# Status of WIMP Searches: from the sky and underground

Jianglai Liu

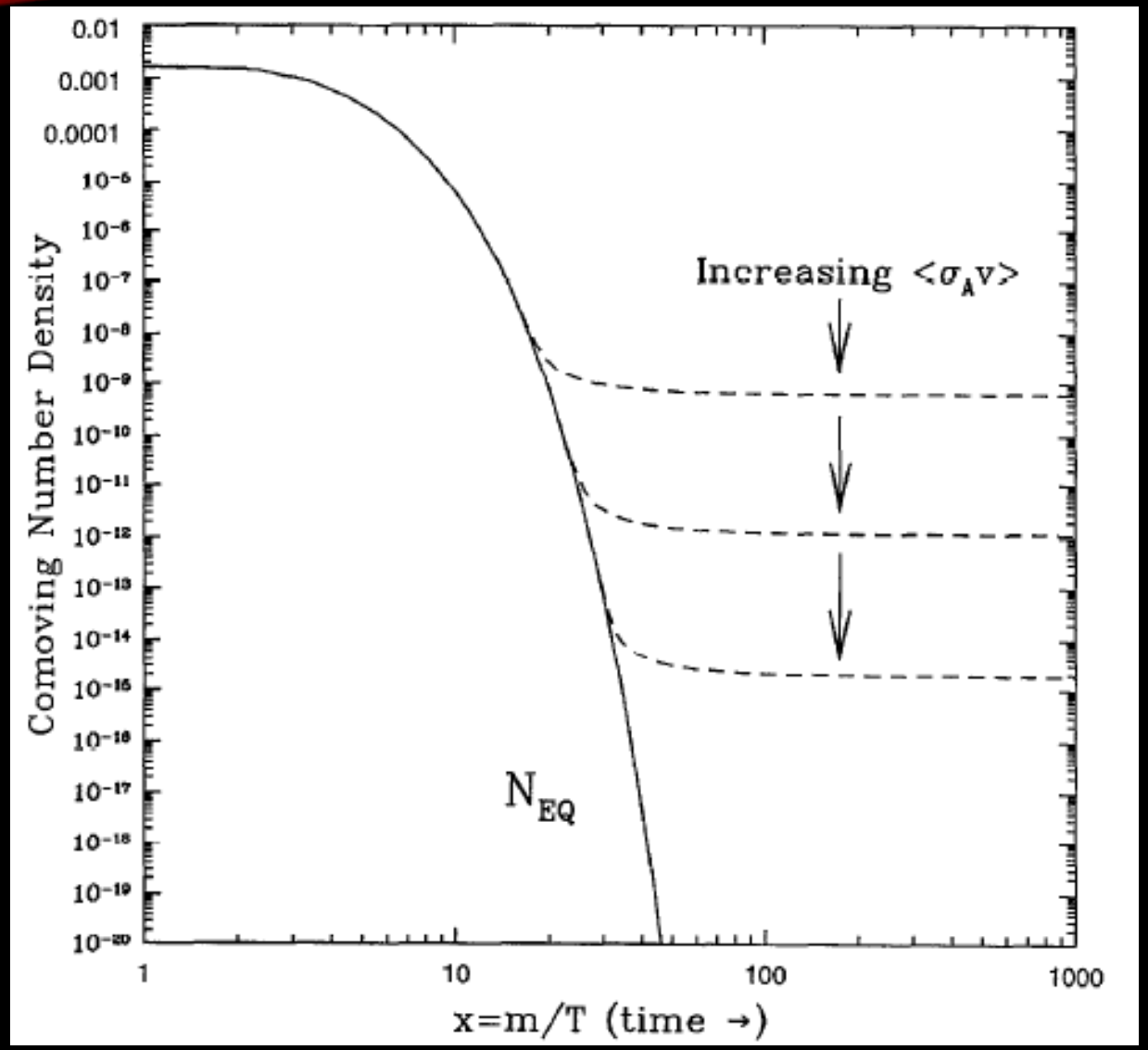
Tsung-Dao Lee Institute and School of Physics and Astronomy

Shanghai Jiao Tong University

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, and Sming Tsai for materials

# WIMP thermal freeze-out




Early Universe Boltzmann Equation

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

Requires:

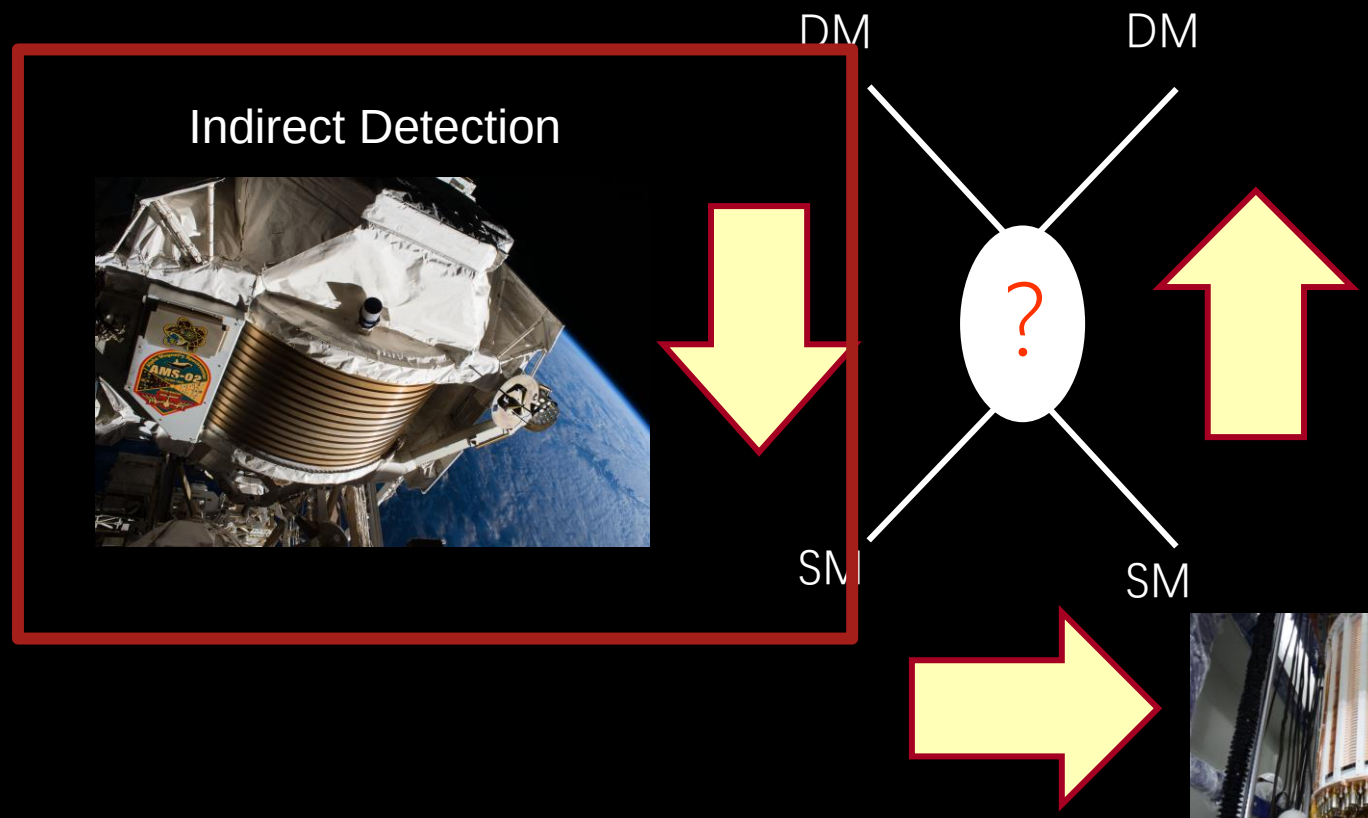
$\langle\sigma_{ann}\mathrm{v}\rangle$ =3x10$^{-26}$cm$^3$/s

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



# Dark Matter Indirect Detection

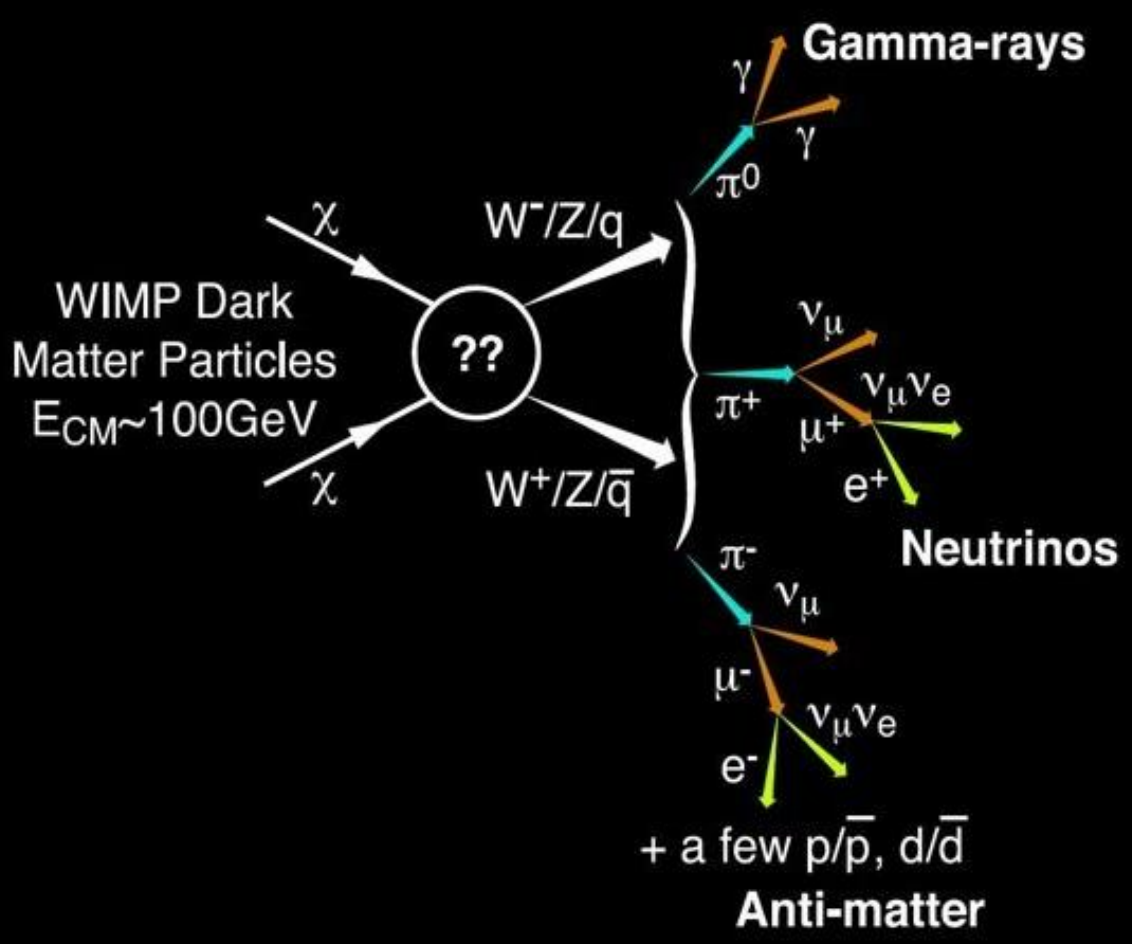




Image credit: Fermi-LAT


Image credit: LHAASO

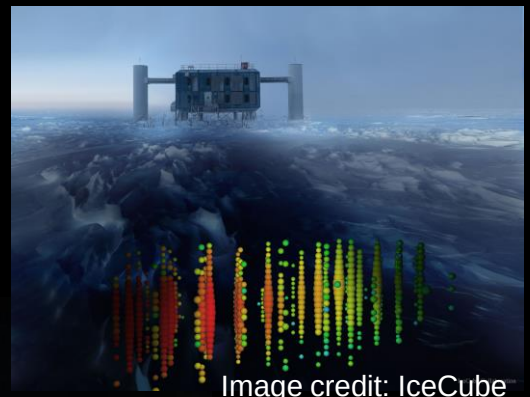
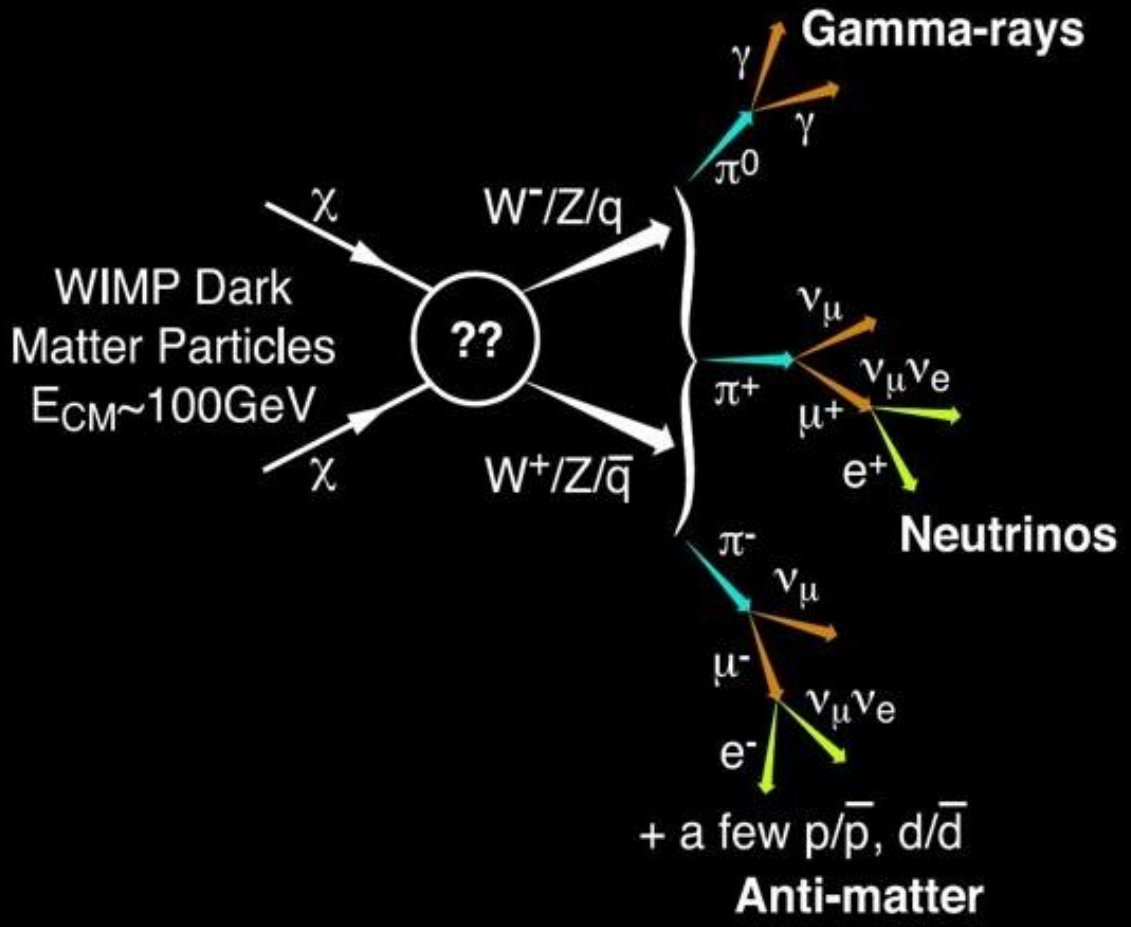


Image credit: IceCube

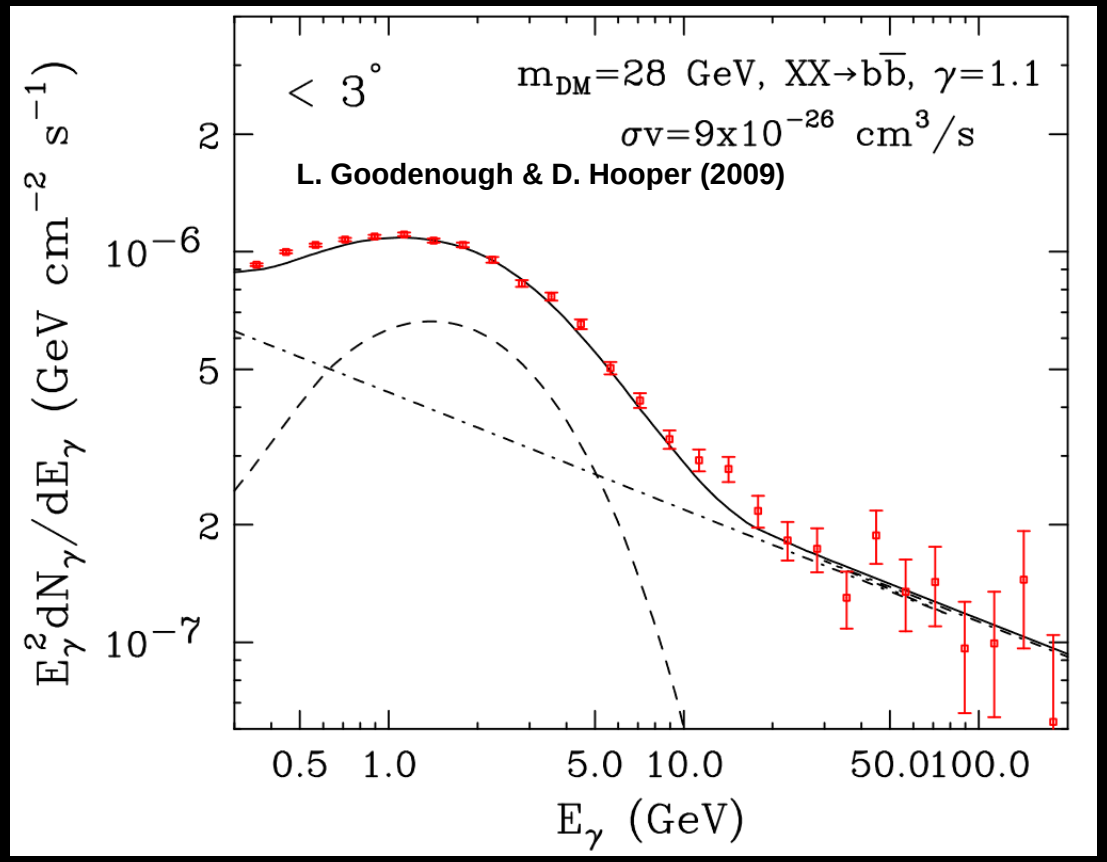
Image credit: AMS-02

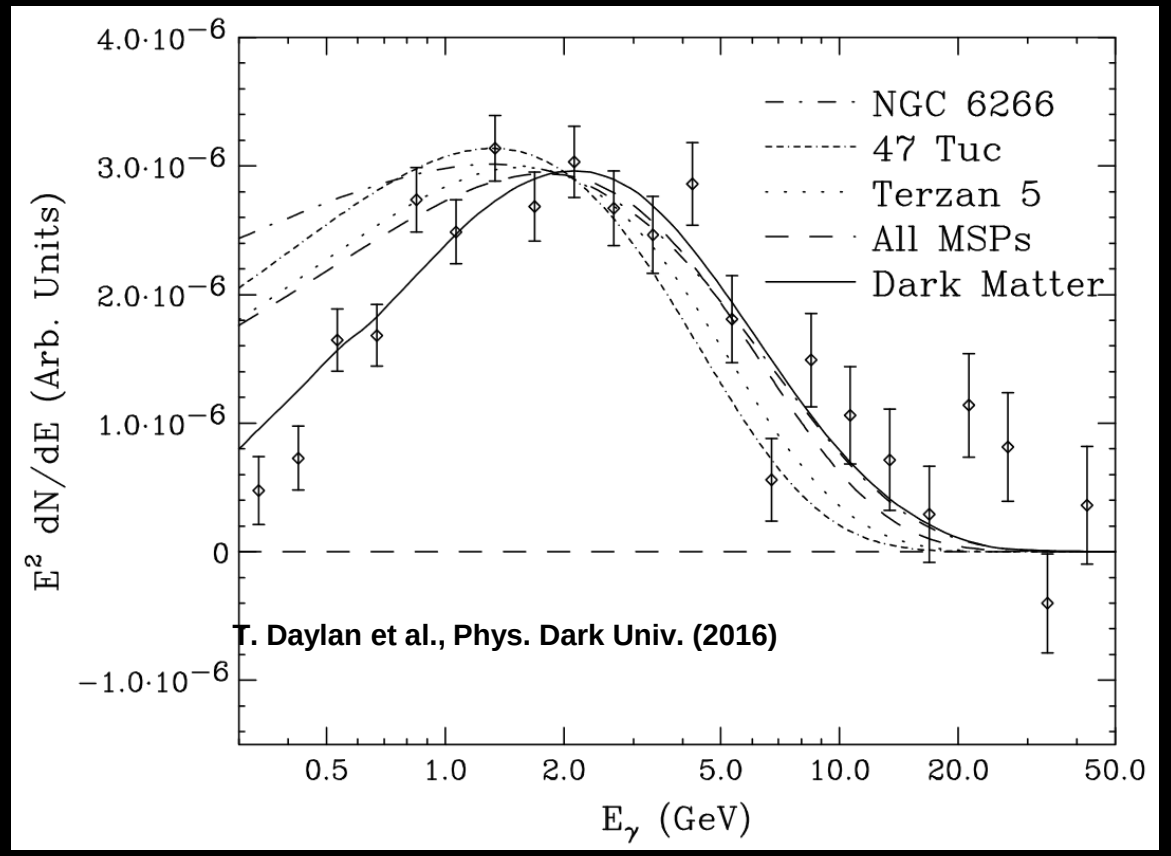
# Dark Matter Indirect Detection




- 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”

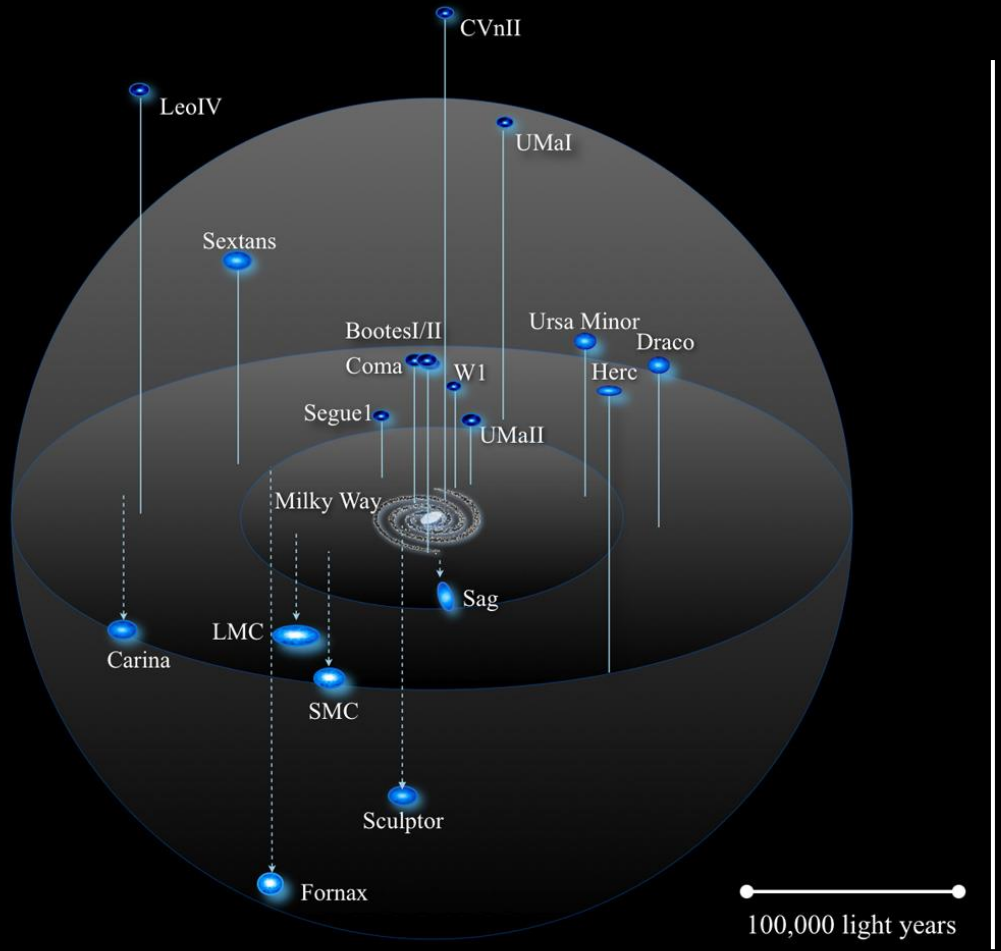


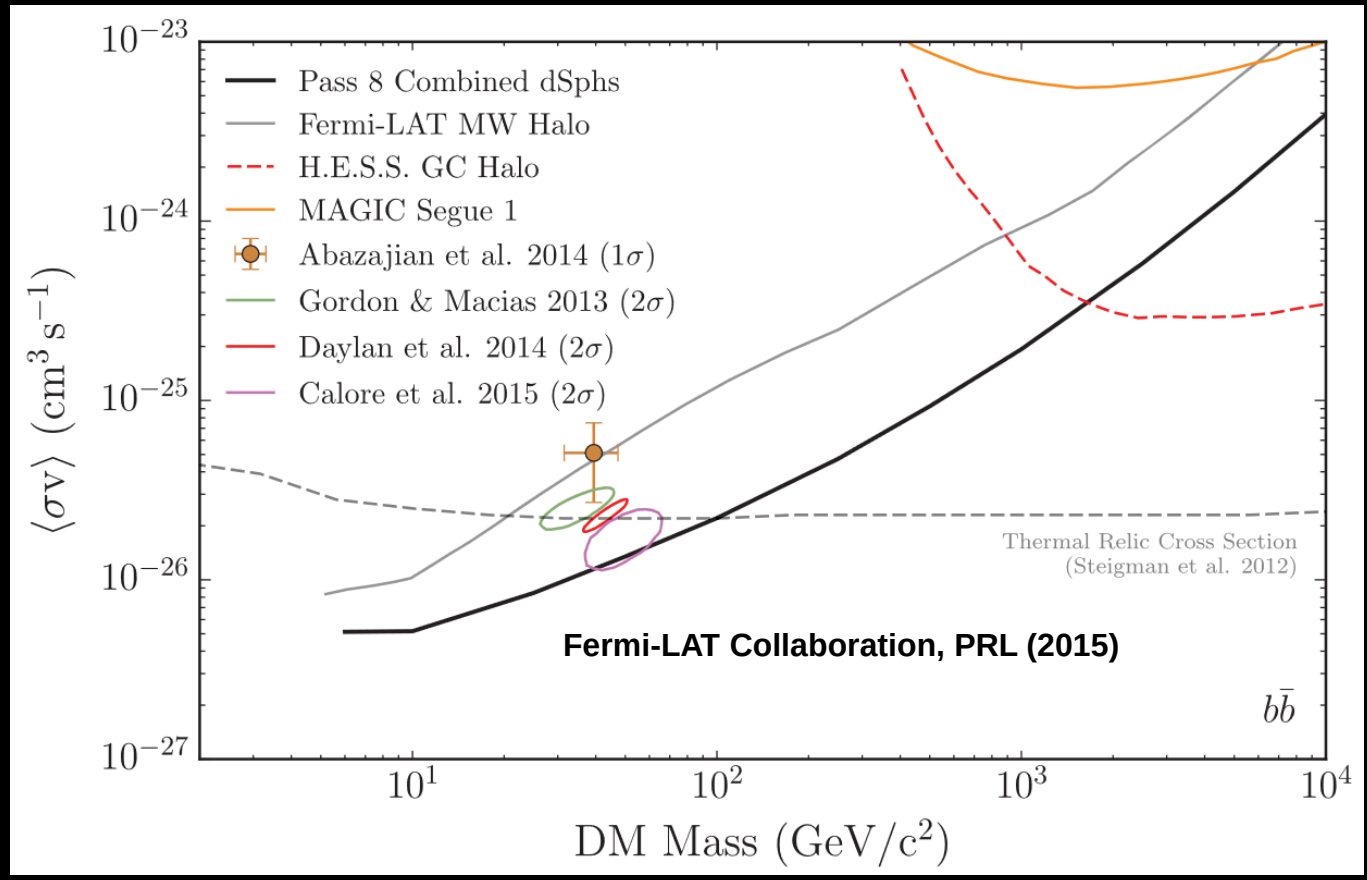




D. Hooper and L. Goodenough, PLB (2011)
Abazajian & Kaplinghat (2012), Gordon & Macias (2013), Calore, Cholis, Weniger (2015), Ackermann, et al. (2017)

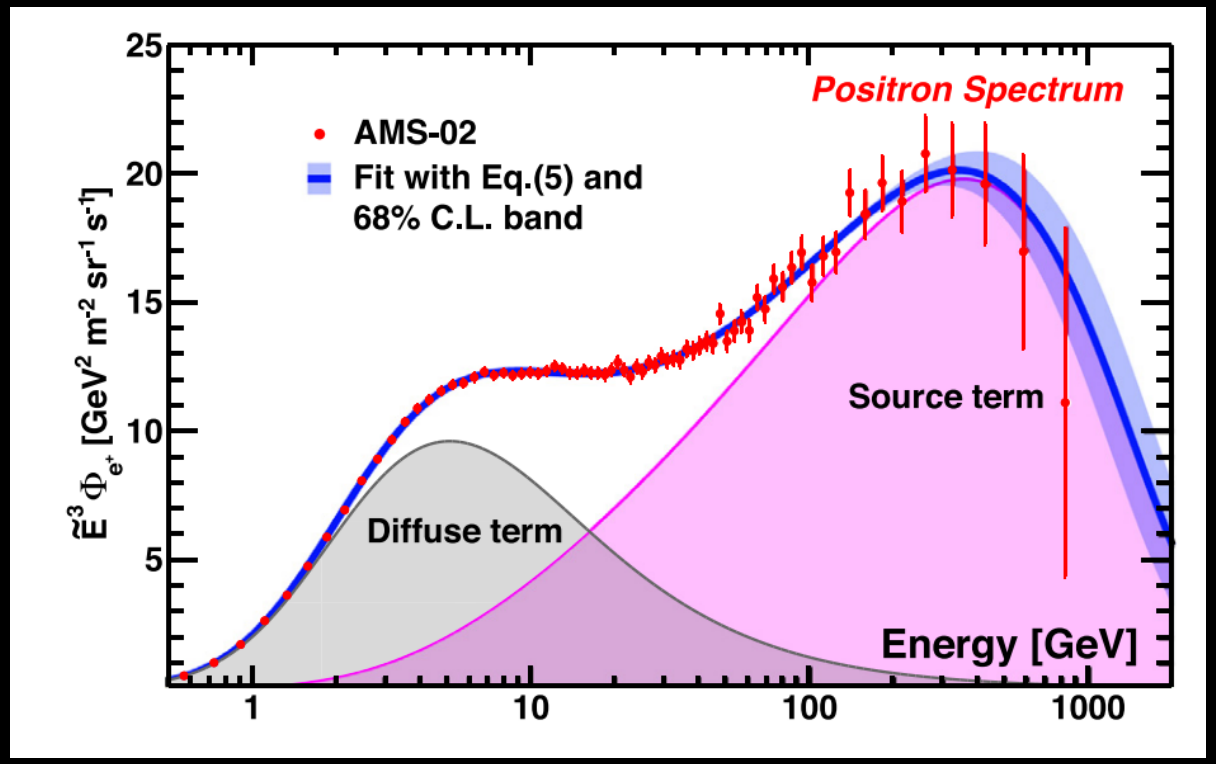
Interpretation highly model dependent, e.g. data may be at tension with pulsar interpretation

# Dwarf galaxy: DM hypothesis checks

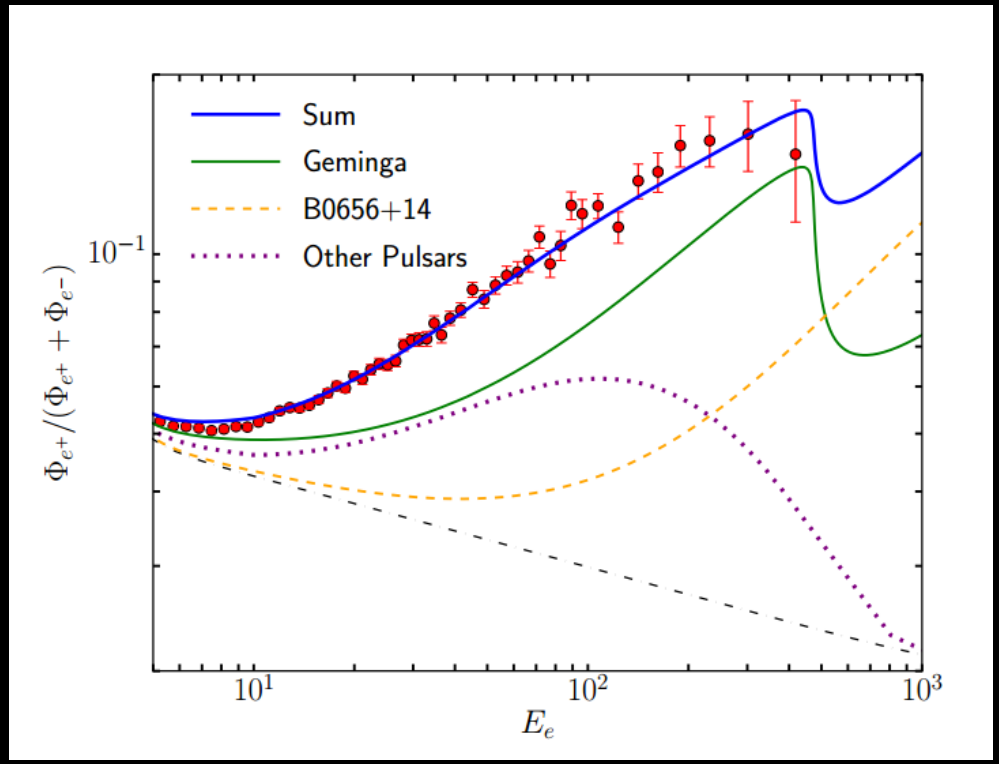


# Positron excess

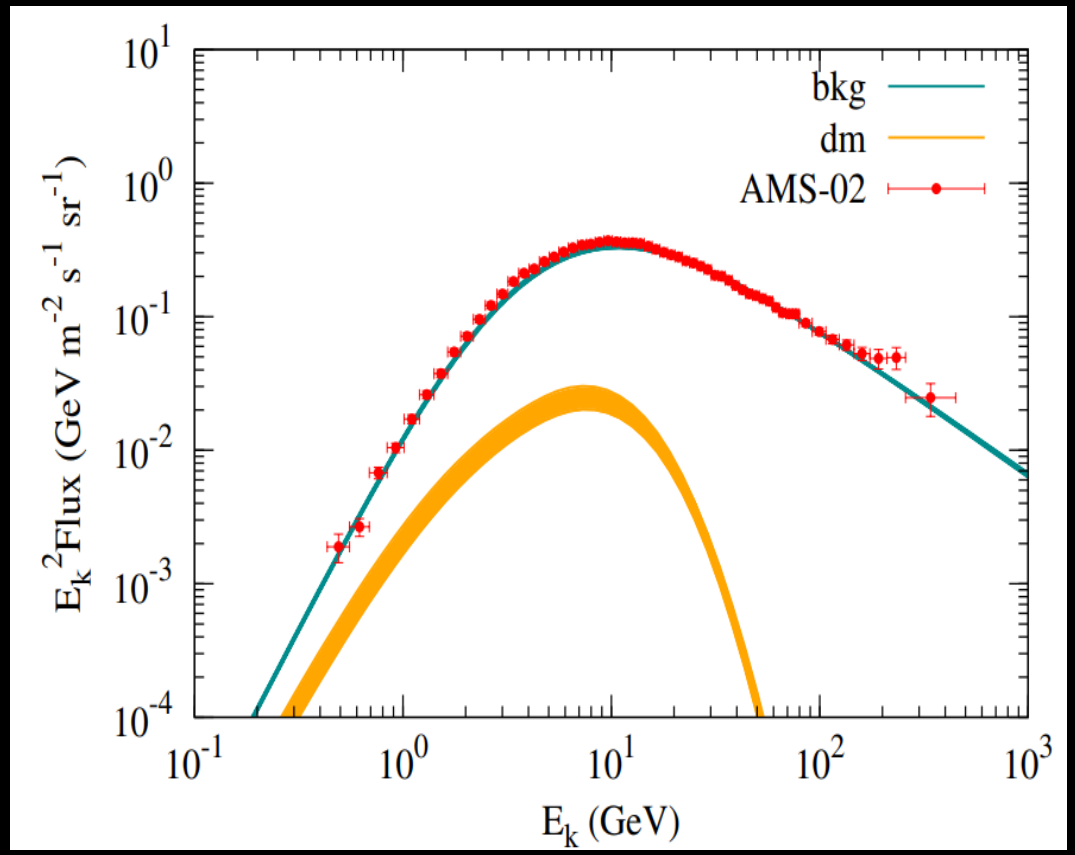



AMS-02, Physics Reports, Vol 894, 1-116 (2021)

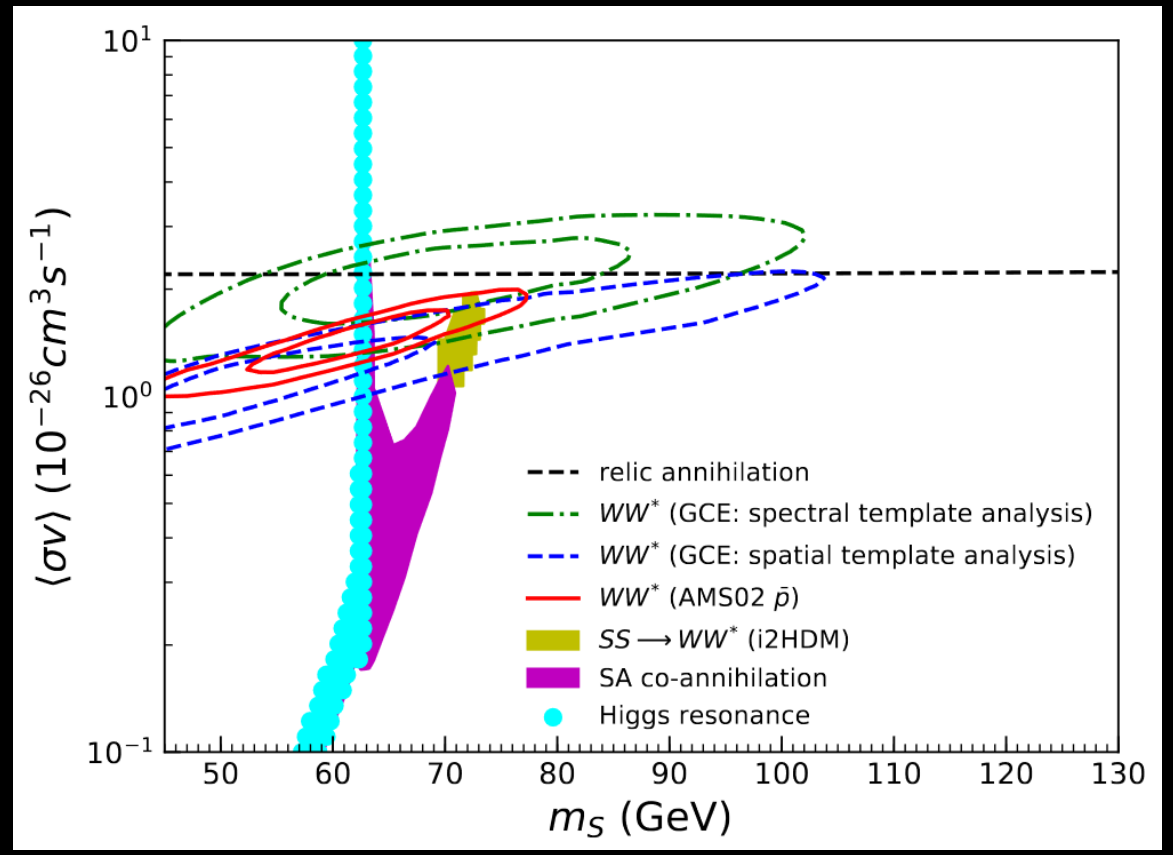



Alternative explanations from pulsars, 1702.08436, but challenged by Hawk observation, SCIENCE 2017

# Antiproton excess

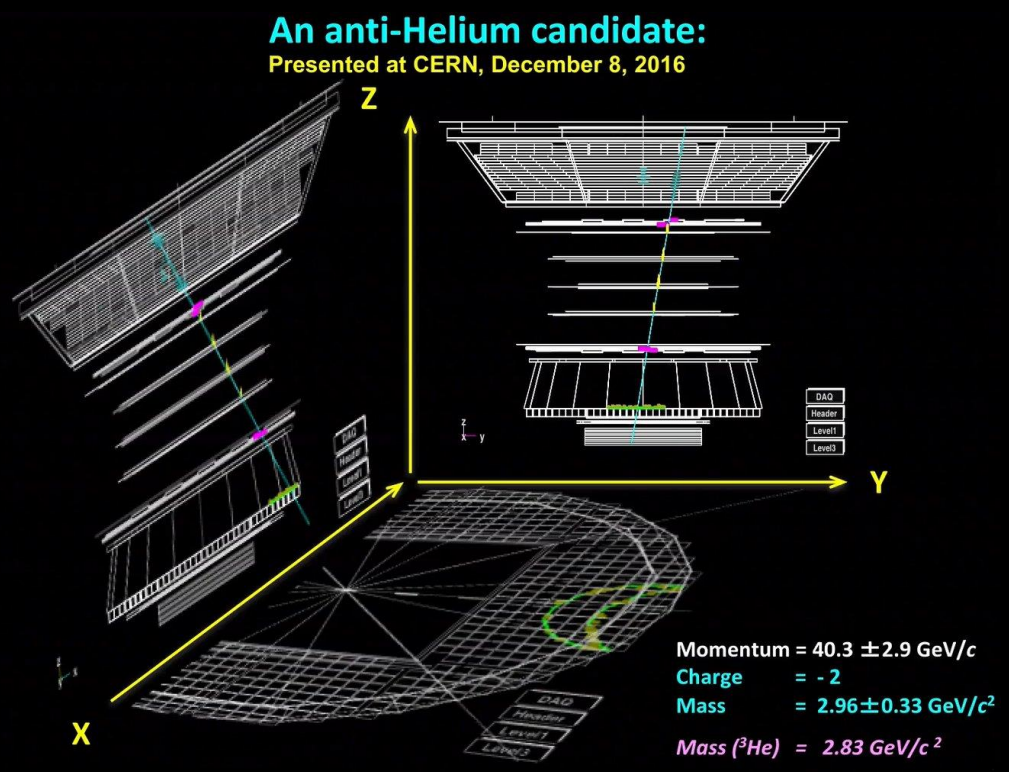


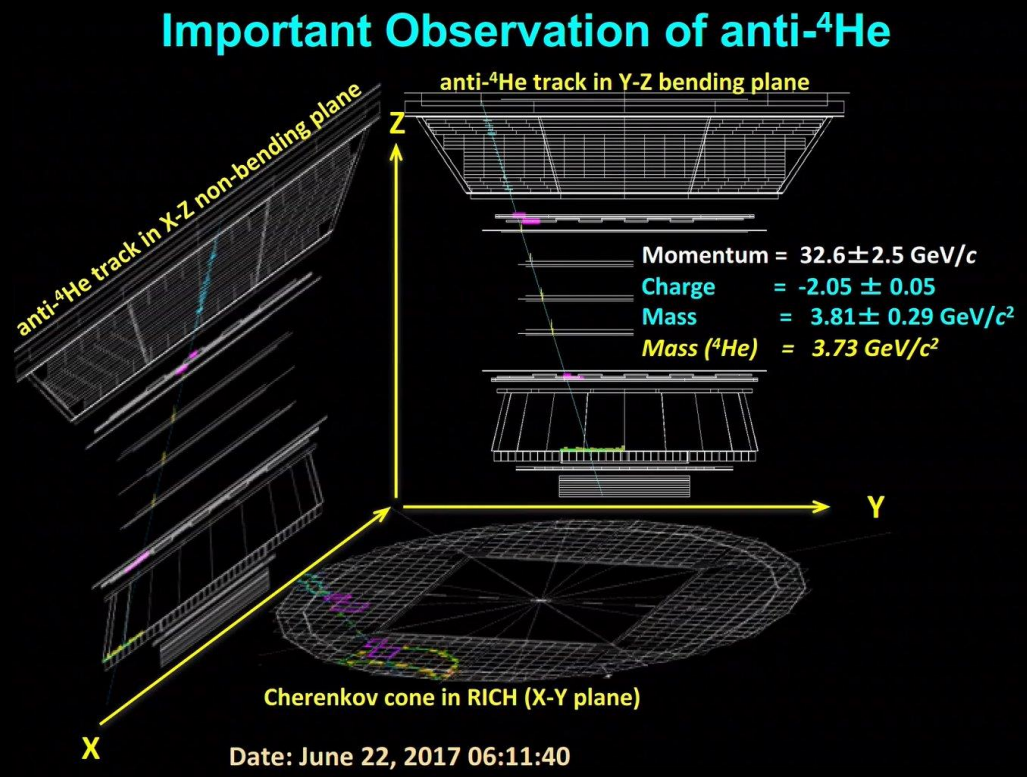

Cui, Yuan, Tsai, Fan, PRL 2017
Cuoco, Krämer, and Korsmeier, PRL 2017




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

# Anti-Helium

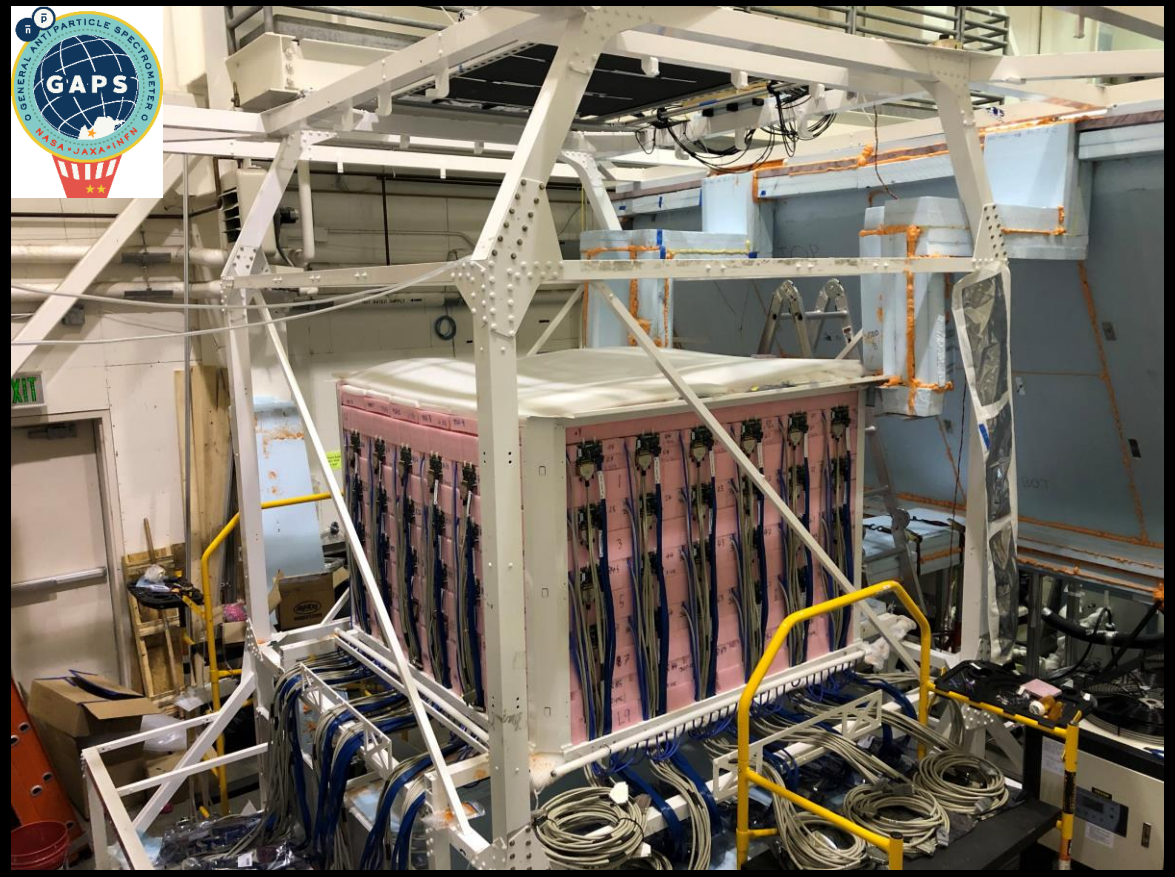


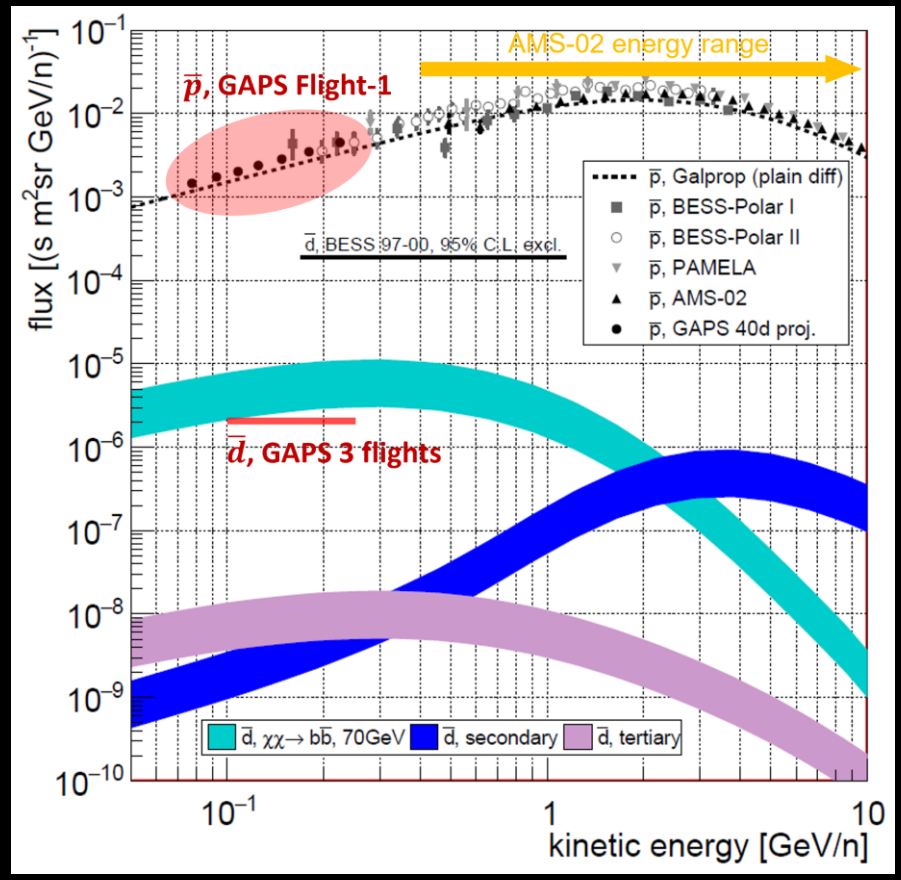




**2018:** "To date, we have observed *eight* events…with *Z* = *-2*. All eight events are in the helium mass region." – S. Ting (La Palma, AMS overview)

# New experiment on anti-matter

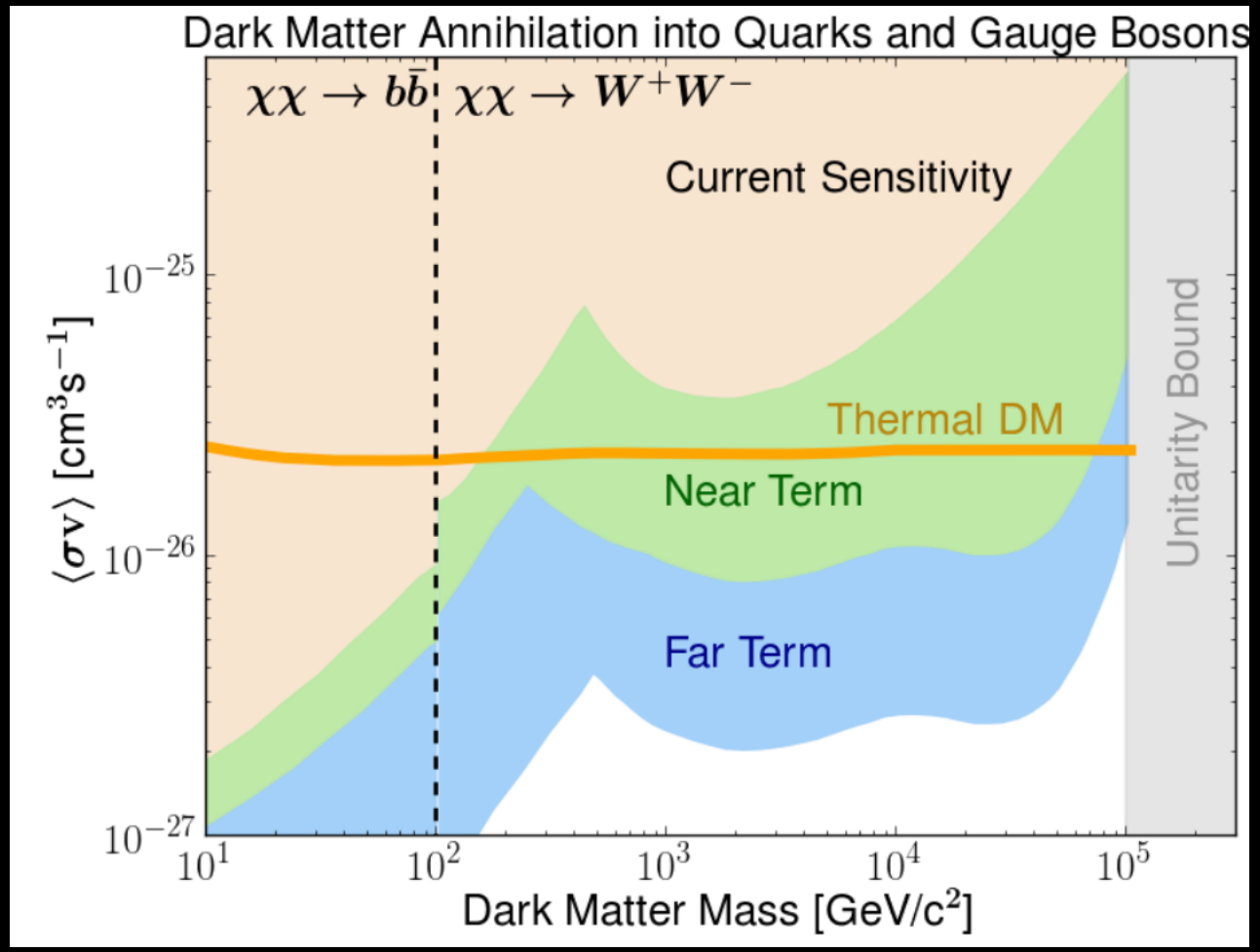
- GAPS: looking into anti-p and anti-d at lower KE





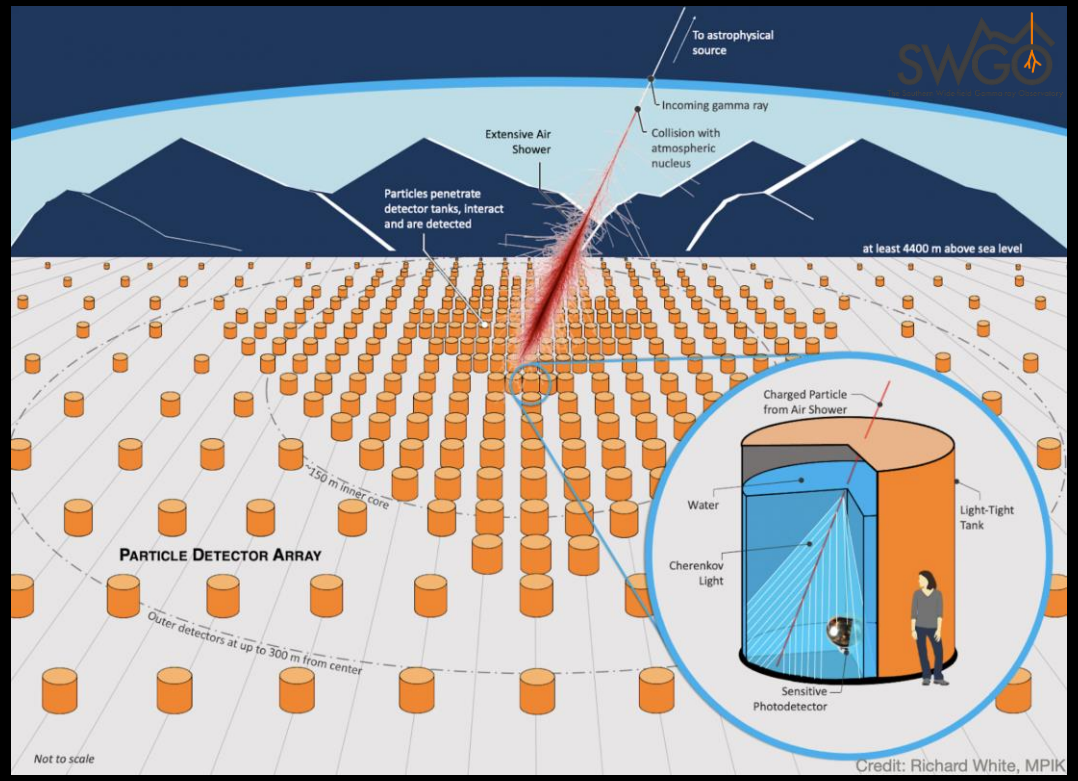

First flight: 2024!

# 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!)

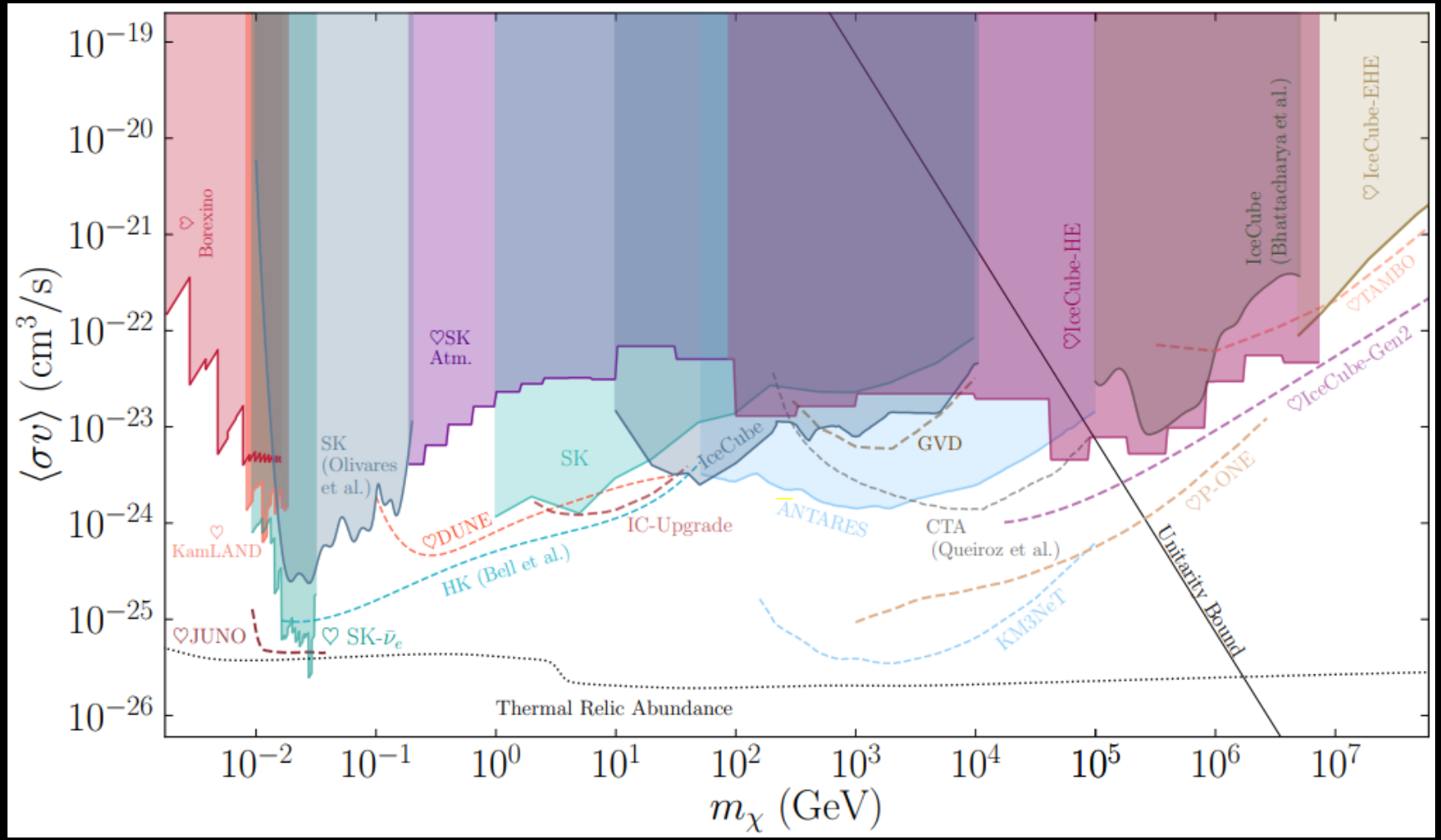
# Upcoming instruments: CTA and SWGO


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

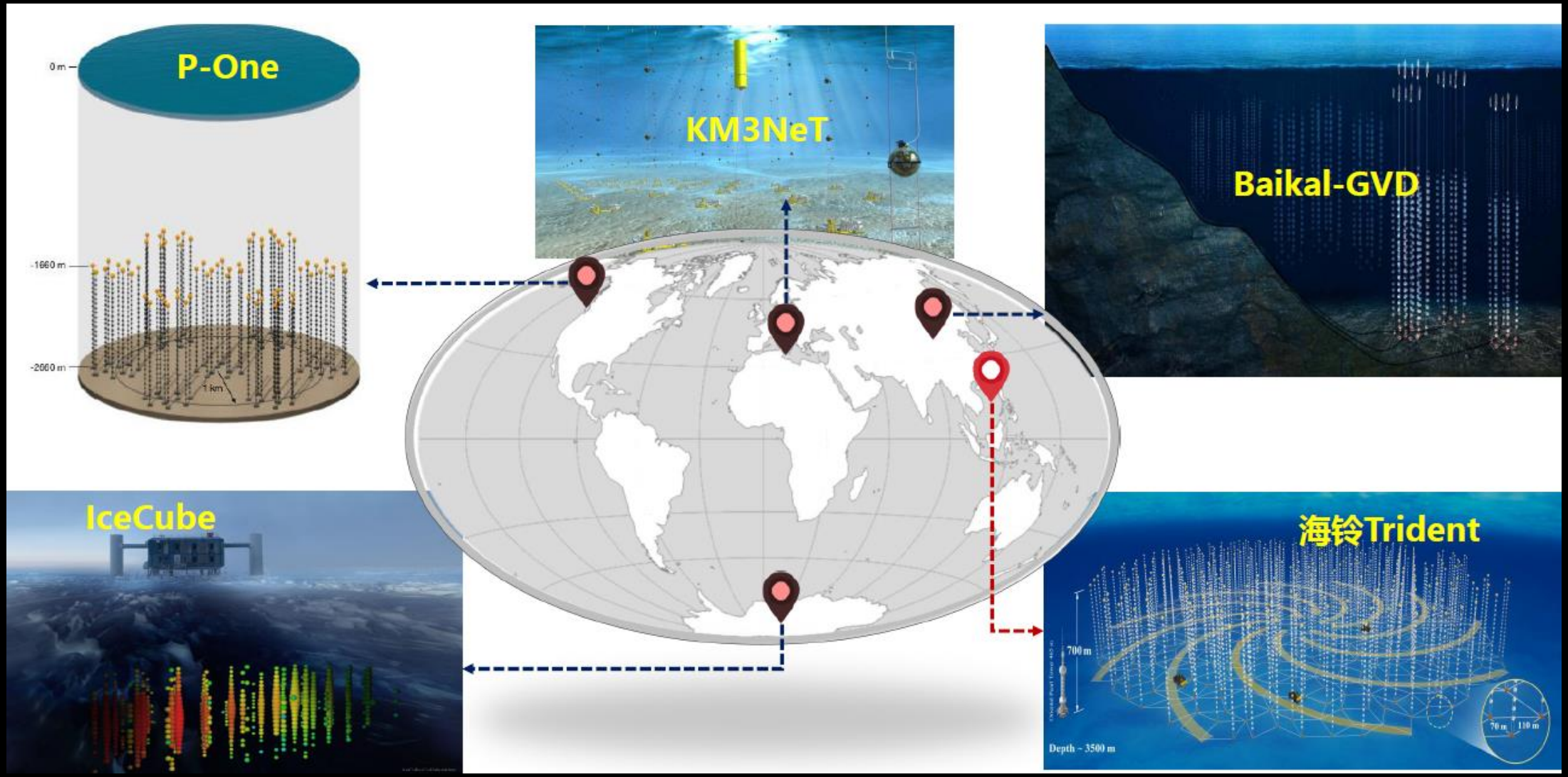
SWGO: 100 GeV - PeV, large field of view (45 degrees), R&D

# Closing the WIMP window: neutrinos!



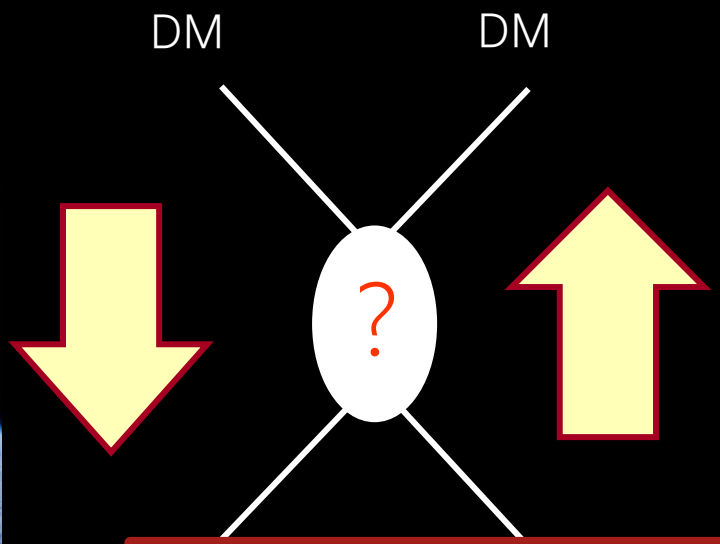

Rev. Mod. Phys. 93, 35007 (2021)

# Closing the WIMP window: neutrinos!

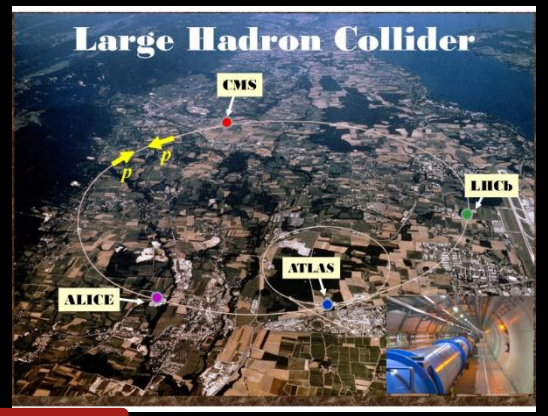


# A fully testable idea

Indirect Detection

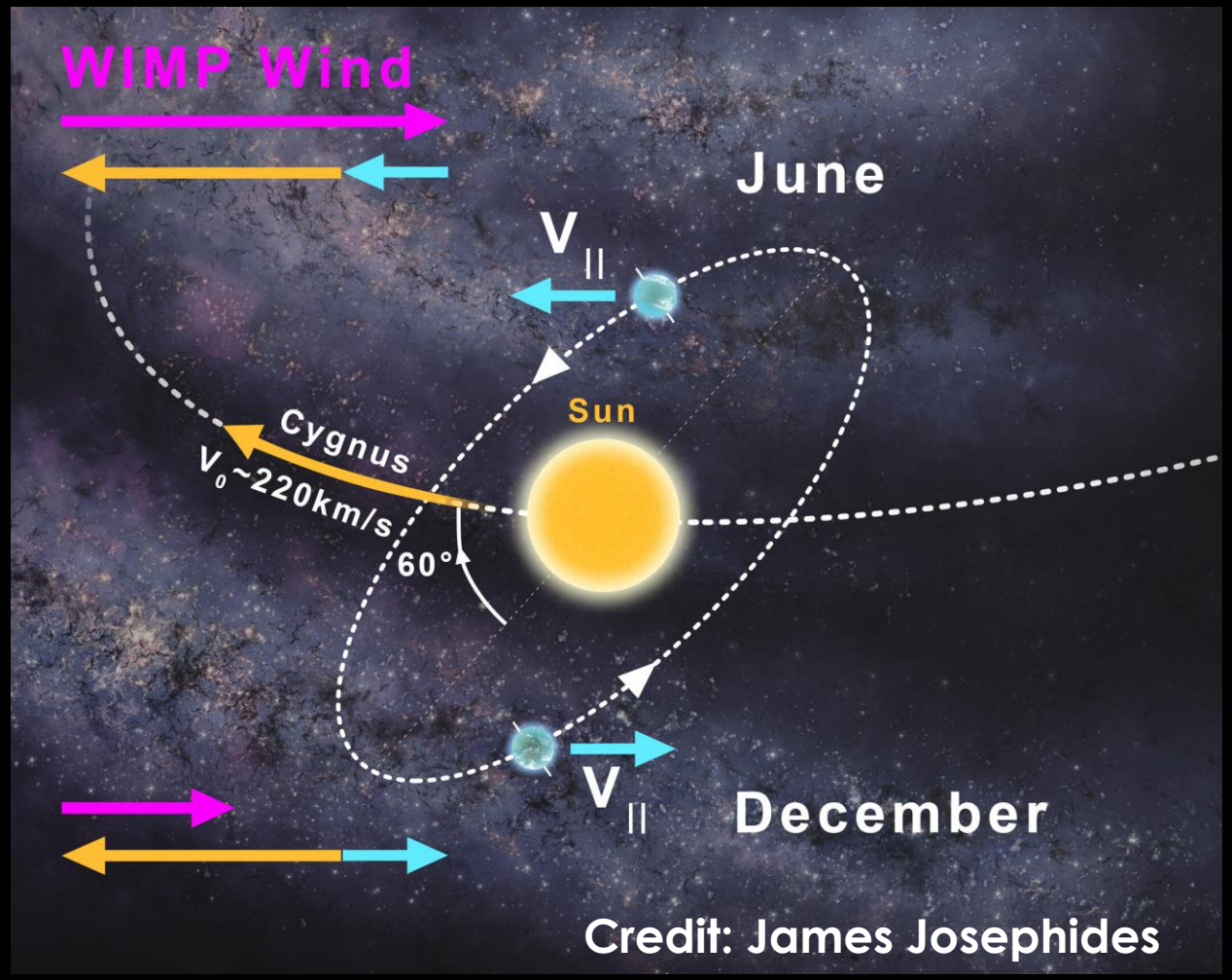


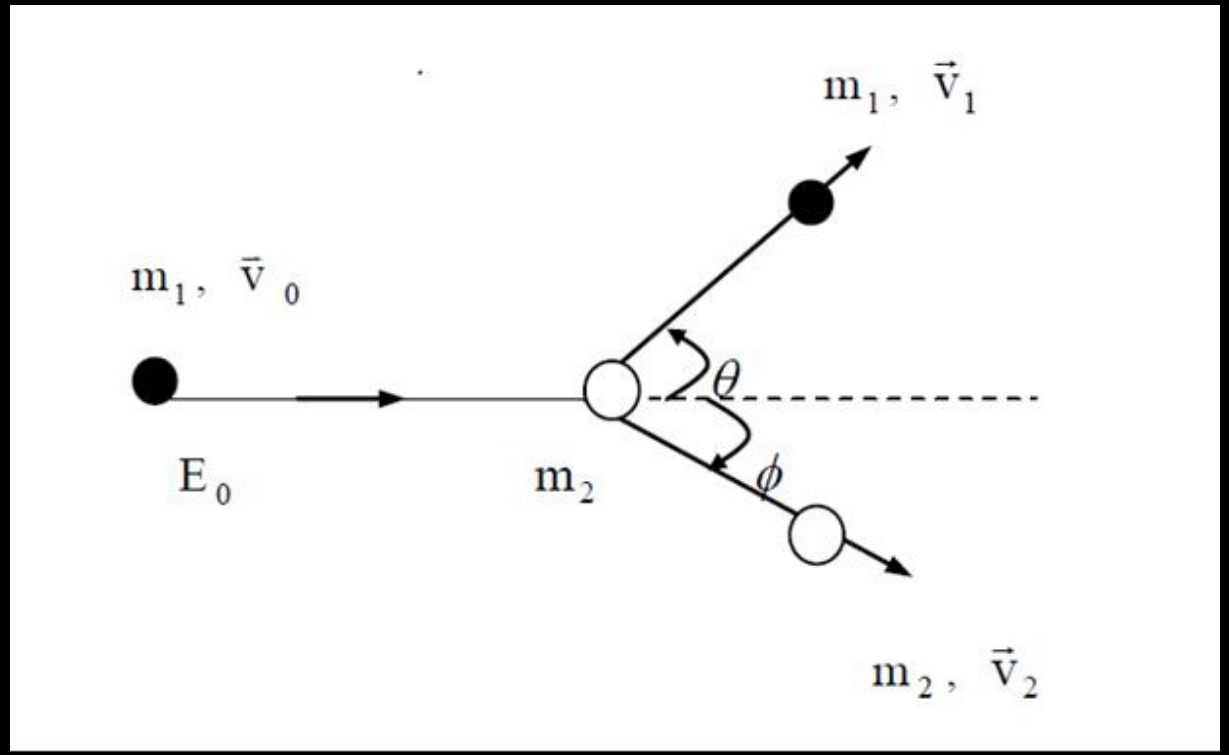

Collider Search




Direct Detection

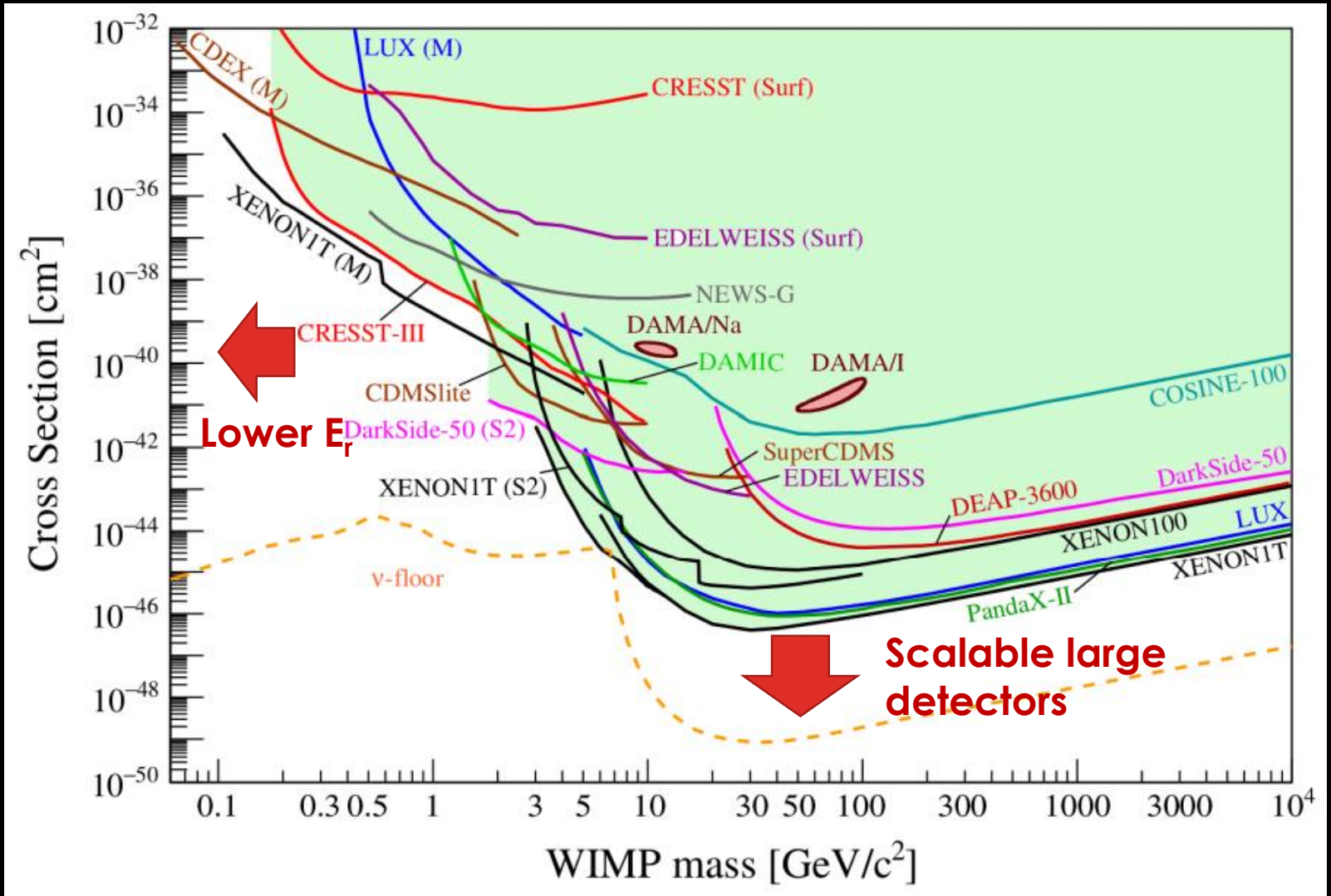
# DM direct detection: classical beam experiment



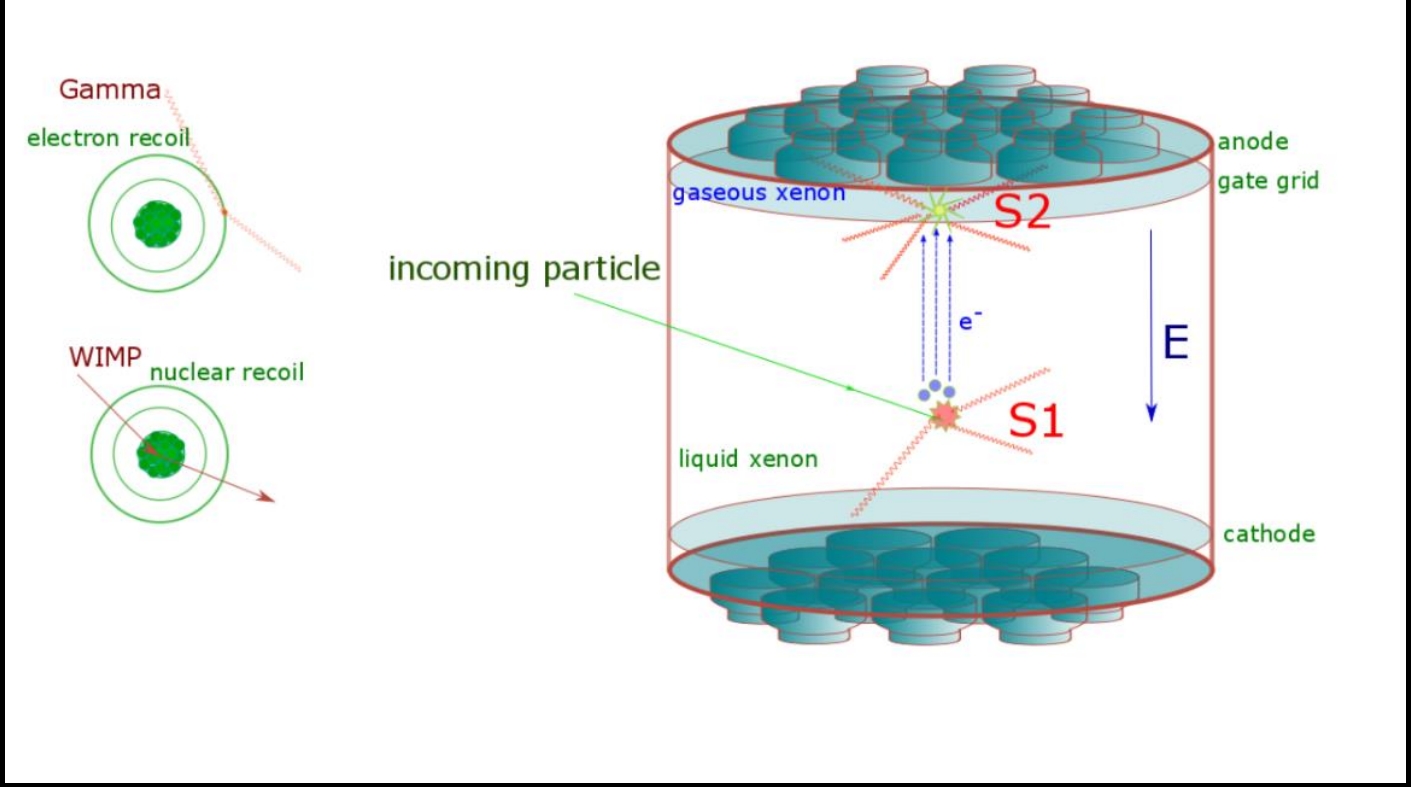

$$\frac{dR}{dE_R} = \frac{\rho_{\rm loc}}{m_A m_{\rm DM}} \int_{v \geq v_{\rm min}(E_R)} {\rm d}^3 v \, v f(\vec{v} + \vec{v}_{\rm obs}(t)) \frac{{\rm d}\sigma}{{\rm d}E_R}$$

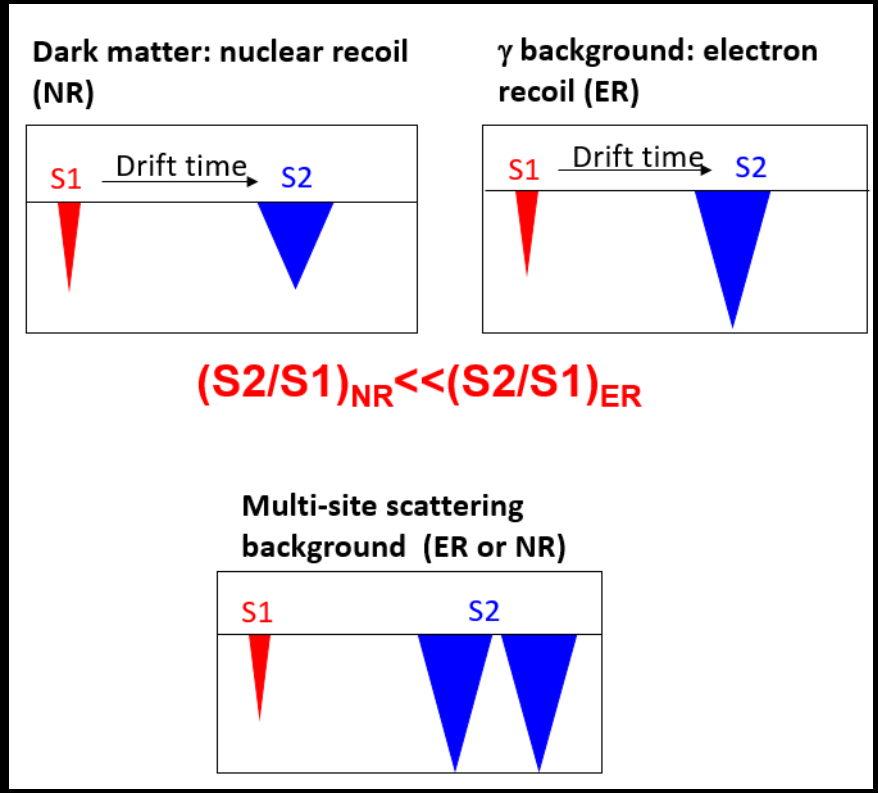
# Global status: hide & seek




2104.07634, APPEC report on dark matter direct detection

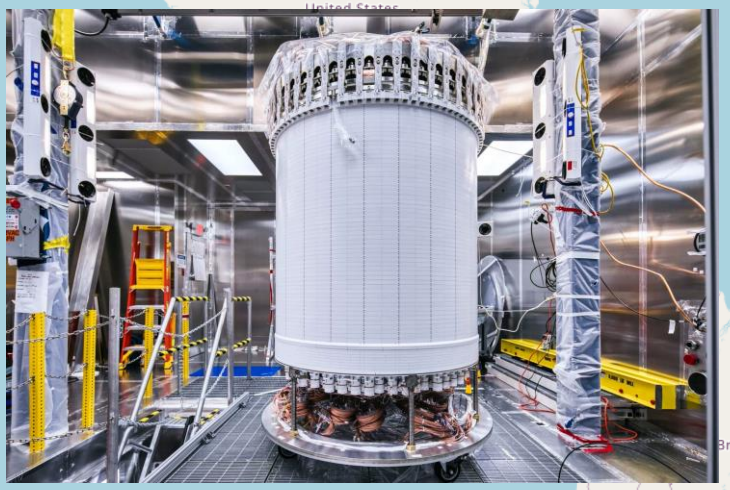
# Nobel-liquid dual-phase time projection chamber



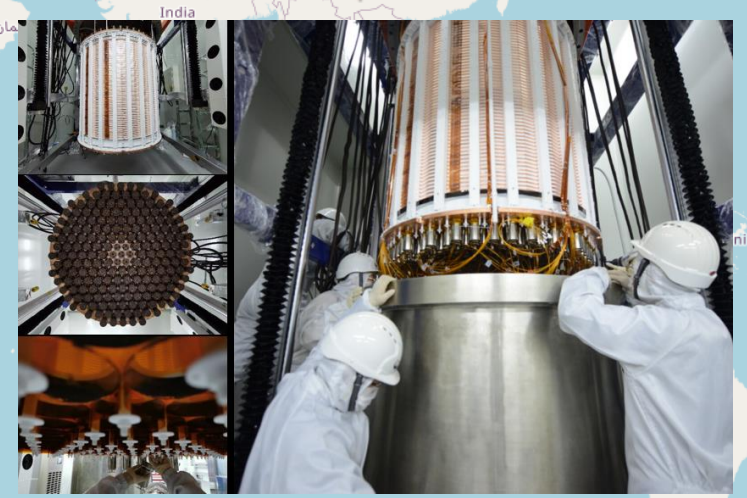
# Liquid xenon experiments

**Sanford Lab, LZ, 7 ton**

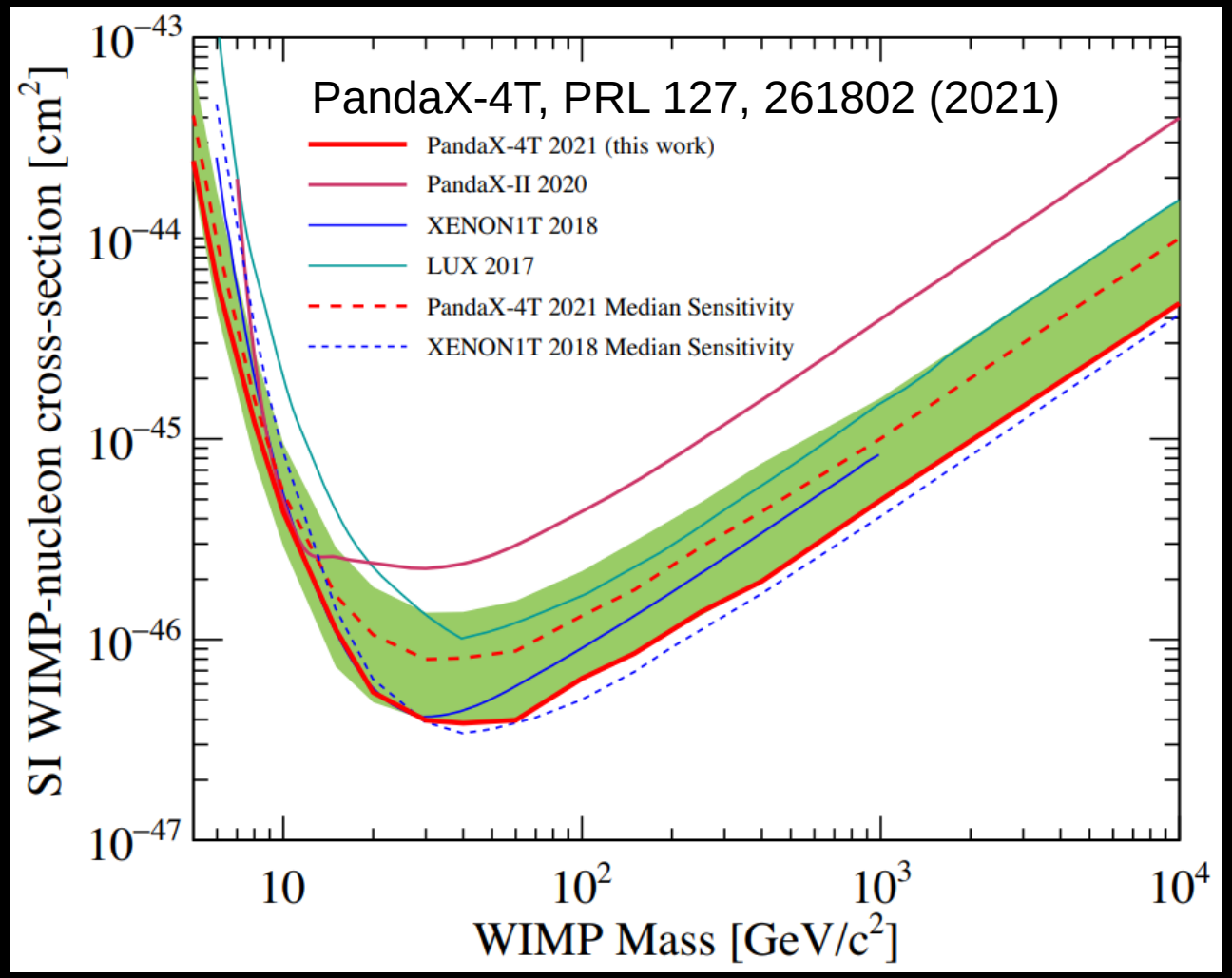


**LNGS, XENONnT, 6.5 ton**

**CJPL, PandaX-4T, 3.7 ton**

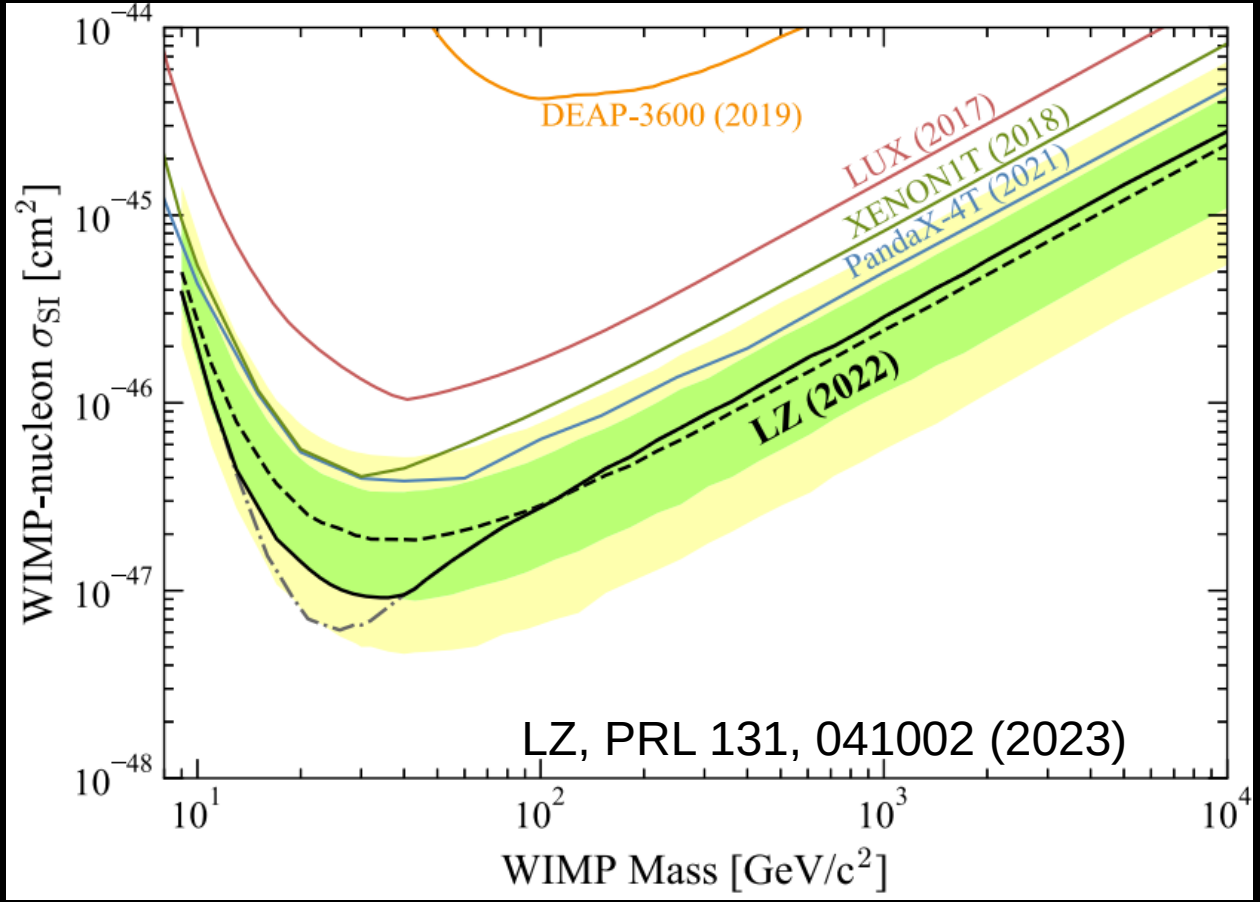


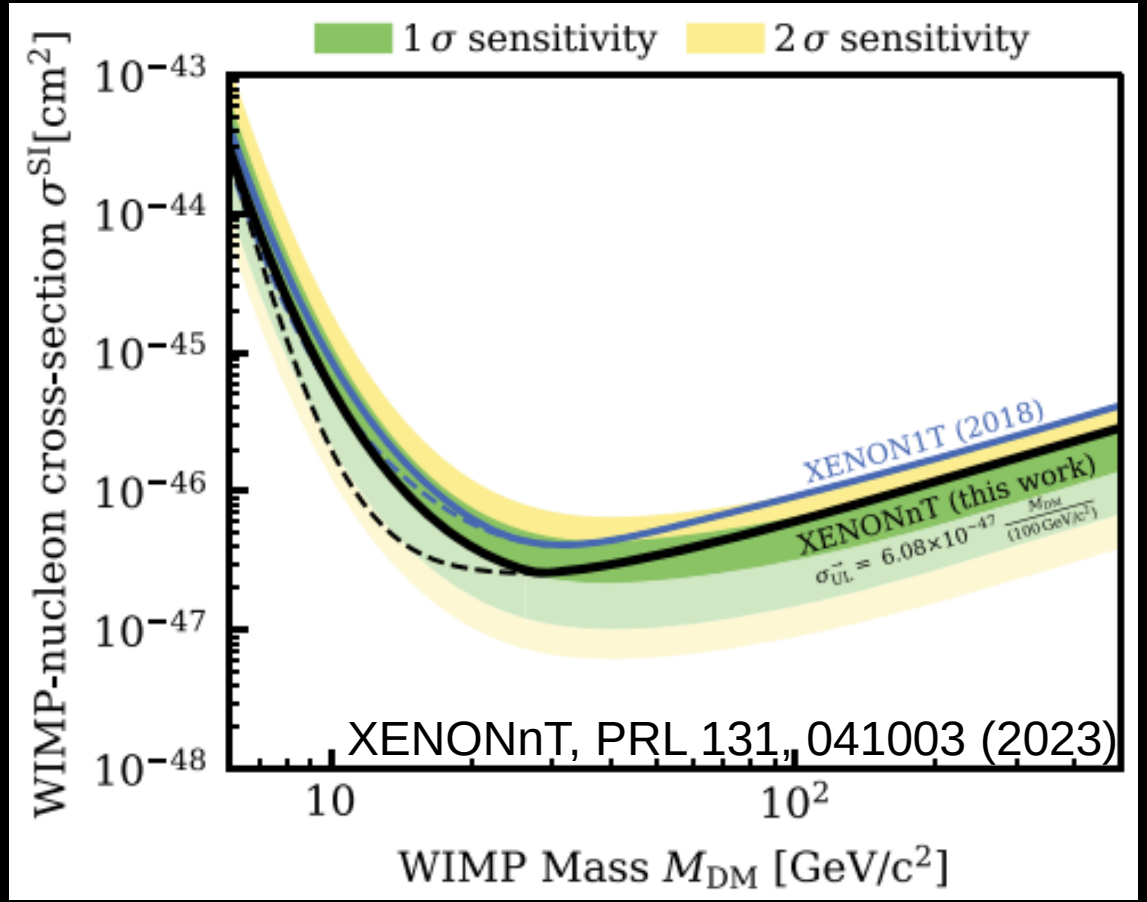
# First results from multi-ton xenon experiments




- 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



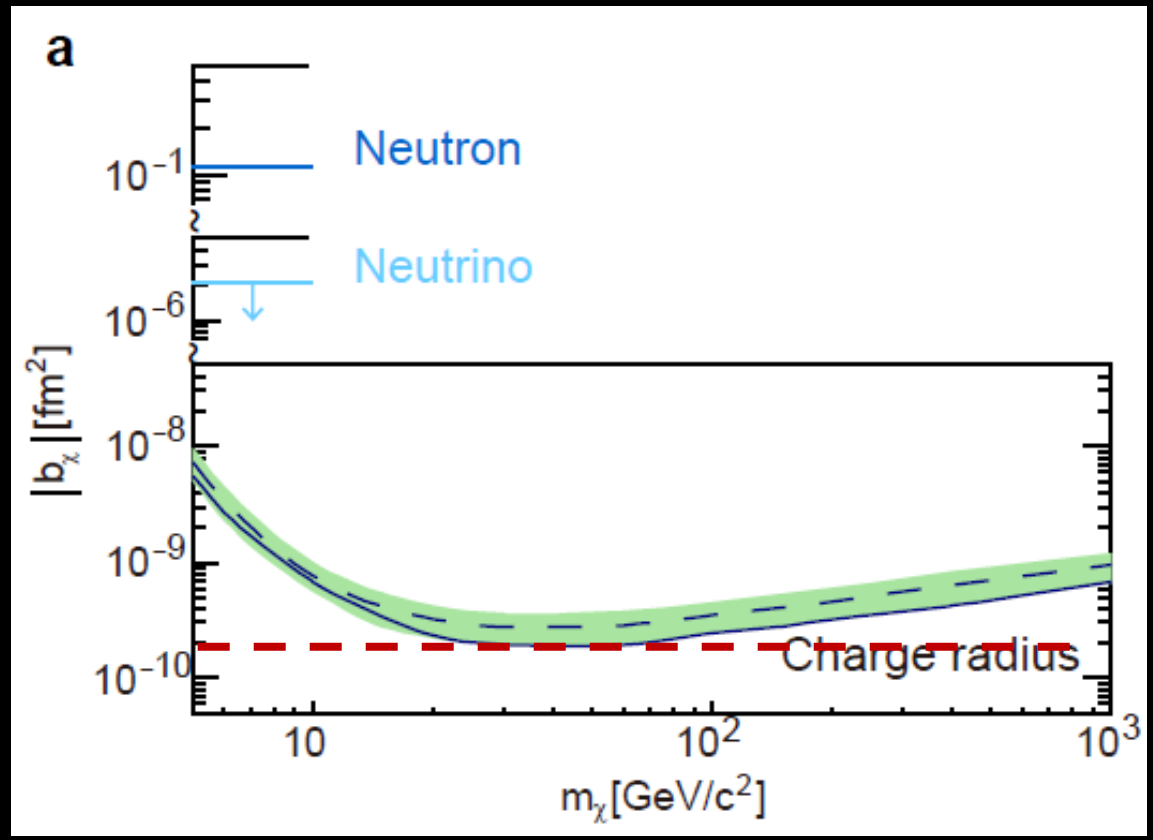



# How dark is dark matter?

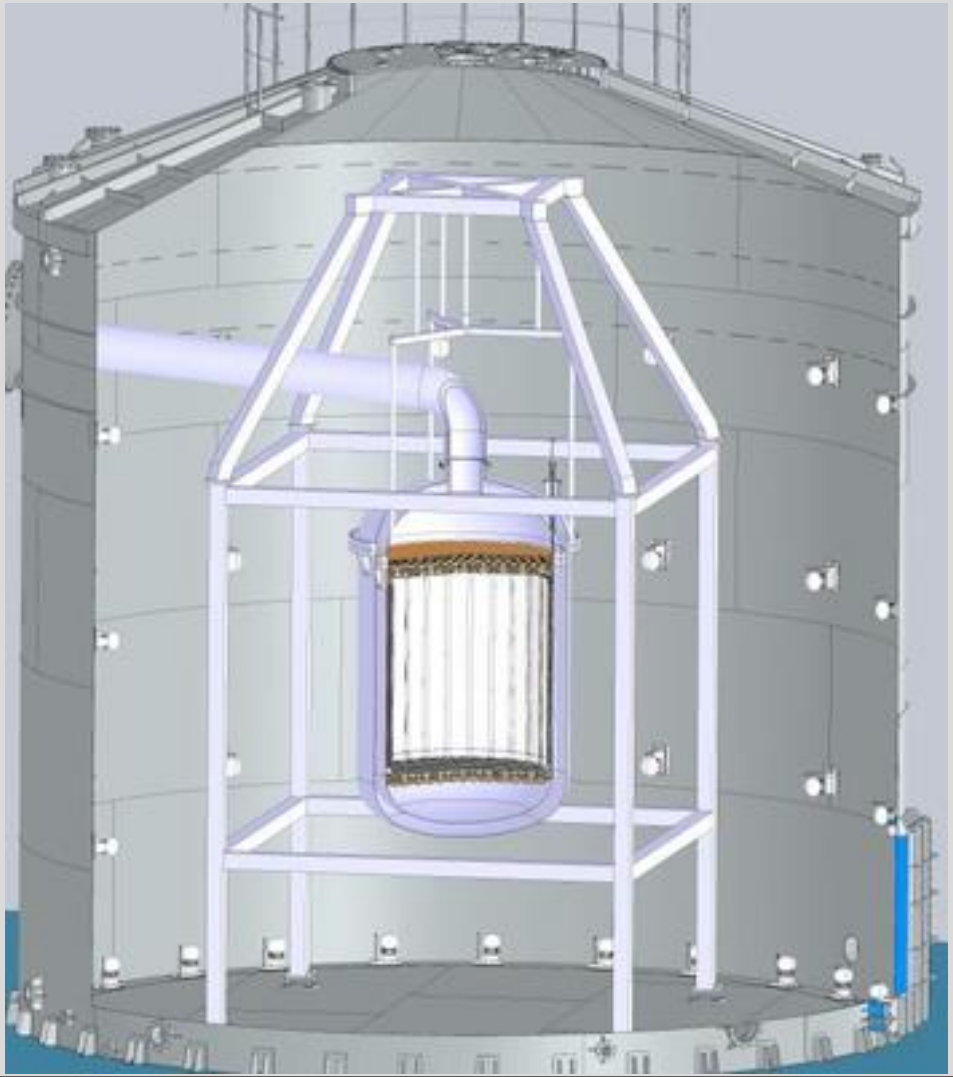
Nature 618, p47–50 (2023)

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

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

# DARWIN/XLZD

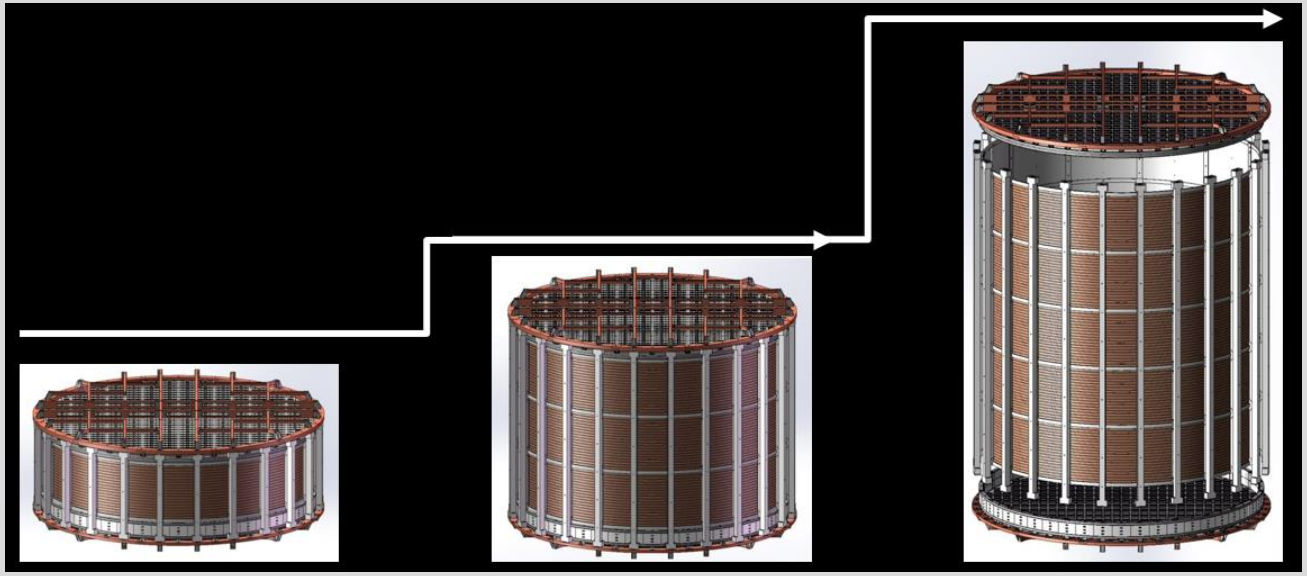


40/60-ton LXe TPC

General-purpose observatories on

- Dark matter
- Neutrinos
- Neutrinoless double beta decay ($^{136}$Xe)
- Other ultra-rare phenomena

# PandaX-xT



- Step-wise upgrade towards 43-ton (active), 47-ton (total) natural xenon: hinges on the advantage of CJPL, leverages technological challenges, and maintains continuous scientific output
- Technological readiness for a competitive 0vDBD program will mature along the way
- Versatile configuration with isotopic-separated 136Xe in the next future

# Global Ar Collaboration

C. Galbiati, UCLA-DM 2023

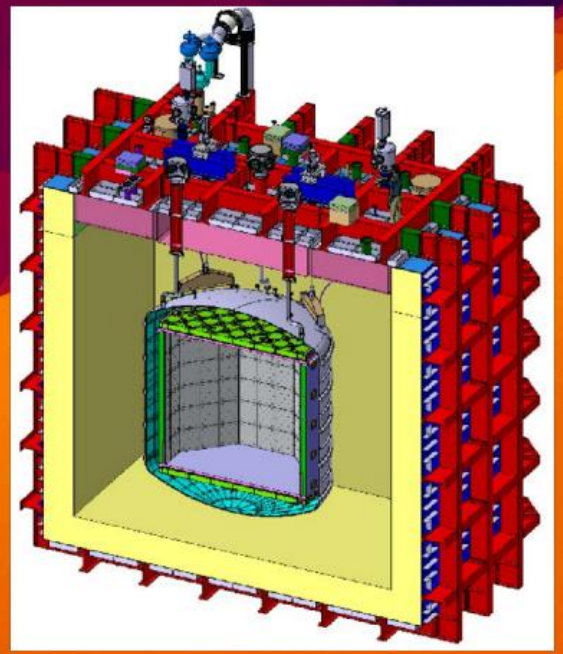
## Since 2017

### The Global Argon Dark Matter Collaboration (GADMC)

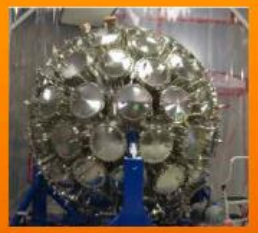
GADMC unified in a single Collaboration more than 400 scientists interested in DM searches with argon to explore heavy (and light) dark matter to the neutrino floor and beyond

DEAP-3600

DarkSide-50



MiniCLEAN



ARDM

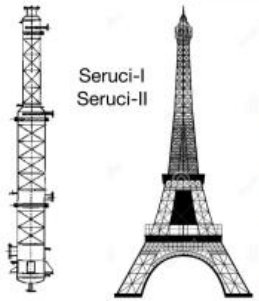
DarkSide-20k => ARGO

# Industrial-scale underground Ar mass production

C. Galbiati, UCLA-DM 2023

## Production – URANIA – Cortez, CO, US

- Industrial scale extraction plant
- Extraction rate: 250-330 kg/day
- Production capability ≈ 120 t over two years for DS-20k
- UAr purity: 99.99%

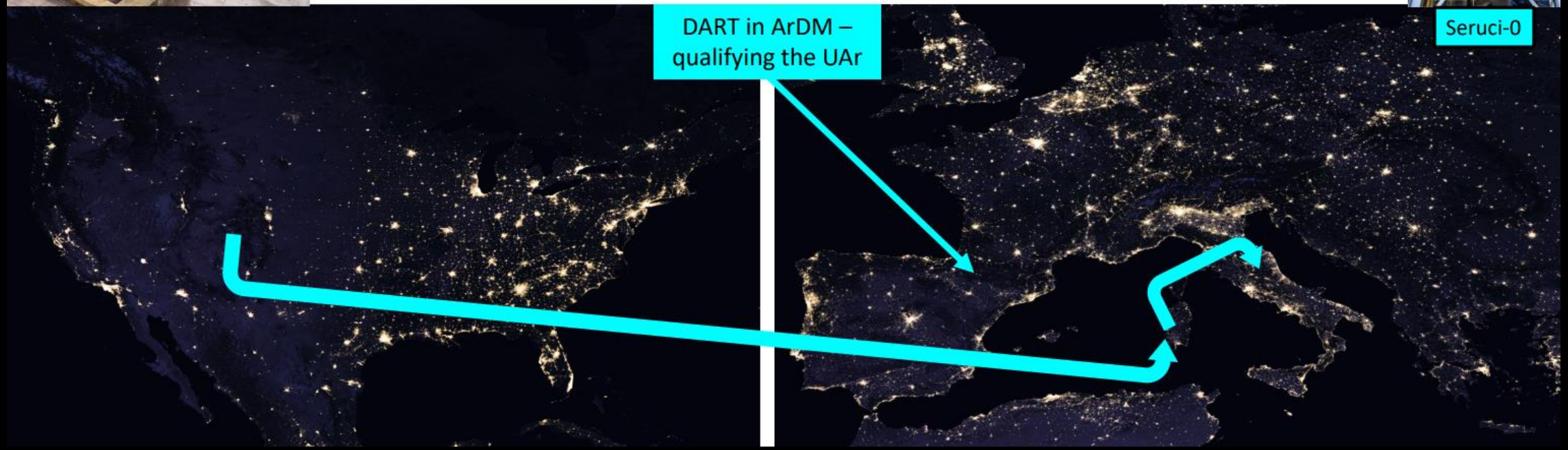



## Purification – Aria – Sardinia, IT

Eur. Phys. J. C (2021) 81:359

- Seruci-0 (demonstrator) tested
- 350 m cryogenic distillation column
- O(1 tonne)/day capability
- Resulting UAr purity: 99.999%

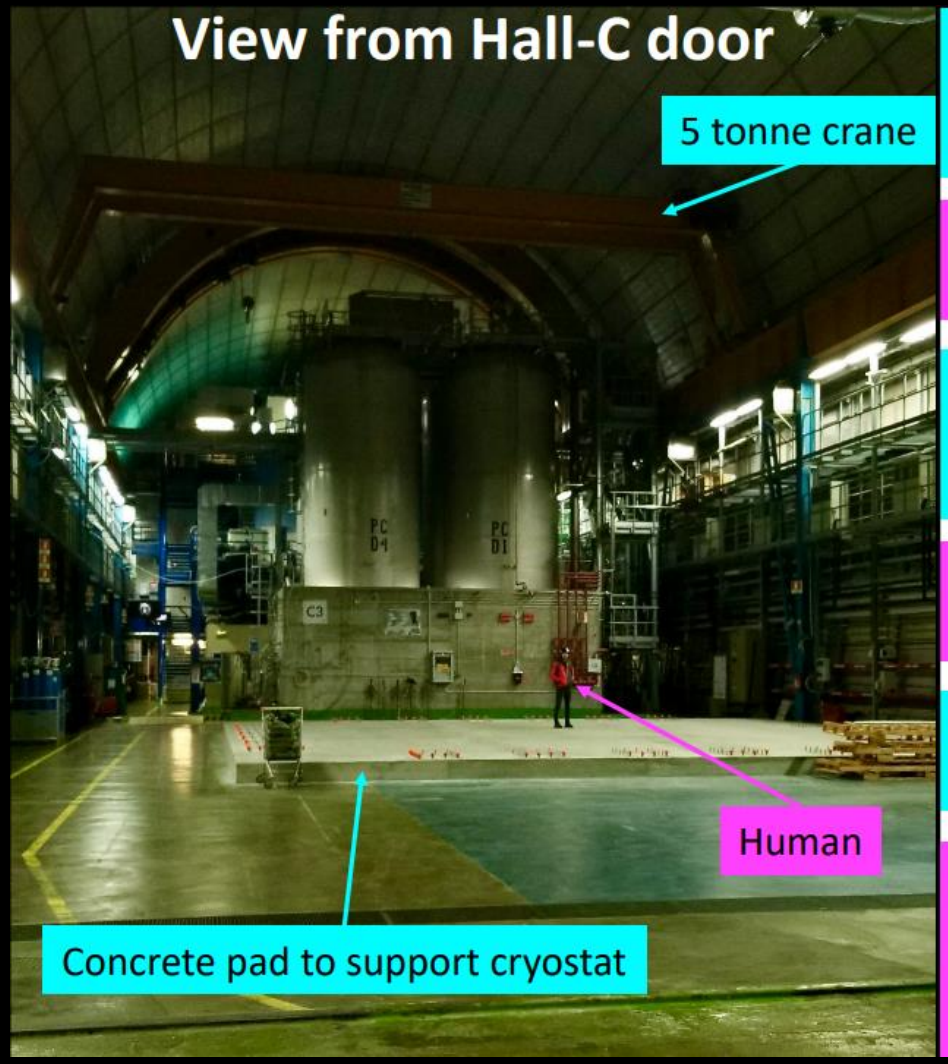

Seruci-0



# Status of DS-20K

C. Galbiati, UCLA-DM 2023

Expect to operate by 2026




Membrane "ProtoDUNE-like" cryostat

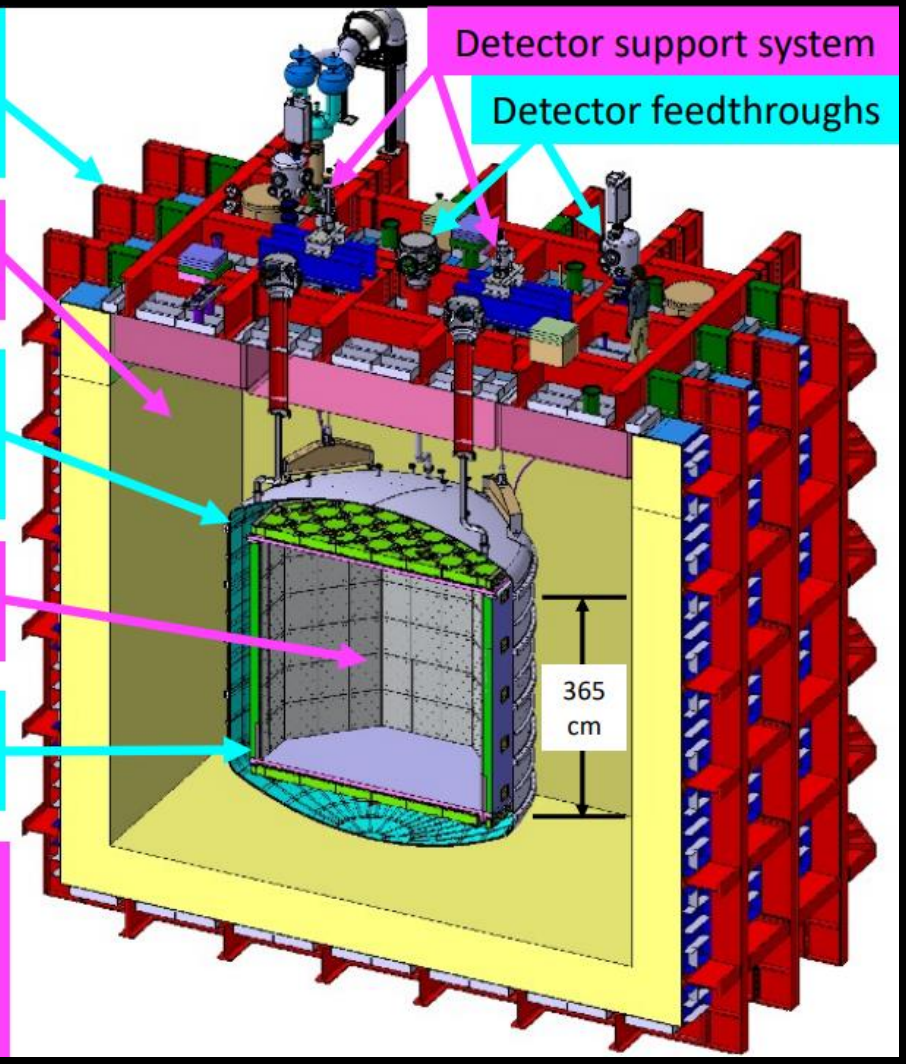
Atmospheric argon (AAr) volume (≈700 t)

Vacuum vessel containing UAr and TPC/veto

Underground argon (UAr) volume (≈100 t)

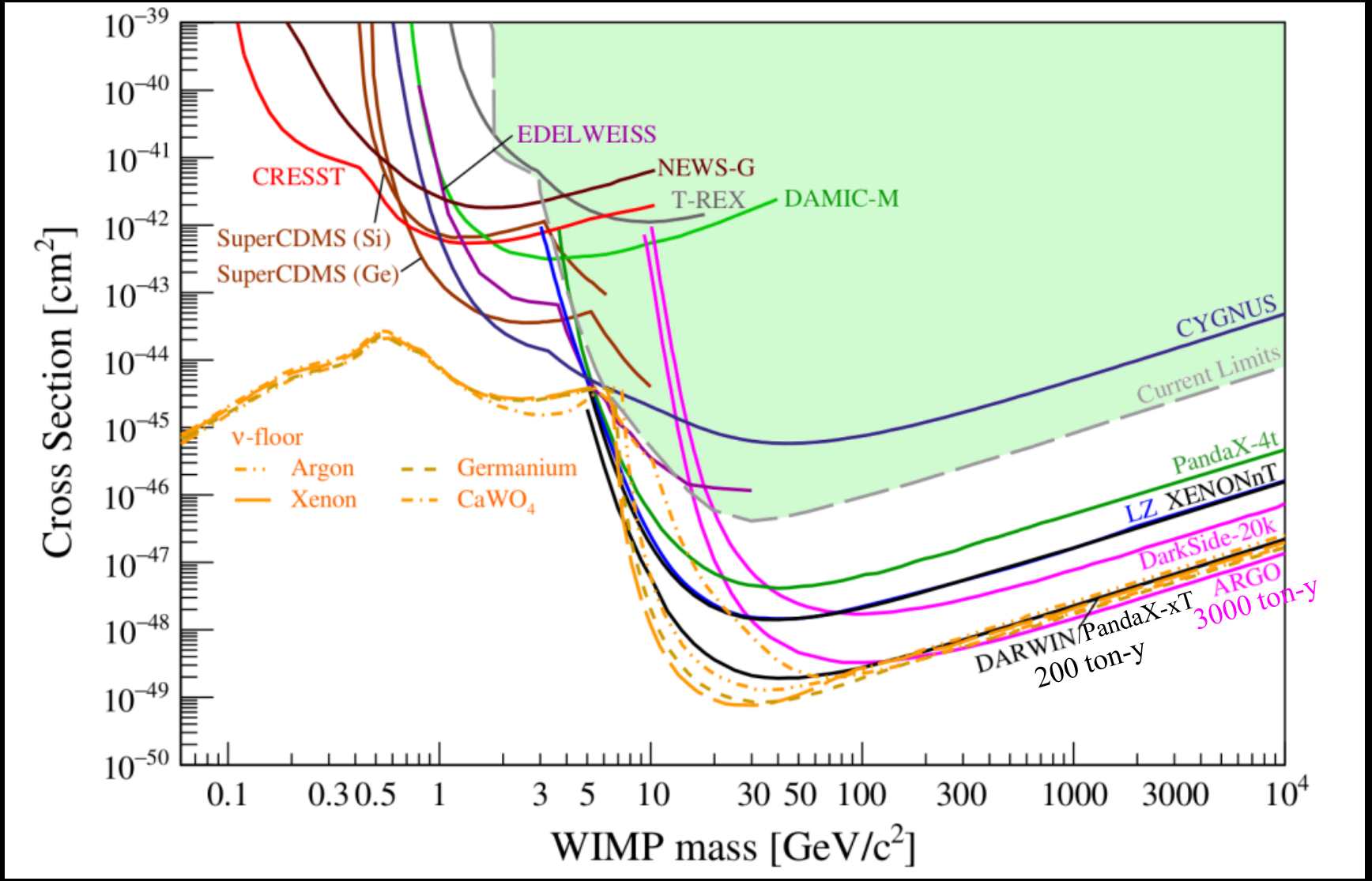
"Inner detectors", TPC and neutron veto

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

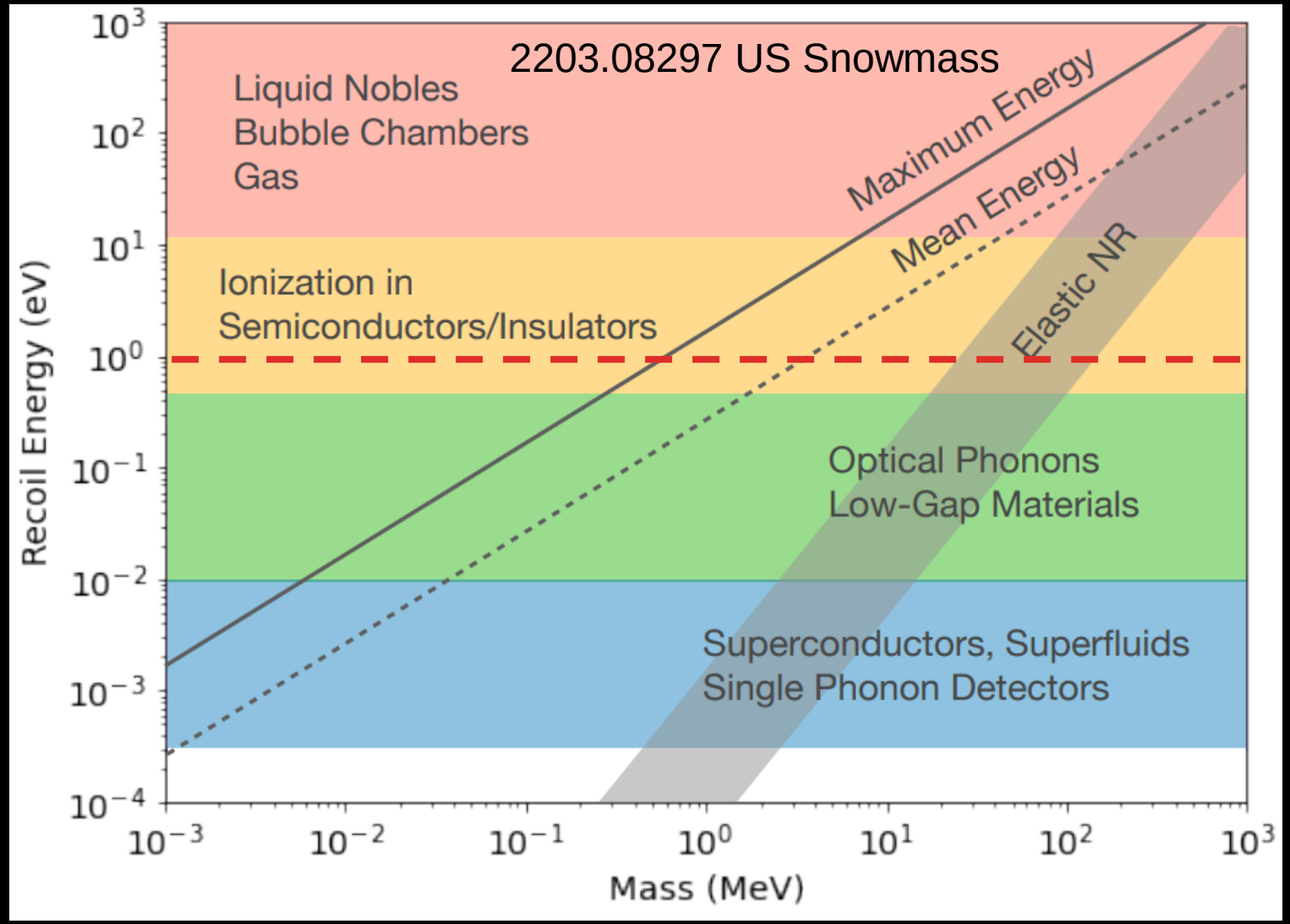


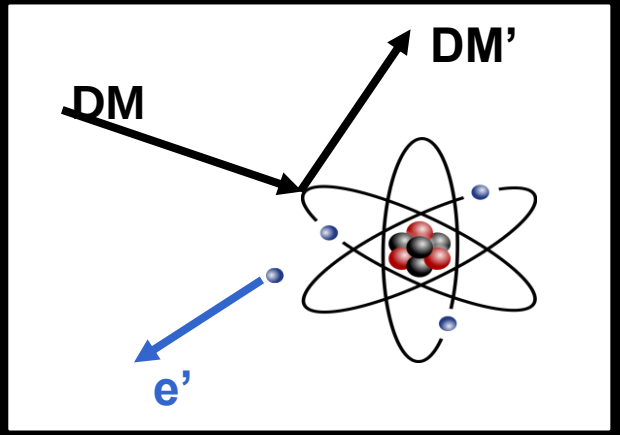
# SI sensitivity: future projection

APPEC DM report: 2104.07634



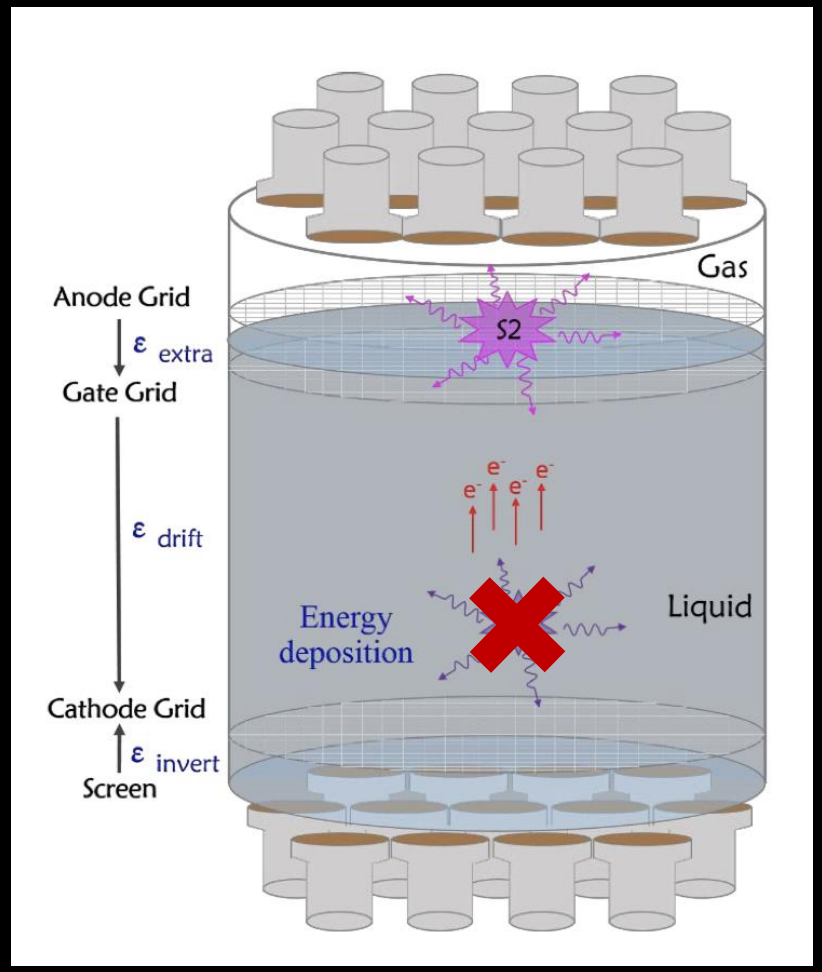
# Low mass DM detection techniques

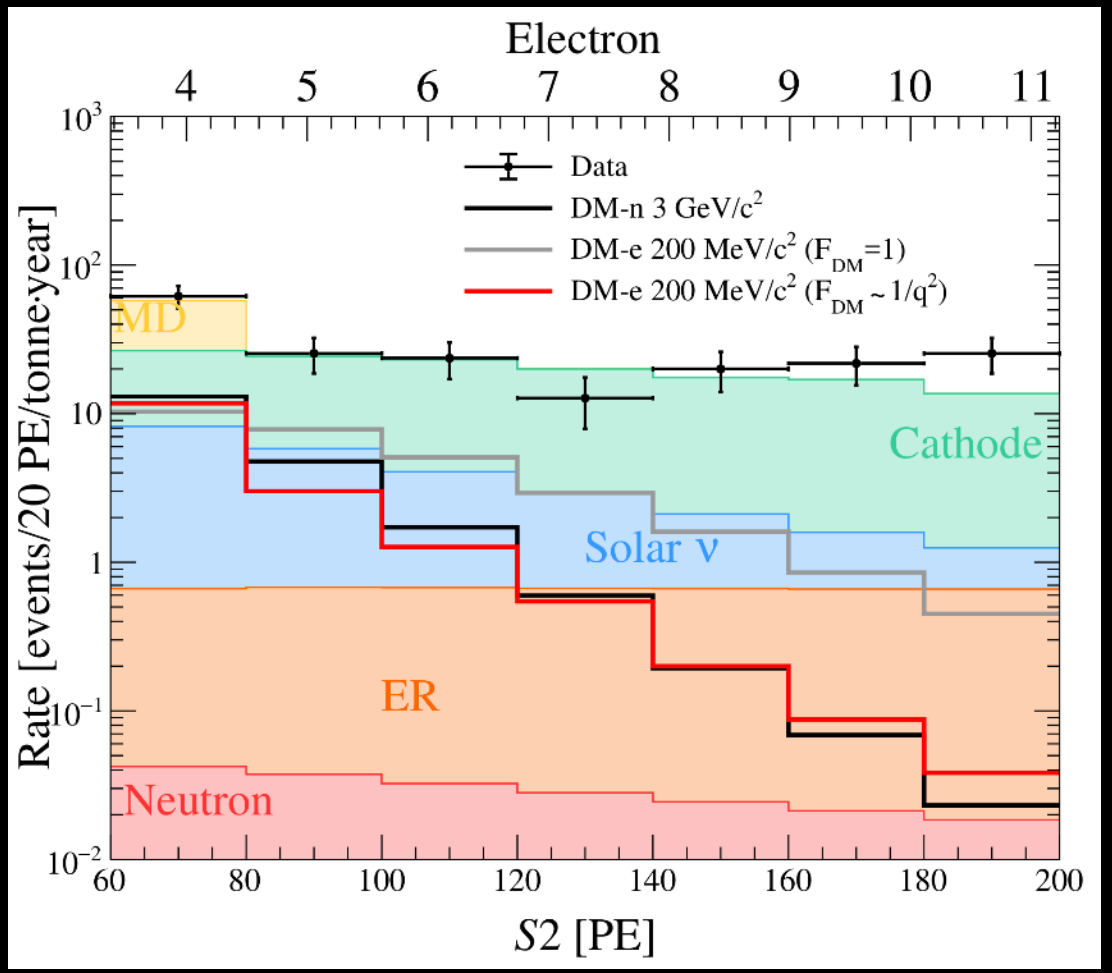


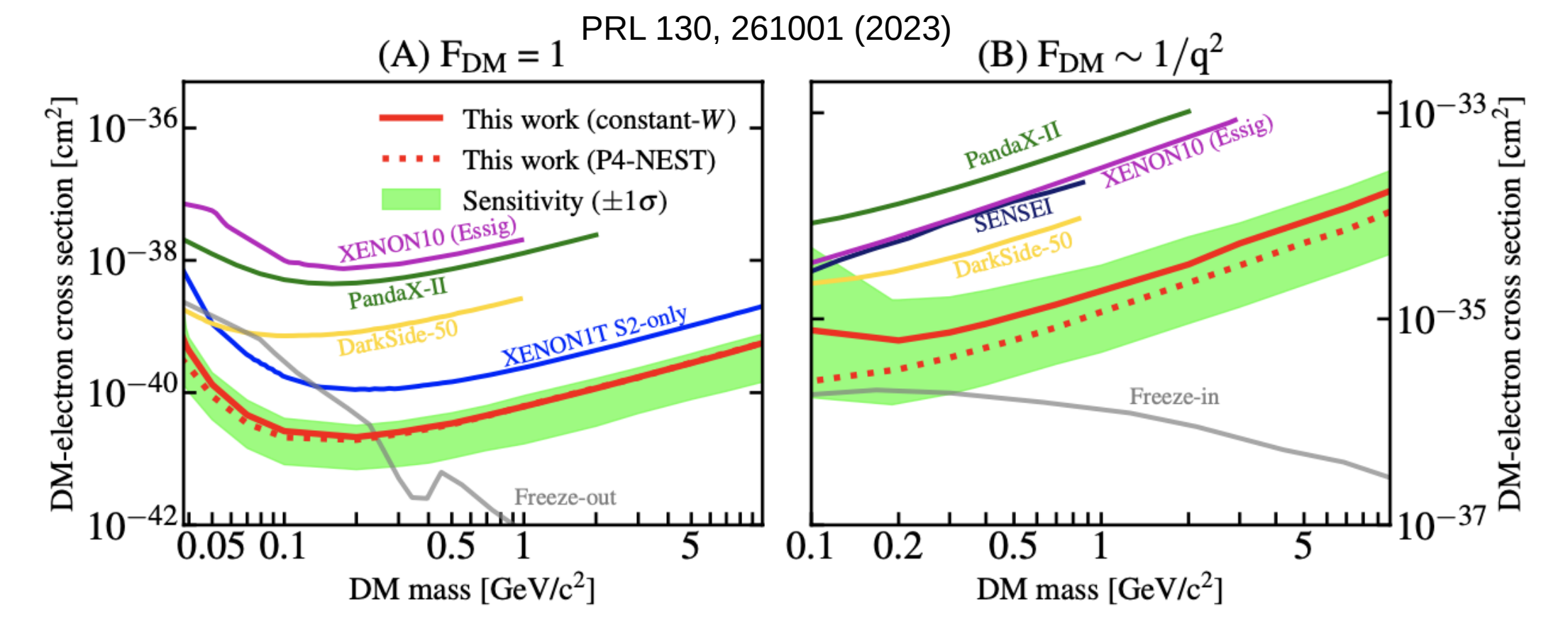

Atomic inelastic scattering: accessing full DM KE-binding. Essig, Mardon, Volansky, PRD 85, 076007 (2012)

# S2-only approach

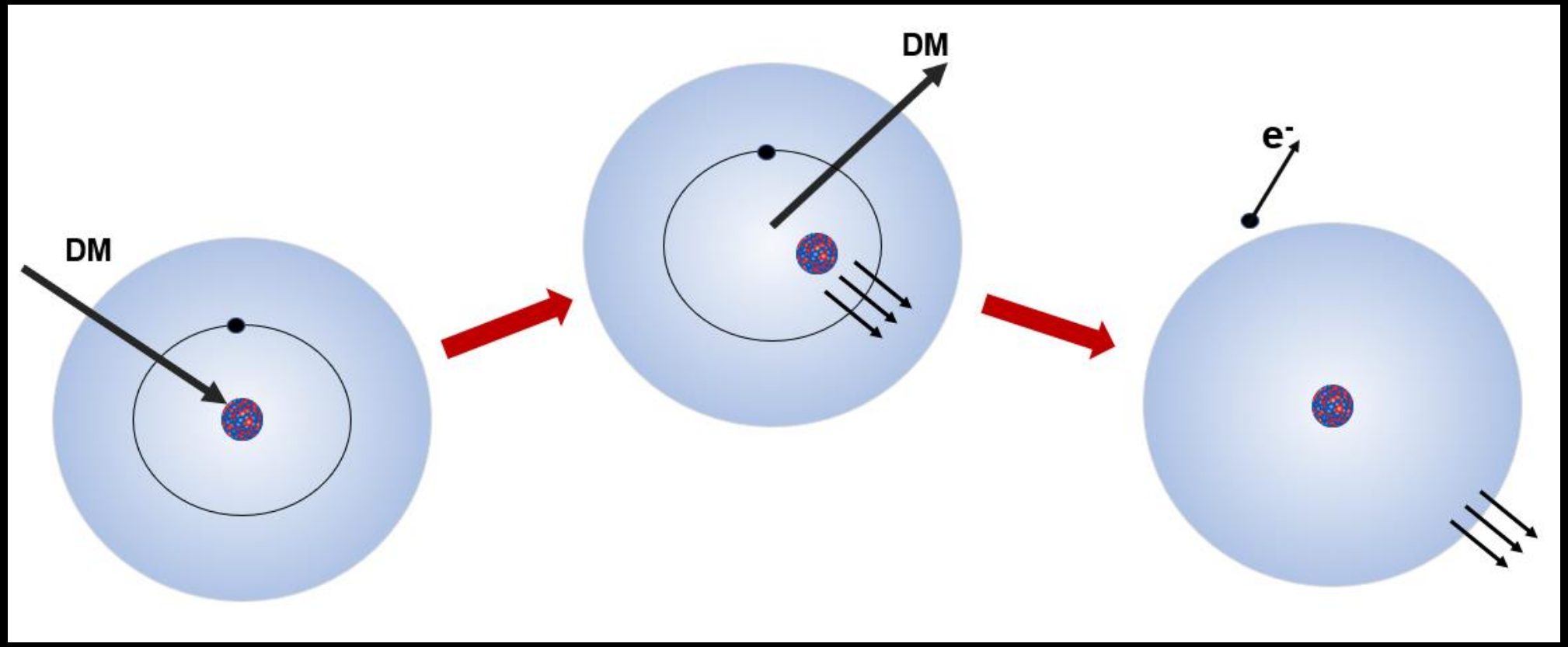


# Tight limits on DM-e scattering

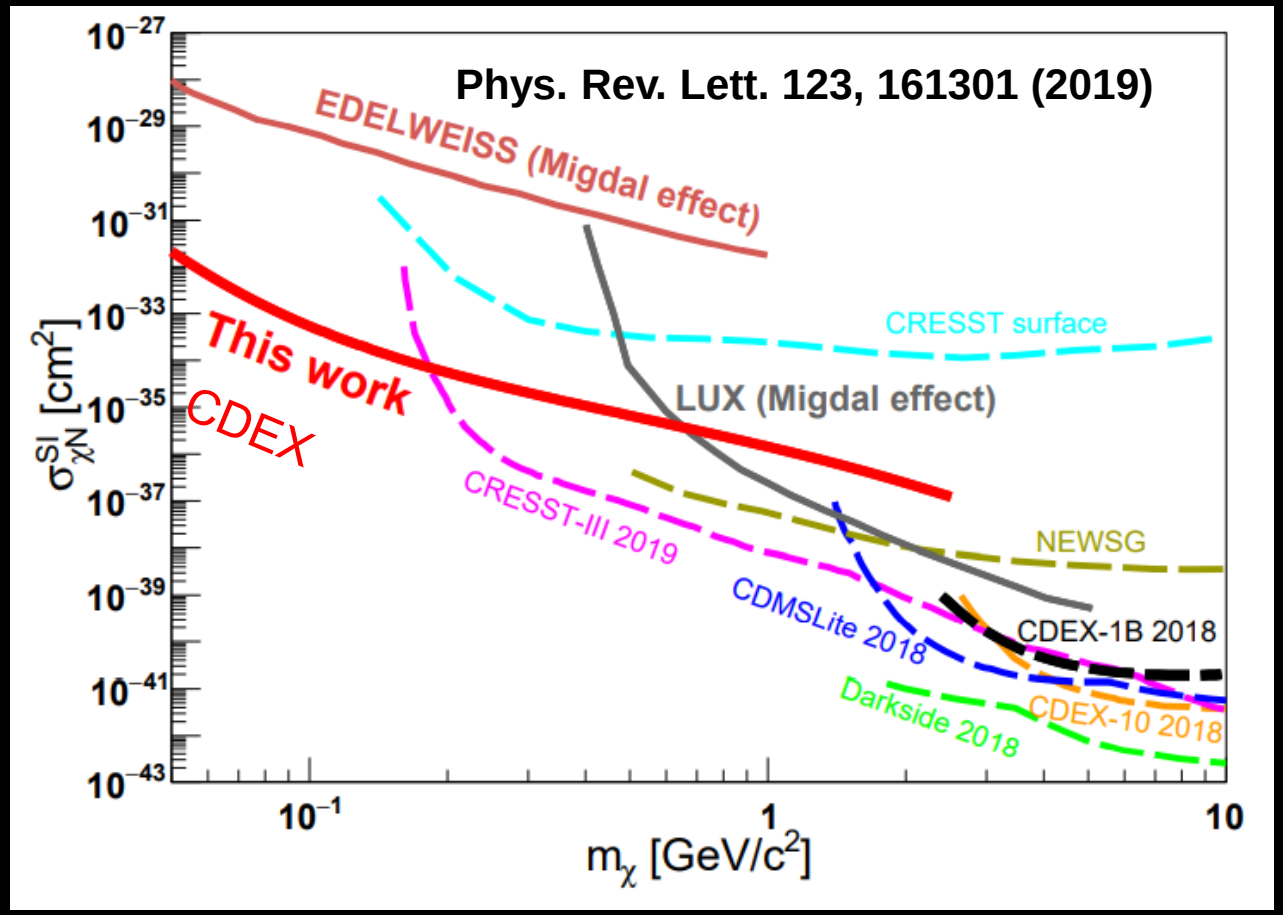


# Migdal effects in DM-N scattering

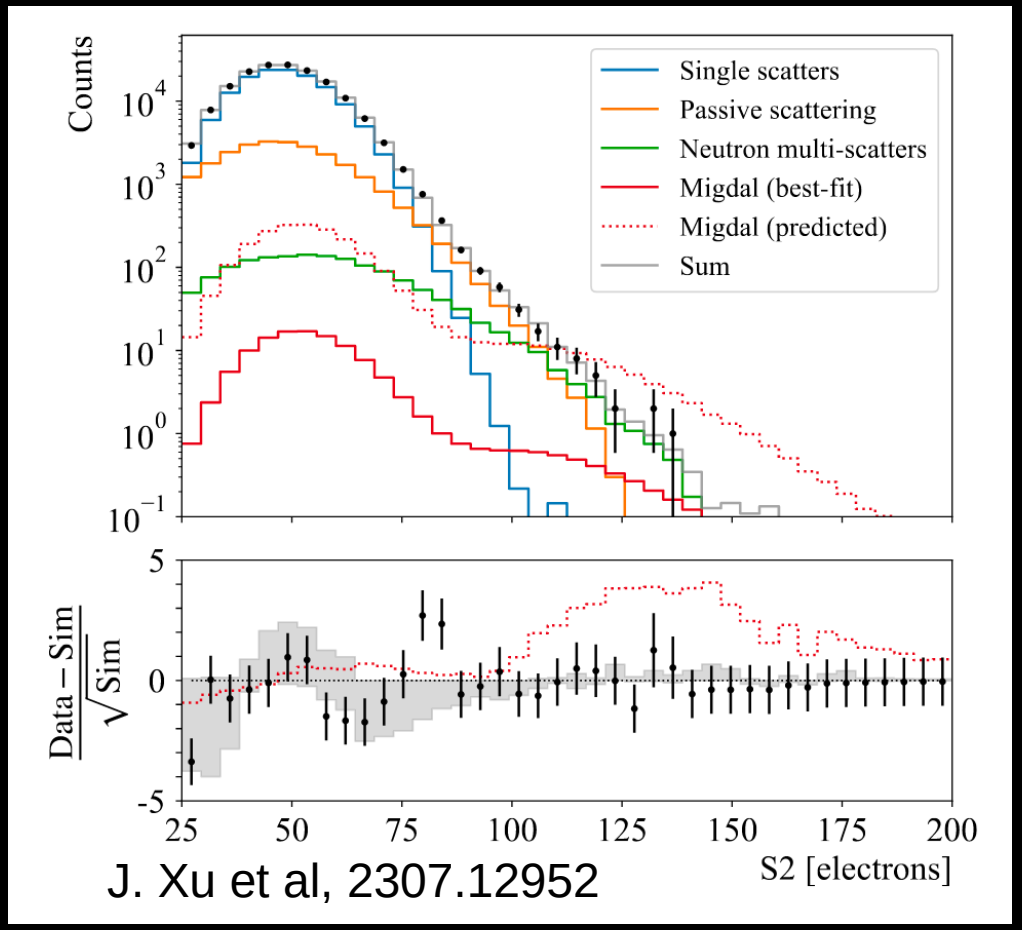



- Reformulated: Ibe et al., JHEP 2018, 194 (2018); Dolan et al., PRL 121, 101801 (2018)
- Direct DM-e ionization and Midgal-induced ionization probability are closely related, Essig, Pradler, Sholapurkar, and Yu, PRL 124, 021801 (2020)

# Low mass DM with Migdal



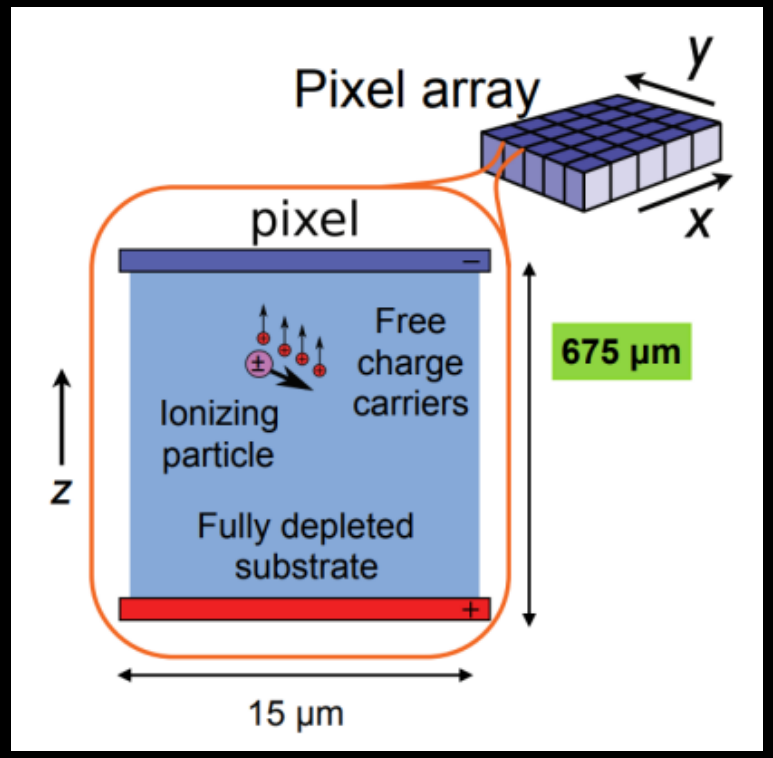

Widely used to extend to search to lower mass

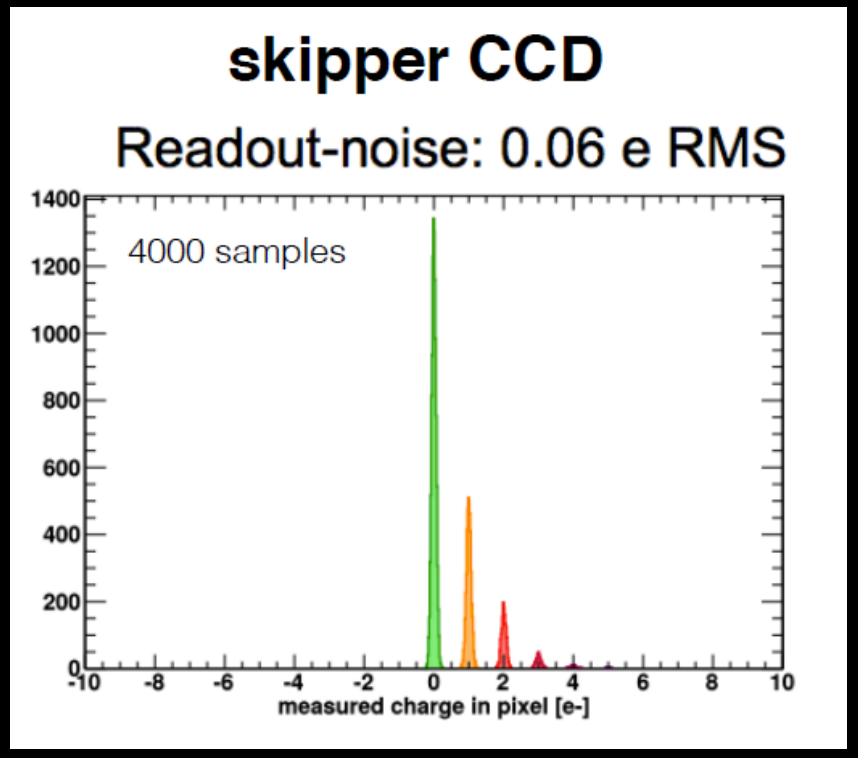



However, not yet seeing it yet in neutron calibration!

# 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



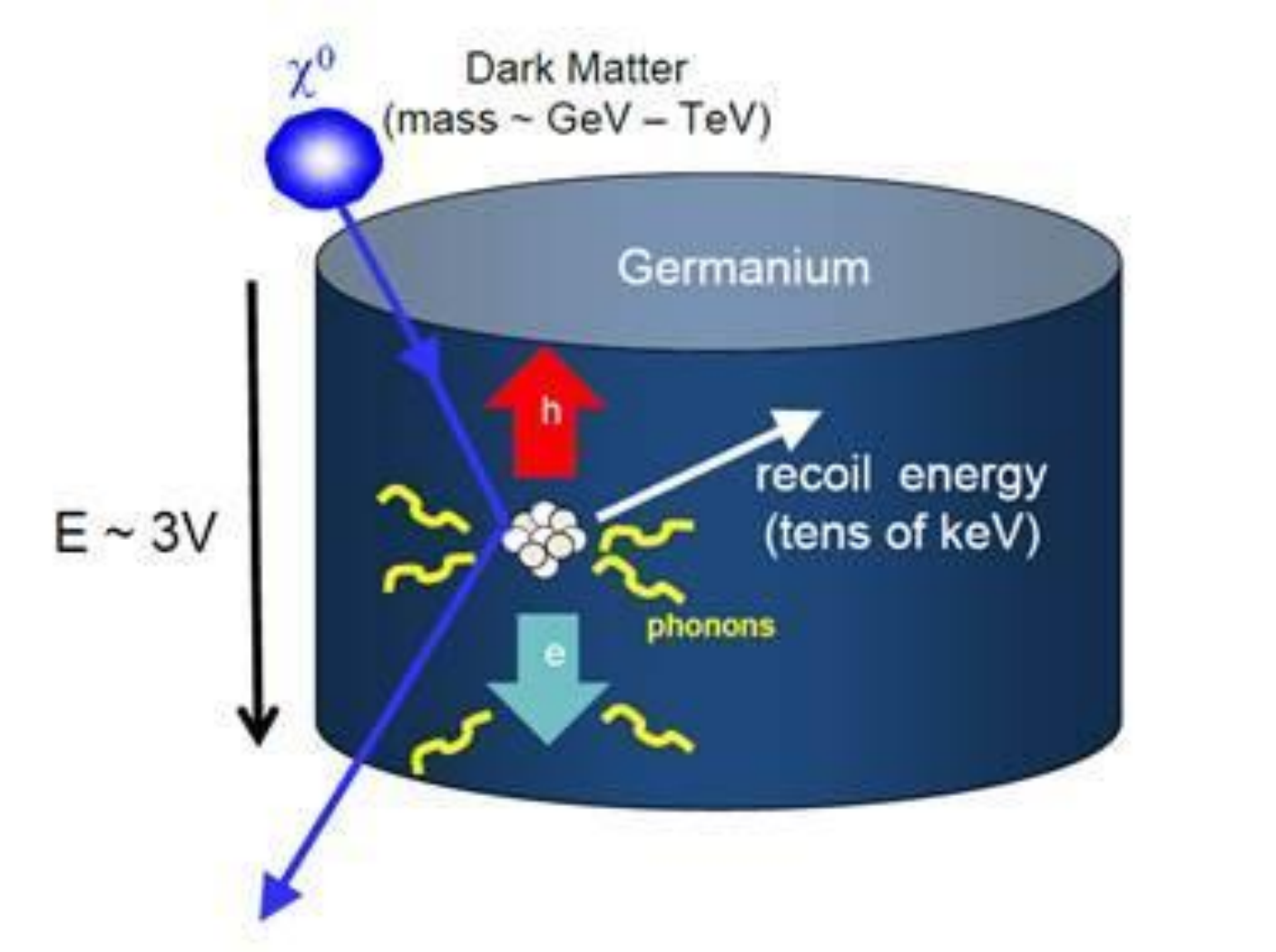




PRL 119 (2017) 13, 131802

Ongoing effort:

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

# Cryogenic bolometer



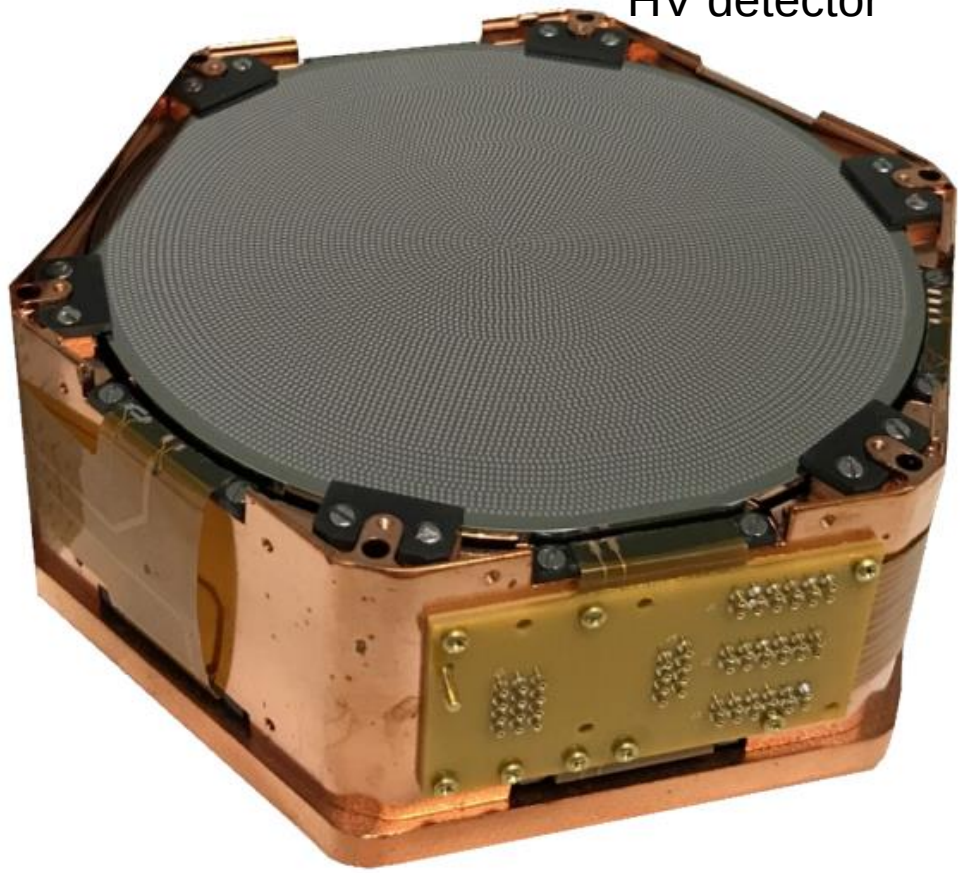

- Energy deposition converted to lattice vibration
- $\delta T = \delta E / C$, where $C \propto T^3$, so low temp is the key (5 mK)
- Temperature change is “traditionally” measured by transitional edge sensor (TES)
- Some accompanying energy in ionization or photons

# Cryogenic bolometers

SuperCDMS (Ge/Si)

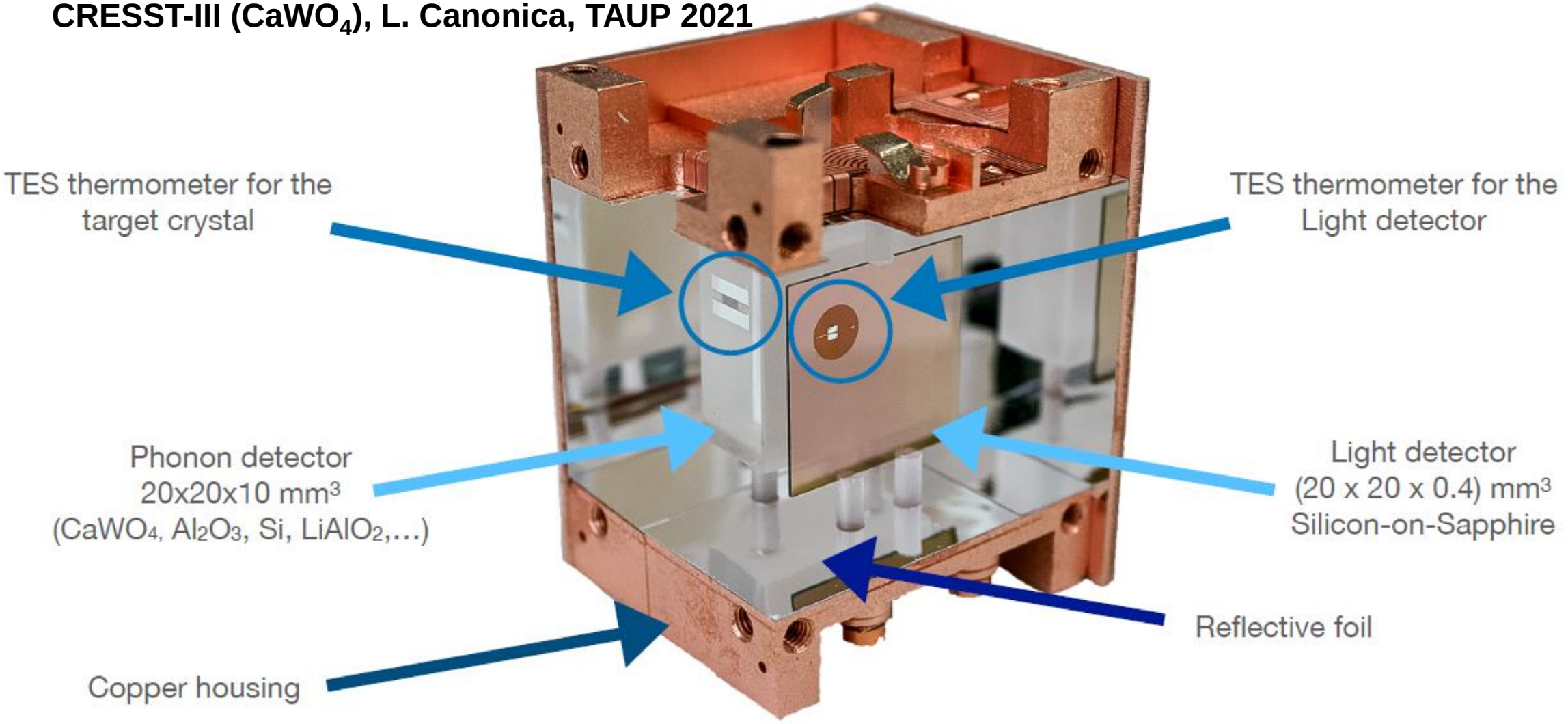
iZIP detector

HV detector

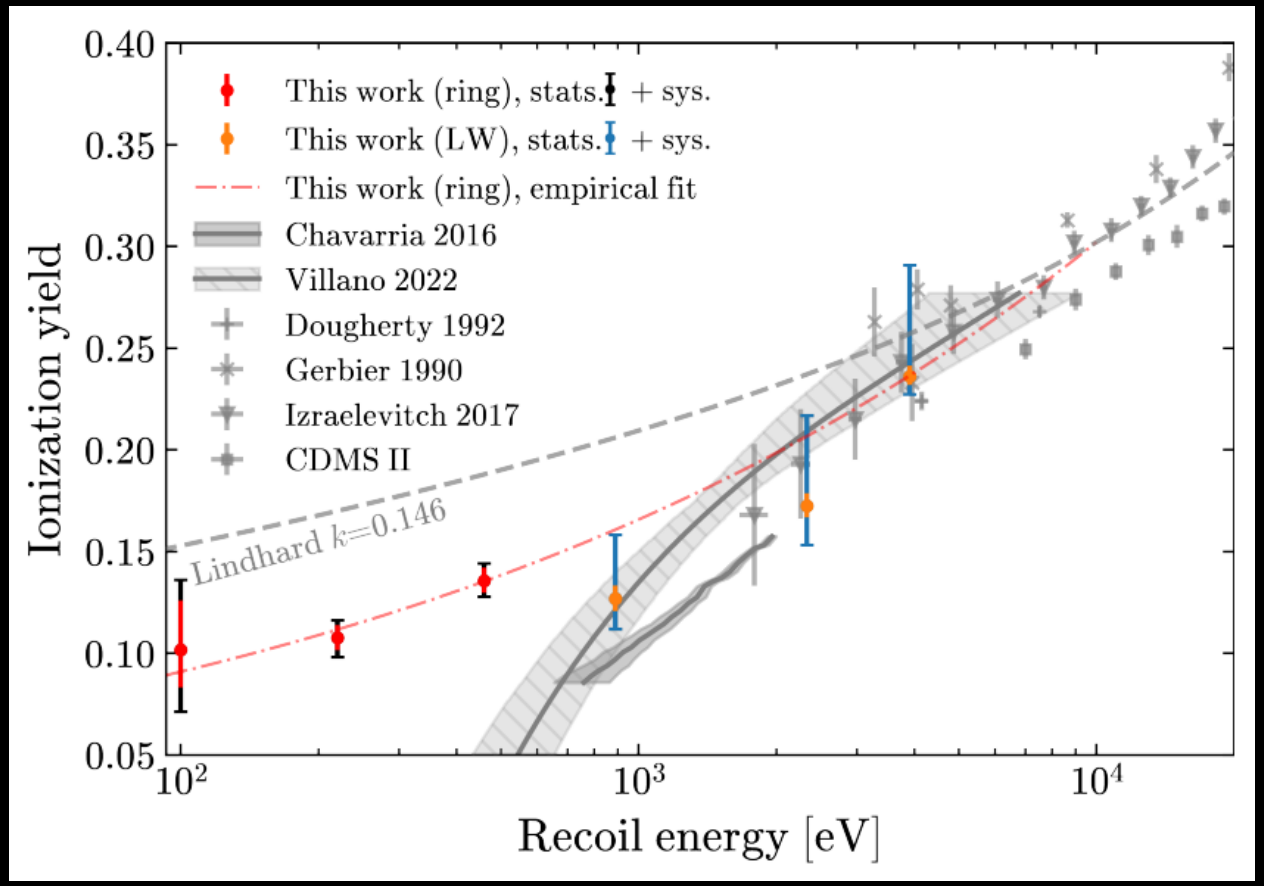


# Cryogenic bolometers

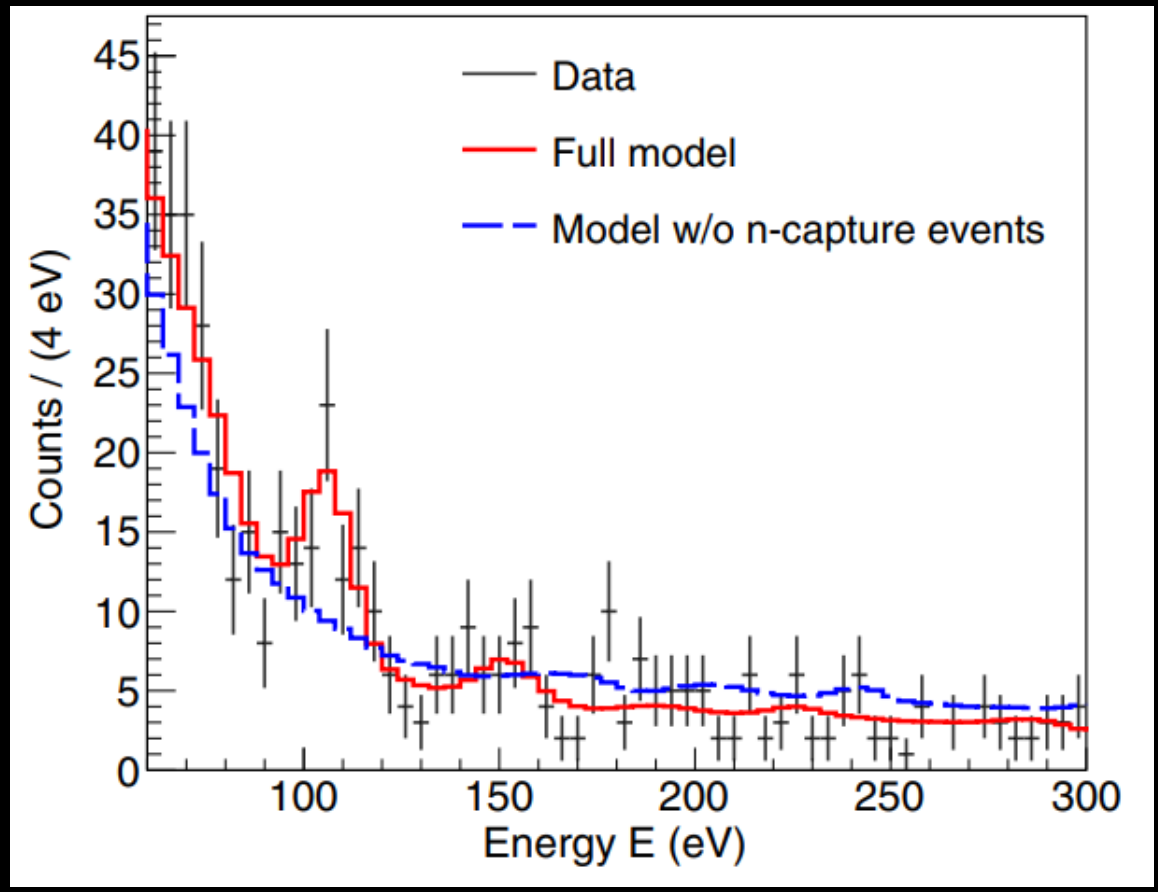
**CRESST-III ($CaWO_4$), L. Canonica, TAUP 2021**



# Detector characterization highlights

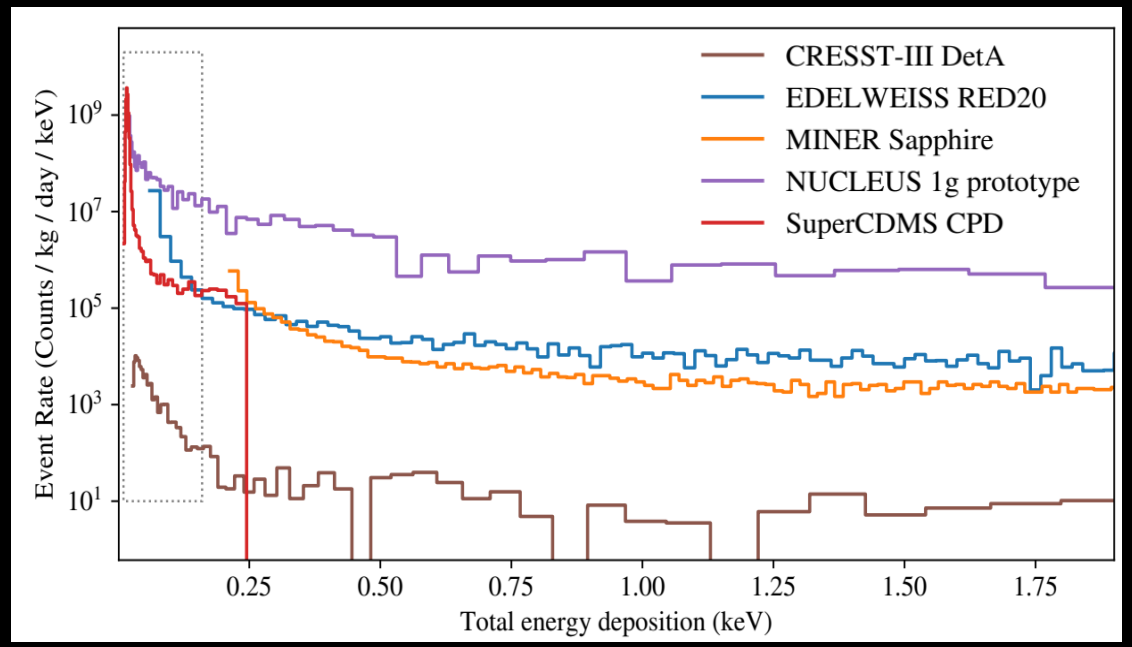


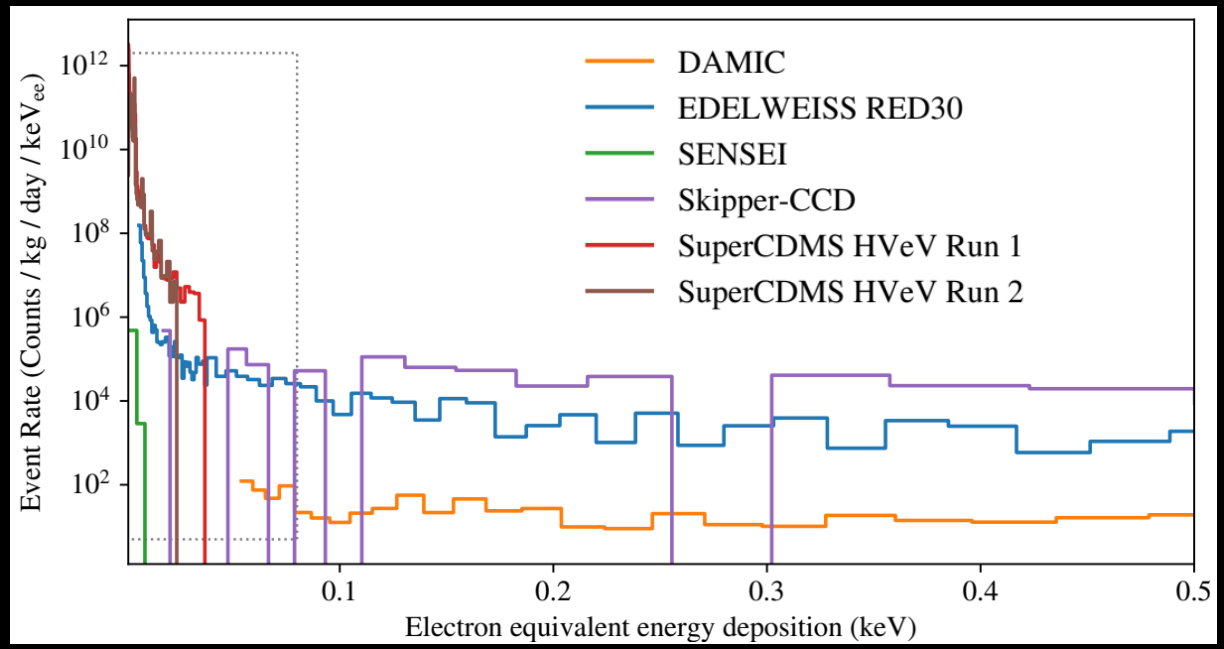

SuperCDMS, PRL 131, 091801 (2023)
Ionization yield to NR for Si down to 100 eV




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

# Low energy excesses



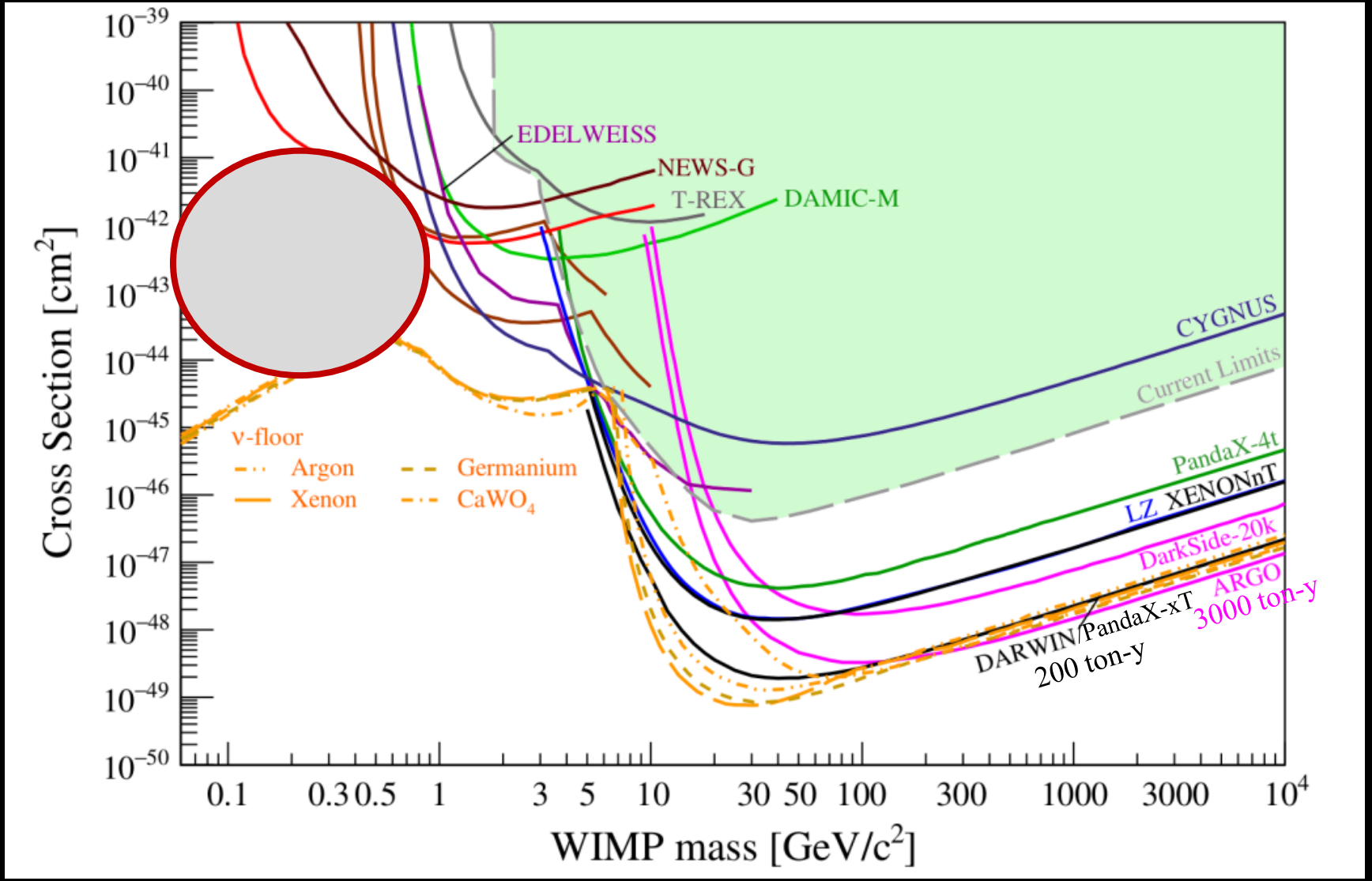




- Physics? Unlikely!
- Material background
- Structure issues (stress, etc.)

**The Excess Workshop: 2202.05097**

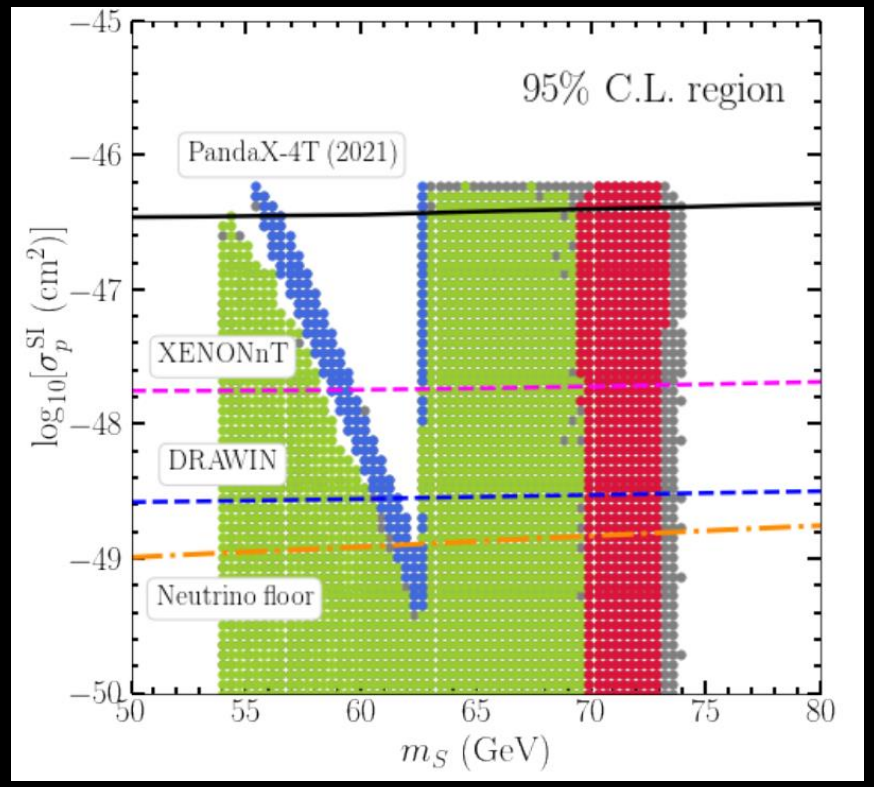
# SI sensitivity: future projection

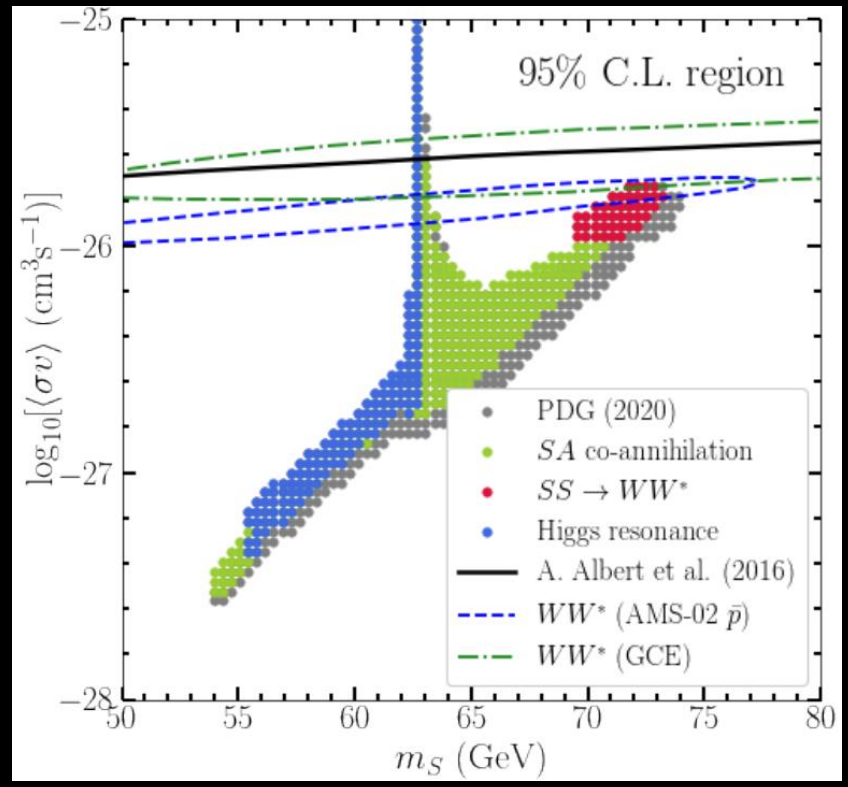
APPEC DM report: 2104.07634



# 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!!!

# Summary

- WIMP searches: huge experimental processes in the past 15-20 years
  - Indirect searches: hints/bounds coexist
  - Direct searches: no convincing signals
- Significant “traditional” WIMP parameters unexplored (with known experimental techniques!)
- Both theorists and experimentalists are thinking harder on alternatives (low-mass)
- Keep the flagship effort going, while investing on alternatives