暗物质直接探测

王力

北京师范大学

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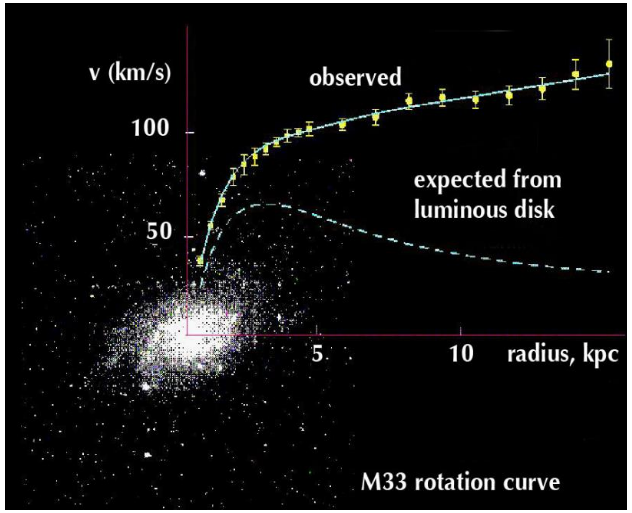
提纲

- 暗物质及其探测
- 暗物质直接探测实验
  - 低温固体探测器
  - 电荷耦合器件
  - 液态稀有气体探测器
  - 其它探测技术

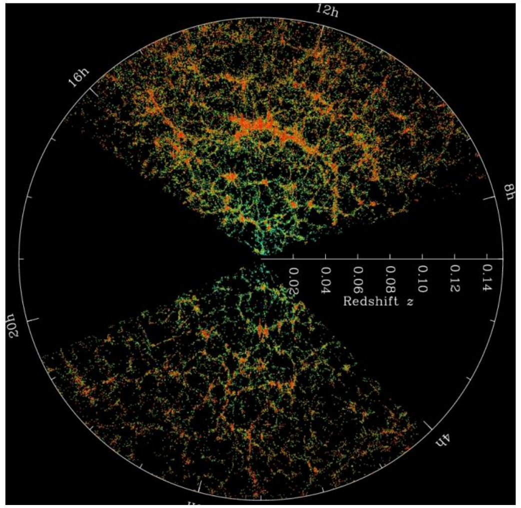
暗物质问题

- 暗物质是笼罩20世纪末和21世纪初现代物理学的最大乌云，它将预示着物理学的又一次革命。—— 李政道

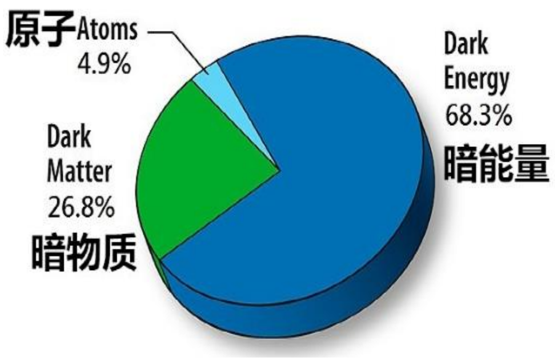


星系旋转曲线

子弹星系



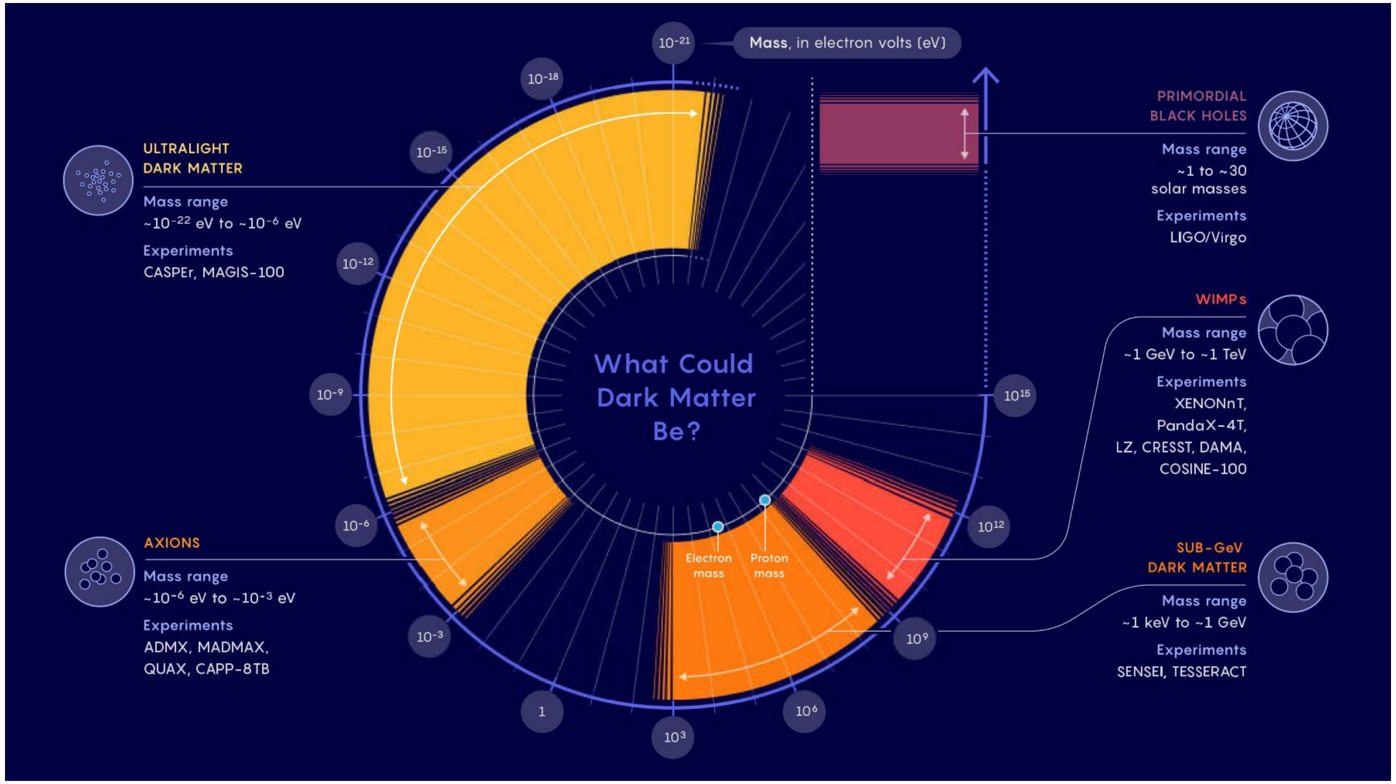
宇宙大尺度结构



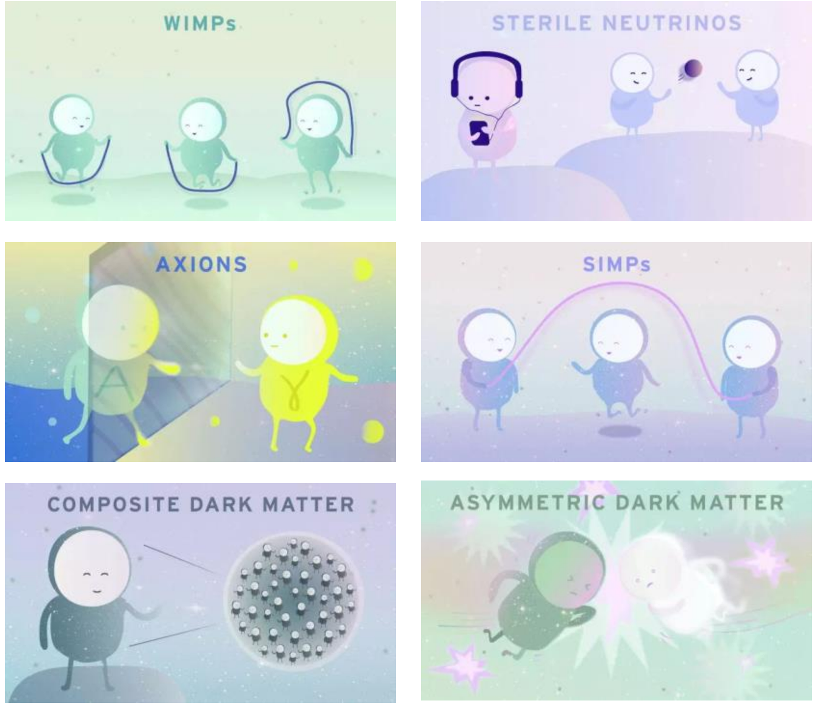
宇宙组分

暗物质候选者

- 众多候选者，覆盖极其宽广的质量区域



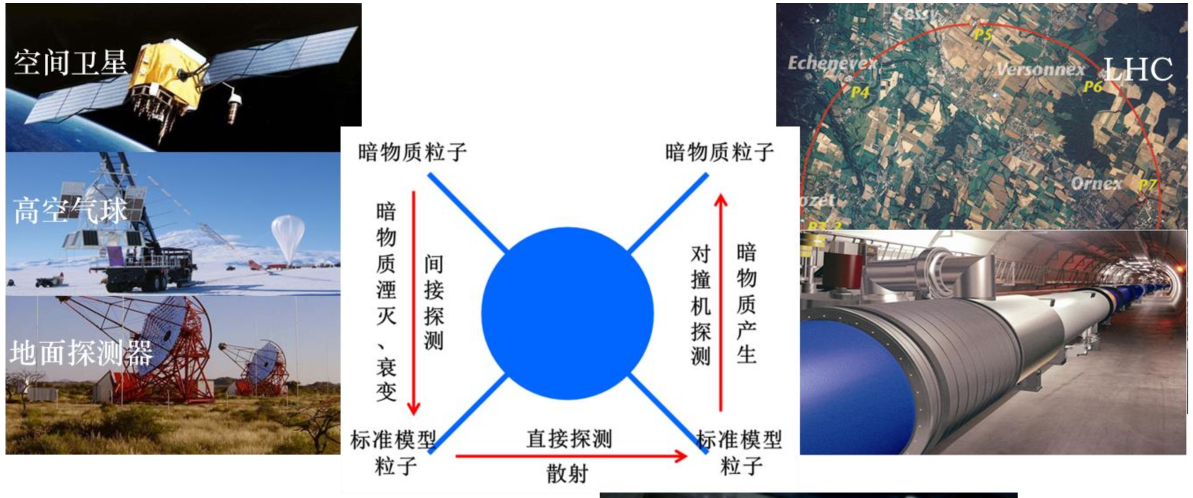
Samuel Velasco/Quanta Magazine



Artwork by Sandbox Studio, Chicago/Symmetry Magazine

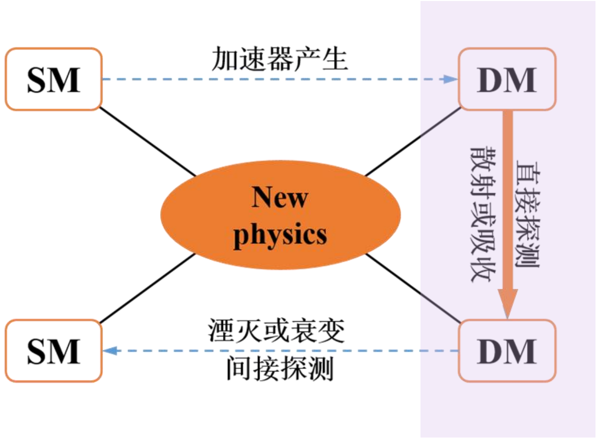
暗物质探测实验

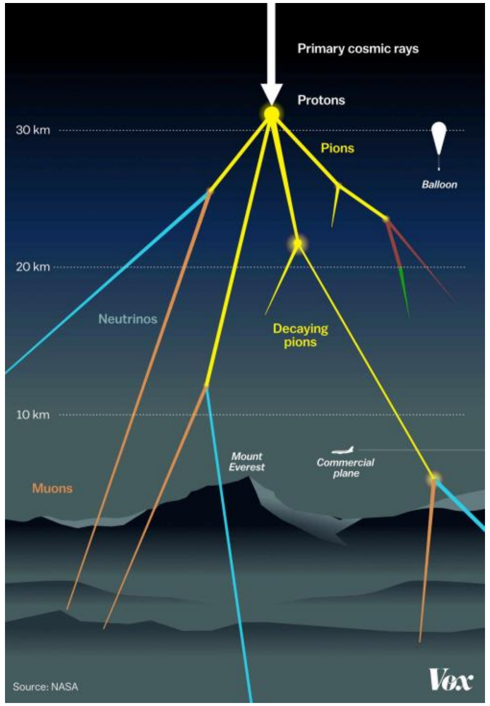
- 直接探测实验：暗物质粒子入射，与探测器靶原子（核）发生散射的信号
- 间接探测实验：探测宇宙暗物质衰变或湮灭的产物
- 对撞机探测实验：高能粒子对撞产生暗物质



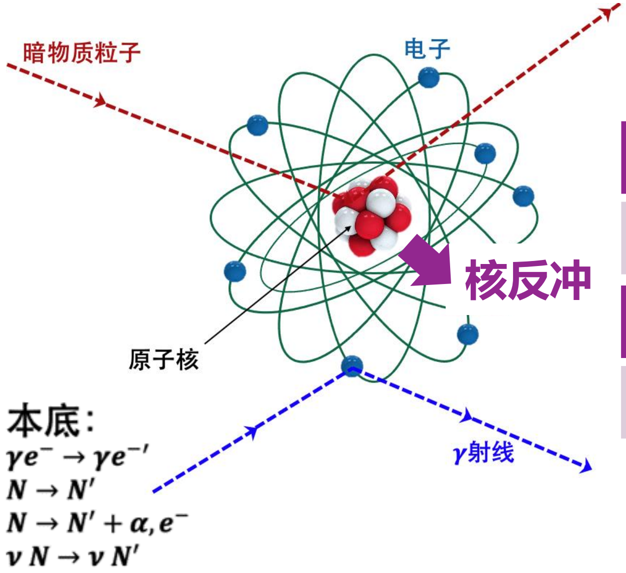
暗物质直接探测实验

- WIMP粒子与靶原子（核）散射
  - 沉积能量少、作用概率低
- 低本底、低阈值





宇宙射线



能量很小

keV及以下

概率极低

<1evt/(kg·yr)

辐射本底干扰

能量较大

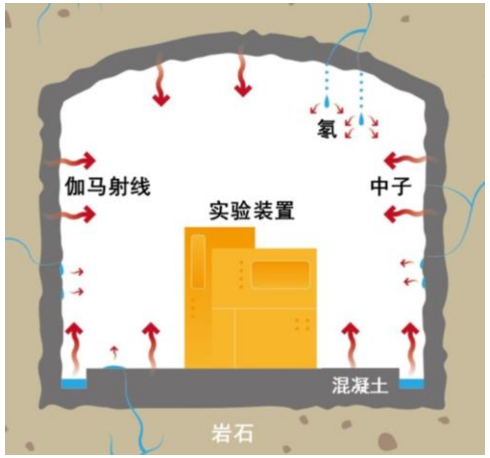
MeV及以下

概率很高

宇宙射线本底

环境辐射本底

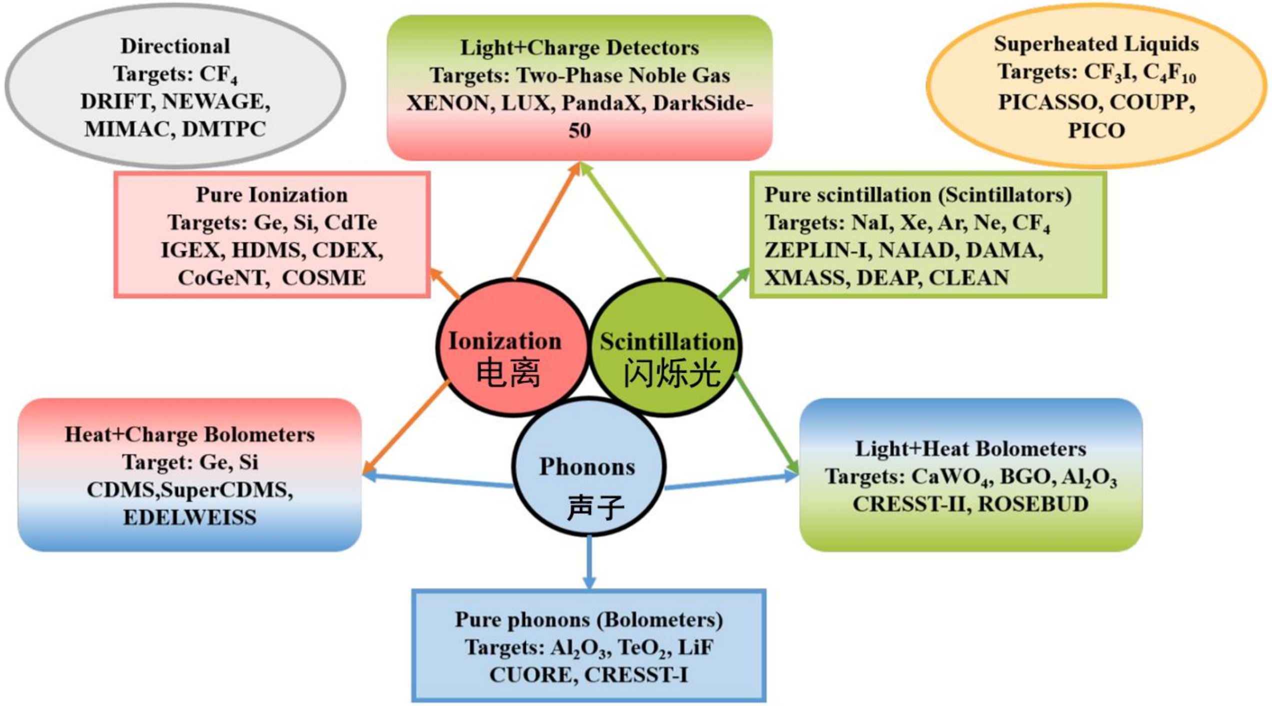
实验装置自身本底

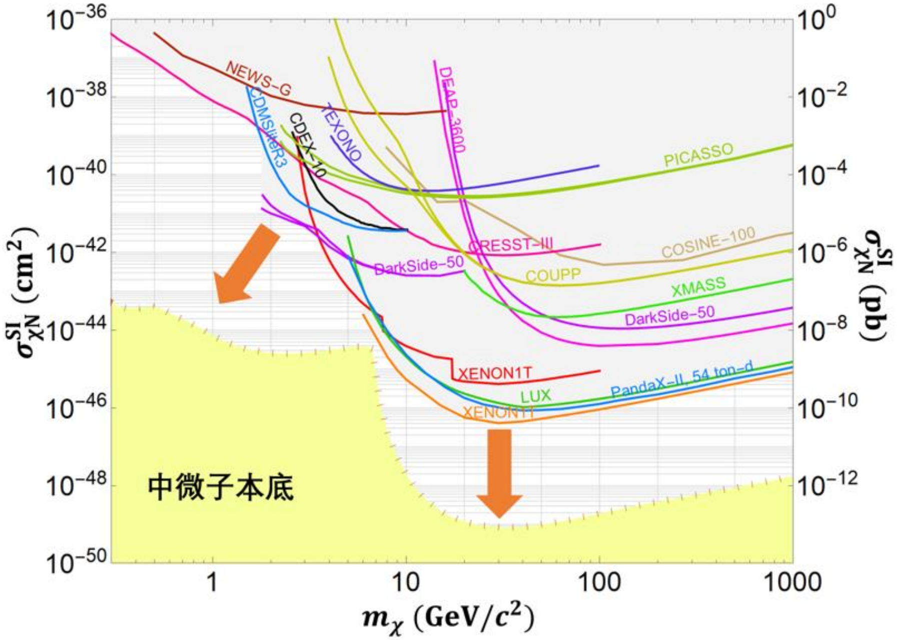


环境辐射

暗物质直接探测实验进展

- 国际地下实验室热点研究方向
- 多种探测器技术“百花齐放”
- 趋势：更低本底、更低阈值、更大规模

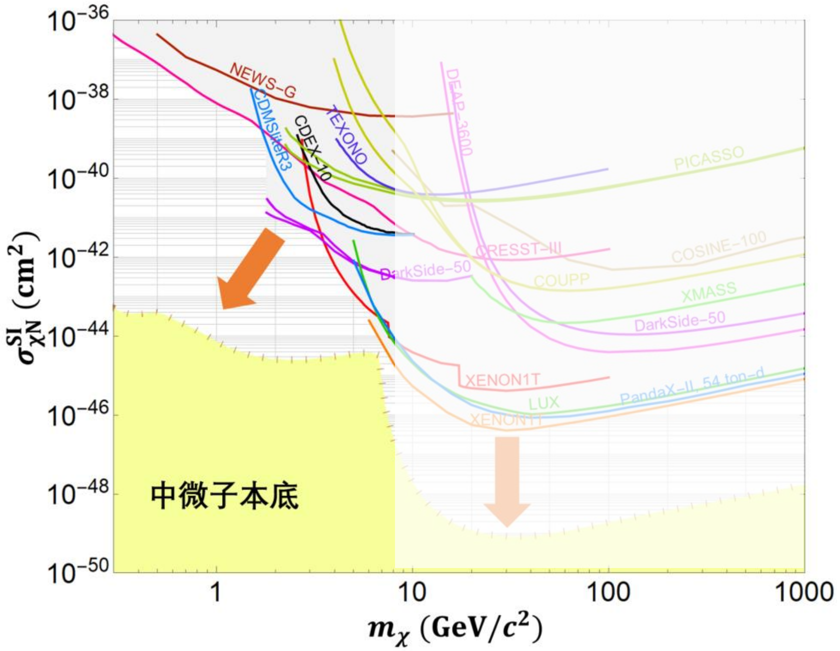


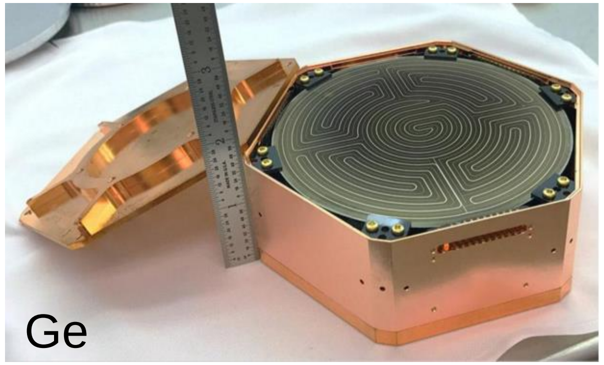


Dark Matter Limit Plotter,
https://supercdms.slac.stanford.edu/dark-matter-limit-plotter

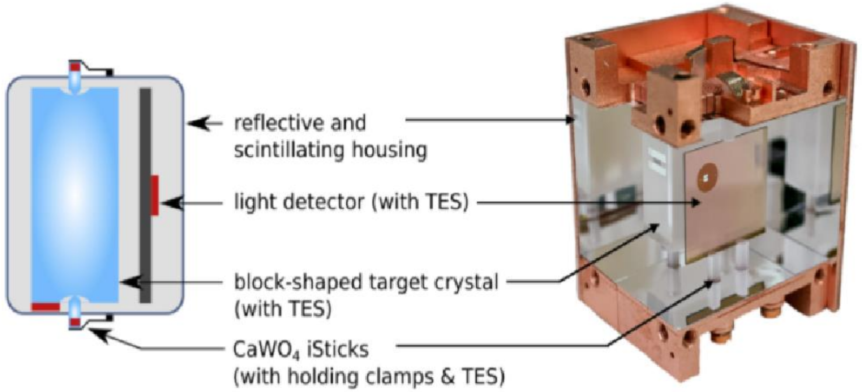
低温固体探测技术

- SuperCDMS
- Edelweiss
- CRESST
- CDEX

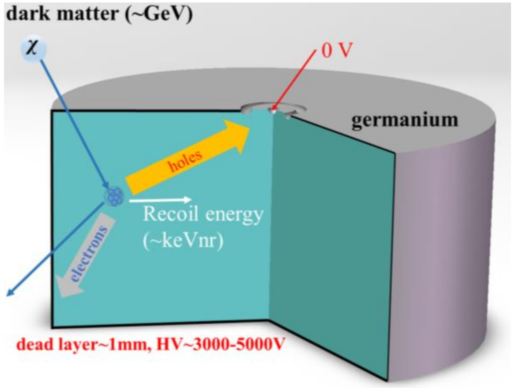




SuperCDMS



CRESST

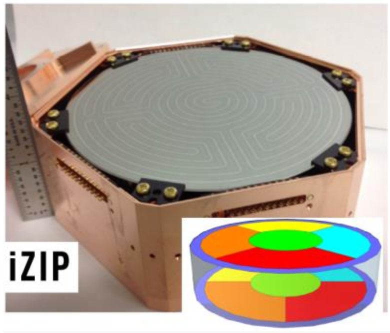


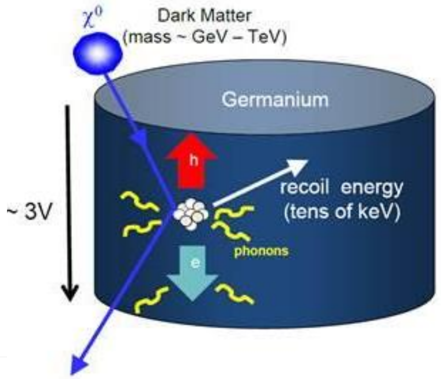
CDEX

SuperCDMS实验

- 实验室：Soudan → SNOLAB
- 探测器：高纯Ge、Si
  - 工作温度：~15 mK
  - iZIP：声子+电离，电子反冲本底甄别
  - HV：声子放大，更低阈值，~100V (eg. CDMSLite, 1.5GeV/c²)

Interleaved Z-sensitive Ionization and Phonon (iZIP) detectors





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

iZIP

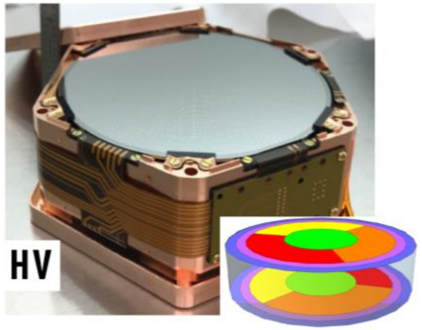
	Si	Ge
σ_{ph}	19 eV	33 eV
σ_{ch}	180 eV	160 eV
$Threshold_{ph}$	175 eV	350 eV

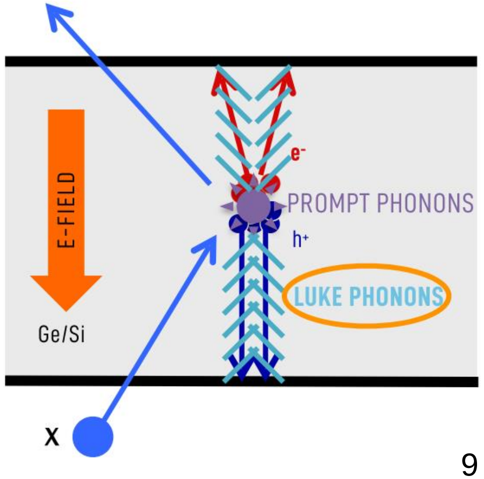
HV

	Si	Ge
σ_{ph}	13 eV	34 eV
$Threshold_{ph}$	100 eV	100 eV

arXiv:2203.08463

High Voltage (HV) detectors



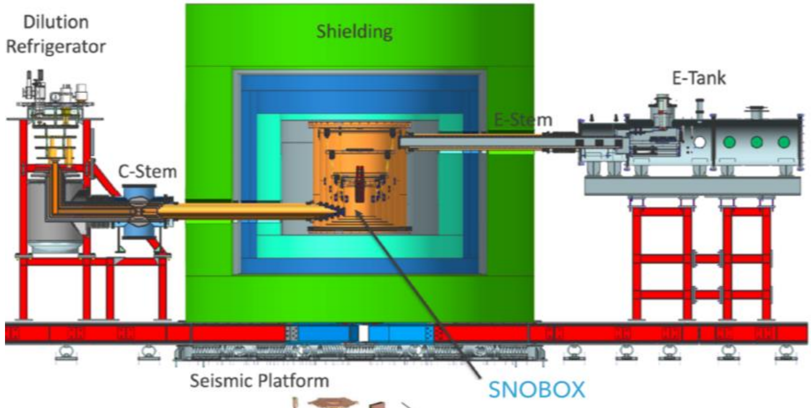


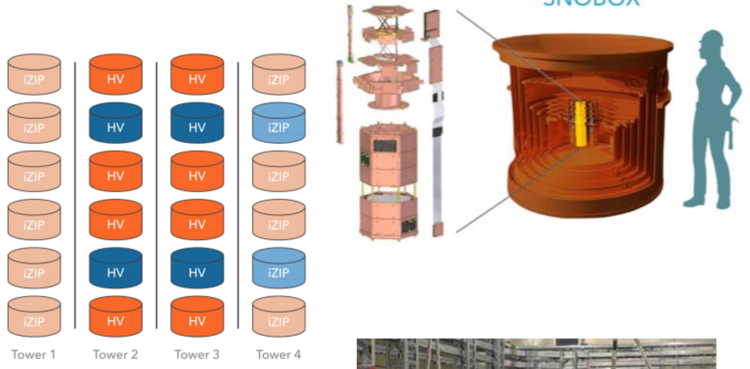
12 phonon channels
High bias voltage (~ 100 V)
Low threshold

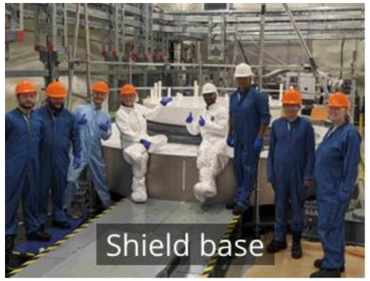
SuperCDMS实验

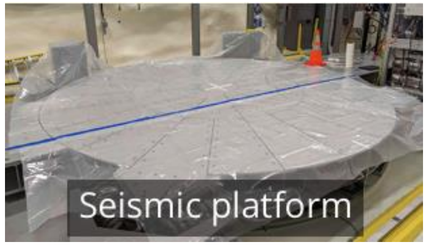
- 探测器@SNOLAB(initial payload)
  - Φ100x33.3 mm，1.39(0.61)kg Ge(Si)
  - Ge: 更大曝光量
  - Si: 更低阈值(100eV核反冲测量 *PRL 131, 091801, 2023*)
  - ~30kg，6X4 det,12 iZIP(10+2), 12 HV(8+4)

- 实验计划
  - Infrastructure at SNOLAB under construction
  - Full-tower testing underway at CUTE and SLAC
  - Commissioning of the full experiment- mid of 2025
  - First science data-taking- the end of 2025



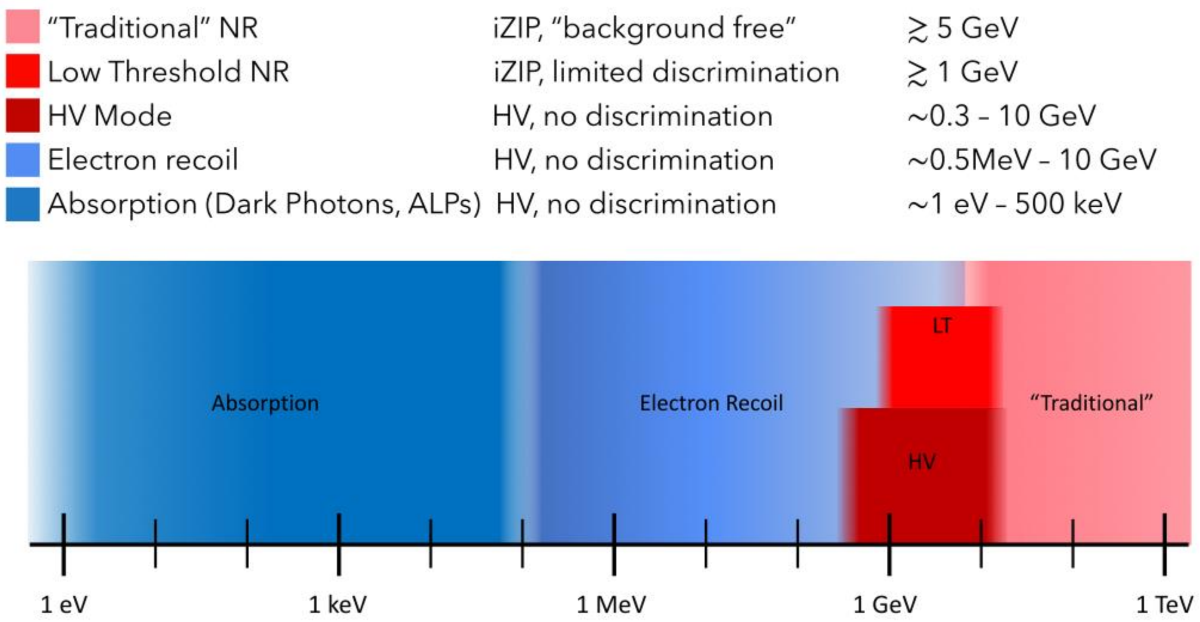


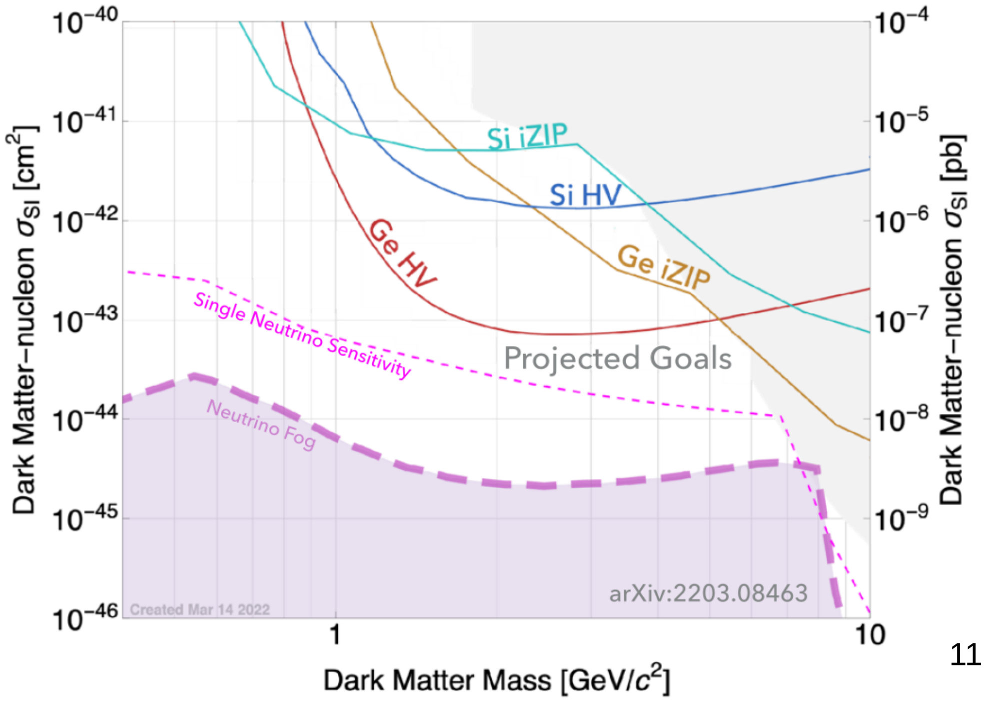




SuperCDMS实验

- 物理目标
  - WIMPs (incl. AM, Migdal…)
  - 10^{-43}~10^{-44} cm^2
  - 暗光子、类轴子
- 挑战
  - 晶体杂质：能量部分沉积
  - 放射性本底：~ eV范围
  - 红外和光学光子成为显著本底
  - 暗/漏电流成为显著本底，且在阈值附近主导本底

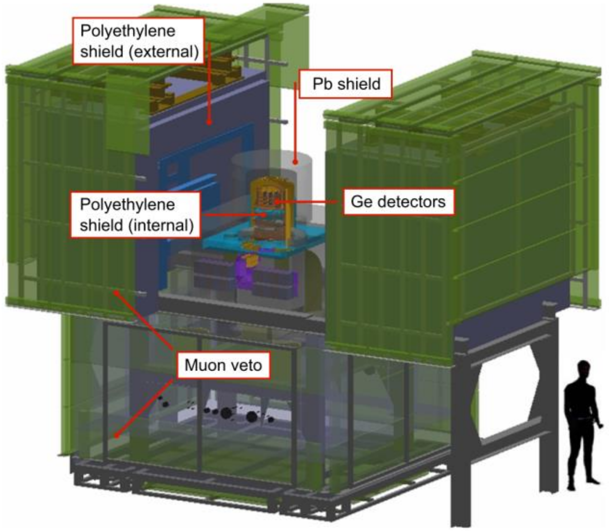


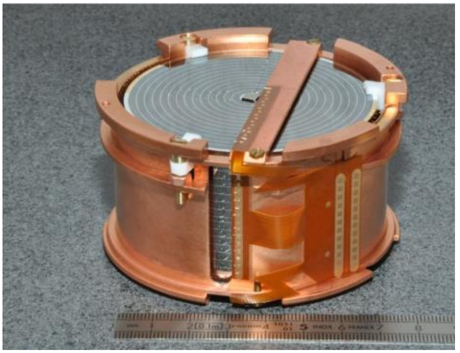


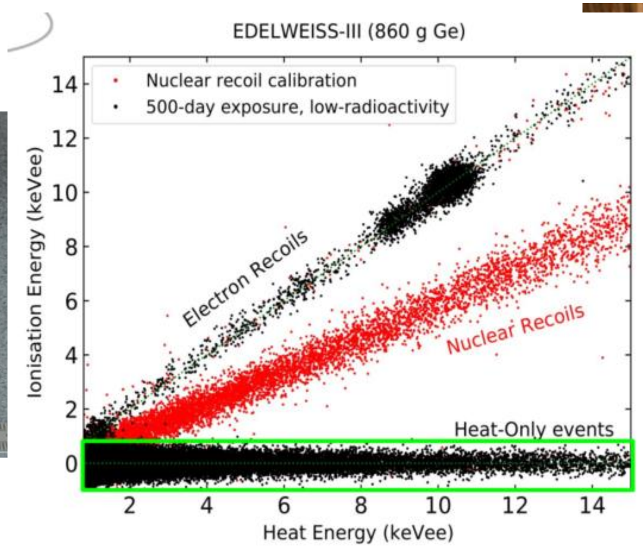
Edelweiss实验

H. Lattaud, IDM 2022
J. Gascon, IDM 2018; TAUP 2019
E. Armengaud et al, JINST 2017

- 实验室：Modane
- 探测器：高纯Ge
  - 工作温度：18 mK
  - Φ70x40 mm，~870g/det，~20 kg
  - 双相：电离+量热

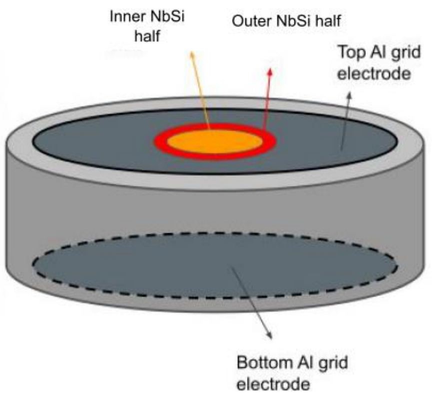




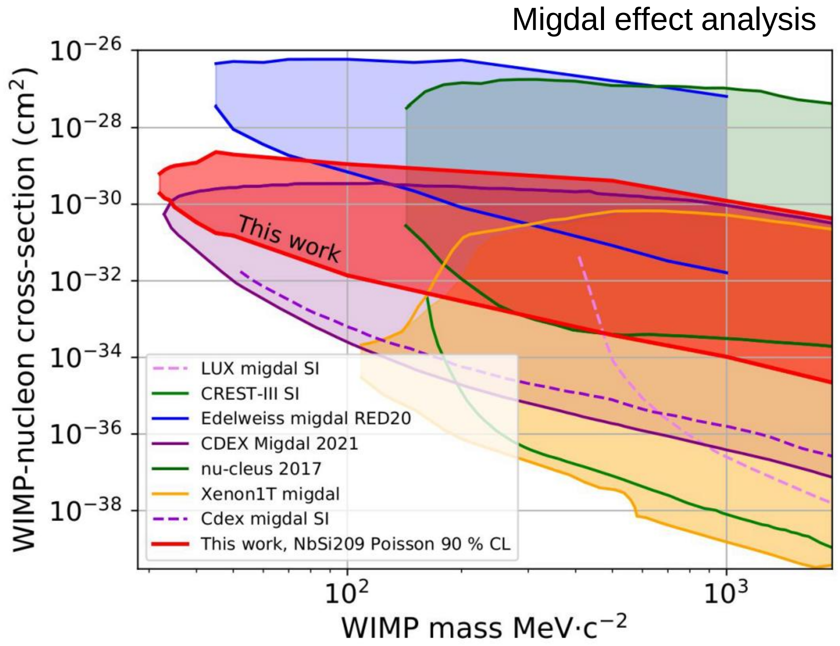


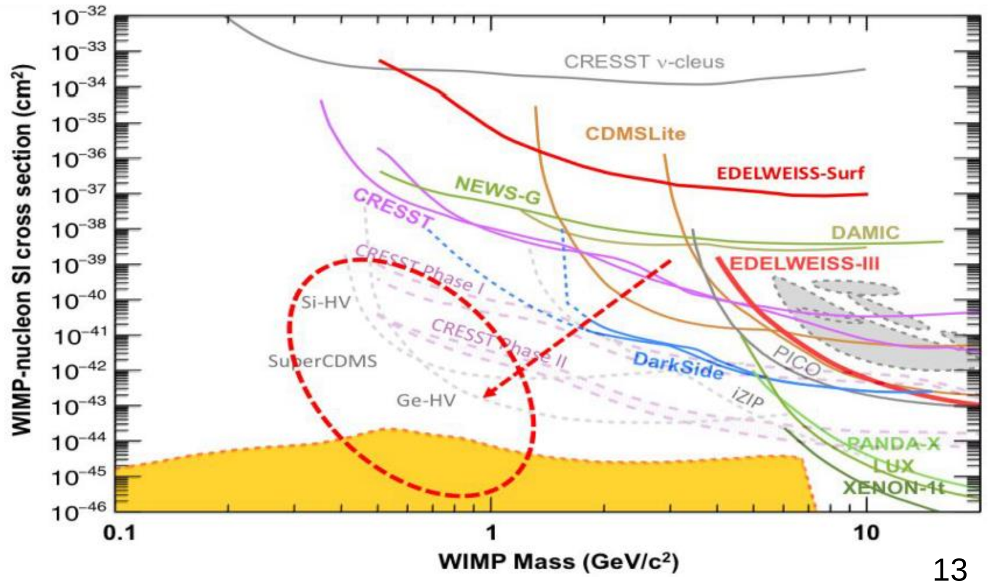
Edelweiss实验

- 技术挑战
  - 探测器：~1kg
  - 电离分辨率：20 eVee
  - 声子分辨率：17→10 eV
    - FET(100K)→HEMT(1K)
  - 高压（声子放大）模式运行
    - 33+200g运行@Modane
    - 200g: NbSi Transistor Edge Sensor (TES)
  - 新型探测器技术CRYOSEL
    - 40g Ge detector, $\sigma_{声子}$ = 20 eV, 200 V bias
    - 降低Heat-only本底
- 物理目标
  - MeV-GeV，电子反冲、核反冲
  - 双相: $\mathcal{O}(10^{-43})\mathrm{cm}^2$ @ 1GeV/c^2



能量分辨率：4.46 eVee
分析阈值：30 eVee

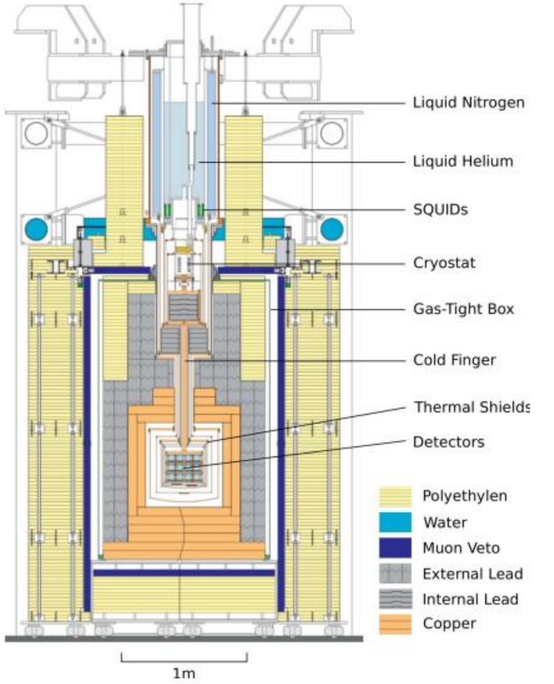




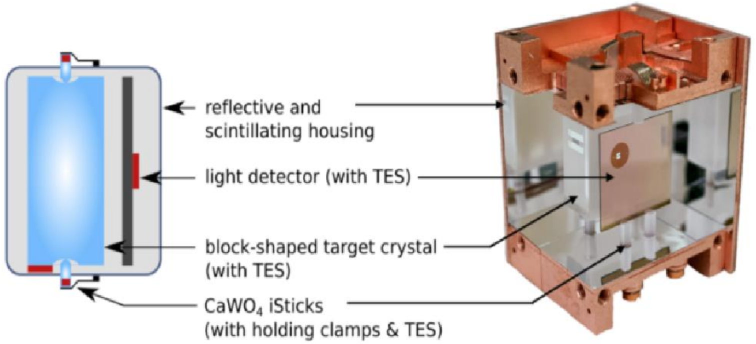
CRESST实验

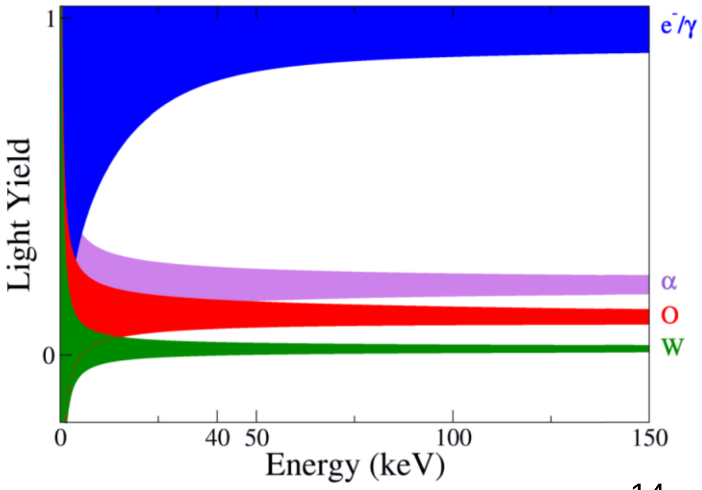
H. Kluck, TAUP 2019
J. Cooley, IDM 2020
C. Strandhagen IDM 2022

- 实验室：LNGS
- 探测器：$CaWO_4$晶体等
  - 工作温度：15 mK
  - ~24g/det，~240g
  - 双相：闪烁光+量热
- CRESST-III phase2
  - Run3: 2020.11-2021.8
  - SD results from Li1 detector
- 计划
  - →~2 kg(100det)
  - DAQ升级
  - 探测器技术研发
    - 更低阈值
    - 更纯晶体…
  - 低能区本底研究
    - 200eV以下能谱抬升待解释



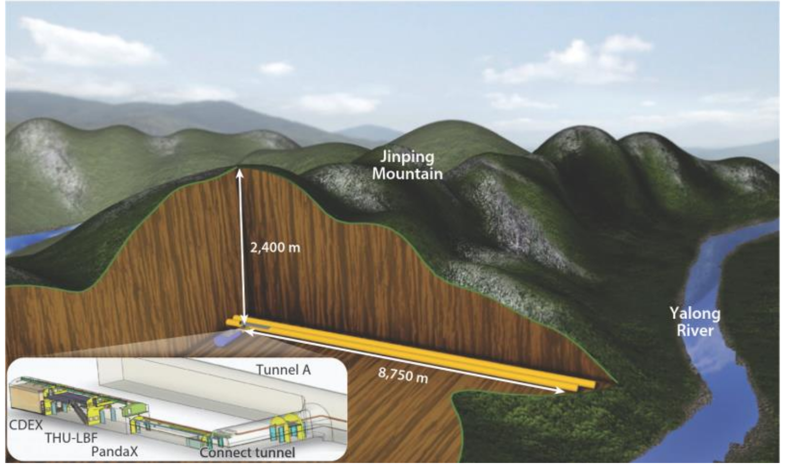
Main absorber:
(2x2x1) cm^3
e.g. $CaWO_4$ (24 g)
Al_2O_3-sapphire (16 g)
$LiAlO_2$ (10 g)
Si (9 g)

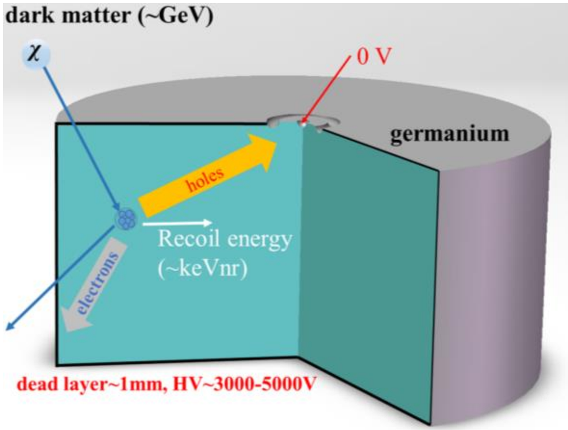


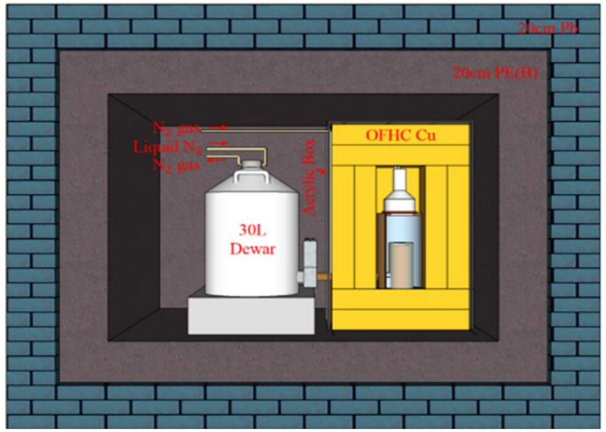


CDEX实验（盘古计划）

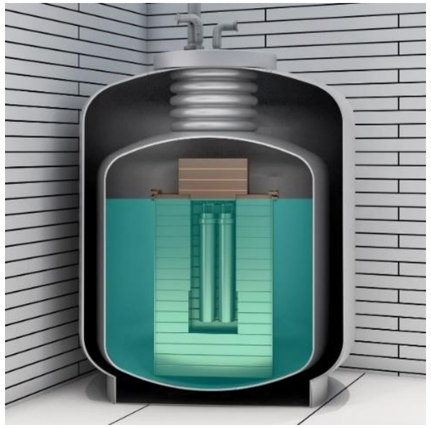
- 实验室：CJPL
- 探测器：高纯锗
  - 工作温度：77 K
  - >10 kg PPC Ge（单相: 电离, ~1kg/det）
  - 冷指制冷+固体屏蔽→液氮浸泡（制冷+屏蔽）







CDEX-1A/B (2011-2018)
2 x PPC(~1 kg)

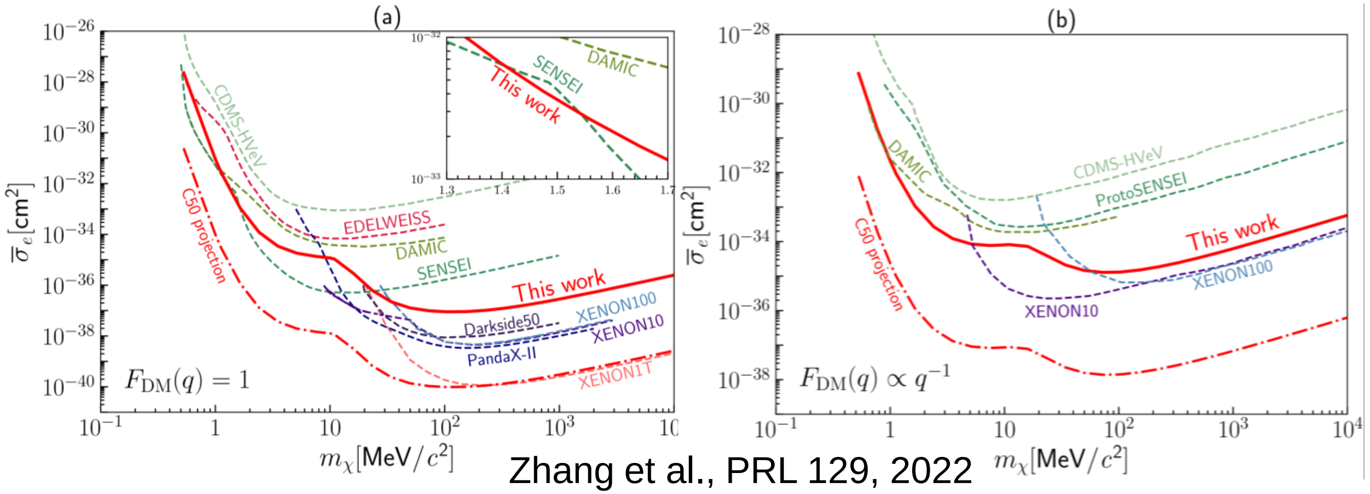


CDEX-10 (2016-)
10 kg 真空封装阵列
液氮直接浸泡

CDEX results

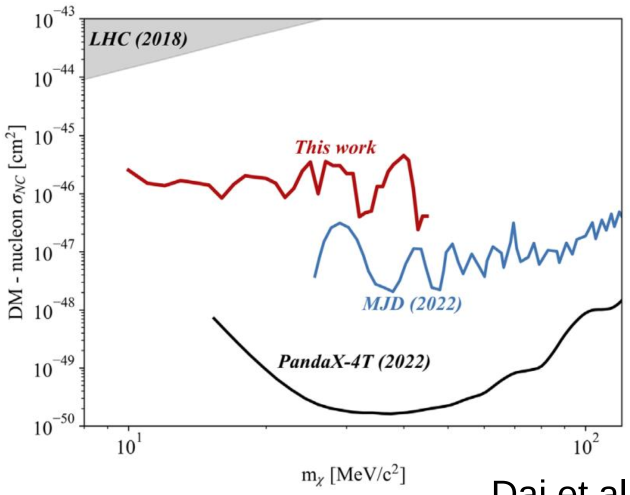
- 更低本底、更低阈值
  - ~2 cts/(keV·kg·day) , 160 eV_{ee}
- 多物理通道
  - SI/SD（PRL 120, 2018）
  - Migdal效应 (PRL 123, 2019-1)
  - 年度调制效应（PRL 123, 2019-2）
  - 太阳轴子 / 轴子暗物质（PRD 101, 2020）
  - 太阳暗光子 / 暗光子暗物质 (PRL 124, 2020)
  - 电子反冲 (PRL 129, 2022-1)
  - 宇宙线加速 (PRD 106, 2022)
  - 奇异暗物质(PRL 129, 2022-2)
  - 太阳反射暗物质电子反冲（PRL 132, 2024）

DM-electron recoil

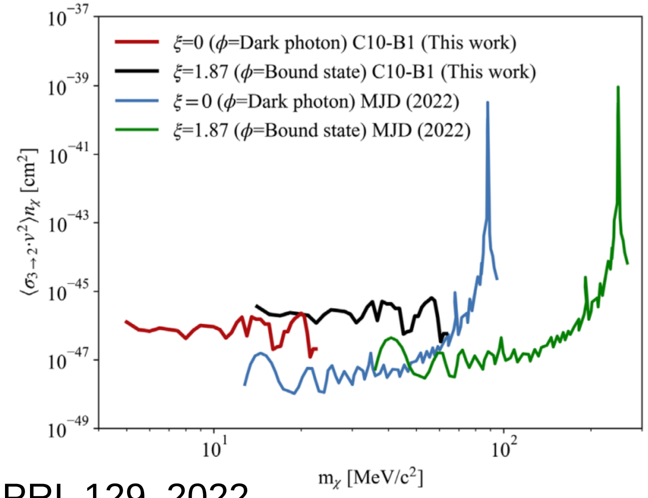


Zhang et al., PRL 129, 2022

Fermionic DM absorption



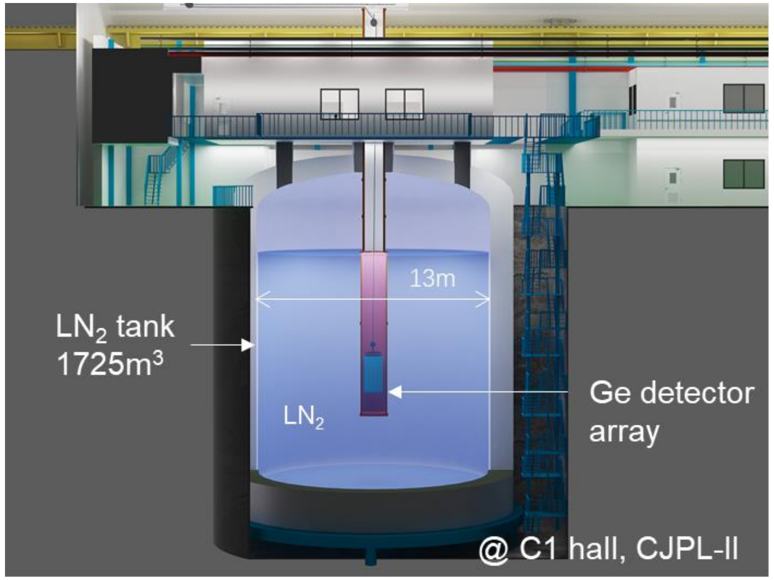
DM-nucleus 3 → 2 scattering



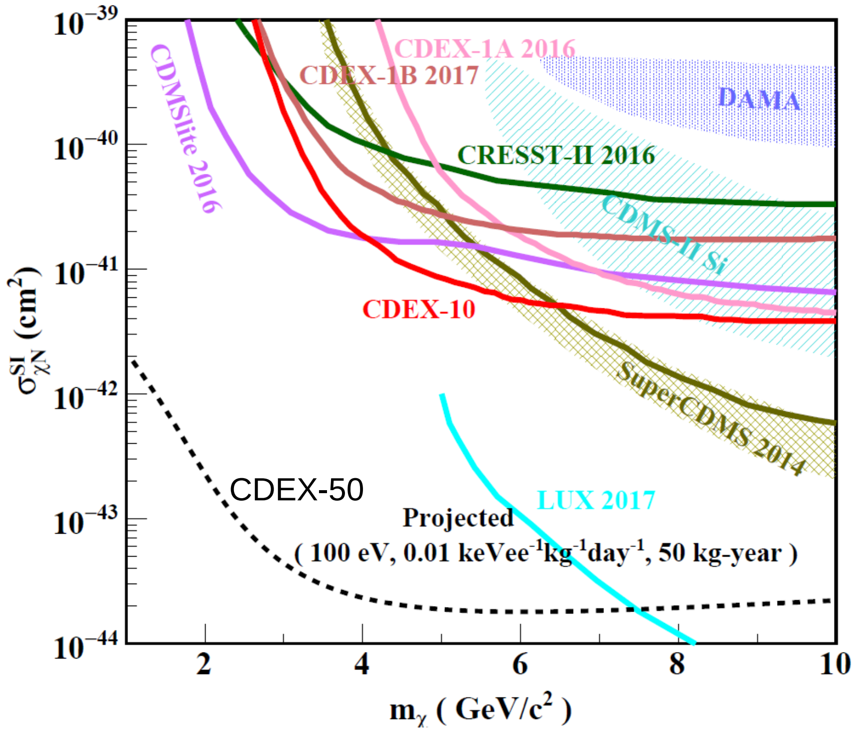
Dai et al., PRL 129, 2022

CDEX实验

- CDEX-50
  - CJPL-II，大型液氮恒温器
  - ~50 kg阵列PPC/BEGe

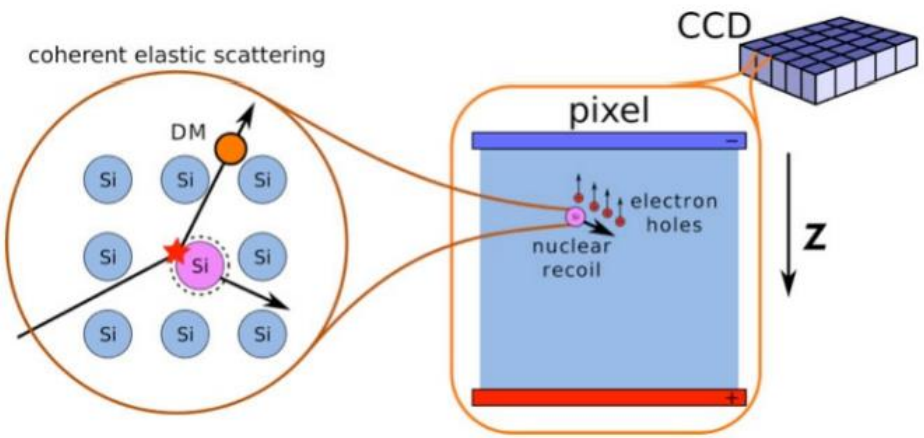


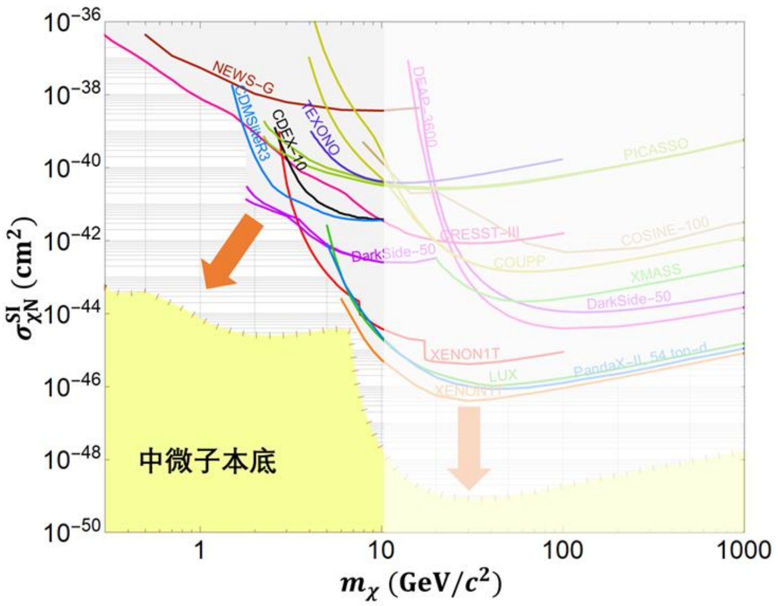
- 暗物质探测灵敏度
  - 本底 < 0.01 cts/(keV·kg·day)
  - 阈值 100-200 eV
  - 曝光量 ~50 kg·year
  - SI Sensitivity ~10^{-44} cm^2



电荷耦合器件（CCD）探测技术

- DAMIC
- SENSEI
- OSCURA

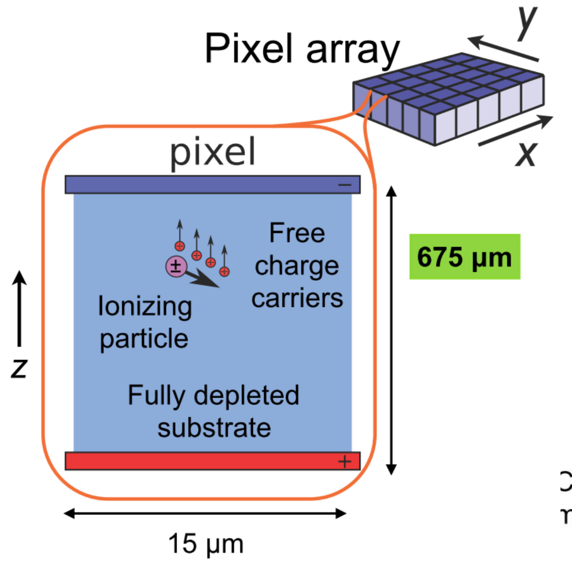


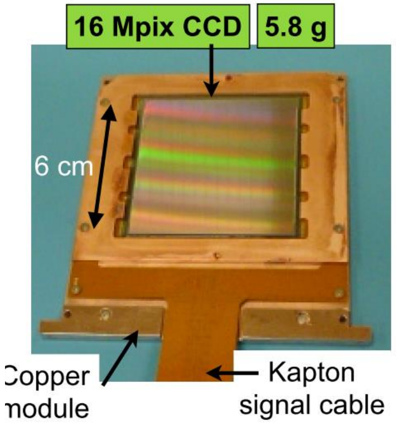


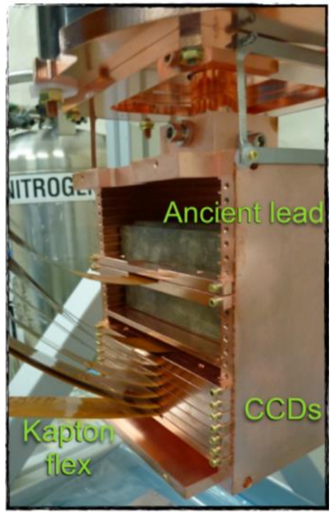
DAMIC实验（Dark Matter In CCDs）

A.E. Chavarria, TAUP 2019
P. Privitera, TAUP 2019
D. Norcini, IDM 2022
P. Privitera, TAUP 2023

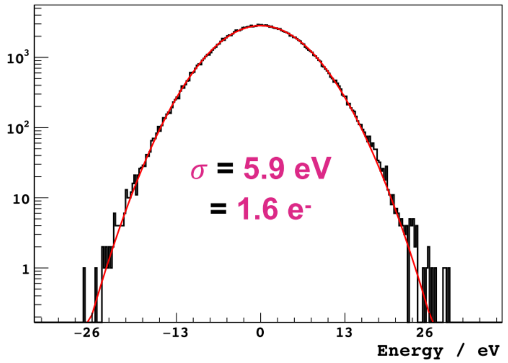
- 实验室：SNOLAB
- 探测器：CCD
  - 7 CCDs，~40g
  - 工作温度：~100 K
  - 径迹本底甄别能力
  - 非常低的噪声和暗电流
    - < 0.001 e/pixel/d
    - 2×10^{-22} A/cm^2

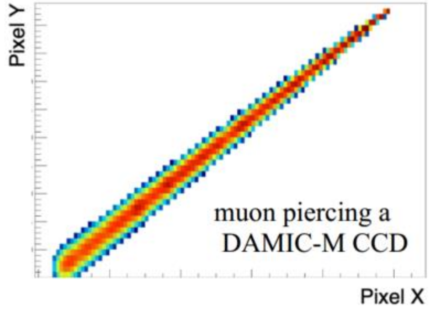


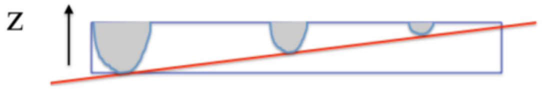


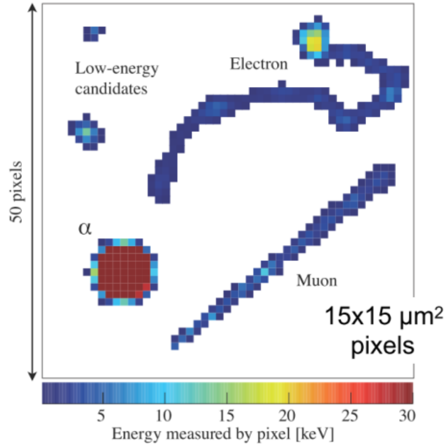


Pixel charge distribution





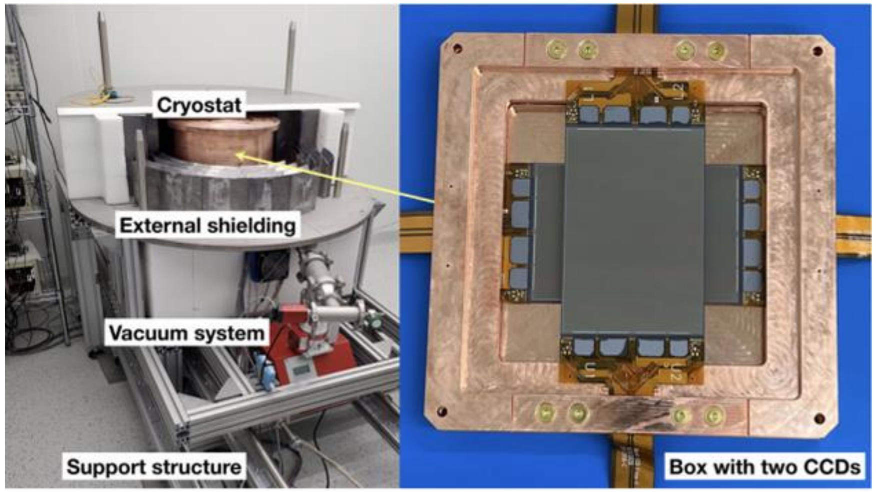




DAMIC实验

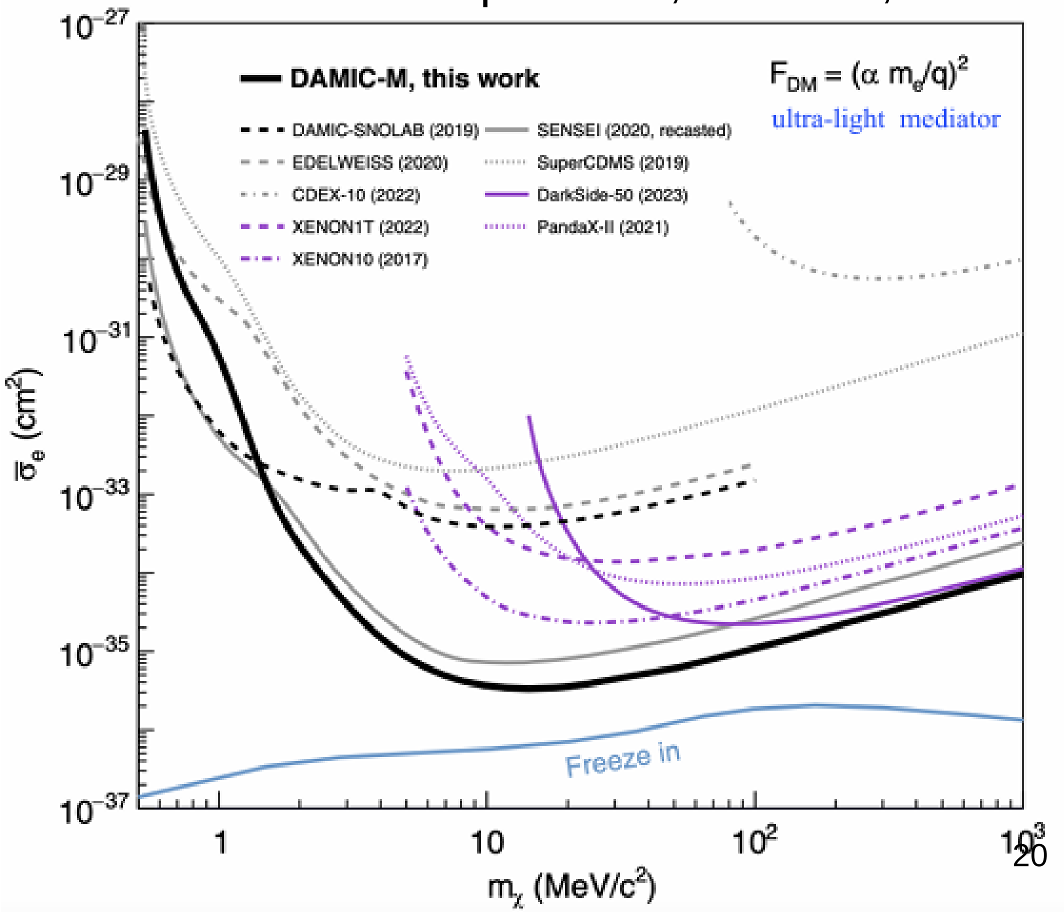
- **DAMIC-Modane**
  - 200 CCDs, ~3.5 g/det, 6k x 1.5k pixels
  - Skipper读出，0.2e- (< 1eV) at 650 skips
  - 原型系统
    - 2个 6k x 4k CCDs, ~17g靶质量
    - 电子反冲 (PRL 130, 2023)
    - 日调制效应 (arXiv:2307.07251)

地下电解铜



原型实验系统

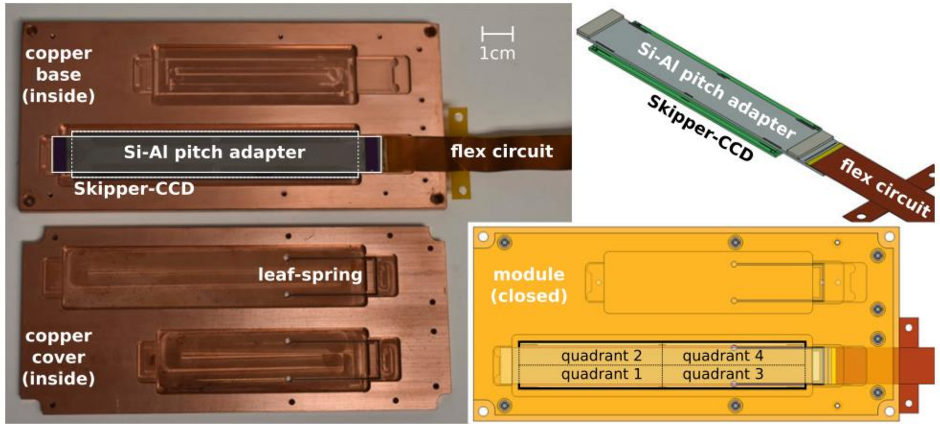
I. Arnquist et al, PRL 130, 2023

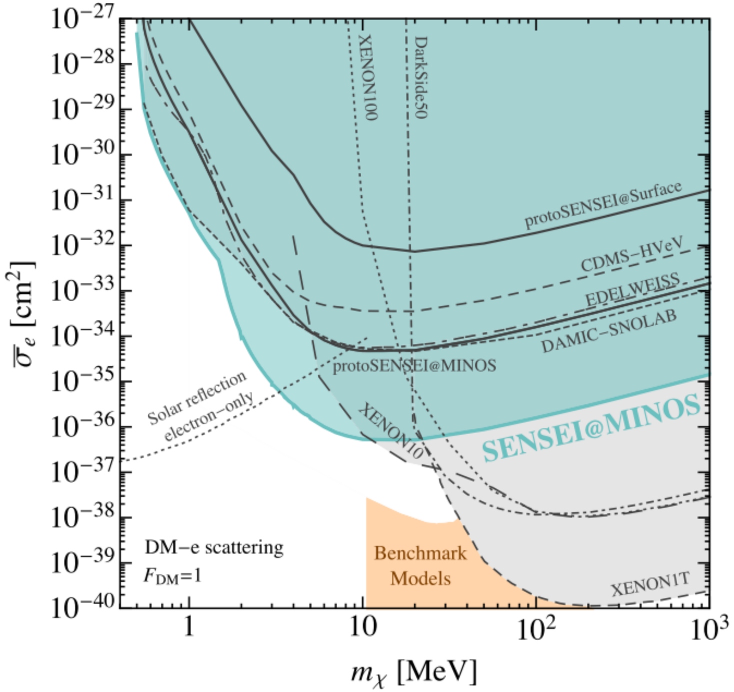


SENSEI实验

L. Barak et al, PRL 2020
Lauren Hsu, ICHEP 2020
J. Cooley, IDM 2020
M. Cababie, IDM 2022
N. Saffold, IDM 2022/TAUP2023

- 实验室：MINOS Hall @Fermilab
- 探测器：skipper CCD
  - 高阻性硅, 675 μm厚
  - 1.59 × 9.42 cm^2, ~2 g
  - ~5.5 Mpixels of 15x15x675 μm^3 each
  - 亚电子噪声

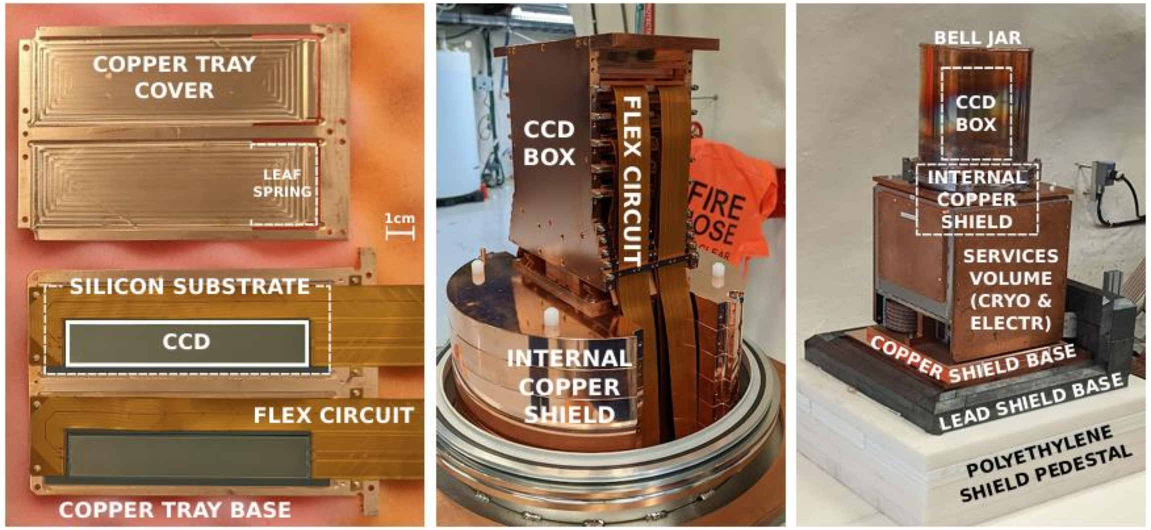




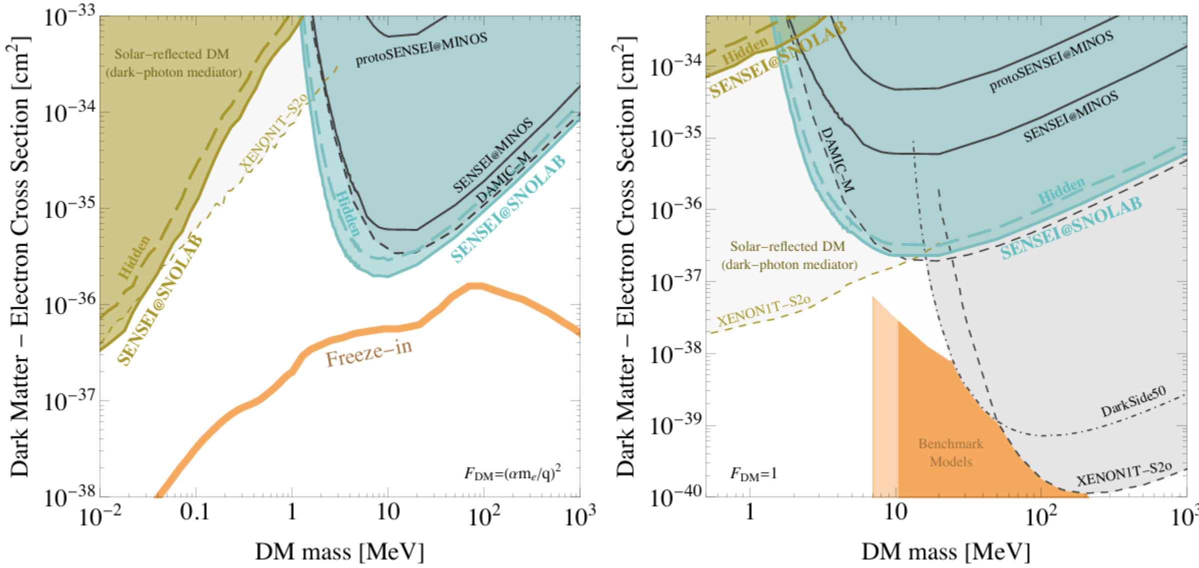
SENSEI实验@SNOLAB

- 现状与计划
  - 12 skipper CCDs (~25g) deployed
  - 冷指制冷，125-145K
  - →48 skipper CCDs （100g）in total

arXiv:2312.13342



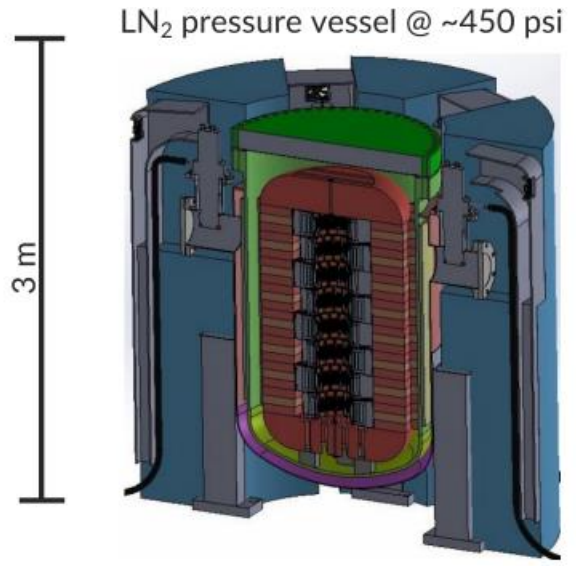
SENSEI@SNOLAB



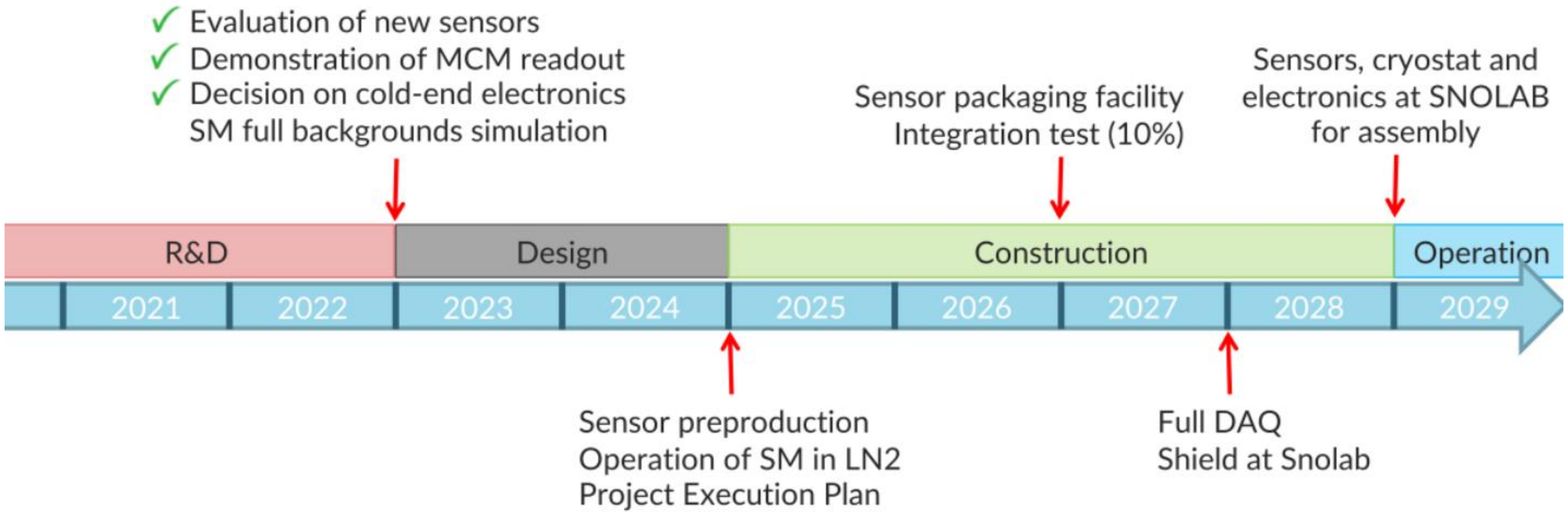
DM-e interaction

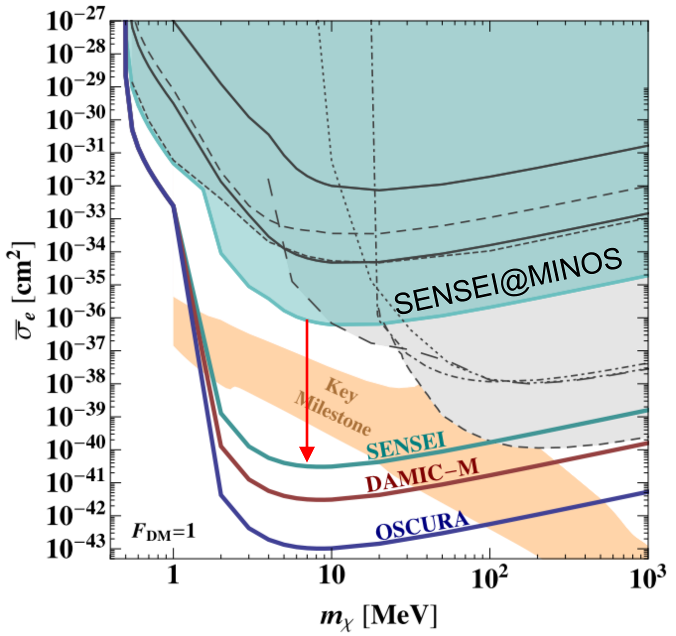
OSCURA实验

- 美国CCD实验组联合组成
- →10 kg skipper CCDs，浸泡在液氮中
- → 2-order bkg reduction
- 电子反冲，30 kg-y



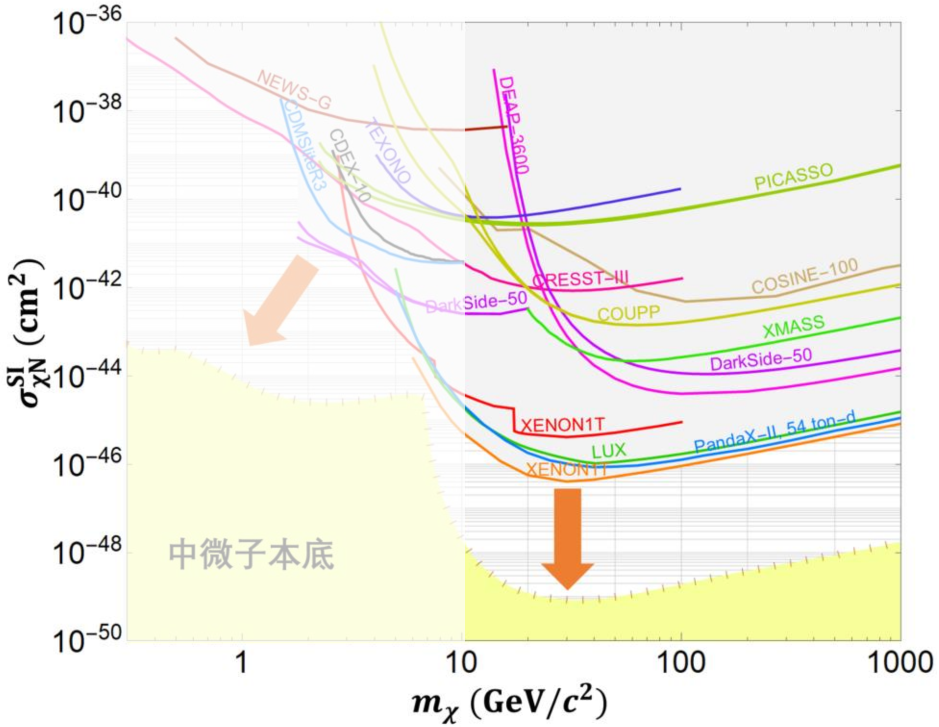
arXiv:2202.10518

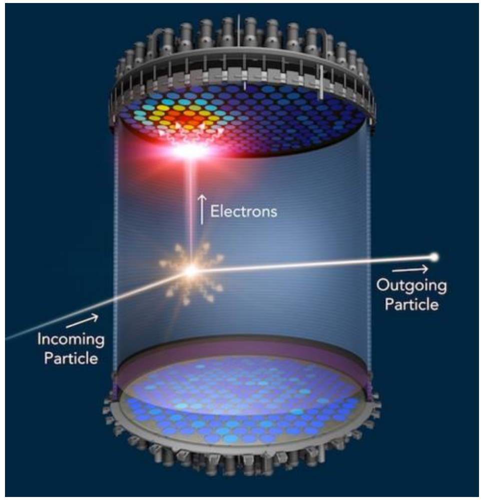




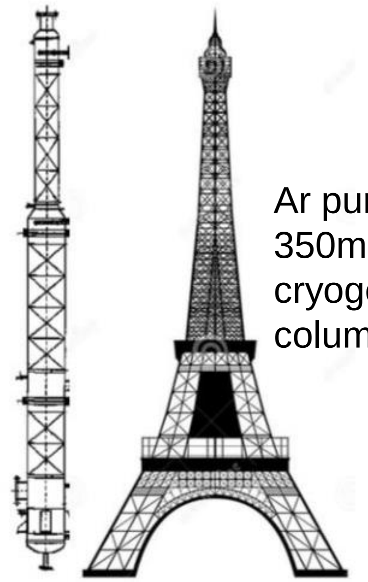
液态稀有气体探测器

- 低温液氙探测技术
  - XENONnT
  - LZ
  - PandaX
- 低温液氩探测技术
  - DarkSide-20k
- 低温液氦探测技术



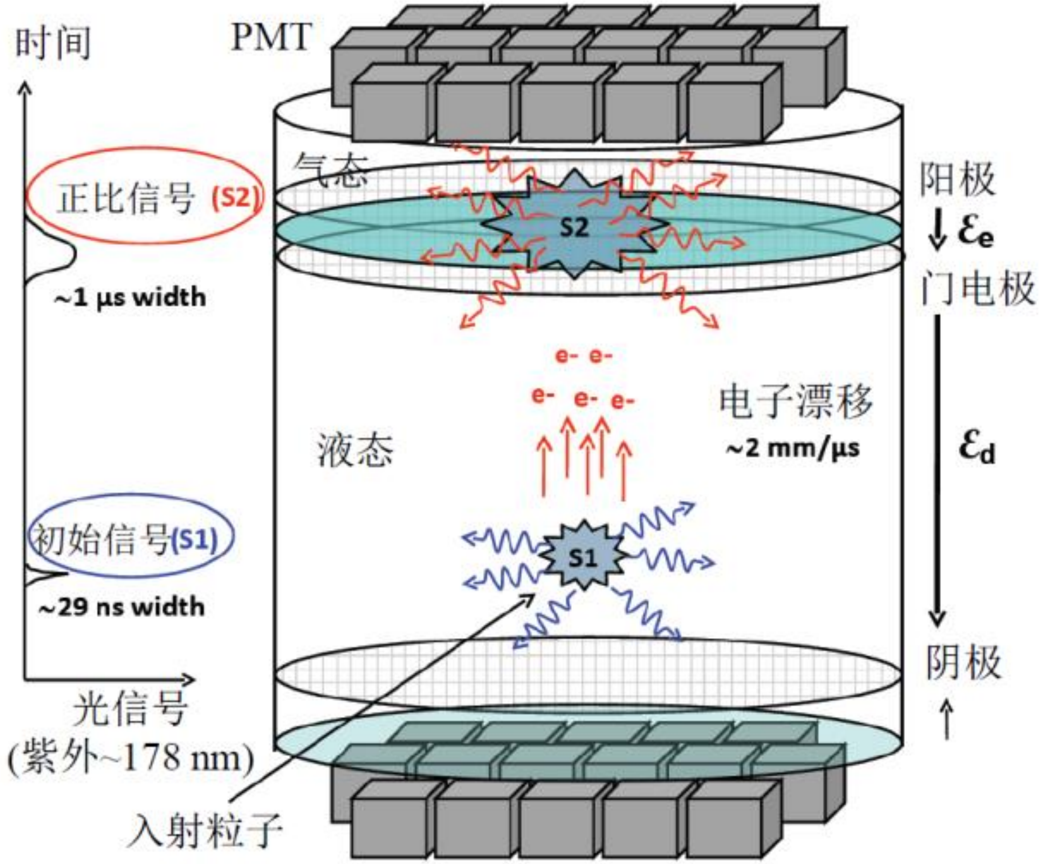


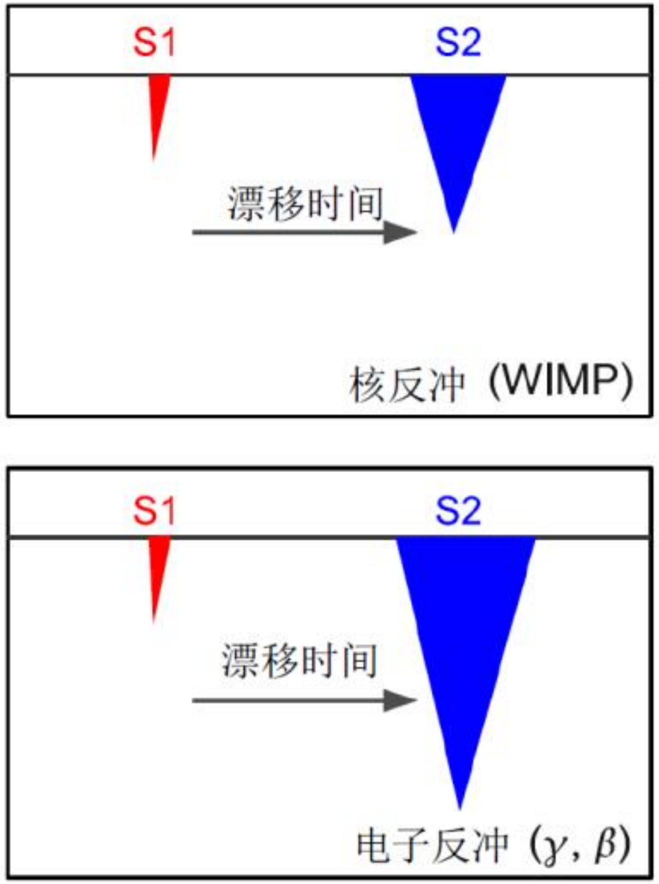
Dual phase TPC



Ar purification by 350m high cryogenic distillation column

液氙TPC探测实验（G2）





液氙TPC探测实验（G2）

PandaX-4T @CJPL

3.7t LXe target

Running 2020-

LZ @SURF

7t LXe target

Running 2021-

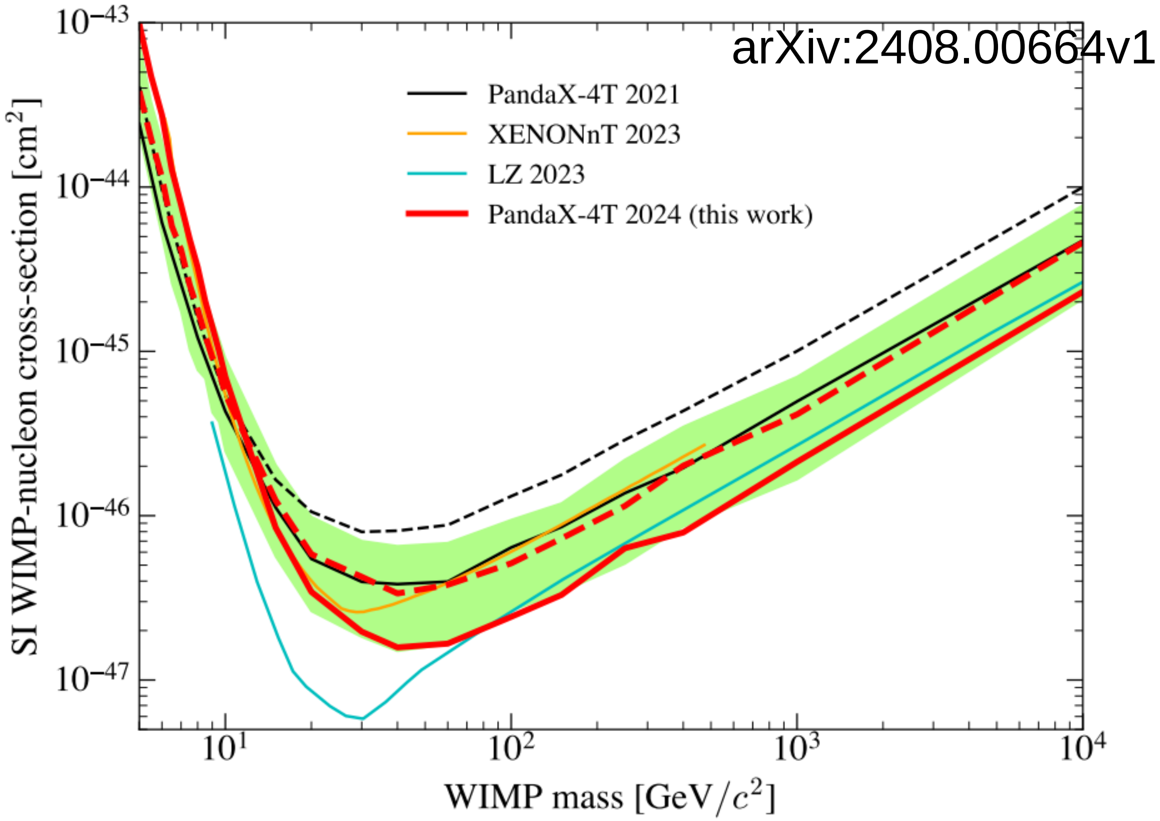
XENONnT @LNGS

6t LXe target

Running 2021-

WIMP-Nucleon SI Exclusion Limits from PandaX

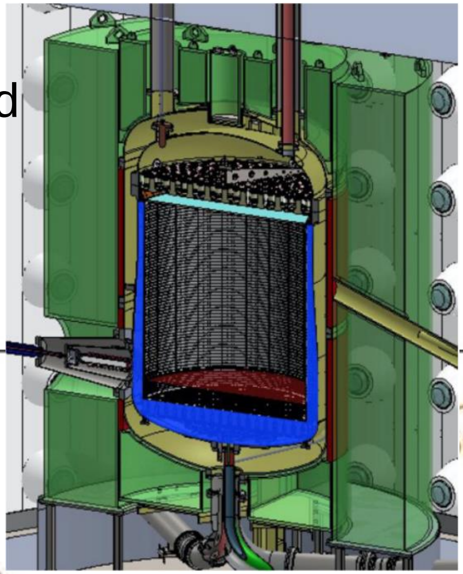
- Stable data running period: 1.54 ton-yr exposure
- The most stringent constraint for a dark matter mass above 100 GeV/c^2
- Dived into previously unexplored territory, Approaching the "low E" neutrino floor.



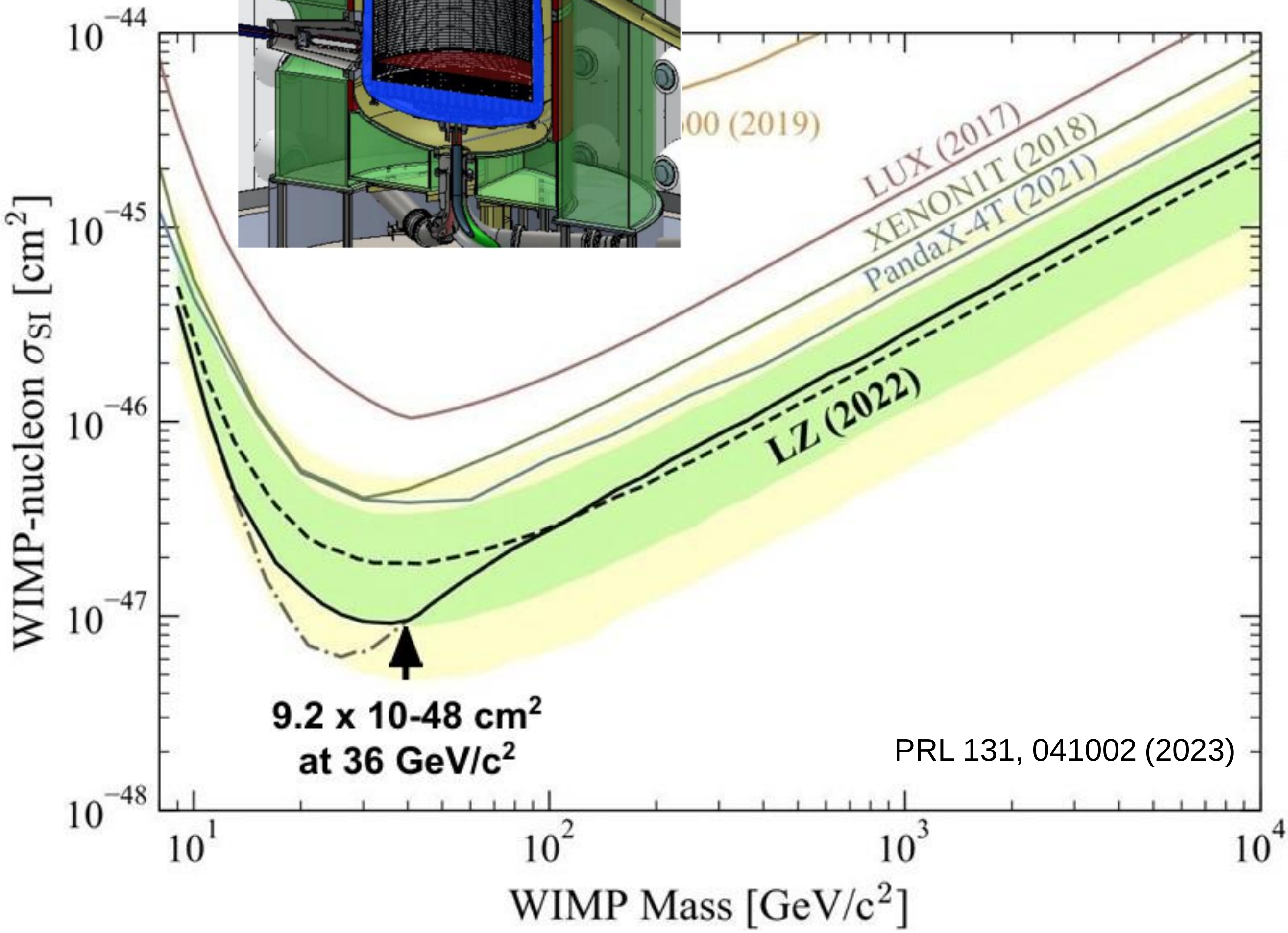
LZ results

A. Fan, IDM 2022
B. Boxer, TAUP 2023

Outer Detector
17 tonnes Gd-loaded liquid scintillator in acrylic vessels…



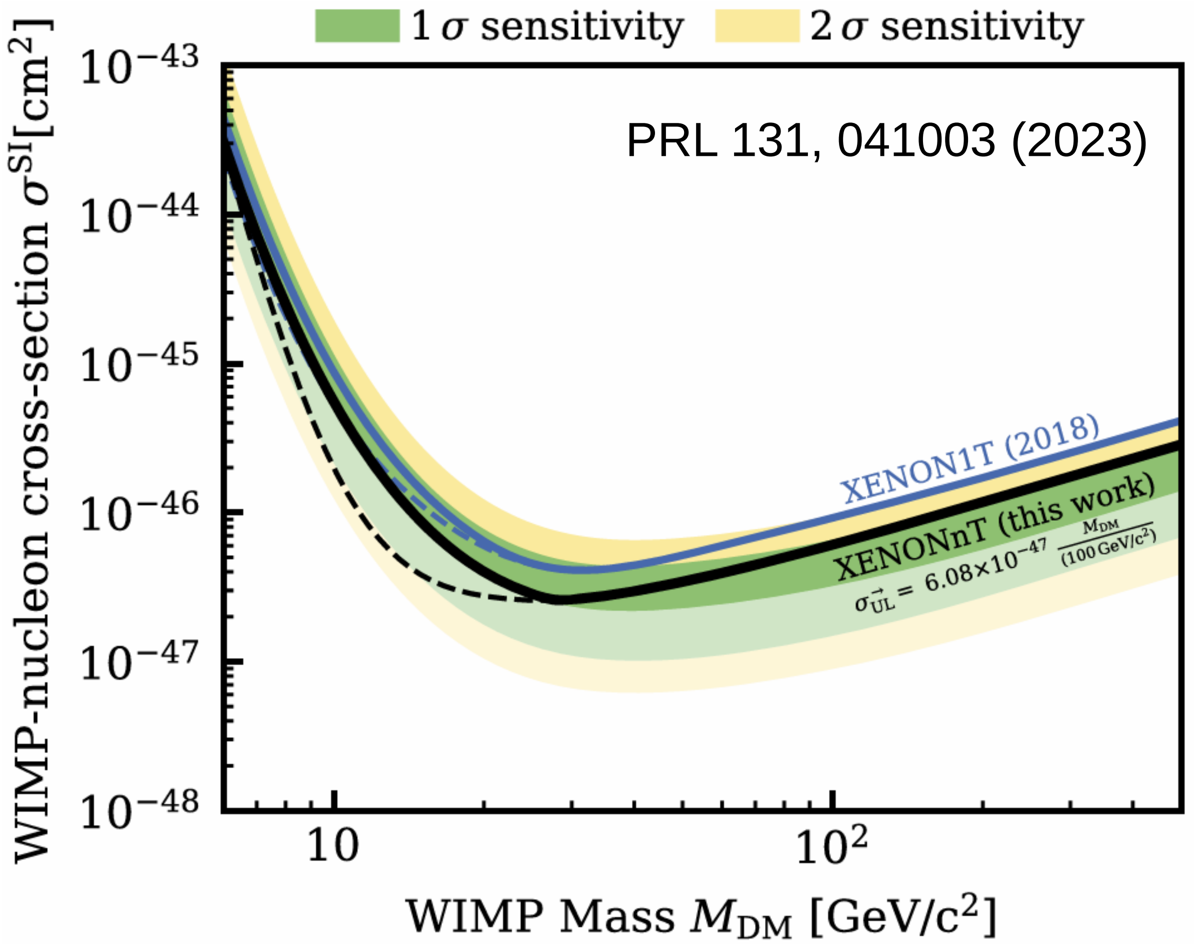
- SR1 data taking 23 Dec 2021 to 18 Apr 2022
- 60 live days exposure using a fiducial mass of 5.5 t
- Highest sensitivity to SI WIMP-nucleon scattering for masses greater than 9 GeV/c^2
- Planning for a total 1000 live days (x 17 more exposure than SR1



The green and yellow bands are the 1σ and 2σ sensitivity bands.
The dotted line shows the median of the sensitivity projection.

XENONnT results

- WIMP分析(SR0)
  - 1.09±0.03 ton yr
  - 2.58×10^{-47} cm^2 @ 28 GeV/c^2
- SR1
  - Lower ^{214}Pb background rate (~ 50% SR0 level)
  - Insert Gd into neutron veto to further improve tagging efficiency
  - More exposure

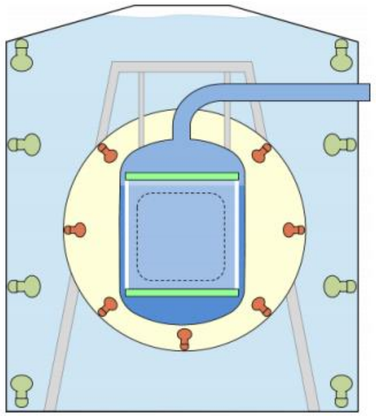


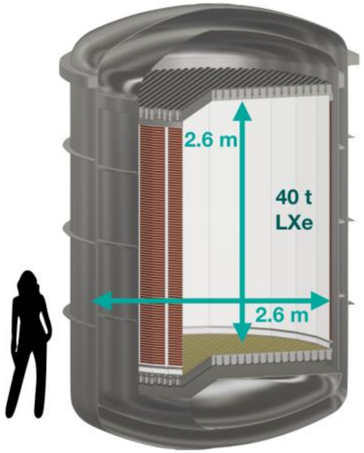
Upper limit on spin-independent WIMP-nucleon cross section at 90% confidence level

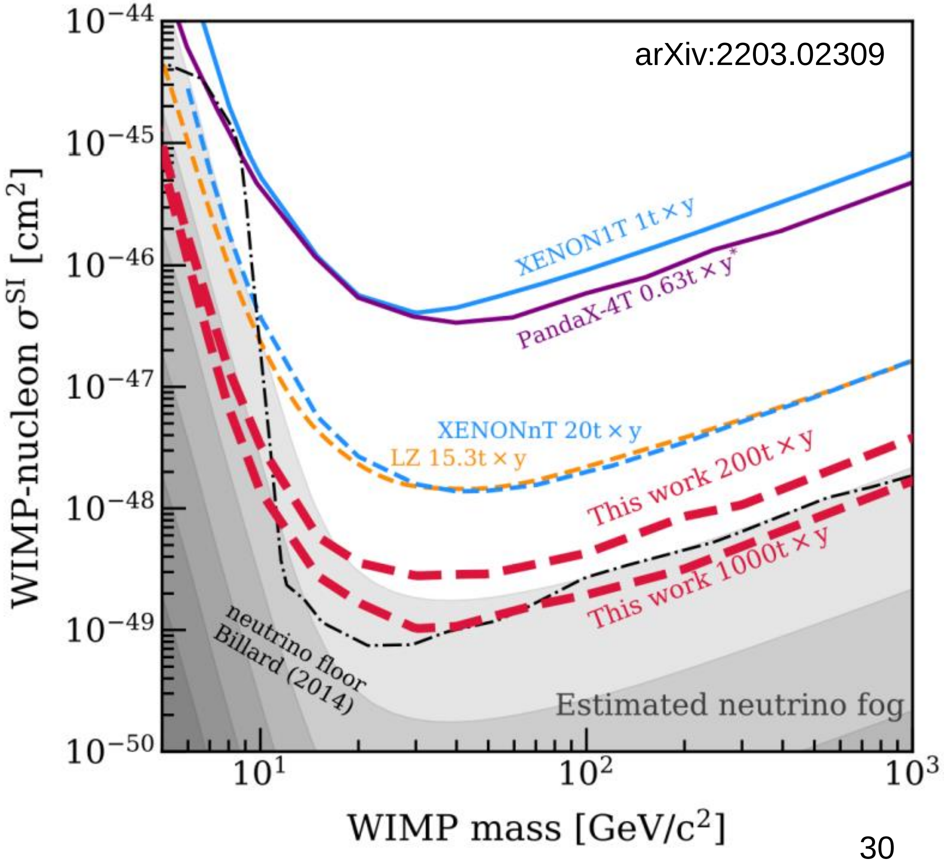
下一代液氙实验(G3)

M. Galloway, IDM 2022

- PandaX-30T：关键技术预研
- DARWIN: DARk matter WImp search with liquid xenoN
  - Two-phase LXe/GXe TPC
  - 50 t total LXe (40 t target)
  - Top and bottom photosensors (~1800 3” XENON PMTs)
  - PTFE reflectors and Cu field-shaping rings
  - In-situ purification plus krypton and radon distillation (background mitigation)
  - Veto detectors: water Cerenkov for muons with Gd doping for neutrons



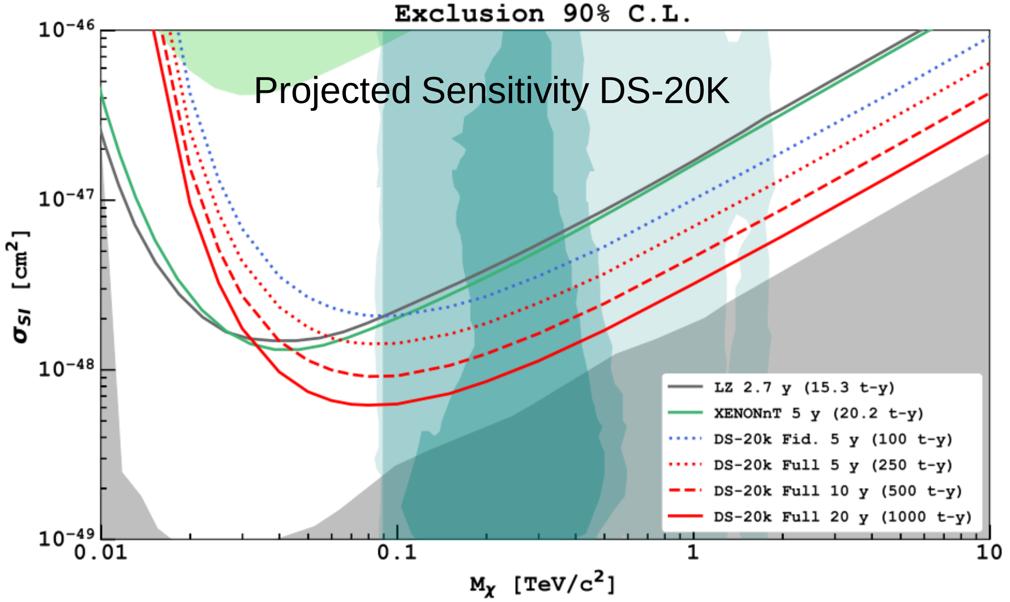


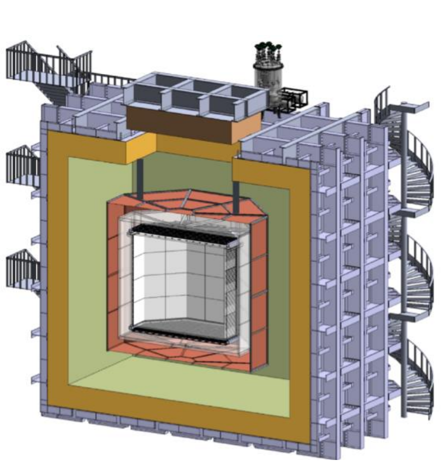


T. Thorpe, IDM 2022
M. Galloway, IDM 2022
Y. Wang, TAUP2023

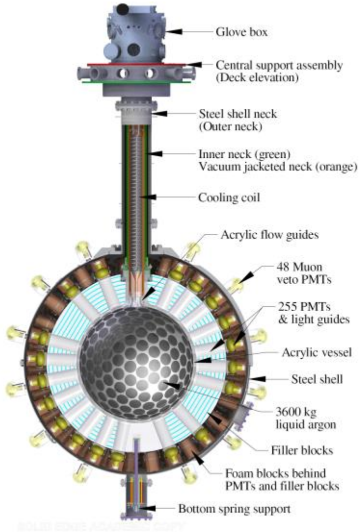
液氩TPC

- DarkSide-20k (20t fiducial mass)
  - DS50+DEAP-3600+ArDM+MiniCLEAN
  - 50t UAr dual-phase-TPC in 700t AAr cryostat
  - Fill the detector by the end of 2026
  - 200 t-yr exposure
- UAr source and purification
  - Extraction of 250 kg/day, with 99.9% purity in Colorado
  - 350-m tall cryogenic distillation column in Sardinia
  - O(1 tonne/day) with 10^3 reduction of all chemical impurities
  - Isotopically separate ^{39}Ar from ^{40}Ar (10 kg/day in Seruci-I)
- GADMC: Global Argon Dark Matter Collaboration
  - Multi-national collaboration, >500 scientists from >100 institutions
  - ARGO, ~300t TPC, 3000 t-yr exposure for high mass WIMPs
  - Darkside-LowMass, 1 t-yr





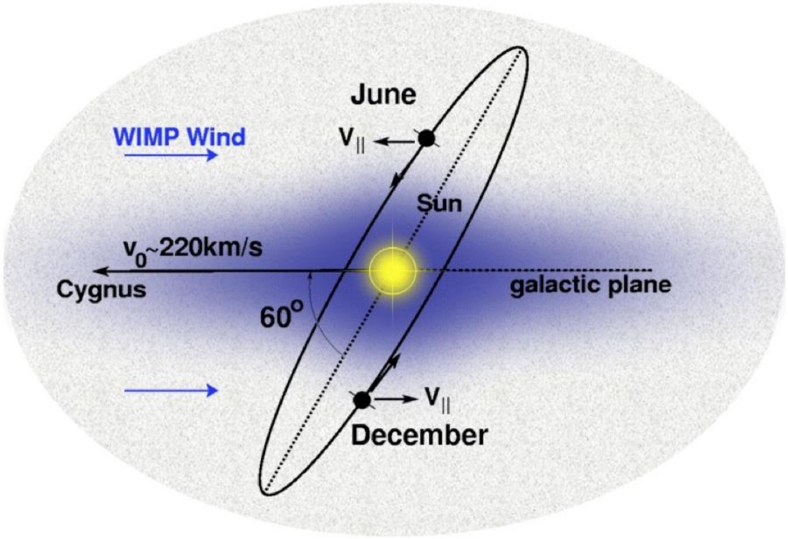
DS-20k

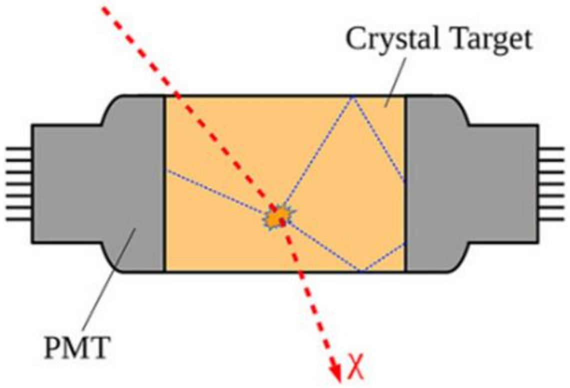


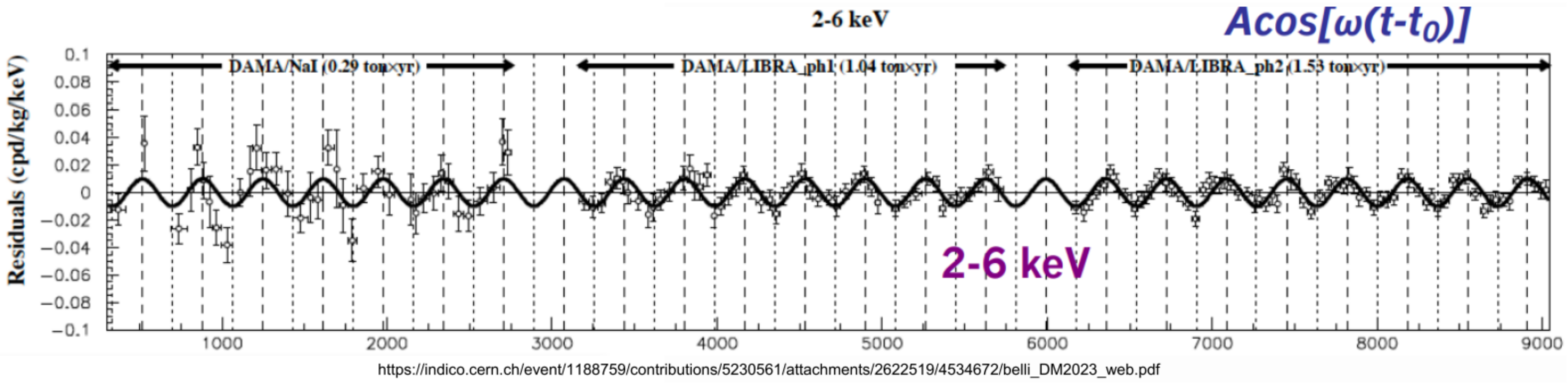
DEAP-3600

其它探测技术：室温闪烁体

- 年度调制效应探测
  - DAMA/LIBRA
  - ANAIS-112
  - COSINE-100





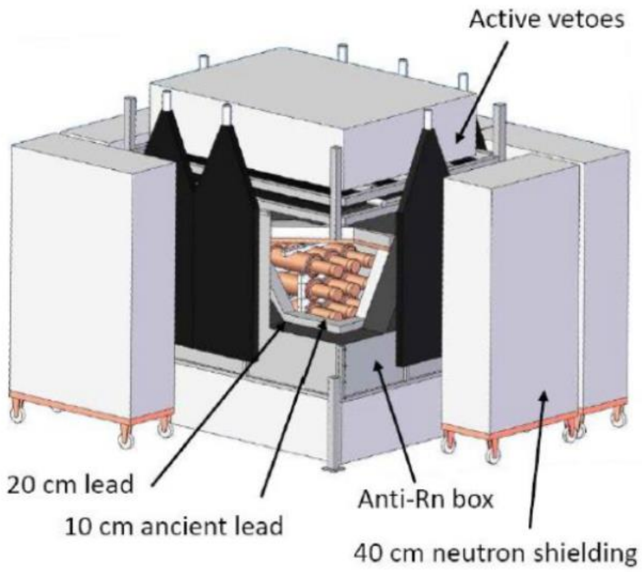


Annual modulation from DAMA results

DAMA的验证实验

Astroparticle Physics European Consortium (APPEC) Recommendation: "The long-standing claim from DAMA/LIBRA […] needs to be independently verified using the same target material."

- ANAIS-112@LSC
  - 9 NaI(Tl) crystals (112.5 kg)
  - No modulation and discard DAMA with ~3σ sensitivity
  - 5σ sensitivity in late 2025



- COSINE-100@Y2L
  - 106 kg NaI(Tl) crystals, ended in Mar. 2023
  - ~7σ negative modulation (opposite phase) from the COSINE-100 data using DAMA/LIBRA's method
  - Upgrade and move to Yemilab

1-6 keV modulation amplitude

COSINE-100	**0.0067 ± 0.0042**
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	-0.0034 ± 0.0042

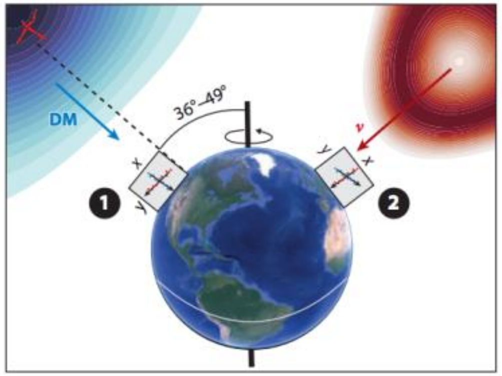
Iván Coarasa, TAUP 2023
Hyunsu Lee, TAUP 2023

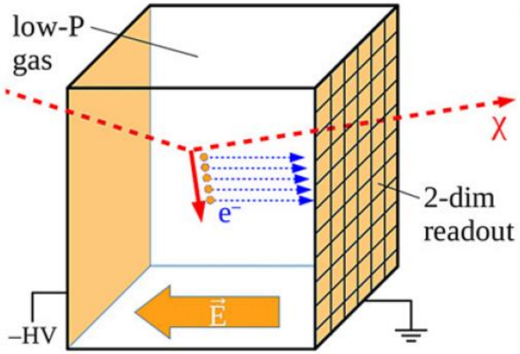
E. Baracchini, IDM 2022
J. Billard et al 2022 Rep. Prog. Phys. 85 056201
Jean-Marie Coquillat, TAUP 2023
Valeri Tioukov, TAUP 2023

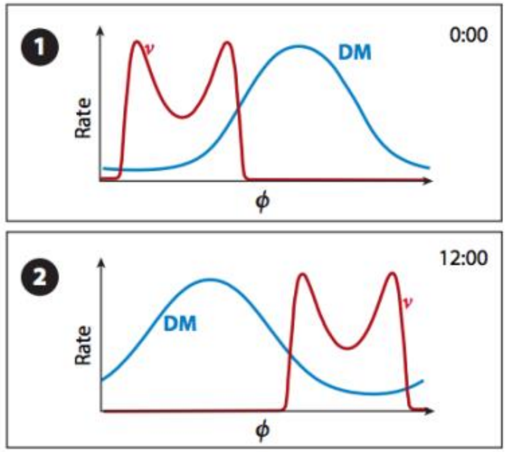
其它探测技术：方向探测实验

- NEWS-G
  - Spherical proportional counters
  - Tested in LSM and operated in SNOLAB
- CYGNUS
  - 1000 m^3 gaseous NITPC detector for WIMP searches through nuclear recoils
  - Helium/Fluorine gas mixtures at 1 bar
  - Multiple underground sites and staged expansion(Boulby, Kamioka, LNGS, Stawell)
- NEWSdm @LNGS
  - Directional dark matter search with nuclear emulsions
  - Nano imaging tracker

Directional detection helps to penetrate neutrino fog



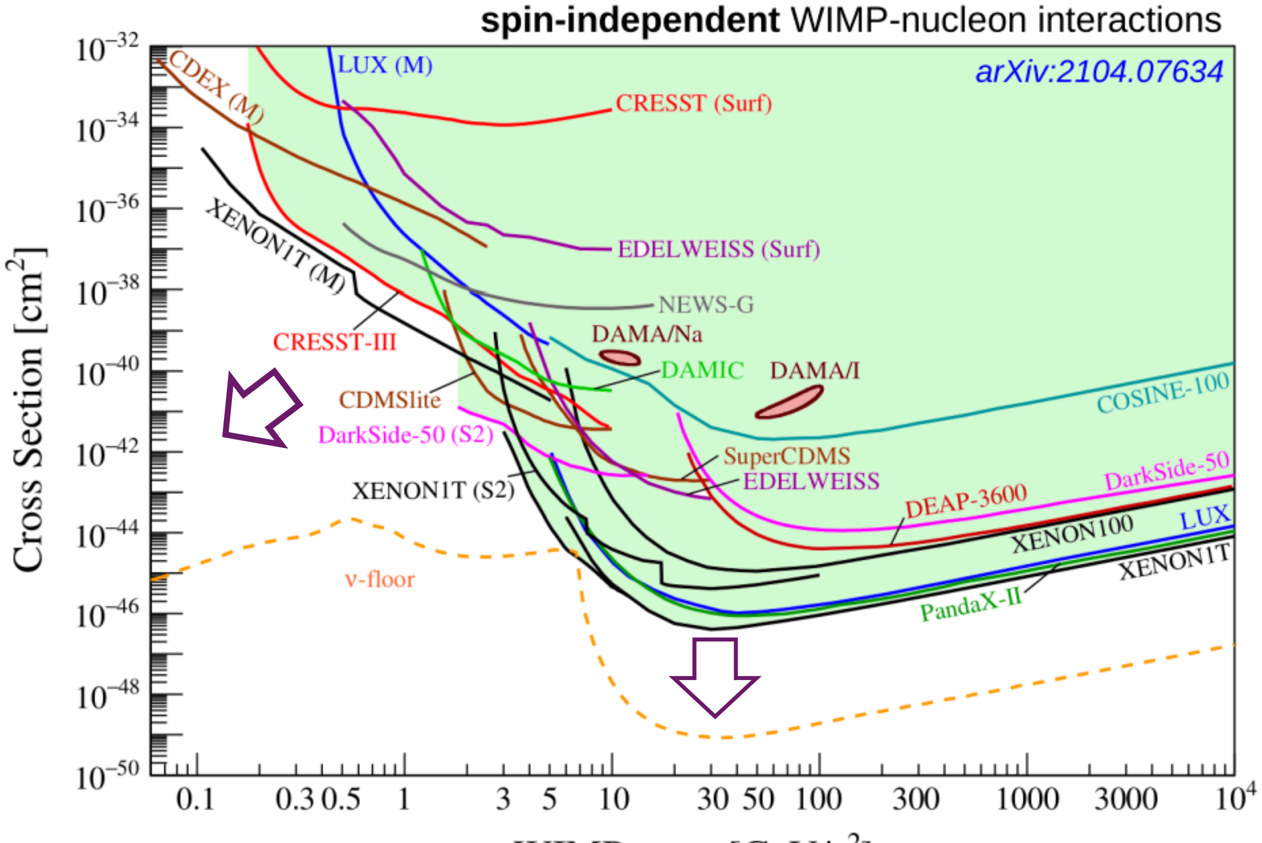




DM and solar neutrinos event rate as a function of some angle ϕ on a two-dimensional readout plane at 12 h time distance or 180 degree of longitude

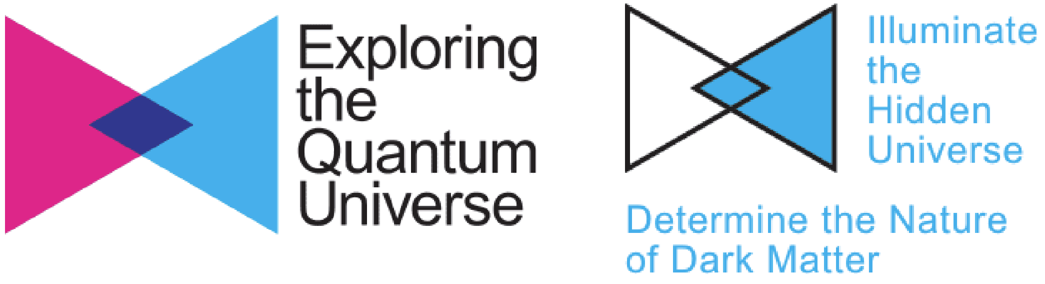
暗物质直接探测实验

- →更低本底、更低阈值、更大曝光量
- →中微子地板



APPEC report

Report of the 2023 Particle Physics Project Prioritization Panel (P5)

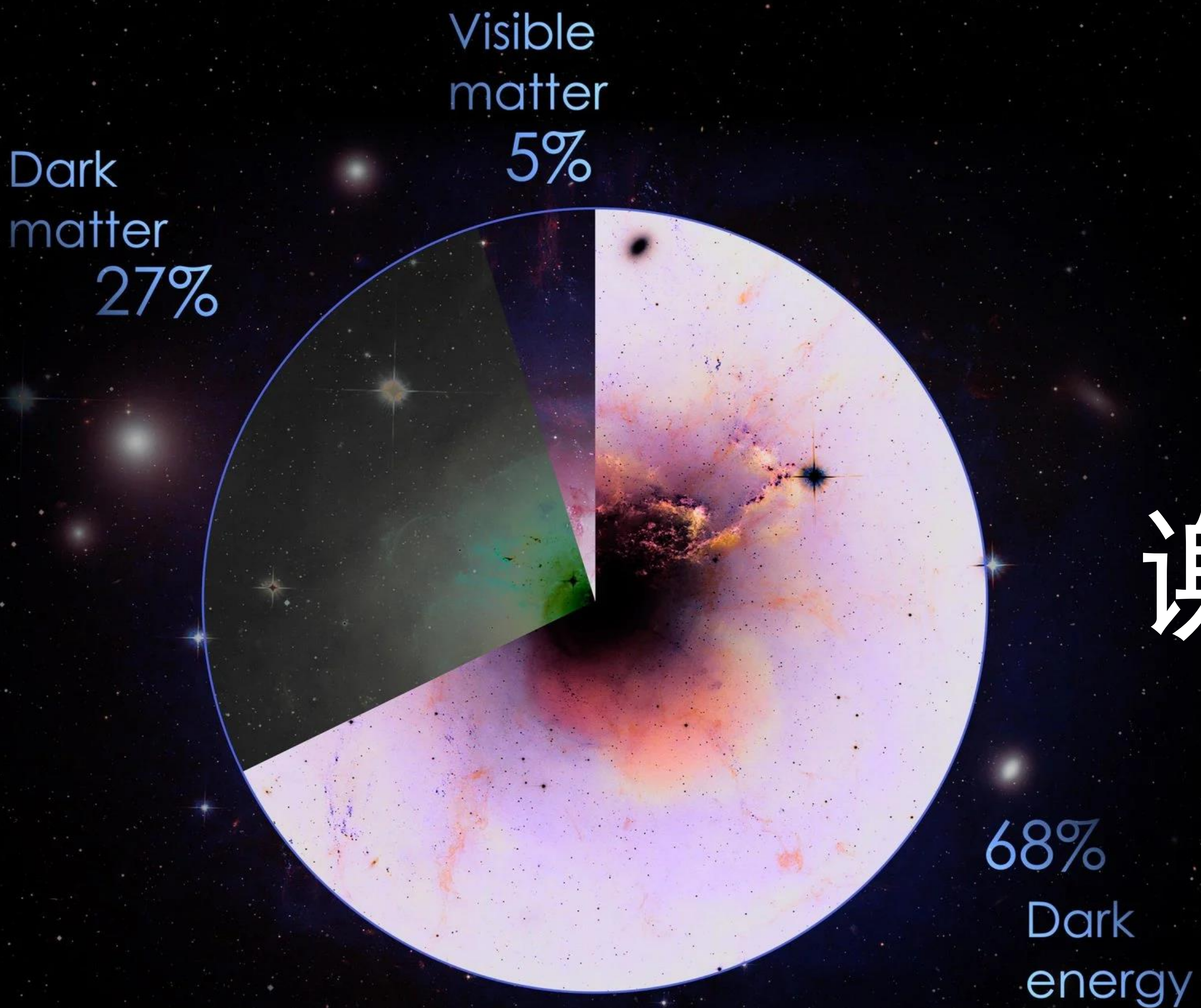


A comprehensive program that includes a **Generation 3 (G3) Dark Matter experiment** will probe the enigmatic nature of dark matter... The recommended program also invests in **multi-messenger observatories with dark matter sensitivity,** including IceCube Gen-2**,** and **small-scale dark matter experiments** using innovative technologies.

https://www.usparticlephysics.org/2023-p5-report/

总结

- 暗物质探测是重大前沿课题，探测到它并研究其性质，将带来重大的物理学变革
- 暗物质直接探测实验竞争激烈，将进入中微子地板
  - 低温固体探测器实验：低阈值，高分辨率
  - CCD实验：全方位降低本底
  - 液态稀有气体探测实验：G3终极实验，进入中微子地板
  - DAMA年度调制效应结果有待检验
  - 基于新探测技术的小型实验发展迅速



谢谢！

Credit: NASA’s Goddard Space Flight Center