

地下暗物质探测实验

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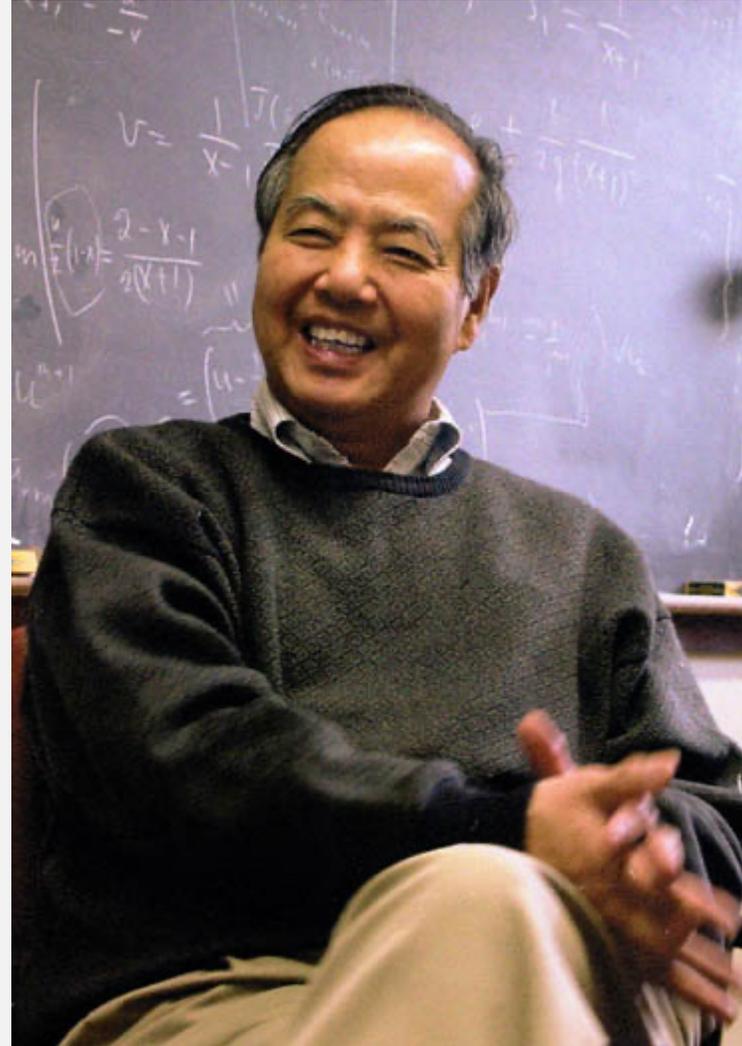
2024-08-10

提纲

- 暗物质证据
- 暗物质间接探测
- 暗物质直接探测
- 暗物质对撞机探测

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

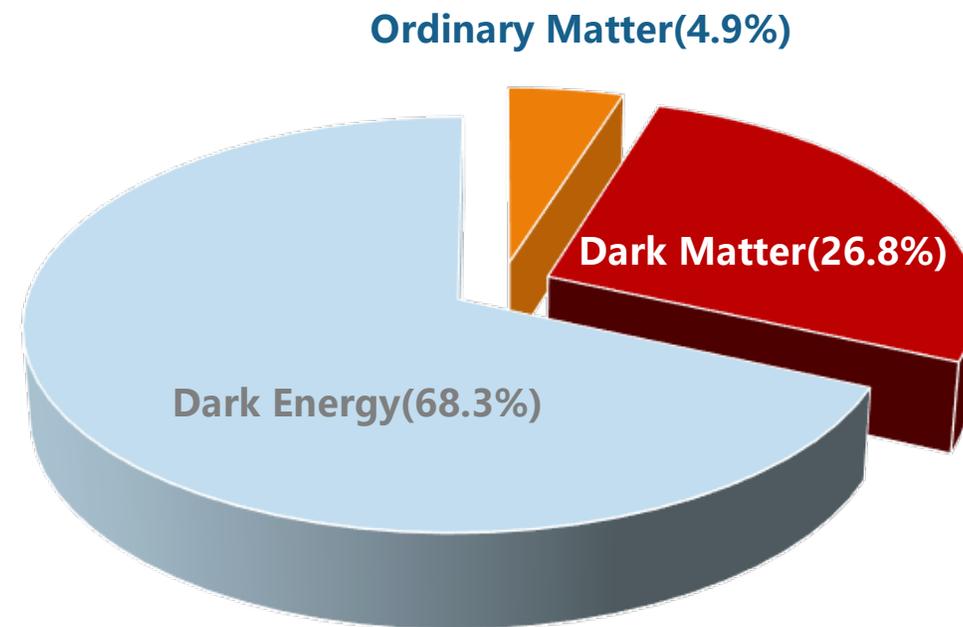


关于李政道先生引言的参考文献：

秦波，精确宇宙学时代的暗物质问题，《现代物理知识》2007 Vol19 (5):17-24

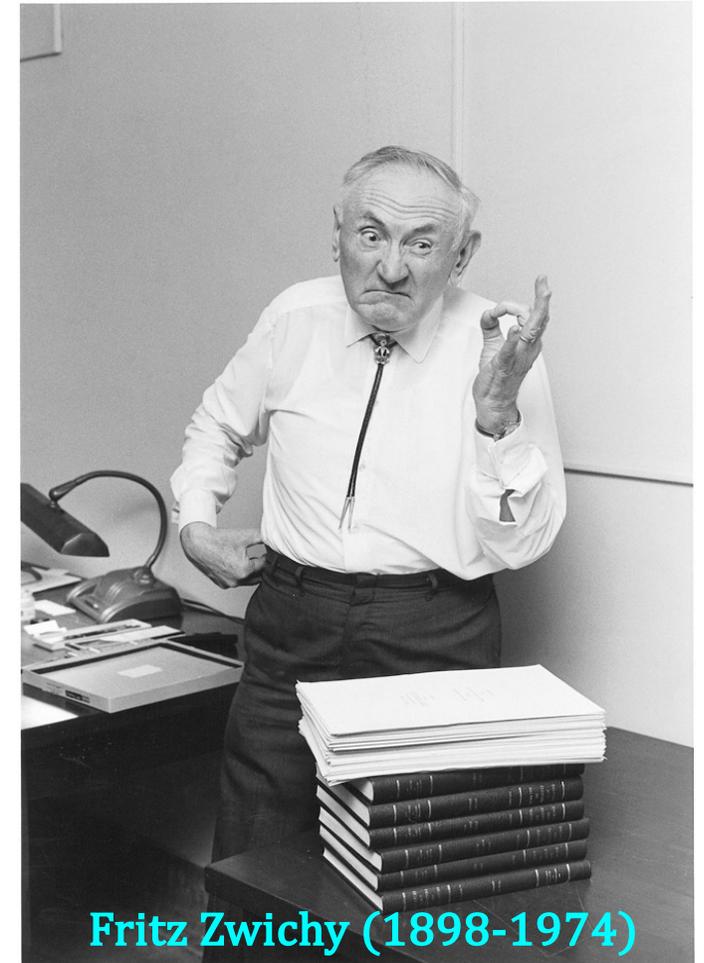
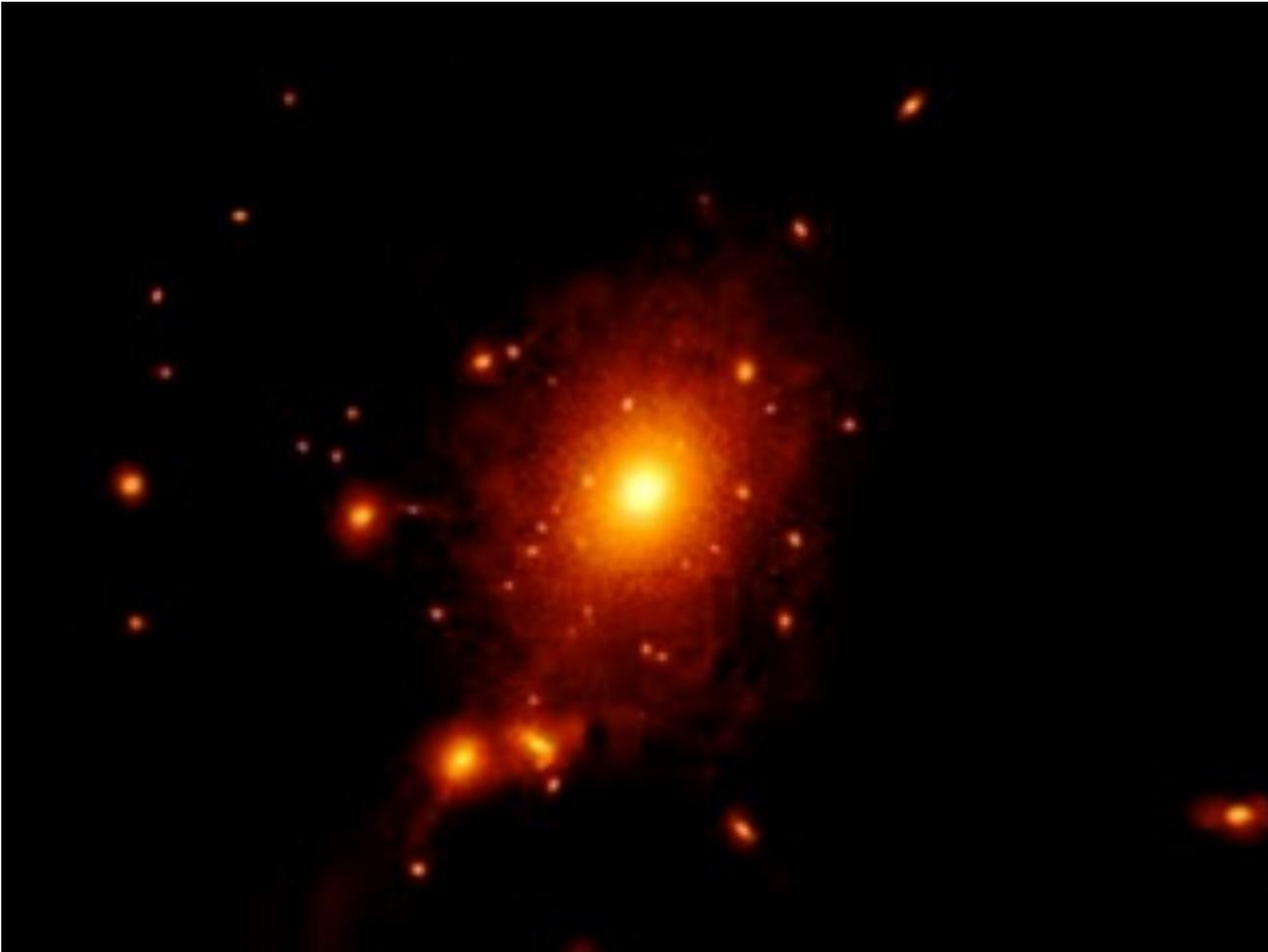
暗物质问题

- **不发光、不吸收光**
 - 无法被当今主要观测手段所看到
- **暗物质的发现：引力相互作用**
 - 星系旋转
 - 引力透镜
 - 宇宙结构
- **暗物质的基本性质仍然是个谜团**
 - 质量、自旋、相互作用强度



证据一：后发座星系团 (Coma Cluster)

- 99 Mpc from the Milky Way ($1\text{pc} = 3.2616\text{ ly}$)



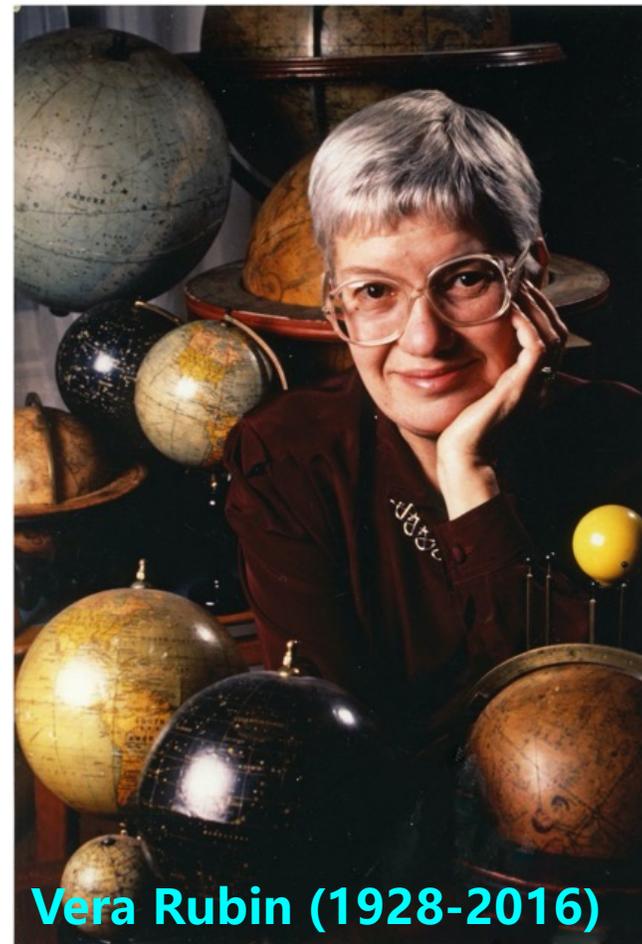
星系团质量

- 1933年, Fritz Zwicky计算了后发星系团质量
 - Virial Theorem: $\langle T \rangle = -\frac{1}{2} \langle V \rangle$
 - $T = \frac{1}{2} v^2 \sim \frac{3}{2} \sigma^2$, σ dispersion velocity ~ 1000 km/s
 - 引力势能: $V \sim \frac{3}{5} \frac{GM}{R}$, ($R \sim 2 \times 10^6$ light year in Coma)
- 后发星系团位力质量: $M > 5 \times 10^{14} M_{\odot}$
 - 比发光物质质量大400倍: 不可见物质
- Fritz Zwicky称之为 “**Dunkle Materie**” (暗物质)
 - 1937年预言暗物质可以用引力透镜来研究 (于1990s实现)

证据二：星系旋转曲线

- 1970s: 首个高置信度的暗物质证据

Andromeda Galaxy, M31
仙女座星系



Vera Rubin (1928-2016)

星系旋转曲线

- 引力相互作用

- Orbital velocity $v^2 \propto G \frac{M(r)}{r}$

- 星系核心区域

- $M(r) = 4\pi r^2 \rho$

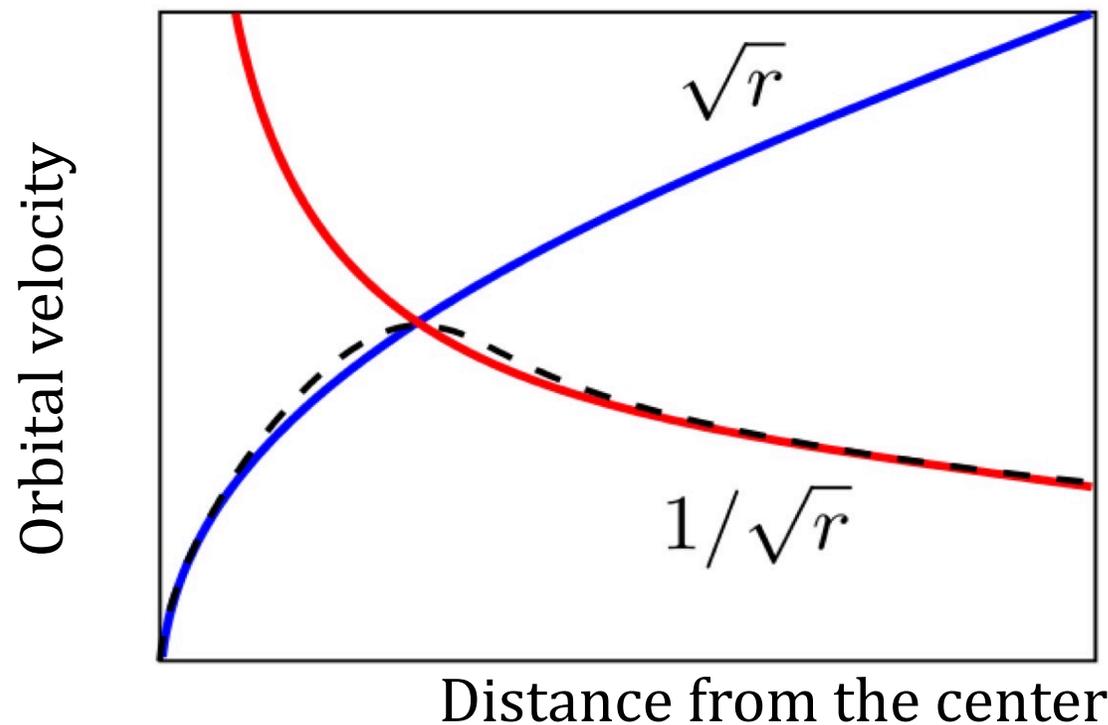
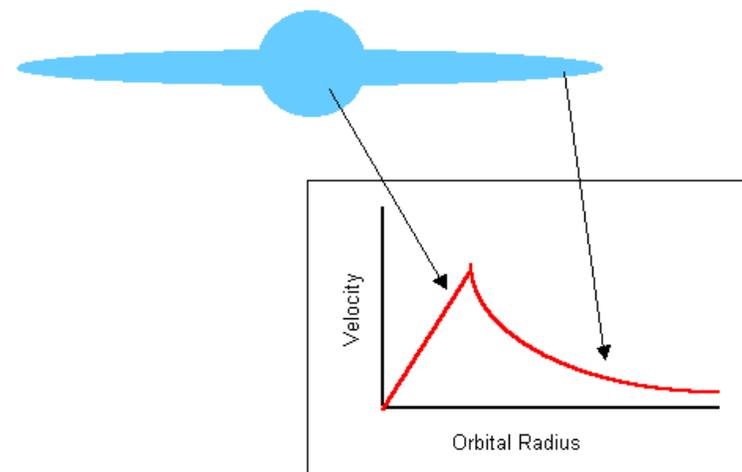
- $v \sim \sqrt{r^2/r} = \sqrt{r}$

- 星系盘区域

- $M = M_{total}$

- $v \sim \sqrt{1/r}$

"Expected" Galactic Rotation Speeds

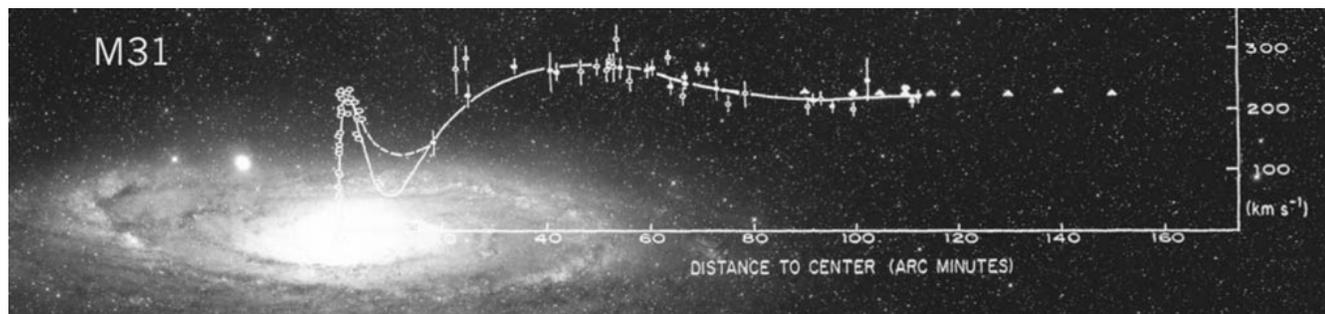


星系旋转曲线

- M31 Flat Rotation Curve

- $v^2 \propto G \frac{M(r)}{r} \sim \text{constant}$

- $M(r) \propto r$

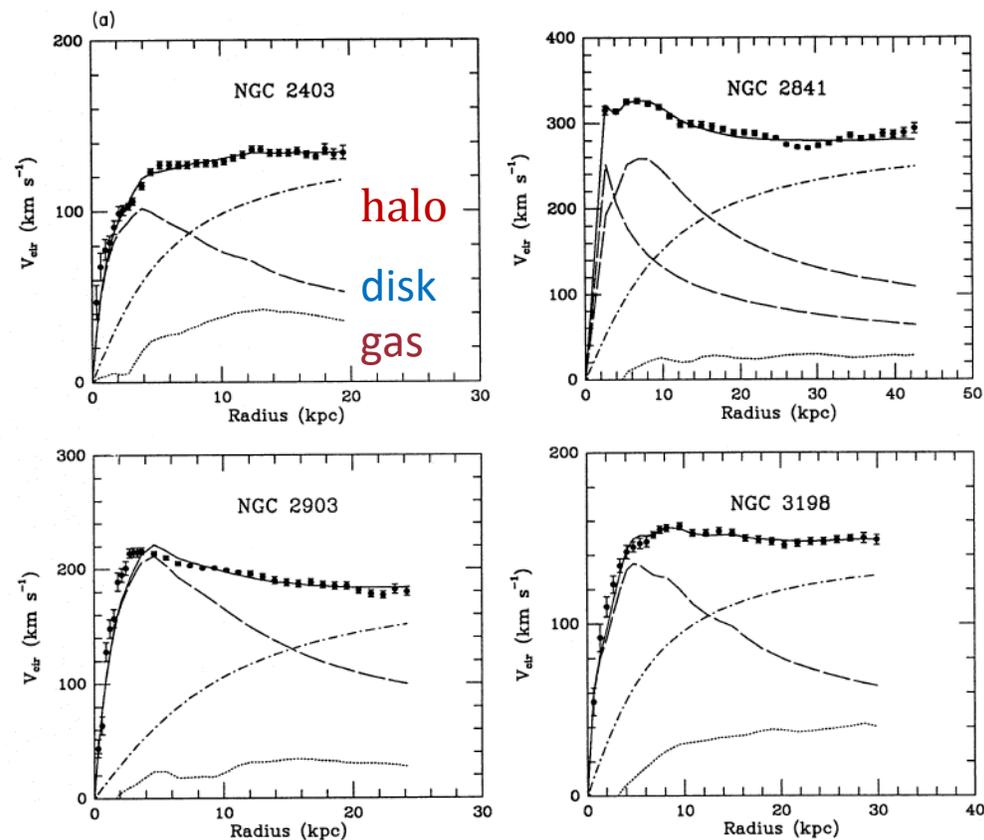


- 暗物质晕 (Dark matter halo)

- 星系中需要存在大量的暗物质提供引力

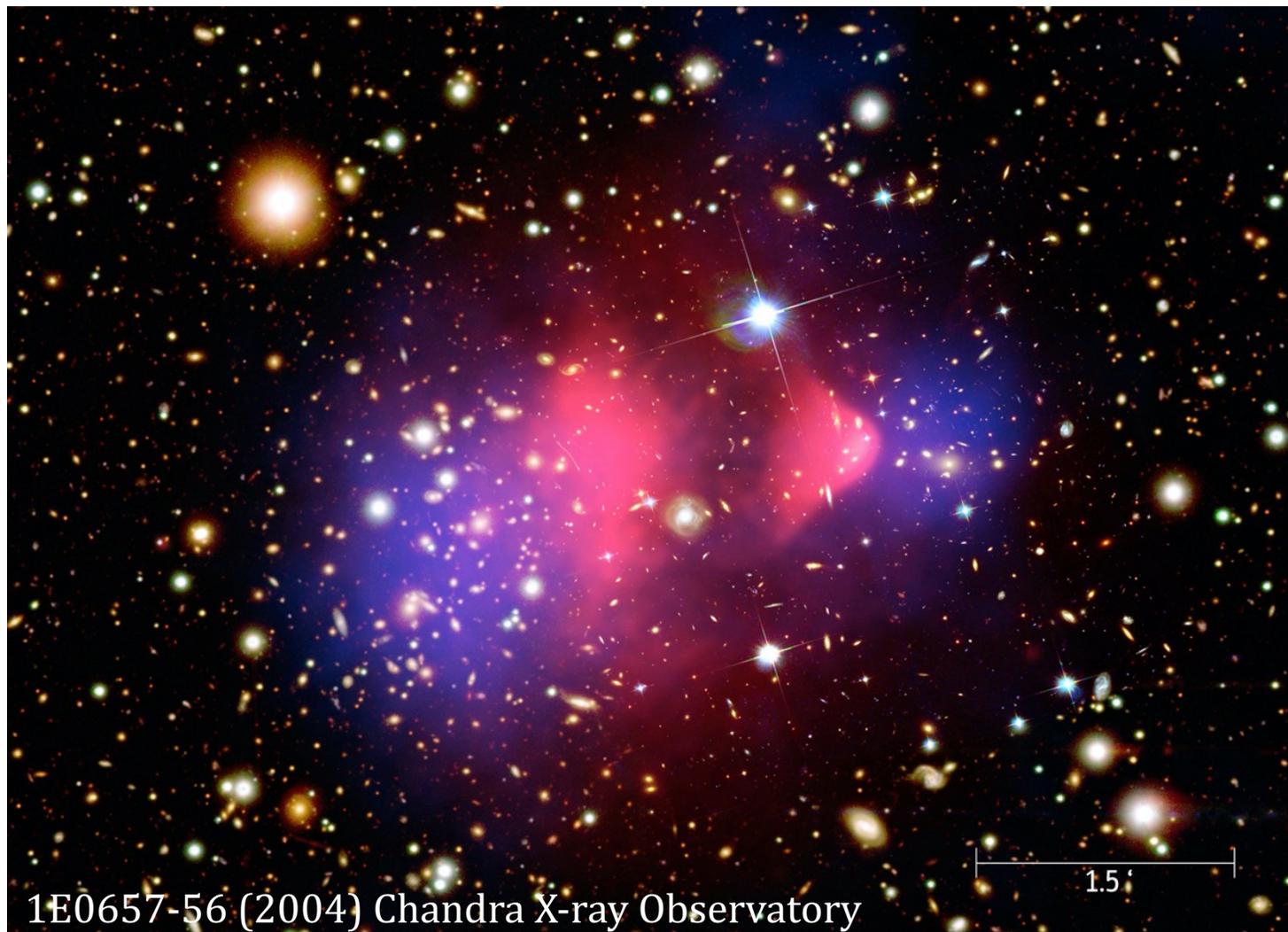
- 几乎所有研究过的星系都有类似的现象

- 包括银河系



证据三：“子弹头”星团 (Bullet Cluster)

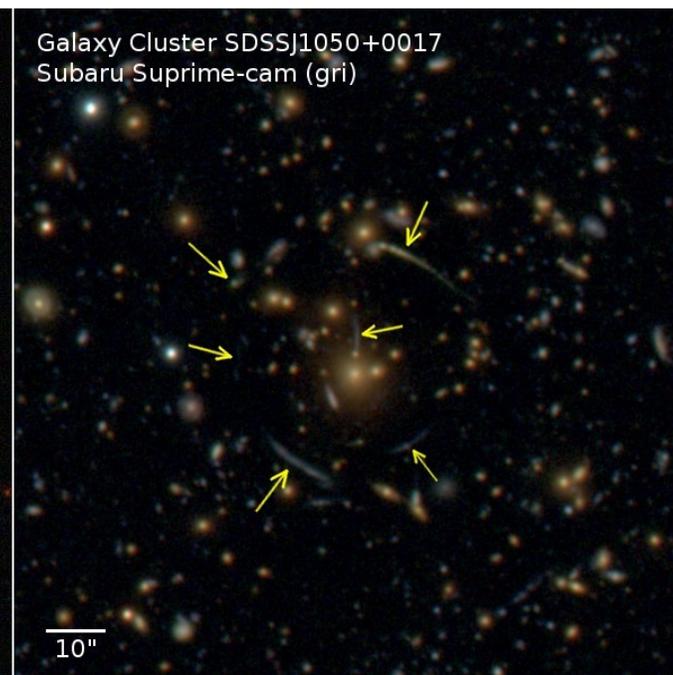
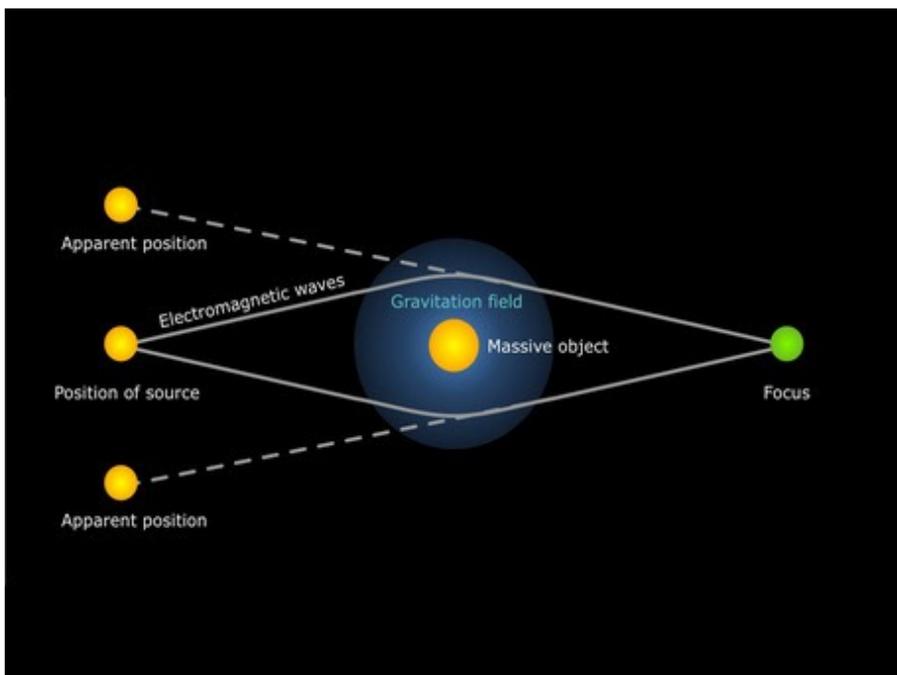
- 暗物质存在至今最好的证据



X-ray image (pink) superimposed over a visible light image (galaxies), with matter distribution calculated from gravitational lensing (blue).

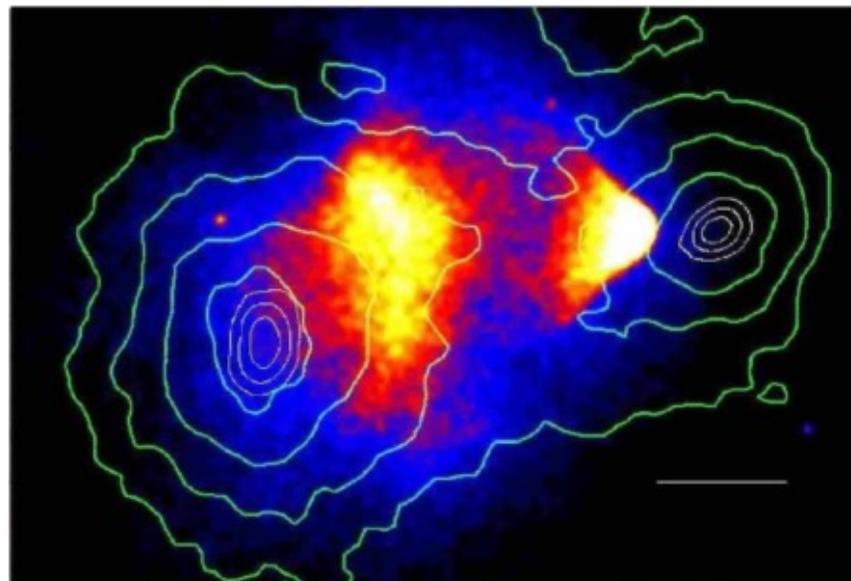
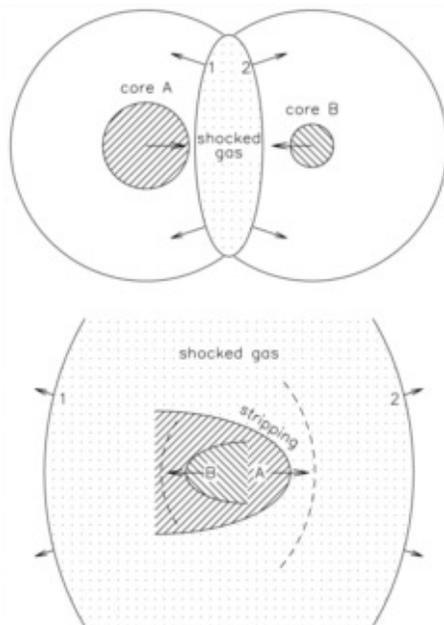
引力透镜 (Gravitational Lensing)

- 广义相对论
 - 大质量物质引起空间弯曲
- 分析引力透镜弧探知物质的质量分布，准确测量星系团质量



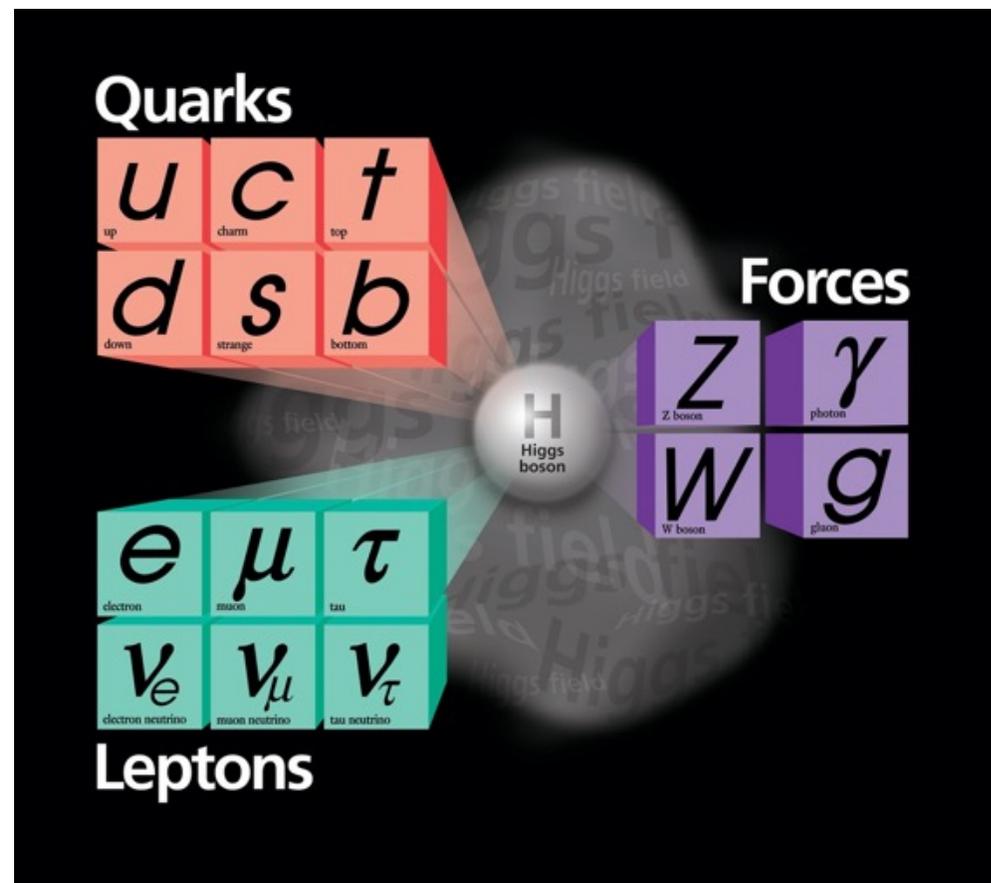
“子弹头”星团

- 两个星系团发生碰撞
 - 星际气体，普通物质的主要成分，碰撞发射出X-射线
 - 但是，大部分的星系物质穿越对方
- 否定了“引力修正派”，暗物质之间没有强的相互作用



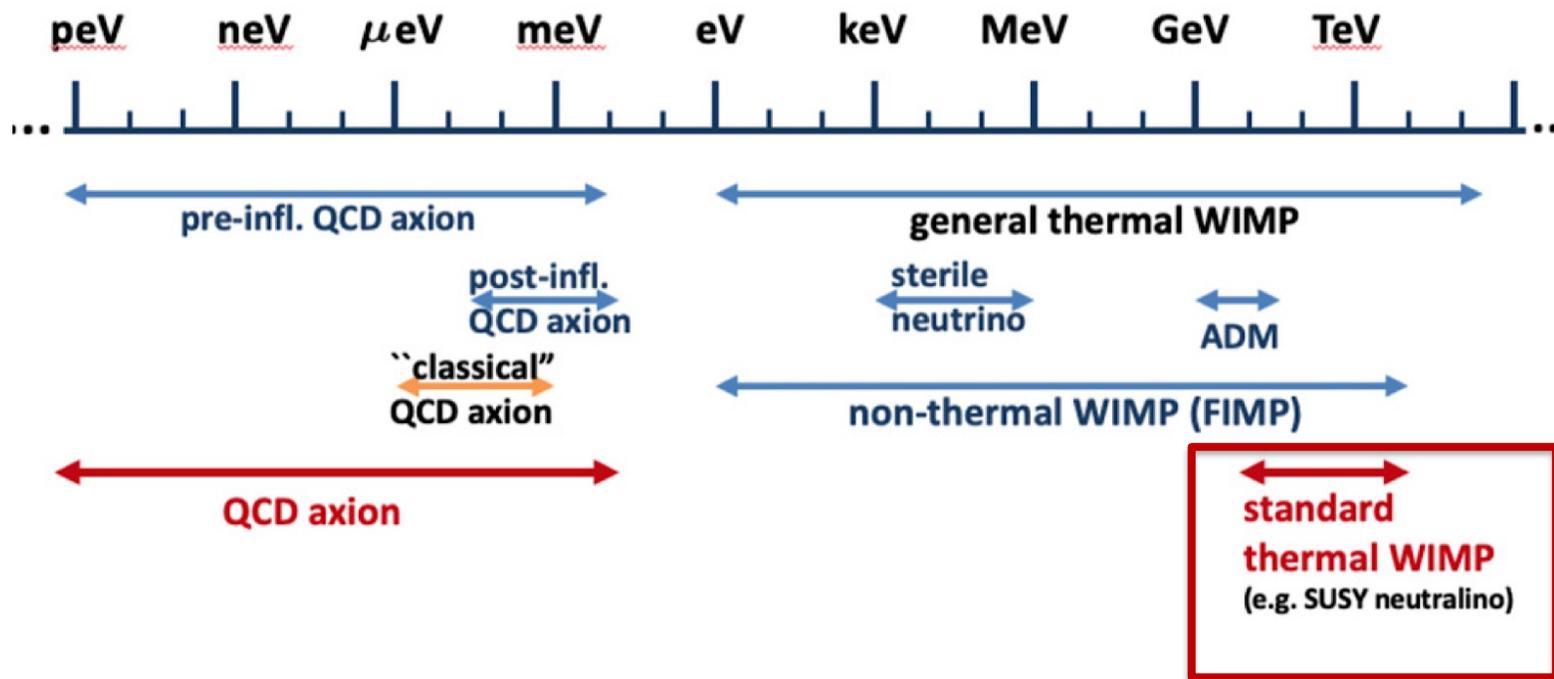
暗物质是什么？

- 暗物质有引力相互作用，无显著电磁相互作用，相互作用强度弱
- 标准模型(The Standard Model)不存在冷暗物质候选
 - 中微子质量 $\sum m_i = 0.1\text{eV}$ 可以贡献 0.2%的暗物质
 - 中微子只能是温暗物质的候选



暗物质粒子候选

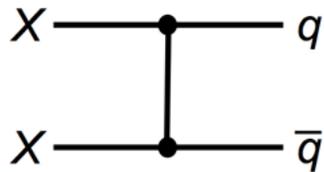
- 多种可能的理论模型
- 暗物质候选粒子的质量横跨多个量级



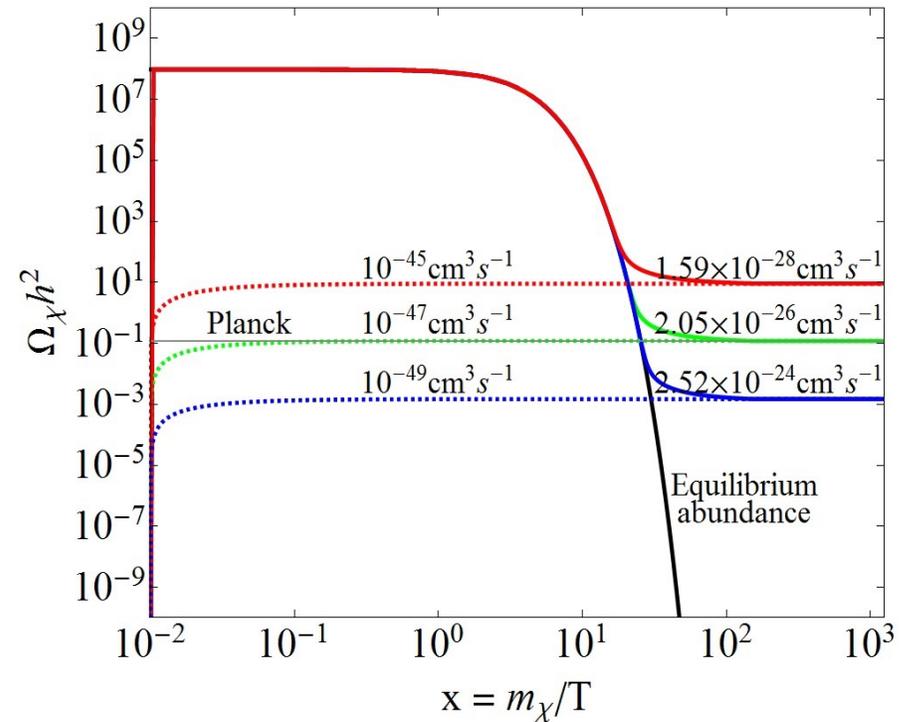
WIMP奇迹

- Weakly Interacting Massive Particle
- 100 GeV质量暗物质，弱相互作用尺度的某种**新相互作用**可以自然实现目前观测的暗物质残余密度

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



$$m_X \sim 100 \text{ GeV}, g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$$



This mass scale has nothing to do with EWSB

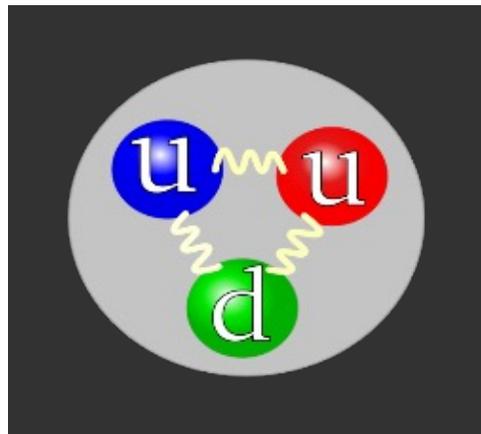
相互作用



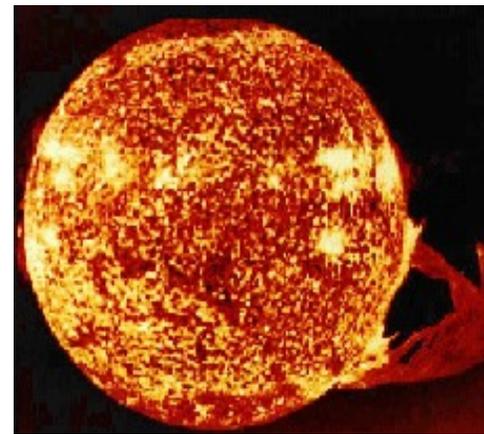
万有引力



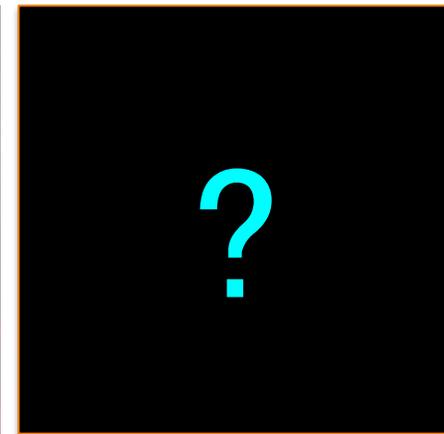
电磁力



强作用力



弱作用力

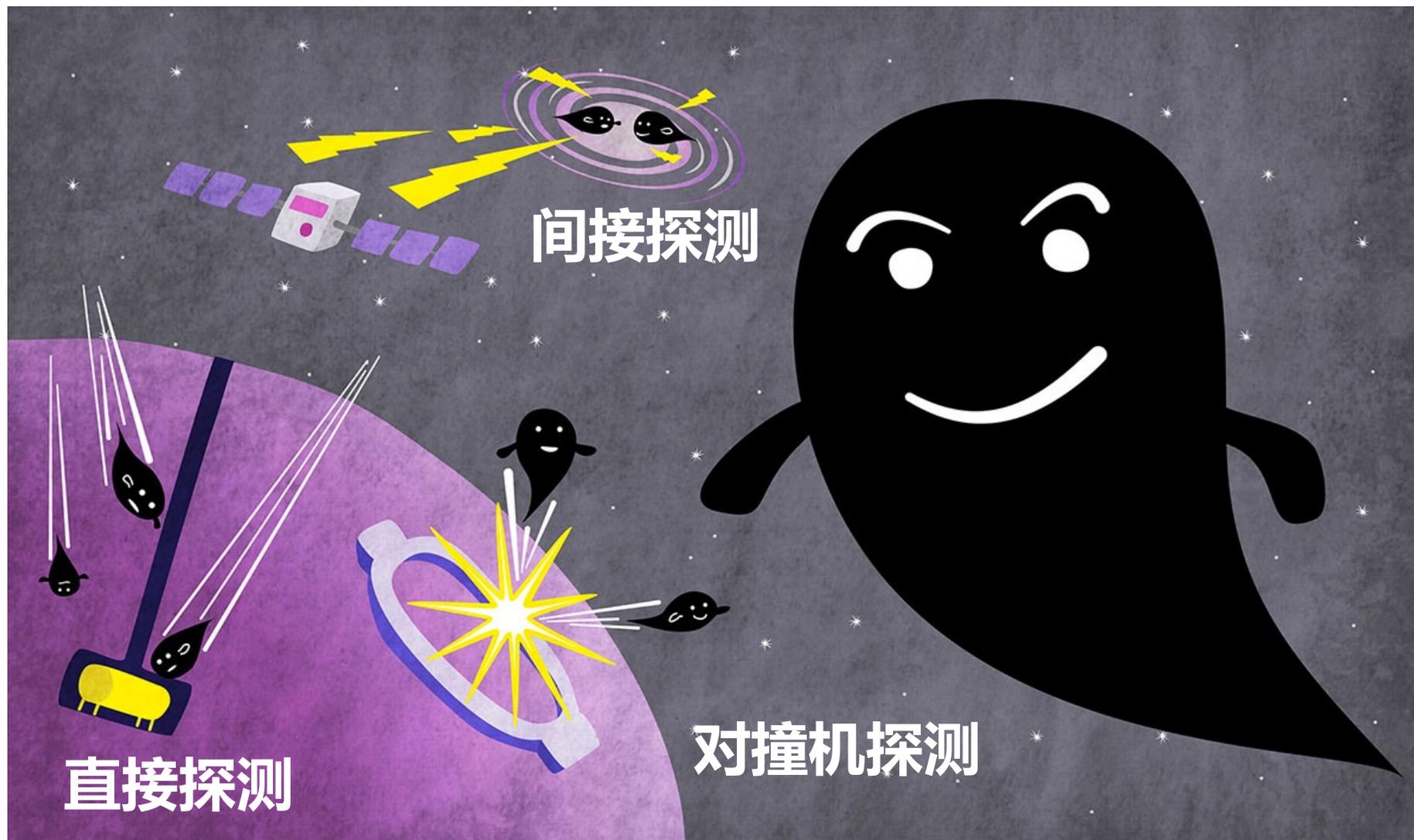


新相互作用

- 如果暗物质和普通物质之间有**微观相互作用**，我们可以通过粒子探测器直接“看到”他们

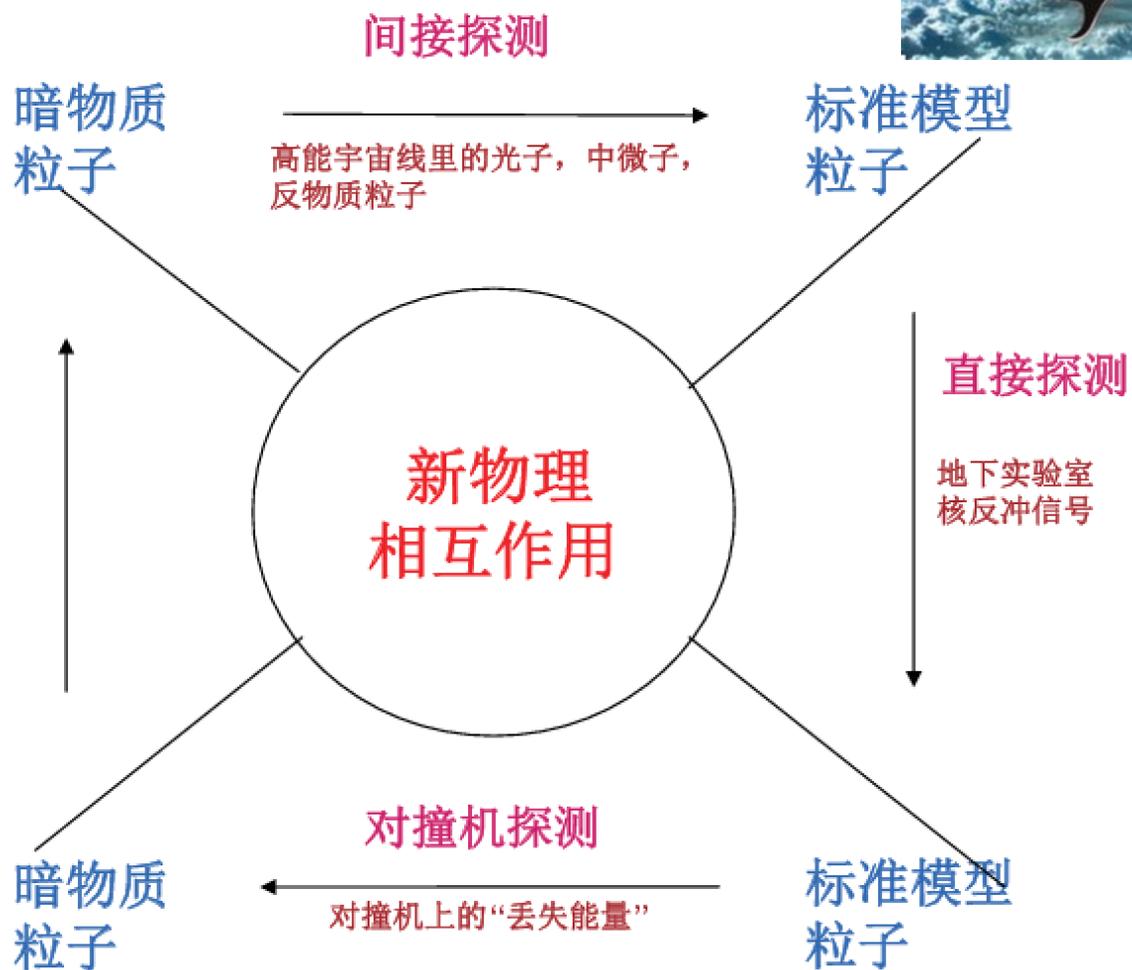
暗物质实验探测

- 目标：在实验室发现暗物质并研究暗物质的本质



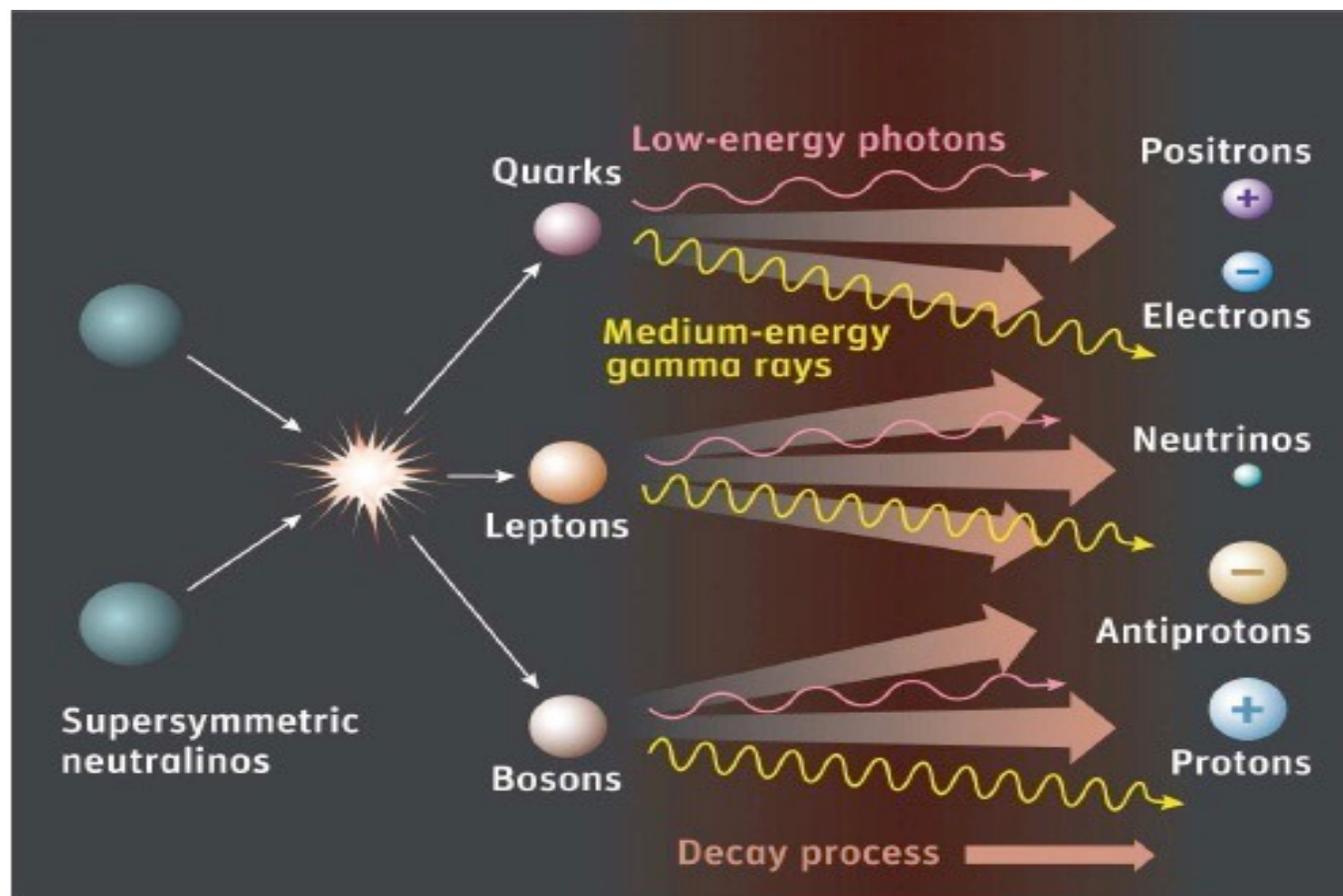
暗物质实验探测

- 三种探测方式相互补充



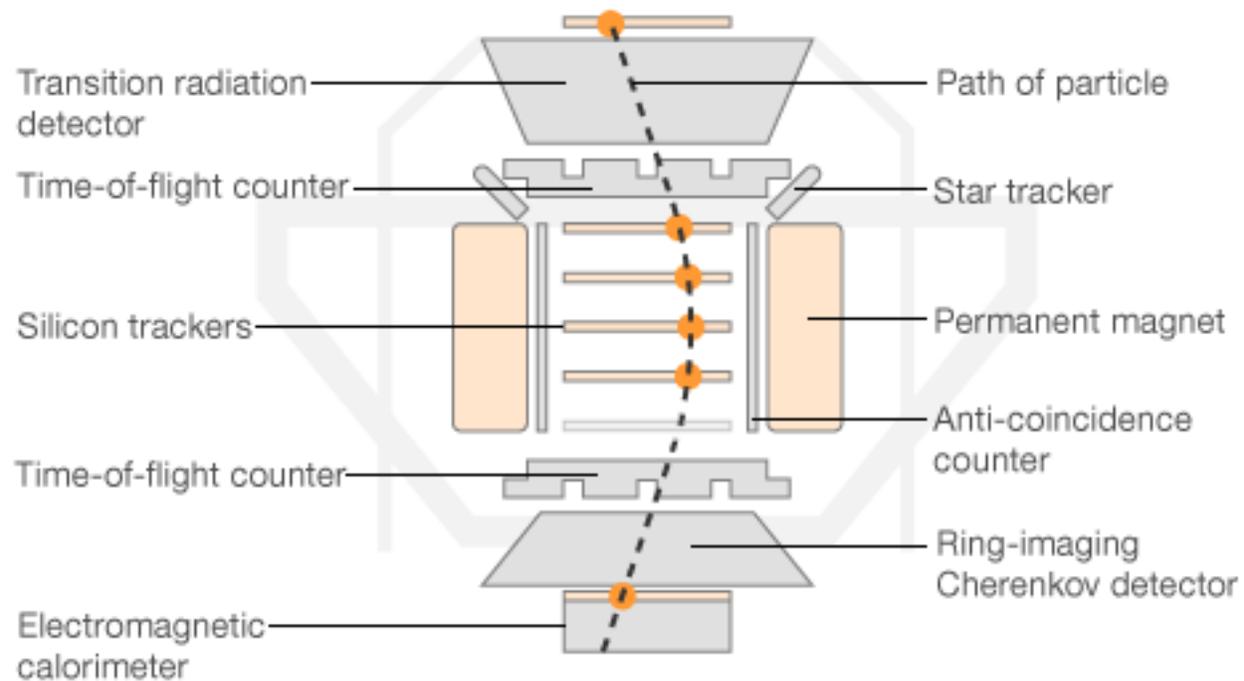
暗物质间接探测

- 暗物质密度大的区域：银河系中心，其他星系，暗物质团等
- 探测暗物质湮灭或衰变的信号
 - 正负电子
 - 正反质子
 - 光子
 - 中微子



带电宇宙线粒子探测实验

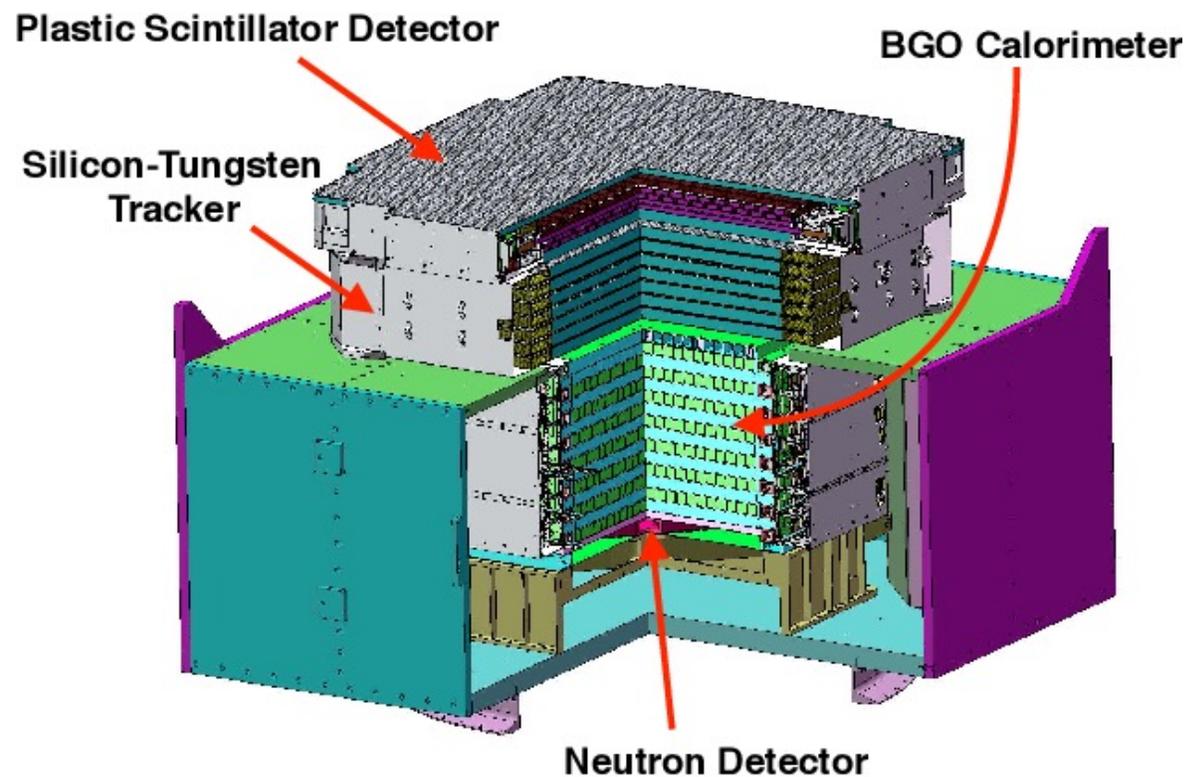
- 空间粒子探测器
- AMS-02实验
 - 强磁场，径迹探测器：鉴别粒子电荷



Source: CERN

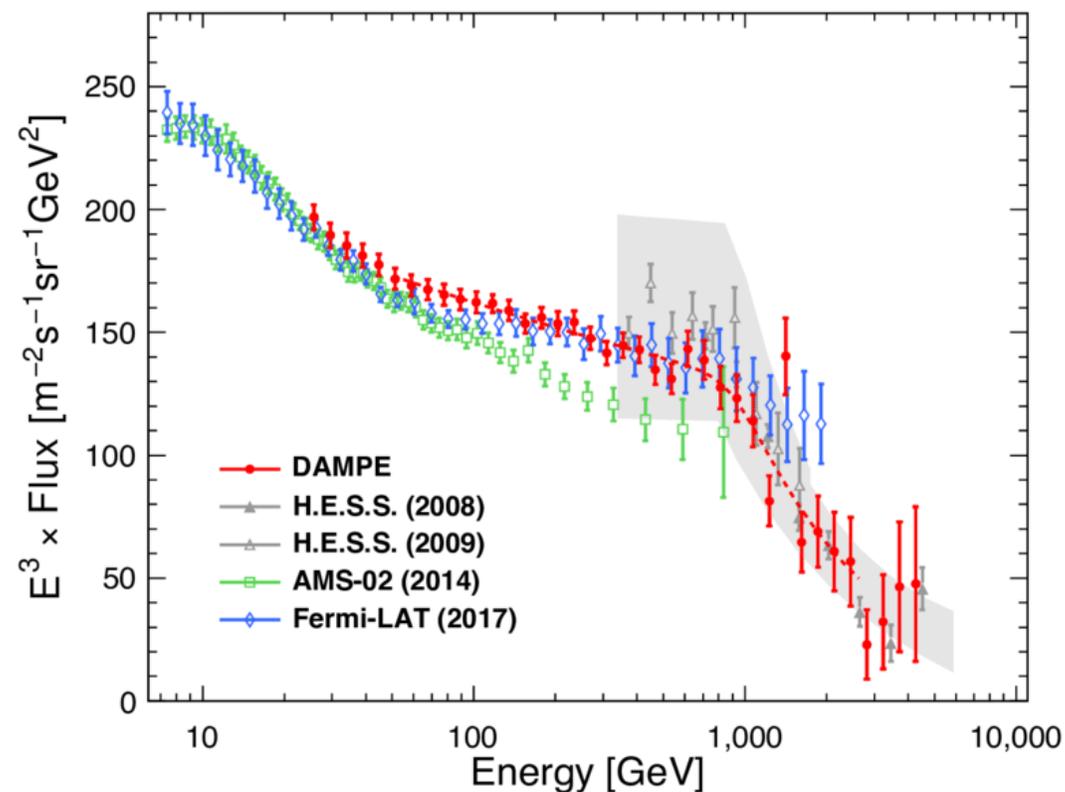
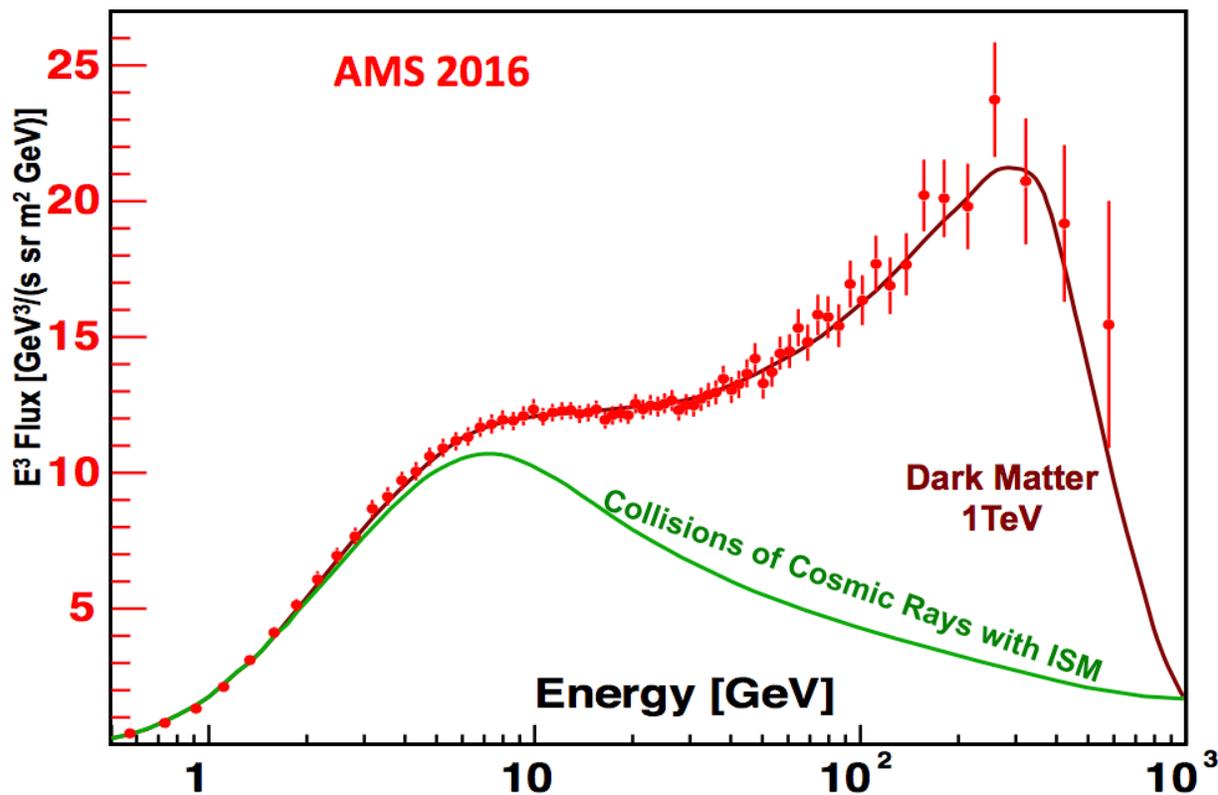
悟空暗物质探测卫星

- Dark Matter Particle Explorer, DAMPE
 - 高能光子、电子、质子等



卫星实验结果

- AMS02 发现高能反电子有异常超出
- DAMPE 发现高能电子（正反） 在高能有异常拐点或超出

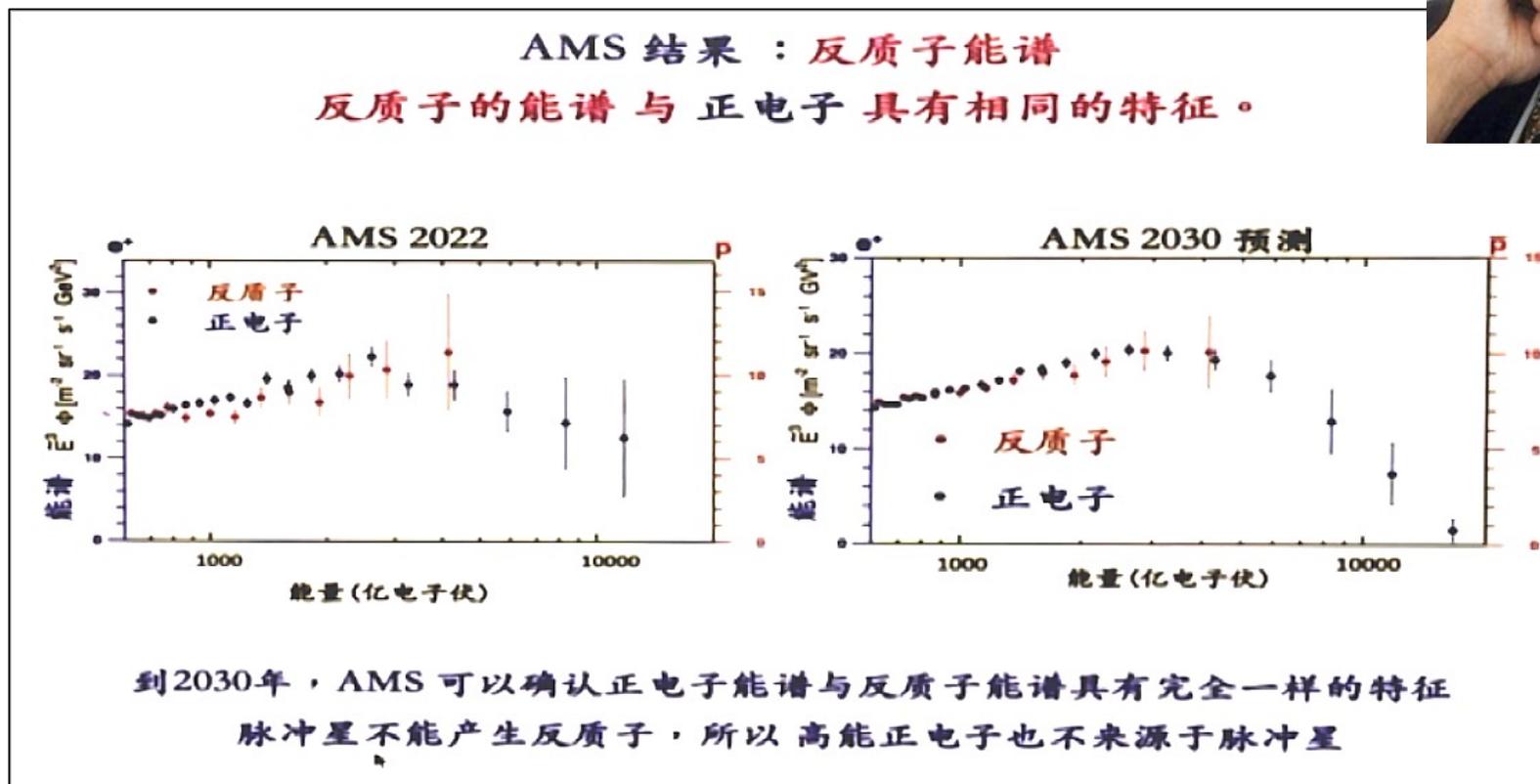


暗物质探测的机遇

• 诺贝尔物理学奖获得者 丁肇中先生

- “AMS实验测量的反质子与正电子具有类似的能谱特征，预示高能反质子和高能正电子可能有相同的来源...”

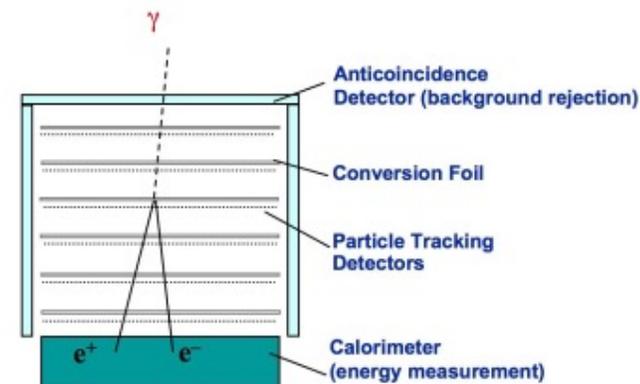
[中国科学院讲座 2023.05.16]



高能光子探测实验

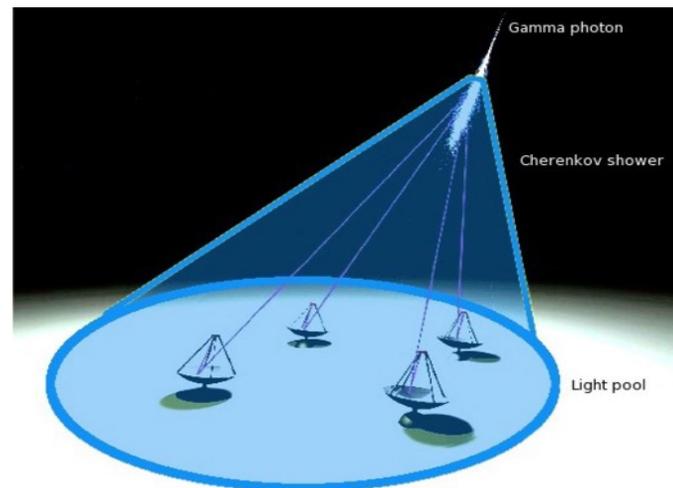
- 空间实验: FermiLAT卫星

 - 量能器



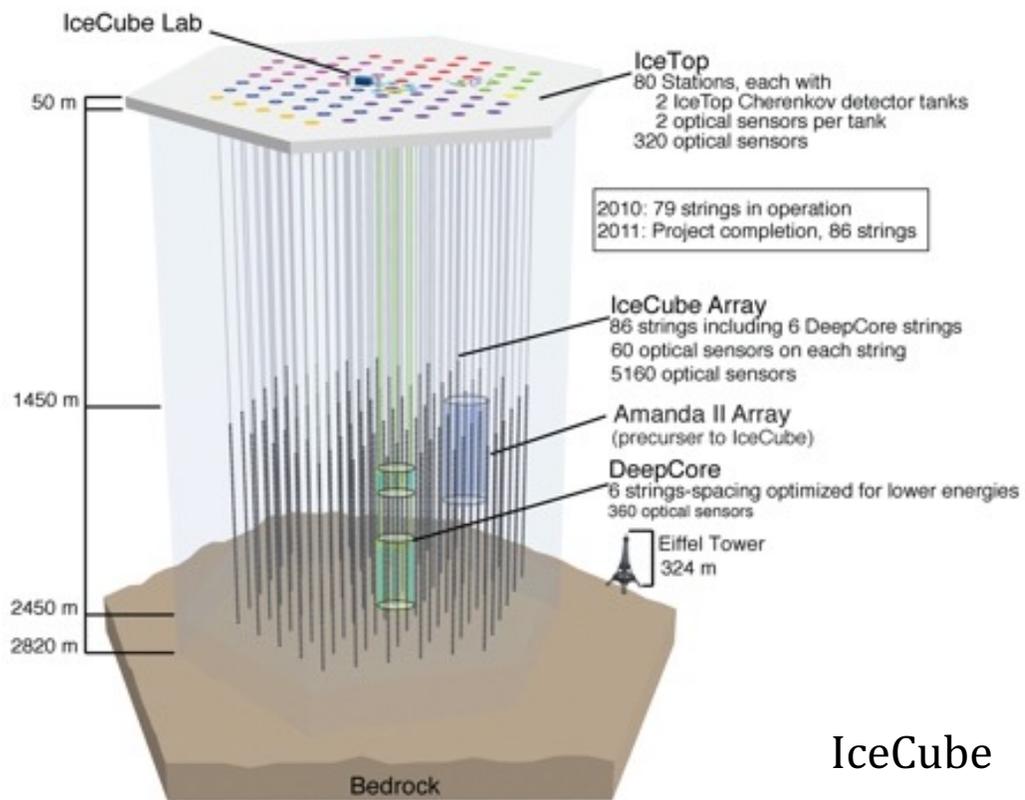
- 地面实验: HESS望远镜

 - 切伦科夫辐射

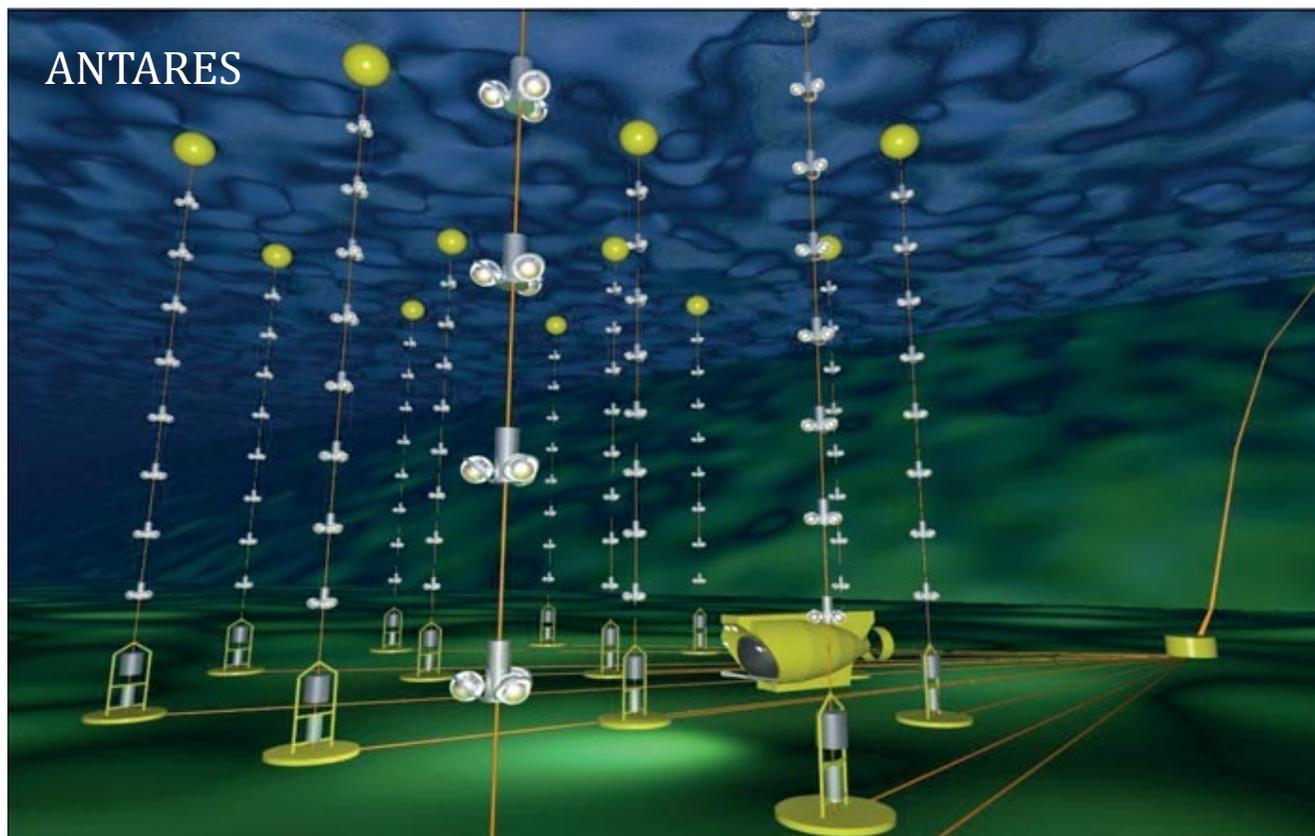


宇宙中微子探测实验

• 大型中微子探测阵列

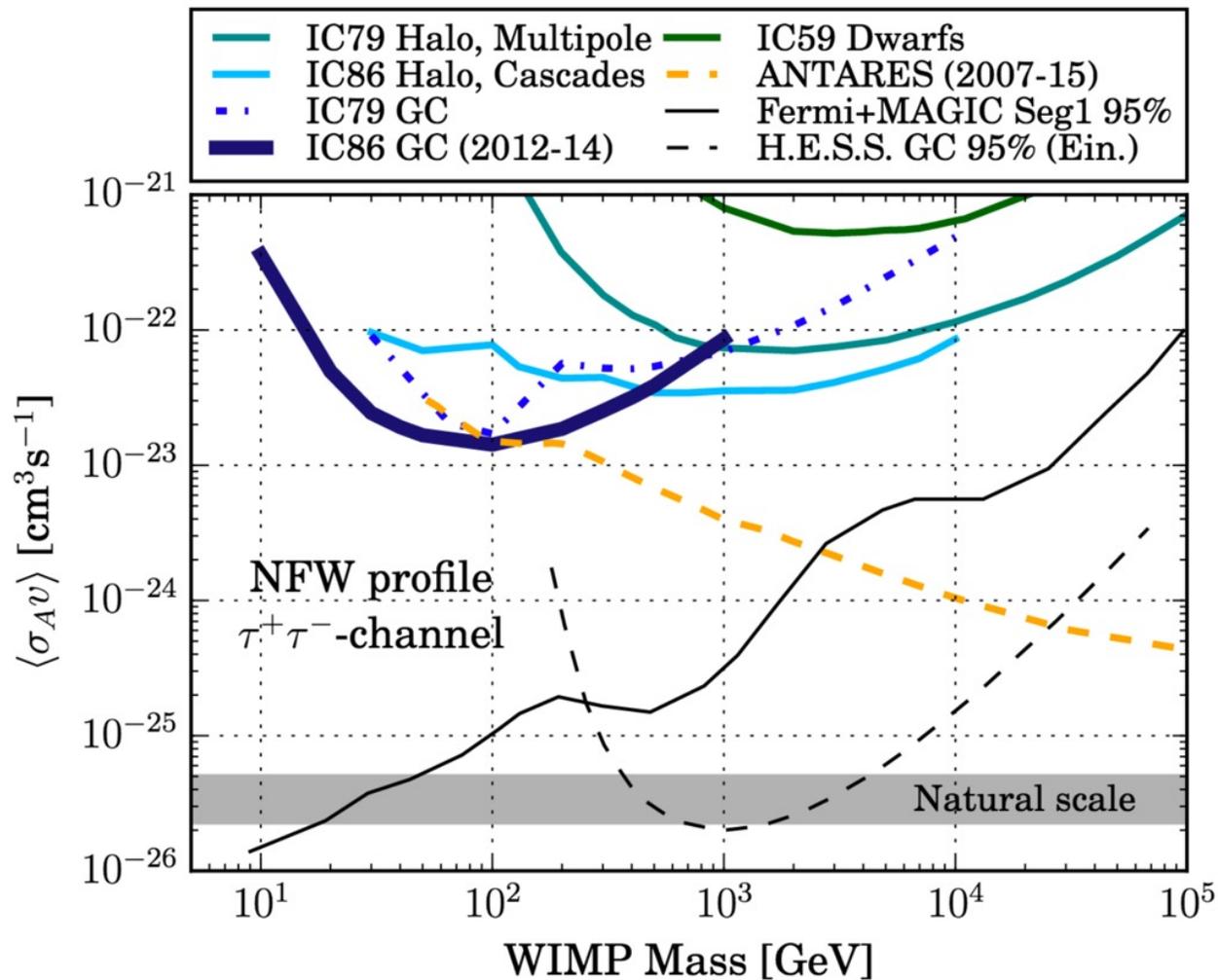


IceCube

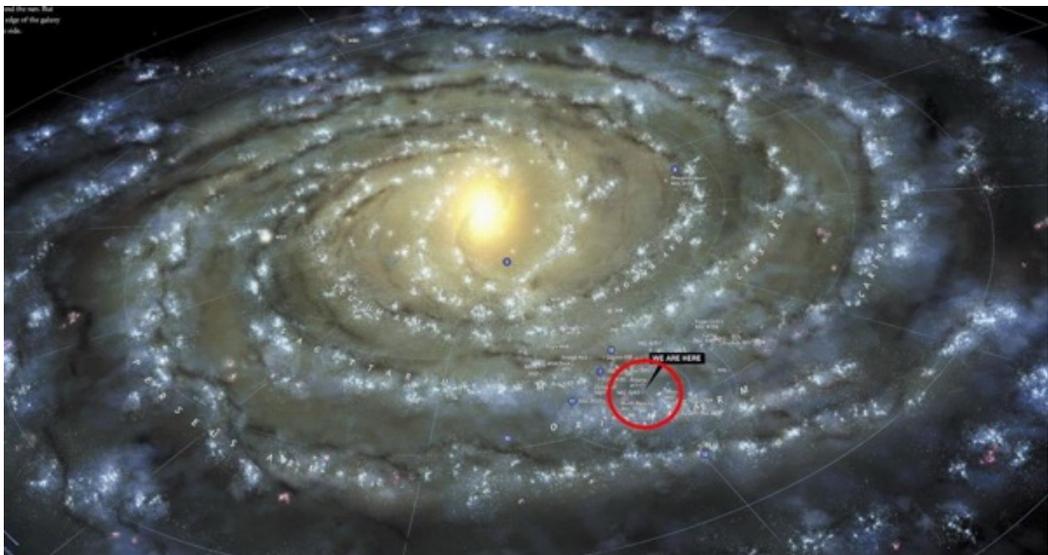


中微子探测结果

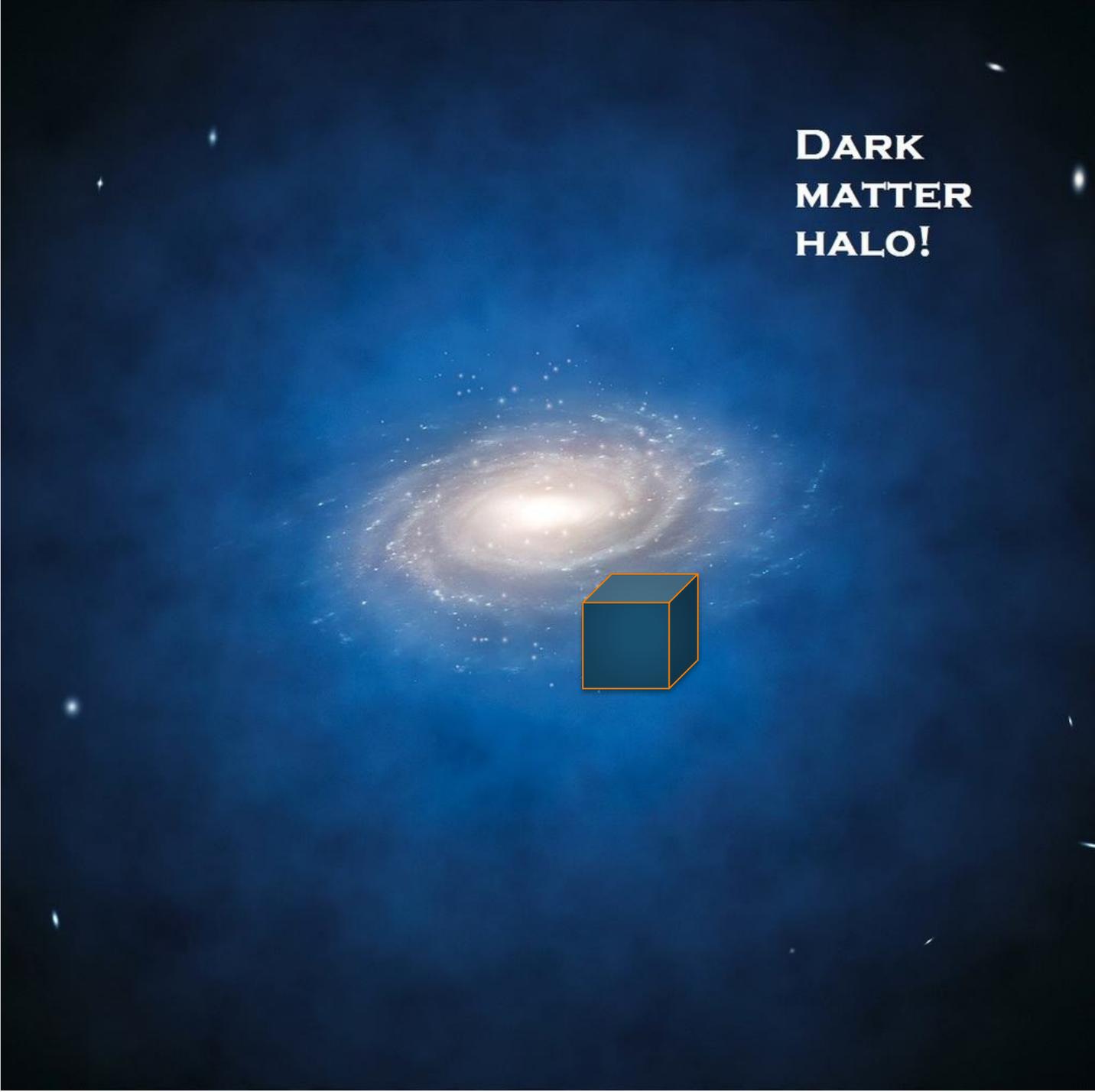
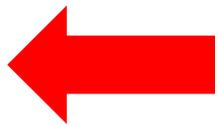
- 对暗物质湮灭截面给出限制



星系中的“雾霾”



- 太阳系附近
- 每立方厘米有1/3质子重量的暗物质



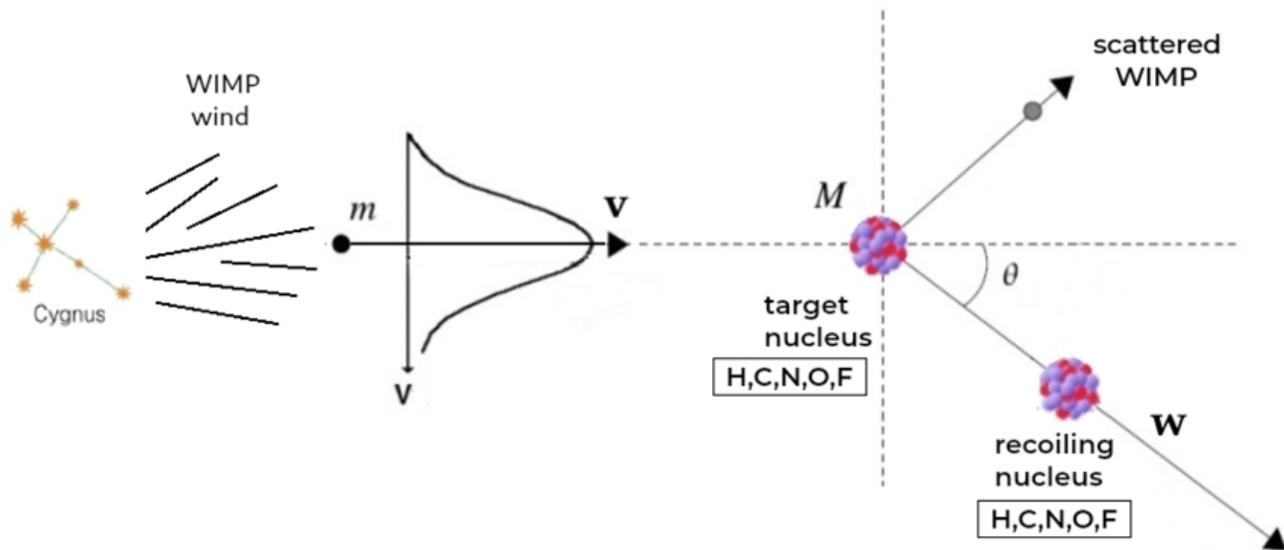
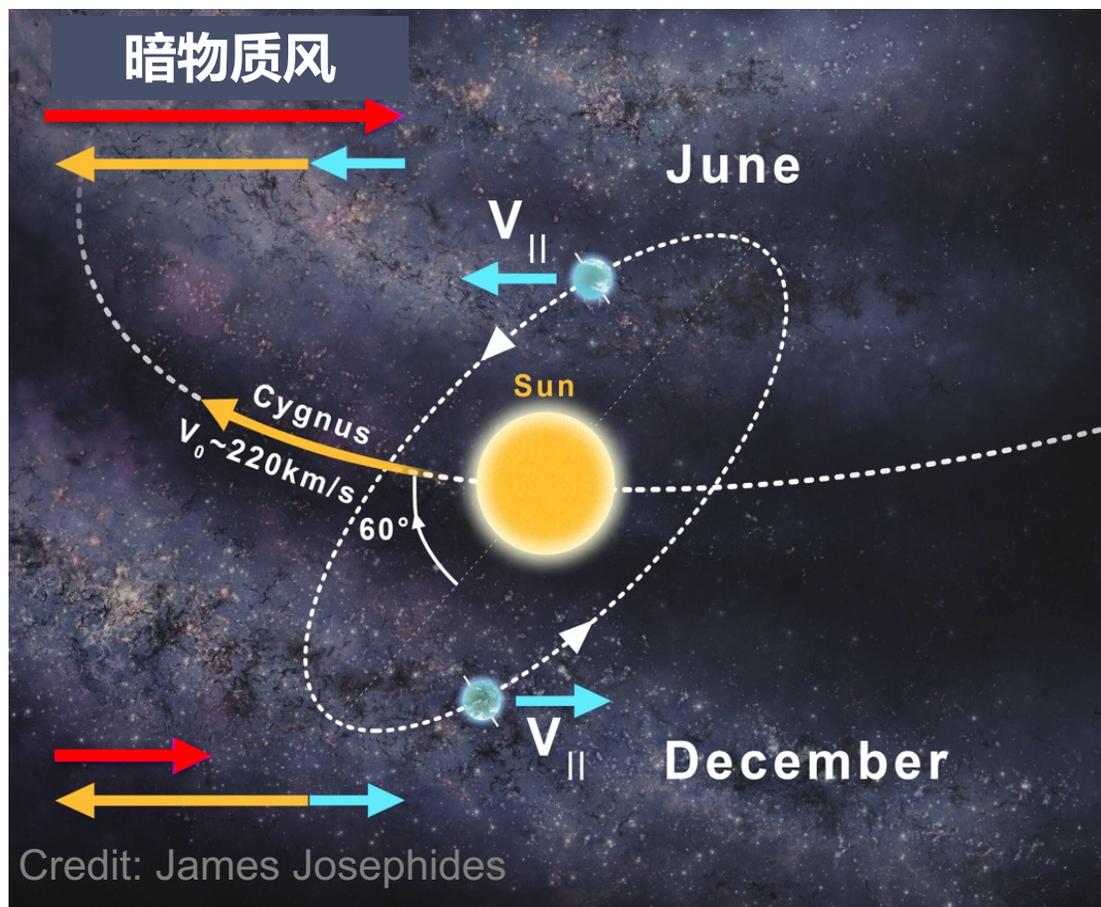
地球上的“暗物质流”

- 太阳系围绕银河中心高速旋转：220公里每秒



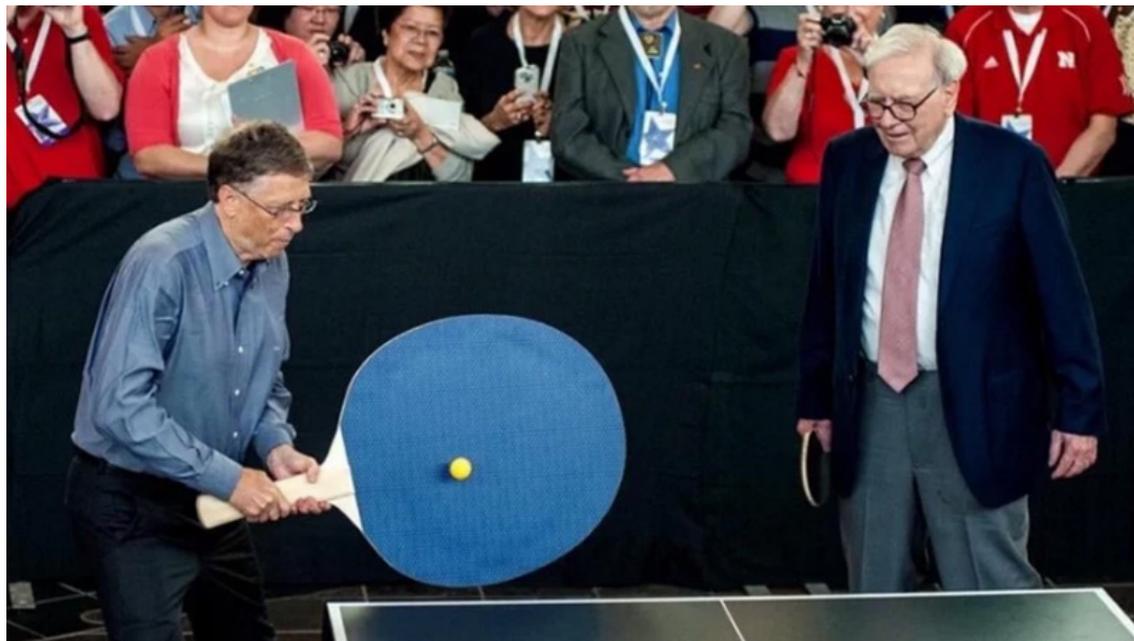
暗物质直接探测

- 测量暗物质和**靶物质碰撞**后原子核**反冲**的信号
 - 1985年提出 (Goodman & Witten), 30年以来探测灵敏度推进六个数量级



什么叫“碰撞”

- 粒子物理学家的语言
– 相互作用



- 当乒乓球和球拍碰上了 => 发生相互作用
 - 暗物质和普通物质有相互作用：会碰撞！
- 相互作用强度越大：越容易碰撞
 - 用球拍的大小来衡量相互作用强度：碰撞截面

什么叫“靶物质”

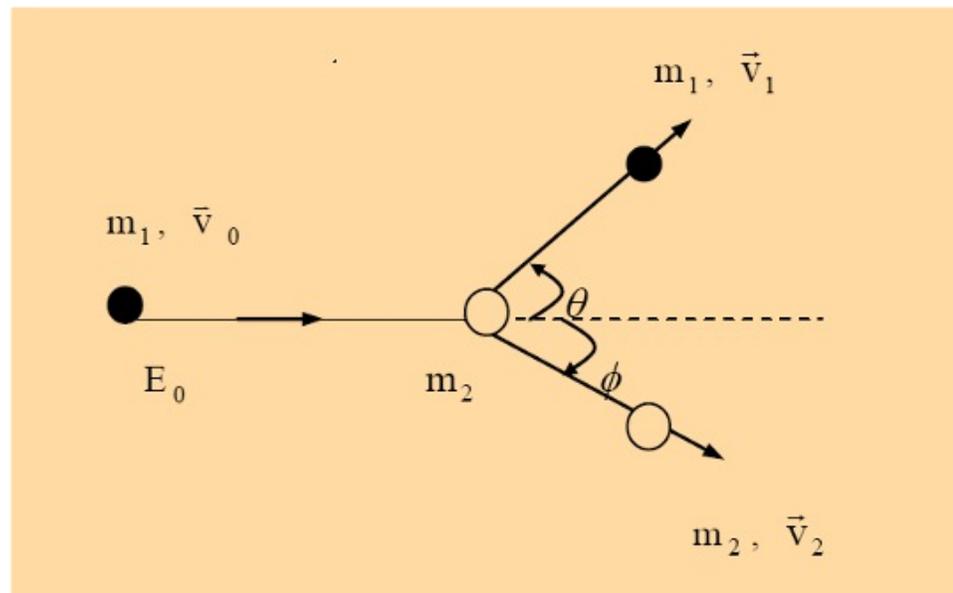
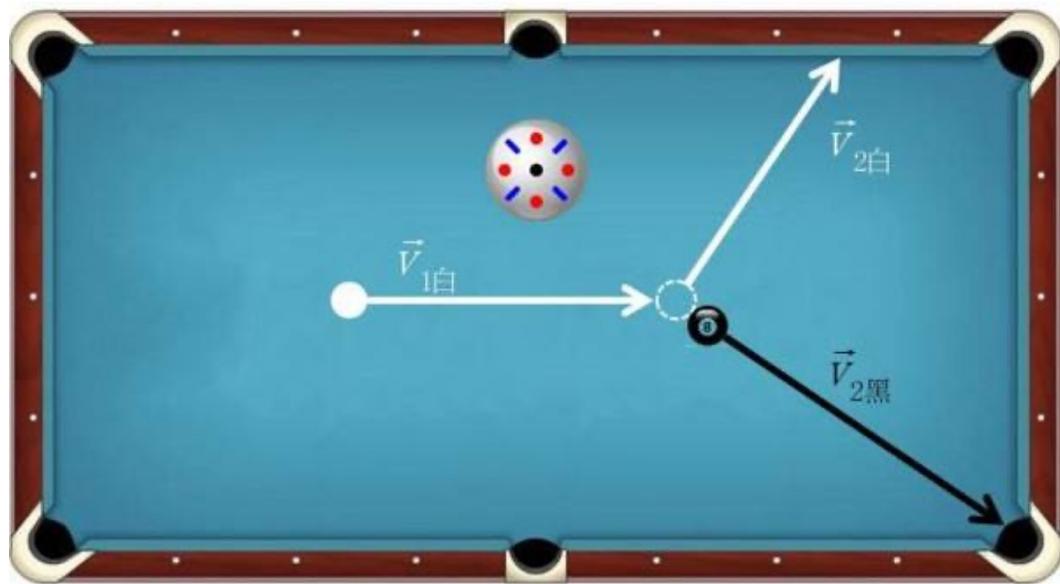
- 怎样可以探测到微弱的“相互作用”

- 大量大量的原子 => 一整块普通物质

- 每人身上有1000000000000000000000000000000000000000(10²⁹)个原子



什么叫“反冲”



- 反冲后的原子携带能量
- 暗物质直接探测就是可以将反冲转化为可观测信号
 - 推断暗物质粒子的质量
 - 测量同普通物质的相互作用强度

暗物质和普通物质容易碰撞么

- 每秒有1000000000(10^9)个暗物质粒子穿过我们
- 每个人身上有 10^{29} 个靶原子
- 可是每年暗物质和每个人碰撞次数 **< 1 次!**



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Dark matter collisions with the human body

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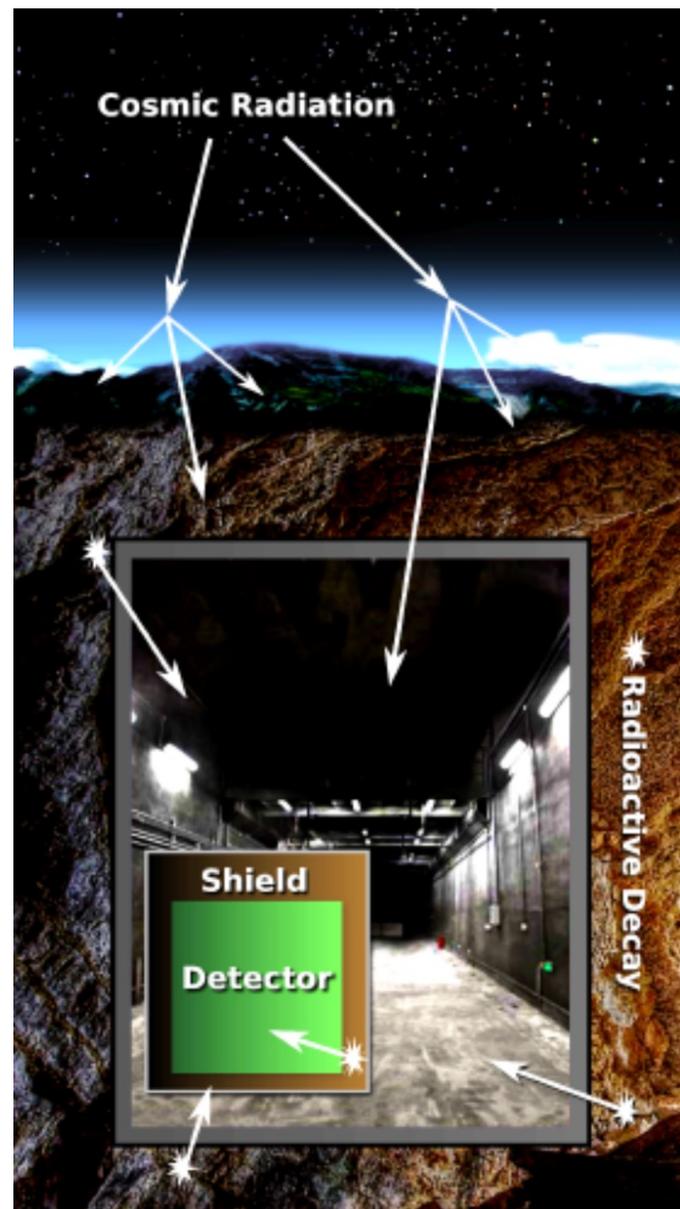
Received 6 September 2012, Accepted 19 September 2012, Available online 24 September 2012.

Editor: S. Dodelson



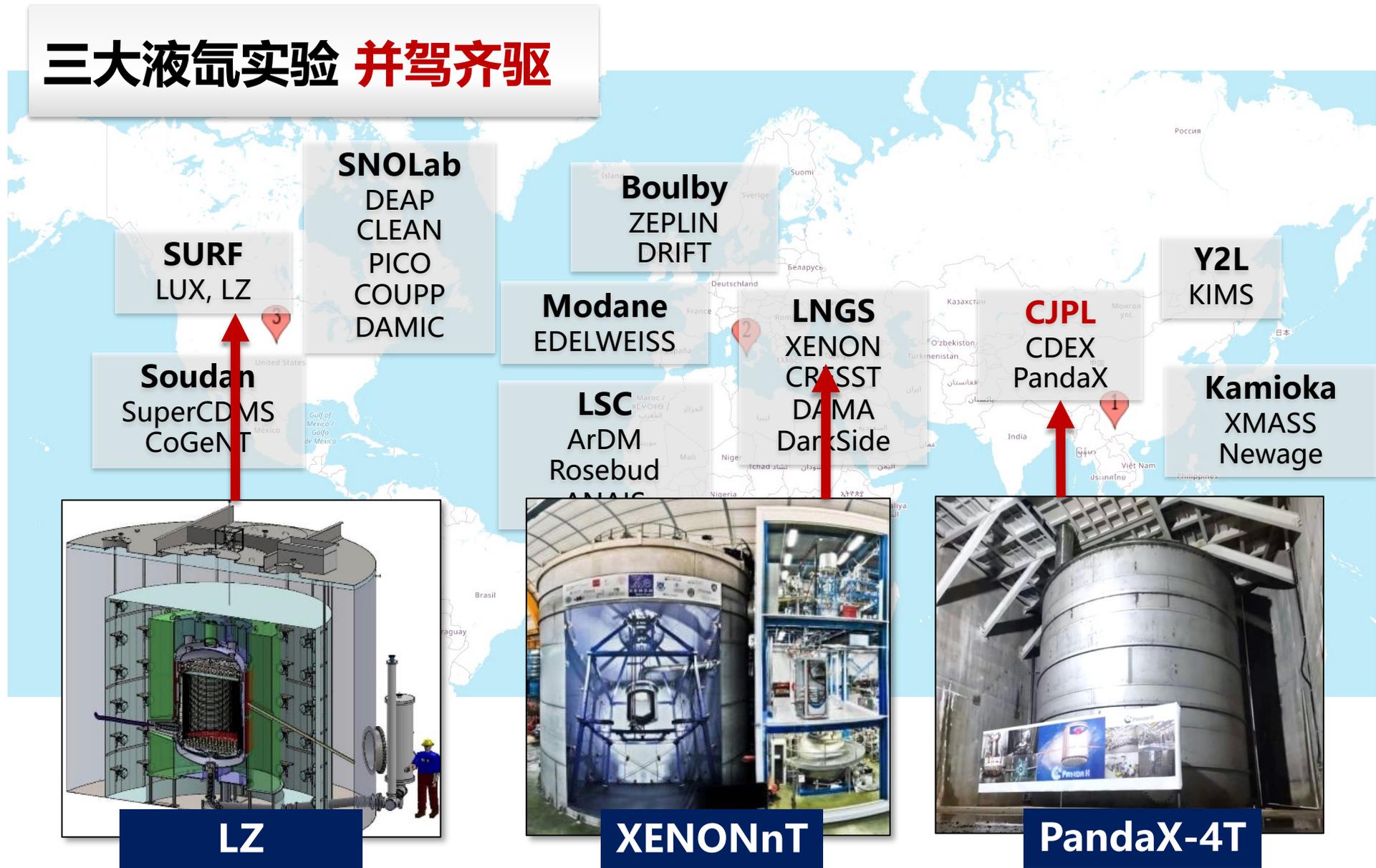
在哪里找暗物质

- 而我们的身体每天和环境中的**宇宙射线**和**伽马射线**碰撞 10^8 次!
 - 宇宙射线：来自宇宙的高能粒子
 - 伽马射线：来自周围原子核衰变
 - 这些假信号的学名叫“**本底**”或“**噪声**”
- 将实验室藏到极深的**地下**，并且将探测器用厚厚的屏蔽层包裹起来



暗物质探测的激烈竞争

三大液氙实验 并驾齐驱



中国地形



图



Gran Sasso mountain, Italy



JinPing mountain, China

Kamioka Observatory, Japan

S

Xenon: 835 kilograms
 : Reported 6.7 days of data.
 or a 1.5-tonne experiment in
 at a cost of US\$12 million.

NIOO

Xenon: 62 kilograms
 : Reported 225 days of data.
 uction begins in 2013 for
 illion tonne-scale experiment.

Xenon: 350 kilograms
 : Taken surface data and has
 orted below ground. Plans for
 onne experiment in 2016-17,
 st of \$30 million.

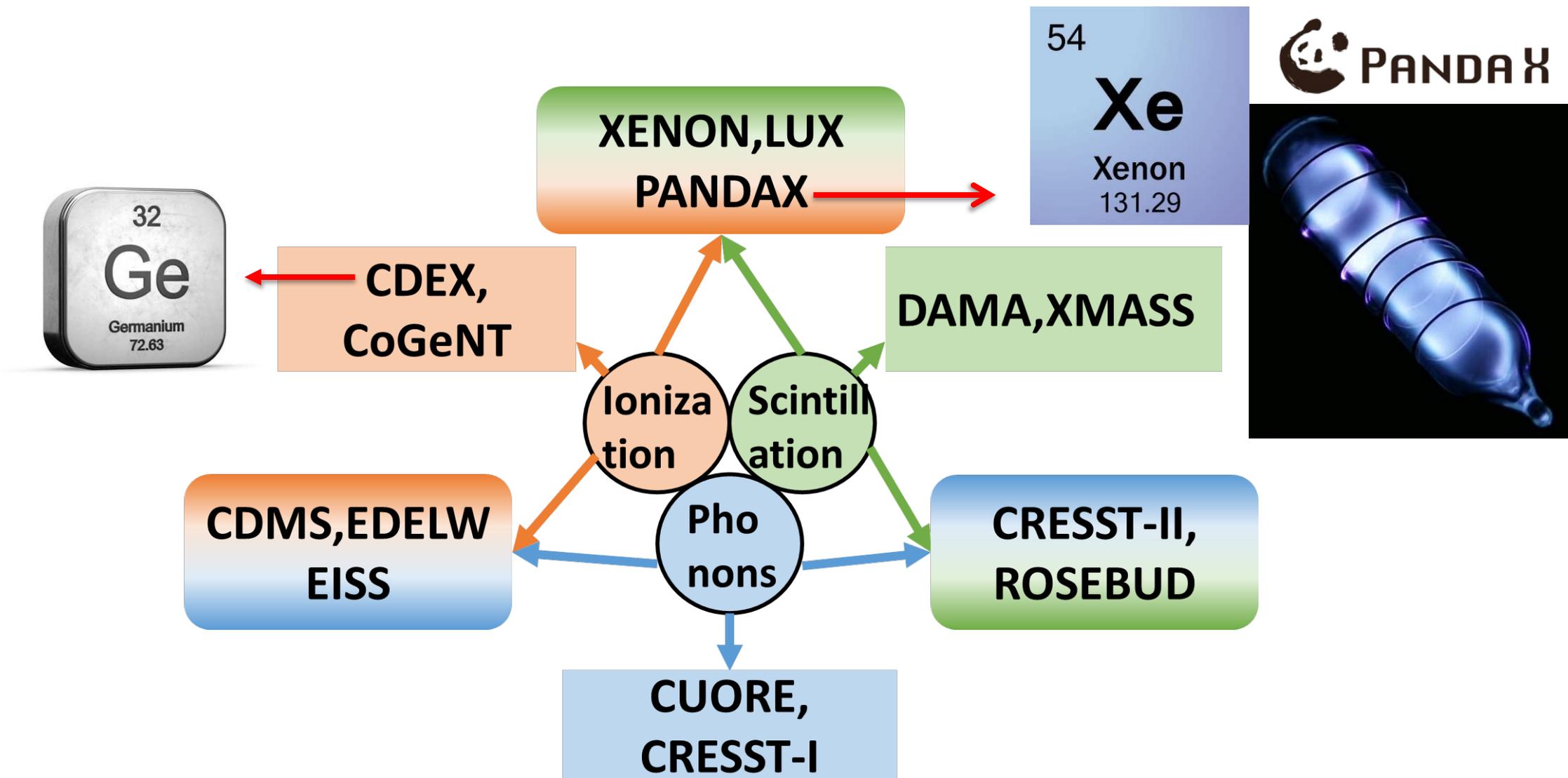
AX

Xenon: 120 kilograms
 : Yet to take data. Plans for
 scale experiment in 2016 at
 of \$15 million.

MASS: Xe detector for weakly interacting massive particles; LUX: Large Underground Xenon detector; PANDAX: Particle and physical Xenon Time Projection Chamber

直接探测信号

- 能量沉积：光、电、热



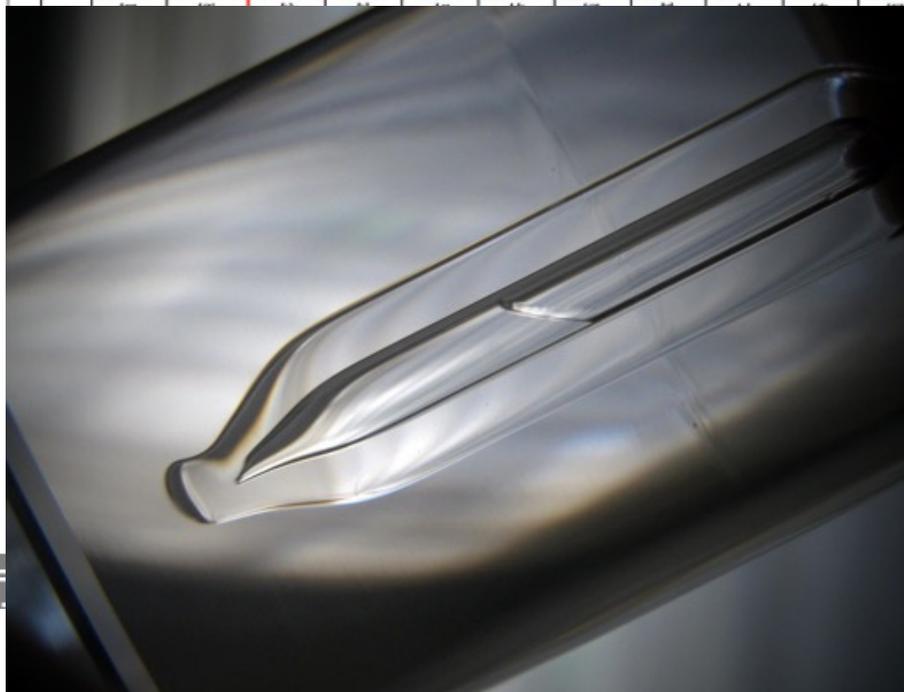
氙: xenon

- 惰性气体
- 空气中0.0087%
- 无色无味
- 密度(液):3g/ml
- 沸点: -100°C
- 全世界年产量: 60吨



元素周期表

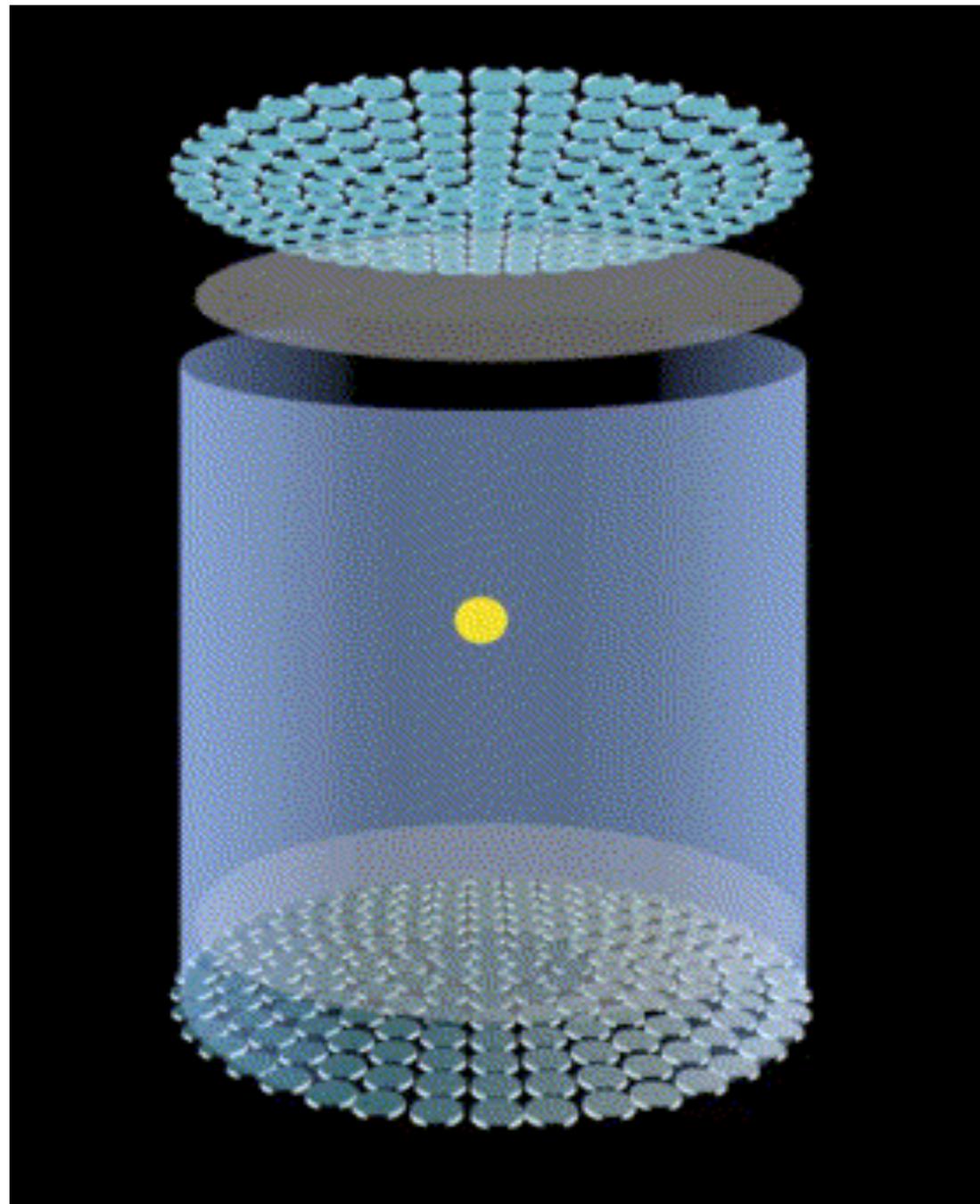
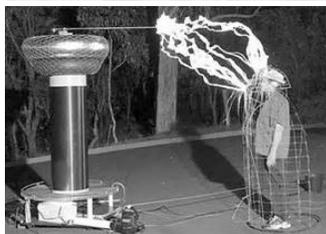
周期	族	I A	II A	III B	IV B	V B	VI B	VII B	VIII	IX	X	IB	II B	III A	IV A	V A	VI A	VII A	0	18	电子层	0 族	电子数											
1		1 H 氢 1.008 1s ¹																	2 He 氦 4.003 1s ²		K		2											
2		3 Li 锂 6.941 2s ¹	4 Be 铍 9.012 2s ²											5 B 硼 10.81 2s ² 2p ¹	6 C 碳 12.01 2s ² 2p ²	7 N 氮 14.01 2s ² 2p ³	8 O 氧 16.00 2s ² 2p ⁴	9 F 氟 19.00 2s ² 2p ⁵	10 Ne 氖 20.18 2s ² 2p ⁶		L		8											
3		11 Na 钠 22.99 3s ¹	12 Mg 镁 24.31 3s ²											13 Al 铝 26.98 3s ² 3p ¹	14 Si 硅 28.09 3s ² 3p ²	15 P 磷 30.97 3s ² 3p ³	16 S 硫 32.06 3s ² 3p ⁴	17 Cl 氯 35.45 3s ² 3p ⁵	18 Ar 氩 39.95 3s ² 3p ⁶		M		8											
		19 K 钾	20 Ca 钙	21 Sc 钪	22 Ti 钛	23 V 钒	24 Cr 铬	25 Mn 锰	26 Fe 铁	27 Co 钴	28 Ni 镍	29 Cu 铜	30 Zn 锌 65.41 4s ¹	31 Ga 镓	32 Ge 锗	33 As 砷	34 Se 硒	35 Br 溴	36 Kr 氪 83.80 4s ¹		N		8											
													37 Rb 铷 85.47 5s ¹	38 Sr 锶	39 Y 钇	40 Zr 锆	41 Nb 铌	42 Mo 钼	43 Tc 锝 98.906 5s ¹	44 Ru 钌	45 Rh 铑	46 Pd 钯	47 Ag 银 107.868 5s ¹	48 Cd 镉 112.411 5s ²	49 In 铟	50 Sn 锡	51 Sb 锑	52 Te 碲	53 I 碘	54 Xe 氙 131.3 5s ²		O		8
													55 Cs 铯 132.905 6s ¹	56 Ba 钡	57 La 镧	58 Ce 铈	59 Pr 镨	60 Nd 钕	61 Pm 钷 144.9126 6s ¹	62 Sm 钐	63 Eu 铕	64 Gd 钆	65 Tb 铽	66 Dy 镝	67 Ho 铥	68 Er 铒	69 Tm 铥	70 Yb 镱	71 Lu 镥		N		8	
													72 Hf 铪	73 Ta 钽	74 W 钨	75 Re 铼	76 Os 锇	77 Ir 铱	78 Pt 铂	79 Au 金	80 Hg 汞 200.59 6s ²	81 Tl 铊	82 Pb 铅	83 Bi 铋	84 Po 钋	85 At 砹	86 Rn 氡 222 6s ²		M		18			
													87 Fr 钫	88 Ra 镭	89 Ac 锕	90 Th 钍	91 Pa 镤	92 U 铀 238.02891 5f ³ 6d ¹ 7s ²	93 Np 镎	94 Pu 钚	95 Am 镅	96 Cm 锔	97 Bk 锫	98 Cf 锿	99 Es 镄	100 Fm 镆	101 Md 镎	102 No 镎	103 Lr 铹		L		8	
													104 Rf 𨨏	105 Db 𨨐	106 Sg 𨨑	107 Bh 𨨒	108 Hs 𨨓	109 Mt 𨨔	110 Ds 𨨕	111 Rg 𨨖	112 Uub 𨨗	113 Nh 𨨘	114 Fl 𨨙	115 Mc 𨨚	116 Lv 𨨛	117 Ts 𨨜	118 Og 𨨝		K		2			



注: 相对原子质量取自2001年国际原子量表, 并全部取4位有效数字。

两相型氙探测器

- 大靶子
- 极灵敏的量能器
- 3D照相机
- 信号和噪声甄别
- 强大的自屏蔽



PandaX Experiment

- 不断增大探测靶质量
- 不断降低探测器噪声

PandaX start



2009

PandaX-I
120kg



2010-2014

PandaX-II
580kg



2015-2019

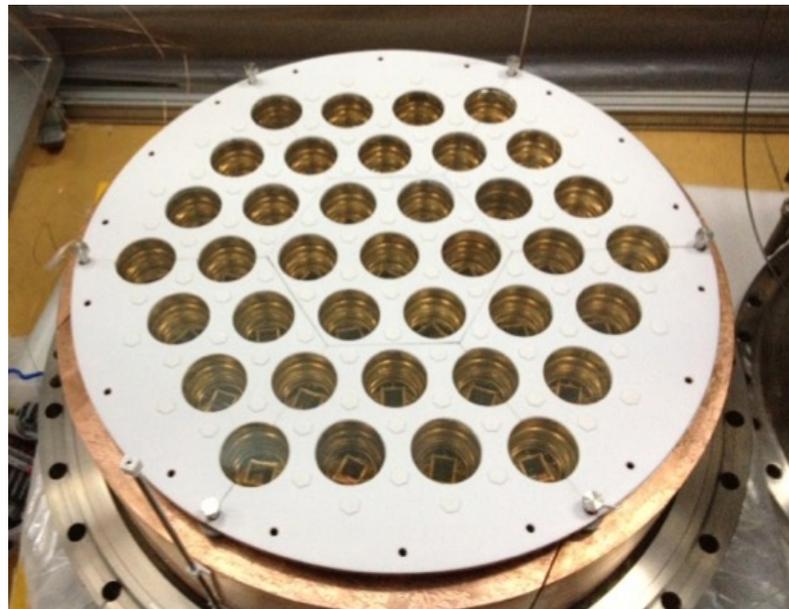
PandaX-4T
(3.7 tonne)



2020-

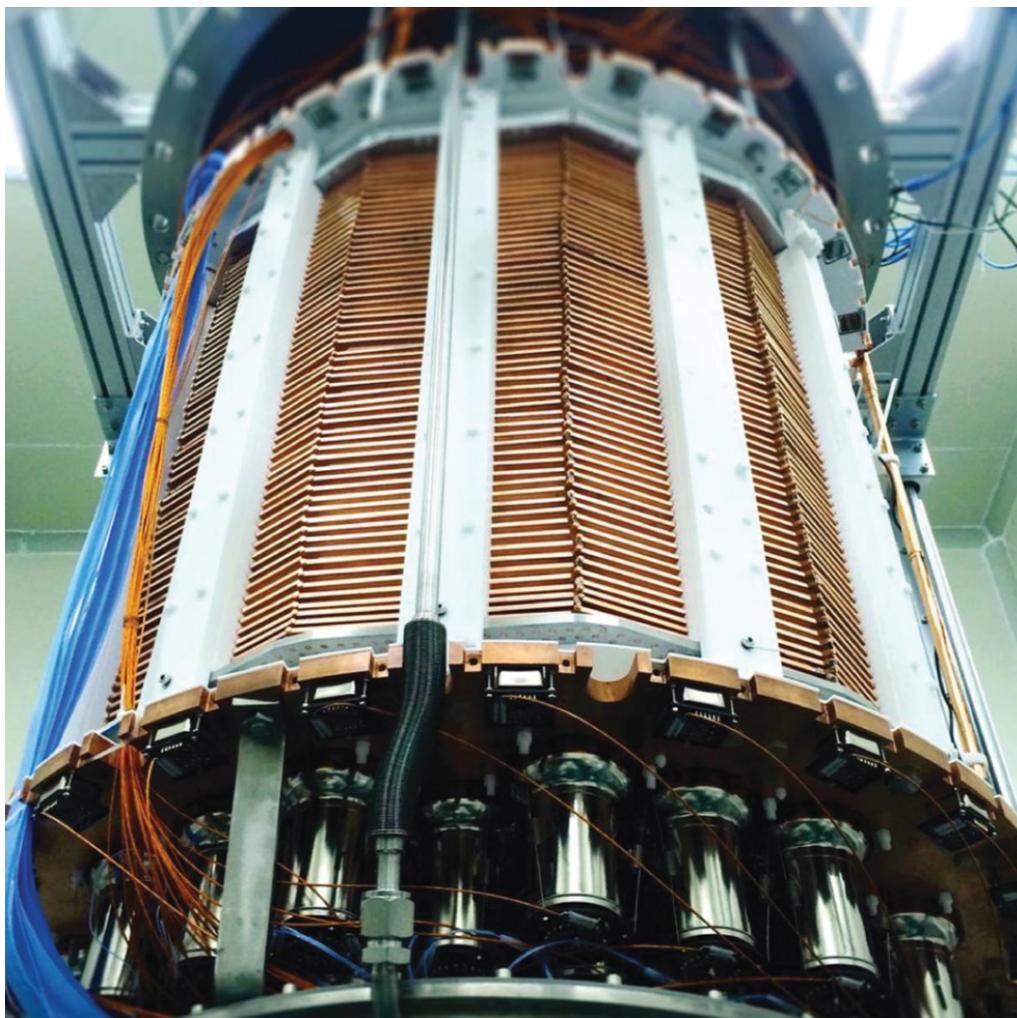
2009-2014: PandaX首期实验

- 用了5年时间，建成了第一个
120公斤的液氙“蛋糕”

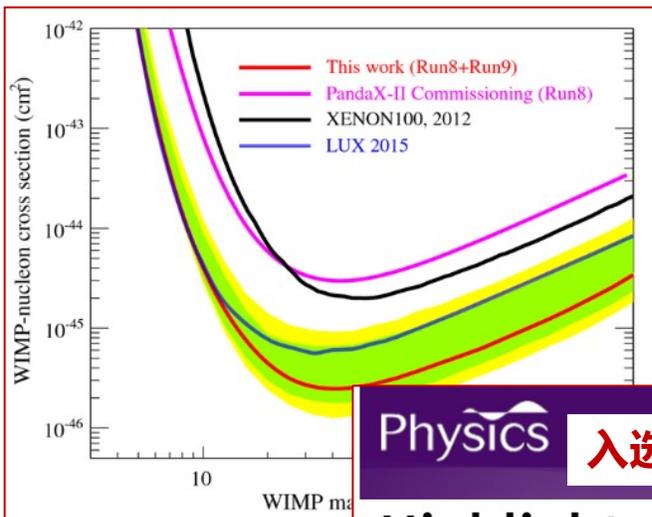
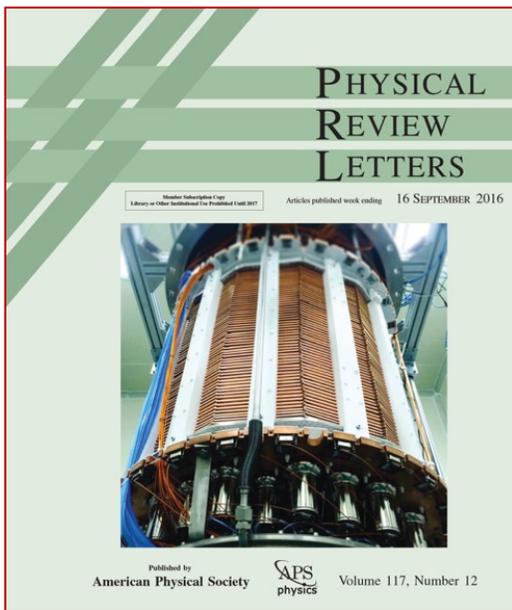


2015-2019: PandaX二期实验

- “蛋糕”升级成了一个580公斤的“冰淇淋桶”



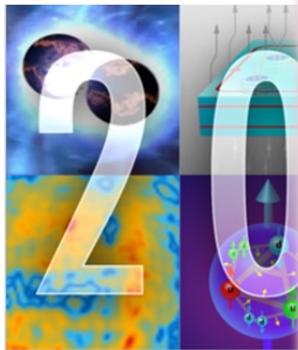
PandaX二期成果



PandaX-II PRL

Physics 入选APS《物理

Highlights of the Year



Writing in January about the null results from PandaX-II in China, Jodi Cooley said that some of the simplest WIMP model (see Viewpoint: Dark Matter) when XENON1T in Italy (2000 kg) and PandaX-II WIMP searches had also come up empty, Dark Matter research was in “a state of major disruption” (for Dark Matter).

科技导报2017,35(3)



2016年中国重大科学、技术和工程进展

陈广仁, 刘志远, 田恬, 祝叶华

《科技导报》编辑部, 北京 100081

摘要 本着门类类别、本刊推荐、专家遴选、宁缺毋滥、叙述事实的原则,从国内外重要科技期刊和科技新闻媒体所报道的中国科技成果中,按科学、技术、工程3个类别,由《科技导报》编辑部遴选、推荐候选条目,经《科技导报》编委、审稿人等专家通信评选,推选出2016年度中国重大科学、技术、工程进展30项。1) 2016年中国重大科学进展10项: 精子RNA可作为记忆载体将获得性性状跨代遗传; 构建出世界上首个非人类灵长类自闭症模型; 提出基于胆固醇代谢调控的肿瘤免疫治疗新方法; 首次在原子尺度揭示水的核量子效应; 实验证实马约拉纳费米子的存在; 揭示RNA剪接的关键分子机制; PandaX-II实验对暗物质粒子特性给出迄今最强的限制; 揭示水稻产量性杂种优势的分子遗传机制; 在玻色-爱因斯坦凝聚态中实现来自二维自旋-轨道耦合; 揭示胚胎发育过程中关键信号通路的表现遗传调控机理。2) 2016年中国重大技术进展10项: 新型钴基催化剂可将CO₂高效清转化

高等学校科学研究优秀成果奖 (科学技术)

证书

项目名称: 液氦暗物质探测研究

奖励类别: 自然科学奖

奖励等级: 一等奖

获奖者: 上海交通大学



证书编号: 2022-050-D01

2022年教育部自然科学一等奖

2016中国重大科学进展

实验物理学家的真实生活

- **2015年漫长的调试，解决了无数预期不到的问题**

- 《五年青春，我成为了一名山底洞人》（作者：谈安迪）

- 可惜事与愿违，探测器经过包括2015年春节在内的三个月紧张的安装后进入调试运行，发现有漏，氙气以不可接受的速率泄漏到外真空层并造成损失。

- 修复了这个压力容器泄漏的问题，又过了一个多月，我们发现了探测器出现了奇怪的信号，紧接着经过了两个月的研究，我们推断它来自于电极加工的不完美，这种奇怪的信

- 又过了两个月，第三次失败，谁还没经历过一些失败呢，过一过二不过.....过一过二过三不过四嘛.....

- 又过了两个月，出现了一种新的干扰信号，第四次失败.....

- **最终我们在11月22日准备完成，开始数据采集！！！！**

- **19天后，我们发现了一种新的内部本底氦85... 停止采集数据！！！！**

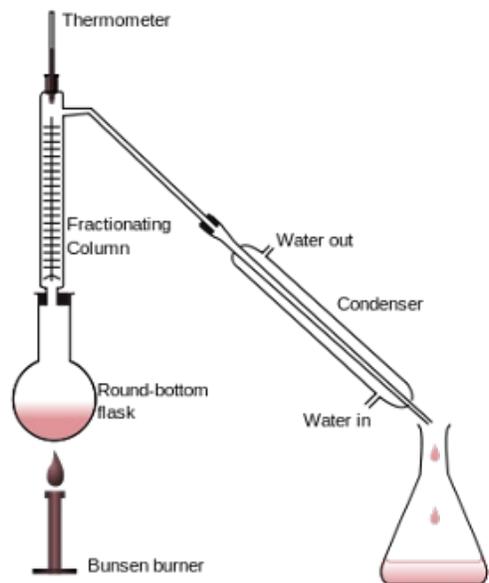
放射性气体：氪气

- 空气中有0.000001的**氪气**
- ^{85}Kr (贝塔衰变, 半衰期10年) 是核时代的产物, 大约占天然氪的0.000000000002 (2×10^{-11})
- 但是, 即使是稀少的氪气混入探测, 也会产生讨厌的本底噪声信号!



氦精馏系统

- 通过不同沸点分离不同气体



- PandaX实验建了一个10米高精馏塔，要求氦气含量降到 10^{-12} 量级！
 - 1公斤氦中仅100个氦-85原子

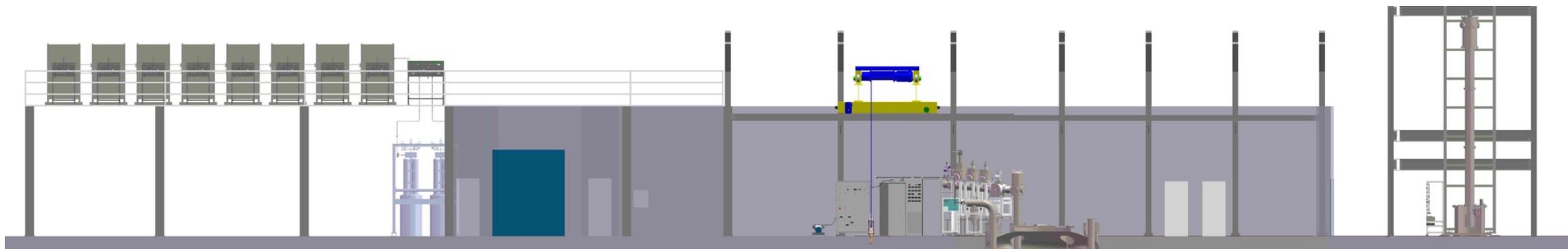


PandaX-4T 建设历程

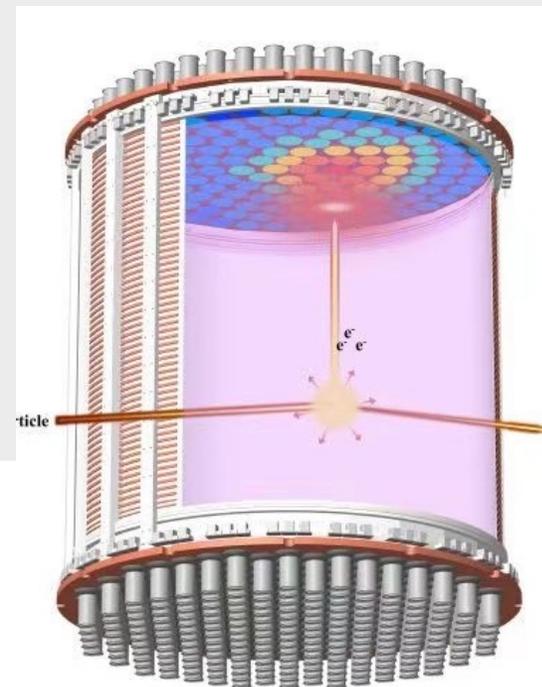
- **2018/04/02**
 - 开始建设B2大厅
- **2019/08/19**
 - 完成基础建设，探测器进驻大厅
- **2020/05/06**
 - 完成全部氙的离线精馏
- **2020/05/28**
 - 实验安装完成
- **2020/11/28 – 2021/04/16**
 - 实验调试运行



PandaX-4T @ CJPL-II

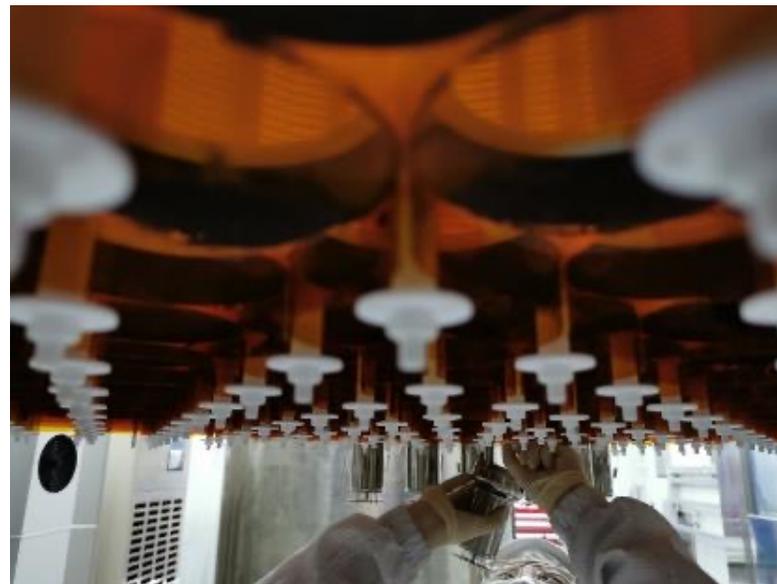
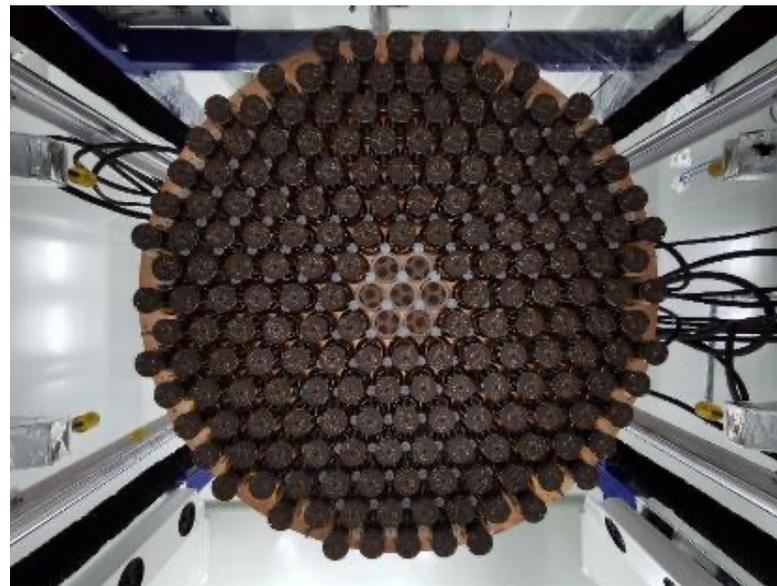


- **高纯水屏蔽体**
 - 13m H x 10m D ~ 900 m³
- **TPC探测器: 3.7-tonne of LXe**
 - 1.2m H x 1.2m D
- **3-inch PMTs: 169 顶部 / 199 底部**

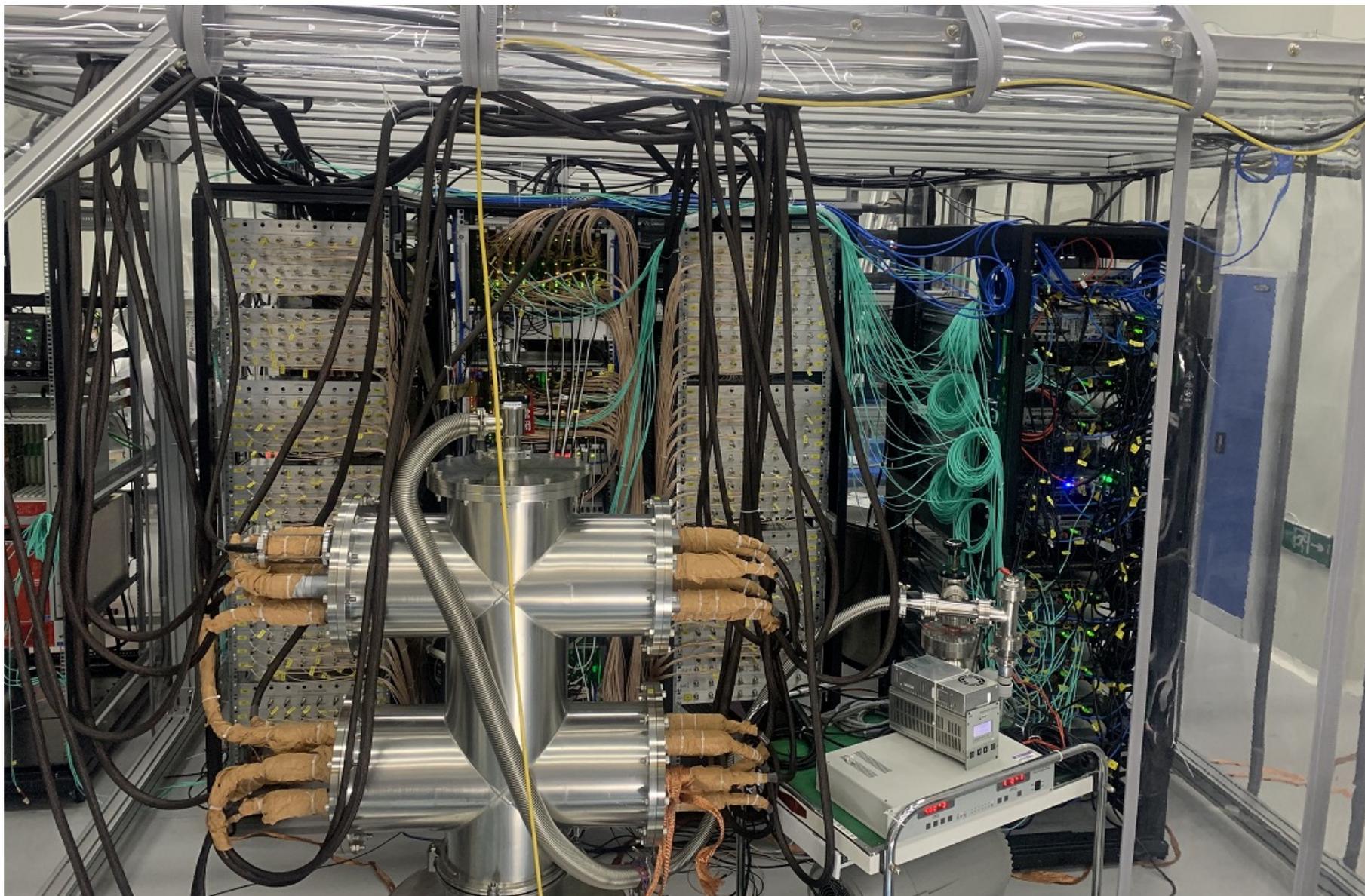




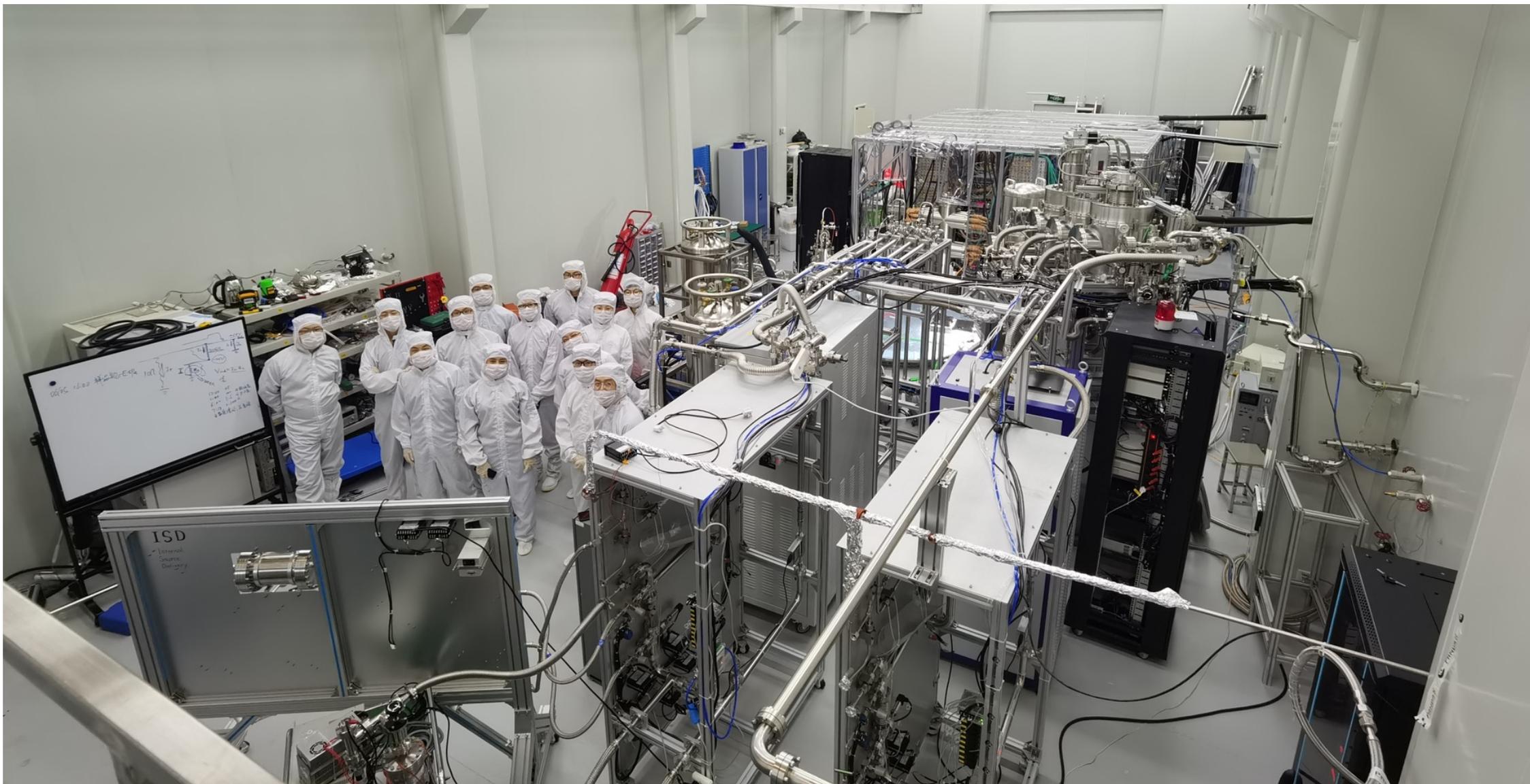
时间投影室和光电读出系统



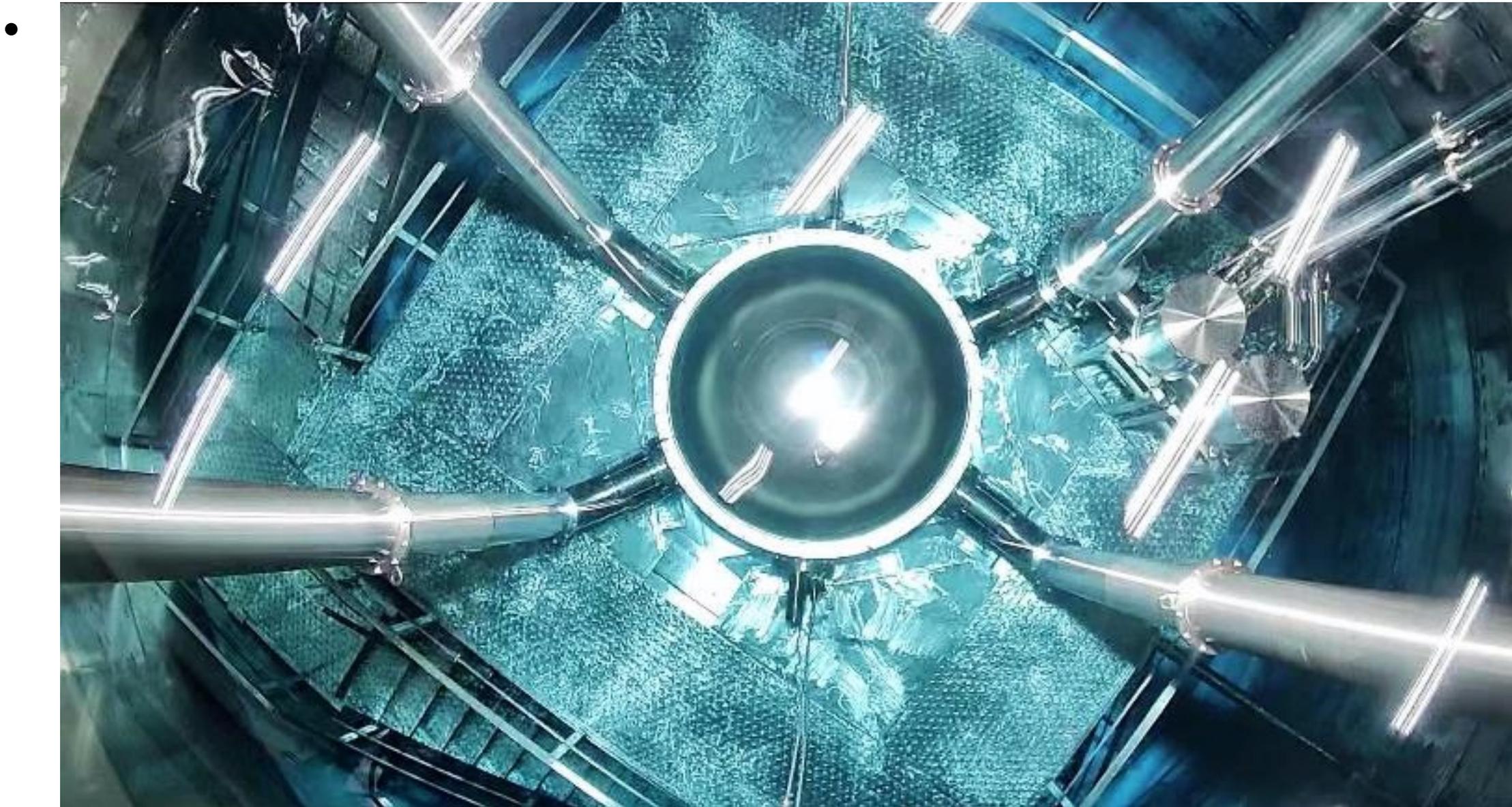
电子学和数据获取系统



制冷和提纯系统

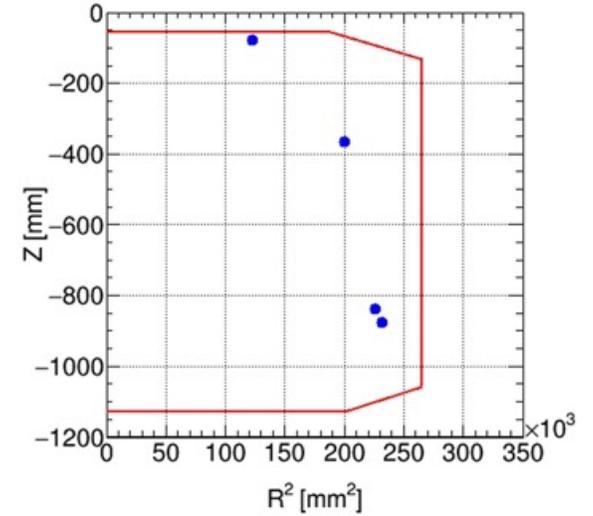


PandaX-4T试运行

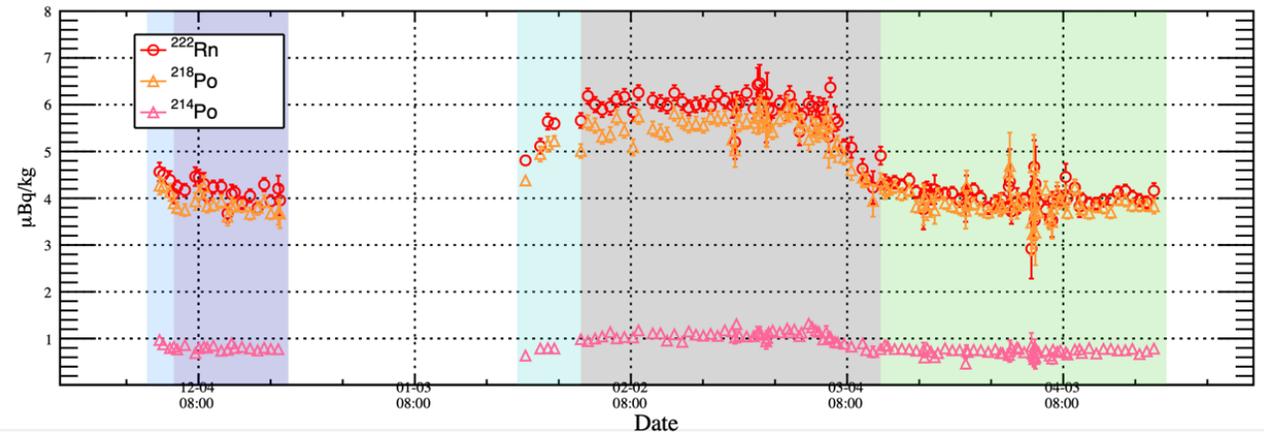


PandaX-4T重大改进

- 采用无触发读出模式，有效降低阈值
 - 每个PMT过阈 (20ADC ~ 1/3 PE) 读出
 - 单光子效率 96%
- 放射性杂质 ^{85}Kr ，比PandaX-II降低20倍
 - 达到0.3 ppt mol/mol
- 放射性杂质 ^{222}Rn ，比PandaX-II降低6倍
 - 达到 ~ 5 uBq/kg

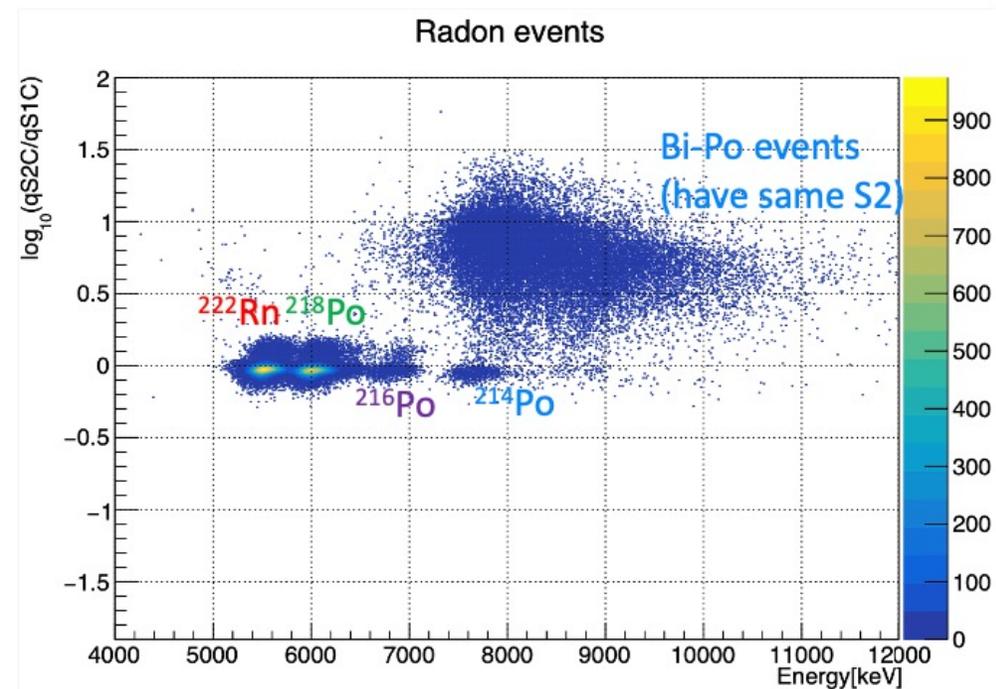
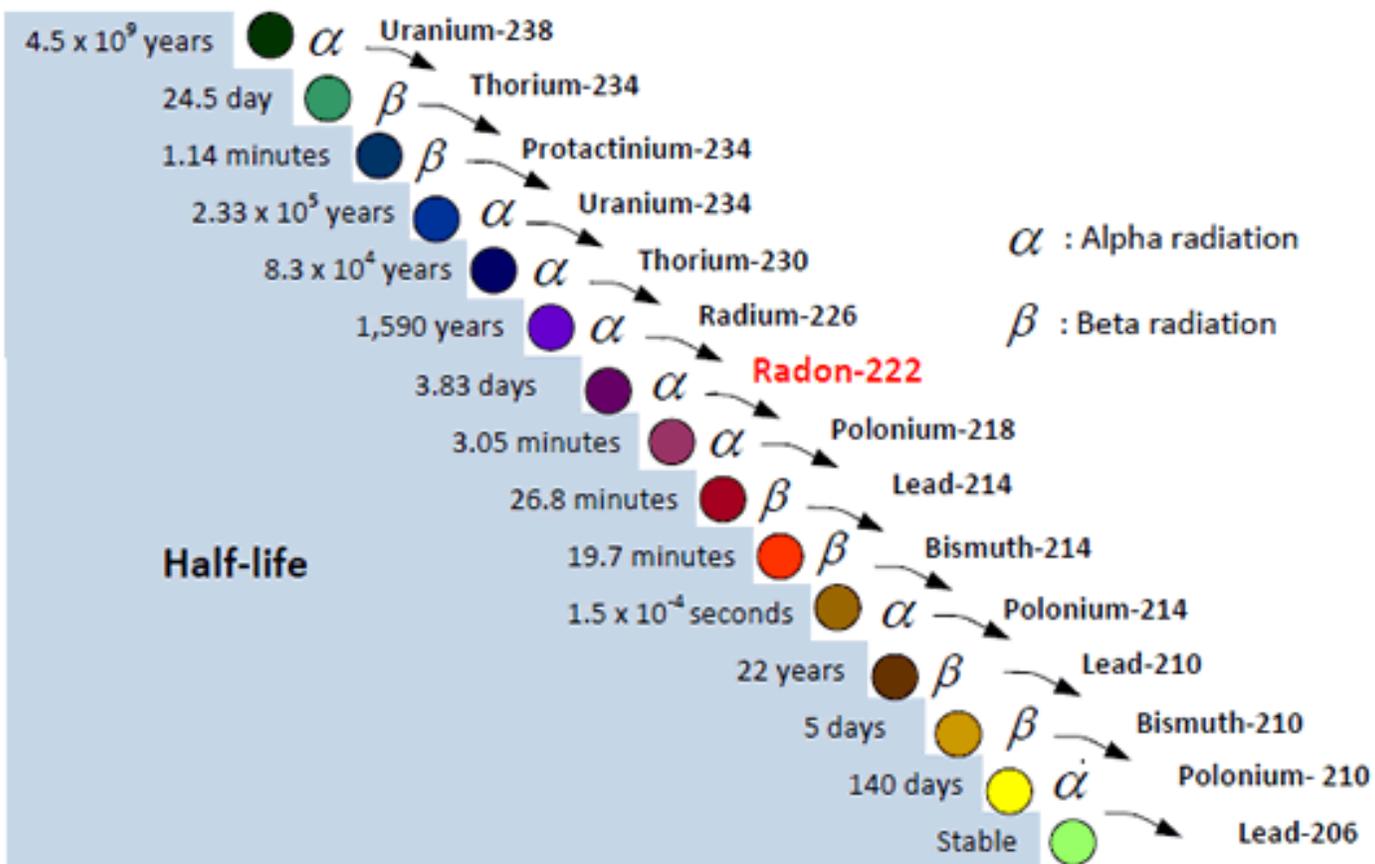


Vertex distribution of β - γ candidates



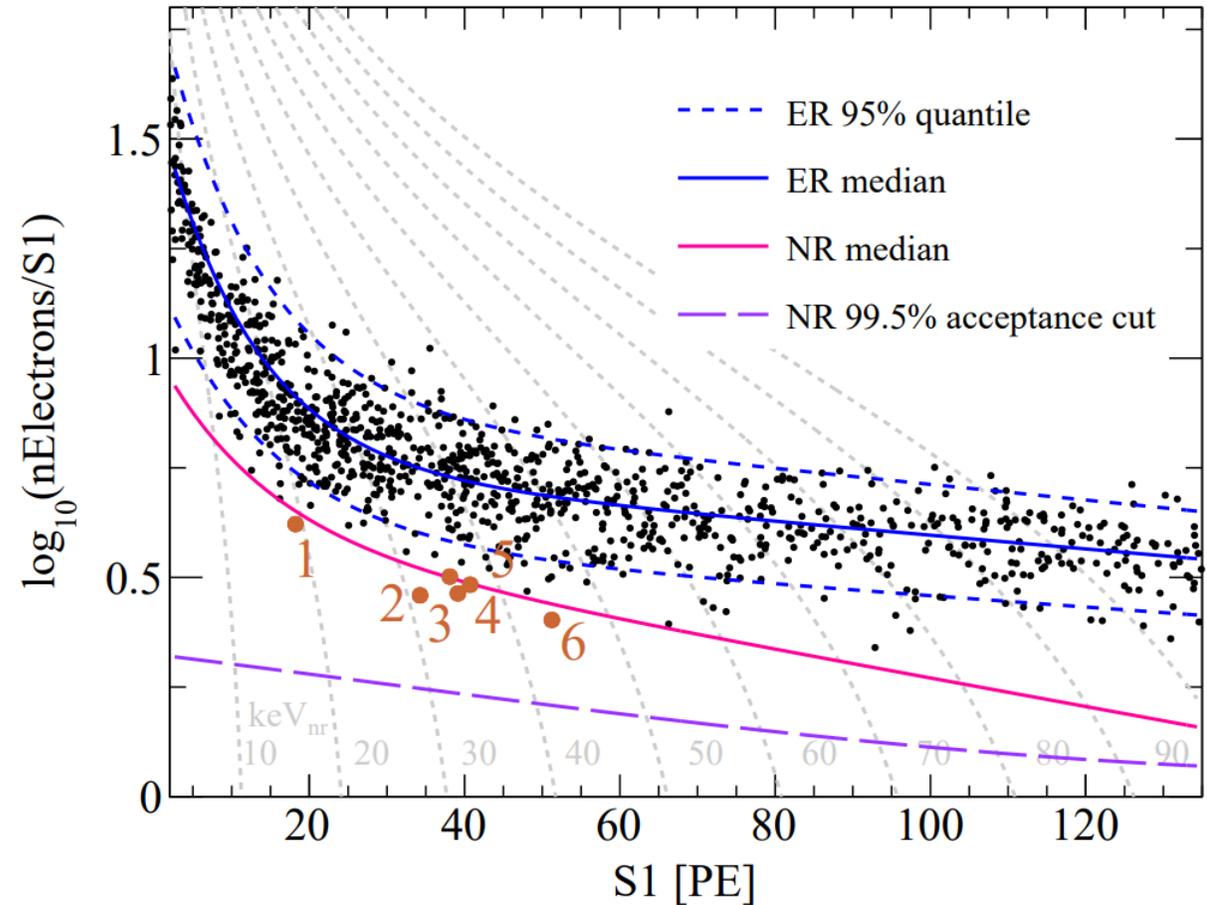
放射性氡杂质

- ^{222}Rn
 - long-lived daughter



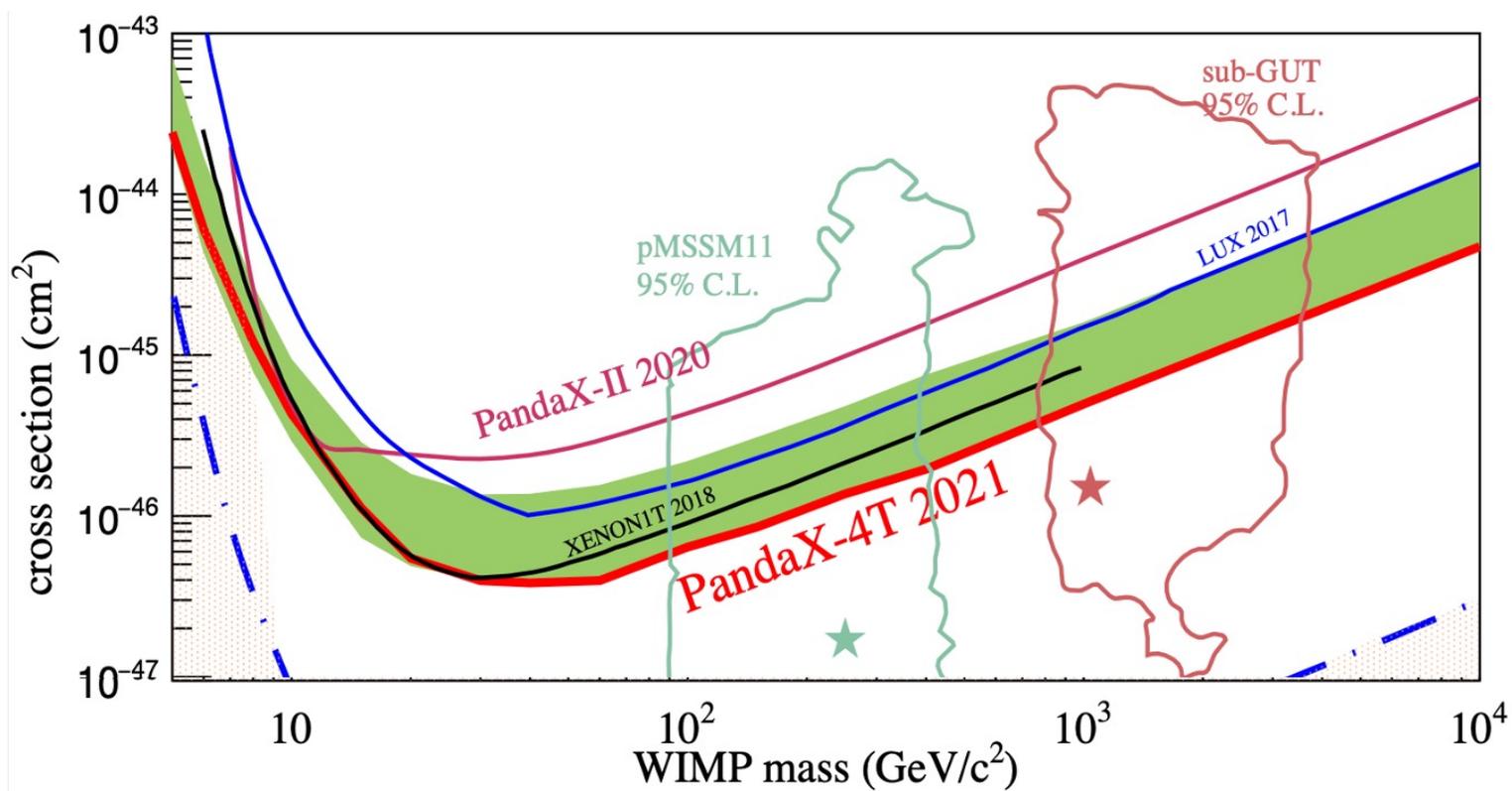
95天试运行数据

- 置信区间氦量: 2.67 tonne
- 曝光量: 0.64 tonne-year
- 事例筛选条件
 - S1: 2 – 135 PE
 - S2raw: > 80 PE
 - S2 < 20000
- 置信区间数据
 - 1058 candidates
 - 6 below NR median line



PandaX-4T首批数据结果

- **超越**XENON实验之前最好结果，**刷新**暗物质和核子自旋无关散射截面的上限，扫描**更大范围**理论预言参数空间



How dark is dark matter?

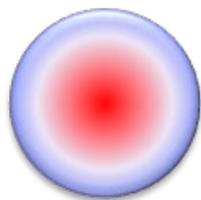


暗物质电磁属性

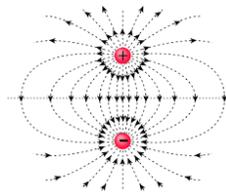
- 类比已知中性粒子，暗物质也可能存在一些**极其微弱的电磁属性**



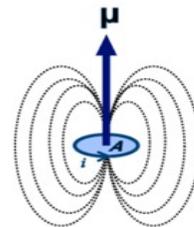
微弱电荷
millicharge



电荷半径
charge radius



电偶极矩
electric dipole



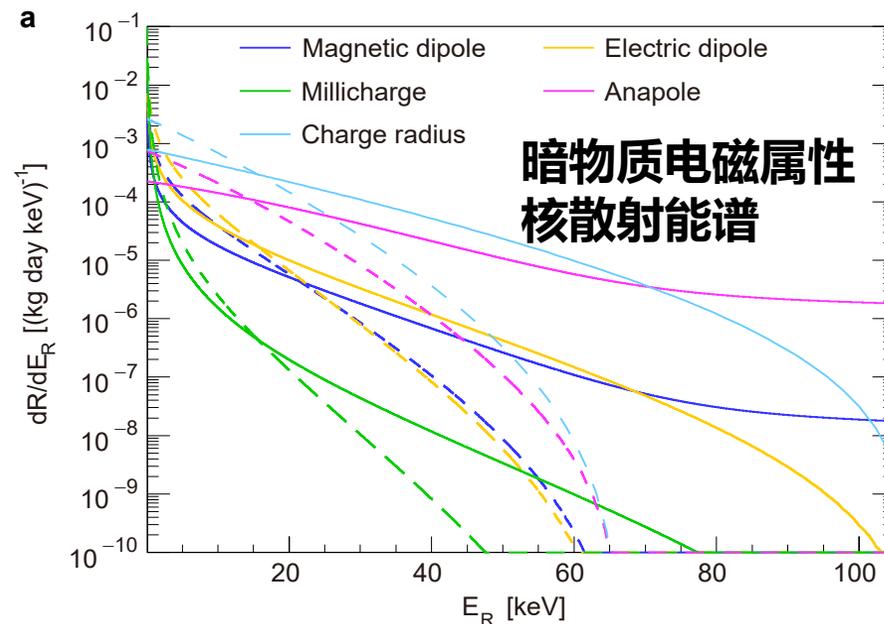
磁偶极矩
magnetic dipole



零极矩
anapole

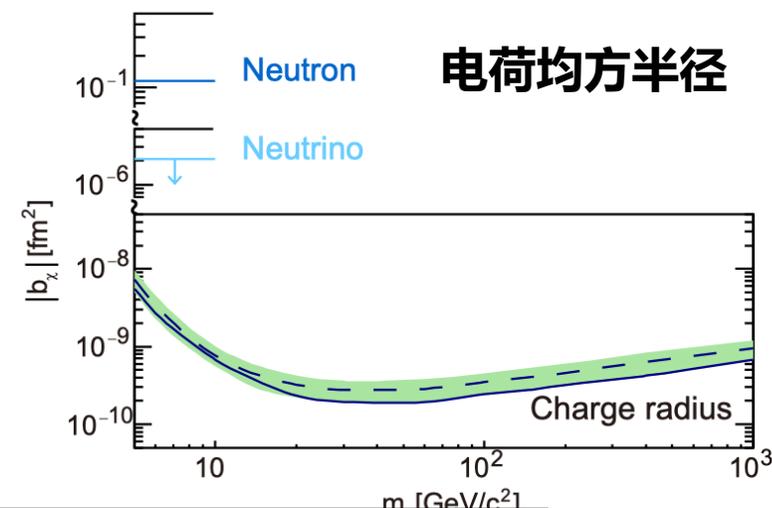
➤ 不同电磁属性产生的原子核散射能谱有显著差异

- 分析PandaX-4T高灵敏数据，**针对性研究**暗物质可能的电磁属性



暗物质电磁属性

- 暗物质电荷半径的**首个**实验结果
 - 40GeV/c²暗物质：电荷均方半径上限比中微子小4个数量级，换算成尺寸比质子半径小10万倍
- 其他电磁属性限制提升3至10倍



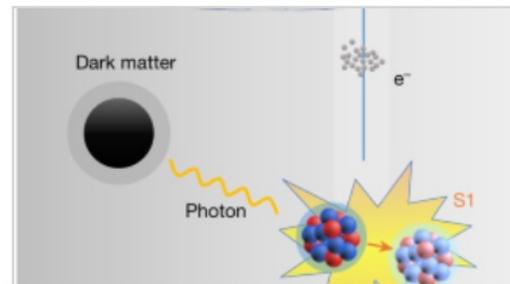
[nature](#) > research articles

Limits on the luminance of dark matter from xenon recoil data

A direct search for effective electromagnetic interactions between dark matter and xenon nuclei that produce a recoil of the latter is carried out and the first constraint on charge radius of dark matter is derived.

Xuyang Ning, Abdusalam Abdukerim ... Yubo Zhou

Article | 17 May 2023



Nature 618, 47-50 (2023)

通过**最灵敏**的数据对“暗物质有多暗”这个问题给出**系统定量**的实验回答

科学影响力

•



Tightening the Net on Two Kinds of Dark Matter

December 23, 2021 • *Physics* 14, s164

New dark matter results strengthen constraints

The PandaX-4T Collaboration also finds no dark matter signal in their data, allowing them to claim **the most stringent constraint on the interaction rate of WIMPs** with nucleons for WIMPs of mass 40 GeV. Currently, the collaboration is working to lower

[nature](#) > [nature.italy](#) > [news.feature](#) > [article](#)

NEWS FEATURE | 15 September 2021

Will dark matter be detected at Gran Sasso?

XENONnT has two direct competitors based on the same technology. **A 4-tonne experiment called PandaX-4t has been running for 100 days in China JinPing Underground Laboratory (CJPL) in Sichuan, and has already improved the limits previously set by XENON1T, according to its first data presented at a conference in July.** At the Sanford Underground Research Facility in the US, the first scientific run

The WIMP Paradigm: Theme and Variations¹

Jonathan L. Feng

Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA

The field of direct detection is extremely active, with sensitivities increasing by an order of magnitude every few years over the last few decades. The current state of affairs is summarized in Fig. 12 for spin-independent searches. **At present, the leading bounds are from one- to multi-tonne-scale liquid noble gas detectors, including XENON1T [49], PandaX-4T [50], and LZ [51].** For dark matter masses $\sim 20-100$ GeV, the upper bound on the dark matter-nucleon cross section, assuming $f_p = f_n$, is at the 10^{-47} cm² level.

How significant is this progress? The current bounds are probing the heart of WIMP theory parameter space, with many otherwise successful WIMP theories being excluded by direct detection. At the same time, there are WIMP theories with almost arbitrarily small

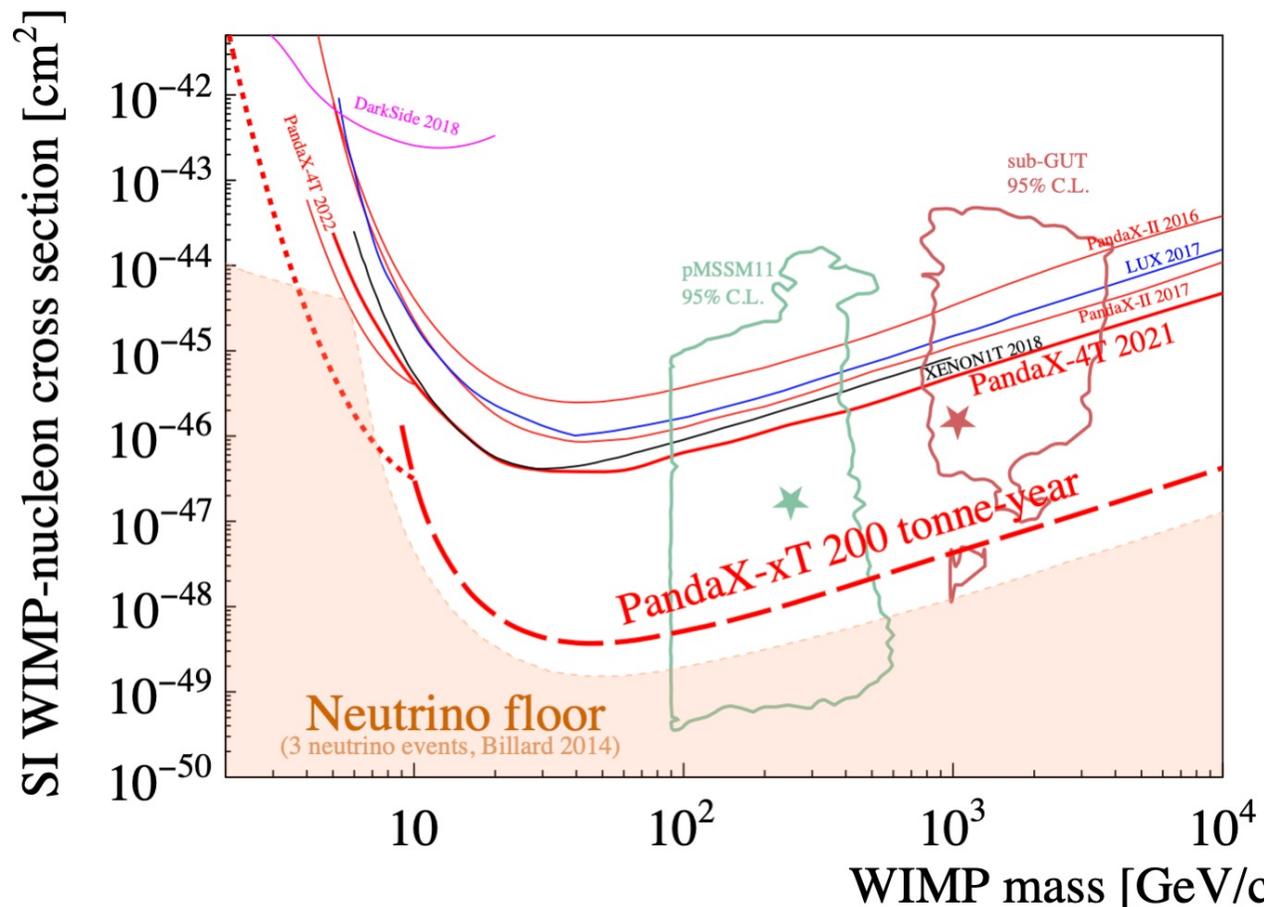
美国物理学会《**Physics**》期刊亮点报道，评论PandaX-4T给出了WIMP暗物质和核子作用截面**世界最好的限制**。

《**Nature**》发表文章评论了PandaX-4T**运行100天就已经超越了欧洲XENON1T实验结果**。

美国物理学会会士、加州大学教授**Jonathan L. Feng**评论说，这个成果的重要意义在于**实验开始扫描到了WIMP暗物质理论的核心区域**。

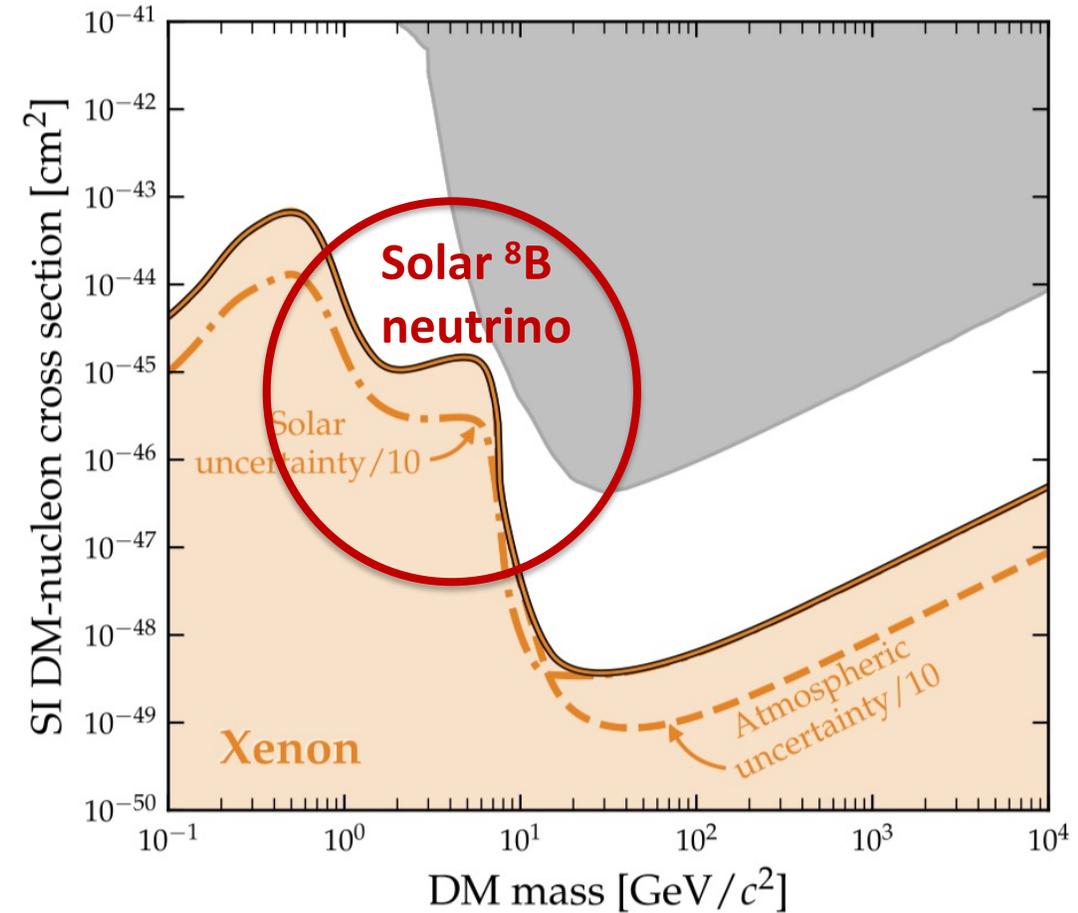
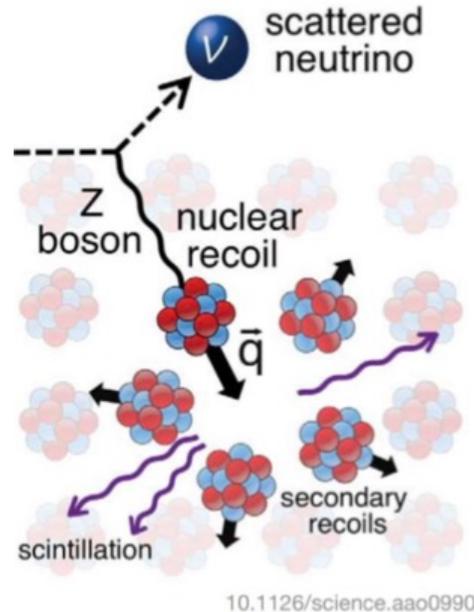
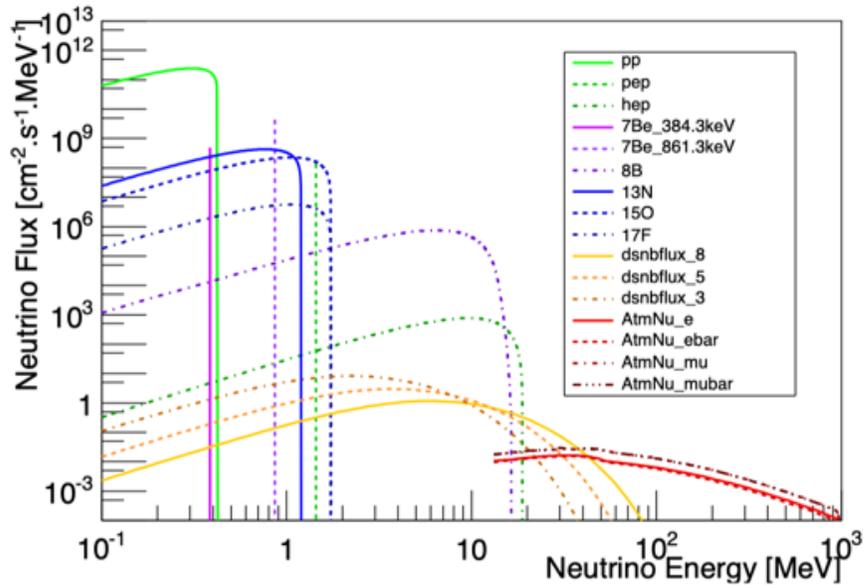
下一代液氙探测实验PandaX-xT

- 立足中国本土，开展数十吨级液氙探测关键技术的研发
 - 低本底、大尺寸探测器、高速采样、液氙循环、同位素精馏
- 根据可用氙量，可以实现**逐步升级**
- 将探测灵敏度向中微子信号水平（中微子地板）推进，对主流暗物质候选粒子给出**确定性结论**



Neutrino Floor

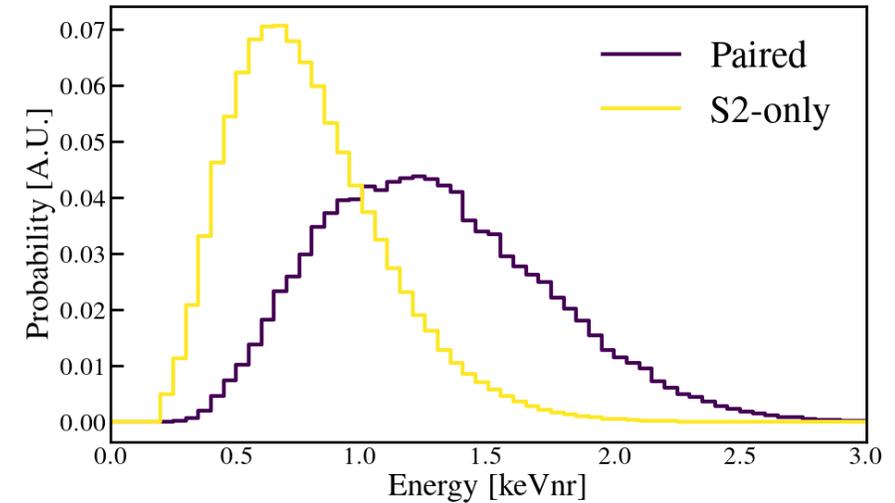
- Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)



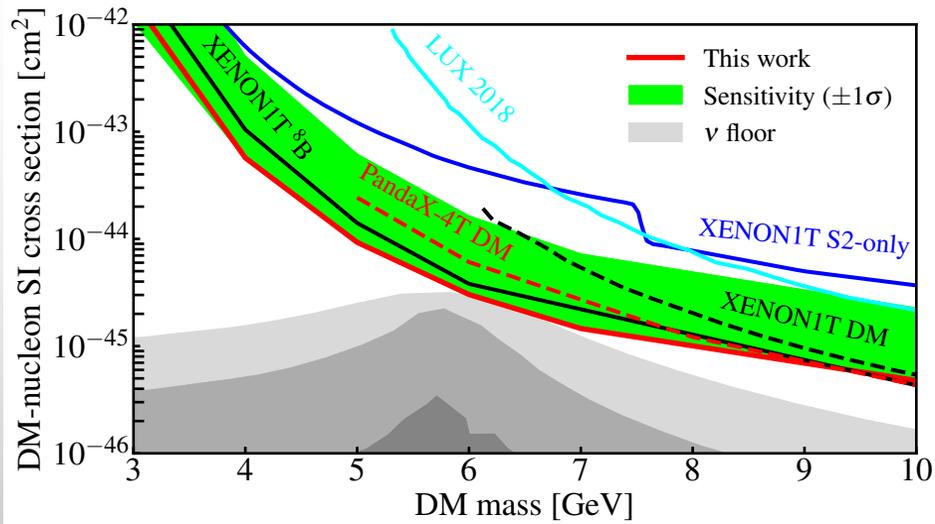
C. O'Hare PRL 127, 251802 (2021)

Solar ^8B neutrino

- **Low threshold detection mode**
 - low threshold paired ROI
 - Ionization S2-only ROI

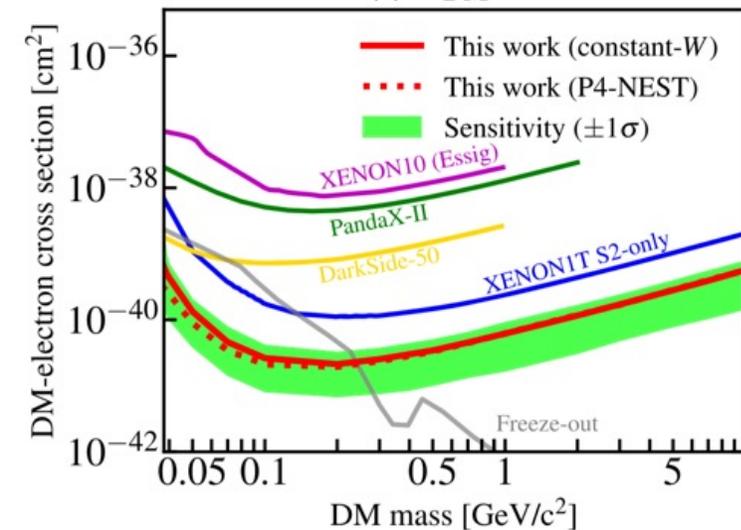


Low threshold paired ROI



PRL 130, 021802 (2023)

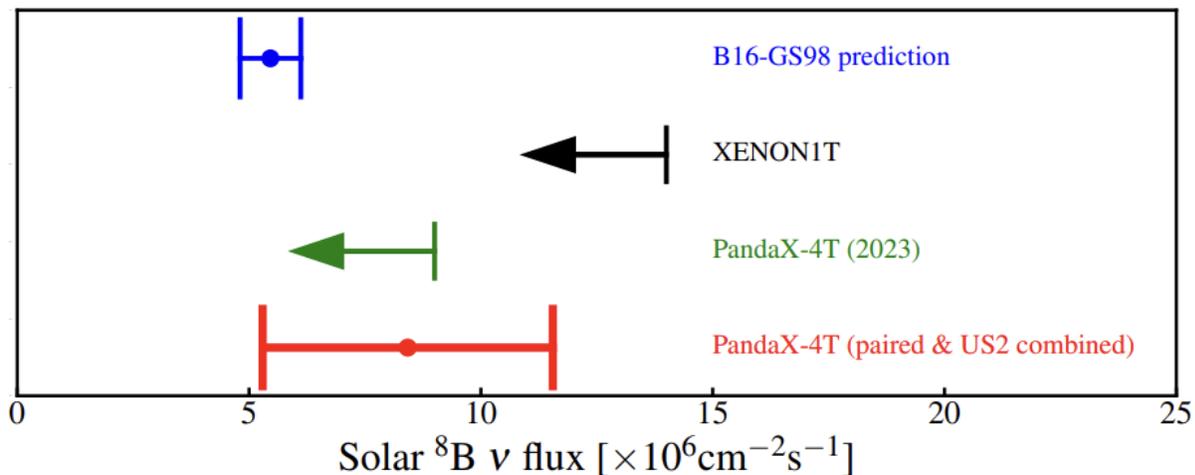
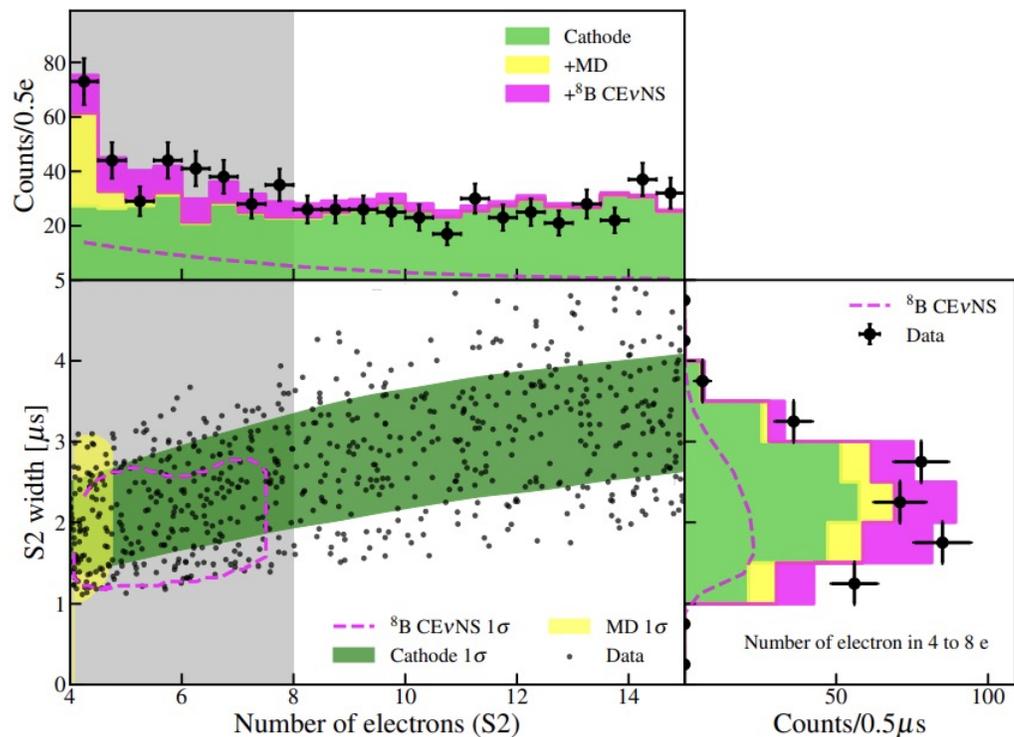
Ionization S2-only ROI



PRL 130, 261001 (2023), Editors' Suggestion

Solar B8 neutrino

•

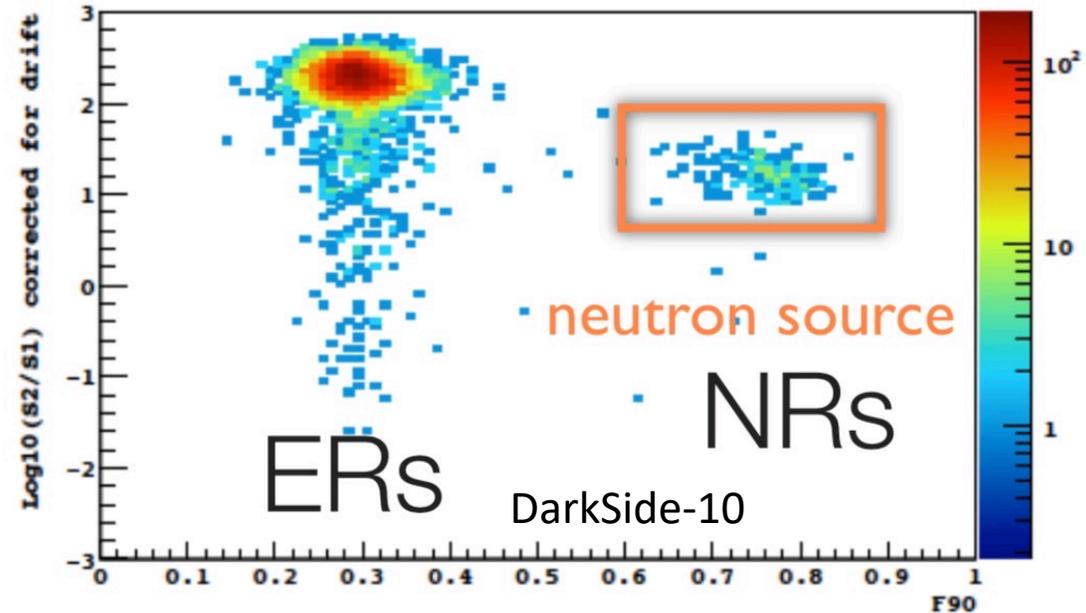
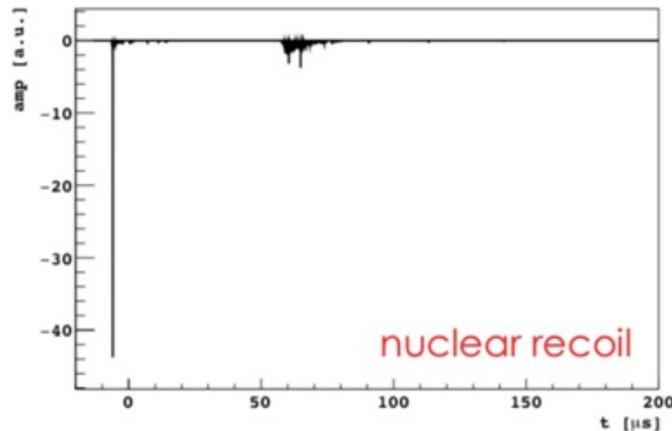
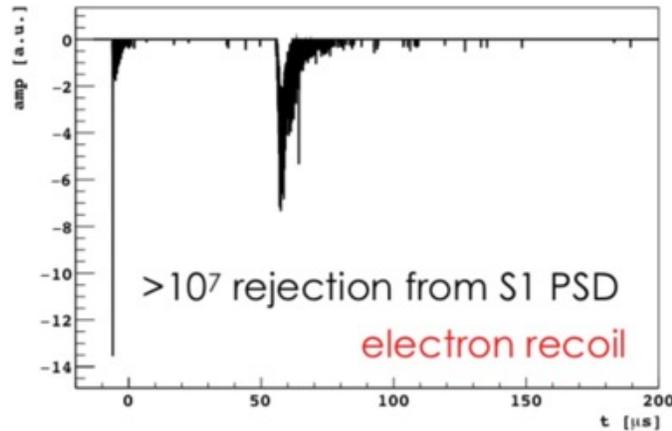


$$8.4 \pm 3.1 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

Best-fit	paired	s2only
B8 number	3.5 ± 1.3	75 ± 28
P-value	0.004	
significance	2.64σ	

Argon Detectors

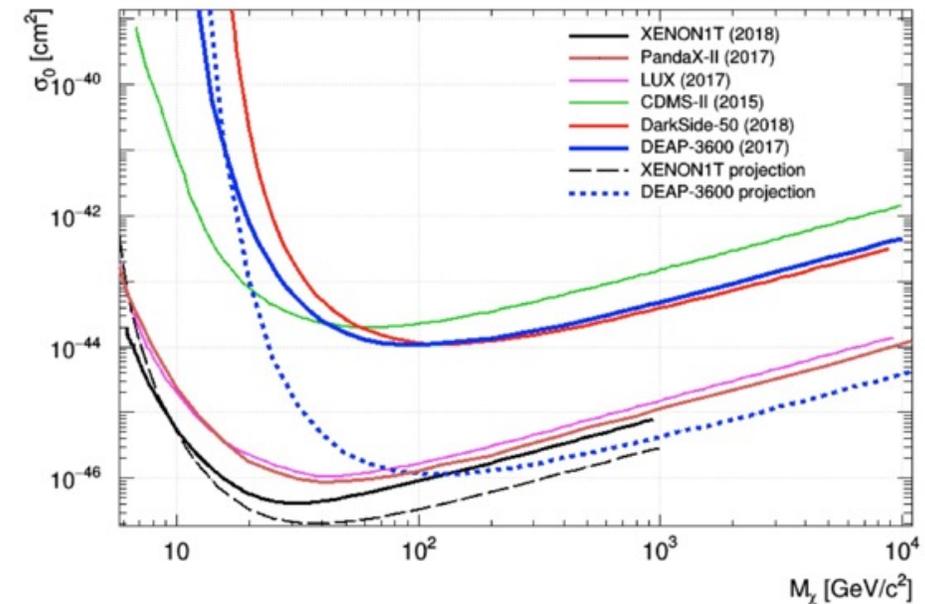
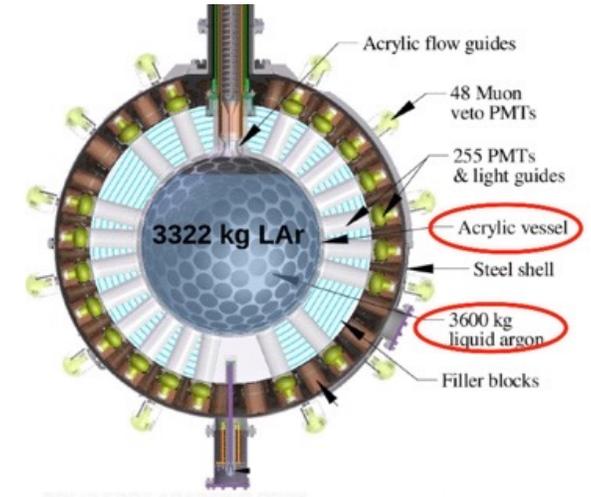
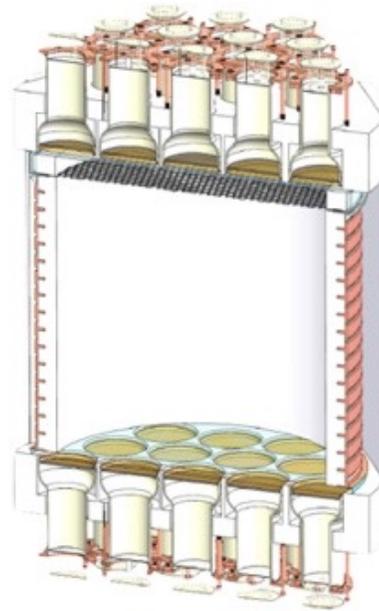
- **Pulse shape of prompt scintillation signal**
 - Singlet (6ns) and triplet (1.5 μ s)
- **Dual-phase: Ionized electron vs prompt scintillation light**



F90: the fraction of light collected within the first 90ns

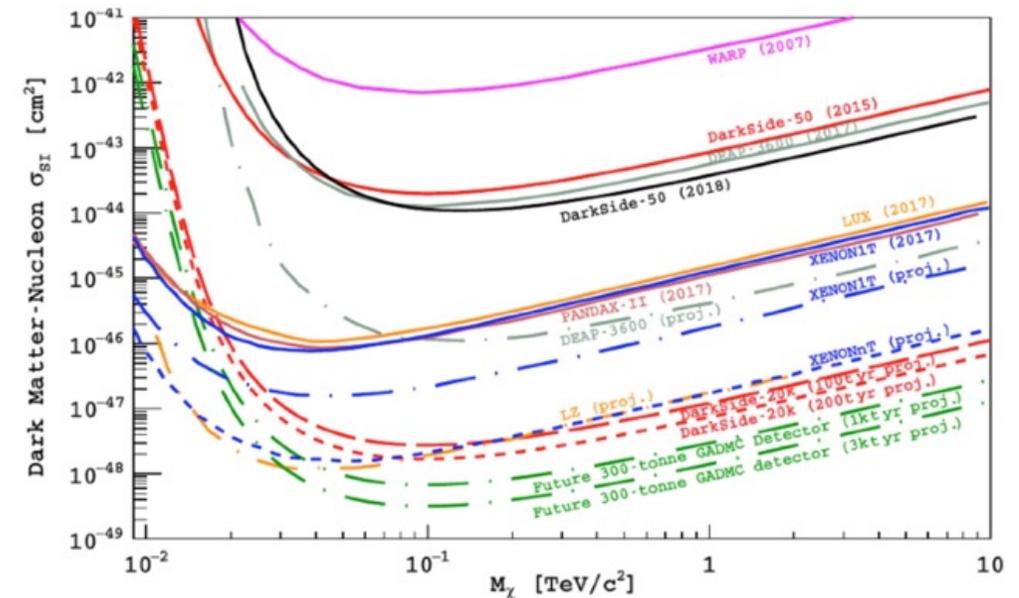
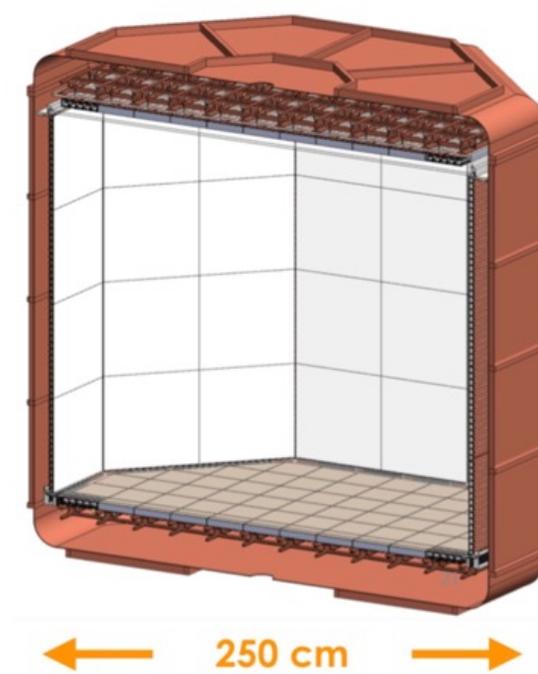
Argon Detectors

- **DarkSide-50 @LNGS**
 - 46 kg underground Argon
 - Dual-phase
- **DEAP-3600 @SNOLAB**
 - 3600 kg natural Argon
 - Containing ^{39}Ar (269 year)
 - Single-phase, R=85cm

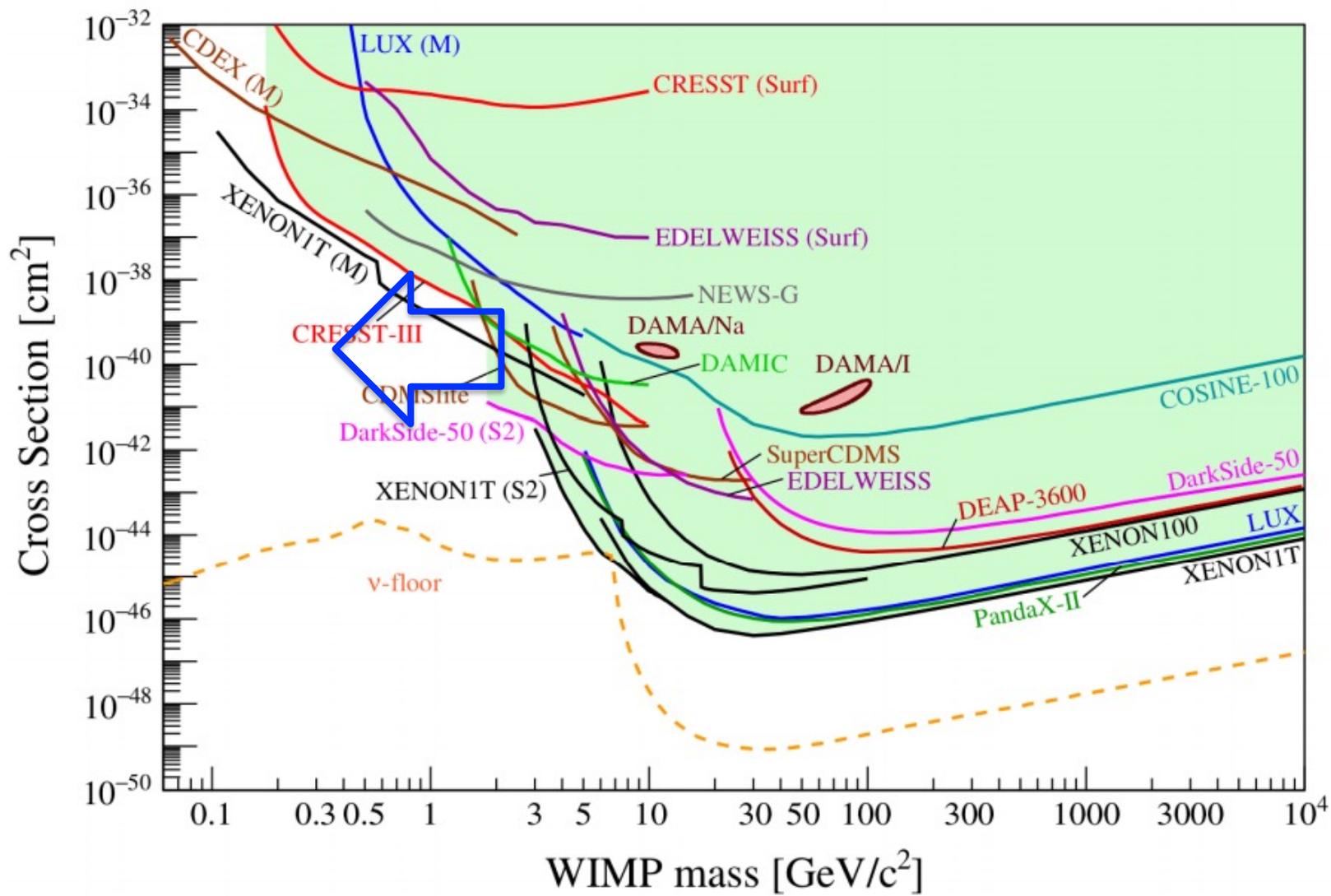


GADMC

- **Global Argon Dark Matter Collaboration**
- **DarkSide-20k (2021 -)**
 - dual-phase, low radioactivity Ar
 - 50 tonne total mass, 30 tonnes fiducial mass
 - $> 20 \text{ m}^2$ of SiPM coverage



轻质量暗物质区域



CDEX 盘古计划

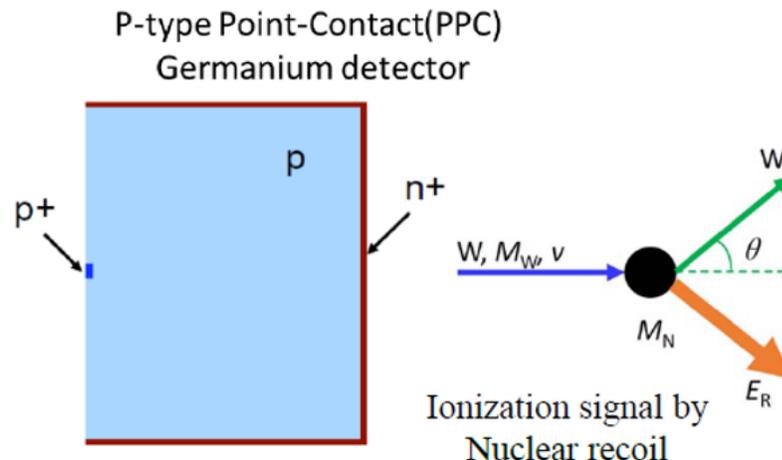


• CDEX发展历程

- 2005年, 韩国Y2L, 5g HPGe
- 2009年, CDEX合作组成立
- 2011年, CJPL-I, 1 kg 点电极高纯锗
- 2016年, 10 kg 阵列点电极高纯锗

• CDEX合作组

- 清华大学牵头, 11个单位, 70余人
- 10+ kg PPC Ge (单相: 电离)
- 新建液氮恒温器 @ CJPL-II

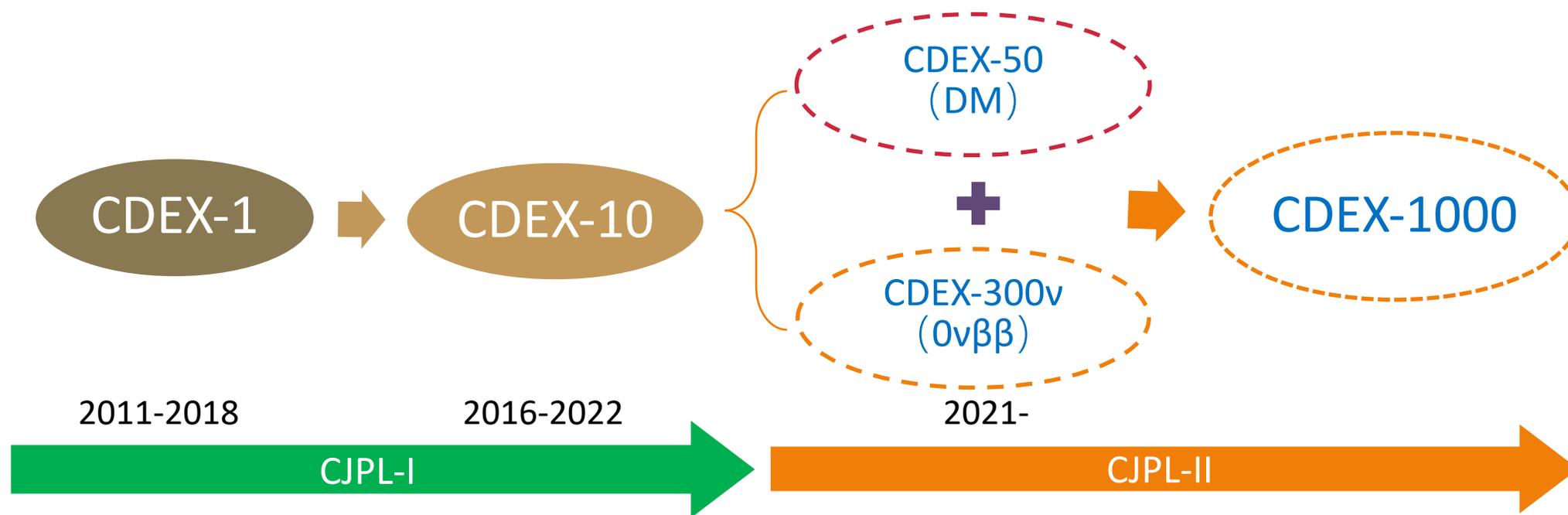


Direct detection of low-mass WIMPs w/ Ge detector at CJPL.



CDEX “盘古” 计划

- CDEX-1 (2011-2018) : 发展点电极高纯锗探测器技术, 开展本底研究;
- CDEX-10 (2016-2022) : 液氮直冷高纯锗阵列性能研究;
- CDEX-50 (2021-) : 50公斤级液氮直冷高纯锗阵列实验系统;

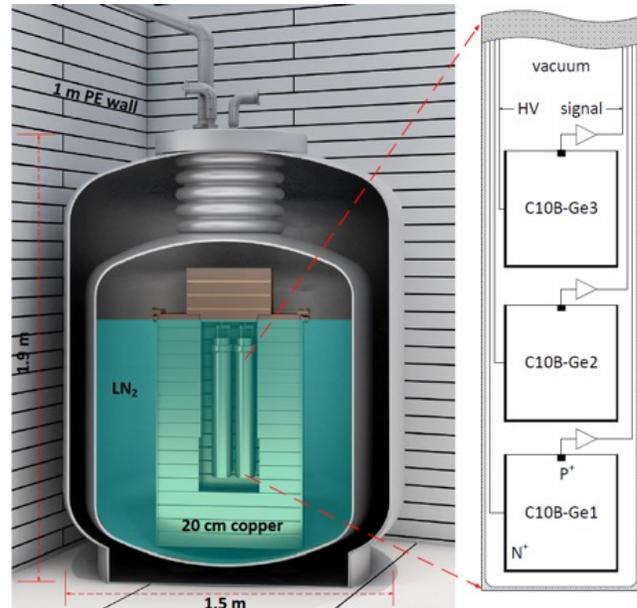


CDEX-10阶段

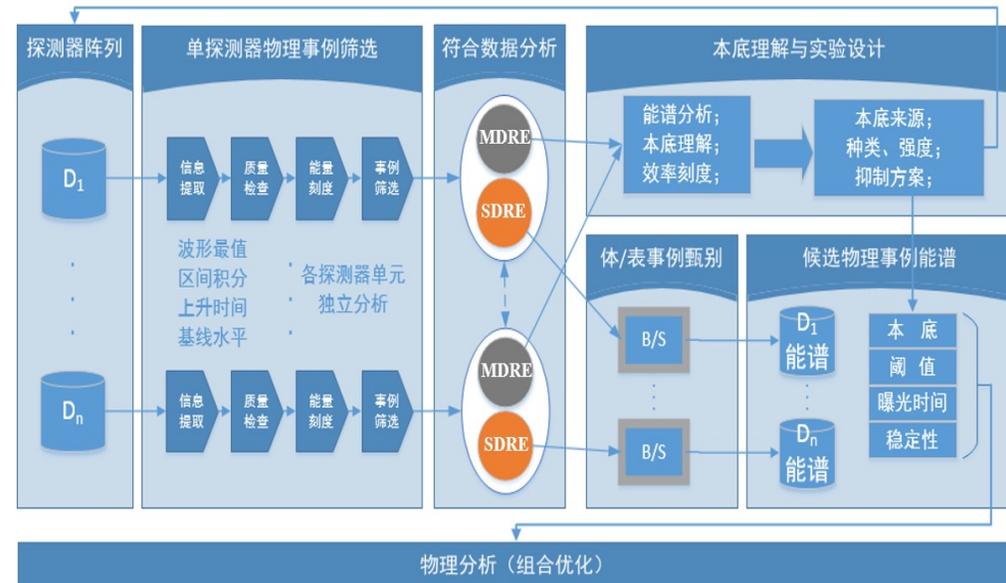
- 建立了国际上首个液氮直冷高纯锗阵列系统，探测器质量~10kg；
- 发展了阵列化探测器系统的数据合成方法，以及多探测器联合的物理分析框架；
- 建立了<2keV低能区能量刻度方法：中子活化法、 γ 源激发法、多通道比较法等；



CDEX-10暗物质实验系统



Science China-PMA 62, 031012 (2019)

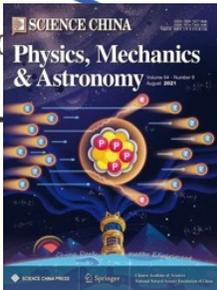
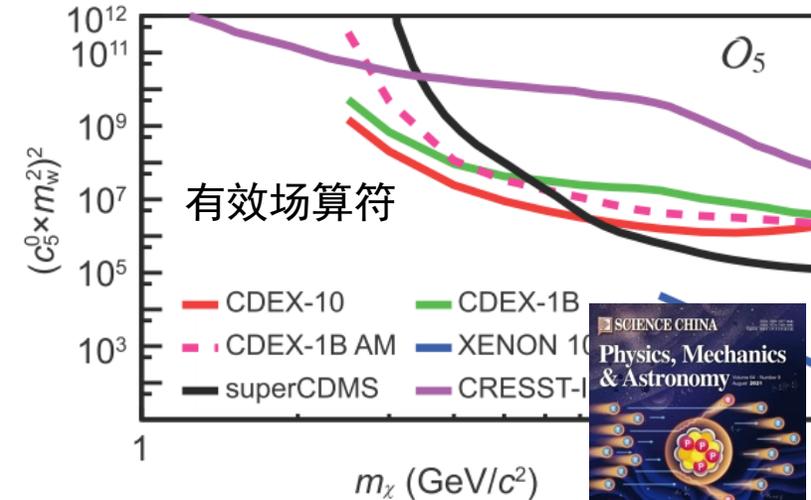


阵列化探测器系统数据合成方法框图

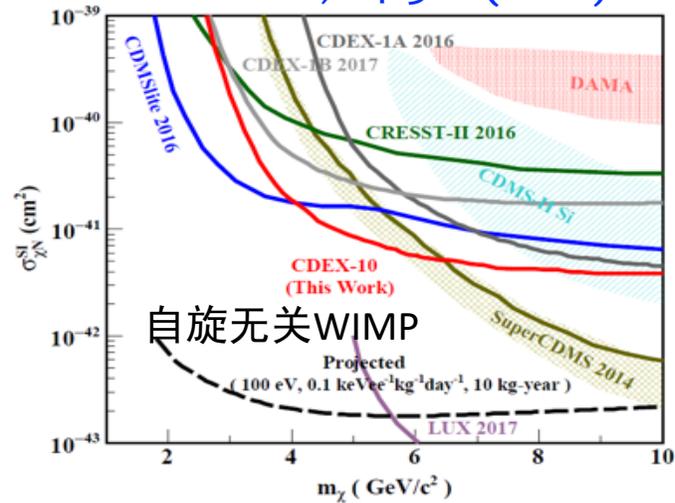
CDEX-10物理结果

- **WIMP:** 4-5 GeV自旋无关国际最灵敏实验结果
- **暗光子:** 10-300 eV太阳暗光子动量混合参数限制国际最好的直接探测实验结果

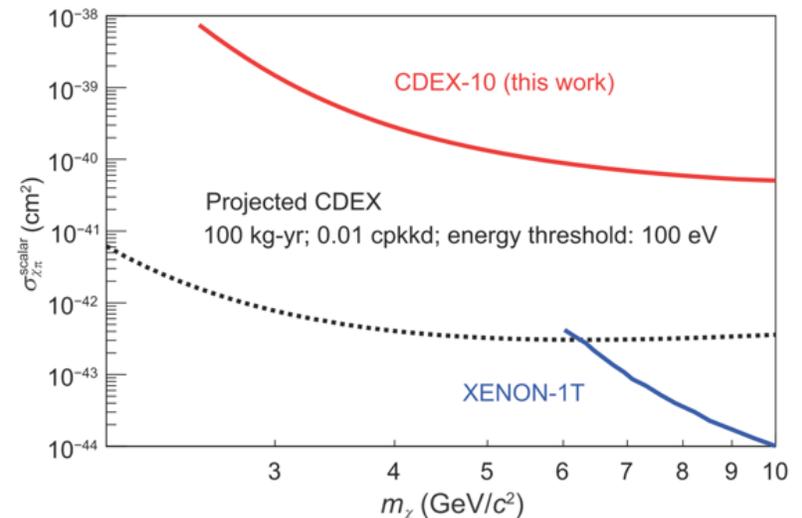
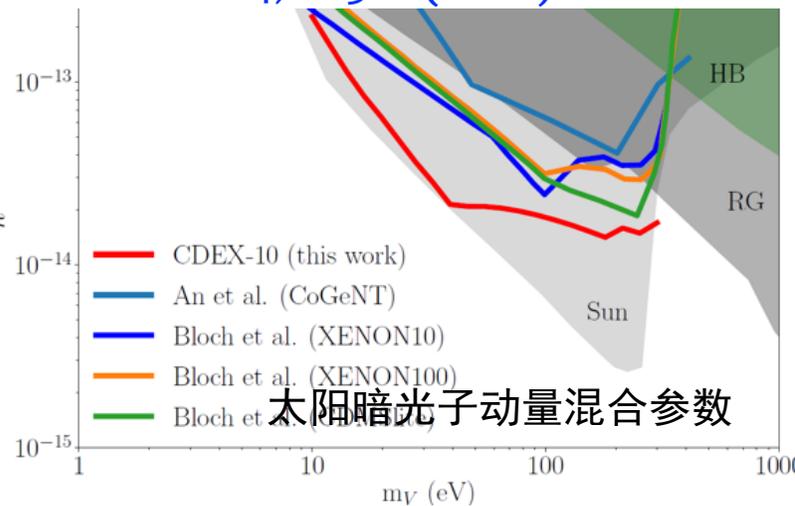
SCPMA Vol. 64 No. 8: 281011



PRL 120, 241301 (2018)



PRL 124, 111301 (2020)

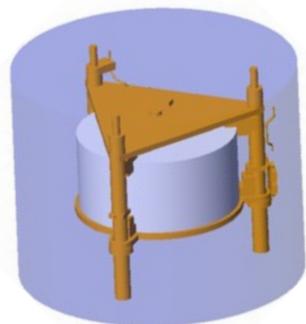


CDEX-50计划

- 液氮直冷的高纯锗探测器阵列;
- 由7串组成, 每串7个探测器;
- 有效靶质量~50kg;
- 宽能高纯锗BEGe+点电极高纯锗PPCG

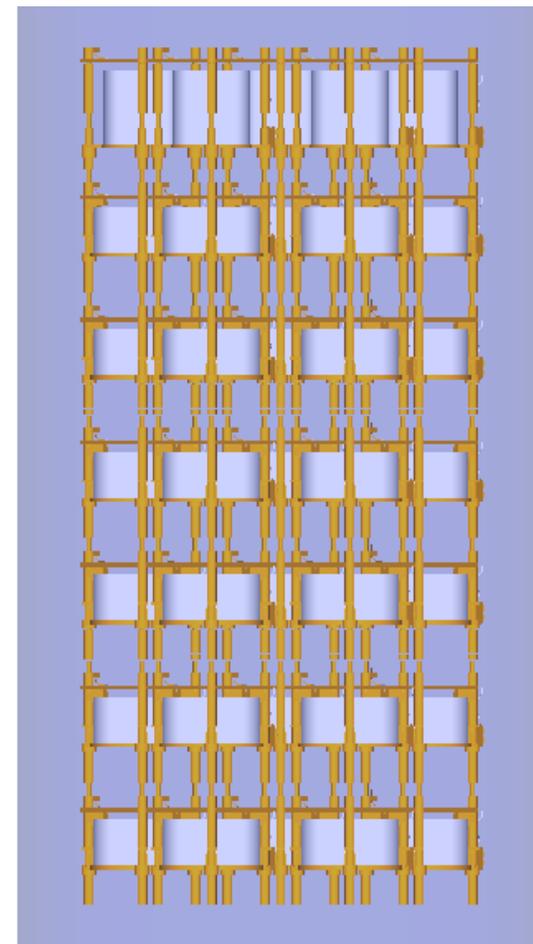
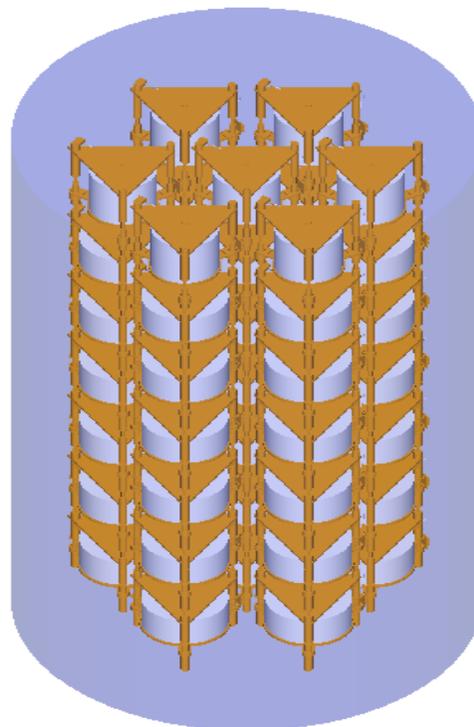
BEGe

- Mass: 1-1.2 kg;
- Size: $\varphi 80\text{mm} \times 40\text{mm}$;
- Dead layer: 0.6mm;



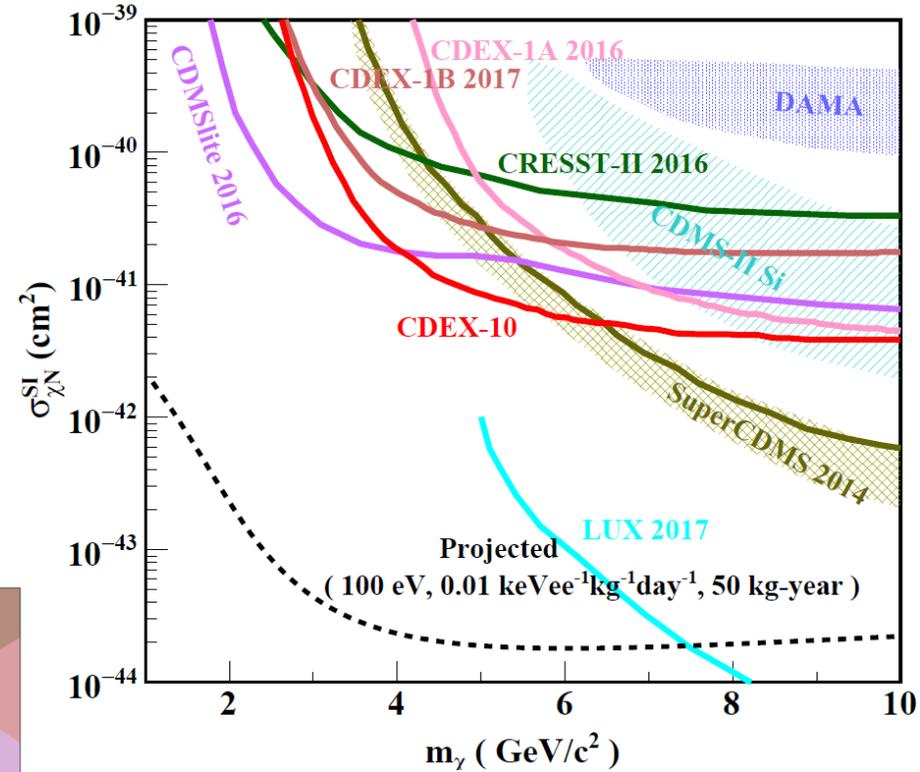
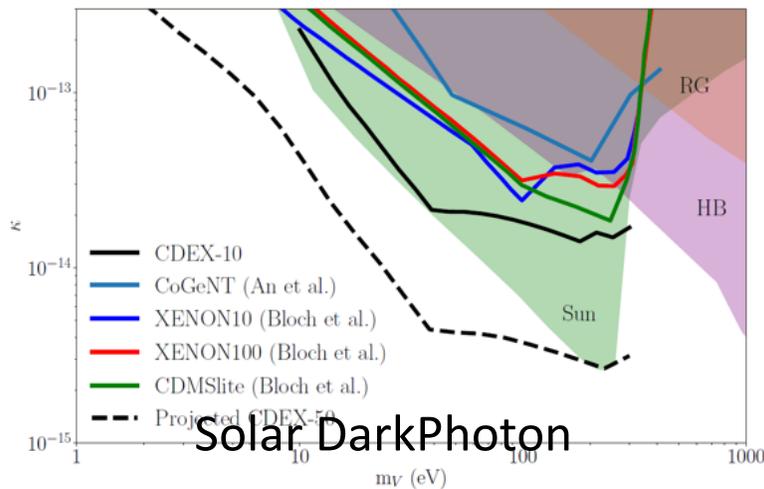
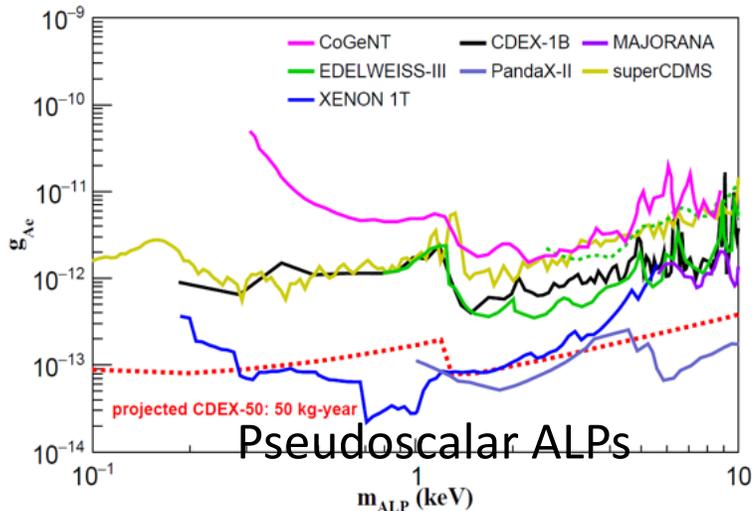
PPCGe

- Mass: ~1 kg;
- Size: $\varphi 62\text{mm} \times 62\text{mm}$;
- Dead layer: 0.8 mm;



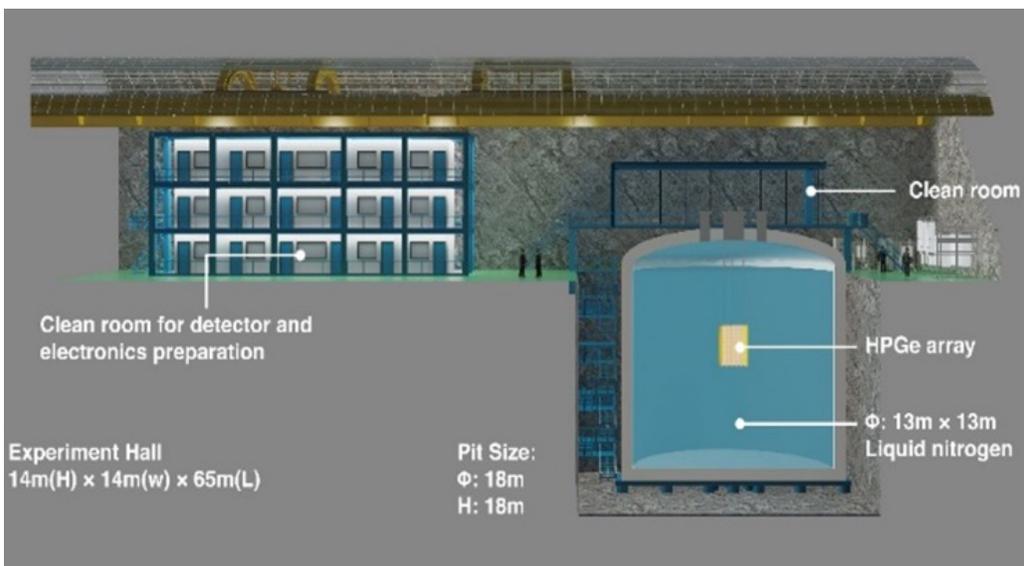
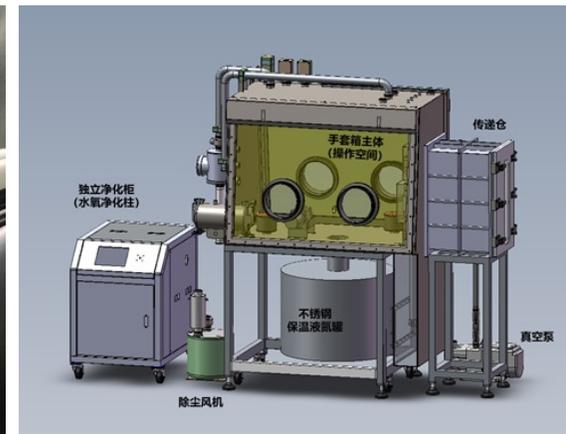
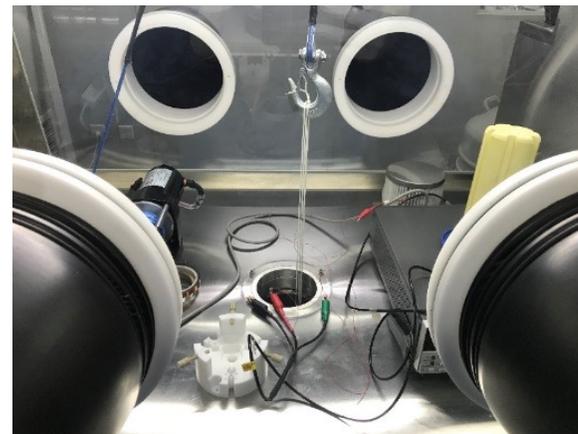
CDEX-50计划

- 本底水平 < 0.01 cts/(keV·kg·day) @1 keV;
- 实验数据分析阈值100 eV;
- 有效曝光量~50 kg·year;
- WIMP自旋无关灵敏度达到 10^{-44} cm²水平;
- 同时, 开展轴子、暗光子等实验研究;



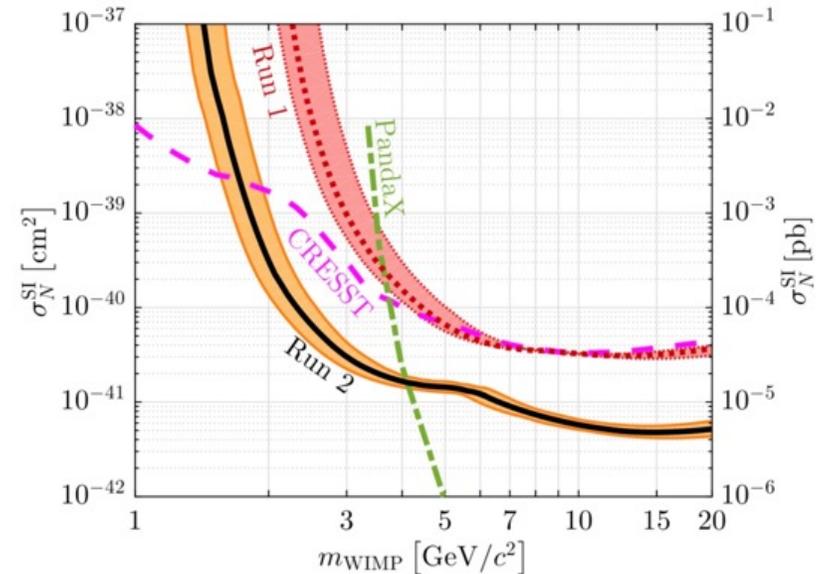
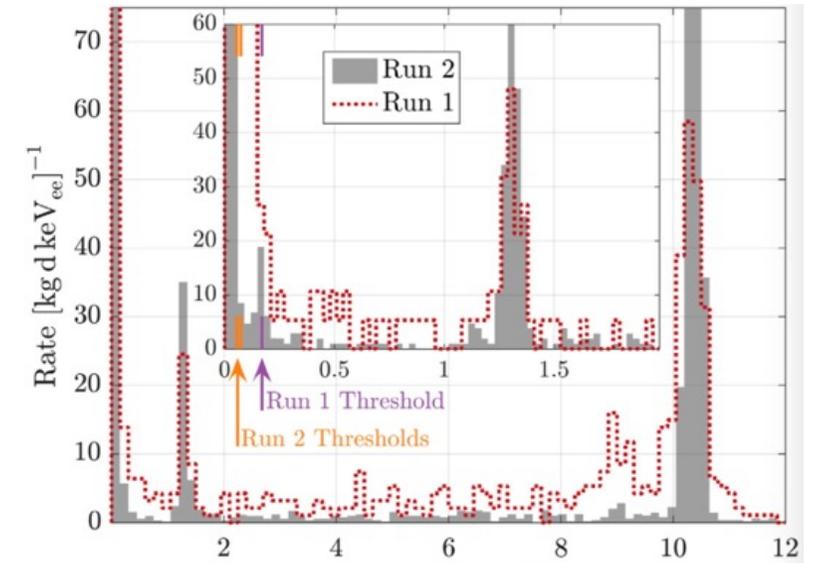
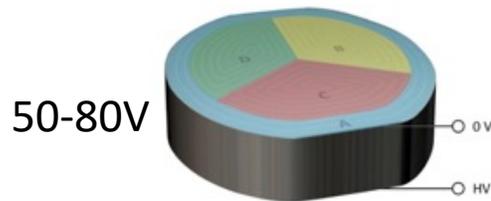
CDEX-50 @ CJPL

- 探测器单元与小阵列测试@CJPL-I
- 锦屏大设施建设@CJPL-II
- 1725m³液氮屏蔽装置@CJPL-II;
- 计划2024年探测器阵列试运行;



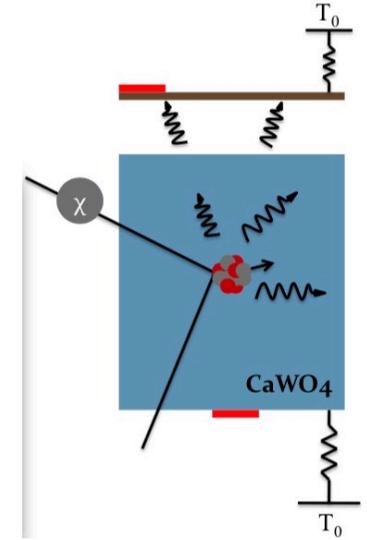
Low Mass DM: Germanium detectors

- **SuperCDMS experiment @Soudan**
- **Standard iZIP mode:** phonon and ionization, ER/NR discrimination
- **CDMSlite HV mode:** phonon only
 - Ionization electrons generate a large number of NTL phonons
 - => **Low threshold** 56 eVee

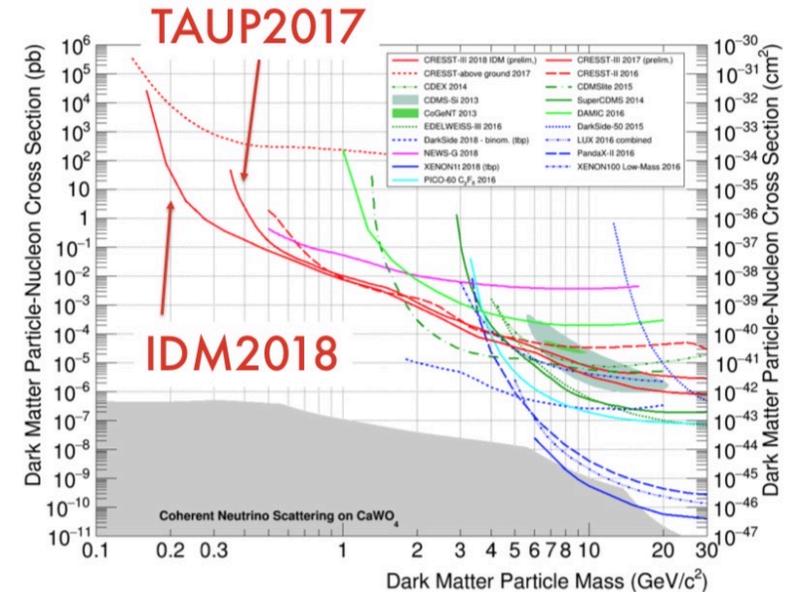
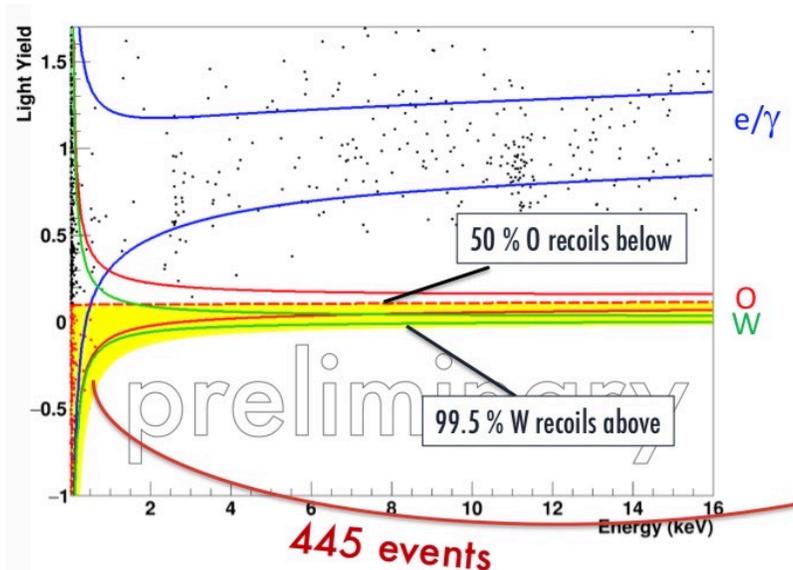


Low Mass DM: Crystal detector

- CRESST-III experiment
- CaWO_4 crystal, 24g, @ $\sim 15\text{mK}$
 - Phonon signal: precise measurement of deposited energy
 - Scintillation light: particle-type dependent
 - Nuclear recoil threshold $30.1\text{ eV} \Rightarrow$ subGeV WIMP



F. Reindl, IDM2018

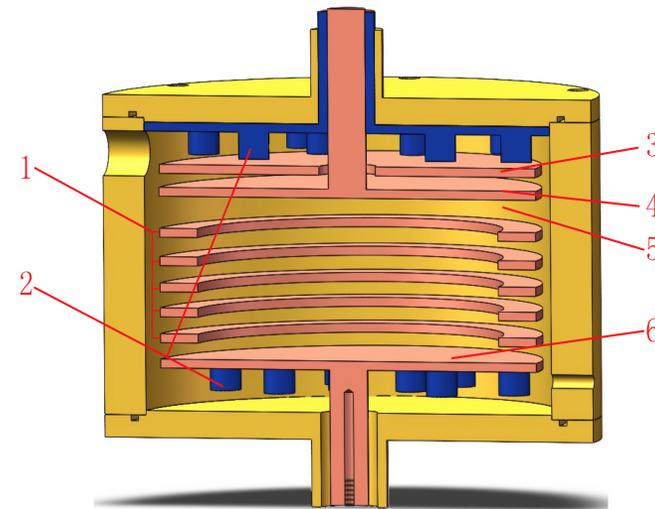
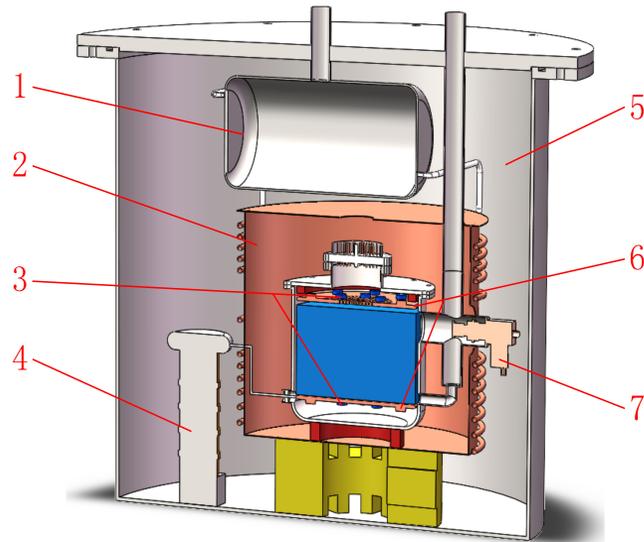


液氦直接探测实验研发

• ALETHIA实验

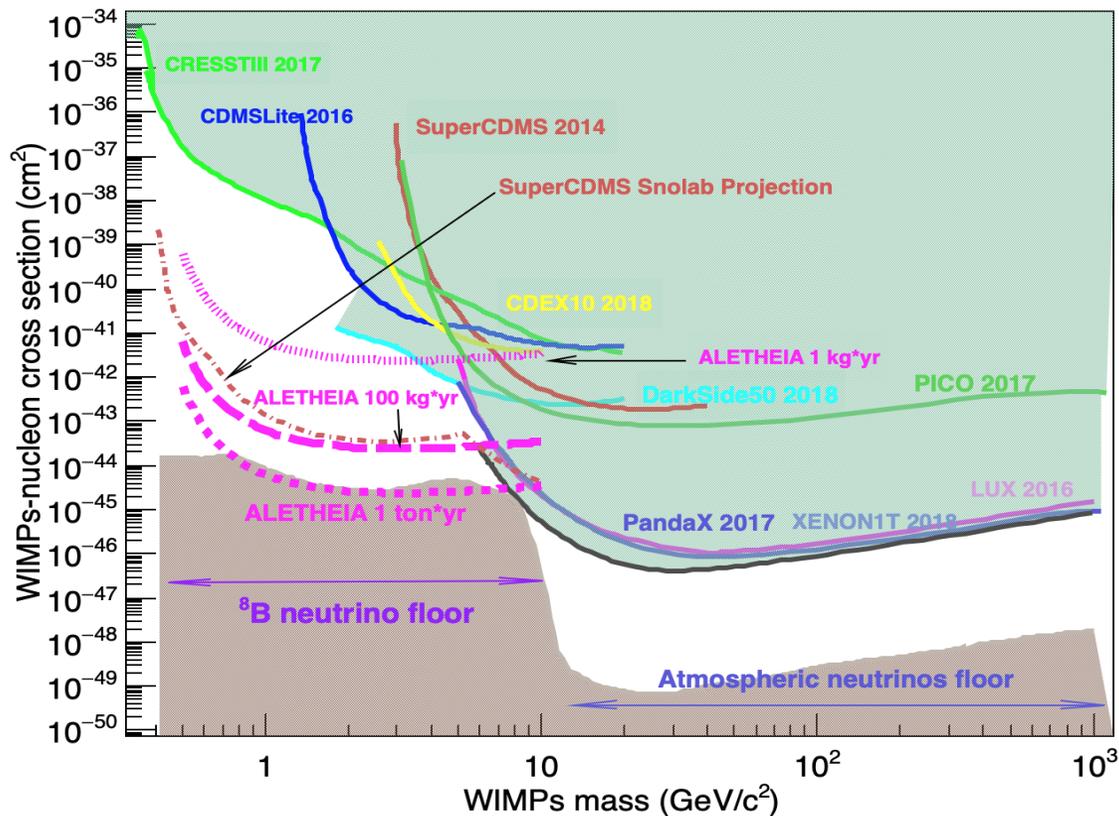
– A Liquid Helium Time Projection Chamber in Dark Matter

- Left plot: The whole LHe detector system. 1: LHe repository; 2, LN cooling system; 3, SiPMs; 4, HV power supply; 5, Cryostat (vacuum); 6, HV electrodes; 7, LHe cooling source.
- Right plot: The LHe TPC. 1, HV rings; 2, SiPMs; 3, Anode; 4, Gate; 5, TPC wall; 6, Cathode.



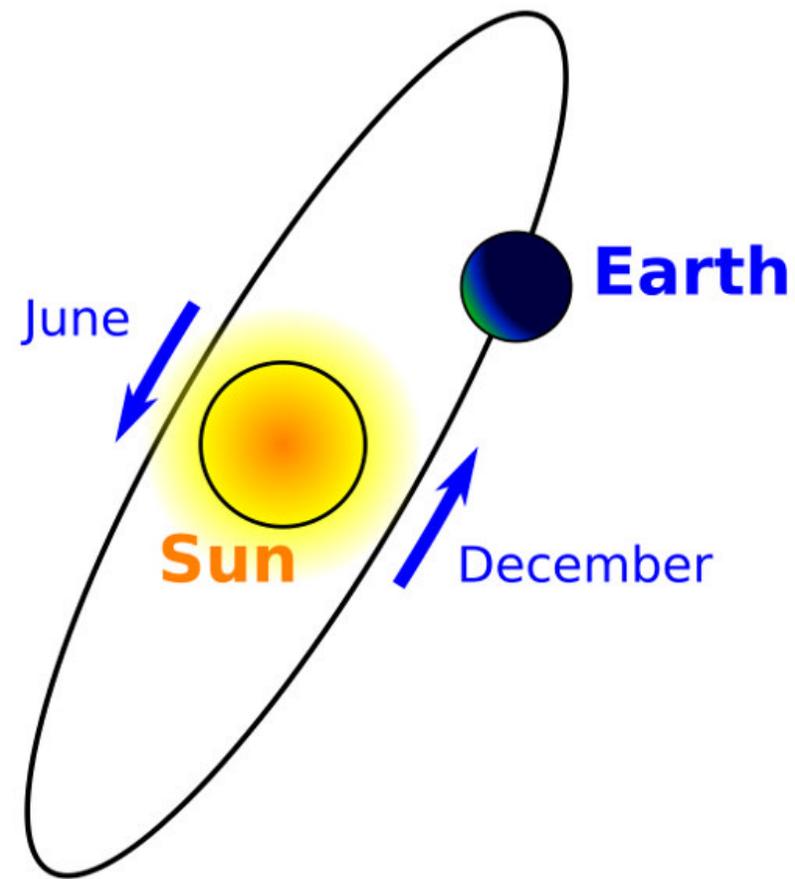
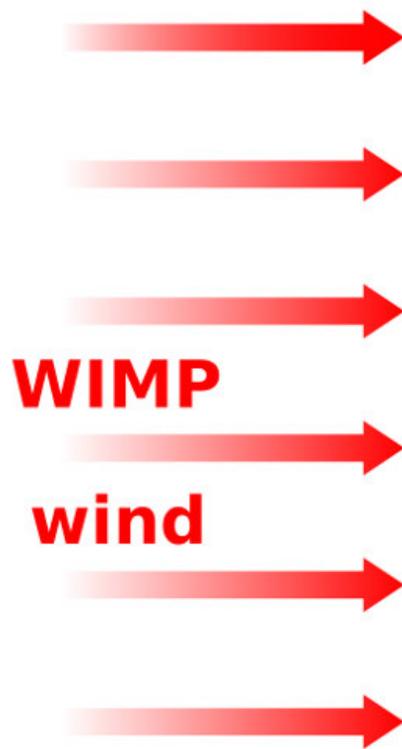
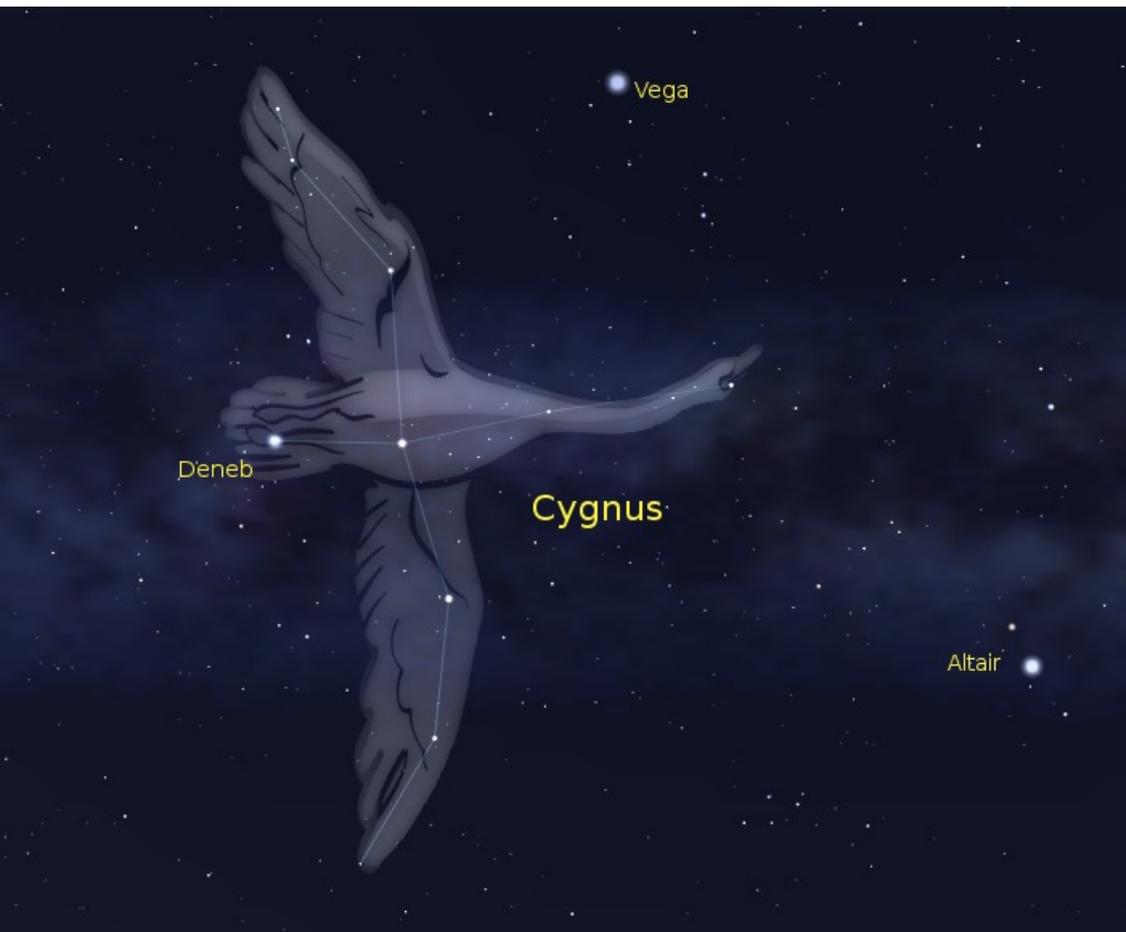
液氦直接探测实验研发

- ALETHEIA实验预期1 吨-年曝光量可全面覆盖 ^8B 中微子地板
- 目前组装30g LHe 探测器, 在原子能院开展测试



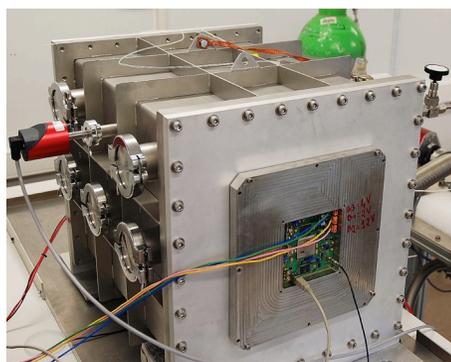
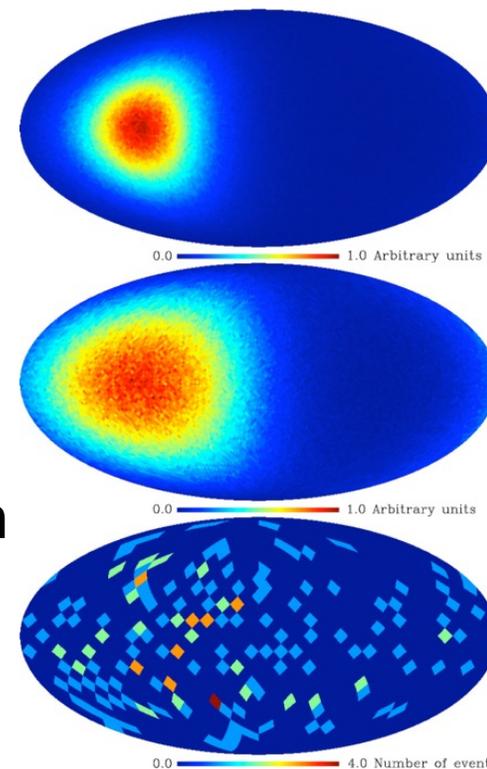
方向性直接探测

•



方向性直接探测

- **Directionality:**
 - Cygnus direction
 - Can help with neutrino floor!
 - 30deg angular resolution necessary to distinguish Cygnus from
- **To reconstruct the recoil track**
- **R&D work in progress**



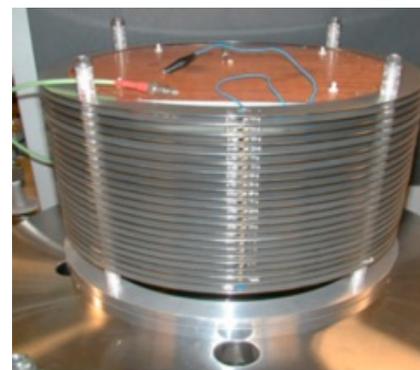
MIMAC

Micromegas



DRIFT

Negative ion MWPC



DMTPC

CCD

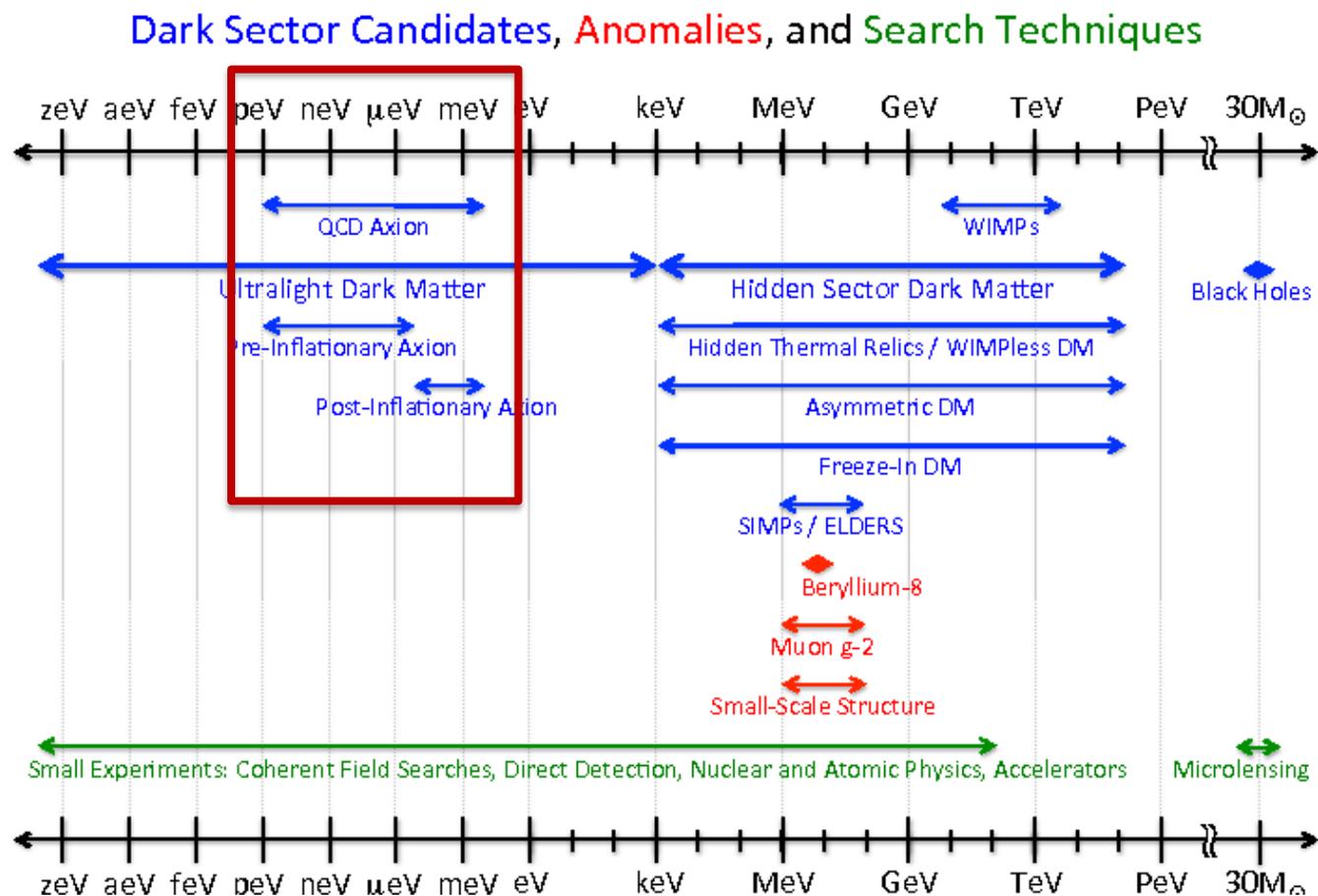


NEWAGE

Micro pixel

极轻质量的暗物质探测

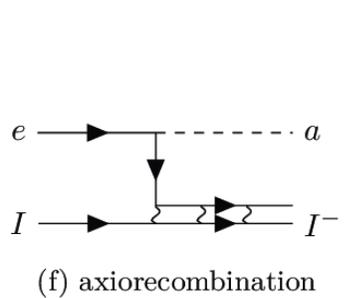
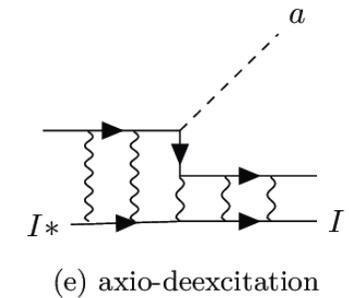
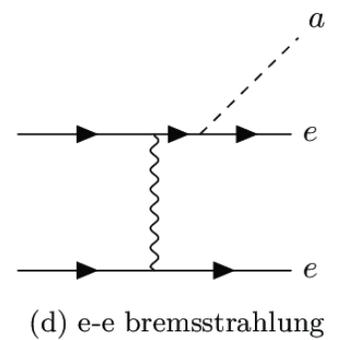
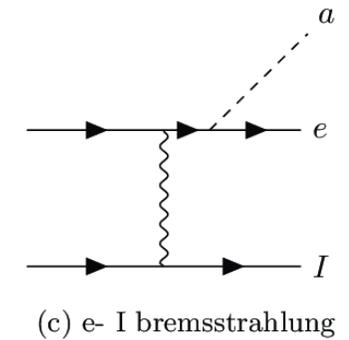
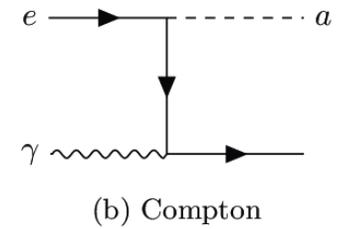
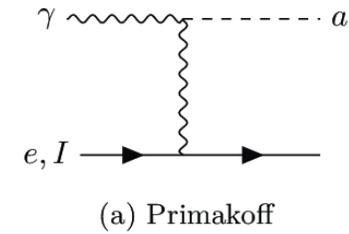
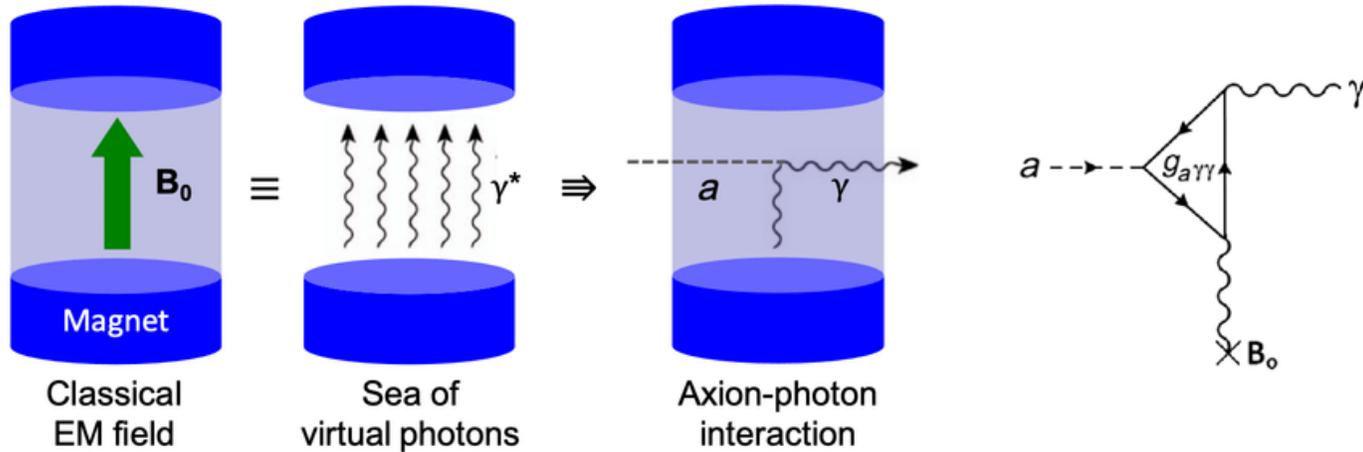
- 轴子: below meV scale



Axion Interaction

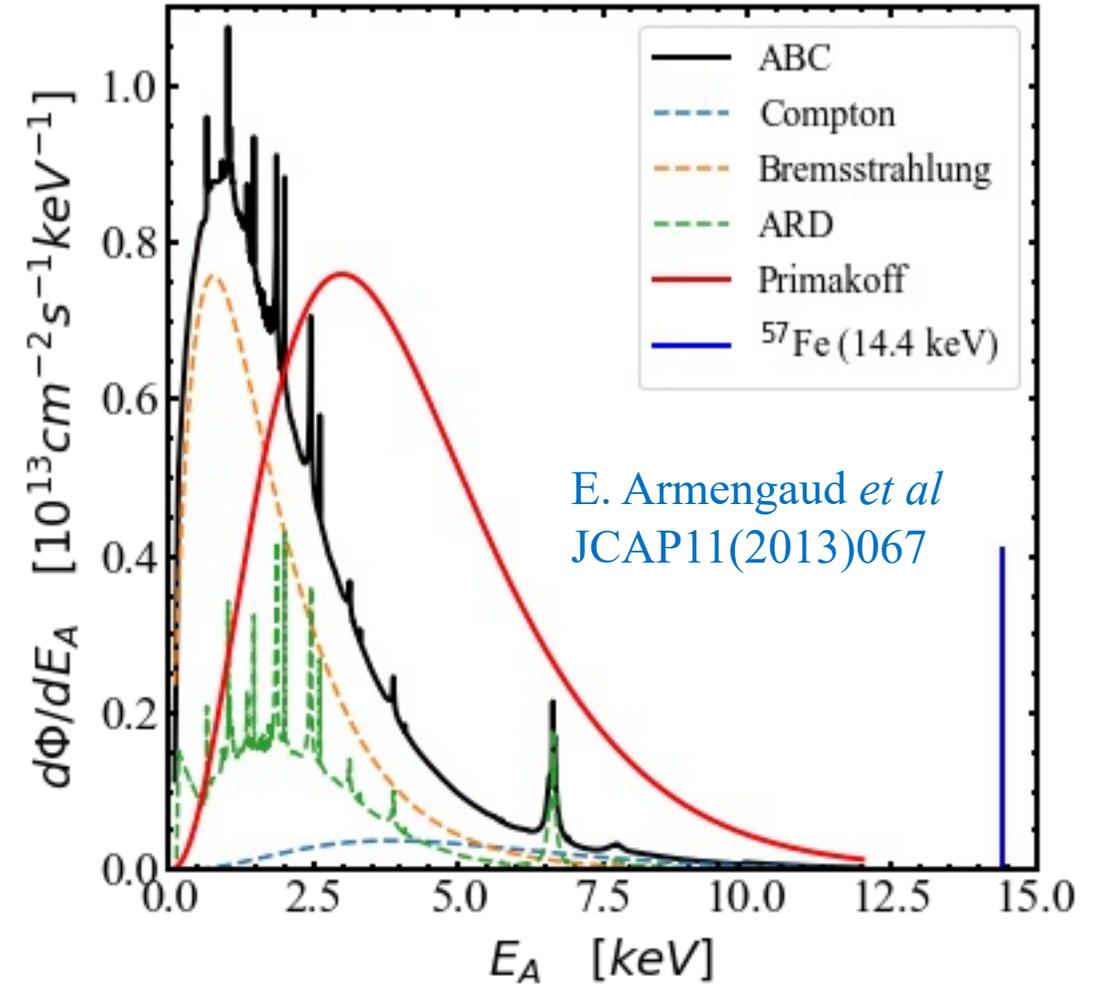
- Axion Formalism**

$$L \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \sum_f i g_{af} a \bar{f} \gamma_5 f - ia \bar{N} \gamma_5 (g_{aN}^0 + g_{aN}^3 \tau^3) N$$



Solar Axion

- **Production in the sun**
 - ABC Process: Atomic recombination and deexcitation (ARD), Bremsstrahlung, and Compton
 - Primakoff effect
 - M1 nuclear transition of ^{57}Fe (14.4 keV).

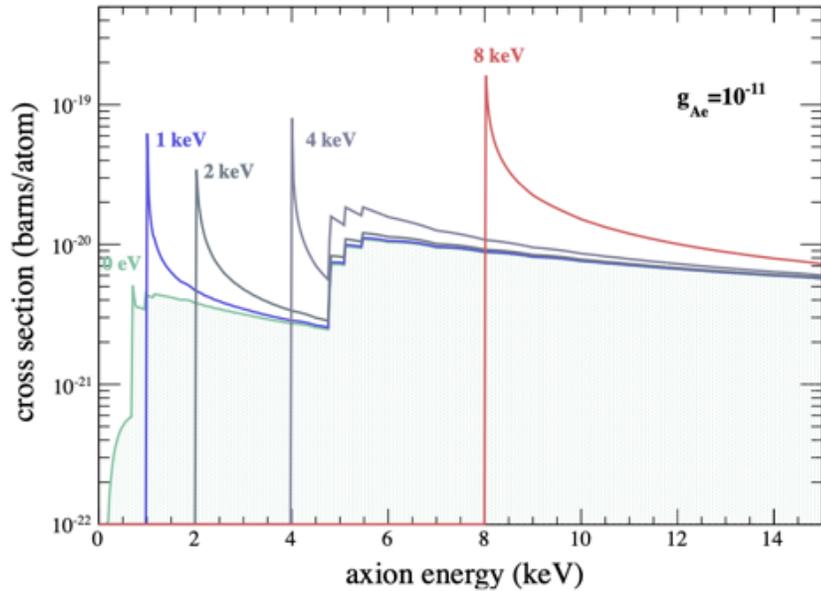


Corresponding axion couplings in flux

$$g_{ae} = 1 \times 10^{-11}, g_{a\gamma\gamma} = 1 \times 10^{-9} \text{GeV}^{-1}, g_{aN}^{eff} = 3 \times 10^{-6}.$$

ER Signals from Axio-electric Effect

Astroparticle Physics Volume 44, April 2013, Pages 59-67



The approximate cross section of axio-electric effect:

$$\sigma_{Ae}(E) = \sigma_{pe}(E) \frac{g_{Ae}^2}{\beta} \frac{3E^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta^{\frac{2}{3}}}{3}\right)$$

where $g_{Ae} = C_{ae} m_a / f_a$, C_{ae} is model dependent.

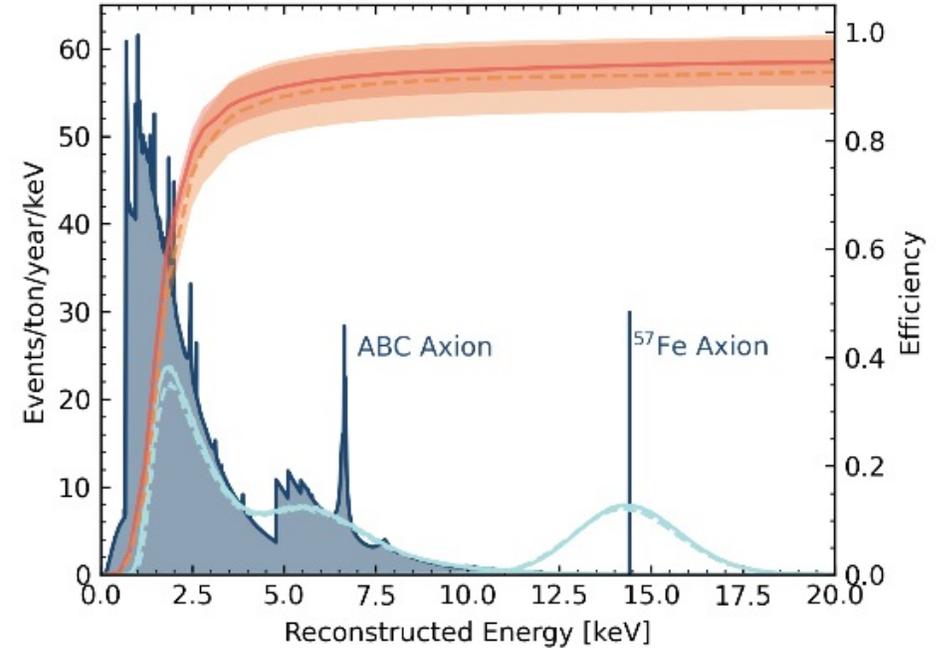
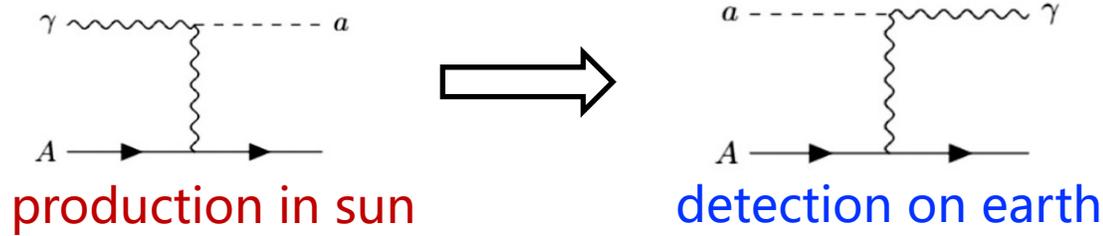


FIG. 1: Expected energy spectrum for ABC process with a coupling $g_{Ae} = 3.1 \times 10^{12}$ (red), and nuclear magnetic transition process of ^{57}Fe with coupling $g_{An}^{eff} = 8.3 \times 10^7$ (orange). The solid and dashed orange lines are total efficiencies including reconstruction efficiency and quality cuts efficiency for Run0 and Run1, respectively.

ER Signals from Inverse Primakoff Effect



$$\frac{d\sigma}{d\Omega} = \frac{\alpha g_{a\gamma\gamma}^2 E_a^3 p_a \sin^2 \theta}{4\pi(E_a^2 + p_a^2 - 2E_a p_a \cos \theta)^2} \times \left| \int d^3 \mathbf{x} e^{-i\mathbf{q}\cdot\mathbf{x}} \langle A_0 | \rho(\mathbf{x}) | A_0 \rangle \right|^2$$

$$= \frac{\alpha g_{a\gamma\gamma}^2 E_a^3 p_a \sin^2 \theta}{4\pi(E_a^2 + p_a^2 - 2E_a p_a \cos \theta)^2} \times |Z - F(\mathbf{q})|^2$$

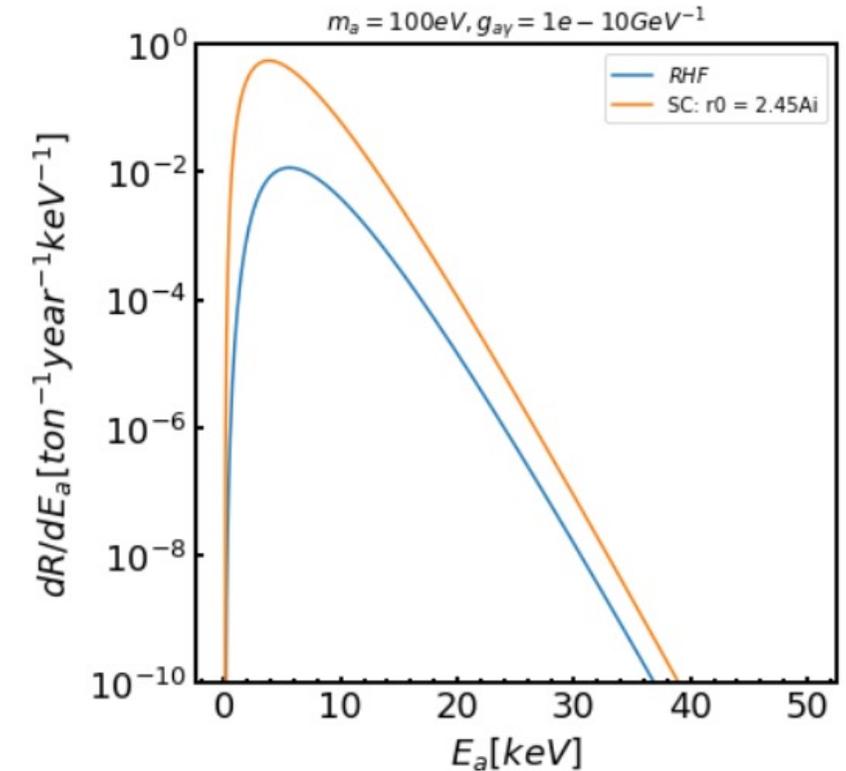
Two kind of form factors:

(1) Screened Coulomb potential (SC):

$$F_{SC}(q; r_0) = \frac{Z}{1 + q^2 r_0^2}$$

(2) Relative Hartree-Fock wavefunction (RHF):

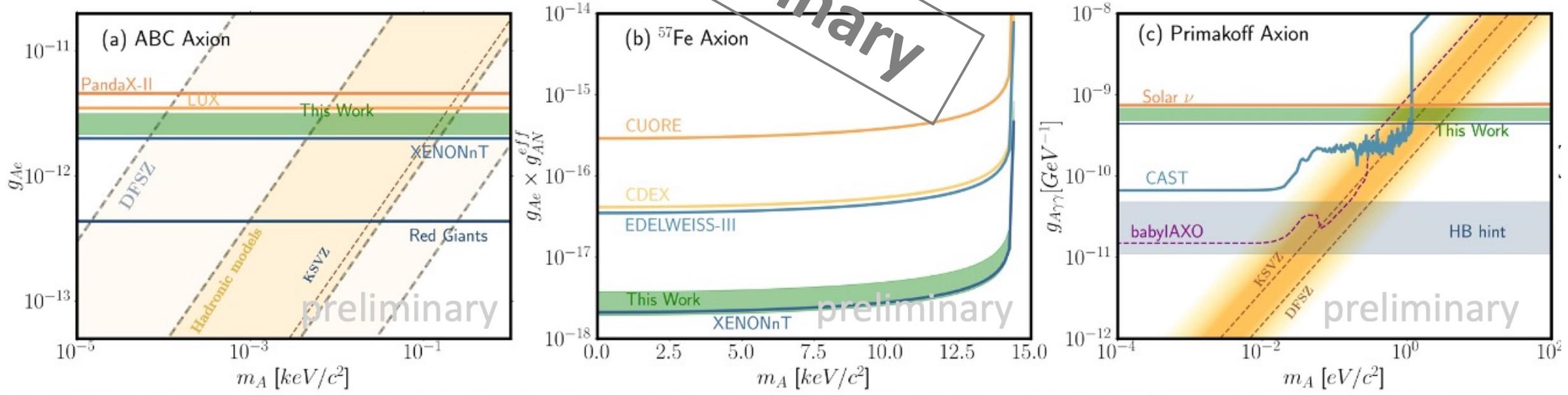
$$F(q) \simeq \sum_{i=1}^4 a_i \exp \left[-b_i \left(\frac{|\mathbf{q}|}{4\pi} \right)^2 \right] + c$$



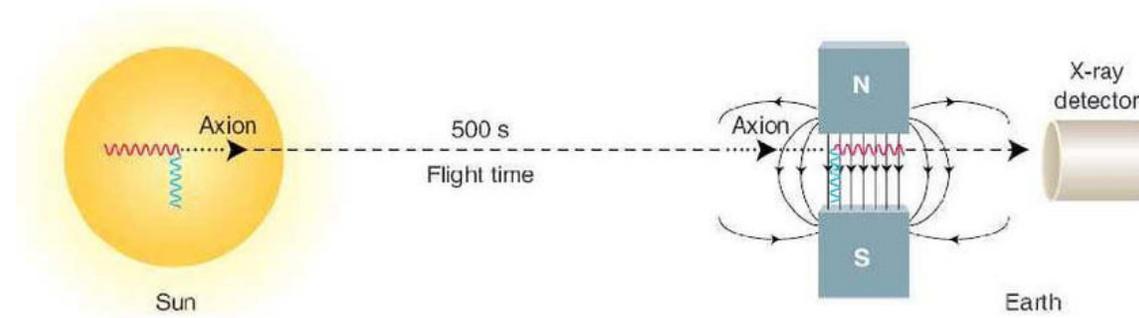
Constraints on Solar Axions

- PandaX-4T results

Preliminary



CAST Experiment



轴子暗物质探测

微波谐振腔测量方案

- 圆柱腔体+金属棒：可调频腔，搜寻 8GHz附近轴子质量

Assumption: DM is mostly axions

Resonant cavities (Sikivie, 1983)

- Primakoff conversion inside a “tunable” resonant cavity
- Energy of photon = $m_a c^2 + O(b^2)$

Primakoff conversion of DM axions into microwave photons inside cavity

$$P_0 = g_{a\gamma}^2 V B^2 C \frac{\rho_a}{m_a} Q$$

Axion DM field
Non-relativistic
Frequency \leftarrow axion mass

B_0

Cavity dimensions smaller than de Broglie wavelength of axions

If cavity tuned to the axion frequency, conversion is “boosted” by resonant factor (Q quality factor)

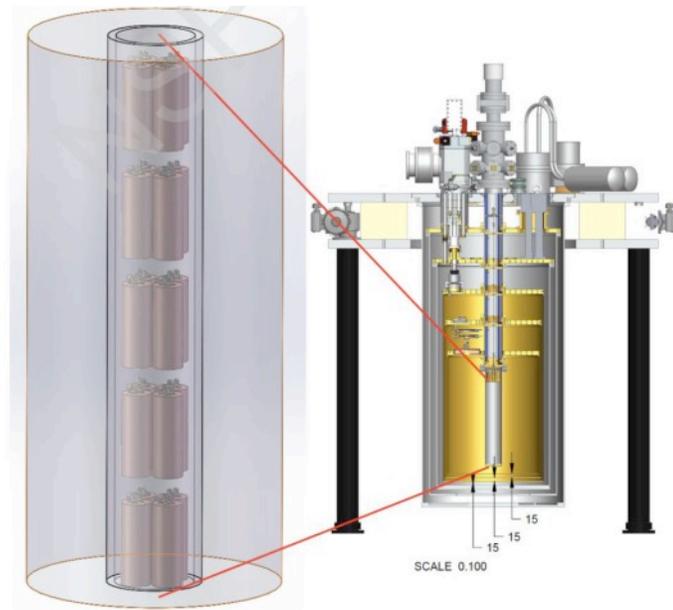
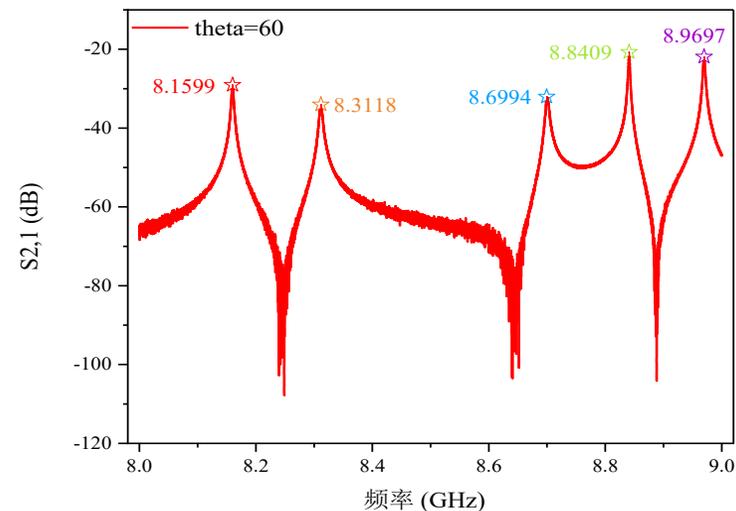


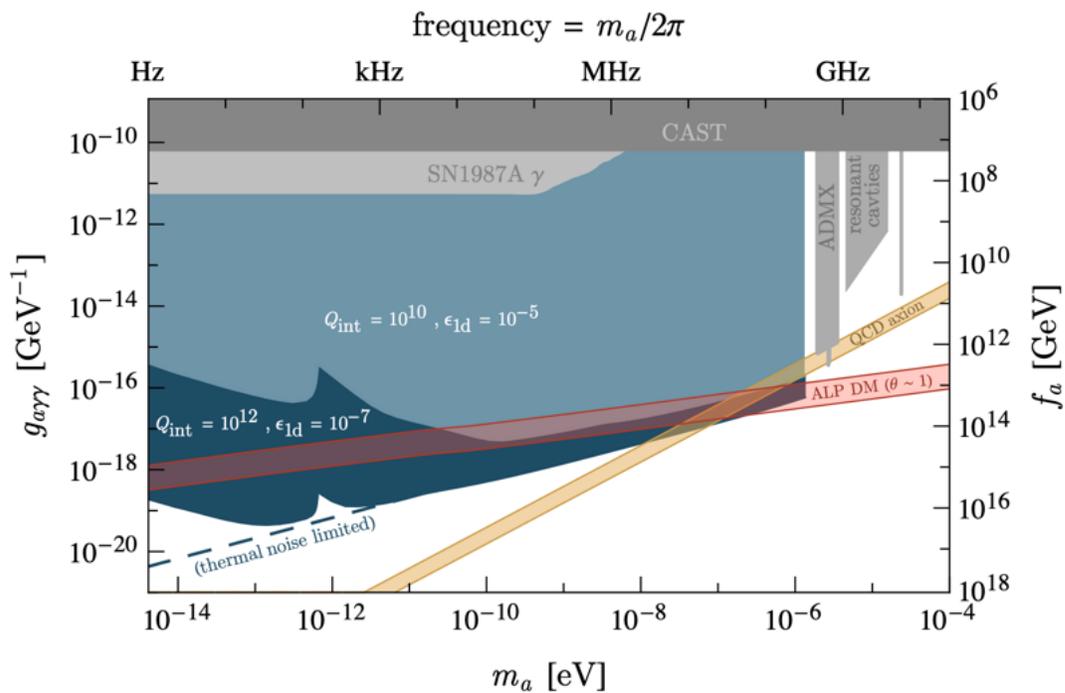
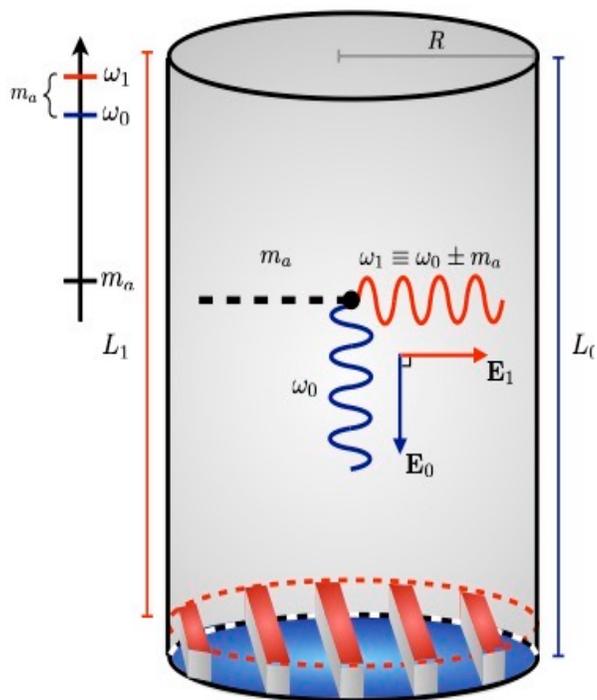
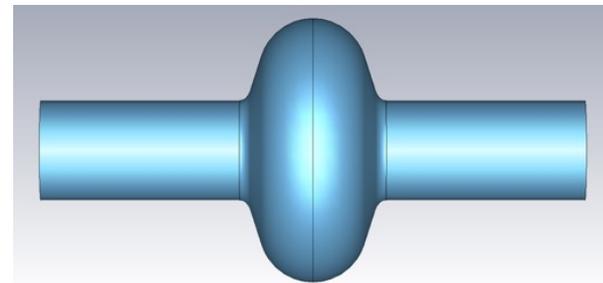
图11. 共振腔安装在稀释制冷机中。



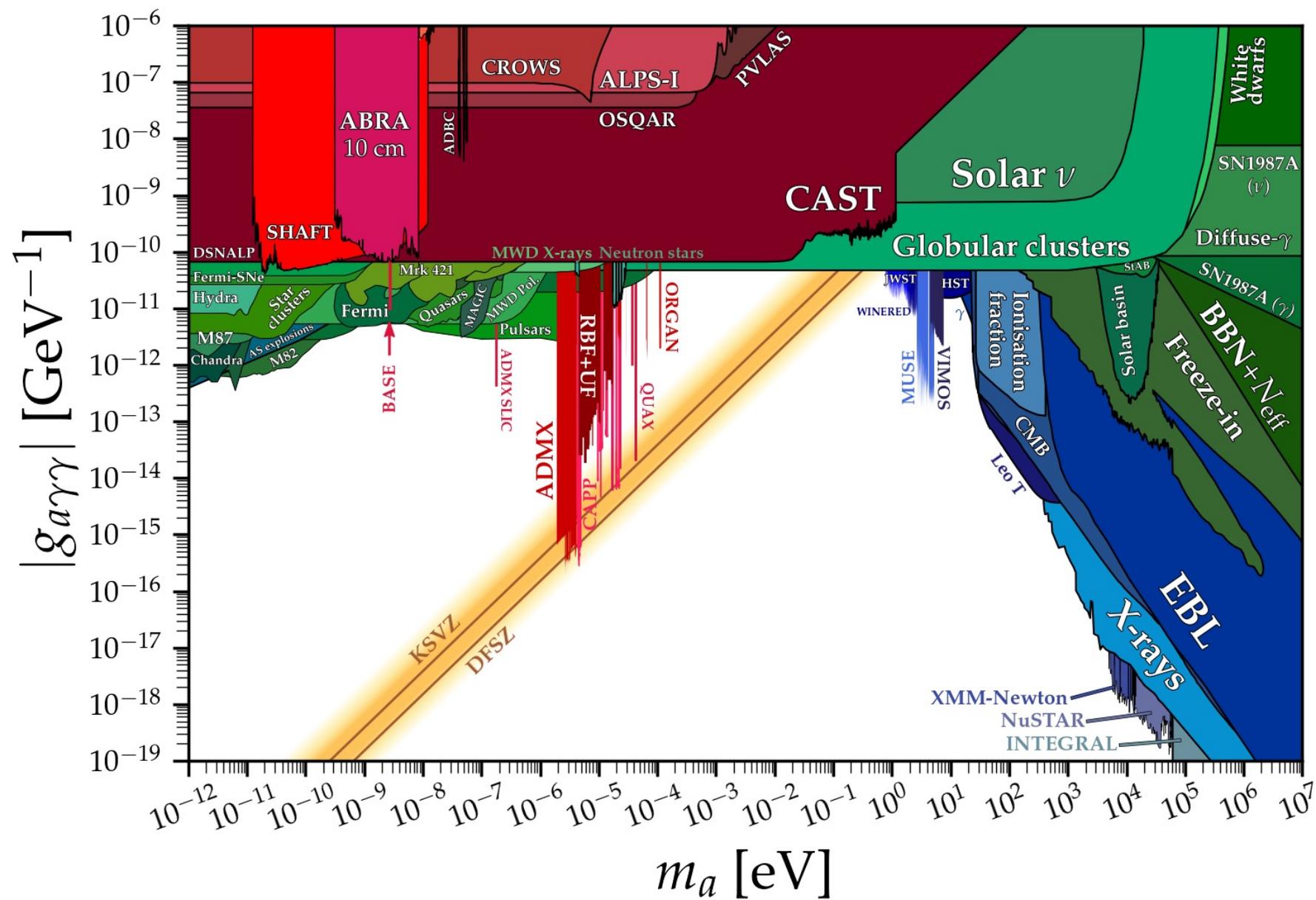
轴子暗物质探测

• 超导射频谐振腔

- 注入振荡磁场：实现宽频搜寻轴子质量 1Hz to 500MHz
- 测试: TM020 2.7GHz信号模，搜寻200MHz附近轴子



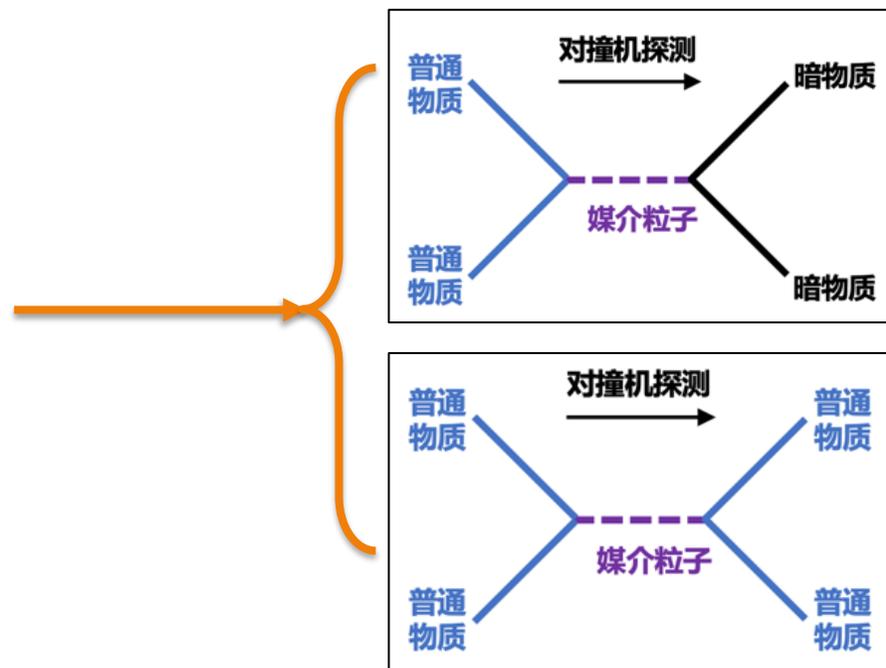
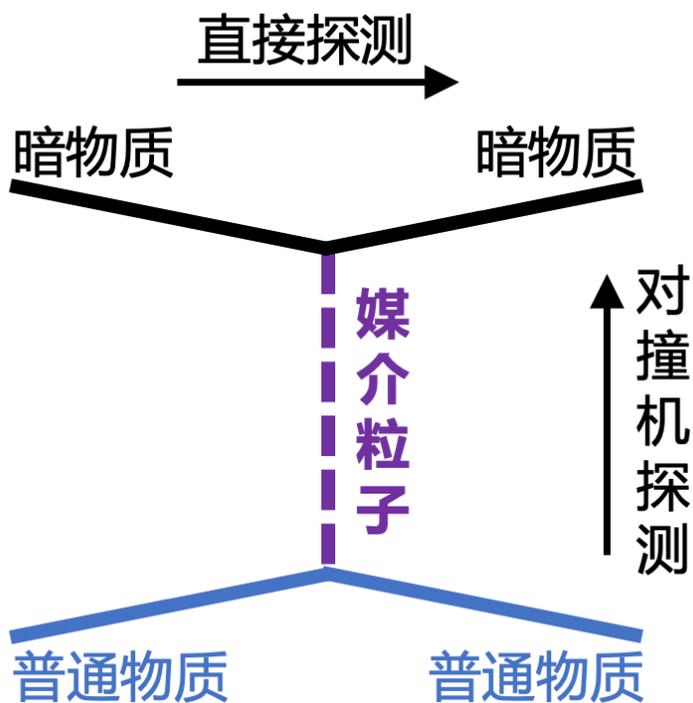
轴子探测



暗物质相互作用机制

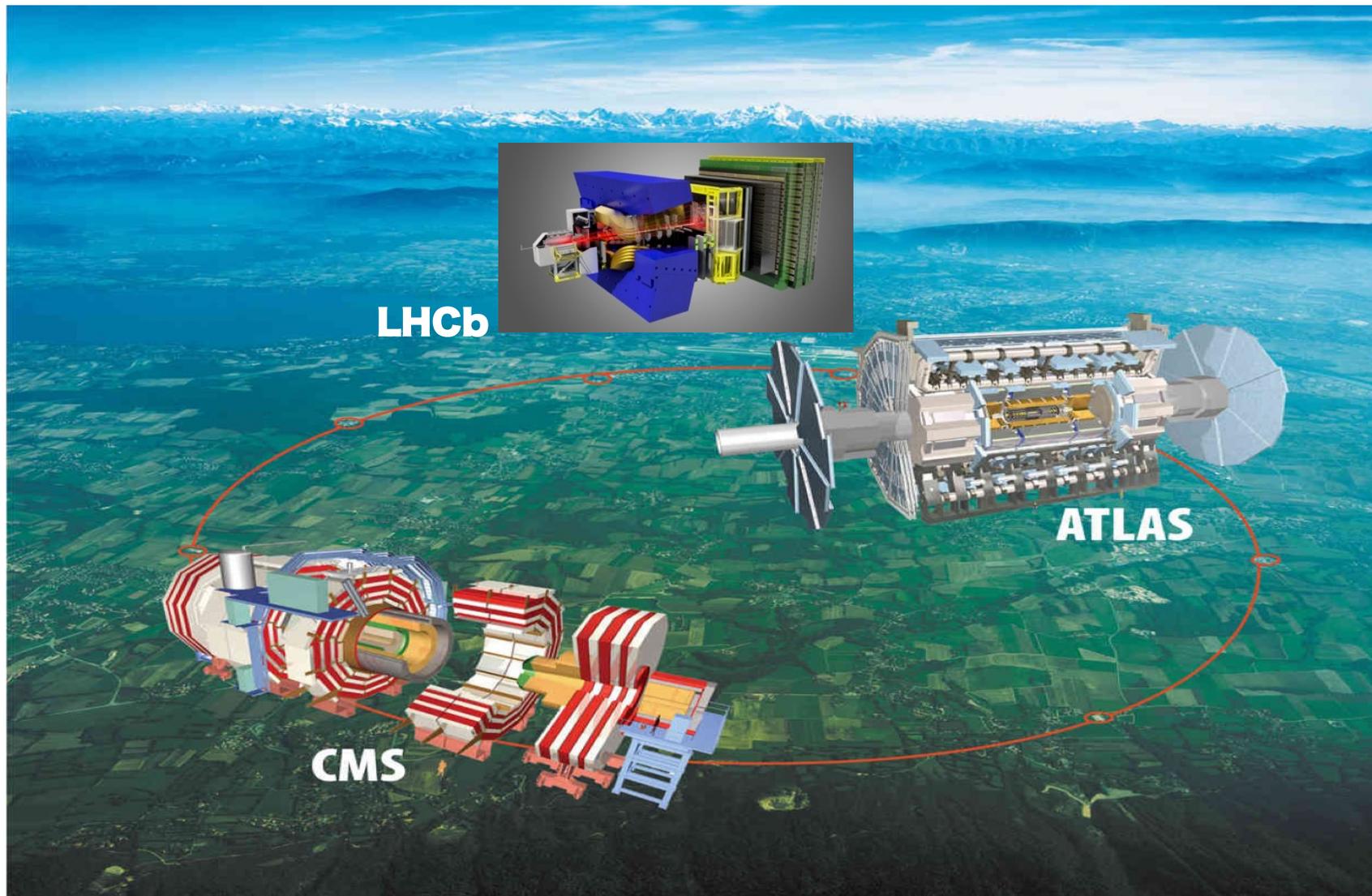
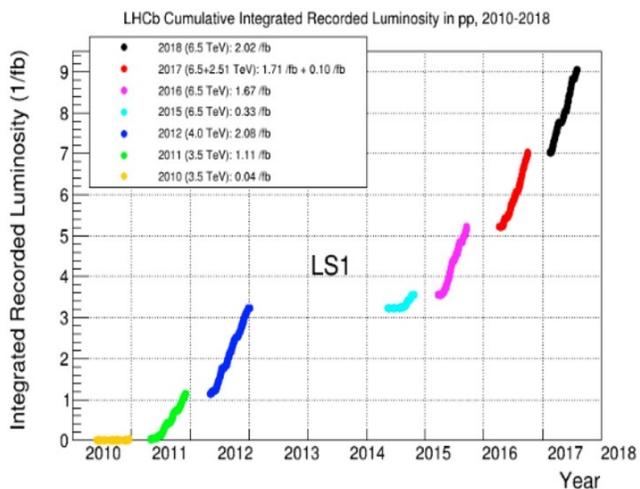
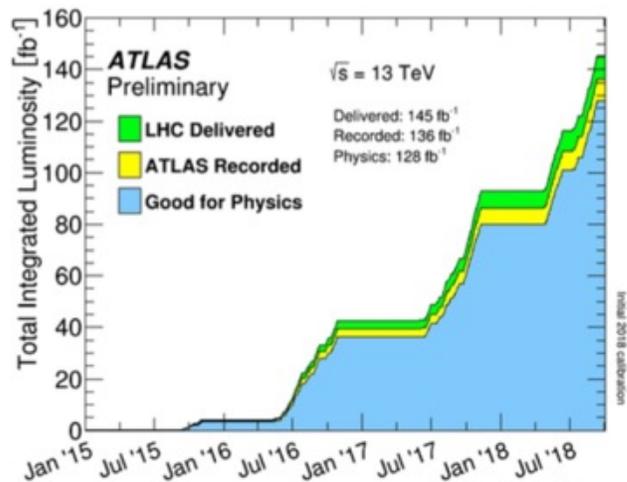
• **难点：**直接探测相互作用能标太低，无法探究媒介粒子作用机制

- **对撞机探测围绕相同作用机制**
- **对撞机独特优势：**产生媒介粒子并测量其衰变产物



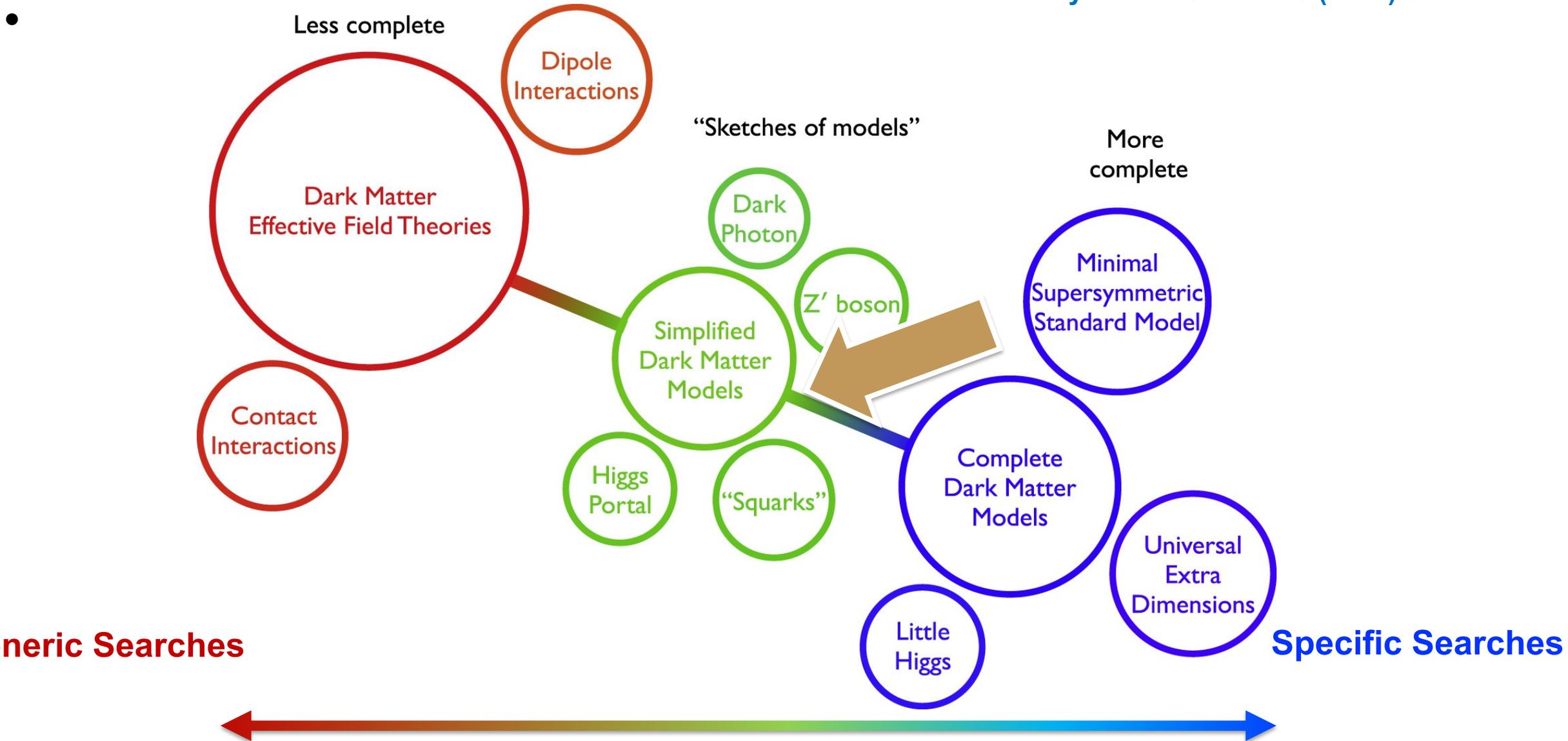
对撞机探测

- 高能标准模型粒子碰撞产生暗物质



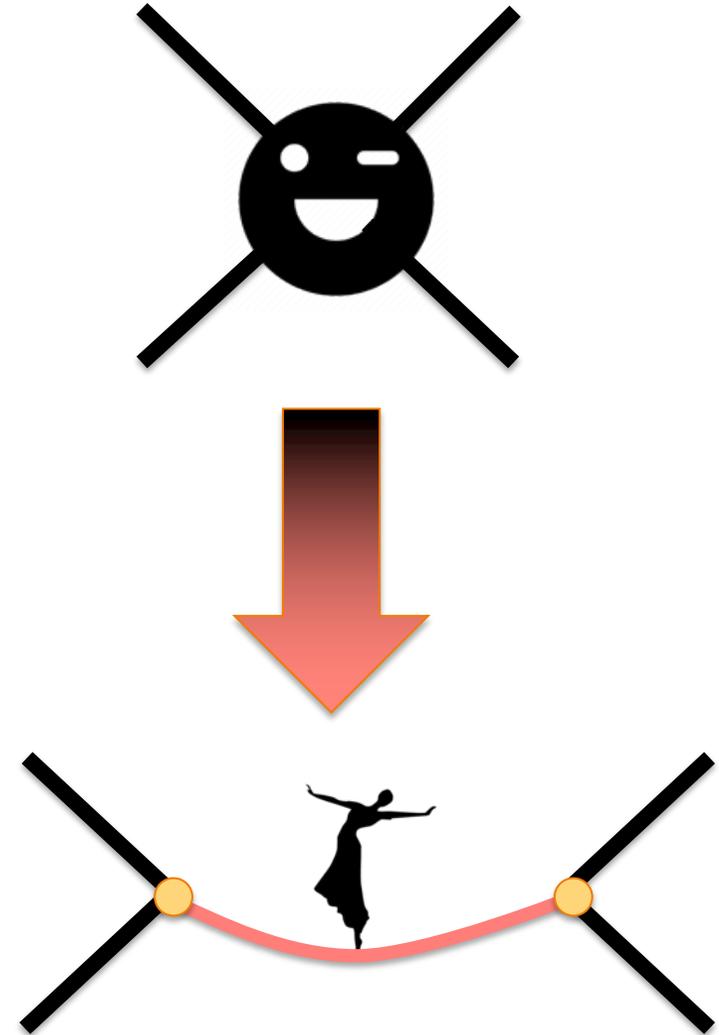
Dark matter models

Phys. Dark Univ. 9-10 (2015) 8-23



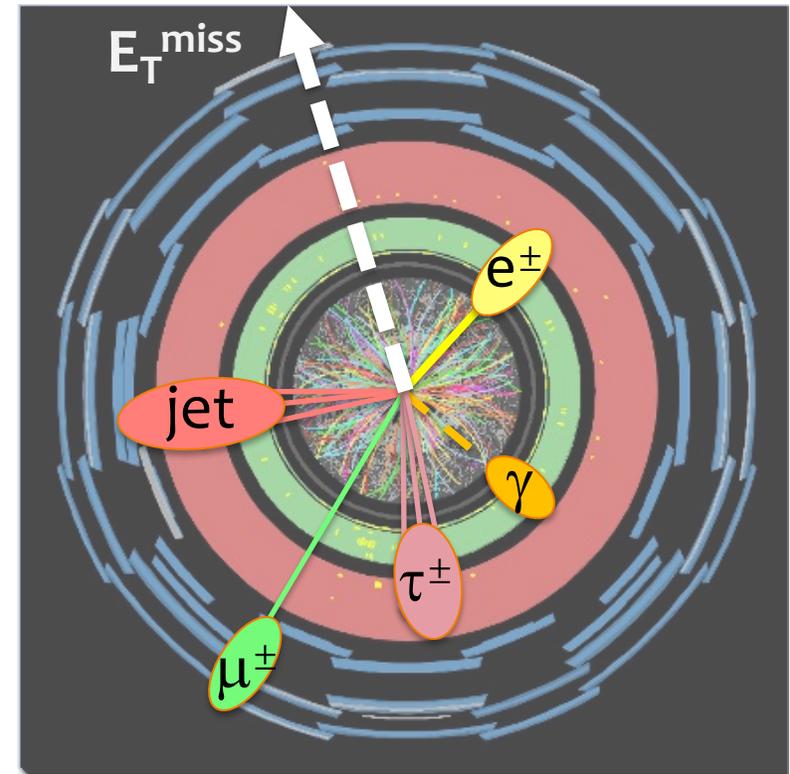
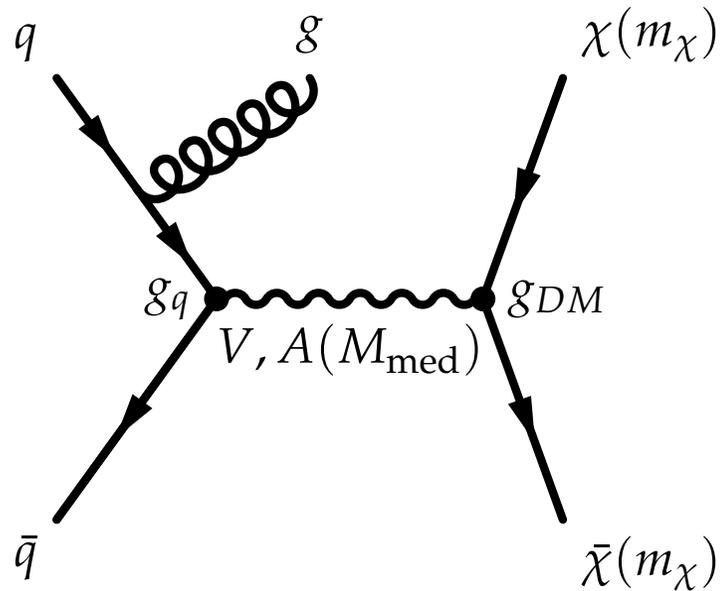
Simplified model with mediator

- **keep the mediator information**
 - mass: $m_{Z'}$
 - spin : vector, axial-vector, etc
 - coupling: g_q g_l g_{DM}
- **simplified model:**
 - starting point to build complete theories
 - colliders can search for the mediator directly



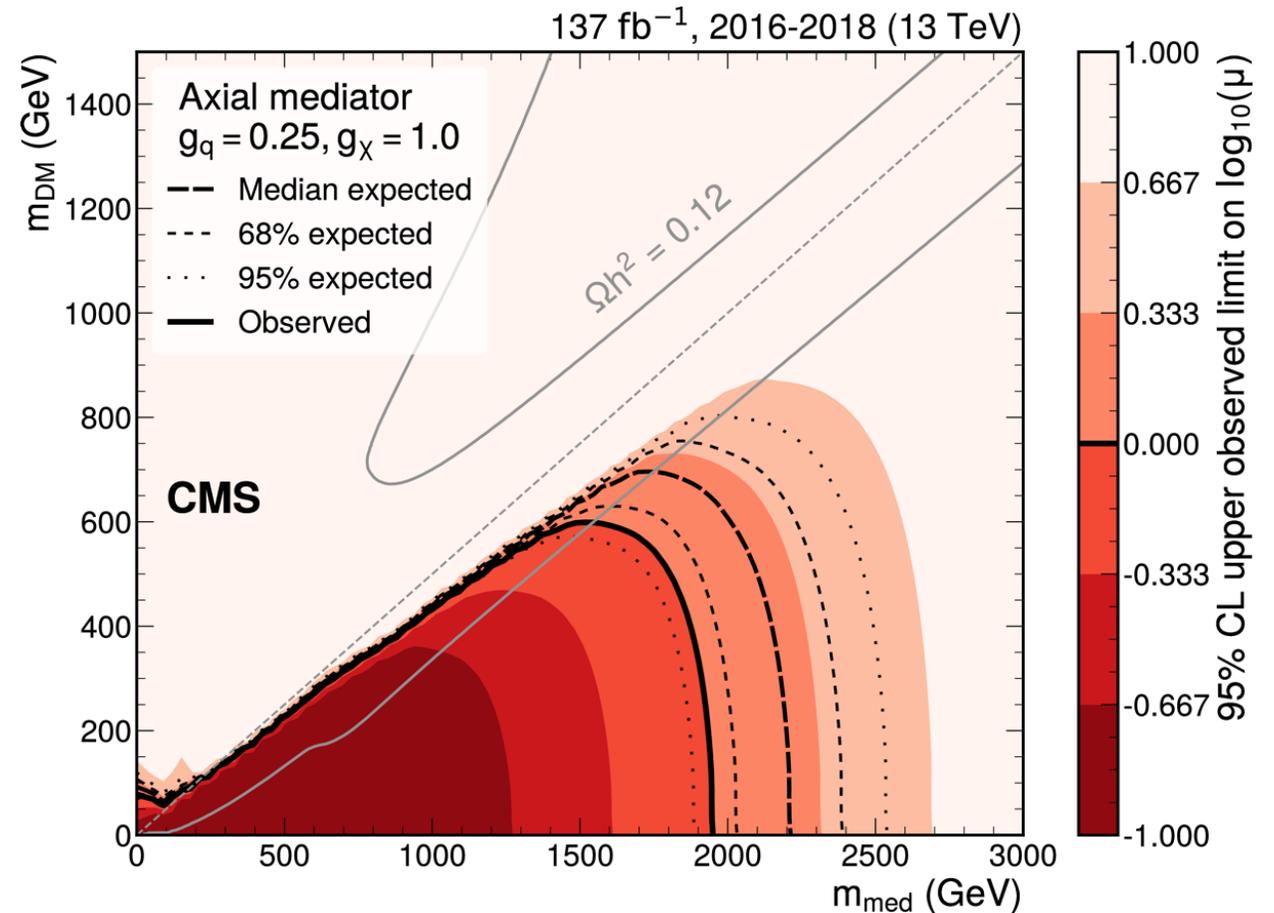
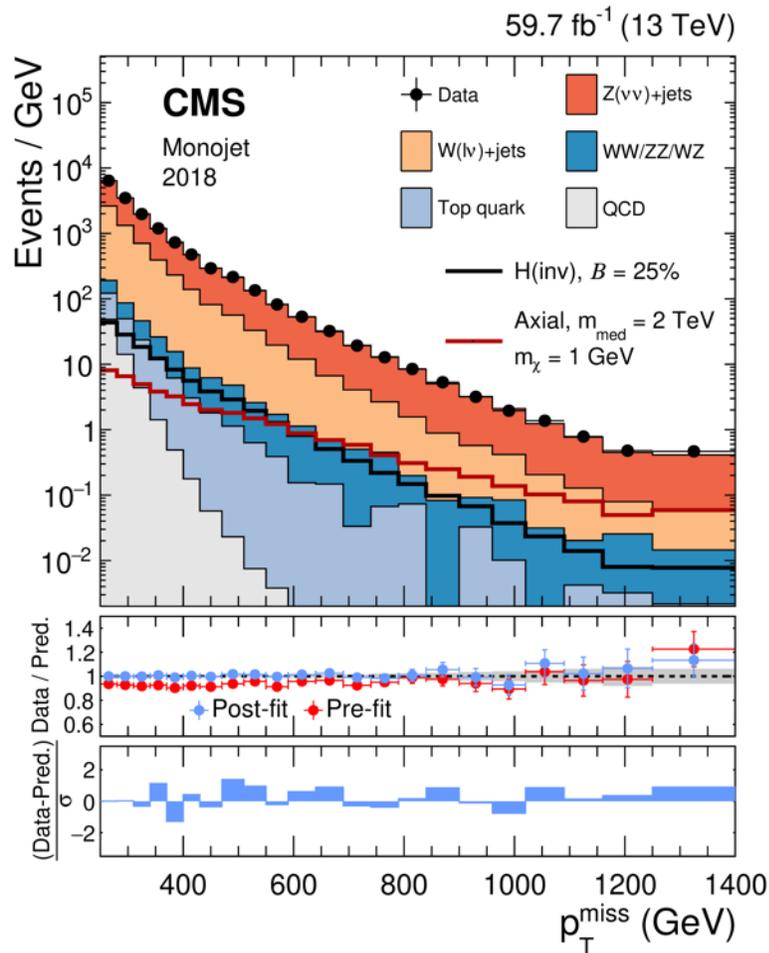
Mono-X search

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



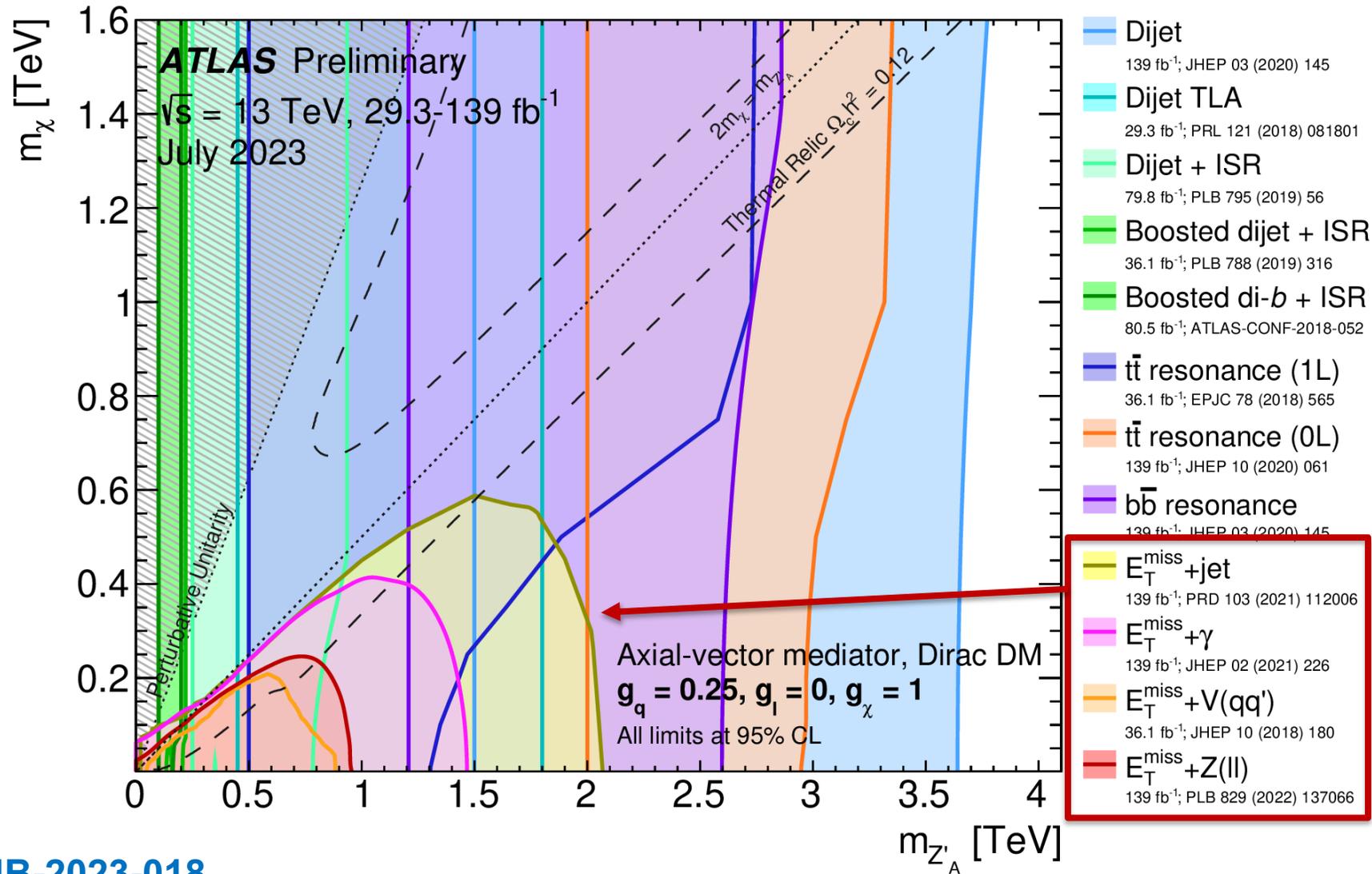
Mono-jet

- ISR gluon/quark: largest cross section
- provide strong sensitivity



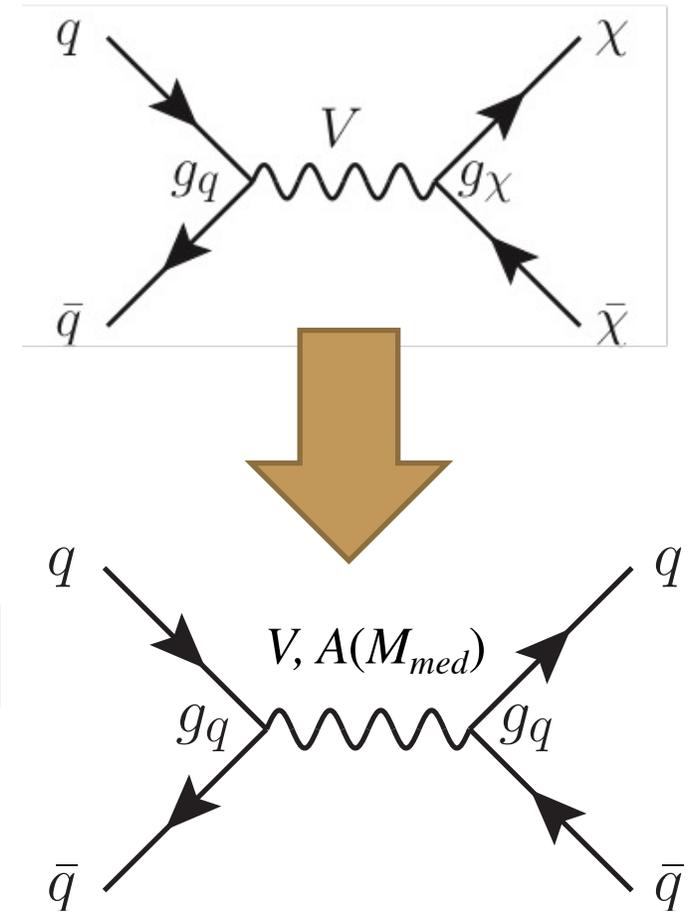
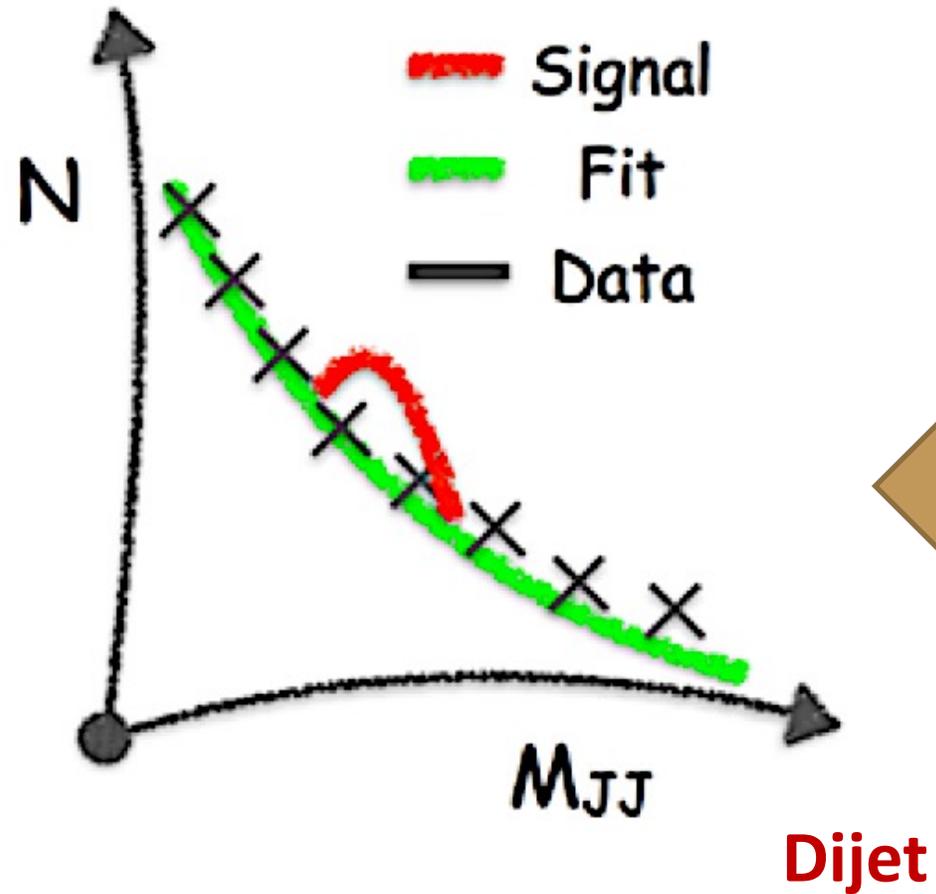
JHEP 11 (2021) 153

Constraints from mono-X



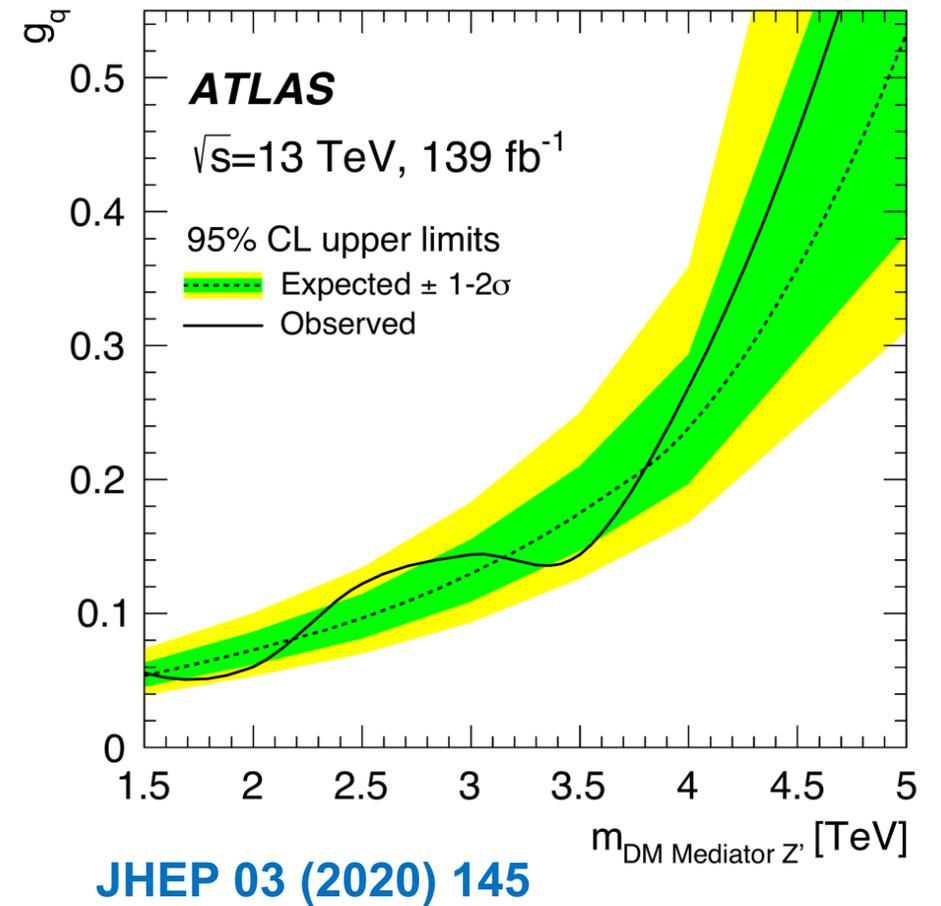
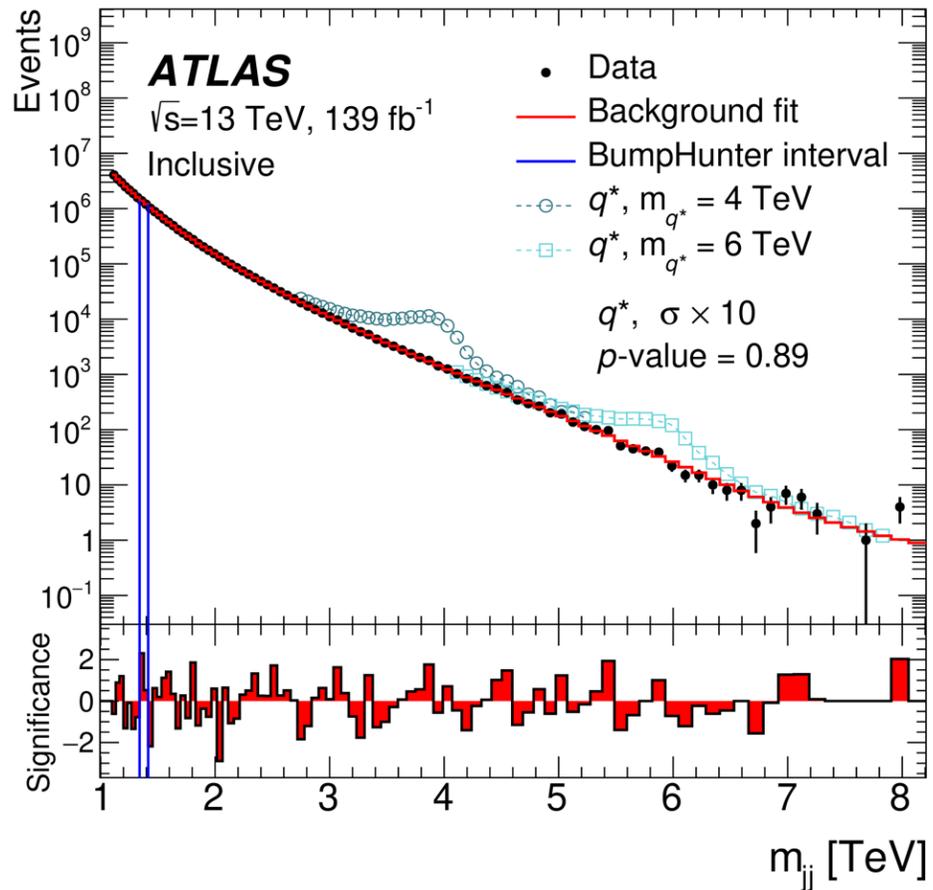
Mediator search

- Direct search of the produced mediator



Resonance of dijet

- dijet resonance: inclusive, 1 or 2 b-jets

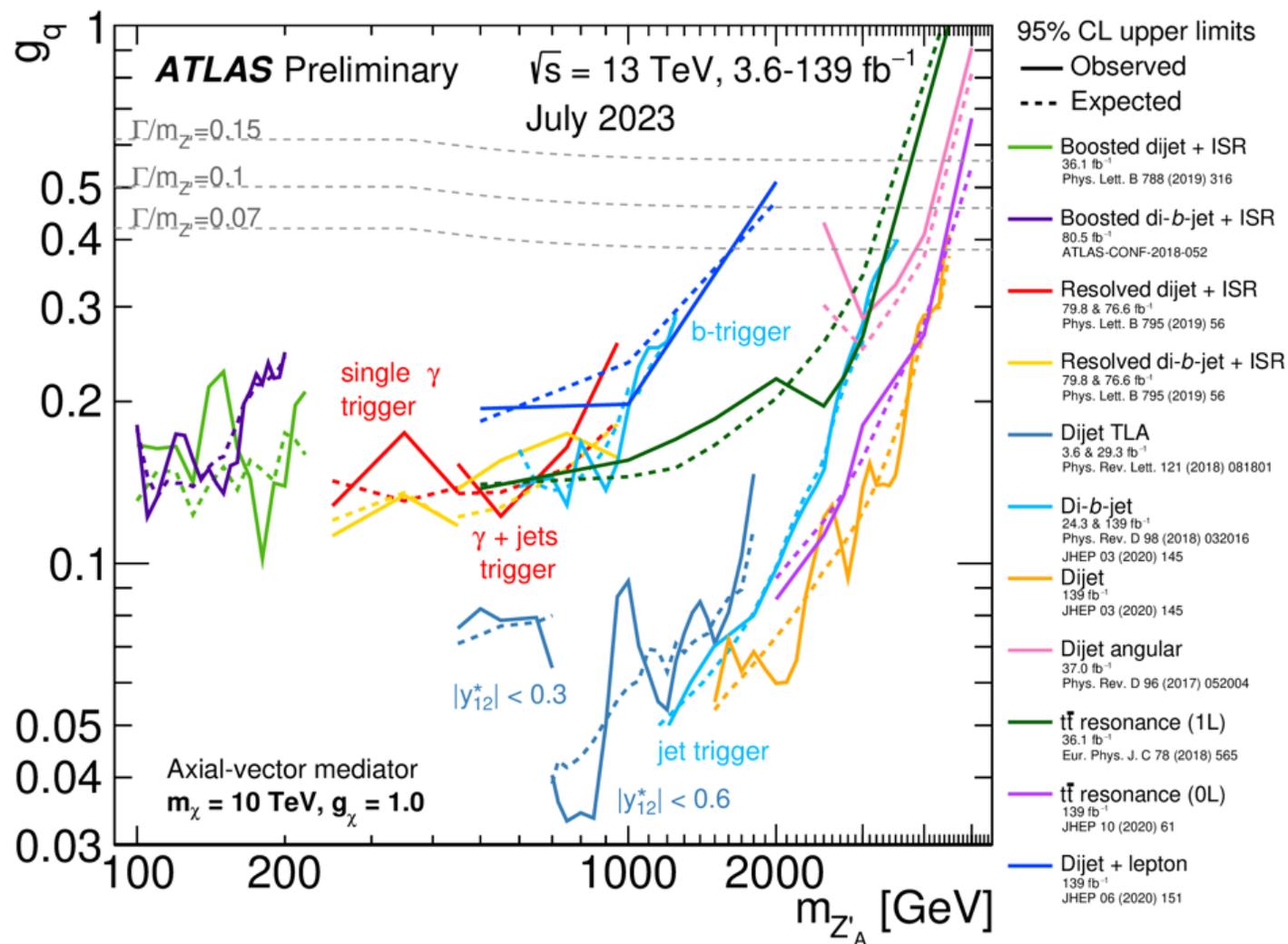


Extending to low mass region

- Various techniques to extend to lower or higher mediator mass region

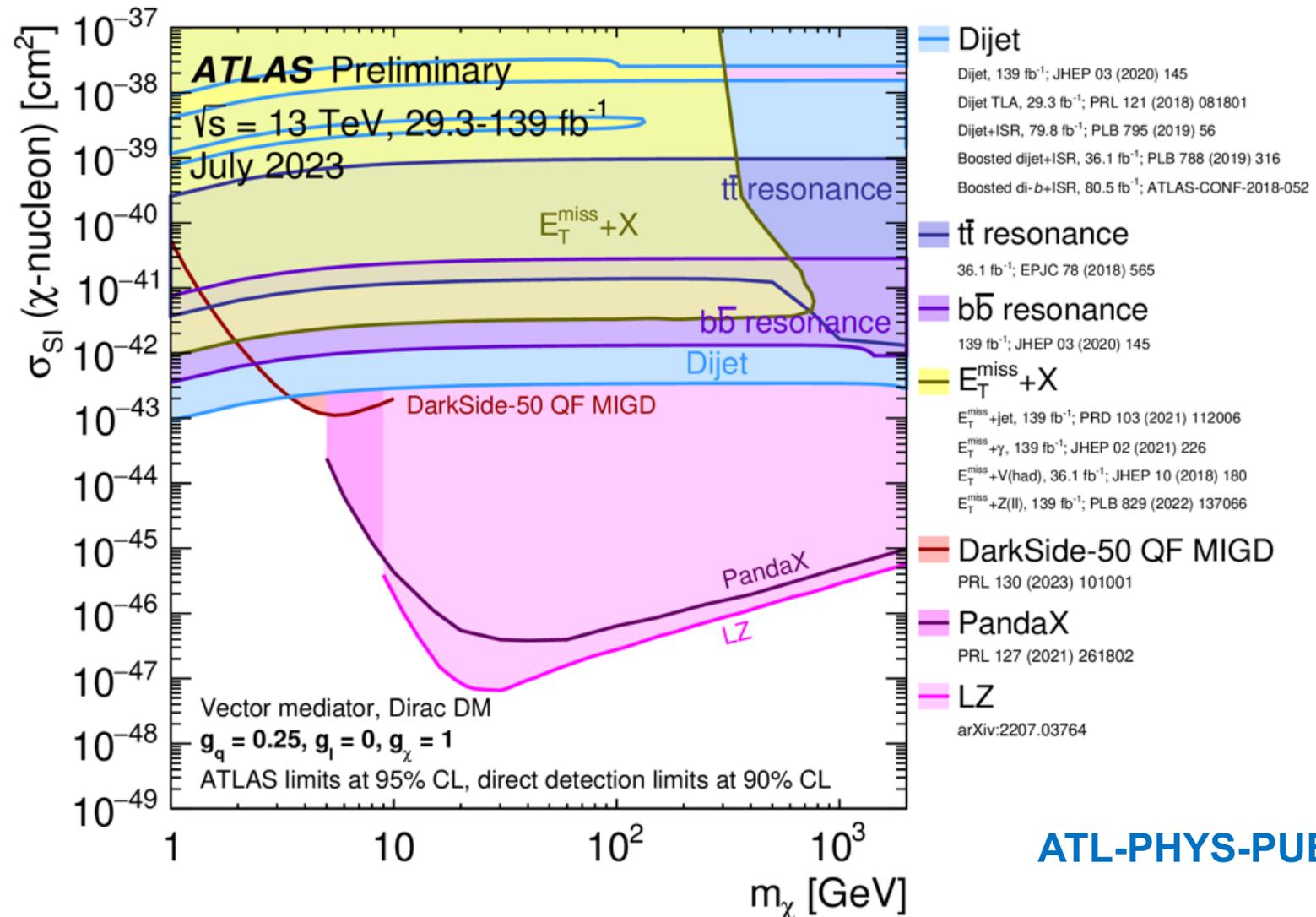
- dijet+ISR
- dijet TLA
- dijet angular

ATL-PHYS-PUB-2023-018



Combination with direct detection

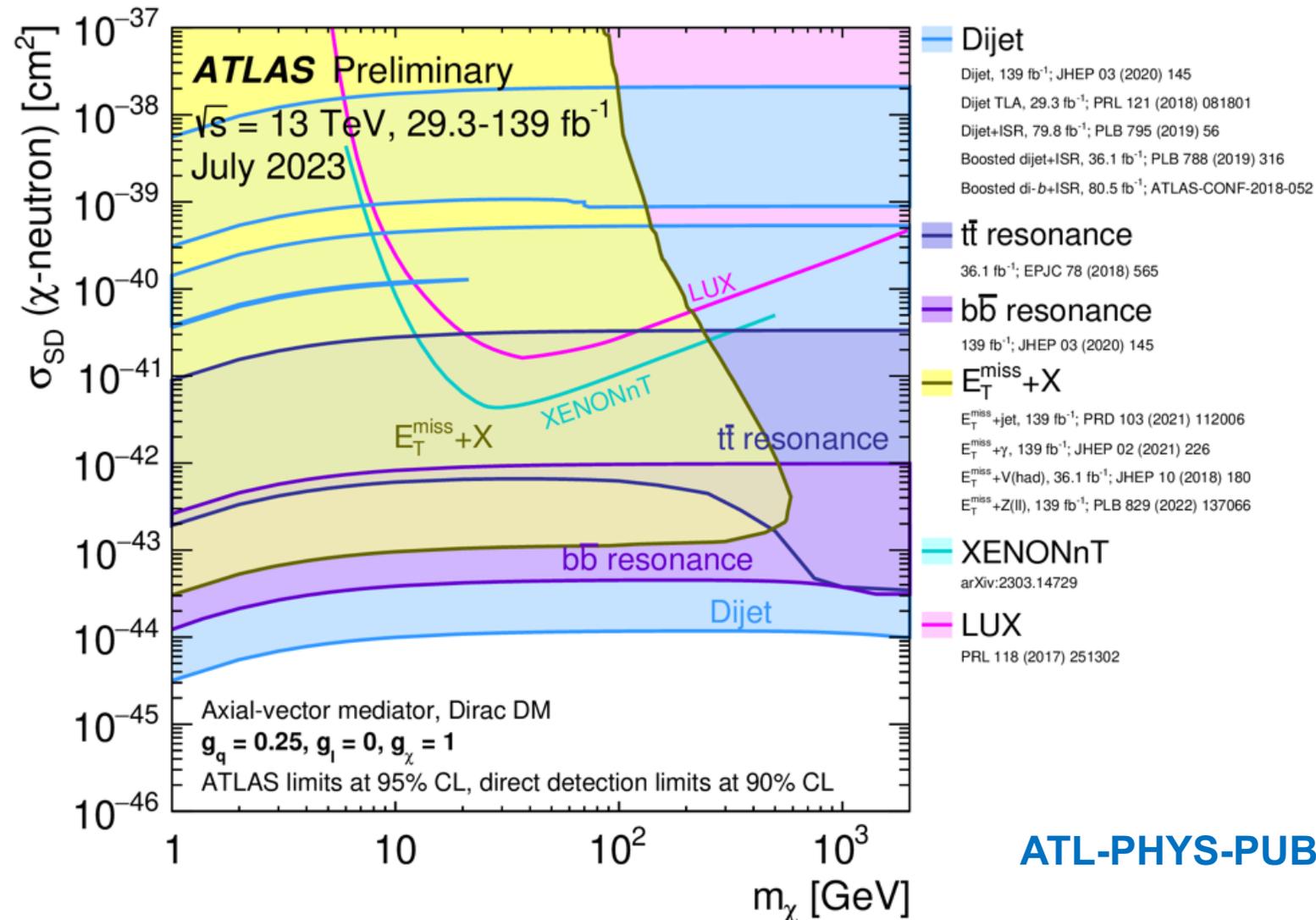
- vector mediator – spin independent interaction in direct detection



ATL-PHYS-PUB-2023-018

Combination with direct detection

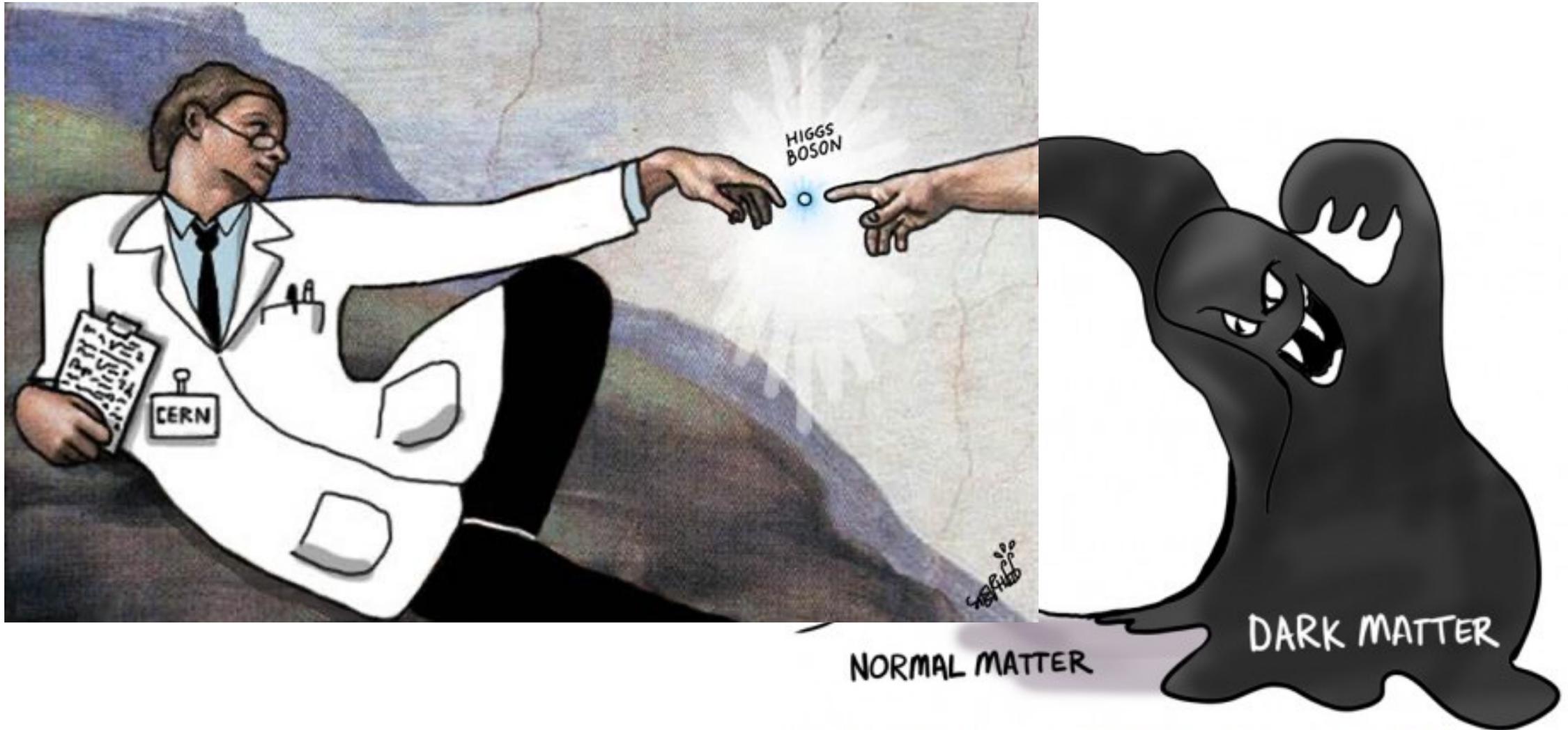
- axial-vector mediator – spin dependent interaction in direct detection



ATL-PHYS-PUB-2023-018

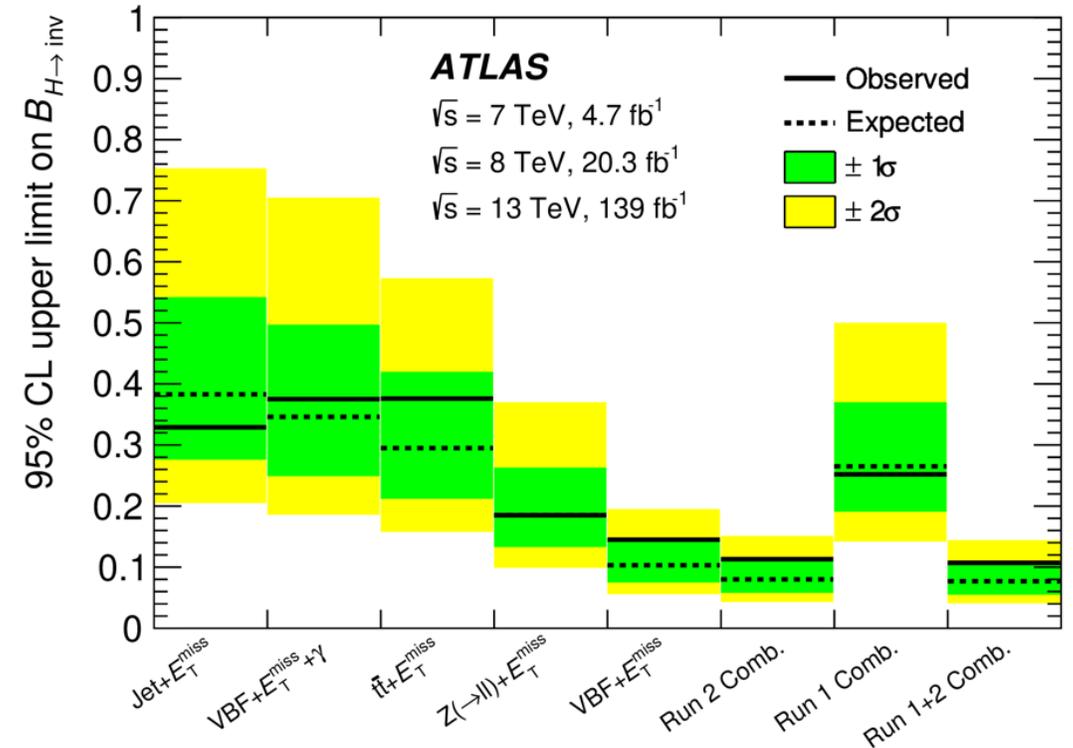
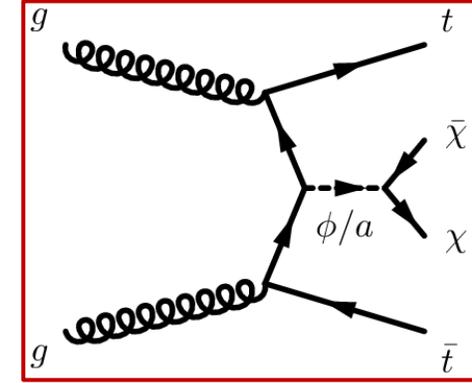
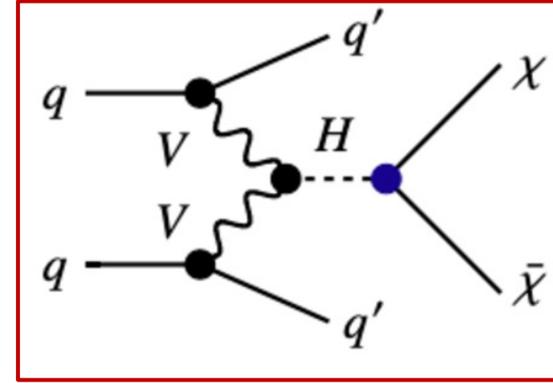
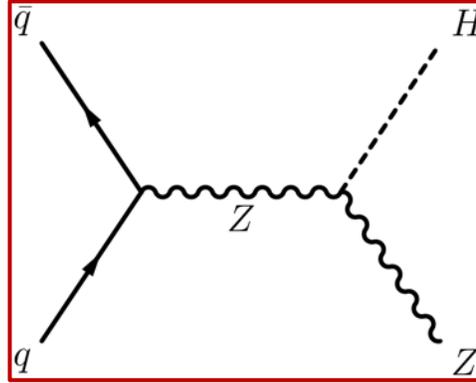
Dark matter and Higgs

- Higgs may connect to the dark sector



Invisible Higgs

- Higgs-portal DM model
- signatures
 - Z/W+H(inv)
 - VBF H(inv)
 - ttbar H(inv)
- combined constraints
 - **Br(inv) < 0.11** at 95%CL from ATLAS

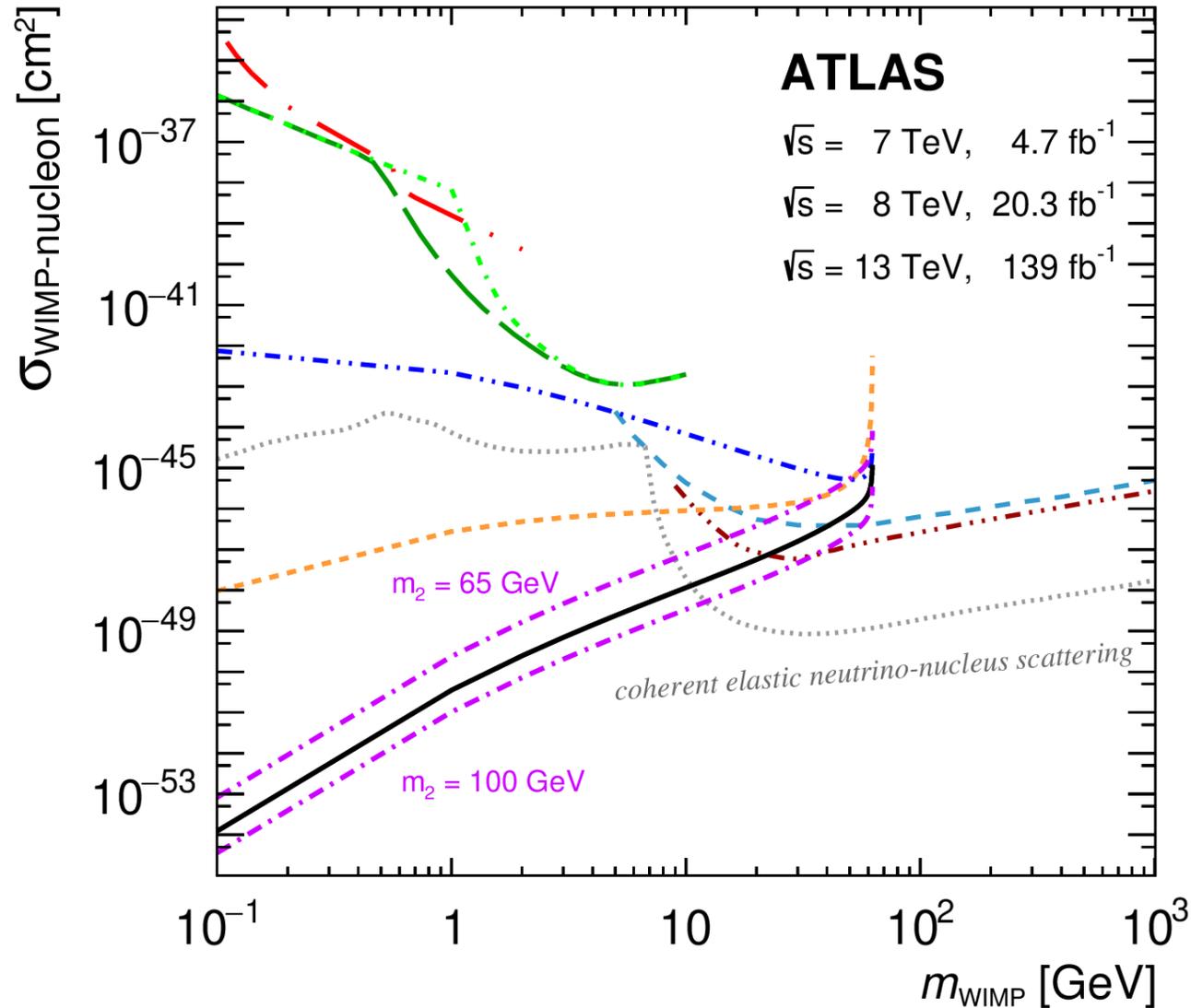


Phys. Lett. B 842 (2023) 137963

Higgs-portal DM

- **scalar mediator**
 - spin-independent interaction
- **sensitive to**
 $m_{\text{DM}} < \frac{1}{2} m_{\text{Higgs}}$

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$B_{\text{H} \rightarrow \text{inv}} < 0.093$
 All limits at 90% CL

Higgs Portal WIMP:

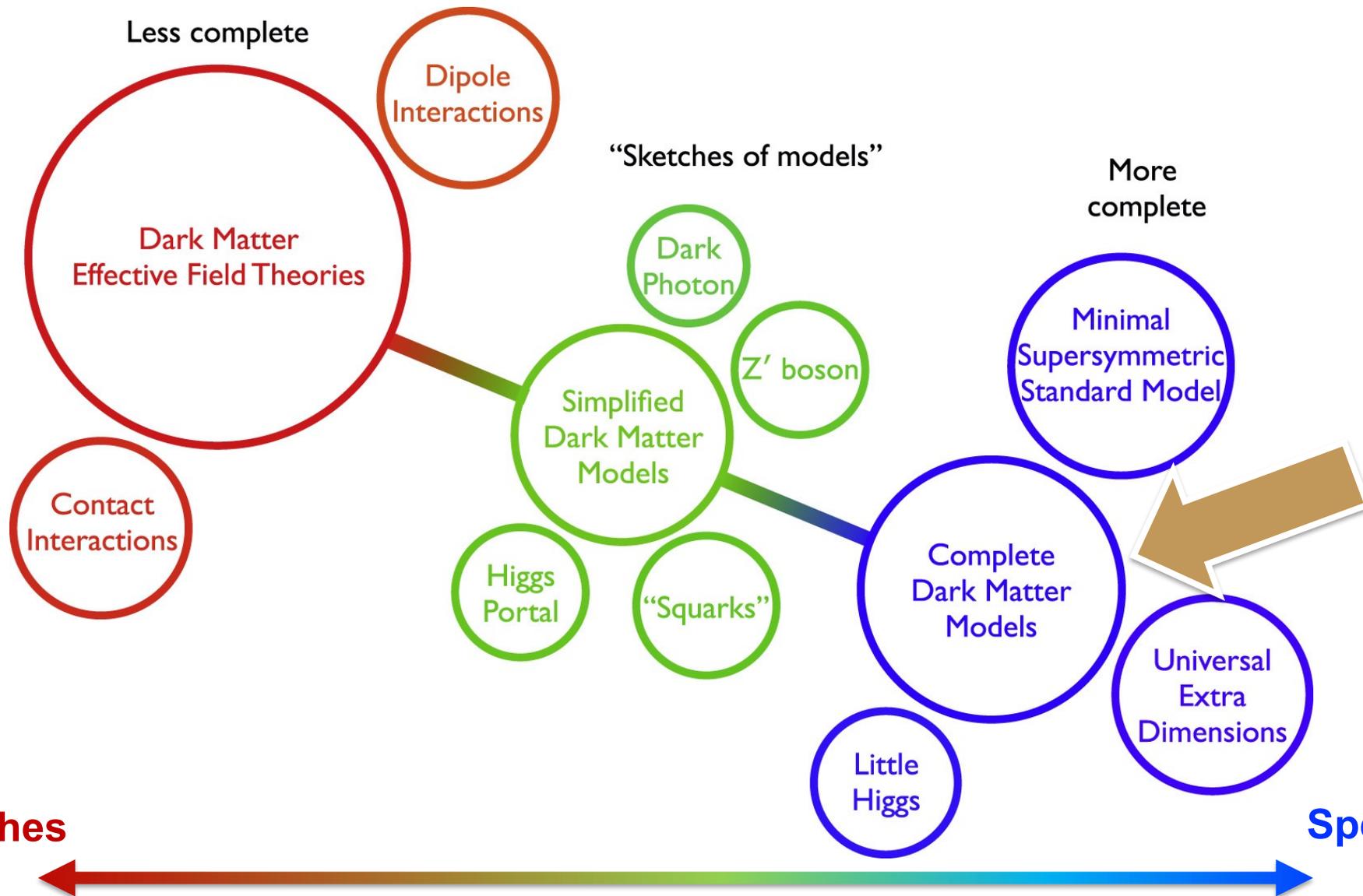
- Scalar
- - - Majorana
- Vector_{EFT}
- · - Vector_{UV model, $\alpha = 0.2$}

Other experiments:

- · - Xenon1T-Mig
- · - DS50-MigNQ
- - DS50-MigQF
- - PandaX-4T
- · - LUX-ZEPLIN

Complete models

Phys. Dark Univ. 9-10 (2015) 8-23



2HDM Model

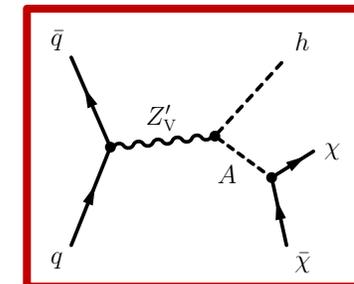
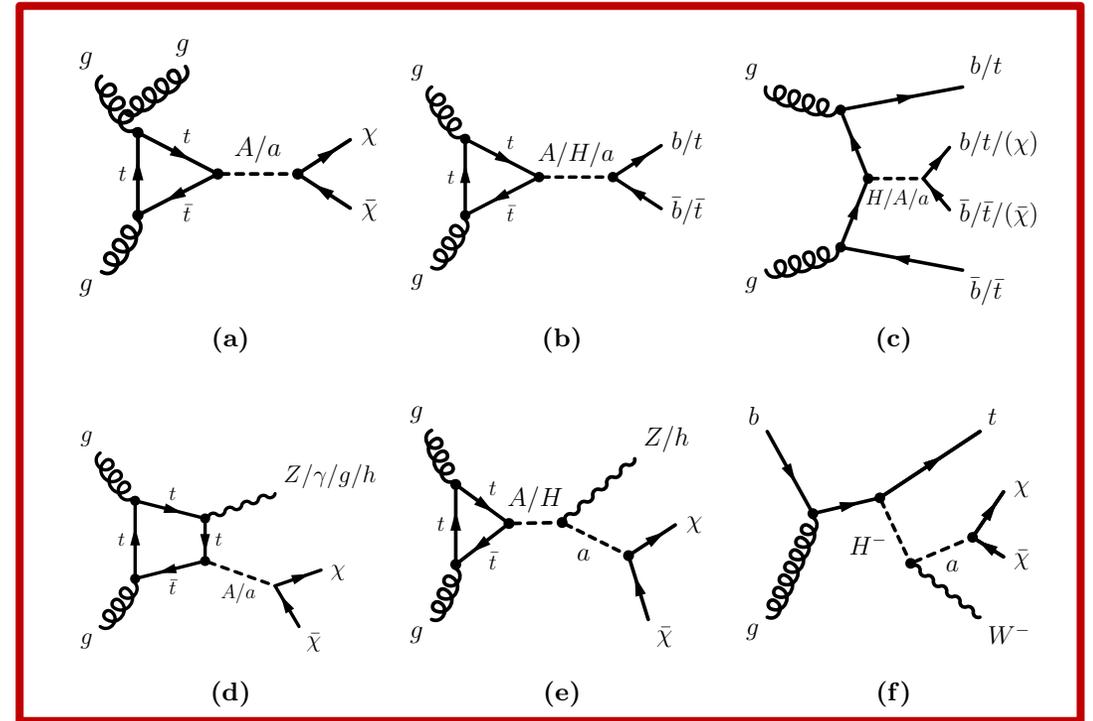
- Two benchmark models: 2HDM+a, 2HDM+Z'

- 2HDM+a

- based on type-II 2HDM (h, H^0, H^\pm, A)
- additional pseudo-scalar mediator a
- rich phenomenology

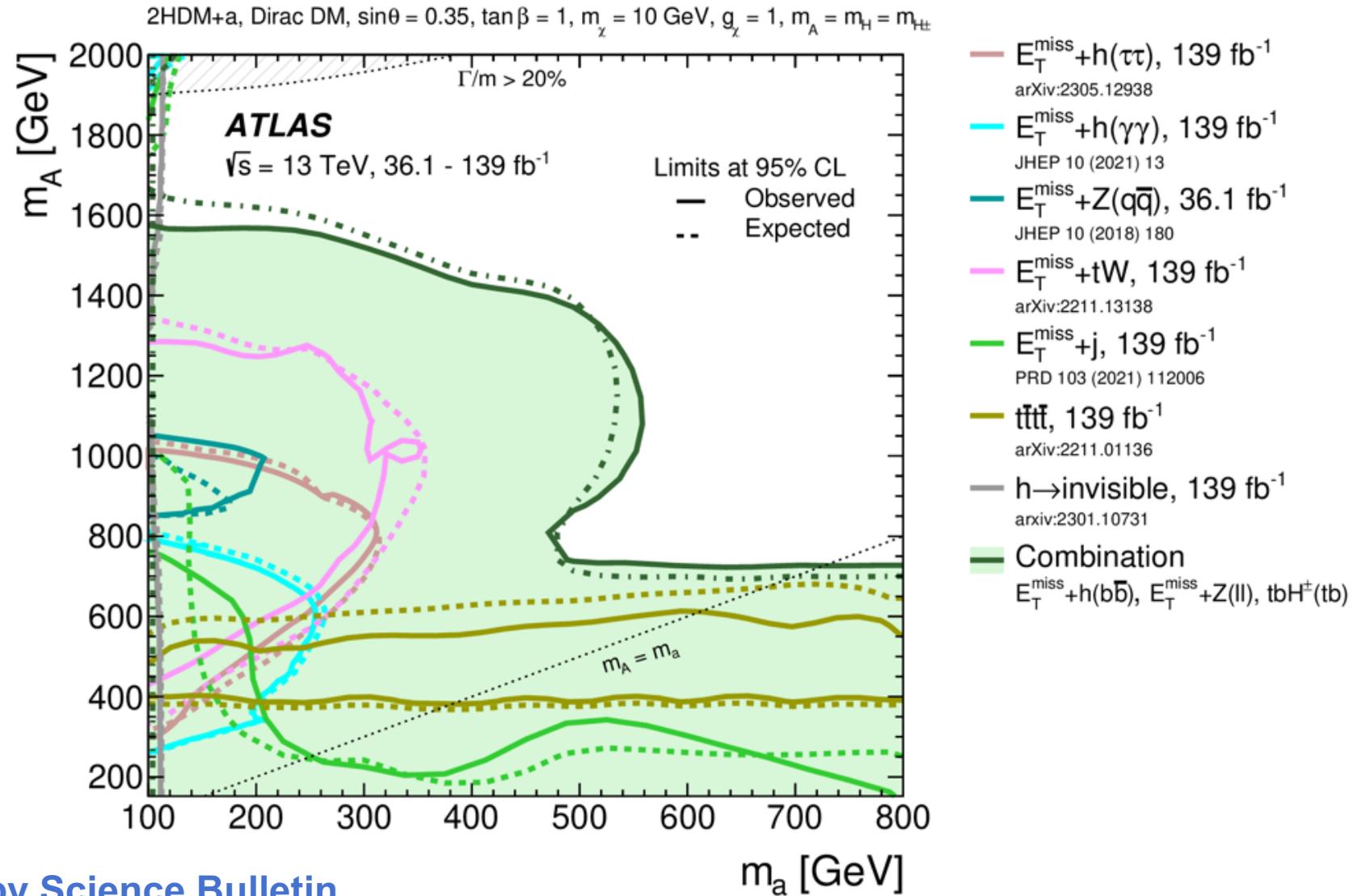
- 2HDM+Z'

- additional vector mediator Z'



2HDM+a

- mono-Higgs
- mono-Z
- invisible Higgs
- 4top channel

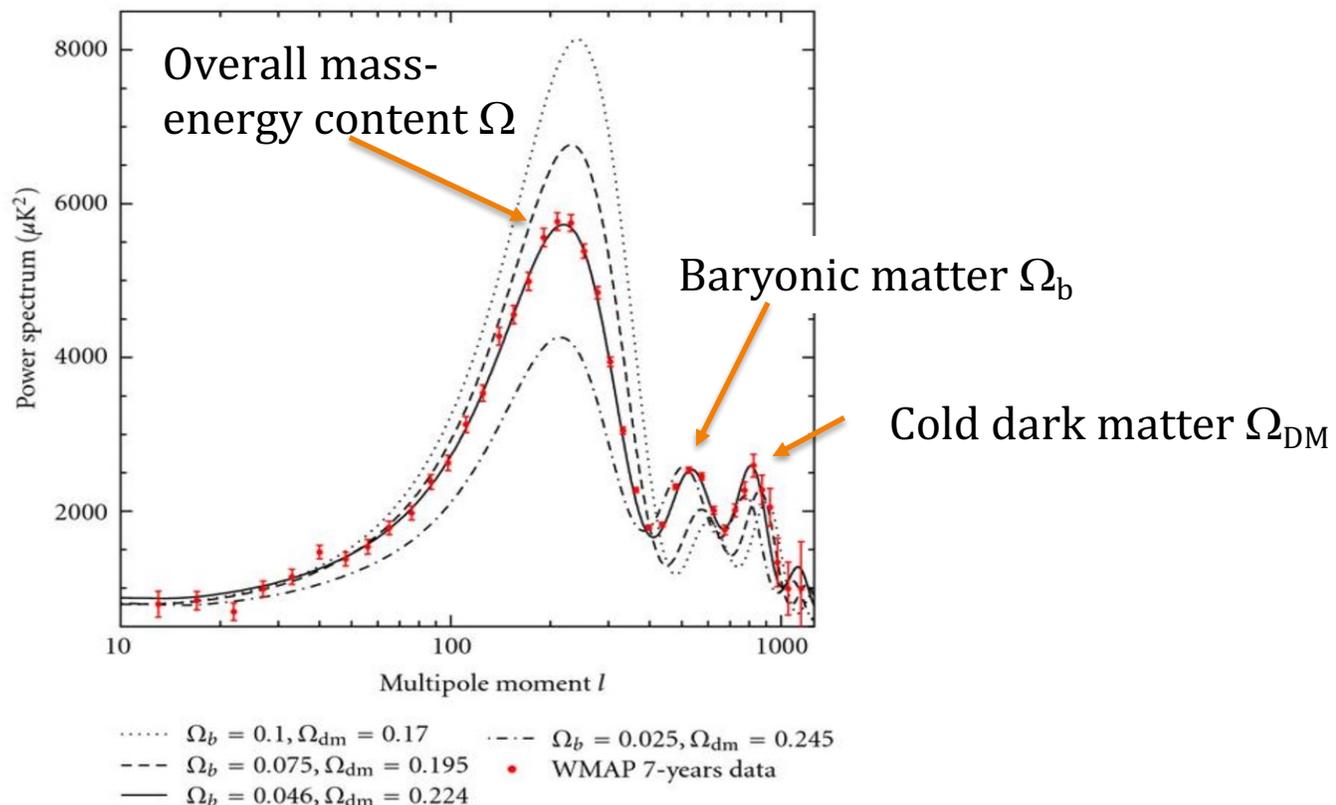


暗物质实验小结

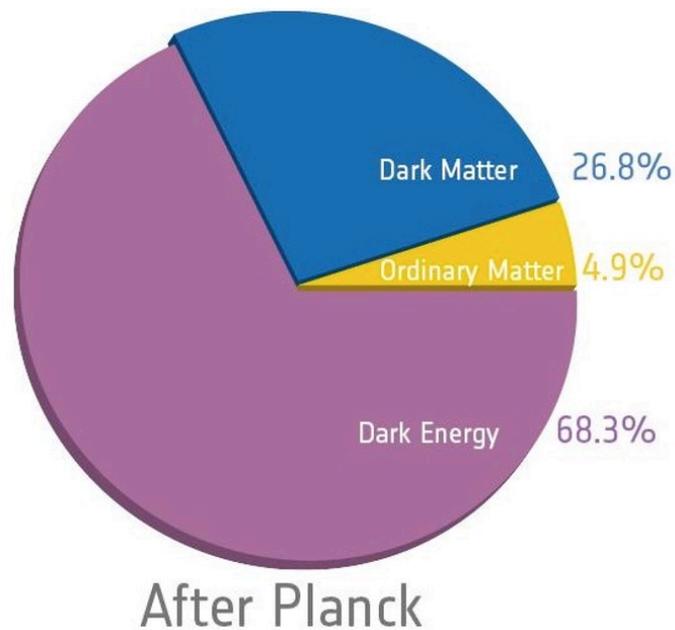
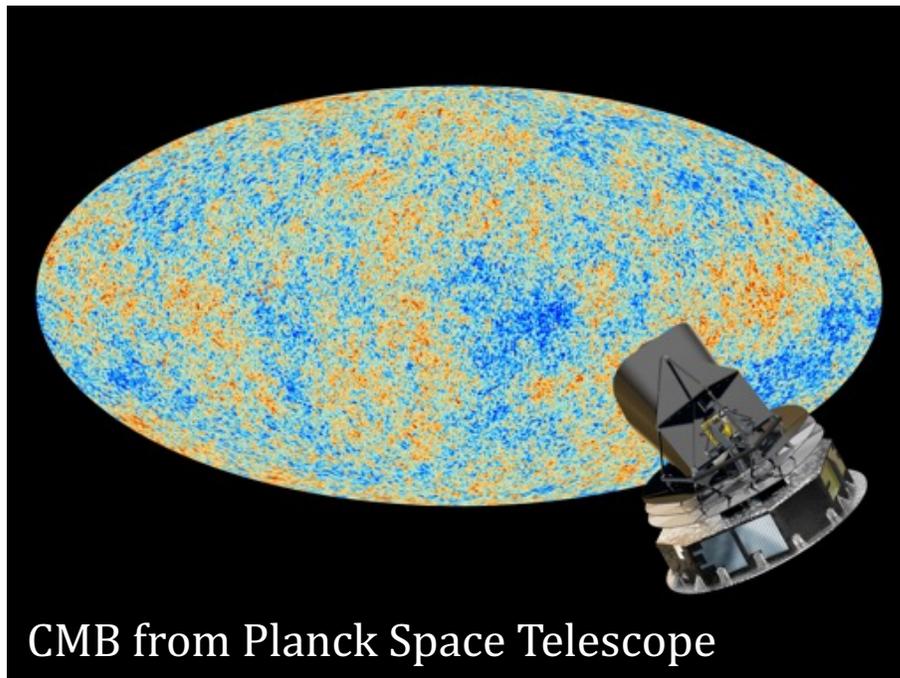
- **暗物质探测是新物理探索的重要组成**
- **在实验室探测到暗物质并研究其物理属性，将带来物理学和天文学的重大变革**
- **中国过去10年培养出相当规模的队伍，主导暗物质实验取得国际先进成果**
- **暗物质探测近年来迅速发展，面临重要发现机遇**

证据四：宇宙尺度证据

• 宇宙背景微波辐射各向异性

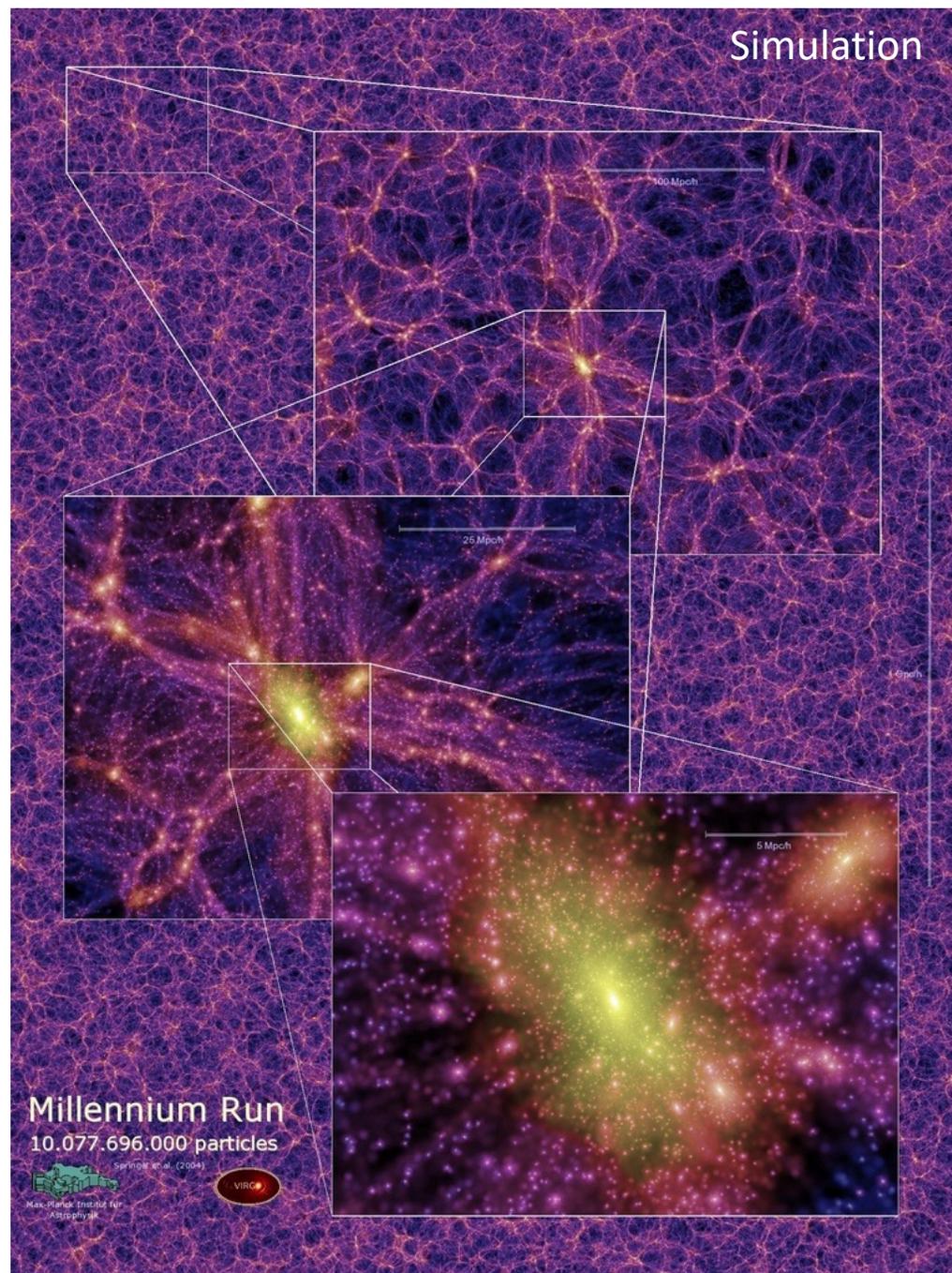


• 引入冷暗物质来描述这个宇宙



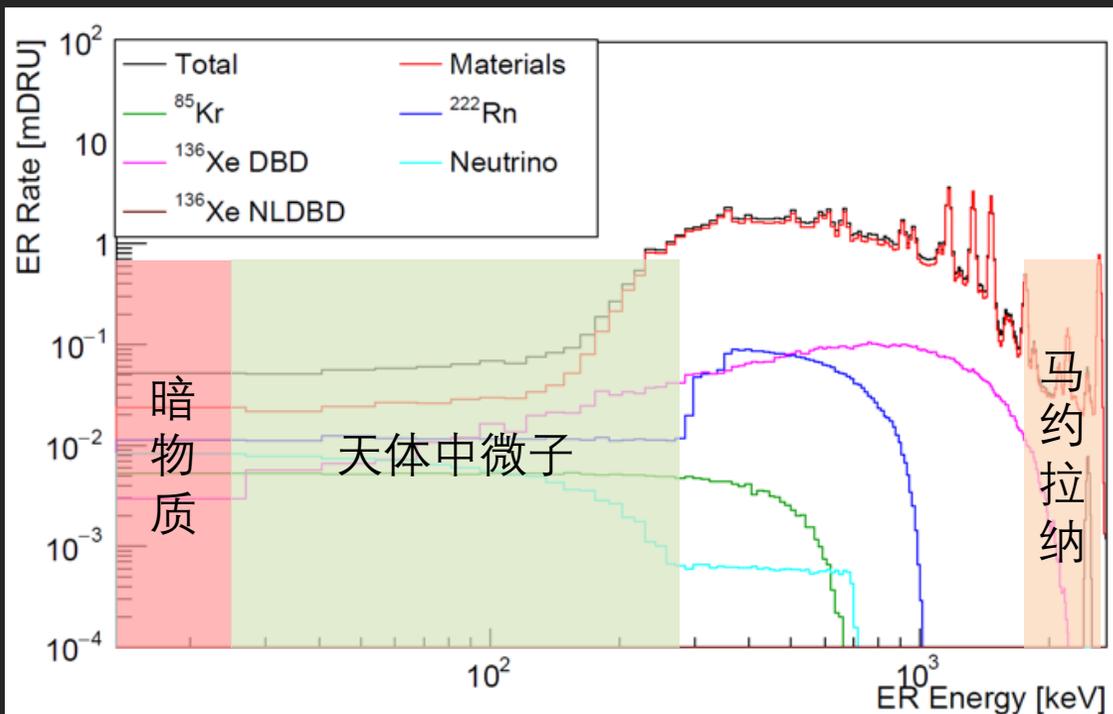
宇宙大尺度结构

- 大爆炸之后，原初密度涨落造成物质坍缩形成恒星、星系、星团
- 普通物质密度涨落被辐射抹平
 - 无法形成宇宙结构
- 需要暗物质的存在

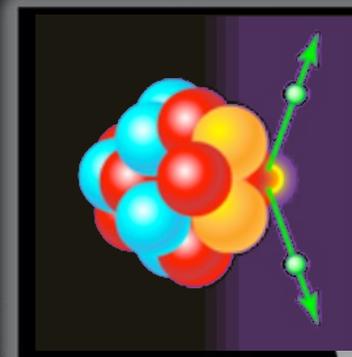


Multi-Physics Targets

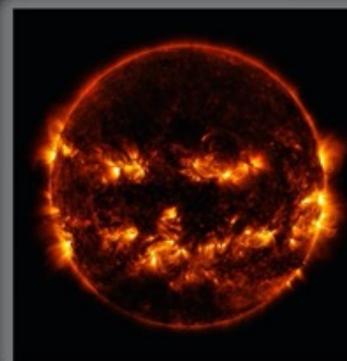
Large energy range: keV ~ MeV



暗物质
信号区 1keV - 10keV



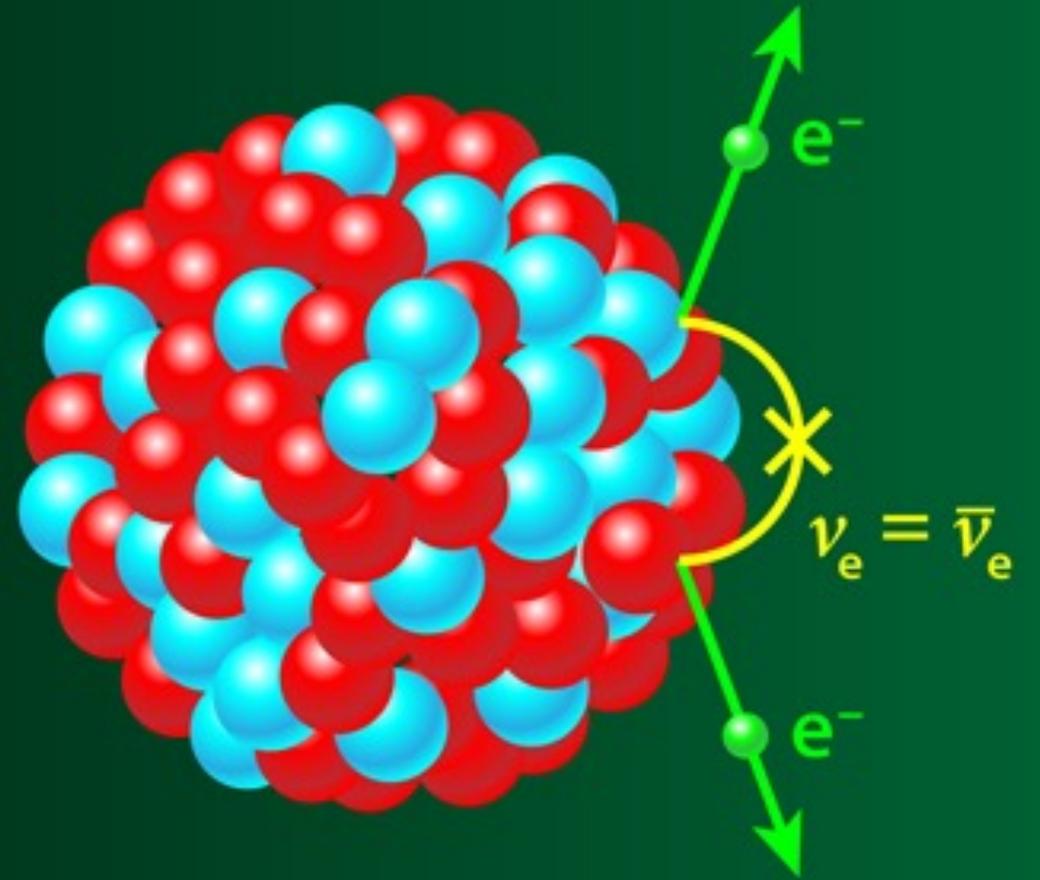
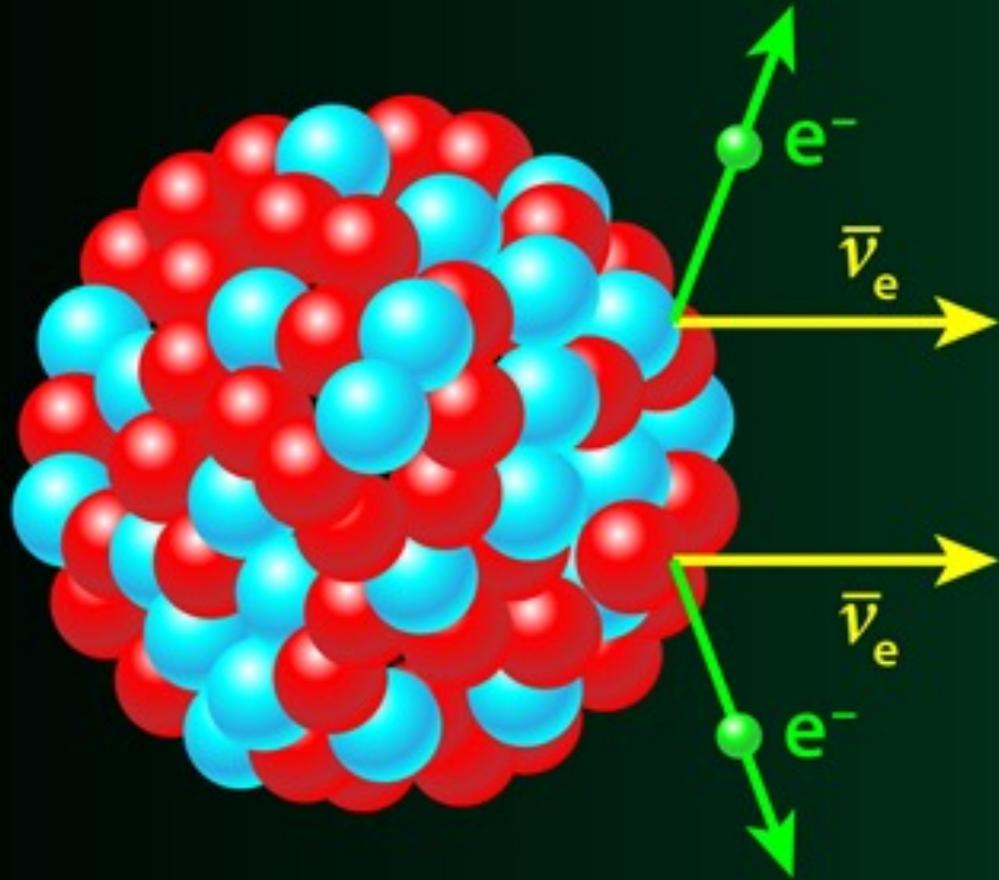
马约拉纳中微子
信号区 $> 2\text{MeV}$



天体中微子
信号区 $< 200\text{keV}$

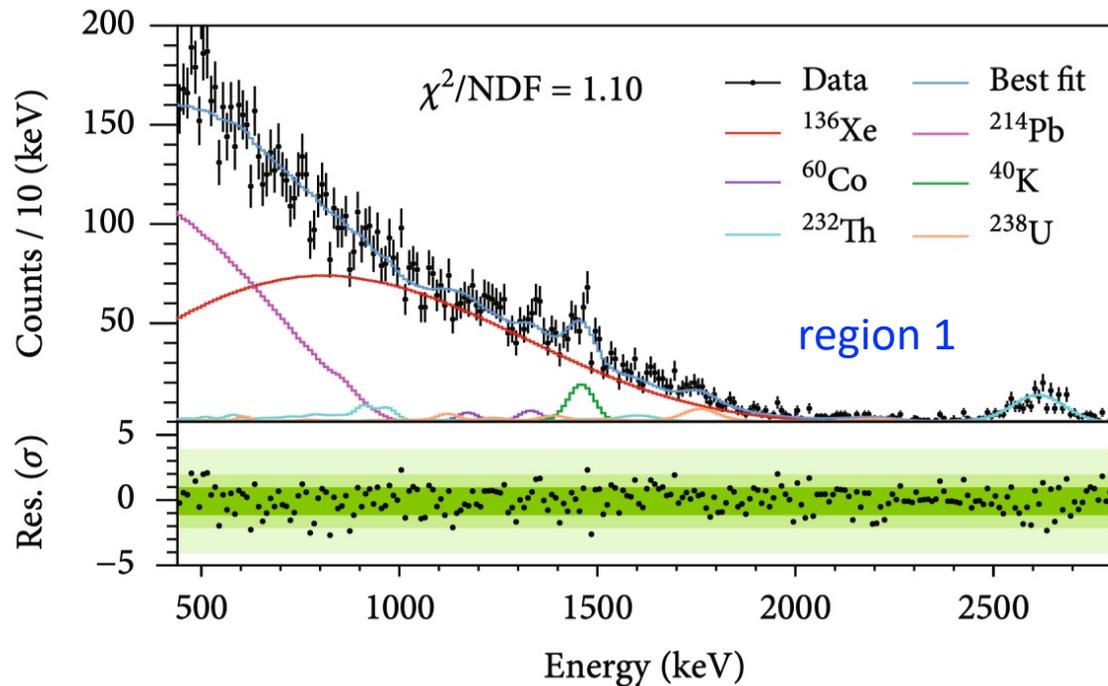


Majorana Neutrino

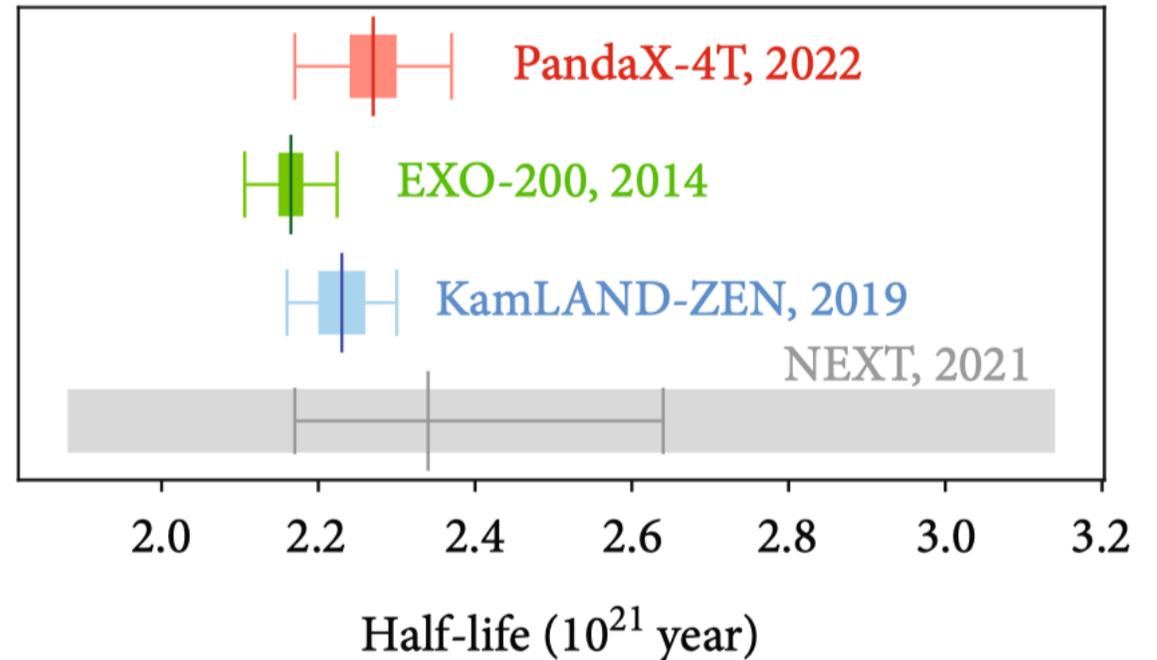


^{136}Xe $2\nu\text{DBD}$ Half-life Measurement

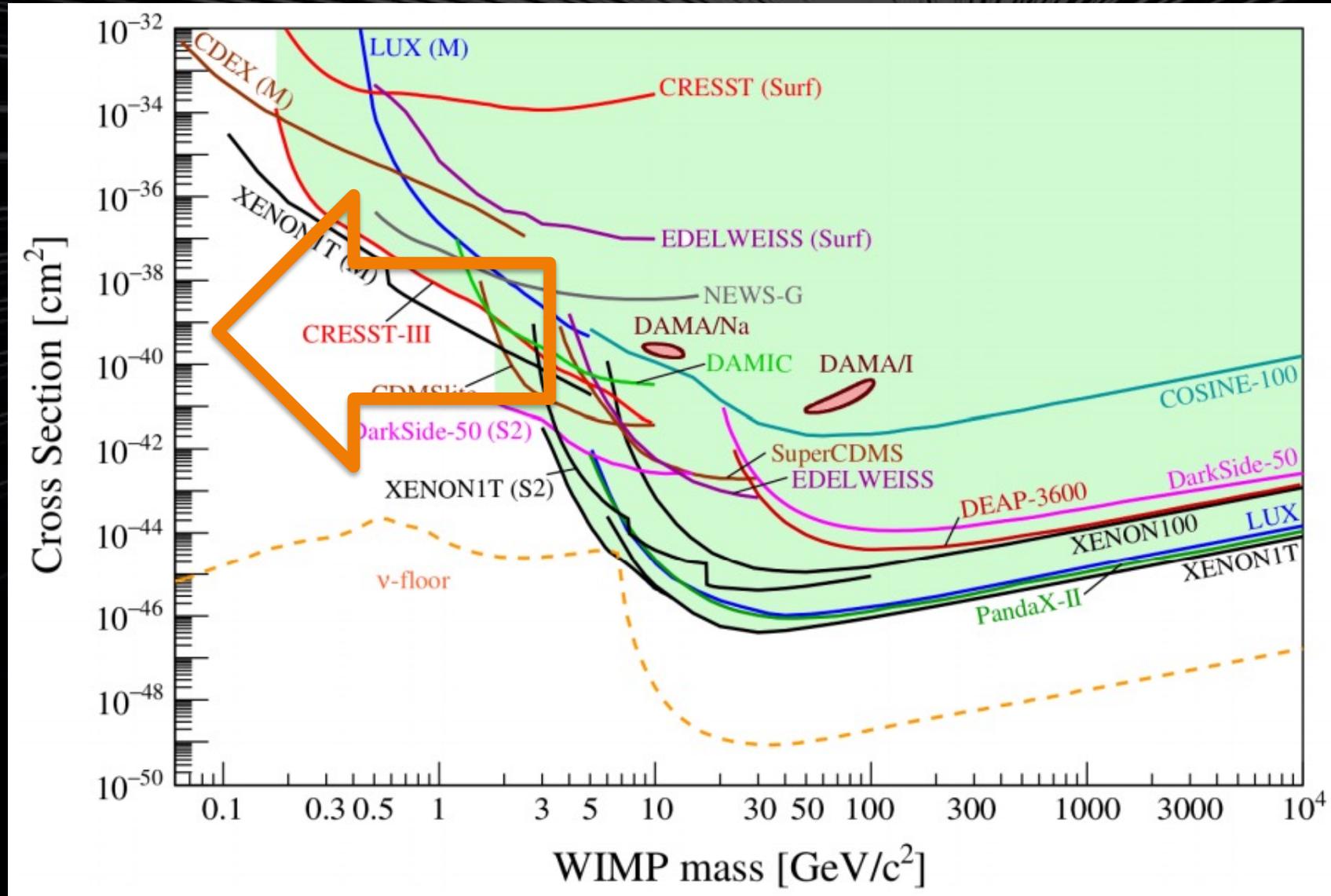
- **First result derived from natural xenon experiment**
 - 2.27 ± 0.03 (stat) ± 0.10 (syst) $\times 10^{21}$ years
 - One of the most precise measurements to date
 - **Comparable with enriched ^{136}Xe experiments**



Research Vol 2022, 9798721 (2022)

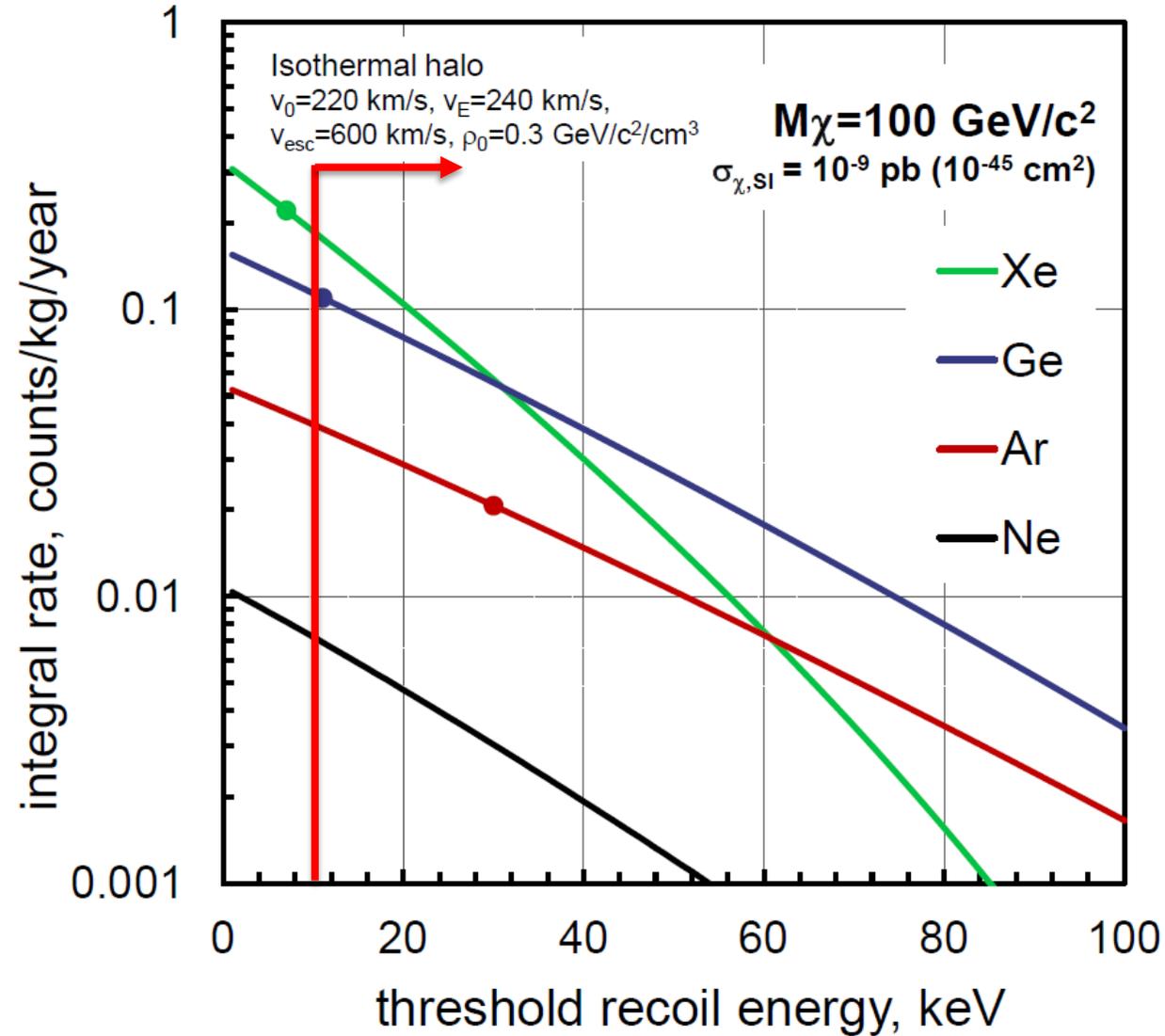


How to detect light dark matter?



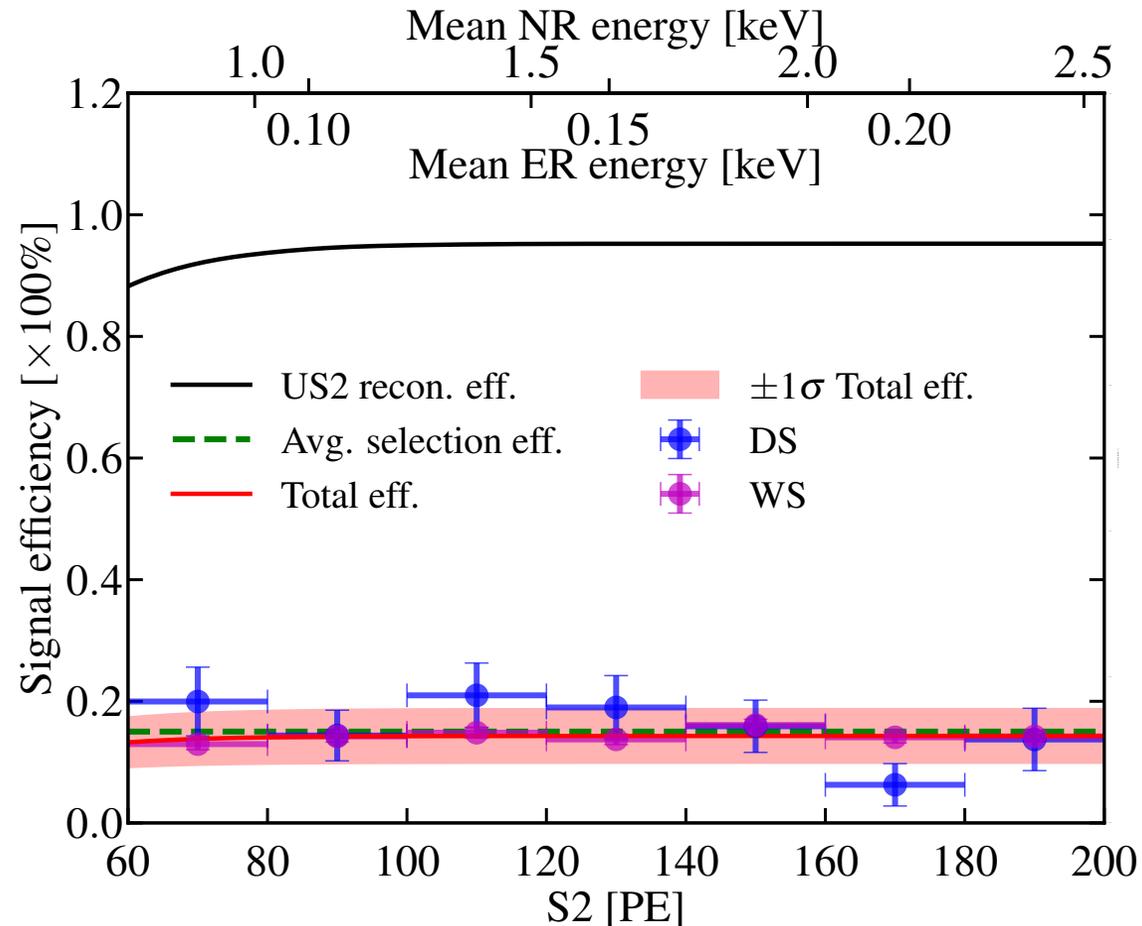
Lowering detection threshold

•
PRL 126, 211803 (2021)
PRL 130, 261001 (2023)



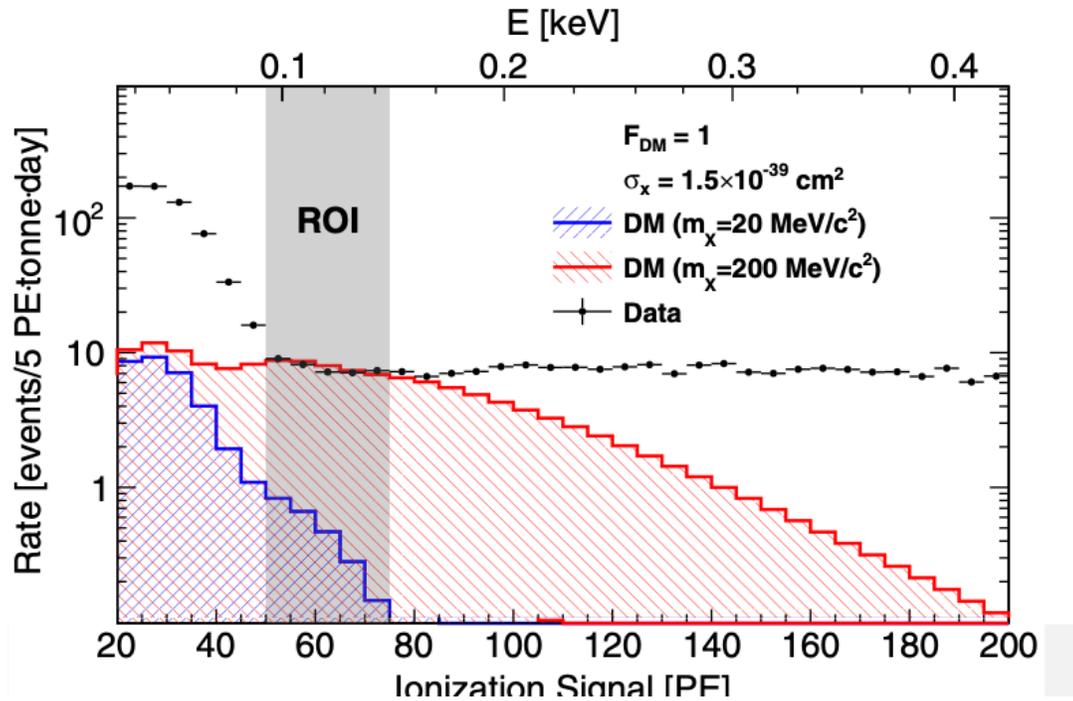
Lower Threshold

- **Ionization-Only: no scintillation signal requirement**
 - ROI S2 [60, 200]PE: threshold down to ~ 100 eV (from ~ 1 keV)

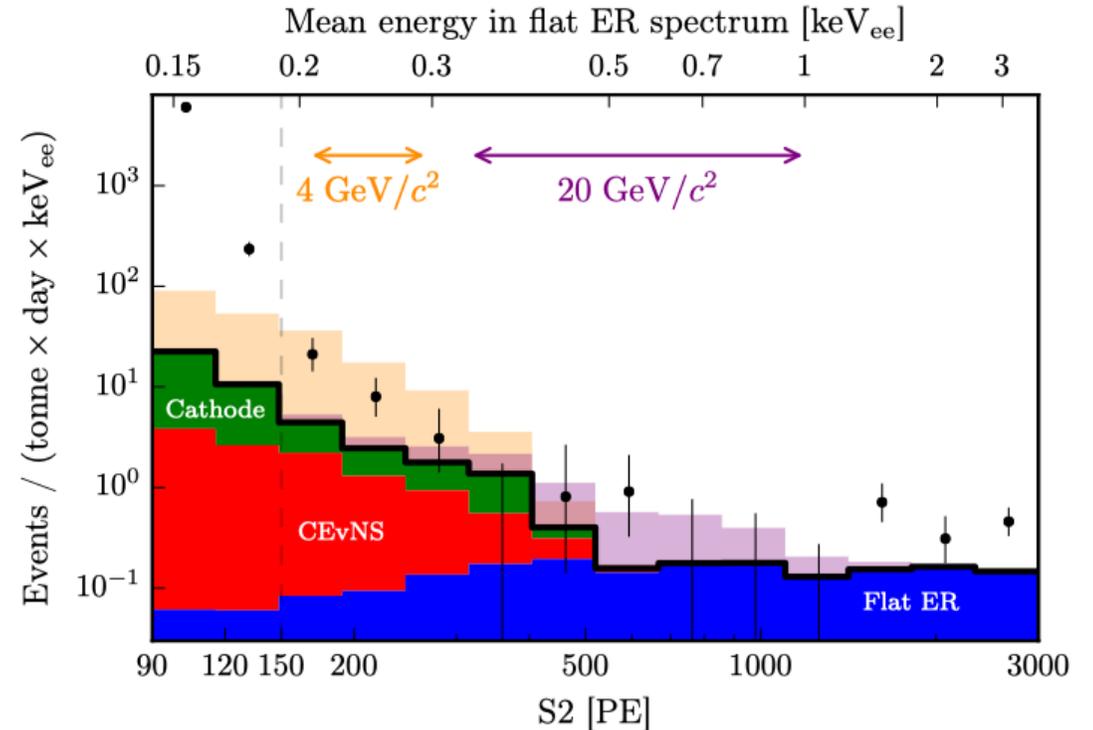


Ionization-only ROI

- **Key challenge: background components**
 - No full picture in previous xenon-based experiments
 - Conservative results only



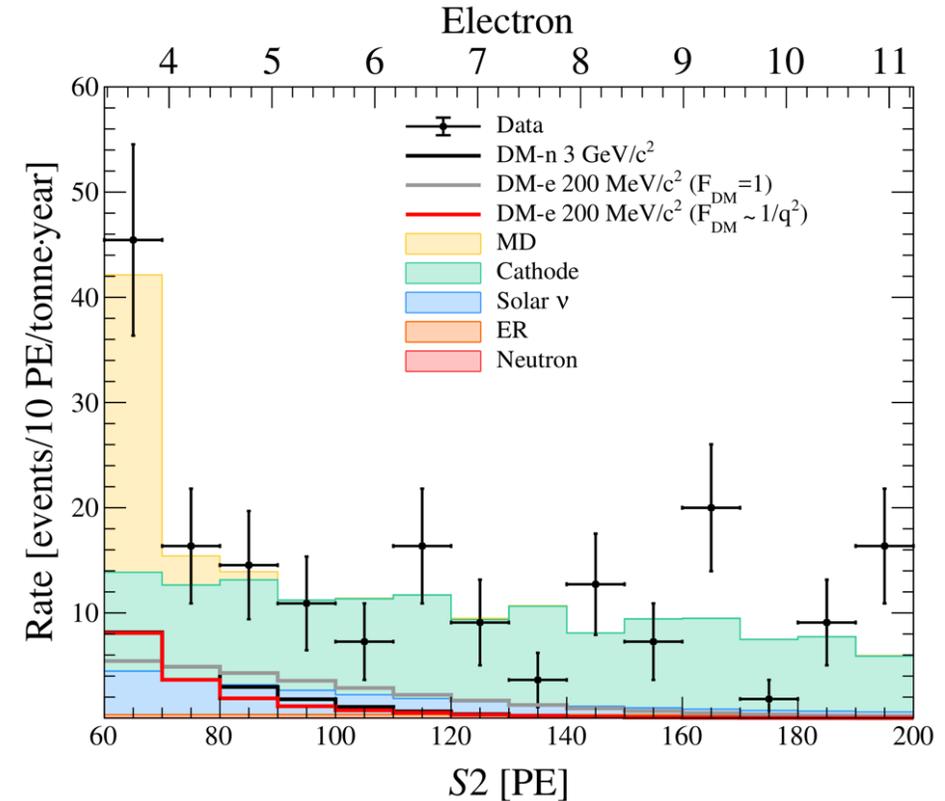
PandaX-II PRL



XENON1T PRL

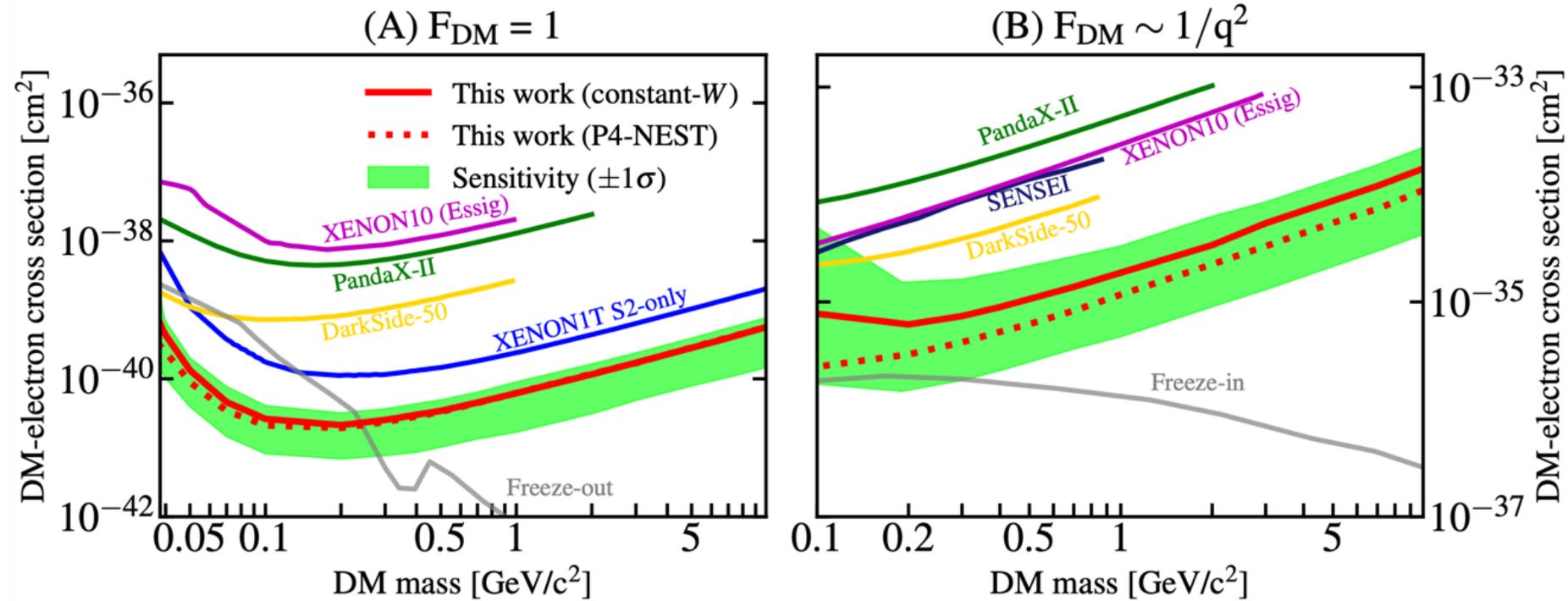
Ionization-only Data

- **First complete understanding of all the main background**
 - Micro-discharging (MD)
 - Small charge, strong run-condition dependence
 - Cathode activity
 - Large charge, large pulse-shape width
- **Blind analysis of 0.55 tonne-year exposure**
 - 105 events
 - Best-fit background: 95.8 ± 11.3 events



Constraints on DM-electron scattering

- Most stringent constraints are derived
 - DM-electron interaction with heavy mediator, $2 \times 10^{-41} \text{ cm}^2$



Can light dark matter be boosted?

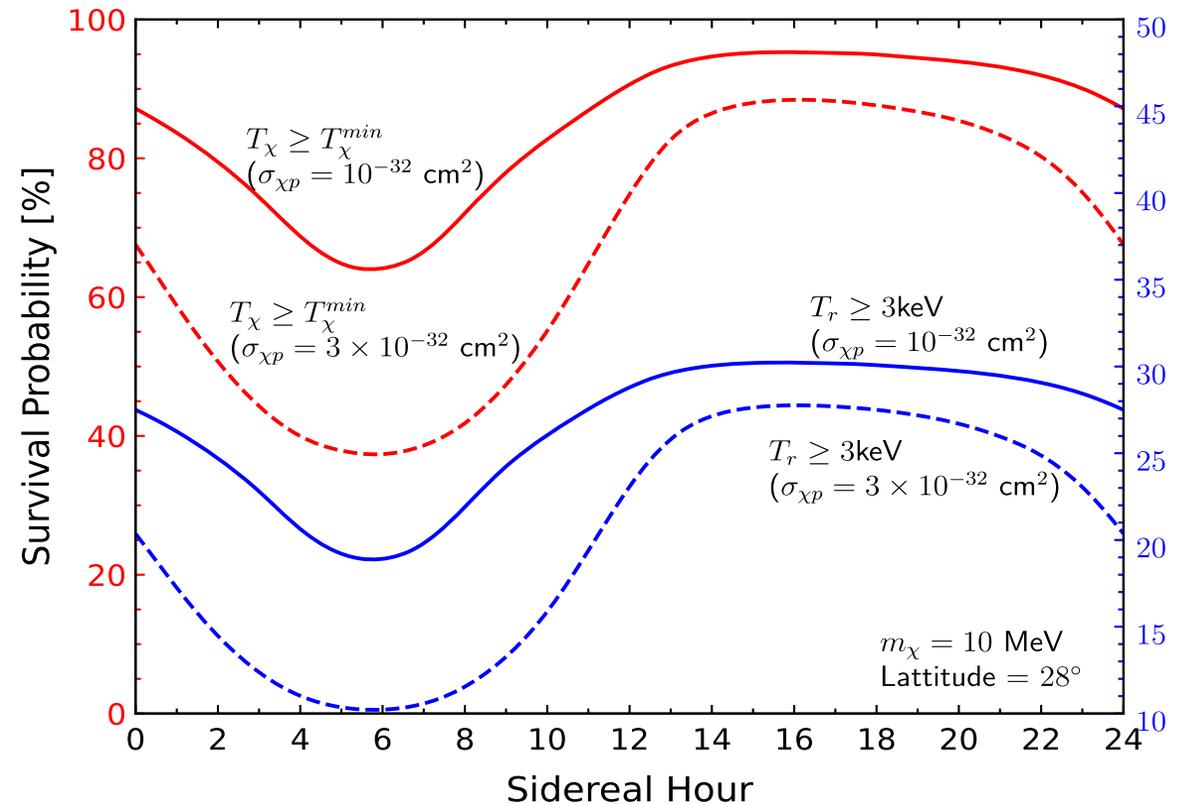
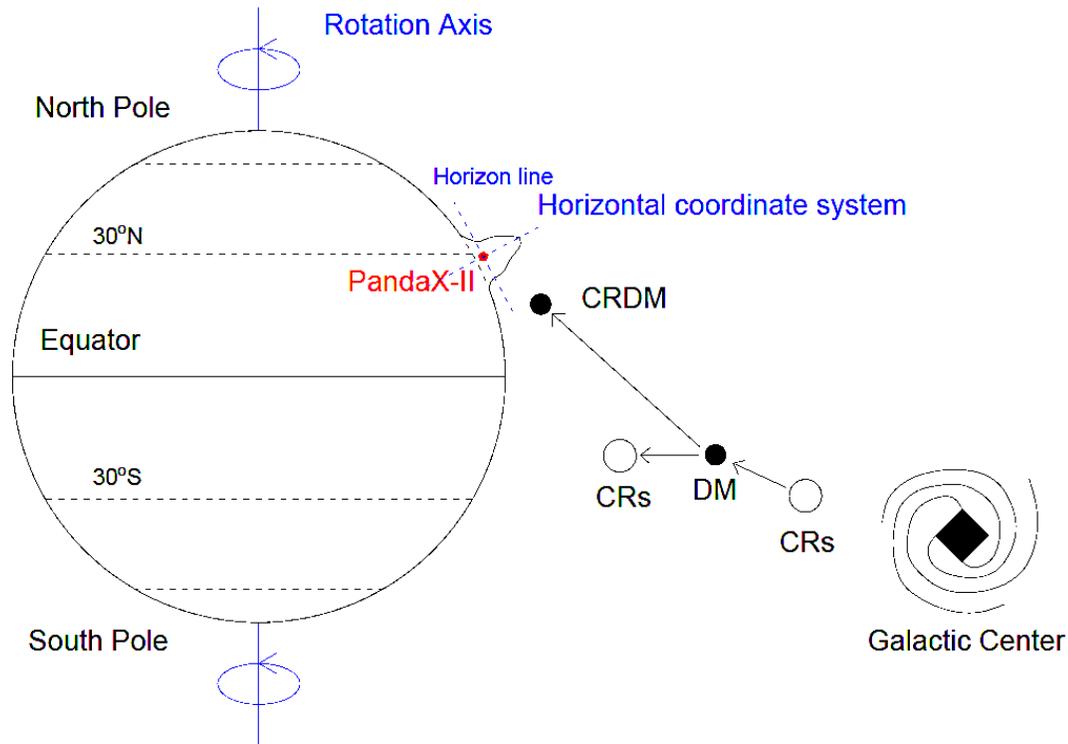
PRL 126, 091804 (2021)

PRL 128, 171801 (2022)

PRL 131, 041001 (2023)

Cosmic-ray Boosted Dark Matter

- Light DM with cosmic ray boosting
- New signature: **diurnal modulation** due to earth shielding



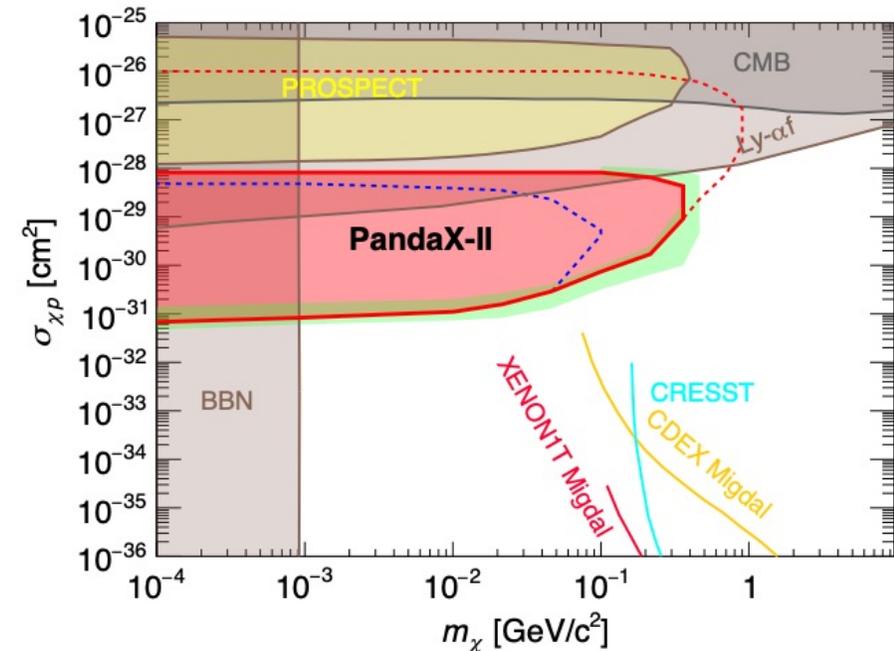
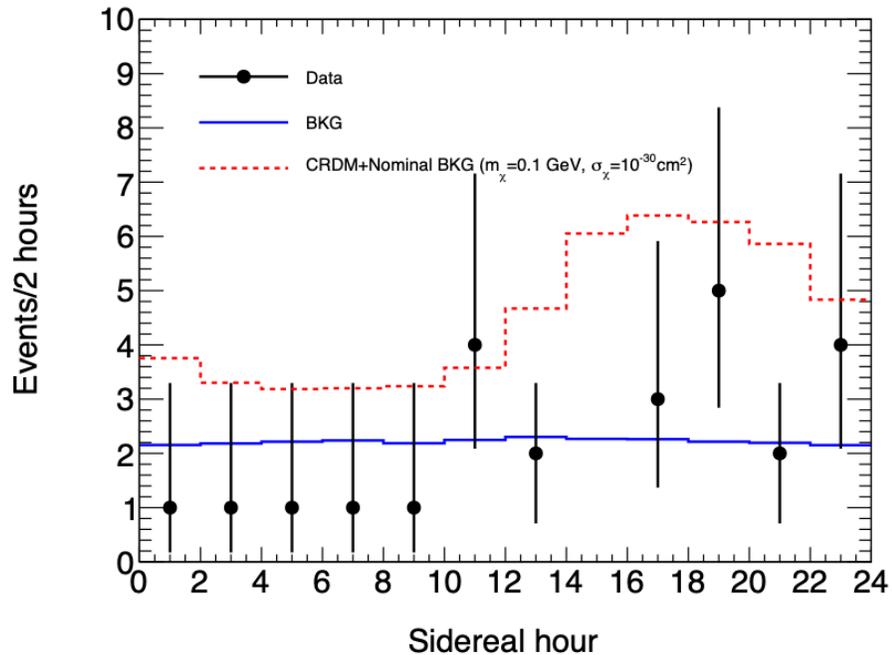
Diurnal Modulation Search

- **PandaX-II data**

- Using events below NR median: 25 events (expected 26.6 background)

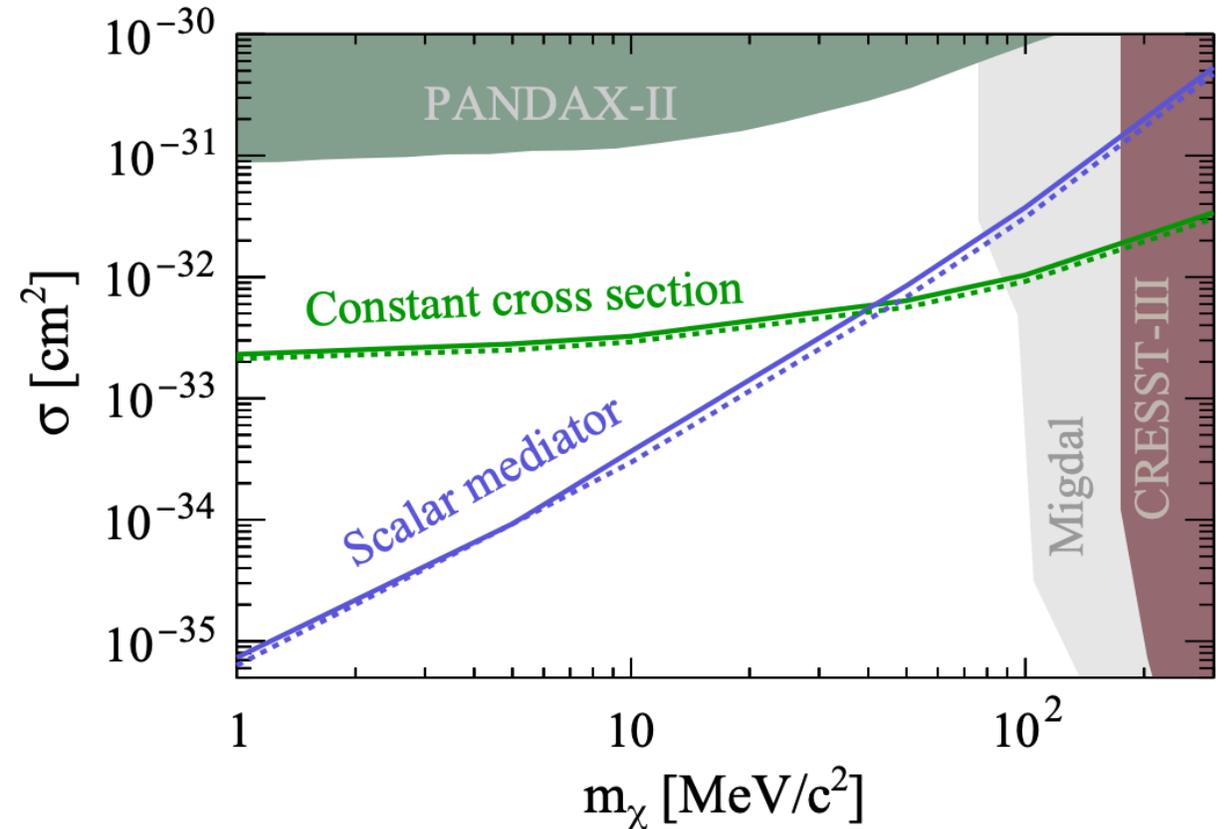
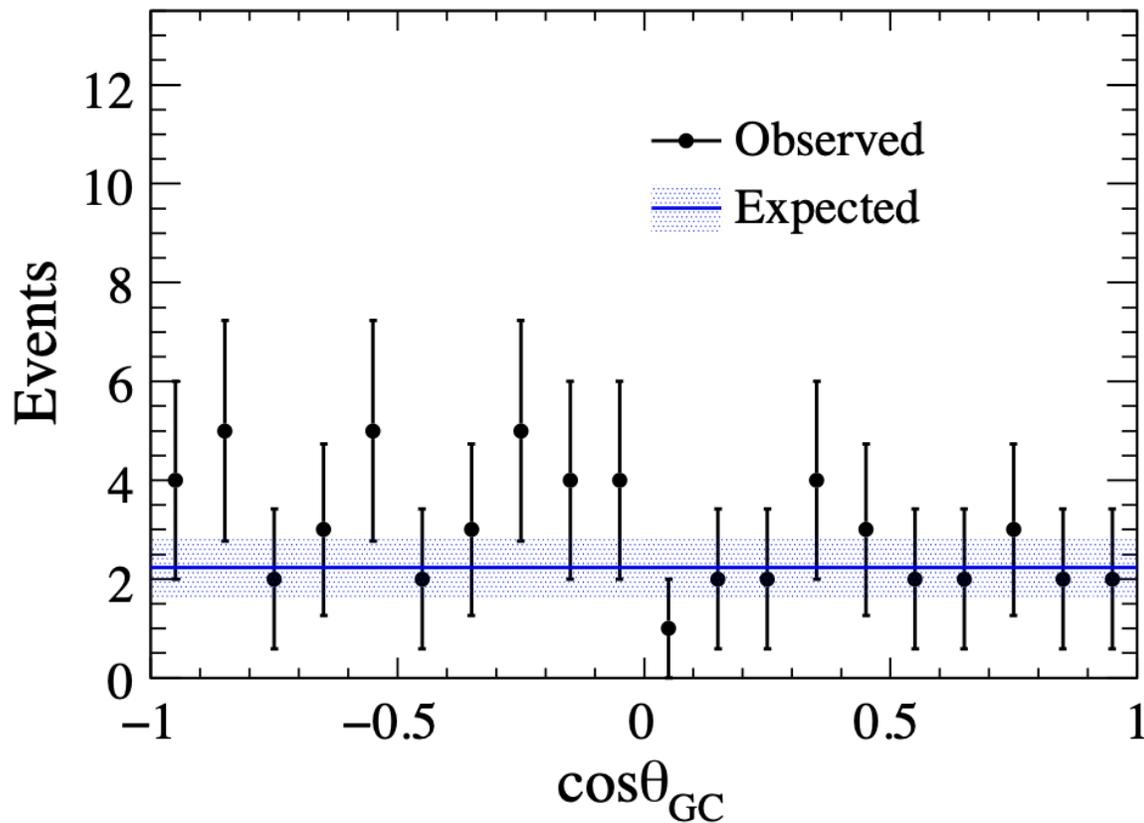
- **Extend the DM search window to sub-GeV**

- Expand to the region beyond the astrophysical and cosmological



New results from Super-K

- 20 years' data from Super-Kamiokande [PRL 130, 031802 \(2023\)](#)
- Directional detection of cosmic-ray boosted DM



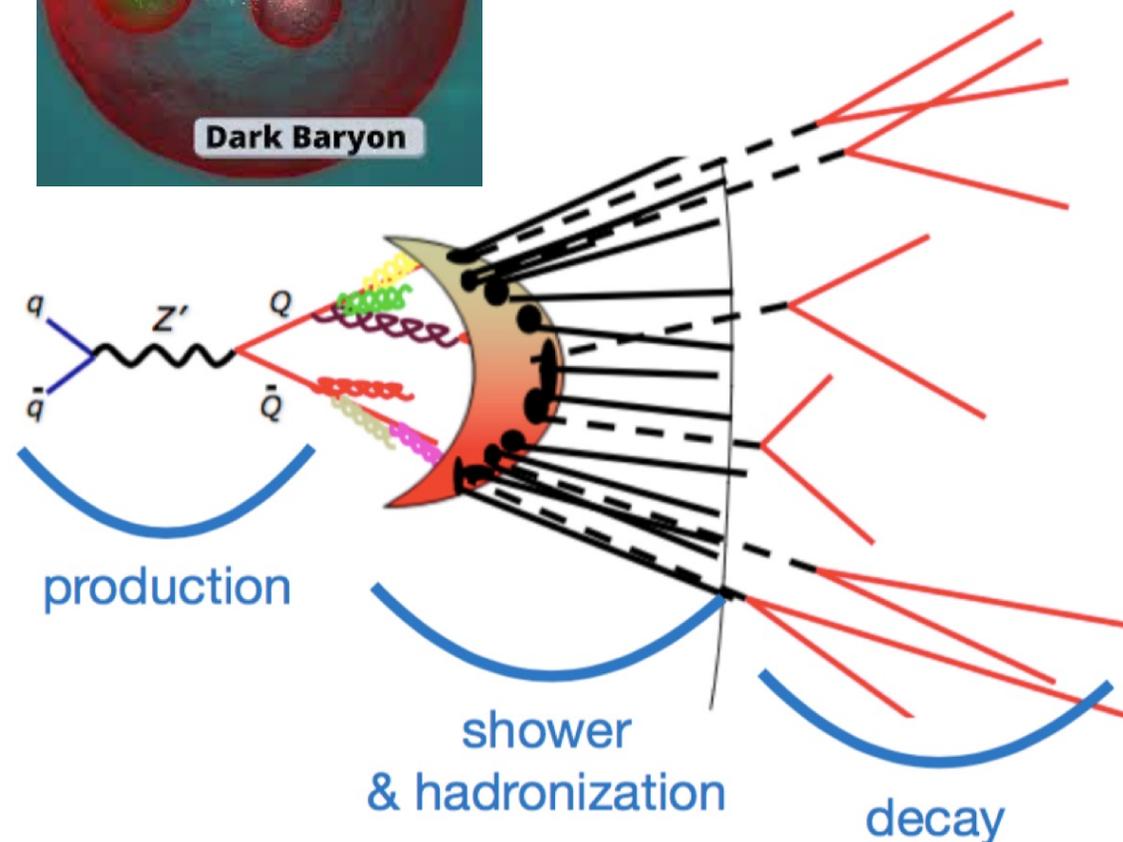
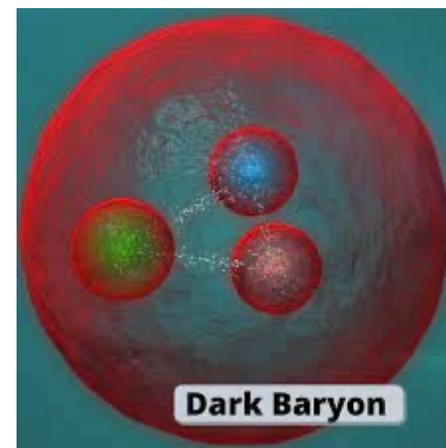
Dark sector

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



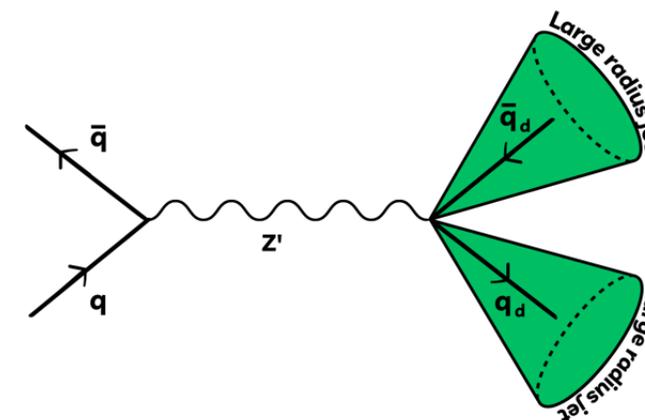
Dark quarks

- **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 quarks**
 - SM quark shower and hadronization

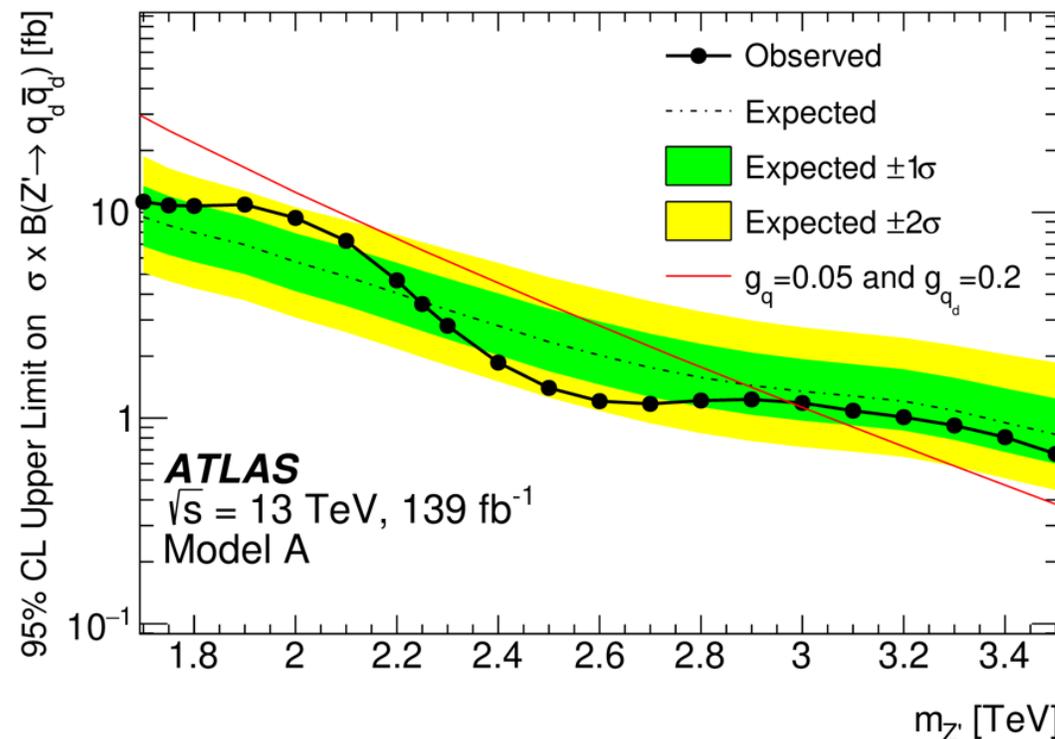
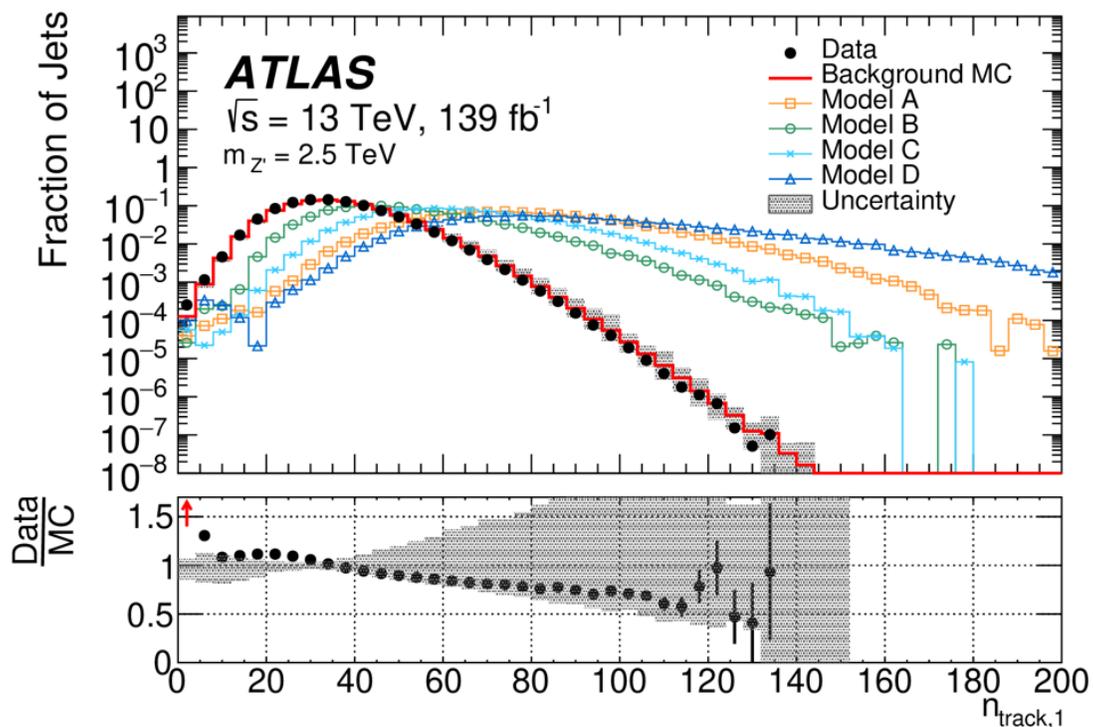


Resonance of dark quarks

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

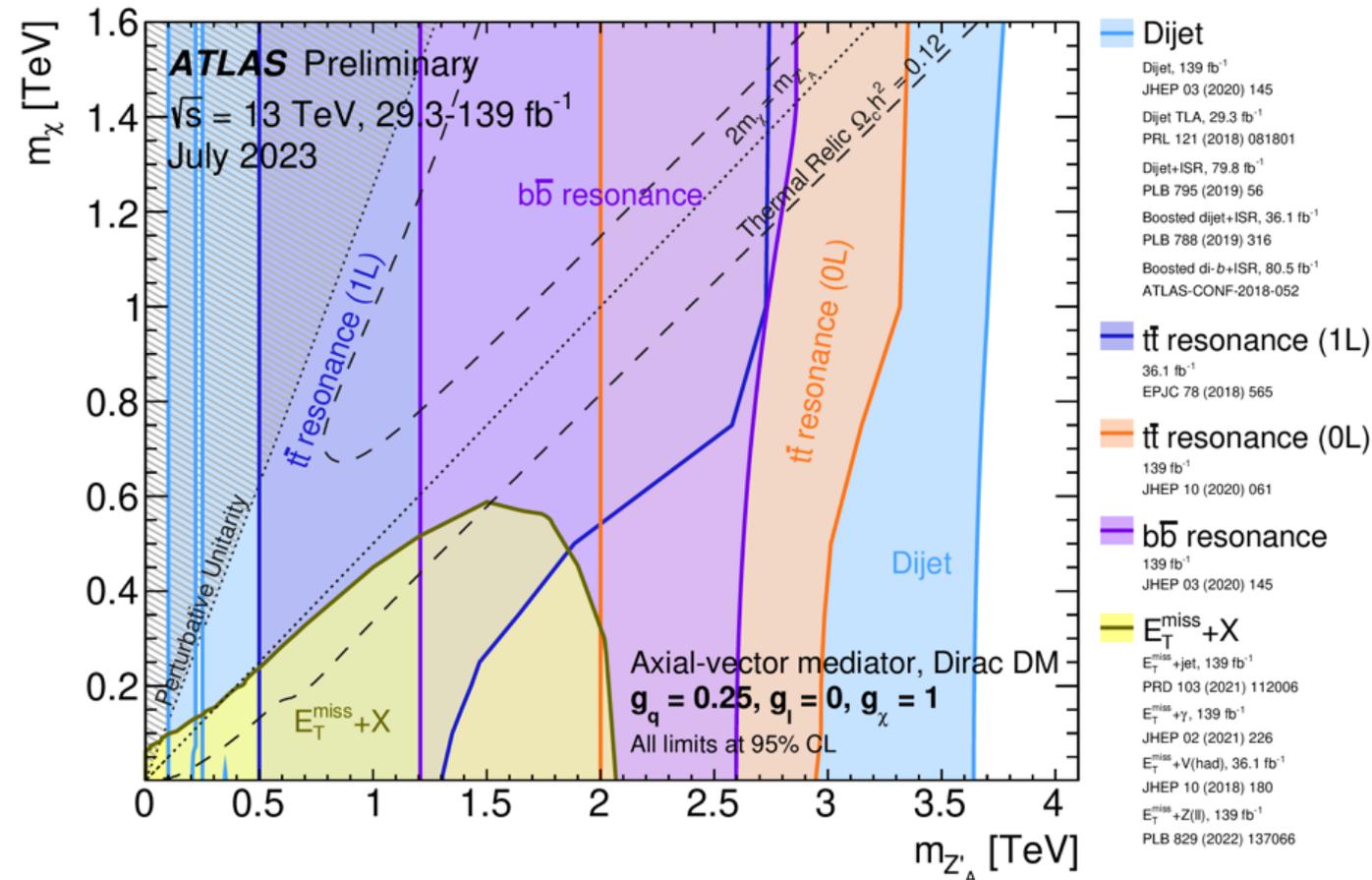


arXiv:2311.03944



Combined constraints

- DM – mediator parameter space
- dijet resonance search covers mediator mass upto ~ 3.6 TeV/ c^2



$g_q = 0.25$
 $g_l = 0$
 $g_\chi = 1$

Combined constraints

- DM – mediator parameter space

very sensitive
to the
couplings

$g_q: 0.25 \rightarrow 0.1$
 $g_l: 0 \rightarrow 0.01$

