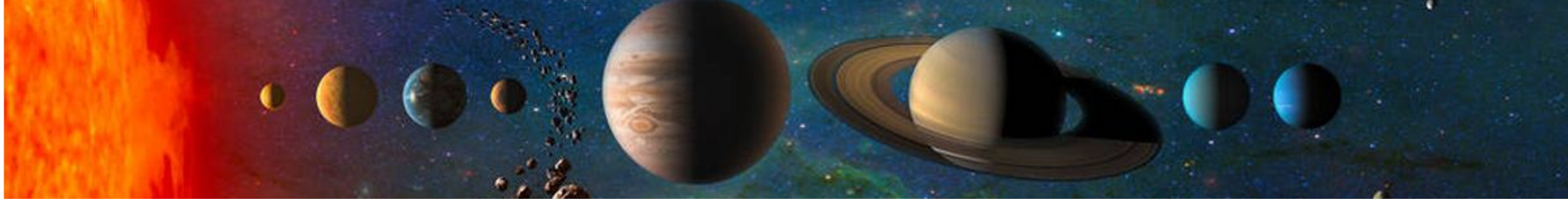

Status of Dark Matter Direct Detection Experiments

Speaker：Qing Lin

University of Science and Technology of China

Lomonosov Conference @ Moscow, 2025.08.22

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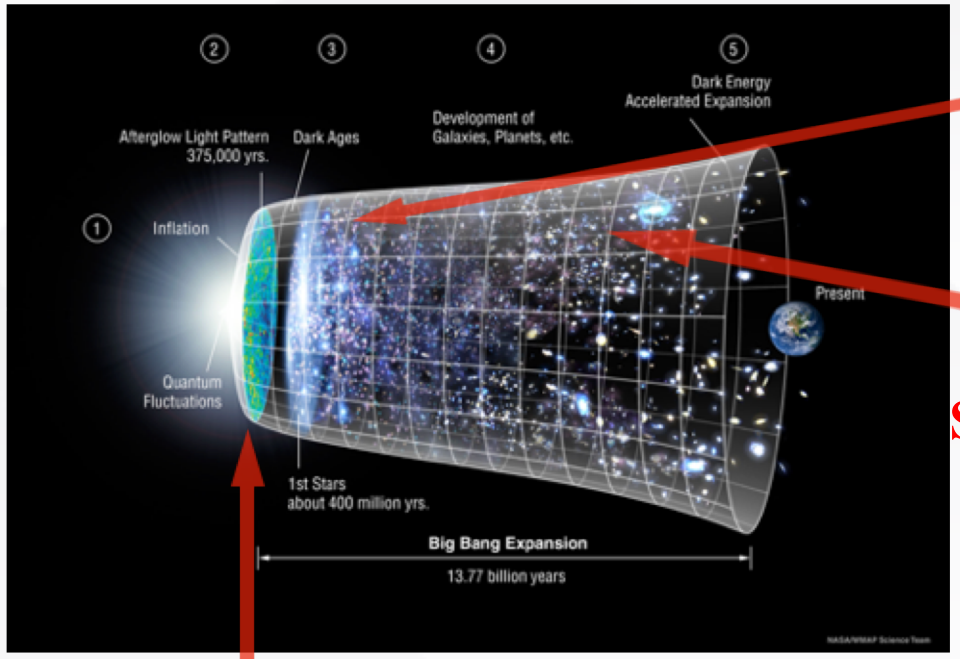
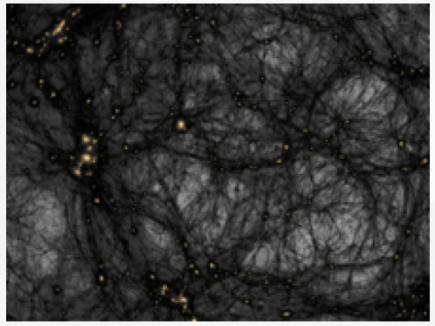
Disclaimer: Apology for omittance!

** Most materials are borrowed from public talks, especially from Prof J. Liu, Prof. Q. Yue's, and talks from IDM2024.**

Dark Matter and its Gravitational Evidence



Large Structure

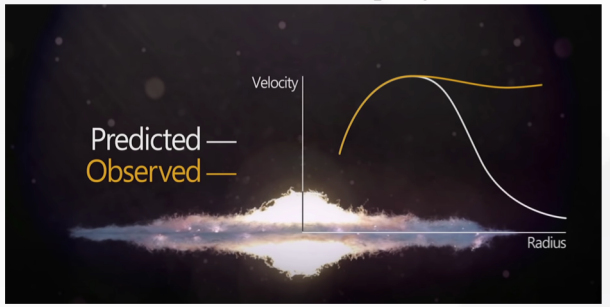


Courtesy of NASA

Credit: https://youtu.be/sI23cwbbNqs

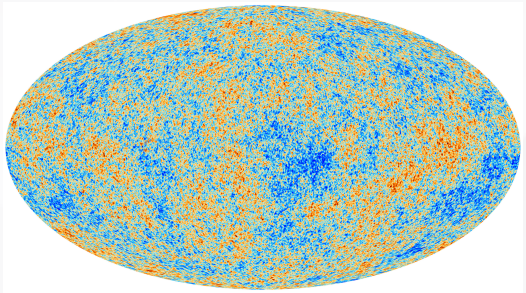
Small Structure

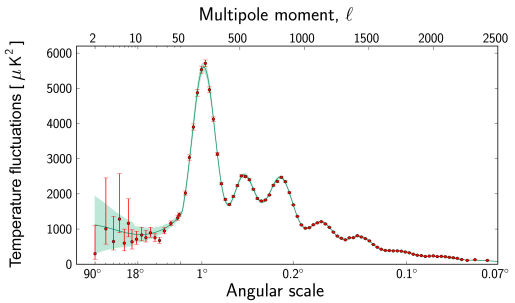
Bullet cluster collision



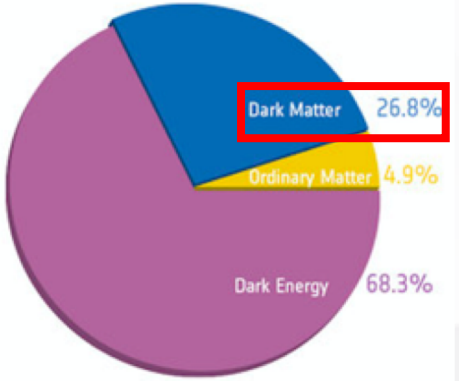
Galaxy rotation curve

Primordial Universe



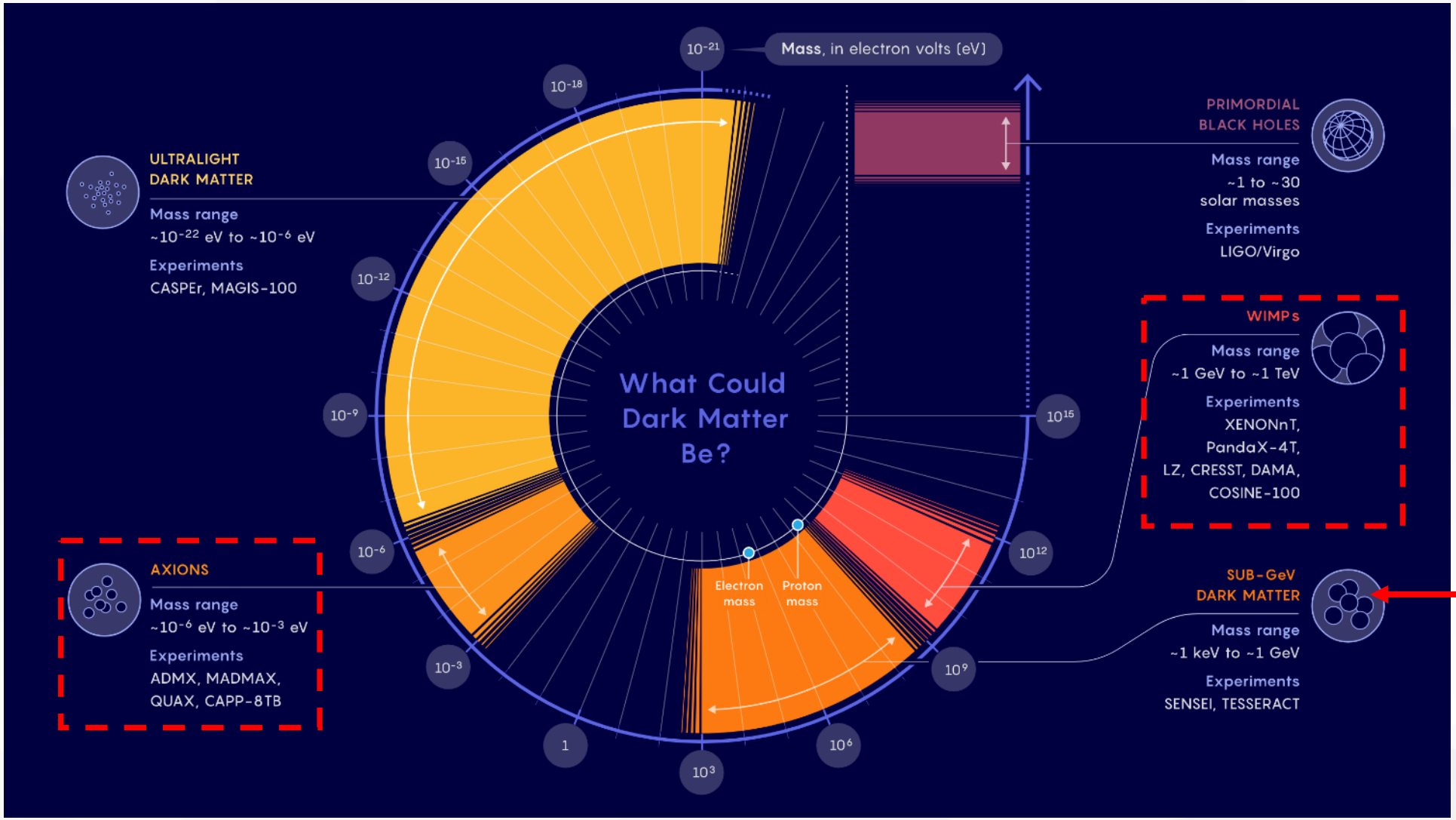


Courtesy of PLANCK



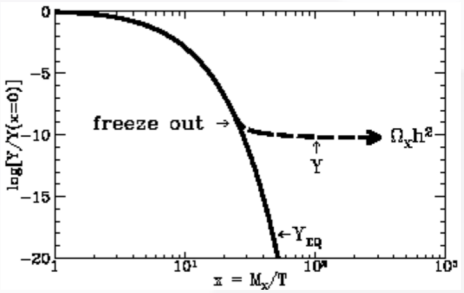
Gravitational evidences suggest dark matter is the dominant form of matter in Universe!

Many Possibilities

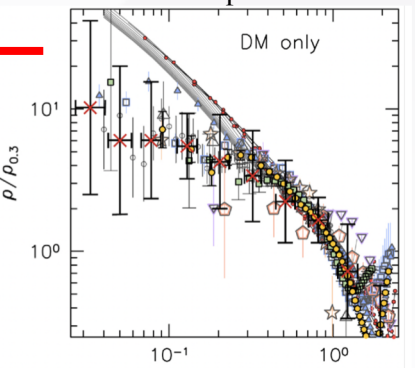


Samuel Velasco/Quanta Magazine

This talk!



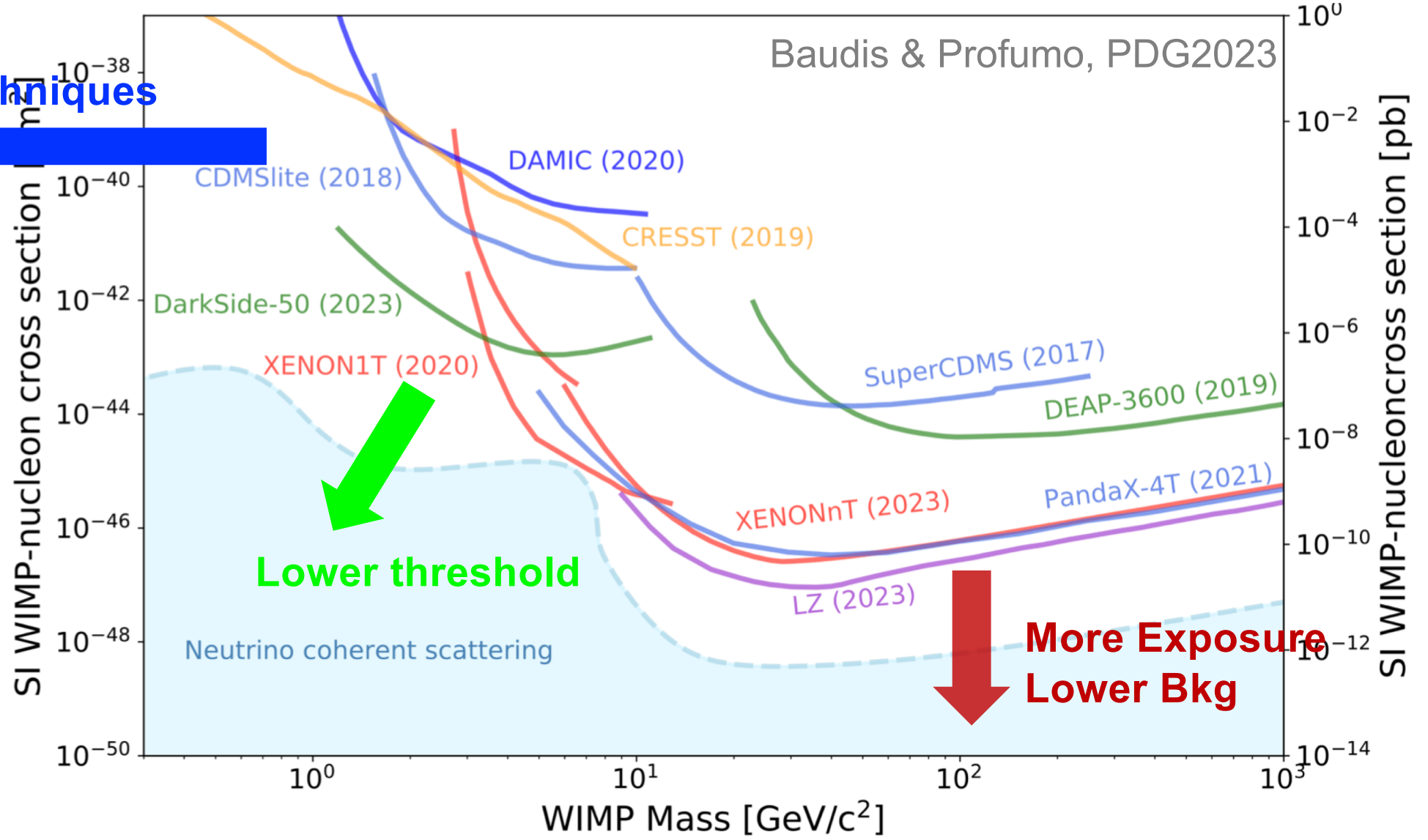
Core-cusp Problem



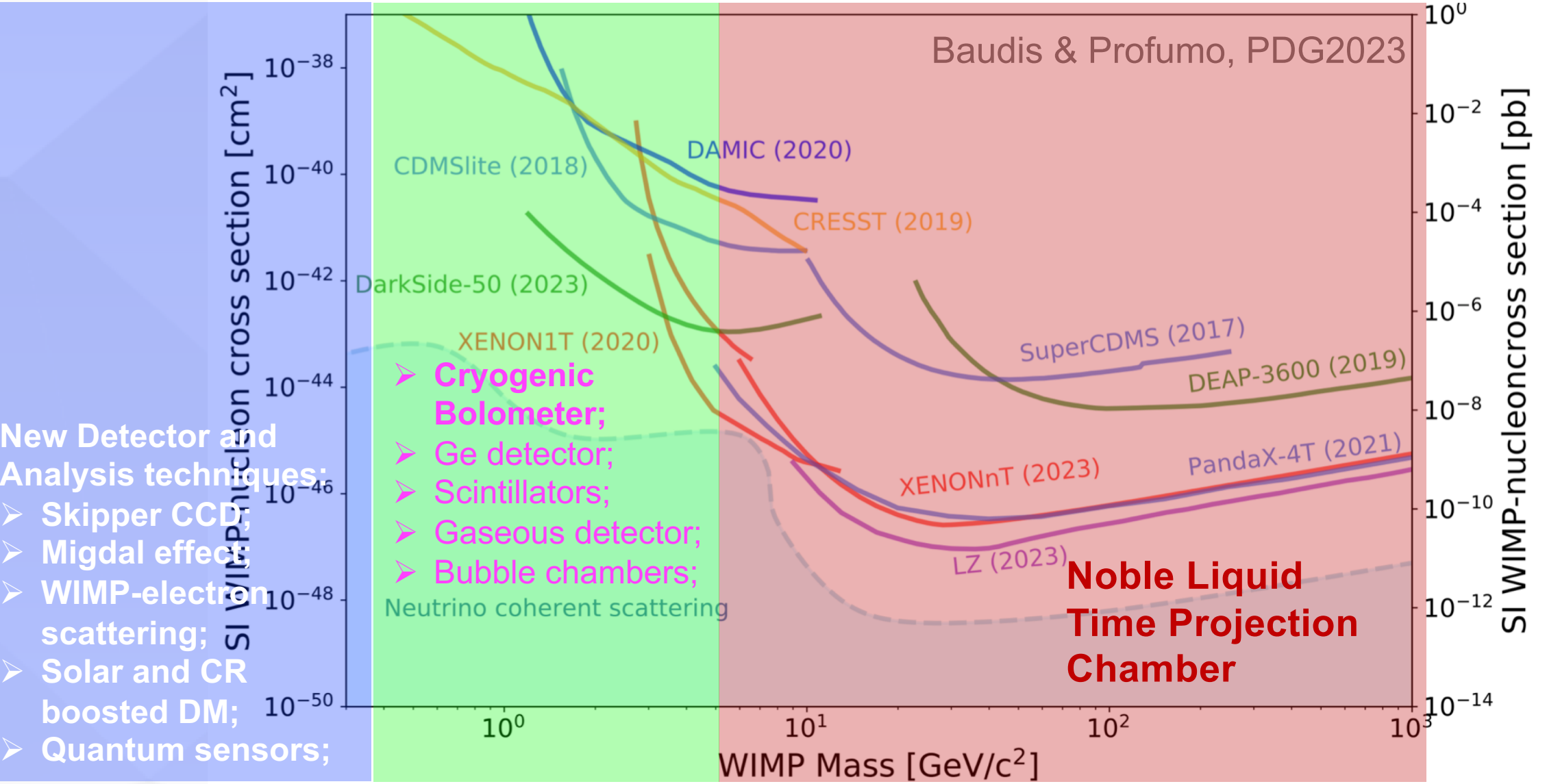
From Prof. Yifu Cai

Direct Search Overview

New Techniques



Direct Search Overview



- **Cryogenic Bolometer;**
- Ge detector;
- Scintillators;
- Gaseous detector;
- Bubble chambers;

Noble Liquid Time Projection Chamber

New Detector and Analysis techniques:

- **Skipper CCD;**
- **Migdal effect;**
- **WIMP-electron scattering;**
- **Solar and CR boosted DM;**
- **Quantum sensors;**

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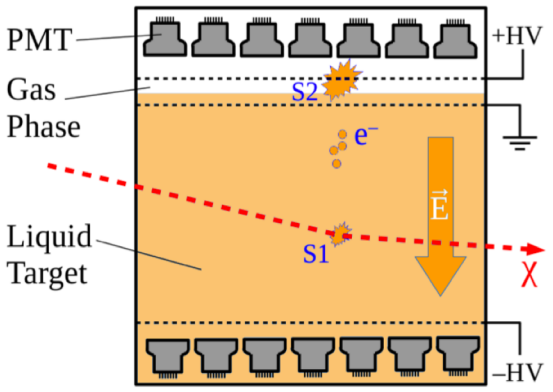
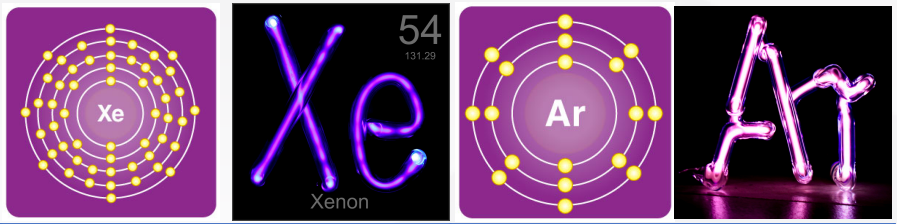
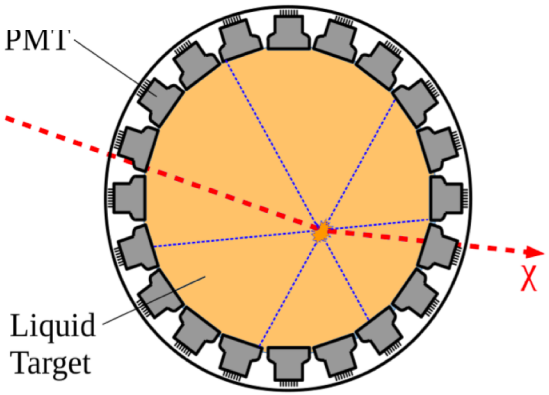
Noble Liquid



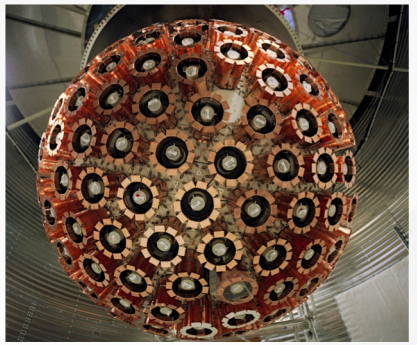


Scalability	Good	Good
Density	3 kg/L	1.4 kg/L
A	133	40
Long-lived bkg	Xe136 Negligible	Ar39 (1 Bq/kg in ^{nat}Ar, T_{half}=269yr)
Bkg rej.	S2/S1, 3D pos.	S2/S1, Pulse shape, 3D pos.
Scintillation light	178 nm	128 nm (need WLS)
Cost	¥15000/kg	¥20/kg for ^{nat}Ar

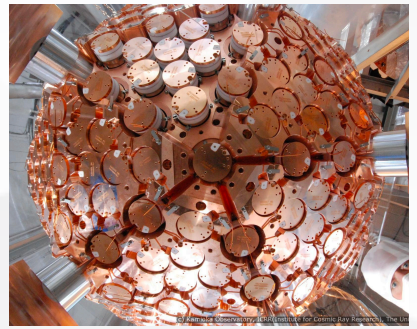


DarkSide-50
(DarkSide-20k
ARGO)

PandaX-4T
XENONnT
LZ
(XLZD
PandaX-xT)



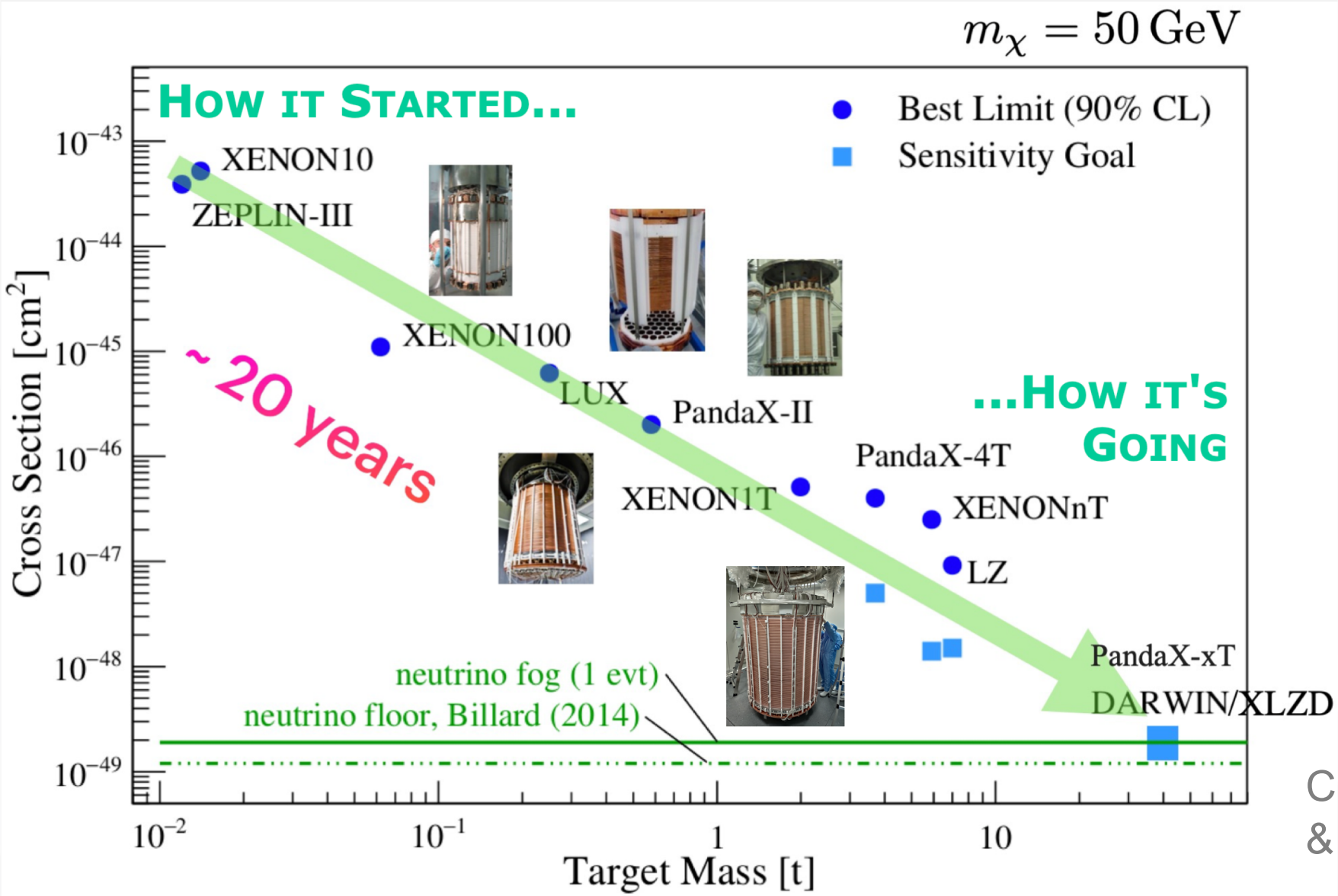
DEAP-3600



XMASS

- High sensitivity to >10GeV DM due to its good scalability and bkg discrimination;
- Liquid xenon dual-phase TPC currently has the world-leading sensitivity to >10GeV DM.

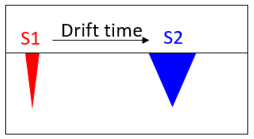
Evolution of Noble Liquid Sensitivities



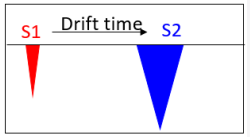
Courtesy to P. Ullio & M.E. Monzani

Liquid Xenon Dual phase Time Projection Chamber

Dark matter: nuclear recoil (NR)

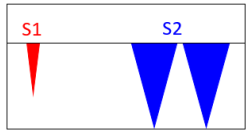


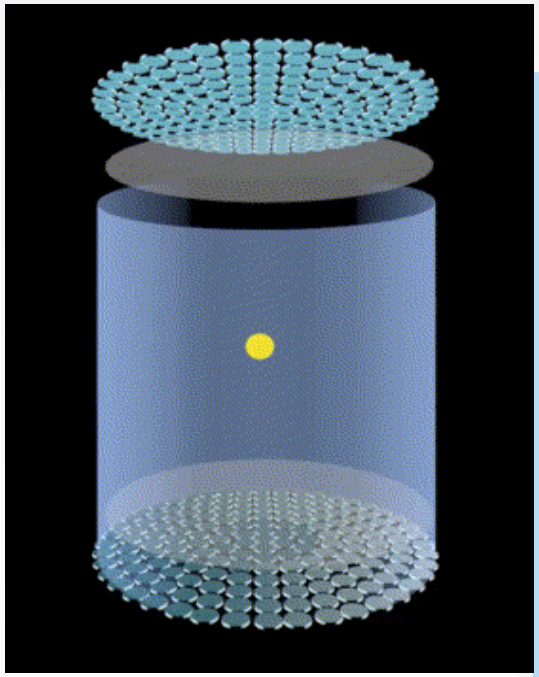
γ background: electron recoil (ER)



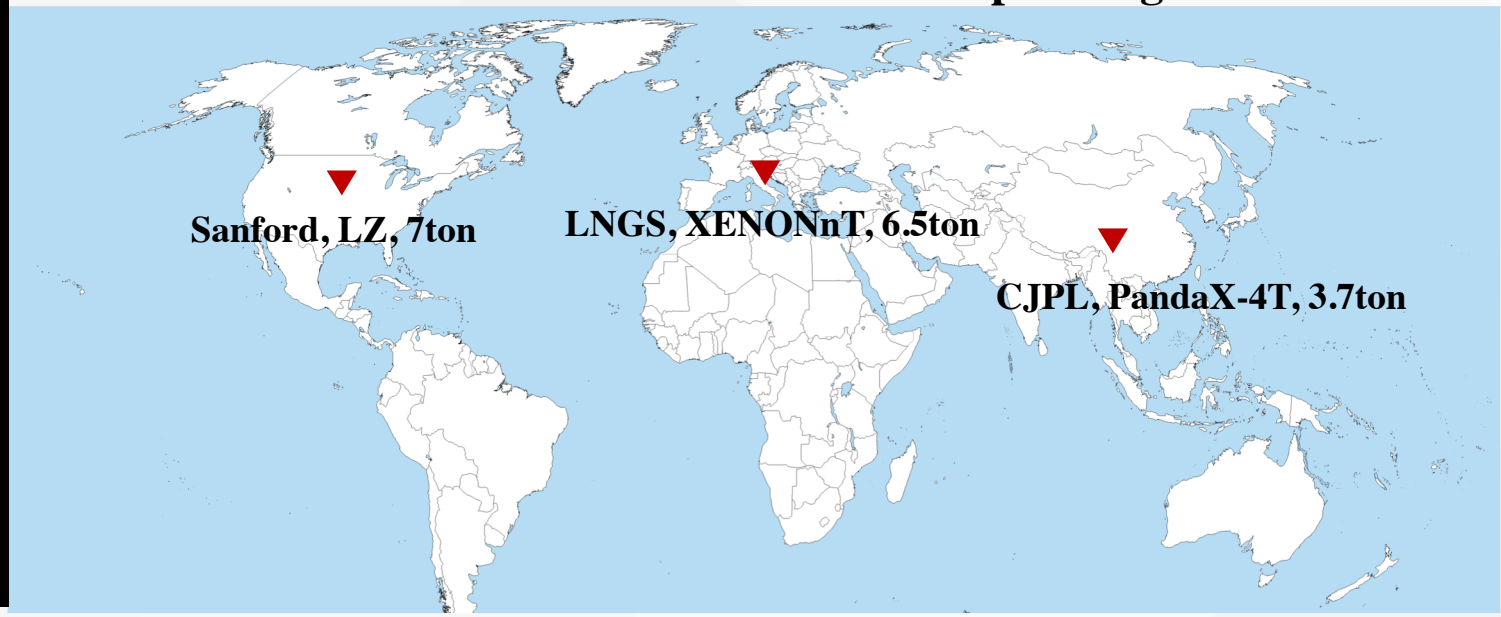
$(S2/S1)_{NR} << (S2/S1)_{ER}$

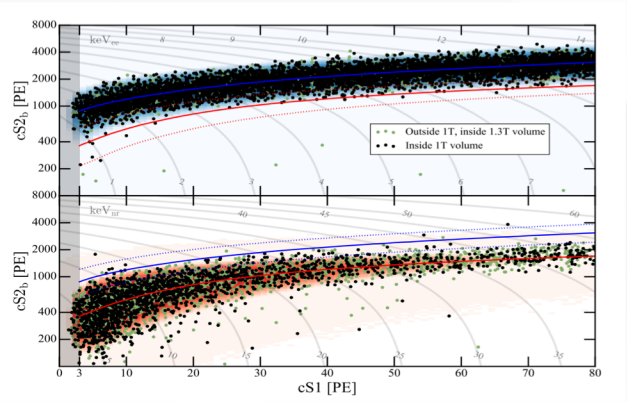
Multi-site scattering background (ER or NR)

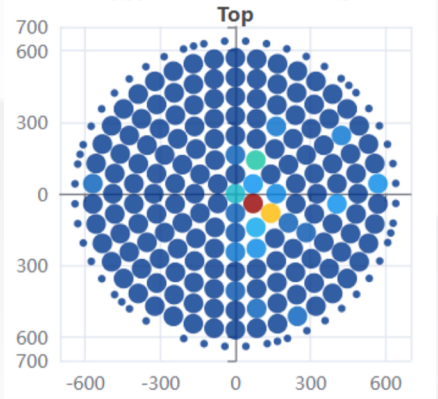




Three multi-tonne detectors operating.

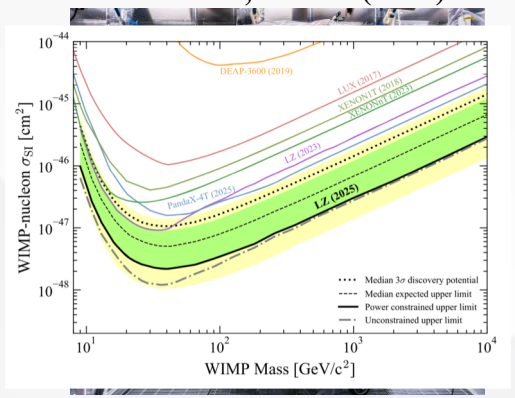






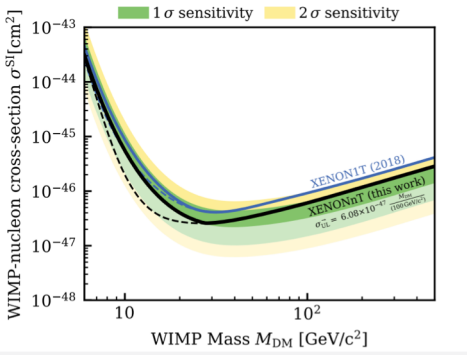
LZ

PRL135, 011802 (2025)



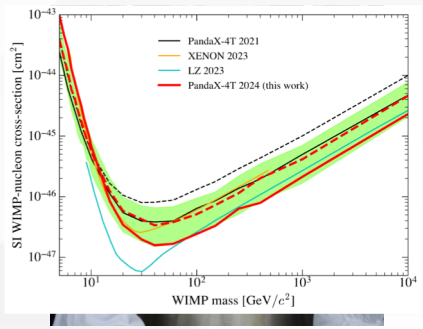
XENONnT

PRL131, 041003 (2023)

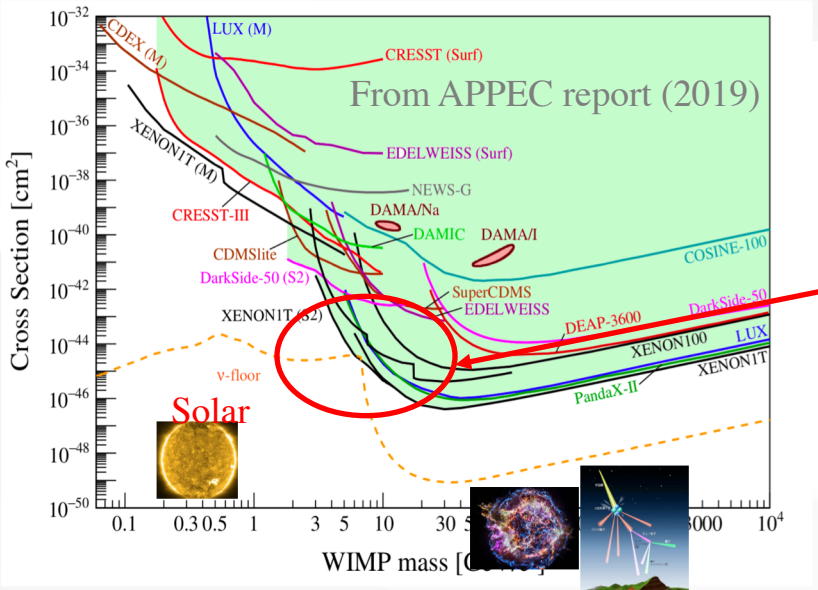


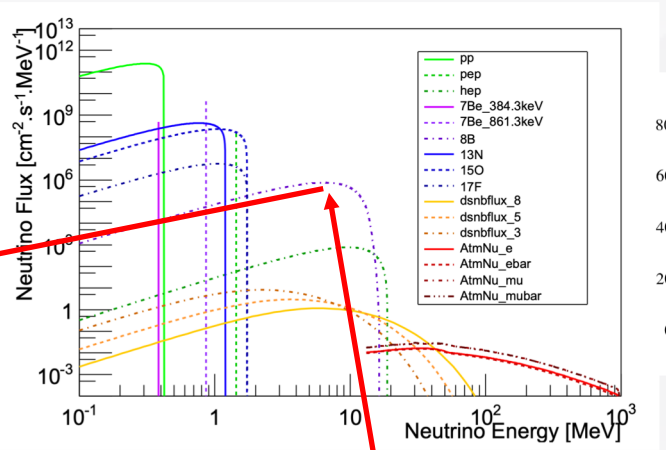
PandaX-4T

PRL134, 011805 (2025)



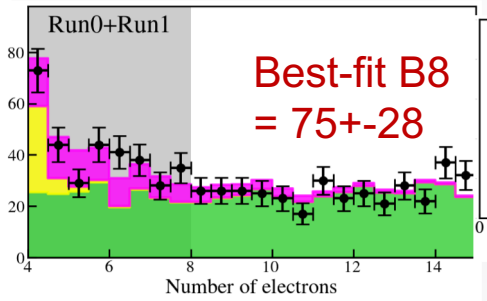
Touching neutrino fog

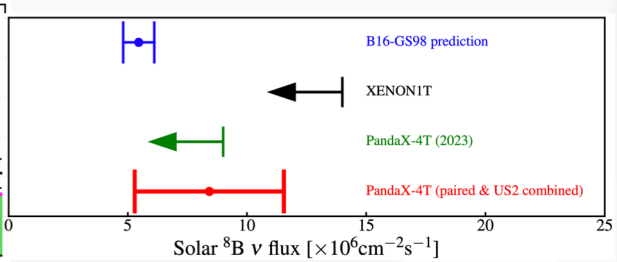




SN Atomspheric

PandaX-4T (1.05 t-yr;2.64σ)

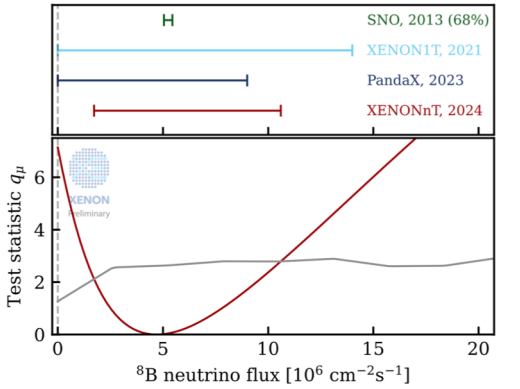




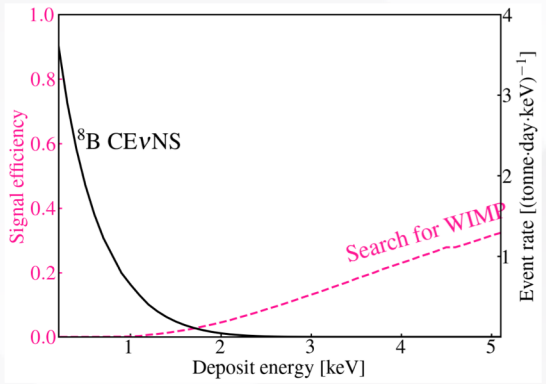
Q. Lin, IDM2024 PRL 133, 191001 (2024)

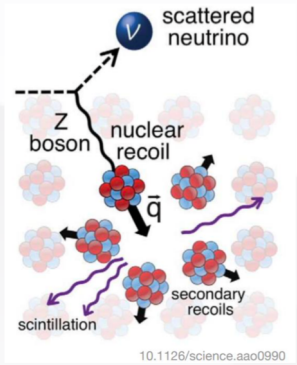
XENONnT (3.51 t-yr; 2.73σ)

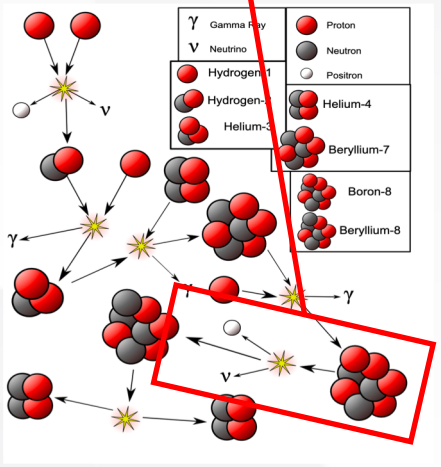
Component	Background only fit	Background + ^{8}B fit	Nominal Expectation
AC - SR0	7.55	7.36	7.48 ± 0.52
AC - SR1	18.26	17.90	17.77 ± 1.23
ER	0.74	0.54	0.68 ± 0.68
NR	0.50	0.45	0.47 ± 0.32
Total Background	27.05	26.24	26.4 ± 1.5
^{8}B	-	10.71	11.9 ± 3.1
Observed		37	



F. Gao, IDM2024 PRL 133, 191002 (2024)



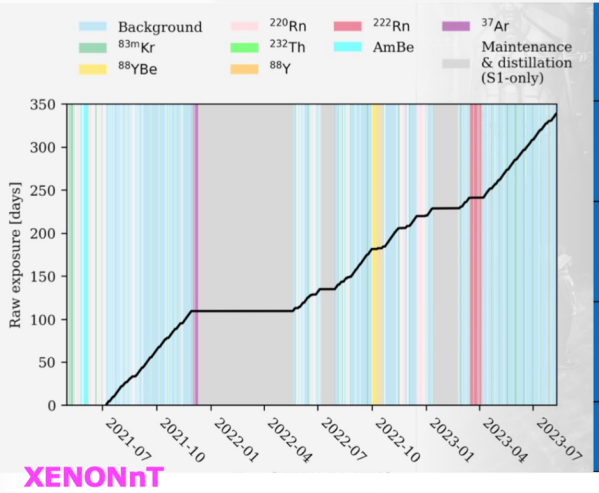




Lower the threshold!!!

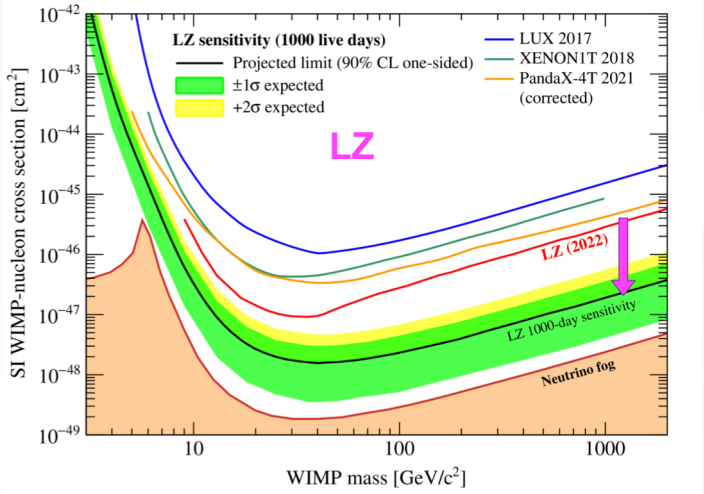
Future LXeTPC

2nd-generation LXe-TPCs continue taking data!



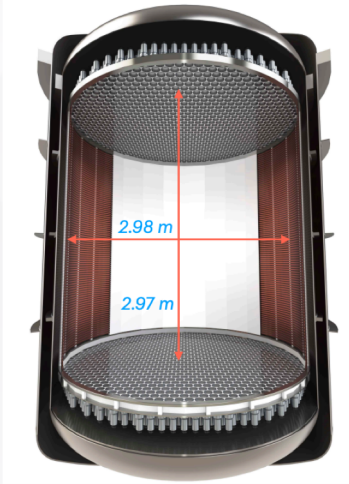
2020/11 – 2021/04	**Commissioning (Run 0)** 95 days
2021/07 – 2021/10	**Tritium removal** xenon distillation, gas flushing, etc
2021/11 – 2022/05	**Physics run (Run 1)** 164 days **PandaX-4T**
2022/09 – 2023/12	**CJPL B2 hall renovation** xenon recuperation, detector upgrade
Current Status	**Resuming physics data-taking**

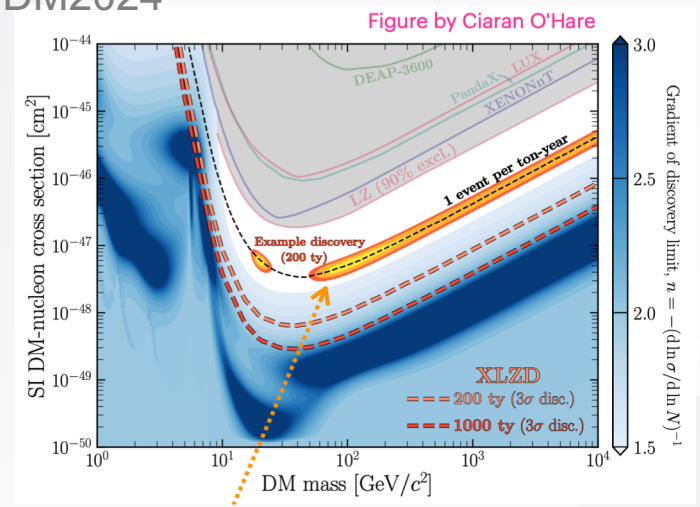
Courtesy to M. E. Monzani, IDM2024



XLZD (XENON-LZ-DARWIN); > 60t

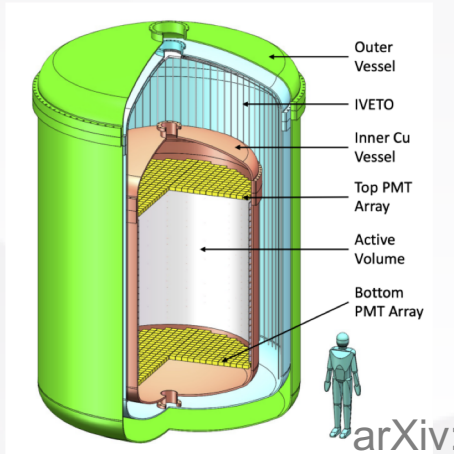
Courtesy to L. Baudis, IDM2024

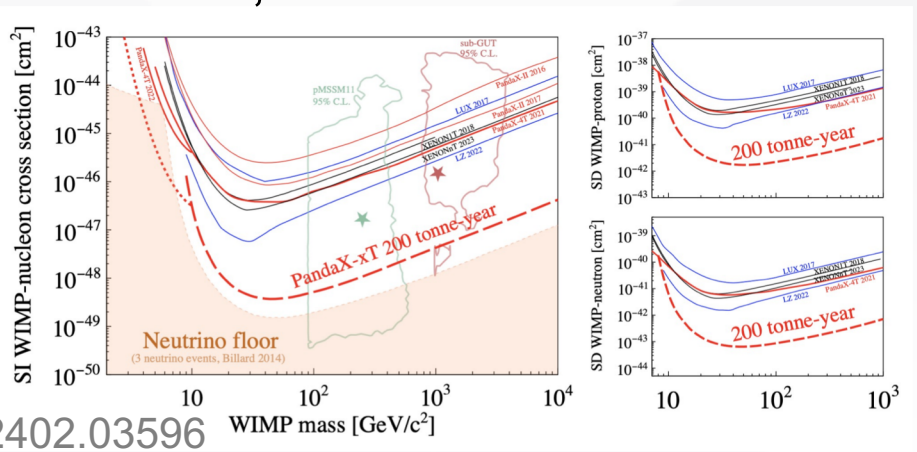




Confidence intervals for 200 tonne-yr (1-, 2-, 3-σ)

PandaX-xT; ~43 tonne

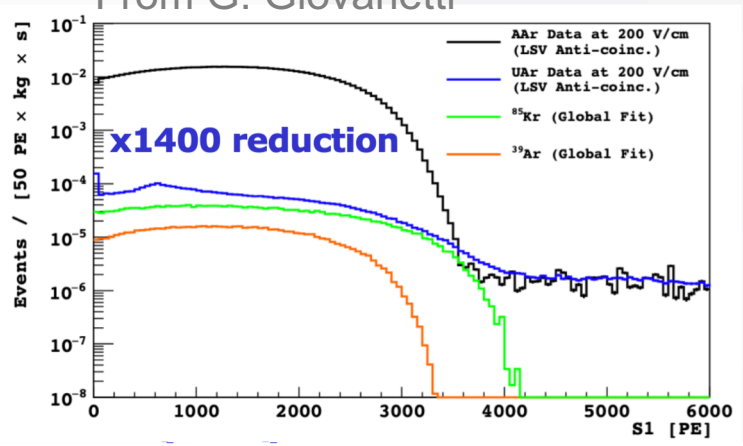


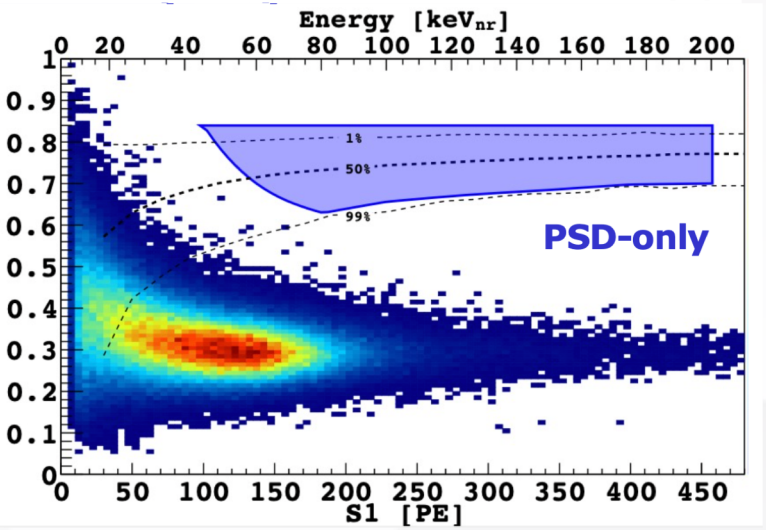


arXiv: 2402.03596

LAr-TPC work force

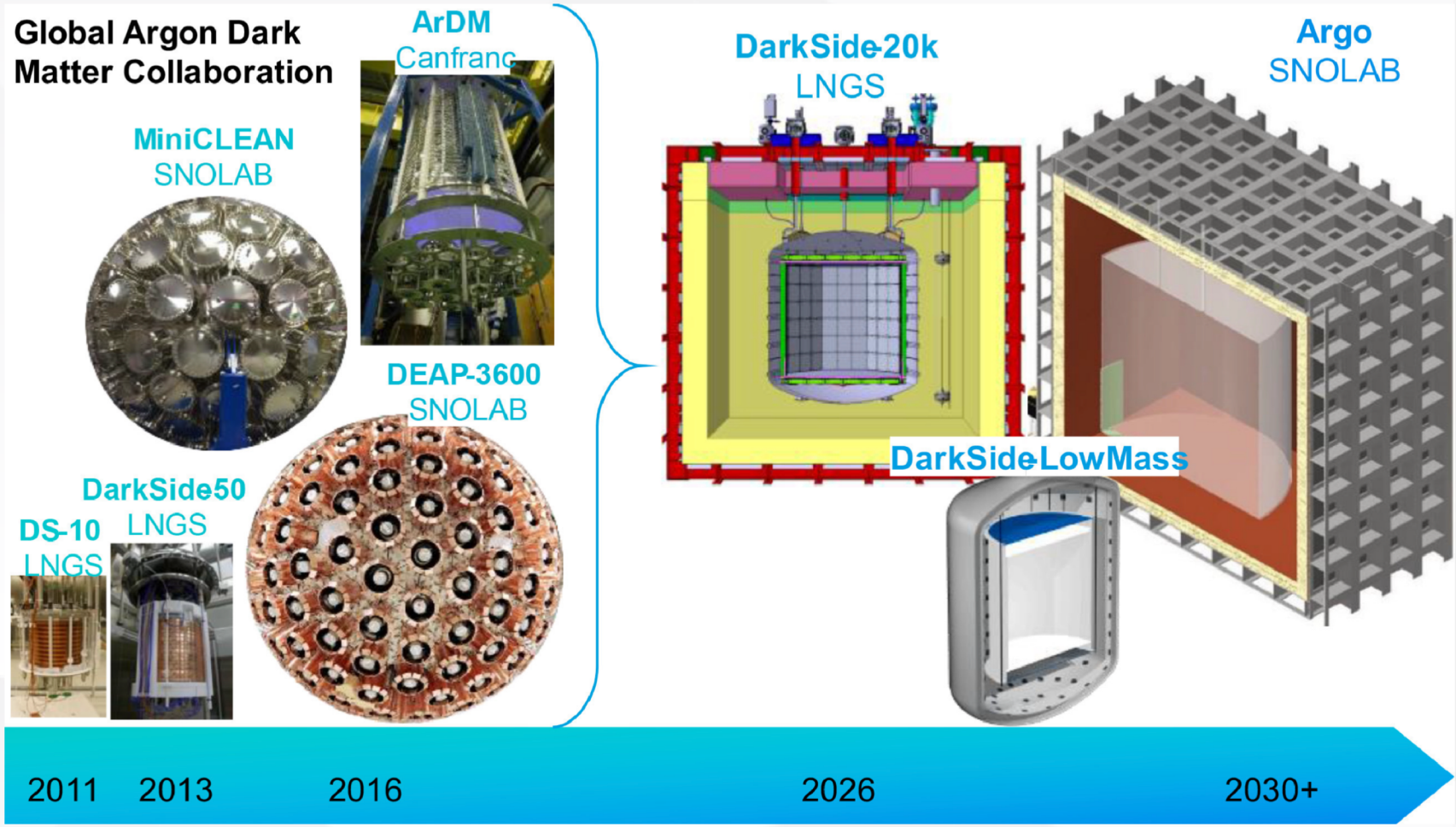
From G. Giovanetti





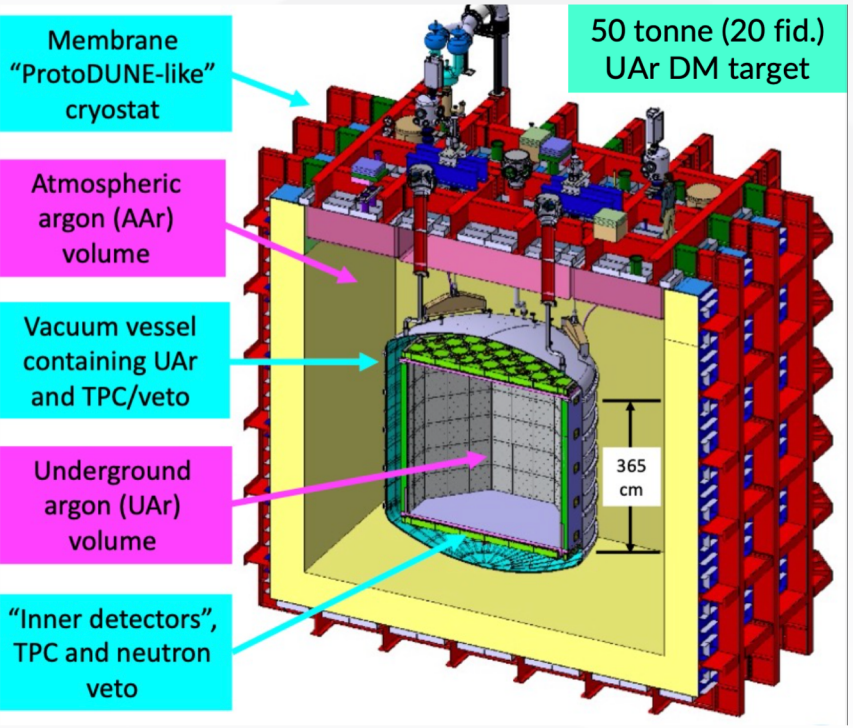
Higher intrinsic bkg with natural Ar, but with PSD discrimination!

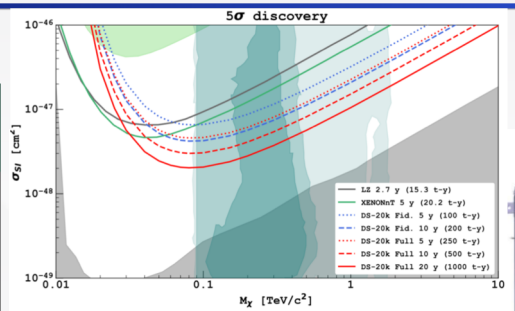
From M. E. Monzani, IDM2024



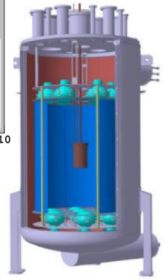
DarkSide-20k

From M.E. Montani, IDM2024

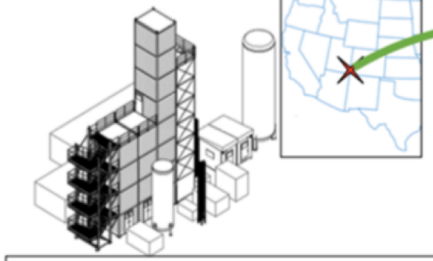




From Roberto Santorelli - La Thuile 2022



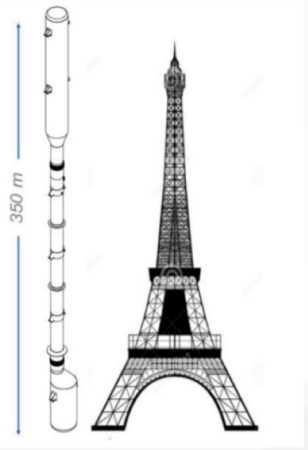
Characterisation: DArT
Measurement of the ^{39}Ar depletion factor

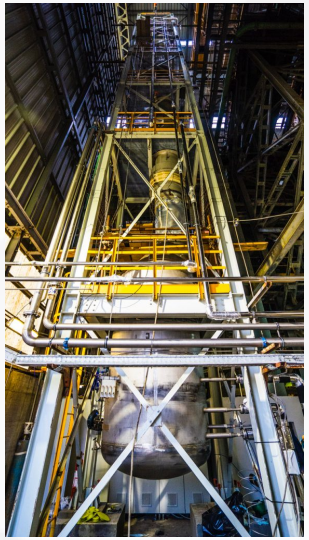


UAr transported via boat for final purification at Aria

Production: Urania
- Commercial-scale plant to extract UAr
- Located in Southwestern Colorado
- UAr extracted from CO_2 well gas at the tonne scale

Purification: Aria
- 350 m tall cryogenic distillation column to purify UAr and isotopically separate argon and other elements
- Located in refurbished carbon mine shaft in Sardinia, Italy
- Will chemically purify the UAr for DS-20k to detector grade





- Under construction,;
- 50-tonne total mass;
- 20t fiducial mass for 10-year exposure;
- SiPM 4pi coverage;

Courtesy to J. Monroe, IDM2024

- UAr mined from Urania;
- Further distillated at Aria facility;

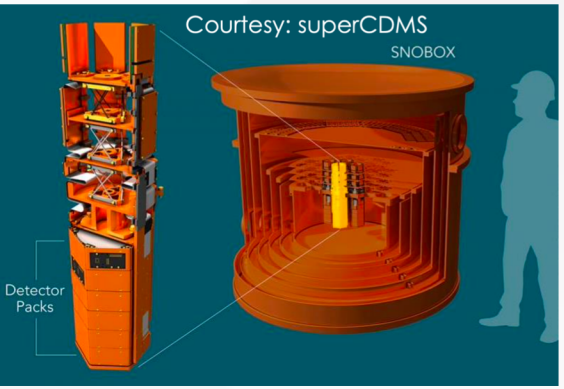
CONTENTS

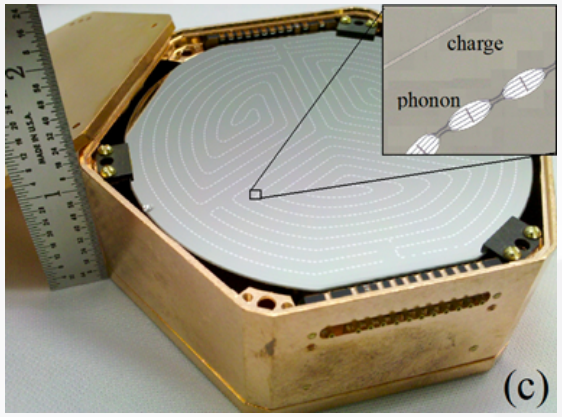
Disclaimer: Apology for omittance!

** Most materials are borrowed from public talks, especially from Prof J. Liu, Prof. Q. Yue's, and talks from IDM2024.**

Ultra-low temperature: Bolometer

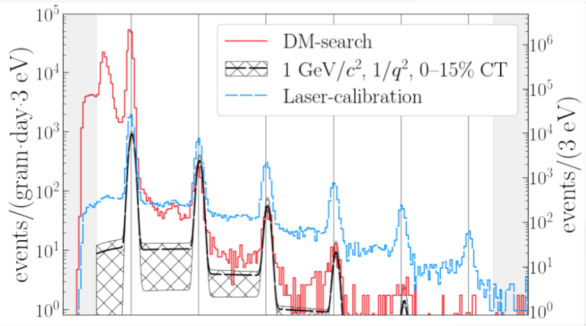
SuperCDMS @ SNOLAB



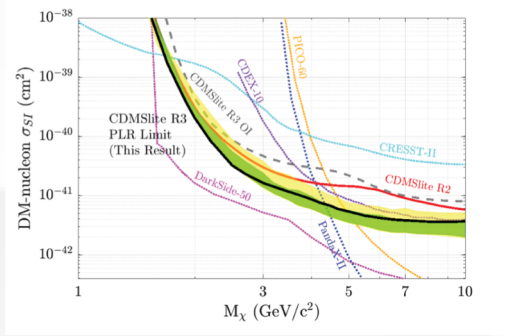


PHYSICAL REVIEW LETTERS 121, 051301 (2018)

Phys. Rev. D 102, 091101 (2020)



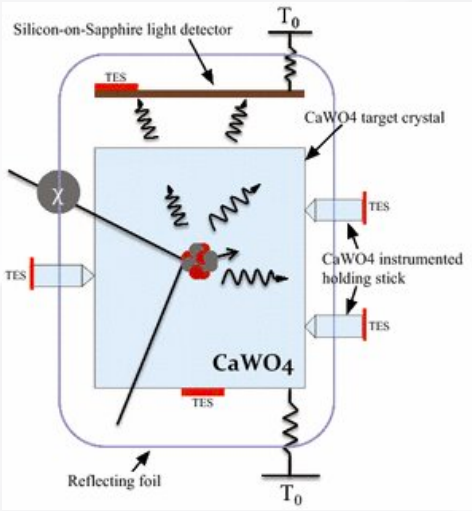
PHYS. REV. D 99, 062001 (2019)

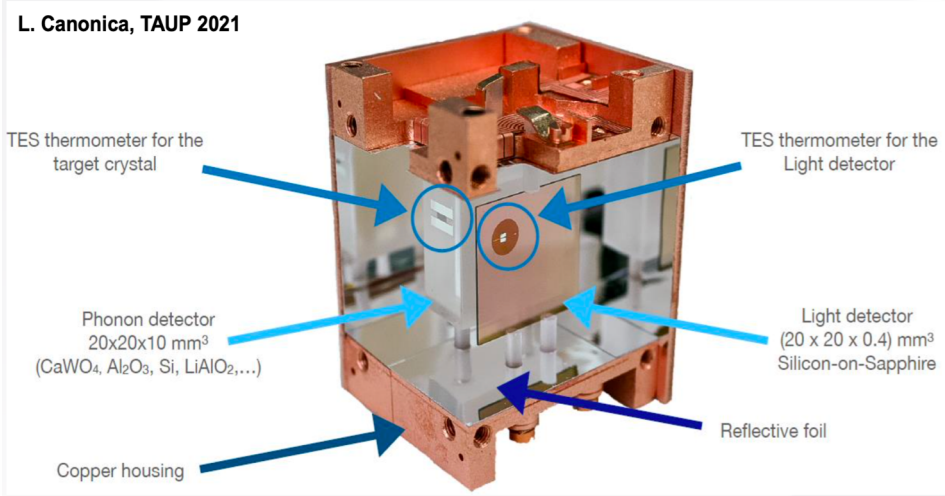


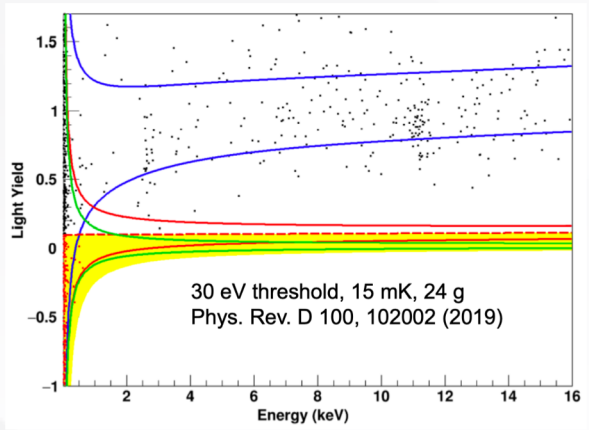
- Super-high resolution, 3% to single e-h pair;
- High sensitivity to GeV WIMP.
- **Current status: Detector under construction**

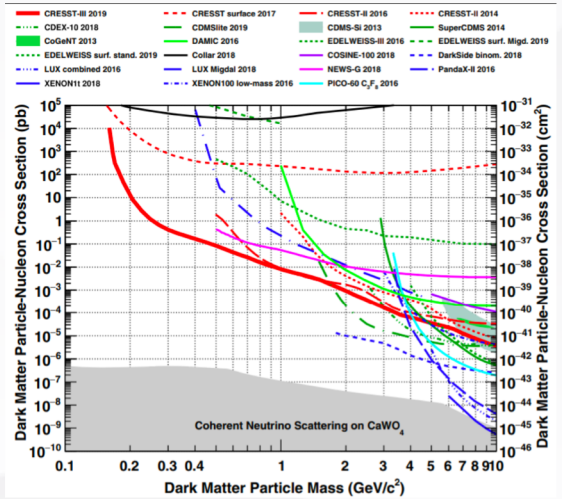
CRESST @ LNGS

M. Mancuso, Journal of Low Temperature Physics 199, 547 (2022)





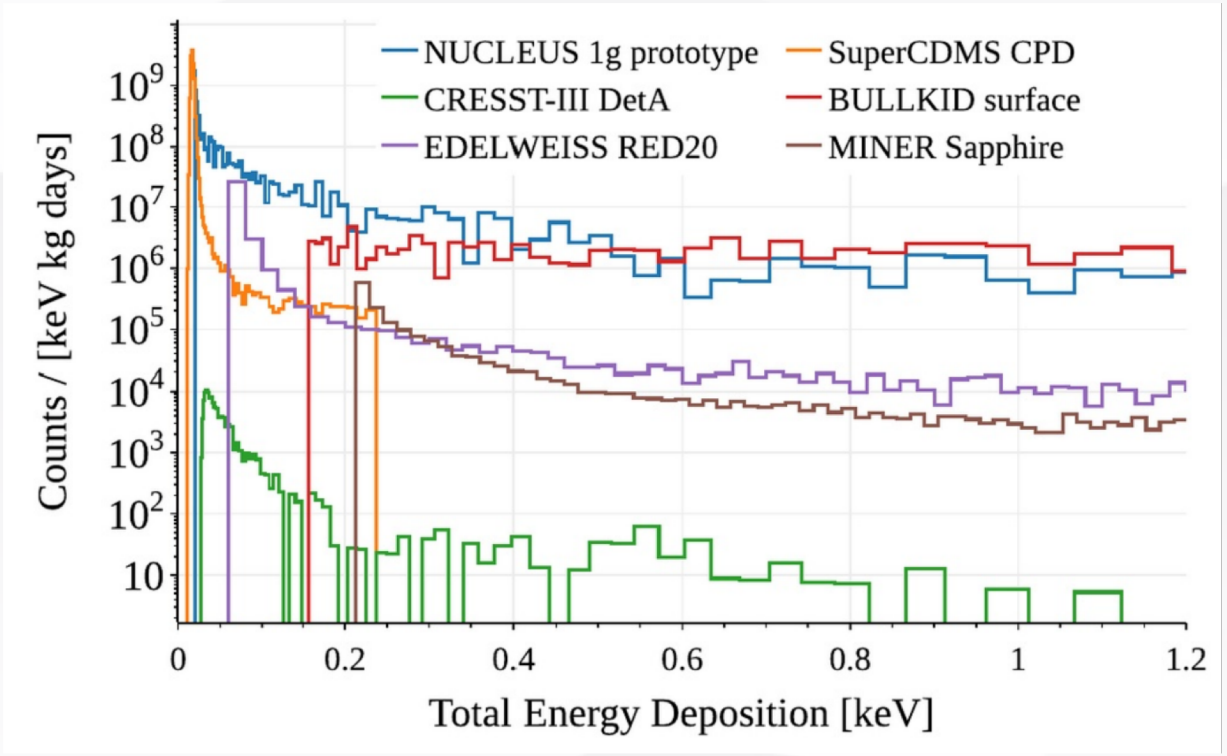




- Great background rejection power.
- **Status: Upgrade detector and readout**

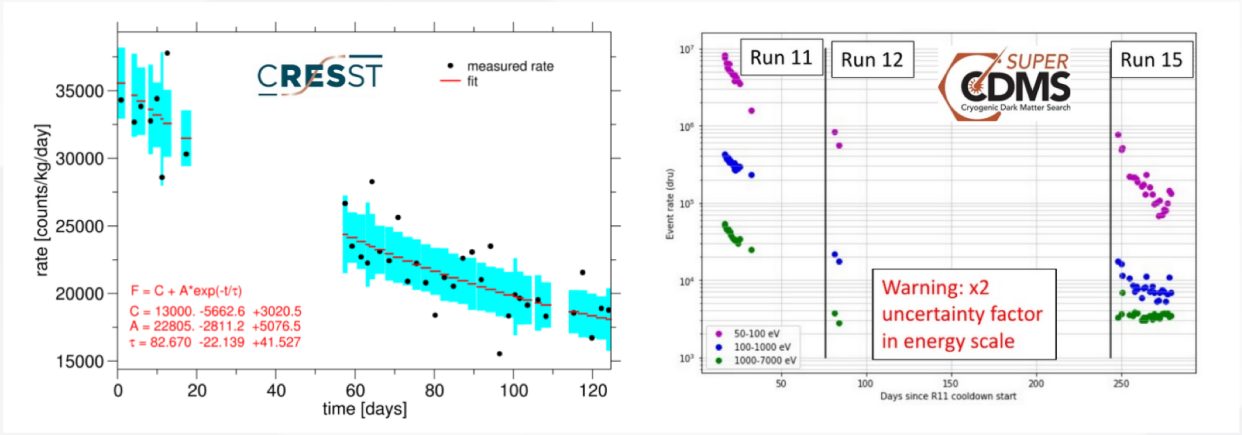
Low energy excess in Cryogenic Crystal Detectors

Distinct excess rates among experiments!

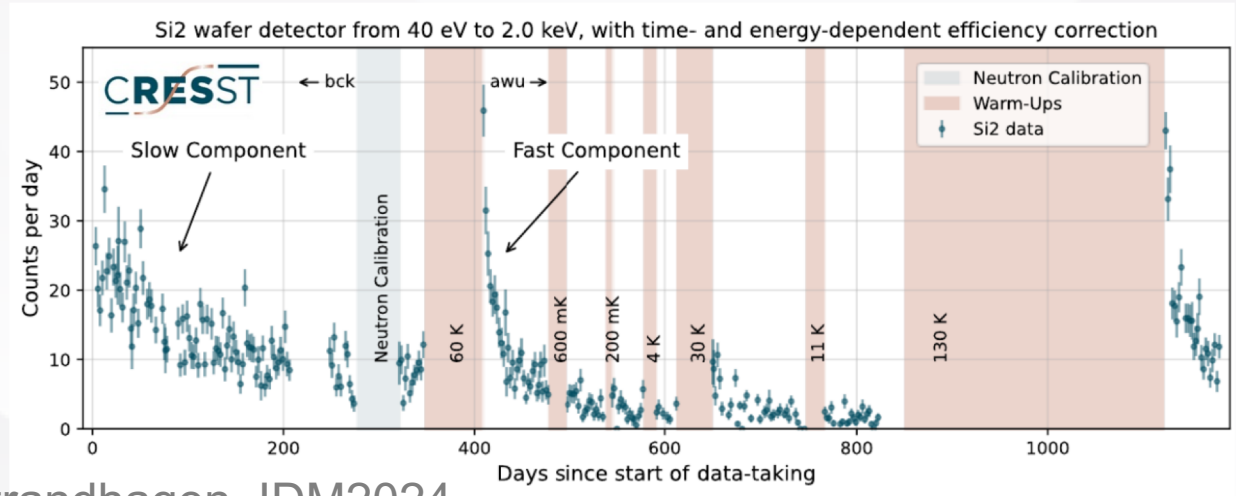


https://github.com/fewagner/excess

NOT DM since it decreases over time!



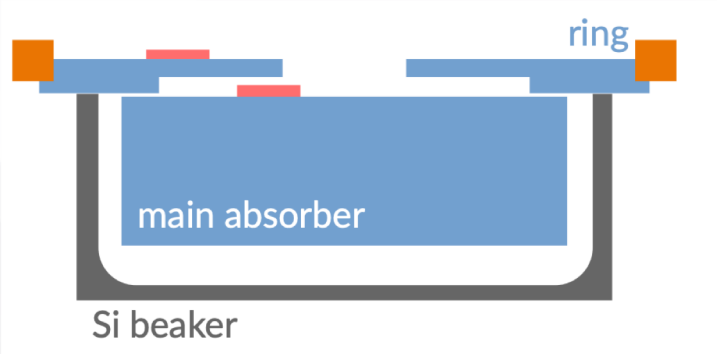
Also activated with thermal cycles!

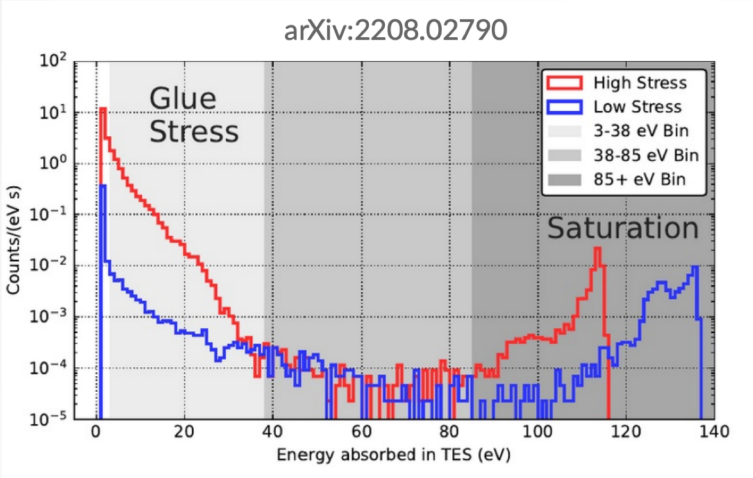


Courtesy to C. Strandhagen, IDM2024

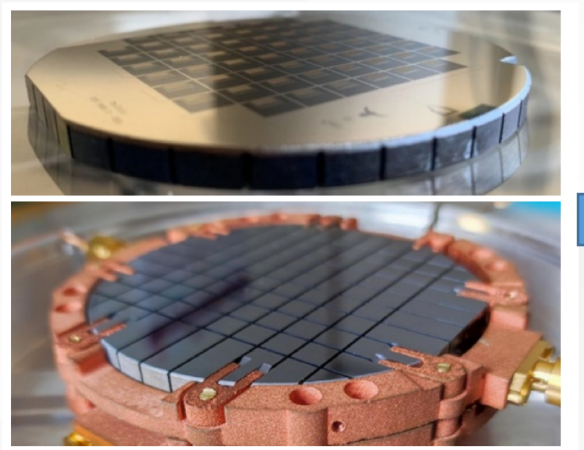
Understanding the LEE

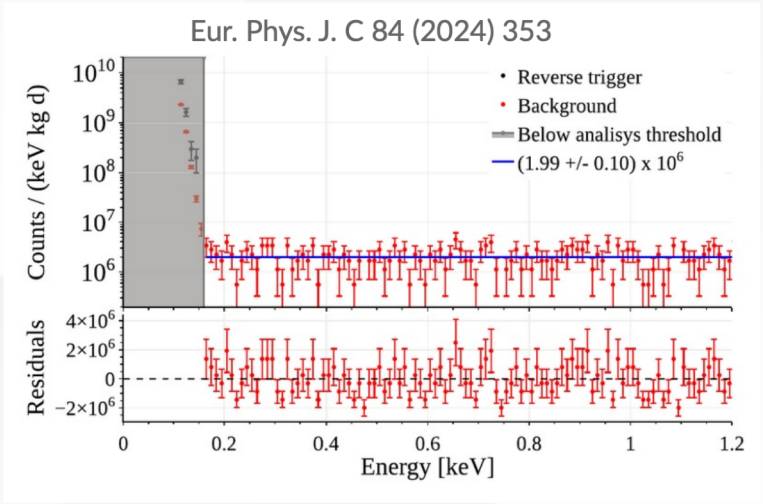
Stress due to holders!



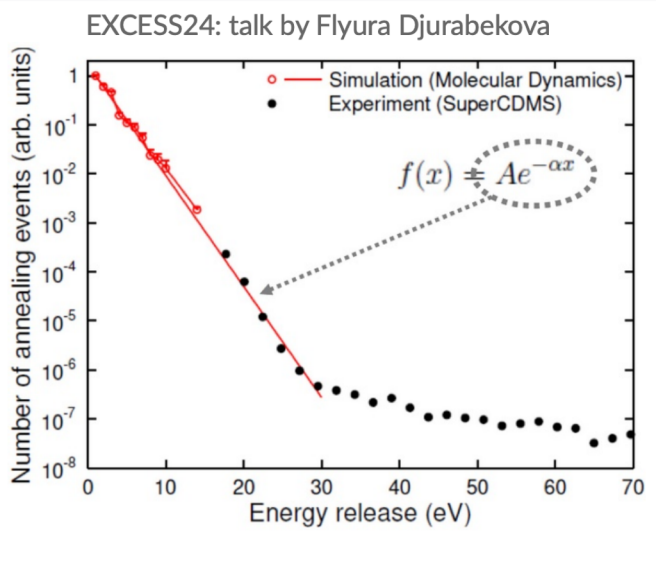


Pixelized -> less LEE!



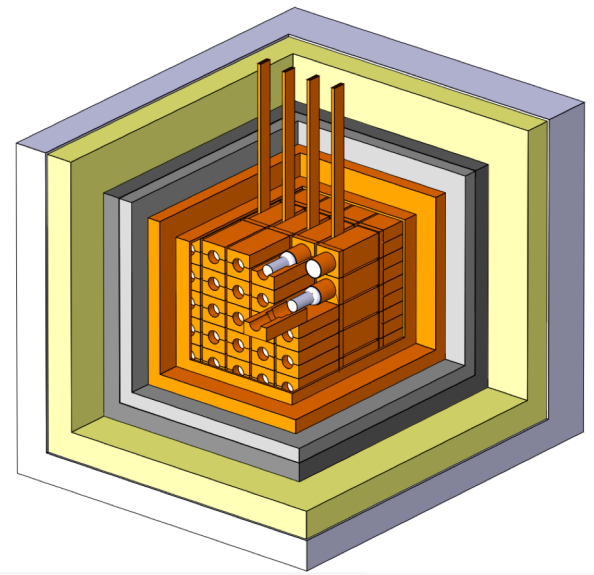


Sim of internal defects match data!



Courtesy to C. Strandhagen, IDM2024

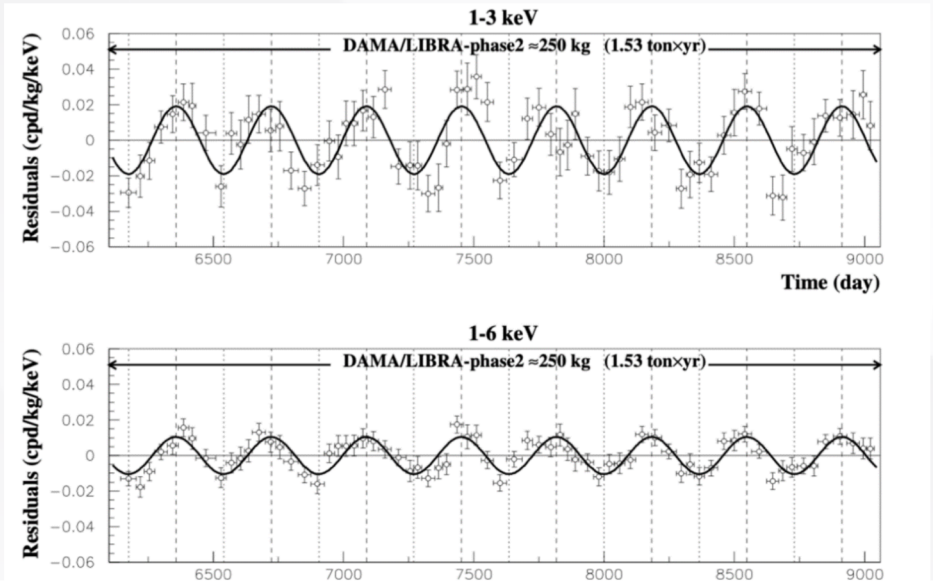
DAMA/LIBRA (Scintillator)

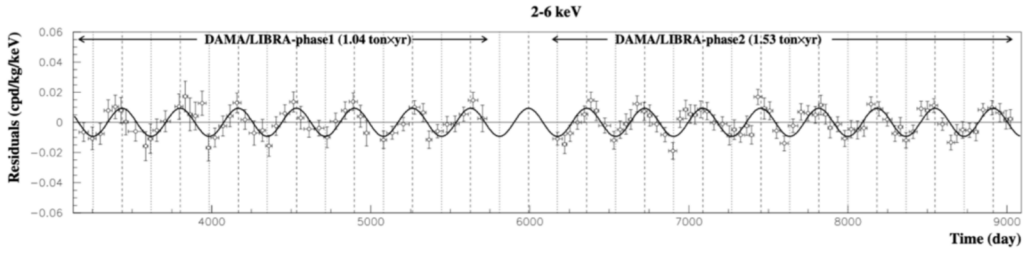


- NaI crystal coupled with PMT at both ends.
- Crystal array embedded in copper cage, then shielded by PE and lead.
- No PID, bkg high;

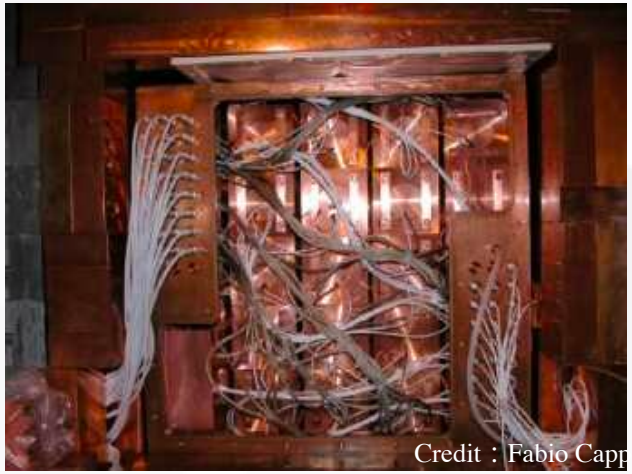
✓ **Annual Modulation Signal**

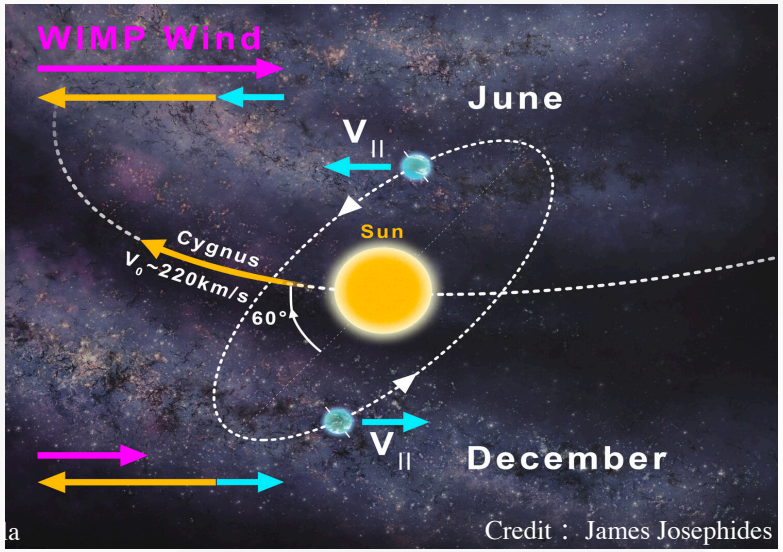
Full exposure 13.7**σ**





Nuclear Physics and Atomic Energy.


Credit：Fabio Cappella



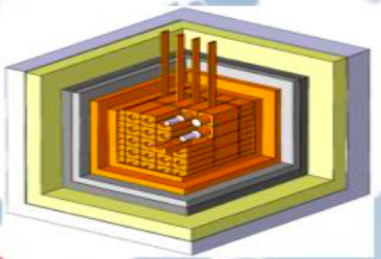
Credit： James Josephides

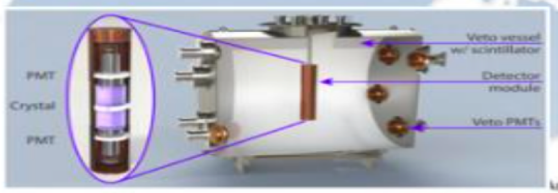
Annual modulation validation working force

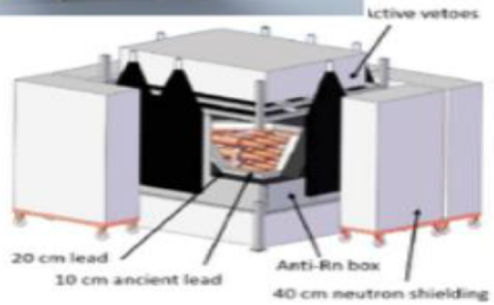
COSINUS @ LNGS

DAMA @ LNGS

SABRE @ LNGS

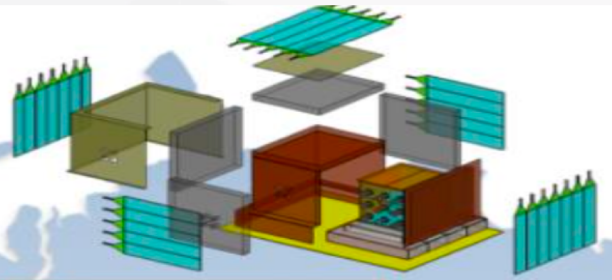






ANAIS @Canfranc

In Data-taking



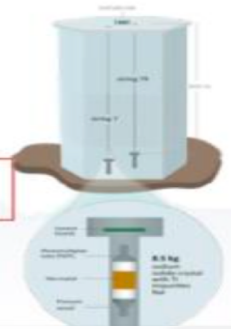
KIMS/COSINE @ Yangyang

In Data-taking

PICO-LON @ Kamioka

SABRE @ Stawell

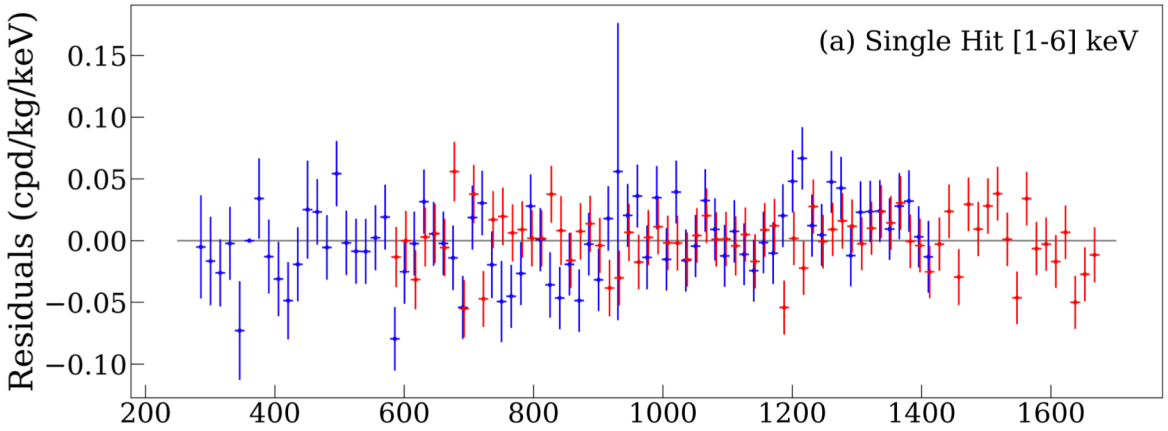
DM-Ice @ South Pole

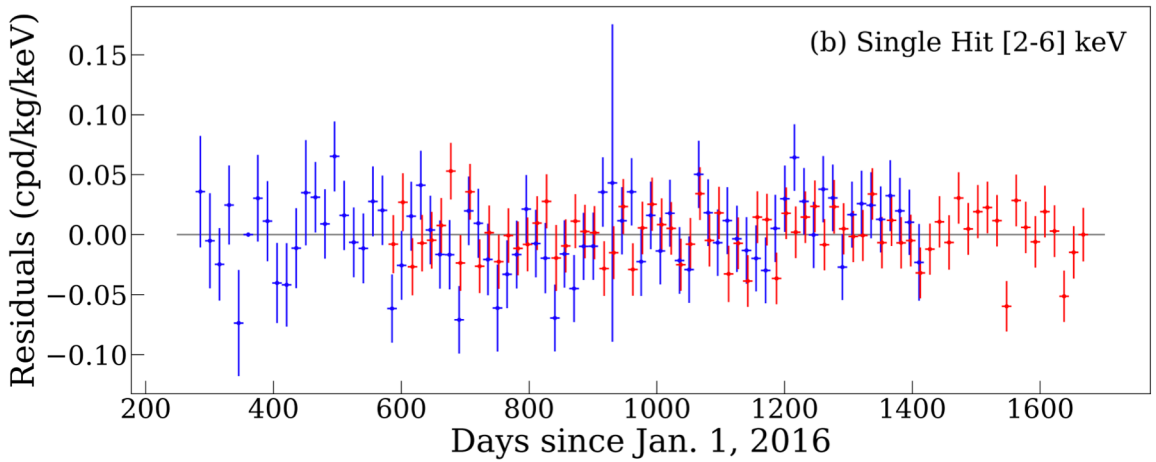


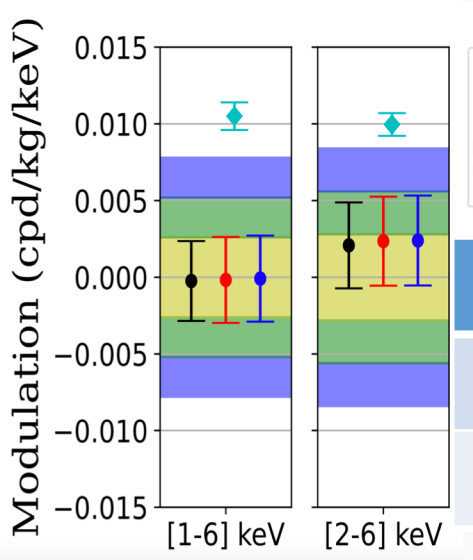
Same NaI(Tl) technology, different locations, even south/north hemisphere (seasonal variation)

Hyun Su Lee,
GRC Particle Physics 2019

Joint analysis between COSINE and ANAIS

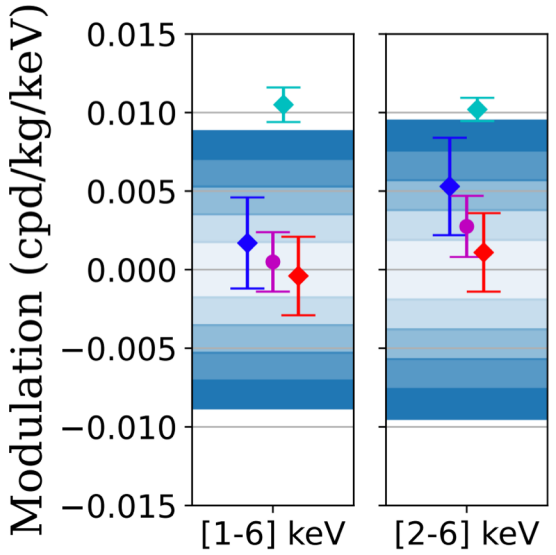






3-yr results

Energy	Amplitude [dru]	DAMA exclusion
1-6 keV	-0.0002+-0.0026	3.7**σ**
2-6 keV	0.0021+-0.0028	2.6**σ**



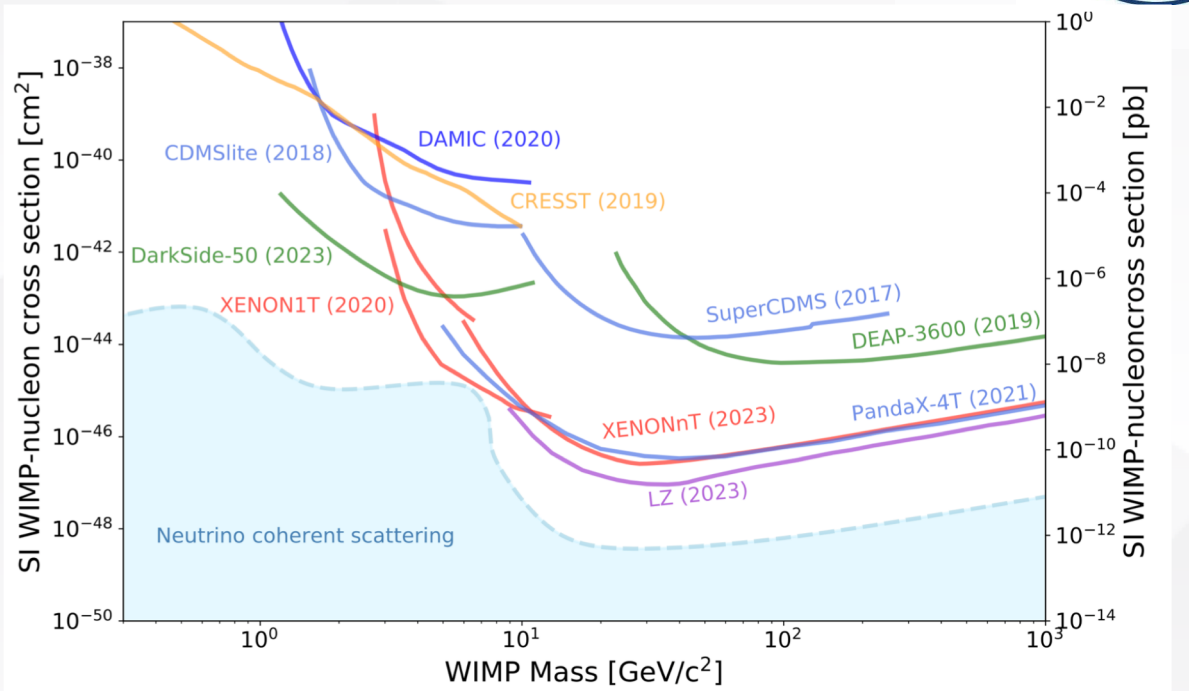
6-yr results

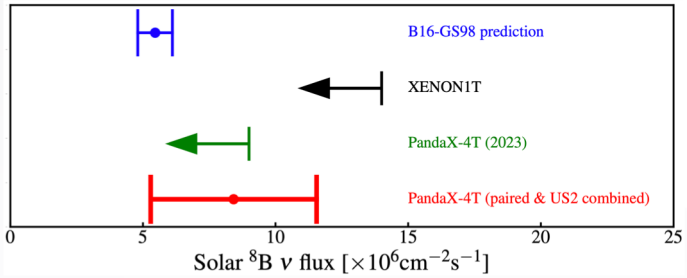
Energy	Amplitude [dru]	DAMA exclusion
1-6 keV	0.0005+-0.0019	4.7**σ**
2-6 keV	0.0027+-0.0021	3.5**σ**

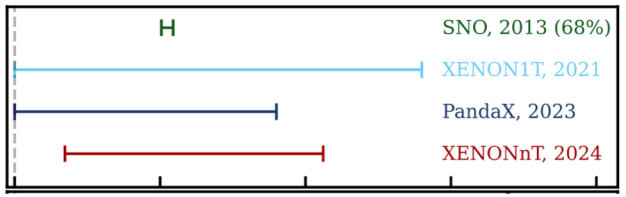
arXiv: 2503.19559

Summary

- Liquid xenon TPCs currently are leading the DM search with mass >10GeV;
- Neutrino floor has been touched with a significance of ~2.6**σ**;
- Semi-conductors and bolometers are the main forces for ~GeV and sub-GeV DM searches;
- DAMA/LIBRA's annual modulation DM signals have been almost vetoed by COSINE/ANAIS joint data, with significance of 4.7 **σ**;







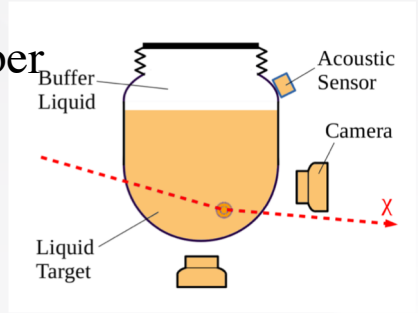
Thank you for your attention!!

Backup

Detection Techniques

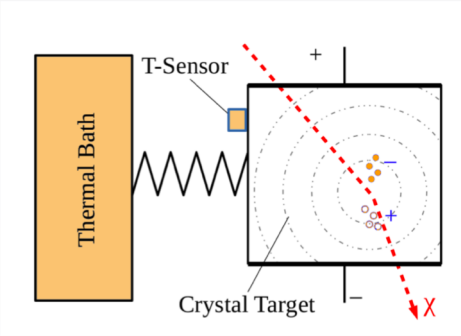
Coutesy of APPEC report

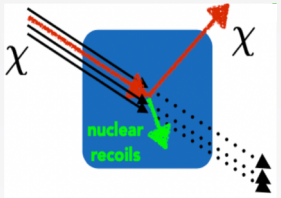
Bubble Chamber

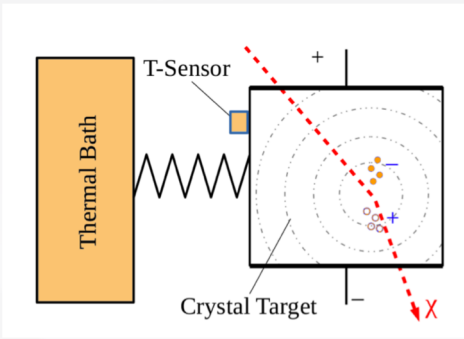


Heat

Bolometer

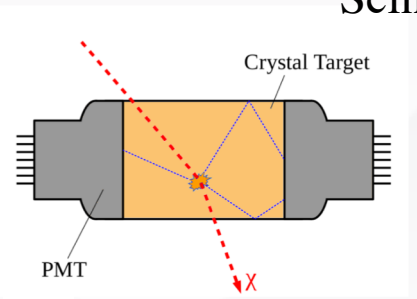




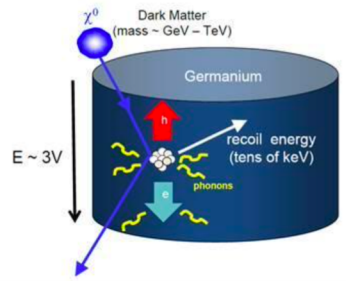


Bolometer

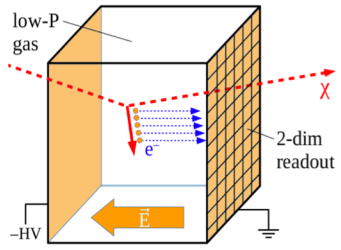
Scintillator



Point-contact Ge

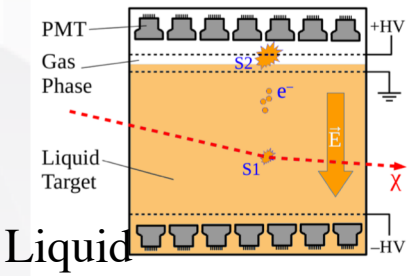


Gaseous TPC

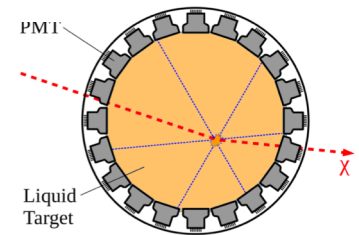


Charge

Light

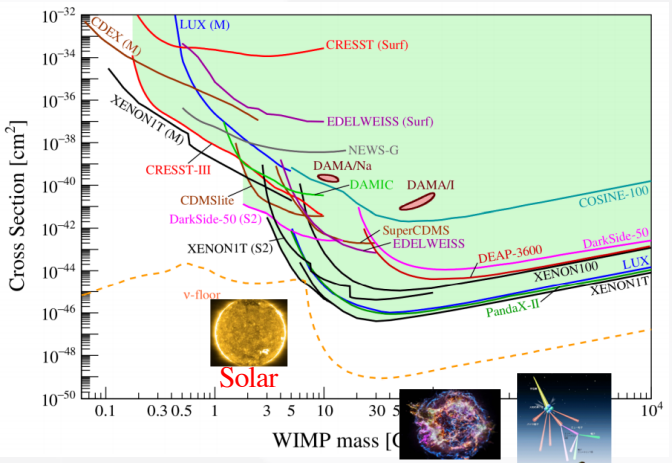


Dual-phase Noble Liquid

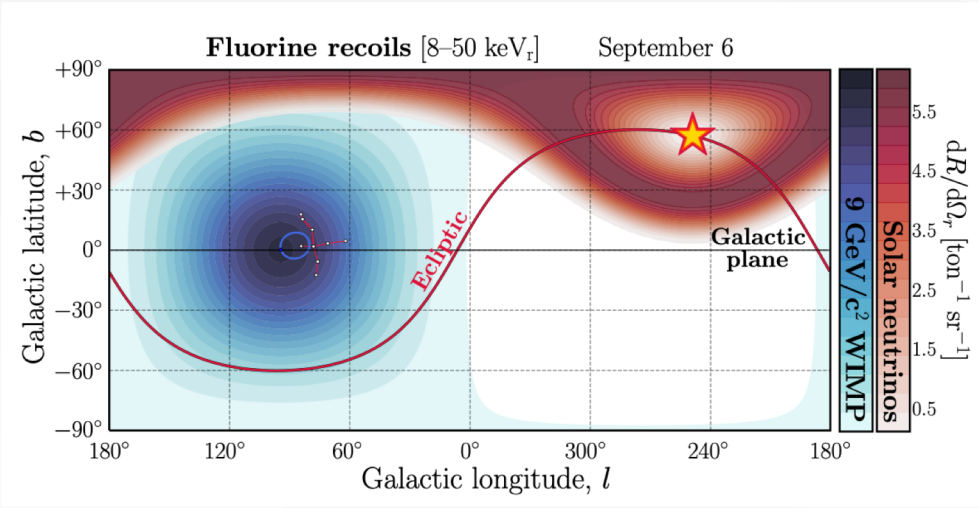


Single-phase
Noble Liquid

Directional Detector: Gaseous TPC

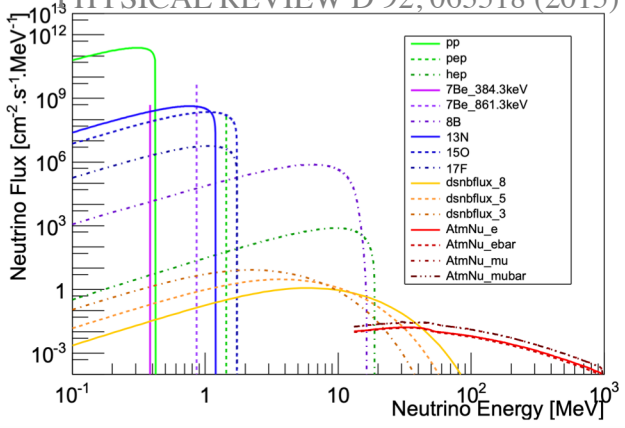


SE. Vahsen et al., arXiv:2008.12587

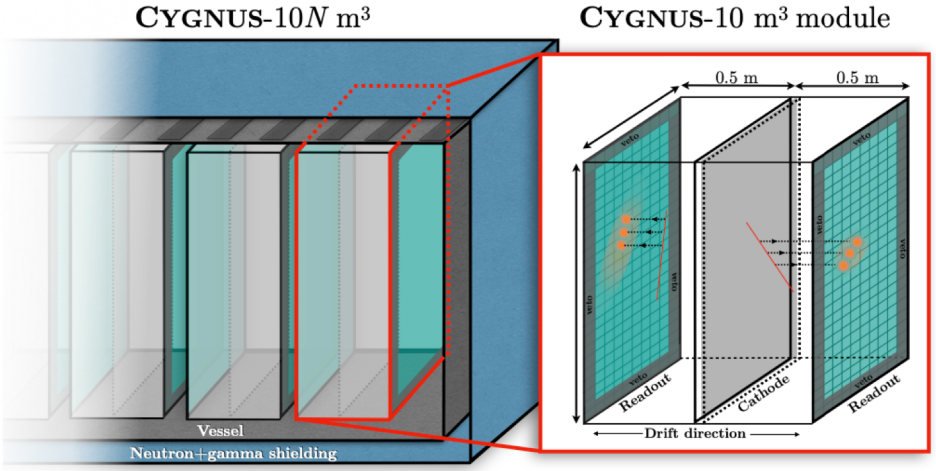


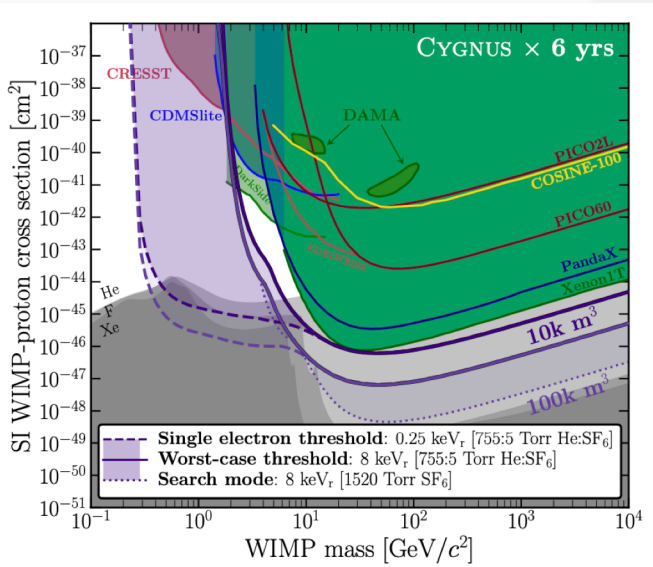
- Low-pressure gaseous TPC;
- Highly pixelized charge readout for high track resolution;
- Directionality can help go beyond neutrino floor to some extent.

PHYSICAL REVIEW D 92, 063518 (2015)



Ultimate background: neutrinos

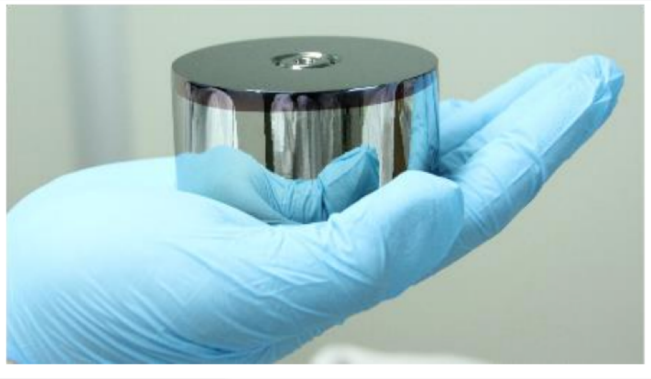


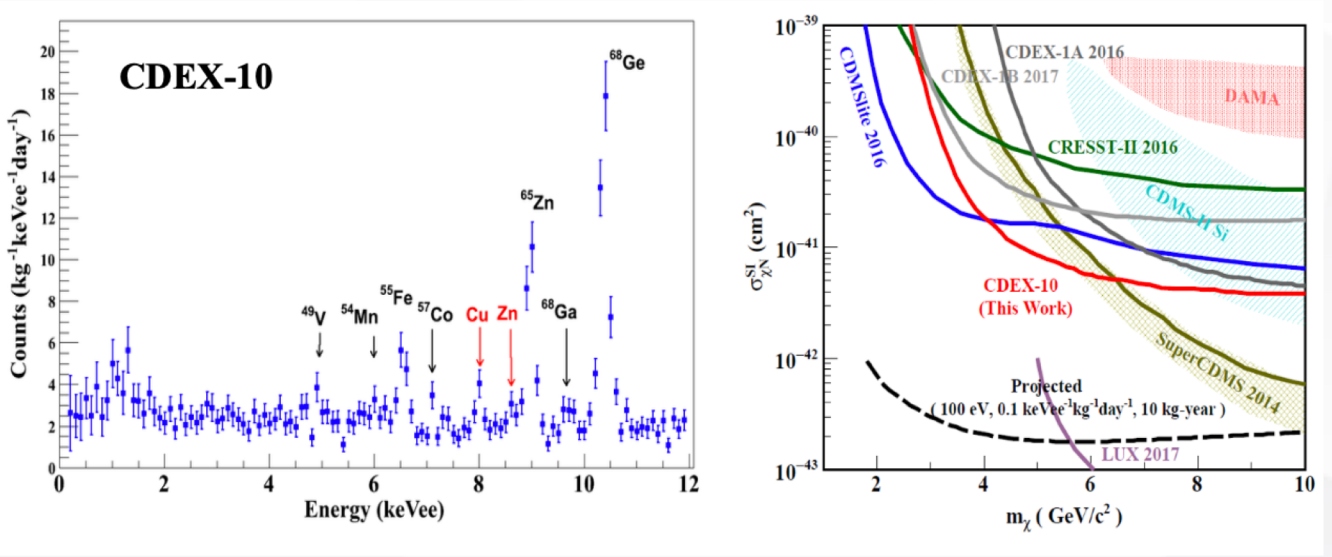


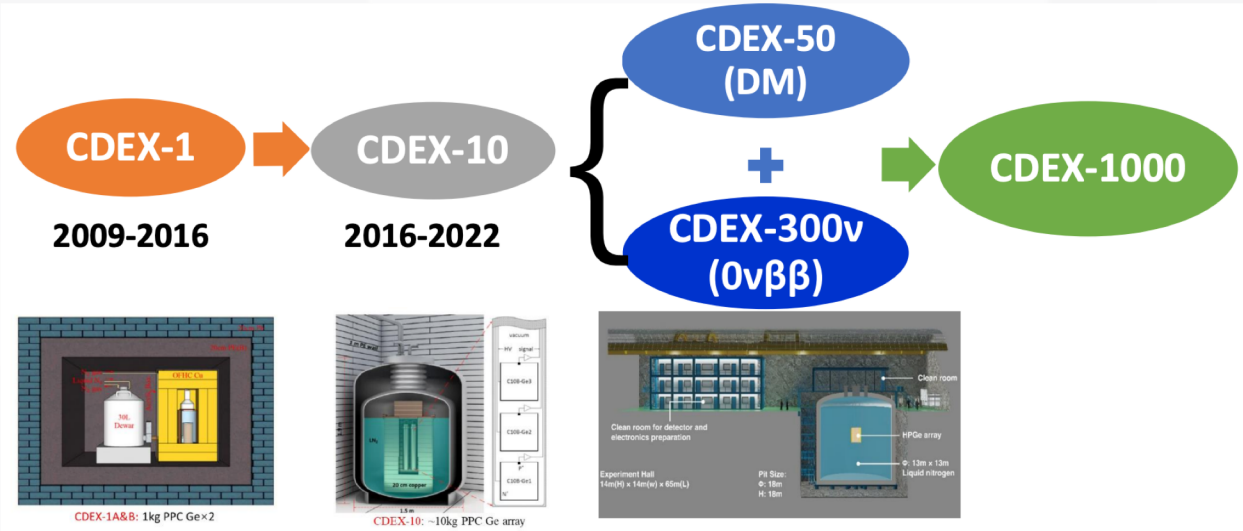
CDEX @ CJPL

From Q. Yue

PRL120, 241301 (2018)





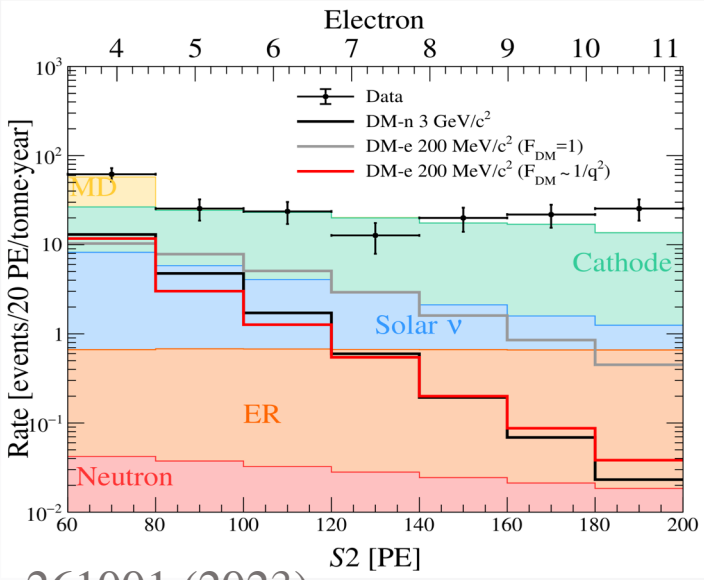


From Litao Yang, IDM2024

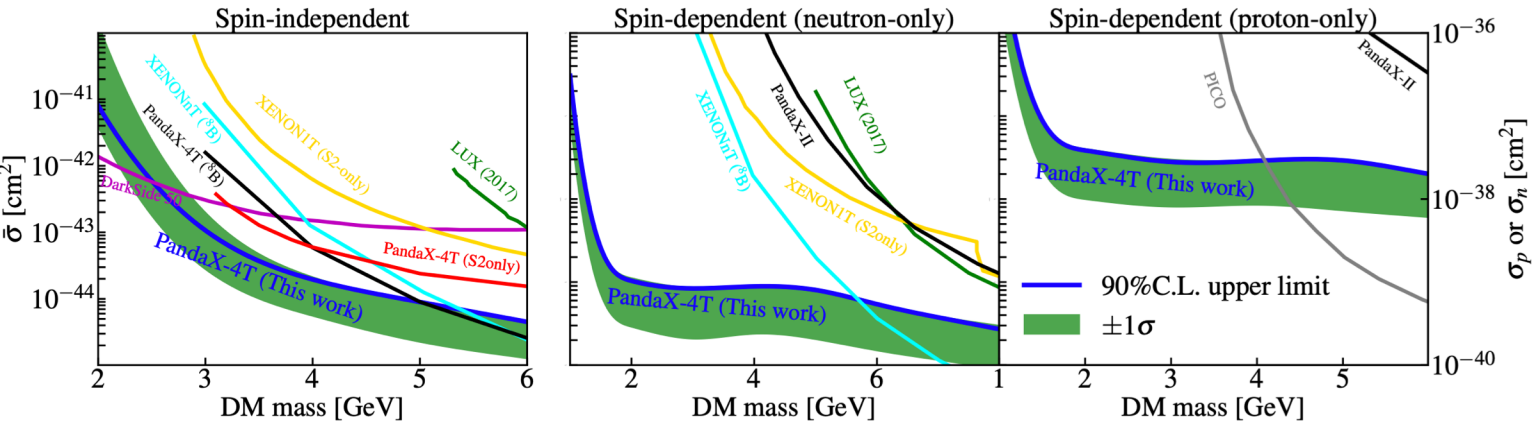
- LN2 temperature; HPGe collects pure ionization signal;
- Point-contact detector (small cap. ~pF; low electronic noise);
- Background level ~2 counts/kg/keV/day (2-4keV);
- CDEX-10, threshold ~160eV;

S2-only in Noble Liquid Detectors

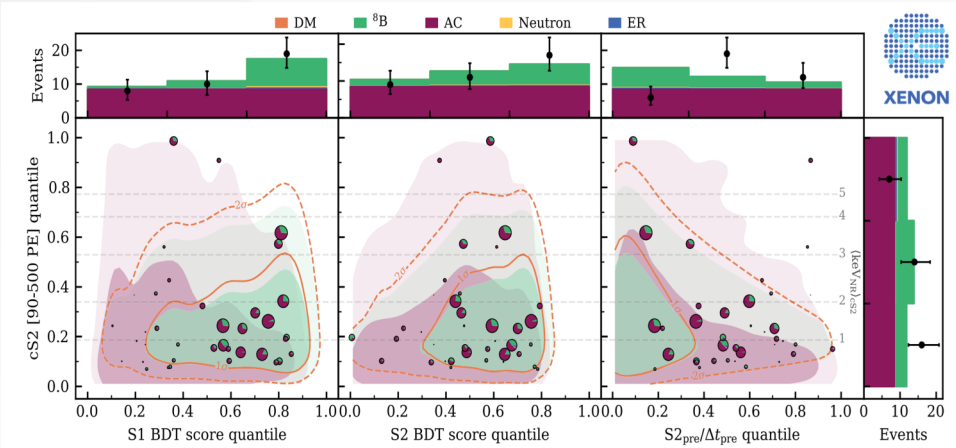
- Greatly lower the threshold for Noble Liquid TPCs;
- Combine with large exposures, can reach leading sensitivities for ~100 MeV LDM (WIMP-e scattering);

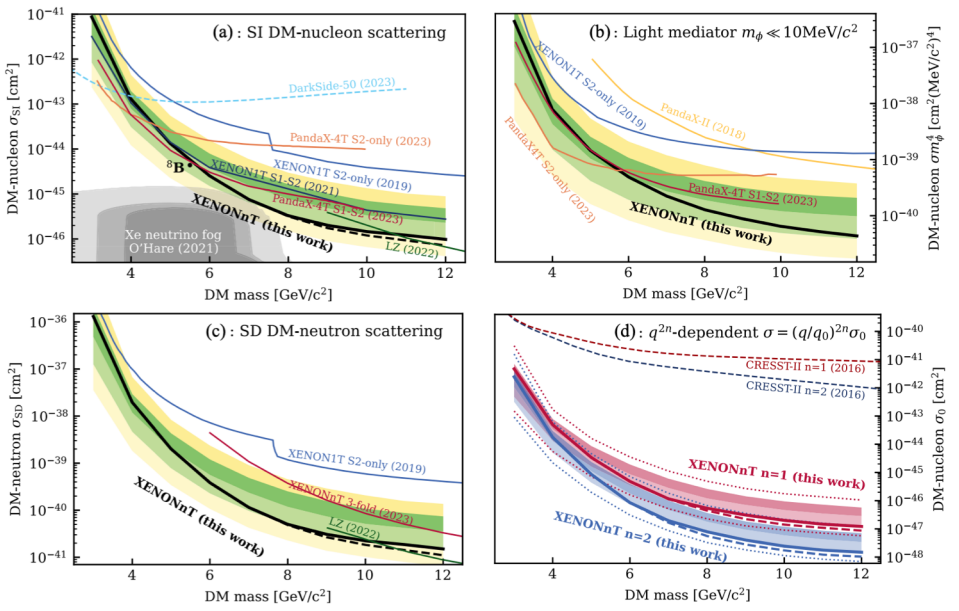


PandaX-4T, PRL 130, 261001 (2023)
arXiv: 2507.11930 (2025)



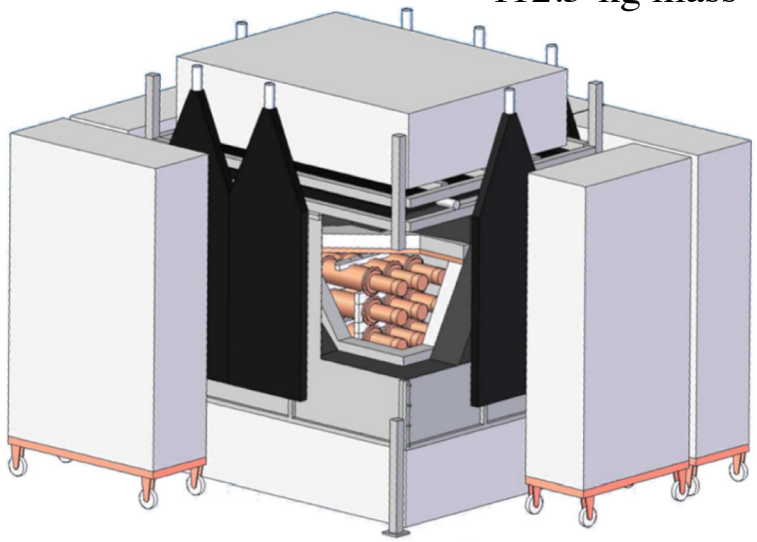
XENONnT, PRL 134, 111802 (2025)



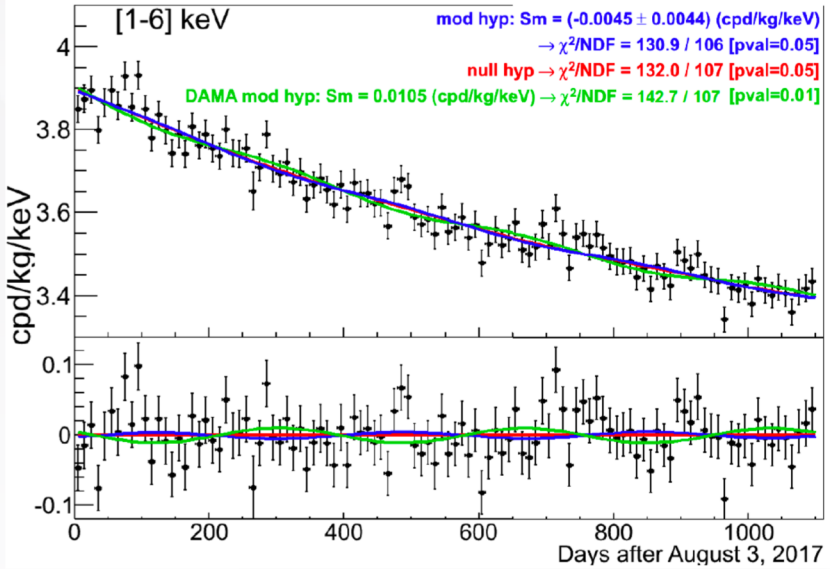


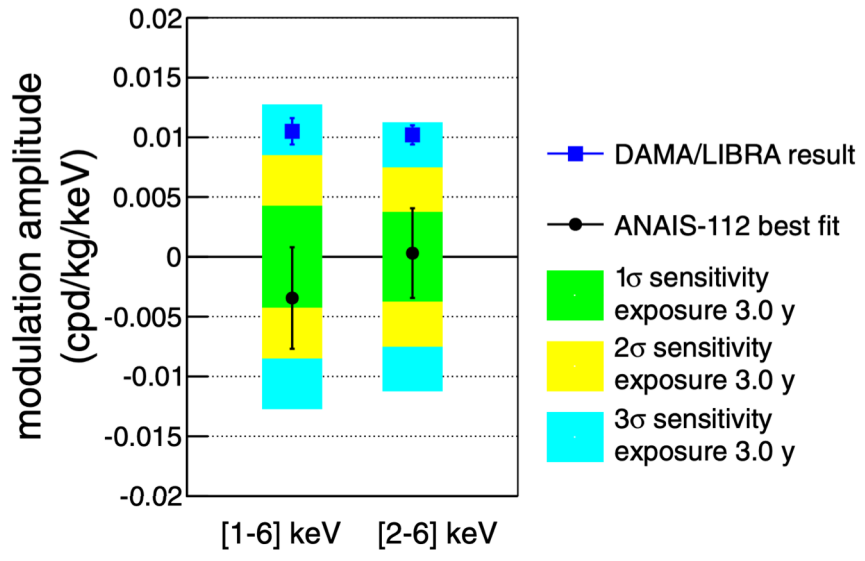
ANAIS-112

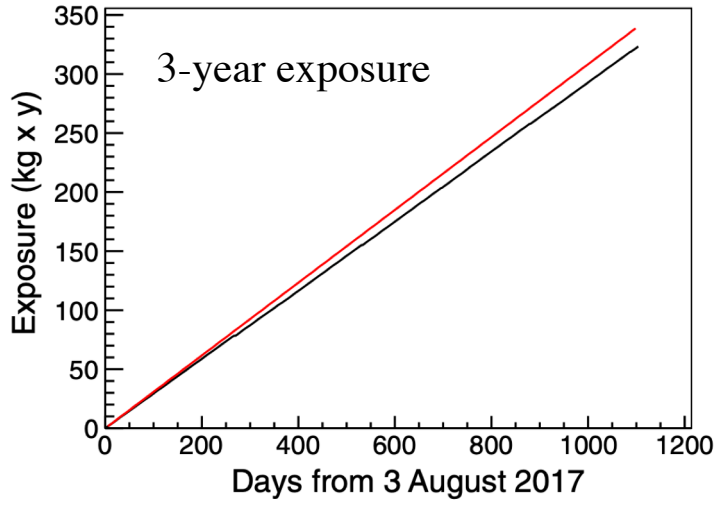
112.5-kg mass



Phys. Rev. D 103, 102005 (2021)



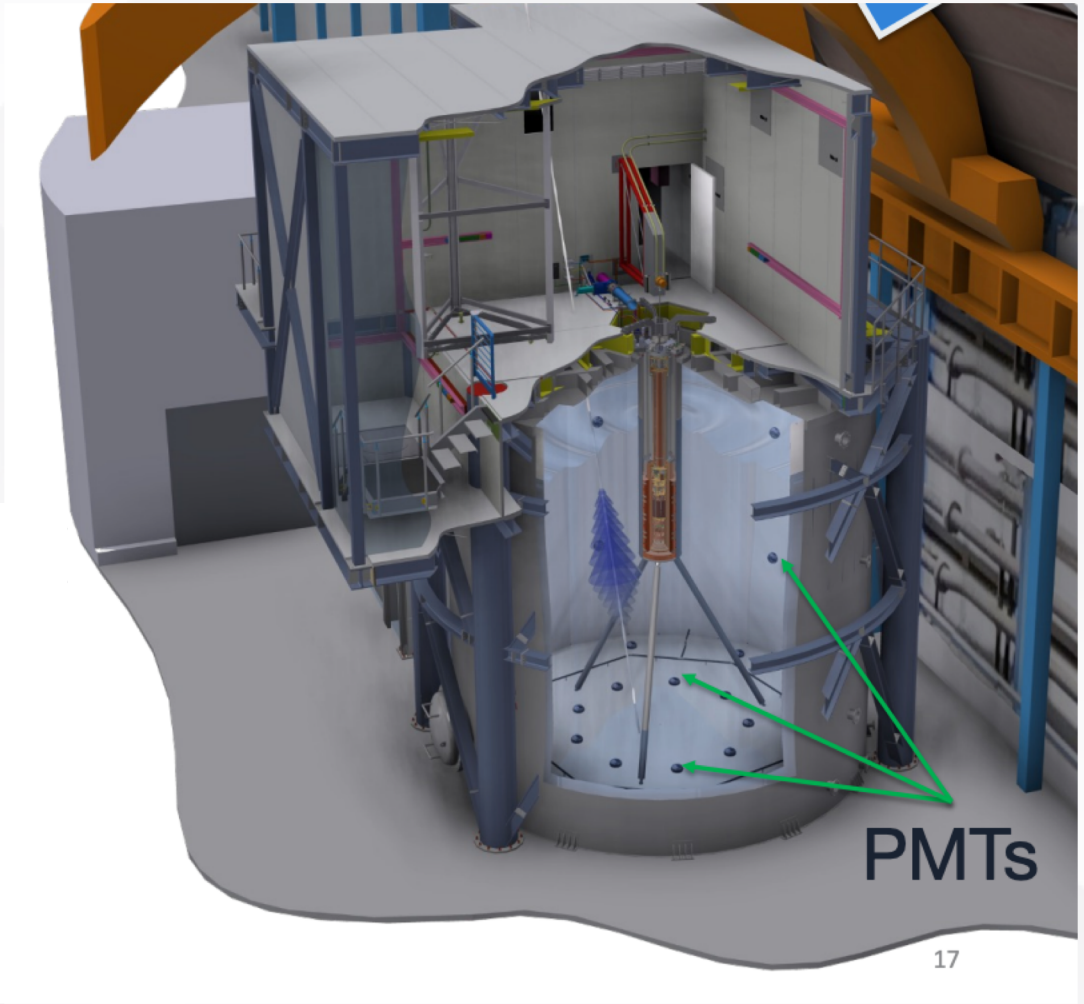


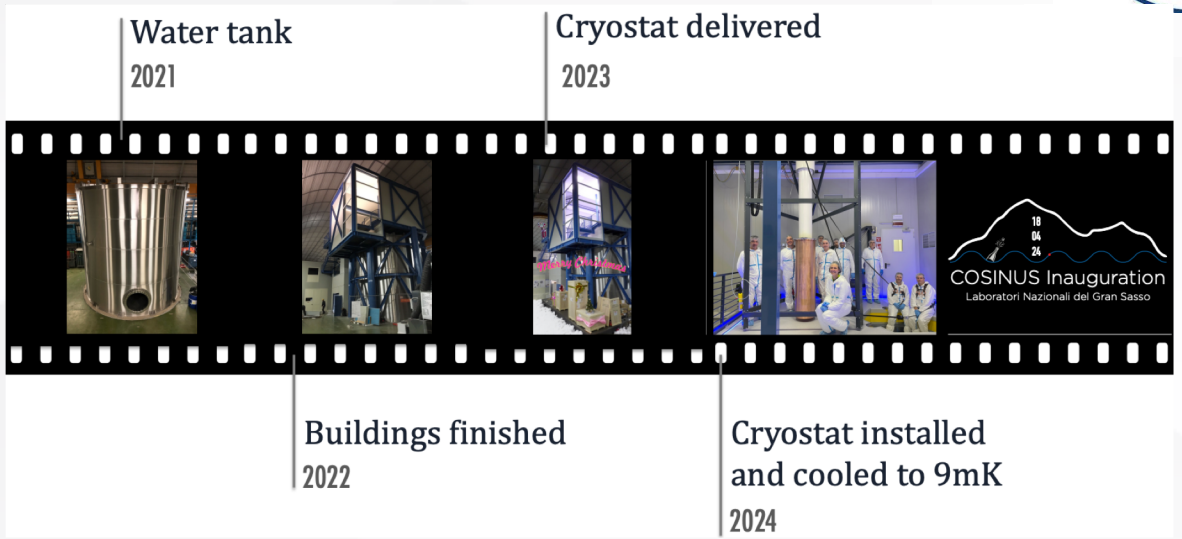


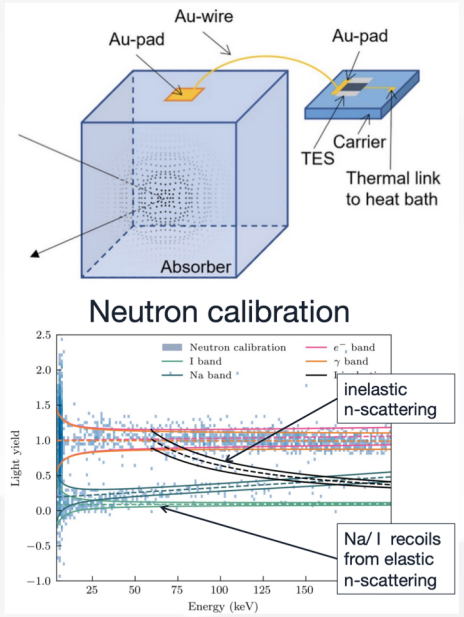
- ANAIS-112's 3-year results support the absence of annual modulation;
- The results are incompatible with DAMA/LIBRA at **3.3 (2.6) σ** for energy window of 1-6 (2-6) keV.

COSINUS Experiment @ LNGS

Courtesy to F. Reindl, IDM2024







- Start data taking in 2025;
- Cryogenic NaI detector with light and phonon readout;
- Event-by-event discrimination;
- Counting & Modulation searches;

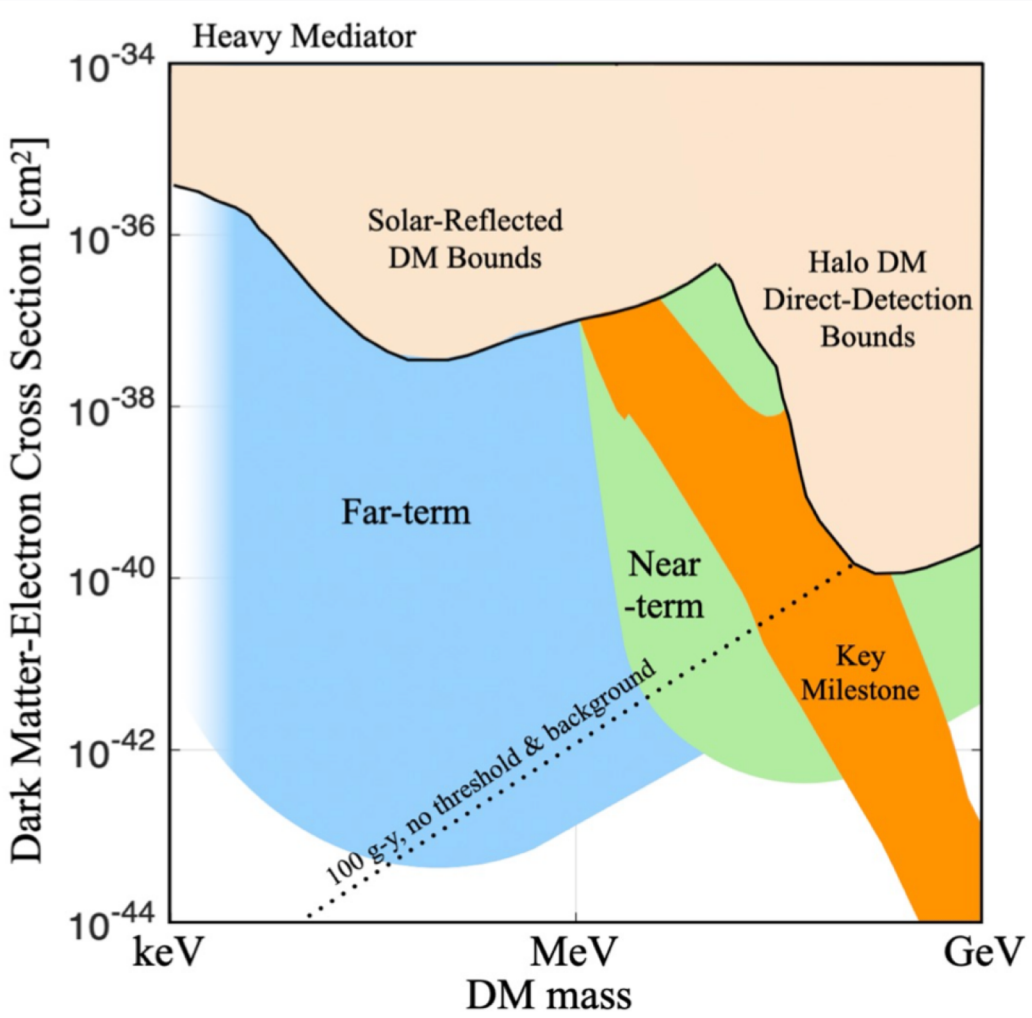
CONTENTS

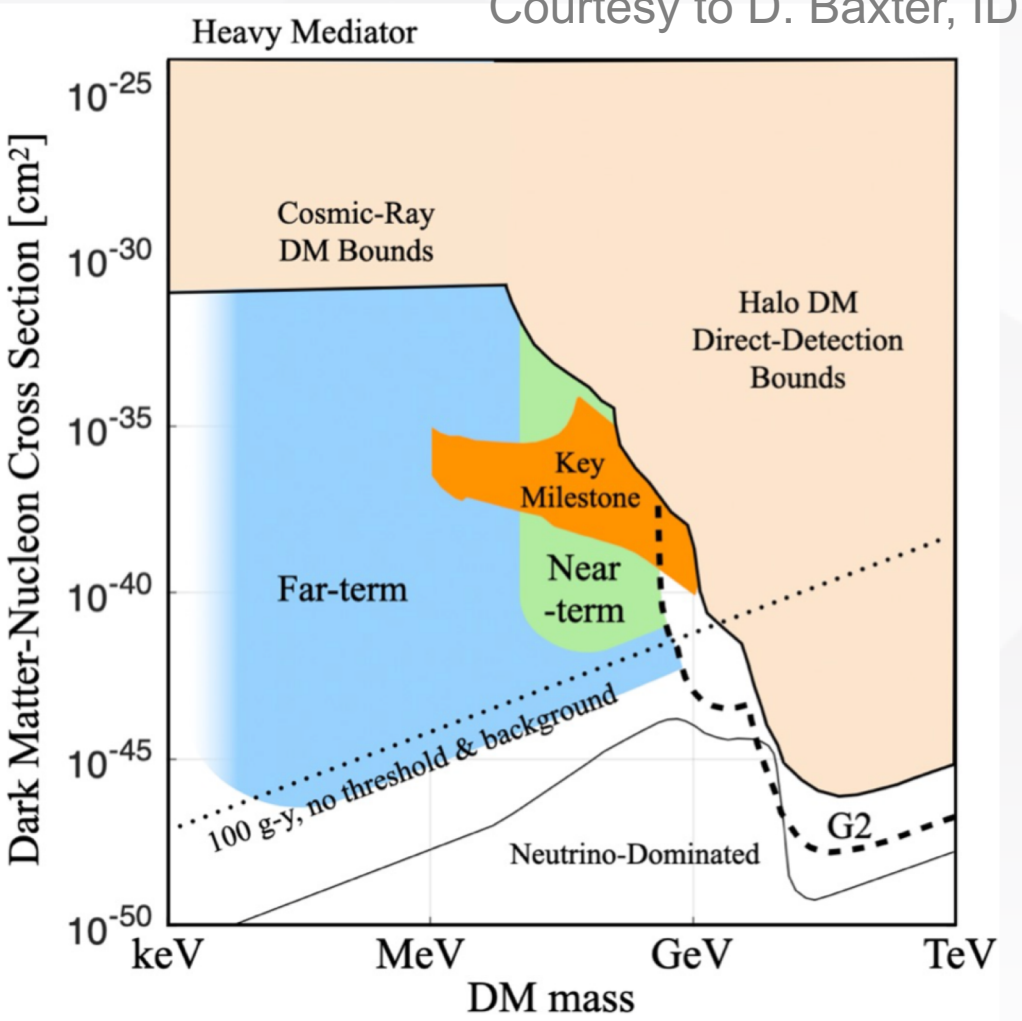
Disclaimer: Apology for omittance!

** Most materials are borrowed from public talks, especially from Prof J. Liu, Prof. Q. Yue's, and talks from IDM2024.**

Low energy regimes

Courtesy to D. Baxter, IDM2024

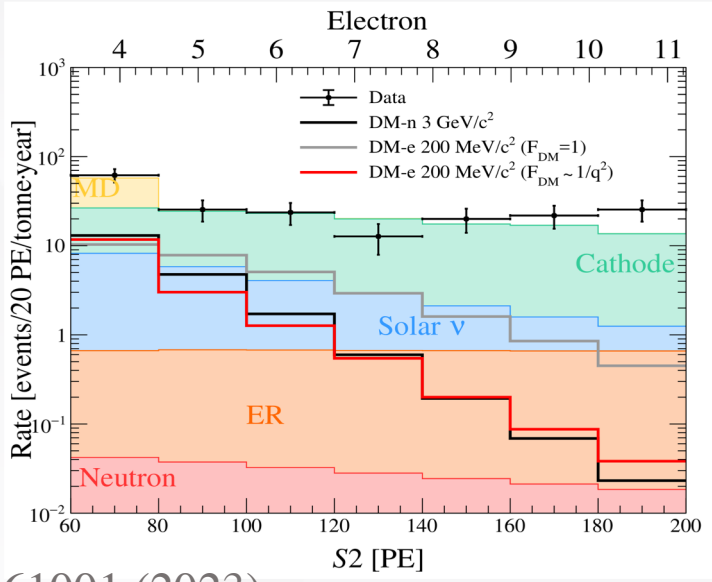




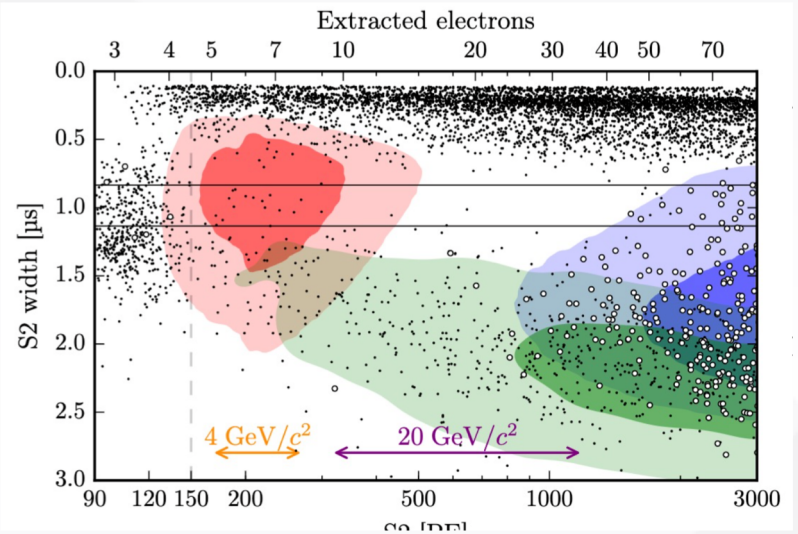
Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

S2-only in Noble Liquid Detectors

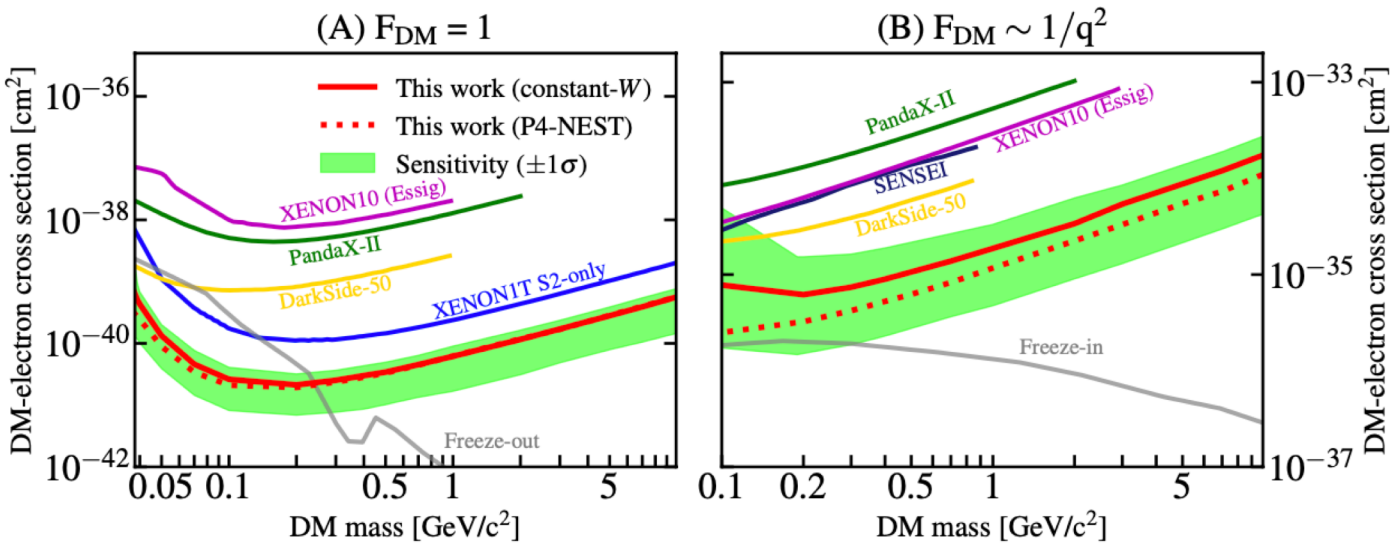
- Greatly lower the threshold for Noble Liquid TPCs;
- Combine with large exposures, can reach leading sensitivities for ~100 MeV LDM (WIMP-e scattering);

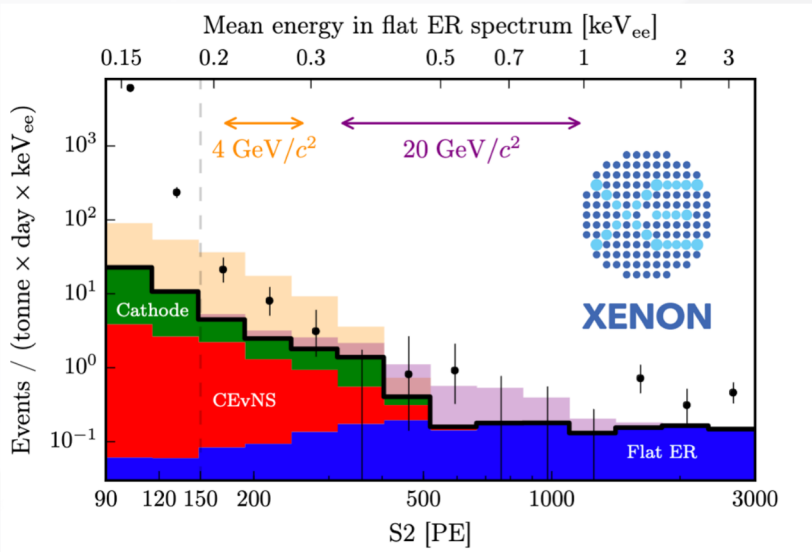


XENON1T, PRL 123, 251801 (2019)

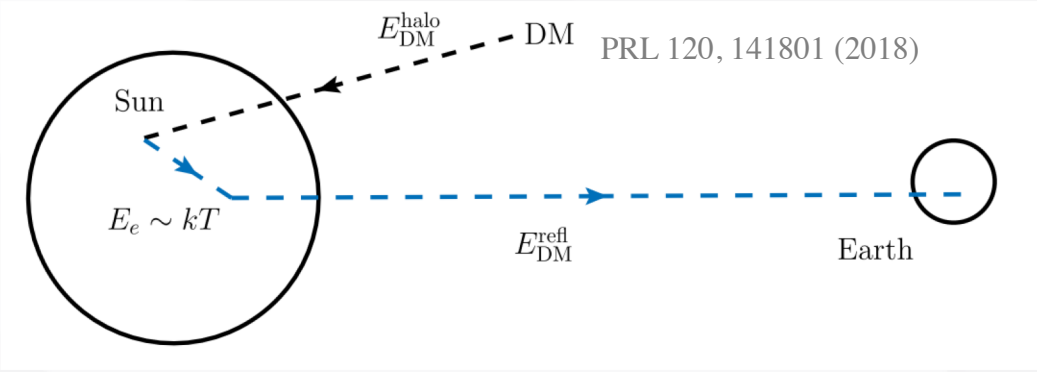


PandaX-4T, PRL 130, 261001 (2023)

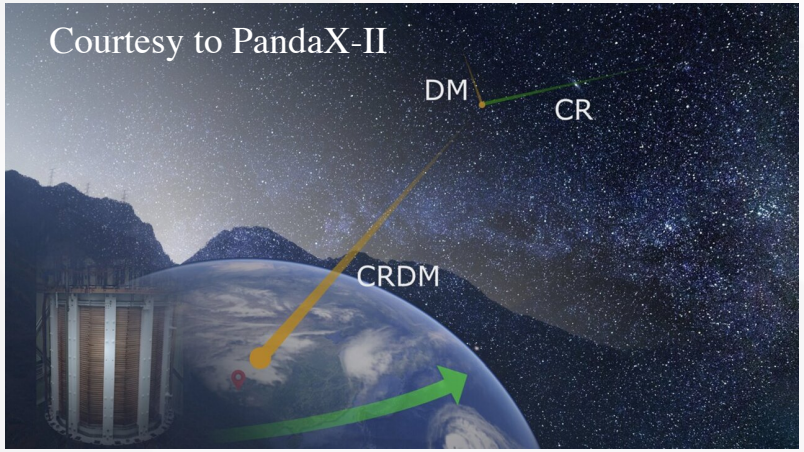


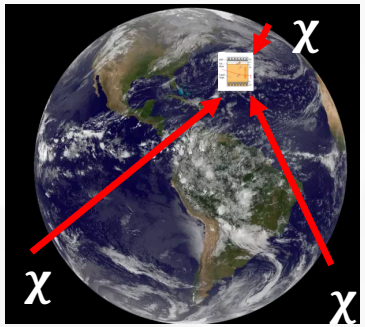


Solar reflected and cosmic ray boosted DMs

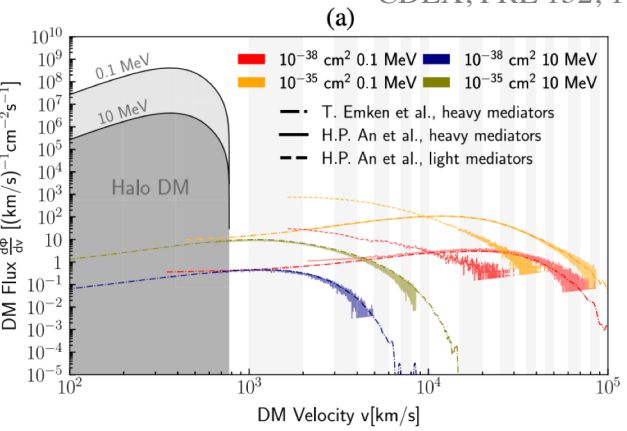


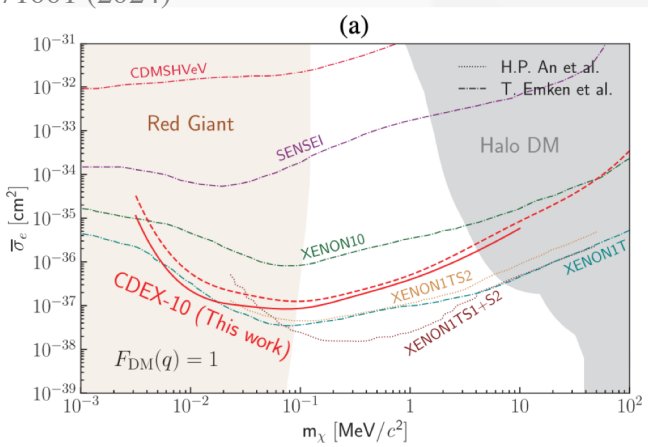
PRL 120, 141801 (2018)



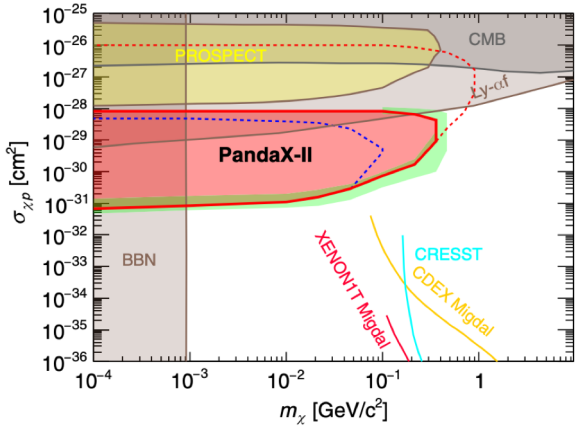


CDEX, PRL 132, 171001 (2024)

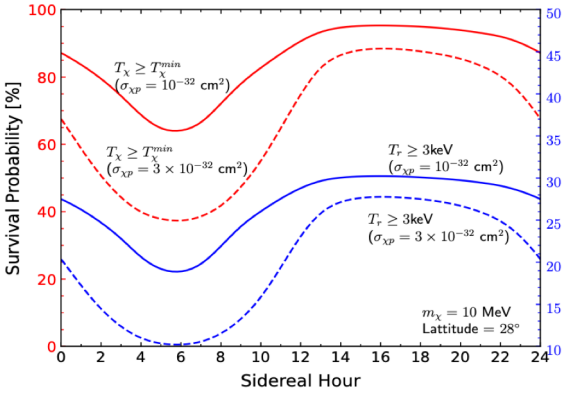




PandaX-II, PRL 128, 171801 (2022)



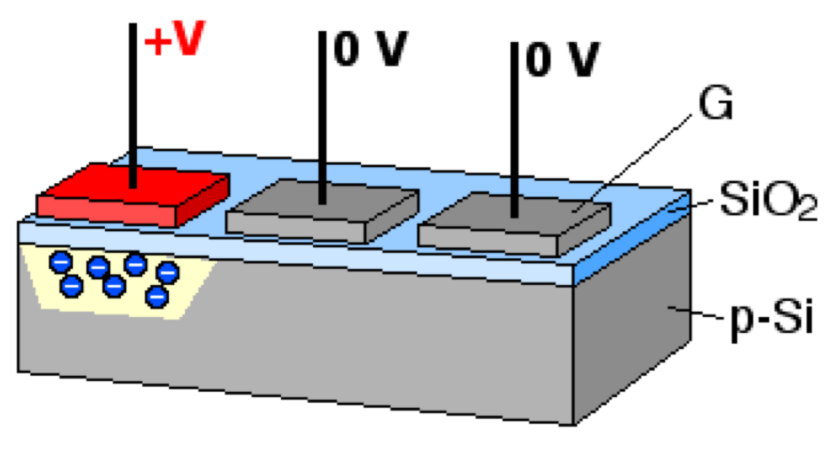
Ge, Shao-Feng, et al. PRL 126, 091804 (2021)

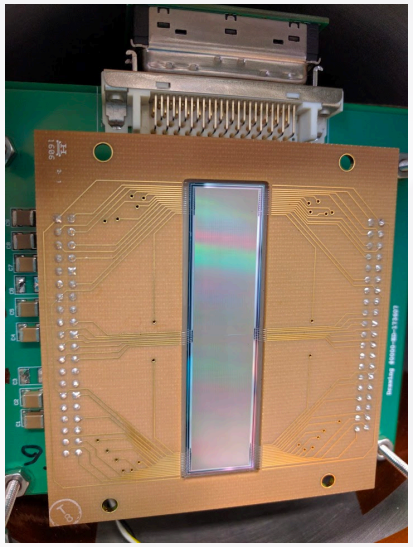


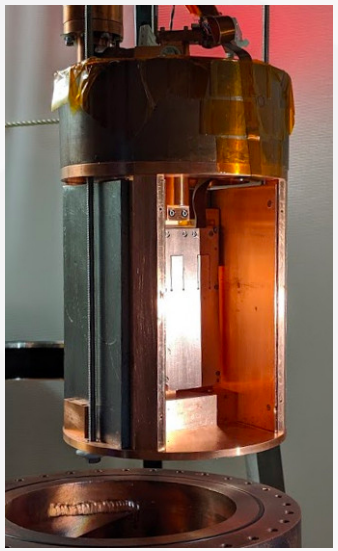
Diurnal Effect

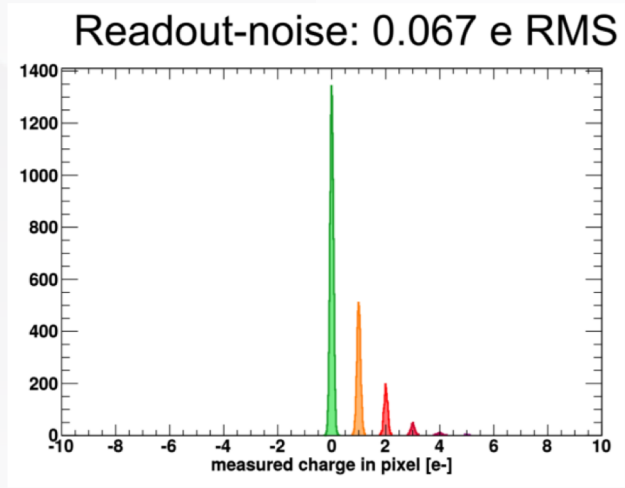
Accelerated DM by solar electrons or “heated” cosmic rays in center of MW surpass thermal speed!

CCD detectors



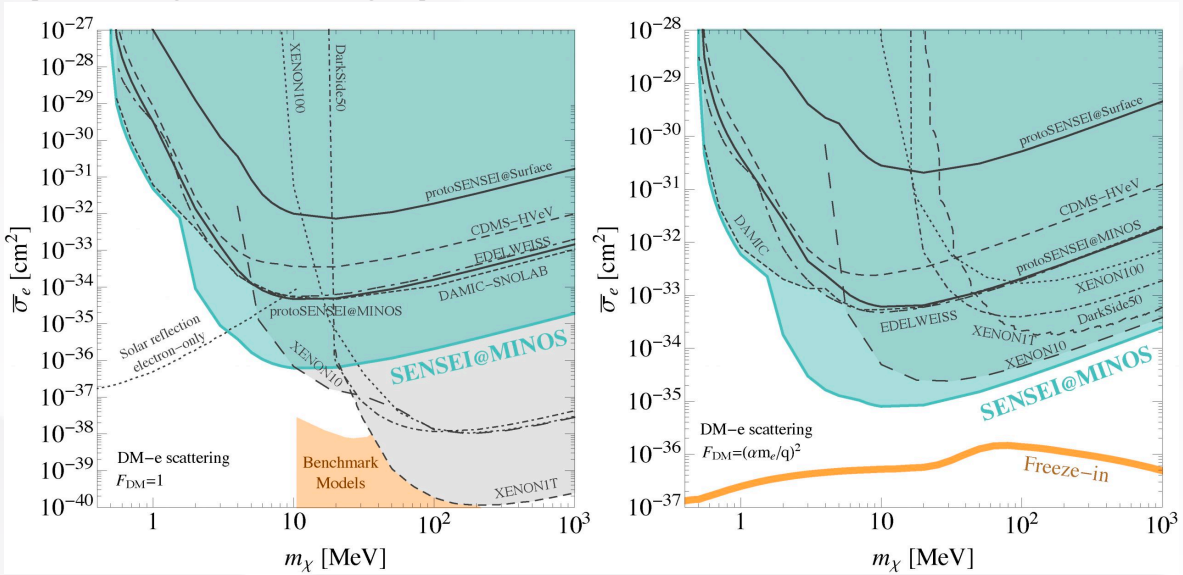






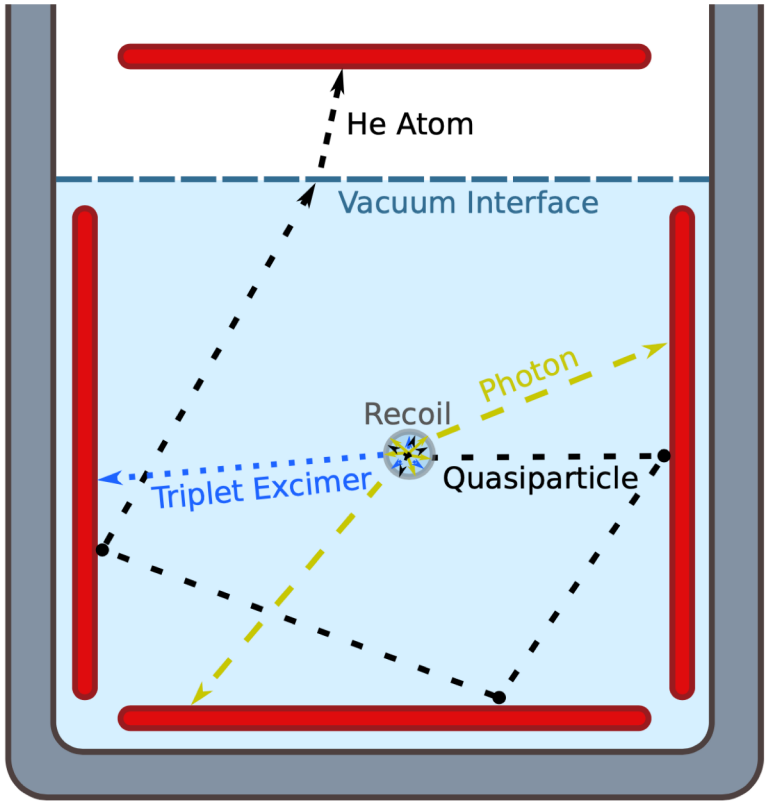
https://news.fnal.gov/2020/06/sensei-gets-quiet/

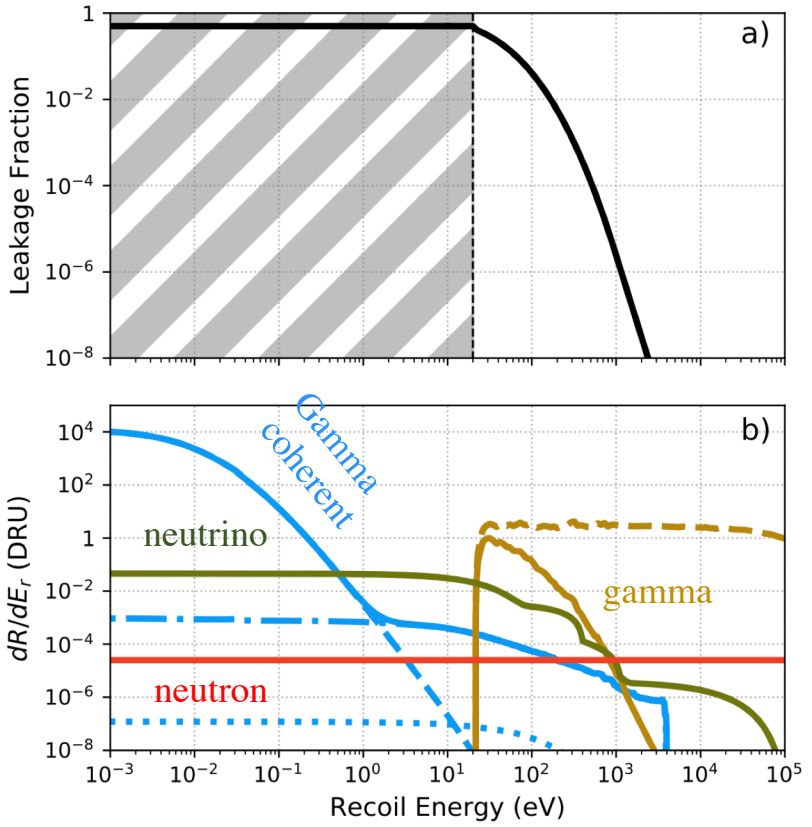
- 0.01 g Si Skipper CCD;
- Reduce noise through non-destructively measure charge multiple times;
- Single electron sensitivity with resolution to 6.7%.

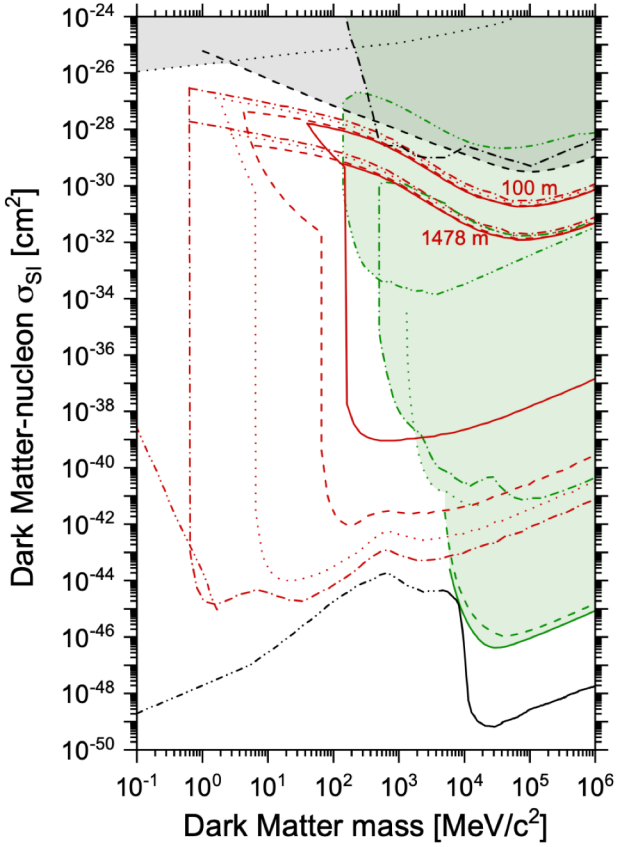


Superfluid Helium Detector

Phys. Rev. D **100**, 092007 (2019)

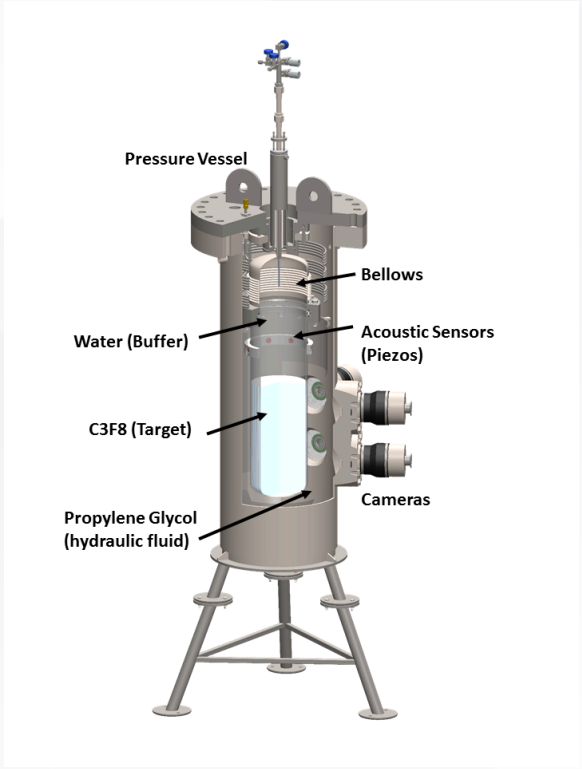


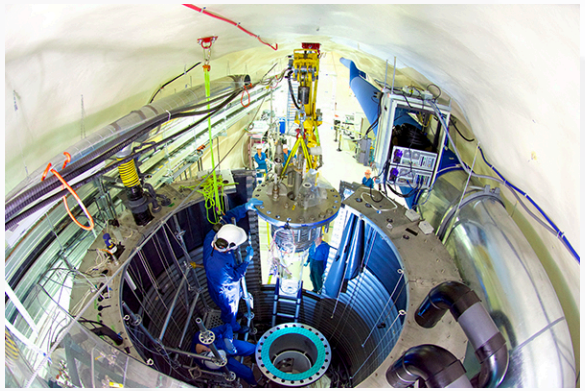




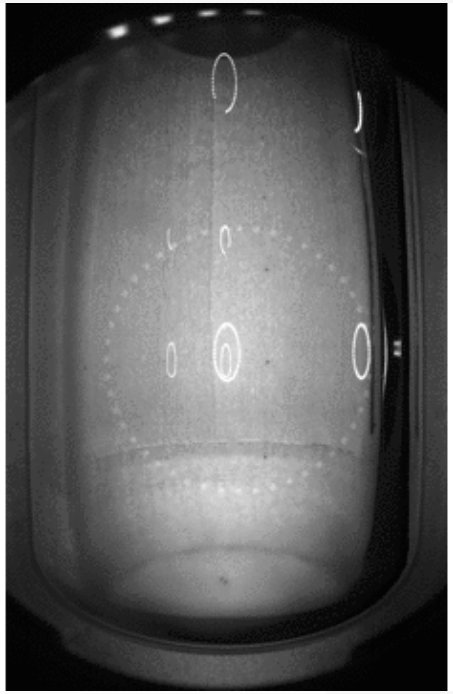
- Very low W value for roton and phonon;
- Quasiparticle propagate ballistically, including directionality;
- Background dominated by gamma and neutrino coherent scattering;

Bubble Chamber: PICO

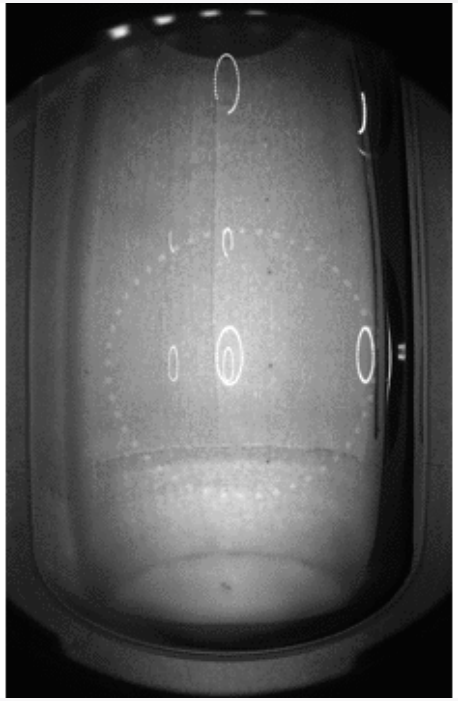




Single Scatter

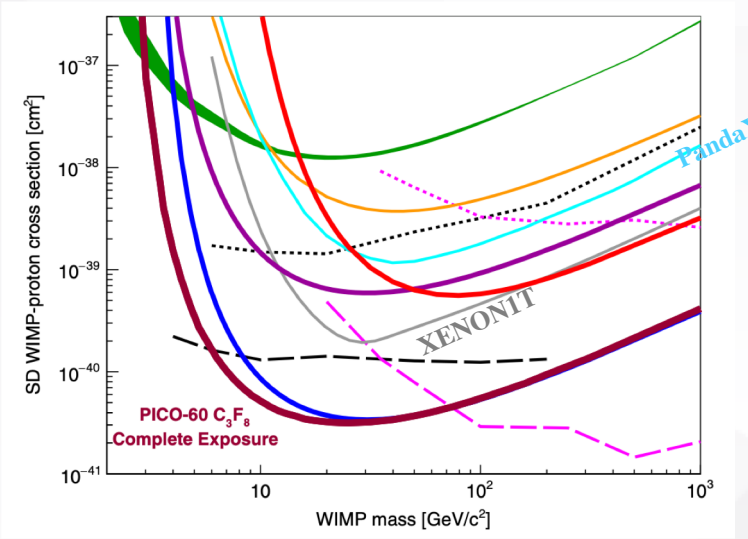


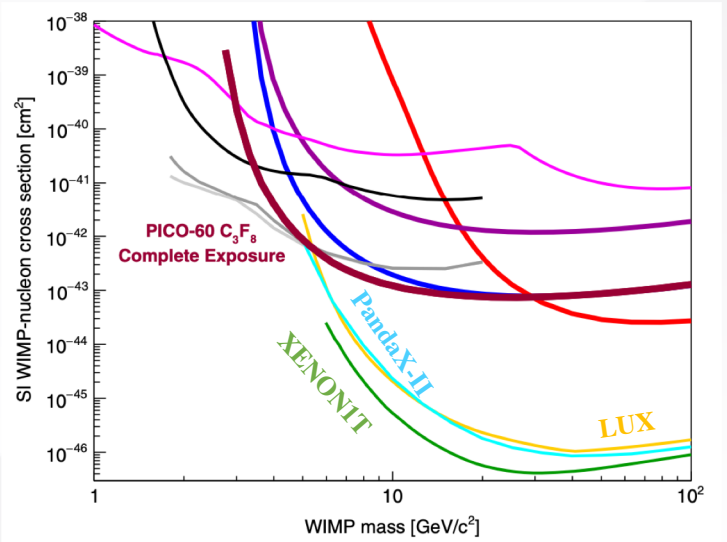
Multi-Scatter



https://www.picoexperiment.com/pico-60/

- Largest bubble chamber with superheated C_3F_8;
- No bkg from gamma, e and muons;
- Discrimination against neutron through single and multiple scatter images;

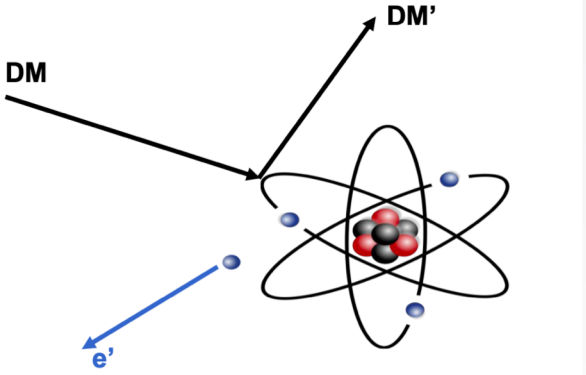


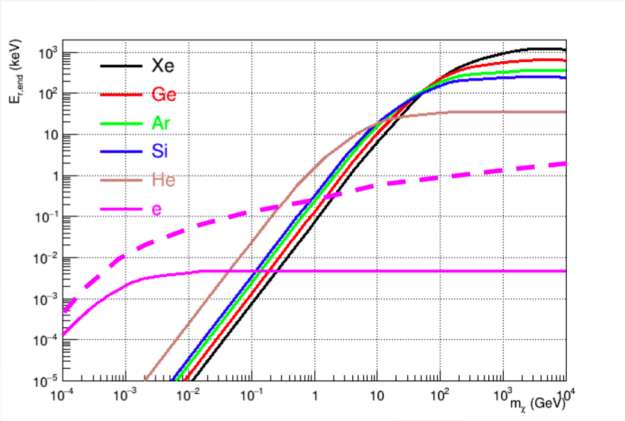


DM-e scattering and Migdal effect

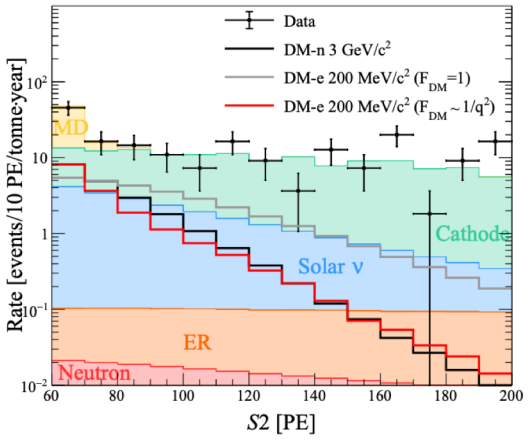
DM-electron scattering

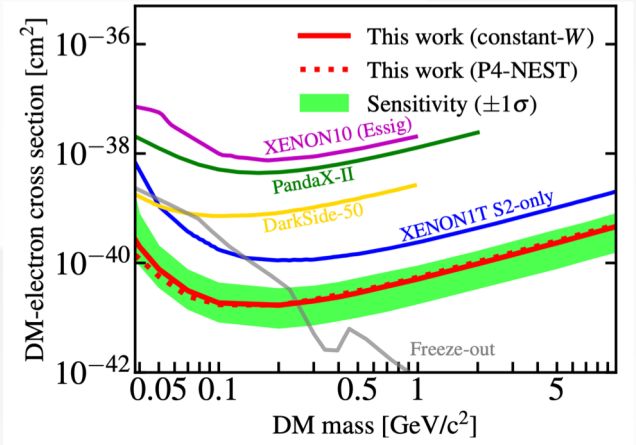
Essig, Mardon, Volansky, PRD 85, 076007 (2012)





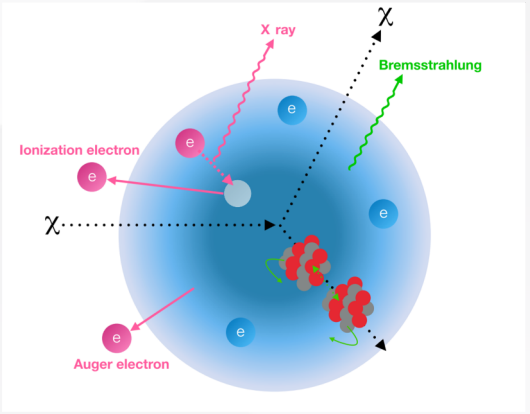
PandaX collaboration, arXiv: 2212.10067 (2022)

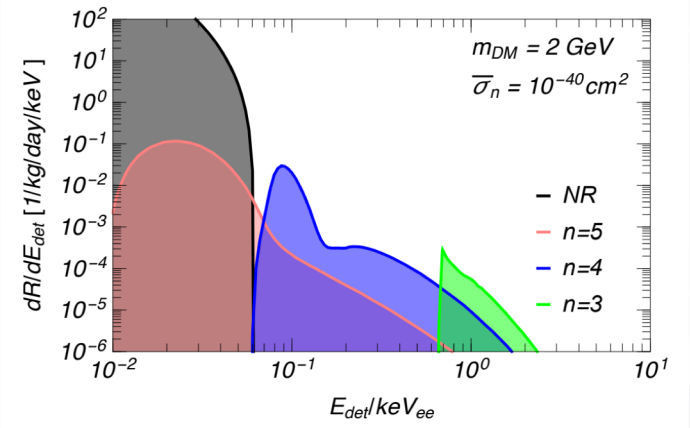




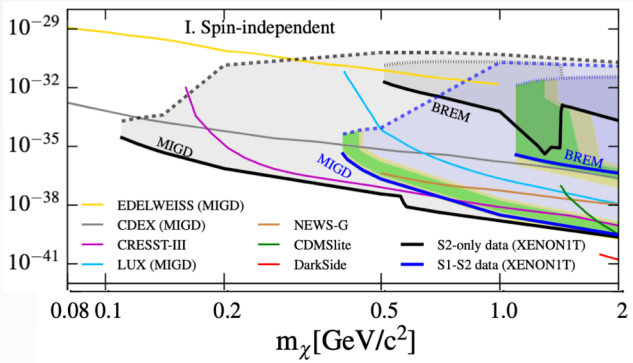
Migdal Effect

M. Ibe et al., Journal of High Energy Physics 2018.3 (2018)
XENON collaboration, PRL 123, 241803 (2019)

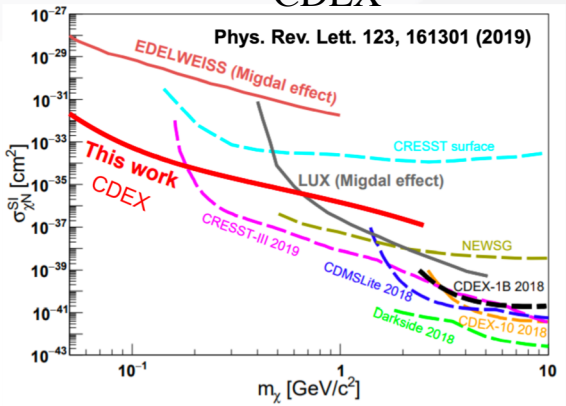




XENON1T

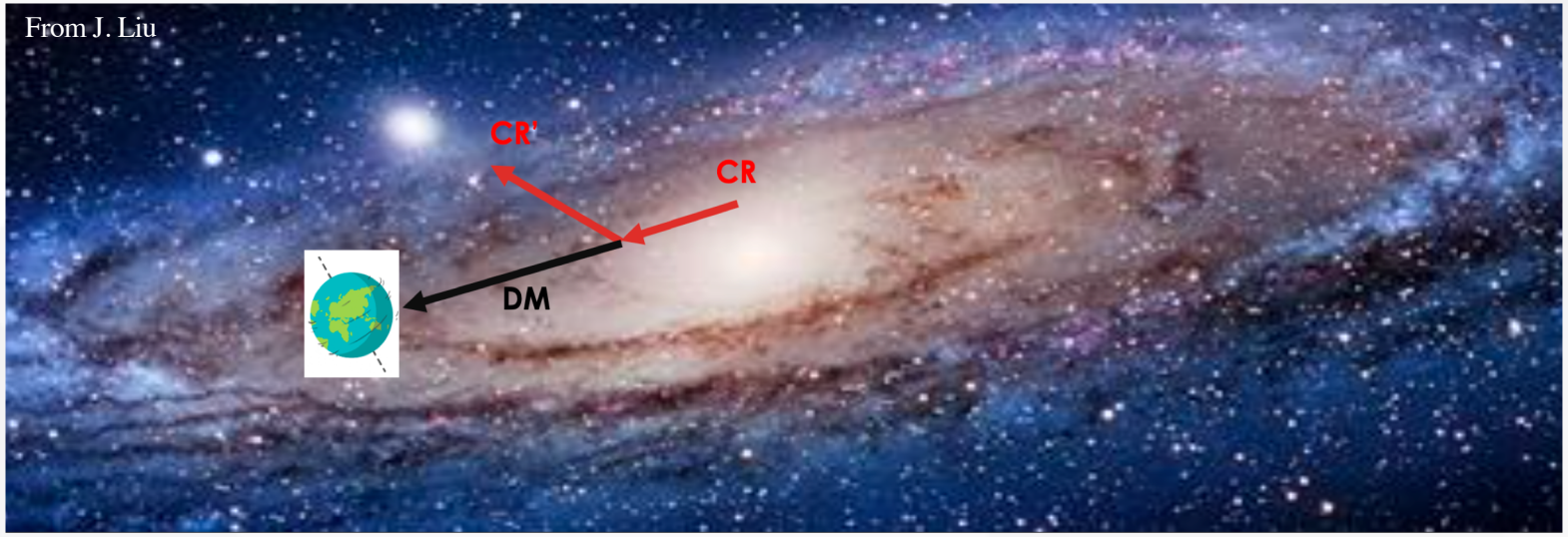


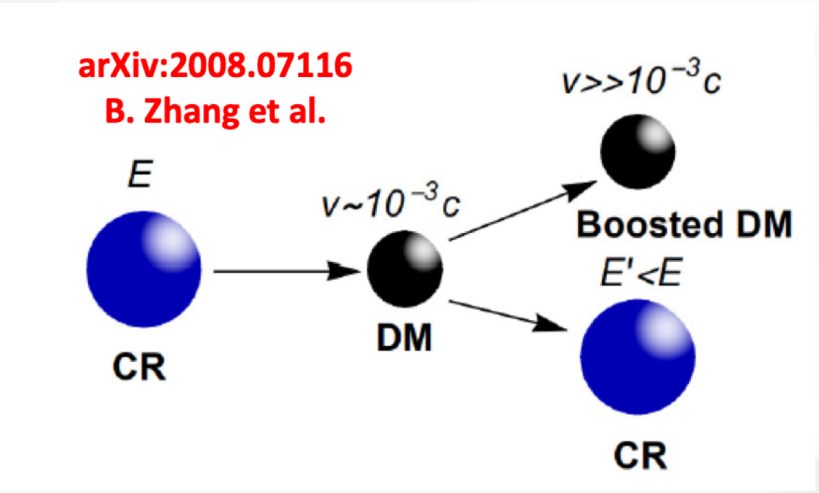
CDEX

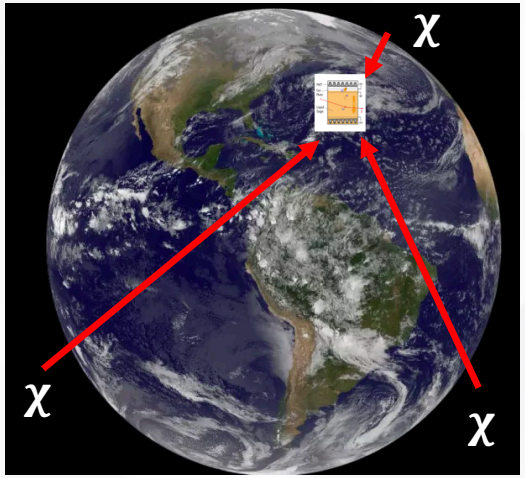


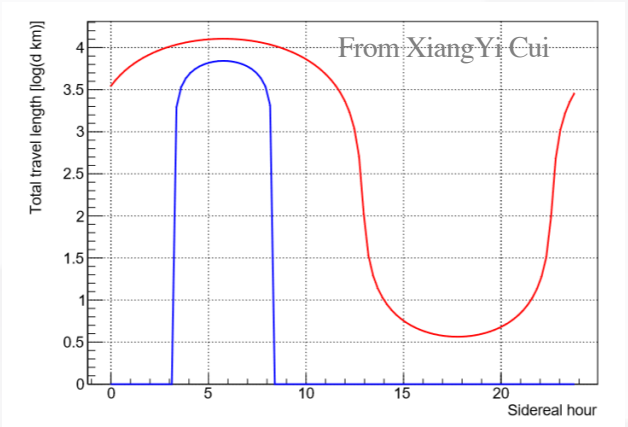
Capable of Probing light dark matter due to high momentum transfer

Diurnal Modulation

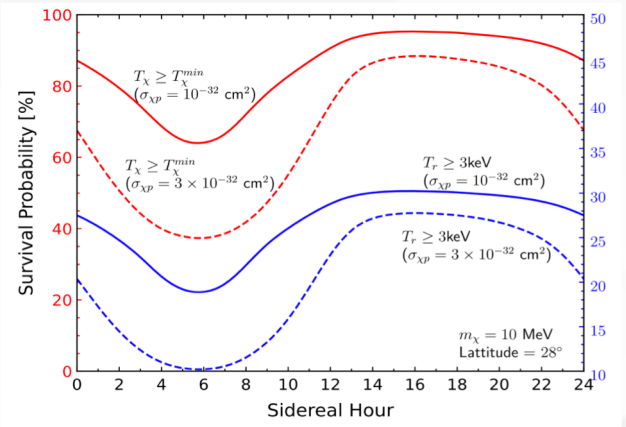




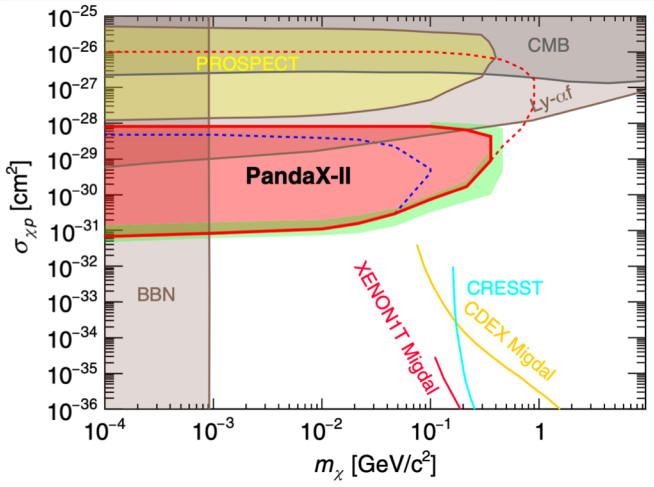




PHYSICAL REVIEW LETTERS 126, 091804 (2021)

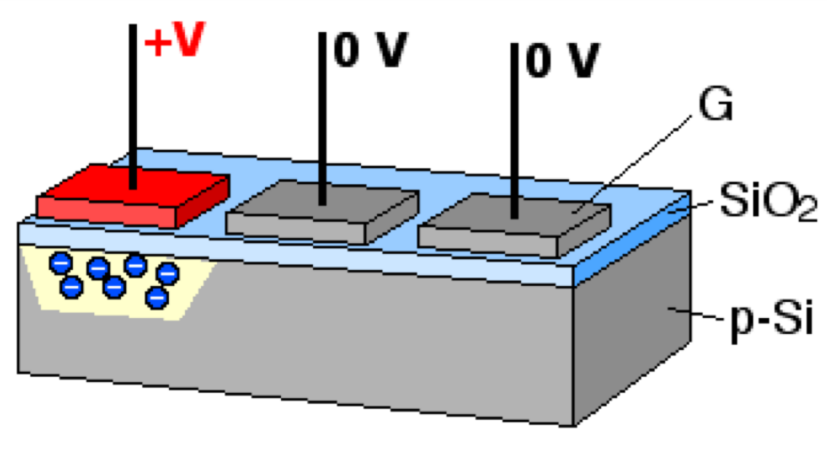


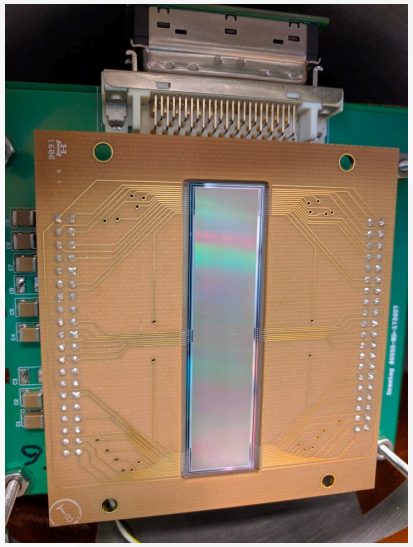
PHYSICAL REVIEW LETTERS 128, 171801 (2022

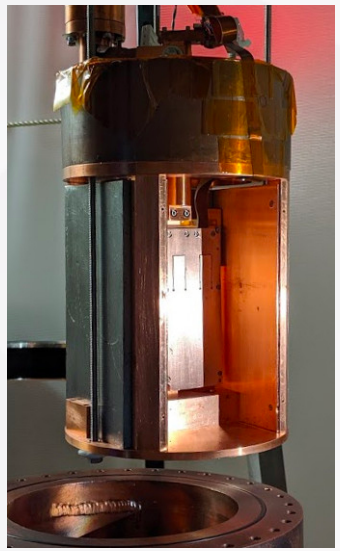


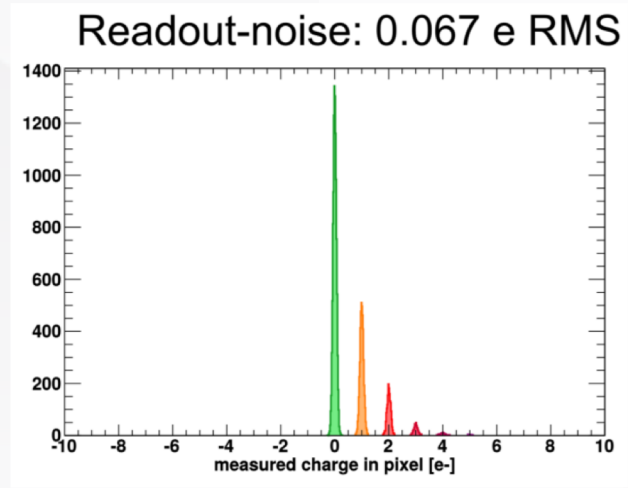
Expected diurnal modulation due to traveling length's day-night difference for transpassing boosted DM.

Skipper CCD technique: SENSEI









https://news.fnal.gov/2020/06/sensei-gets-quiet/

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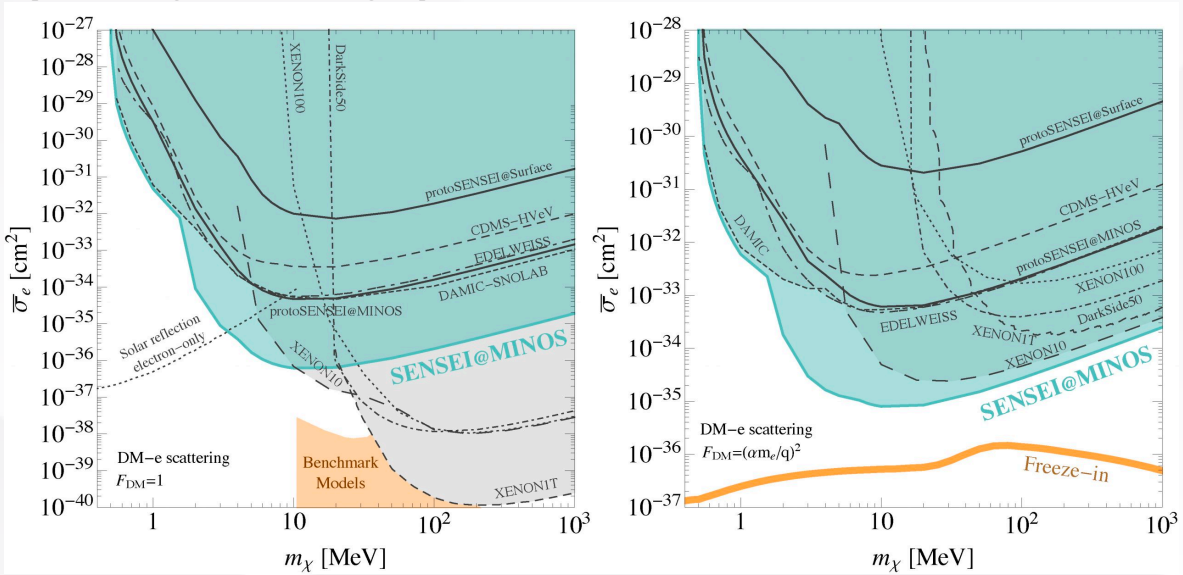
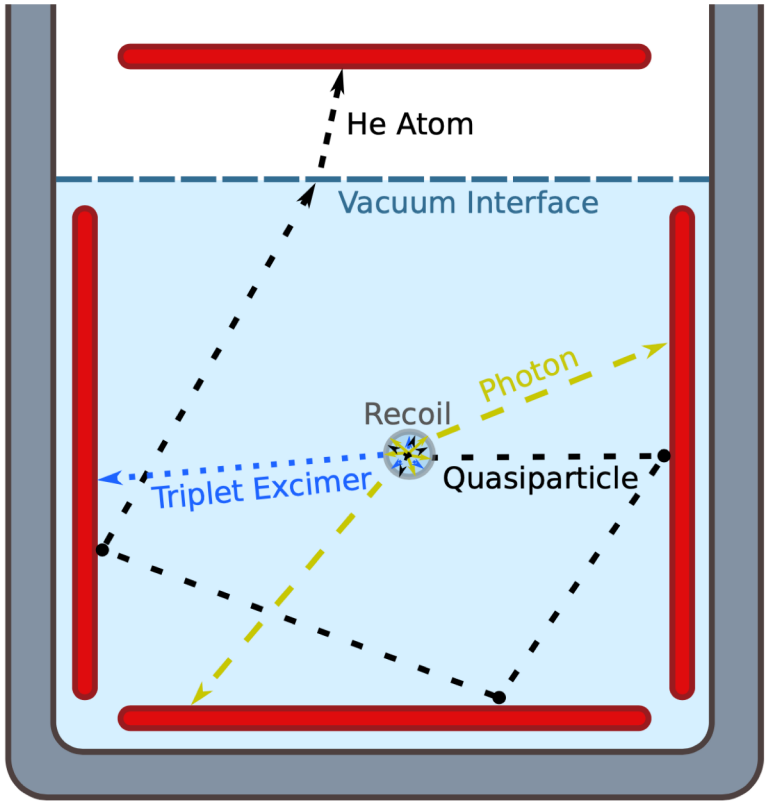
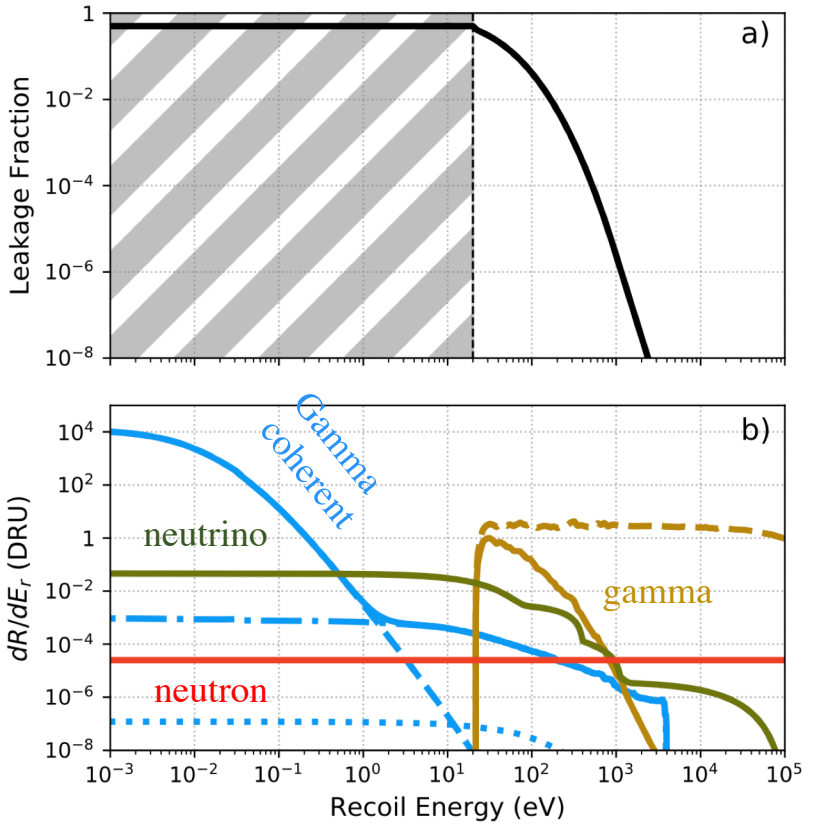
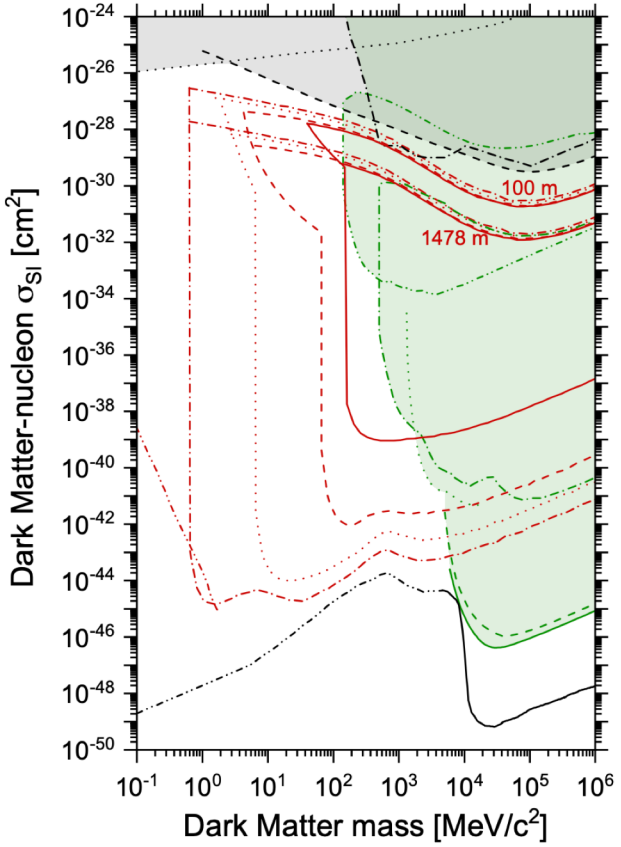


Helium Detector

Phys. Rev. D **100**, 092007 (2019)



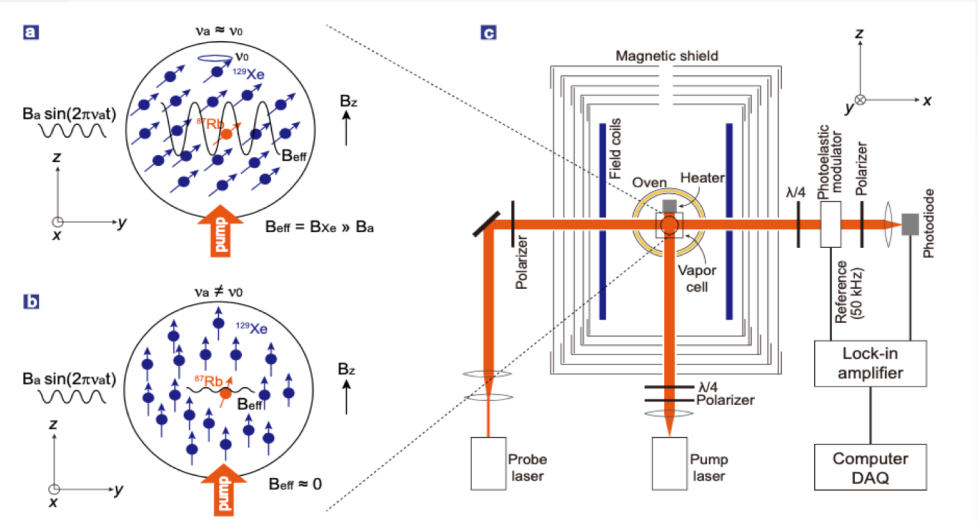




- Very low W value for roton and phonon;
- Quasiparticle propagate ballistically, including directionality;
- Background dominated by gamma and neutrino coherent scattering;

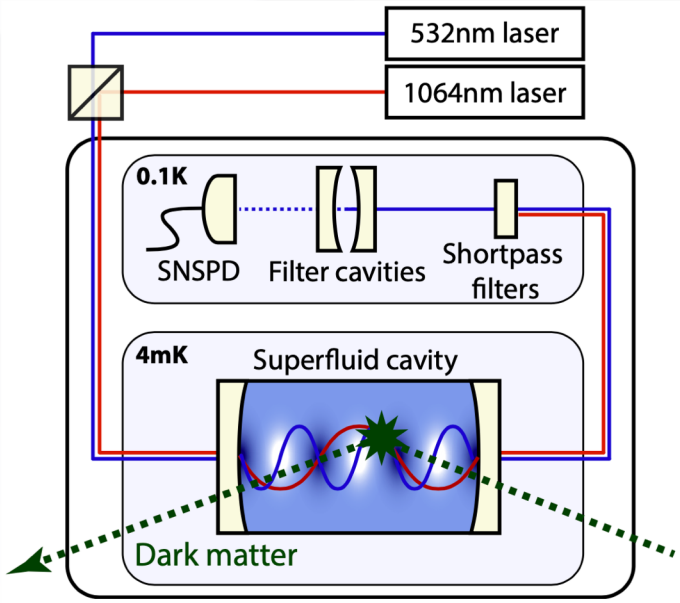
Quantum sensors

Magnetometer



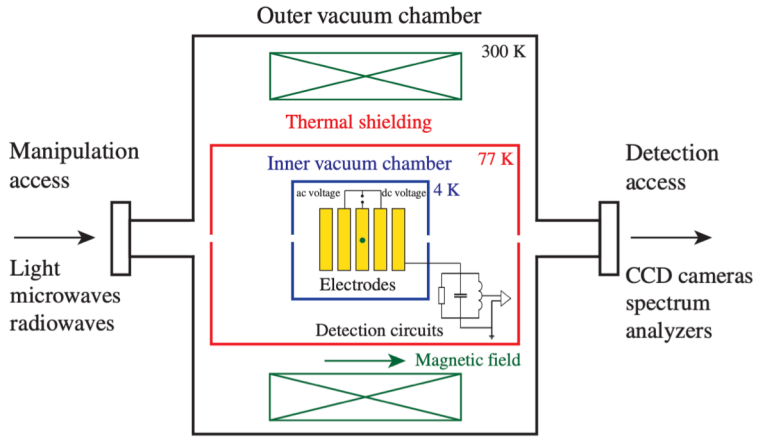
Nature Phys. 17, 1402–1407 (2021).

Optimechanical



arXiv: 2306.09726

Ion Trap



PRX QUANTUM **3,** 010330 (2022)