15th International Workshop on the Identification of Dark Matter 2024

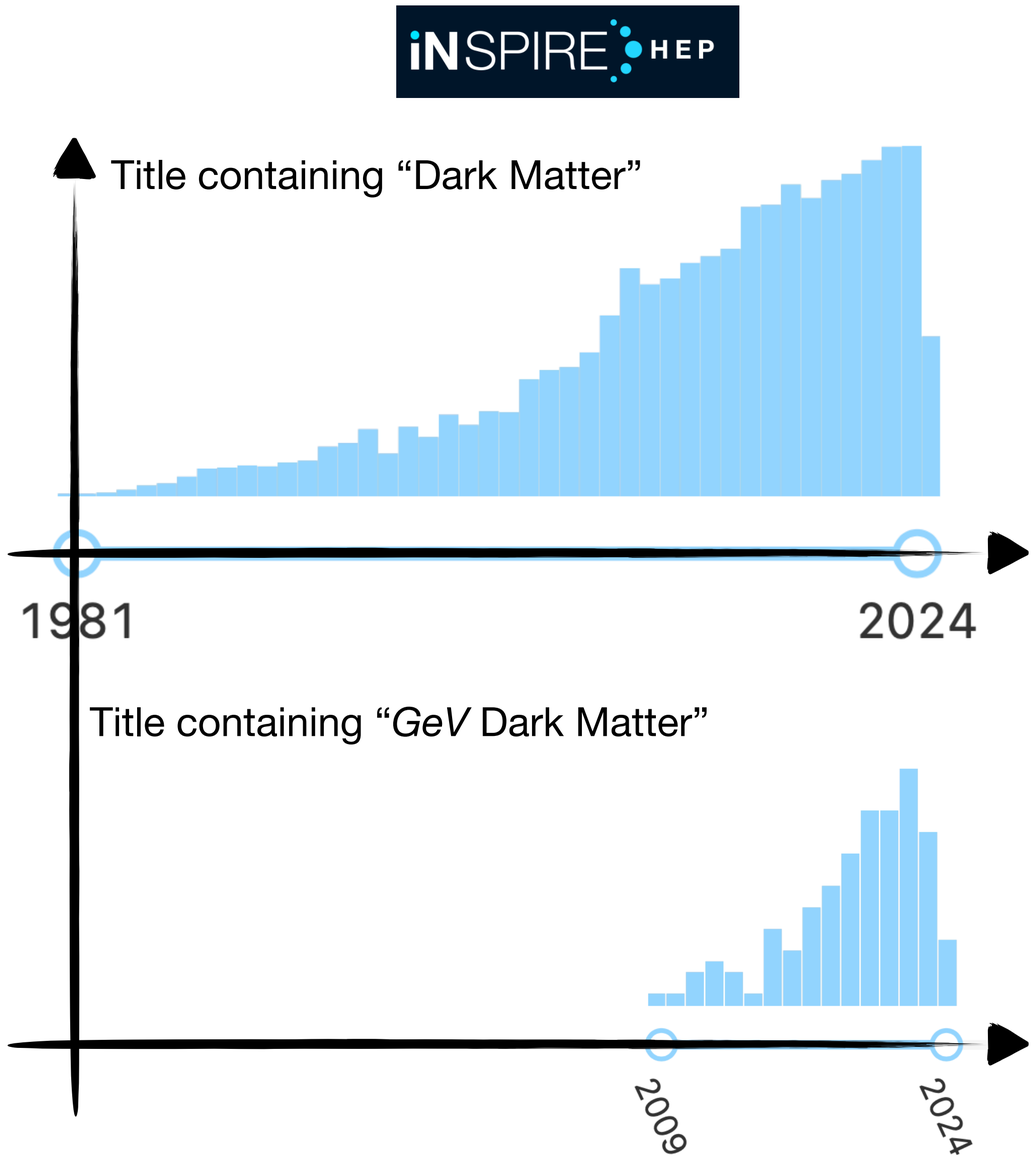
Experimental Dark Matter searches at the GeV scale

Lucia Canonica
Università degli studi di Milano Bicocca & INFN

L'Aquila, 8-12 July 2024

This talk

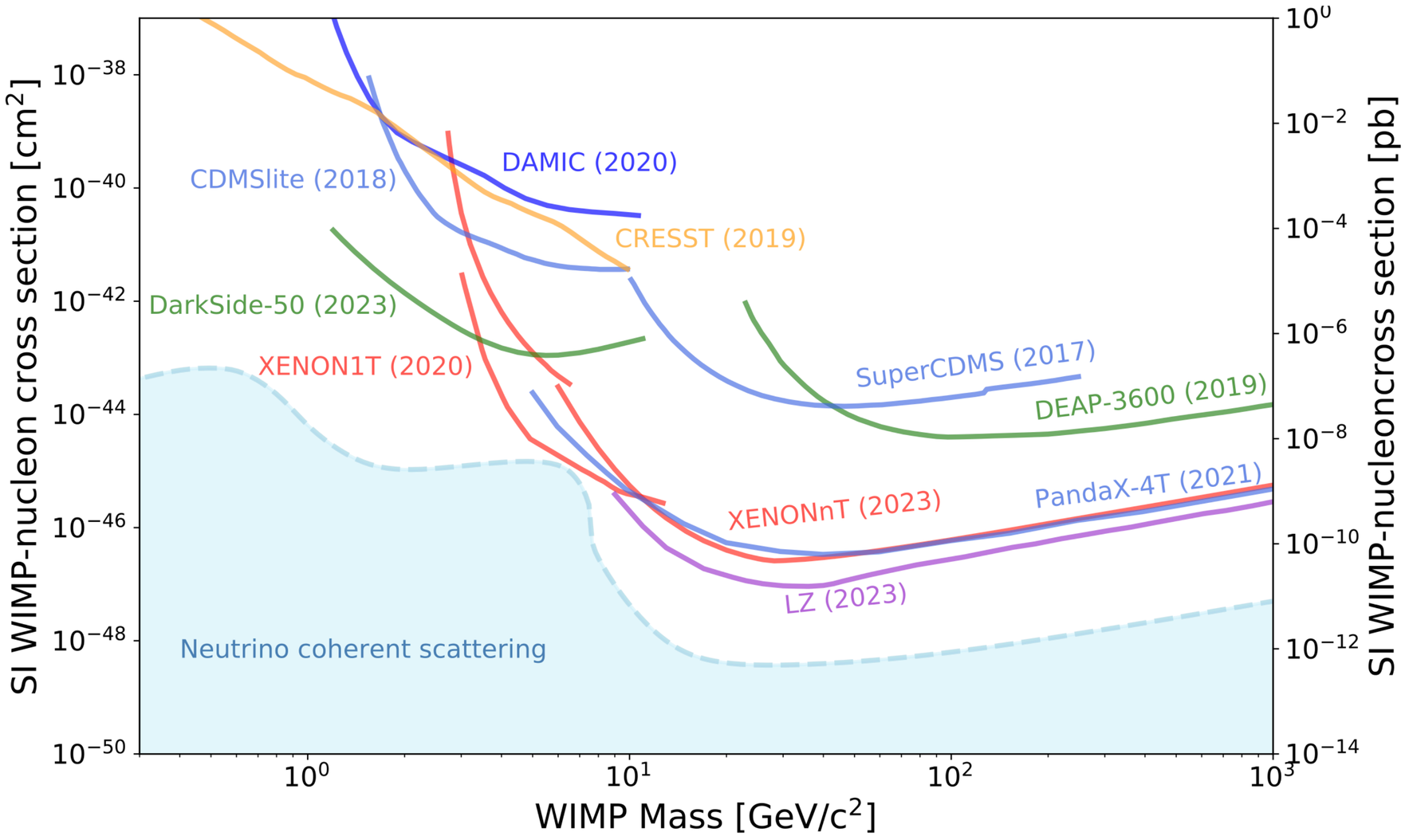
- Direct detection experiments at the GeV scale is an extremely active field of research.
- Multiple R&D initiatives and small-scale project
- I apologise if I missed selecting your preferred project.
- **Focus on differences and complementarities of different experimental techniques, not on results**



L. Canonica

This talk

[Baudis & Profumo, PDG 2023]



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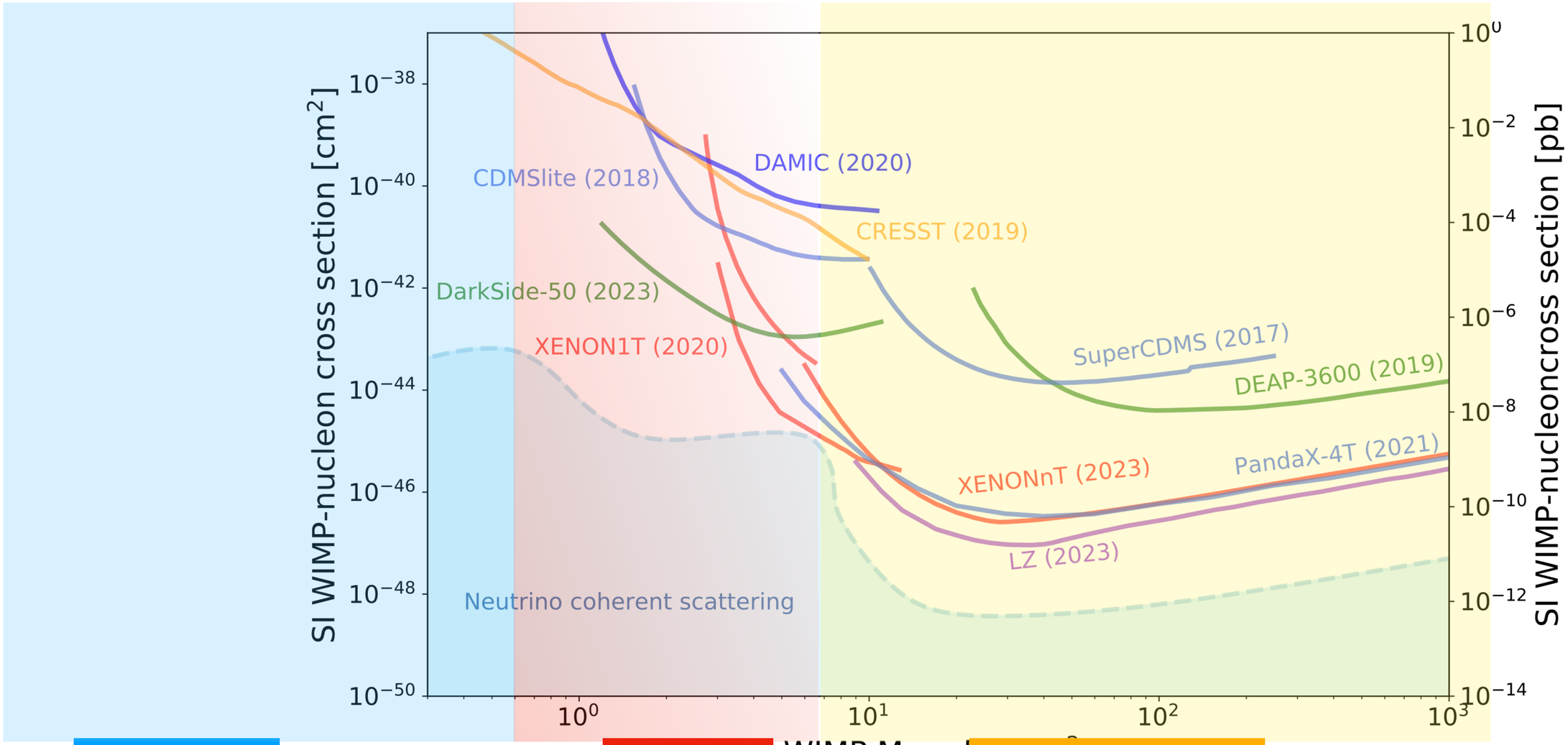
[Baudis & Profumo, PDG 2023]



Next talk

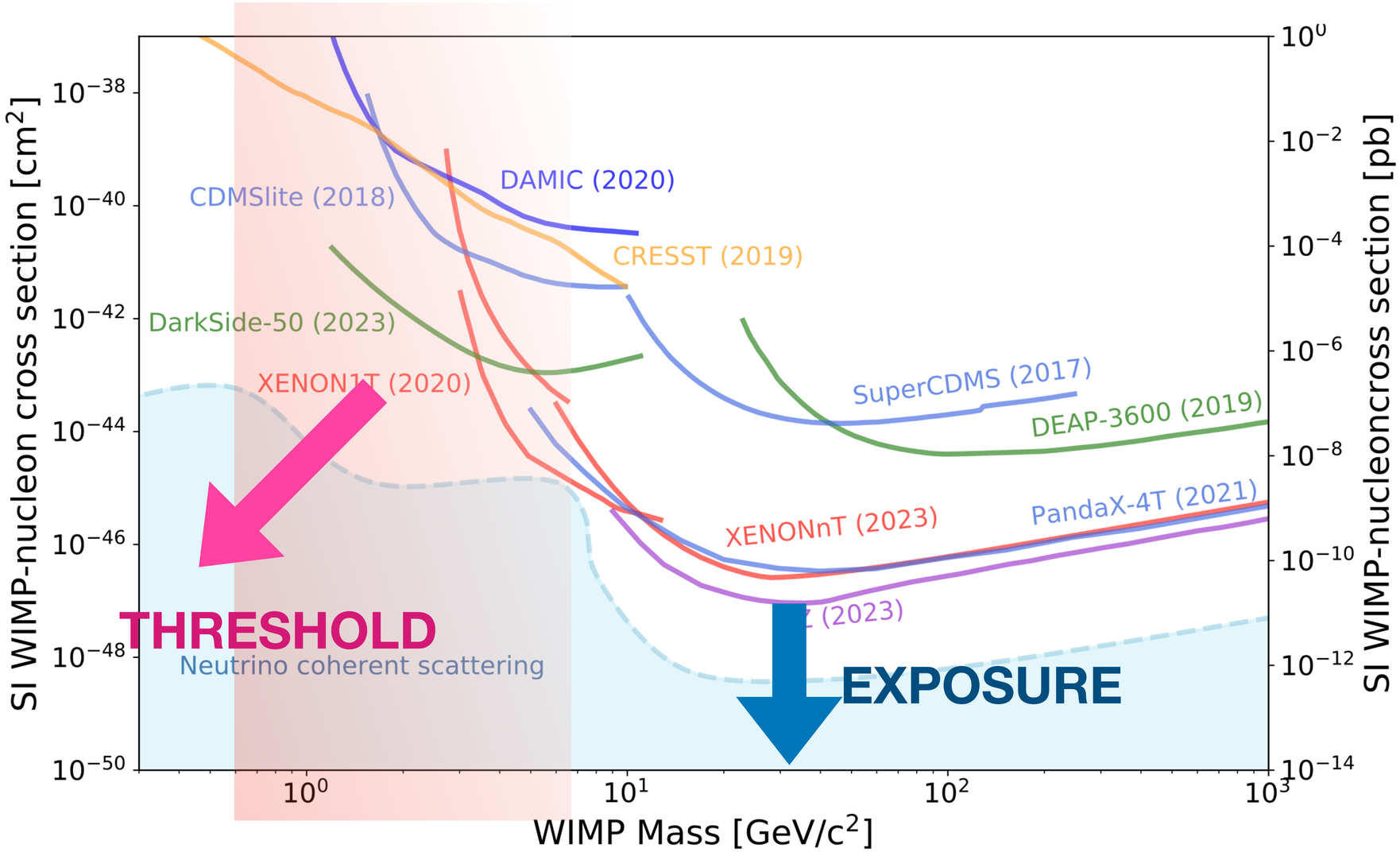
My talk

Previous talk

My talk

- Large parameter space still to be explored
- **Low threshold** and/or **light target** materials to improve the sensitivity

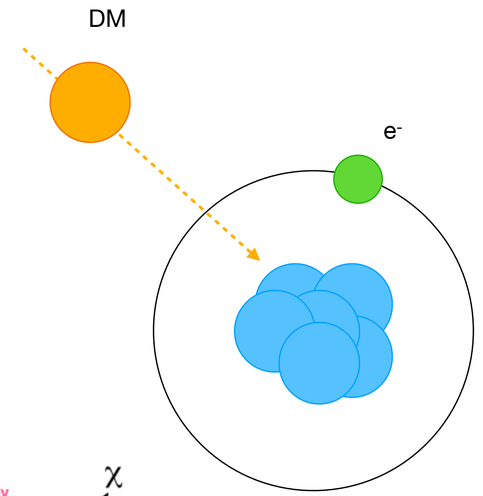
[Baudis & Profumo, PDG 2023]



Dark matter interactions and signals @ GeV scale

Possible detection channels in direct detection experiments:

- DM - nucleus *elastic* scattering: nuclear recoil
  - can occur via spin-dependent (**SD**) or spin-independent interactions (**SI**)



- DM - nucleus *inelastic* scattering: Migdal effect
  - DM-nucleus interaction with subsequent electron ionization

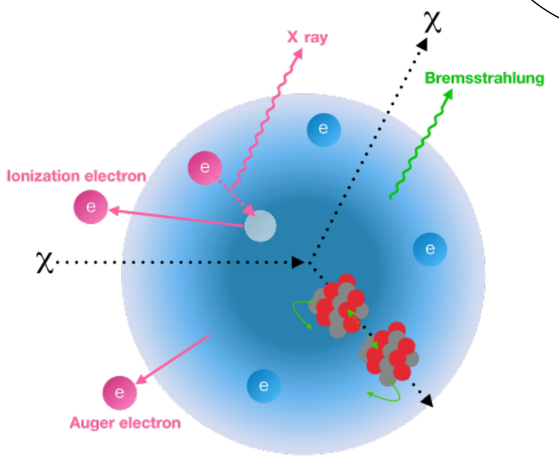


Figure from: *Phys.Rev.Lett.* 123 (2019) 24, 241803

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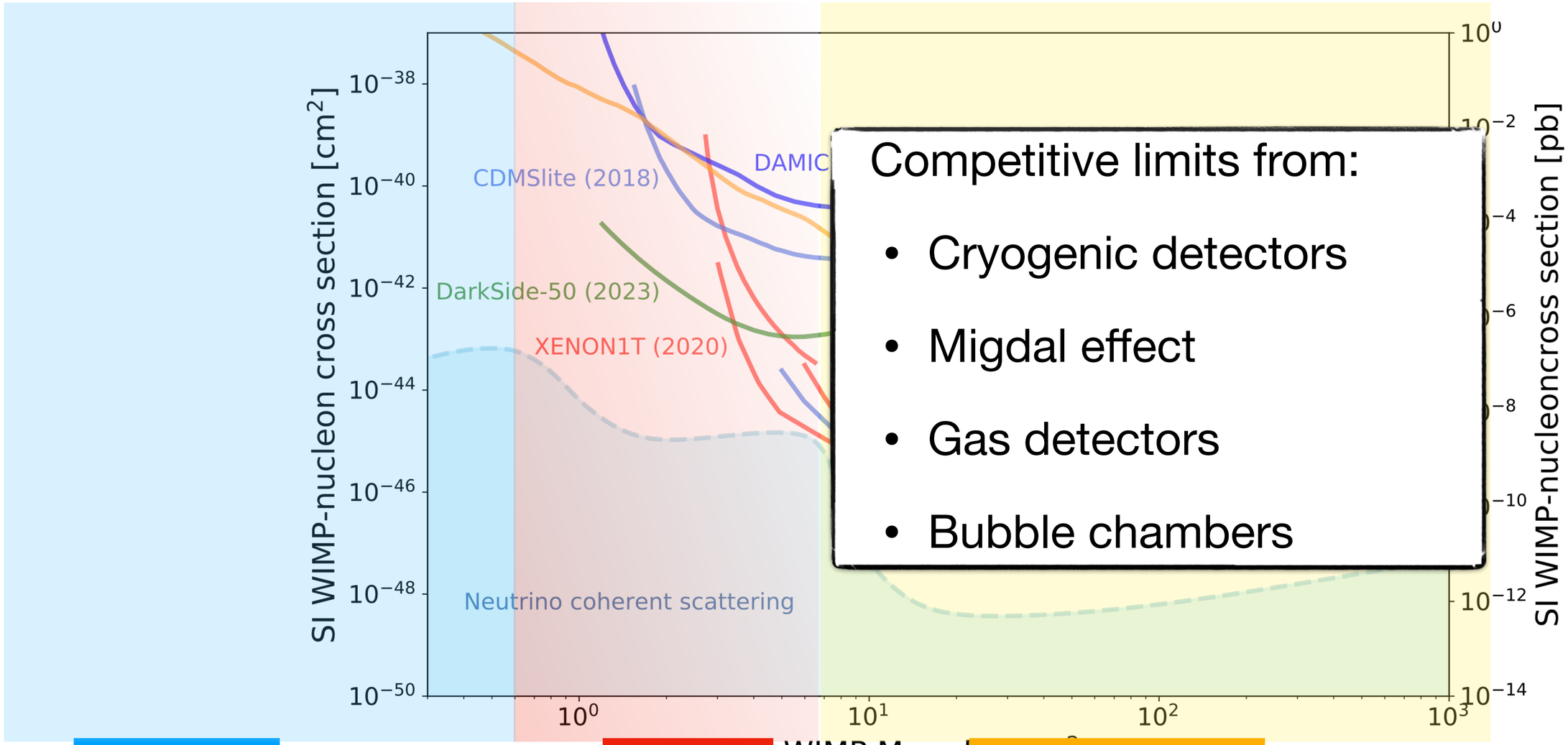
This talk

[Baudis & Profumo, PDG 2023]



Next talk

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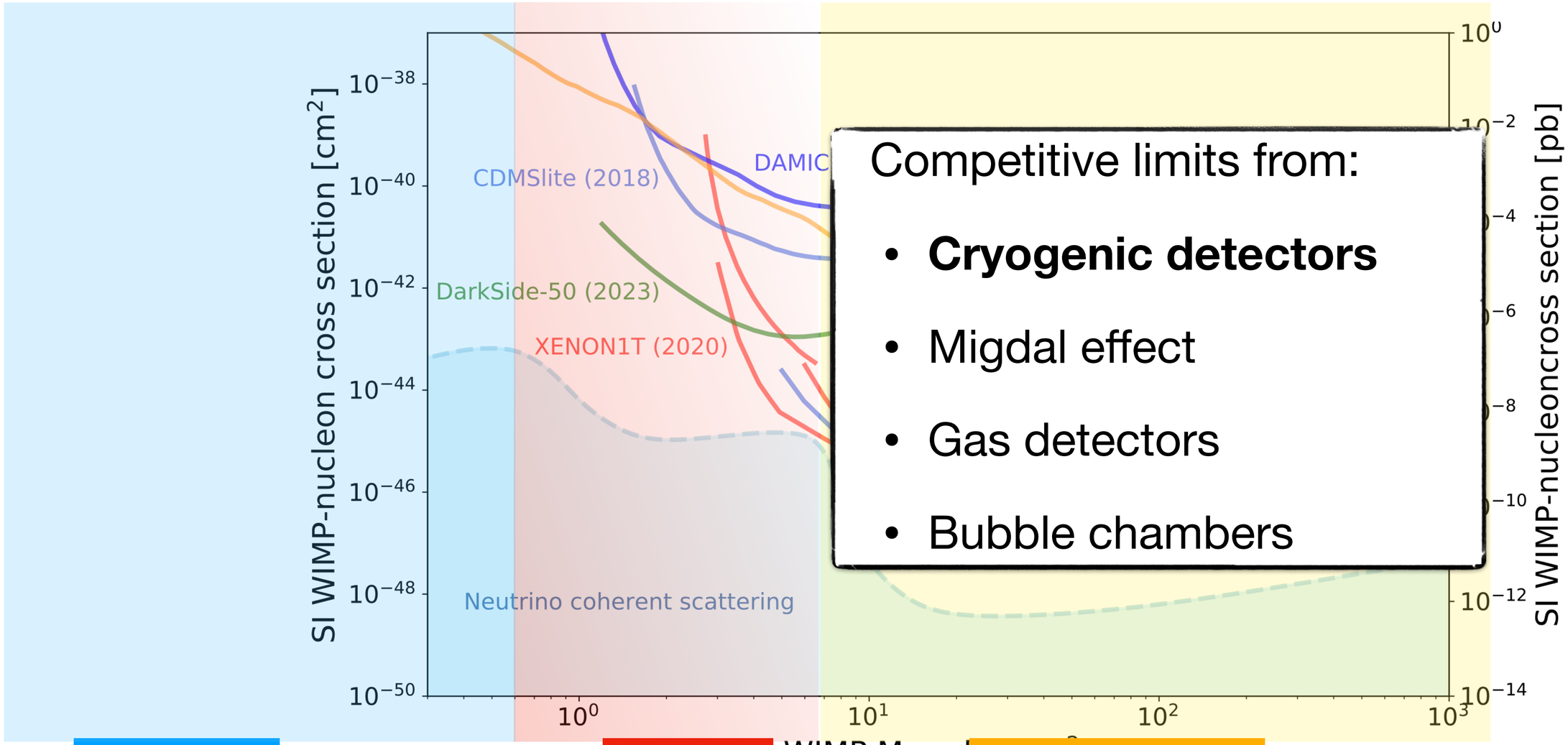
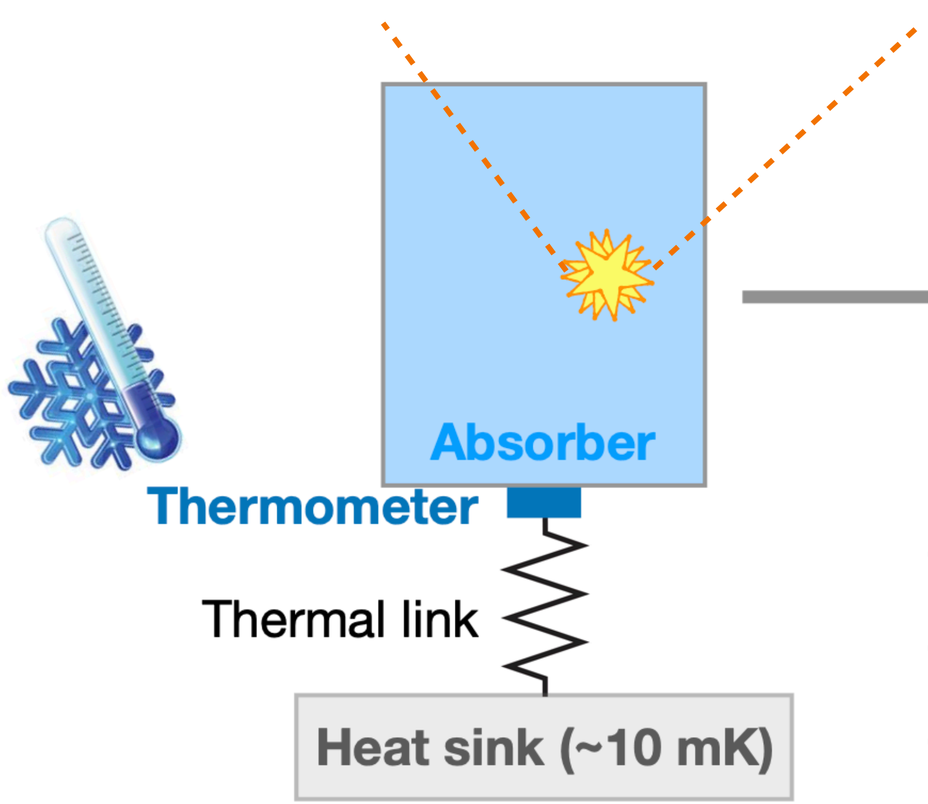


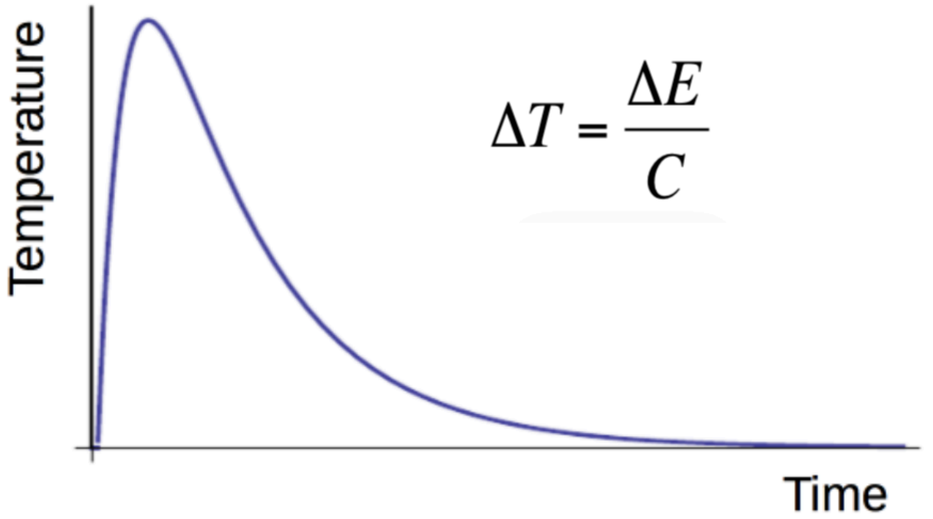
Competitive limits from:

- **Cryogenic detectors**
- Migdal effect
- Gas detectors
- Bubble chambers

Next talk **My talk** **Previous talk**

Cryogenic detectors





$$\Delta T = \frac{\Delta E}{C}$$

- Direct measurement of the (almost) full energy deposition
- Low threshold achievable (few eV)
- mK operating temperature
- **Second detection channel for background discrimination**

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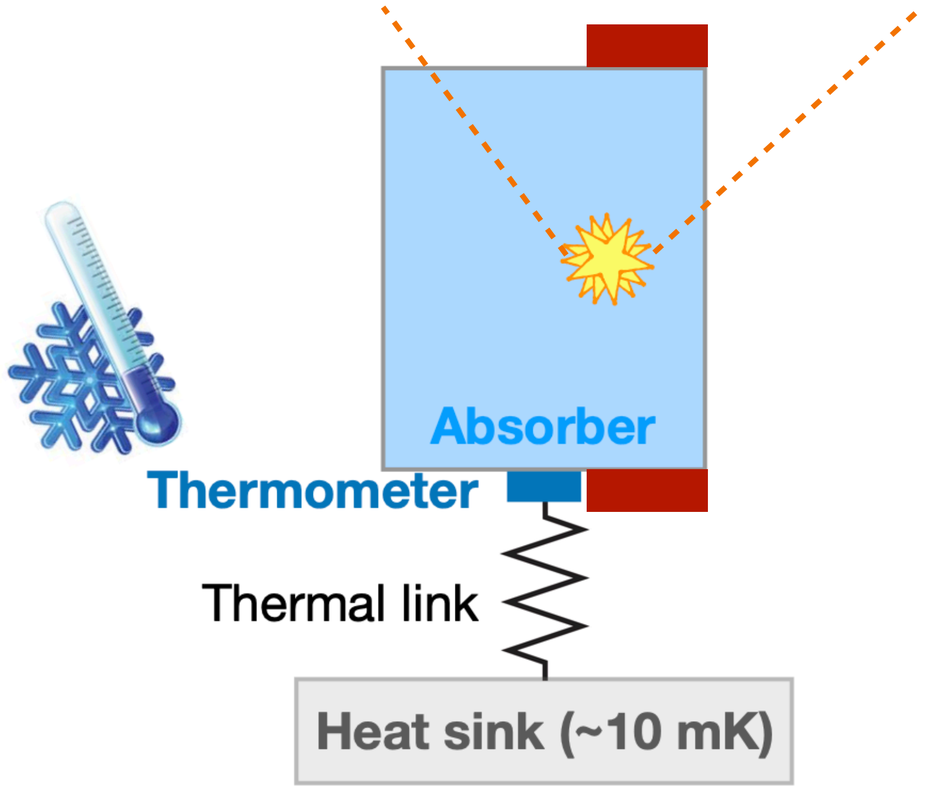
Cryogenic detectors: semiconductor

SuperCDMS, Edelweiss



- Energy deposits in the absorbers create e^-/h^+ pairs and phonons in the semiconducting target crystal
- The simultaneous readout of **phonons** (TES or NTD) and **charge** (electrodes on the surfaces) allows for **particle identification**
- How to reduce the energy threshold: operate the crystals with HV electric field applied to the crystal drifts charges:
  - secondary phonons
  - signal amplification
  - sensitivity to single e^-/h^+ pairs

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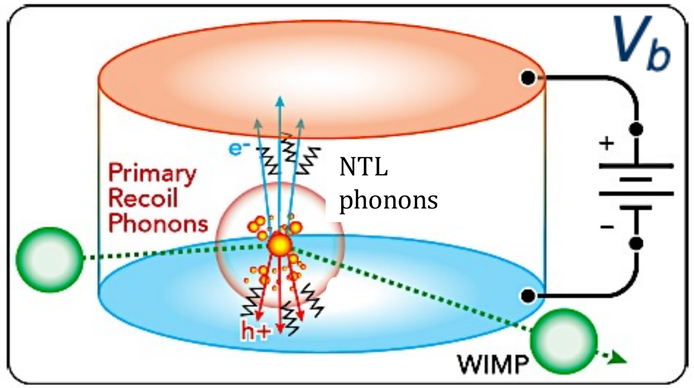
SuperCDMS

Super Cryogenic Dark Matter Search

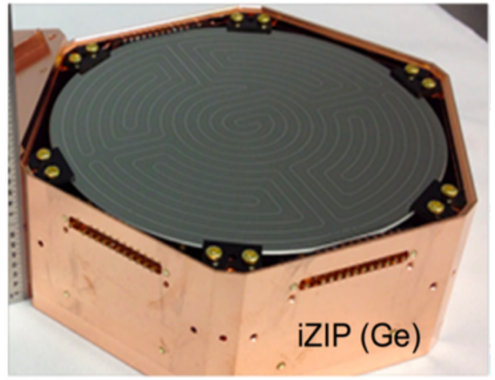
See talk from
S. Dharani



$$E_t = E_r + (N_{eh} \cdot e \cdot V_b)$$

E_t: phonon energy

E_r: recoil energy



- **HV detector (Ge of 1.4 kg)**: Vb ~100V generates a large number of secondary phonons.

  No ER/NR discrimination, but **low threshold**

- **iZIP detector (Si of 0.6 kg)**: **I**nterleaved **Z**-sensitive **I**onizaion and **P**honon detector

  Low bias voltage (Vb ~ 2-6 V). Phonon and charge sensors on both sides provides **ER/NR discrimination** and surface rejection.

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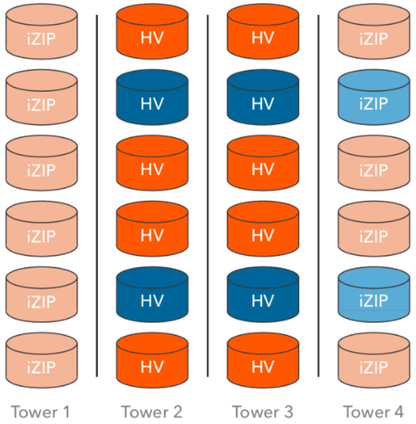
SuperCDMS @ SNOLAB

Status and strategy

See talk from S. Dharani

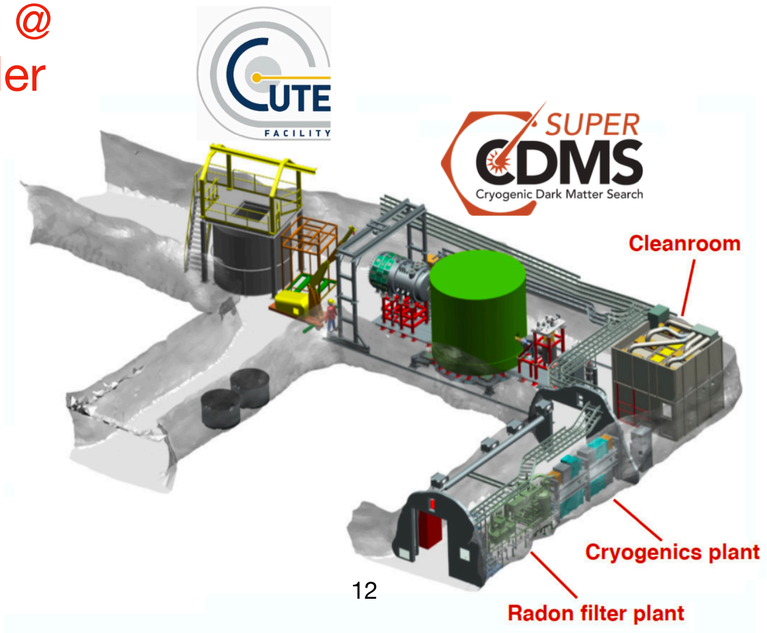


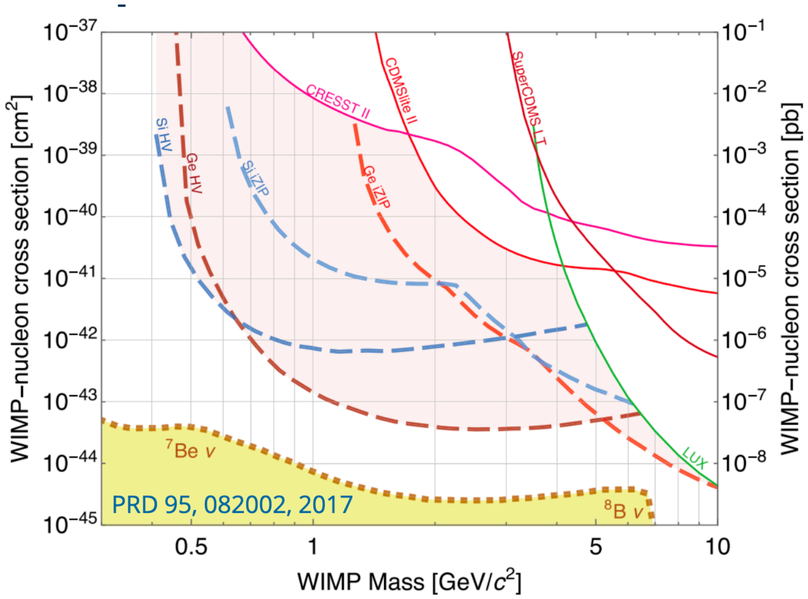
Complementary Targets and **Multiple** Functionality:

- @SNOLAB: Germanium and Silicon detectors in HV/iZIP mode
  - iZIP: NR/ER discrimination → background studies
  - HV: low-threshold → low-mass sensitivity

	iZIP		HV	
	Ge	Si	Ge	Si
Number of detectors	10	2	8	4
Total exposure [kg·yr]	45	3.9	36	7.8
Phonon resolution [eV]	33	19	34	13
Ionization resolution [eV_{ee}]	160	180	–	–
Voltage Bias ($V_+ - V_-$) [V]	6	8	100	100

Infrastructure @ SNOLAB under construction





See posters from K. Kennard and M. Wilson

WORK IN PROGRESS

SuperCDMS @ SURFACE

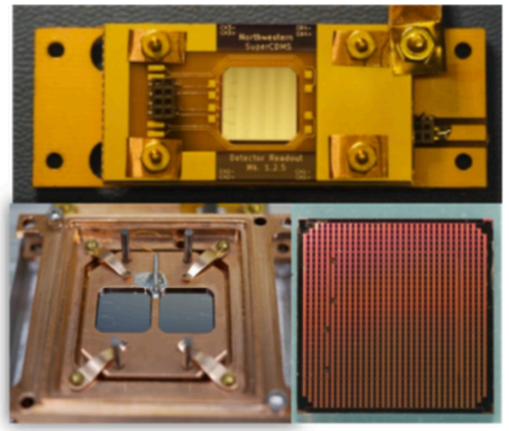
R&D detector program

Most recent results limited by an excess of events at low-energy with unknown origin.

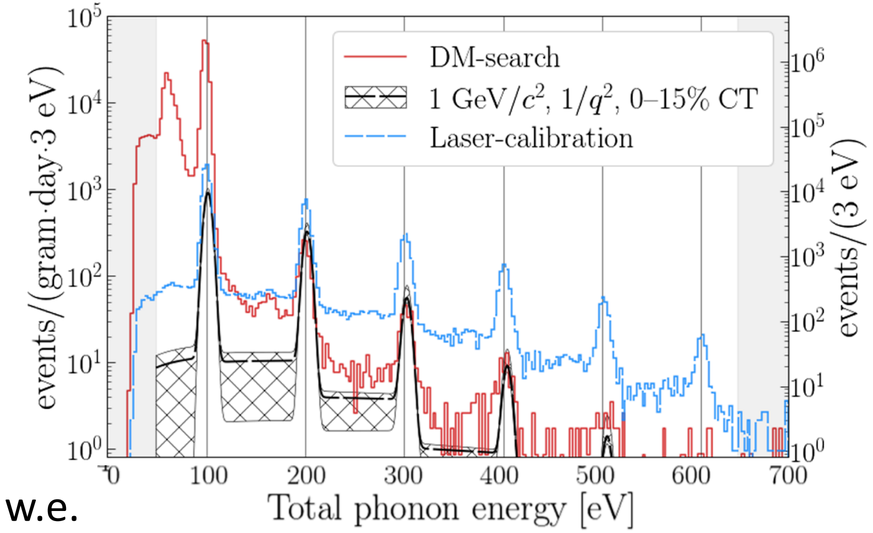
HVeV detectors

Si wafer, 1 cm^2 x 4 mm (~1g). Like a small HV detector with single e-h resolution

NR E_{thr}: 9.2eV (lates performance: σ_e=1.097±0.003 eV)



@NEXUS (Fermilab) 300 m w.e.

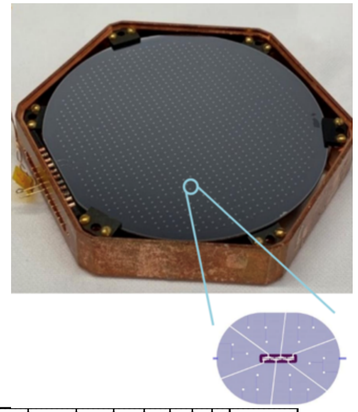


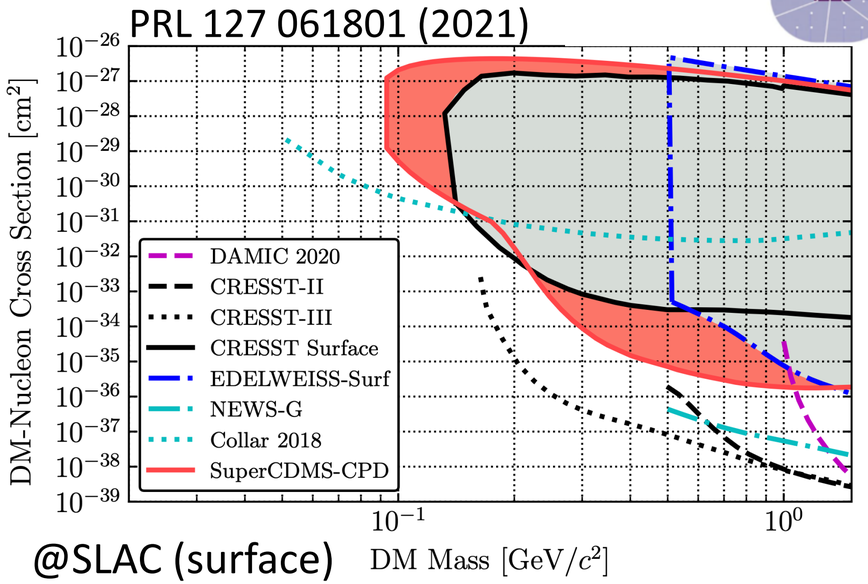
PRD 102 091101 (2020)

0V detector (aka CPD)

Si wafer, 10.6 g

NR E_{thr}: 16.3 eV





@SLAC (surface)

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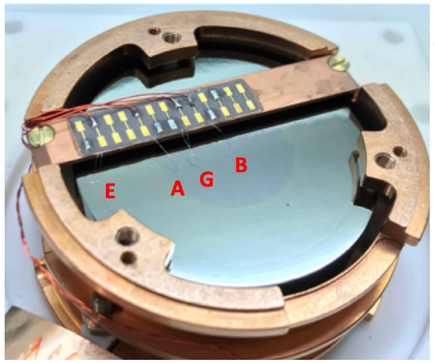
Edelweiss

EDELWEISS - III: Large exposure underground (LSM, France) with sensitivity in the 5 – 30 GeV WIMPs

- Ge semiconductor cylindrical crystals (4 → 800g)
- Simultaneous measurement: heat & ionization
- Operated at cryogenic temperature ~16mK

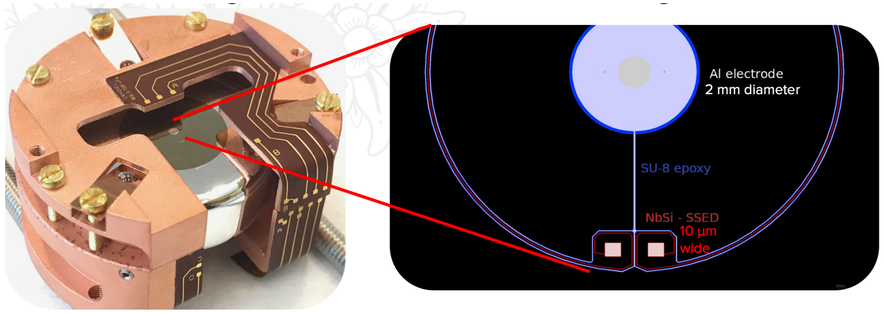
New detector designs



200 g Ge

Readout: NbSi TES to tag heat only events

PRD 108 (2023) 022006



JTLP 215 (2024) 268 : arXiv:2311.01554

CRYOSEL:

New program for sub-GeV searches

38g Ge, with Ge-NTD with NTL amplification for single electron energy resolution and charge tag using NbSi film

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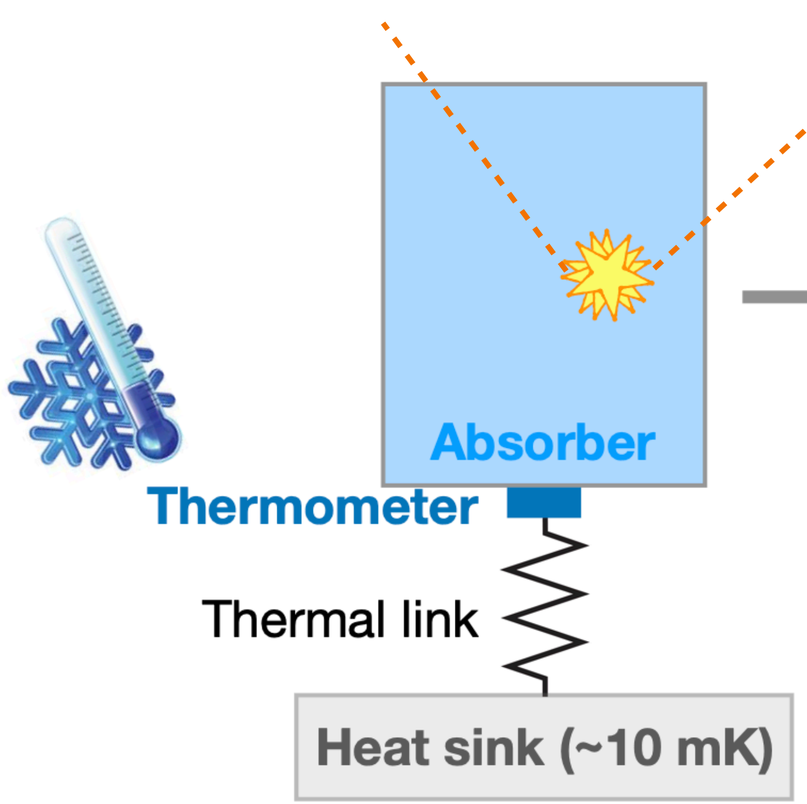
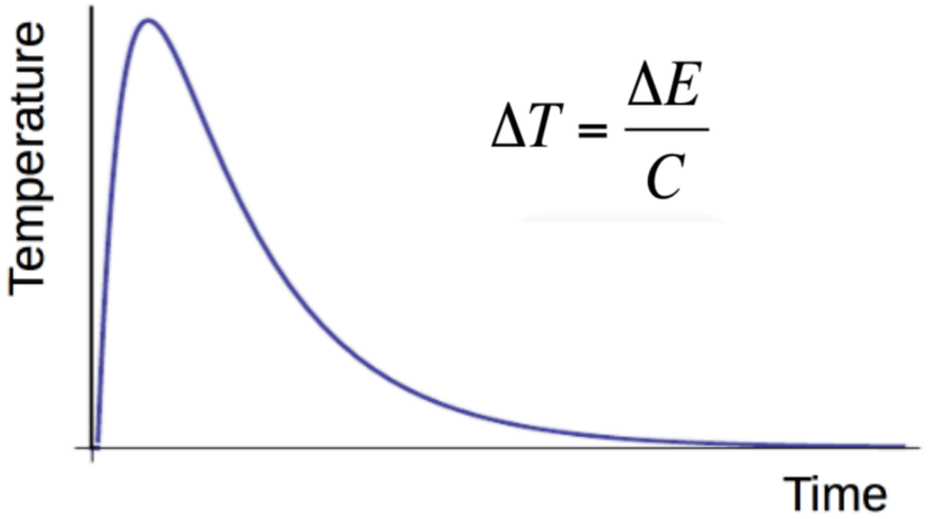
Cryogenic detectors





$$\Delta T = \frac{\Delta E}{C}$$

- Direct measurement of the (almost) full energy deposition
- Low threshold achievable (few eV)
- mK operating temperature
- **Second detection channel for background discrimination**

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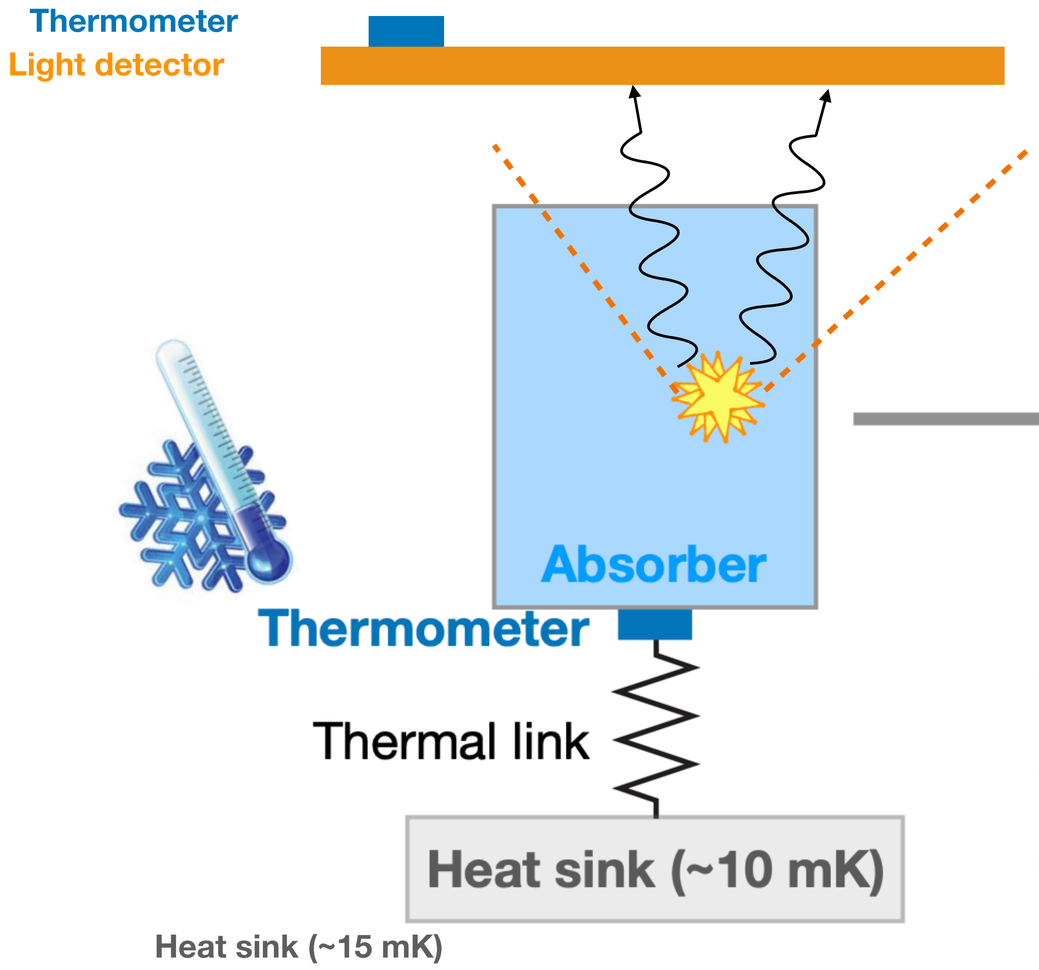
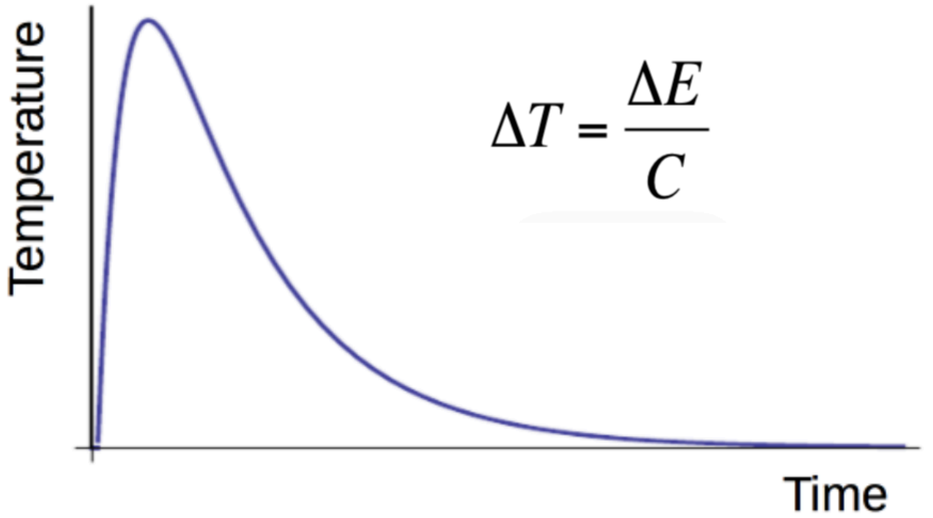
Scintillating cryogenic detectors





$$\Delta T = \frac{\Delta E}{C}$$

- Direct measurement of the (almost) full energy deposition
- Low threshold achievable (few eV)
- mK operating temperature
- **Second detection channel for background discrimination**

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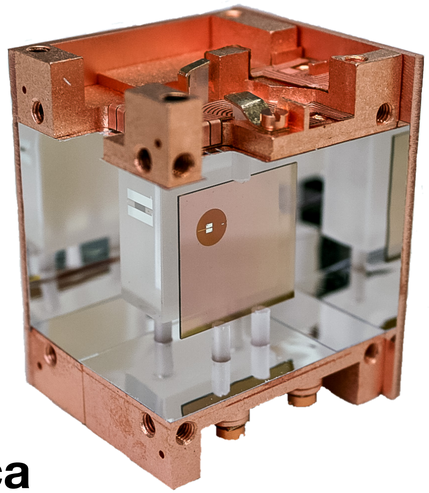
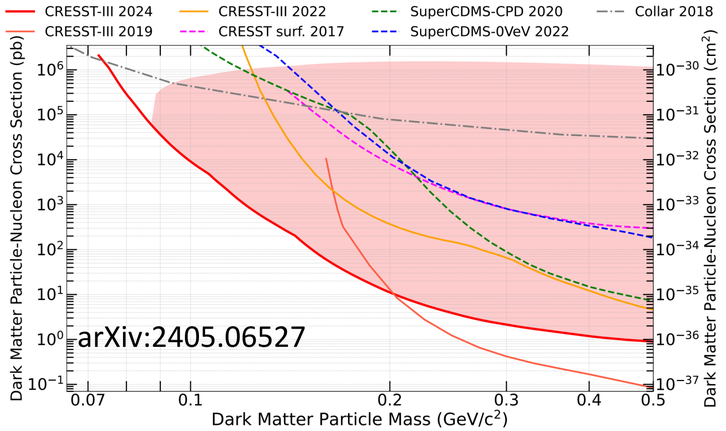
See talk from A. Bertolini and posters from F. Pucci L. Meyer and S. Kuckuck

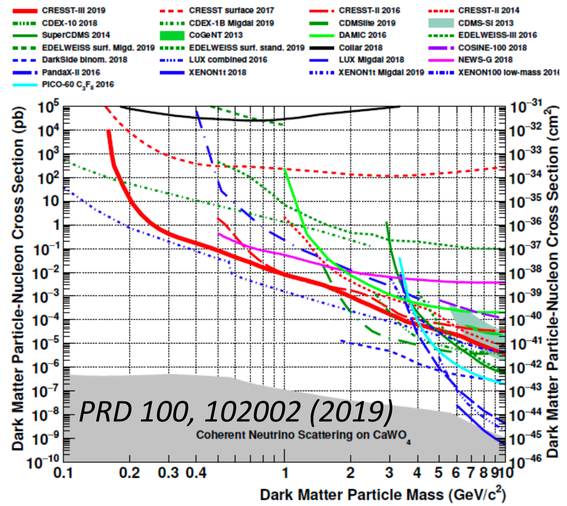
CRESST

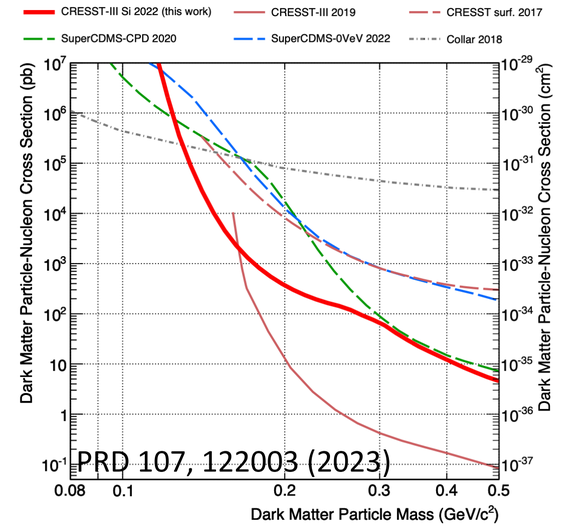
Cryogenic Rare Event Search with Superconducting Thermometers

- Main absorber: (2x2x1) cm^3 , broad choice of materials e.g. $CaWO_4$ (24g), Al_2O_3 - sapphire (16 g), $LiAlO_2$ (10g), Si (9 g).
- Operated @ LNGS (Italy) in a low-background dilution refrigerator
- Thin wafer detector: (2x2x0.04) cm^3, Si or silicon-on-sapphire (SOS) as light detector for scintillating absorbers









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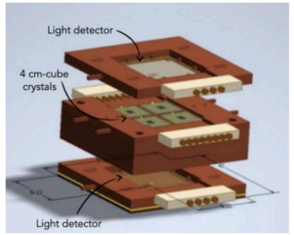
CRESST strategy

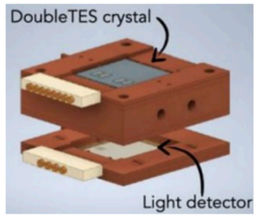
- Current data taking campaign devoted to understand the origin of the excess of events at low energy
  - 2 new detector designs

Cm Cube



Mass ~6 g —> Low energy threshold achievable

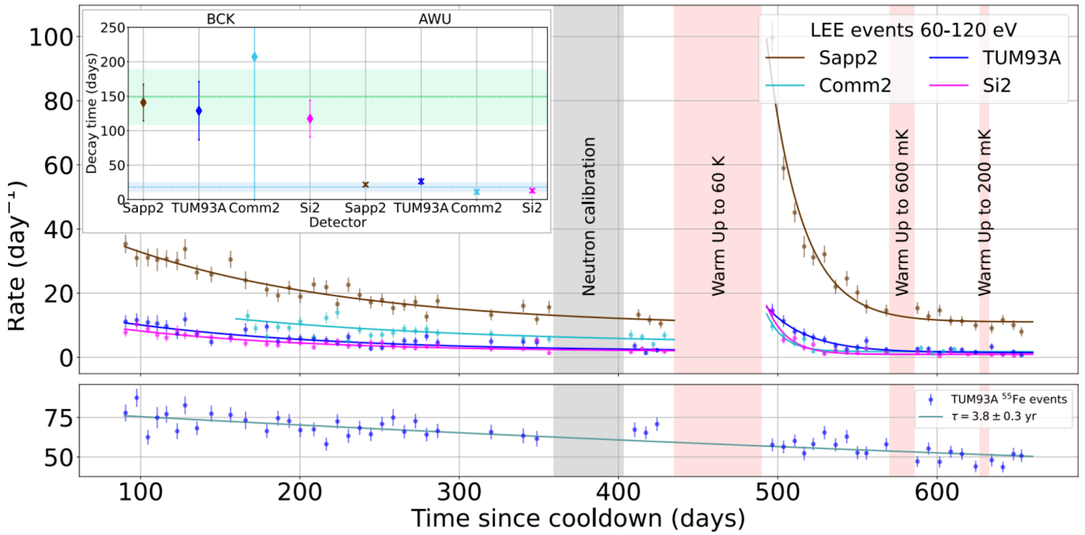
DoubleTES



2 TESs on the same wafer. To study low energy excess counts

e-Print: 2404.02607

CRESST, SciPost Phys. Proc. 12, 013 (2023)



Planning for a *O(*100*)* detector underground exposure

- Complementary target materials
- upgrade LNGS cryogenic infrastructure

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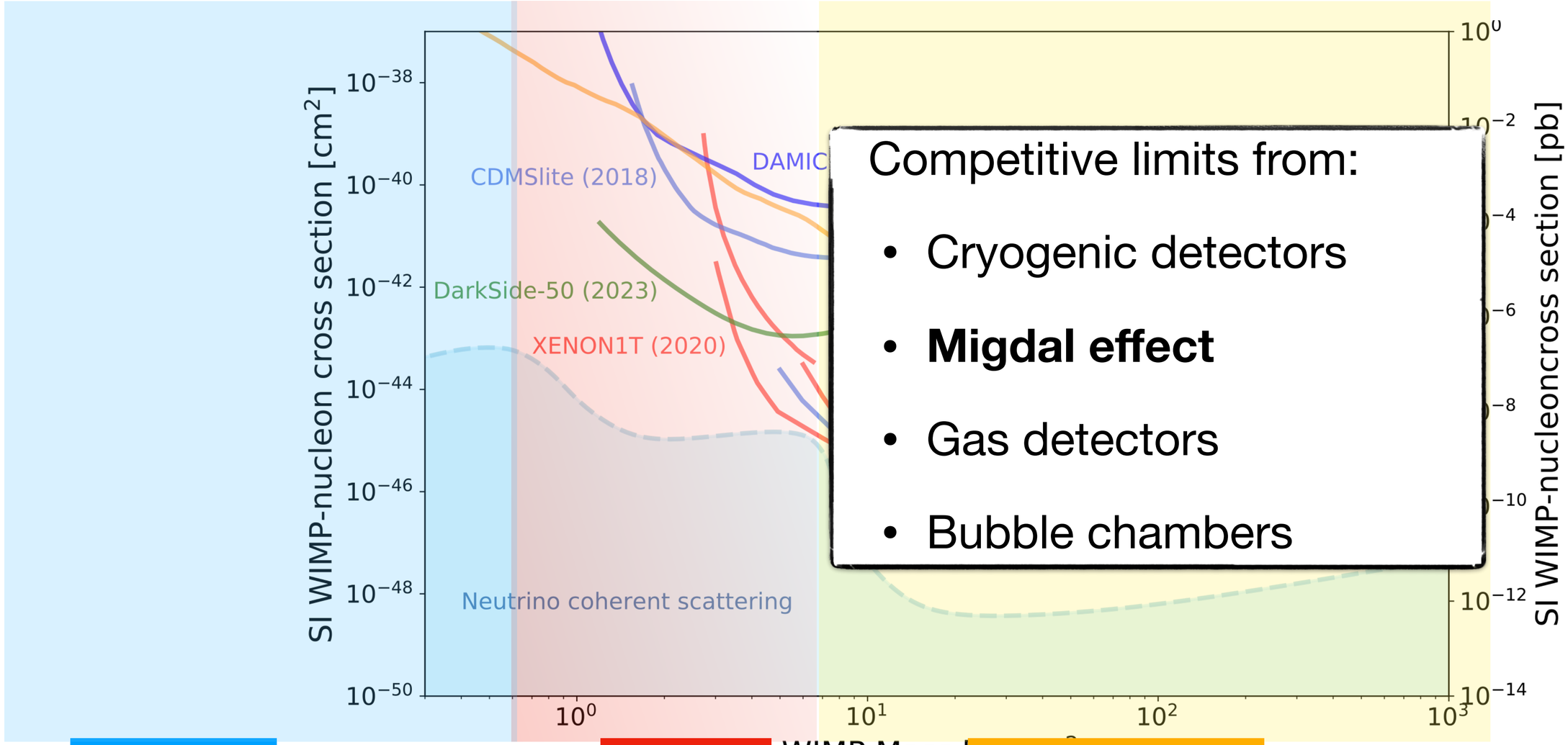
This talk

[Baudis & Profumo, PDG 2023]



Competitive limits from:

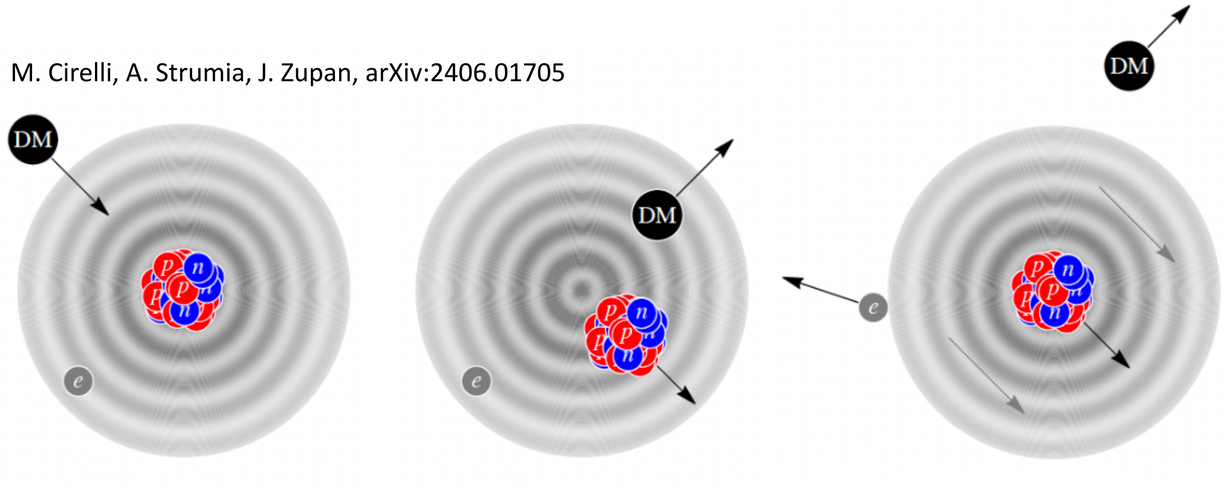
- Cryogenic detectors
- **Migdal effect**
- Gas detectors
- Bubble chambers

Next talk **My talk** **Previous talk**

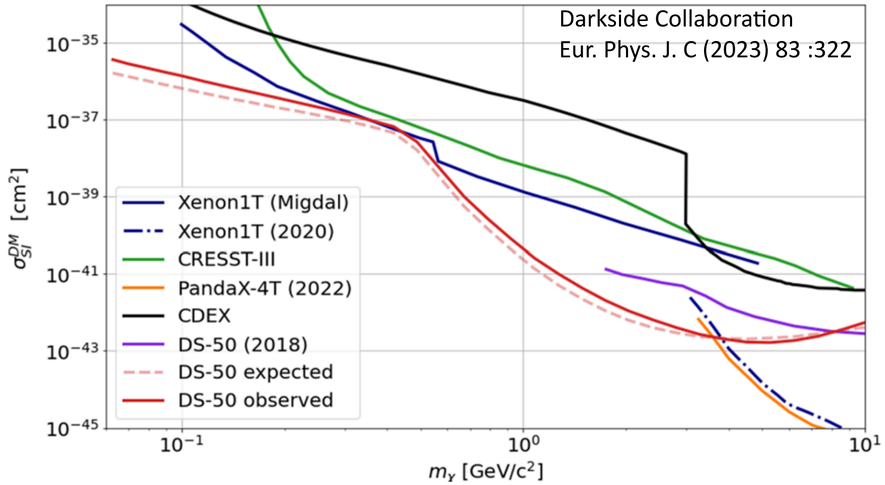
Migdal Effect

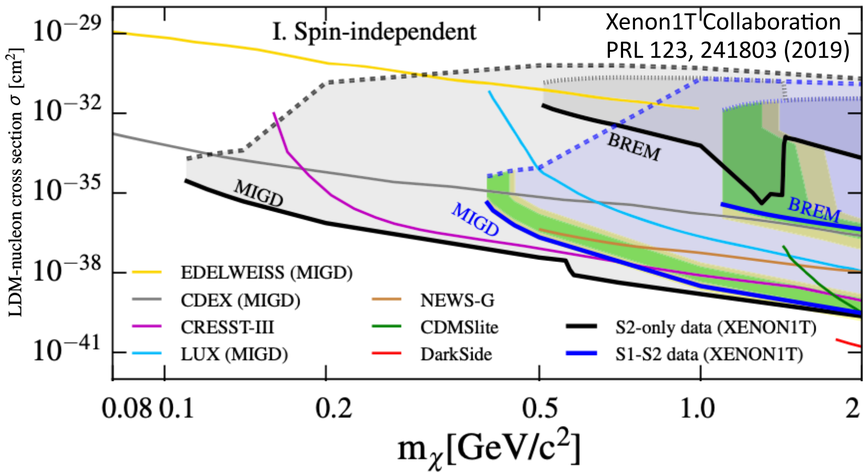
Talks from T. Marley, K. Nakamura, L. Wu

M. Cirelli, A. Strumia, J. Zupan, arXiv:2406.01705



- Irreducible dark matter–nucleus inelastic scattering
- It is predicted that the displacement of a nucleus relative to the electron shells in a scattering process can, with a small probability, ionize the atom.
- Detectable ionization (~keV electron recoil) for low-mass DM (~sub-keV nuclear recoils)
- Allows dark matter direct detection experiments to gain sensitivity to sub-GeV masses.





But… the Migdal effect has not yet been proven experimentally.

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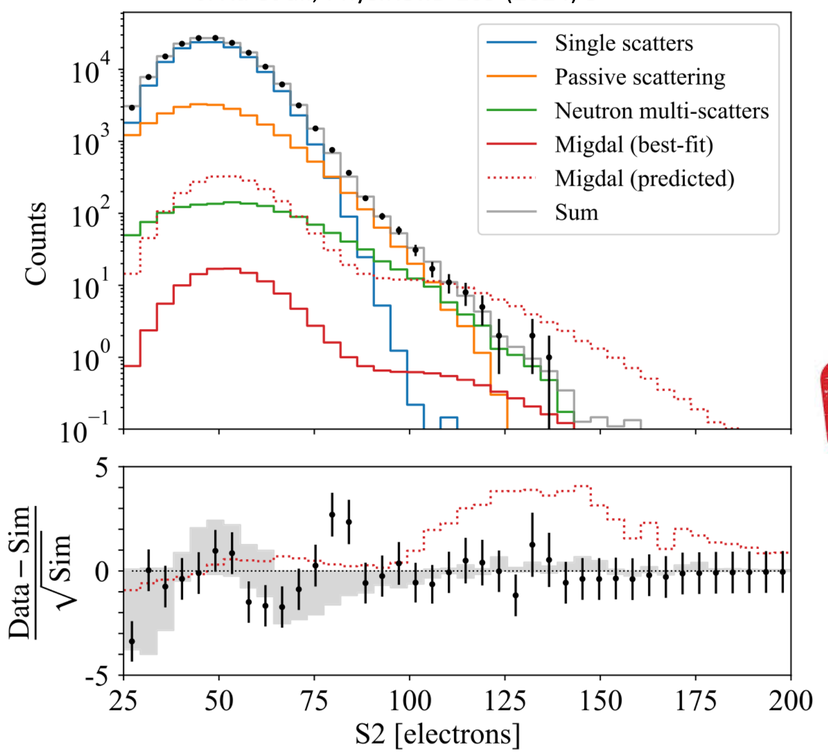
Search for the Migdal effect in liquid xenon

- Experimental setup at LLNL
  - 14.1MeV neutrons —> @ 15.4 deg NR of (7.0±1.6) keV

J. Xu et al., Phys.Rev.D 109 (2024) 5



WORK IN PROGRESS

- Independently on the fit range choice, **Migdal events statistically consistent with 0 signals**
  - Predicted rate too high?
  - Enhanced electron-ion recombination in the LXe?

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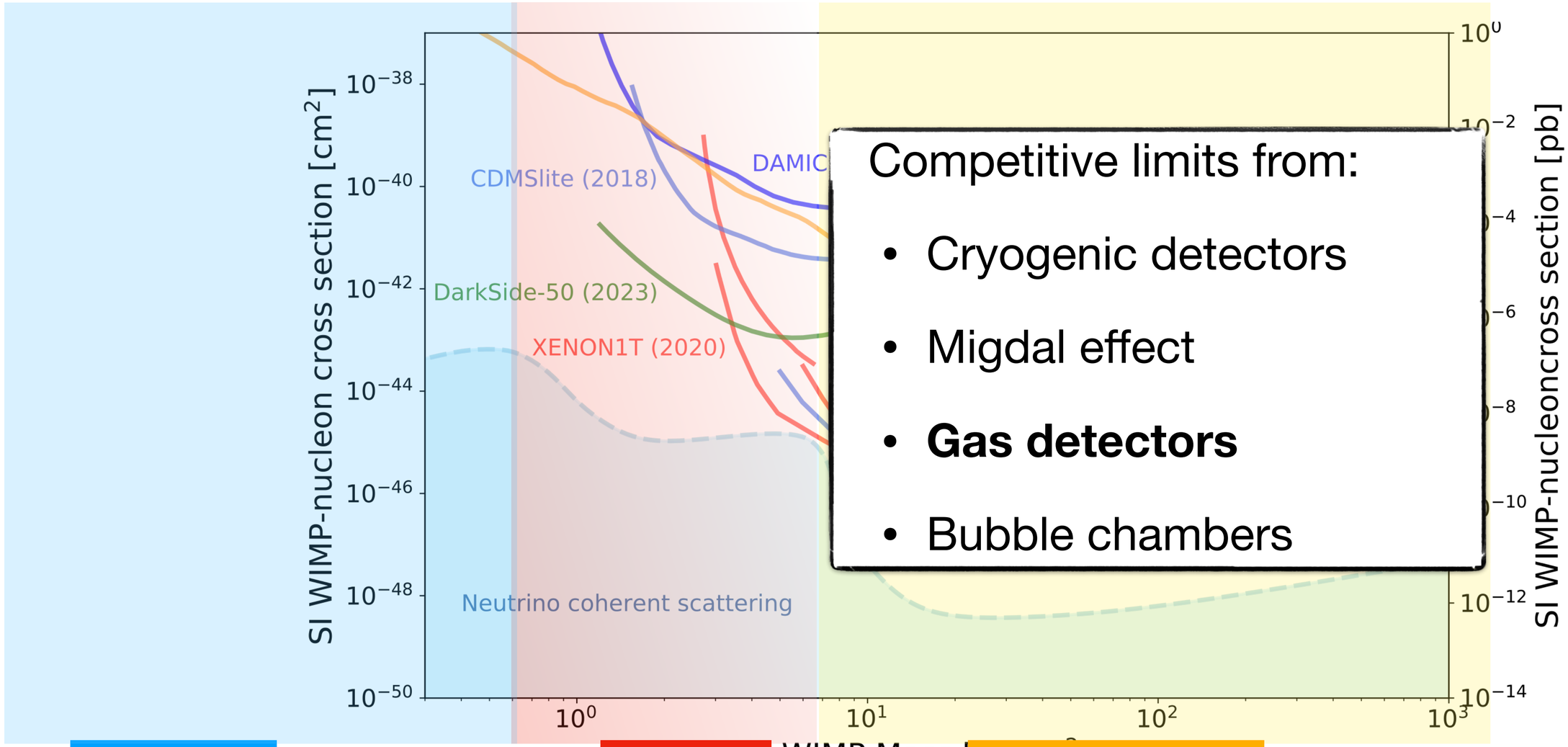
This talk

[Baudis & Profumo, PDG 2023]

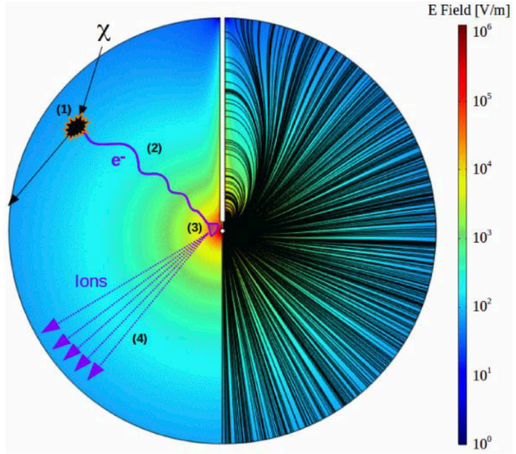


Next talk **My talk** **Previous talk**

Spherical proportional counters

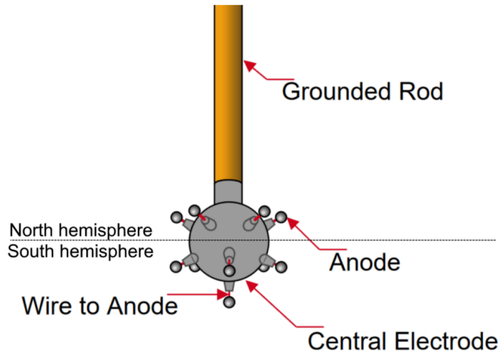
Talk from I. Manthos

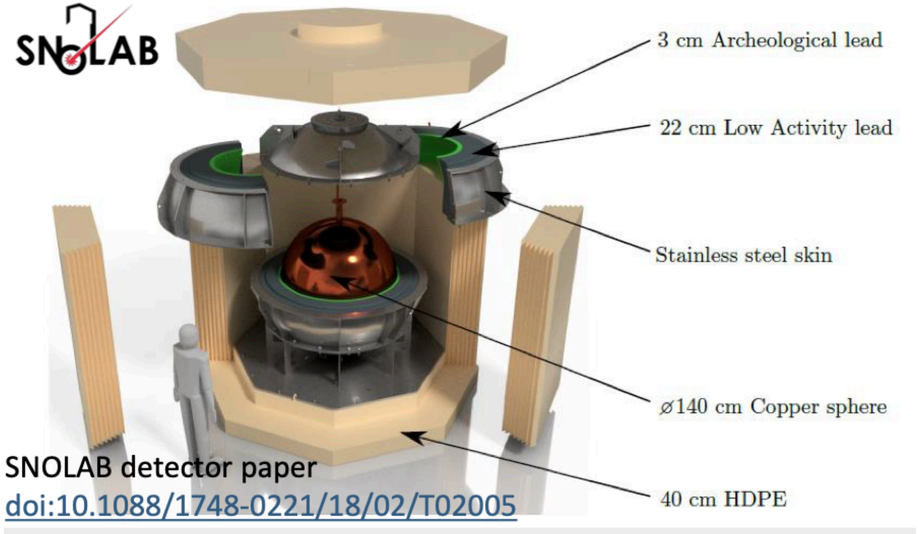
NEWS-G



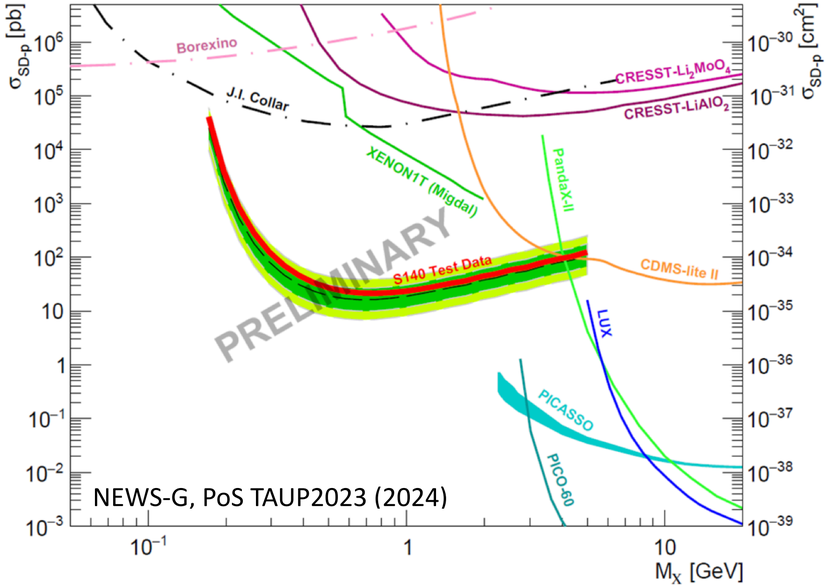
Metallic sphere filled with gas, with a central anode producing a radial electric field

- different gases and mixtures (Ne, He, H)
- low threshold (single-ionization)
- sphere provides optimal volume/surface ratio





SNOLAB detector paper
doi:10.1088/1748-0221/18/02/T02005



Limit obtained with 10 days of data taken at LSM with CH4 before shipping the detector to SNOLAB

New results from SNOLAB data taking campaign!

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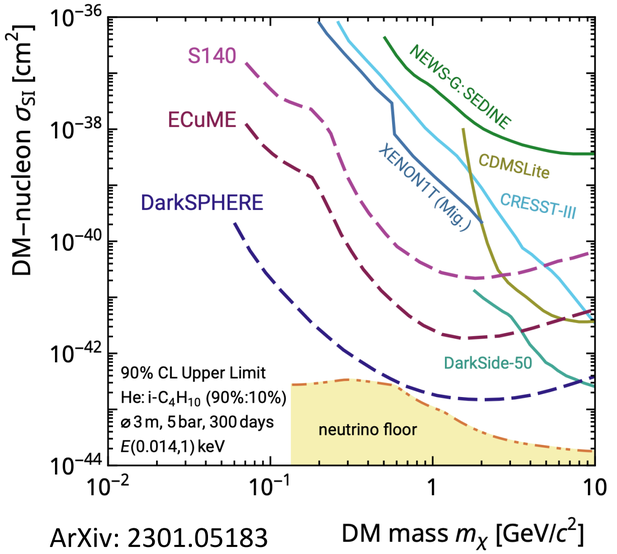
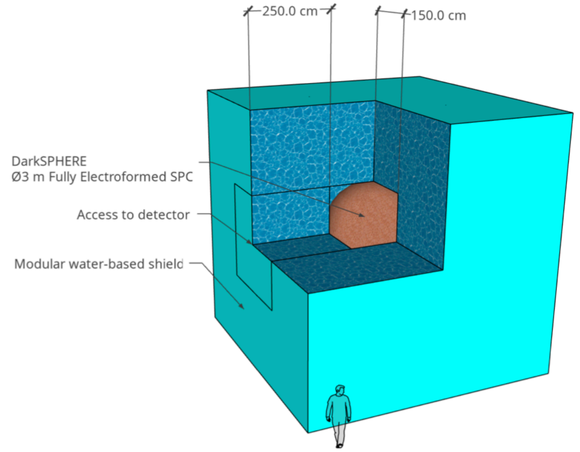
Spherical proportional counters: future

ECuME, DarkSPHERE

- **ECuME**
  - Sphere 140 cm of diameter, fully underground electroformed Cu , operated in SNOLAB
  - MiniECuME: prototype (30 cm diameter) electroformed at PNNL to demonstrate the principle and assess low-energy backgrounds
- **DarkSPHERE**
  - Proposal for building a sphere 3 m of diameter, fully electroformed Cu. Operated in a water shield, in Boulby Laboratory (UK)



ArXiv: 2301.05183



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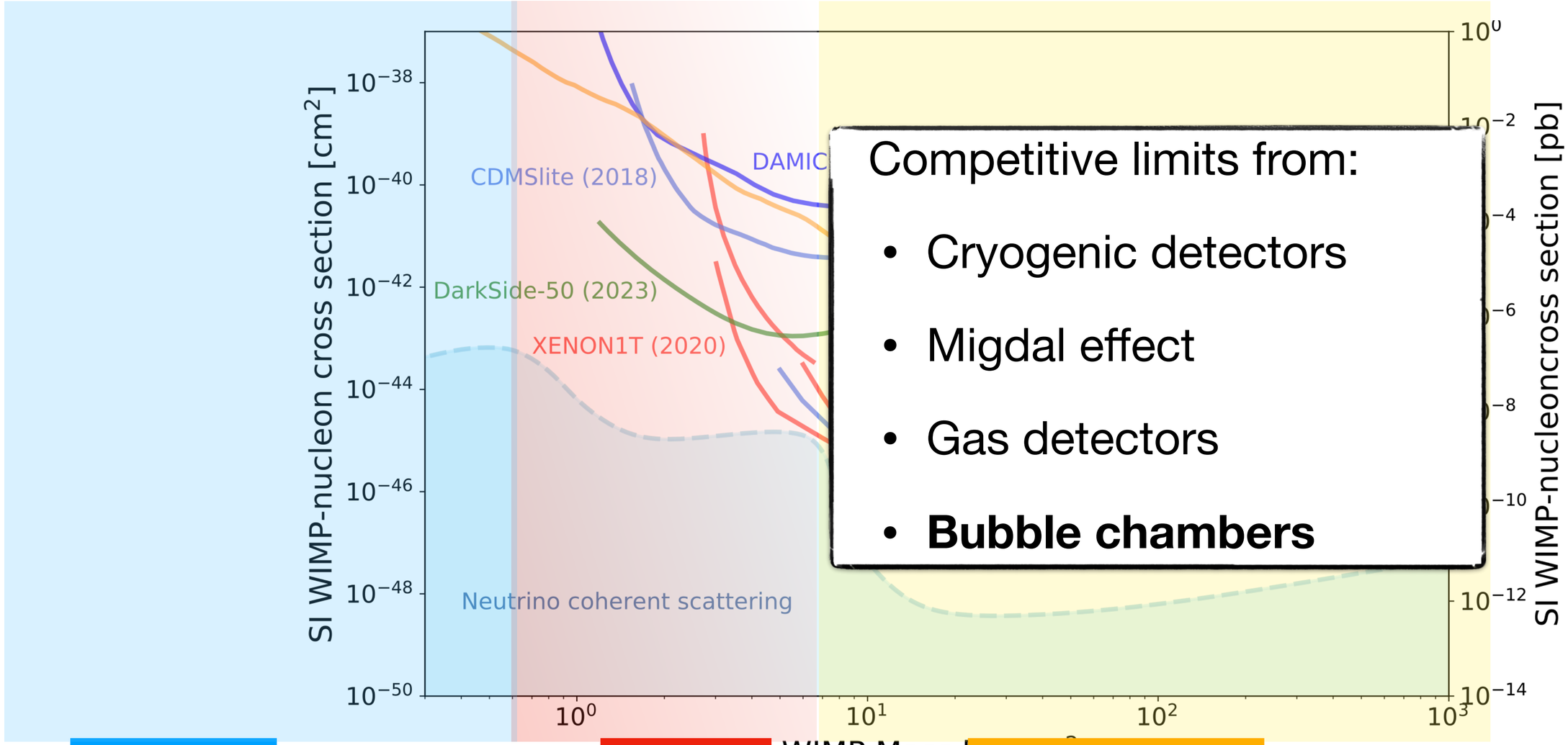
This talk

[Baudis & Profumo, PDG 2023]



Bubble chambers

PICO and SBC-Scintillating Bubble Chamber

Pico40L: D. Cranshaw talk
PICO500: J. Savoie poster

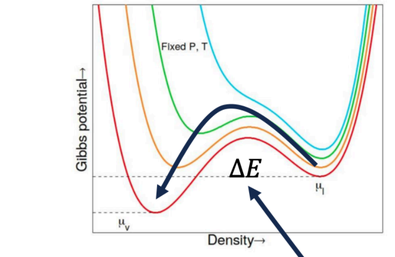
- Superheated state of the liquid: bubble nucleation when a particle (such as a dark matter candidate or a neutron) causes a sufficiently energetic nuclear recoil.
- Great potential for nuclear recoil discrimination: insensitive to electron-recoil DM (bubble nucleation requires highly localized energy deposition).

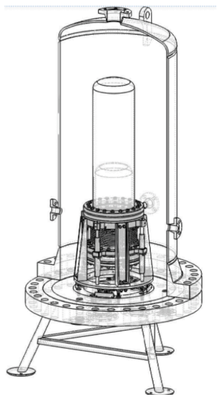
PICO: superheated C_3F_8 as the target material, with the possibility to change target fluids (i.e. CF_3I) @ SNOLAB

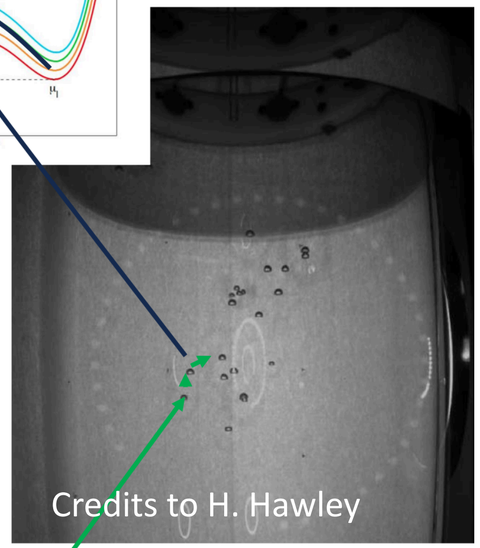
- Highly sensitive to spin-dependent NR interactions.
- Nucleation Threshold determined by T, P —> no precise energy information except by tuning conditions

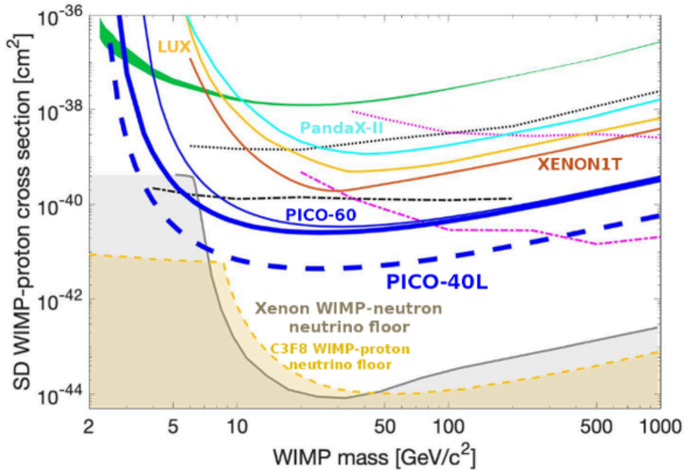
SBC: (Scintillating bubble chambers)

- Use scintillation of noble liquids to measure the energy event-by-event.
- Current plan: first physics-scale demonstrator is SBC-LAr10 (10-kg LAr).









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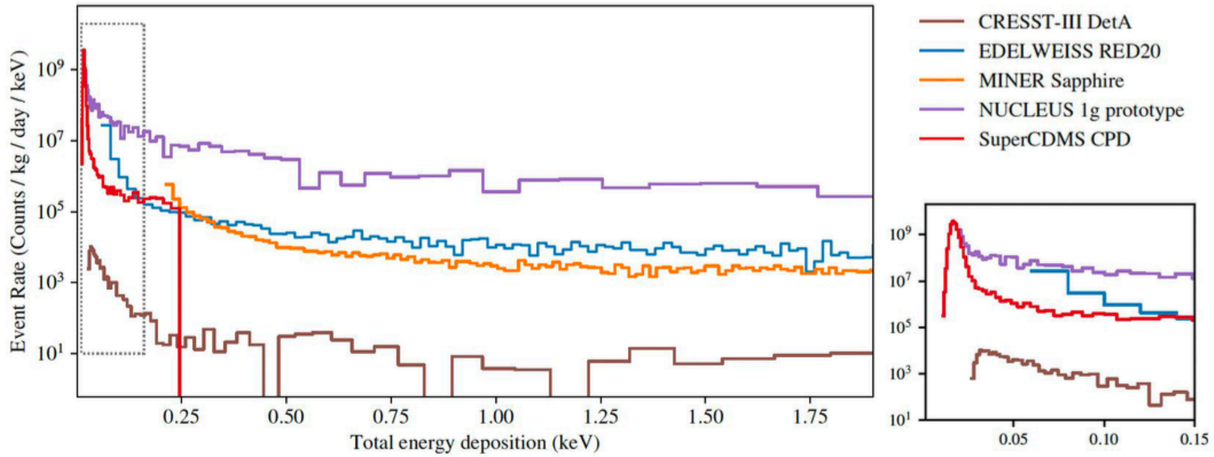
Final considerations (1)

Low Energy Excess

See talk from C. Strandhagen

- Now that experiments have lowered their recoil energy thresholds, down to ~10 eV, they observe steeply rising counts above known backgrounds
- Strong impact on their sensitivity
- Very active field of research
- Yearly workshop, since 2021: a community effort has been initiated to study the observations.

Rome, 6 July 2024
https://agenda.infn.it/event/39007/



- The LEE is currently limiting the sensitivity in the DM (and CEvNS) community

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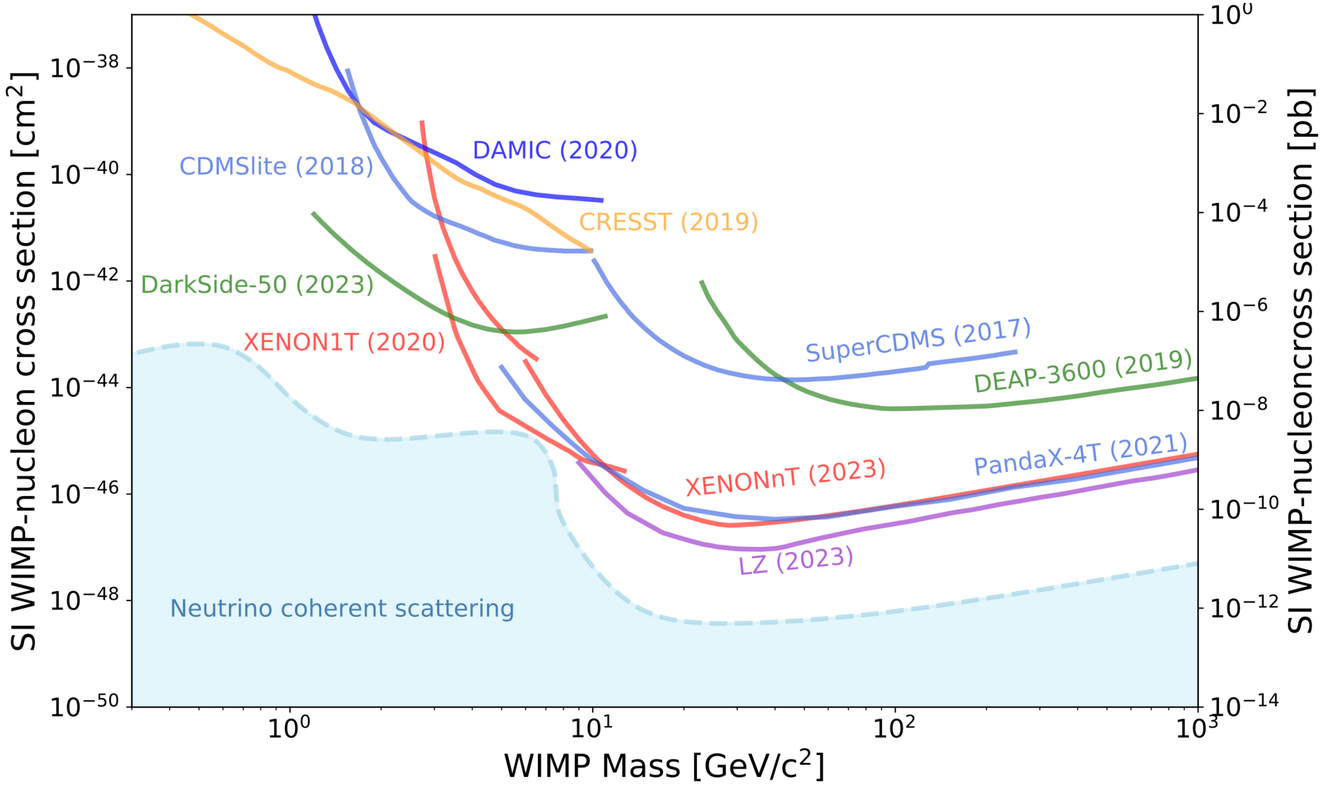
Final considerations (2)

The landscape

- Spin-independent searches with noble liquid TPCs will reach the neutrino floor/fog very soon.
- Large region of parameters at the GeV scale (and below) still to be explored
- For a known *energy density* of dark matter, *lower-mass* DM candidates imply *higher number densities*, and can be probed by *smaller experiments.*
- **Different and complementary experiments will be crucial and essential to probe the nature of DM interaction.**

[Baudis & Profumo, PDG 2023]



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Thank you for your attention!

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