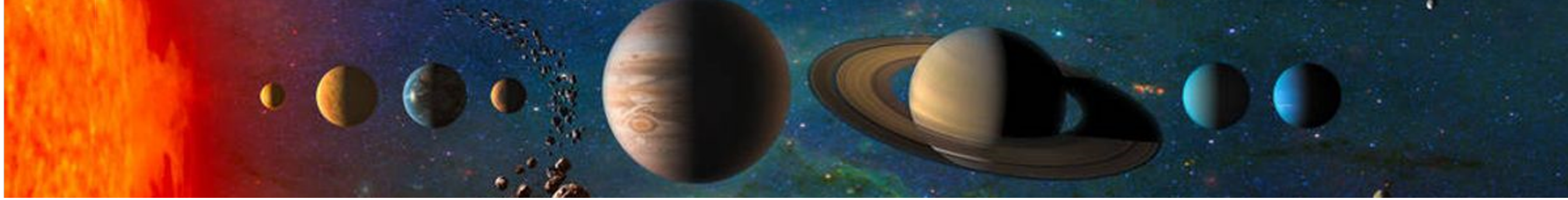

# Dark Matter Direct Detection Experiments


**Speaker：Qing Lin**

University of Science and Technology of China


WIN2023 (Zhuhai) @ 2023.07.07

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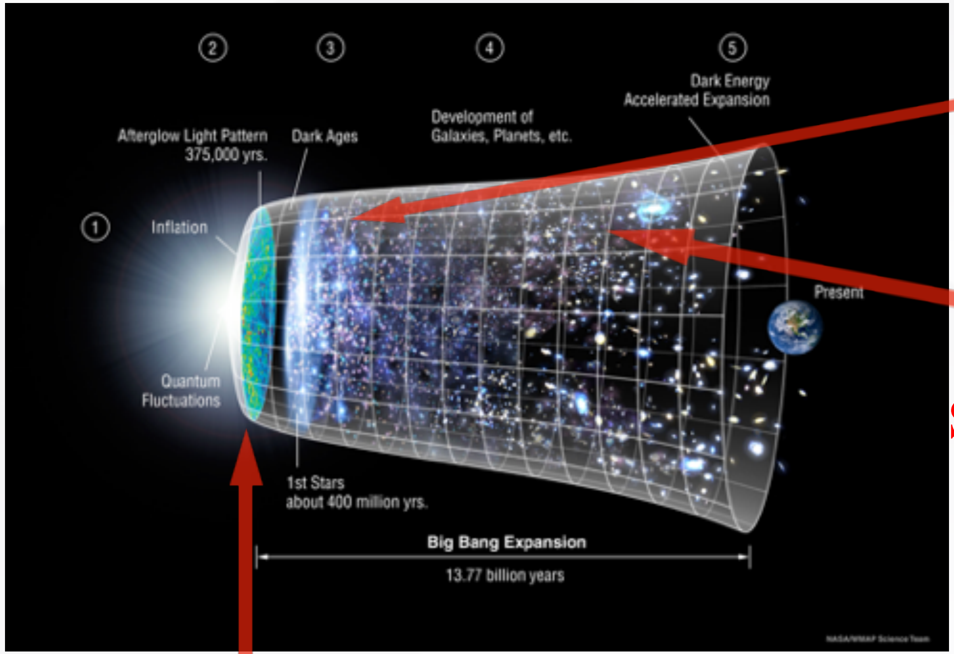
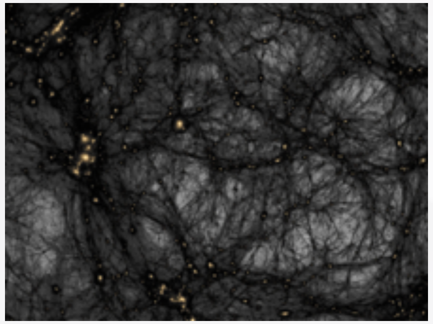
**Disclaimer: Apology for omittance!**

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

# Dark Matter and its Gravitational Evidence




Large Structure



Courtesy of NASA

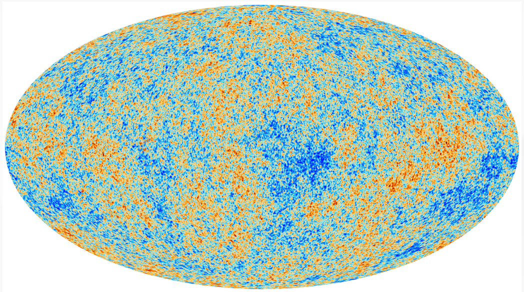
Credit: https://youtu.be/sI23cwbbNqs

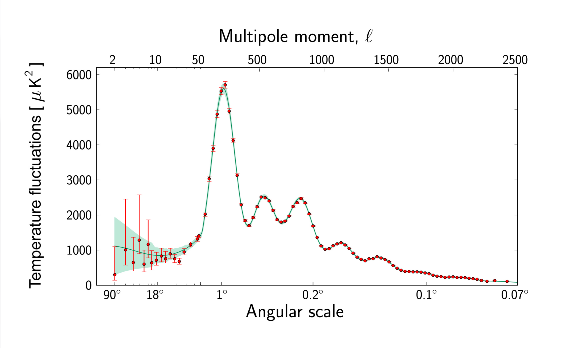
Small Structure

Bullet cluster collision

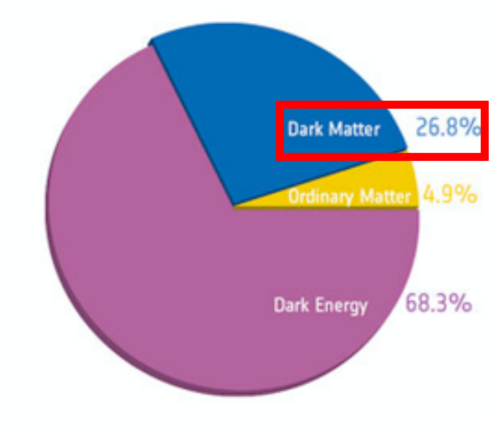

Galaxy rotation curve

Primordial Universe



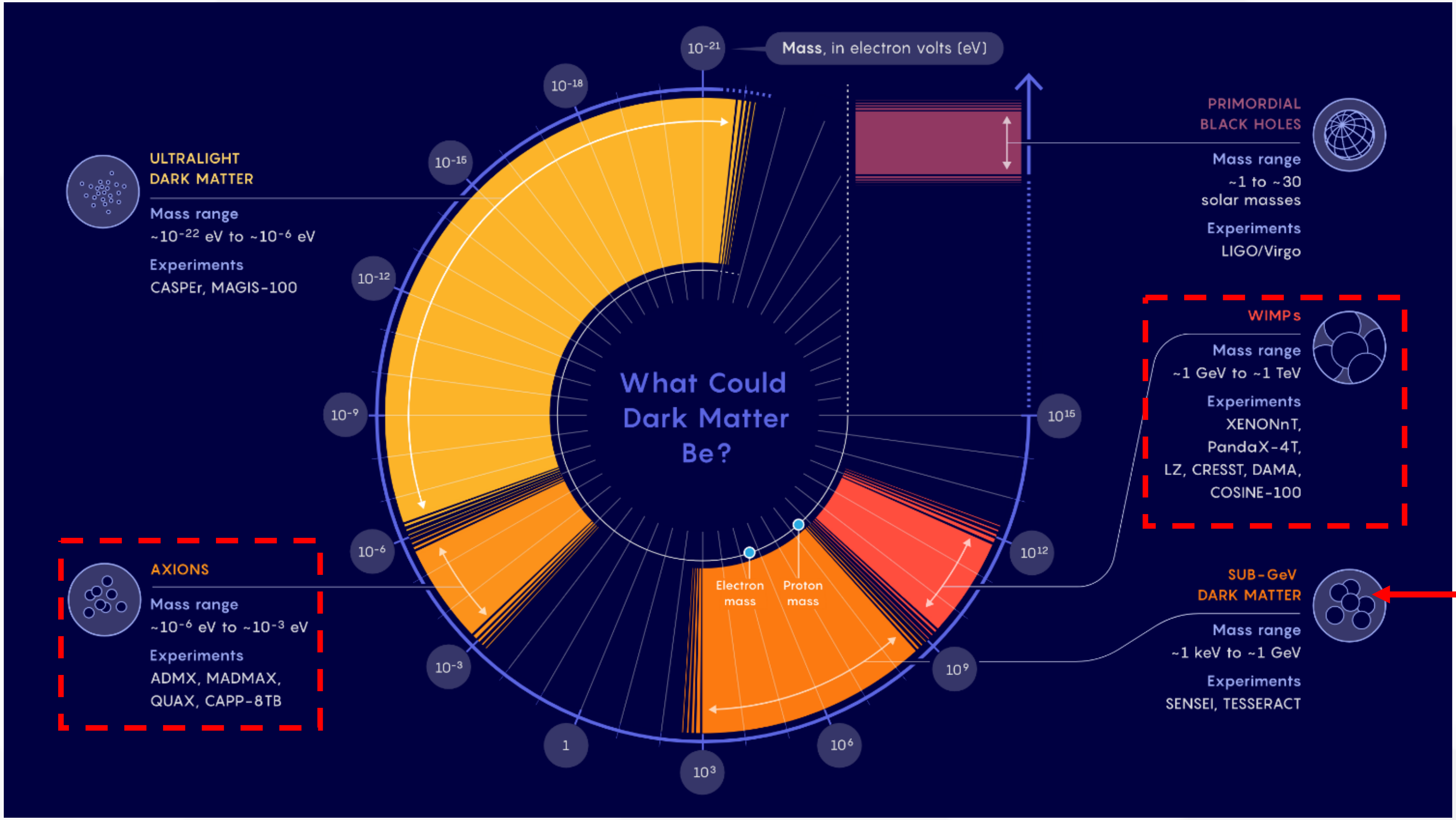



Courtesy of PLANCK

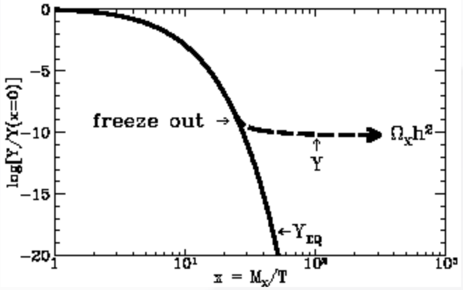



Gravitational evidences suggest dark matter is the dominant form of matter in Universe!

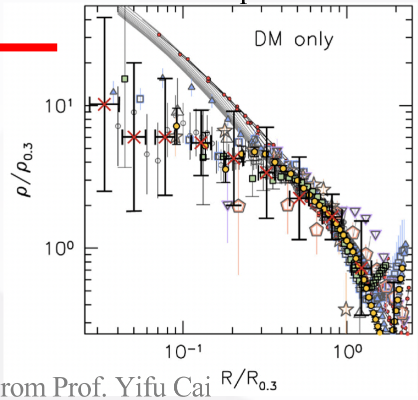
# Many Possibilities




Samuel Velasco/Quanta Magazine




Core-cusp Problem

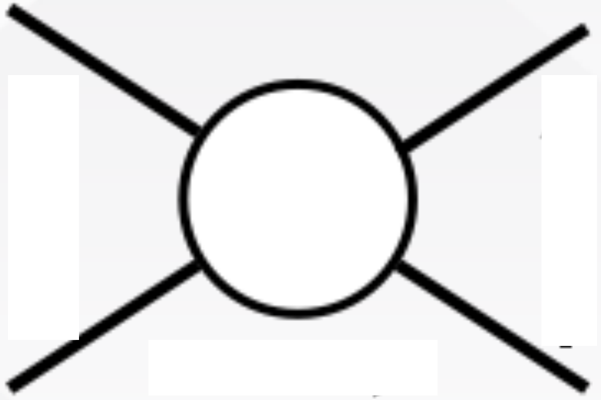



From Prof. Yifu Cai

# Detection Scenarios

SM particle SM particle’

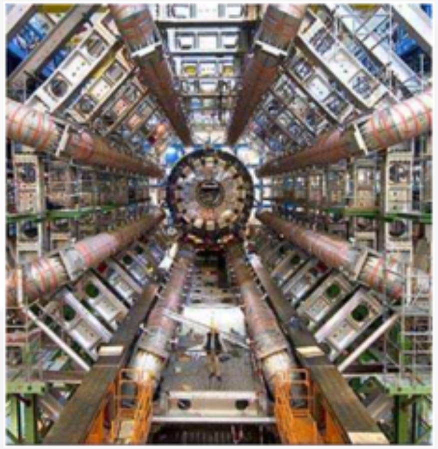
Collider Search



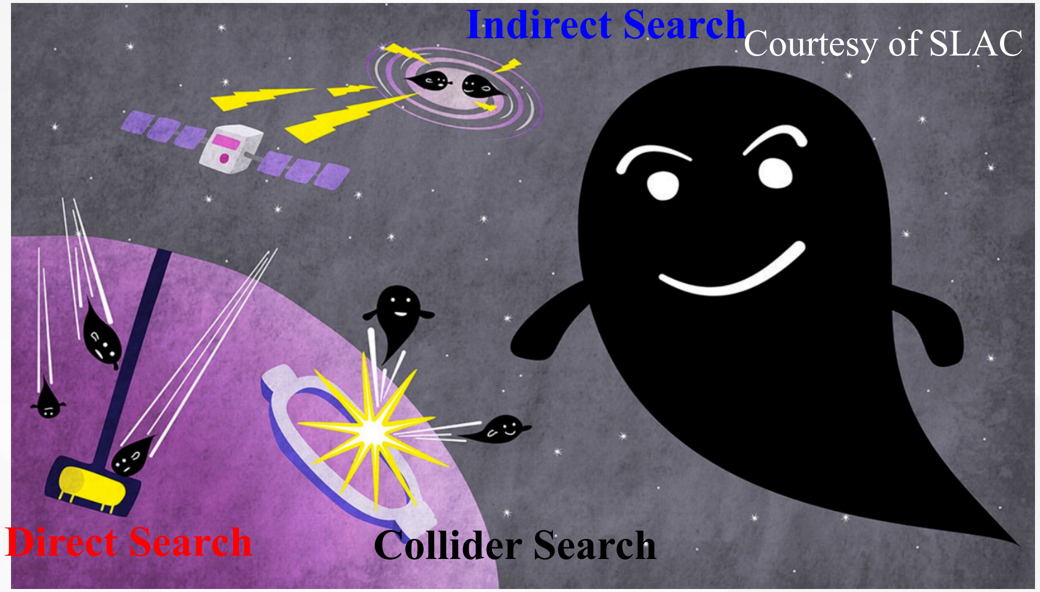
Indirect Search

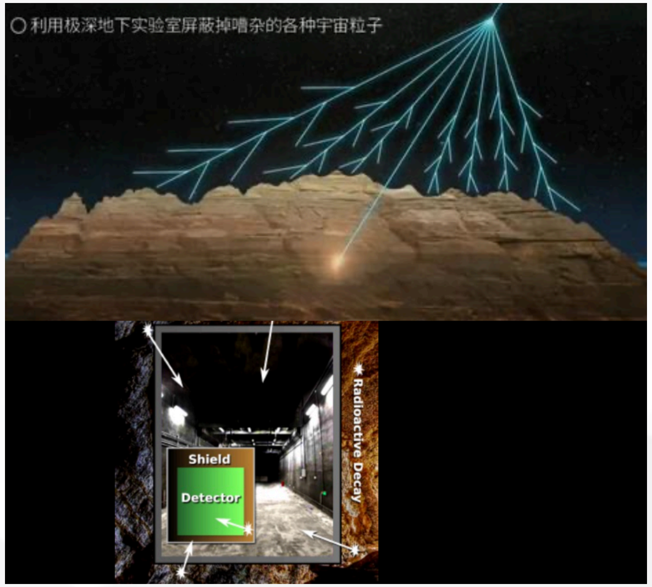
DM particle **Direct Search** DM particle’

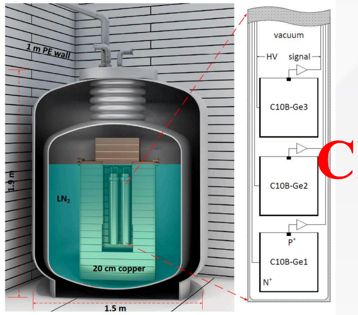
LHC



DAMPE

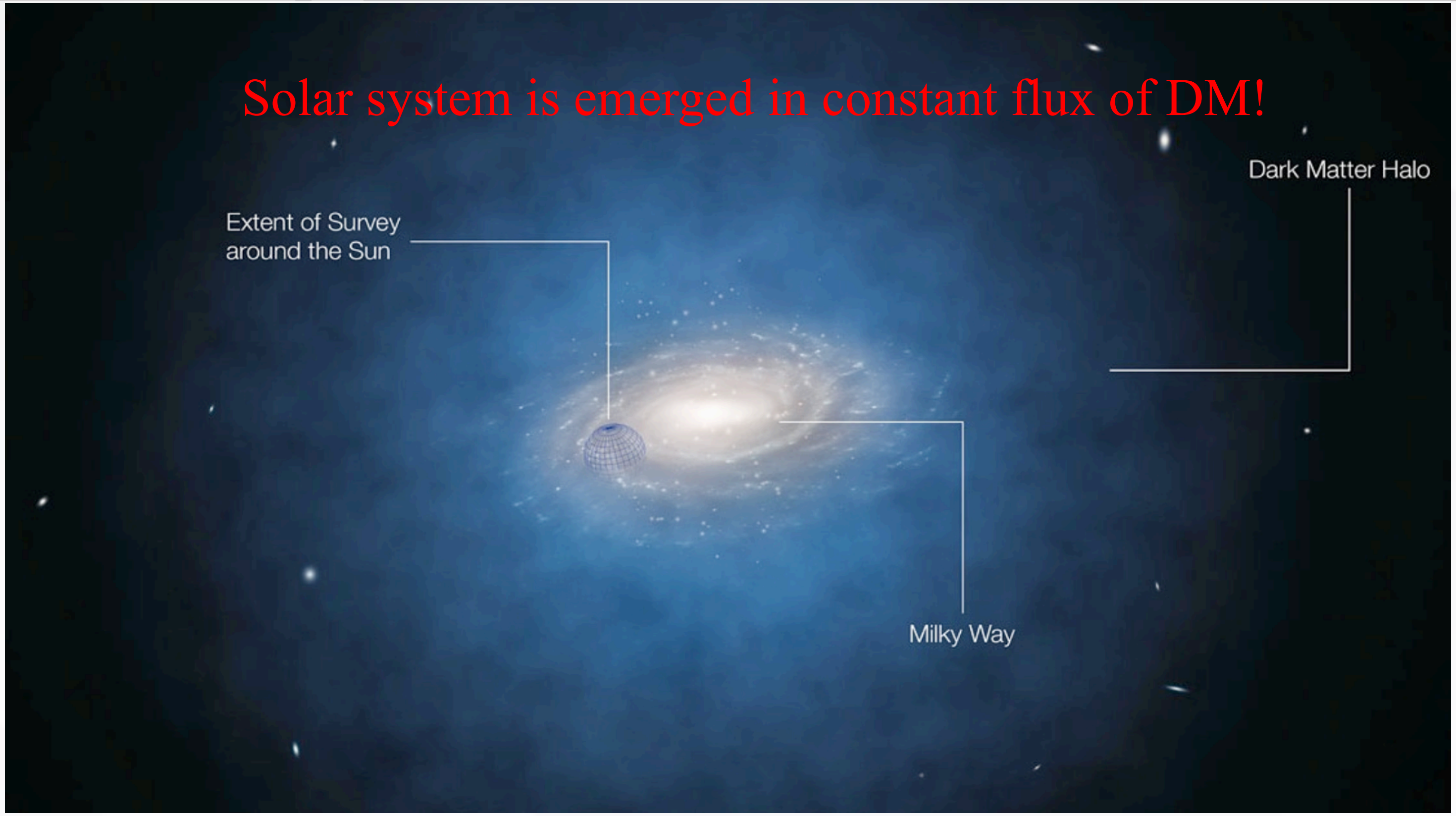




CDEX

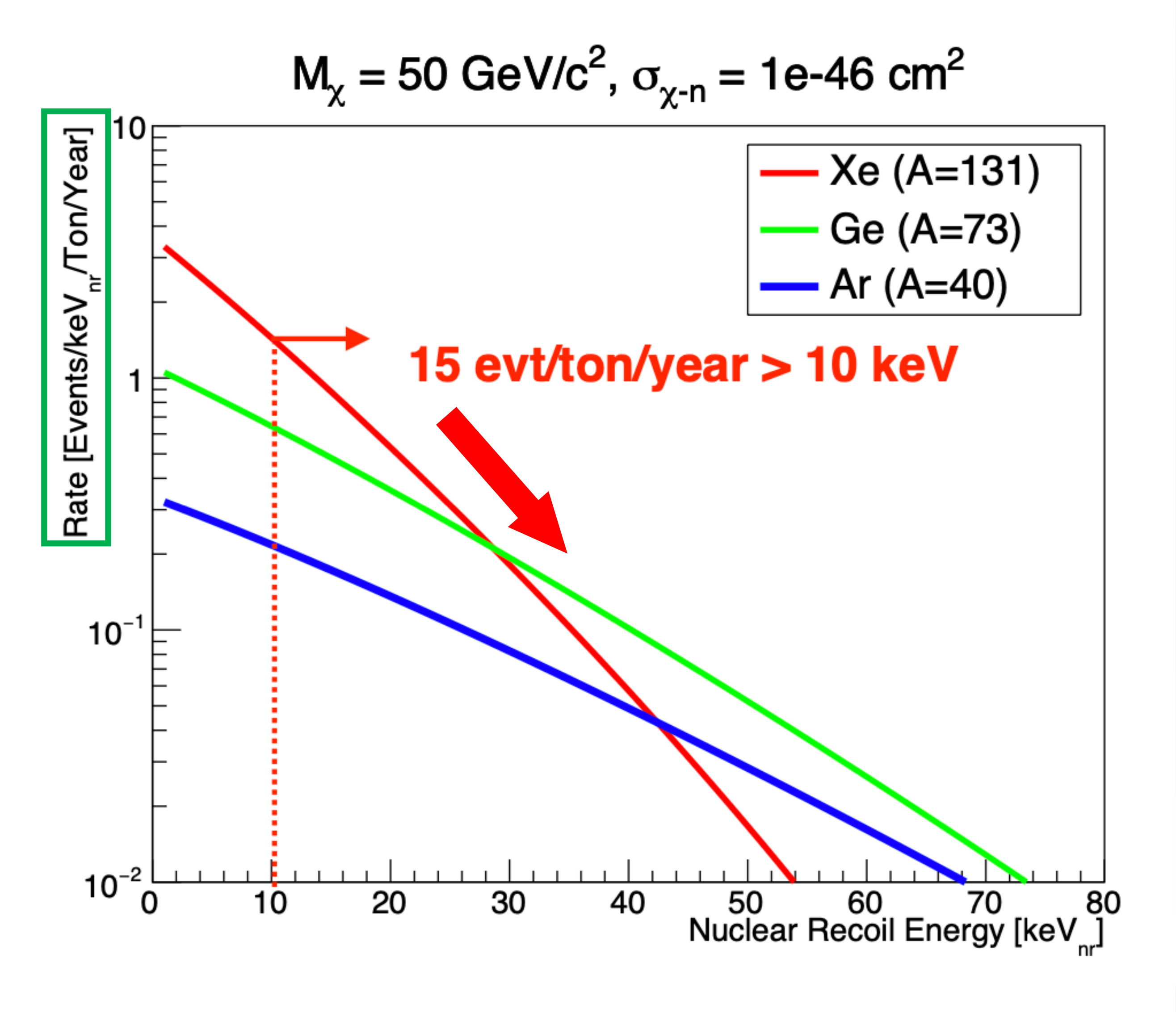
PandaX-4T

# Current view of local DM




- **100000000** (1e8) DM particle crossing single human body (~1e29 atoms) **every second**!
- **Every year DM interacts with human body less than 1 (current experimental results).**
- **Every day, there are 100000000 (1e8) energy depositions in human body caused by cosmic rays and background gamma radiation.**

# Detector Requirements




- **Low threshold**
- **Low background**
- **Large volume**

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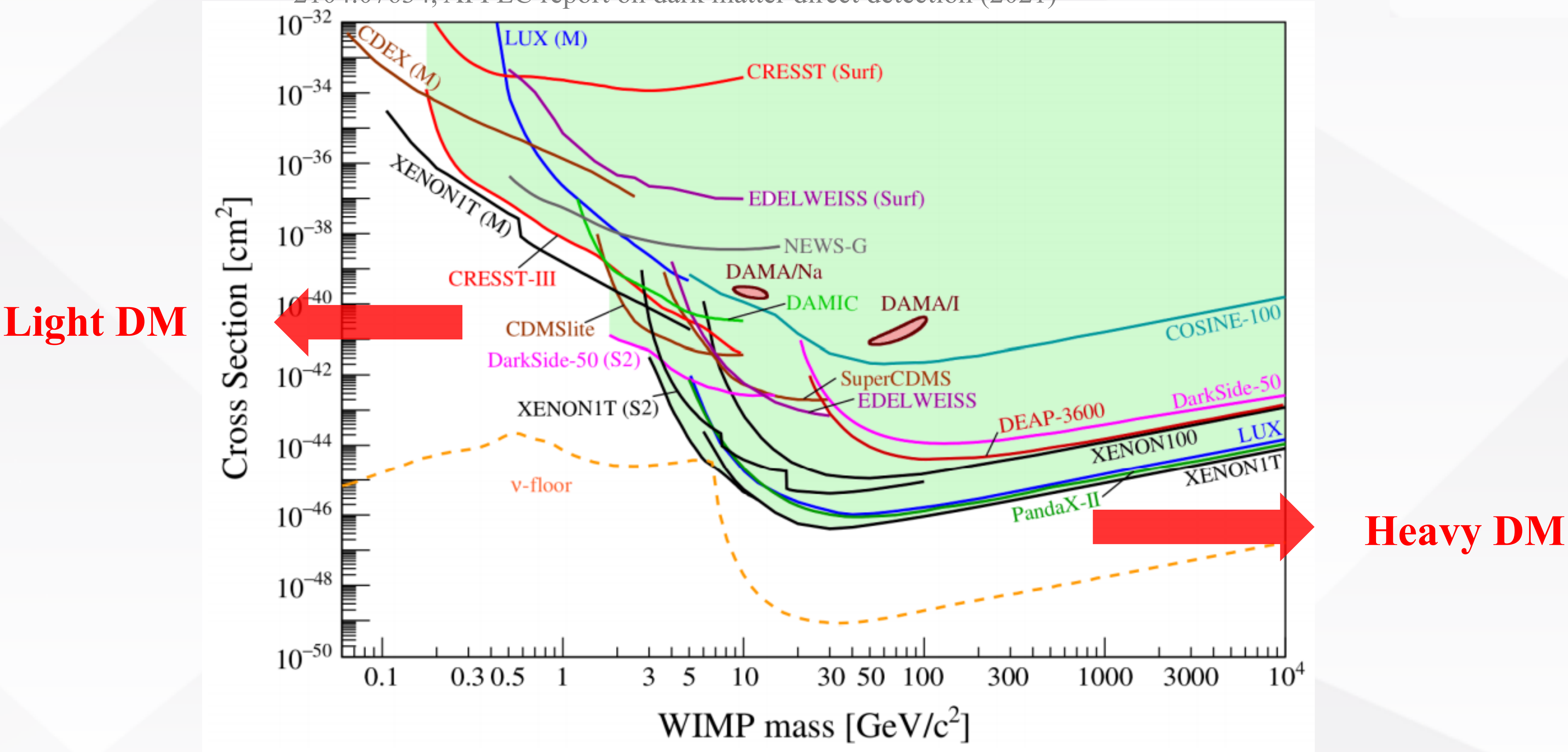
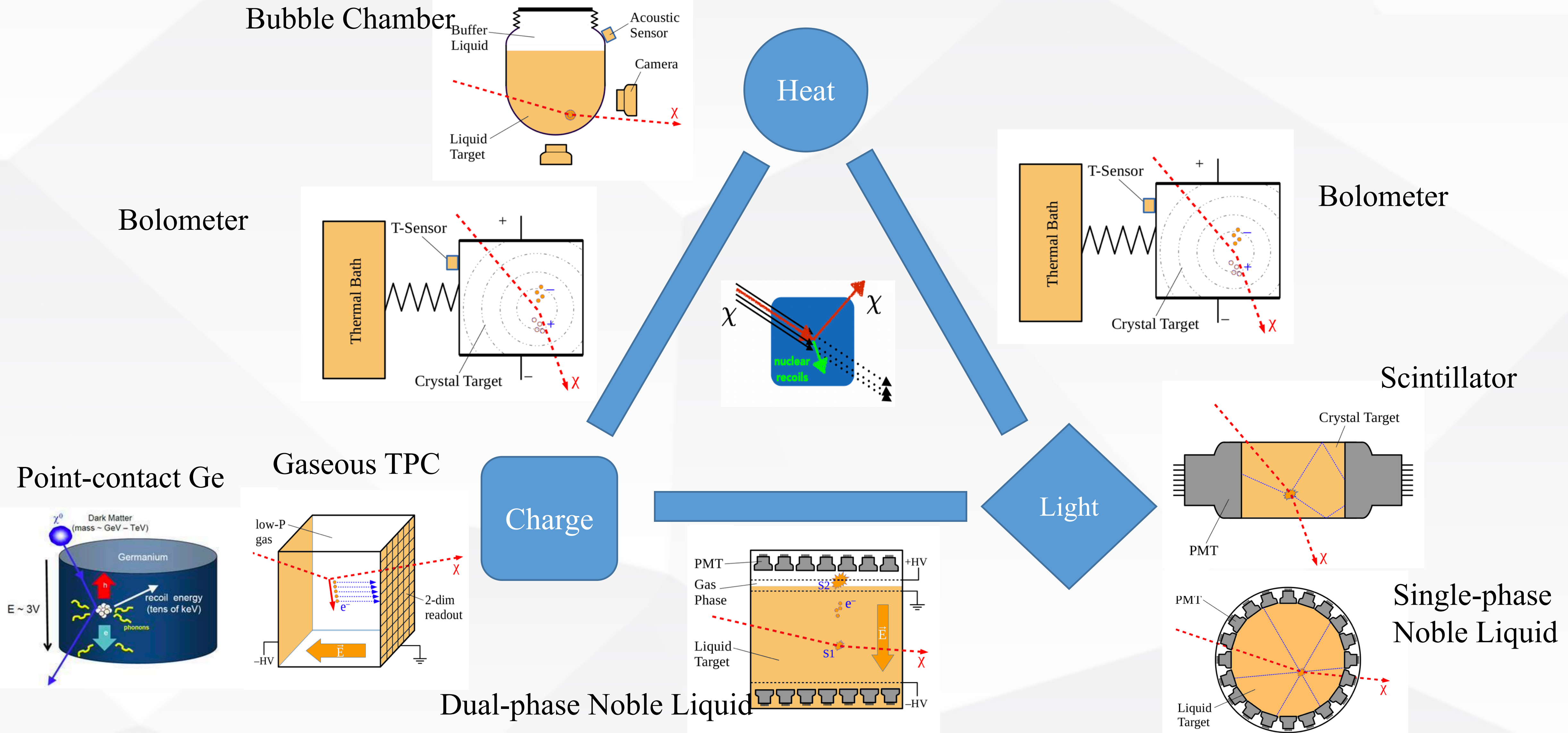
# Current Status: Hide and Seek

2104.07634, APPEC report on dark matter direct detection (2021)

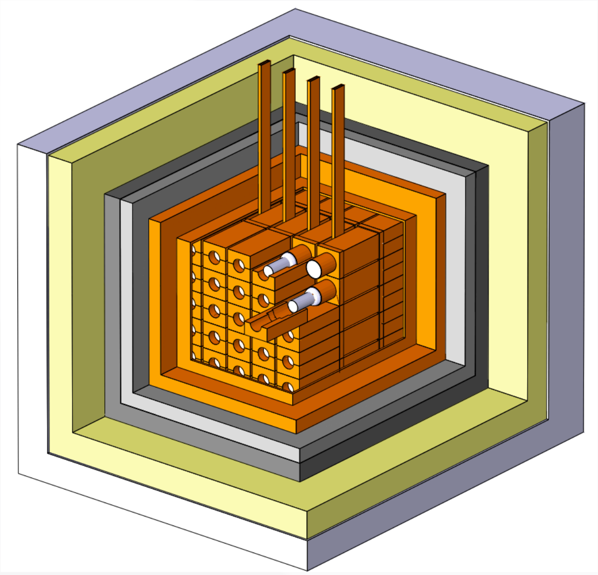


# Detection Techniques

Coutesy of APPEC report

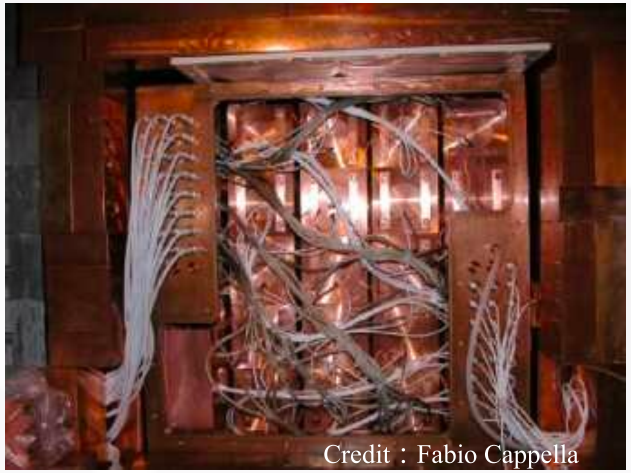


# DAMA/LIBRA (Scintillator)

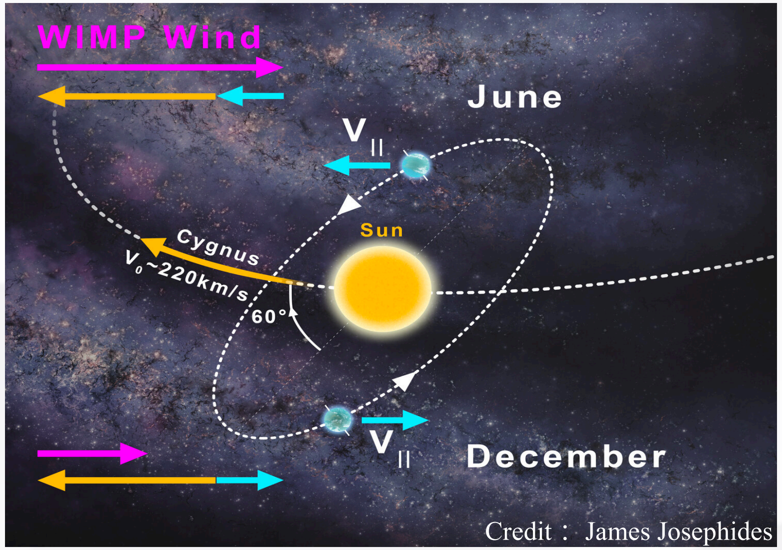


- ➢ NaI crystal coupled with PMT at both ends.
- ➢ Crystal array embedded in copper cage, then shielded by PE and lead.
- ➢ No PID, bkg high;

✓ **Annual Modulation Signal**

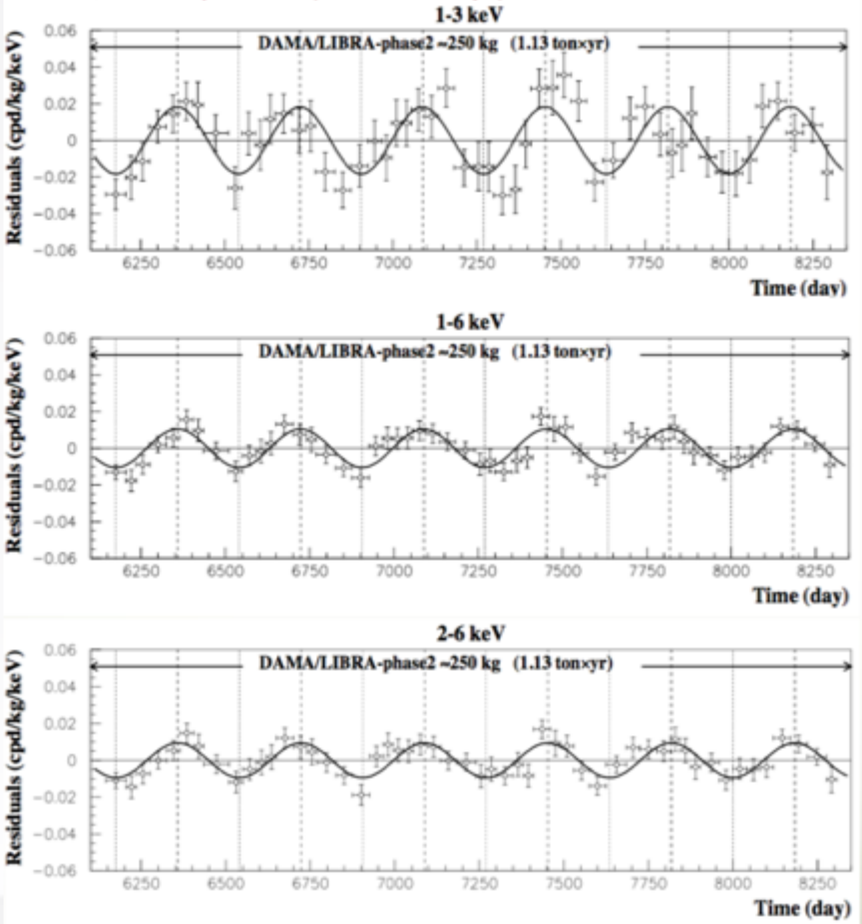


Credit：Fabio Cappella

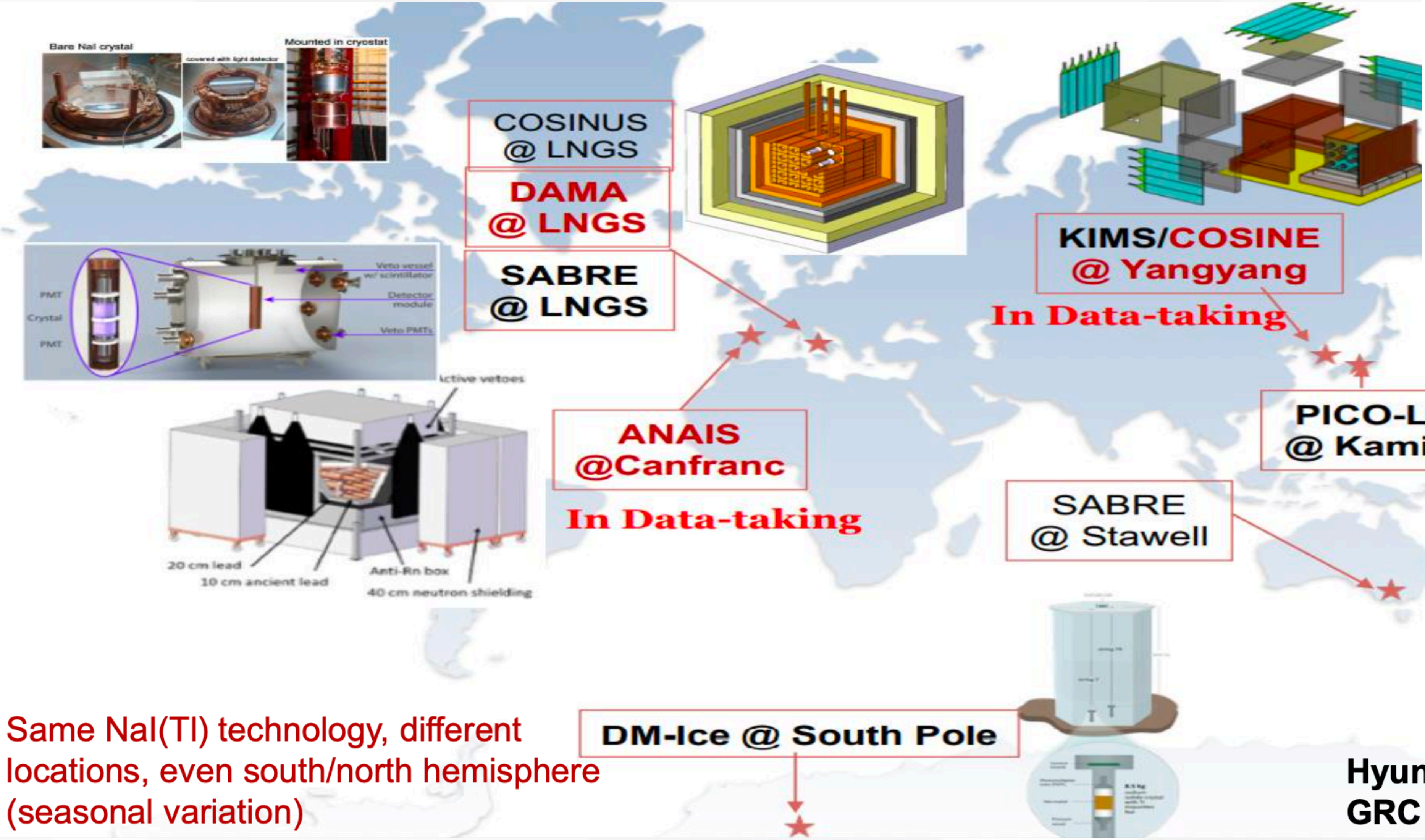


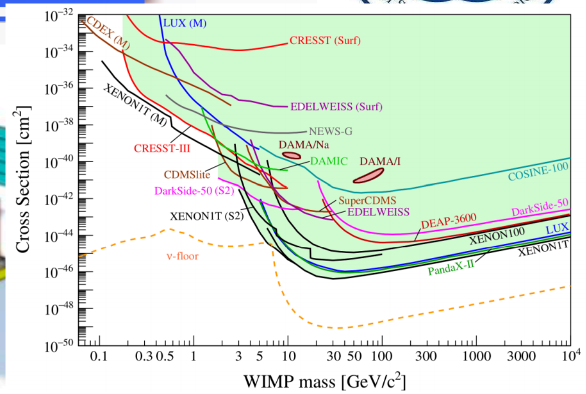

Credit： James Josephides

DAMA/LIBRA-phase2 (1.13 ton × yr)



# Annual modulation validation working force



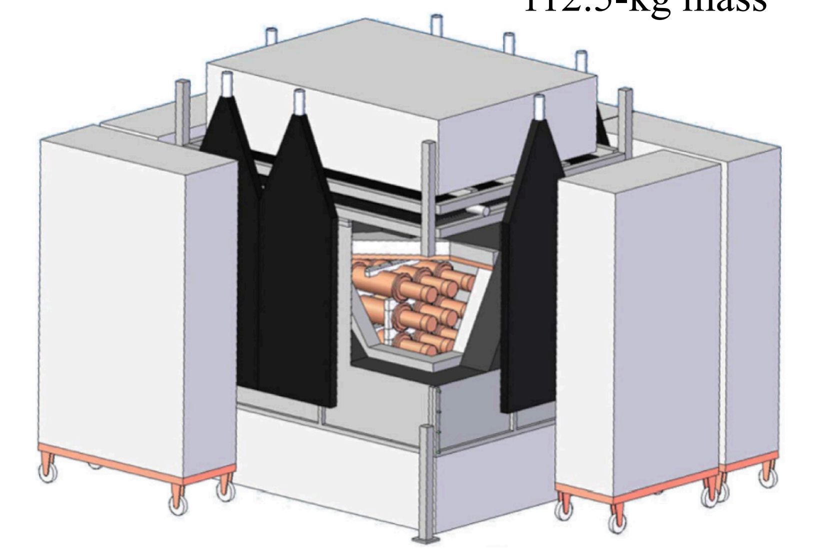

Same NaI(Tl) technology, different locations, even south/north hemisphere (seasonal variation)

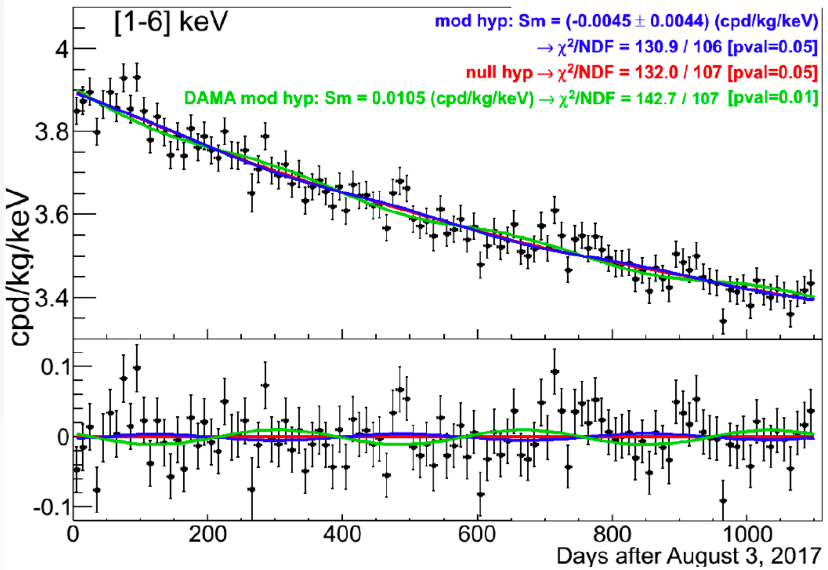
Hyun Su Lee, GRC Particle Physics 2019

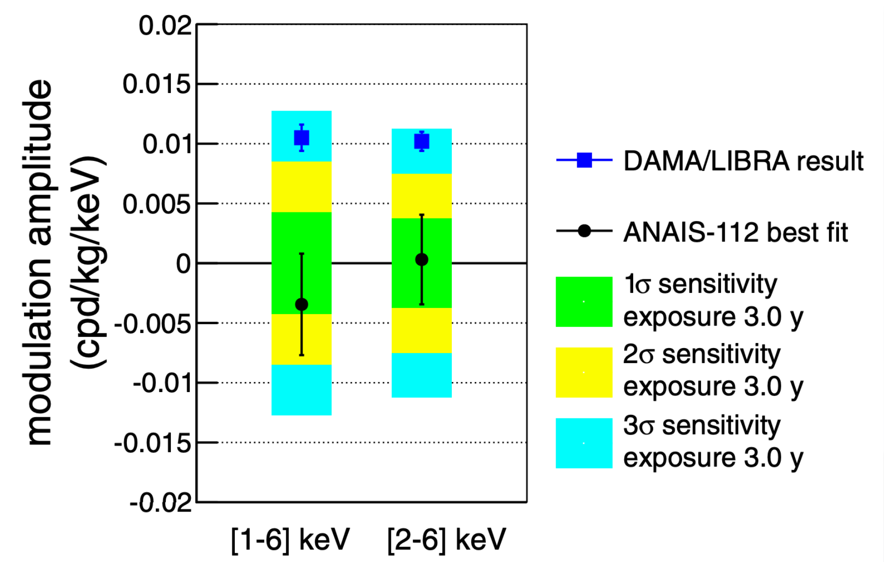
# ANAIS-112

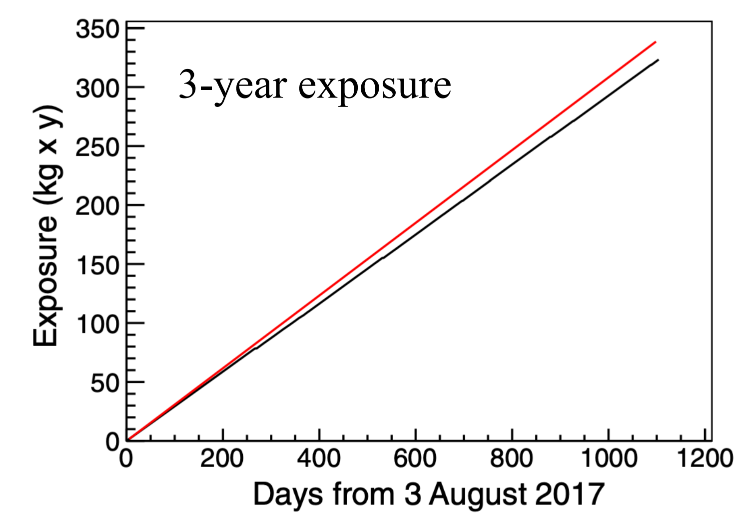
Phys. Rev. D 103, 102005 (2021)

112.5-kg mass





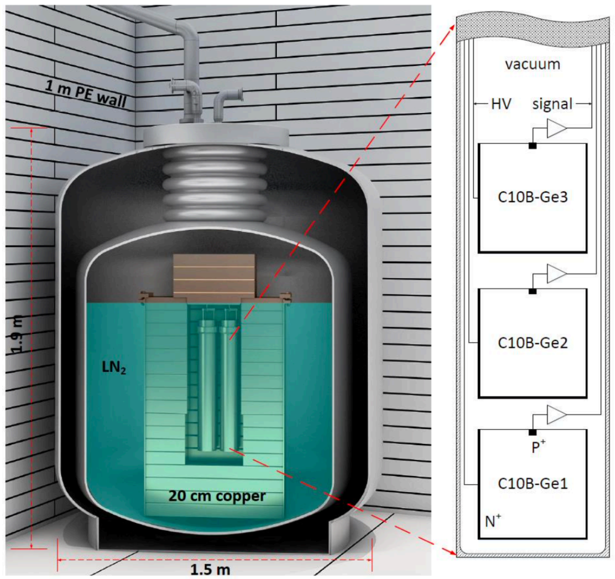



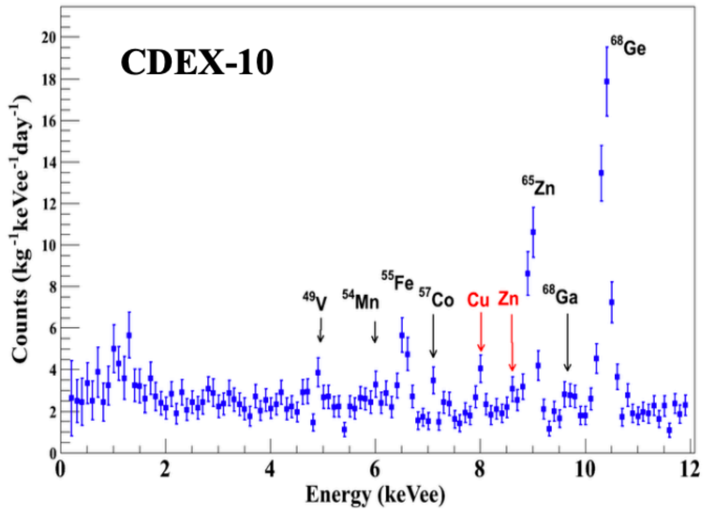

- ➢ ANAIS-112's 3-year results support the absence of annual modulation;
- ➢ The results are incompatible with DAMA/LIBRA at **3.3 (2.6)** **σ** for energy window of 1-6 (2-6) keV.

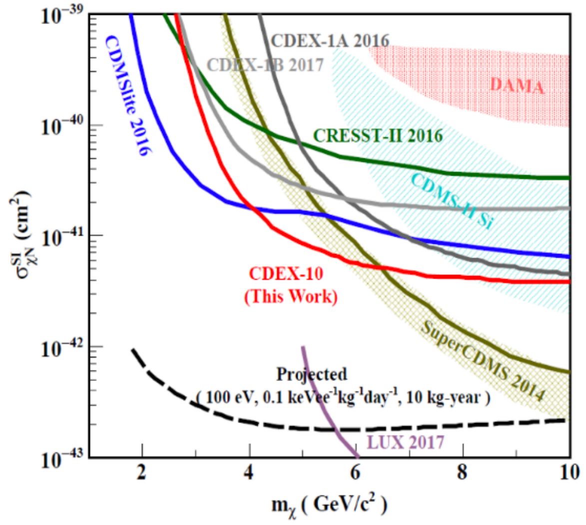
# Point contact Ge: CDEX

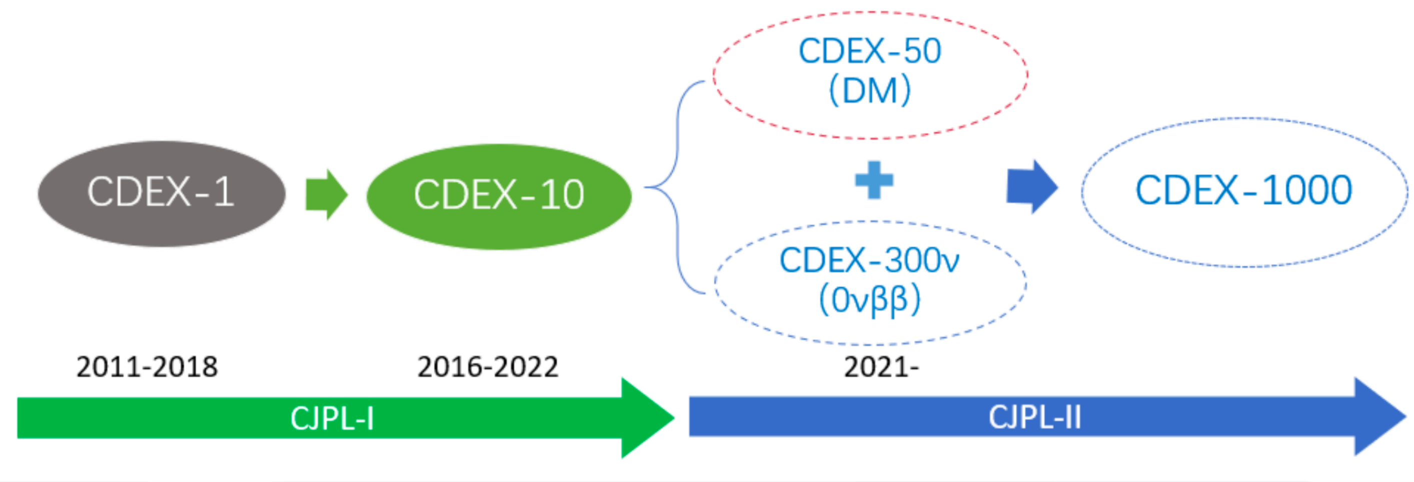
From Q. Yue

PRL120, 241301 (2018)



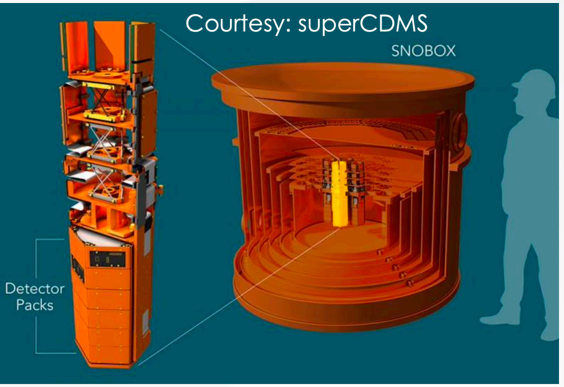



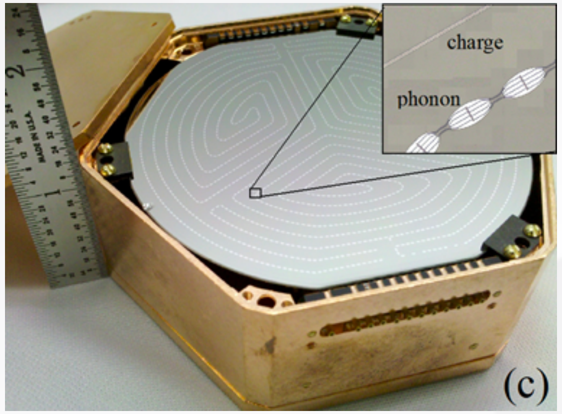




- LN2 temperature; HPGe collects pure ionization signal;
- Point-contact detector (small cap. ~pF; low electronic noise);
- Background level ~2 counts/kg/keV/day (2-4keV);
- CDEX-10, threshold ~160eV;

# Ultra-low temperature: Bolometer

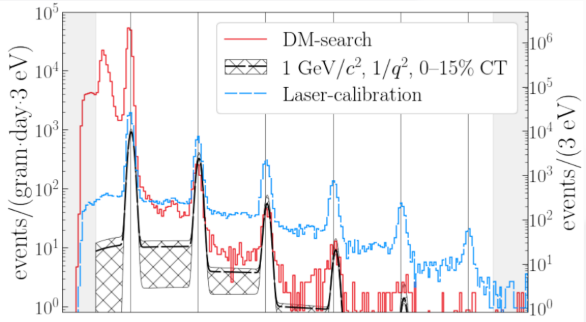
## SuperCDMS



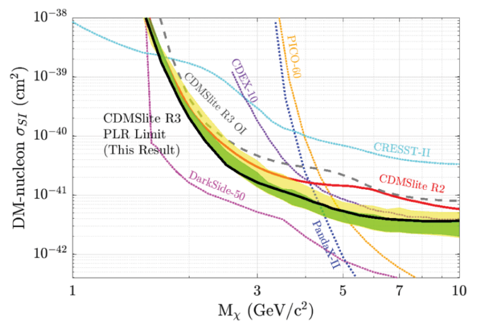




PHYSICAL REVIEW LETTERS 121, 051301 (2018)

Phys. Rev. D 102, 091101 (2020)



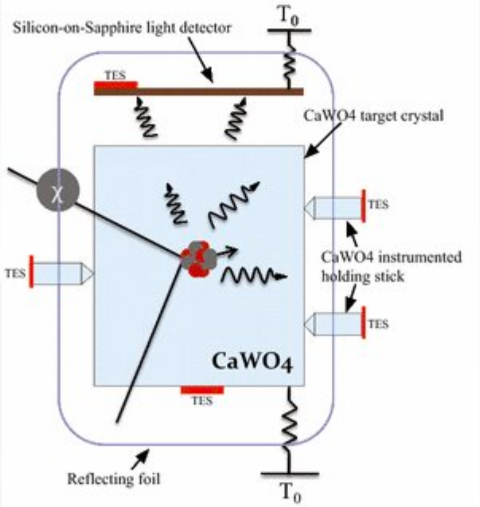

PHYS. REV. D 99, 062001 (2019)

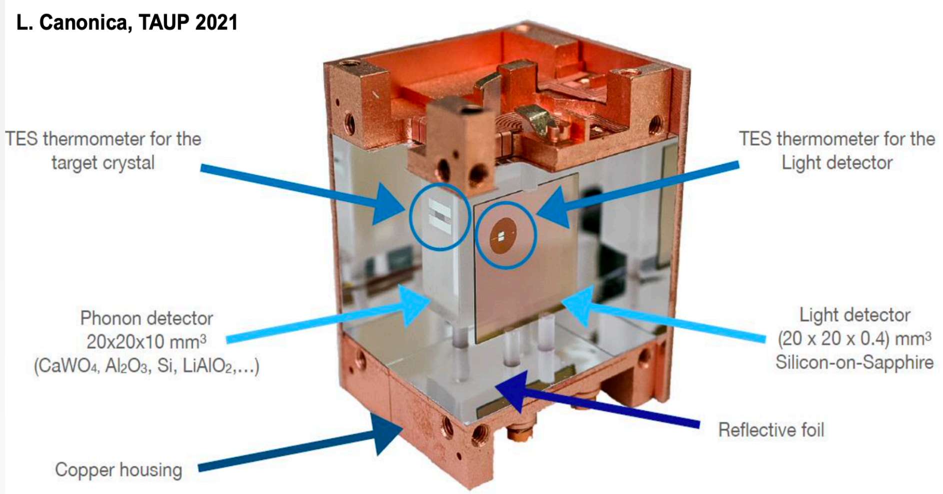


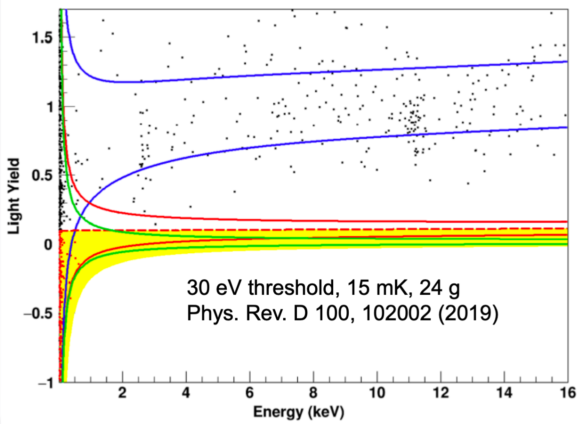

- Super-high resolution, 3% to single e-h pair;
- High sensitivity to GeV WIMP.

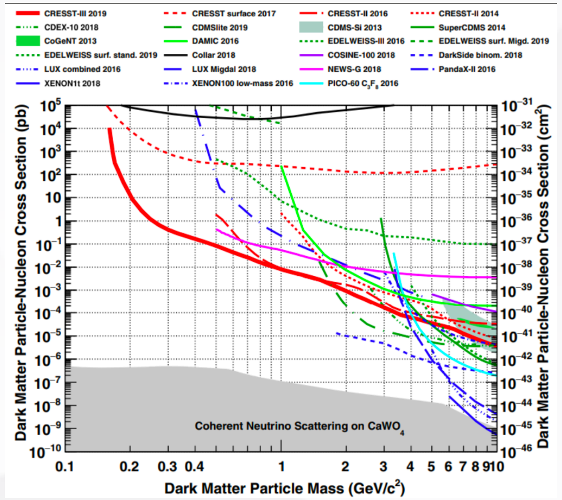
M. Mancuso, Journal of Low Temperature Physics 199, 547 (2022)

## CRESS-III



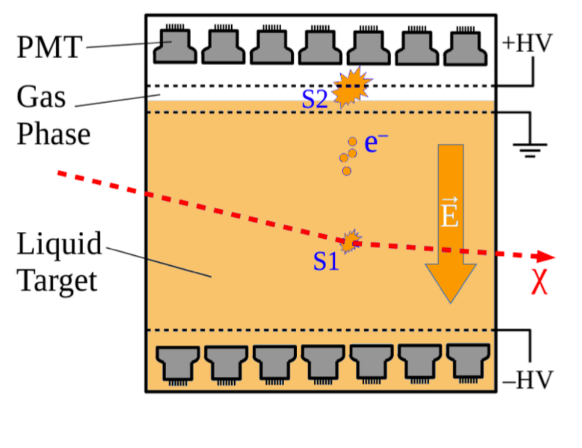



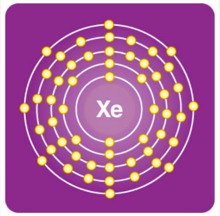



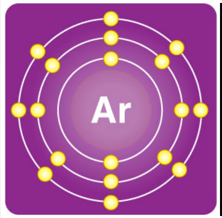

- Great background rejection power.

# Noble Liquid

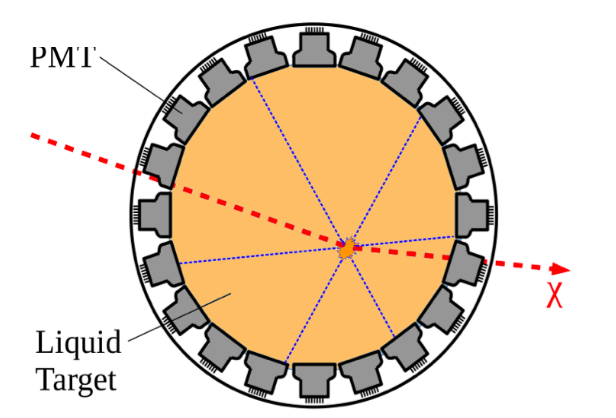








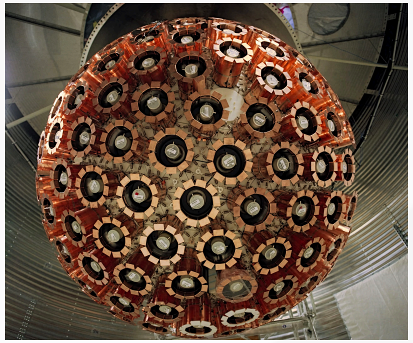



| Scalability | Good | Good |
|---|---|---|
| Density | 3 kg/L | 1.4 kg/L |
| A | 133 | 40 |
| Long-lived bkg | Xe136 Negligible | Ar39 (1 Bq/kg in $^{nat}$Ar, $T_{half}$=269yr) |
| Bkg rej. | S2/S1, 3D pos. | S2/S1, Pulse shape, 3D pos. |
| Scintillation light | 178 nm | 128 nm (need WLS) |
| Cost |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

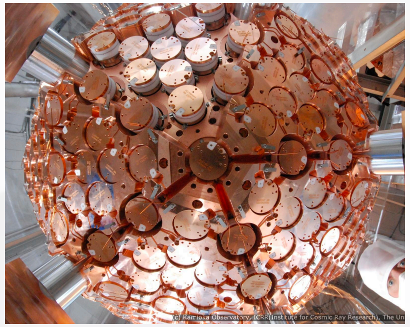
- High sensitivity to >10GeV DM due to its good scalability and bkg discrimination;
- Liquid xenon dual-phase TPC currently has the world-leading sensitivity to >10GeV DM.

DarkSide-50

PandaX-4T
XENONnT
LZ

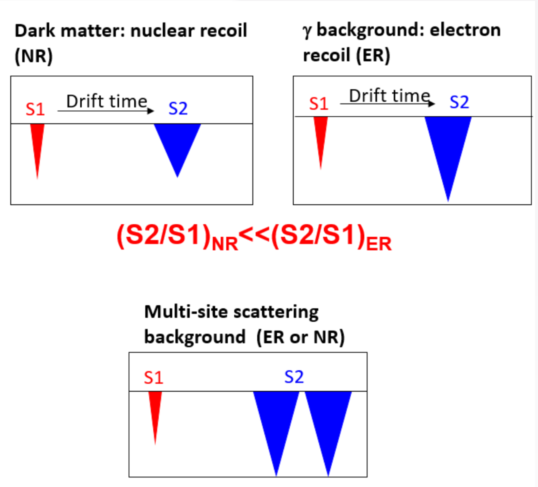


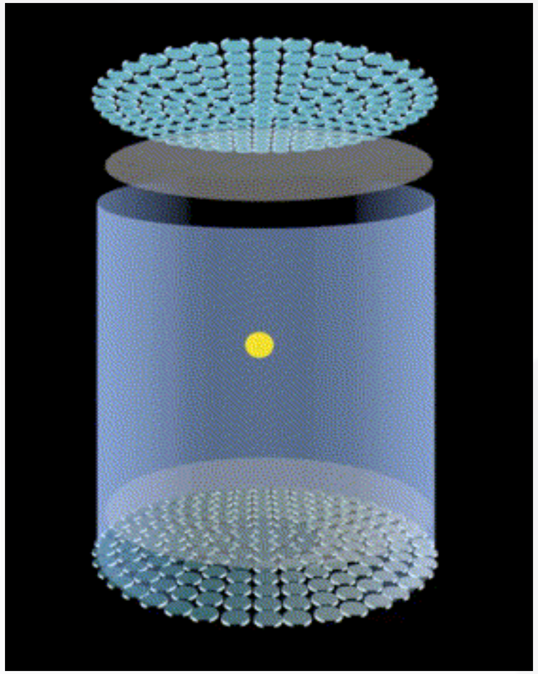
DEAP-3600

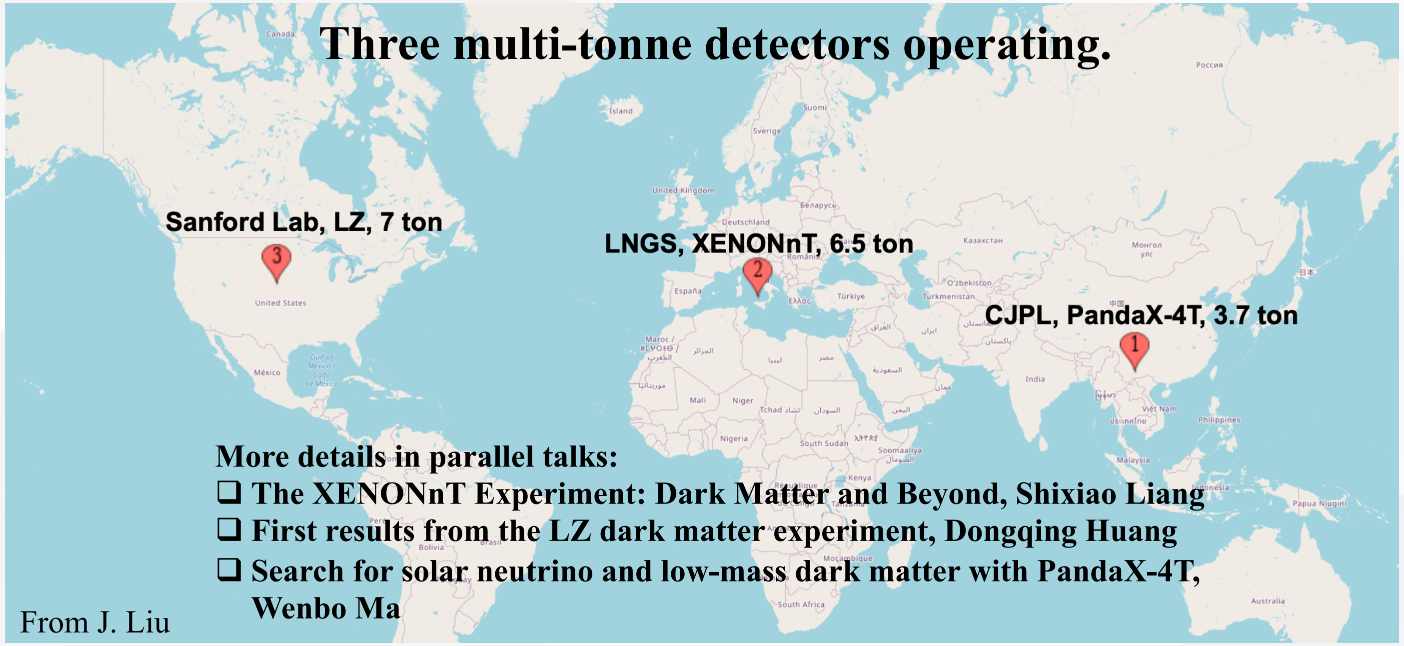


XMASS

# Liquid Xenon Dual phase Time Projection Chamber



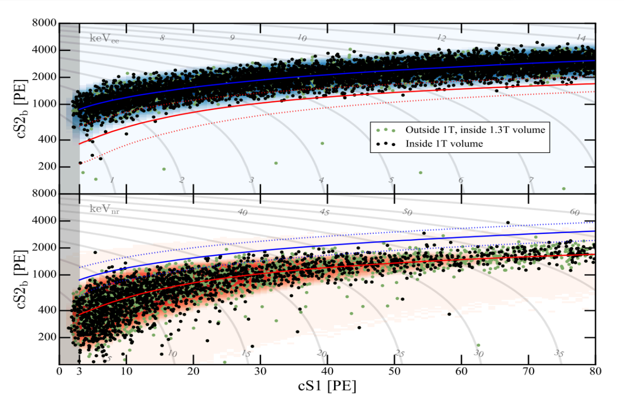


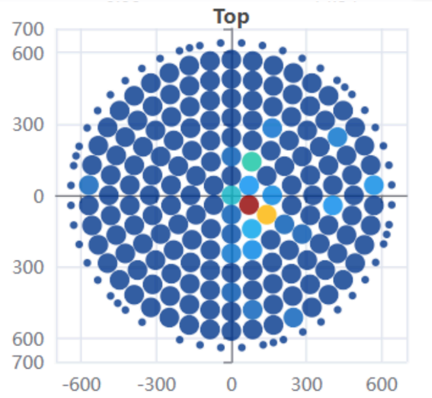

**Three multi-tonne detectors operating.**

More details in parallel talks:

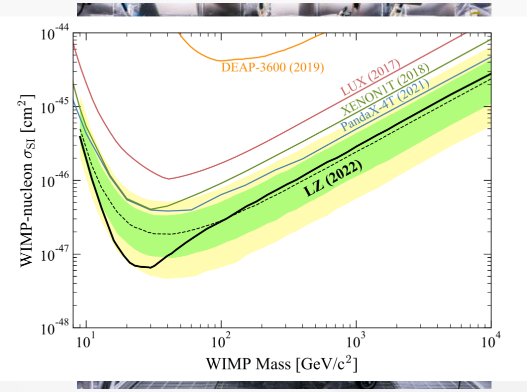
- ❑ The XENONnT Experiment: Dark Matter and Beyond, Shixiao Liang
- ❑ First results from the LZ dark matter experiment, Dongqing Huang
- ❑ Search for solar neutrino and low-mass dark matter with PandaX-4T, Wenbo Ma

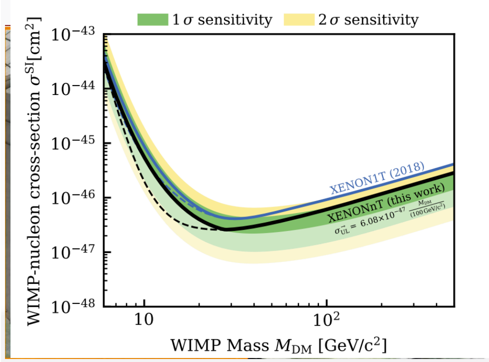
From J. Liu

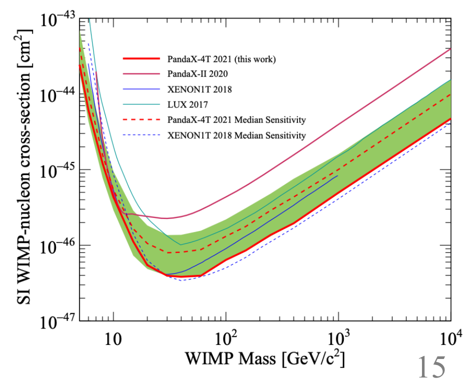



**LZ** **XENONnT** **PandaX-4T**



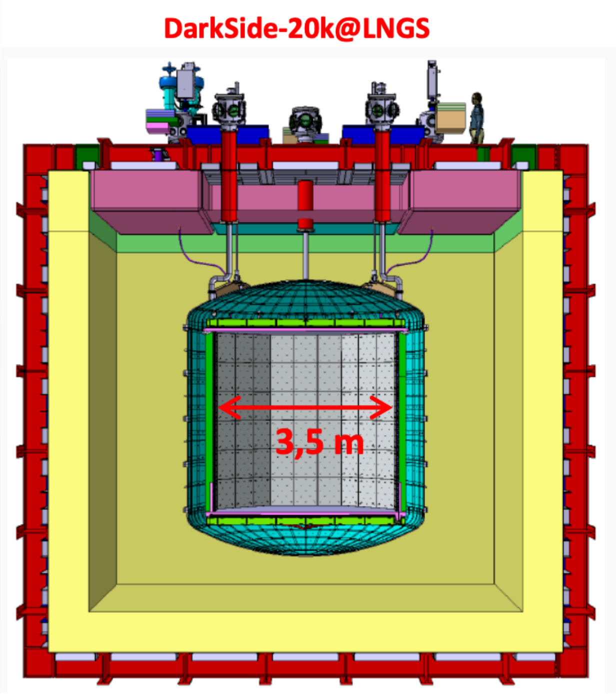



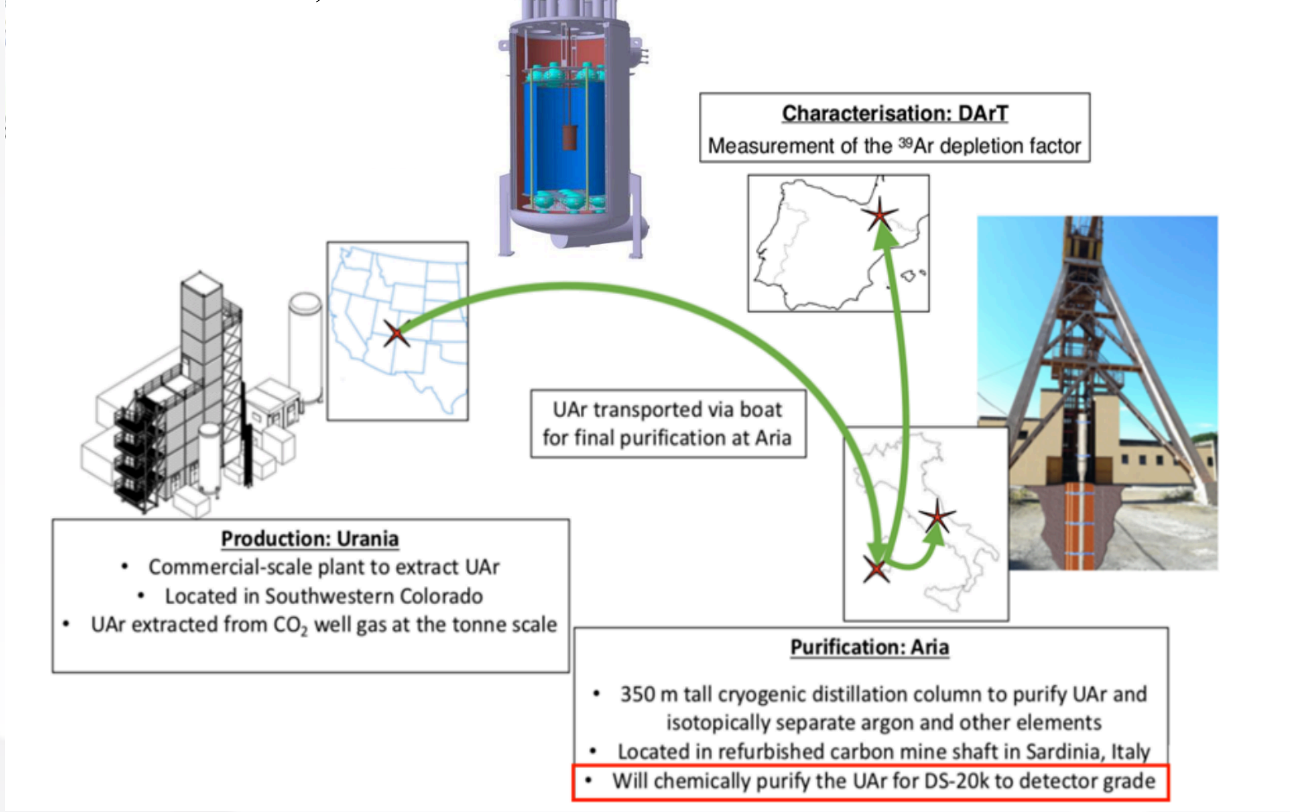
# Liquid Argon Dual phase Time Projection Chamber

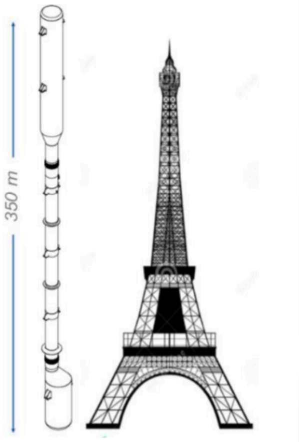
From Roberto Santorelli - La Thuile 2022

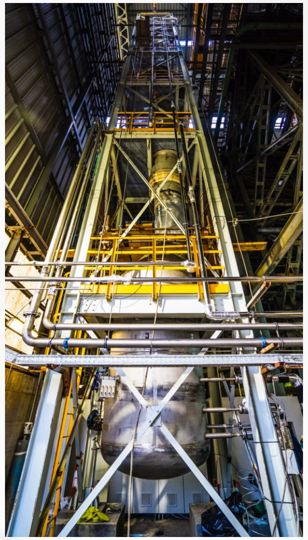
More details in parallel talks:

- ❑ The DarkSide-20k experiment, Tianyu Zhu
- ❑ Opportunities to light dark matter searches with the DarkSide-LowMass detector, Maxim Gromov



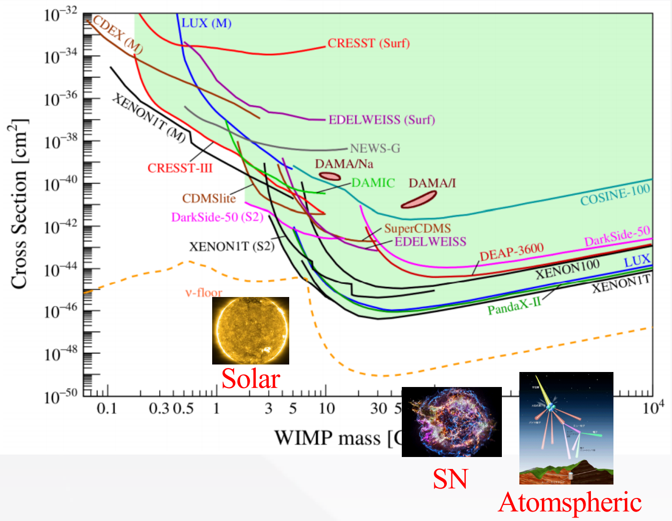



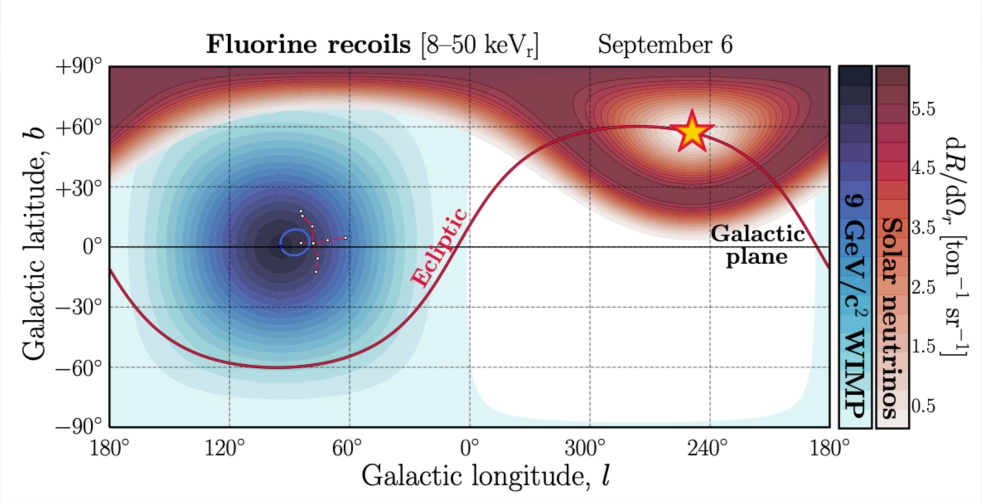
- ❑ 2022 construction, 2025 data taking;
- ❑ 50tonne total mass;
- ❑ 20t fiducial mass for 10-year exposure;

- ❑ UAr mined from Urania;
- ❑ Further distilled at Aria facility;

# Directional Detector: Gaseous TPC

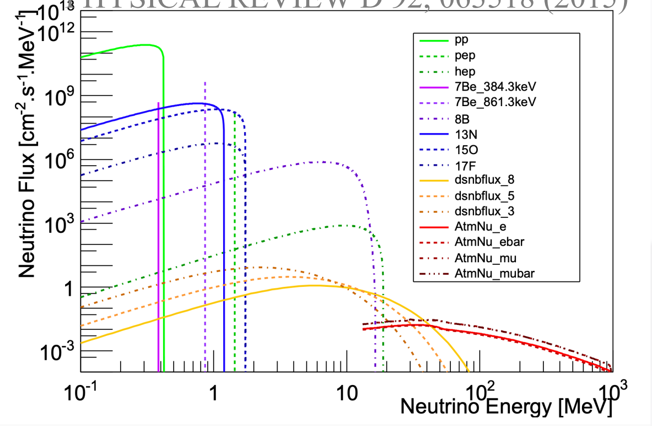
SE. Vahsen et al., arXiv:2008.12587

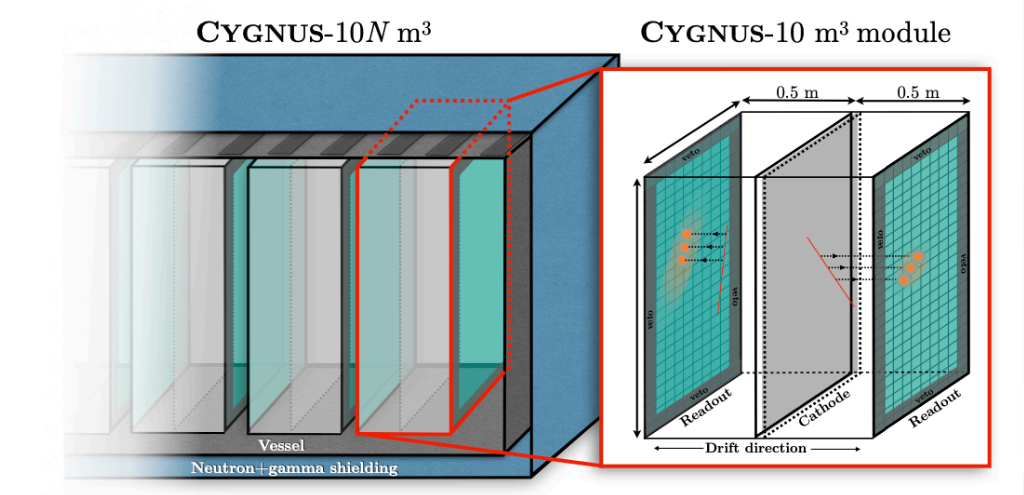


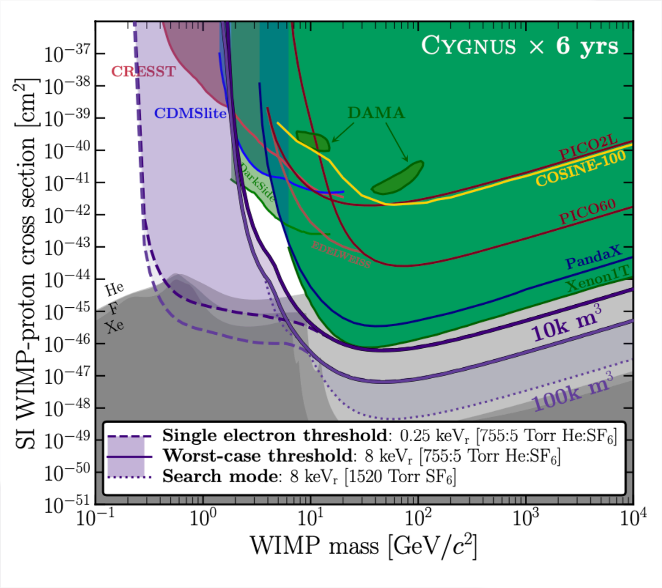




- Low-pressure gaseous TPC;
- Highly pixelized charge readout for high track resolution;
- Directionality can help go beyond neutrion floor to some extent.

PHYSICAL REVIEW D 92, 063518 (2015)




**Ultimate background: neutrinos**

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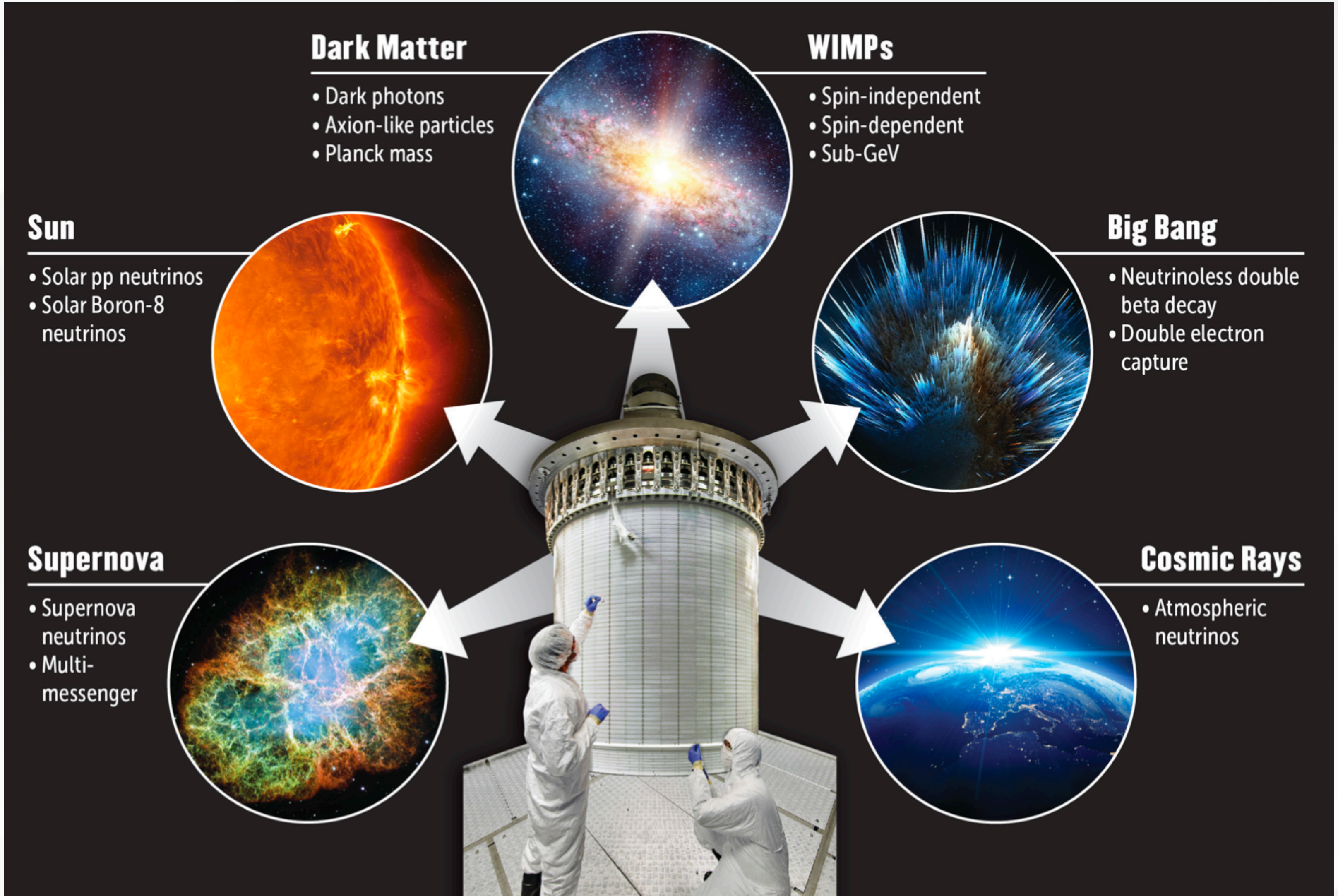
# DM detector for neutrino detection



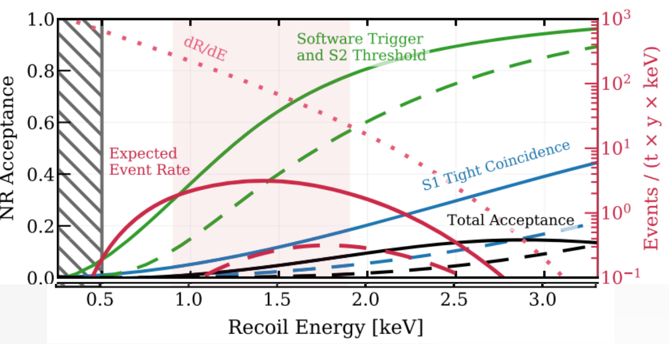

*From R. Lang et al., Journal of Physics G: Nuclear and Particle Physics* 50.1 (2022): 013001

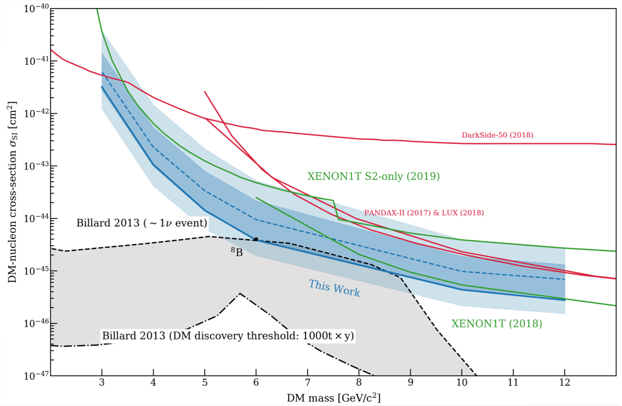
- Coherent Elastic Neutrino-Nucleus Scattering caused by Cosmic Neutrinos (Solar, Supernova etc.)
- Neutrinoless double beta decay search.

# Search for Solar B8 neutrino

## XENON1T

PRL 126, 091301 (2021)

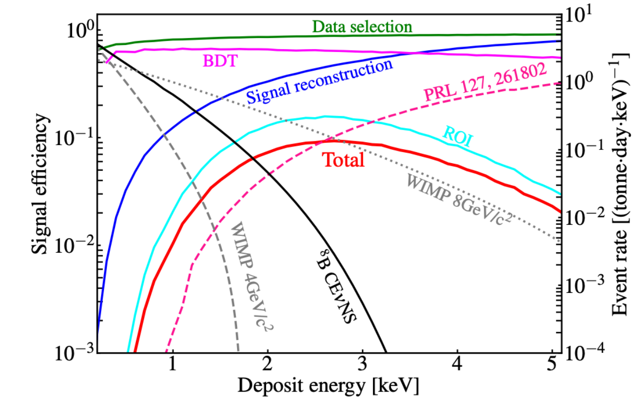


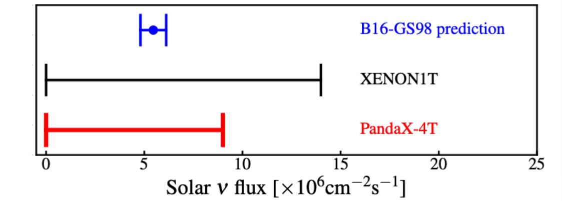



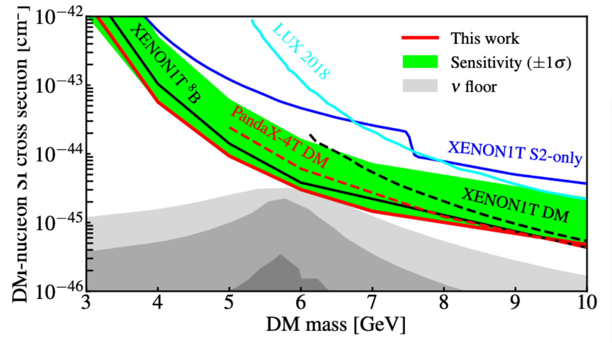

| S1 hit properties | | Science data | | | |
|---|---|---|---|---|---|
| Hit category | LHA | AC | ER | Total BG | CE$\nu$NS |
| 2 Hits, 1+ in TA | ≥2 PE | 0.09 | 0.01 | 0.10 | 0.13 |
| | <2 PE | 3.54 | 0.04 | 3.58 | 0.44 |
| 2 Hits, 0 in TA | ≥2 PE | 0.03 | 0.03 | 0.06 | 0.23 |
| | <2 PE | 1.47 | 0.09 | 1.58 | 0.79 |
| 3 Hits | ≥2 PE | 0.00 | 0.01 | 0.02 | 0.17 |
| | <2 PE | 0.01 | 0.03 | 0.05 | 0.36 |
| Total | | 5.14 | 0.21 | 5.38 | 2.11 |

## PandaX-4T

PRL 130, 021802 (2023)




| $N_{hit}$ | $S2$ range [PE] | BDT | ER | NR | Surf | AC | Total BKG | $^8$B | Obs |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 65-230 | pre | 0.04 | 0.10 | 0.14 | 62.43 | 62.71 | 2.32 | **59** |
| | | post | 0.02 | 0.04 | 0.03 | 1.41 | 1.50 | 1.42 | **1** |
| 3 | 65-190 | pre | 0.01 | 0.05 | 0.08 | 0.79 | 0.93 | 0.42 | **2** |
| | | post | 0.00 | 0.02 | 0.03 | 0.02 | 0.07 | 0.29 | **0** |

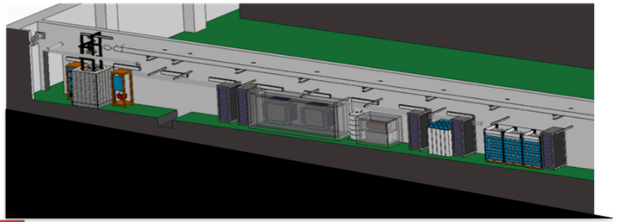
**Parallel talk: Search for solar neutrino and low-mass dark matter with PandaX-4T, Wenbo Ma**

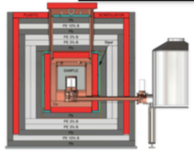
# Search for Reactor neutrino CEνNS

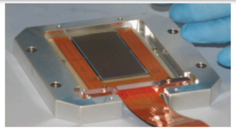
M. Vivier,
Magnificent CEvNS 2020

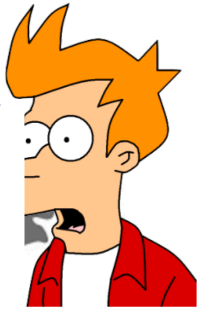
| Experiment | Technology | Location | Source |
|---|---|---|---|
| COHERENT | CsI, Ar, Ge, NaI | USA | πDAR |
| CCM | Ar | USA | πDAR |
| ESS | CsI, Si, Ge, Xe | Sweden | πDAR |
| BULLKID | Si/Ge | Italy | Reactor |
| CONNIE | Si CCDs | Brazil | Reactor |
| CONUS | HPGe | Germany | Reactor |
| NEWS-G | Ar+2%CH4 | Canada | Reactor |
| MINER | Ge/Si cryogenic | USA | Reactor |
| NEON | NaI(Tl) | Korea | Reactor |
| NUCLEUS | $CaWO_4$ , $Al_2O_3$ cryogenic | Europe | Reactor |
| νGEN | Ge PPC | Russia | Reactor |
| RED-100 | LXe dual phase | Russia | Reactor |
| Ricochet | Ge, Zn, Al, Sn cryogenic | France | Reactor |
| TEXONO | p-PCGe | Taiwan | Reactor |
| Dresden II | PCGe | USA | Reactor |
| SBC | Scintillating Bubble Chamber | Fermilab (R&D) | Reactor |

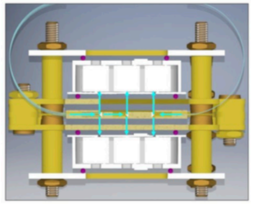
+DM detectors, +directional detectors +Solar/SN detectors…
**many novel low-background, low-threshold technologies!!**

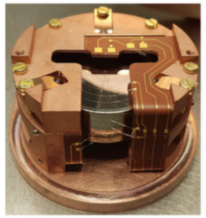


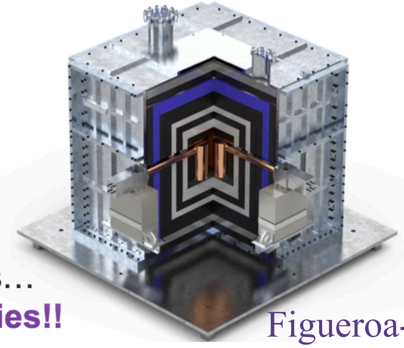


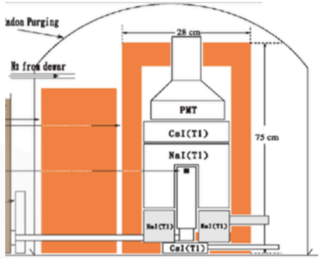


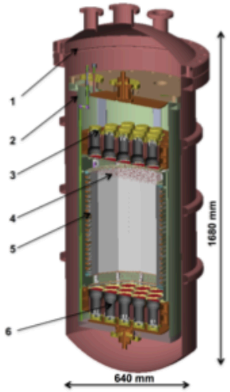









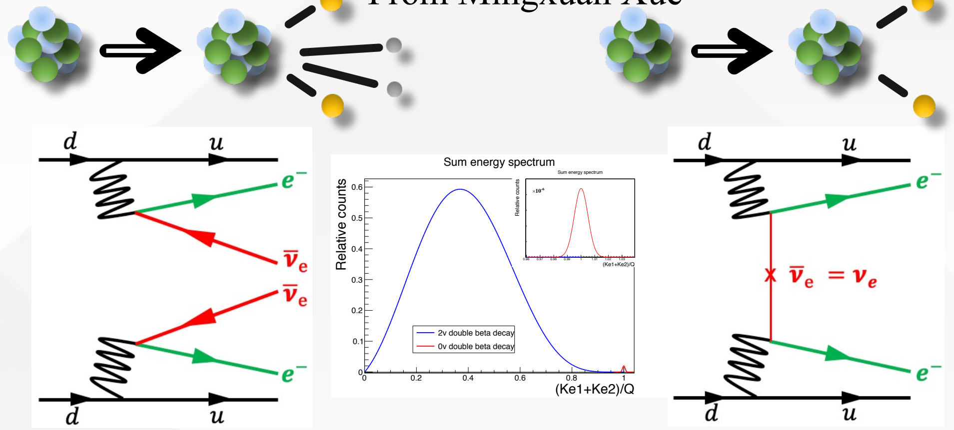



Figueroa-Feliciano (Magnificent CEvNS 2023)

# Search for 0nbb

From Mingxuan Xue



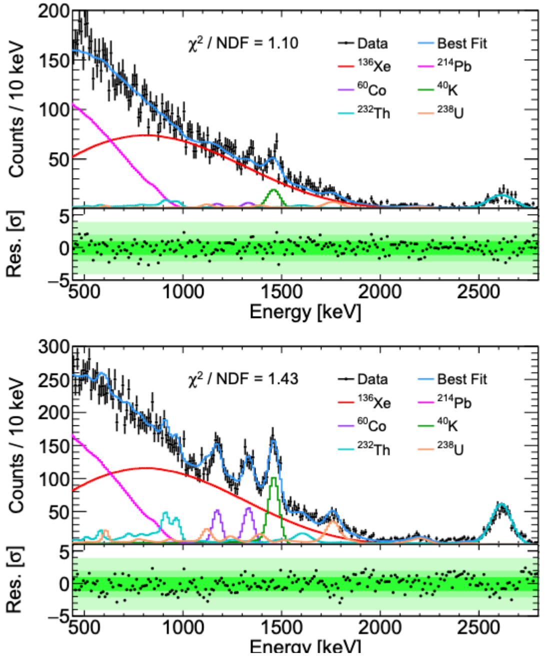

$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

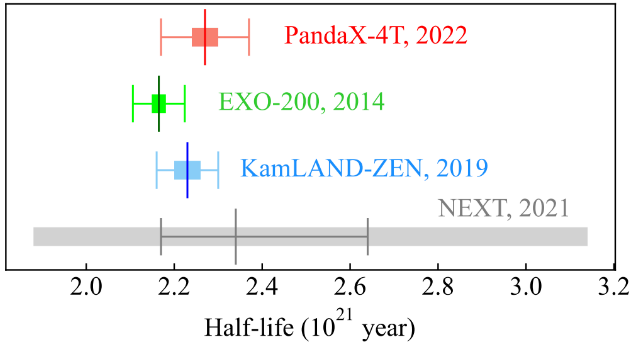
$(A, Z) \rightarrow (A, Z+2) + 2e^-$

| Nuclide | Half-life, $10^{21}$ years | Mode | Transition | Method | Experiment |
|---|---|---|---|---|---|
| $^{48}$Ca | $0.064^{+0.007}_{-0.006} \pm ^{+0.012}_{-0.009}$ | $\beta^-\beta^-$ | | direct | NEMO-3[11] |
| $^{76}$Ge | 1.926 ±0.094 | $\beta^-\beta^-$ | | direct | GERDA[10] |
| $^{78}$Kr | $9.2^{+5.5}_{-2.6} \pm 1.3$ | εε | | direct | BAKSAN[10] |
| $^{82}$Se | 0.096 ± 0.003 ± 0.010 | $\beta^-\beta^-$ | | direct | NEMO-3[10] |
| $^{96}$Zr | 0.0235 ± 0.0014 ± 0.0016 | $\beta^-\beta^-$ | | direct | NEMO-3[10] |
| $^{100}$Mo | 0.00693 ± 0.00004 | $\beta^-\beta^-$ | | direct | NEMO-3[10] |
| | $0.69^{+0.10}_{-0.08} \pm 0.07$ | $\beta^-\beta^-$ | $0^+ \rightarrow 0^+_1$ | | Ge coincidence[10] |
| $^{116}$Cd | 0.028 ± 0.001 ± 0.003<br>$0.026^{+0.009}_{-0.005}$ | $\beta^-\beta^-$ | | direct | NEMO-3[10]<br>ELEGANT IV[10] |
| $^{128}$Te | 7200 ± 400<br>1800 ± 700 | $\beta^-\beta^-$ | | geochemical | [10] |
| $^{130}$Te | 0.82 ± 0.02 ± 0.06 | $\beta^-\beta^-$ | | direct | CUORE-0[12] |
| $^{124}$Xe | 18 ± 5 ± 1 | εε | | direct | XENON1T[13] |
| $^{136}$Xe | 2.165 ± 0.016 ± 0.059 | $\beta^-\beta^-$ | | direct | EXO-200[10] |
| $^{130}$Ba | (0.5 – 2.7) | εε | | geochemical | [14][15] |
| $^{150}$Nd | $0.00911^{+0.00025}_{-0.00022} \pm 0.00063$ | $\beta^-\beta^-$ | | direct | NEMO-3[10] |
| | $0.107^{+0.046}_{-0.026}$ | $\beta^-\beta^-$ | $0^+ \rightarrow 0^+_1$ | | Ge coincidence[10] |
| $^{238}$U | 2.0 ± 0.6 | $\beta^-\beta^-$ | | radiochemical | [10] |

## PandaX-4T 2nbb

**Research. 2022 Nov 25**



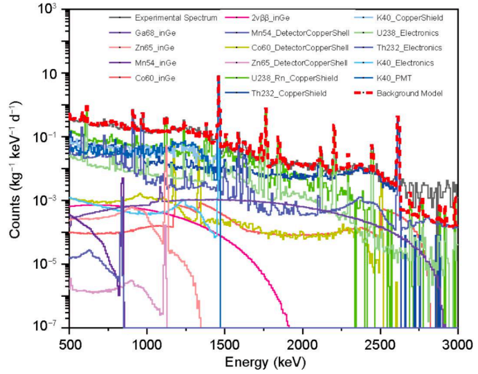



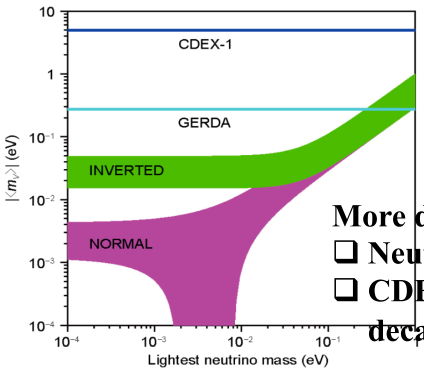

## CDEX-1A 0nbb

- 0νββ (304 kg·day data)
  - Natural Ge crystal;

$$T_{1/2}^{0\nu} \geq 6.43 \times 10^{22}\ yr,\ \ 90\%\ C.L.$$

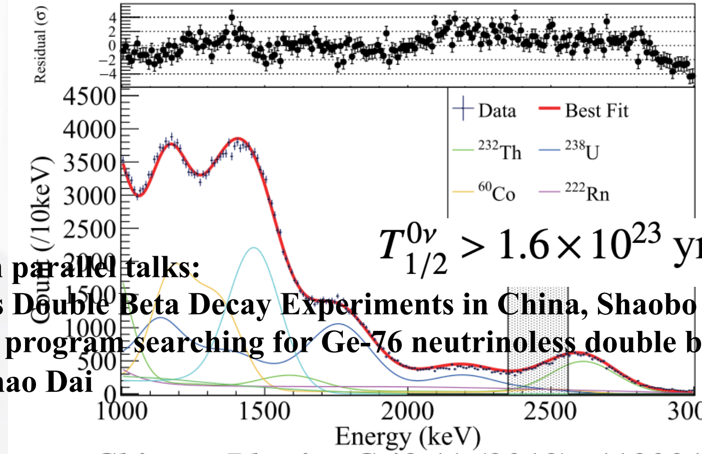
*Science China PMA (2017) 60: 071011*




From Yue Qian

## PandaX-II 0nbb




$$T_{1/2}^{0\nu} > 1.6 \times 10^{23}\ \text{yr}$$

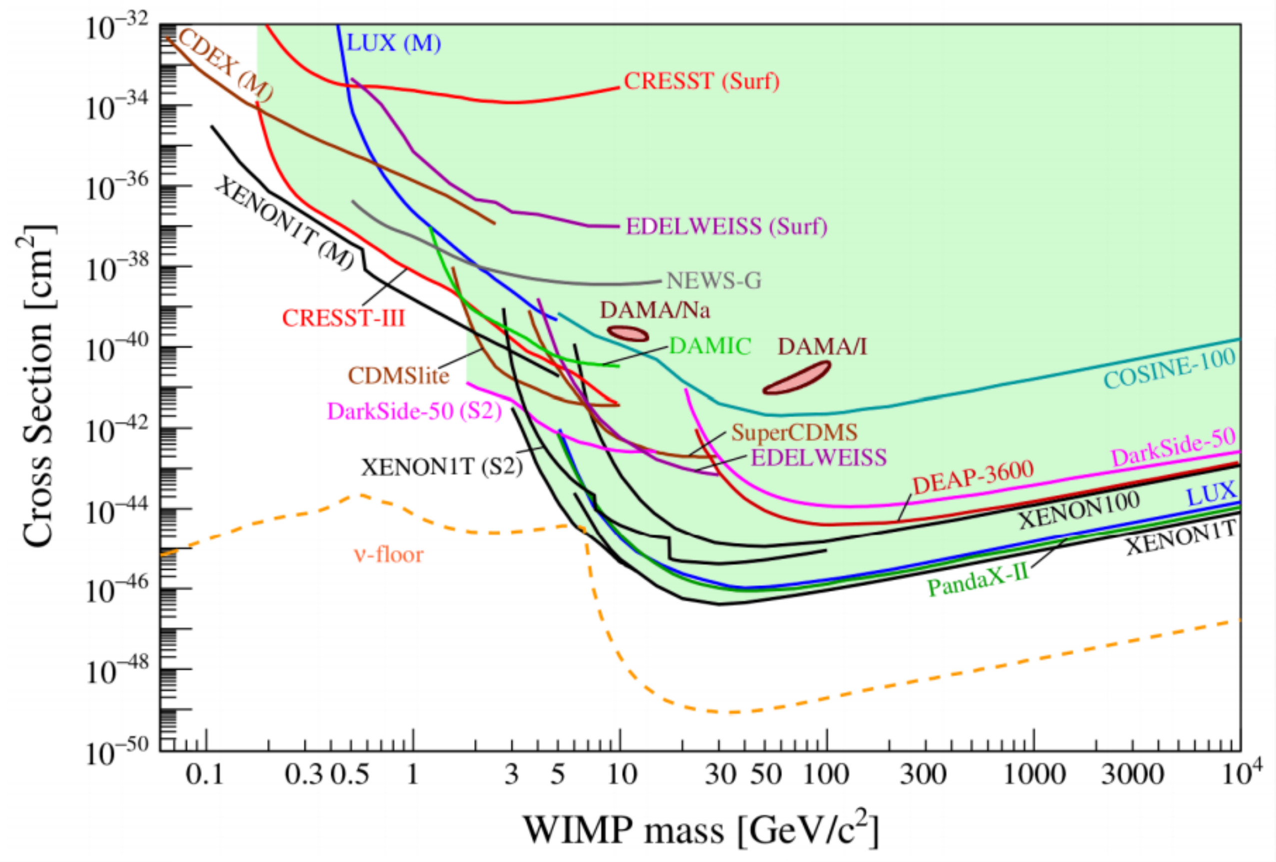
**More details in parallel talks:**

- ❑ **Neutrinoless Double Beta Decay Experiments in China, Shaobo Wang；**
- ❑ **CDEX-300ν program searching for Ge-76 neutrinoless double beta decay, Wenhao Dai**

*Chinese Physics C 43.11 (2019): 113001*

# Summary

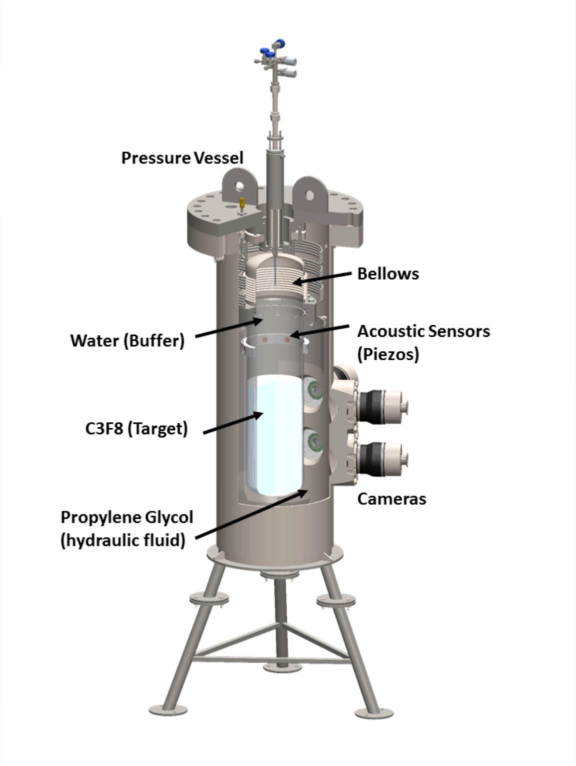
- Efforts have been paid heavily on >10GeV heavy DM and <10GeV light DM searches; No positive signal found yet;
- Bolometer and semi-conductor are leading the search for light DM;
- Liquid xenon time projection chamber is leading the search of >10GeV DM;
- DM detectors are getting used in neutrino measurements.

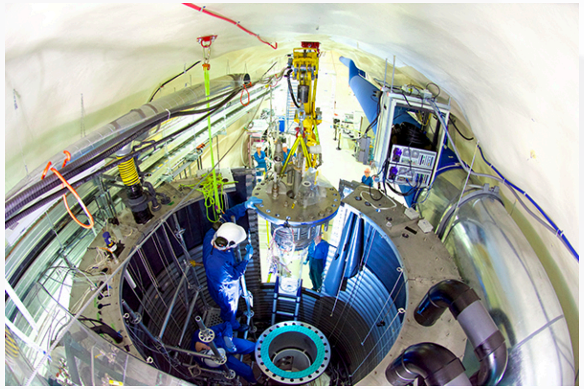


Thank you for listening!

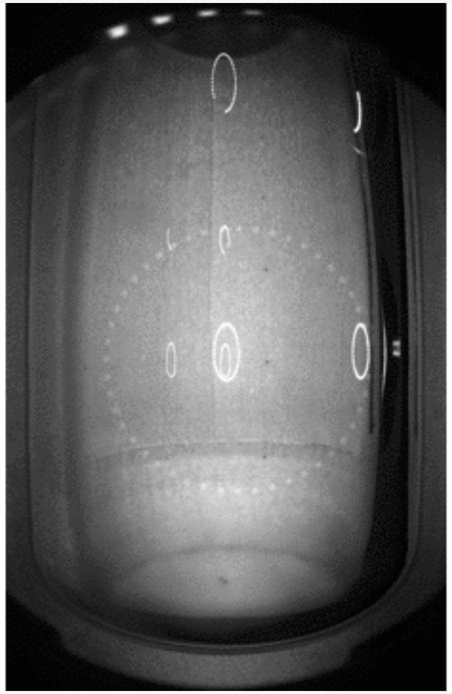
# Backup

# Bubble Chamber: PICO

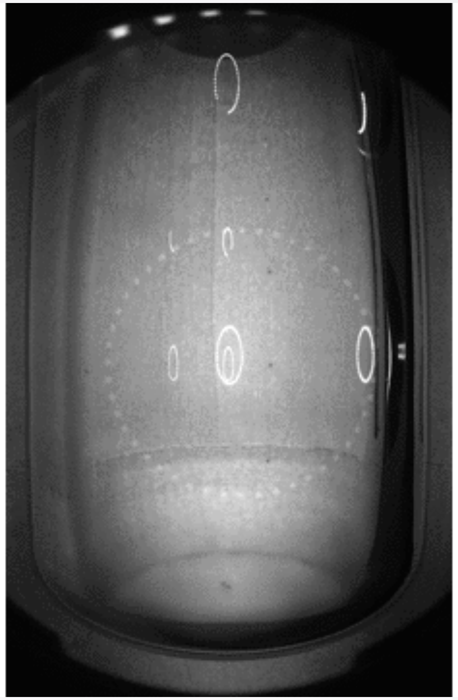


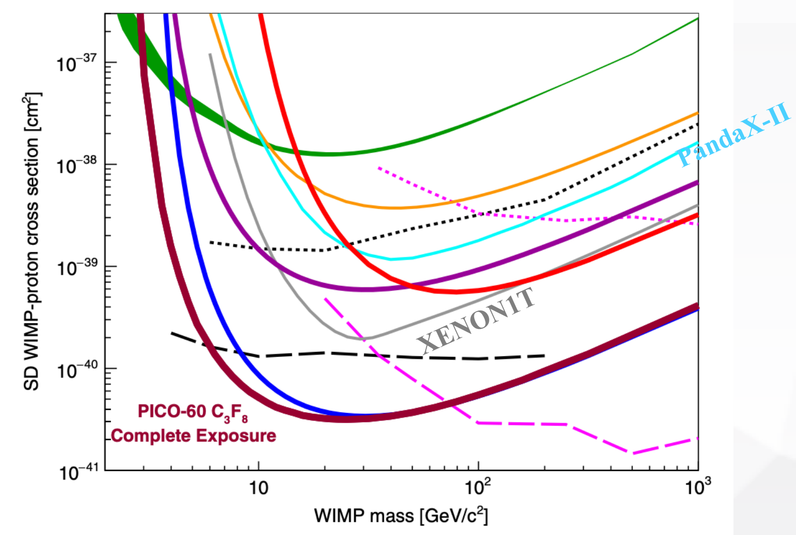
Single Scatter

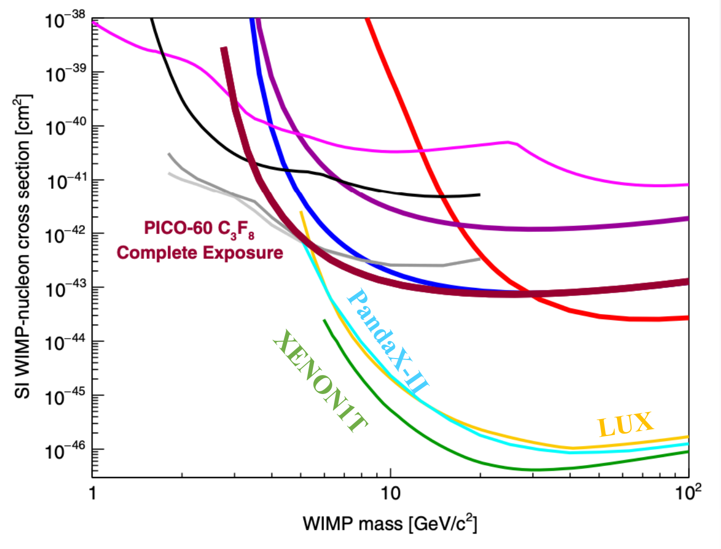


Multi-Scatter



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



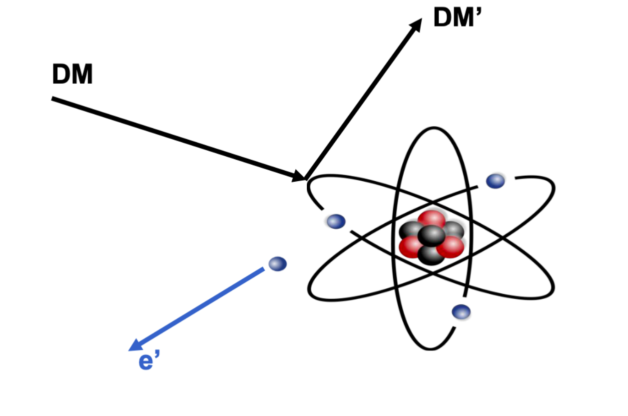

- Largest bubble chamber with superheated $C_3F_8$;
- No bkg from gamma, e and muons;
- Discrimination against neutron through single and multiple scatter images;

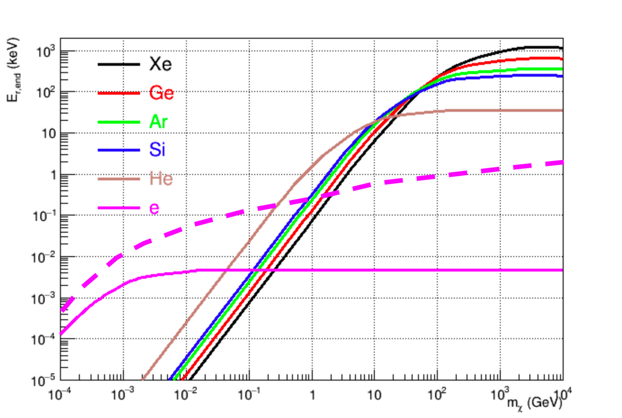
# CONTENTS

# DM-e scattering and Migdal effect

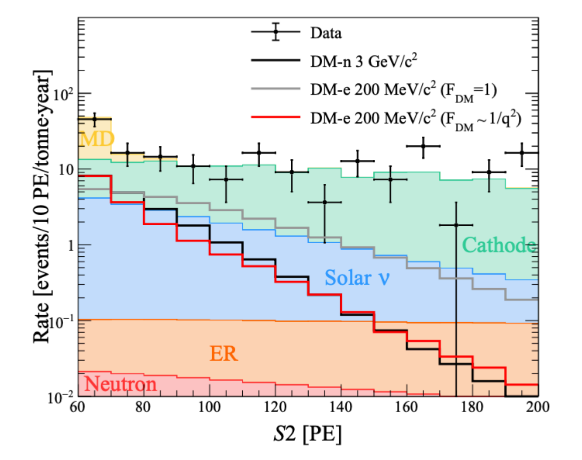
## DM-electron scattering

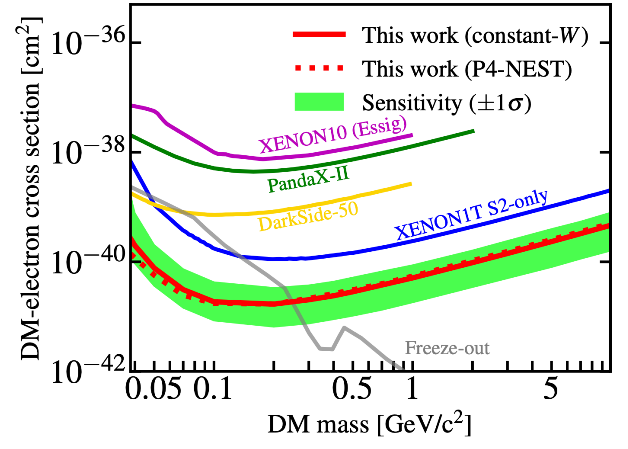
Essig, Mardon, Volansky, PRD 85, 076007 (2012)




PandaX collaboration, arXiv: 2212.10067 (2022)

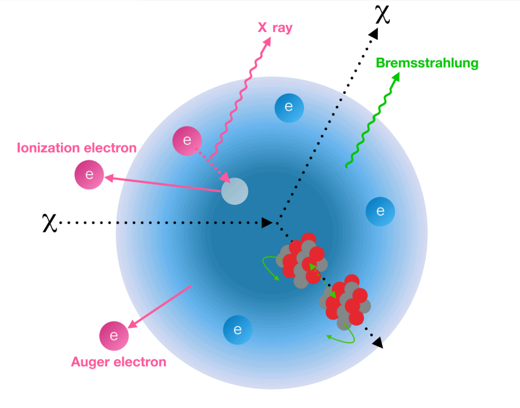


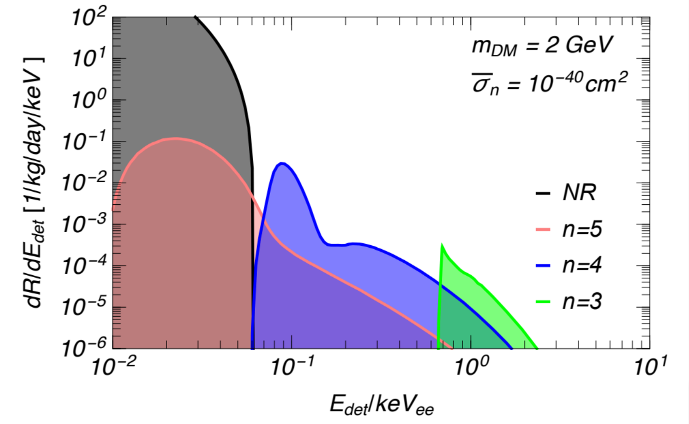




## Migdal Effect

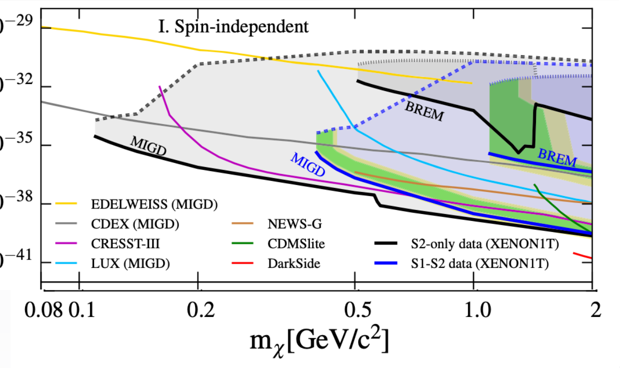
*M. Ibe et al., Journal of High Energy Physics* 2018.3 (2018)

*XENON collaboration, PRL 123, 241803 (2019)*

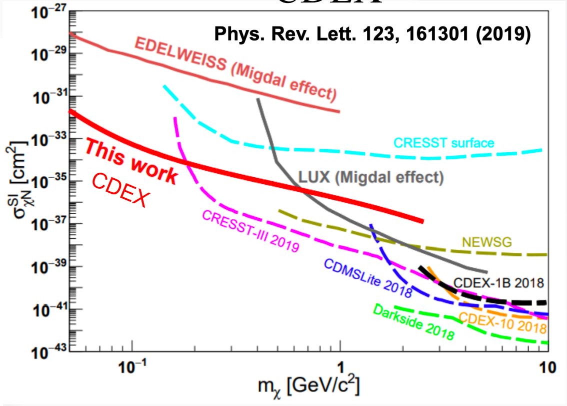



XENON1T

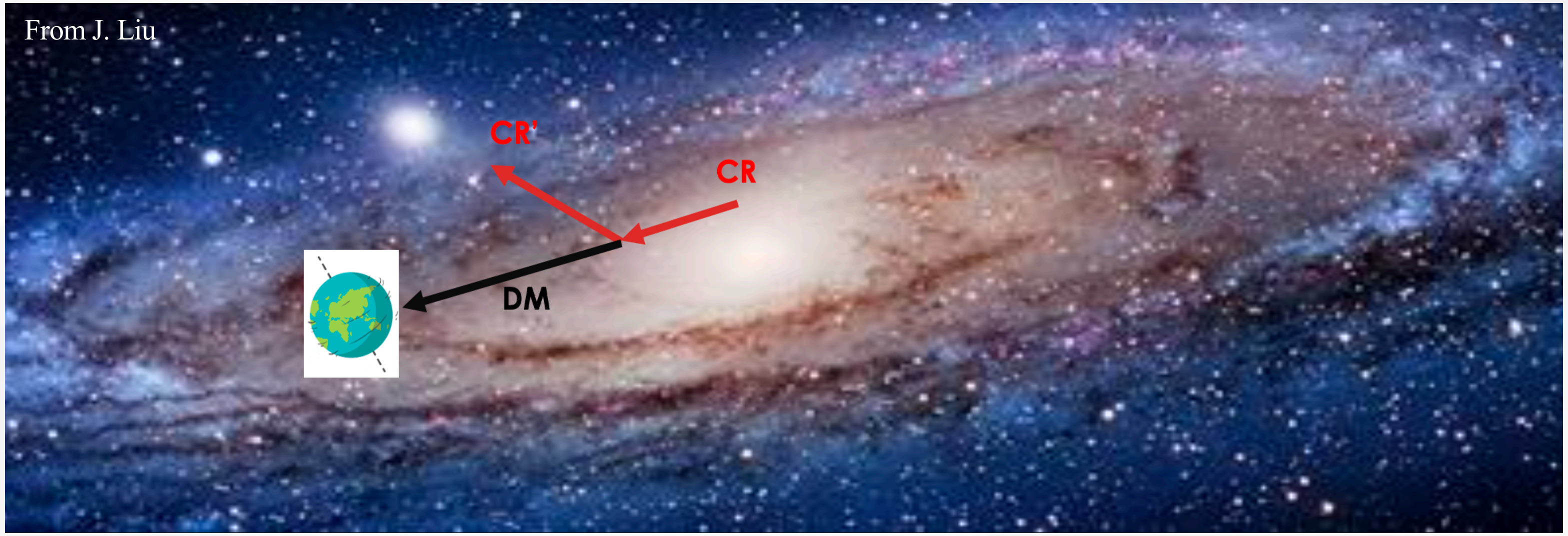


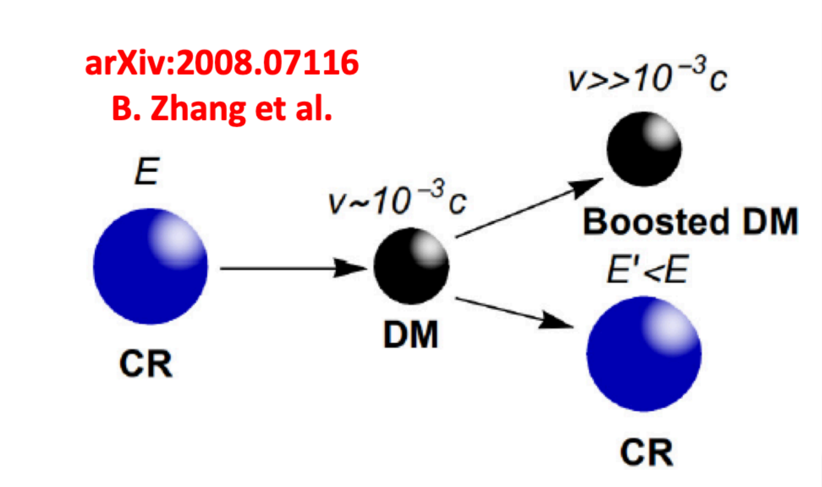

CDEX

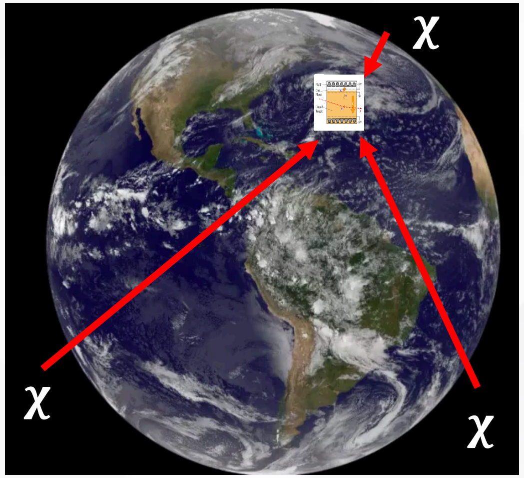


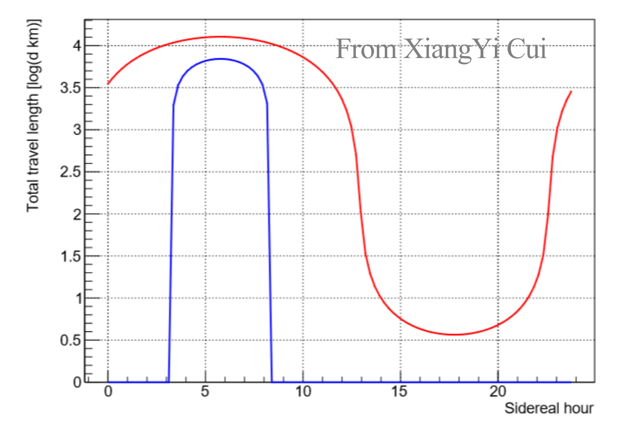

Capable of Probing light dark matter due to high momentum transfer

# Diurnal Modulation

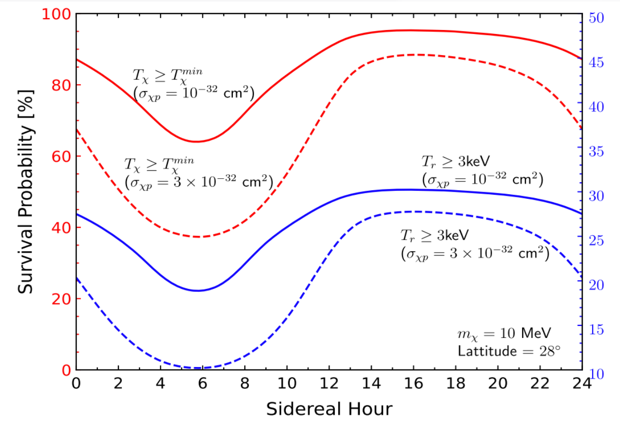


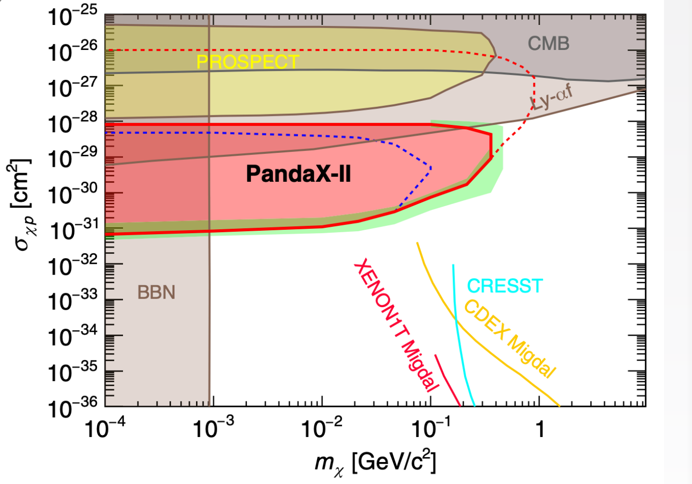




PHYSICAL REVIEW LETTERS 126, 091804 (2021)

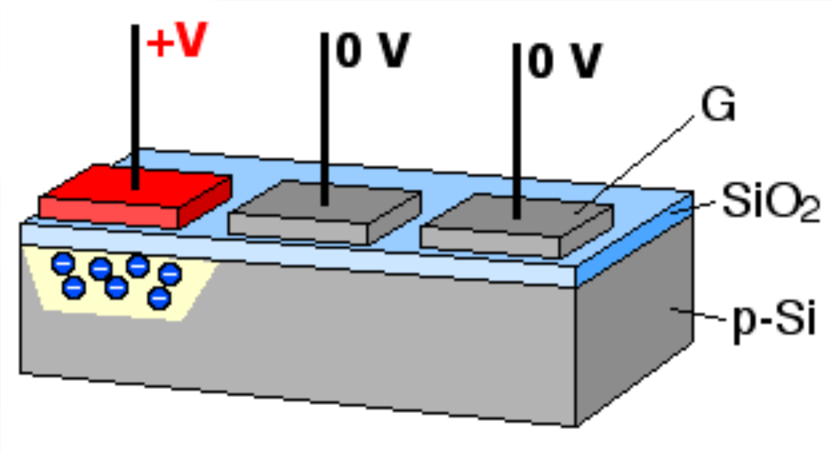


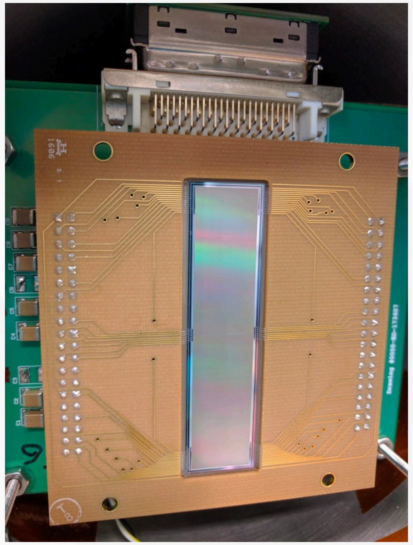

PHYSICAL REVIEW LETTERS 128, 171801 (2022

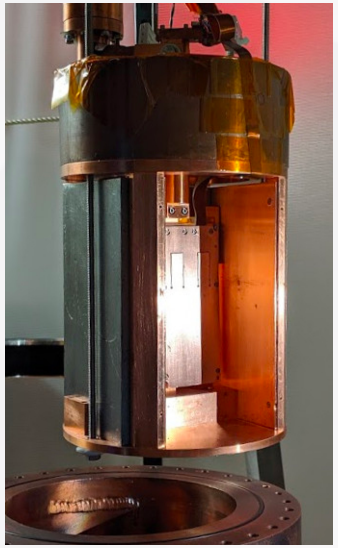


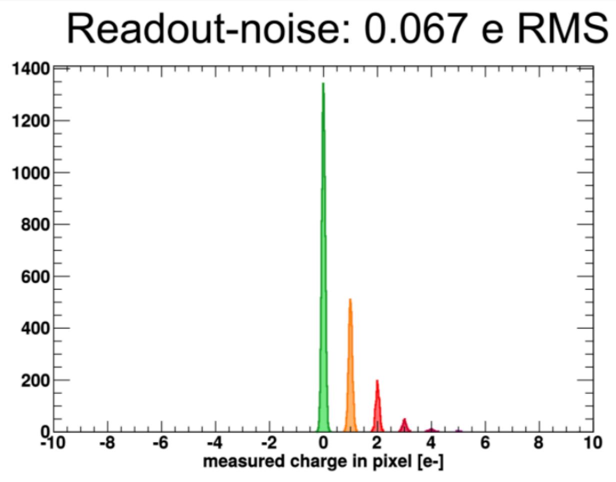

Expected diurnal modulation due to traveling length's day-night difference for transpassing boosted DM.

# Skipper CCD technique: SENSEI



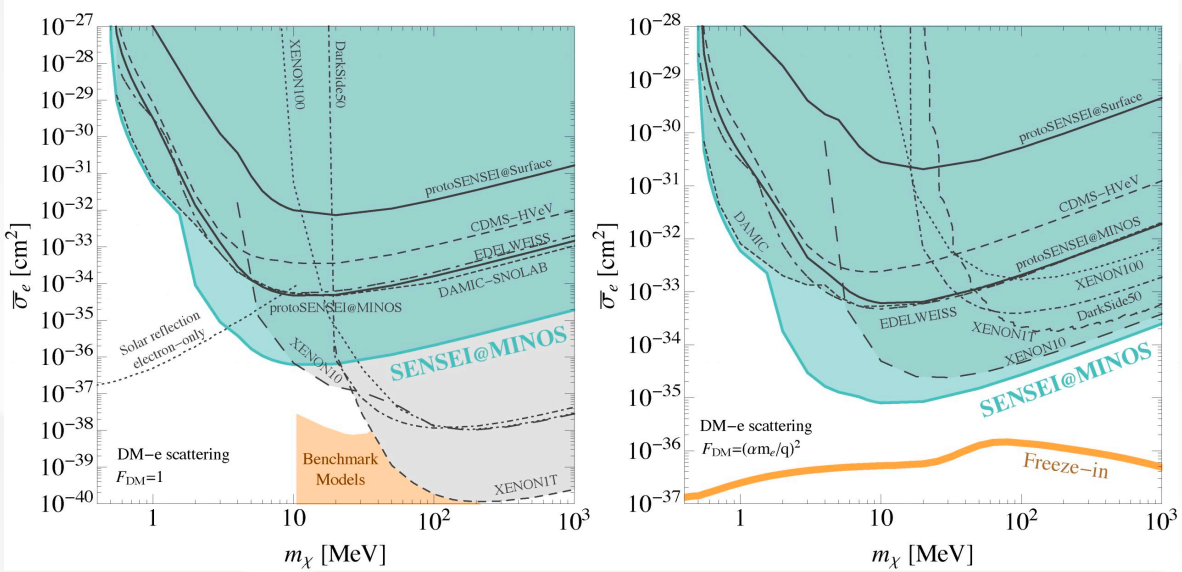







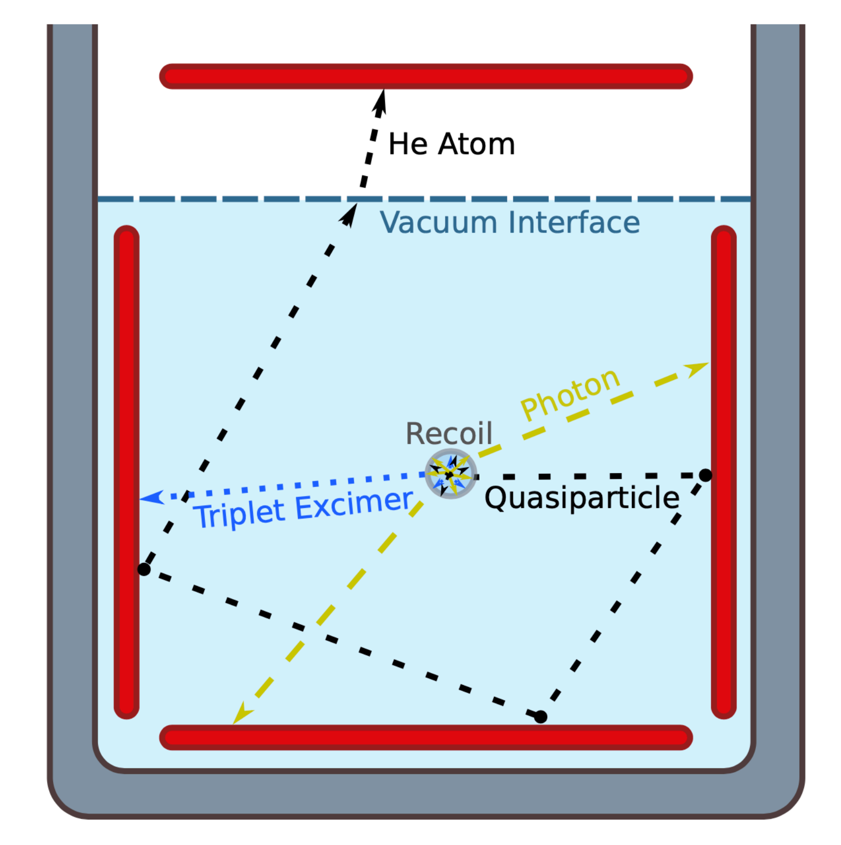

https://news.fnal.gov/2020/06/sensei-gets-quiet/

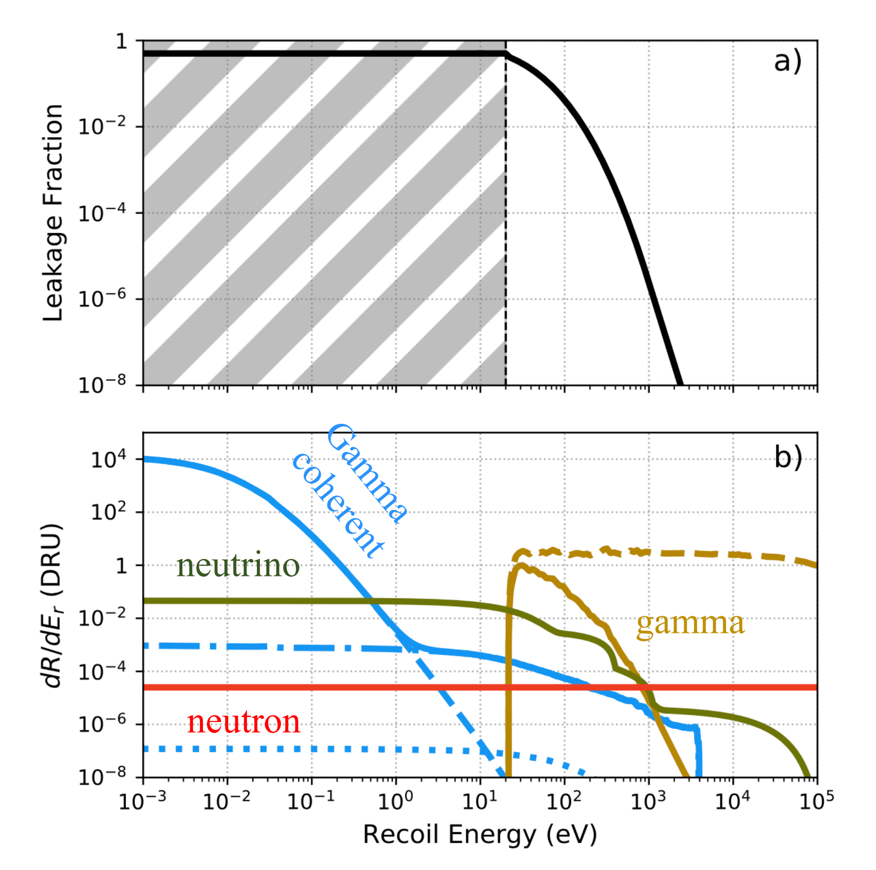
- 0.01 g Si Skipper CCD;
- Reduce noise through non-destructively measure charge multiple times;
- Single electron sensitivity with resolution to 6.7%.

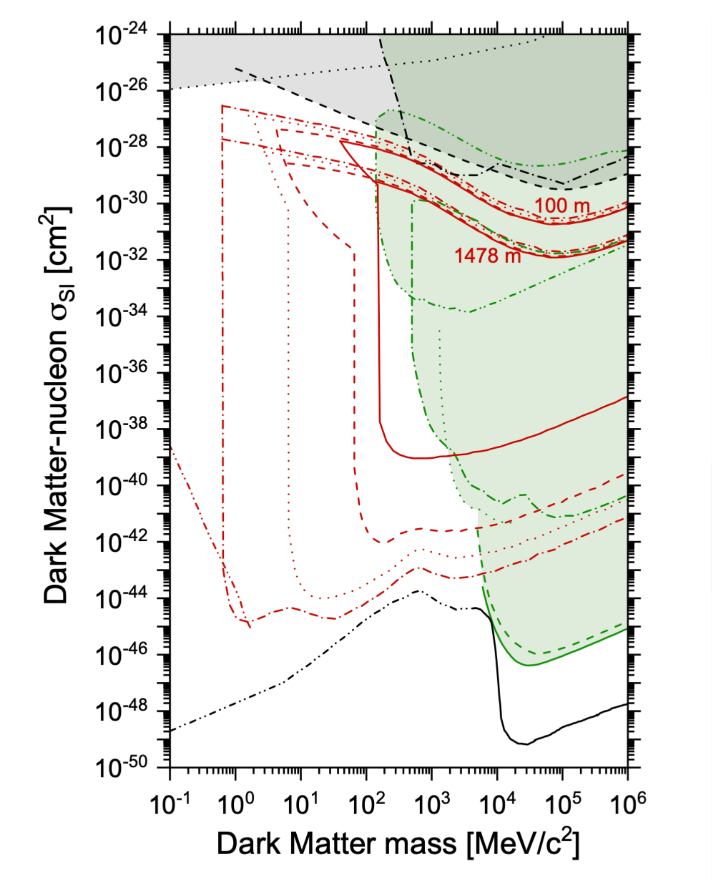


# Helium Detector

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



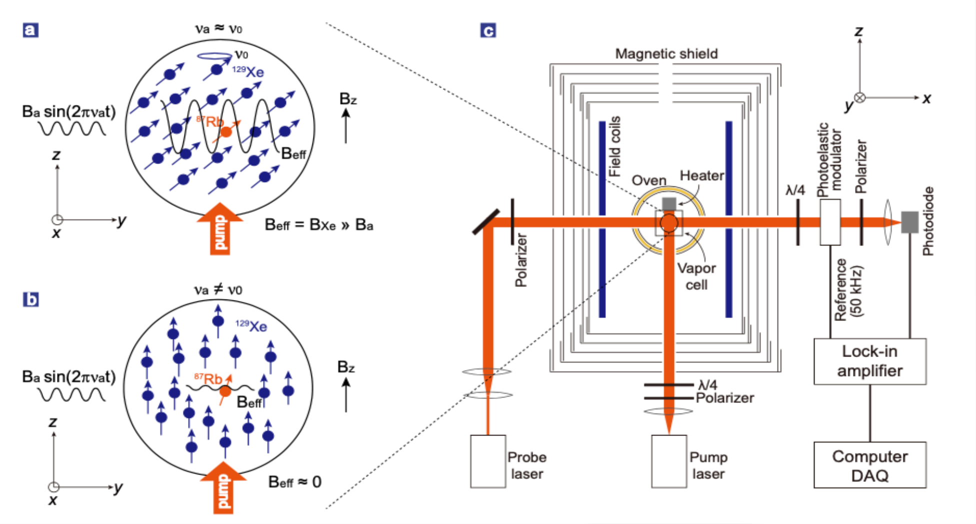




- ➢ Very low W value for roton and phonon;
- ➢ Quasiparticle propagate ballistically, including directionality;
- ➢ Background dominated by gamma and neutrino coherent scattering;

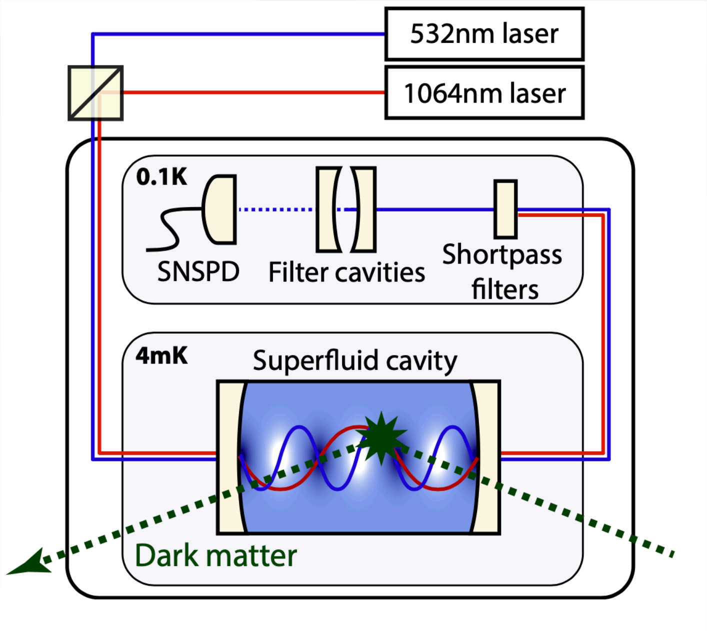
# Quantum sensors

## Magnetometer



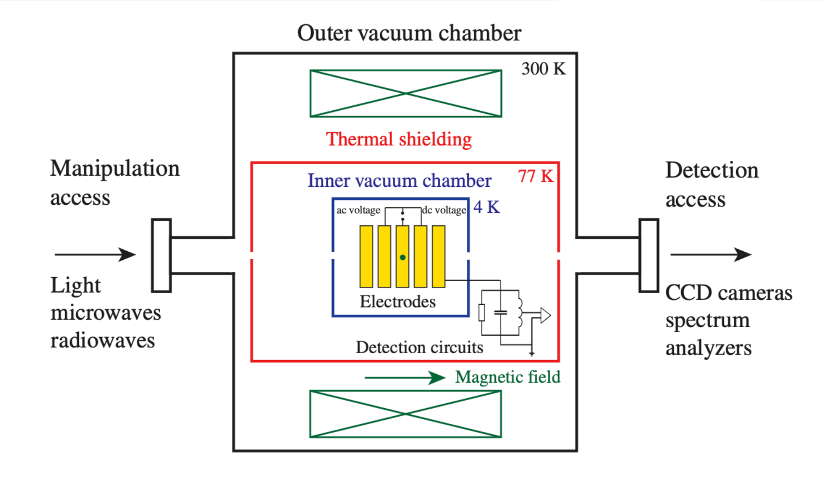

Nature Phys. 17, 1402–1407 (2021).

## Optimechanical




arXiv: 2306.09726

## Ion Trap




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