2021中国粒子物理战略研讨会

非加速器方向

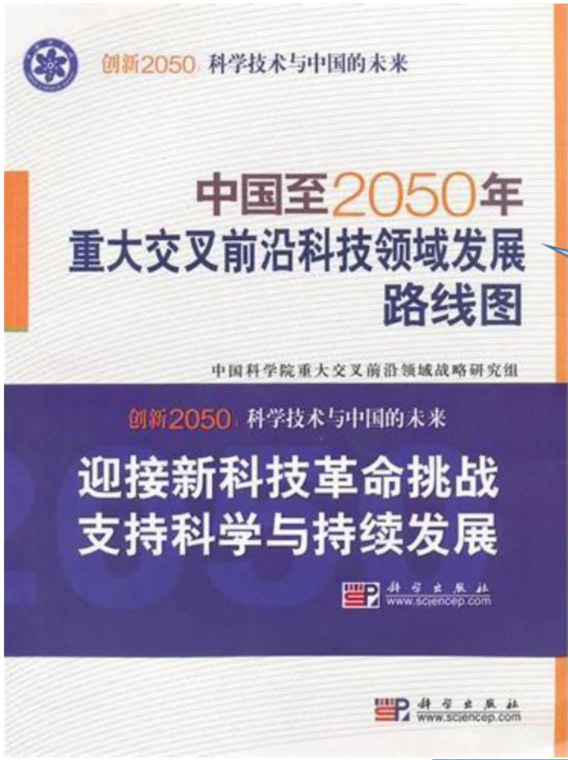
暗物质研究

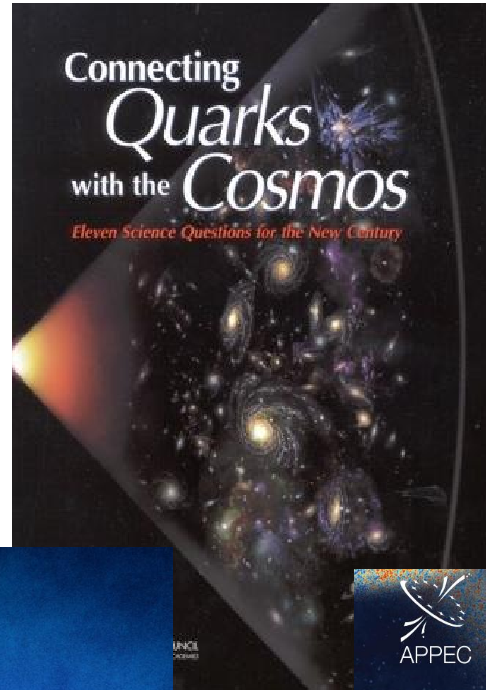
清华大学

岳骞

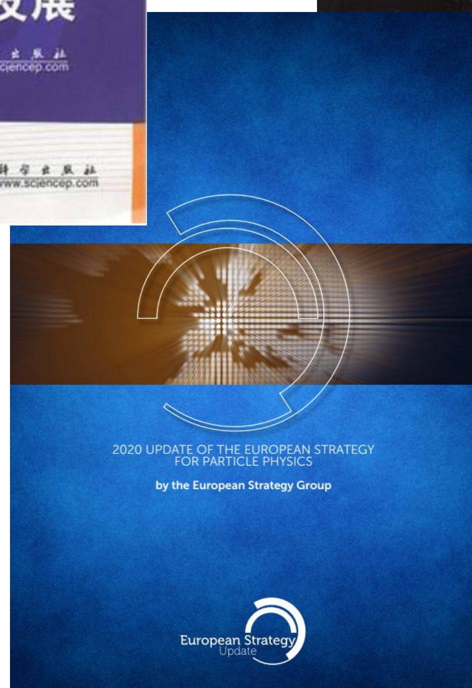
2021.10.12

物理学重大前沿问题


创新2050 科学技术与中国的未来
中国至2050年
重大交叉前沿科技领域发展
路线图
中国科学院重大交叉前沿领域战略研究组
创新2050 科学技术与中国的未来
迎接新科技革命挑战
支持科学与持续发展
科学出版社
www.sciencep.com


Connecting
Quarks
with the Cosmos
Eleven Science Questions for the New Century


Building for Discovery
Strategic Plan for U.S. Particle Physics in the Global Context
May 2014

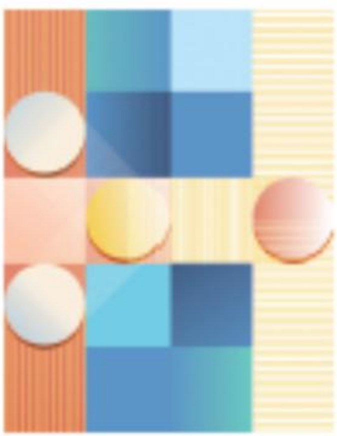

2020 UPDATE OF THE EUROPEAN STRATEGY
FOR PARTICLE PHYSICS
by the European Strategy Group
European Strategy
Update


APPEC
European Astroparticle
Physics Strategy
2017-2026

US P5 report

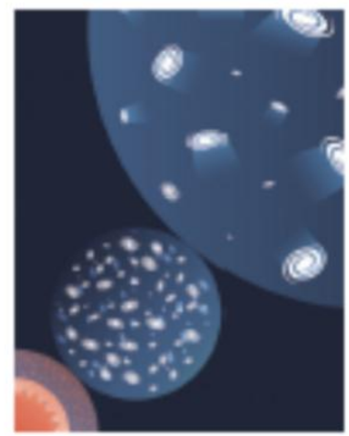
Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:

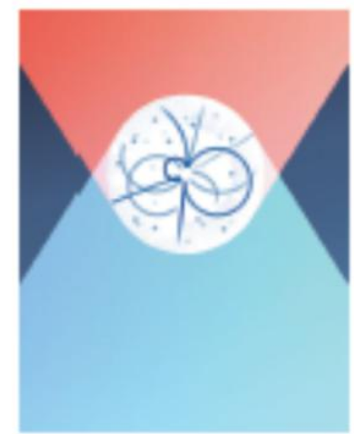
- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles


Higgs boson


Neutrino mass


Dark matter


Cosmic acceleration

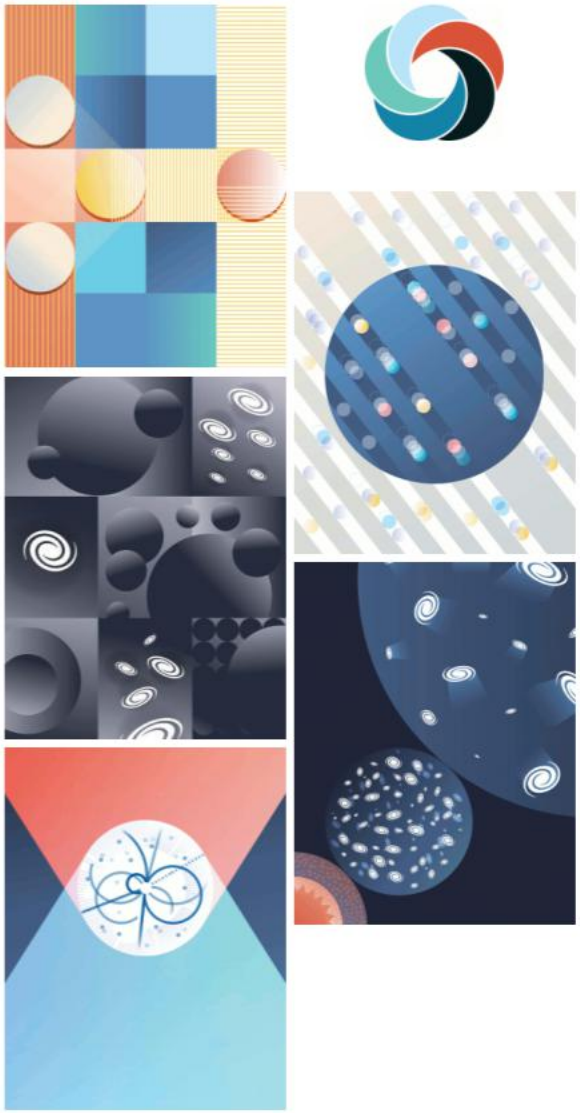

Explore the unknown

P5: Science Drivers of Particle Physics

P5 distilled the 11 groups of physics questions from Snowmass into 5 compelling lines of inquiry that show great promise for discovery over the next 10 to 20 years:

- Use the **Higgs boson** as a new tool for discovery. **2013*
- Pursue the physics associated with **neutrino mass.** **2015*
- Identify the new physics of **dark matter.**
- Understand **cosmic acceleration**: dark energy and inflation. **2011*
- **Explore the unknown**: new particles, interactions, and physical principles

** Since 2011, three of the five science drivers have been lines of inquiry recognized with Nobel Prizes*



欧洲粒子物理与粒子天体物理战略

< 首页 | 新闻

2020欧洲粒子物理战略发布

中科院高能所
一年前 中科院高能物理研究所官...

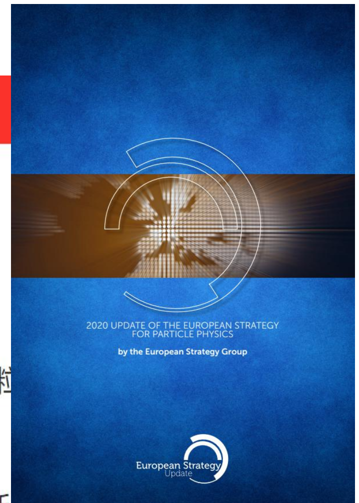
6月19日，欧洲核子中心（CERN）理事会全票通过欧洲粒
全球高能物理的未来发展具有重要而深远的影响。

这份欧洲粒子物理战略确定了先建设一台正负电子希格斯（Higgs）工厂，再建设一台高能质子对撞机的路线图。这和我国高能物理学界倡议的环形正负电子对撞机-超级质子对撞机（CEPC-SPPC）设想是高度一致的。该战略聚焦的几项关键技术在CEPC-SPPC项目中也已经全面展开，部分已取得显著进展。同时，欧洲粒子物理战略就未来可能的、更为深入开放的国际合作也表明了态度。

该战略主要内容包括：

01

粒子物理要探索基本物理规律的奥秘，包括暗物质、正反物质不对称、中微子质量等，其答案隐藏在时空最微小的结构中。Higgs粒子是与这些根本问题相关的基本粒子，基于正负电子对撞机的Higgs工厂可精确测量Higgs粒子性质，是"优先级最高的未来对撞机项目",并且未来期望建设能量尽可能高的质子对撞机，为上述问题提供答案。

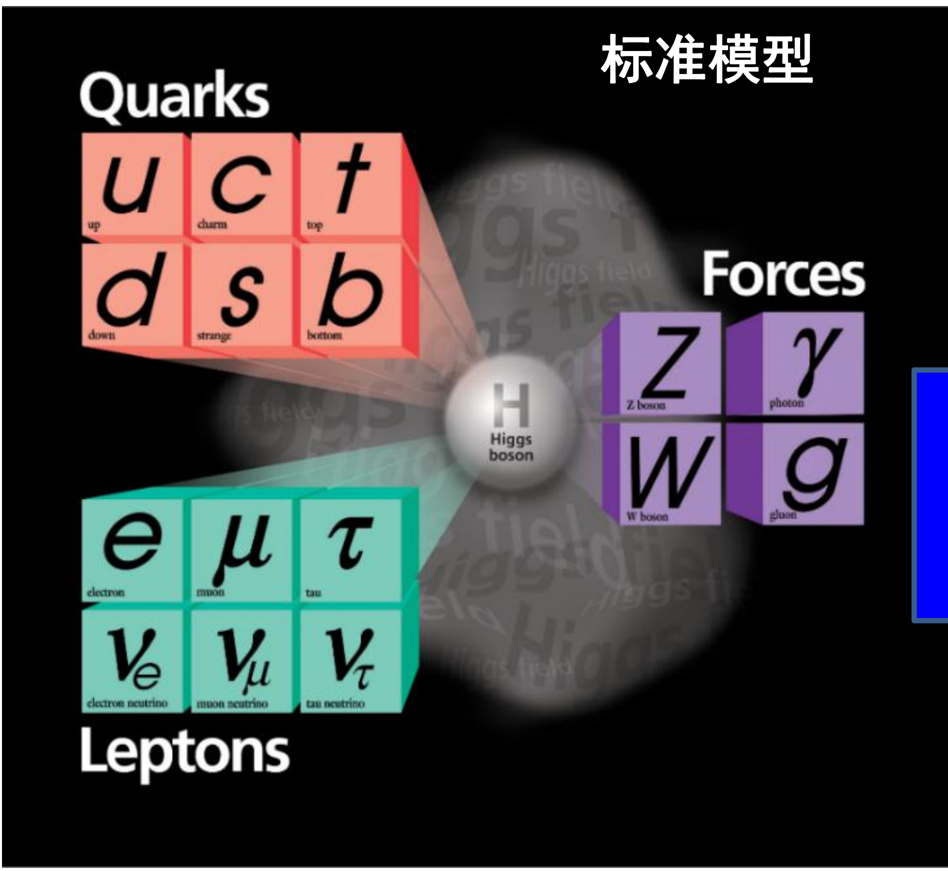


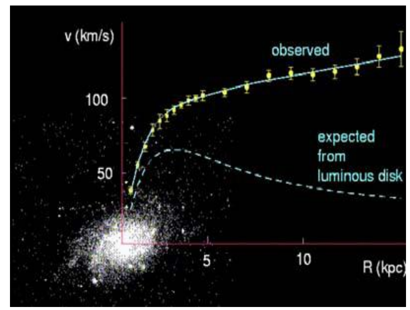
5. Dark Matter

Elucidating the nature of Dark Matter is a key priority at the leading tip of astroparticle physics. Among the plethora of subatomic particles proposed to explain the Dark Matter content of our Universe, one category stands out: the Weakly Interacting Massive Particle (WIMP). WIMPs arise naturally, for instance, in supersymmetric extensions of the Standard Model of particle physics.

粒子物理学标准模型和暗物质问题

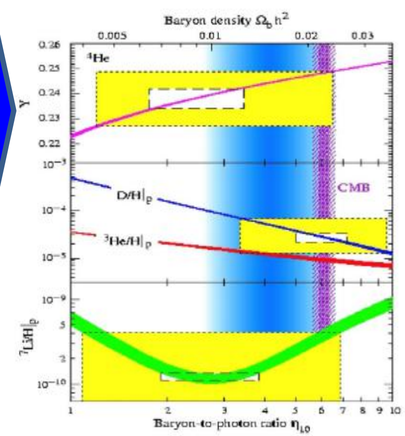
- 暗物质问题存在已近百年，和**新物理**紧密关联。



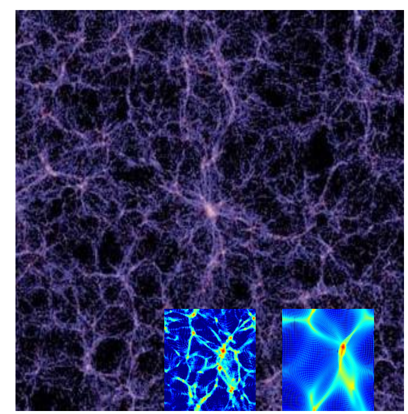


星系旋转曲线

子弹星云

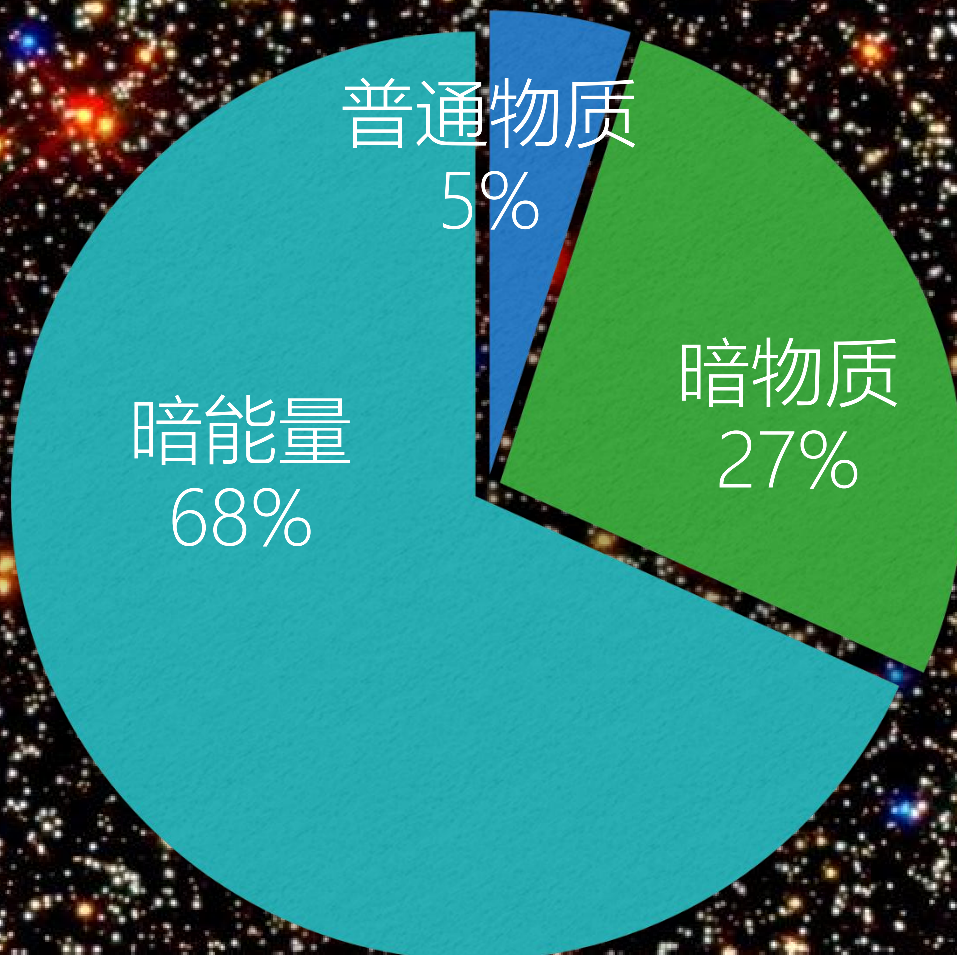


大爆炸核合成

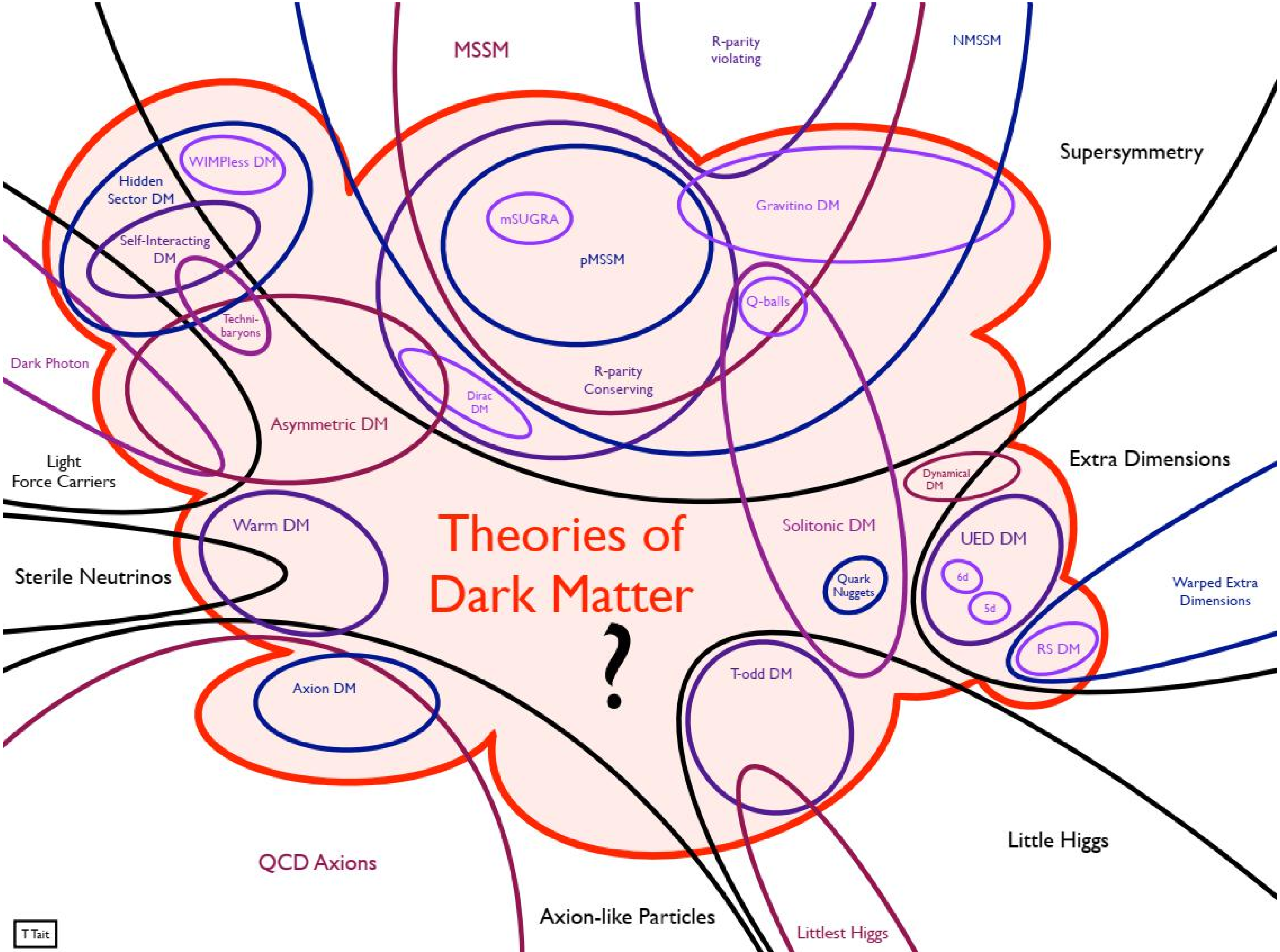


宇宙大尺度结构

宇宙构成



暗物质理论研究


MSSM
R-parity violating
NMSSM
Supersymmetry
Hidden Sector DM
WIMPless DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
6d
5d
Sterile Neutrinos
Quark Nuggets
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

暗物质候选者

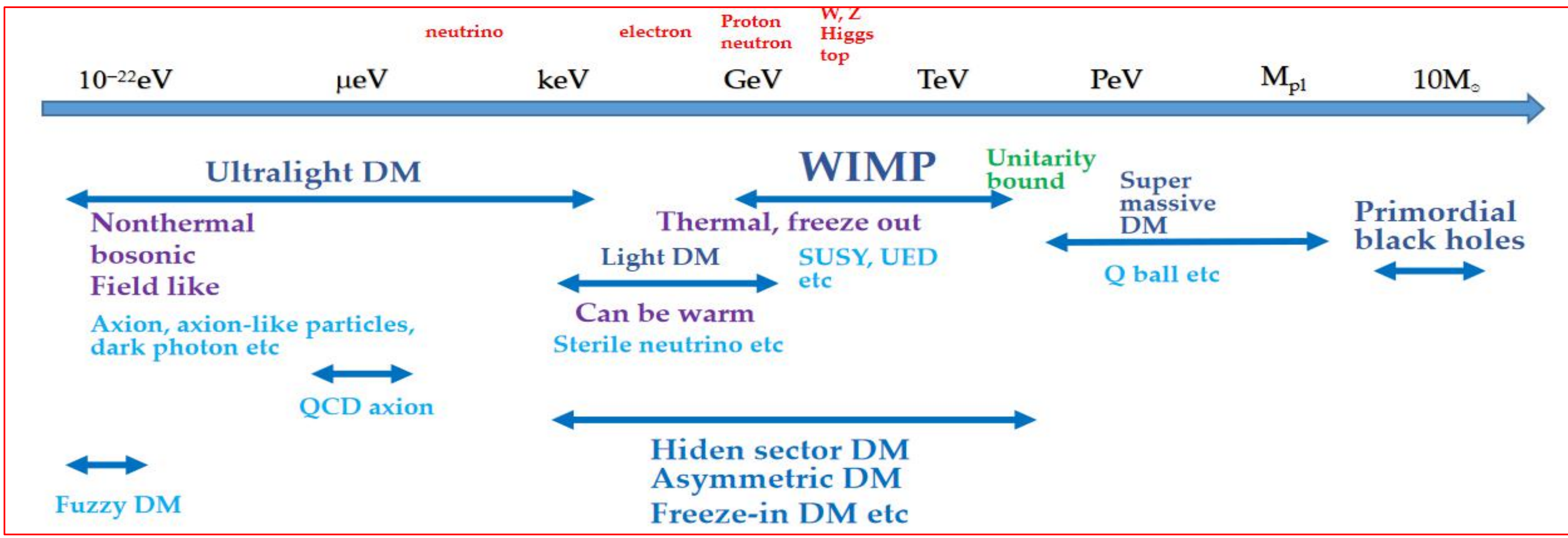
Dark Matter 基本特点

1. 有质量（参与引力作用）
2. 稳定粒子（寿命长于宇宙年龄）
3. 不带电荷（基本无电磁相互作用）
4. 非重子物质（不由夸克组成）
5. 非相对论性运动（冷暗物质）

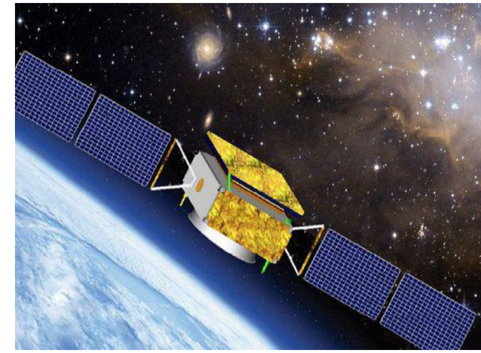
DM 非任何已知基本粒子 ！

- 原初黑洞： 10^{40} -10^{55} GeV
- 超重暗物质WIMPzilla：10^{15} GeV
- 常规 WIMPs ： 1 GeV- 1 TeV
- 轻DM 粒子 (keV)　Sterile neutrinos
- 极轻暗物质 (10^{-10}-10^{-22} eV)

  Axion and Axion-like particles，　Fuzzy DM



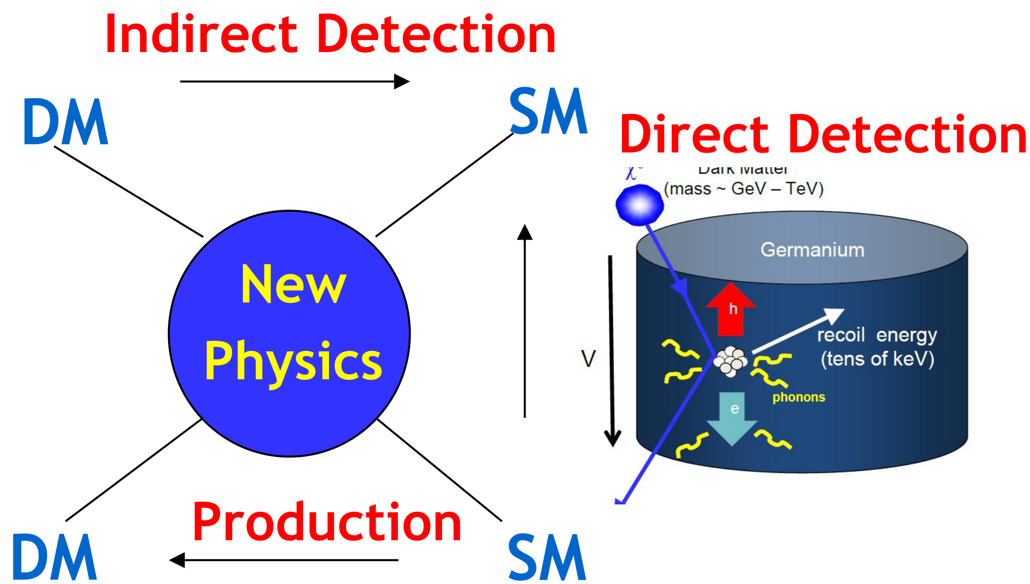
暗物质实验探测



主要探测目标：

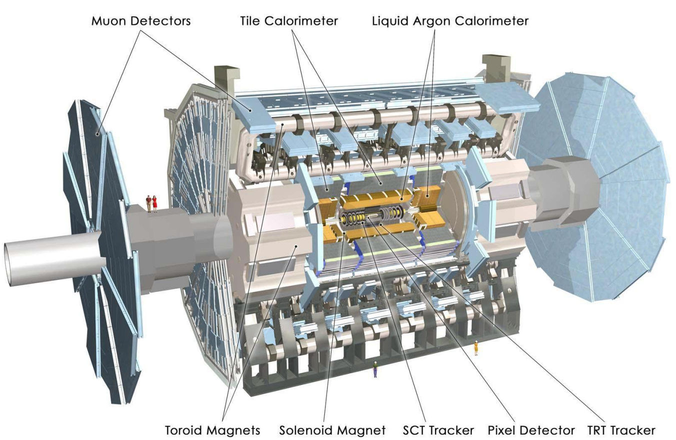
- WIMP；
- Sub-GeV DM；
- Axion and ALP；
- Dark photon；
- ……

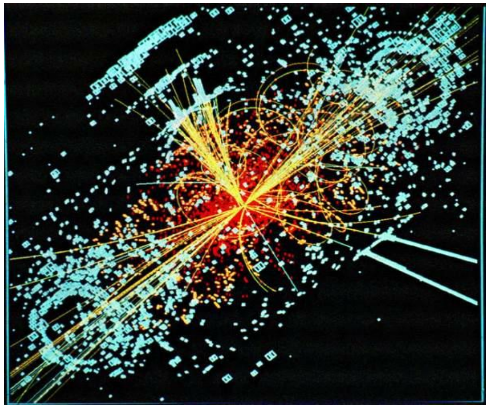
- 研究方法

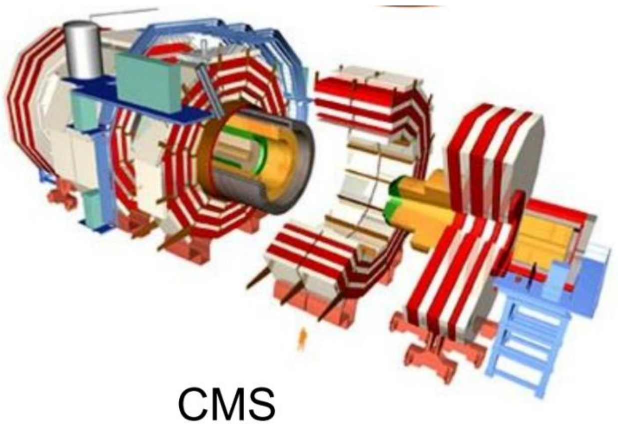


暗物质加速器实验


ALICE
CMS
ATLAS
LHCb

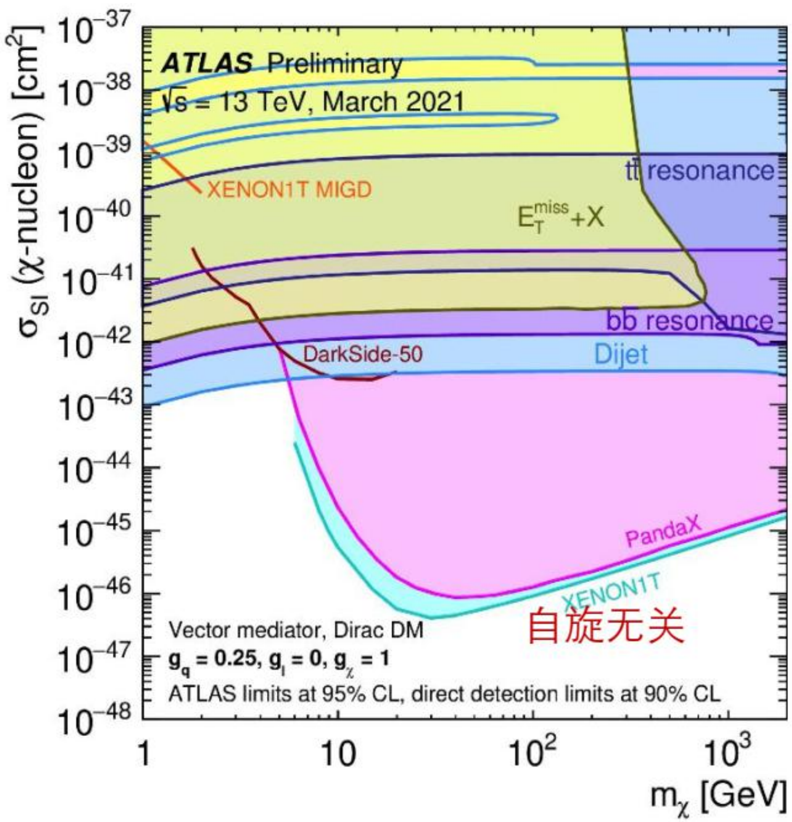

Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

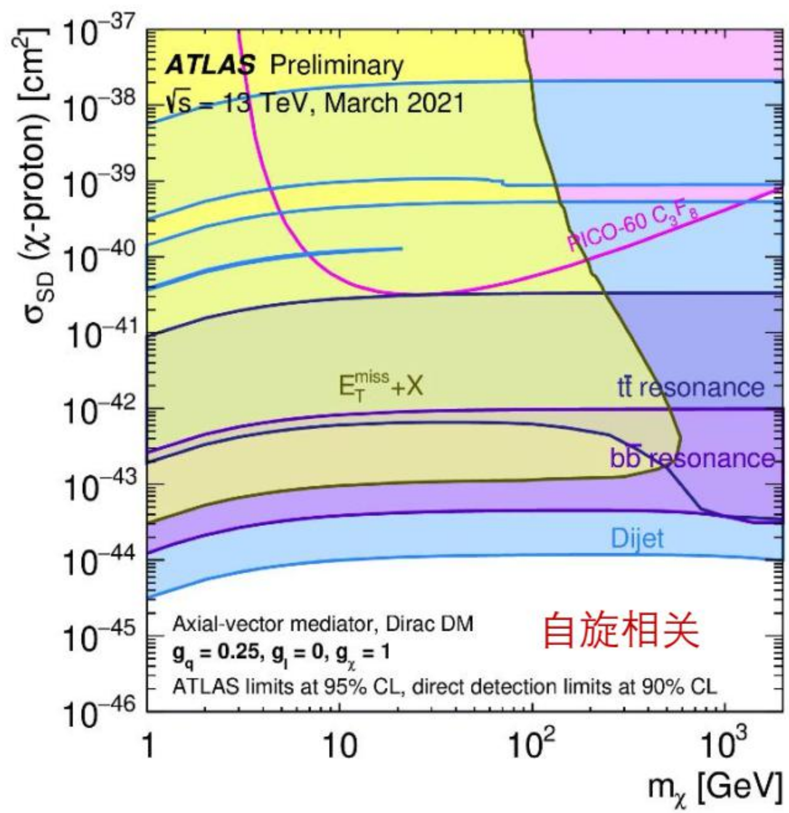



CMS

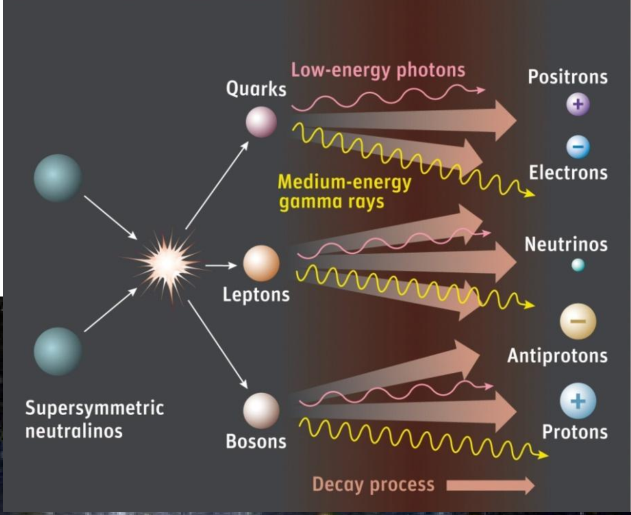
暗物质加速器实验

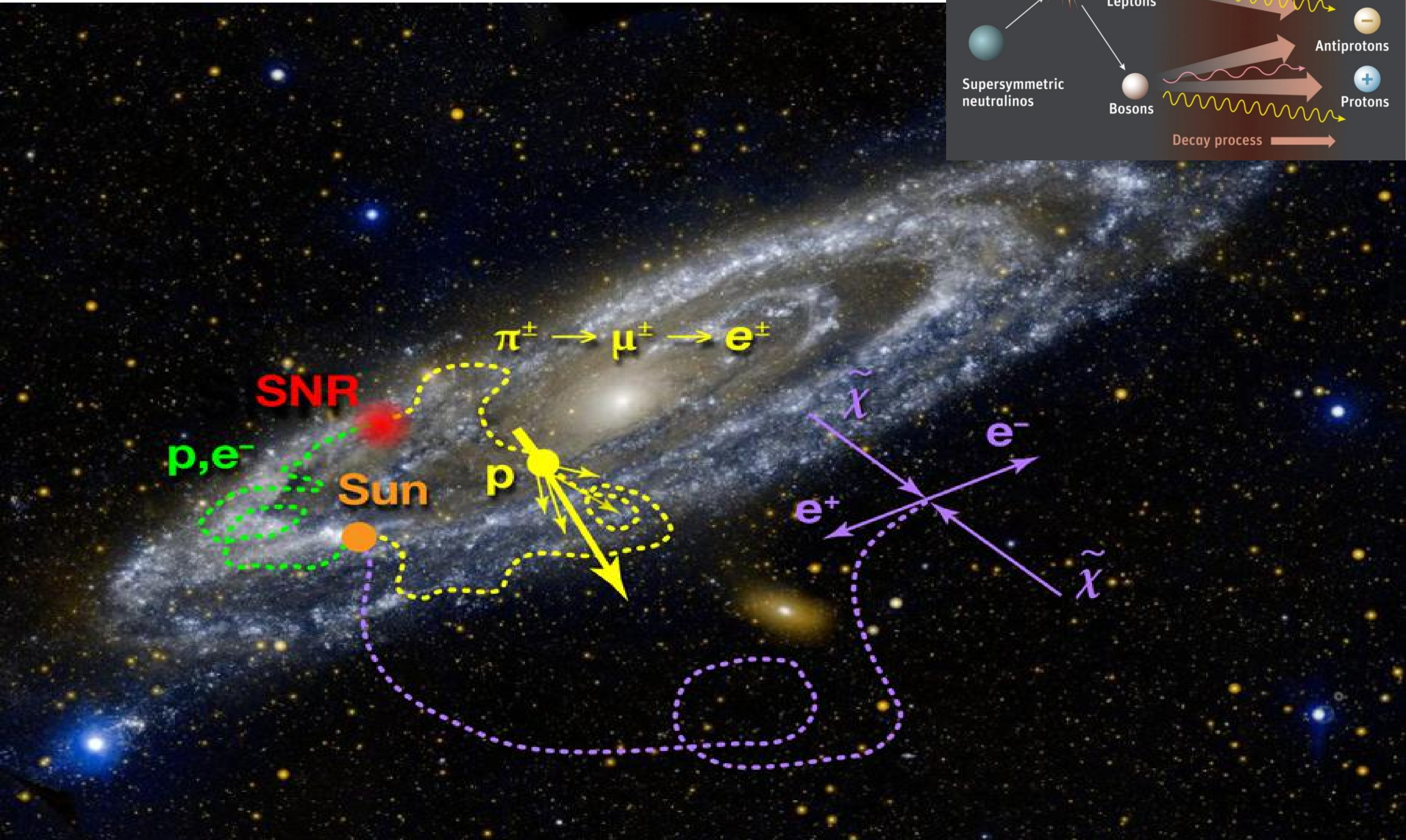
- 研究高能粒子对撞过程中可能的暗物质产生过程；
- EFT理论模型，寻找Mediator等，研究暗物质粒子特性。



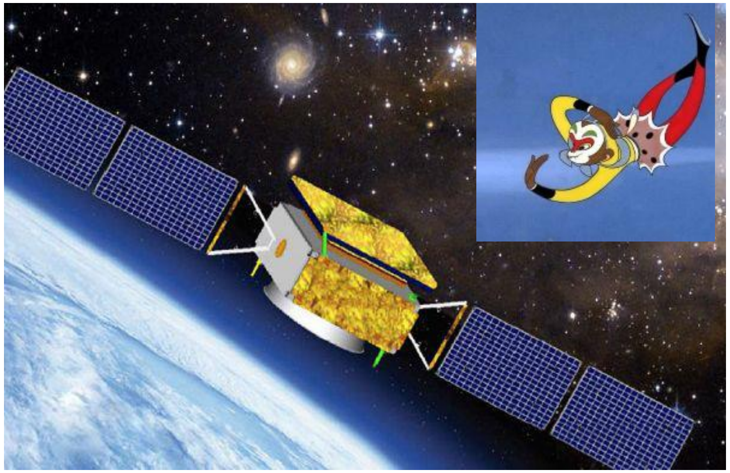


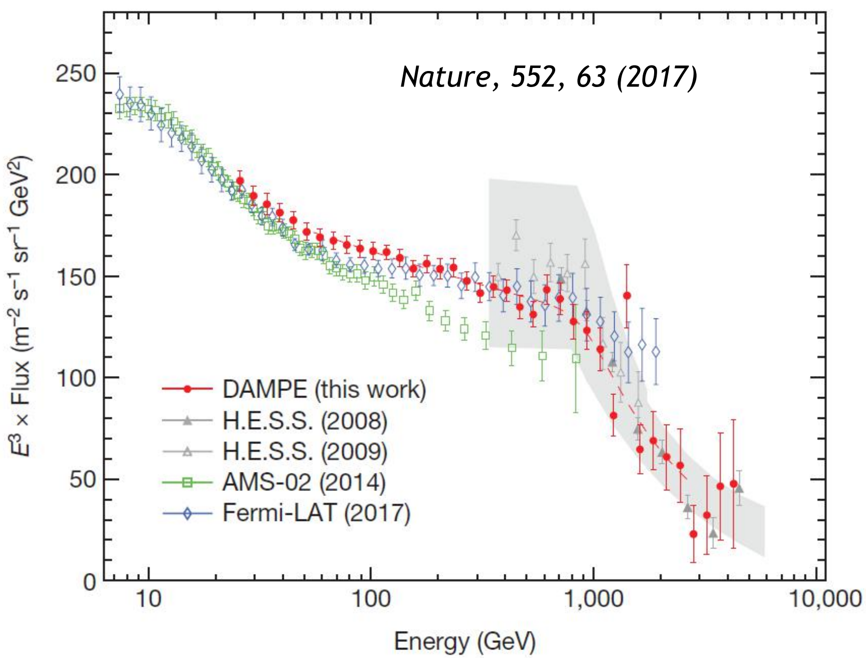
暗物质间接探测


Low-energy photons
Quarks
Positrons
Electrons
Medium-energy gamma rays
Neutrinos
Leptons
Antiprotons
Supersymmetric neutralinos
Bosons
Protons
Decay process


$\pi^{\pm} \longrightarrow \mu^{\pm} \longrightarrow e^{\pm}$
SNR
p,e⁻
Sun
p
$\tilde{\chi}$
e⁻
e⁺
$\tilde{\chi}$

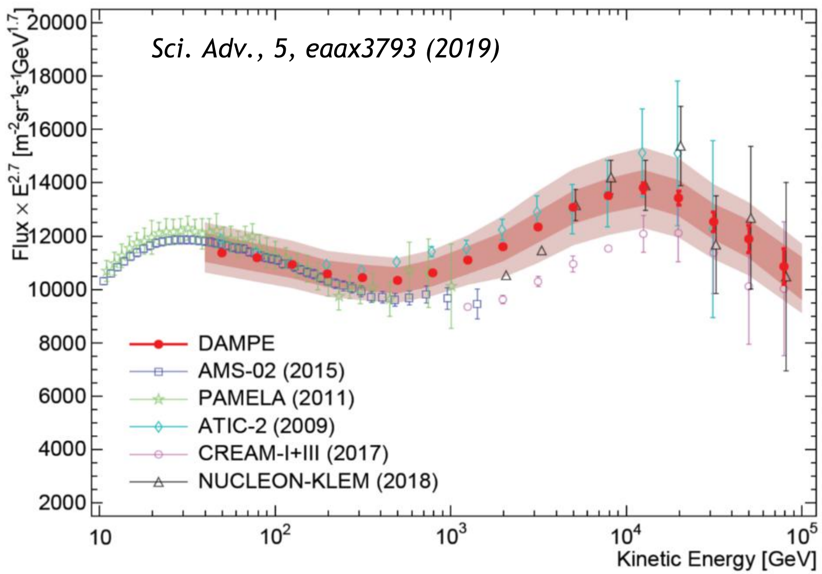
暗物质间接探测——DAMPE



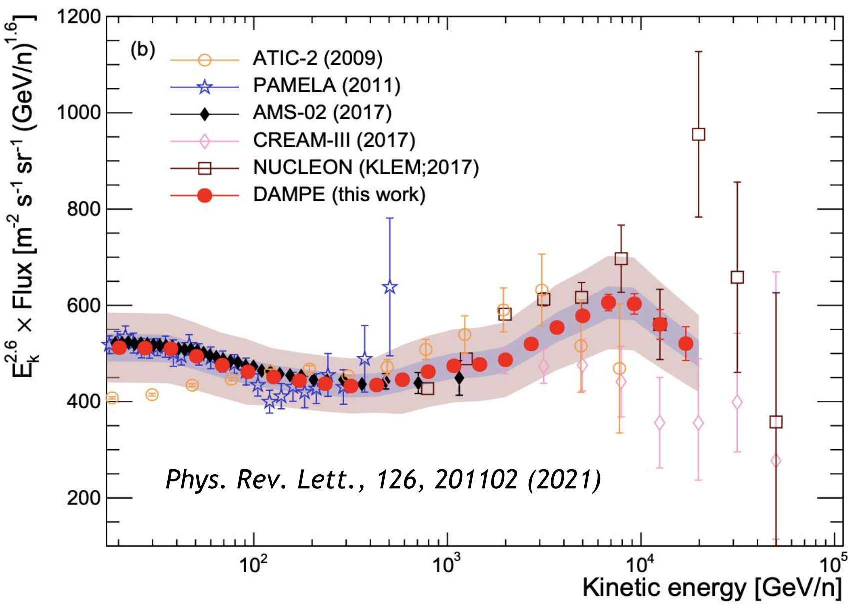


- ✧ 获得：最精确的TeV宇宙线正负电子能谱；
- ✧ TeV拐折：国际上第一次直接探测到；对于理论家判断sub-TeV的正电子超出是否来自于暗物质起源有关键意义。
- ✧ 1.4TeV峰：如果真实，那么要求源离地球较近，而且加速出的电子宇宙线基本上居于单能态。这表明宇宙中存在非常奇特的高能加速器。需要更多的数据量来确认真实与否。

暗物质间接探测——DAMPE

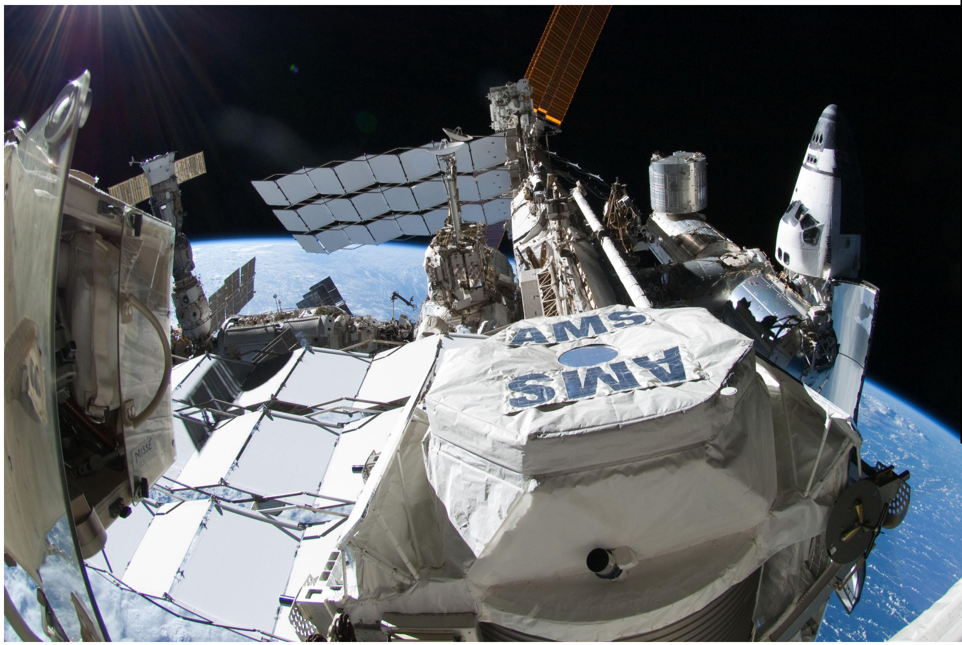


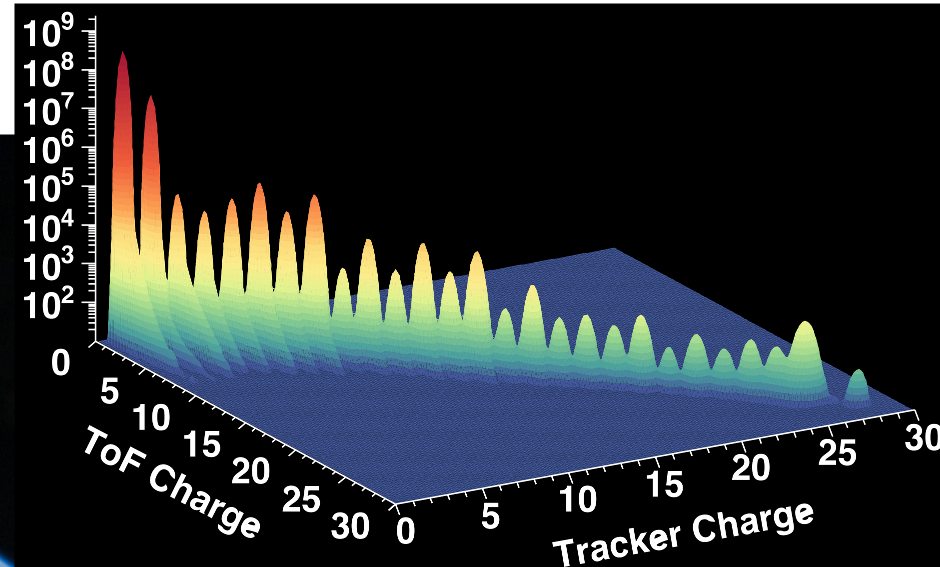
✧ 质子能谱测量结果，高置信度发现14TeV处能谱拐折；获得了最精确的TeV宇宙线正负电子能谱。

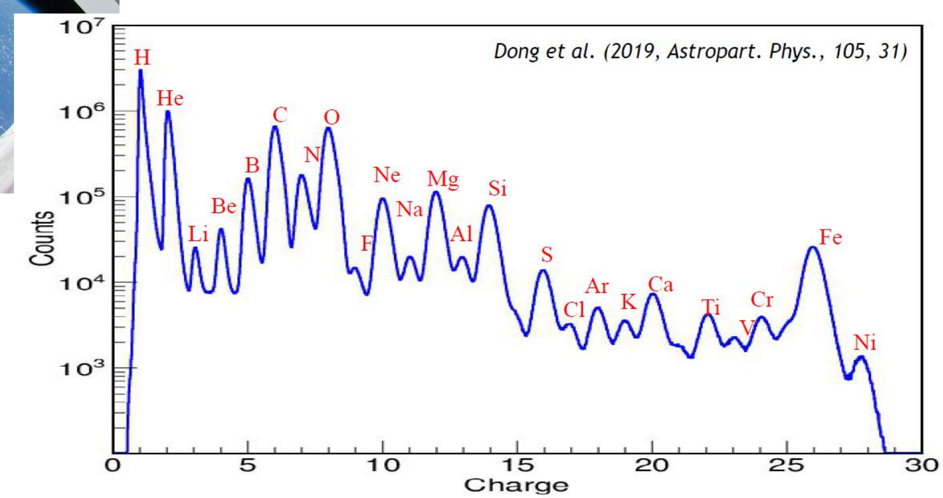


✧ DAMPE的氦核结果确认了其能谱在几百GeV/n处的变硬特征，发现了在~34TeV处的能谱变软结构。其起源可能与质子谱具有相同物理过程。

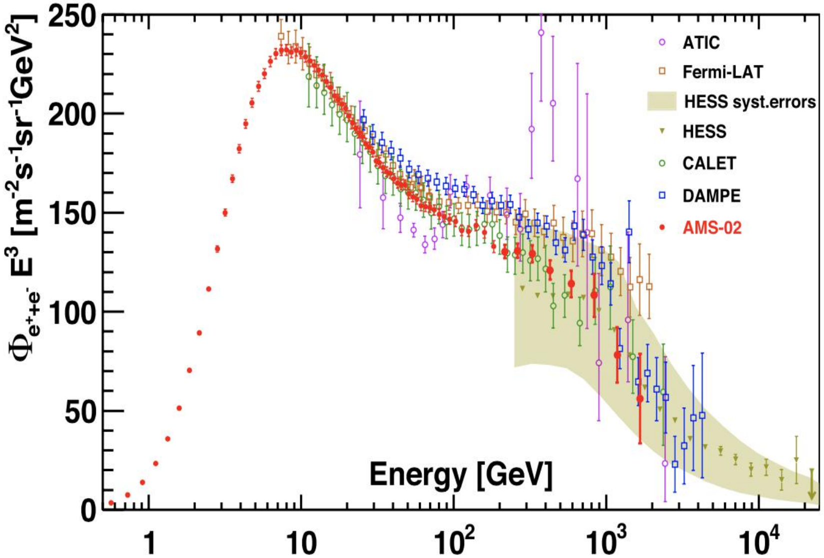
暗物质间接探测——AMS


AMS

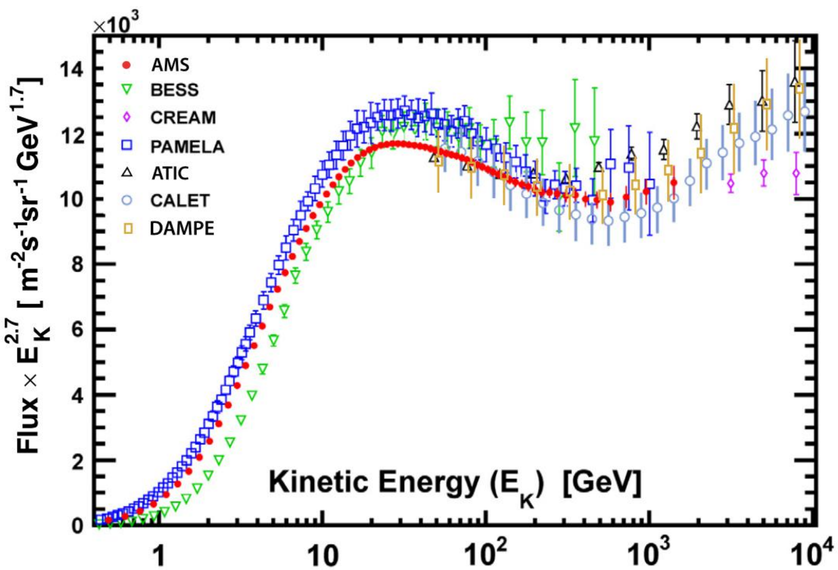

10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
0
5
10
15
20
25
30
ToF Charge
0
5
10
15
20
25
30
Tracker Charge


Dong et al. (2019, Astropart. Phys., 105, 31)
10^7
10^6
10^5
10^4
10^3
Counts
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
S
Cl
Ar
K
Ca
Ti
V
Cr
Fe
Ni
0
5
10
15
20
25
30
Charge

暗物质间接探测——AMS



- ✧ Fermi-LAT2017没有发现拐折
- ✧ CALET2018没有发现拐折
- ✧ AMS-02合作组2021年在～0.9TeV处发现电子能谱拐折

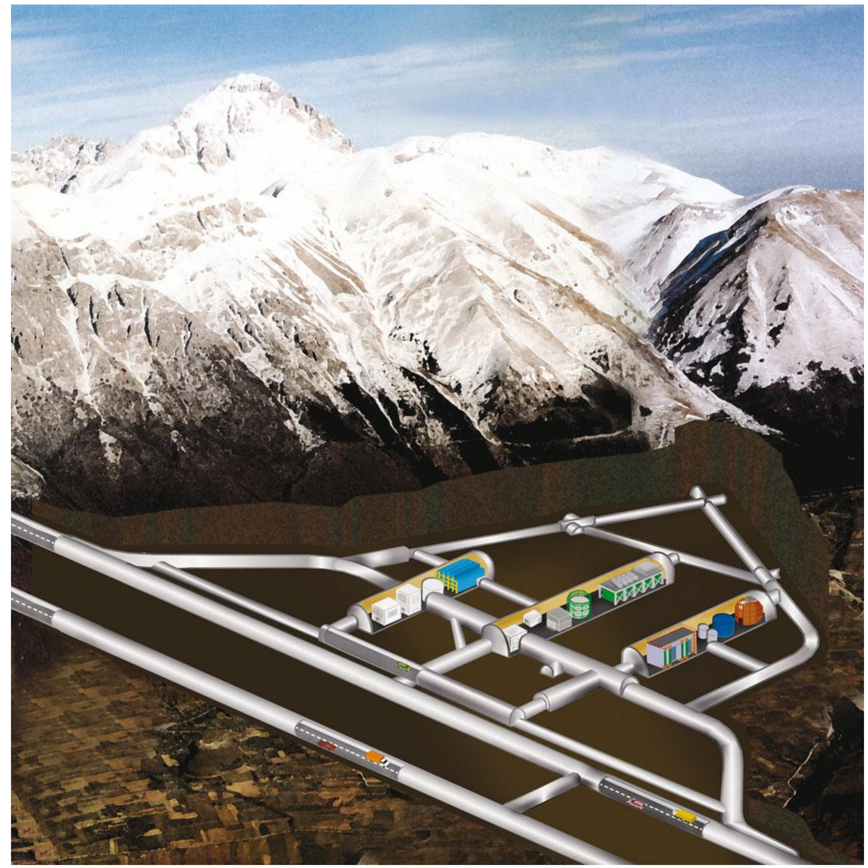


- ✧ 2021 Phys. Rep. 894, 1: AMS-02合作组最新质子能谱测量结果与DAMPE一致。

国际暗物质直接探测实验

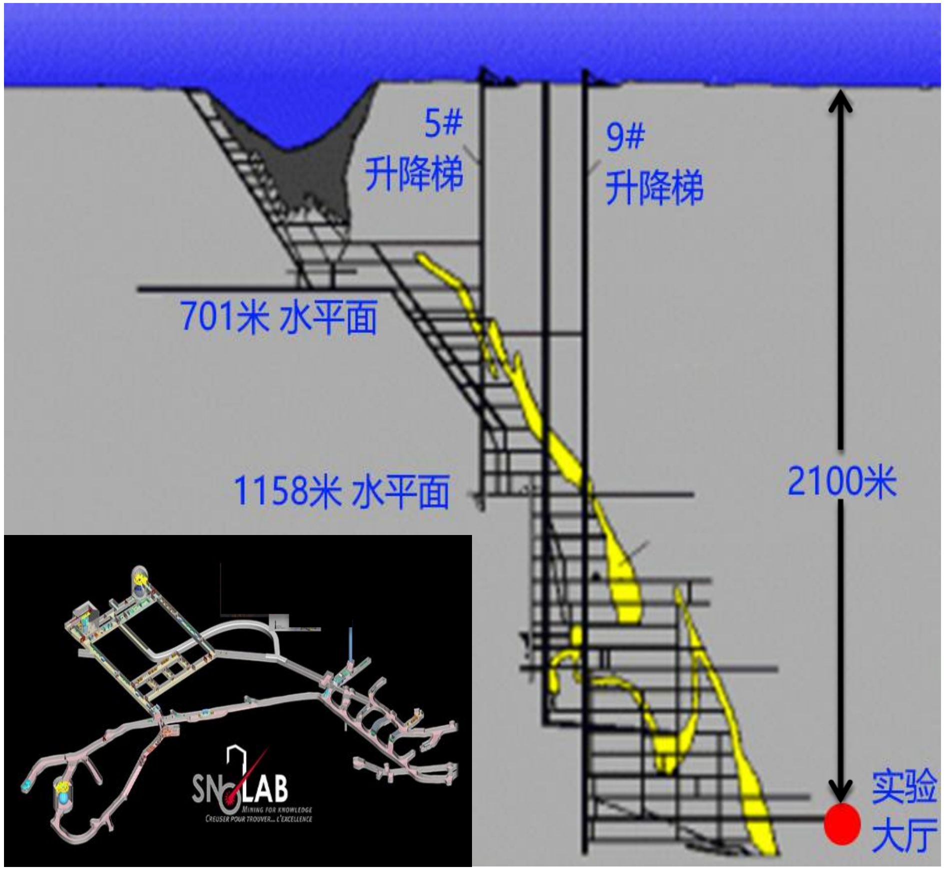
意大利格兰萨索地下实验室

- CJPL建设之前国际最大的地下实验室。
- 空间18万立方米，岩石覆盖厚度1400米，隧道型；
- 主要开展的物理实验：
  - 暗物质: XENON、CRESST等
  - 双贝塔衰变: GERDA、CUORE 等
  - 太阳中微子: Borexino等
  - ……



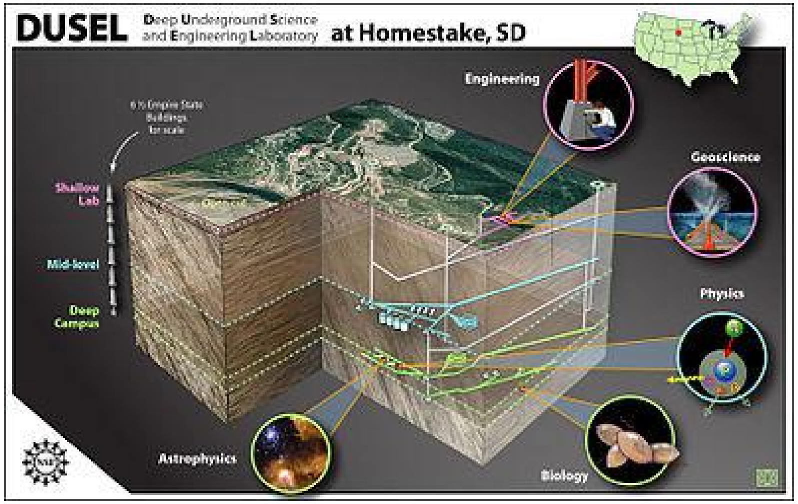
加拿大斯诺地下实验室

- CJPL建设之前世界最深的地下实验室；
- 深度2100米，空间5万立方米，矿井型；
- 主要开展实验：
  - 暗物质:SuperCDMS…
  - 双贝塔: nEXO
  - 中微子: SNO+、
  - 超新星中微子: HALO
  - 深部岩石地震信号: POLARIS
  - ……

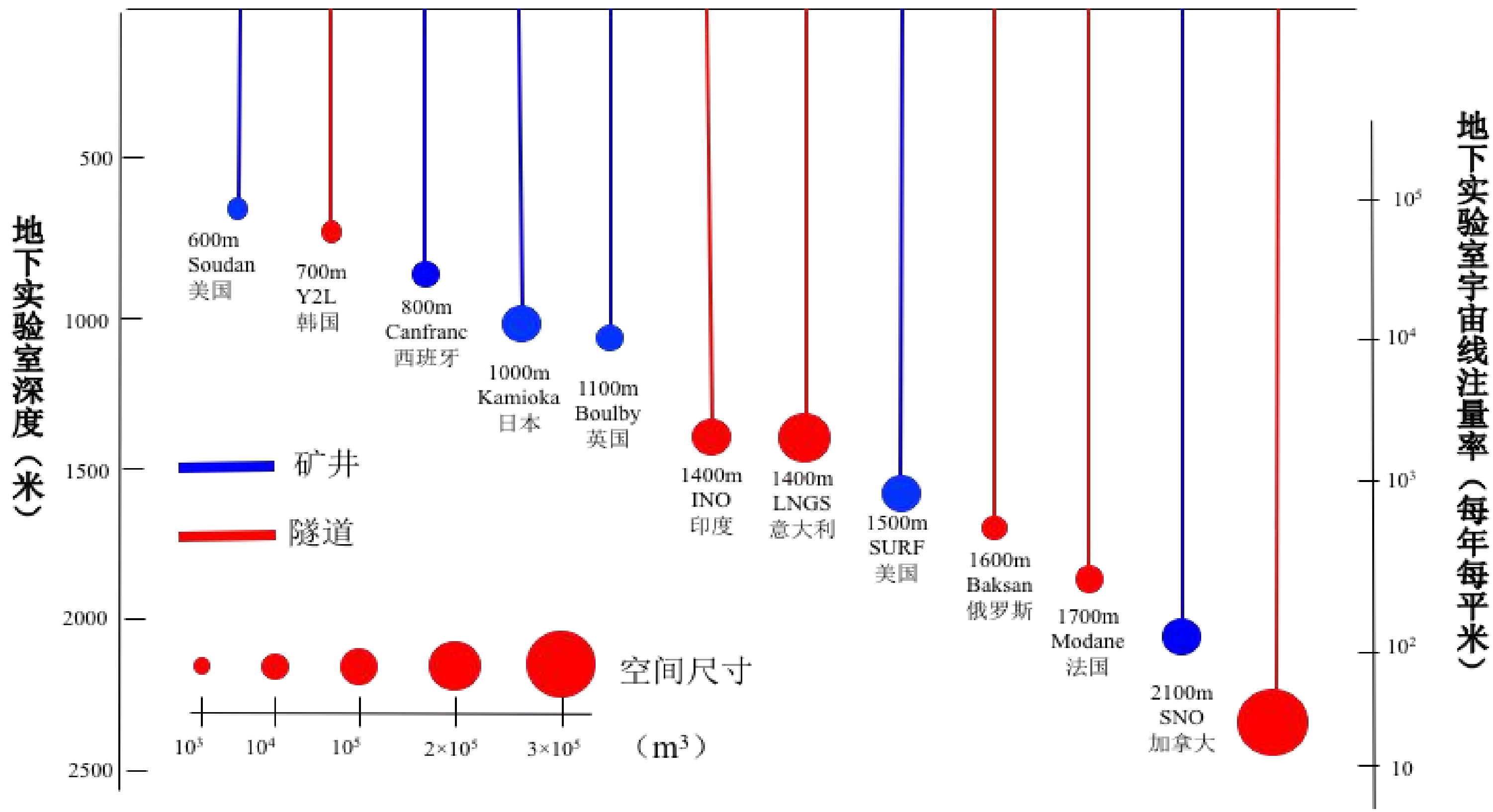


美国圣福德（Sanford）地下实验室

- 深度1500米，空间2万立方米，矿井型；
- 主要开展实验：
  - 暗物质:LZ
  - 双贝塔:Majorana
  - 中微子：DUNE
- 曾计划6.4亿美元建设DUSEL深地实验室，08年计划取消；
- 目前1500m深度建设长基线中微子探测系统。



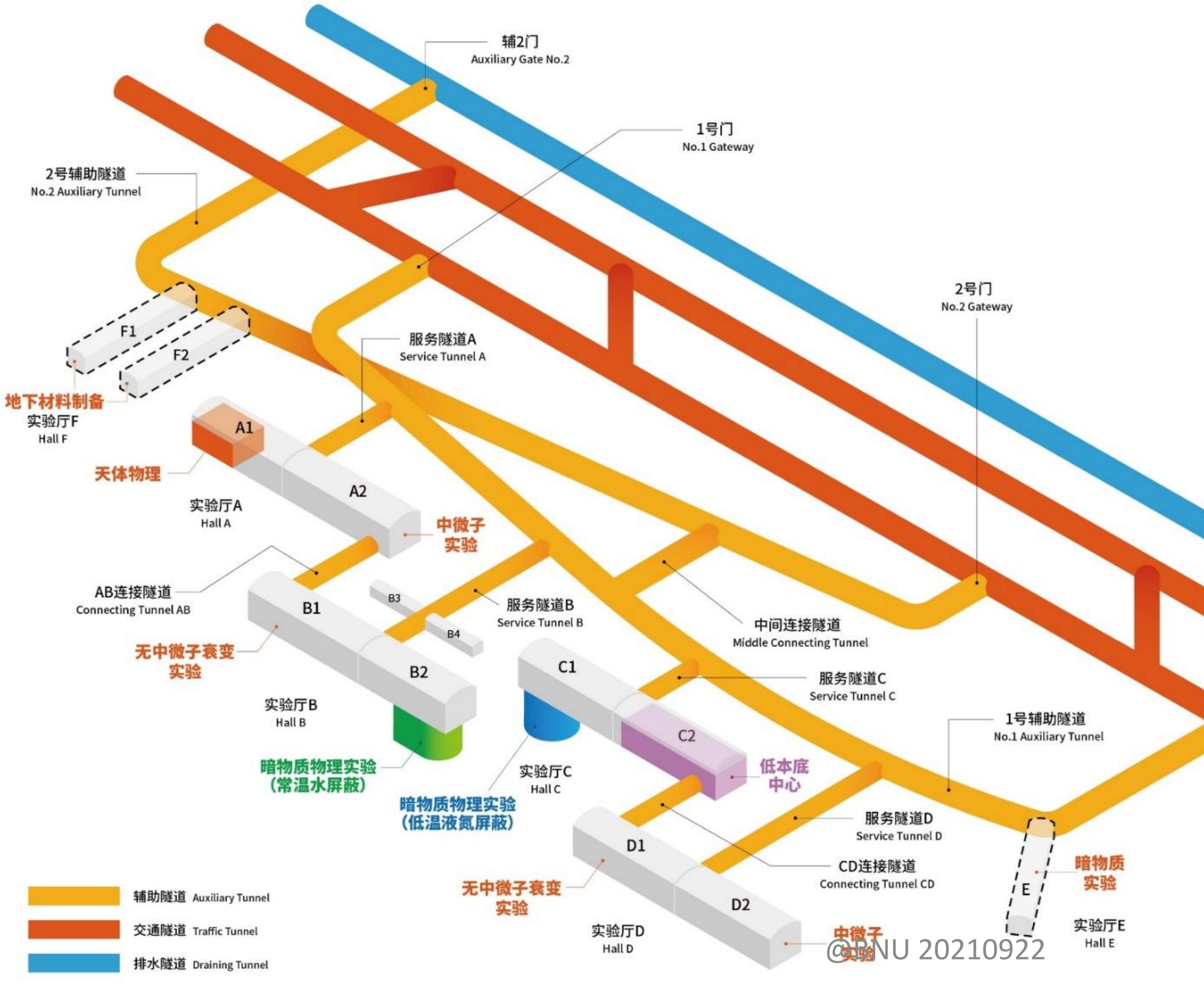
深地实验平台



- 岩石覆盖厚度超过2km的，称为**极深地下实验室，**
- 两个极深地下实验室：**中国锦屏和加拿大SNO；**
- **CJPL为科学家提供了一流的深地实验平台。**

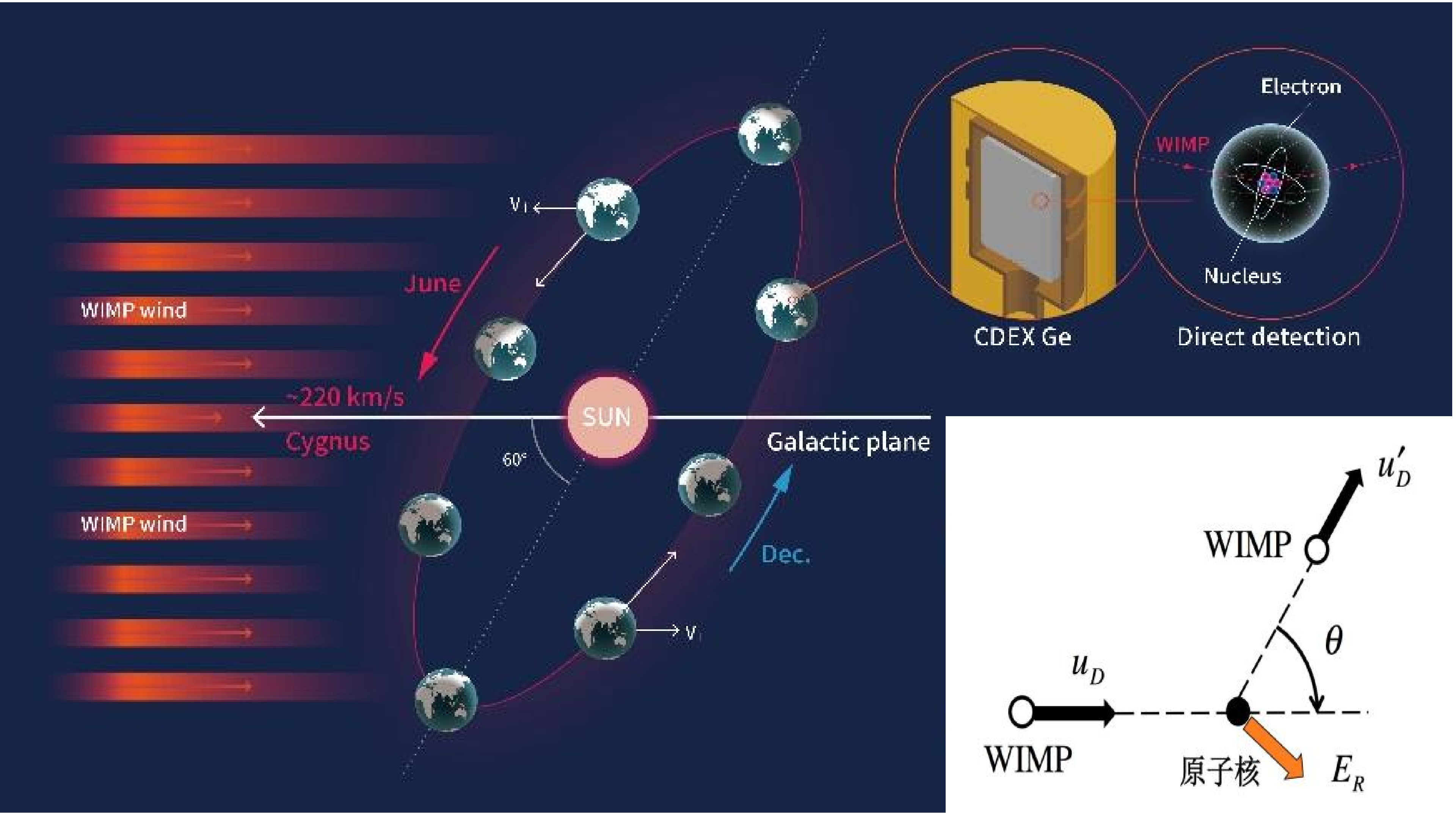
十三五国家重大科技基础设施

- 2020年，CJPL-II项目启动，8个14m*14m*65m实验厅，~30万立方米。

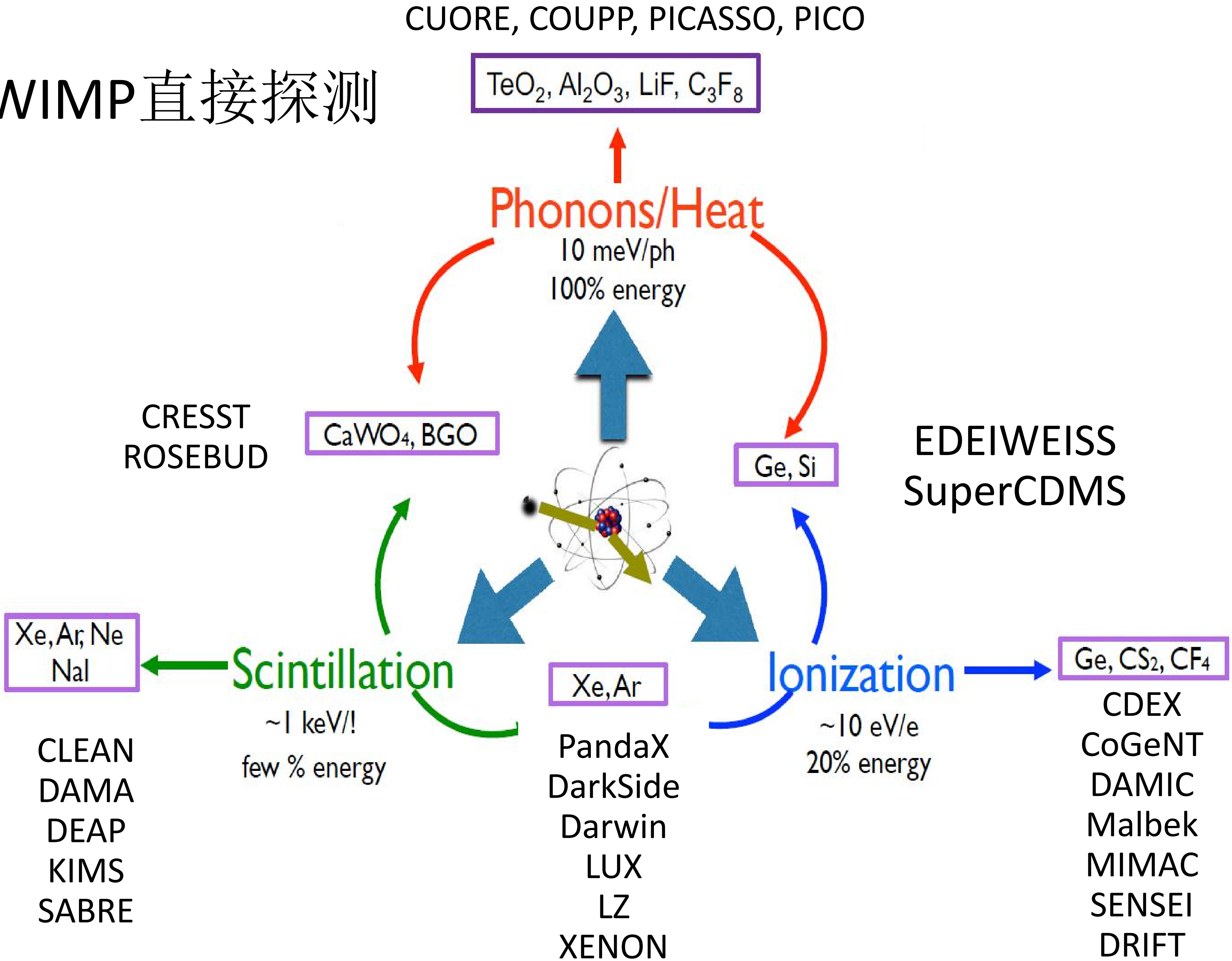


WIMP直接探测

✧ 测量反冲核信号、电子信号等，年度调制、日调制等特征信号！

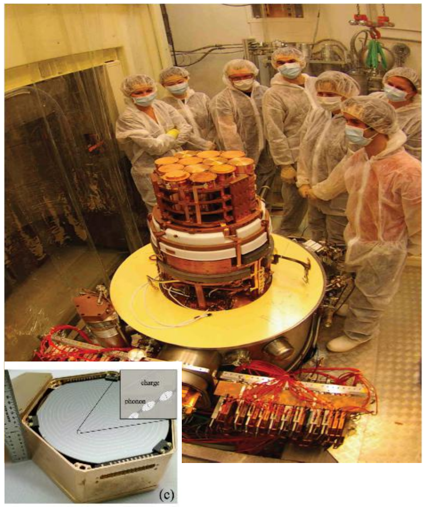


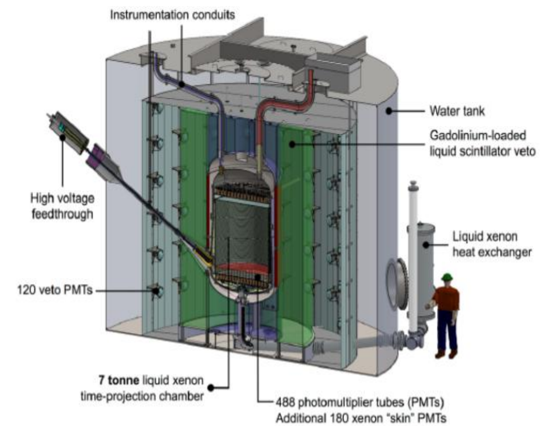
WIMP直接探测


CUORE, COUPP, PICASSO, PICO
TeO2, Al2O3, LiF, C3F8
Phonons/Heat
10 meV/ph
100% energy
CRESST
ROSEBUD
CaWO4, BGO
Ge, Si
EDEIWEISS
SuperCDMS
Xe, Ar, Ne
NaI
Scintillation
~1 keV/!
few % energy
Xe, Ar
Ionization
~10 eV/e
20% energy
Ge, CS2, CF4
CLEAN
DAMA
DEAP
KIMS
SABRE
PandaX
DarkSide
Darwin
LUX
LZ
XENON
CDEX
CoGeNT
DAMIC
Malbek
MIMAC
SENSEI
DRIFT

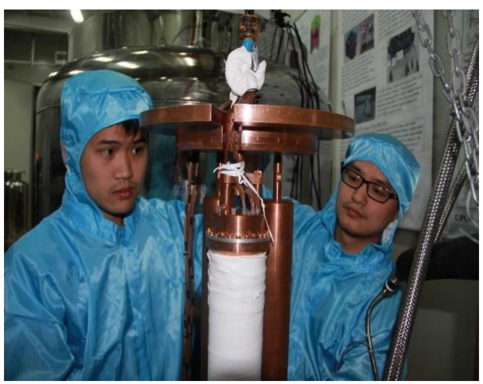
WIMP直接探测——中大型实验

国外



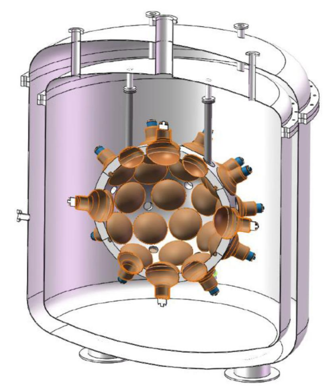


国内



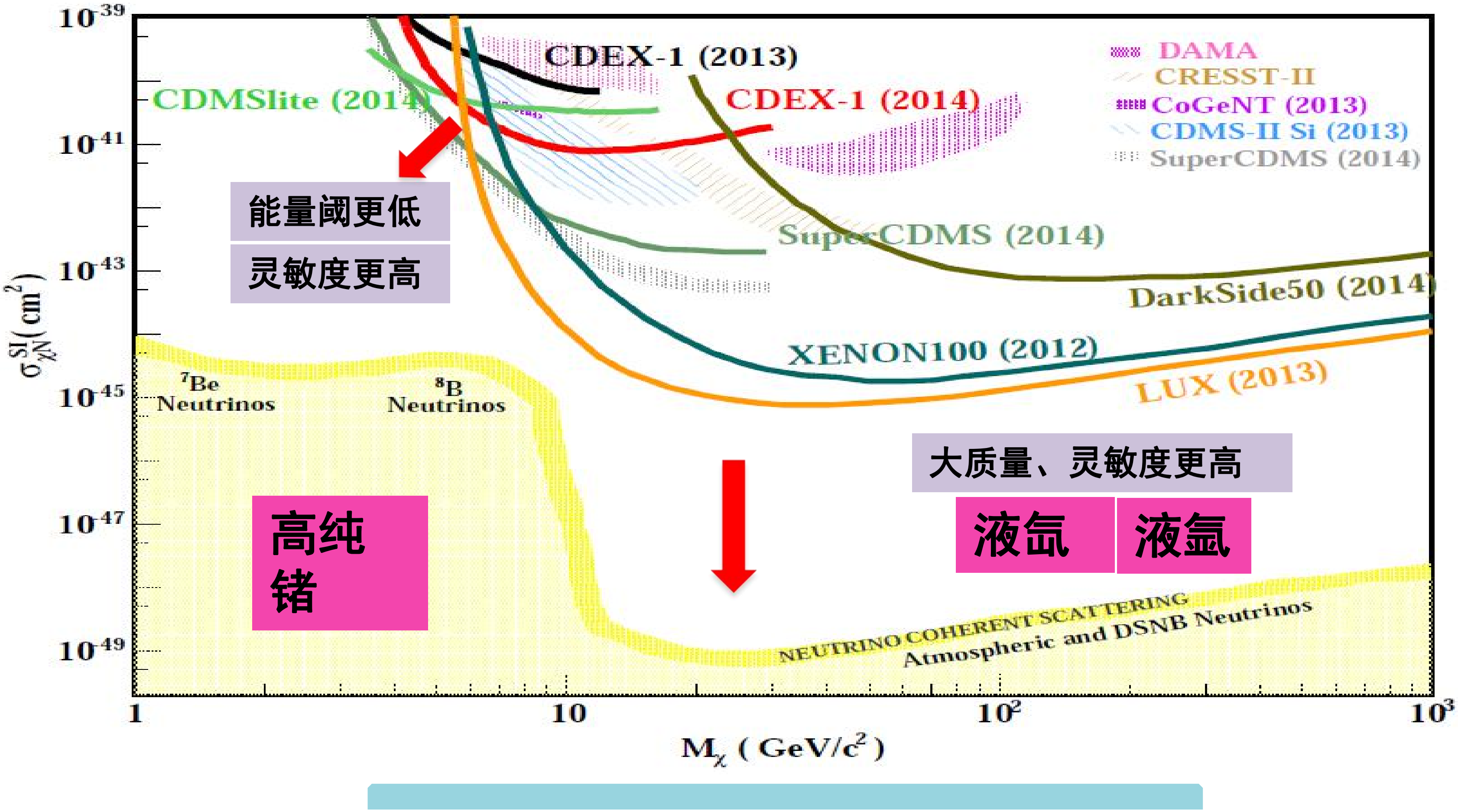
10GeV以下
轻质量区
锗——清华大学

10~500GeV
中重质量区
液氙——上交大



100~1000GeV
重质量区
液氩——高能所

深地暗物质直接探测实验发展趋势



暗物质直接探测实验发展趋势

- 探测GeV至MeV的轻暗物质，两个途径：

✓ 发展新技术，降低探测阈值：

--CDEX：小电容点电极、自放大；

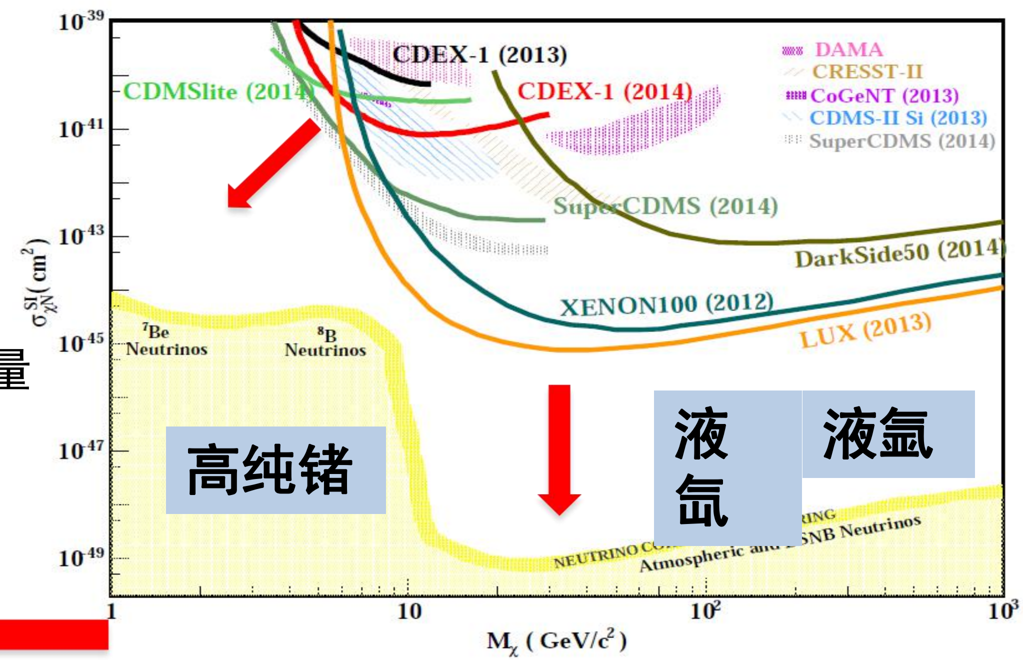
--SCDMS：声子放大；

--SENSEI:S-CCD单电子读出；

✓ 利用新的物理模型，在同样探测器能量阈值下探测更轻的暗物质粒子。

--Migdel效应；

--宇宙线加速；



暗物质直接探测国际形势

高纯锗轻质量暗物质探测：

- 中国“盘古”CDEX：10kg实验结束运行，在建50公斤；
- 美国SuperCDMS：9kg实验结束运行，在建50kg。

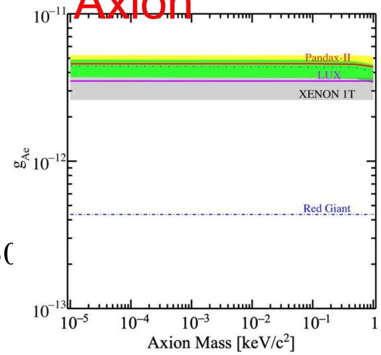
液氙/液氩重质量暗物质探测：

- 欧美XENONnT：6吨液氙测试运行；
- 美国LZ：7吨液氙测试运行；
- 欧美DarkSide：20吨液氩，2023年运行；
- 中国PandaX：4吨液氙测试运行；
- 中国液氩：吨级关键技术研究。

PandaX液氙实验

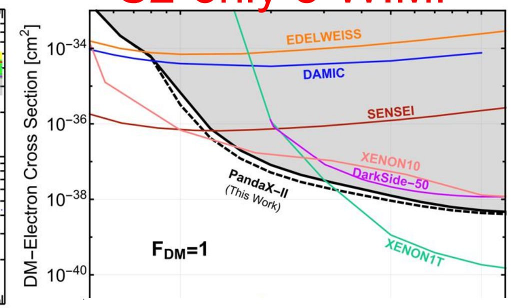
- PandaX-II：580公斤级液氙
  - 2019年结束运行，全部132吨天曝光量
  - WIMP原子核反冲 Chin. Phys. C 44 125001
  - WIMP电子反冲 Phys. Rev. Lett. 126 211803
  - 轴子、中微子反常磁矩 Chin. Phys. Lett. 38 01130

PandaX-II Axion



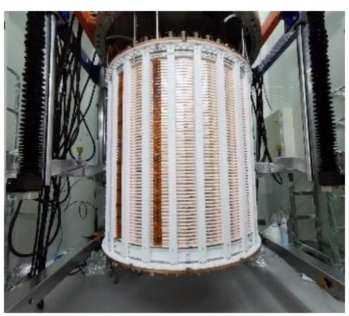
CPL 38 (2021) 011301

PandaX-II S2-only e-WIMP

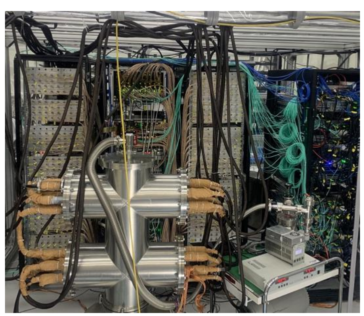


PRL 126 (2021) 211803

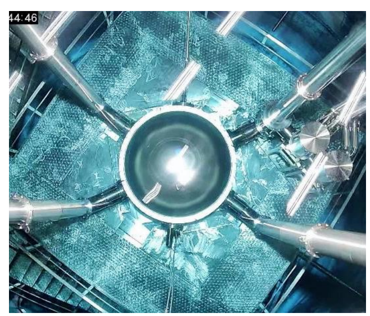
- PandaX-4T：四吨级液氙实验
  - 2020年12月-2021年4月：试运行0.63吨-年
  - 大质量WIMP原子核反冲世界最强的排除限 arXiv:2107.13438



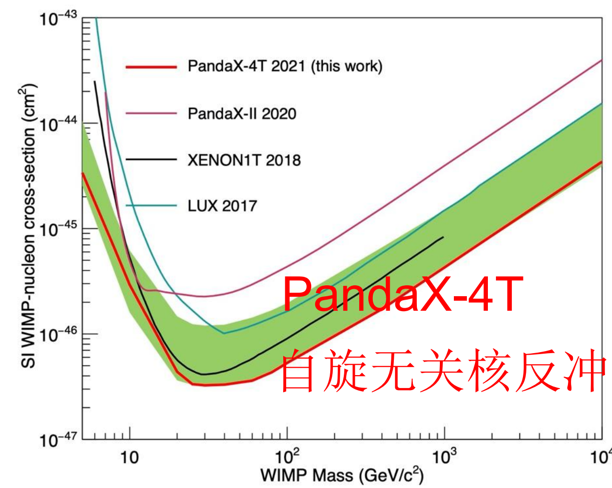
时间投影室



电子学



高纯水屏蔽体

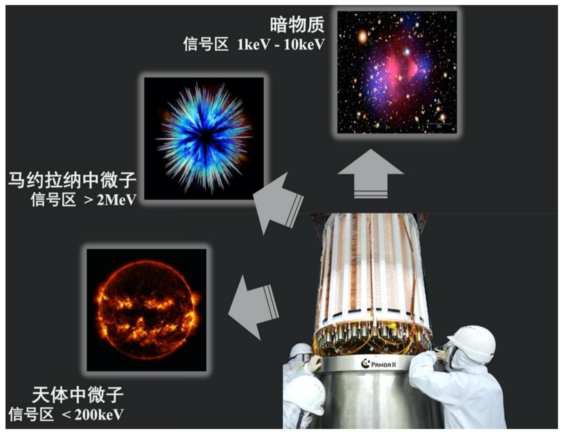


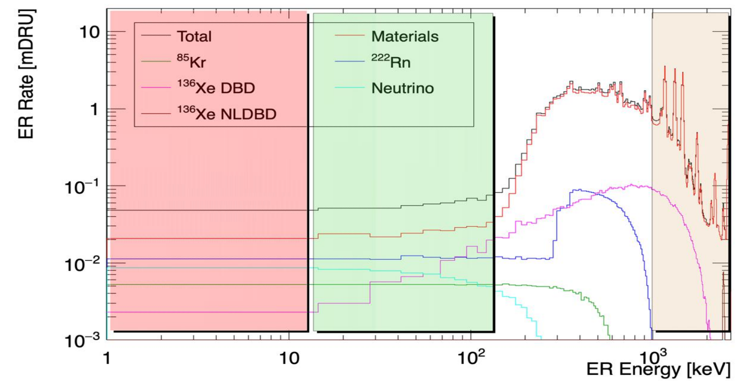
PandaX-4T 自旋无关核反冲

arXiv: 2107.13438

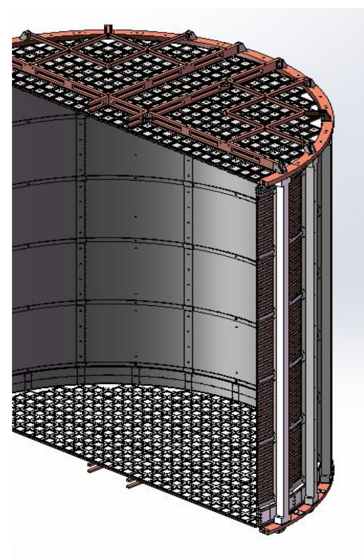
PandaX液氙实验

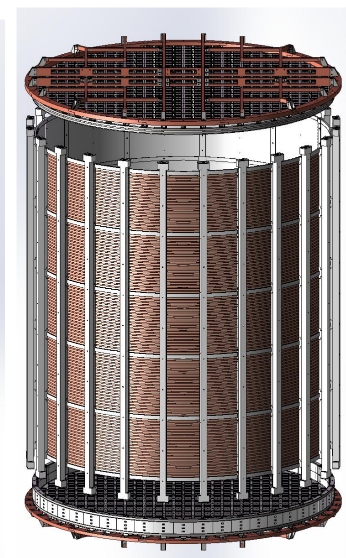
- PandaX-4T：多物理目标
  - 暗物质
  - 马约拉纳中微子
  - 天体中微子





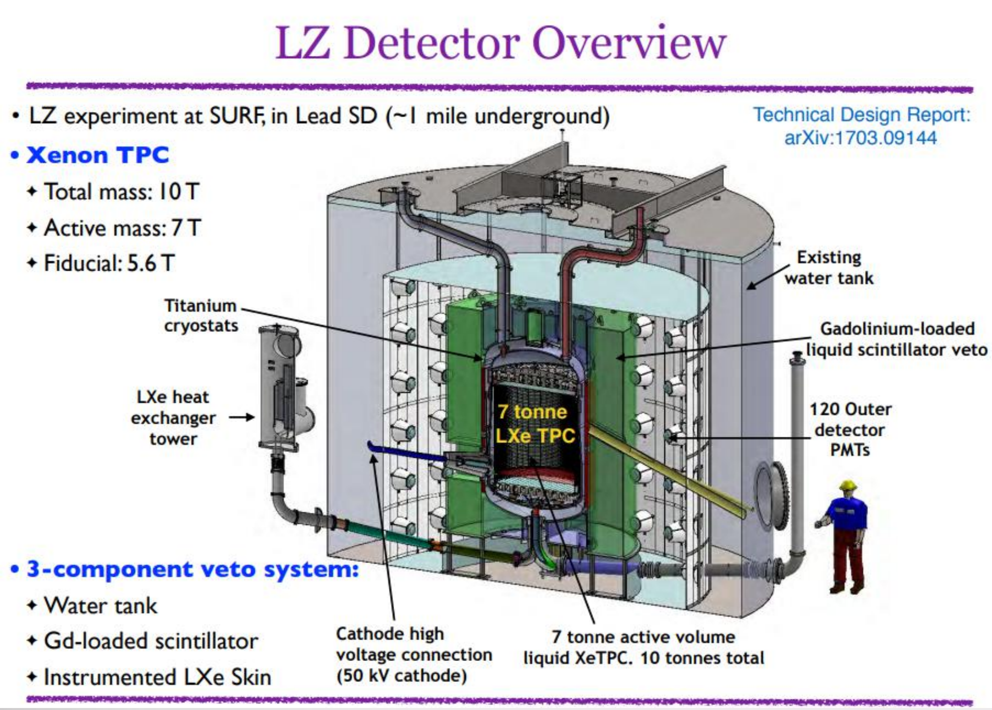
- PandaX-xT：几十吨级液氙
  - 开展未来“终极”液氙暗物质探测关键技术预研
  - 200吨年：中微子地板

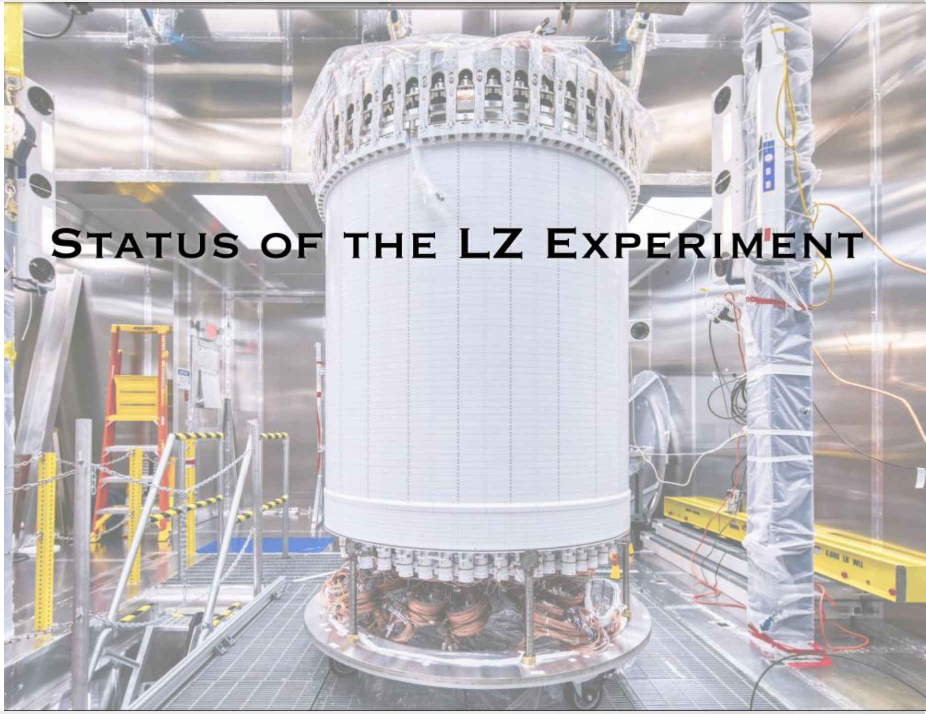




LZ collaboration

36 institutions ~250 scientists, engineers, and technicians





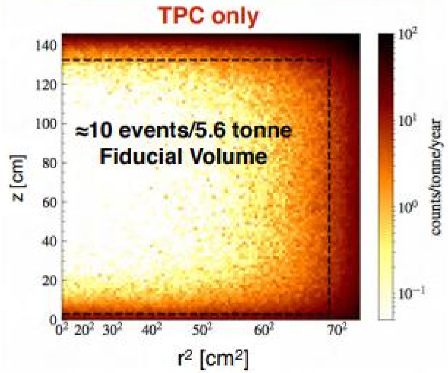
1) Center for Underground Physics (Korea)
2) LIP Coimbra (Portugal)
3) MEPhI (Russia)
4) Imperial College London (UK)
5) Royal Holloway University of London (UK)
6) STFC Rutherford Appleton Lab (UK)
7) University College London (UK)
8) University of Bristol (UK)
9) University of Edinburgh (UK)
10) University of Liverpool (UK)
11) University of Oxford (UK)
12) University of Sheffield (UK)
13) Black Hill State University (US)
14) Brandeis University (US)
15) Brookhaven National Lab (US)
16) Brown University (US)
17) Fermi National Accelerator Lab (US)
18) Lawrence Berkeley National Lab (US)
19) Lawrence Livermore National Lab (US)
20) Northwestern University (US)
21) Pennsylvania State University (US)
22) SLAC National Accelerator Lab (US)
23) South Dakota School of Mines and Technology (US)
24) South Dakota Science and Technology Authority (US)
25) Texas A&M University (US)
26) University at Albany (US)
27) University of Alabama (US)
28) University of California, Berkeley (US)
29) University of California, Davis (US)
30) University of California, Santa Barbara (US)
31) University of Maryland (US)
32) University of Massachusetts (US)
33) University of Michigan (US)
34) University of Rochester (US)
35) University of South Dakota (US)
36) University of Wisconsin – Madison (US)

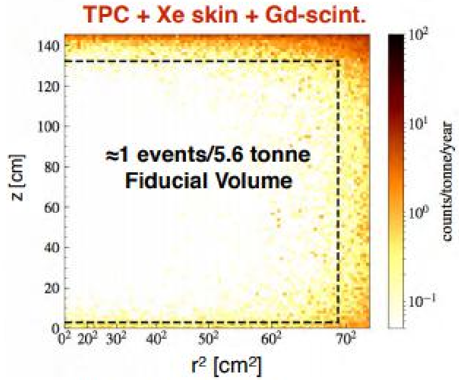
Expected backgrounds for 5.6 T fiducial - 1000 days

Background Source	ER (cts)	NR (cts)
Detector Components	**9**	**0.07**
Surface Contamination	**40**	**0.39**
Laboratory and Cosmogenics	**5**	**0.06**
Xenon Contaminants	**819**	**0**
222Rn	681	0
220Rn	111	0
natKr (0.015 ppt g/g/)	24.5	0
natAr (0.45 pub g/g)	2.5	0
Physics	**258**	**0.51**
136Xe 2νββ	67	0
Solar neutrinos (pp+7Be+13N)	191	0*
Diffuse supernova neutrinos	0	0.05
Atmospheric neutrinos	0	0.46
Total	**1131**	**1.03**
with 99.5% ER discrim., 50% NR eff.	**5.66**	**0.52**

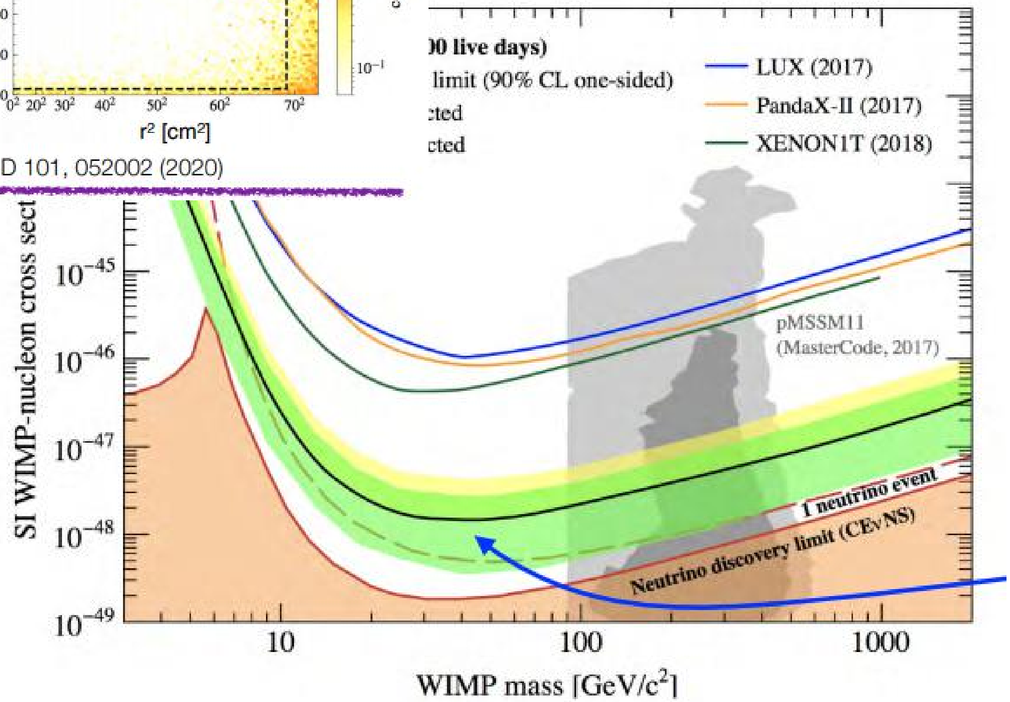
Radon is the dominant background!

* 6 keV NR threshold used

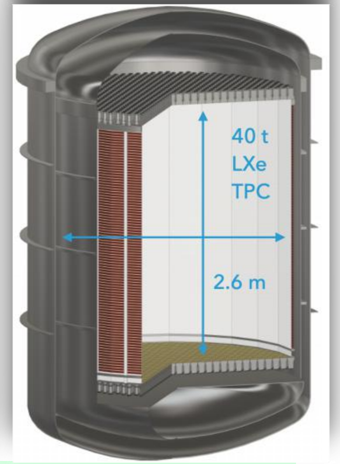




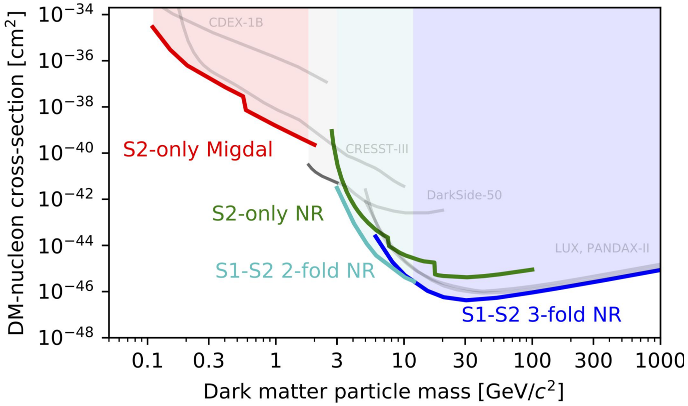
D.S. Akerib et al (LZ collaboration) Phys. Rev. D 101, 052002 (2020)



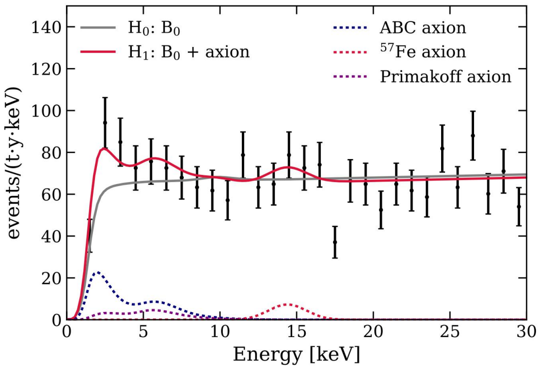
XENON/DARWIN国际合作实验



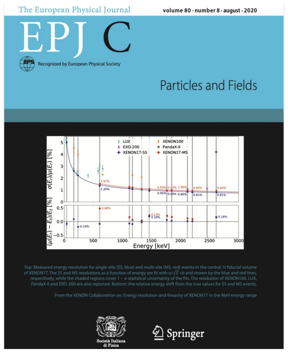
XENON10	XENON100	XENON1T	XENONnT	DARWIN
2005-2007	2008-2016	2012-2018	2019-2025	2026-?
25 kg	161 kg	3.2 ton	8.6 ton	~40 ton
$\sim10^{-43}$ cm^2	$\sim10^{-45}$ cm^2	$\sim10^{-47}$ cm^2	$\sim10^{-48}$ cm^2	$\sim10^{-49}$ cm^2



世界最佳暗物质探测灵敏度

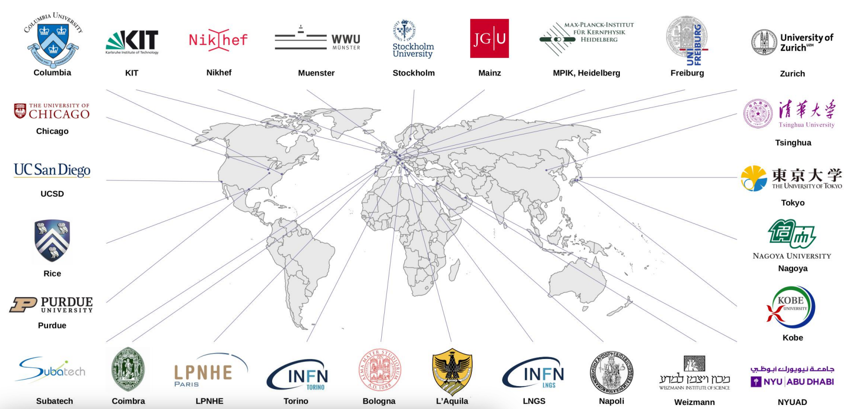


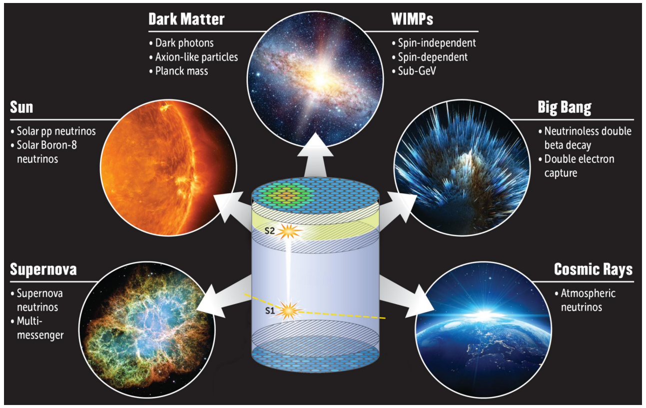
类似太阳轴子的电子反冲超出



对双贝塔衰变信号的探索

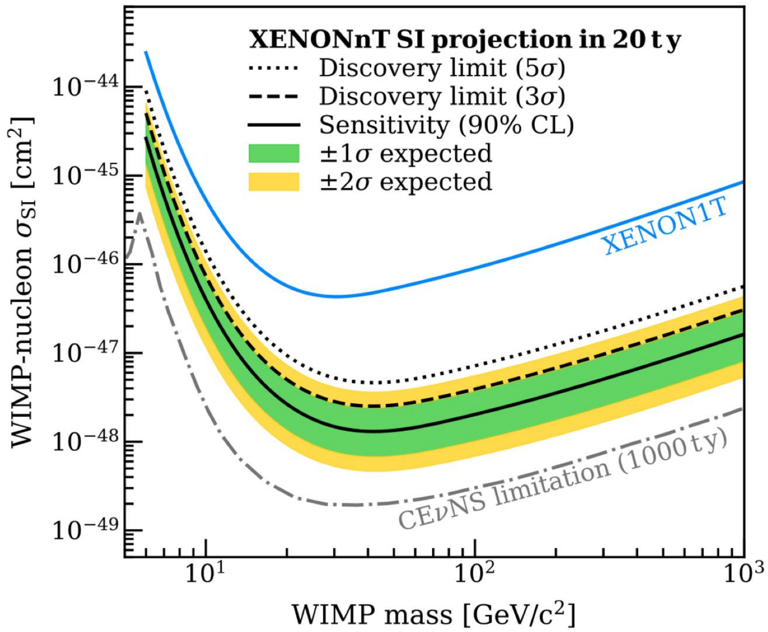
XENONnT实验：2019-2025



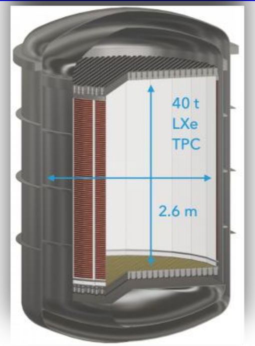


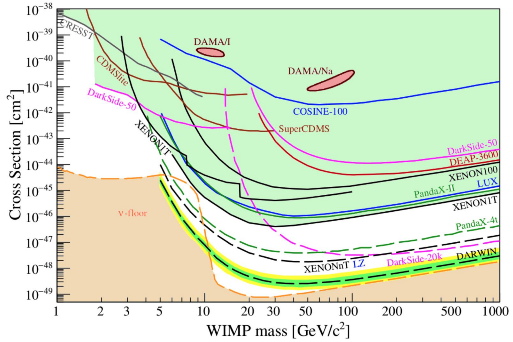
XENONnT目标（相对XENON1T）：
- 4倍有效质量（4吨）
- 1/6电子反冲本底
- 中子本底约1/(20ton-year)

XENONnT目前状态：
- 正在试运行
- 主要物理目标包括：
  - 验证XENON1T实验的电子反冲超出信号
  - 寻找原子核反冲信号
  - 太阳中微子信号
  - 无中微子双贝塔衰变
  - …

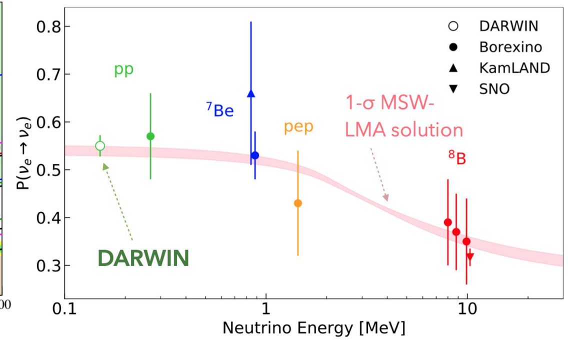


DARWIN:暗物质和中微子观测站

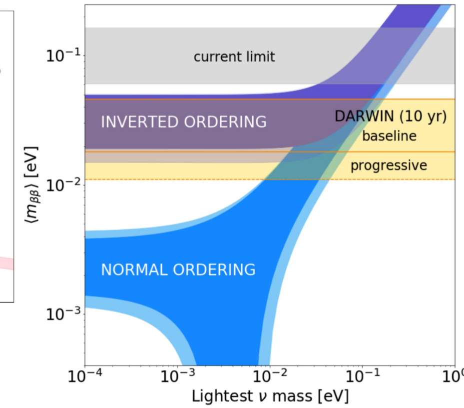




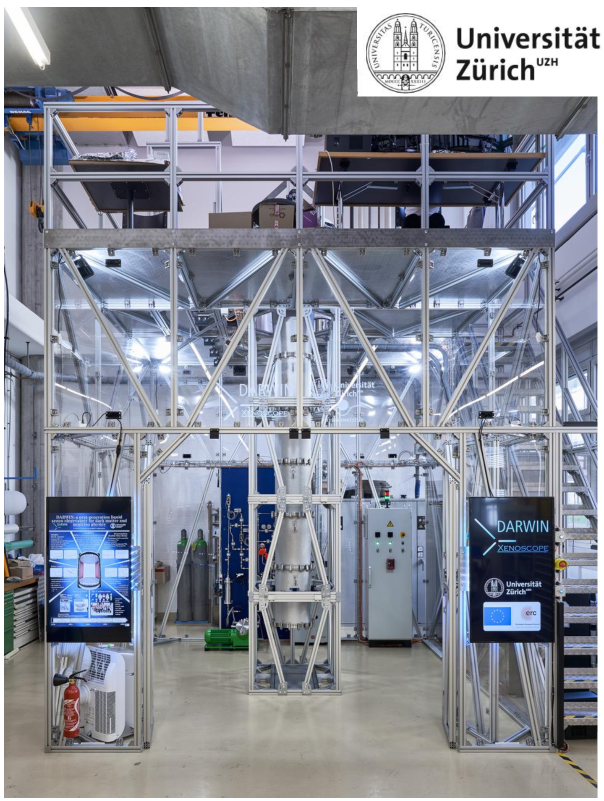
暗物质探测灵敏度

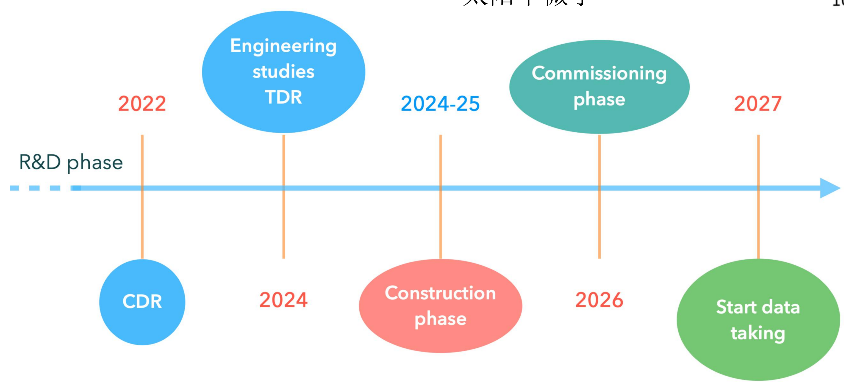


太阳中微子



无中微子双贝塔衰变





XENON/DARWIN与LZ将共同建设下一代液氙暗物质探测器!

[20.07.2021] DARWIN and LZ join forces to build next-generation Dark Matter Detector

The XENON/DARWIN and LUX-ZEPLIN (LZ) collaborations have now joined forces to work together on the de
tonne scale xenon observatory to explore dark matter. The detector will be highly sensitive to a wide range c
with visible matter. Over the last 20+ years, experiments using liquefied xenon targets have delivered world
detection. This next-generation detector aims to continue the pursuit.

Dark matter makes up 85% of the matter in the Universe, but its nature remains a mystery. The direct ider
highest priorities in science and also one of the most challenging. The primary science goal of the new joint
matter in our galaxy by at least a factor of 10 beyond that of the current generation of detectors.

Laura Baudis from the University of Zurich and spokesperson of DARWIN says: "Xenon-based detectors are
the upcoming years if nature decided to put it in reach of any direct detection instrument."

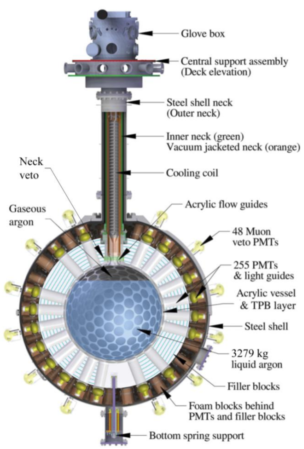
The current xenon-based experiments **XENONnT** and **LUX-ZEPLIN** will start their first science runs in 2021
and interactions. These experiments employ 5.9 and 7.0 tonnes of liquid xenon for the search, respectively.

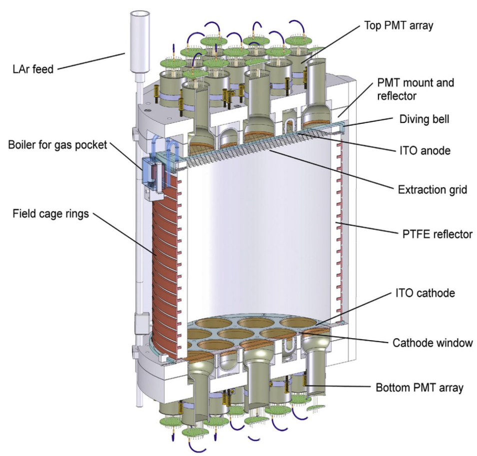
The scientists that have signed the Memorandum of Understanding between members of the XENON/DARWIN and LUX-ZEPLIN Collaborations towards a Next-Generation Liquid Xenon Experiment (July 6, 2021)

List last updated July 22, 2021:

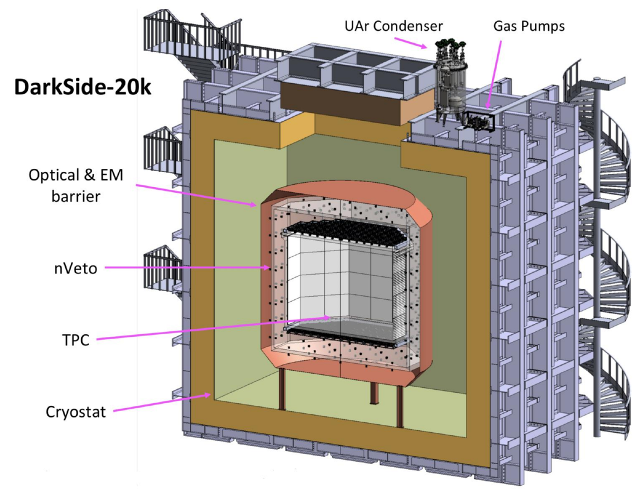
Daniel Akerib, SLAC National Accelerator Lab, United States
Elena Aprile, Columbia University, United States
Henrique Araujo, Imperial College London, United Kingdom
Francesco Arneodo, New York University Abu Dhabi, United Arab Emirates
Laura Baudis, University of Zurich, Switzerland

液氩探测器:Darkside-50 和DEAP-3600





DarkSide-20k@LNGS
2023~



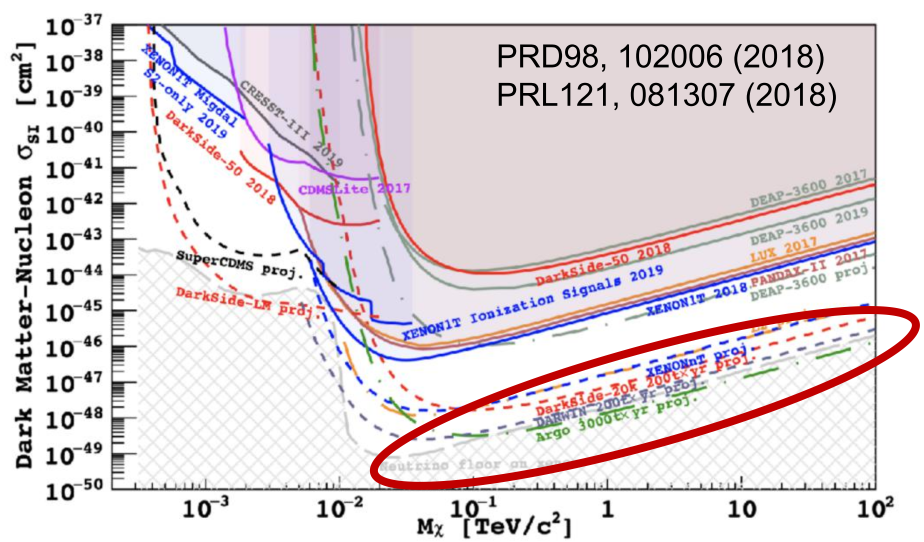
ARGO液氩
暗物质探测
器其灵敏度
将能达到中
微子平台

ARGO
~300t

2029~

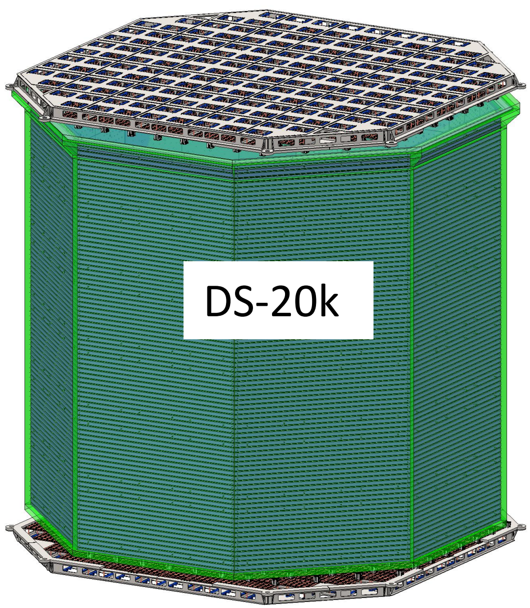
单相液氩探测器:
DEAP-3600
有效质量~3.3吨
加拿大SNOLAB

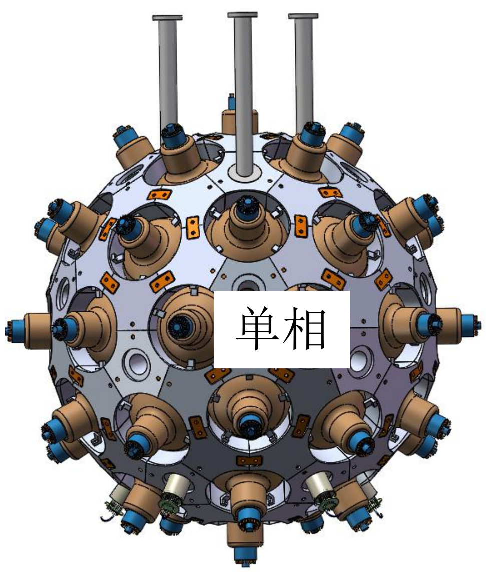
两相氩TPC探测器:
DarkSide-50
有效质量~46千克
意大利LNGS

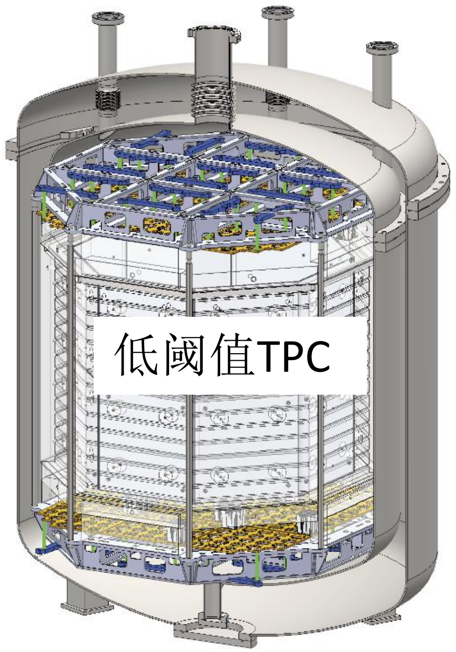


国内液氩暗物质实验计划

- 深入参与DarkSide-20k实验，负责中心探测器的设计和集成安装，反符合探测器研发等重要任务；
- 进行单相液氩探测关键技术的研究；
- 进行低阈值双相氩时间投影室的研究，并将其应用于反应堆中微子与核子相干散射实验，低质量WIMP（1~10 GeV/c^2）直接探测实验等。



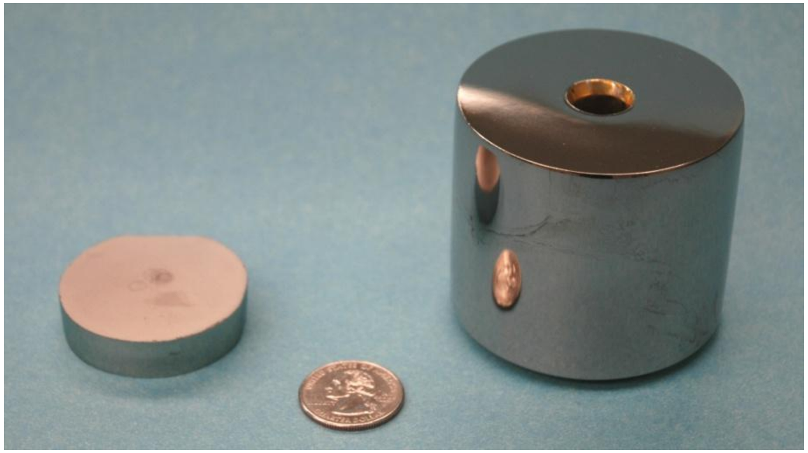




液氙/液氩暗物质实验总结

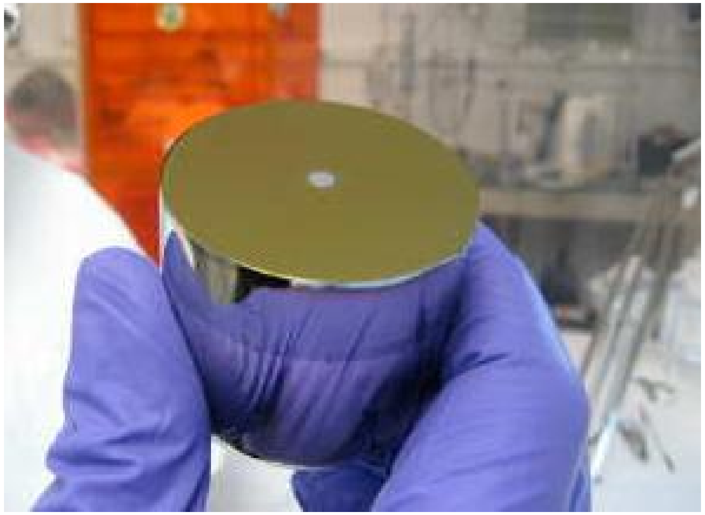
- 三个数吨级实验进入了数据获取阶段，预计2022年会有第一批灵敏度提升数倍的实验结果出来；
- 今后三年左右，液氙实验进入数十吨级实验阶段，国际竞争激烈；
- 数十吨级实验中，氡本底、单相/二相技术、阈值等将是重要技术挑战；
- 20吨液氩实验结果对于下一步是否启动数百吨级液氩实验意义重大。

液氮温区高纯锗探测器暗物质实验

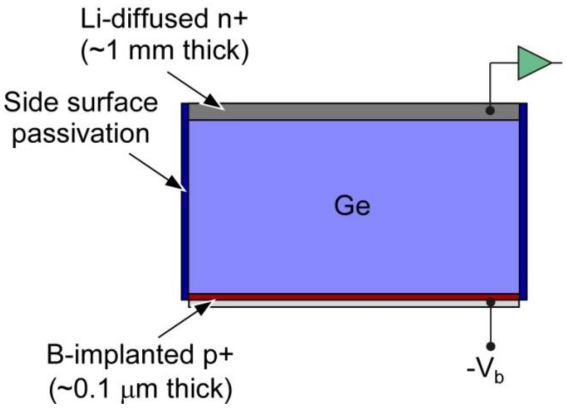


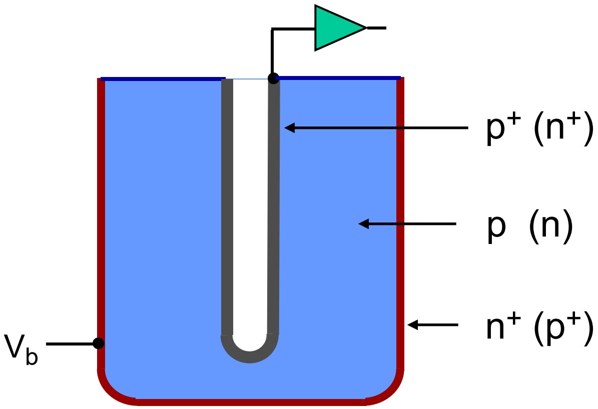
平面型

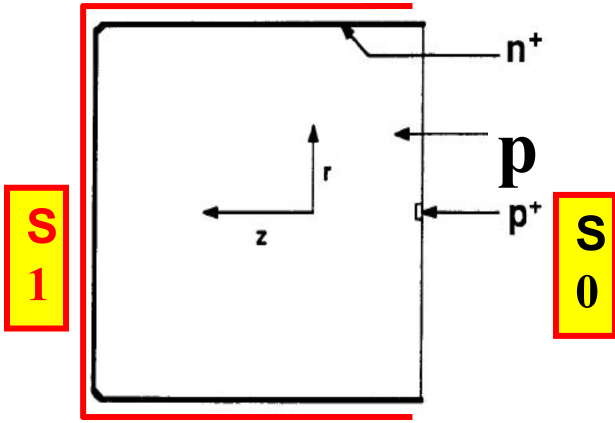
同轴型



点电极型

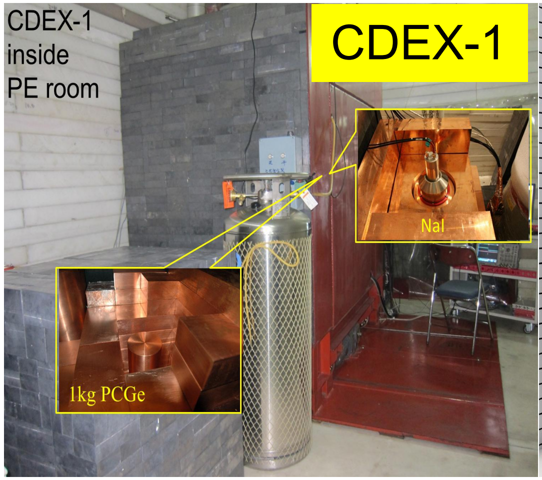


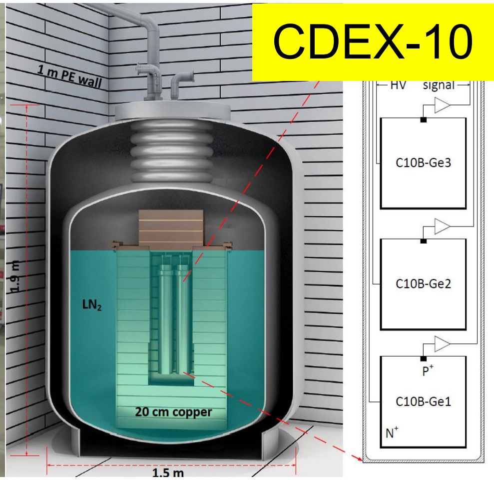


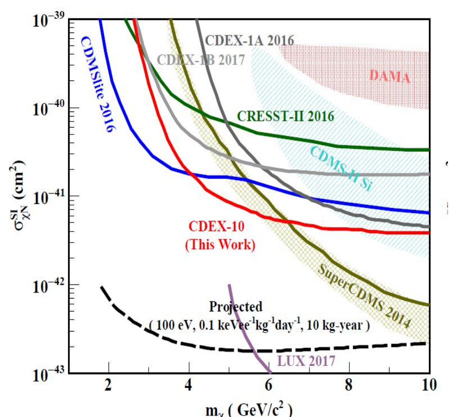


CDEX暗物质实验结果

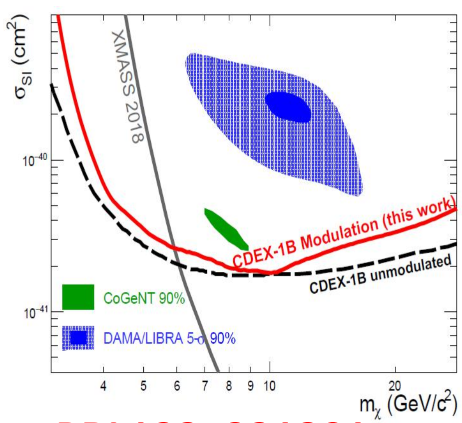
- 完成CDEX-1和CDEX-10两阶段实验;
- 积累连续4年多的实验数据;
- 在多个暗物质物理通道上取得国际最灵敏结果。



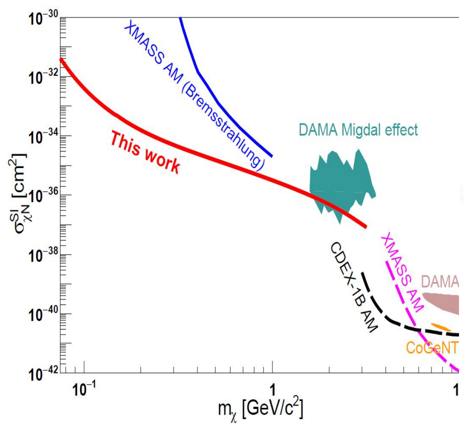




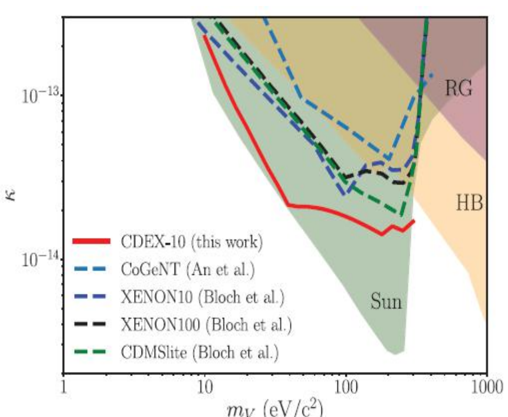
PRL120, 241301, 2018
暗物质探测灵敏度



PRL123, 221301, 2019
暗物质年度调制效应



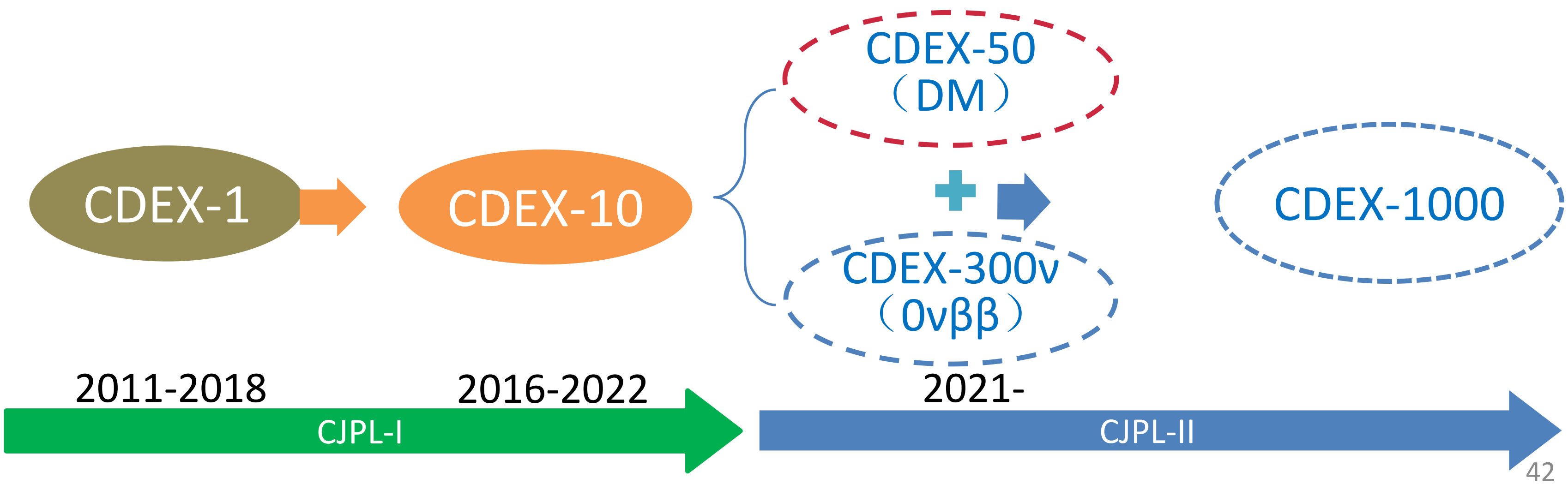
PRL123, 161301, 2019
暗物质Migdal Effect效应



PRL124, 111301, 2020
太阳暗光子实验

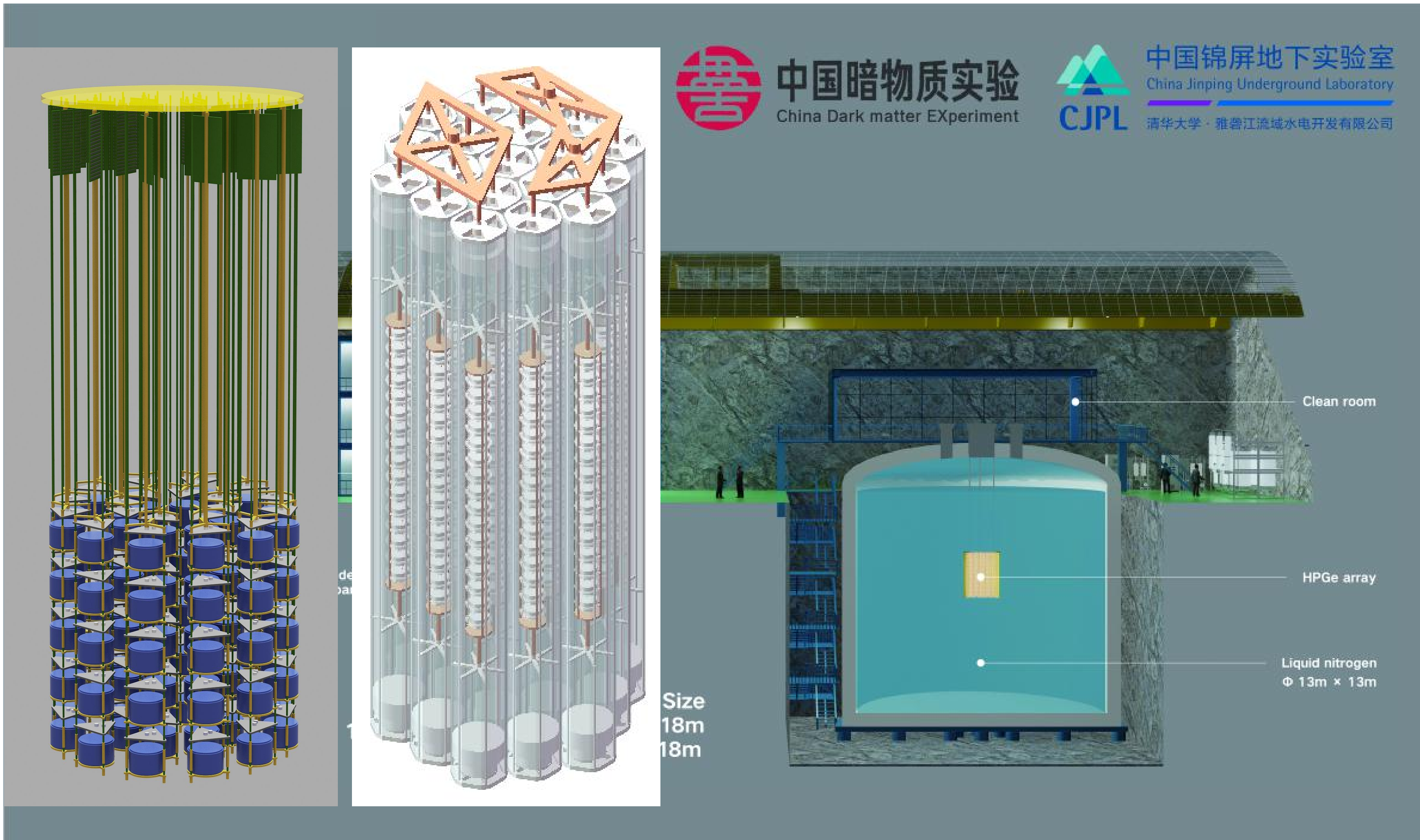
CDEX“盘古”计划

- 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-300ν（2021-）：300公斤富集锗0νββ实验
- CDEX吨级实验

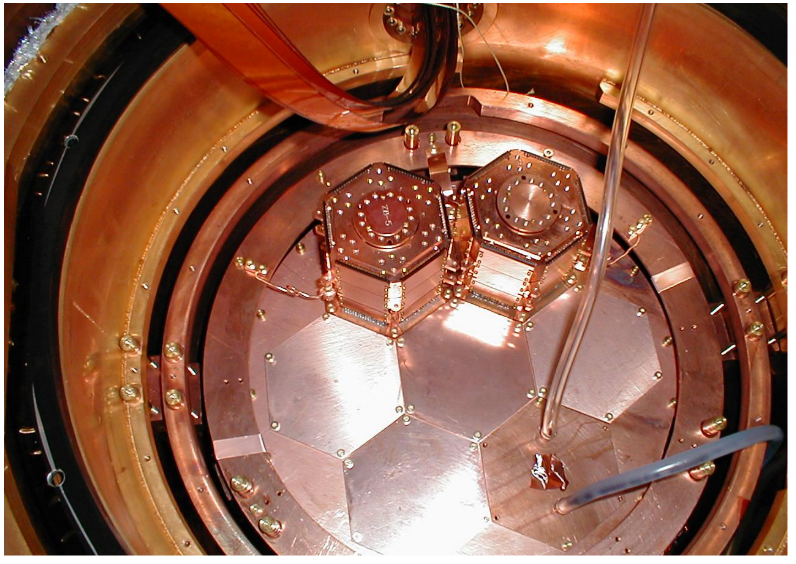


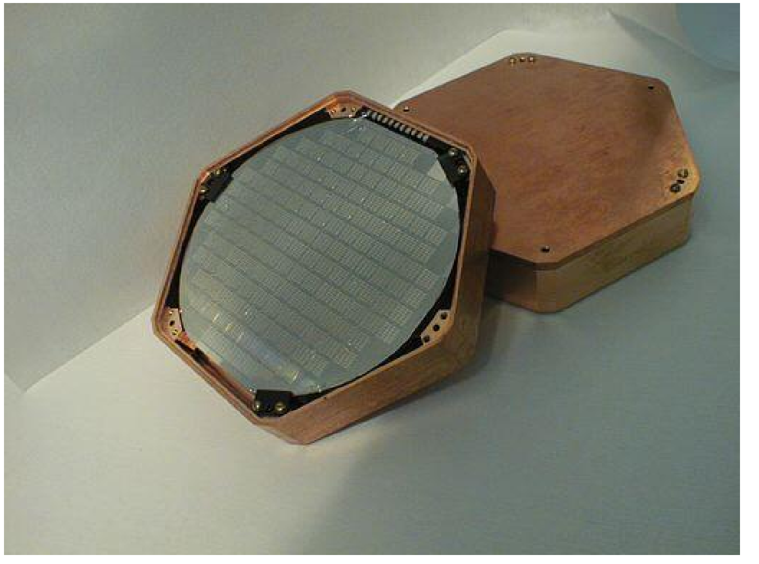
CDEX-50和CDEX-300

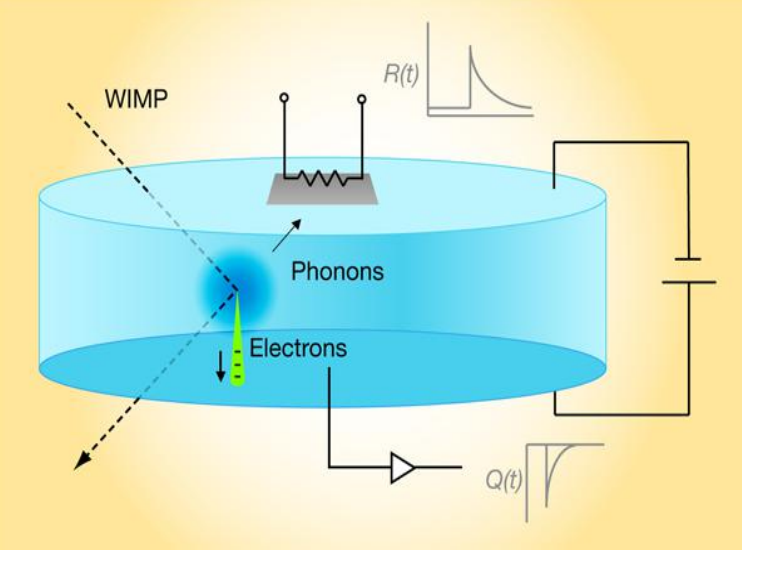
- 开展暗物质和0νββ实验



CDMS 几十mK极低温探测器系统

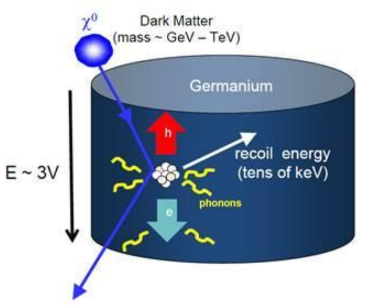


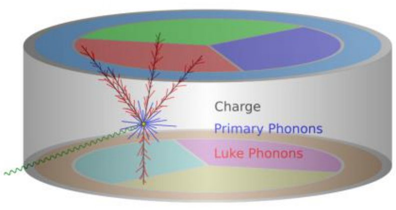


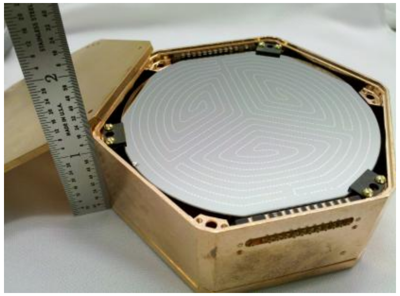


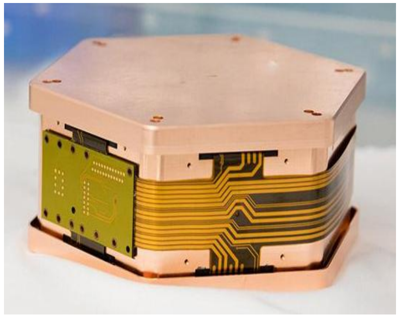
SuperCDMS experiment

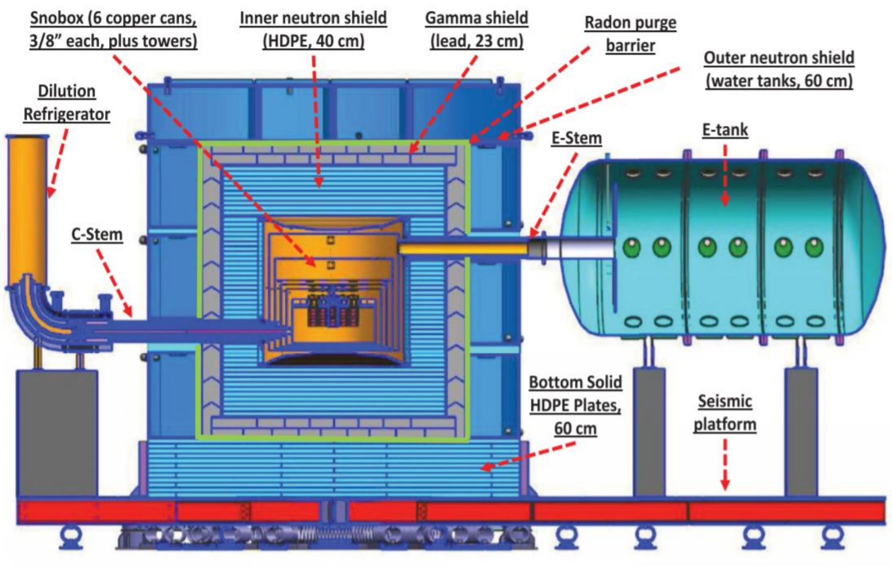
- 前期实验在美国Soudan，目前正在SNOLab建设新一代探测系统；
- Ge(Si) : 同时探测电荷信号和声子信号；
- 可以只探测声子信号，以降低阈值（CDMSLite）；
- 利用Luke效应进一步放大声子信号，降低阈值；









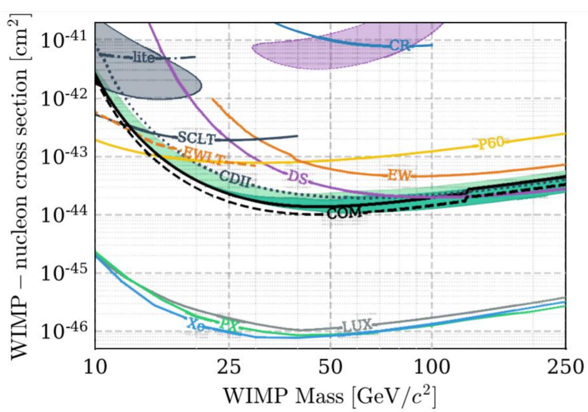


SuperCDMS experiment

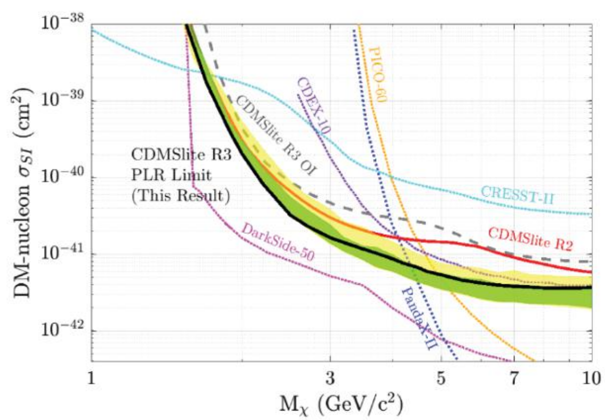
	CDMS II	SCDMS Soudan	SCDMS Soudan
Detector	ZIP	iZIP	CDMSlite
Mass per Detector [kg]	0.25	∼0.62	∼0.62
Number of Detectors	19	15	2
Phonon Channels per Det.	4	8	4
Phonon Energy Res. [eV]	∼180	∼200	∼70
Trigger Threshold [eV]	∼2000	∼3000	∼50
Charge Energy Res. [eV]	∼300	∼450	–
Voltage between faces [V]	3	4	∼70

ZIP：Z-sensitive Ionization and Phonon
iZIP: s interleaved Z-sensitive Ionization and Phonon
目标：CDMS： DM> 10 GeV
CDMSlite： DM<10 GeV
SuperCDMS：两个区域兼有

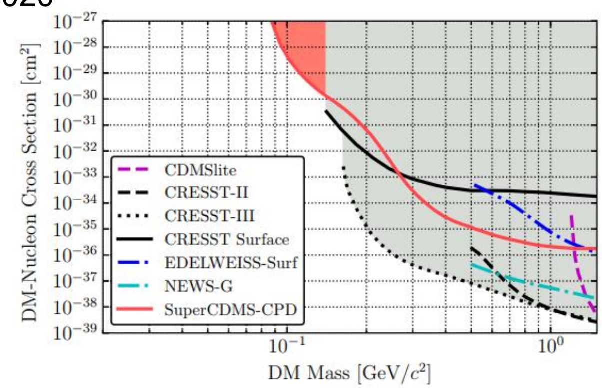
CDMS iZIP: PRL120, 061802, 2018



CDMSlite: PRD99,062001, 2019

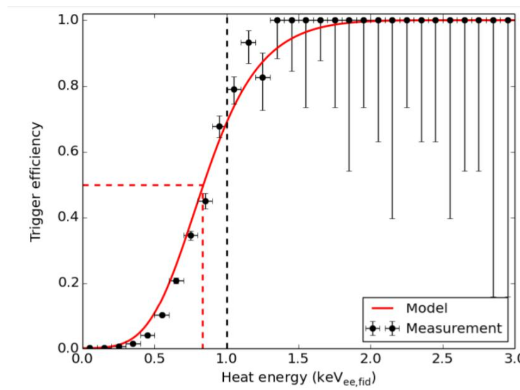


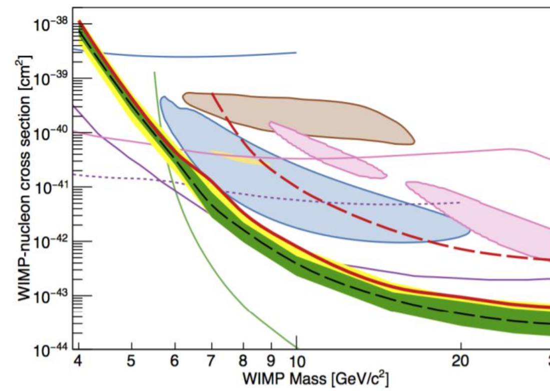
SuperCDMS new Si CPD @ Ground 2020

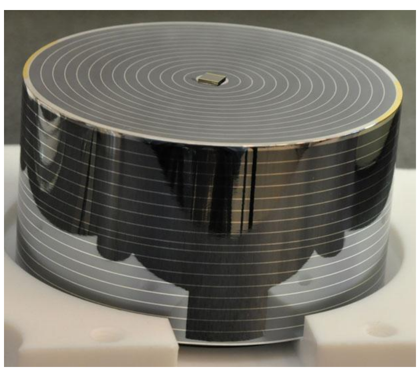


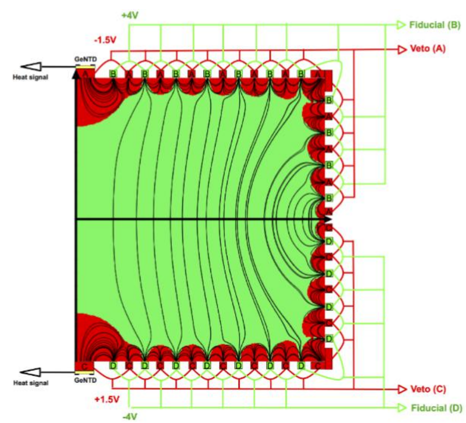
Edelweiss experiment

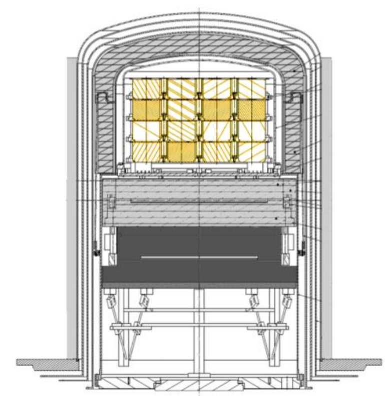
- 位于法国LSM
- 24个 820-890g Ge(edelweiss III)
- 同时测量电离和声子信号
- 暗物质目标区域~4-30 GeV
- 能量阈：~1 keVee
- 目前正在发展新的探测单元技术
- 讨论和SuperCDMS合作





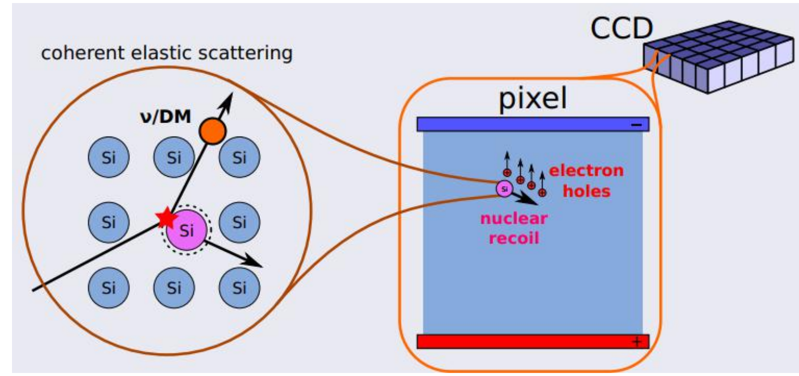




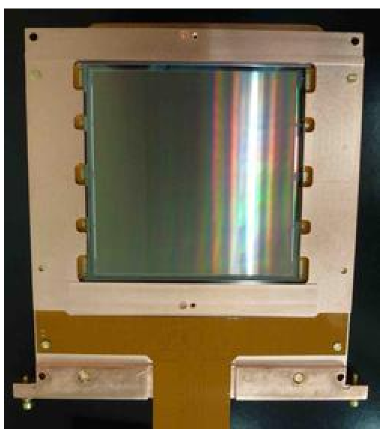


DAMIC

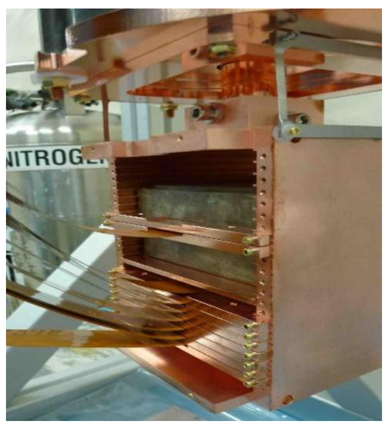
- DAMIC @SNOLab: 6g*7，~ 5 cpkkd;
- DAMIC-M @ LSM： 20g CCD单元
- 反冲核探测灵敏度由读出电子学噪声和反冲核电离产额决定;
- 今年7月利用11kg-d数据发布新结果。



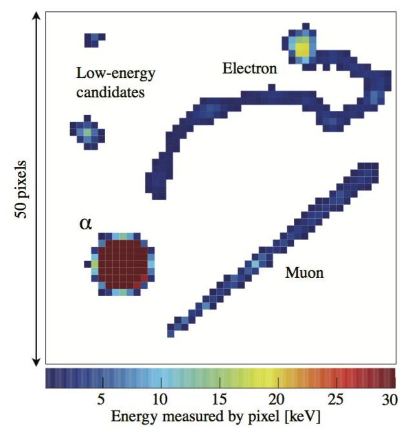
arXiv:2007.15622



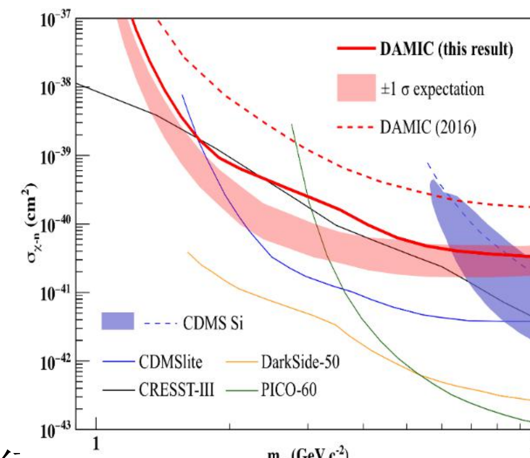
Area: 6cm*6cm*1mm



T=130K



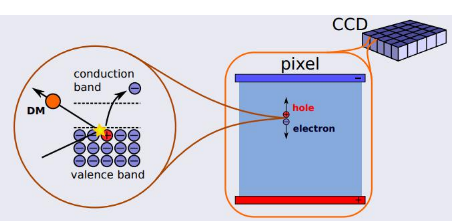
不同入射粒子产生的径迹

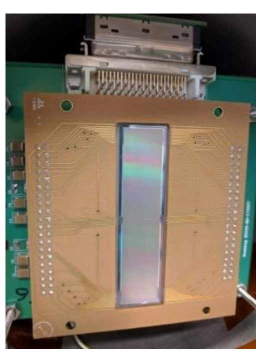


SENSEI

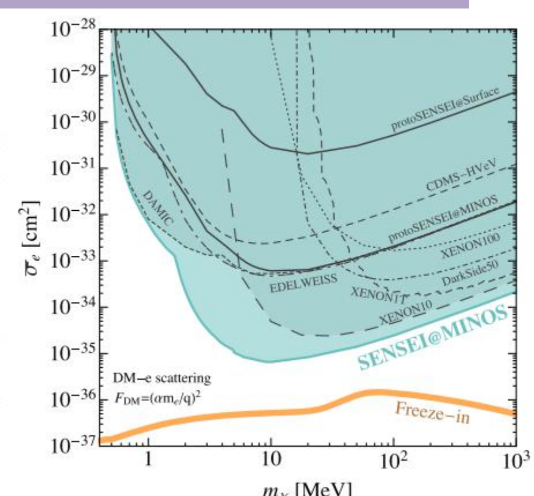
- 测量暗物质粒子与电子的作用，要求噪声水平低；
- SkipperCCD技术的全耗尽硅探测器，百万量级像素的单电子读出；
- 原理：多次对同一像素取样，求和得到像素电荷值，噪声水平小于1个电子；
- 探测MeV-GeV DM；
- 探测器：~1g，下一步100g。

Rouven Essig, Stony Brook University
Javier Tiffenberg, Fermilab
Tomer Volansky, Tel Aviv University
Tien-Tien Yu, University of Oregon
Four founders of SENSEI collaboration shared the New Horizons Prize in Physics 2021.



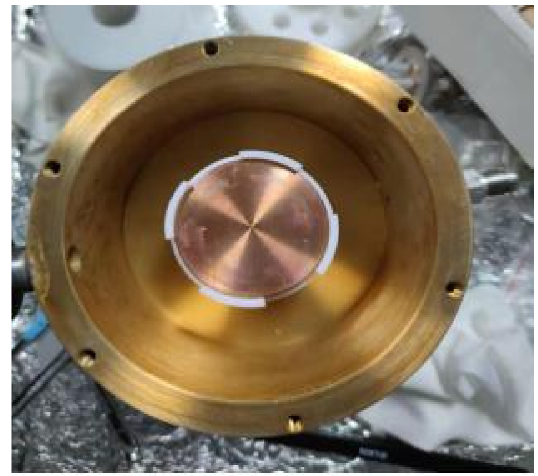


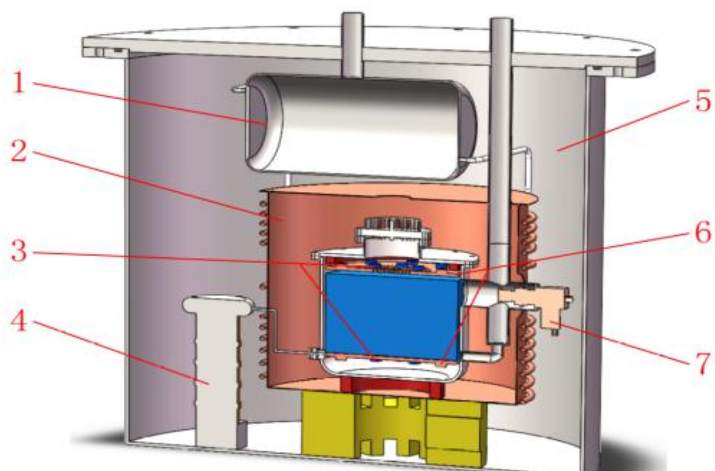
Characteristic	Value	Unit
Format	4126 × 866	pixels
Pixel scale	15	μm
Thickness	200	μm
Operating temperature	140	Kelvin
Number of amplifiers	4	
Dark current[a]	$<10^{-3}$	e^-/pixel/day
Readout time (1 sample)	10	μs/pixel/amp
Readout noise (1 sample)	3.55	e^-rms/pixel
Readout noise (4000 samples)	0.068	e^-rms/pixel

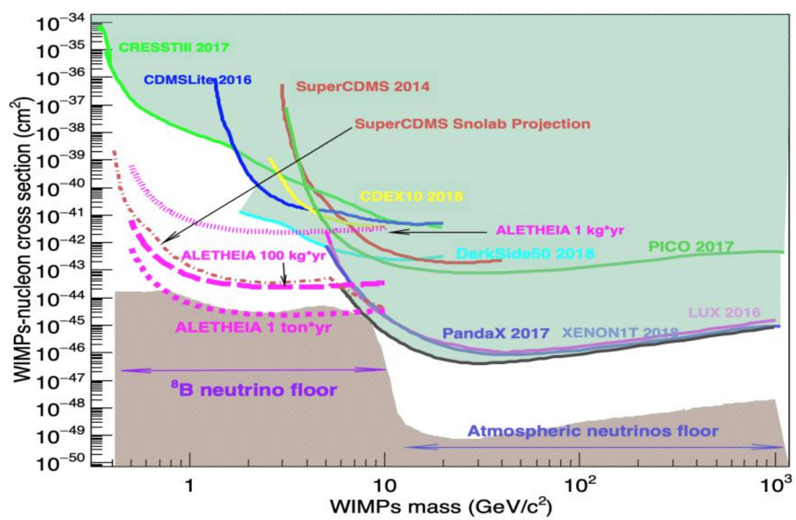


ALHETHEIA液氦TPC

- CIAE+PKU+…开展30g低阈值液氦原型探测器技术研发





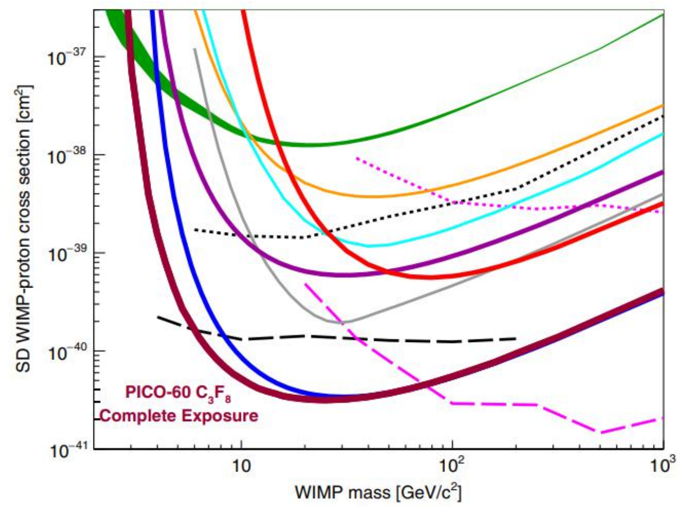


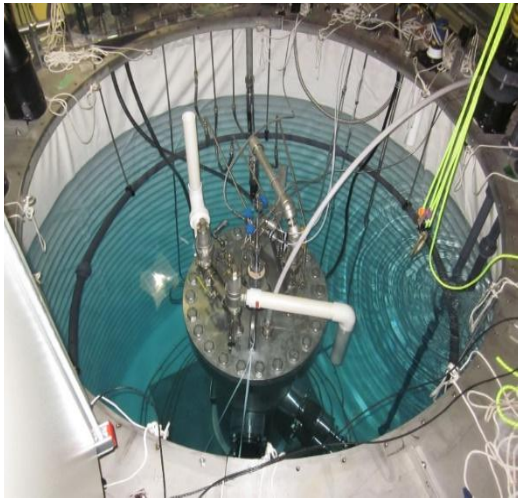
气泡室暗物质探测实验

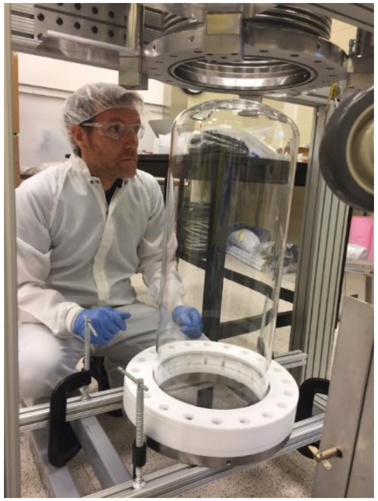
PRD 100, 022001, 2019

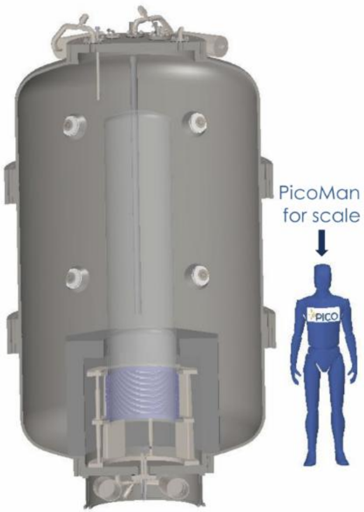
- PICO（PICASSO and COUPP）
- 压力容器中的过热液体，入射粒子电离引起沸腾产生气泡，相机拍照，压电晶体“听声”；
- PICO-2L → PICO 60L → PICO 40L → PICO 500L

  2014-2017 Now





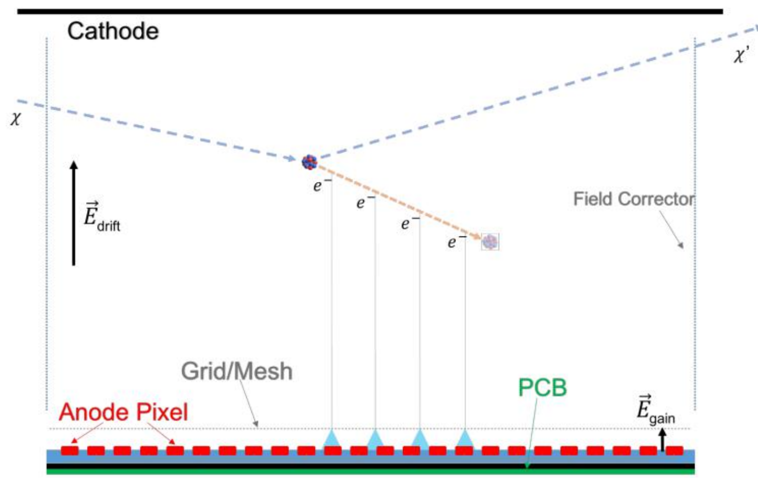


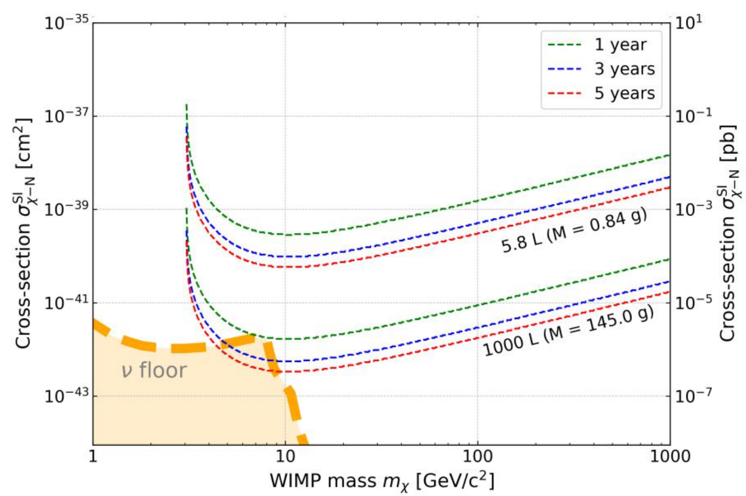


暗物质方向探测实验

- 探测反冲核径迹；
- 需要有好的角分辨能力；
- 平衡径迹探测和靶物质质量；
- 多个实验组在持续探索。

Exp.	V [L]	Gas	P [mbar]	Drift [cm]	E_{ee}^{th} [keV]	Readout	Ref.
DRIFT	800	73%CS_2 + 25%CF_4 + 2%O_2	55	ion^-, 50	20	MWPC, GEM	[97]
MIMAC	5.8, 1000	70%CF_4 + 28%CHF_3 + 2%iC_4H_{10}	50	e^-, 25	1	Micro-megas	[96,98]
NEWAGE	39, 16	CF_4, SF_6	100	e^-, 41	50	GEM	[99]
DMTPC	1000	CF_4	40	e^-, 27	20	CCD, PMT	[57]
D^3	25	70%He + 30%CO_2	1013	e^-, 50	$\mathcal{O}(1)$	GEM	[100]
CYGNO	1000	60%He + 40%CF_4	1013	e^-, 50	2	GEM, CMOS, PMT	[101-102]

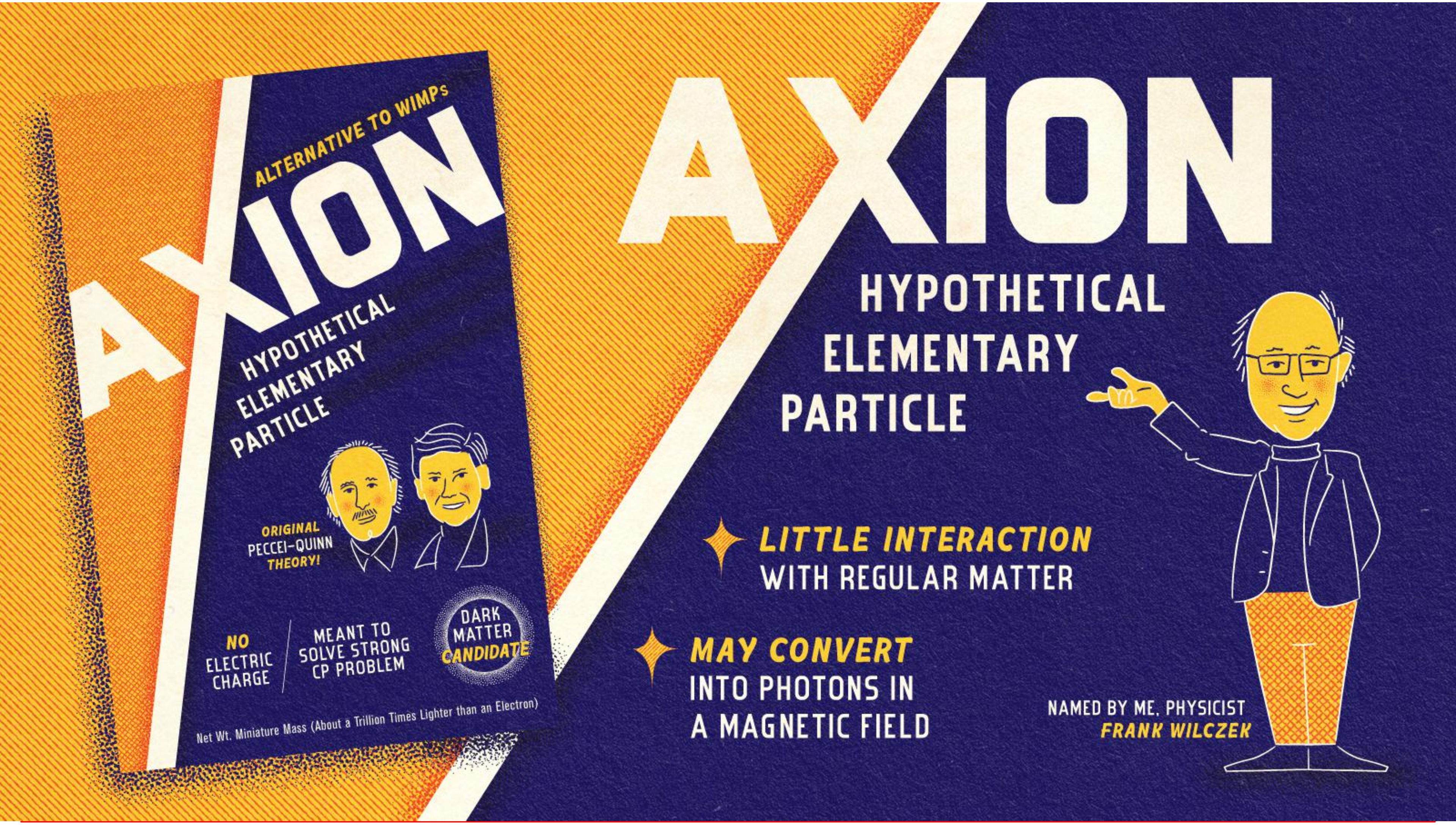




暗物质直接探测实验
发展现状、趋势、挑战

实验技术	主要关注能区	实验名称	实验地点	探测器介质	介质质量	靶质量	灵敏区质量	规模	下一阶段	挑战
半导体	10GeV以下	CDEX	CJPL	Ge	1kg * 100	100 kg	100 kg	中大	1T	✓宇生本底 ✓阈值 ✓成本
		EDELWEISS	SNOLab	Ge	4 kg	4 kg	100 kg		1T	
		SuperCDMS	SNOLab	Ge、Si	50 kg	50 kg	50 kg			
		DAMIC	SNOLab	Si（SCCD）	6 g * 7	6 g * 7	6 g * 7	小型	~1kg	✓本底 ✓靶质量
		SENSEI	FNAL	Si（SCCD）	~1 g	---	---		~100g	
液态惰性气体	10GeV以上	LZ	Surf	LXe	10 Ton	7 Ton	~5.6 Ton	中大	30T	✓技术 ✓氡本底 ✓阈值 ✓成本
		PandaX	CJPL	LXe	6 Ton	4 Ton	~3 Ton			
		XENON	LNGS	LXe	8.6 Ton	5.9 Ton	~4 Ton			
		Darkside	LNGS	LAr	50 Ton	46 Ton	25 Ton		300T	
	<10GeV	ALHET		LHe/LNe	30 g			预研		
晶体低温量热	10GeV以上	CRESST	LNGS	$CaWO_4$	300g -> 24g 10个单元	240g	240g	中等	——	✓本底 ✓阈值
气泡室（过热介质）	1-10³ GeV（SD）	PICO-40	SNOLab	C3F8	40 L	——	——	预研	500L	✓本底 ✓靶质量
气泡室		闪烁气泡室	SNOLab	LAr	——	——	——	预研	——	
径迹室	1-10³GeV	MIMAC等	LSM	CF_4	5.8L(50mbar)，电子漂移距离25cm			预研	1000L	✓靶质量

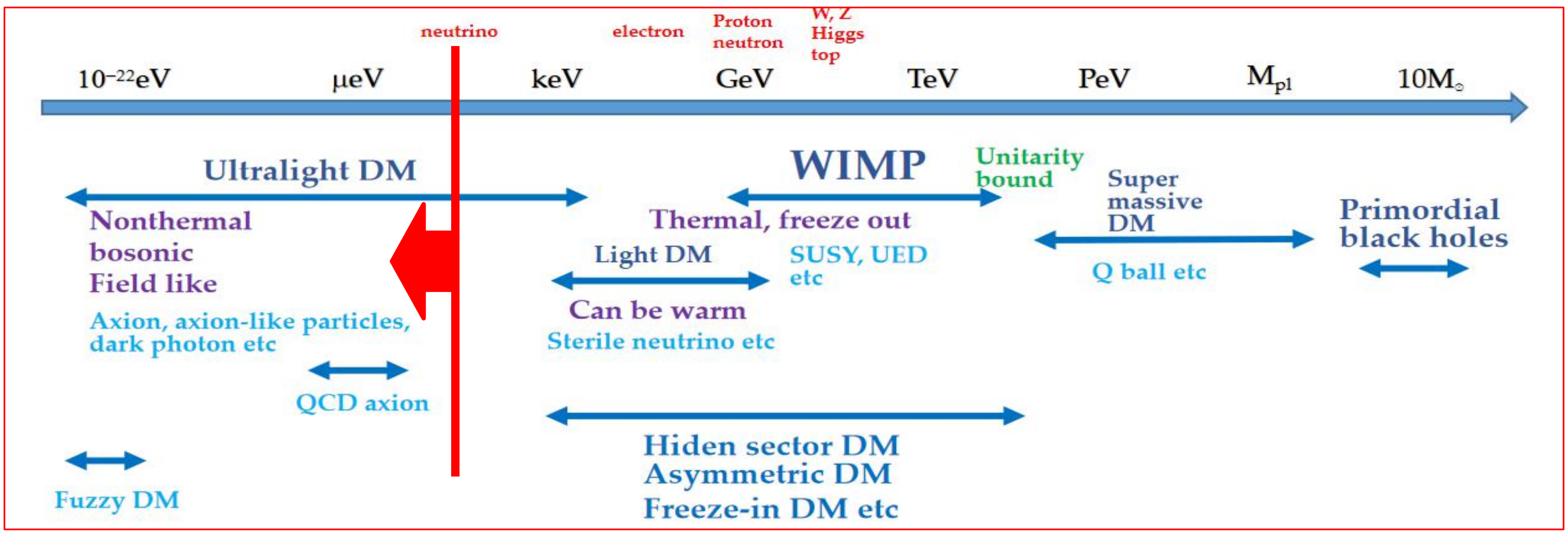
轴子暗物质探测



ALTERNATIVE TO WIMPs
AXION
HYPOTHETICAL
ELEMENTARY
PARTICLE
ORIGINAL
PECCEI-QUINN
THEORY!
NO
ELECTRIC
CHARGE
MEANT TO
SOLVE STRONG
CP PROBLEM
DARK
MATTER
CANDIDATE
Net Wt. Miniature Mass (About a Trillion Times Lighter than an Electron)
AXION
HYPOTHETICAL
ELEMENTARY
PARTICLE
LITTLE INTERACTION
WITH REGULAR MATTER
MAY CONVERT
INTO PHOTONS IN
A MAGNETIC FIELD
NAMED BY ME, PHYSICIST
FRANK WILCZEK

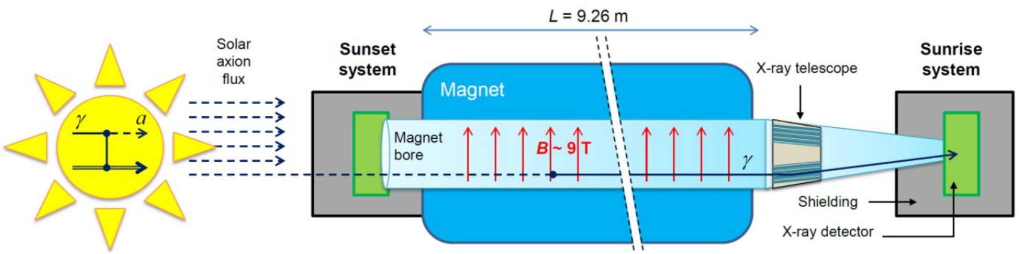
轴子暗物质探测

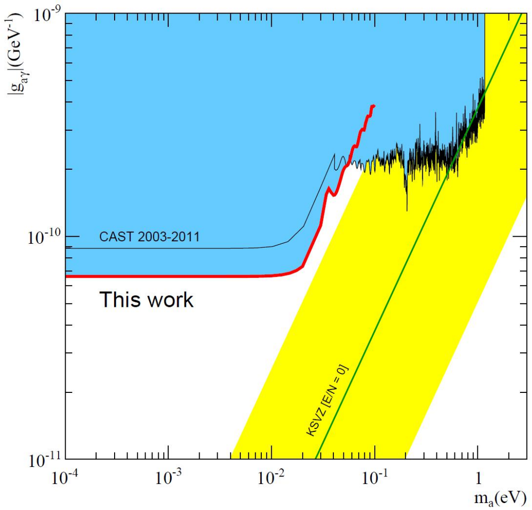
- 轴子可以在meV以下质量区间，质量跨度很宽；
- 主要实验技术：共振腔。



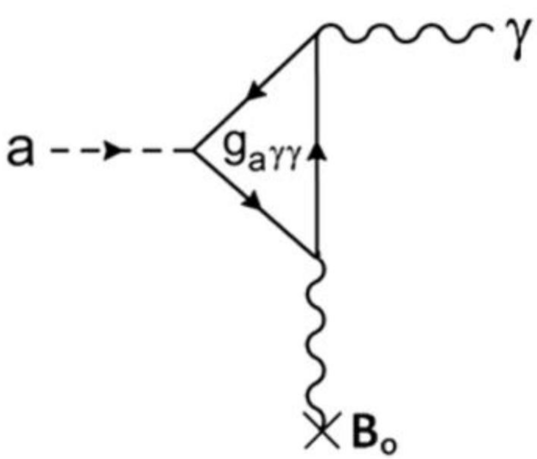
轴子暗物质探测

CERN Axion Solar Telescope (CAST)





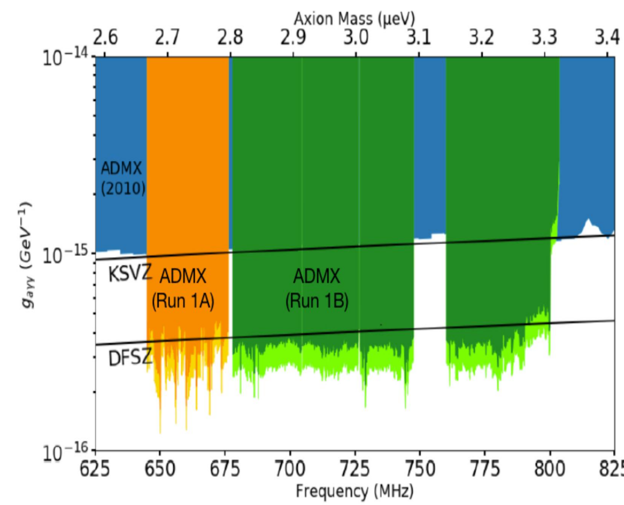
The CAST searches for x-rays that are expected after a conversion in the 9 T magnetic field of a refurbished LHC test magnet (L = 9.26 m) that can be directed toward the Sun. The magnet can move by ±8° vertically and ±40° horizontally, enough to follow the Sun for about 1.5 h at dawn and dusk with opposite ends.

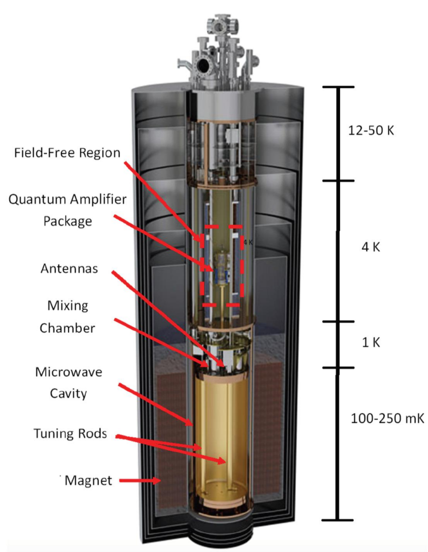


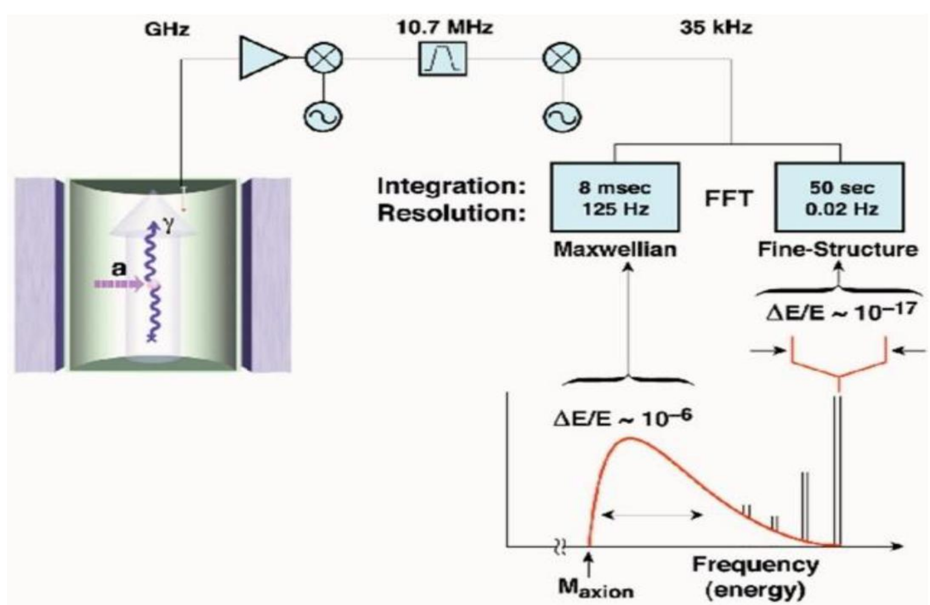
轴子暗物质探测

Axion Dark Matter eXperiment (ADMX)

- ADMX at the UW, Seattle.
- Microwave cavity (φ0.59m*3m).
- The superconducting solenoid magnet is operated typically at just under 8 T.



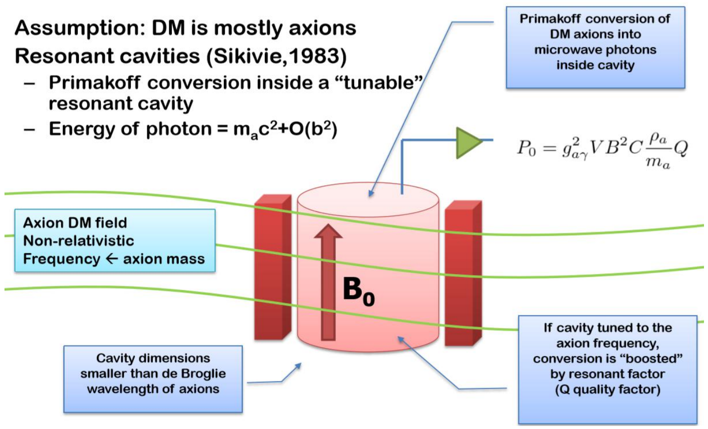




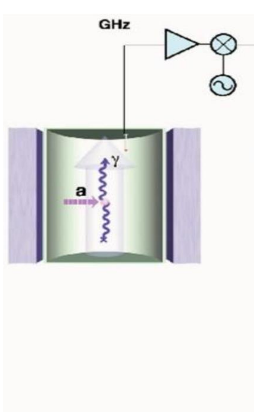
我国轴子暗物质探测计划

轴子暗物质共振腔探测（轴子质量搜寻范围约32-40μeV）

参与单位：理论所*、物理所、高能所、北京量子院、湖南师范大学、暨南大学等



磁场诱导的暗物质轴子衰变
⬇
单频电磁信号
⬇
低温电磁信号精密测量



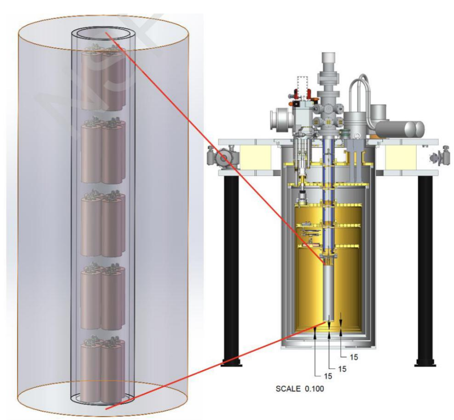


图11. 共振腔安装在稀释制冷机中。

磁铁	磁场强度：9T 磁场有效区域内径：10cm 磁场有效区域长度：70cm
微波共振腔	实验设计探测目标：8-10GHz 试运行频率：从 8GHz 开始，每隔 0.2GHz 分配一个共振腔进行测试。在磁场有效覆盖空间内设置 1-5 层，每层放置 1-4 个共振腔。 计划在共振腔中增加调谐杆或调谐滑块调频。 共振腔的品质因数：10^5
低温系统(稀释制冷机)	环境物理温度：10-100mK
接收机系统	系统温度（物理温度+噪声温度）：0.5K

暗光子暗物质探测

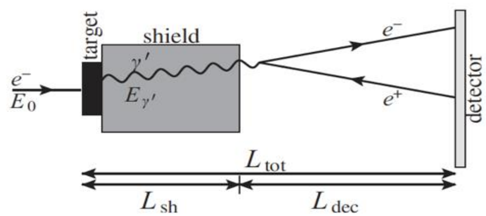
高能加速器实验产生和寻找暗光子

❖ **通过电子对撞或打靶产生暗光子，探测暗光子的衰变末态**

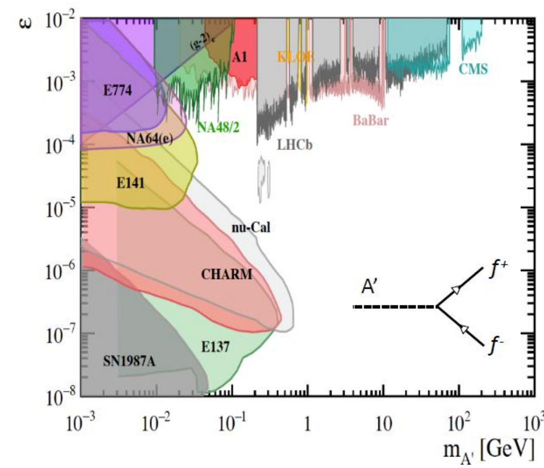
$$e^+e^- \to \gamma A', eZ \to eZA'$$

❑ **探测方式：可见衰变**

正负电子对末态要经过两次普通物质与暗光子作用顶点转换，产生几率很低



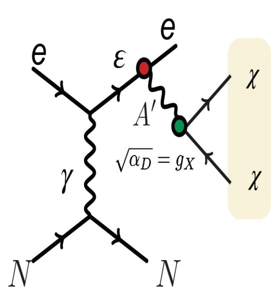
$$N \propto \epsilon^4 \quad \ll \quad N \propto \epsilon^2(1-\epsilon^2) \approx \epsilon^2$$

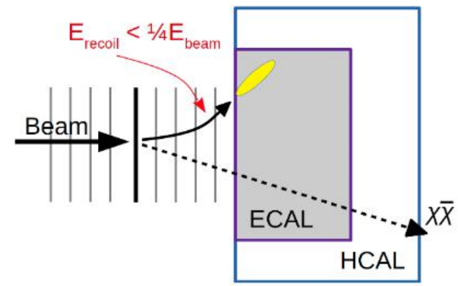


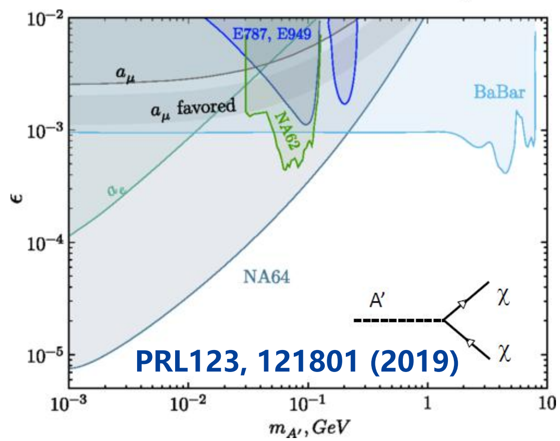
INVISIBLE DECAY MODE $m'_A > 2m_\chi$

❑ **探测方式：不可见衰变**

暗光子与暗物质相互作用几率大实验探测灵敏度高







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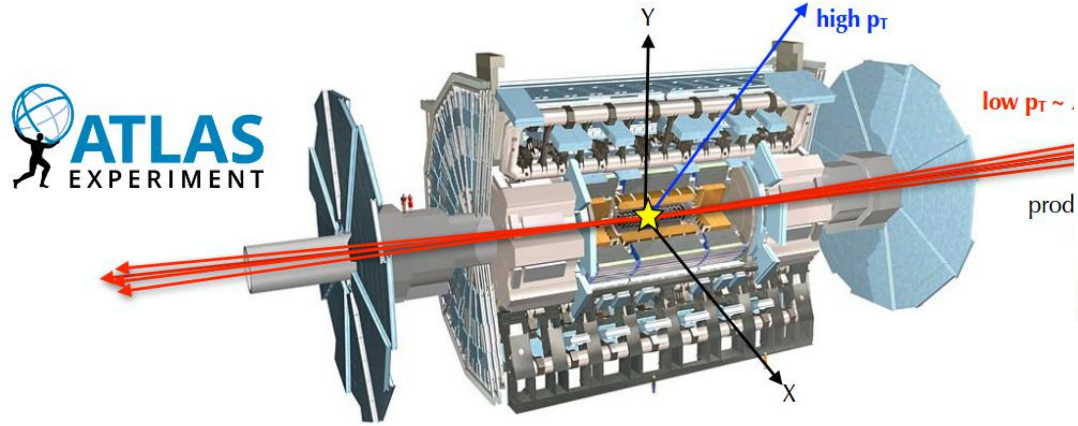
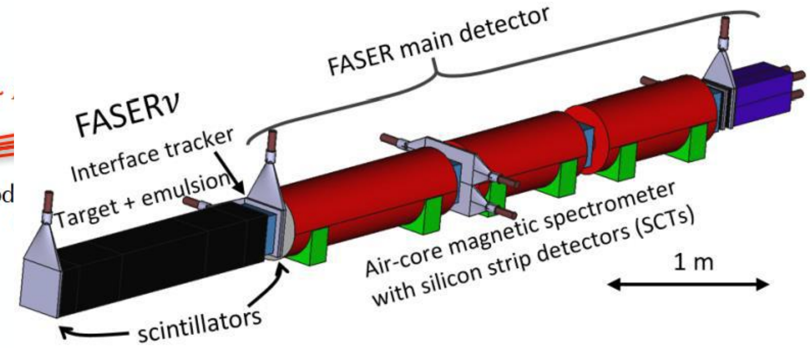
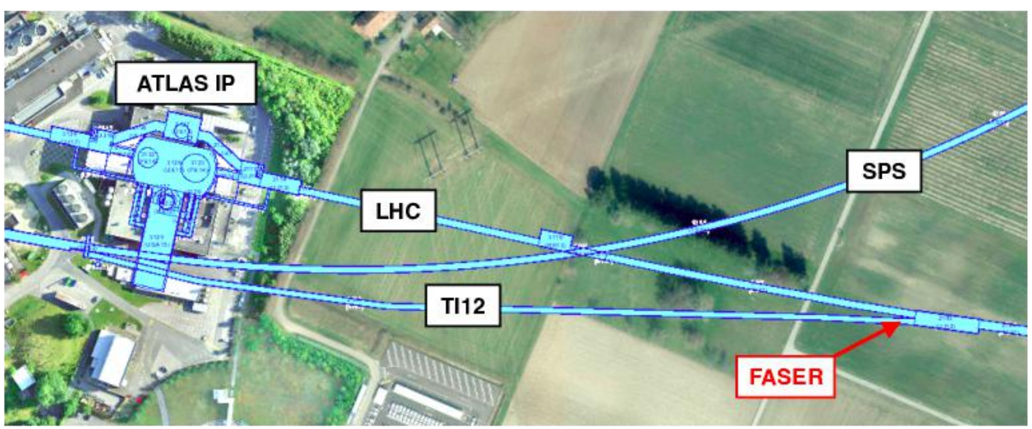
FASER实验

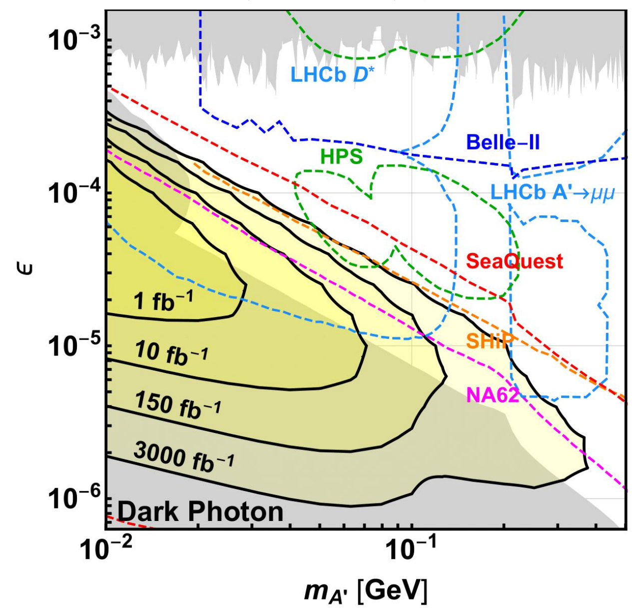






FASER实验寻找类轴子、暗光子等长寿命粒子

暗光子灵敏度区间

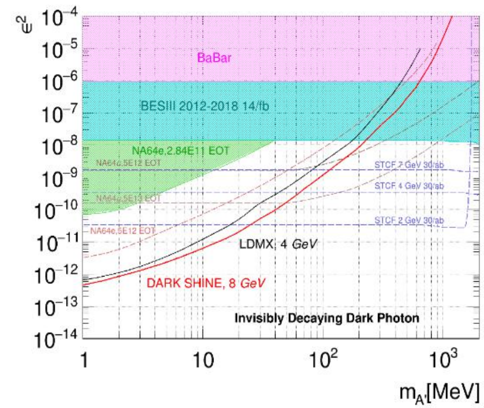


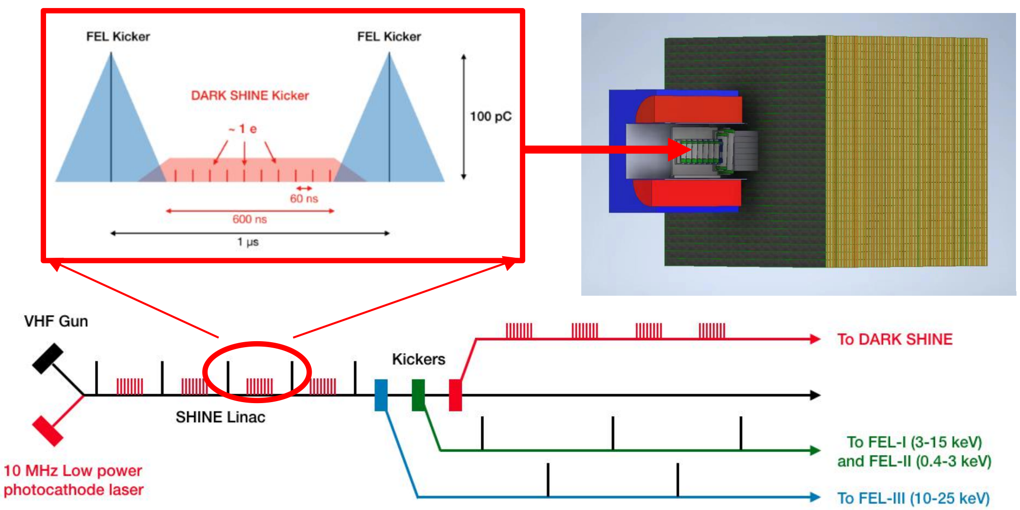
Dark SHINE 暗光实验

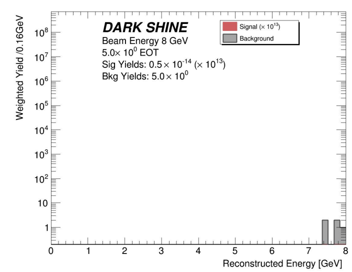
- 电子能量：8 GeV，流强：100pC，频率：1 MHz
- 上海张江科学园区，建设中 (2018 – 2026)
- 上海高研院和上海科大：提供高频单电子束流线(10MHz)
- 每年电子打靶次数： ~ 3×10^{14} EOT
- 交大/李所和复旦等：暗光实验探测器装置的设计和预研

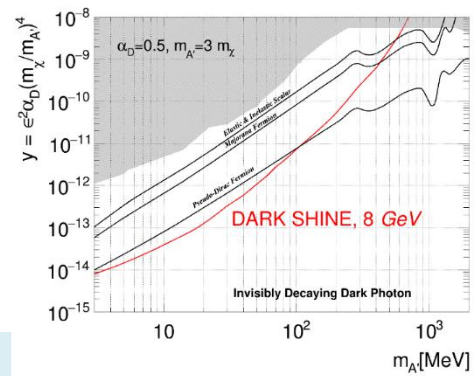
探测器关键技术预研：

- 硅微条探测器
- 电磁量能器(晶体)
- 强子量能器(闪烁体)
- 读出电子学









暗光实验运行一年，预计灵敏度比NA64实验提高2个数量级；检验相关理论预测。

总结

- 暗物质研究是新物理研究的重要方向；
- 暗物质研究需要结合直接、间接和加速器研究，实验和理论研究共同推进；
- 基于CJPL、暗物质卫星、加速器等研究平台，我国科学家开展了多种形式的暗物质研究，近些年取得了很好的研究成果和进展，是我国粒子天体物理学和粒子物理学领域的重要方向；
- 希望暗物质研究能够得到领域、国家的支持，在激烈国际竞争的态势下继续保持国际竞争力！

- 感谢周宇峰、殷鹏飞、高飞、周宁、王毅、马豪、杨丽桃、杨海军、李翔等提供材料，一并致谢！