

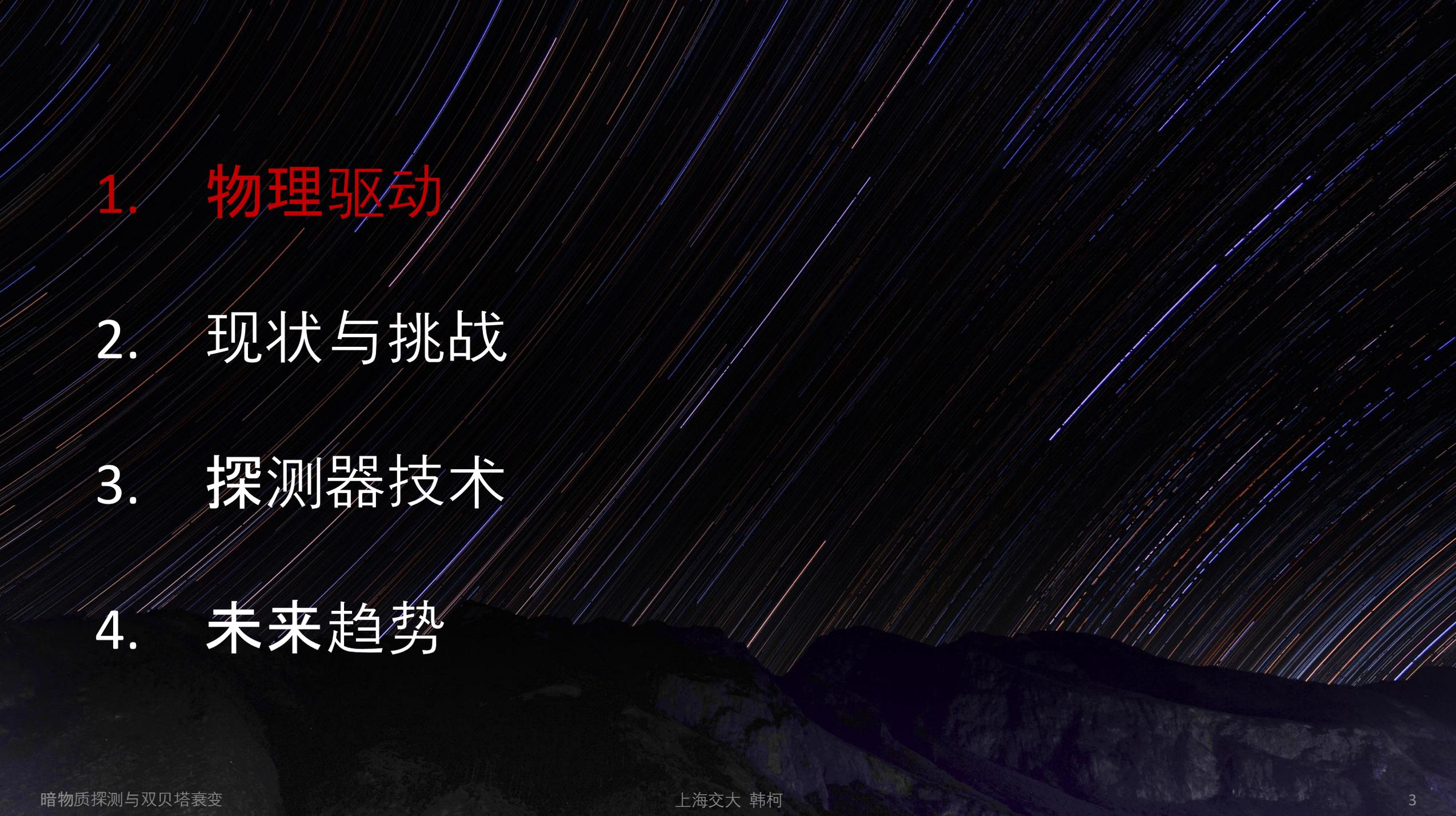
暗物质直接探测与双贝塔衰变

韩 柯

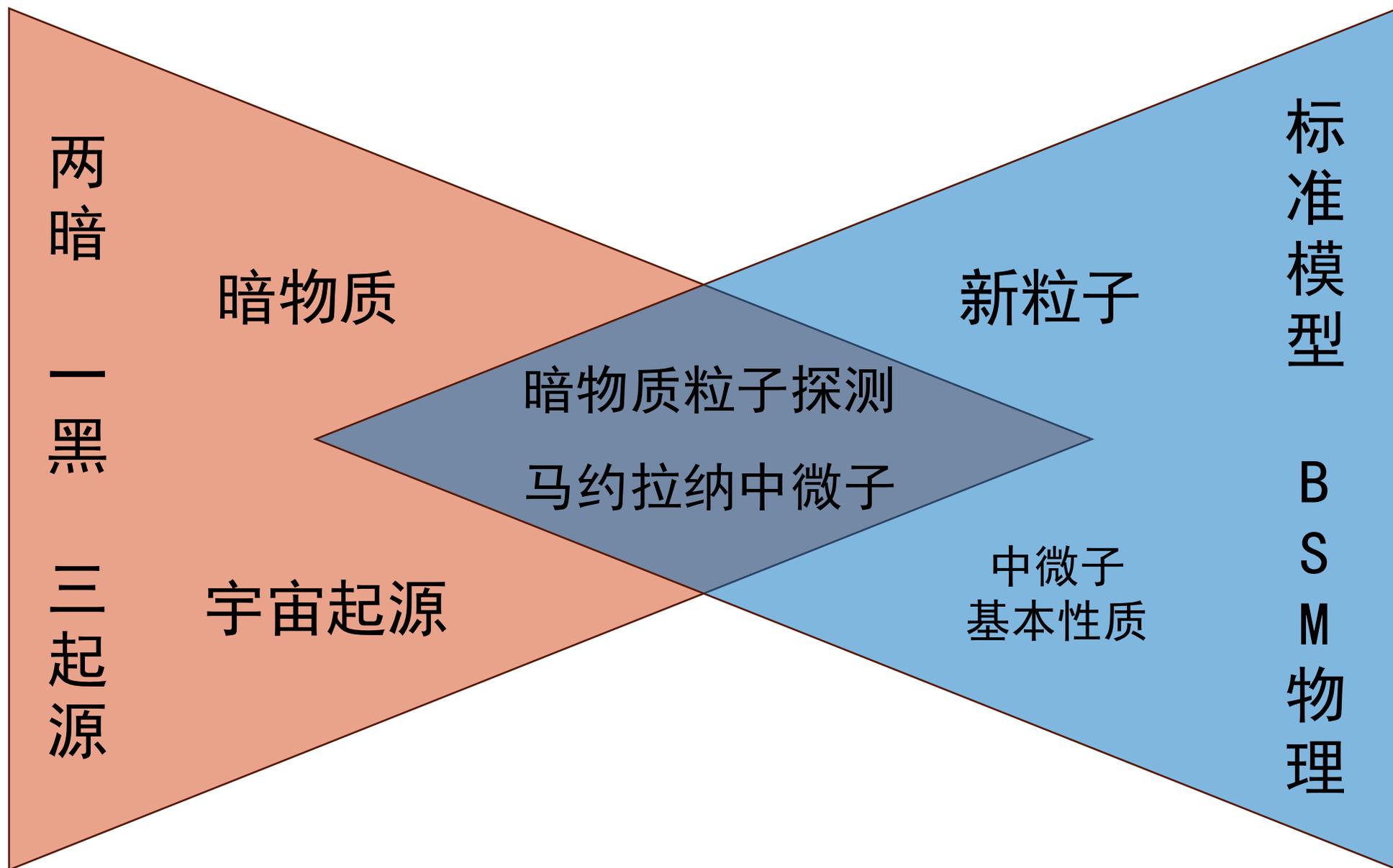
上海交通大学

2024/8/14

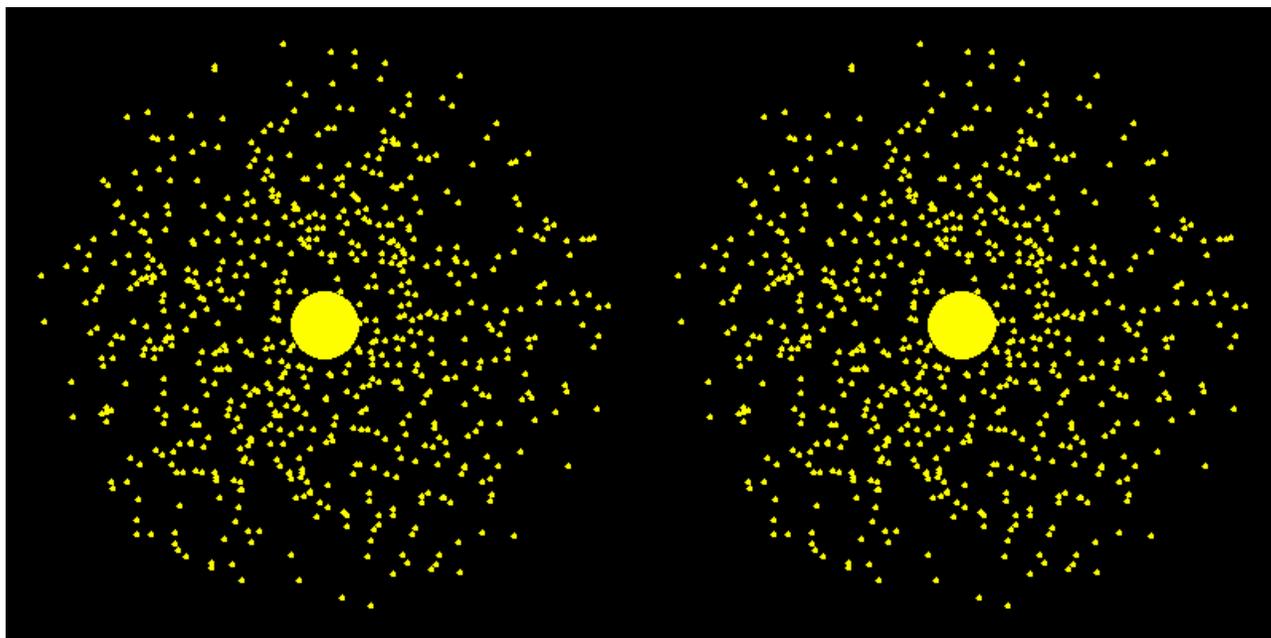
1. 物理驱动
2. 现状与挑战
3. 探测器技术
4. 未来趋势

- 
1. 物理驱动
 2. 现状与挑战
 3. 探测器技术
 4. 未来趋势

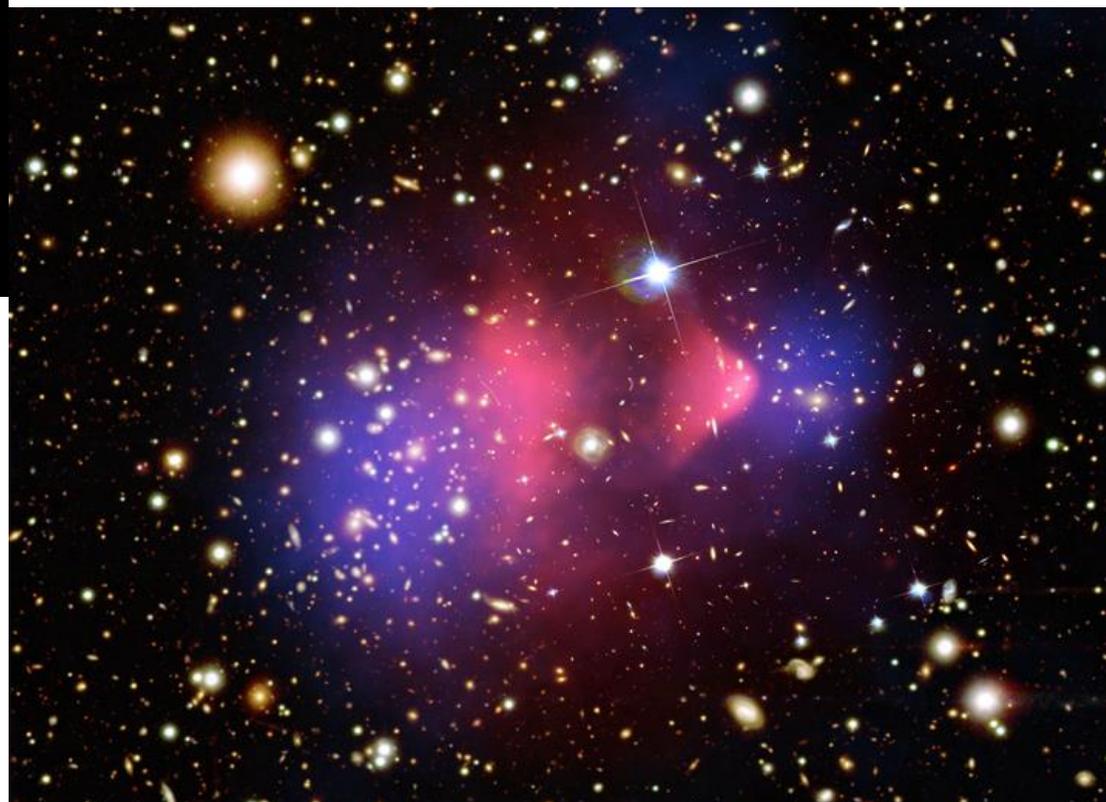
天体粒子物理学 (AstroParticle Physics)



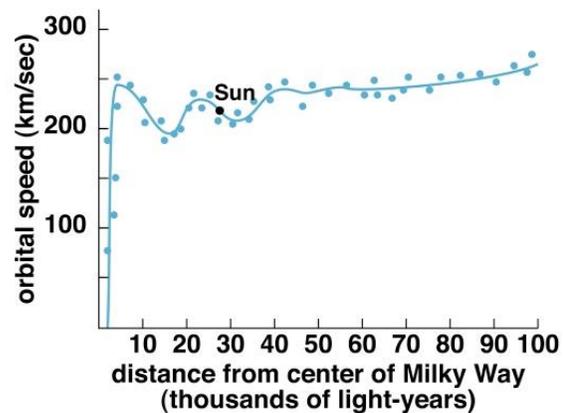
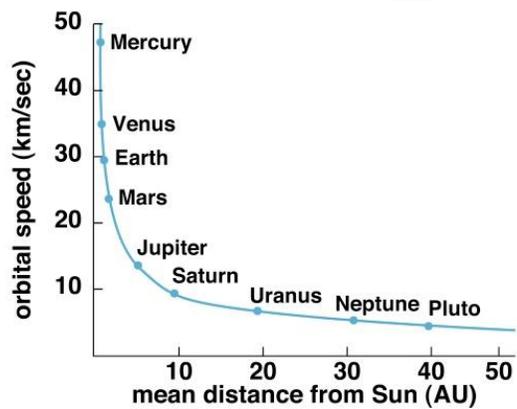
暗物质存在的确切证据

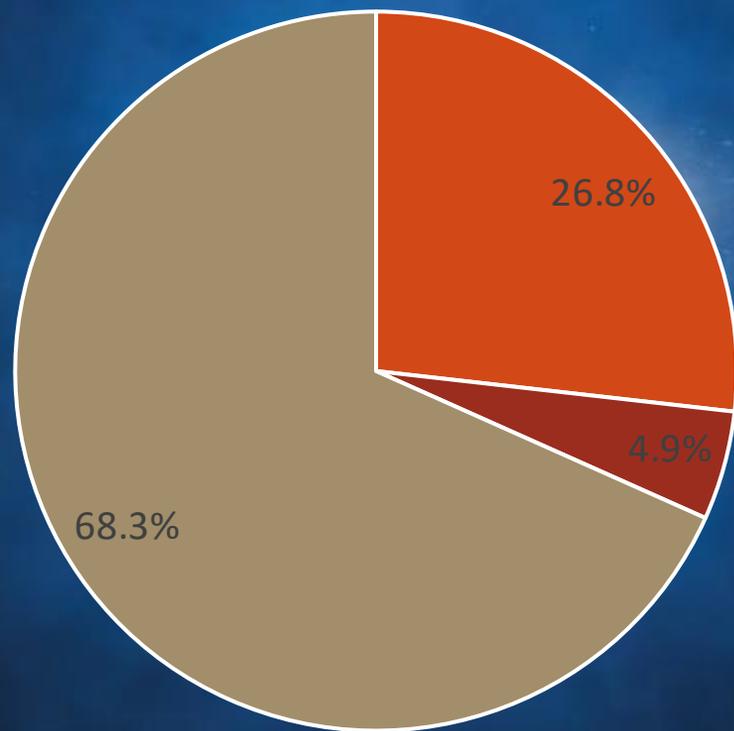


子弹星系团碰撞



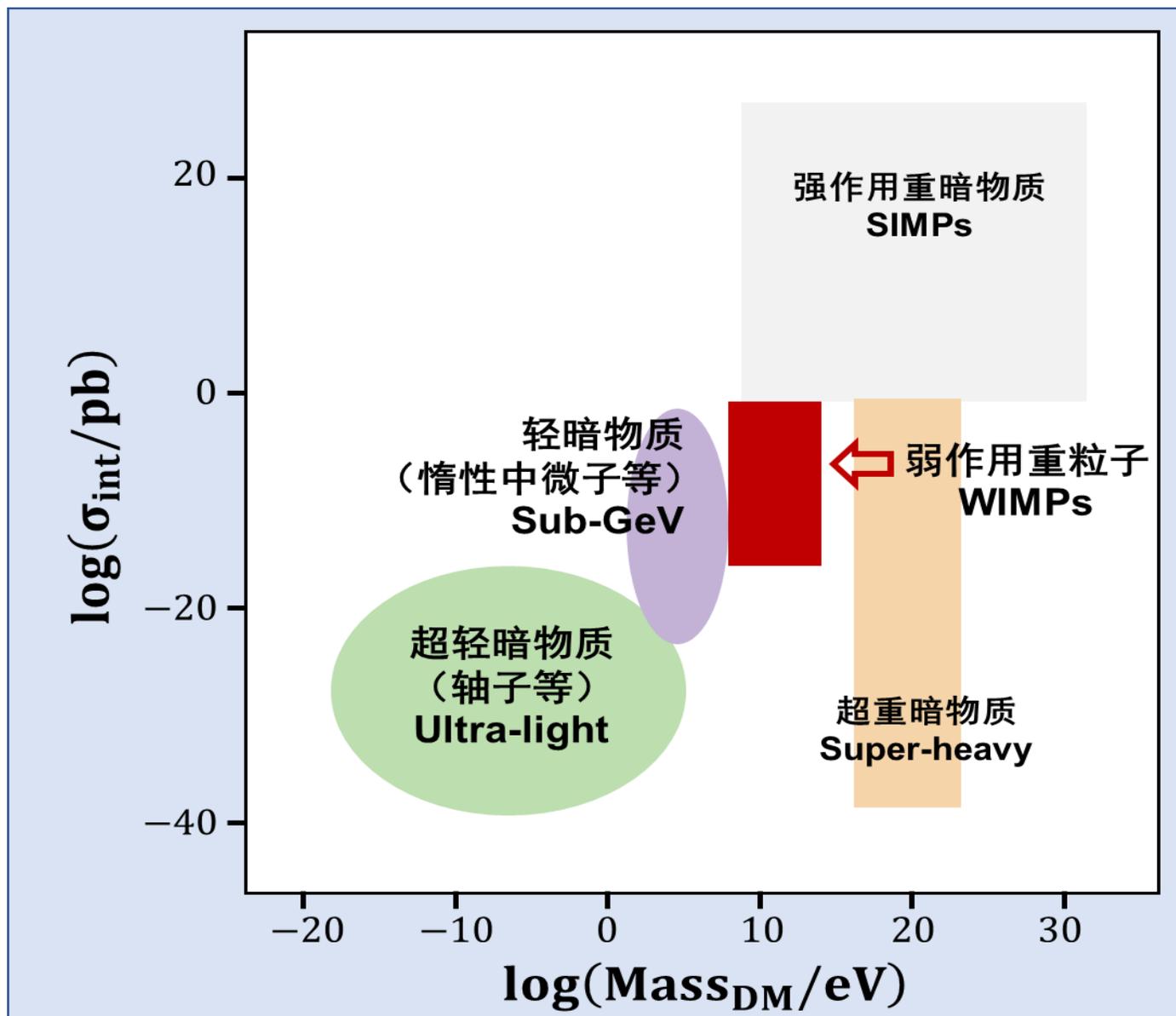
星系旋转曲线

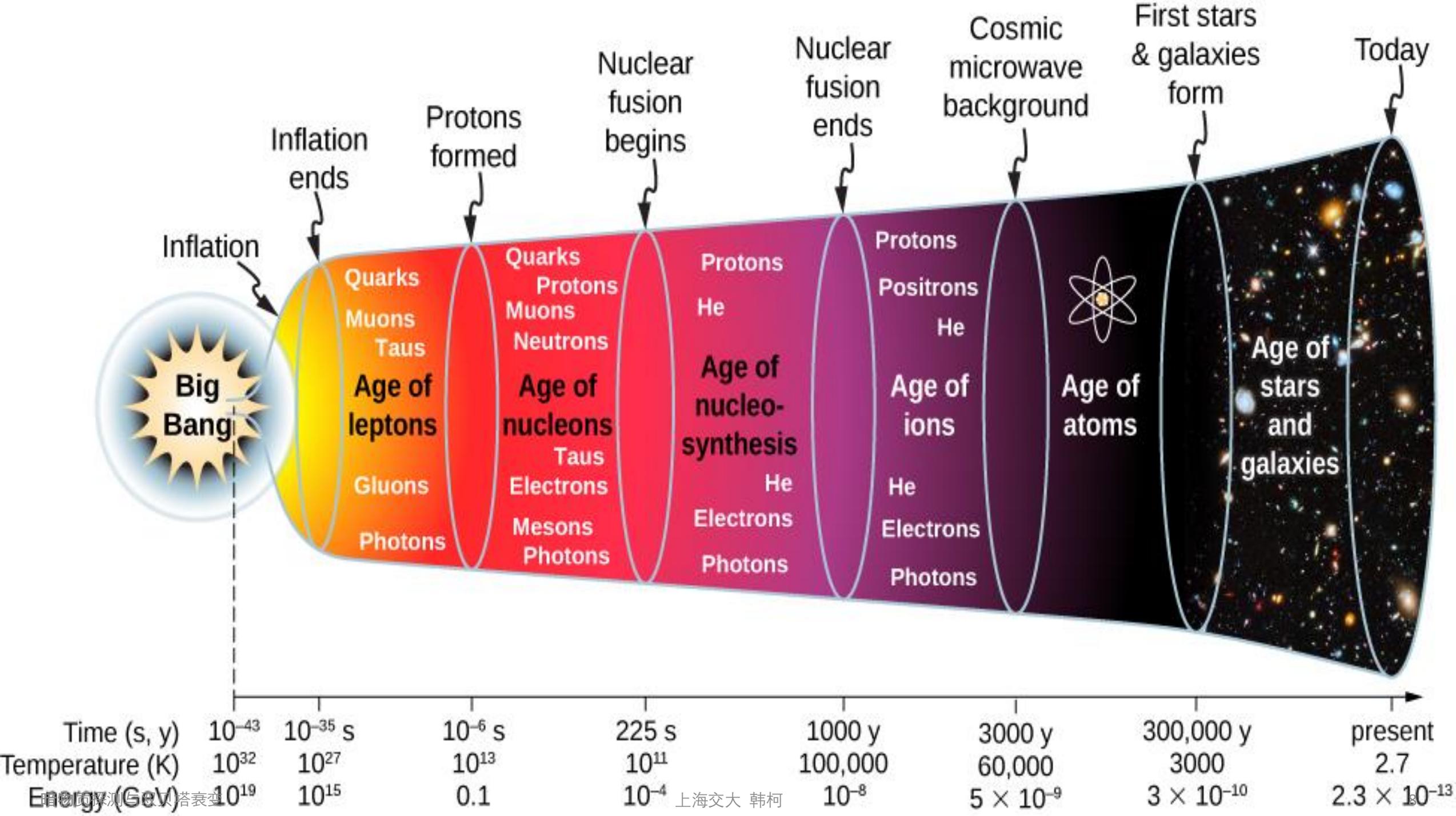


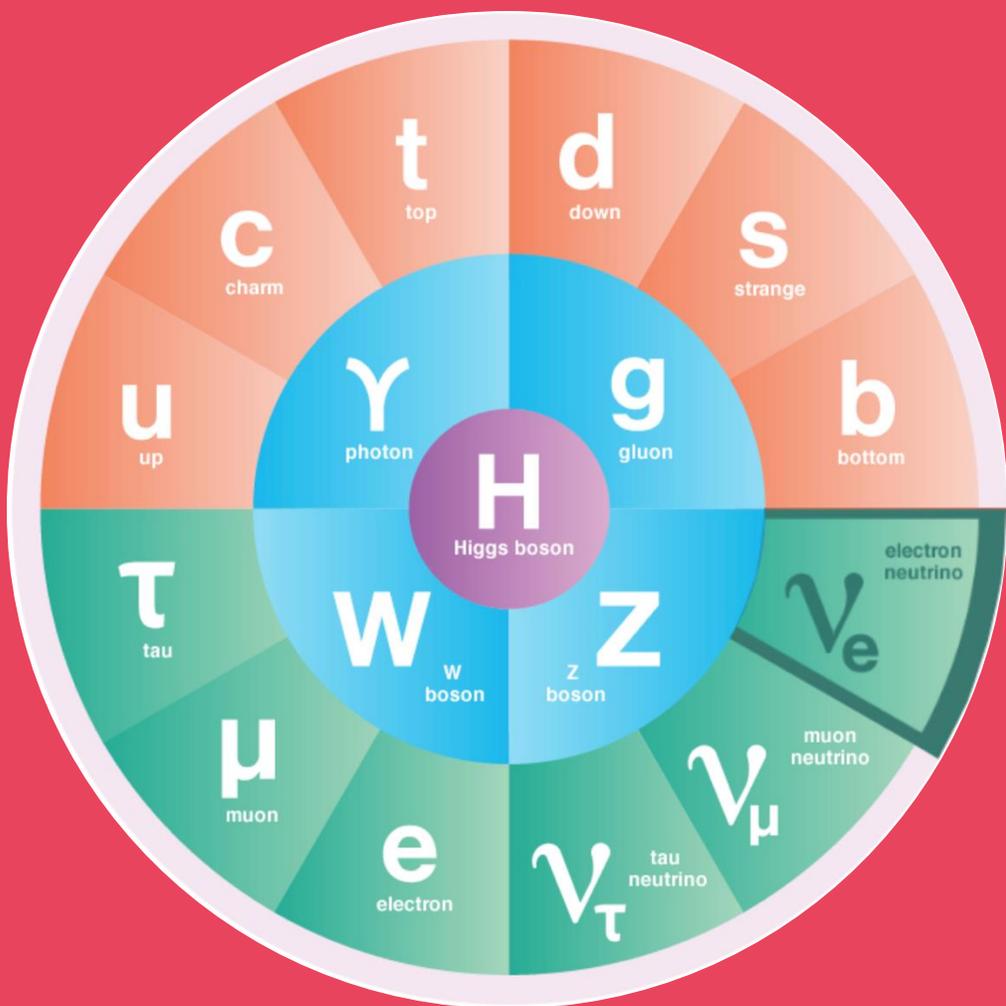


■ 暗物质 ■ 可见物质 ■ 暗能量

暗物质是什么？是不是一种粒子？







正物质

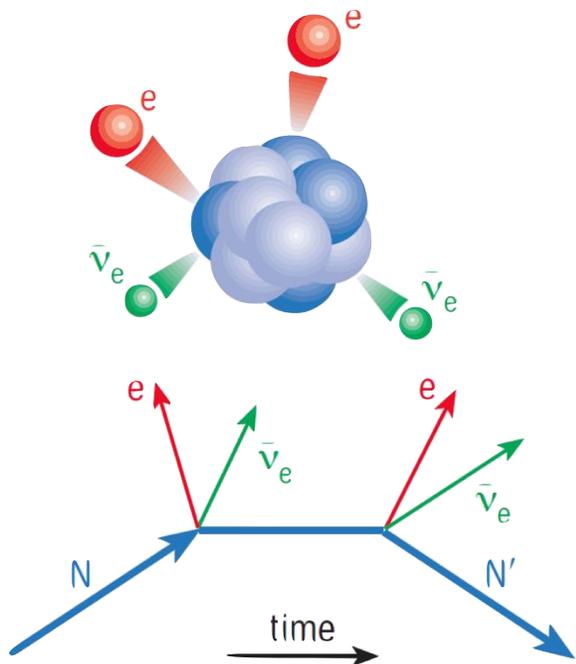
反物质



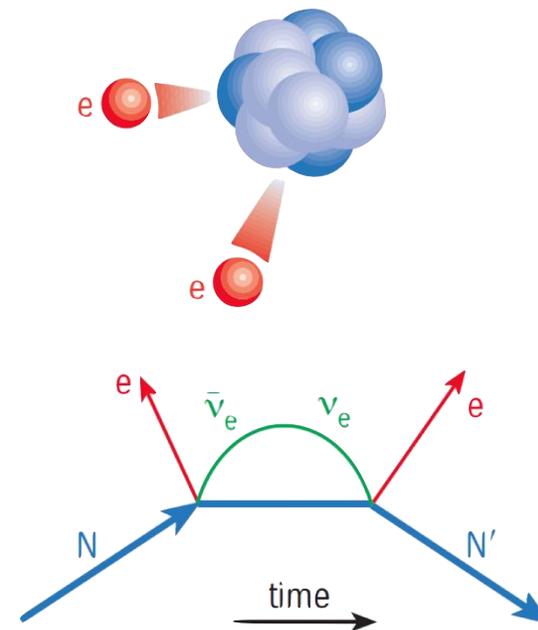
正物质



马约拉纳中微子 无中微子双贝塔衰变



$$\bar{\nu} = \nu$$



1935, Goeppert-Mayer

双贝塔衰变

Two-Neutrino double beta decay

1937, Majorana

马约拉纳中微子

Majorana Neutrino

1939, Furry

无中微子双贝塔衰变

Neutrinoless double beta decay

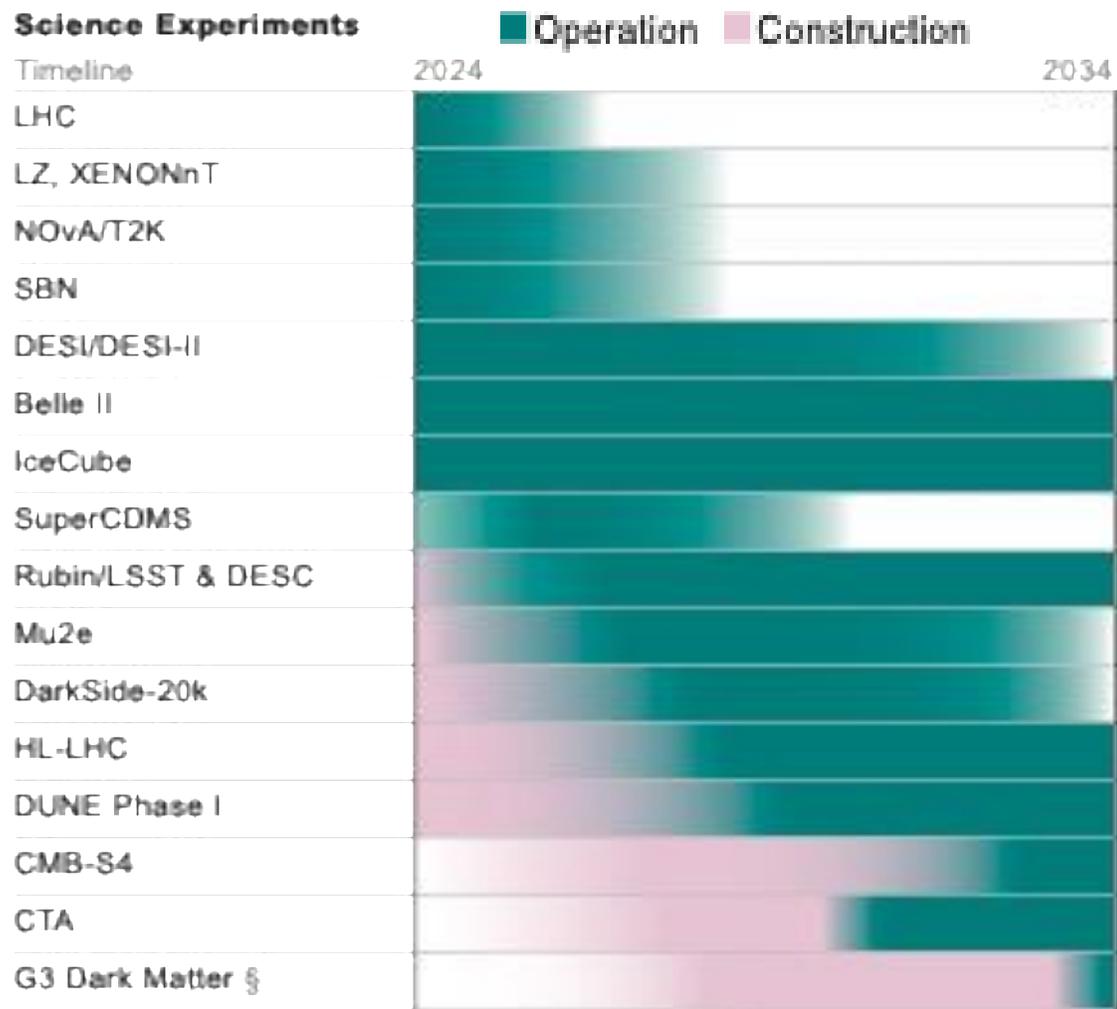
1. 物理驱动
2. 现状与挑战
3. 探测器技术
4. 未来趋势

高能物理重要问题

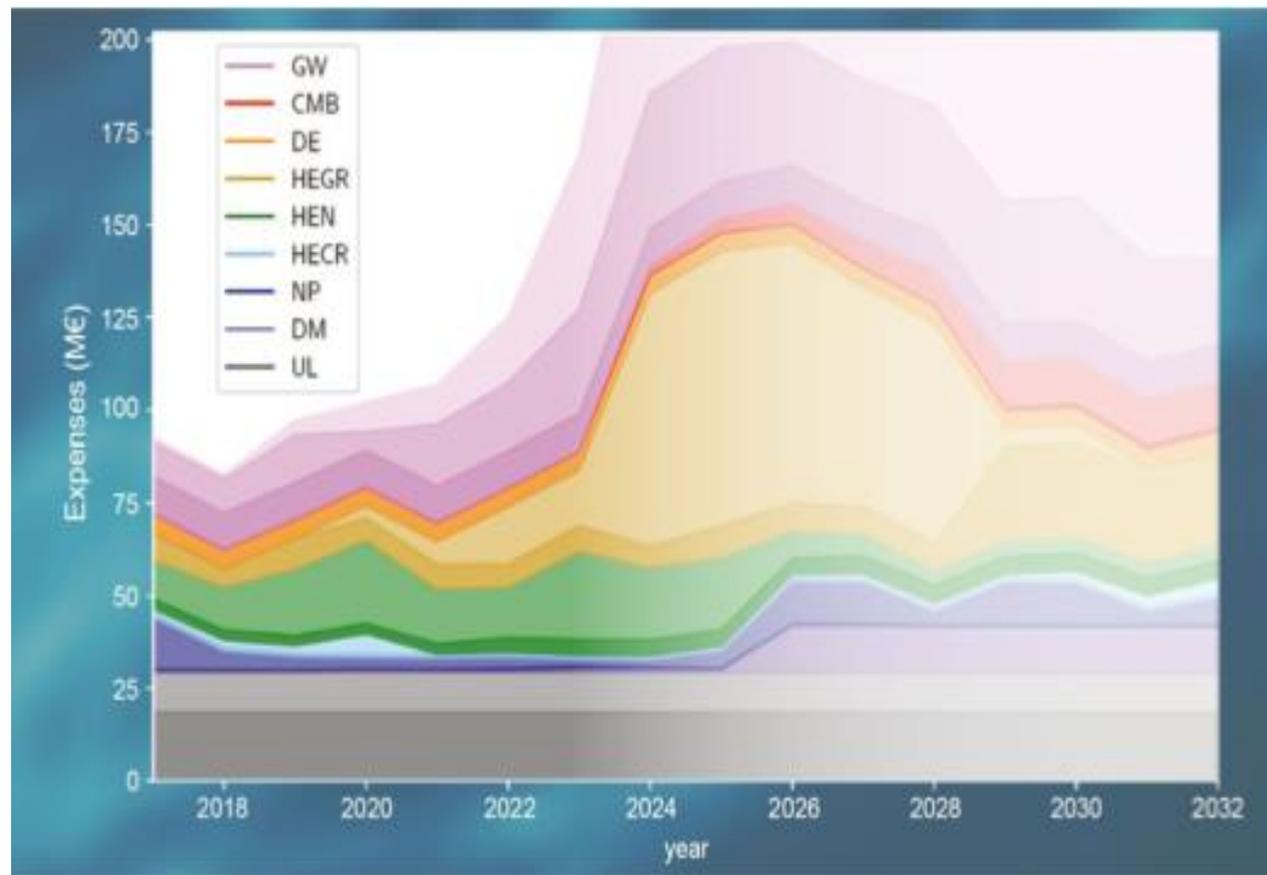
6个科学驱动 (突破口)	美国		欧洲		日本	
	现状	未来	现状	未来	现状	未来
以希格斯为探针 发现新物理		Muon Collider	LHC	FCC, CLIC		ILC
确定中微子的 质量及属性	NOvA EXO	DUNE nEXO	Gerda CUPID KARTIN	XLZD LEGEND	Super-K, T2K	Hyper-K
探索暗物质的本质	LZ, ADMX	XLZD LEGEND	Darkside CAST		CALET XMASS	
理解宇宙加速 (暗能量和暴胀)	LSST, DESI, BICEP3	CMB-S4	WMAP EUCLID		POLARBEAR	LiteBird
探索新粒子、相互 作用和物理原理	g-2 Mu2e	Muon Collider	LHC	Faser, SHiP...	COMET	
破解味物理谜题	K-decays		LHCb	PANDA	K-decays Belle-II/ Super-KEKB	

中国科学院“重大科技基础设施战略研究” 高能物理组 规划研究报告

暗物质探测



美国P5



Roadmap Update 2023: Projected annual capital investment

欧洲APPEC

无中微子双贝塔衰变

- 国内学科发展战略研究专题（2021）



- 美国核科学10年规划

RECOMMENDATION II 2015

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

RECOMMENDATION 2 2023

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

如何探测暗物质粒子？

PHYSICAL REVIEW D

VOLUME 31, NUMBER 12

15 JUNE 1985

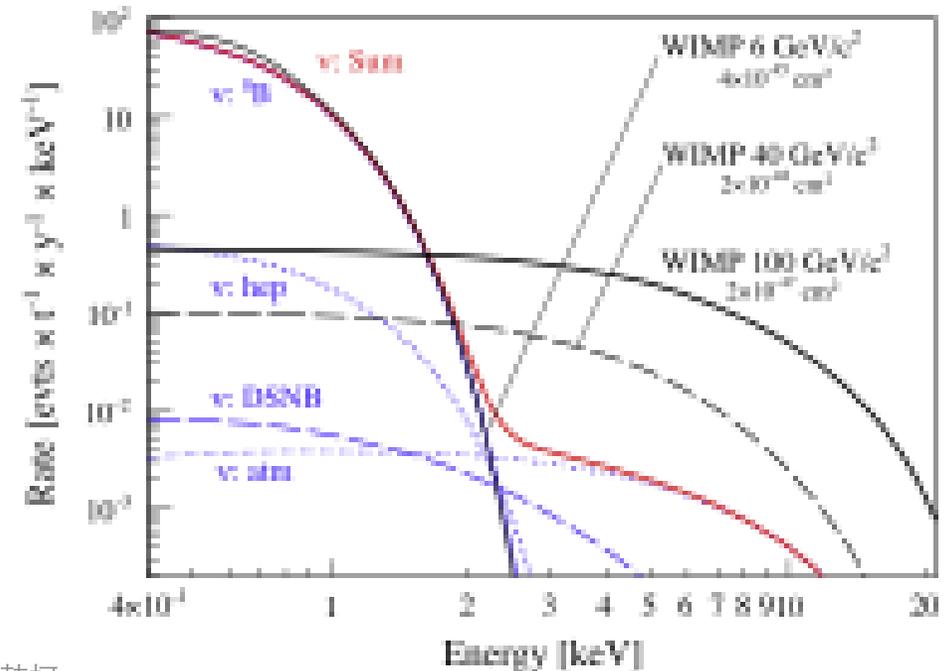
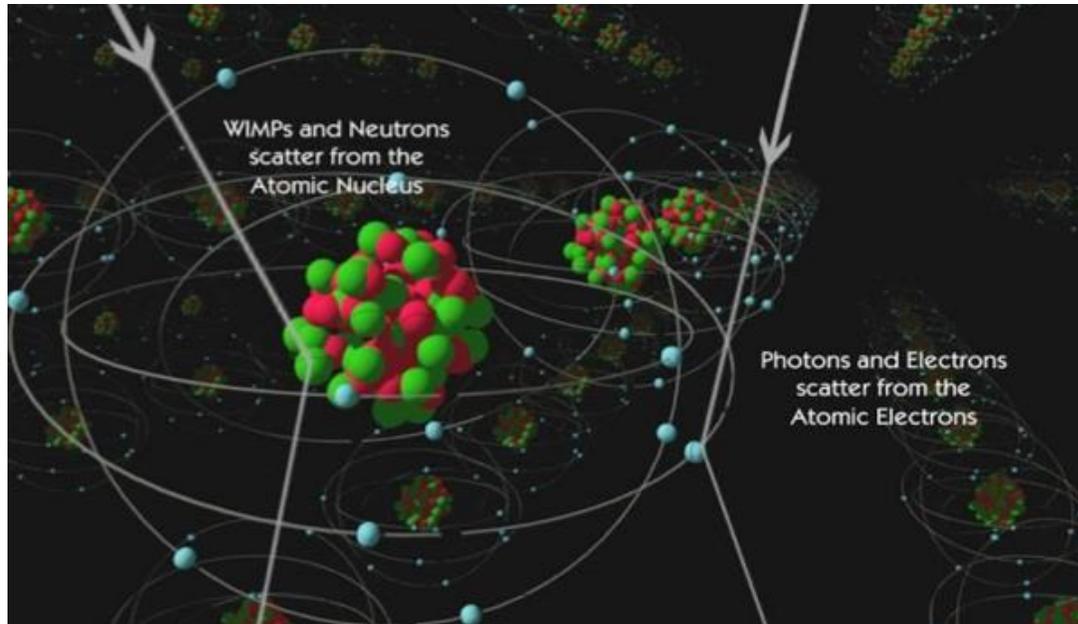
Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten

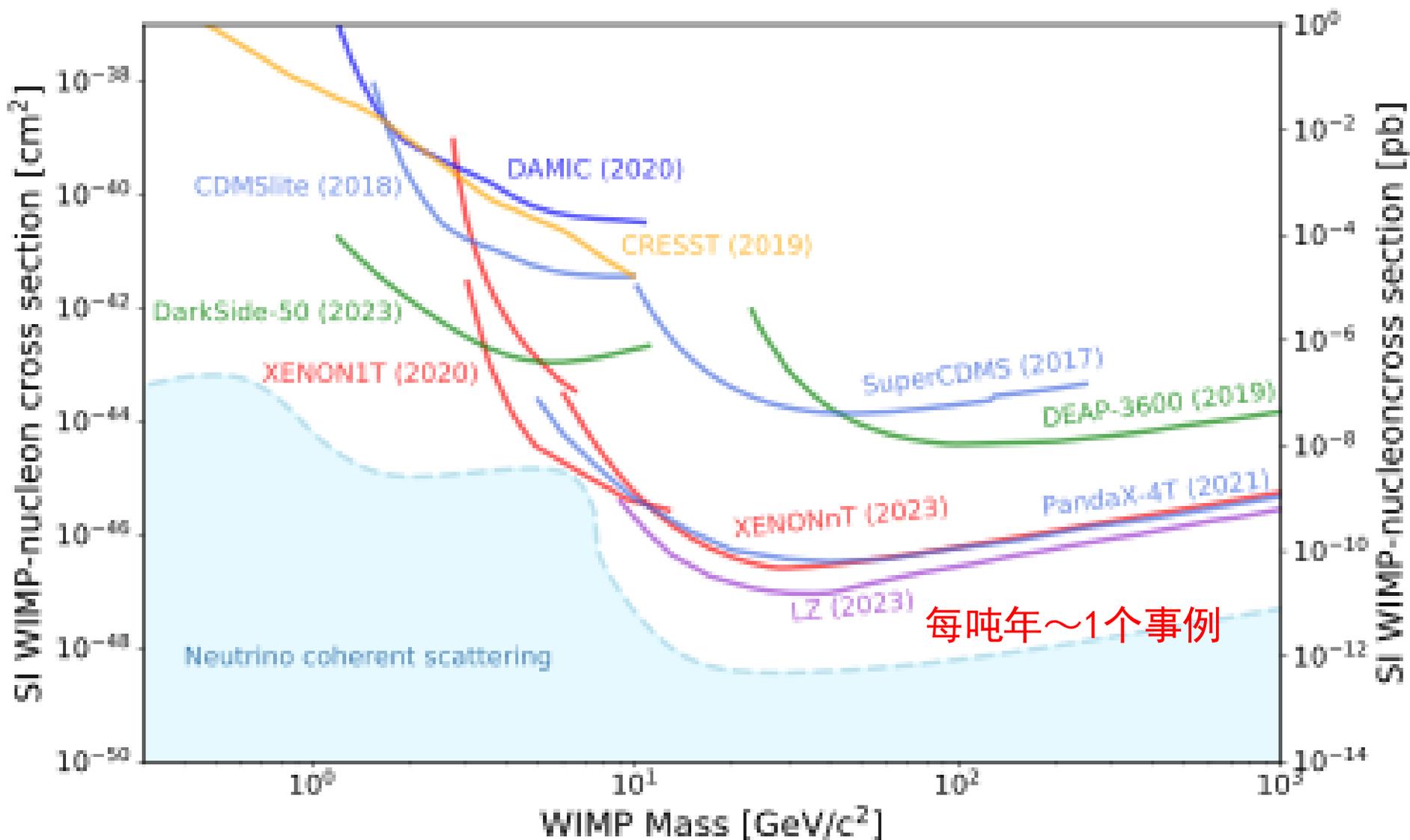
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.



暗物质探测全景图



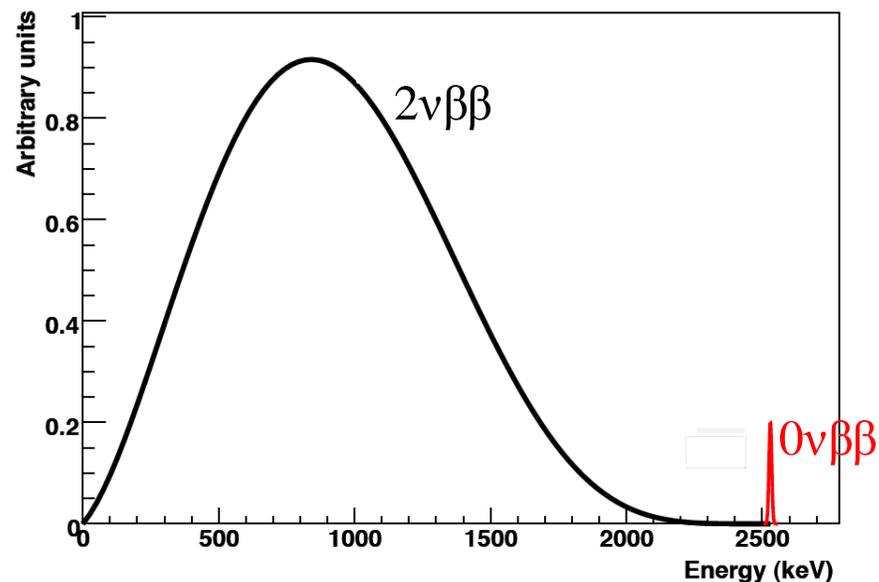
PDG 2024

如何探测无中微子双贝塔衰变

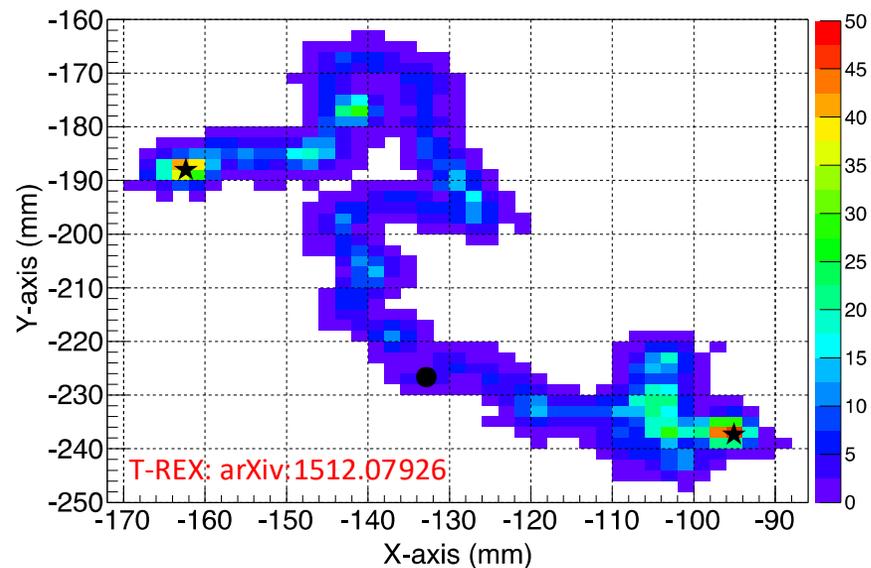
例子:



- 测量双电子的能量 ($\sim\text{MeV}$)
- 测量双电子的径迹 ($\sim 10\text{ cm}$)
- 鉴别衰变子核



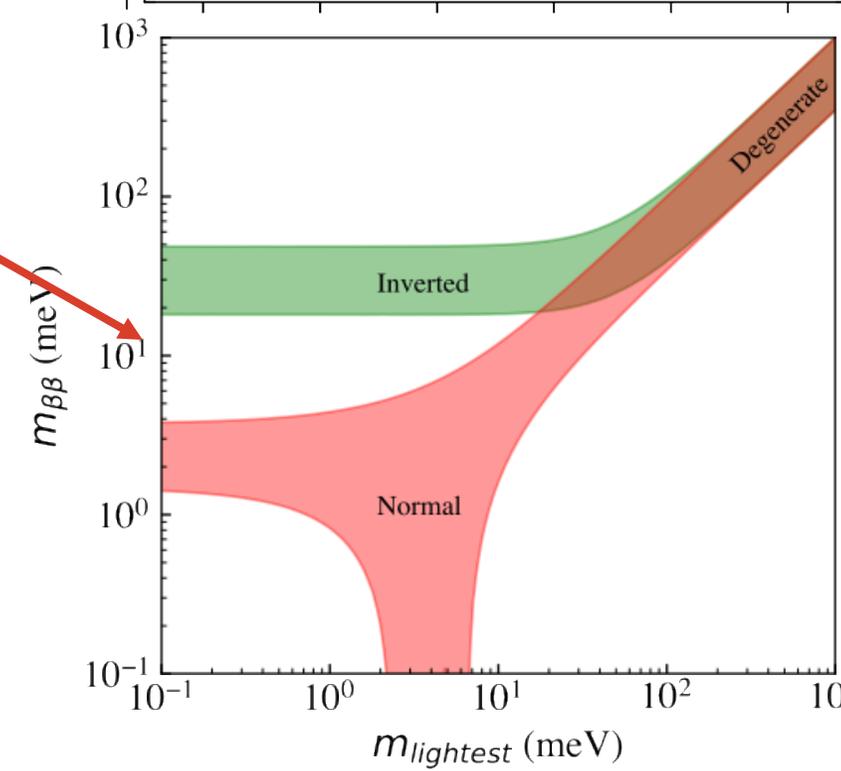
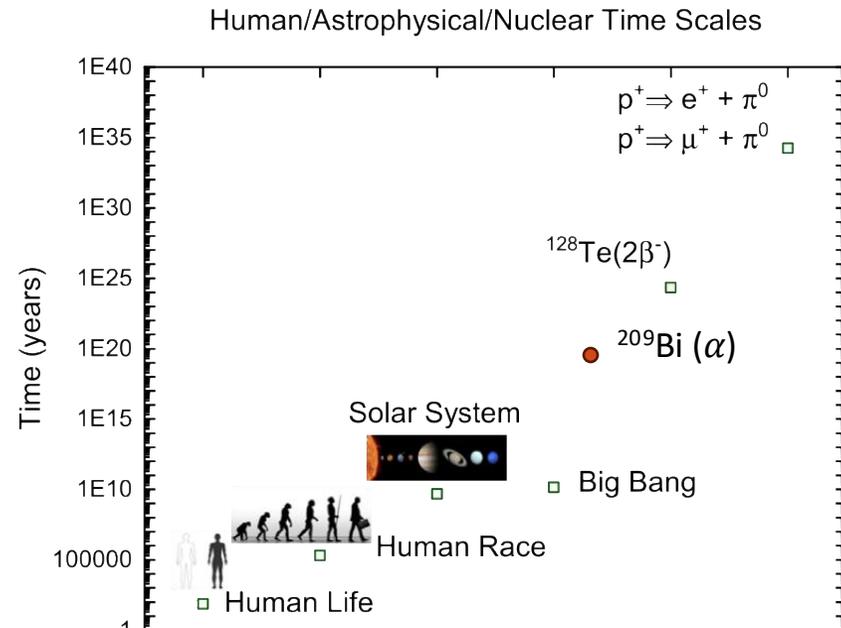
Sum of two electrons energy



Simulated track of $0\nu\beta\beta$ in high pressure Xe

超长半衰期，极低信号量

- 双贝塔衰变：二阶弱衰变；半衰期 $\sim 10^{20}$ 年
- 下一代实验的NLDBD半衰期最低限制约 10^{27} 年
 - 吨级探测器，每年 ~ 1 个信号



Half life sensitivity $\propto \eta \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$



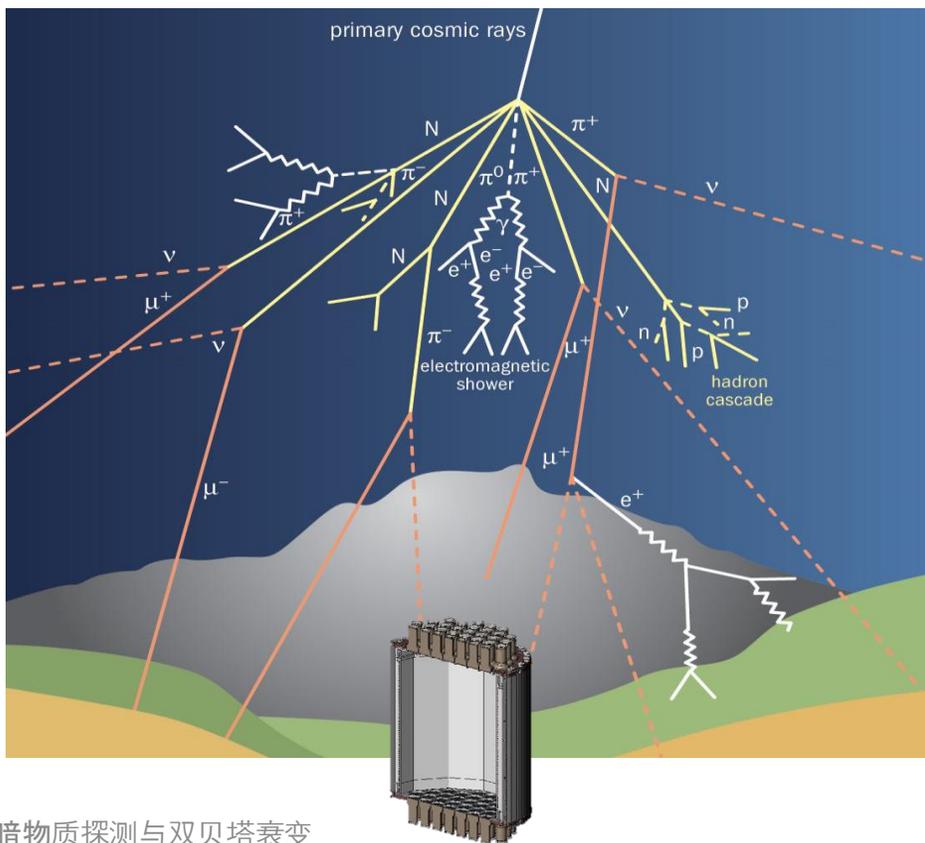
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \frac{|\langle m_{\beta\beta} \rangle|^2}{m_e^2}$$

Phase space factor

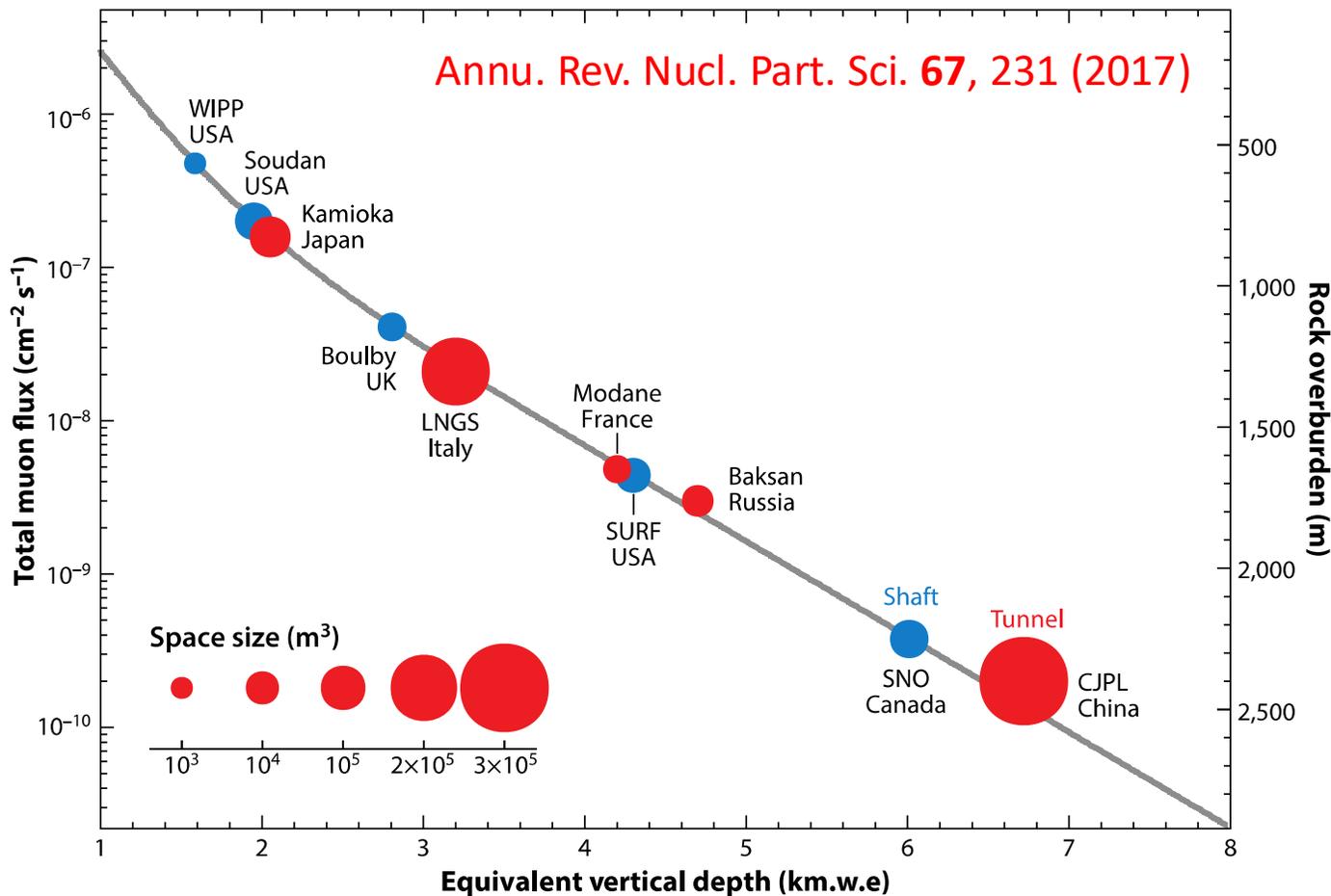
Nuclear matrix element

本底控制-地下实验室抑制缪子影响

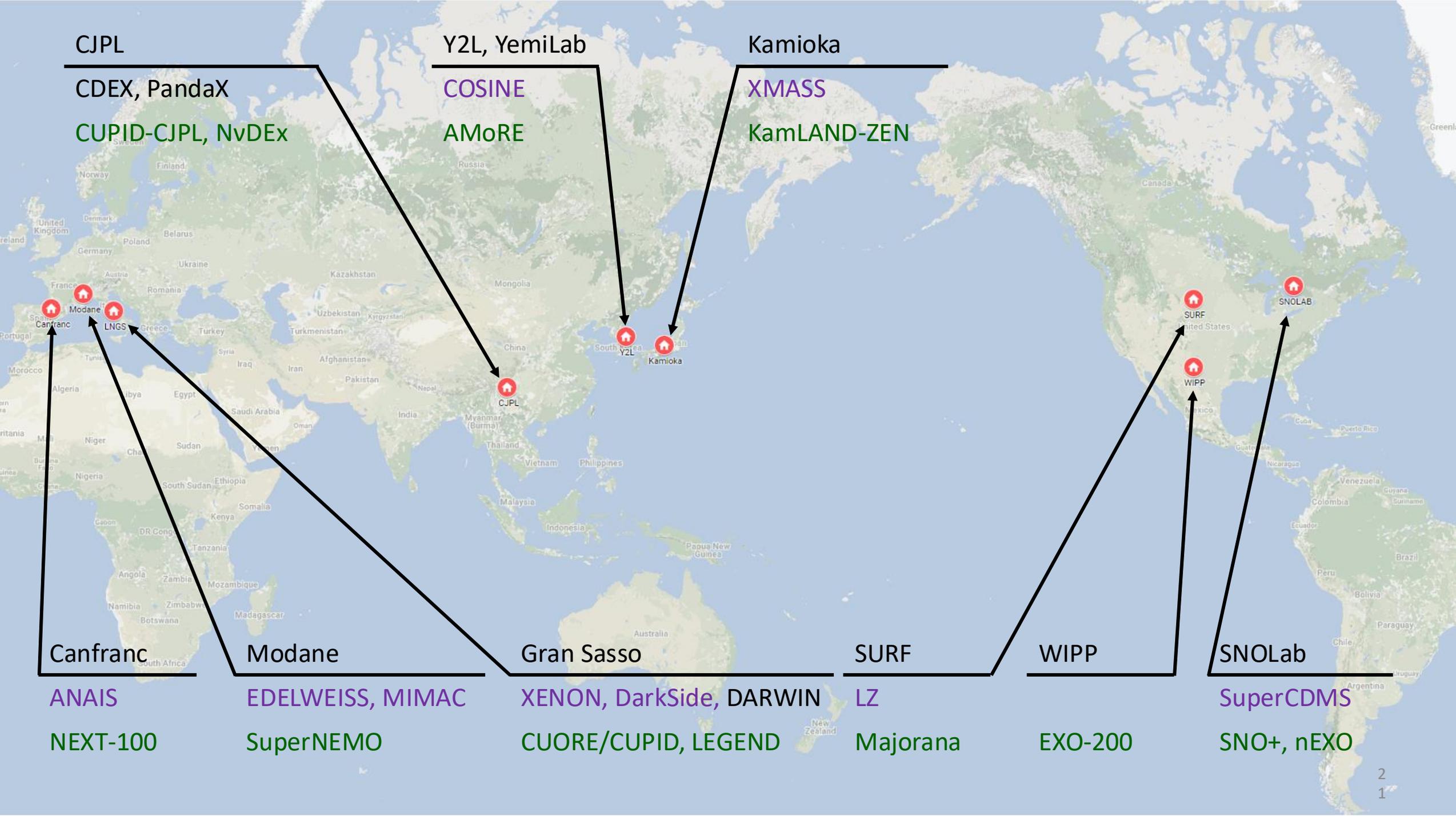
- 缪子直接击中探测器
- 宇生放射性
 - 地下存储, 地下加工



暗物质探测与双贝塔衰变



上海交大 韩柯



CJPL

CDEX, PandaX

CUPID-CJPL, NuDEx

Y2L, YemiLab

COSINE

AMoRE

Kamioka

XMASS

KamLAND-ZEN

Canfranc

ANAIS

NEXT-100

Modane

EDELWEISS, MIMAC

SuperNEMO

Gran Sasso

XENON, DarkSide, DARWIN

CUORE/CUPID, LEGEND

SURF

LZ

Majorana

WIPP

EXO-200

SNOLab

SuperCDMS

SNO+, nEXO

本底控制-低放射性材料筛选

- 探测器材料天然放射性
 - 天然放射性 1-100 Bq/kg
 - 实验要求至少1 mBq/kg
- 探测器部件表面放射性
 - 表面处理方式
 - 氦气抑制
- 地下实验室环境放射性
 - 额外低放射性屏蔽体

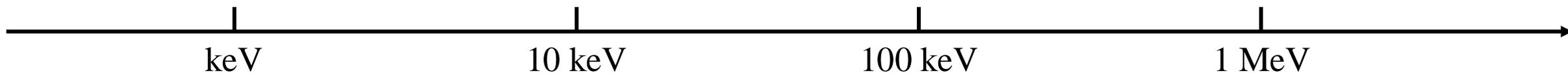
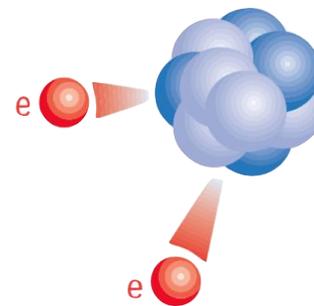
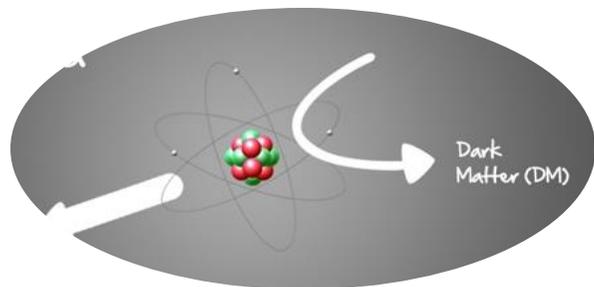


U/Th



K

探测器性能要求

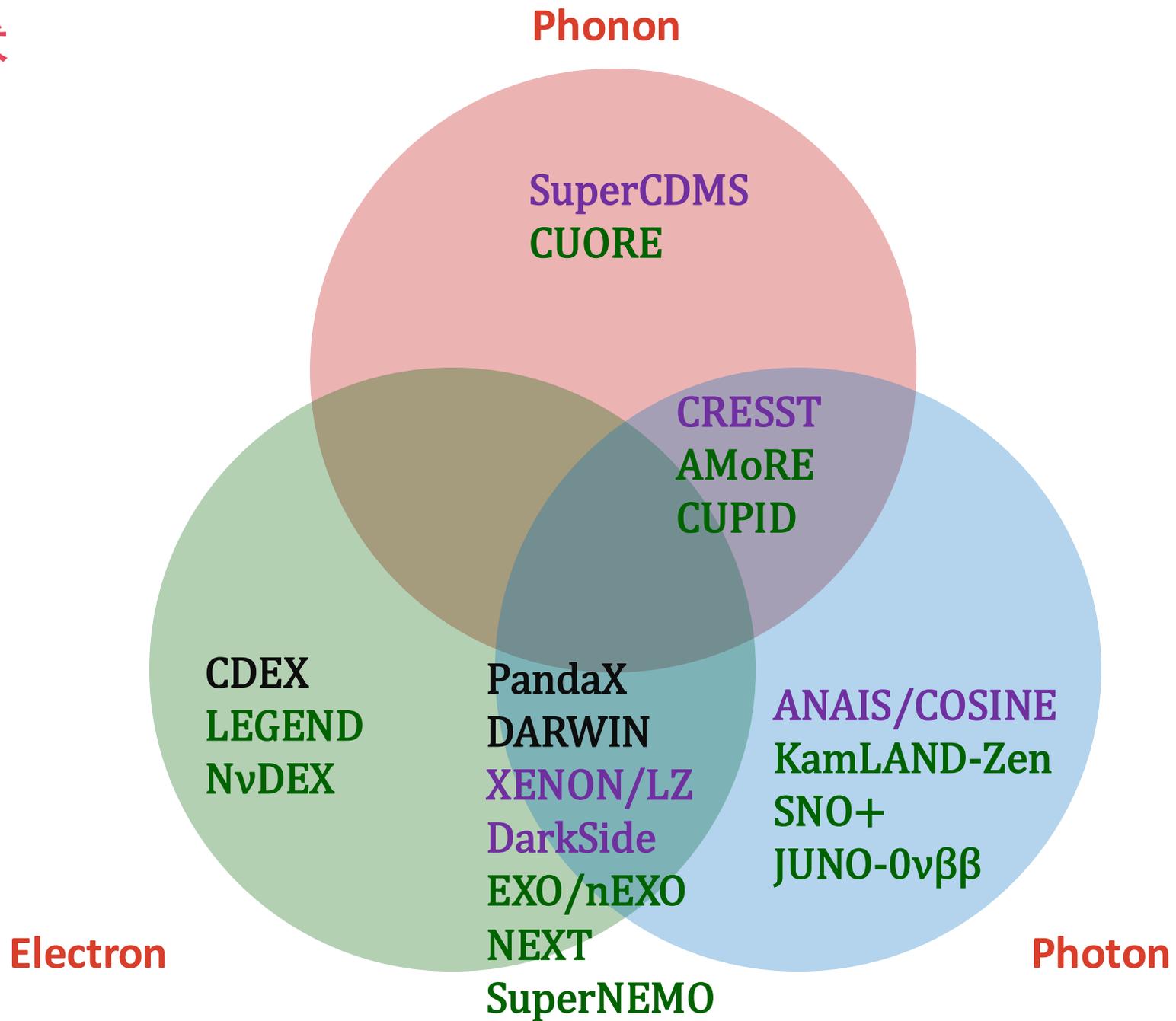


- 大体量
- 极低能量阈值（本征噪声低）
- 核反冲鉴别

- 大体量
- 高能量分辨率（本征噪声低）
- 粒子鉴别

1. 物理驱动
2. 现状与挑战
3. 探测器技术
4. 未来趋势

探测器技术



低温量能器

- CRESST

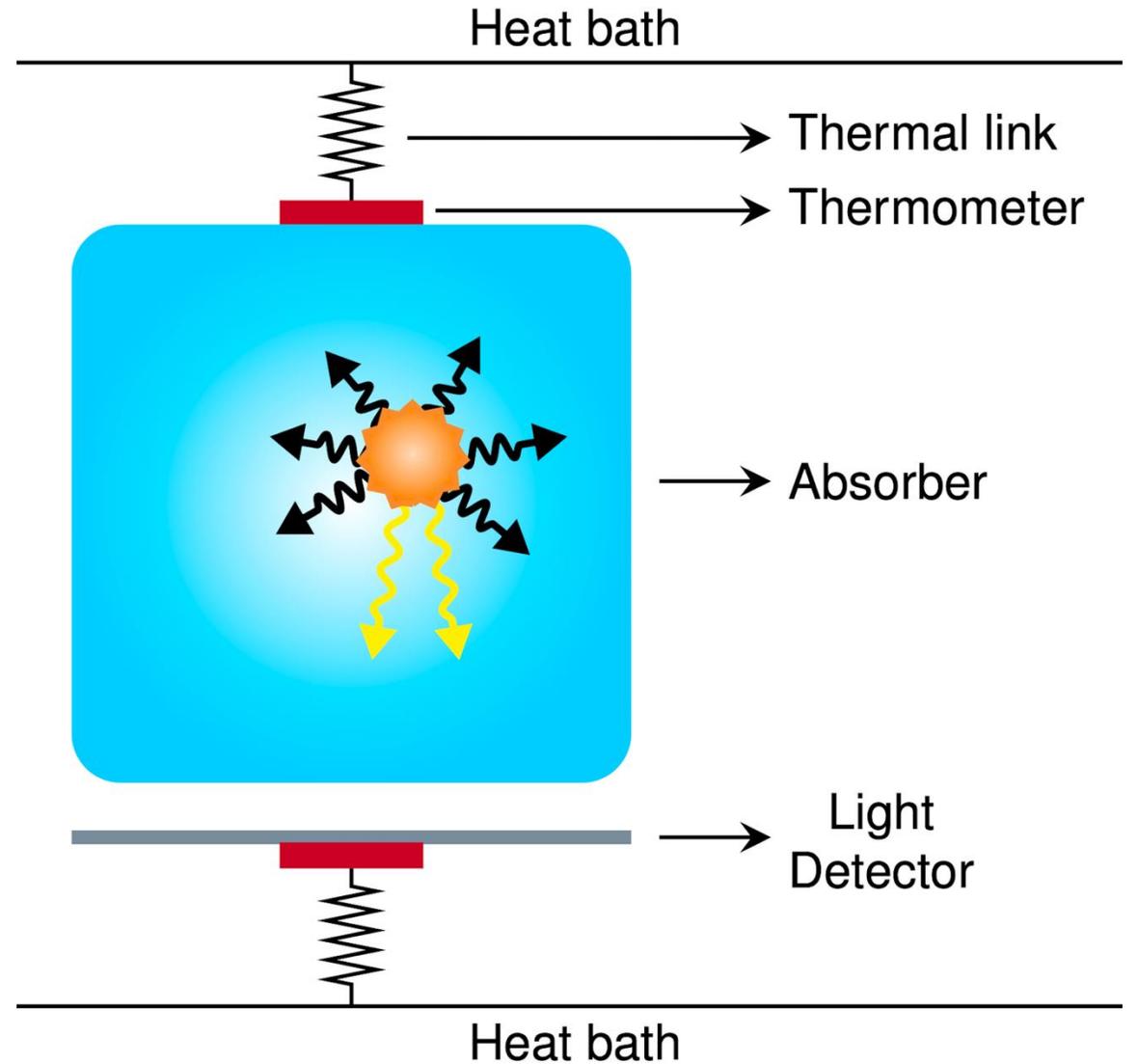
- 克量级 CaWO_4 晶体，低质量暗物质
- 能量阈值 $< 10 \text{ eV}$

- SuperCDMS

- Ge/Si 晶体
- 能量阈值 100 eV

- AMoRE/CUORE/CUPID/CUPID-CJPL

- 千克量级 $\text{TeO}_2/\text{Li}_2\text{MoO}_4$ 晶体，无中微子双贝塔衰变
- 吨级阵列
- 2-3 MeV能量分辨率：5-10 keV



闪烁体探测器

- ANAIS/COSINE

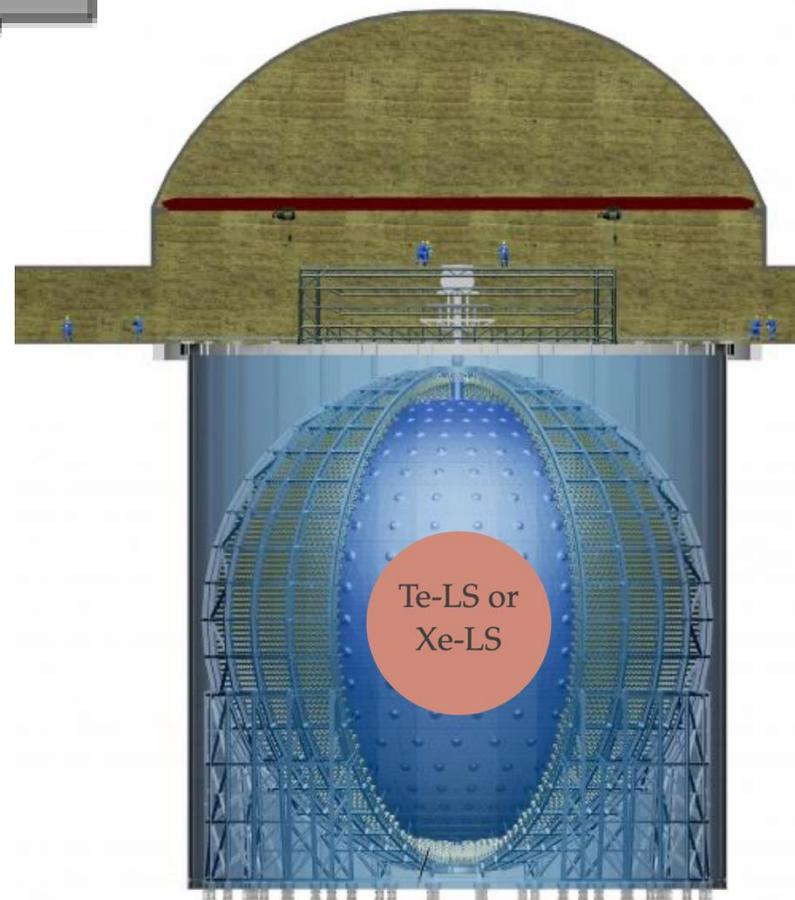
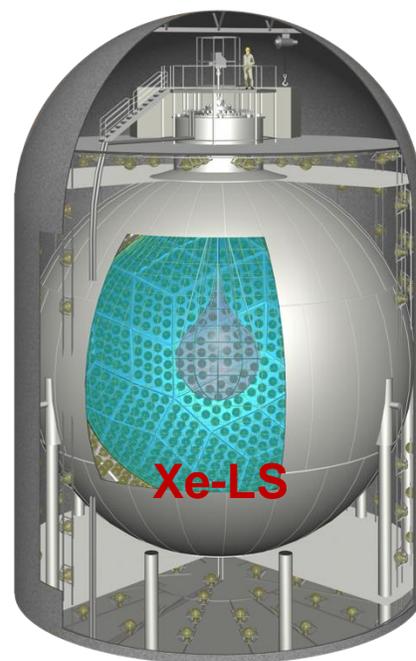
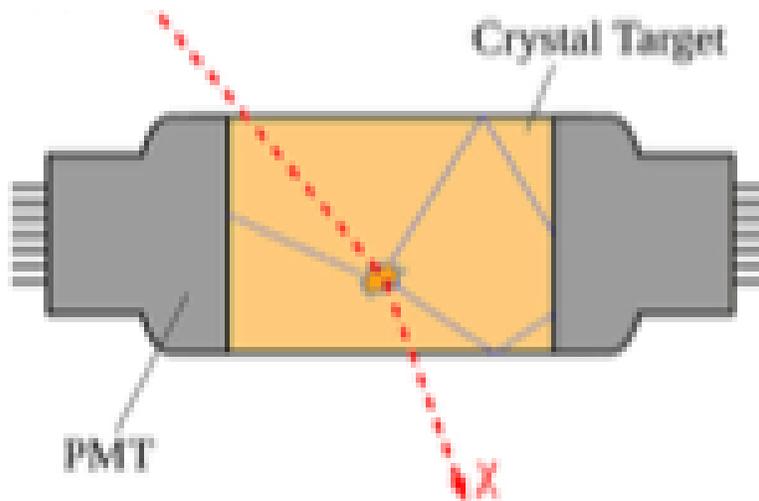
- 极低本底 NaI 晶体闪烁体,
- 验证或者否定DAMA疑似暗物质信号

- KamLAND-ZEN (and SNO+)

- 千吨液体闪烁体
- 内部气球充满含 ~ 800 kg ^{136}Xe 的液闪
- 国际领先的无中微子双贝塔衰变实验

- JUNO- $0\nu\beta\beta$

- 20 kton LS 可掺约100吨量级Te/Xe
- 10^{28} 年量级的半衰期灵敏度
- 高能量分辨率 $<3\%$ @ 1 MeV



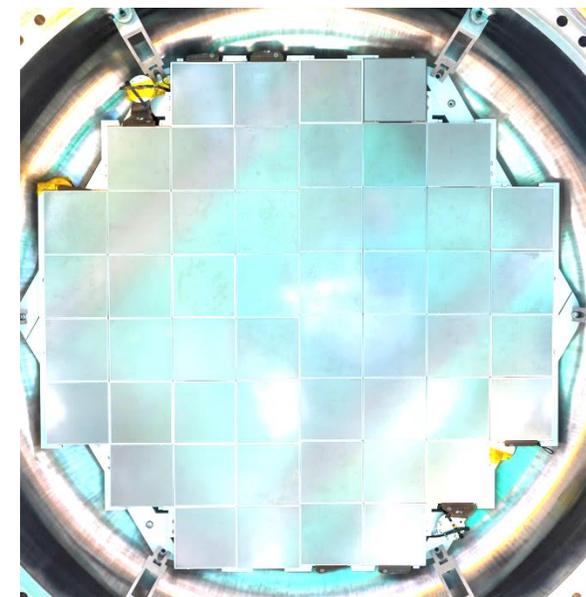
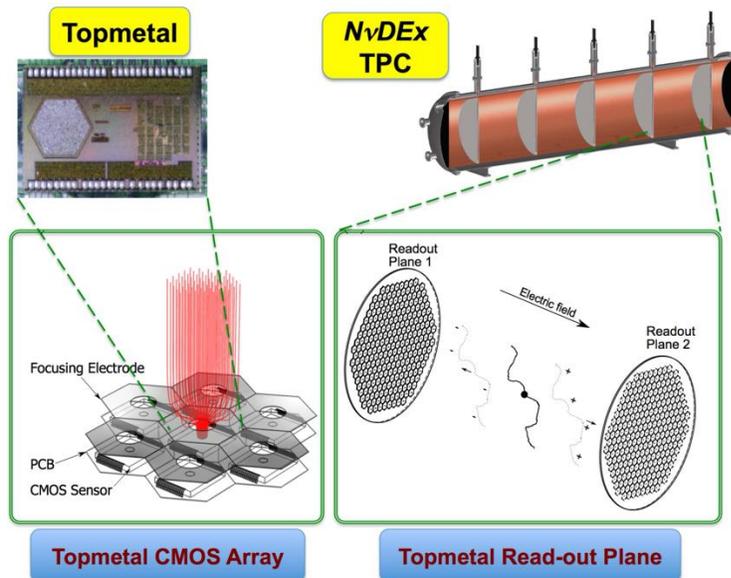
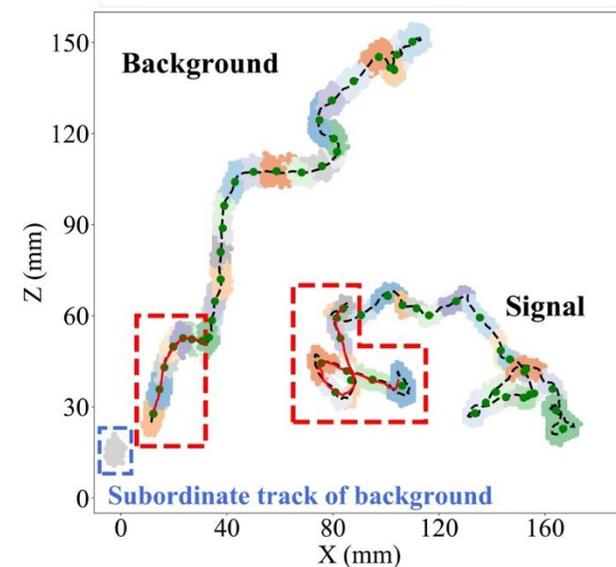
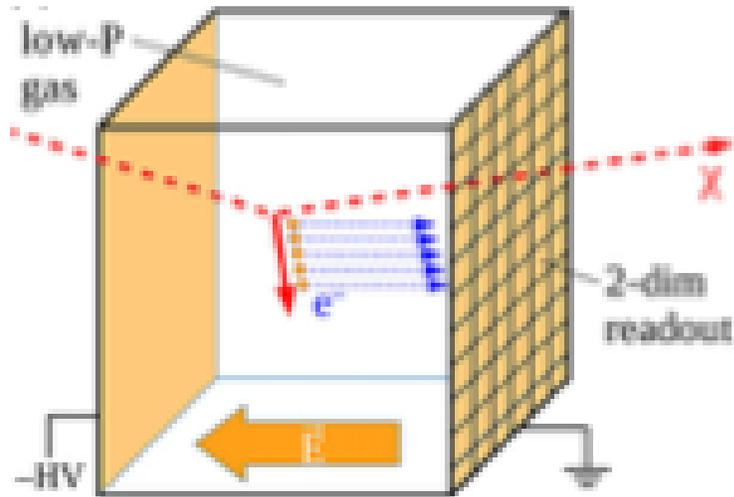
气体探测器

- MIMAC等低气压气体探测器

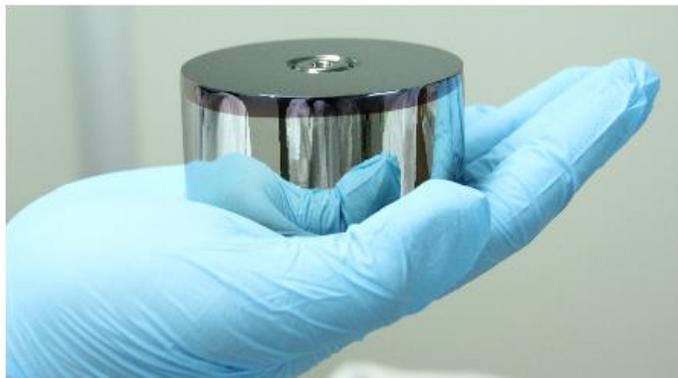
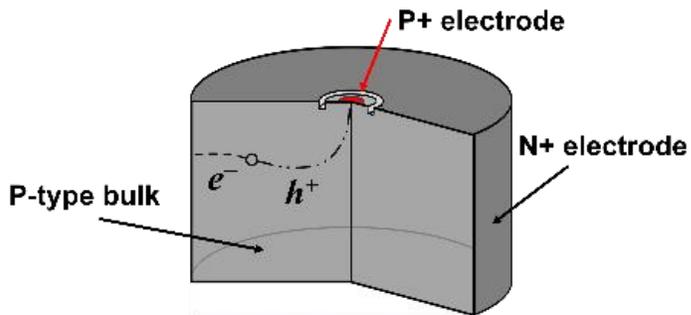
- 记录核反冲方向：暗物质方向性探测
- 目前立方米量级探测器

- AXEL/NEXT/ N ν DEX /PandaX-III
高压气体探测器

- 利用双贝塔衰变的径迹特征提取信号，压低本底
- 多种探测器读出技术
- 当前目标建成百公斤级探测器



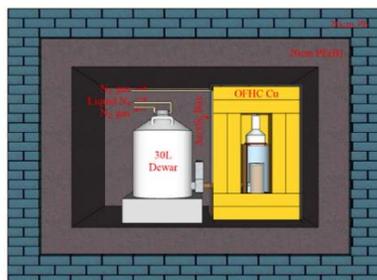
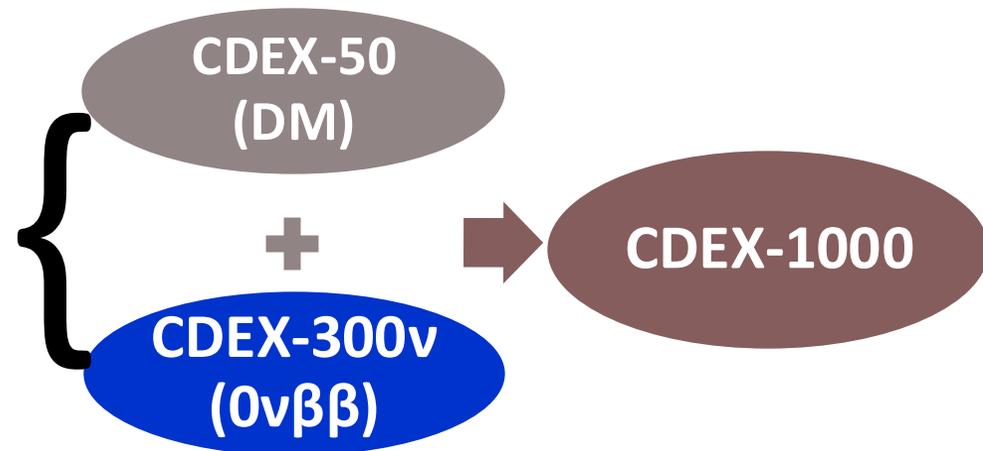
高纯锗：CDEX实验



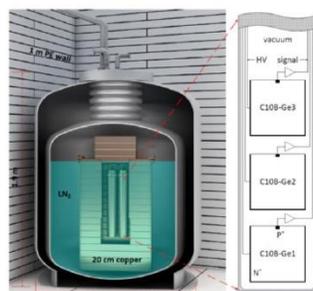
CDEX-1
2009-2016



CDEX-10
2016-2022



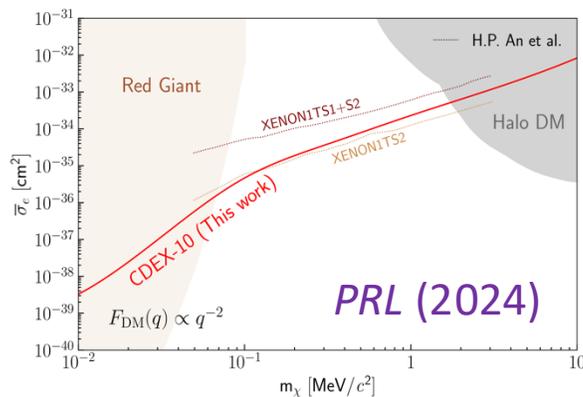
CDEX-1A&B: 1kg PPC Ge×2



CDEX-10: ~10kg PPC Ge array

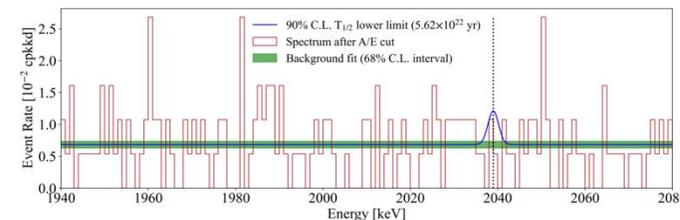
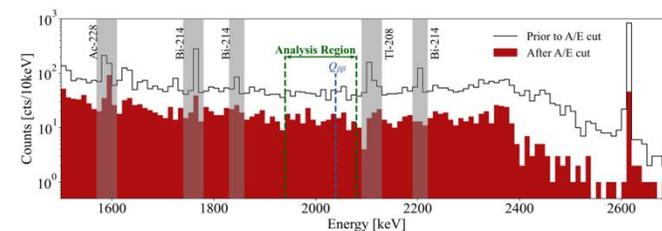


- 屡次发表轻质量暗物质区域国际领先的结果
- 国内首个⁷⁶Ge的无中微子双贝塔衰变结果



CDEX-10 SRDM results

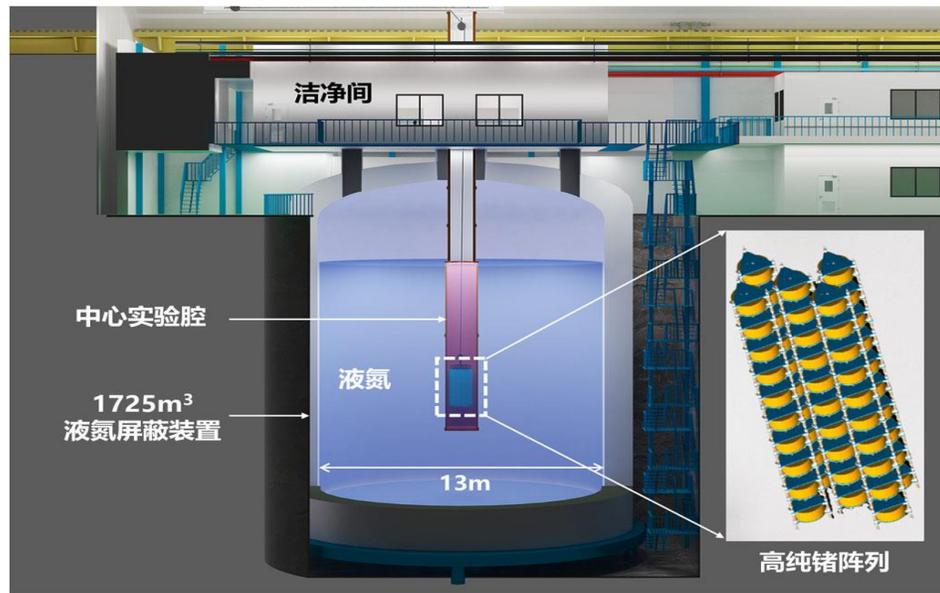
上海交大 韩柯



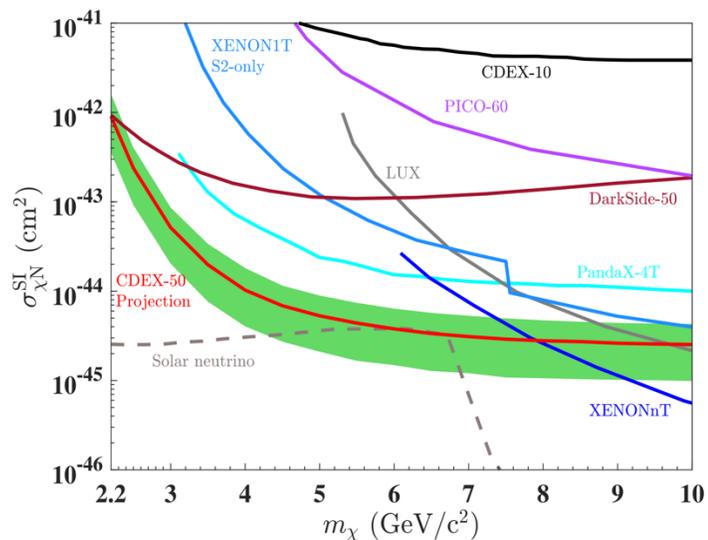
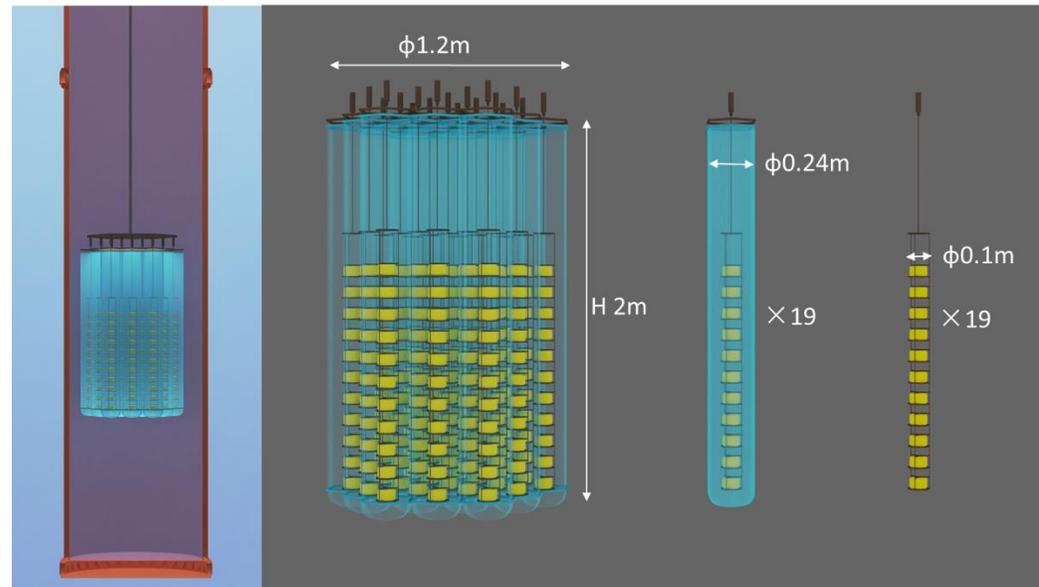
PRD (2022)

暗物质探测与无中微子双贝塔衰变并行开展

CDEX-50



CDEX-300v



Parameter	CDEX-300
^{76}Ge mass	>225 kg
BI@2039keV	10^{-4} cpkky
E_R @2039keV	2.5 keV (FWHM)
Run time	5 y (2027-2031)
Exposure	1.125 t·y
$T_{1/2}$	$>1 \times 10^{27}$ y
$m_{\beta\beta}$	28.5~68.0 meV

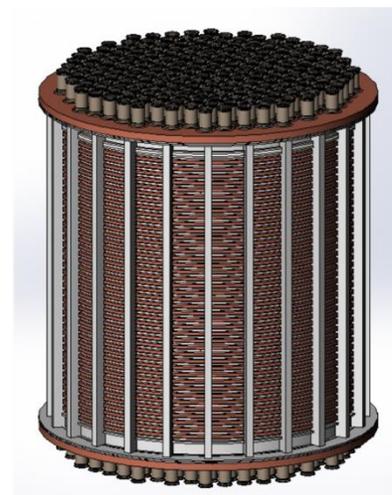
液氙探测器：PandaX



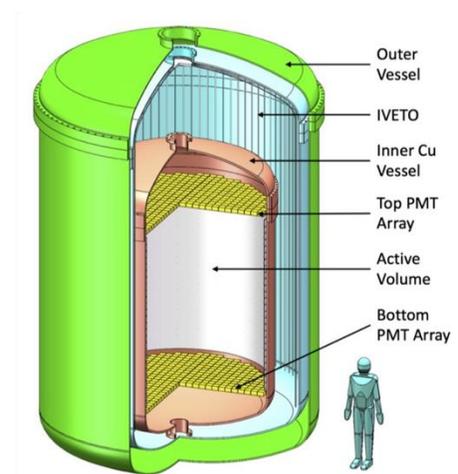
PandaX-I: 120kg
LXe (2009 – 2014)



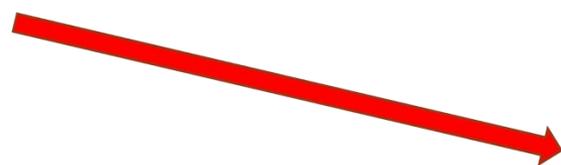
PandaX-II: 500kg
LXe (2014 – 2018)



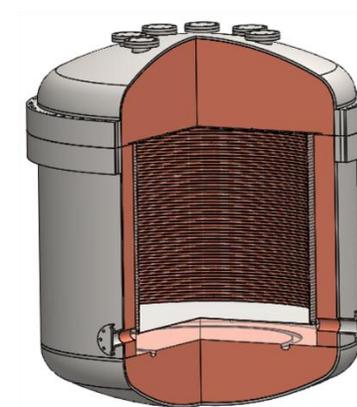
PandaX-4T LXe
(2020-)



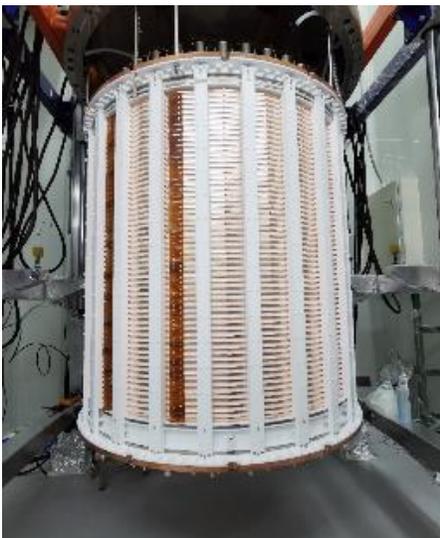
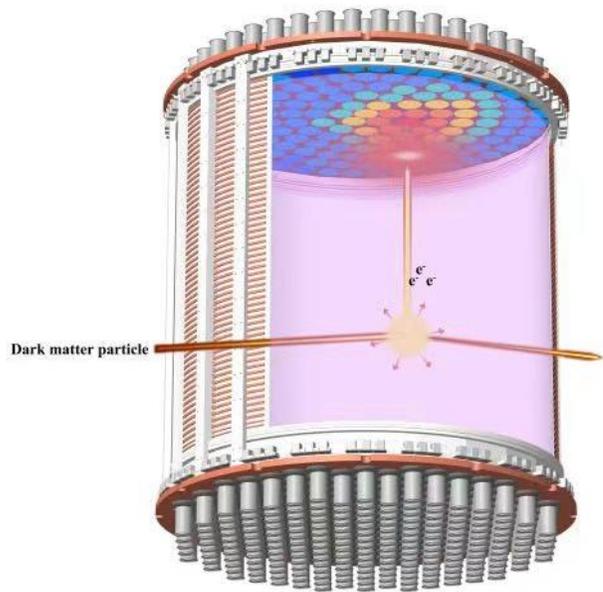
PandaX-xT LXe
(future)



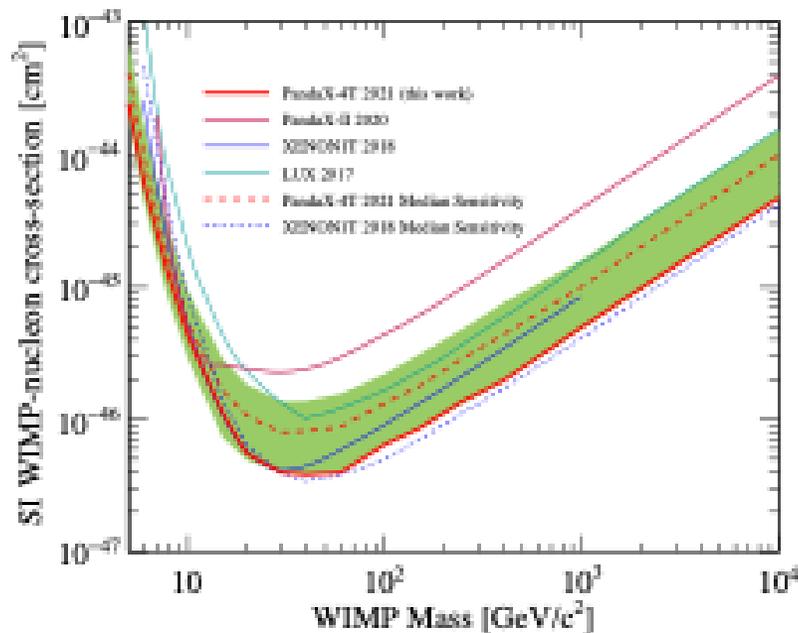
PandaX-III: 100kg - 1 ton
HPXe for $0\nu\beta\beta$ (future)



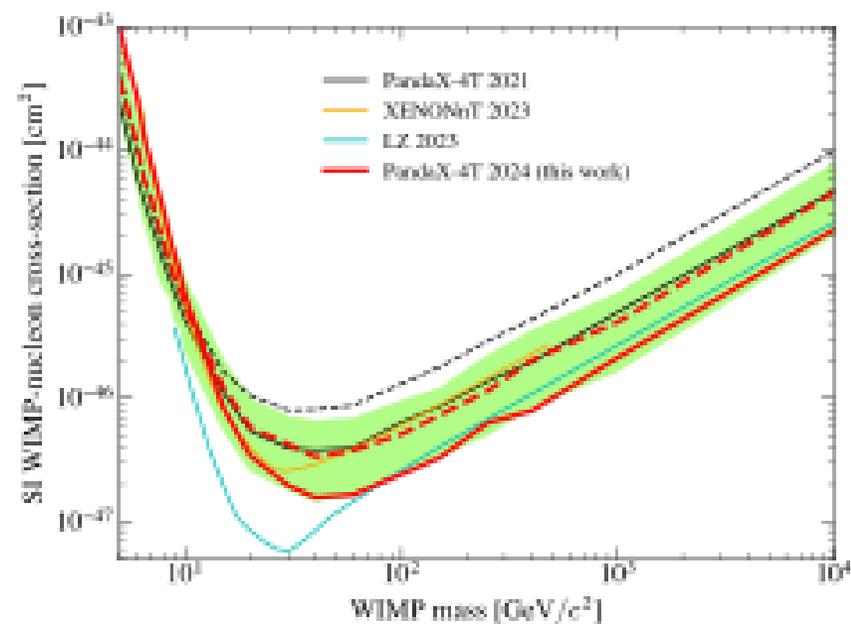
PanaX-4T暗物质探测



- 液氩探测器具有ER/NR鉴别，有效自屏蔽等优点
- 在高暗物质质量区与XENONnT，LZ实验交替领先
- 最新结果在100GeV以上区域在此再次领跑



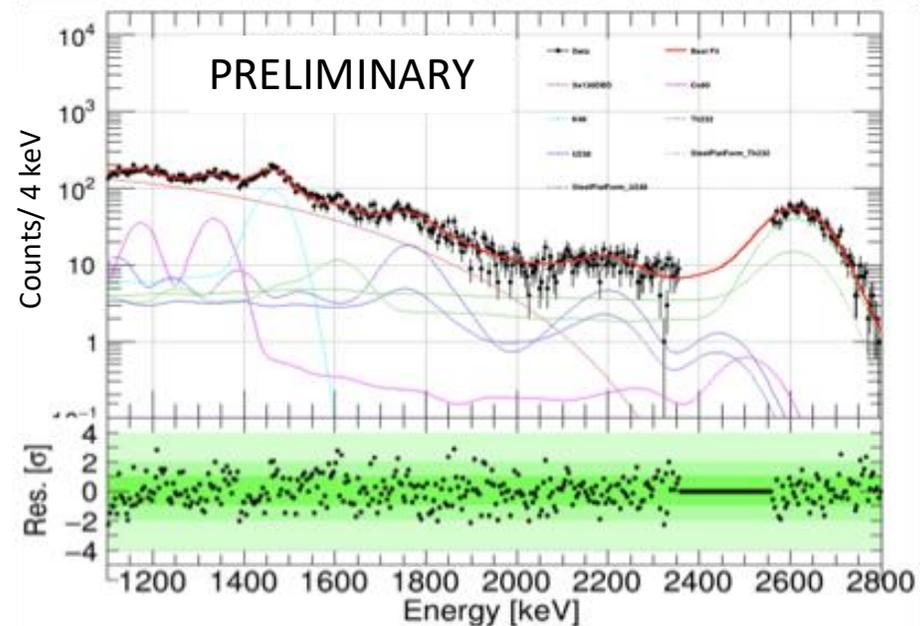
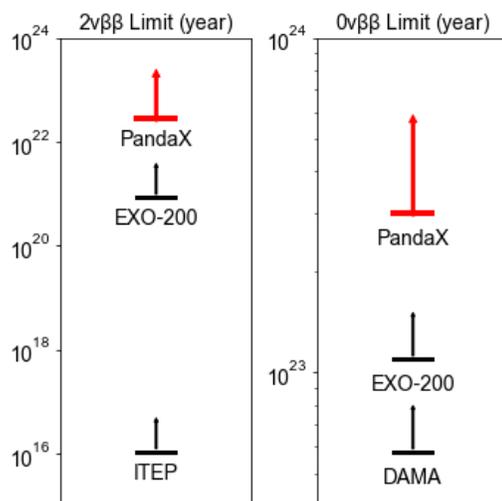
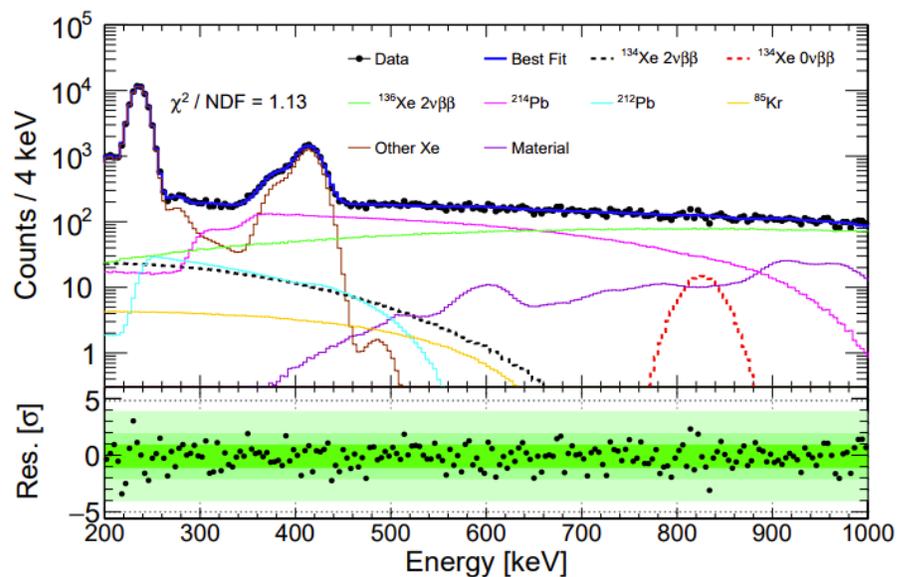
PRL 2021



arXiv:2408.00664 陶奕报告

PanaX-4T 无中微子双贝塔衰变

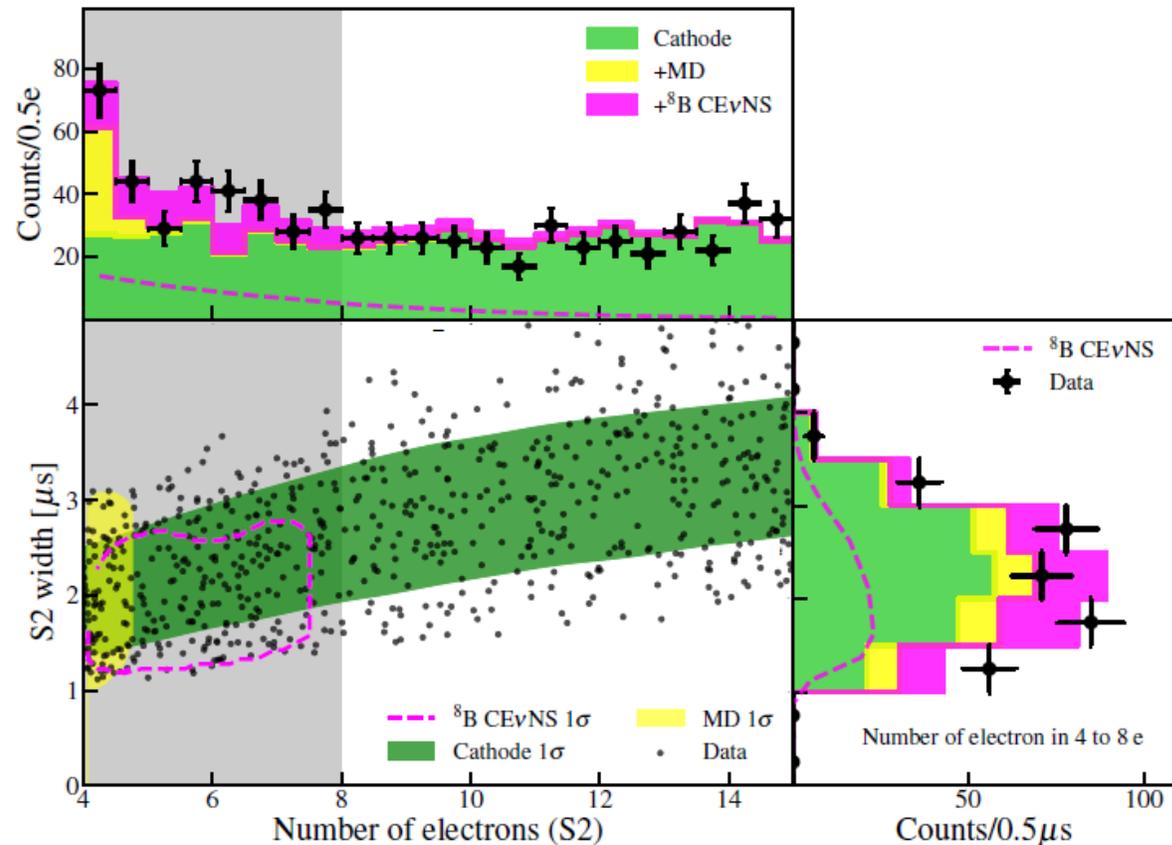
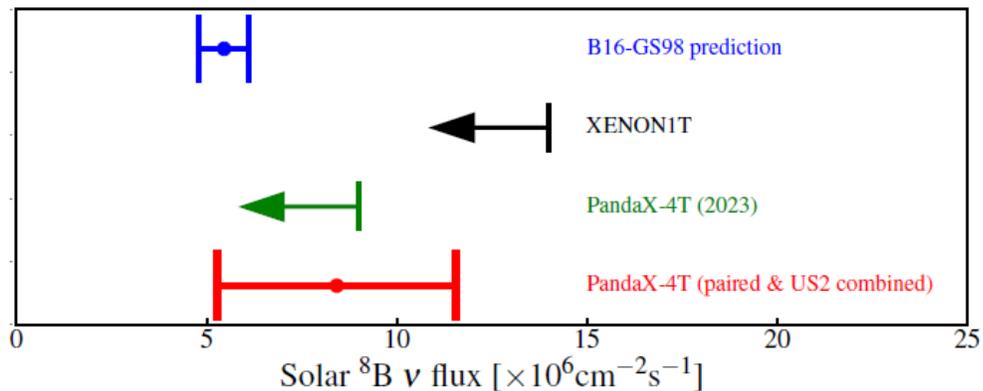
- 克服高能信号饱和等问题，MeV能区标定能量分辨率达到1.5%
- 给出多个双贝塔衰变结果，最灵敏 ^{134}Xe (NL)DBD 半衰期限制
- 预期 ^{136}Xe NLDBD 半衰期灵敏度 2×10^{24} 年，比PandaX-II结果提升一个数量级



PRL (2024) 颜玺雨报告

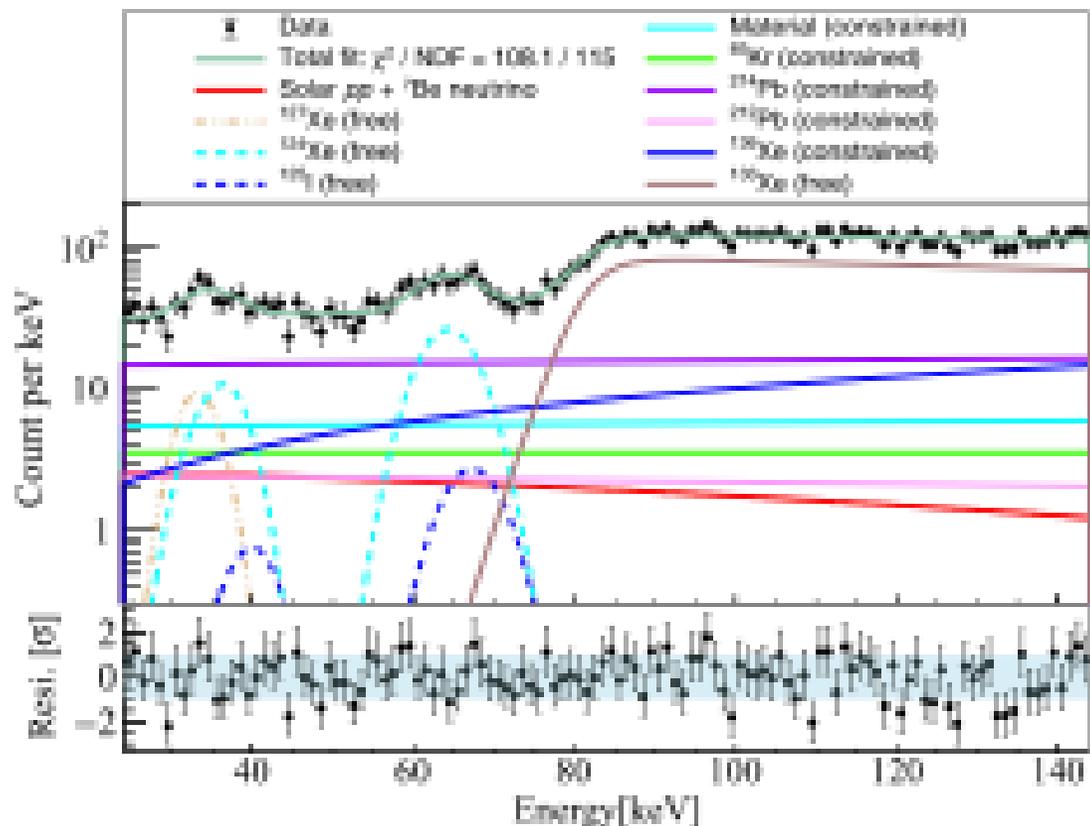
首个太阳中微子-氦核散射的迹象 (indication)!!!

- 1.5 tonne-year 曝光量
- (S1+S2) and (S2-only) 数据
- 2.64 σ !
- 7.8 IDM2024 公布, 7.15 arXiv, 投稿 PRL

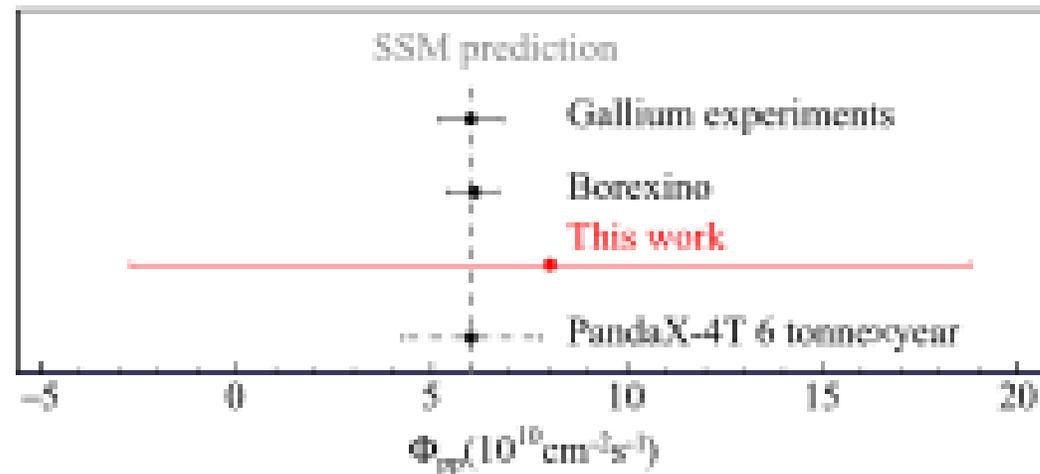


国际竞争: XENONnT 2.73 σ , 7.10 IDM公布, 8.6日arXiv

首个 $E_e < 150$ keV 的 pp 中微子结果



Chin. Phys. C **48**, 091001 (2024)



Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten

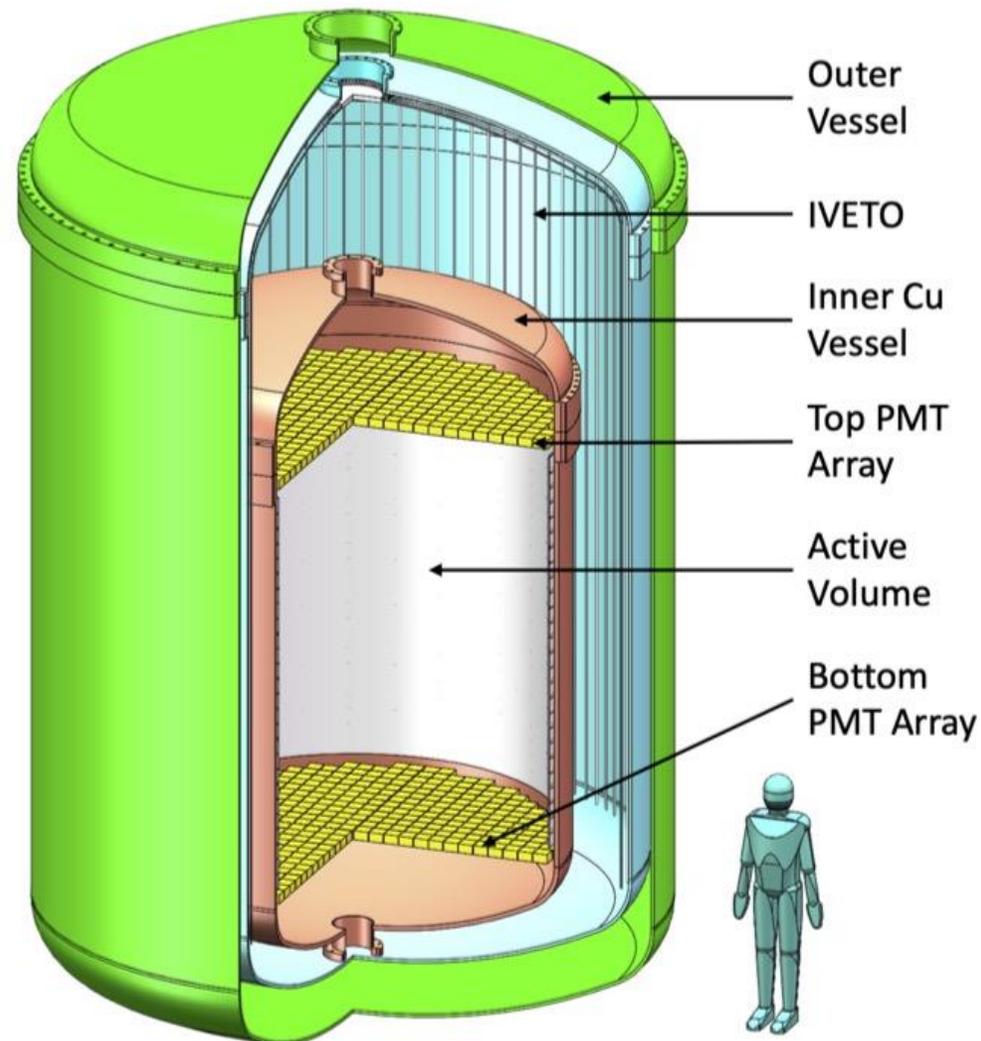
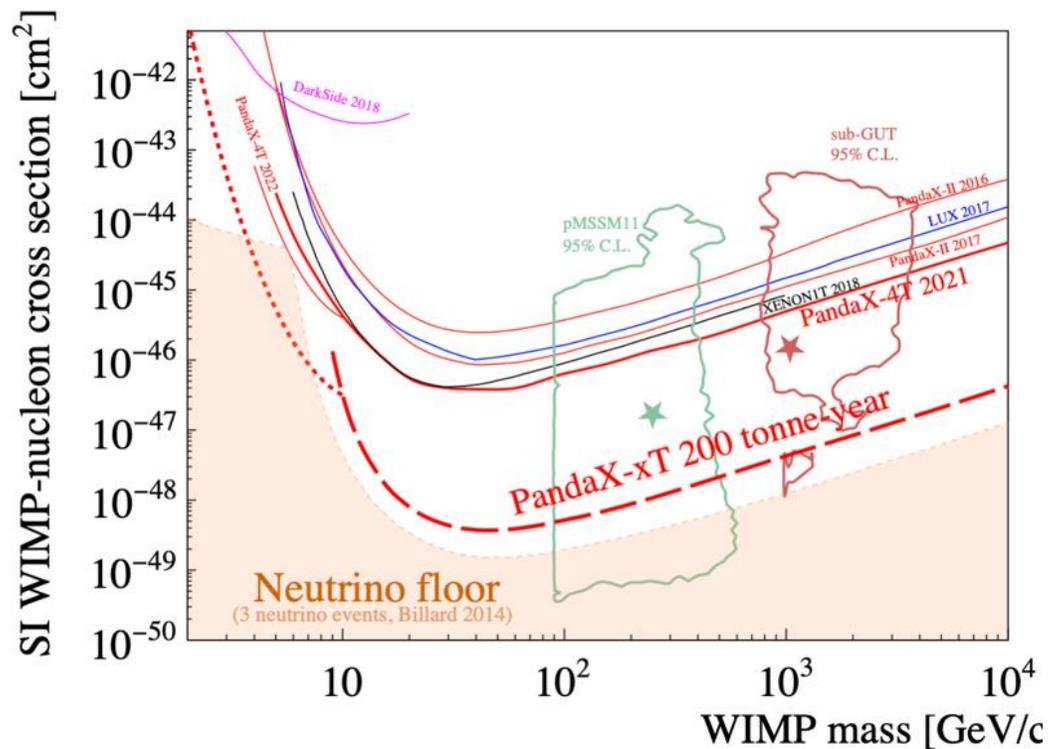
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

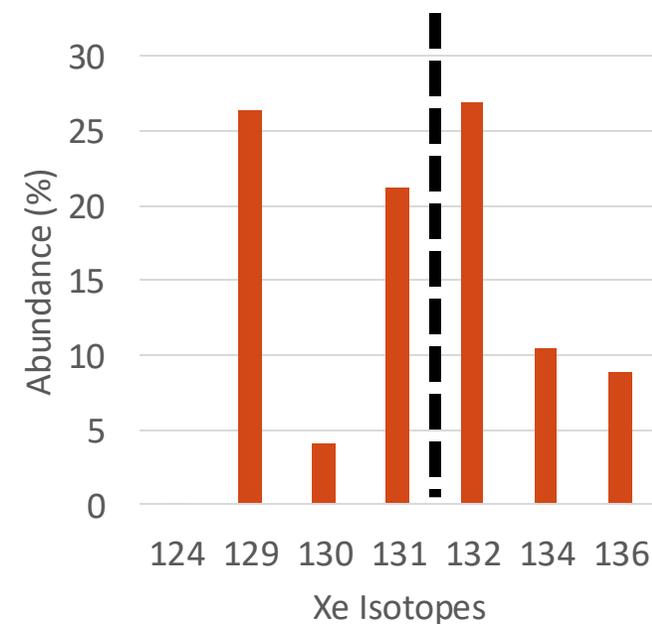
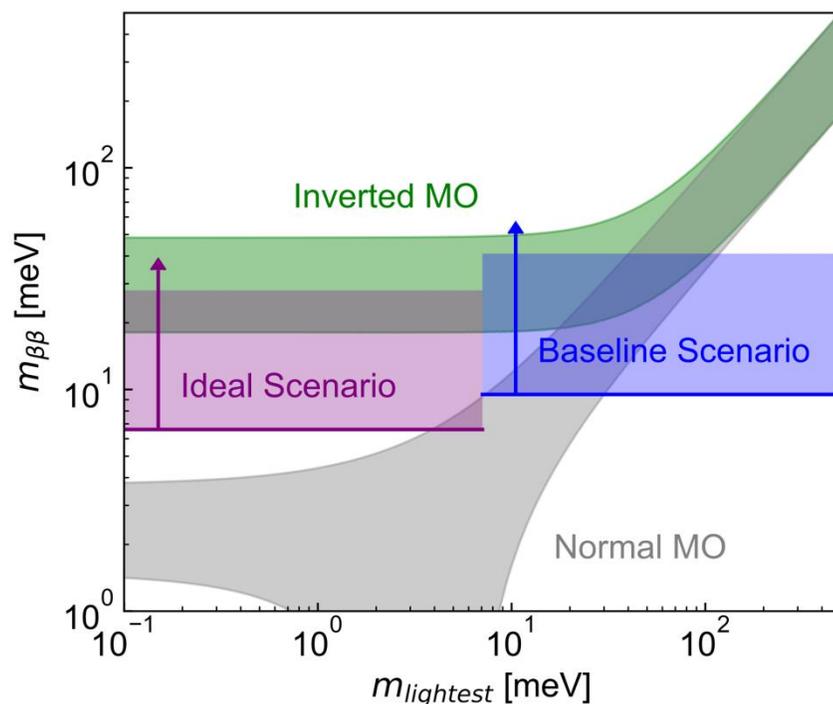
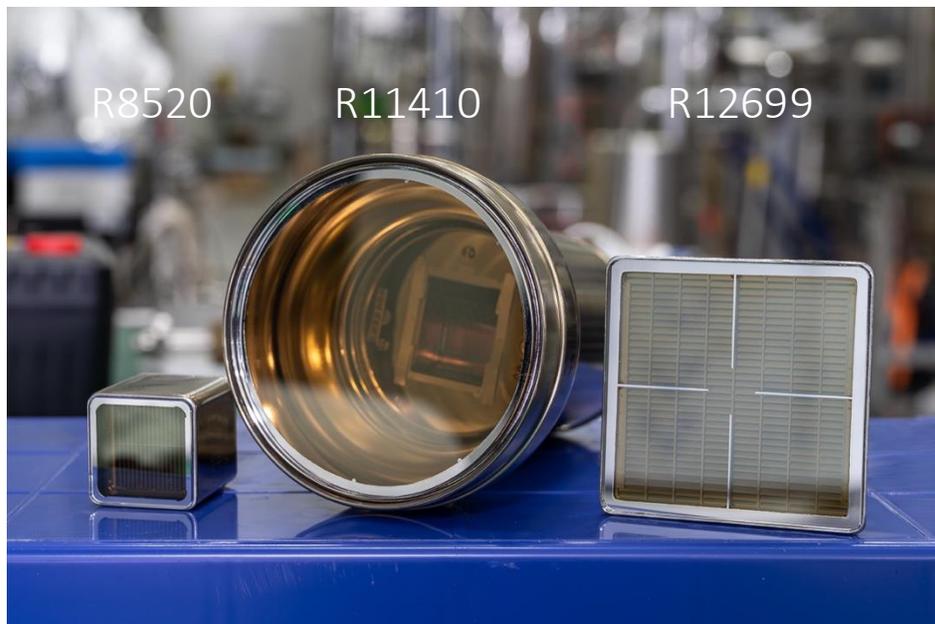
PandaX-xT 暗物质与中微子实验

- 有效体积43吨自然氙：国际最大型同类探测器之一
- 趋近暗物质探测的中微子地板



PandaX-xT 暗物质与中微子实验

- 改进的PMT读出平面，反符合系统，罐体等更加有效的开展MeV能区研究
- 预期灵敏度覆盖中微子反质量序区间，与国际最领先专有实验持平
- 积极推进同位素精馏富集，未来使用富集材料寻找双贝塔衰变



arXiv:2402.03596

1. 物理驱动
2. 现状与挑战
3. 探测器技术
4. 未来趋势

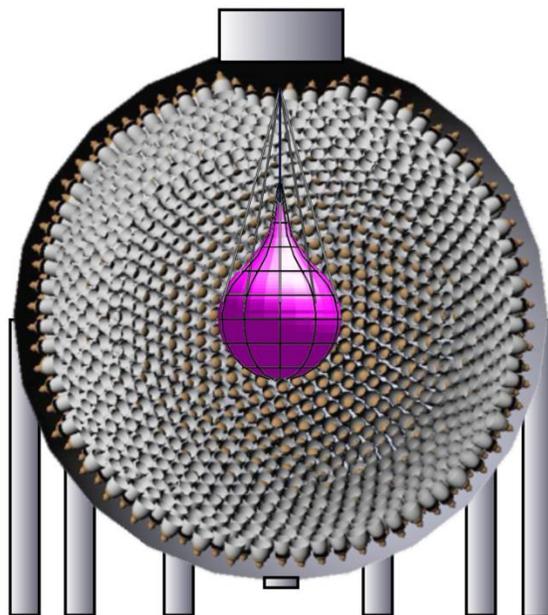
未来趋势

- 暗物质与双贝塔衰变的融合交叉
 - 共同的探测器技术
 - 一致的大体量诉求
 - 类似的低本底挑战

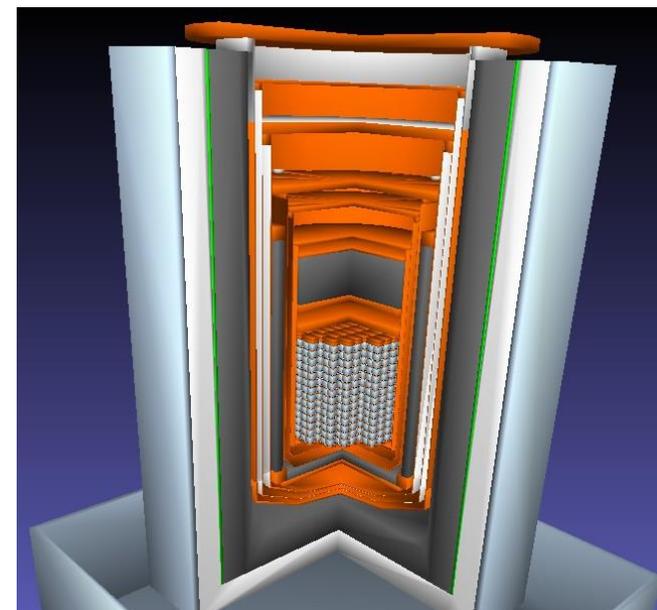
未来趋势

- 暗物质与双贝塔衰变的融合交叉
 - 共同的探测器技术
 - 一致的大体量诉求
 - 类似的低本底挑战
- 探测器做大、做精
 - 吨级、十吨级双贝塔衰变实验

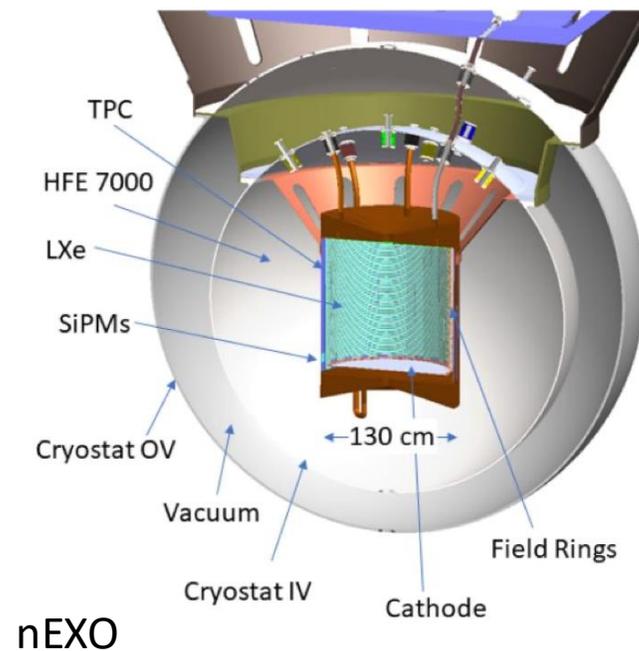
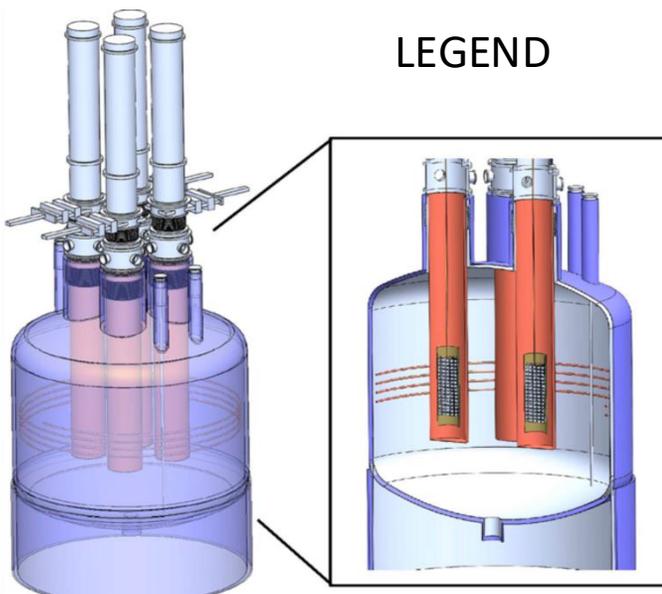
KamLAND2-ZEN



CUPID



LEGEND



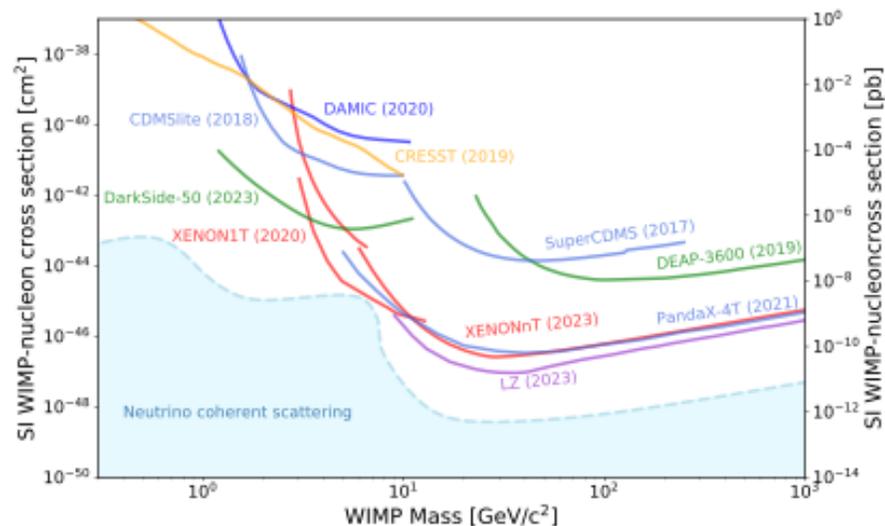
未来趋势

- 暗物质与双贝塔衰变的融合交叉

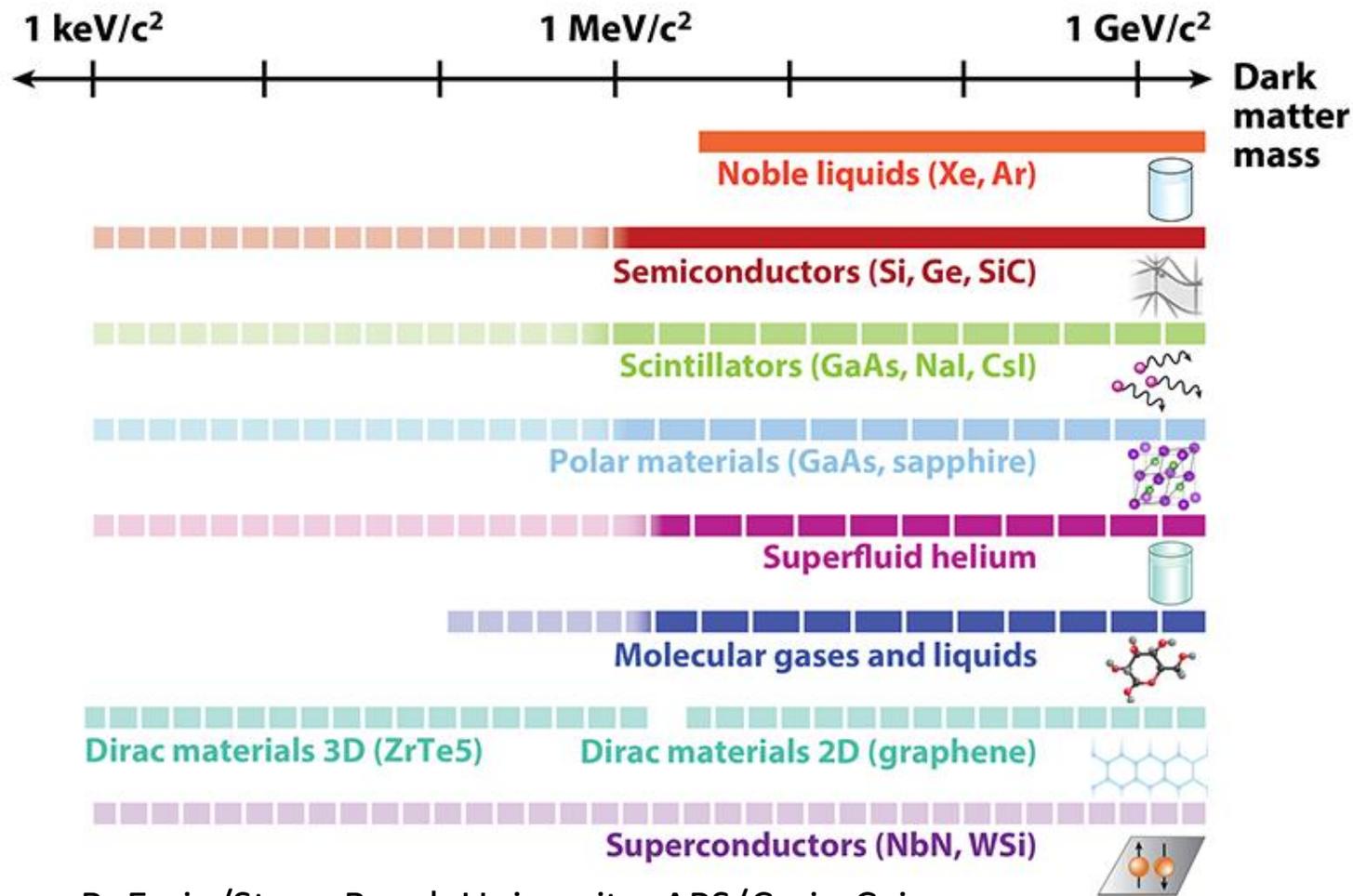
- 共同的探测器技术
- 一致的大体量诉求
- 类似的低本底挑战

- 探测器做大、做精

- 吨级、十吨级双贝塔衰变实验
- 低质量暗物质探测百花齐放



暗物质探测与双贝塔衰变

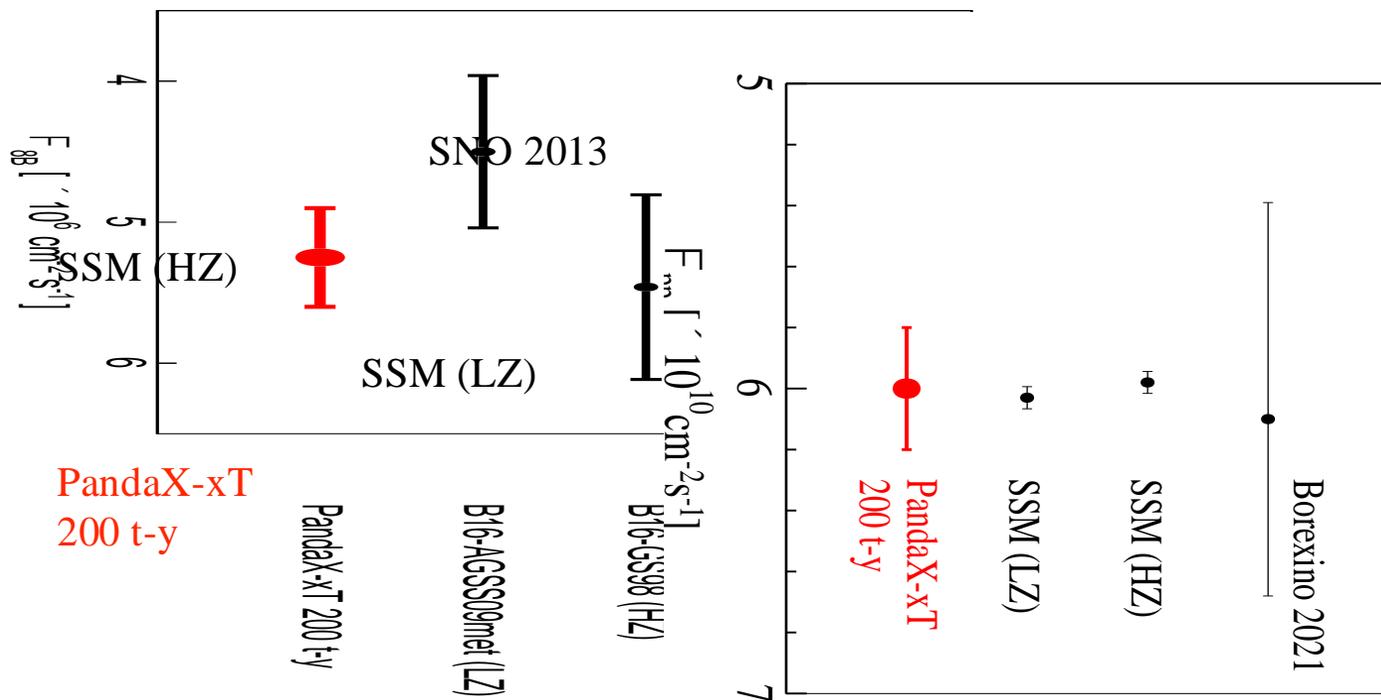


R. Essig/Stony Brook University; APS/Carin Cain

未来趋势

- 暗物质与双贝塔衰变的融合交叉
 - 共同的探测器技术
 - 一致的大体量诉求
 - 类似的低本底挑战
- 探测器做大、做精
 - 吨级、十吨级双贝塔衰变实验
 - 低质量暗物质探测百花齐放
- 物理目标的外延：探测中微子
 - 低本底、低能量阈值
 - 与现有更大型中微子探测器相辅相成

PandaX-xT预期中微子物理结果



arXiv:2402.03596

总结

- 暗物质直接探测与双贝塔衰变实验试图解决天体粒子物理的核心问题，是深地实验的两颗明珠
- 高性能、低本底探测器开辟新的窗口
 - 更大型的多物理目标探测器
(科学技术化)
 - 更精巧的新型探测器
(技术科学化)

