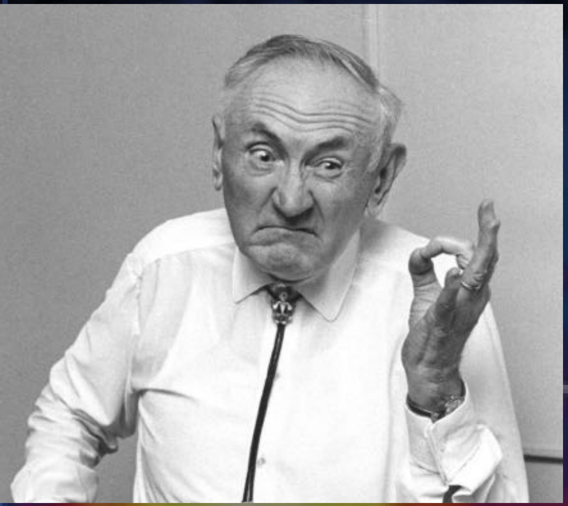
Overview of Dark Matter Physics

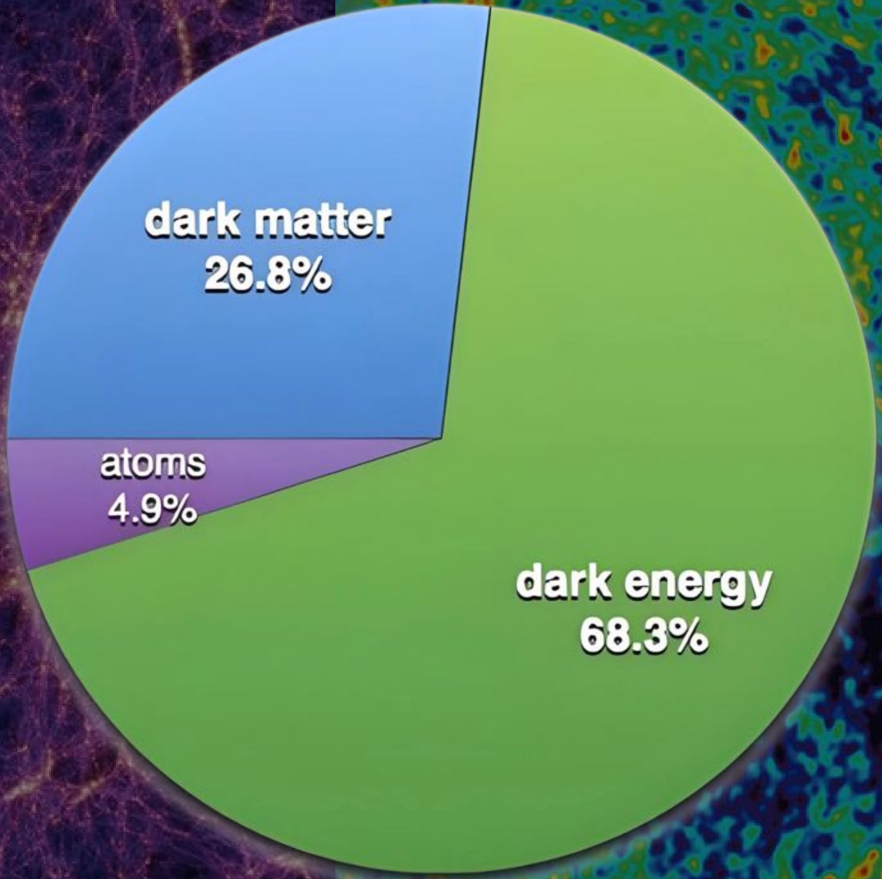
Ning Zhou
Shanghai Jiao Tong University

Search for New Physics at Colliders
Nanjing, 2026.04.17



Fritz Zwichy
1933

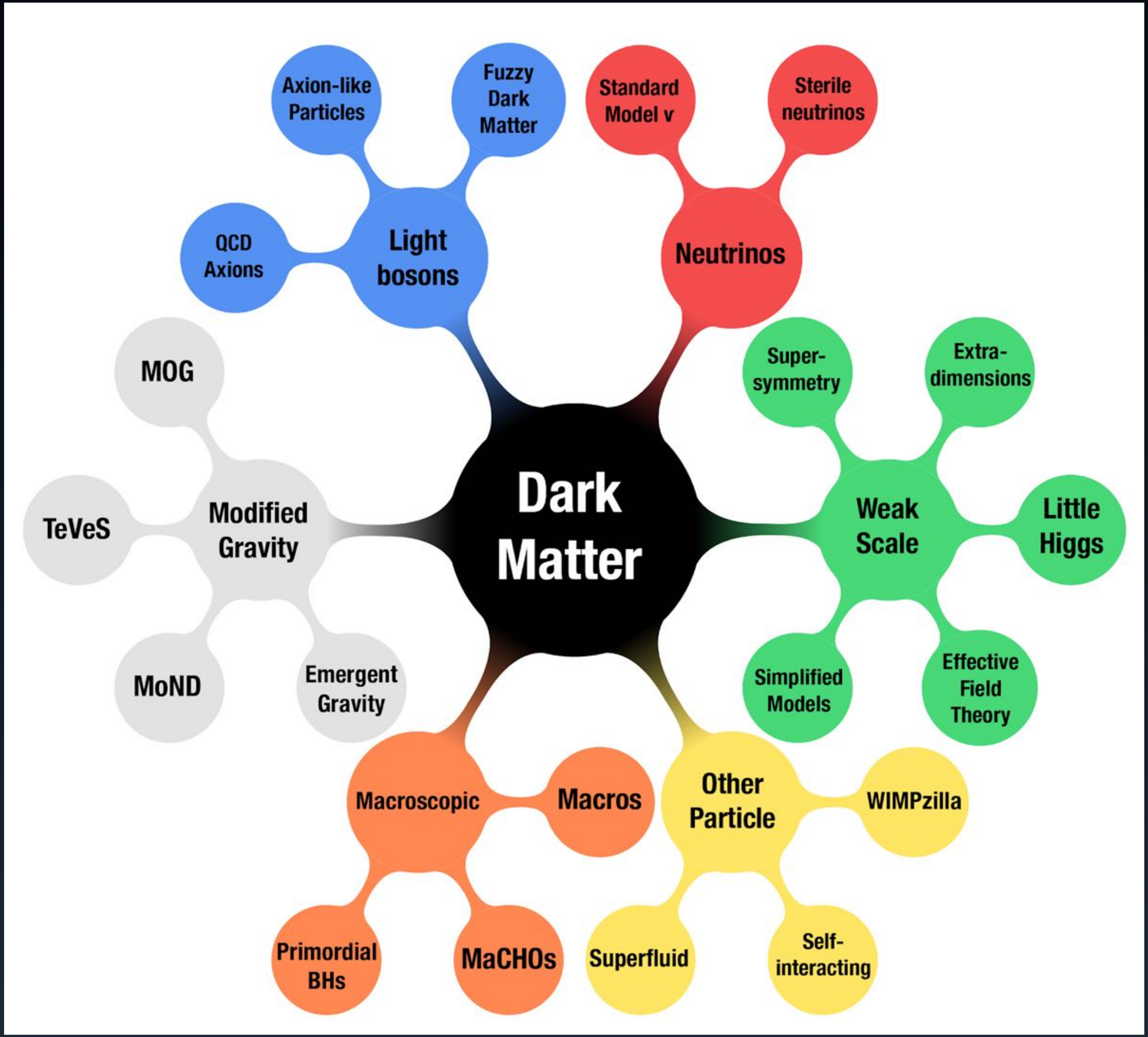
James Peebles
2019



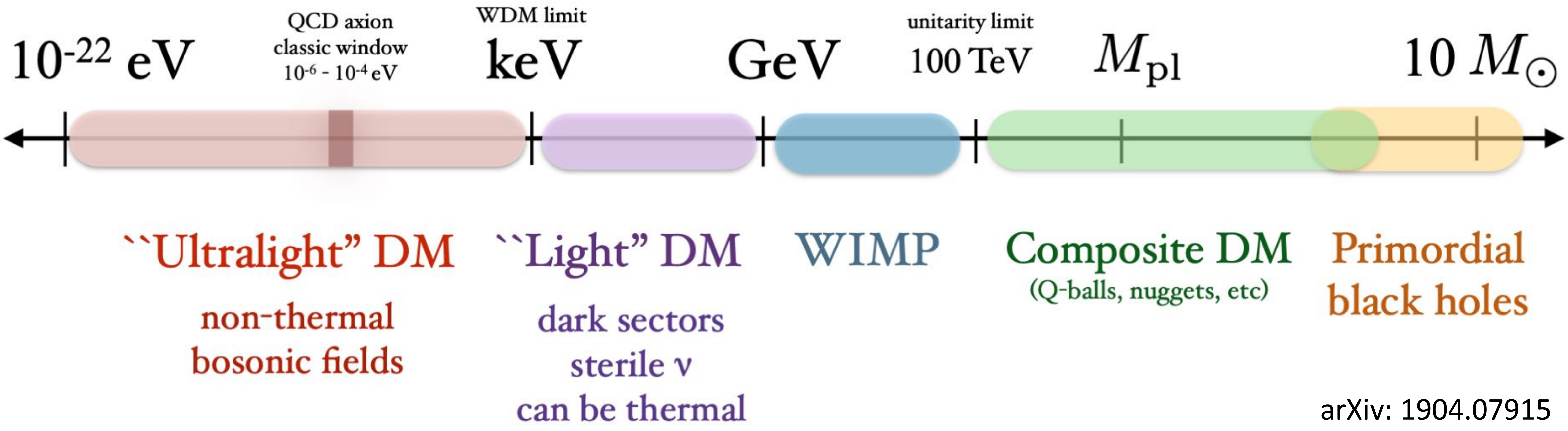
Mystery of Dark Matter

Physical properties?

BSM Interaction?


Dark Matter
Light bosons
QCD Axions
Axion-like Particles
Fuzzy Dark Matter
Neutrinos
Standard Model ν
Sterile neutrinos
Weak Scale
Super-symmetry
Extra-dimensions
Little Higgs
Effective Field Theory
Simplified Models
Other Particle
WIMPzilla
Self-interacting
Superfluid
Macroscopic
Macros
MaCHOs
Primordial BHs
Modified Gravity
MOG
TeVeS
MoND
Emergent Gravity

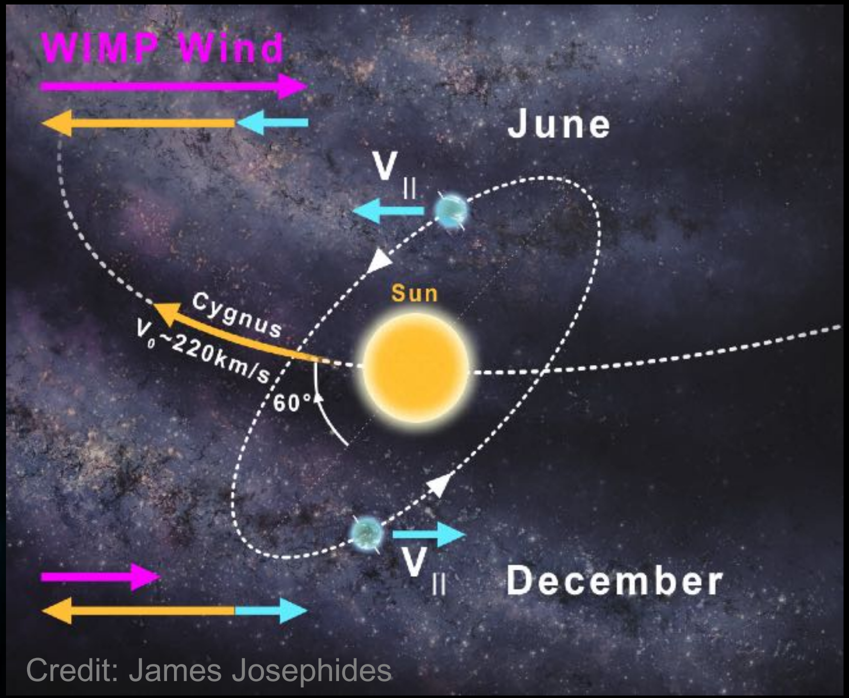
- **DM Candidates**

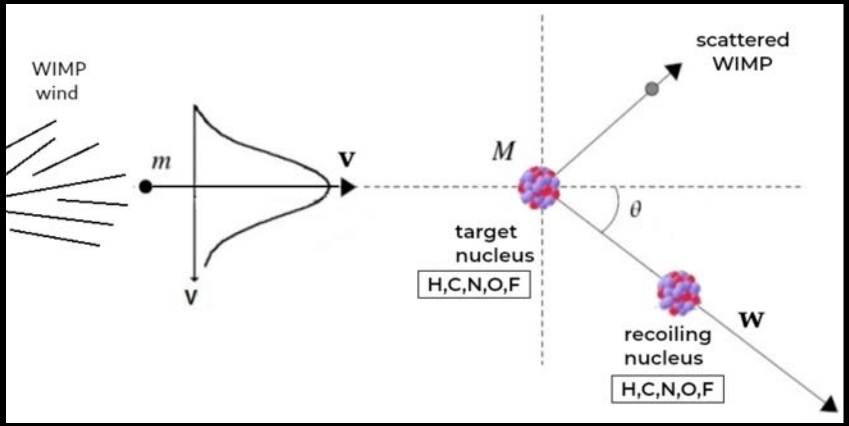


arXiv: 1904.07915

Dark Matter Direct Detection

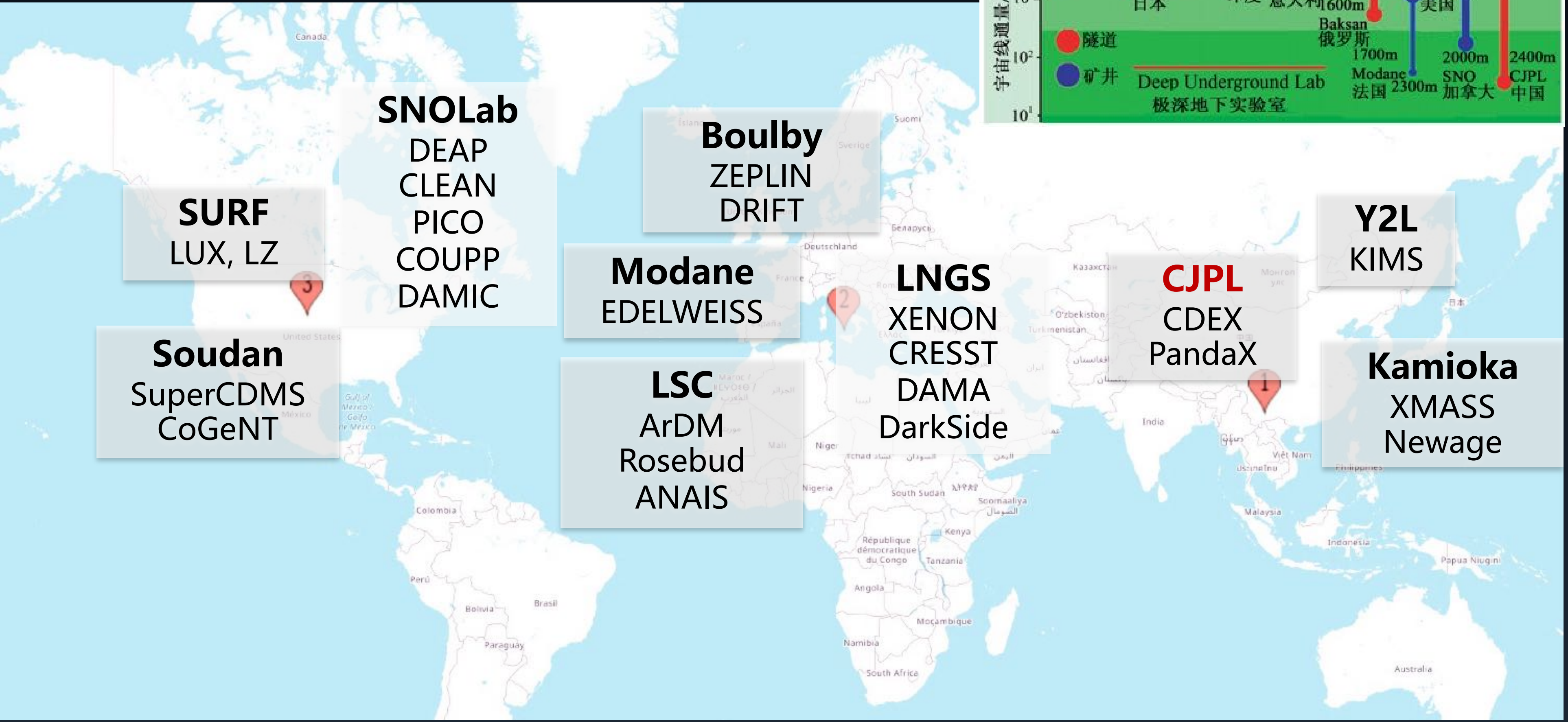
- **Local density**
  - 0.3 GeV/cm^3
- **Isothermal velocity distribution**
  - v_0~220 km/s
- **Nuclear recoil (NR)**
- **Electron recoil (ER)**

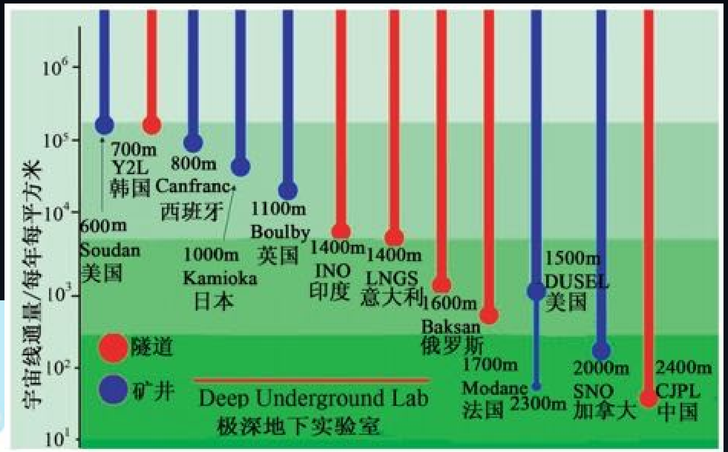




World-wide Efforts

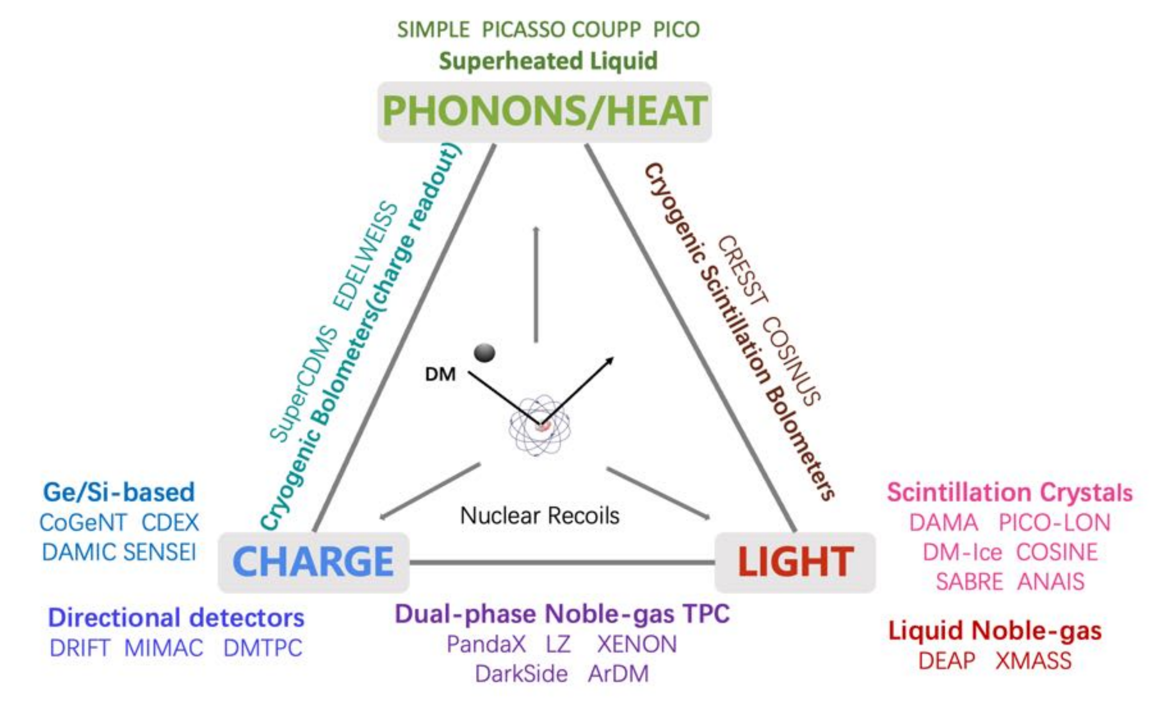
- **Underground laboratories**

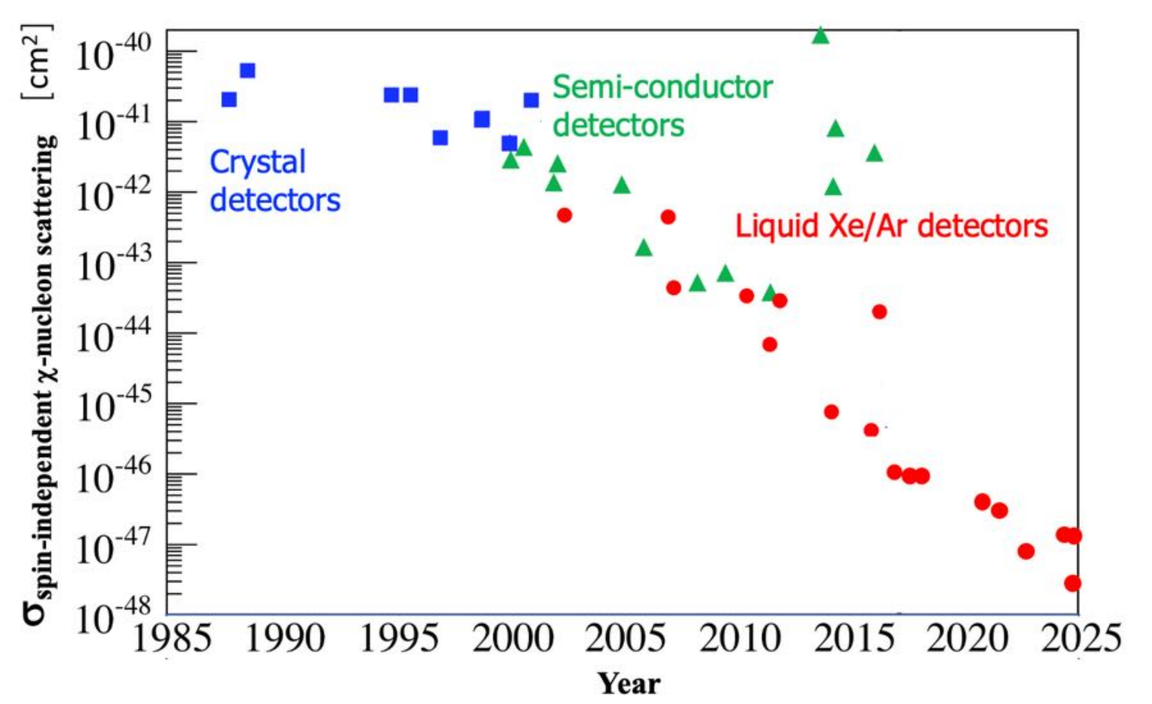




World-wide Efforts

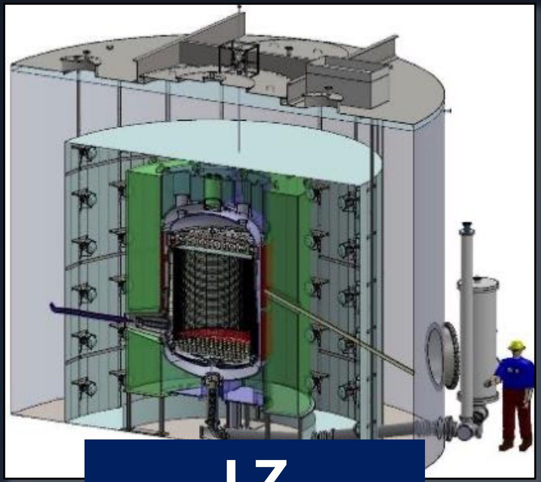
- **Various target materials, detecting photon/electron/phonon**
- **Pushing to lower background and lower threshold**





Noble LXe Time Projection Chamber

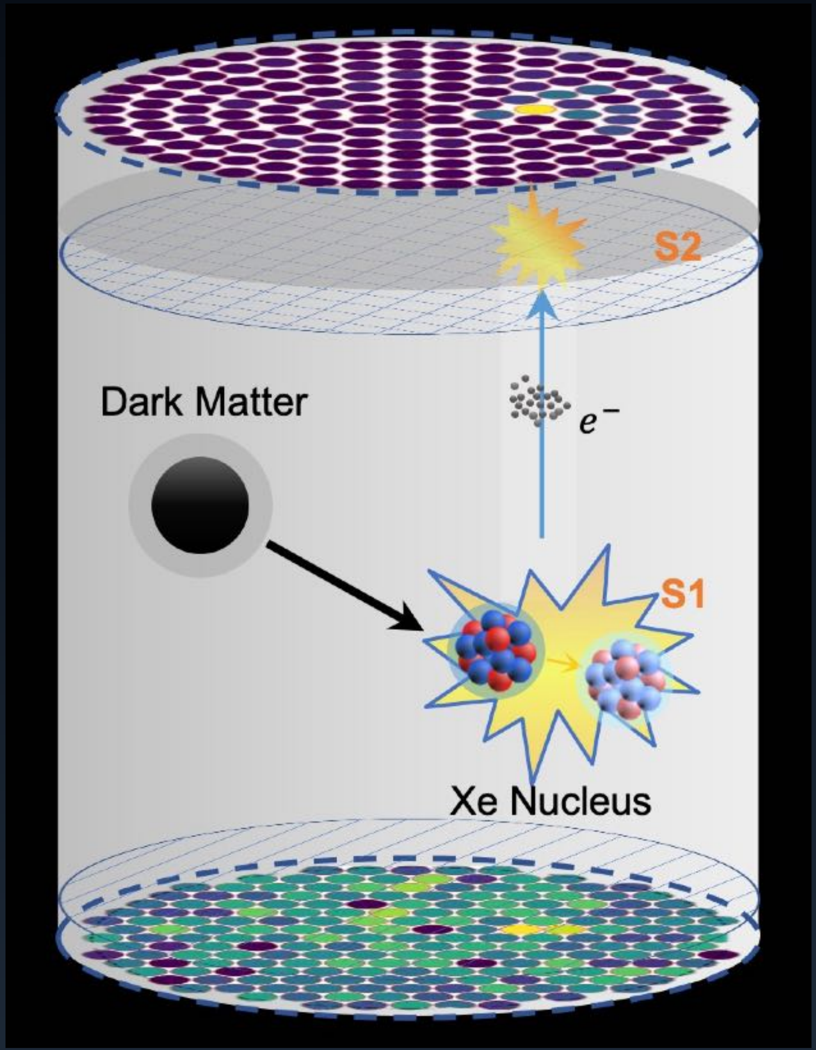
- **Scintillation light S1 and ionized electron S2**
- **Three leading xenon detectors**
  - – **LZ**@SURF: 7-ton sensitive target
  - – **XENONnT**@LNGS: 6-ton sensitive target
  - – **PandaX-4T**@CJPL: 4-ton sensitive target



LZ

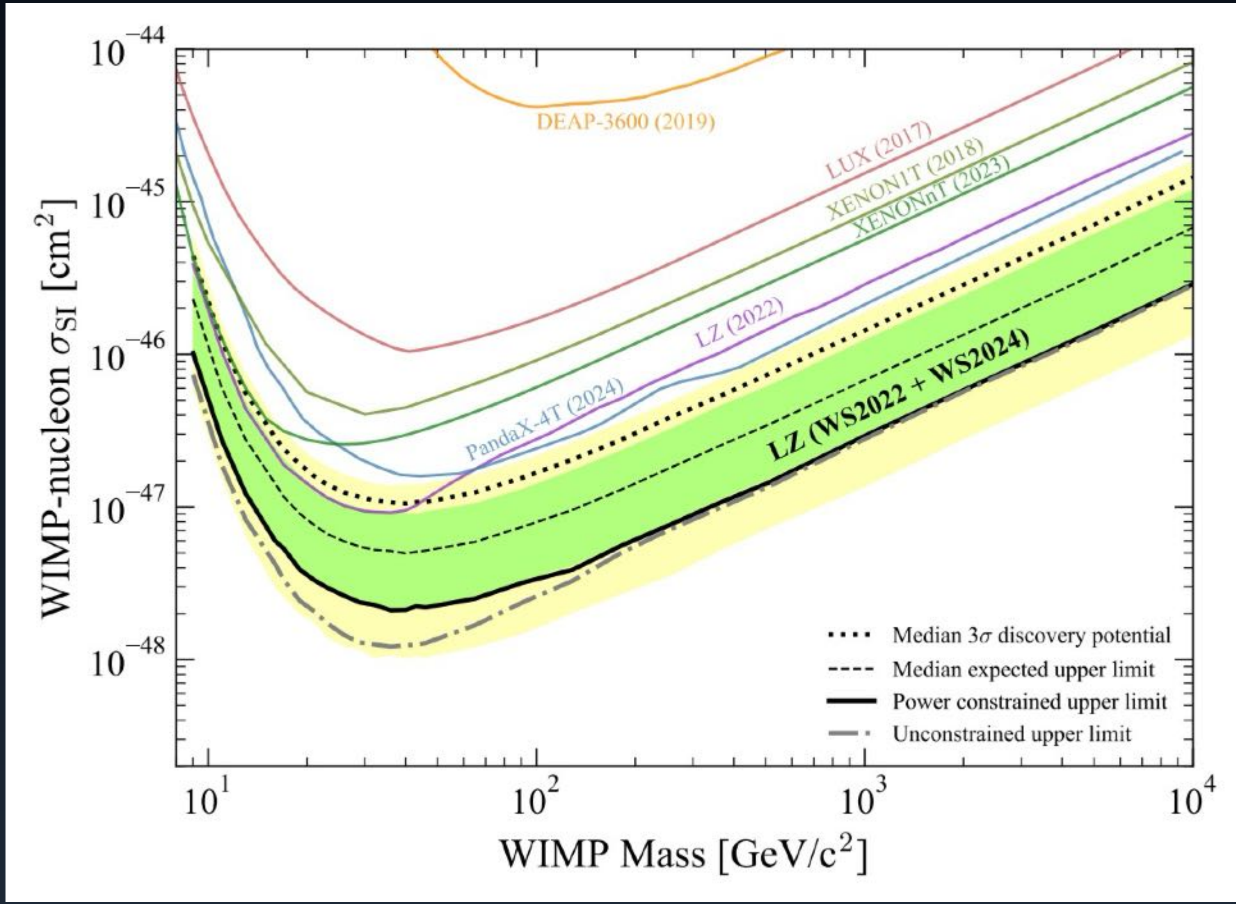
XENONnT

PandaX-4T



Noble LXe Time Projection Chamber

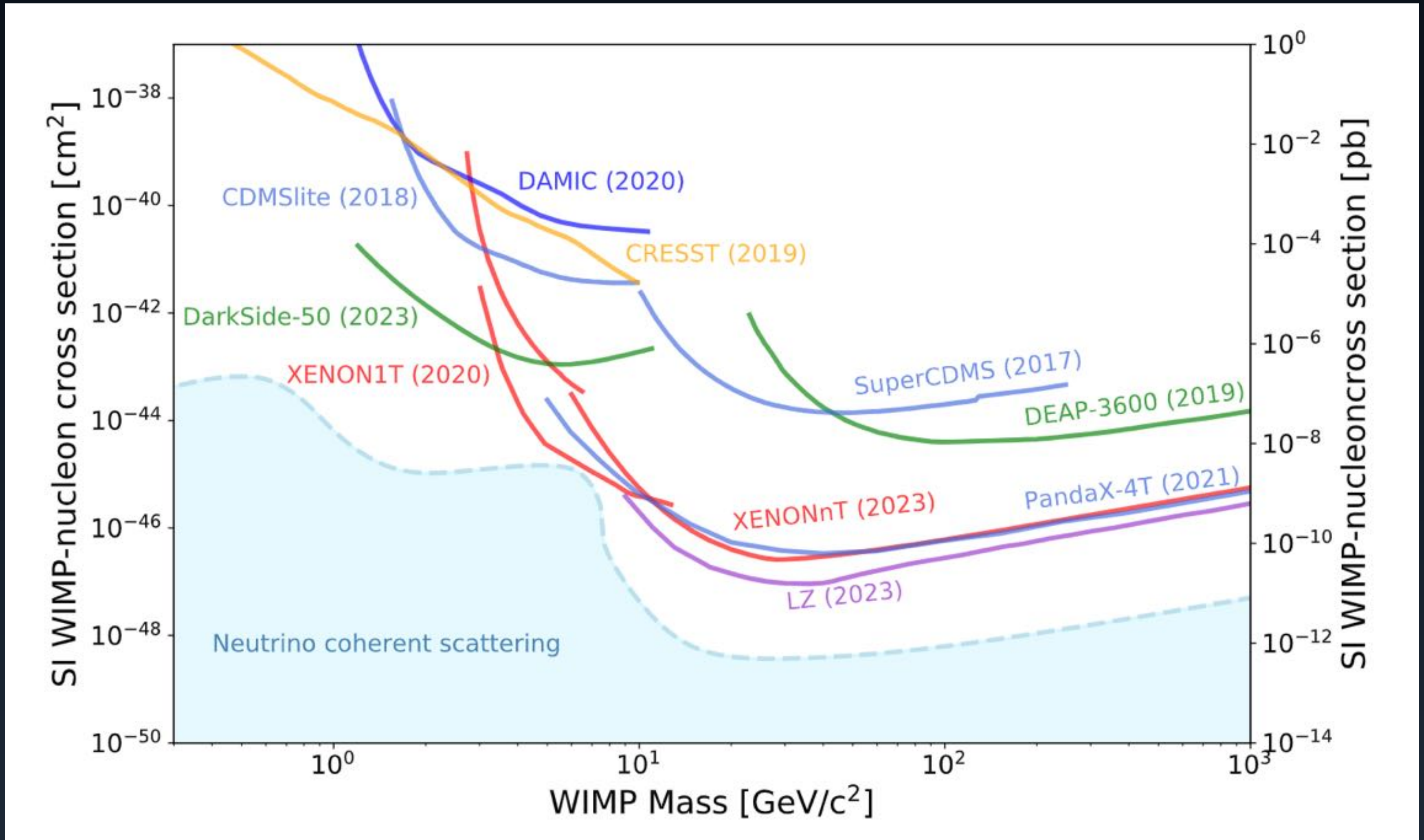
- **DM-nucleus elastic scattering**
  - Limits of σ_{SI} reaches 2×10^{-48} cm^2 at ~40 GeV/c^2 DM



arXiv:2410.17036
PRL 135, 011802 (2025)

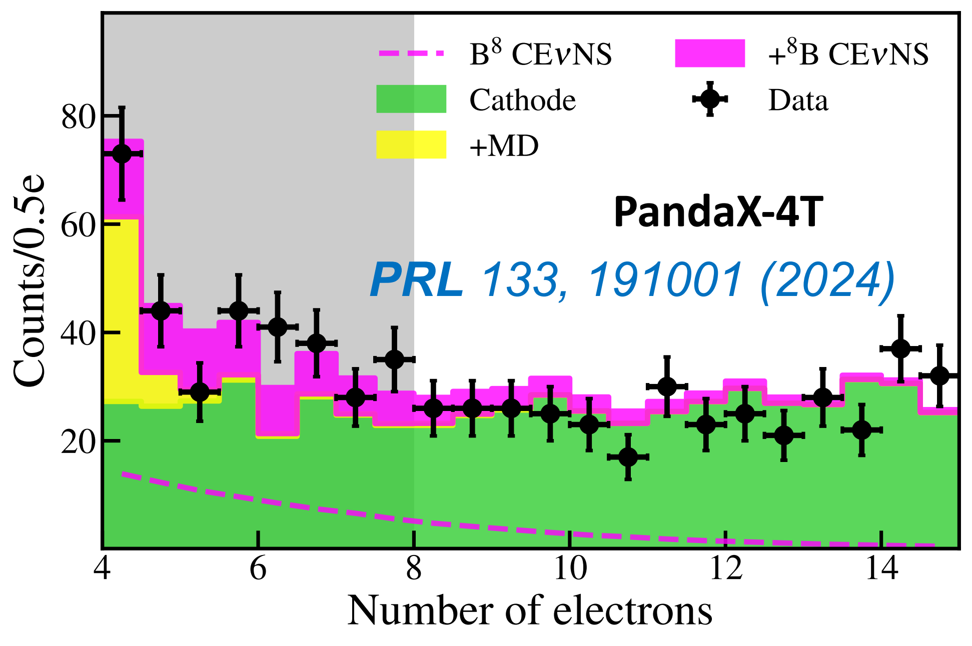
Towards Low Mass Dark Matter

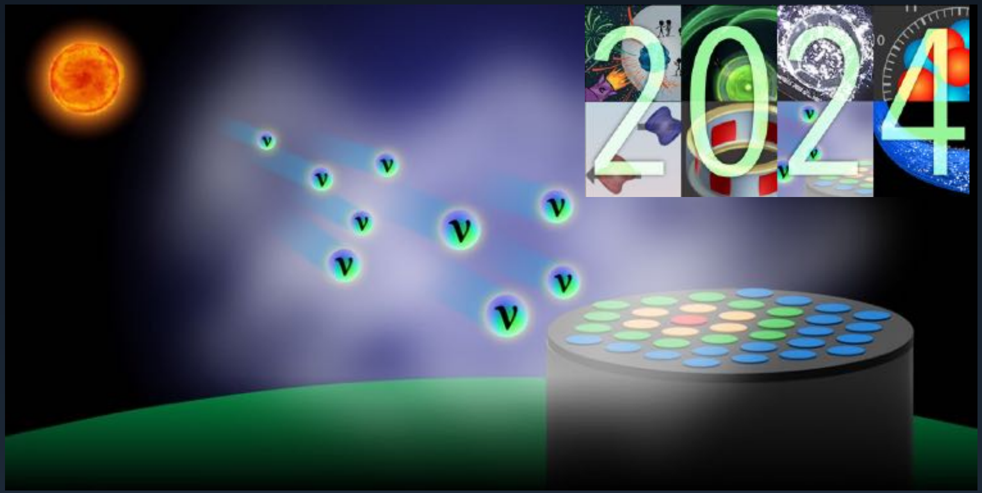
- **Sensitivity decreases significantly for DM mass < 10 GeV**
  - Limited by scintillation light signal detection



First Indication of Solar ^{8}B Neutrino CEvNS

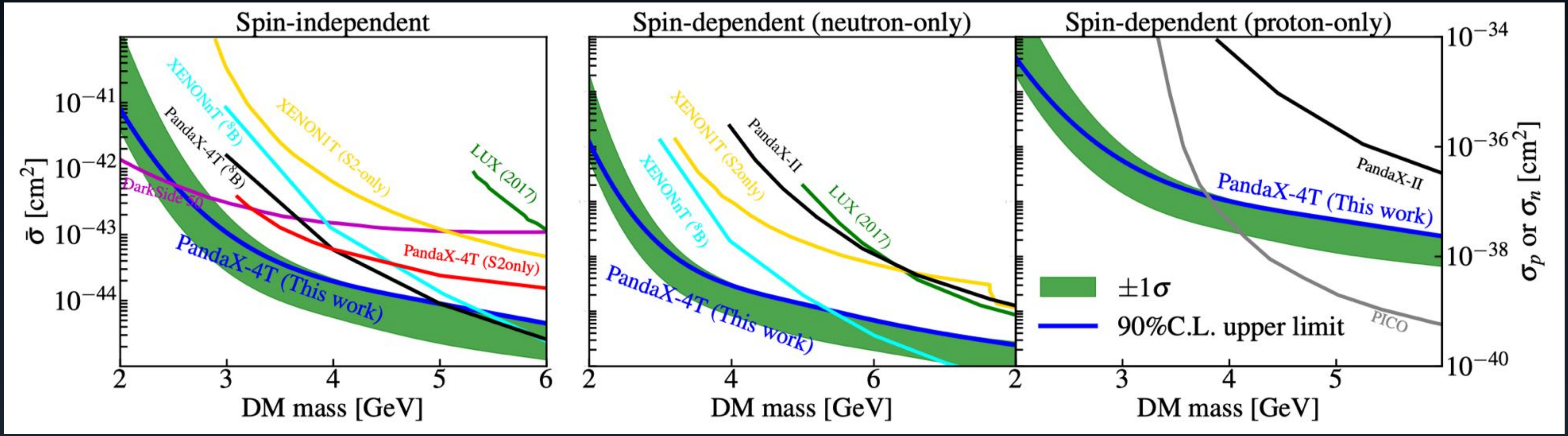
- **Low threshold detection: S2-only**
  - Threshold 3keV->0.3keV
- **PandaX-4T: 1.0 tonne-year**
  - S2only and Paired ROIs: 2.64σ
  - Best-fit ^{8}B yield
    - Paired: **3.5 ± 1.3** events
    - S2only: **75 ± 28** events
- **Demonstrating low-mass DM detection capability**





Low-threshold Detection for Low Mass

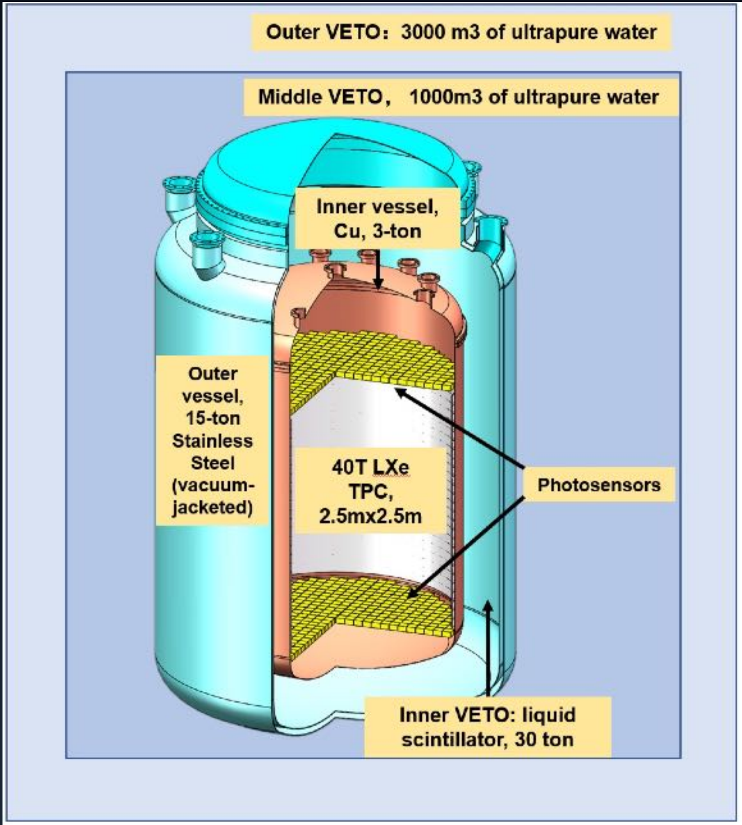
- **Extending LXe high-sensitive region to 2–6 GeV/c^2**
  - SI ~10^{-41}–10^{-44} cm^2, SD-neutron ~10^{-39} cm^2, SD-proton ~10^{-38} cm^2

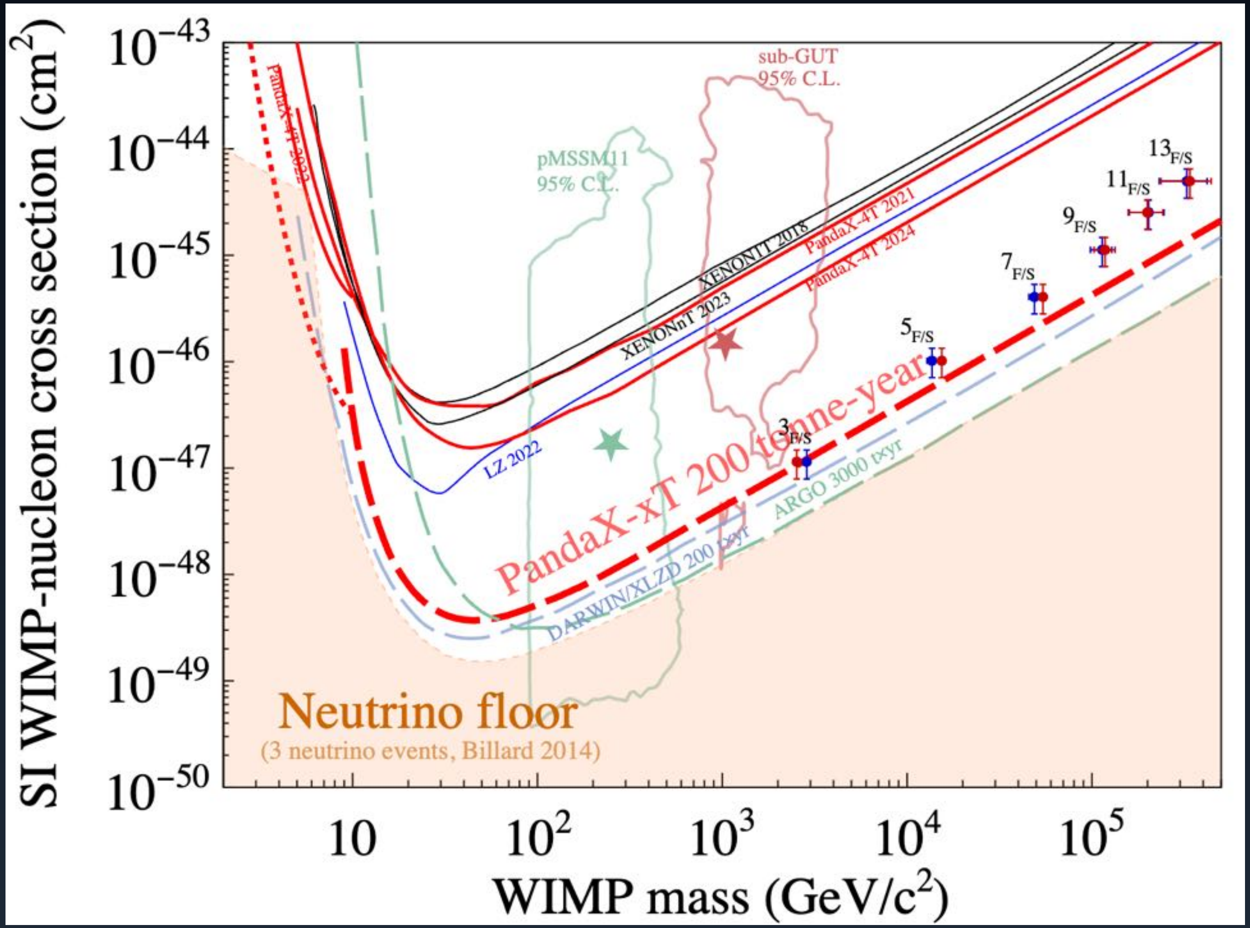


PRL 135, 211001 (2025)

Future Experiment: PandaX-xT

- **200 tonne-year Exposure**
  - Key tests on WIMP and Dirac/Majorana neutrino

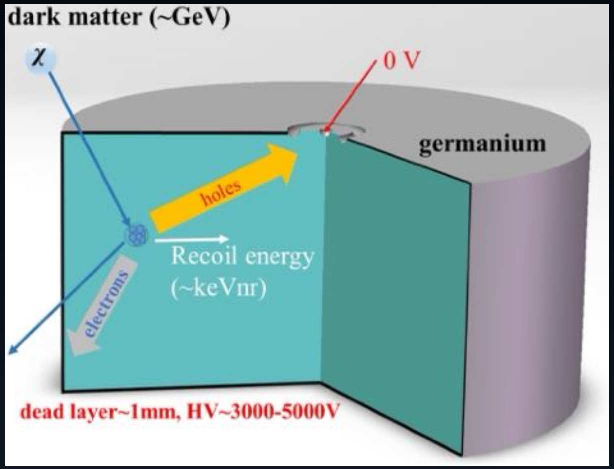




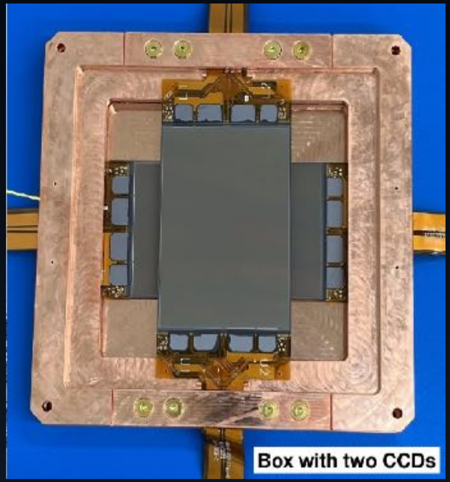
arXiv:2402.03596, ***SCPMA*** *68, 221011 (2025)*

Solid Target Detectors

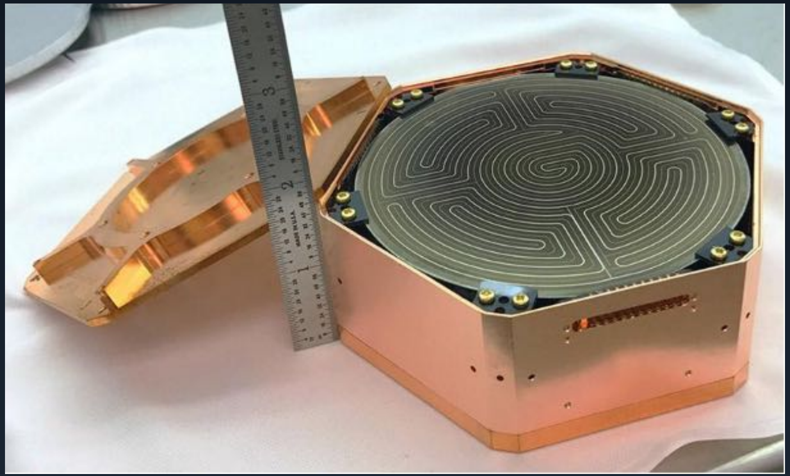
- **Low threshold detectors**
  - Cryogenic solid target
  - Ge, Si, $CaWO_4$, Skipper CCD



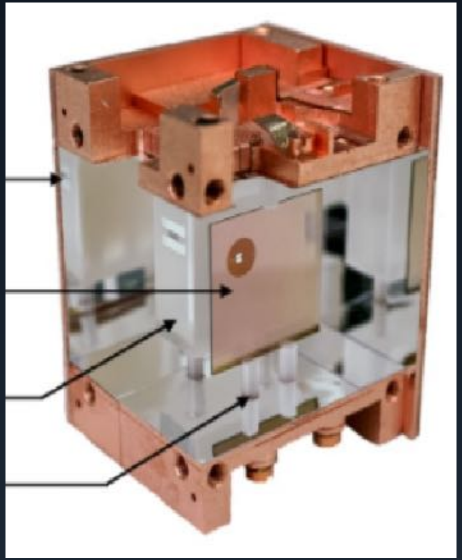
CDEX



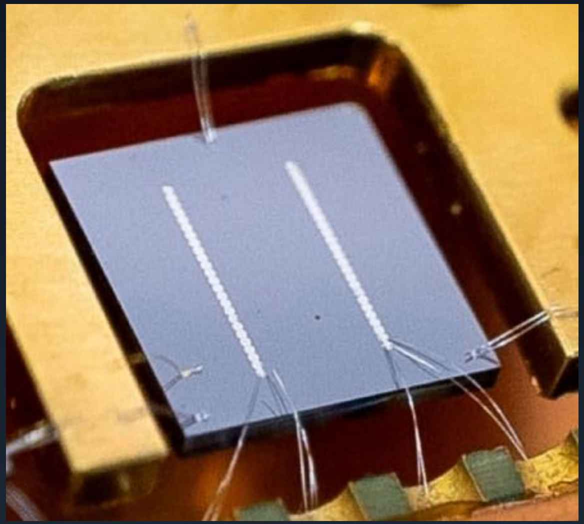
DAMIC-M



SuperCDMS



CRESST

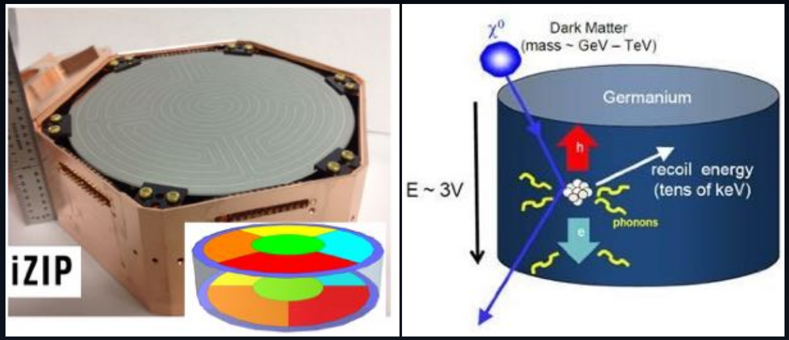


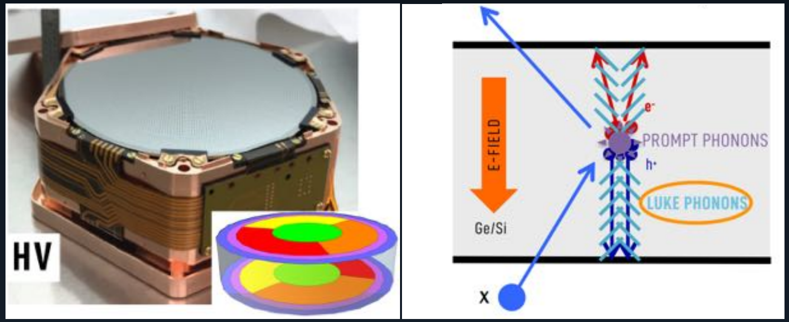
TESSERACT

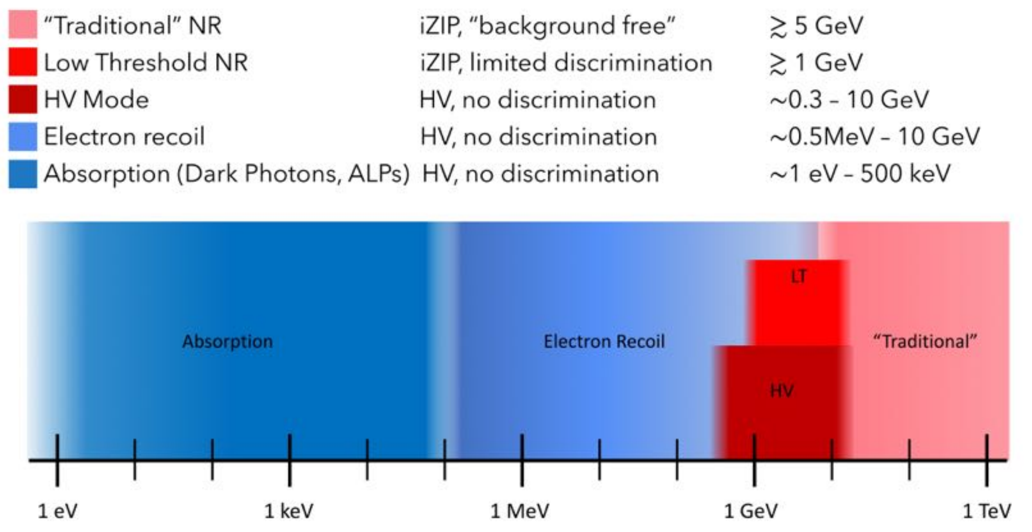
SuperCDMS

arXiv:2203.08463

- **Low threshold heat and ionization detector primarily for low mass**
  - Phonon readout via Transition edge sensors
  - Charge readout via interleaved electrodes
  - Threshold can be lowered to ~100eV NR

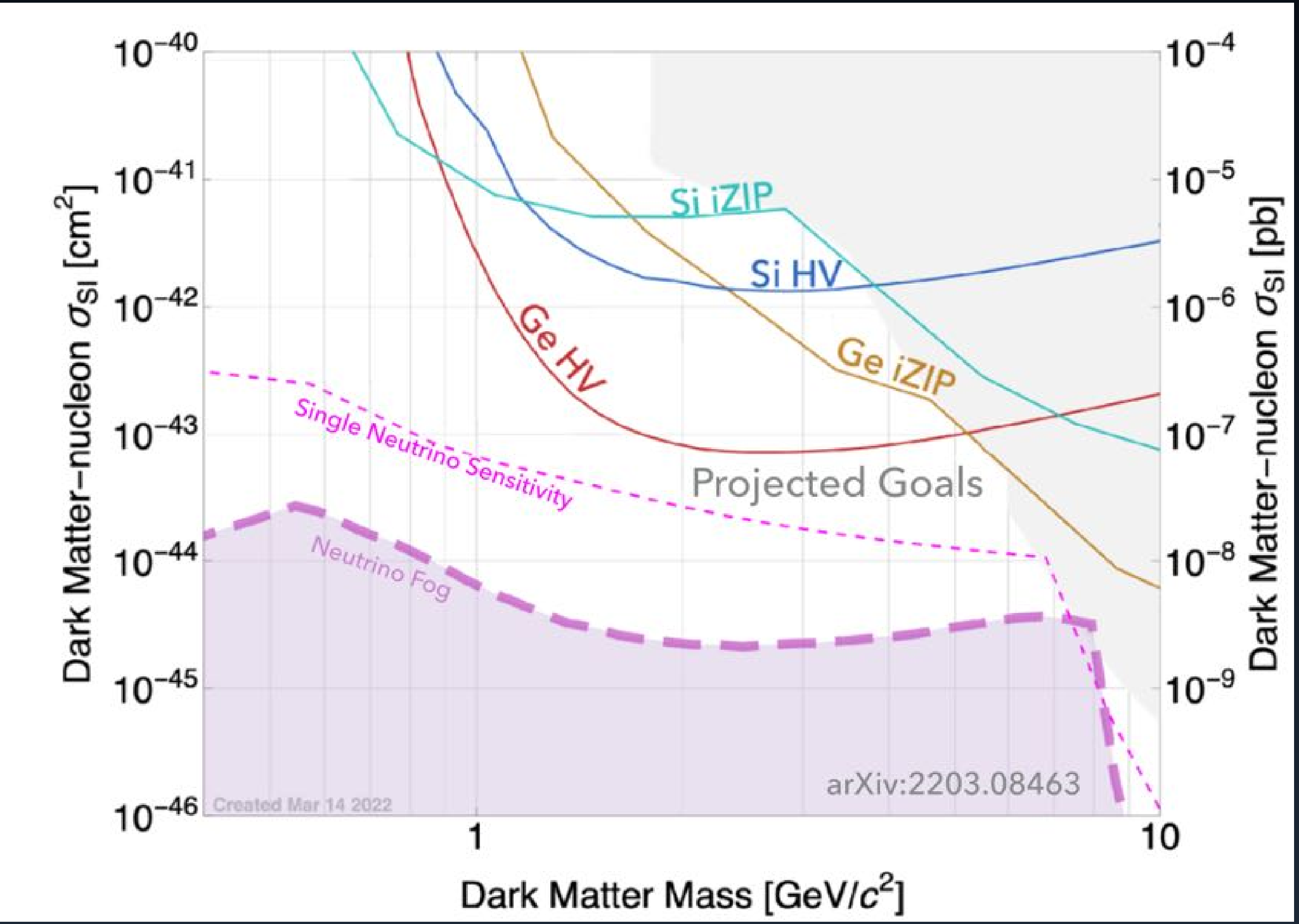






SuperCDMS

- **Expected to cover ~1 GeV/c^2 DM**

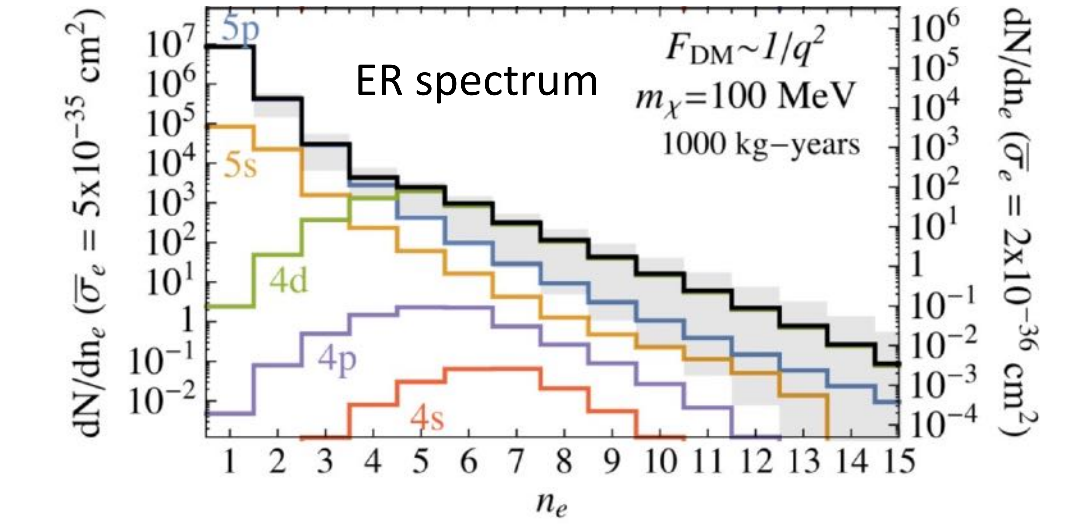


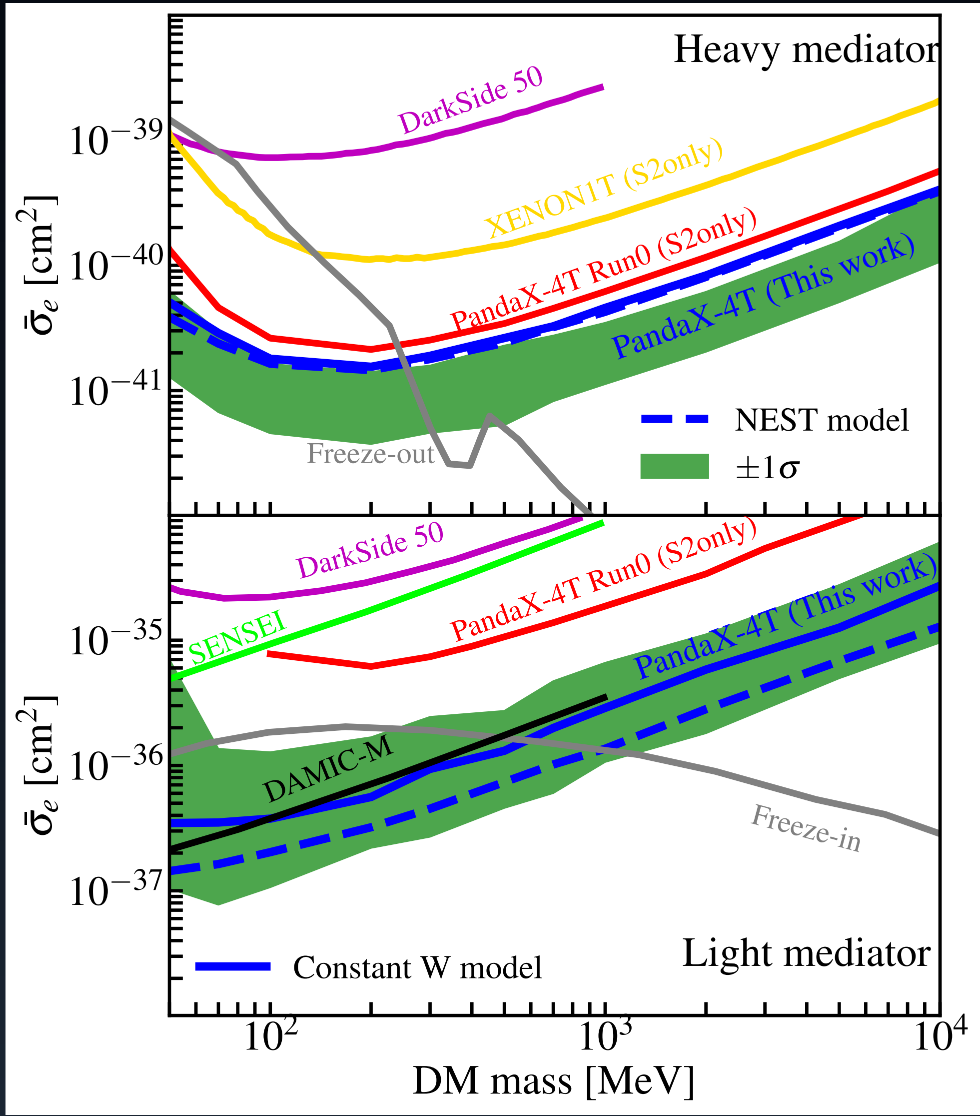
WIMP-Electron Scattering

- **WIMP-electron coupling**
  - Heavy mediaor or light mediator

$$\frac{dR}{d\ln E_{\rm er}} = N_T \frac{\rho_\chi}{m_\chi} \sum_{nl} \frac{d\langle \sigma_{\rm ion}^{nl} v\rangle}{d\ln E_{\rm er}}$$

$$\frac{d\langle \sigma_{\rm ion}^{nl} v\rangle}{d\ln E_{\rm er}} = \frac{\overline{\sigma}_e}{8\,\mu_{\chi e}^2} \int dq\, q\, |f_{\rm ion}^{nl}(k', q)|^2 \, |F_{\rm DM}(q)|^2 \, \eta(v_{\rm min})$$

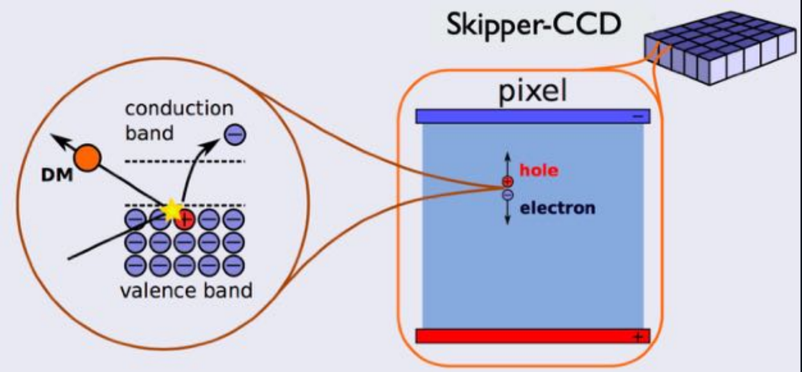




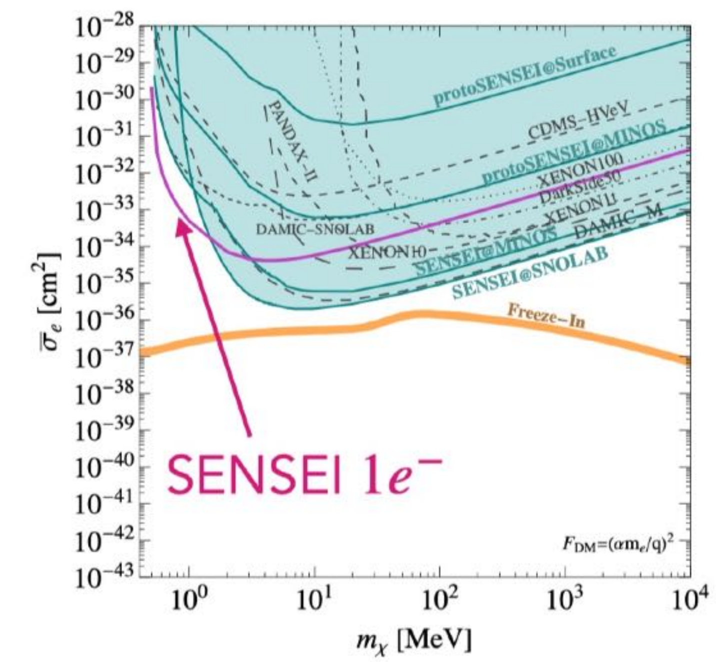
- **Probing DM mass ~100MeV/c² in LXe**

SENSEI / DAMIC-M

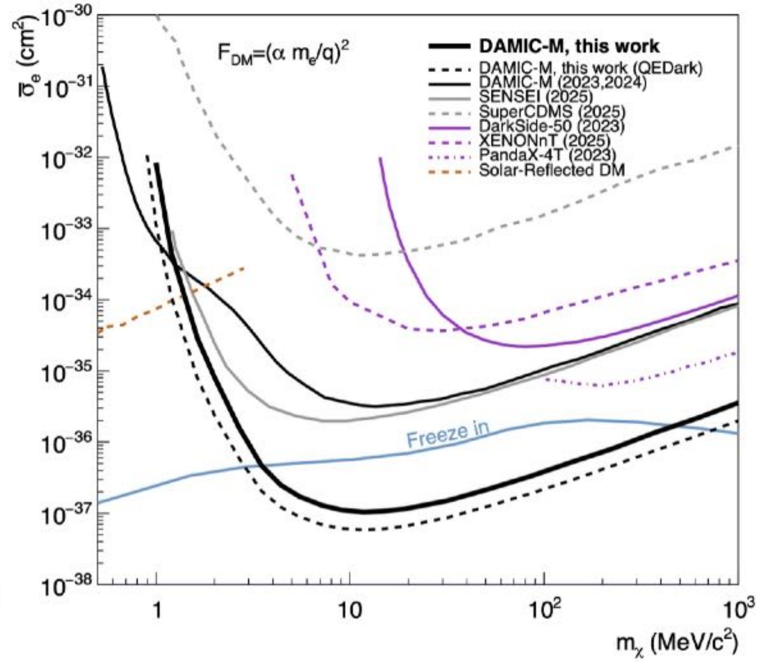
- **Skipper-CCDs, probing DM ~MeV/c²**
  - going down to 1e⁻ threshold
- **SENSEI @SNOLAB**
  - 19 Skipper-CCDs (~40g)
  - ~39.8 e⁻ /g/day
- **DAMIC-M @Modane**
  - 26.4g, 2e⁻ to 4e⁻
  - exposure ~1.3 kg-day
  - will scale up to ~700g



arXiv:2410.18716

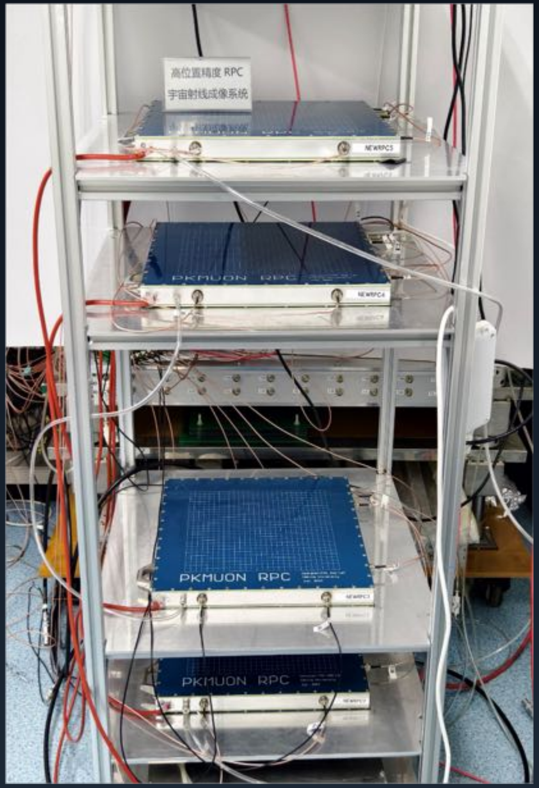


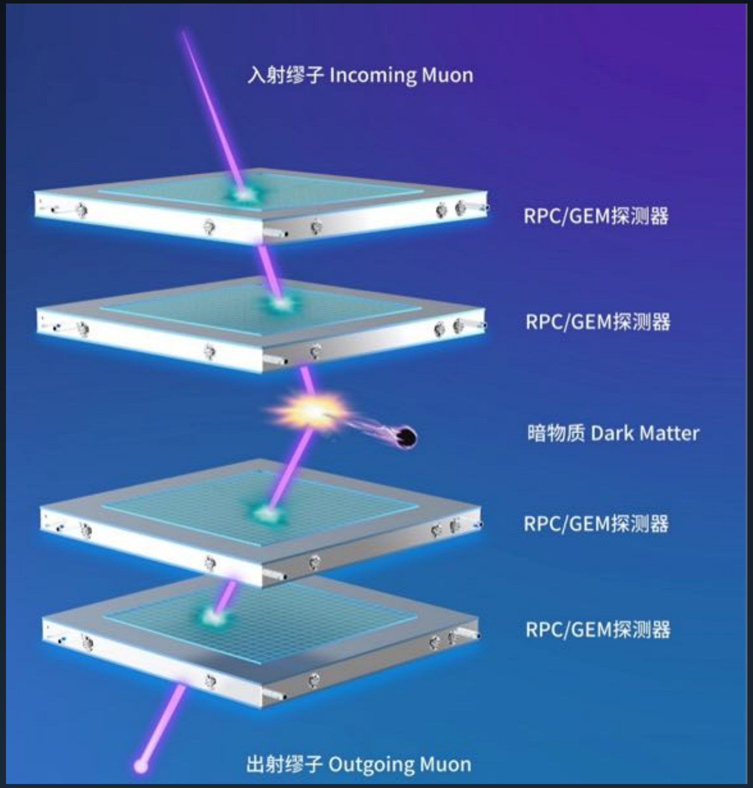
arXiv:2503.14617

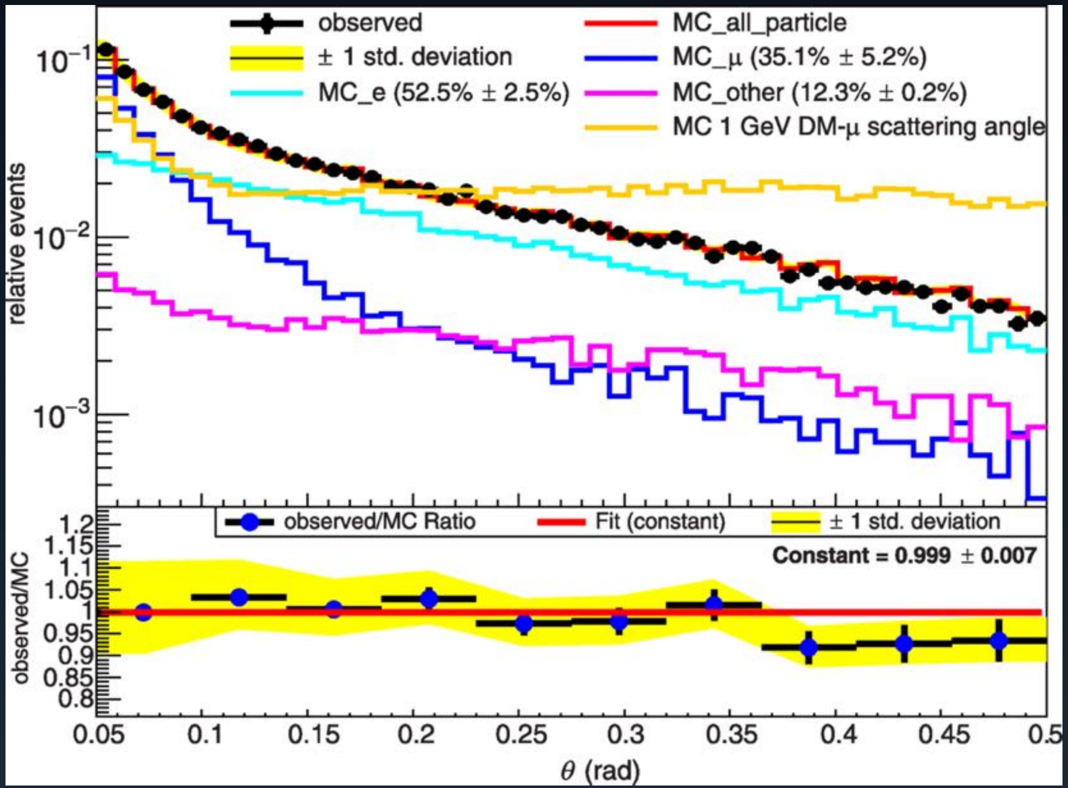


PKMu: Probing and Knocking with Muon

- **Muon Tomography**
  - 63-day campaign from Feb 12, 2025, 1.18 million cosmic ray scattering events recorded.

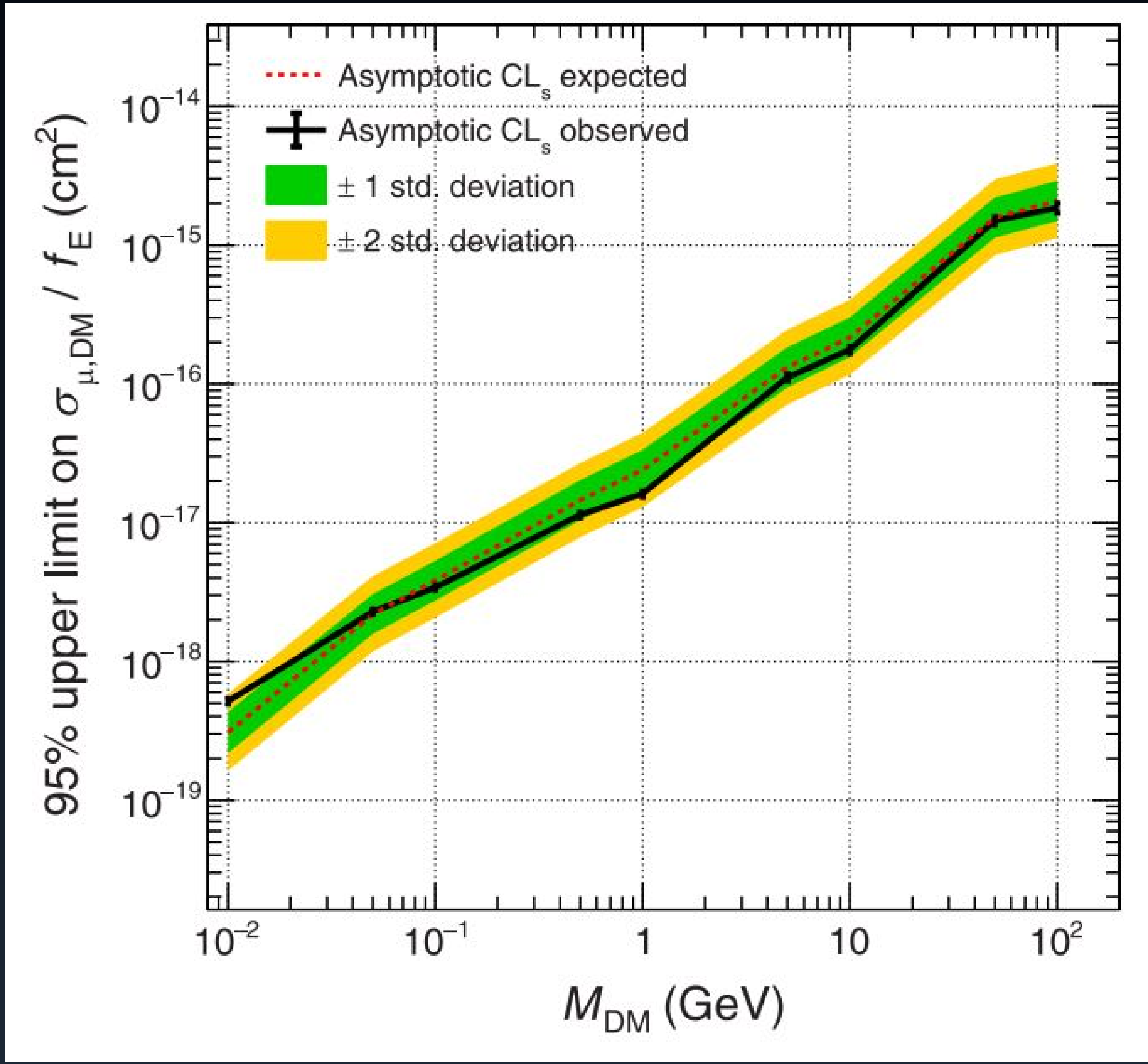






PKMu: Probing and Knocking with Muon

- **Use the scattering angle to scan 0.01~100 GeV/c² muon philic DM**



Qite Li, Chen Zhou, Qiang Li et.al.

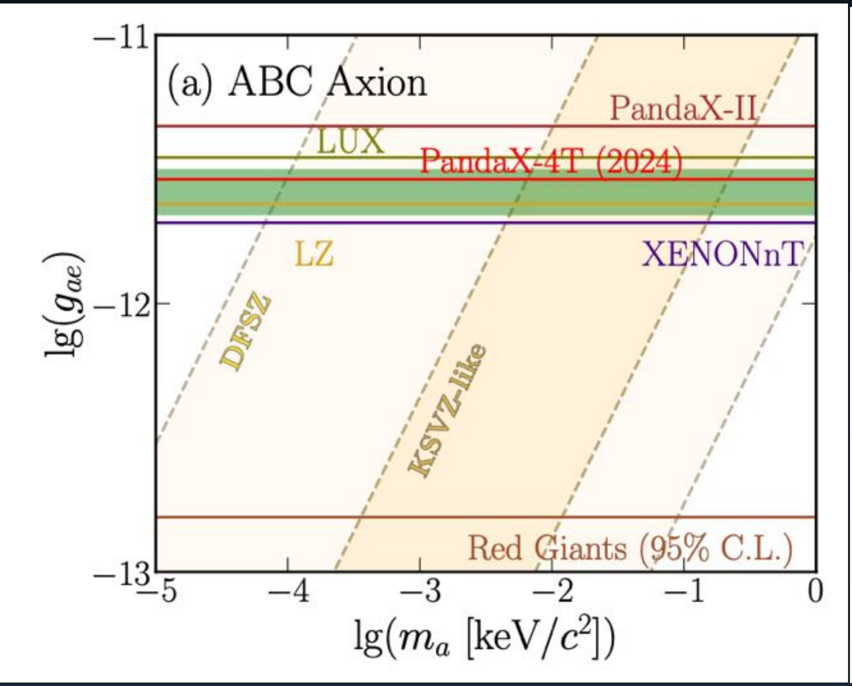
***PRL** 136, 151001 (2026)*

Accelerated Low Mass DM

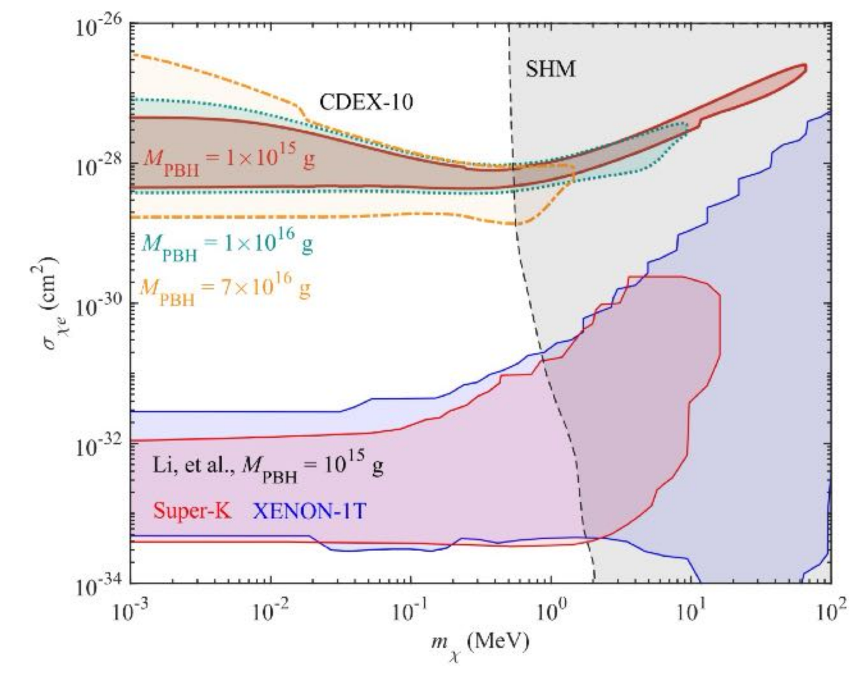
- The Universe is a big accelarator
- Accelerating light DM based on the same interaction

Accelerated Low Mass DM

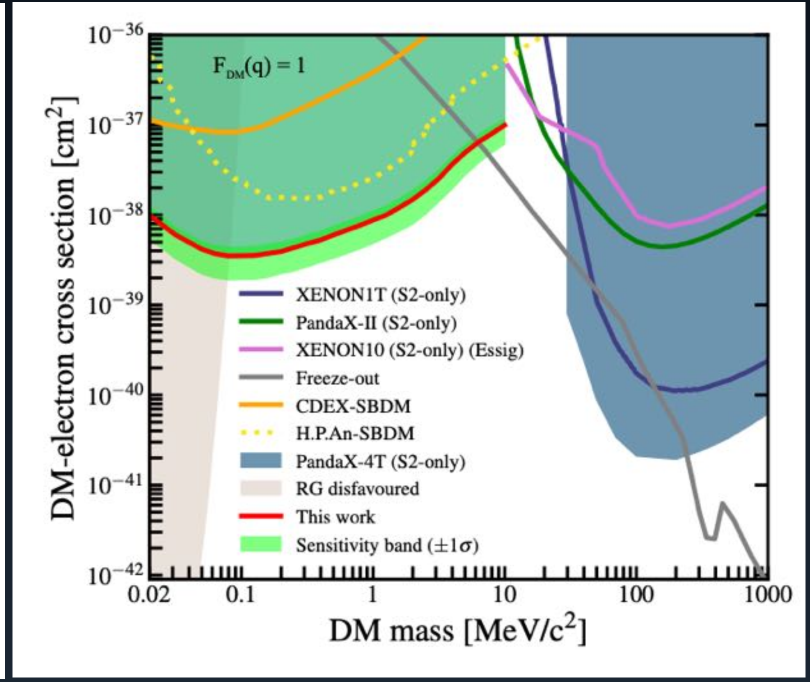
- The Universe is a big accelarator
- Accelerating light DM based on the same interaction
- Covering DM mass ~keV/c²



Solar Axion *arXiv:2408.07641*



DM from PBH *arXiv:2403.20263*



Solar boosted DM *arXiv:2412.19970*

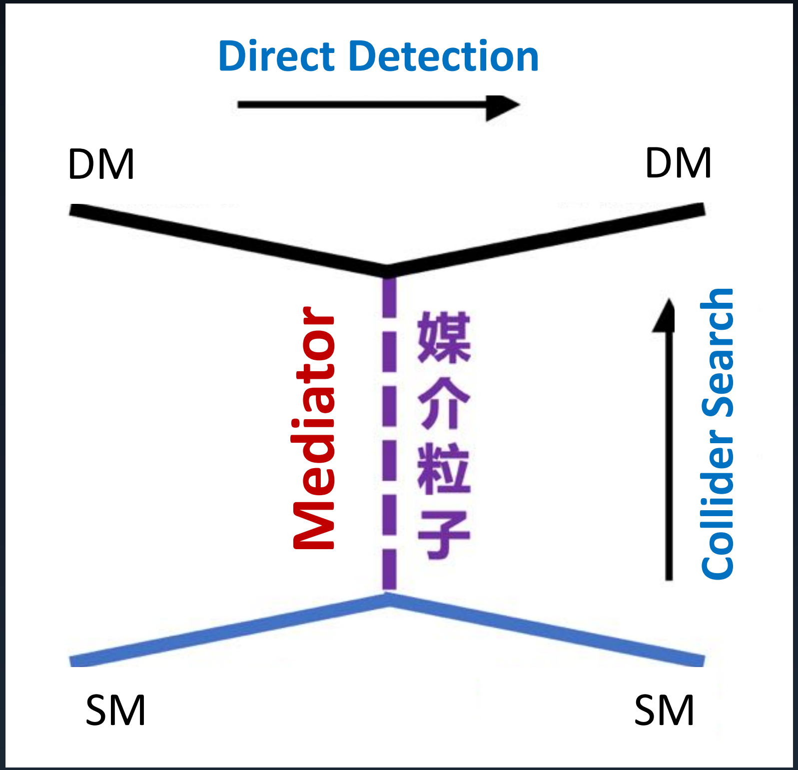
DM Interaction Mediator

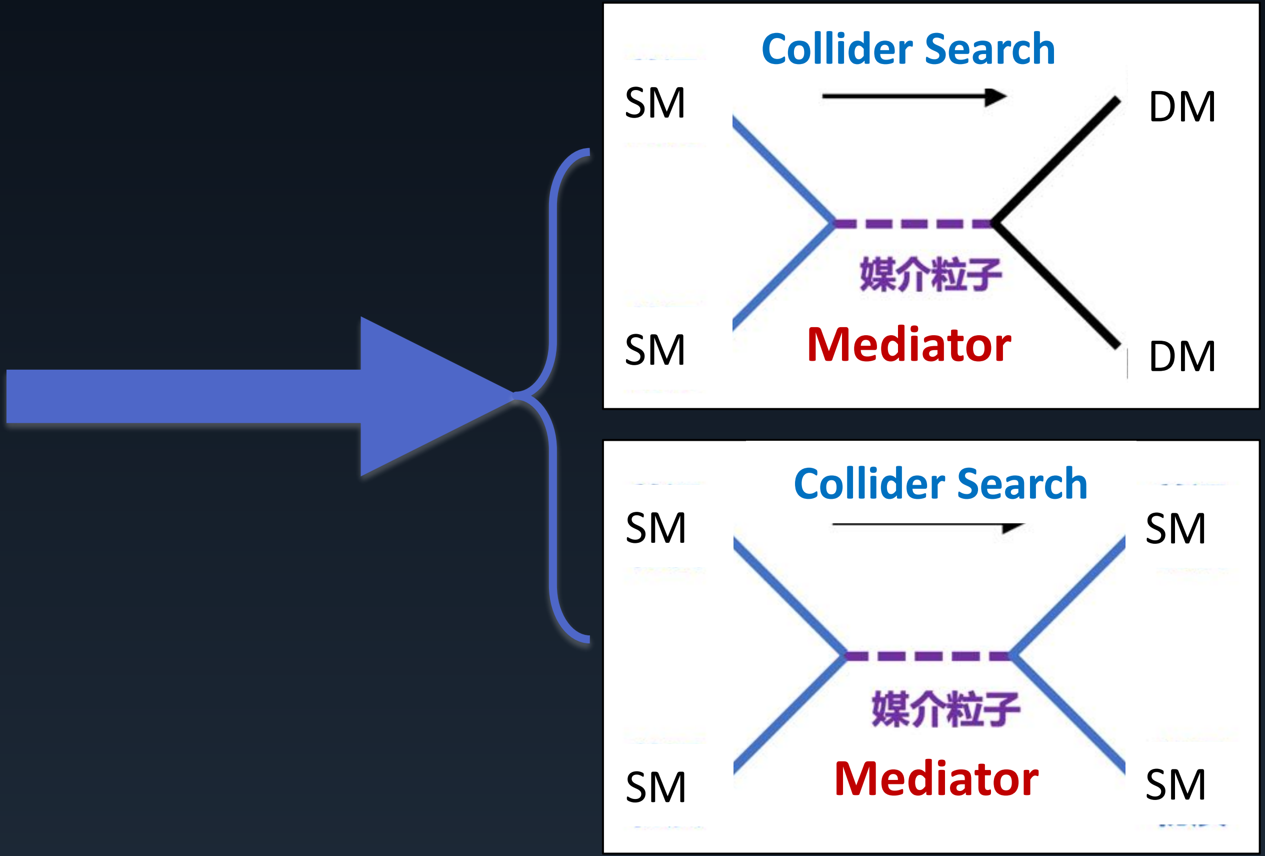
Direct detection:

Interaction energy too low to study the mediator

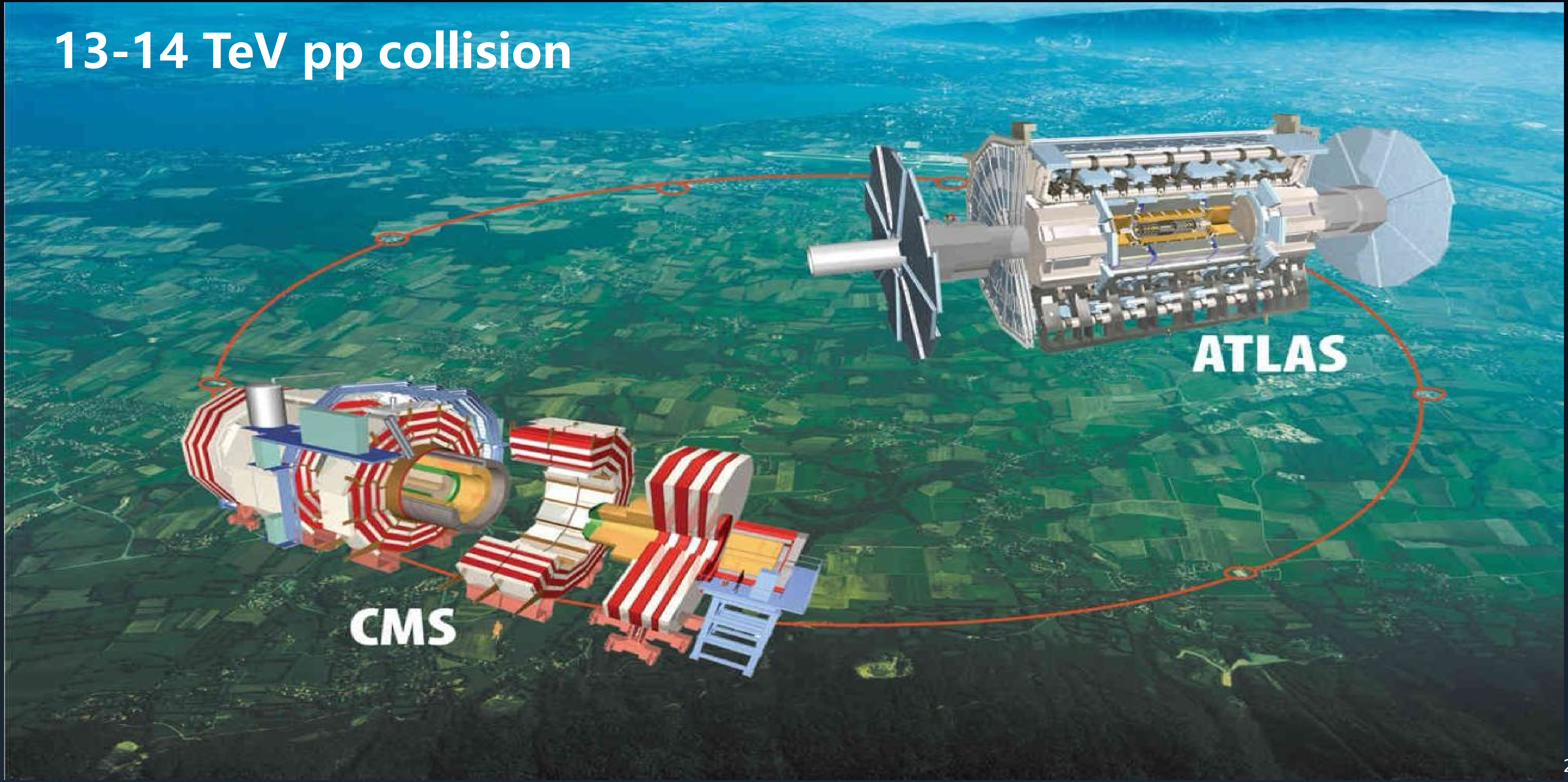
Collider search:

Study the same interaction, can produce the mediator



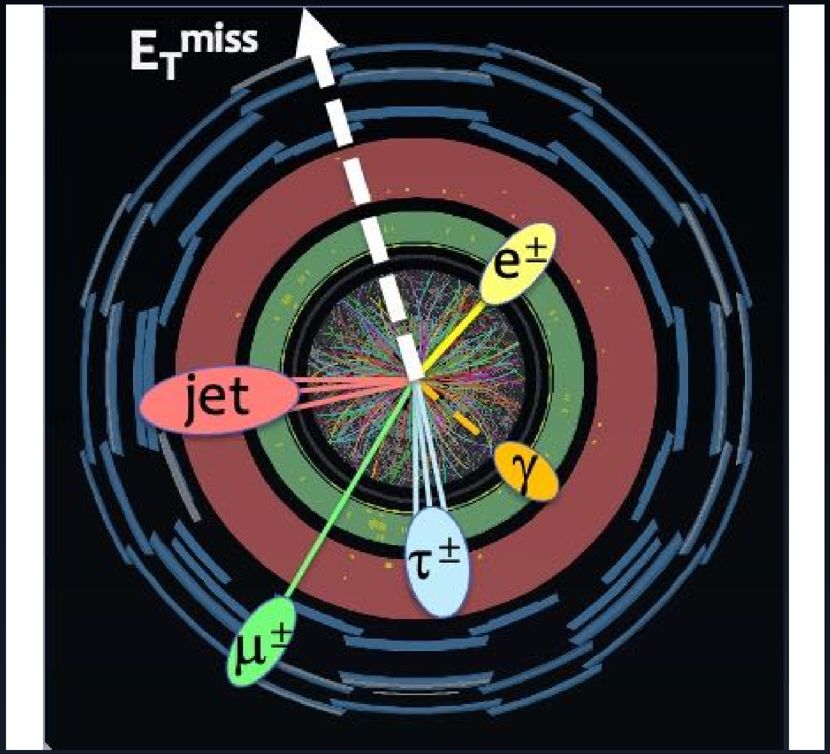


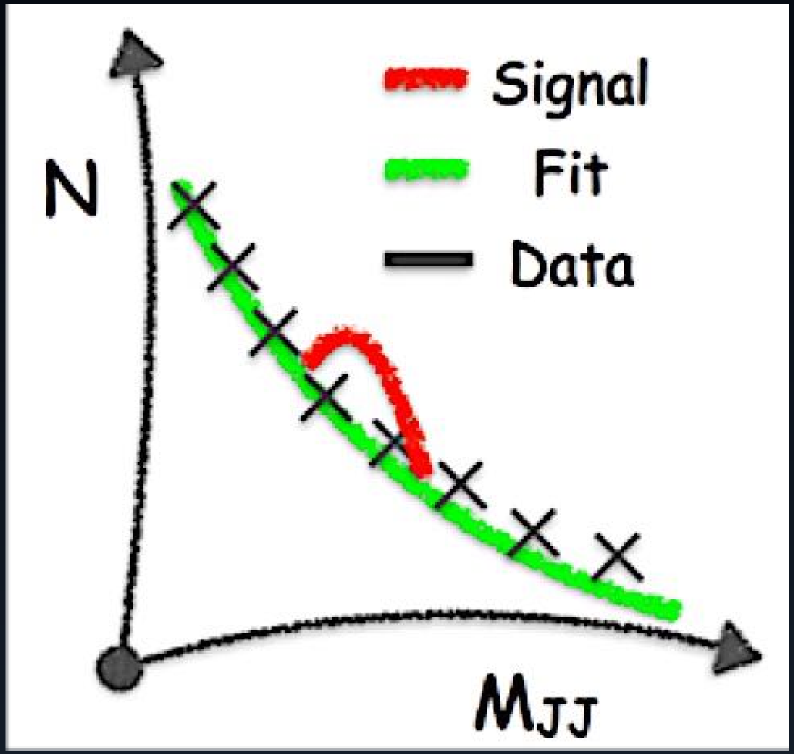
Large Hadron Collider

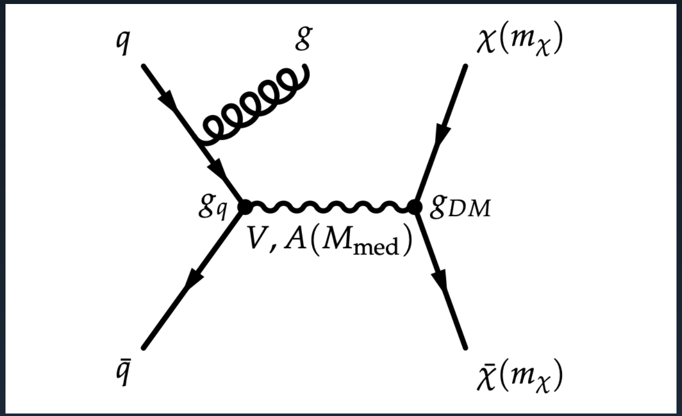


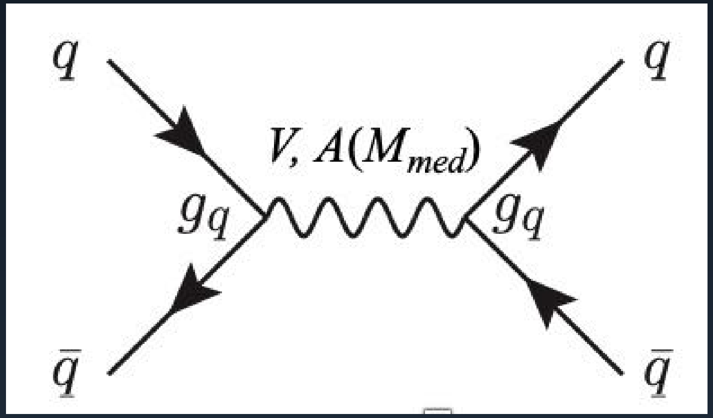
Collider Search

-



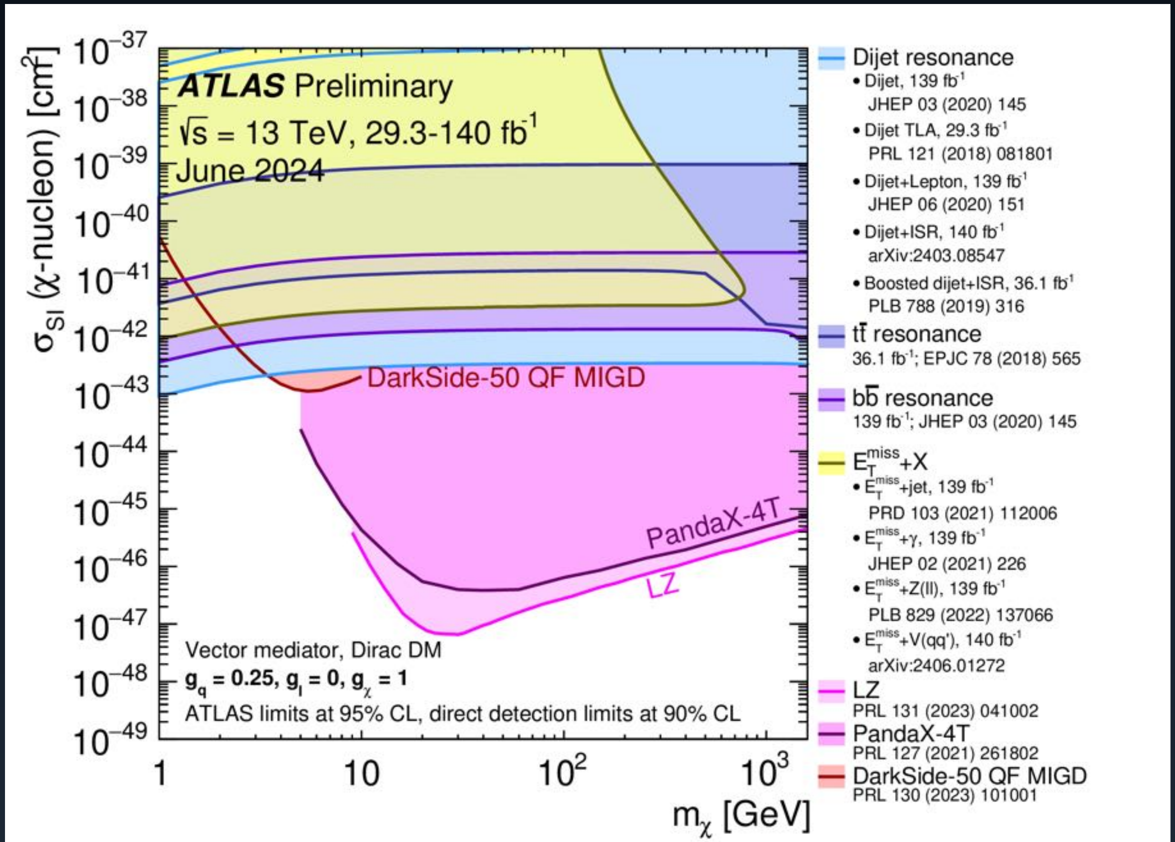


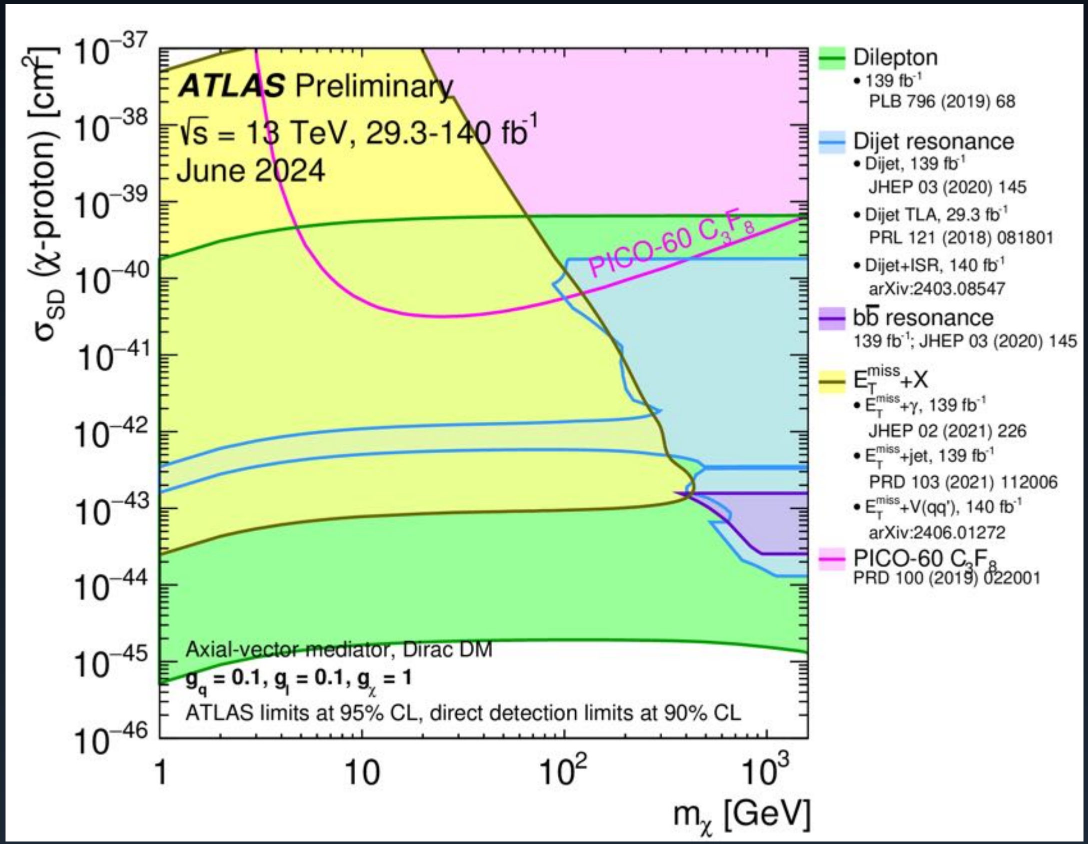




Constraints on Simplified Model

- **Vector mediator: spin independent interaction**
- **Axial-vector mediator: spin dependent interaction**





Dark Sector

- **Dark quark, dark fermion, dark photon, dark Higgs, etc.**

Dark Baryon

- **Strongly coupled dark quarks**
  - Dark QCD mediated by dark gluon
  - **Dark quark shower and hadronization**
- **Stable dark hadrons**
  - DM candidate
- **Unstable dark hadrons decay into SM quarks**
  - SM quark shower and hadronization

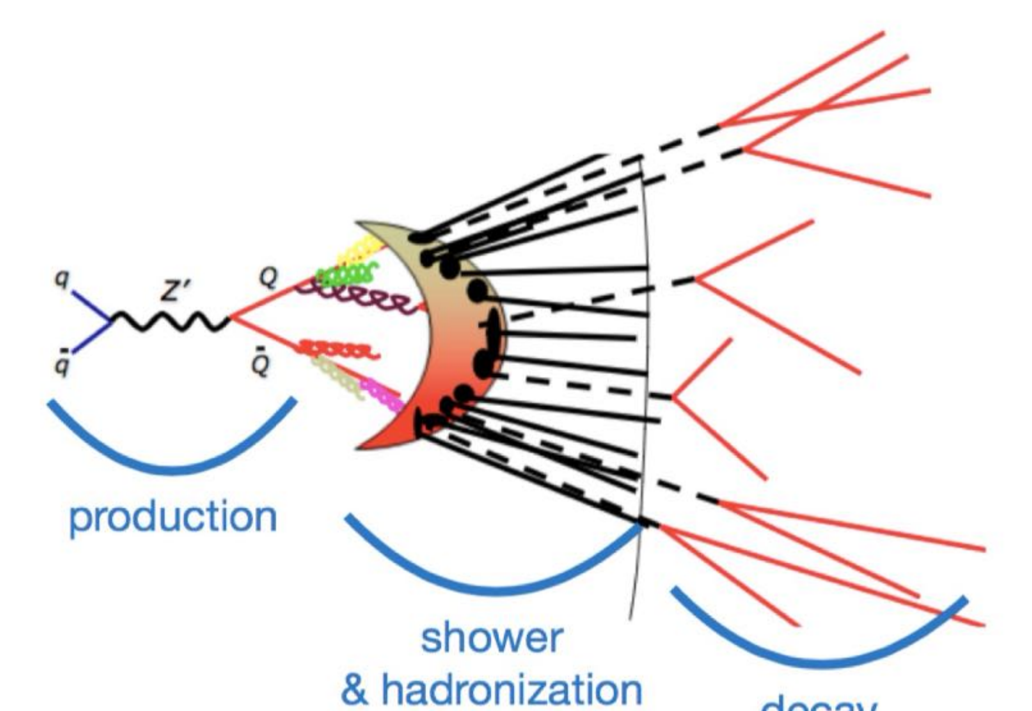


Image from M. Strassler

Dark Glueball

Motivation: Why Glueball Dark Matter?

- A pure dark Yang–Mills sector is arguably the **simplest confining dark sector**.
- Once the theory confines, it inevitably produces a tower of **glueball bound states**.
- In the absence of dark fermions, the glueballs are **cleanly defined**: there are no mesons, baryons, or fermionic bound states that can mix with them.
- This makes the low-energy spectrum theoretically **simple**, **predictive**, and directly tied to the confinement scale.
- Lattice studies indicate that the scalar 0^{++} glueball is the **lightest state** in the spectrum.
- Therefore, in a sufficiently secluded dark sector, the lightest 0^{++} glueball naturally becomes the leading **dark-matter candidate**.

Minimal logic

pure $SU(N)_D$ Yang-Mills

$\Downarrow$ confinement

glueball tower

0^{++} lightest

$\Longrightarrow$ DM candidate

Take-home message

Glueball dark matter is minimal, clean, and predictive: confinement alone is enough to generate a well-defined dark-matter candidate.

Talk to 王志伟, if interested

arXiv:2602.18753

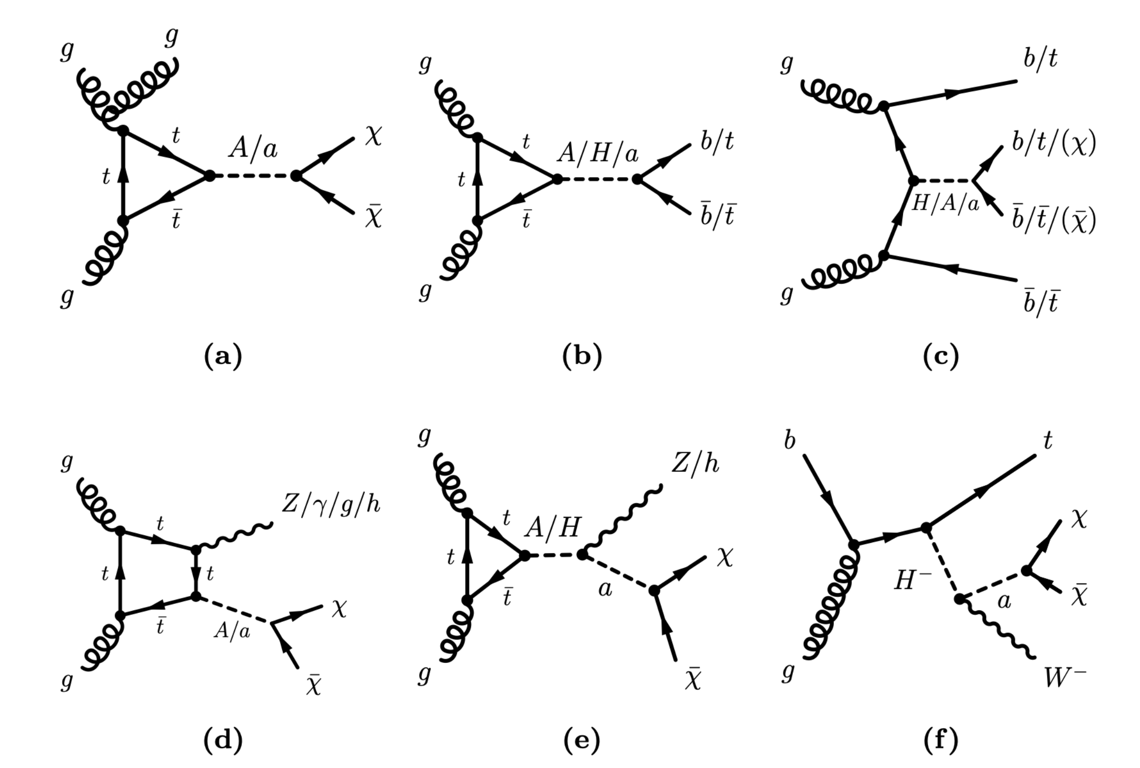
Dark Matter and Higgs

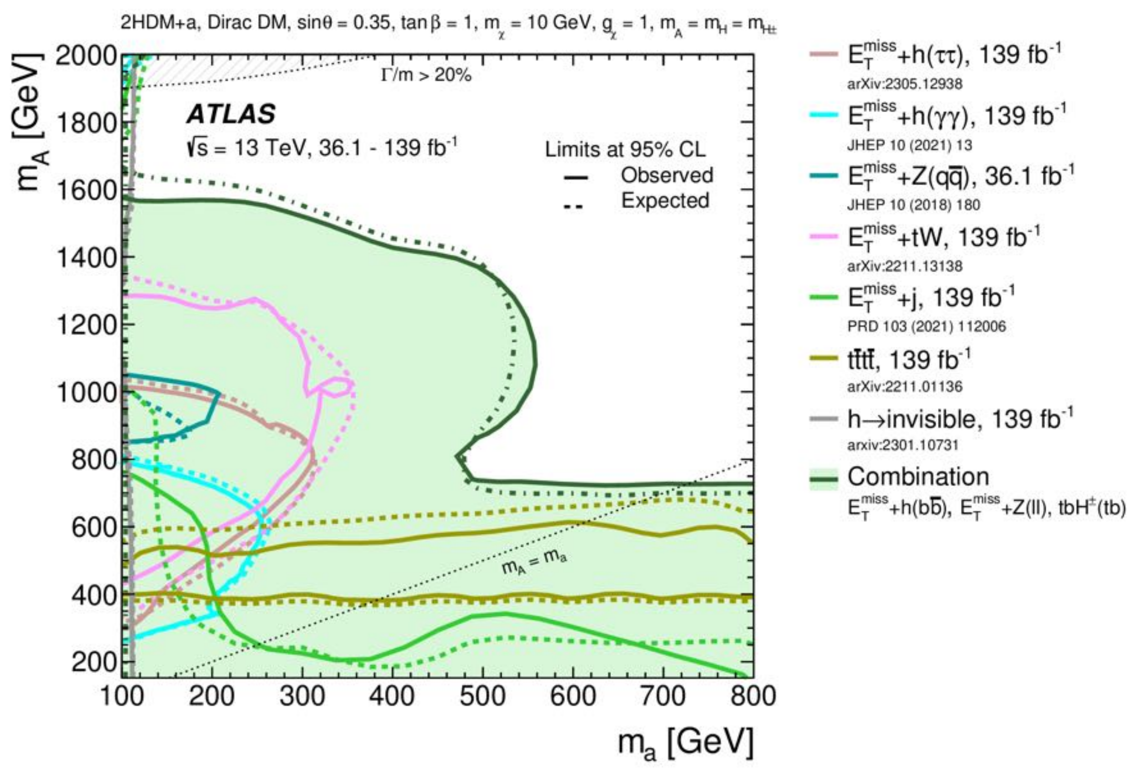
- **Higgs may connect to the dark sector**

Two-Higgs-Doublet-Model

- Type-II 2HDM (*h, H⁰, H±, A*) with additional pseudo-scalar mediator *a*
  - rich phenomenology at LHC

arXiv:2306.00641, Science Bulletin





Two-Higgs-Doublet-Model

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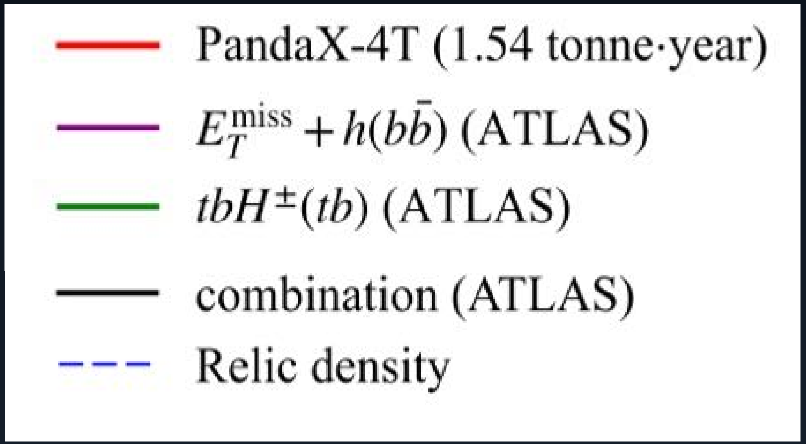
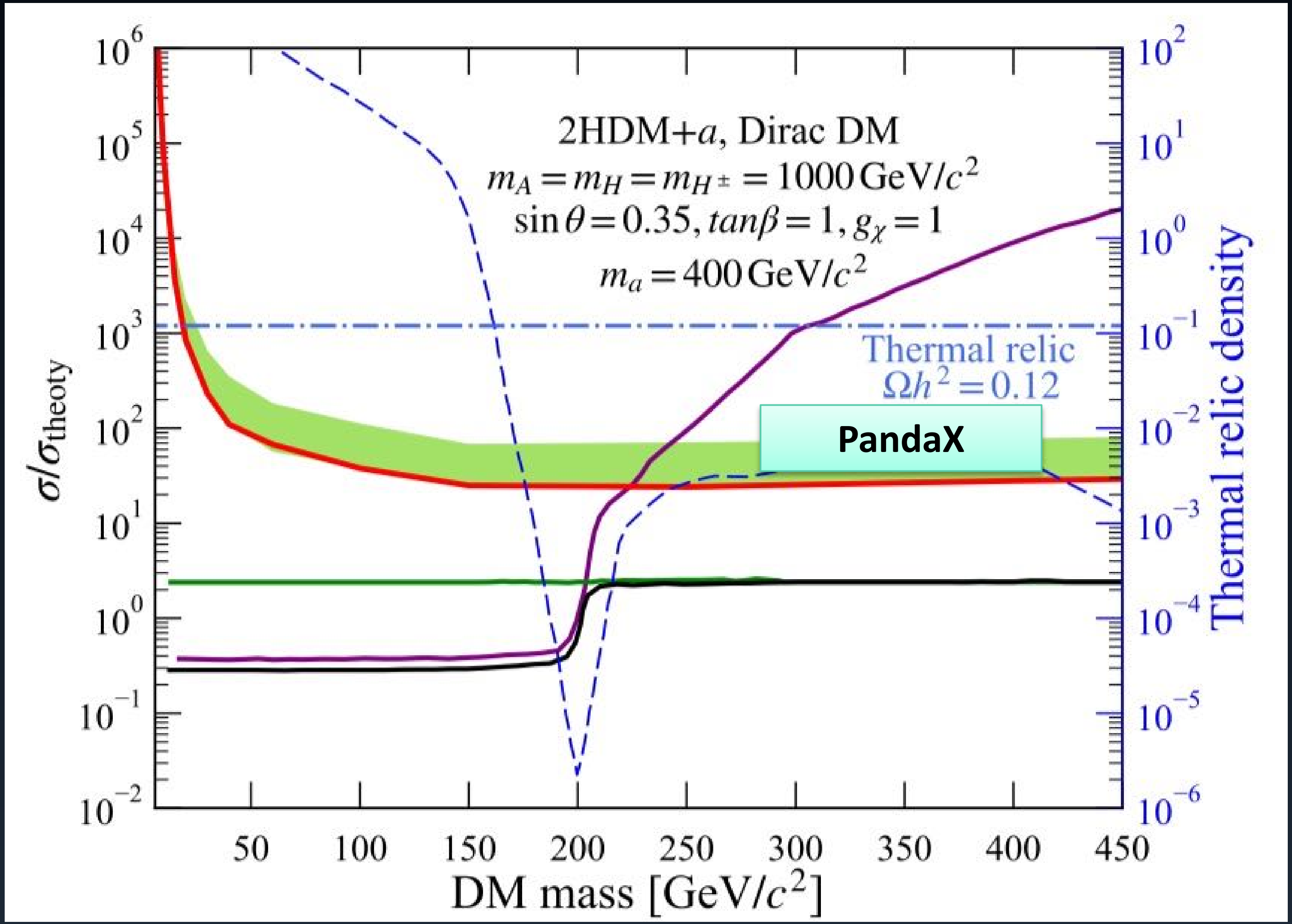
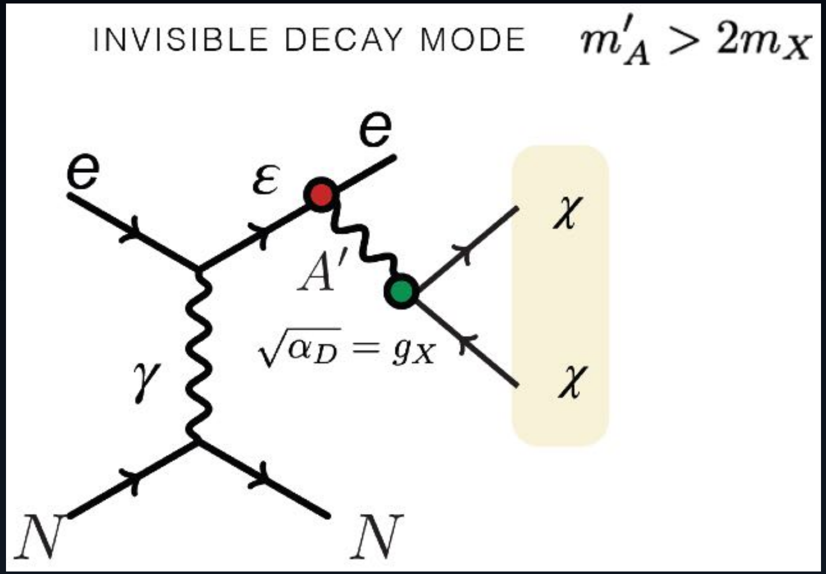


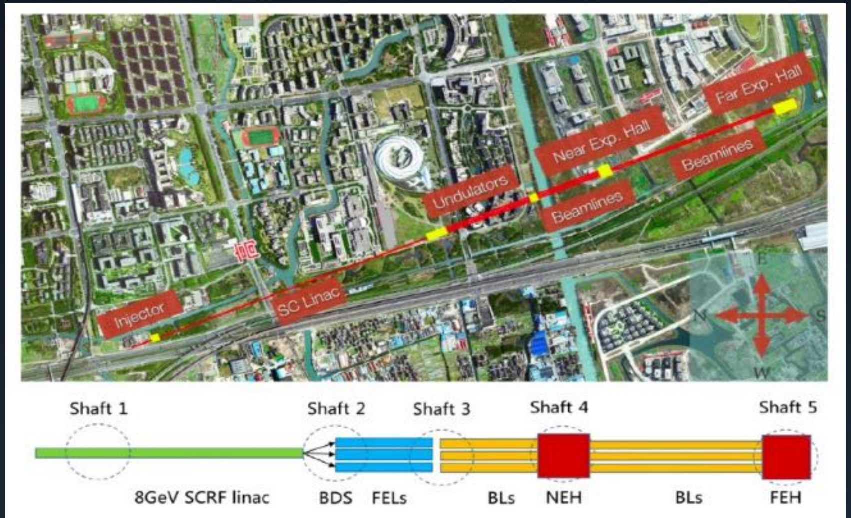


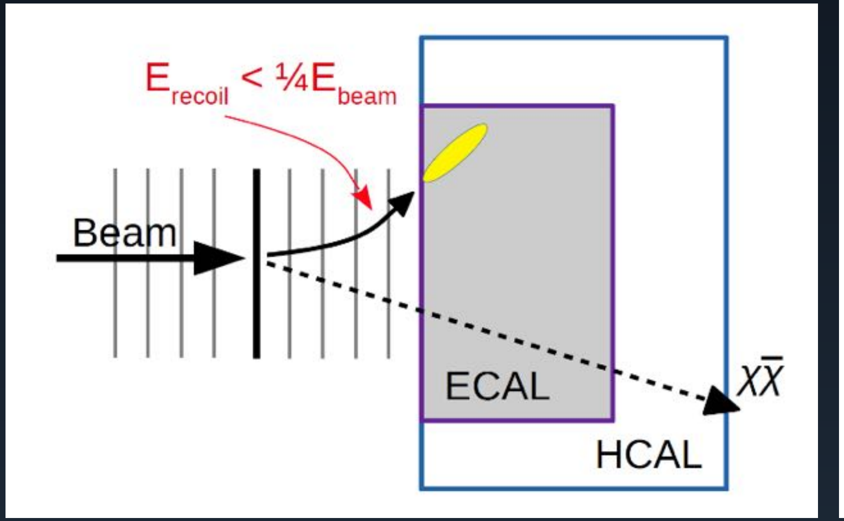
arXiv:2408.00664
PRL 134, 011805 (2025)

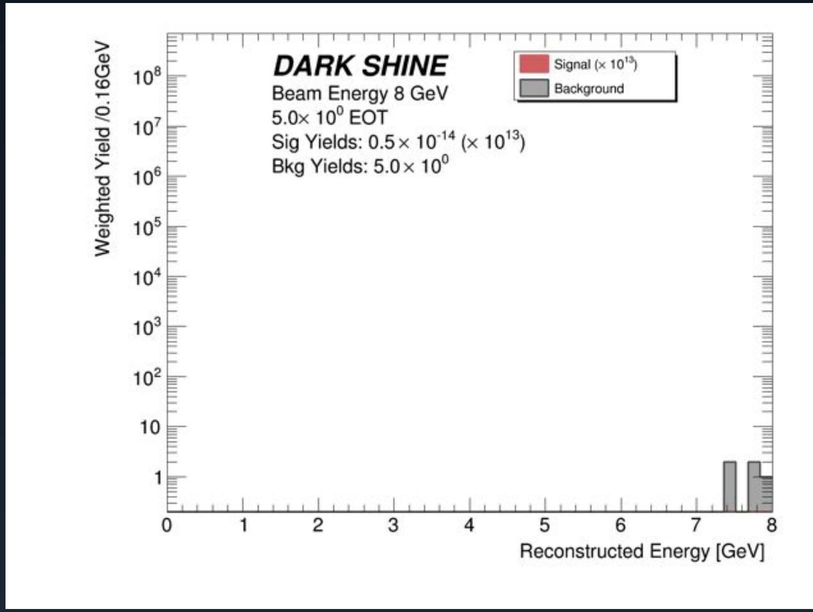
DarkSHINE Experiment

- **Fixed target experiment searching for light dark matter**
  - Electron energy: 8 GeV, frequency: 1MHz
  - ~3x10^{14} electrons-on-target (EOT)



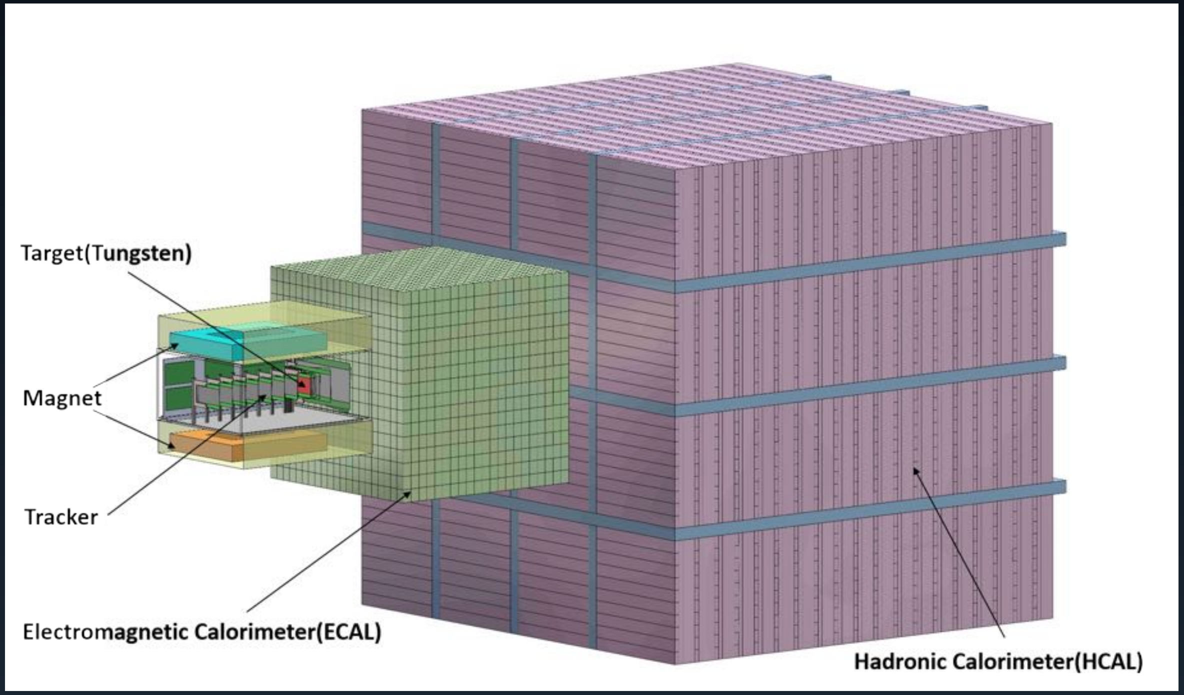


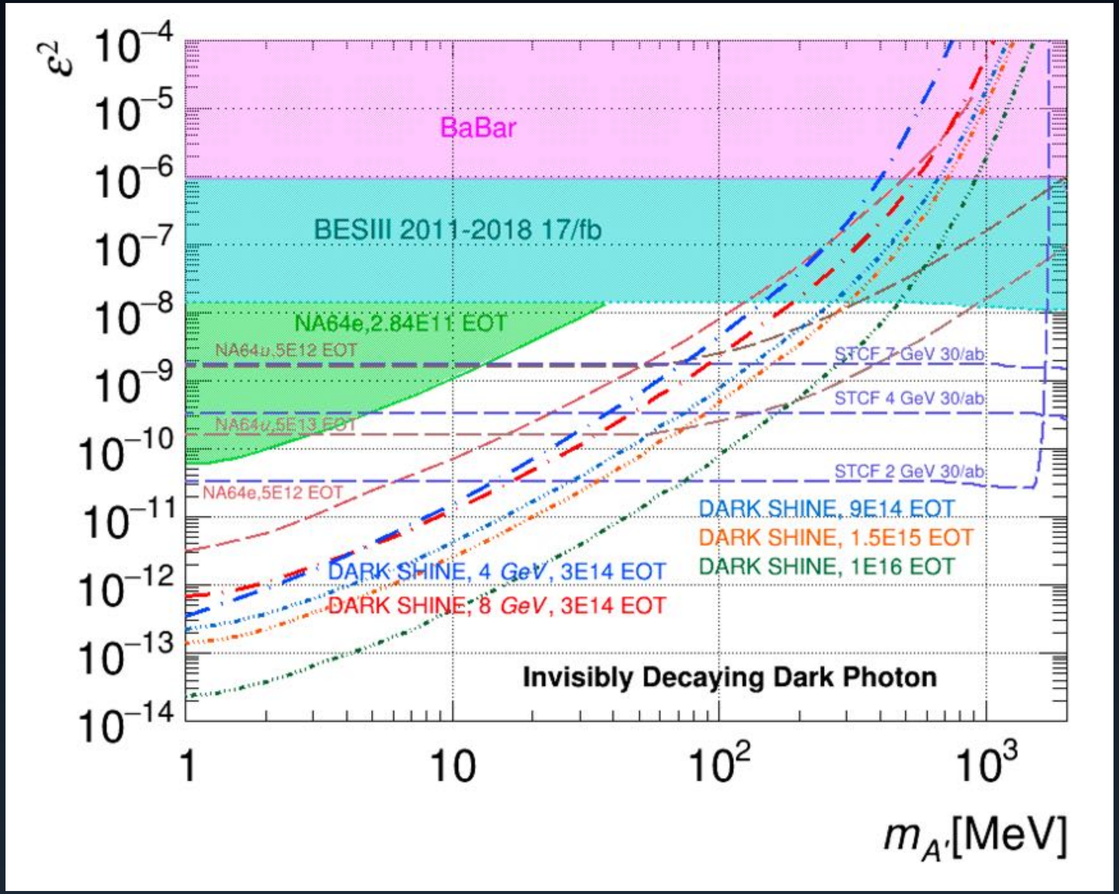




DarkShine Experiment

- **Detector key technology R&D is ongoing**
  - CDR is released arXiv:2411.09345

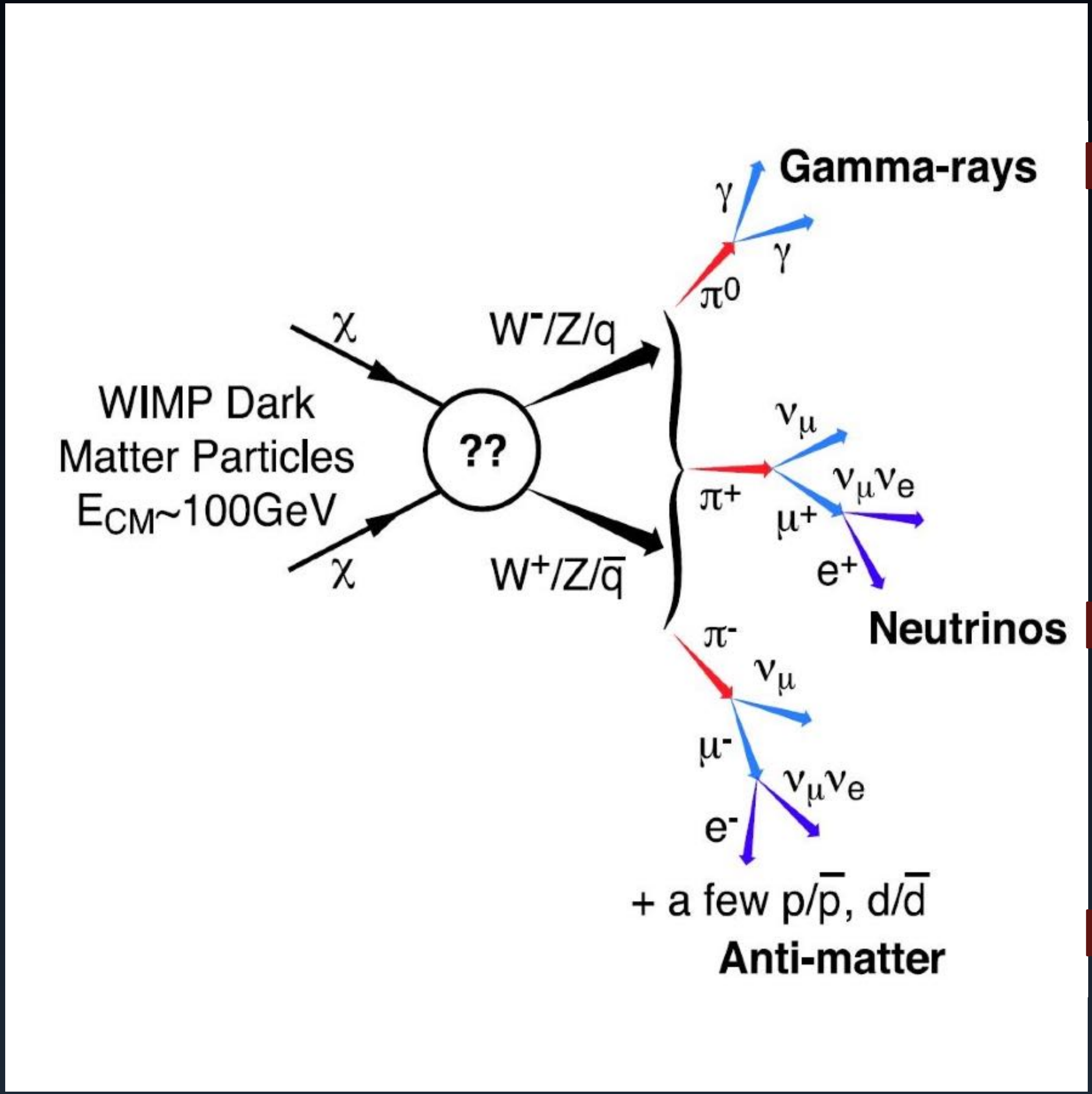


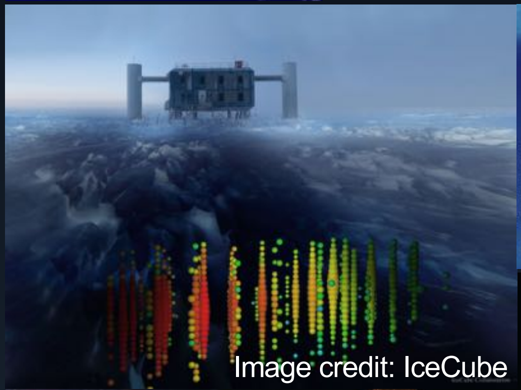


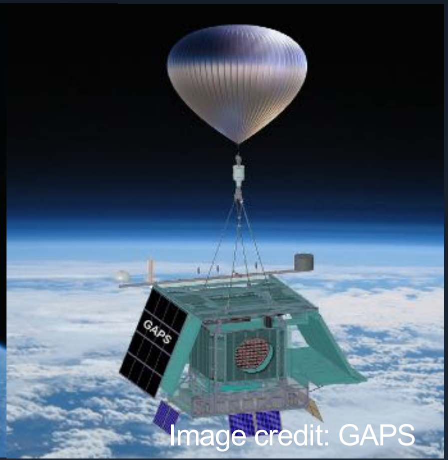
[Sci. China-Phys. Mech. Astron., 66(1): 211062 (2023)]

- 高能粒子对撞湮灭，产生出暗物质
- 但是，对撞机上产生出来的看不见的新粒子不一定是宇宙中暗物质的主要组成

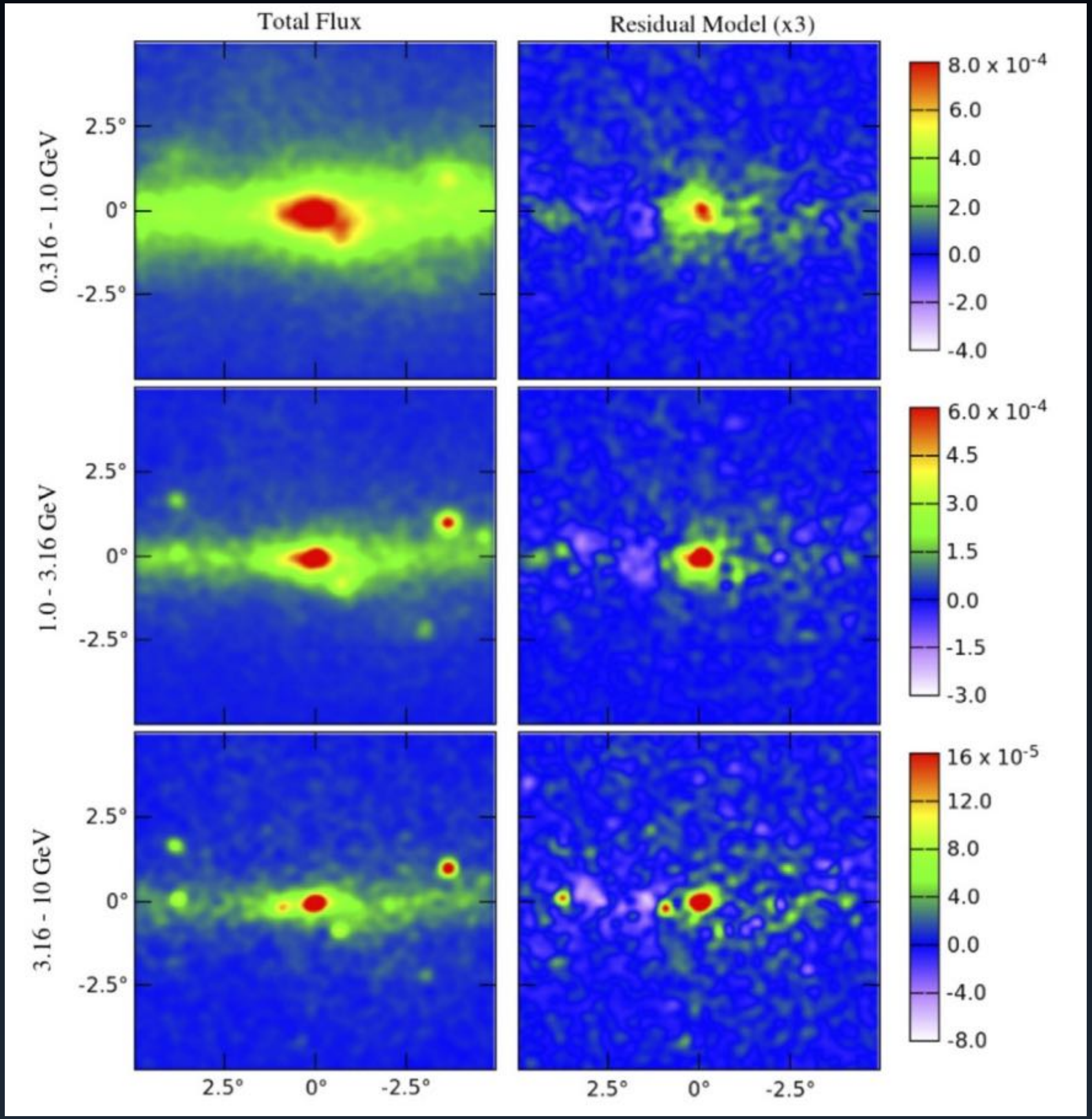
Indirect Detection





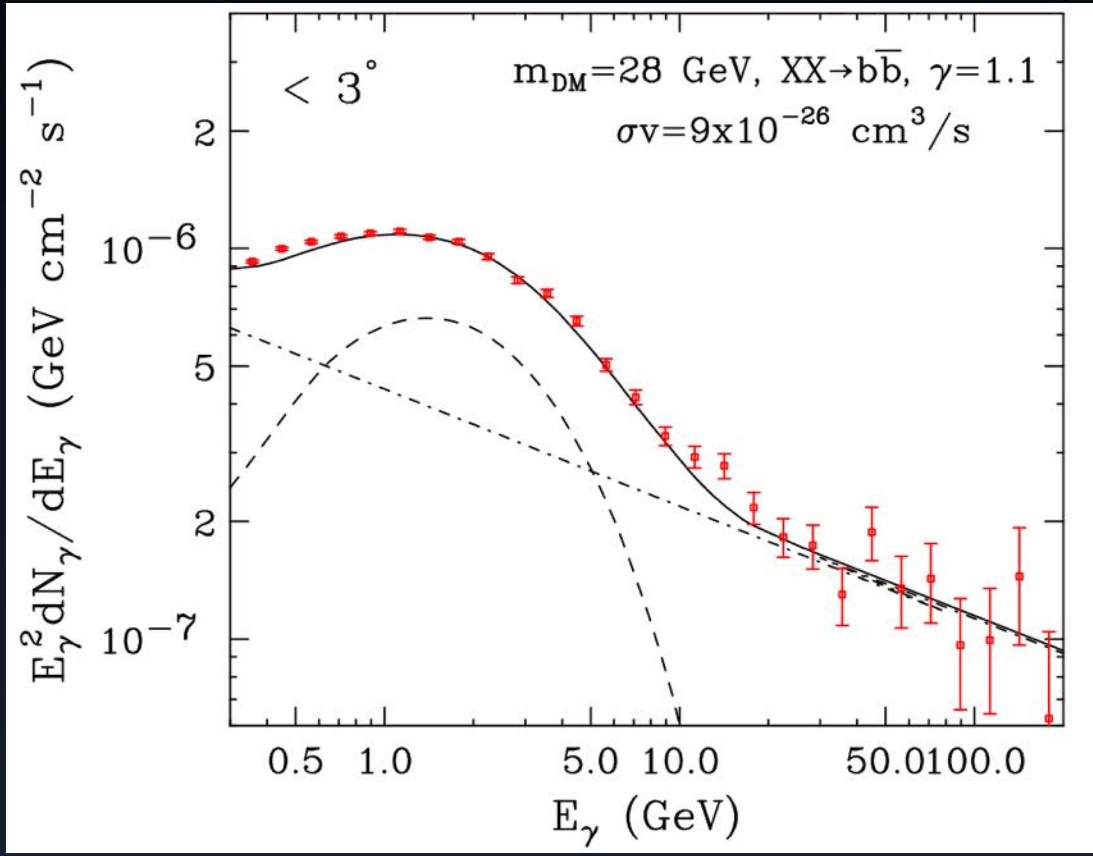


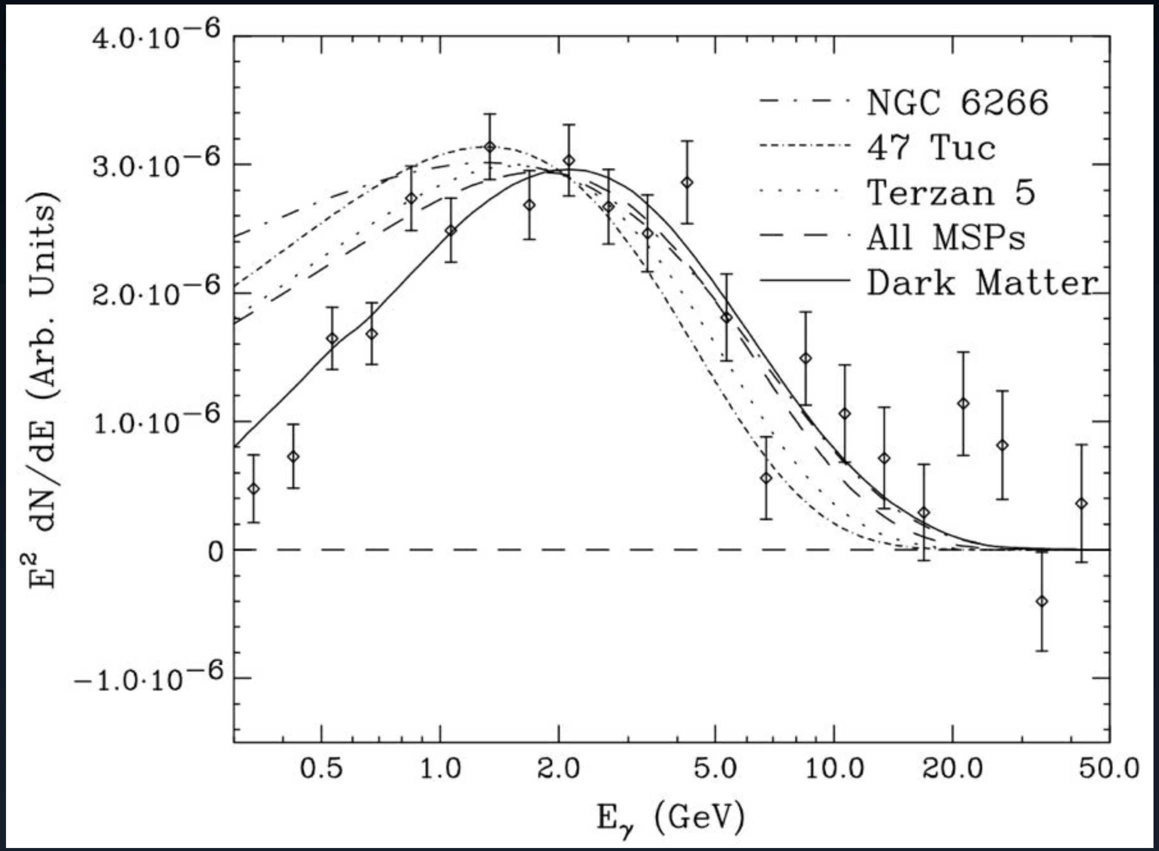
GeV Excess in the Galaxy Center



NASA's Fermi gamma-ray telescope

GeV gamma Excess in Galaxy Center





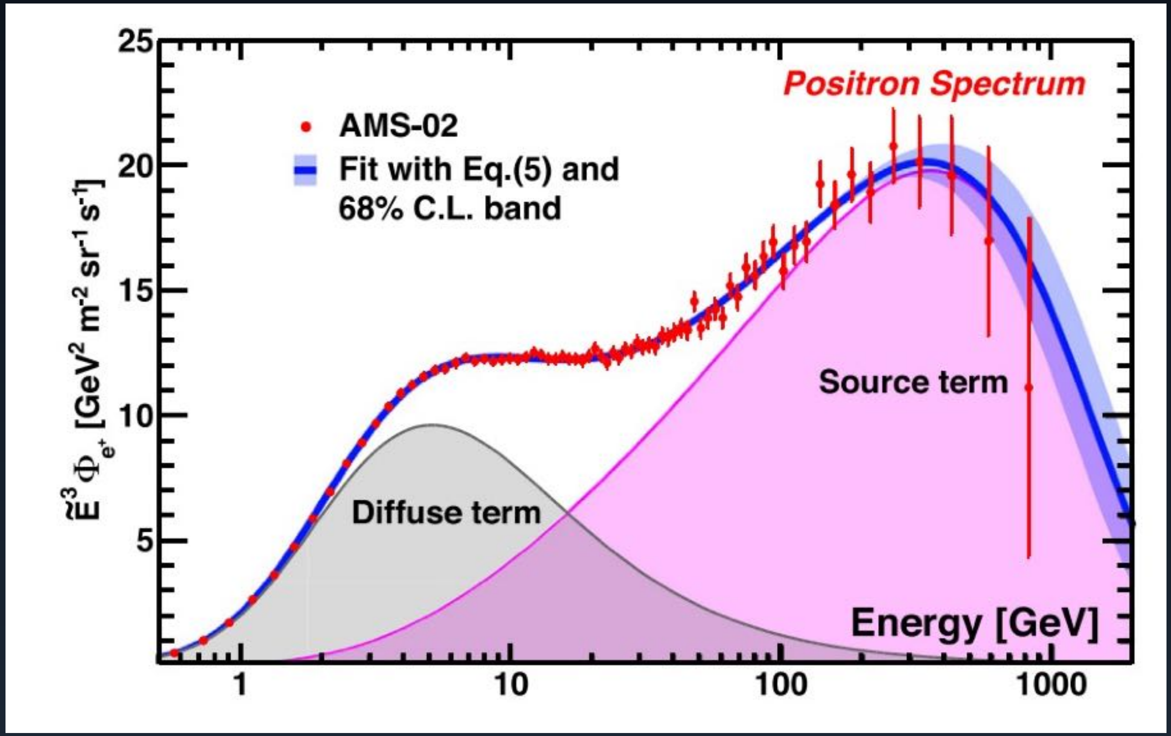
- D. Hooper and L. Goodenough, PLB (2011)
- Abazajian & Kaplinghat (2012), Gordon & Macias (2013)
- Calore, Cholis, Weniger (2015), Ackermann, et al. (2017)

Space Particle Detectors

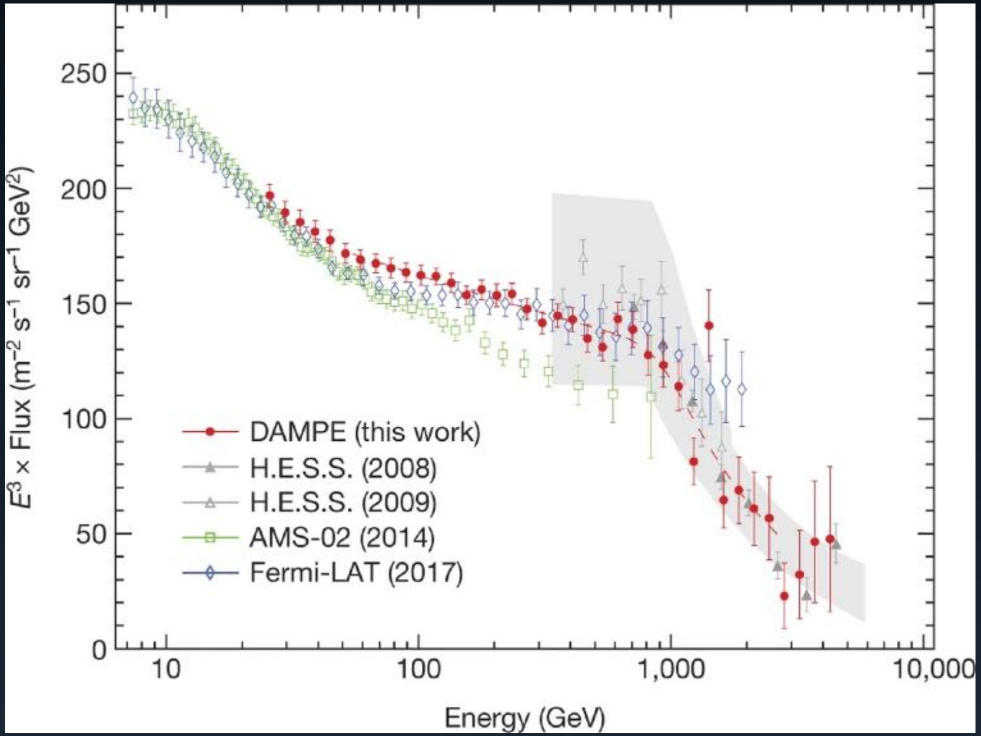
- AMS-02实验：强磁场+径迹探测器，鉴别粒子电荷
- DAMPE悟空实验：高能光子、电子、质子等

Anti-electron/Electron Excess

- **TeV scale dark matter?**
  - Alternative explanations from pulsars (*PRD 2017*), but challenged by the HAWC observation (*SCIENCE 2017*).



- AMS-02 Collaboration, Phys. Rep., Vol 894 (2021)

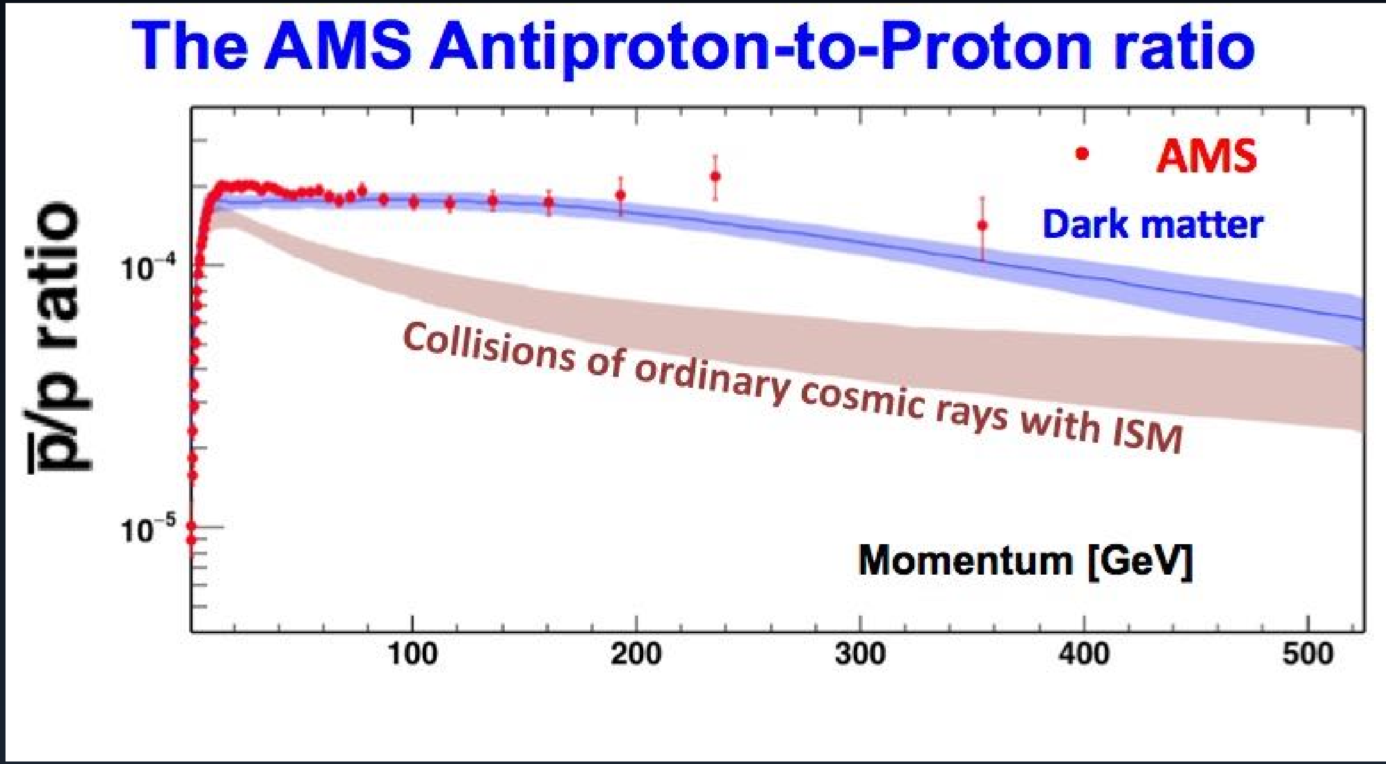


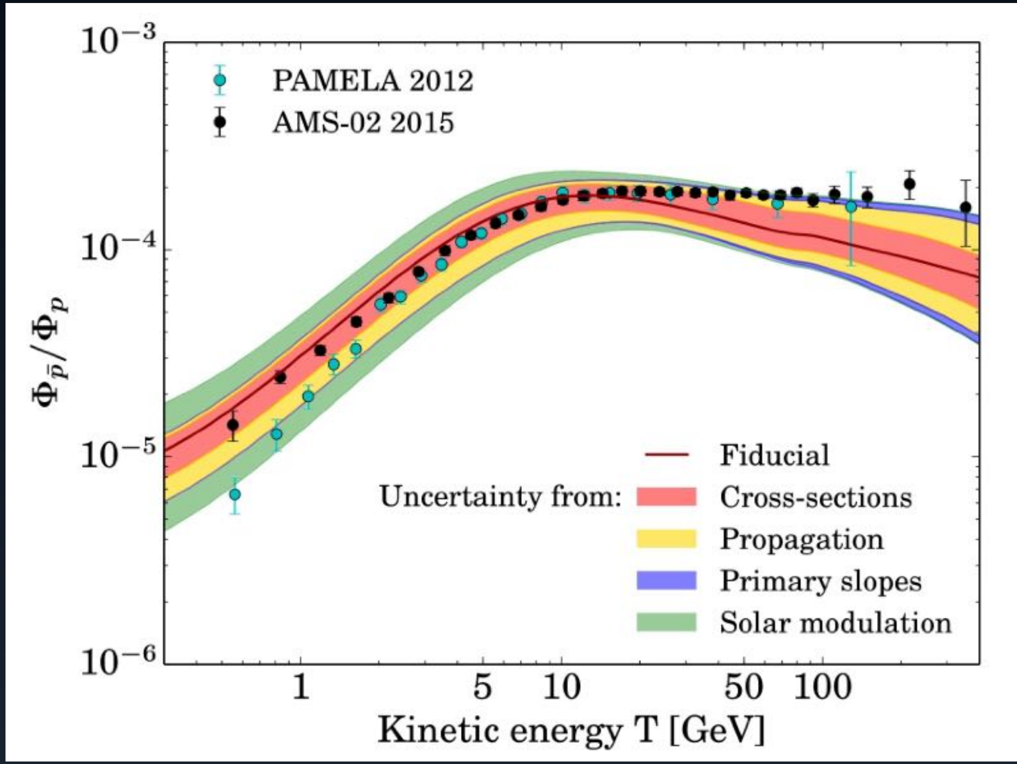
- DAMPE Collaboration, Nature (2017)

Anti-proton Excess

•

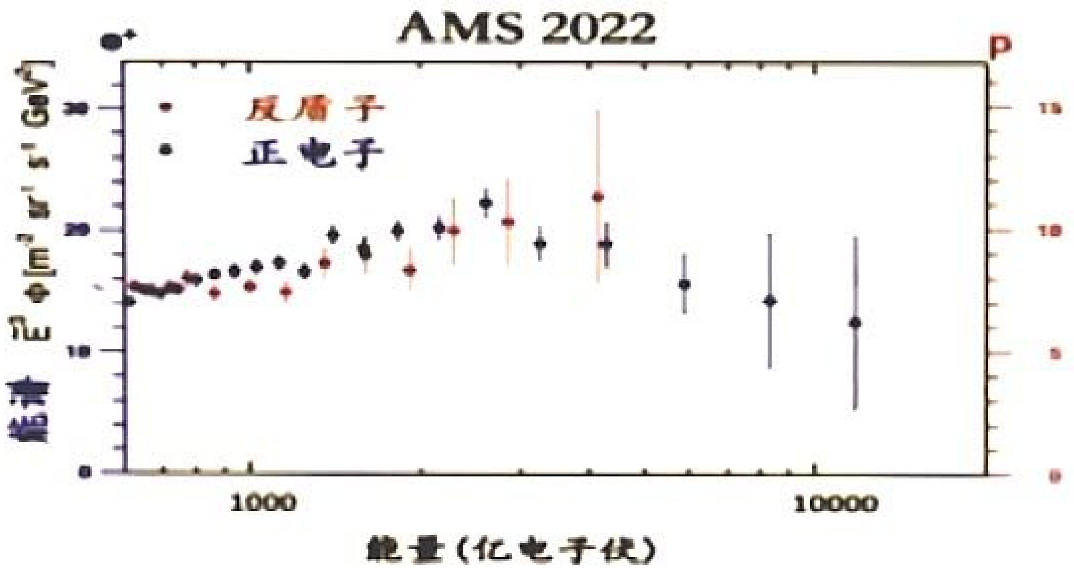
G. Giesen, et al., JCAP (2015)

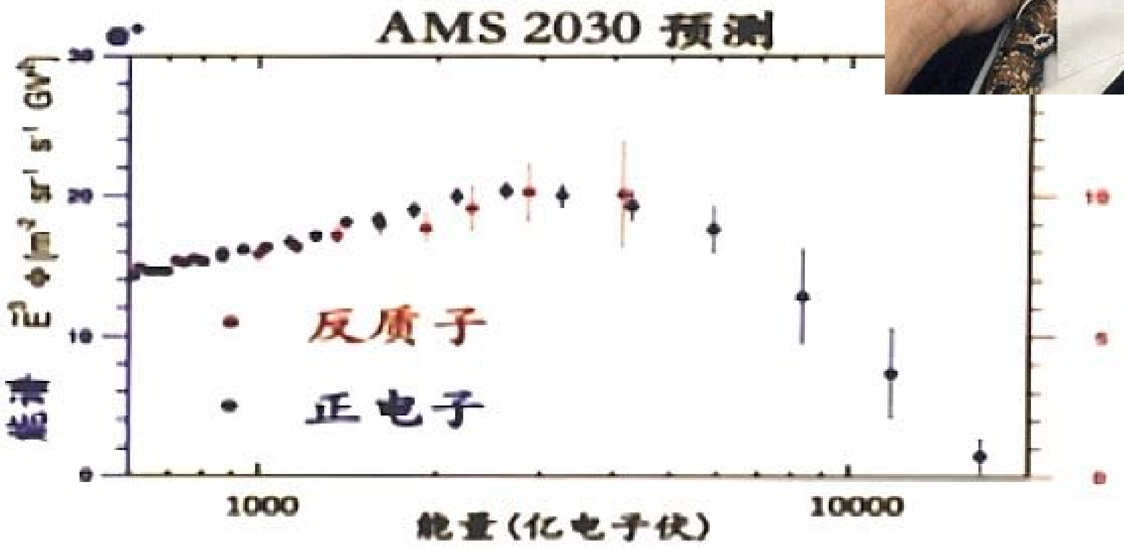




AMS 结果 ：反质子能谱

反质子的能谱与正电子具有相同的特征。



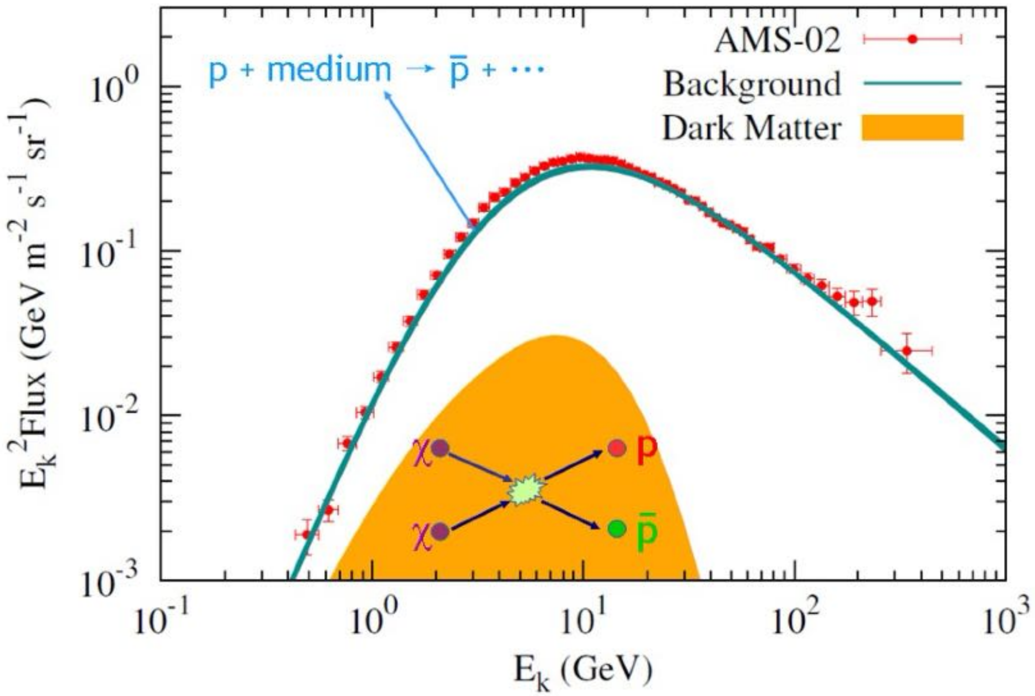


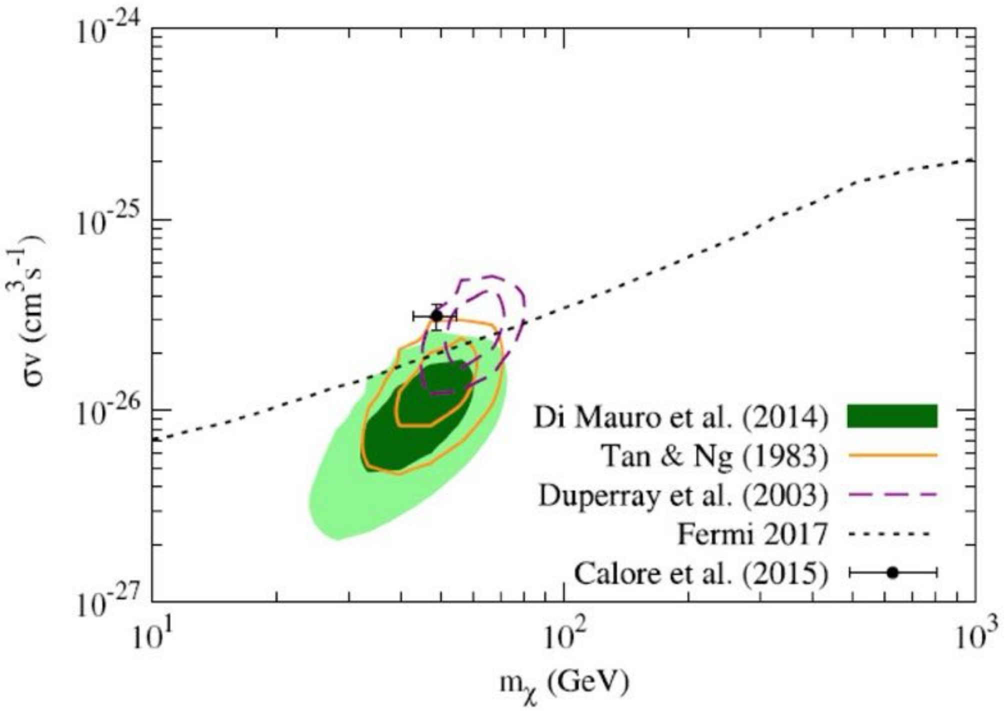
到2030年，AMS 可以确认正电子能谱与反质子能谱具有完全一样的特征

脉冲星不能产生反质子，所以高能正电子也不来源于脉冲星

反质子超出和暗物质模型解释

From 袁强



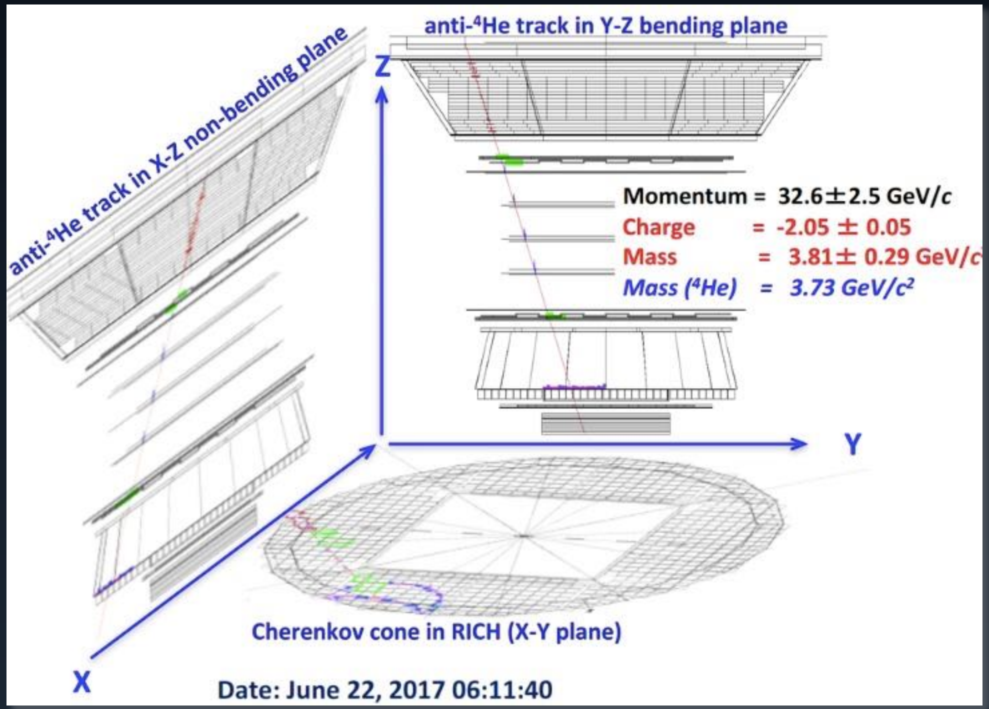


- 通过改进反质子背景模型计算，发现次级反质子流量和AMS观测数据相比在1-10 GeV存在超出(Cui et al., 2017, PRL, 118, 191101; Zhu et al., 2022, PRL, 129, 231101)
- 该超出可用50-80 GeV暗物质湮灭到bb-bar夸克解释，而且该参数空间和解释银心伽马射线超的参数空间正好对应

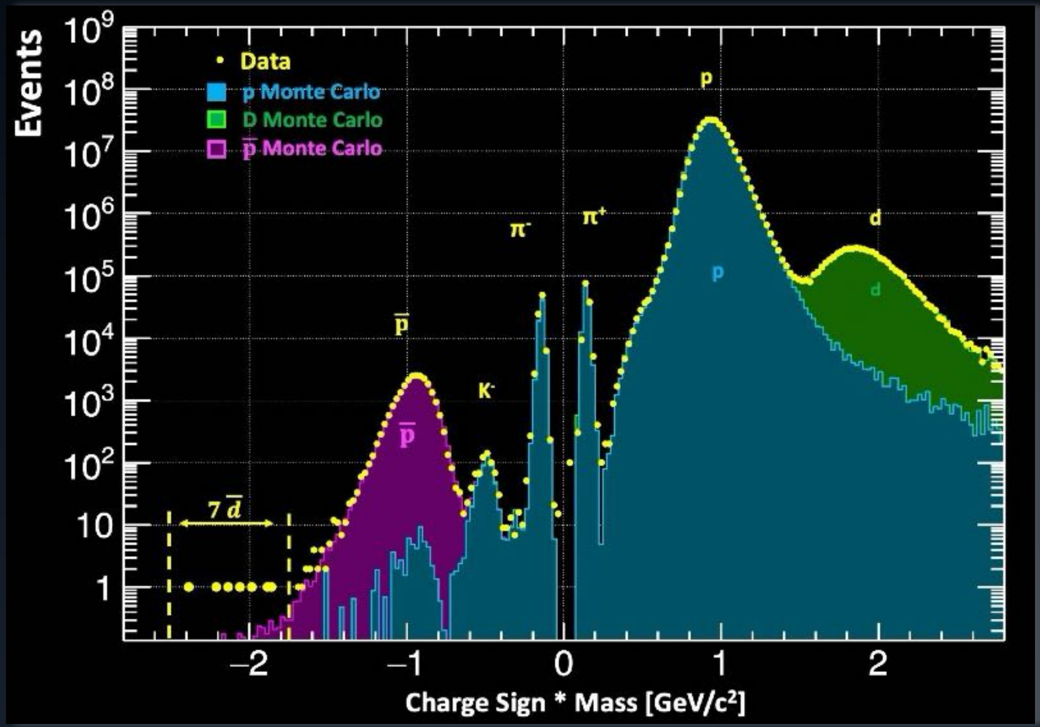
Anti-Helium/Deuteron

- **2018:** "To date, we have observed eight events… with Z = -2. All eight events are in the helium mass region."
  – Prof. Ting (La Palma, AMS overview)

AMS Candidate Anti-He4 event (p = 32.6 GeV/c)



from AMS-02 conference talk

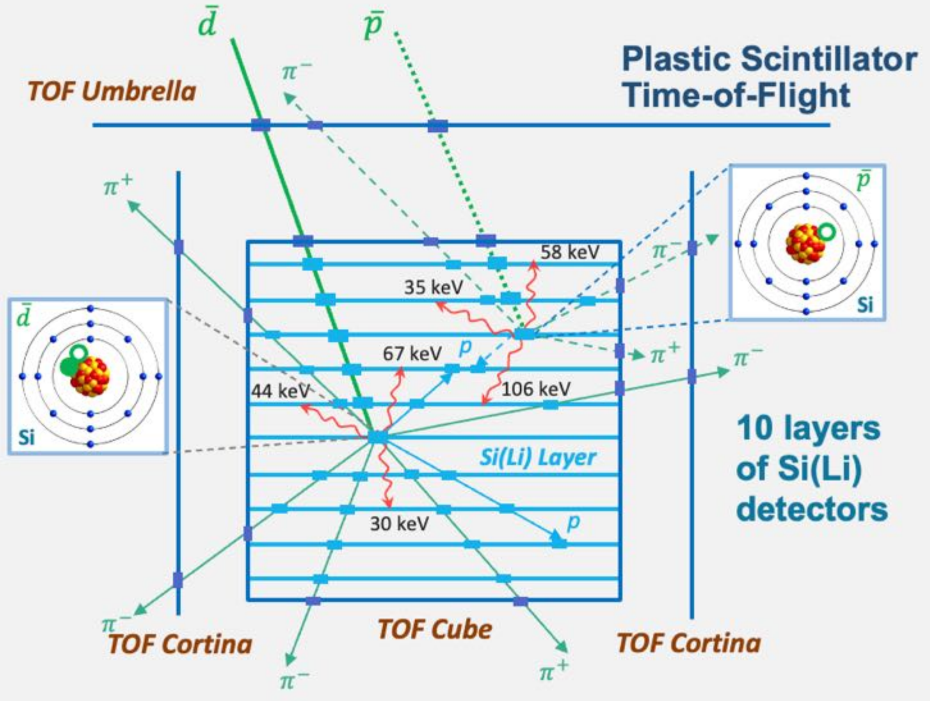


❑ Several antideuterons with large β measured.

Low Energy Anti-Deuteron Measurement

- **Low-energy cosmic antideuterons are essentially background-free signature of dark matter, and MEASURABLE!!**

From 肖梦姣



Extoic atom technique verified at KEK: Aramaki+ Astropart.Phys. 49, 52-62 (2013)
GAPS sensitivity to antideuterons: Aramaki+ Astropart.Phys. 74, 6 (2016)

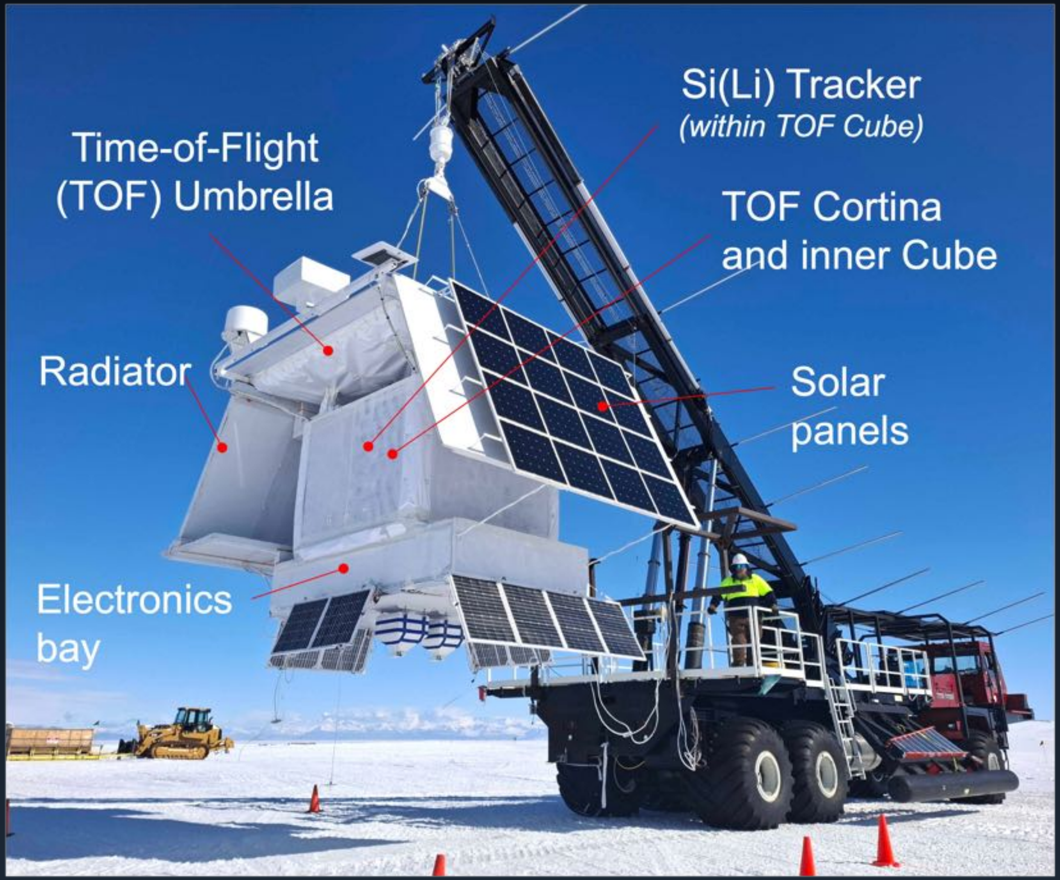
Time-of-flight system: measures velocity, incoming angle and dE/dx, fast trigger, tracks of outgoing particles

Si(Li) tracker acts as:

- ***Target*** to slow/capture an incoming antiparticle into an *exotic atom*
- ***X-ray Spectrometer*** to measure the decay *X-rays*
- ***Particle Tracker*** to measure the resulting dE/dX, stopping depth and annihilated *hadrons*

GAPS 南极高空气球项目

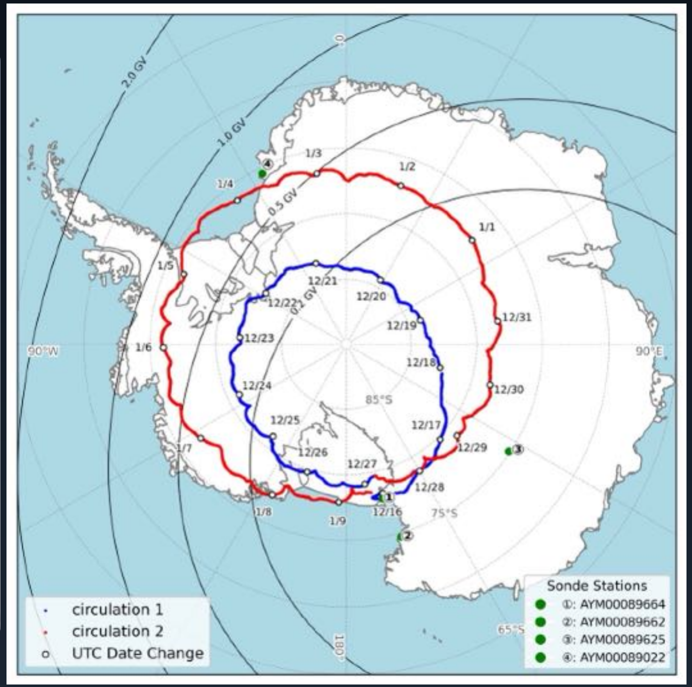
- **GAPS=General AntiParticle Spectrometer**
  - 上海交大承担建设 Si(Li) Tracker

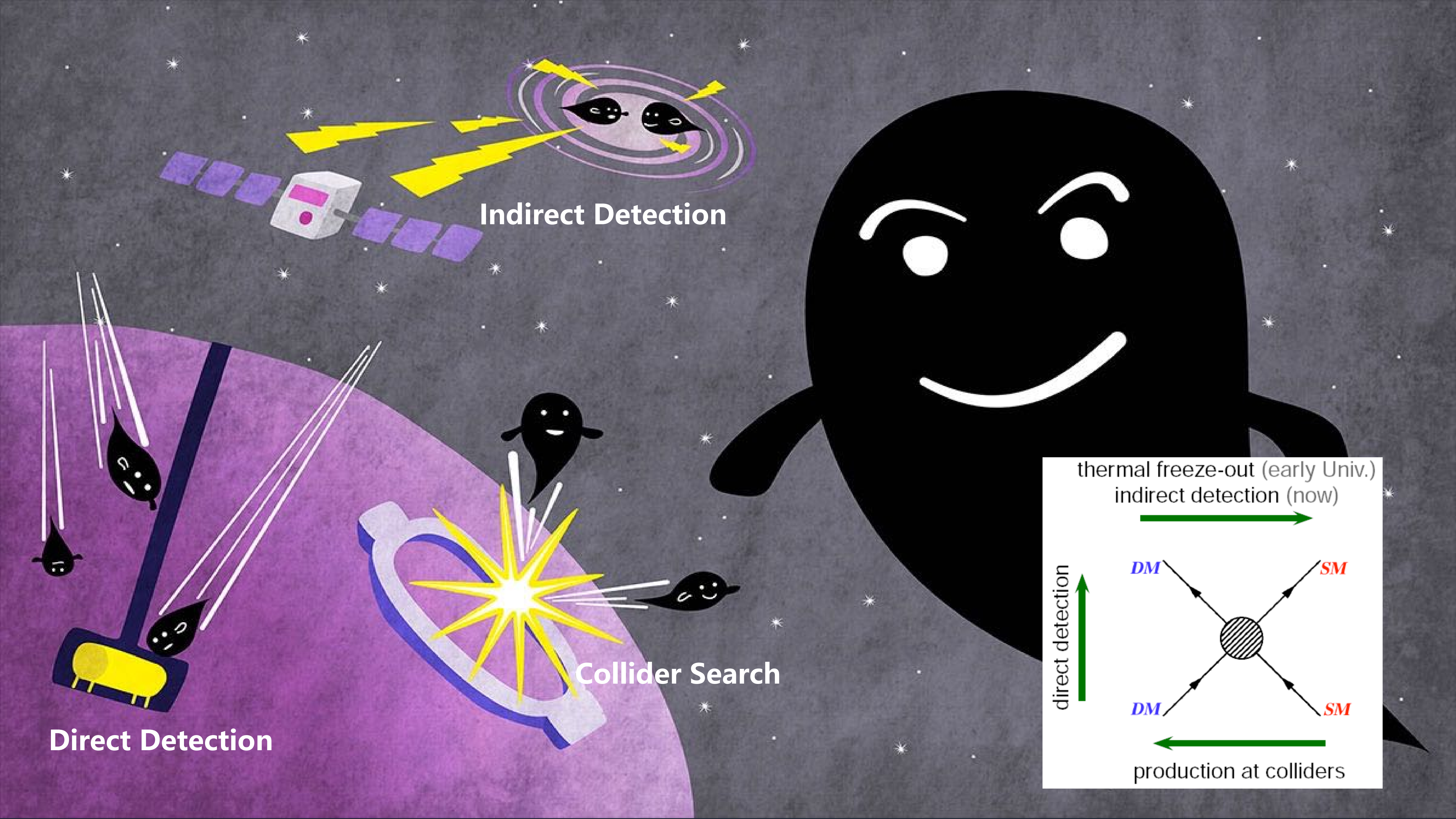


GAPS 南极高空气球项目

- **2025年12月16成功从南极麦克默多科考站升空，绕南极大陆两周，25天数据采集**
- **数据分析进行中…**






Indirect Detection
Collider Search
Direct Detection
thermal freeze-out (early Univ.)
indirect detection (now)
DM
SM
DM
SM
direct detection
production at colliders

Summary

- The detection of dark matter is a crucial component in the exploration of new physics
- Experiments are developing rapidly, presenting significant opportunities for important discoveries
- Further develop flagship experiments and unlock their new potential
- Actively expand new detection methods to cover a broader parameter space

Thank You！