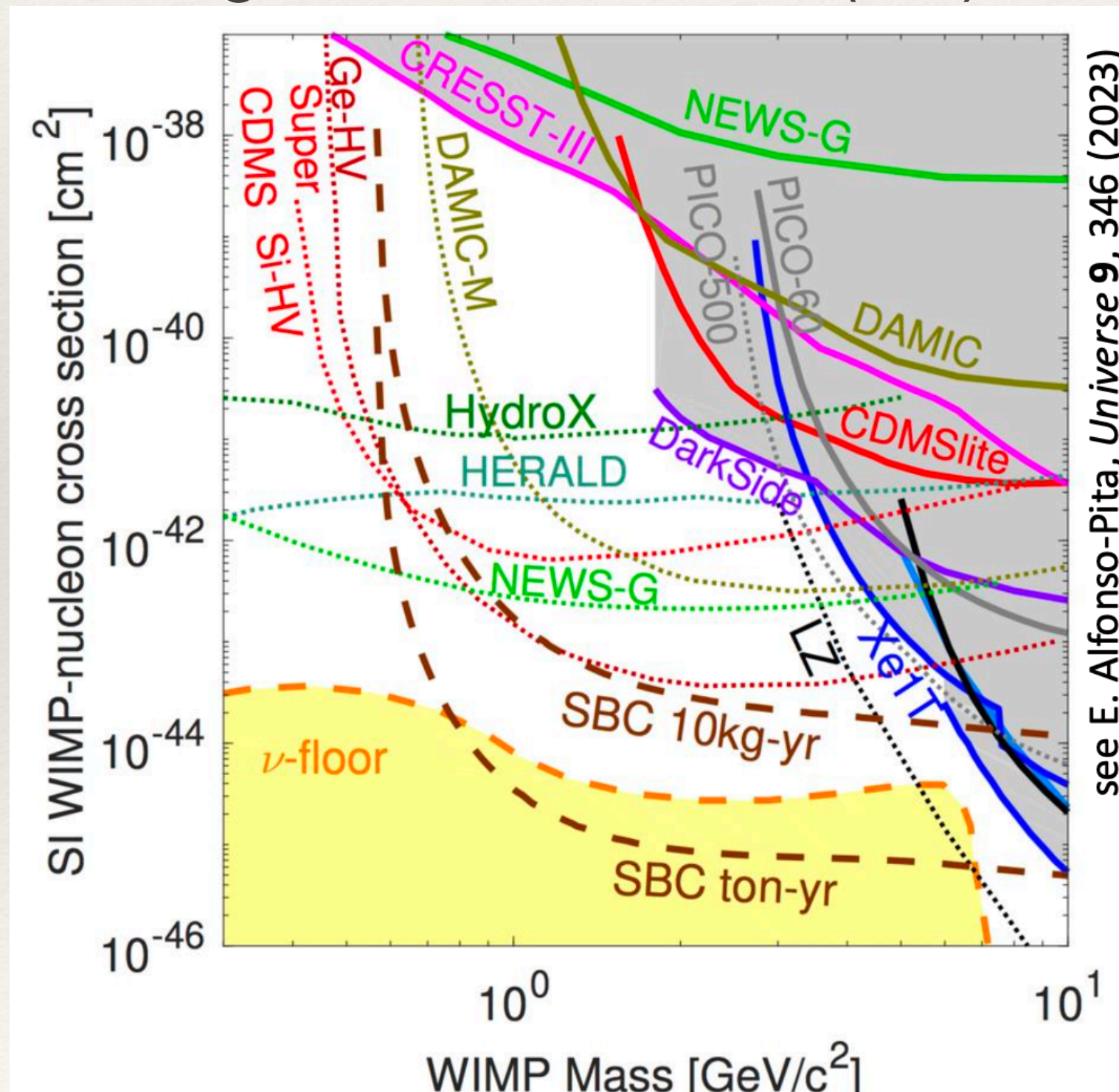
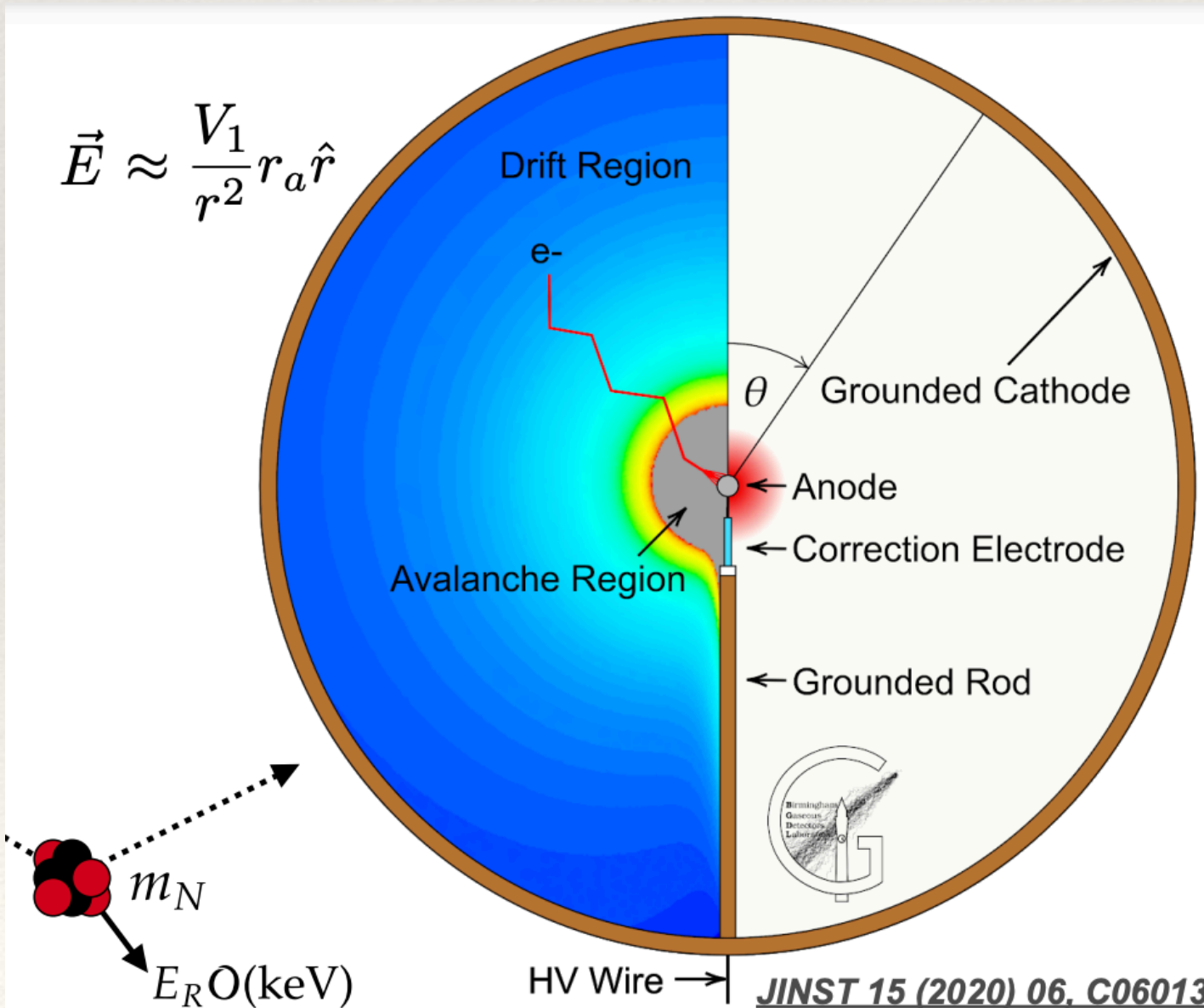
- Bubble chambers have a benefit of being insensitive to electron recoils
  - the  $dE/dx$  is too low to nucleate a bubble
  - but need to worry about alphas and neutrons
  - additional acoustic or optical channels help



# Technologies new and old



- Signals from nuclear recoils
- Semiconductor targets: Si, Ge
- Scintillating bolometers CaWO<sub>4</sub>
- Spherical Proportional Counter
- Scintillating Bubble Chamber (LAr)





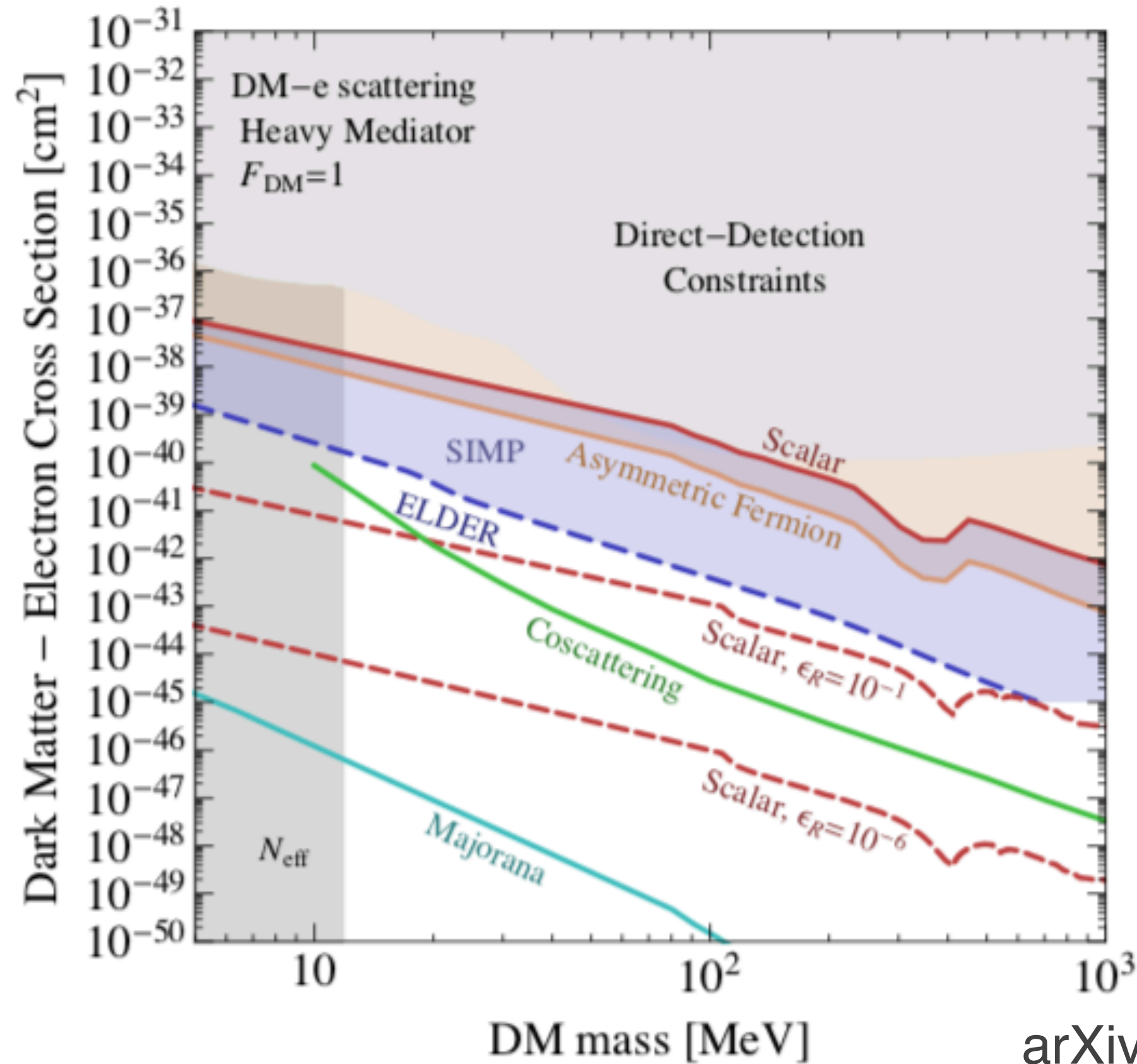
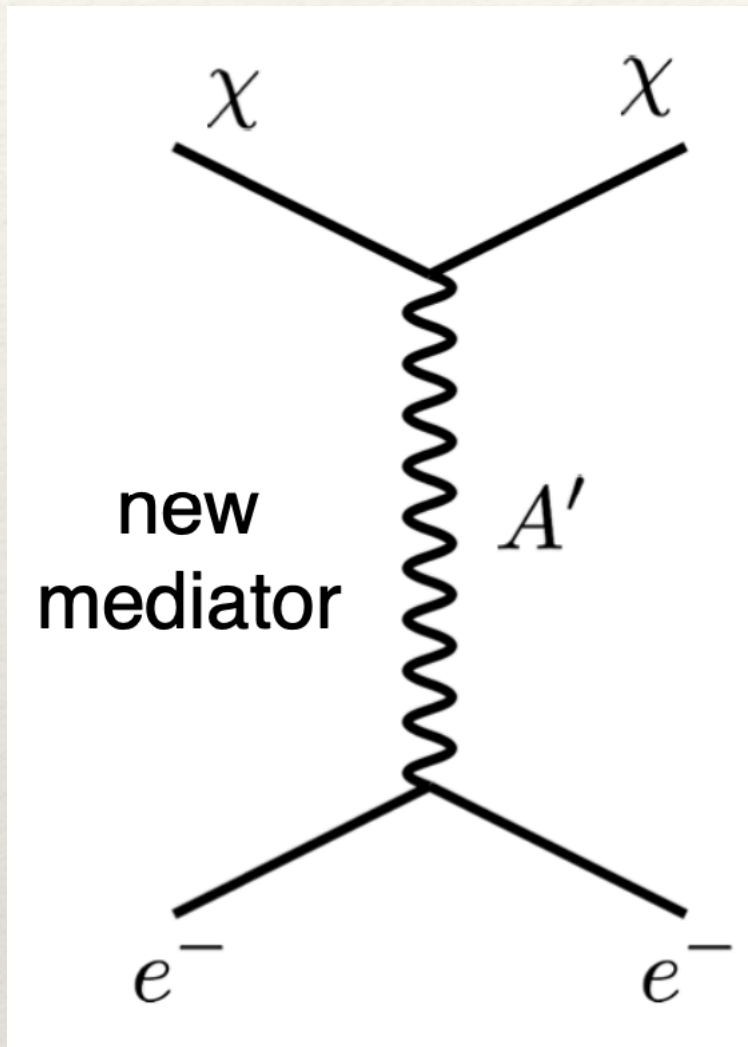


For DM masses  $< 1 \text{ GeV}/c^2$ ,  
gram scale detectors can produce leading results.  
Lots of new ideas, many exploiting quantum technologies.  
There are many unknowns.

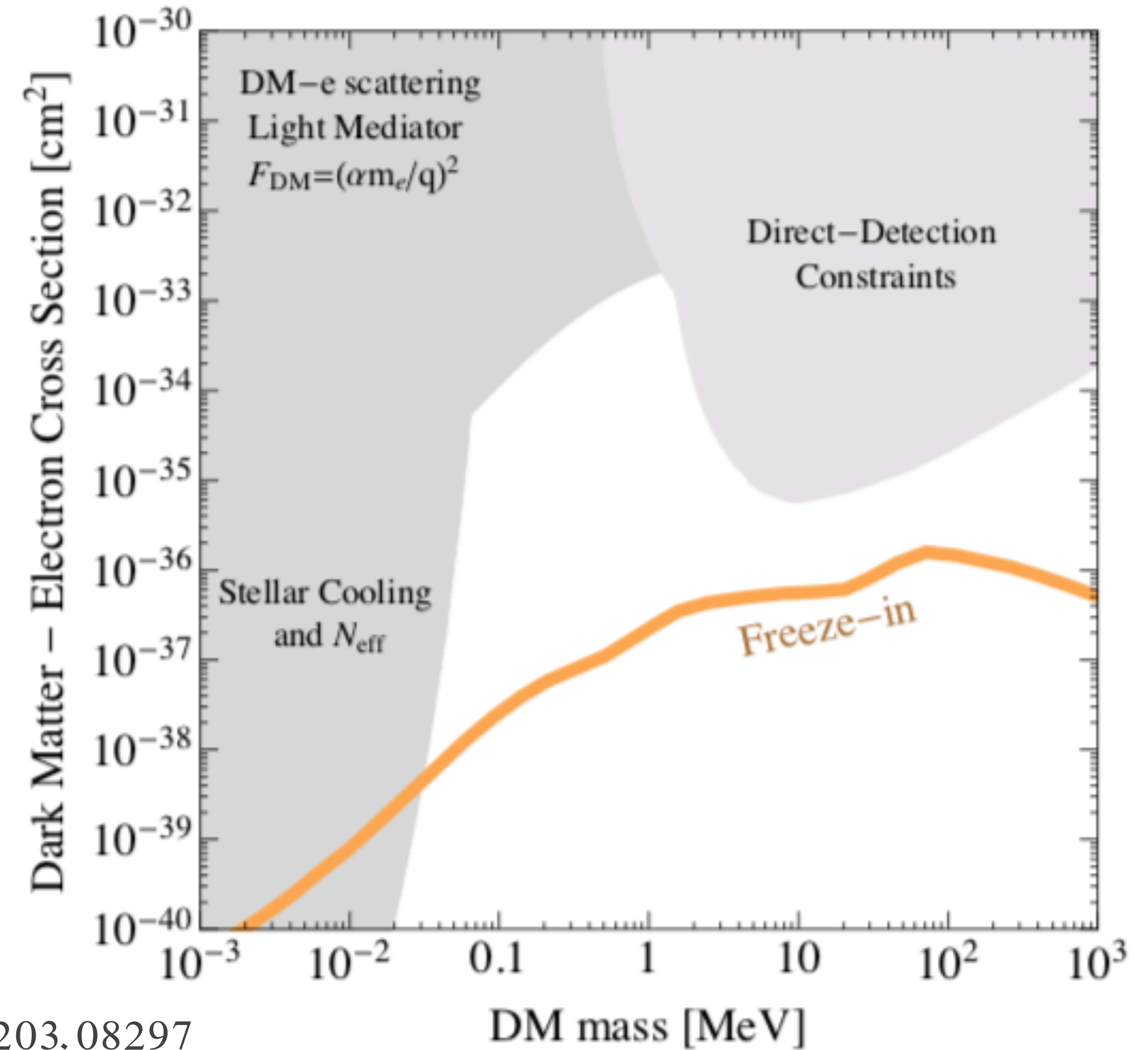


# Below a GeV: models

- New dark sector, new mediator dark photon  $A'$
- Simple benchmark models depend on mediator mass
  - Heavy mediator: freeze-out; Light mediator: freeze-in
- Primarily accessed by DM-electron scattering
- Energy deposits on the order of eV
- Detectors are getting to meV thresholds

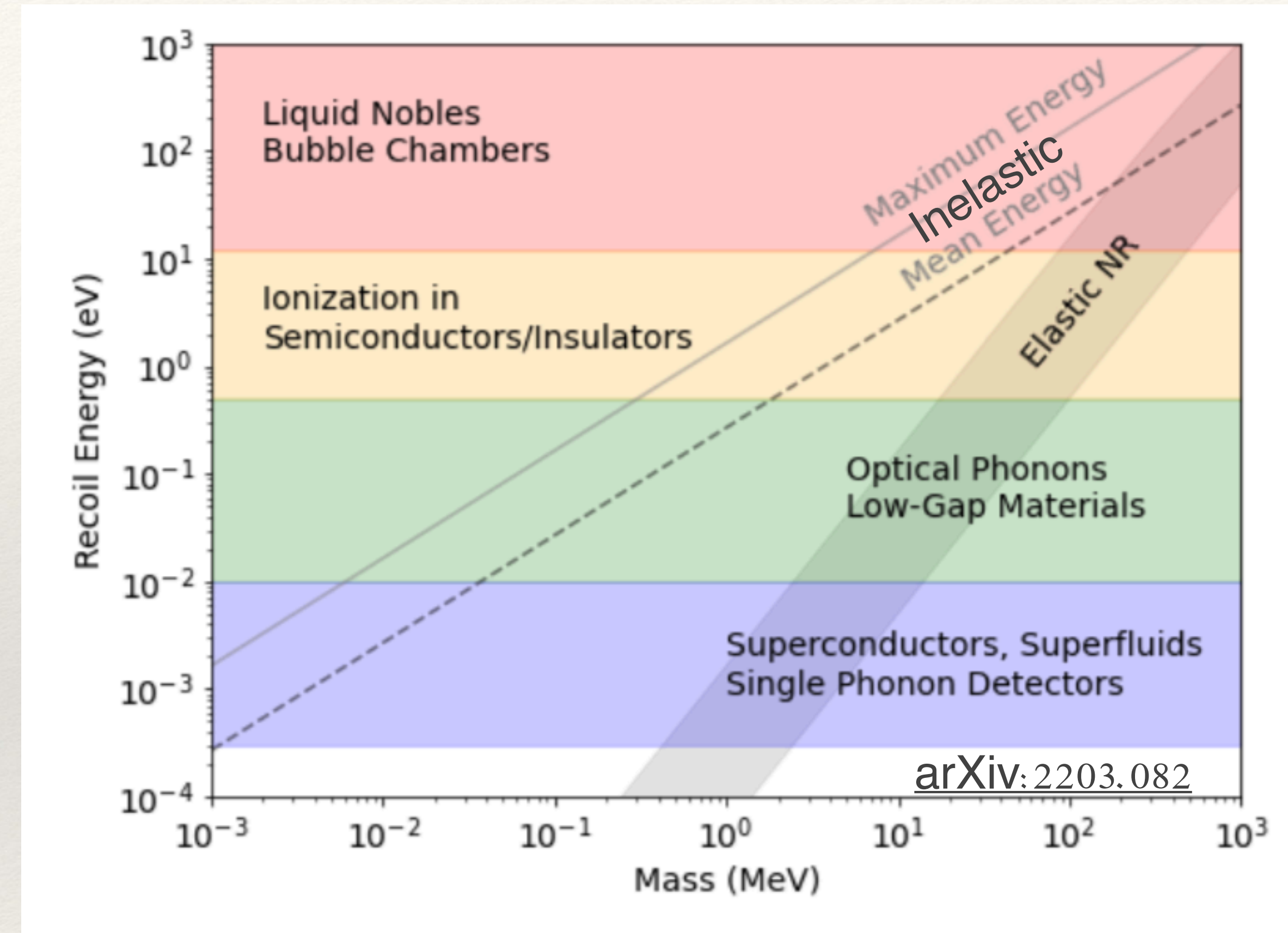
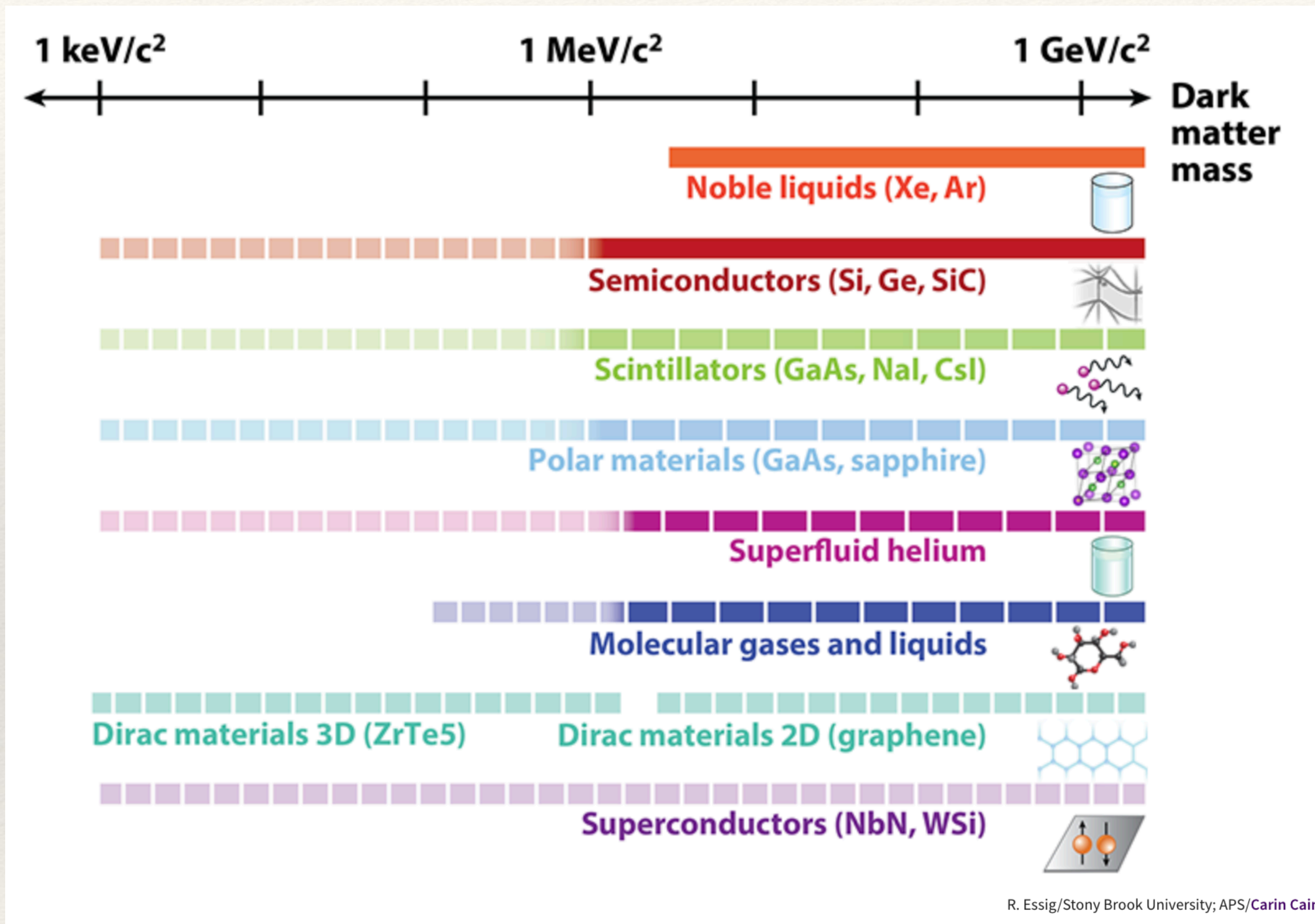


[arXiv:2203.08297](https://arxiv.org/abs/2203.08297)





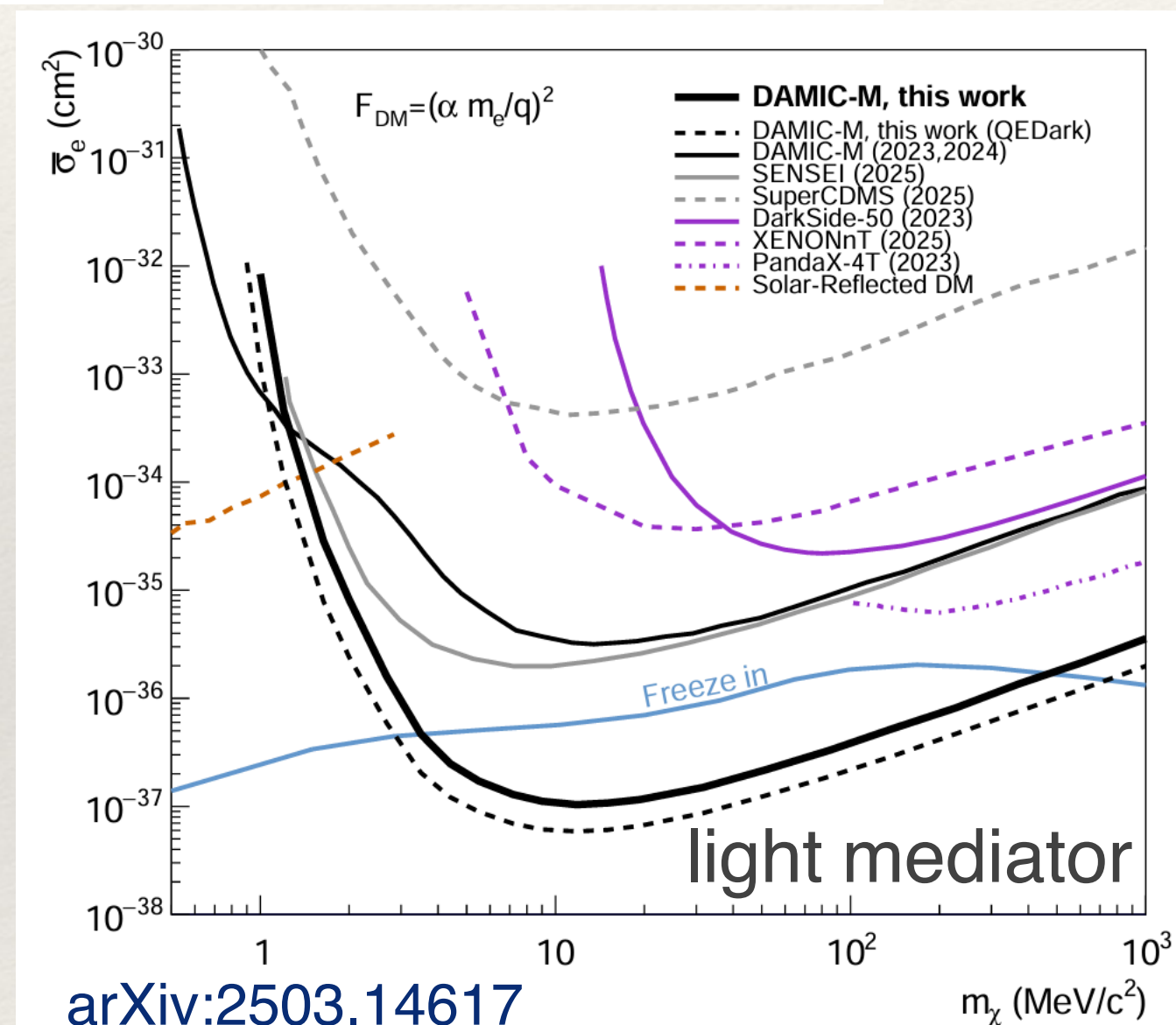
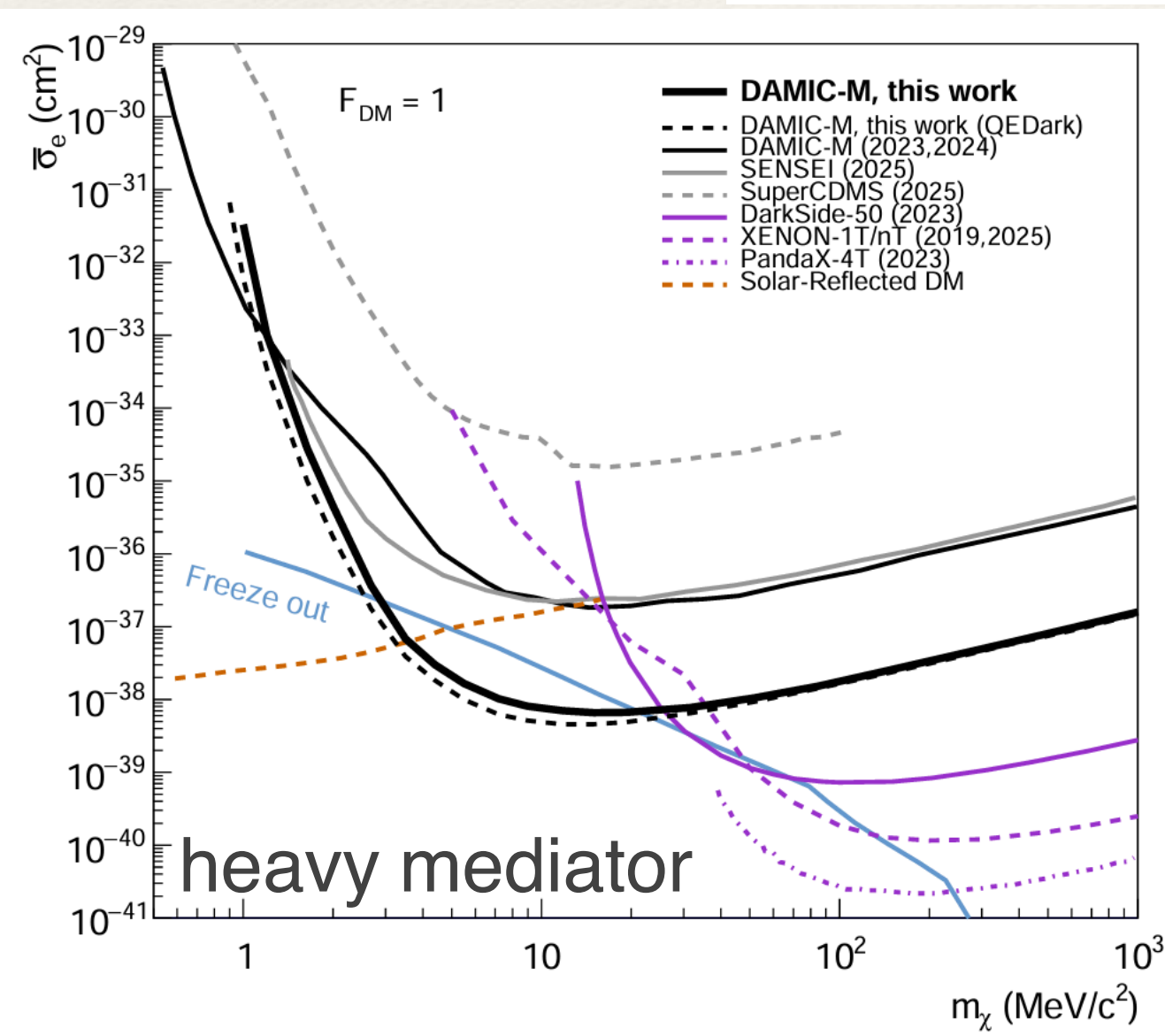
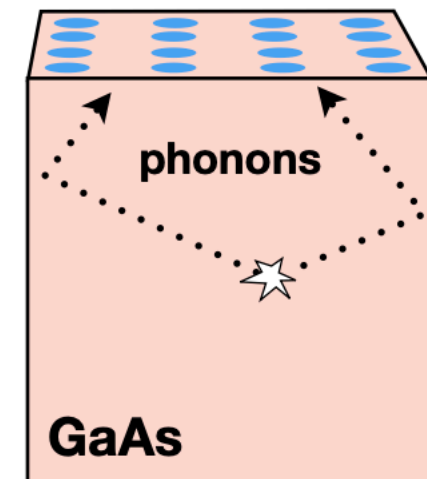
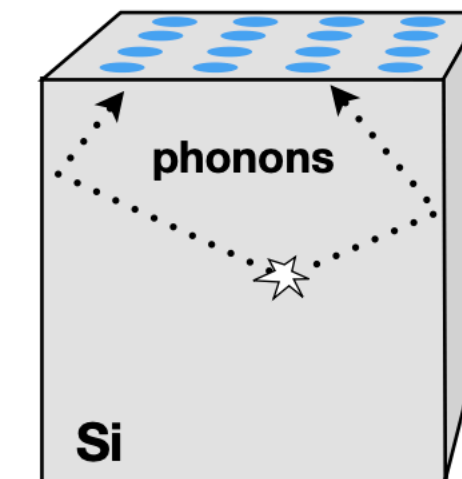
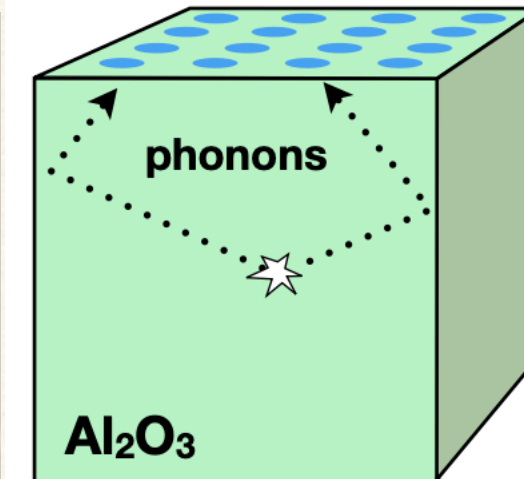
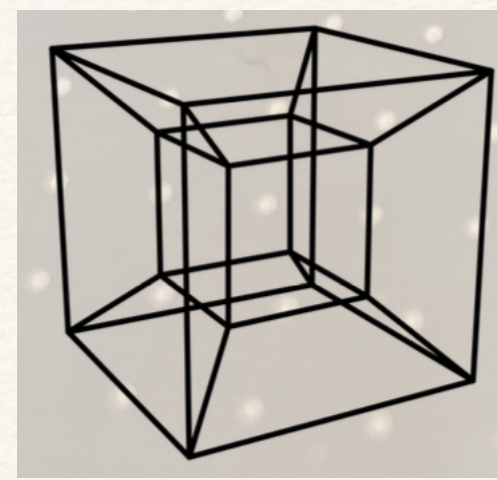
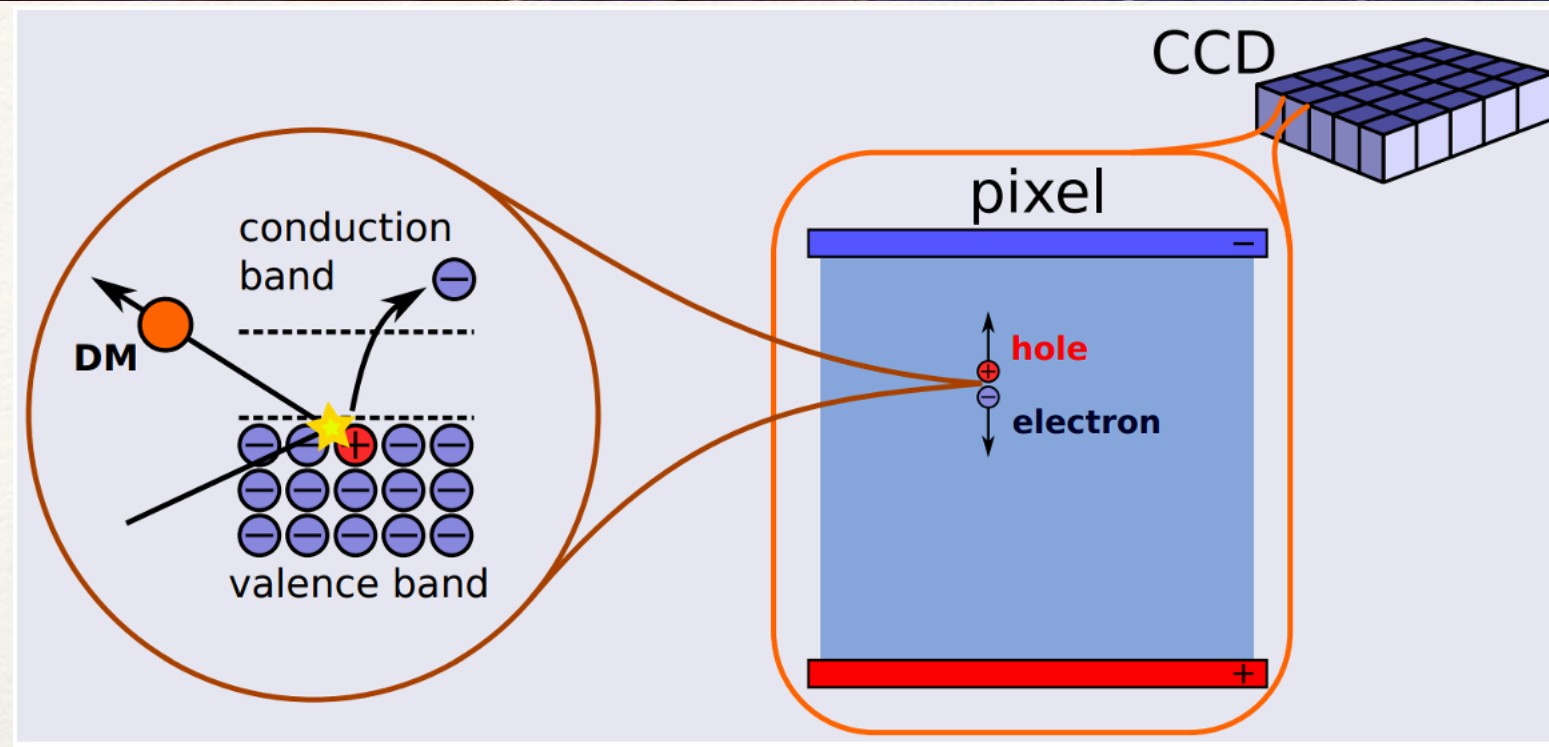
# Below a GeV: technologies



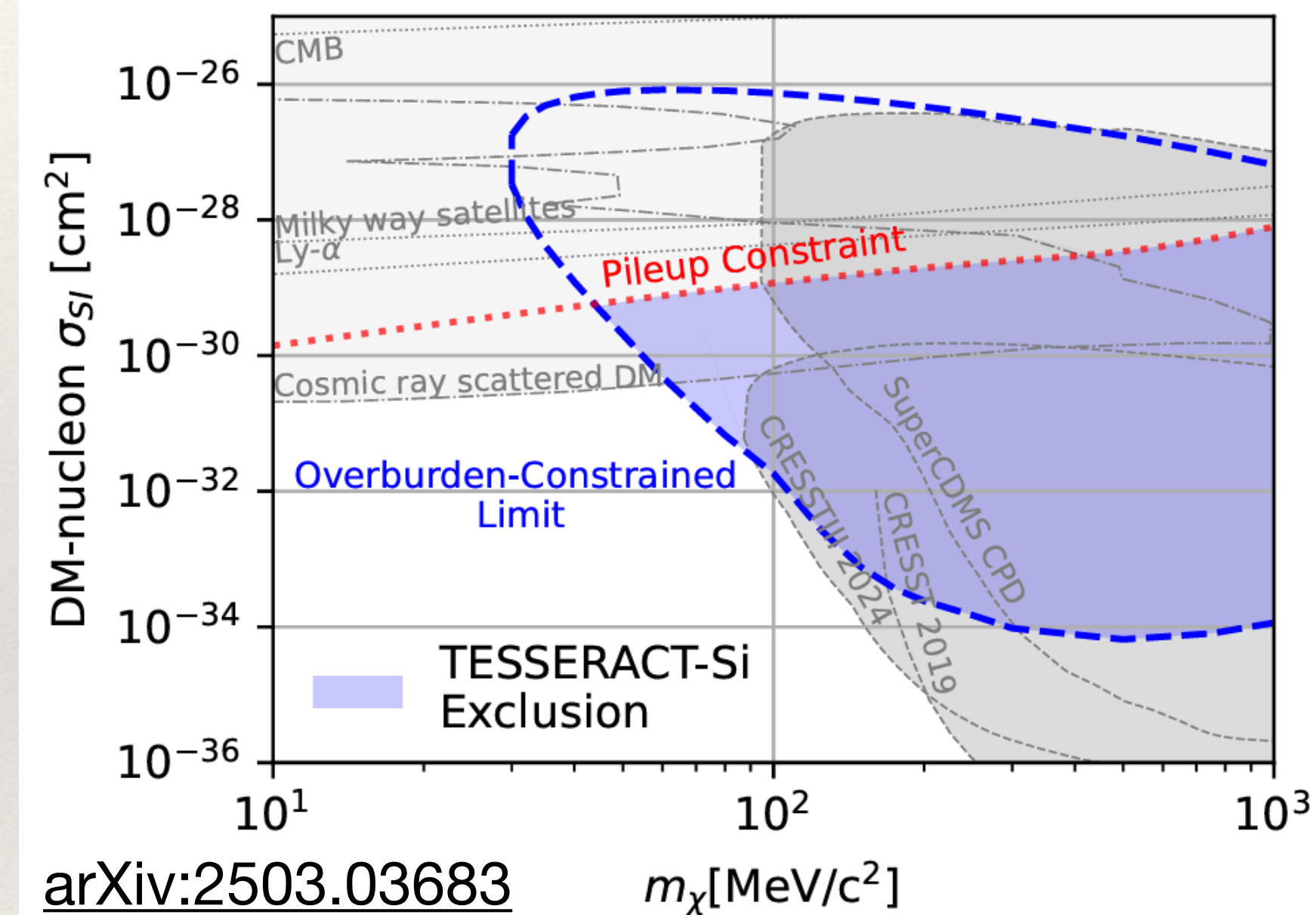
DM-electron scattering and absorption now of interest



# Recent Updates



[arXiv:2503.14617](https://arxiv.org/abs/2503.14617)



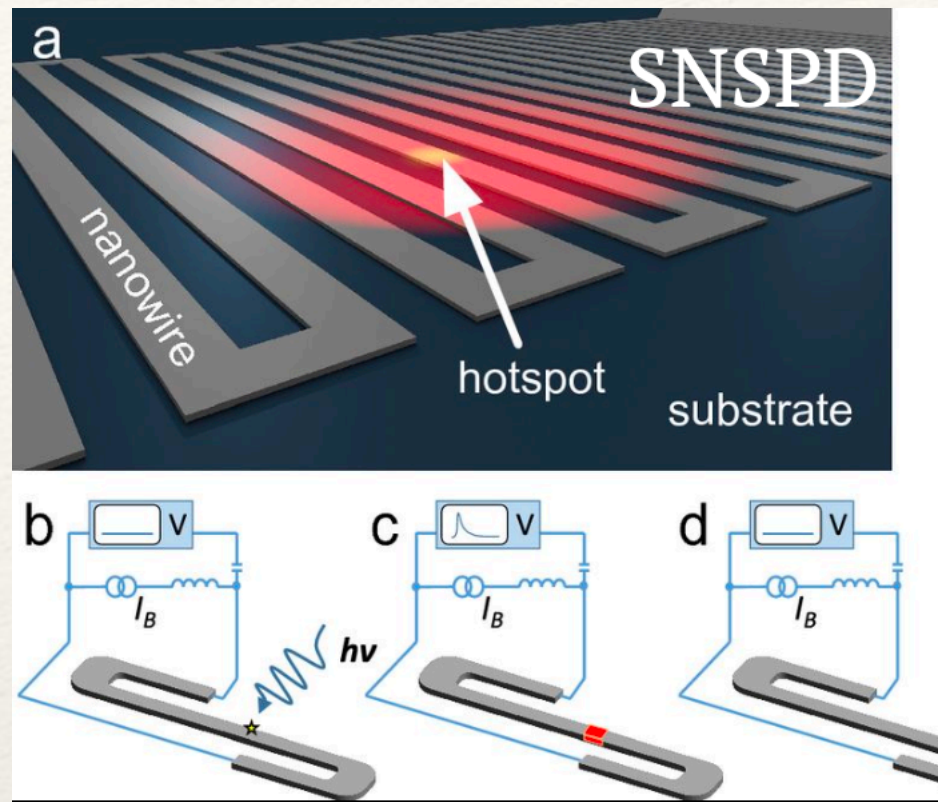
[arXiv:2503.03683](https://arxiv.org/abs/2503.03683)

- DAMIC-M prototypes at LSM with 1.3 kg-day : limits on DM- electron
- (New updates from SENSEI running at SNOLab with 1 e- threshold)
- DAMIC-M running this year-> going for kg-yr exposure
- OSCURA planned for 2029 with 10 kg

- TESSERACT with <3 g-hr on surface SI nucleon interactions
  - energy resolution of ~360 meV
- TESSERACT planned for 2028 operations

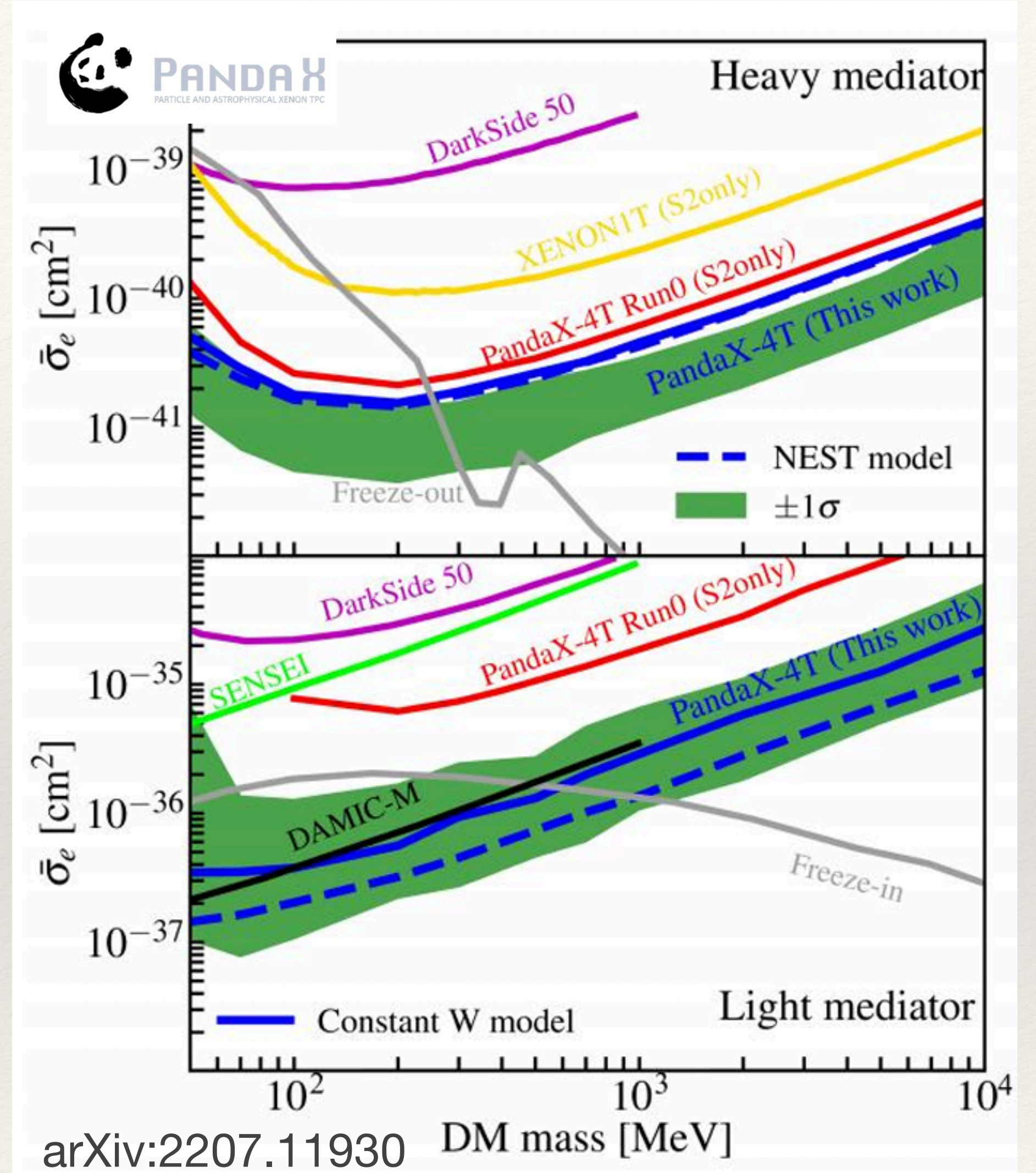
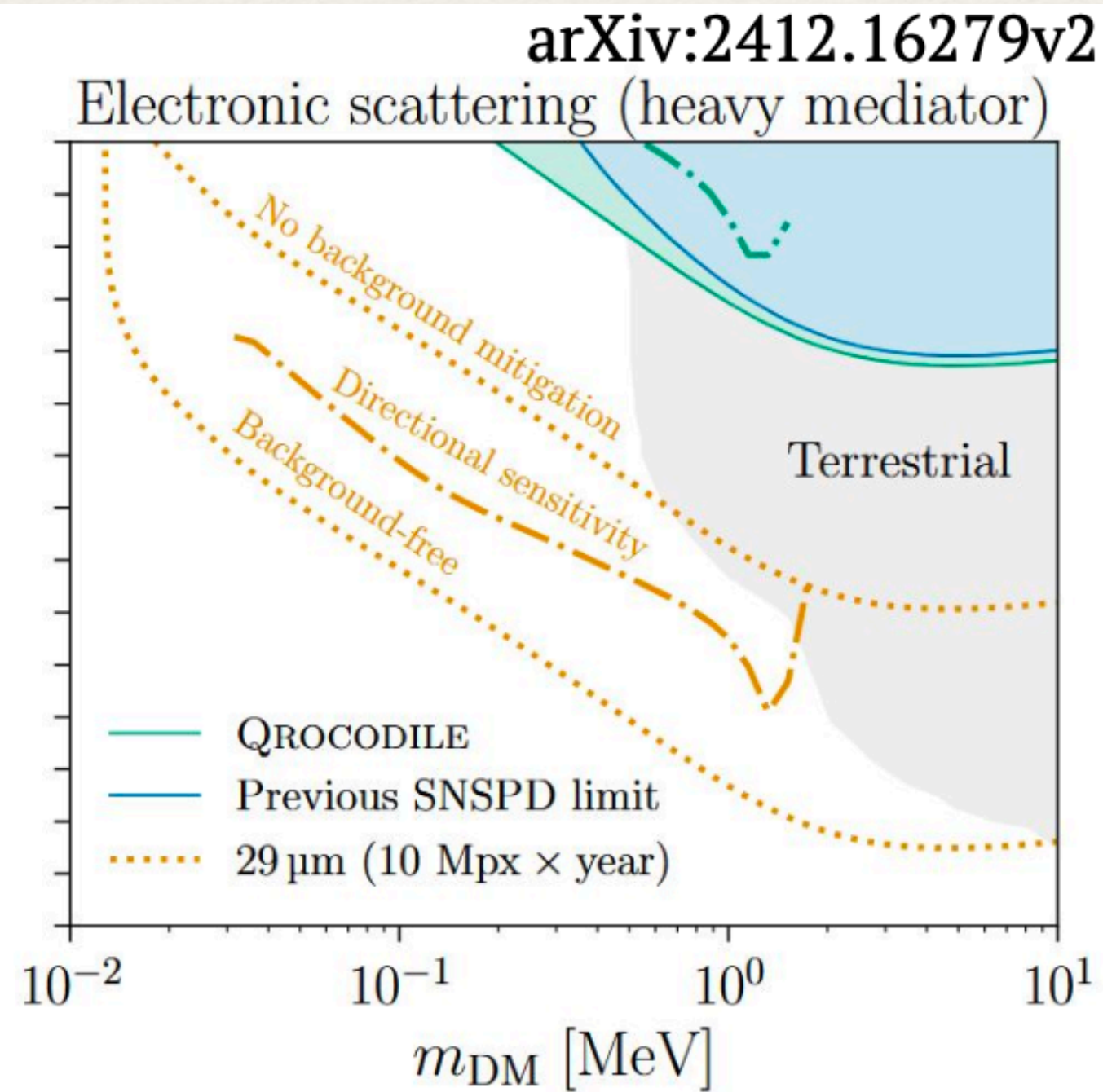
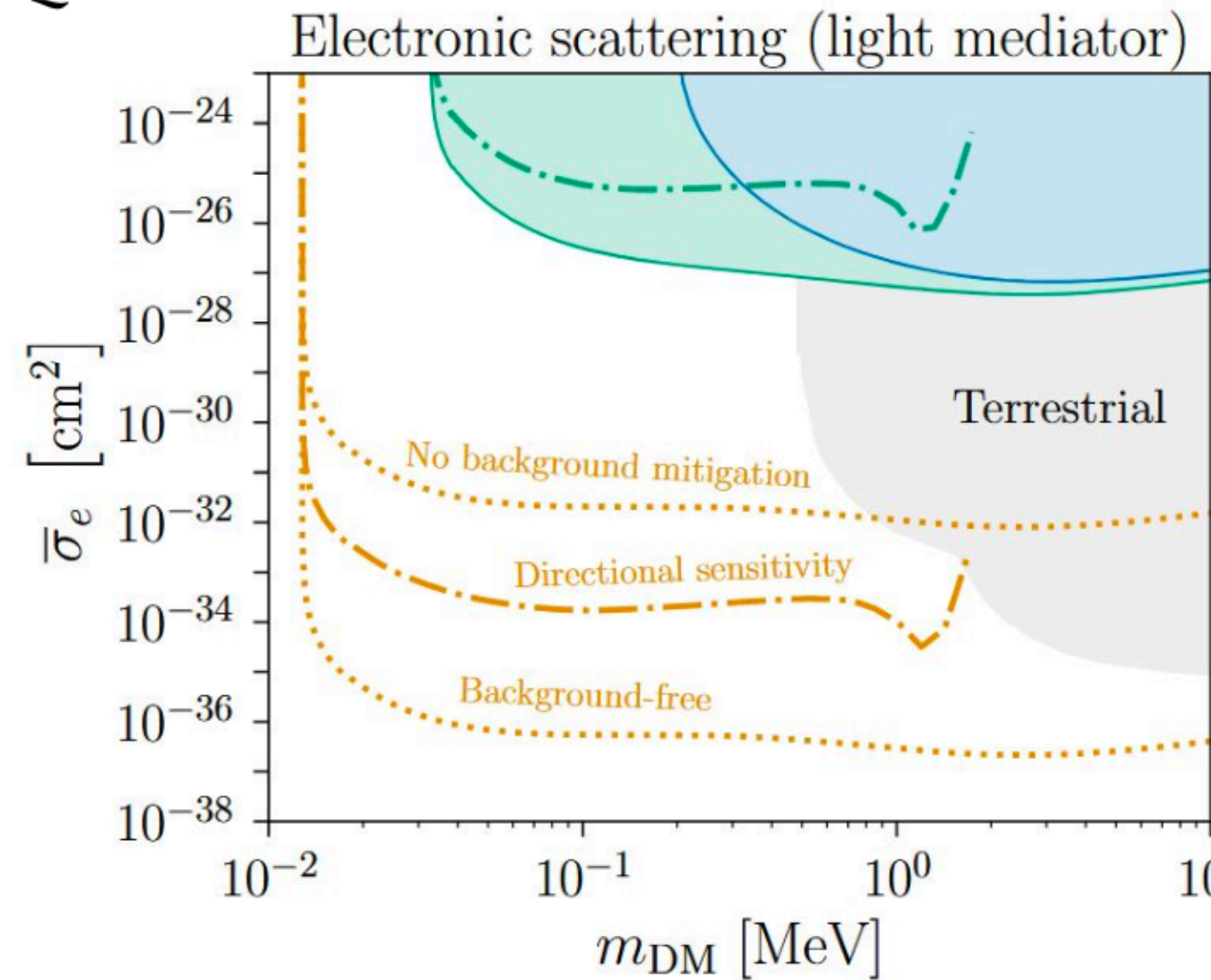


# More Recent Updates



- SNSPD devices also get to 100s of meV
- clean digital signals with low backgrounds
- And once again, LXe!

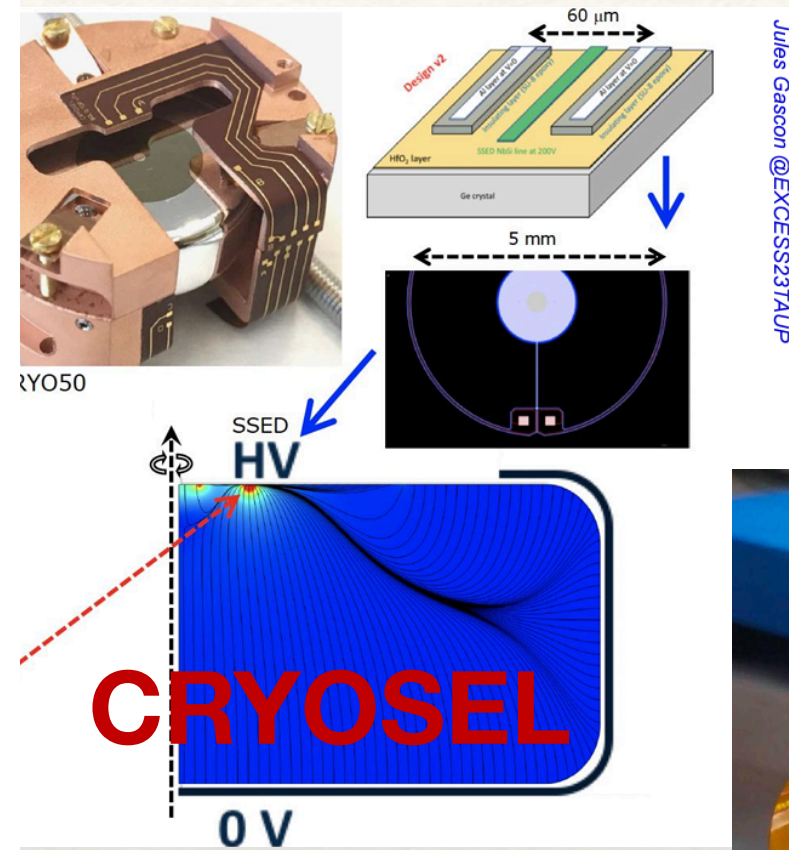
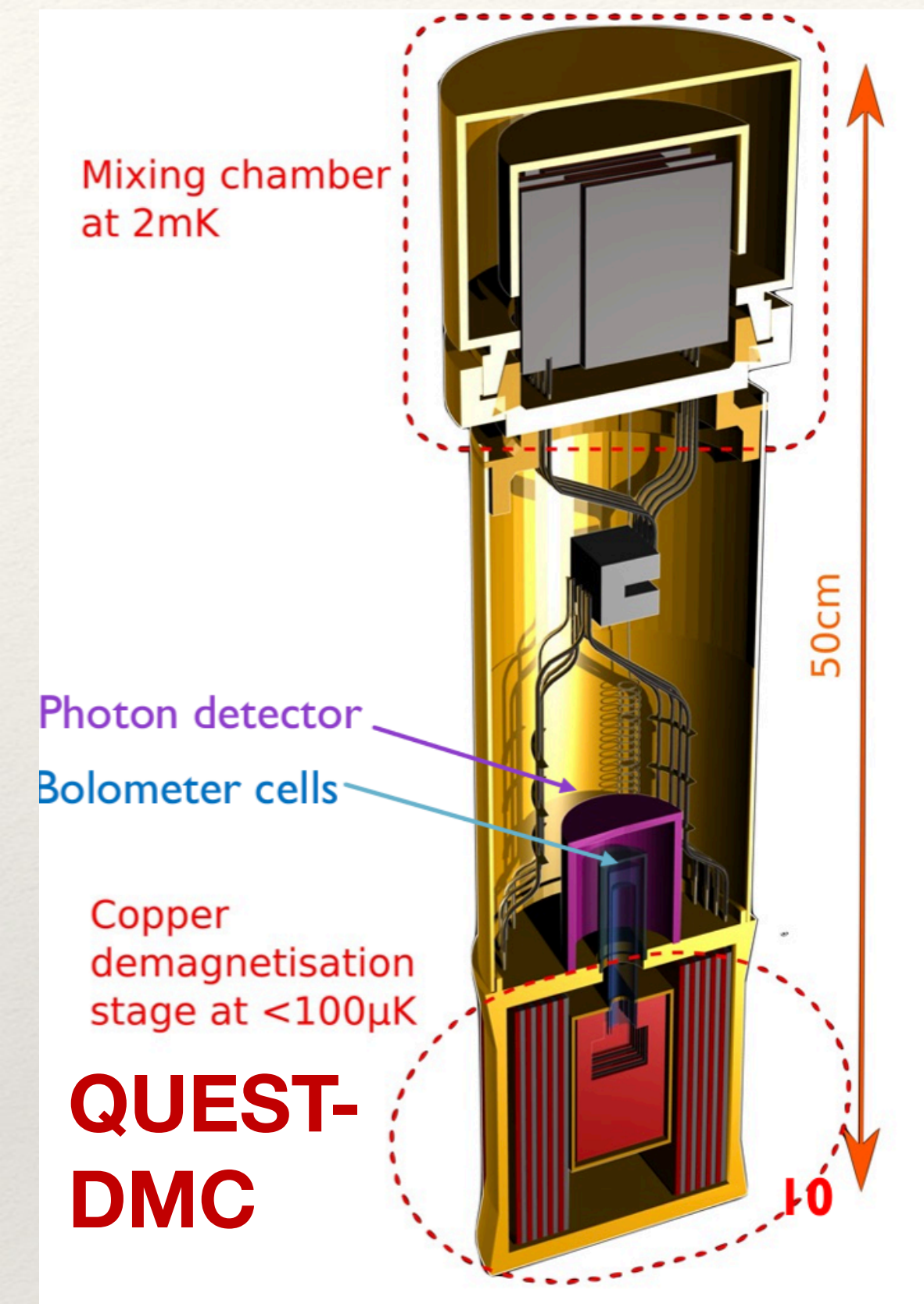
## QROCODILE



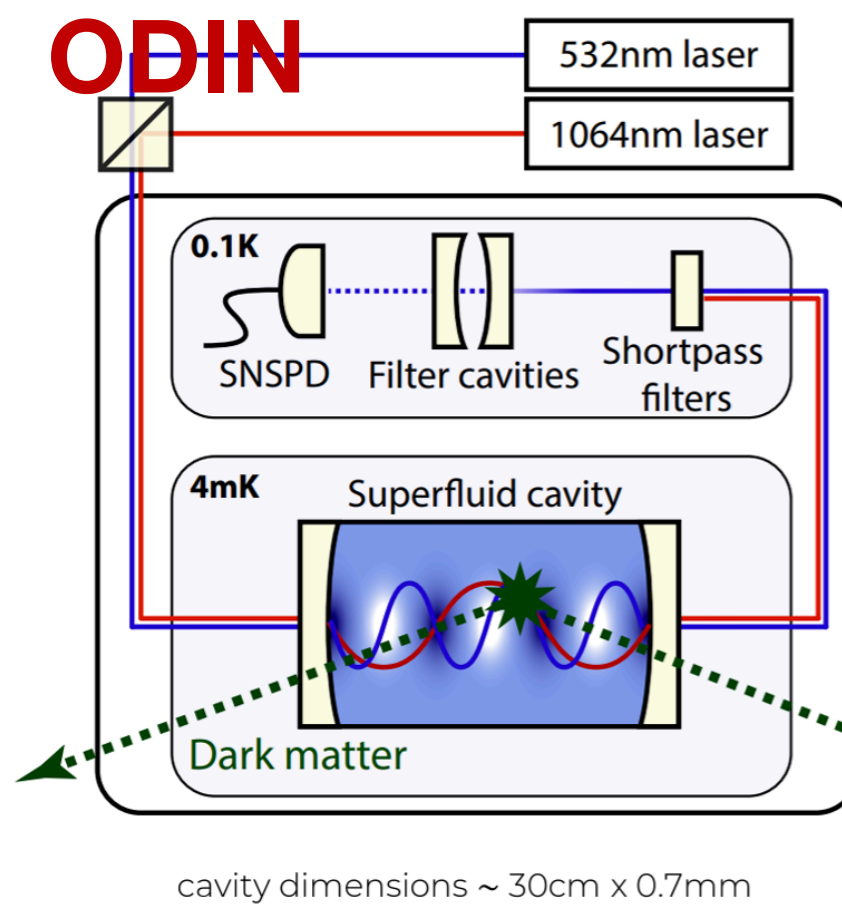
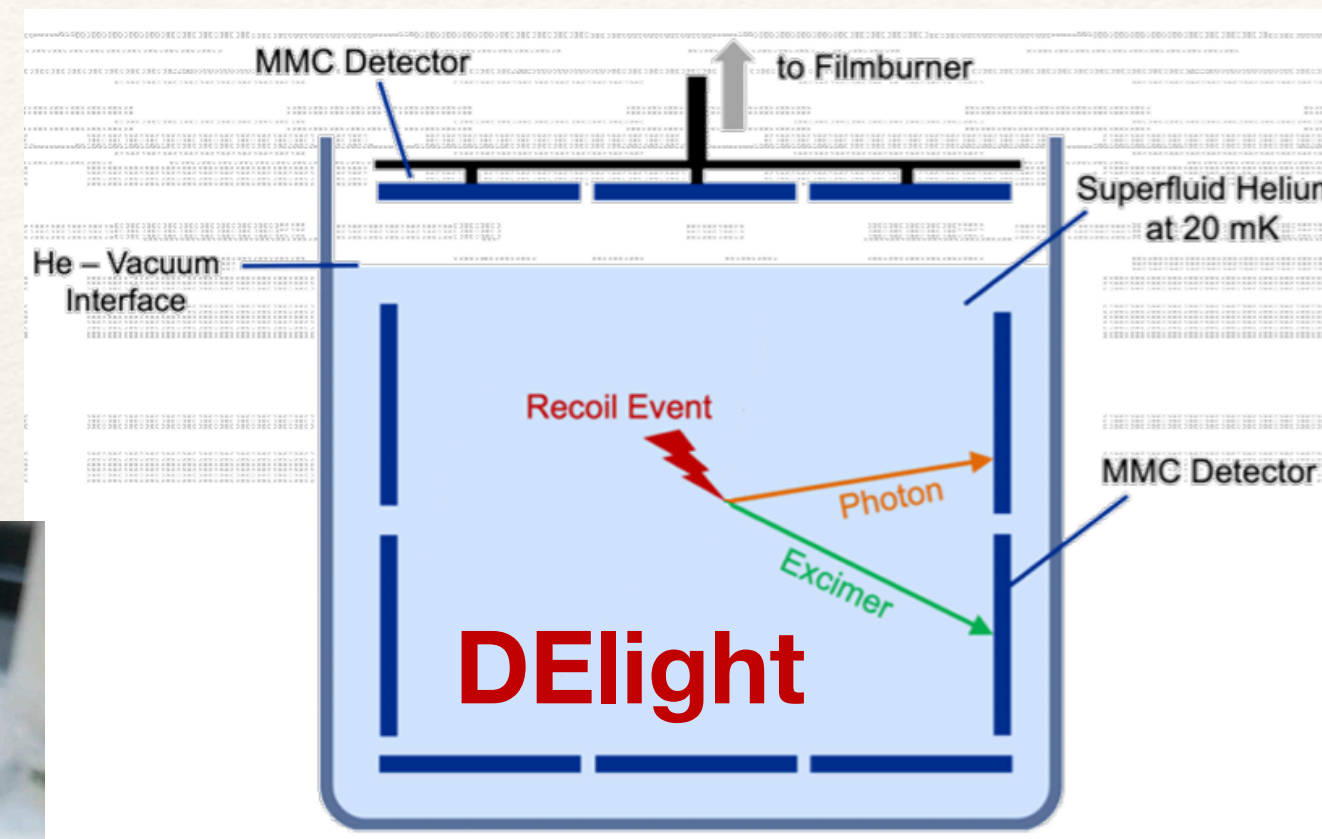
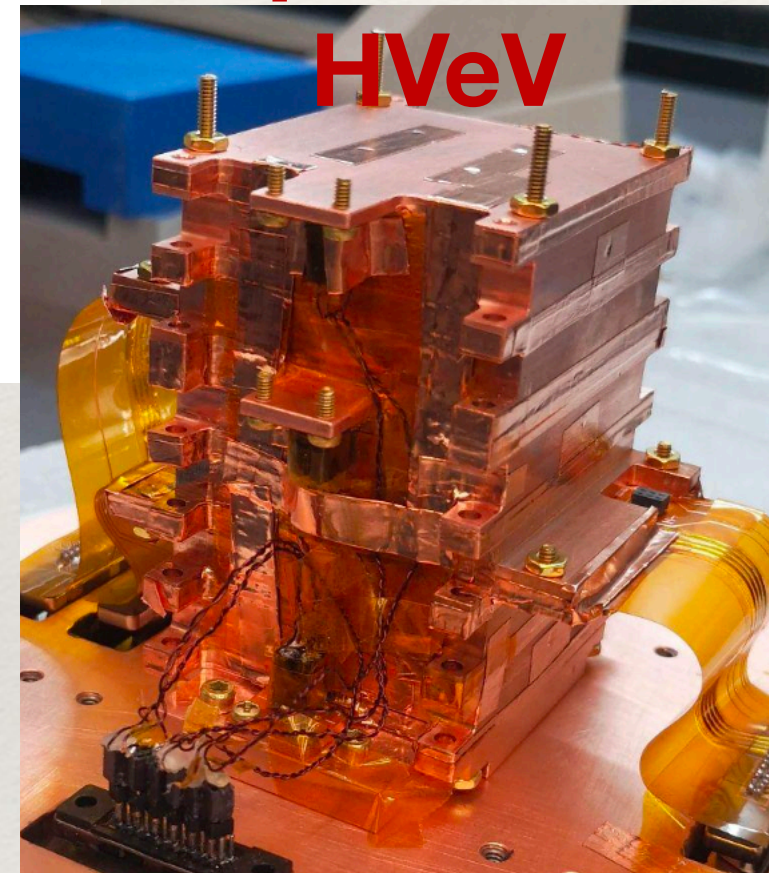


# So many new detectors...

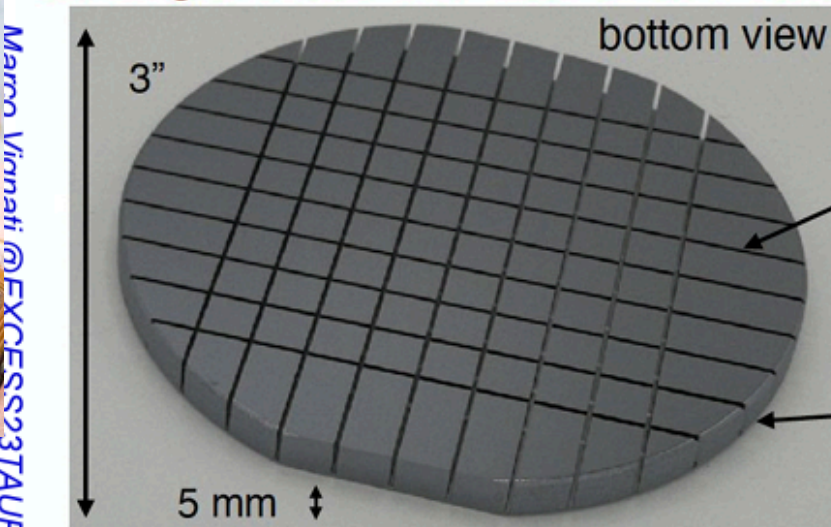
so many ~~hot~~ **cold** technologies: SNSPDs, TESs, KIDs, MMCs, superfluid He, superconducting QUBITs ...



**SuperCDMS**



carving of dices in a thick silicon wafer

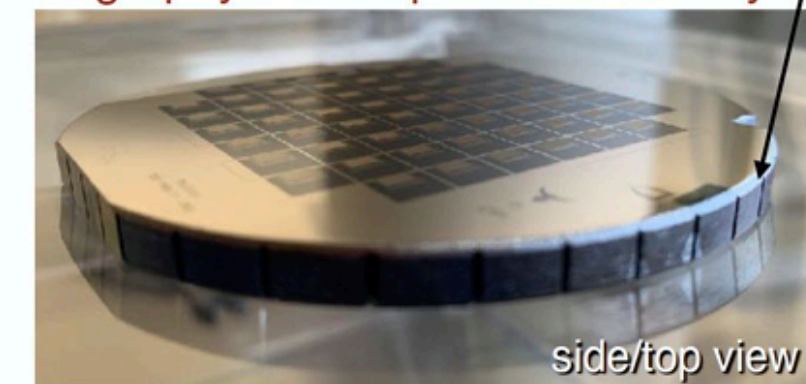


**BULLKID**

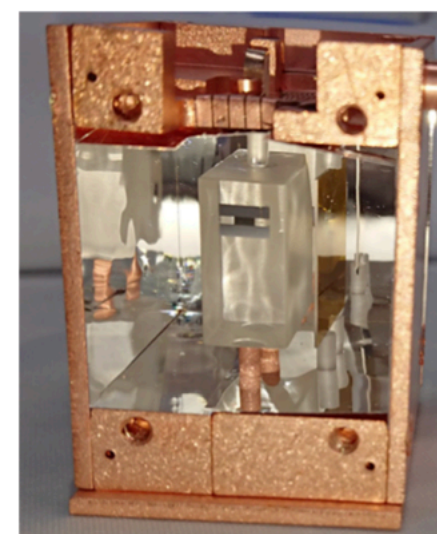
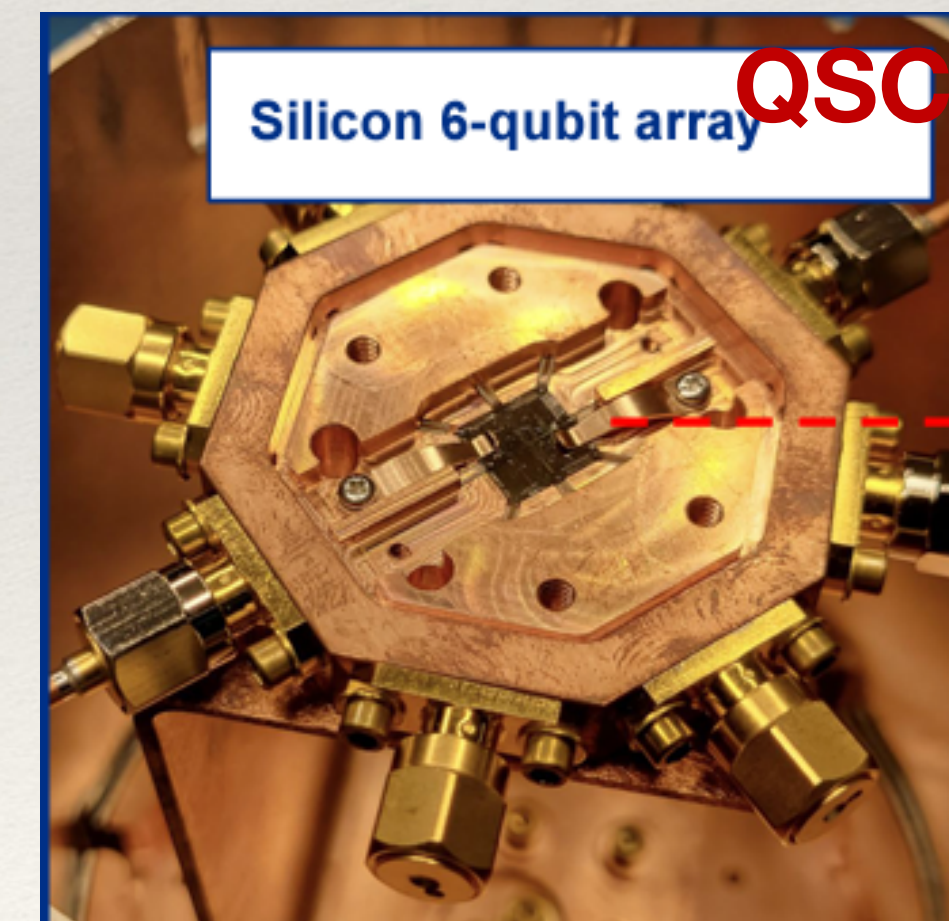
4.5 mm deep grooves  
- 6 mm pitch  
- chemical etching

0.5 mm thick common disk:  
- holds the structure  
- hosts the KIDs

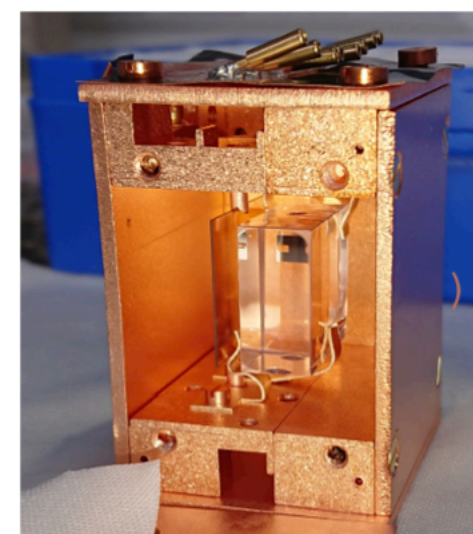
lithography of multiplexed KID array



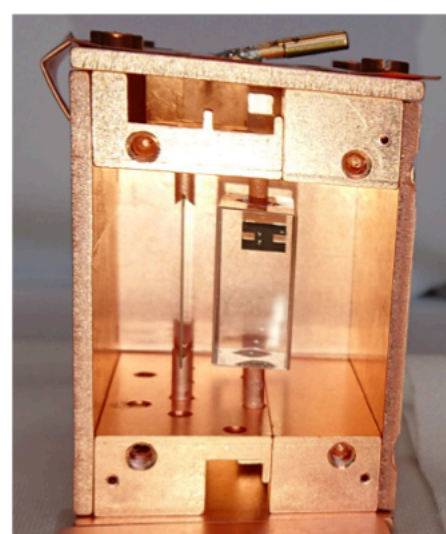
KID array  
- 60 nm aluminum film  
- 60 KIDs lithography



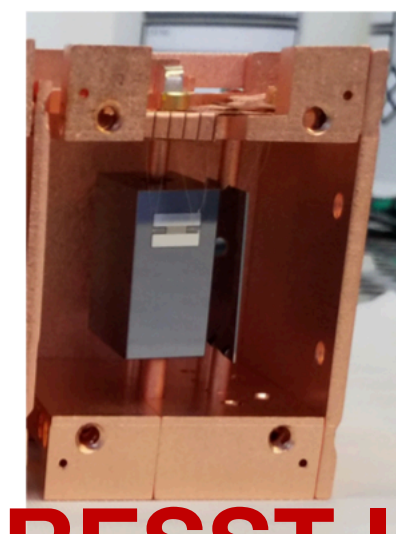
CaWO<sub>4</sub> grown at TUM



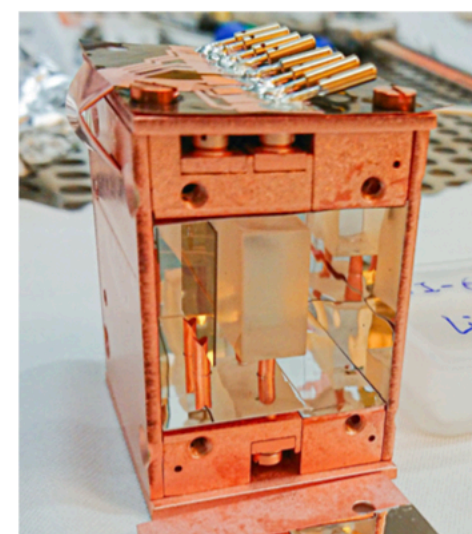
Commercially grown CaWO<sub>4</sub>



Al<sub>2</sub>O<sub>3</sub>



**CRESST-III**

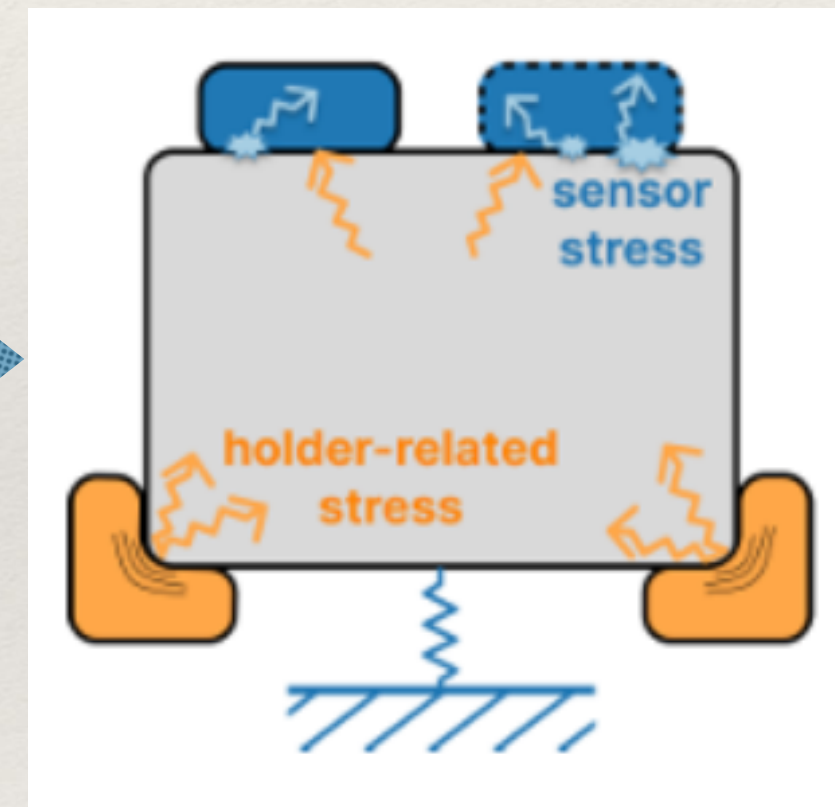
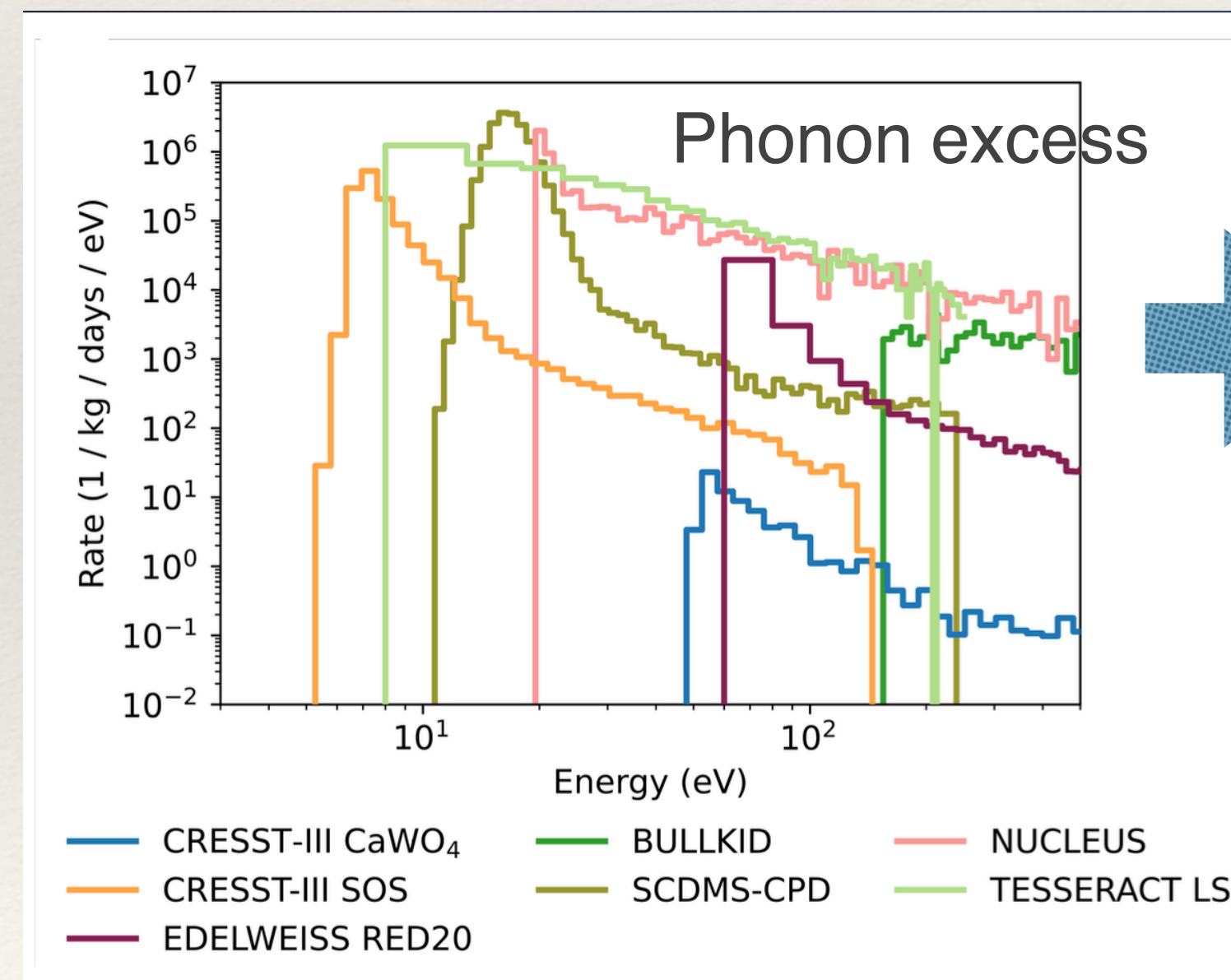
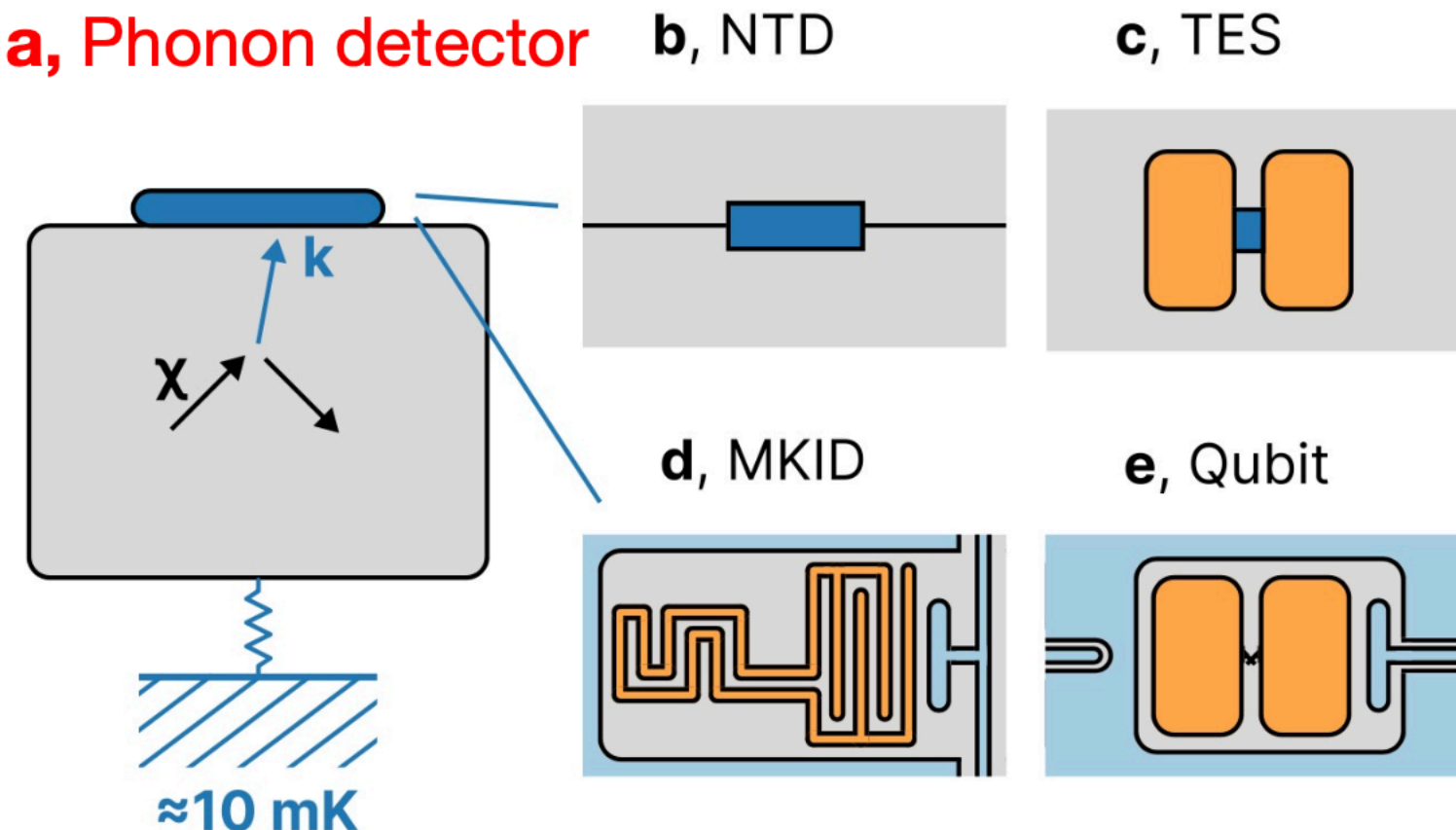
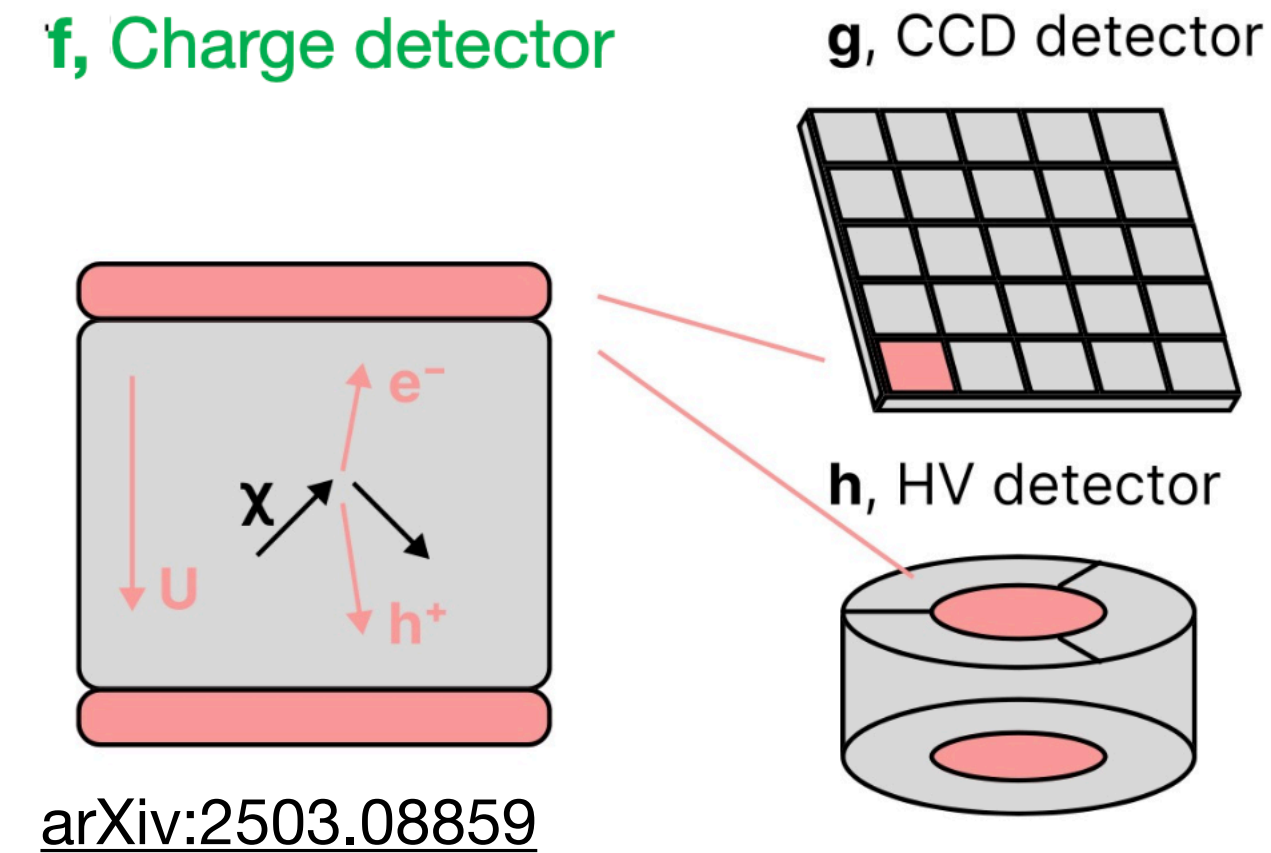
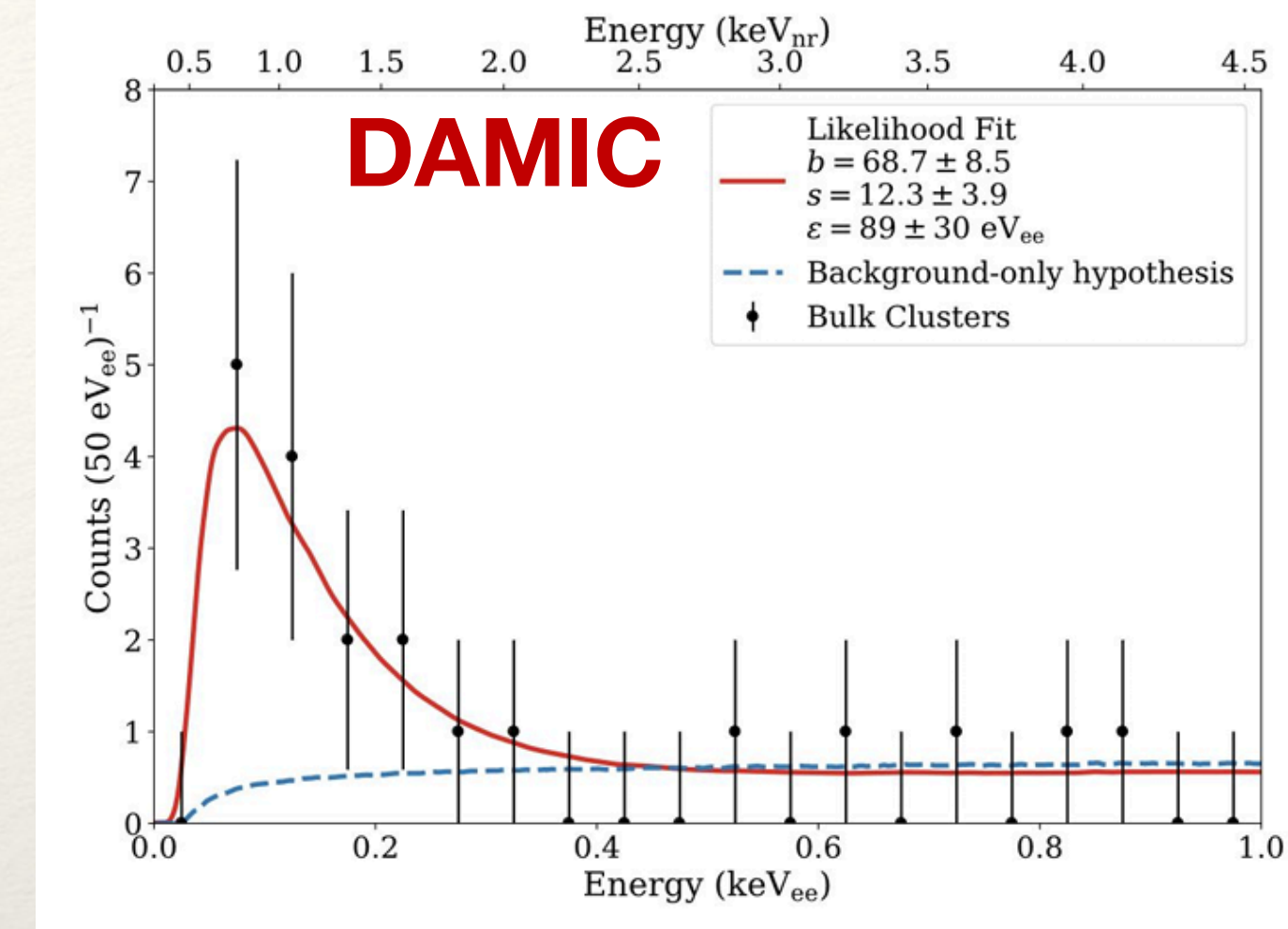
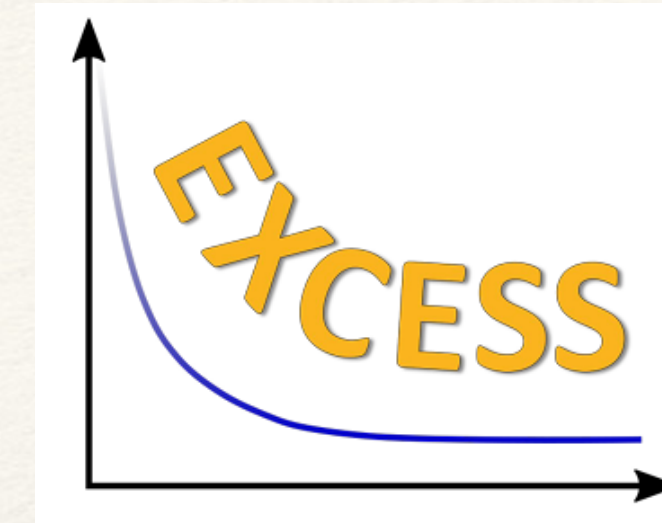


LiAlO<sub>2</sub>



# Low energy excess (LEE)

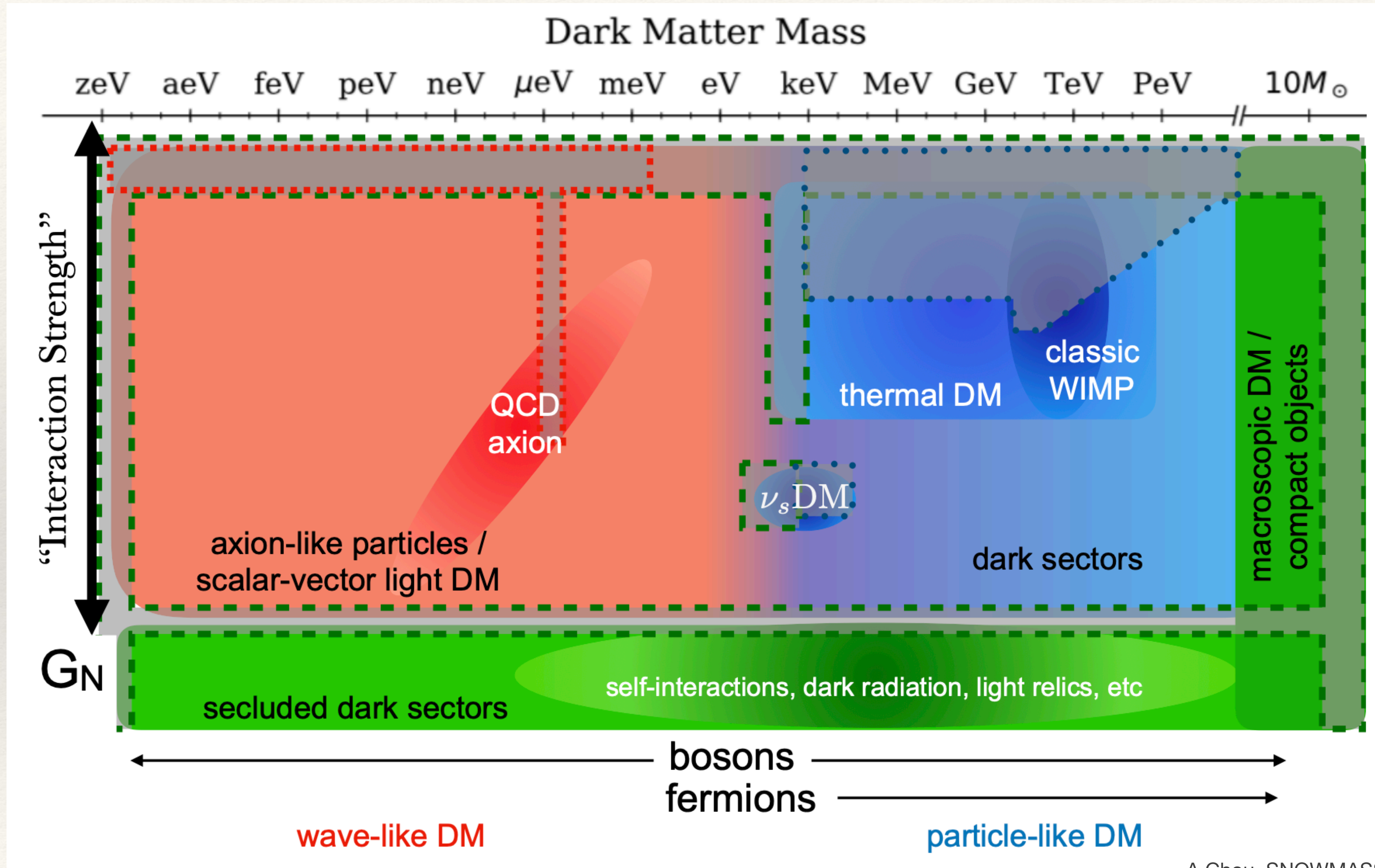
EXCESS initiative: SciPost Phys. Proc. 9, 001 (2022)



- Not Dark Matter
- Not (all) the same backgrounds
  - Phonons affected by both holder and inter-layer sensor stresses
  - Charge readout affected by radiation induced backgrounds
- DAMIC (SNOLAB) LEE levels not yet probed by new experiments
- General quantum effect? Wider Impact



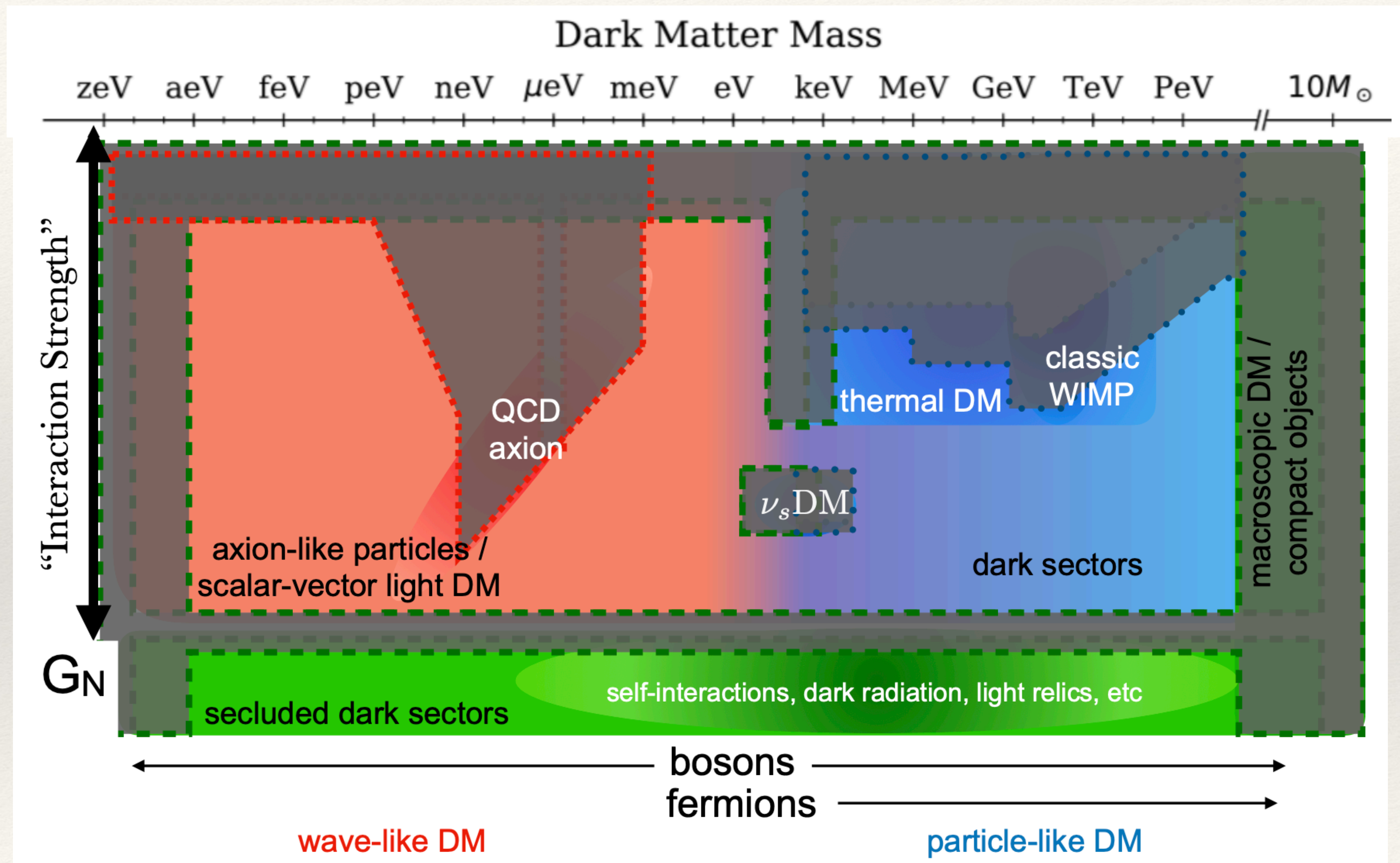
# Our Current Status



A Chou, SNOWMASS Dark Matter Plenary



# If we Search Deep and Wide, in 20 years



A Chou, SNOWMASS Dark Matter Plenary



# The Future



But particle astrophysicists want DETECTORS to find Dark Matter

Even these relatively small and affordable technologies are under threat

Uncertainty for OSCURA in US, TESSERACT needed French support





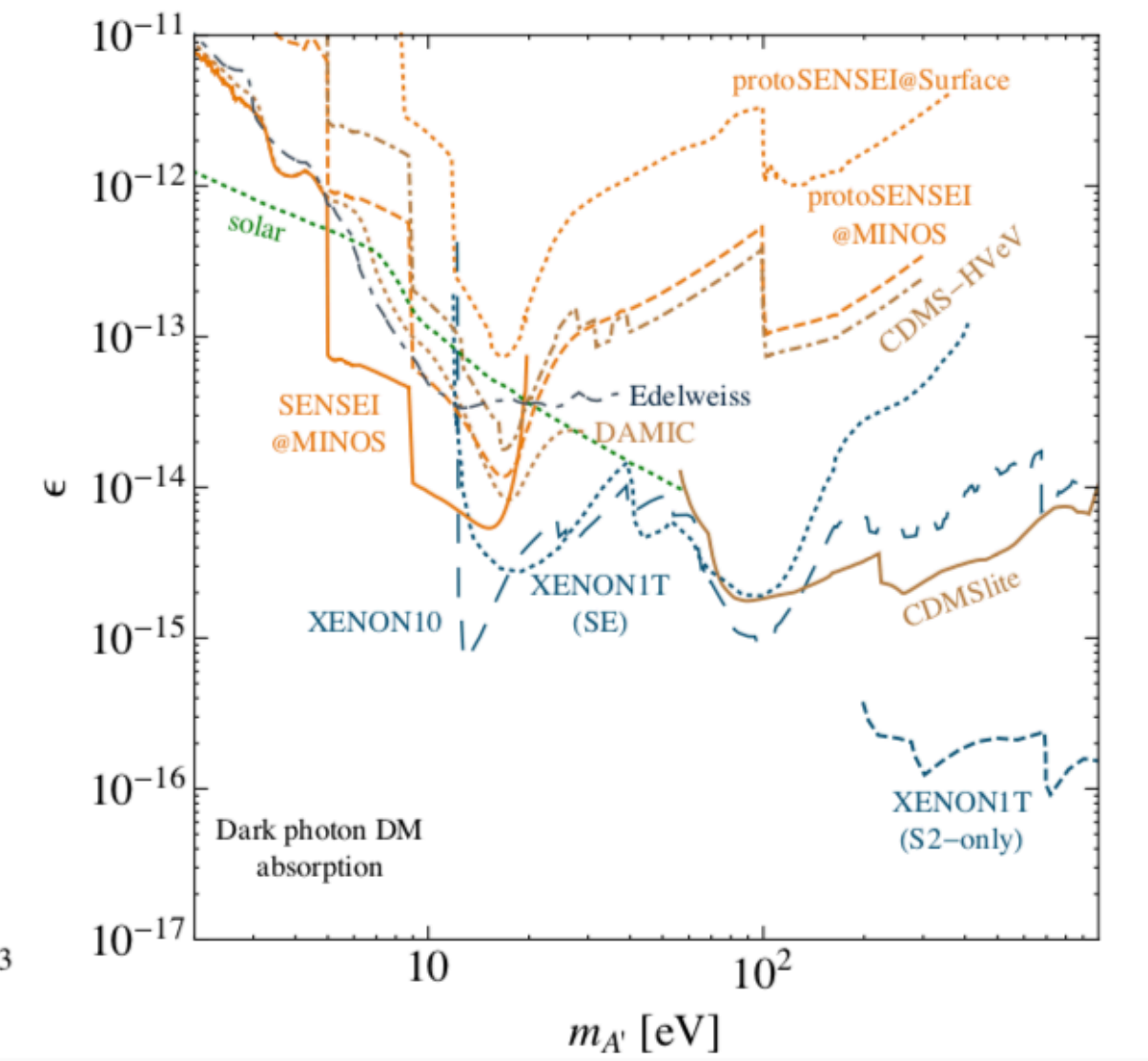
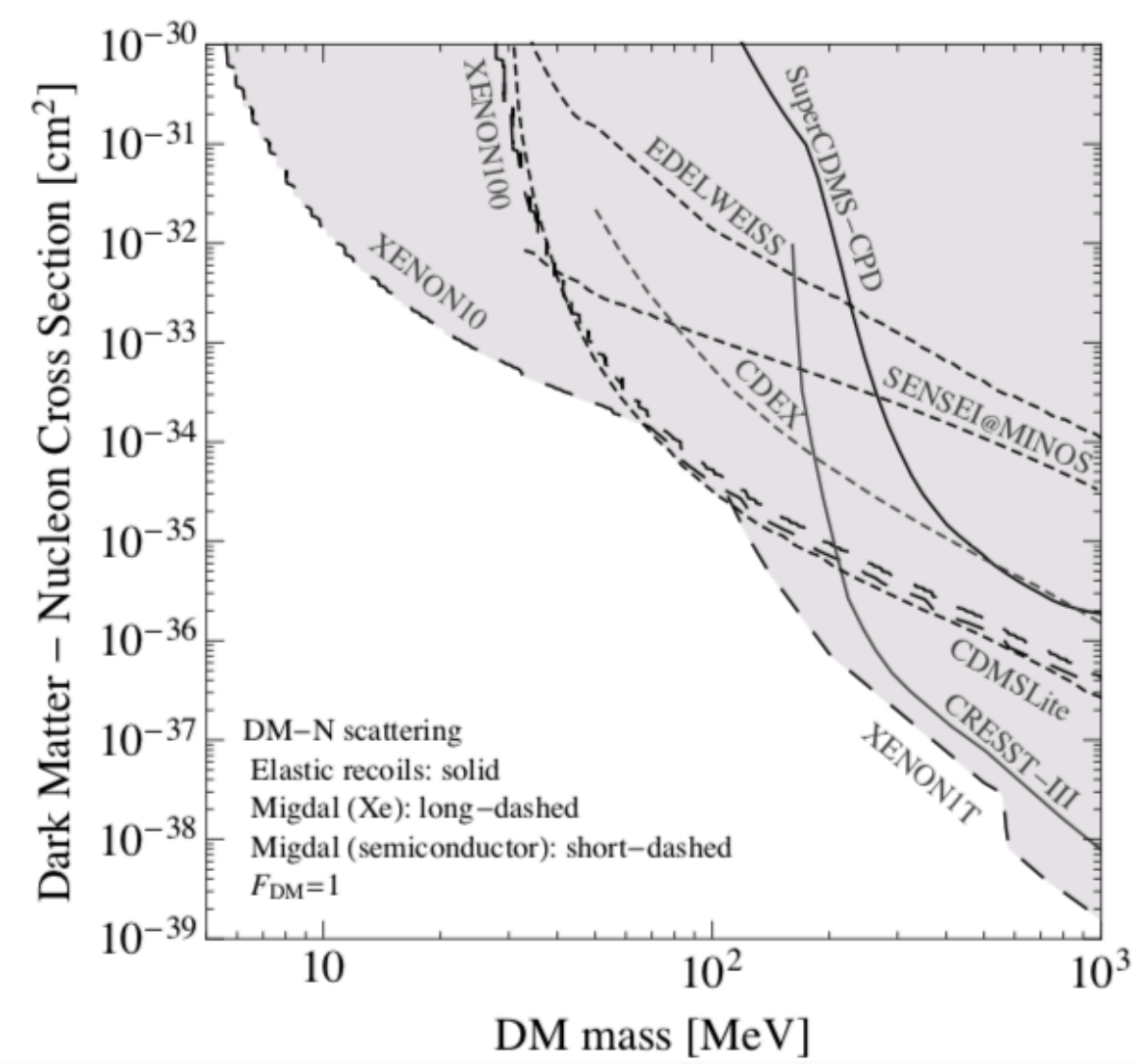
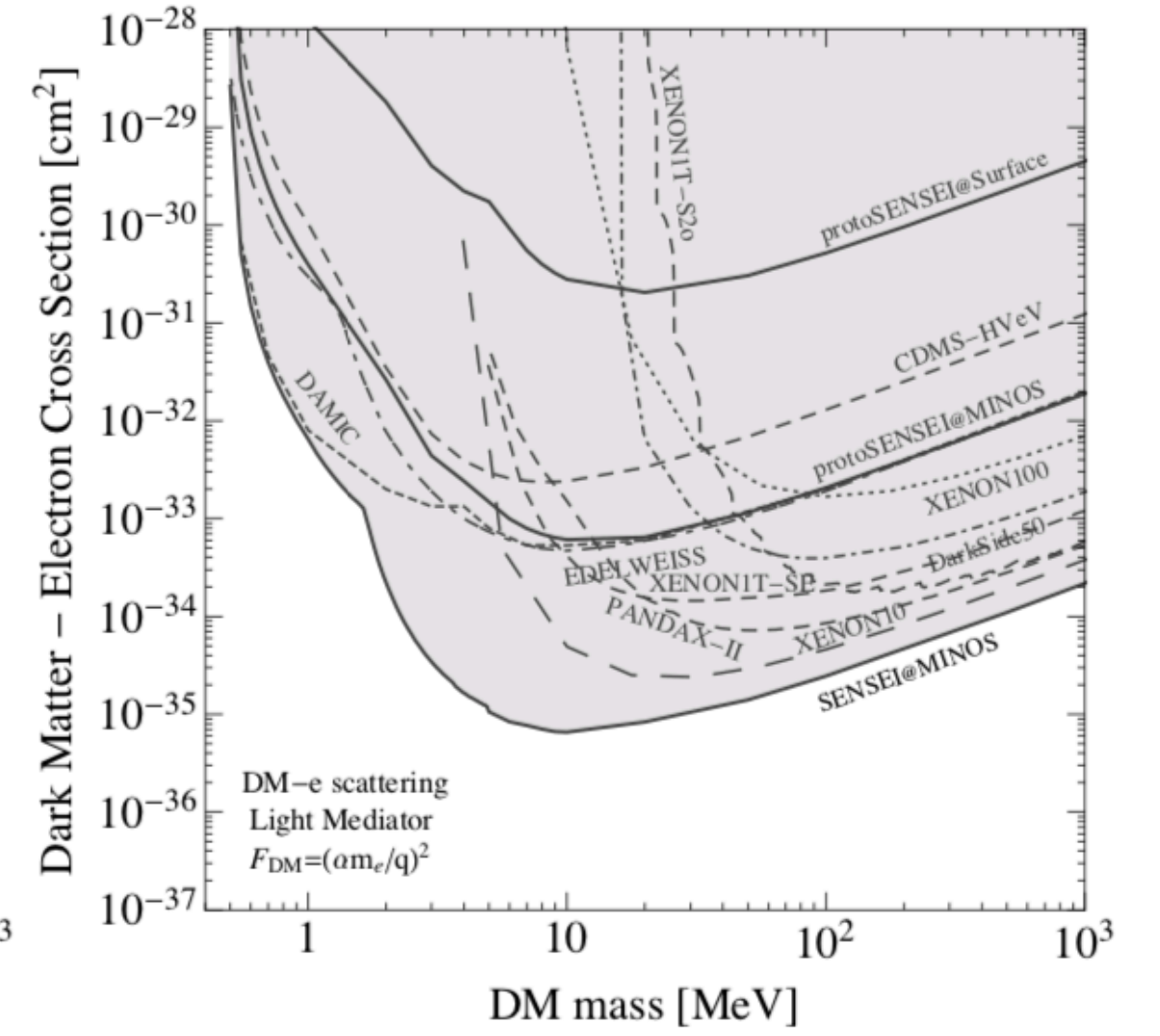
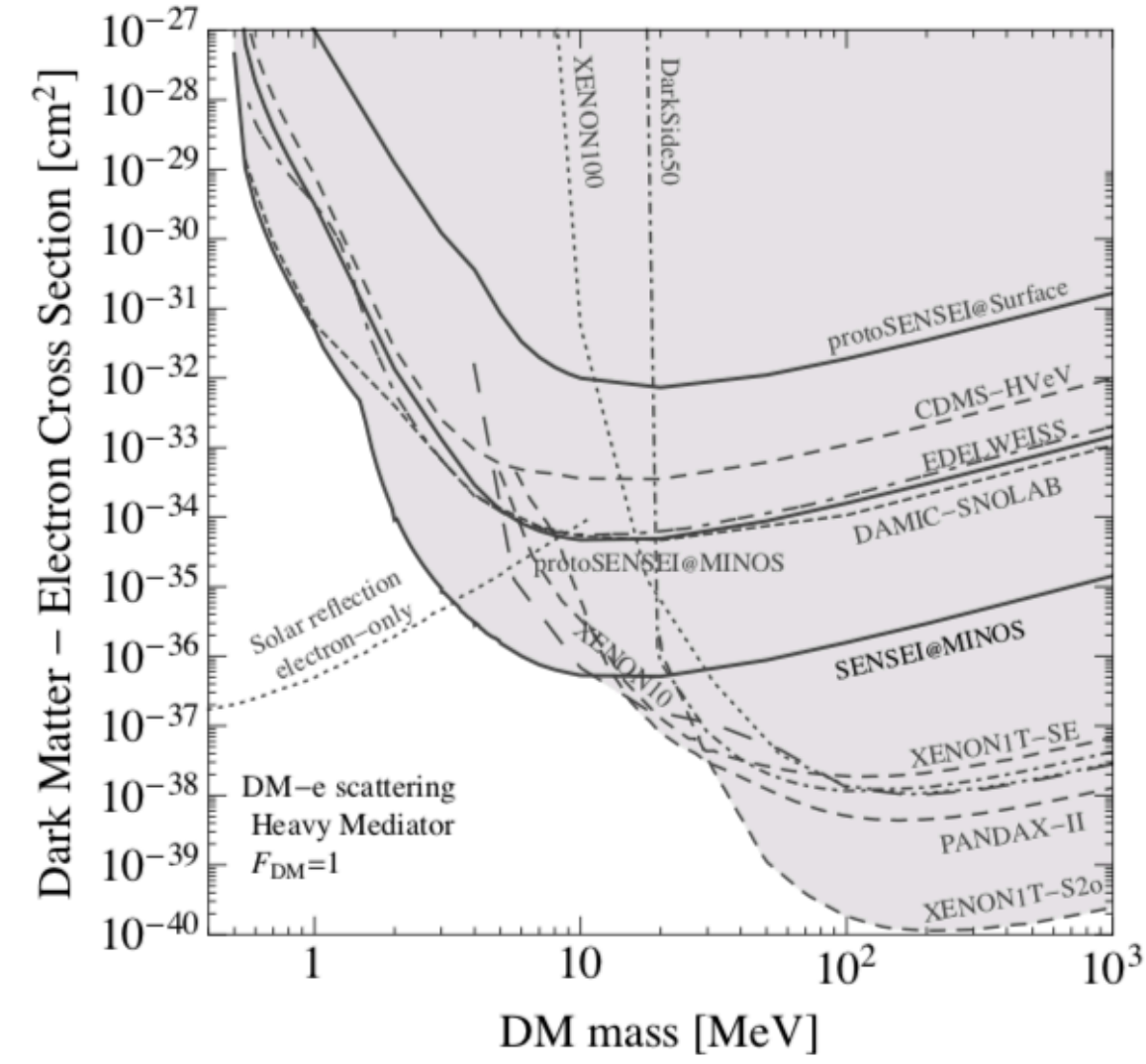
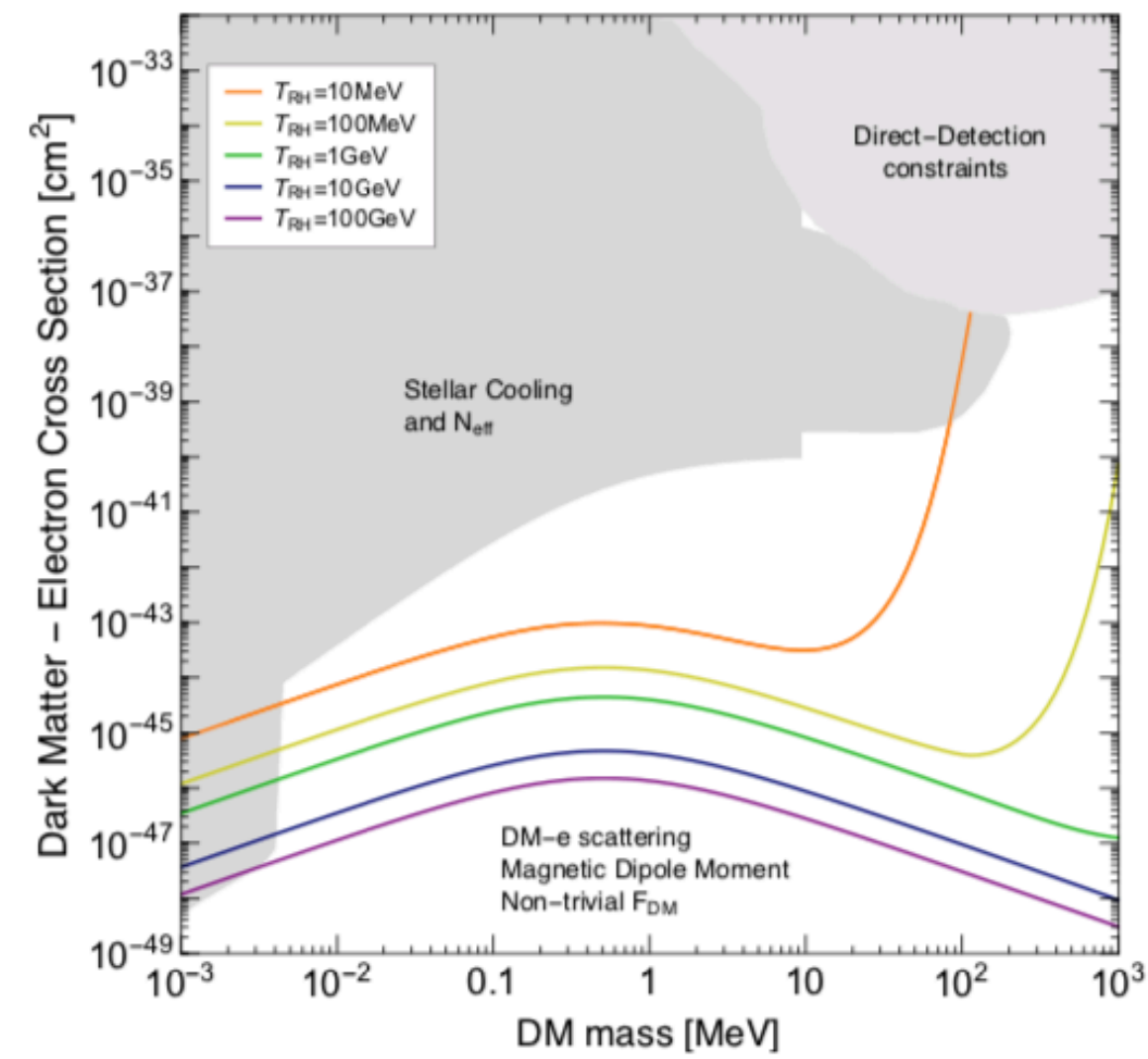
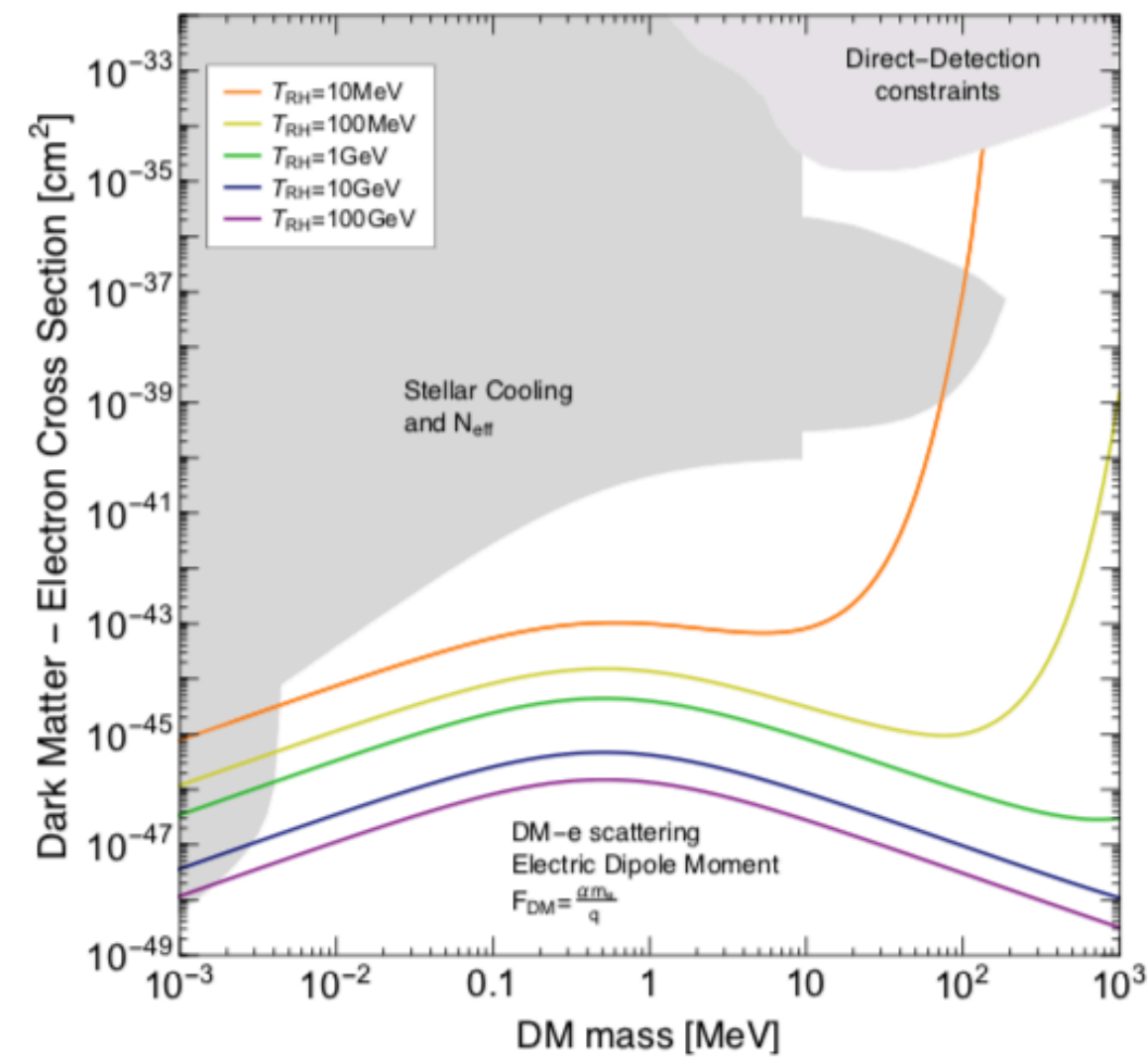
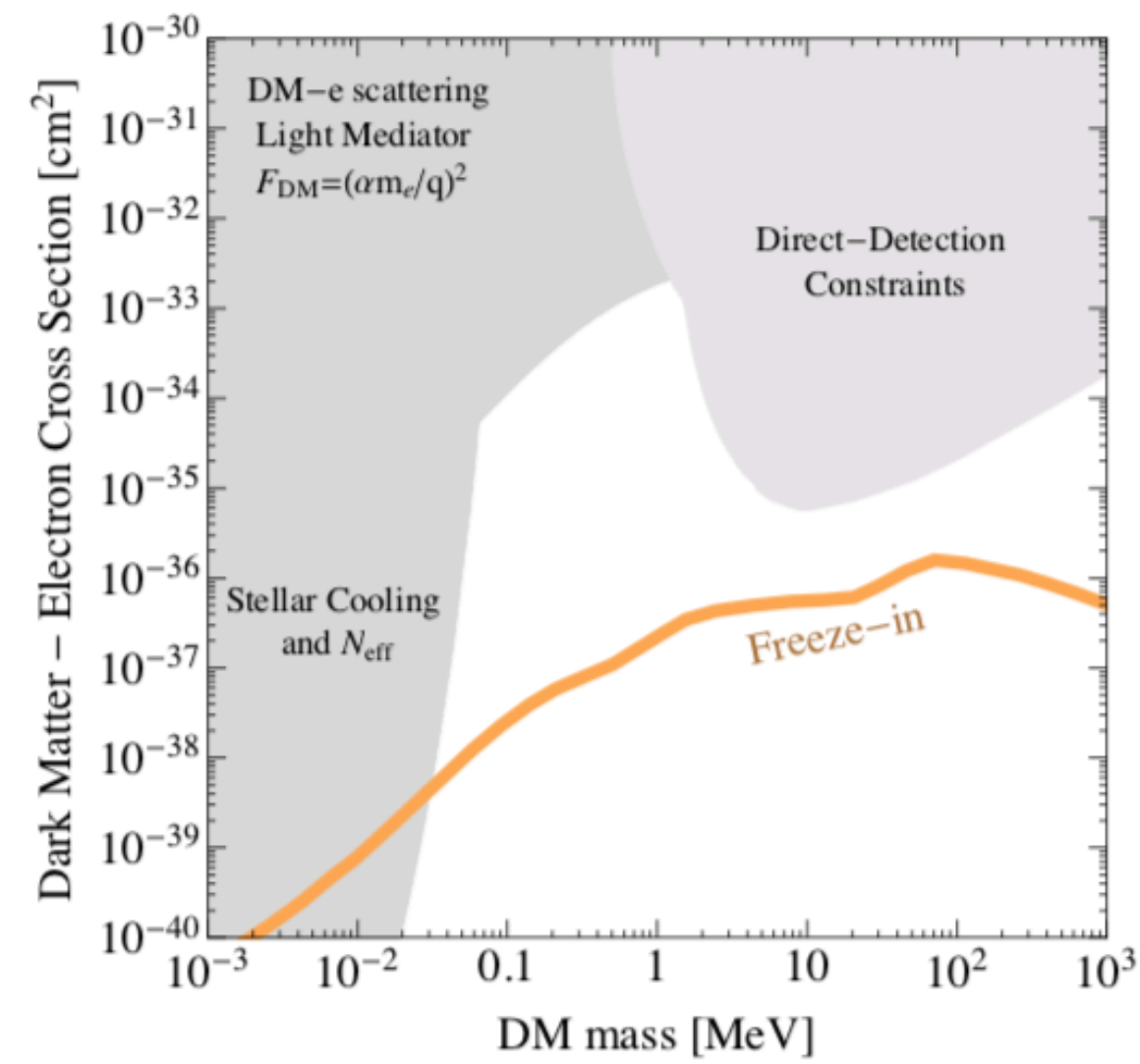
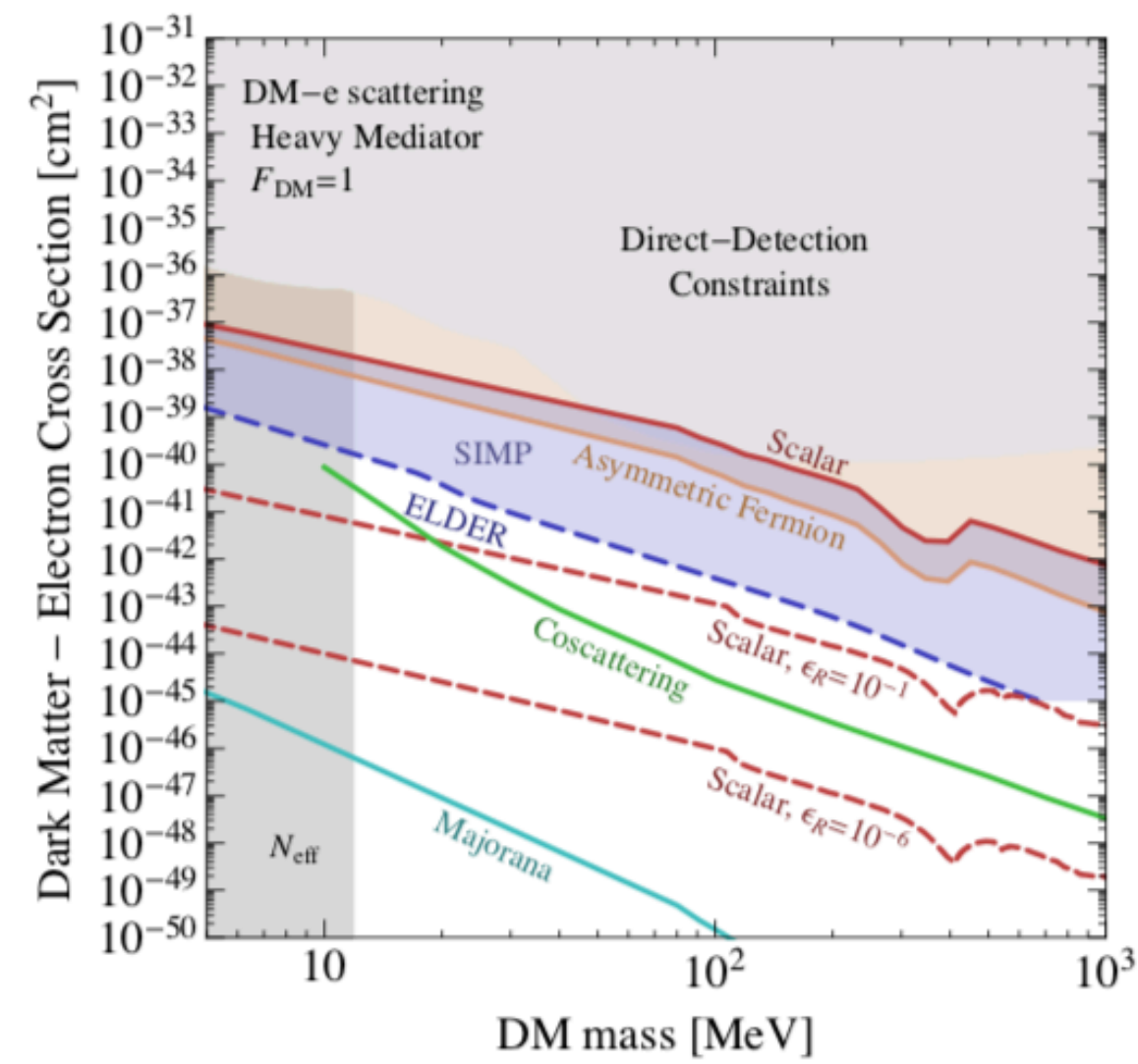
Developments in theory for low mass particle dark matter has matched progress in quantum sensors, making this new parameter space accessible.

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.

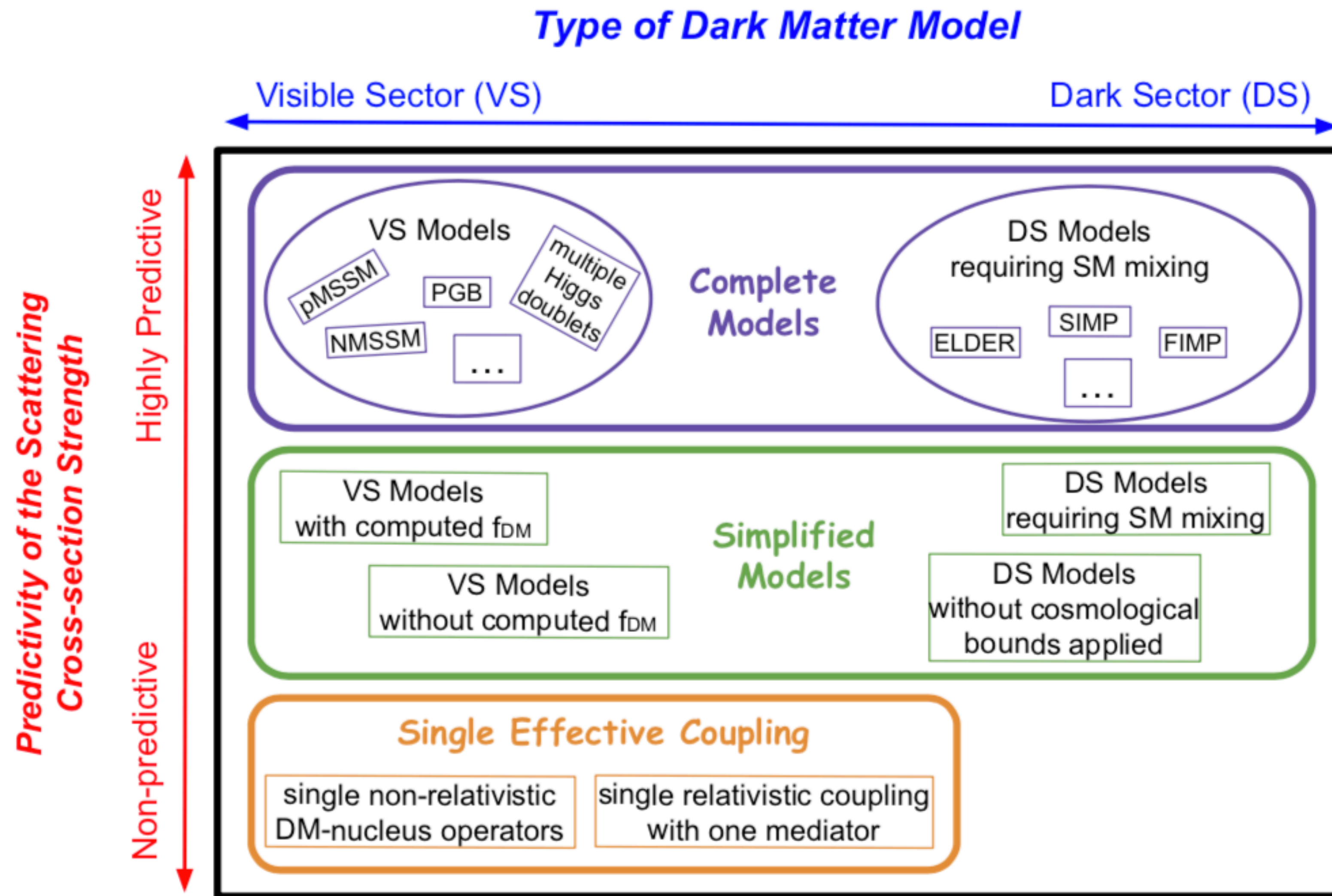


# Low Mass models and sensitivity



arXiv: 2203.08297





arXiv:2203.08084