Dark matter laboratory search overview

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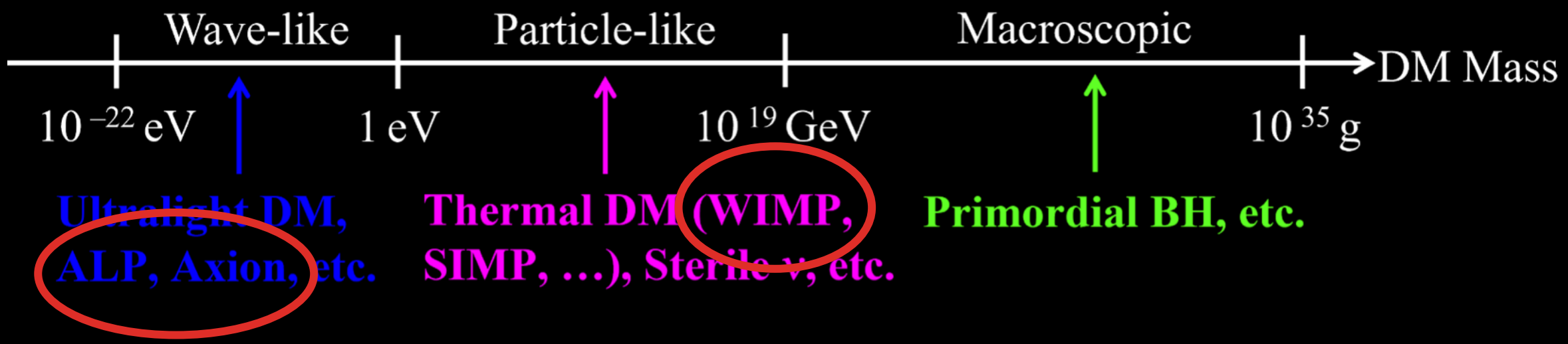
Disclaimer: This is a very vast field, so I have to make hard and personal choices on what's covered here.

Special thanks to Dr. Yi Tao, Mengjiao Xiao, Sming Tsai, Dan Zhang and Ning Zhou for materials

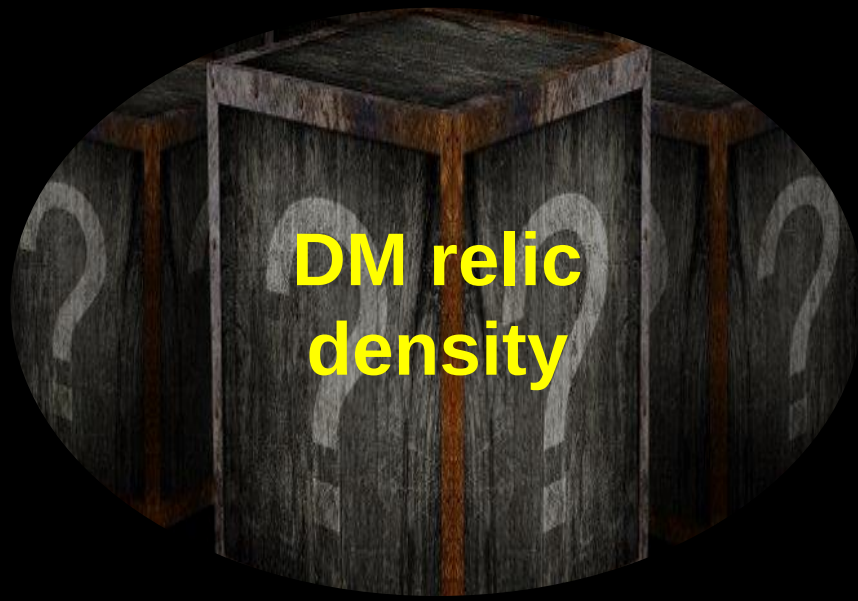
The dark matter landscape



Credit to Shigeki Matsumoto
https://member.ipmu.jp/shigeki.matsumoto/index.html

The WIMP Miracle

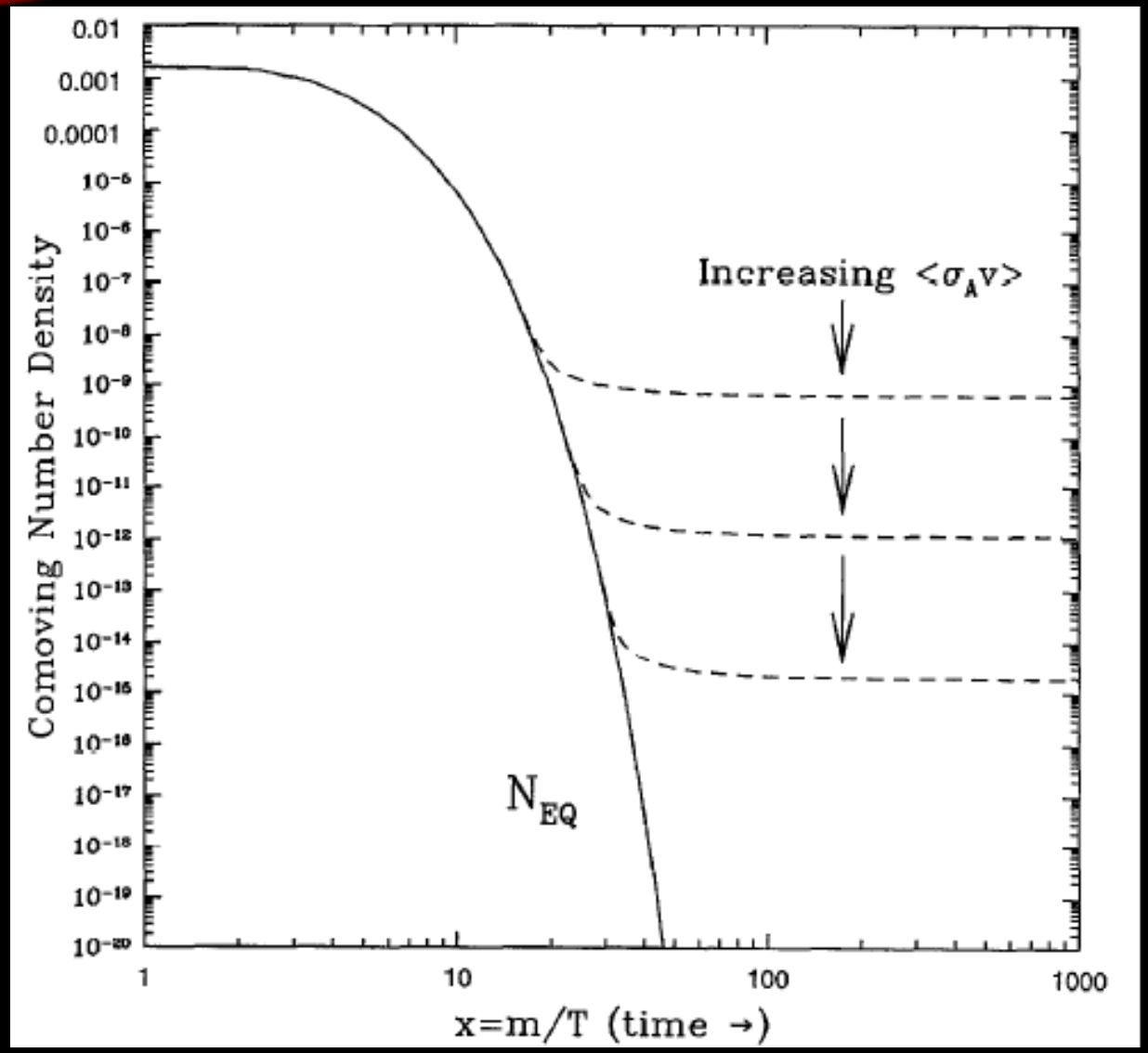
Beyond SM Particle Theories



DM relic density

Weakly Interacting Massive Particle (WIMP) Miracle!

WIMP thermal freeze-out



Early Universe Boltzmann Equation

$$0.23 = \Omega_\chi \approx \frac{6\times10^{-27}\ cm^3/s}{\langle\sigma_{ann}\mathrm{v}\rangle}$$

$\langle\sigma_{ann}\mathrm{v}\rangle$ =3x10^{-26}cm^3/s

Weak-scale coupling

$$\langle\sigma_{ann}\mathrm{v}\rangle \sim \frac{\alpha_w 2}{M^2} \sim \frac{\alpha_w 2}{(1\mathrm{TeV})^2}$$

$$\approx O(10^{-26}\ \mathrm{cm}^3/\mathrm{s})$$

A fully testable idea

Indirect Detection

DM

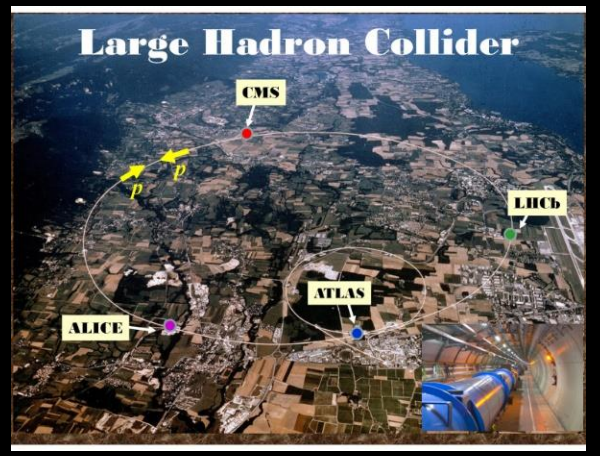
DM

?

SM

SM

Collider Search



Direct Detection

Dark Matter Indirect Detection

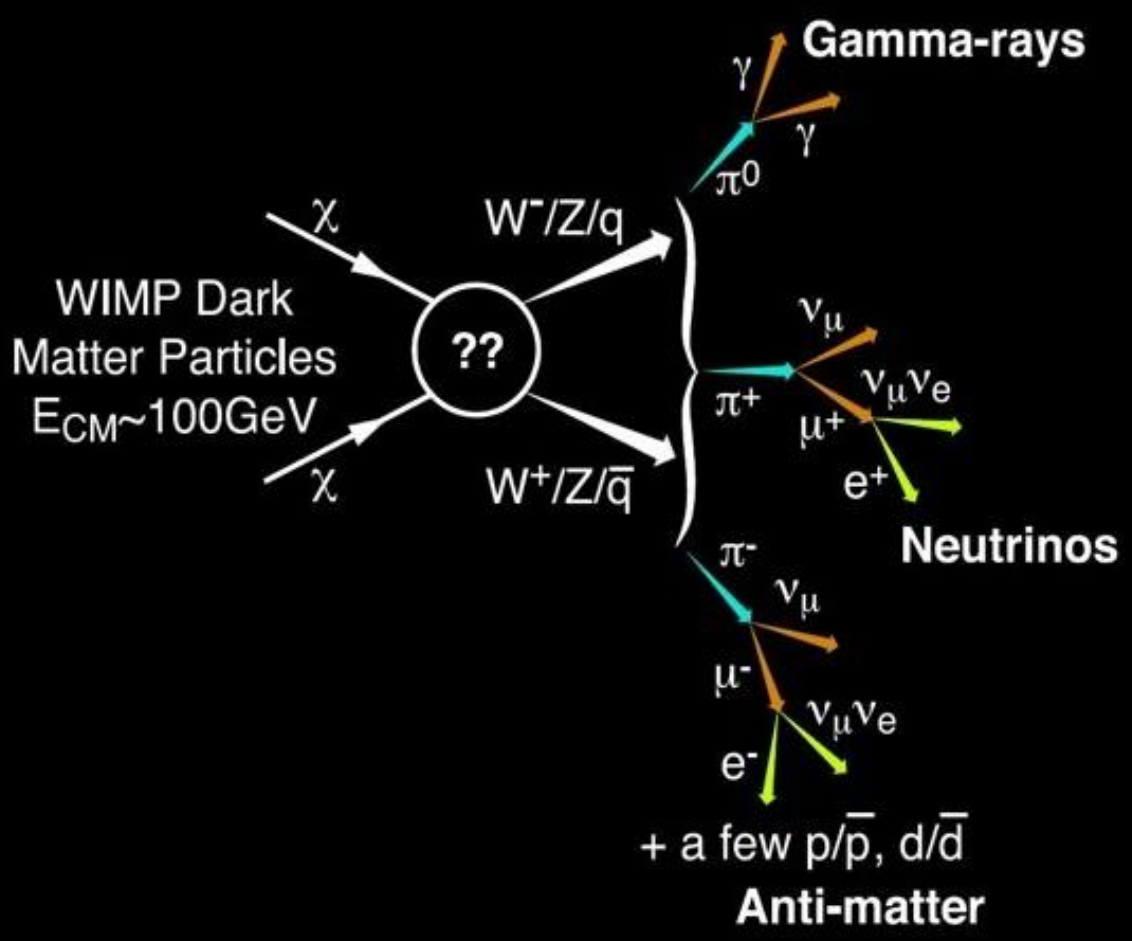



Image credit: Fermi-LAT


Image credit: LHAASO

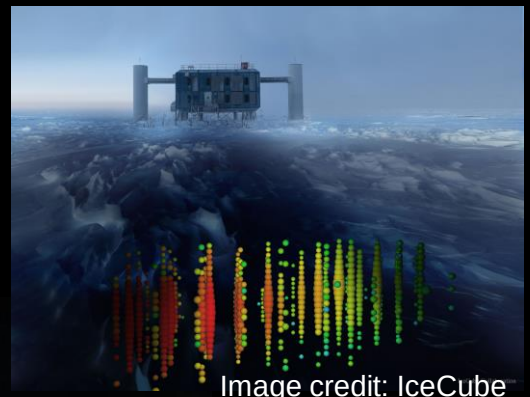
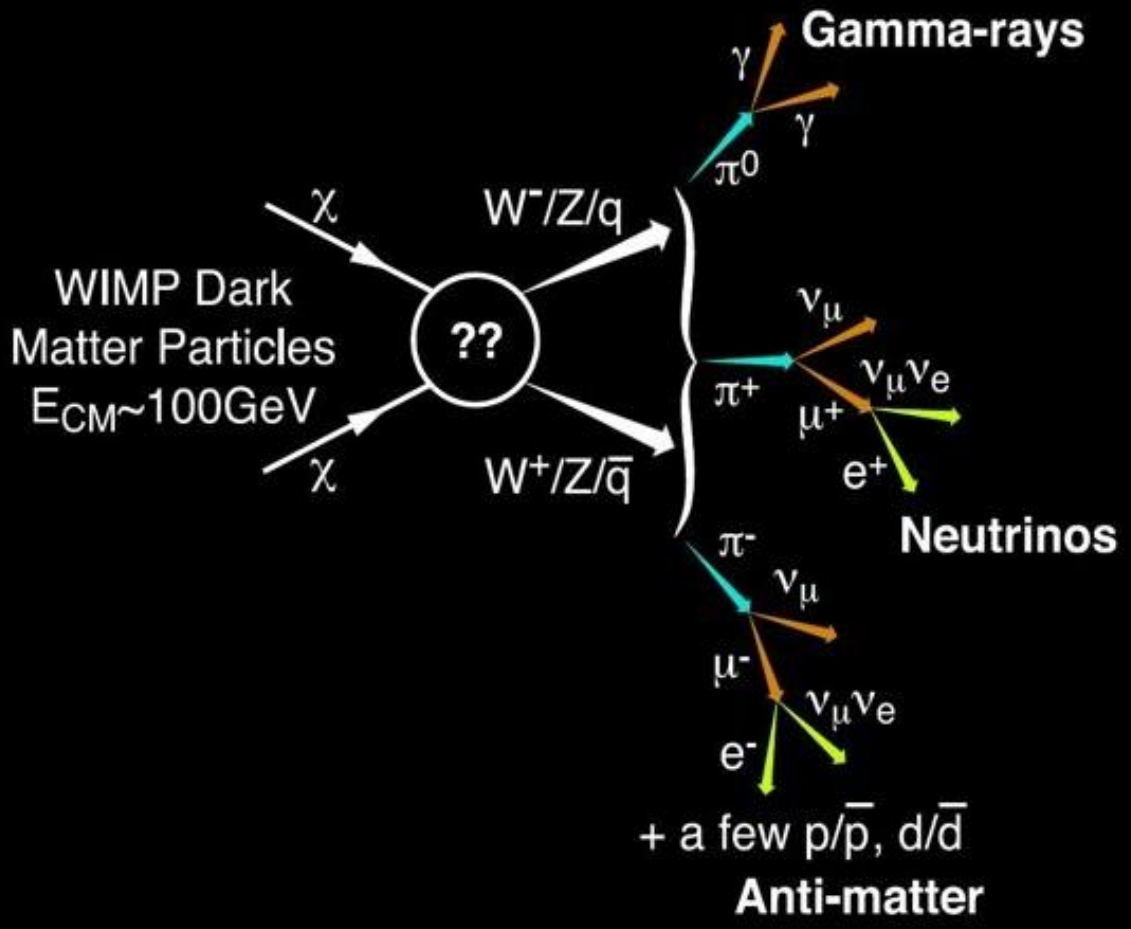


Image credit: IceCube

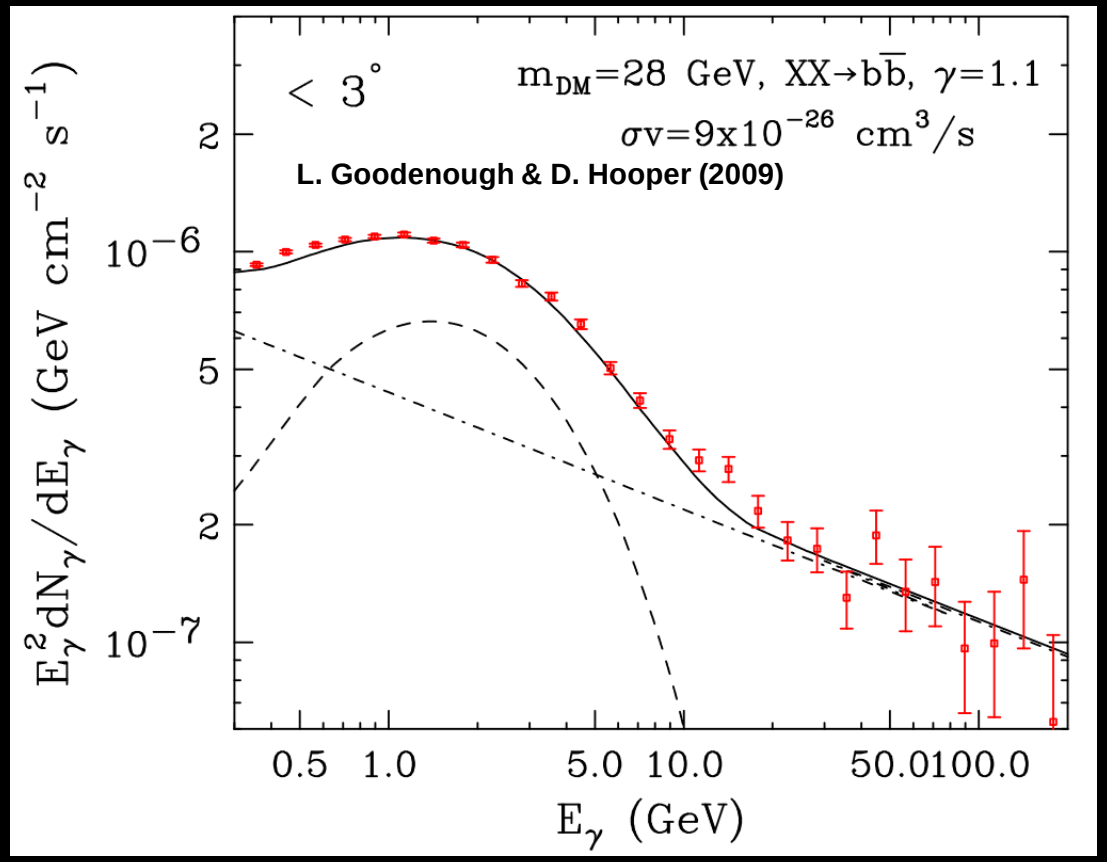

Image credit: AMS-02

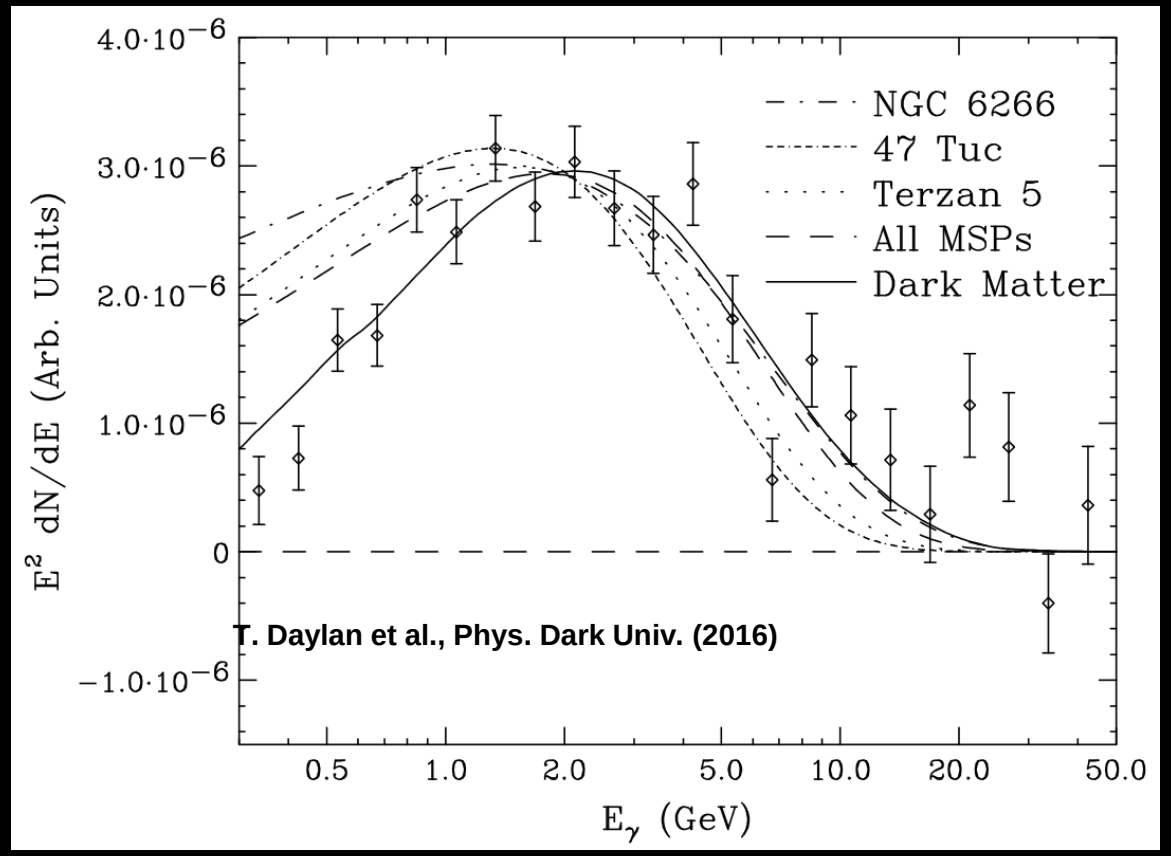
Dark Matter Indirect Detection



- Directly probes process that sets DM abundance!
- But, large systematic uncertainties
  - Comic ray propagation uncertainty
  - Hadronic interaction
  - Backgrounds related to astrophysical sources
  - DM distribution profiles
  - DM annihilation final states
  - ….

GC “GeV excess”

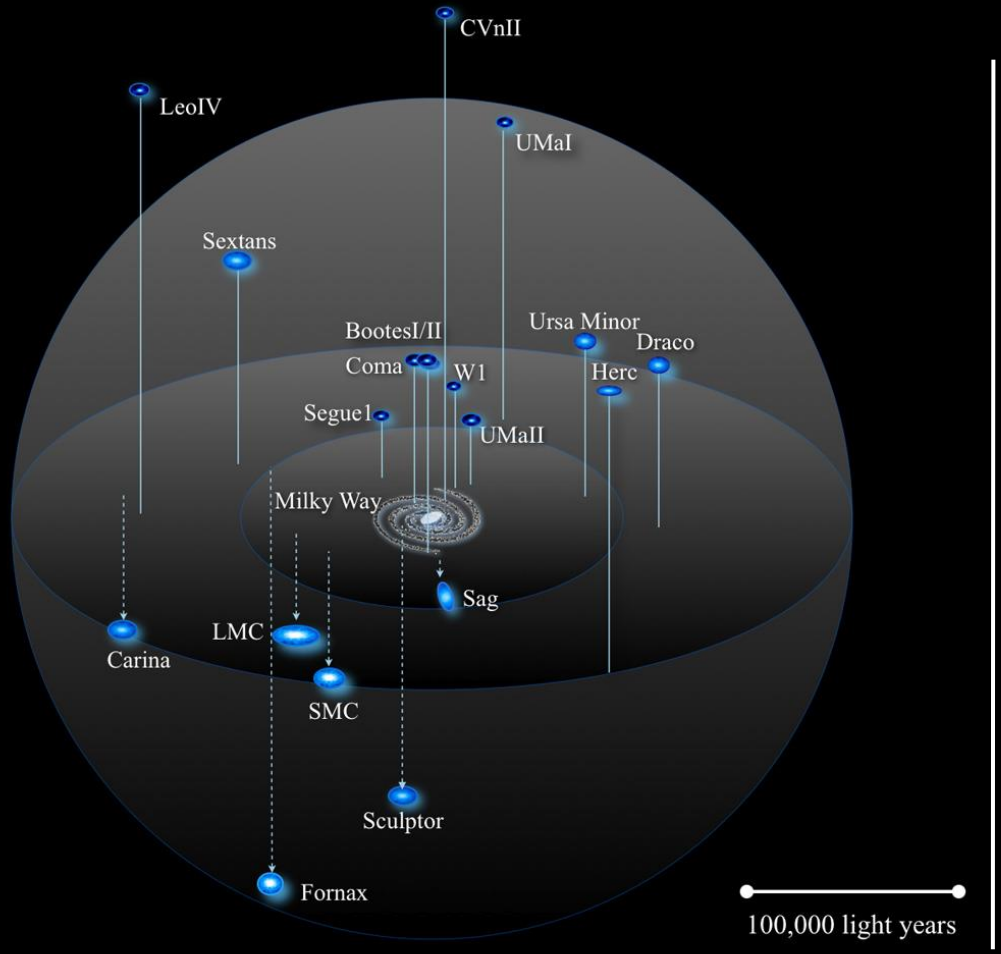


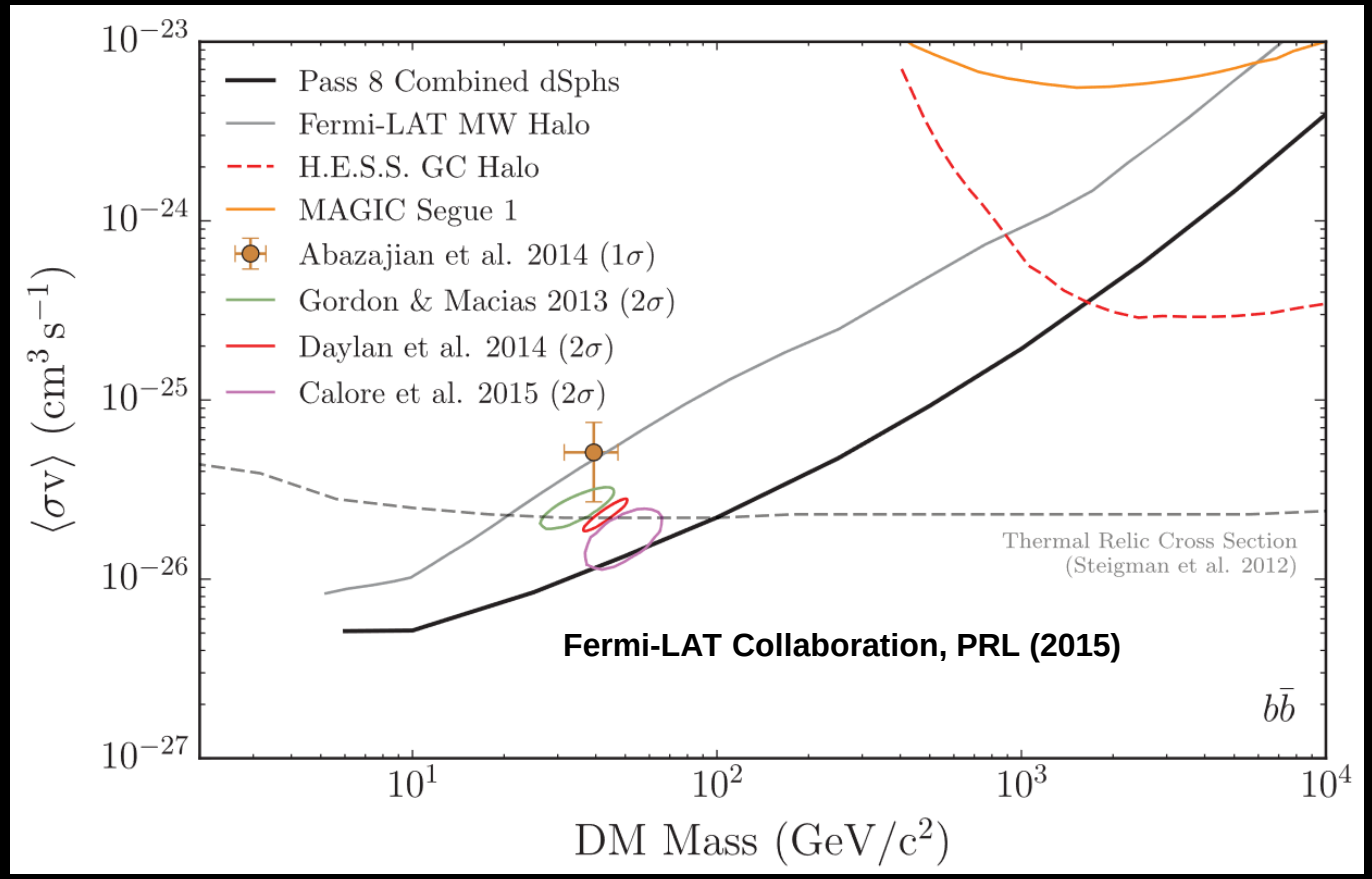


D. Hooper and L. Goodenough, PLB (2011)
Abazajian & Kaplinghat (2012), Gordon & Macias (2013), Calore, Cholis, Weniger (2015), Ackermann, et al. (2017)

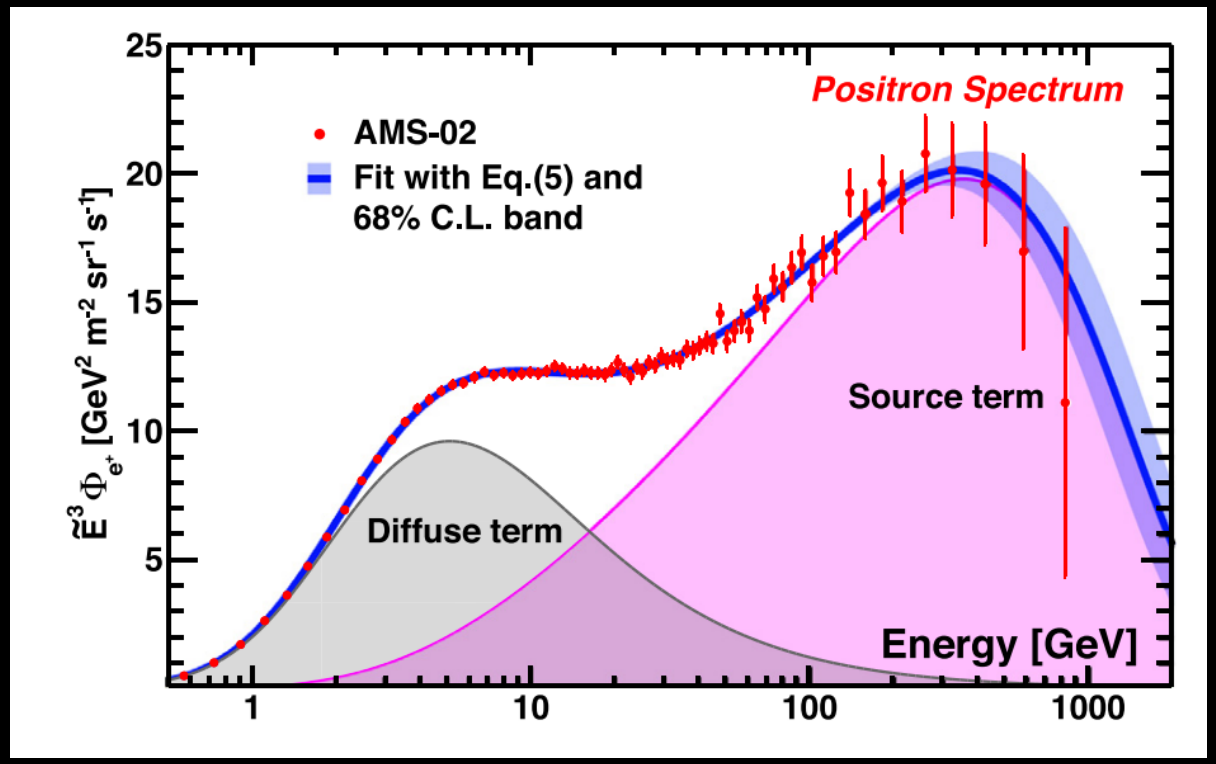
Interpretation highly model dependent, e.g. data may be at tension with pulsar interpretation

Dwarf galaxy: DM hypothesis checks

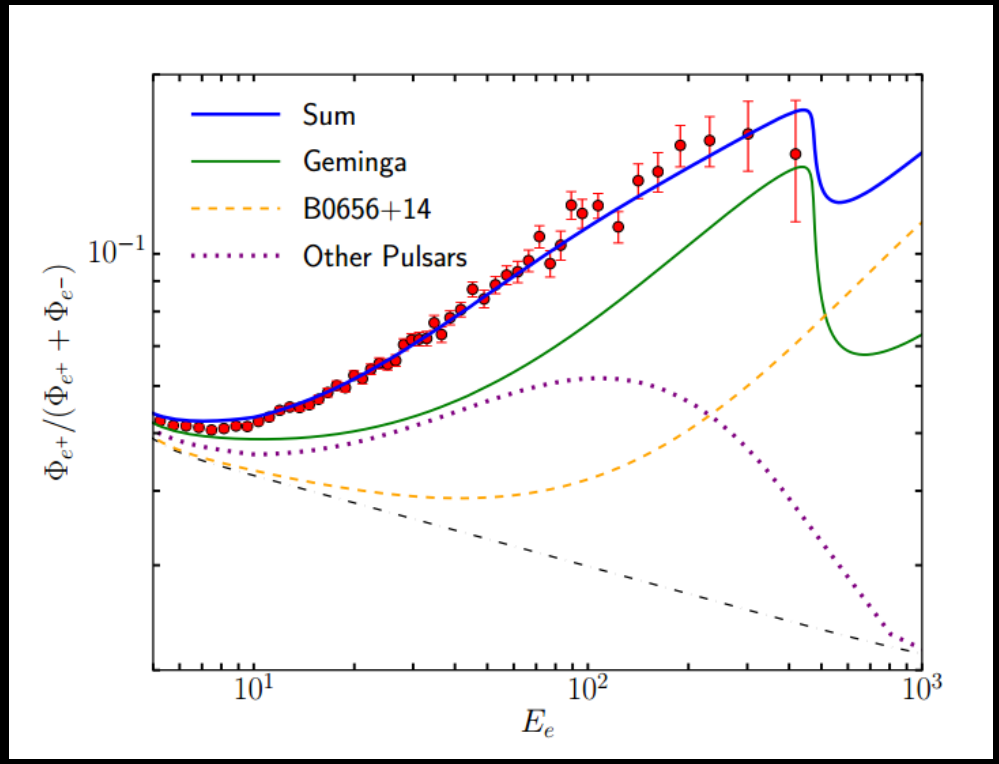




Positron excess

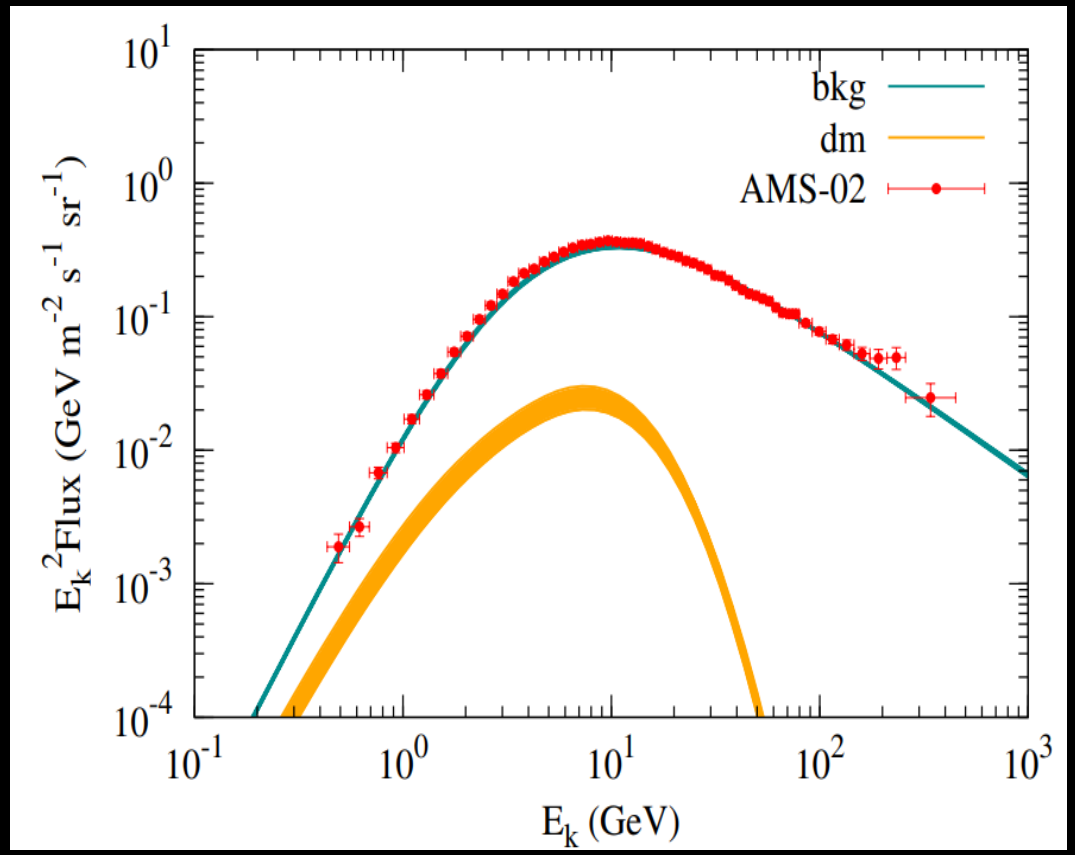


AMS-02, Physics Reports, Vol 894, 1-116 (2021)

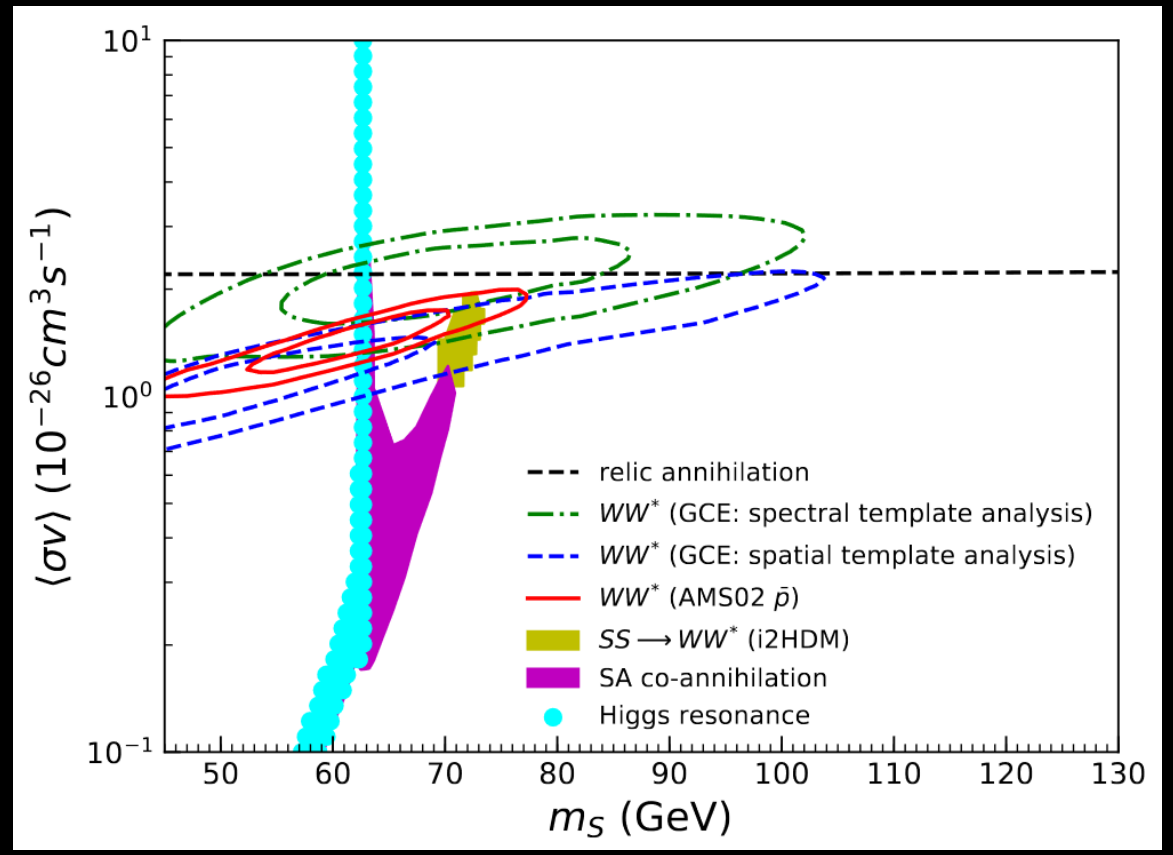


Alternative explanations from pulsars, 1702.08436, but challenged by Hawk observation, SCIENCE 2017

Antiproton excess

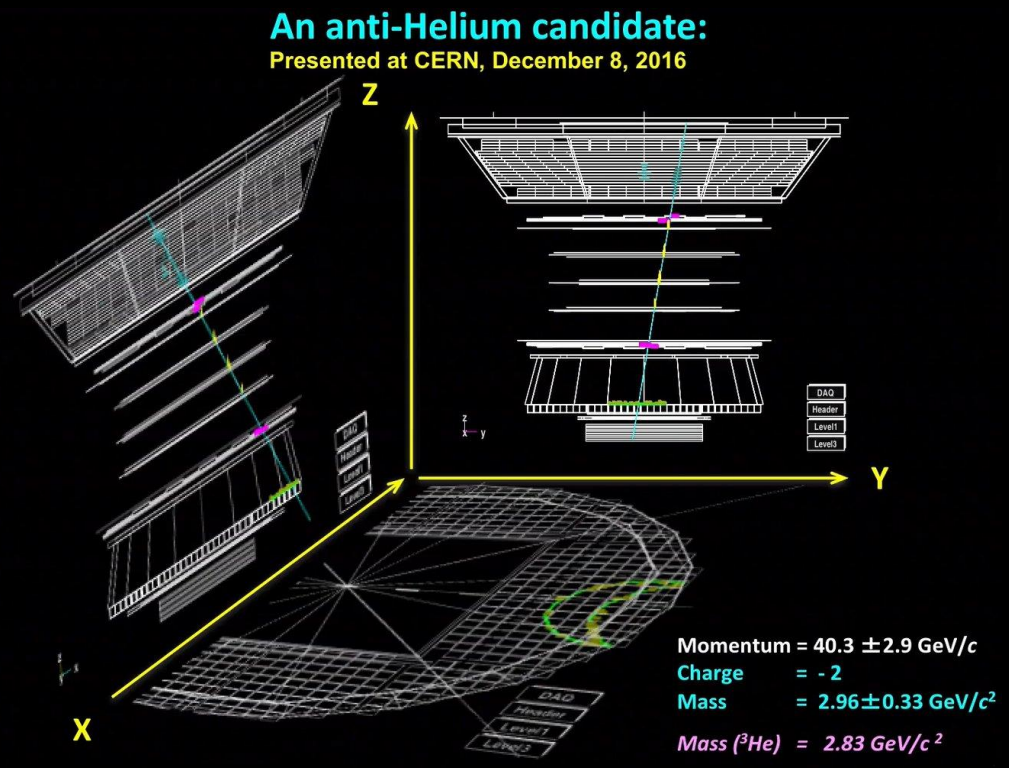


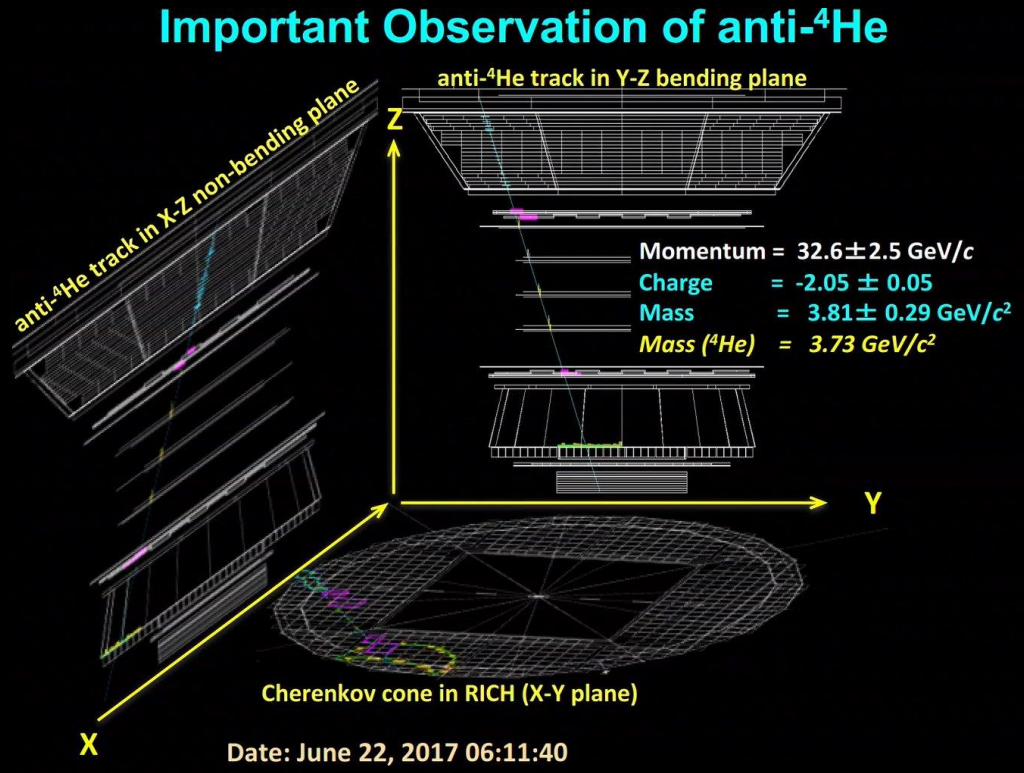
Cui, Yuan, Tsai, Fan, PRL 2017
Cuoco, Krämer, and Korsmeier, PRL 2017



Zhu, Cui, Xia, Yu, Huang, Yuan, Fan, PRL (2022)

Anti-Helium

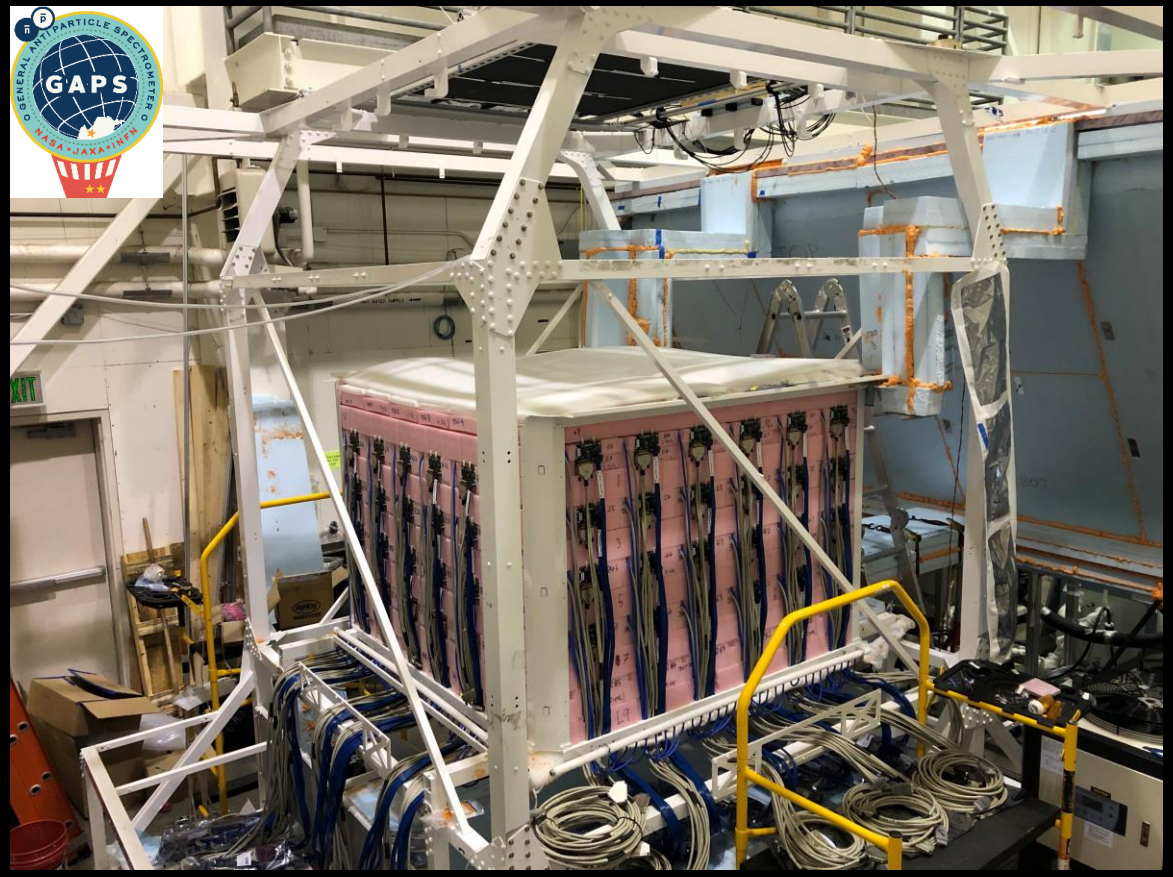


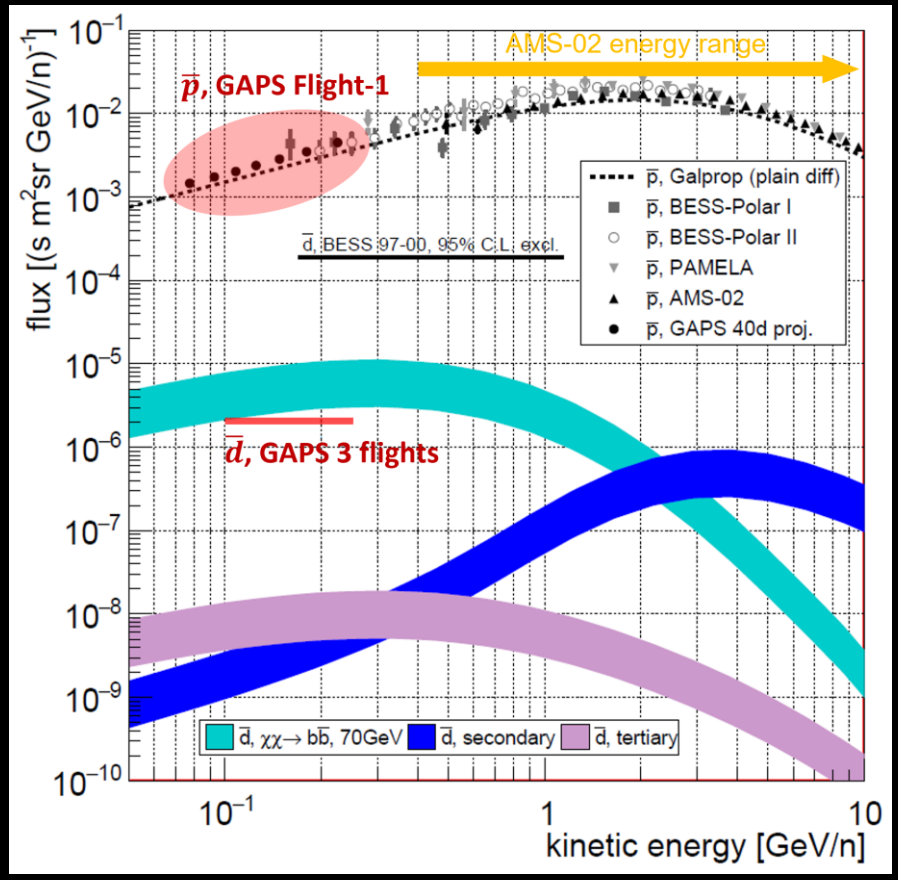


2018: "To date, we have observed *eight* events…with *Z* = *-2*. All eight events are in the helium mass region." – S. Ting (La Palma, AMS overview)

New experiment on anti-matter

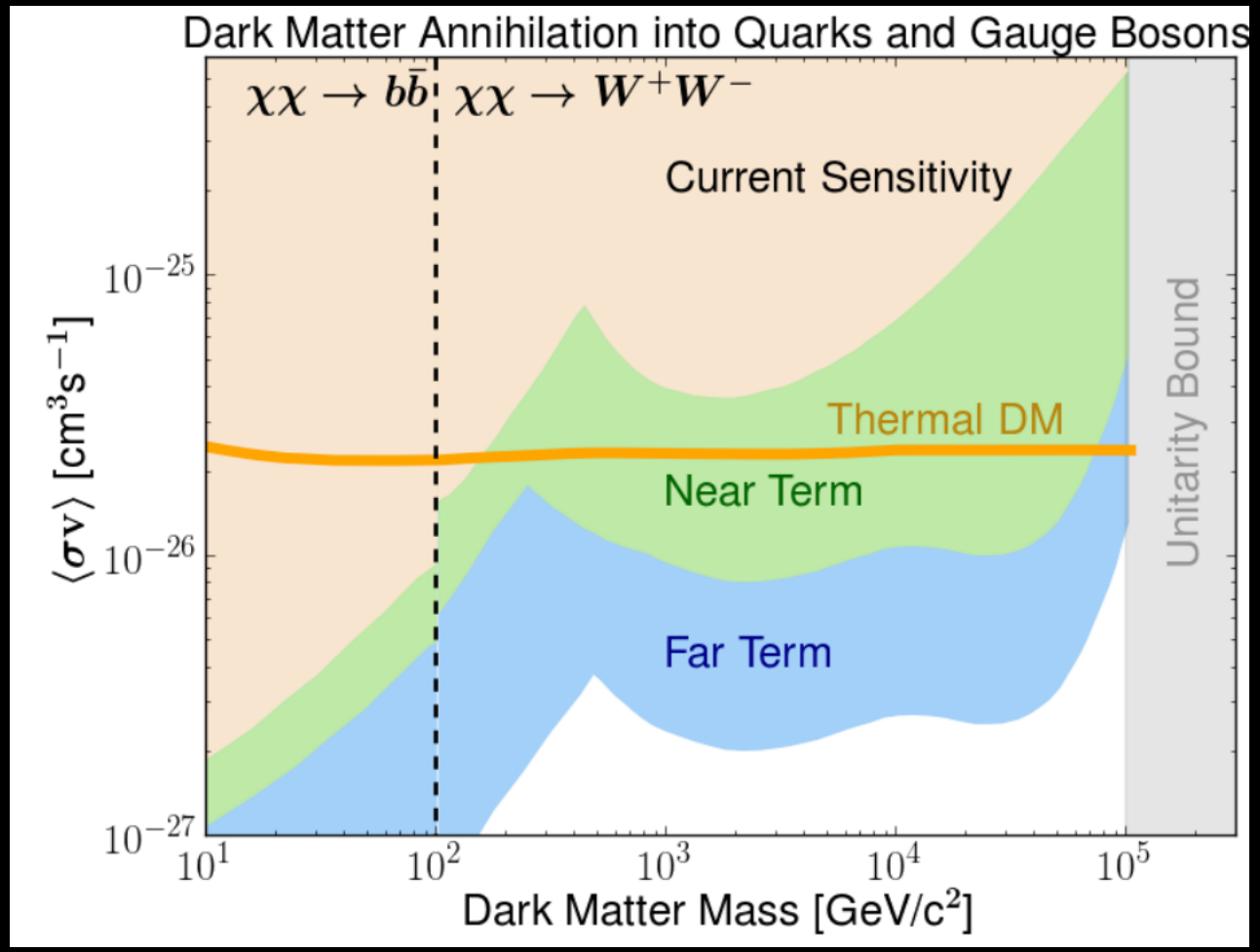
- GAPS: looking into anti-p and anti-d at lower KE





First flight: 2024!

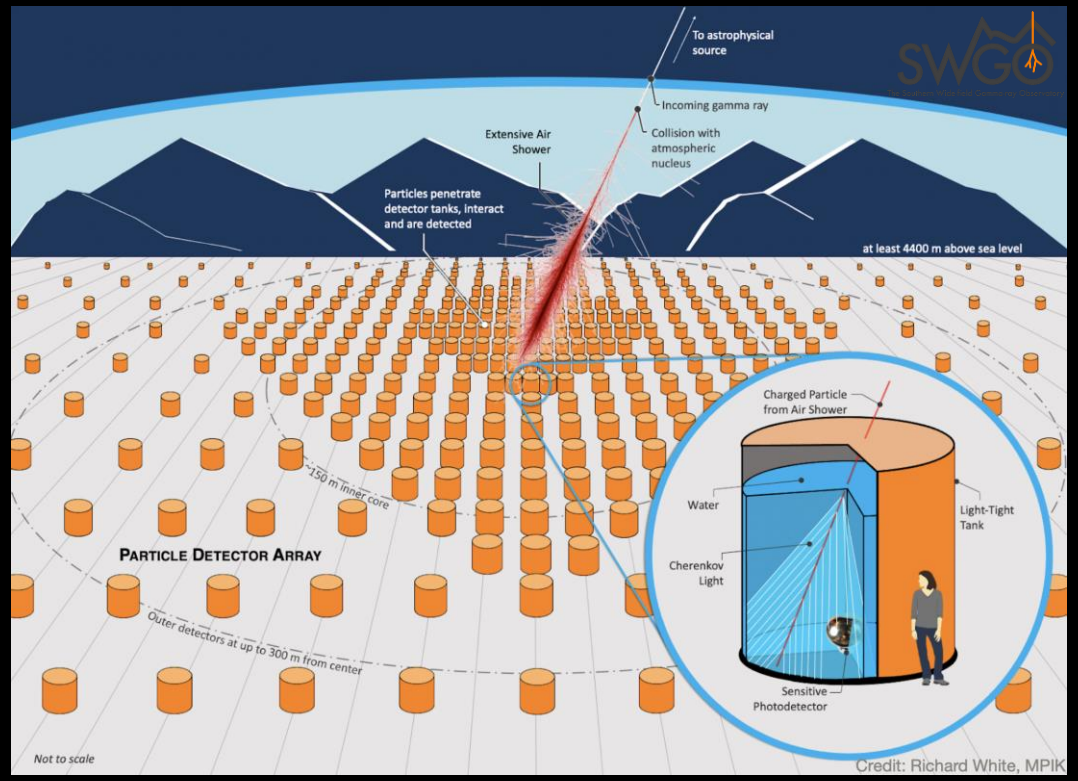
Current exclusion and sensitivity: global status



- For higher mass WIMPs, the current searches are running out-of-steam
- Bigger and more sensitive ground gamma array (viewing GC!)

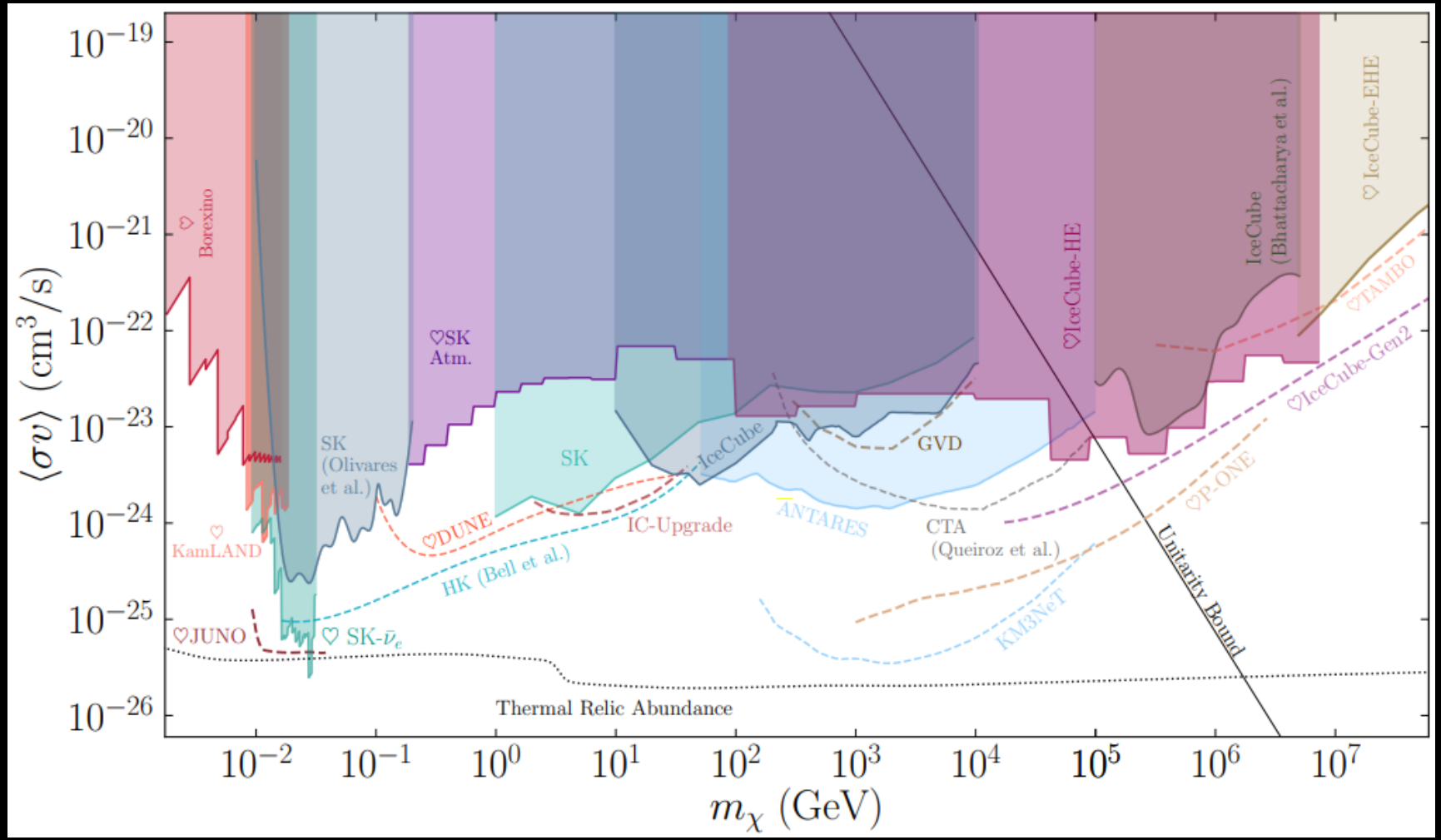
Upcoming instruments

CTA: 20 GeV - 300 TeV, funding in place for construction during 2022 – 2027. Commissioning underway.



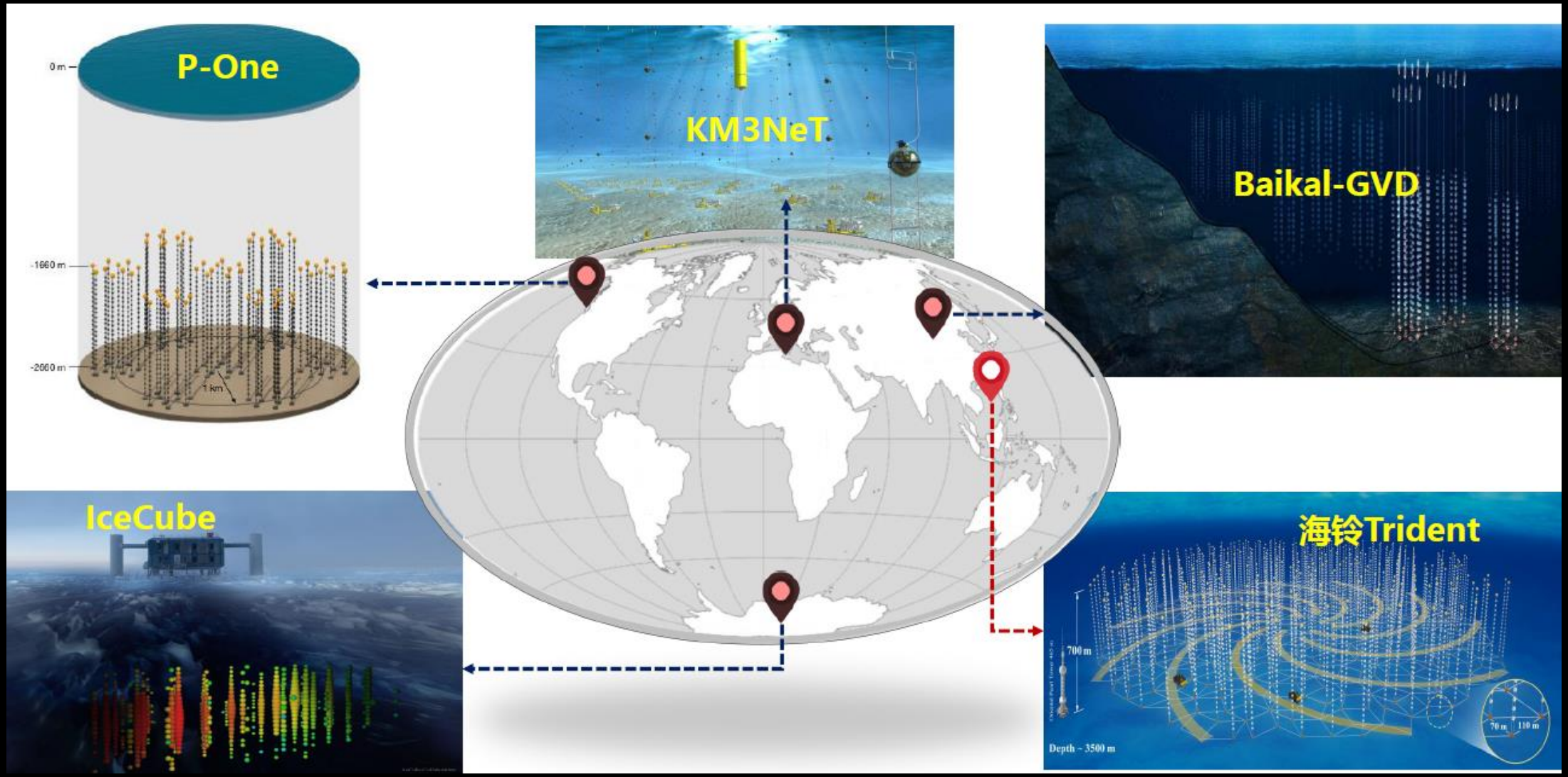
SWGO: 100 GeV - PeV, large field of view (45 degrees), R&D

Closing the WIMP window: neutrinos!



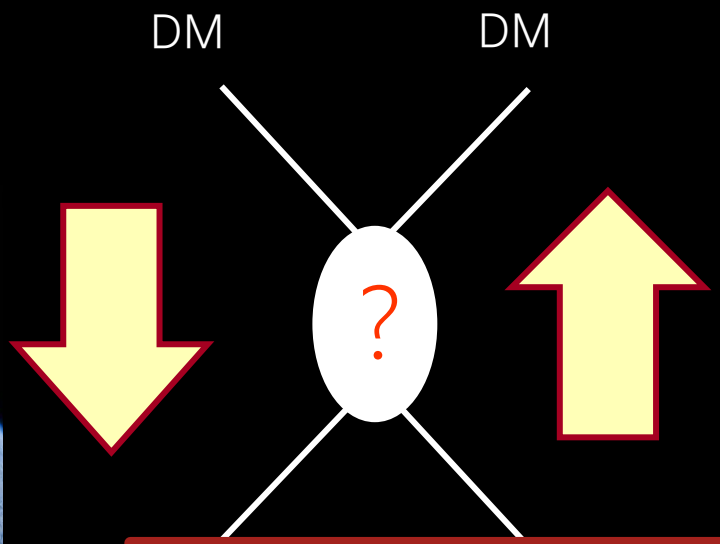
Rev. Mod. Phys. 93, 35007 (2021)

Closing the WIMP window: neutrinos!

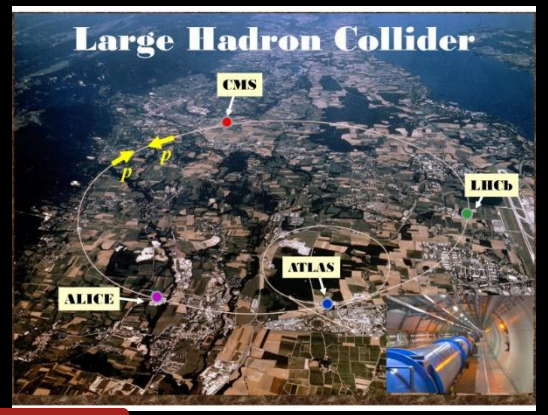


A fully testable idea

Indirect Detection

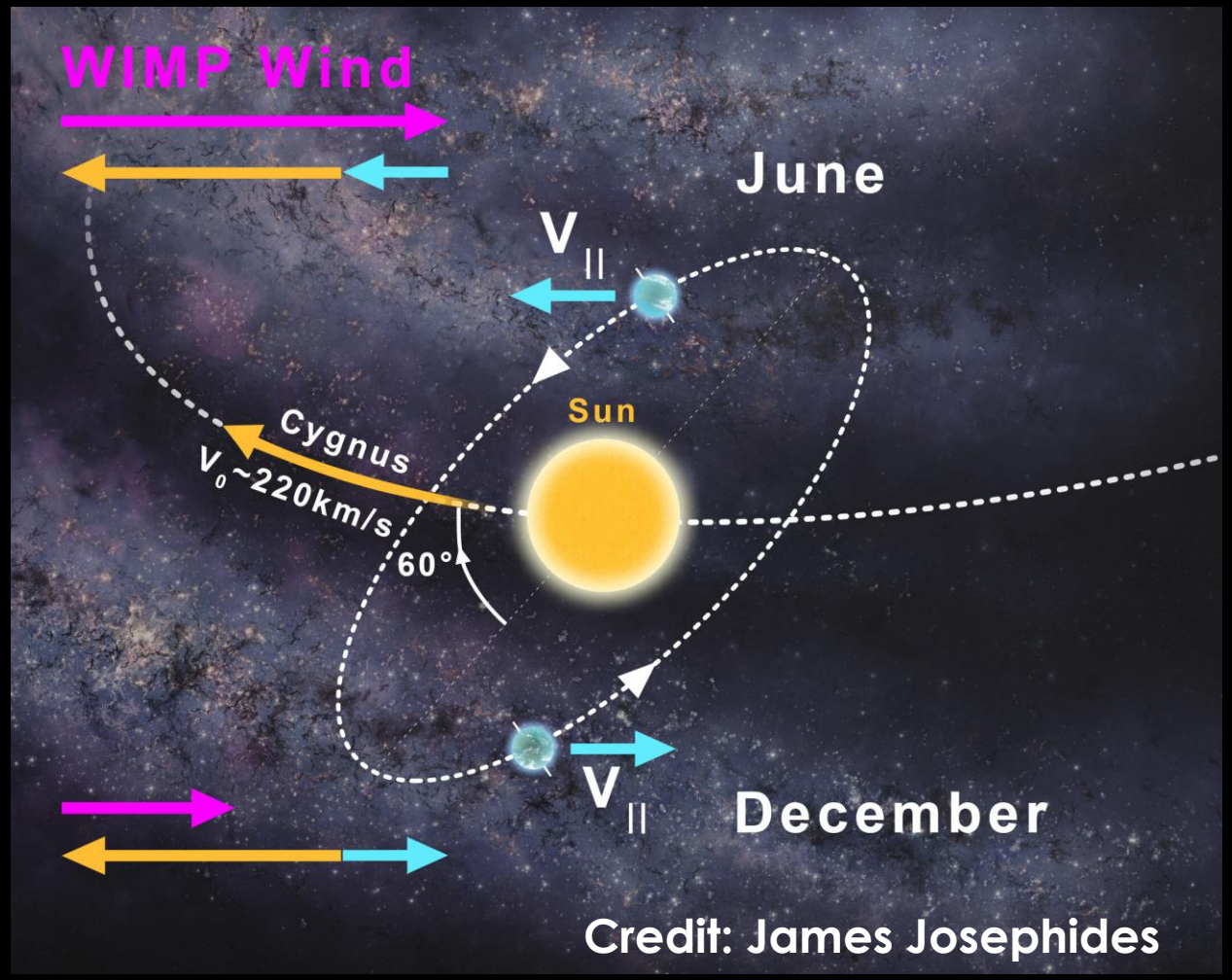


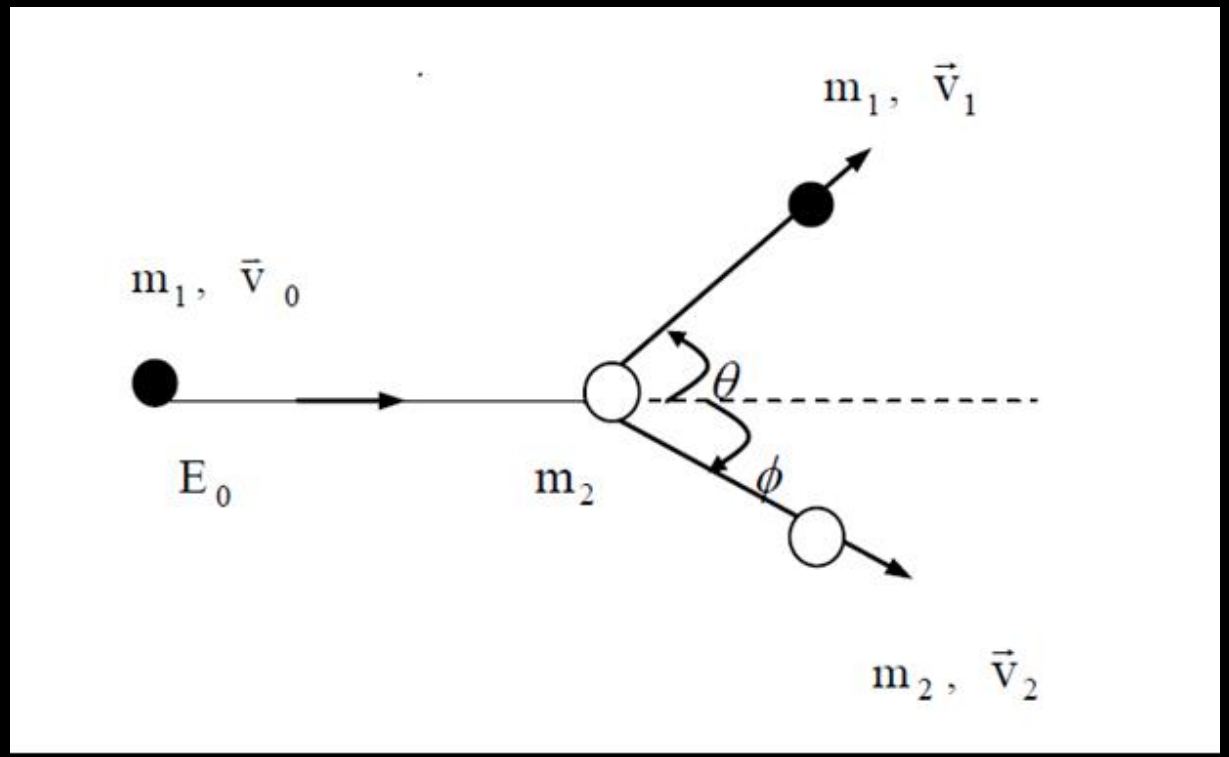
Collider Search



Direct Detection

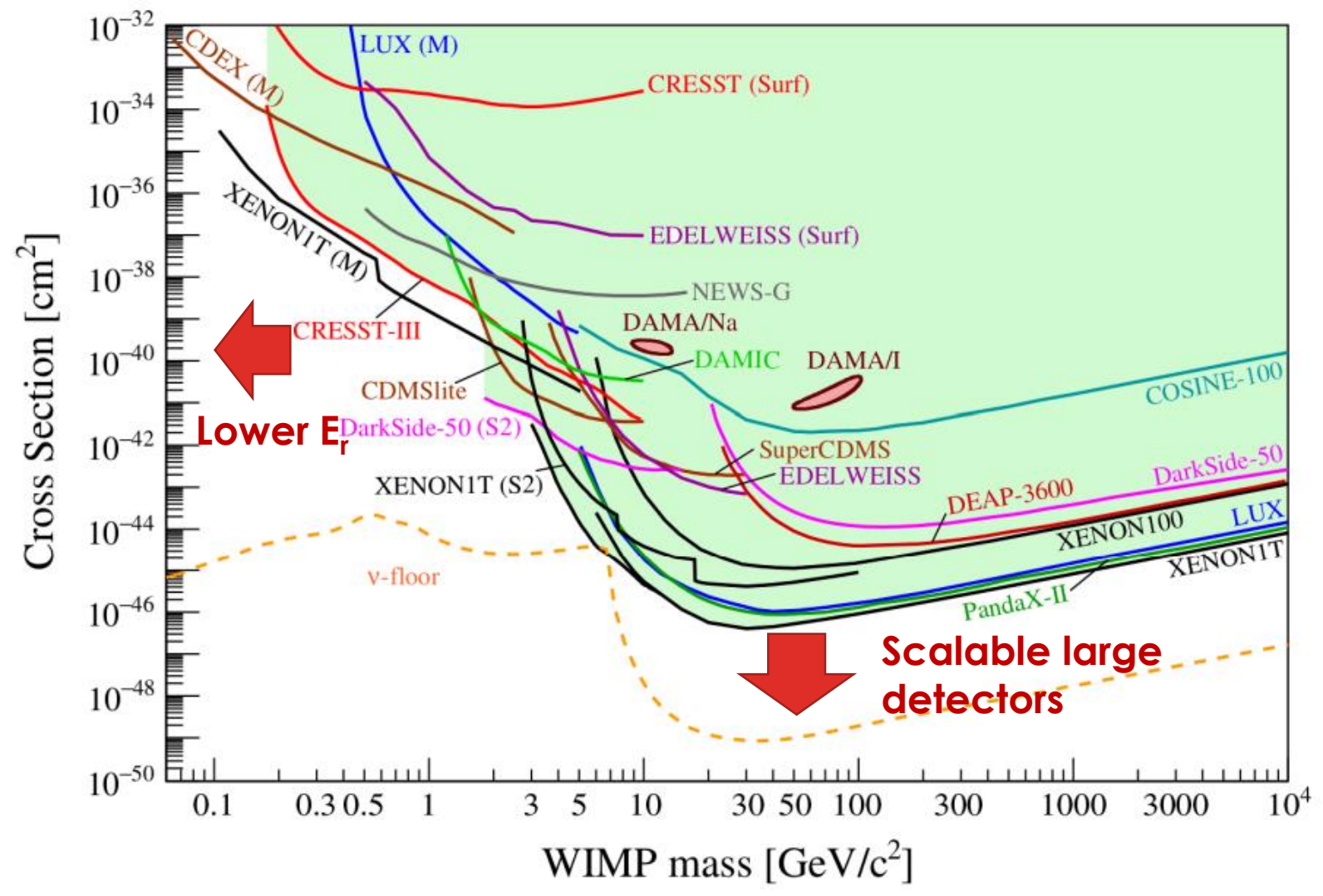
DM direct detection: classical beam experiment





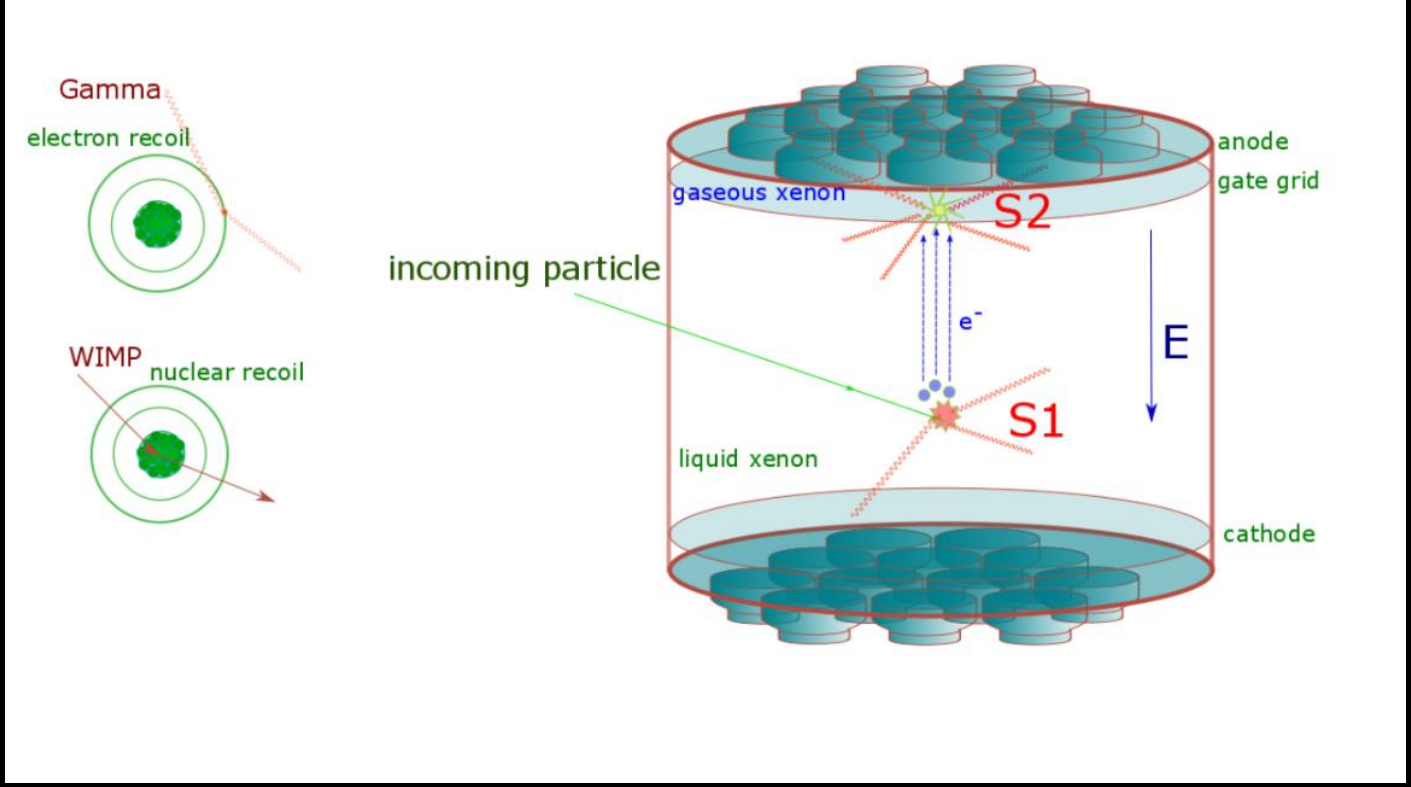
$$\frac{dR}{dE_R} = \frac{\rho_{\rm loc}}{m_A m_{\rm DM}} \int_{v \geq v_{\rm min}(E_R)} {\rm d}^3 v \, v f(\vec{v} + \vec{v}_{\rm obs}(t)) \frac{{\rm d}\sigma}{{\rm d}E_R}$$

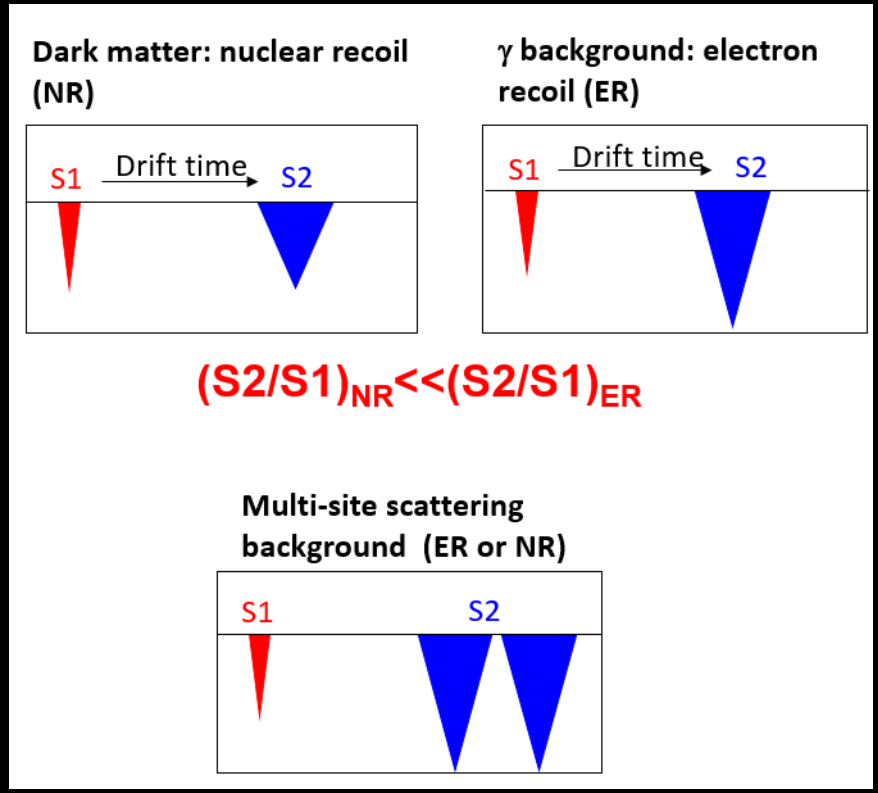
Global status: hide & seek



2104.07634, APPEC report on dark matter direct detection

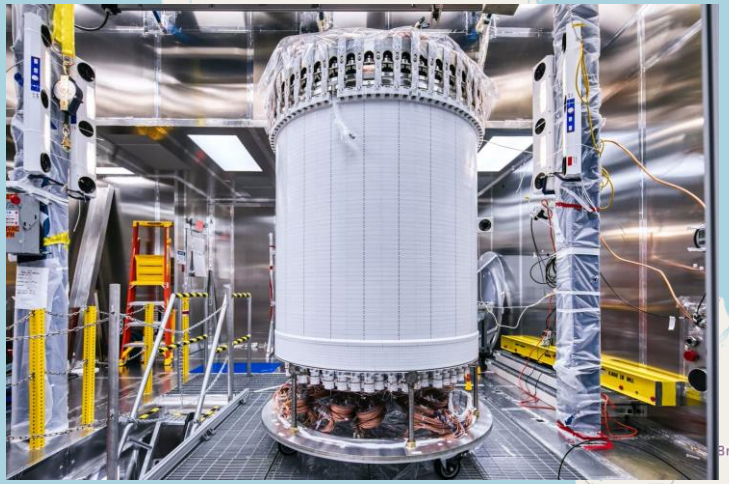
Nobel-liquid dual-phase time projection chamber





Liquid xenon experiments

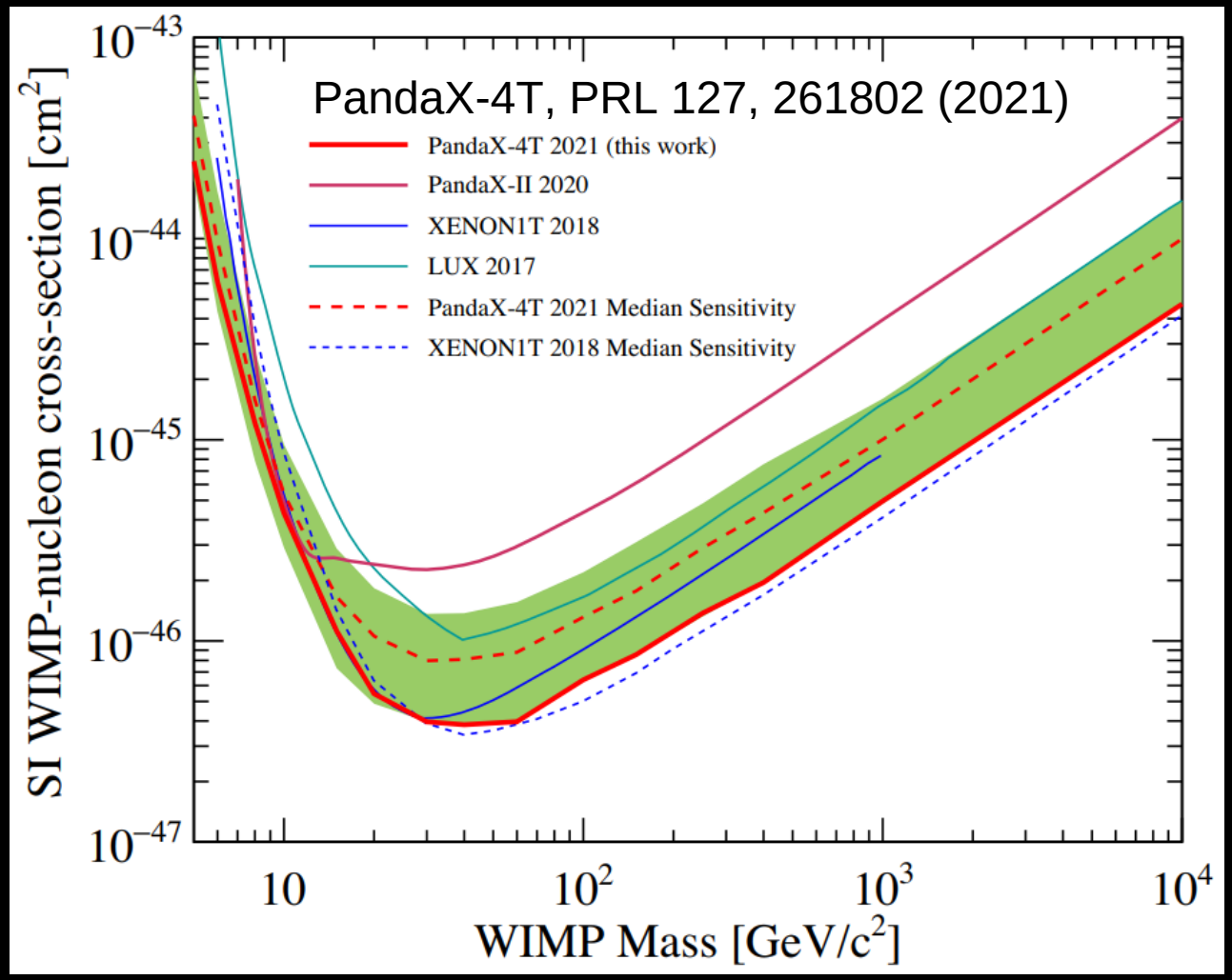
Sanford Lab, LZ, 7 ton



LNGS, XENONnT, 6.5 ton

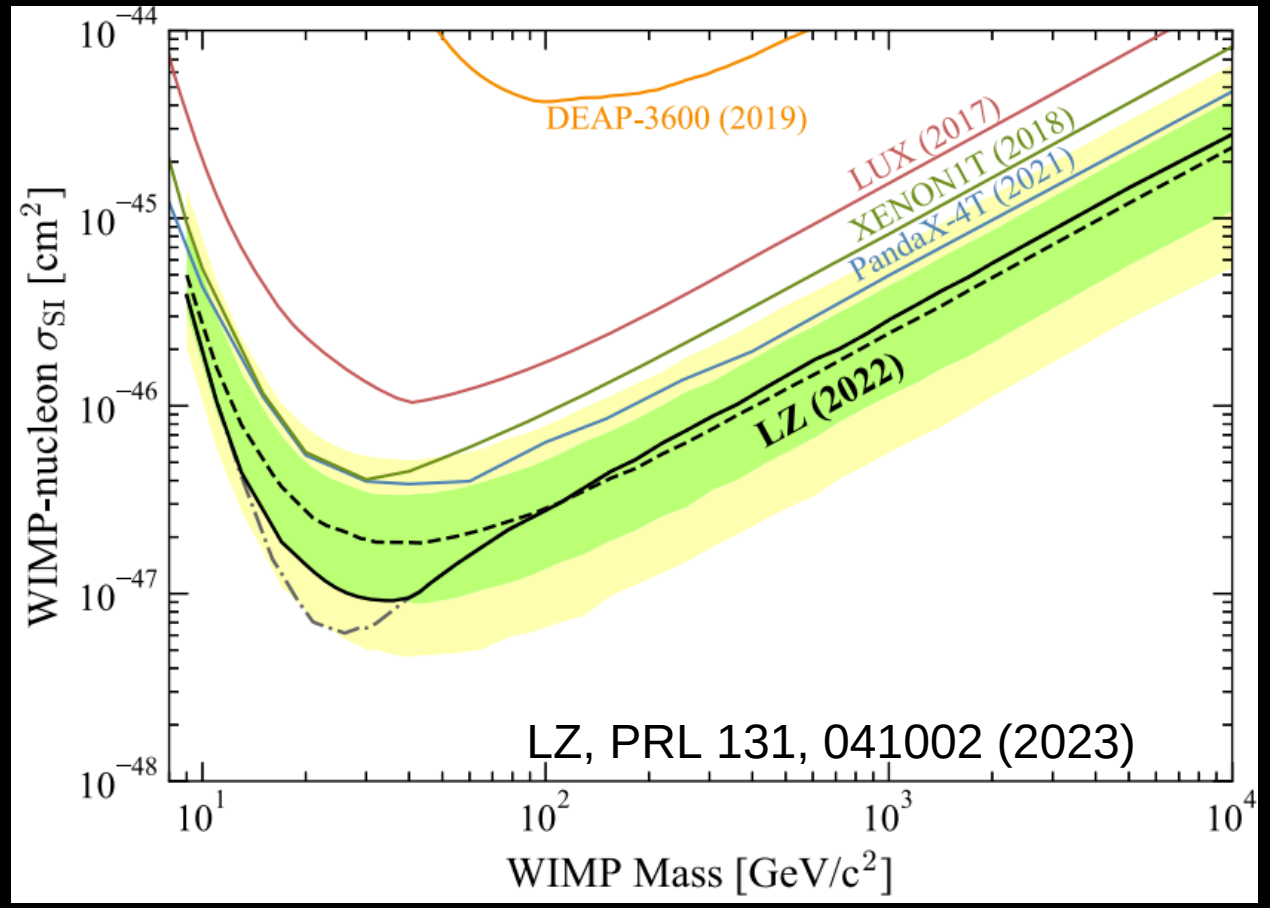
CJPL, PandaX-4T, 3.7 ton

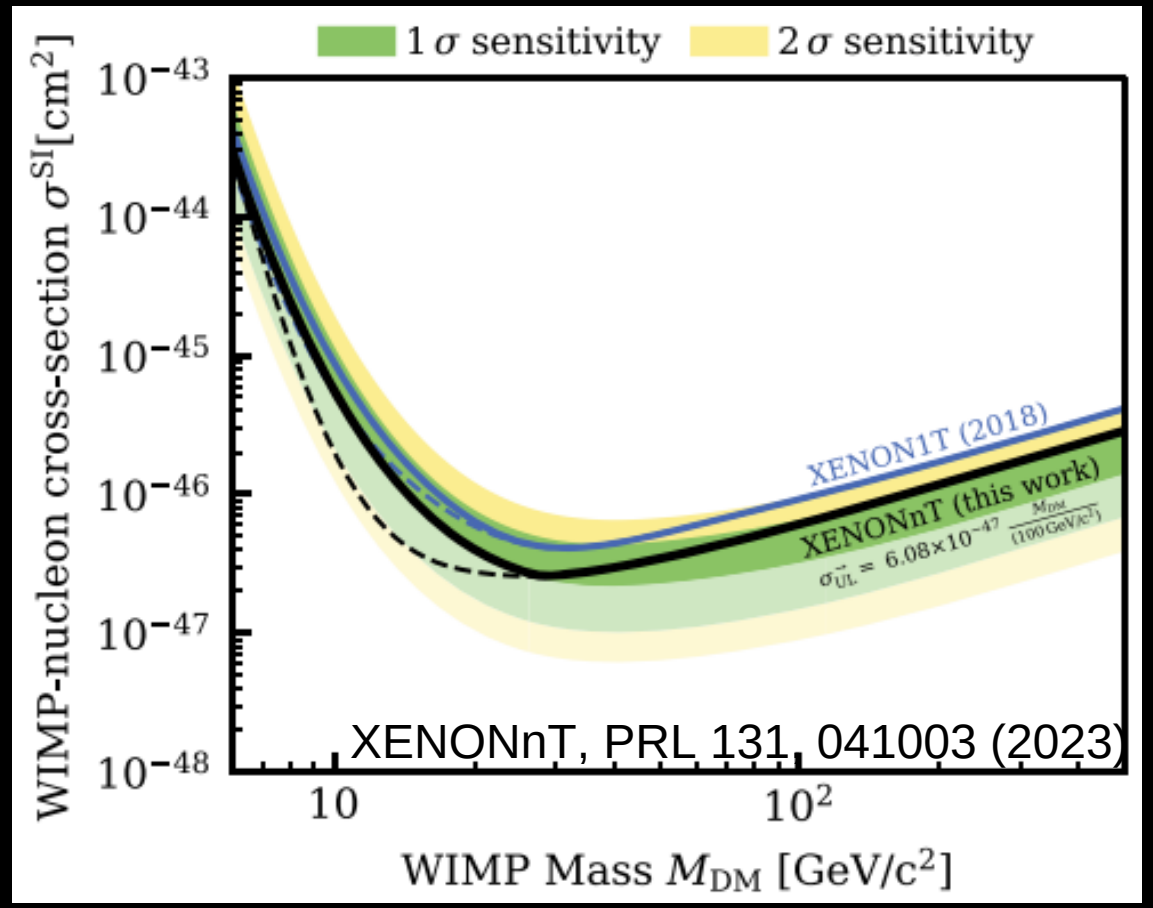
First results from multi-ton xenon experiments



- Exposure: 0.63 tonne•year
- Sensitivity improved from PandaX-II final analysis by 2.6 times (40 GeV/c^2)

First results from multi-ton xenon experiments



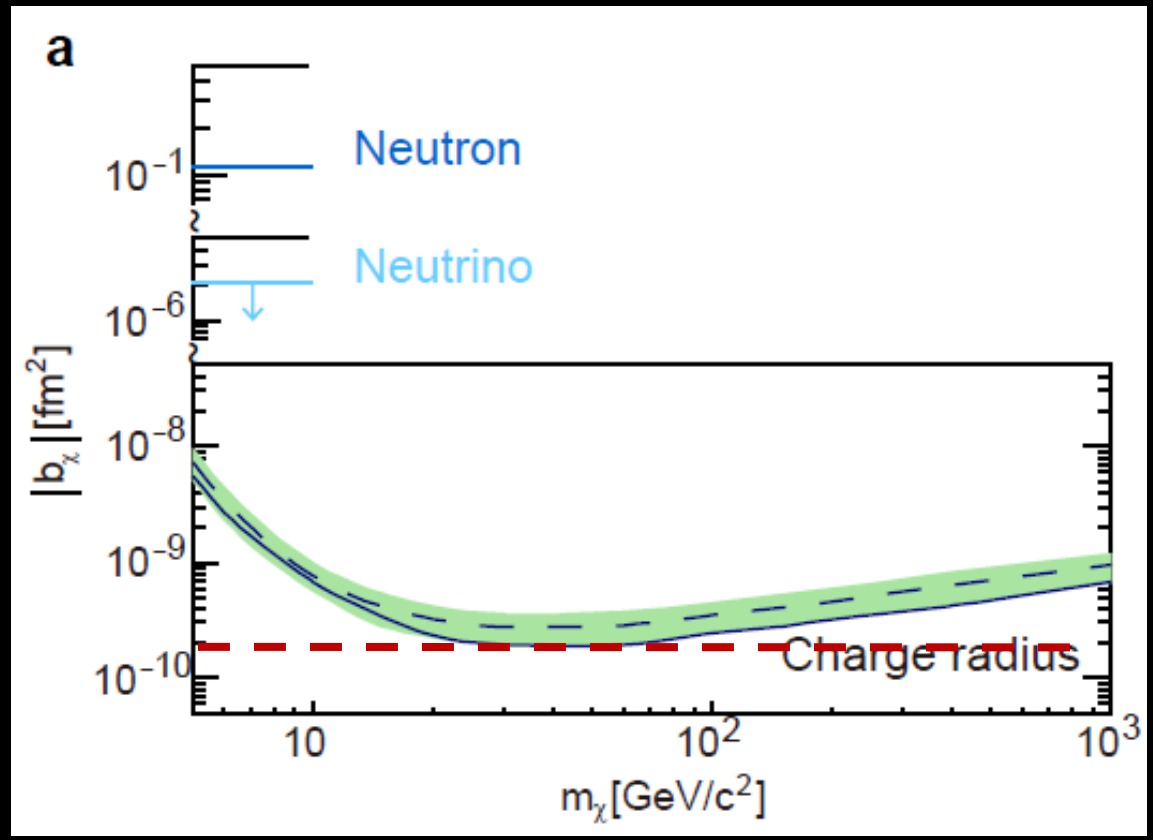


How dark is dark matter?

Nature 618, p47–50 (2023)

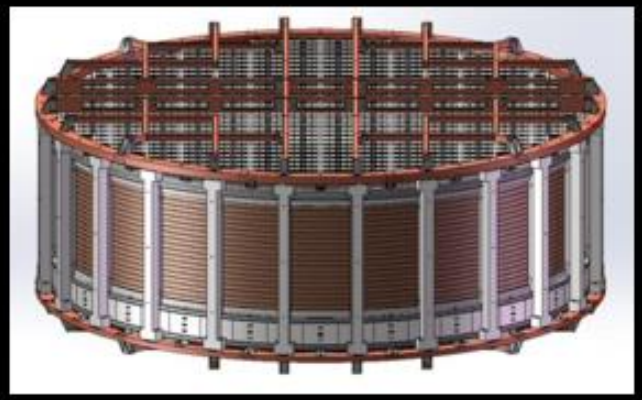
$$\mathcal{L} = Qe\bar{\chi}\gamma^{\mu}\chi A_{\mu} + \frac{\mu_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + i\frac{d_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\gamma^{5}\chi F_{\mu\nu} + b_{\chi}\bar{\chi}\gamma^{\mu}\chi\partial^{\nu}F_{\mu\nu} + a_{\chi}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\partial^{\nu}F_{\mu\nu}$$

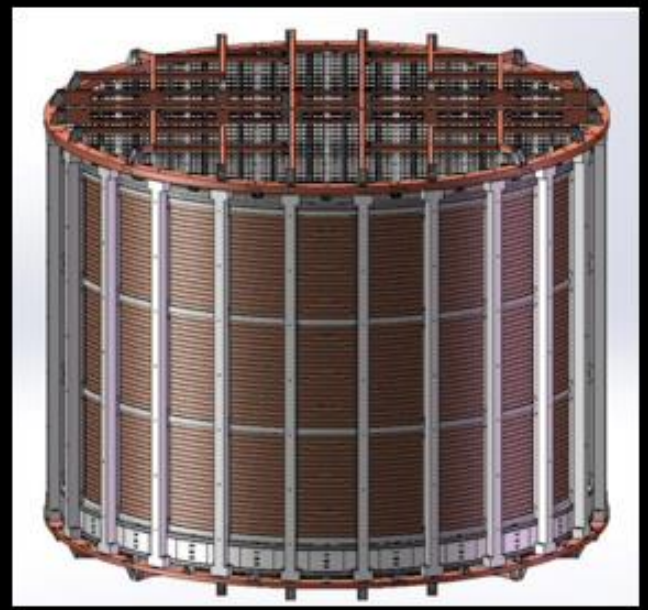
Milicharge, charge radius, electric dipole, magnetic dipole, anapole



Next Generation

PandaX-xT: step-wise strategy to a 40-ton-scale LXe observatory





Global Ar Collaboration

C. Galbiati, UCLA-DM 2023

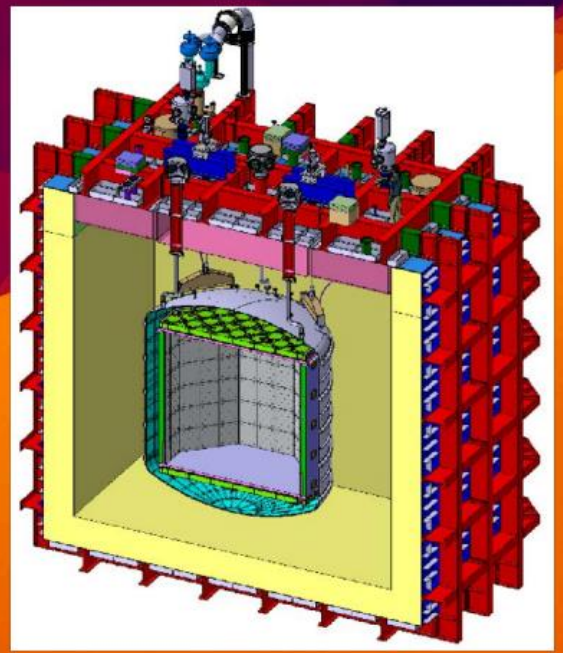
Since 2017

The Global Argon Dark Matter Collaboration (GADMC)

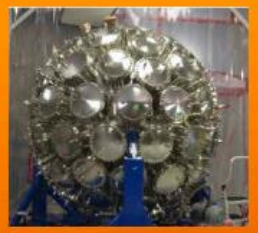
GADMC unified in a single Collaboration more than 400 scientists interested in DM searches with argon to explore heavy (and light) dark matter to the neutrino floor and beyond

DEAP-3600

DarkSide-50



MiniCLEAN



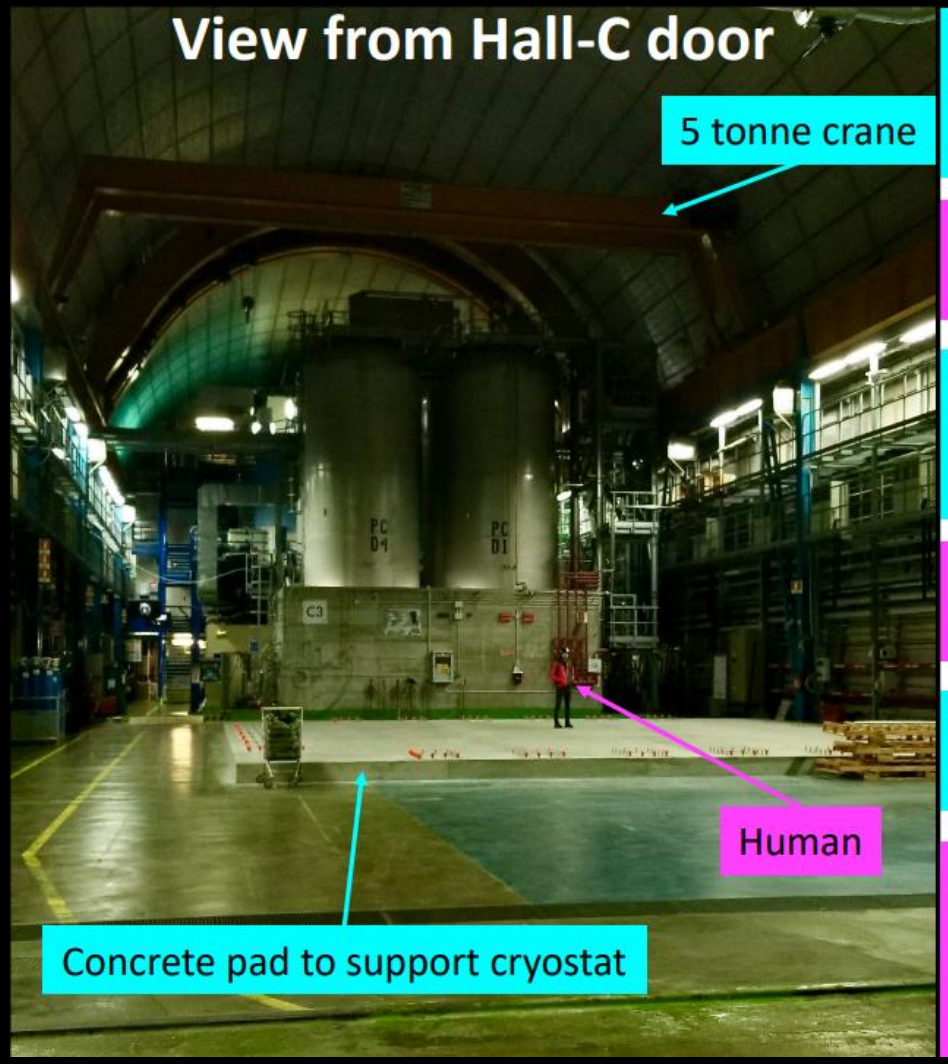
ARDM

DarkSide-20k => ARGO

Status of DS-20K

C. Galbiati, UCLA-DM 2023

Expect to operate by 2026



Membrane "ProtoDUNE-like" cryostat

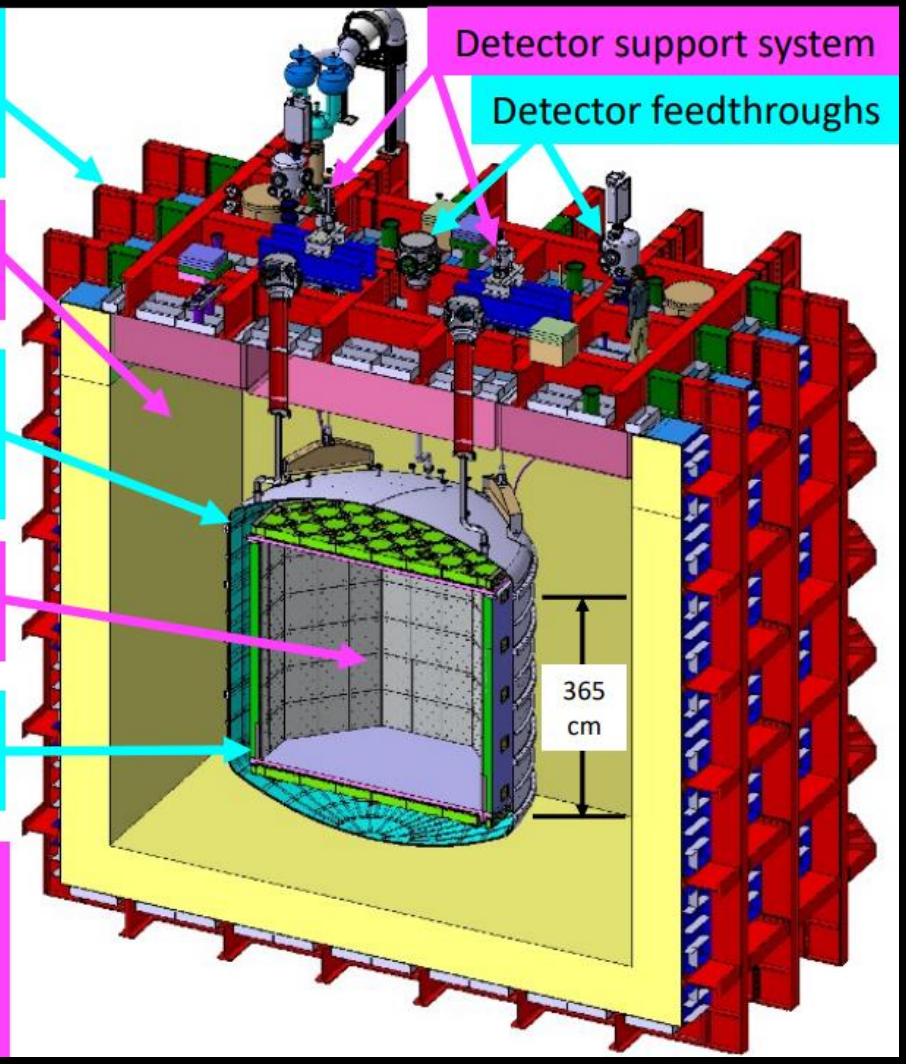
Atmospheric argon (AAr) volume (≈700 t)

Vacuum vessel containing UAr and TPC/veto

Underground argon (UAr) volume (≈100 t)

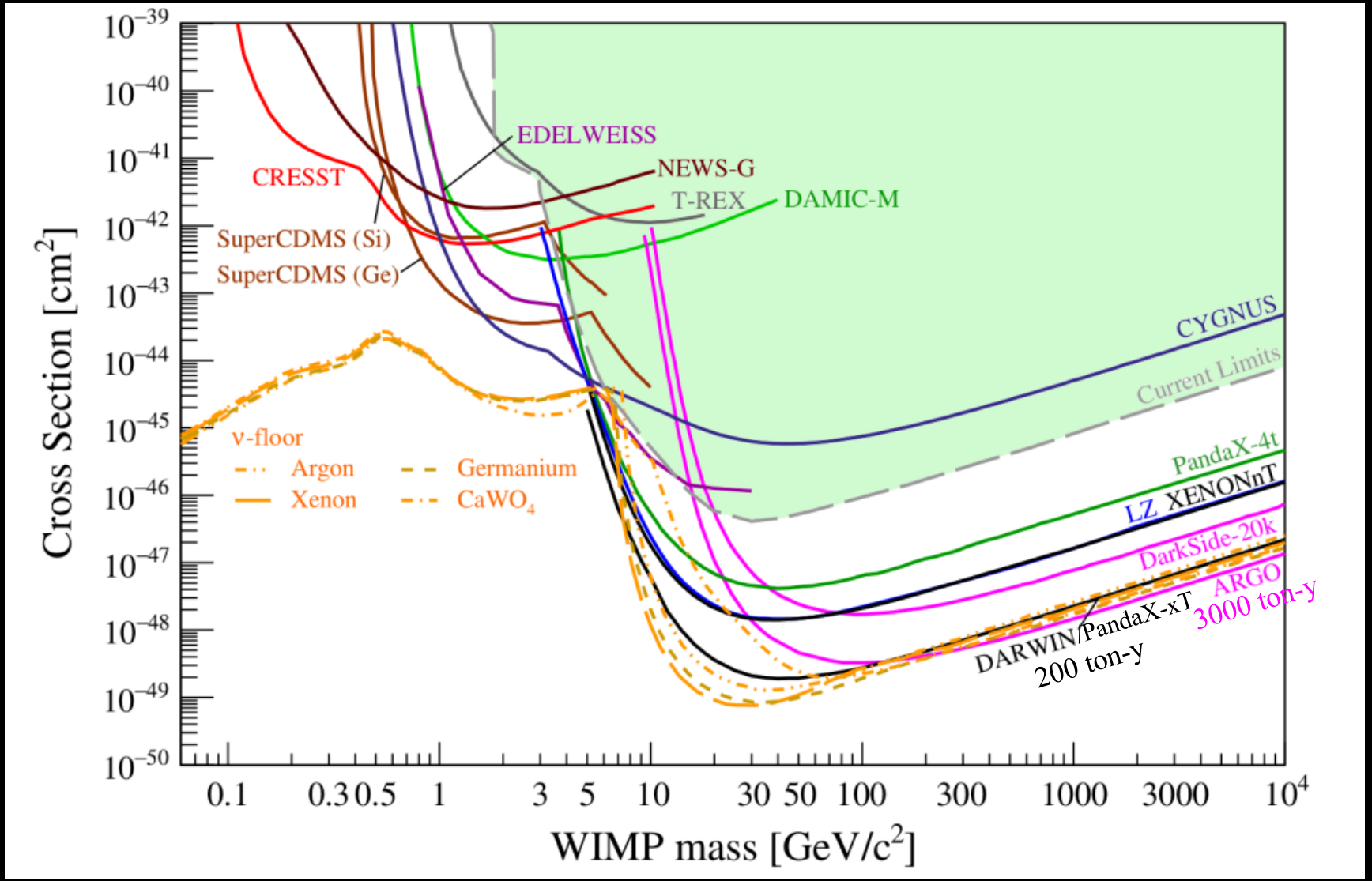
"Inner detectors", TPC and neutron veto

Outer veto will consist of SiPM arrays near the cryostat walls looking inward

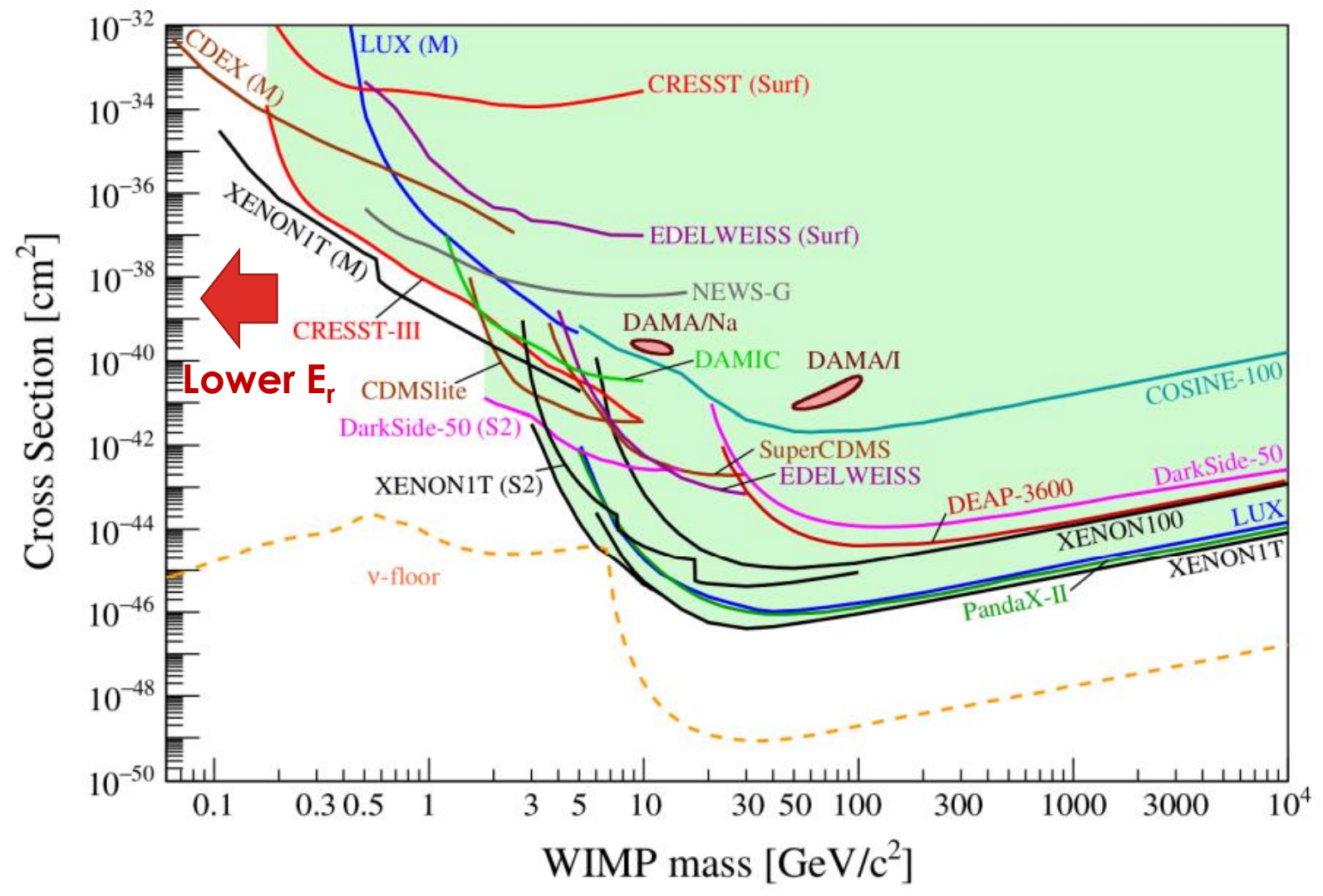


SI sensitivity: future projection

APPEC DM report: 2104.07634

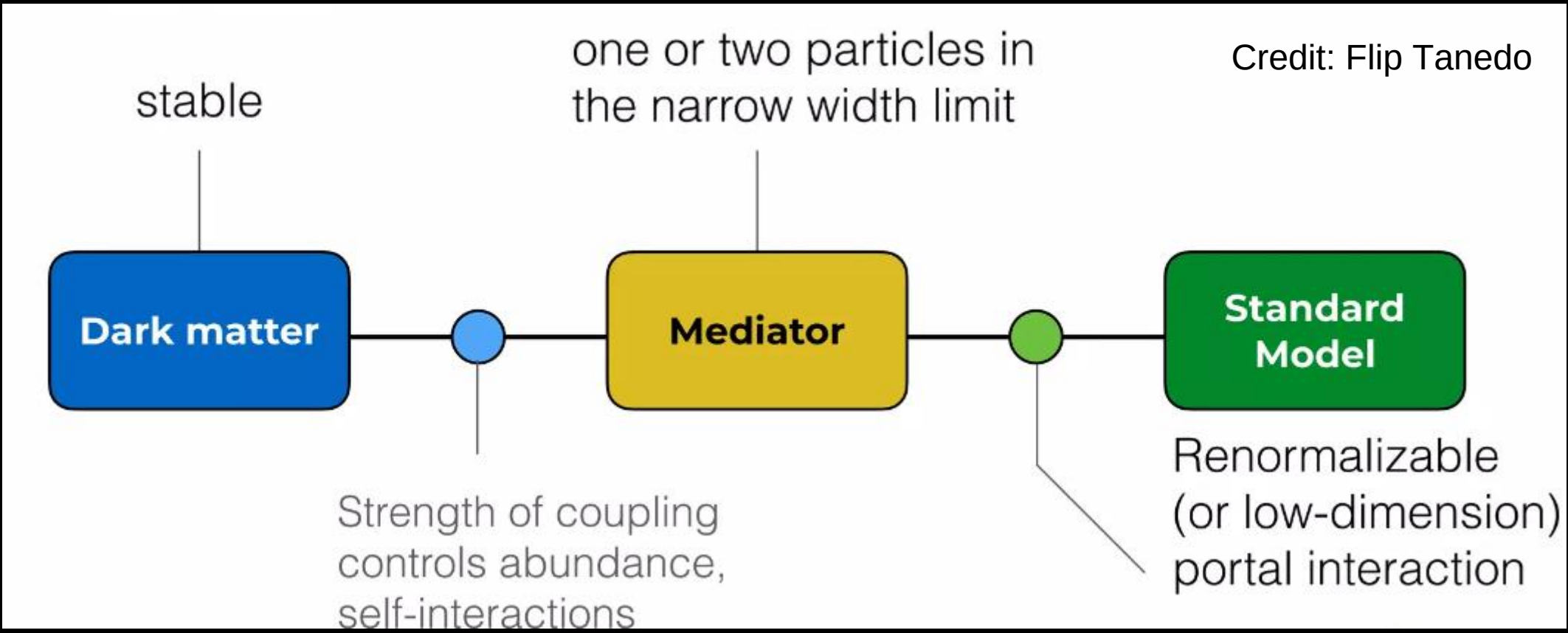


Global status: hide & seek



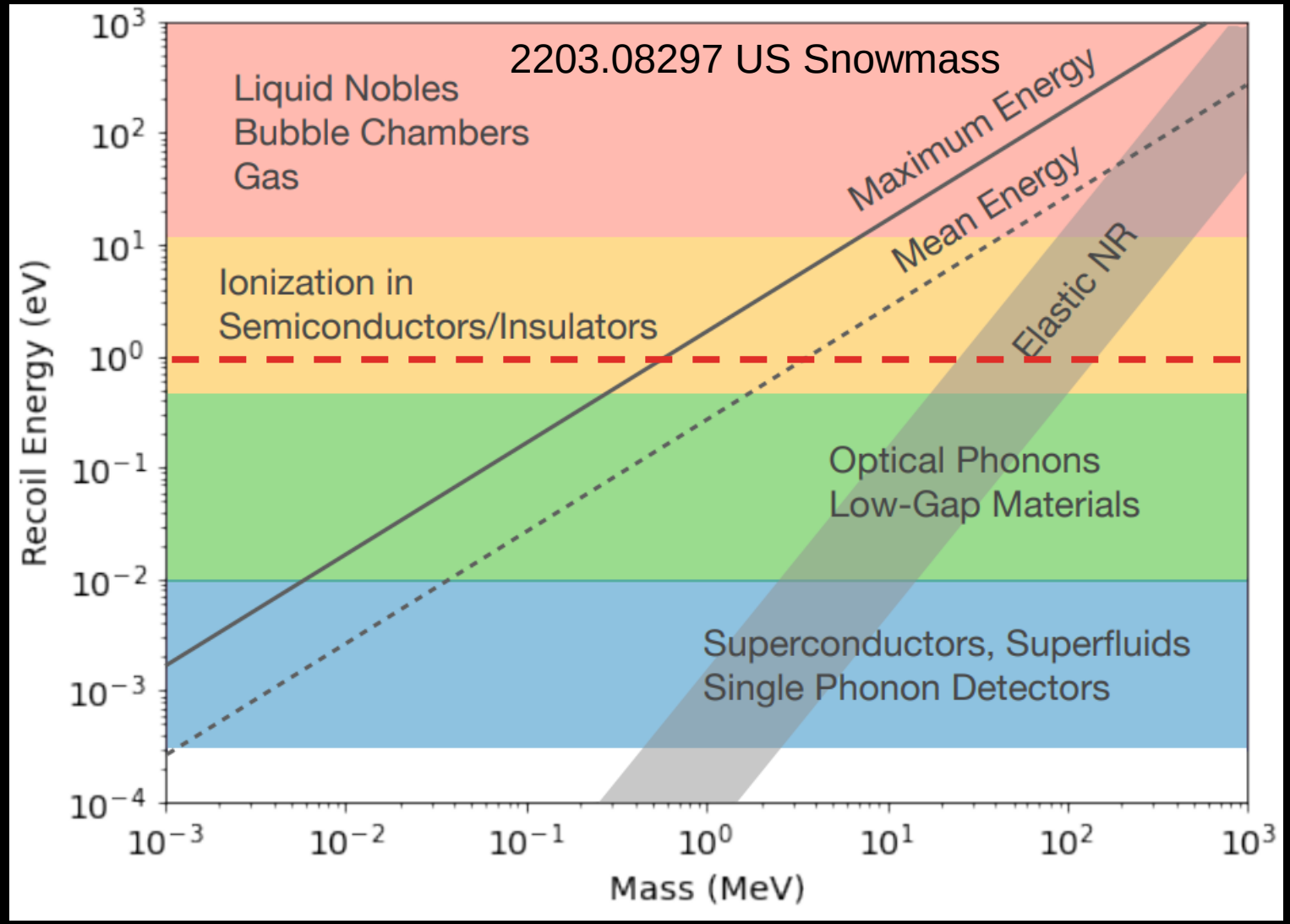
2104.07634, APPEC report on dark matter direct detection

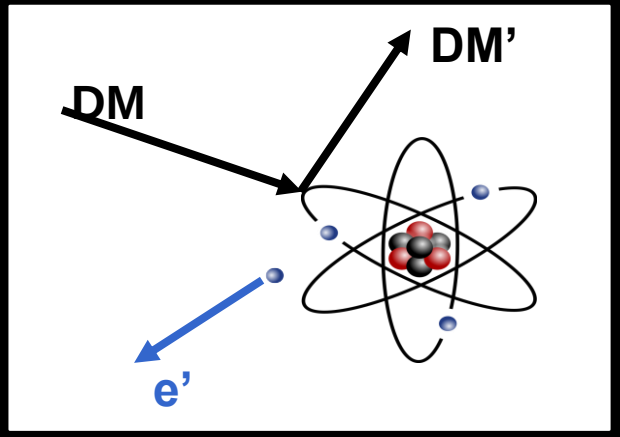
Away from Standard WIMP: the dark sector



Bottom-line: the prejudice of “massive” particle is eliminated, wide search for sub-GeV dark matter (and mediators)

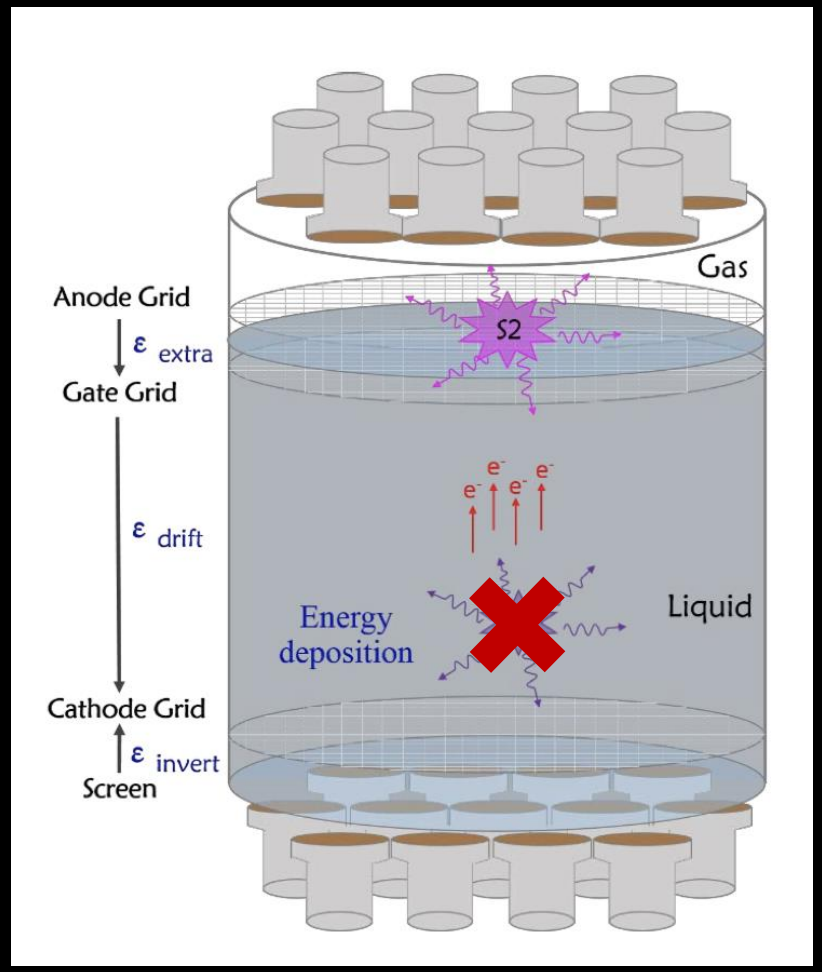
Low mass DM detection techniques

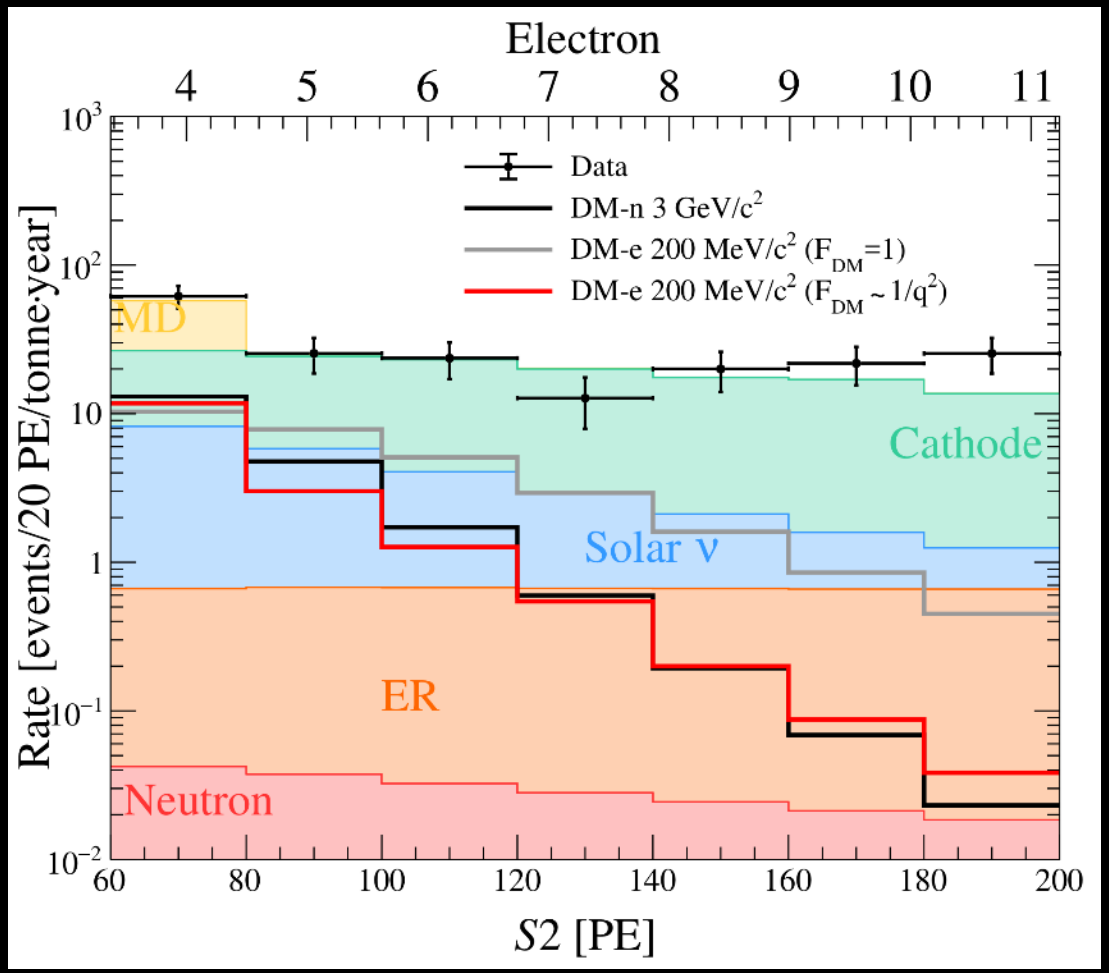




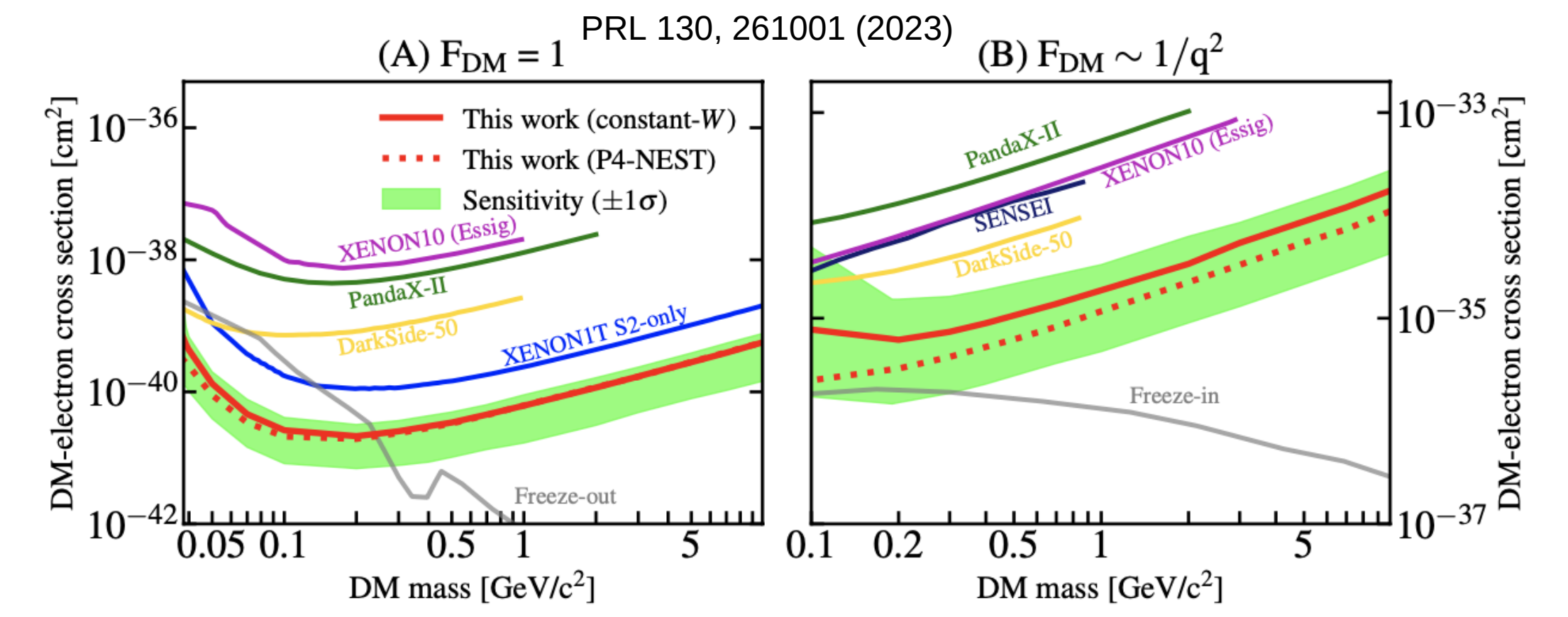
Atomic inelastic scattering: accessing full DM KE-binding. Essig, Mardon, Volansky, PRD 85, 076007 (2012)

S2-only approach

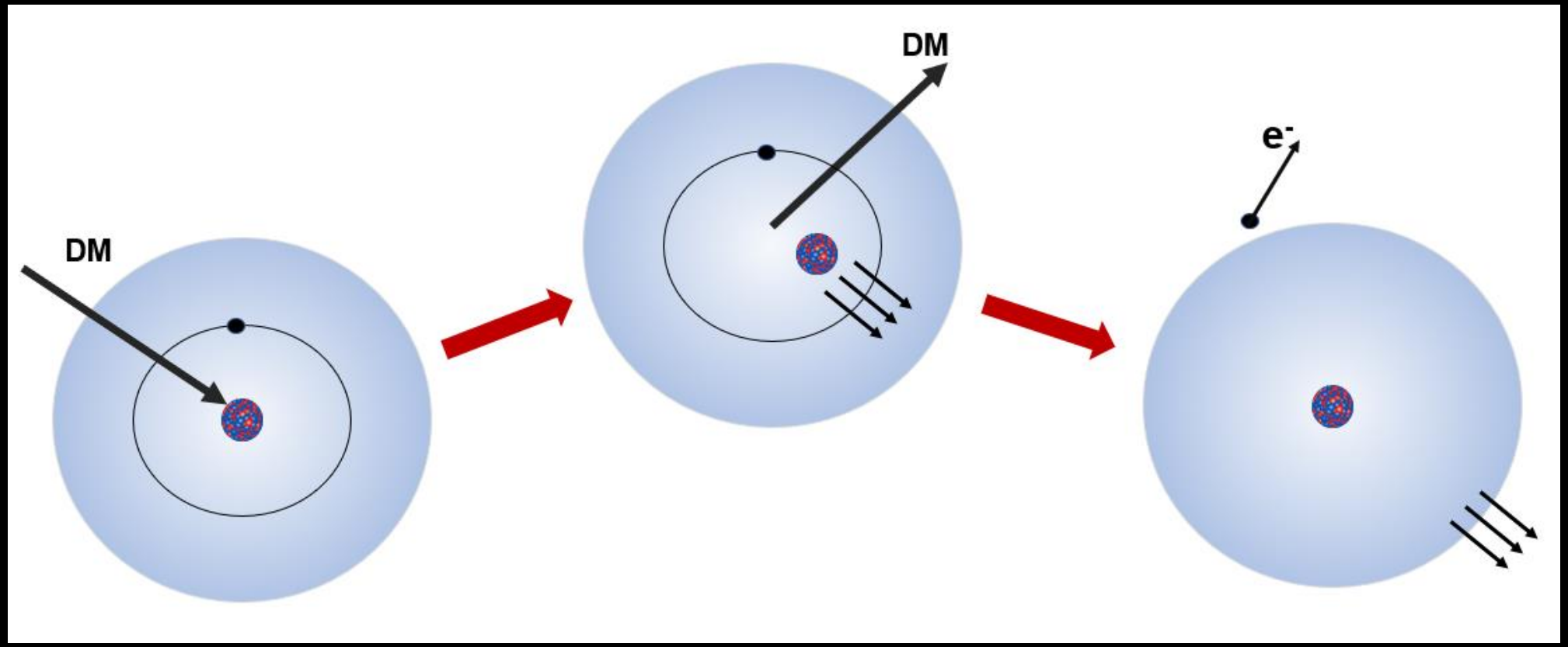




Tight limits on DM-e scattering

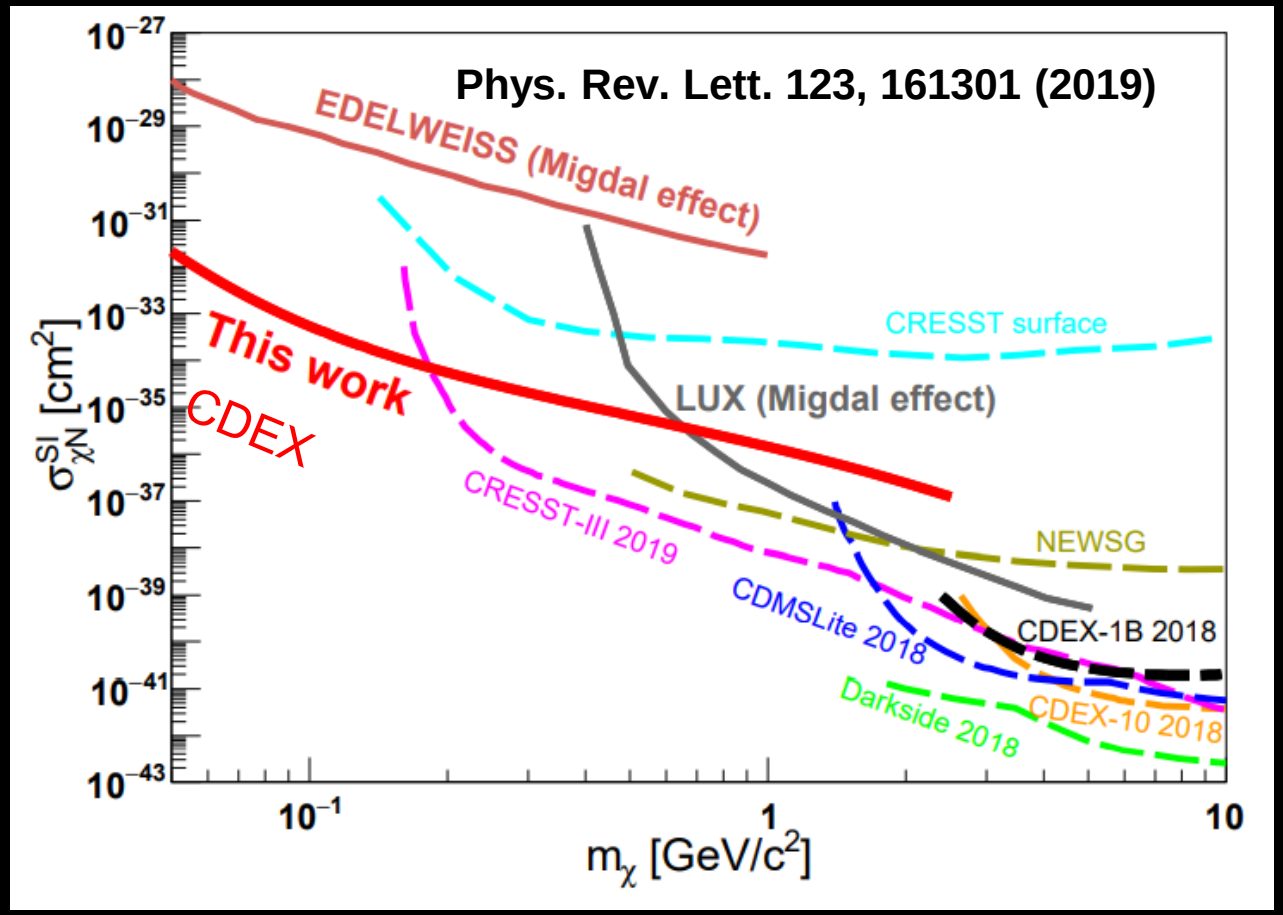


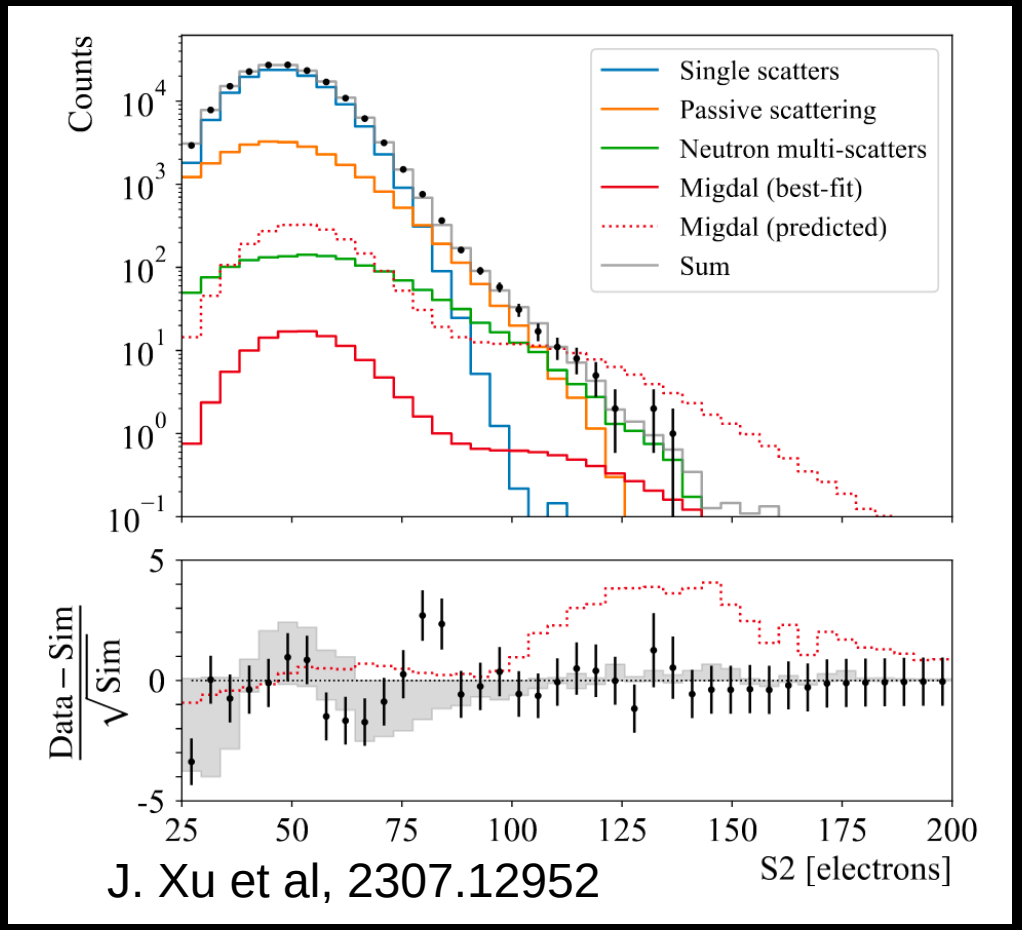
Migdal effects in DM-N scattering



- Reformulated: Ibe et al., JHEP 2018, 194 (2018); Dolan et al., PRL 121, 101801 (2018)
- Direct DM-e ionization and Midgal-induced ionization probability are closely related, Essig, Pradler, Sholapurkar, and Yu, PRL 124, 021801 (2020)

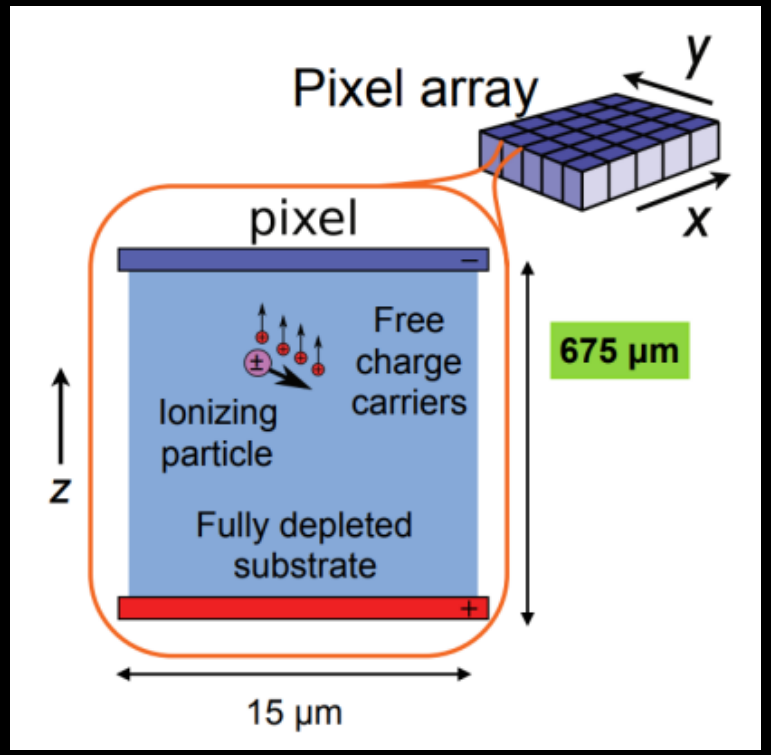
Low mass DM with Migdal

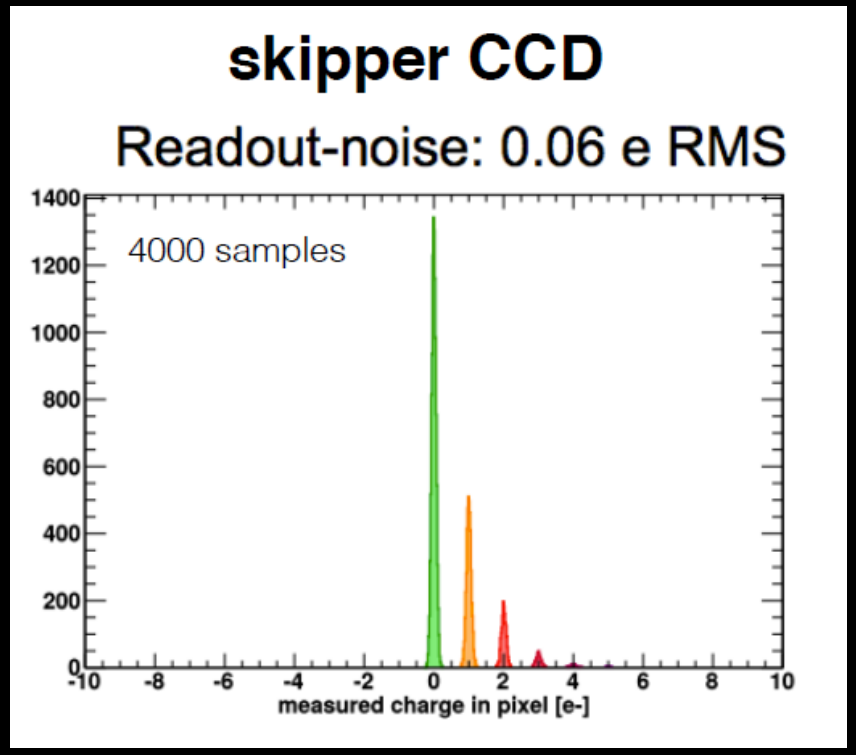




Skipper CCD

- Old idea: small amount of energy by DM-N or DM-e can be converted to e-h pairs in CCD pixels
- Si: 1.2 eV for an e-h pair production



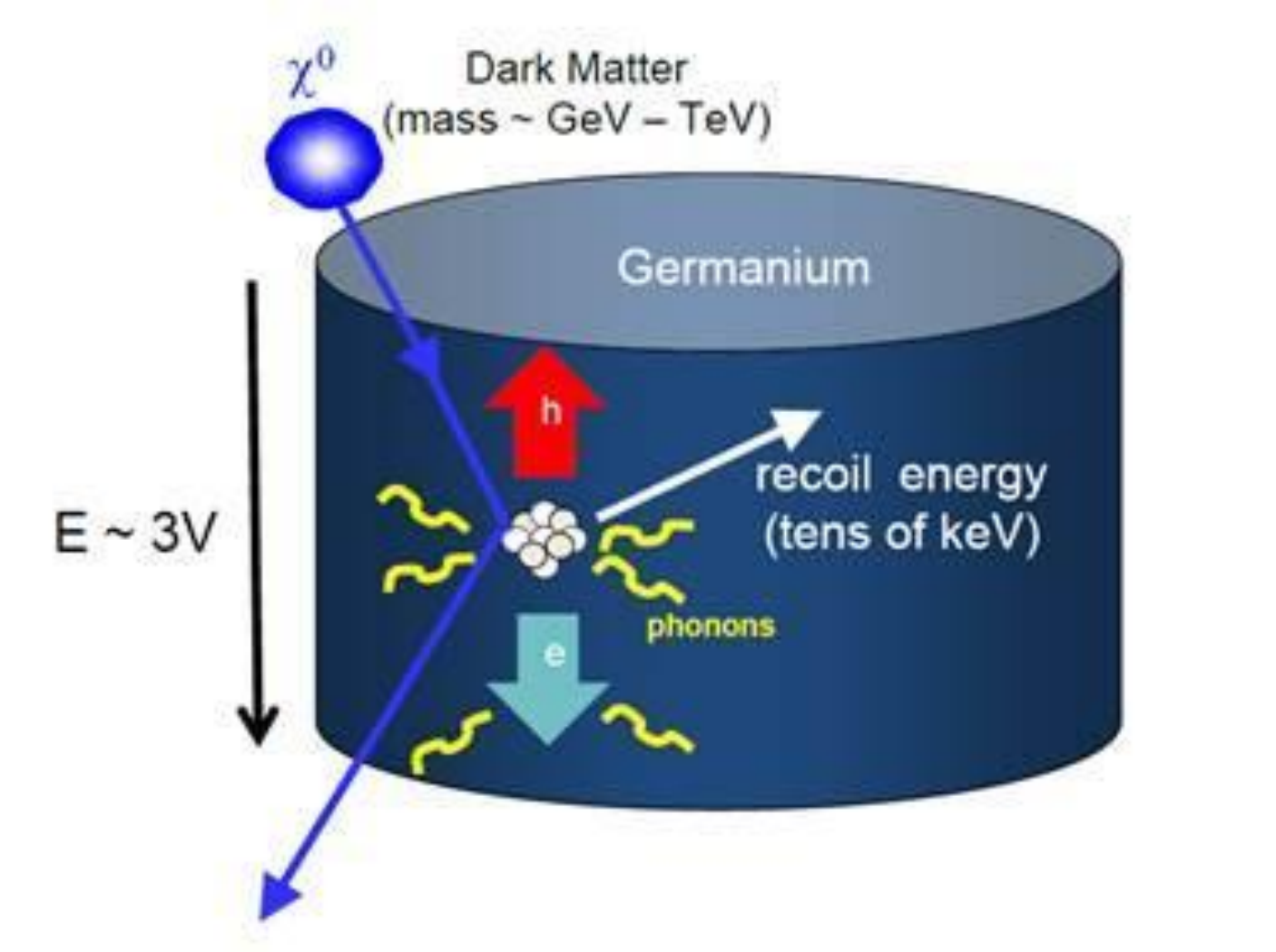


PRL 119 (2017) 13, 131802

Ongoing effort:

- DAMIC SNOLAB (42 g)
- SENSEI (2g->100 g)
- DAMIC-M (1kg)
- Oscura: 10 kg

Cryogenic bolometer



- Energy deposition converted to lattice vibration
- $\delta T=\delta E/C$, where $C \propto T^3$, so low temp is the key (5 mK)
- Temperature change is “traditionally” measured by transitional edge sensor (TES)
- Some accompanying energy in ionization or photons

Cryogenic bolometers

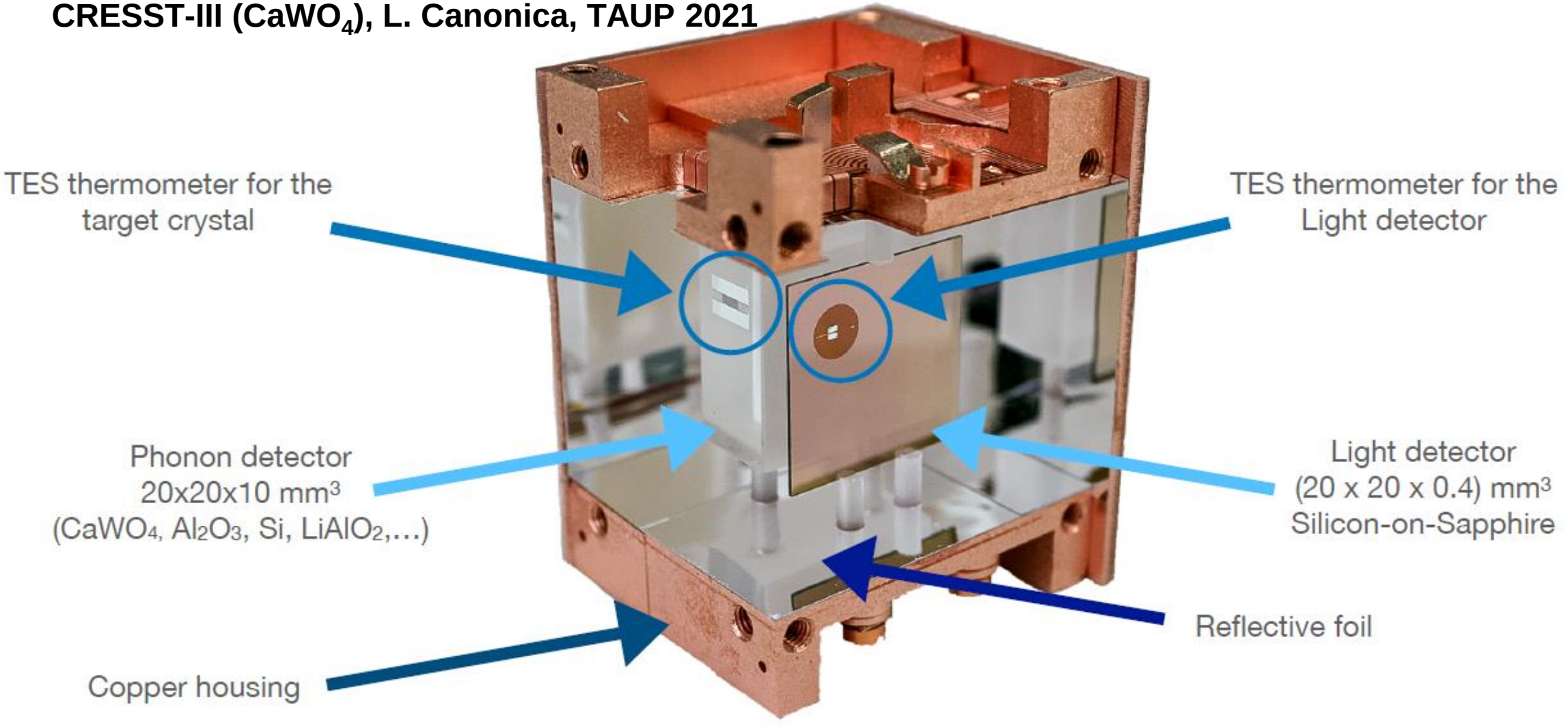
SuperCDMS (Ge/Si)

iZIP detector

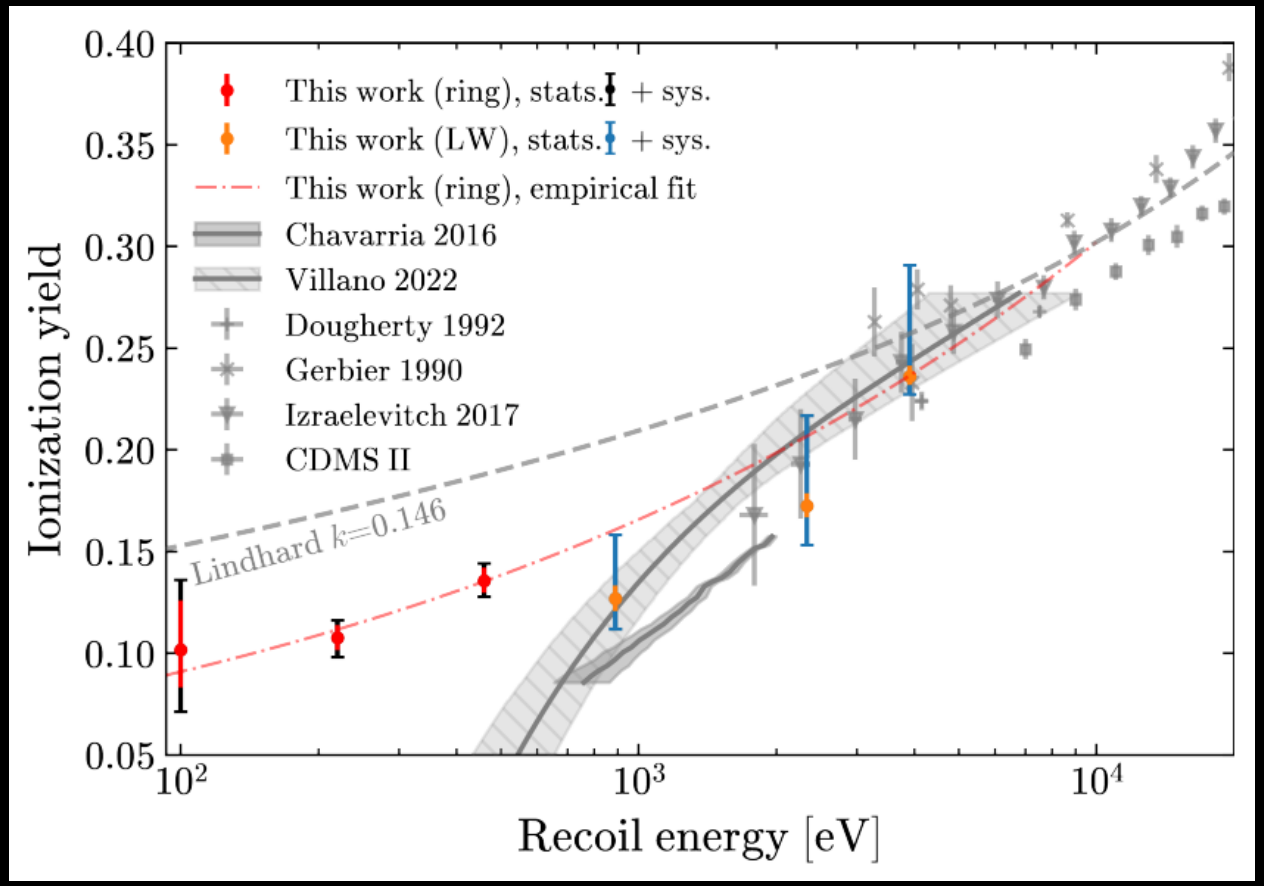
HV detector

Cryogenic bolometers

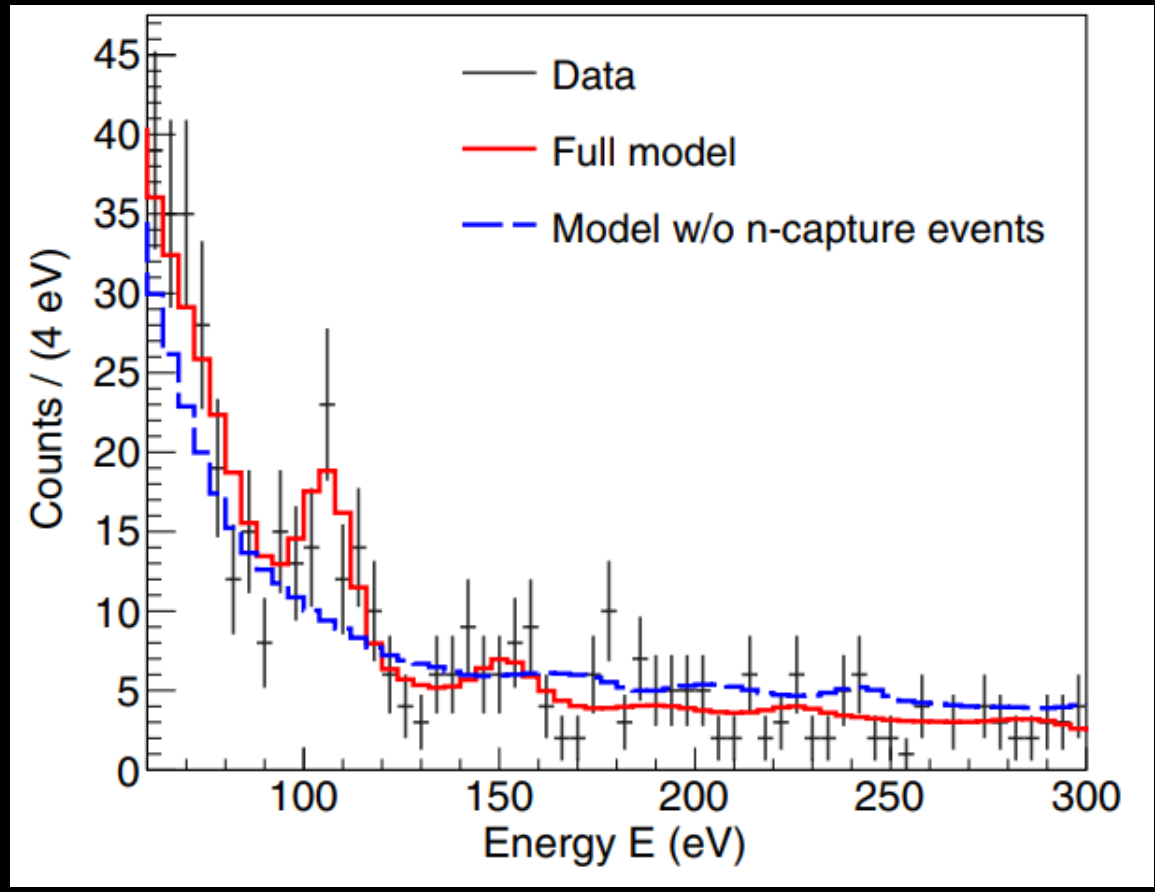
CRESST-III ($CaWO_4$), L. Canonica, TAUP 2021



Detector characterization highlights

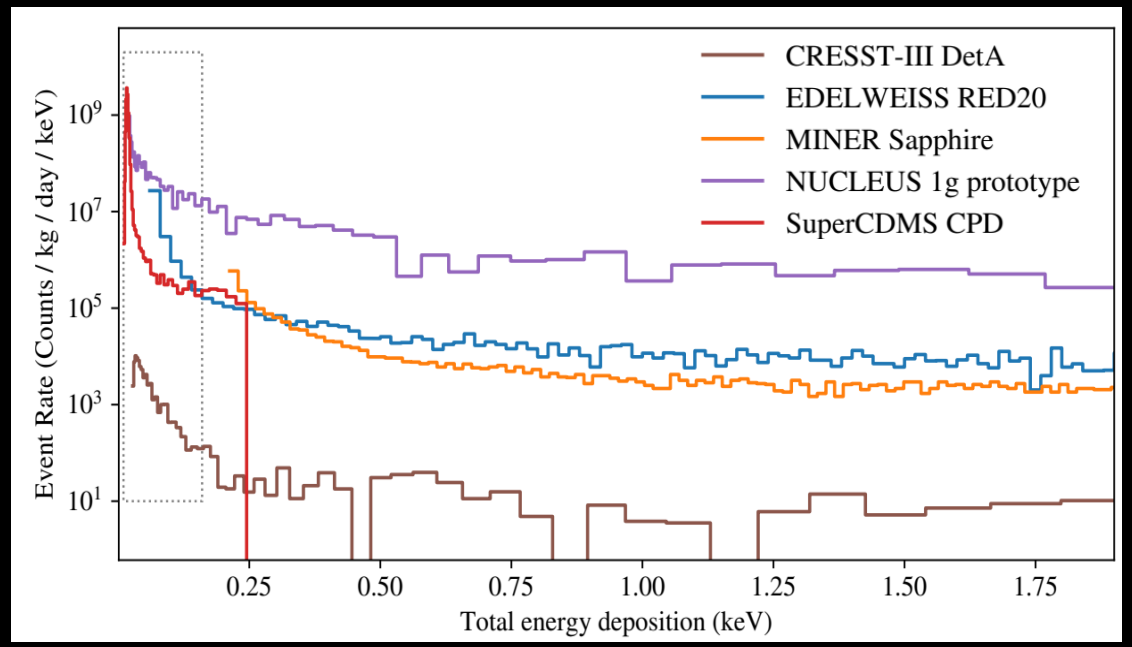


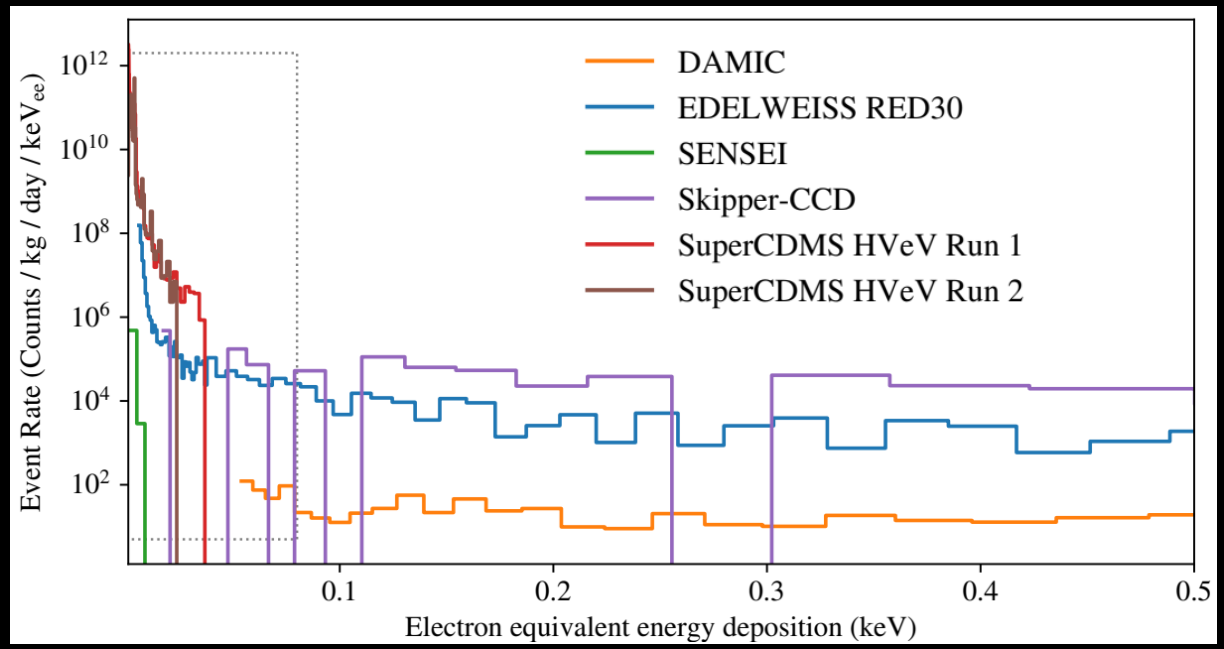
SuperCDMS, PRL 131, 091801 (2023)
Ionization yield to NR for Si down to 100 eV



Nucleus, PRL 130, 211802 (2023)
First observation of n-W capture NR energy

Low energy excesses



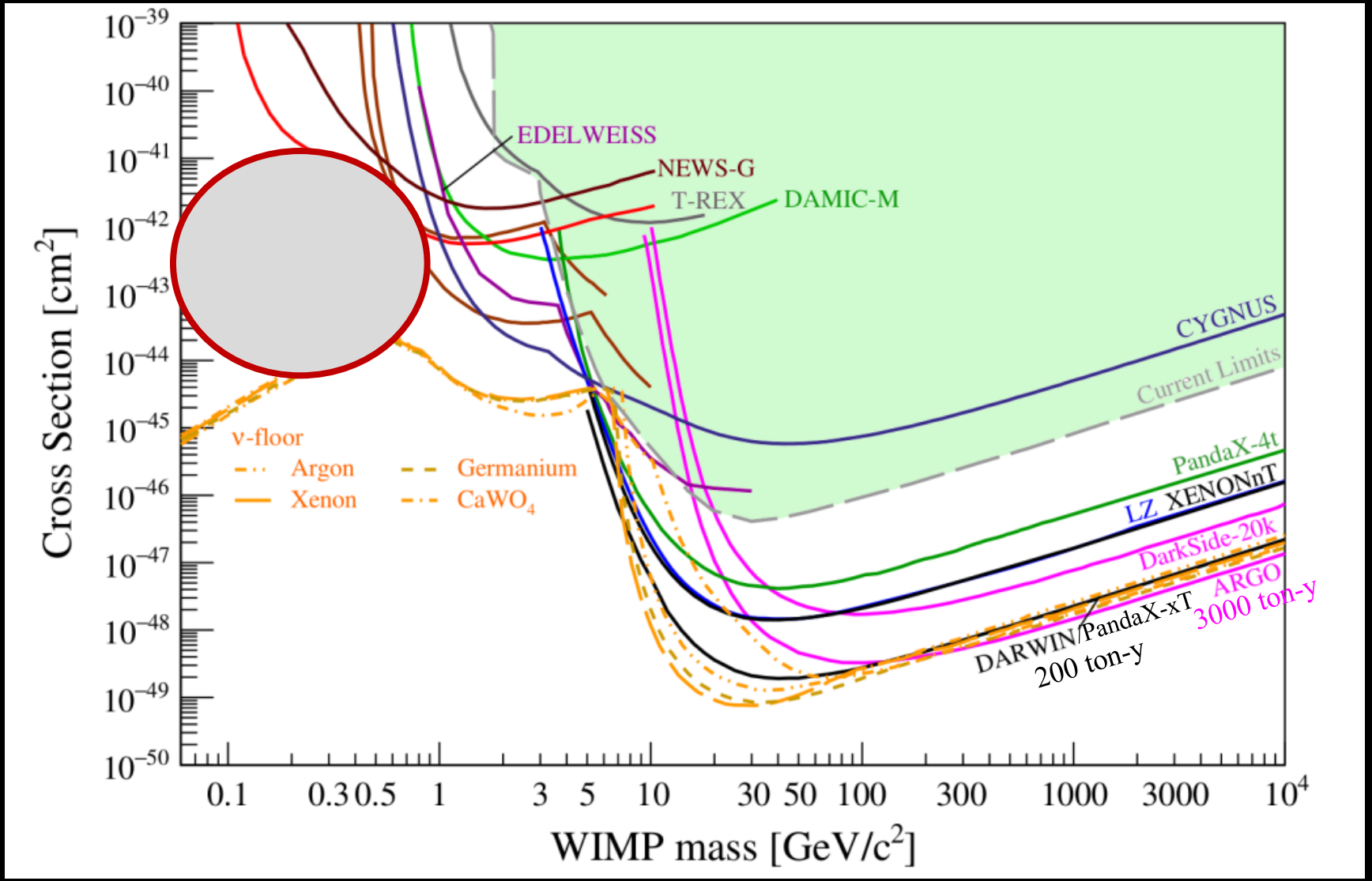


- Physics? Unlikely!
- Material background
- Structure issues (stress, etc.)

The Excess Workshop: 2202.05097

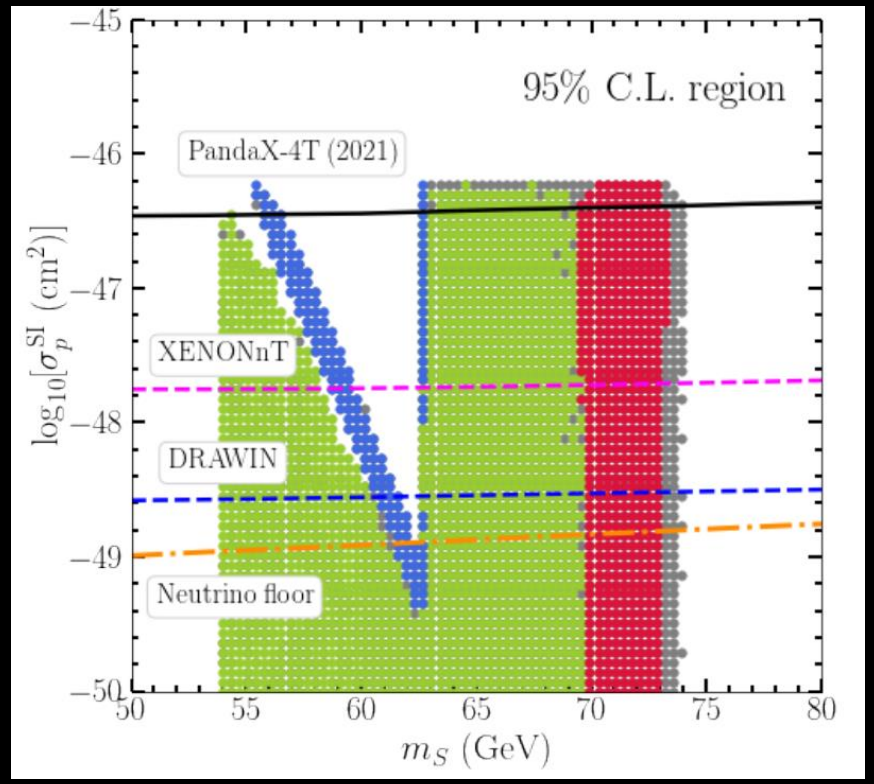
SI sensitivity: future projection

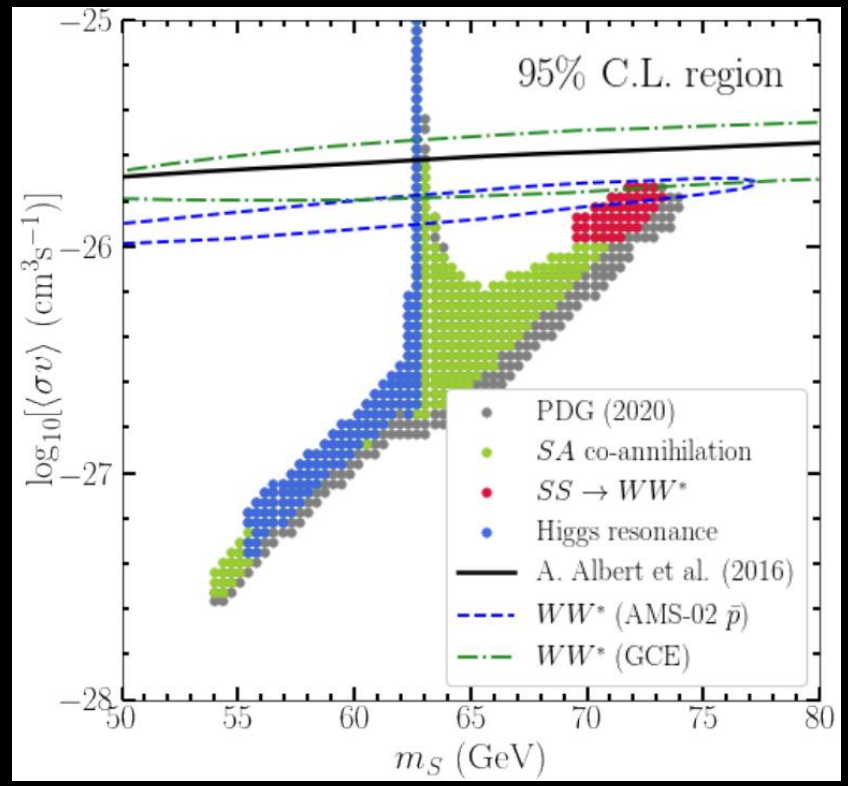
APPEC DM report: 2104.07634



A combined statement?

Combined studies including all DM searches, e. g. PRL 129, 091802 (2022), Fan, Tan, Tsai, Wu (inert-two-Higgs-doublet model)

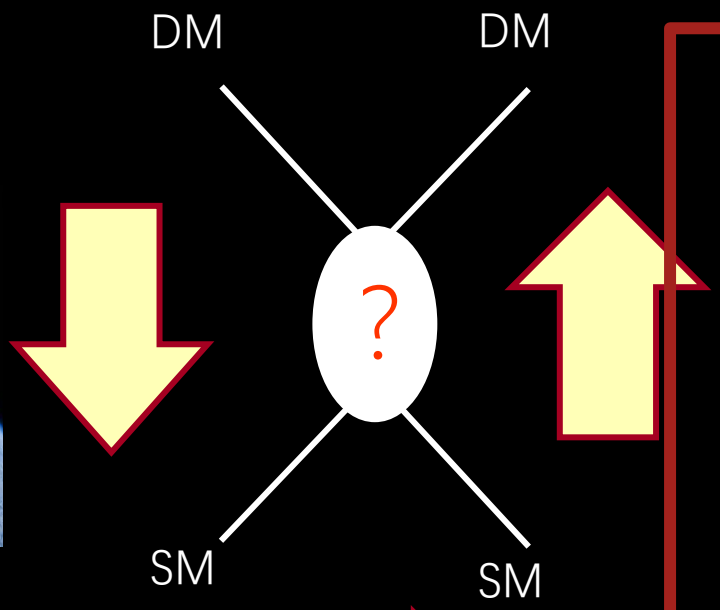




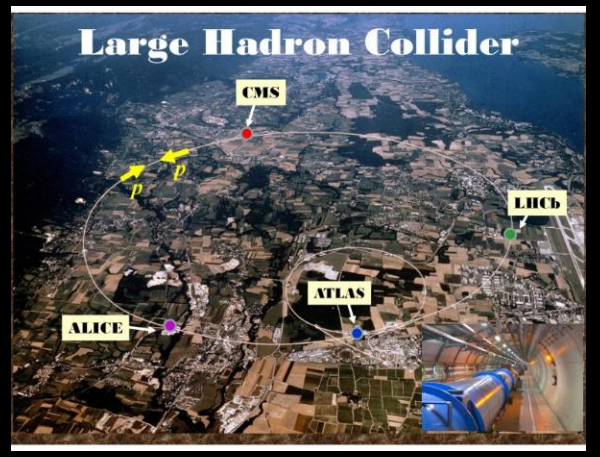
- But the short answer is: keep searching!!!

A fully testable idea

Indirect Detection

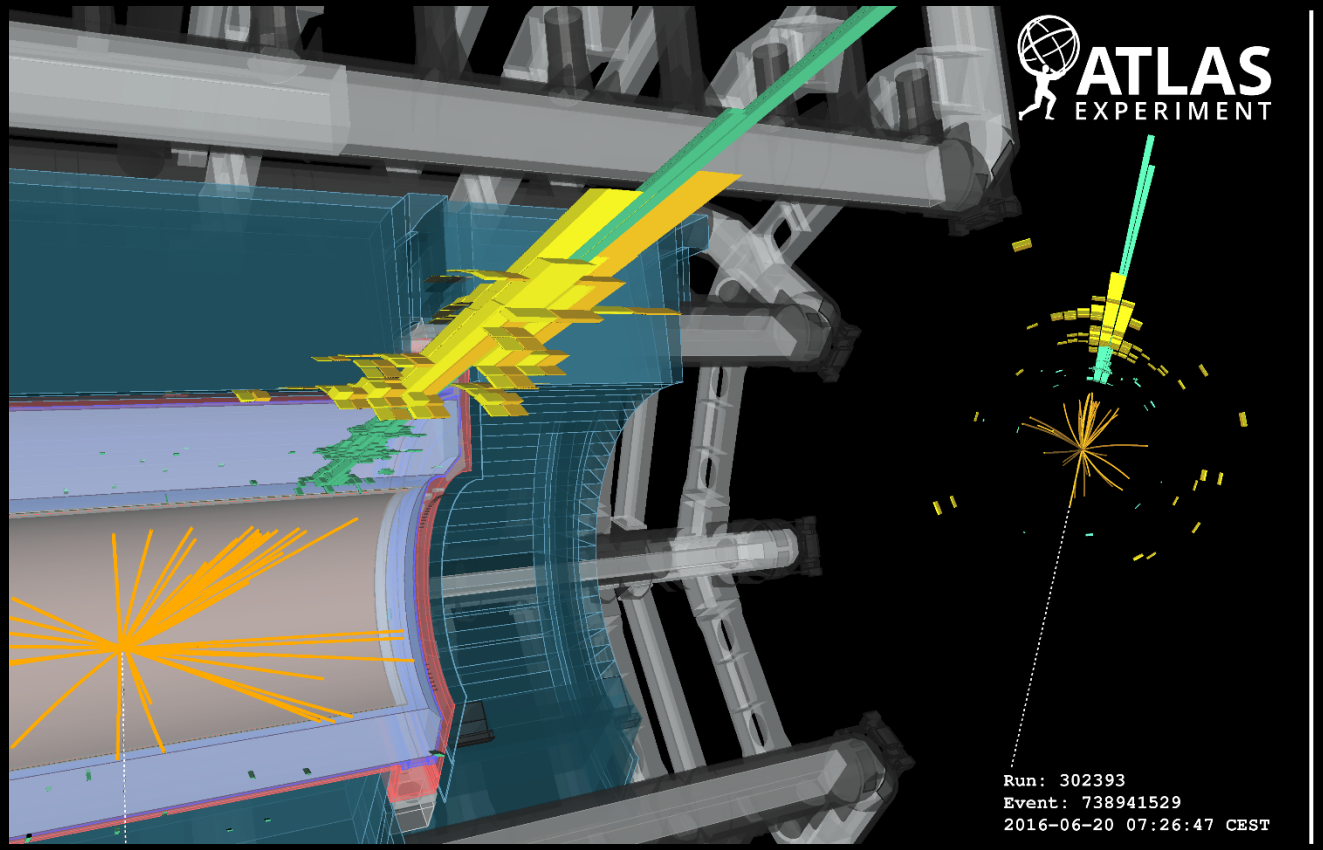


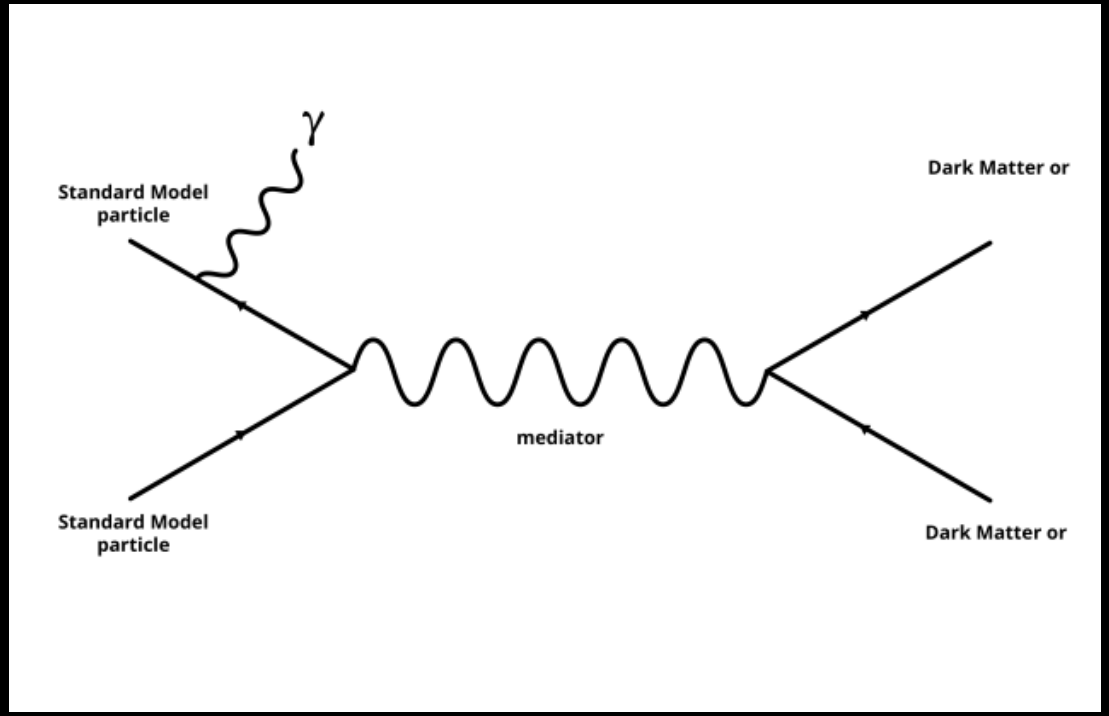
Collider Search



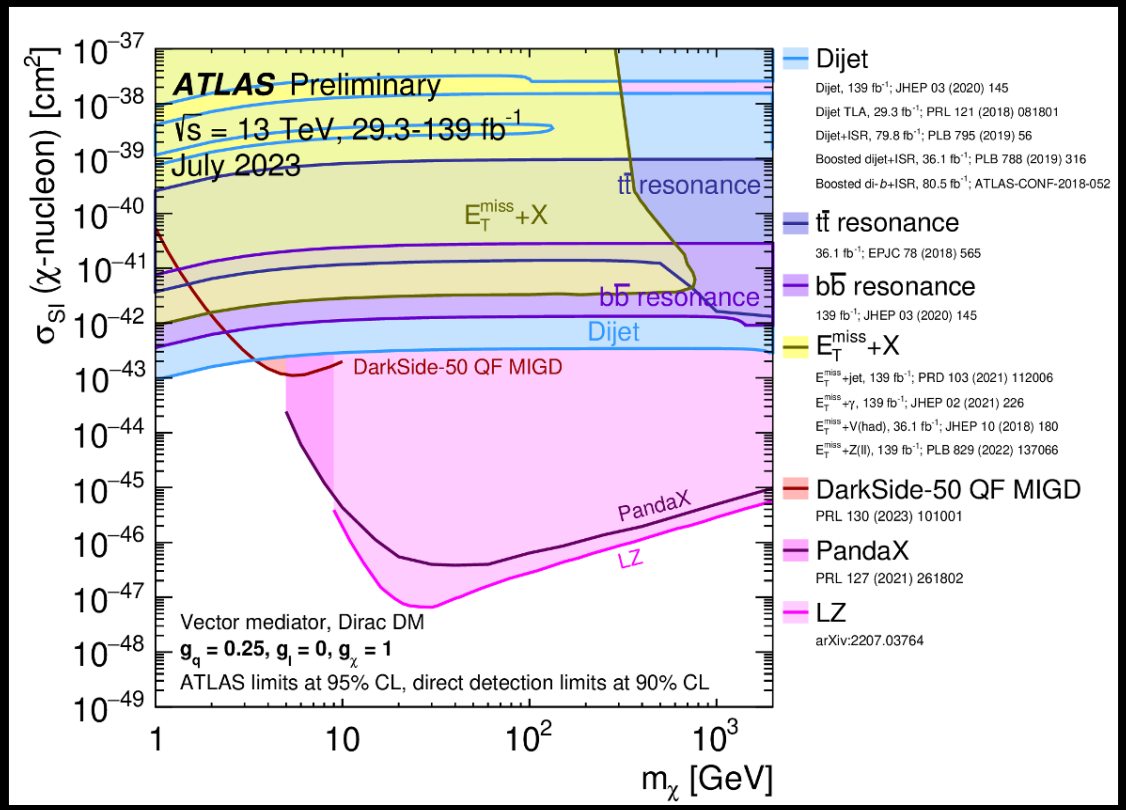
Direct Detection

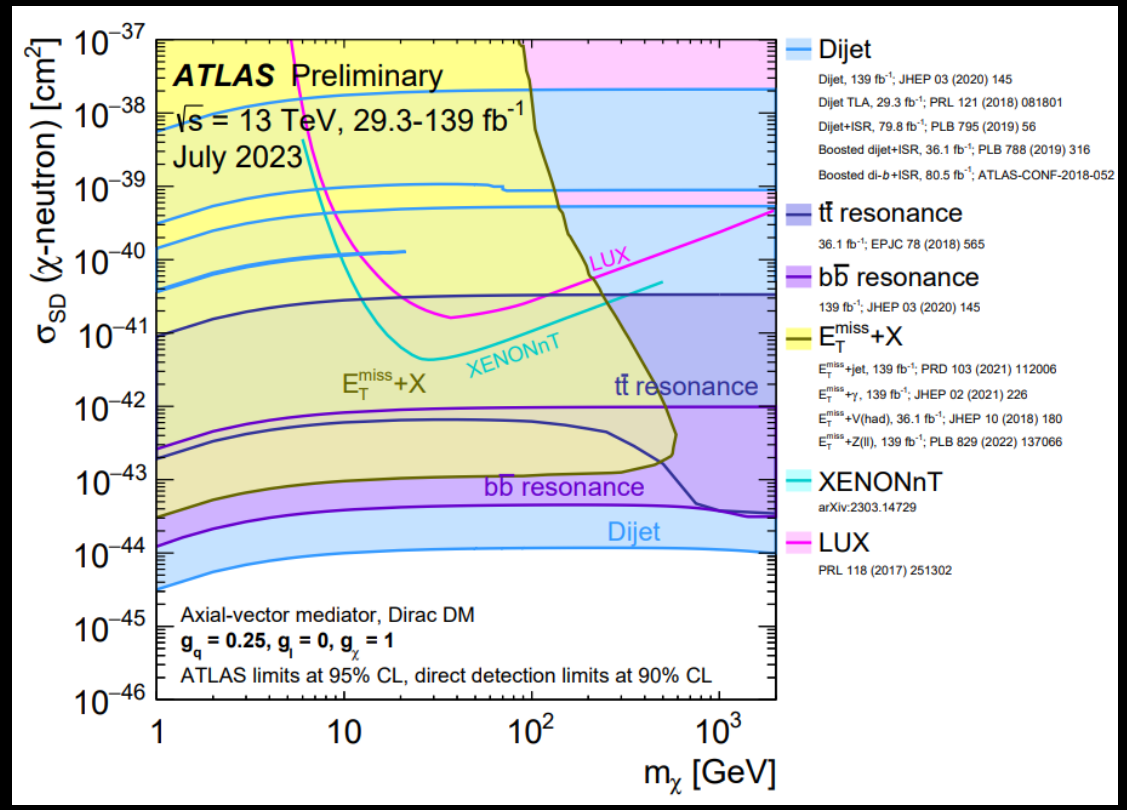
Invisible and Visible Final States





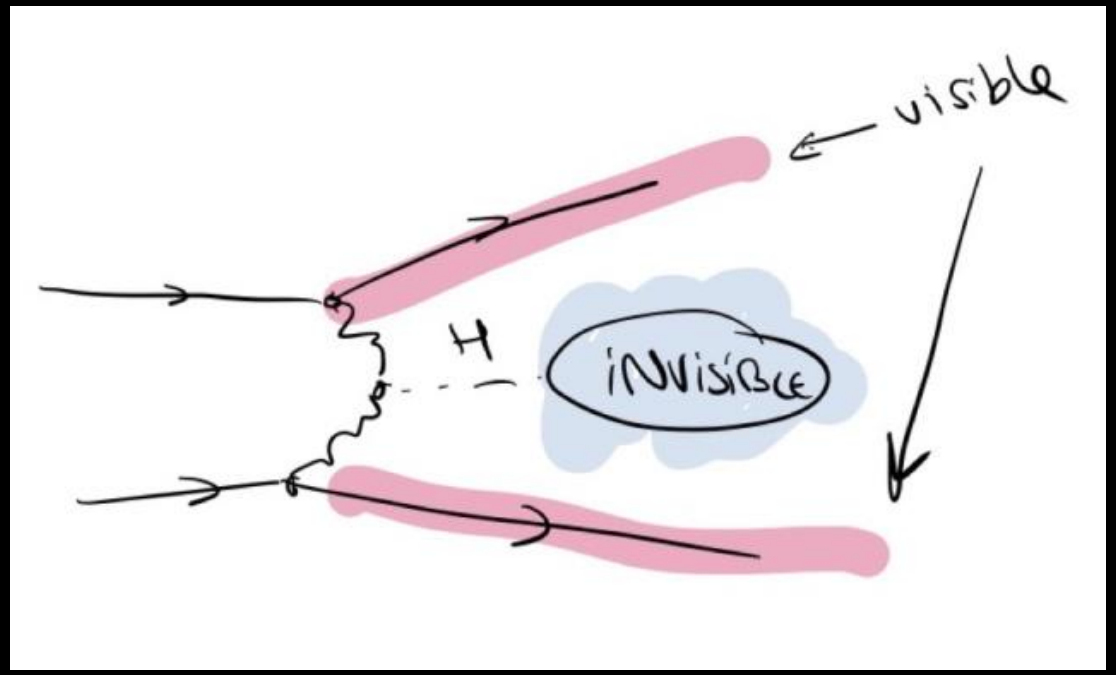
Complementarity with direct detection

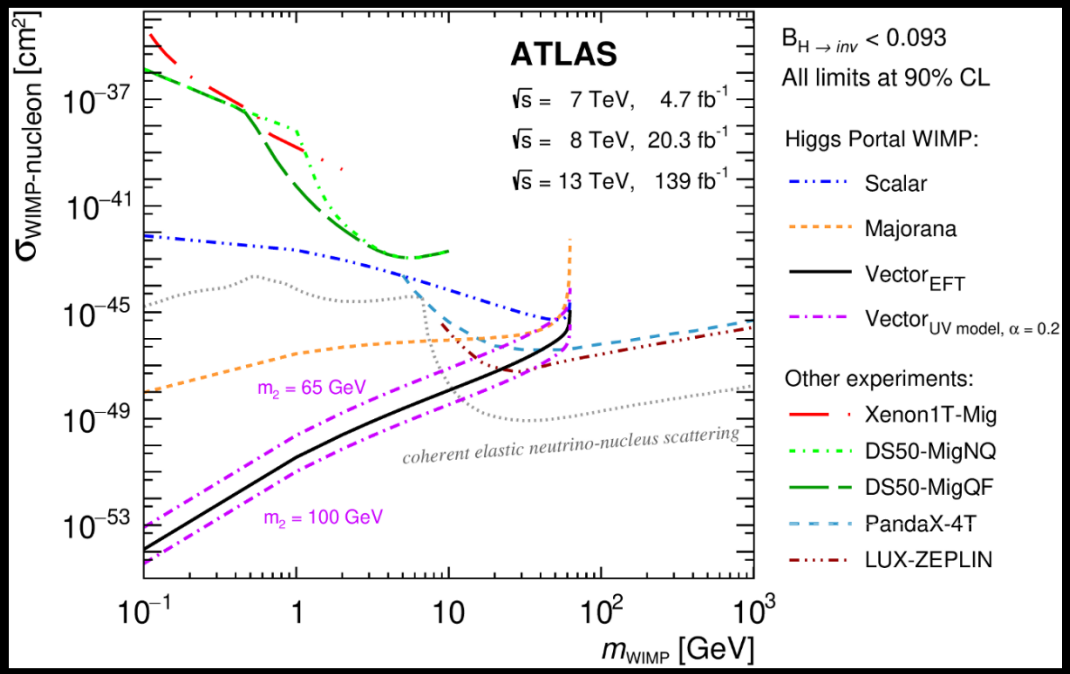




ATLAS-PHYS-PUB-2023-018

A model-independent model

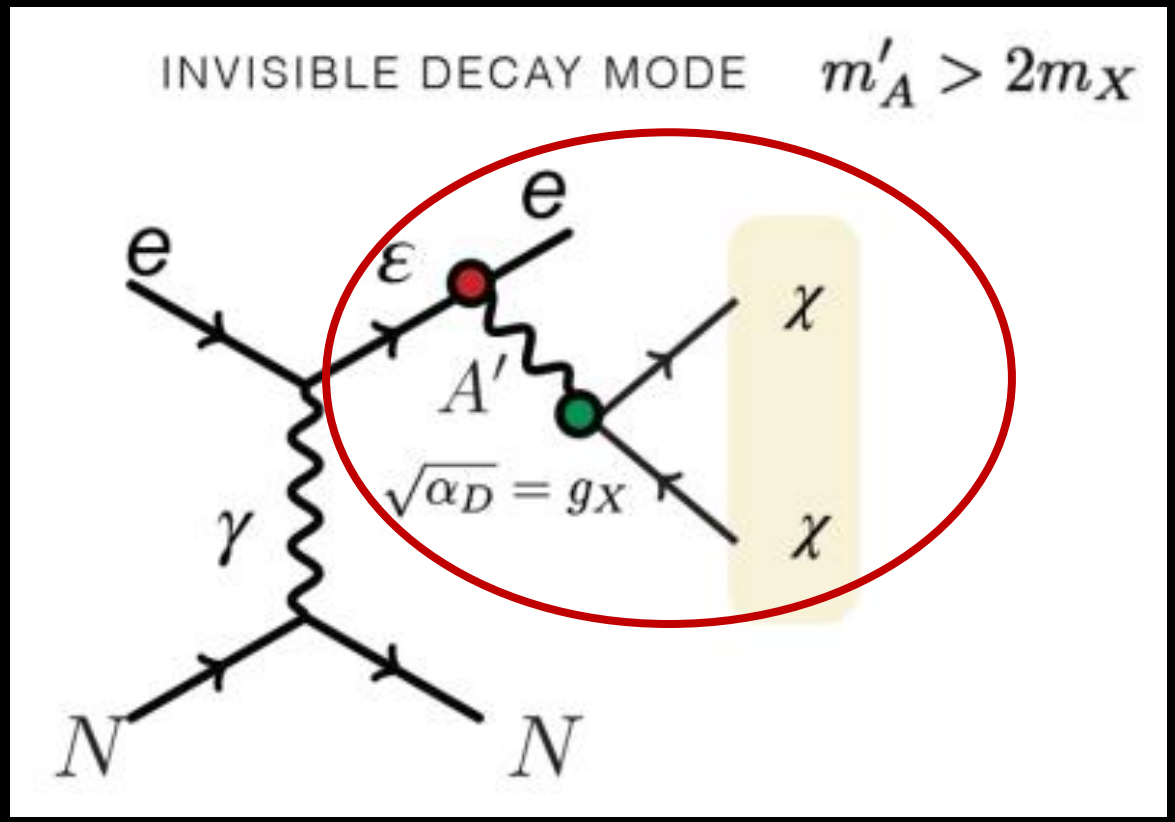




ATLAS-PHYS-PUB-2023-018

Alternative approach

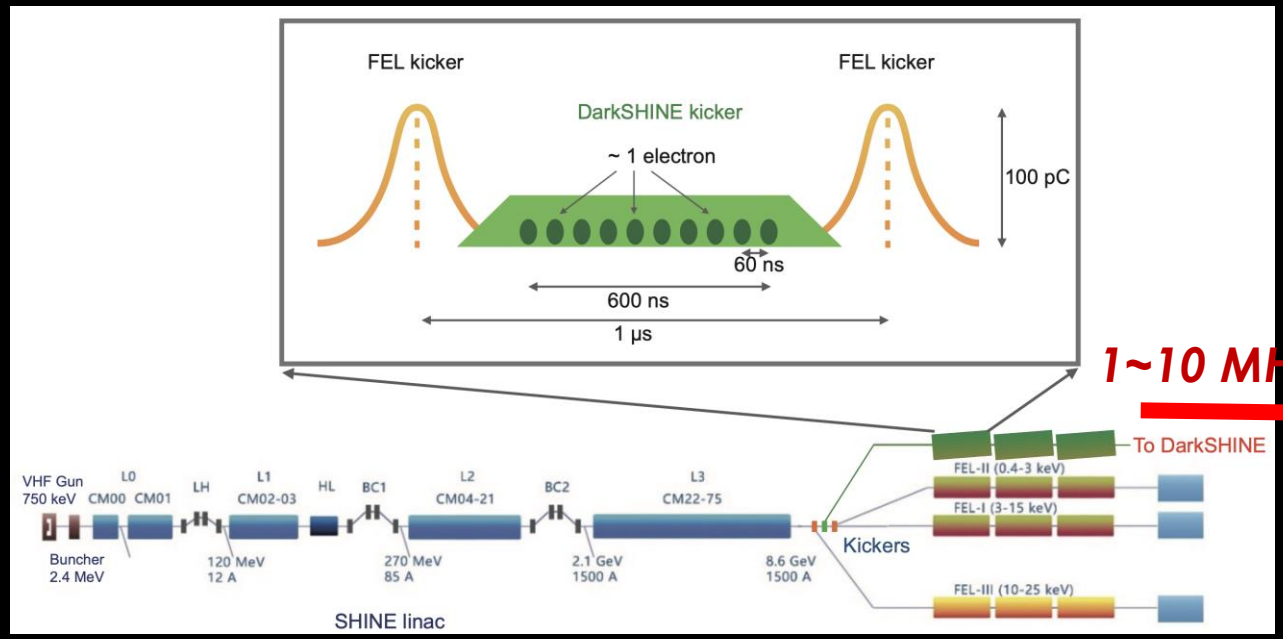
- Fixed target or beam dump experiments for the dark mediator and DM (“dark sector”)
- Many experiments! For example:



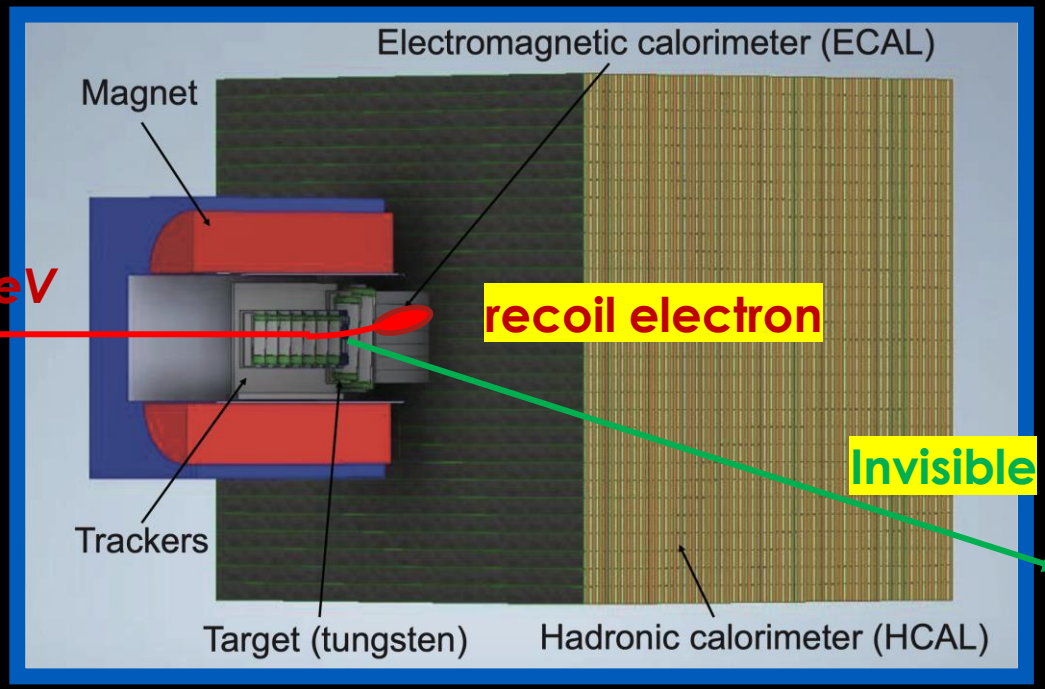
Connection directly to the early Universe and Direct detection!

DarkSHINE in Shanghai

Shanghai High Repetition-Rate XFEL and Extreme Light Facility (SHINE) high repetition rate single electron beams

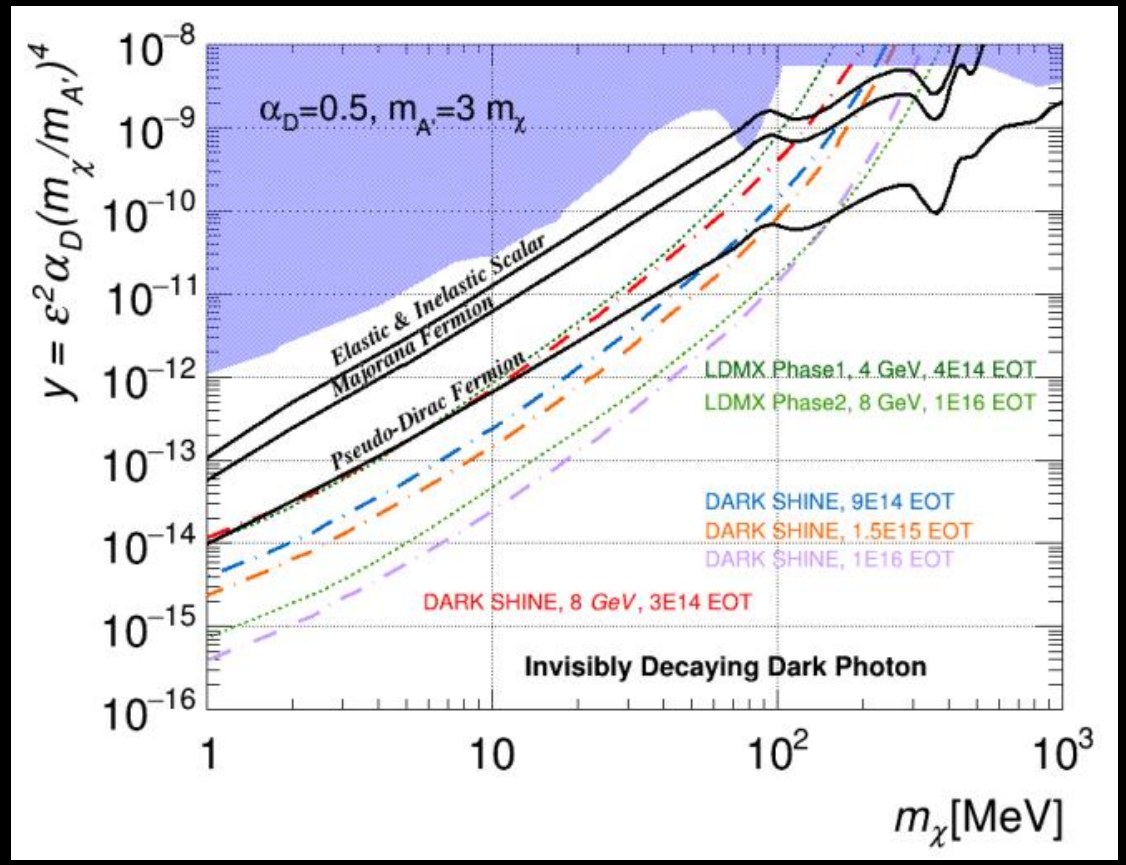


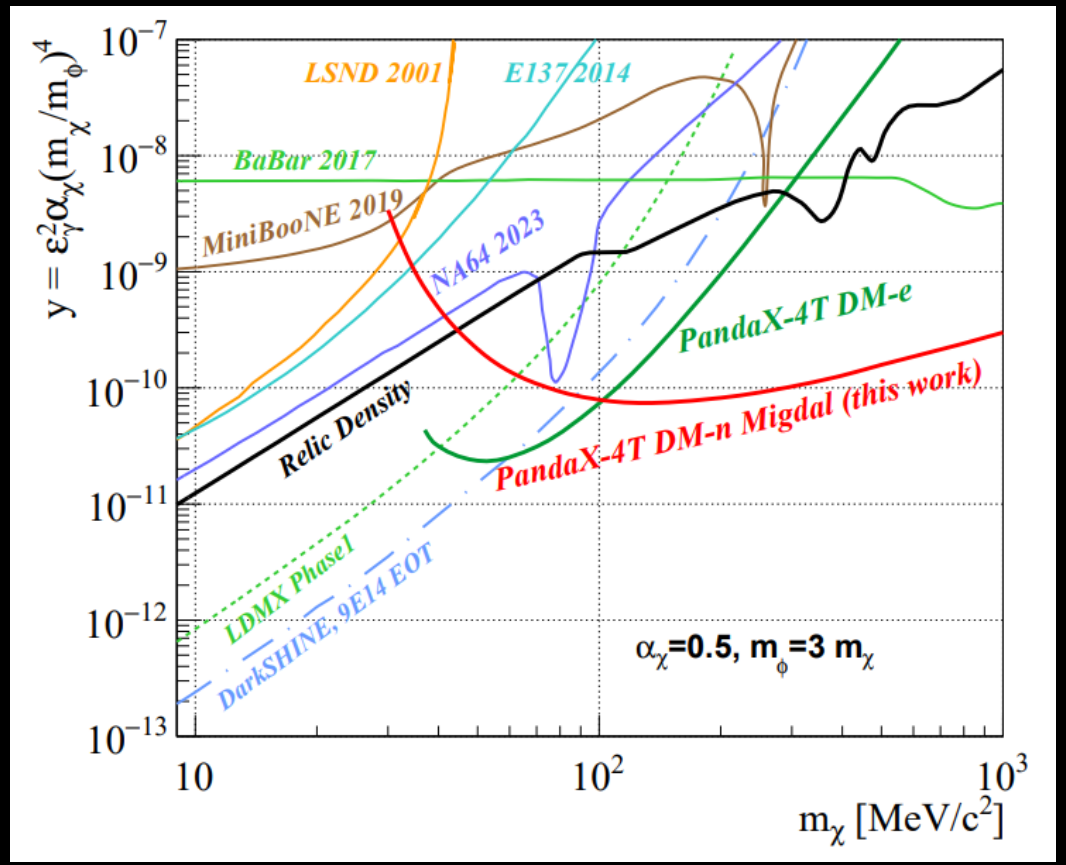
1~10 MHz@8GeV



Sci. China-Phys. Mech. Astron. 66(1): 211062 (2023)

Sensitivity to thermal DM





PandaX, PRL 131.191002 (2023)

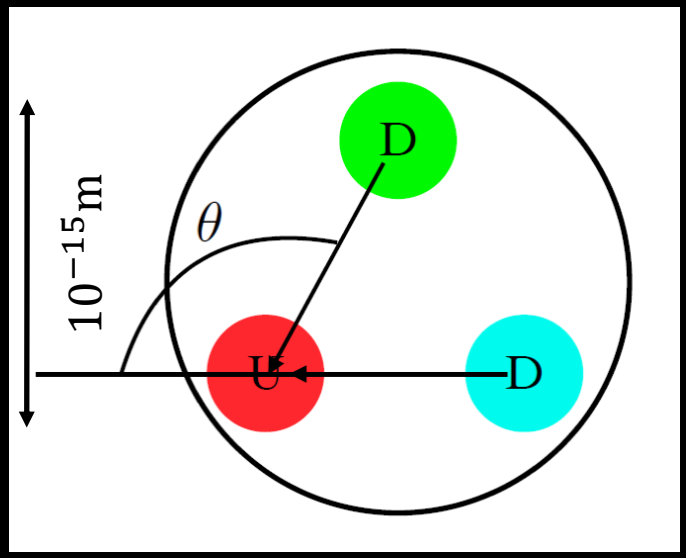
Strong CP Problem

- The strong interaction theory QCD have a phase term $\boldsymbol{\theta}$ contributing to CP violation
- Neutron electric dipole moment

$$d_n \sim \boldsymbol{\theta}\, 10^{-16}\mathrm{e}\cdot\mathrm{cm}$$

- nEDM collaboration at PSI (C. Abel et al, 2020)

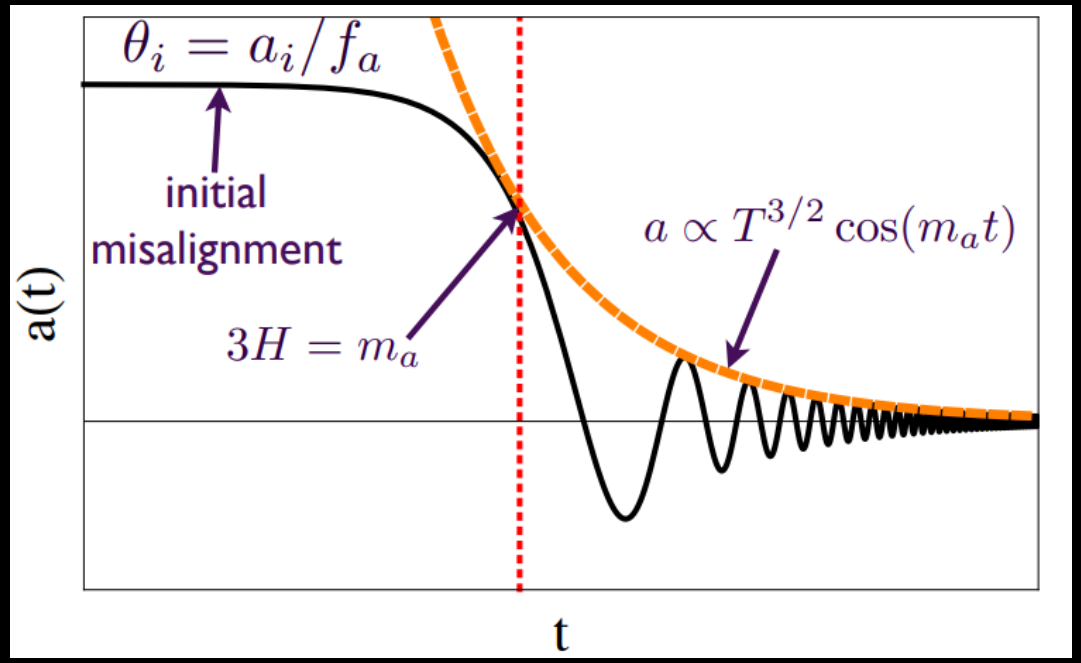
$$d_n < 1.8 \times 10^{-26}\mathrm{e}\cdot\mathrm{cm}$$



A. Hook, TASI lecture note, https://arxiv.org/abs/1812.02669

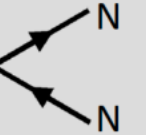
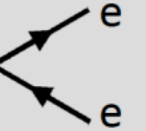
Axion: natural solution to the strong CP problem

- Solution: $\theta \Rightarrow$ dynamic field a(x,t)/f_a, $U_{\mathrm{PQ}}(1)$ symmetry [Peccei & Quinn 1977]
- QCD axion! [Weinberg 1978, Wilczek 1978]
- Cosmological DM!



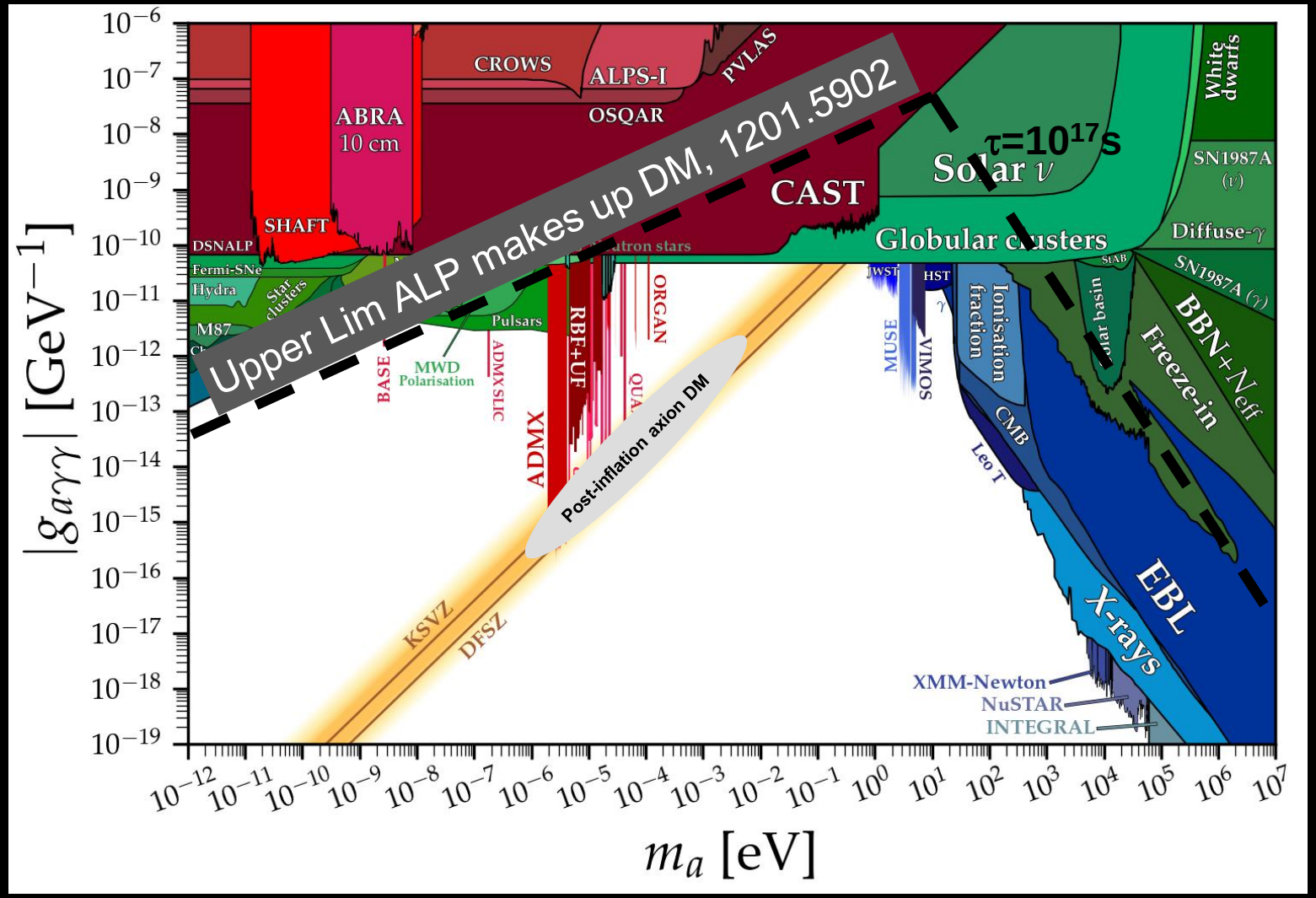
Ben Safdi

Axion properties

Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$	
Mass (generic)	$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d} \frac{m_\pi}{f_\pi f_a} \approx \frac{6\ \mu\text{eV}}{f_a/10^{12}\ \text{GeV}}$	
Photon coupling	$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\ \mathbf{E}\cdot\mathbf{B}\ a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	
Pion coupling	$\mathcal{L}_{a\pi} = \frac{C_{a\pi}}{f_\pi f_a}(\pi^0\pi^+\partial_\mu\pi^- + \cdots)\partial^\mu a$	
Nucleon coupling (axial vector)	$\mathcal{L}_{aN} = \frac{C_N}{2f_a}\overline{\Psi}_N\gamma^\mu\gamma_5\Psi_N\partial_\mu a$	
Electron coupling (optional)	$\mathcal{L}_{ae} = \frac{C_e}{2f_a}\overline{\Psi}_e\gamma^\mu\gamma_5\Psi_e\partial_\mu a$	

A. Mirizzi, Next Frontiers in the Search for Dark Matter 2019

Current landscape and axion DM

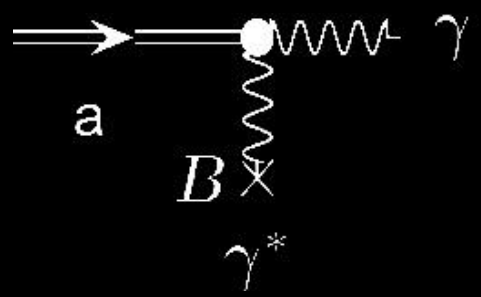


Data by Ciaran O'Hare https://cajohare.github.io/AxionLimits/

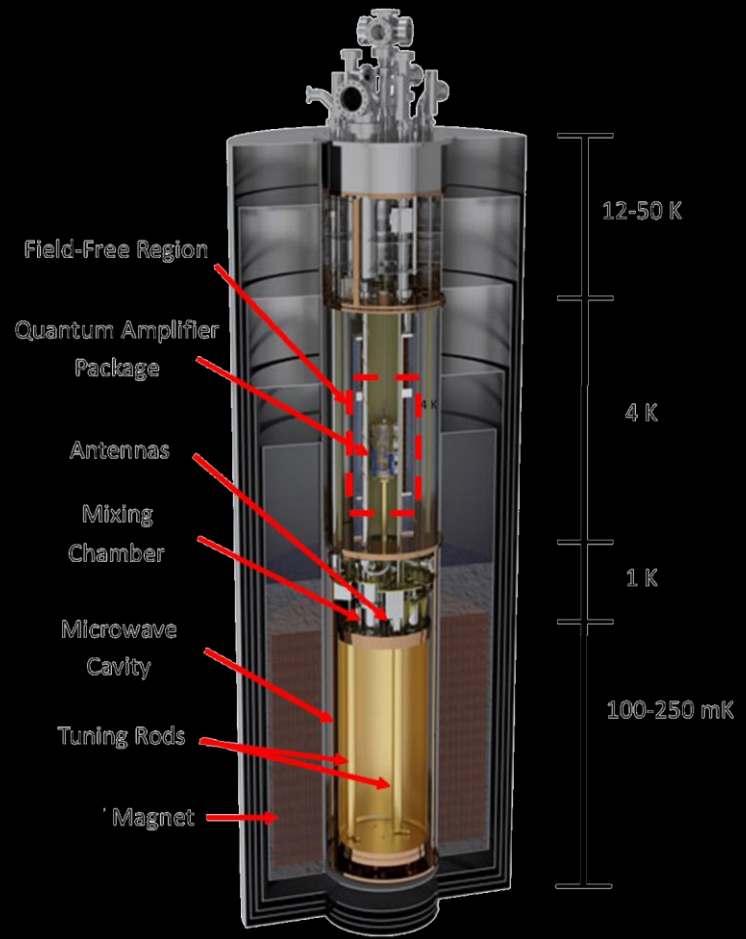
Axion/ALP Terrestrial Experiment

- Haloscopes (halo DM)
- Helioscopes (solar axion)
- Light-shining-through-walls (production-detection)
- Many others, e.g. axion with fermions, axion as force mediator …

Haloscope

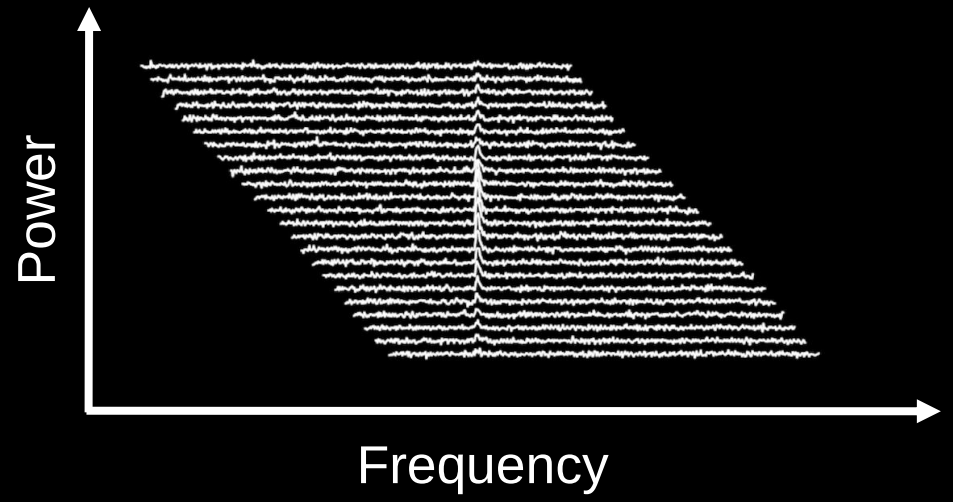


$$P_{\mathrm{a}} \propto {B_0}^2 QVC$$



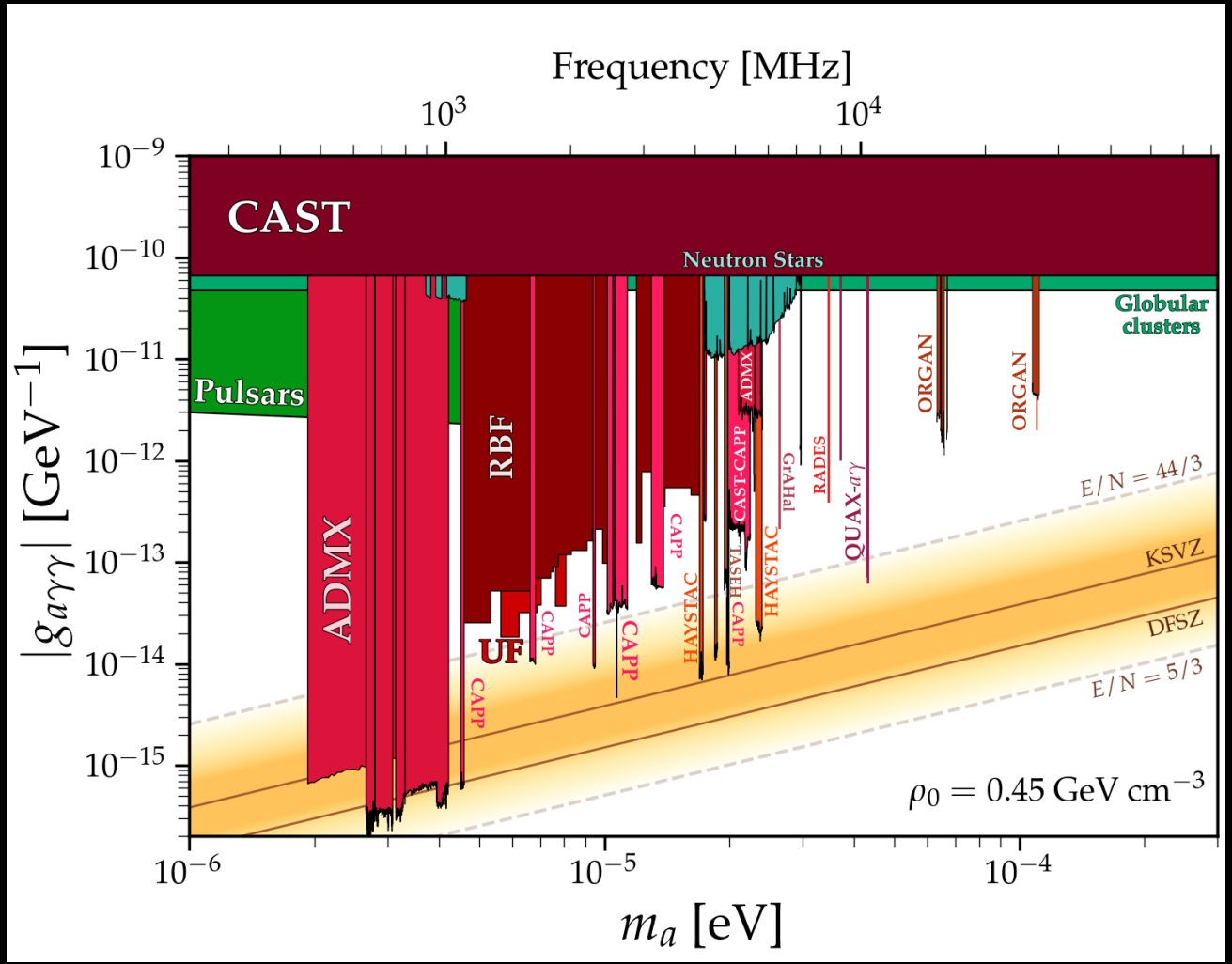
ADMX: B field ~7.6 T

- E.g. ADMX and CAPP, …
- Resonator design + microwave readout chain with quantum amplifiers



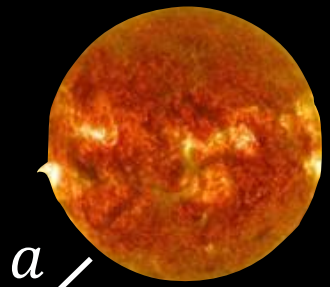
Mean Signal Power ~ $10^{-23} Watts$

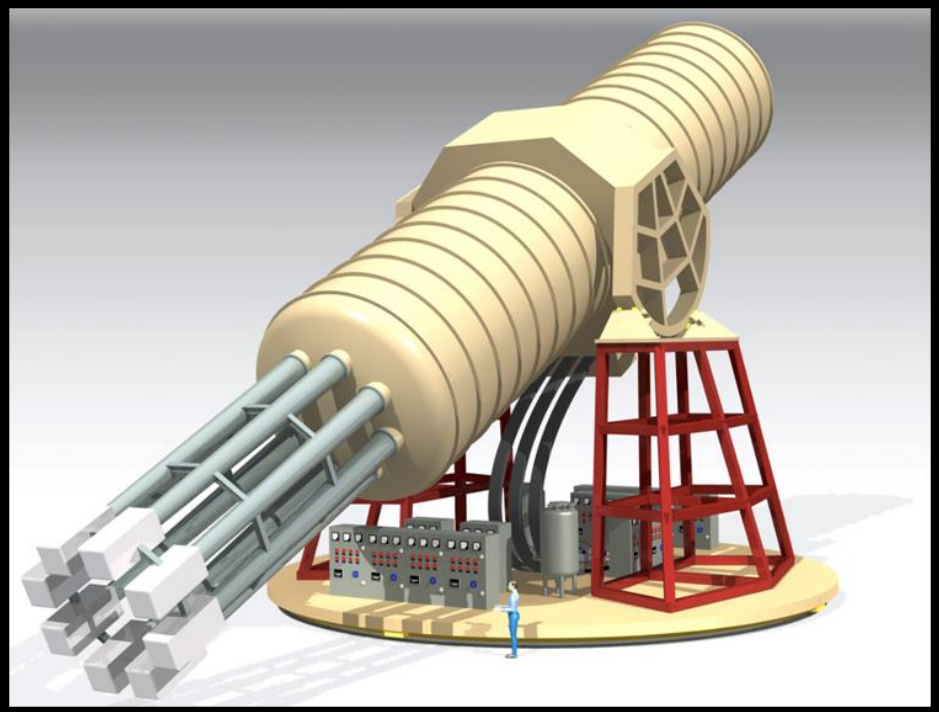
Approaching QCD axion and DM “sweet spot”



Data by Ciaran O'Hare https://cajohare.github.io/AxionLimits/

Helioscope





- The sun is an axion beam
  - Solar axions will carry ~keV kinetic energy
- Inverse Primakoff effect
  - Generate X-rays in a strong magnetic filed
- E.g. CAST, Baby-IAXO, IAXO

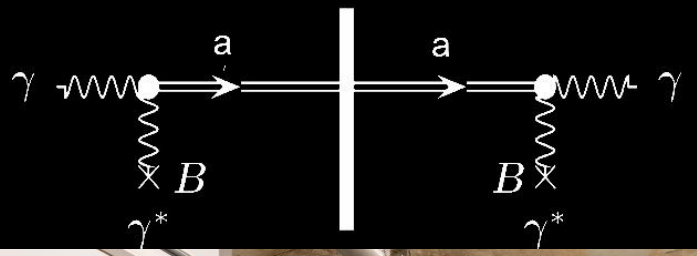
https://doi.org/10.48550/arXiv.2010.12076

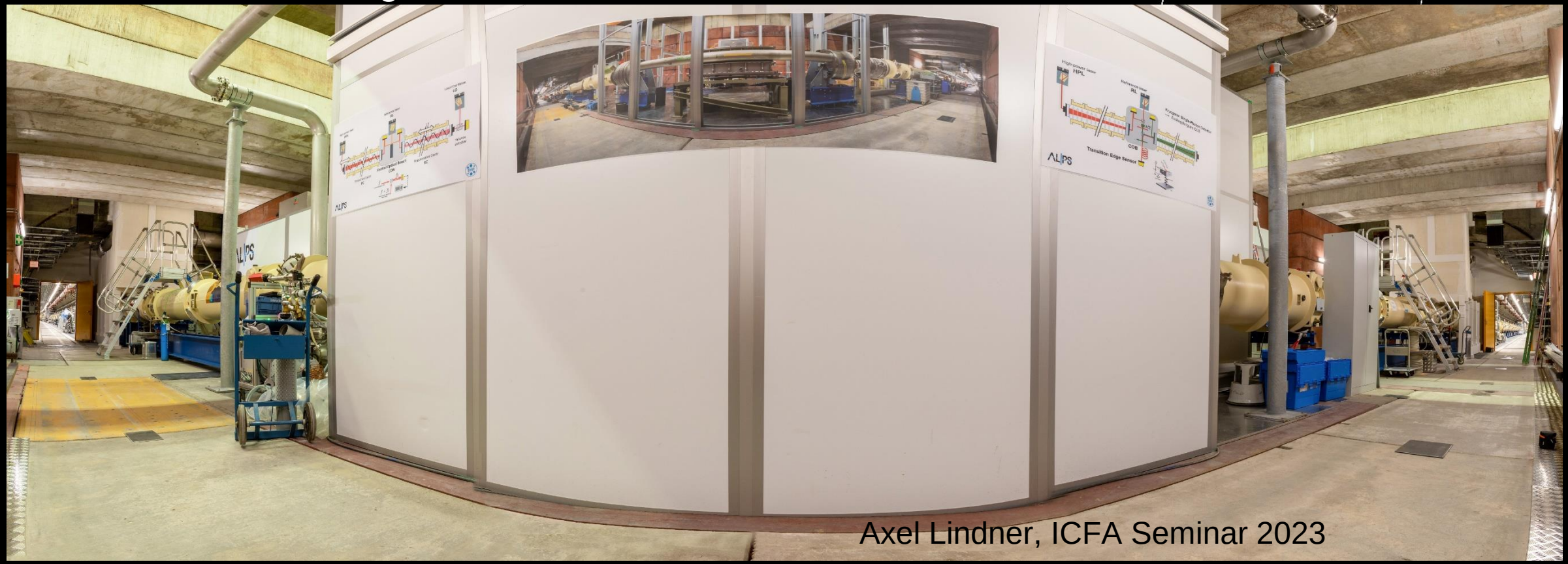
$$P_{\mathrm{a}} \propto {B_0}^2 L^2 A$$

Extra L enhancement by coherence

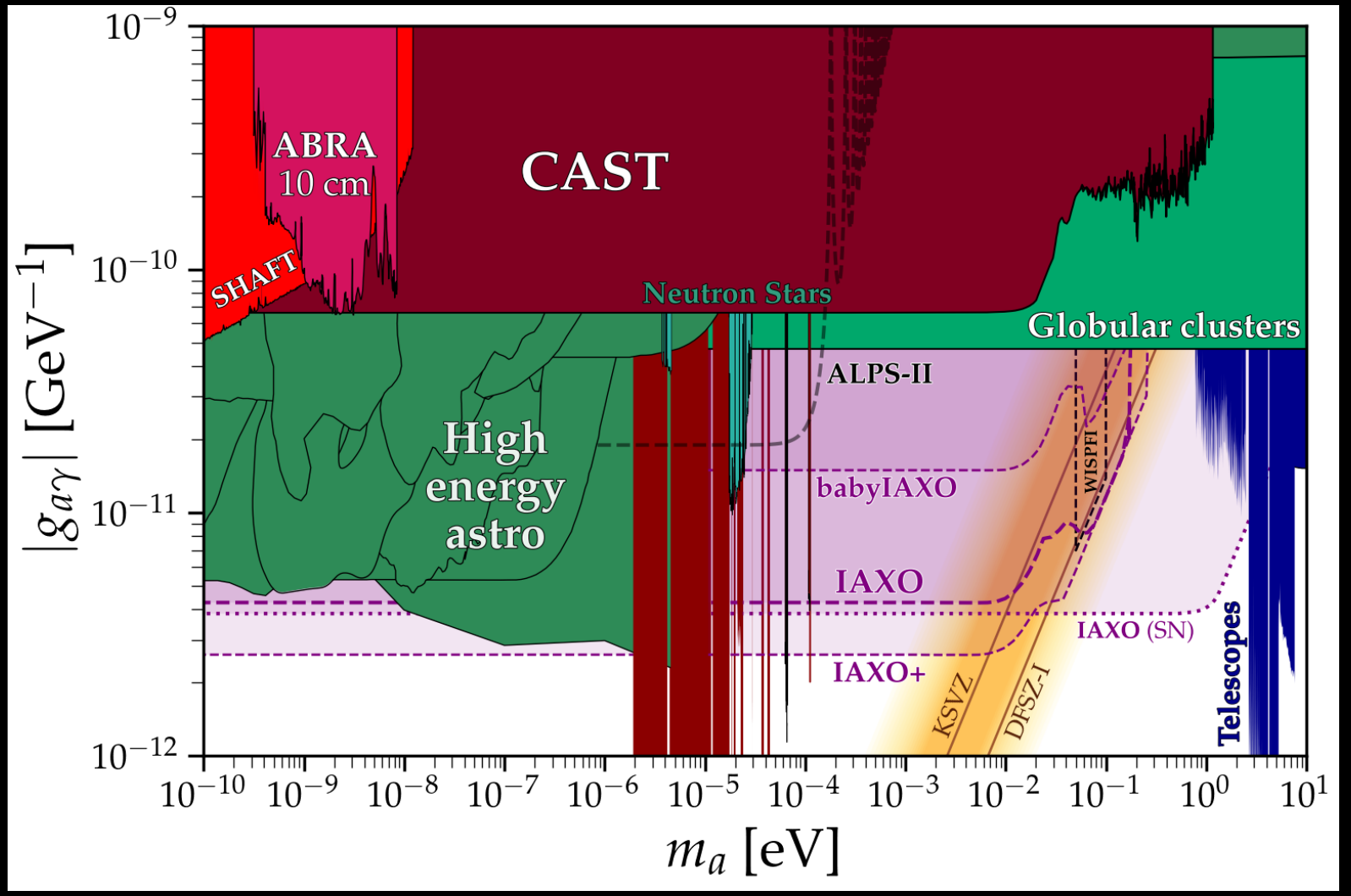
Light-shining-through-walls

- Produce axion and convert axion with microwave cavities
- Independent of astrophysics or cosmic assumptions!
- 2023: commissioning started





“Near” future



Data by Ciaran O'Hare https://cajohare.github.io/AxionLimits/

Summary

- DM laboratory searches: huge experimental processes in the past few decades years
  - Significant “traditional” WIMP parameters unexplored (with known experimental techniques!)
  - Many near future experiments are pushing to the preferred QCD axion dark matter
- Let us be hopefully for a laboratory discovery (may just be around the corner)!