Overview on
Direct Dark Matter Search

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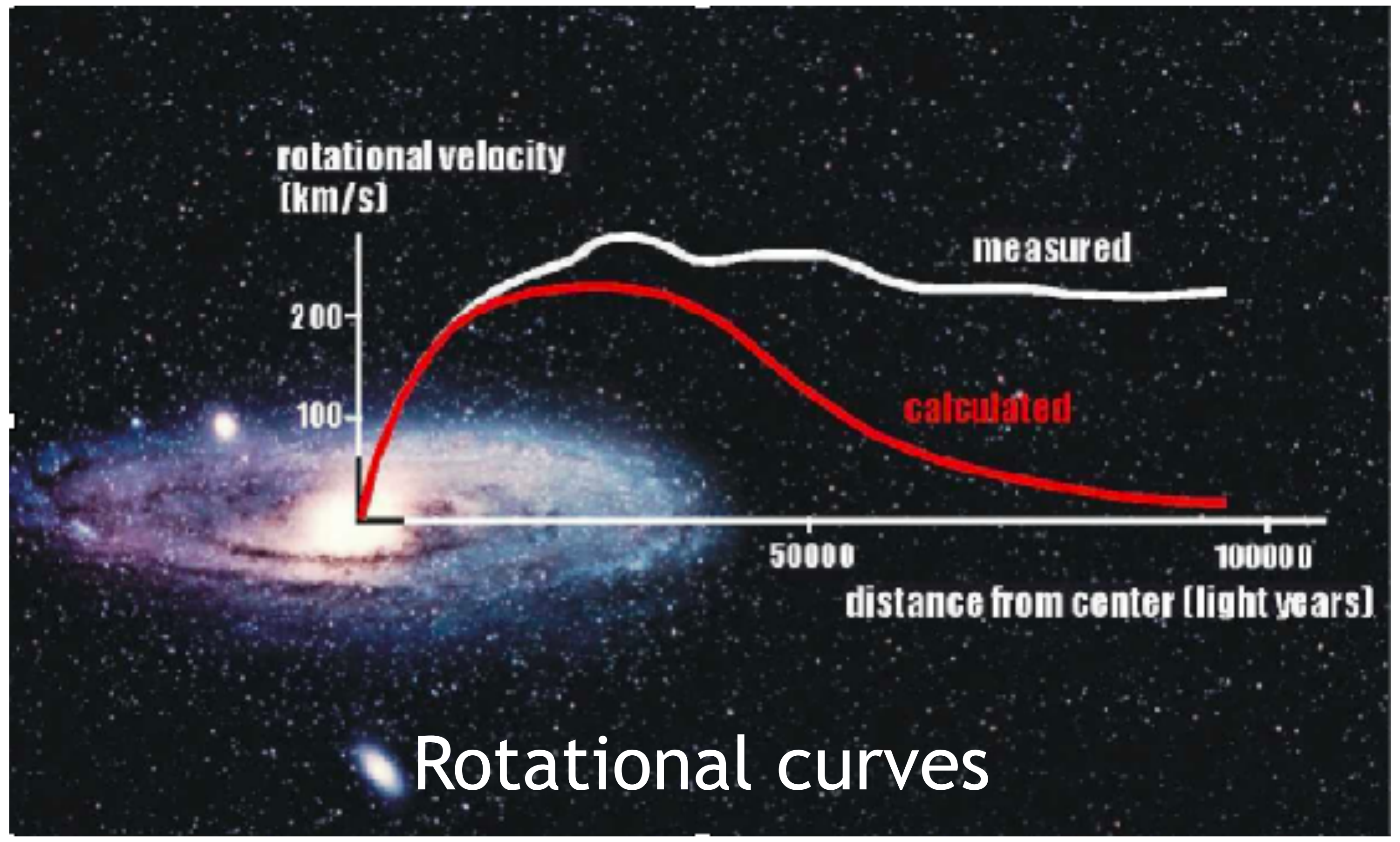
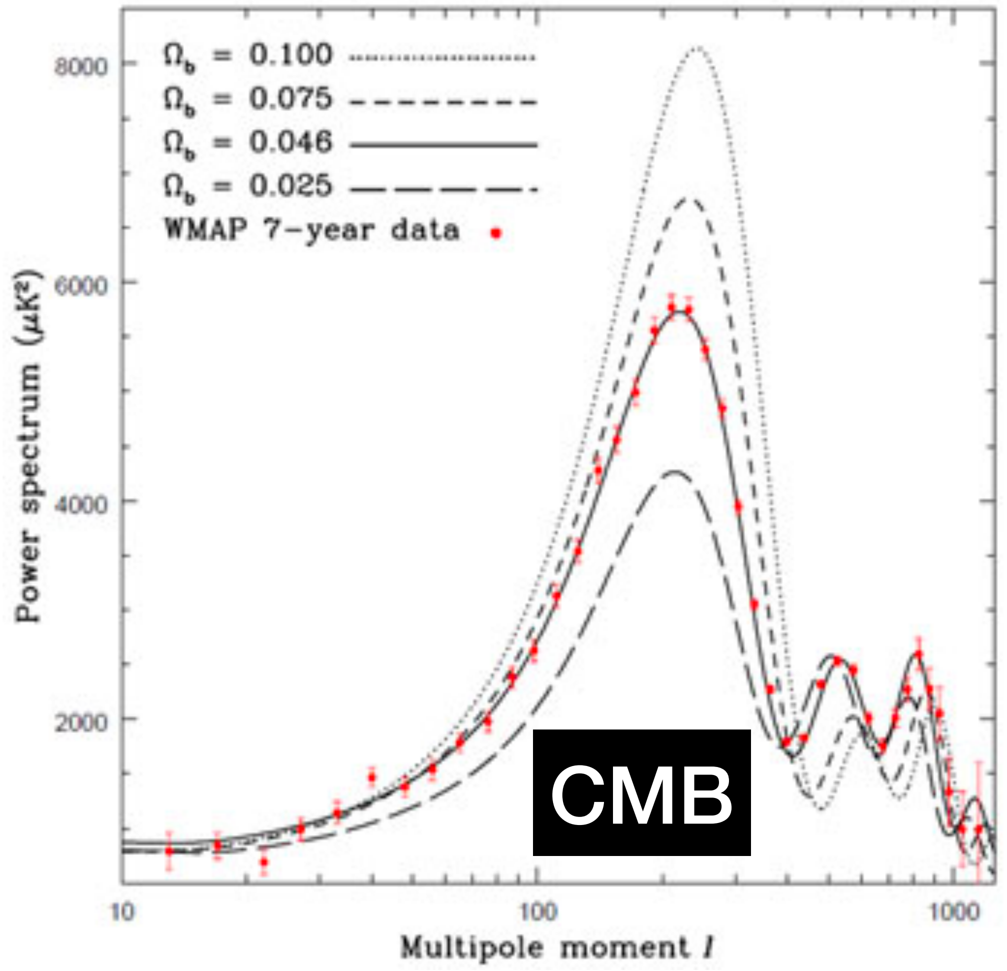
Laboratorie APC

SFP - 31/03/2022

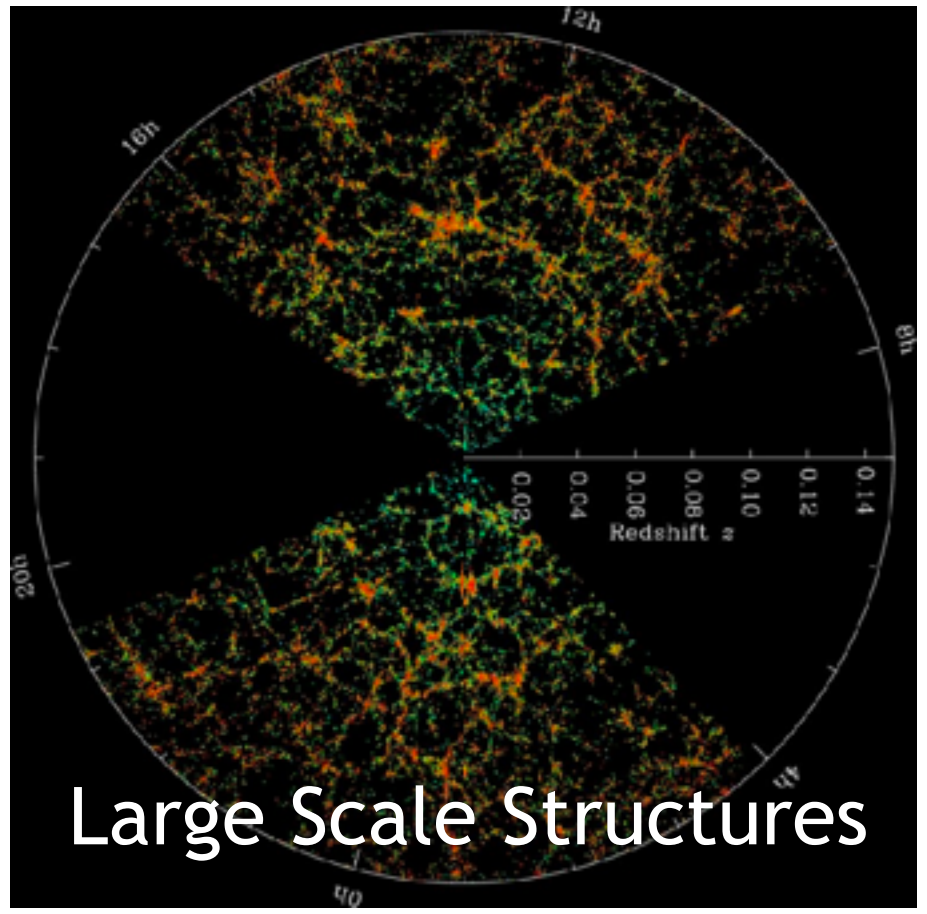
Dark Matter?



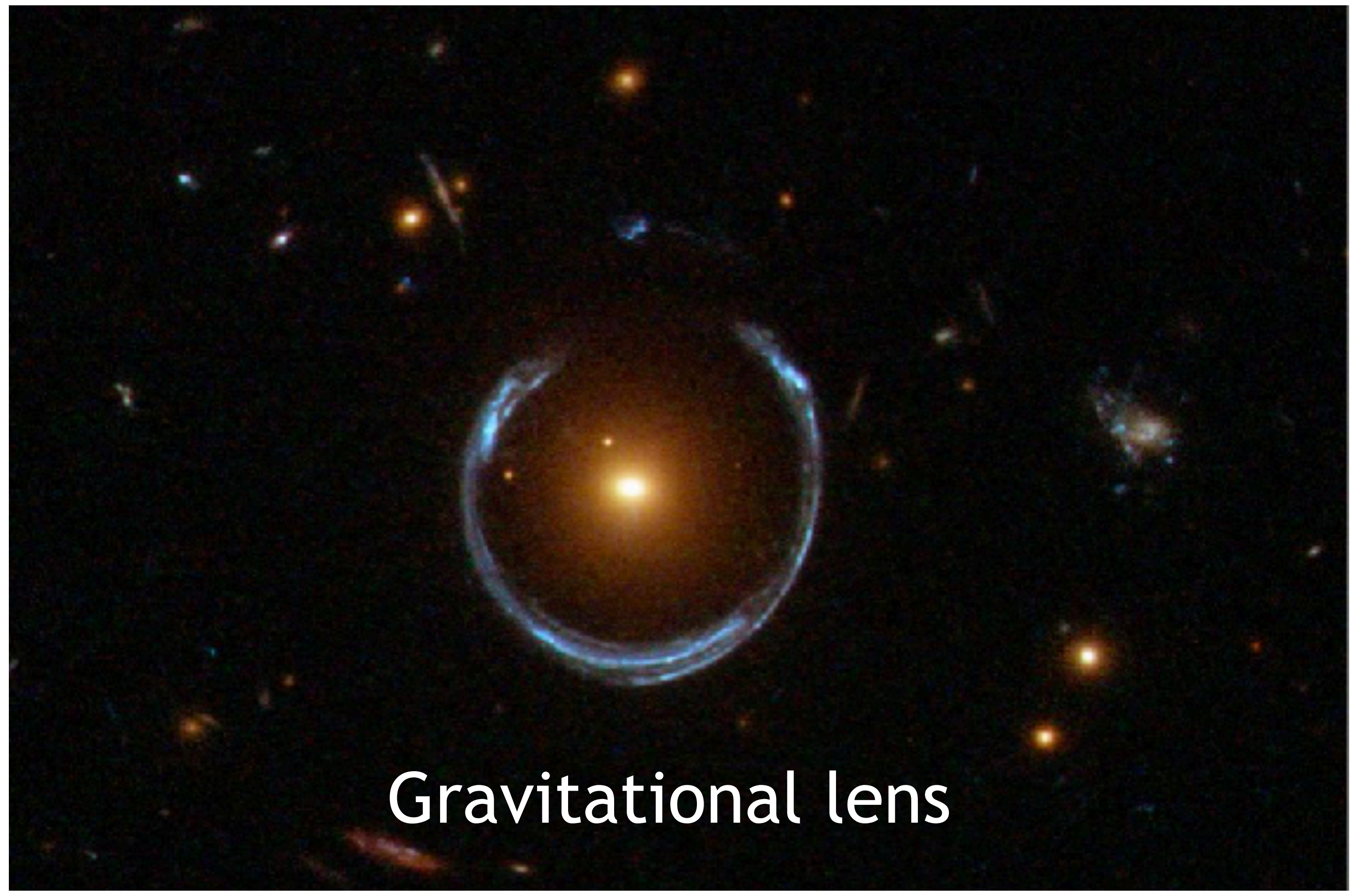
Rotational curves



CMB



Large Scale Structures

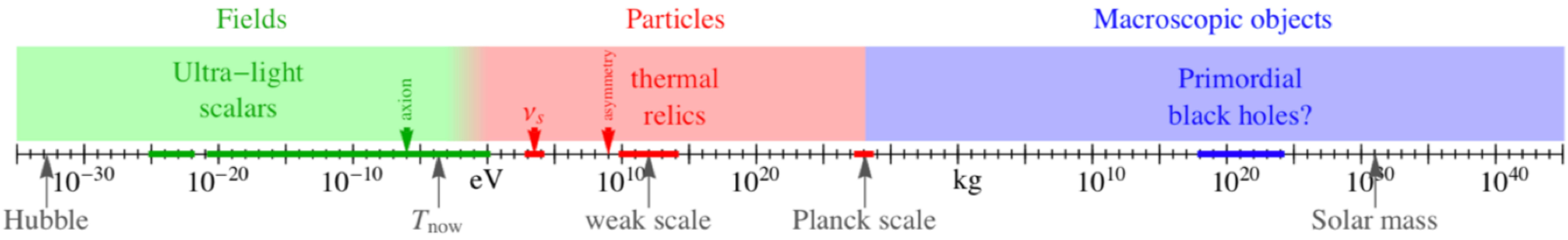

Gravitational lens

Bullet Cluster

What about the DM particle candidate?

- 25% total energy or 80% total mass of the Universe
- New unknown particle
- Not hot, better cold
- Neutral particle (dark)
- Stable or long lived
- Possibly a relic from Early Universe
- Very feebly interacting

Dark Matter Particles?



AXION ?

- Solve CP problem in QCD

Sterile Neutrino ?

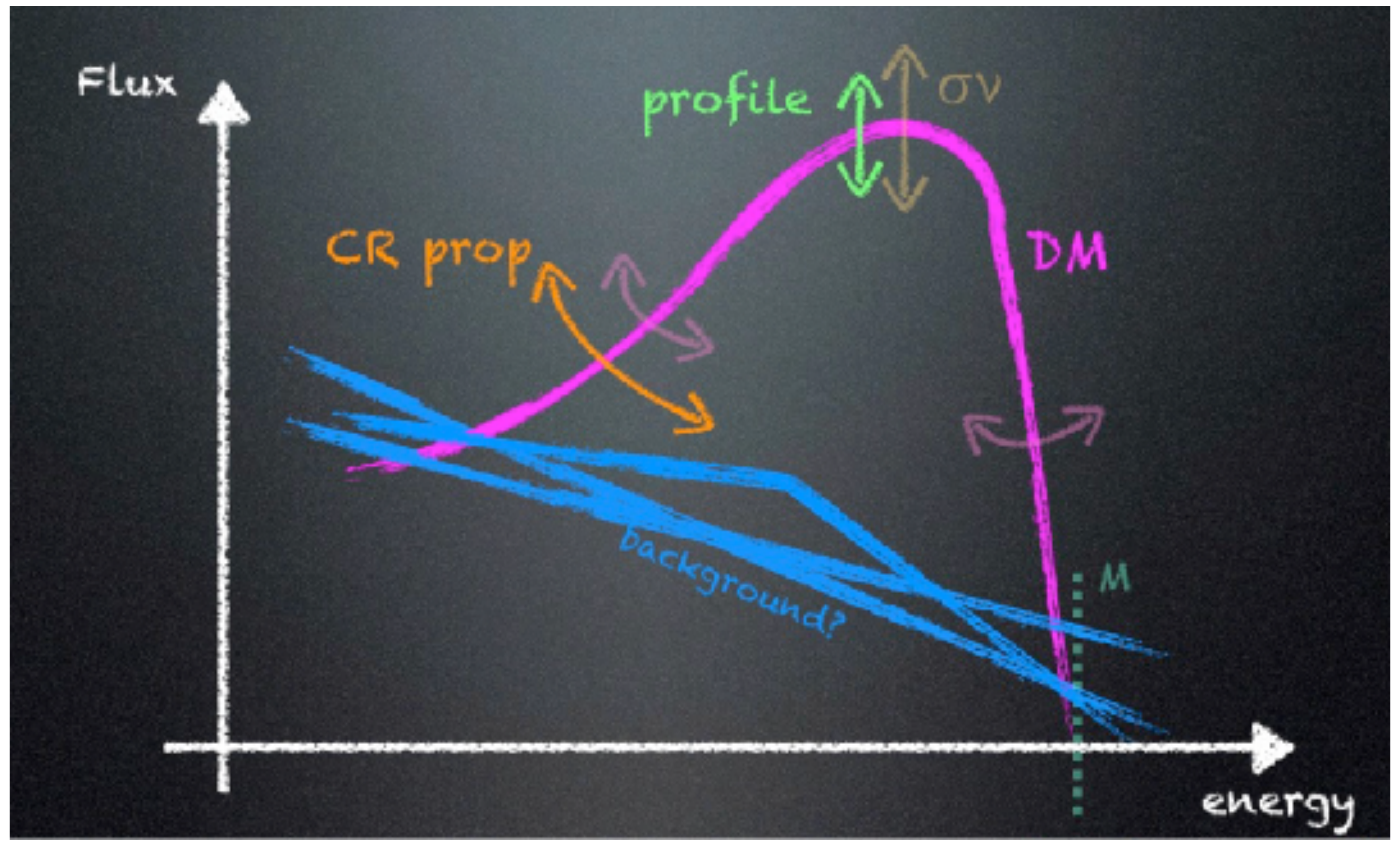
- 3.5 keV X-ray from indirect observation
- Cold: > 7 keV mass scale

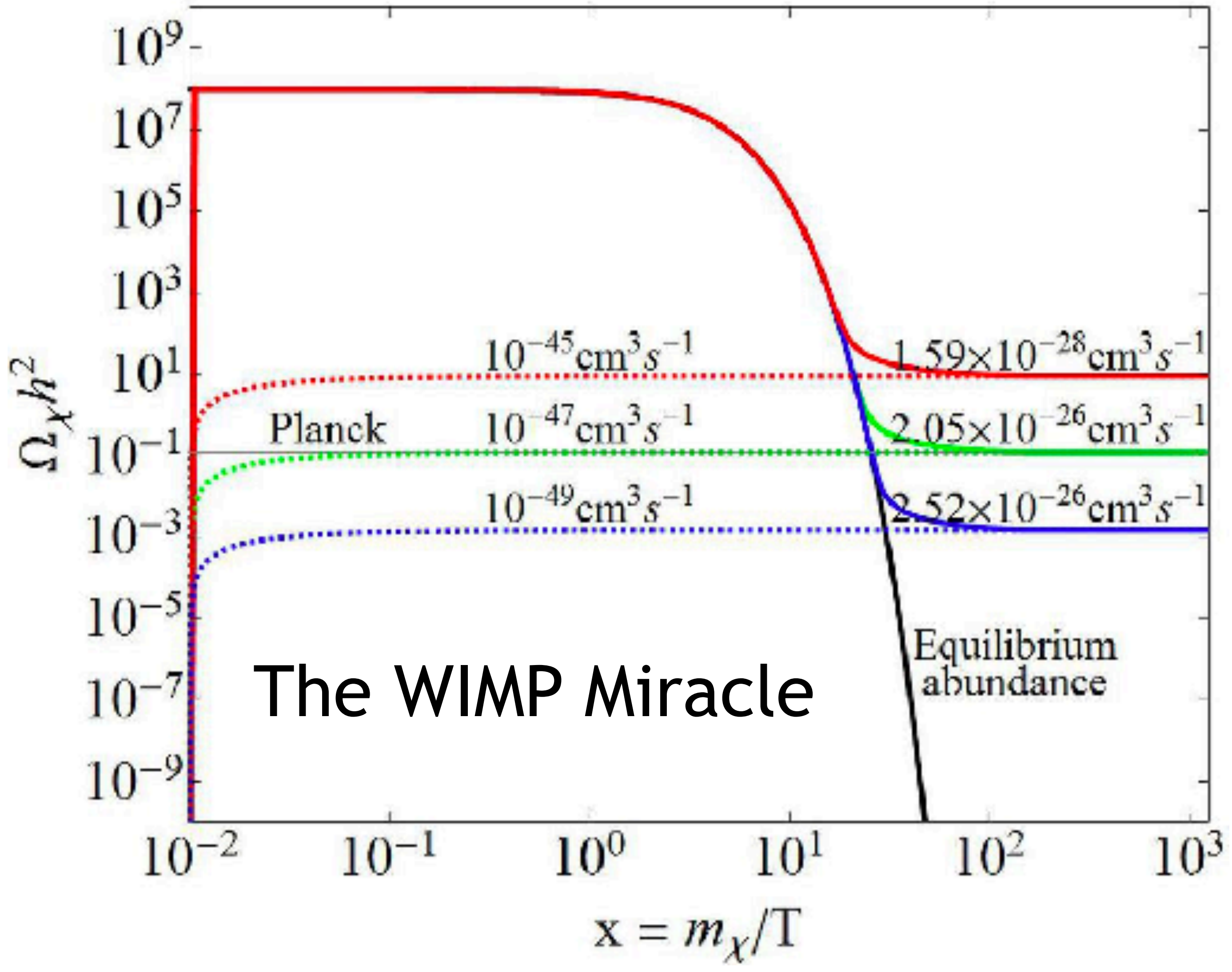
WIMP ?

- Supersymmetry (getting weaker…)
- Naturally matches current DM density

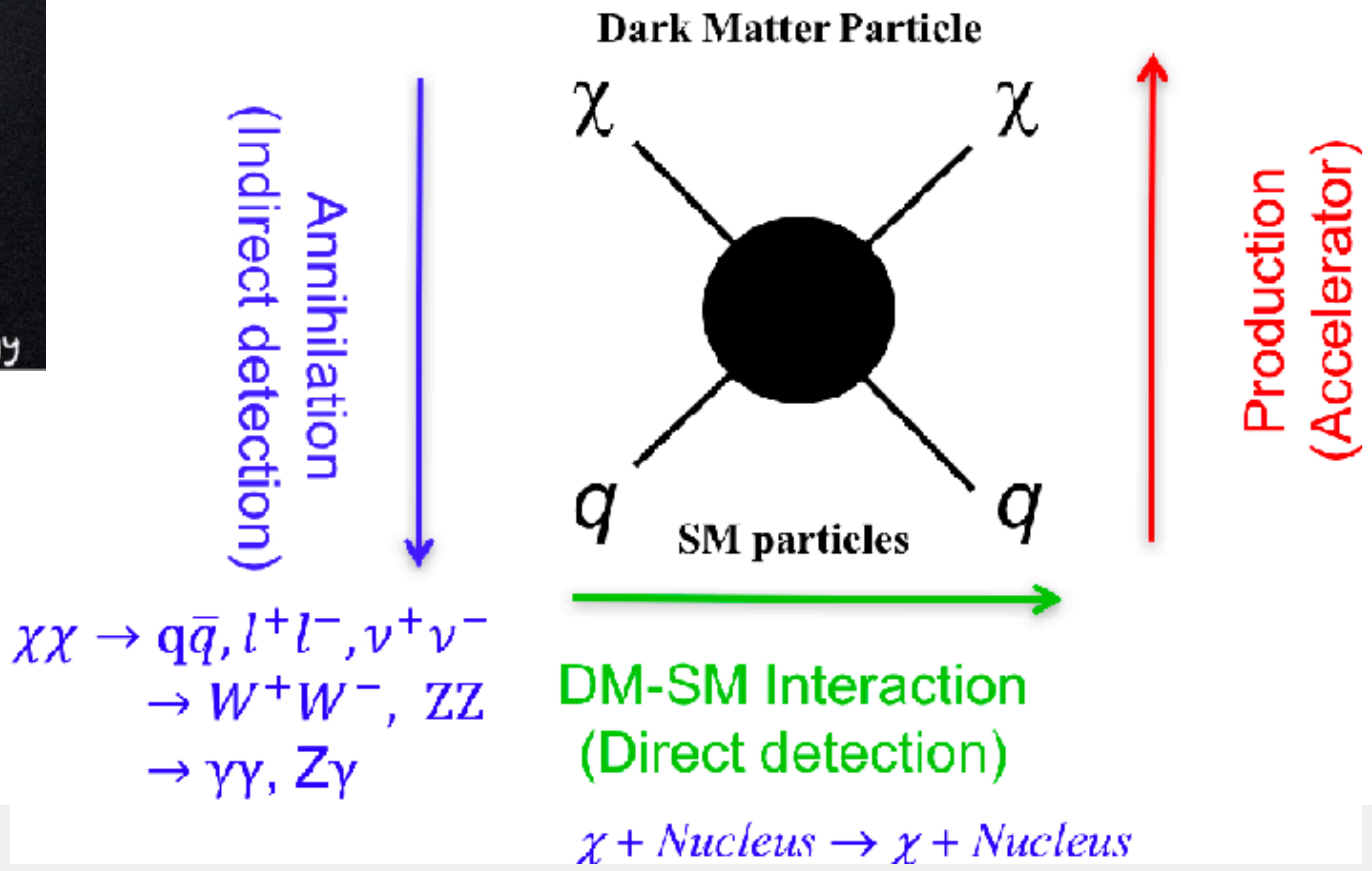
Weakly Interacting Massive Particles

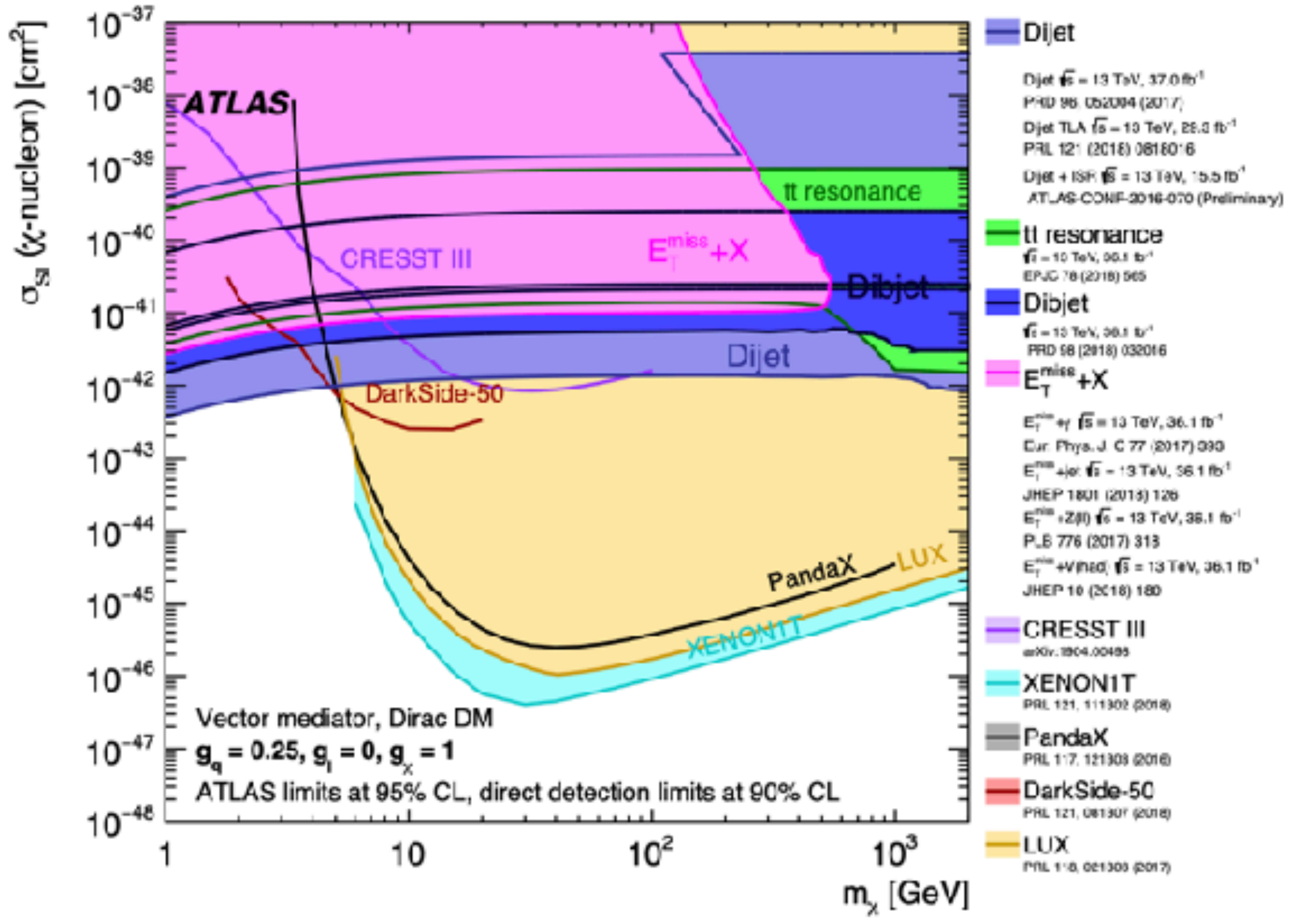
Indirect detection



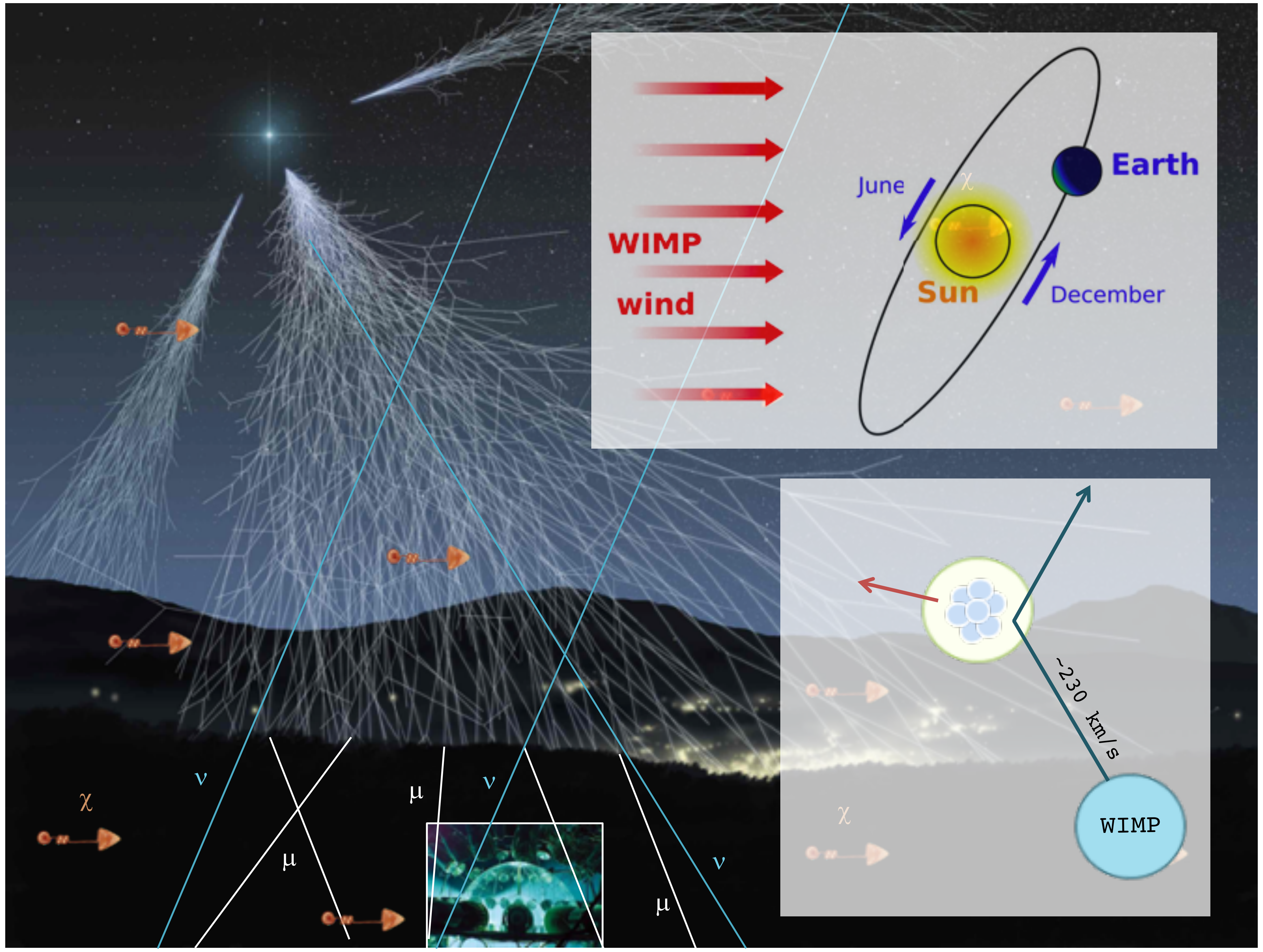


Production at colliders



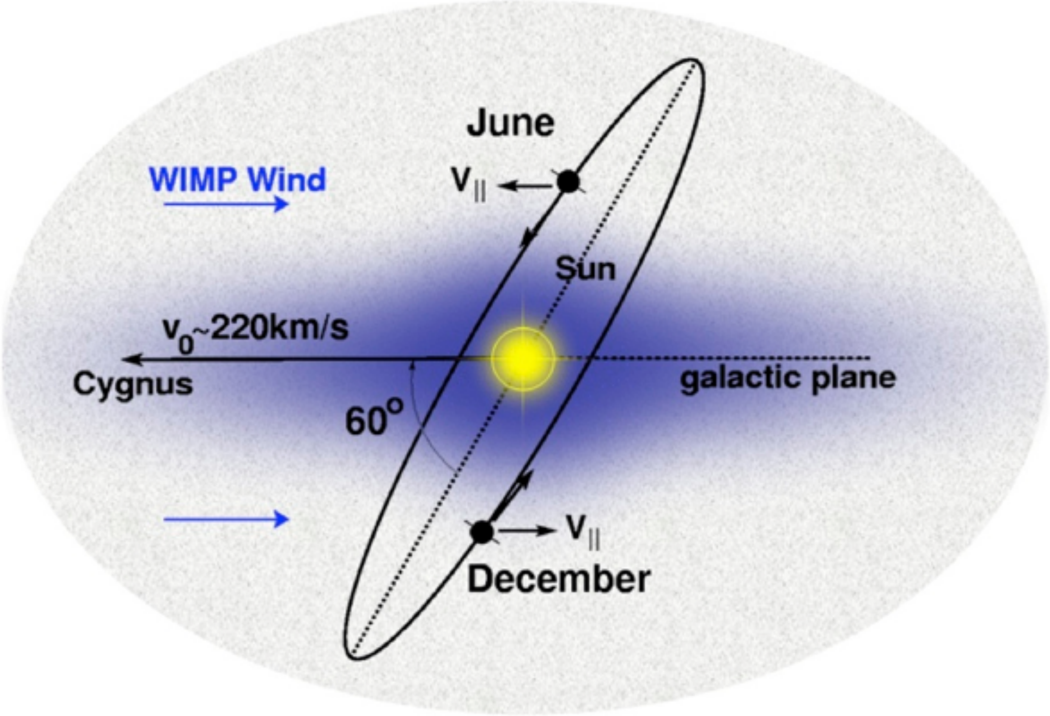


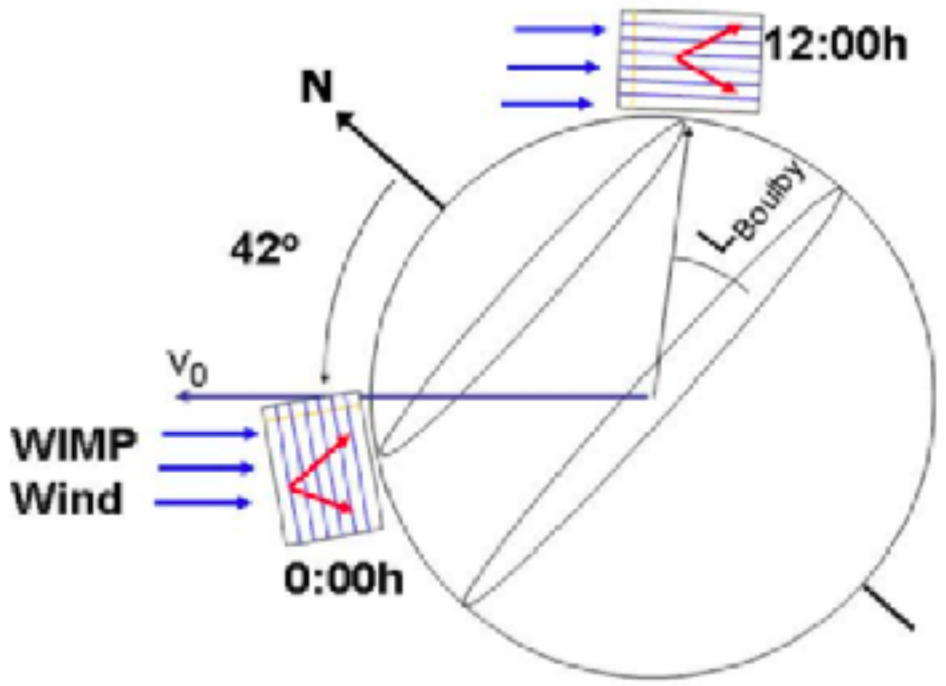
Direct Detection: Observables



Annual Modulations

Earth rotation around the Sun => largest speed of the dark matter particles in the Milky Way halo relative to the Earth around June 2nd and smallest in December
Expected seasonal variation at 2-10% level





Directionality

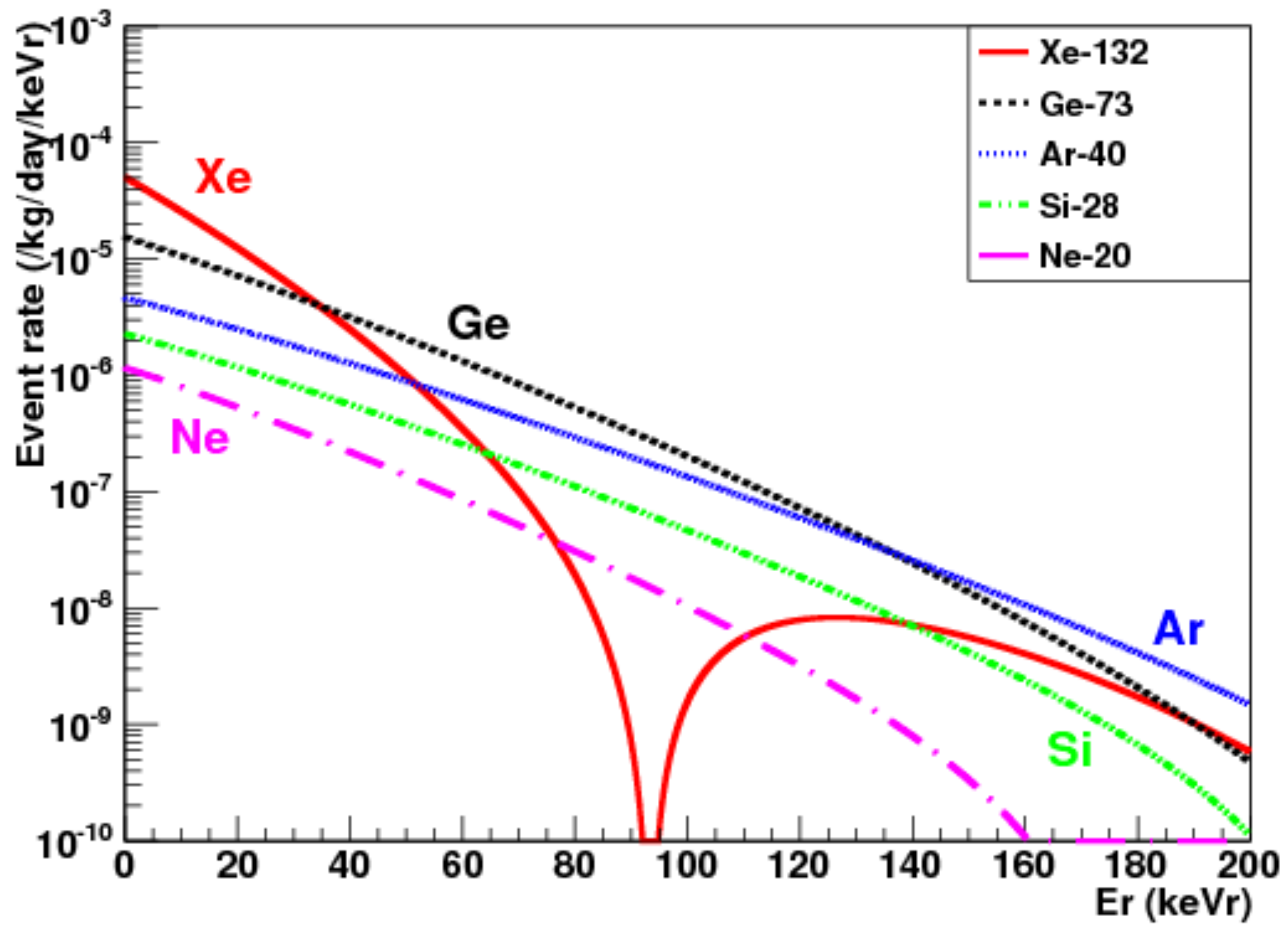
The recoil rate, in the Galactic rest frame, is highly anisotropic: the rate in the forward direction is roughly an order of magnitude larger than that in the backward direction

Statistics?

Event rate: $R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \cdot \langle v \rangle$

- ρ_χ local dark matter density = 0.3 GeV/cm³ (~1 100 GeV WIMP in an American coffee cup)
- m_χ : WIMP mass
- $\sigma_{\chi N}$: cross section
- <V> ~ 230 km/s

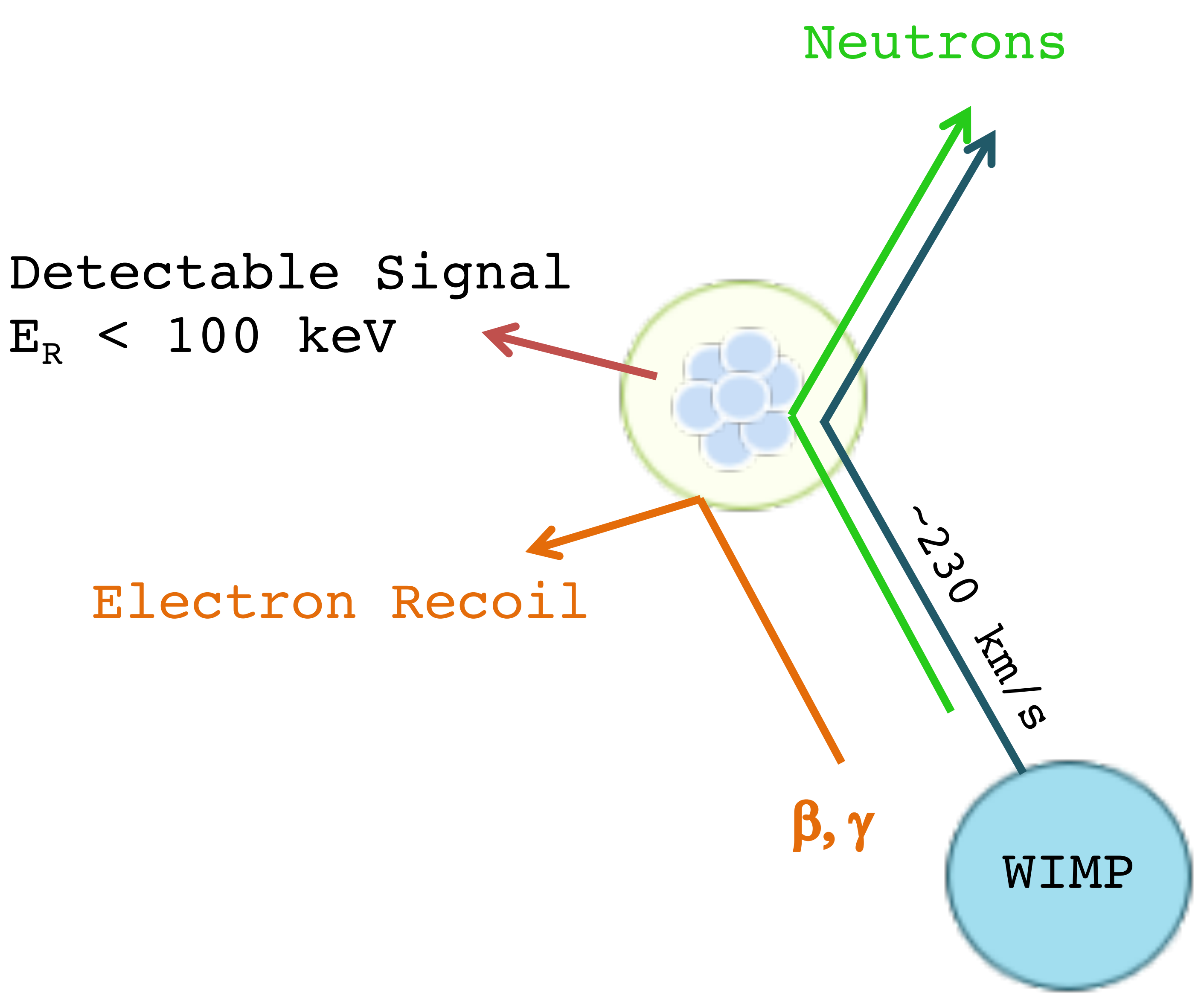
Assuming **m_χ = 100 GeV/c³** and **$\sigma_{\chi N}$ = 10^{-47} cm²**, R ~ **1 event / ton / year** in a liquid argon target



Complementarity

if an excess of events is observed, a verification with a detector with a different target is necessary.

Backgrounds and Detector Requirements



Backgrounds

- Cosmic rays and cosmogenic isotopes
- Natural (^{238}U,^{232}Th,^{235}U,^{222}Rn,…) and anthropogenic (^{85}Kr,^{137}Cs,…) radioactivity
- Neutrinos (solar, atmospheric, diffuse supernovae)

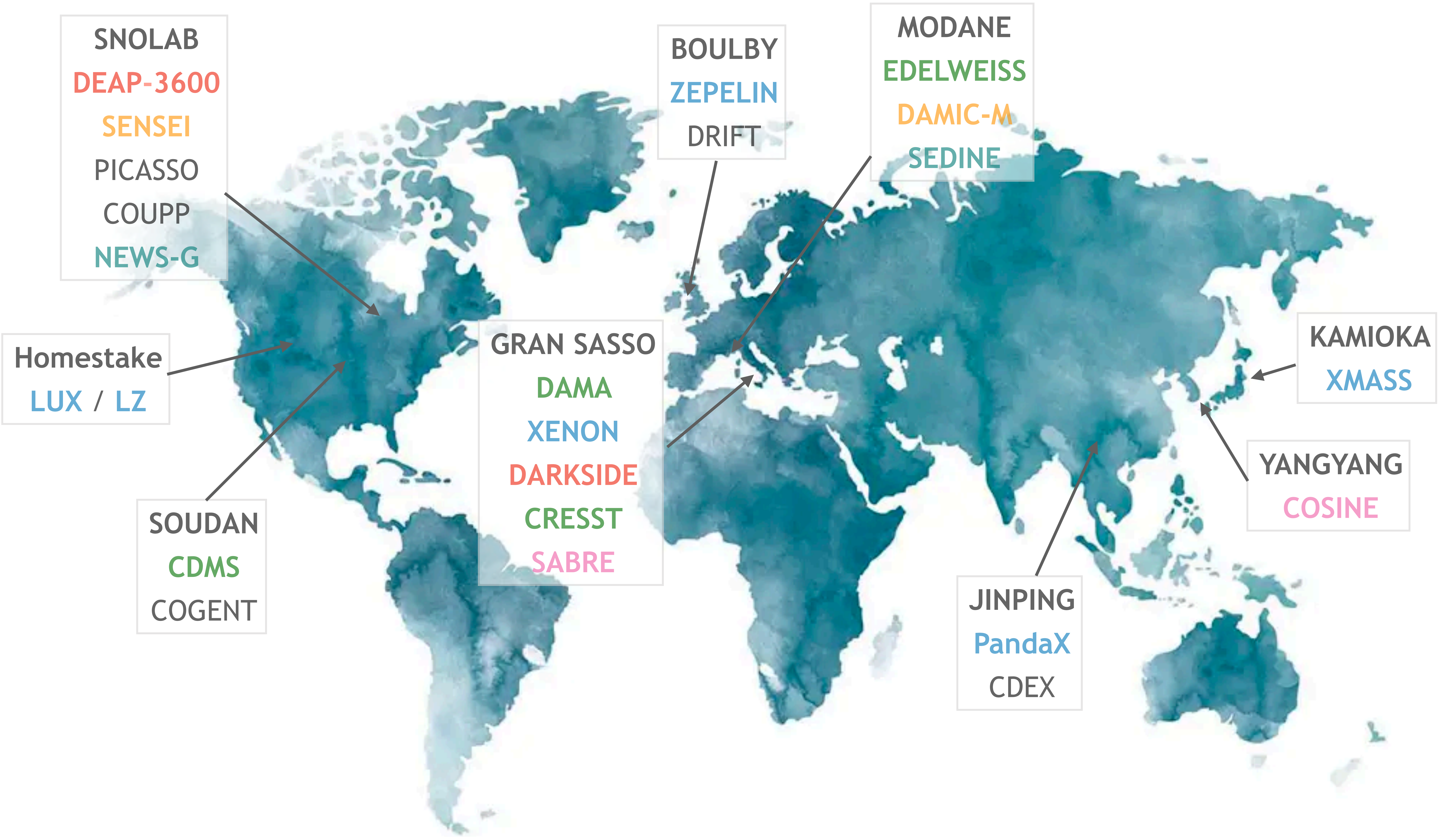
Electron / Nuclear Recoils

- The majority of events induce electron recoils
- Just a tiny faction, mostly neutrons, are responsible of nuclear recoils, which perfectly mimic WIMP interactions

WIMP detector requirement:

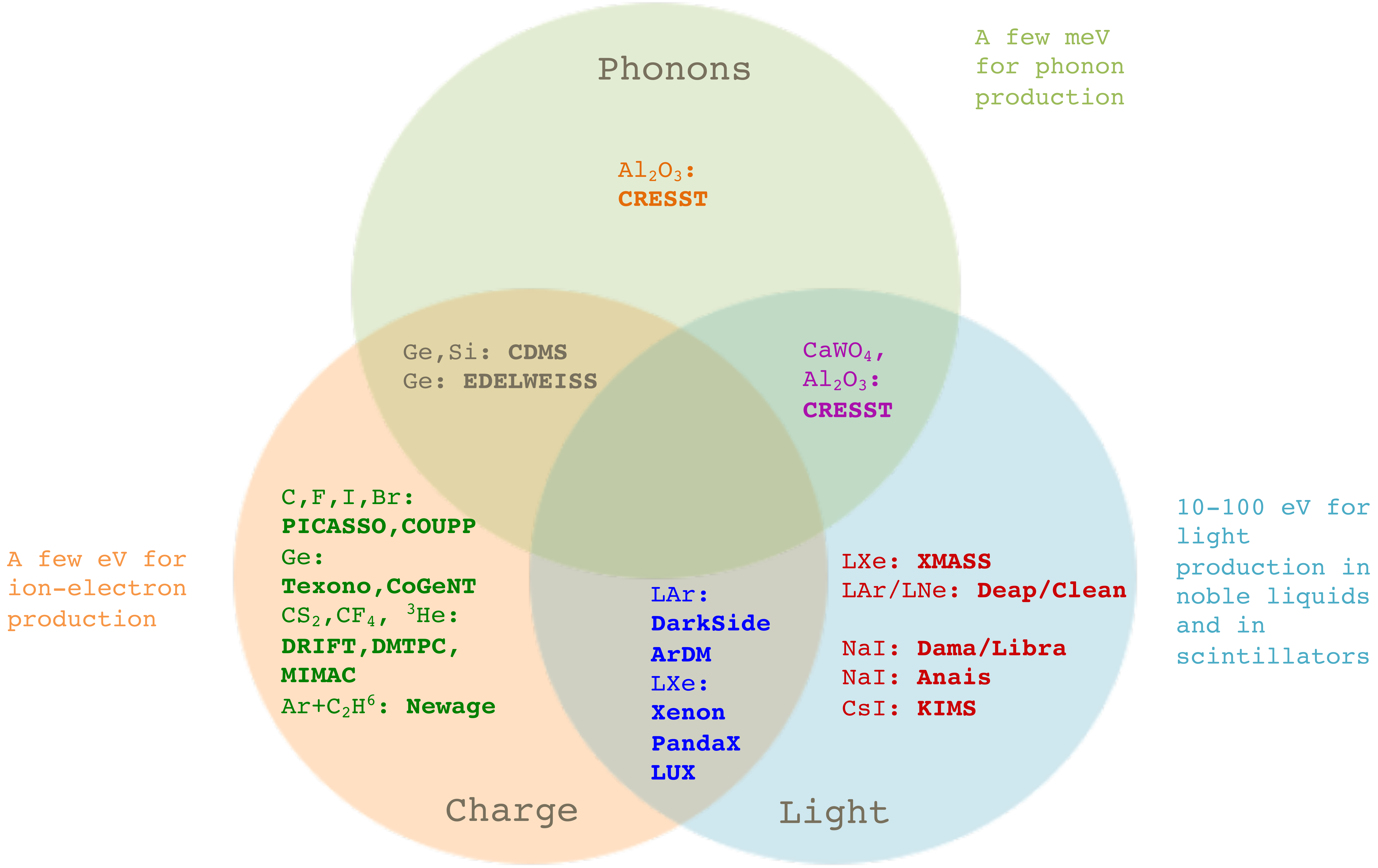
- **Massive** target
- **Low-energy** threshold
- **Ultra-low** background
- Signal/background **discrimination**

Dark Matter Experiments



Xenon
Argon
Bolometers
Scintillators
Si Detectors
Gas Detectors

Direct Detection Techniques

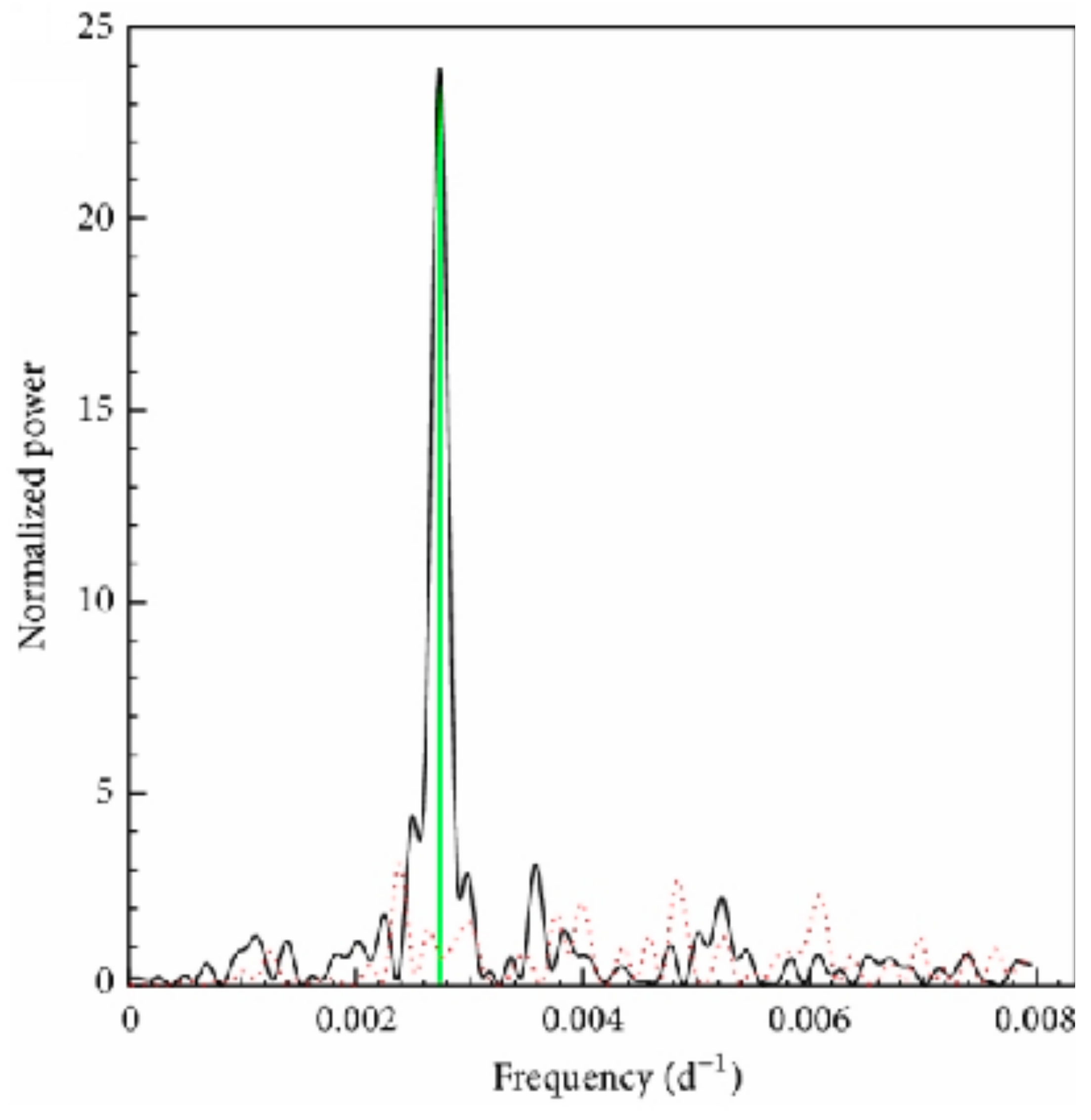


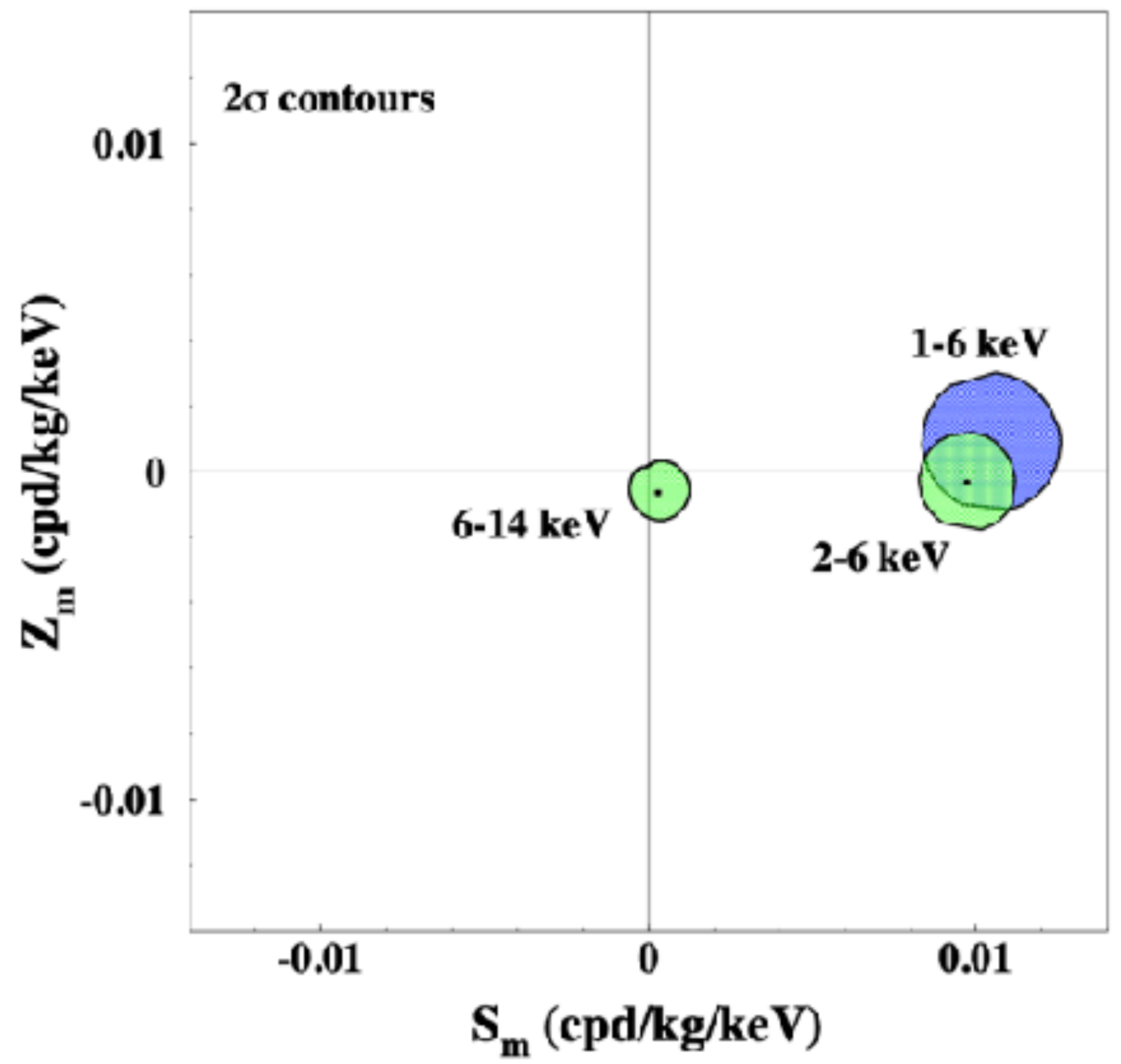
The DAMA/LIBRA modulation

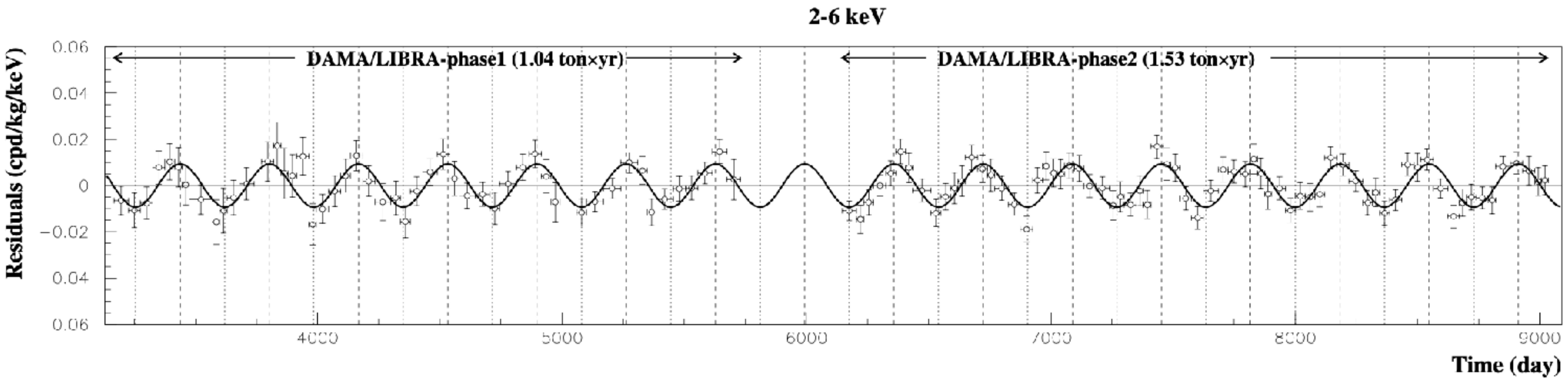
e-Print: 2110.04734

- Annual modulations with high radio-purity **NaI crystals**
- Exposure: 2.86 ton/year
- Phase: compatible with June 2nd within 2σ
- Evidence at **~14 σ**

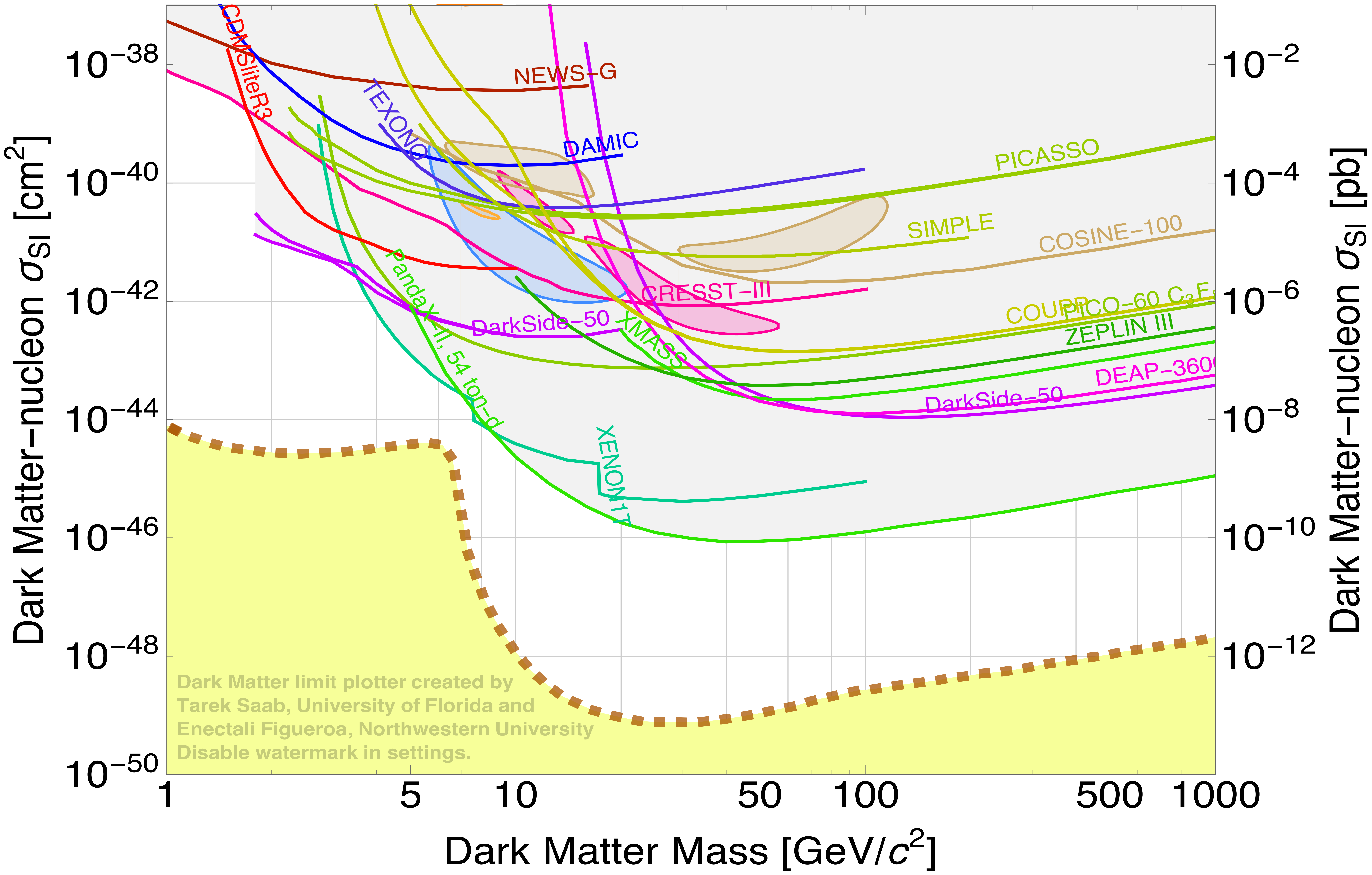
Period = **0.99834±0.00067 yr**
Phase = **142.4±4.2 d** (expected 153)



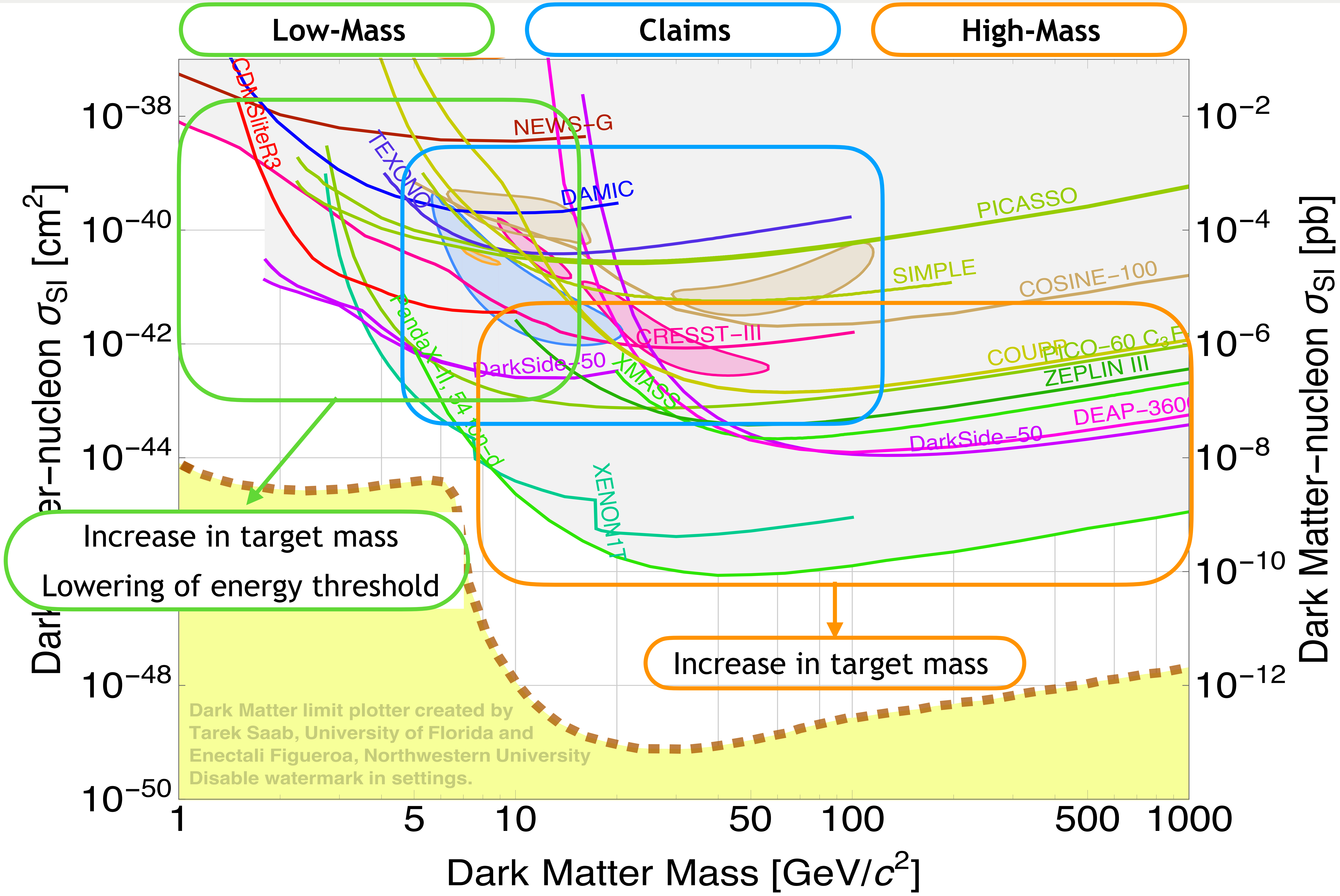




State of the Art



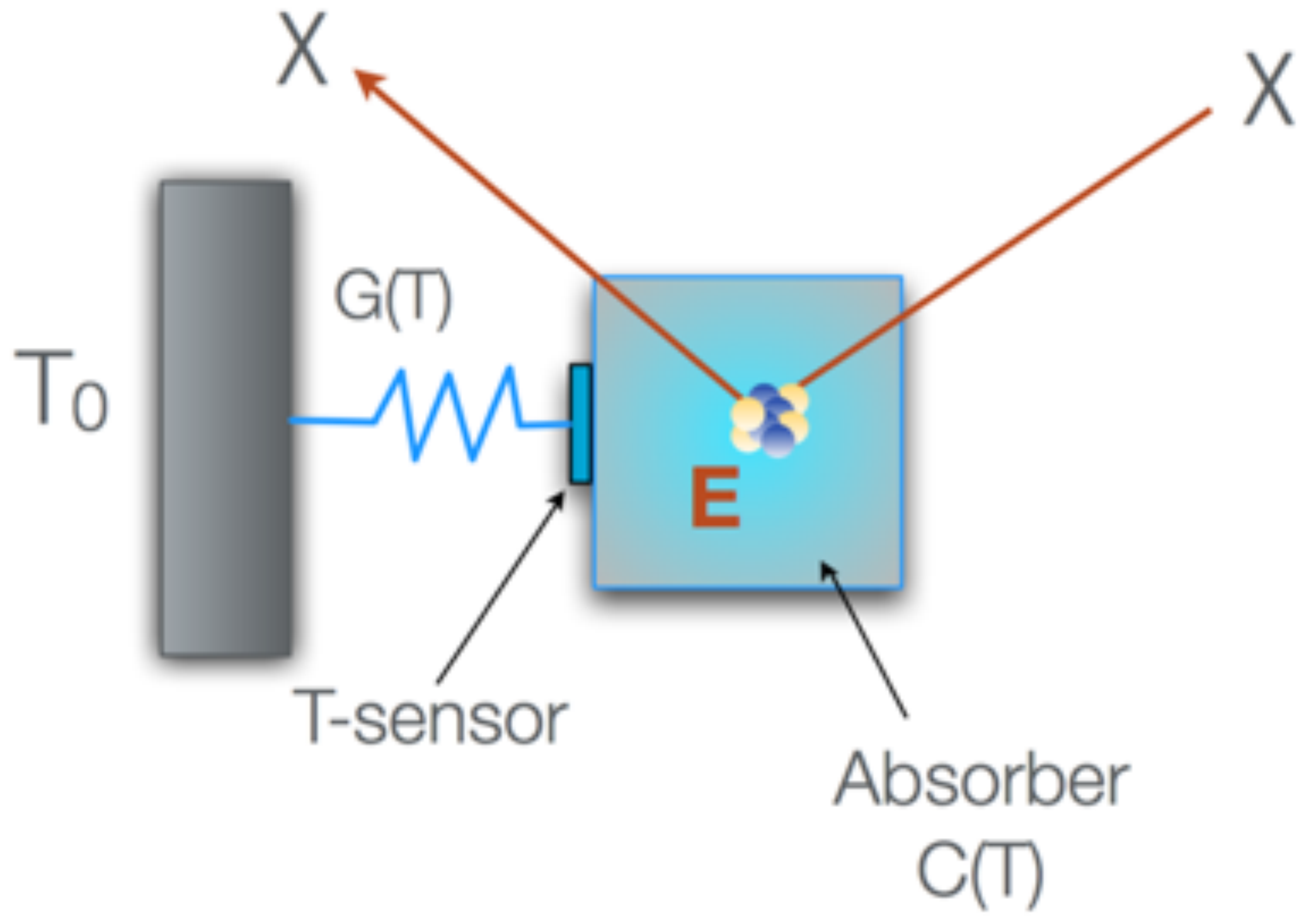
State of the Art



Bolometers: Phonons vs Photons

Characteristics

- Operating at mK temperature
- Excellent energy resolution
- Very low thresholds >0.2 keV
- Limited crystal sizes (4 g – 1.4 Kg)
- Good discrimination with phonon vs light/charge



CRESST-III: at Gran Sasso lab (Italy)

10 24 g $CaWO_4$ scintillating bolometers at 15 mK

30 eV energy threshold achieved

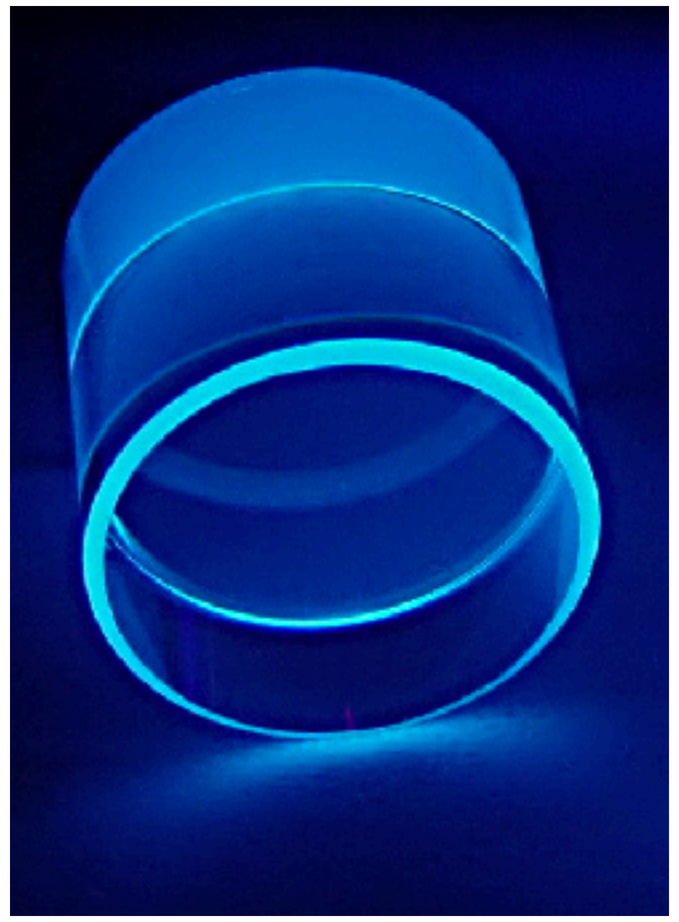
Run 3 started on July 2020

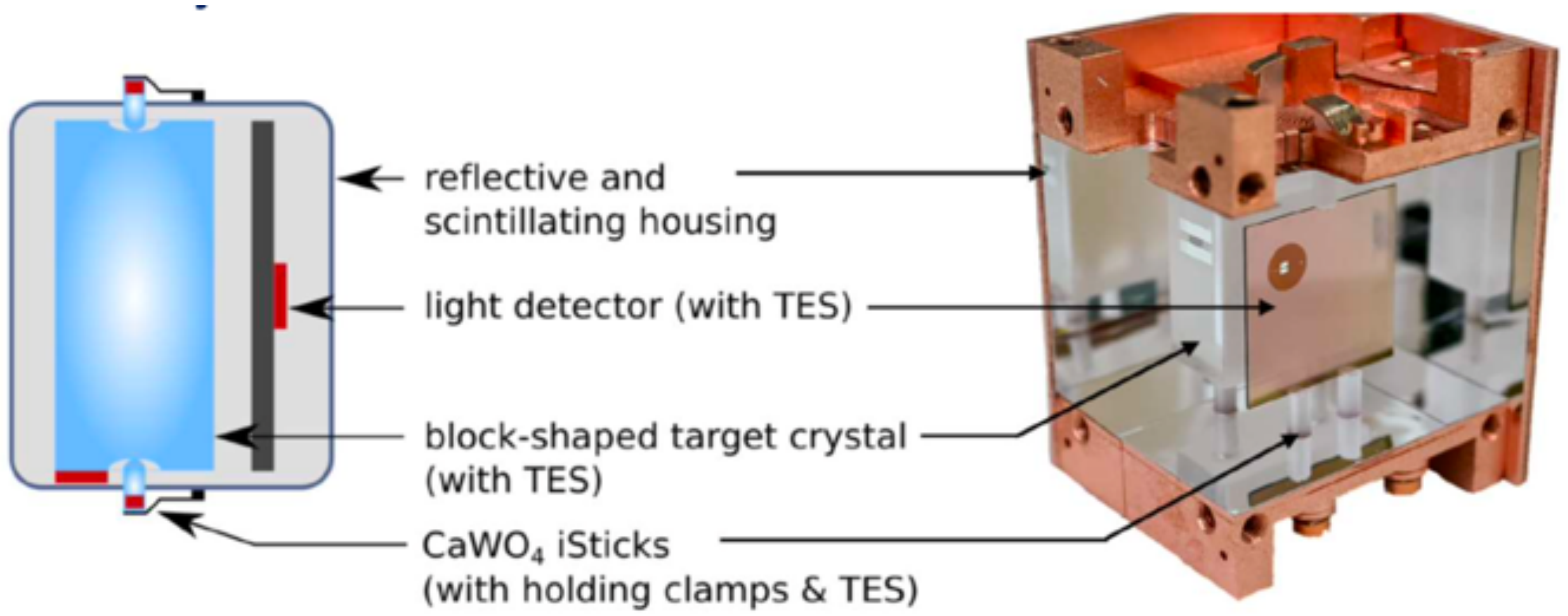
→ best limits for WIMP-NR **down to 160 MeV**

A.H. Abdelhameed et al, Phys. Rev. D 100 (2019) 102002

Phase 2:

100 crystals
Goal 10 eV threshold





Bolometers: Phonons vs Charge

EDELWEISS-III: at Modane lab (France)

24 Ge detectors, 870 g each, 200 eV_{ee} threshold

→ very good results at **5-30 GeV** and limits also on ALP

L. Hehn et al, Eur. Phys. J. C 76 (2016) 10 548

EDELWEISS-subGeV: above ground and at Modane

33 g Ge bolometers, 55 eV energy threshold (heat)
→ exploring DM mass down to **45 MeV with Migdal** + dark photons

E. Armengaud et al, Phys. Rev. D 99 (2019) 082003
Q. Arnaud et al, arXiv:2003.01046

SuperCDMS: at Soudan lab (US)

15 Ge detectors, 600 g each, 70 eV threshold

Exploiting the Neganov-Luke (NTL) effect at high bias voltage (HV) to convert charge into heat

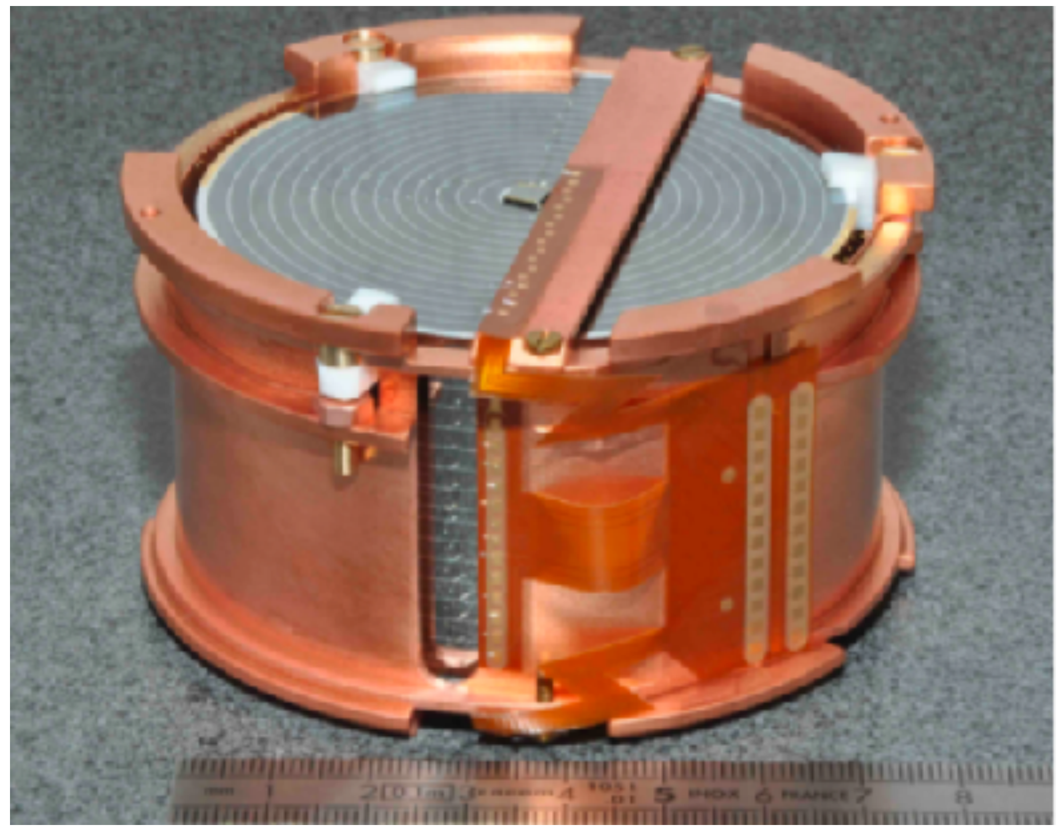
→ results down to **1.5 GeV** from different analyses

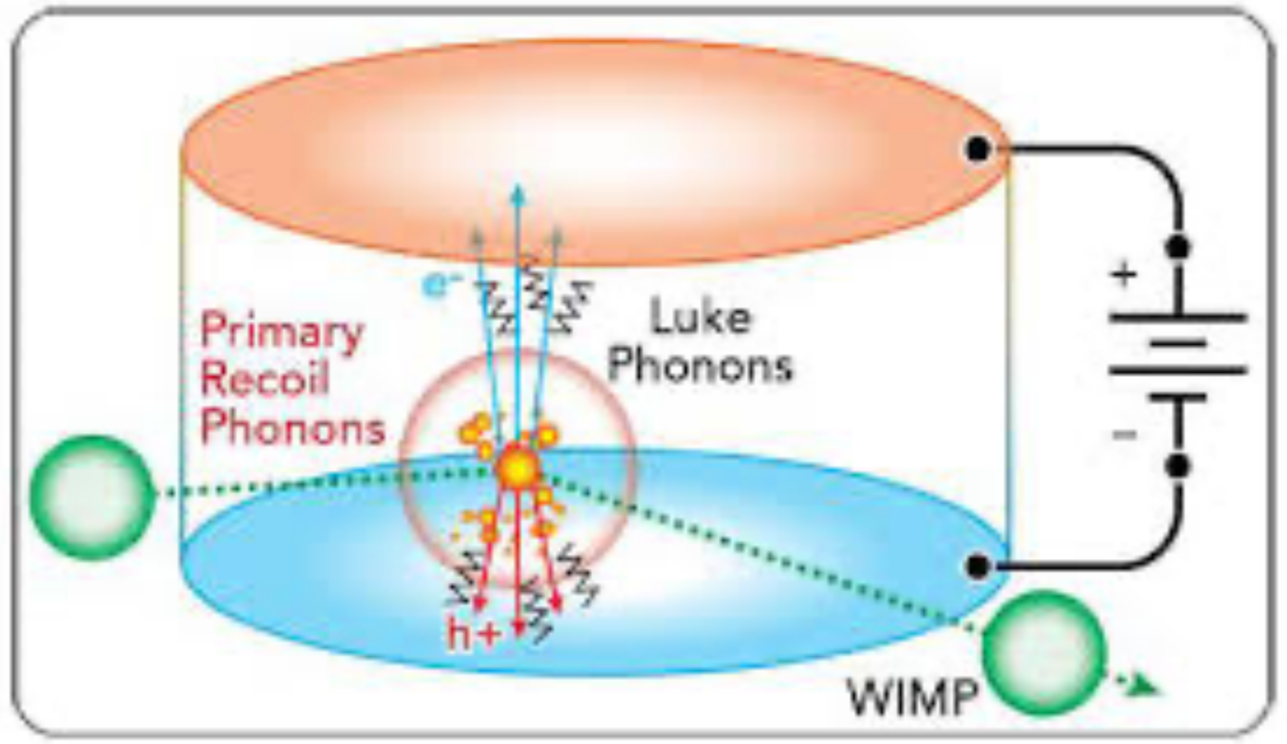
R. Agnese et al, Phys. Rev. Lett. 120 (2018) 061802; Phys. Rev. D 99 (2019) 062001

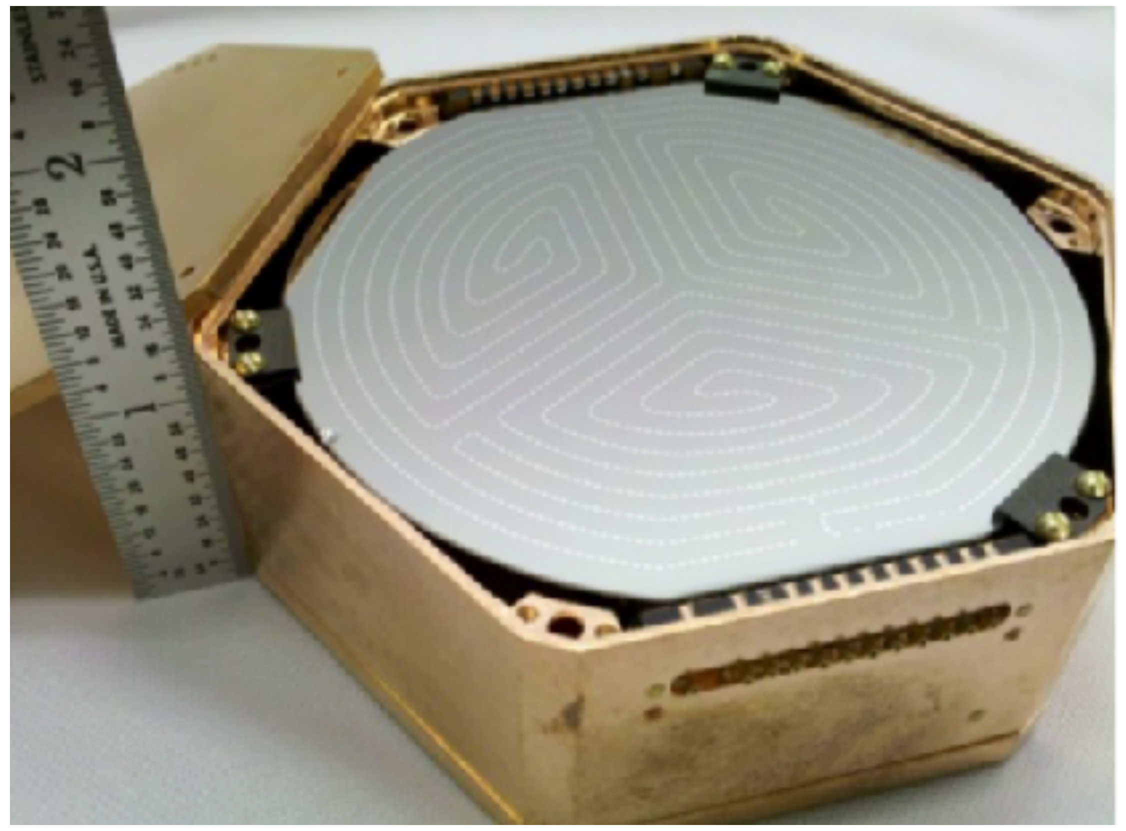
0.93 g / 10.6 g Si detectors on surface → results on e- scattering and dark photons / nucleon scattering

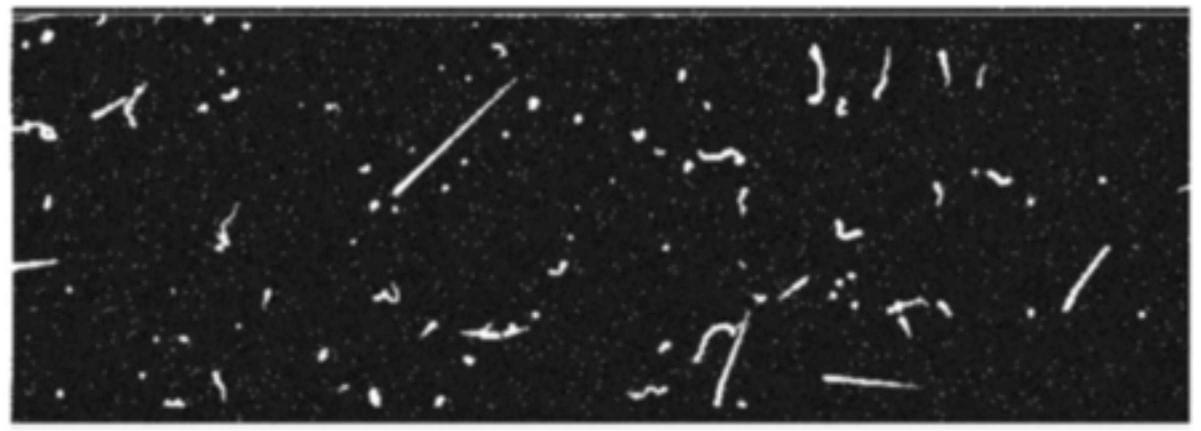
D. W. Amaral, et al, arXiv:2005.14067, I. Alkhatib et al, arXiv:2007.14289

SuperCDMS: at SNOLAB (Canada)
Start mid-2021, 30 kg, Ge and Si NTL detectors





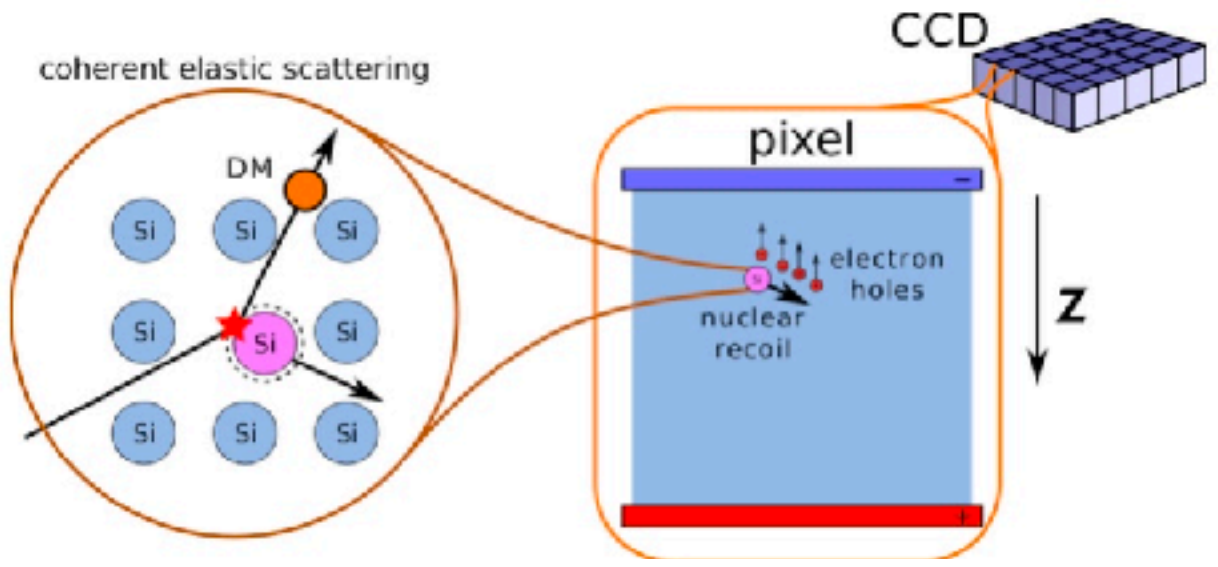


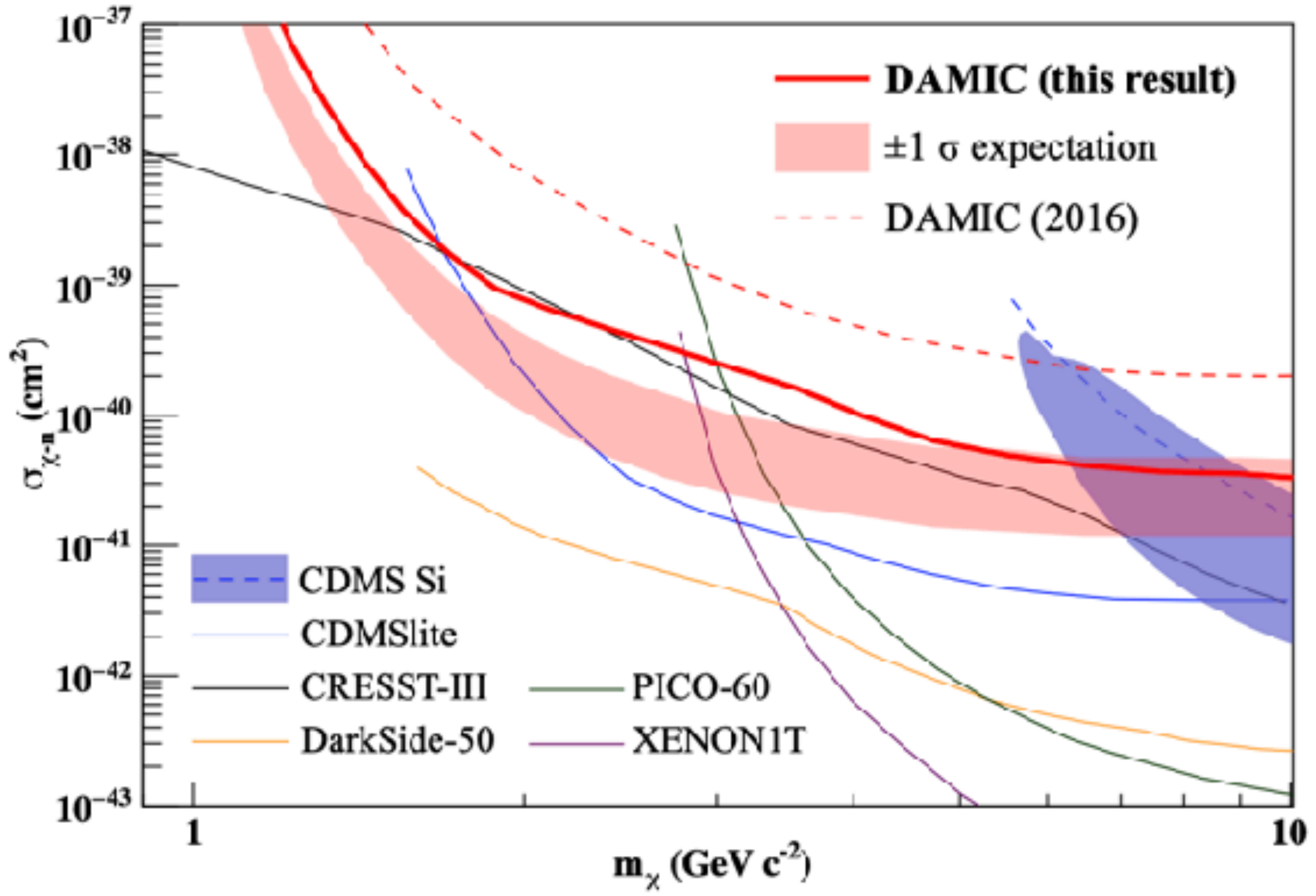


Low-Mass: CCDs

Silicon charge-coupled devices (CCDs): charge produced in the interaction drifts towards the pixel gates, until readout.

+ 3D position reconstruction possible: interaction correlated from charge diffusion
+ Effective particle identification and background rejection





DAMIC at SNOLAB

- 7 CCDs (6 g each) since 2017 - Threshold 50 eV_{ee}
  → results also on e scattering and hidden photon DM
  PRL 118, 141803 (2017); PRL 123 (2019) 181802
  → recent on nucleon scattering from 11 kg day: excess of ionization events at 50-200 eV_{ee}?
  A. Aguilar-Arevalo et al, arXiv:2007.15622

DAMIC-M at Modane

- 50 CCDs (13.5 g each) for kg-year exposures - Commissioning in 2023. → **Skipper readout**: reduce noise and achieve single electron counting with high resolution

SENSEI at Fermilab

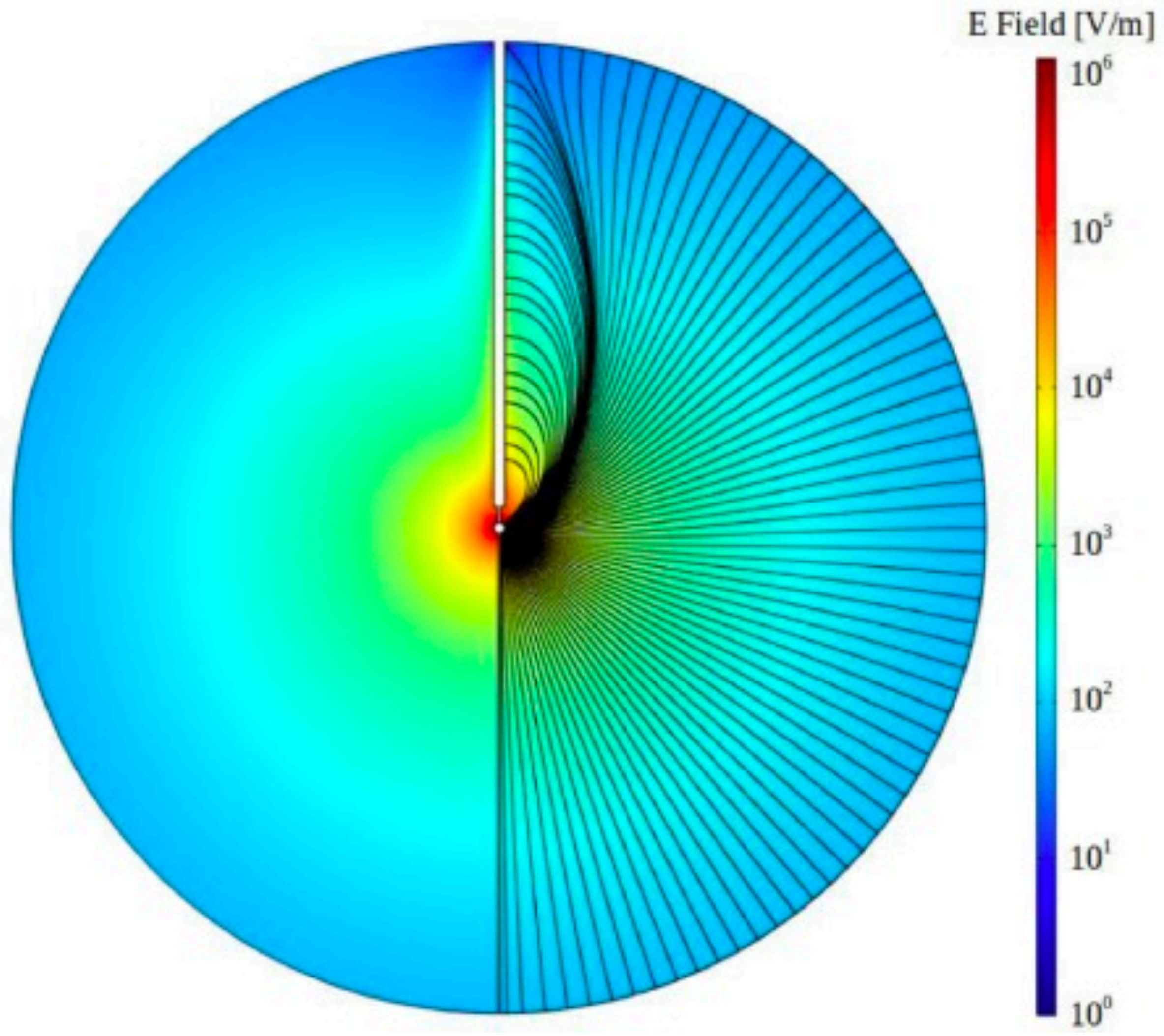
- Prototypes with 0.0947 g and 2 g total active mass at MINOS Hall (100 m underground) → constraints on e scattering and hidden-sector candidates
- Proposal to install a 100-g detector (48 CCDs) at SNOLAB

OSCURA: 10 kg in 2027

Spherical gaseous detectors

Spherical Proportional Counter: very low energy threshold and very low capacitance (<1 pF). Anode: small ball at the center, avalanche region.

I. Giomataris et al, JINST 2008 P09007

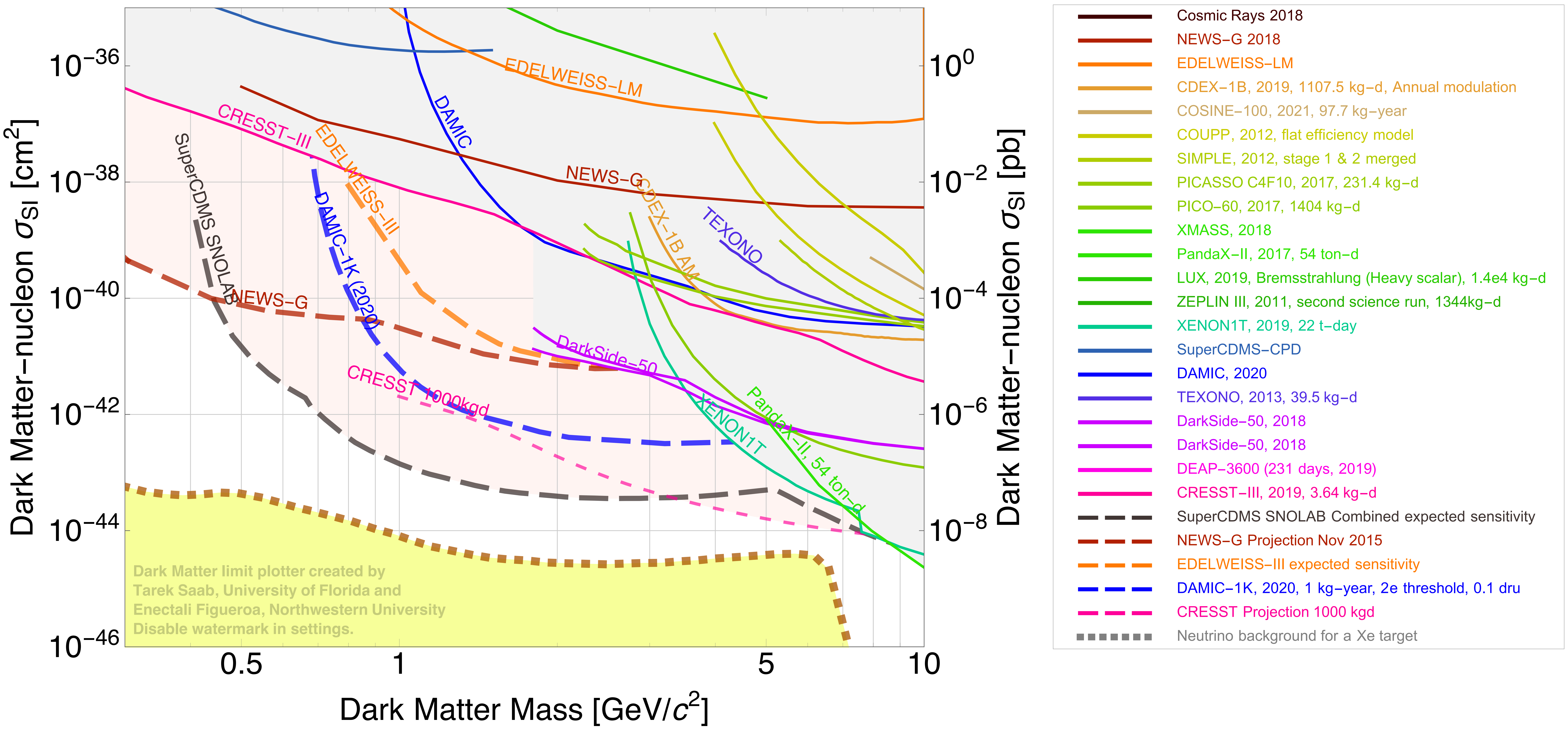


- **SEDINE detector at Modane**
- 60-cm NOSV copper sphere
- Filled with Ne-CH_4(0.7%) at 3.1 bar (280 g active mass)
- 42 d WIMP search run, 50 eVee threshold
  Q. Arnaud et al, Astropart. Phys. 97, 54 (2018)

NEWS-G at SNOLab

- 140-cm low activity copper sphere, built in France, commissioning data with CH4, now at SNOLAB.
- Lighter targets: H, He
- Single electron response (gain, drift and diffusion times, ...)
- Q. Arnaud et al, Phys. Rev. D 99 (2019) 102003

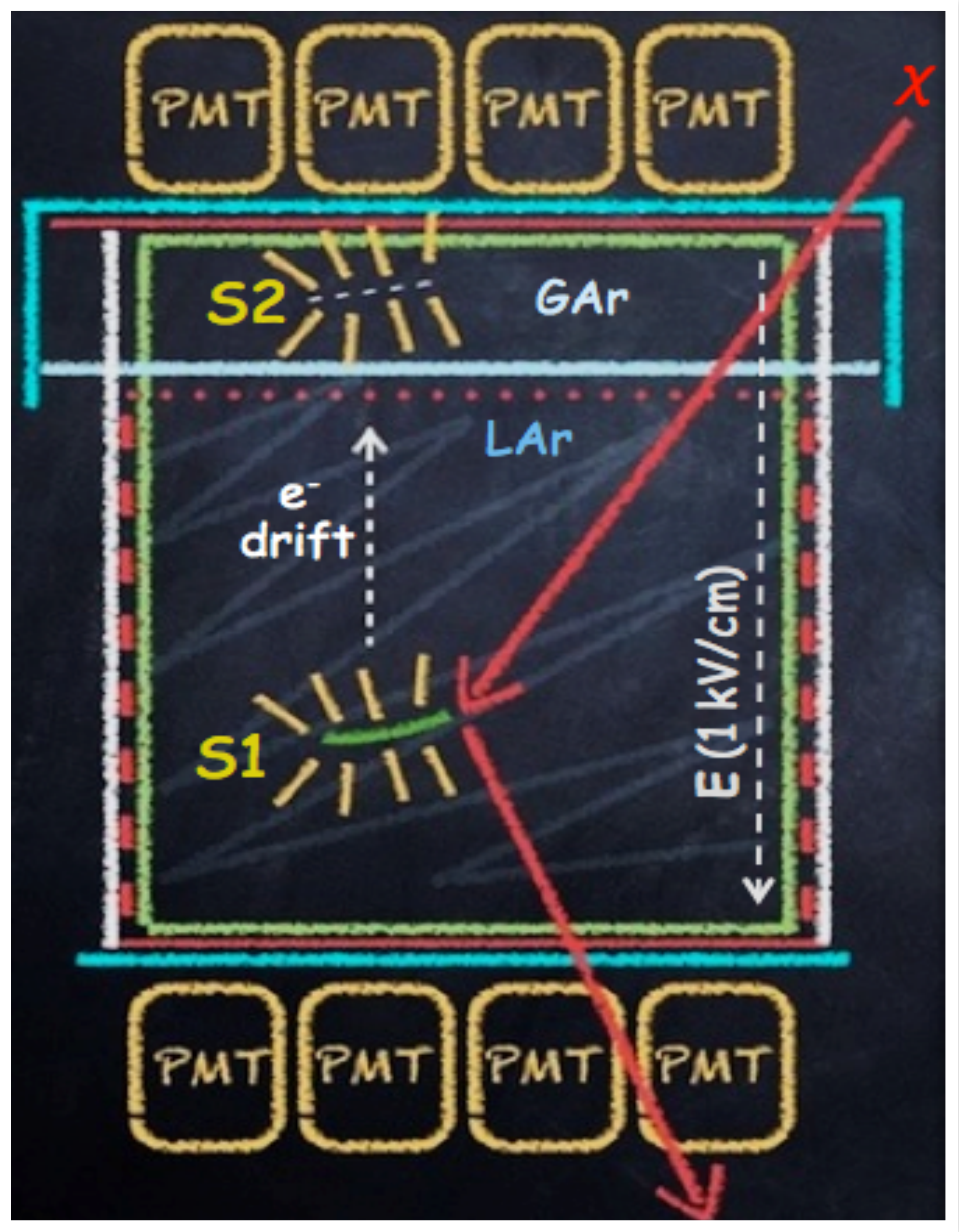
Perspectives in the low-mass range



Noble liquids: Xenon vs Argon

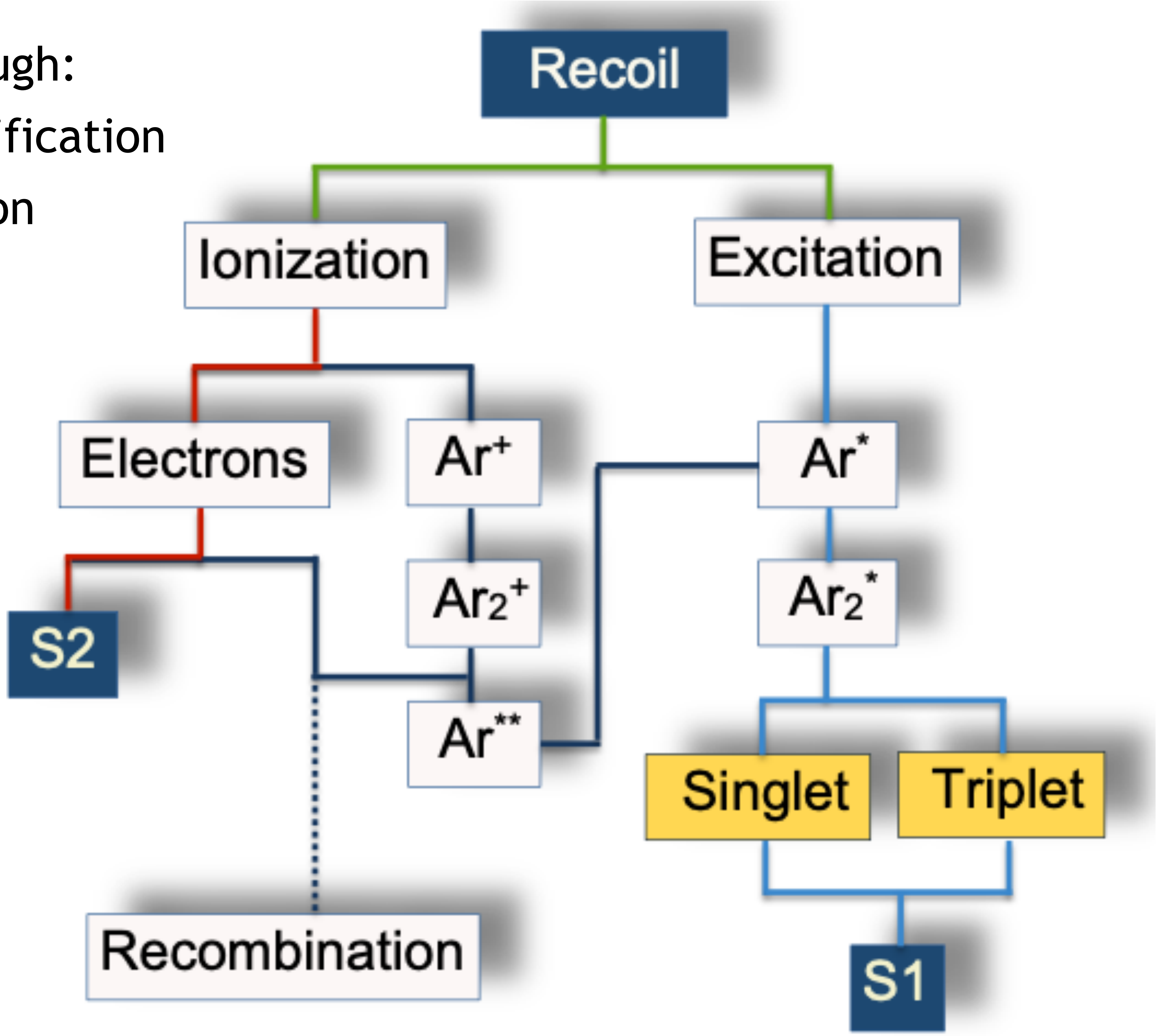
	LAr	LXe
WIMP SI cross section	Lower cross-section => need more massive target	Higher-cross section
WIMP SD cross section	Not accessible	Accessible
Kinematics	Lighter nucleus and higher scintillation efficiency: low ionization threshold	Heavier nucleus and higher quenching: >1 GeV/c^2
Radio-purity	^{39}Ar contamination (fixed: see next slides)	Intrinsically pure
Density	1.4 g/cm^3	3.1 g/cm^3
Temperature	87.2 K (close to nitrogen)	166.4 K
S1 Pulse Shape Discrimination	Yes (singlet ~7 ns; triplet ~1600 ns)	Very limited (singlet: ~2 ns; triplet: ~27 ns)
Cost and availability	Generically cheap (~$/kg) + extra costs for underground extraction Abundant	Expensive (~kDollar/kg) Limited world production

Dual-phase Time Projection Chamber

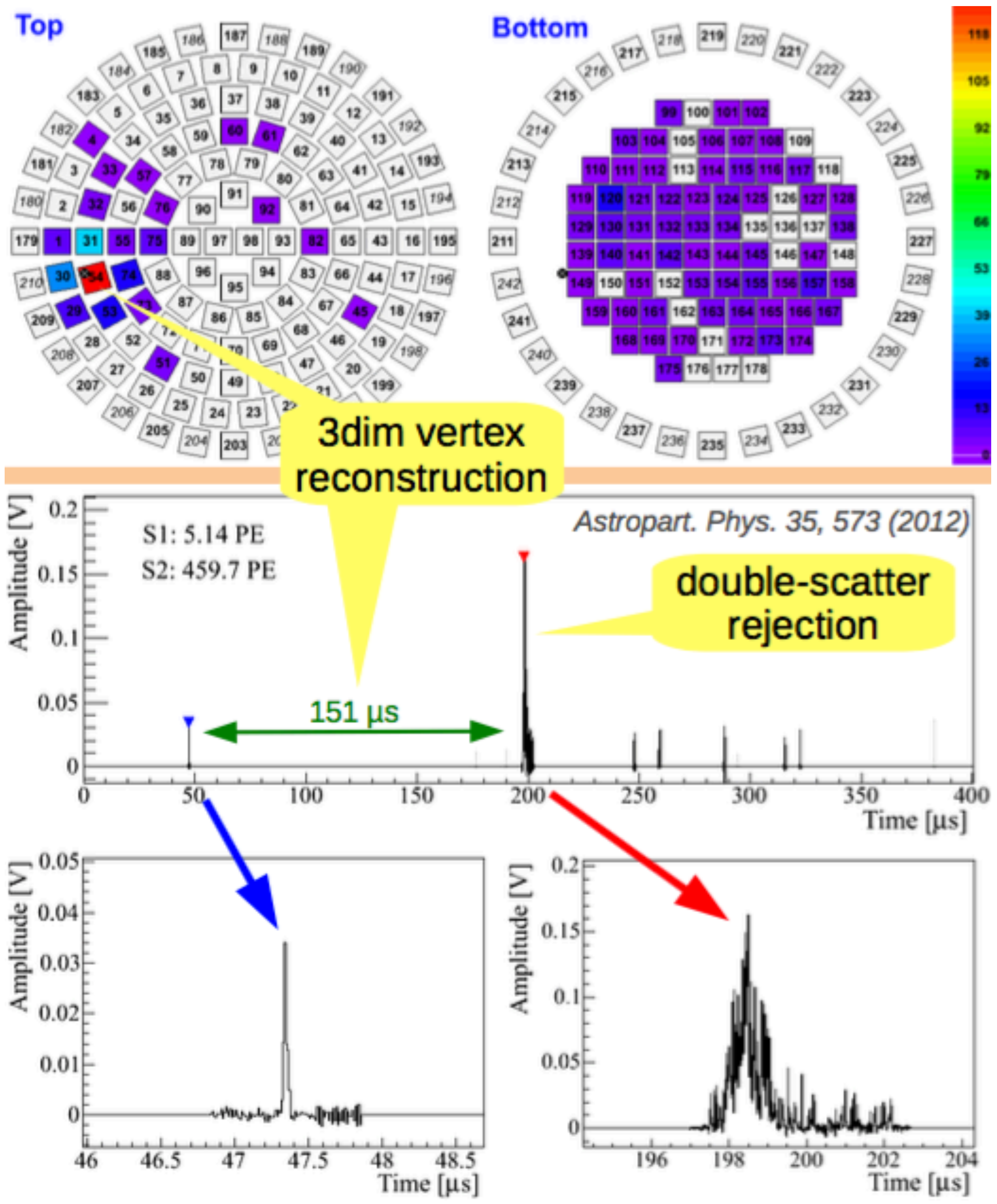


Particle discrimination through:

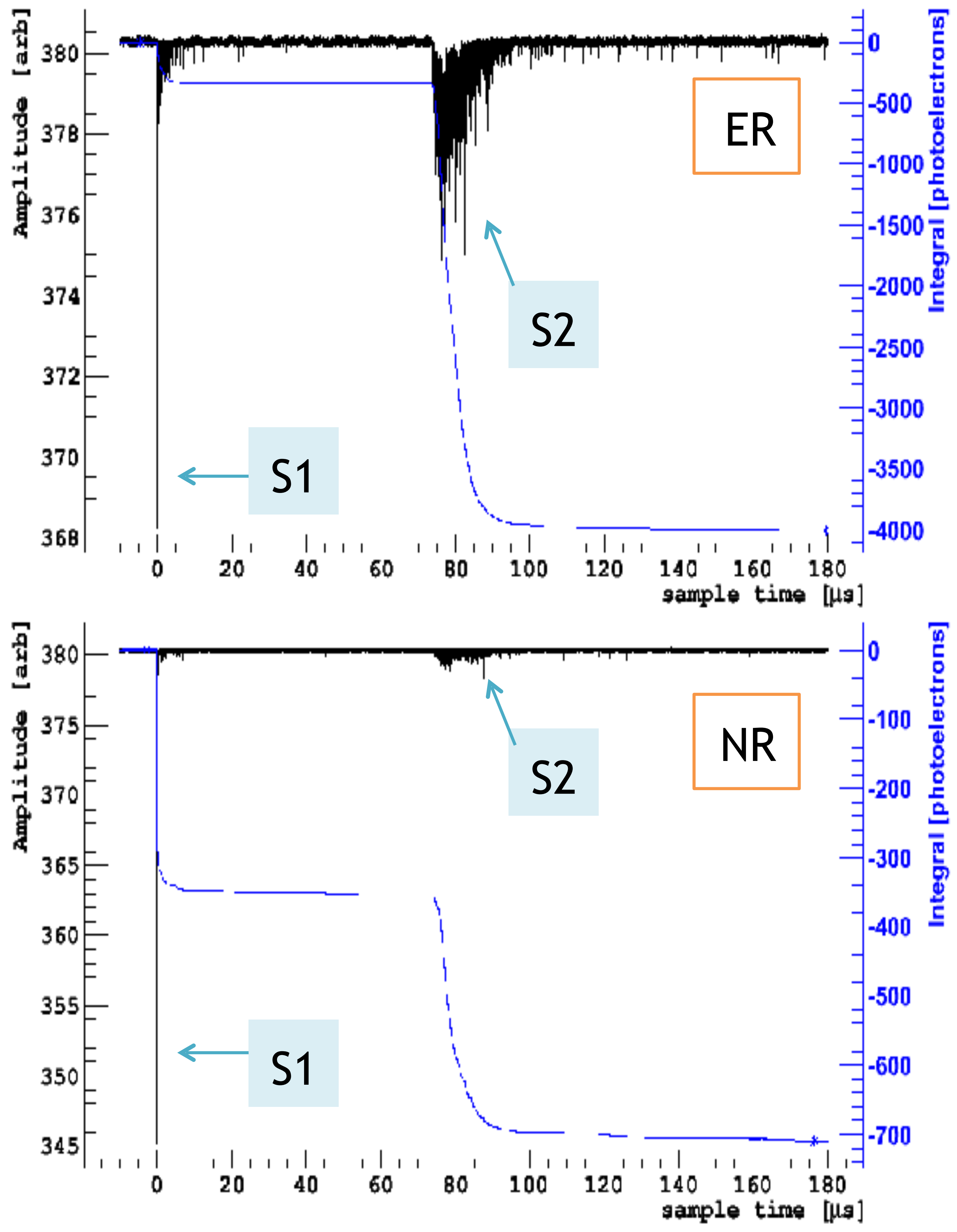
- Accurate 3D **position** identification
- **Multiple**-scattering rejection
- **S2/S1** ratio
- S1 **PSD** (if available)



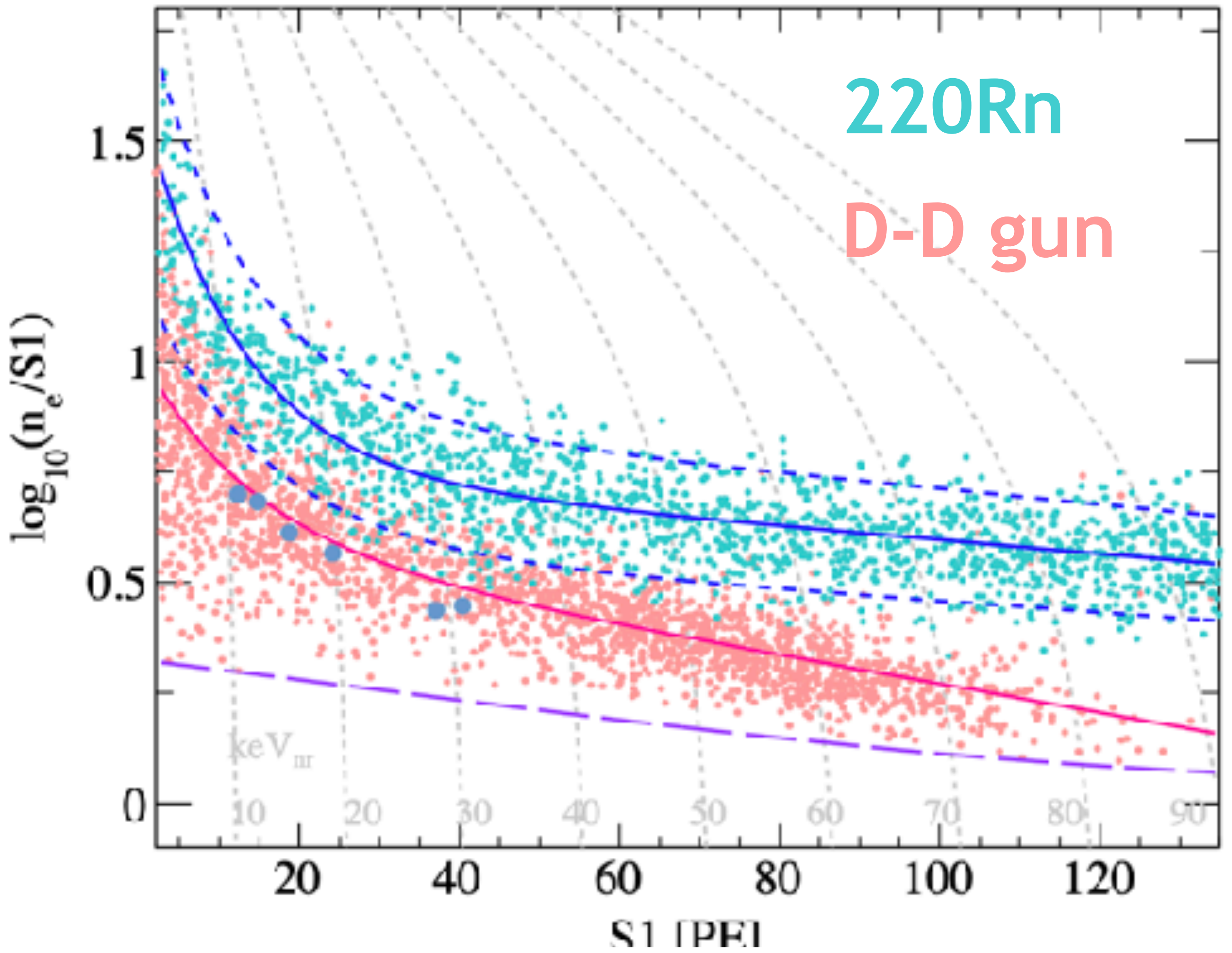
Multiple Scatter Rejection

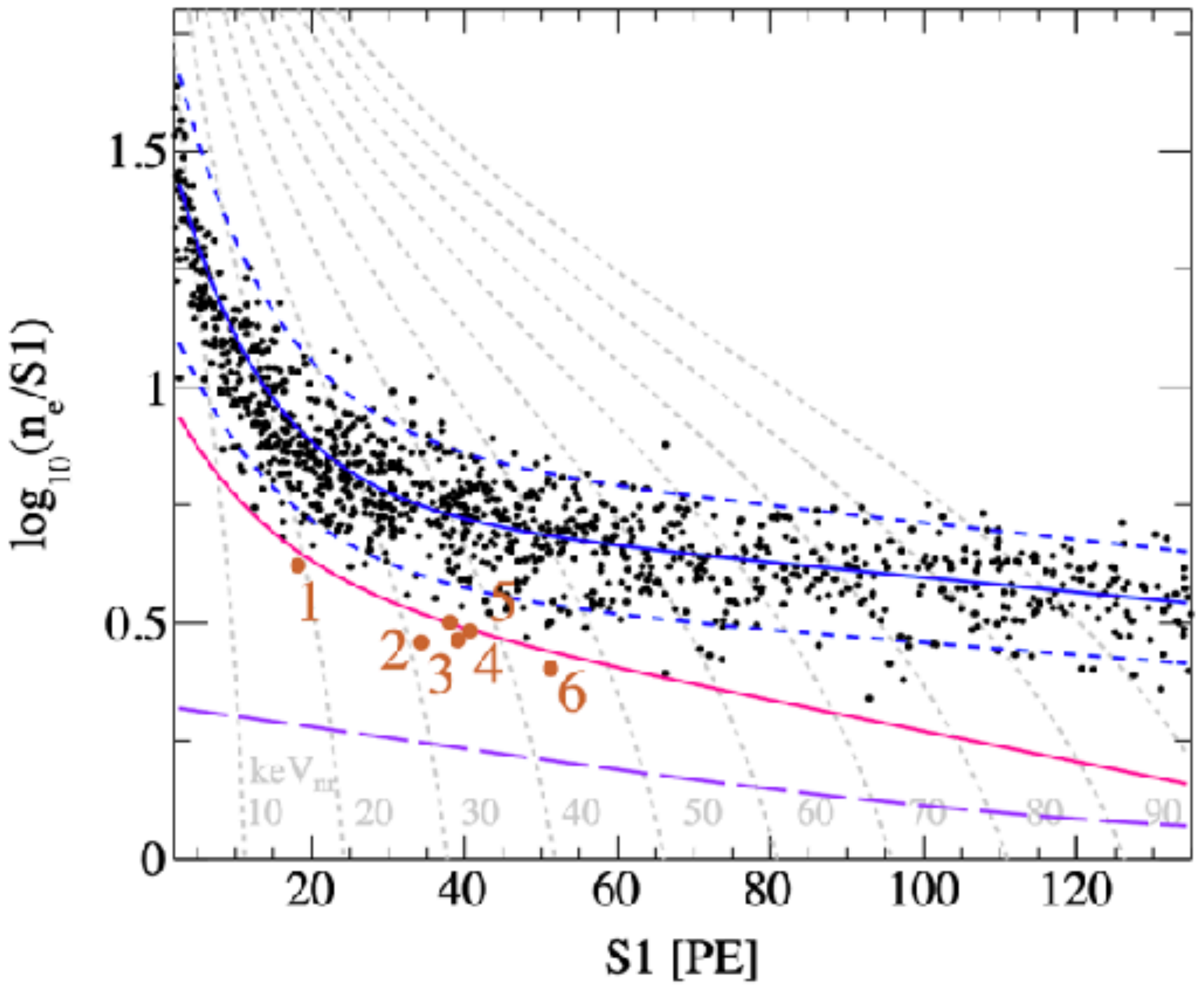


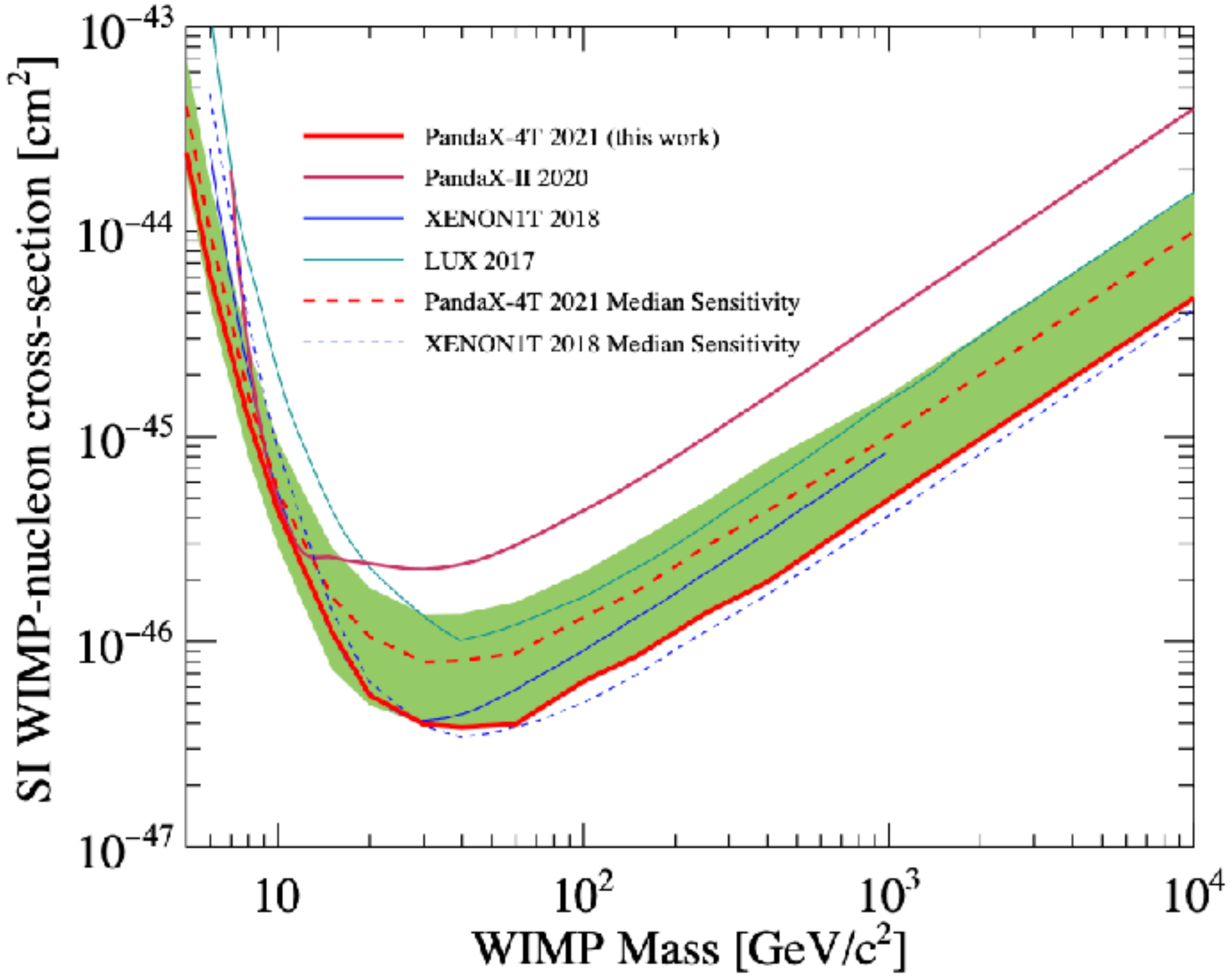
S2/S1 Particle Discrimination

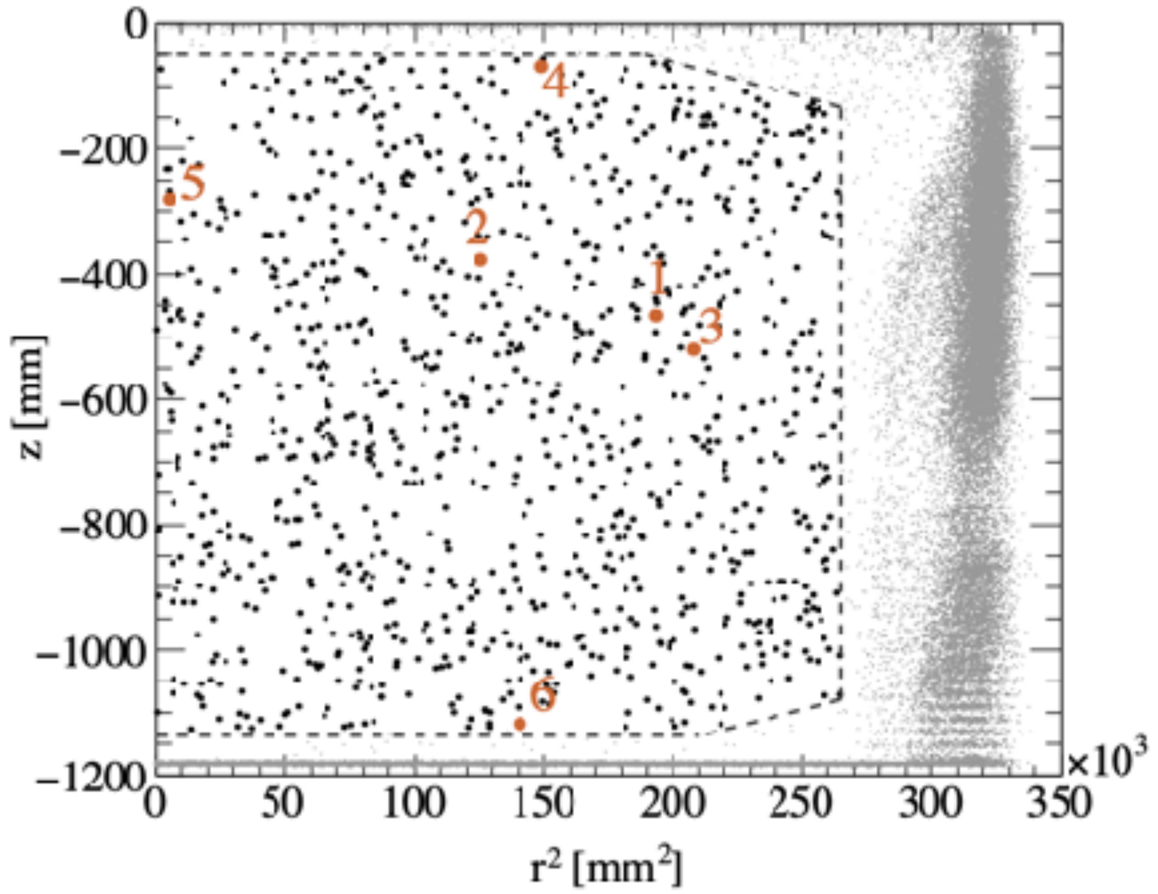


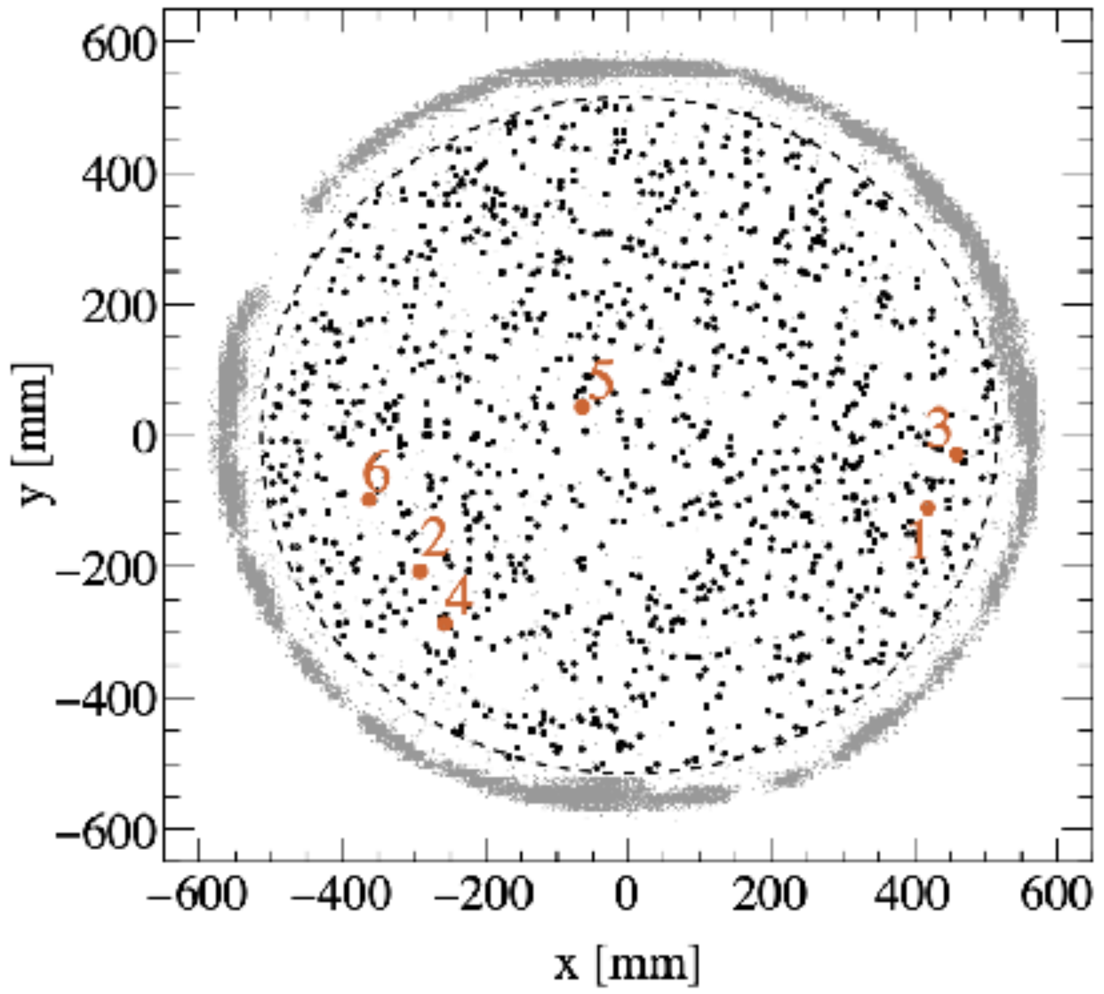
LXe High-Mass Results: PandaX-4T







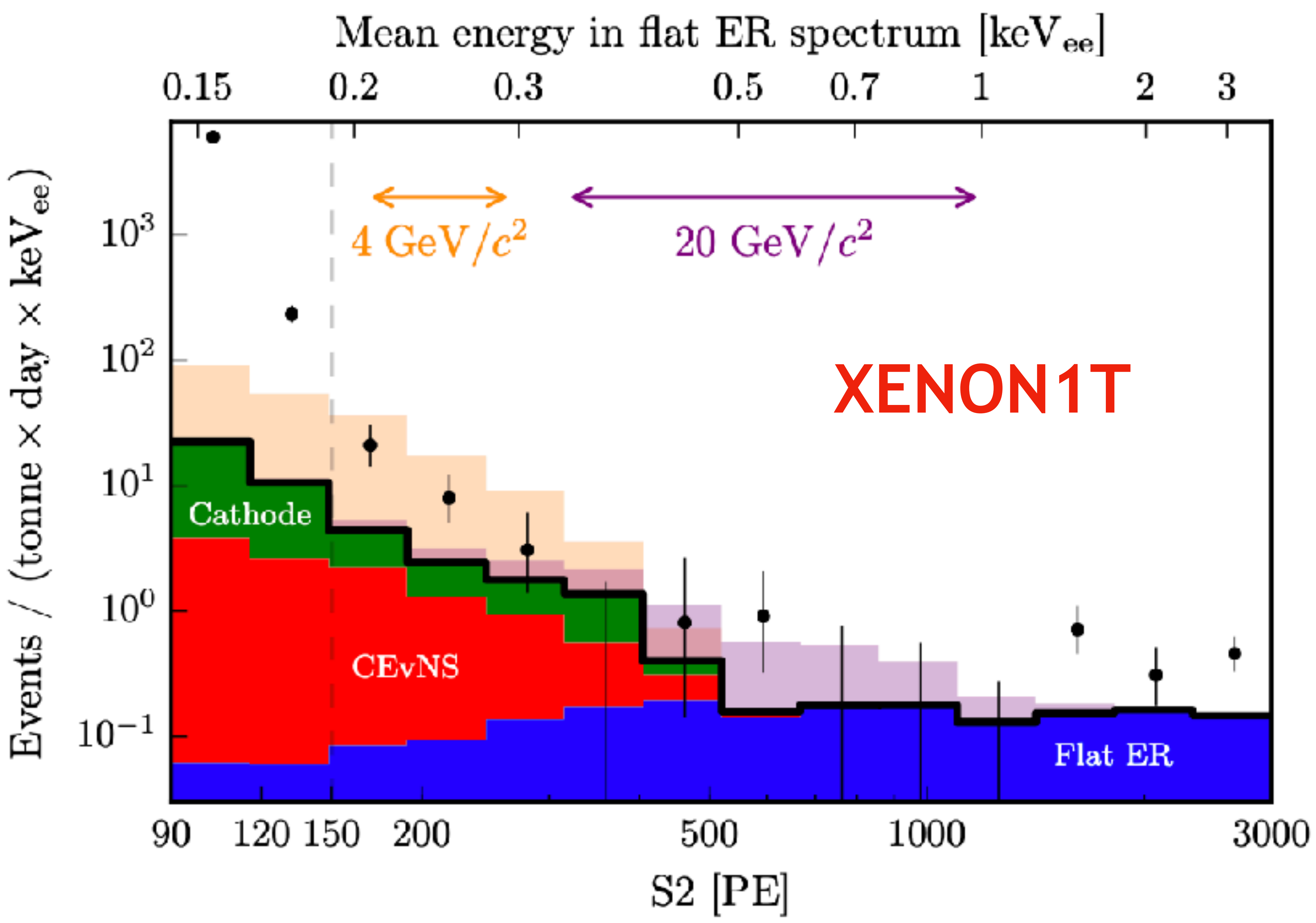




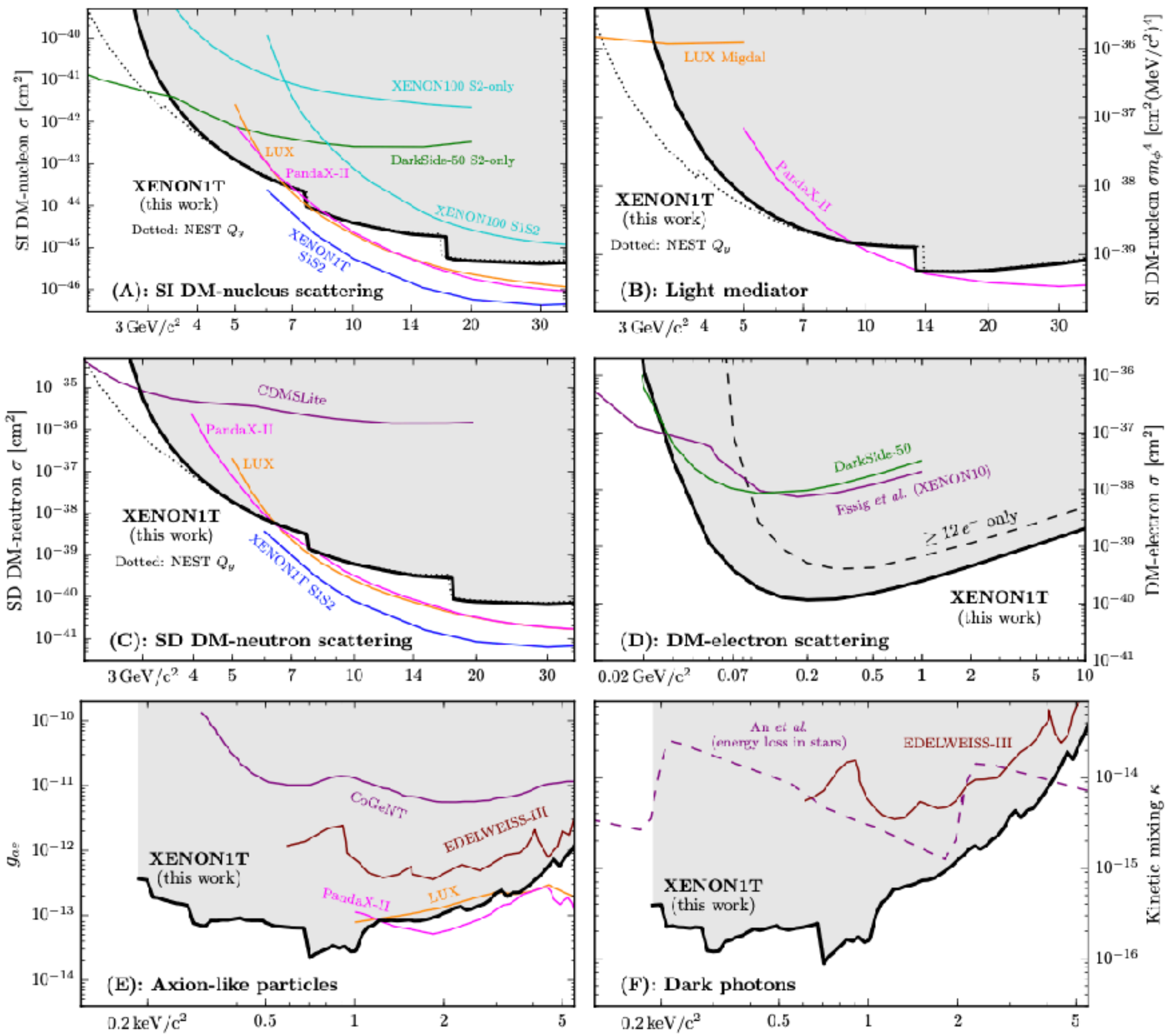
S2-only analysis

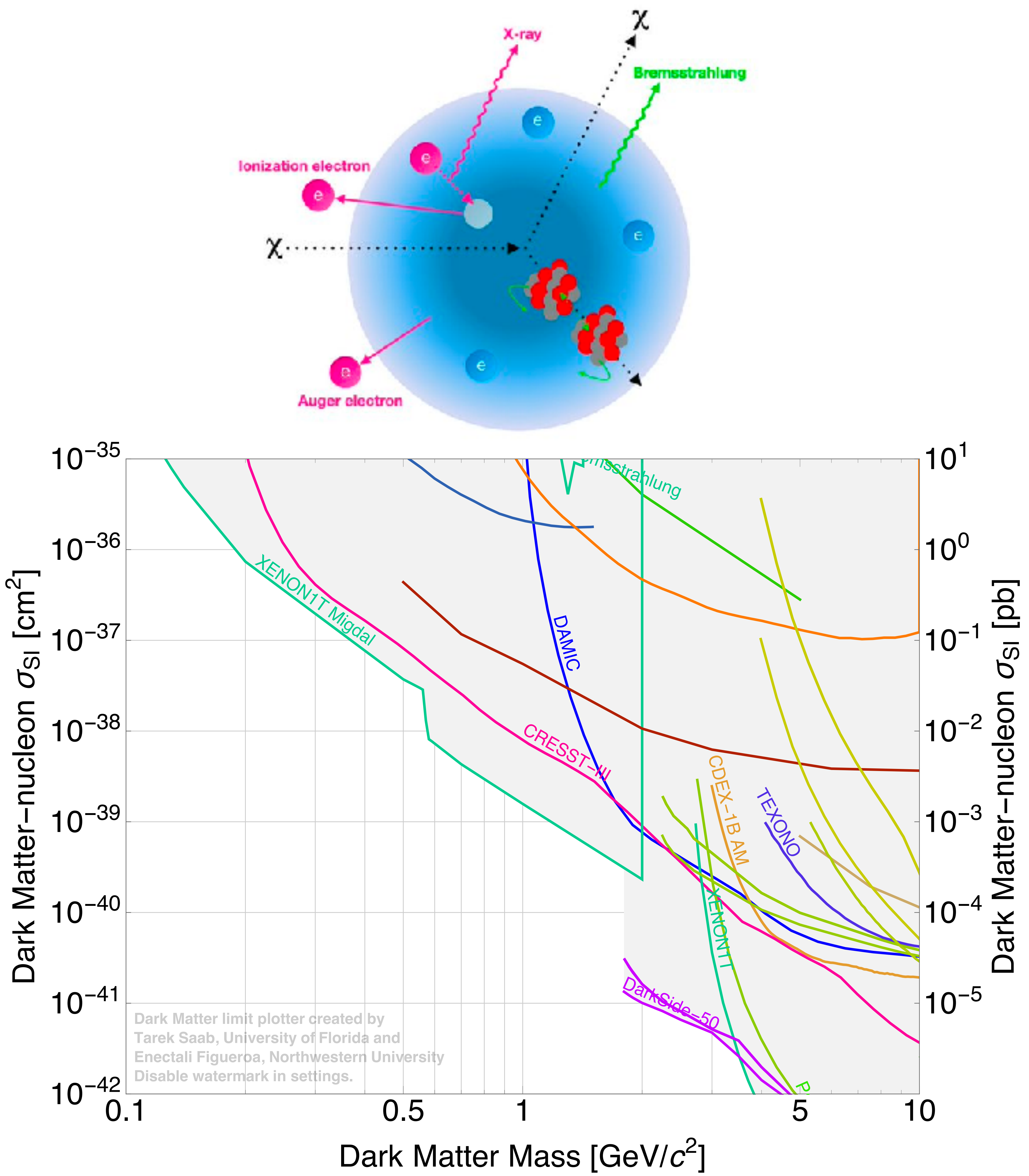
- S1 detection efficiency ~10-20% => dropped
- Ionization electron amplification factor ~10-30

- Very low threshold
- Quite high-resolution
- Very massive if compared with solid-state detectors
- Much higher radiopurity
- Limited background discrimination (only multiple scatters rejection)



SI, SD, Lephotphilic, and Migdal Effect

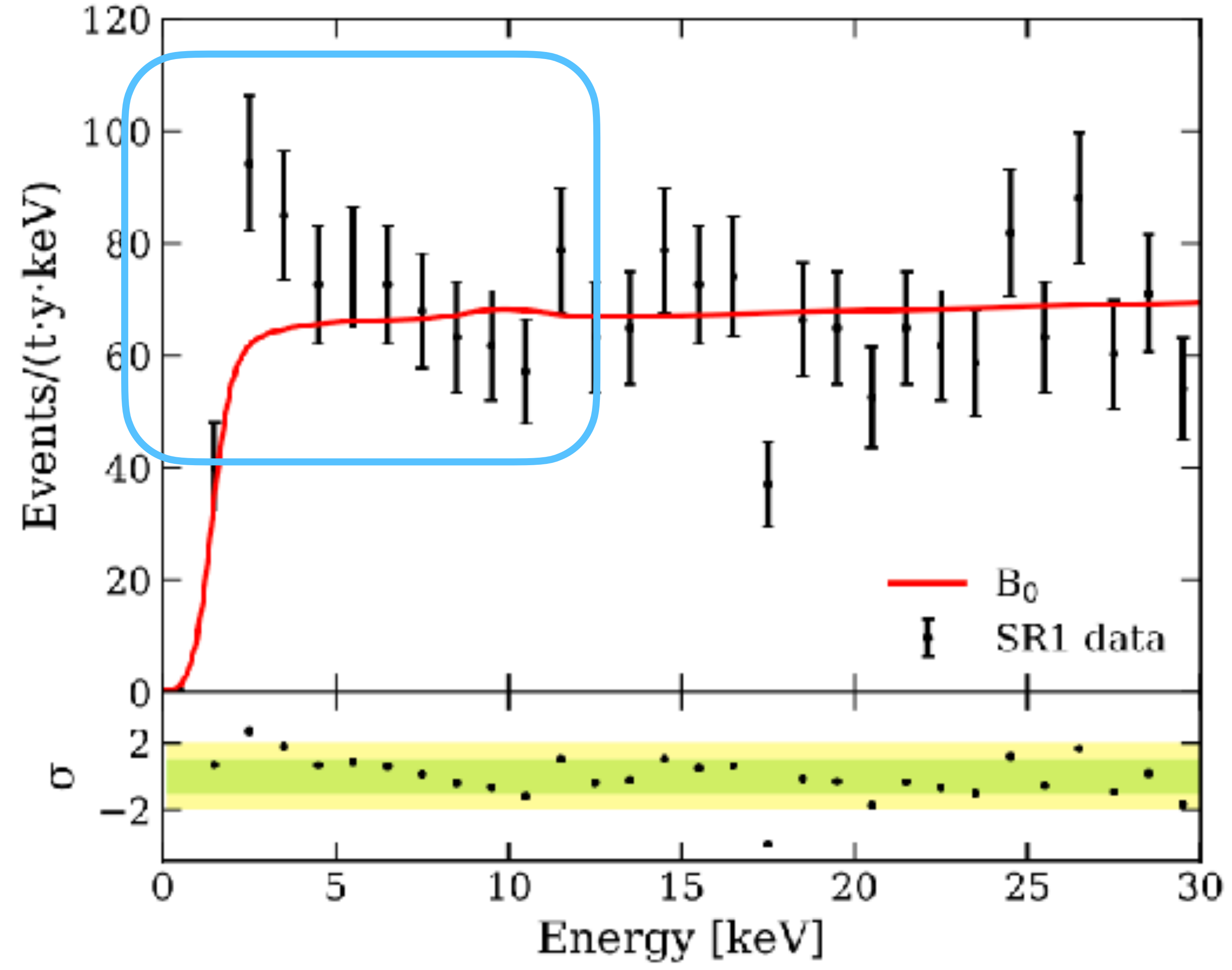




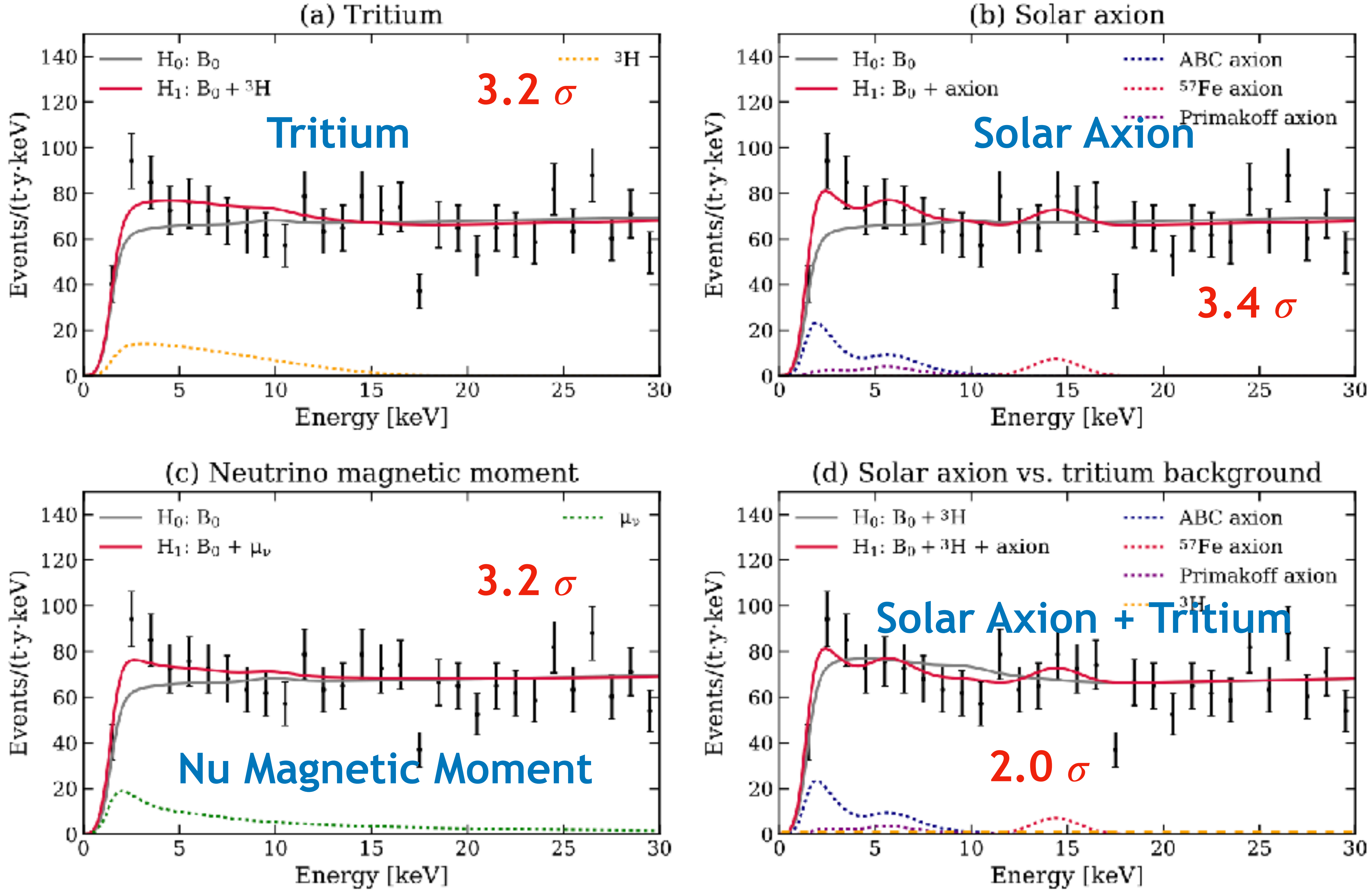
Phys.Rev.Lett. 123 (2019) 25, 251801   *Phys.Rev.Lett.* 123 (2019) 24, 241803

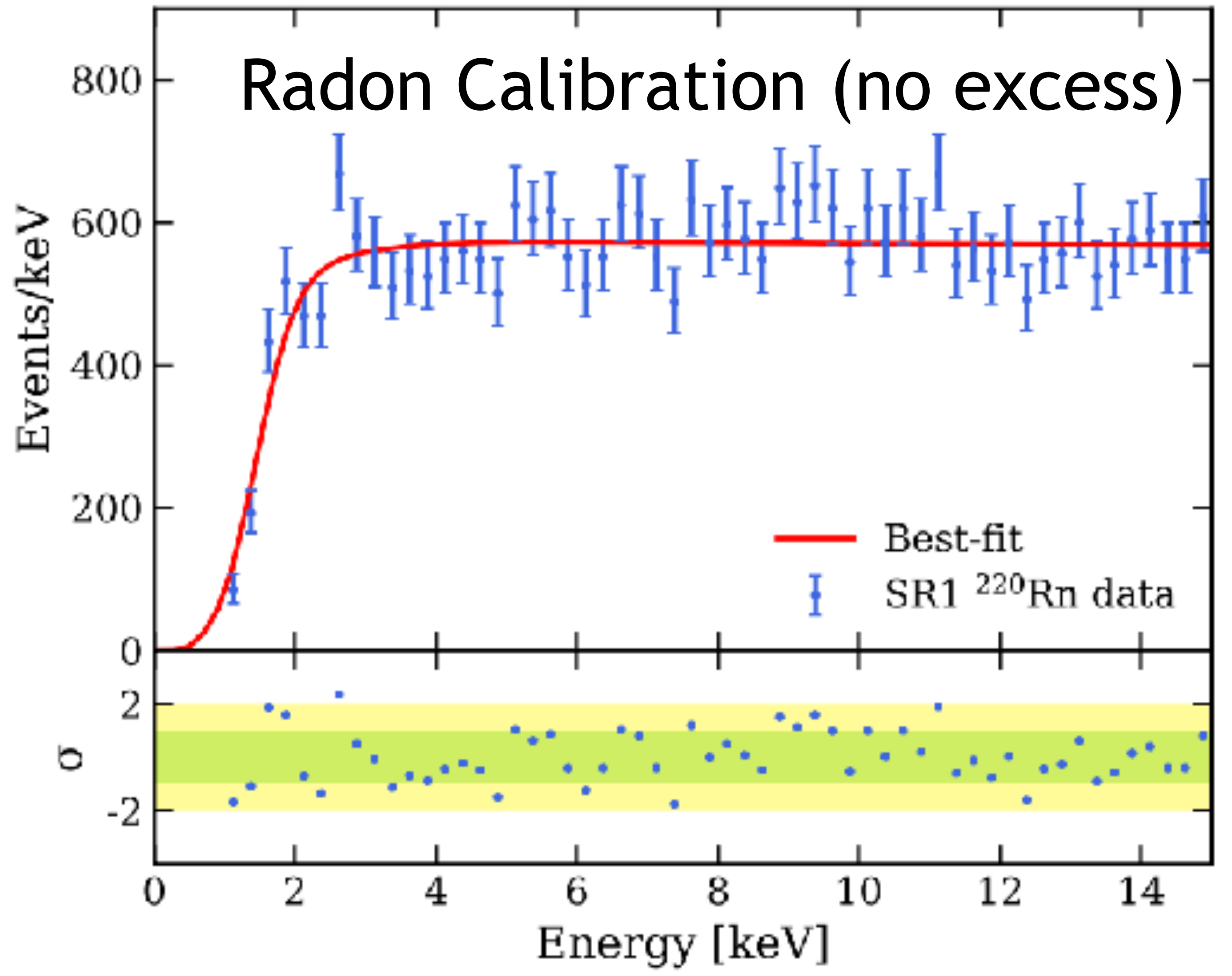
The XENON1T excess

Data Excess



0.65 tonne-years with only 76 ± 2 events/(tonne × year × keV) between 1–30 keV





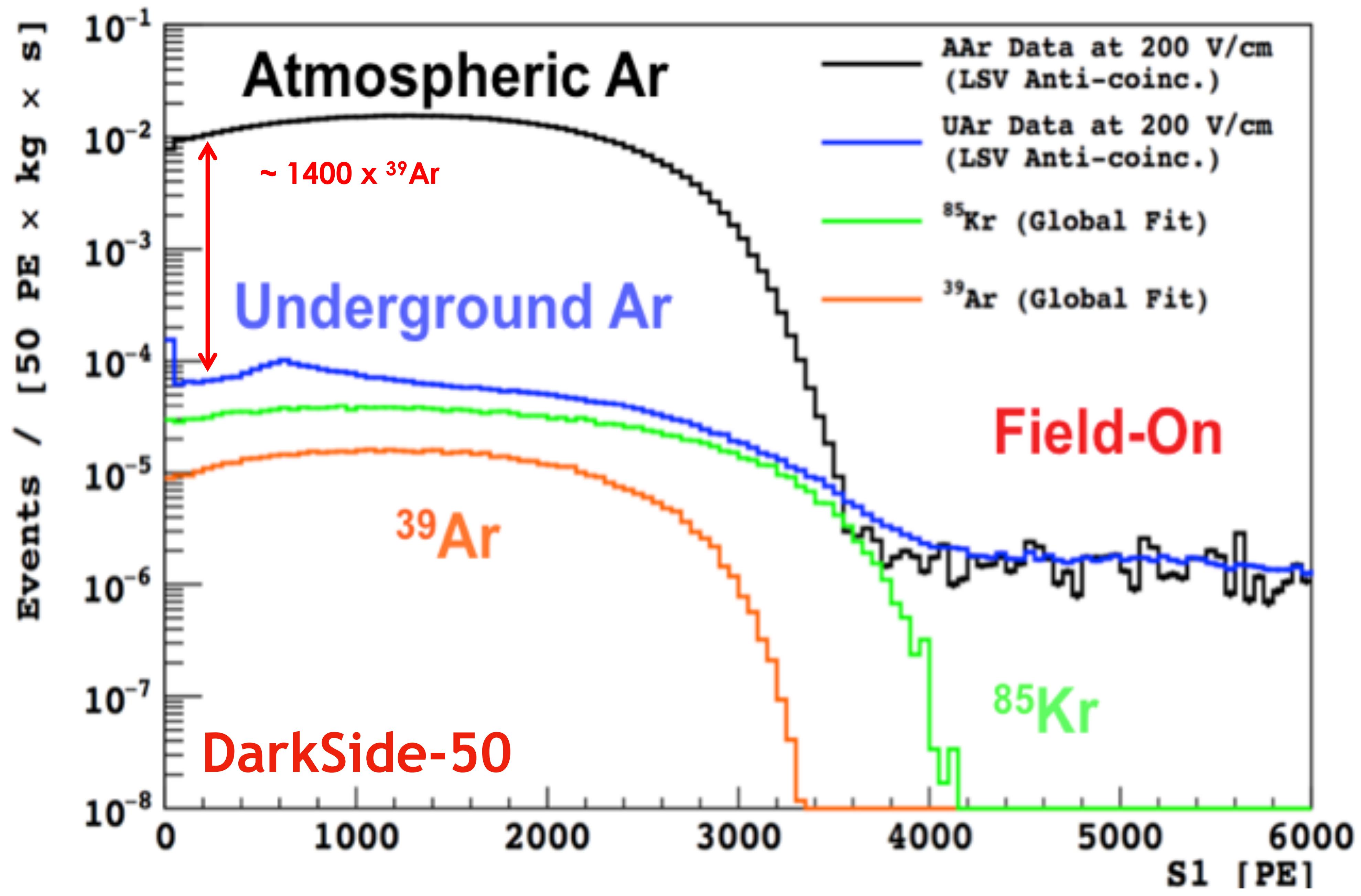
Phys.Rev.D 102 (2020) 7, 072004

LAr: DarkSide and the ^{39}Ar issue

SOLVED

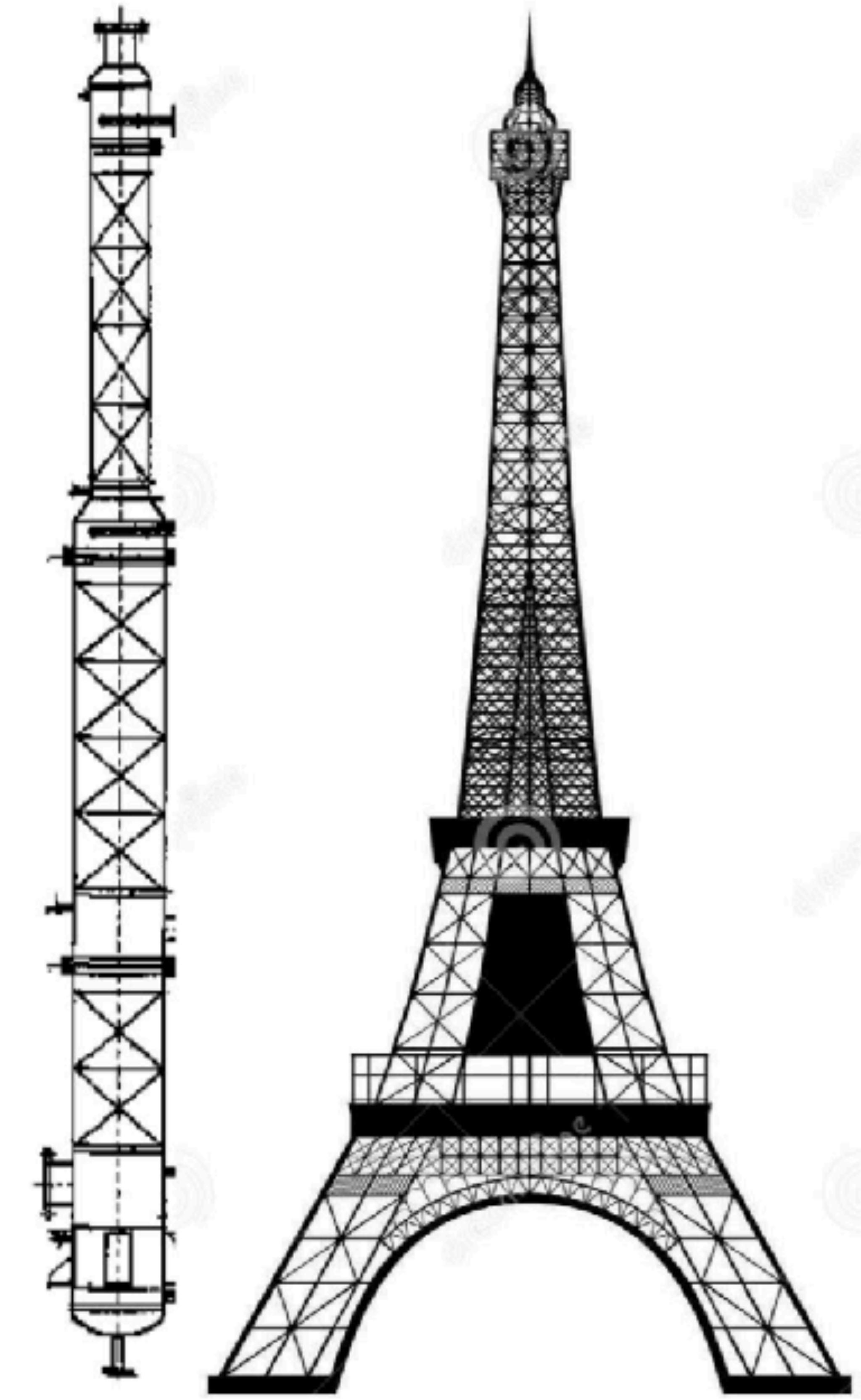
URANIA

- 39Ar produced from cosmic ray interactions primarily from 40Ar in the atmosphere
- 39Ar activity in atmospheric LAr ~ 1Bq/kg
- LAr extracted from Colorado CO_2 wells ~ 0.7 mBq / kg



ARIA

- cryogenic isotopic distillation plant
- being installed in a mine shaft at CarboSulcis, S.p.A. in Nuraxi-Figus (SU), Italy
- cryogenic isotopic distillation plant
- being installed in a mine shaft at CarboSulcis, S.p.A. in Nuraxi-Figus (SU), Italy
- 350m tall distillation column
- designed to reduce ^{39}Ar isotopic fraction in UAr by factor 10 per pass



The LAr Pulse Shape Discrimination

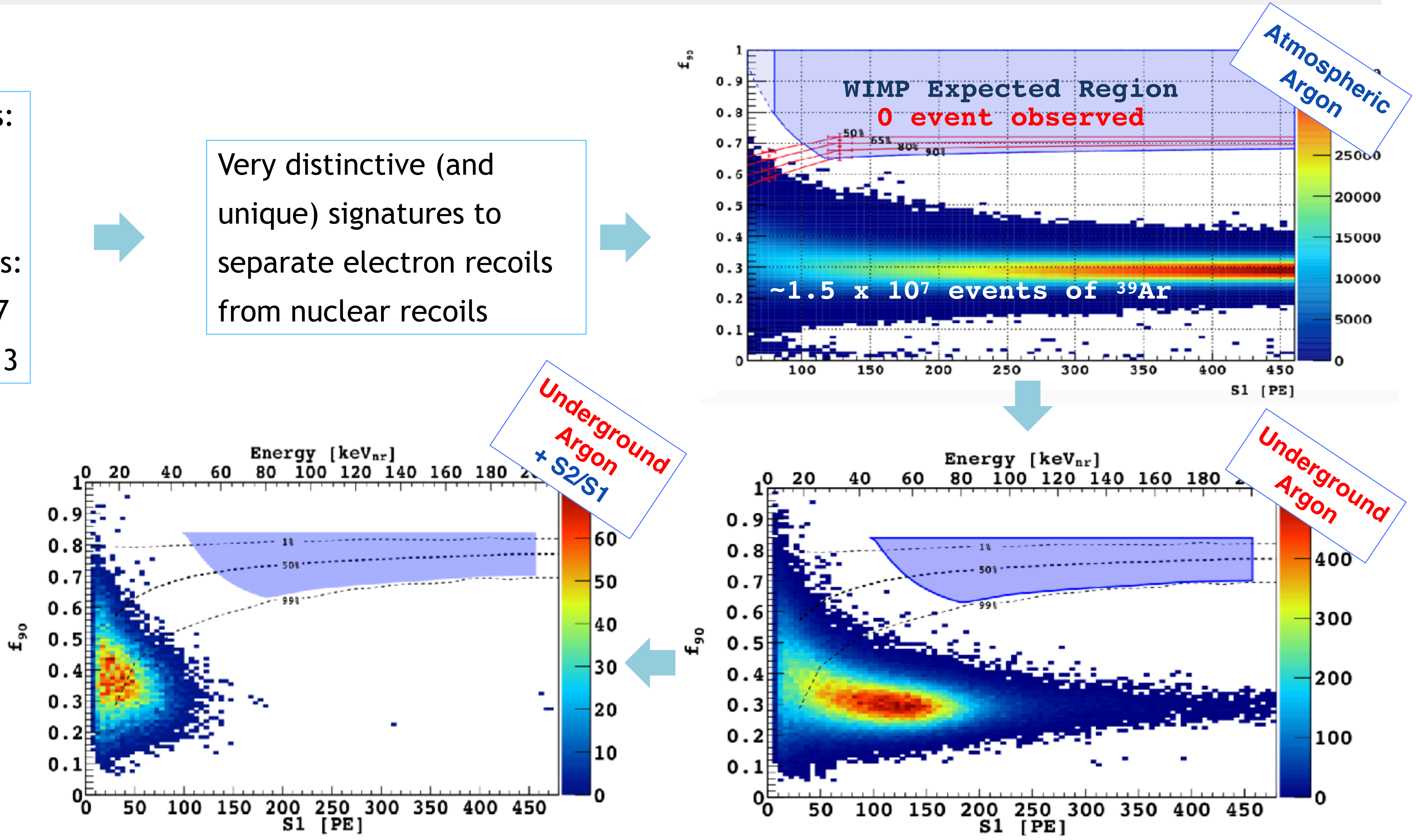
LAr scintillation times:

- singlet ~ 6 ns
- Triplet ~ 1600 ns

Singlet-to-triplet ratios:

- Nuclear recoils ~ 0.7
- Electron recoils ~ 0.3

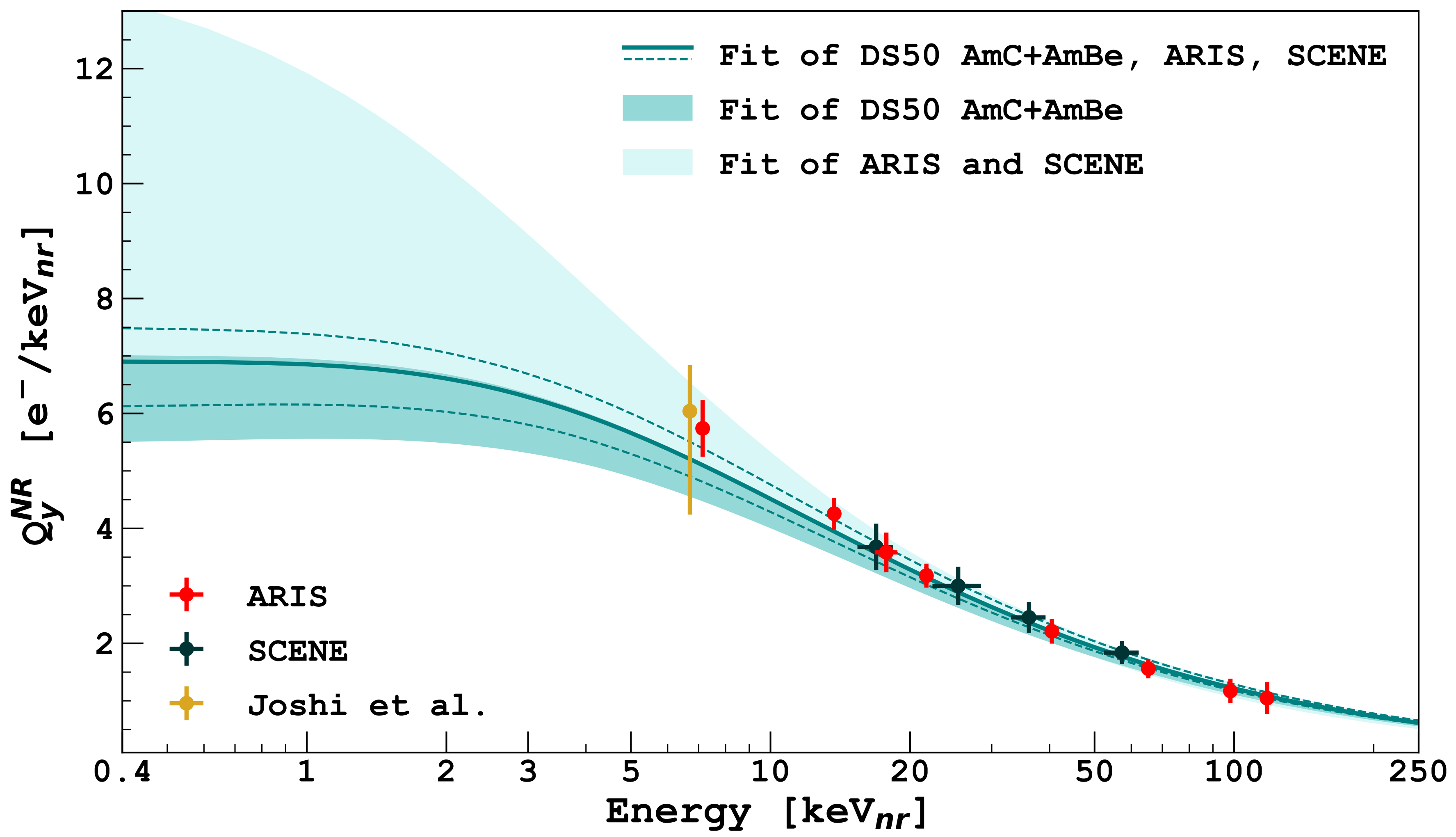
Very distinctive (and unique) signatures to separate electron recoils from nuclear recoils

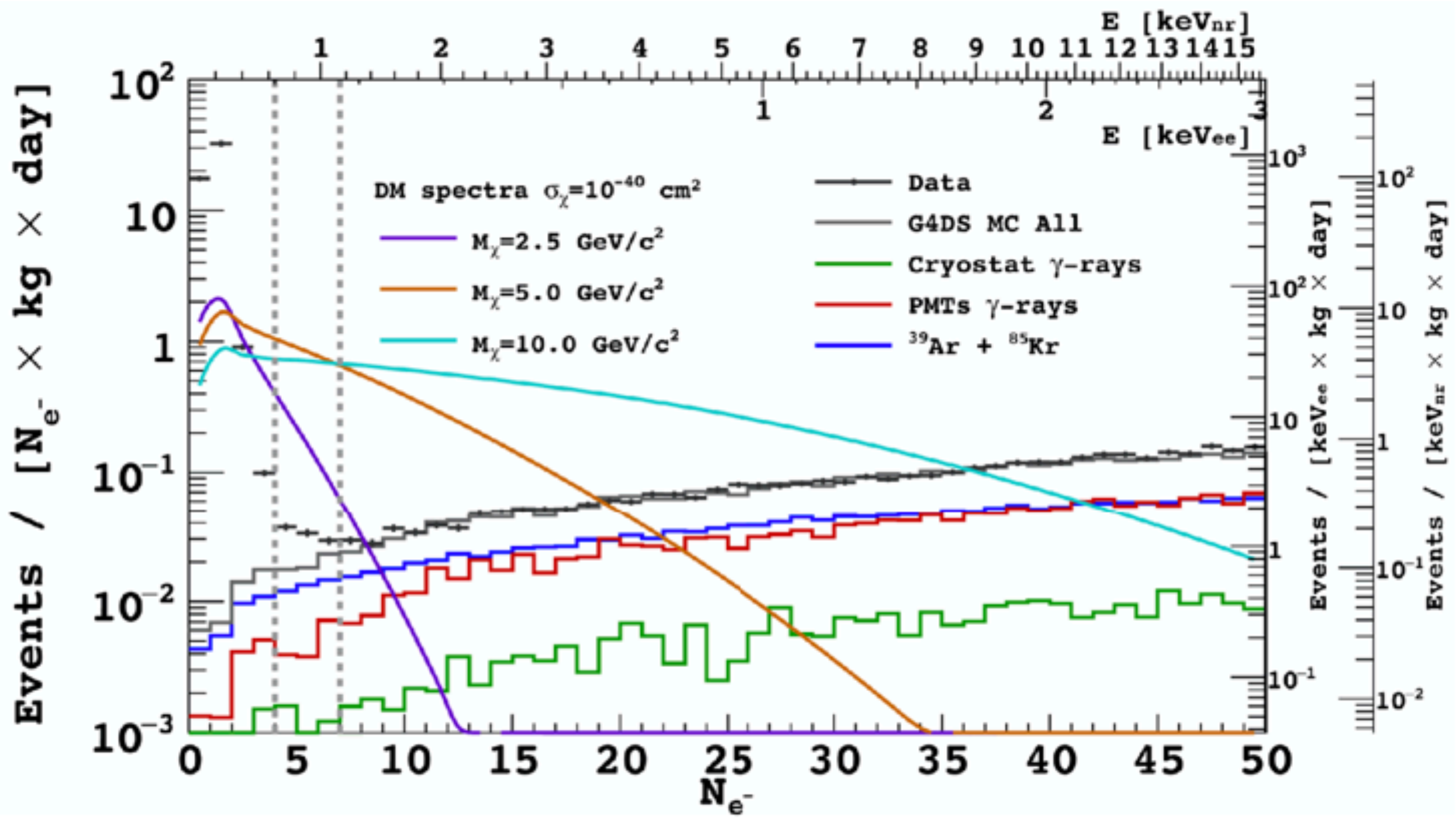


Background-free over more than 530 days!

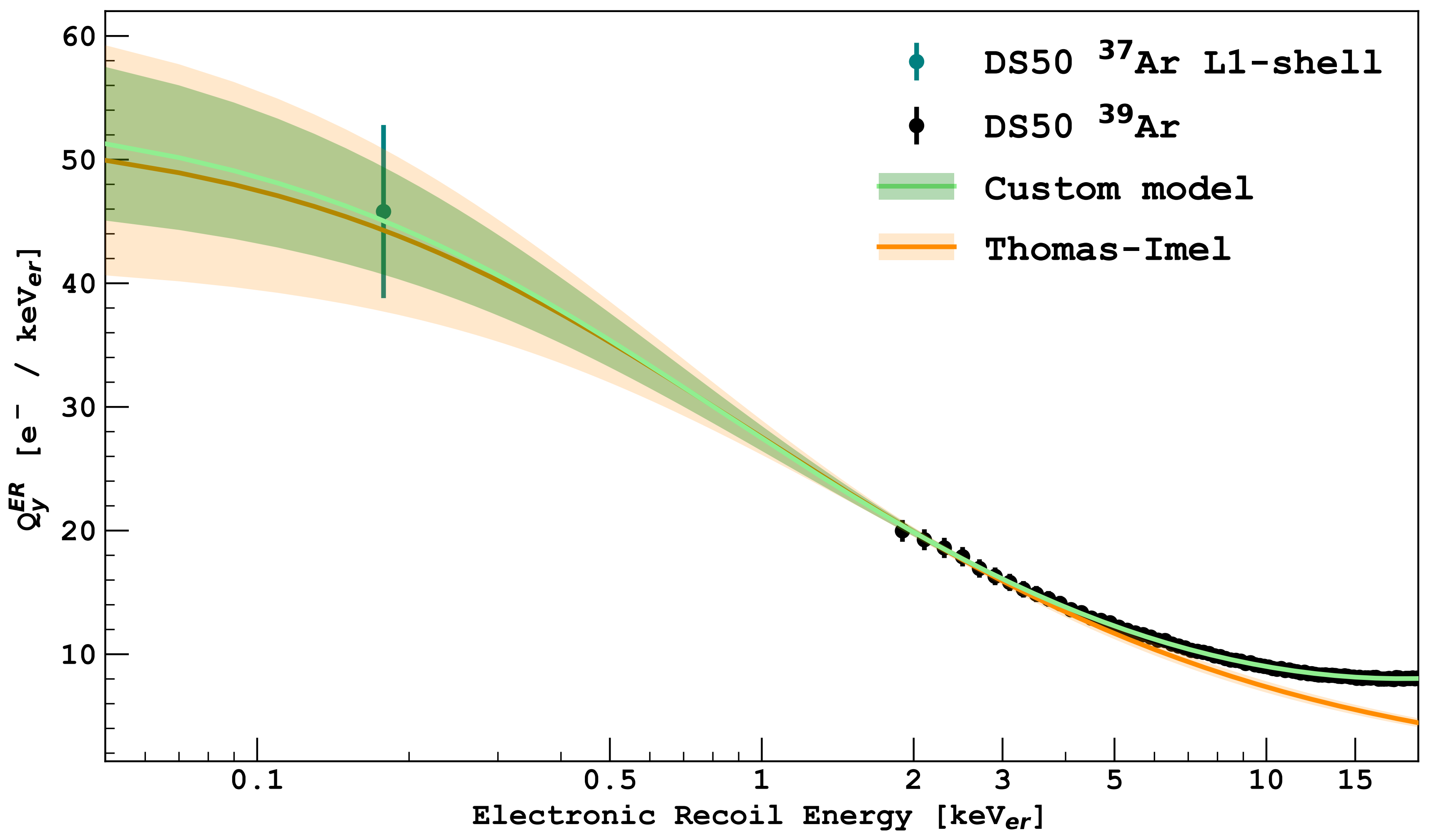
The S2-only analysis with DarkSide-50

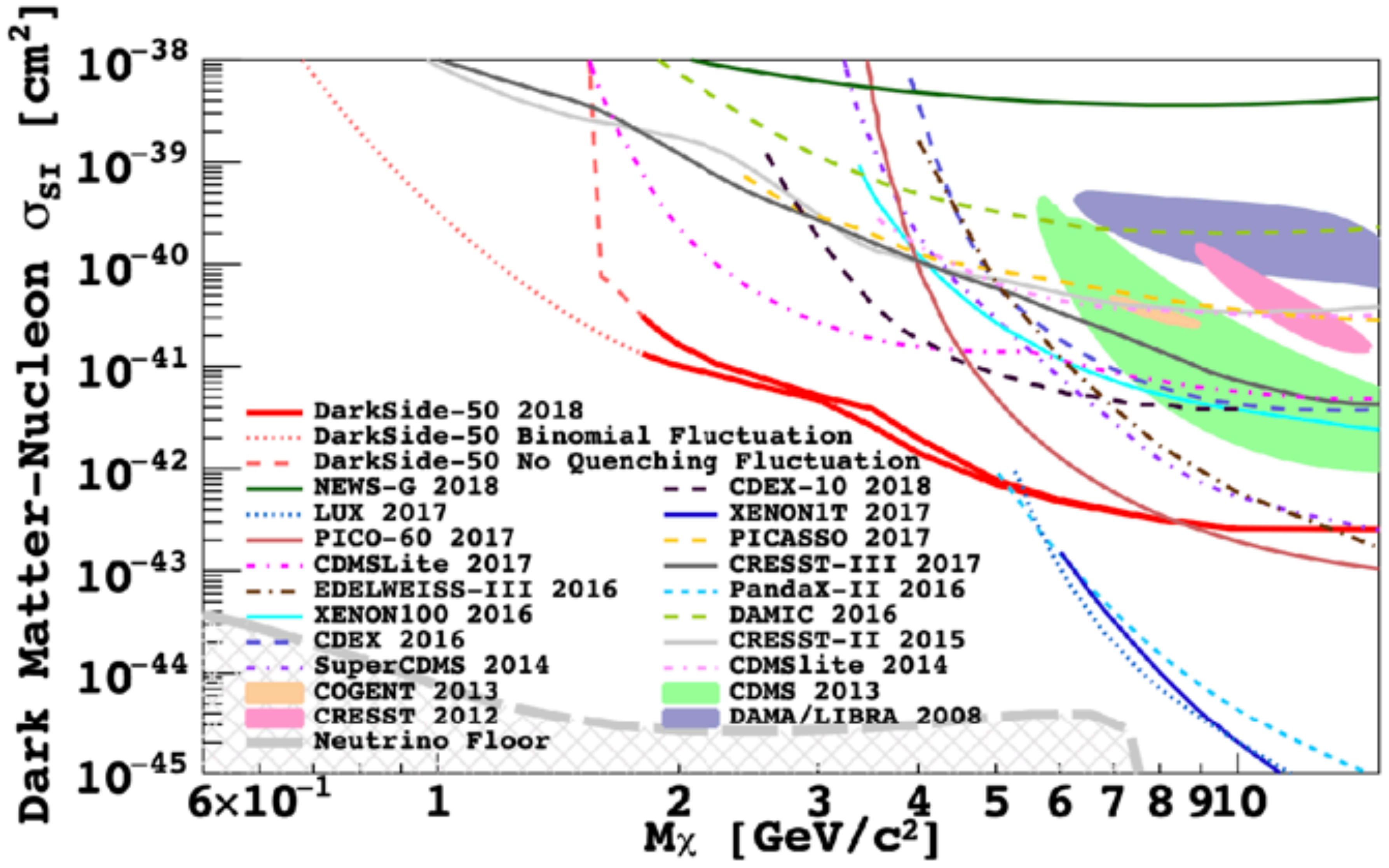
NR ionization response





ER ionization response



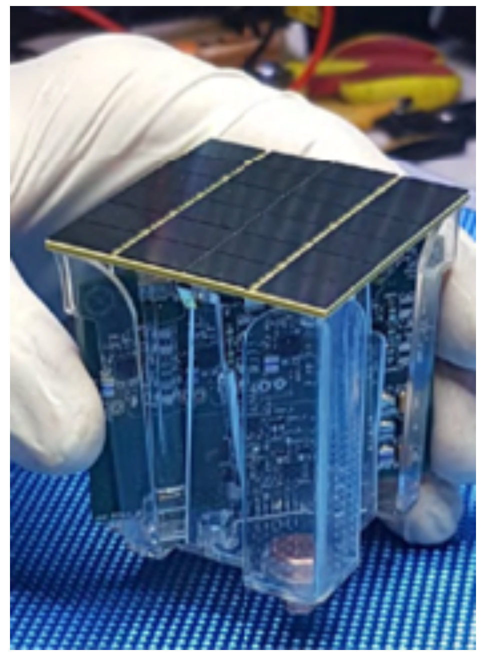


arxiv:2109.04770 (2021)

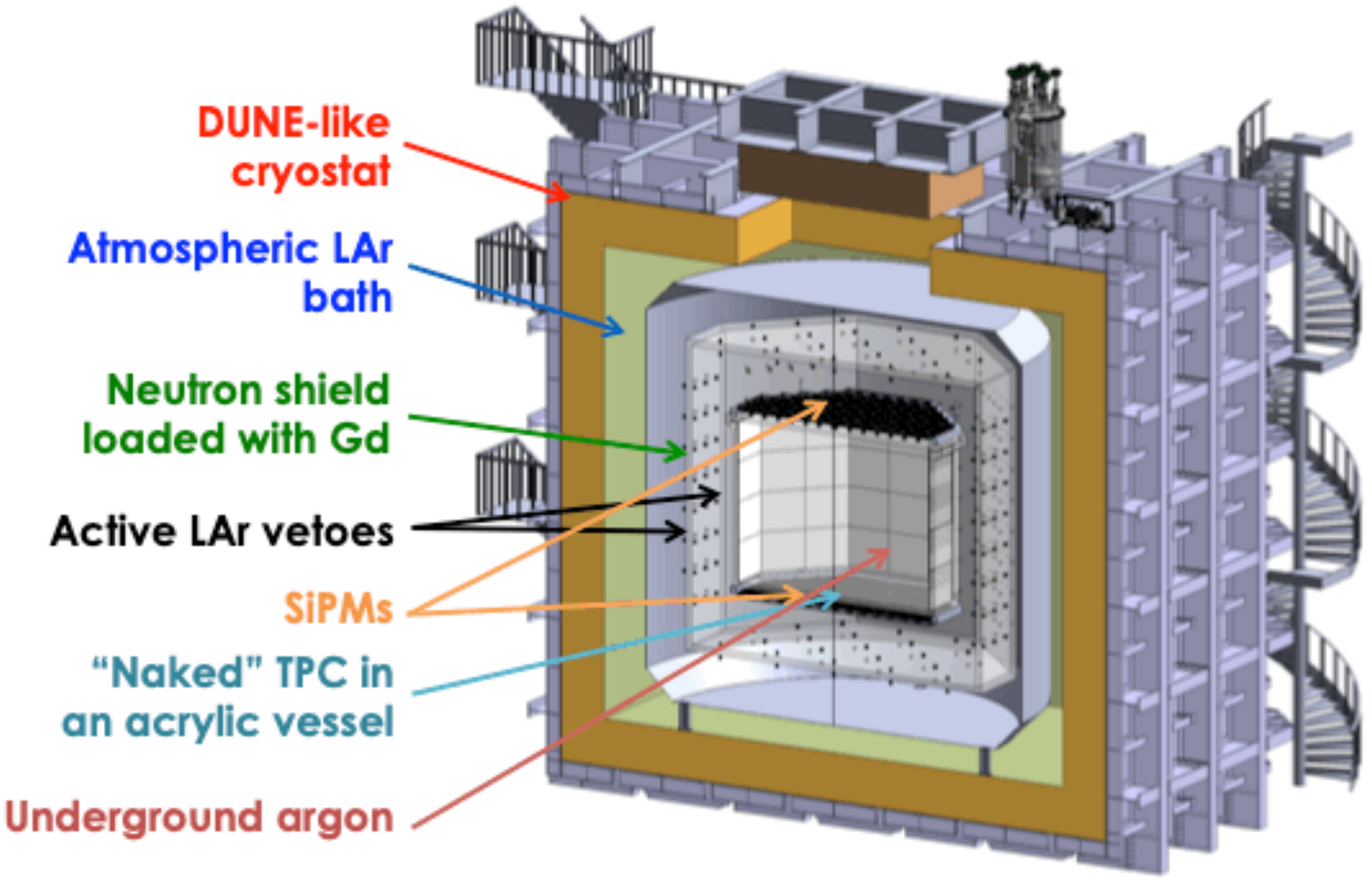
Phys. Rev. Lett. 121 (2018) 081307

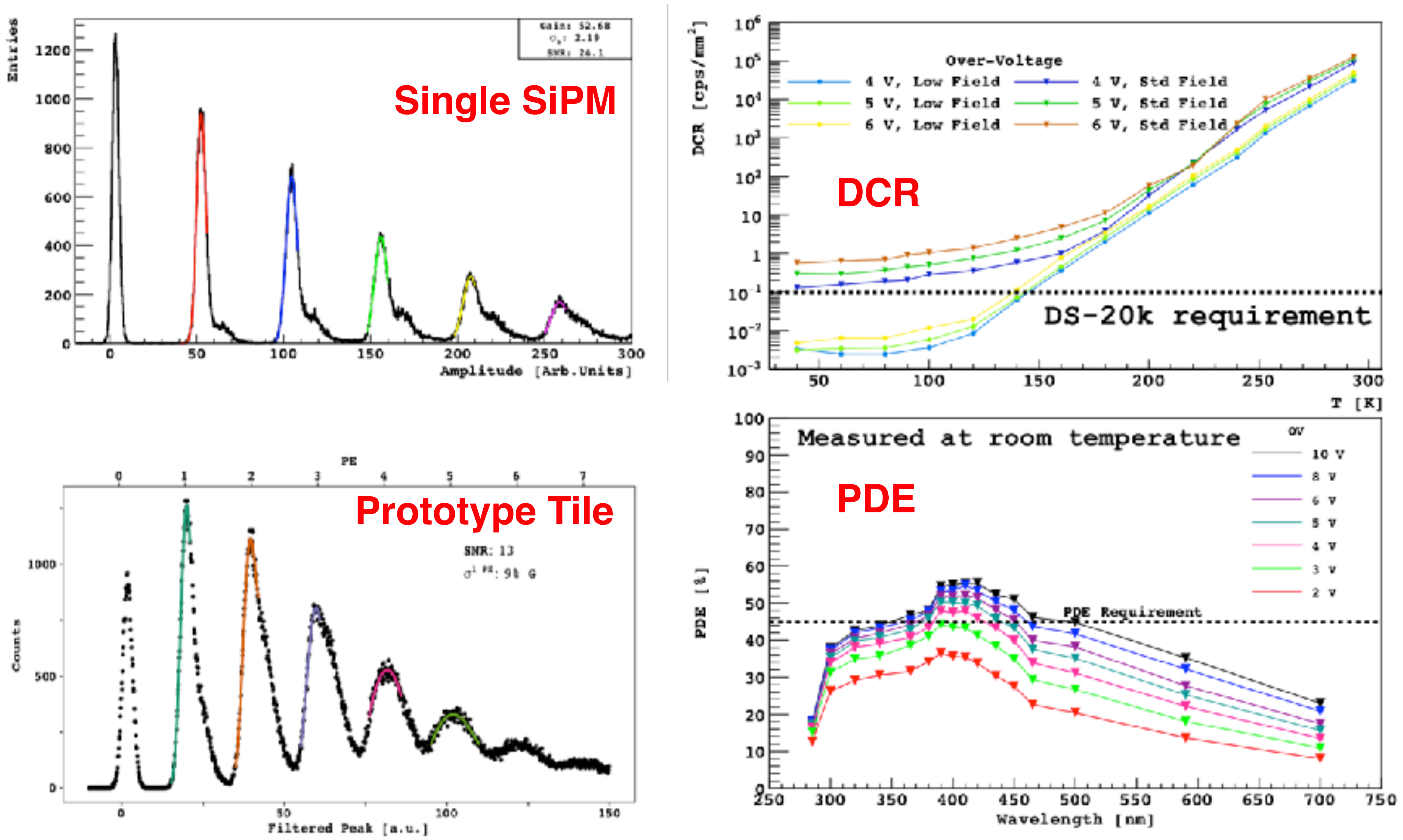
New technologies with DarkSide-20k

- The TPC directly immersed in a LAr bath (600 ton) => minimisation of TPC materials and hence contamination
- Equipped with 15 m^2 of SiPM (~200,000 SiPM)
- Gd-acrylic veto

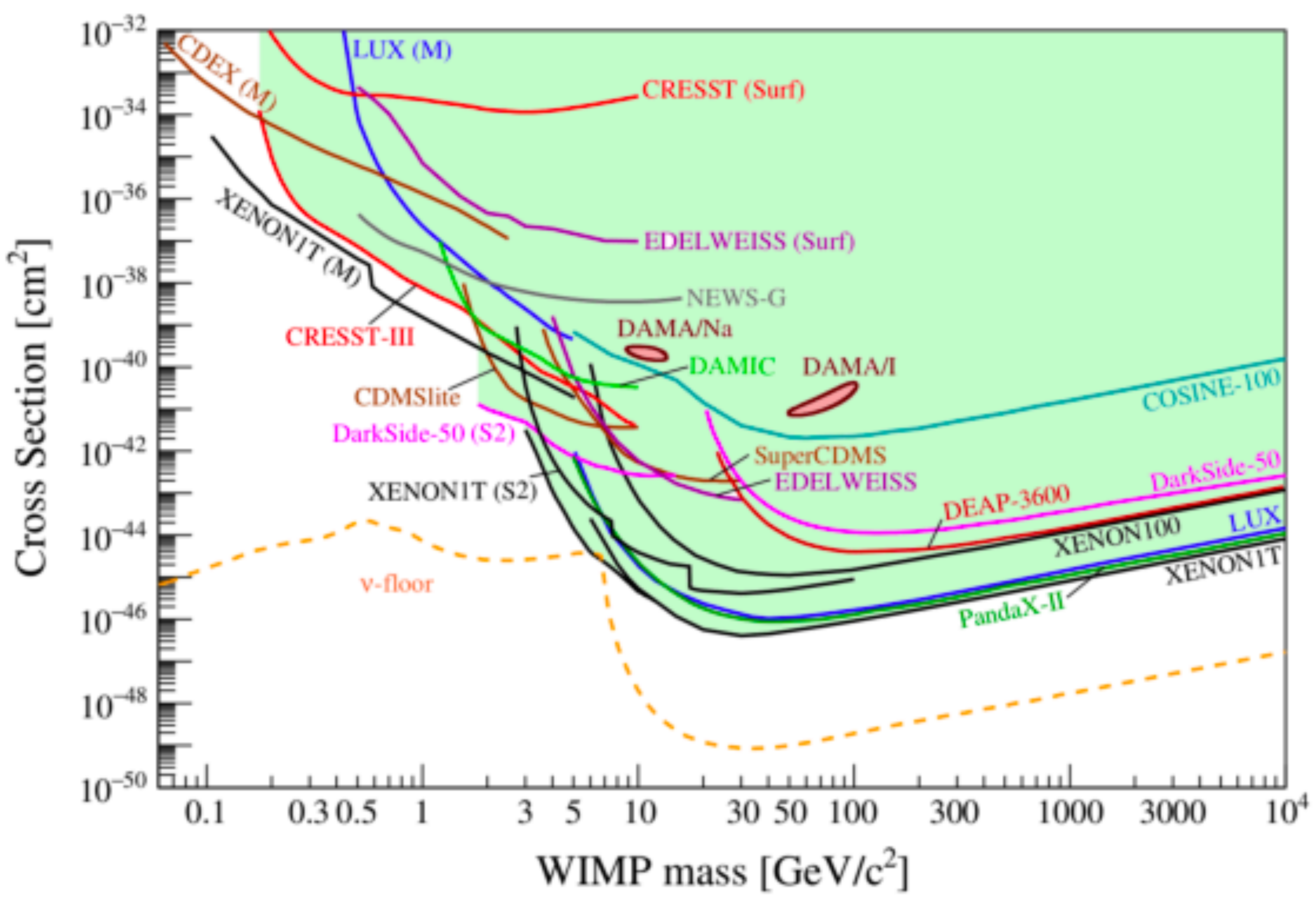


	DS-20k requirement	SiPM tile (PDM)	
Surface	5x5cm^2	24cm^2 prototype 25cm^2 final PDM	✓
Power dissipation	<250mW	~170mW	✓
PDE	>40%	50% · ε_{geom} = 45%	✓
Noise Rate	<0.1cps/mm^2	0.004cps/mm^2	✓
Time Resolution	O(10ns)	16ns	✓
Dynamic Range	>50	~100	✓

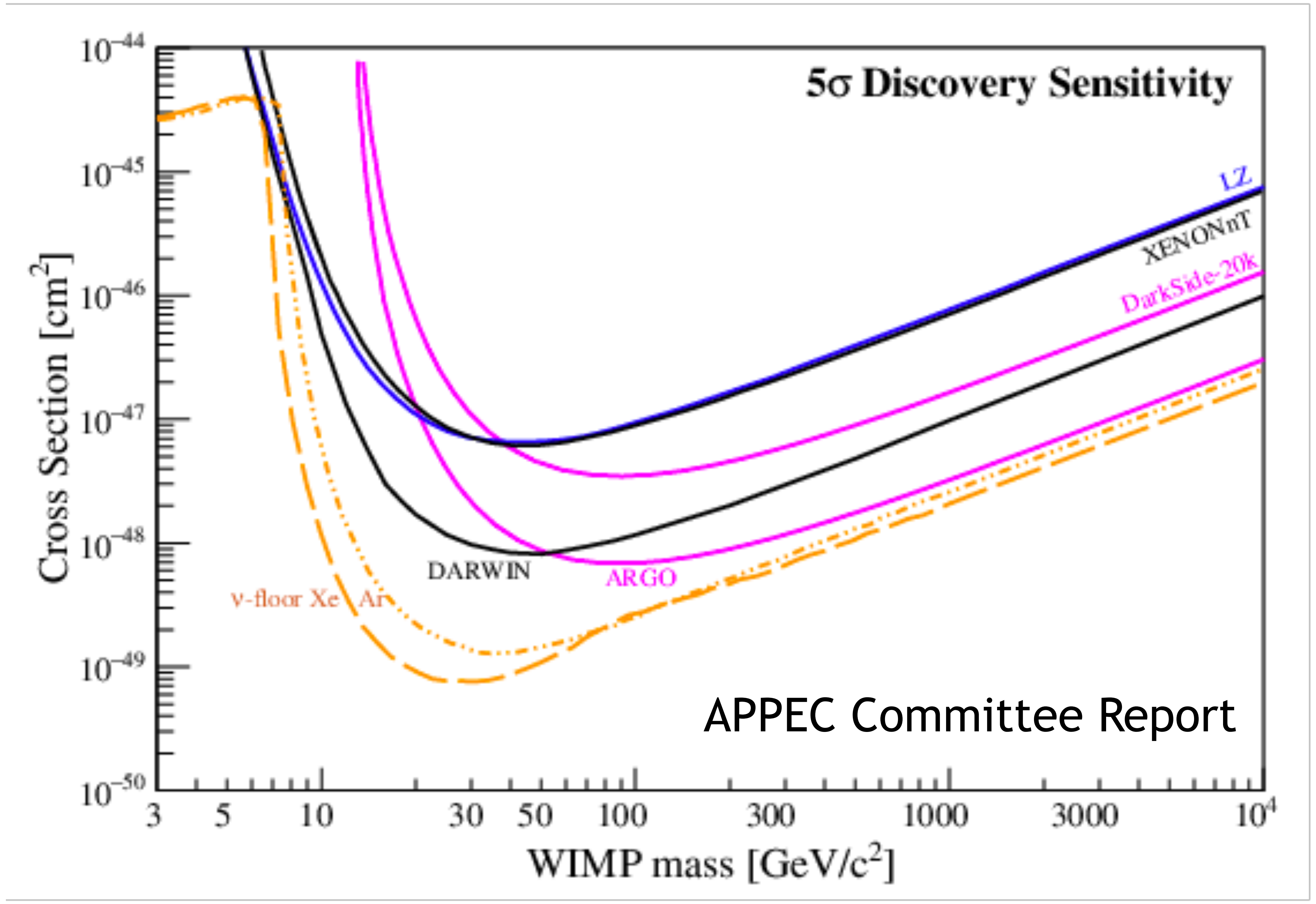




Today



2022-2032



Conclusions

Light-dark matter candidates

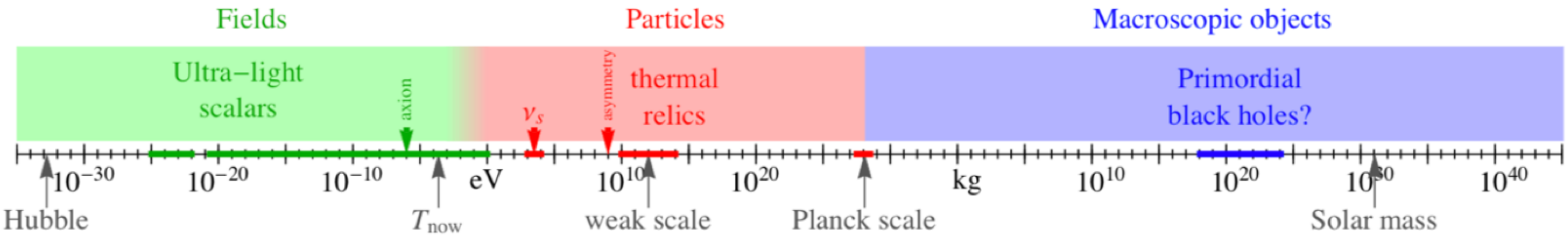
- Several channels to explore (WIMP-NR + Migdal, leptophilic, dark photons, axions)
- Several experiments / different techniques
  - Solid-state cryogenic detectors: scintillating bolometers, small mass Ge and Si crystals.
  - Liquid noble detectors (Xe, Ar): operated in S2 only mode
  - Purely ionization detectors: Ge, CCDs, gas detectors
  - Bubble chambers

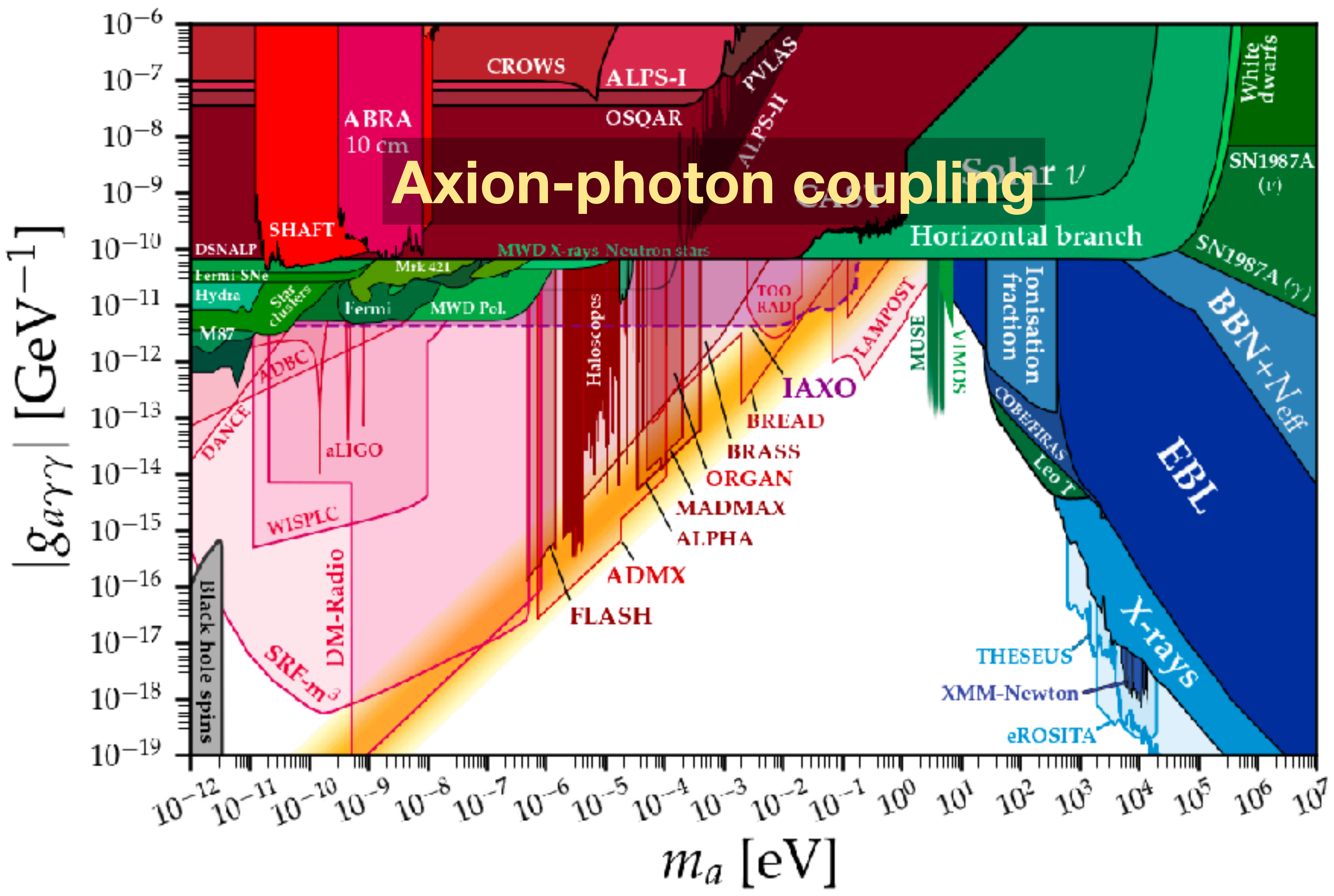
High-mass WIMPs:

- the community is moving towards two large experiments based on LXe (e.g. DARWIN) and LAr (e.g. ARGO)
- Need of LXe / LAr complementarity
- In about 10 years we will reach the neutrino floor: **what next?**

Extras

Dark Matter Particles?





AXION ?

- Solve CP problem in QCD

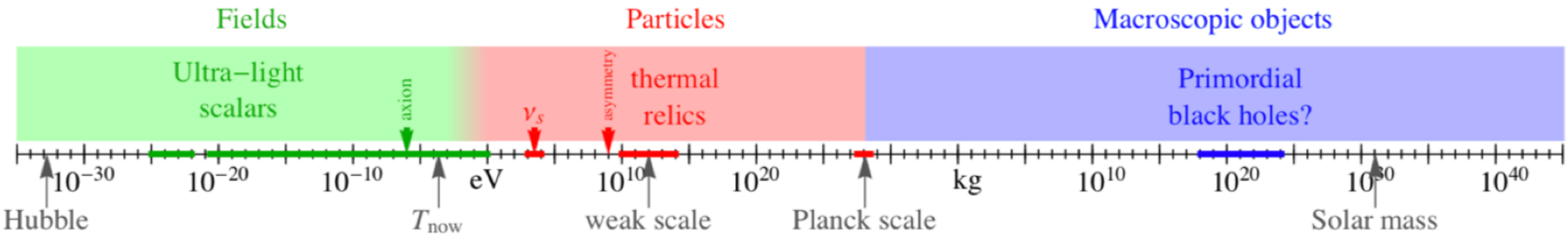
Sterile Neutrino ?

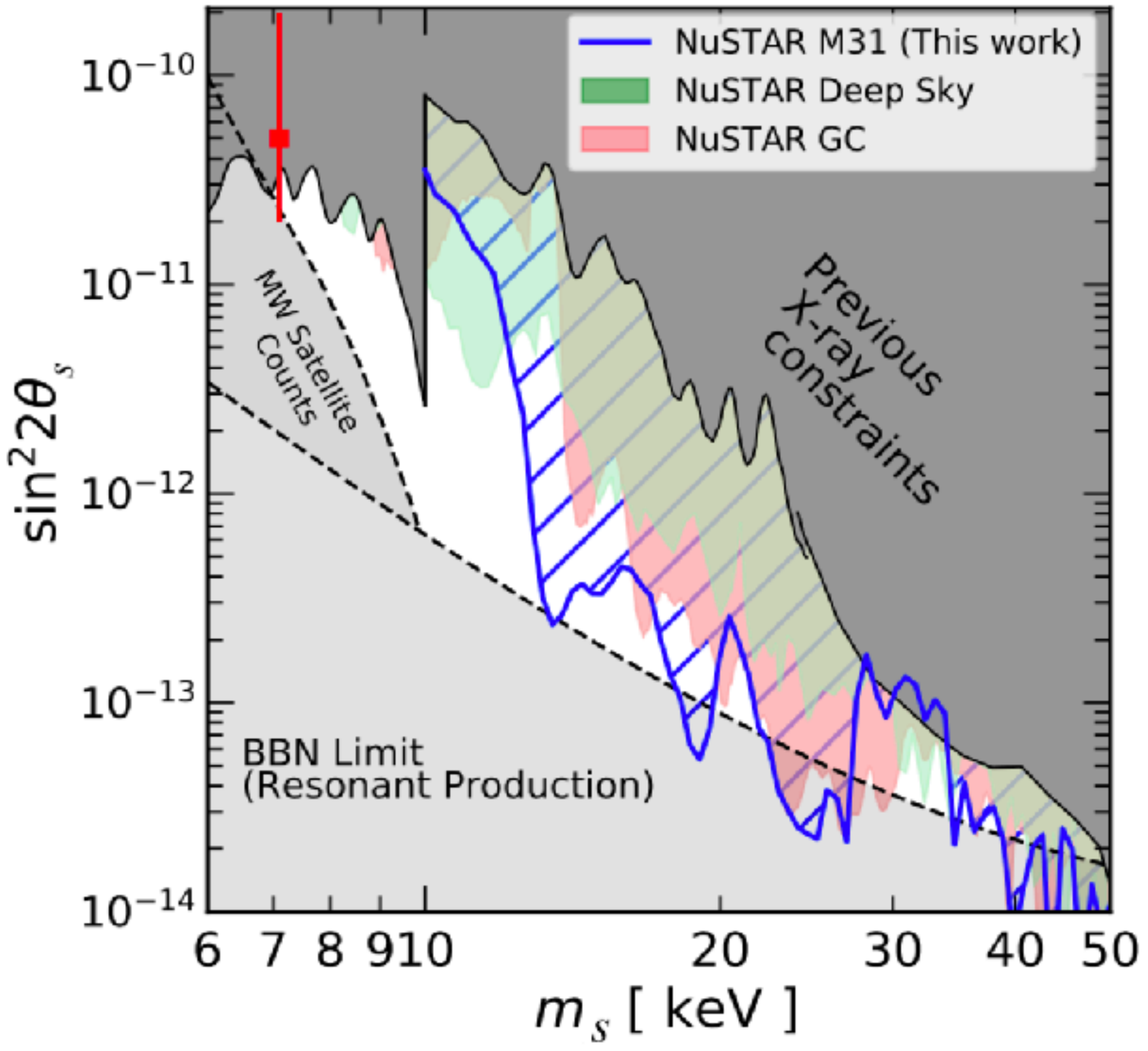
- Natural candidate

WIMP ?

- Supersymmetry (getting weaker…)
- Naturally matches current DM density

Dark Matter Particles?





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