暗物质探测

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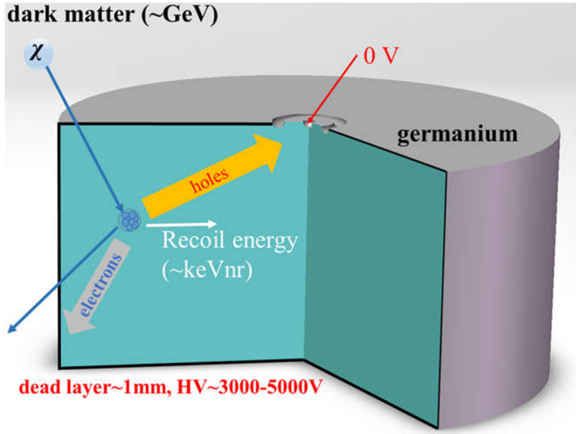
清华大学

2022.8.9

高能物理分会学术年会，大连（线上），2022.8

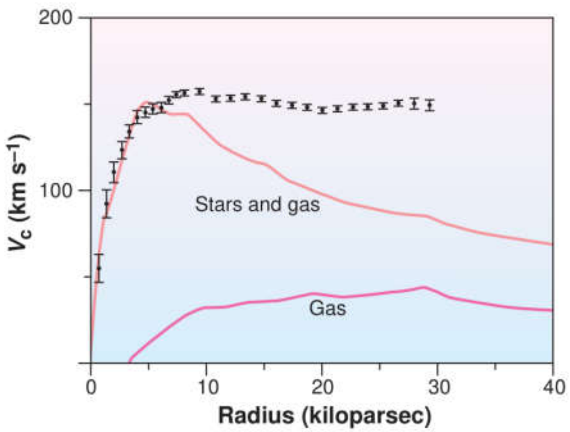
提纲

- 直接探测实验
  - ○ WIMP直接探测
  - ○ （类）轴子探测
- 间接探测实验
- 对撞机探测实验

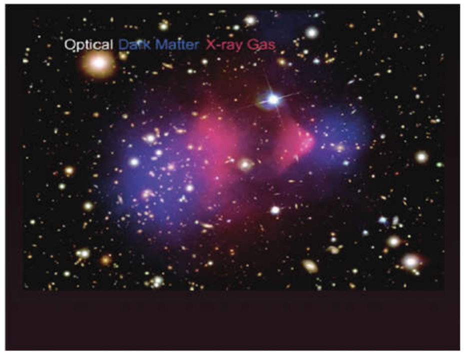


暗物质问题

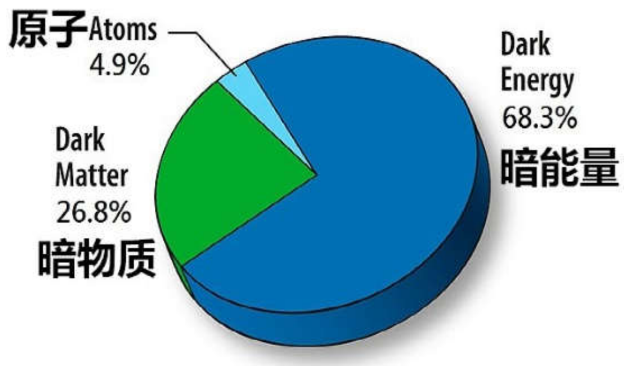
- 暗物质是笼罩20世纪末和21世纪初现代物理学的最大乌云，它将预示着物理学的又一次革命。—— 李政道



星系旋转曲线



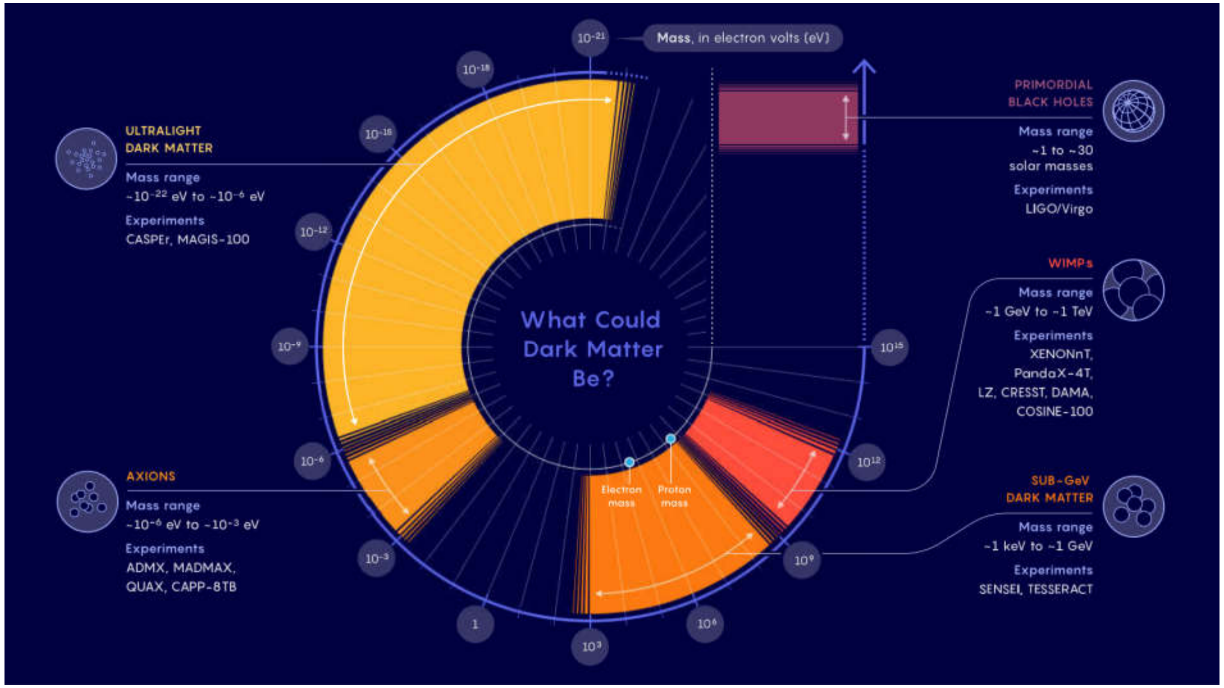
子弹星系



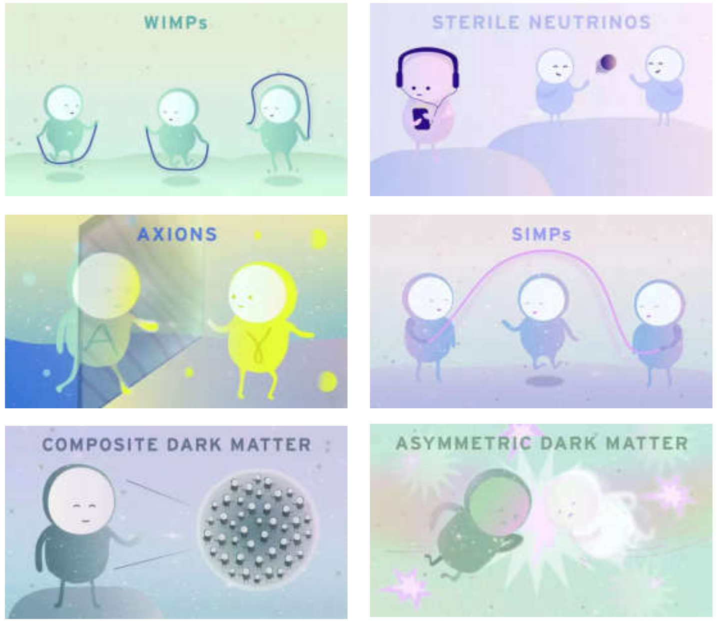
宇宙组分

暗物质候选者

- 众多候选者，覆盖极其宽广的质量区域



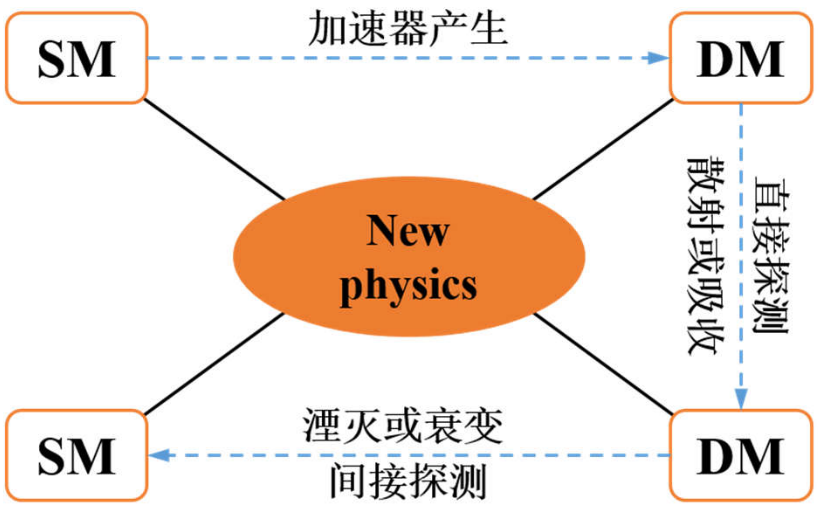
Samuel Velasco/Quanta Magazine

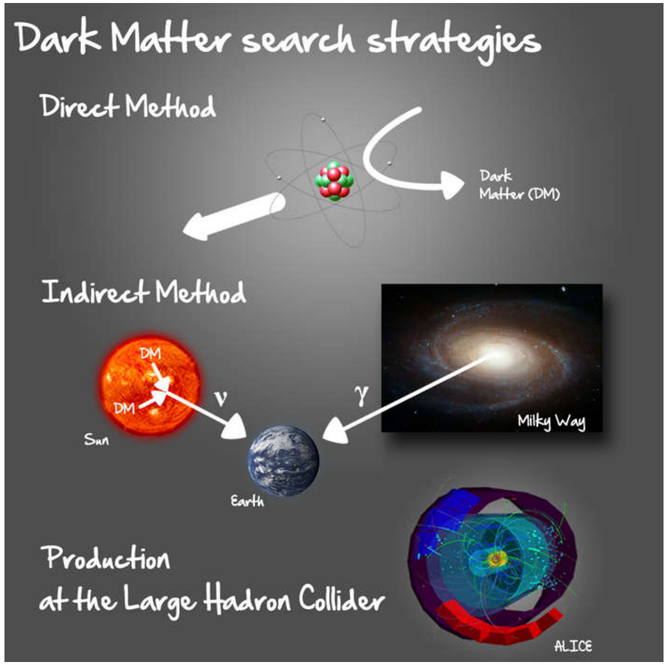


Artwork by Sandbox Studio, Chicago/Symmetry Magazine

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

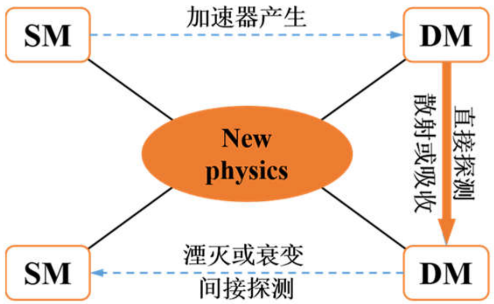


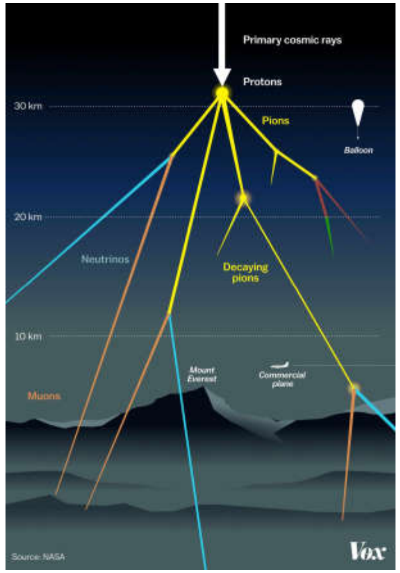


暗物质直接探测实验

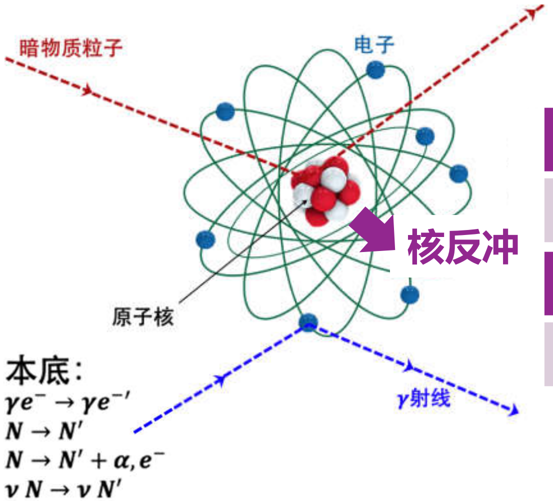
- WIMP粒子与靶原子（核）散射
  - 沉积能量小、作用概率低

- 低本底、大质量、低阈值





宇宙射线

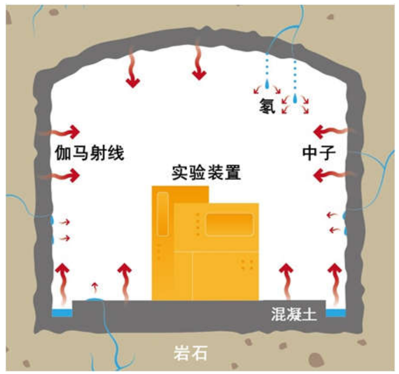


能量很小
keV及以下
概率极低
<1evt/(kg·yr)

辐射本底干扰

能量较大
MeV及以下

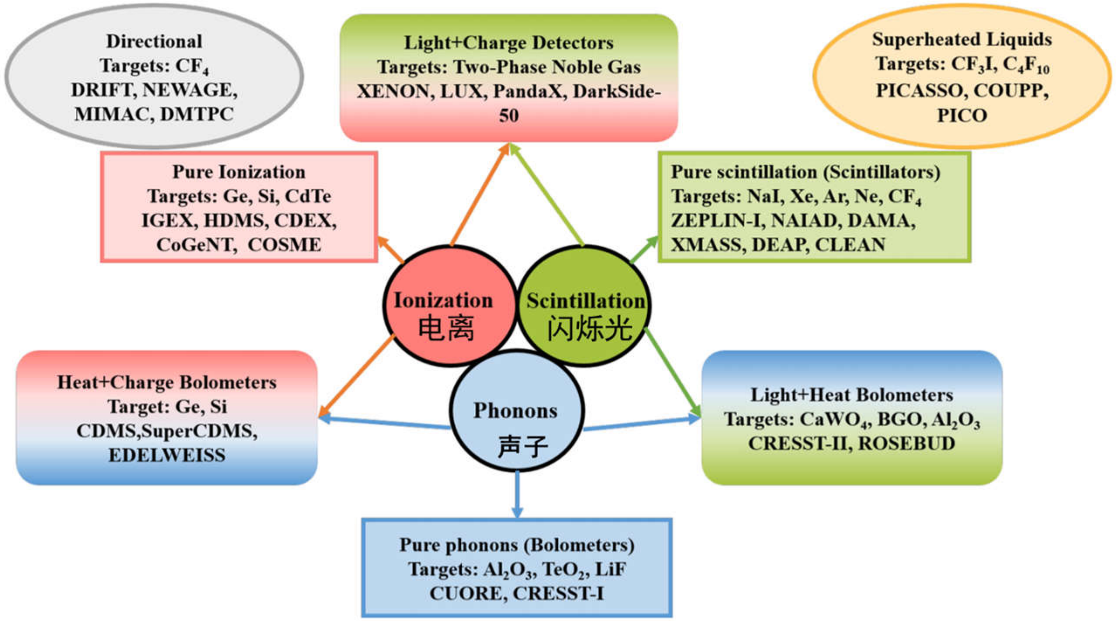
概率很高
宇宙射线本底 > 50 evt/(kg·d)
环境辐射本底 >1000 evt/(kg·d)
实验装置自身本底 > 1evt/(kg·d)

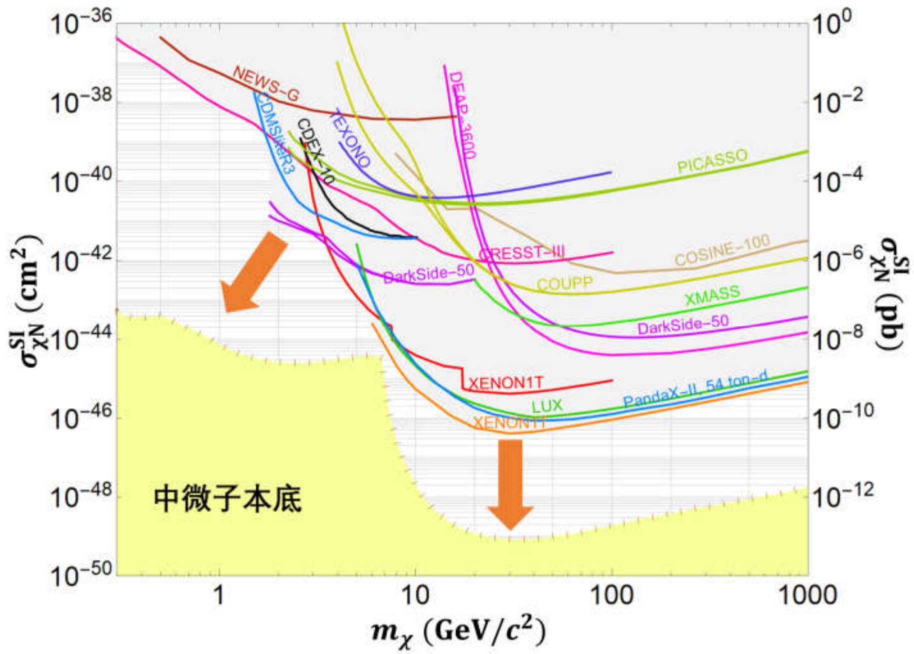


环境辐射

直接探测实验进展

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

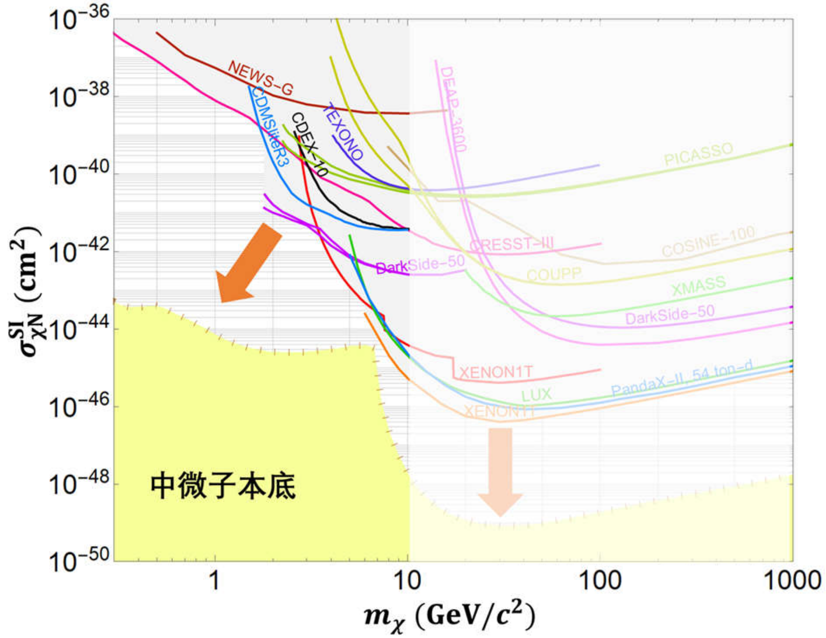


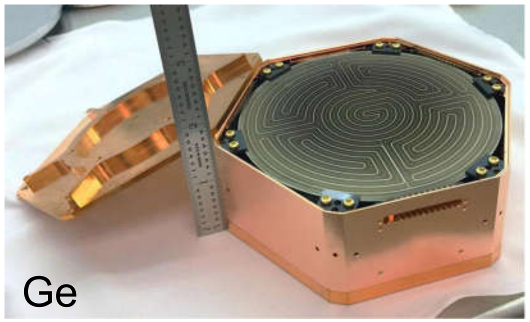


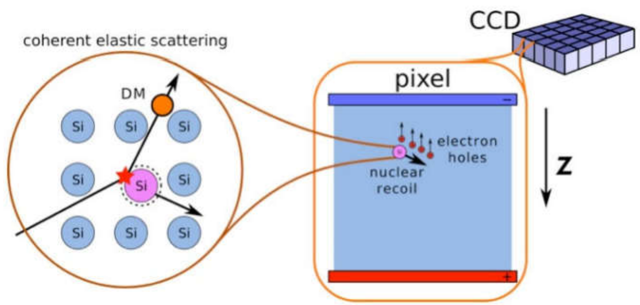
轻质量WIMP直接探测

- 固体低温探测技术
  - SuperCDMS/Edelweiss
  - CRESST
  - CDEX

- 电荷耦合器件（CCD）探测技术
  - DAMIC
  - SENSEI

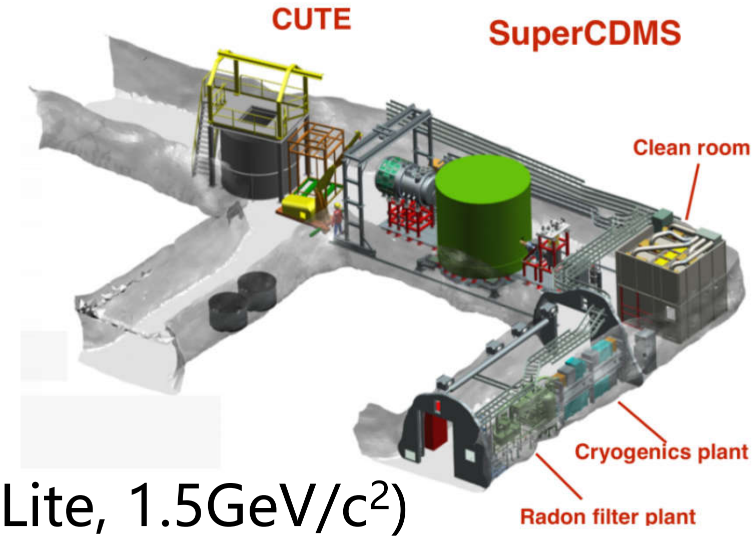






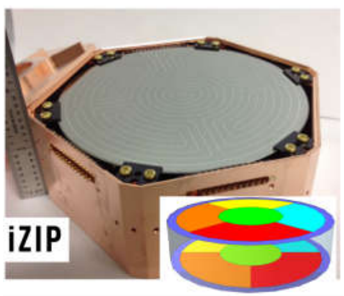
M. Wilson, IDM 2022
M. Albakry et al. arXiv:2203.08463

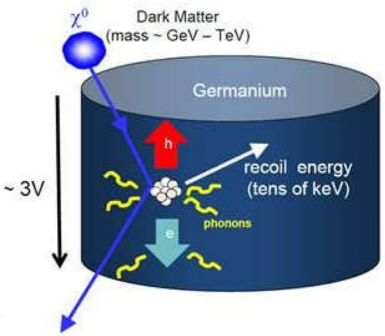
SuperCDMS实验



- 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/c^2)

Interleaved Z-sensitive Ionization
and Phonon (iZIP) detectors





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

iZIP

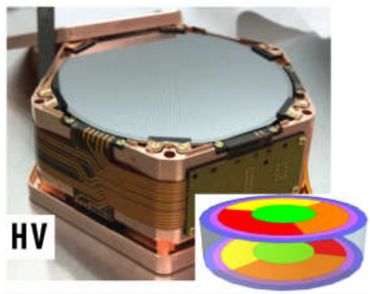
	Si	Ge
σ_{ph}	19 eV	33 eV
σ_{ch}	180 eV	160 eV
$Threshold_{ph}$	175 eV	350 eV

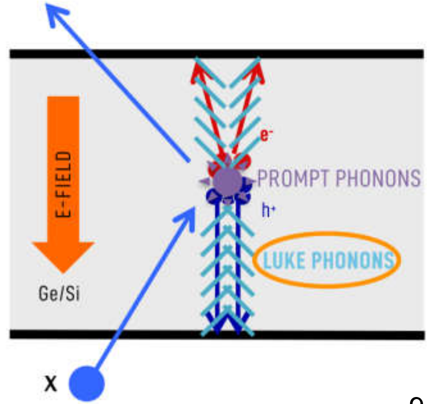
HV

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

arXiv:2203.08463

High Voltage (HV) detectors

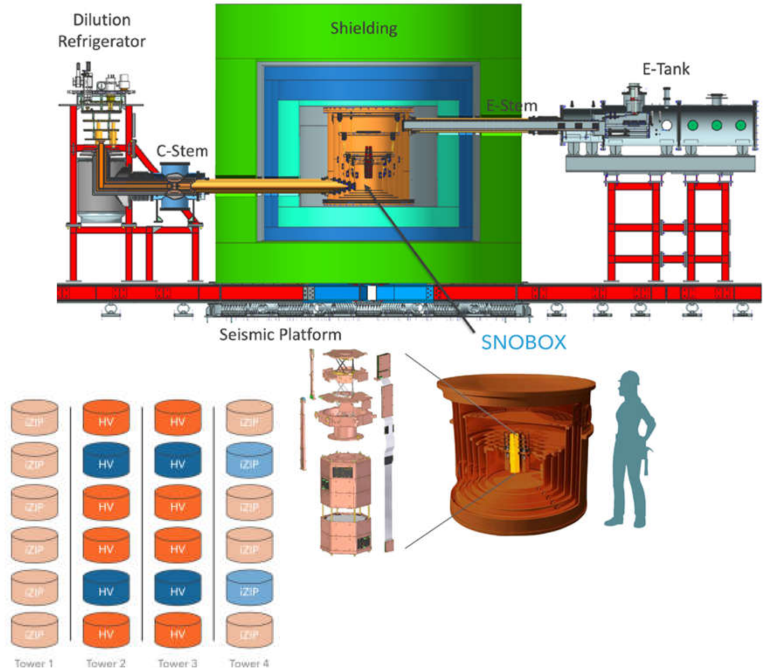




12 phonon channels
High bias voltage (~ 100 V)
Low threshold

SuperCDMS实验

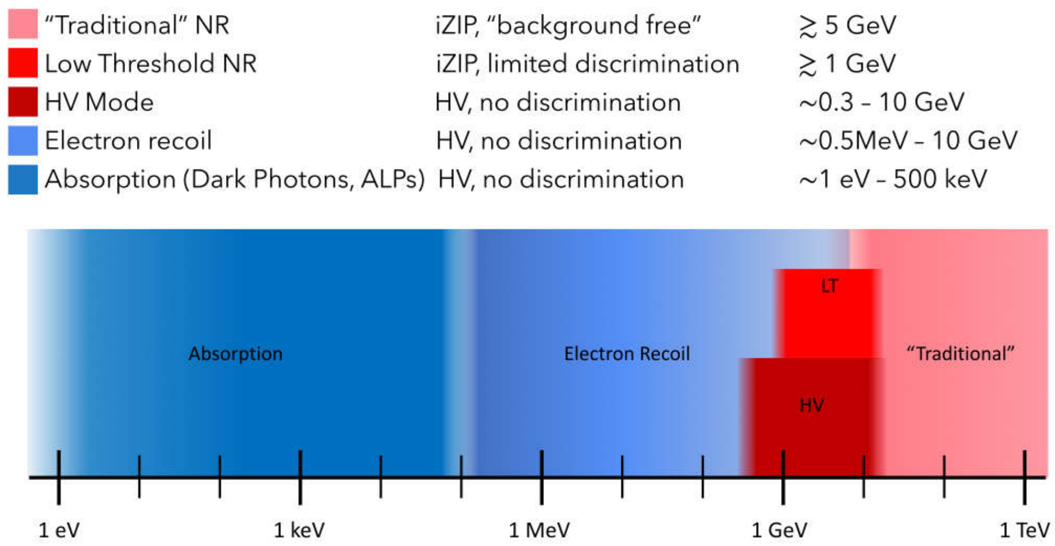
- 探测器@SNOLAB(initial payload)
  - Φ100x33.3 mm，1.39(0.61)kg Ge(Si)
  - Ge: 更大曝光量；Si: 更低阈值
  - ~30kg，6X4 det,12 iZIP(10+2), 12 HV(8+4)

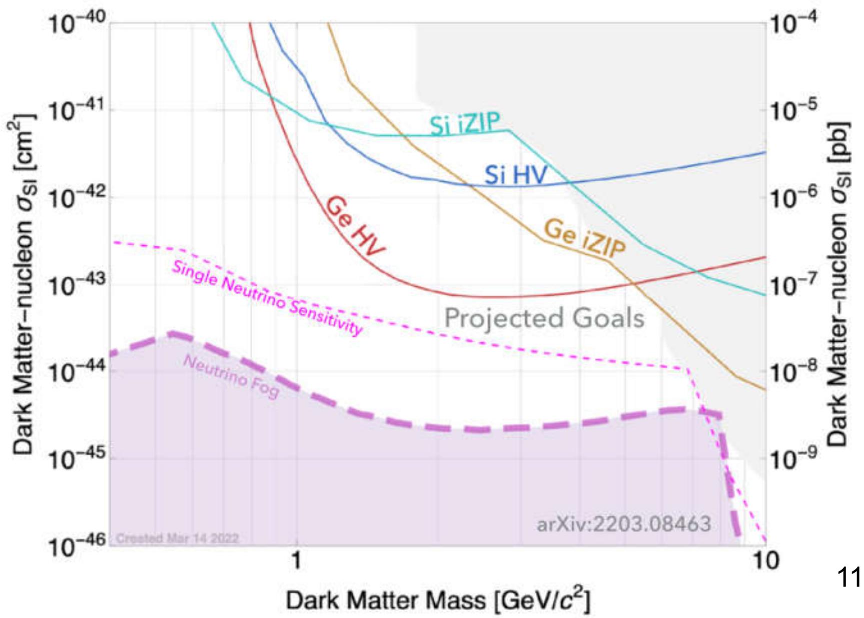


- 实验计划
  - SuperCDMS SNOLAB commissioning - 2023
  - First underground testing and early science - 2024
  - First science run with initial payload - early 2024
  - First results - 2025

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
  - 精细能带结构
  - 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

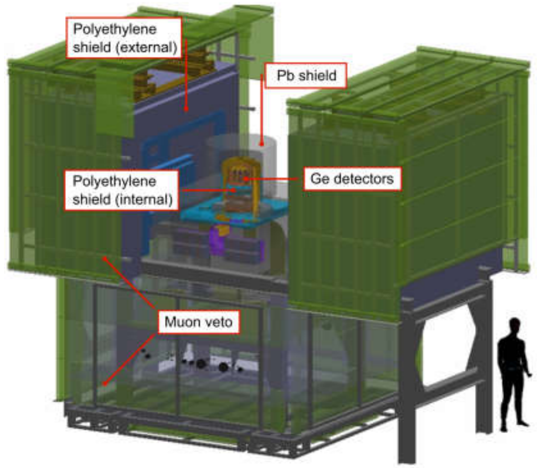


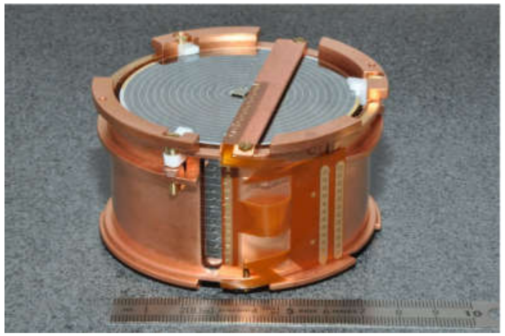


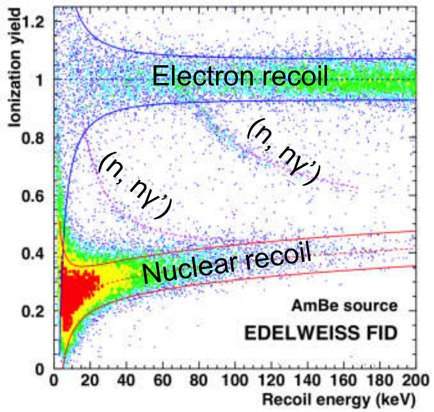
Edelweiss实验

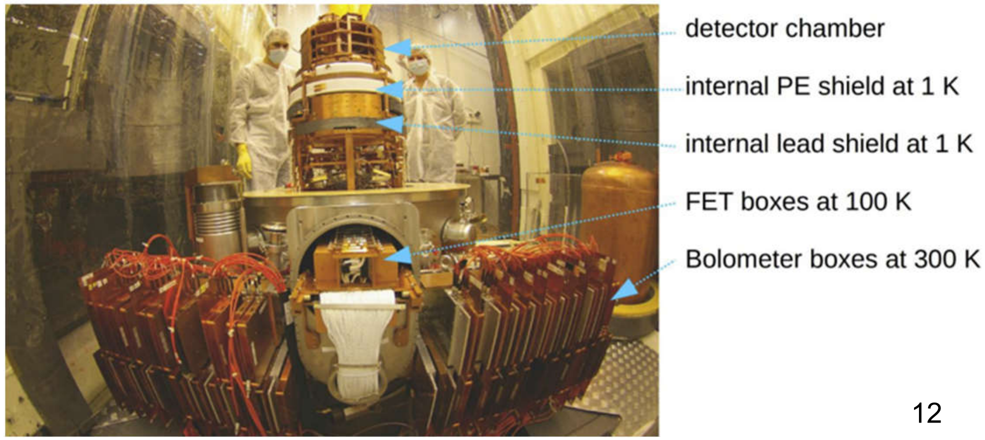
H. Lattaud, IDM 2022
J. Gascon, IDM 2018; TAUP 2019
E. Armengaud et al, JINST 2017

- 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



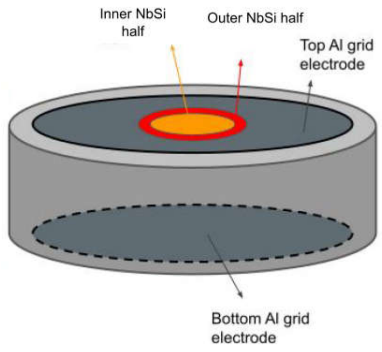






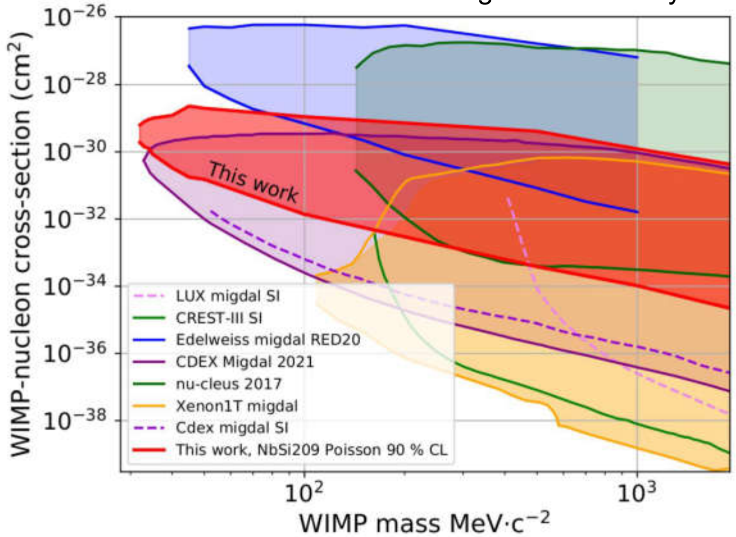
Edelweiss实验

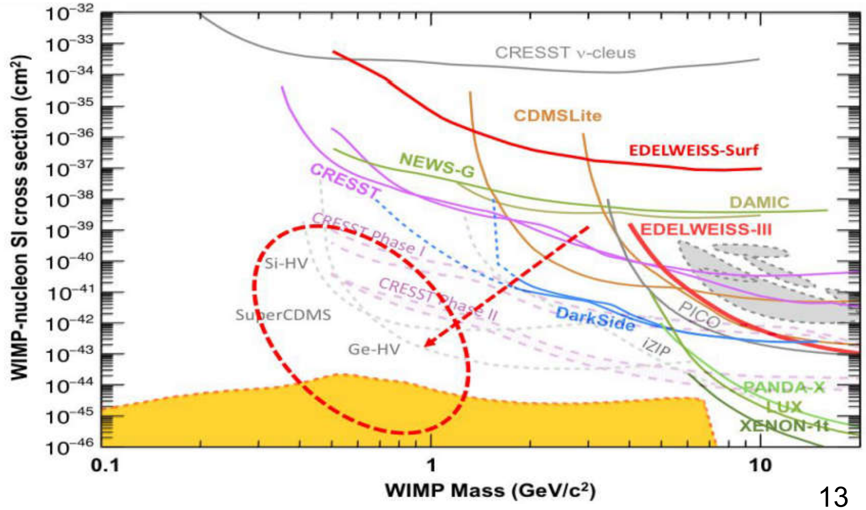
- 技术挑战
  - 探测器：~1kg
  - 电离分辨率：20 eVee
  - 声子分辨率：20→10 eV
    - FET(100K)→HEMT(1K)
  - 高压（声子放大）模式运行
    - 33+200g运行@Modane
    - 200g: NbSi Transistor Edge Sensor (TES)
  - 新型探测器技术CRYOSEL
    - 40g Ge detector, $\sigma_{声子}$ = 20 eV, 200 V bias
    - 降低Heat-only本底
- 物理目标
  - MeV-GeV，电子反冲、核反冲
  - 双相: $\mathcal{O}(10^{-43})\mathrm{cm}^2$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



能量分辨率：4.46 eVee
分析阈值：30 eVee

Migdal effect analysis

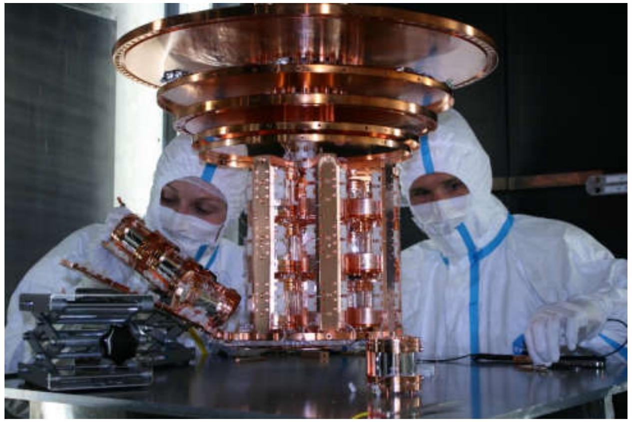


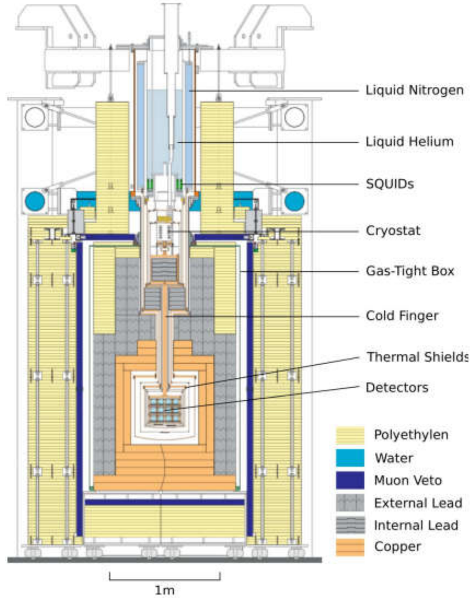


H. Kluck, TAUP 2019
J. Cooley, IDM 2020
C. Strandhagen IDM 2022

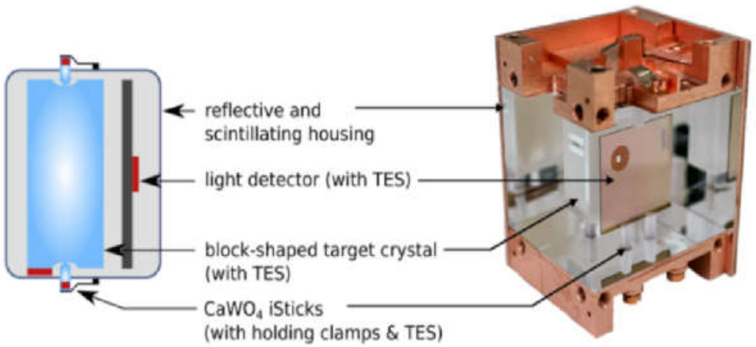
CRESST实验

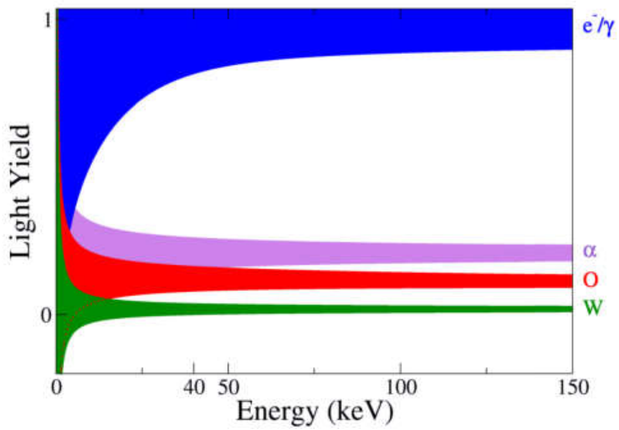
- 实验室：LNGS
- 探测器：$CaWO_4$晶体等
  - 工作温度：15 mK
  - ~24g/det，~240g
  - 双相：闪烁光+量热





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



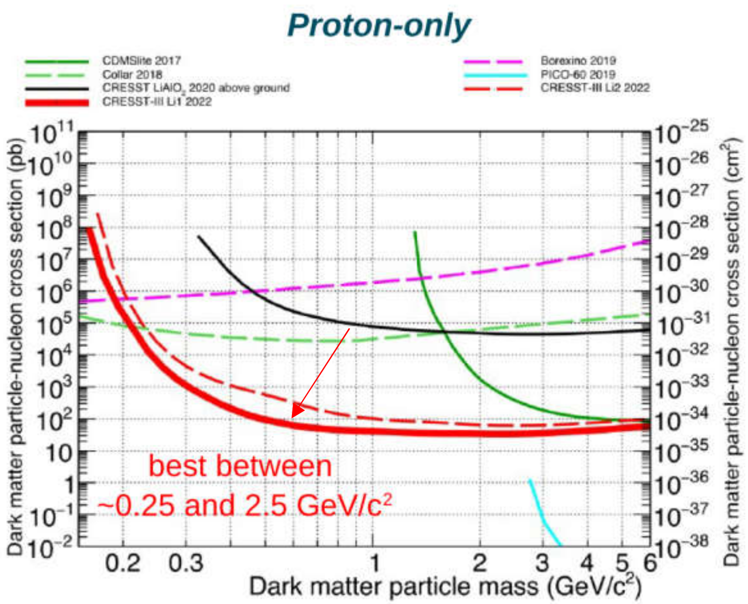


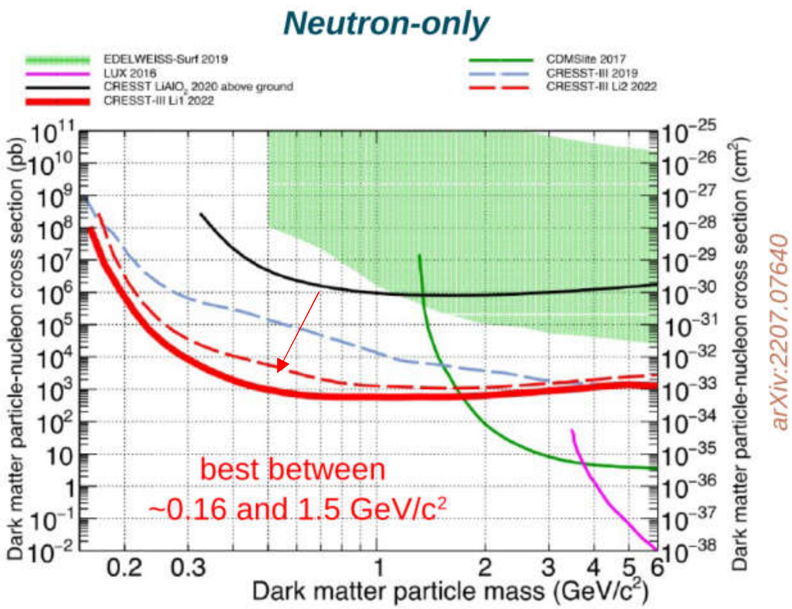
CRESST实验

Name	Material	Holding	Foil	Mass	Threshold
Comm2	$CaWO_4$	bronze clamps	no	24.5 g	29 eV
TUM93A	$CaWO_4$	2 Cu + 1 $CaWO_4$	yes	24.5 g	54 eV
Sapp1	Al_2O_3	Cu sticks	no	15.9 g	157 eV
Sapp2	Al_2O_3	Cu sticks	yes	15.9 g	52 eV
Li1	$LiAlO_2$	Cu sticks	yes	11.2 g	84 eV
Si2	Si	Cu sticks	no	0.35 g	10 eV

- CRESST-III phase2
  - Run3: 2020.11-2021.8
  - SD results from Li1 detector

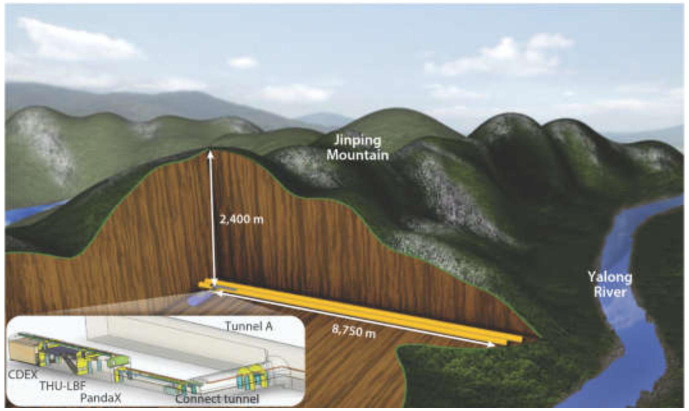
- 计划
  - →~2 kg(100det)
  - DAQ升级，2023
  - 探测器技术研发
    - 更低阈值
    - 更纯晶体…
  - 低能区本底研究
    - 200eV以下能谱抬升待解释

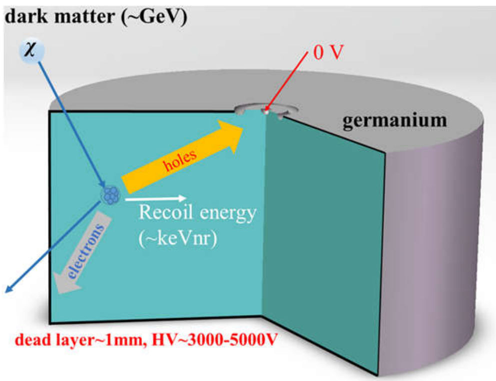


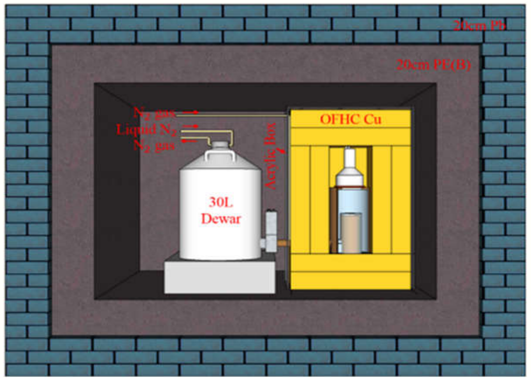


CDEX实验（盘古计划）

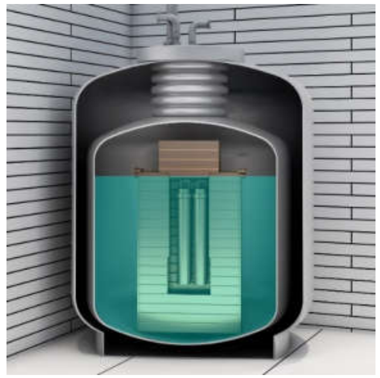
- 实验室：CJPL
- 探测器：高纯锗
  - 工作温度：77 K
  - >10 kg PPC Ge（单相: 电离, ~1kg/det）
  - 冷指制冷+固体屏蔽→液氮浸泡（制冷+屏蔽）







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



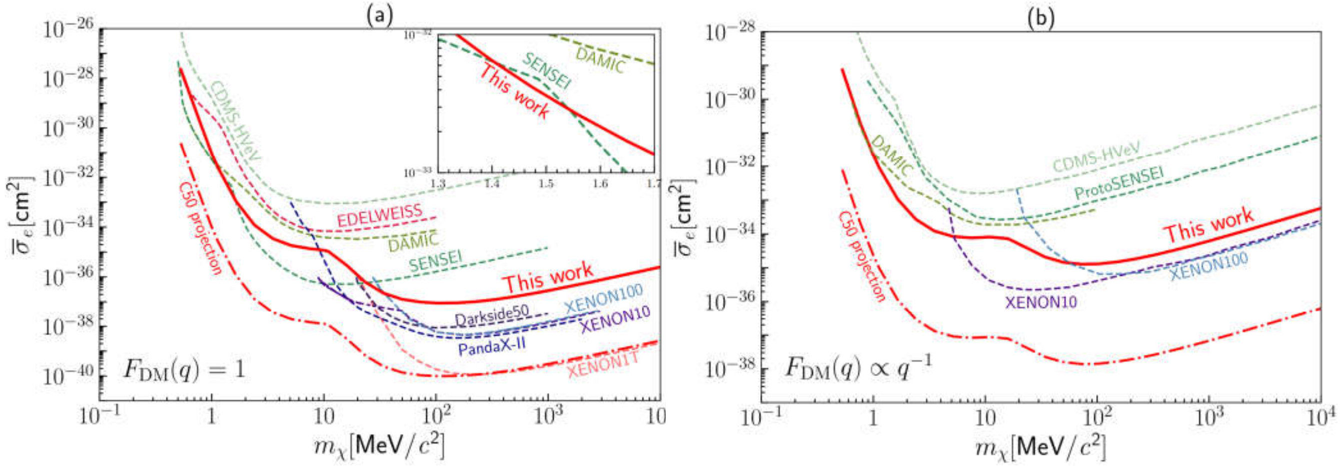
CDEX-10 (2016-)
10 kg 真空封装阵列
液氮直接浸泡

CDEX results

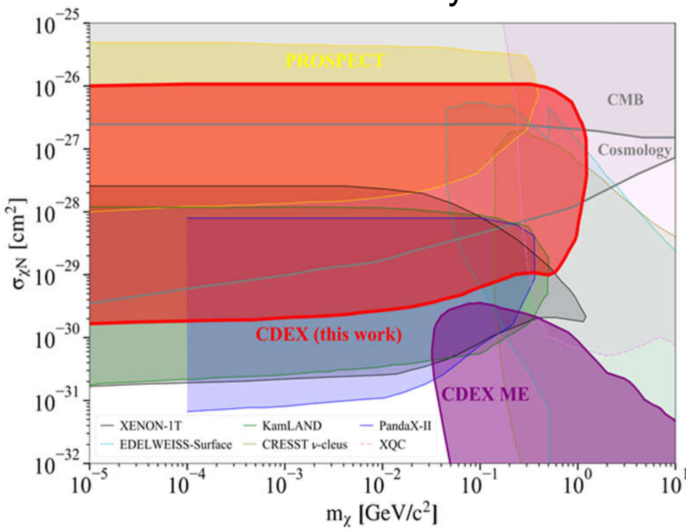
- 更低本底、更低阈值
  - ~2 cts/(keV·kg·day) , 160 eV_{ee}
- 探索多个物理通道
  - WIMP
    - SI/SD（PRL 120, 2018）
    - Migdal效应 (PRL 123, 2019-1)
    - 年度调制效应（PRL 123, 2019-2）
    - 电子反冲 (arXiv: 2206.04128)
    - 宇宙线加速 (arXiv: 2201.01704)
  - 轴子
    - 太阳轴子 / 类轴子暗物质（PRD 101, 2020）
  - 暗光子
    - 太阳暗光子 / 暗光子暗物质 (PRL 124, 2020)

DM-electron recoil

arXiv: 2206.04128



Cosmic ray boosted DM



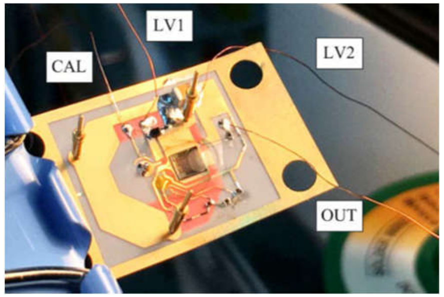
arXiv: 2201.01704

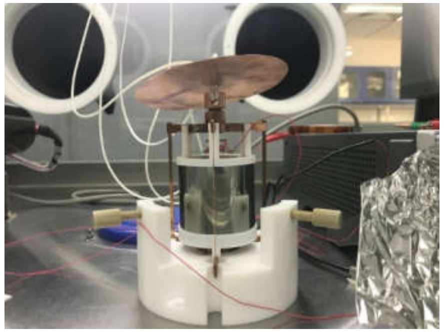
More stringent limit than cosmology in 10keV/c²-1GeV/c²

CDEX实验技术发展

- 探测器
  - 定制探测器改进本底、阈值
  - 自研探测器：真空封装、裸露晶体
  - 高纯锗晶体生长
- 电子学
  - 低本底、低噪声ASIC读出
  - 高精度波形采样
- 低本底
  - 低本底材料筛选测量：GeTHU
  - 地下电解铜
    - ~10 μBq/kg U, ~1 μBq/kg Th

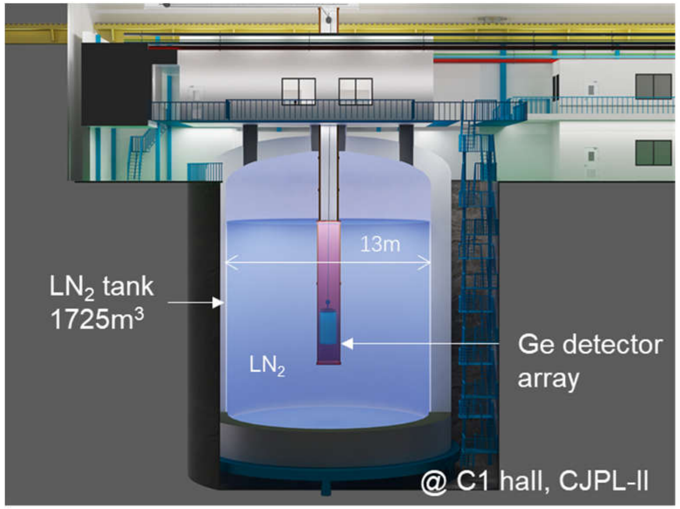


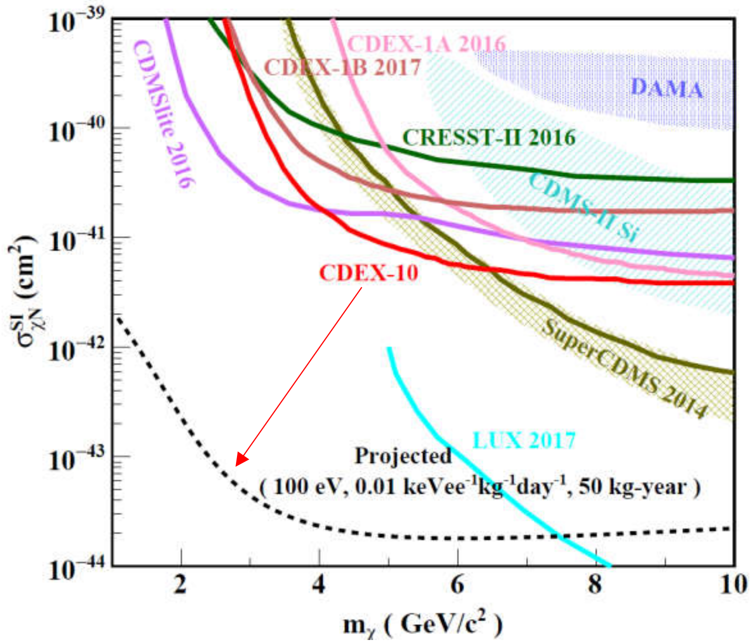




CDEX实验

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

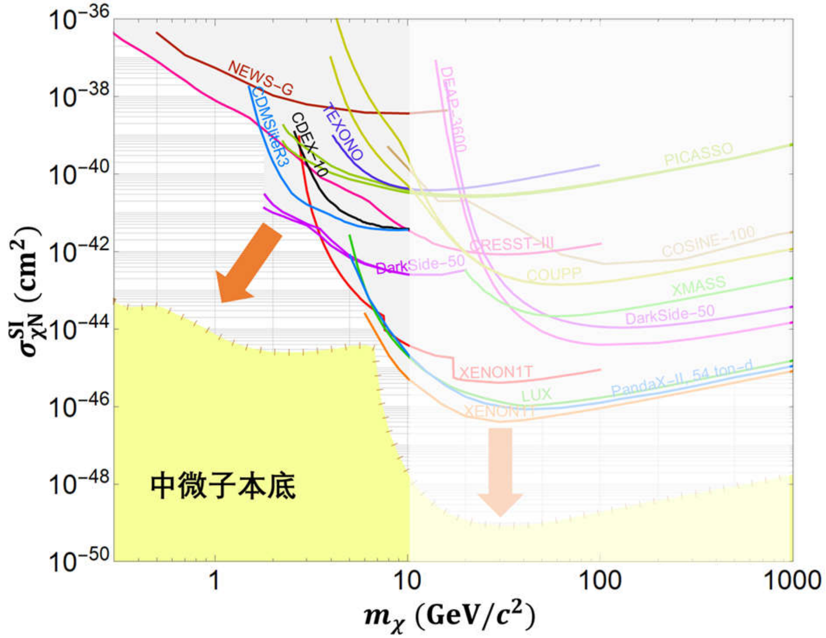


- 暗物质探测灵敏度
  - 本底 < 0.01 cts/(keV·kg·day)
  - 阈值 100-200 eV
  - 曝光量 ~50 kg·year
  - SI Sensitivity ~10^{-44} cm^2

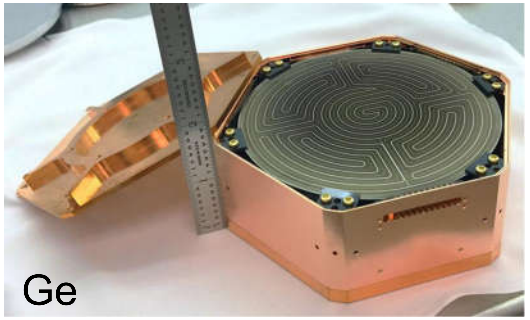


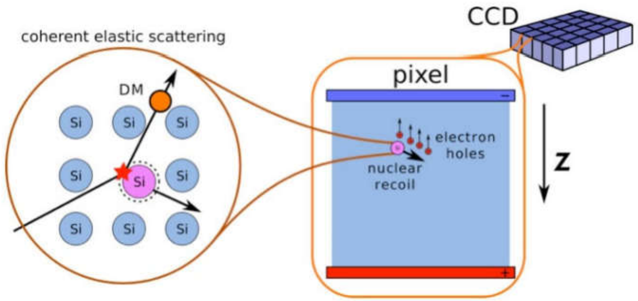
轻质量WIMP直接探测

- 固体低温探测技术
  - SuperCDMS/Edelweiss
  - CRESST
  - CDEX



- 电荷耦合器件（CCD）探测技术
  - DAMIC
  - SENSEI

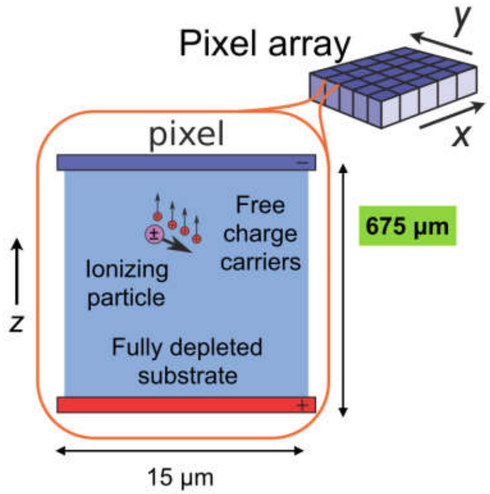


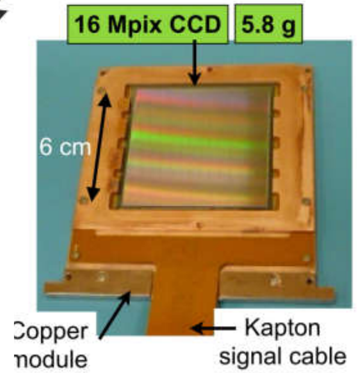


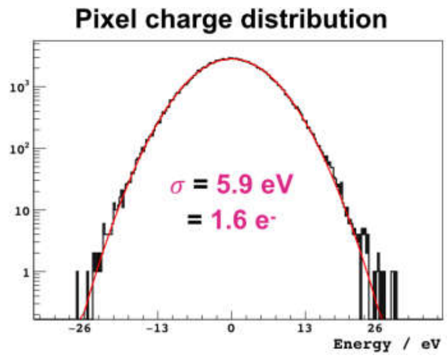
DAMIC实验（Dark Matter In CCDs）

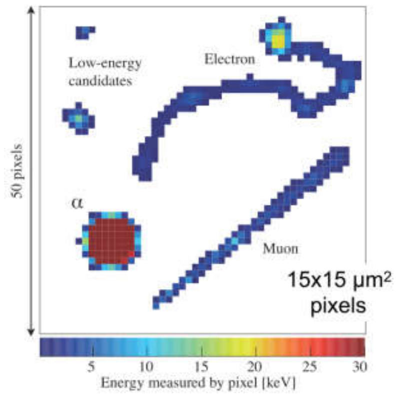
A.E. Chavarria, TAUP 2019
P. Privitera, TAUP 2019
D. Norcini, IDM 2022

- 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
    - 2x10^{-22} A/cm^2



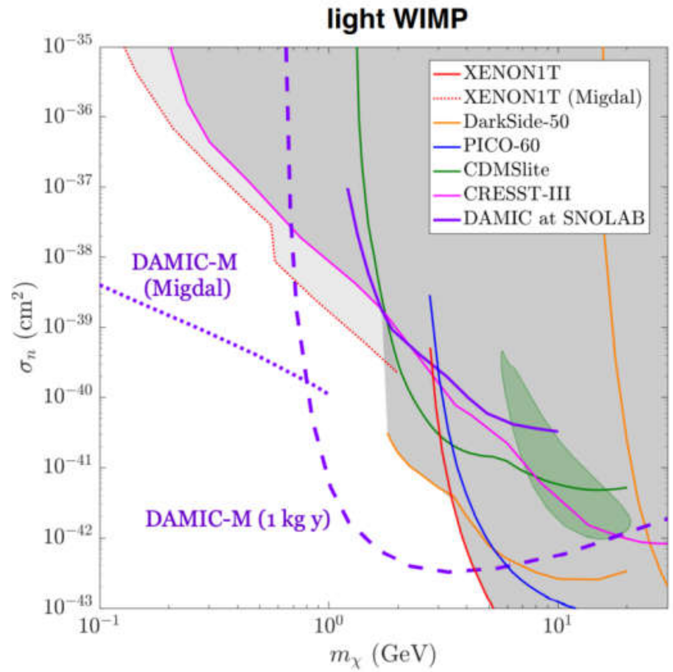


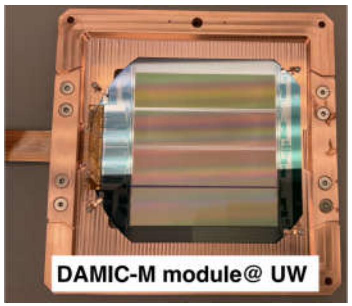


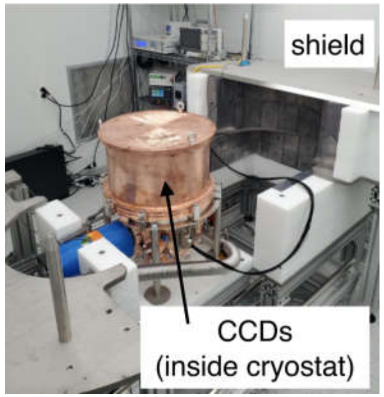


DAMIC实验

- **DAMIC-Modane**
  - 200 CCDs, ~3.5 g/det, 6k x 1.5k pixels
  - Skipper读出，0.2e- (< 1eV) at 650 skips
  - 地下电解铜
  - 原型系统
    - 2个 6k x 4k CCDs, ~17g靶质量
    - 2022.2运行，电子反冲研究

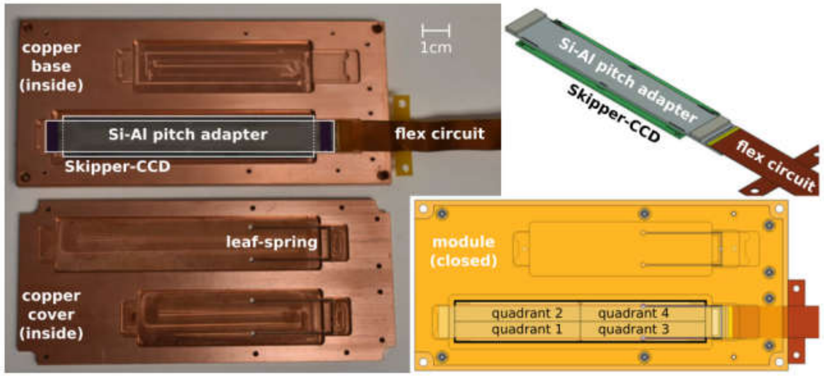




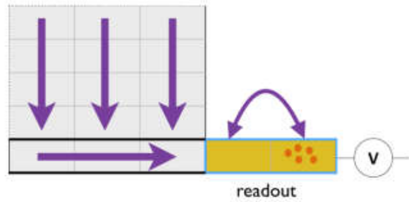


SENSEI实验

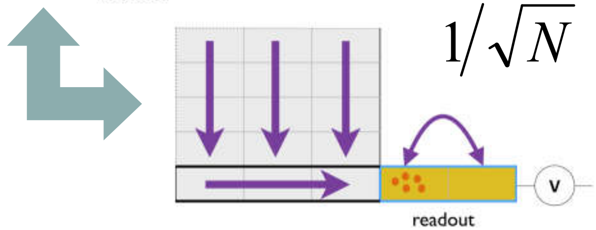
- 实验室：MINOS Hall @Fermilab
- 探测器：skipper CCD
  - 高阻性硅, 675 μm厚
  - 1.59 × 9.42 cm², ~2 g
  - ~5.5 Mpixels of 15x15x675 μm³ each
  - 亚电子噪声

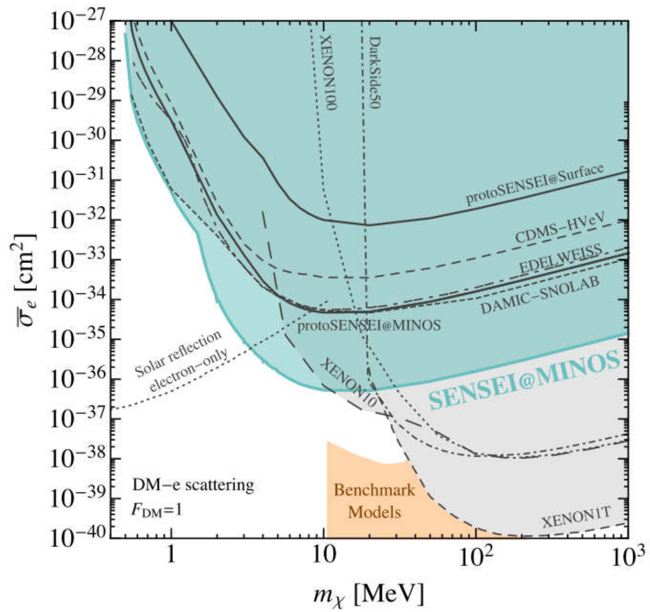


L. Barak et al, PRL 2020
Lauren Hsu, ICHEP 2020
J. Cooley, IDM 2020
M. Cababie, IDM 2022
N. Saffold, IDM 2022



重复读取300次:
2.5e→0.14e



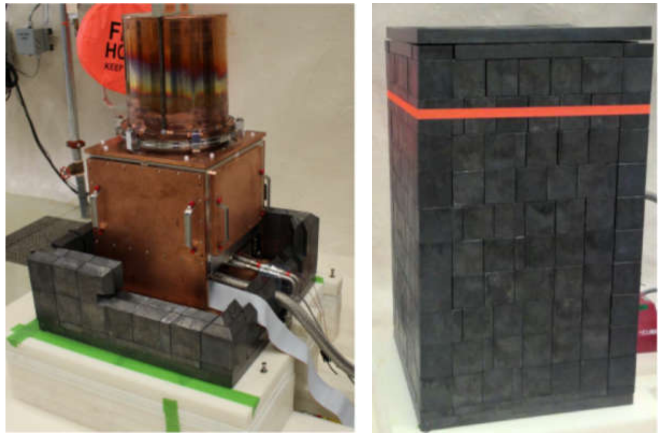


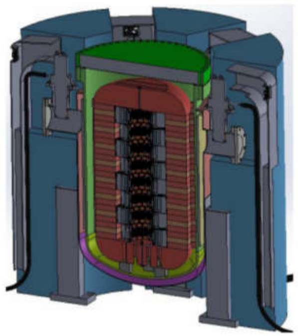
M. Cababie, IDM 2022
N. Saffold, IDM 2022

SENSEI实验

- 现状与计划
  - 12 skipper CCDs (~25g) deployed @SNOLAB
  - 48 skipper CCDs （100g）in total
- OSCURA
  - 美国CCD实验组联合组成
  - 10 kg skipper CCDs
  - 电子反冲，30 kg-y

SENSEI@SNOLAB

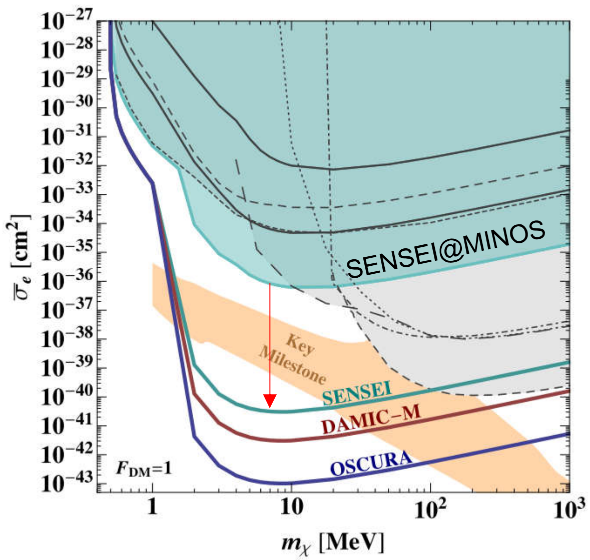




10 kg vessel
Oscura

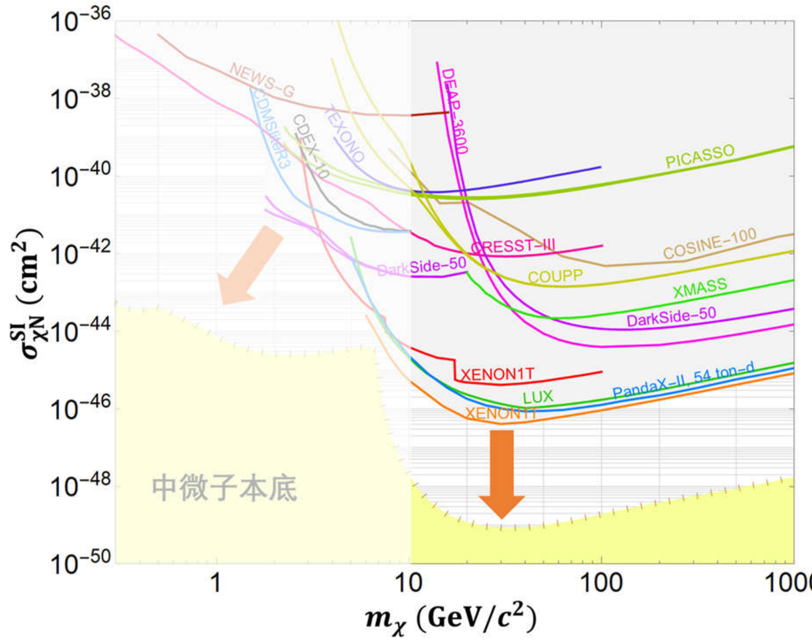
Oscura Timeline

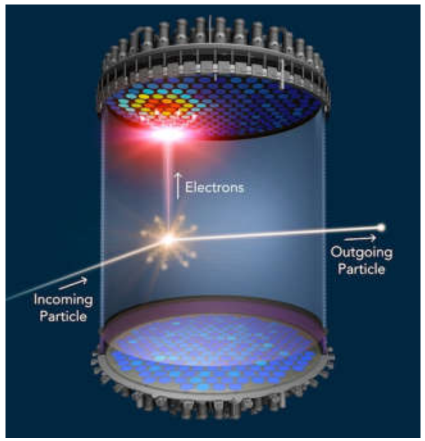
2020-2022	2023	2024	2025-2028	2029...
Research & Development	Design Phase	Final design complete, commission 10% prototype system	Fabrication of full system, installation at SNOLAB	30 kg-yr science exposure



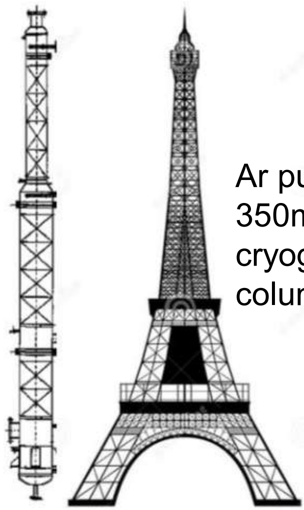
重质量WIMP直接探测

- 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）

PandaX-4T @CJPL

3.7t LXe target

Running 2020-

LZ @SURF

7t LXe target

Running 2021-

XENONnT @LNGS

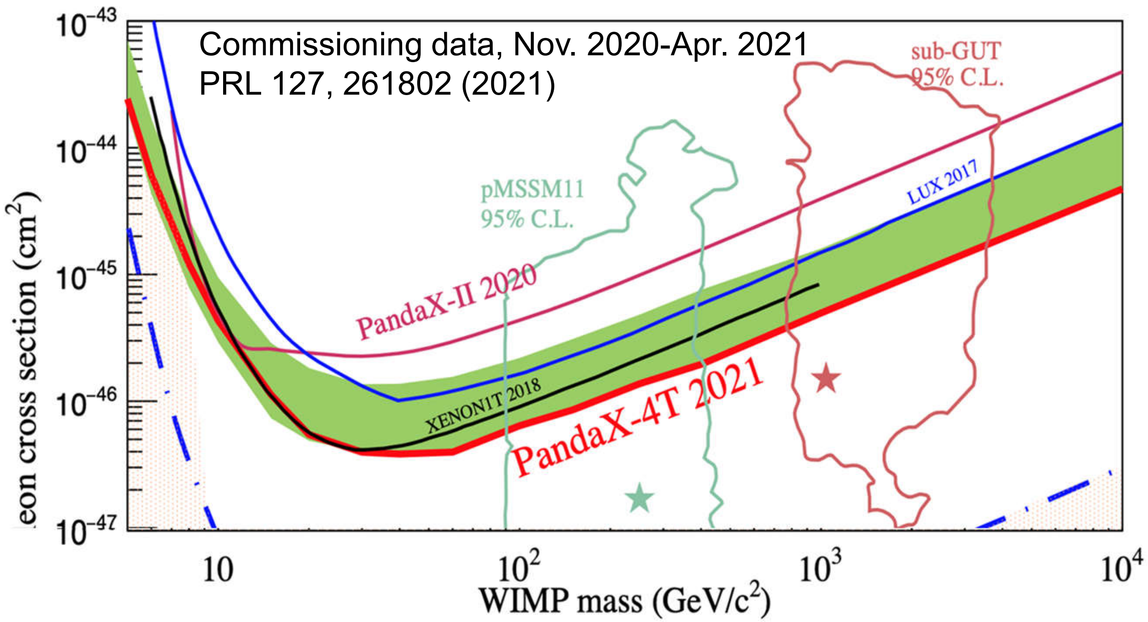
6t LXe target

Running 2021-

WIMP-Nucleon SI Exclusion Limits from PandaX

From N. Zhou

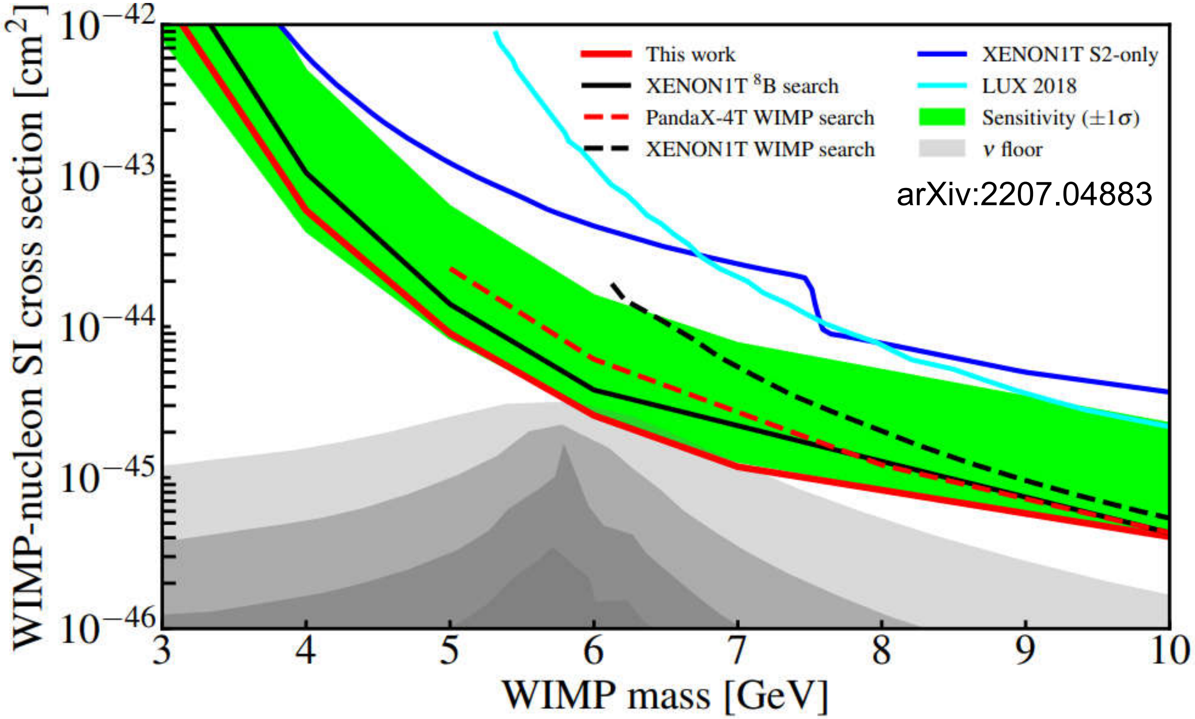
- Stable data running period: 95.0 calendar days (0.63 ton-yr exposure)
- Sensitivity improved from PandaX-II final analysis by 2.6 times at 40 GeV/c^2
- Dived into previously unexplored territory, Approaching the "low E" neutrino floor.
- After tritium removal, expecting another order improvement with a 6 ton-yr exposure.



Low mass DM limits from PandaX

From N. Zhou

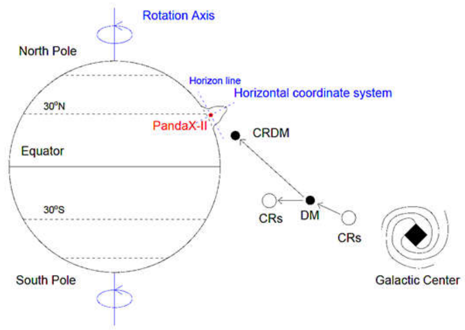
- Lower S1 selection threshold to 2 hits
- Strongest constraints on WIMP in 3-10 GeV region

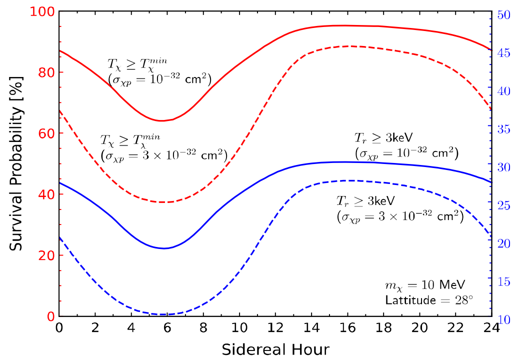


Cosmic-ray Boosted Dark Matter

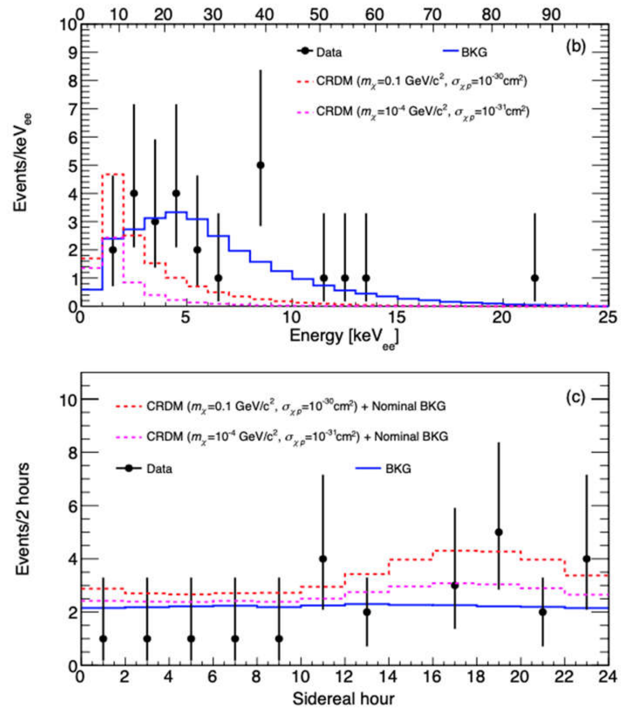
From N. Zhou

- Attenuation due to the earth shielding, diurnal modulation
- Using events below NR median: 25 events (expected 26.6 background)
- Expand to the region beyond the astrophysical and cosmological probes



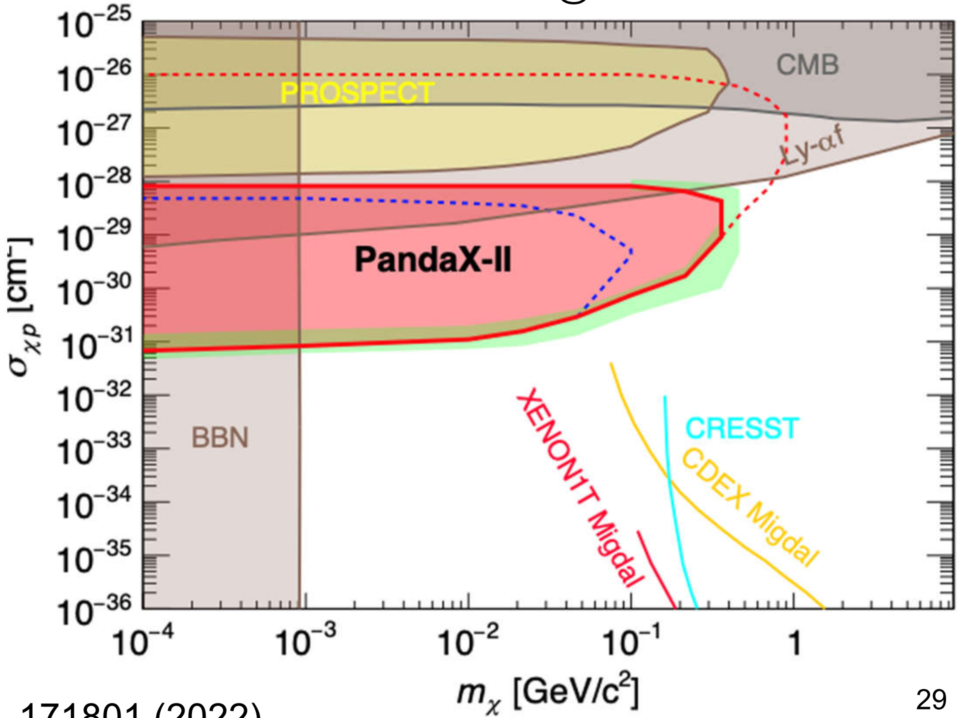


PRL 126 (2021) 9, 091804



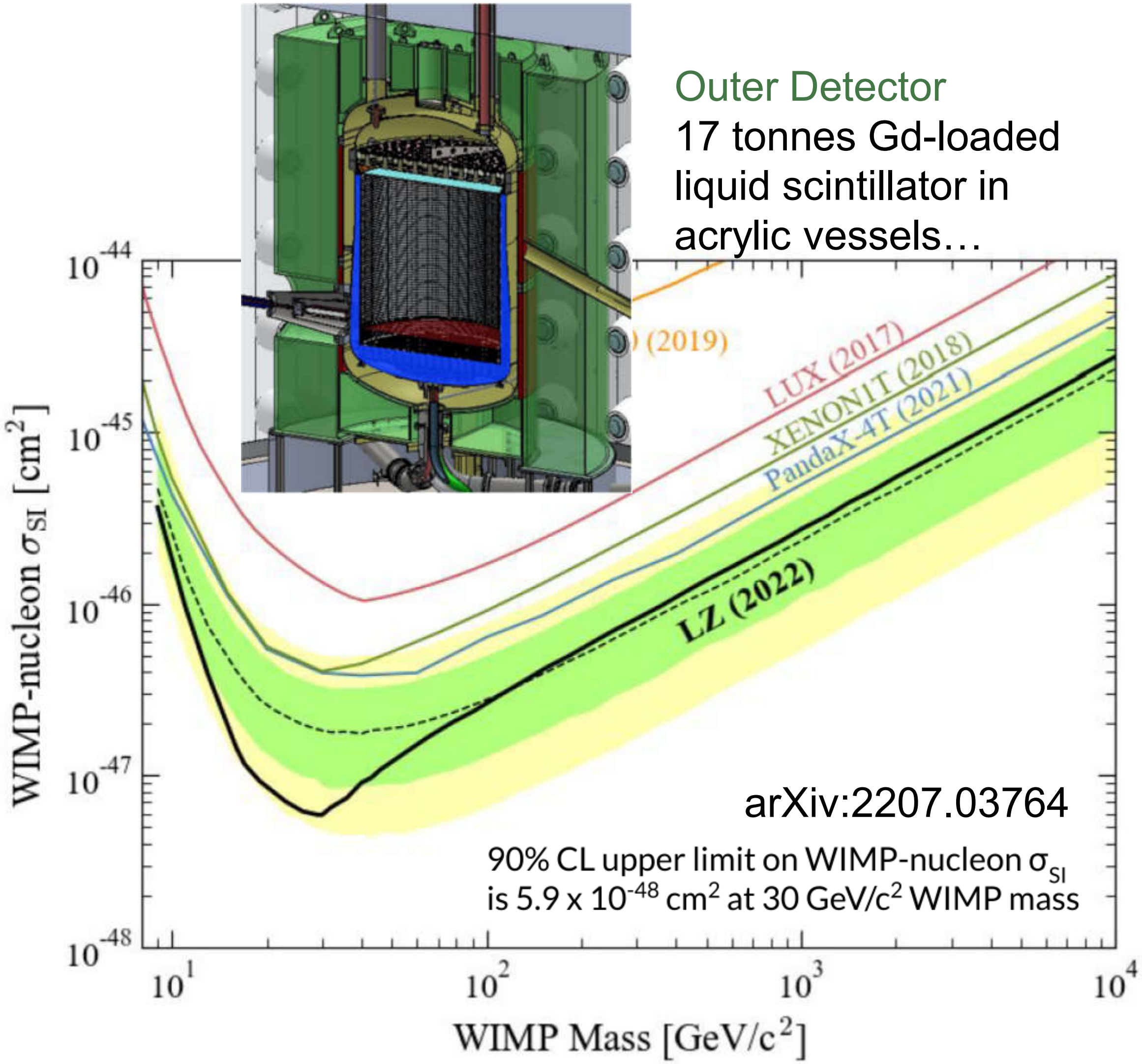
PRL 128, 171801 (2022)

10^{-31} and 10^{-28} cm^2 @ 0.1 MeV-0.1GeV



LZ results

- Data taken 23 Dec 21 to 12 May 22, with breaks for calibrations
- 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



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

arXiv:2207.03764

90% CL upper limit on WIMP-nucleon σ_{SI} is 5.9×10^{-48} cm^2 at 30 GeV/c^2 WIMP mass

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

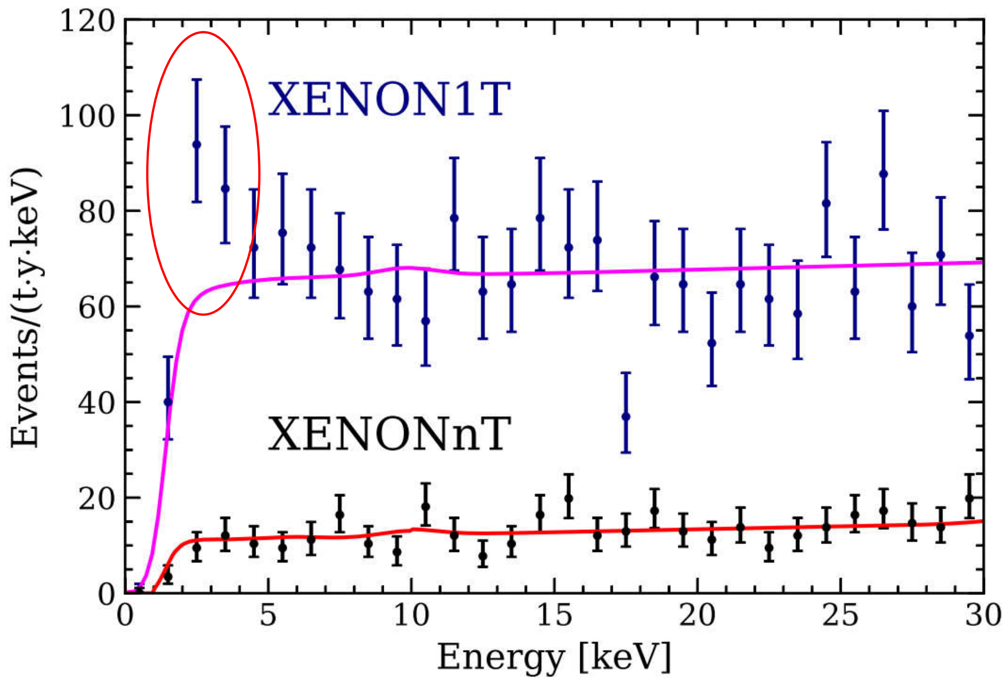
A. Fan, IDM 2022

XENONnT results

Knut Dundas Morå, IDM 2022
F. Gao, private communication

- 1.16 ton-yr exposure (~2 times XENON1T ER search) July 6th-Nov 11th 2021
- Bkg rate: (16.1 ± 0.3) events/(ton-yr-keV) (~20% XENON1T)

XENON1T observed a peak in its ER spectrum below ~7 keV



Most likely explanation of XENON1T excess is a small ^{3}H contamination. XENONnT, taking steps to reduce tritium outgassing sees no excess.

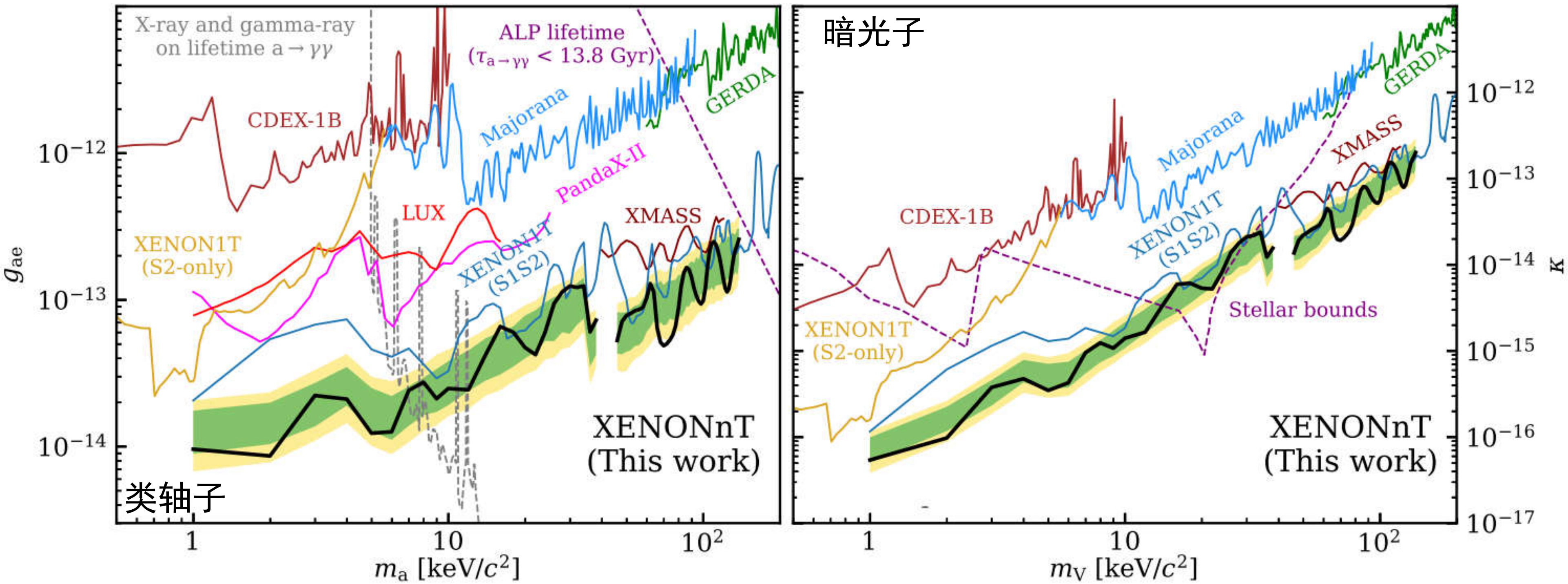
^{3}H control

Two months of outgassing, and purification of gaseous xenon with Zr getters and 3 weeks of gaseous xenon cleaning reduces possible hydrogen contamination.

XENONnT results

Knut Dundas Morå, IDM 2022
F. Gao, private communication

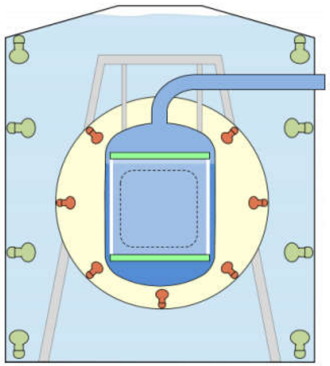
- 类轴子、暗光子暗物质的新限制@1-140 keV
- 正在进行WIMP分析…

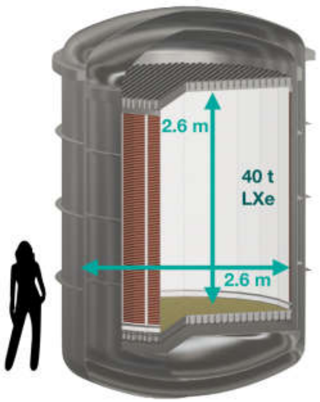


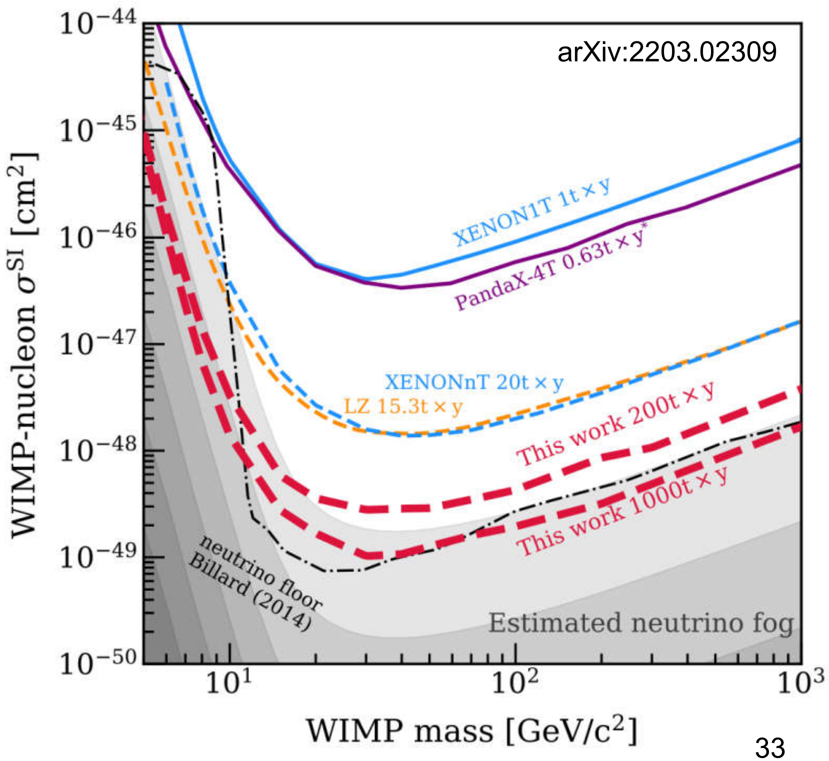
下一代液氙实验(G3)

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







下一代液氙实验(G3)

XLZD Consortium (Xenon LUX Zeplin DARWIN)

- World leading researchers with more than twenty years of successfully building liquid xenon Dark Matter detectors unite forces in the XLZD Consortium
- **MOU signed July 6, 2021** by 106 research group leaders from 16 countries
- **Community whitepaper** with combined science goals, background considerations, priorities - posted March 2022, **arXiv:2203.02309**

A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

Merger of leading collaborations for a

future DARWIN/G3 xenon-based experiment

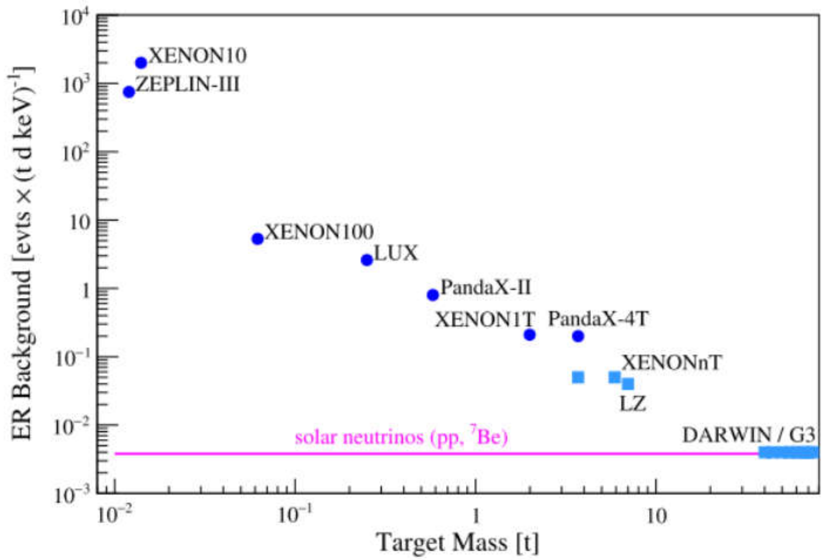
XENON

DARWIN

LZ

Data taking 2027/28

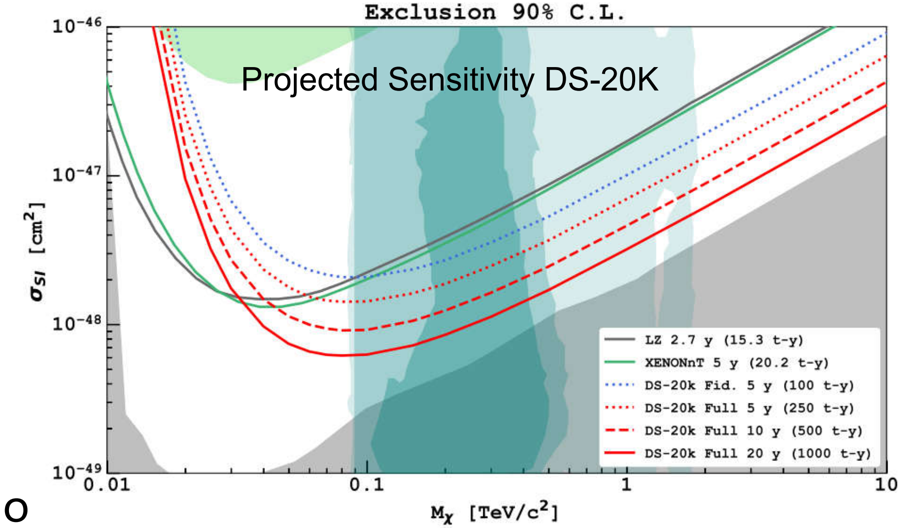
https://xlzd.org/

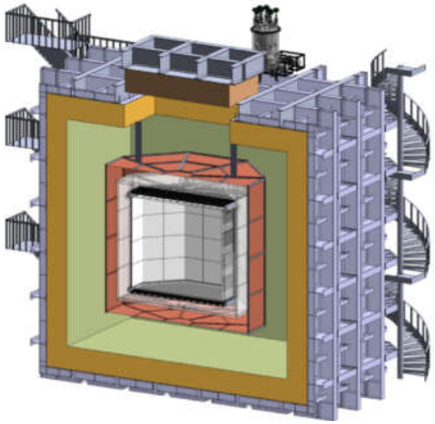


液氩TPC

- DarkSide-20k (20t fiducial mass)
  - DS50+DEAP-3600+ArDM+MiniCLEAN
  - 50t UAr dual-phase-TPC in 700t AAr cryostat
  - 2022- @LNGS
- 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 (at the rate of 10 kg/day in Seruci-I)
- GADMC: Global Argon Dark Matter Collaboration
  - Multi-national collaboration >500 scientists from >80 institutions
  - Next generation: ARGO, ~300t TPC, @SNOLAB

T. Thorpe, IDM 2022
M. Galloway, IDM 2022

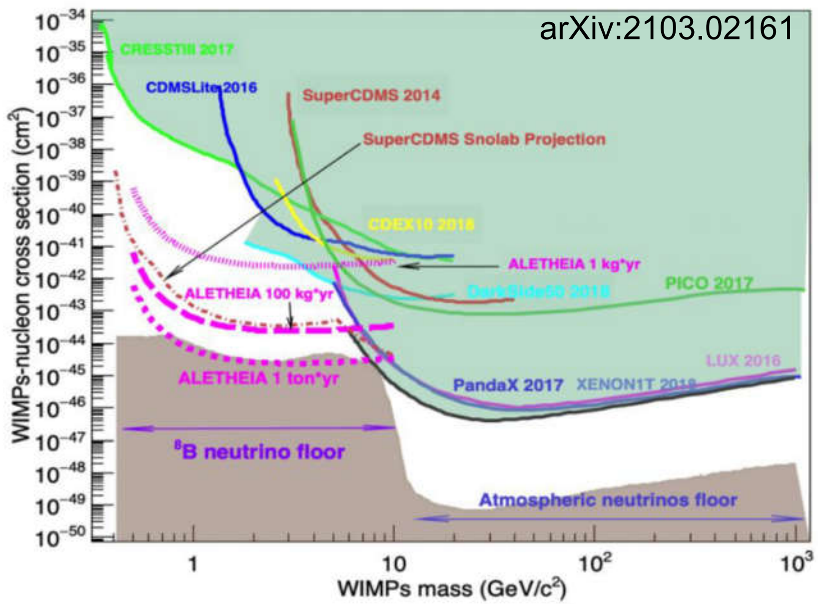




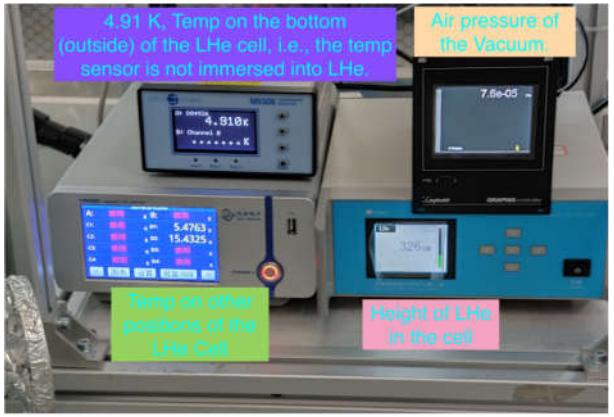
DS-20k

液氦探测技术- ALETHIA实验

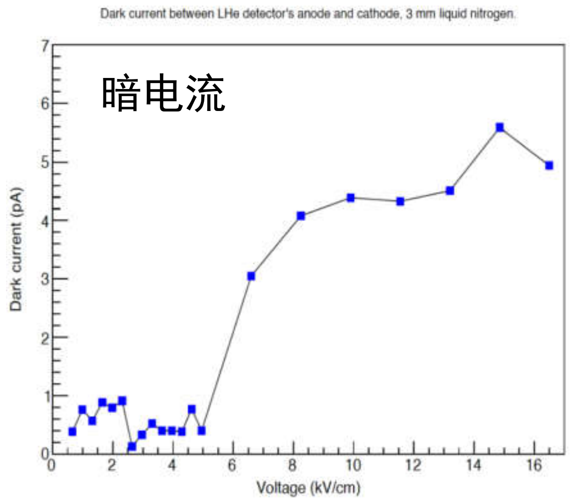
- 液氦TPC技术研发
- 30g-V1探测器成功达到液氦温度（~4.5 K）
- 探测器暗电流 < 10 pA@17kV/cm



30g液氦探测器



液氦温度时的温度计、真空计、液位计读数

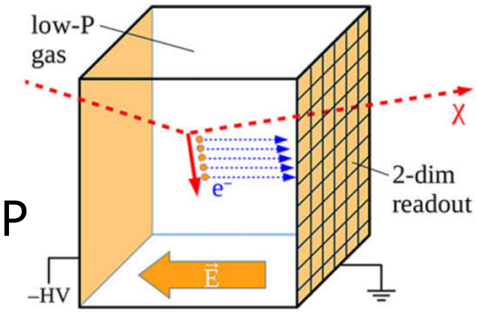


From J. Liao

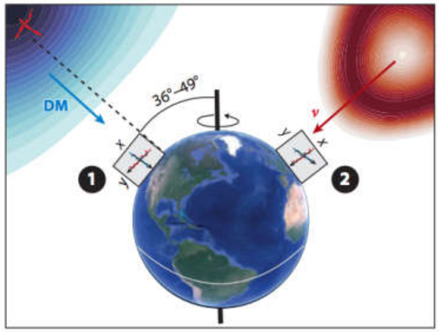
WIMP直接探测实验

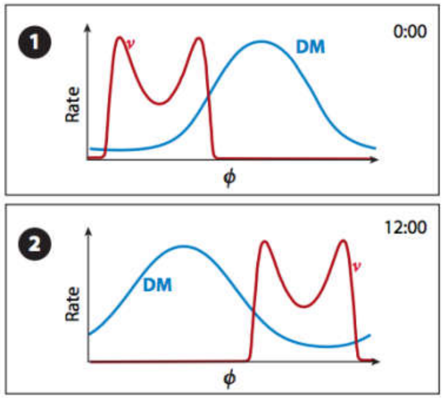
E. Baracchini, IDM 2022
J. Billard et al 2022 Rep. Prog. Phys. 85 056201

- 方向探测
  - MIMAC、NEWS-G
  - 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)



Directional detection helps to penetrate neutrino fog



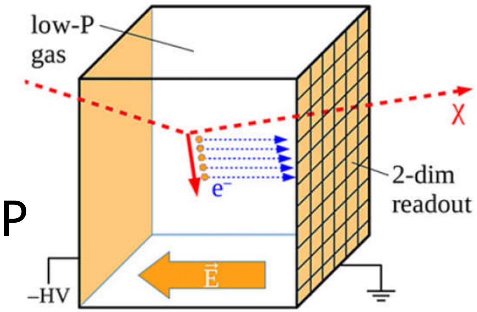


DM and solar neutrinos event rate as a function of some angle ϕ on a two-dimensional readout plane at 12 h time distance or 180 degree of longitude

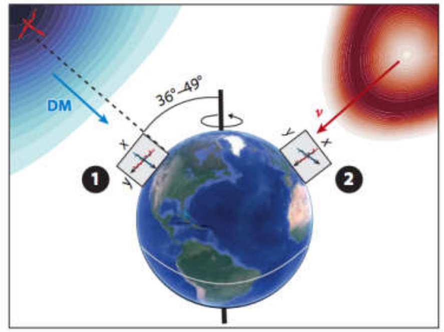
E. Baracchini, IDM 2022
J. Billard et al 2022 Rep. Prog. Phys. 85 056201

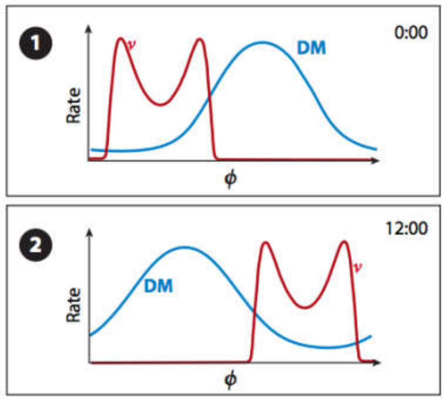
WIMP直接探测实验

- 方向探测
  - MIMAC、NEWS-G
  - 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)
- 年度调制效应
  - DAMA/LIBRA，COSINE100/200
  - ANAIS-112，SABRE、COSINUS



Directional detection helps to penetrate neutrino fog

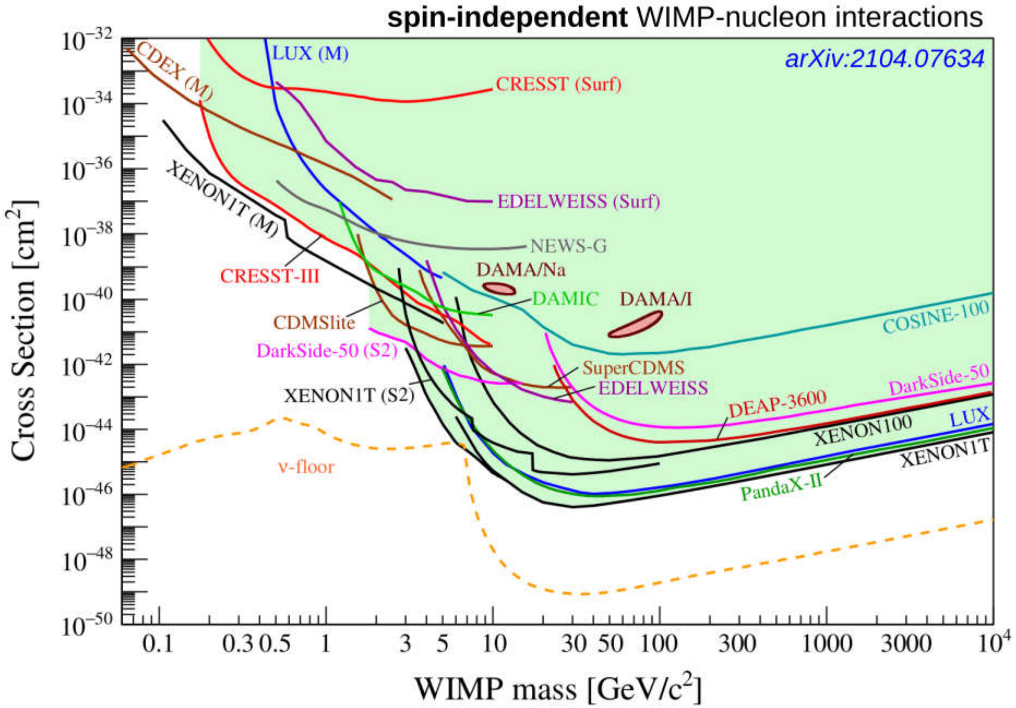




DM and solar neutrinos event rate as a function of some angle ϕ on a two-dimensional readout plane at 12 h time distance or 180 degree of longitude

WIMP直接探测

- 更低本底、更低阈值、更大曝光量
- 中微子地板



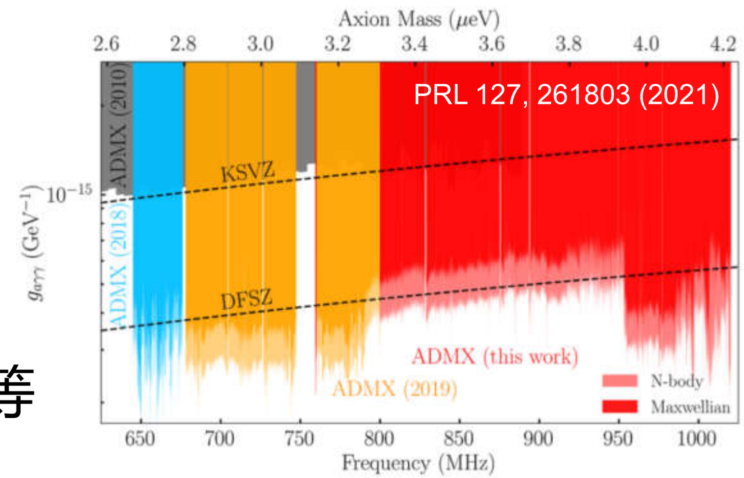
Experiment	Lab	Target	Mass [kg]	Ch	Sensitivity [cm^2@ GeV/c^2]	Exposure [t× year]	Timescale
Cryogenic bolometers (Section 4.6.1)							
EDELWEISS-subGeV	LSM	Ge	20	SI	10^{-43} @ 2	0.14	in prep.
SuperCDMS	SNOLAB	Ge, Si	24	SI	4×10^{-44} @ 2	0.11	constr.
CRESST-III	LNGS	$CaWO_4$+	2.5	SI	6×10^{-43} @ 1	3×10^{-3}	running
LXe detectors (Section 4.6.2)							
LZ	SURF	LXe	7.0 t	SI	1.5×10^{-48} @ 40	15.3	comm.
PandaX-4T	CJPL	LXe	4.0 t	SI	6×10^{-48} @ 40	5.6	constr.
XENONnT	LNGS	LXe	5.9 t	SI	1.4×10^{-48} @ 50	20	comm.
DARWIN	LNGS*	LXe	40 t	SI	2×10^{-49} @ 40	200	~2026
LAr detectors (Section 4.6.3)							
DarkSide-50	LNGS	LAr	46.4	SI	1×10^{-44} @ 100	0.05	running
DEAP-3600	SNOLAB	LAr	3.6 t	SI	1×10^{-46} @ 100	3	running
DarkSide-20k	LNGS	LAr	40 t	SI	2×10^{-48} @ 100	200	2023
ARGO	SNOLAB	LAr	400 t	SI	3×10^{-49} @ 100	3000	TBD
NaI(Tl) scintillators (Section 4.6.4.1)							
DAMA/LIBRA	LNGS	NaI	250	AM		2.46	running
COSINE-100	Y2L	NaI	106	AM	3×10^{-42} @ 30	0.212	running
ANAIS-112	LSC	NaI	112	AM	1.6×10^{-42} @ 40	0.560	running
SABRE	LNGS	NaI	50	AM	2×10^{-42} @ 40	0.150	in prep.
COSINUS-1π	LNGS	NaI	~1	AM	1×10^{-43} @ 40	3×10^{-4}	2022
Ionisation detectors (Section 4.6.4.2)							
DAMIC	SNOLAB	Si	0.04	SI	2×10^{-41} @ 3-10	4×10^{-5}	running
DAMIC-M	LSM	Si	~0.7	SI	3×10^{-43} @ 3	0.001	2023
CDEX	CJPL	Ge	10	SI	2×10^{-43} @ 5	0.01	running
NEWS-G	SNOLAB	Ne,He		SI			comm.
TREX-DM	LSC	Ne	0.16	SI	2×10^{-39} @ 0.7	0.01	comm.
Bubble chambers (Section 4.6.4.3)							
PICO-40L	SNOLAB	C_3F_8	59	SD	5×10^{-42} @ 25	0.044	running
PICO-500	SNOLAB	C_3F_8	1 t	SD	$\sim 1 \times 10^{-42}$ @ 50		in prep.
Directional detectors (Section 4.6.5)							
CYGNUS	Several	He:SF_6	10^3 m^3	SD	3×10^{-43} @ 45	6 y	R&D
NEWSdm	LNGS	Ag,Br,C,...		SI	8×10^{-43} @ 200	0.1	R&D

APPEC report, arXiv: 2104.07634

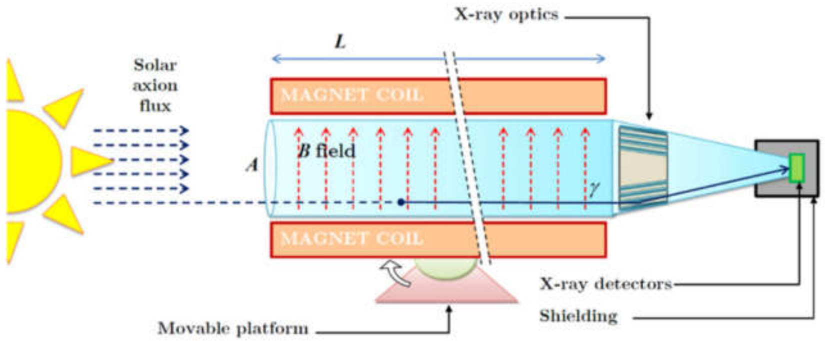
（类）轴子探测：太阳轴子、ALPs

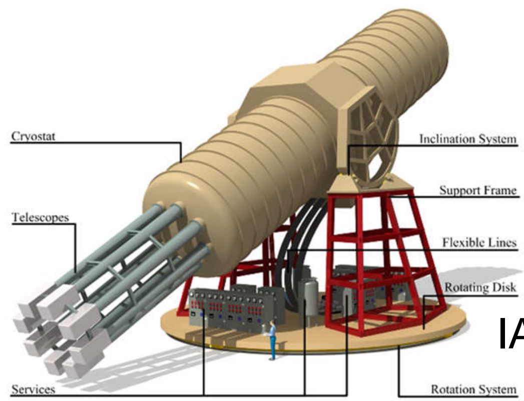
L. Roszkowski, IDM 2022
arXiv:2104.07634

- 暗物质晕望远镜(Haloscopes)
  - 轴子在强磁场中衰变到光子
  - 共振腔频率匹配光子频率
  - 微波谐振腔、抛物面天线、核磁共振等技术
  - ADMX、MADMAX、CASPEr、ABRACADABRA等



- 太阳轴子望远镜(Helioscopes)
  - 太阳轴子
  - CAST、IAXO



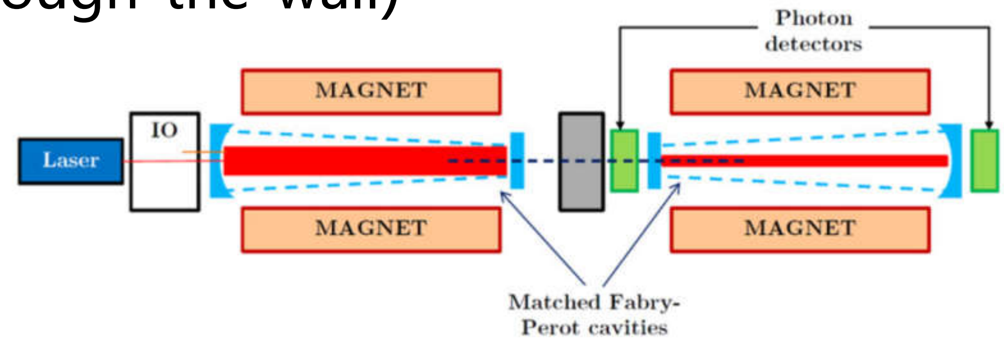


IAXO

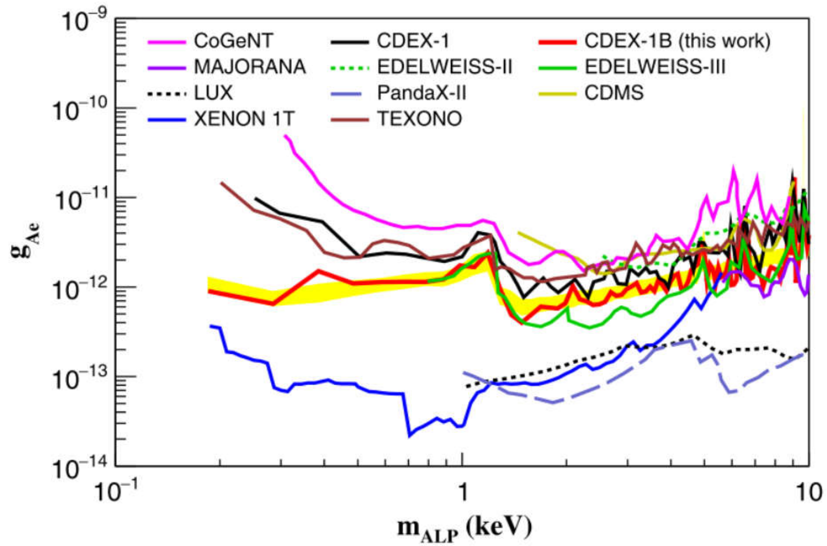
（类）轴子探测

L. Roszkowski, IDM 2022
arXiv:2104.07634

- 光穿墙实验(**LSW**: light-shining-through-the-wall)
  - 激光->轴子->光子
  - ALPS I/II, OSQAR等
  - < ~meV and $g_{a\gamma}$ <5.8×10^{-8} GeV^{-1}

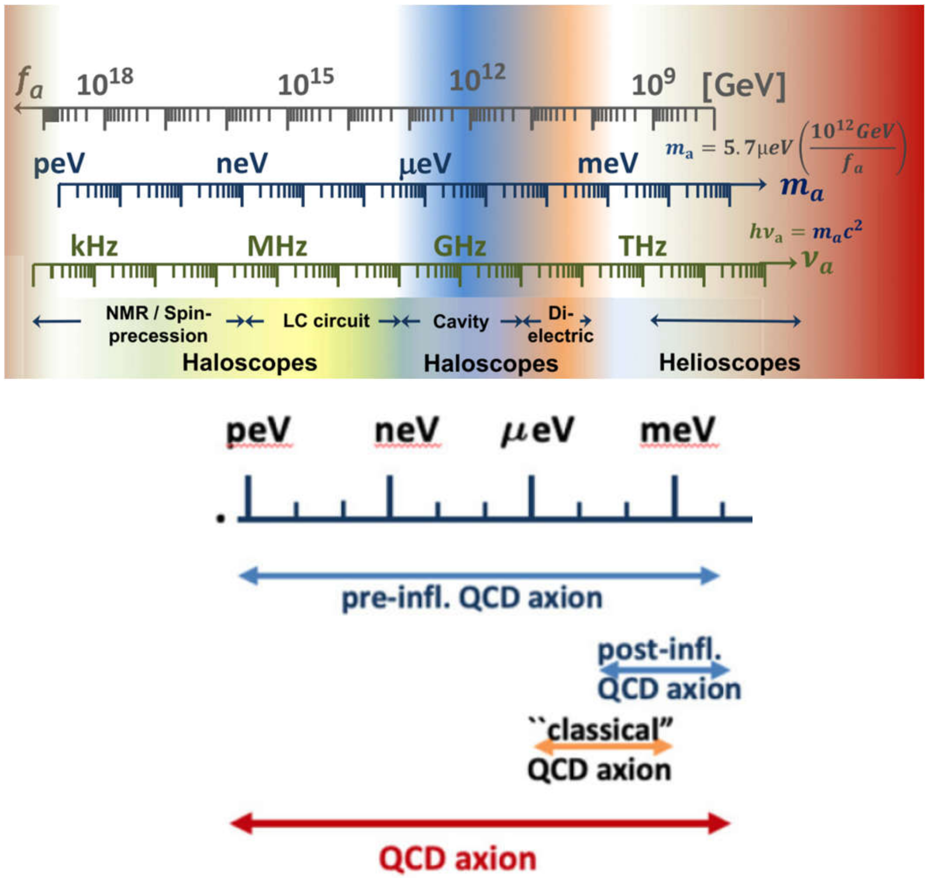


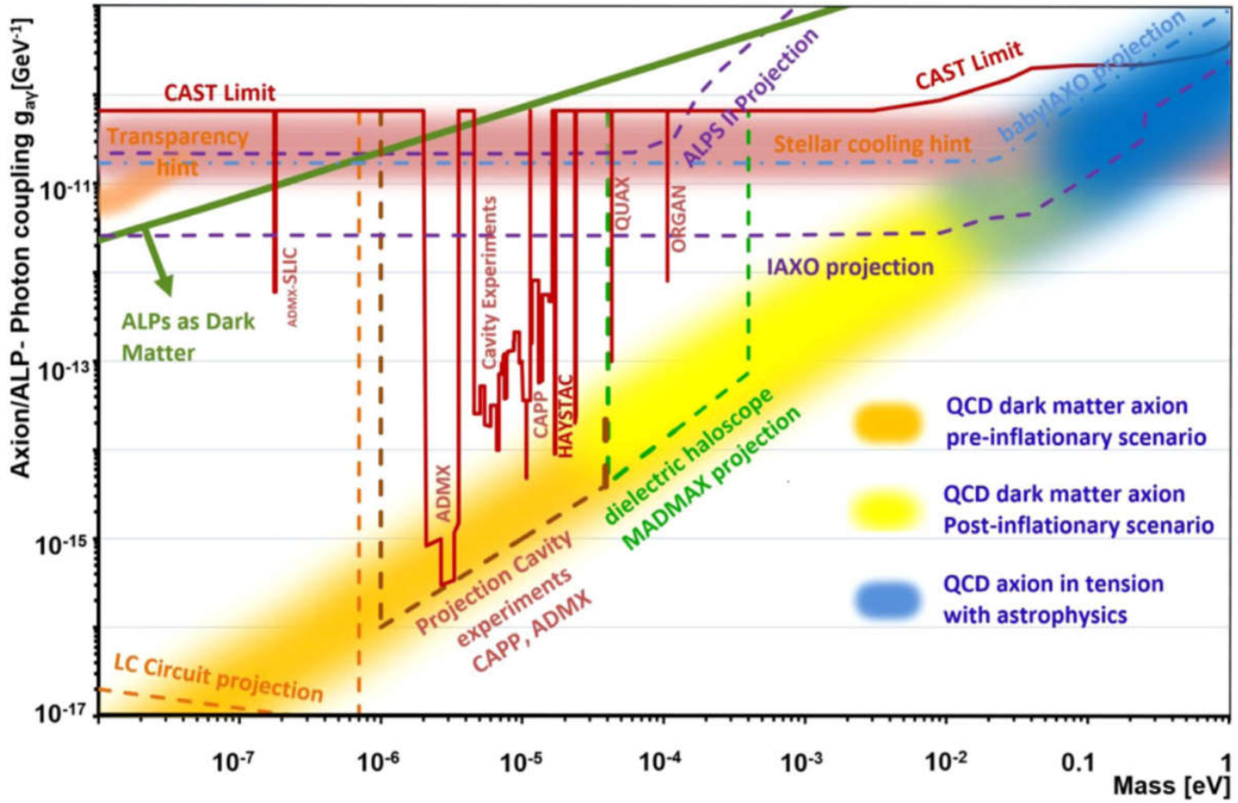
- 低本底实验
  - 轴子-电子耦合
  - XENON、PandaX、CDEX等
  - ~keV



（类）轴子探测

L. Roszkowski, IDM 2022
arXiv:2104.07634

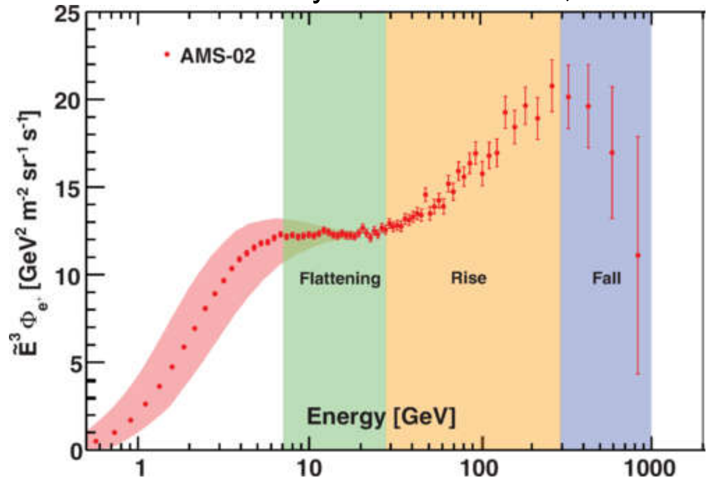


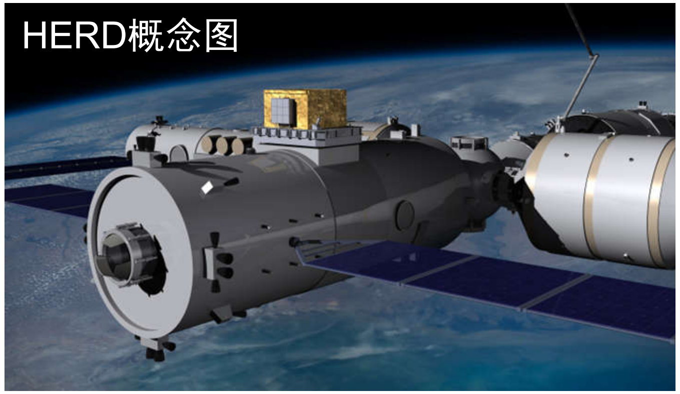


间接探测实验

- 宽能段宇宙线粒子（主要是各种反物质粒子以及电子）和伽马射线的能谱及方向
- AMS正电子能谱观测
  - 25GeV以上的超出可能源于暗物质或其他天体物理来源
- 悟空号暗物质探测卫星
  - 伽马射线谱、正负电子总谱（>1TeV）
- 高能宇宙辐射探测设施HERD
  - 基于我国空间站，三维位置分辨、五面探测
  - 正/负电子、伽马射线
- 甚大面积伽马射线天文台VLAST
  - 伽马射线

Phys. Rev. Lett. 122, 041102

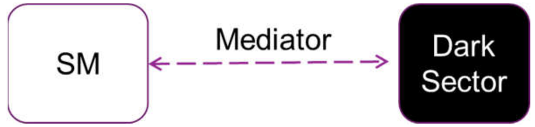




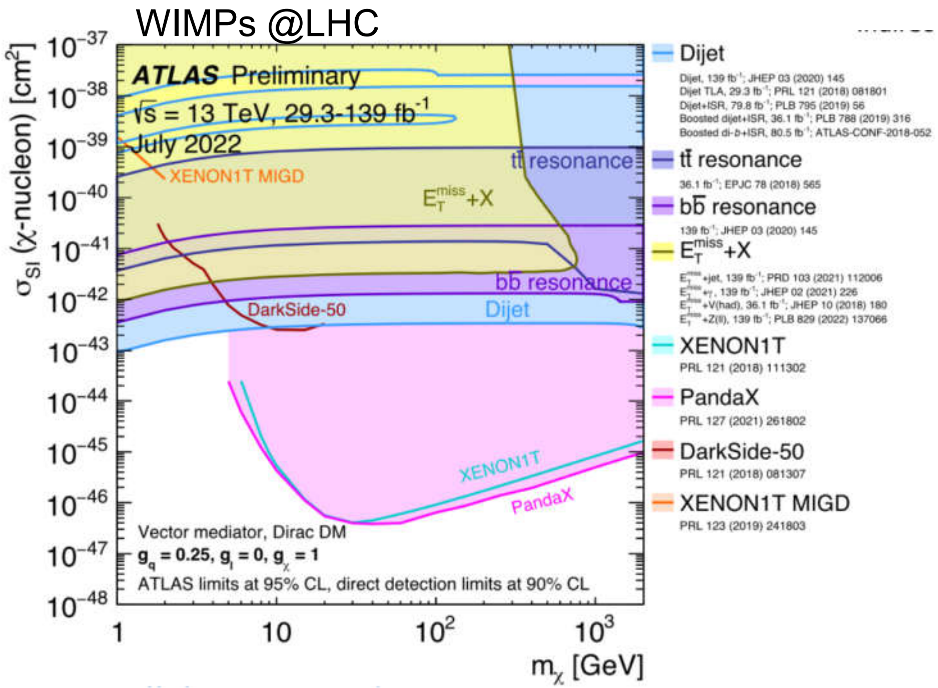
图片来自 http://herd.ihep.ac.cn/index.shtml

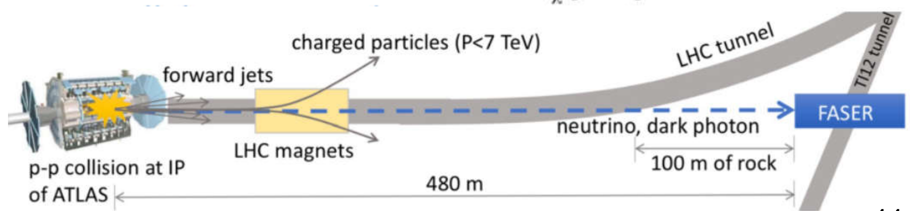
L. Shchutska, IDM 2022

对撞机探测

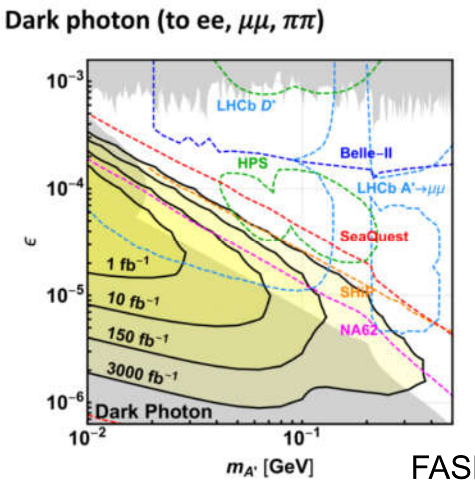


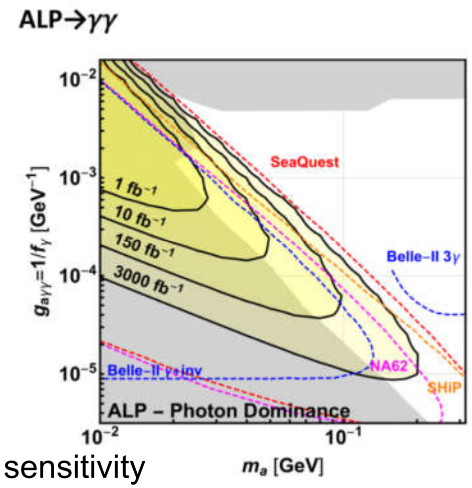
- 探测产生出来的暗物质（包括长寿命粒子）
- 探测媒介子
- Dark sector particle search @LHC
  - CMS、ATLAS、LHCb
  - FASER (ForwArd Search ExpeRiment)
    - 轻媒介子(ALPs, Dark photon,….)
- 类FASER实验@BESIII





FASER

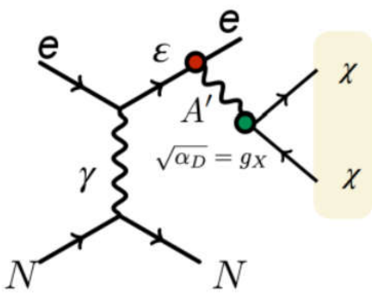




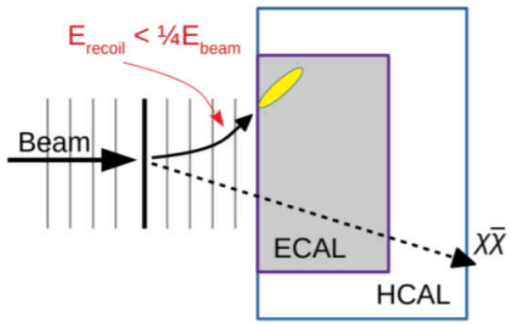
FASER sensitivity

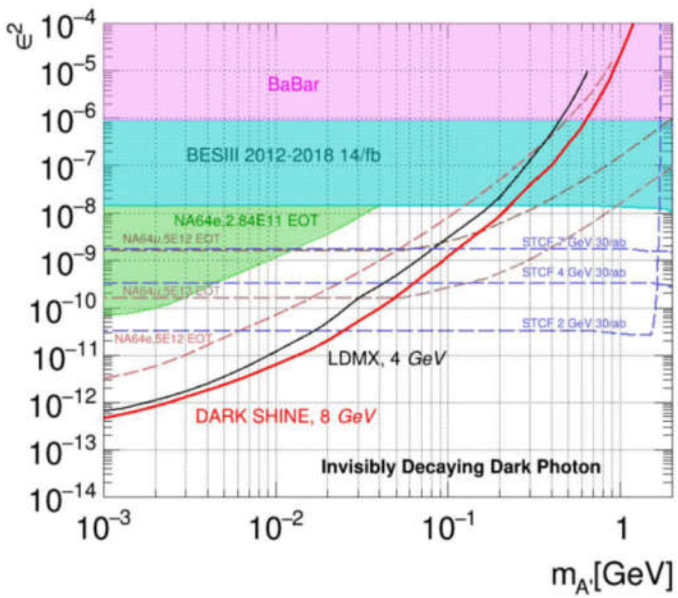
暗光子探测

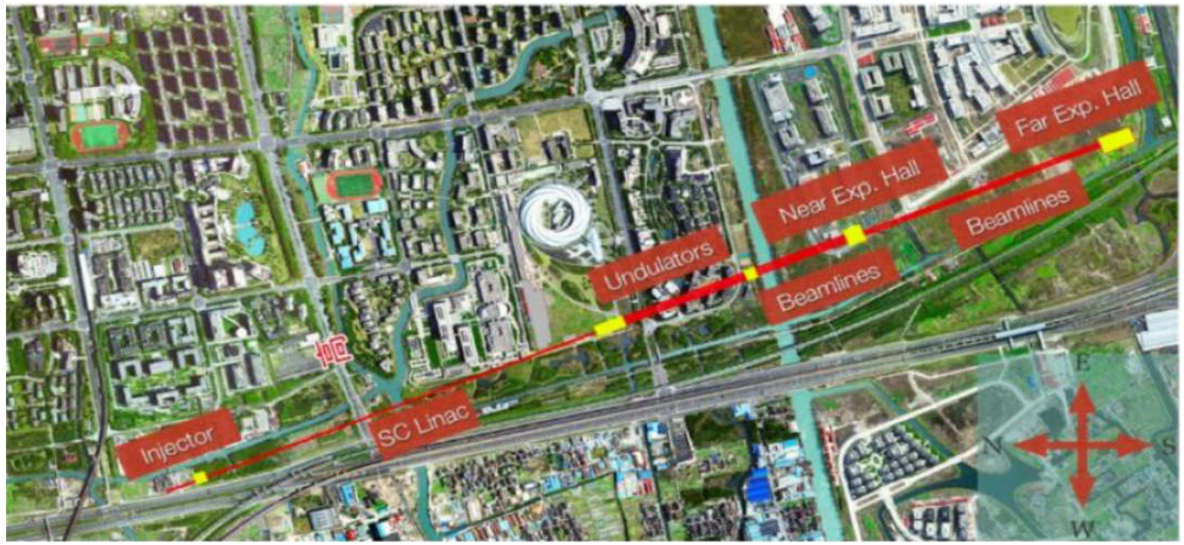
- Dark SHINE实验
  - 上海硬X射线自由电子激光装置
  - 高频单电子束流线（能量8GeV）打靶
  - 产生并探测暗光子（missing momentum& missing energy）



Invisible decay







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
- 暗物质探测实验发展迅速，多种技术路线各具特色
- 暗物质直接探测灵敏度将进入中微子“迷雾”
- 过去10年国内暗物质研究取得了国际先进成果，竞争激烈
- 理论研究与实验发展的紧密配合
- 期待重大突破

谢谢！