1ª Reunión Nacional Planes Complementarios de Astrofísica y Altas Energías

Plan de Recuperación, Transformación y Resiliencia

Financiado por la Unión Europea
NextGenerationEU

LIA5 DIRECT WIMP SEARCHES

CAPA
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

IFCA
Instituto de Física de Cantabria

ita
Instituto Tecnológico de Aragón

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R. Vilar for providing material)

Paraninfo U. Zaragoza, June 6 2024

Outline

- Overview of direct WIMP searches
- LIA5 WIMP experiments:
  - ANAIS-112 & ANAIS+

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Centro de Astropartículas y
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Universidad Zaragoza

  - TREX-DM

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  - DAMIC

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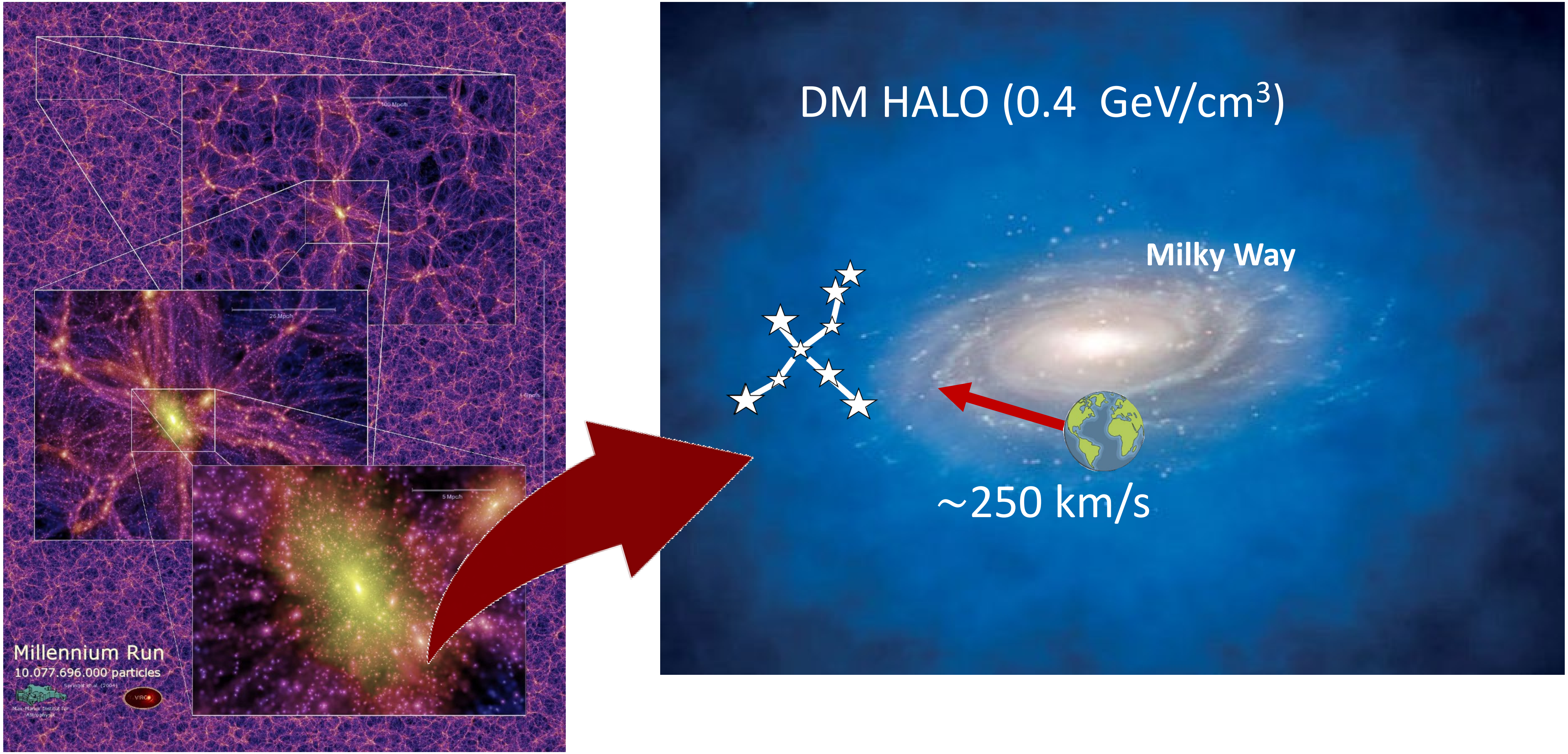
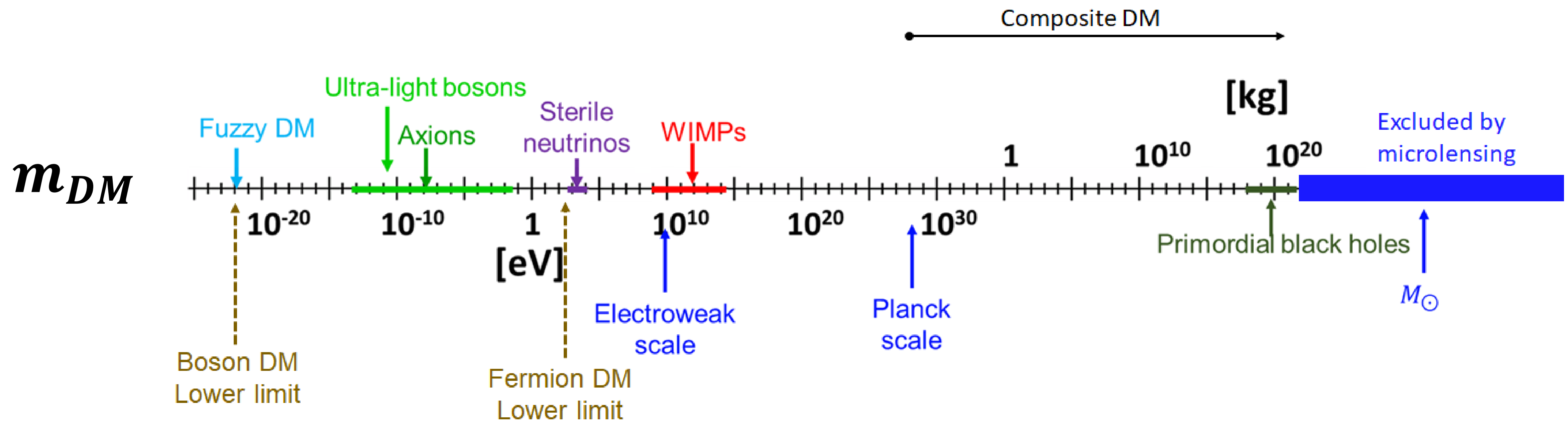
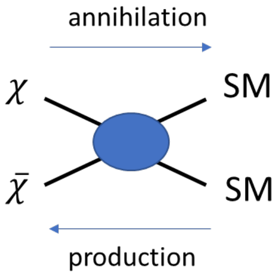
DM Direct detection

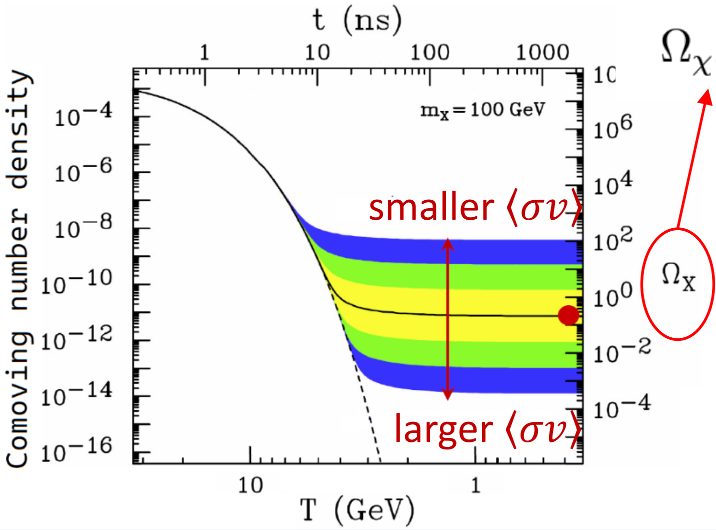


Dark Matter Candidates: WIMPs

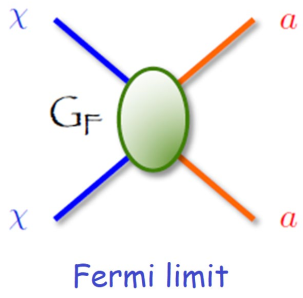


WIMPs production: the freeze-out mechanism explain naturally the observed DM abundance as the relic density of a particle thermally coupled in the early Universe





$$\Omega_\chi h^2 \sim 0.1 \left(\frac{\text{pb}}{\langle \sigma v \rangle} \right)$$



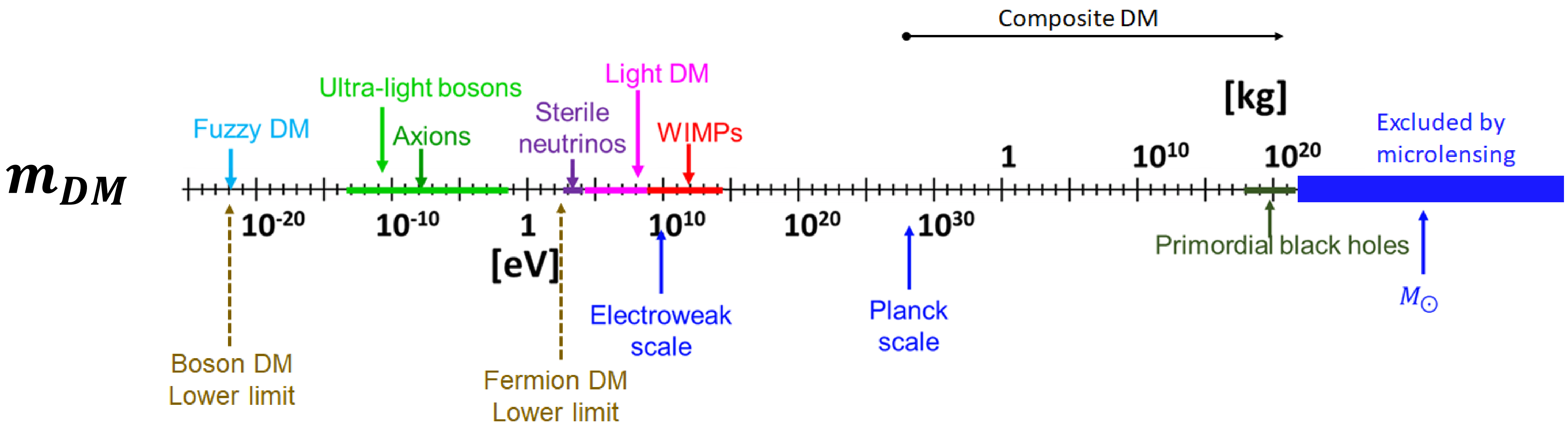
"standard" WIMPs

$$\langle \sigma_{\text{ann}} v \rangle \sim G_F^2 m_{\text{DM}}^2$$

To avoid DM overdensity:

m_χ **> few GeV**

Dark Matter Candidates: WIMPs



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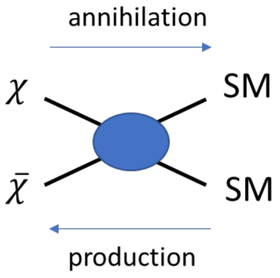
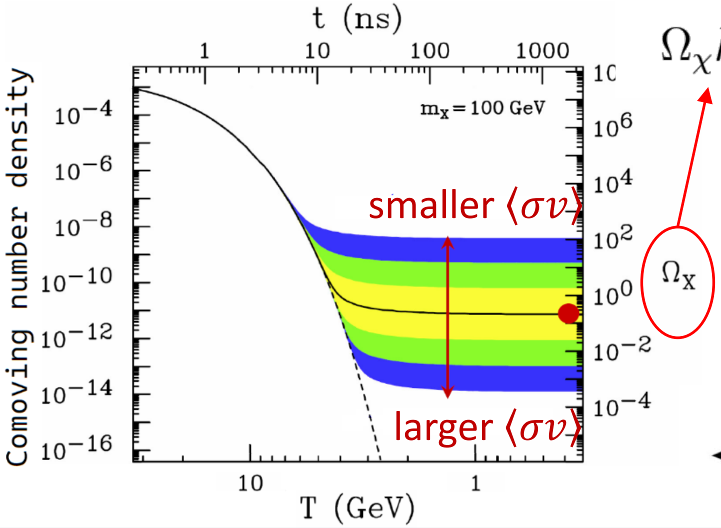
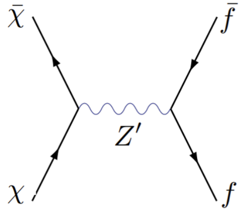




$$\Omega_\chi h^2 \sim 0.1 \left(\frac{\text{pb}}{\langle\sigma v\rangle}\right)$$

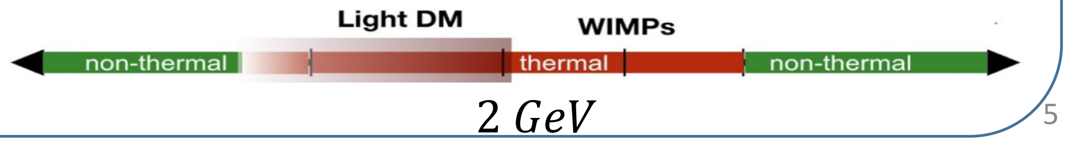
“general” WIMPs



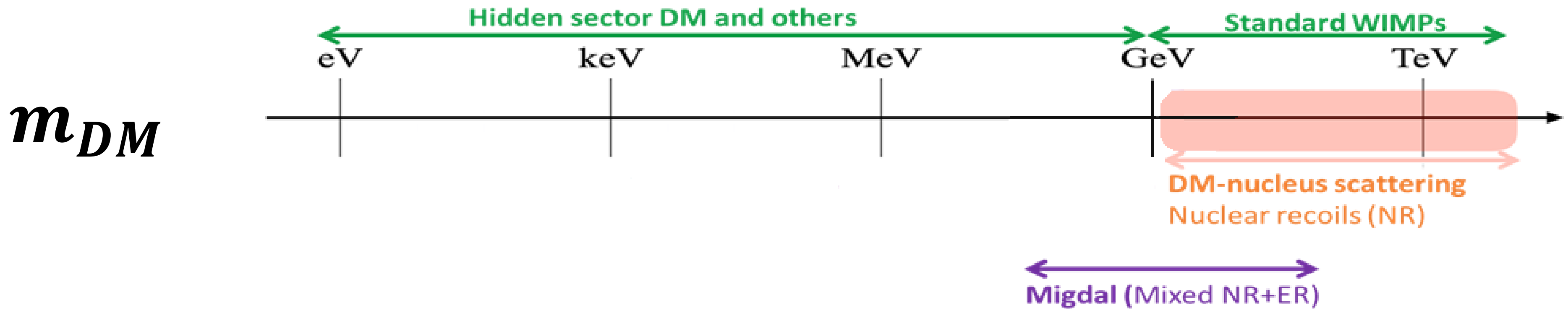
Allowing new mediators

$$\langle\sigma v\rangle \sim \frac{g_\chi^2 g_f^2 m_\chi^2}{m_{Z'}^4}$$ increases

→ allowed masses down to eV



Detecting WIMPs and Light Dark Matter



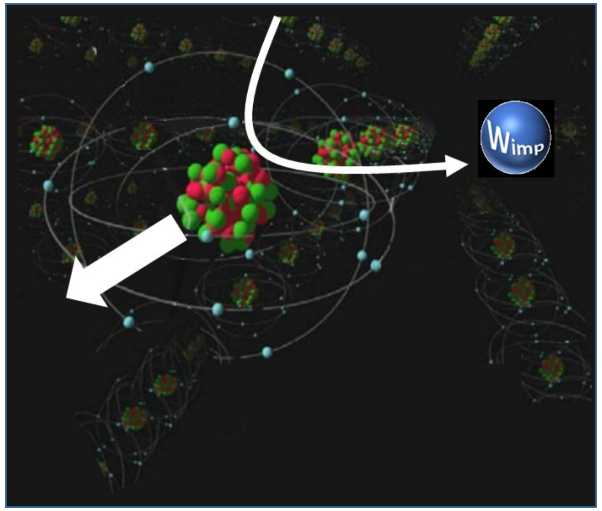
standard WIMP scenarios ($\mathbf{m_W = 10 - 10^3}$ **GeV**) : **Look for NR,** preferred targets with high A

$$\frac{d\sigma}{dE_R} = \left(\frac{d\sigma}{dE_R}\right)_{SI} + \left(\frac{d\sigma}{dE_R}\right)_{SD}$$

$\propto A^2$

Only if $J \neq 0$

$$E_{\rm NR} = \frac{q^2}{2m_N} = \frac{(m_{\rm DM}v)^2}{2m_N} \gtrsim E_{\rm threshold} \sim {\rm keV}$$



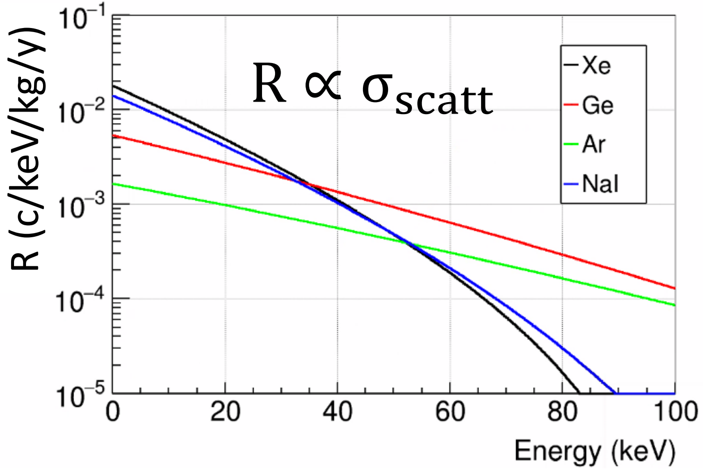
DM numerical density

DM velocity distribution
In detector's frame

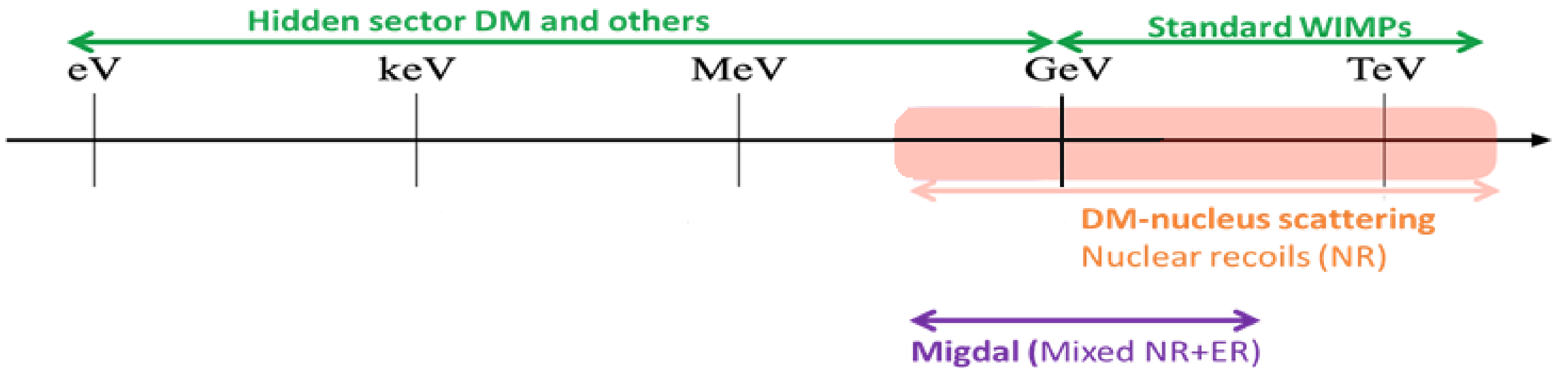
$$\frac{dR}{dE_R} = \frac{M_{det}}{m_N}\frac{\rho_\chi}{m_\chi}\int_{v_{min}}^{\infty}\frac{d\sigma}{dE_R}vf(\boldsymbol{v})d^3\boldsymbol{v}$$

Number of targets

Scattering cross section



Detecting WIMPs and Light Dark Matter


Hidden sector DM and others

Standard WIMPs

eV

keV

MeV

GeV

TeV

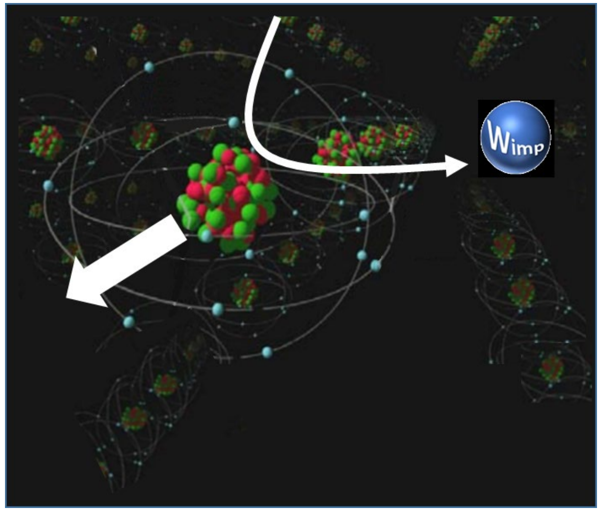
DM-nucleus scattering

Nuclear recoils (NR)

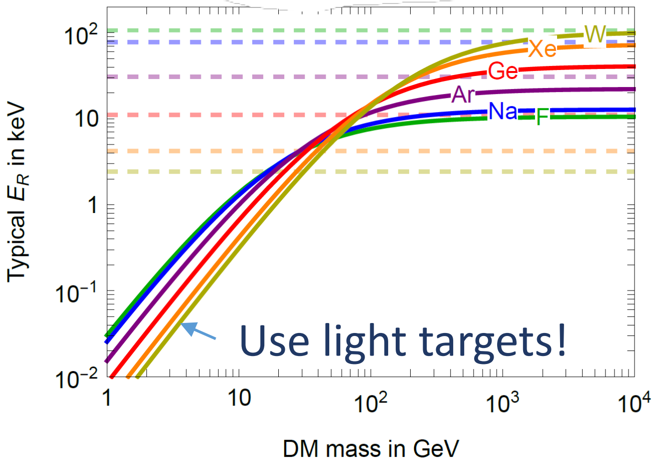
Migdal (Mixed NR+ER)

standard WIMP scenarios ($\mathbf{m_W = 10 - 10^3}$ **GeV**) : **Look for NR,** preferred targets with high A

standard WIMP scenarios ($\mathbf{m_W = 1 - 10}$ **GeV**) : **Look for NR**, **very low energy threshold!**

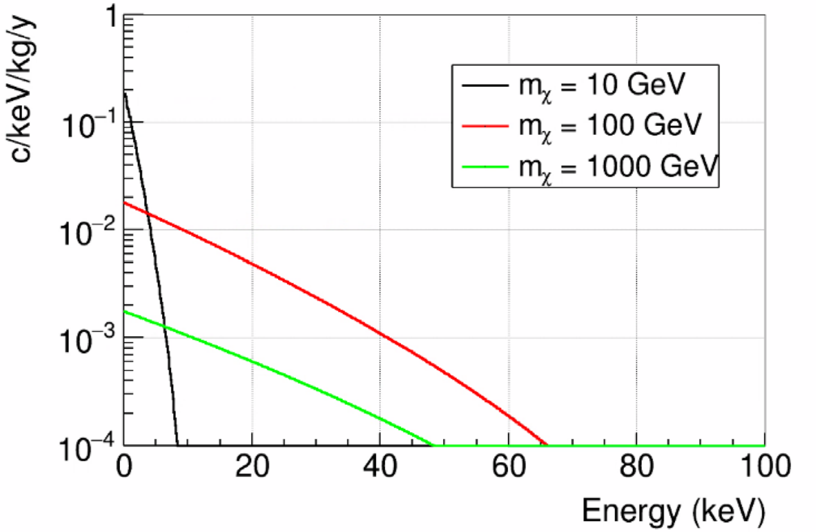


$$E_{\mathrm{NR}} = \frac{q^2}{2m_N} = \frac{(m_{\mathrm{DM}}v)^2}{2m_N} \gtrsim E_{\mathrm{threshold}} \sim \mathrm{keV}$$

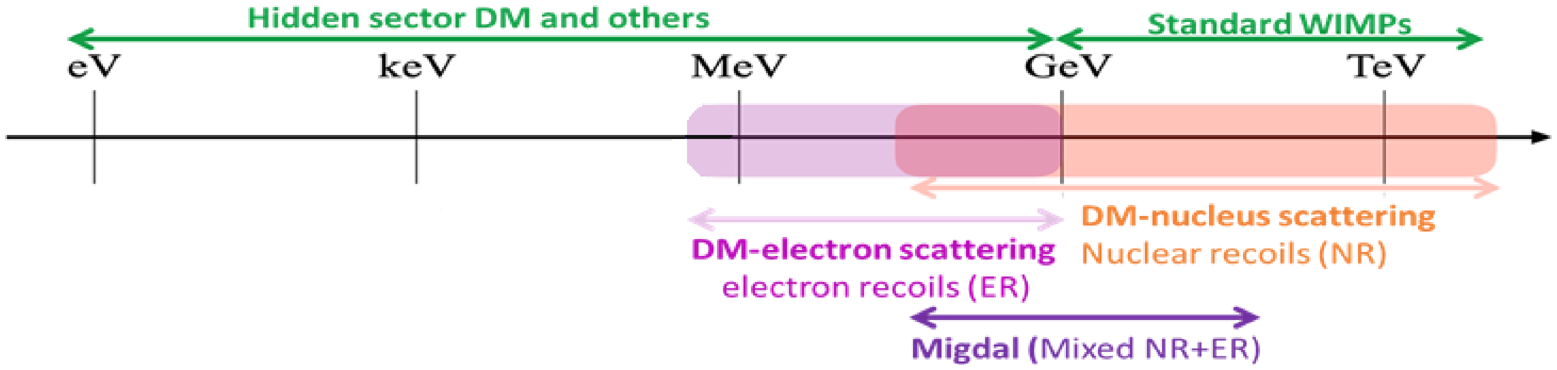


Use light targets!

Expected rate, target: Xe, $\sigma_{SI} = 10^{-45}\mathrm{cm}^2$



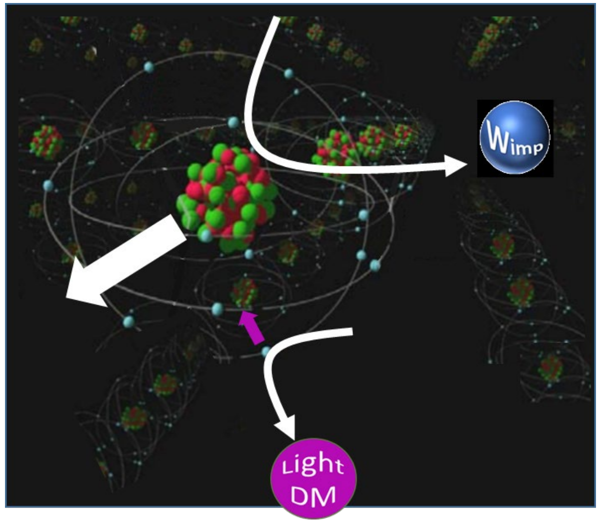
Detecting WIMPs and Light Dark Matter

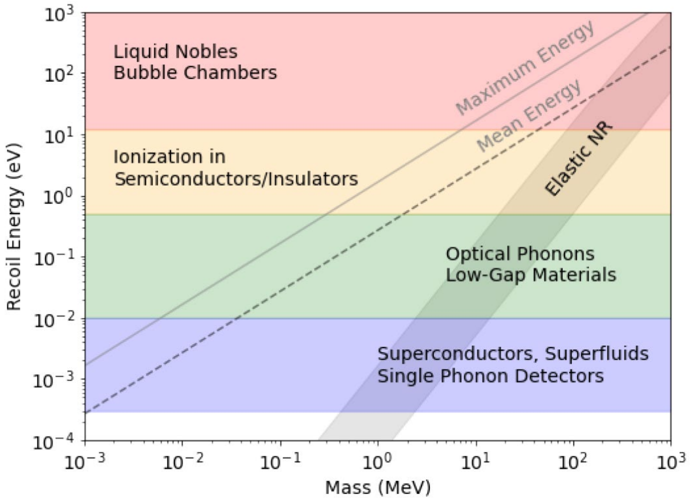


standard WIMP scenarios ($\mathbf{m_W = 10 - 10^3}$ **GeV**) : Look for NR, preferred targets with high A

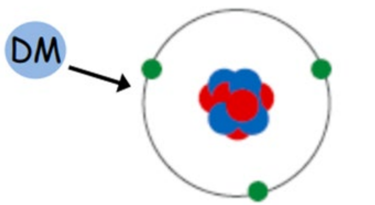
standard WIMP scenarios ($\mathbf{m_W = 1 - 10}$ **GeV**) : Look for NR, **very low energy threshold!**

dark sector couplings ($\mathbf{m_W = 1 - 1000}$ **MeV**) : Inelastic scattering off bound electrons

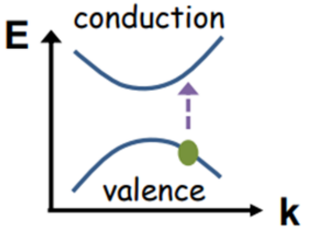




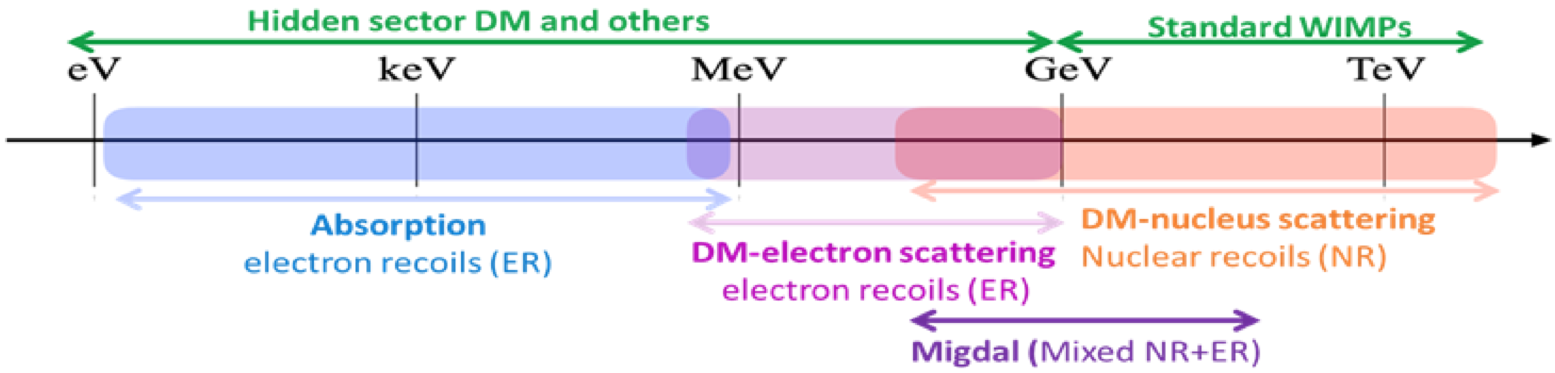
Atomic ionization



Semiconductors



Detecting WIMPs and Light Dark Matter

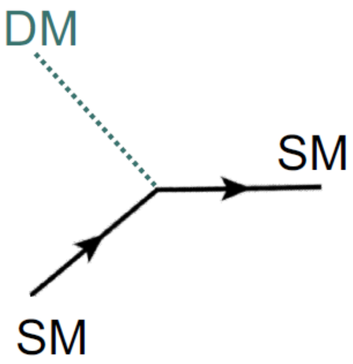


standard WIMP scenarios ($\mathbf{m_W = 10 - 10^3}$ **GeV**) : Look for NR, preferred targets with high A

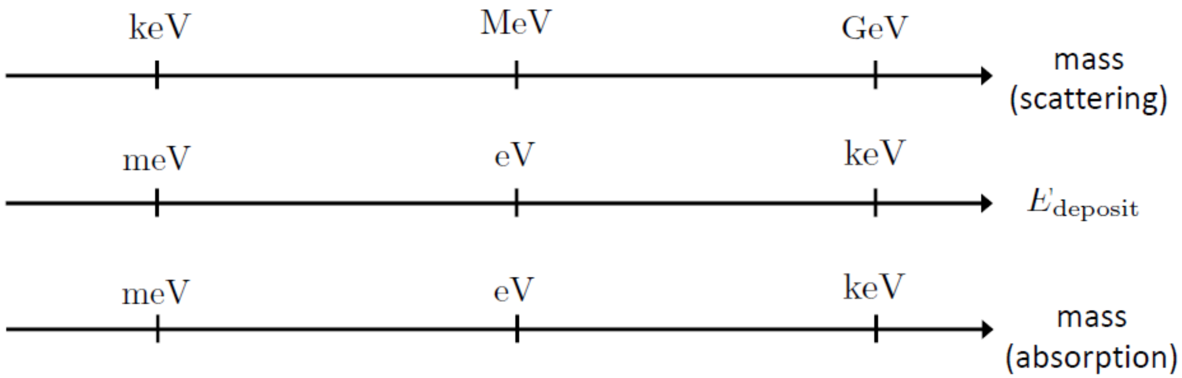
standard WIMP scenarios ($\mathbf{m_W = 1 - 10}$ **GeV**) : Look for NR, **very low energy threshold!**

dark sector couplings ($\mathbf{m_W = 1 - 1000}$ **MeV**) : Inelastic scattering off bound electrons

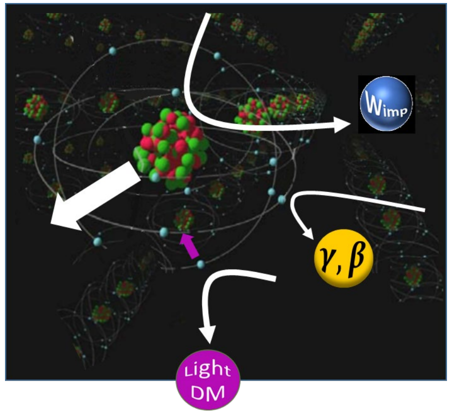
dark sector & ALPS ($\mathbf{m_W = 1 - 10^6}$ **eV**) : DM absorption



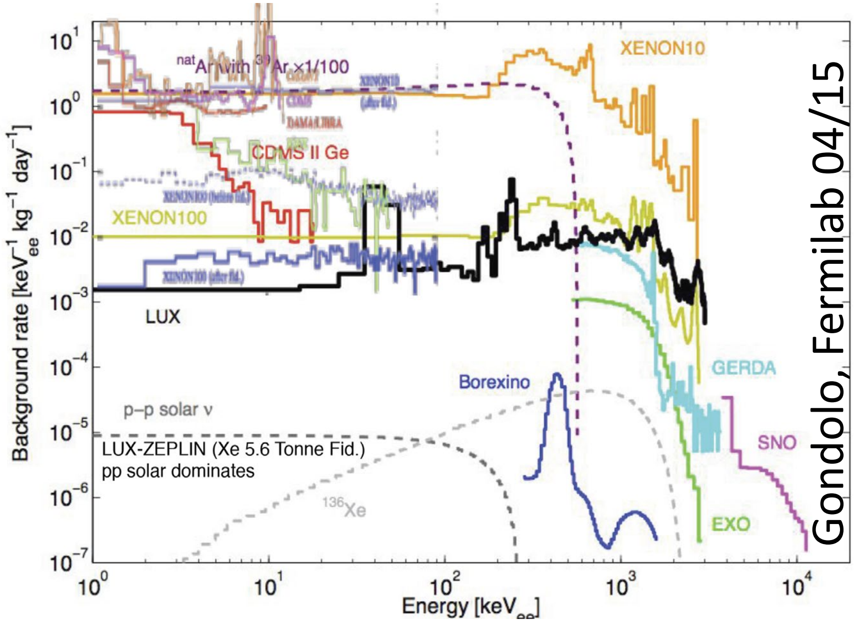
In this case, all the mass-energy of the DM particle is absorbed



Backgrounds



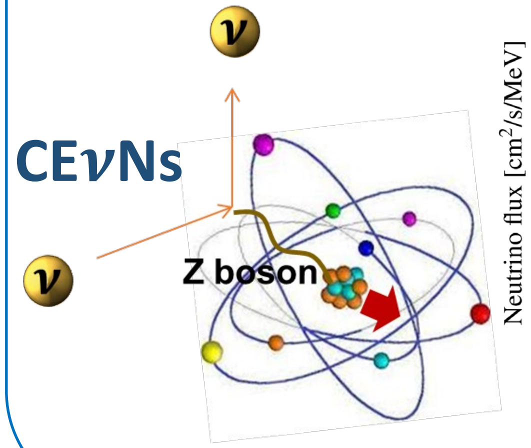
α, β, γ	material selection, shielding, **particle discrimination techniques**
$n\ N \ \rightarrow n\ N$	most critical for NR (mimic WIMP signal). Shielding, active rejection (multiplicity)
$\nu\ e^{-} \rightarrow \nu\ e^{-}$	ultimate background for ER recoils
$\nu\ N \ \rightarrow \nu\ N$ (CEνNs)	ultimate background for NR search **(neutrino fog)**

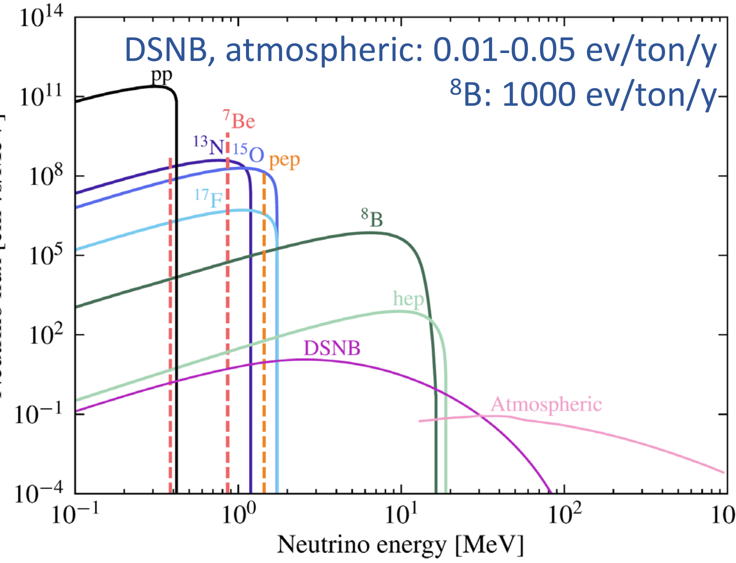


Gondolo, Fermilab 04/15

^{8}B, DSNB and atmospheric neutrinos produce nuclear recoils via CEνNs that cannot be distinguished from WIMP signals!

CEνNs

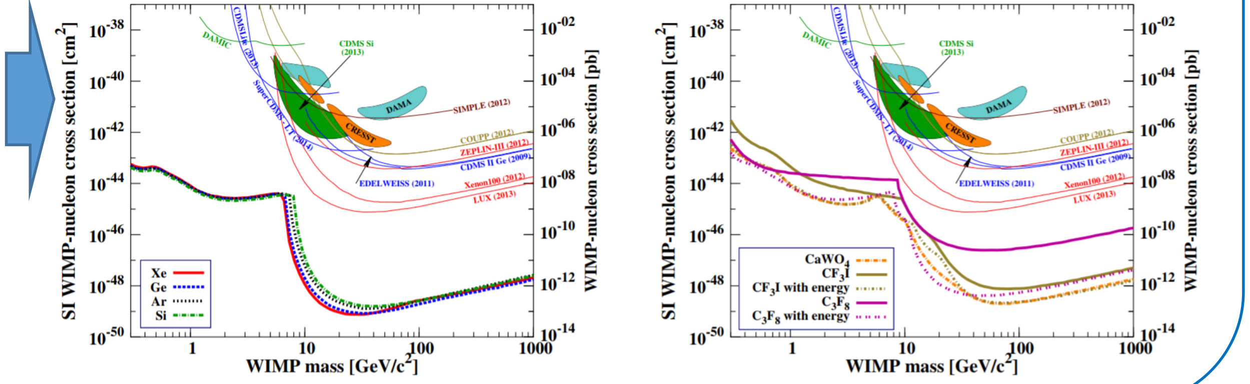




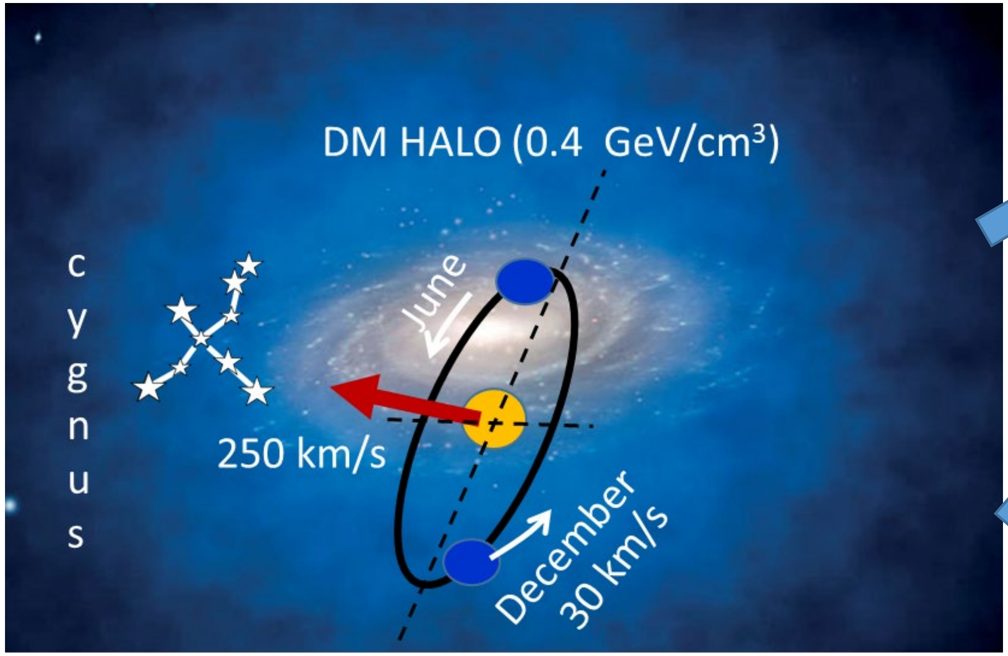
DSNB, atmospheric: 0.01-0.05 ev/ton/y

^{8}B: 1000 ev/ton/y

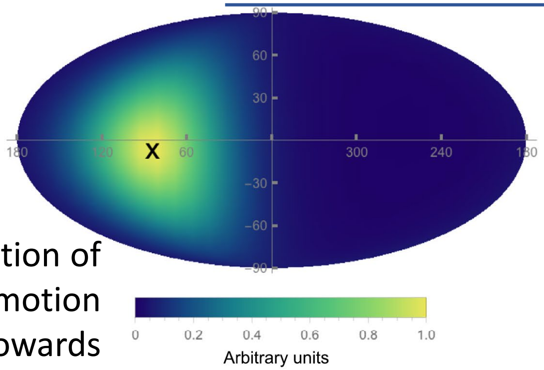
the sensitivity of the experiments does not evolve as in a bkg free experiment, but much slower → lower limit in achievable cross-section (neutrino fog)



Distinctive signatures

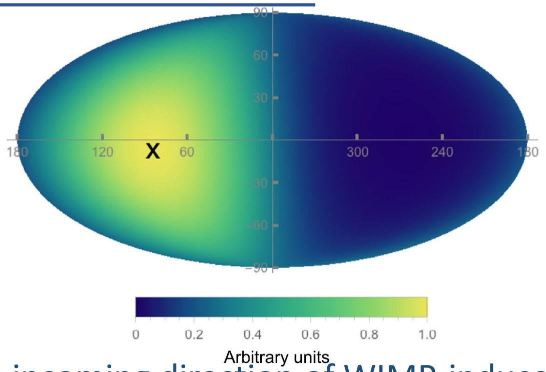


DIRECTIONALITY OF THE RECOIL



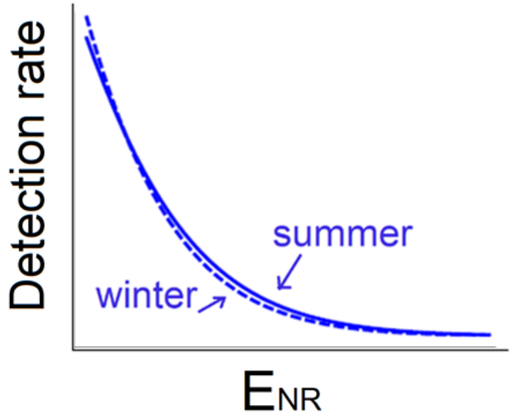
X: direction of Earth motion (towards Cygnus)

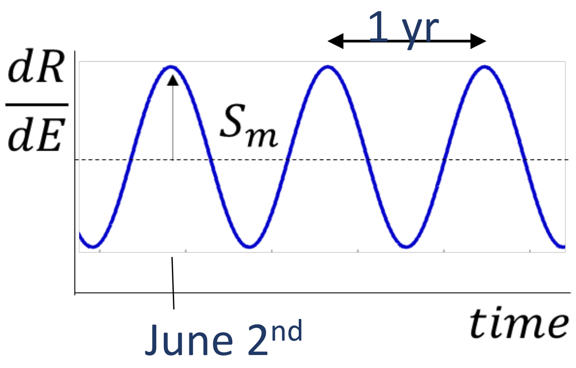
WIMP flux



incoming direction of WIMP-induced recoils (convention: recoil maps as directions where the recoils originate from)

ANNUAL MODULATION IN THE EXPECTED RATE





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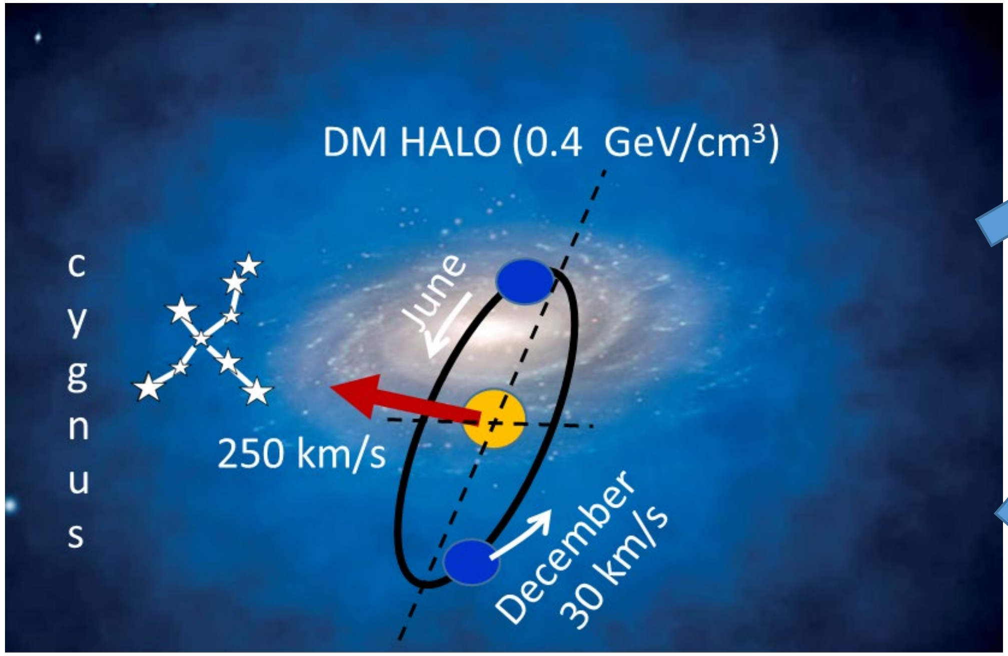
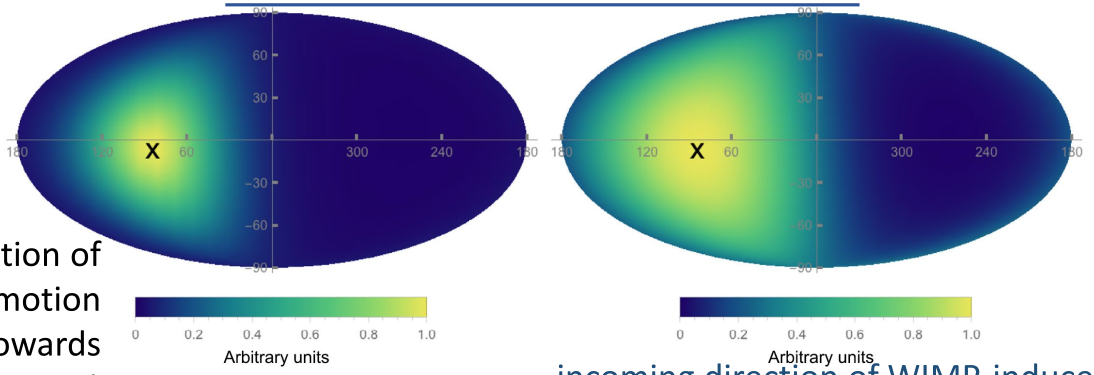


DIRECTIONALITY OF THE RECOIL



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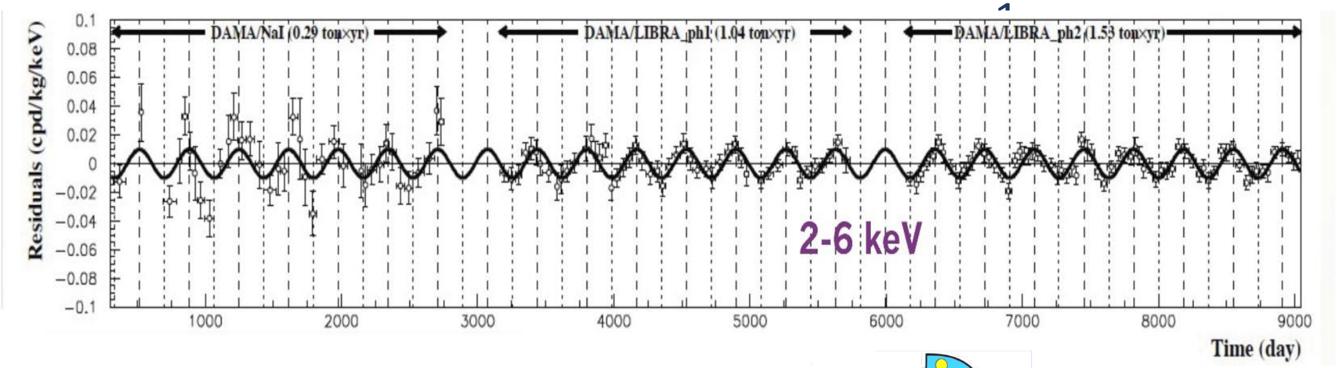
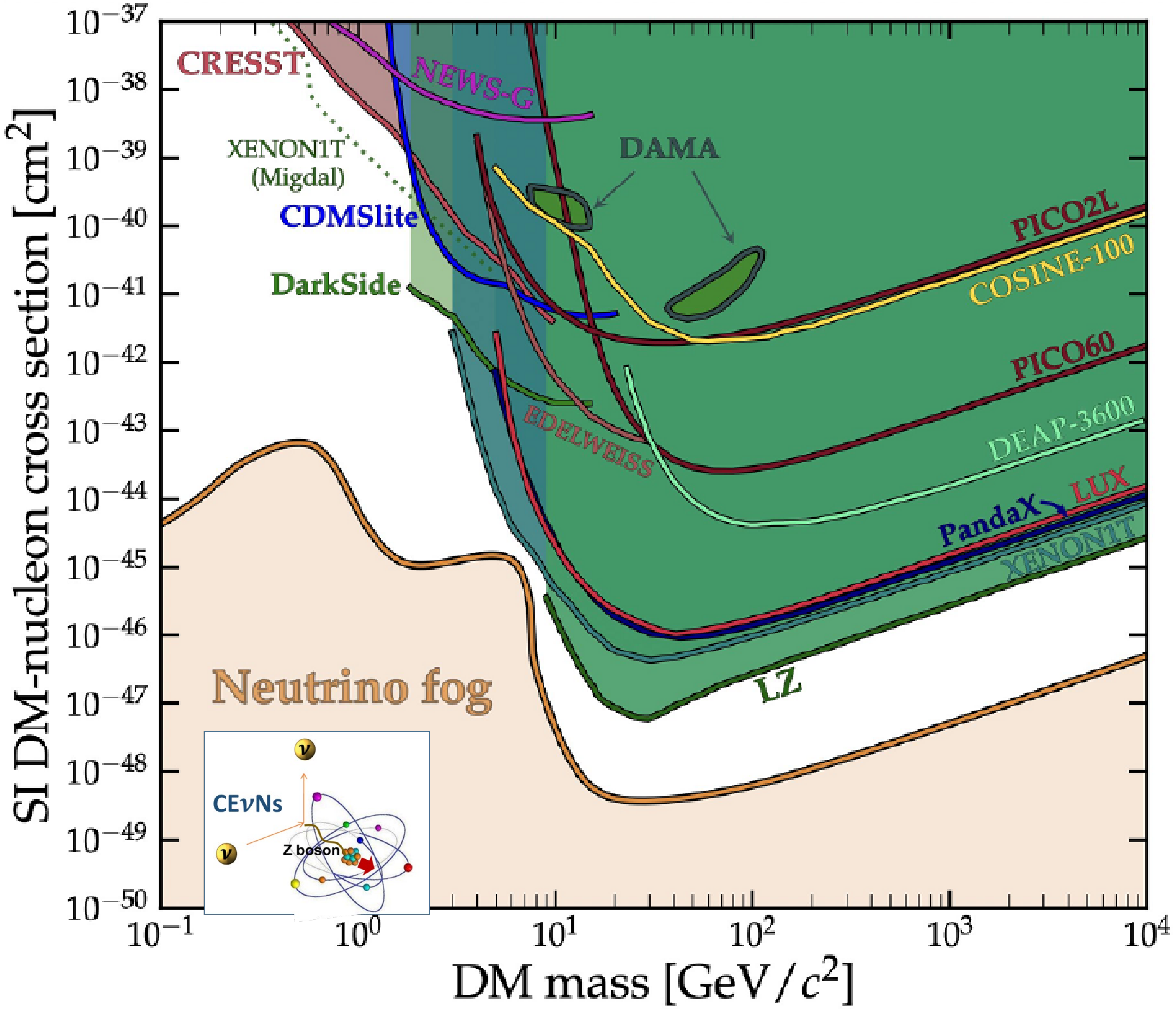
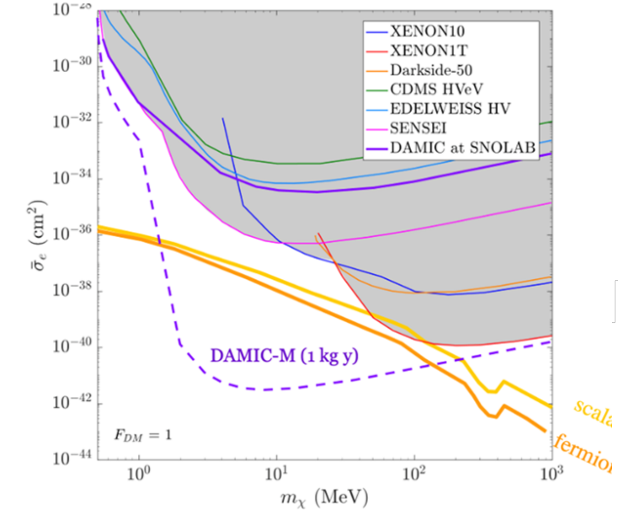


OBSERVED BY DAMA/LIBRA FOR MORE THAN 20 YEARS

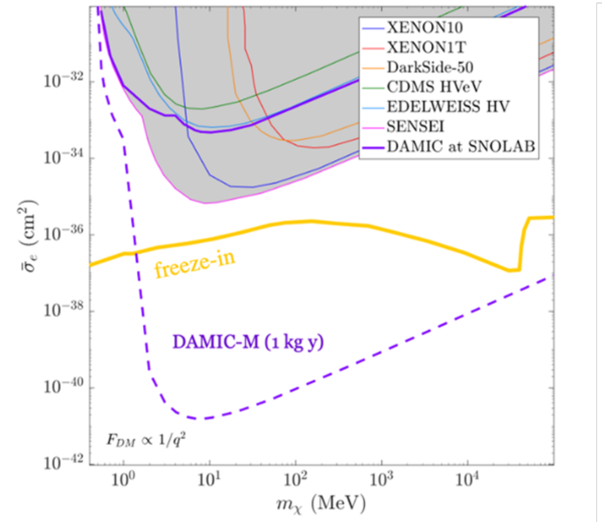
Present status



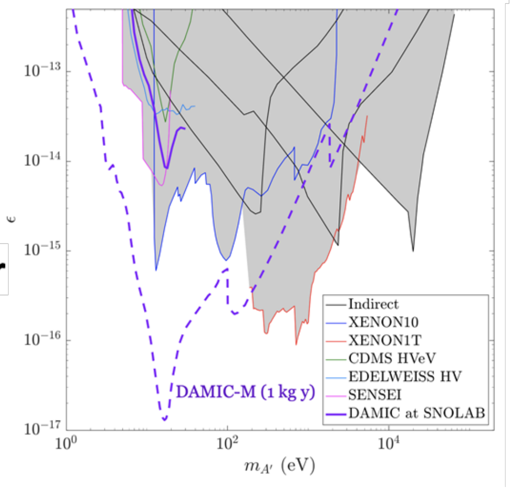
e^- scattering heavy mediator



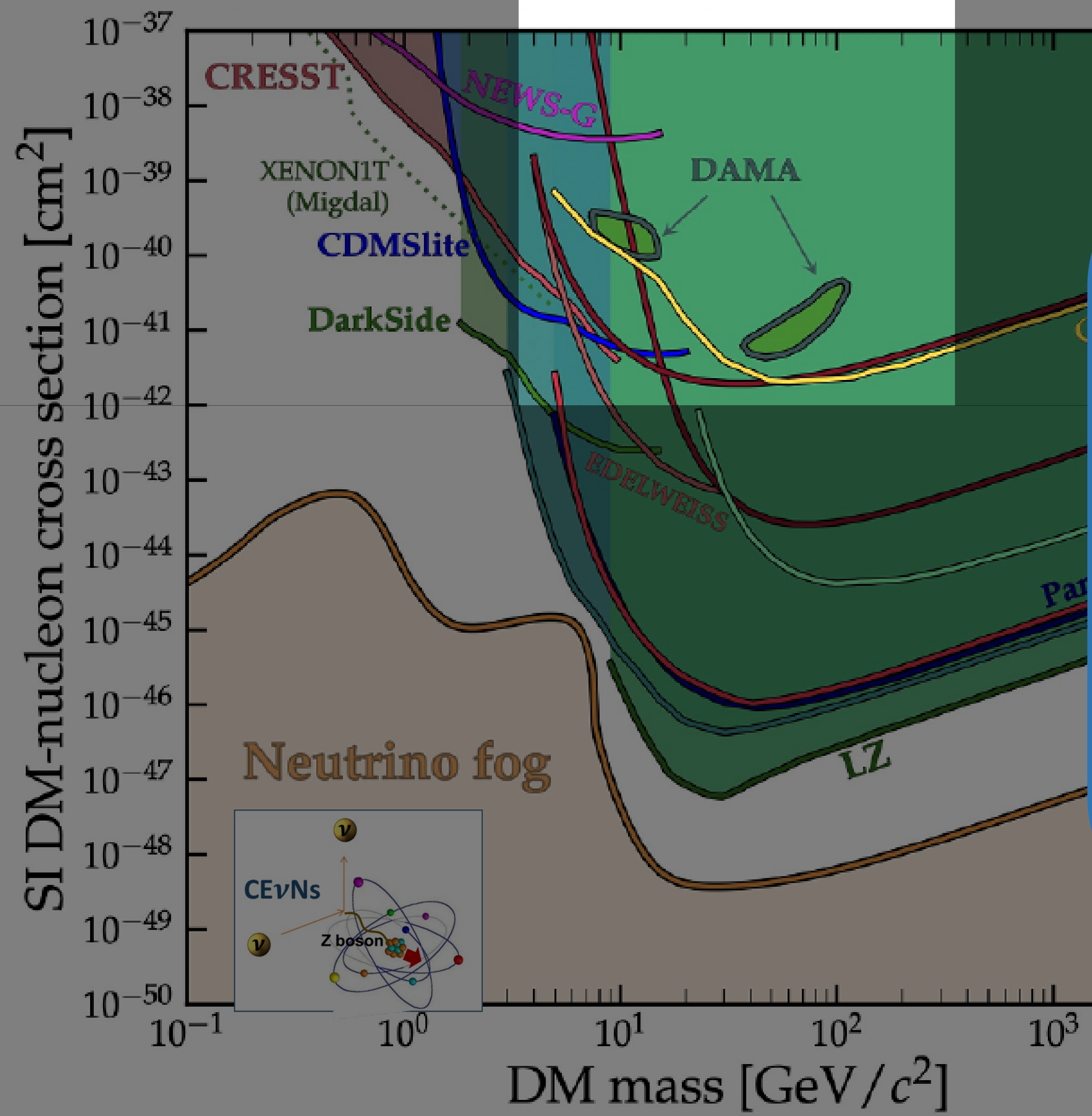
e^- scattering ultra-light mediator

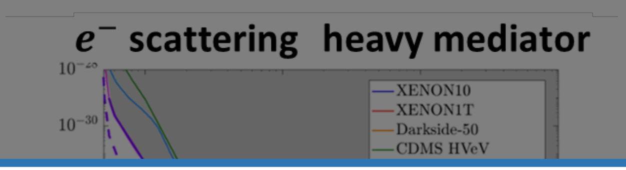


DM absorption

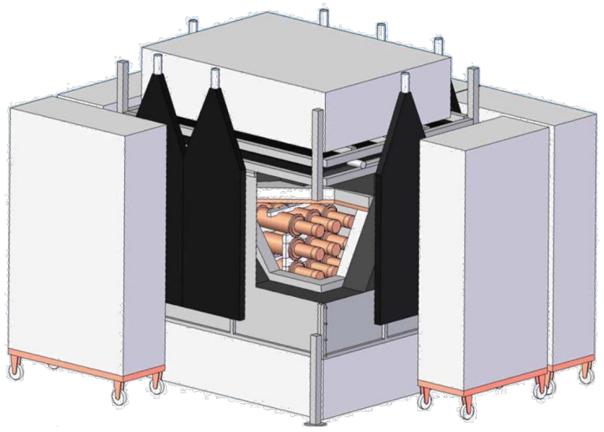


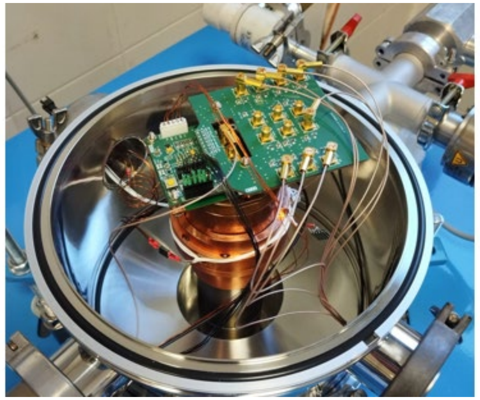
Scope of the LIA5 direct detection experiments



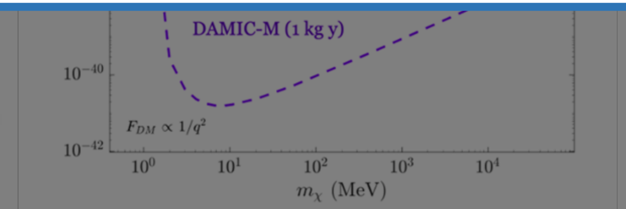


ANAIS-112 & ANAIS+





Test the DAMA/LIBRA signal in a model independent way



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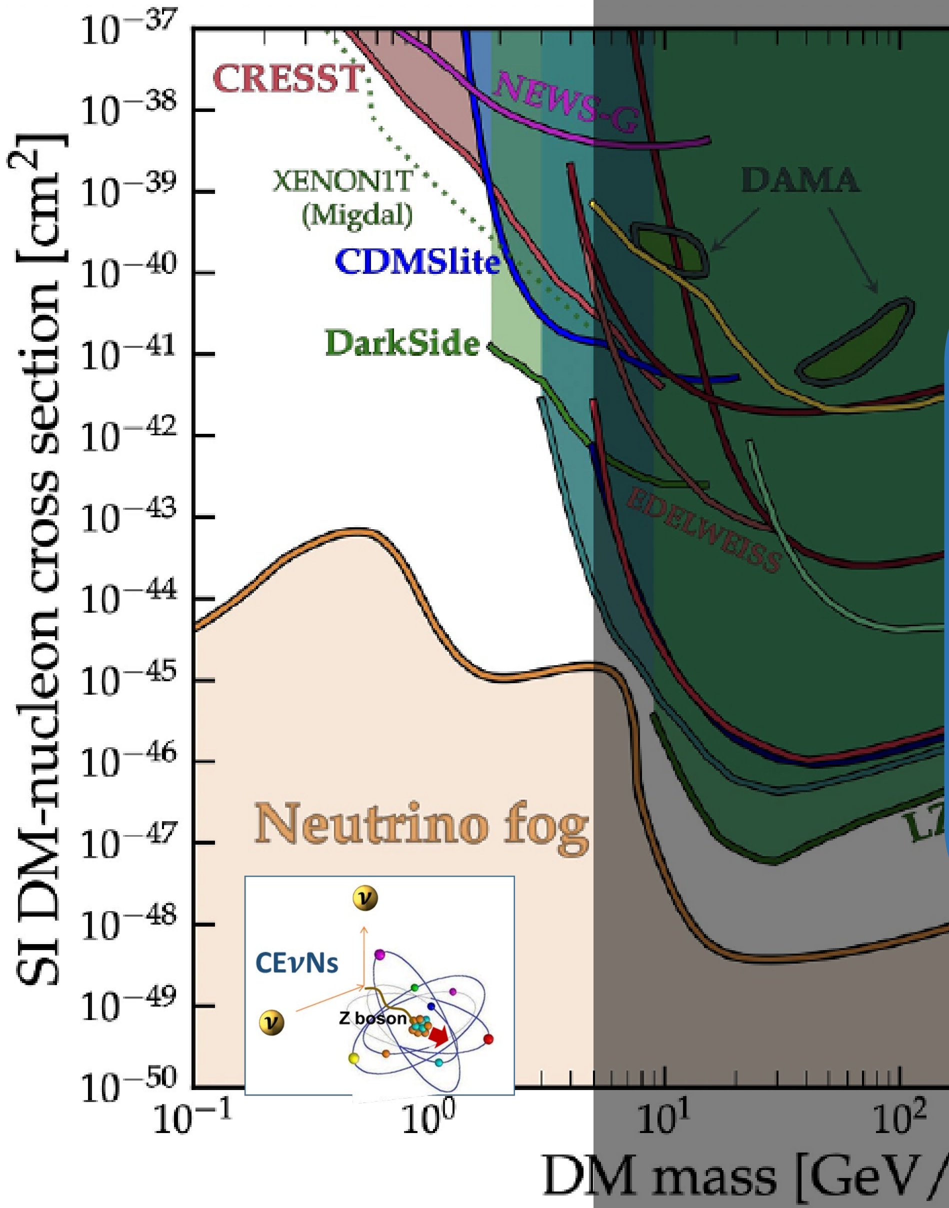
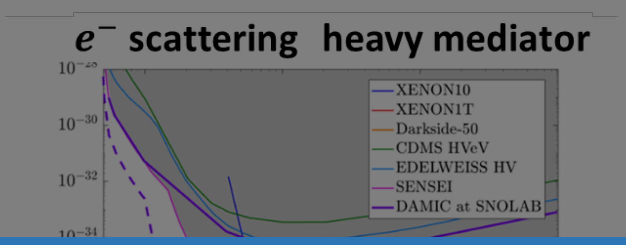
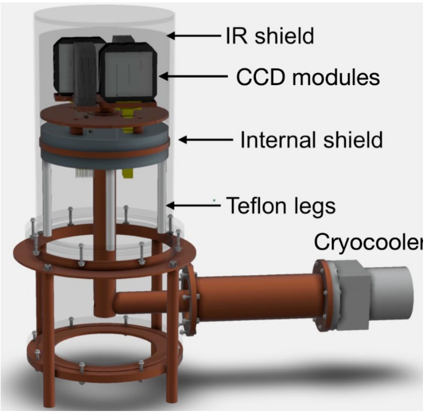
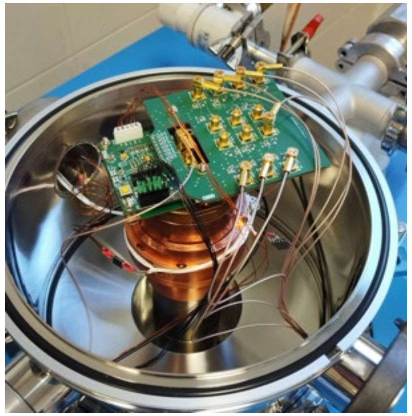


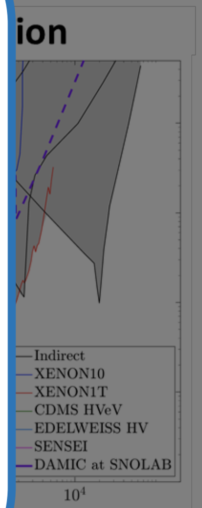


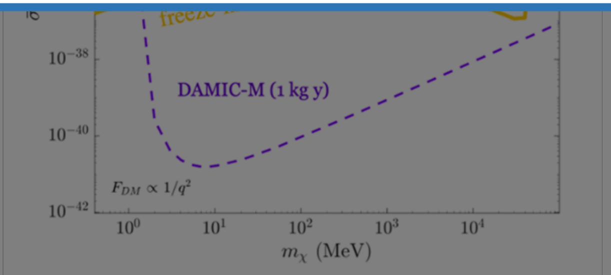
DAMIC TREX-DM ANAIS+



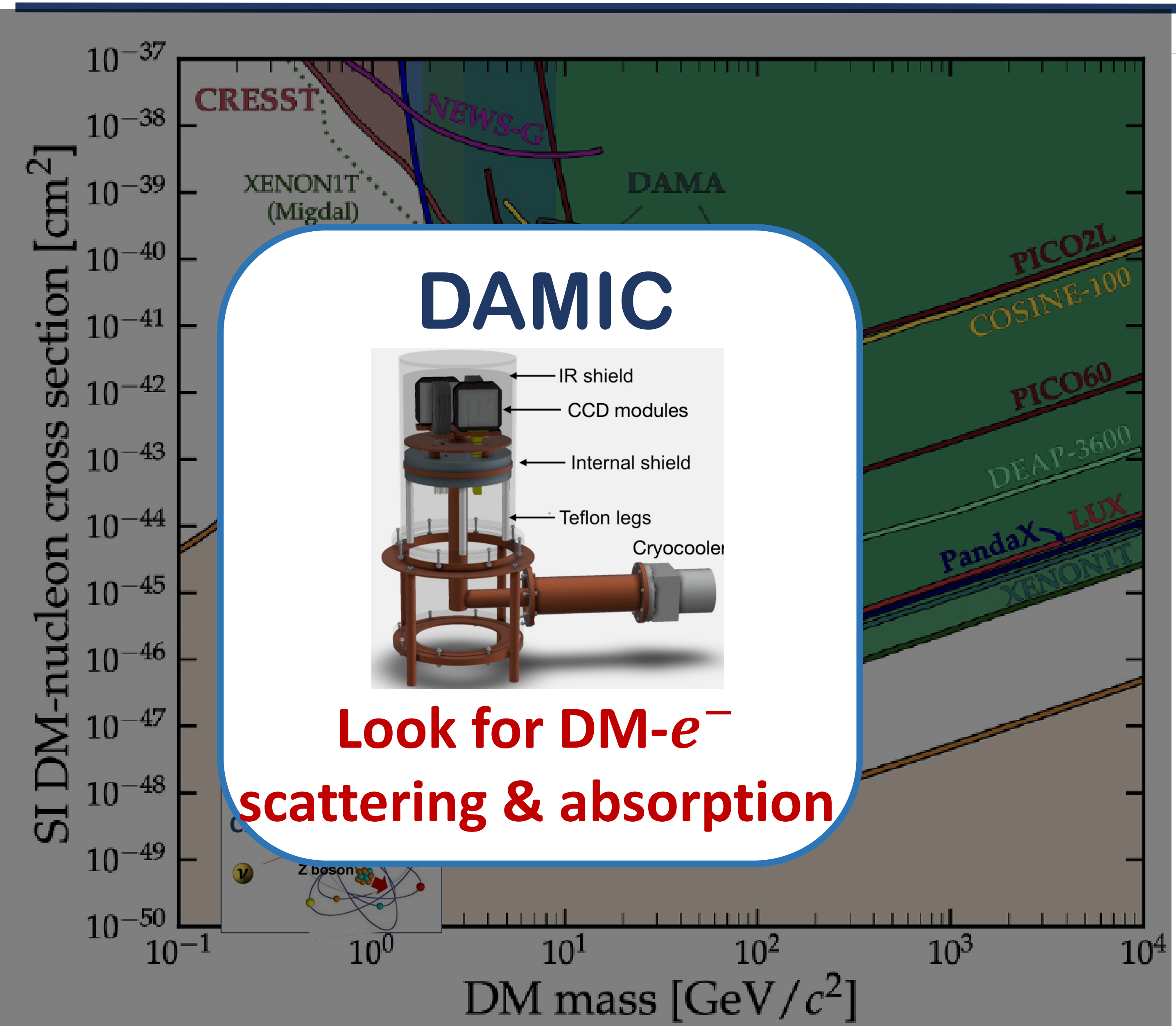


Explore the region of low-mass WIMPs



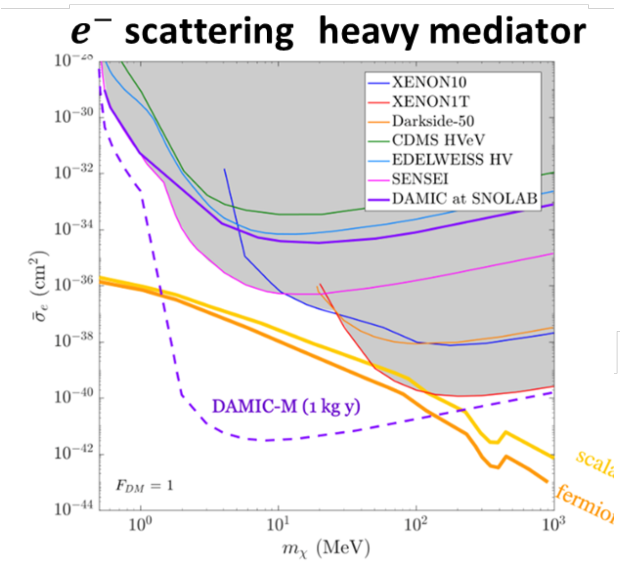


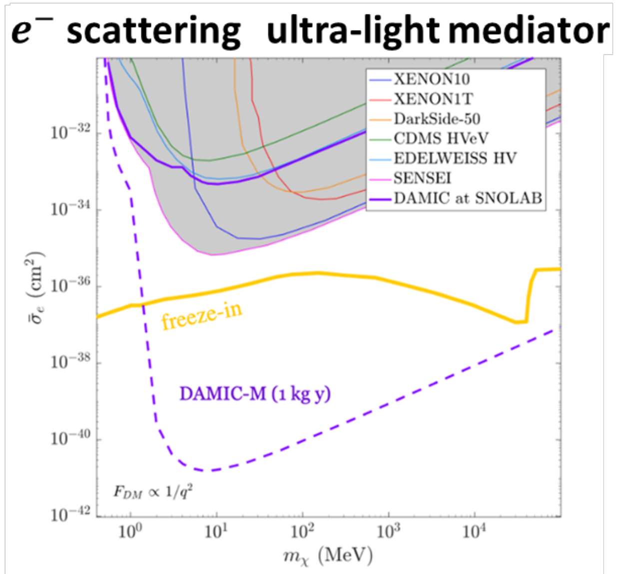
Scope of the LIA5 direct detection experiments

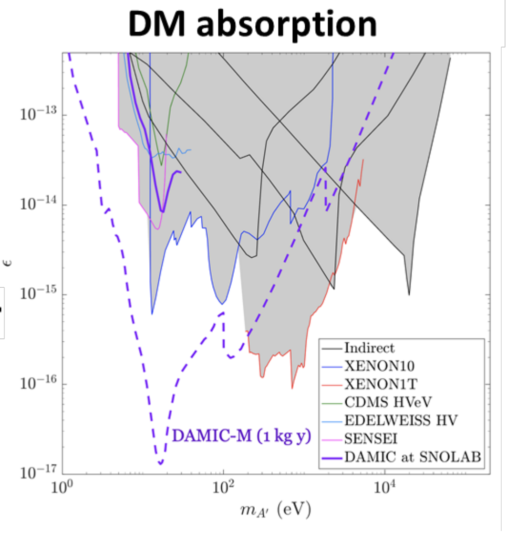


DAMIC

Look for DM-e^- scattering & absorption







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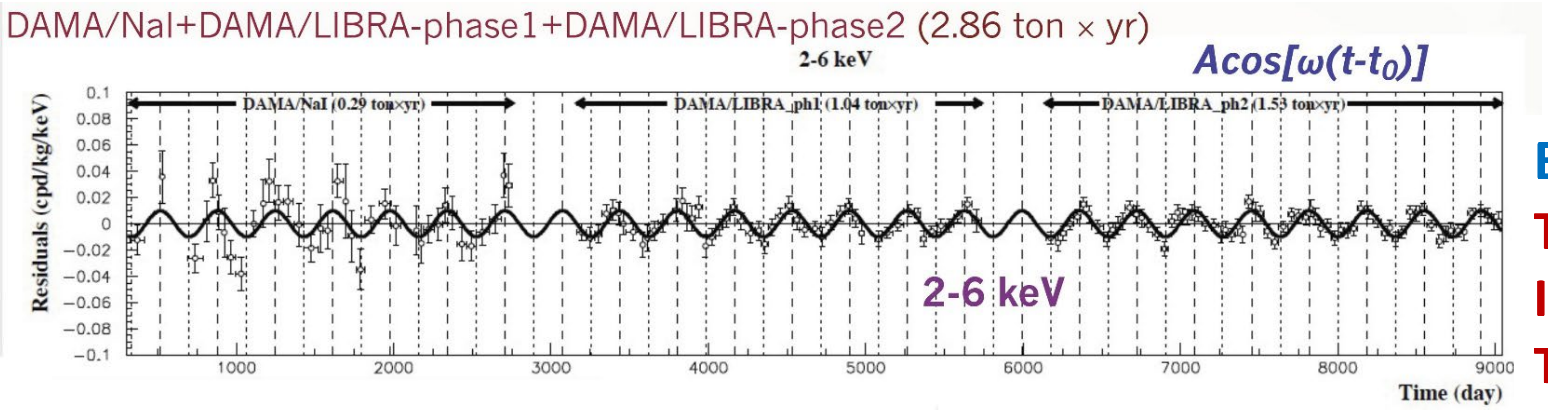
ANAIS-112 & ANAIS+

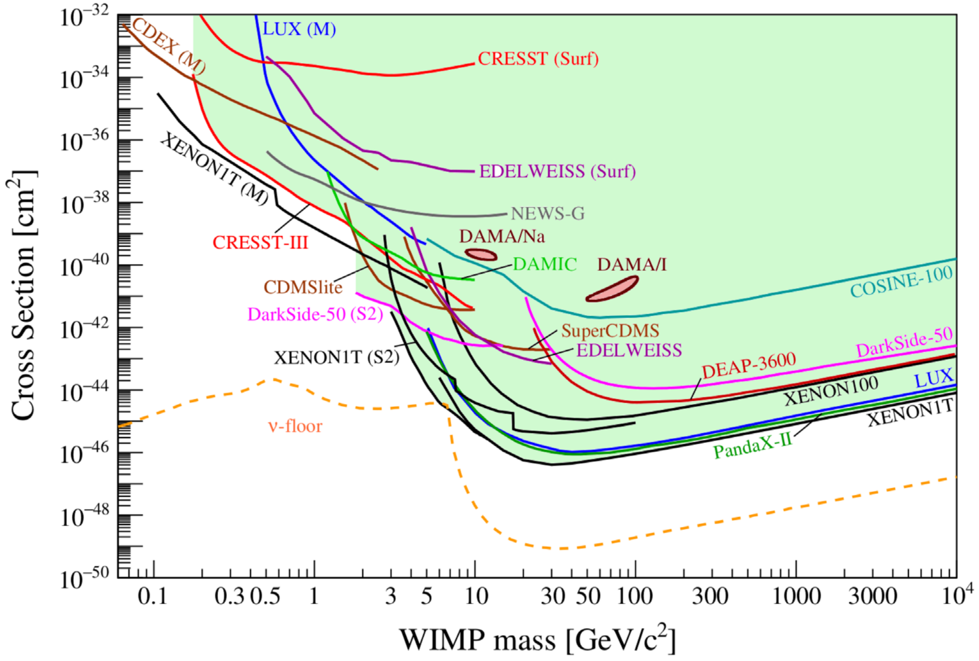
Testing the DAMA/LIBRA signal

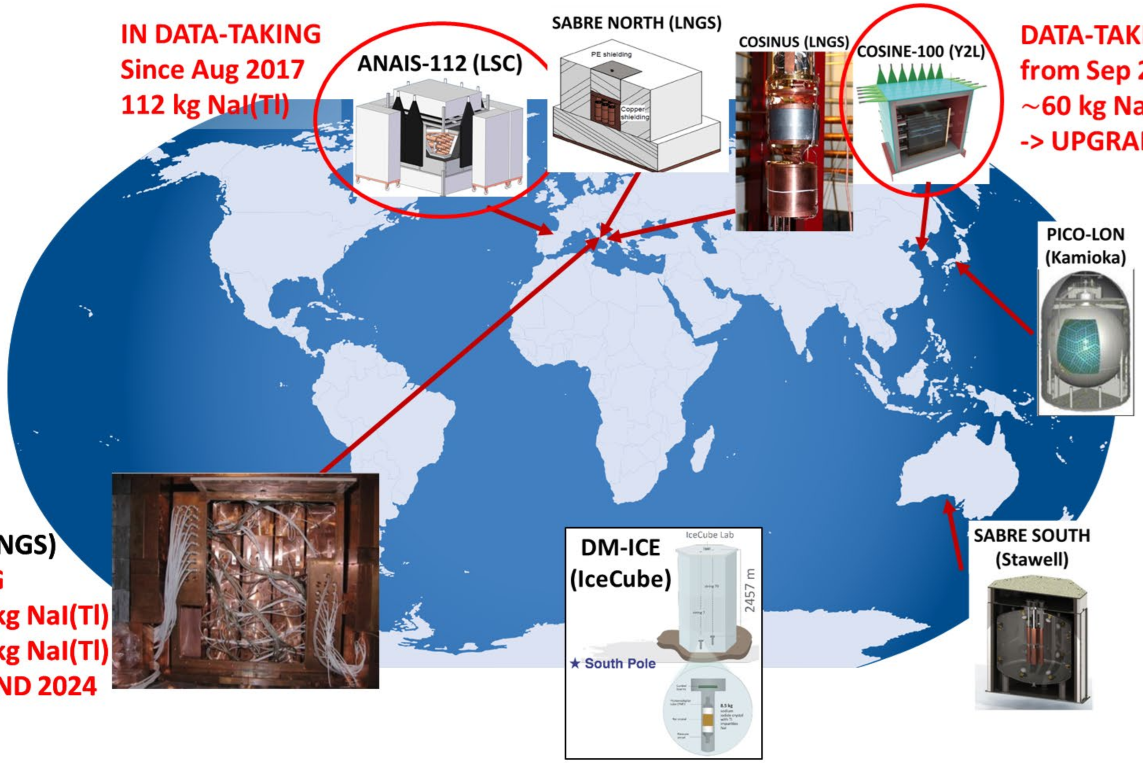


DAMA clearly sees an annual modulation at 12.9σ but **the parameter's region singled out by DAMA/LIBRA is excluded by many DM experiments**

But this comparison is model dependent

TO AVOID ANY MODEL DEPENDENCE, AN INDEPENDENT CONFIRMATION WITH THE SAME TARGET , NaI(Tl), IS REQUIRED





IN DATA-TAKING
Since Aug 2017
112 kg NaI(Tl)

DATA-TAKING
from Sep 2016 – Mar 2023
~60 kg NaI(Tl)
-> UPGRADE COSINE200

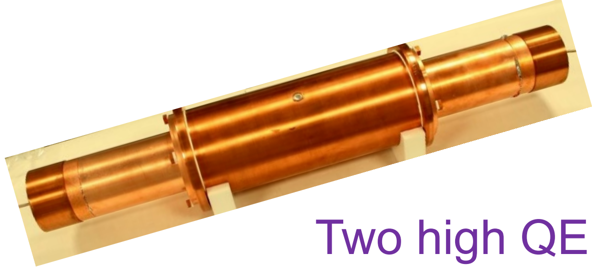
DAMA/LIBRA (LNGS)
IN DATA-TAKING
Since 1995 100 kg NaI(Tl)
Since 2003 250 kg NaI(Tl)
Stop foreseen END 2024

ANAIS-112

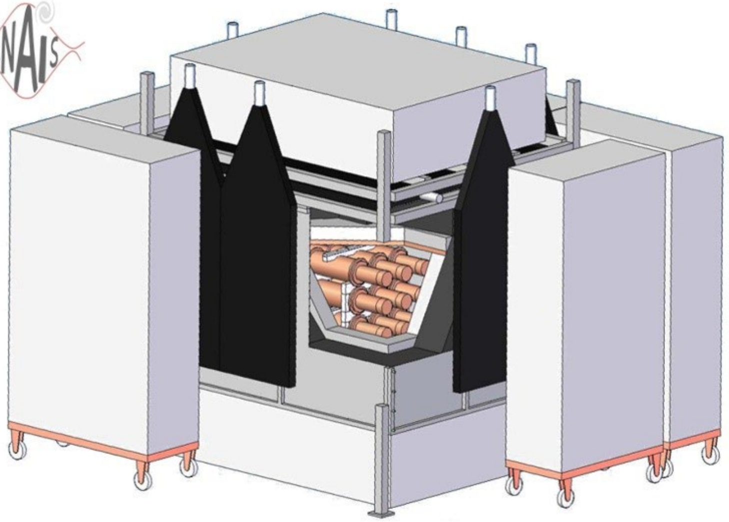
https://gifna.unizar.es/anais/

Annual Modulation with NaI Scintillators

3x3 matrix of 12.5 kg NaI(Tl) cylindrical modules = **112.5 kg** of active mass



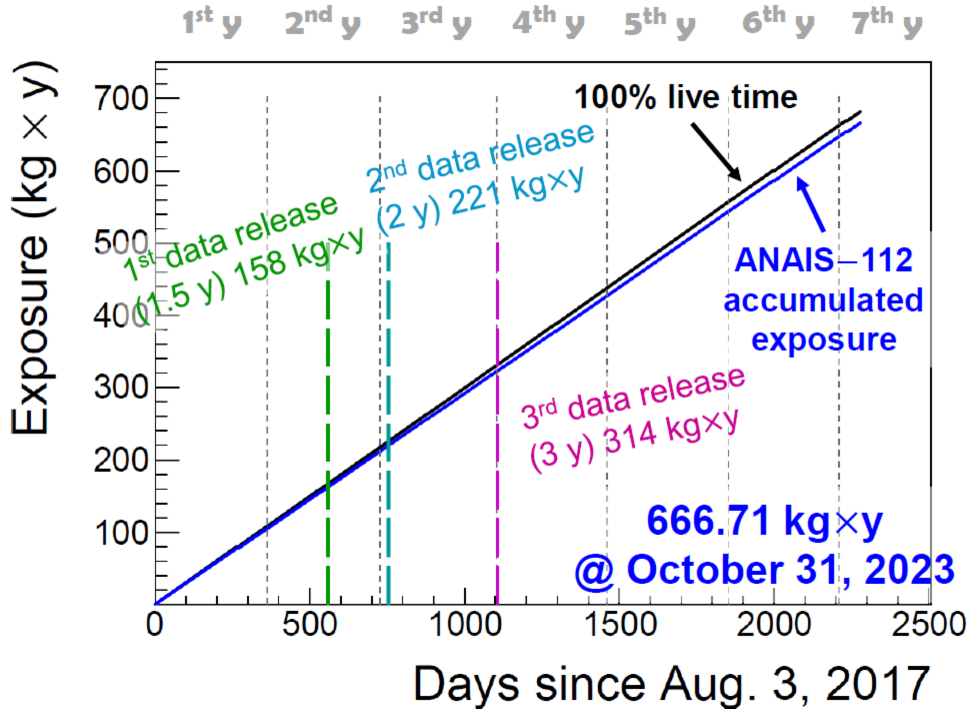
Two high QE PMTs per detector



taking data since August 2017 at the Canfranc Underground Laboratory (LSC) Spain (2450 m.w.e.)

ANAIS-112 data releases:

- 1.5y: Phys. Rev. Lett. 123, 031301 (2019)
- 2y: J. Phys. Conf. Ser. **1468,** 012014 (2020)
- 3y: Phys. Rev. D 103, 102005 (2021
- **3y + ML: 2404.17348**



Improving ANAIS sensitivity

I. Coarasa talk

1. New filtering protocol based on machine learning (ML) techniques
2. Improving the background model (6 years analysis)
3. NR Quenching factor measurements
4. Participation in an underground crystal growing facility at LSC
5. New Data acquisition system (DAQ) in parallel with ANAIS–112 one
6. Towards ANAIS+

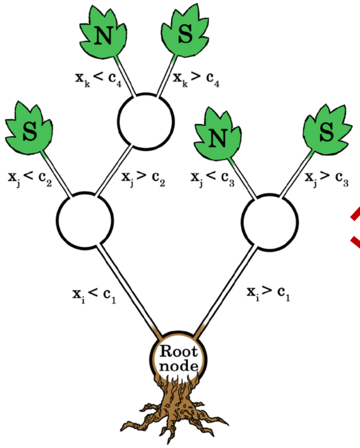
GOBIERNO DE ARAGON

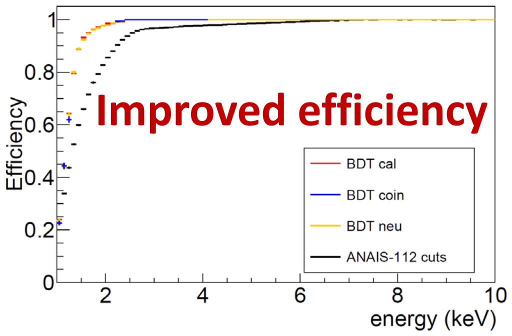
Plan de Recuperación, Transformación y Resiliencia

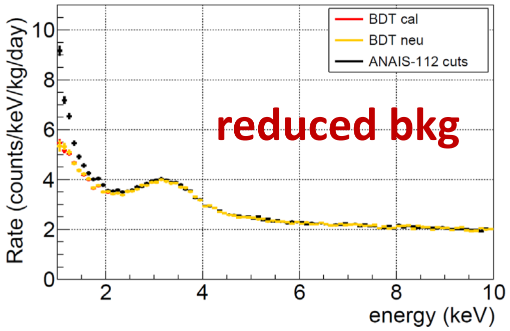
Financiado por la Unión Europea NextGenerationEU

ANAIS-112 3-years annual modulation with ML

BDT for event selection







best fit modulation amplitudes compatible with zero at ~1σ

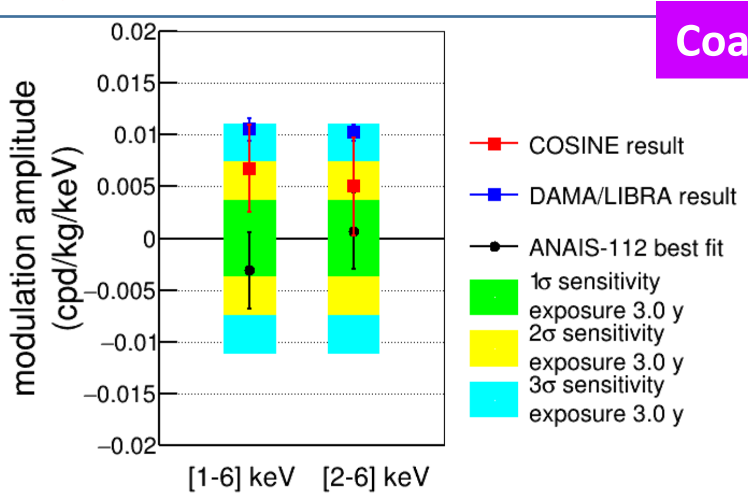
Best fit incompatible with DAMA/LIBRA at 3.9 (2.8) σ for [1-6] ([2-6]) keV

Sensitivity with 3 years data: 2.8σ for [1-6] & [2-6] keV

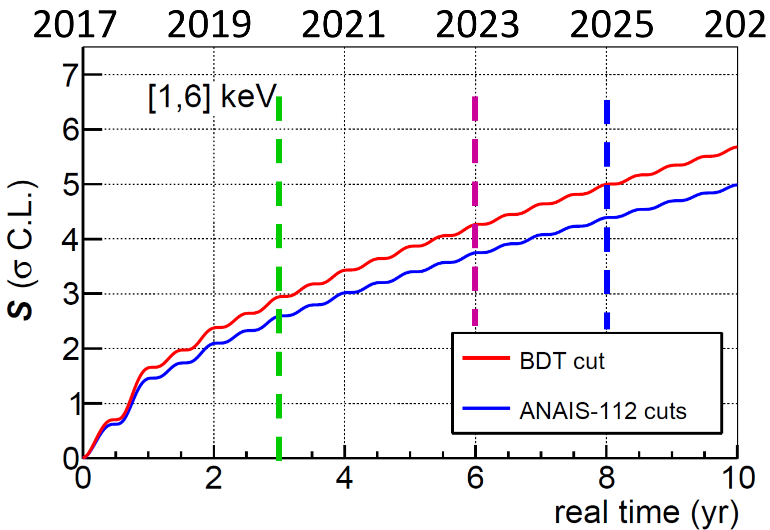
>4*σ* expected this summer (6y unblinding)

5*σ* sensitivity at reach in late 2025

Coarasa et al, 2404.17348



	S_m(cpd/keV/ton)		
E (keV)	**ANAIS-112**	**COSINE-100**	**DAMA/LIBRA**
[1-6]	-3.7±3.7	6.7±4.2	10.5±1.1
[2-6]	0.7±3.7	5.0±4.7	10.2±0.8



ANAIS+

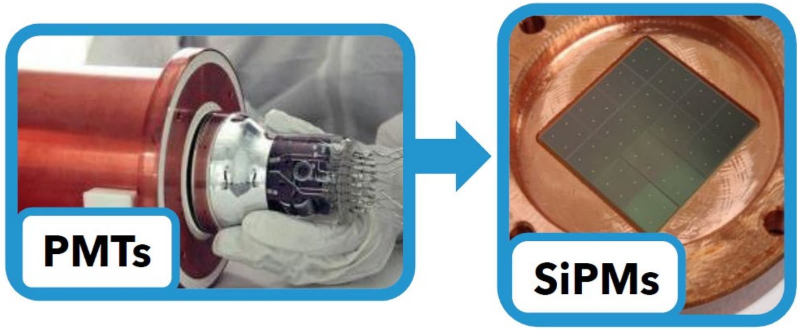
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

INFN LNGS

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

I. Coarasa talk

Goal: Lower the energy threshold Eth <0.5 keV.



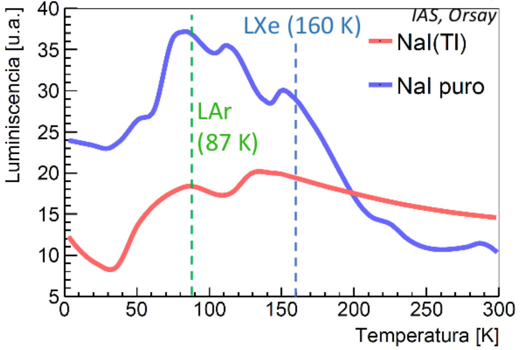
Replace PMTs for SiPM at low T (~100 K)

ADVANTAGES

- High QE.
- High radiopurity.
- Low operating voltage.
- No Cherenkov emission.
- Reduction of spurious light emission

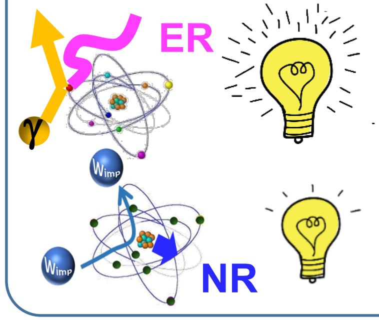
MAIN DRAWBACK: High dark current rate
-> Overcome by working at low T

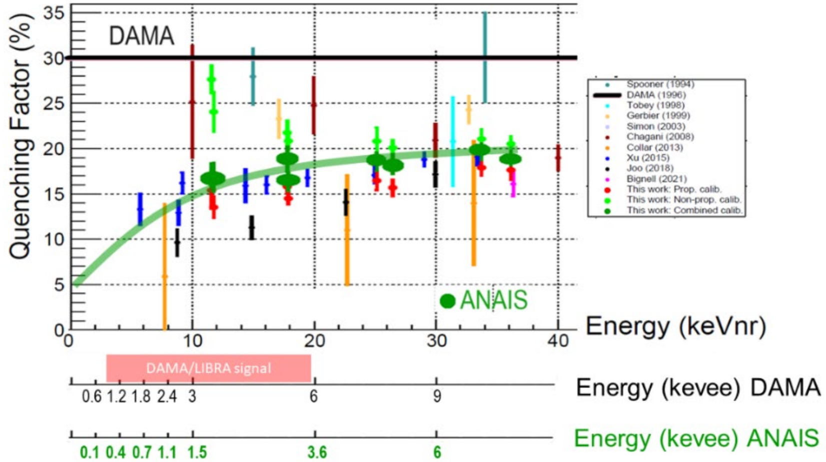
BONUS: NaI pure is a very good scintillator at 100 K



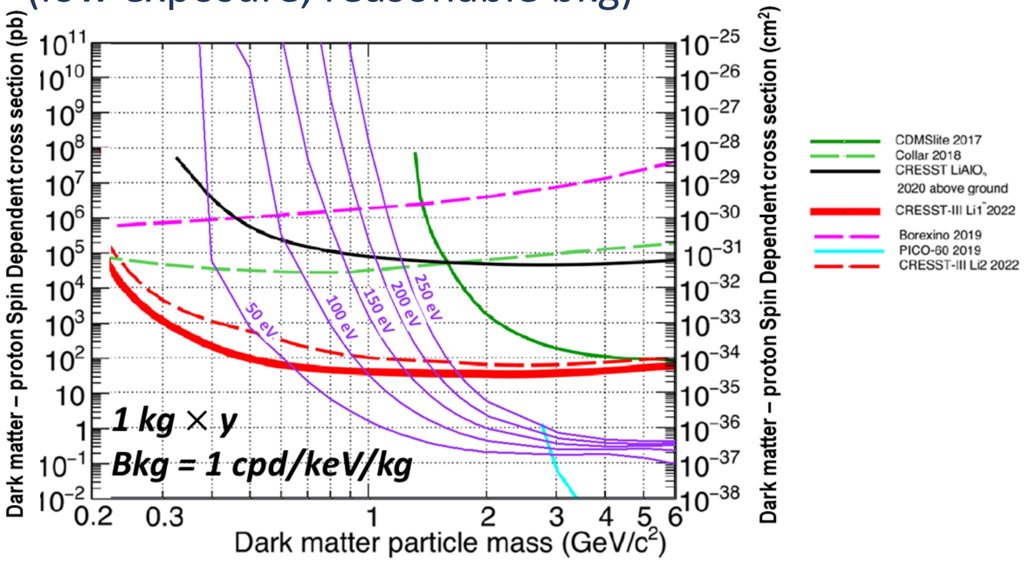
Measurement in collaboration with N. Coron, IAS, Orsay

rule out any effect related to QF differences





Very sensitive to light WIMPs (SI, SD)
(low exposure, reasonable bkg)

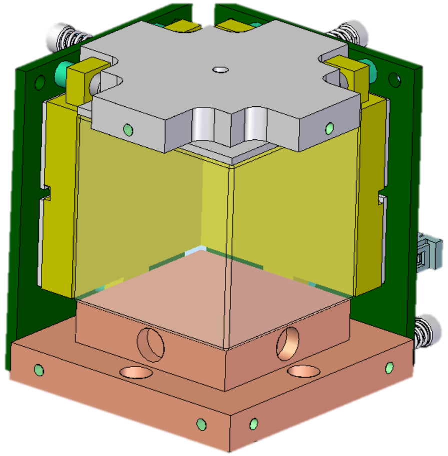


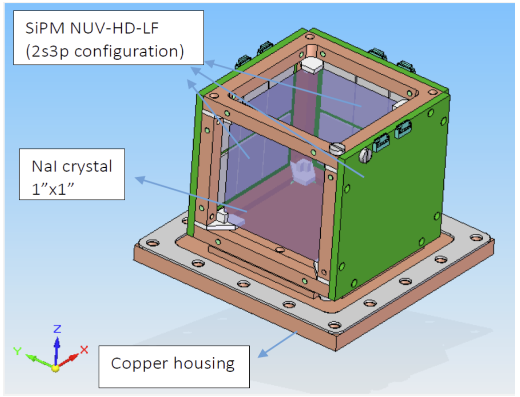
First ANAIS+ prototype

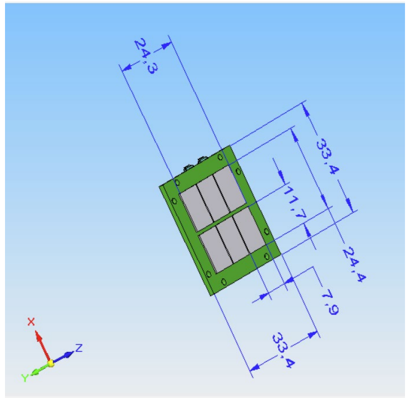
CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

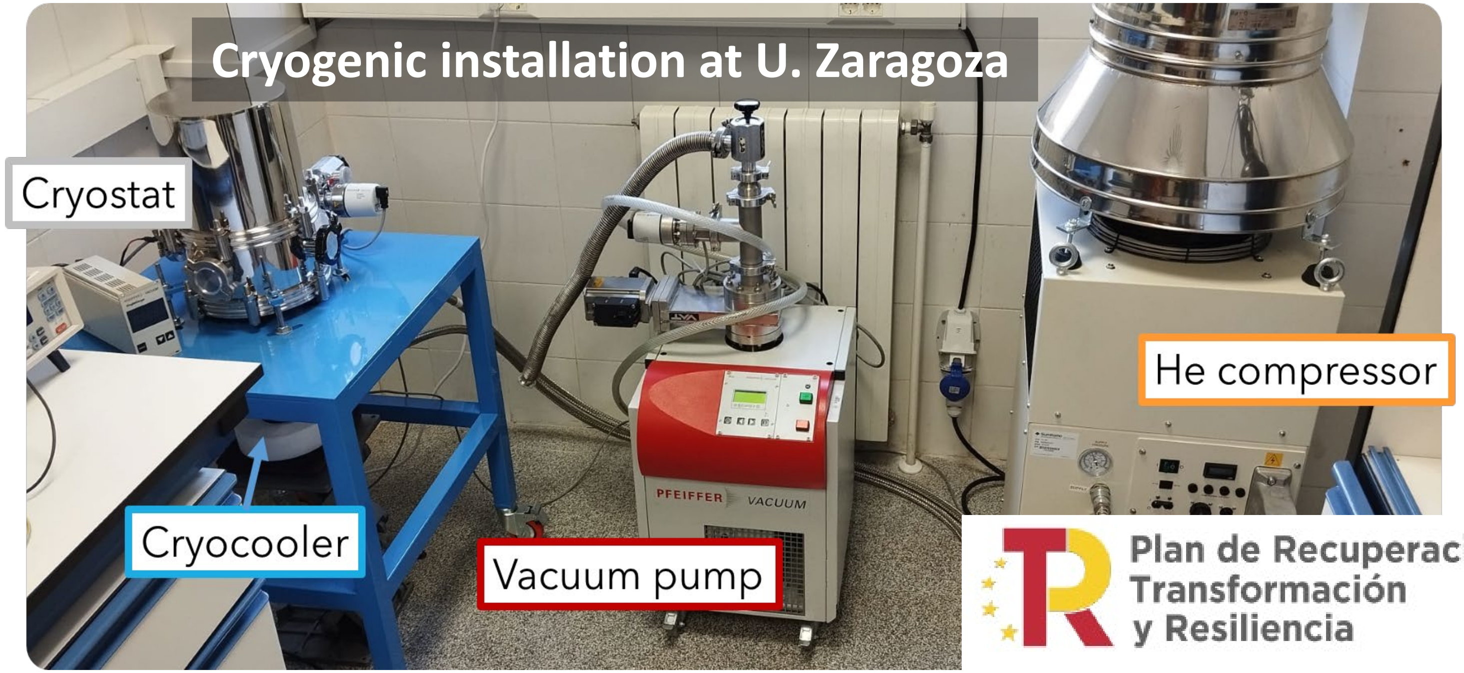
INFN LNGS

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas



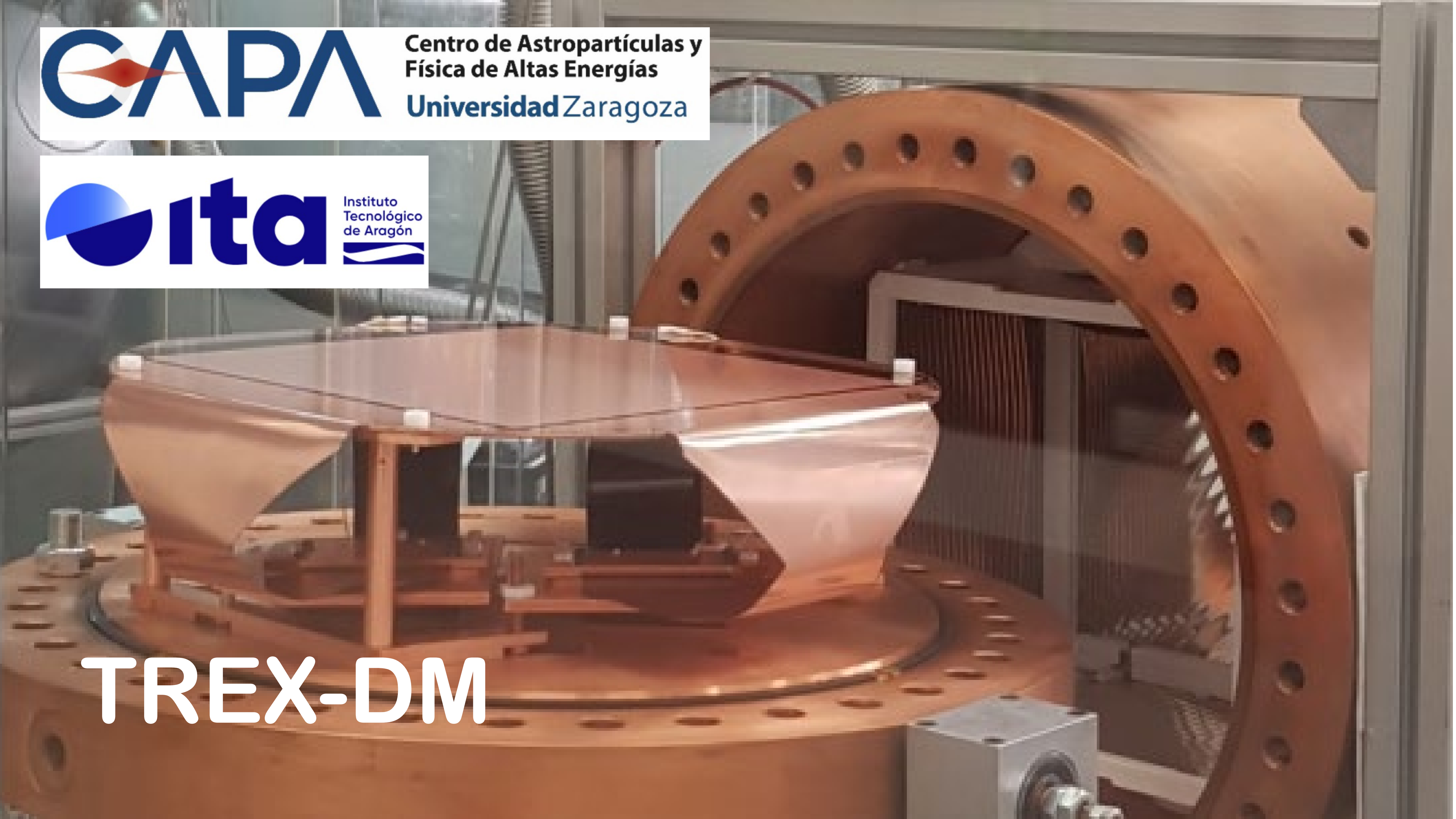






Plan de Recuperación, Transformación y Resiliencia

- SiPMs designed and produced at LNGS
  (4 sides x 6 SiPM /side)
- Structure & PMMA pieces designed & constructed at CAPA
- Testing of the prototype (no NaI) at LNGS (beginning of July).
- Prototype integration and testing@ CAPA cryolab in fall 2024
- Next step: test in LAr at LSC



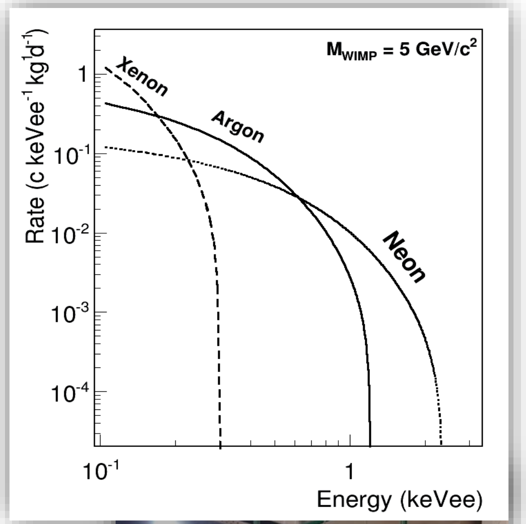
CAPA
Centro de Astropartículas y
Física de Altas Energías
Universidad Zaragoza

ita
Instituto
Tecnológico
de Aragón

TREX-DM

TREX-DM (TPC for Rare Event eXperiments-Dark Matter)

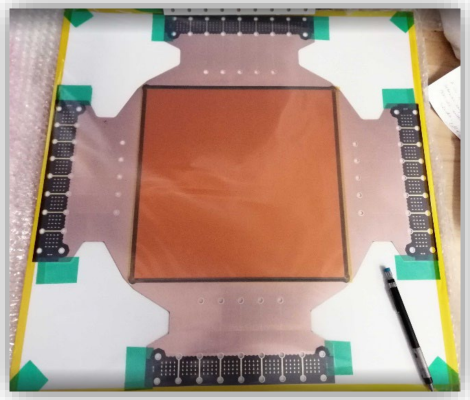
- **A Micromegas TPC for light-WIMPs at the LSC**
- ~20 l of pressurized gas (~0.16 kg Ne at 10 b)
- microbulk Micromegas and AGET-based electronics.
- **Goals: low energy threshold** (< 1 keV) and low background level (~1 (keV kg day)$^{-1}$).
- NOT focused in directionality → operation at high P

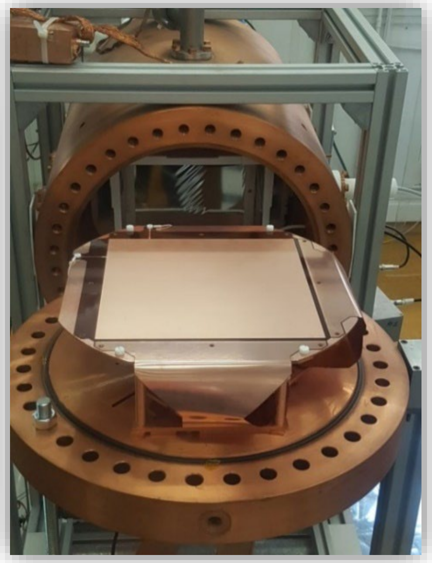


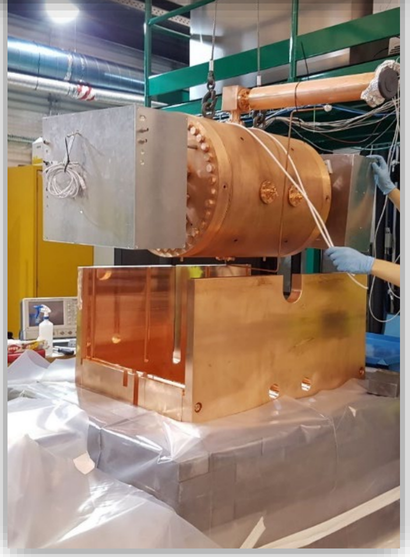
A. Ezquerro talk

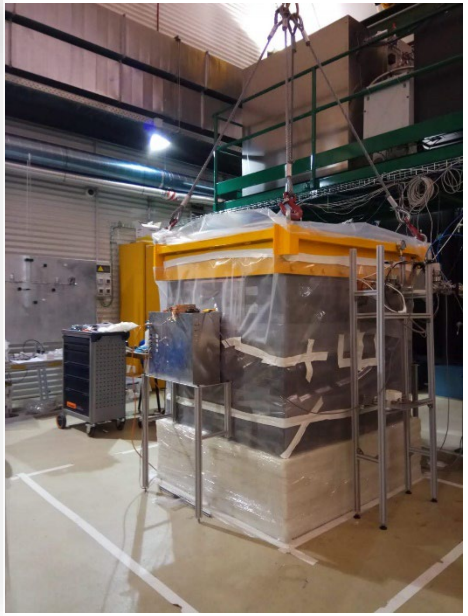
The lighter the target, the more sensitive to low mass

YouTube







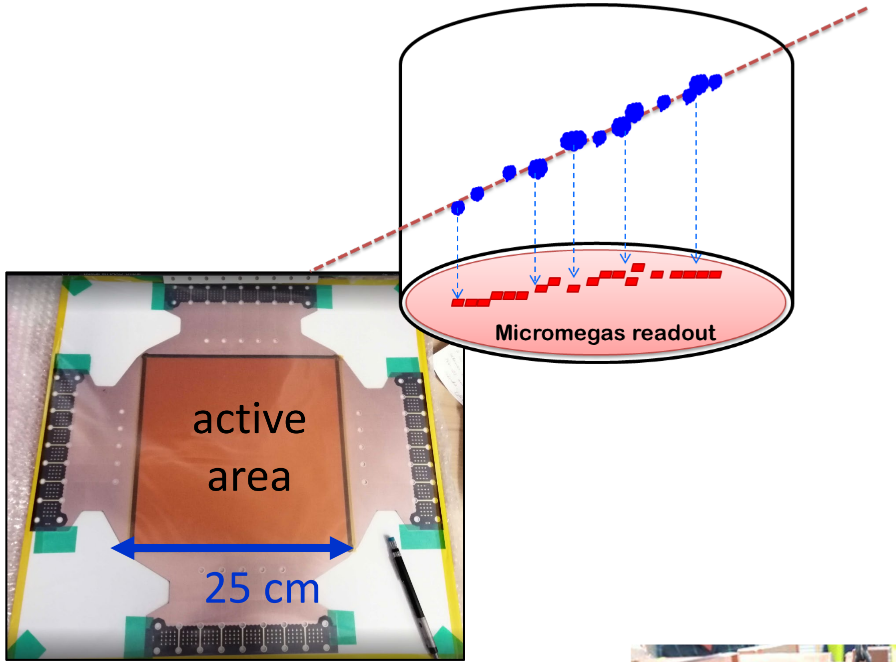


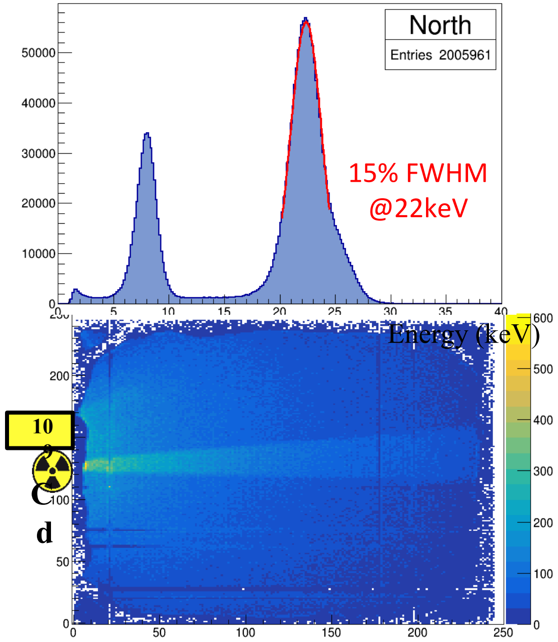
H=0.5 m, D=0.5 m, Central cathode

Why a gas TPC with a Micromegas readout

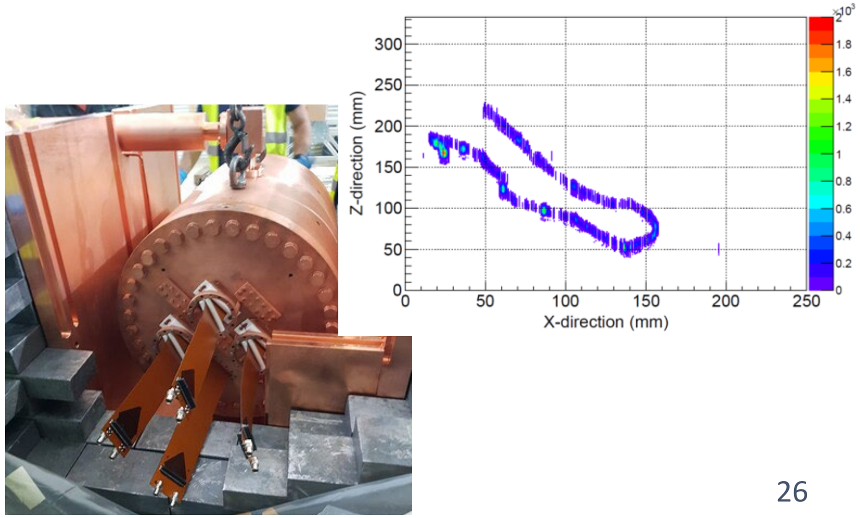
- Gas TPCs, combined with highly segmented readout planes offer:
  - Target selection flexibility
  - Low energy threshold
  - Access to rich topological information

- The microbulk Micromegas of TREX-DM
  - Biggest microbulk surface built
  - Radioactivity Control in process
  - Energy resolution
  - Segmentation 512 channels:
    - 256 X strips, 256 Y strips
  - Scaling up if needed





- At LSC, with a shielding consisting of 5 cm copper + 20 cm lead + Rn-free air (neutron shielding foreseen



Building TREX-DM
with the new mM:

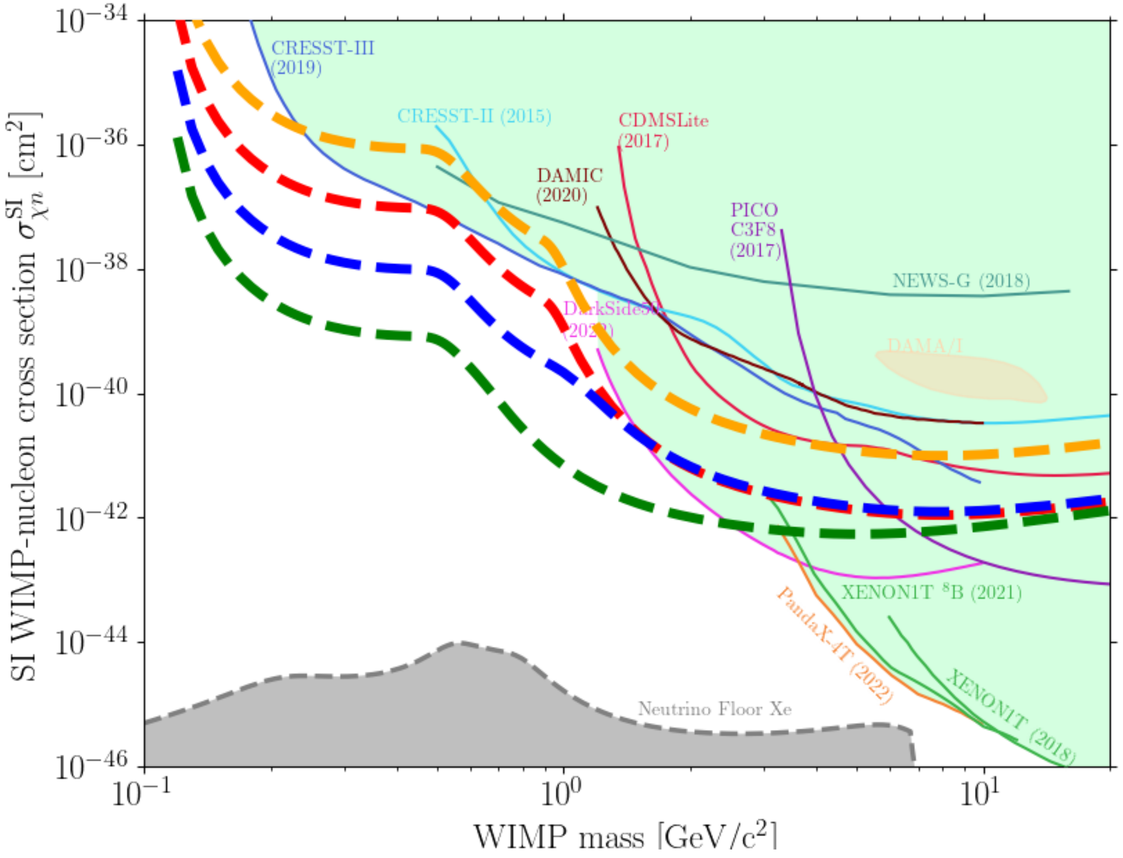
TREX-DM sensitivity prospects

- Background levels
  - ^{210}Pb Surface contaminations→ AlphaCAMM
- Energy threshold
  - Preamplification stage→ GEM-MM, ^{37}Ar calibration
- Gas composition improvement
  - Increasing iC4H10 concentration, varying gases

Exposure 0.32 kg y

	E_{th} (eV$_{ee}$)	B(dru)	Gas
Z	1000	100	Ar-1%Iso
A	50	100	Ar-1%Iso
B	50	1	Ar-1%Iso
C	50	1	Ar-10%Iso
D	50	0.1	Ne-10%Iso

Exposure 1.6 kg y

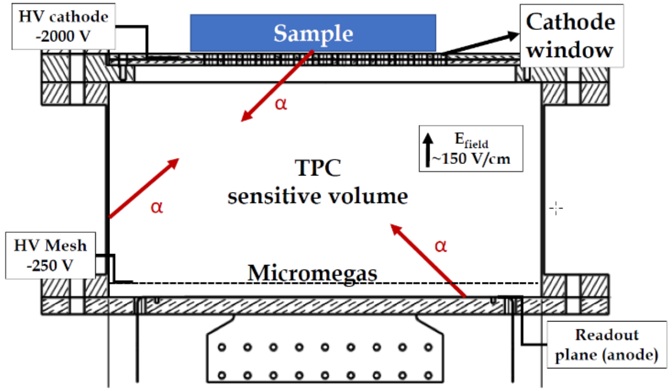


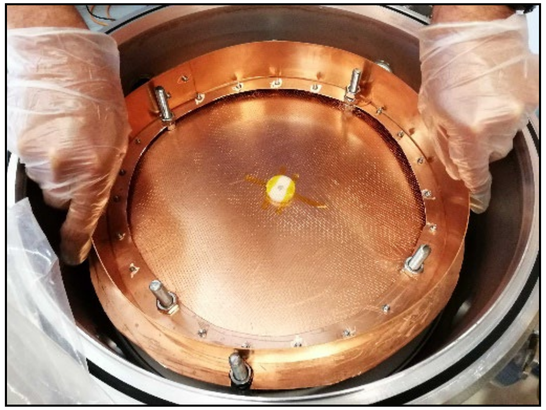
AlphaCAMM (Alpha CAMera Micromegas)

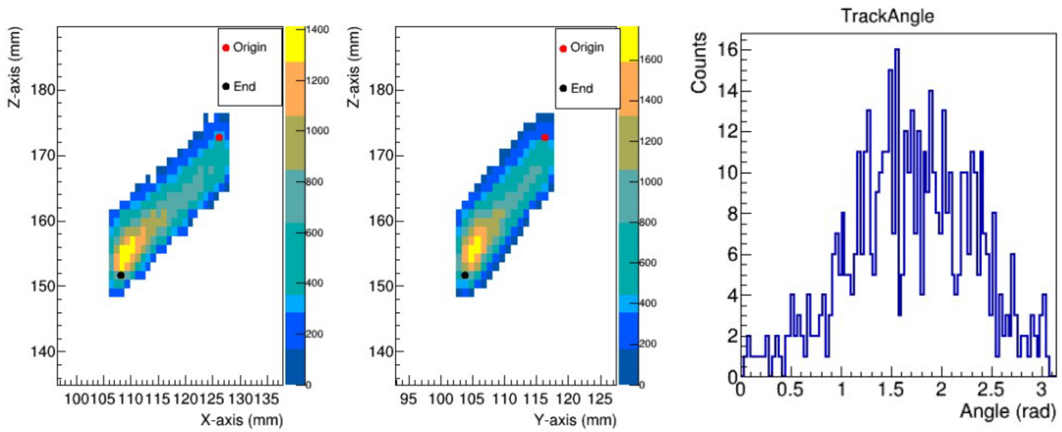
Plan de Recuperación, Transformación y Resiliencia

- ‘Spin-off’ of TREX-DM: gaseous chamber with a segmented mM (25cm x 25cm) to measure ^{210}Pb surface contamination of flat samples down to 100 nBq/cm^2

K. Altenmuller et al, 2022 JINST 17 P08035





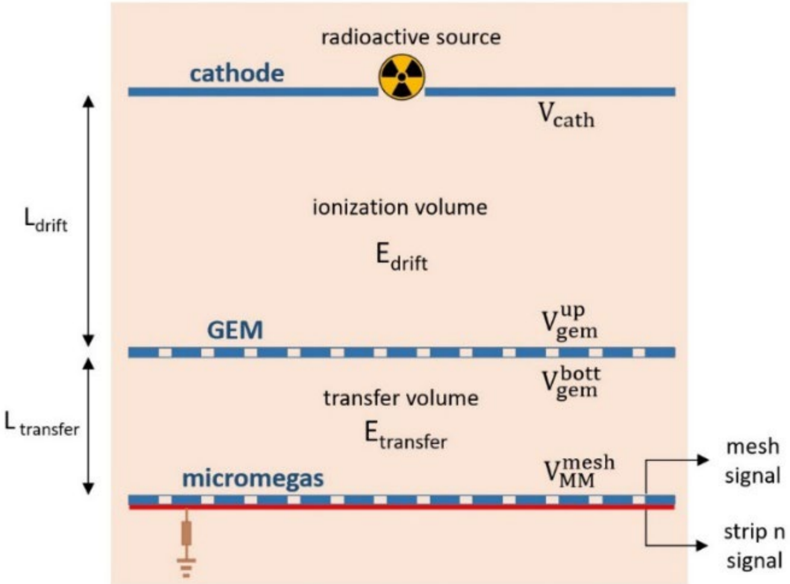


Topological information to reconstruct origin and end of a tracks from **^{210}Po**

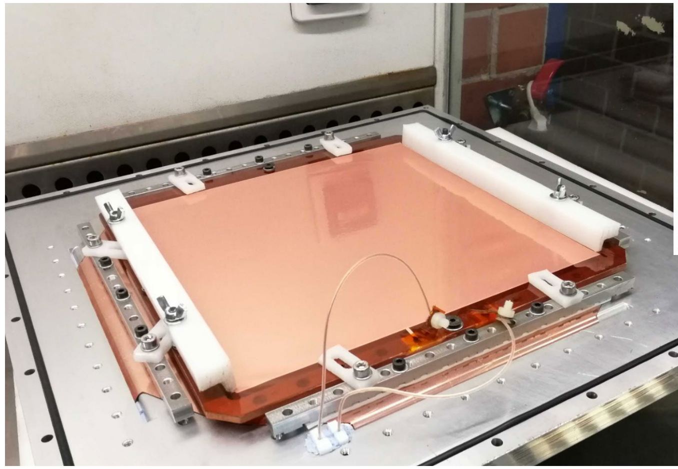
After proof-of-concept with a non-radiopure prototype, a radiopure detector is being commissioned

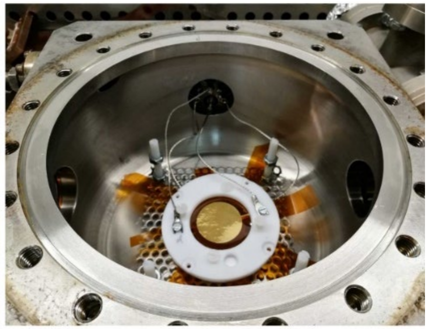
Lower threshold: GEM-MM

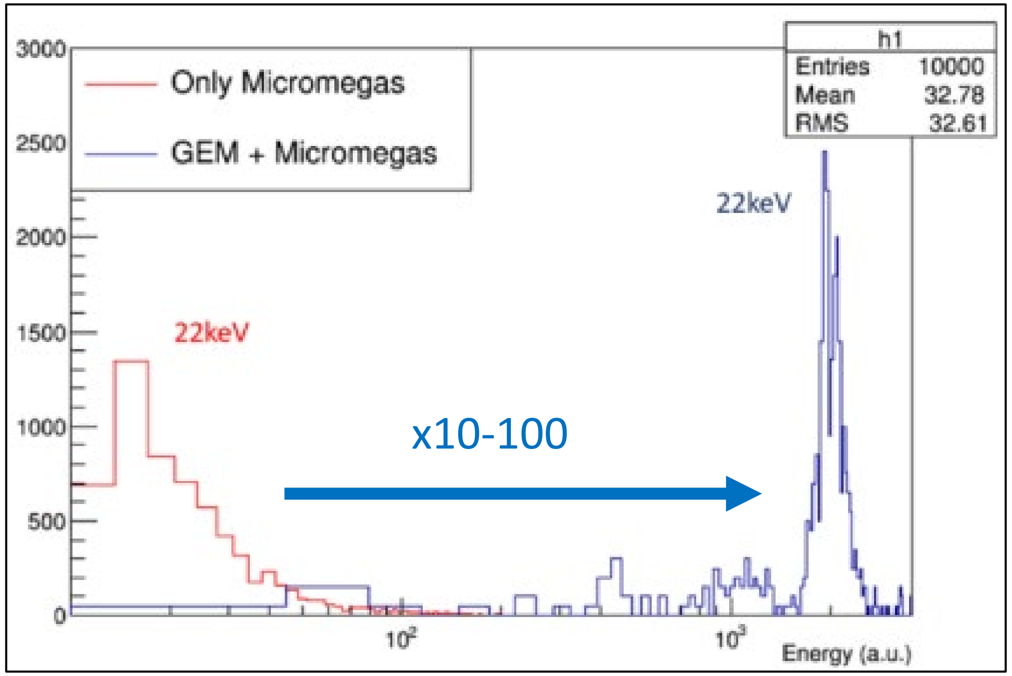
- Energy threshold
  - preamplification volume with a GEM on top of a mM
    factors would allow very low energy threshold (even single electron)
    - Big microbulk mM @1bar (x100)
    - Small microbulk mM @1-10bar (x100 to x10)



publication in preparation







Low energy, volume calibrations

Gas source: distribution in all volume, homogeneous calibration of the readout plane.

Plan de Recuperación,
Transformación
y Resiliencia

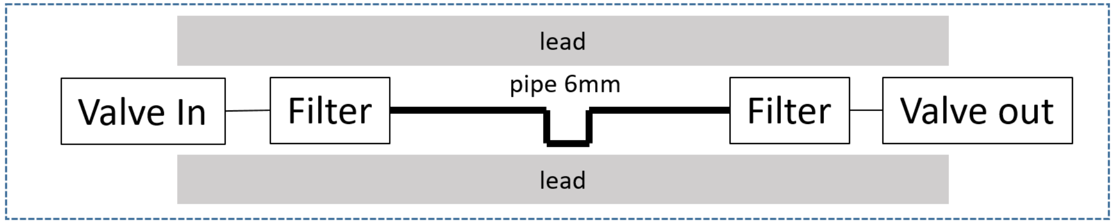
- ^{37}Ar: 2.8 keV (90%), 0.27keV (9%)

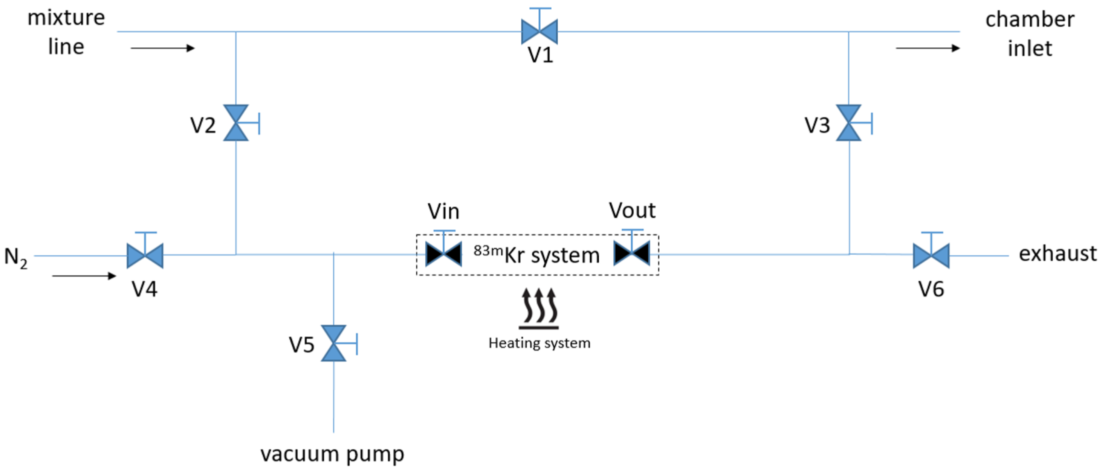
Irradiated CaO powder at CNA in Sevilla

Measurements in progress

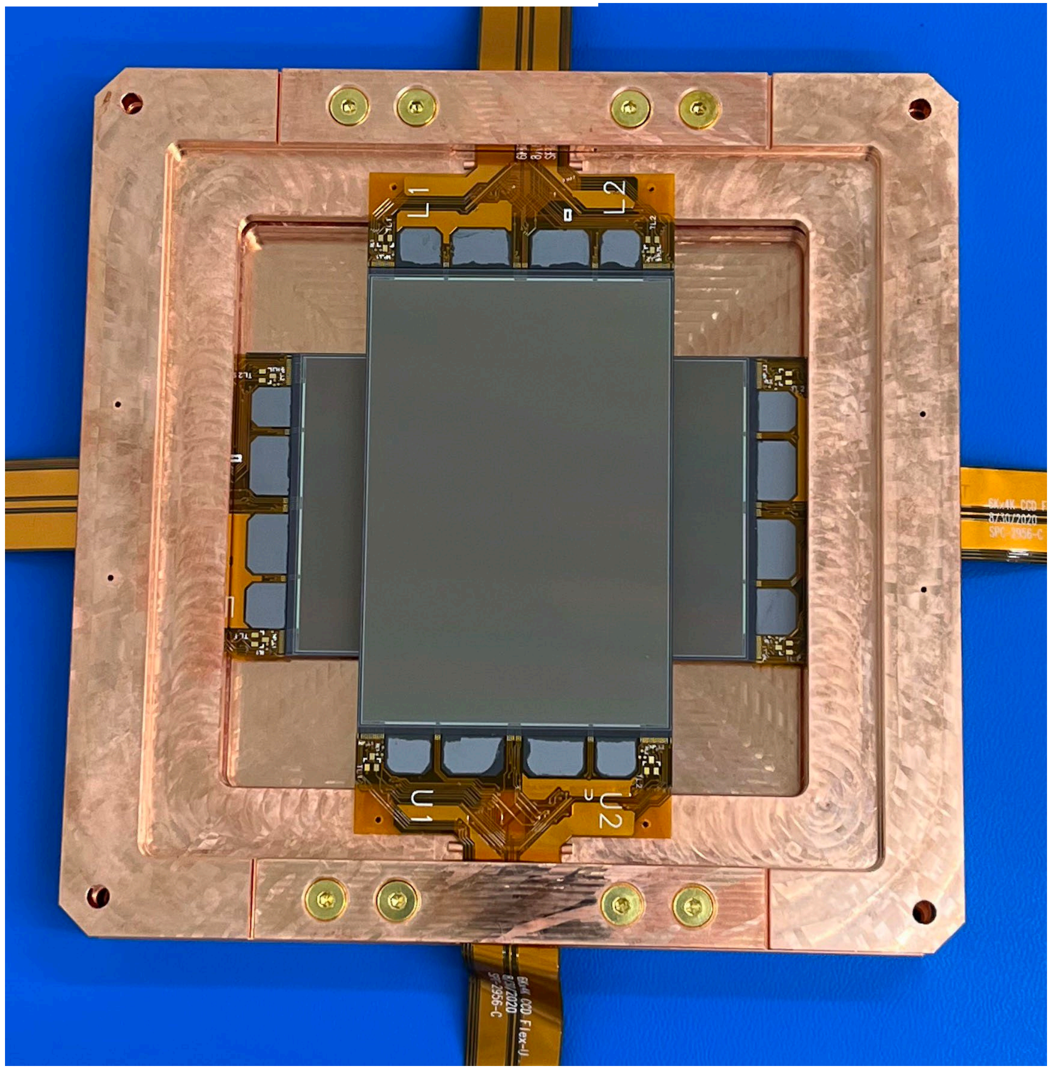
40Ca

- 83mKr: 30keV, 7.6keV, 2.1 keV, 1,8 keV





Instituto de Física de Cantabria

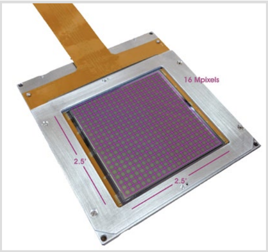


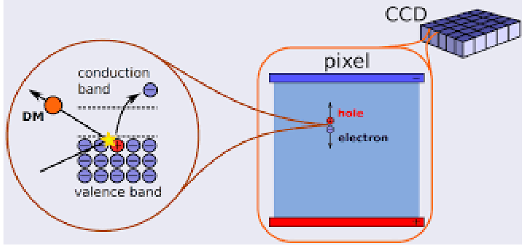
DAMIC

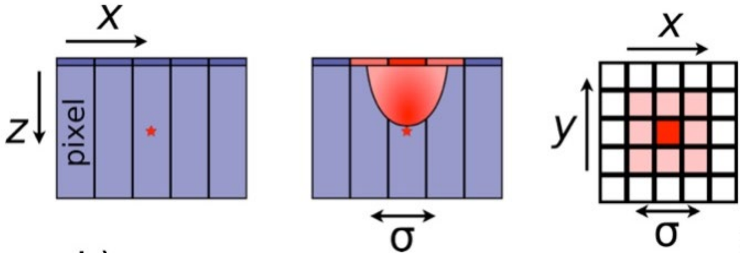
DAMIC Collaboration

CCDs as DM detectors

- Photon detectors → Charge-coupled devices have been used for a long time as telescope cameras
- e-h pairs produce (~3.77 eV required) → Charge is collected near the surface
- Precise spatial resolution and good energy resolution → using the diffusion 3D reconstruction
- Conventional CCDs limited to noise of ~2e- → single e resolution to ionization signals, 2-3 e threshold (~ 5-10 eV)
- Achieved very low dark current rates (2x10-4 e-/pixel/day, PRL 123, 181802 (2019))

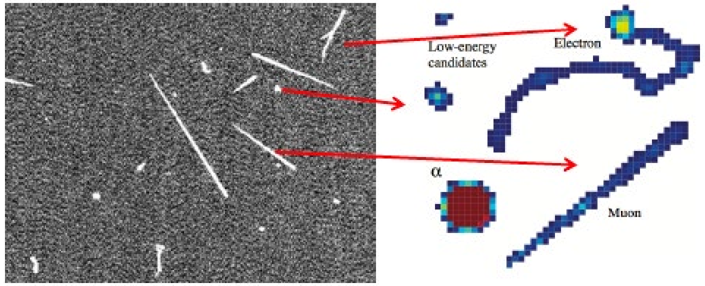






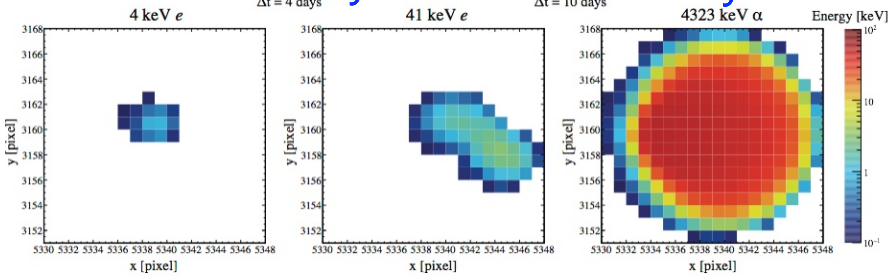
CCDs as DM detectors

- **Scalable** technologies to increase the number of interactions in the target.
- Low and controlled backgrounds
- Exquisite spatial resolution!
  - spatially correlated, time separated energy clusters
  - Measurement (and rejection) of surface and bulk backgrounds
    → **decay chains detected**
- **Low threshold to access smaller WIMP** masses:
  - < 6 GeV (nuclear recoil, NR)
  - ~ eV-MeV (electron recoil/absorption, ER)
- **Skipper-CCDs** allows single electron resolution

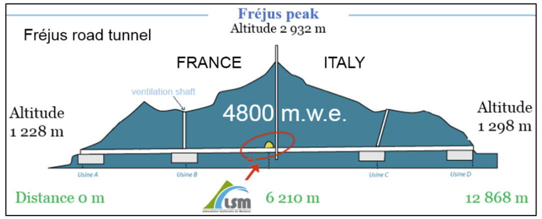


Decay chain of a ^{210}Pb nucleus on the CCD surface:

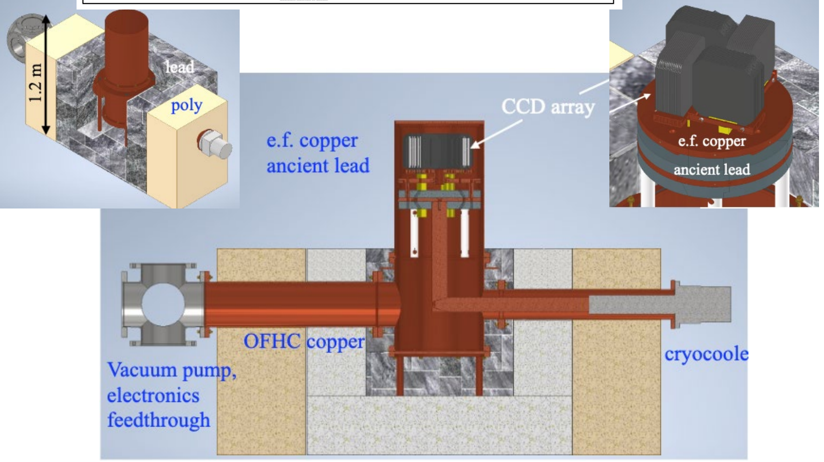
ΔT = 4 days ΔT = 10 days

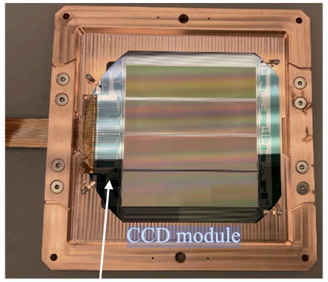


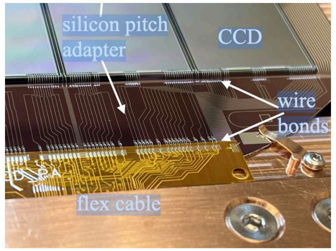
DAMIC-M design and background

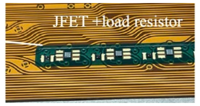


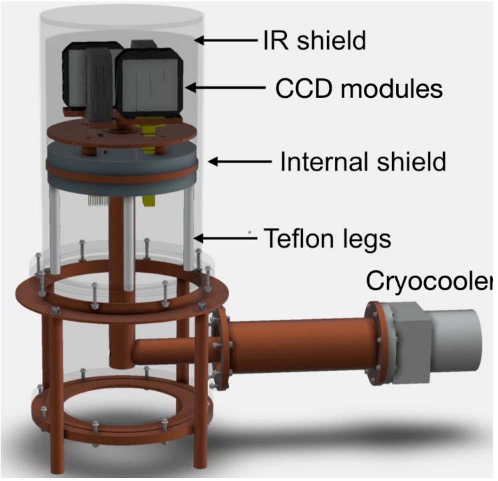
To be installed at Modane Underground Lab.

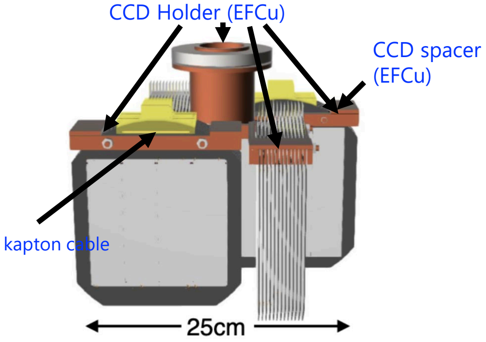












CCDs

- 208 CCDs, 6k x 1.5k pixels (15 x 15 x 675 μm^3), high resistivity (>10kΩcm) n-type, high purity silicon, 47/6 47/6 μm^2 skipper amplifiers
- 4 CCDs glued on a silicon pitch adapter.
- Flex cable glued on the Si pitch adapter → the voltage biases and clocks

Detector

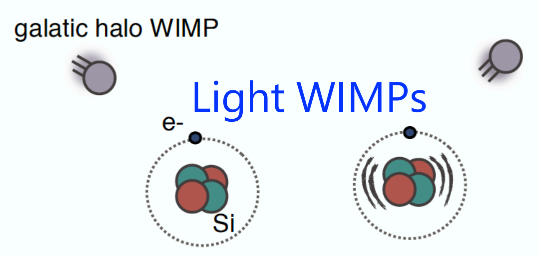
- Total mass of aprox 0.7 Kg of Si, operate at ~120K and ~1e^{-7} mbar
- Electronics chain newly designed, prototyped and integrated with CCDs → excellent noise performance. Resolution (readout noise) ~0.1 eV
- Energy threshold of 2 electrons (~10 eV)
- Very low background → Dedicated R&D with QFlex
- Electro-formed copper cryostat, IR shield
- Layered polyethylene + lead shielding, innermost layer of ancient lead

Background controls

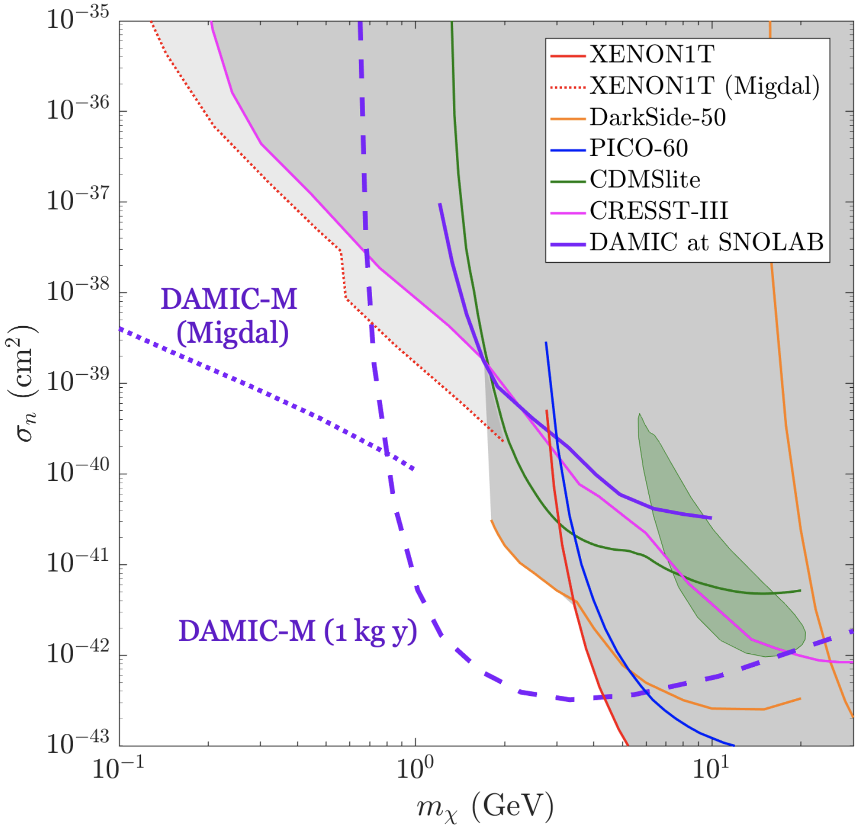
- Limiting the cosmogenic activation of silicon and copper is crucial
  - Silicon: exposure to CR < 2 months to achieve background goal. (So far 2 weeks)
- Copper: e.f. copper produced and machined underground (MAJORANA copper at SURF, and Canfranc).
- CCD treatment to properly clean the surfaces

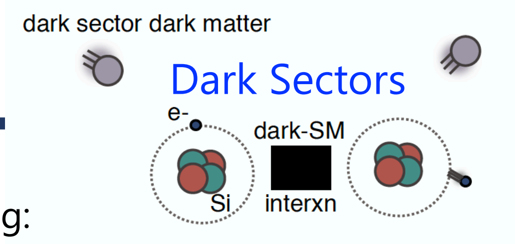
R. Vilar talk

DAMIC-M: Physics reach

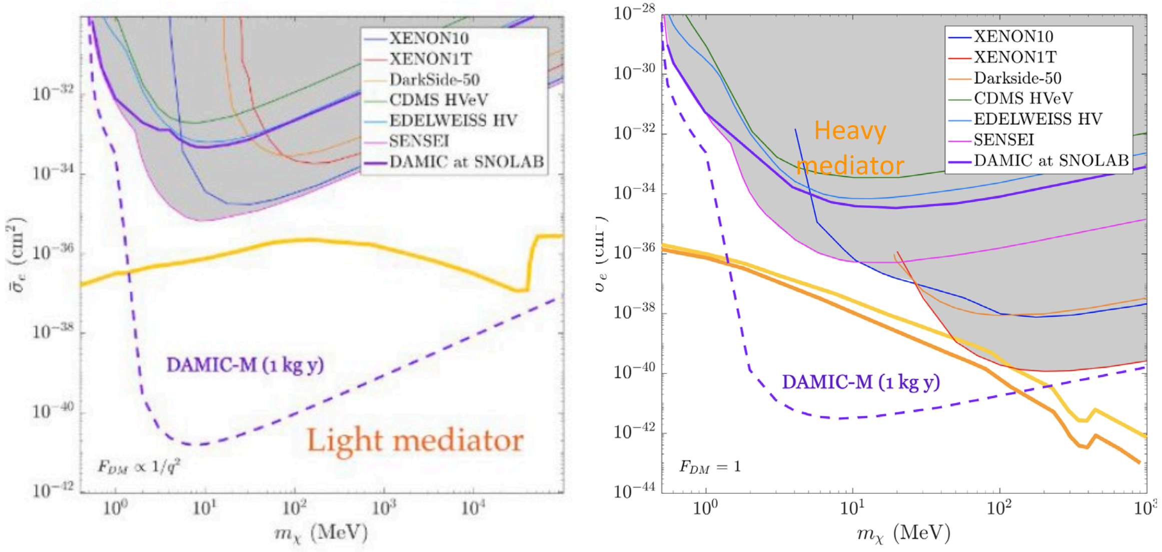


WIMP-nucleus elastic scattering (can also detect secondary electron recoils from inelastic Migdal effect)

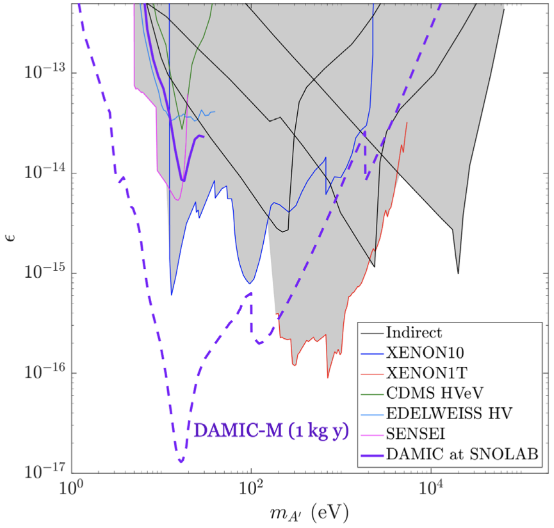




DM - Electron scattering:



DM absorption



Hidden dark photon

R. Vilar talk

DAMIC-M Status

DAMIC-M on-line by 2025!

Calibrations : Different radioactive sources

- ^{241}Am → Calibration of the low-energy Compton background (PRL 106 (2022) 092001)
- ^{241}Am ^{9}Be → Distinguishing nuclear recoils signals from electronic recoil backgrounds (arXiv:2309.07869)
- ^{124}Sb/^{9}BeO-^{124}Sb/Al → Ionisation efficiency of nuclear recoils (Phys. Rev. D 94, 082007 (2016))

Accomplishments

- produced, stored wafers for CCDs with low cosmogenic exposure
- developed low background packaging procedures
- analysis/simulation frameworks ready and continuous efforts for improvements
- installed Low Background Chamber (LBC), first dark matter-electron results and modulation analysis

In Progress

- performing nuclear ionization efficiency measurements
- fabrication, assays of low-background parts
- preparations for on-site work, including CCD packaging, testing, assembly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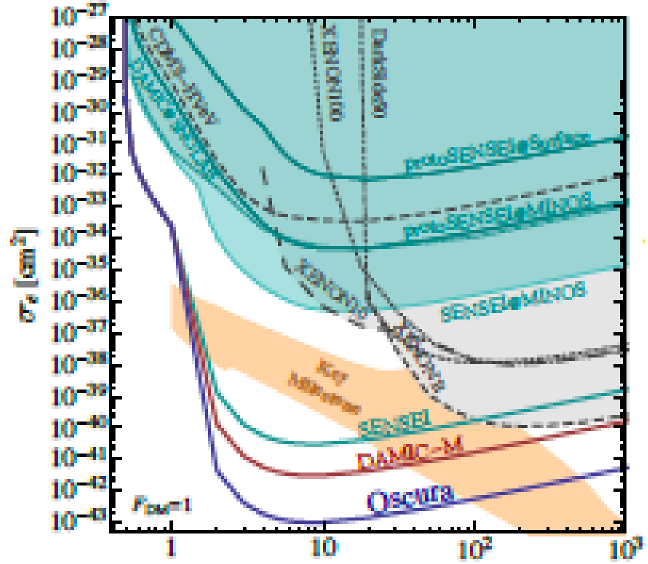
CCDs future: OSCURA

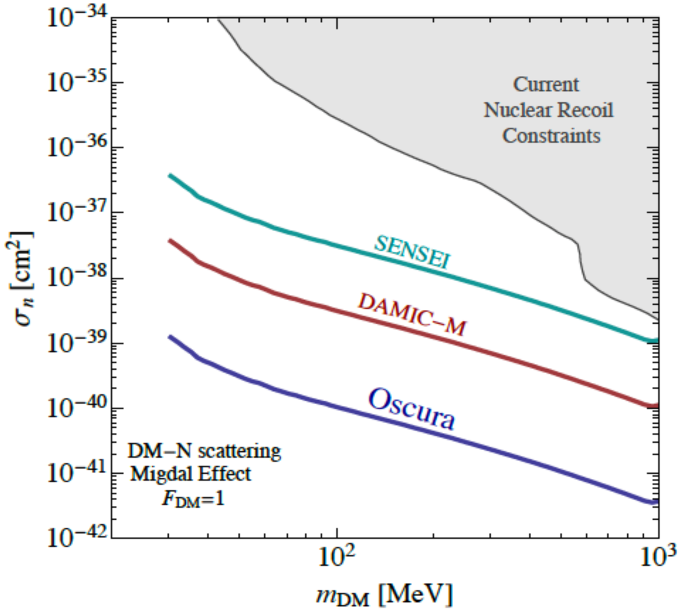
OSCURA: SENSEI + DAMIC-M

Experiment	Mass(kg)	#CCDs	Radiation bckg [dru]	Instrument bkgd [e-/pix/day]	Commissioninig
SENSEI @MINOS	~0.002	1	3400	1.6x10^{-4}	Late-2019
DAMIC @SNOLAB	~0.02	2 (6k x 4k)	10	3 10^{-3}	Late-2021
LBC (DAMIC-M)	~0.02	2 (6k x 4k) (8 6k x 1.5k)	~10	3 10^{-3}	Early-2022
SENSEI-100	~0.1	50	~10 (goal)		Mid-2022
DAMIC-M	~0.7	208	~0.1 (goal)		Late-2024
Oscura	~10	20000	~0.01 (goal)	1.10^{-6}(goal)	~2028

OSCURA challenges: to increase mass (from 10s to 10,000s CCDs) and to reduce the backgrounds (3 orders of magnitude) → Major R&D

Oscura early science (arXiv:2304.08625)





Summary

- Good progress in LIA5 experiments thanks to “planes complementarios”
- LIA5 WIMP experiments are well positioned in the international context to provide relevant insights into the WIMP search:
  - **ANAIS-112 3y data strongly challenges the DAMA/LIBRA annual modulation. Rejection with >4σ at reach this summer and >5σ in late 2025**
  - **ANAIS+ (1 kg NaI+SiPM @ 100 K) can improve current SD-proton sensitivity for low-mass WIMPs and discard QF differences as explanation for DAMA/LIBRA signal**
  - **TREX-DM (Ar/Ne TPC, ~20 l pressurized gas) can lead the sensitivity for mW between 0.1-1 GeV for SI coupling**
  - **DAMIC-M (Si CCD, 1kg) can lead SI sensitivity for mW~few GeV and substantially improve the sensitivity for electron coupling in several orders of magnitude**