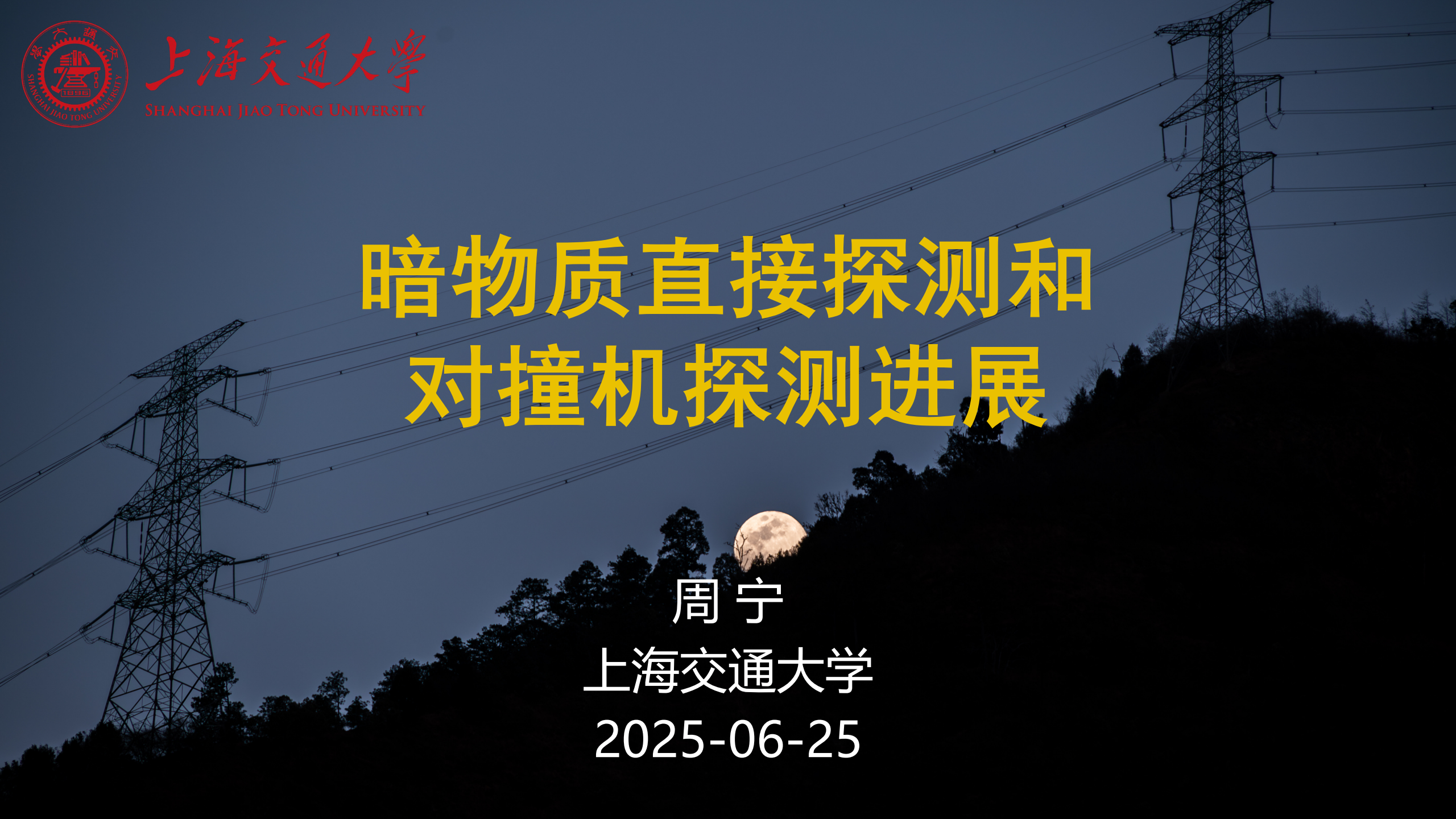
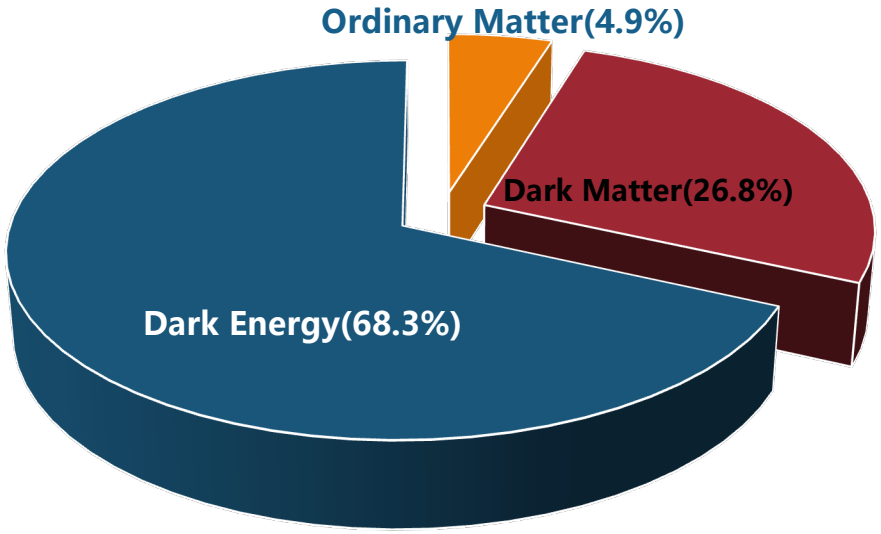


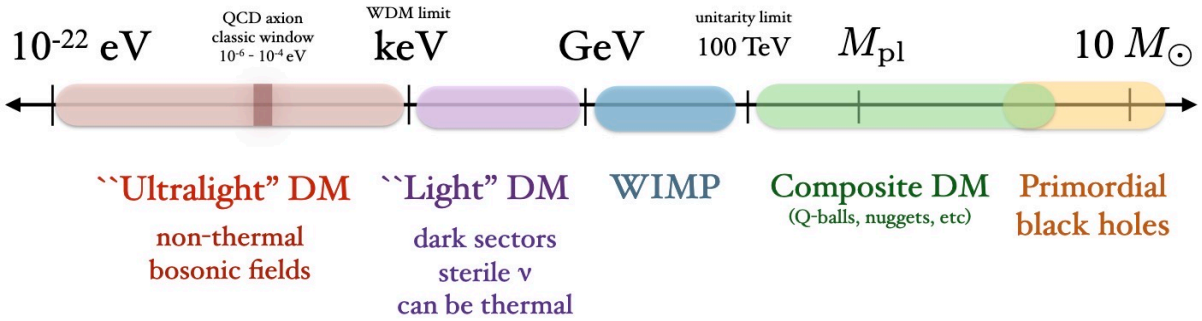
暗物质直接探测和对撞机探测进展

周 宁
上海交通大学
2025-06-25

Dark Matter

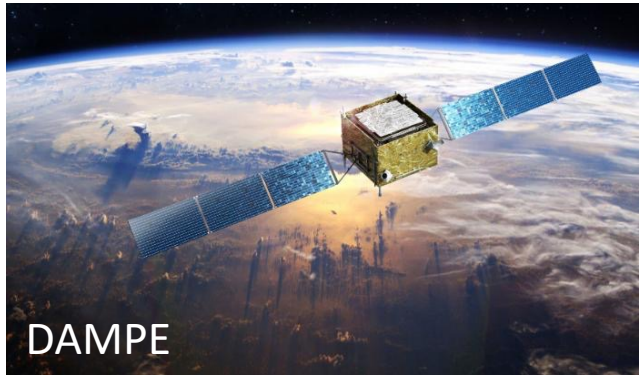
- **Strong evidence of its existence**
- **Little knowledge of its nature**

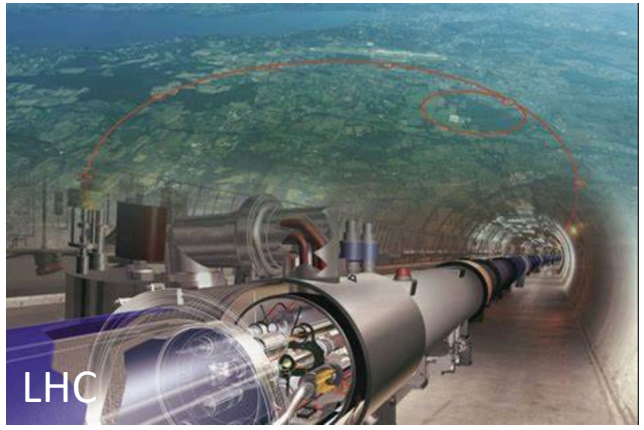


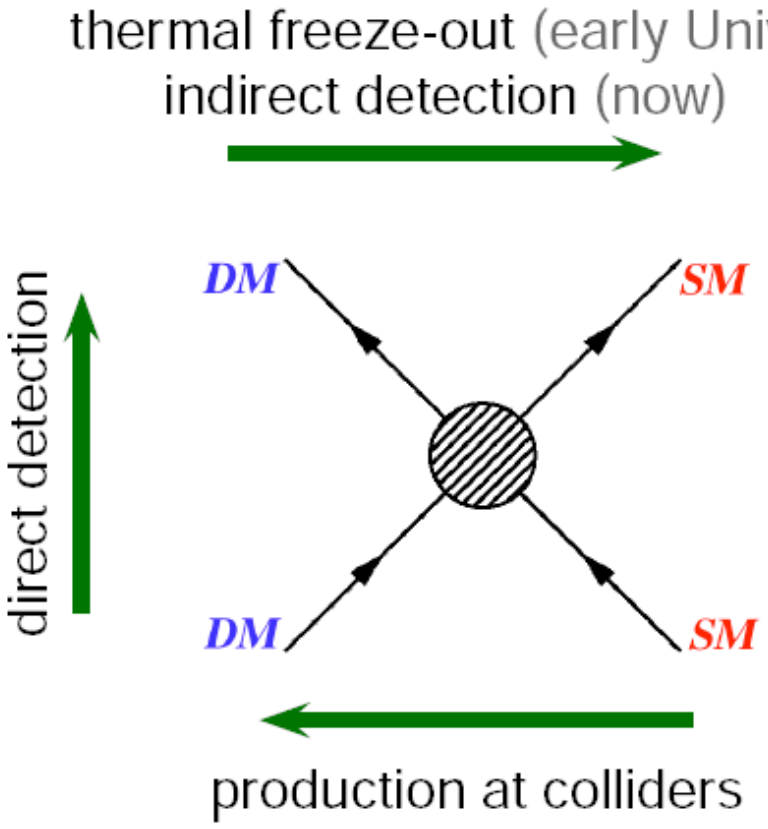


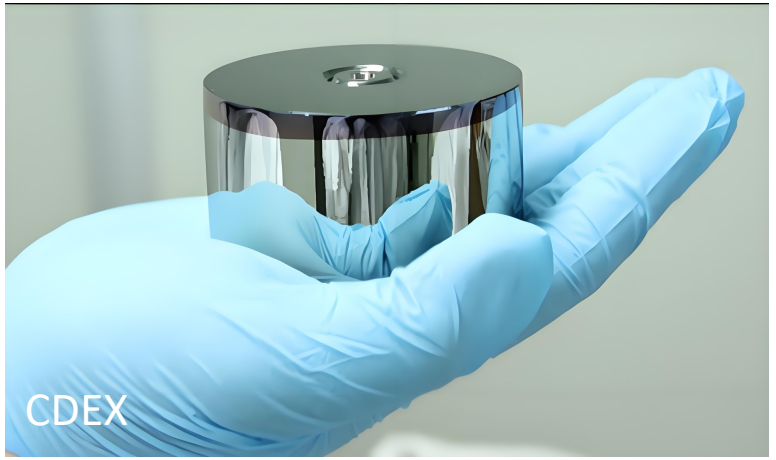
Experimental Searches

- **Direct detection，indirect detection，collider search**



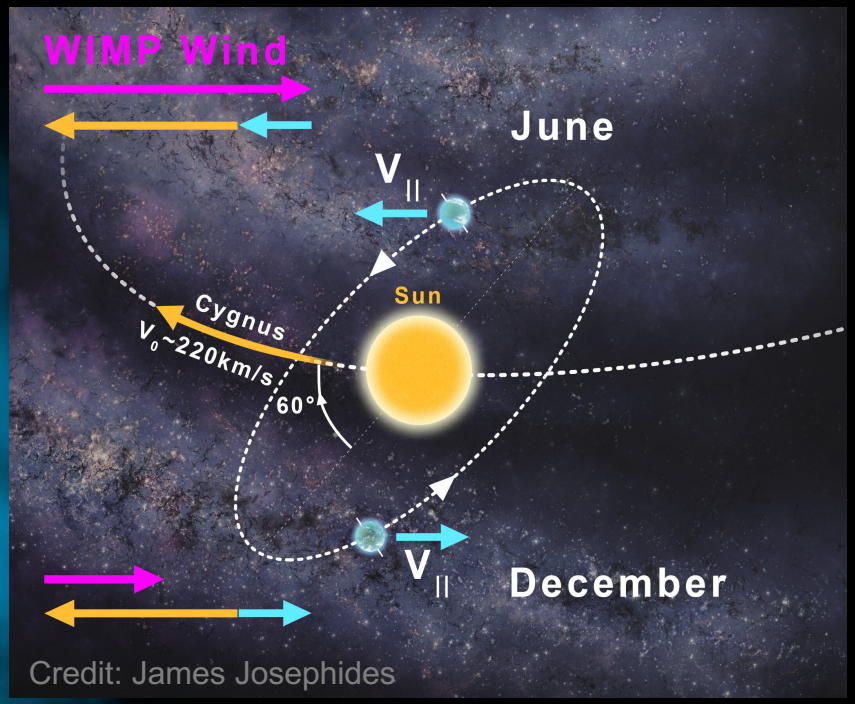


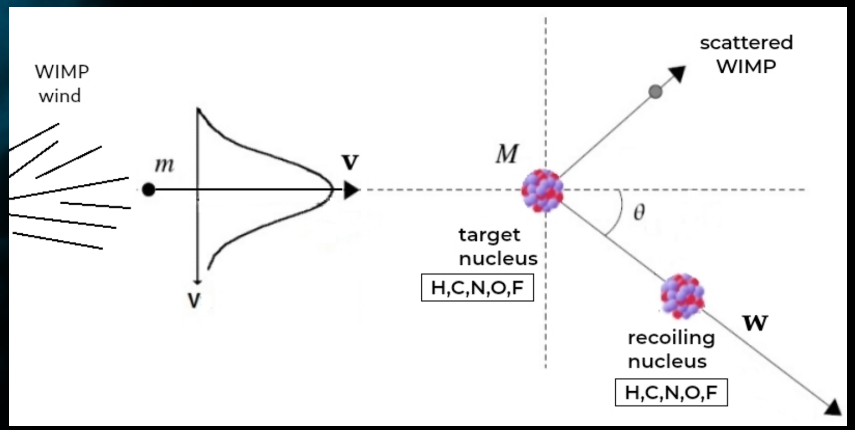




Dark Matter Direct Detection

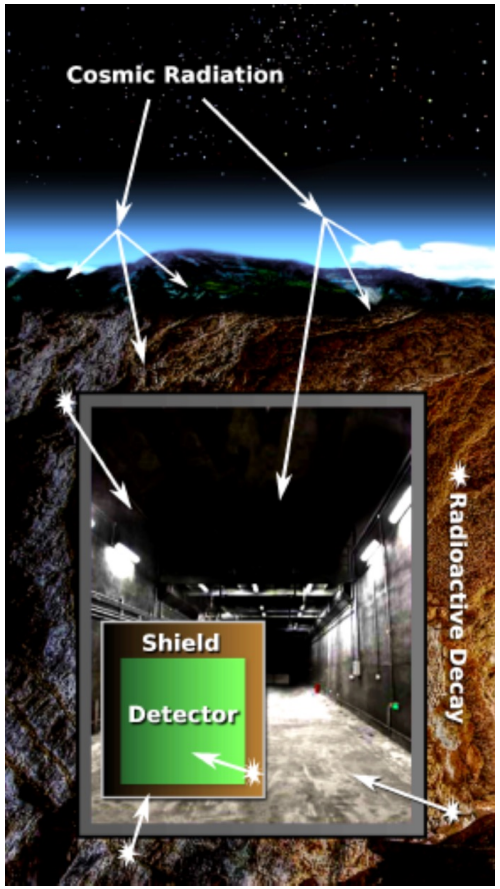
- **Local density**
  - 0.3 GeV/cm^3
- **Isothermal velocity distribution**
  - v_0~220 km/s
- **Nuclear recoil (NR)**
- **Electron recoil (ER)**

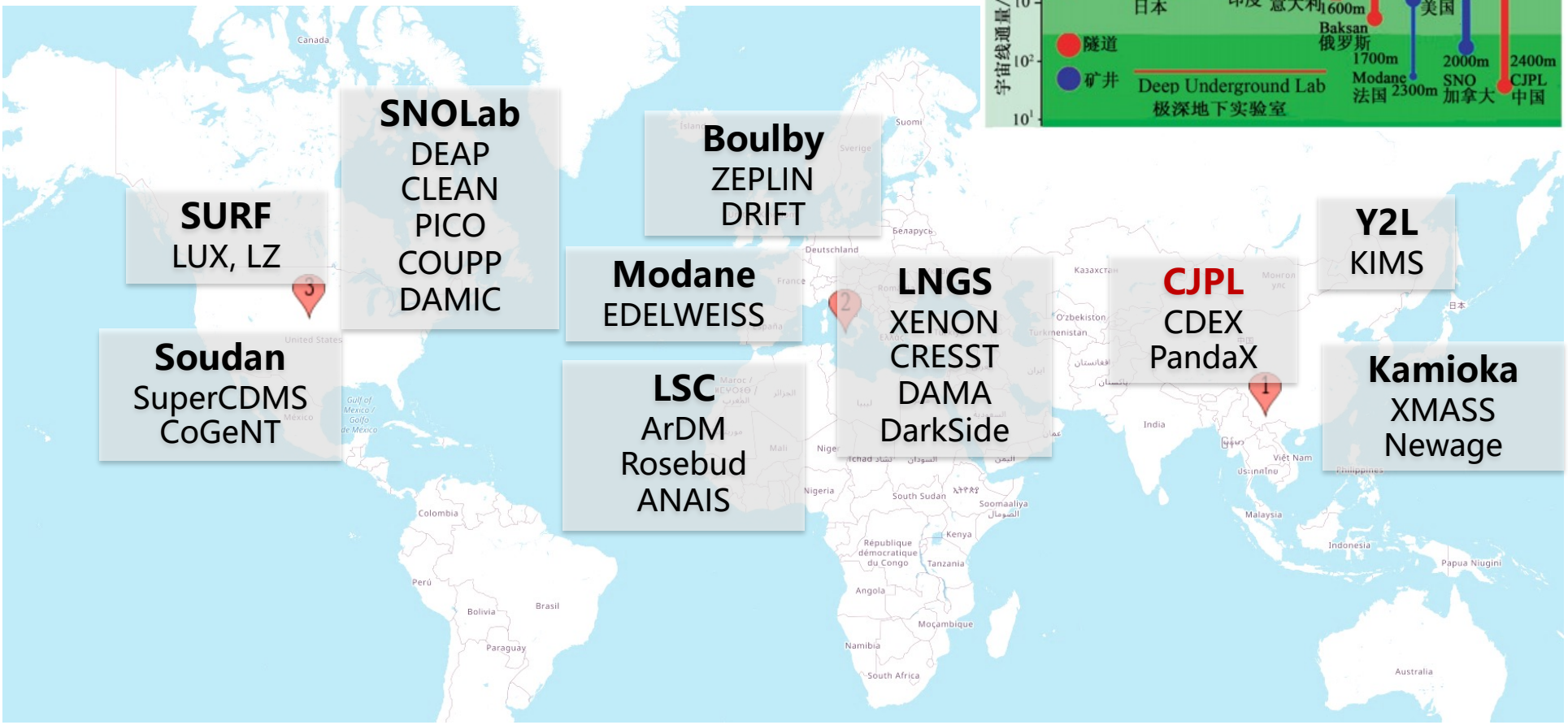


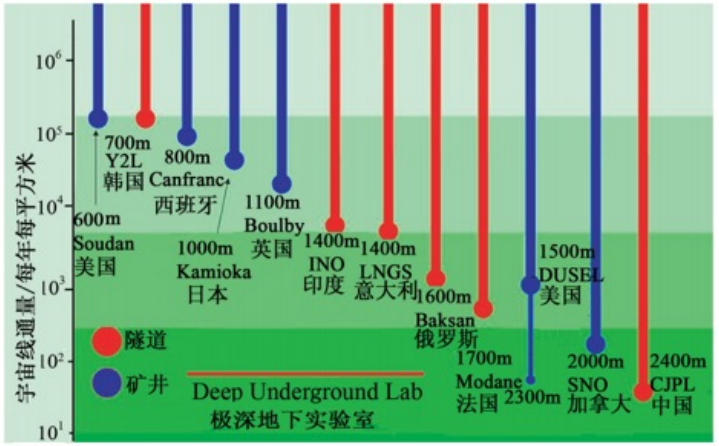


World-wide Efforts

- **Underground laboratories**

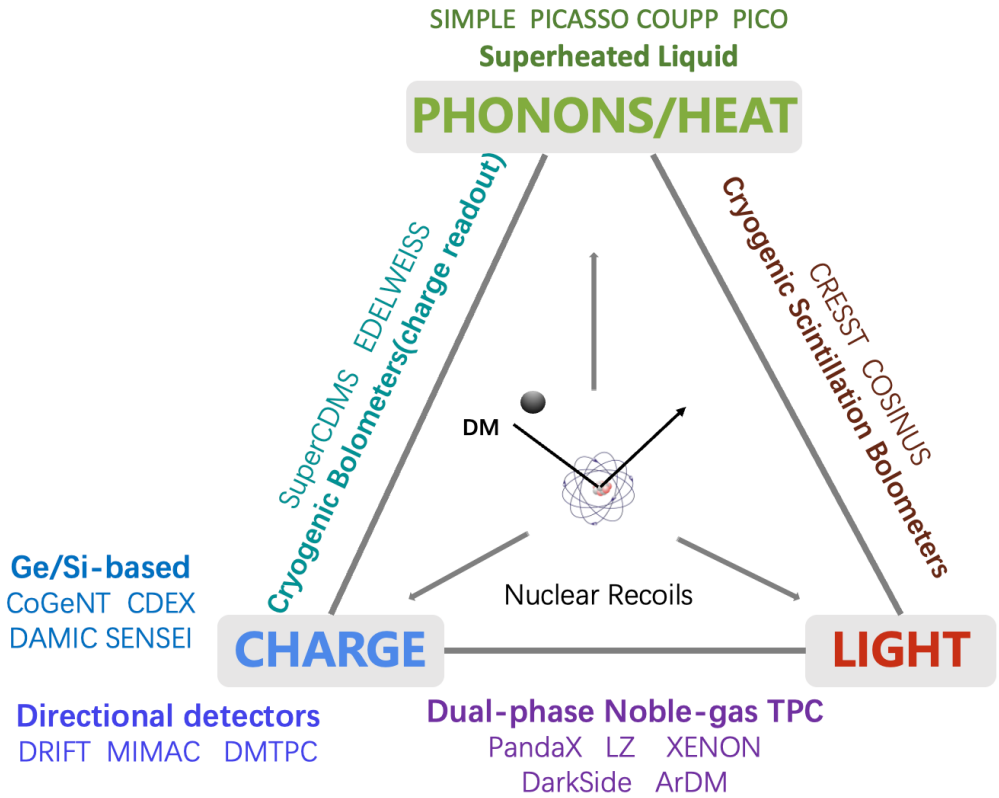


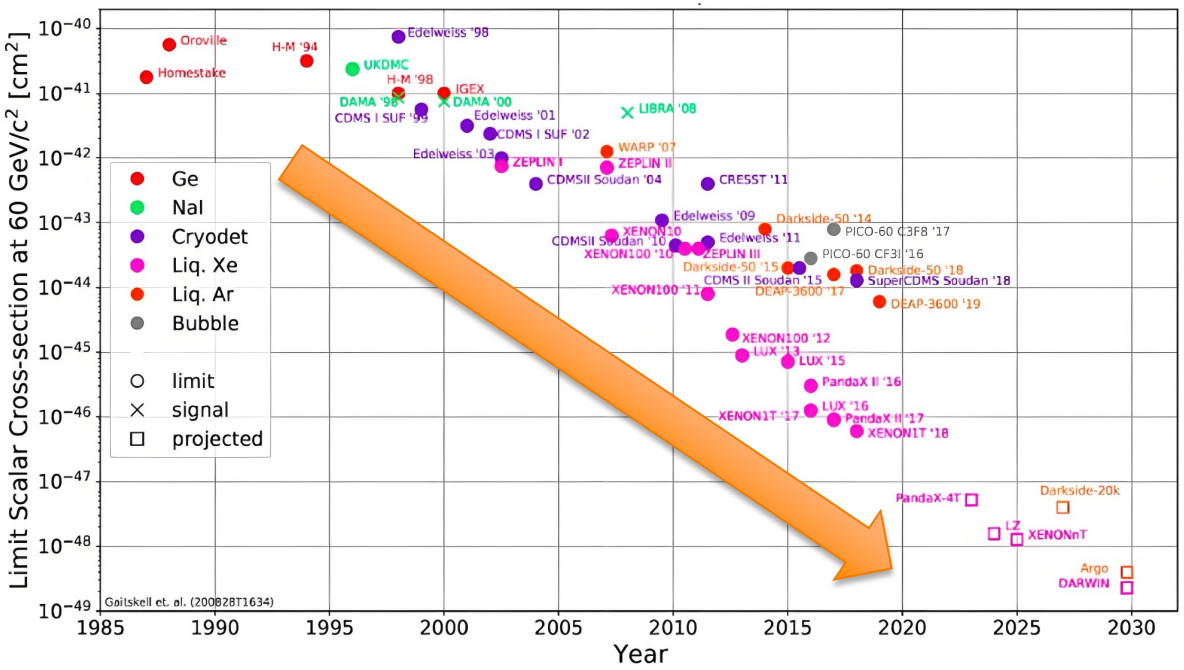




World-wide Efforts

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





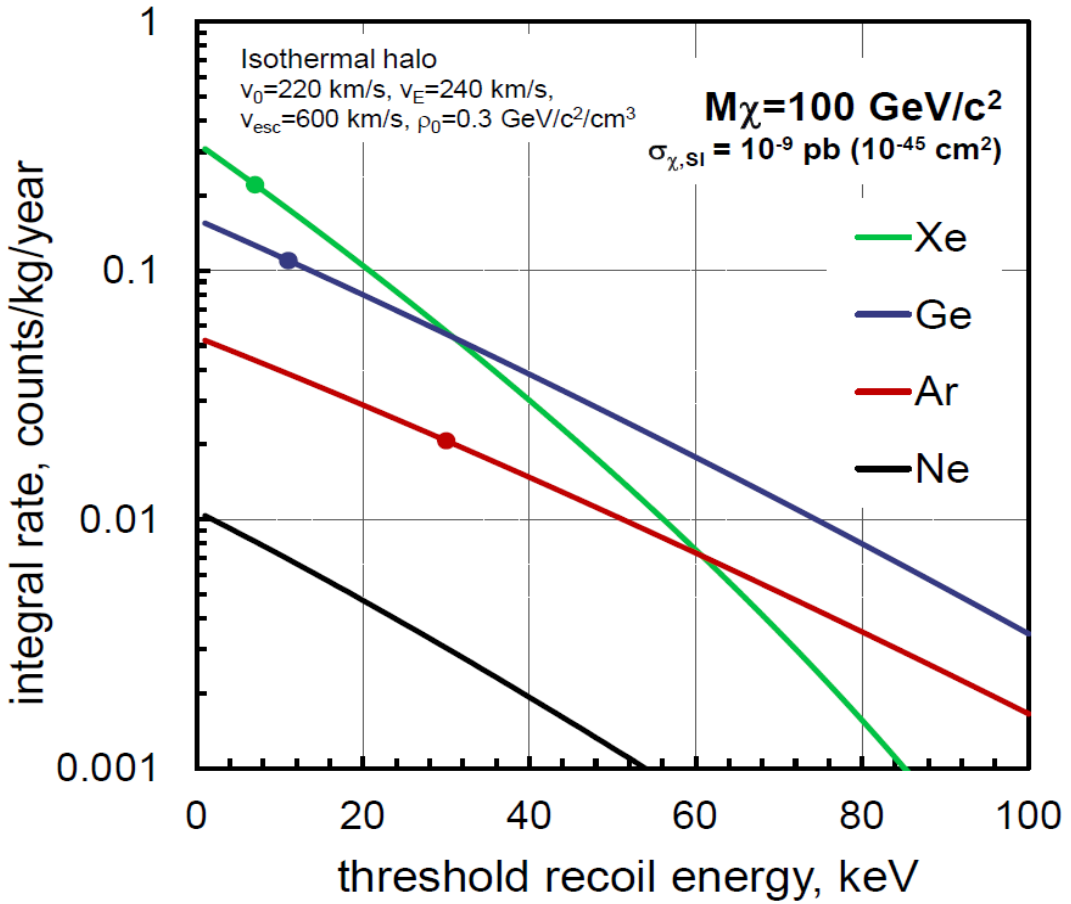
Nuclear Recoil Signature

- **Nuclear recoil rate**
  - Spin-independent, **coherent scattering**
    - $\sigma_N^{SI}(E_R) \propto \boldsymbol{A^2} F^2(E_R)\sigma_n$
  - Spin-dependent, spin structure factor
    - $\sigma_N^{SD}(E_R) \propto \frac{1}{2\boldsymbol{J}+1} S(E_R)\sigma_n$

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} \frac{d\sigma_{\chi N}}{dE_R}(v, E_R) v f(v) dv$$

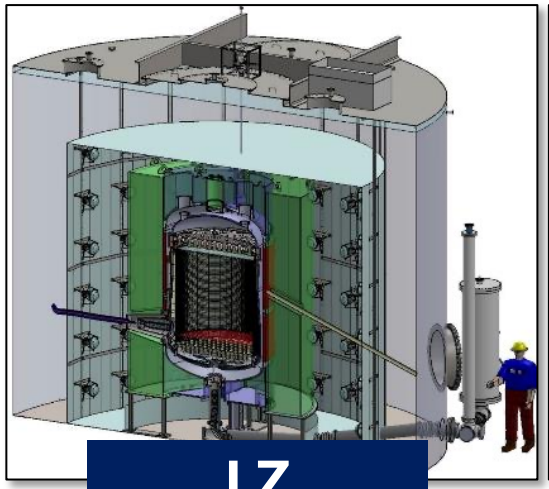
$$\frac{d\sigma_{\chi N}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2}(\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R))$$

NR spectrum



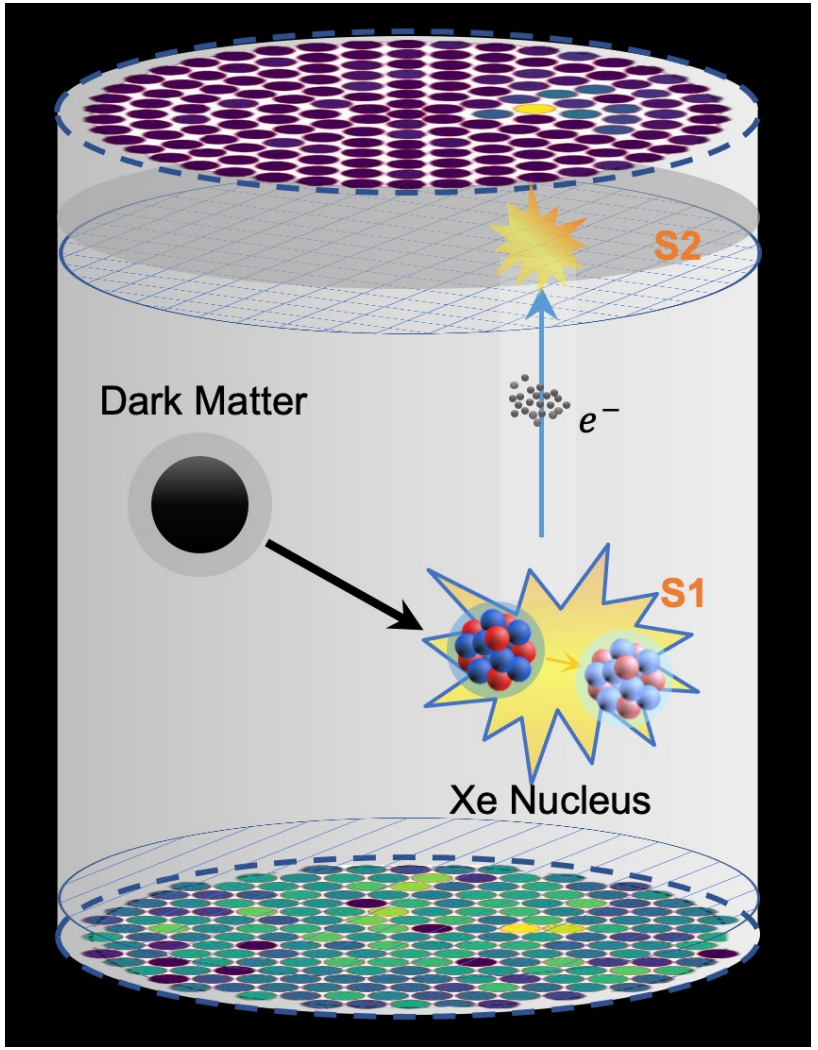
Noble LXe Time Projection Chamber

- **Dual-phase TPC detector**
  - 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

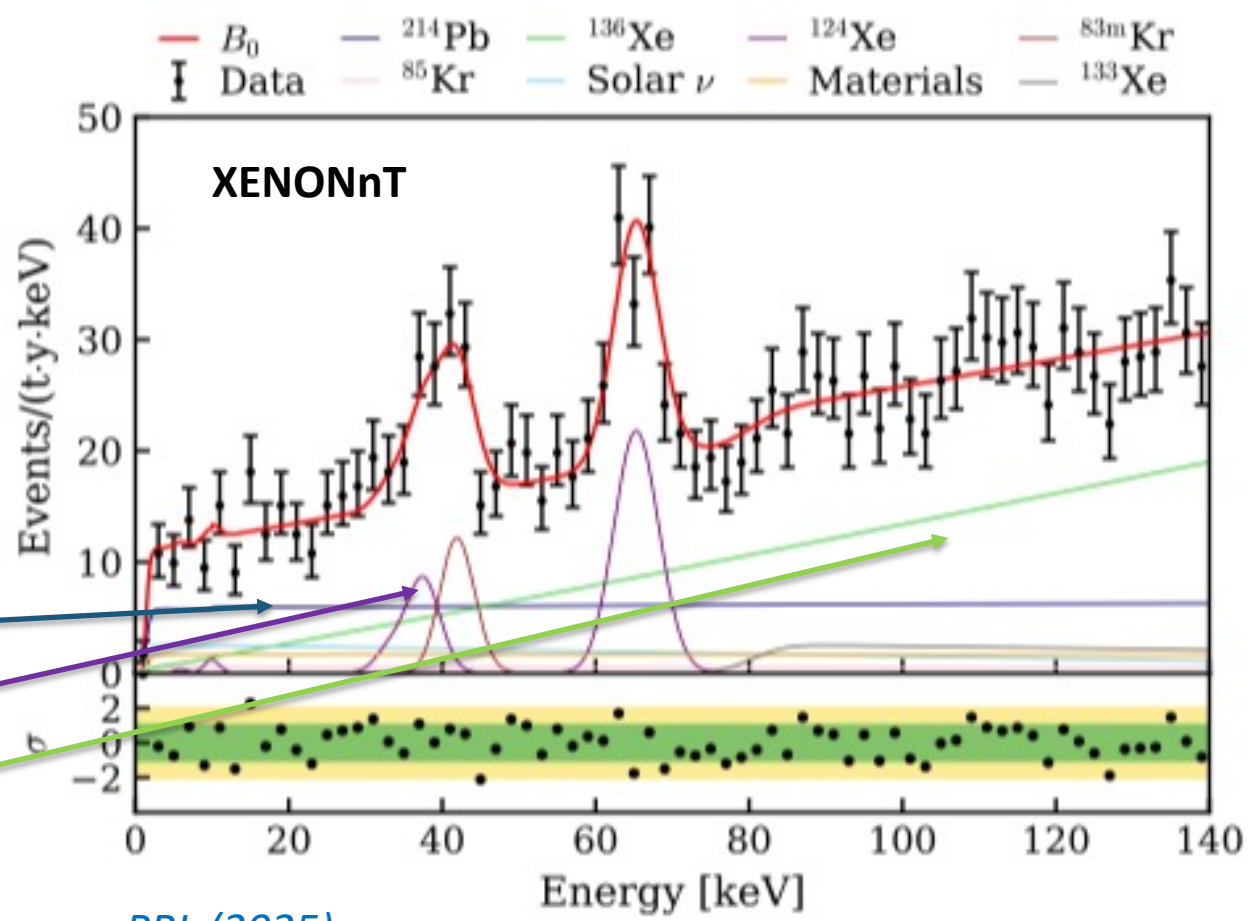

XENONnT


PandaX-4T



Noble LXe Time Projection Chamber

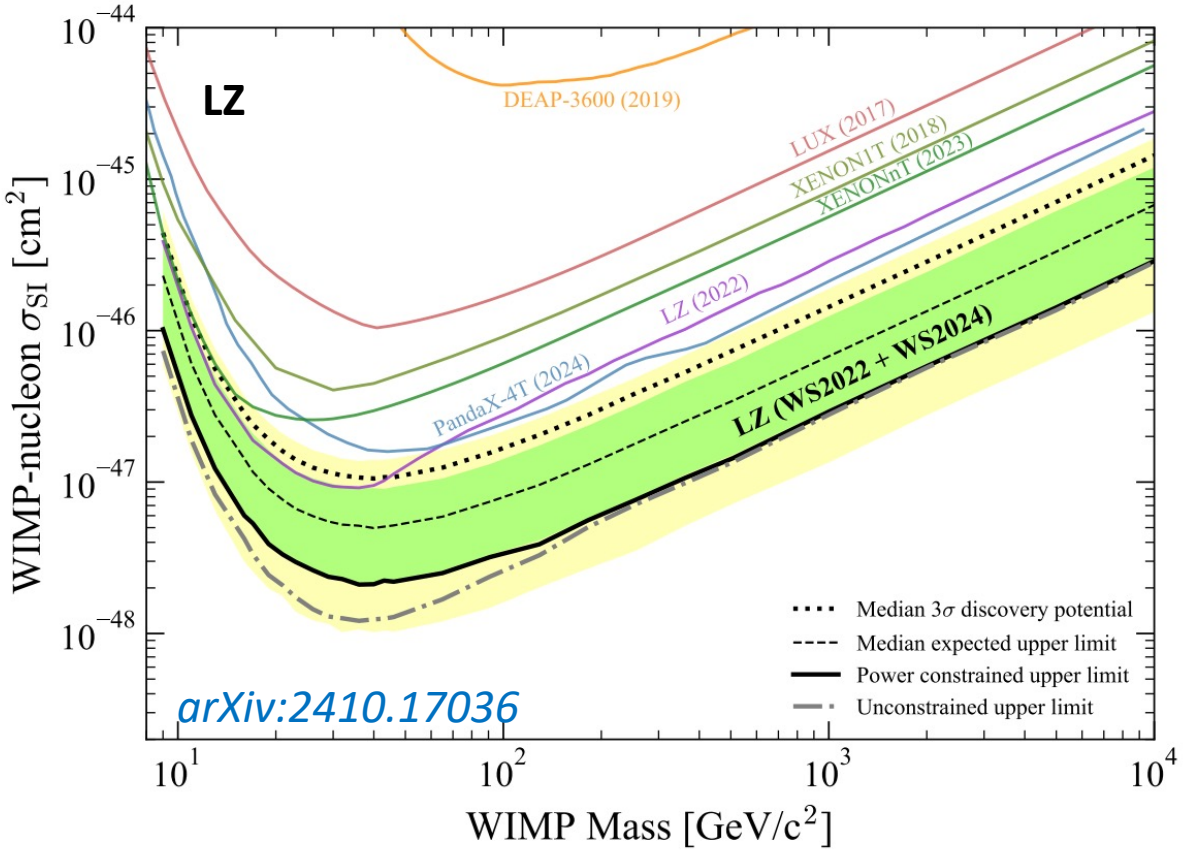
- **Paired S1-S2 events**
  - Reconstructing energy and 3-D position (resolution ~mm)
  - NR vs ER discrimination (50% NR efficiency and ~99.5% ER rejection)
- **Detection energy threshold**
  - ~ 3 keV NR or 1 keV ER
- **Dominant background**
  - Rn-222: online distillation ~1uBq/kg
  - Xe-124: 2vECEC
  - Xe-136: 2vDBD



PRL (2025)

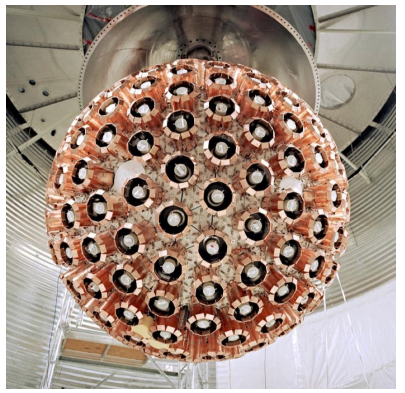
Noble LXe Time Projection Chamber

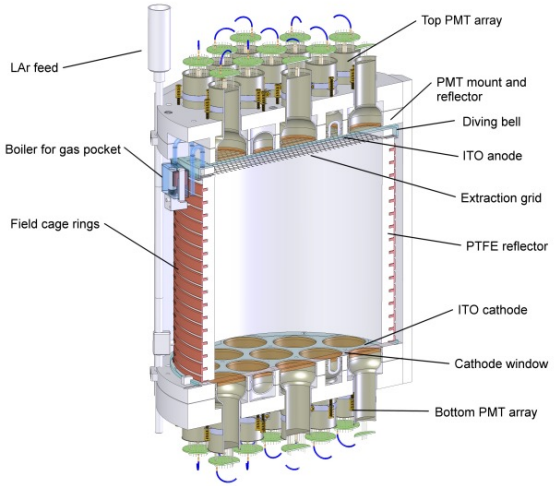
- **LZ experiment**
  - currently the largest exposure 4.2 tonne-year
- **Strongest limits on WIMPs>10 GeV/c^2**
  - Limits of σ_{SI} reaches 2x10^{-48} cm^2 at 36 GeV/c^2 DM
  - Expected sensitivity reaches 5x10^{-48} cm^2 at 40 GeV/c^2)

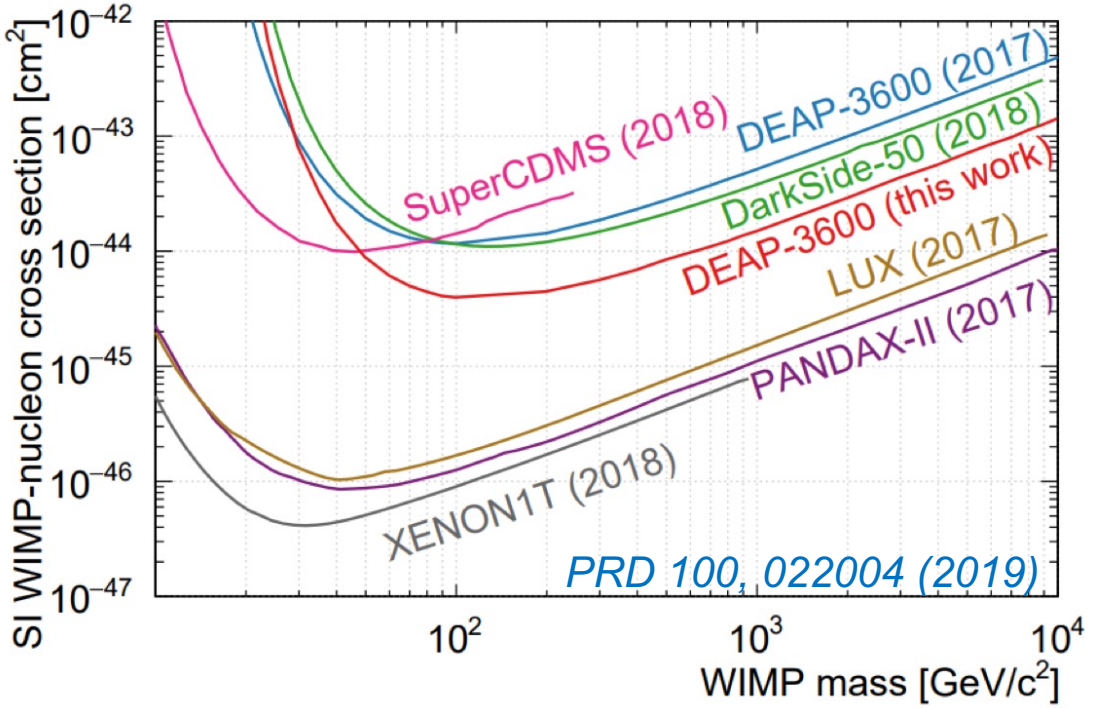


Noble LAr Detector

- **DEAP3600 @SNOLAB**
  - Single-phase, Ar 3.6 tonne
  - PSD for NR/ER separation
  - New position reconstruction algorithm (*arXiv:2503.10383*)
  - Upcoming WIMP results with 831 days' data
- **Darkside-50 @LNGS**
  - Dual-phase
  - Low-radioactive Ar 46.4 kg

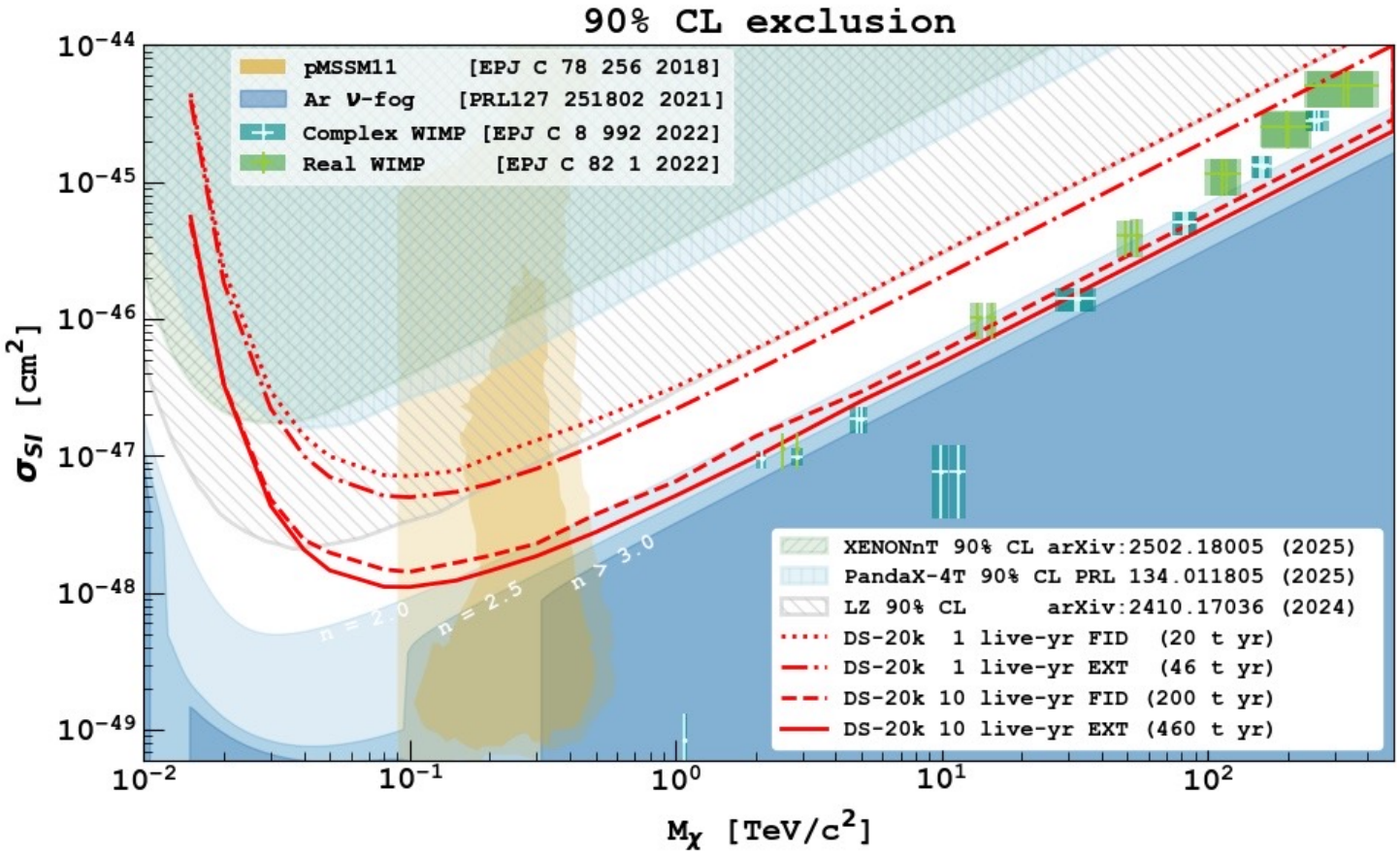


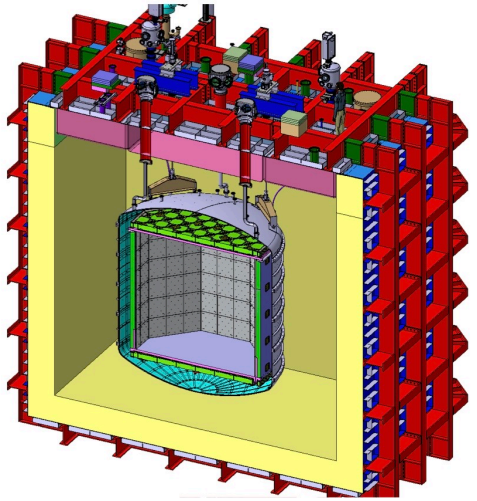




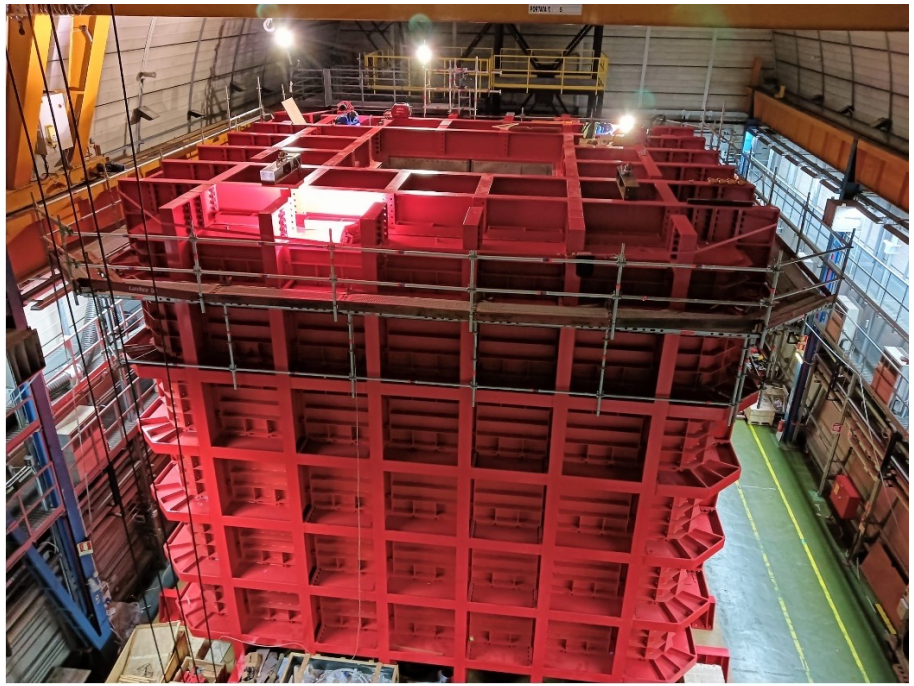
DarkSide-20k in Construction

- **DarkSide-20k @LNGS**
  - Active (fiducial) UAr mass: 49.7 (20.2) t



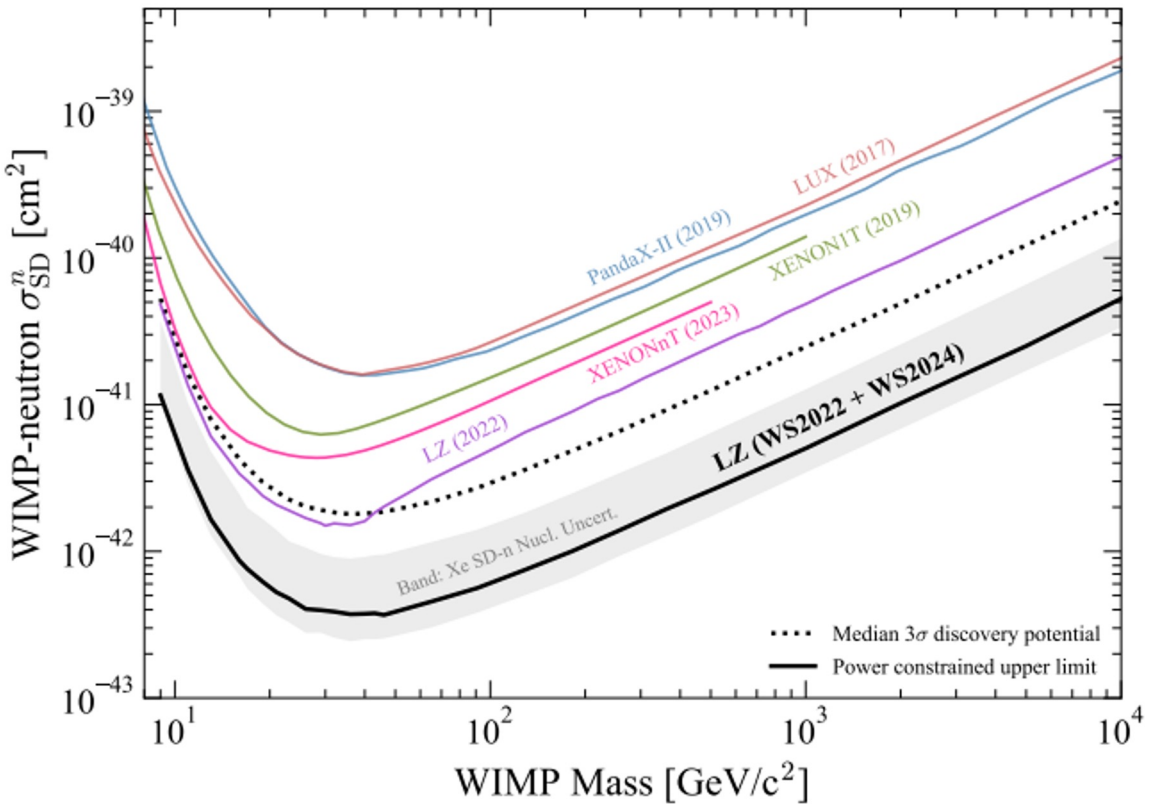


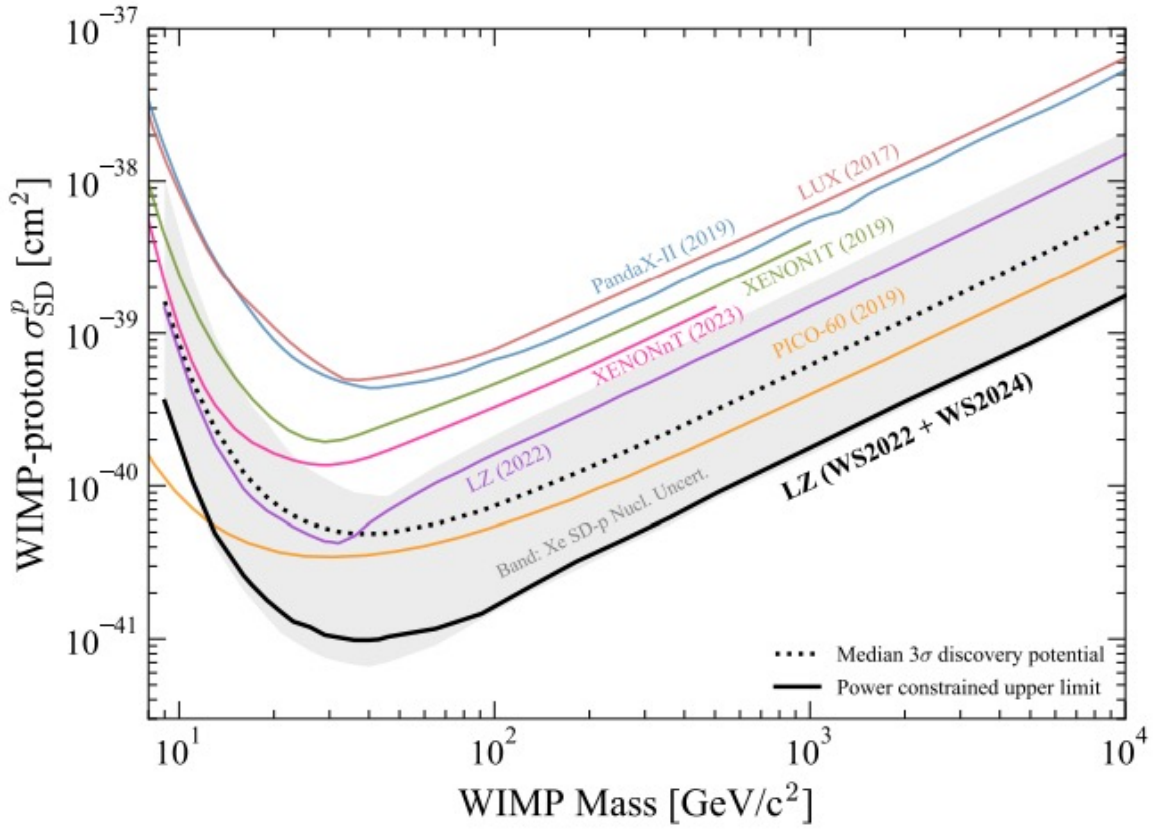
DarkSide-20k



Spin-dependent Nuclear Recoil

- **Xenon: odd-A isotope with unpaired neutron**
  - ^{129}Xe (26.4%, spin-1/2), ^{131}Xe (21.2%, spin-3/2)

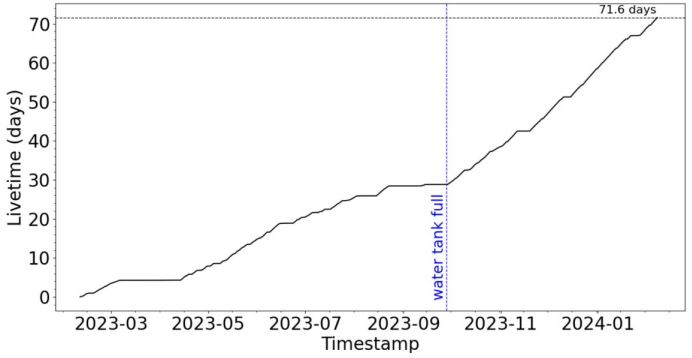


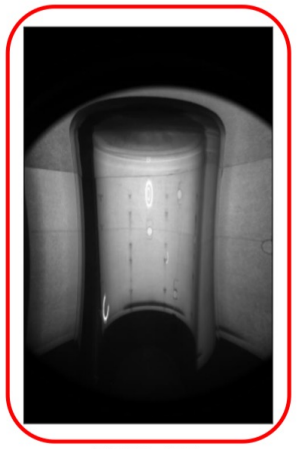


arXiv:2410.17036

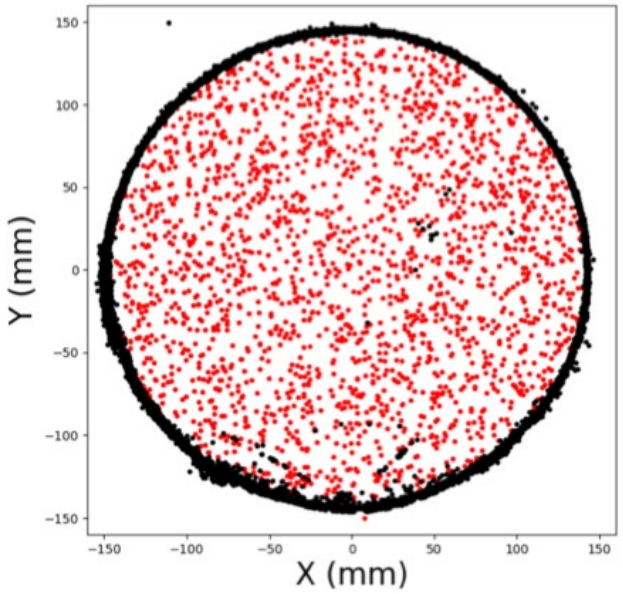
PICO-40L Bubble Chamber

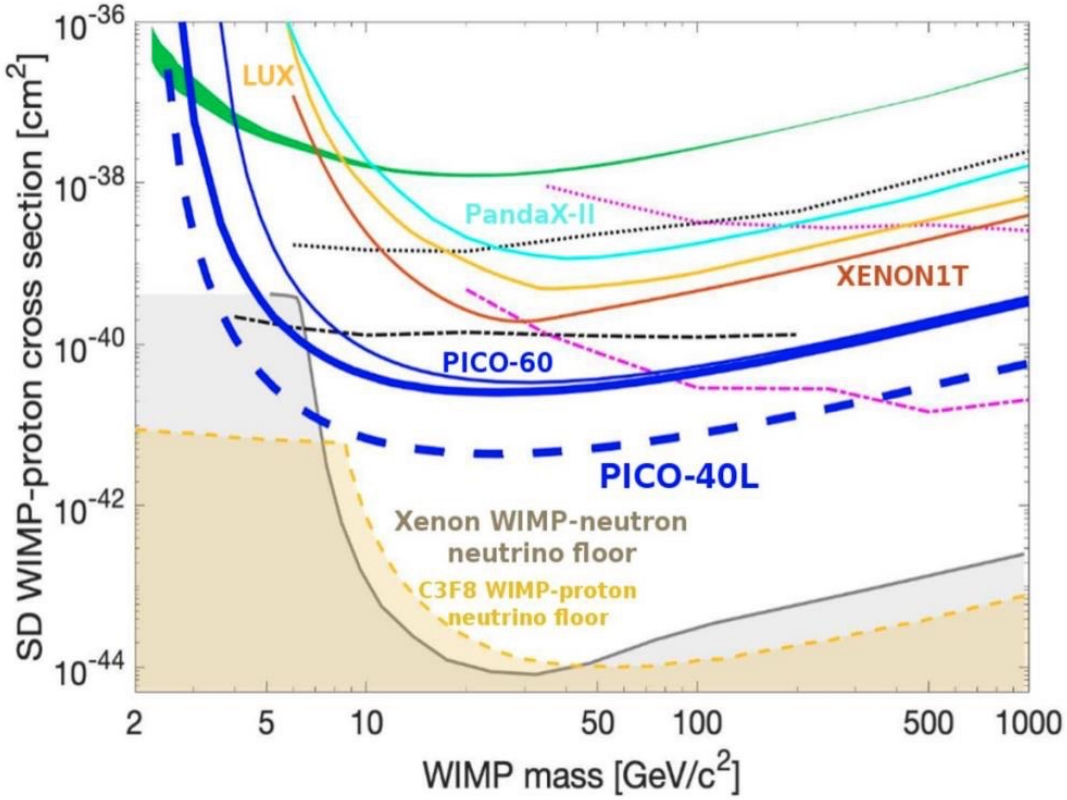
- **Bubble chamber with superheated liquid C_3F_8**
  - ^{19}F with unpaired proton, spin-1/2
  - Passive ER rejection (no bubble for electron recoil)
  - Camera for position reconstruction
  - Acoustic Parameter for alpha rejection




PICO-40L

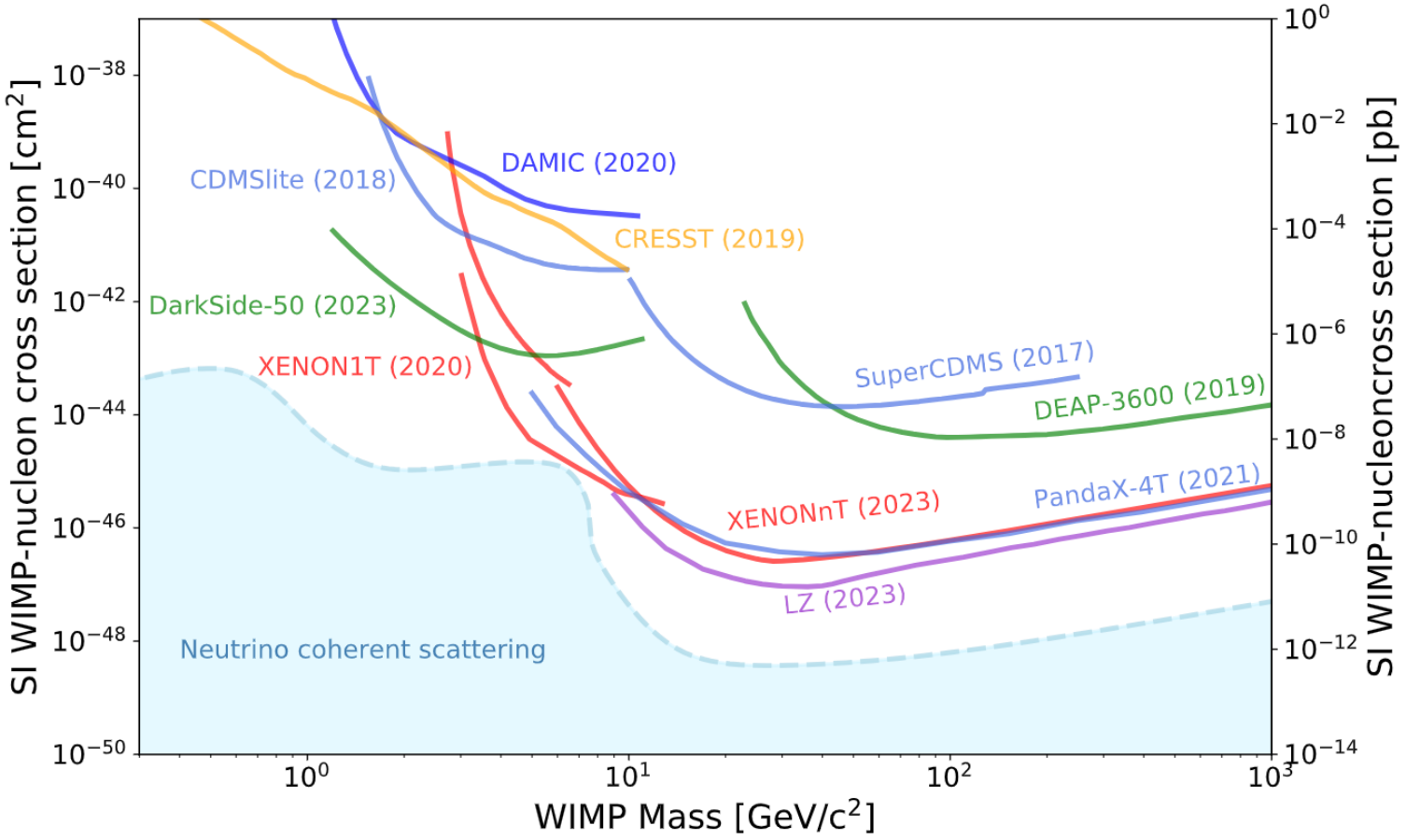

PICO-500





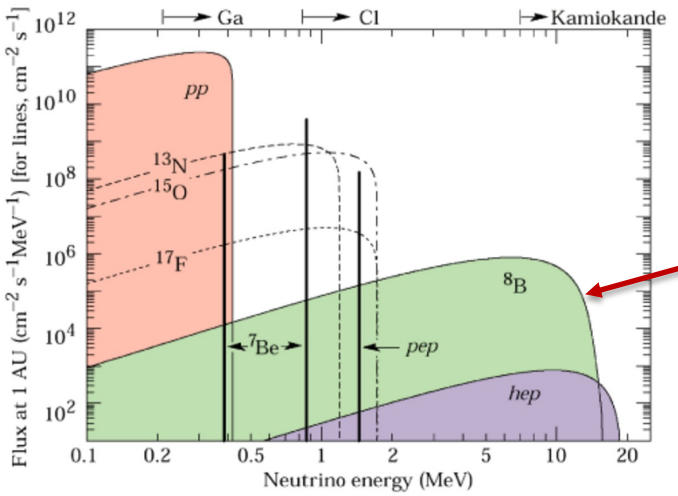
Lowering Detection Threshold

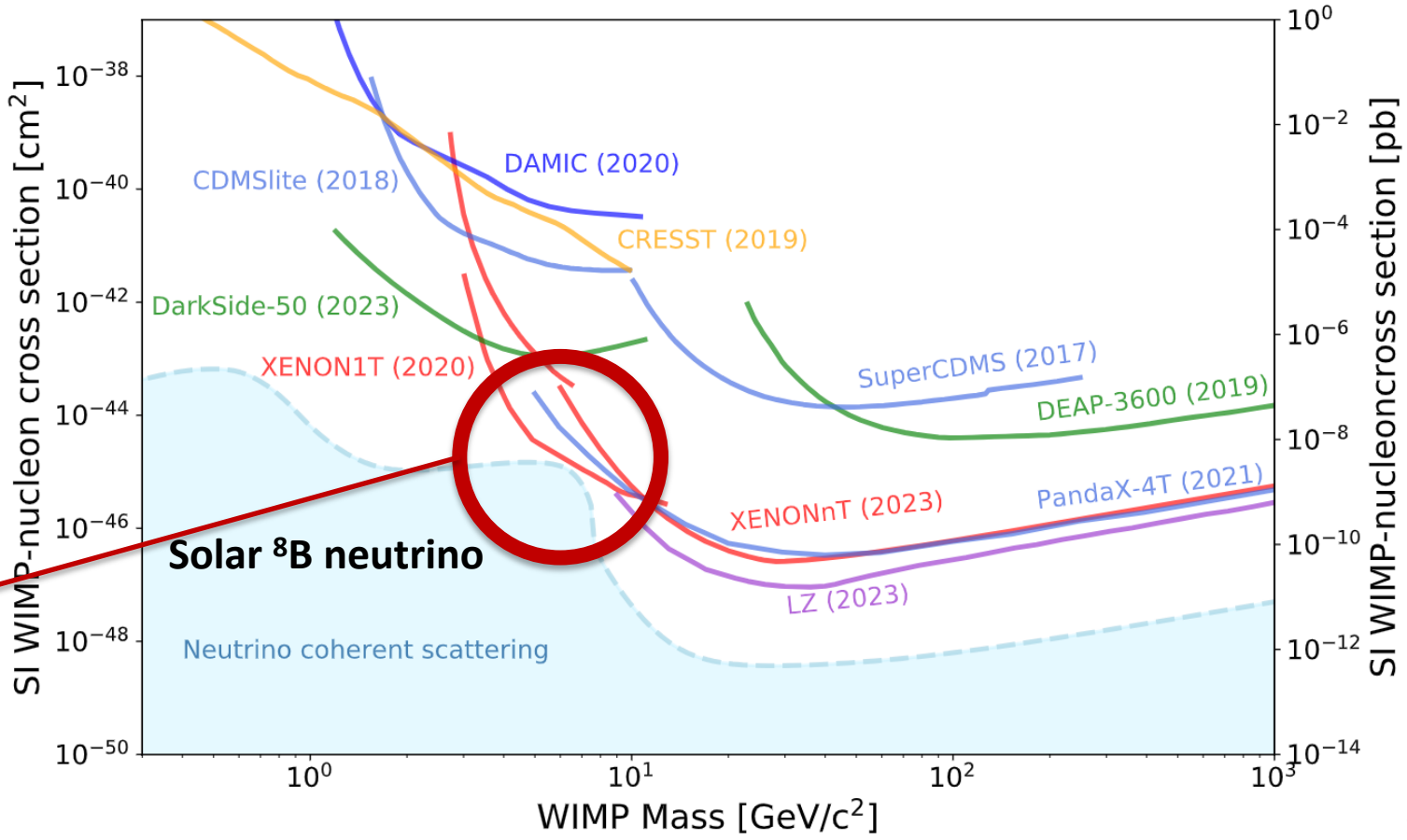
- **Sensitivity decreases significantly for DM mass < 10 GeV**
  - Limited by scintillation light signal detection



Lowering Detection Threshold

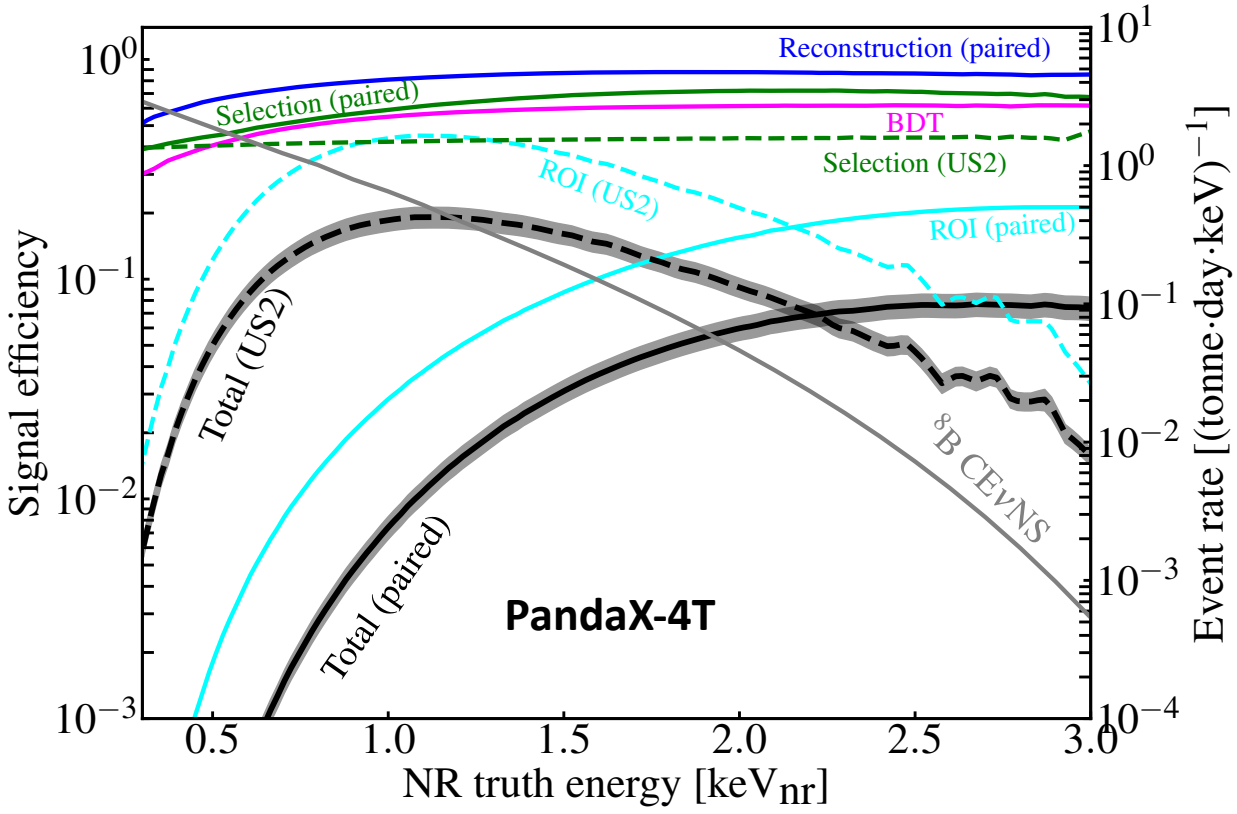
- **Sensitivity decreases significantly for DM mass < 10 GeV**
  - Limited by scintillation light signal detection
- **Low threshold detection**
  - Solar ^{8}B neutrino CEvNS

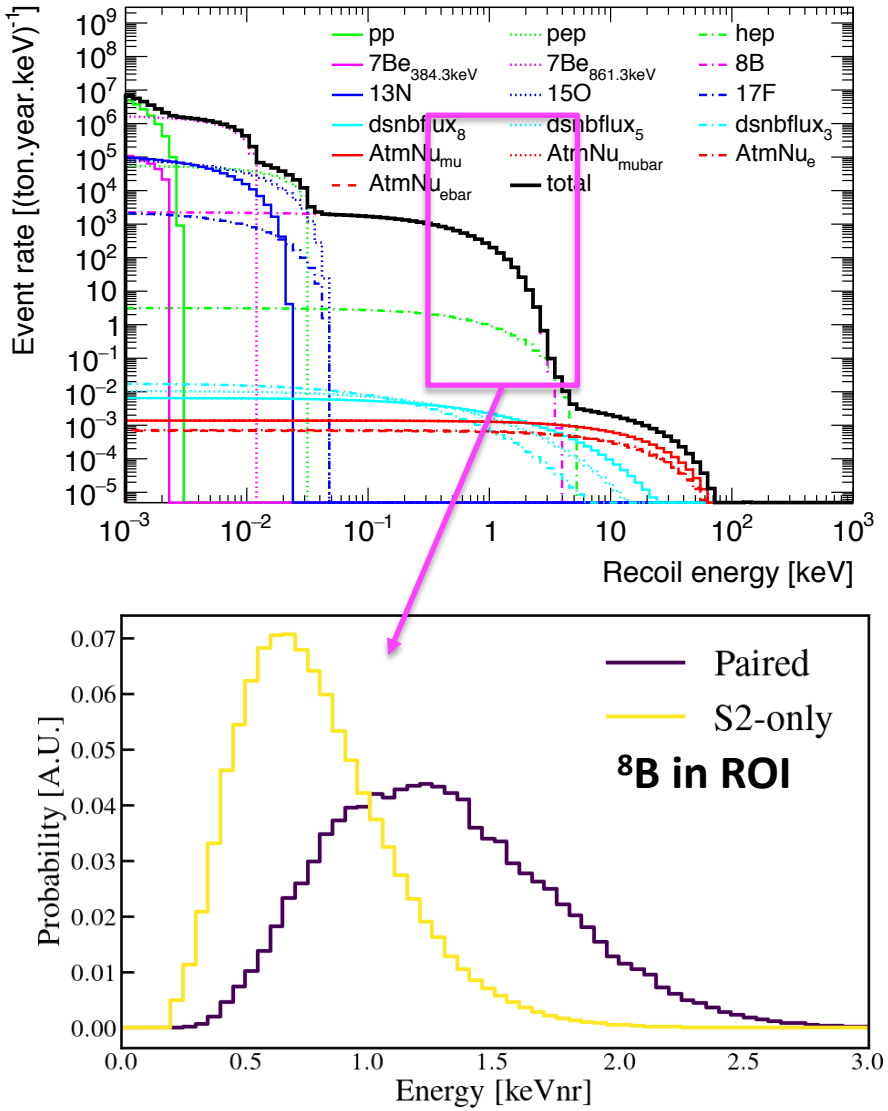




Low-threshold Detection

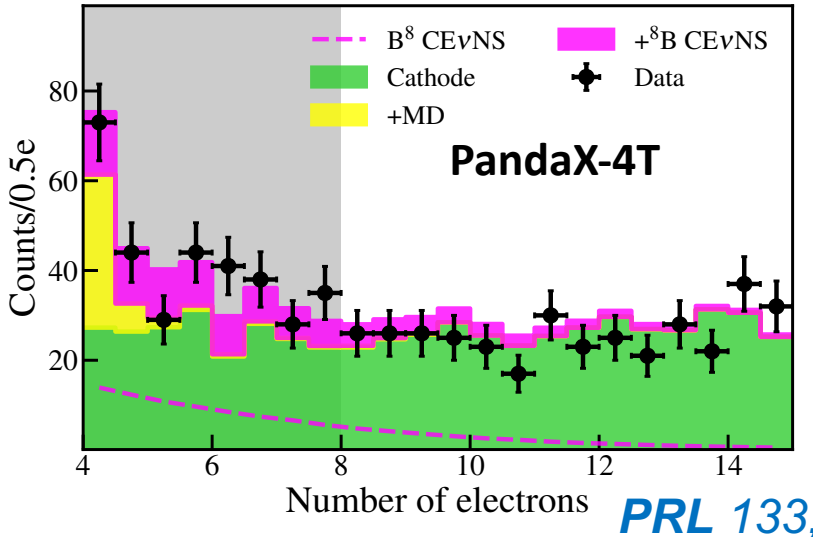
- **Low threshold detection: NR threshold ~3keV –> ~0.3keV**
  - low threshold paired ROI
  - Ionization S2-only ROI





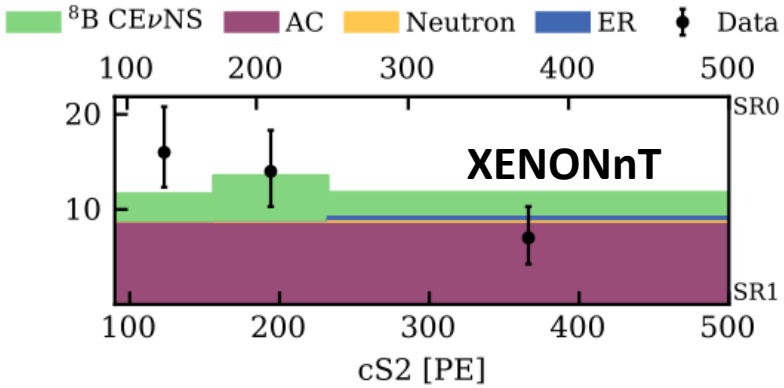
First Indication of Solar ^{8}B Neutrino CEvNS

- **PandaX-4T: 1.0 tonne-year**
  - S2only and Paired ROIs: 2.64 sigma
- **XENONnT: 3.5 tonne-year**
  - Paired ROI: 2.73 sigma



Best-fit ^{8}B yield
Paired: **3.5 ± 1.3** evts
S2only: **75 ± 28** evts

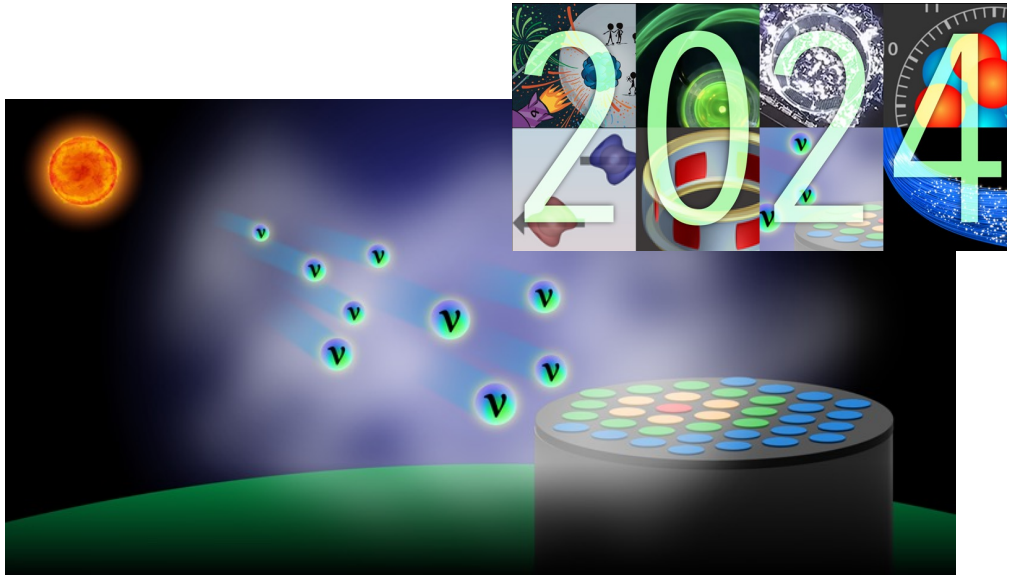
PRL 133, 191001 (2024)



Best-fit ^{8}B yield
Paired: **$10.7\ ^{+3.7}_{-4.2}$** evts

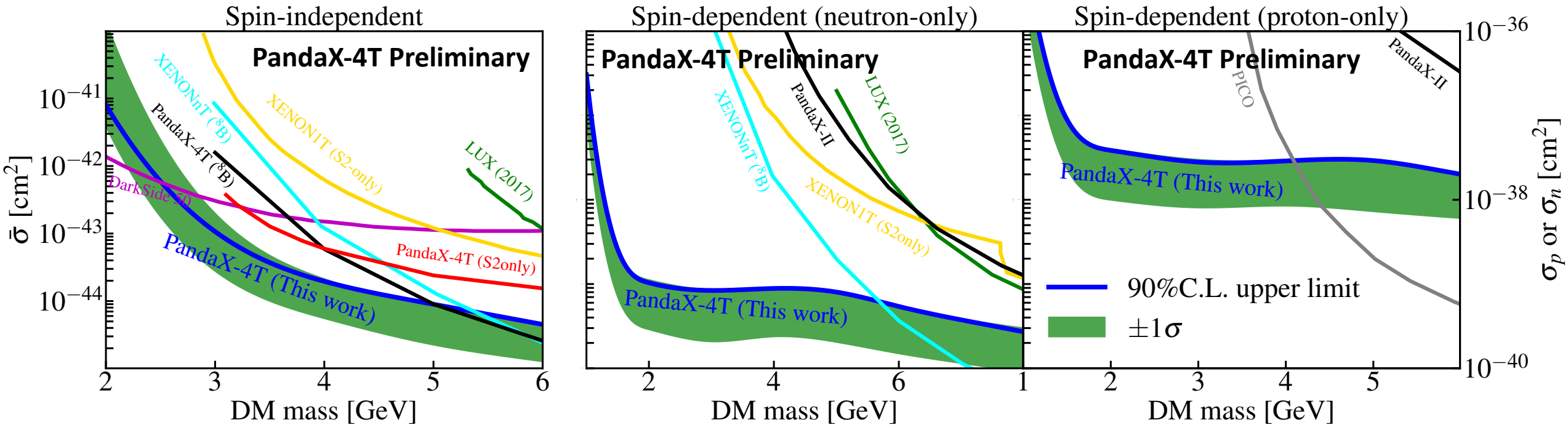
PRL 133, 191002 (2024)

- **Demonstrating low-mass DM detection capability**



Low Mass Dark Matter Detection

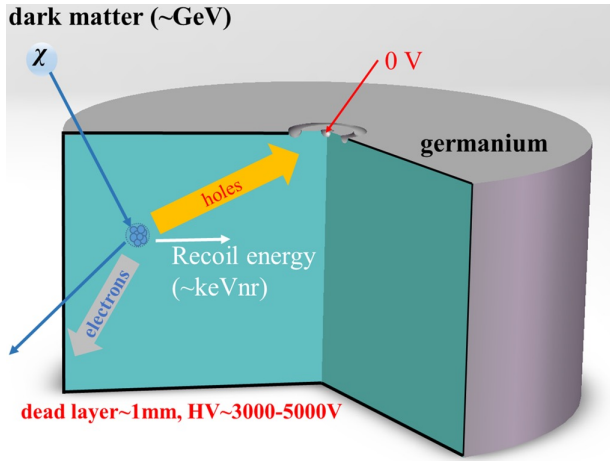
- **Extending high-sensitive region to 2 – 6 GeV/c^2**
  - SI ~10^{-41} – 10^{-44}cm^2, SD-neutron ~10^{-39}cm^2, SD-proton ~10^{-38}cm^2



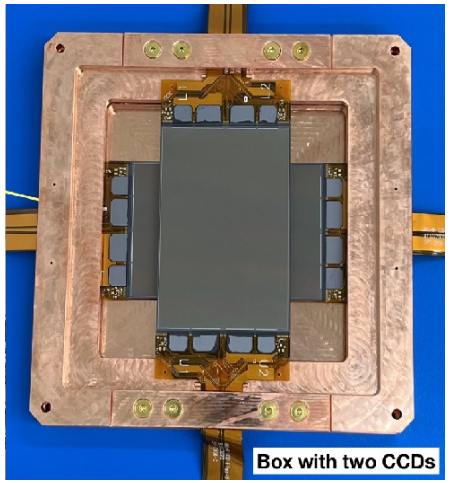
- **Even touching the neutrino floor, can still have sensitivity to DM signals based on the energy spectrum information**

Low Mass Dark Matter Detection

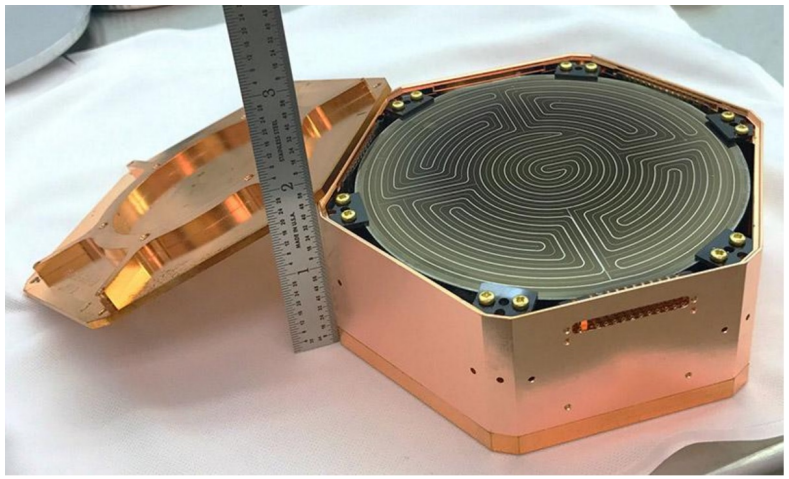
- **Low threshold detectors**
  - Cryogenic solid target
  - Ge, Si, $CaWO_4$, Skipper CCD



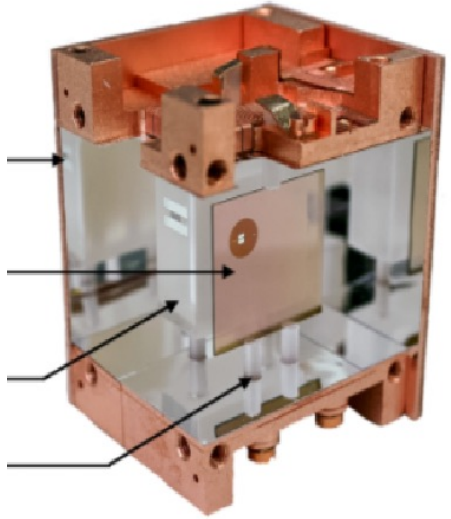
CDEX



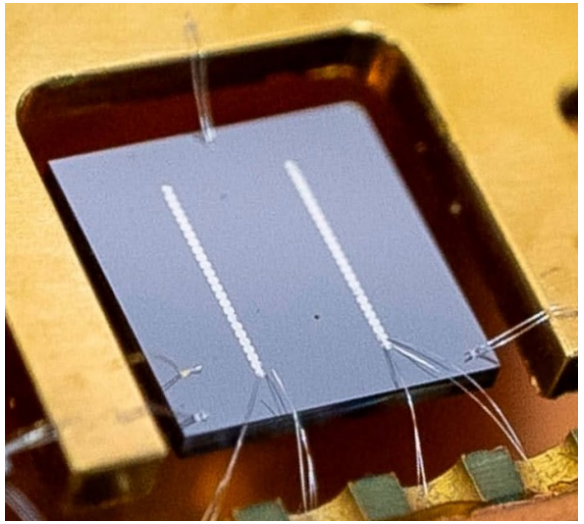
DAMIC-M



SuperCDMS



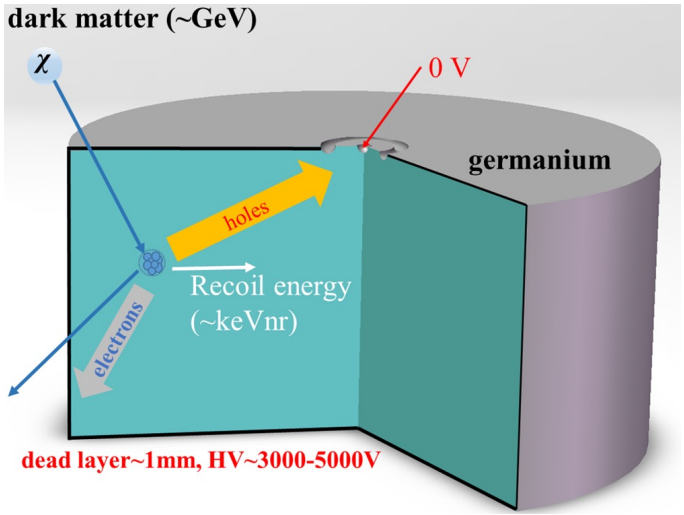
CRESST

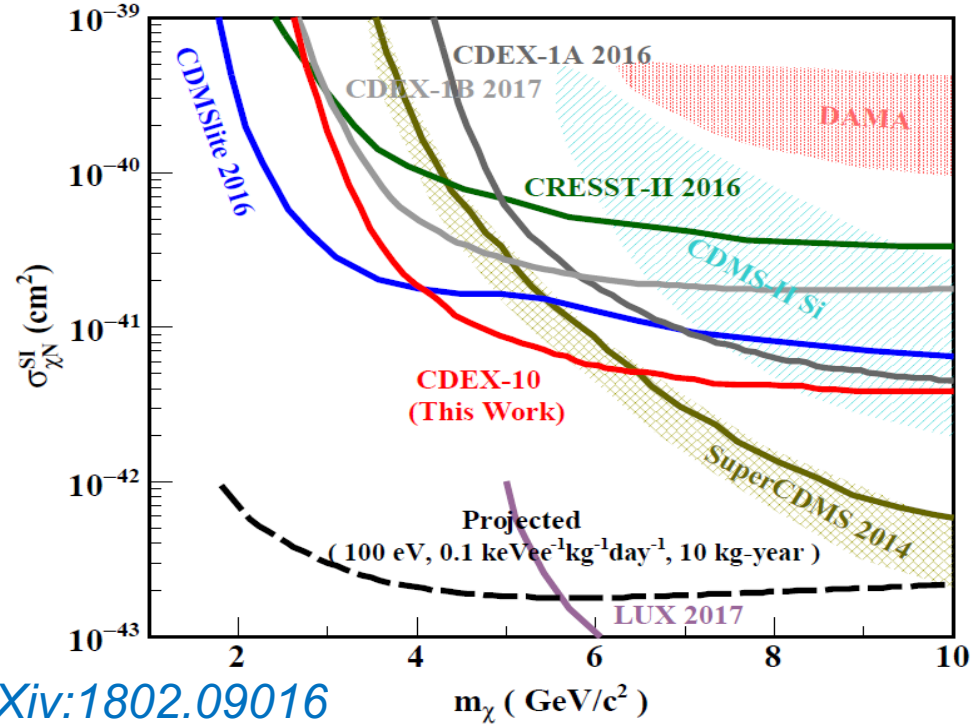


TESSERACT

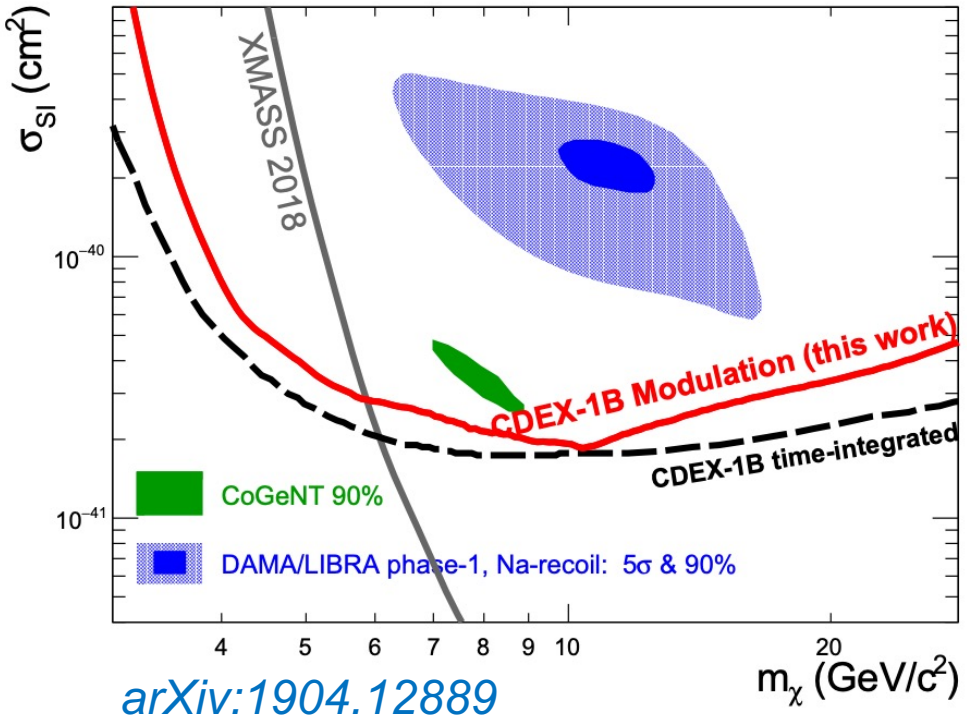
CDEX-10

- **>10 kg PPC Ge**
  - Low background ~2 cts/(keV·kg·day)
  - Low threshold ~160 eV_{ee}





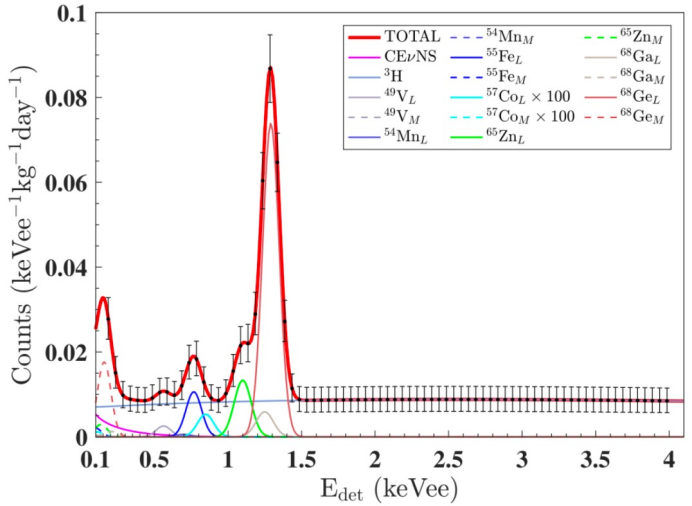
arXiv:1802.09016



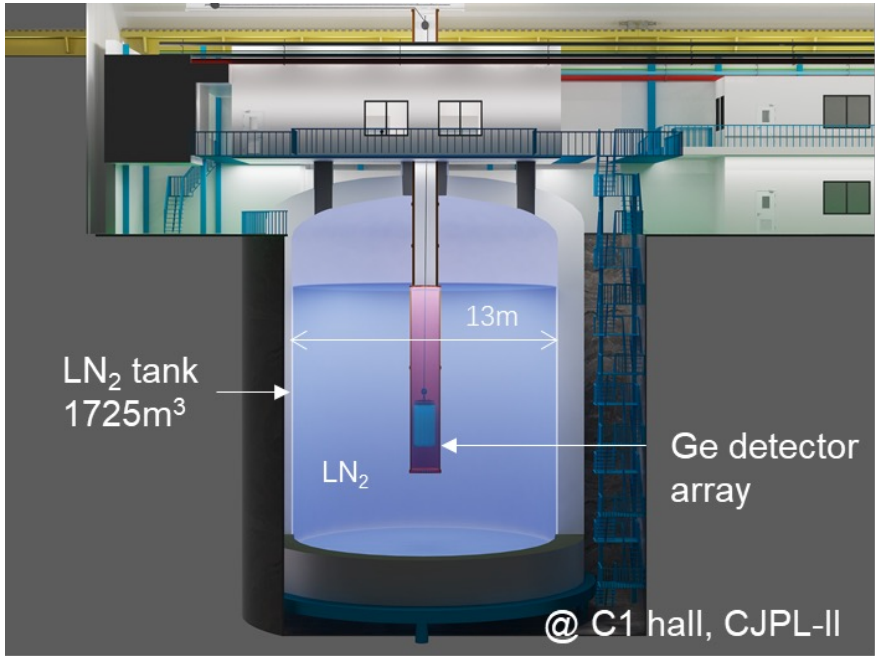
arXiv:1904.12889

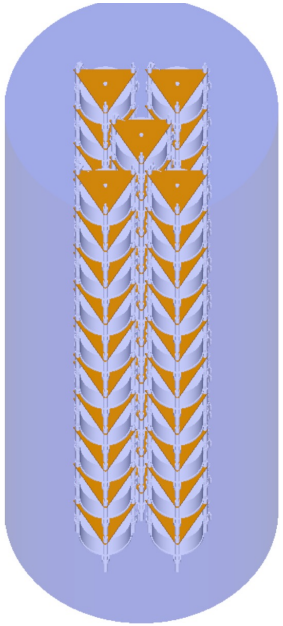
CDEX-50 in Construction

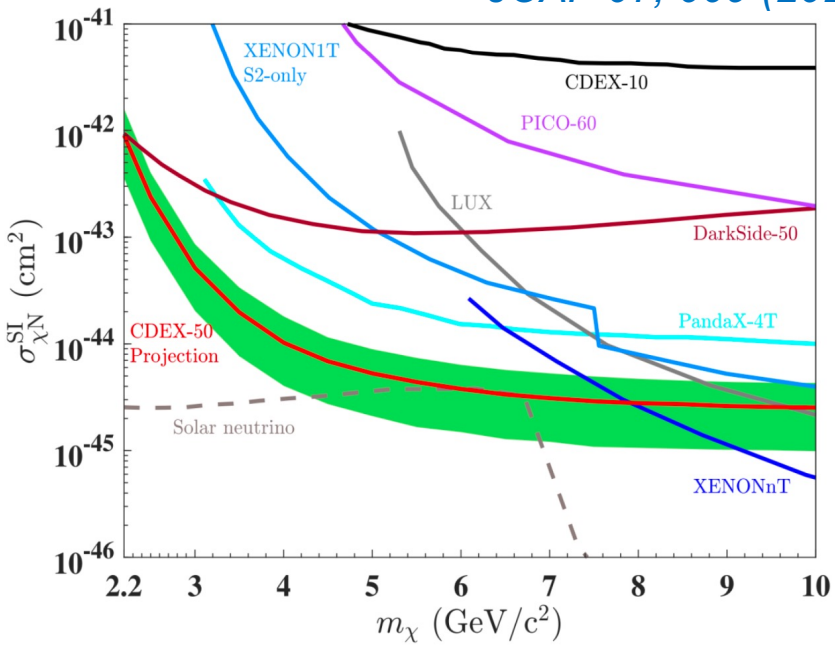
- **CDEX-50**
  - ~50 kg HGe array directly immersed in LN_2
  - Low bkgd < 0.01 cts/(keV·kg·day)
  - Expected exposure ~50 kg·year
  - Sensitivity can reach 10^{-44} cm^2 @2-10 GeV



JCAP 07, 009 (2024)



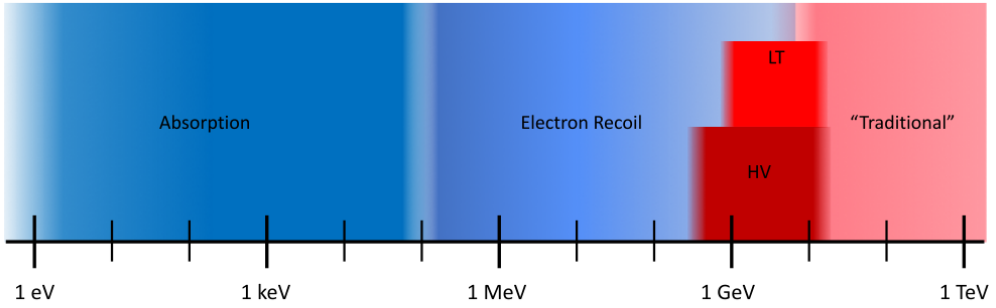




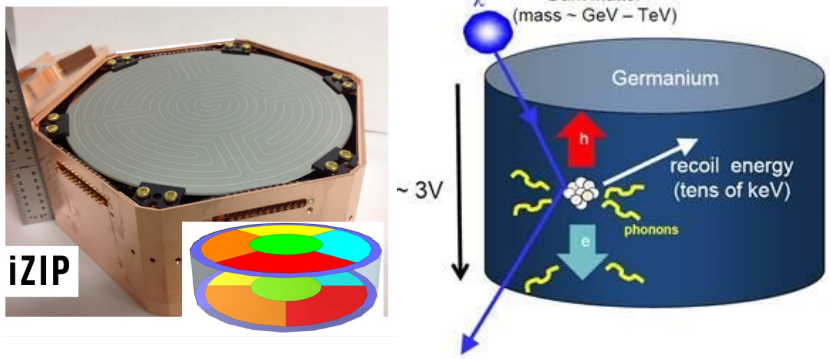
SuperCDMS

- **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

"Traditional" NR	iZIP, "background free"	$\gtrsim$ 5 GeV
Low Threshold NR	iZIP, limited discrimination	$\gtrsim$ 1 GeV
HV Mode	HV, no discrimination	~0.3 – 10 GeV
Electron recoil	HV, no discrimination	~0.5MeV – 10 GeV
Absorption (Dark Photons, ALPs)	HV, no discrimination	~1 eV – 500 keV



Interleaved Z-sensitive Ionization and Phonon (iZIP) detectors



12 phonon channels, 4 charge channels
Low bias voltage (~ 6 V)
ER/NR discrimination

arXiv:2203.08463

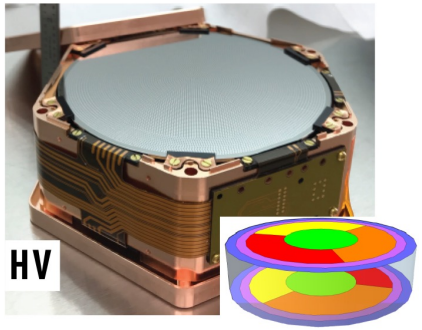
iZIP

	Si	Ge
σ_{ph}	19 eV	33 eV
σ_{ch}	180 eV	160 eV
Threshold$_{ph}$	175 eV	350 eV

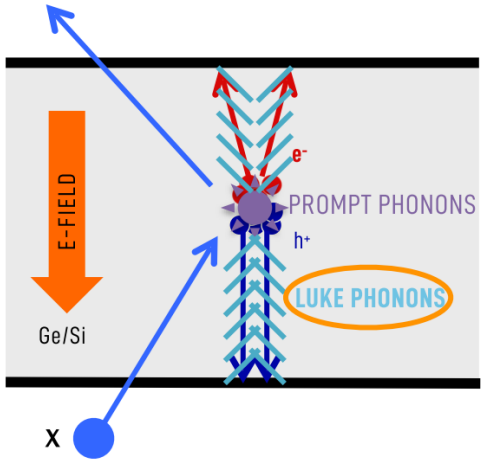
HV

	Si	Ge
σ_{ph}	13 eV	34 eV
Threshold$_{ph}$	100 eV	100 eV

High Voltage (HV) detectors

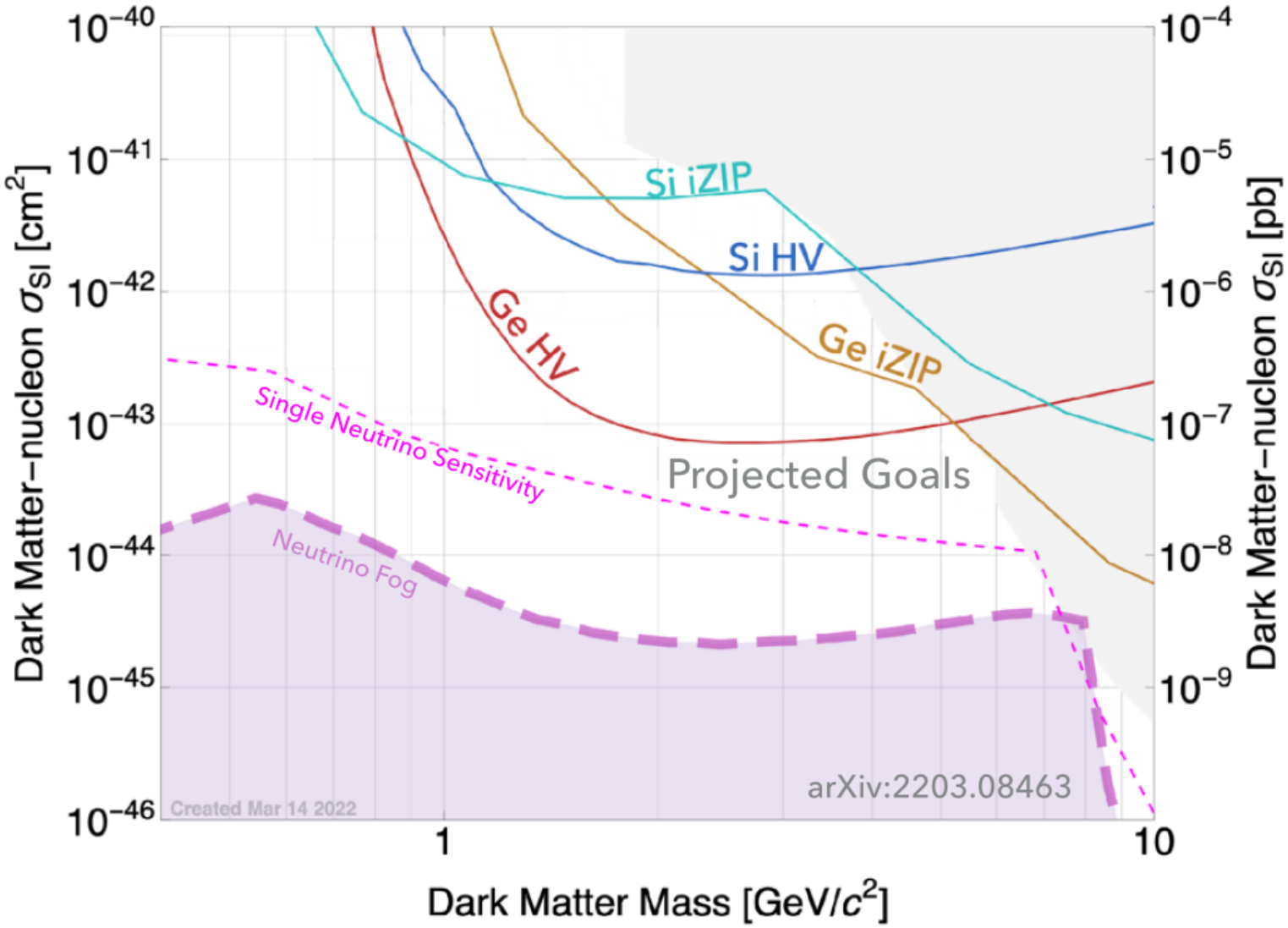


12 phonon channels
High bias voltage (~ 100 V)
Low threshold



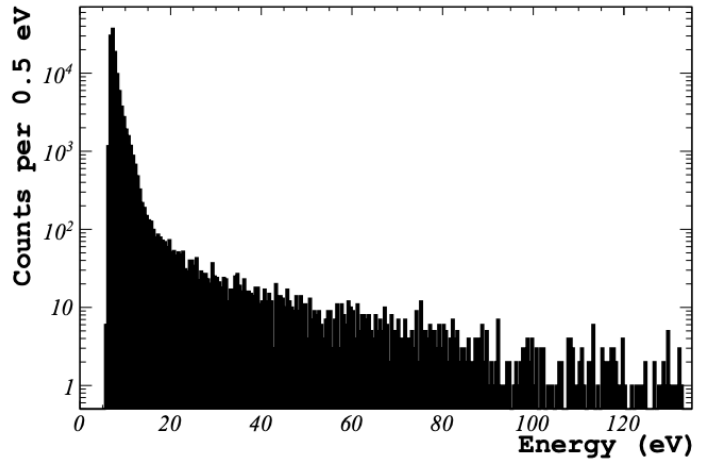
SuperCDMS

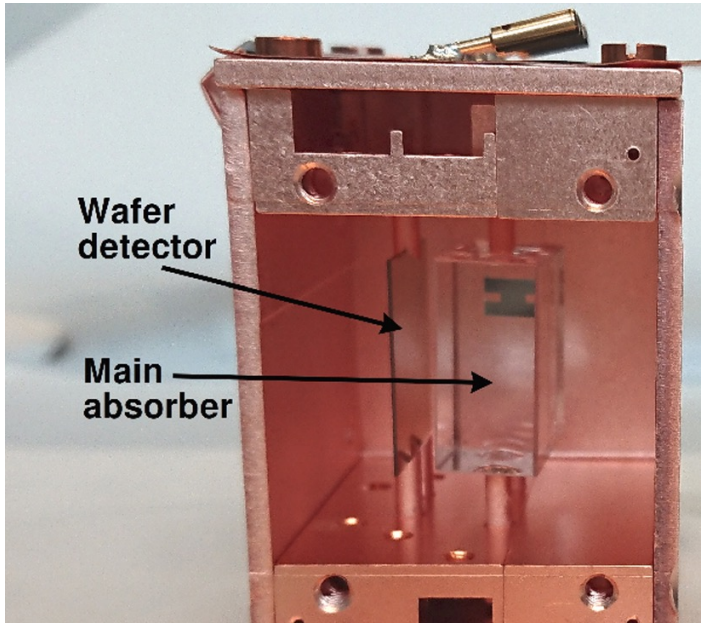
- **Expected to cover ~1 GeV DM**

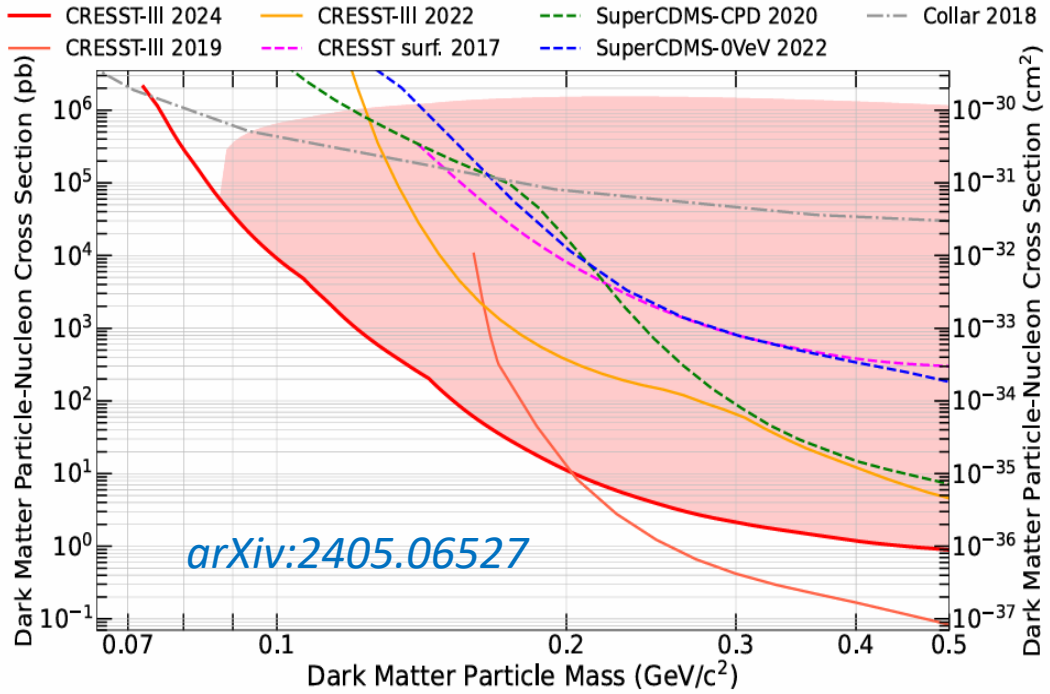


CRESST-III

- **Cryogenic calorimeter**
  - Si-on-Sapphire, 0.6 g, 138 g*day, threshold 6.7 eV
  - Precise measurement of nuclear recoil energy
  - Additional light detector for discrimination
- **Covering DM mass down to 0.1 GeV/c²**





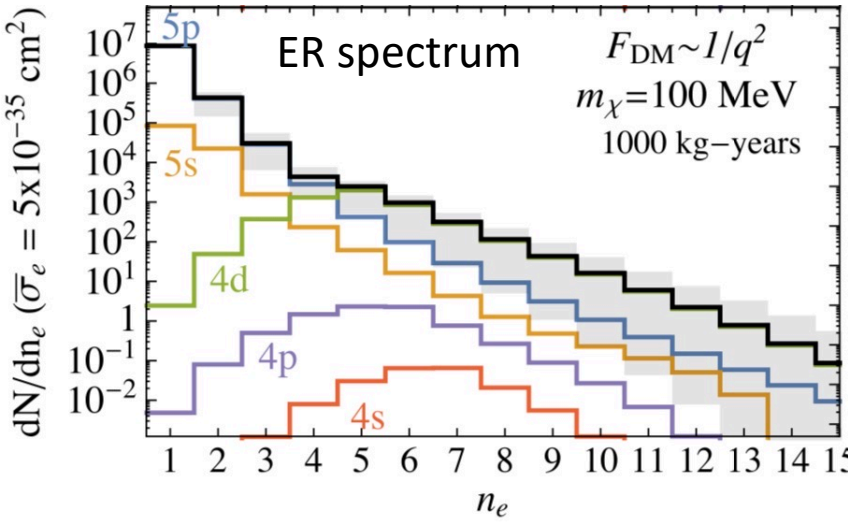


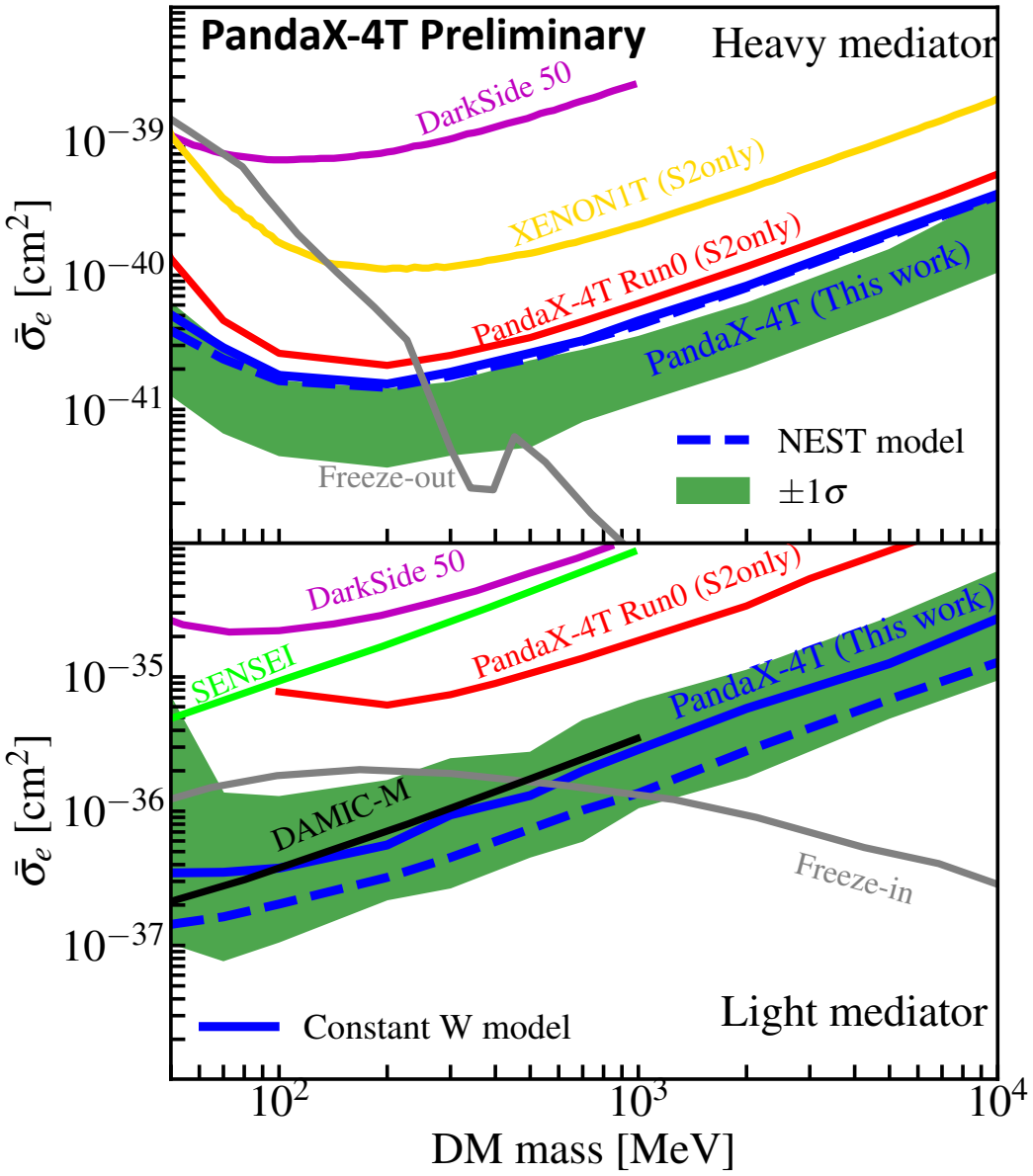
WIMP-electron Scattering

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

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

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

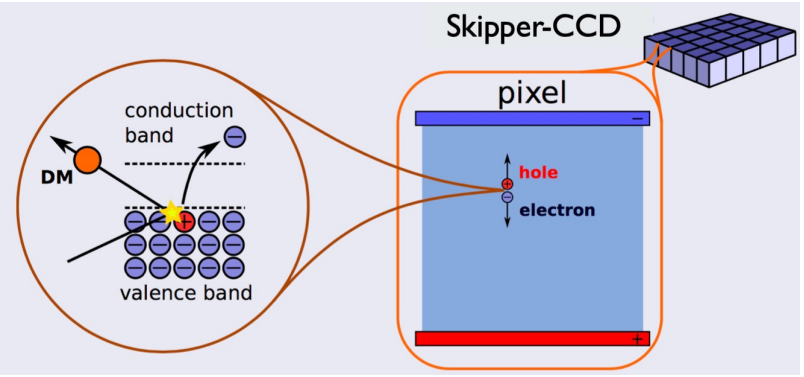




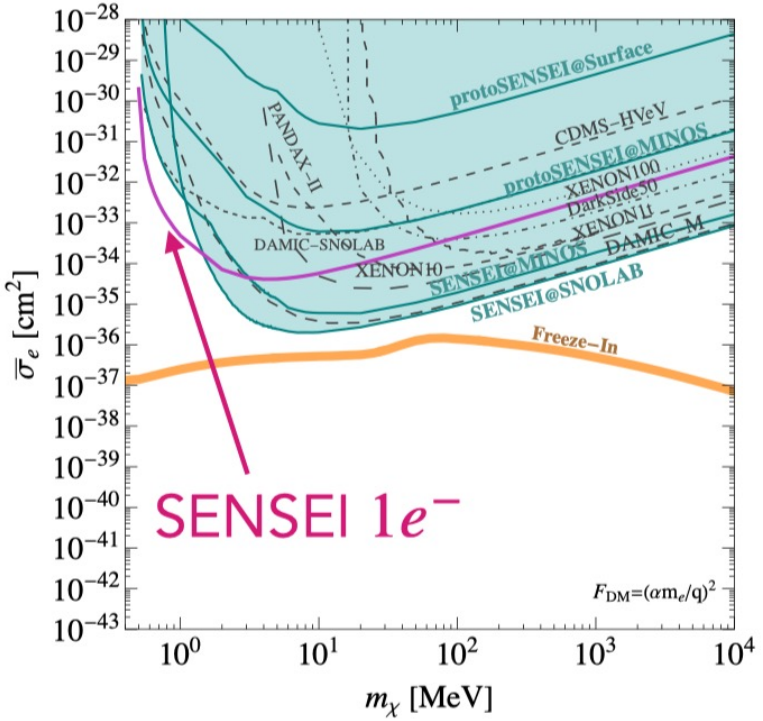
- **Probing DM mass ~100MeV in LXe**

SENSEI / DAMIC-M

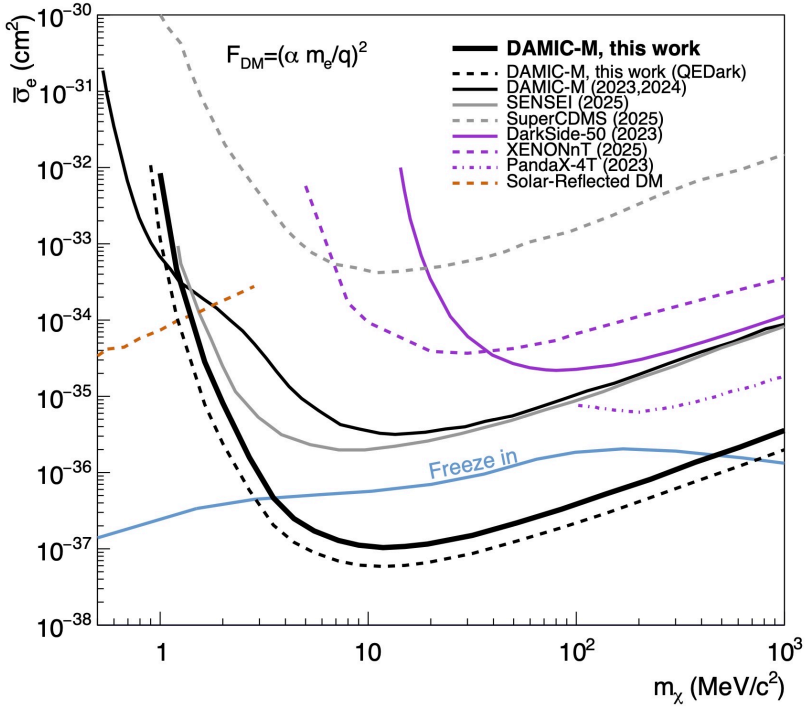
- **Skipper-CCDs, probing DM ~MeV/c²**
  - going down to 1e⁻ threshold
- **SENSEI @SNOLAB**
  - 19 Skipper-CCDs (~40g)
  - ~39.8 e⁻ /g/day
- **DAMIC-M @Modane**
  - 26.4g, 2e⁻ to 4e⁻
  - exposure ~1.3 kg-day
  - will scale up to ~700g



arXiv:2410.18716

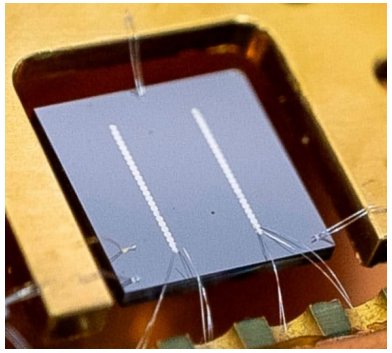


arXiv:2503.14617

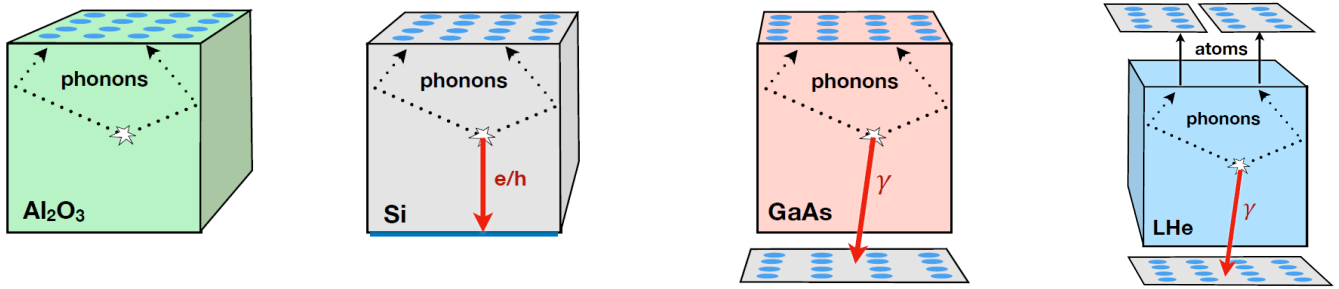


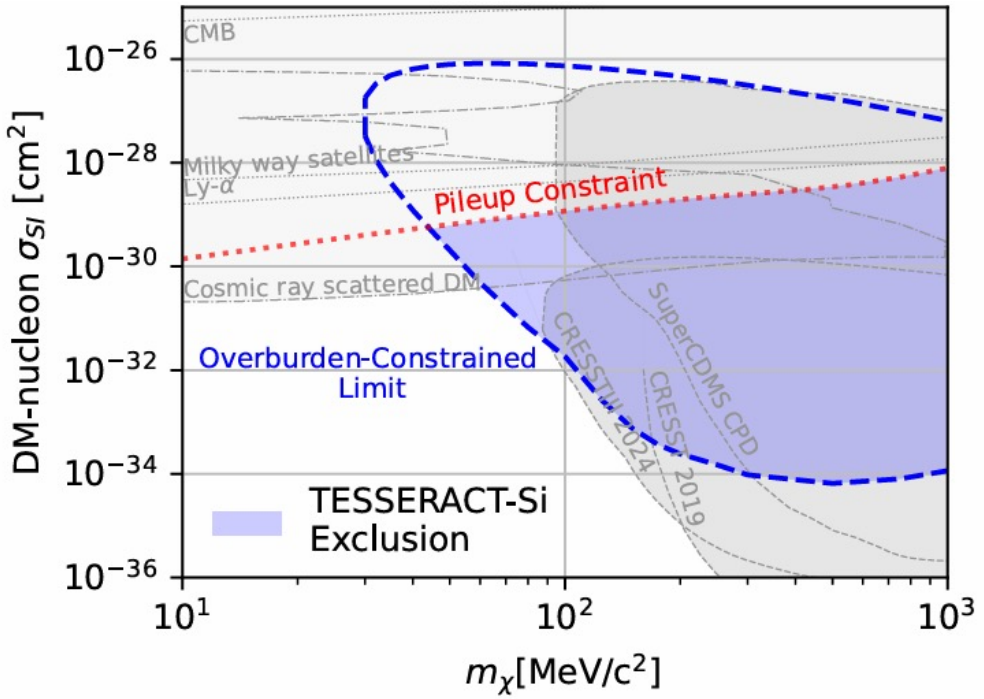
TESSERACT

- **Funded by Dark Matter New Initiative (DMNI)**
  - Apply diverse TES-based methods to the low-mass regime
  - Push phonon sensors to sub-eV thresholds
  - Deploy underground to look from keV-MeV scale dark matter particles



arXiv:2503.03683

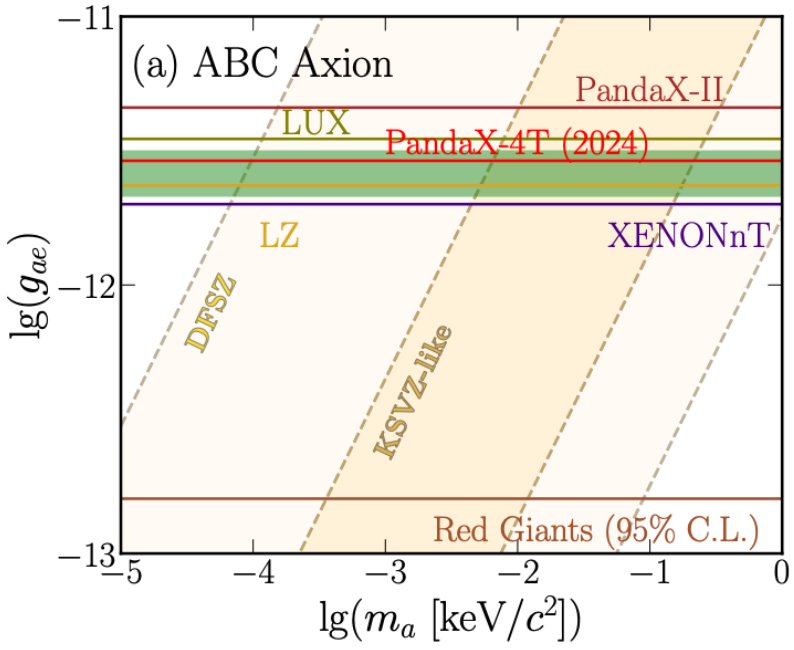




Lowest SI-NR DM search ever done! 44 MeV/c²

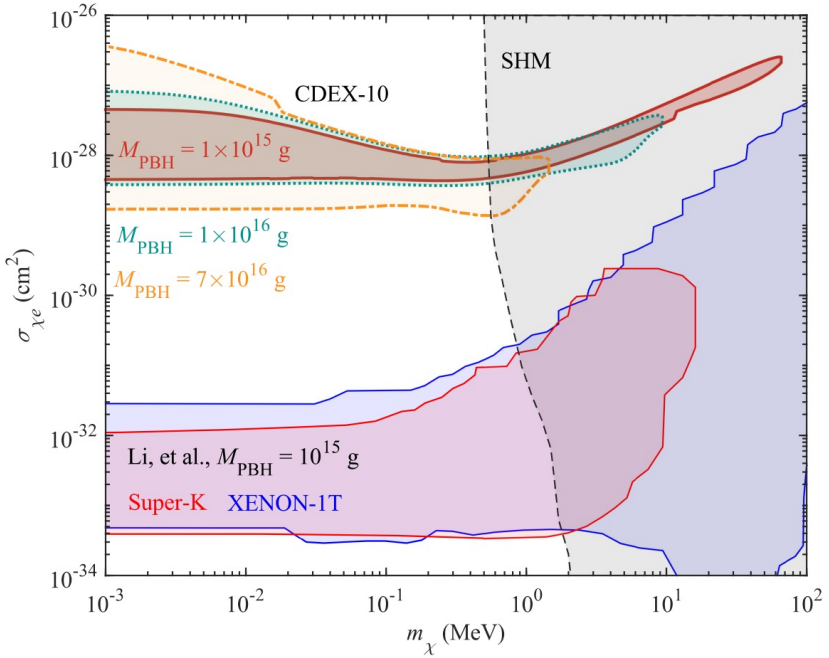
Towards Light Mass DM

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



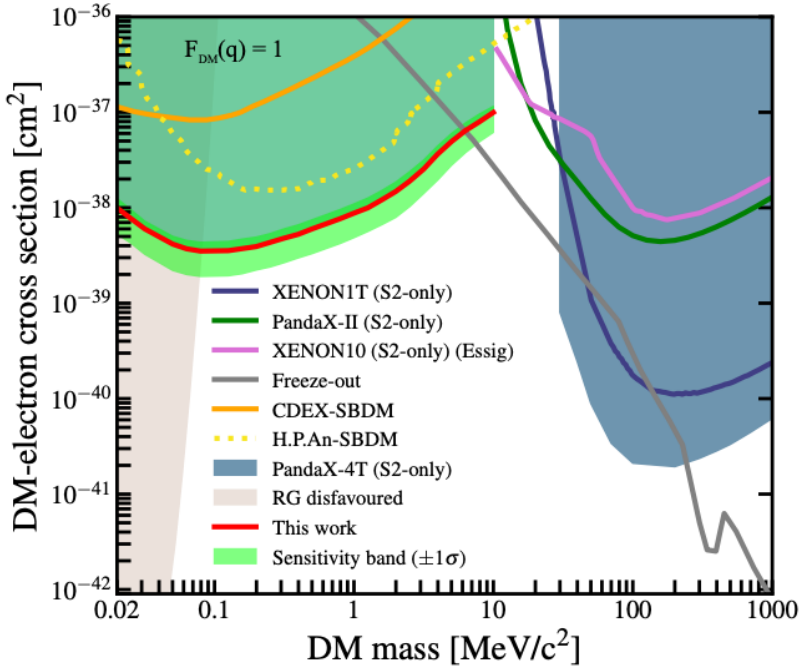
Solar Axion

arXiv:2408.07641



DM from PBH

arXiv:2403.20263



Solar boosted DM

arXiv:2412.19970

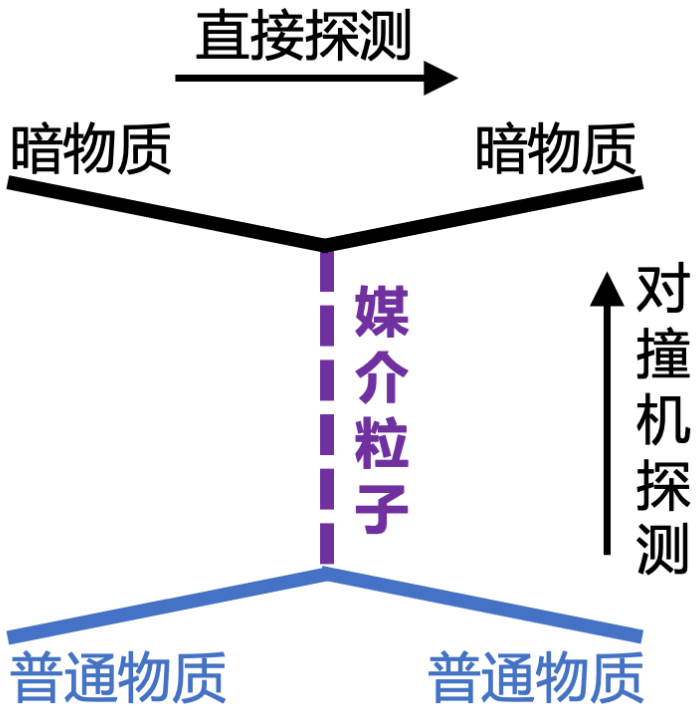
DM Interaction Mediator

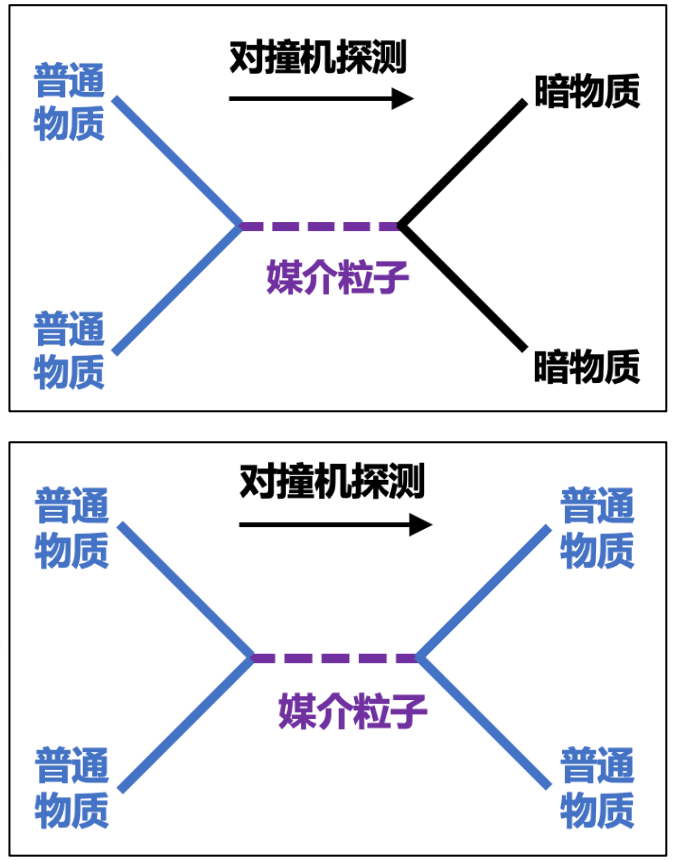
- **Direct detection:**

  Interaction energy too low to study the mediator

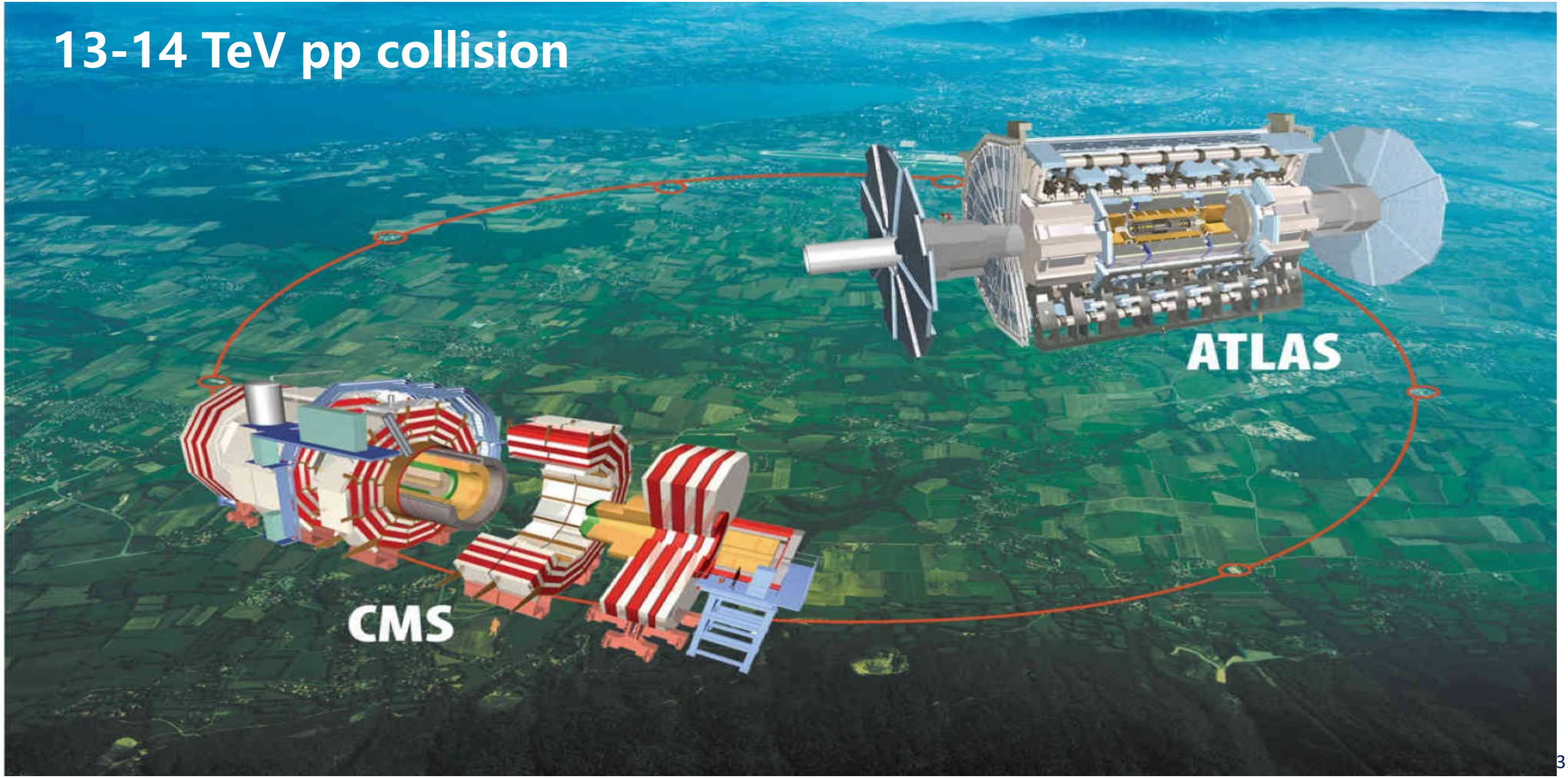
Collider search:

Study the same interaction, can produce the mediator





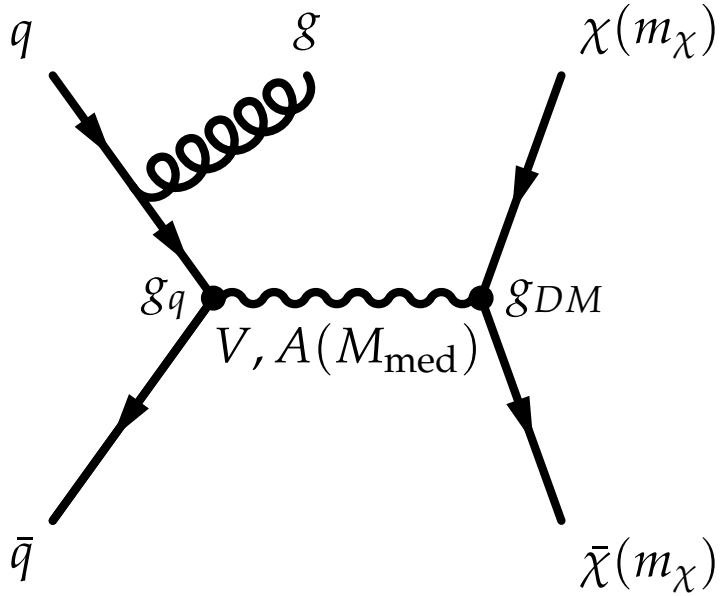
Large Hadron Collider

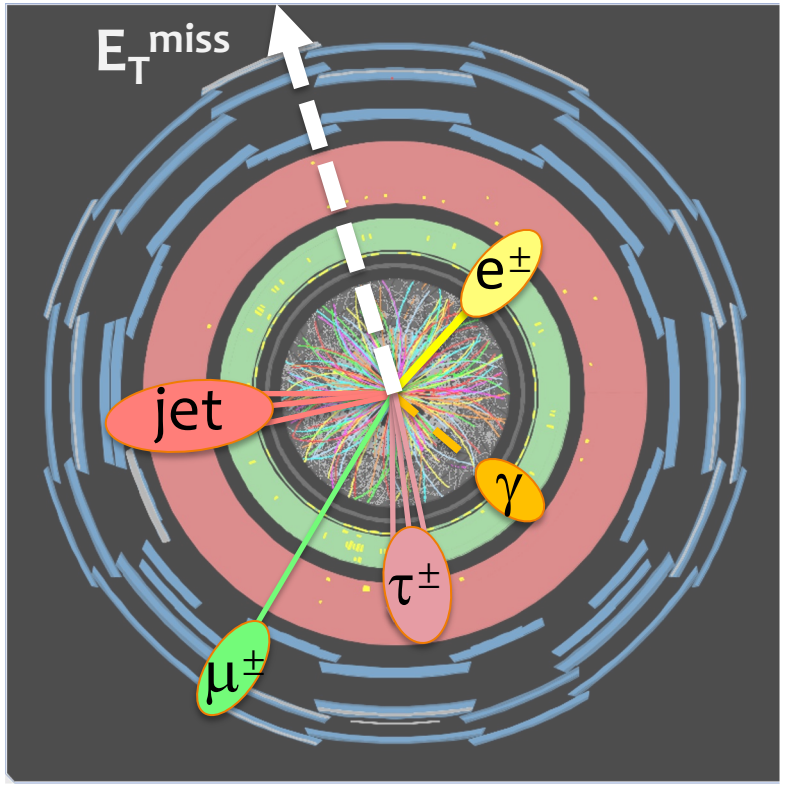


Mono-X Search

- **Dark matter production in association with X**
  - dark matter escape detection
  - **X**: visible particles
  - E_T^{miss}: momentum imbalance in transverse plane

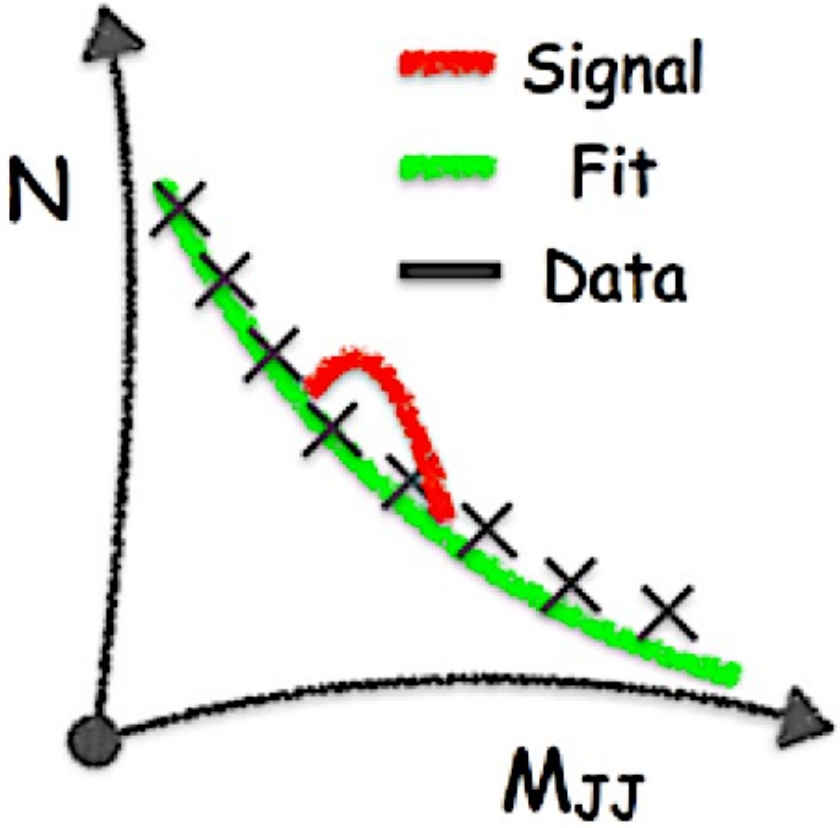
Mono-jet



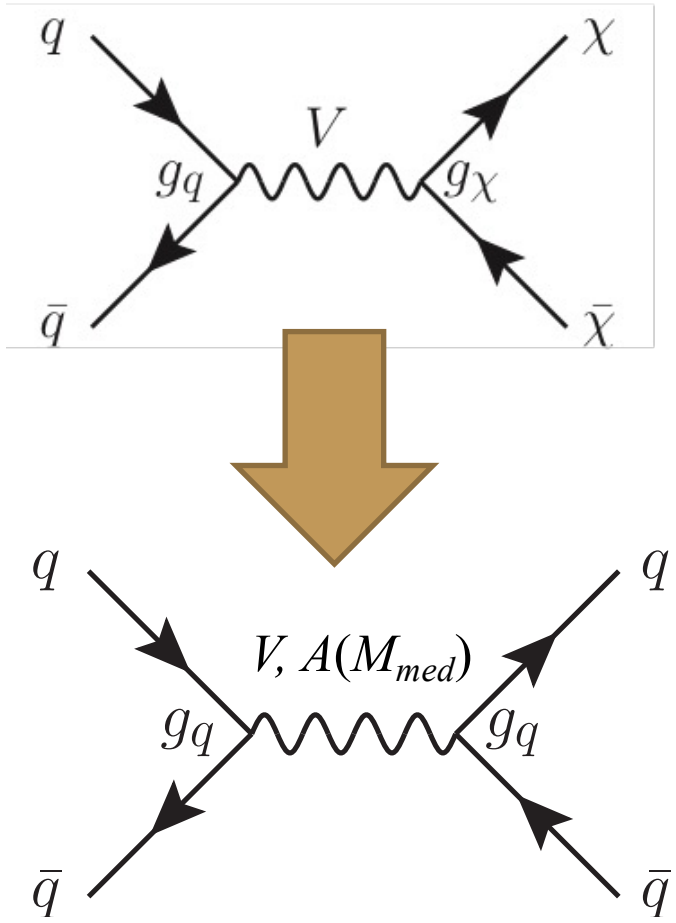


Mediator Search

- **Direct search of the produced mediator**

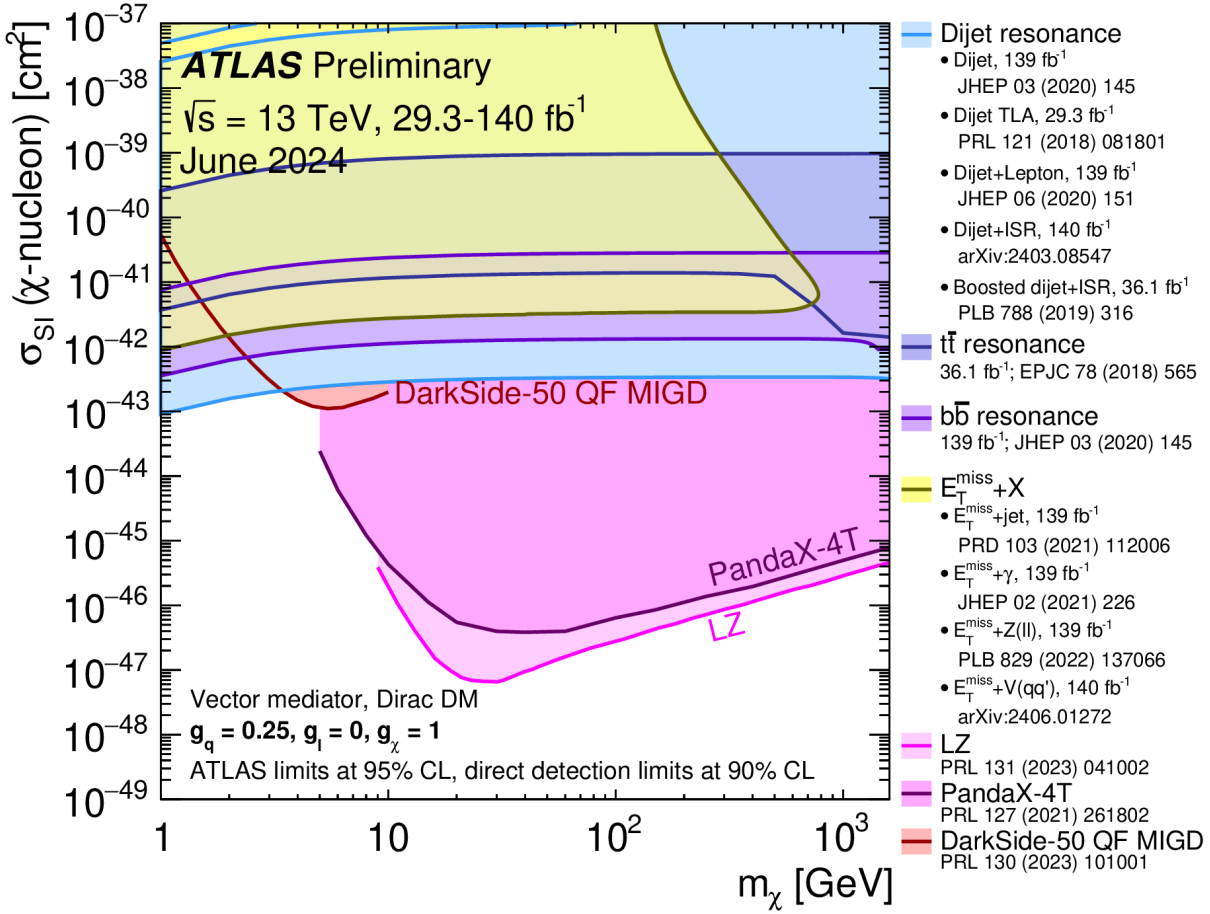


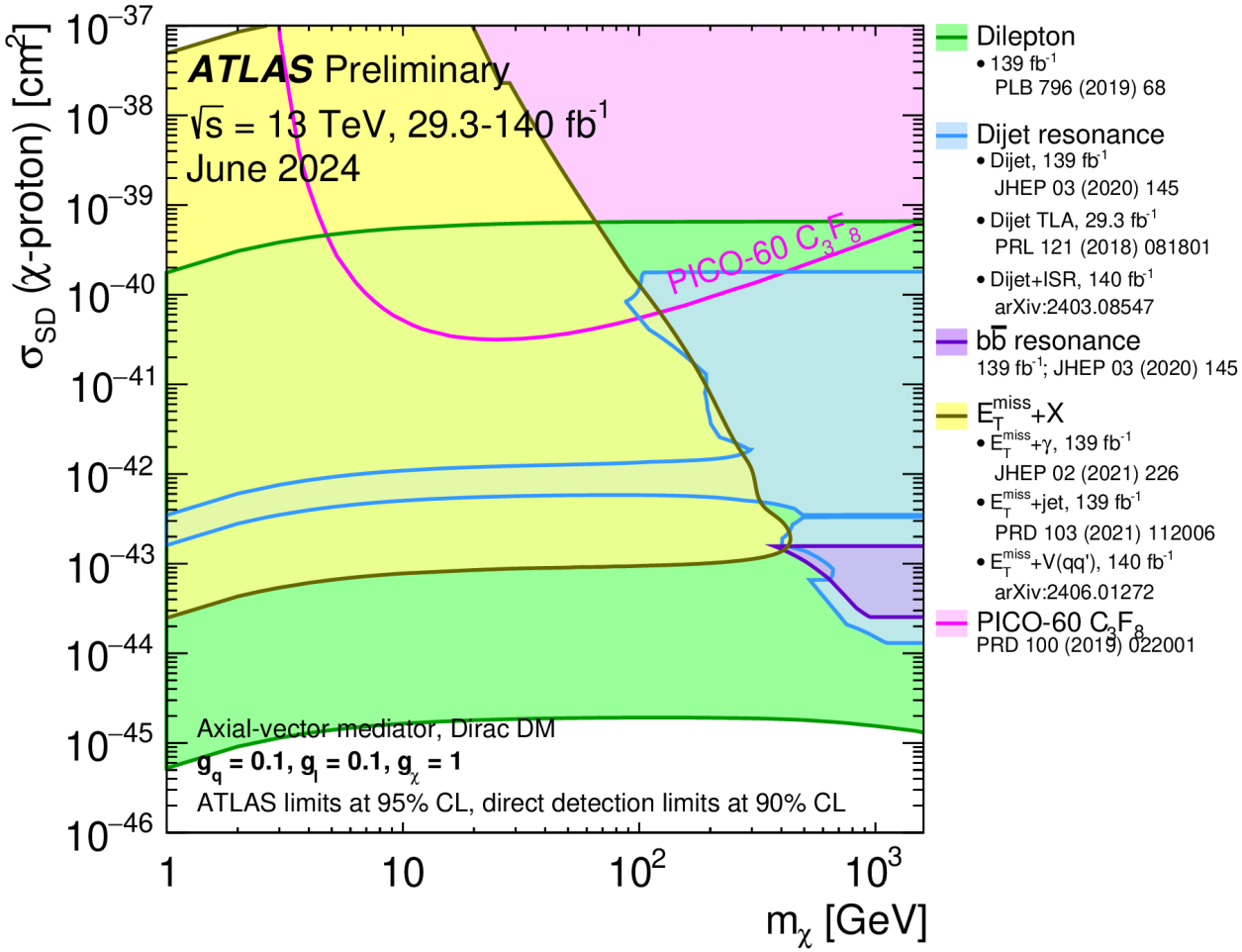
Dijet



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 Quarks

- **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**
  - SM quark shower and hadronization

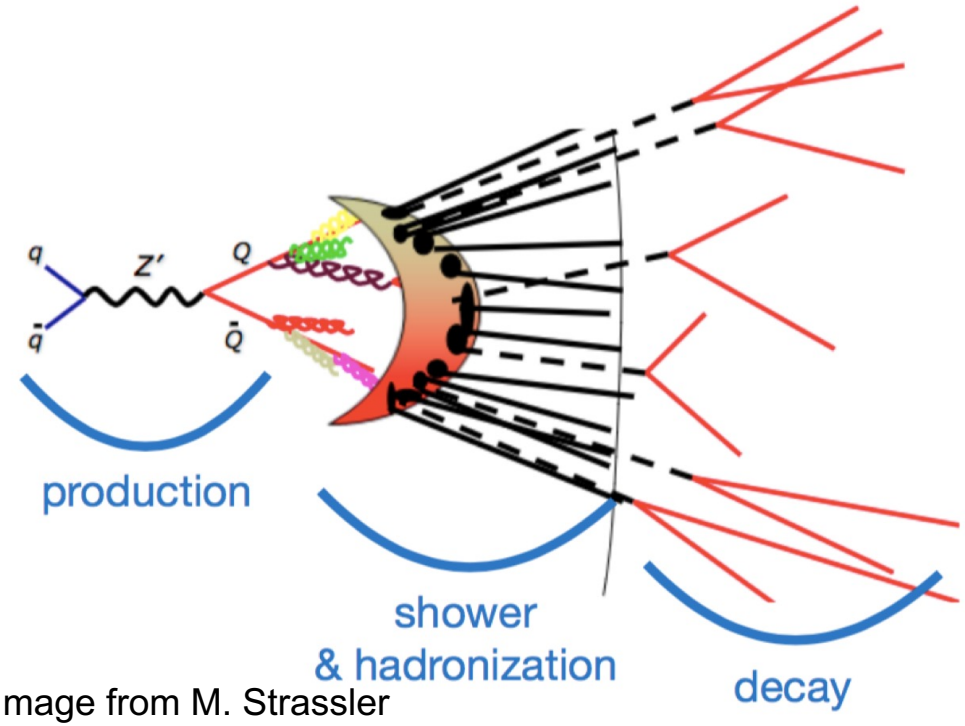
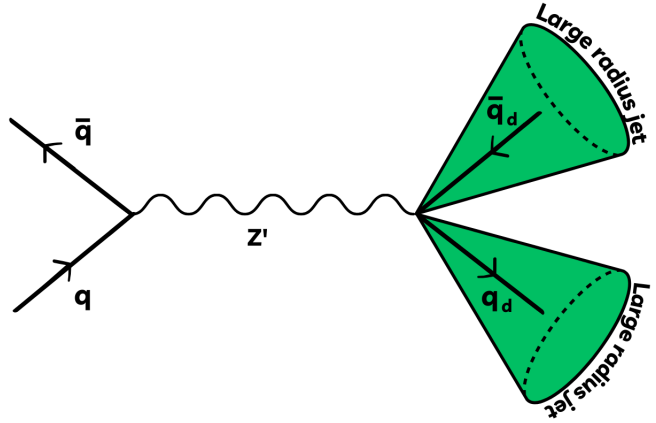


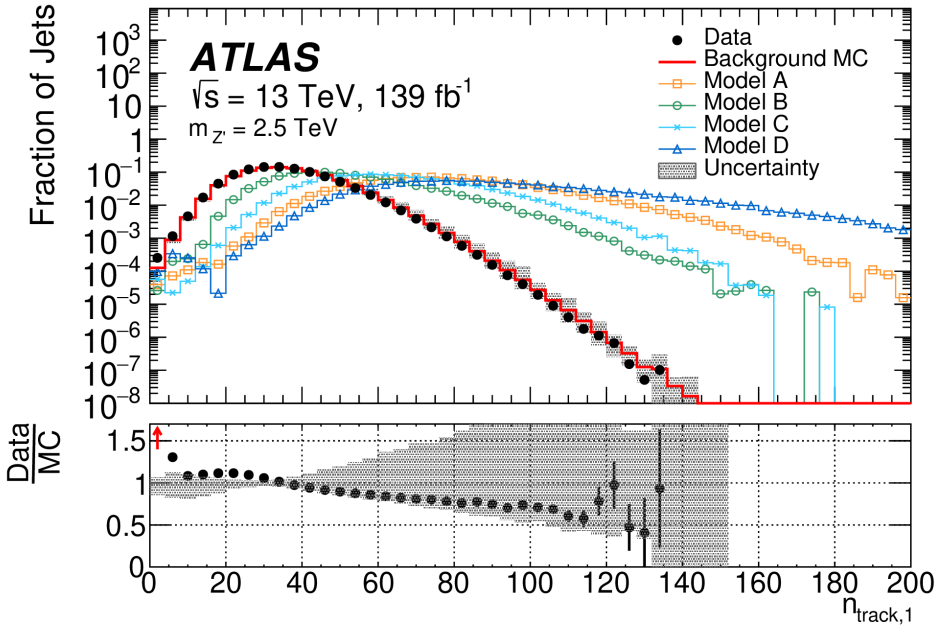
Image from M. Strassler

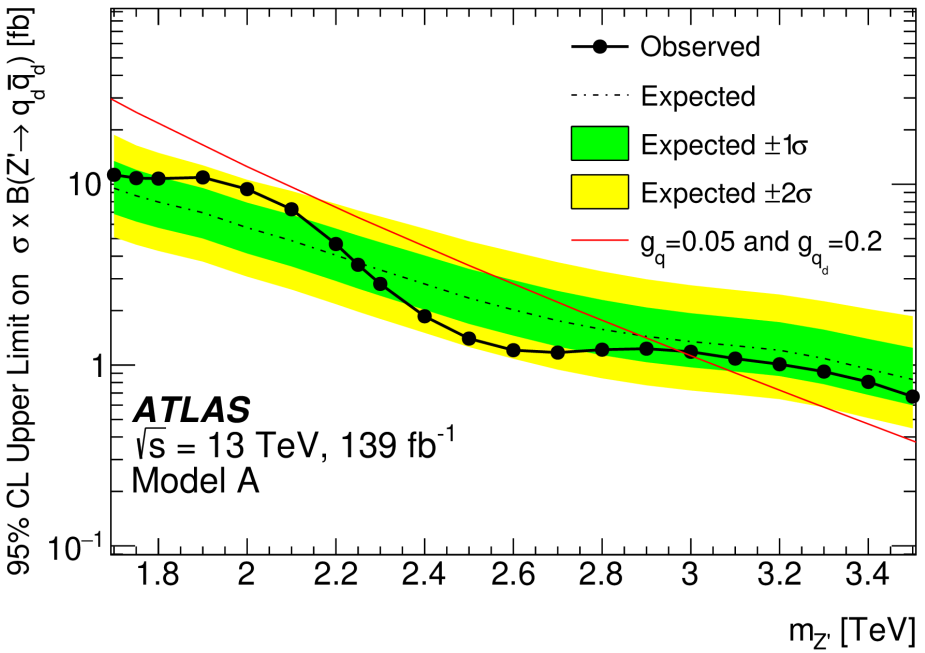
Resonance of Dark Quarks

- **Dark quark → dark hadron**
  - dark pion decays to SM quarks or dark photons
- **Large-radius jets with high track multiplicity**



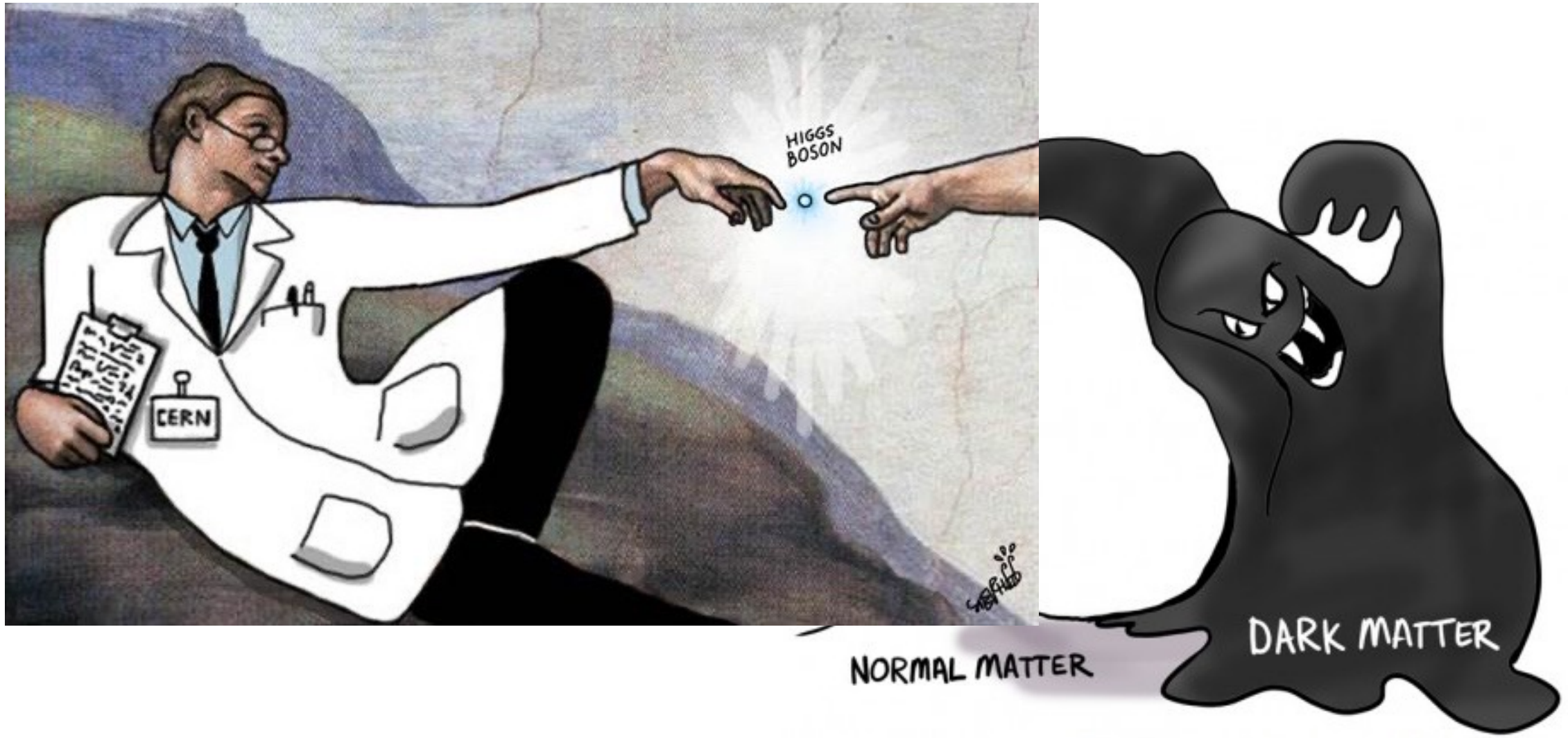
arXiv:2311.03944





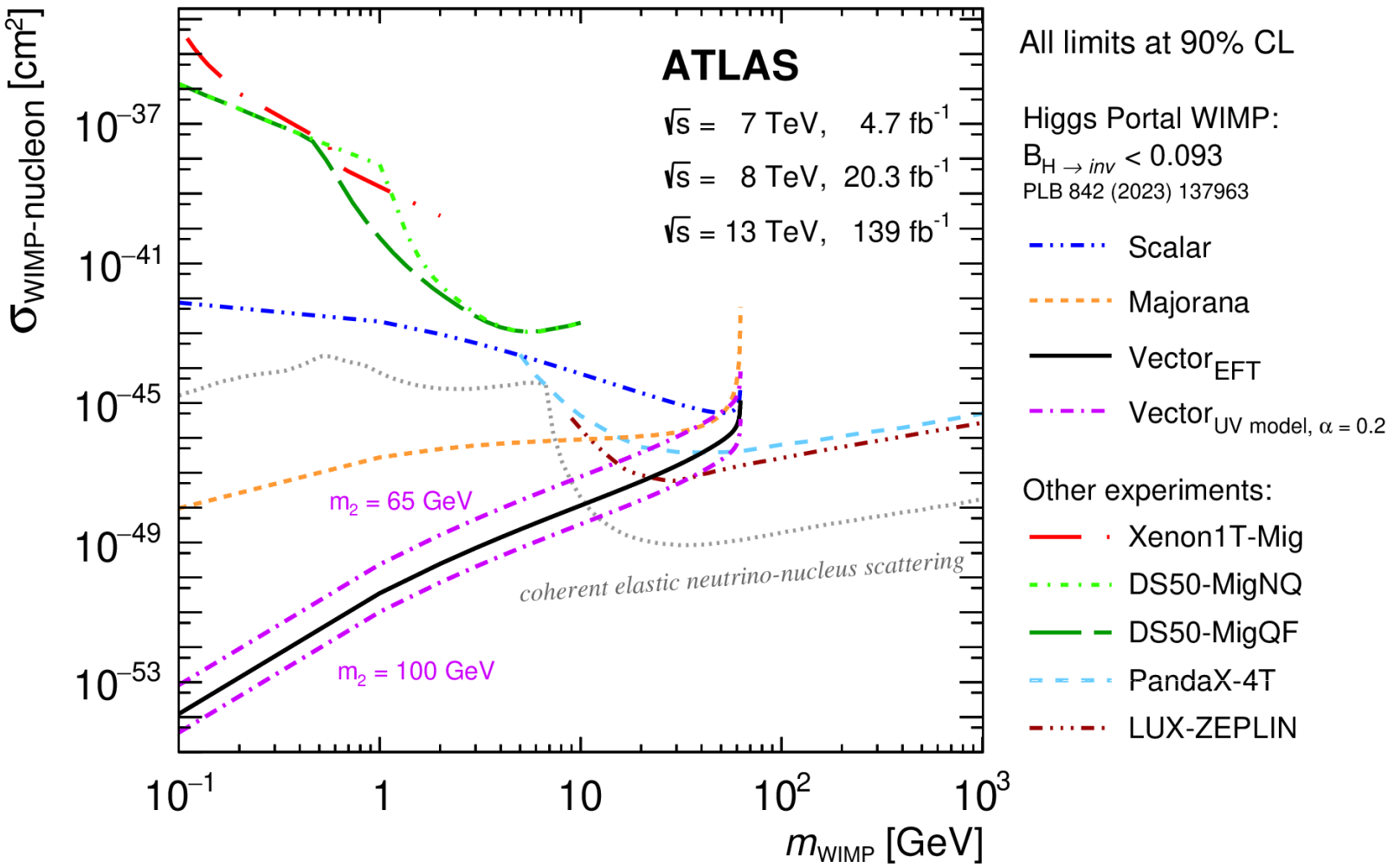
Dark Matter and Higgs

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



Higgs-portal DM

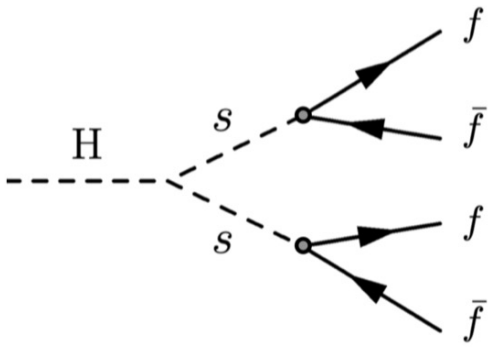
- **Scalar mediator: sensitive to $m_{DM} < ½\ m_{Higgs}$**

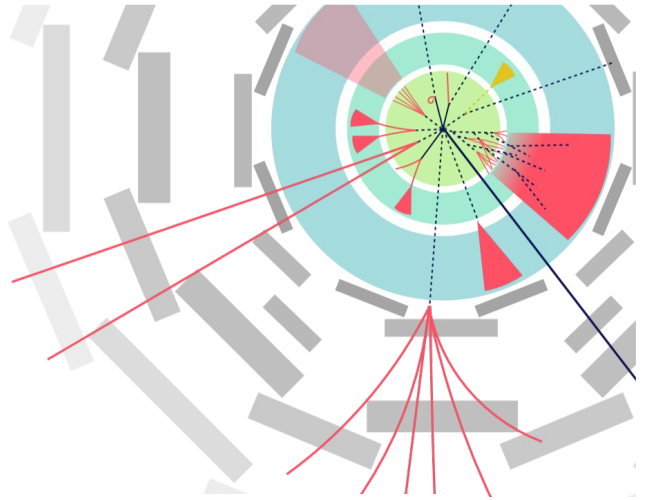


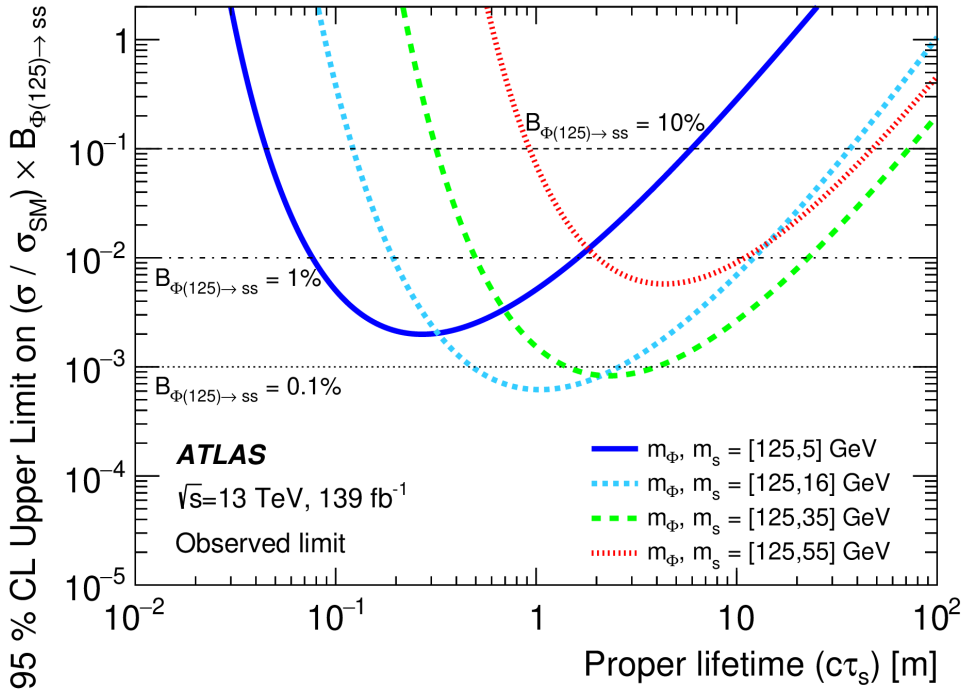
arXiv:2301.10731

Higgs Decays into Long-lived Particles

- **Higgs-portal hidden-sector model**
  - Pair of long-lived particles
- **Technical challenges:**
  - Non-standard reconstruction
- **Advantages:**
  - Probe unexplored models at TeV scale
  - Almost no irreducible SM background



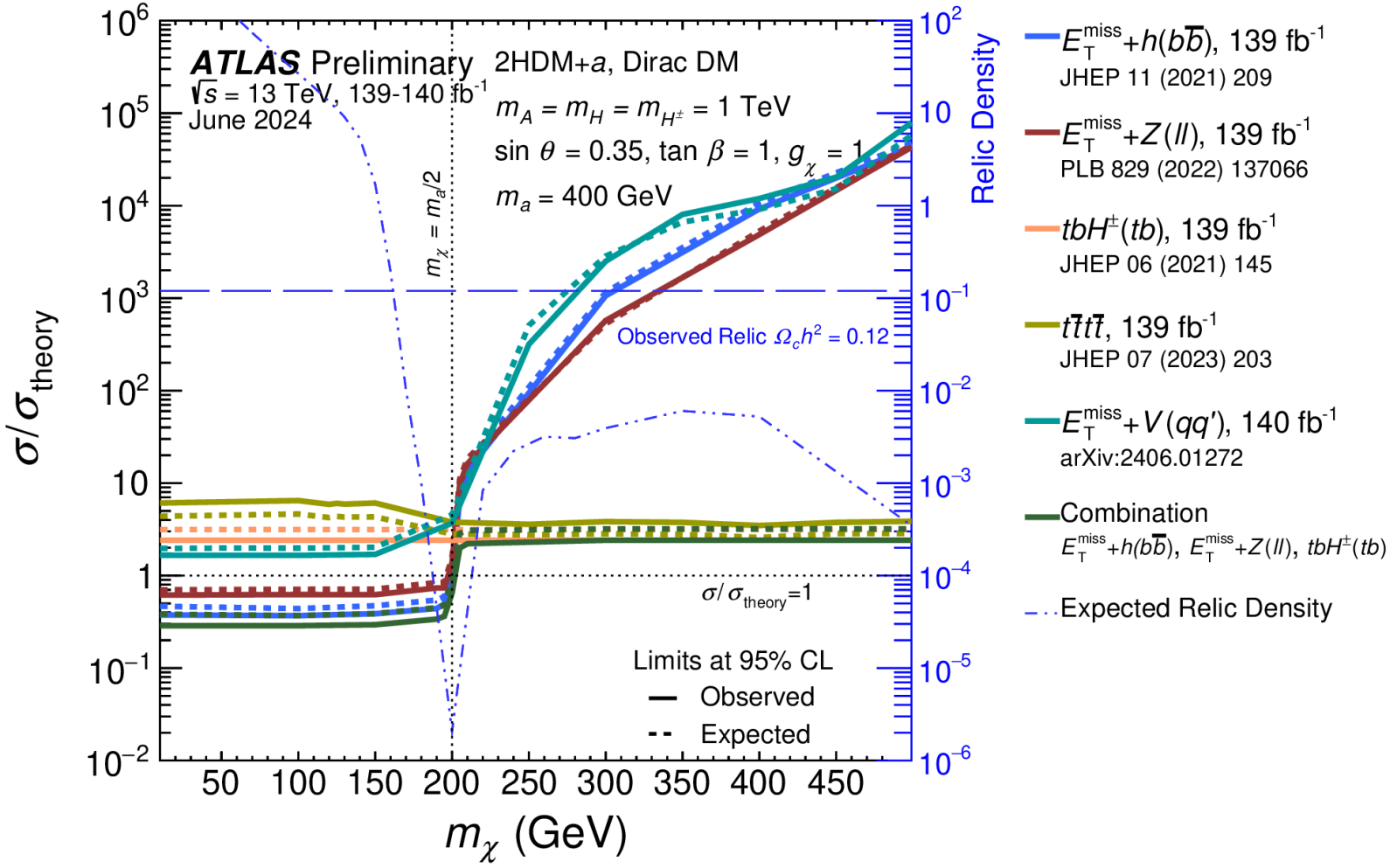




Phys. Rev. D106, 032005 (2022)

A Complete Model: 2HDM+a

- **Based on type-II 2HDM (*h*, H^0, $H^\pm$, *A*) with additional pseudo-scalar mediator *a***
- **Rich phenomenology**
  - mono-Higgs
  - mono-Z
  - invisible Higgs
  - 4top channel



arXiv:2306.00641, Science Bulletin

A Complete Model: 2HDM+a

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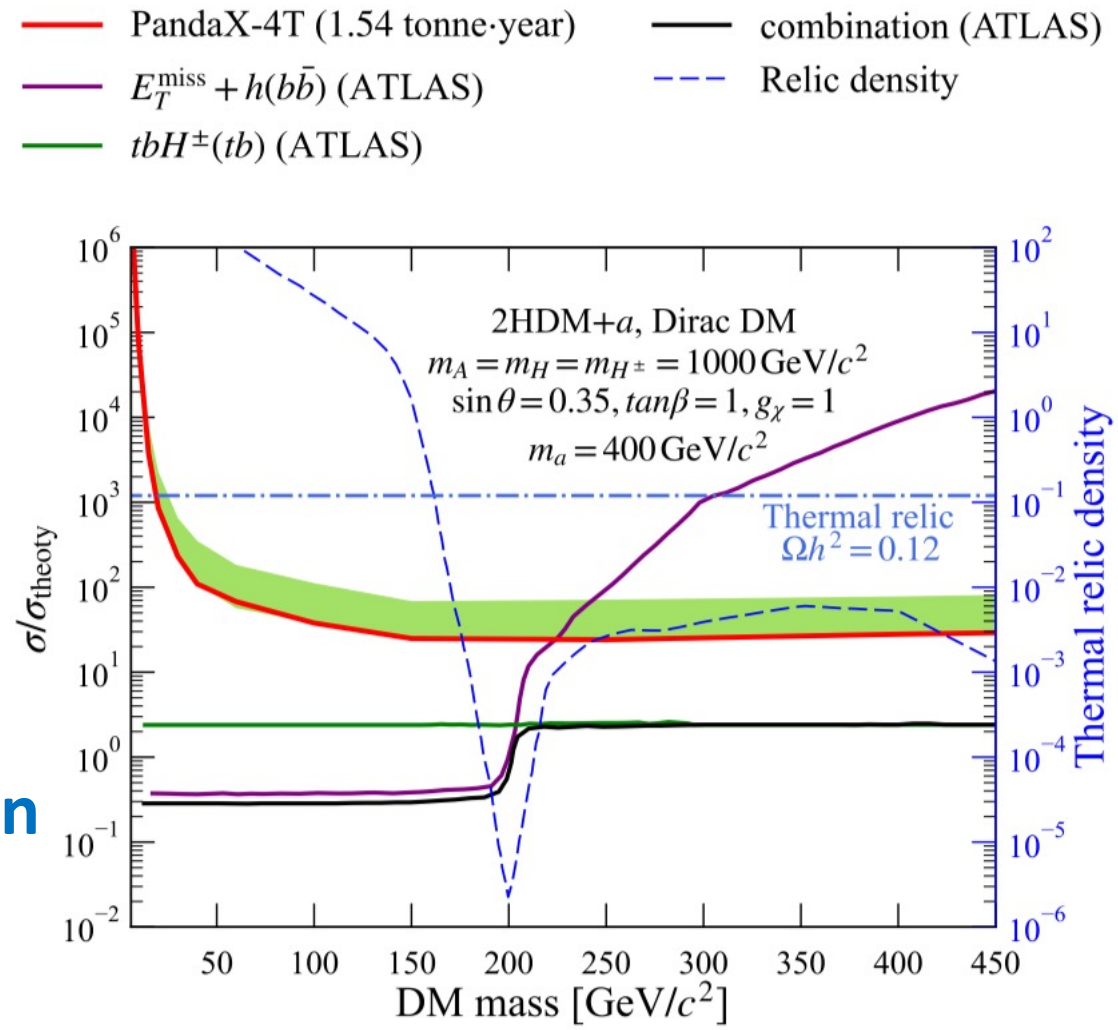
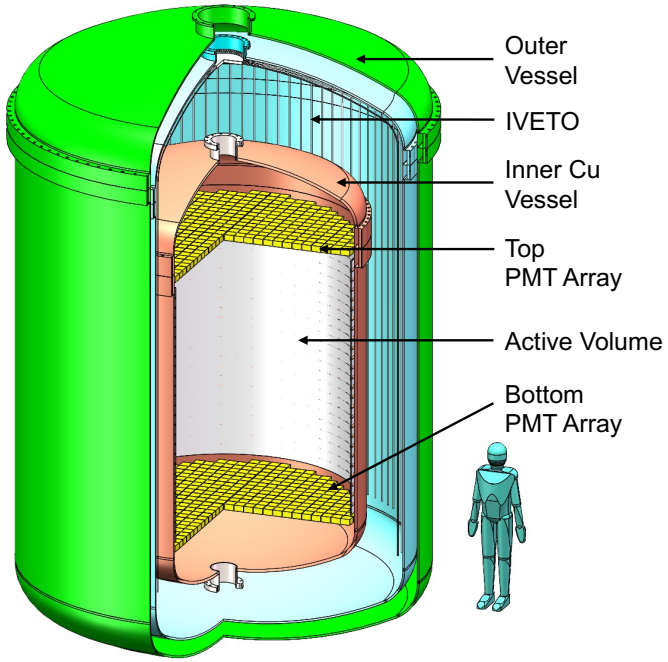


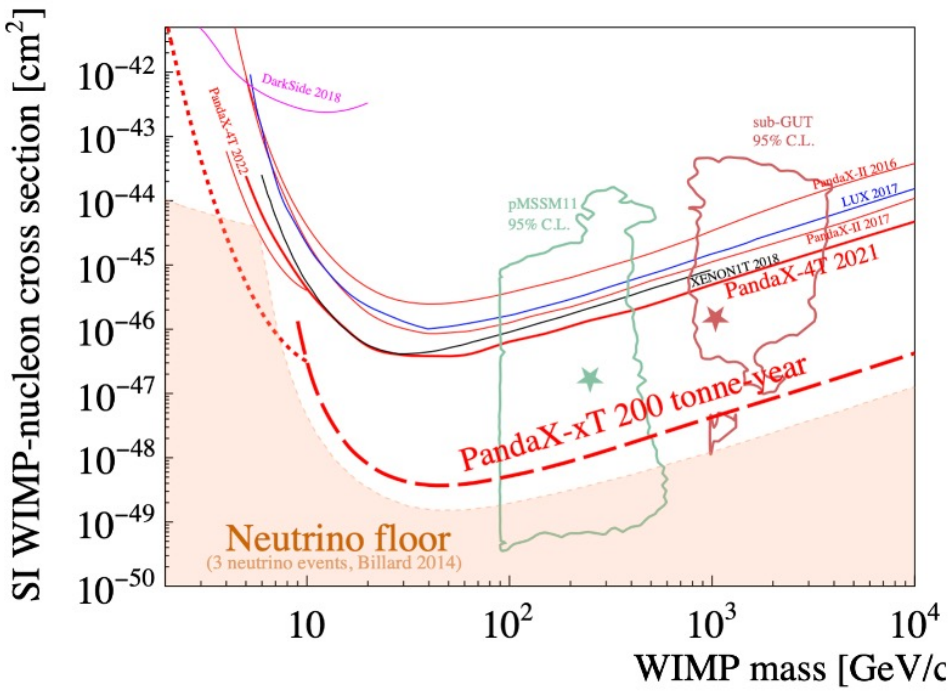
Complementary from direct detection

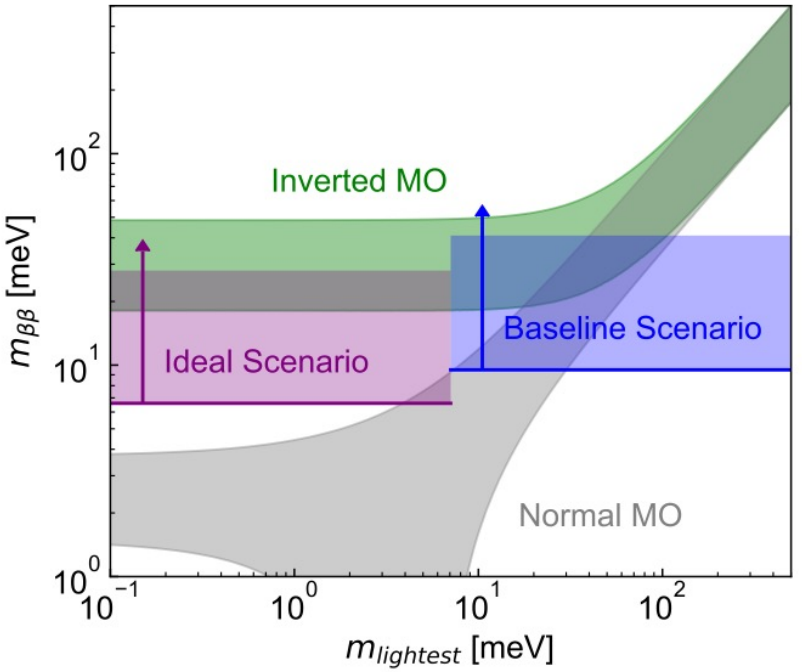
arXiv:2408.00664

Future Experiment: PandaX-xT

- **With ~47 tonne liquid xenon target**
- **Key tests on WIMP and Dirac/Majorana neutrino**





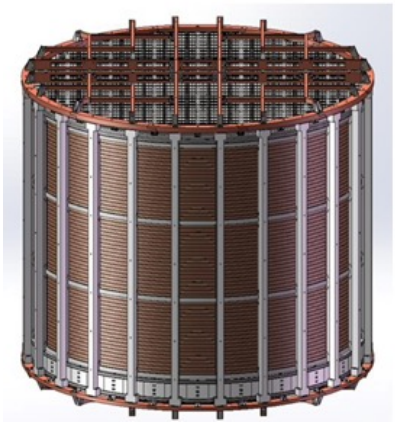


arXiv:2402.03596, ***SCPMA*** *68, 221011 (2025)*

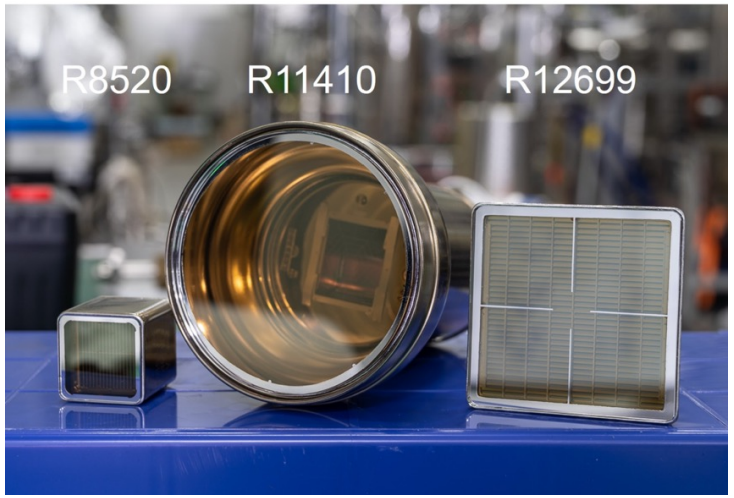
PandaX-20T: Intermediate Stage

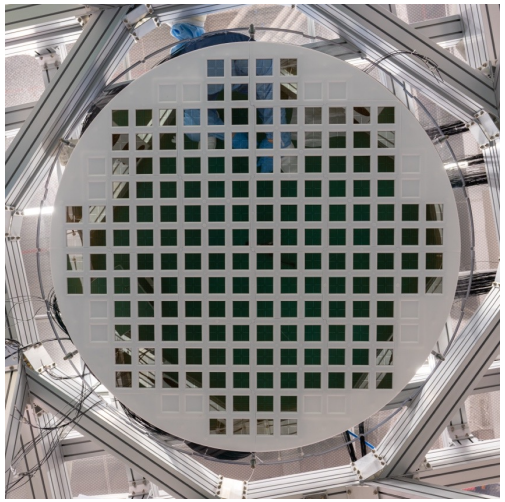
- **Multi-physics targets**
  - Energy range 100eV – 10MeV
- **Estimated timeline**
  - 2026: move to CJPL to start assembling
  - 2027: commissioning

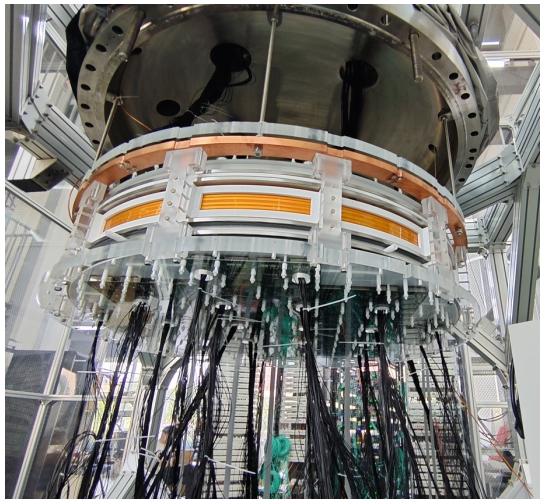
PandaX-20T



PandaX-xT







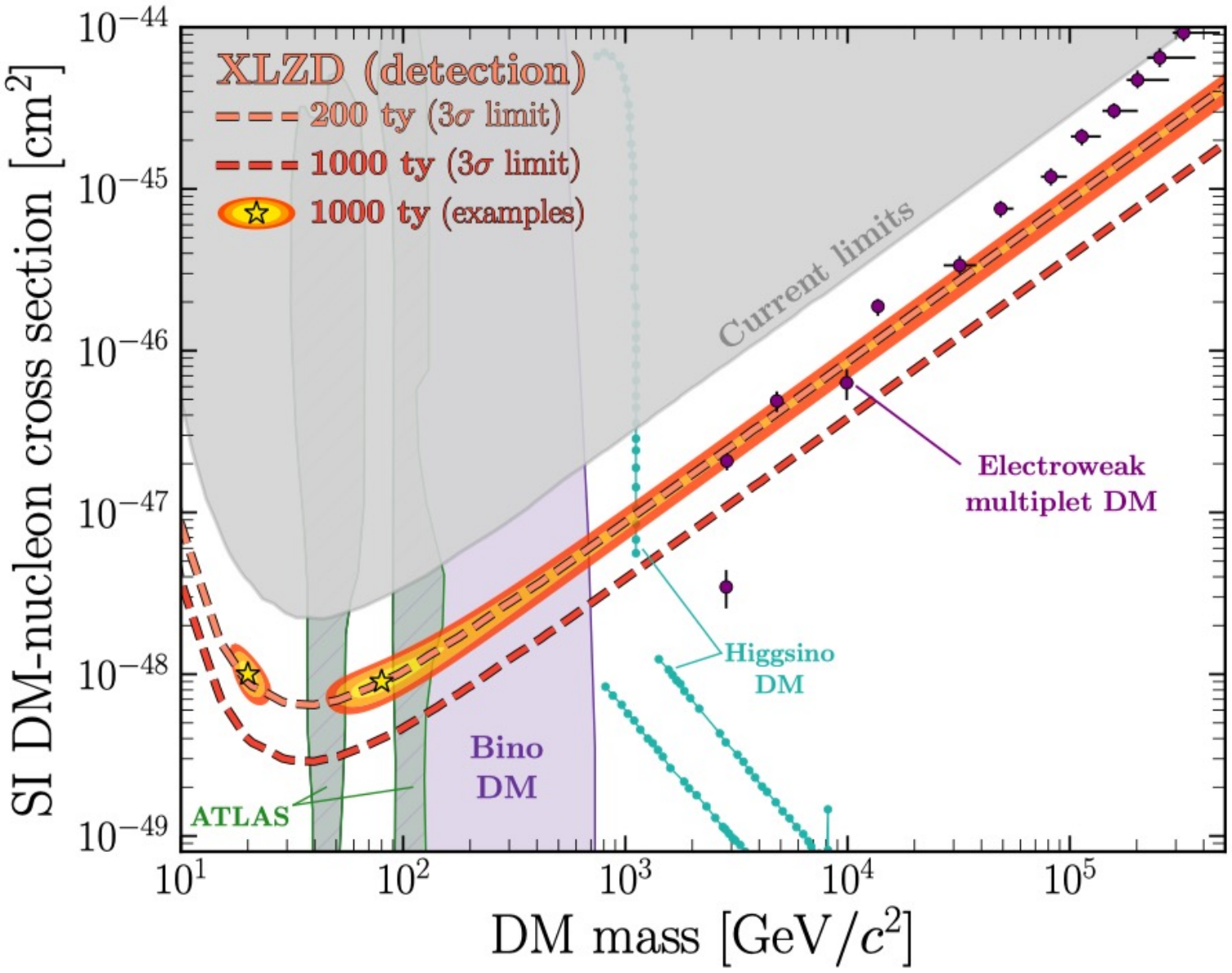
PandaX-xT Layout @CJPL-II B2 Hall

Summary

- 暗物质探测是新物理探索的重要组成，在实验室探测到暗物质并研究其物理属性，将带来物理学和天文学的重大变革
- 暗物质探测近年来迅速发展，面临重要发现机遇
- 中国过去10年培养出相当规模的队伍，主导的多个暗物质实验取得国际先进成果
- 面向未来，一方面深度发展旗舰型实验并开发新潜力，另一方面积极拓展新型探测方式，覆盖更大参数空间

谢谢！

WIMP Candidates



Low Energy Excess

- **LEE observed in solid state phonon and charge detectors**
  - Rise starting below $\mathcal{O}(100\text{eV})$, inconsistent with DM signal

arXiv:2503.08859