LIGHT DARK MATTER SEARCHES

IN LIQUID ARGON TIME PROJECTION CHAMBER

Masayuki Wada

AstroCeNT, Warsaw

November 20 2023

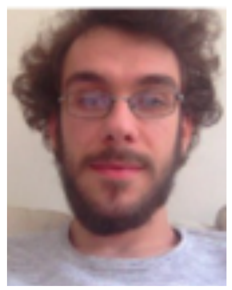
COPIN-IN2P3 workshop

FRENCH-POLAND COLLABORATION

- French groups
- Polish (AstroCeNT) groups

APC group


Davide Franco


Timothee Hessel

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Group 1


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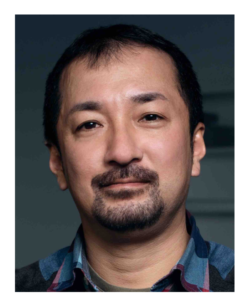
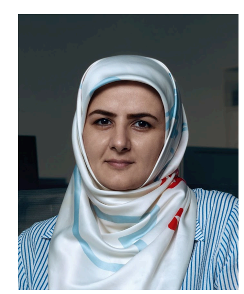
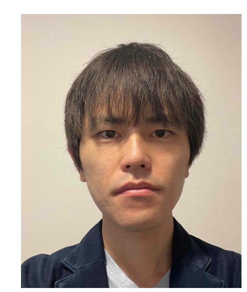
Marek Walczak


Sarthak Choudhary

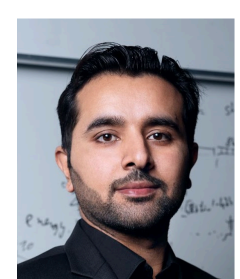
Group 4

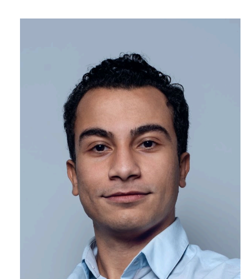

Masazuki Wada


Azam Zabihi


Masato Kimura


Rafał Wojaczyński


Iftikhar Ahmad

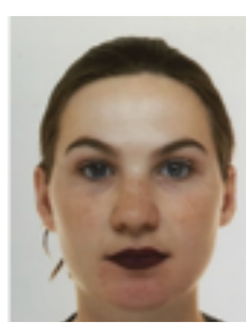

Paul Zakhary


Clea Sunny

CPPM group

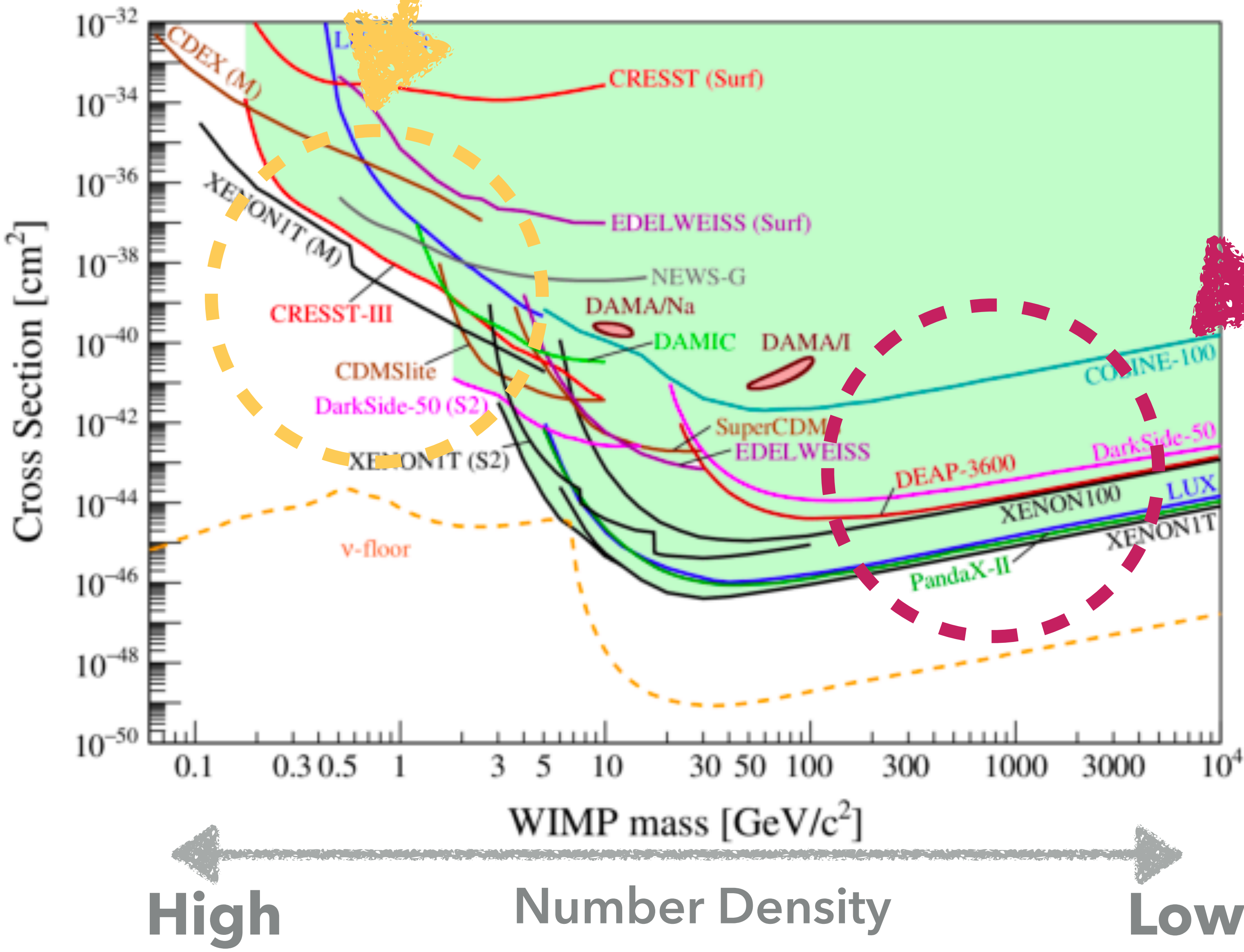

Pascal Pralavorio

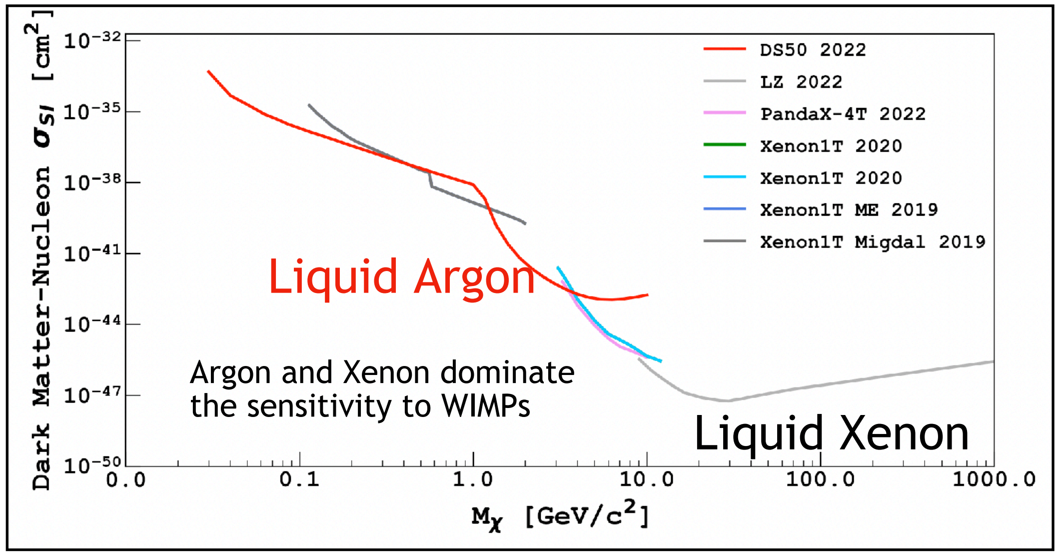

Fabrice Hubaut


Marie Van Uffelen

SENSITIVITY TO HIGH AND LOW MASS WIMPS

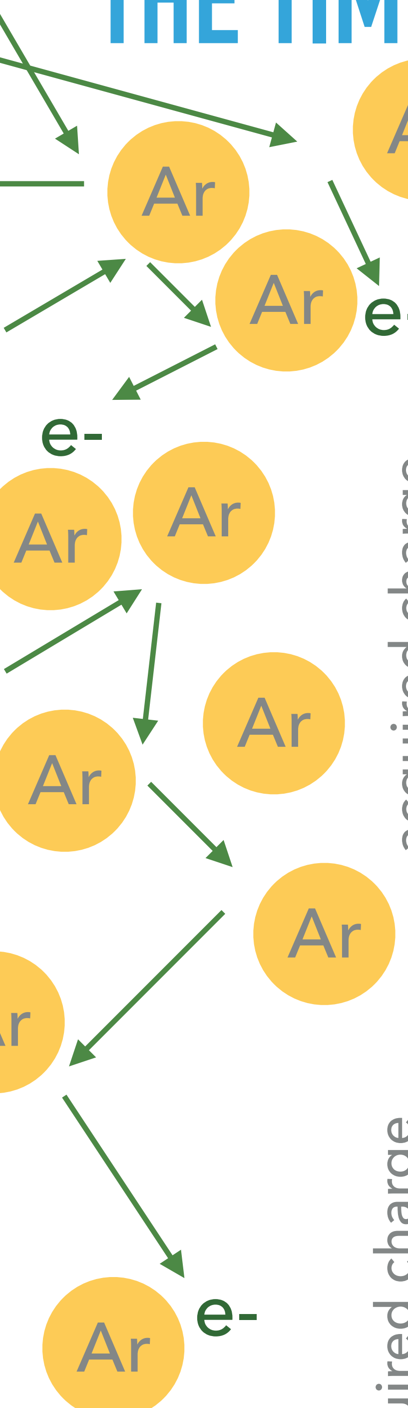
- Sharpe rise at low mass is due to **detection threshold.**
- Need **lower threshold** → **Ionization signal (S2)**
- Rise at high mass is due to **fixed energy density of WIMPs**.
- Need **large target mass.**
- Scalability is important!



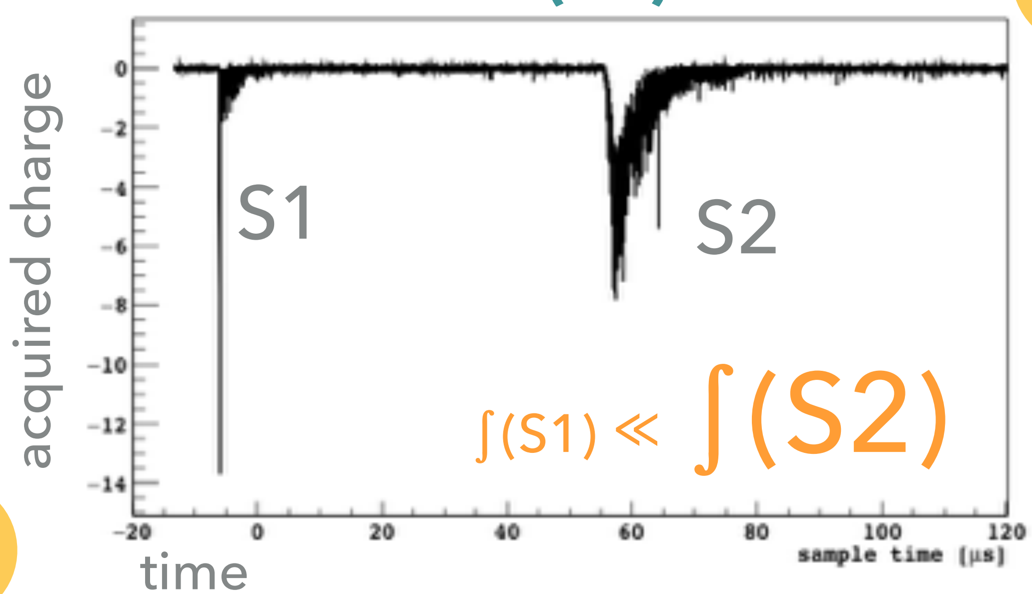


plot credit: http://resonaances.blogspot.ca

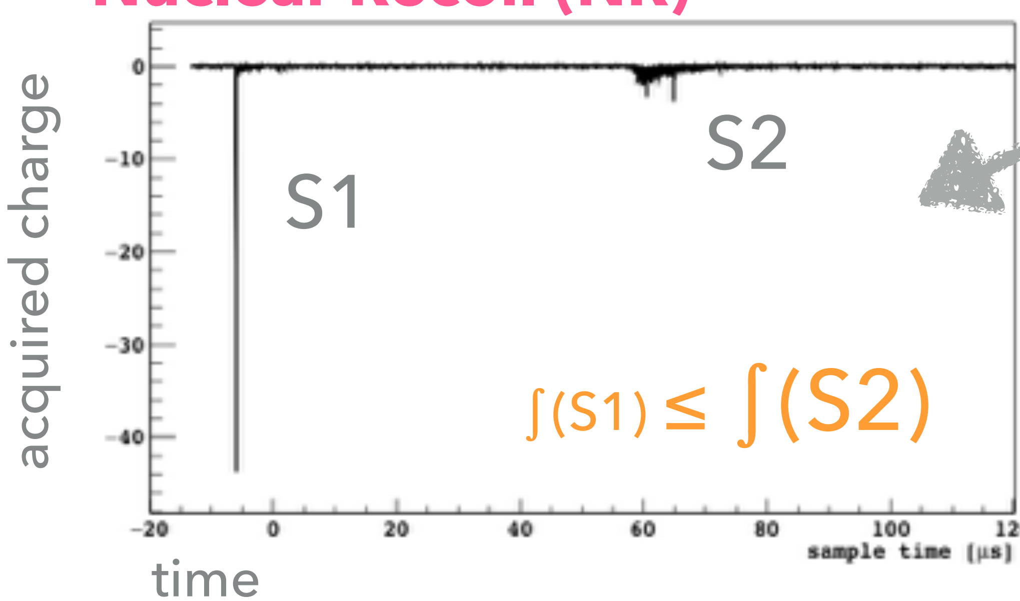
THE TIME-PROJECTION CHAMBER (TPC)

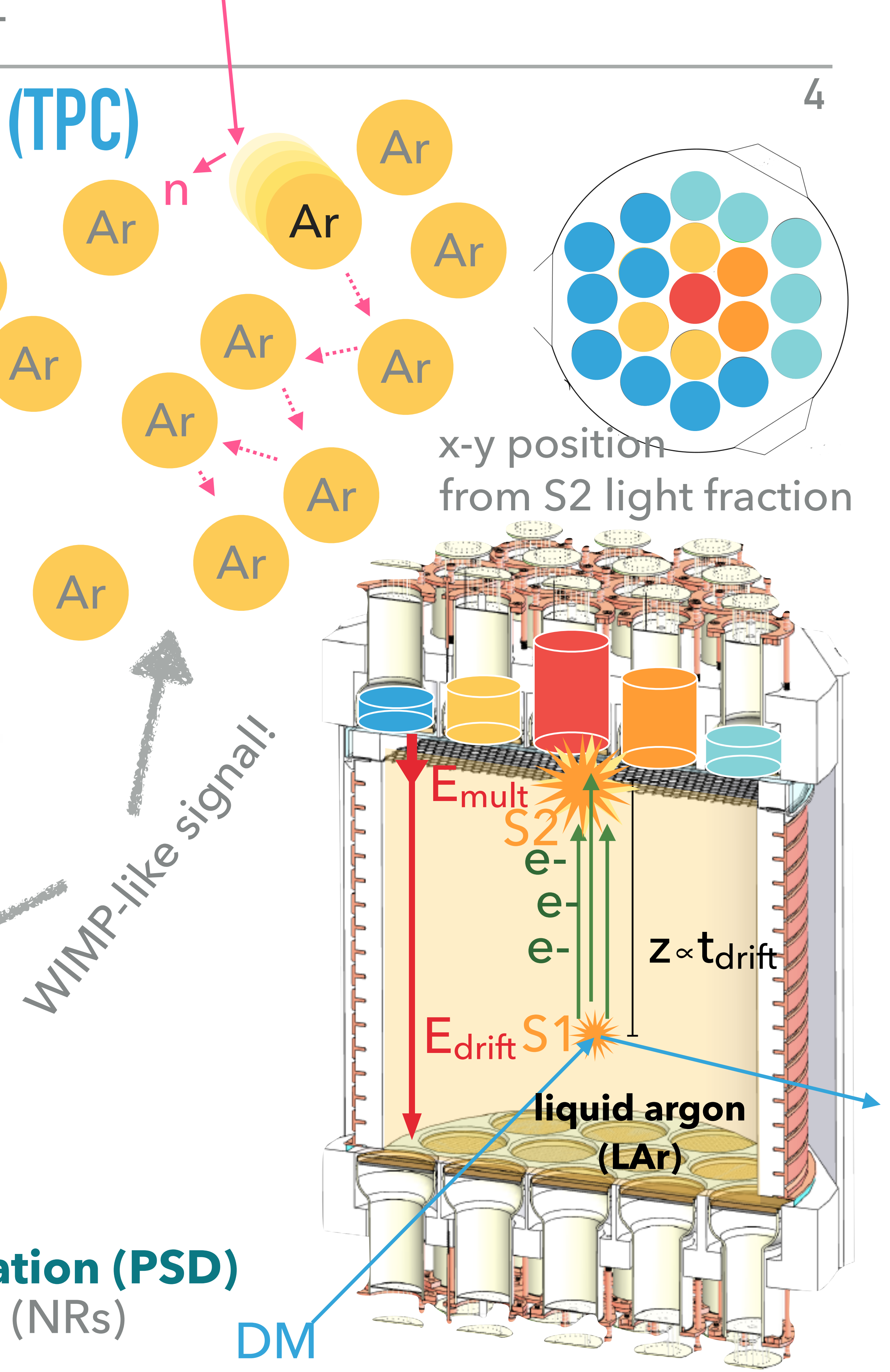


Electron Recoil (ER)



Nuclear Recoil (NR)

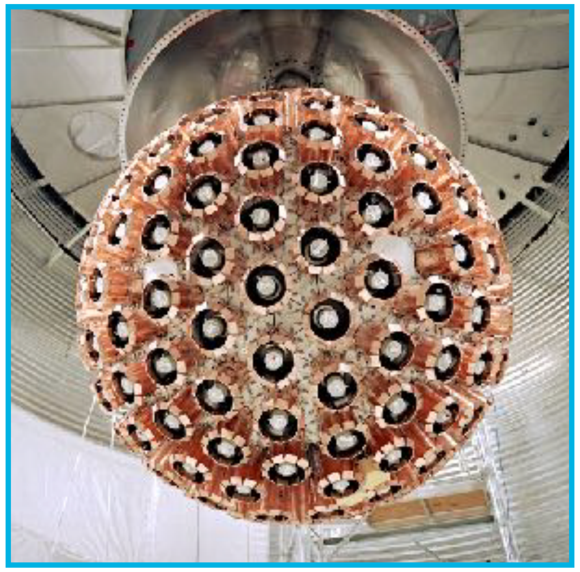




S2/S1 ratio and **Pulse Shape Discrimination (PSD)**

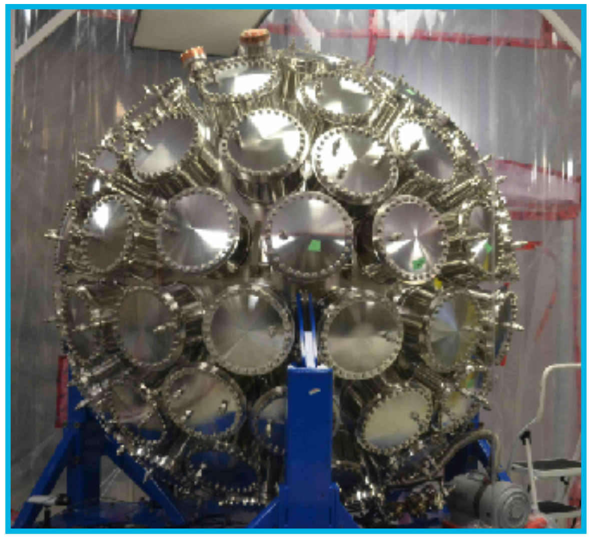
WIMPs will generate nuclear recoils (NRs)

GLOBAL ARGON DARK MATTER COLLABORATION



DEAP-3600

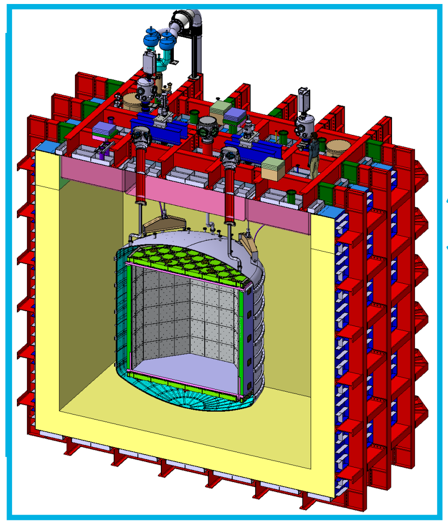
More than 400 scientists from past and present argon-based experiments in a single international argon collaboration: **GADMC**



MiniCLEAN

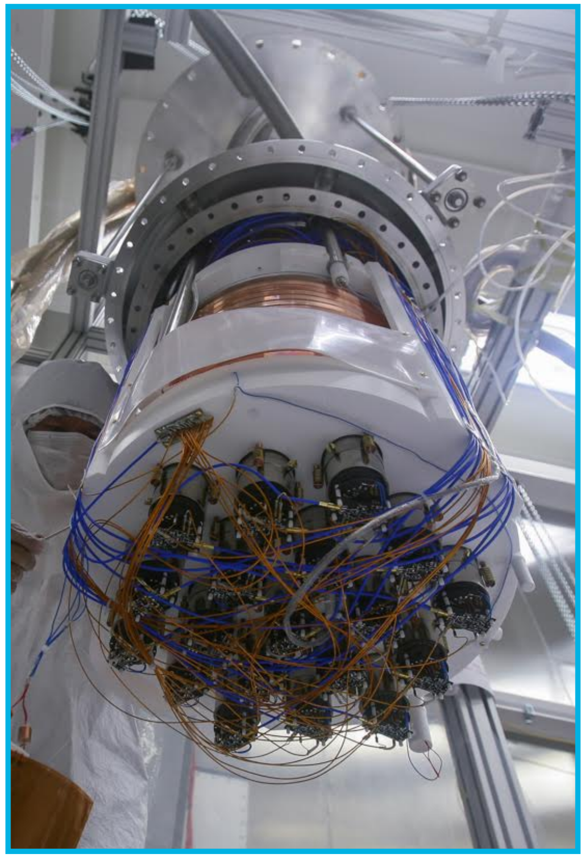
A sequential, two-steps program:

- DarkSide-20k (200 tonne yr fiducial)

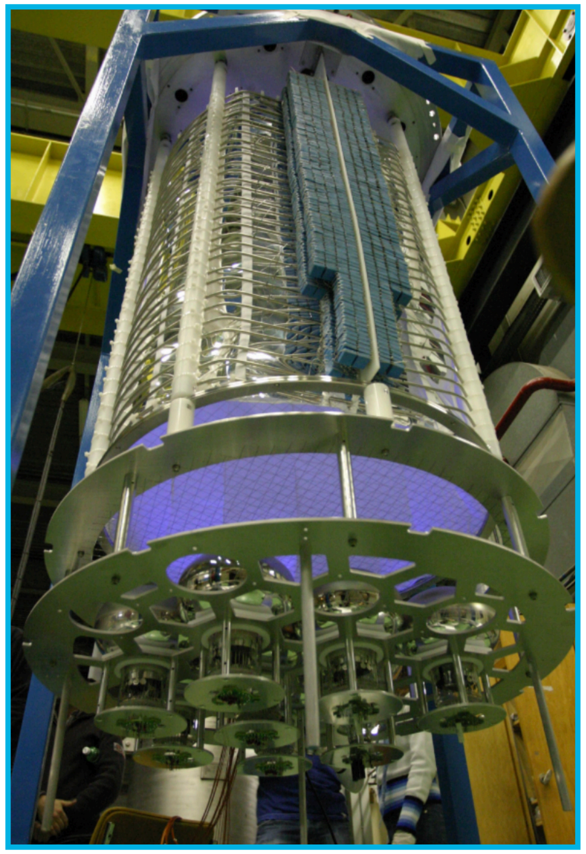


- Argo (3,000 tonne yr fiducial)

At SNOLAB
~203X



DarkSide-50

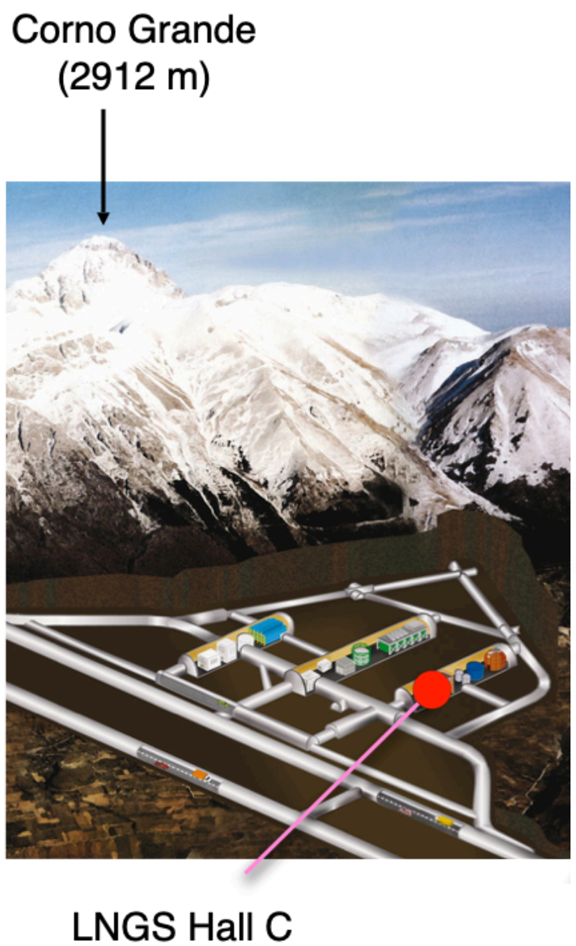


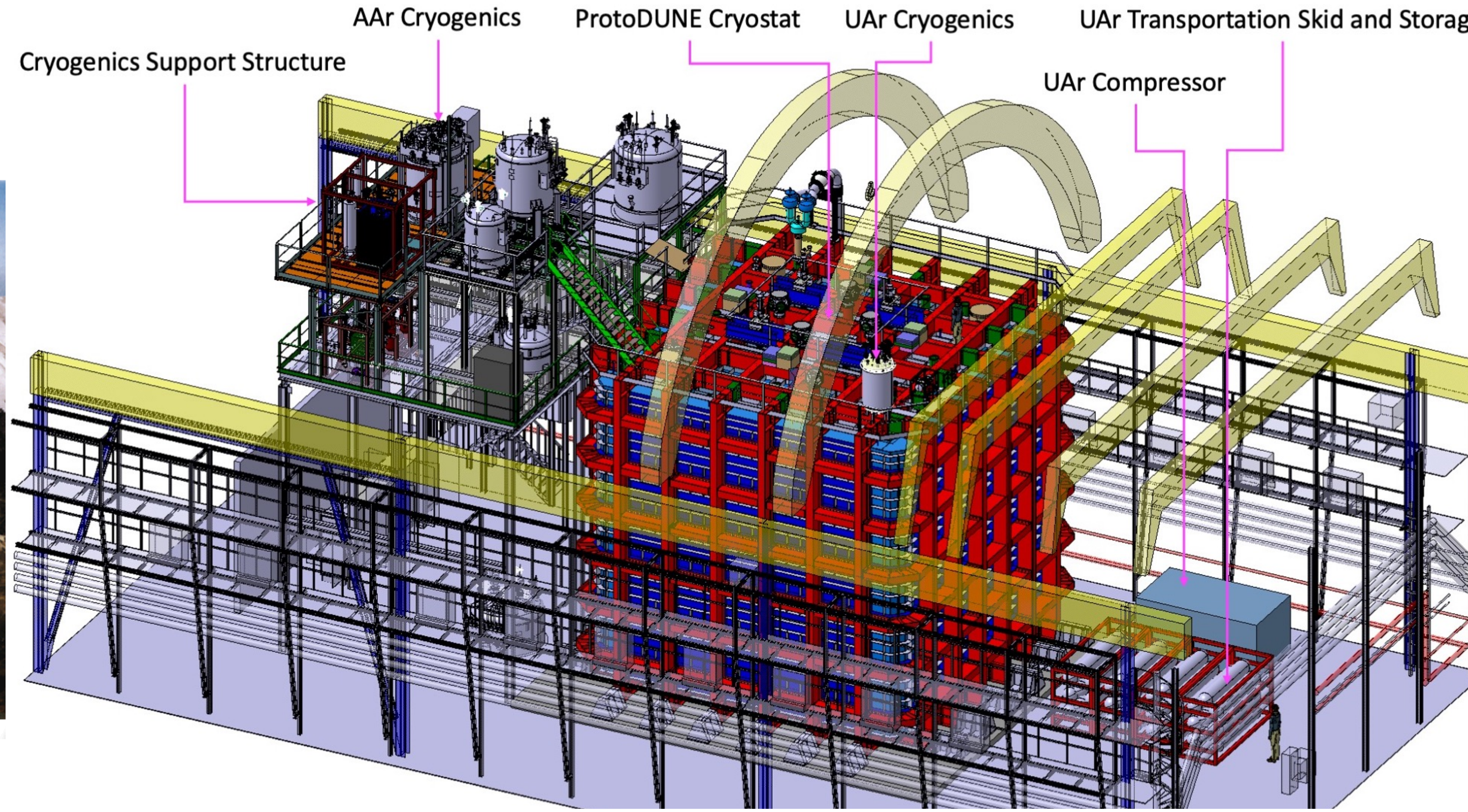
ArDM

The goal: explore heavy dark matter to the neutrino floor and beyond with extremely low instrumental background

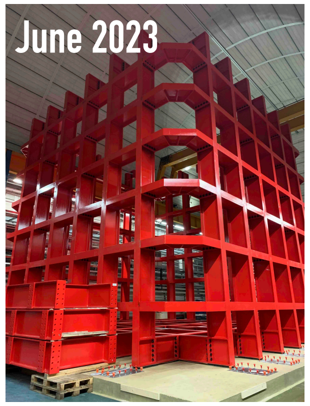

Gran Sasso
3800 m w. e.
Slovenia
Zagreb
Como
Milan
Trieste
Verona
Venice
Padua
Turin
Croatia
Genoa
Bologna
Bosnia and Herzegovina
Zadar
Sarajevo
San Marino
Pisa
Florence
Monaco
Cannes
Split
Italy
Adriatic Sea
National Institute for Nuclear Physics...
Podgorica
Подгорица
Corse
Rome
Bari
Naples
Pompeii
Matera
Taranto
Lecce
Sardegna
Tyrrhenian Sea
Cagliari
Reggio
Deep underground location at LNGS, Italy.

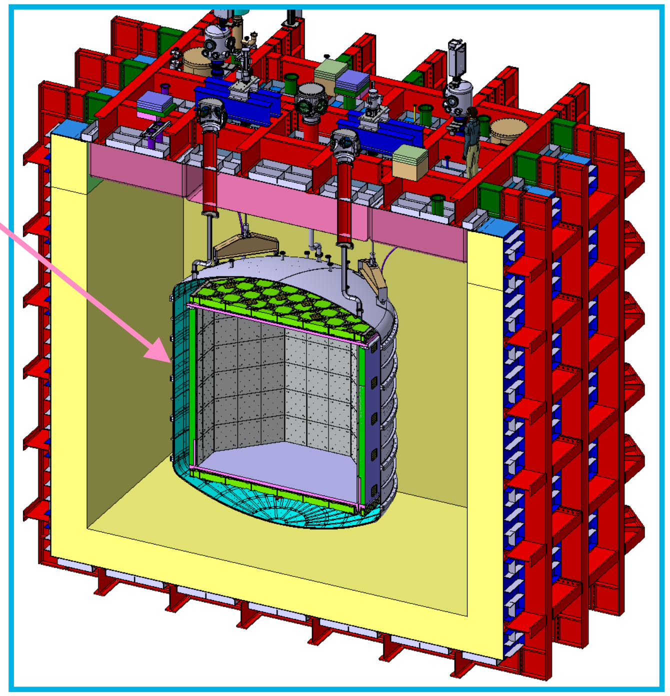
DARKSIDE-20K DETECTOR





- DarkSide-20k will be installed underground at the Gran Sasso National laboratories, in Italy.
- The detector has a nested structure:
  - Titanium Vessel contain liquid underground argon (100 t)
    - Gadolinium loaded acrylic TPC filled with 50 t of UAr
    - Neutron veto buffer between TPC and Ti vessel
  - Membrane cryostat like the ProtoDune one





WHAT WE HAVE DONE

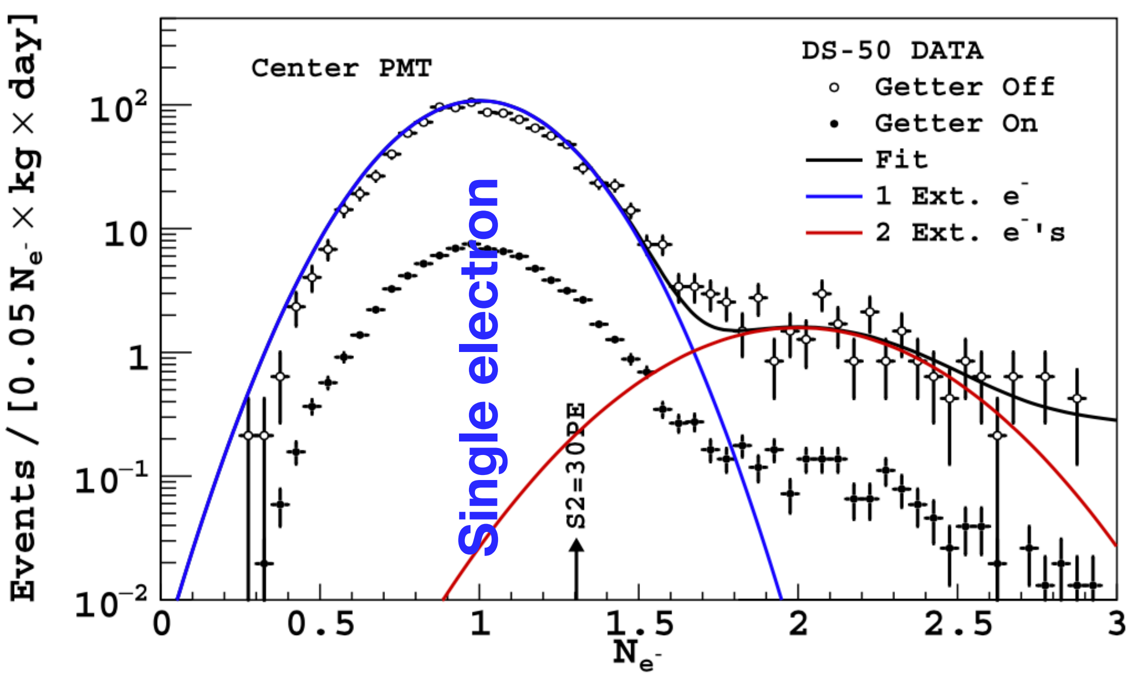
LOW MASS WIMP SEARCH

Ionization Only Analysis

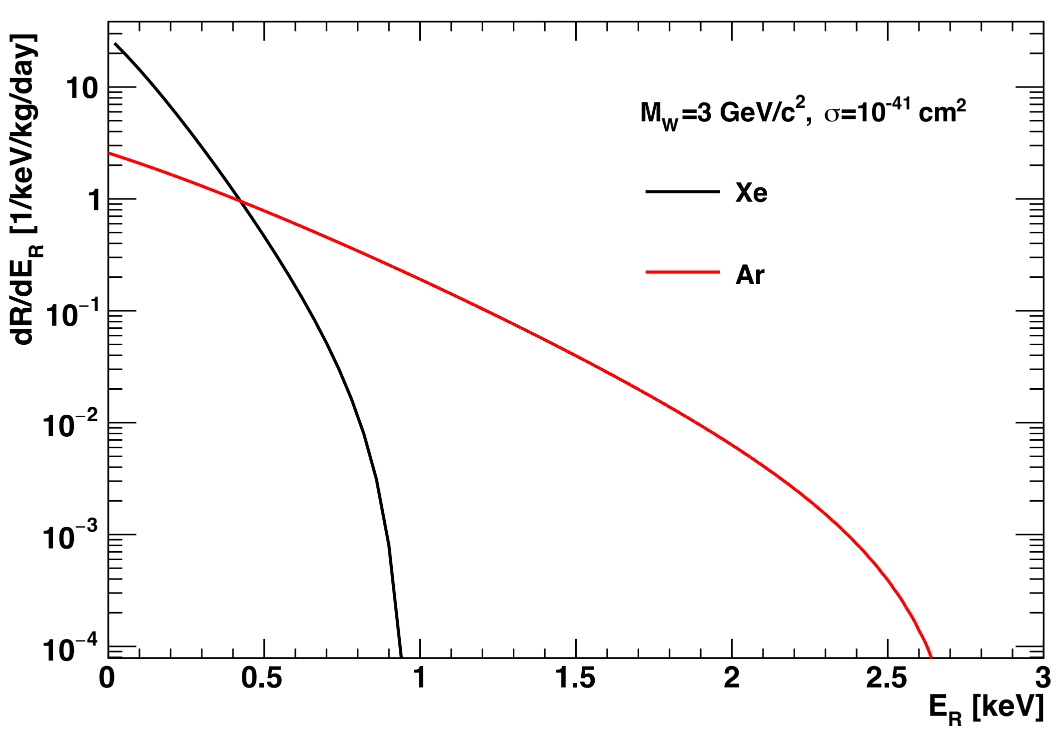
LOW MASS WIMP SEARCH

- **Scintillation signal** (S1): threshold at ~2 keV_{ee} / 6 keV_{nr}
- **Ionization signal** (S2): threshold < 0.1 keV_{ee} / 0.4 keV_{nr} **Can go lower threshold!**

- Use Ionization (S2) Only.
  - Amplified in the gas region (~23 PE/e^- or more)
  - **Sensitive to a single extracted electron!**
  - The electron yield for nuclear recoils increases at low energy



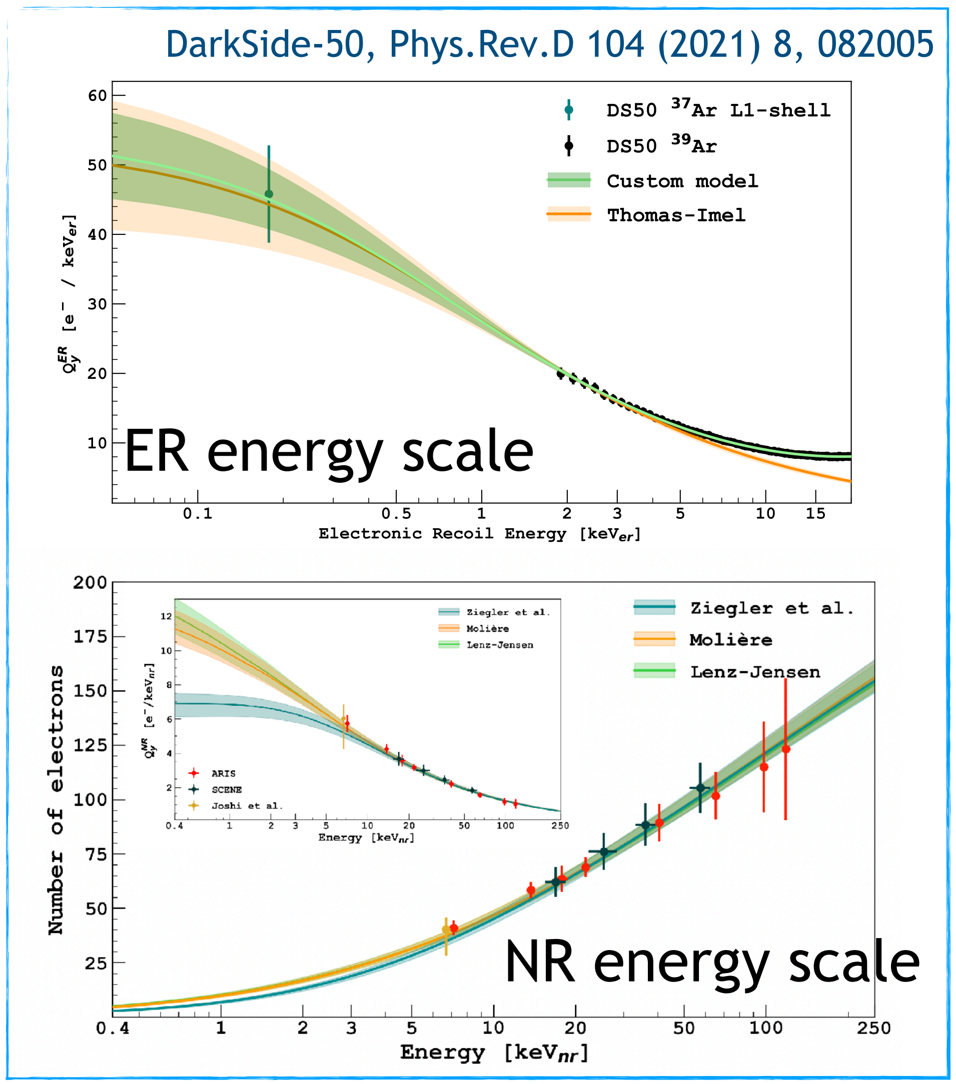
WIMP spectra in Xe and Ar



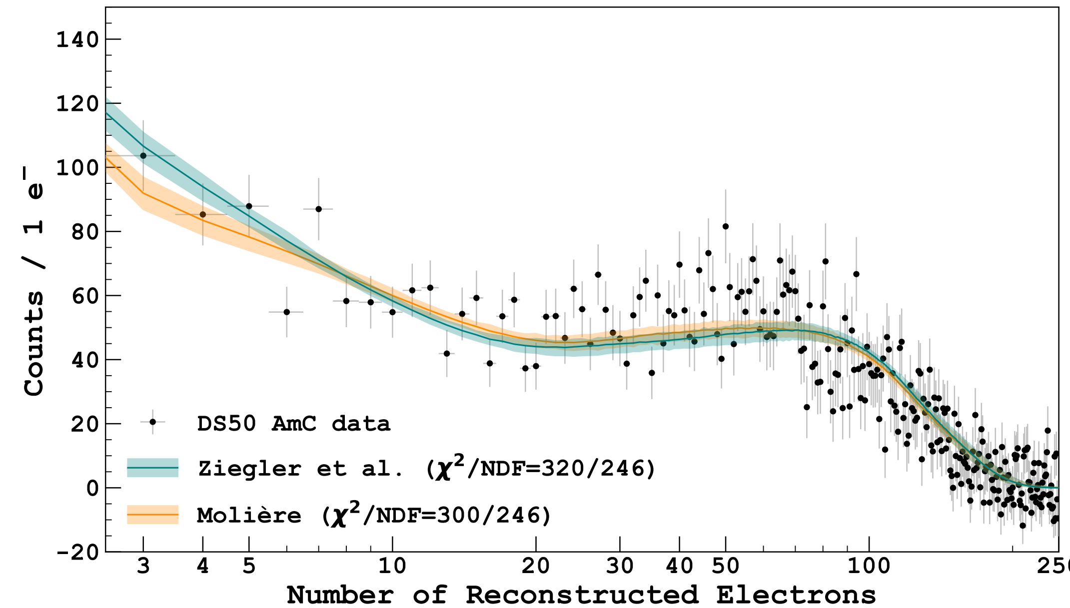
- Ar has lighter mass than Xe. So, more efficient momentum transfer from low mass DM.

How to calibrate the ionization response?

- First-ever sub-keV calibration in LAr



- Rely on the fit of spectral shapes



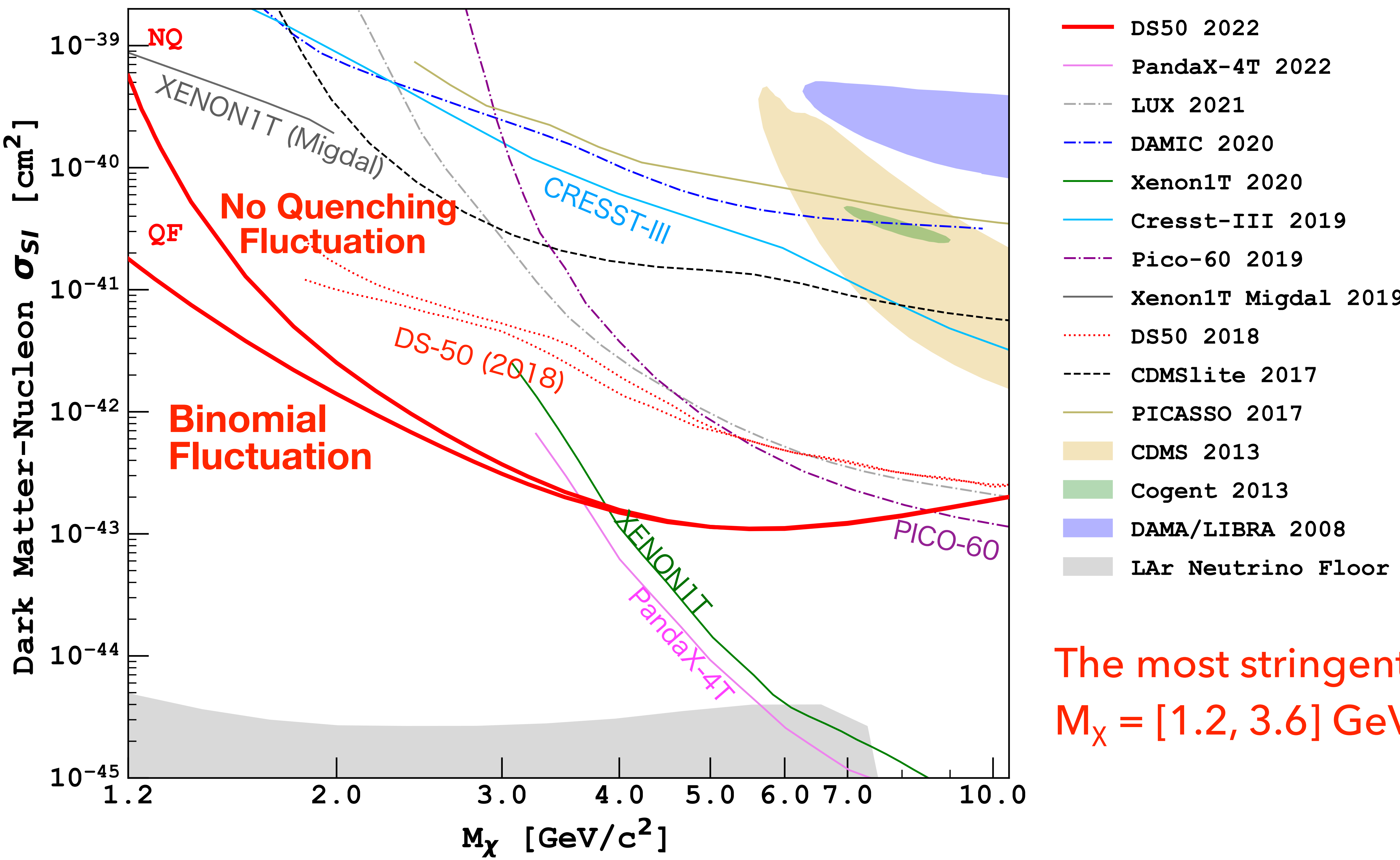
For further improvements, need of monochromatic lines and background suppression.

Low-energy (~100 keV), pulsed, neutron beam!

BLEND
(Boron-10 Low Energy Neutron Detector)

WHAT WE ACHIEVED IN DS-50

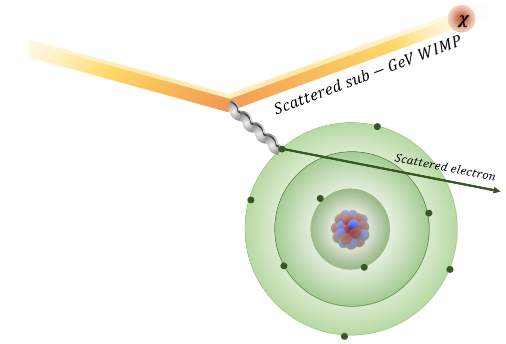
Phys. Rev. D 107, 063001



The most stringent limit at M_χ = [1.2, 3.6] GeV/c²

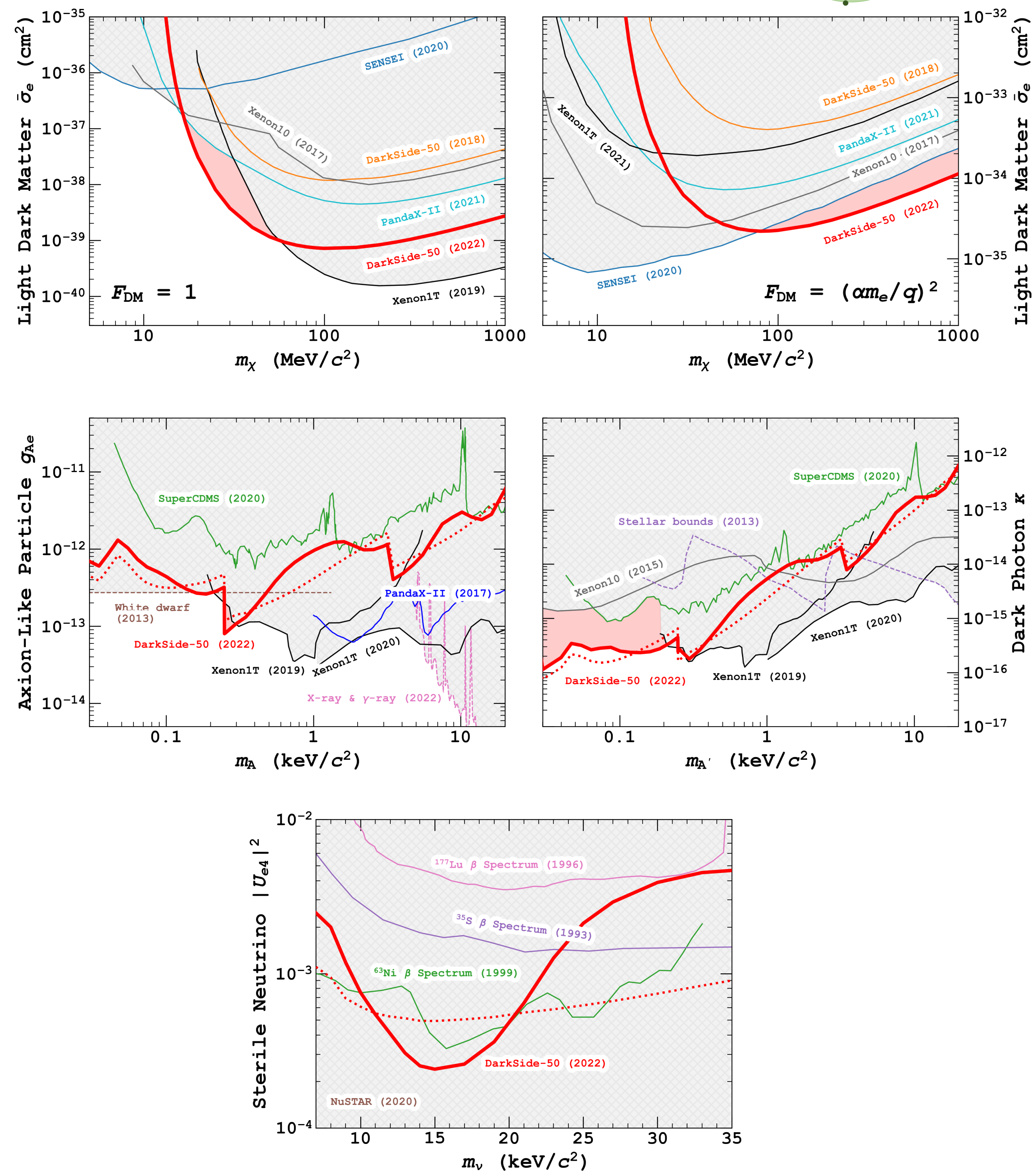
SUB-GEV DARK MATTER

AND OTHER DARK MATTER MODELS



Phys. Rev. Lett. 130, 101002

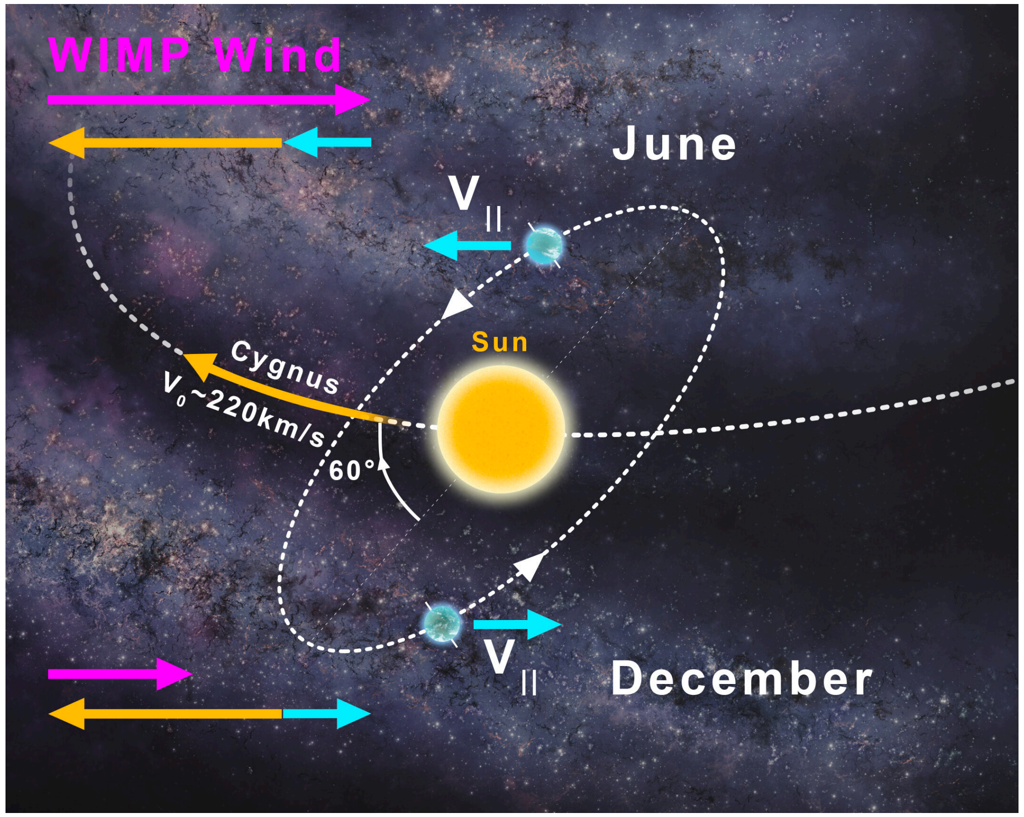
- With the same dataset, we search for other dark matter models.
- In those candidates, DM signals are also ER.
- Ultra-light DM ($m_\chi \ll 1$ GeV) scatter off electrons.
- Two extreme cases of Dark Matter form-factor are considered
  - $F_{DM}=1$ heavy mediator
  - $F_{DM} \propto 1/q^2$ light mediator
- More for Axion-like particles, Dark photons, and Sterile neutrinos.



Also, results with Migdal effect Phys. Rev. Lett. 130, 101001

DM ANNUAL MODULATION SEARCH

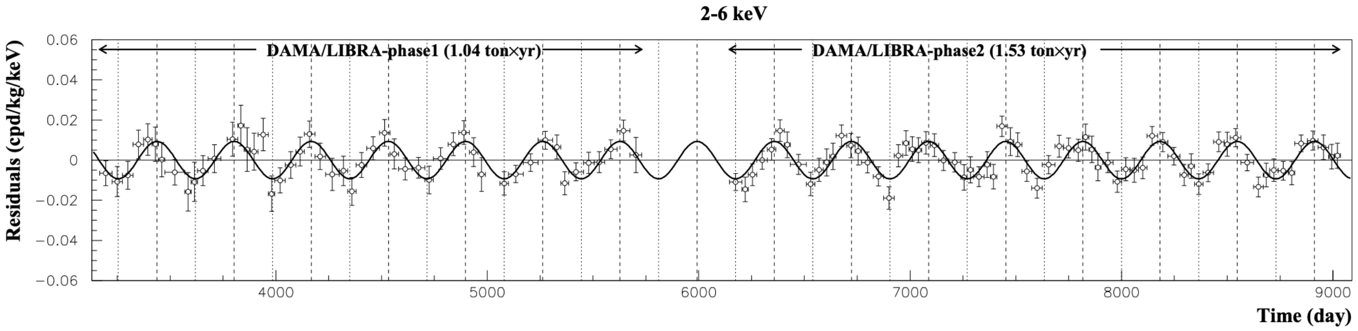
- The Sun moves toward the Cygnus, leading to a boost of the dark matter velocity distribution: "*Dark Matter Wind*"
- The Earth's rotation around the Sun increases the boost around June and decreases around December
  - **Event rate in terrestrial detectors above the energy threshold modulates annually**



(Figure. from J.Phys.G.Nulc.Part.Phys. 47 094002)

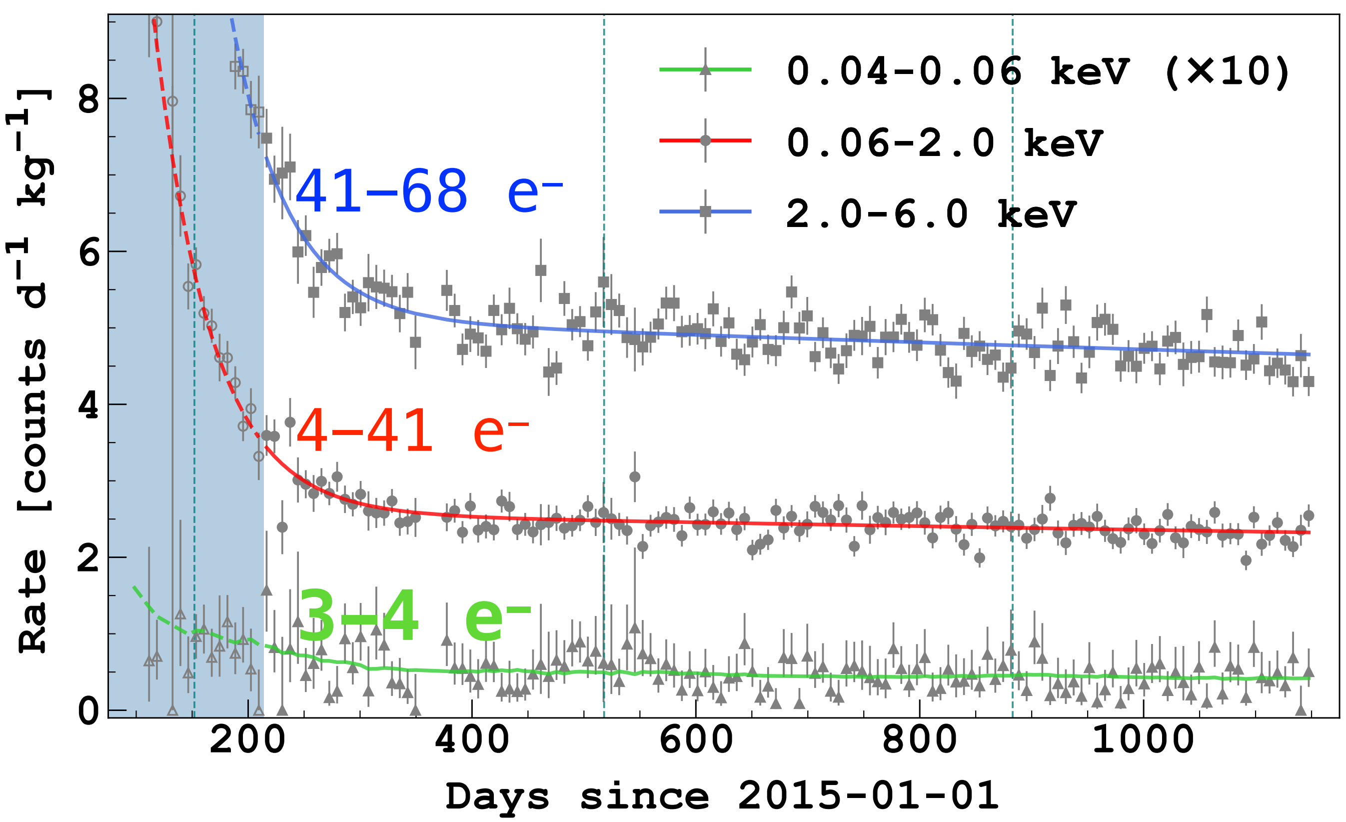
- The DAMA/LIBRA's observation with NaI(Tl) crystal
  - Modulation signature above the energy threshold of 0.75 keV
  - Traditional WIMP model faces challenges from the null-detection in many other experiments

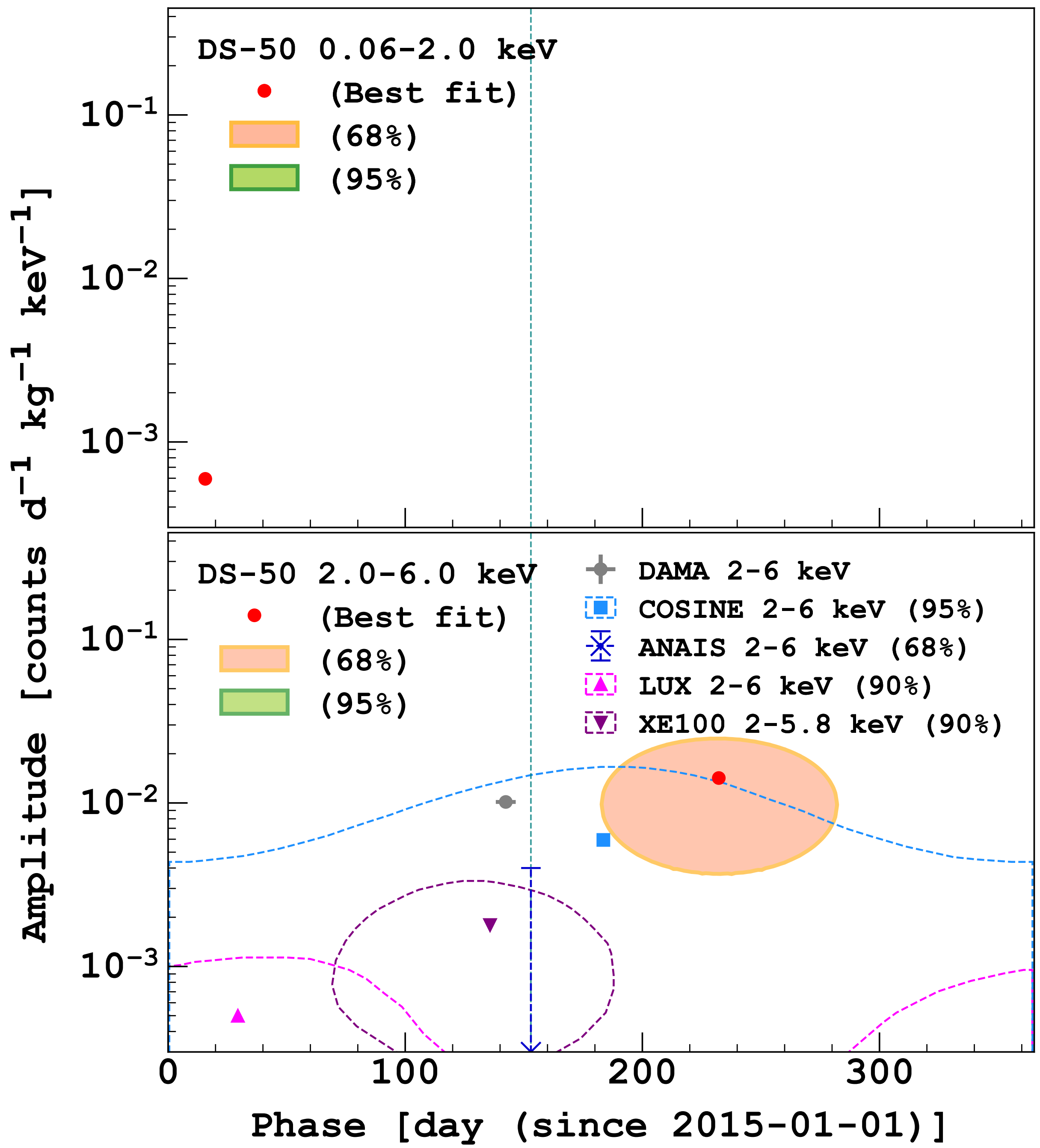
P. Belli, IDM2022



DM-ANNUAL MODULATION SEARCH

arXiv:2307.07249

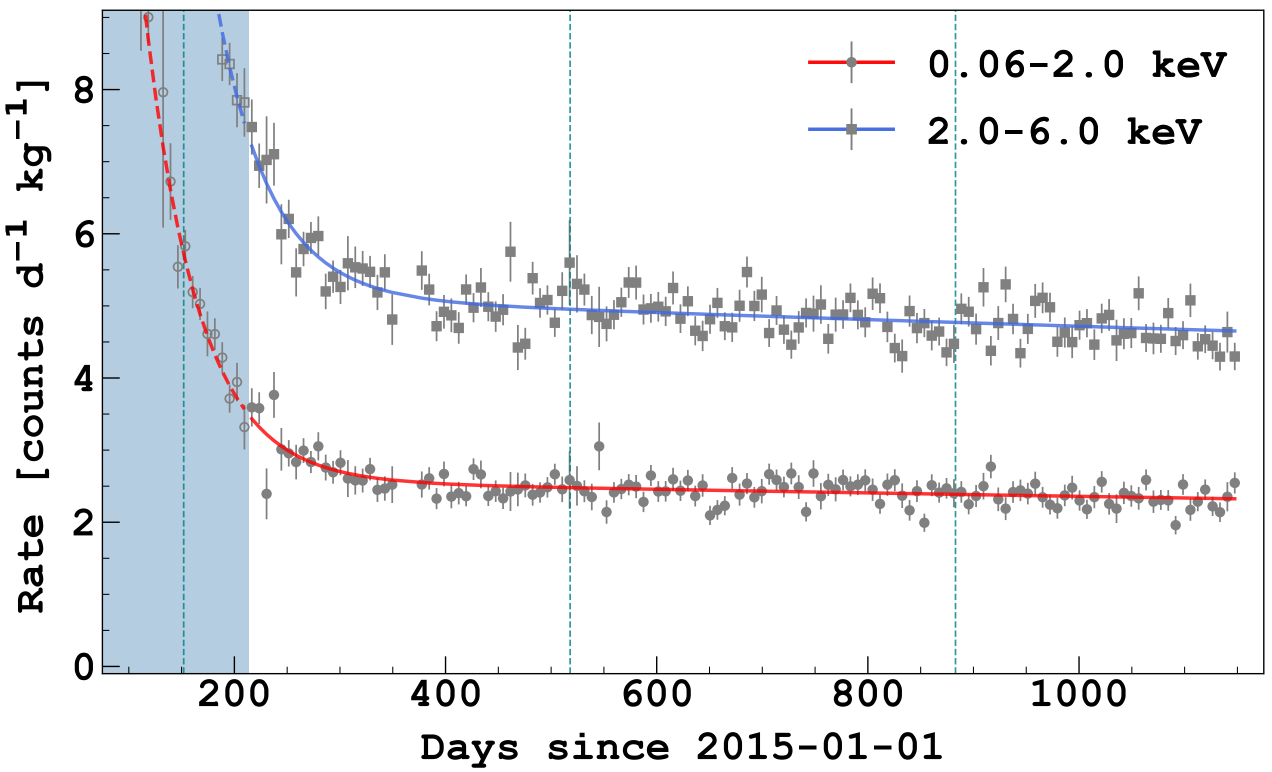


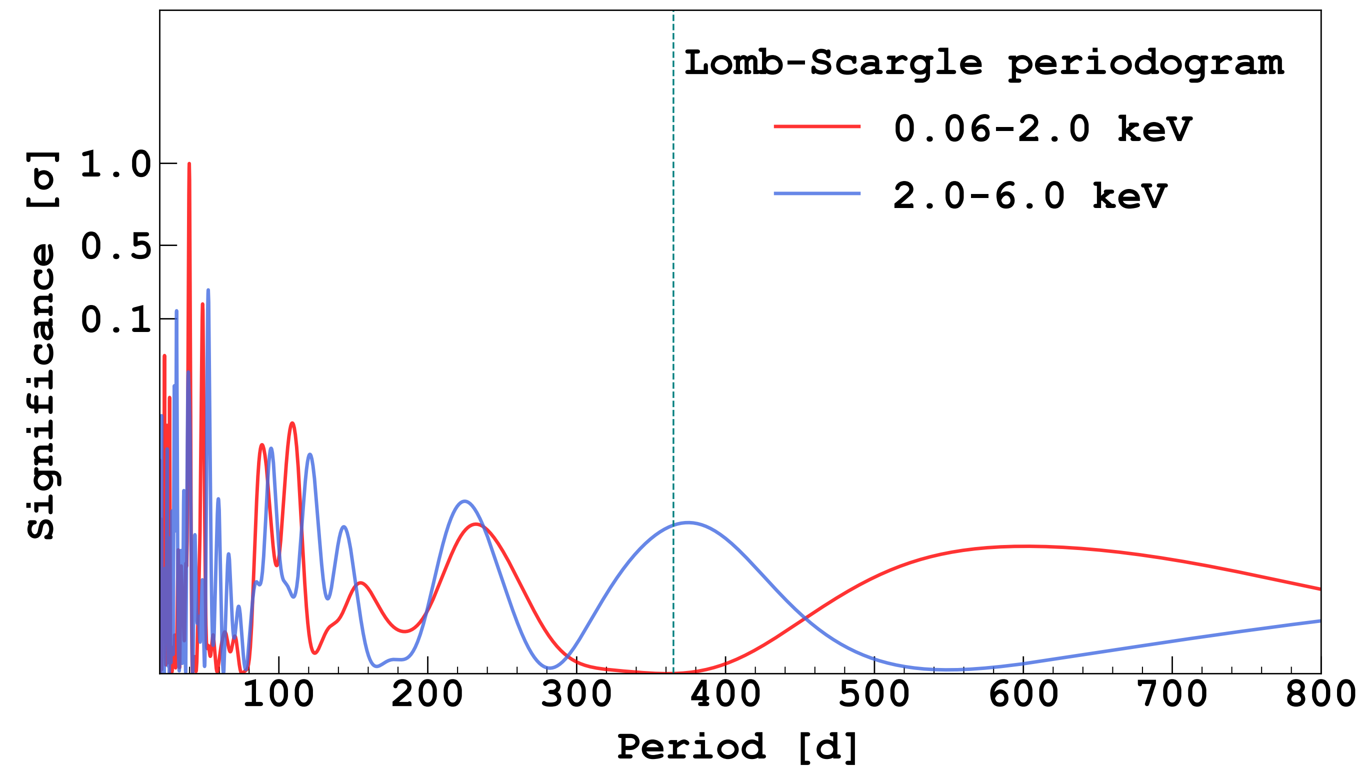


- **Consistent to the background-only model**
  - Neither confirm nor reject the DAMA's observation

PERIODOGRAM ANALYSIS

arXiv:2307.07249

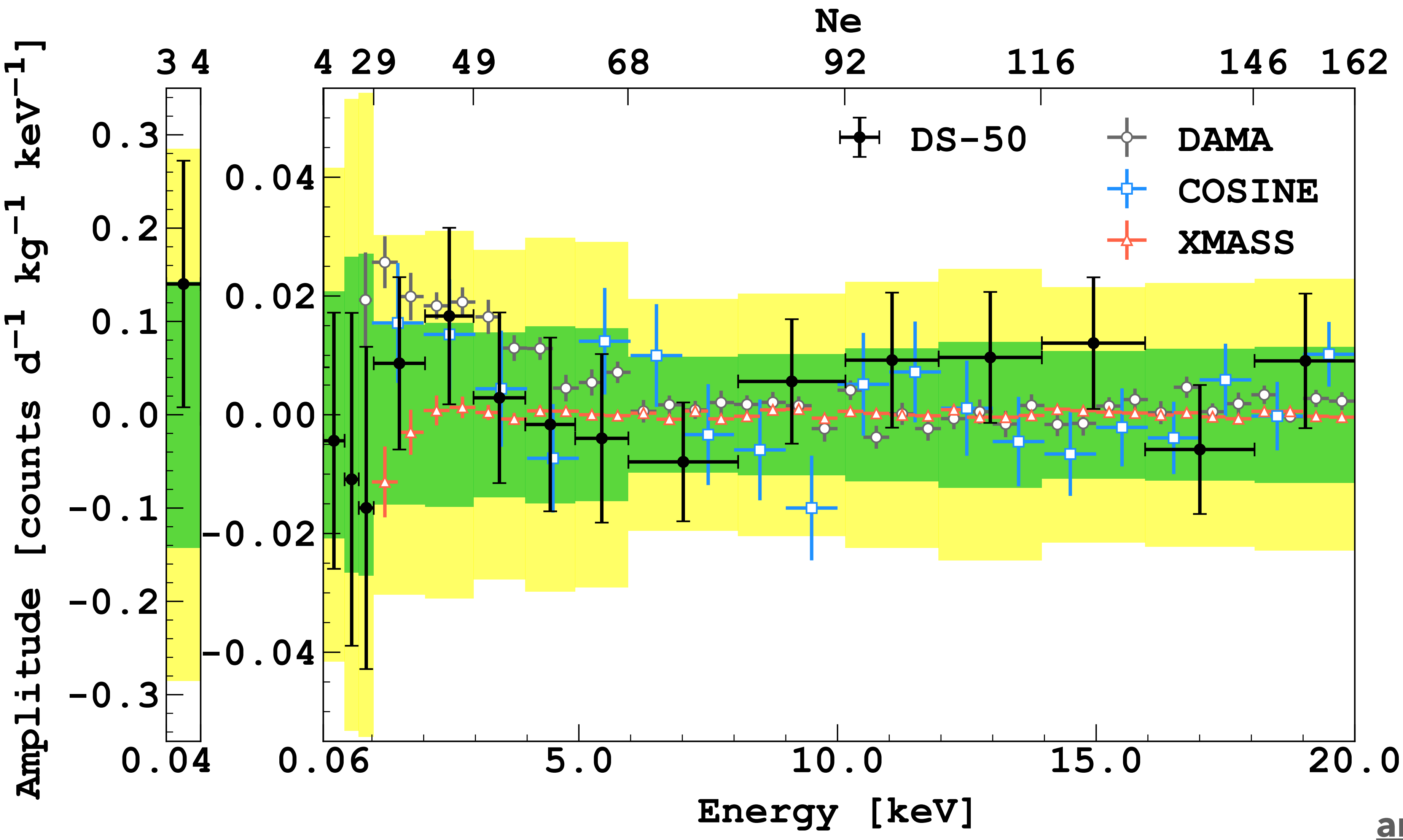




- Lomb-Scargle periodogram is applied to look for any periodical signal
  - Residuals of the background-only fit are converted into the frequency space
- **No significant signal is observed**

DM-ANNUAL MODULATION SEARCH

- Fixed the phase to DM-expectation (event rate takes maximum at June 2nd)
- Simultaneous fit for both time and energy bins (time-dependent background amplitudes are common for all energy bins while the signal amplitude is independent)



arXiv:2307.07249

WHAT IS OUR PLAN?

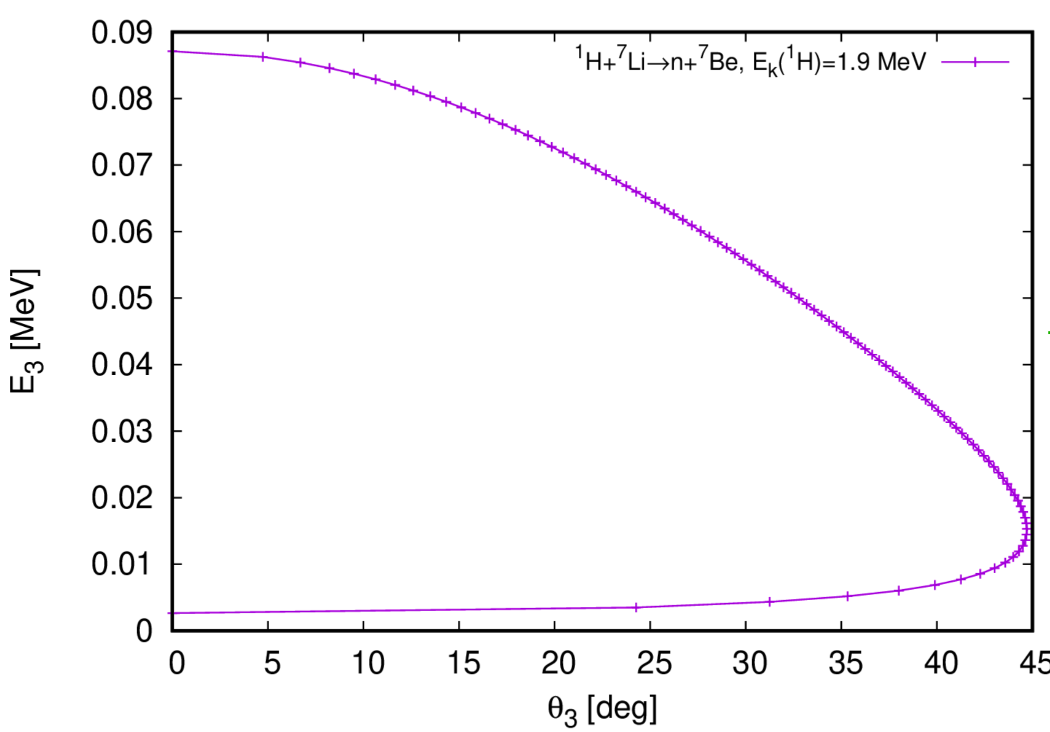
- Sensitivity study for low mass dark matter search in the DarkSide-20k detector.
    - larger fiducial LAr mass
    - significant self-shielding
    - more radiopure photosensors
    - **Significant sensitivity improvement expected!**
- Development of the low-energy neutron detectors.
    - Study response to sub-keV nuclear recoils is crucial to improve our sensitivity for low mass dark matter
    - Necessary to develop efficient neutron detectors at low energy

Measuring NR response at <1 keV$_{nr}$

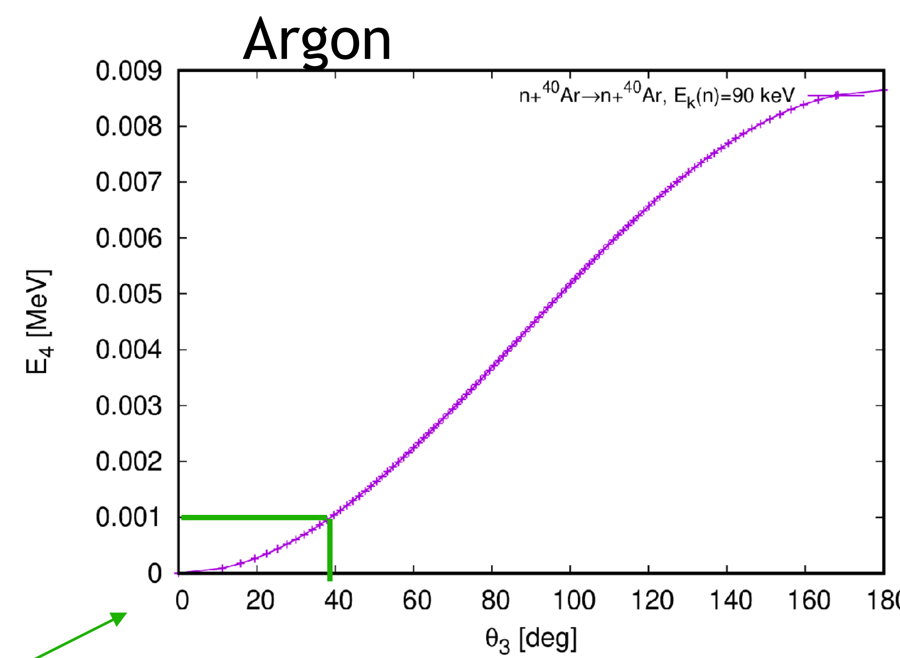
At ALTO

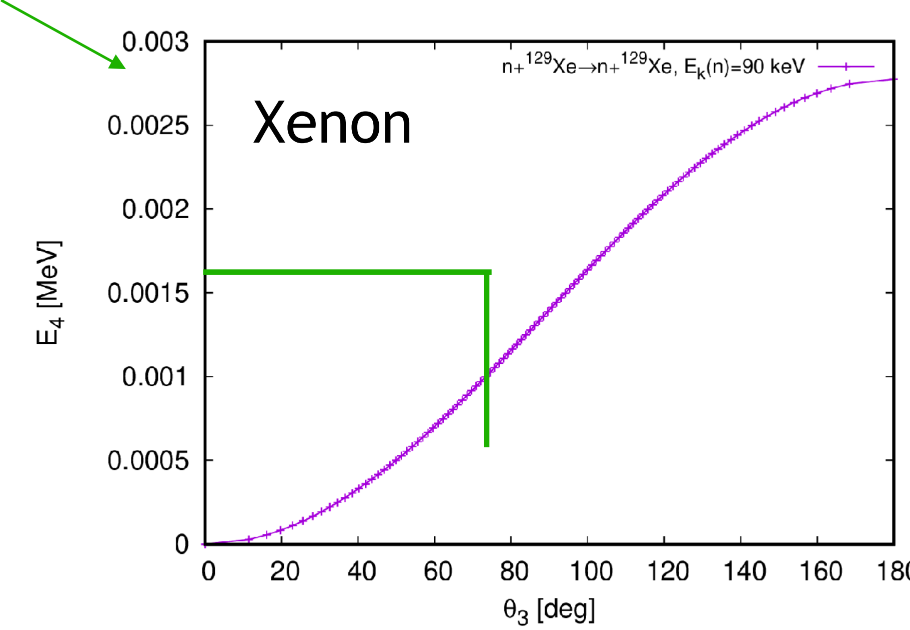
LICORNE source: inverted $^{7}Li(p,n)^{7}Be$ reaction

- Pulsed (1.5 ns width)
- Monochromatic: <6% (mean~1450 keV rms~85 keV)
- Collimated: < 2 degrees
- Correlated 478 keV gammas: ER calibration



Access to the sub-keV range





The **p + ^{7}Li → n + ^{7}Be** reaction at 1.9 MeV, near the reaction threshold, produces ~90 keV neutrons

How to detect scattered neutrons in coincidence?

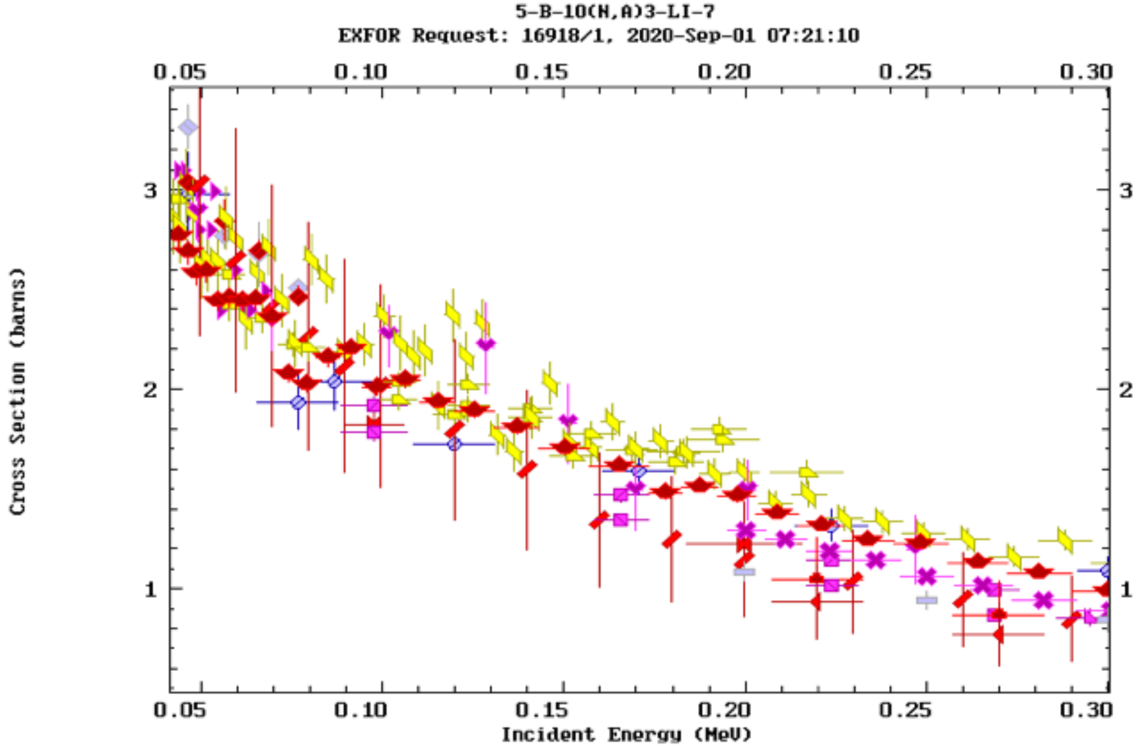
Plastic scintillators are inefficient in this energy range and ^{3}He is not available on the market

⇒ new **neutron detector design:**

- high cross section for **capturing neutrons on the fly** at 100 keV
- **No moderation** / thermalisation (no Hydrogen!)

Boron-10

- ~2 barns capture cross section at 100 keV
- Quite bad neutron moderator (good!)
- Abundant: 20% ^{10}B in natural boron
- Enriched ^{10}B (99.9%) available on the market (~170 euro / g)
- 478 keV gamma follows neutron capture



$$^{10}\mathrm{B} + n \rightarrow \begin{cases} ^7\mathrm{Li}\ (1015\ \mathrm{keV}) + \alpha\ (1775\ \mathrm{keV}) & (6.4\%) \\ ^7\mathrm{Li}^* + \alpha\ (1471\ \mathrm{keV}), ^7\mathrm{Li}^* \rightarrow ^7\mathrm{Li}\ (839\ \mathrm{keV}) + \gamma\ (478\ \mathrm{keV}) & (93.6\%) \end{cases}$$

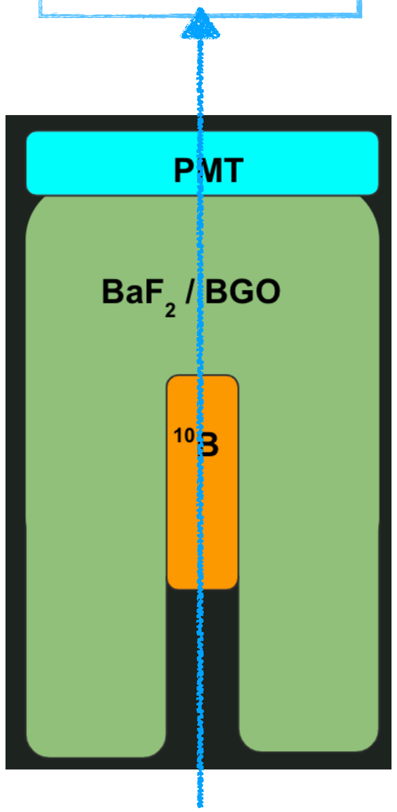
How to detect scattered neutrons in coincidence?

Two available scintillator options

	BaF_2	BGO
Density [g/cm^3]	4.9	7.13
Effective Atomic	52.2	83
Light Yield [ph/keV]	1.9 (fast) / 10 (slow)	8-10
Decay time [ns]	1 / 630	300
Hygroscopic	no	No

Potentially, TOF measurement with BaF_2

100 keV neutron

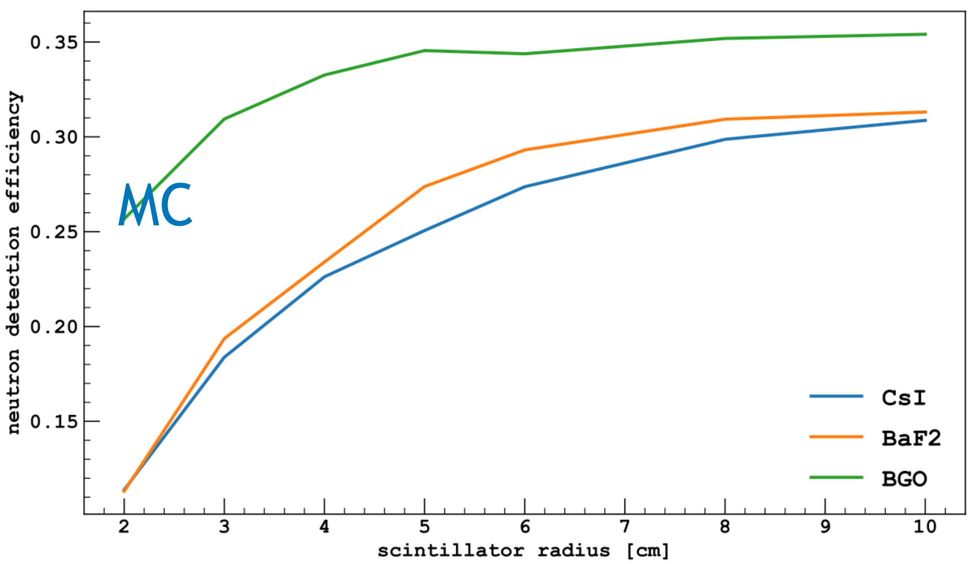


^{10}B target:

- 0.5 cm radius
- 4.2 cm long

12 cm long crystal

Neutron detection efficiency



20-35% neutron detection efficiency by looking at the full absorption peak at 478 keV

Timeline / Objectives

Goal:

- proof of principle and characterisation of completely new type of neutron detectors
- low energy neutron beam test for the first time at ALTO

Deliverables:

(1) calibrating the efficiency to 478 keV gamma detection using a 137Cs source
(2) ND efficiencies with beam neutrons
(3) time-of-flight resolution of the NDs
(4) angular profile of the neutron beam
(5) characterisation of beam-induced 478 keV gamma background
(6) testing lead shielding to protect NDs against gamma background

Preparation:

Six months for assembling the detectors (granted with 10 kEuro by LabEx UnivEarthS):

- Procurements of 2 PMTs, 2x10 g samples of enriched ^{10}B, DAQ
- Sealed aluminium / steel vial for housing ^{10}B powder
- BGO and BaF2 crystals already available
  - BGO: assembly + coupling with PMT
  - BaF_2: drilling + coupling with PMT

Requested: 3 days, with two shifts out of three per day (6 UT)

Outlook: if satisfactory results, ALTO low-energy beam + novel neutron detectors attractive for calibrating LAr / LXe dark matter and neutrino detectors

Going to make a test beam experiment at ALTO in this December 11th to 13th!

SUMMARY

- French-Polish collaboration led the world leading the low mass dark matter searches with DarkSide-50 experiment.
- Through COPIN, we exchanged group members to improve our collaboration work.
- Development of the low-energy neutron detector is crucial to improve the sensitivity of low mass dark matter searches.
- Exciting test beam experiment at ALTO in this December!

Thank you!