Dark Matter Searches with Underground Experiments

Michelle Galloway
University of Zurich

Unraveling the History of the Universe and Matter Evolution with Underground Physics

Tokyo University of Science, 13 June 2022

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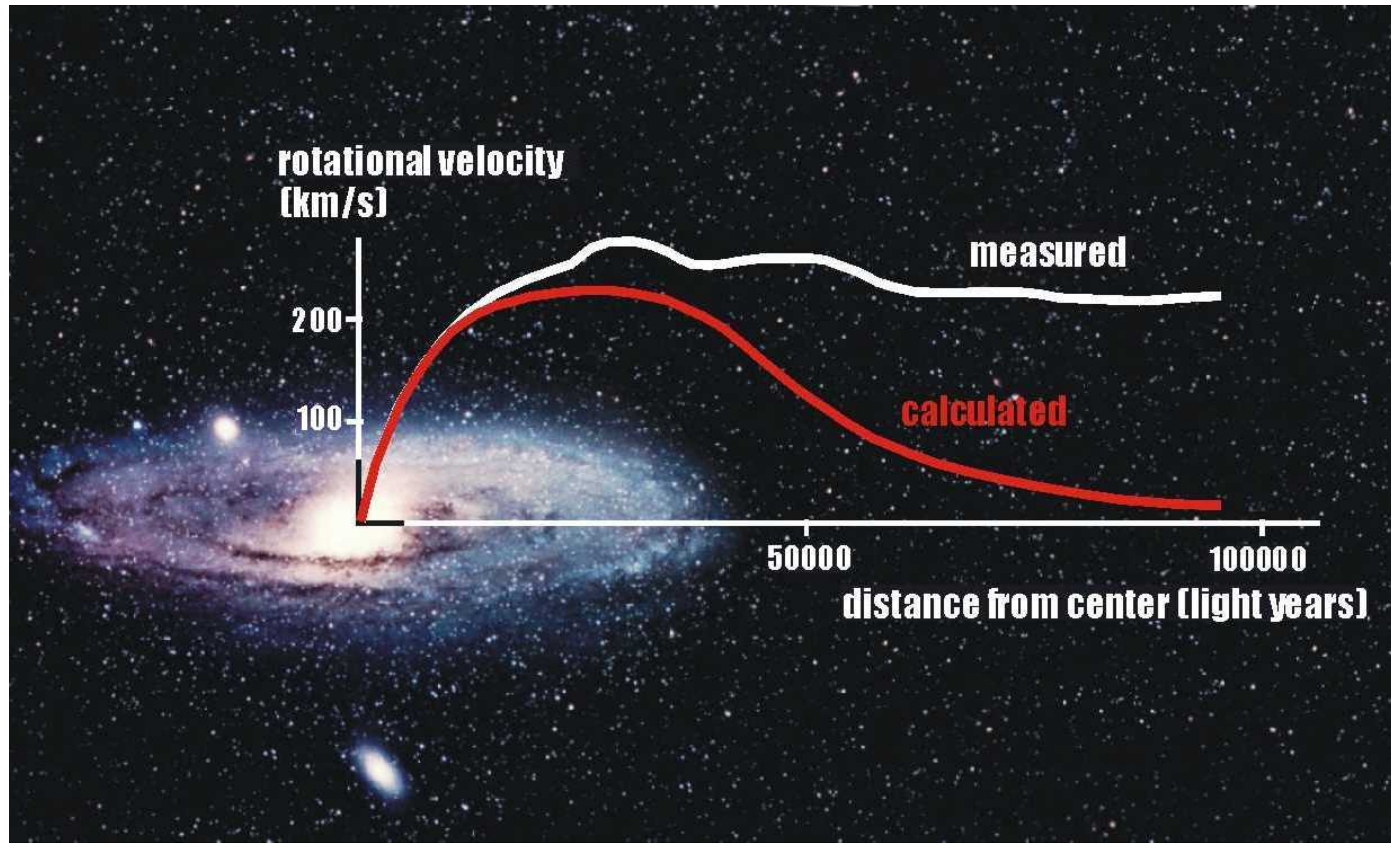
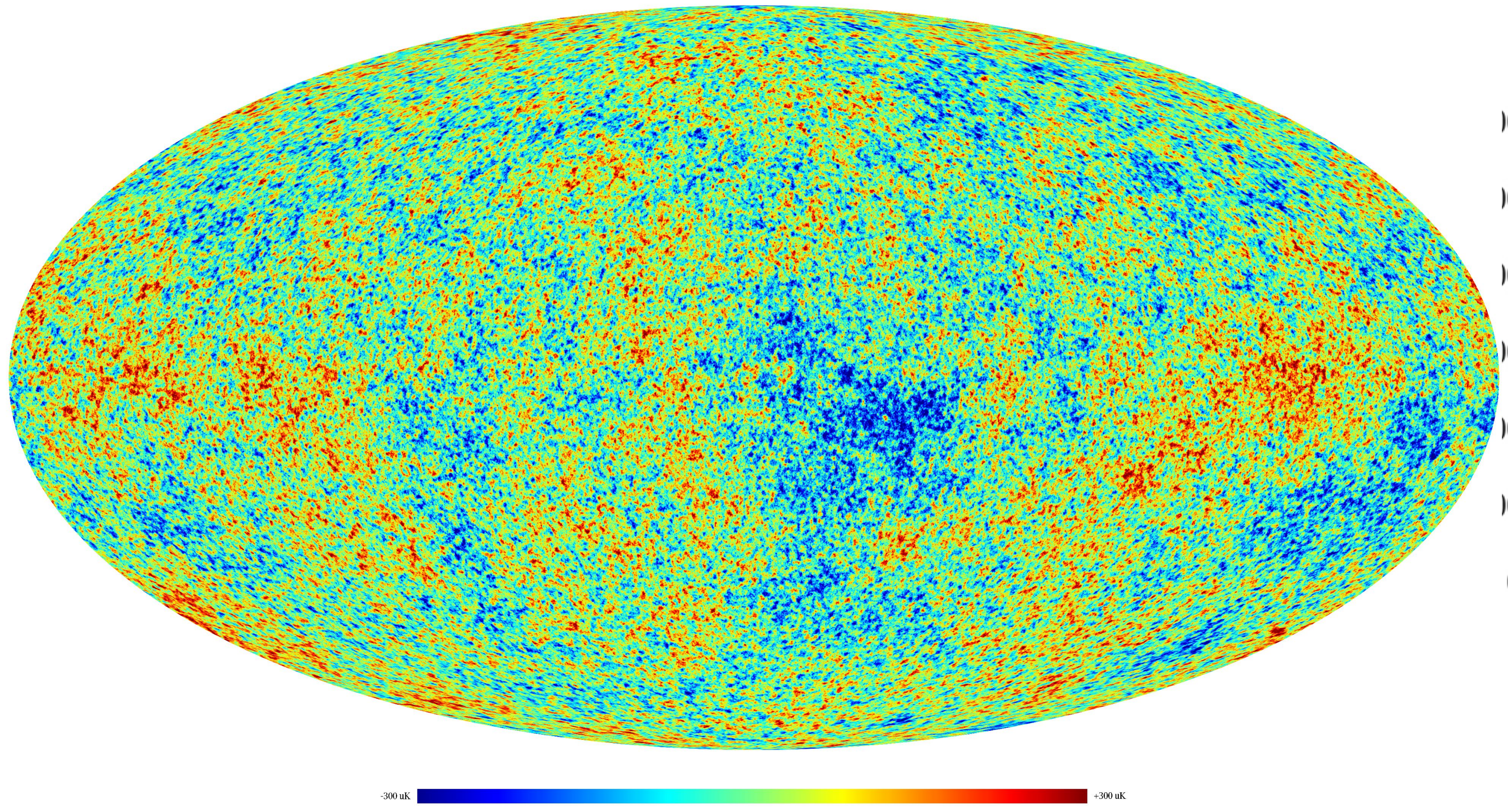
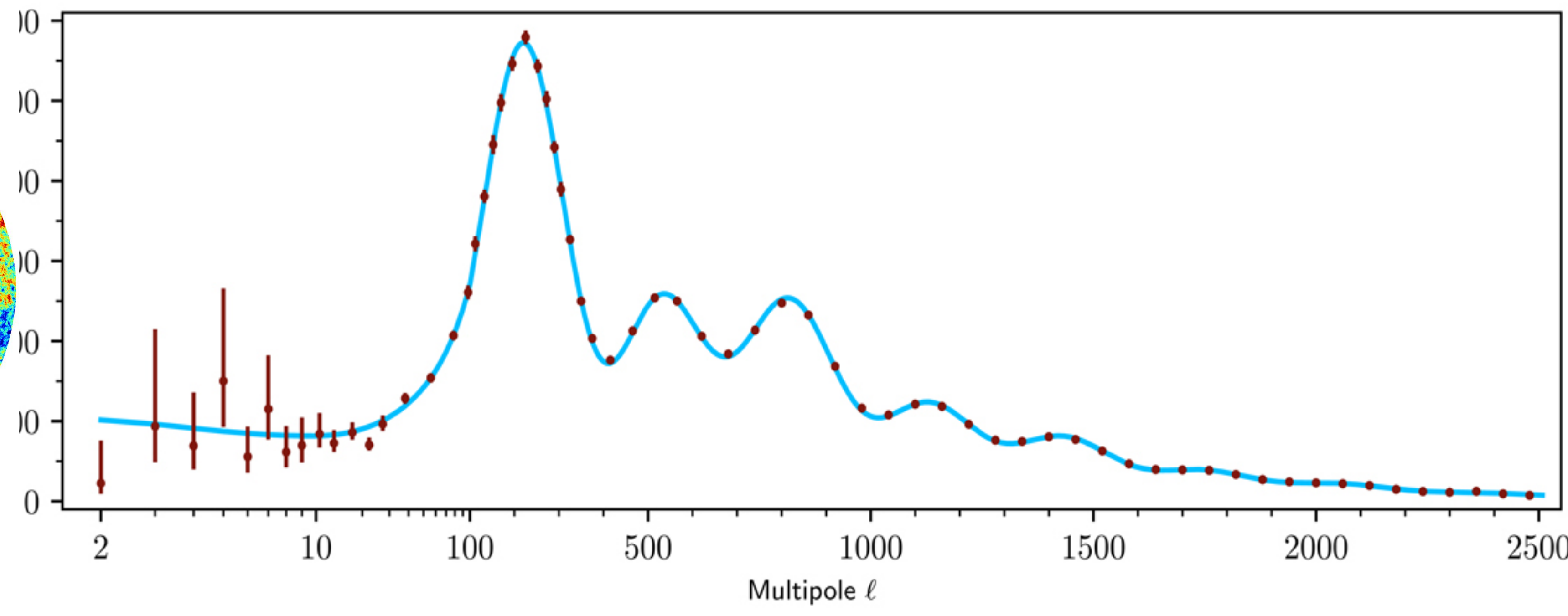
Dark Matter







Planck collaboration, Astron. Astrophys. 641, A1 (2020)

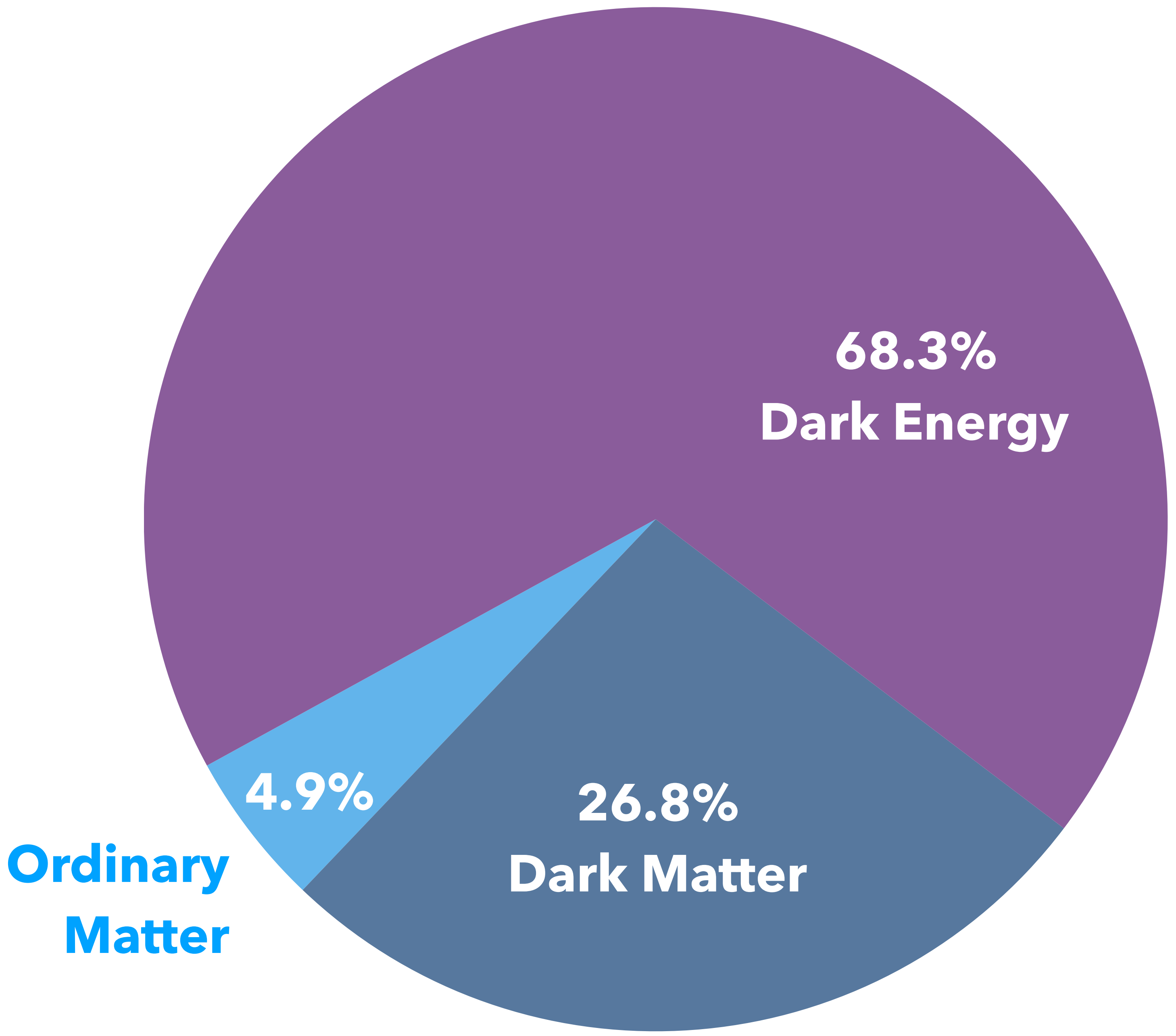
Abell 520, Chandra (x-ray green), optical (red, green) Hubble, DM core (blue) - unanchored

All the observational data are from very different eras:

- CMB ~350,000 years ago
- Galaxy, Lyman-alpha observations
- Mass measurements from gravitational lensing
- Rotation curves - measurements at smaller scales/masses
- BBN - a completely orthogonal measurement to all the others.

DM is not a single piece of data, but is evident throughout the history of the Universe from a variety of experimental techniques

Dark Matter



~10 M_{SUN} 100 TeV ~keV 10^{-22} eV

Primordial black holes

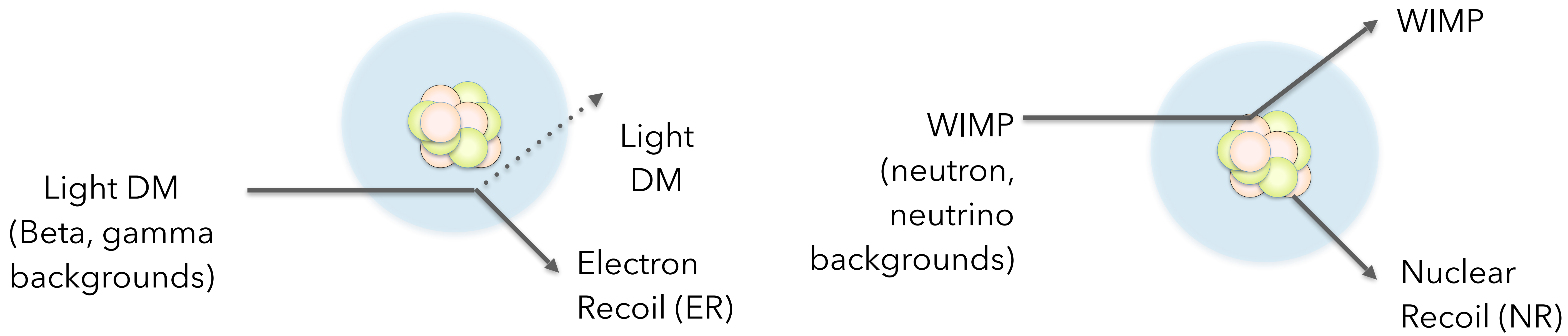
$\underbrace{\text{100 TeV} \quad \text{~keV}}$ DM mass range of particle direct detection

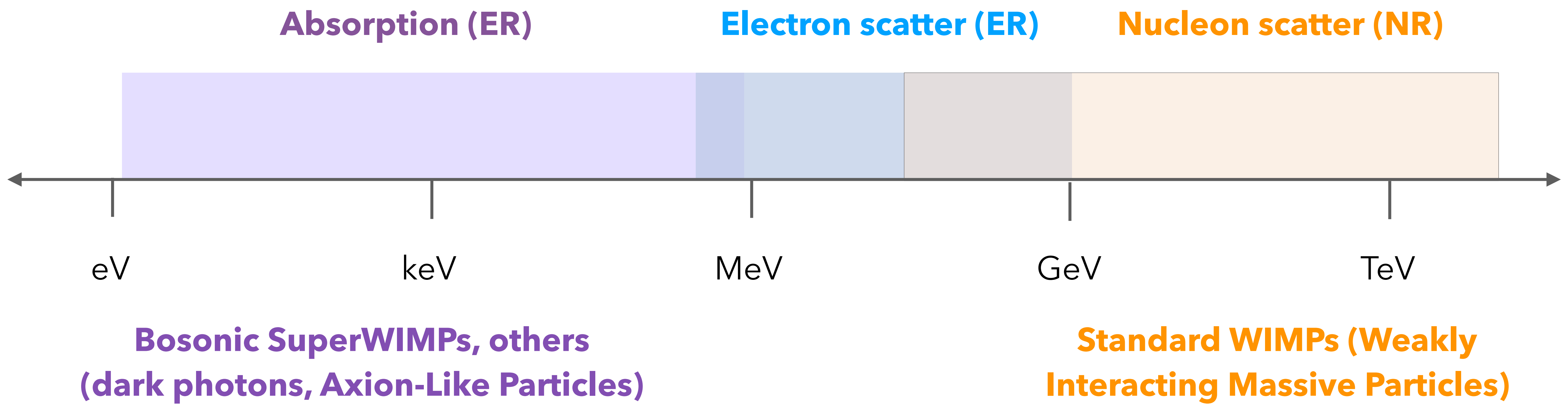
Bosonic fields

Nature 562, 51 (2018)

Direct Detection

Searches for interactions between Standard Model particles and dark matter from the Milky Way halo.





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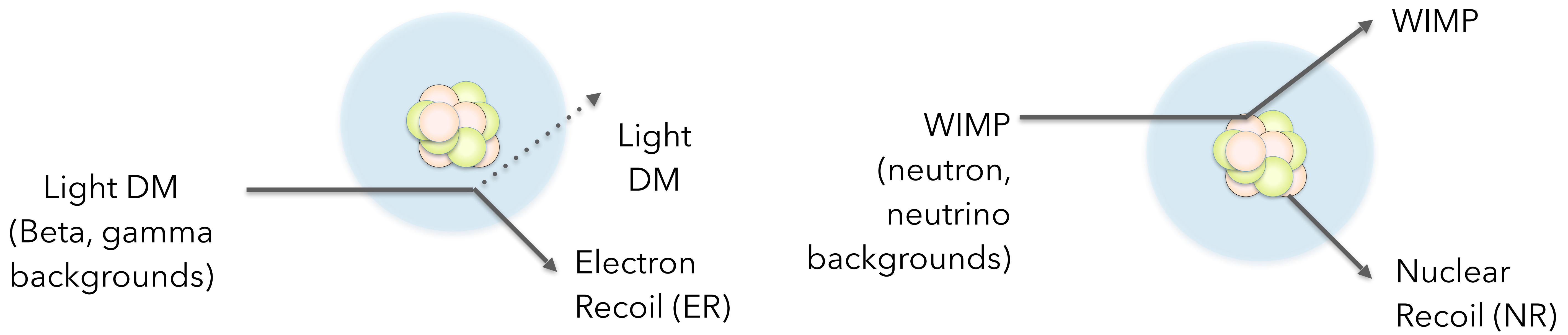

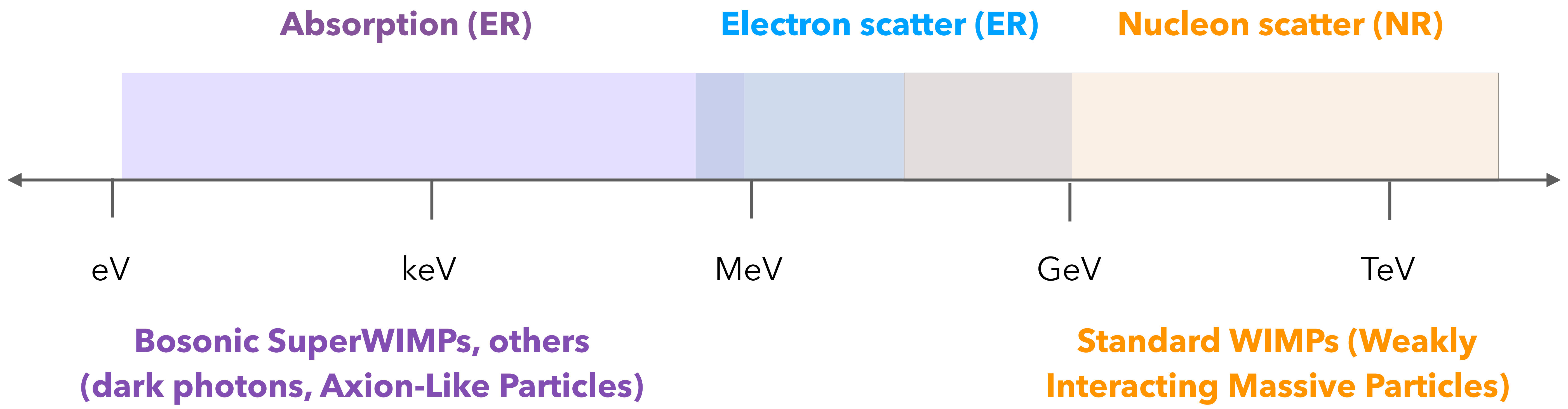

Scattering example:
WIMPs (NR)

$$m_\chi = m_N = 100\ GeV \cdot c^{-2}$$

$$\mathrm{v} \approx 220\ \mathrm{km\ s^{-1}} = 0.75 \times 10^{-3} c$$

where v = mean WIMP velocity relative to target (stationary halo)

$$\langle E_R \rangle = E_0 = \frac{1}{2} m_\chi \mathrm{v}^2$$

$$\langle E_R \rangle \approx 30\ \mathrm{keV}$$

=> mean recoil energy deposited in a detector

WIMP masses in the range of 10 - 1000 GeV c^{-2} typically yield recoil energies of **1 - 100 keV$_{NR}$**.

Direct Detection

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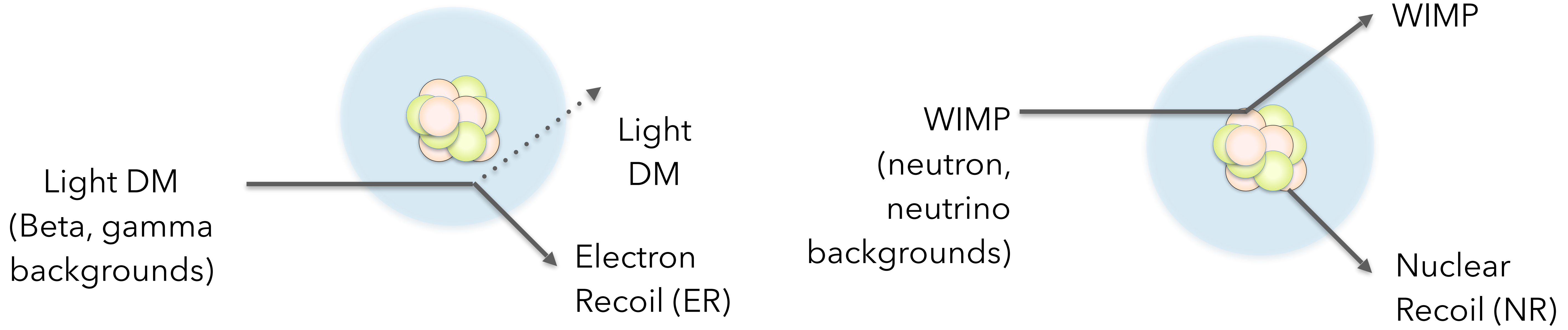
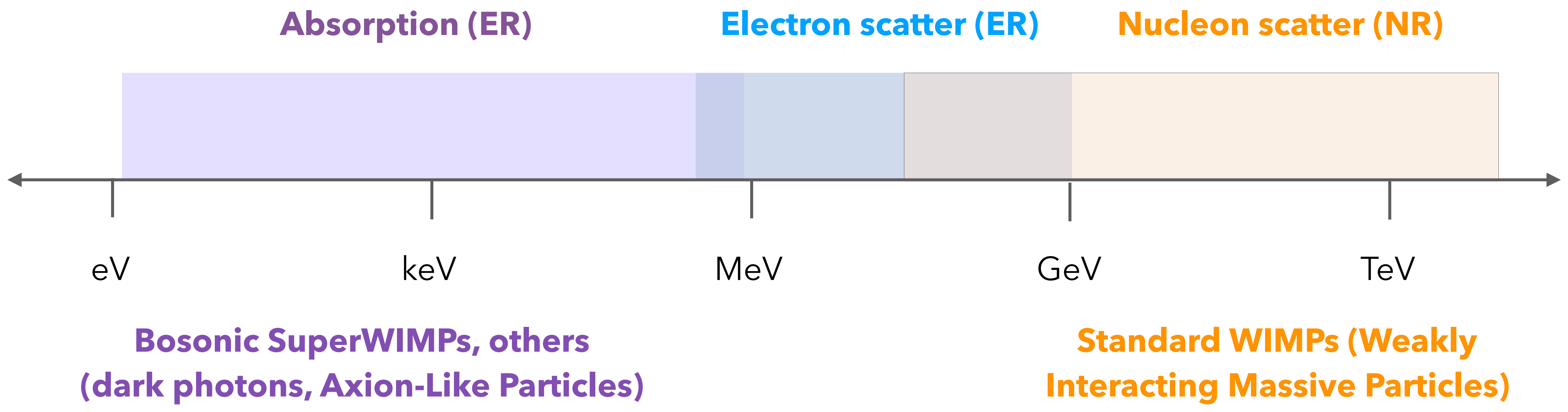


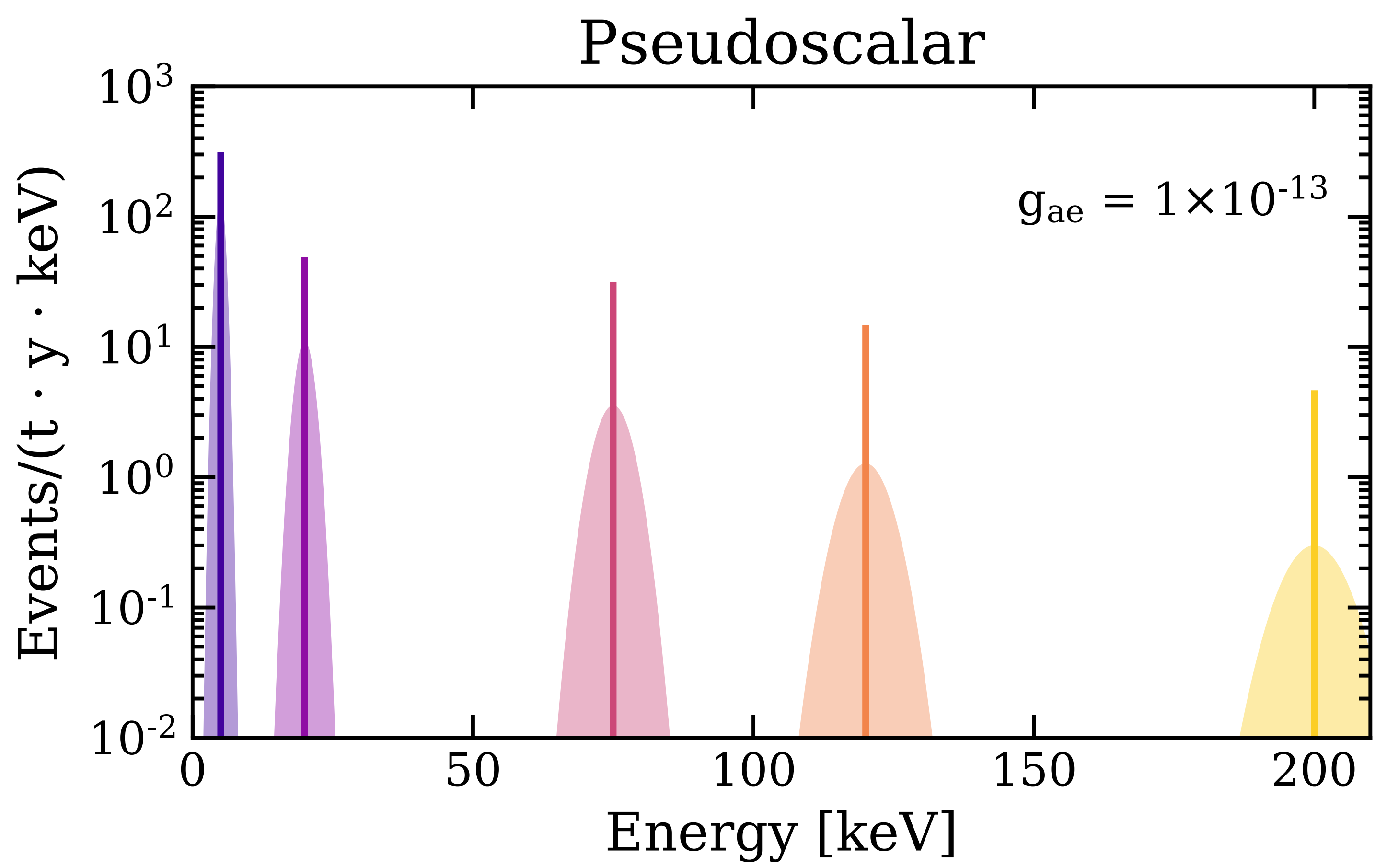


Absorption example: Axion-Like Particles (ER)

Detection via axioelectric effect

$$\sigma_{\mathrm{ae}} = \sigma_{\mathrm{pe}} \frac{g_{\mathrm{ae}}^2}{\beta} \frac{3E_{\mathrm{a}}^2}{16\pi\alpha m_{\mathrm{e}}^2} \left(1 - \frac{\beta^{2/3}}{3}\right)$$

Energy deposition is the particle rest mass (nonrelativistic)



Expected event rates

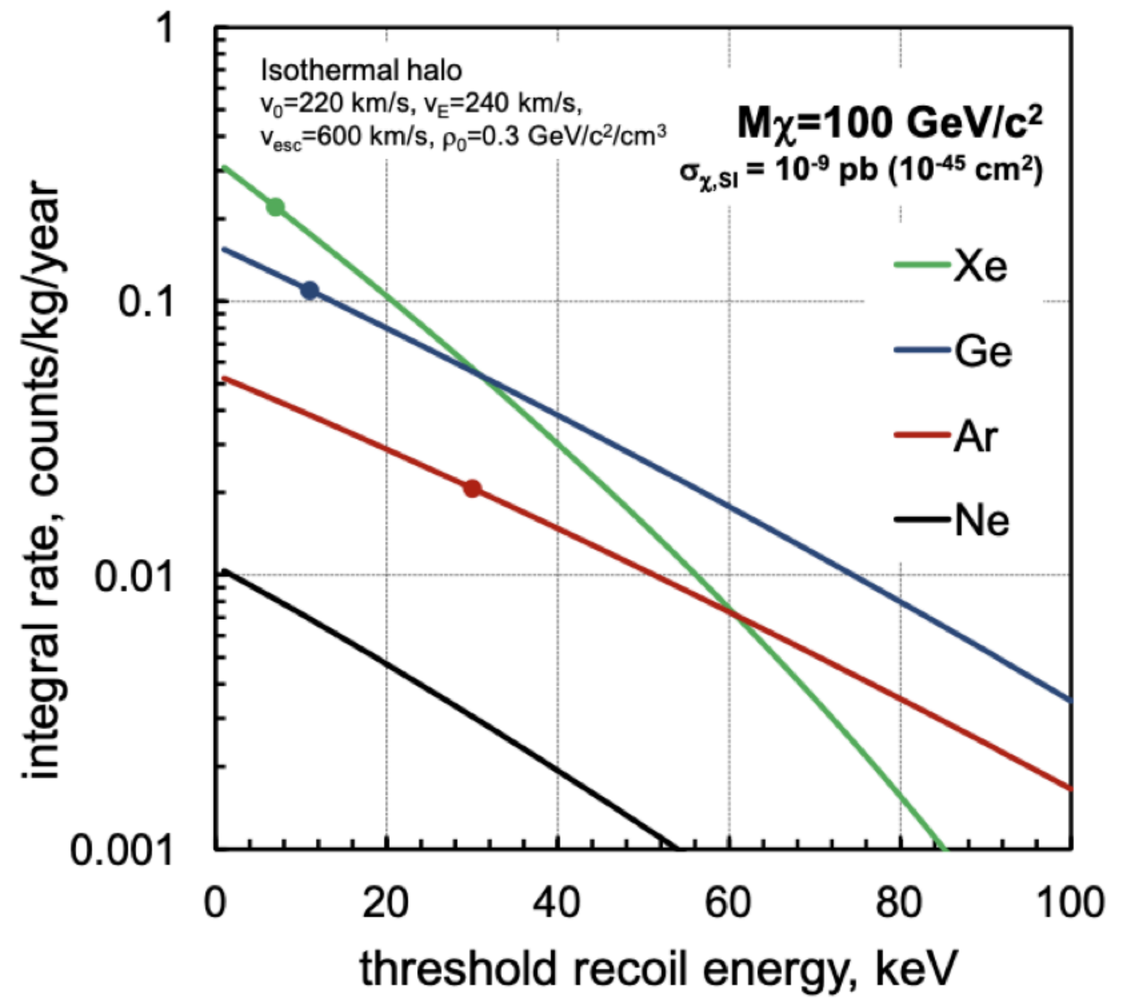
Differential event rate

Nuclear and particle physics -
mass, cross section, form factors

$$\frac{dR}{dE_r} = MT \times \frac{\rho_0 \sigma_0}{2 m_X m_N^2} F^2(E_r) \int_{v_{min}} \frac{f(v)}{v} d^3v$$

Detector
target material,
exposure and response

Astrophysics - DM local
density and distribution



V. Chepel and H. Arau´jo, Journal of Instrumentation 8(04), R04001 (2013)

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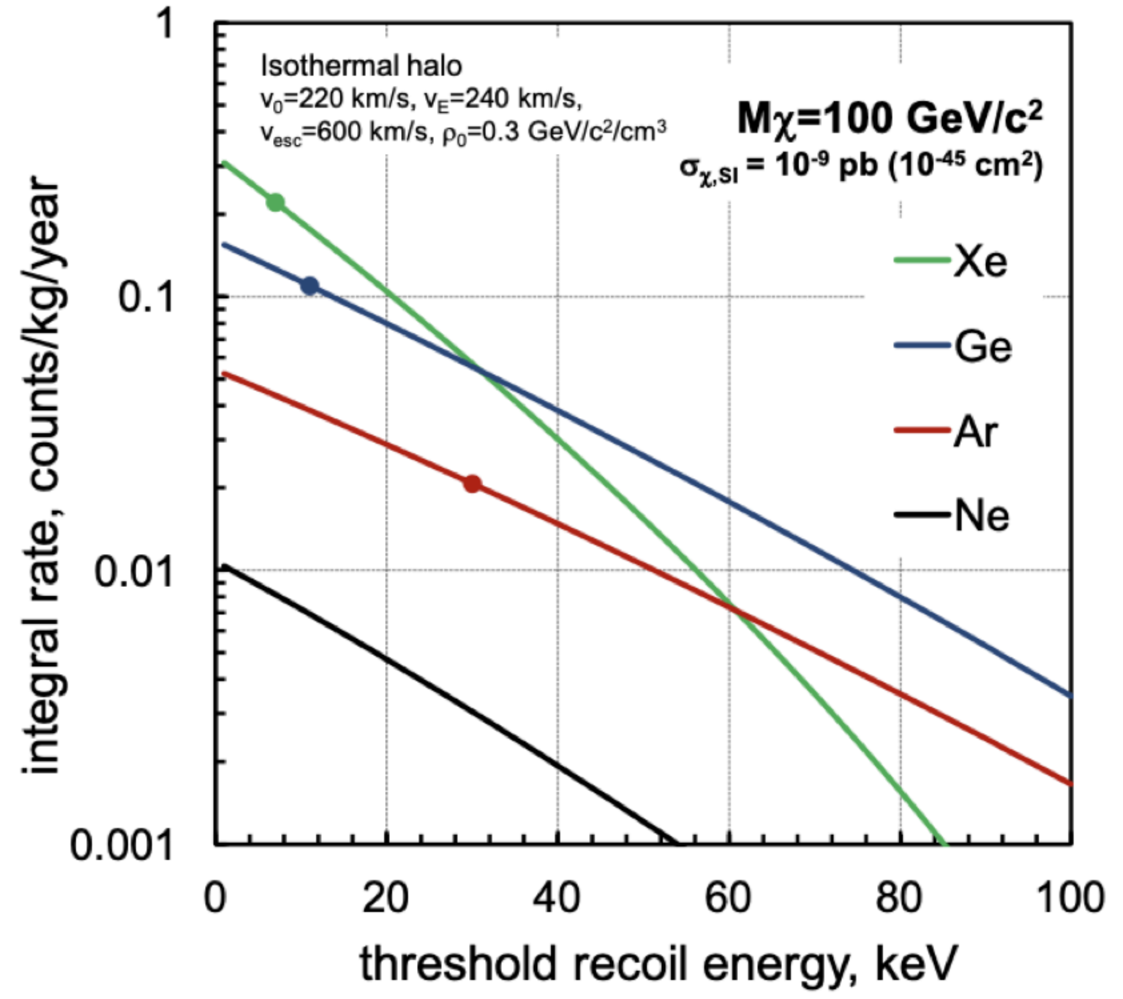


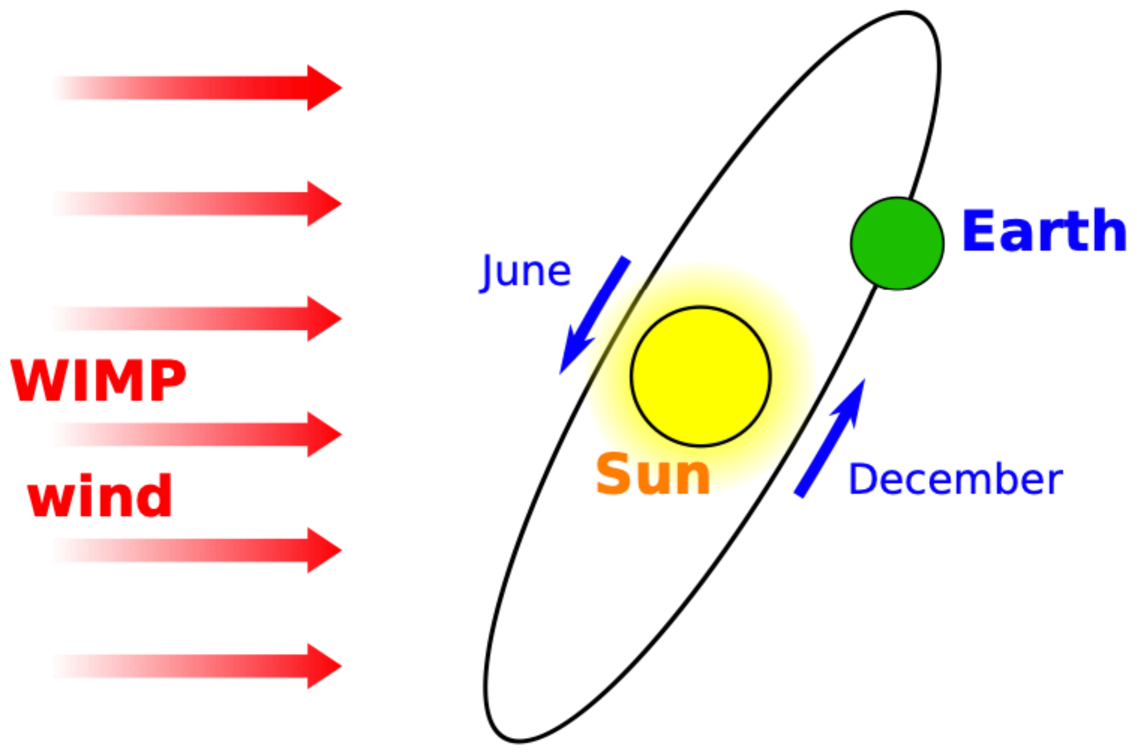
V. Chepel and H. Arau´jo, Journal of Instrumentation 8(04), R04001 (2013)

Annual modulation

$$\frac{dR}{dE_r}(E_r, t) \approx \frac{dR}{dE_r}\left[1 + \Delta(E_r)cos\frac{2\pi(t - t_0)}{T}\right]$$

Modulation
amplitude

T = 1 year
t_0 is phase (max ~June 2)



K. Freese, M. Lisanti and C. Savage, Rev. Mod. Phys. 85, 1561 (2013)

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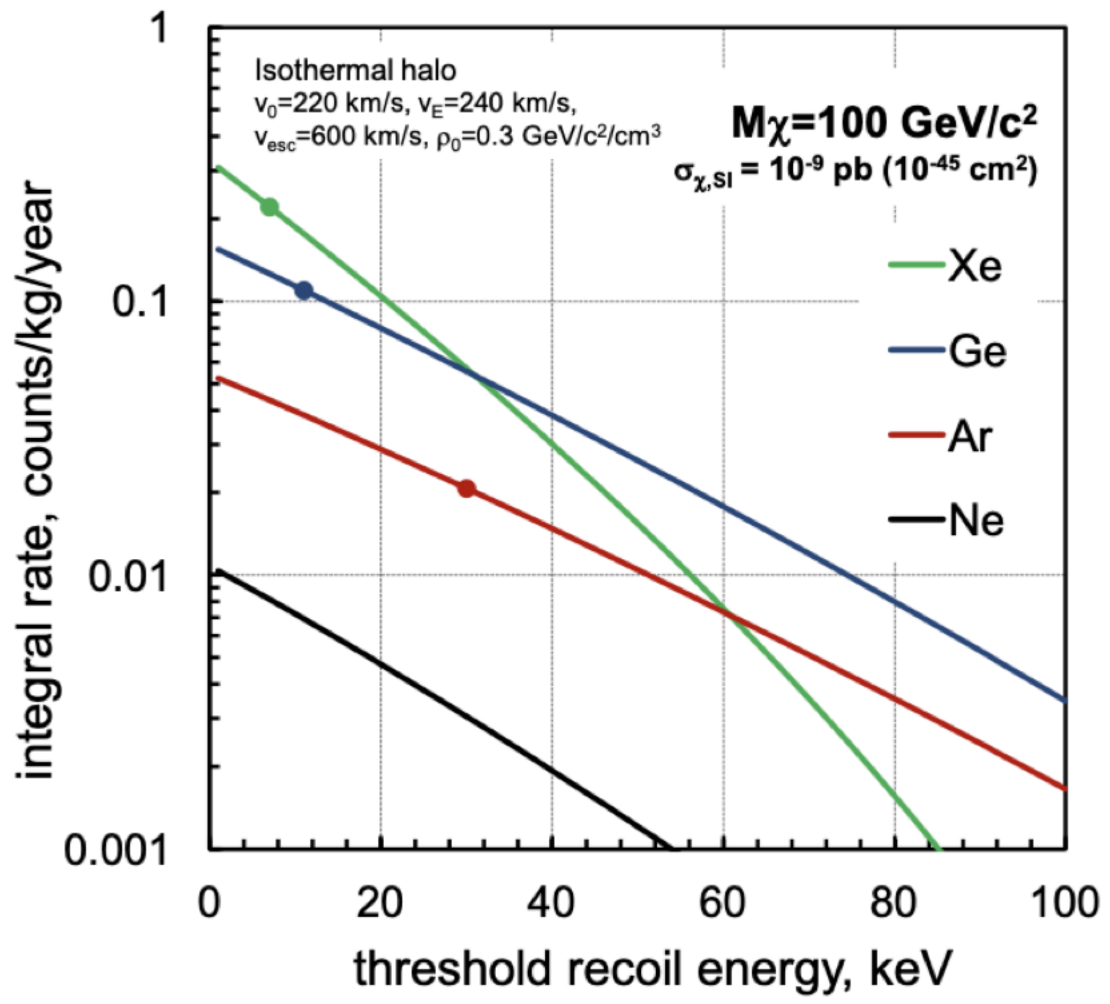

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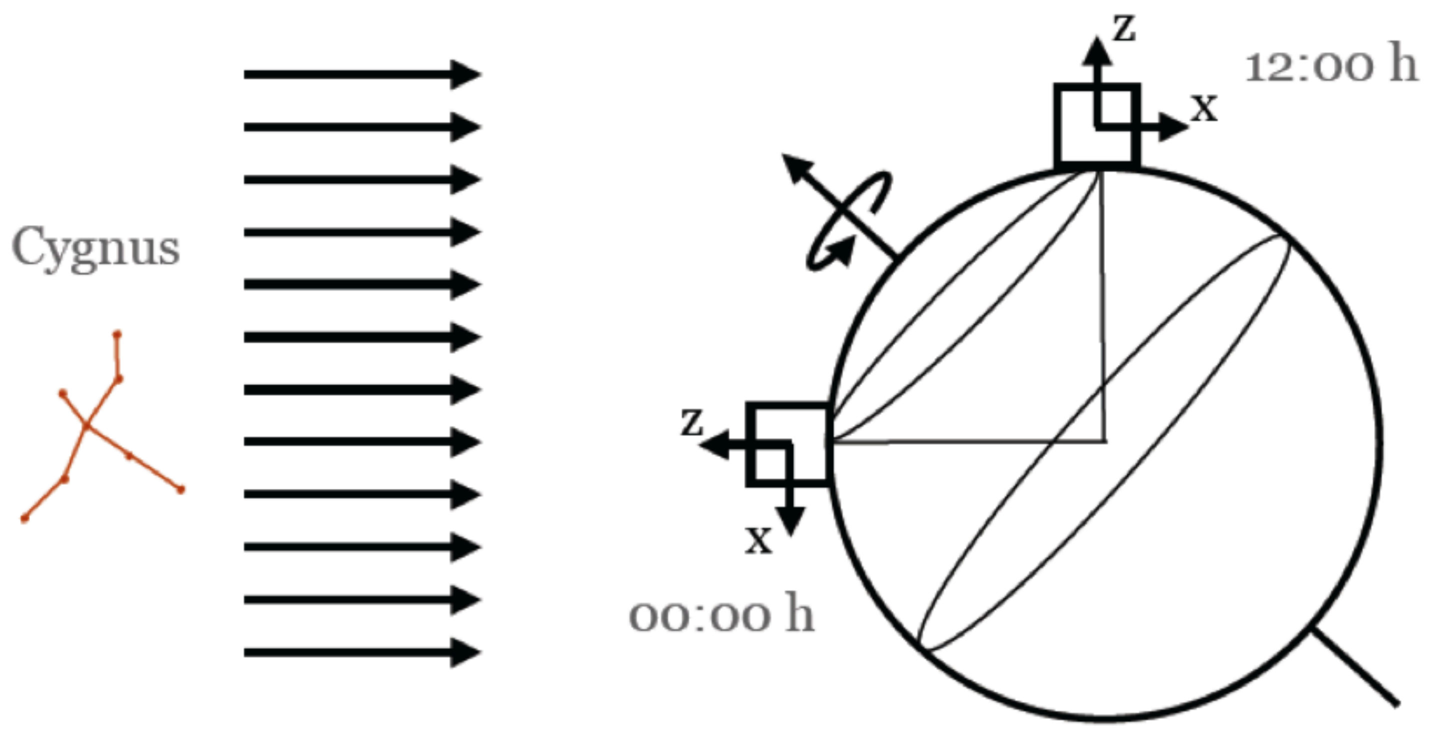


R. W. Schnee, Introduction to dark matter experiments,
doi:10.1142/9789814327183 0014 (2011)

(+ Directional detection)

Interaction cross section vs. mass

Include cosmological and astrophysical constraints, interaction kinematics, detector effects

E_{low} tail of velocity distribution
(minimum velocity to induce a recoil)

$$v_{min} \approx \sqrt{m_N E_R/(2m_\chi^2)}$$

At high energies, recoil spectra ~ indep. of DM mass

$$v_{min} \approx \sqrt{E_R/(2m_N)}$$

Detector dependencies:

target atom (and detectability of recoil energy)

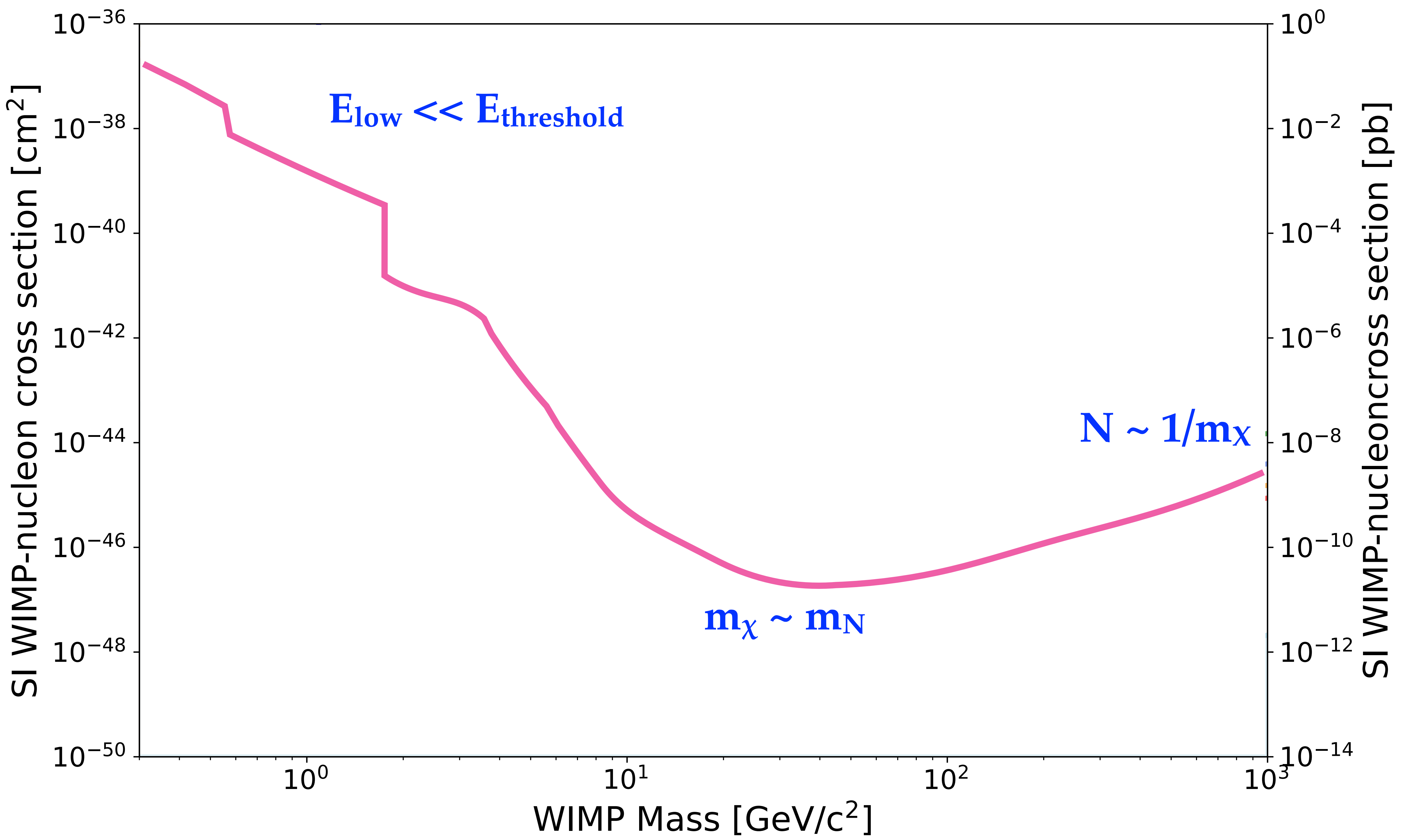
detector effects (threshold, efficiency, resolution)

Higher sensitivity:

total exposure is detector mass M_N
times observation time (t)

$T = M_N \times t$ [kg days]

NR-WIMP cross section vs mass parameter space



increase exposure

lower detector thresholds

lower backgrounds

Interaction cross section vs. mass

Include cosmological and astrophysical constraints, interaction kinematics, detector effects

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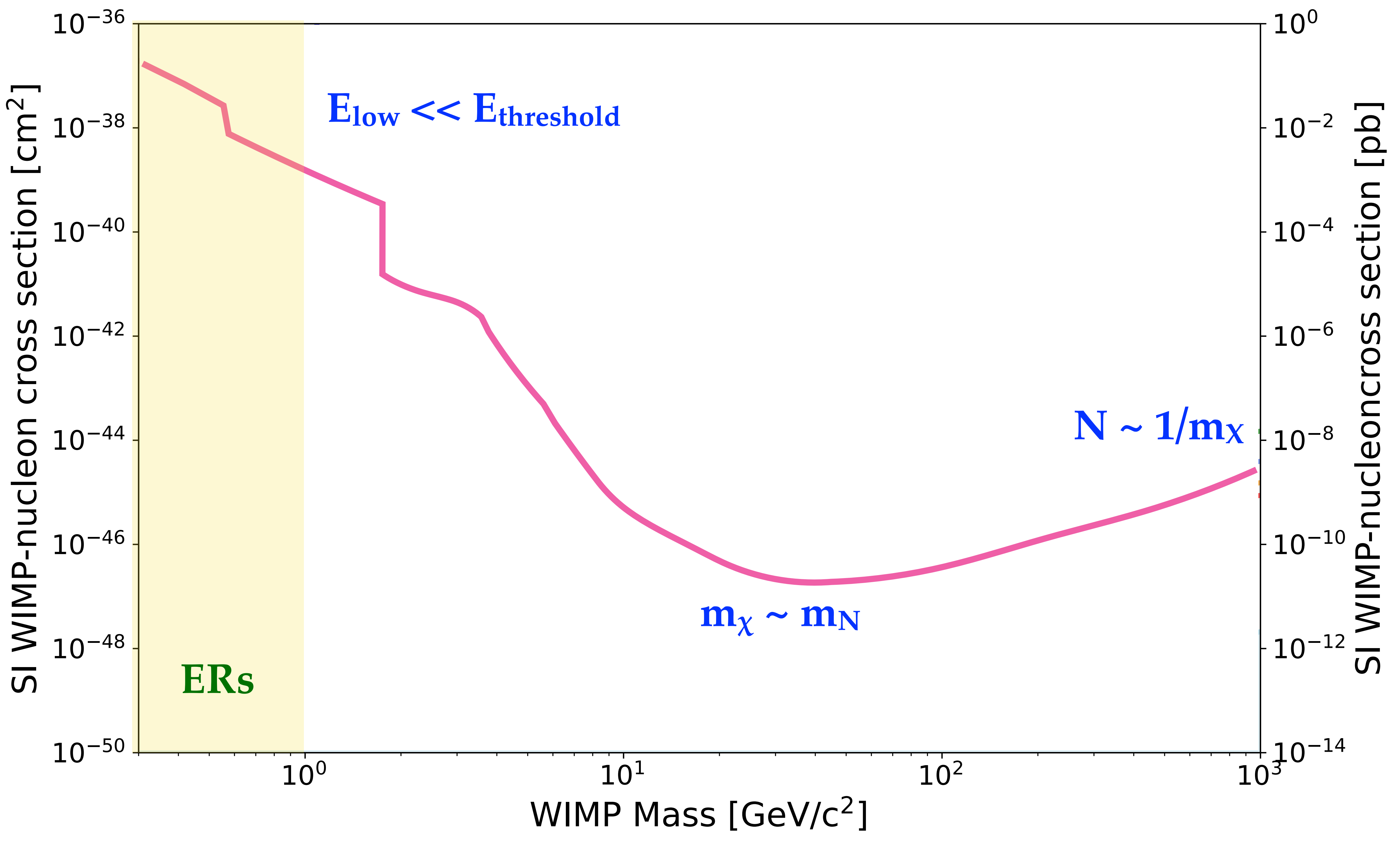


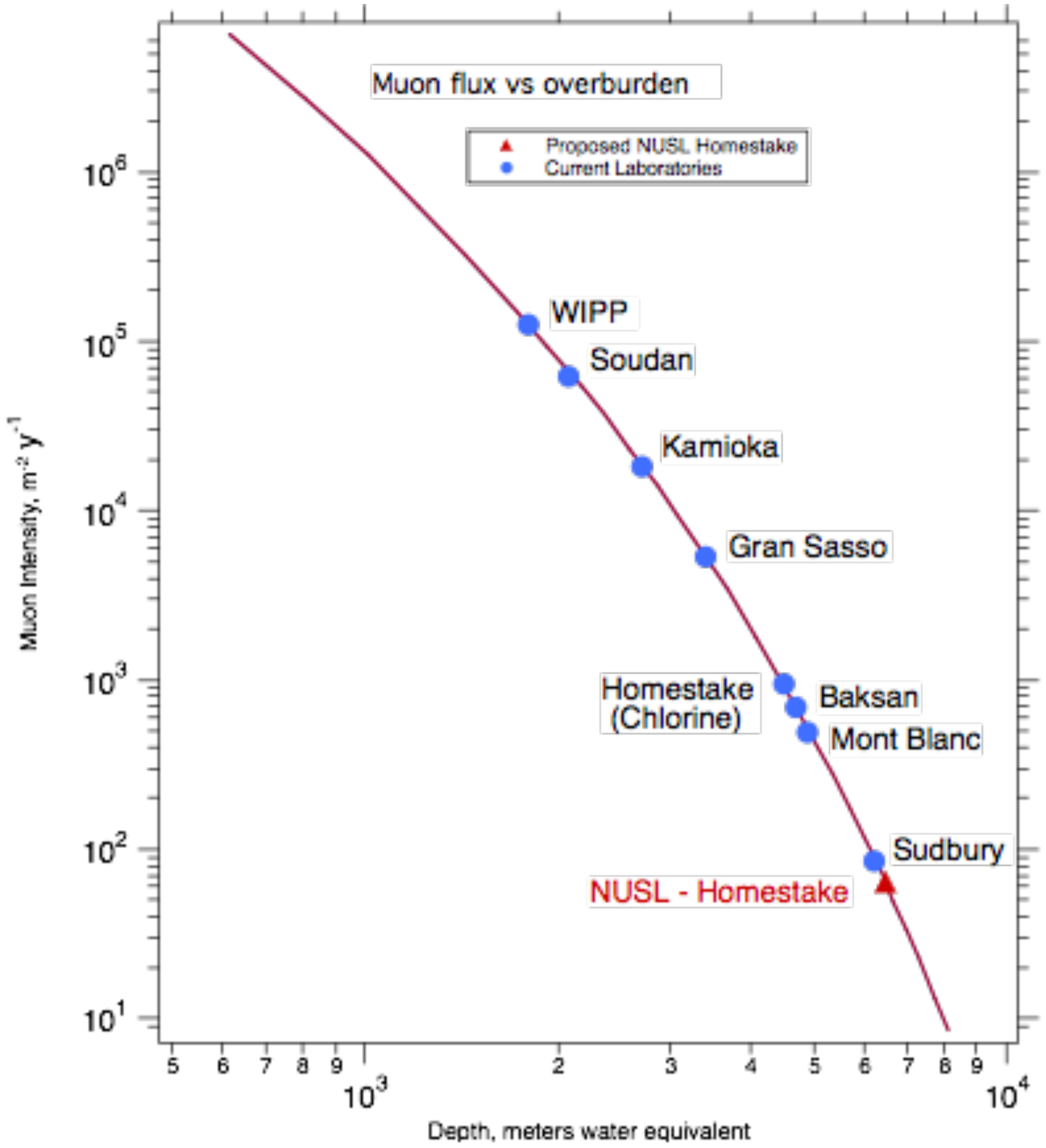
increase exposure

lower detector thresholds

lower backgrounds

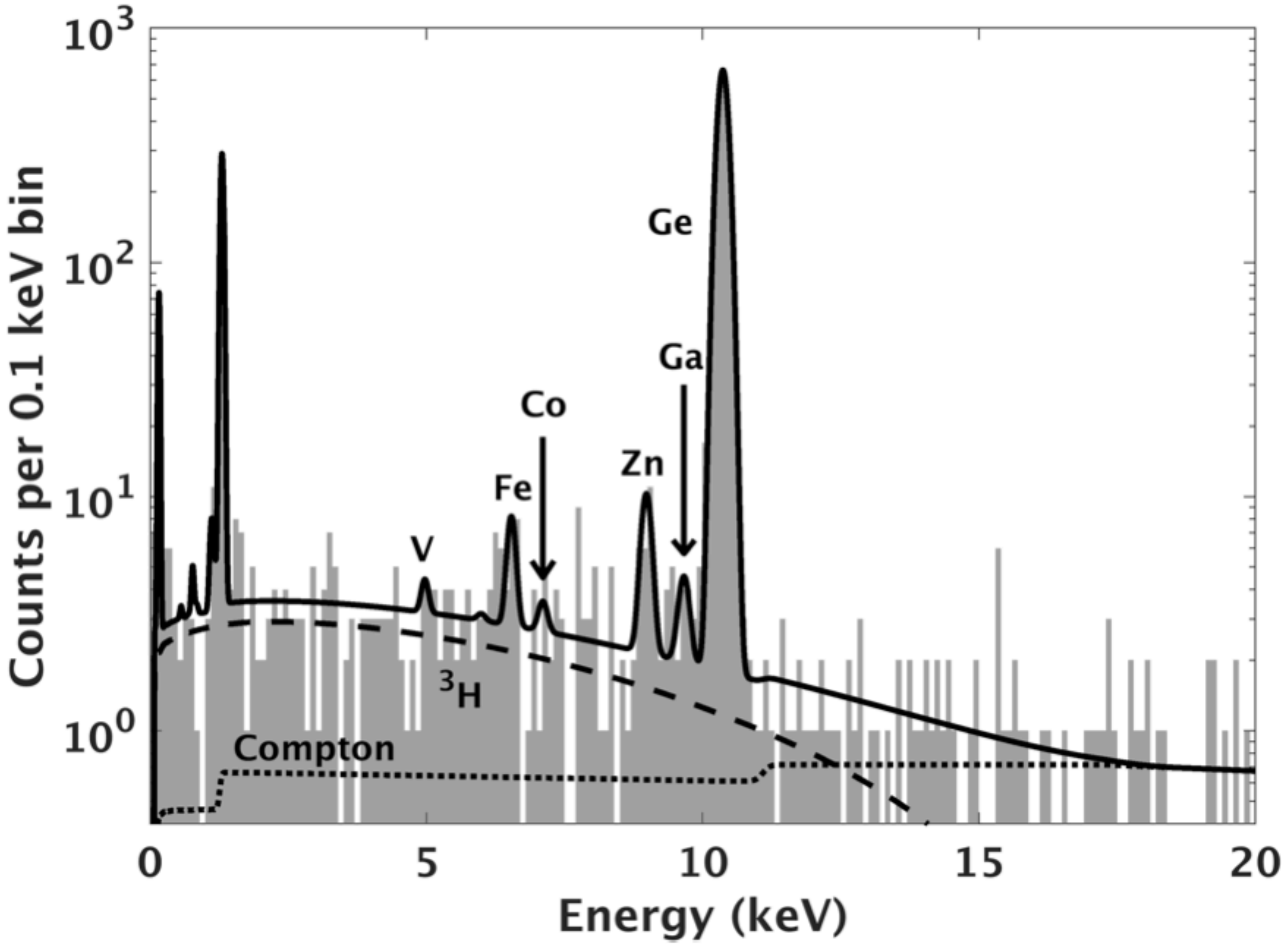
Background suppression

- **Reduce or eliminate:** Underground shielding, secondary shielding, purification and distillation
- **Model and predict:** Materials radioassay, Monte Carlo (GEANT4, ACTIVIA, other) simulations, other constraints (e.g. RGMS)
- **Cut or discriminate:** Fiducialization, active vetos, particle ID via e.g. quenching, pulse shape discrimination, etc.



Gator low-background counting facility underground at LNGS - high purity germanium detector in cryostat (central cylinder)

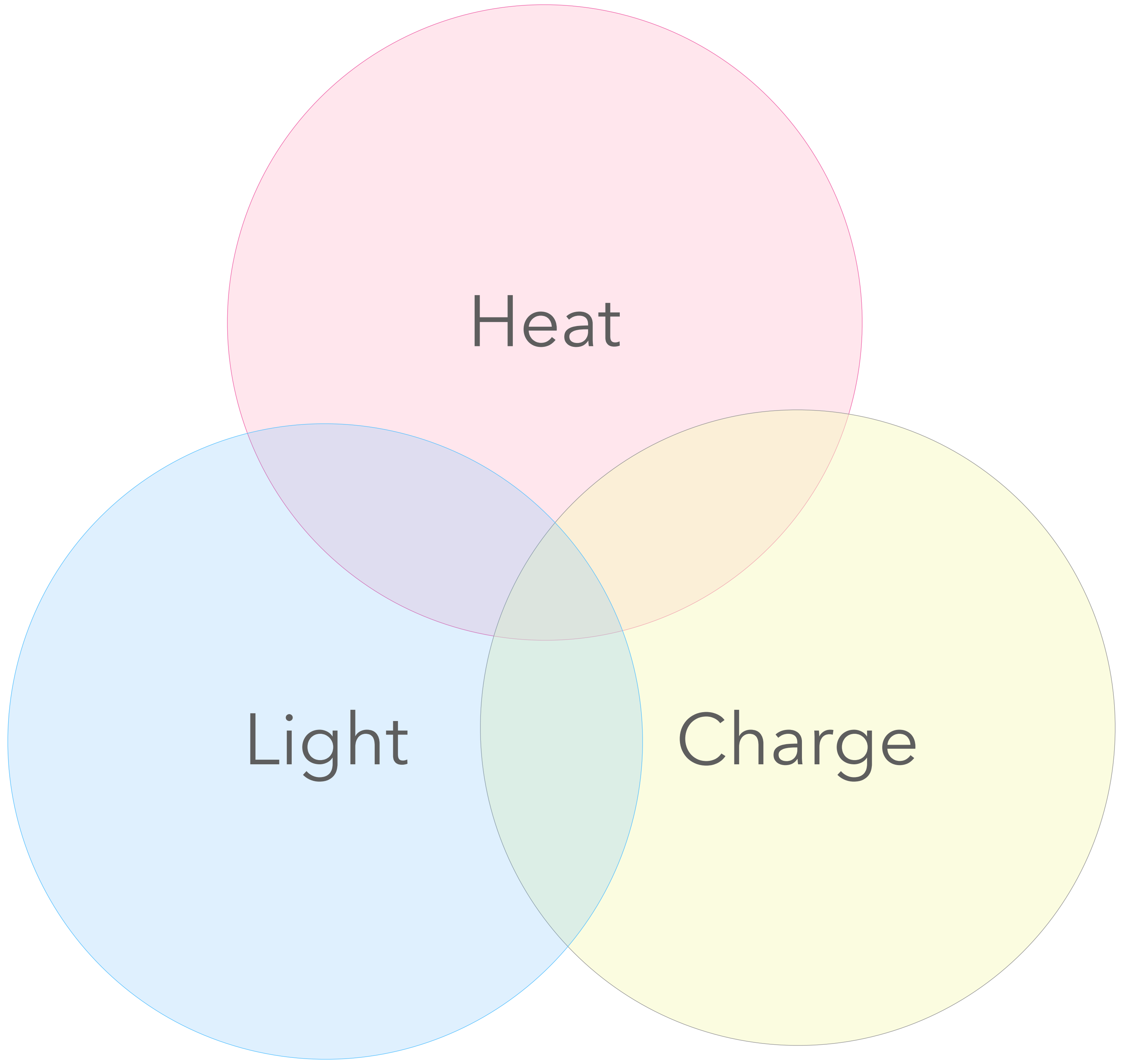
Materials database (Persephone): *https://www.radiopurity.org*



Maximum likelihood fit to extract tritium background in germanium detector (CDMSlite)

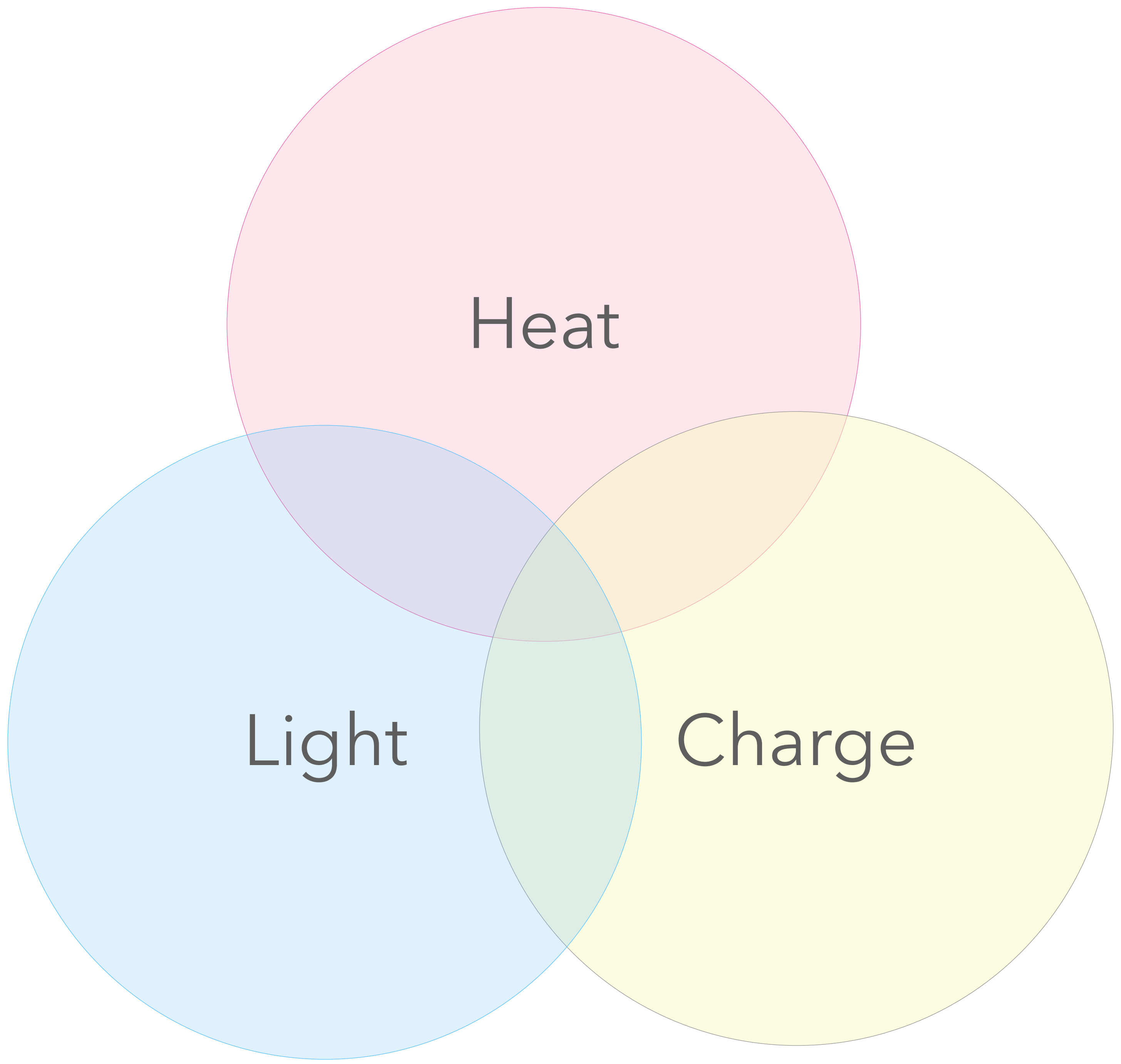
R. Agnese et al. (SuperCDMS Collaboration), Astropart. Phys., 104 (2019)

Detection channels and experiments



Detection channels and experiments

Xe: XMASS
Ar: DEAP-3600
CsI: KIMS
NaI: ANAIS
DAMA/LIBRA,
COSINE, SABRE

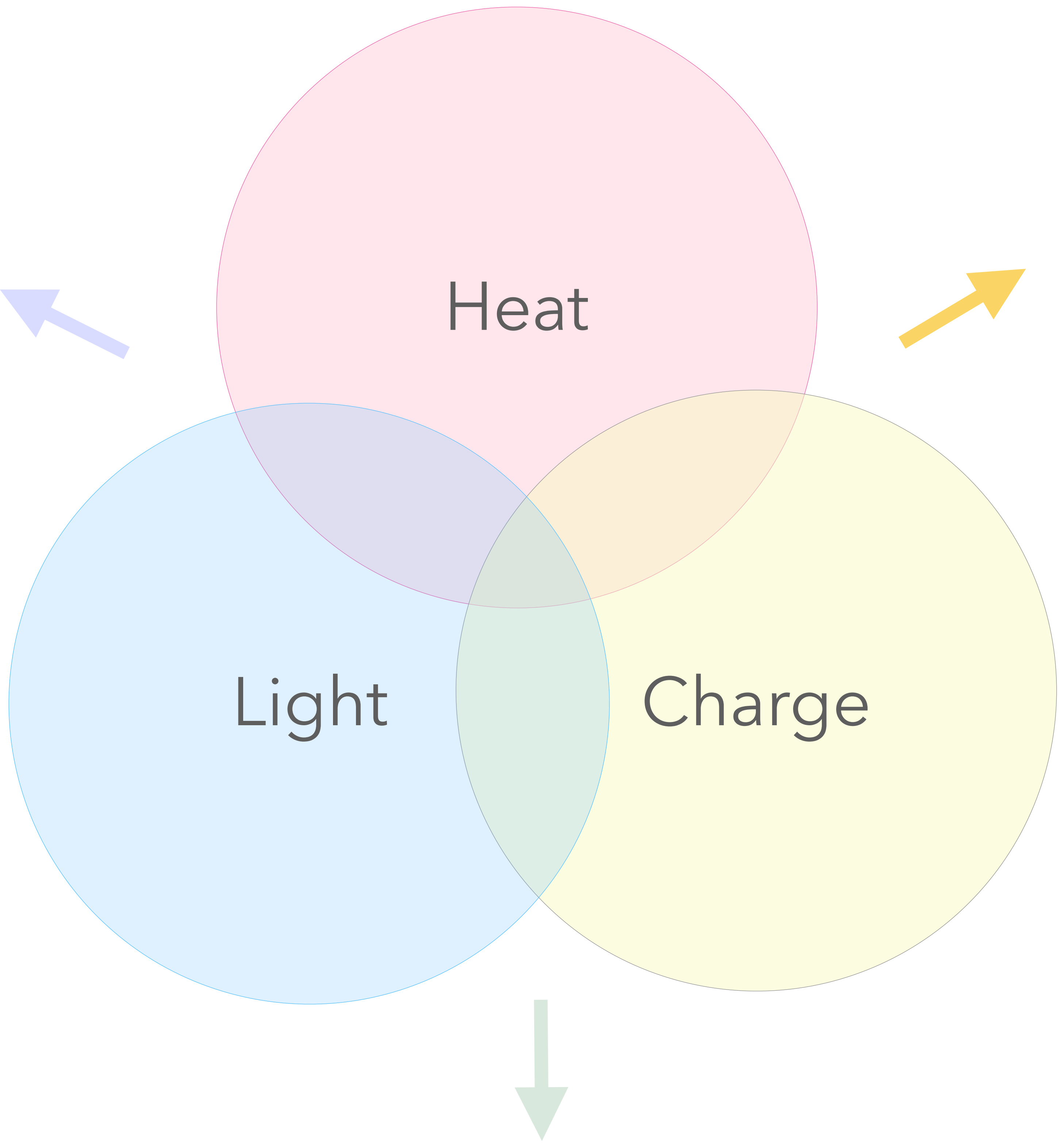


C_3F_8: PICO
Ge: CDEX
Si: DAMIC, SENSEI
Ar, Ne: TREX-DM
He:SF_6: CYGNUS
Ag, Br, C: NEWSdm
H, He, Ne: NEWS-G

Detection channels and experiments

$CaWO_4$: CRESST
NaI: COSINUS

Ge, Si:
SuperCDMS
EDELWEISS



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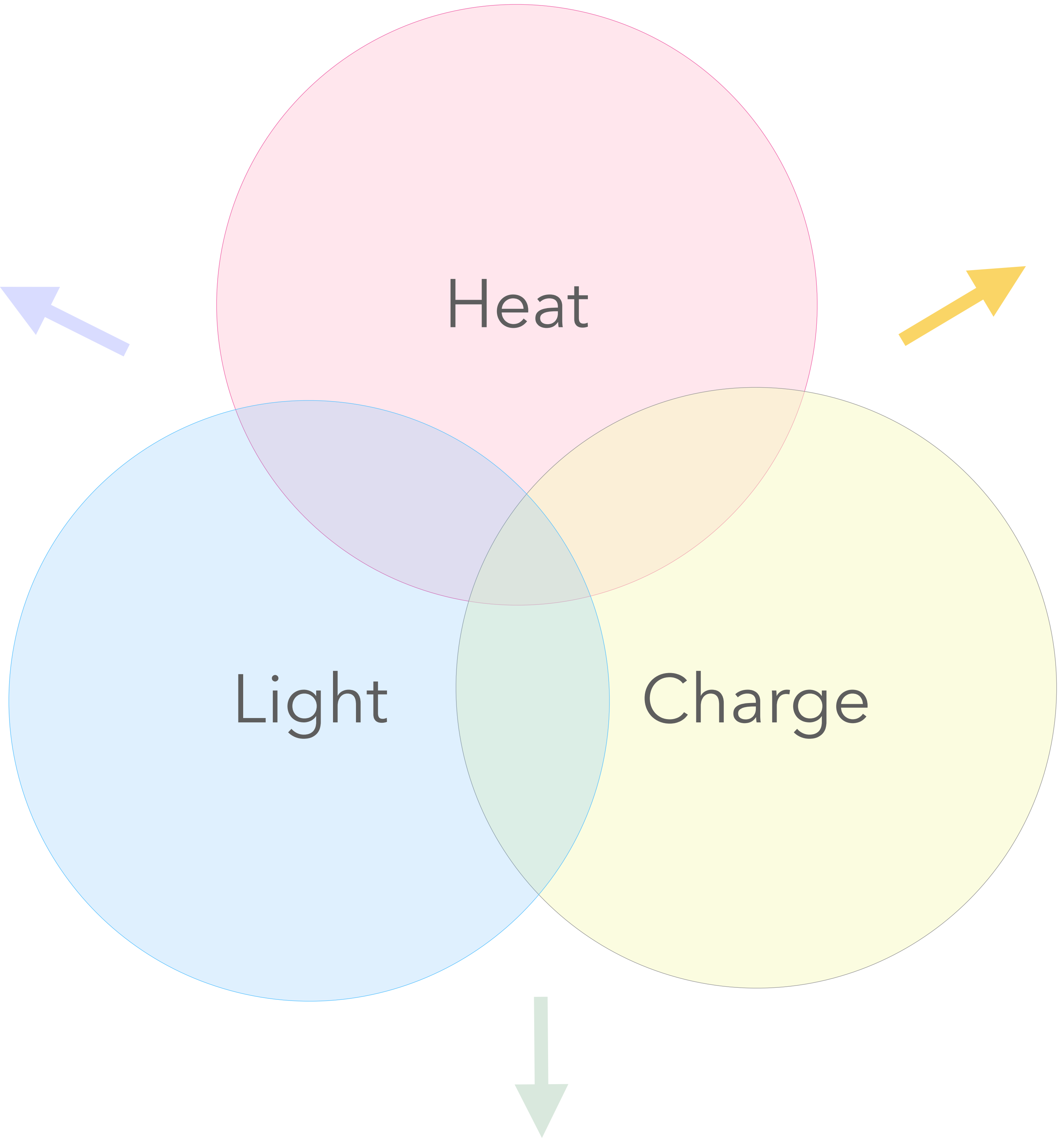
Xe: LZ, PandaX-4T,
XENONnT, DARWIN
Ar: DarkSide-50,
DarkSide-20k, ARGO

Detection channels and experiments

Cryogenic crystals

$CaWO_4$: CRESST
NaI: COSINUS

Ge, Si:
SuperCDMS
EDELWEISS



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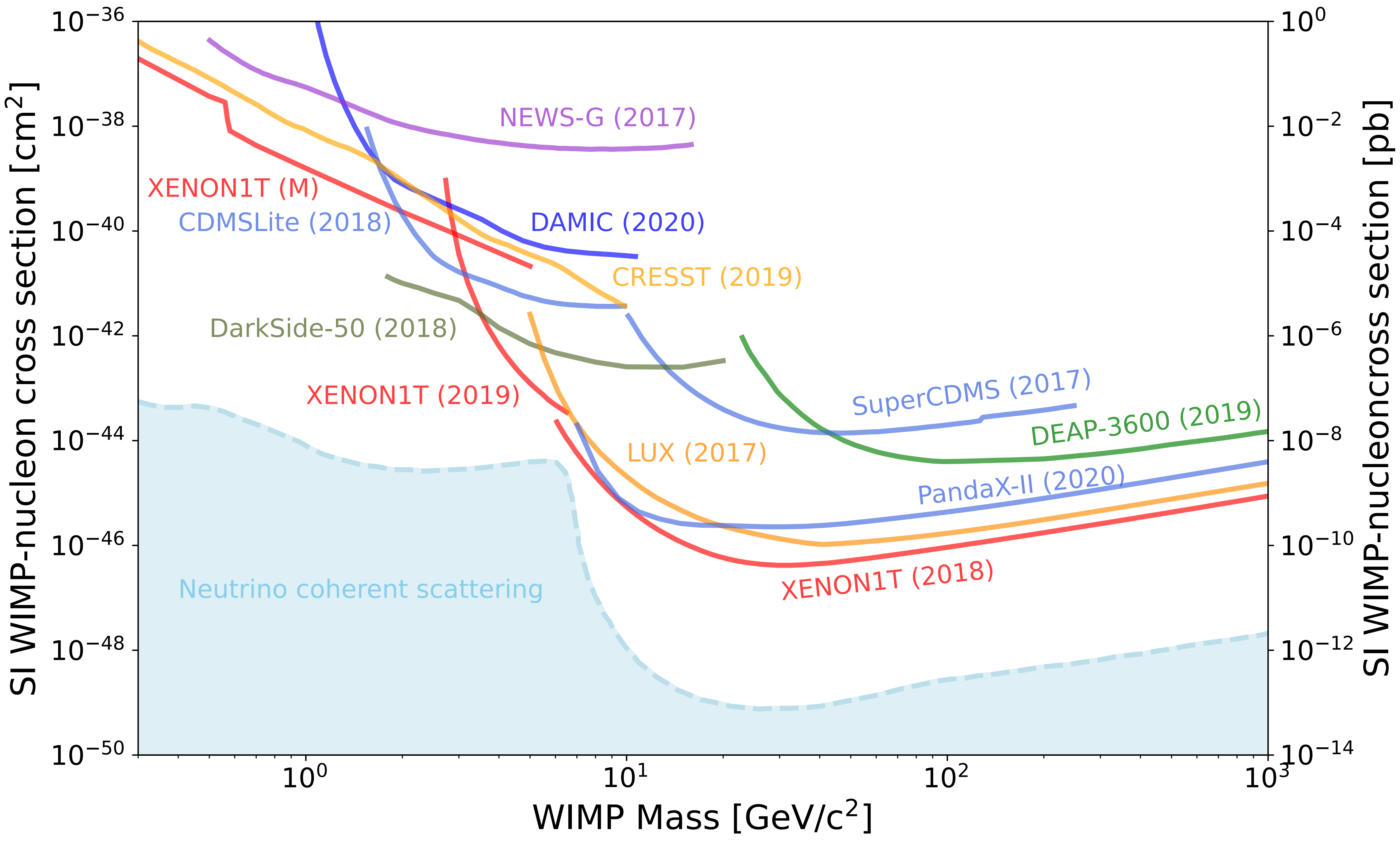
Ionisation only

Noble liquids

Xe: LZ, PandaX-4T,
XENONnT, DARWIN
Ar: DarkSide-50,
DarkSide-20k, ARGO

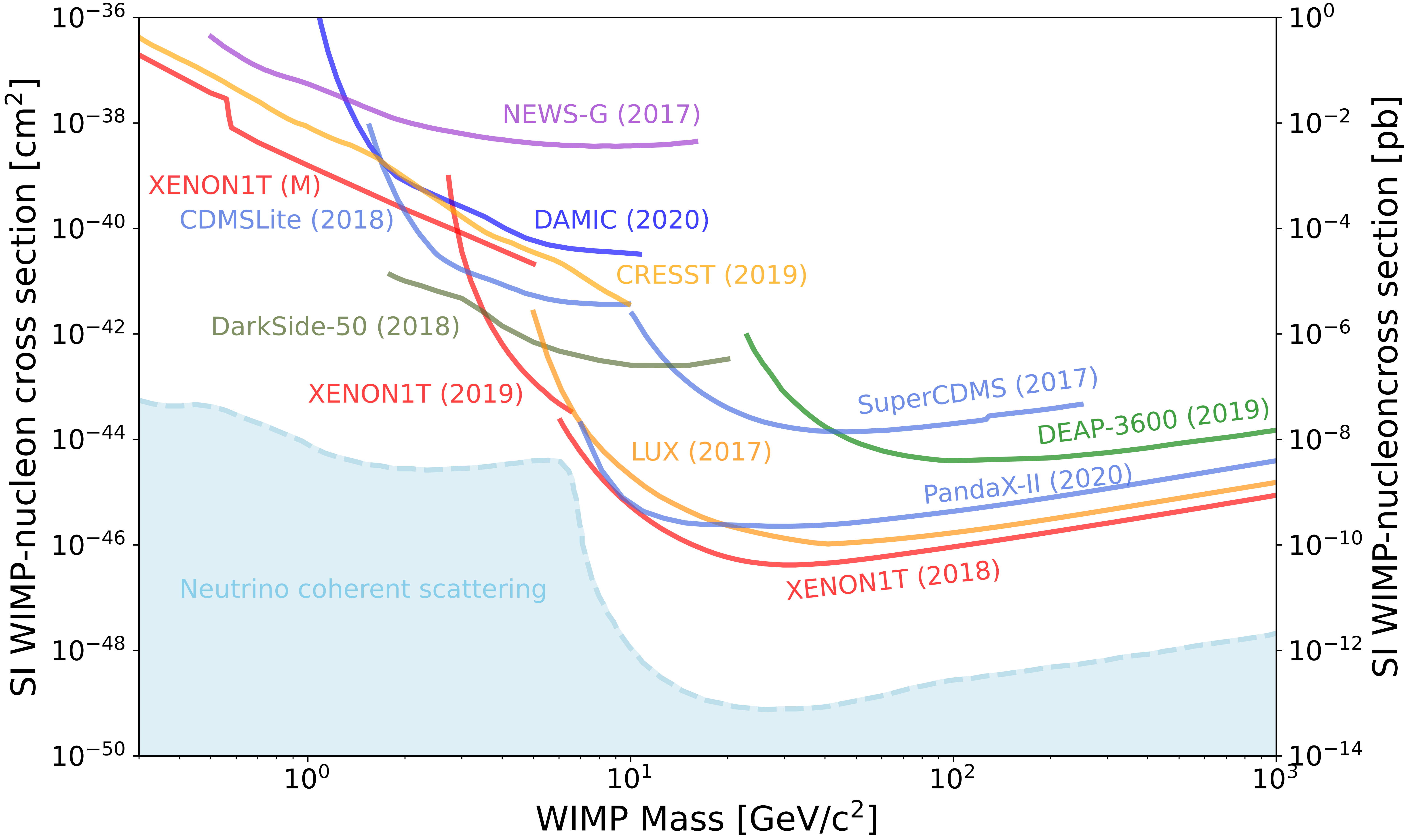
WIMP direct detection landscape



P.A. Zyla et al. (Particle Data Group) (2020)

WIMP direct detection landscape

Bolometers, CCDs, new technologies

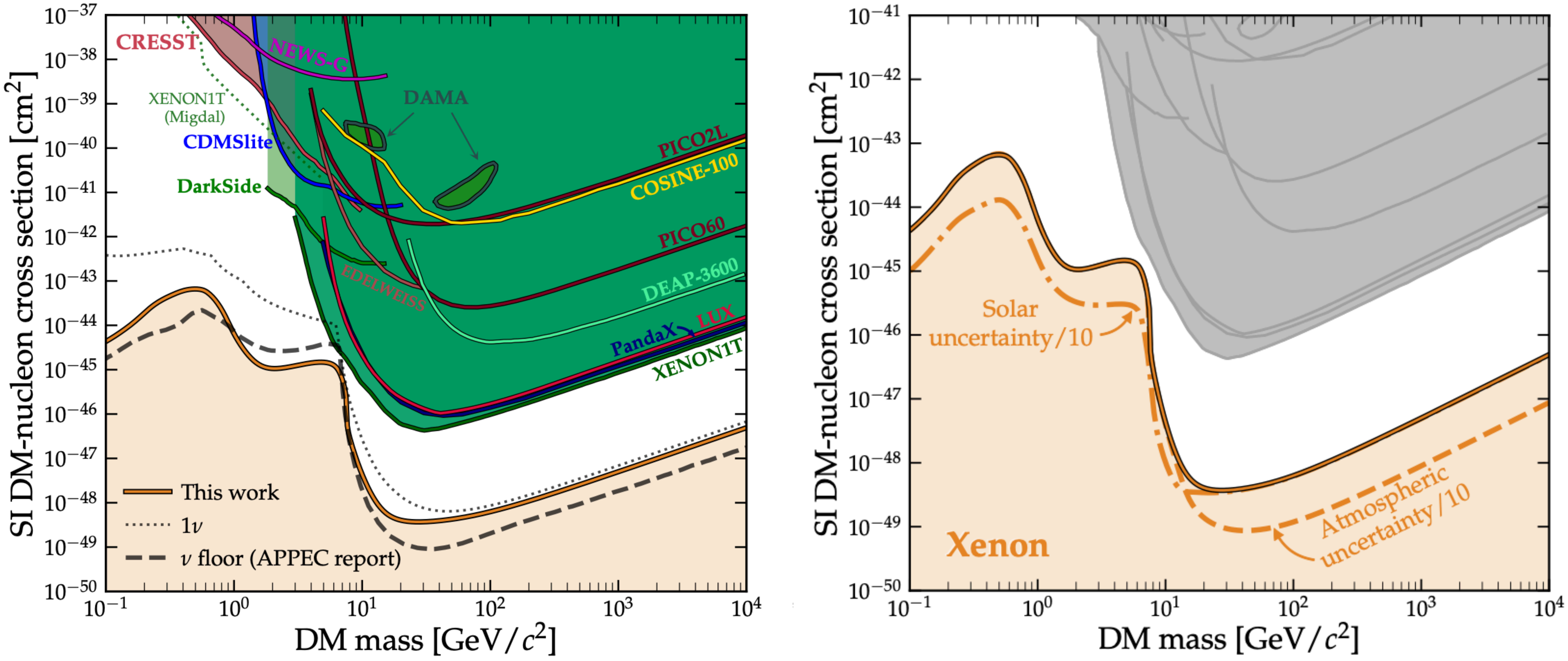


Noble liquids

P.A. Zyla et al. (Particle Data Group) (2020)

Neutrino backgrounds

Fog on the horizon

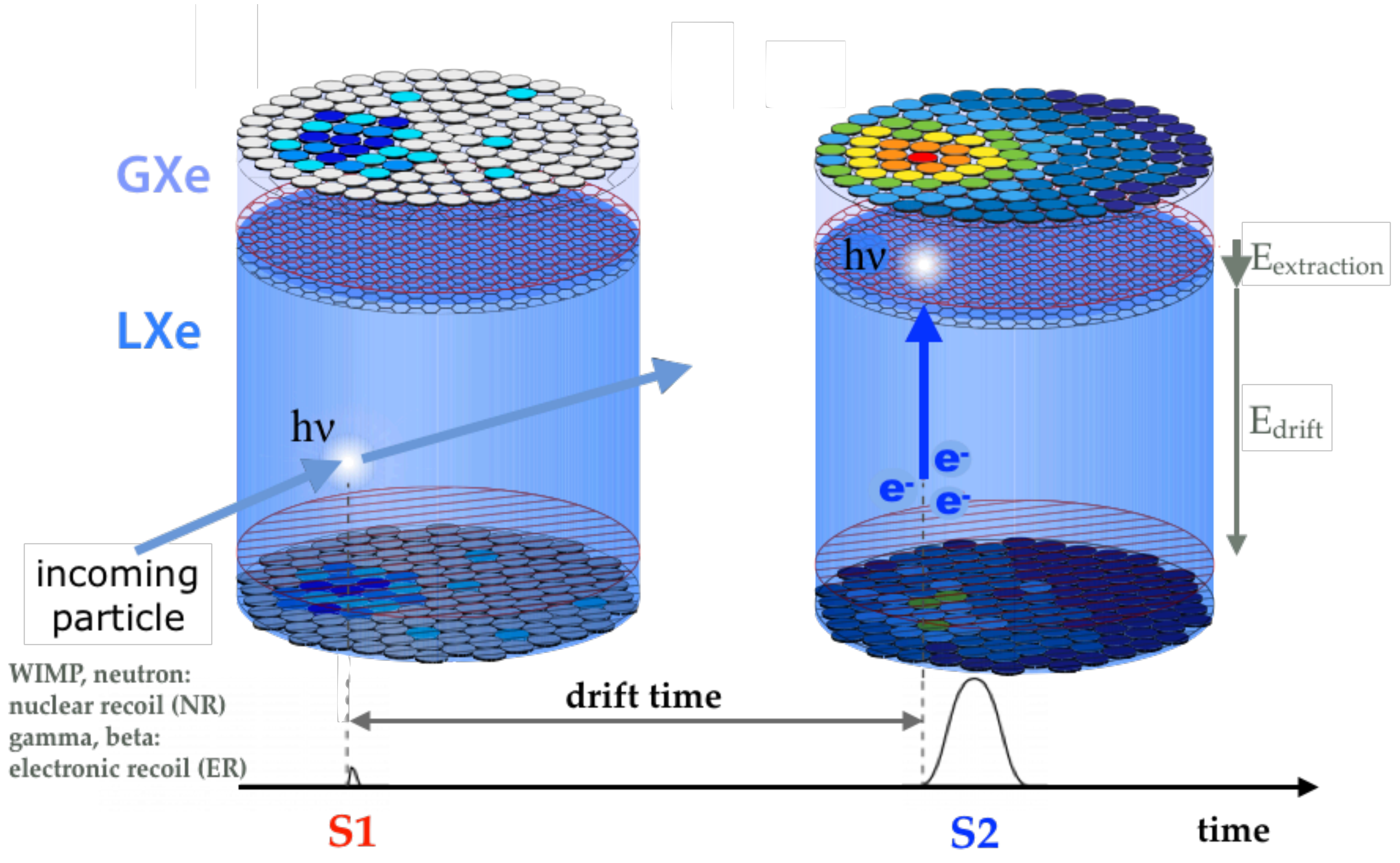


O'Hare, Phys. Rev. Lett. 127 (2021) 251802

Noble liquids

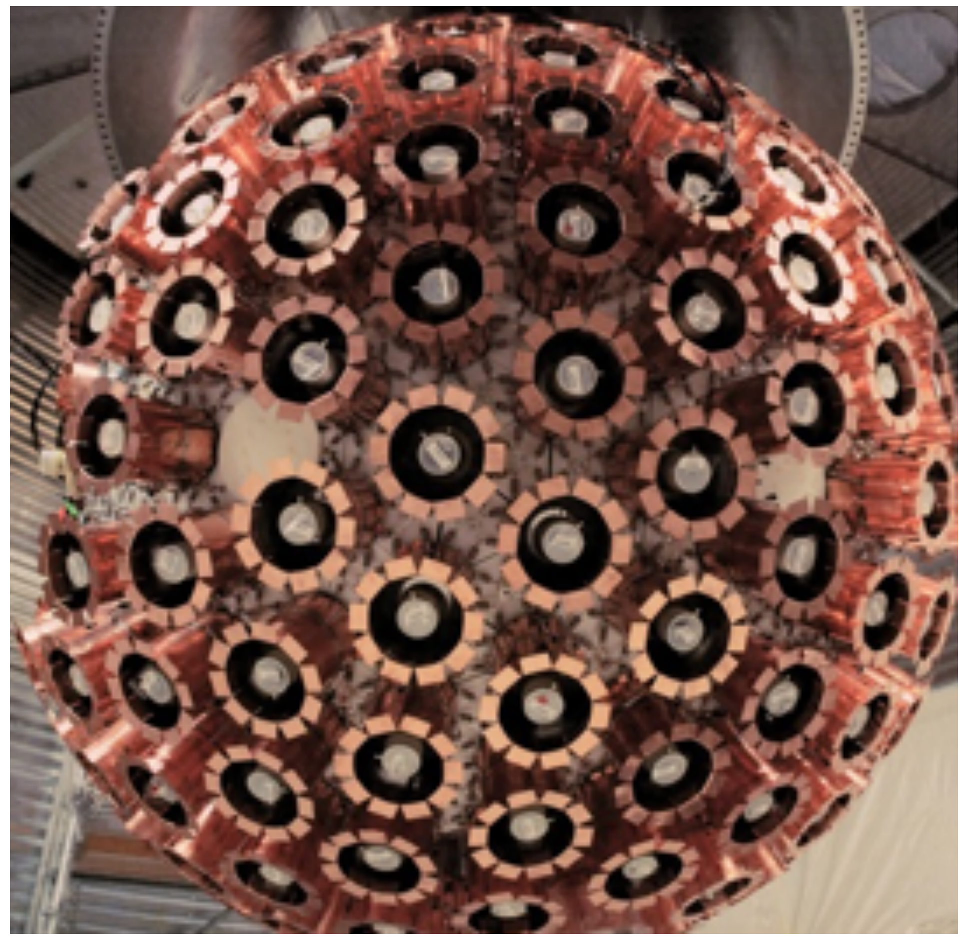
GeV to TeV DM masses

- High atomic number & high density (stopping power, self-shielding, position resolution)
- Can be easily liquified (-100 C) and purified
- Large detector masses feasible due to scalability
- Ar: pulse shape discrimination based on scintillation decay times
- Ar, Xe: Time Projection Chambers discriminate using light + charge
- May see market limits (Xe) and requires large amounts (Ar), stored underground

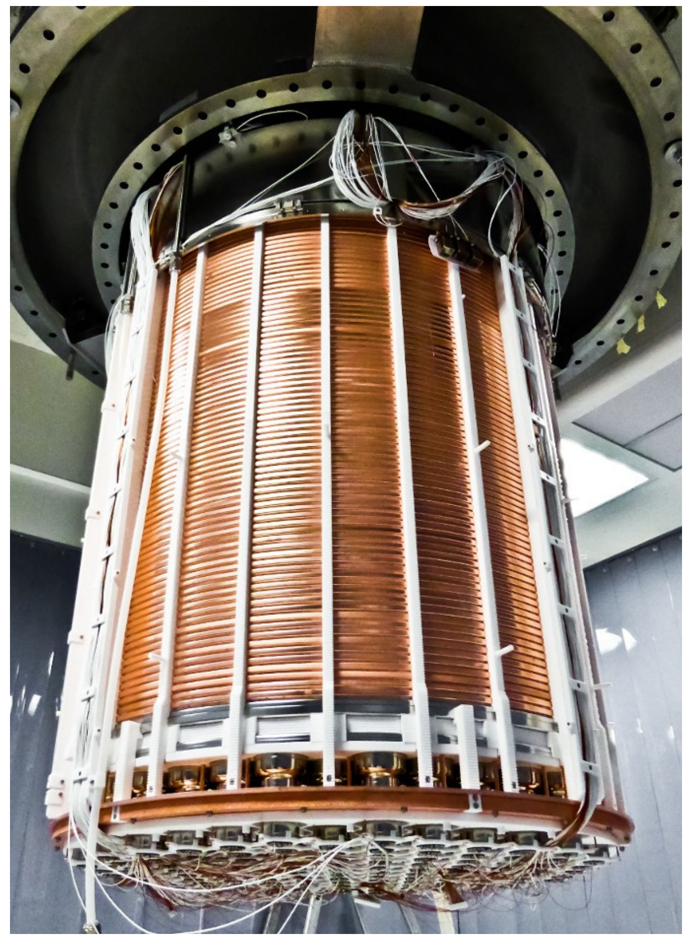


XMASS

DEAP-3600



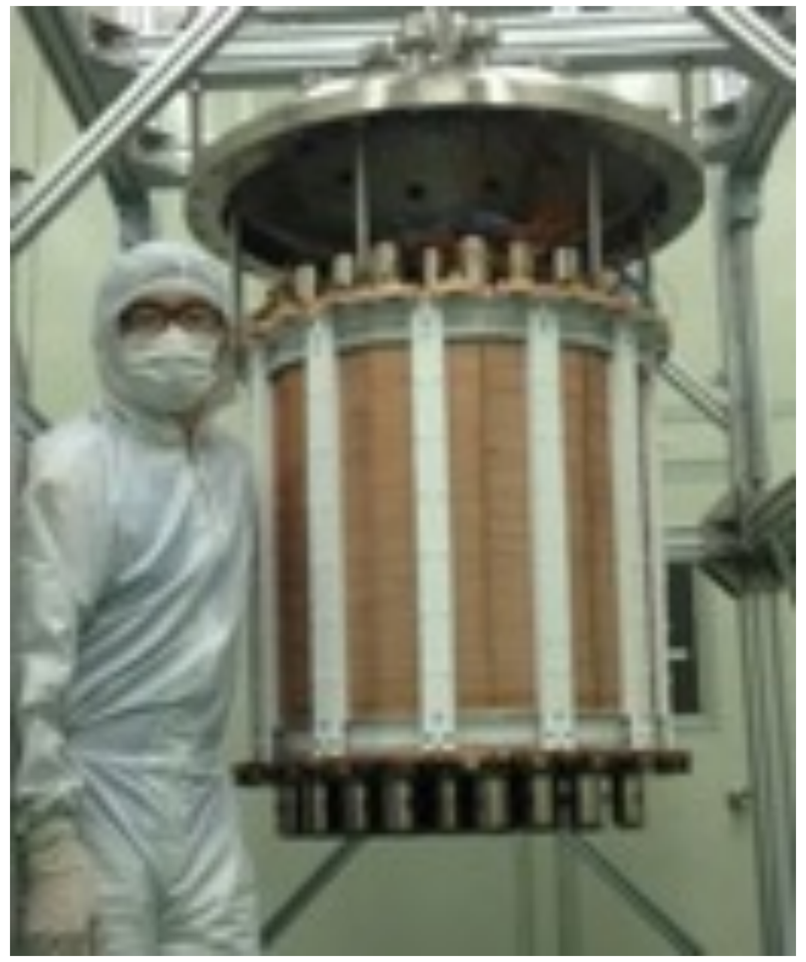
XENON1T



LUX

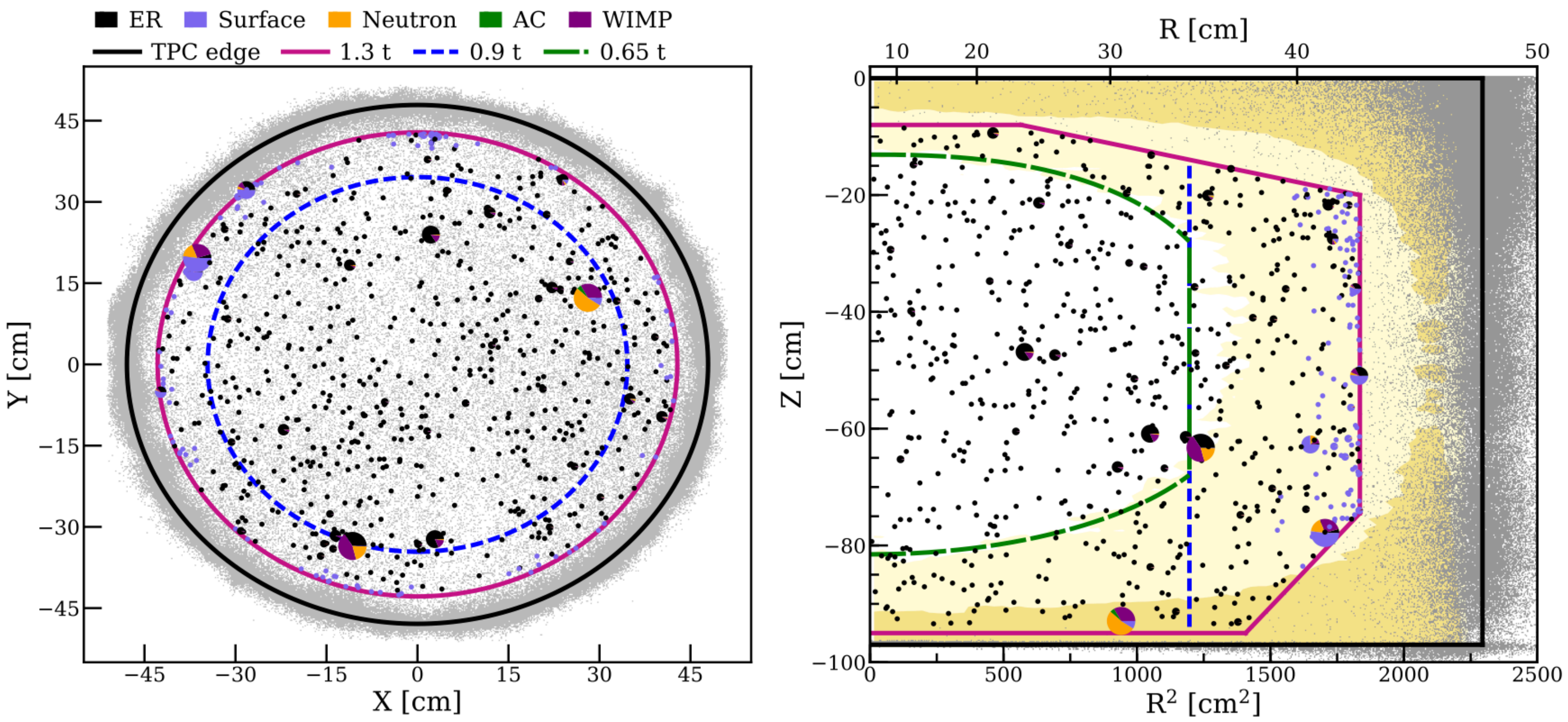
DarkSide-50

PandaX-II

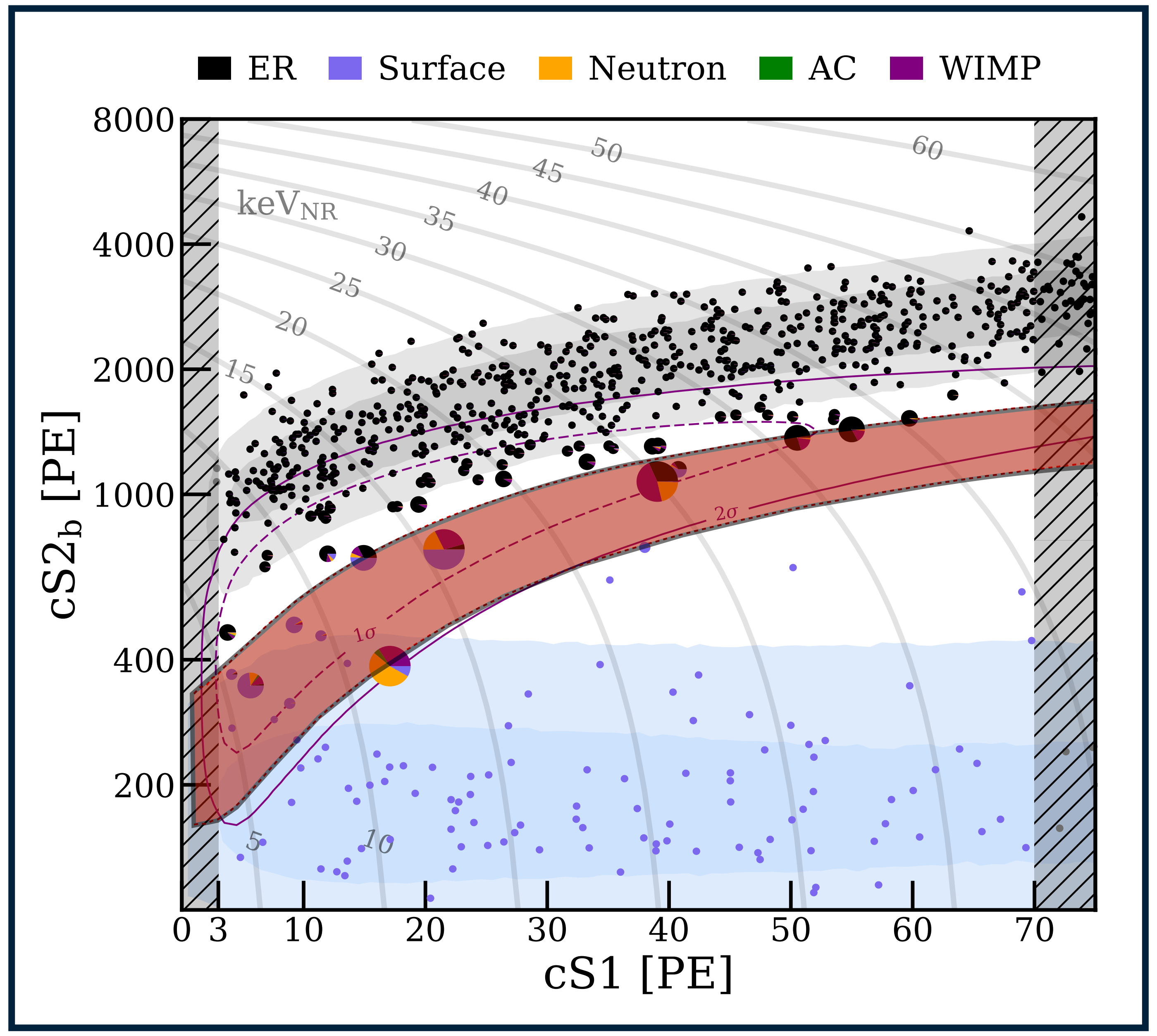


Noble liquids

Example: XENON1T



Nuclear Recoils (NR)
(WIMPs, neutrons)

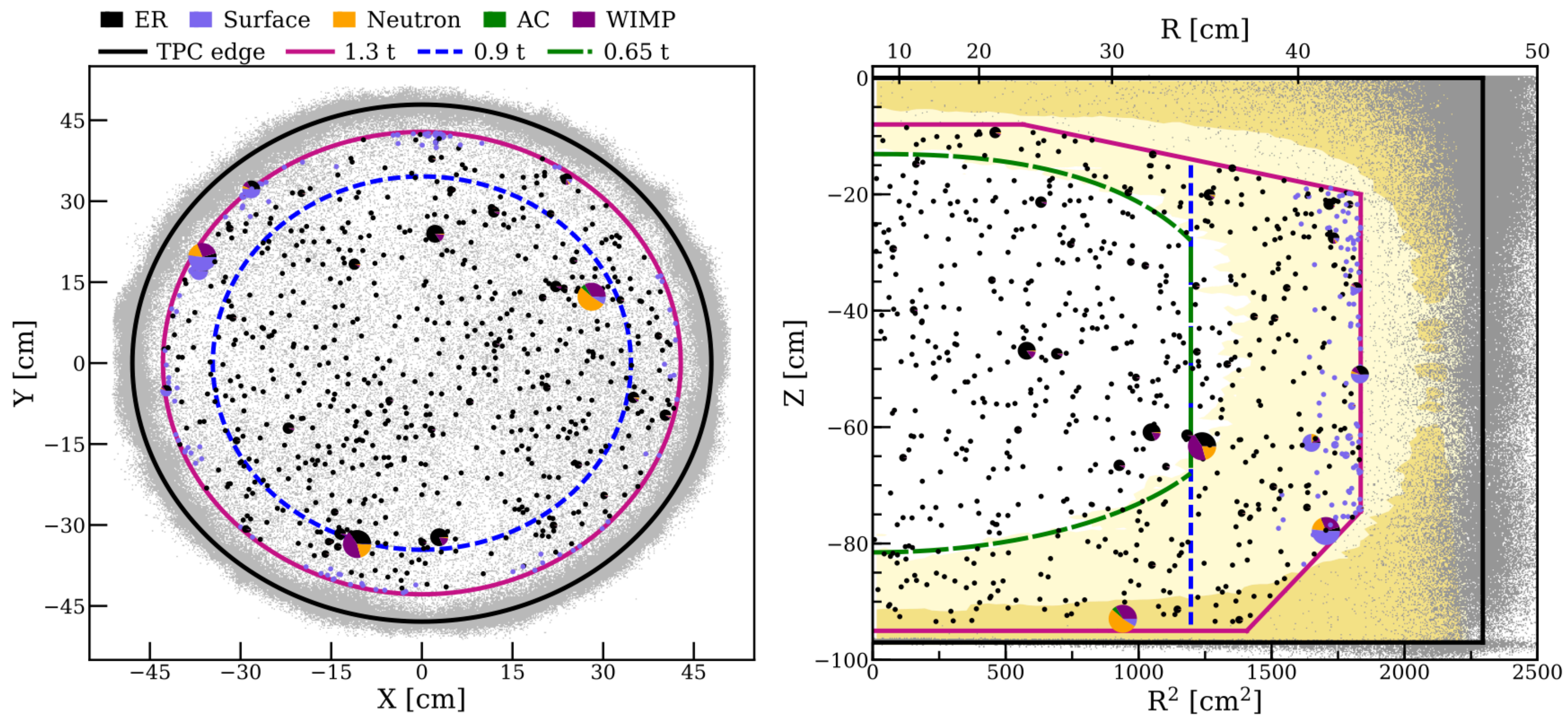


WIMP Dark Matter search channel

- fiducialization: remove events from detector materials
- WIMPs would scatter only once in detector (remove multiple scatters)
- ~1 keV thresholds

Noble liquids

Example: XENON1T



Nuclear Recoils (NR)
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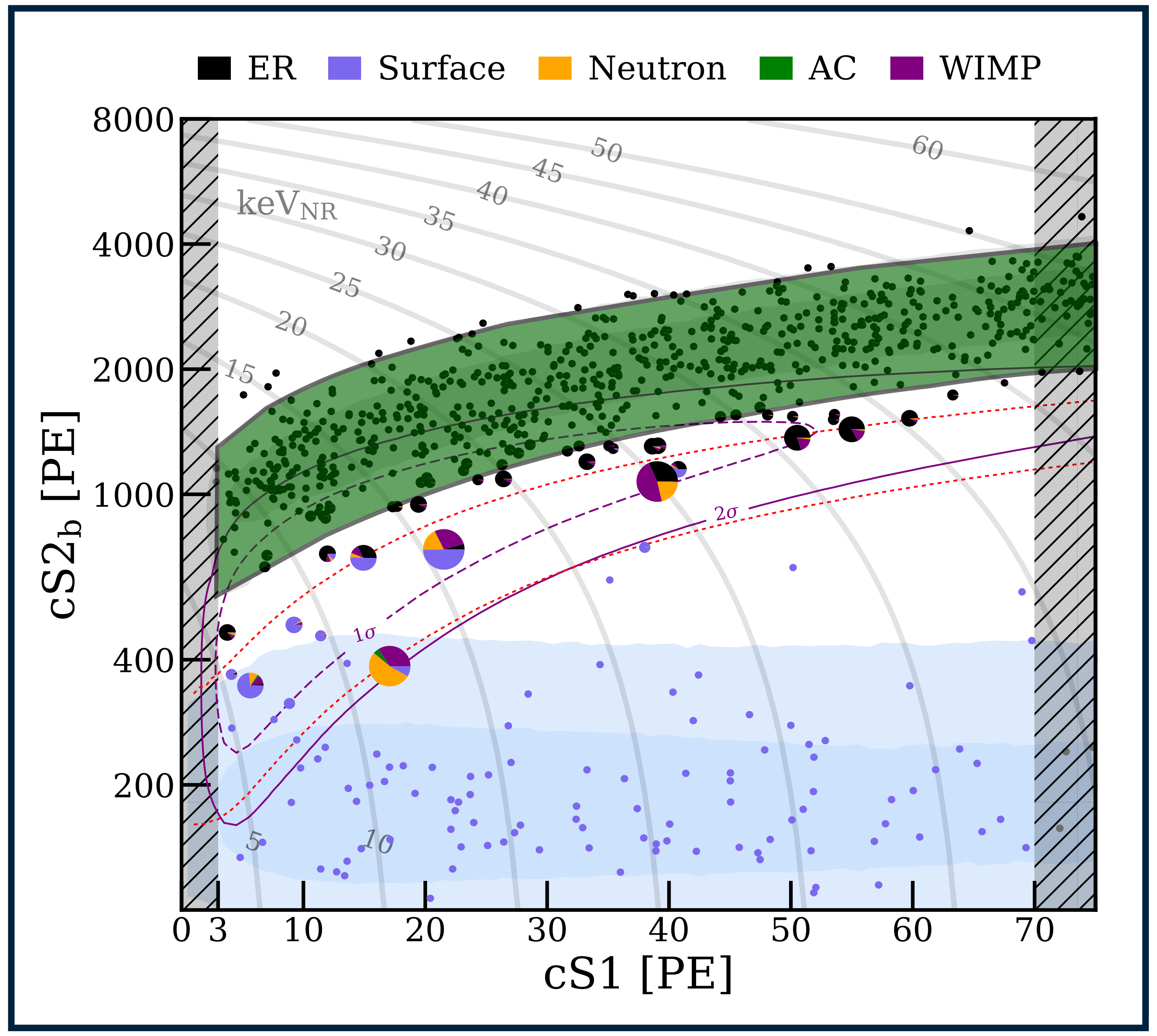
Electronic Recoils (ER)
(gammas, betas, new physics)



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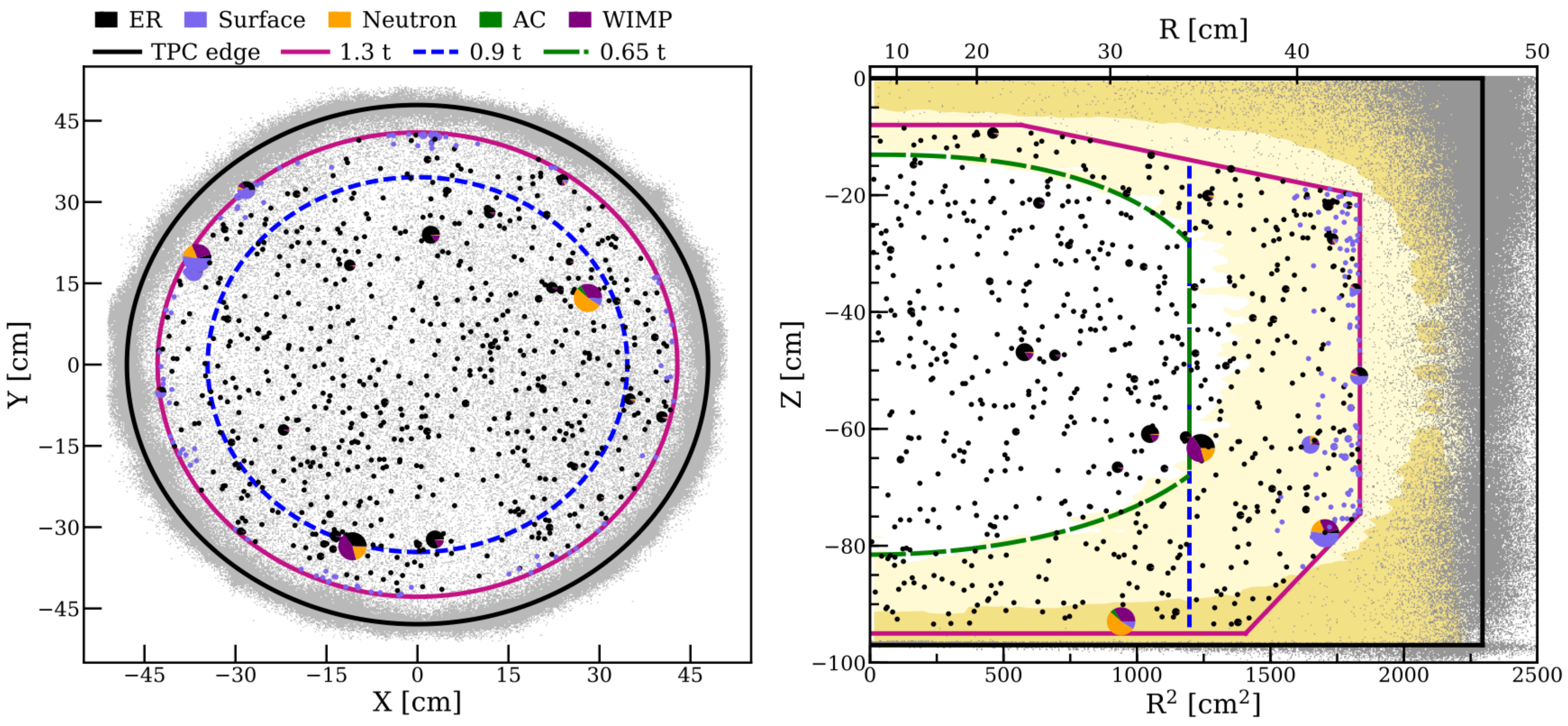

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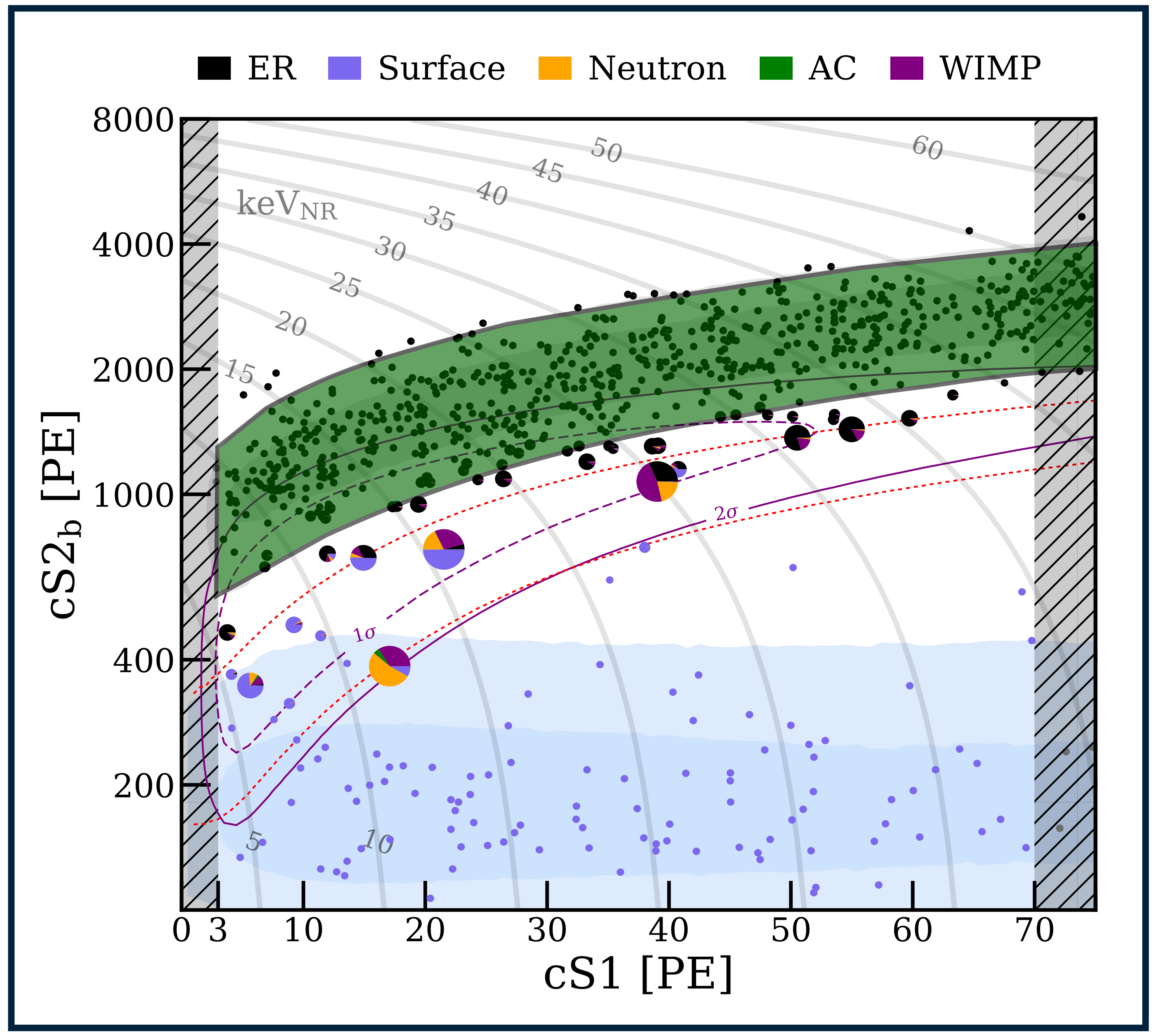

WIMP Dark Matter search channel

- fiducialization: remove events from detector materials
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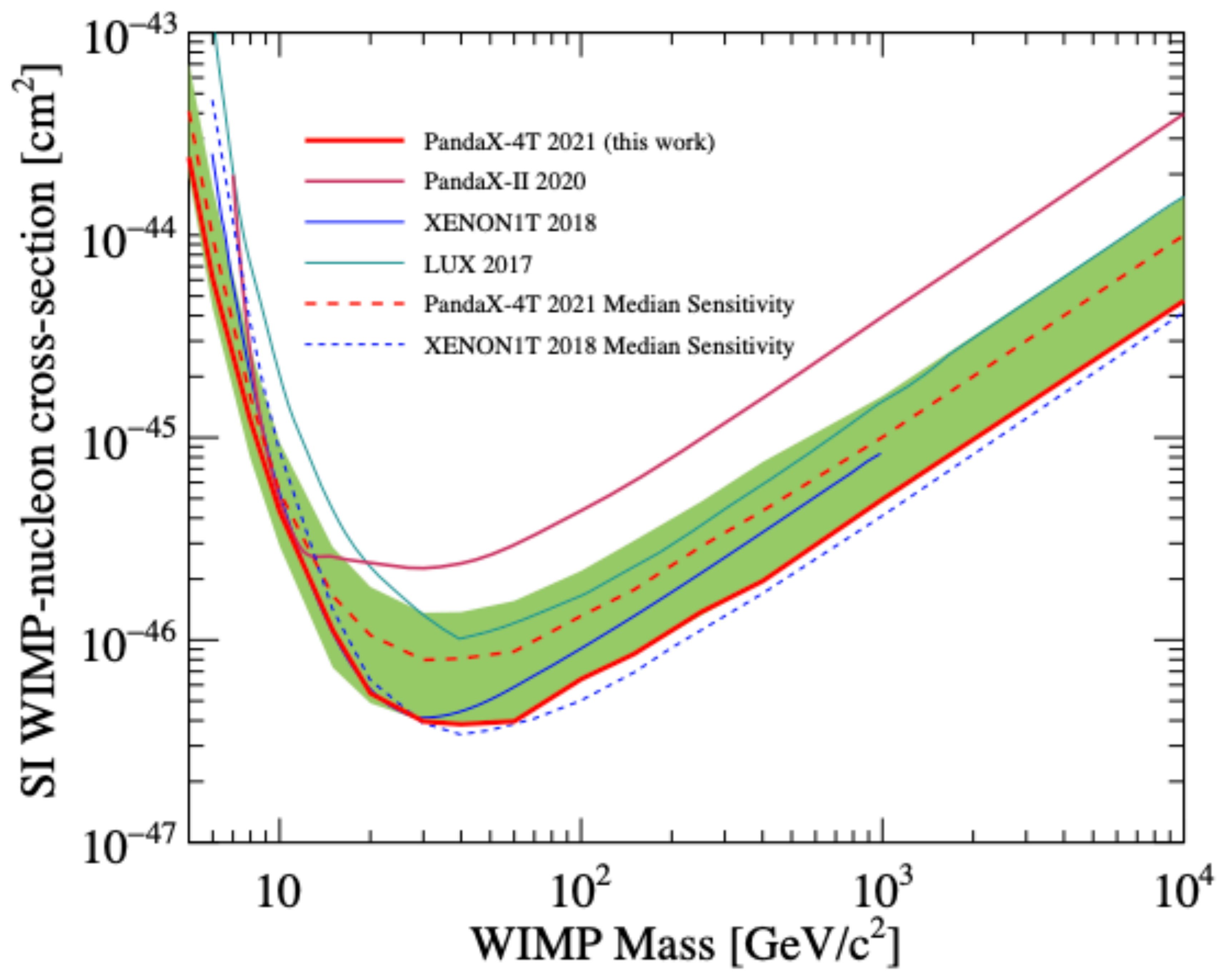
- ~1 keV thresholds

< 100 events/(t/yr/keV$_{ee}$)

Can also search for excess above known ER backgrounds.

Noble liquids

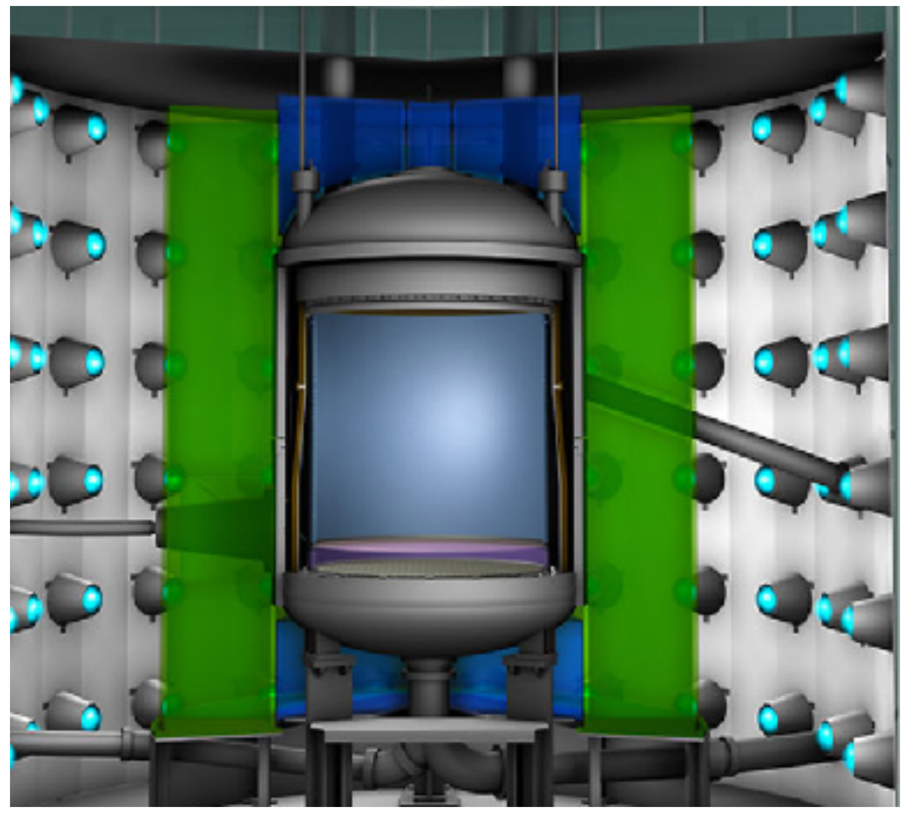
Current and future experiments



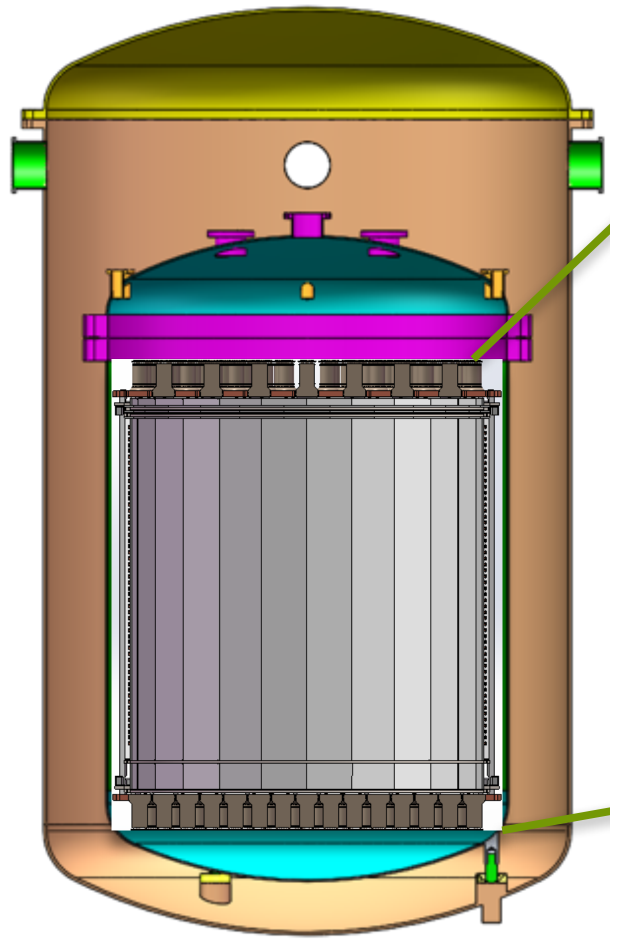
PhysRevLett.127.261802 (2021)

PandaX-4T: 0.63 tonne yr (3.7 t) 90% C.L.

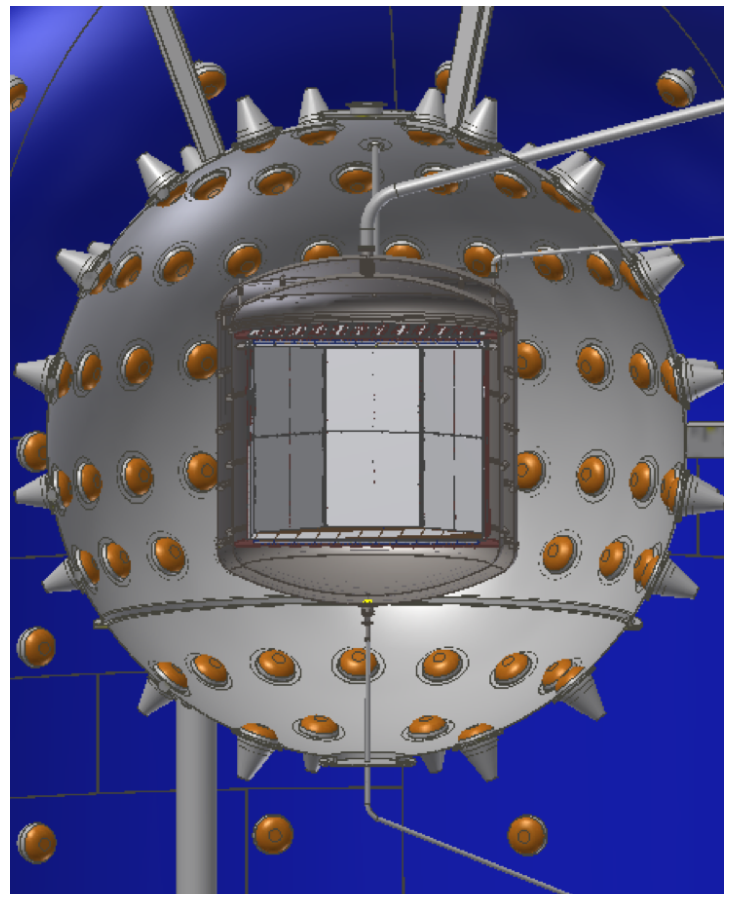
XENONnT: 8.6 t LXe
Data taking 2021



LUX-ZEPLIN: 10 t LXe
Data taking 2021



PandaX-4t LXe
First result 2021

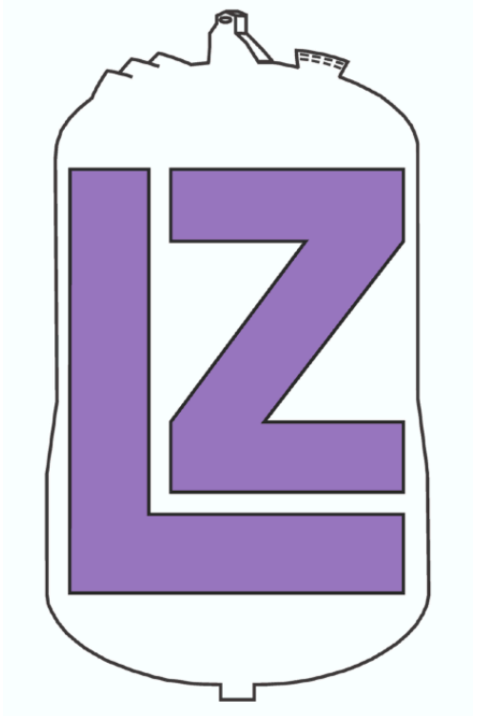


DarkSide: 20 t LAr
Data taking 2023 ->
towards ARGO 360 t

Future xenon-based experiment:

DARWIN

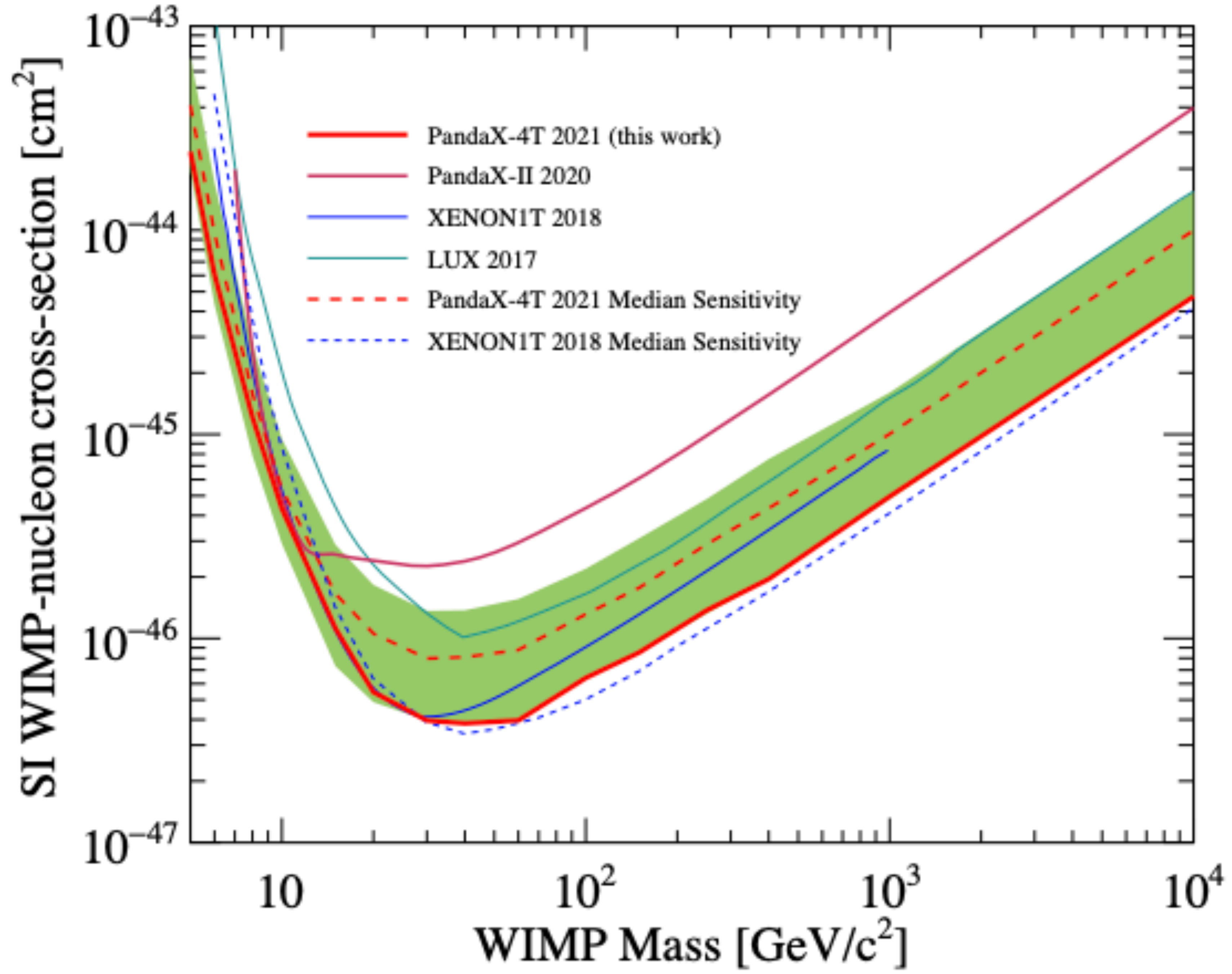
+



~50 t LXe
Data taking ~2027/28

Noble liquids

Current and future experiments



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Noble liquid future includes helium:
see Dan McKinsey talk tomorrow

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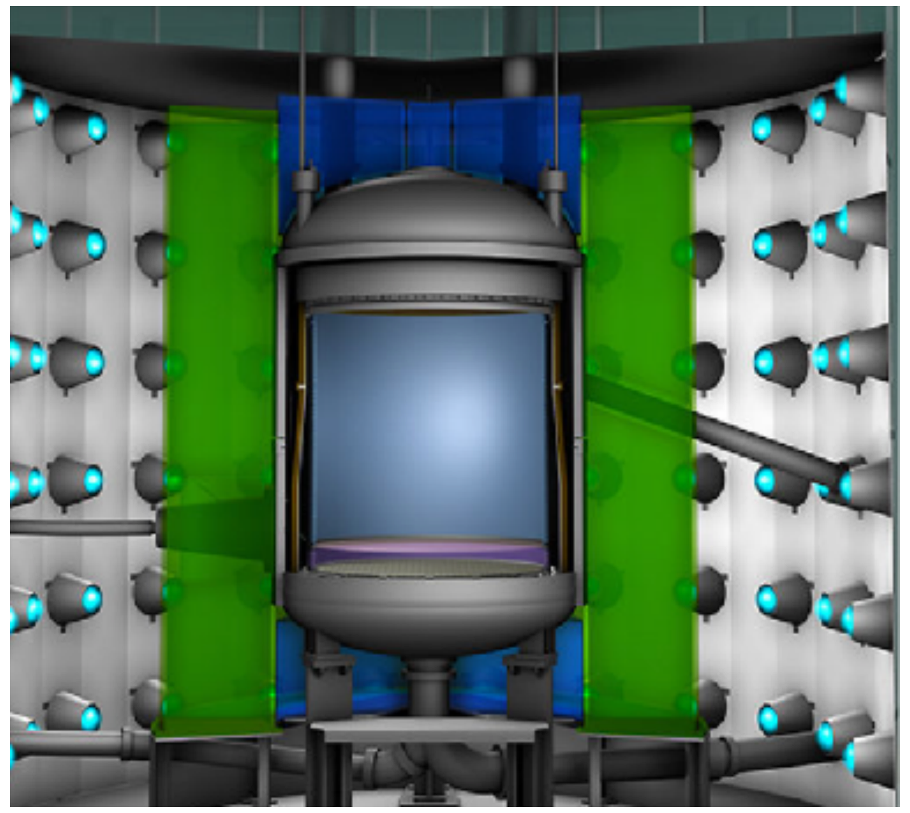

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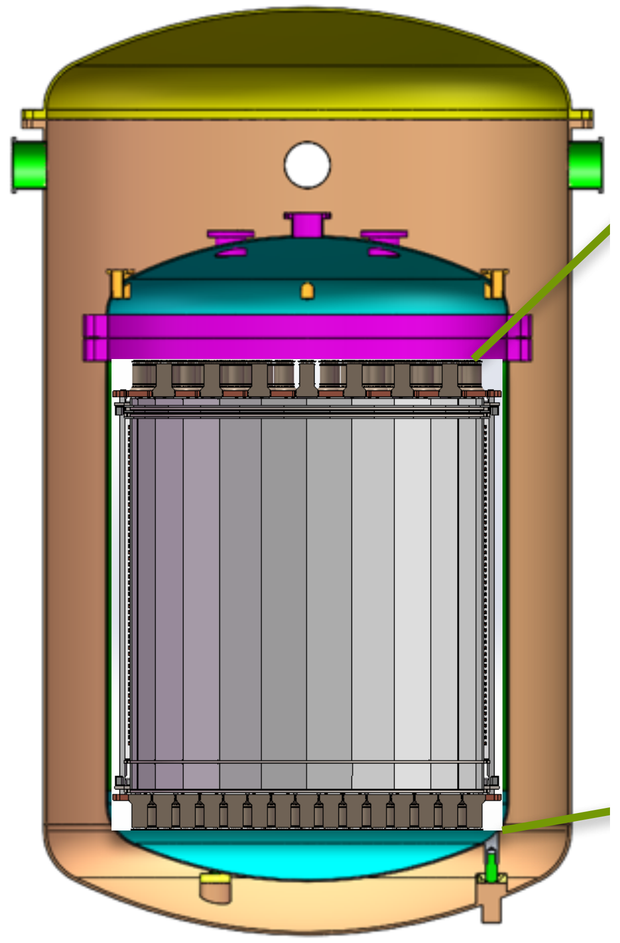
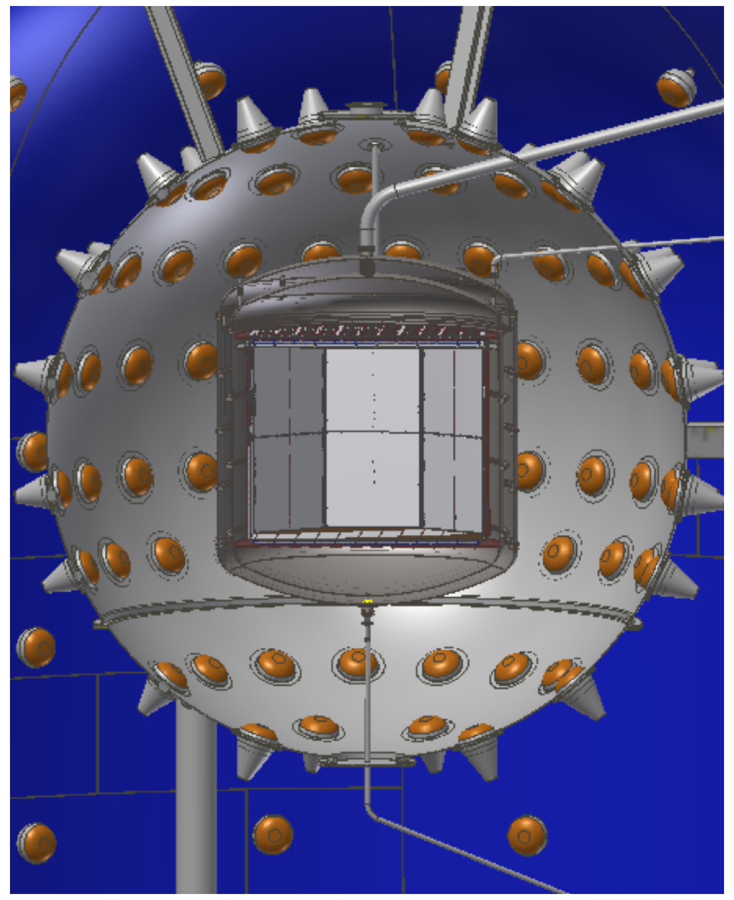


PandaX-4t LXe
First result 2021



DarkSide: 20 t LAr
Data taking 2023 ->
towards ARGO 360 t

Future xenon-based experiment:

DARWIN

+

~50 t LXe
Data taking ~2027/28

Semiconductor cryogenic crystals

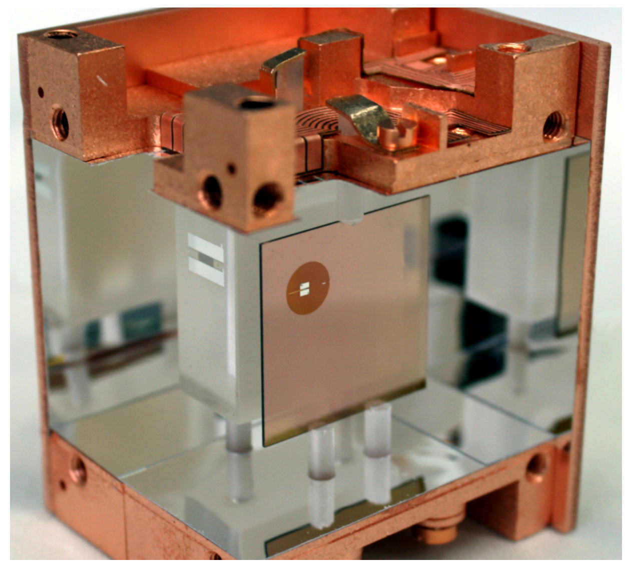
sub-GeV to GeV DM masses

- Temperatures ~mK allow for detection of small temperature increase; direct measure of energy deposition
- Simultaneous scintillation (CRESST - TES) or ionisation (SuperCDMS- TES, EDELWEISS - NTD thermistors)
- Very low thresholds - tens of eV
- Scaling up requires multiple small crystals

Ongoing and future

- CRESST-III: 30 eV threshold; best limits down to 160 MeV
- SuperCDMS relocated to SNOLAB; 30 kg Ge, Si targets to start science run soon.
- EDELWEISS testing TES sensors

CRESST

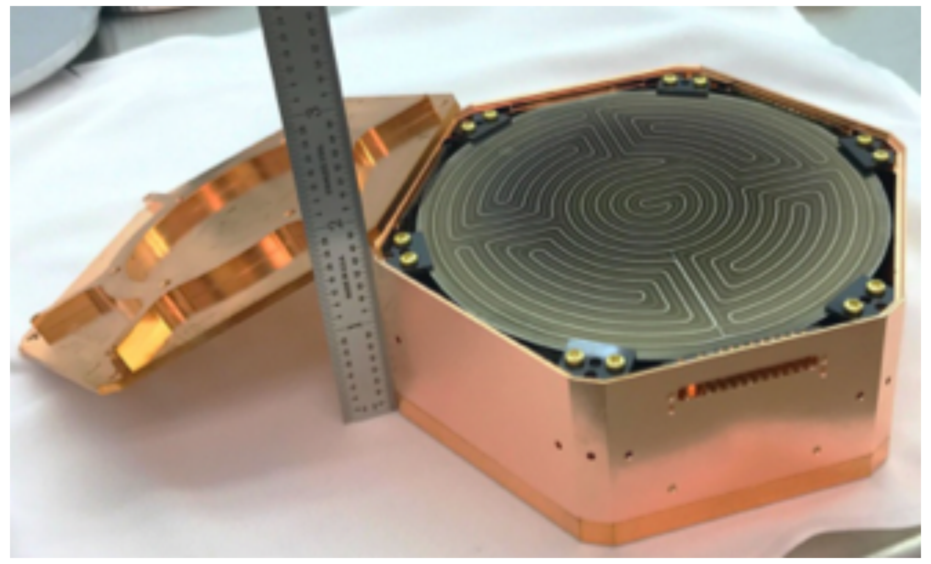


$CaWO_4$, Al_2O_3

EDELWEISS

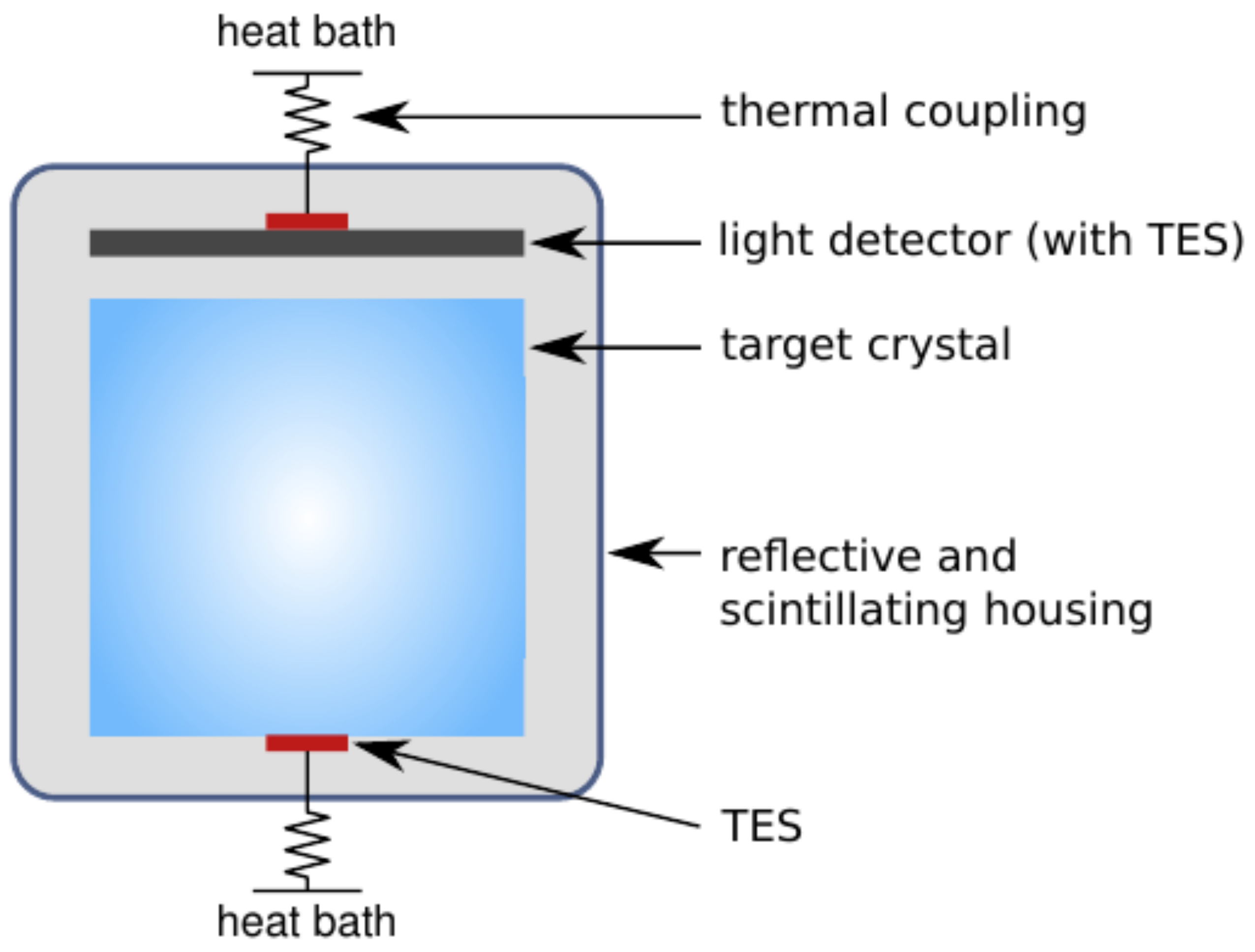
Ge

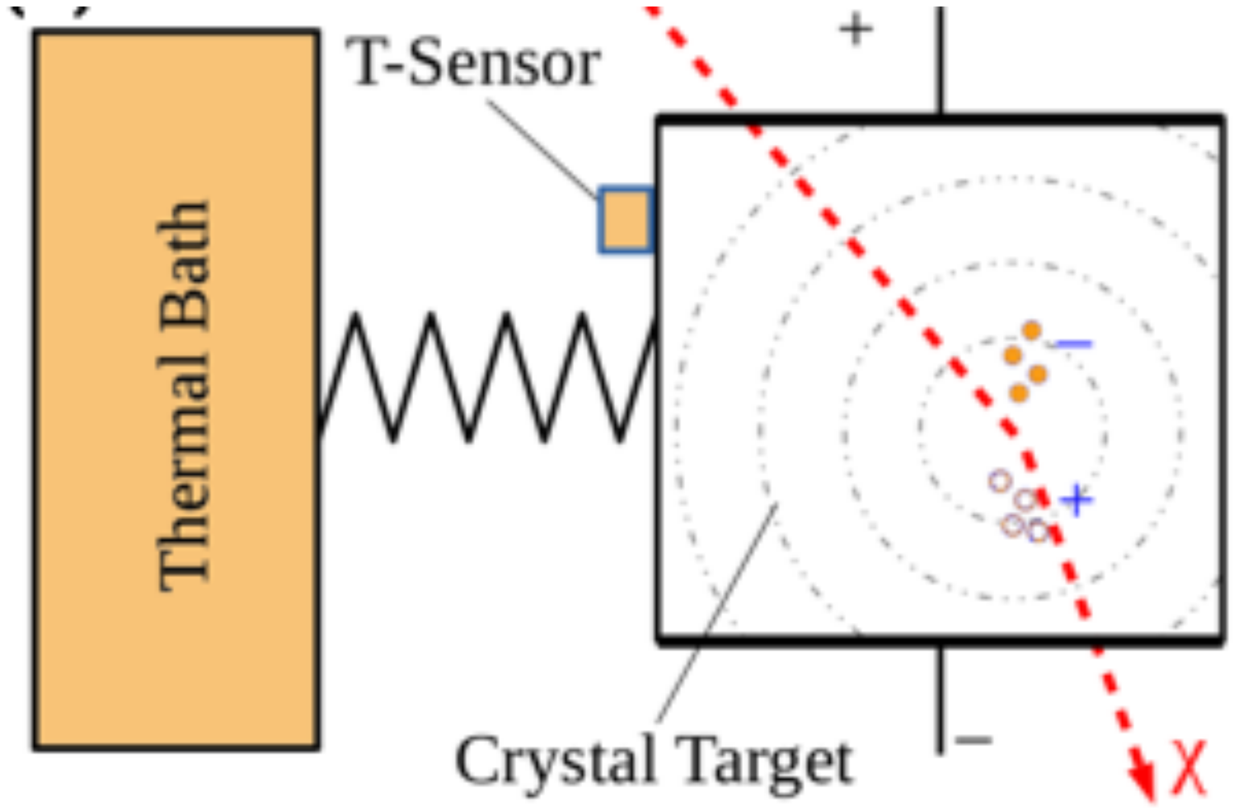
Super-CDMS



Ge, Si

Bolometric technique





APPEC DM Report, Billard et al, arXiv:2104.07634 (2021)

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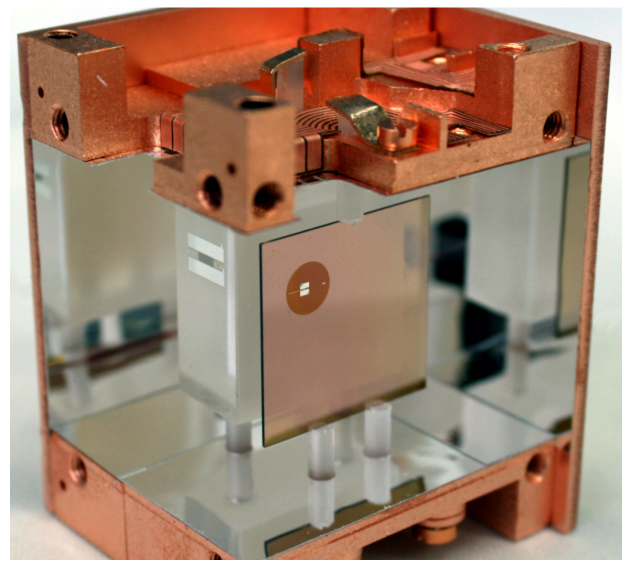
CRESST

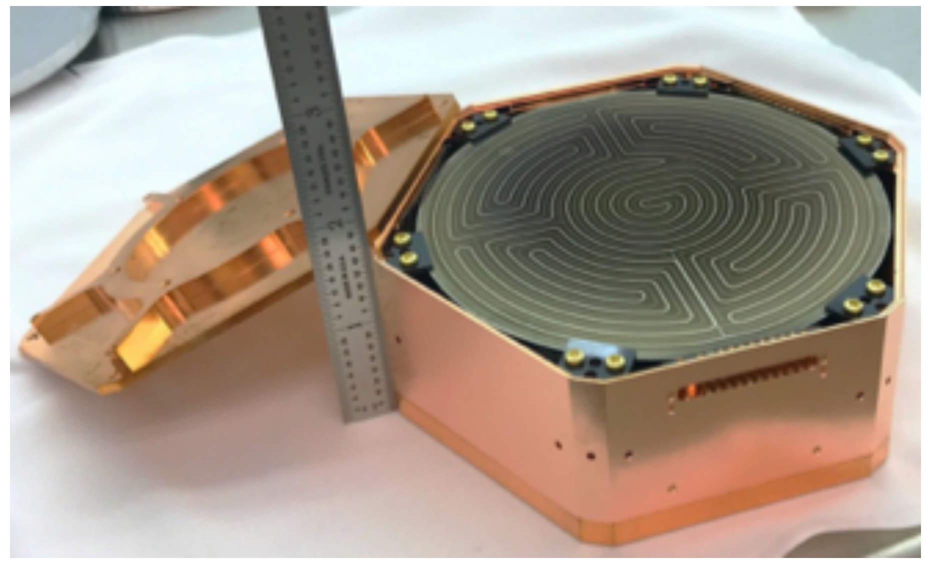


$CaWO_4$, Al_2O_3

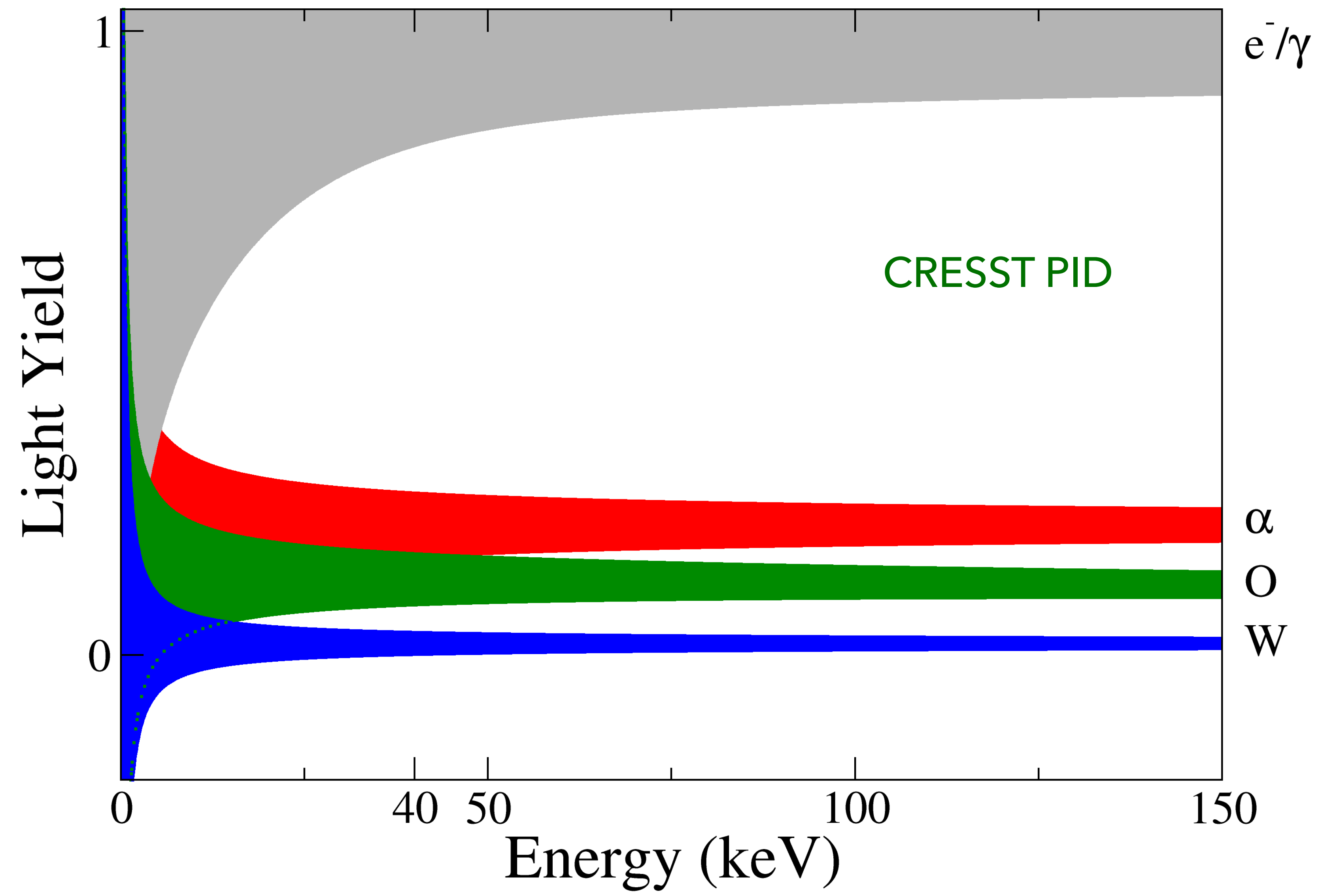
EDELWEISS

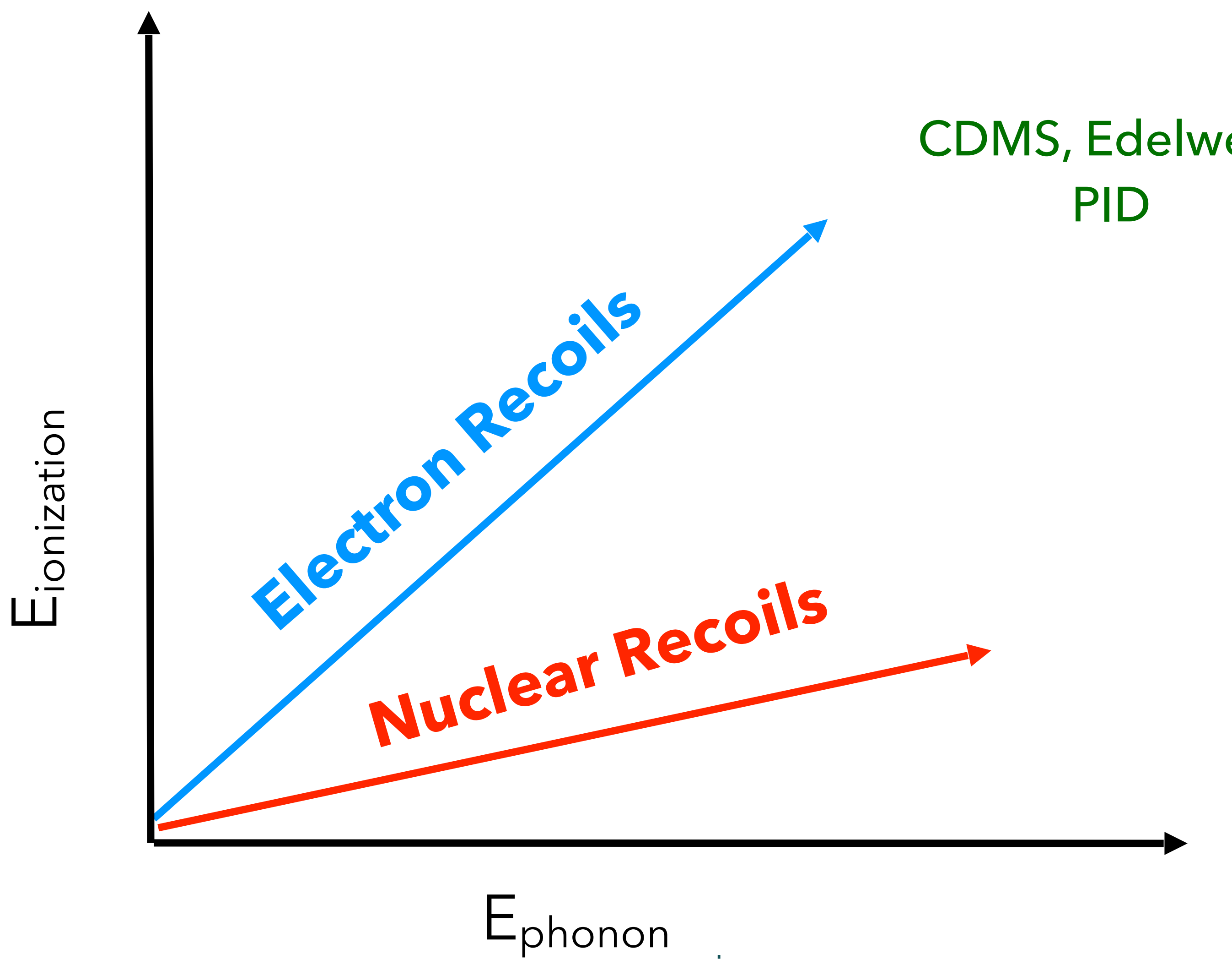
Ge

Super-CDMS



Ge, Si

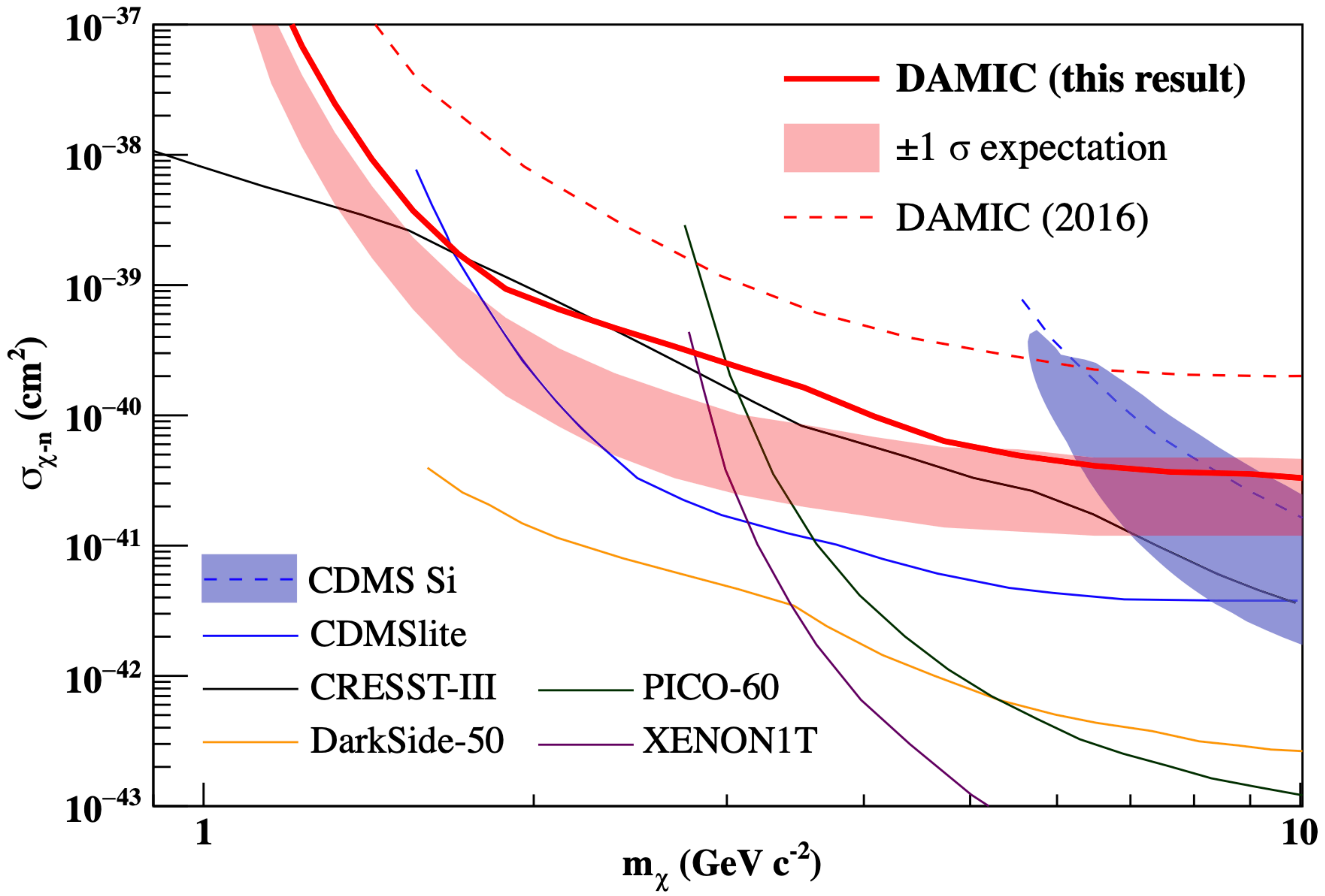




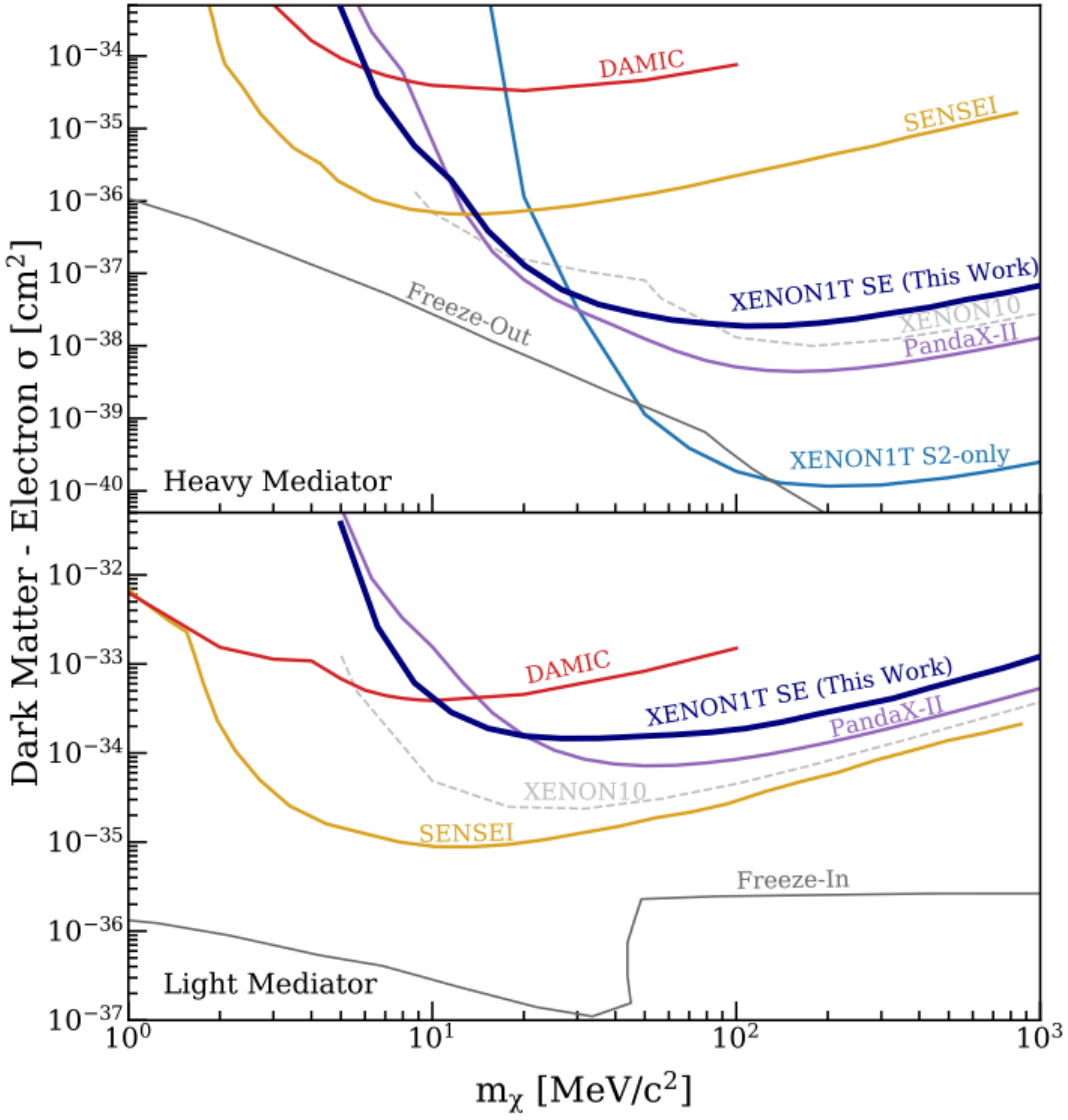
Ionisation-only

MeV to GeV DM masses

- Silicon charge-coupled devices (CCDs) - low ionisation energy, low noise, pixellated, particle tracks for background reduction (DAMIC, SENSEI)
- DAMIC-M from 7 CCDs (SNOLAB) to 50 CCDs (MODANE); x50 reduction in background; commissioning ~2023
- SENSEI - from 2 g to 100 g at SNOLAB



DM-electron scattering



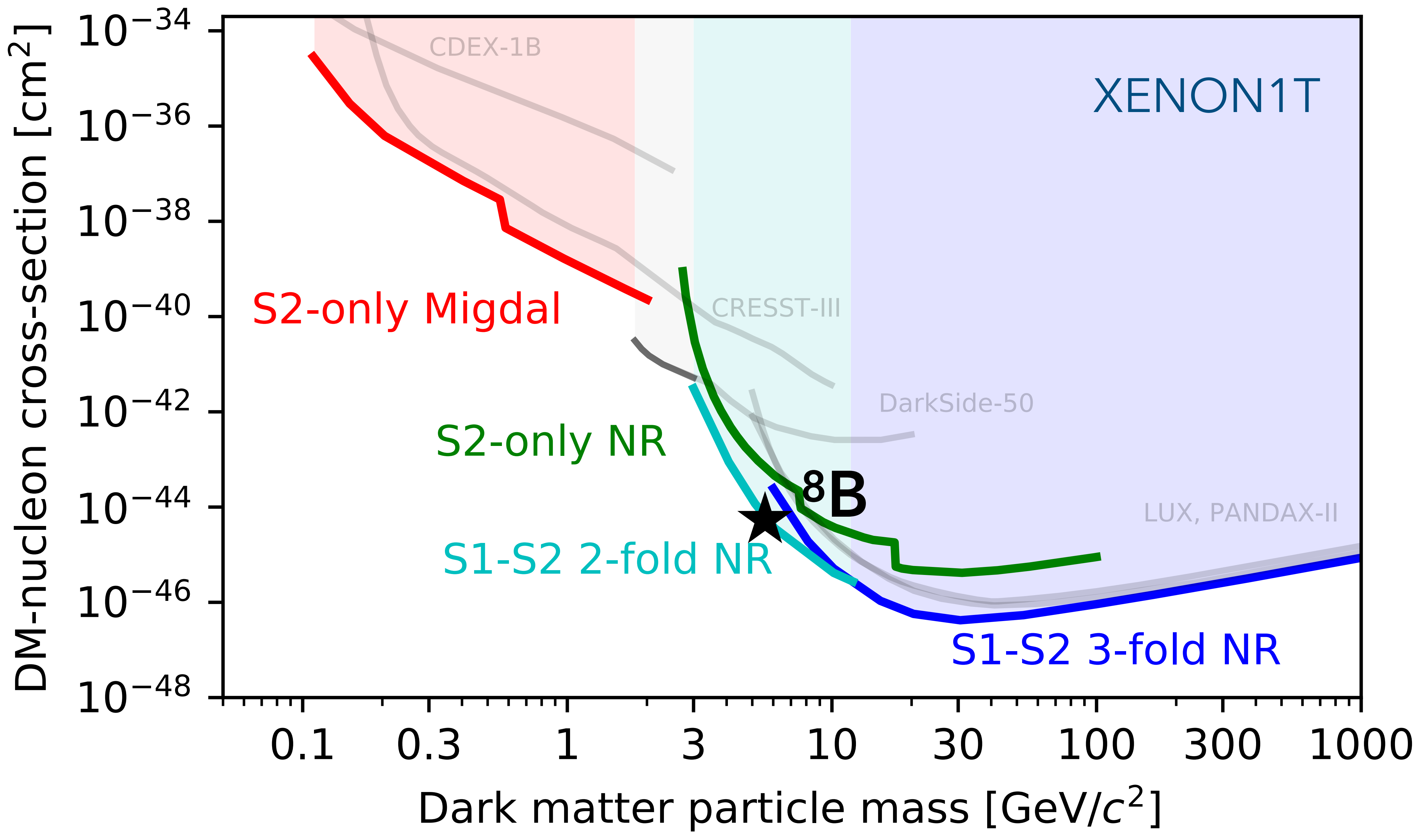
DAMIC, Phys. Rev. Lett. 125, 2020 SENSEI Collab., Phys. Rev. Lett. **122**, 161801 XENON collab., arXiv:2112.12116v1 (2022)

Probing lower DM masses

WIMP-nucleon and WIMP-electron scattering

S2-only channel

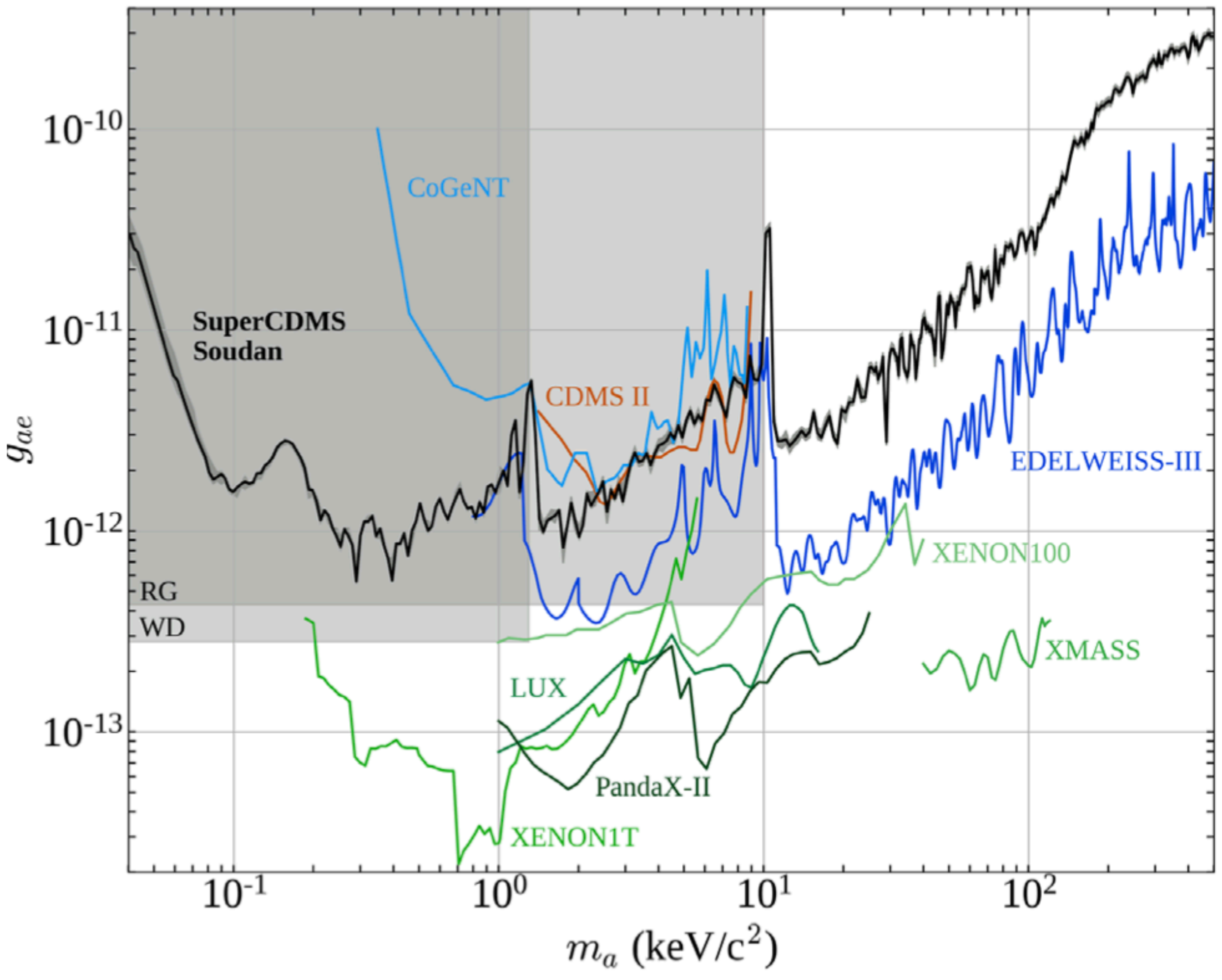
Limit setting only; interpreted as nuclear recoils or electron recoils



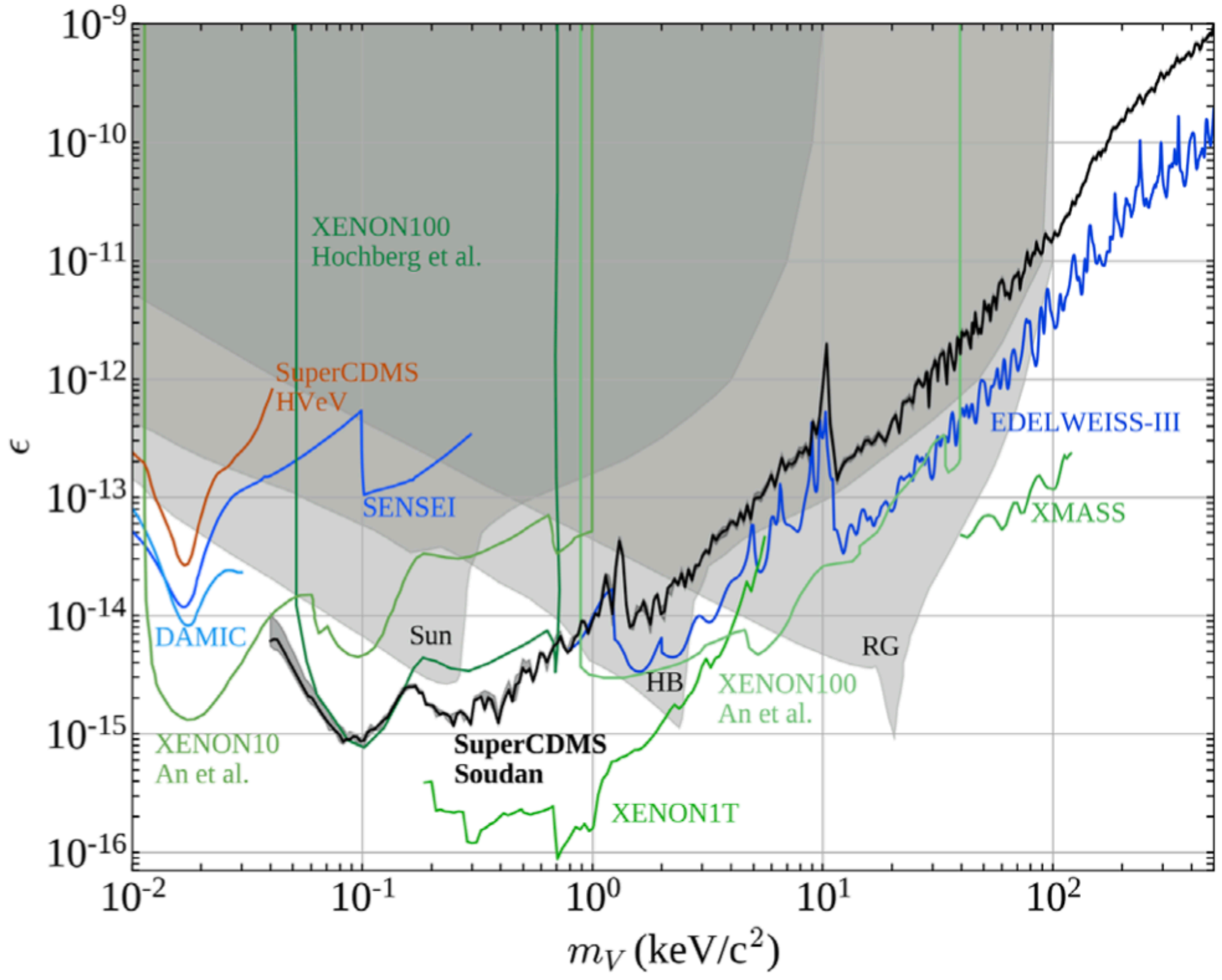
Phys. Rev. Lett. 126 (2021) 091301

Probing lower DM masses

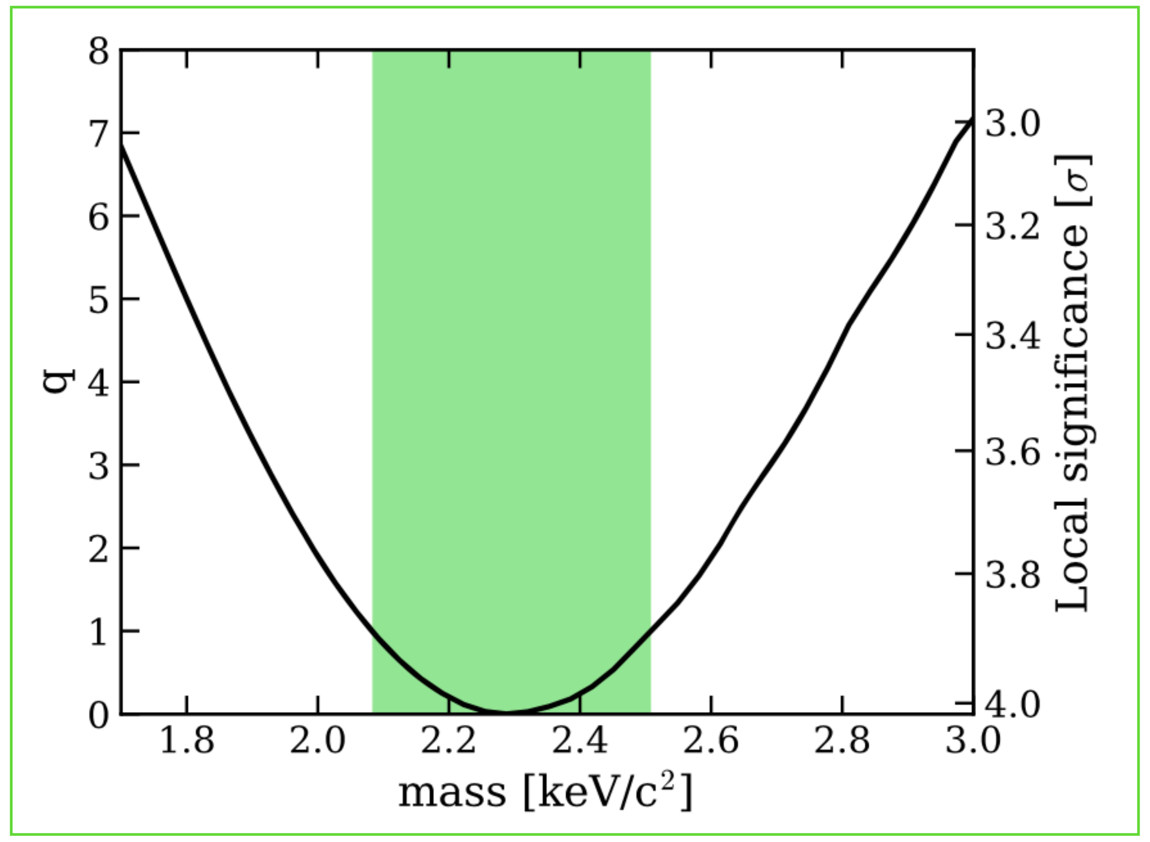
Axioelectric coupling vs ALP (axion-like particle) mass



Kinetic mixing of dark photon vs mass



XENON1T excess

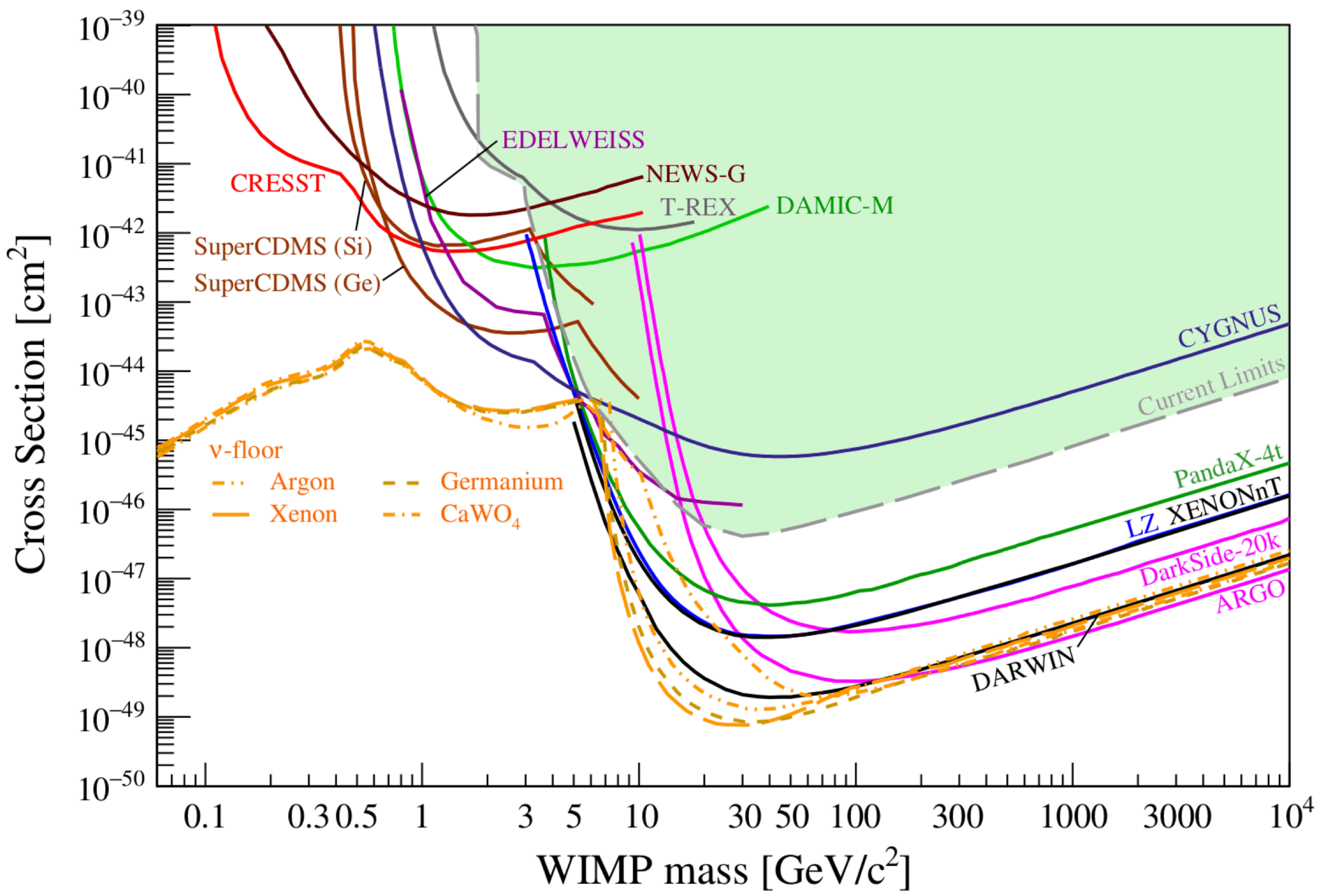


Monoenergetic peak fit

2.3 +/- 0.2 keV

SuperCDMS Collab., PHYSICAL REVIEW D 101, 052008 (**2020**)

WIMP landscape: past, present, future



Projections for current and future experiments

10^{-41}cm^2 in ~1998 to few x 10^{-47} cm^2 in ~2018

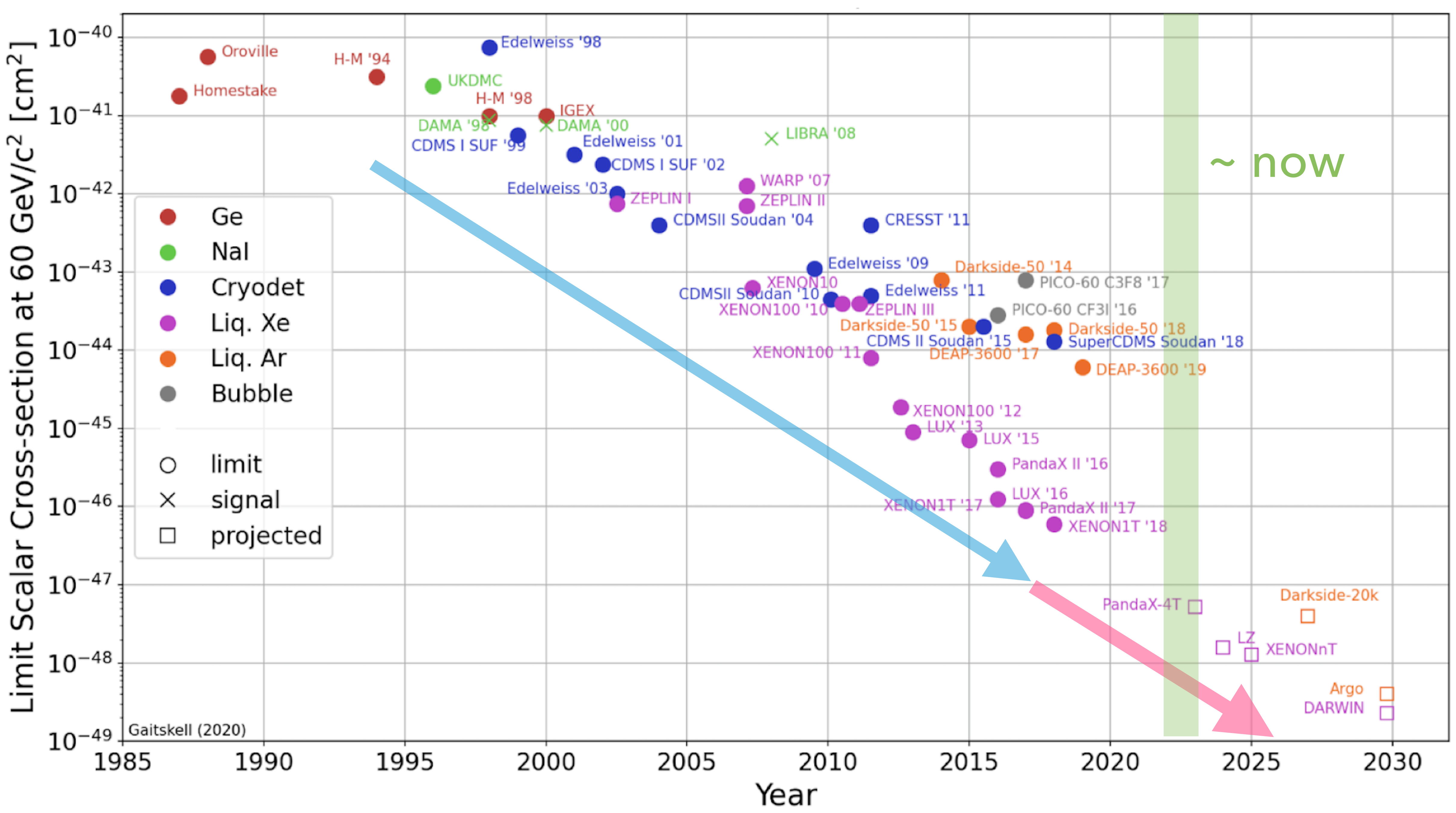
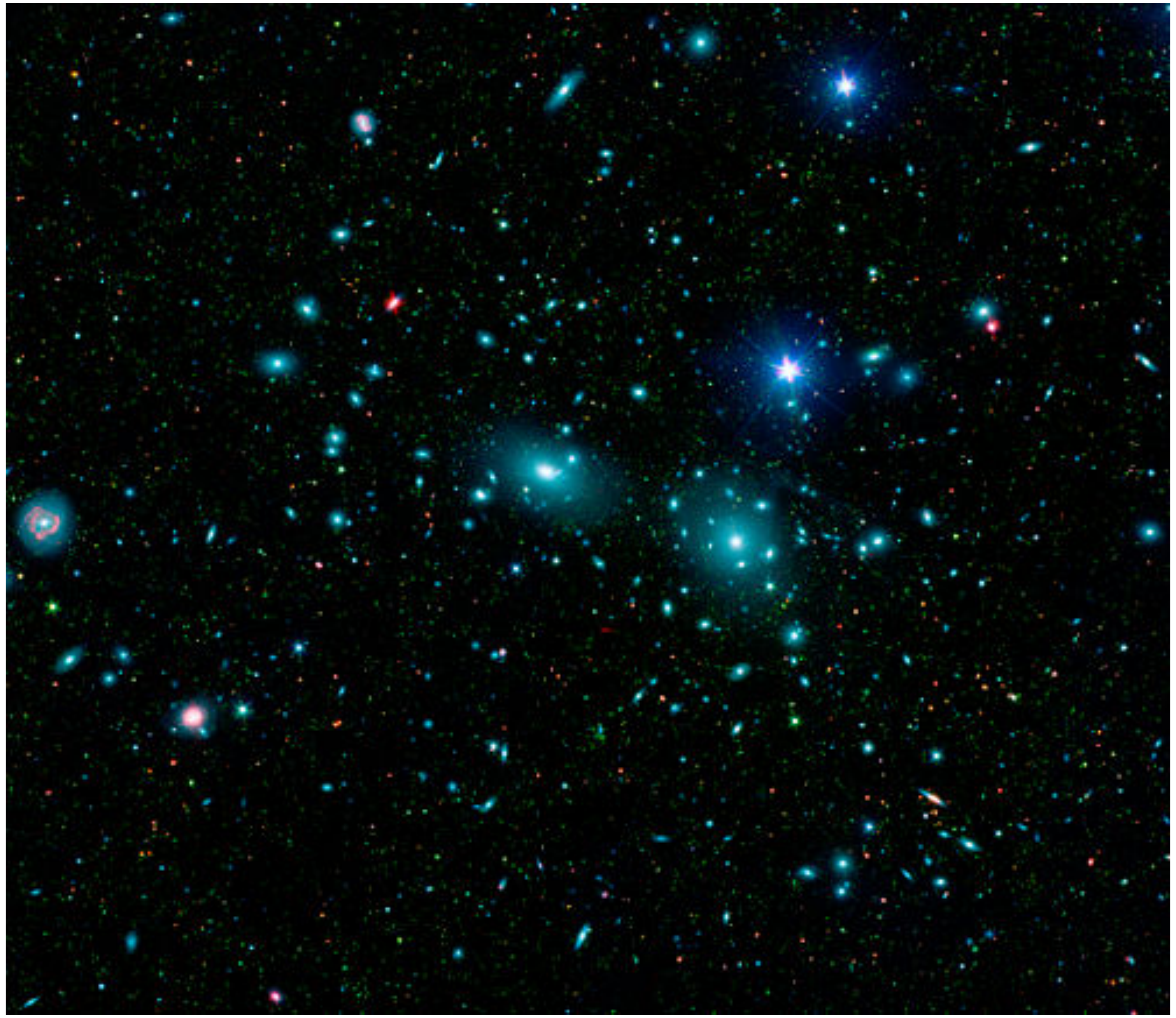


Figure: Rick Gaitskell, 2020

Spin-independent cross section upper limits at 60 GeV WIMP mass

Summary

- Dark matter evidence is abundant, but only observed indirectly via its gravitational interactions
- Over two decades of WIMP searches have covered more than 6 orders of magnitude in cross-section vs mass parameter space.
- Experiments driven by standard WIMP searches, have reached exceedingly low backgrounds, thus opening new detection channels.
- A new generation of multi-ton scale detectors are now taking science data, already with first results.
- The future requires complementarity and collaboration.
- An inevitable neutrino fog is on the horizon, but patience may bring clarity.

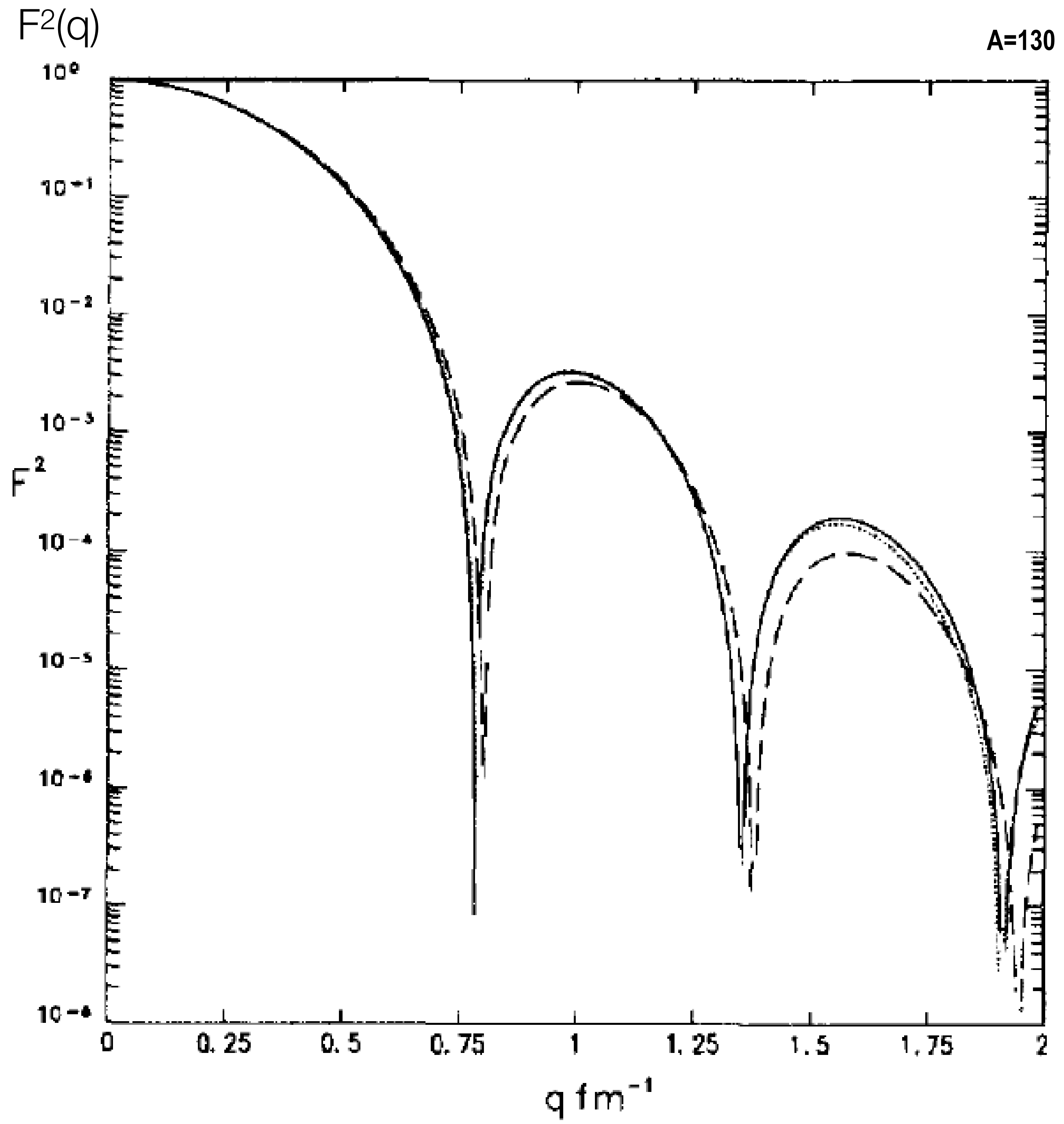


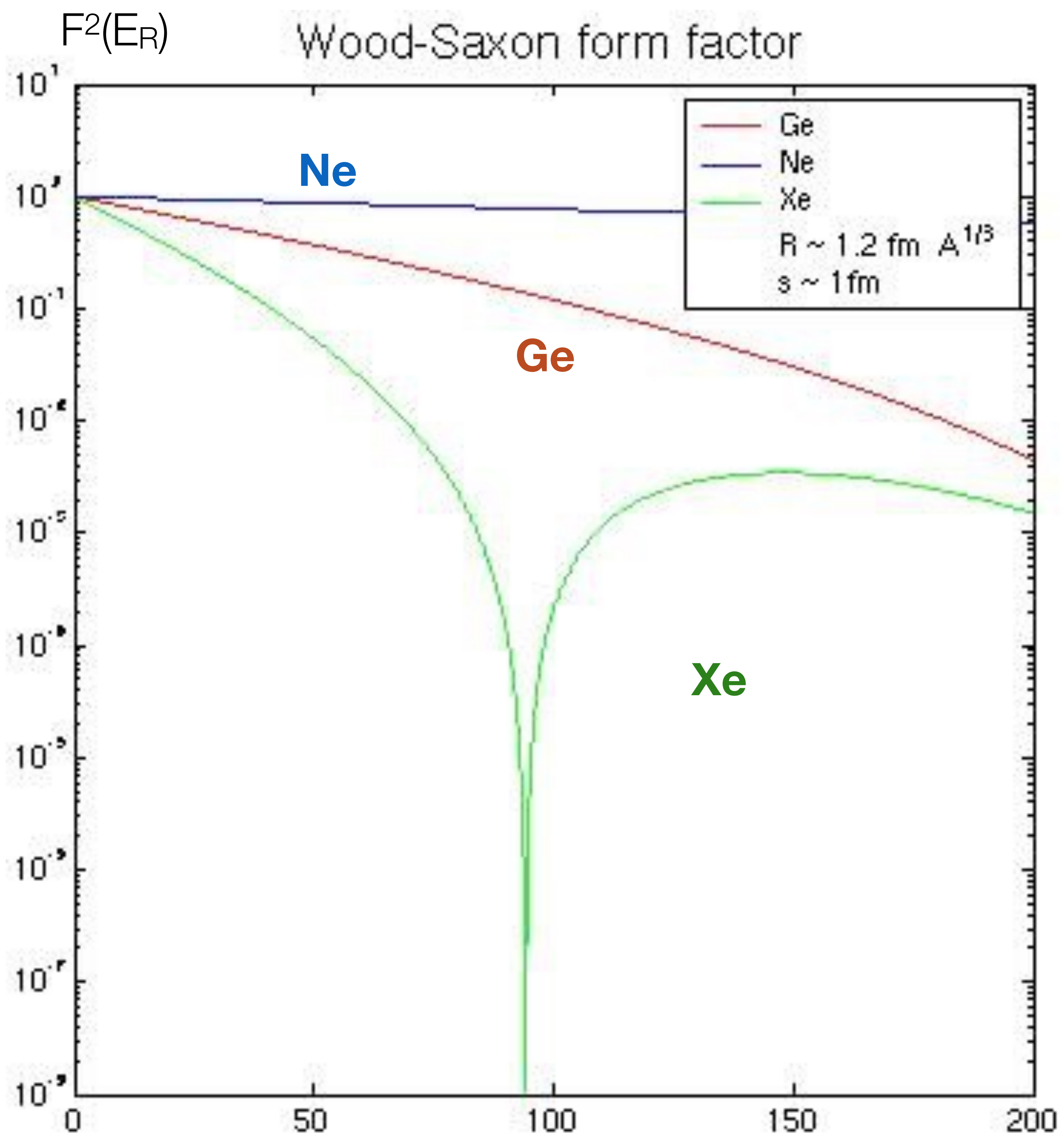
COMA Cluster, NASA/JPL-Caltech/GSFC/SDSS

Form factors

Loss of coherence as larger momentum transfers probes smaller scales:
leads to a suppression in the event rate for heavy WIMPs or nucleons

- Scattering amplitude: Born approximation
- Spin-independent scattering is coherent

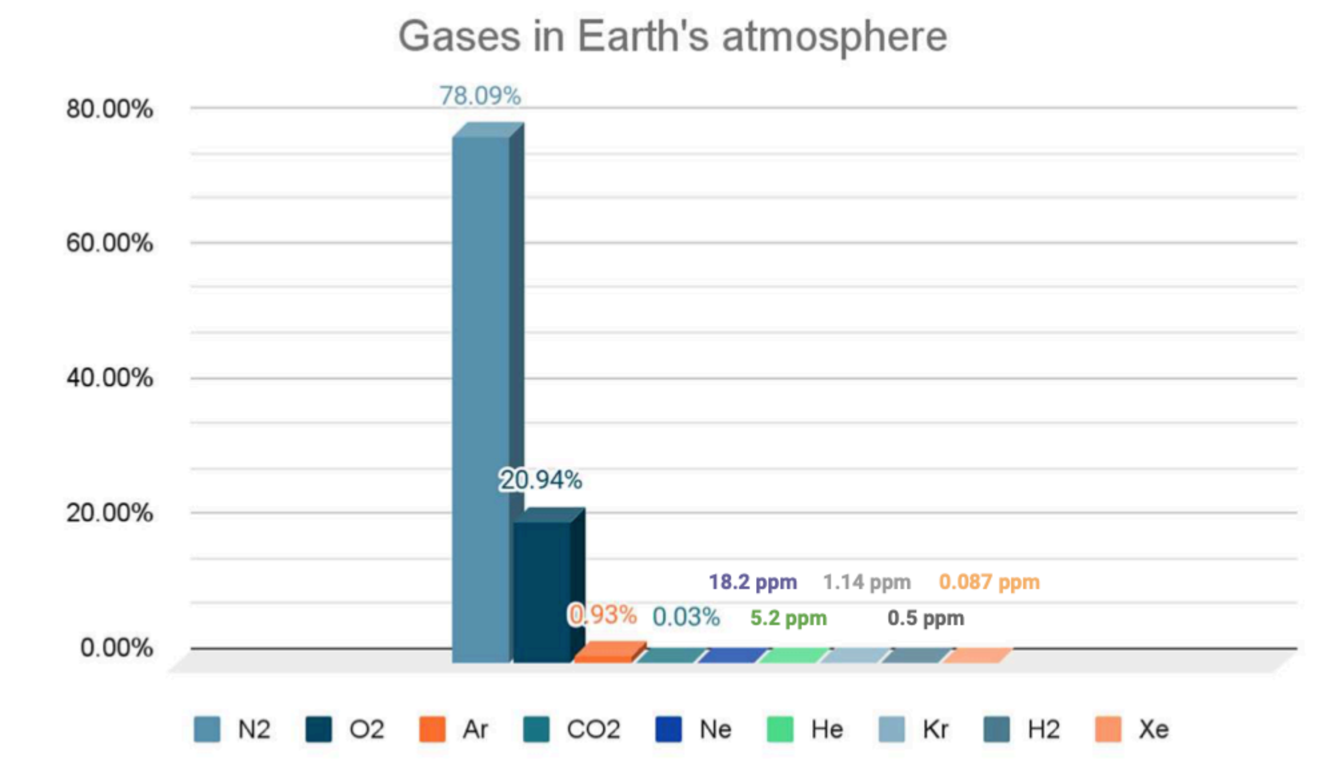




XENON availability

Xenon in the Earth's atmosphere

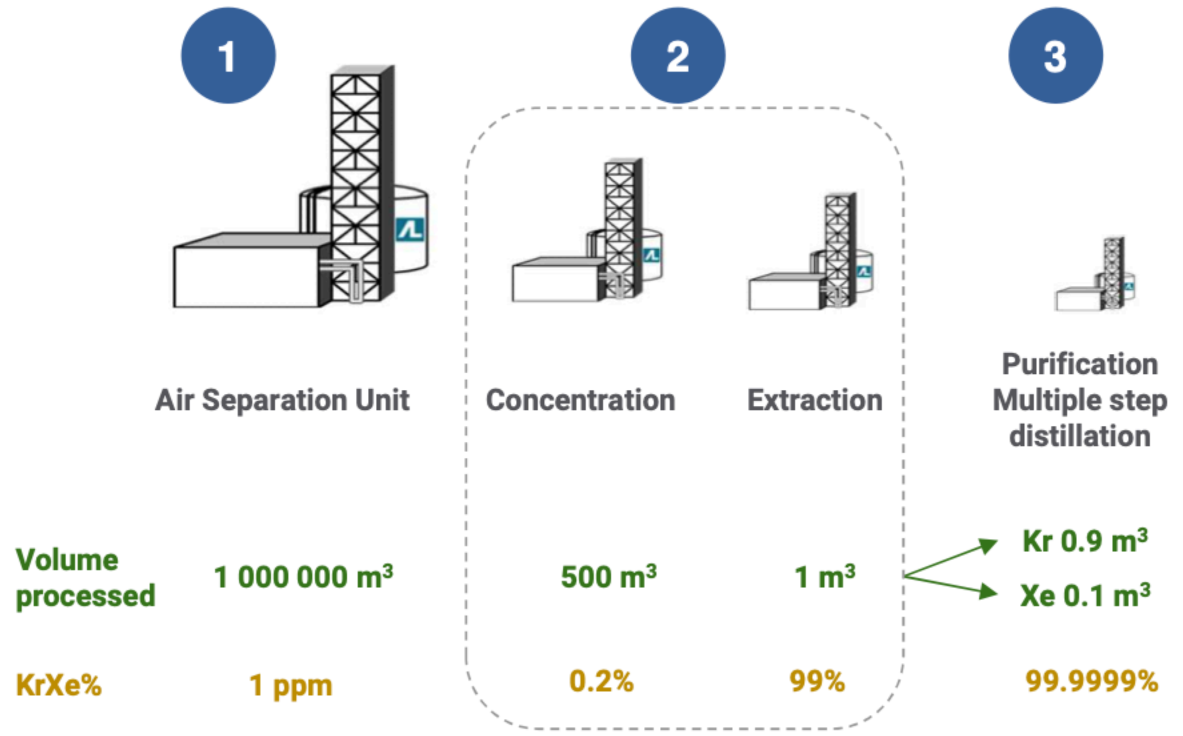
Xenon is obtained from air, where it is present in extremely small amounts.



Gaz	Abundance
N2	78,09 %
O2	20,94 %
Ar	0,93 %
CO2	350 ppm
Ne	18,2 ppm
He	5,2 ppm
Kr	1,14 ppm
H2	0,5 ppm
Xe	0,087 ppm

9 THIS DOCUMENT IS PUBLIC Rare gsaes: a challenge for Science and Industry Air Liquide

Kr and Xe extraction from the air requires multiple steps



Key facts:

- Only very large air separation units (ASUs) can justify extraction of Kr and Xe
- Even large ASUs can only produce a small amount of Kr and Xe
- Increasing Kr/Xe capacity requires investments in very large ASUs which are Kr/Xe ready

⇒ Production of Kr and Xe is managed globally in order to maximize reliability of supply

- Electronics demand for both molecules is meant to continue until 2030
- Space demand for both molecules is booming due to recent Space developments and private investment.
- Long term supply can be affected by:
  - Geopolitical context (Russia? China?)
  - Energetic transition in some supplying countries may have a long-term impact on the krXe production

> Such demand provoked a shortage situation that is meant to continue over the next few years despite the different investments made by industrial players.

https://indico.in2p3.fr/event/20879/contributions/109397/attachments/70773/100454/AirLiquide_Gaffet_XeSAT%202022%20Workshop%20%281%29.pdf

XENON TPC R&D

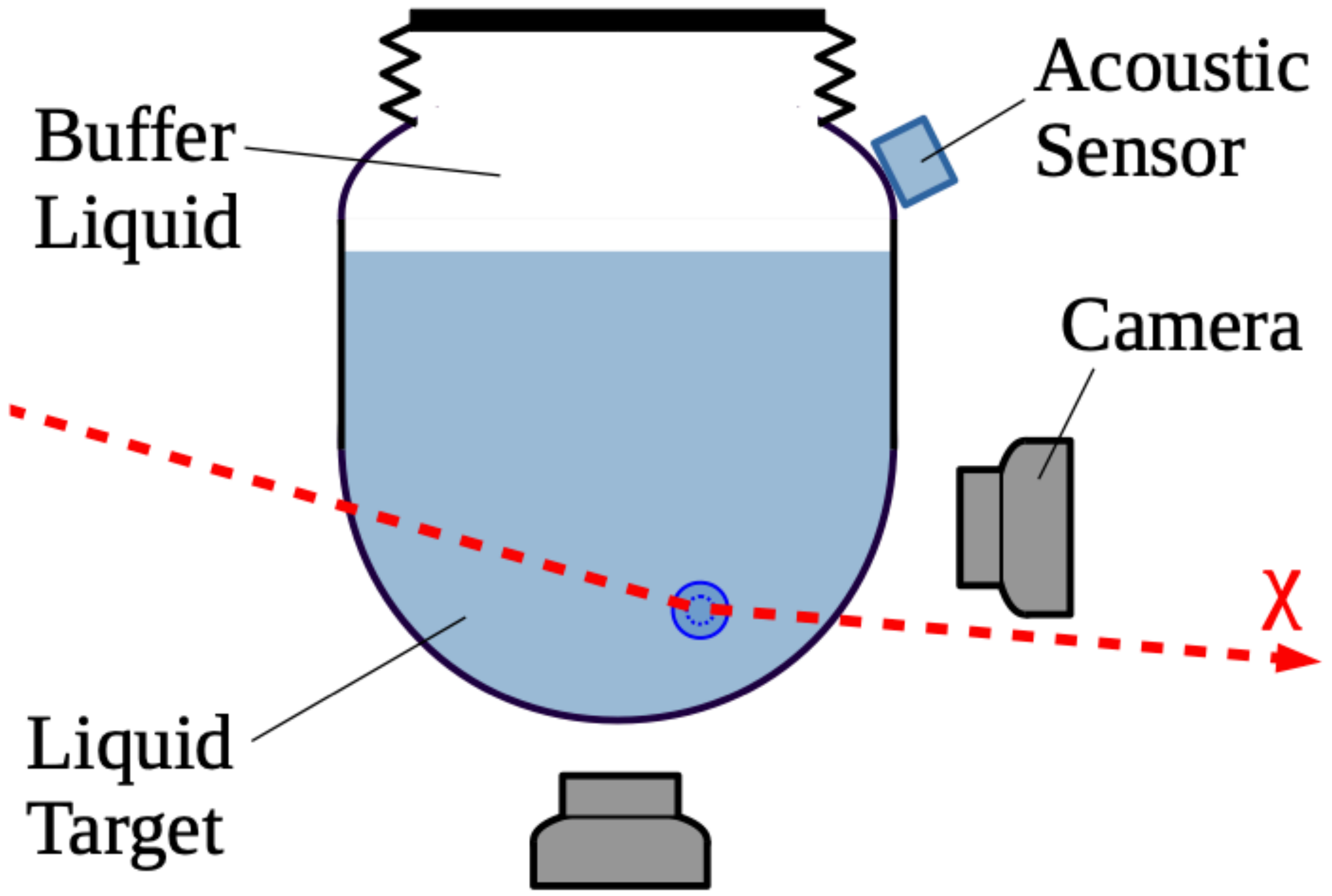
- Detector, Xe target, background mitigation, photosensors, etc
- Two large-scale demonstrators (in z & in x-y) supported by ERC grants: demonstrate electron drift over 2.6 m, operate 2.6 m ø electrodes
- Demonstrators (Xenoscope, 2.6 m tall & Pancake, 2.6 m diam TPCs) in commissioning stage

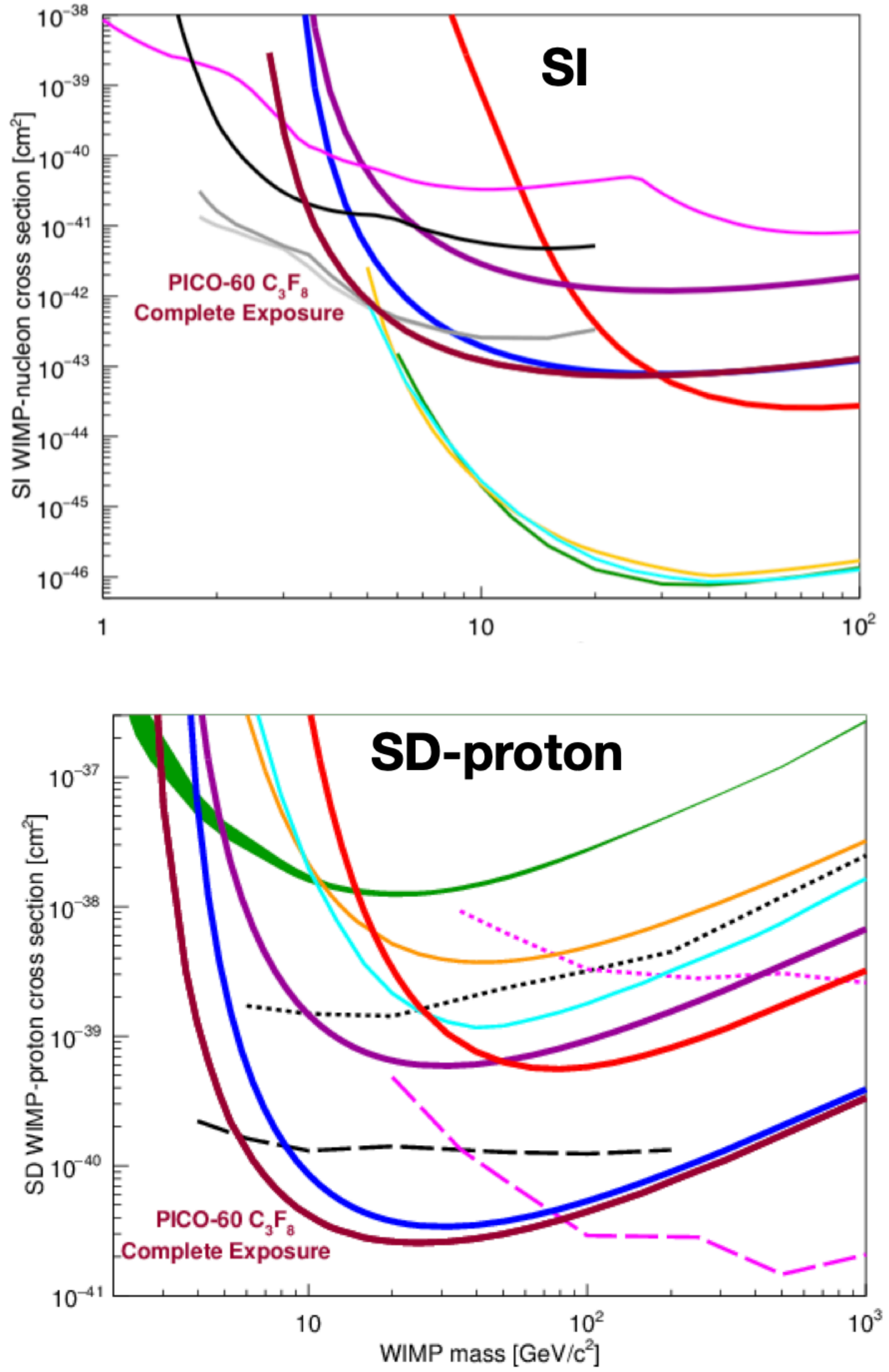
Test e- drift over 2.6 m (purification, high-voltage): U. Zurich (G-floor Assembly Hall)

Test electrodes with 2.6 m diameter: U. Freiburg

Bubble chambers

PICO-60





arXiv:1902.04031
PRD 100, 022001 (2019)

- bubble chamber: 52 kg C_3F_8
- excellent electron recoil and alpha rejection
- 1404-kg-day exposure at 2.45 keV threshold
- previous: 1167-kg-day exposure at 3.3 keV threshold
- larger fiducial volume
- most stringent SD WIMP-proton limit: 2.5e-41 cm² at 25 GeV/c²

Annual Modulation

- Test the DAMA/LIBRA annual modulation anomaly with sodium iodide crystals: NaI(Tl)
- So far, no evidence for annual modulation from ANAIS-112 (3 y of data) and COSINE-100 (1.7 y of data)
- New experiment COSINUS: detects also phonons in undoped NaI (apart from scintillation) at few mK, for active background rejection; construction/data at LNGS 2022/23

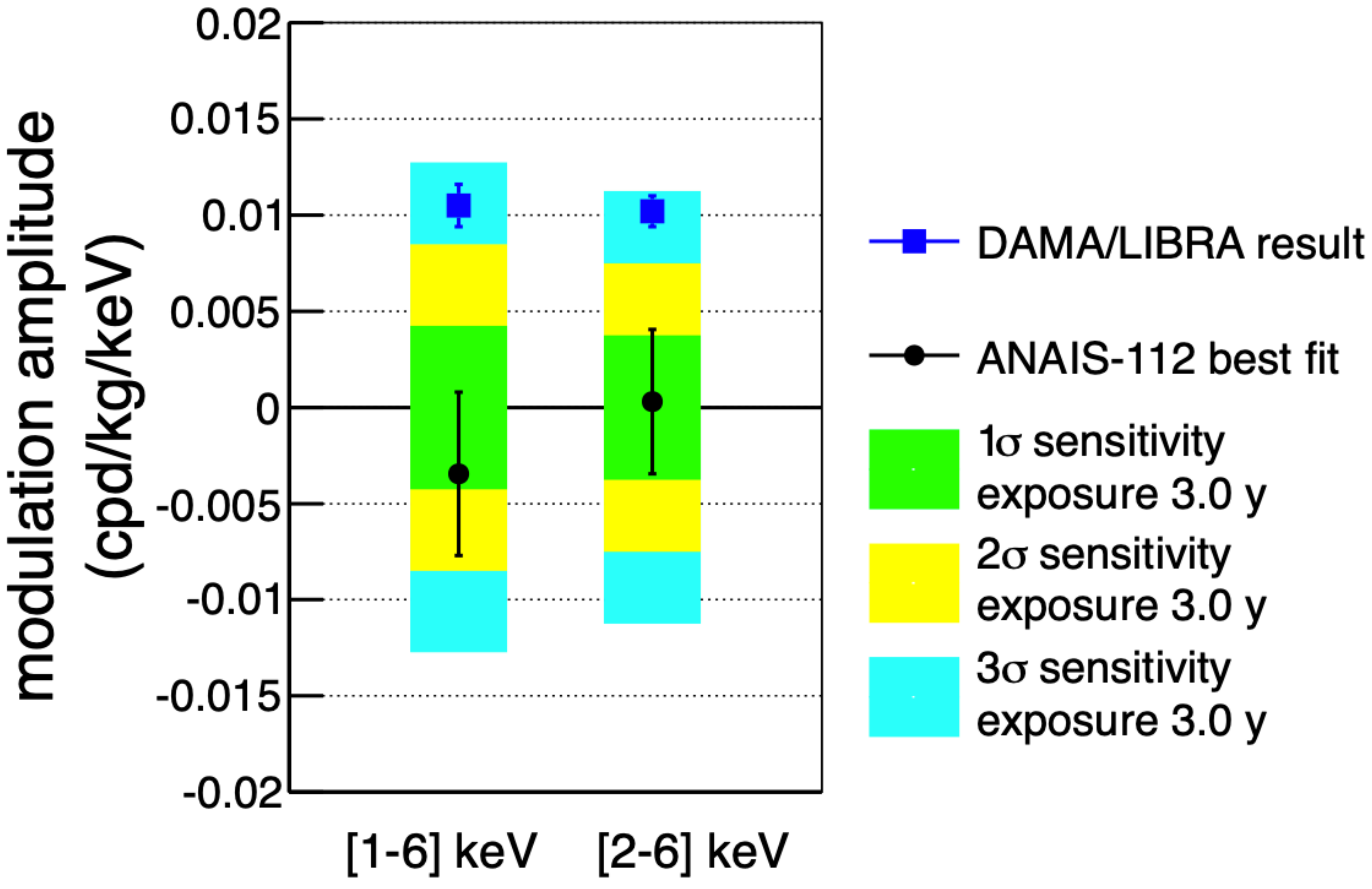


Figure 29: The ANAIS best-fit modulation amplitude result compared with the DAMA/LIBRA best-fit result for both recoil energy ranges considered by DAMA/LIBRA. Figure from Ref. [41].