TESSERACT

TESSERACT @LSM

A new generation light dark matter search cryogenic experiment underground in Modane

The Modane Underground Laboratory
The Direct Dark Matter Search
The TESSERACT Experiment

S. Scorza (LPSC)

LPSC GRENOBLE | MODANE

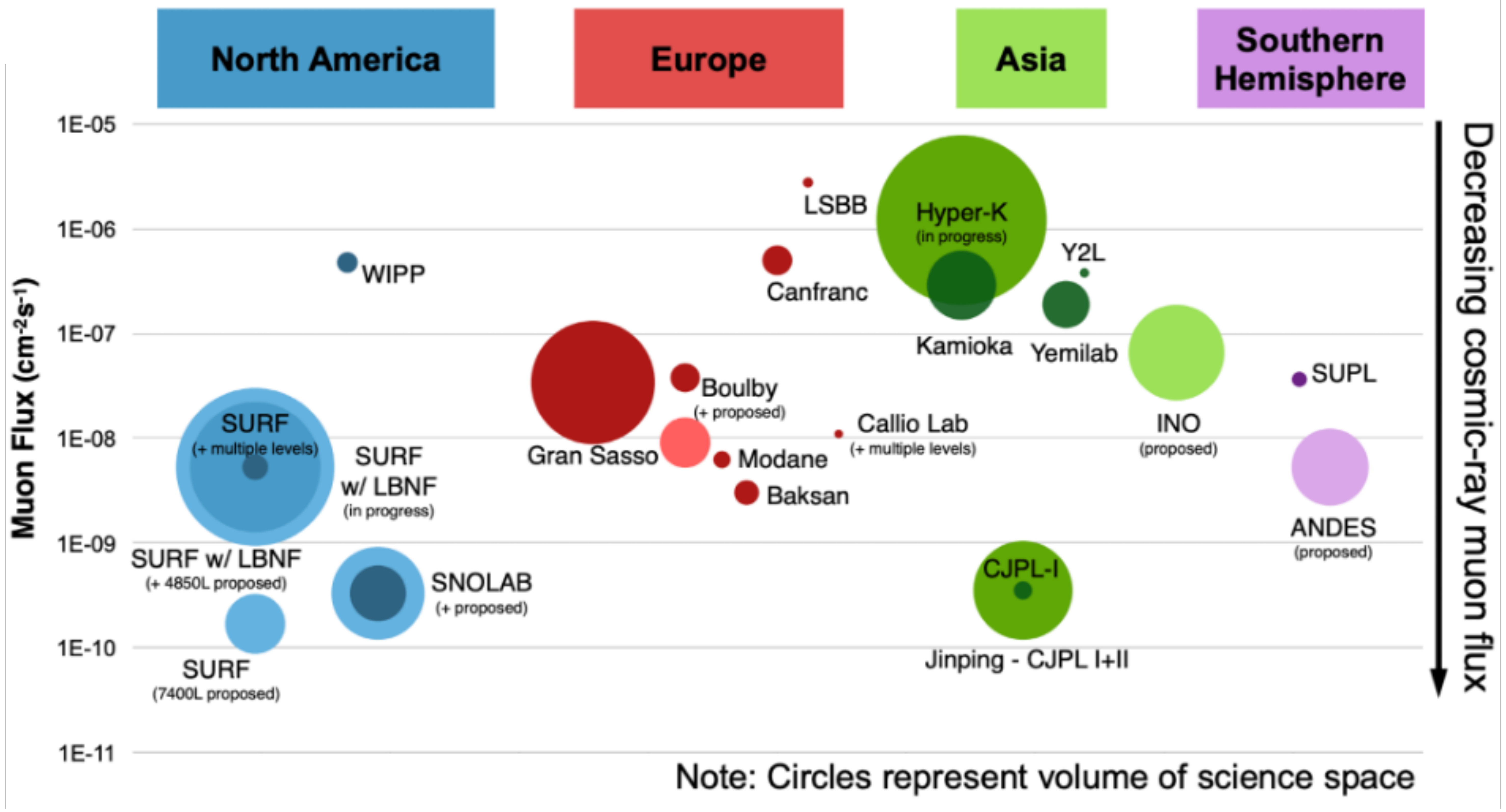
cnrs

Worldwide Underground Laboratory

Underground facilities provide unique environments for astroparticle and multidisciplinary research with the main feature to be the overburden protection from cosmic-ray muons

The LSM is a French National Research Infrastructure

- Experimental site midway in the 13km France/Italy highway road tunnel
- Surface lab (office, garage, small museum)



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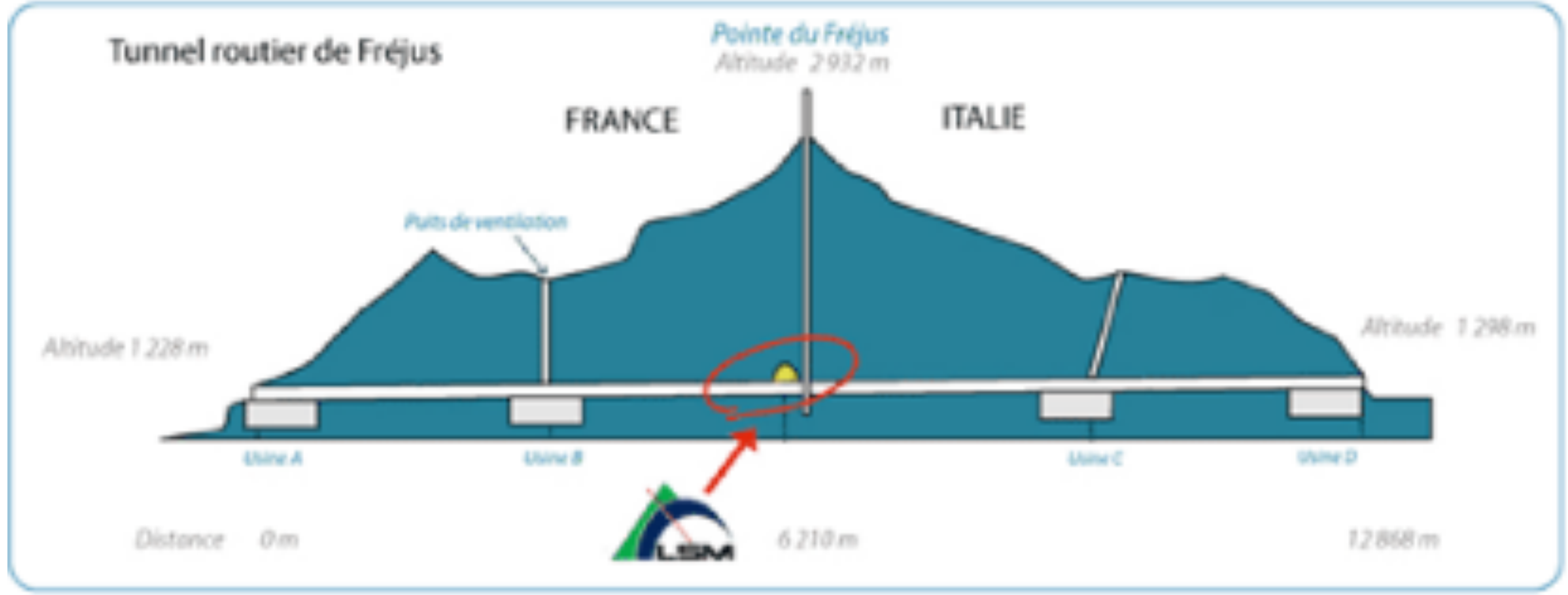
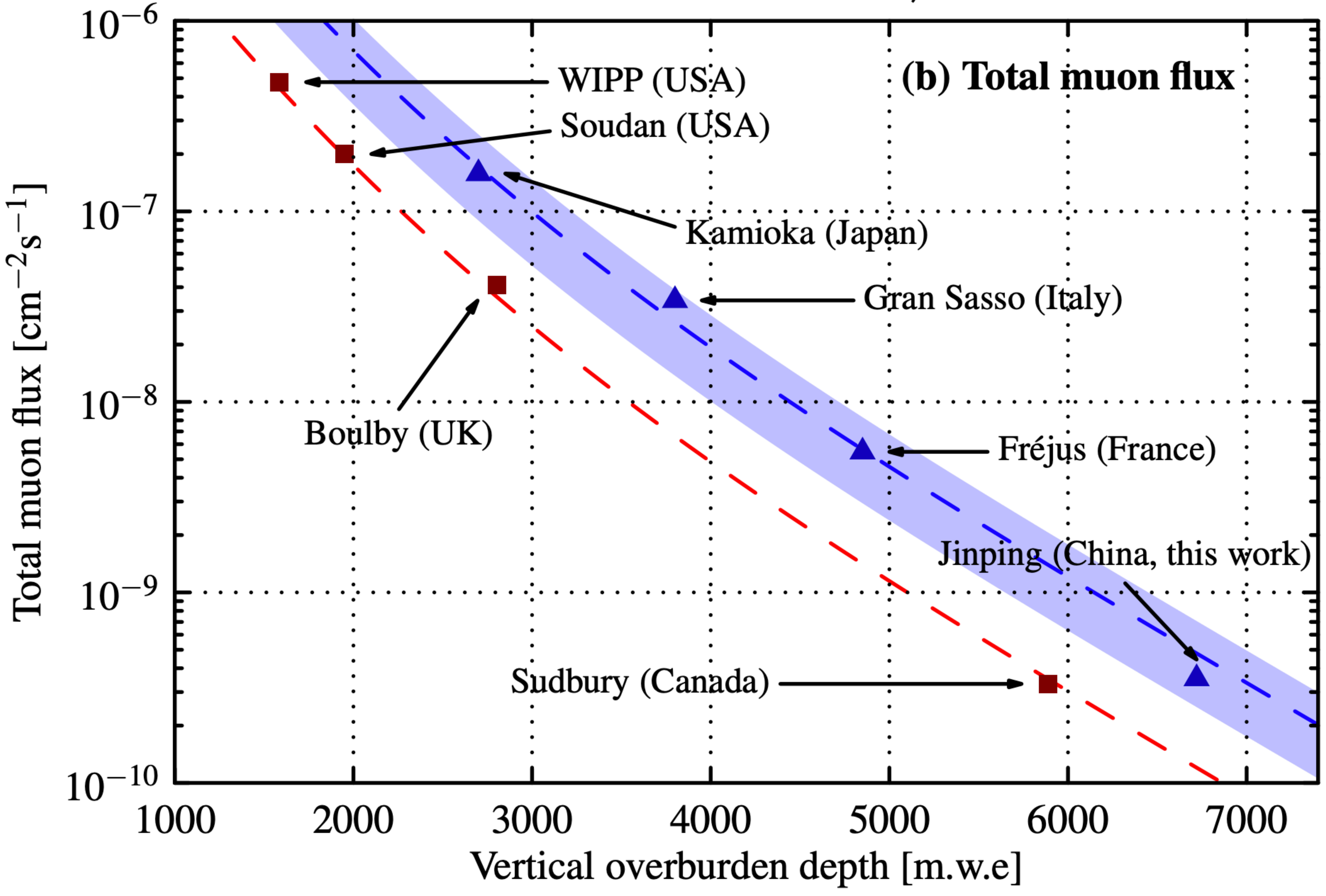


The Modane Underground Laboratory

- Deepest site in Europe dedicated to astroparticle, nuclear & particle physics
- 4800 m.w.e: muon flux reduced by $>10^6$ relative to surface
- Flexible access (hall accessible to trucks up to 9m);
- Natural radioactivity due to radon of about 10-15 Bq/m^3

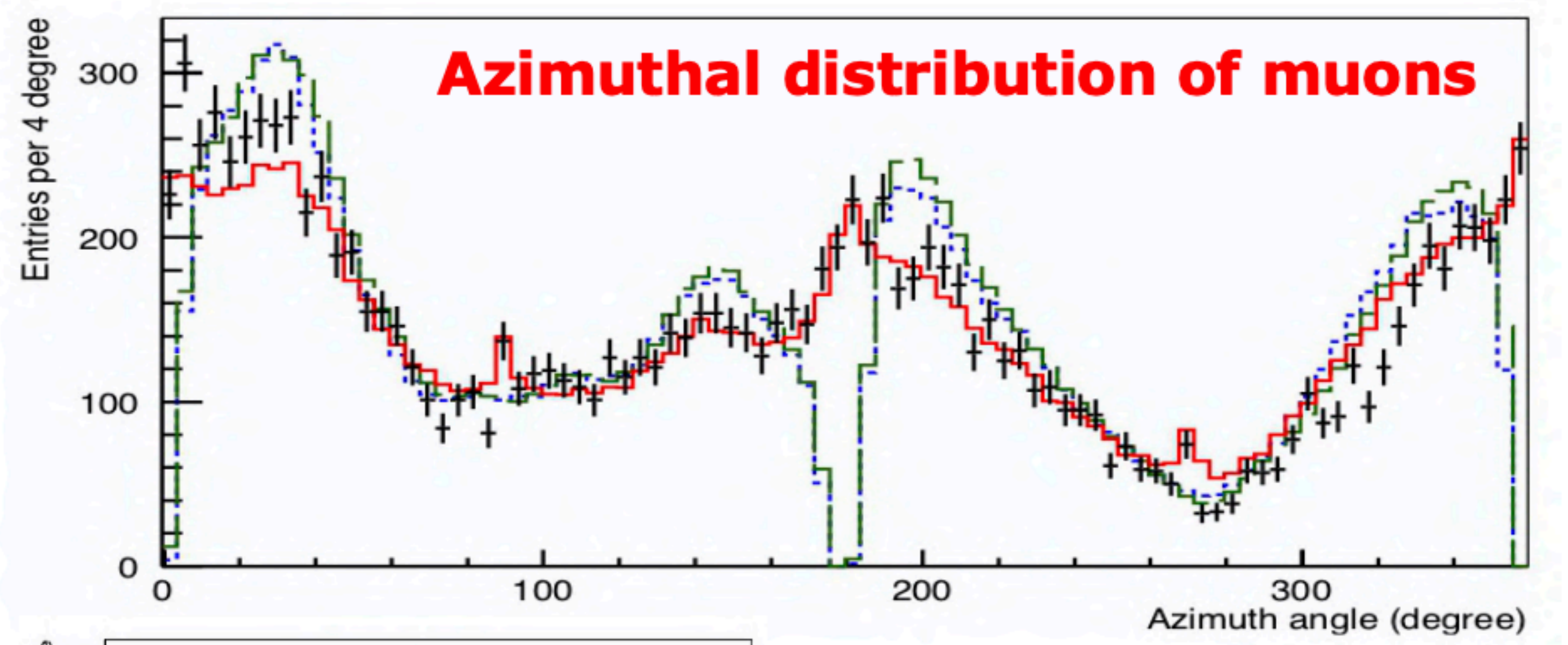
Guo et al., arXiv:2007.15925v2

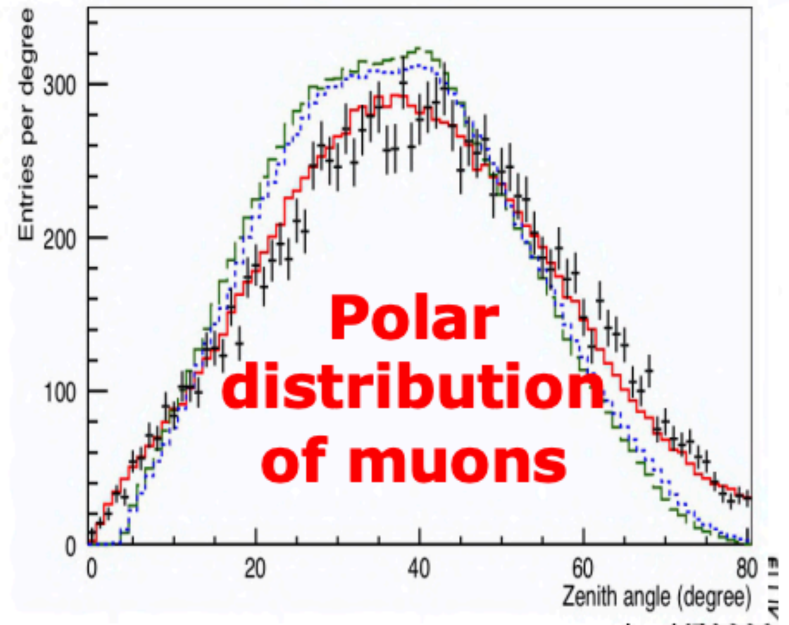


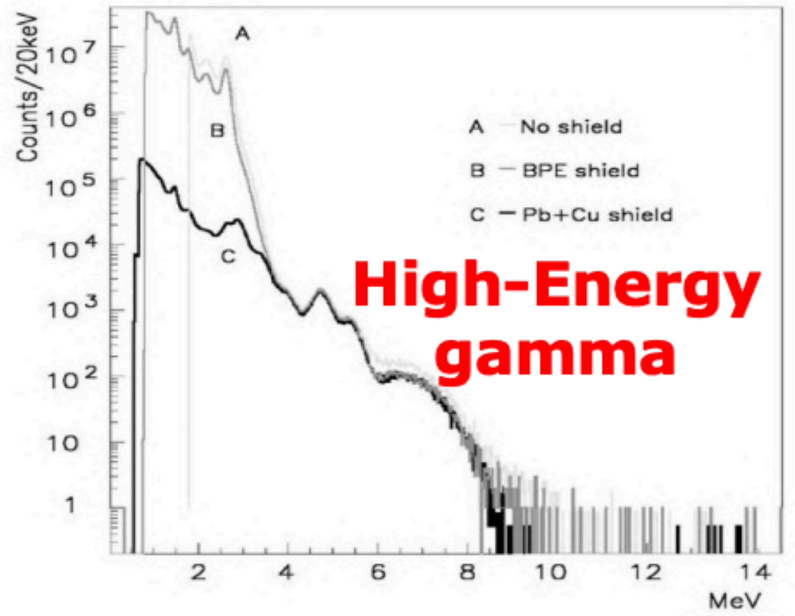
Radioactive Background Measurements

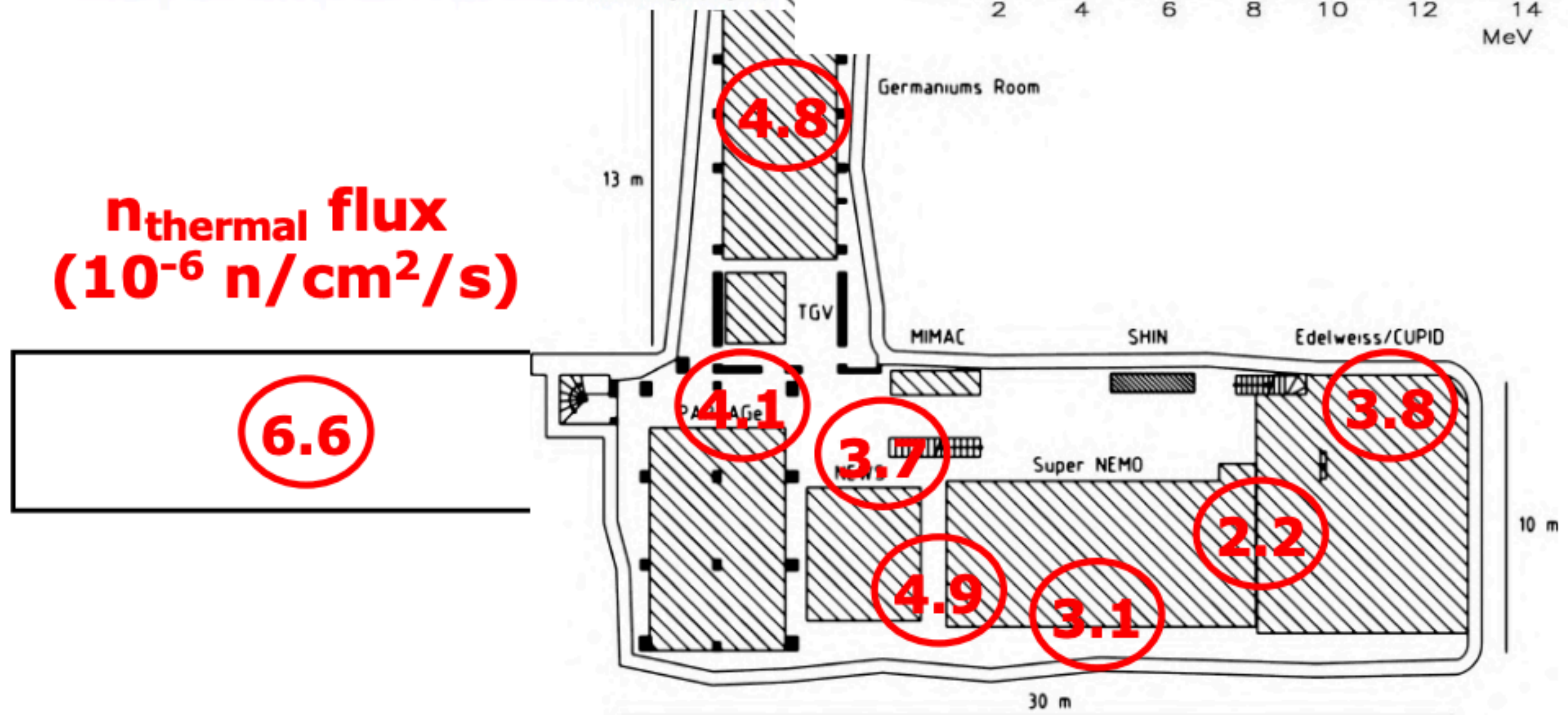
Since 1983, large corpus of measurements of various LSM backgrounds by experiments

- Muons: total flux (4.5 μ/m²/d), and angular map
  [Rhode, PhD Thesis (Ruppertal, 1993) + Schmidt et al, Astrop. Phys. 44 (2013) 28]
- High-energy gamma rays.
  [Ohsumi et al, NIMA 482 (2002) 832]
- Fast neutrons (1.6x10-6 n/cm²/s)
  [Armengaud et al, Astrop. Phys. 47 (2013) 1]
- Thermal neutrons
  [Rozov et al, BRAS 74 (2012) 464; arXiv:1001.4383]
- Radon (~15 Bq/m3)
  [Hodak et al, J. Phys. G 46 (2019) 11 + E. Armengaud et al, JINST 12 (2017) P08010]









Screening and Material Assay Platform

Wide-range program for Astroparticles, Earth Sciences (sediment and ice core sample datation), environmental safety (CEA), biology, etc...

- HPGe gamma spectroscopy
- Alpha surface contamination via the XIA-UltraLo1800 counter
  - Commissioning at LPSC (surface cleanroom)

- Material assays for experiments based at LSM (SuperNEMO, EDELWEISS, CUPID-Mo, DAMIC-M), and also for other experiments (ex: JUNO, RICOCHET)
- Agreement with LNGS for long term (~ year) measurement of ECEC decay of ^{82}Se (6 kg) to excited state on large (600 cc) Obelix HPGe.

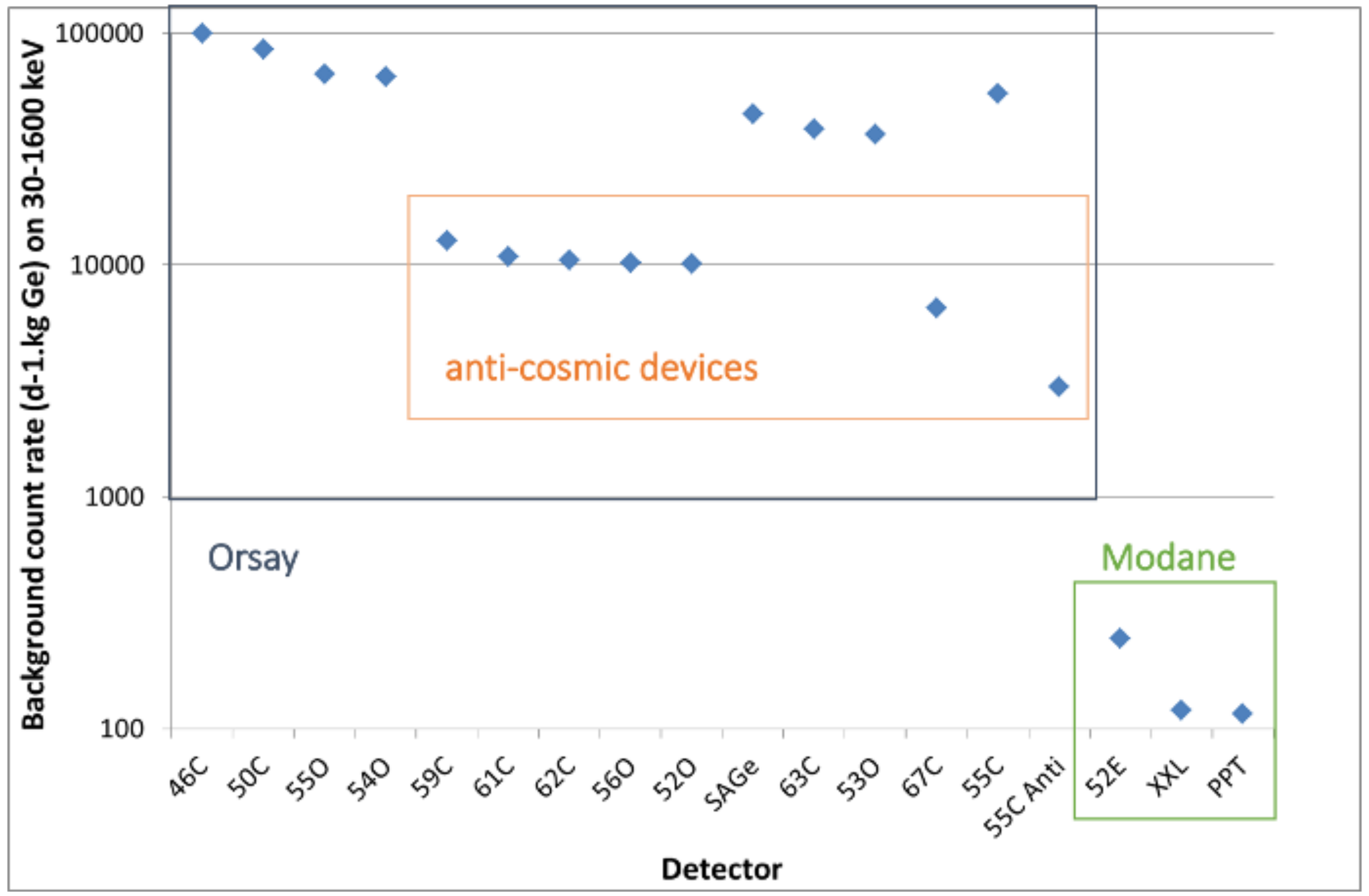
HPGe Obelix at LSM

Screening and Material Assay Platform

Wide-range program for Astroparticles, Earth Sciences (sediment and ice core sample datation), environmental safety (CEA), biology, etc...

- Pluri-disciplinary program open to academic and industrial users and partners

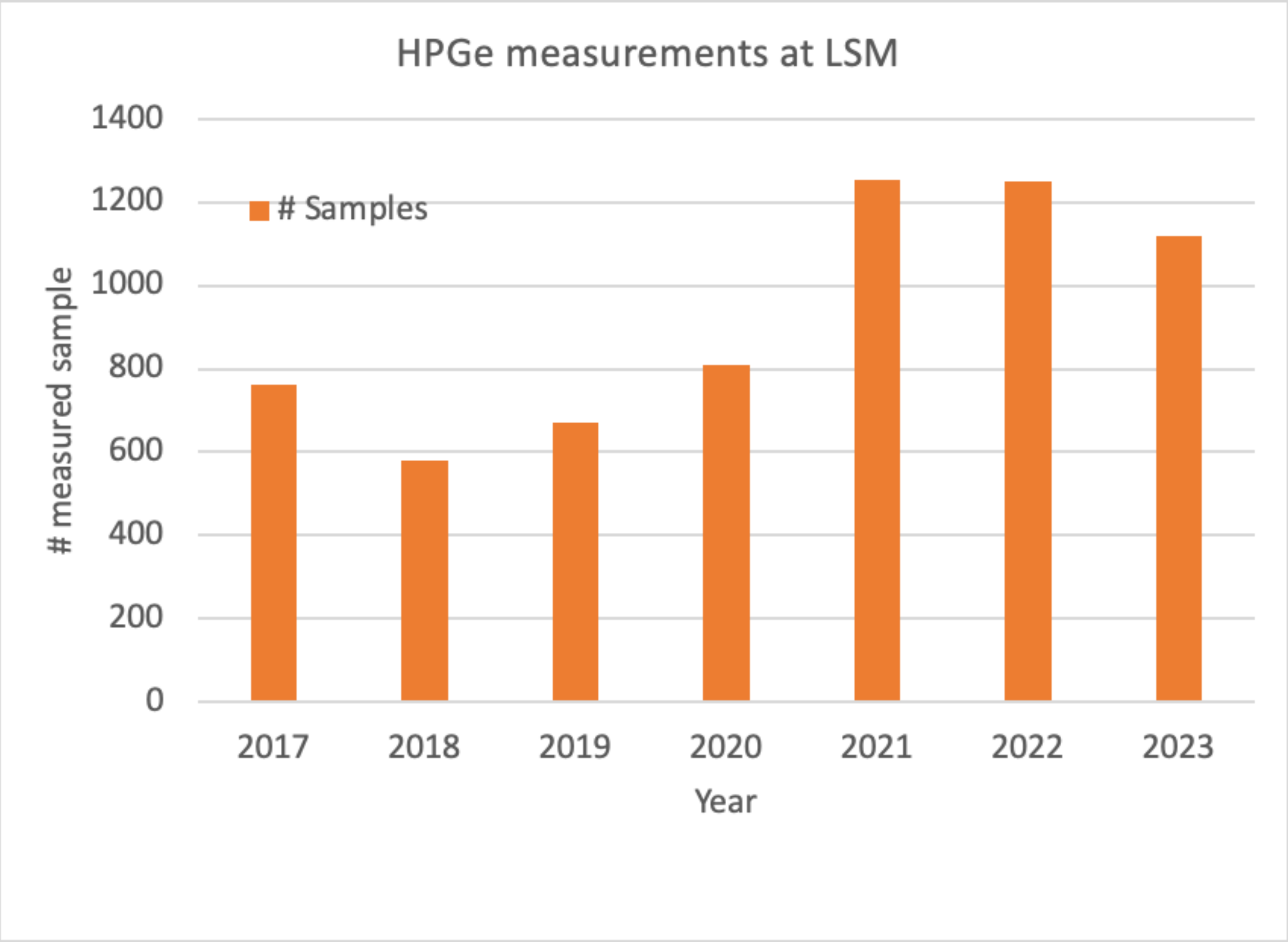
- Covering very lowest-rate background end of their measurements
- France: IRSN, CEA, CENBG, IP2I, LSCE (Université Paris-Saclay, CEA, CNRS), EDYTEM (CNRS, U. Savoie Mont-Blanc)
- International:UTEF Prague and SURO (Czech Republic)

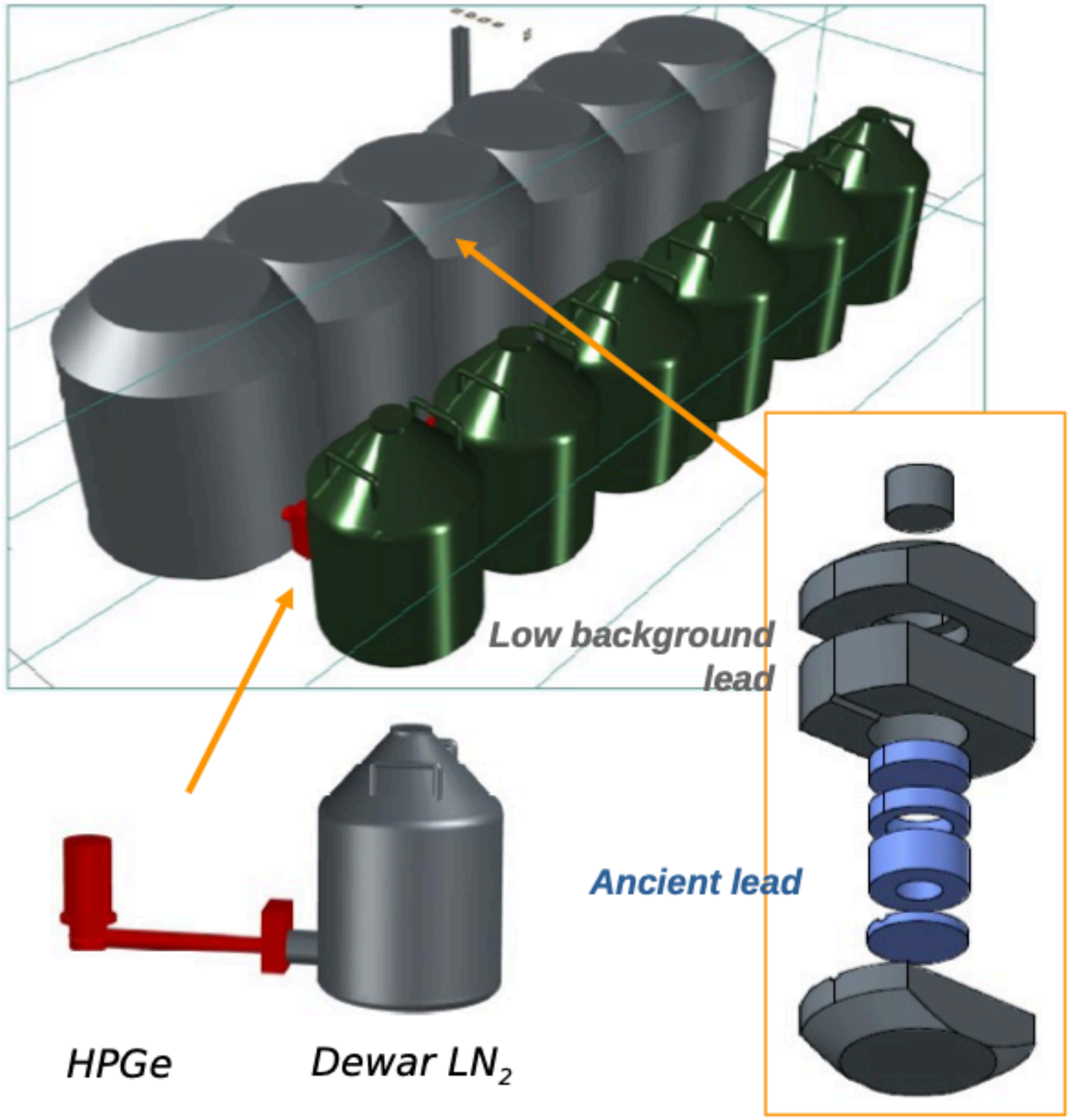


Screening and Material Assay Platform

Footprint optimization for HPGe screening detectors

More efficient use of space
Shielding optimisation
Ease of operation (LN2 refill)





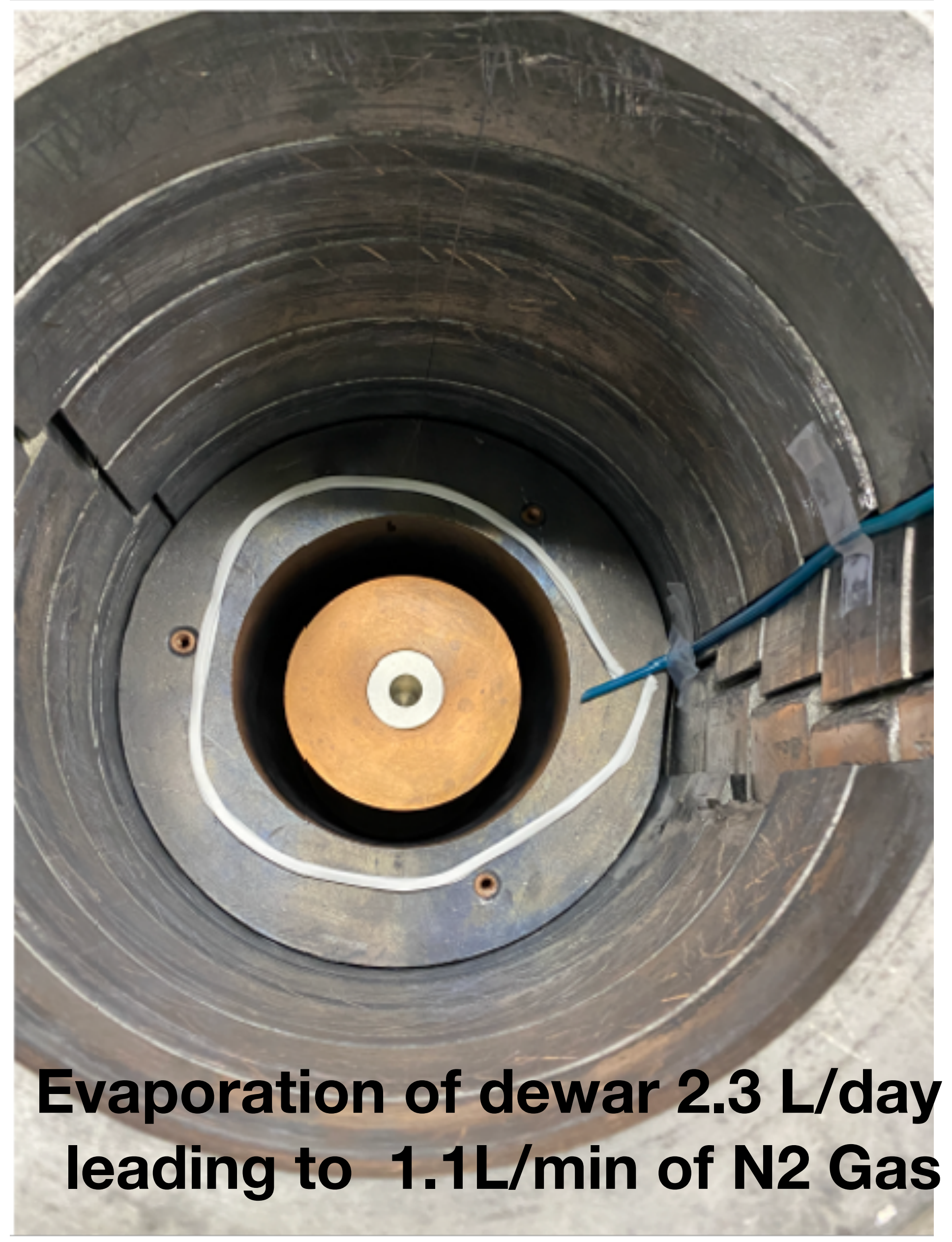
Screening and Material Assay Platform

Footprint optimization for HPGe screening detectors

- 25 detectors in hands at LSM
- 15 installed in PARTAGe
- 5 detectors belonging to LSM
- ~1000 samples/year
-


Robatell outer lead shield


First PARTAGe detector row

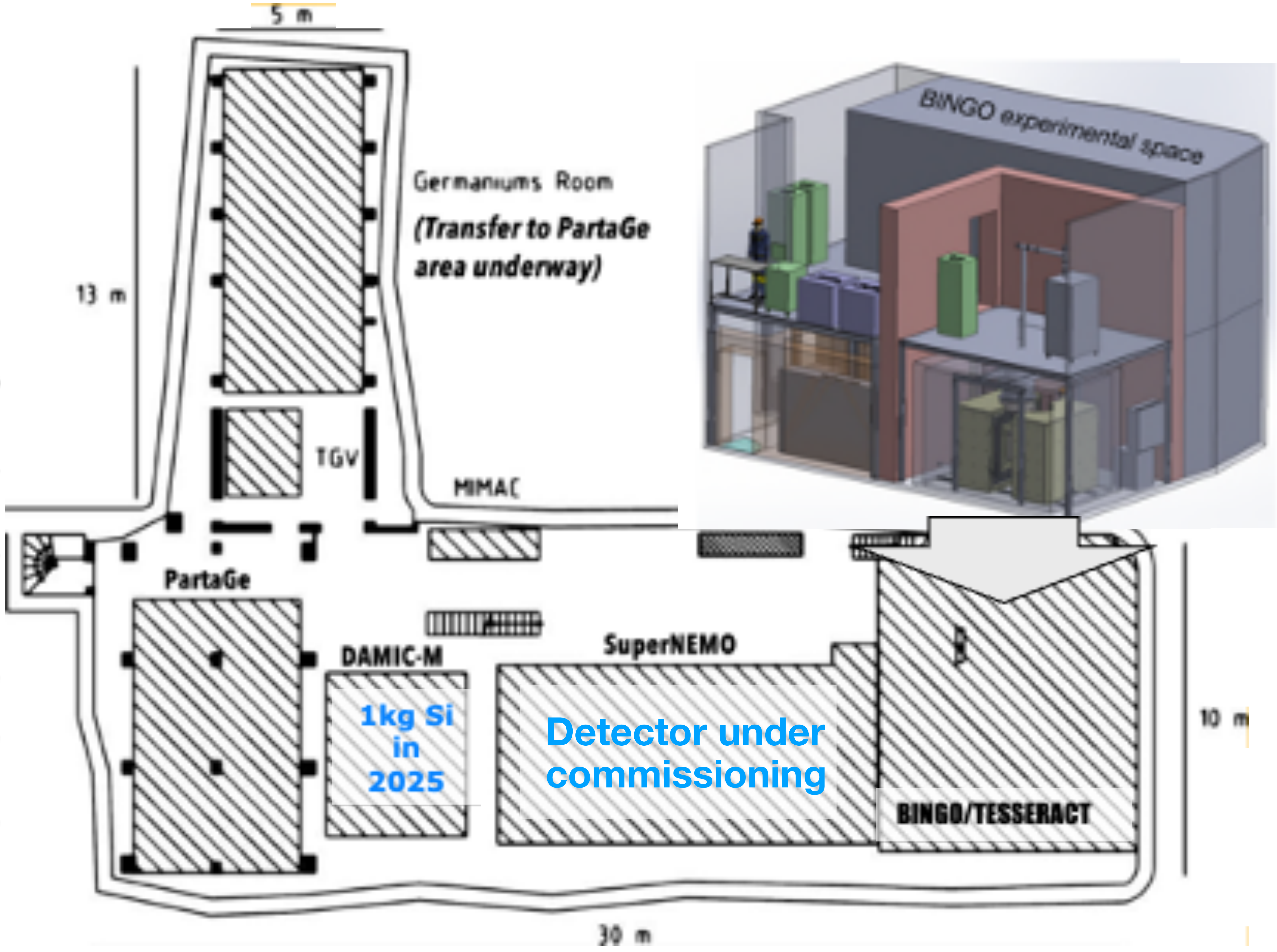

Evaporation of dewar 2.3 L/day leading to 1.1L/min of N2 Gas

LSM Science Program

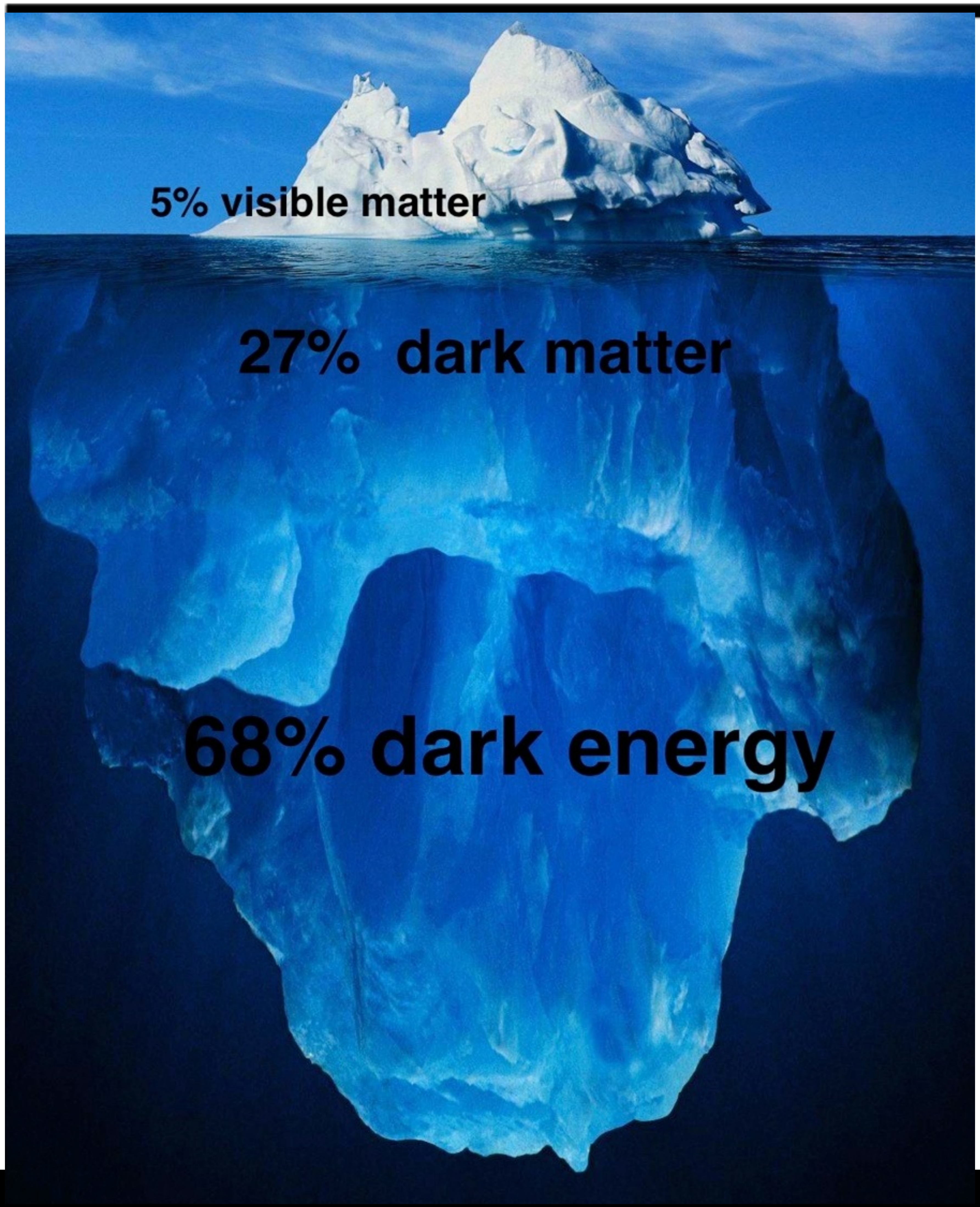
Science programme adapted to LSM size:
- Low-mass Dark Matter Experiments
- 0vBB demonstrators & technologies
- HPGe array for low-radioactivity

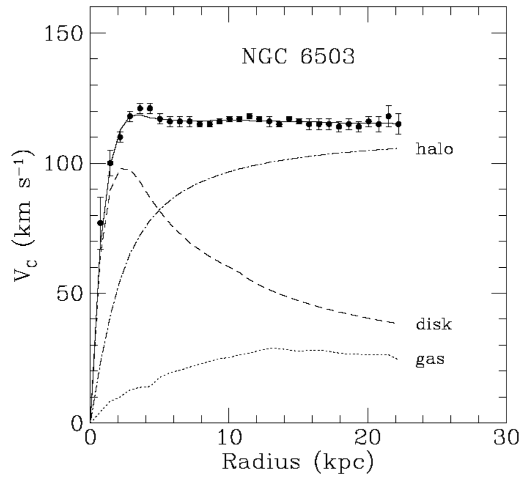
Current experimental activities

Experiment	Focus	Technology	Activities in 2024
SuperNEMO	$0\nu\beta\beta$	Tracking-calorimeter	Commissioning and final shielding installation are ongoing. Physics data taking from summer 2024.
BINGO	$0\nu\beta\beta$	Cryogenic	Cryostat integration underground. Commissioning in summer 2024.
Obelix 82Se	ECEC2ν	Ge ionisation	Counting of 6kg enriched 82Se sample from LNGS started in January 2022: ECEC2ν to excited states. Renewal of agreement *in fieri*.
TGV	$0\nu\beta\beta$	Ge Ionisation	Detector upgrade delayed.
DAMIC-M	DM	Si CCD	Test chamber Physics run in 2022. Installation of kg-stage from September 2024.
MIMAC	DM	TPC	Detector upgrades with commissioning planned in 2025.

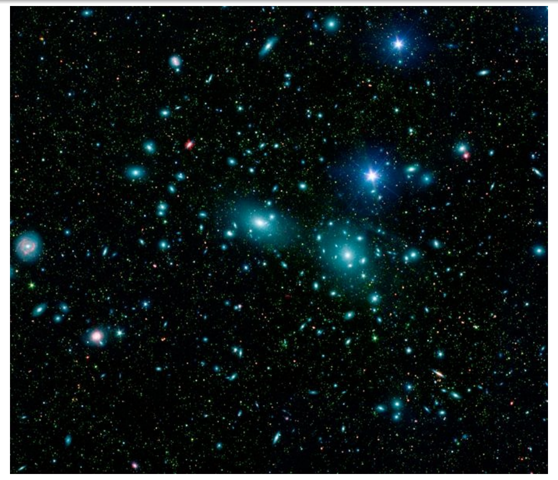


The Dark Matter Challenge



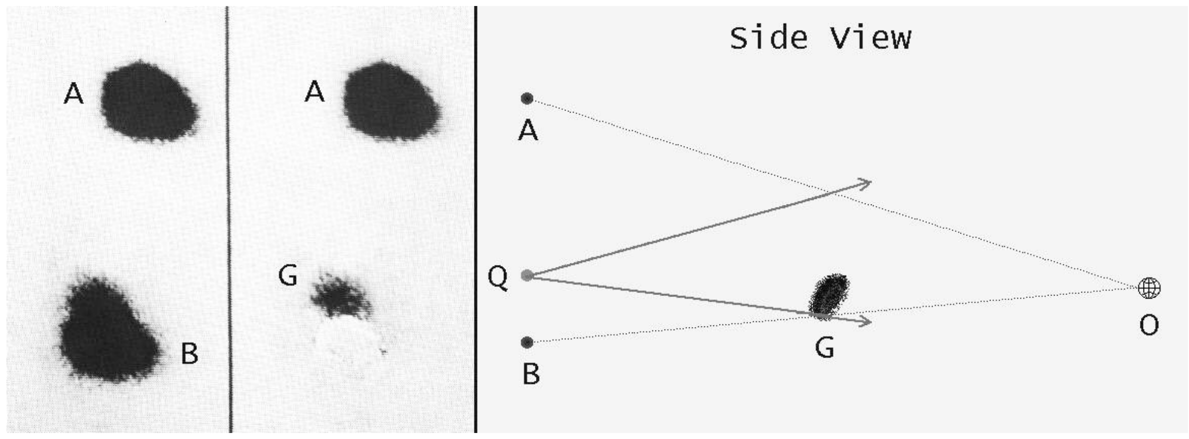


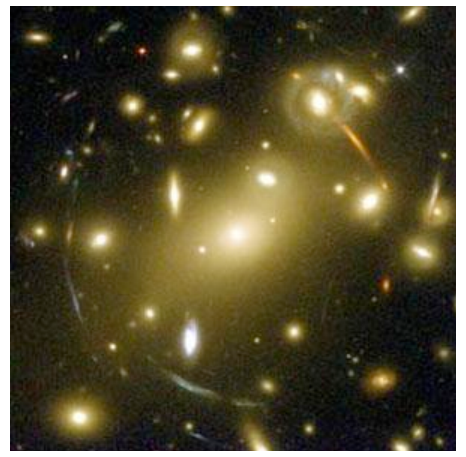
Rotation Curves



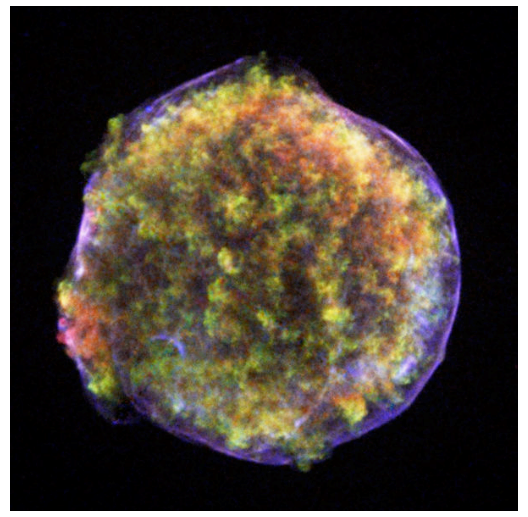
Motion of Galaxies in Clusters

Galaxy clusters

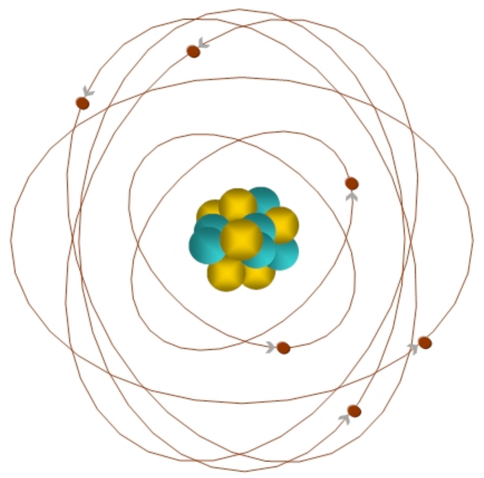




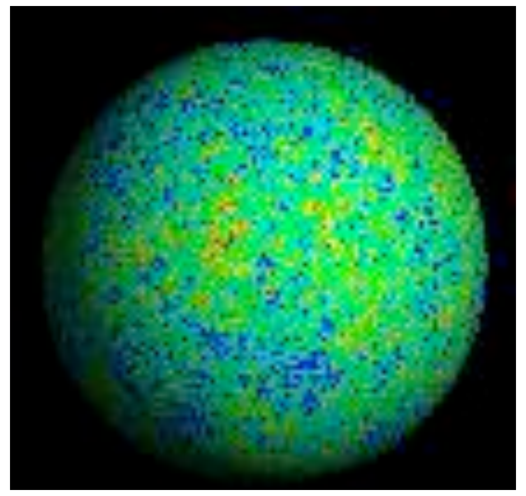
Gravitational Lensing



Supernovae Ia



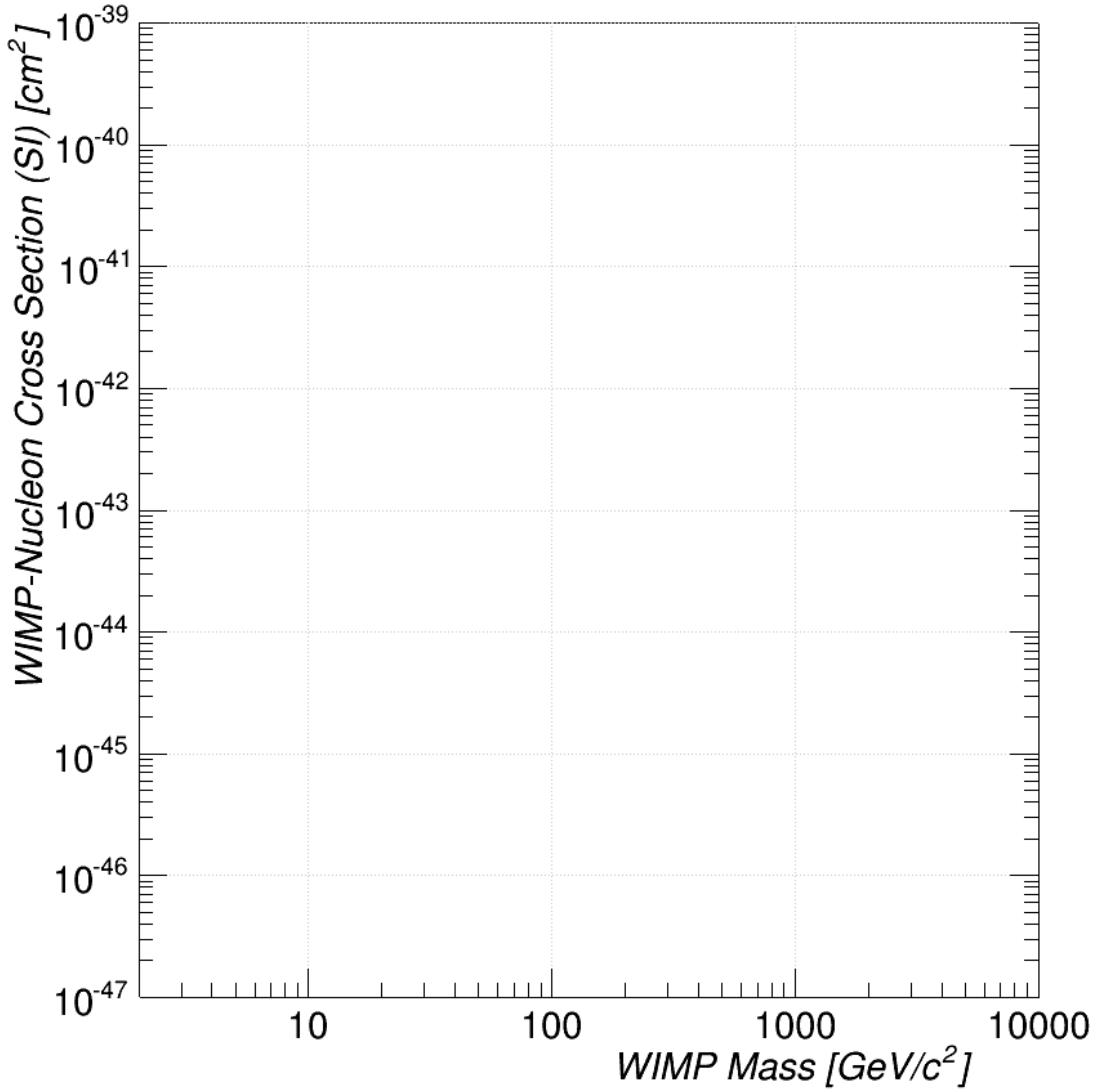
Big Bang nucleosynthesis



Microwave Background

The Direct Dark Matter (DDM) Search Domain

- We don't know (yet) what is the mass of the WIMPs
- We don't know (yet) what is the cross-section for WIMP-nucleus scattering
- Generic searches for ALL WIMPs masses MW and ALL cross-section σ.
- A given experiment will be able to probe a certain region of (MW, σ)



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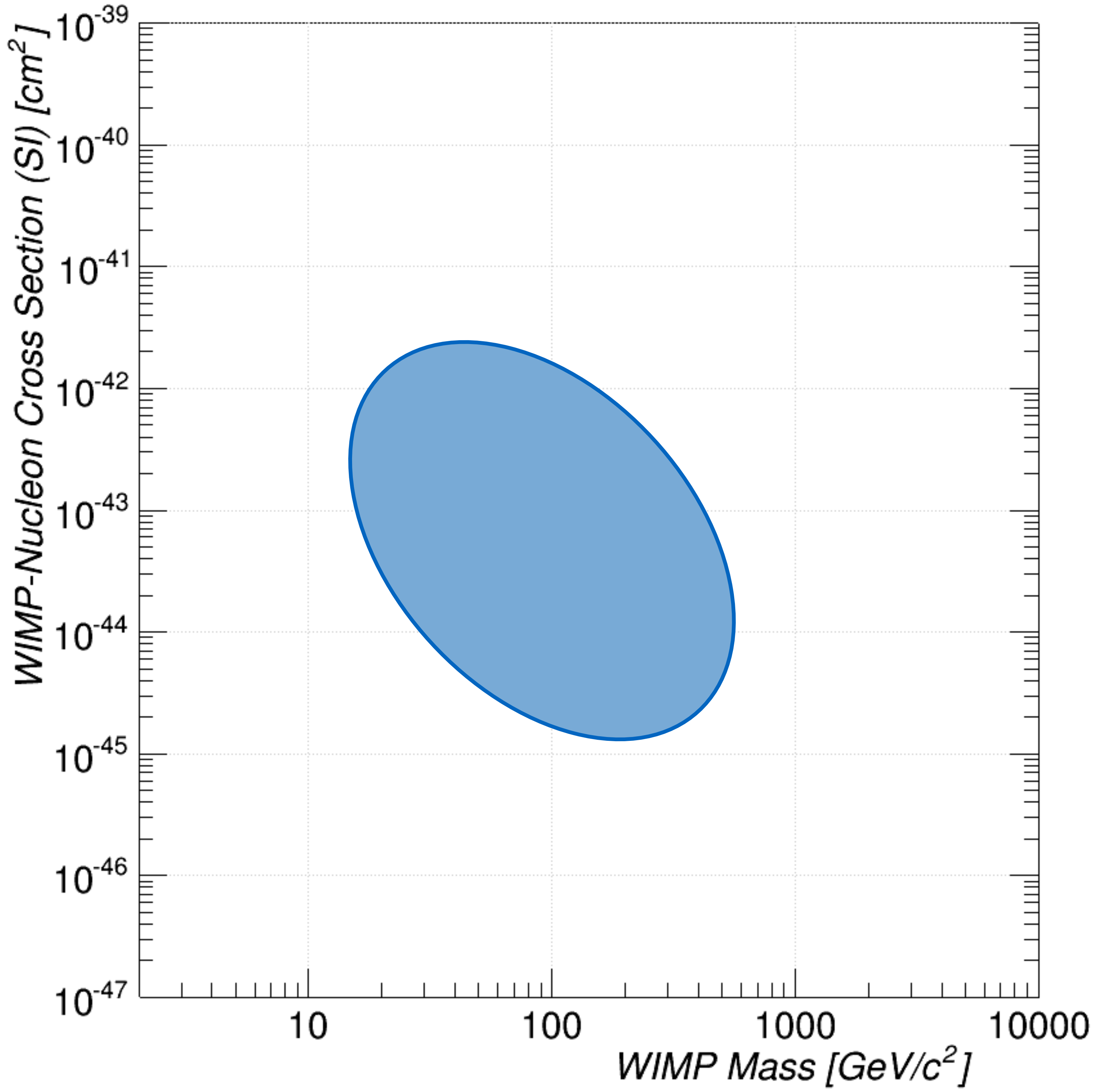

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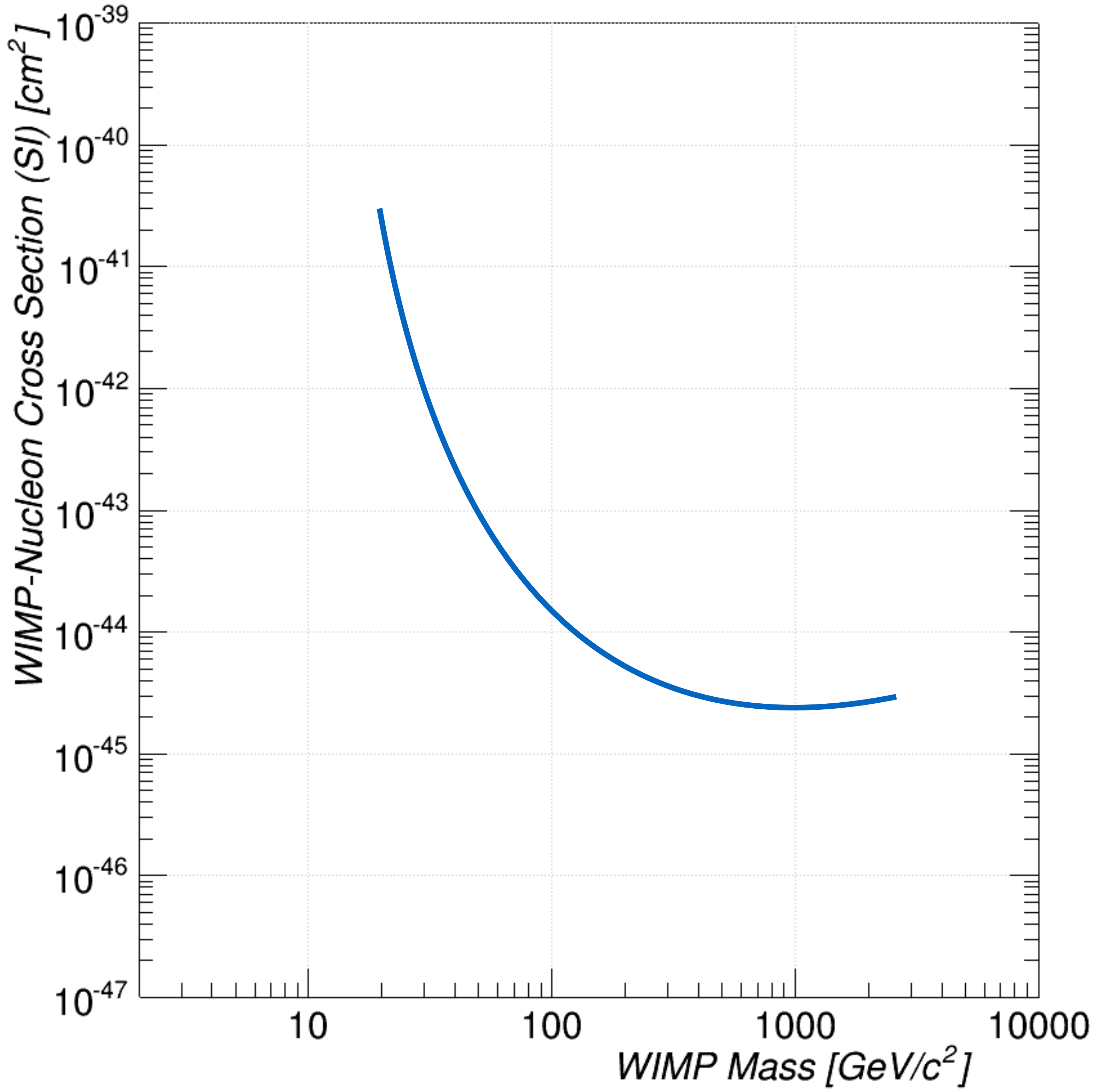
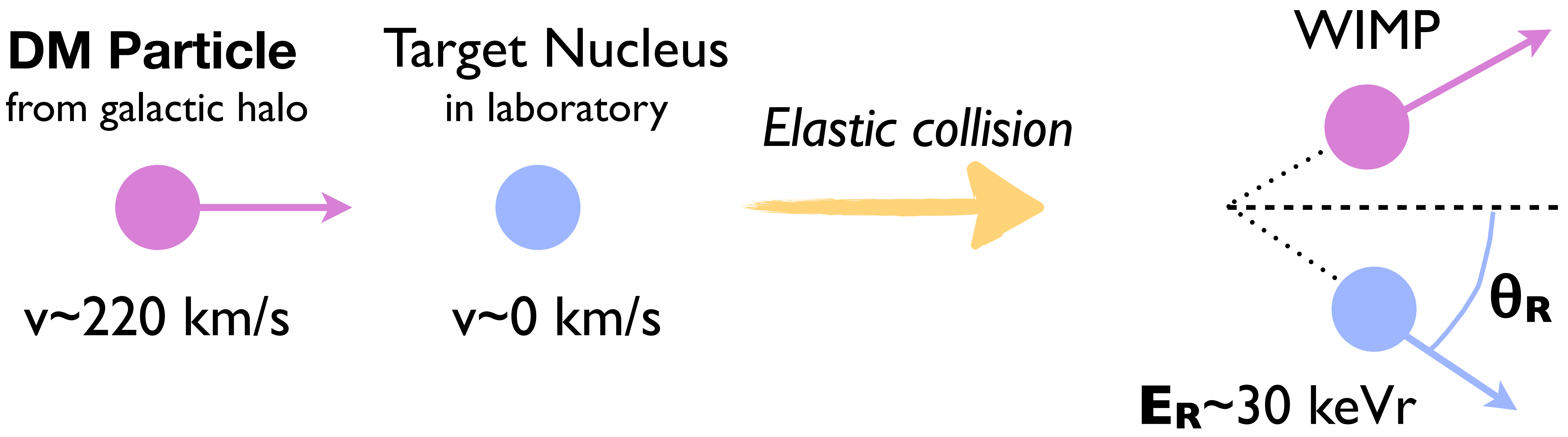


The Direct Search Principle

Detection of the energy deposited due to elastic scattering off target nuclei



Basic Questions

Direct Dark Matter searches are simple: just look at a large number of nuclei and see if any of them recoils due to a hit-and-run collision with a DM particle, but

- How many such events can we expect per unit time and per number of target nuclei?
- How big is the kinetic energy involved in such collisions?
- What is the fake rate and how can we reject it?

The Interaction Rate

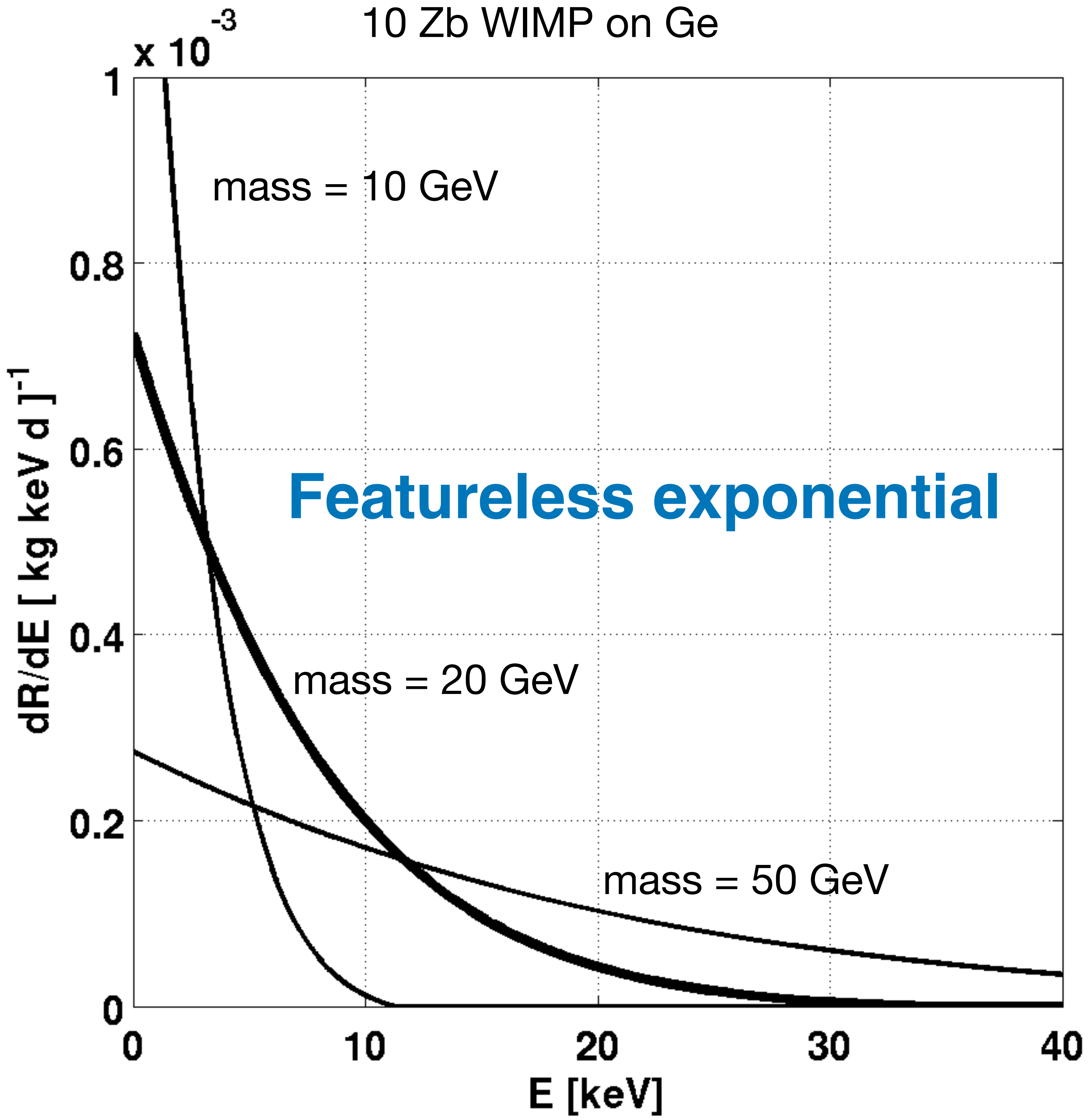
Goodman & Witten (PRD 1985)

$$\frac{dR}{dE_r} = \frac{1}{2m_r^2}\frac{\sigma_0}{m_\chi} F^2(E_r)\, \rho_0 \int \frac{f(\vec{v})}{v} d^3v$$

$F(E_R) \simeq \exp\left(-E_R\, m_N\, R_o^2/3\right)$	"form factor" (quantum mechanics of interaction with nucleus)
$m_r = \dfrac{m_\chi m_N}{m_\chi + m_N}$	"reduced mass"
$T(E_R) = \dfrac{\sqrt{\pi}}{2} v_o \displaystyle\int_{v_{\min}}^{\infty} \frac{f_1(v)}{v} dv$	integral over local WIMP velocity distribution
$v_{\min} = \sqrt{E_R\, m_N/(2m_r^2)}$	minimum WIMP velocity for given E_R

Astrophysics
Nuclear physics
Particle physics

The Interaction Rate



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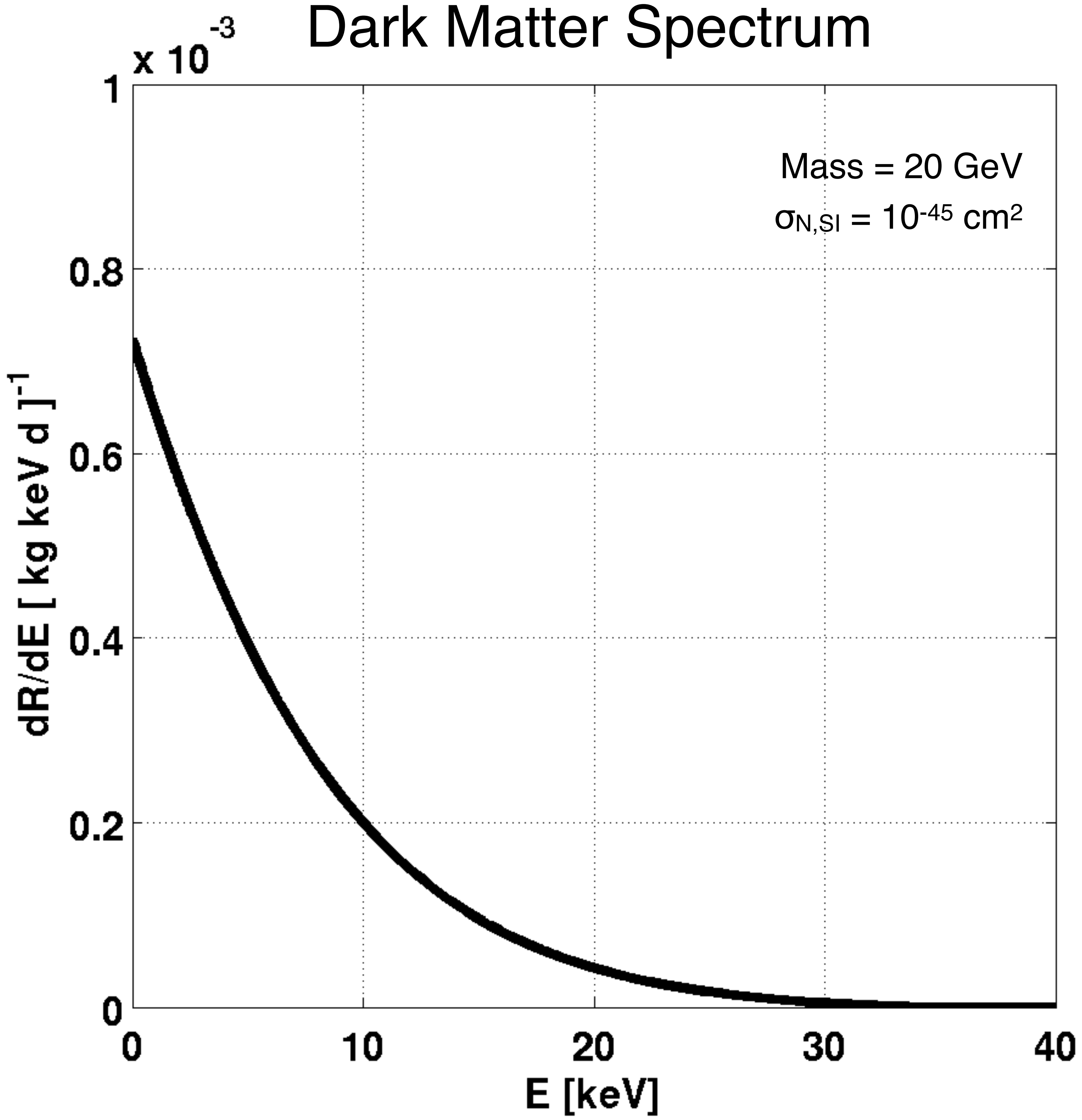
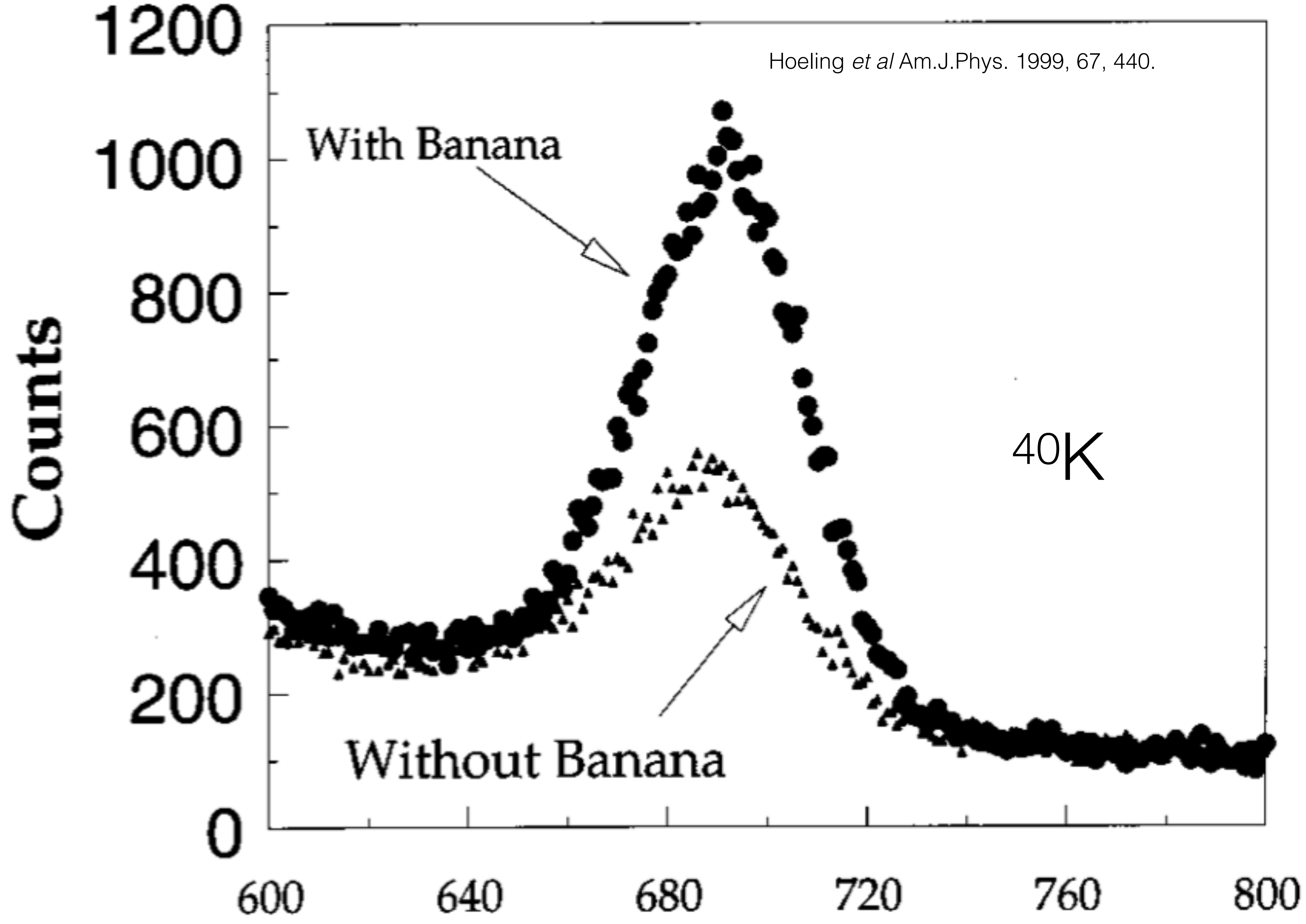
The Interaction Rate

Expected
Dark Matter Spectrum



Measured
Banana Spectrum



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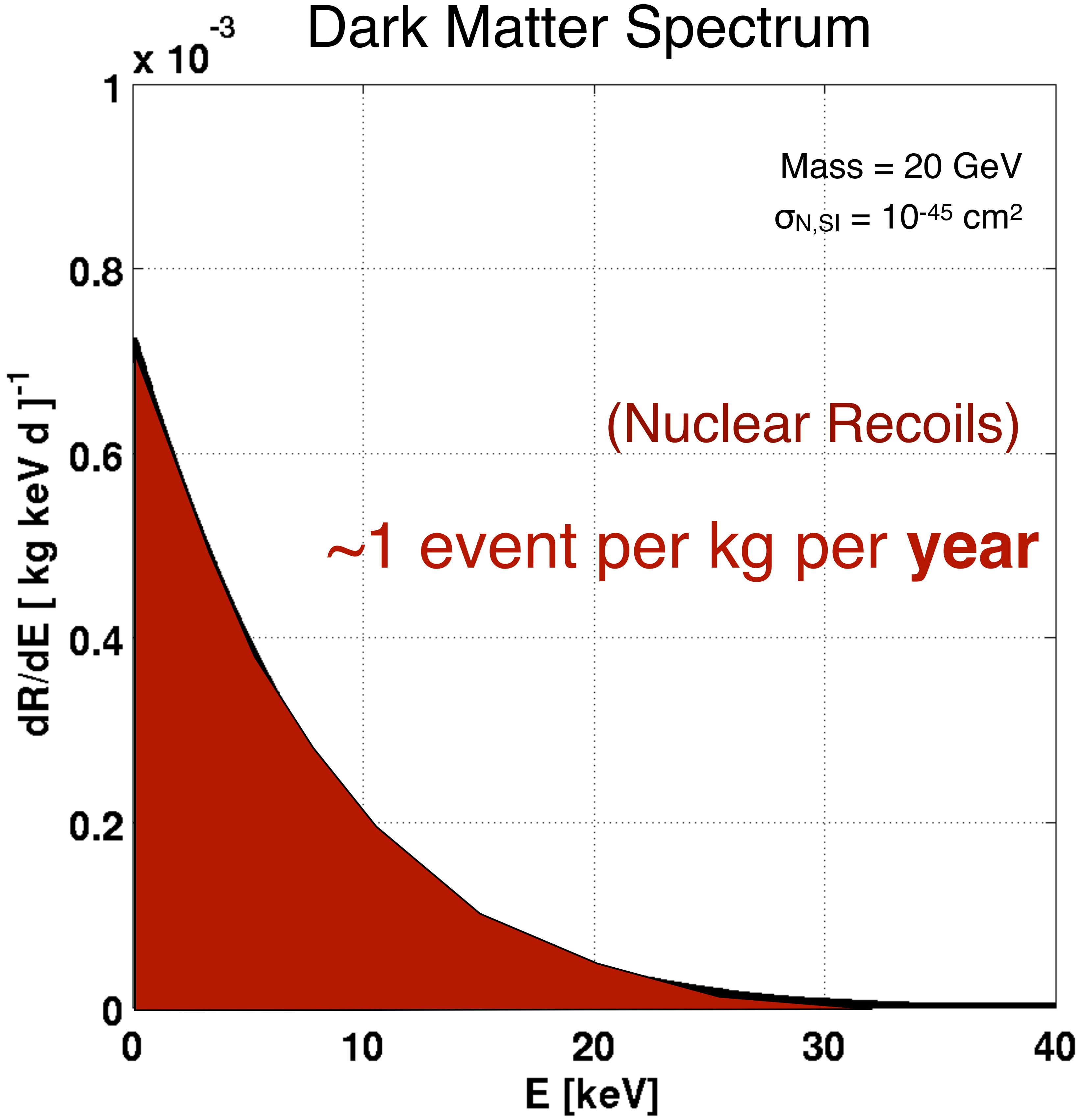

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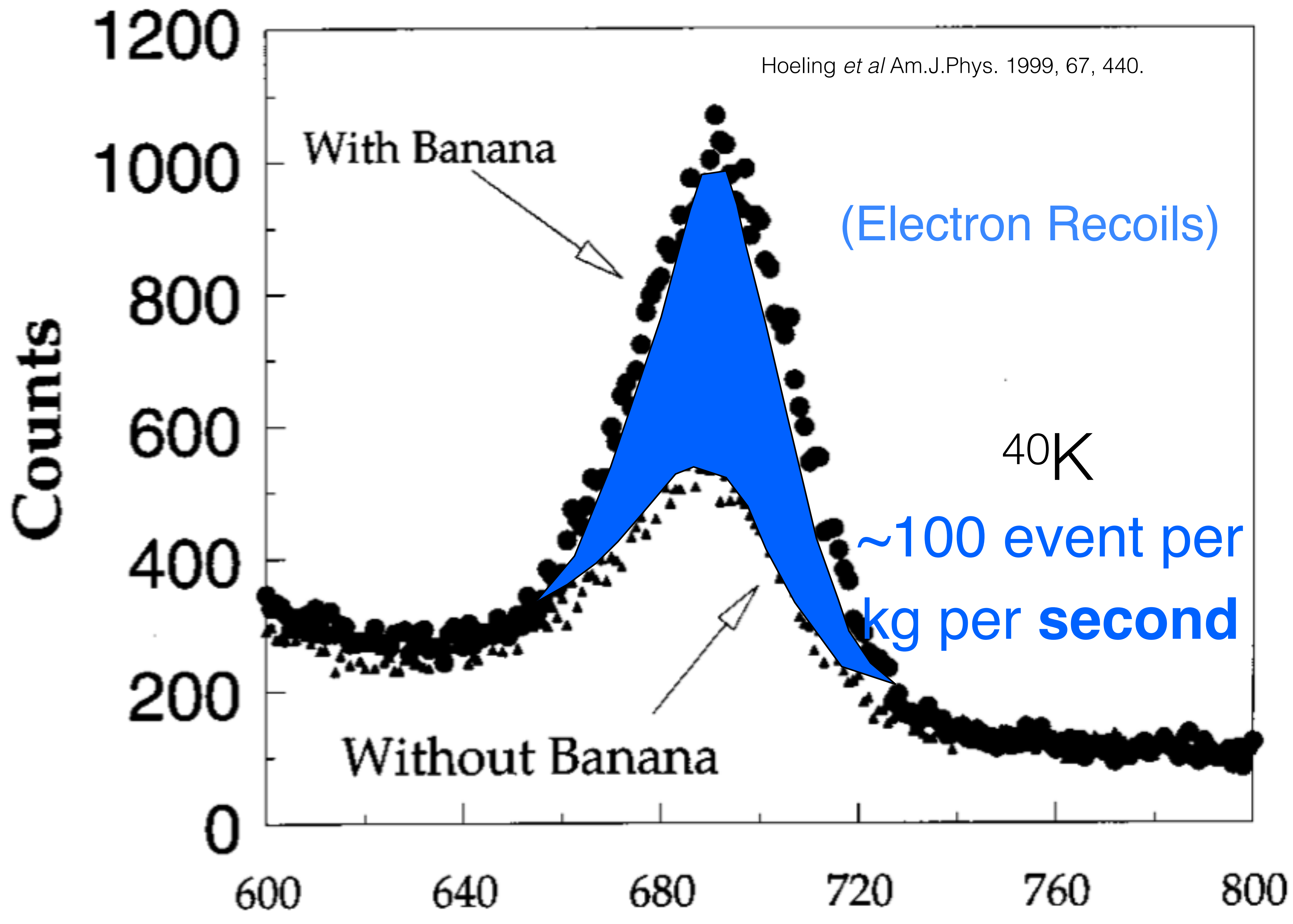


DDM Experiment Wishlist

- **Low** and **controlled** backgrounds
- **Discrimination** between signal and background

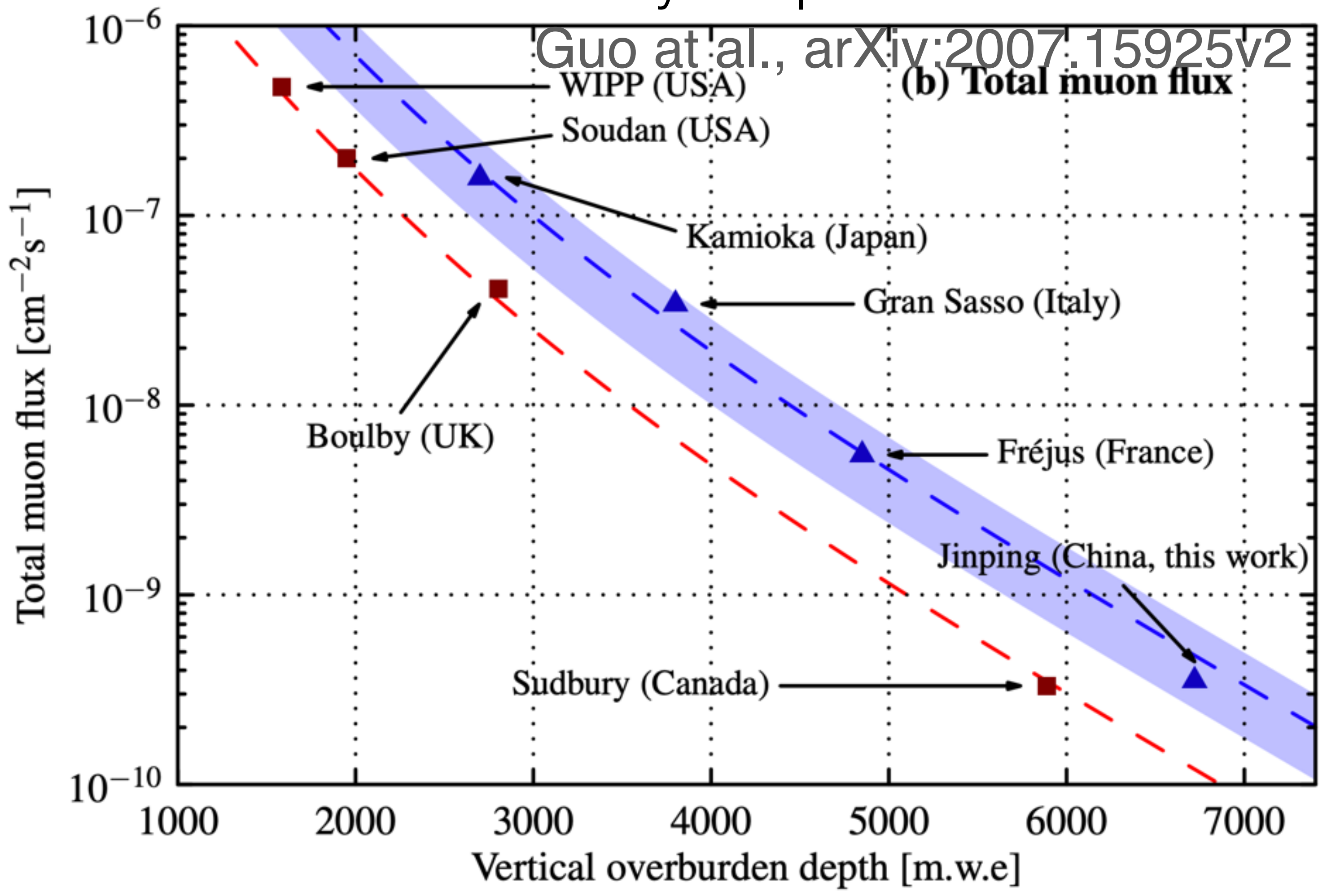
  Simultaneous measurements of two signals allows ER/NR discrimination on an event-by-event basis

  Detector technology background rejection and fiducialization
- **Large exposure** (*few events per ton-year*)

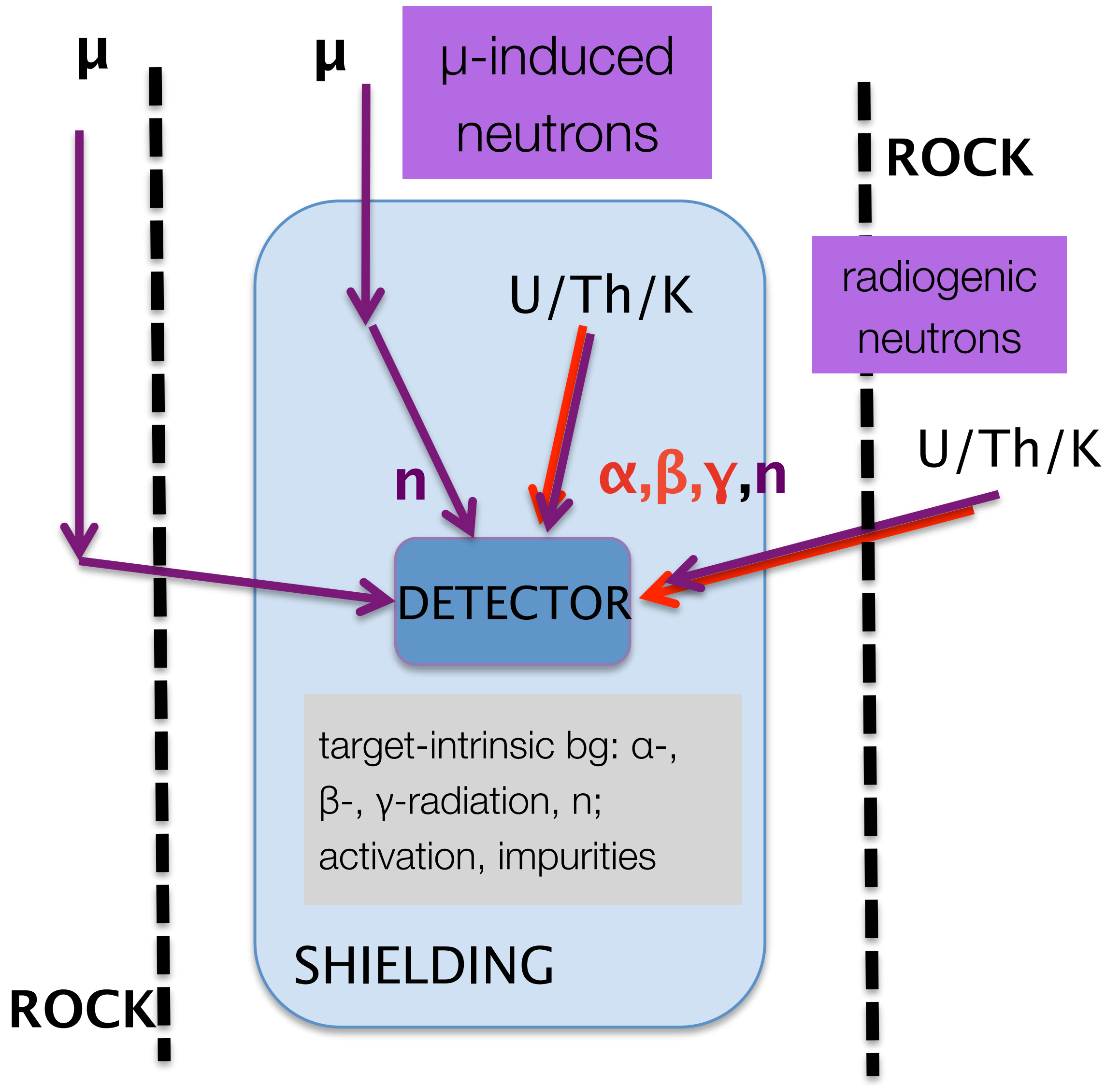
Background limit:
neutrino-nucleus scattering (solar, atmospheric and supernovae neutrinos)

Go deep **underground**

Fewer cosmic rays to produce neutrons.



Material screening and assay
Cleaning and purification techniques
Move underground detector fab and material purification



Passive/Active shielding
Reduce backgrounds from natural (^{238}U, ^{232}Th, ^{40}K) radioactivity

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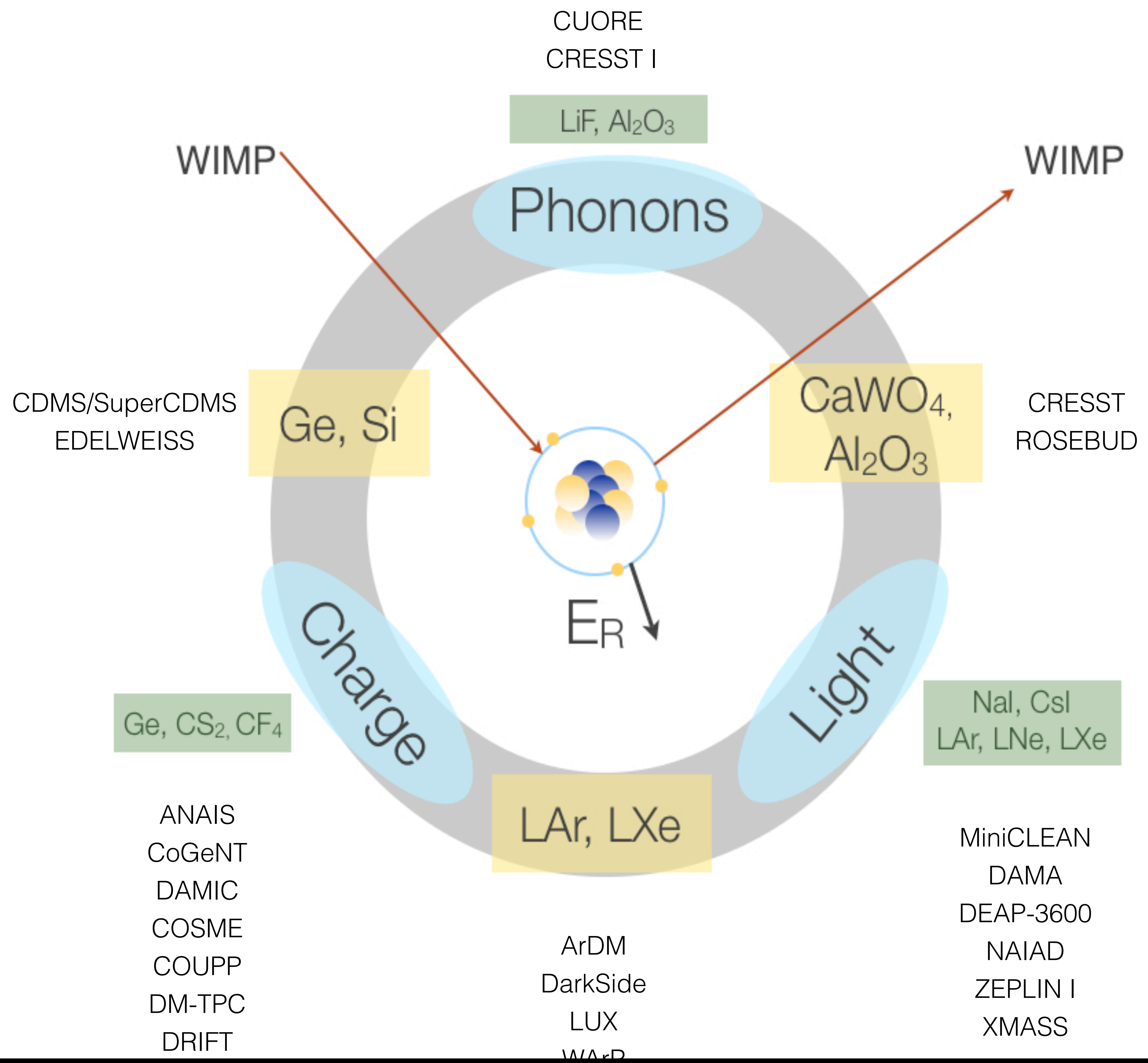

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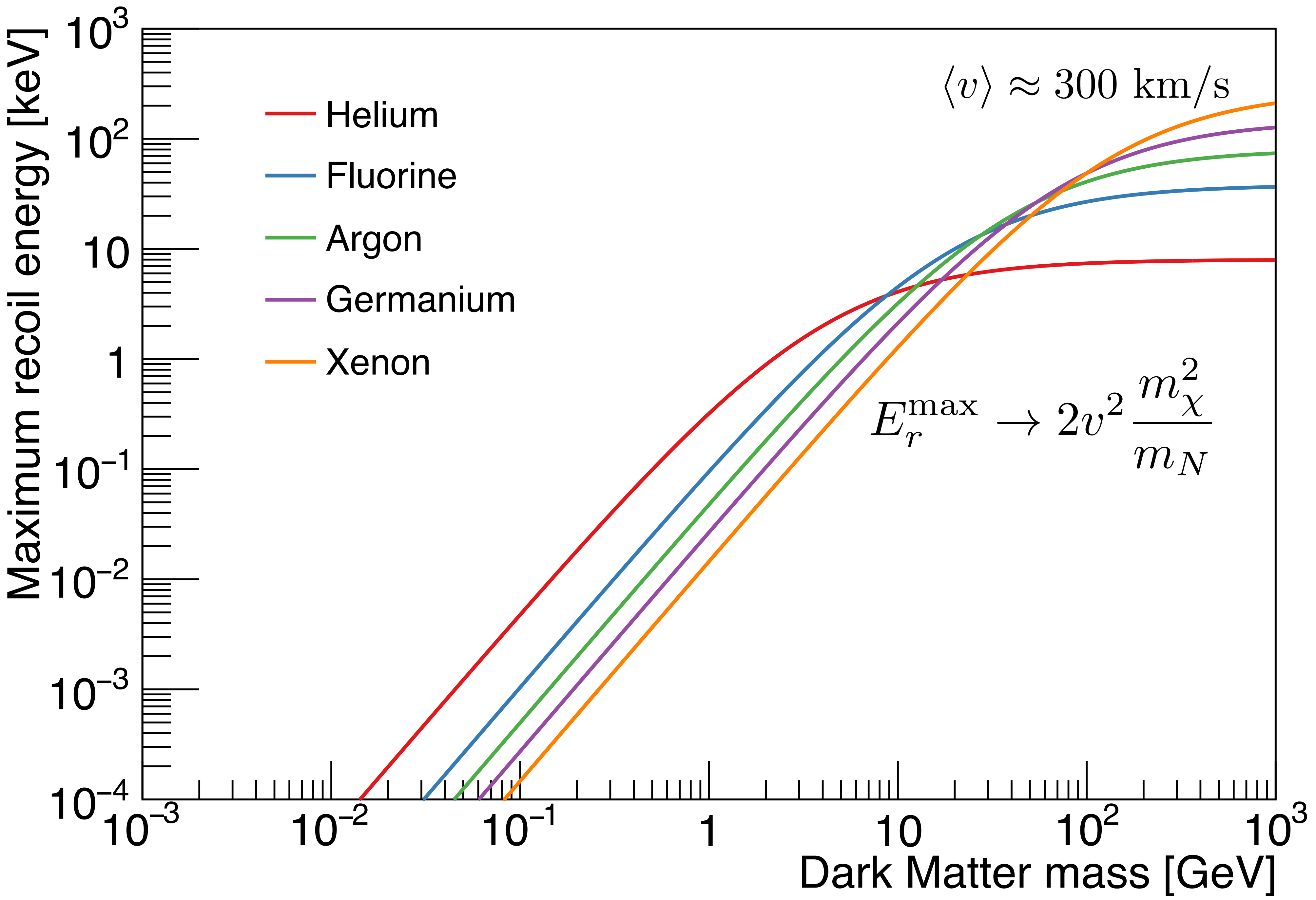
Transfer of DM kinetic energy inefficient when M_n >> M_{DM} for elastic scatters



Direct detection of Sub-100 MeV dark matter via nuclear recoil is nearly impossible!

DDM Experiment Wishlist

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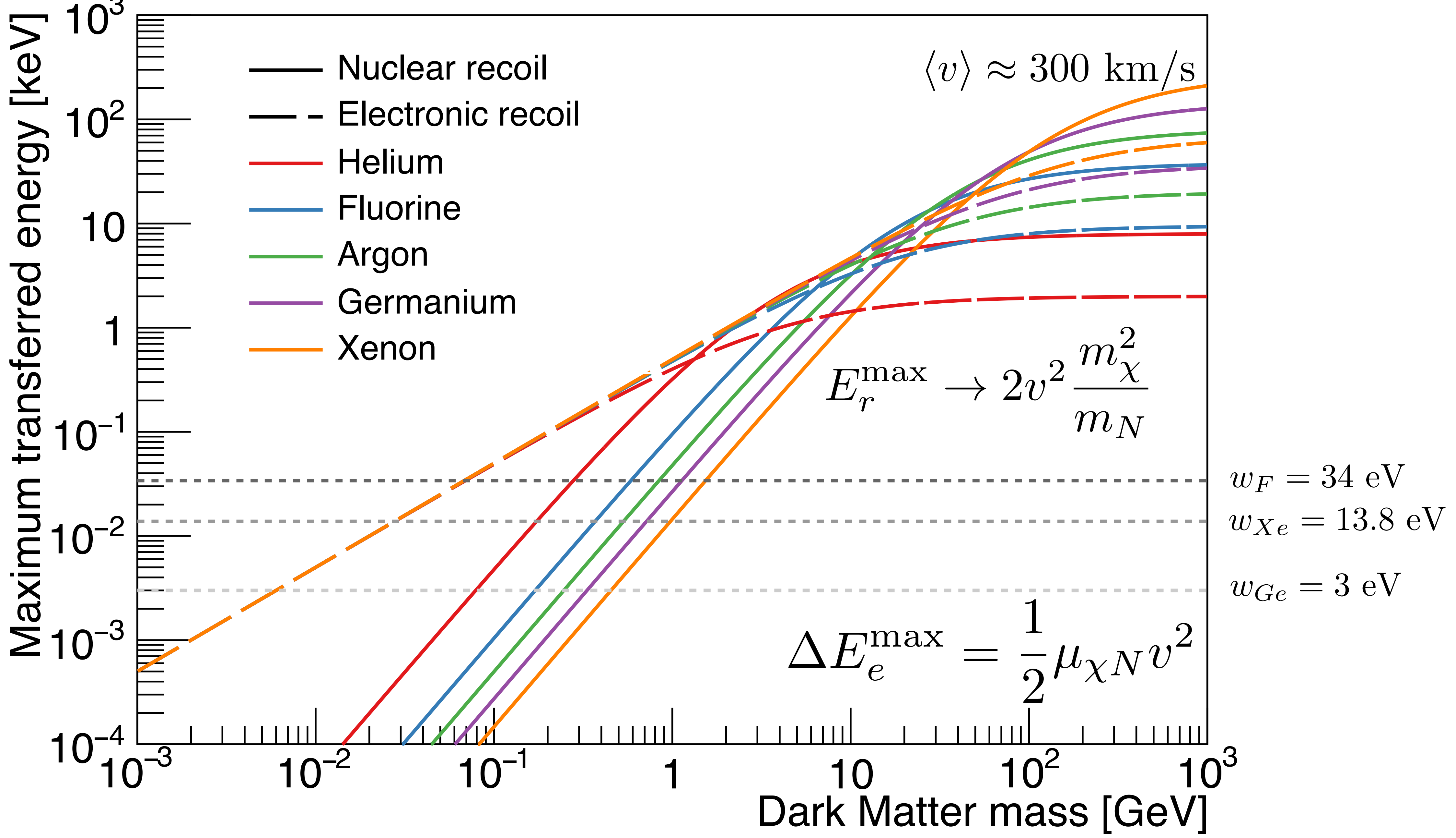
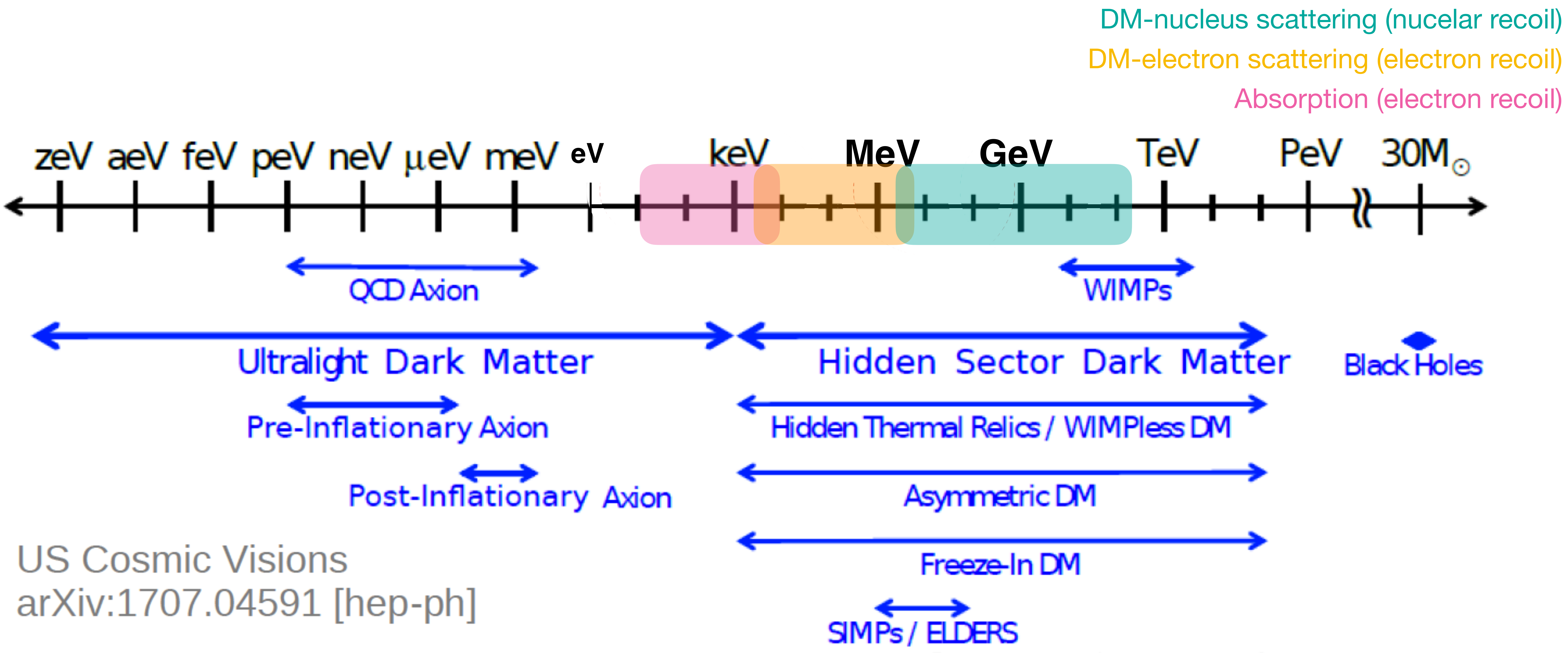
Dark Matter - electron scattering



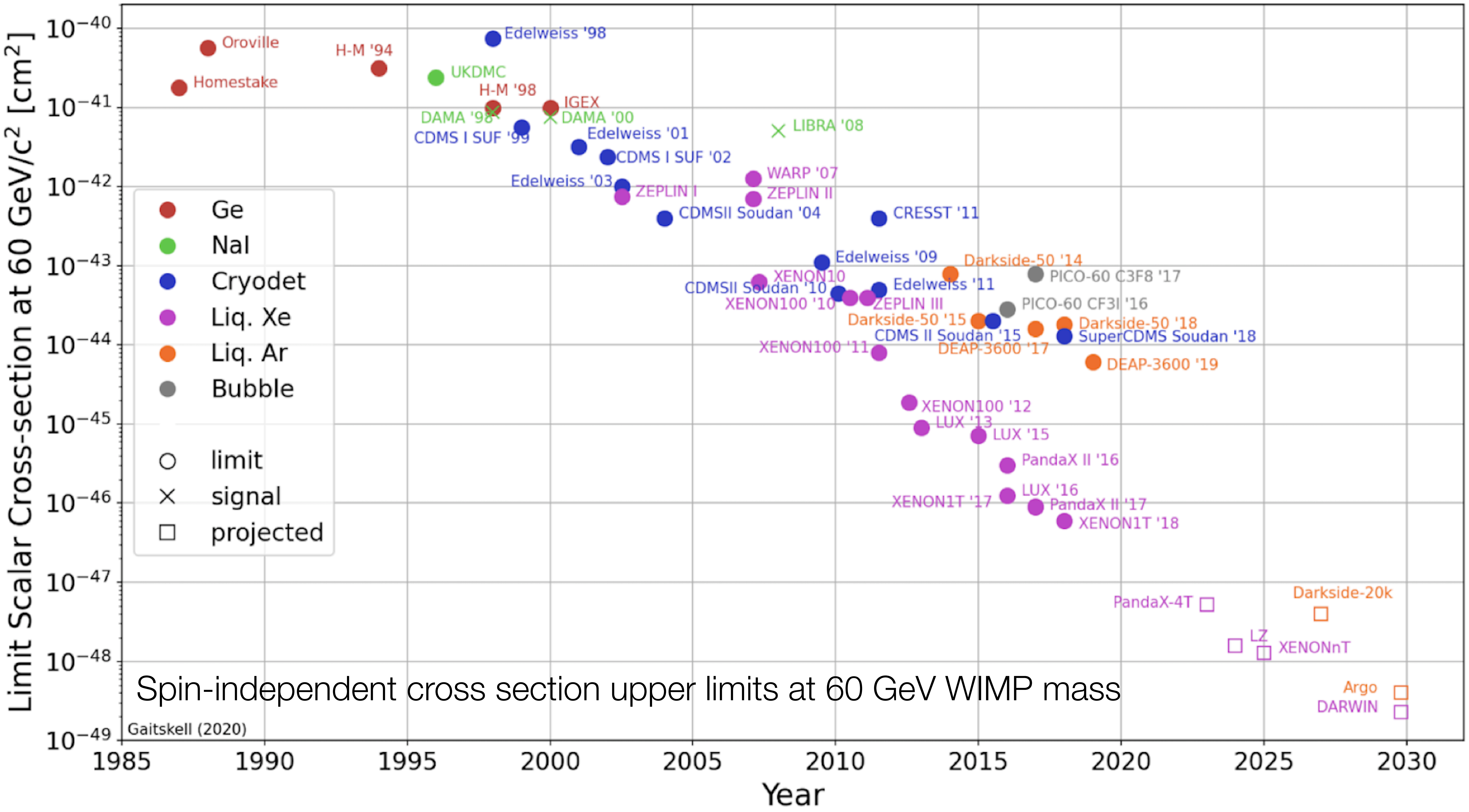
For DM masses below 100 MeV switch to DM-electron scattering searches

DDM Experiment Wishlist

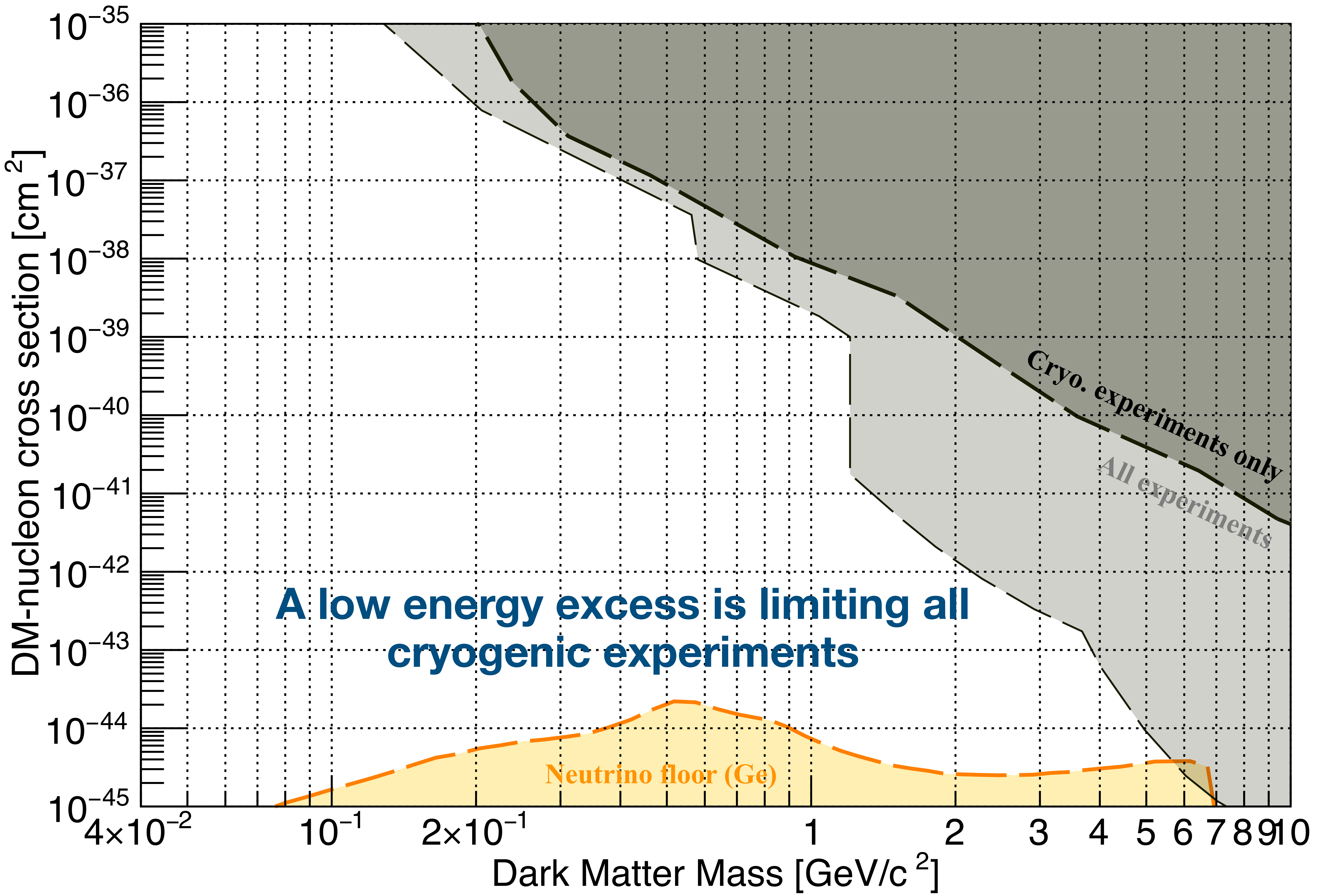


US Cosmic Visions
arXiv:1707.04591 [hep-ph]

DDM Sensitivities



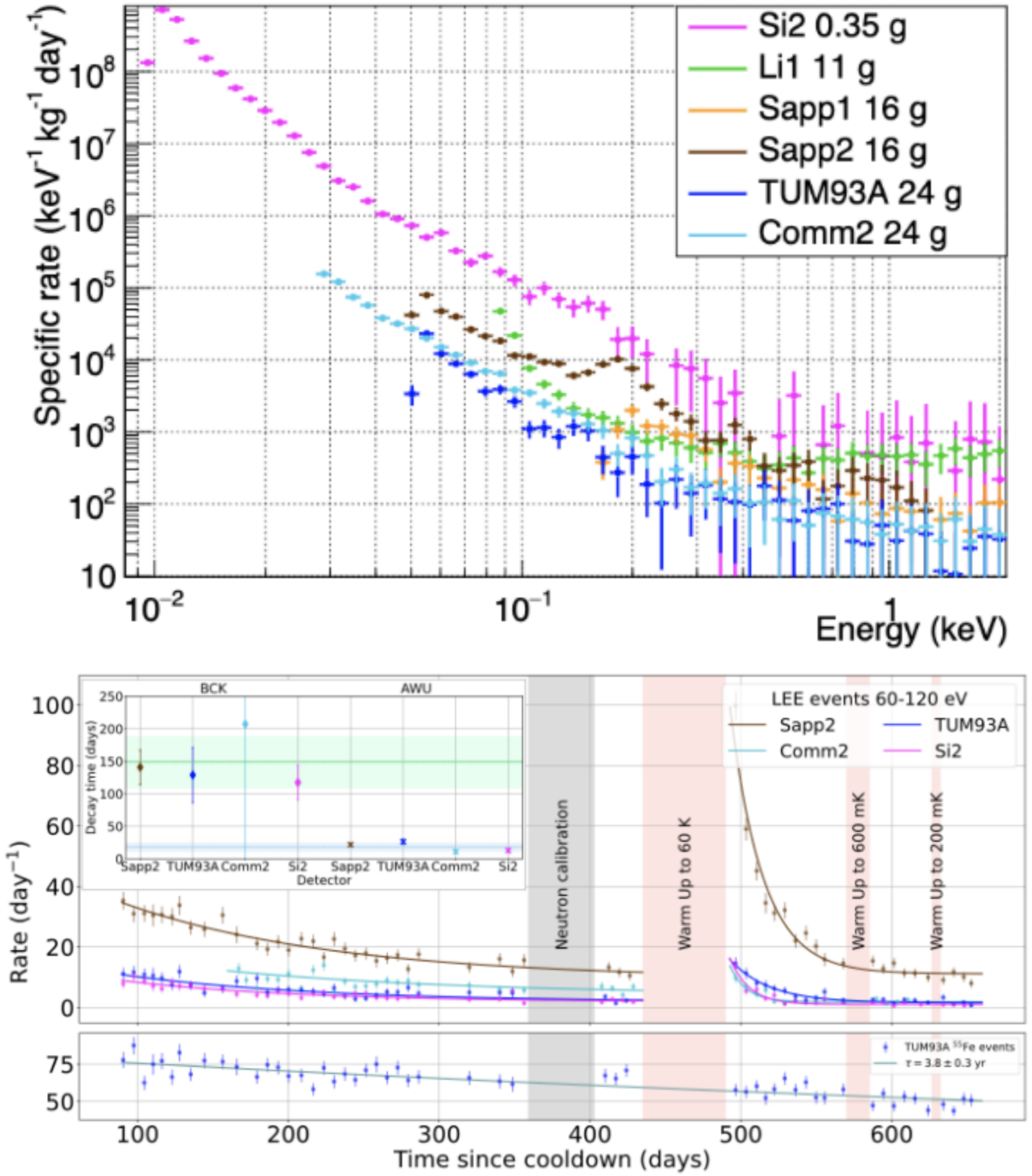
Cryogenic DDM



Why cryogenic DDM experiments aren't leading the sub-GeV search region ?

Cryogenic DDM: Low Energy Excess

- Currently, all cryogenic experiment which have reached sub eV threshold are seeing such an excess limiting their DM search
- LEE characteristics : time dependant, non ionising (“Heat Only”), mostly independent of sites, dependance with holder/vibrations (?)
- Design driver of TESSERACT :
  - Mitigate LEE
  - Develop new technologies to reject it



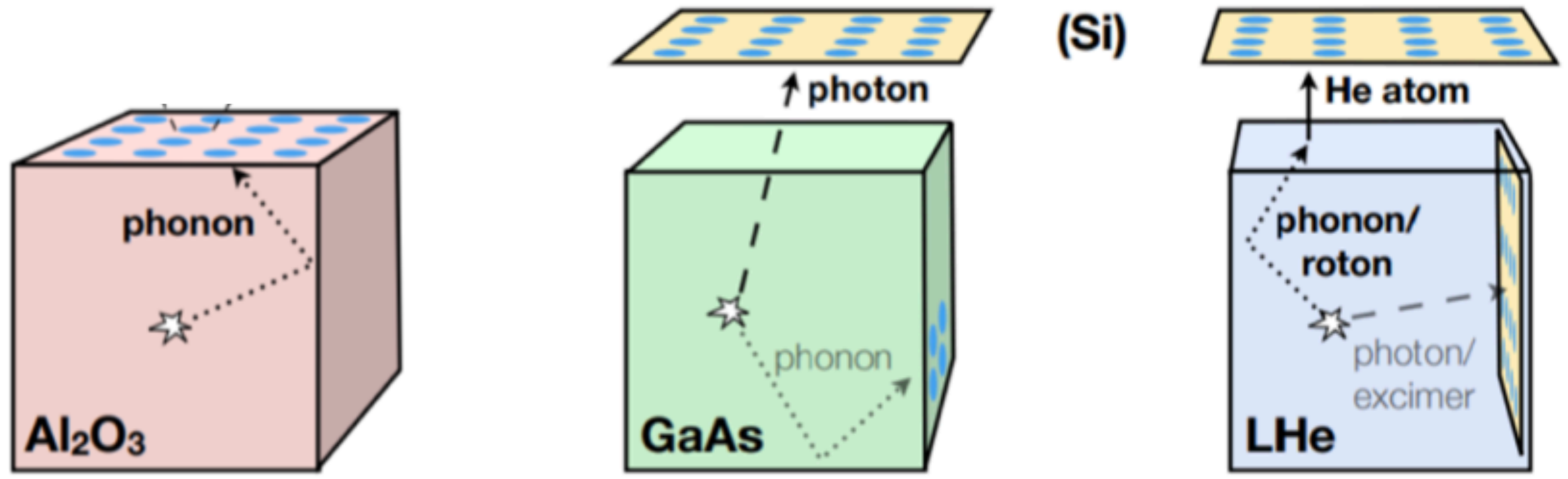
CRESST Collaboration, SciPost Pays.proc 12 (2023) 013

TESSERACT

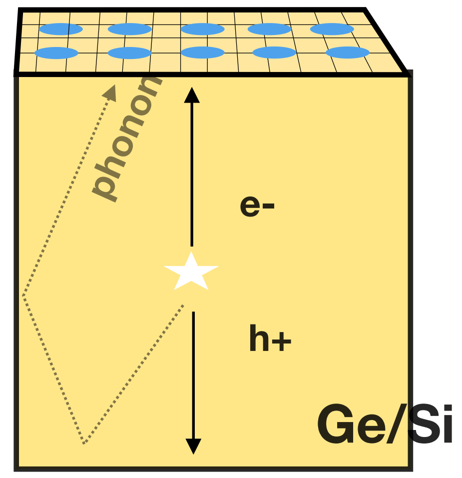
[Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets]

aims at extending the Dark Matter mass search window from meV-to-GeV with ultra low-threshold cryogenic detectors with multiple targets and particle identification capabilities

TESSERACT@LSM



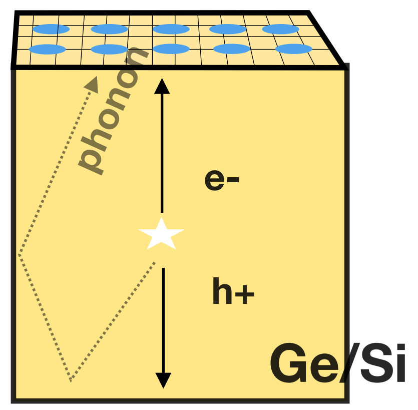
- DOE Funding for R&D and project development began in June 2020 (Dark Matter New Initiative)
- One experimental design, and different target materials with complementary DM sensitivity, all using TES (Al_2O_3 and **GaAs, LHe**)

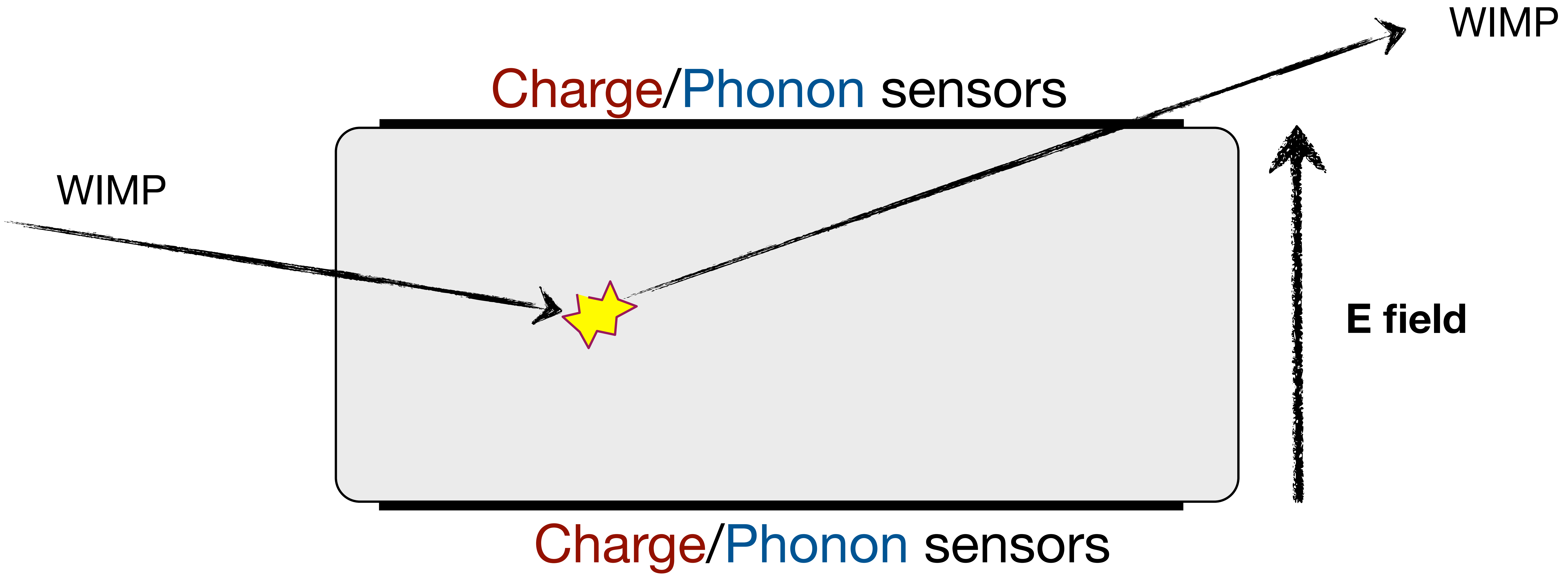


TESSERACT @LSM proposal:

1. Include the French semiconductor Ge bolometer technology to the TESSERACT science program
2. Deploy the future TESSERACT experiment at LSM via the TES4DM Project

Introduction to the dual heat and ionization readout:





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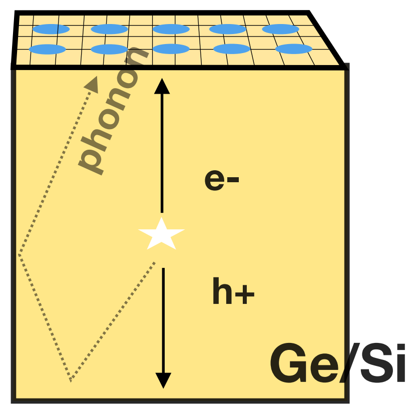
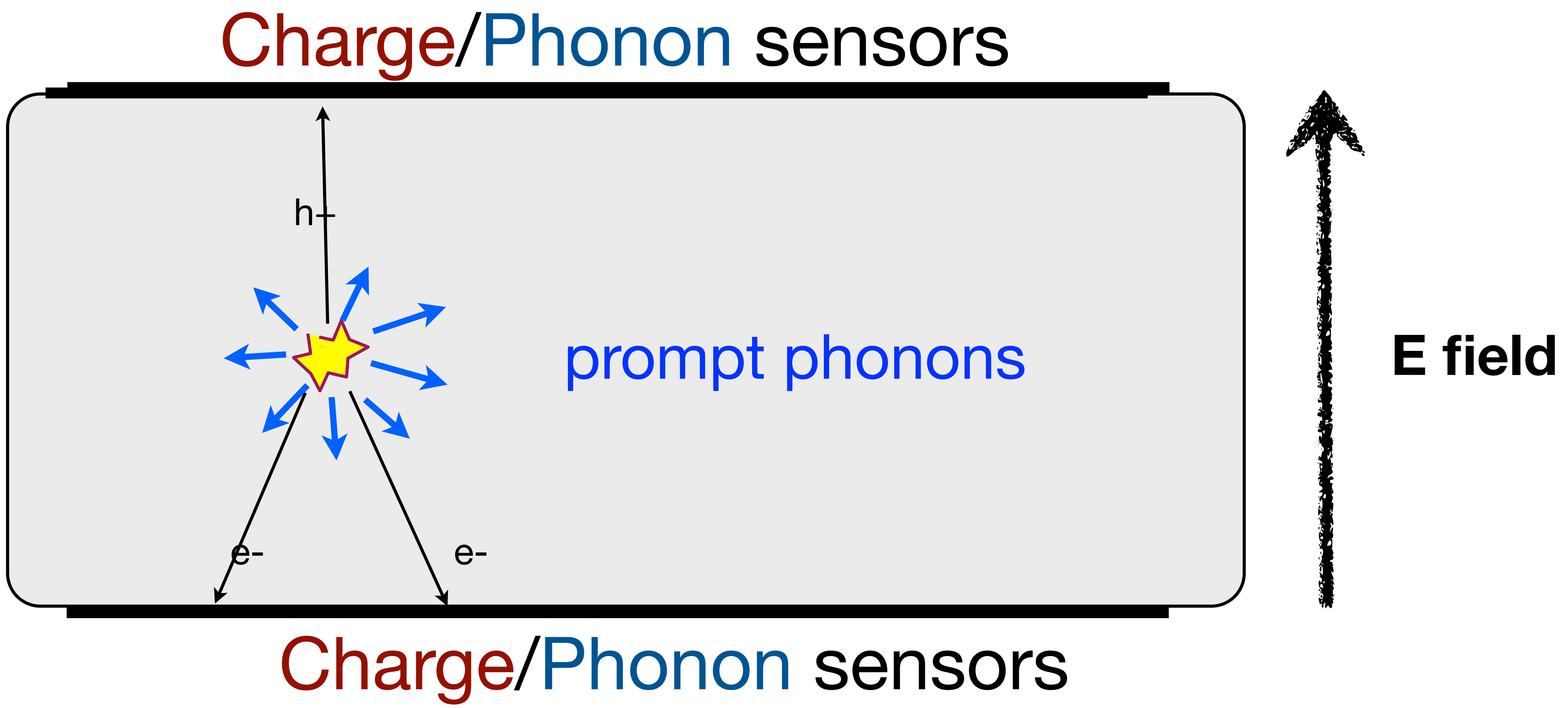
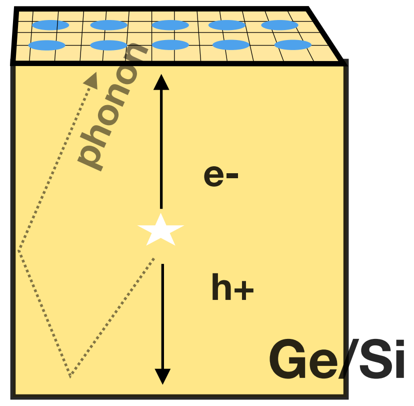






Introduction to the dual heat and ionization readout:

Charge/Phonon sensors

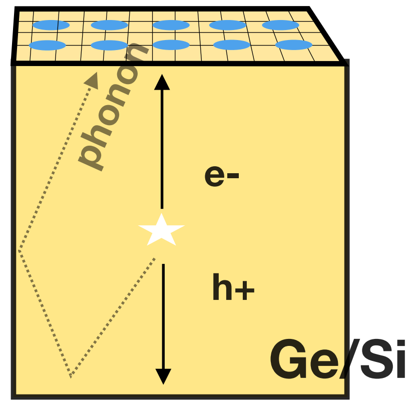
Charge/Phonon sensors

$$E_{total} = E_{recoil} + E_{luke}$$

$$= E_{recoil} + \frac{1}{3\ eV} E_{ion} \Delta V$$

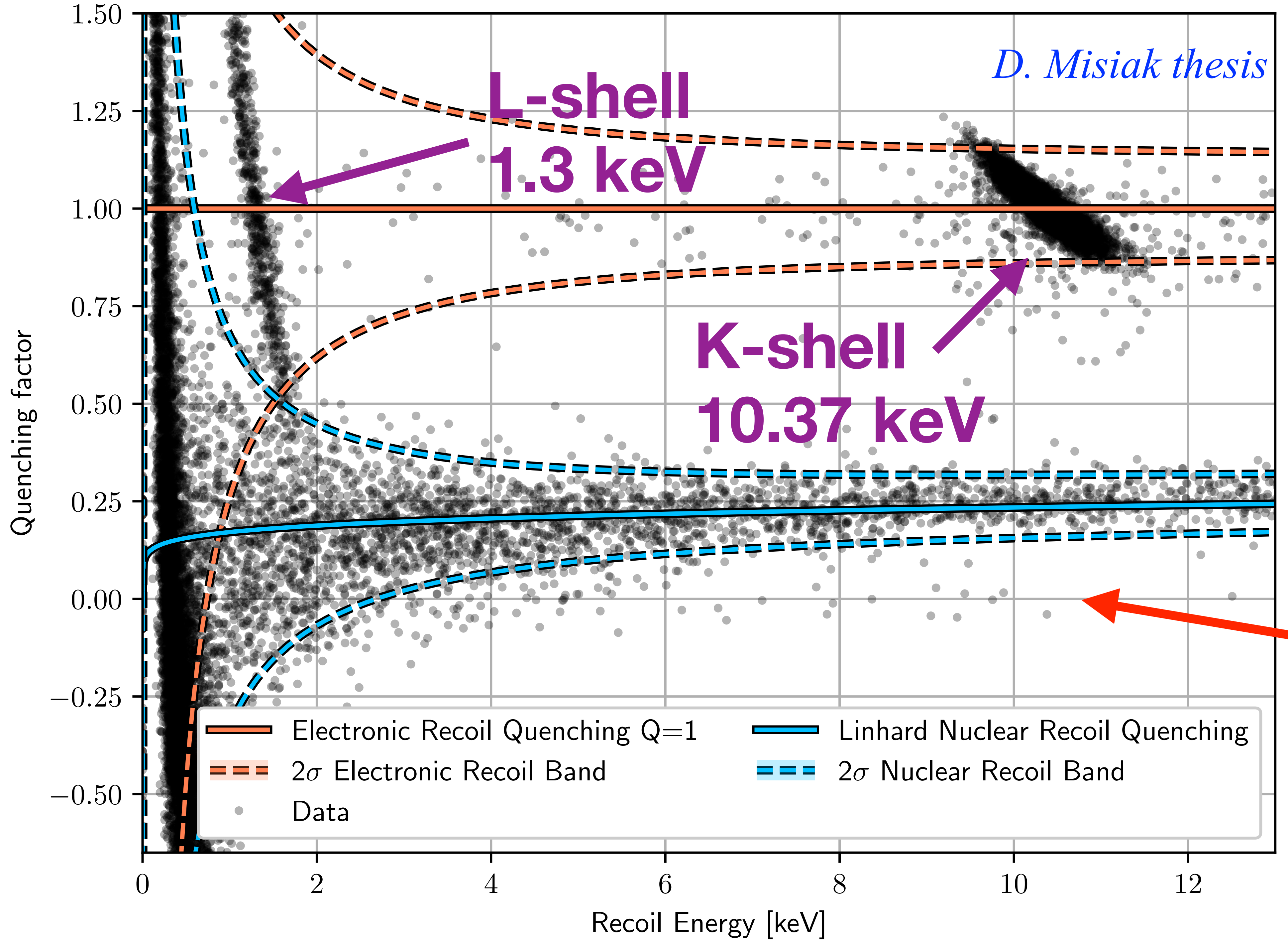
]TESSERACT@LSM: Ge/Si semiconductors

$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + \frac{1}{3\,eV} E_{ion}\Delta V$$

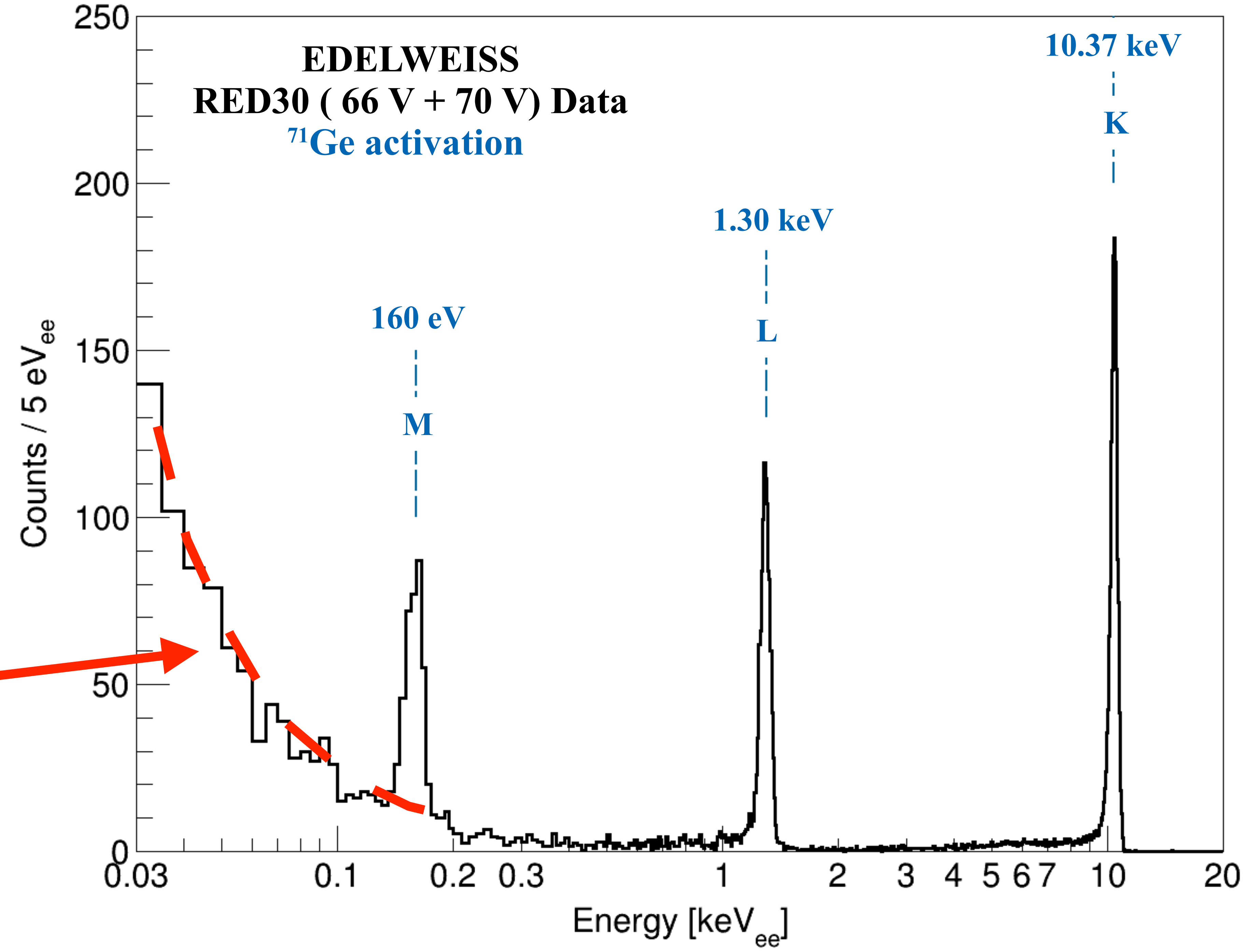


Low Voltage mode
Part. ID + Fid

High Voltage mode
single e/h - No PID

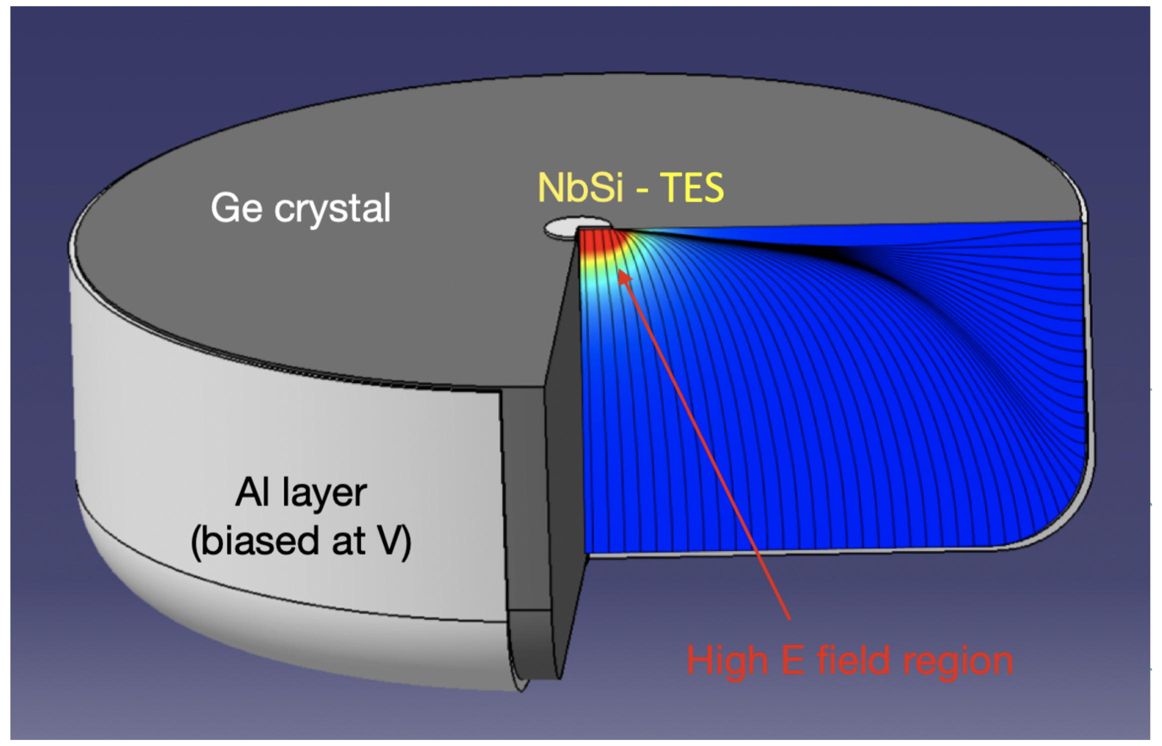


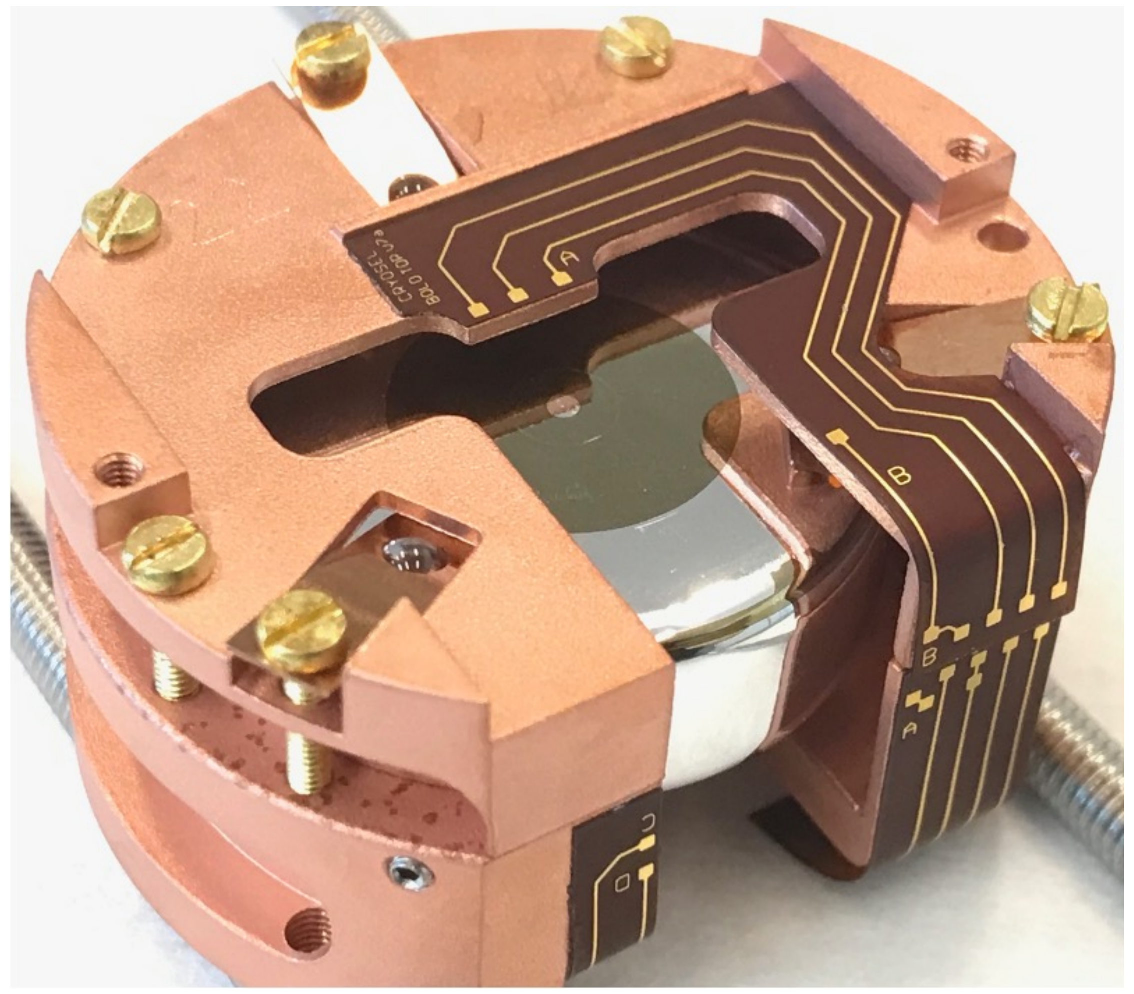
LEE



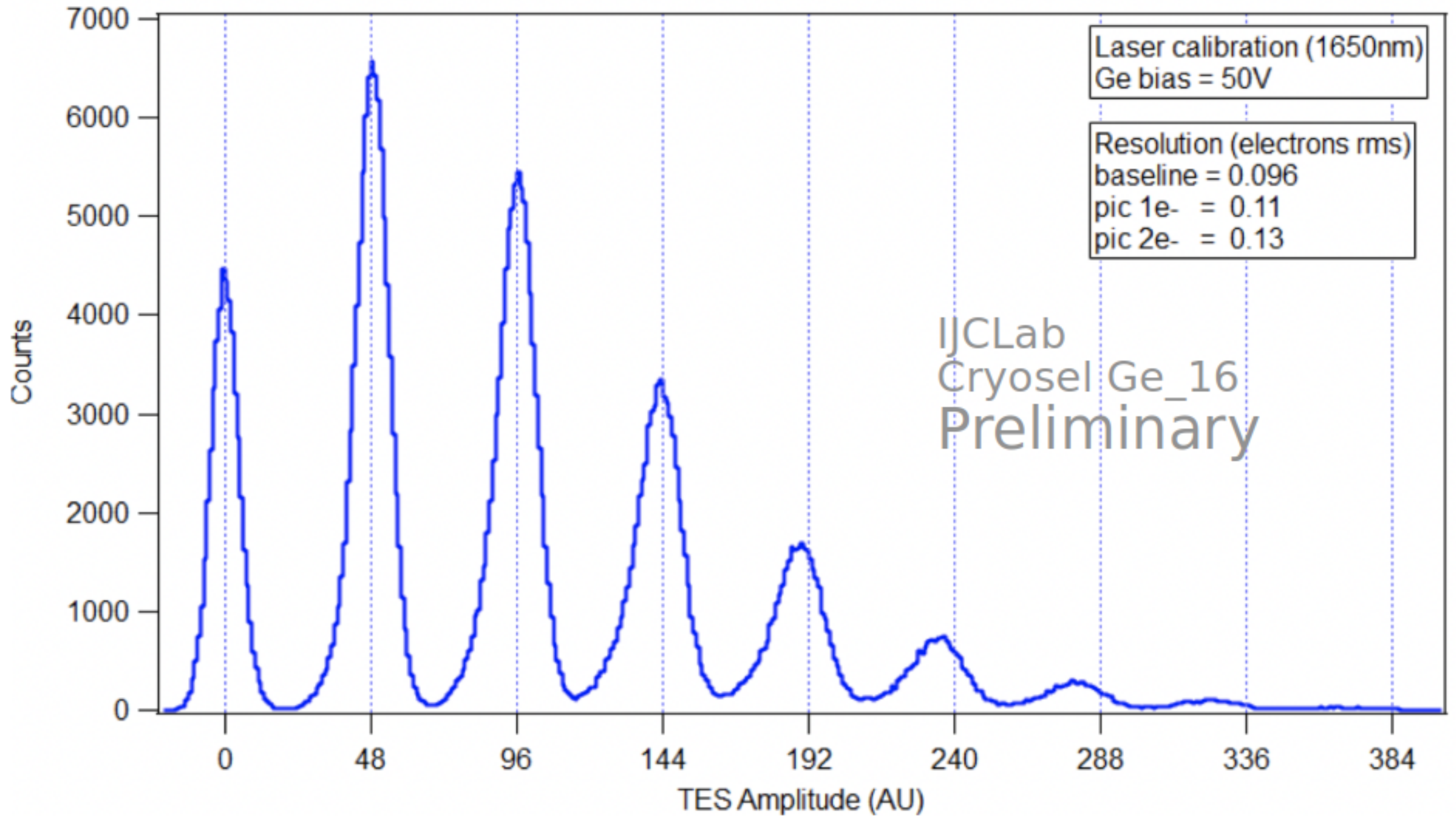
TESSERACT@LSM: Ge semiconductors

High-Voltage approach for optimal ERDM sensitivity





First observation of a single-electron sensitivity in a massive (40g) Ge cryogenic detector !



CRYOSEL performance goals: 200 V bias + single e-h sensitivity + SSED LEE tagging efficiency > 1000

First R&D results shown at TAUP2023:

- Stable operation up to 60 V
- Confirmation that first NbSi SSED acts as efficient LEE veto
- New prototype currently being tested with significantly improved performance

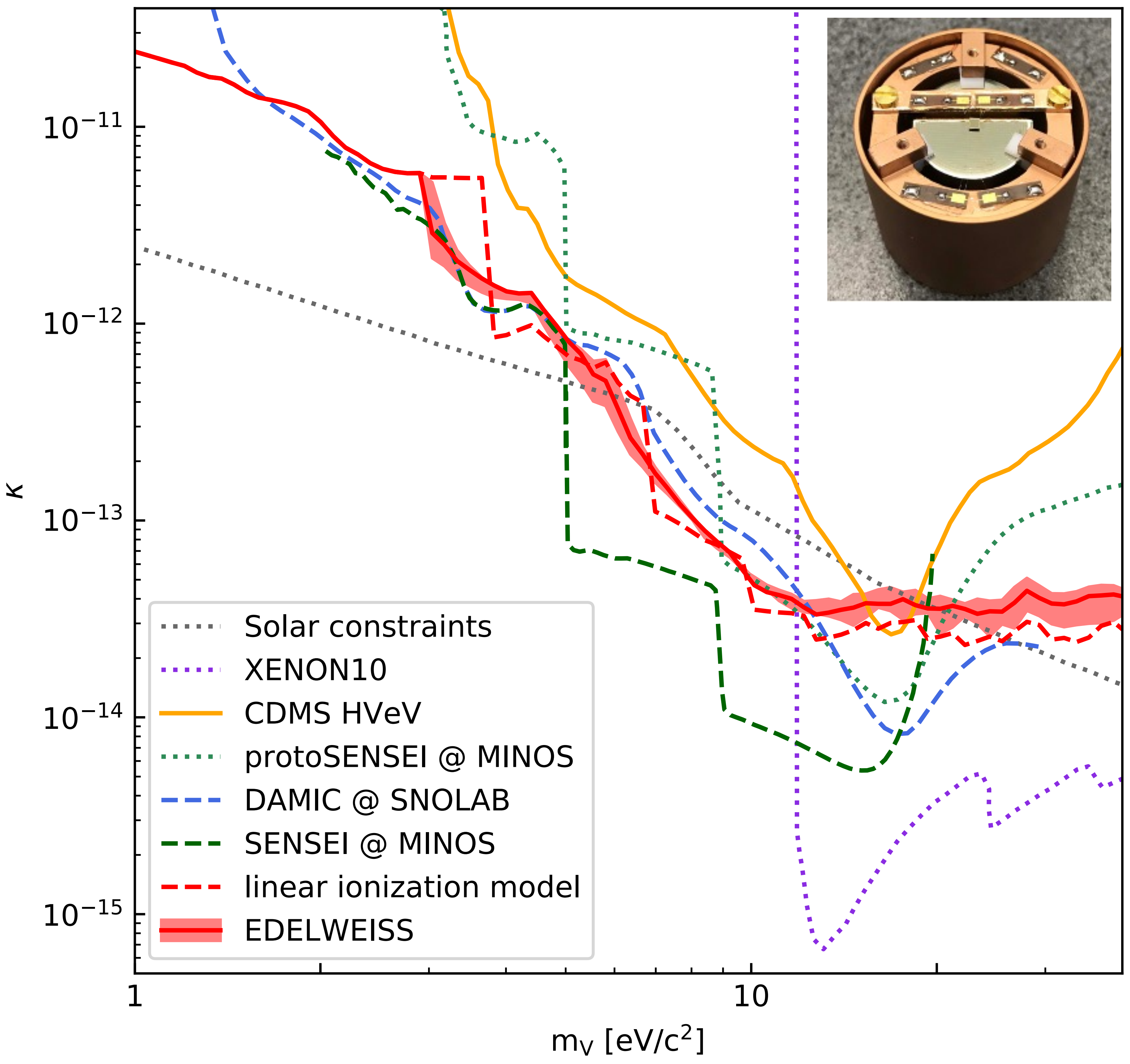
For TESSERACT:

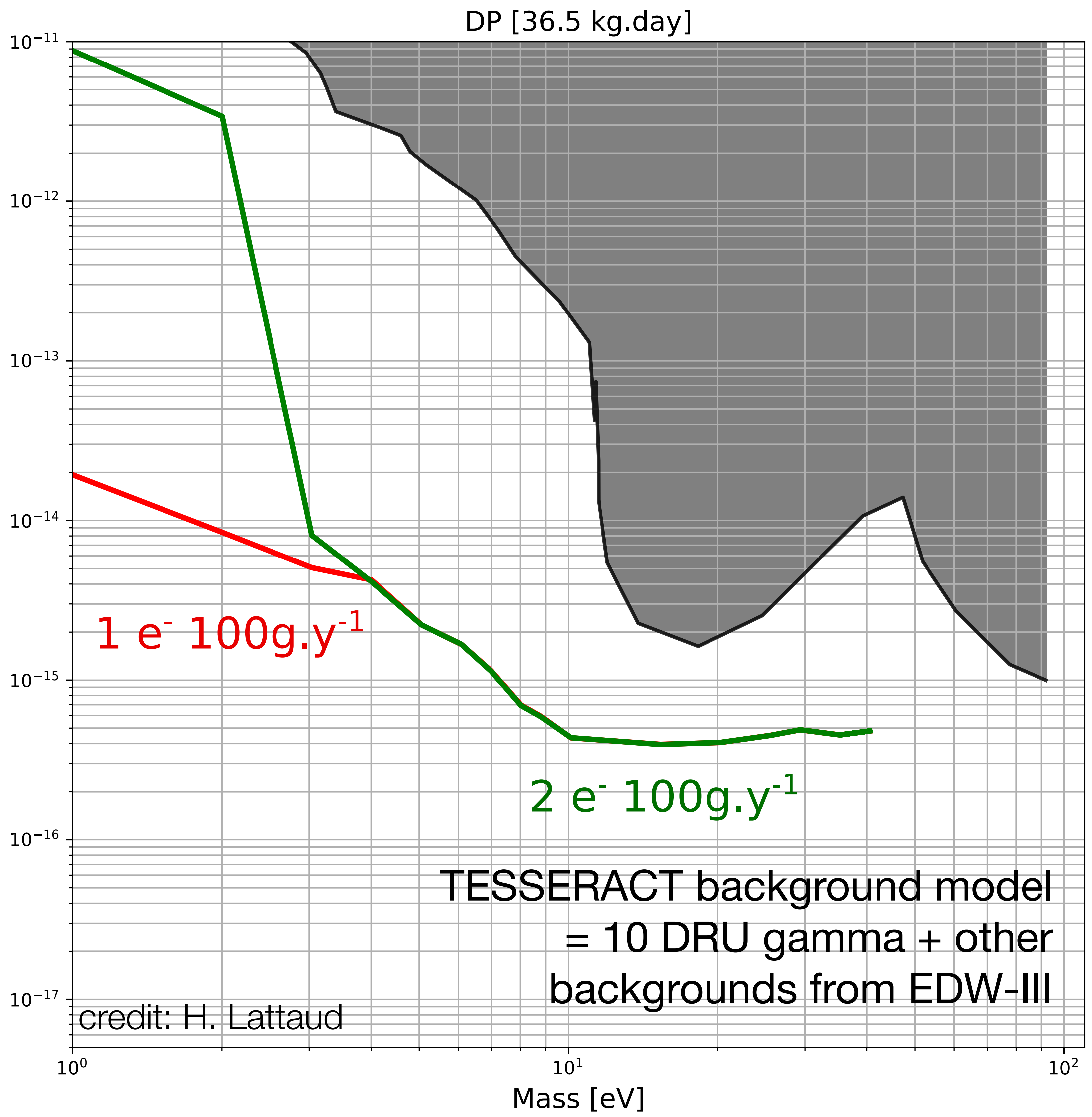
- Switch to low-imp. TES for sub-eV SSED energy threshold
- High control of IR backgrounds and charge leakage
- LEE discrimination down single e-h pair
- Exquisite sensitivities to ERDM with LEE discrimination

TESSERACT@LSM: Ge semiconductors

High-Voltage approach for optimal ERDM sensitivity

EDELWEISS collaboration, PRL 125, 141401 (2020)



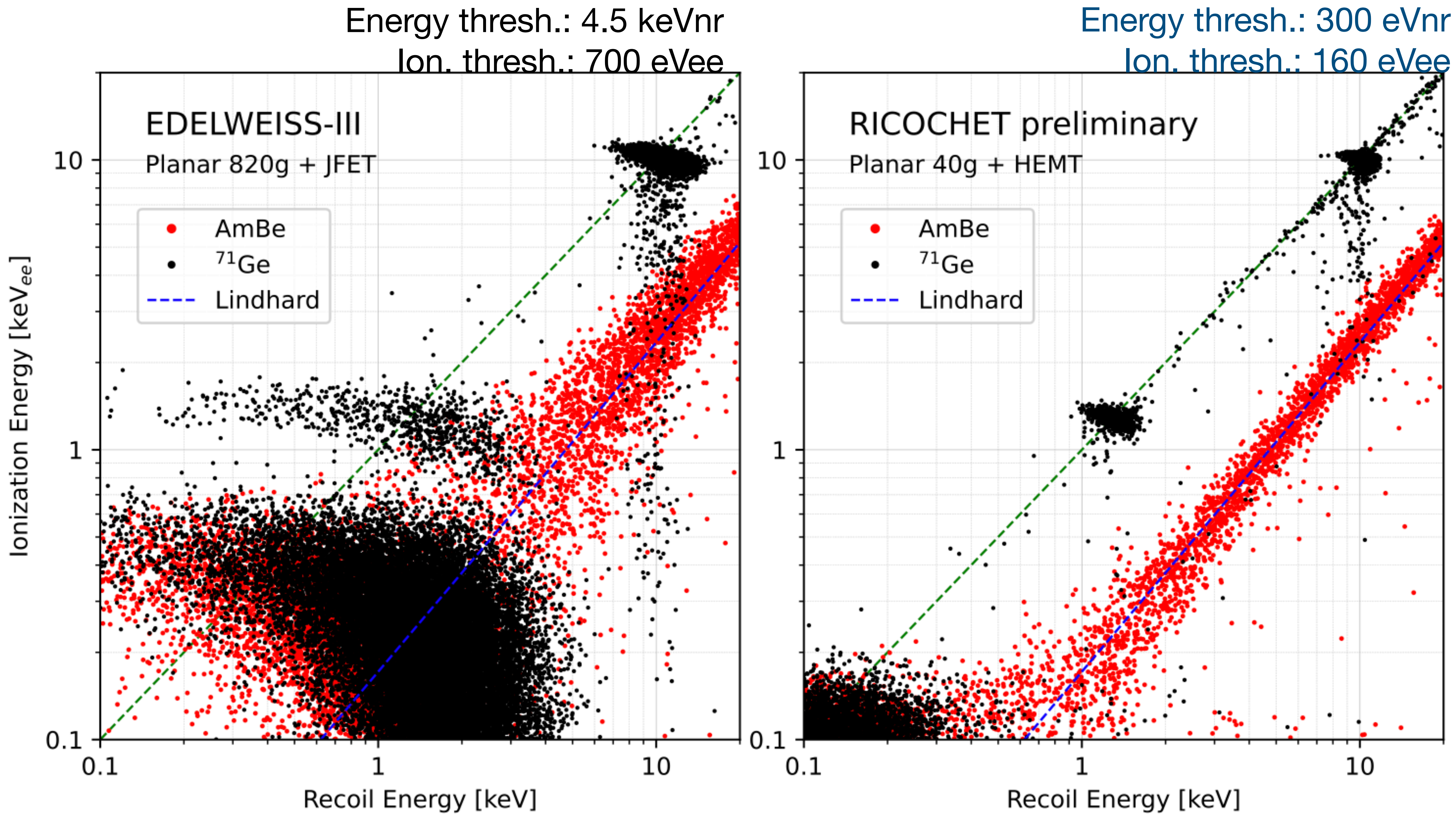


In 2020 EDELWEISS-III achieved one of the best ERDM sensitivity with sub-electron energy resolution with a 33 g Ge crystal operated at 78V.

The HV technology (SSED + TES + 200V) in TESSERACT will allow to achieve orders of magnitude improved sensitivities

TESSERACT@LSM: Ge semiconductors

Low-Voltage approach for optimal NRDM sensitivity



Presented at: TAUP2023, IDM2023, Nobel Symposium 2023 (NS-182 « Dark Matter »)

- ER/NR discrimination threshold has been **improved by about one order of magnitude** w.r.t EDW and SuperCDMS
- Ricochet can now probe reactor neutrinos (CEvNS) and equiv. 3 GeV WIMP with highly efficient LEE and ER rejection

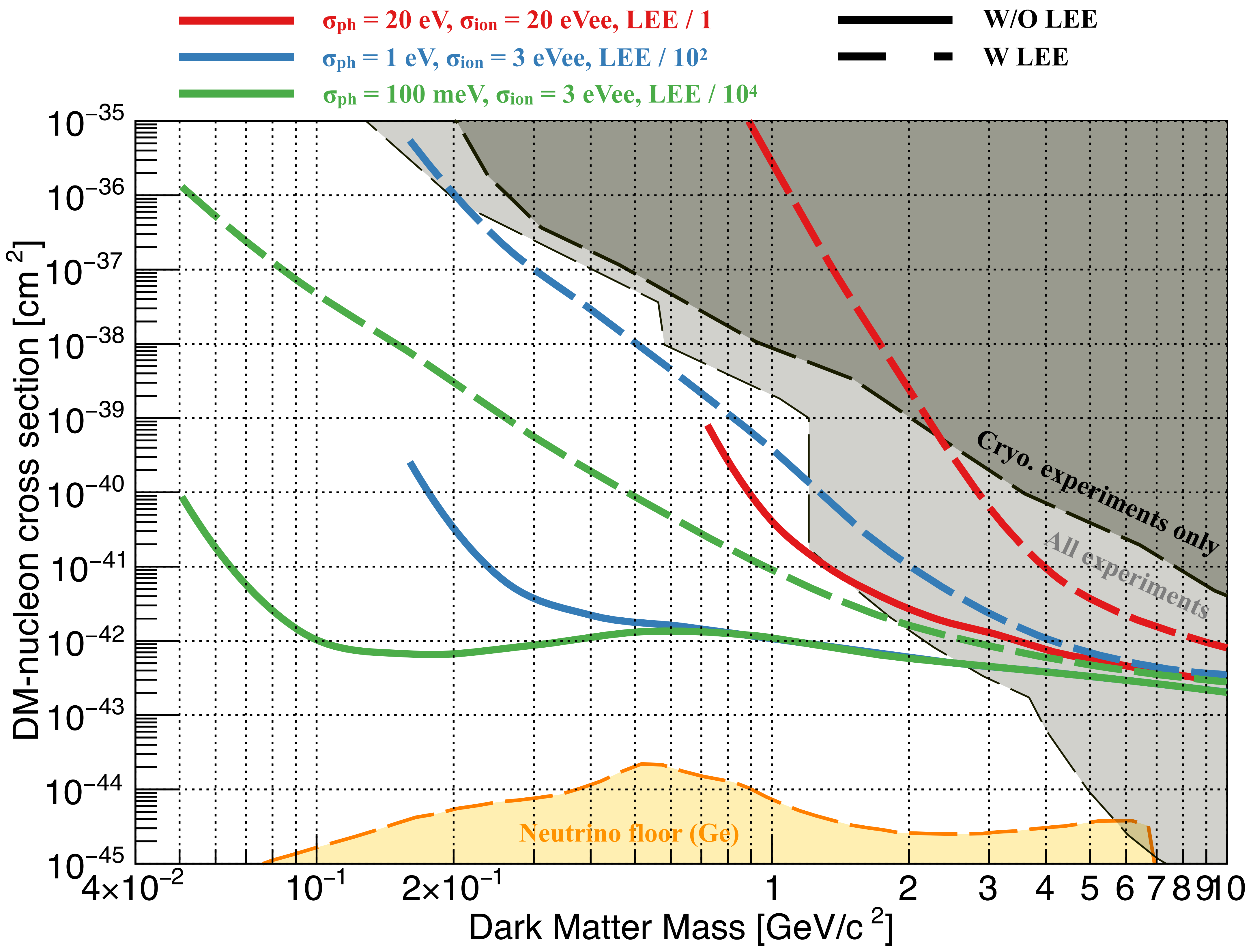
Ricochet resolution goals: 20 eV (heat) + 20 eVee (ionisation) - almost achieved (by a factor of ~2)

For TESSERACT:

- Switch to TES for sub-eV heat energy threshold and reduced LEE, and aiming for 3-6 eVee ion. resolution
- ER/NR identification down to 10s of eVnr + LEE discrimination down to 50 eVnr (Lindhard)
- Ideal for low-mass NRDM with PID

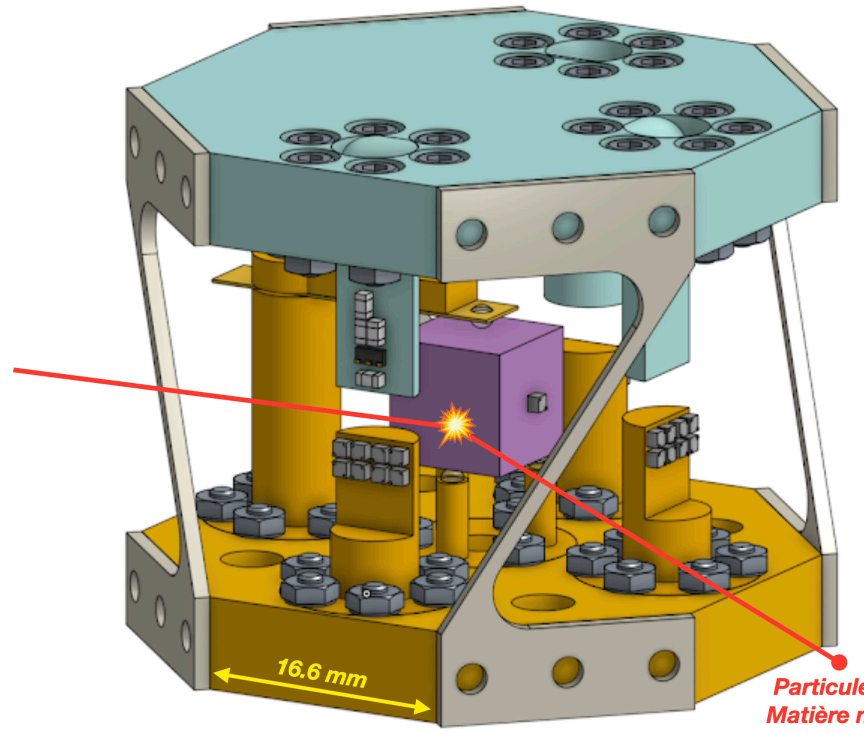
TESSERACT@LSM: Ge semiconductors

Low-Voltage approach for optimal NRDM sensitivity



TESSERACT background model = 10 DRU gamma + other backgrounds from EDW-III

credit: J. Colas *(FRAMA and RI2 proposals)*



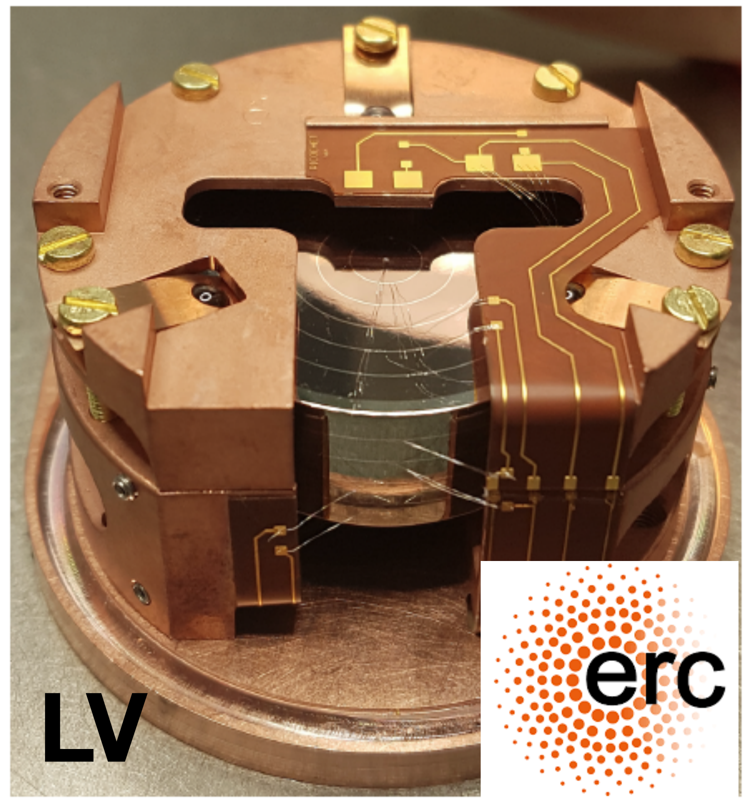
The LV technology in TESSERACT will allow to vastly extend the NRDM searches down to 100 MeV with particle ID and LEE rejection in a region of the parameter space inaccessible to non-cryogenic experiments.

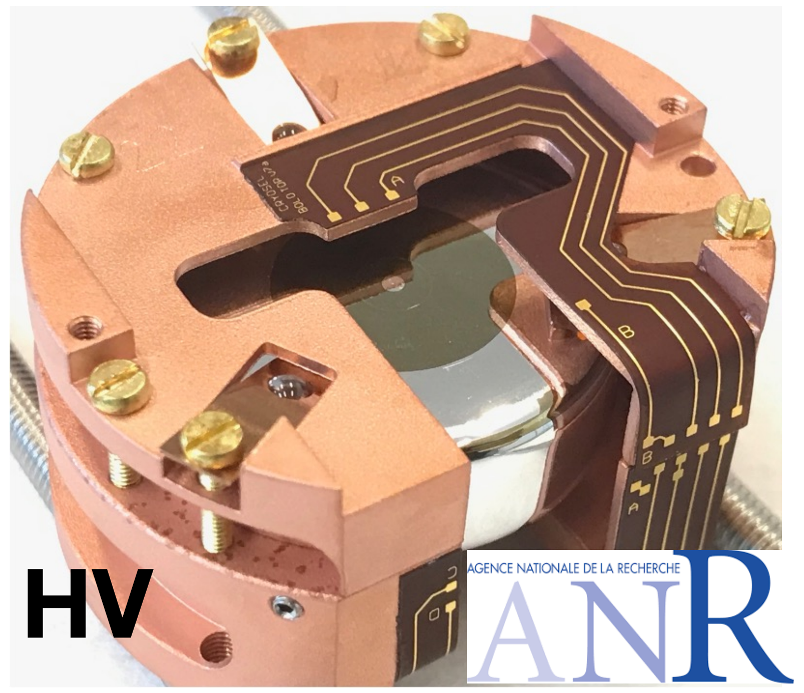
TESSERACT@LSM: Detector technology summary

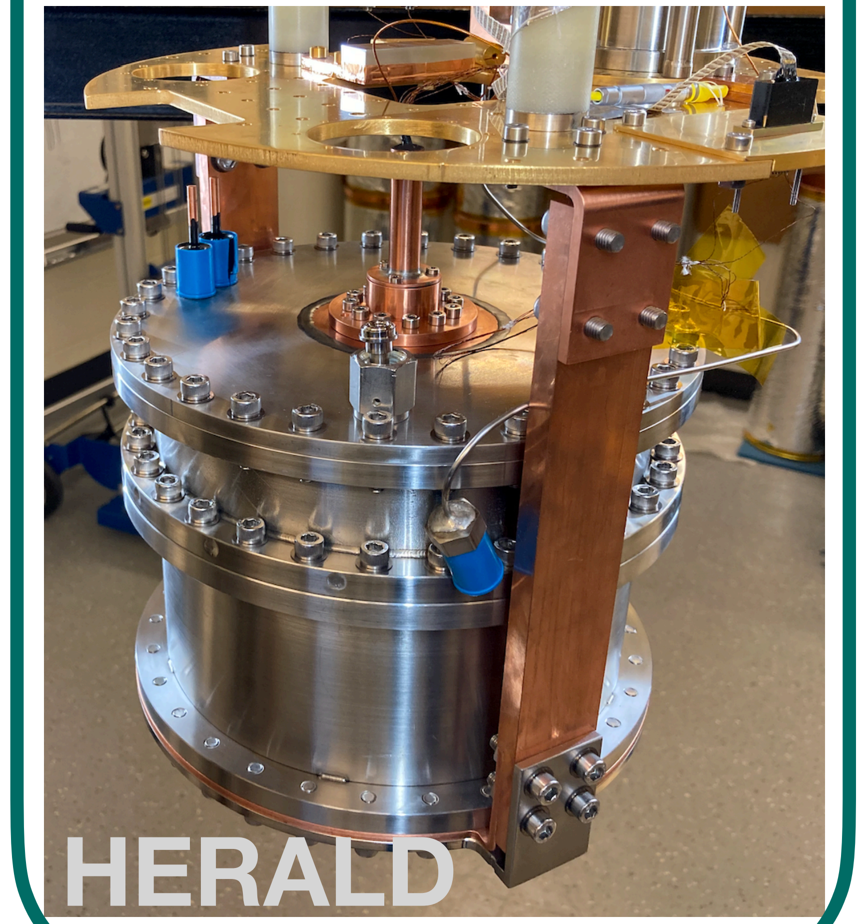
All detector technologies will be featuring:

1. athermal phonon TES with sub-eV energy thresholds,
2. drastically mitigated LEE (under intense investigation),
3. payloads between 10g to 100g

	Target	Search type	Mass range	LEE rejection	Particle ID
SPICE Polar crystals	Al_2O_3, SiO_2	ERDM	100 meV - MeV	Dual TES channel	None
SPICE Scintillator	GaAs	NRDM/ ERDM	eV - MeV MeV - GeV	Phonon/ photon coïncidence	Dual Phonon-photon readout
HeRALD LHe	He	NRDM	MeV - GeV	Multiple He4/ photon	Pulse shape discrimination
Semicon. High V	**Ge, Si**	**ERDM**	**eV - MeV**	**SSED**	**None**
Semicon. Low V	**Ge, Si, C**	**NRDM**	**MeV - GeV**	**Phonon/ Ionization coincidence**	**Dual phonon-ionisation readout**





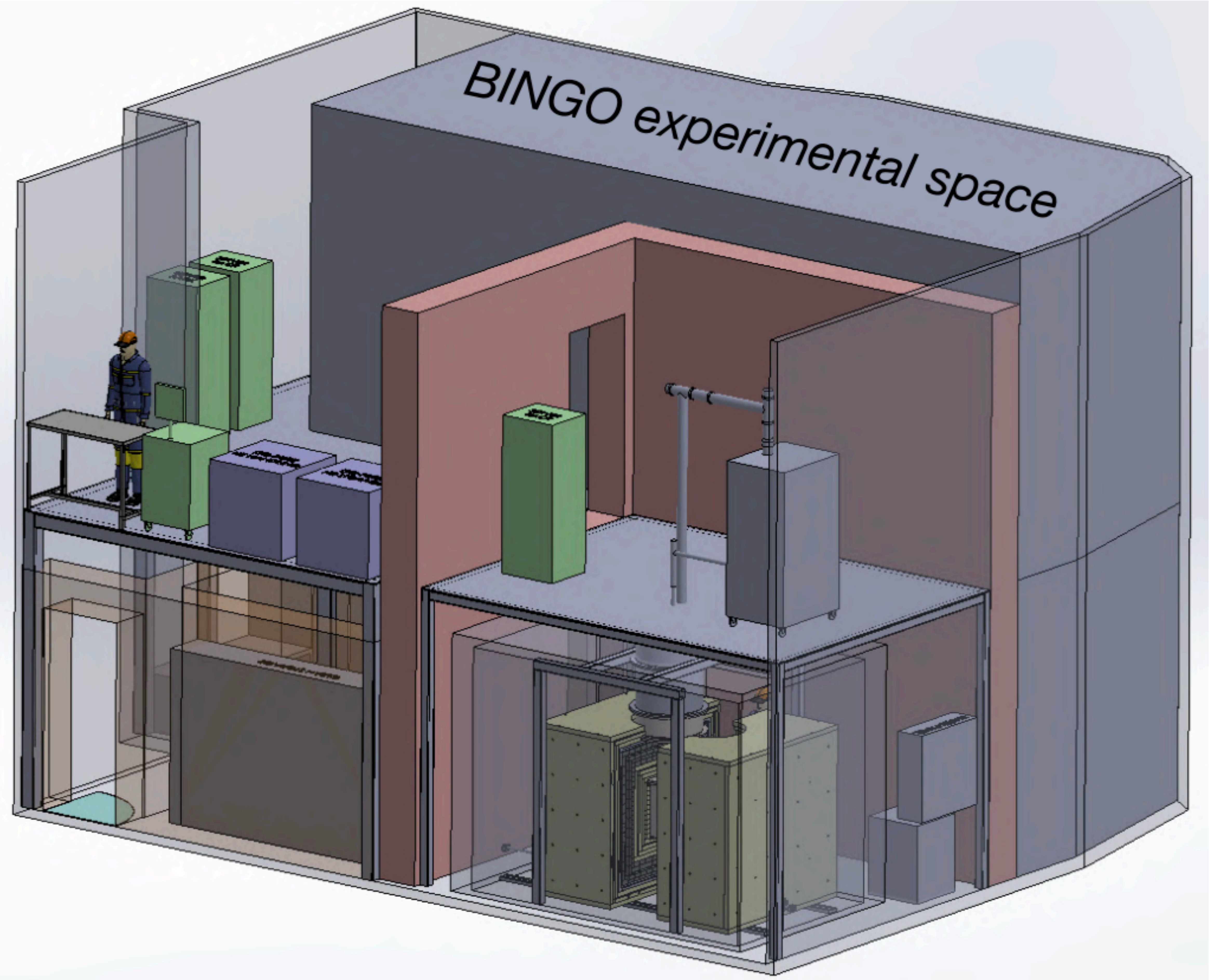


TESSERACT: Integration at LSM

- Two copies of the setup, for enabling both:
  - underground R&D and detector optimisation
  - DM science data taking in parallel

- Each detector technologies is designed to achieve major breakthrough in short time scales (few months) hence allowing fast turnarounds

- The two setups will be deployed at the same underground laboratory (LSM).
- Installation of 1st cryostat via the TES4DM project at LSM in the next 3 years is timely for the TESSERACT collaboration.



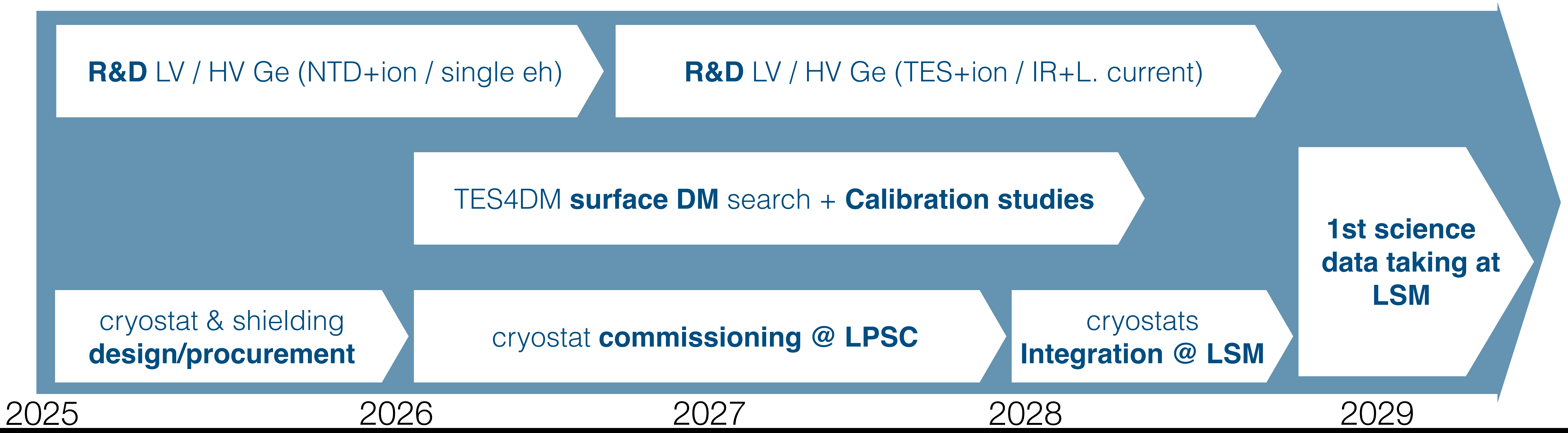
TESSERACT: Integration at LSM

TESSERACT Features

- Multi-target cryogenic detectors
- LEE mitigation
- Particle Identification
- Low impedance TES phonon sensors
- LSM ultra-low background environnement

TESSERACT Requirements

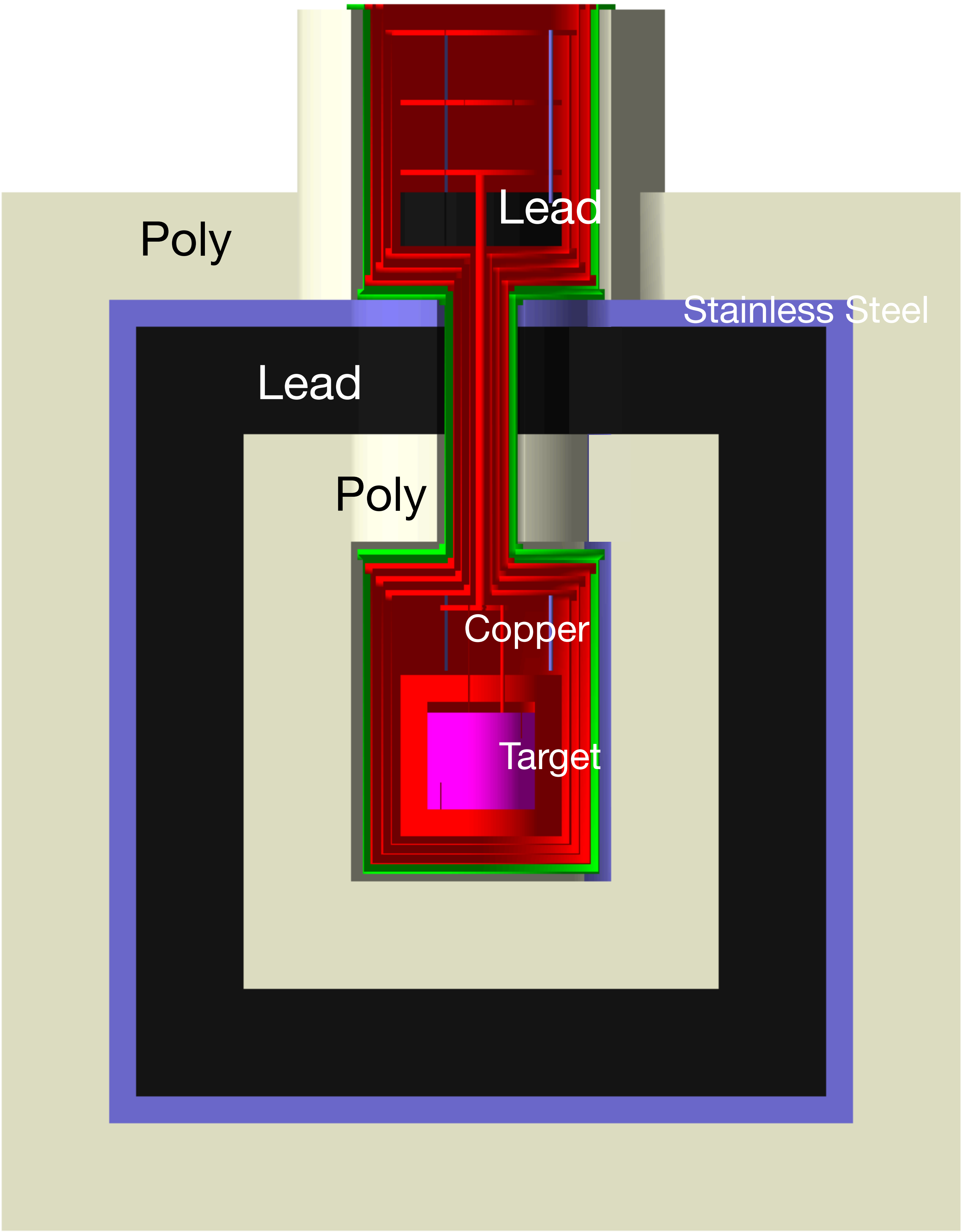
- Ultra-low threshold
- Optimal for both NRDM and ERDM
- Broader DM mass range covering



TESSERACT: Integration at LSM

Ongoing work on the shielding design for the lowest background possible (few DRU):

- Ongoing simulations predict: ~1 DRU ER / <1e-3 DRU NR
- Favoured option with a «neck» that will require significant cryogenic R&D
- Need efficient material screening and assay to start well ahead of construction
- Commissioning of the TESSERACT cryostat above-ground (at LPSC)



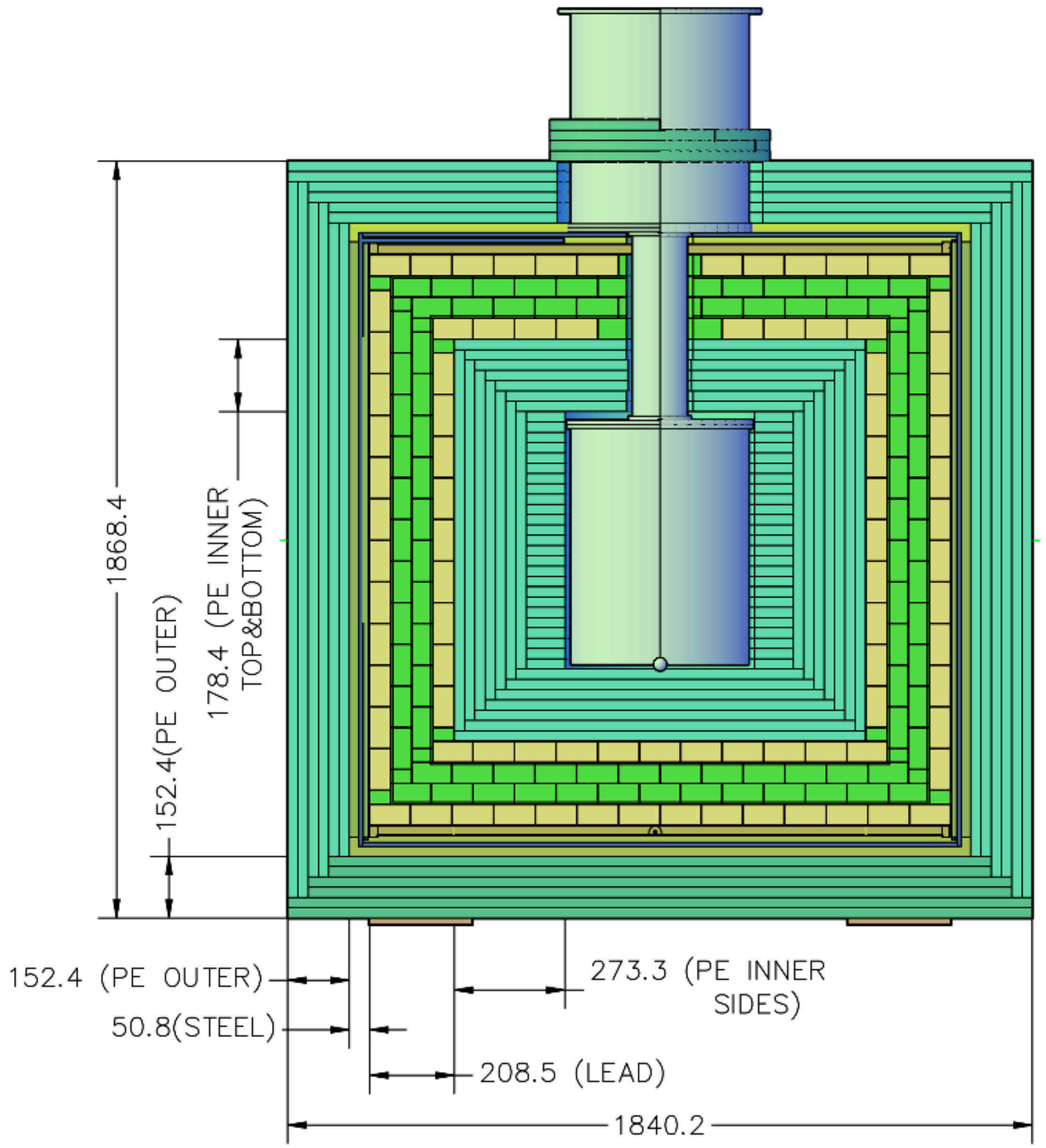
Shielding Design

Final shielding design from iterations of different geometries

The shielding is designed to be assembled from the bottom up and the outside inwards.

All single pieces are small enough to be easily moved into the experimental hall.

Cleaning and sealing the lead at suitable facilities at the surface to minimize risk and waste production underground.

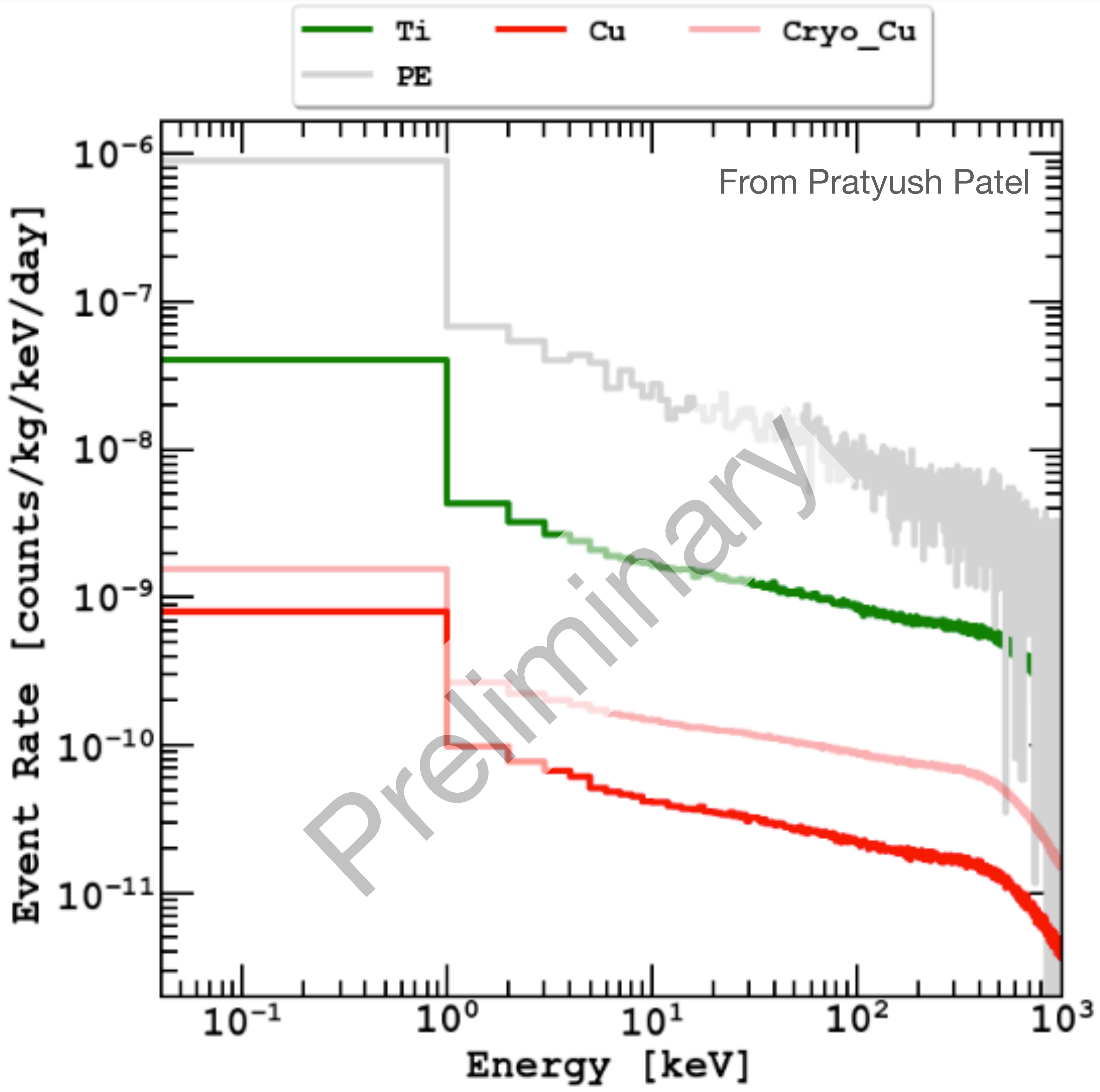


Initial Simulations

External neutron sources

Titanium, stainless steel, polyethylene, copper

The rate for neutron internal backgrounds is almost negligible



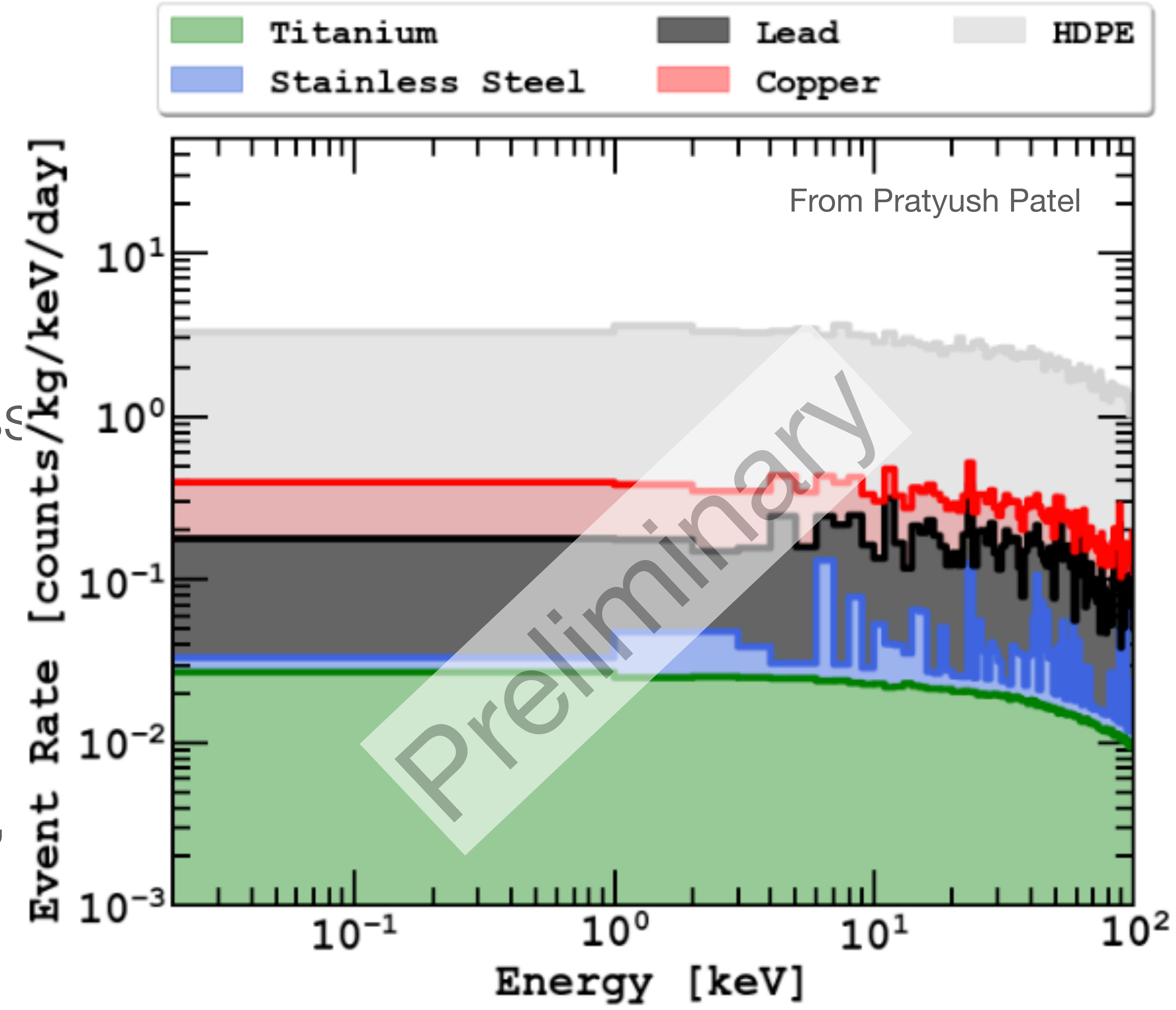
Initial Simulations

External gamma sources

Copper, polyethylene, lead, titanium, stainless steel all from EDELWEISS published data

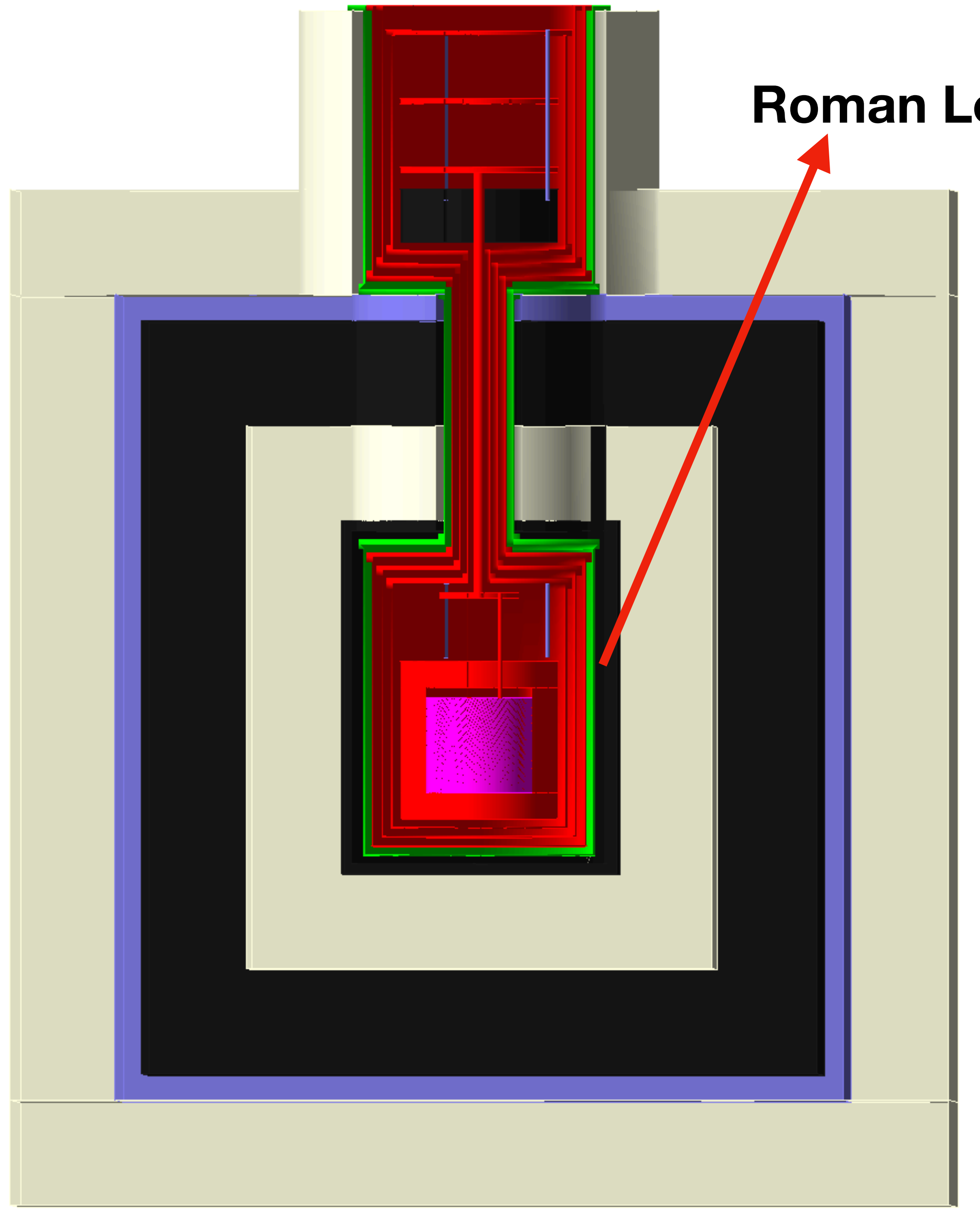
The rate for internal backgrounds is dominant, 3DRU in He target

Plan to have a inner layer of high-z materials, likely roman lead or copper.

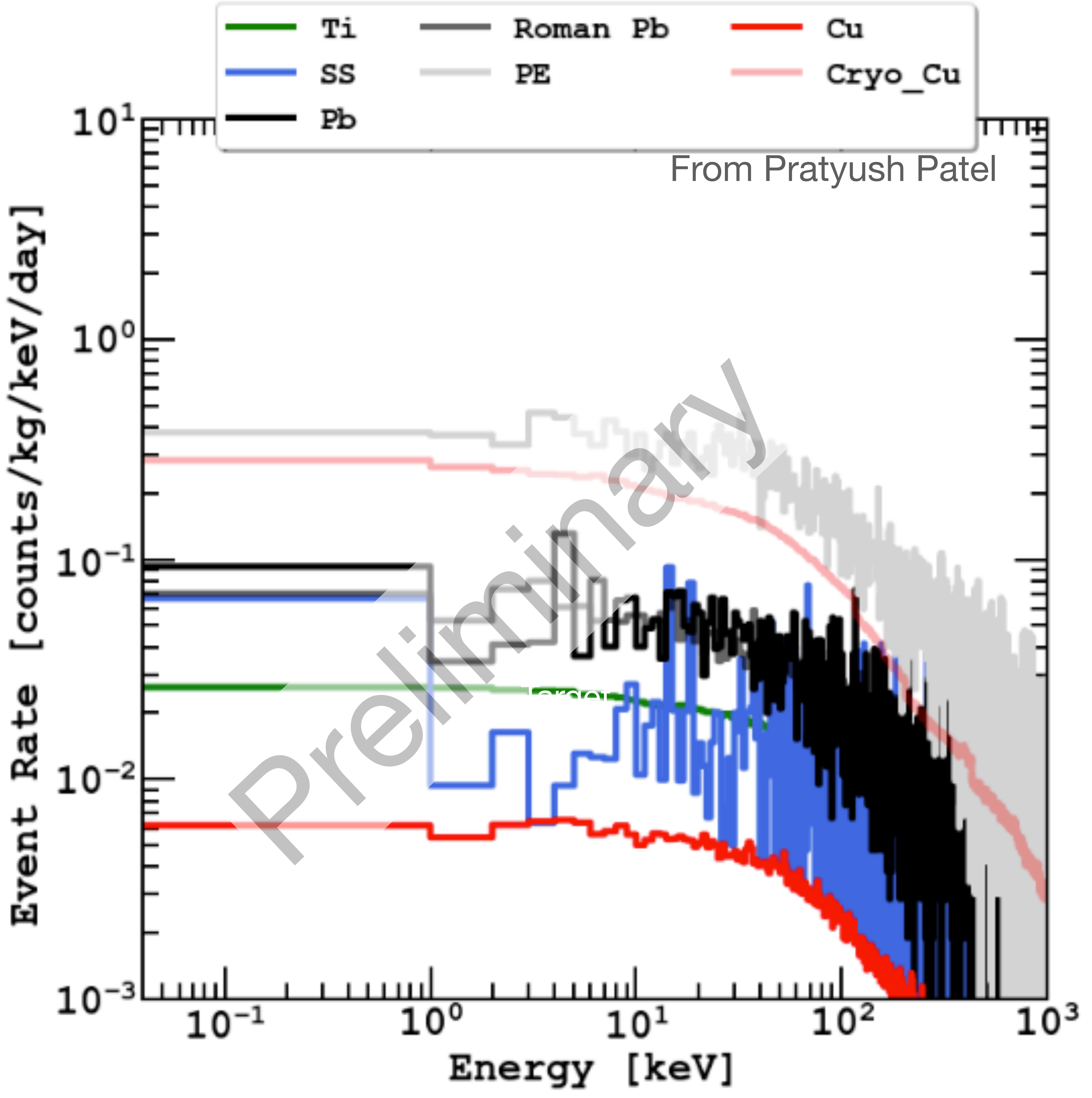


Initial Simulations

External gamma sources



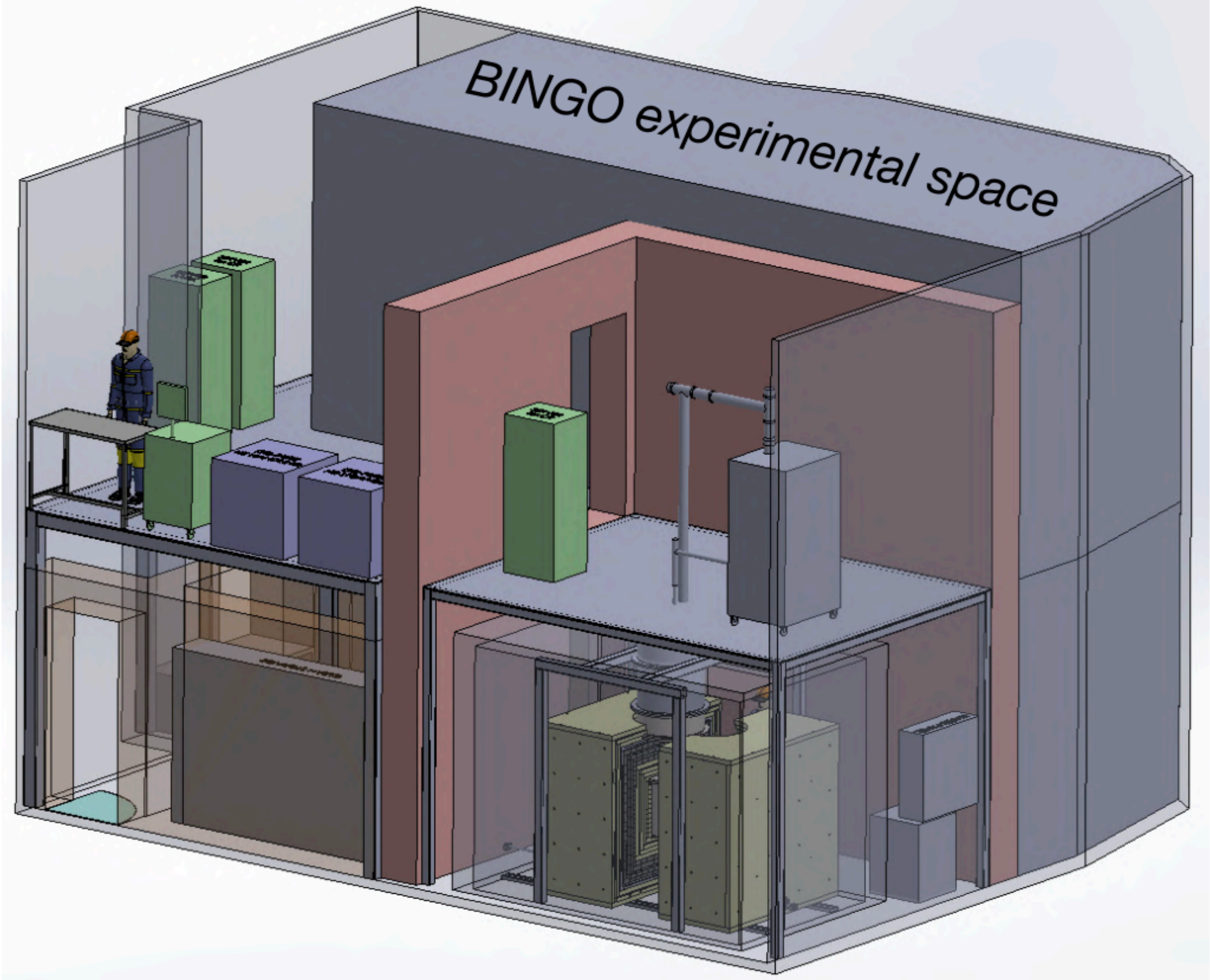
An additional internal roman lead shield of ~5cm, brings gamma internal budget down to <1 DRU



TESSERACT: Conclusion

Extending the Dark Matter mass search window from meV-to-GeV with **ultra low-threshold cryogenic detectors** with **multiple targets** and **particle identification and LEE rejection capabilities** with two identical cryogenic setups installed in the **ultra-low background environment underground at LSM**

Unique opportunity to build the next leading cryogenic light DM experiment at LSM, featuring French bolometer technology, benefiting from decades of experience from EDELWEISS, CUPID, and Ricochet




That's all Folks!