Direct searches of Dark Matter

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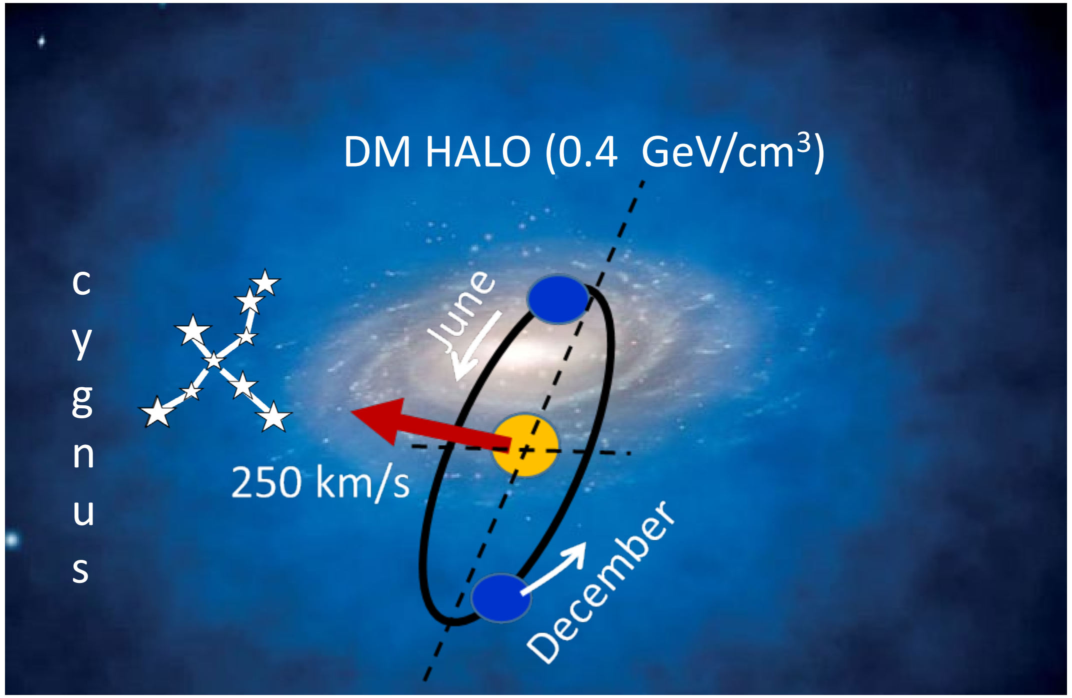
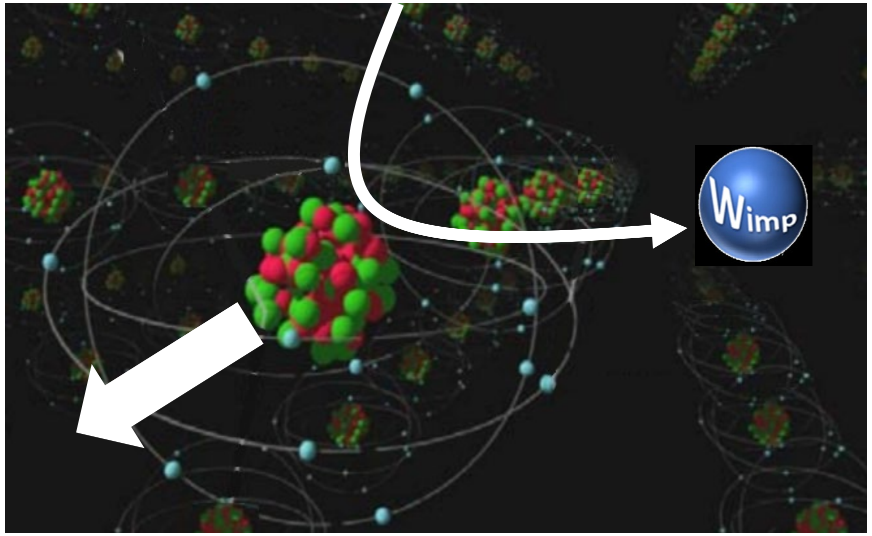
Dark Ghosts
Granada, 31st March – 1st April 2022
3rd GNN Workshop on Indirect Dark Matter Searches with Neutrino Telescopes

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

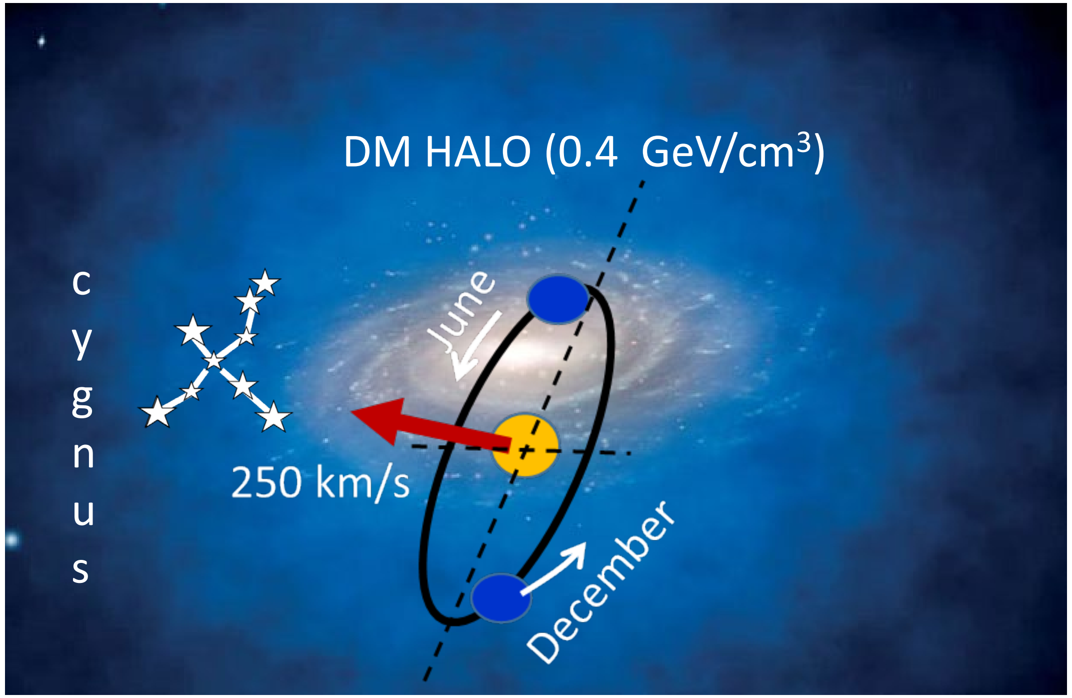
araid FUNDACIÓN AGENCIA ARAGONESA PARA LA INVESTIGACIÓN Y EL DESARROLLO
Universidad Zaragoza 1542
LSC Laboratorio Subterráneo de Canfranc

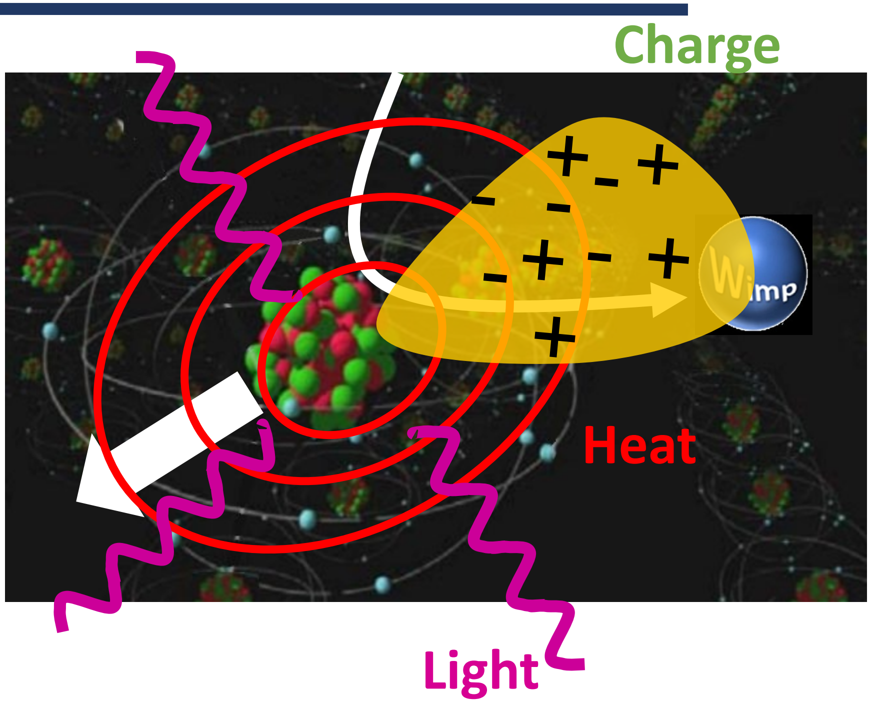
DM direct detection





DM direct detection





DM local density

DM velocity distribution in detector's frame

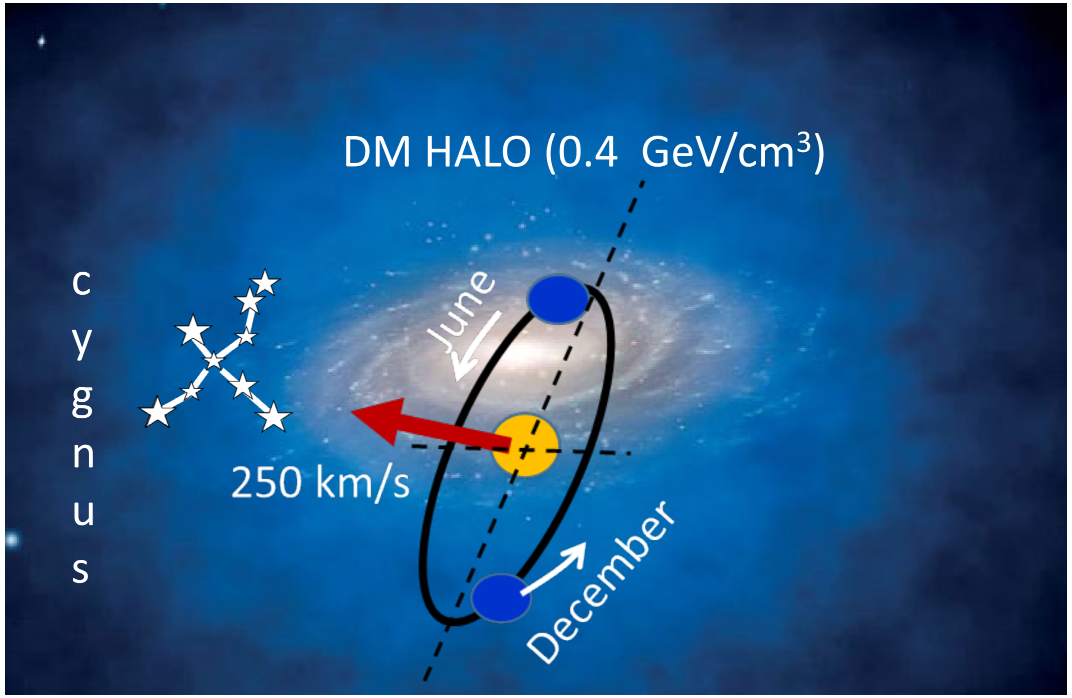
$$\frac{dR}{dE_R} = \frac{M_{det}\rho_\chi}{2m_\chi \mu_{\chi N}^2} \sigma^0 F^2(q) \int_{v_{min}}^{v_{esc}} \frac{f(v,t)}{v} d^3\boldsymbol{v}$$

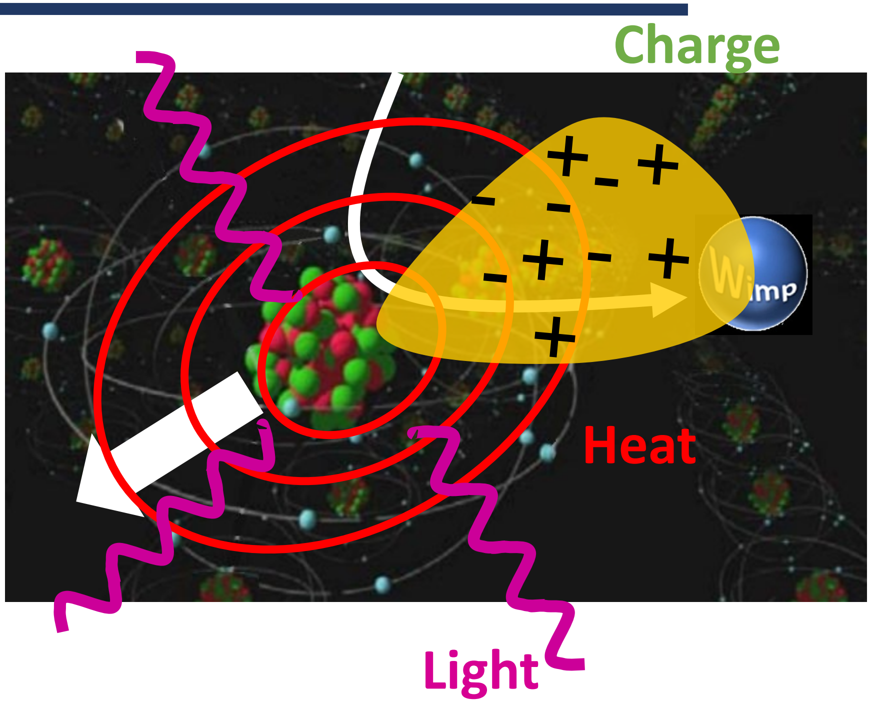
DM mass

scattering cross section

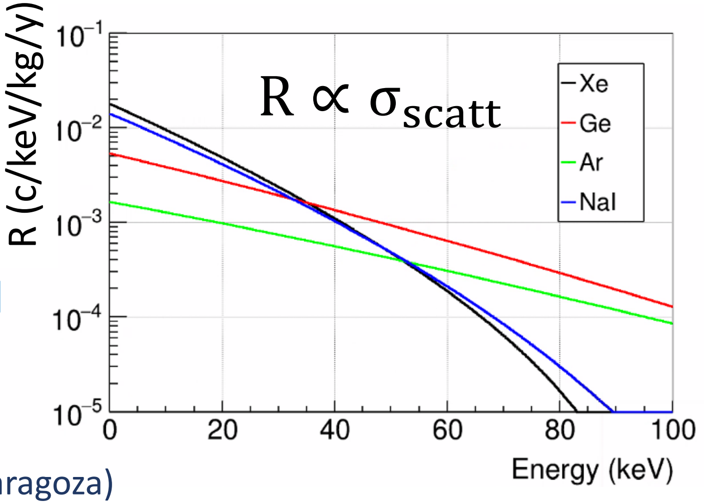
where $v_{min} = \sqrt{\frac{E_R m_N}{2\mu_{\chi N}^2}}$

DM direct detection





- Very low rates! → go **underground** and shield!
- Low energy → **low energy threshold!**
- Distinctive signatures: **annual modulation**, **directionality**



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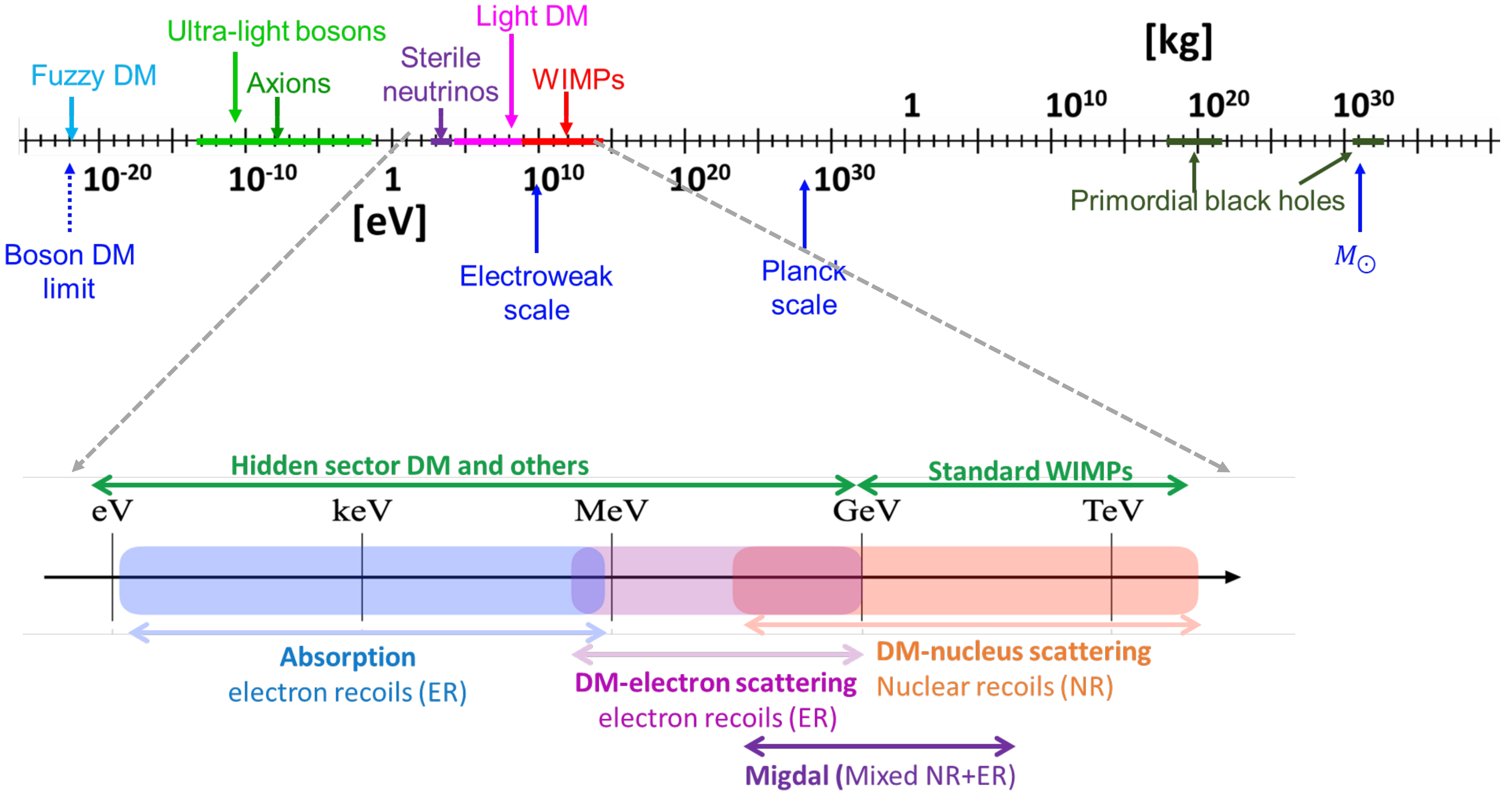
DM mass

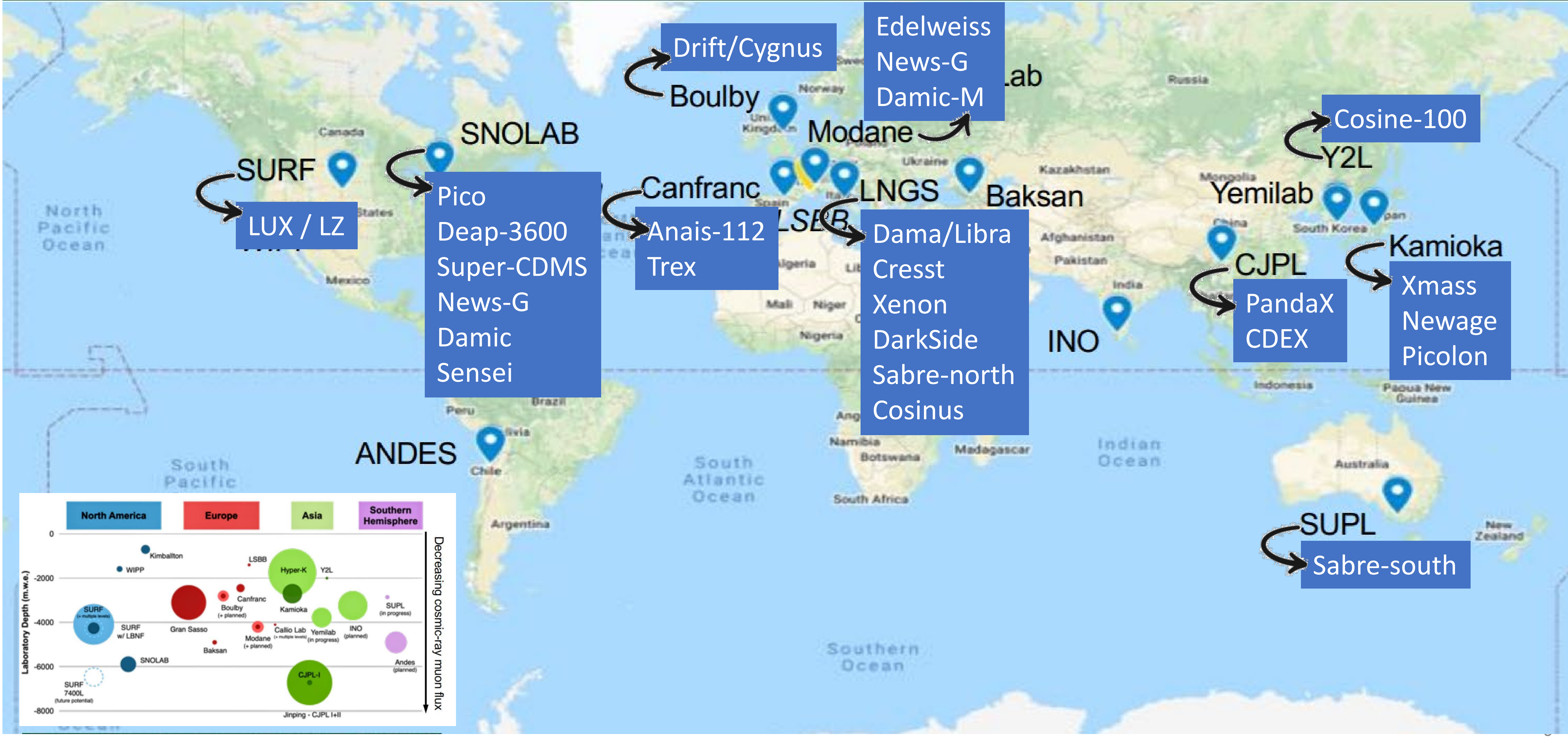
scattering cross section

where $v_{min} = \sqrt{\frac{E_R m_N}{2\mu_{\chi N}^2}}$

Direct detection: mass ranges

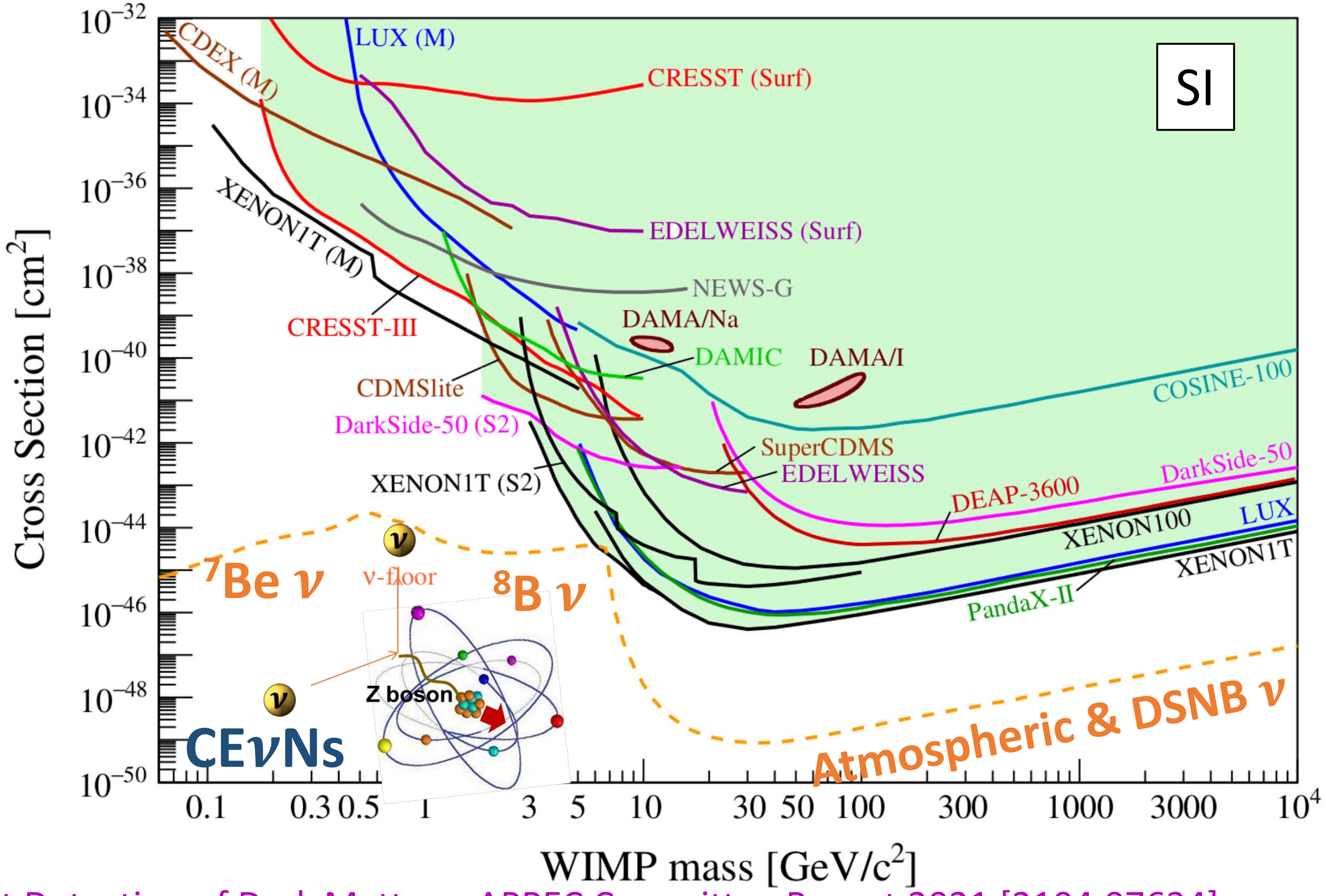


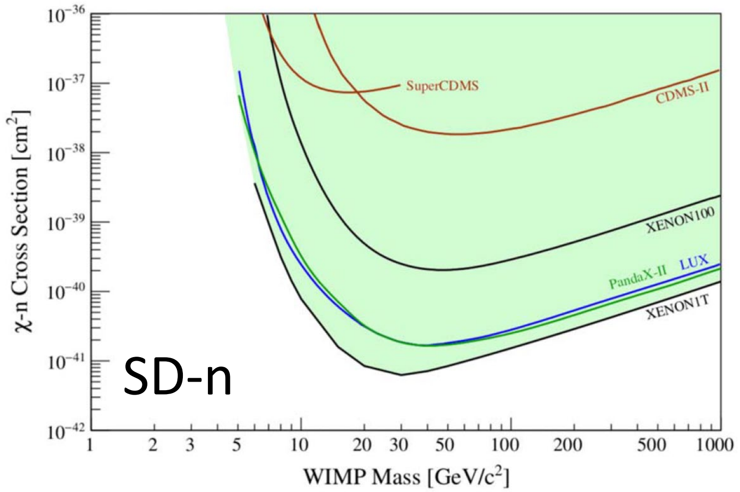
Underground DD searches

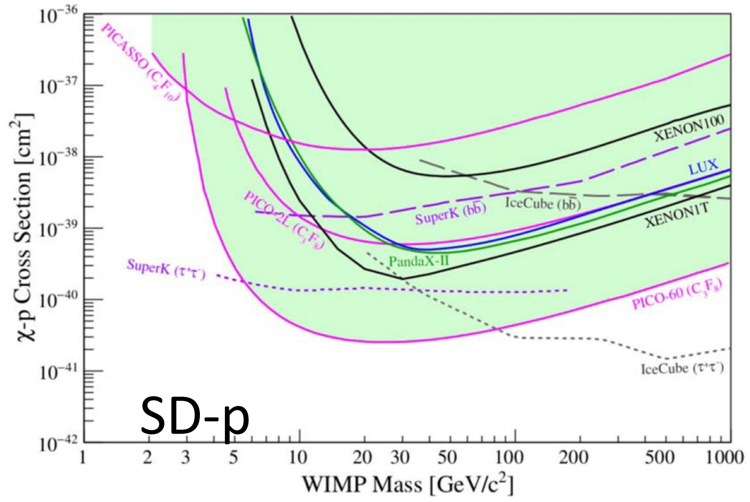


Experimental sensitivity @ 2021

- Exclude WIMPs that would produce a measurable rate over known backgrounds
- Assuming WIMPs coupling only spin-independent (SI) or only spin-dependent to neutrons (SD-n) or protons (SD-p)



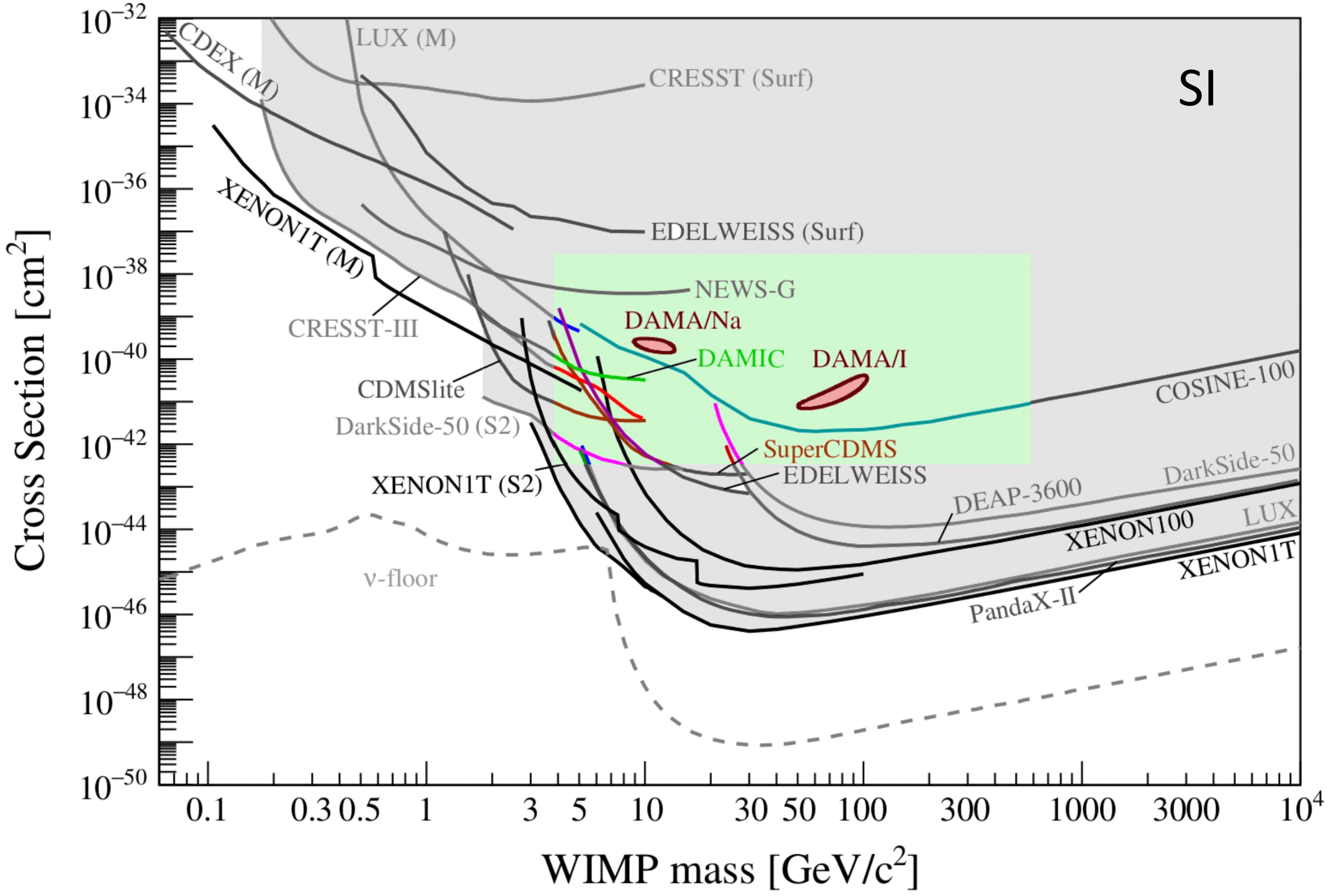


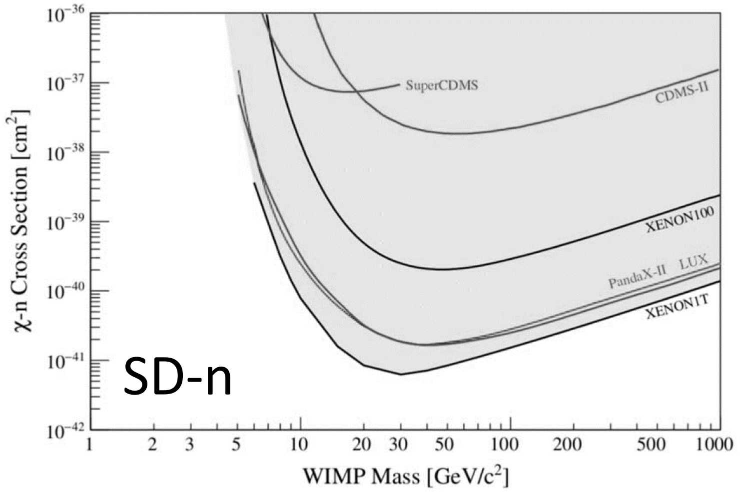


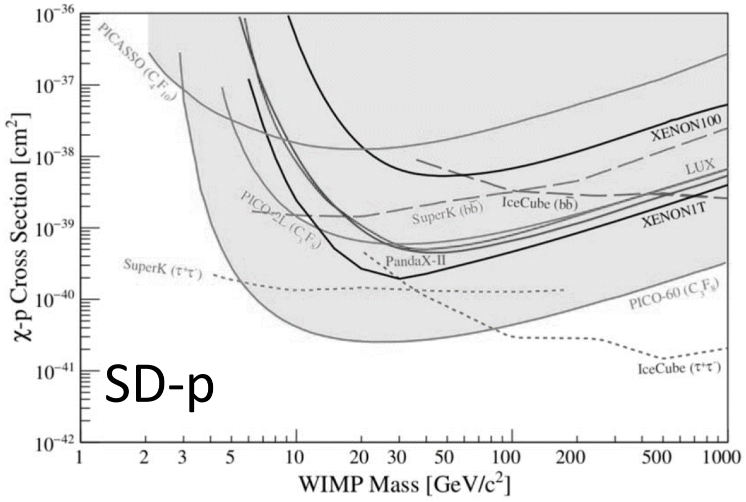
Direct Detection of Dark Matter – APPEC Committee Report 2021 [2104.07634]

The DAMA/LIBRA annual modulation positive signal

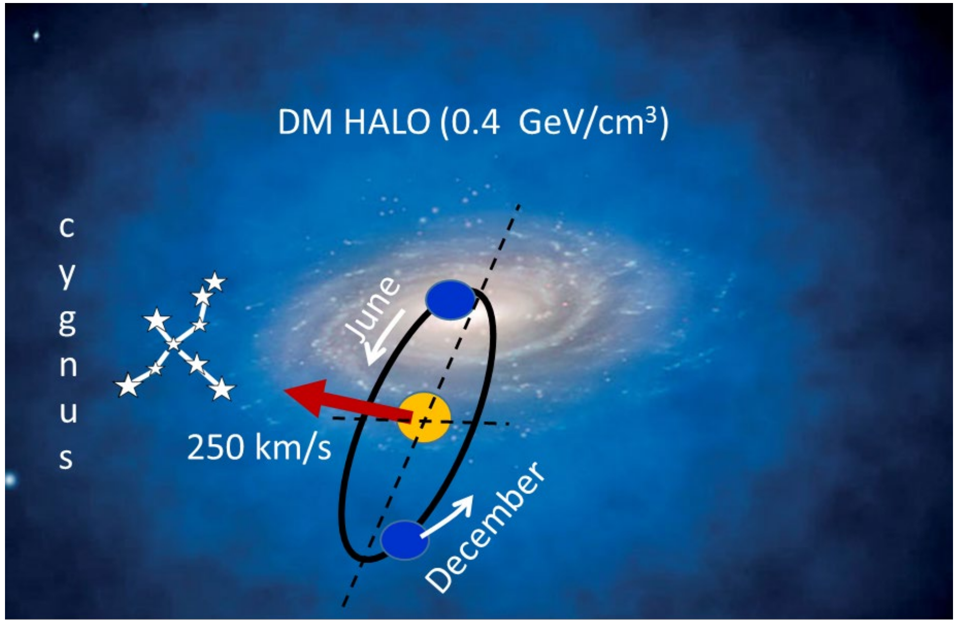
Direct Detection of Dark Matter – APPEC Committee Report 2021
[2104.07634]



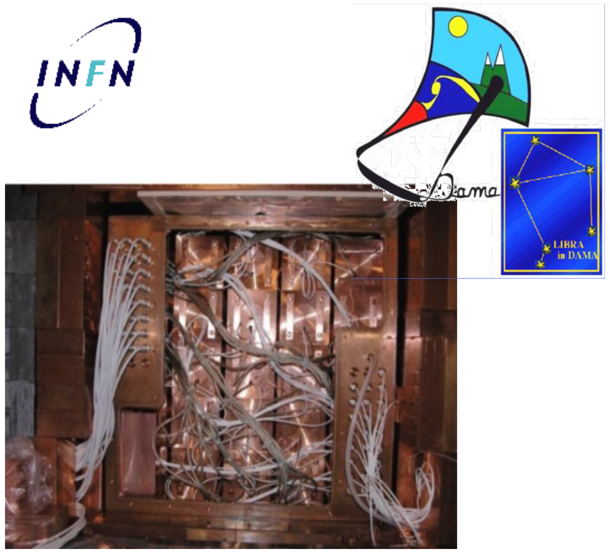




The DAMA/LIBRA annual modulation positive signal



LABORATORI NAZIONALI DEL GRAN SASSO



DAMA / NaI (1995-2002)

- 100 kg NaI(Tl) scintillators
- Eth = 2 keVee
- 7 annual cycles

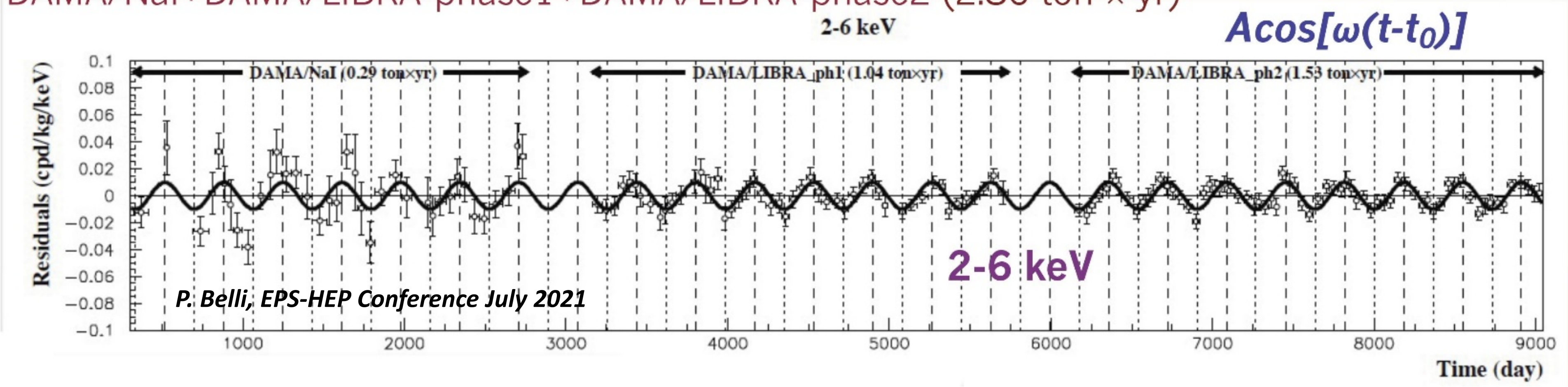
DAMA / LIBRA ph1 (2003-2010)

- 250 kg NaI(Tl) scintillators
- Eth = 2 keVee
- 7 annual cycles

DAMA / LIBRA ph2 (2011-today)

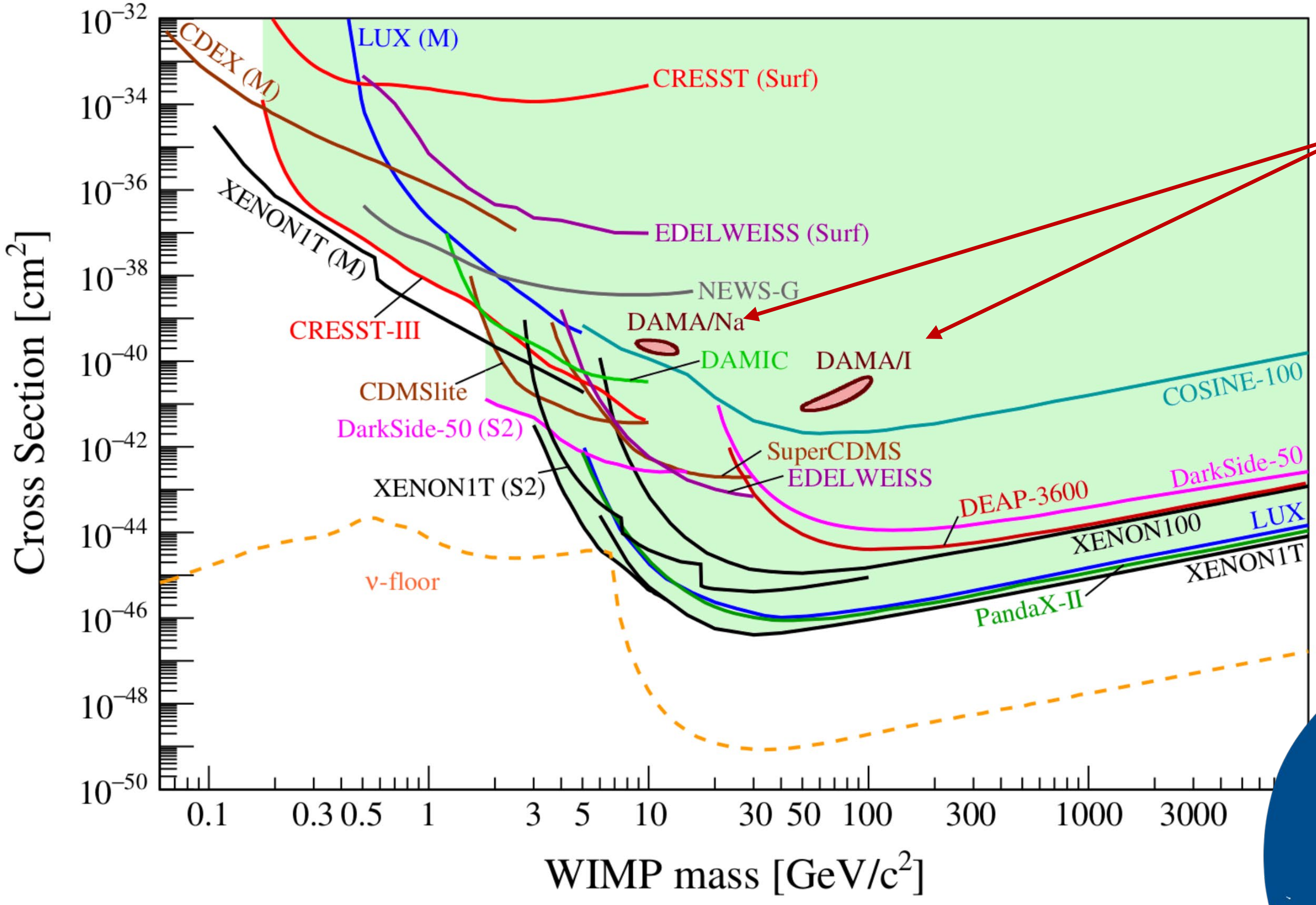
- 250 kg NaI(Tl) scintillators
- Eth = 1 keVee
- 10 annual cycles

DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.86 ton × yr)



DAMA clearly sees an annual modulation at 13.7σ C.L.

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

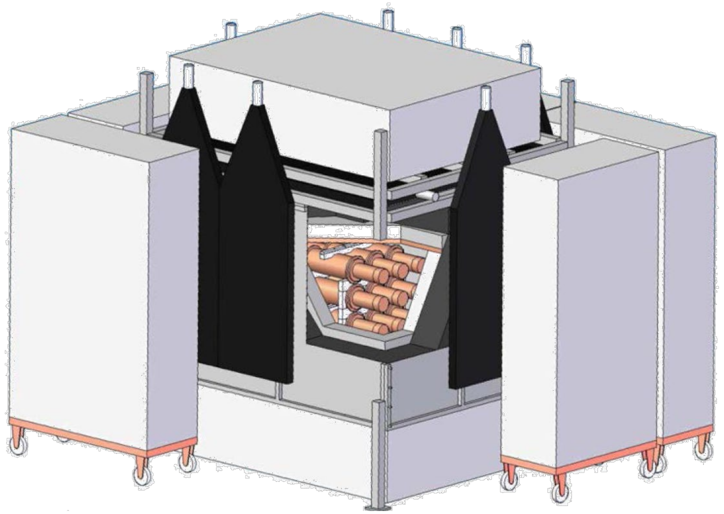
TO AVOID ANY MODEL DEPENDENCE, AN INDEPENDENT CONFIRMATION WITH THE SAME TARGET , NaI(Tl), IS REQUIRED

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

ANAIS-112 vs DAMA/LIBRA

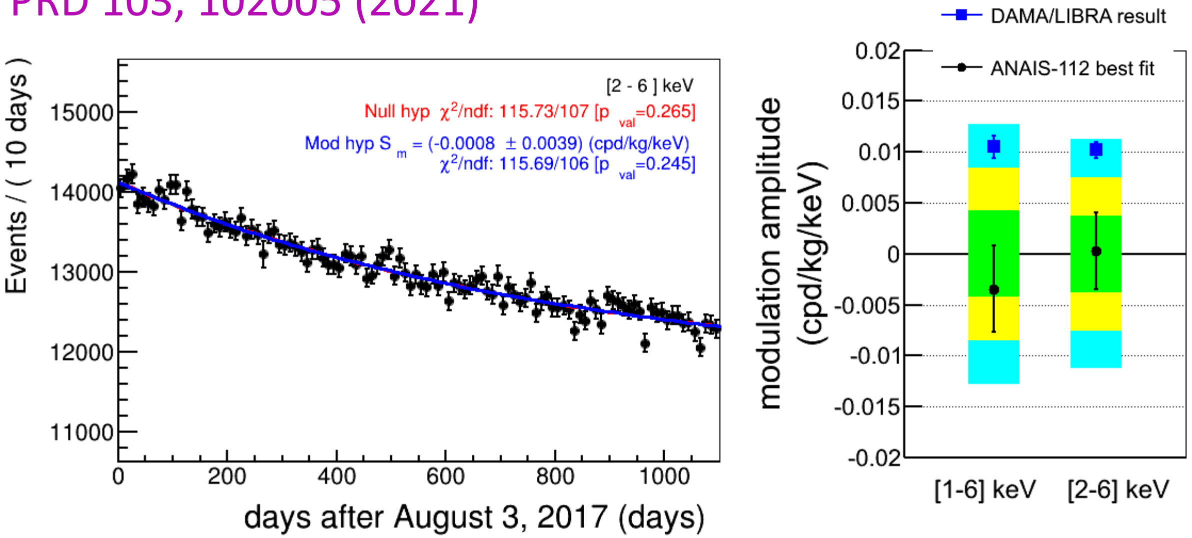
ANAIS-112: First model independet test of the DAMA/LIBRA signal (same target and technique)

112 kg NaI(Tl) scintillators
@ Canfranc Underground Laboratory
In data-taking since August 2017
1 keVee energy threshold
Background @ ROI x3 DAMA/LIBRA



3 years results

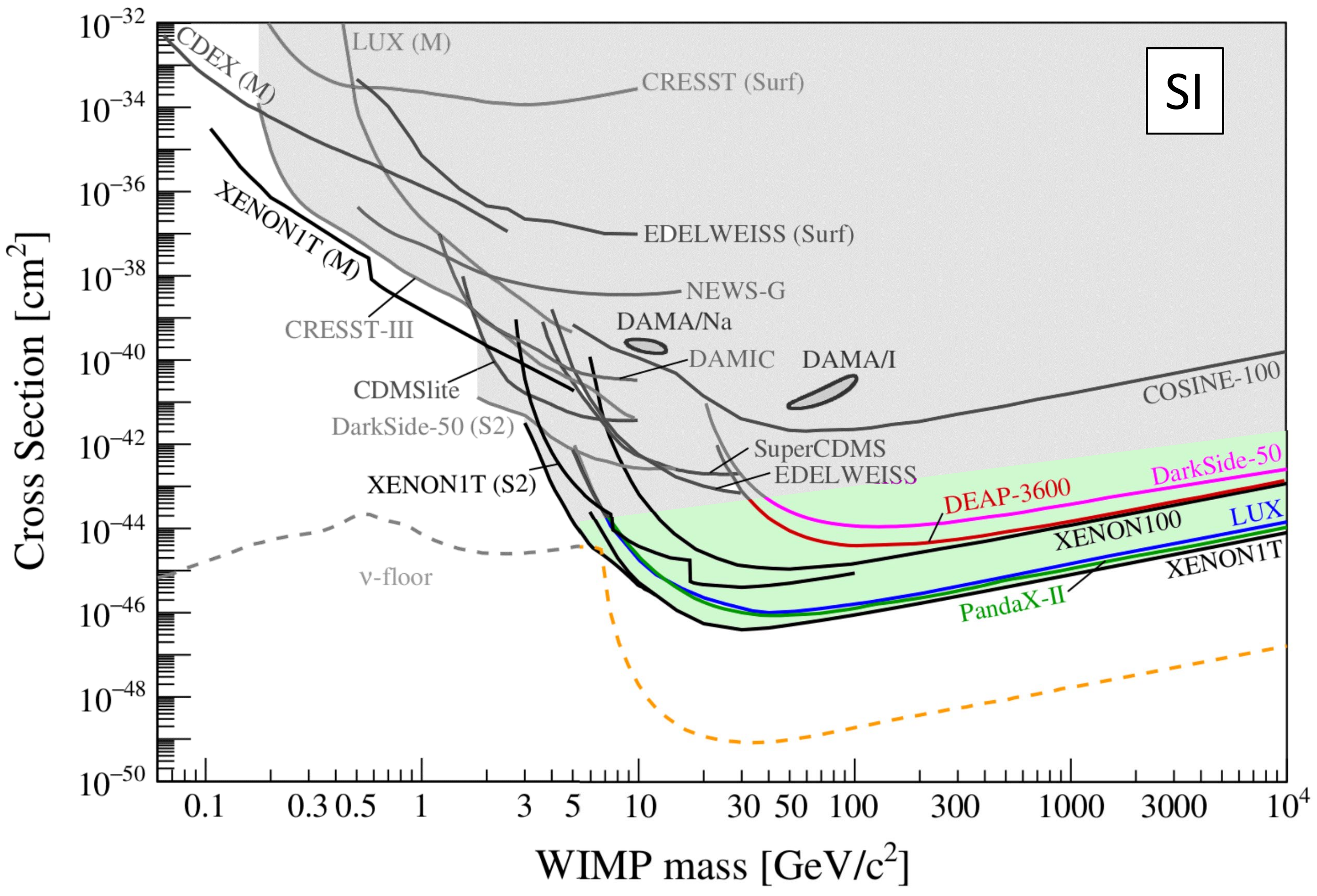
PRD 103, 102005 (2021)

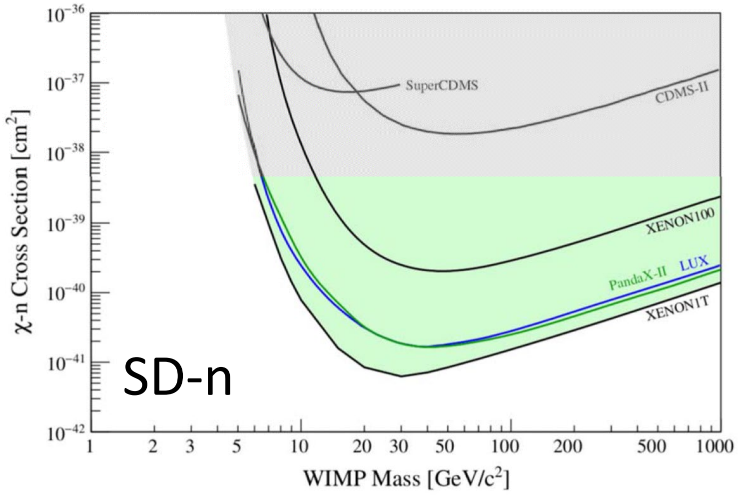


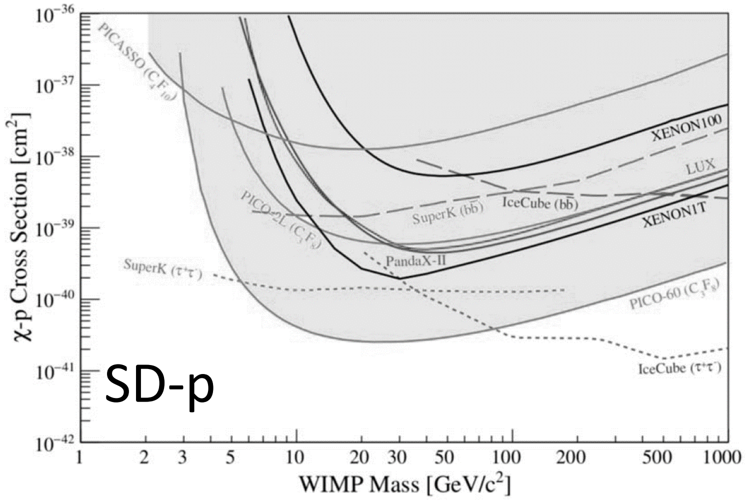
Best fit incompatible with DAMA/LIBRA at 3.3 (2.6) σ
Current sensitivity: 2.5-2.7σ

High WIMP mass

- Double-phase noble elements TPC: Lux/LZ, PandaX, Xenon, DarkSide
- noble liquid (single pase): Deap, XMass



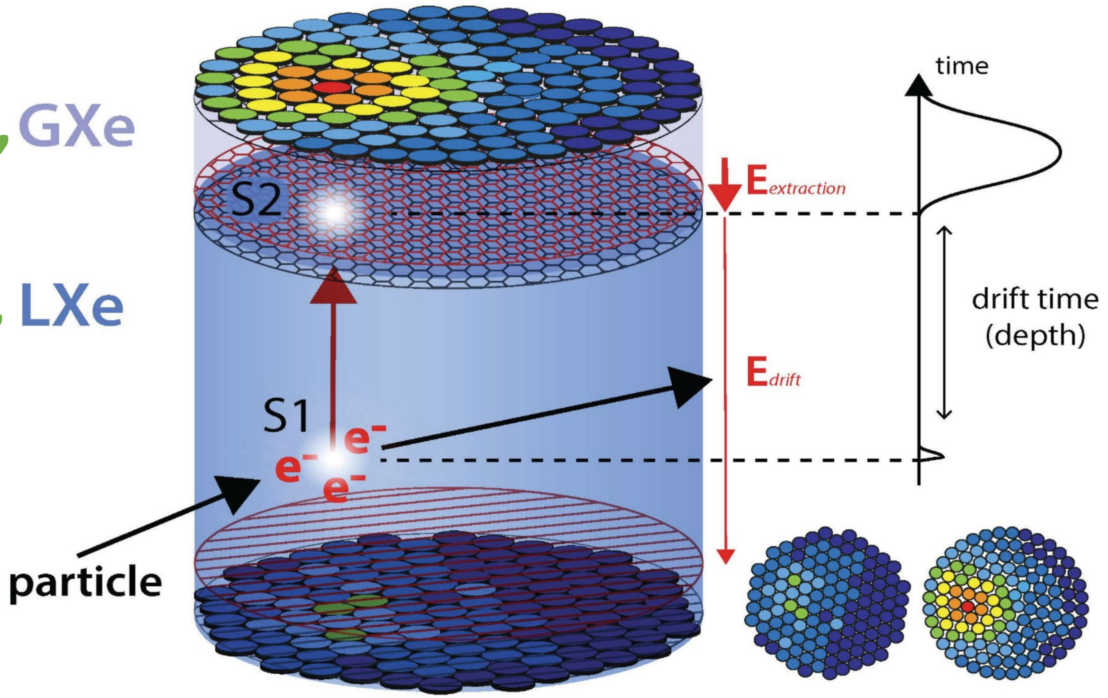


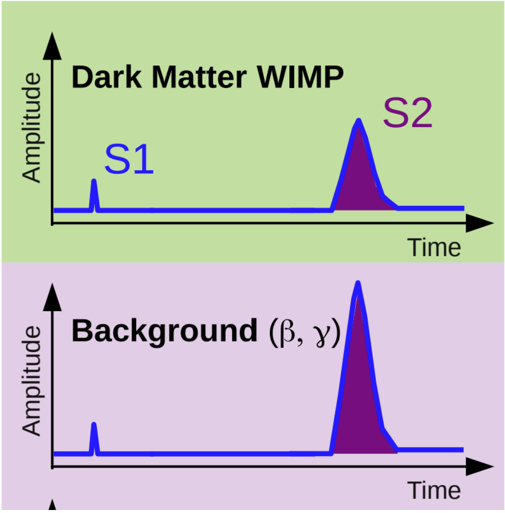


Double-pase noble elements TPC (light + charge)

GAr, GXe

LAr, LXe



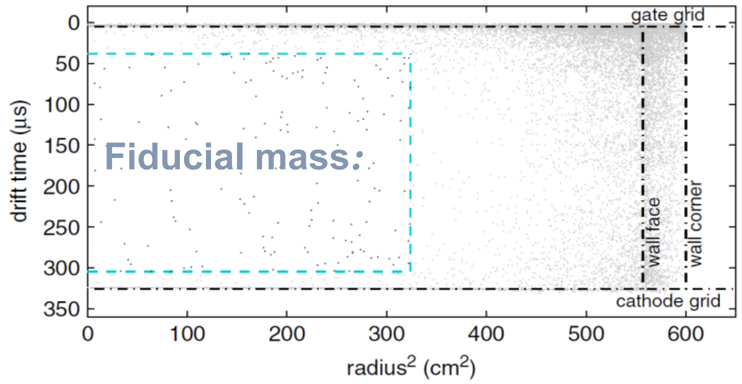


The ratio S1/S2 is different for nuclear recoils (WIMPs) or electron recoils (background)

Reconstruction of the hit position
- Top/bottom photomultipliers → (x, y)
- Drift time → z

→ fiducialization (use only the inner (cleaner) part)

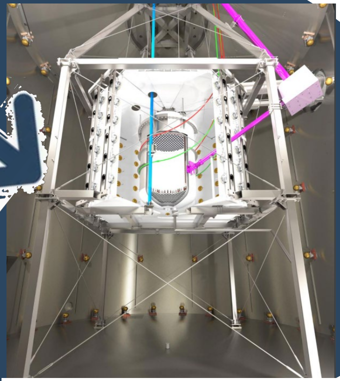
- ER Background rejection
- Fiducialization
- Possibility to reduce the threshold working only with charge readout (no bkg discrimination!)



Present and future of noble-TPCs

Ar

Xenon 1T
(1 ton LXe)
(decomissioned)



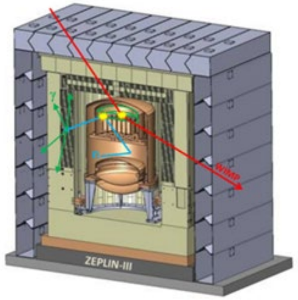
Xenon nT
(5.9 ton LXe)
STARTED IN 2021

PANDAX-4T
(4 ton LXe)
STARTED IN 2021

DarkSide-50
(50 kg LAr)
(decomissioned)

Deap-3600
(3.6 ton LAr)

ArDM (1 ton LAr)
(decomissioned)



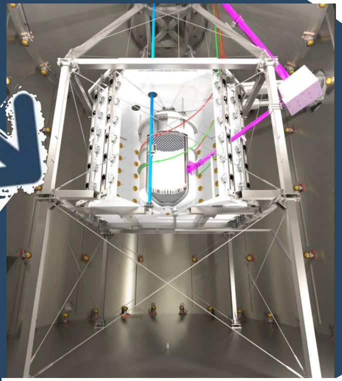
ZEPLIN-III
(6 kg LXe)
(decomissioned)

LUX
(100 kg LXe)
(decomissioned)

Present and future of noble-TPCs

Ar

Xenon 1T
(1 ton LXe)
(decomissioned)



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(5.9 ton LXe)
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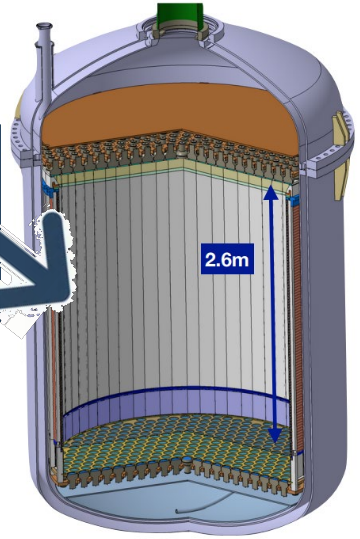


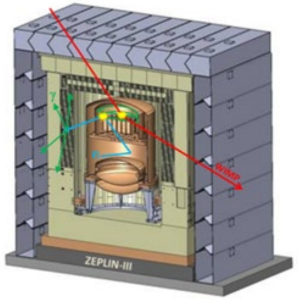
Future: DARWIN
(50 ton LXe)

PANDAX-4T
(4 ton LXe)
STARTED IN 2021

DarkSide-50
(50 kg LAr)
(decomissioned)

Deap-3600
(3.6 ton LAr)

ArDM (1 ton LAr)
(decomissioned)



ZEPLIN-III
(6 kg LXe)
(decomissioned)

LUX
(100 kg LXe)
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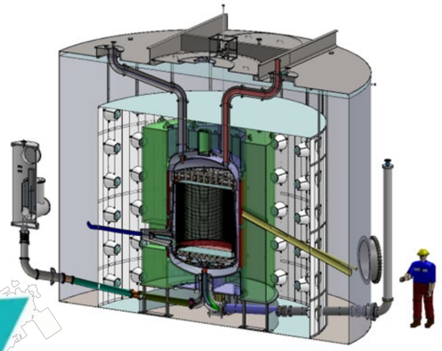
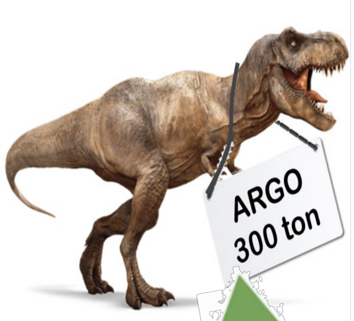
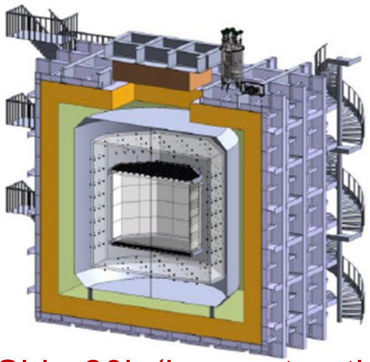


LZ (in construction @ SURF)
(7 ton-fiducial LXe)



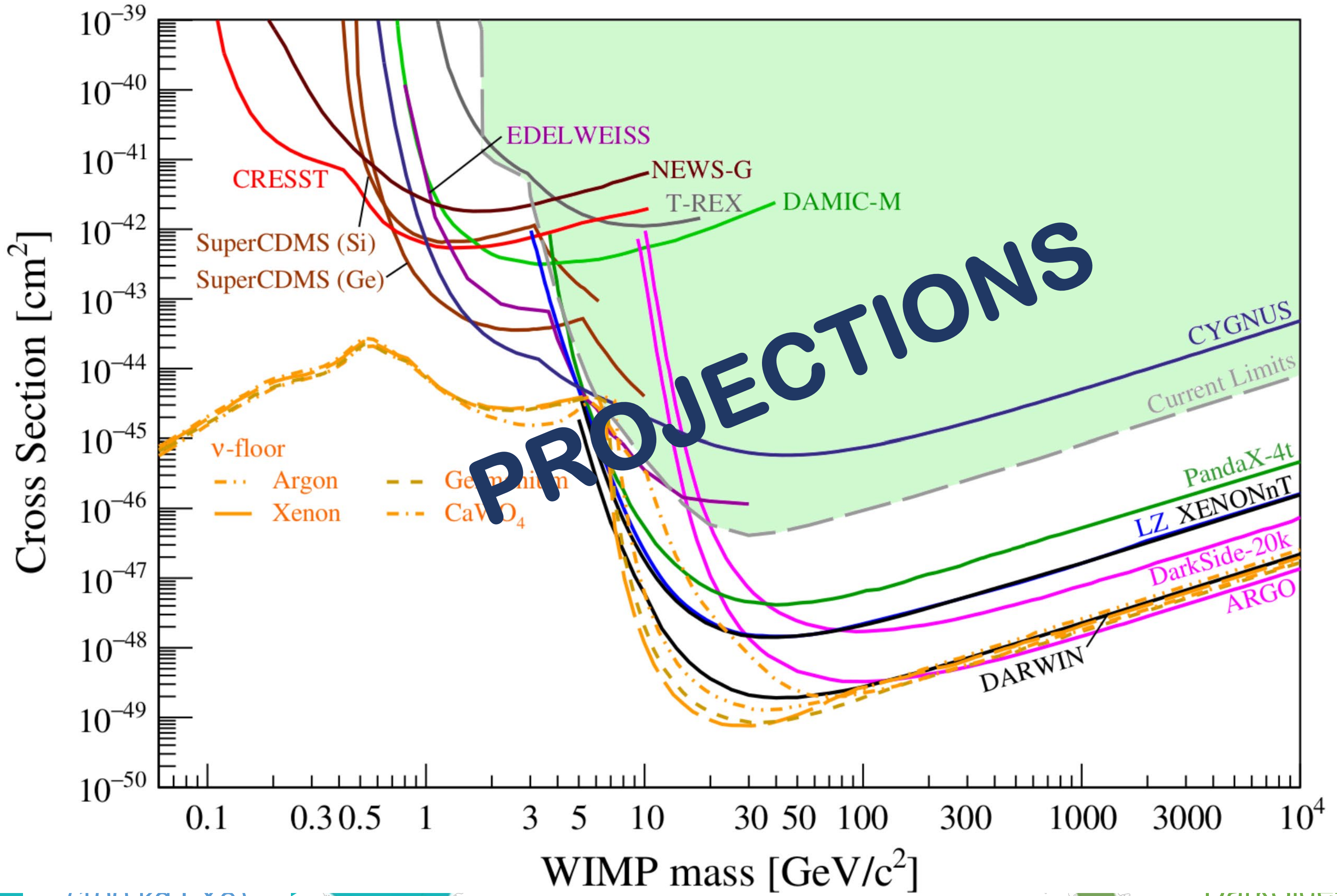


DarkSide-20k (in construction @ LNGS)
(50 ton LAr , 20 ton fiducial)

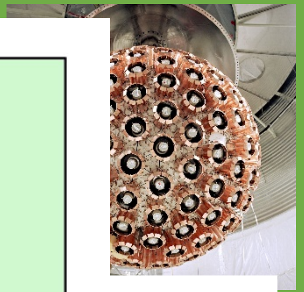
Present and future of noble-TPCs

Ar

Xenon 1T
(1 ton LXe)
(decomissioned)

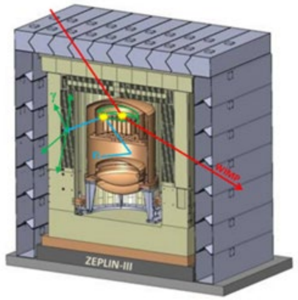


DarkSide-50
(50 kg LAr)
(decomissioned)



…ap-3600
…ton LAr)

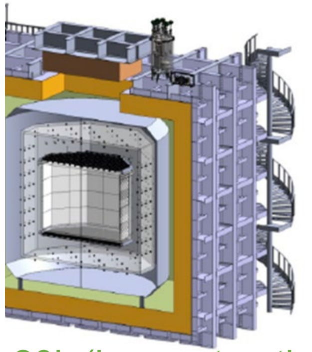
ArDM (1 ton LAr)
(decomissioned)



ZEPLIN-III
(6 kg LXe)
(decomissioned)

(100 kg LXe)
(decomissioned)

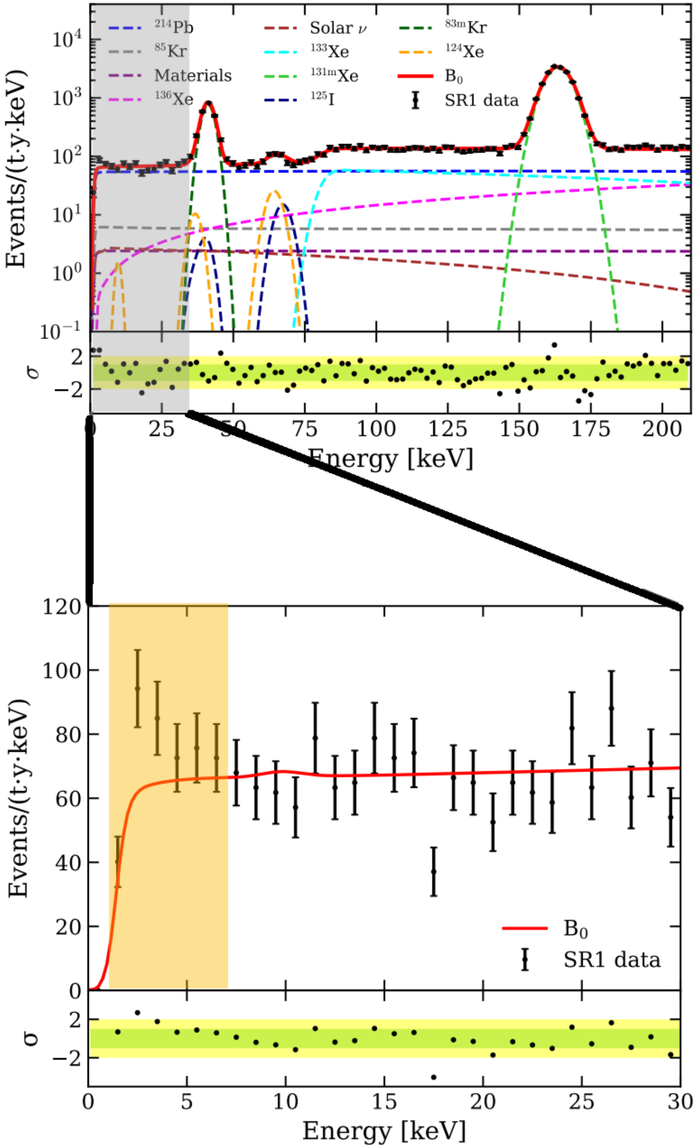
LZ (in construction @ SURF)
(7 ton-fiducial LXe)



…-20k (in construction @ LNGS)
(50 ton LAr , 20 ton fiducial)

Xenon1T electronic excess

PRD 102, 072004 (2020)

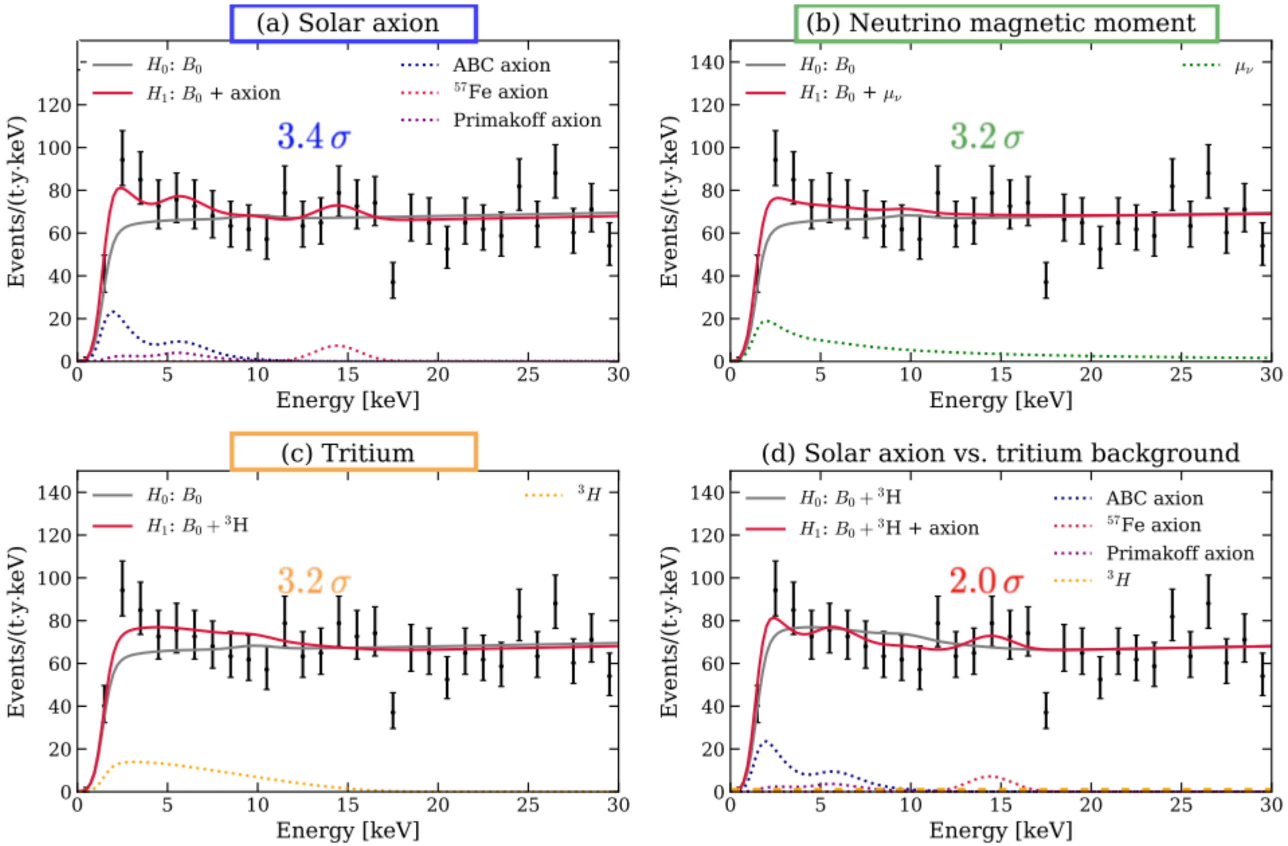


No electron recoil discrimination

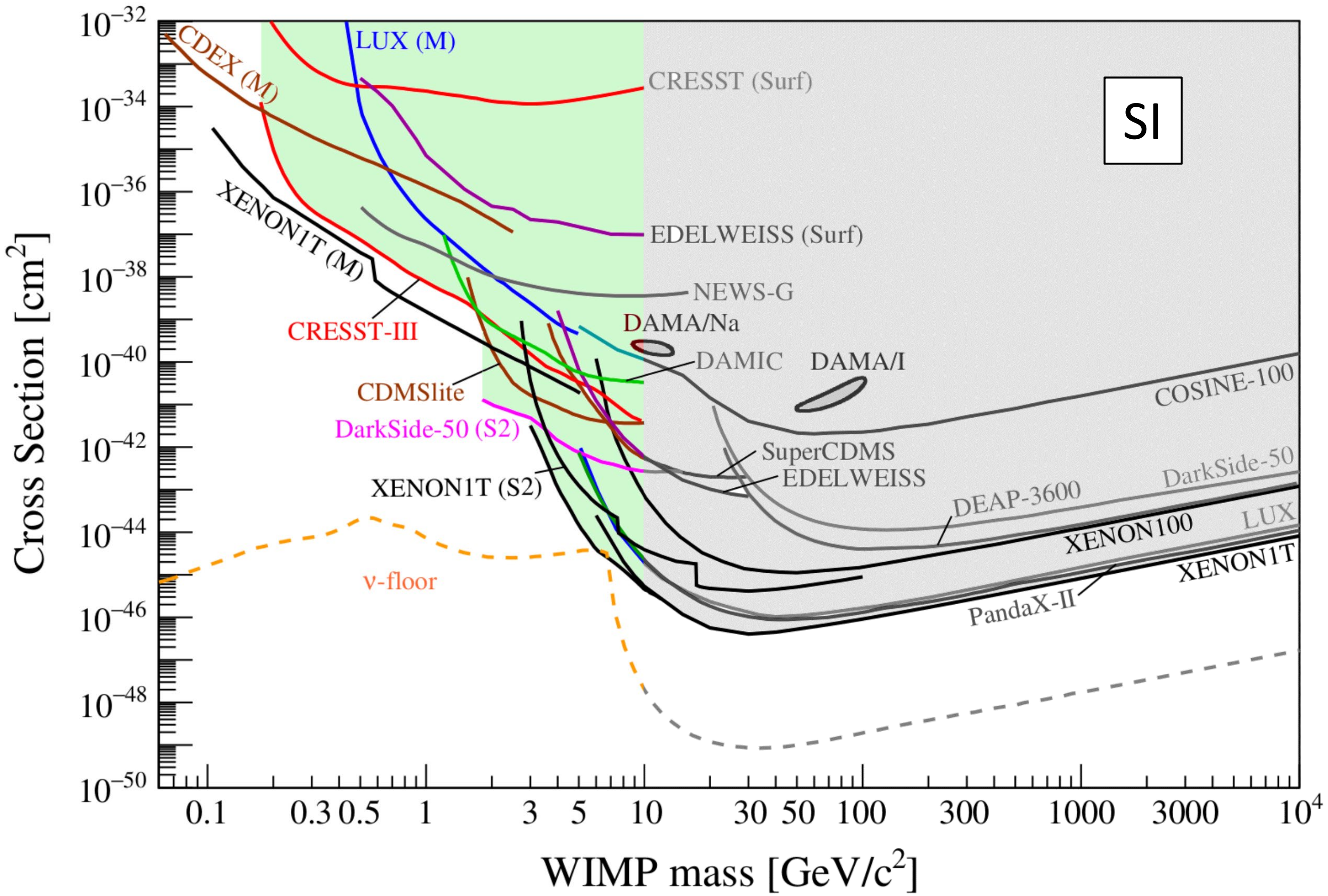
Background-only Fit

From 1-7keV:
expected: 232
Observed: 285

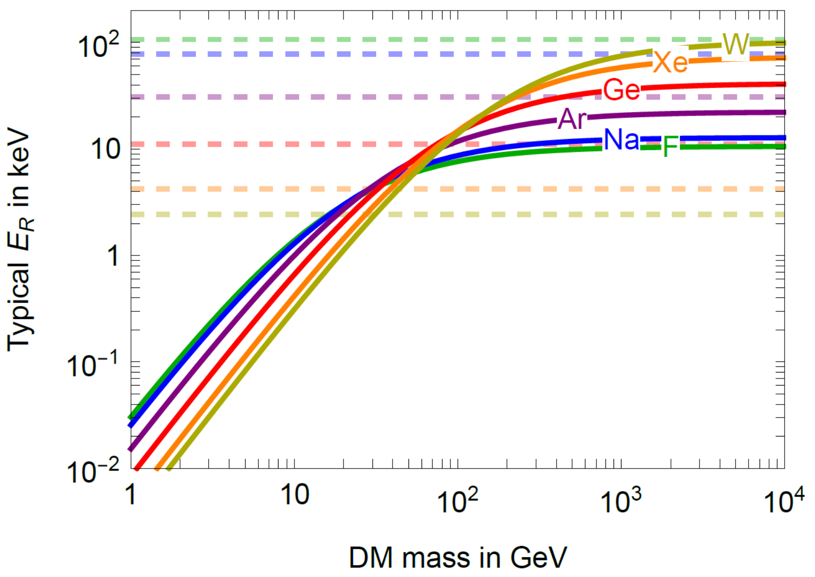
Possible explanations:



Low WIMP mass



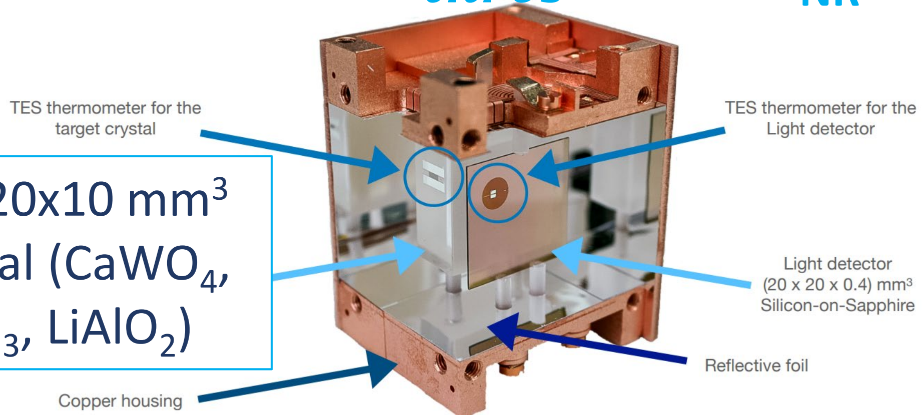
A very low energy threshold is needed to explore the low-mass region



- **Cryogenic detectors: Edelweiss, CRESST, SuperCDMS**
- **CCds: Damic, Sensei**
- **High-pressure gas chambers: News-G**

Cryogenic detectors & p-type Ge for low-mass WIMPs

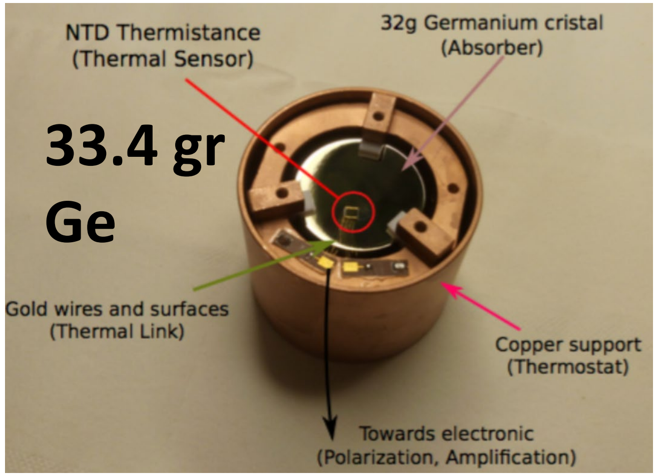
CRESST: E_{thres}= 30 eV_{NR}



20x20x10 mm^3 cristal ($CaWO_4$, Al_2O_3, $LiAlO_2$)

PRD 100 (2019) 102002

EDELWEISS: E_{thres}= 6 eV_{ee}

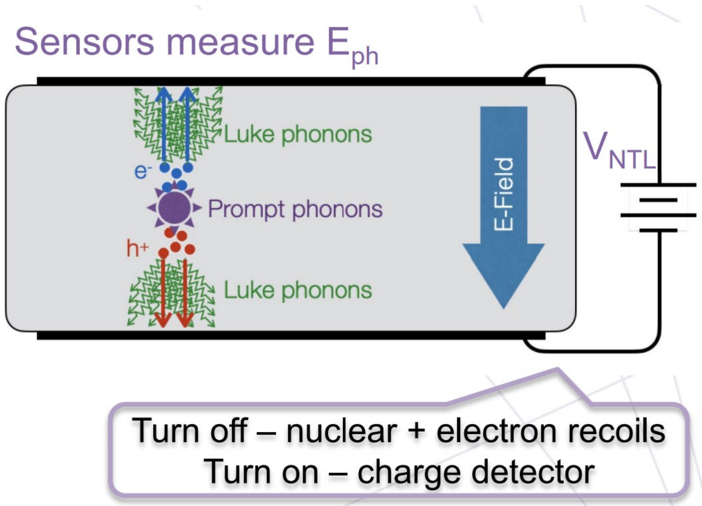


PRL 125 (2020) 14, 141301

CDMSLite E_{thres} = 70 eV

600 gr SuperCDMS detectors operated at high voltage → Neganov-Trofimov-Luke (NTL) amplification

PRD 99 (2019) 062001

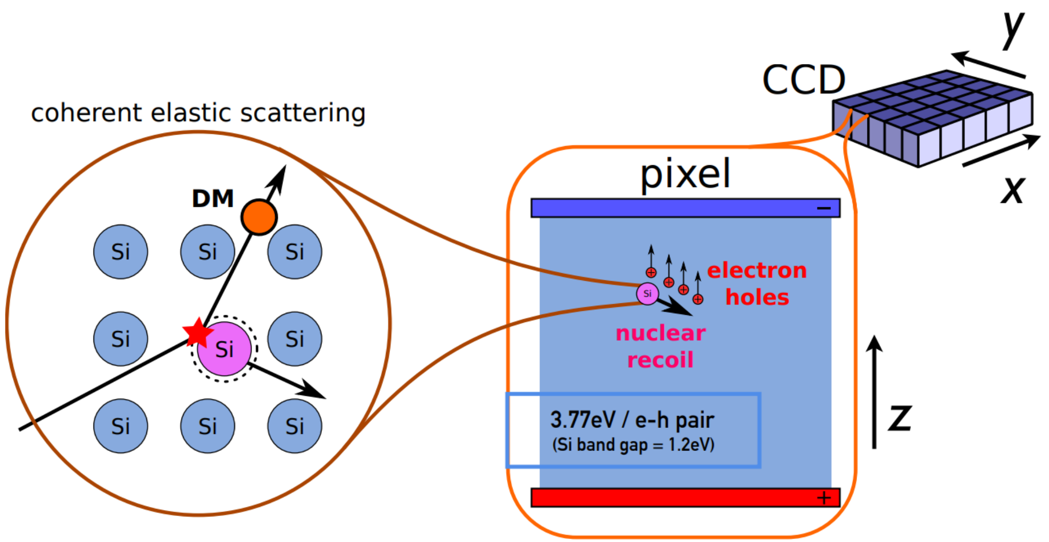


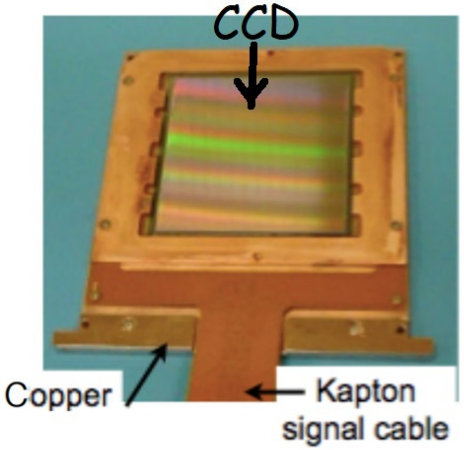
CDEX E_{thres} = 160 eV

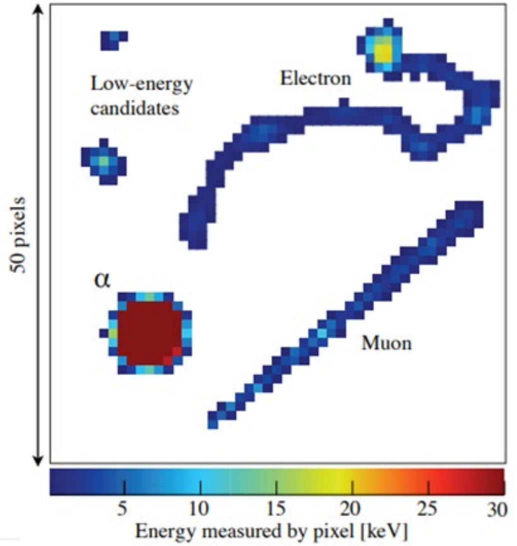
~1 kg p-type point contact Ge

PRL 123 (2019) 161301

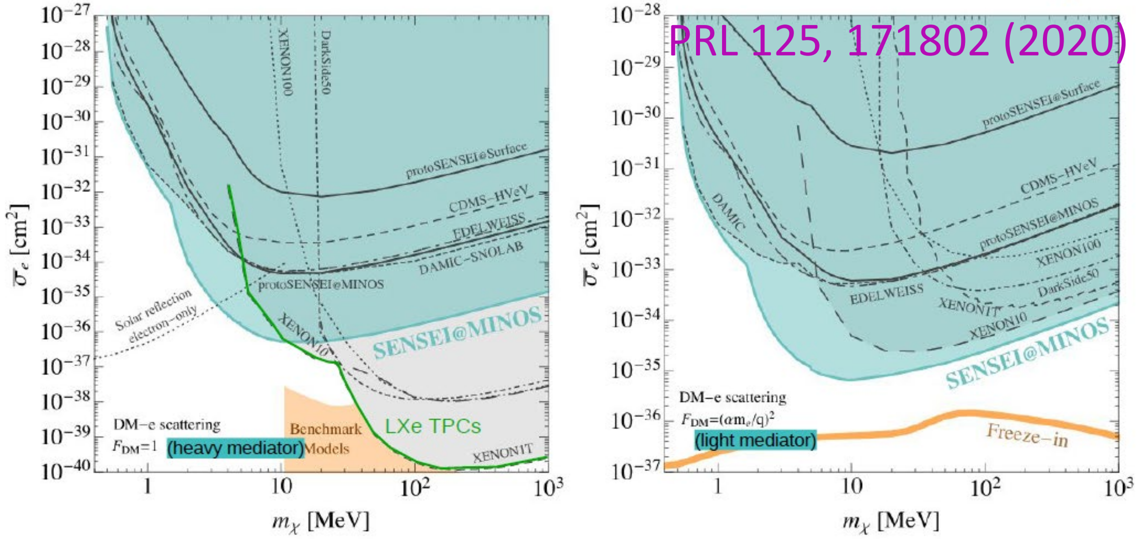
CCDs for low-mass & e$^-$ scatteting: DAMIC, Sensei







WIMP–e$^-$ scattering



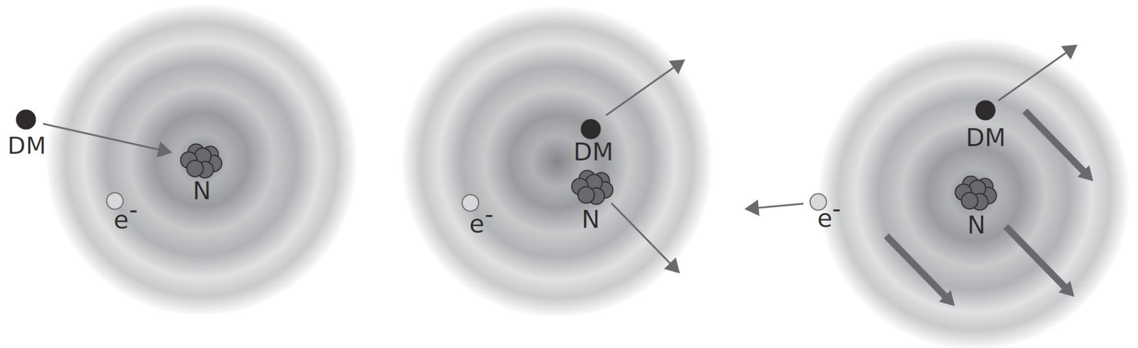
DAMIC @ SNOLAB: 42 gr Si (7 CCDs), Eth = 50 eV
Future: DAMIC-M (LSM) (1 kg)

SENSEI @ MINOS: ~2 gr Si-CCD, Eth few eV
Future: 100 gr @ SNOLAB

OSCURA (O(10) kg), in development

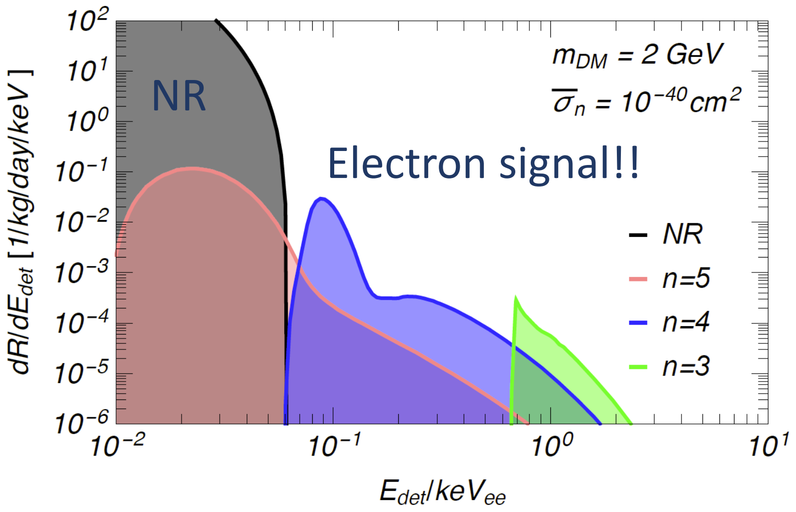
Migdal effect

M. J. Dolan, “Directly Detecting Sub-GeV Dark Matter with Electrons from Nuclear Scattering”, Phys.Rev.Lett. 121, 101801 (2018) [arXiv:1711.09906]



Migdal approximation: immediately after the collision the nucleus moves relative to the surrounding electron cloud. The electrons eventually catch up with the nucleus, but individual electrons can be “lost”, leading to ionization of the recoiling atom

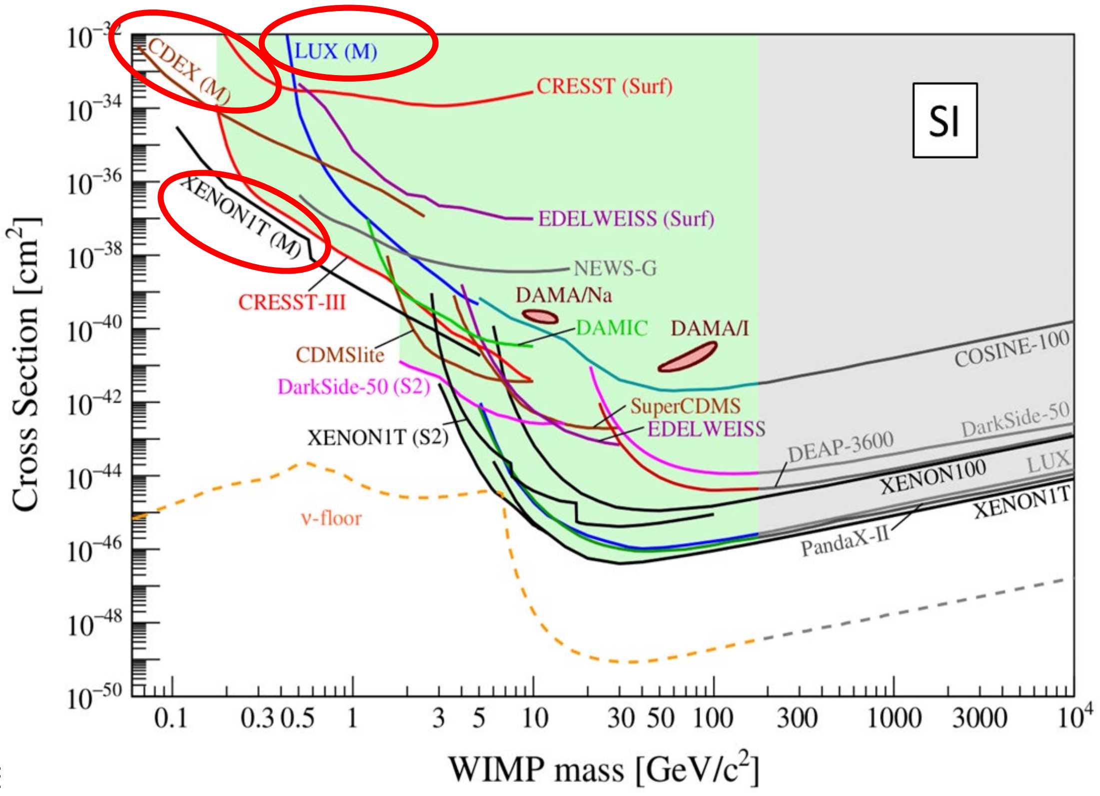
New detection channels (e-) for light dark matter with a mass in the GeV range.



M. Ibe et al, “Migdal effect in dark matter direct detection experiments”, JHEP03(2018)194 [1707.0725

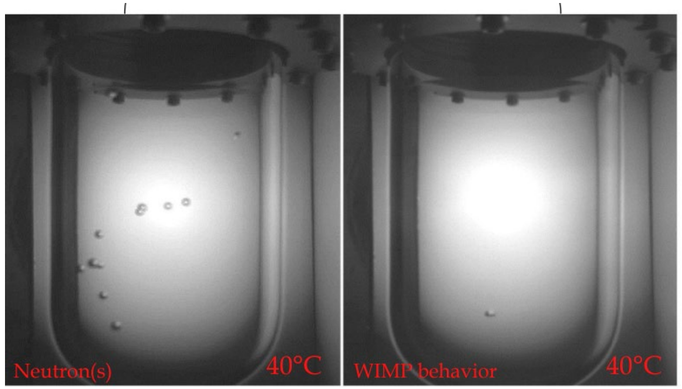
CAVEAT: EFFECT NOT YET PROVED EXPERIMENTALLY!!

(but maybe will be proved son by the **MIGDAL** collaboration)



Bubble chambers for SD-p

Best DD SD-p limits come from bubble chambers experiments that use targets with F (highest sensitivity to SD WIMP-proton couplings)

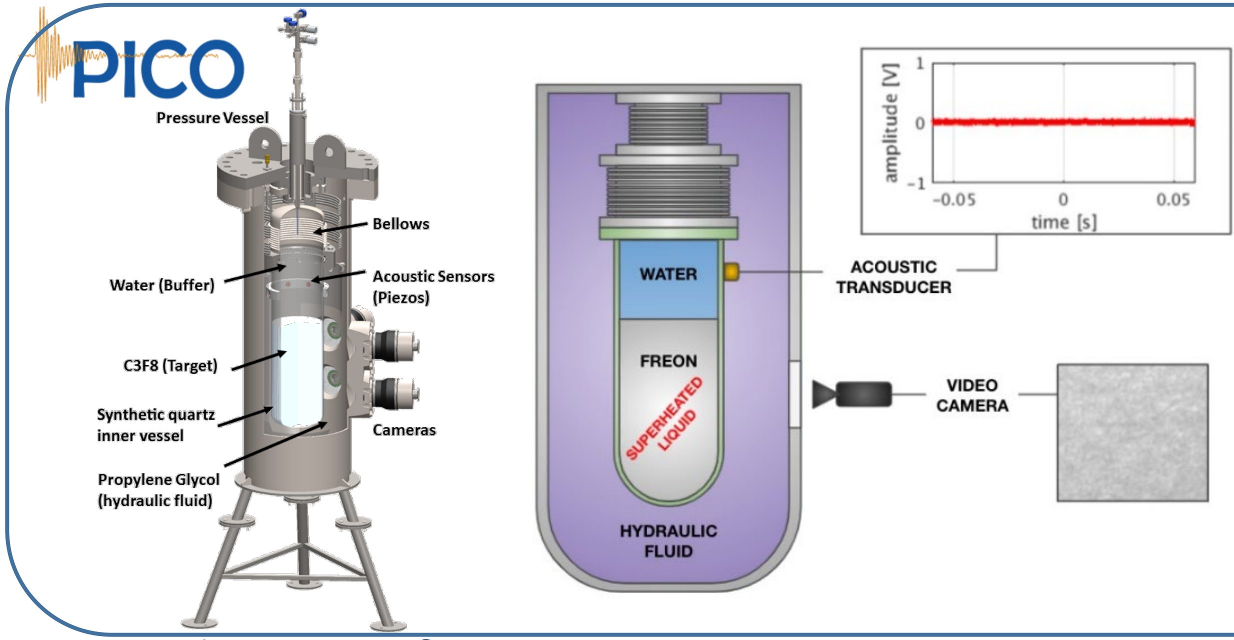


- Freon in metastable superheated state
- Tune the chamber to be unresponsive to most backgrounds. Only recoiling nuclei produce bubbles!
- Tune the chamber to set a nucleation energy threshold

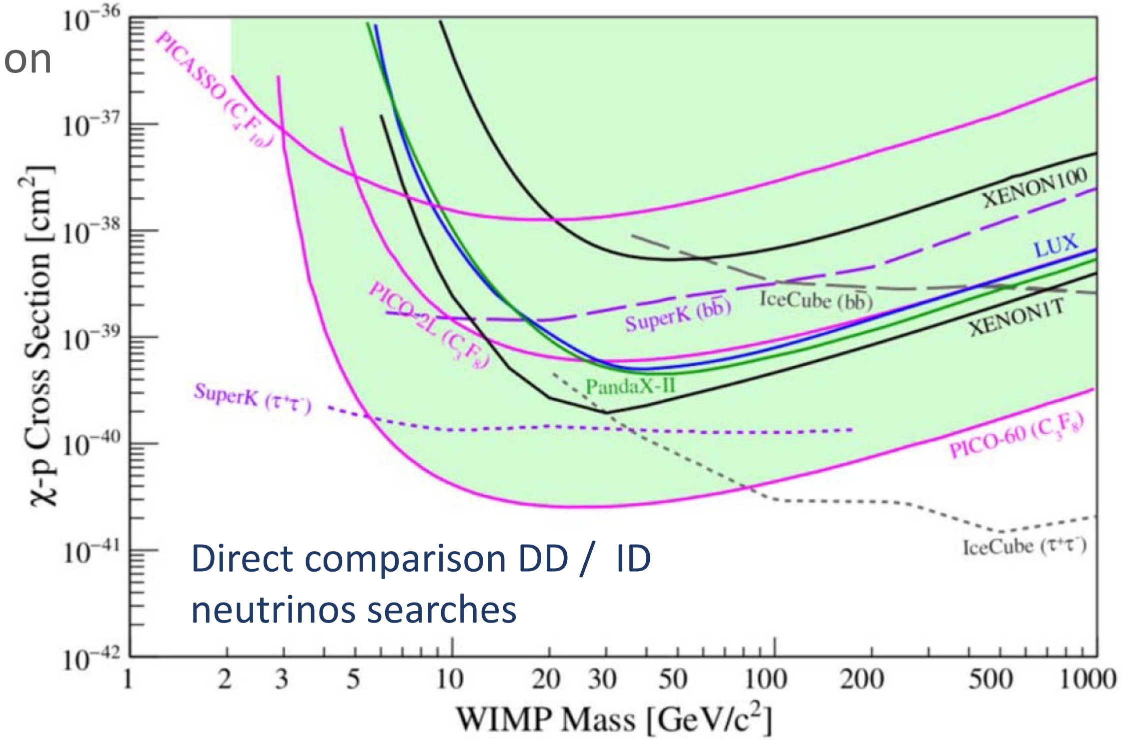
2-4 GeV: PICASSO (3 kg C_4F_{10})
Astropart. Phys. 90 (2017) 85

5-100 GeV: PICO-60 (52 kg C_3F_8)
PRD 100 (2019), 2 022001

> 100 GeV: Icecube ($\tau^+\tau^-$)

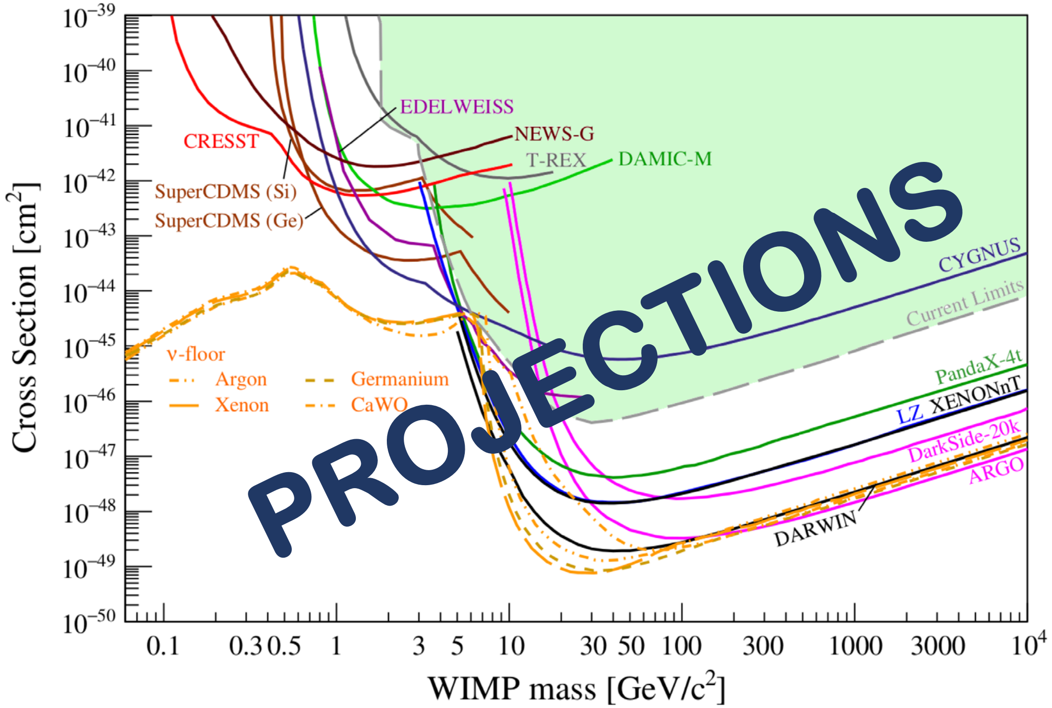


Alphas are 4x louder than neutrons!

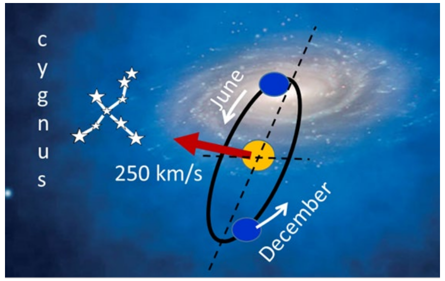


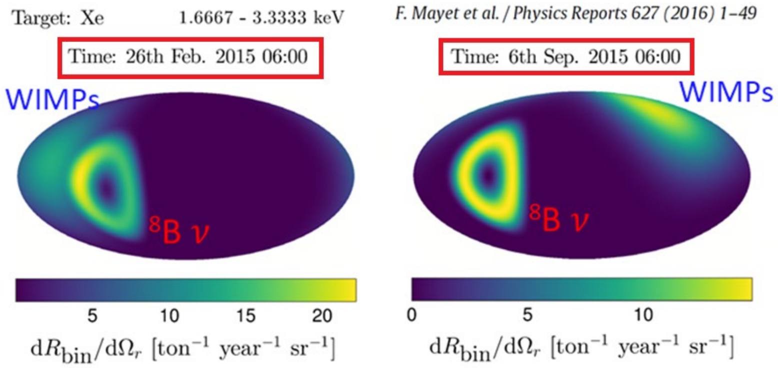
Direct comparison DD / ID neutrinos searches

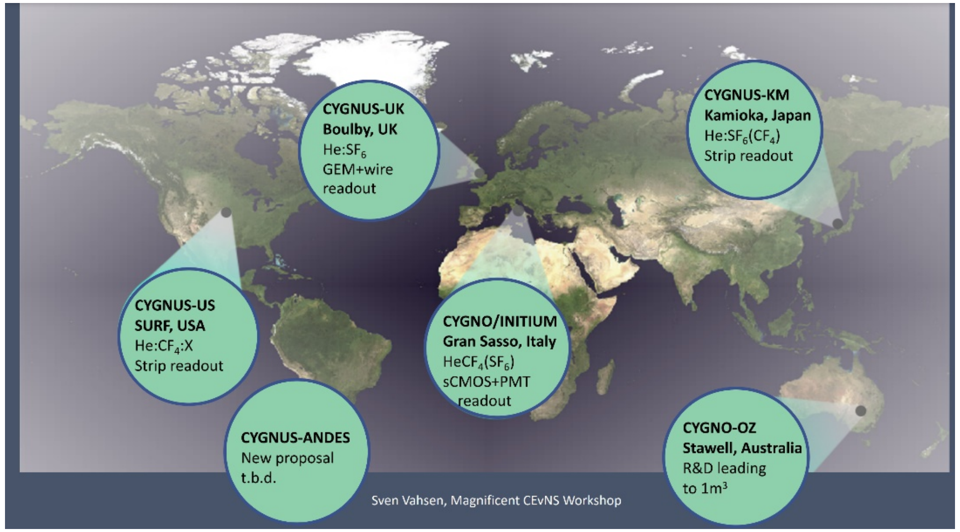
Outlook & prospects



- DAMA/LIBRA positive signal tested at almost 3σ by ANAIS-112/COSINE-100 experiments
- Xenon1T electronic excess – new physics or just background?
- Xe&Ar experiments planned to reach the neutrino floor in the next decade
- Many new ideas/experiments to explore DM excenarious in the GeV (NR), MeV (ER), keV -> eV (absorption) regions
- Beyond the neutrino floor? Directionality? → **CYGNUS collaboration**





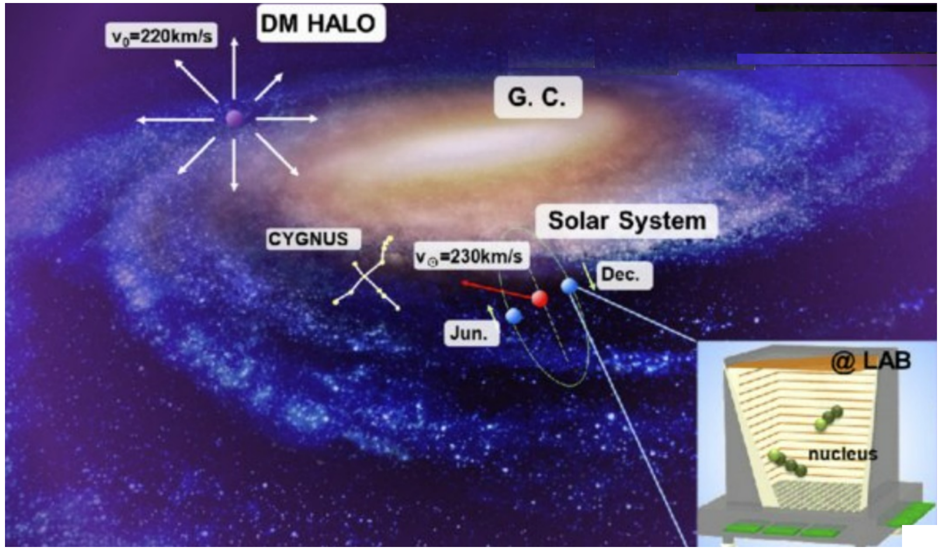


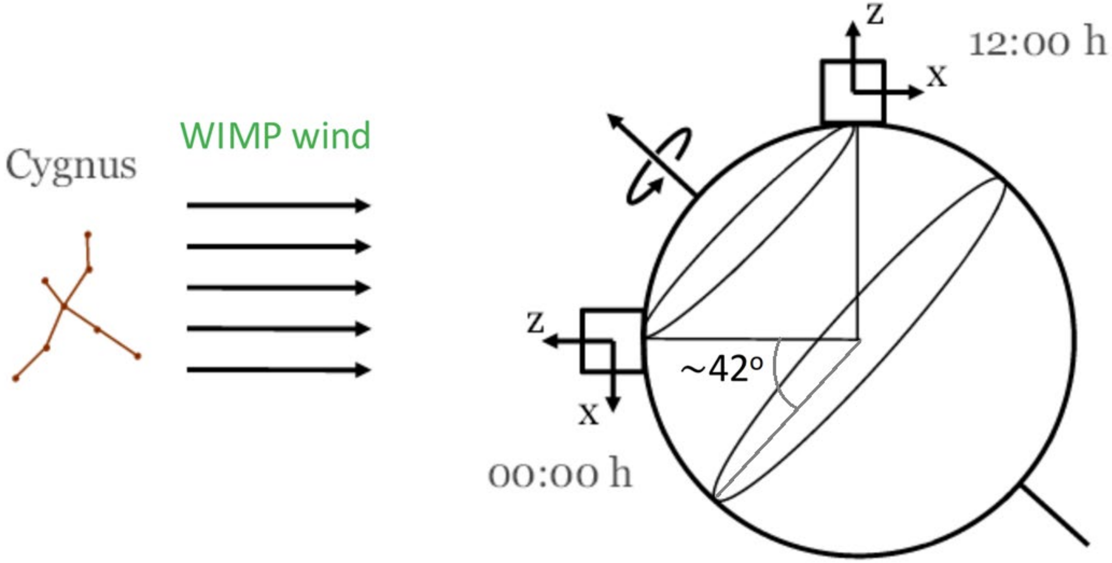
Vahsen et al, "Cygnus: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos", 2008.12587

backup

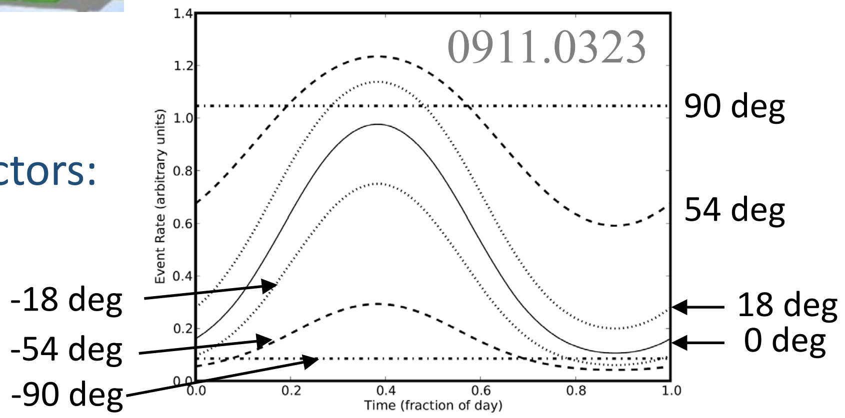
Directionality & daily modulation

There is a strong forward/backward asymmetry. However, the mean recoil direction oscillates due to the rotation of the Earth, with a period of a sideral day (23h 56m)





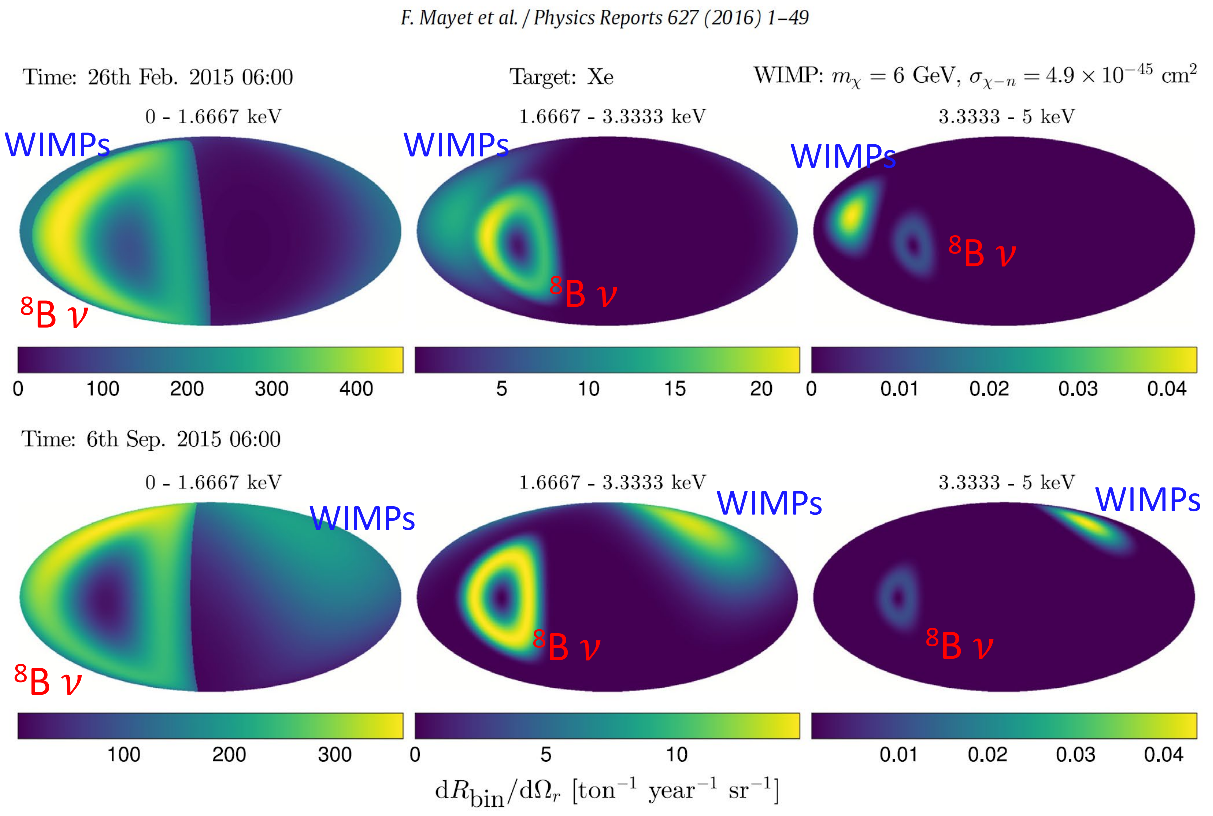
→ Daily modulation in anisotropic detectors:



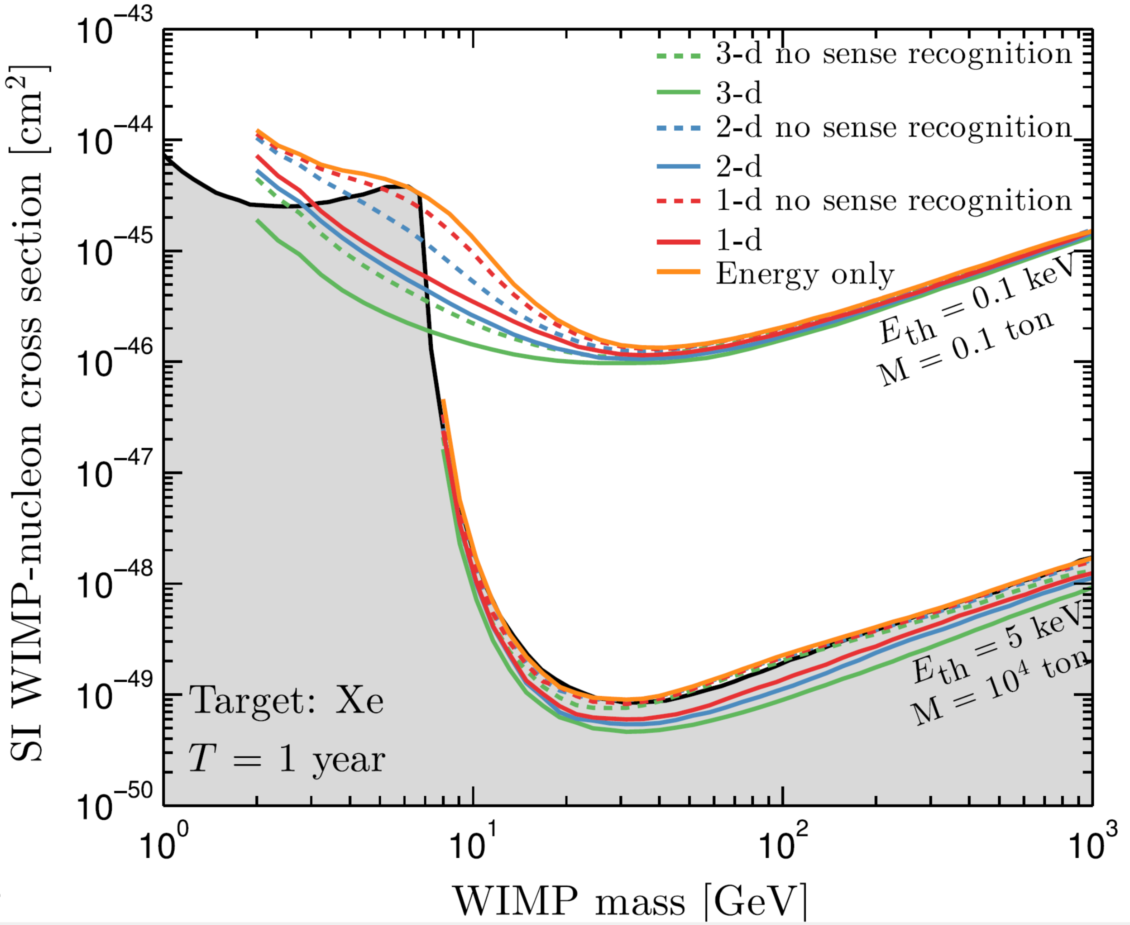
Most of the underground laboratories are at latitudes 35 – 45 deg N

Wimps Vs ^{8}B neutrinos

F. Mayet et al, "A review of the discovery reach of directional Dark Matter detection", Phys. Rep. 627, 1 (2016)



Mollweide projections of WIMP- & ^{8}Bν-induced recoils in lab frame



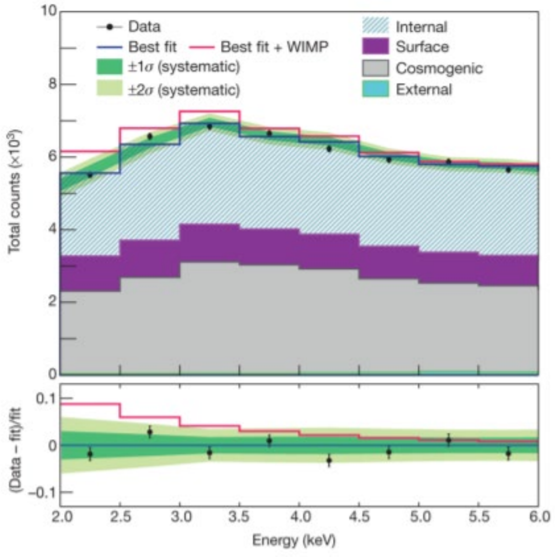
M. Martinez. F. ARAID & CAPA (U. Zaragoza)

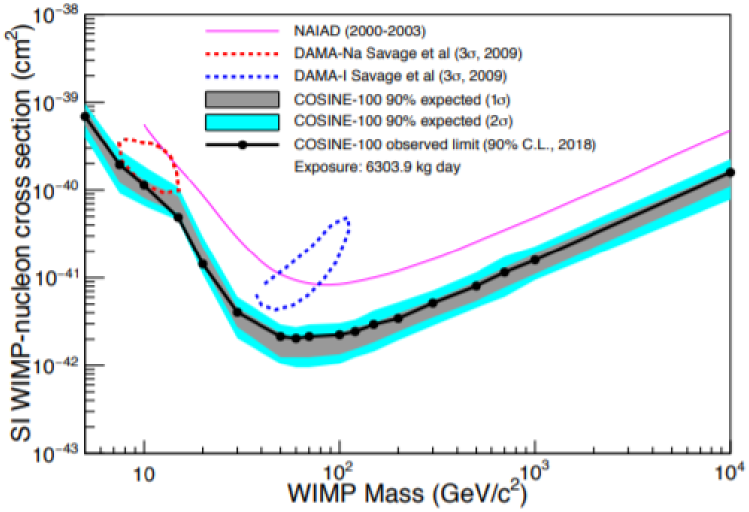
COSINE-100 results: model dependent analysis

MODEL DEPENDENT ANALYSIS: background model + WIMP signal fit to data

SET1 (59.5 days) (2 keV threshold)

Nature 564 (2018) 83

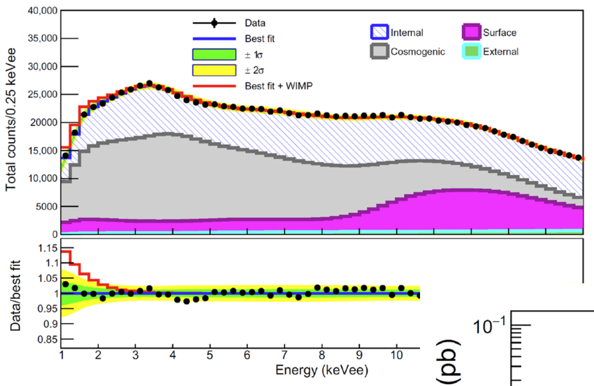


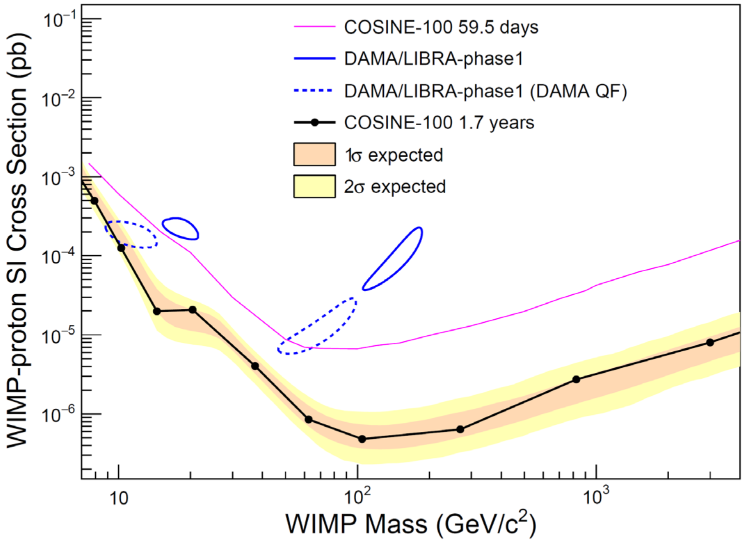


90% CL COSINE limits excluded DAMA region in SI scenarios

SET2 (1.7 y, 97.7 kg·year exposure, 1 keV threshold)

Sci. Adv. **7**, eabk2699 (2021)

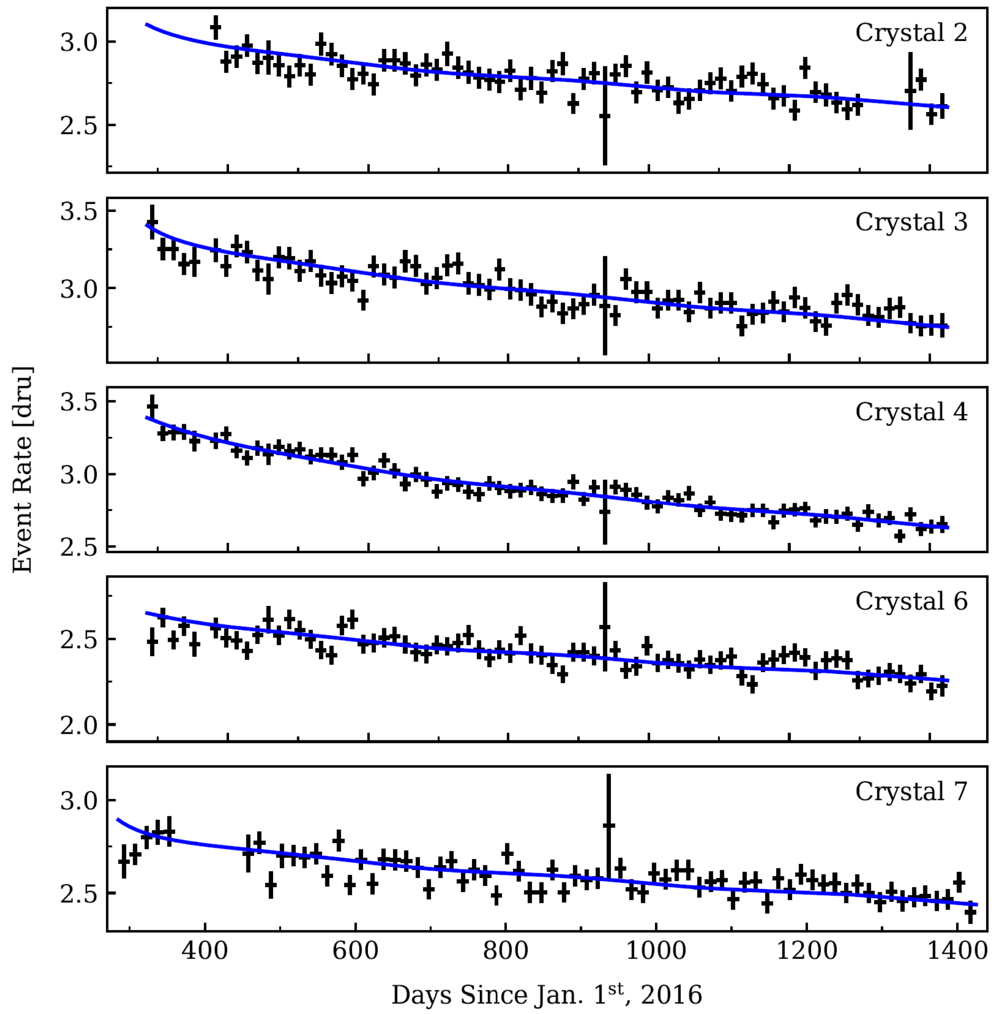




- 1 keV threshold
- **Using COSINE QF measurement**
- Strong constraint also in other alternative scenarios

COSINE-100 results: 3-year annual modulation

[2111.08863] Data: 2.82 yr livetime utilizing an active mass of 61.3 kg for a total exposure of 173 kg×yr.



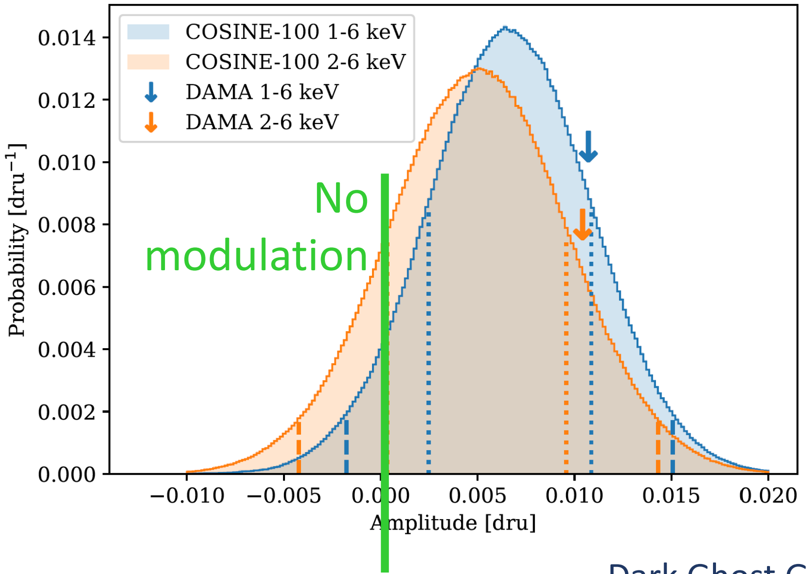
$$R_i(t|S_m,\alpha_i,\beta_i) = \alpha^i + \sum_{k=1}^{N_{bkgd}} \beta_k^i e^{-\lambda_k t} + S_m \cos(\omega(t-t_0)).$$

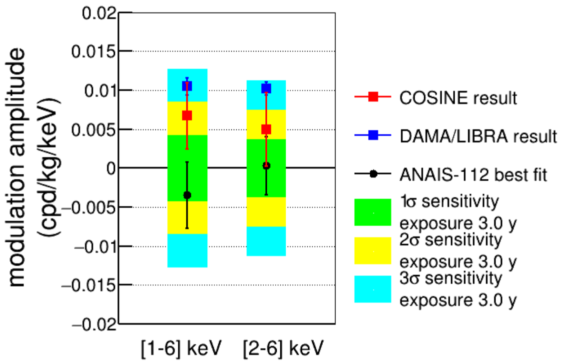
$N_{bkgd} = 8$ background components (λ_k fixed)

α_i, β_k^i free (45 parameters)

[1 – 6] keV: $S_m = 0.0067 \pm 0.0042$ cpd/keV/kg

[2 – 6] keV: $S_m = 0.0050 \pm 0.0047$ cpd/keV/kg





ANAIS vs COSINE

ANAIS: Phys. Rev. D 103, 102005 (2021)
COSINE: [2111.08863]

	S_m (counts/keV/kg/day)		
	ANAIS-112	COSINE-100	DAMA/LIBRA
[1-6] keV	-0.0034±0.0042	0.0067±0.0042	0.0105±0.0011
[2-6] keV	0.0003±0.0037	0.0050±0.0047	0.0102±0.0008