DM, neutrino scattering and new physics in Xenon-based experiments

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第十七届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会

贵州财经大学，贵阳

2024年07月14日

合作者：陈羽、张炳隆、孙铭辰、陈思远、赵诗涵、宁云松、余涛、高睿萱、林海星、袁意、白爱毓等

*Ref: [1] Z.-H Lei.; **J. Tang**; B.-L. Zhang Chin. Phys. C 2022, 46 (8), 085103.*

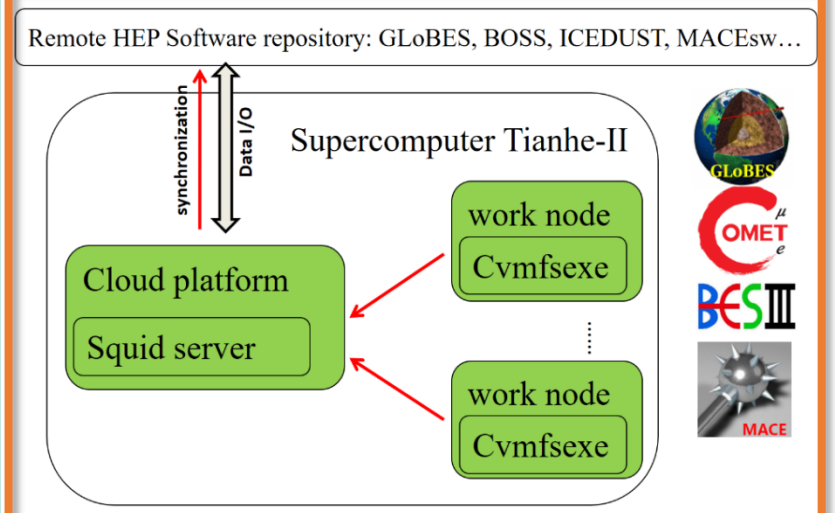
*[2] **J. Tang**, B. L. Zhang, Phys.Rev.D 108 (2023) 6, 062004. **https://github.com/zhangblong/AsymptoticAnalysisAndNeutrinoFog***

*[3] **J. Tang**, B. L. Zhang, arXiv: 2403.05819 , **https://github.com/zhangblong/DistinctionLimit***

内容概述

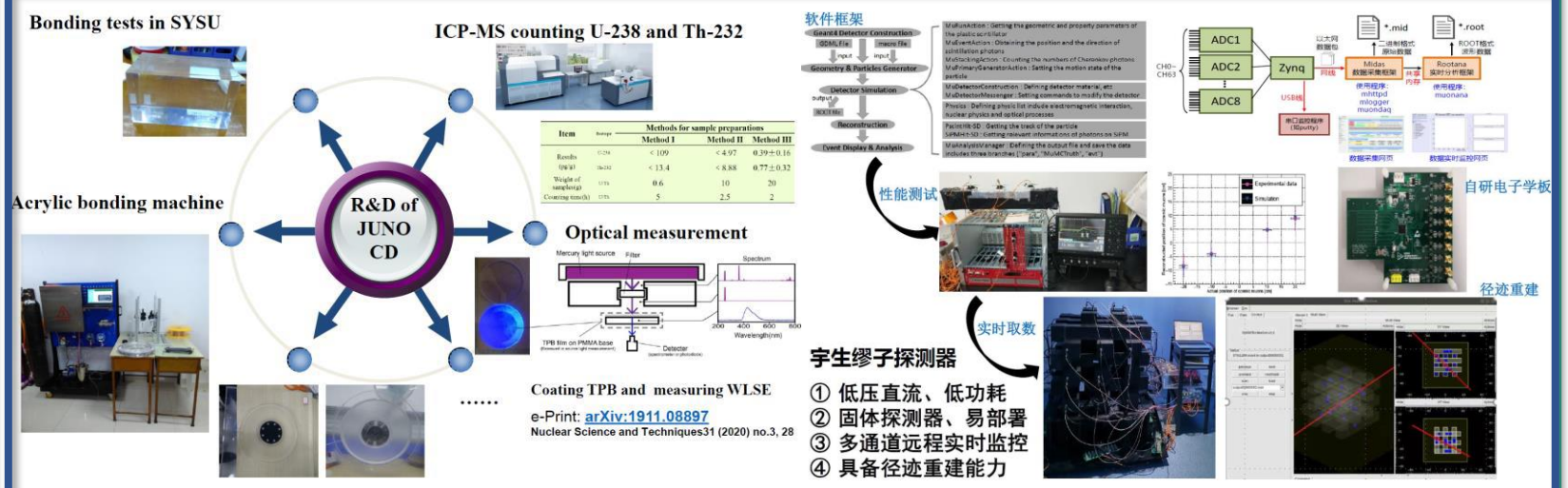
- 这些年，这些事儿
- 暗物质实验的机遇
- 暗物质探测和中微子散射
- 总结和展望

以轻子为探针寻找超越标准模型新物理



依托超级计算机“天河二号”

建设粒子物理实验大数据平台



参与国际大科学合作实验

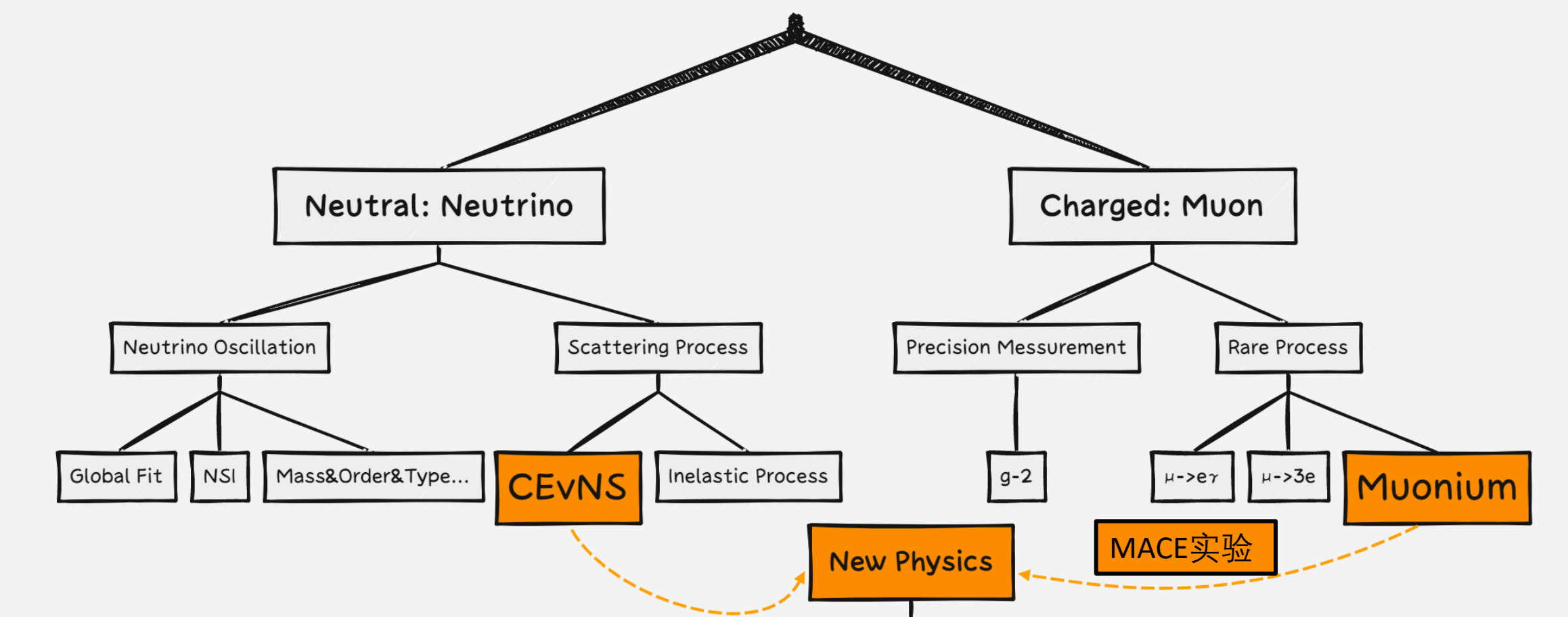
突破低本底探测器关键技术

建设缪子前沿科学与技术应用实验室

积累探测器核心技术面向多学科应用

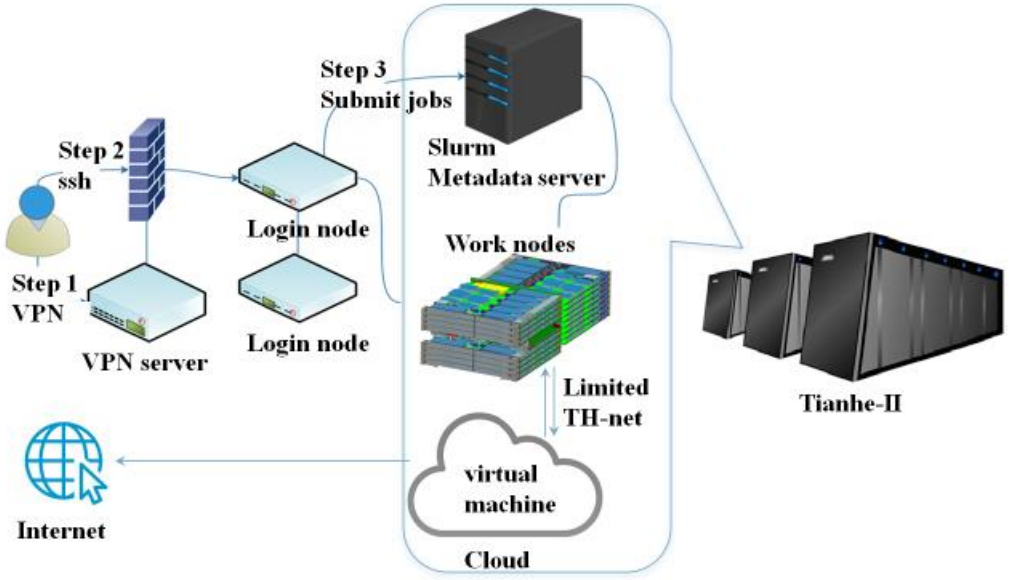
工欲善其事必先利其器，软件平台和硬件研发同步推进

以轻子为探针寻找超越标准模型新物理

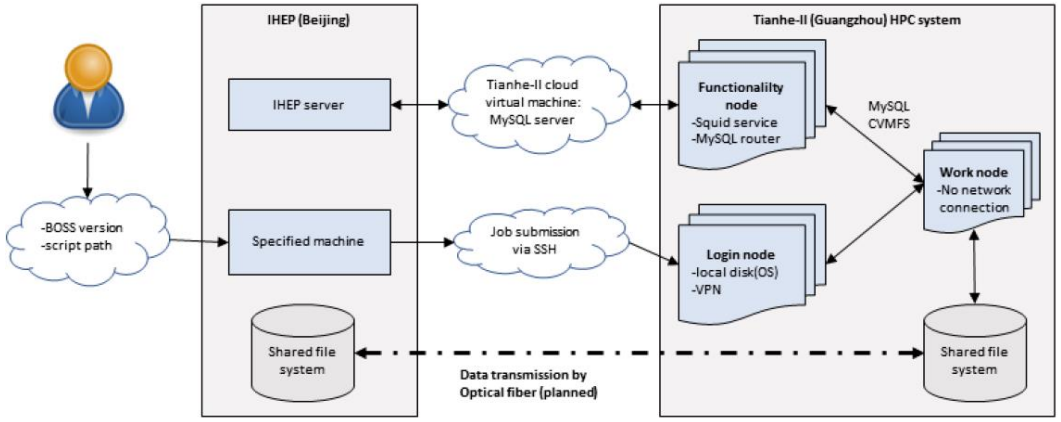


Credit: 张炳隆

超算中心“天河二号”部署粒子物理实验大数据平台



JINST 18 (2023) 03, T03003




荣誉证书

中山大学唐健团队：

贵团队“天河二号超级计算机在BESIII实验上的应用”项目在2022年度“天河二号”超算优秀应用评选活动中，荣获“2022‘天河之星’优秀应用奖”。

特发此证，以资鼓励。

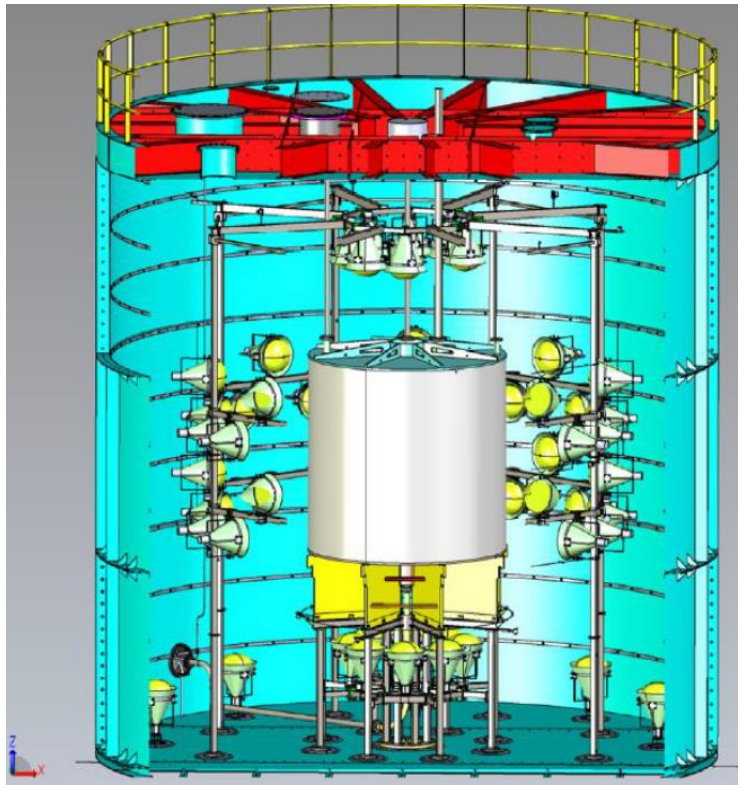
国家超级计算广州中心

2023年12月1日

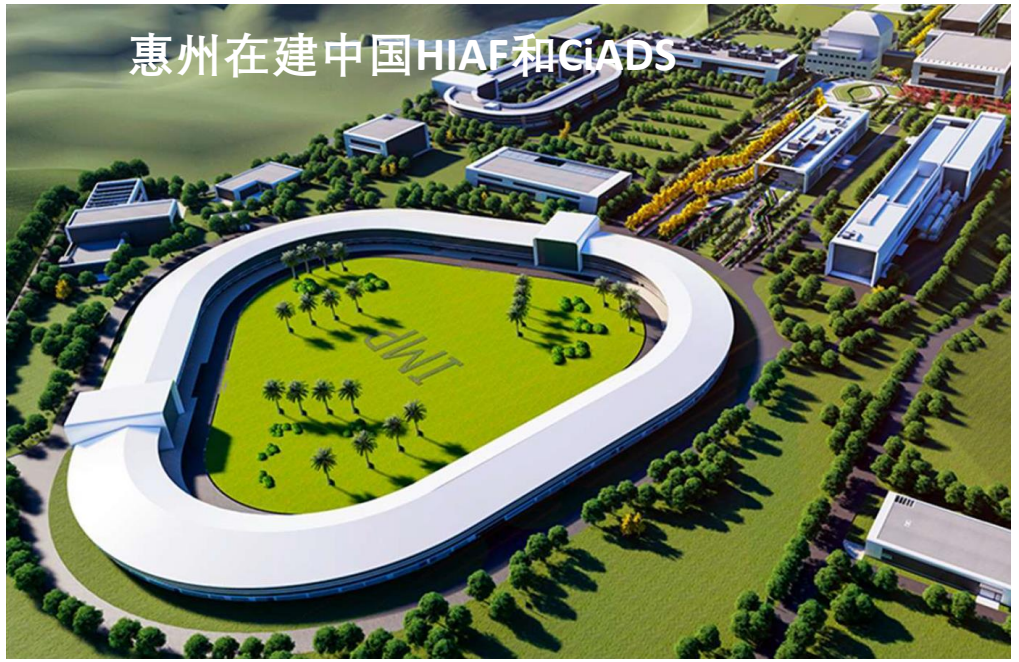
tangjian5@mail.sysu.edu.cn

突破中微子实验探测器关键技术

- 技术应用：
  （1）世界上最大的有机玻璃球形探测器，直径35.4米，厚度12厘米，重约600吨
  解决支撑节点强度不足的工艺问题，满足苛刻的物理需求。
  （2）**国际大科学工程**江门中微子实验采用中山大学开发的工艺技术
  （3）**成功研制并交付**同类型探测器，监测液闪痕量级同位素Rn-222



粤港澳大湾区是强流加速器的聚集地



Ref：中科院高能所，王生研究员报告

Ref：中科院近物所，东江实验室詹文龙院士报告

(1) 国际上加速器缪子源，已有美国FNAL，瑞士PSI，日本J-PARC，英国ISIS

(2) 依托粤港澳大湾区的强流加速器（ CSNS, CiADS, HIAF），即将建设国内强流加速器缪子源？

(3) 基于加速器缪子源开展前沿研究?

欢迎参加第二届惠州大科学装置高精度物理研讨会， 8月23日-26日，广州

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Snowmass2021 whitepaper

March 23, 2022

arXiv: 2203.11406

Muonium to antimuonium conversion: Contributed paper for Snowmass 21

Ai-Yu Bai,[1] Yu Chen,[1] Yukai Chen,[2] Rui-Rui Fan,[2] Zhilong Hou,[2] Han-Tao Jing,[2] Hai-Bo Li,[2] Yang Li,[2] Han Miao,[2,3] Huaxing Peng,[2,3] Alexey A. Petrov (Coordindator),[4] Ying-Peng Song,[2] Jian Tang (Coordinator),[1] Jing-Yu Tang,[2] Nikolaos Vassilopoulos,[2] Sampsa Vihonen,[1] Chen Wu,[5] Tian-Yu Xing,[2] Yu Xu,[1] Ye Yuan,[2] Yao Zhang,[2] Guang Zhao,[2] Shi-Han Zhao,[1] and Luping Zhou[2]

[1] *School of Physics, Sun Yat-sen University, Guangzhou 510275, China*
[2] *Institute of High Energy Physics, Beijing 100049, China*
[3] *University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
[4] *Department of Physics and Astronomy Wayne State University, Detroit, Michigan 48201, USA*
[5] *Research Center of Nuclear Physics (RCNP), Osaka University, Japan*

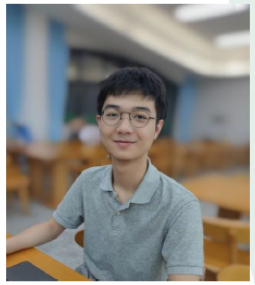
The spontaneous muonium to antimuonium conversion is one of the interesting charged lepton flavor violation processes. It serves as a clear indication of new physics and plays an important role in constraining the parameter space beyond Standard Model. MACE is a proposed experiment to probe such a phenomenon and expected to enhance the sensitivity to the conversion probability by more than two orders of magnitude from the current best upper constraint obtained by the PSI experiment two decades ago. Recent developments in the theoretical and experimental aspects to search for such a rare process are summarized.

- 欢迎更多同行的加入，共同推进MACE实验

Snowmass2021后的反响

Progress of Muonium-to-Antimuonium Conversion Experiment (MACE)

Workshop on a Future Muon Program at Fermilab



2023-03-28

Shihan Zhao

zhaoshh7@mail2.sysu.edu.cn

Muonium-to-Antimuonium Conversion Experiment

MACE working group: Ai-Yu Bai,[1] Yu Chen,[1] Yukai Chen,[2] Rui-Rui Fan,[2] Zhilong Hou,[2] Han-Tao Jing,[2] Hai-Bo Li,[2] Yang Li,[2] Han Miao,[2] Huaxing Peng,[2] Ying-Peng Song,[2] Jian Tang,[1] Jing-Yu Tang,[2] Nikolaos Vassilopoulos,[2] Chen Wu,[3] Tian-Yu Xing,[2] Yu Xu,[1] Ye Yuan,[2] Yao Zhang,[2] Guang Zhao,[2] Shihan Zhao,[1] and Luping Zhou[2]

[1]*School of physics, Sun Yat-sen University, China*

[2]*Institude of High Energy Physics, Chinese Academy of Science, China*

[3]*Research Center of Nuclear Physics, Osaka University, Japan*

Reference: Snowmass2021 Whitepaper: Muonium to antimuonium conversion, arXiv:2203.11406

受邀参加美国费米实验室未来缪子源研讨会，线上报告

会议文集https://arxiv.org/abs/2309.05933

受邀参加德国海德堡大学CLFV2023，大会报告

MACE工作组

July 13, 2024

Conceptual Design of Muonium-to-Antimuonium Conversion Experiment (MACE)

Ai-Yu Bai,[1] Hanjie Cai,[2] Xurong Chen,[2] Siyuan Chen,[1] Weibin Cheng,[3] Yu Chen,[1] Yukai Chen,[4] Rui-Rui Fan,[4] Li Gong,[3] Yinyuan Huang,[3] Zhilong Hou,[4] Huan Jia,[2] Han-Tao Jing,[4] Xiaoshen Kang,[3] Hai-Bo Li,[4,5] Yang Li,[4] Guihao Lu,[1] Han Miao,[4,5] Yunsong Ning,[1] Huaxing Peng,[4,5] Alexey A. Petrov,[6] Ying-Peng Song,[4] Mingchen Sun,[1] Jian Tang,[1] Jing-Yu Tang,[4] Nikolaos Vassilopoulos,[4] Sampsa Vihonen,[1] Chen Wu,[7] Rong Wang,[2] Weizhi Xiong,[8] Tian-Yu Xing,[4,5] Yu Xu,[1] Ye Yuan,[4,5] Yao Zhang,[4] Guang Zhao,[4] Shihan Zhao,[1] and Luping Zhou[4]

[1]*School of Physics, Sun Yat-sen University, Guangzhou 510275, China*

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[4]*Institute of High Energy Physics, Chinese Academy of Science Beijing 100049, China*

[5]*University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*

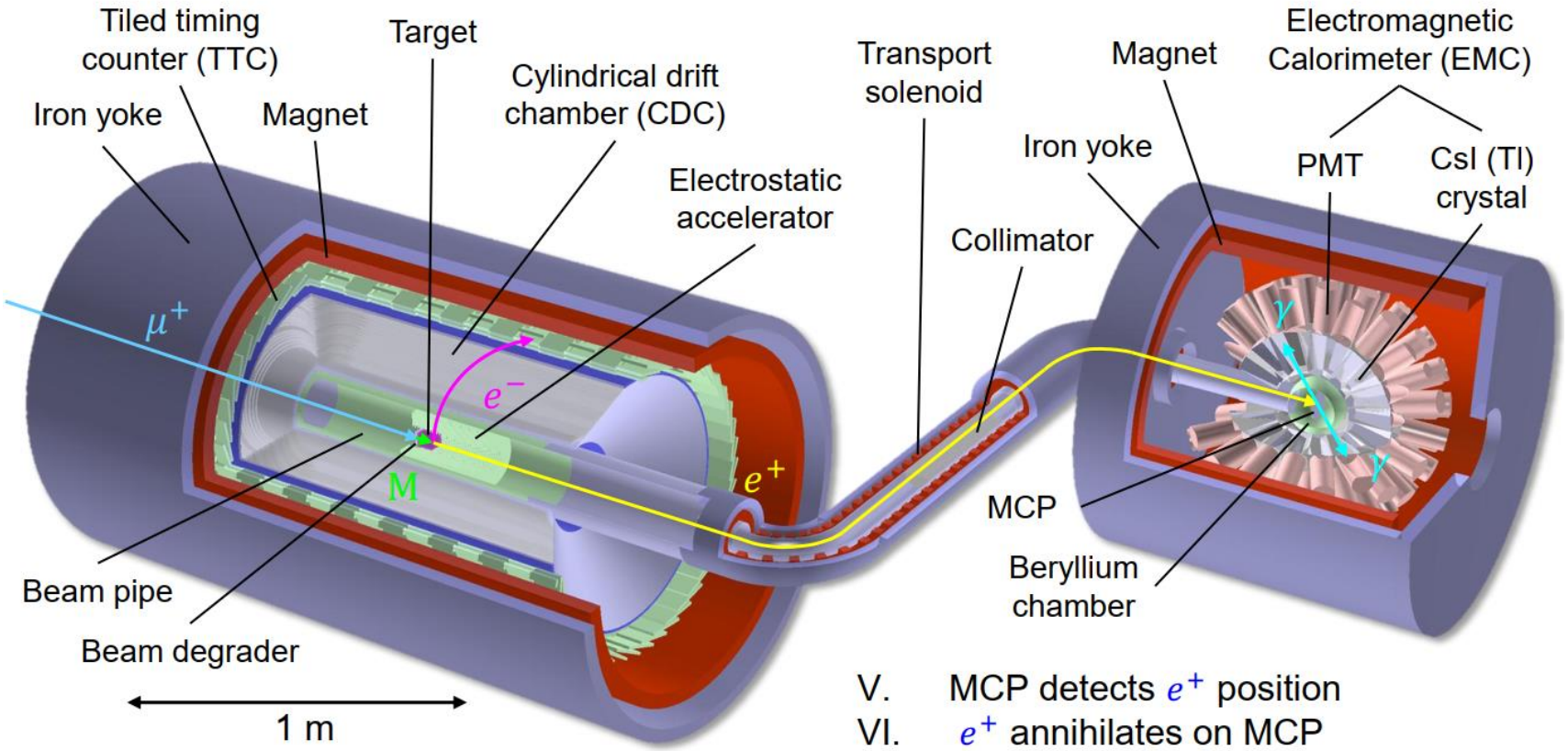
[6]*Department of Physics and Astronomy Wayne State University, Detroit, Michigan 48201, USA*

[7]*Research Center of Nuclear Physics (RCNP), Osaka University, Japan*

[8]*Institute of Frontier and Interdisciplinary Science, Shandong University*

- 欢迎更多同行的加入，共同推进MACE实验

MACE实验设计的进展



I. Surface muon → target → muonium
II. Decay in a vacuum: $\bar{M} \rightarrow e^+e^-\nu_\mu\bar{\nu}_e$
III. CDC detects Michel e^- track
IV. Transport atomic e^+ to MCP (conserving transverse position)
V. MCP detects e^+ position
VI. e^+ annihilates on MCP
VII. EMC detects 2 back-to-back annih. γ

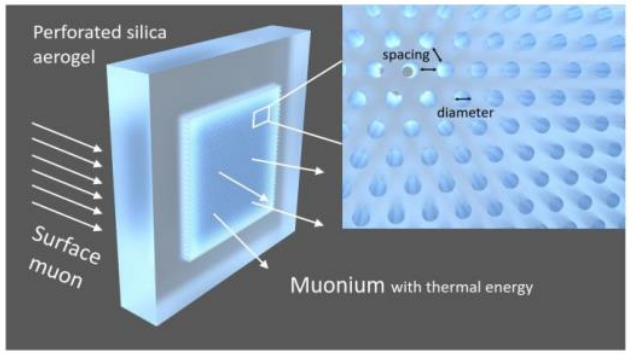
Triple coincidence:

➢ **CDC/TTC + MCP + EMC**

↓

Michel e^- Atomic e^+

Shihan Zhao and Jian Tang, Optimization of muonium yield in perforated silica aerogel, Phys. Rev. D 109, 072012



- 参与撰写惠州大科学装置计划书
- 正电子输运和量能器的技术文章
- MACE实验CDR积极撰写中…
- 攻坚克难，合作共赢

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CRμSR谱仪→低能大气中微子建模

$$K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu}_{\mu}), \pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu}_{\mu})$$

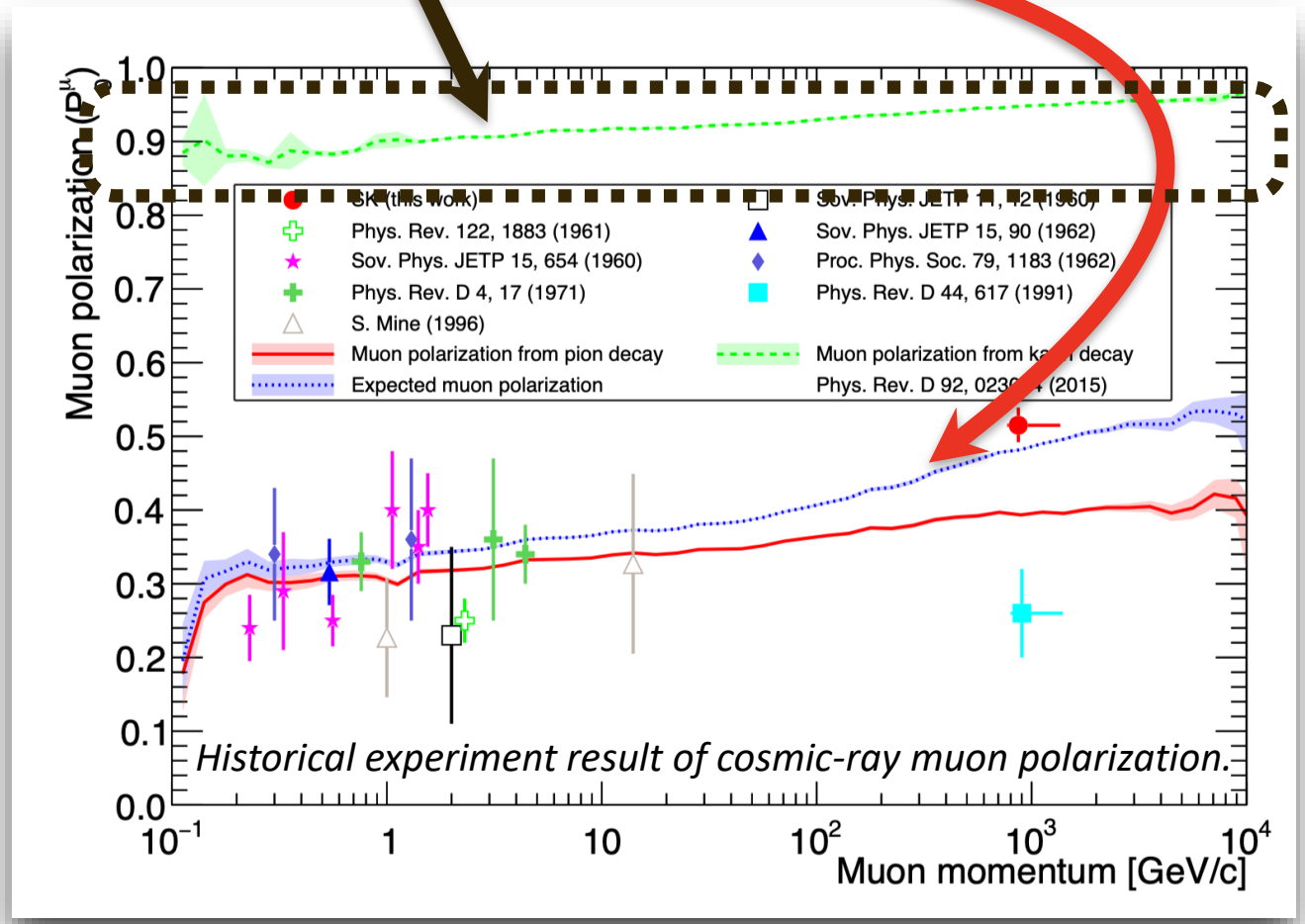
- $\pi - K$ ratio will improve precision of atmospheric neutrino model.

Muon polarization effect by the initial momentum

- $m(\pi^{\pm}) \simeq 139\mathrm{MeV}, m(K^{\pm}) \approx 493\mathrm{MeV}$.

$$|\vec{p}_{\mu,K}| > |\vec{p}_{\mu,\pi}|$$

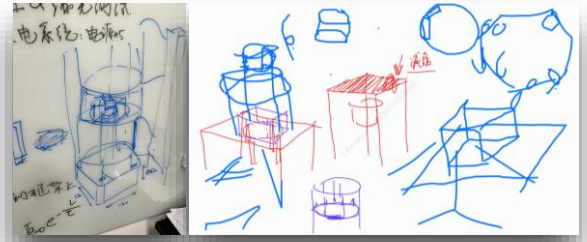
- Measuring the magnitude of cosmic-ray muon polarization helps constrain the $\pi - K$ ratio to the muon flux.



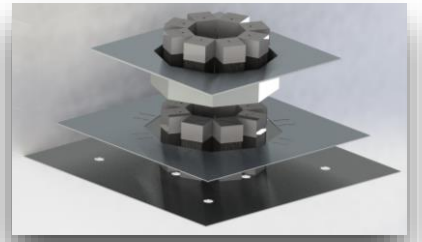
Ref: Super-Kamiokande Collaboration. arXiv: 2403.08619

CRμSR谱仪的研制

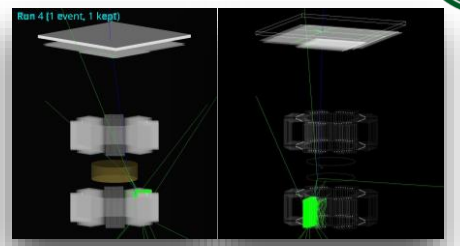
CRμSR during data acquiring process.



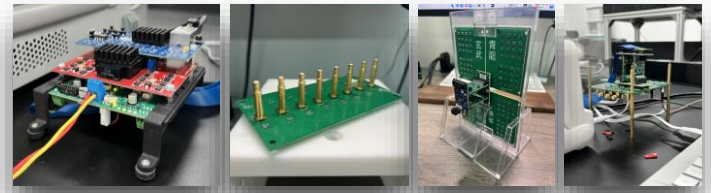
Strange thought during the nucleic acid for Covid .



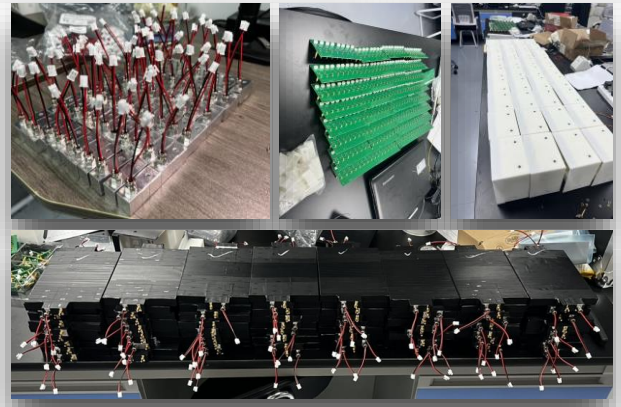
First design for 2 PDR



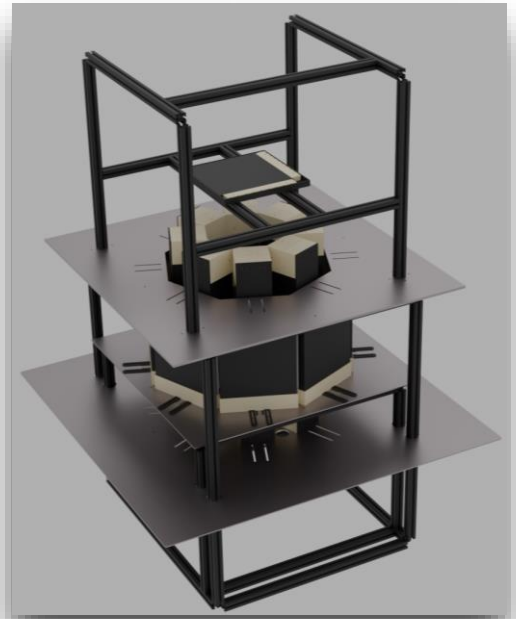
Signal and background simulation



Develop and testing the electronic.(Mainly by Yi Yuan and Yu Chen)

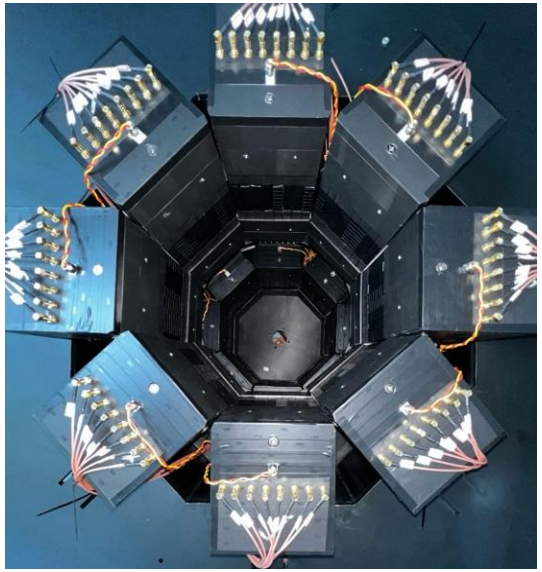


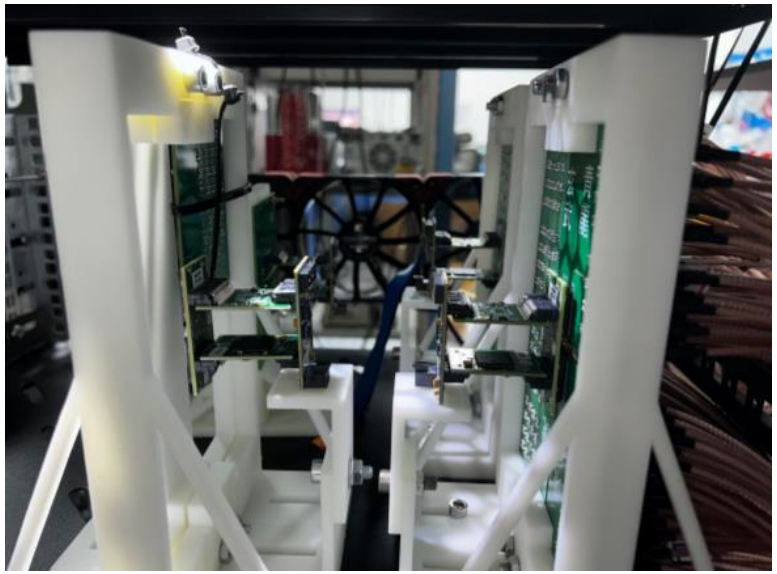
Encapsulation progress. (By SMOOTH lab)

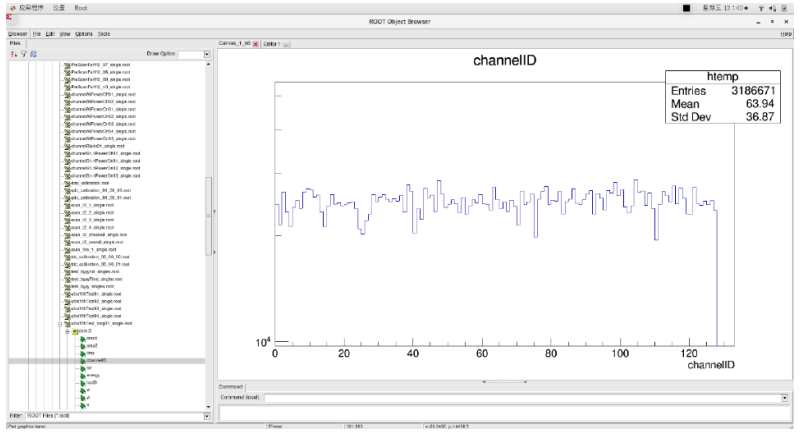


Final design of CRmuSR

CRμSR谱仪的研制







Credit: *孙铭辰、余涛、宁云松、白爱毓等*

“优秀的工程师会给自己留够余量”

By *宁云松*

不走寻常路，期待有惊喜!

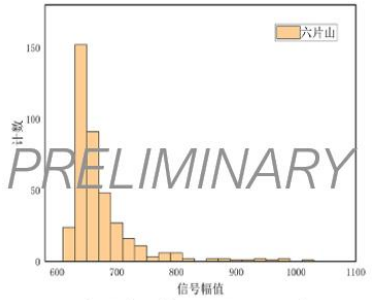
缪子探测：教学与科研融合

架设CRμSR探测器阵列的物联网

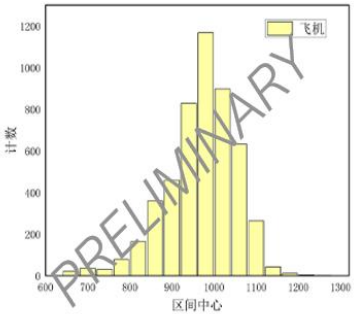
SMOOTH Portable Cosmic-ray Muon detector (SMOOTH-PCμ)

SMOOTH Portable cosmic-ray muon detector

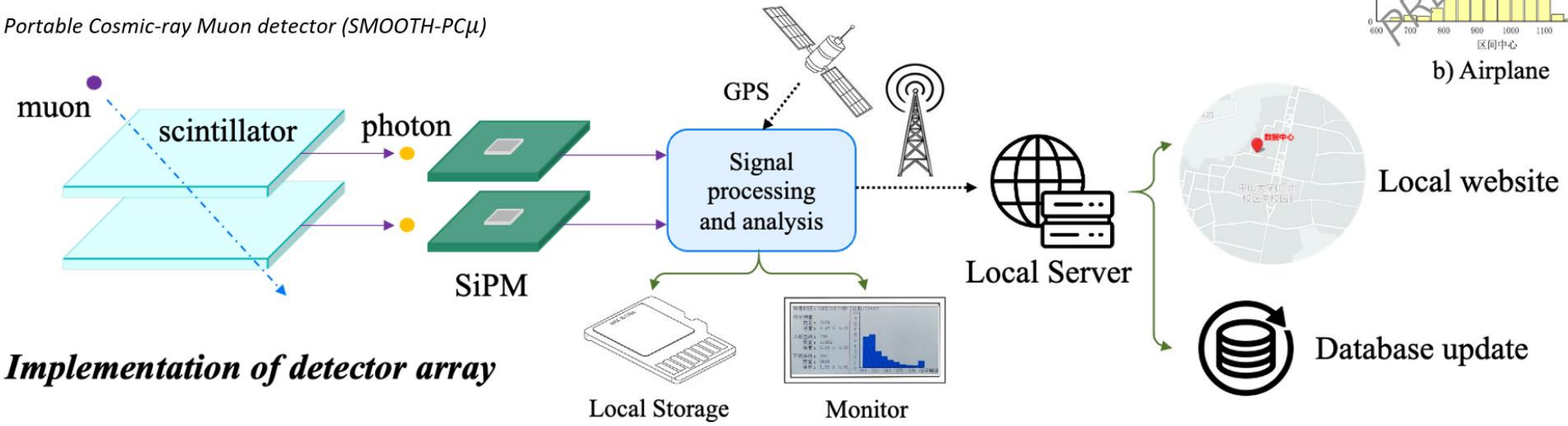
- Contains location information, signal magnitude and flux.
- Implementing data backhaul using base stations.
- Successfully completed field test.



a) Liupian Mountain



b) Airplane



Implementation of detector array

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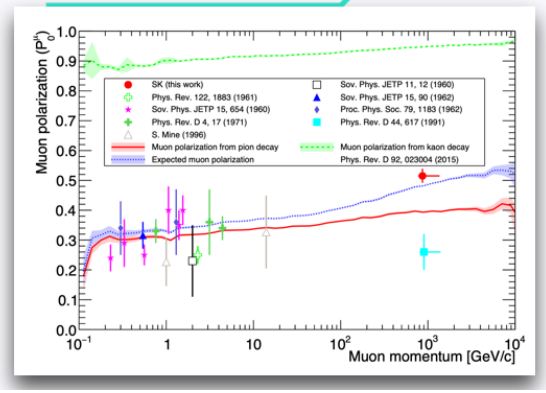
星星之火可以燎原

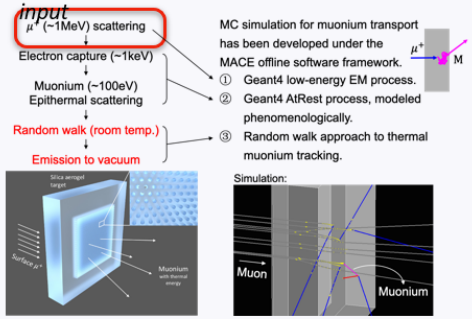
Study of low energy cosmic-ray muon with spin spectroscopy array

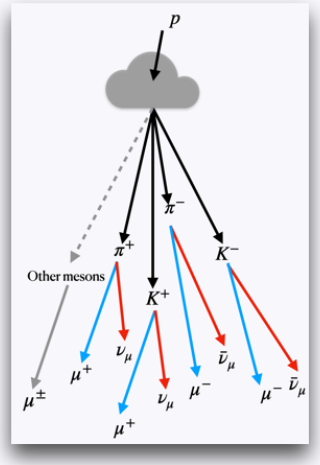
Motivation
- atmospheric neutrino model
- future experiments
- muon related application

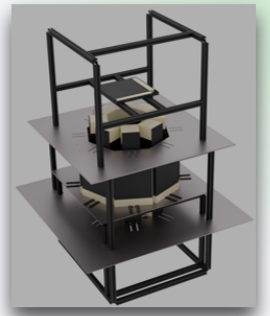
P_μ in history
- high energy (Super-K)
- low energy (update before 1980)

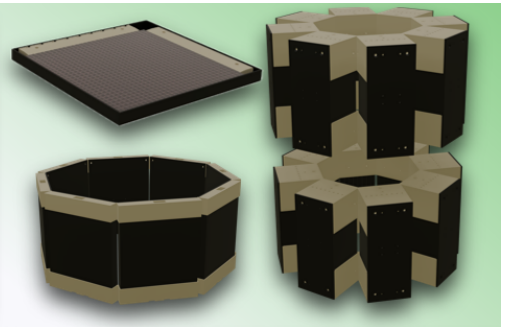


Polarization

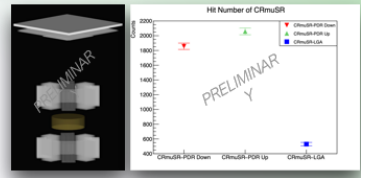






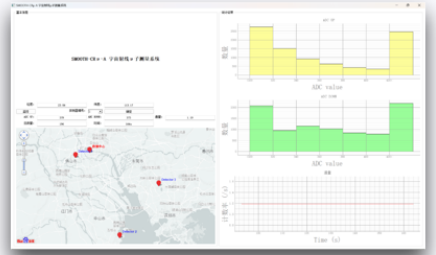


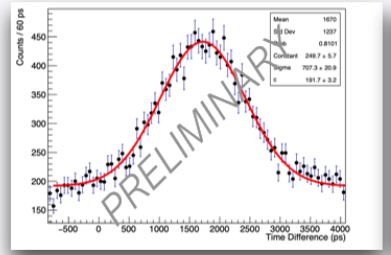
CRmuSR design
- measure the cosmic-ray muon momentum direction — LGA
- measure the Michel electron azimuth angular distribution — PDR
- Veto

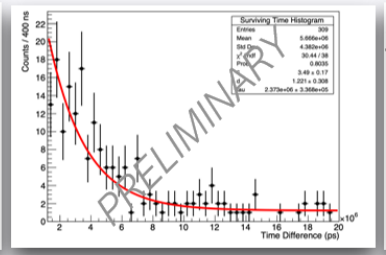


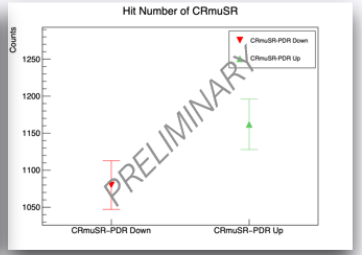
CRmuSR simulation & result
- simulation result
  - LGA performance
  - Michel electron up-down asymmetry
- experiment data
  - PDR performance
  - cosmic-ray muon lifetime
  - Michel electron up-down asymmetry

system of array — UI





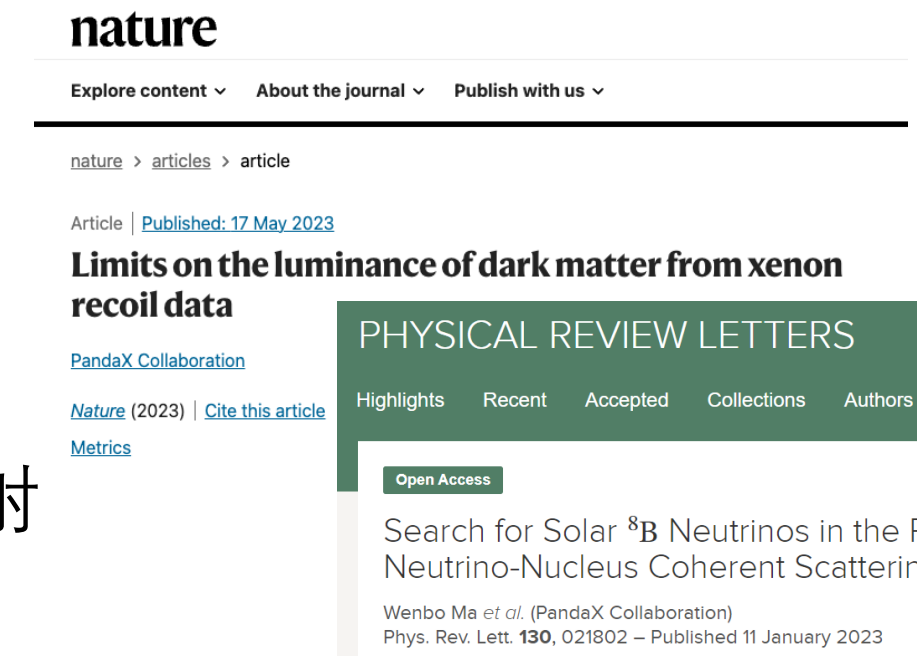




tangjian5@mail.sysu.edu.cn

内容概述

- 这些年，这些事儿
- 暗物质实验的机遇
- 暗物质探测和中微子散射
- 总结和展望



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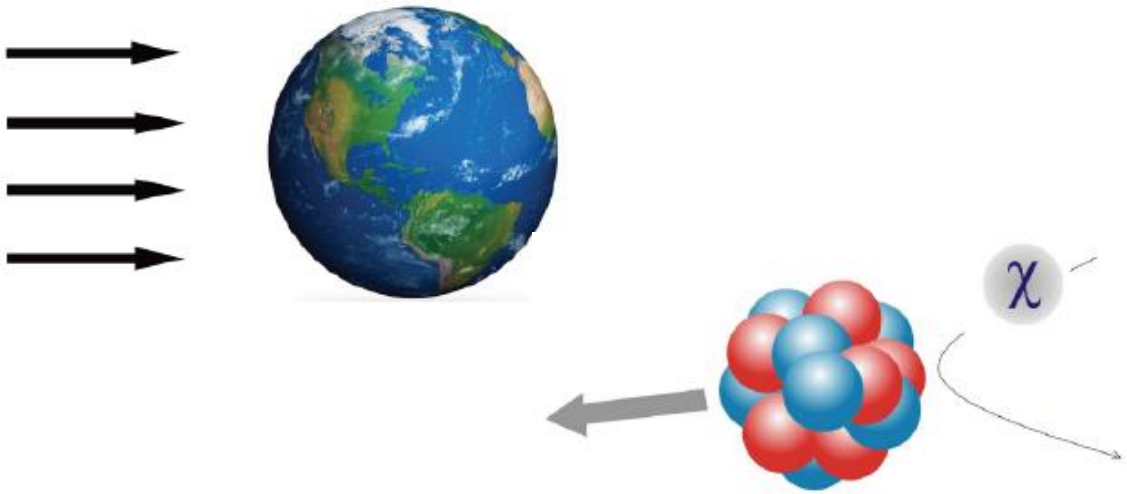
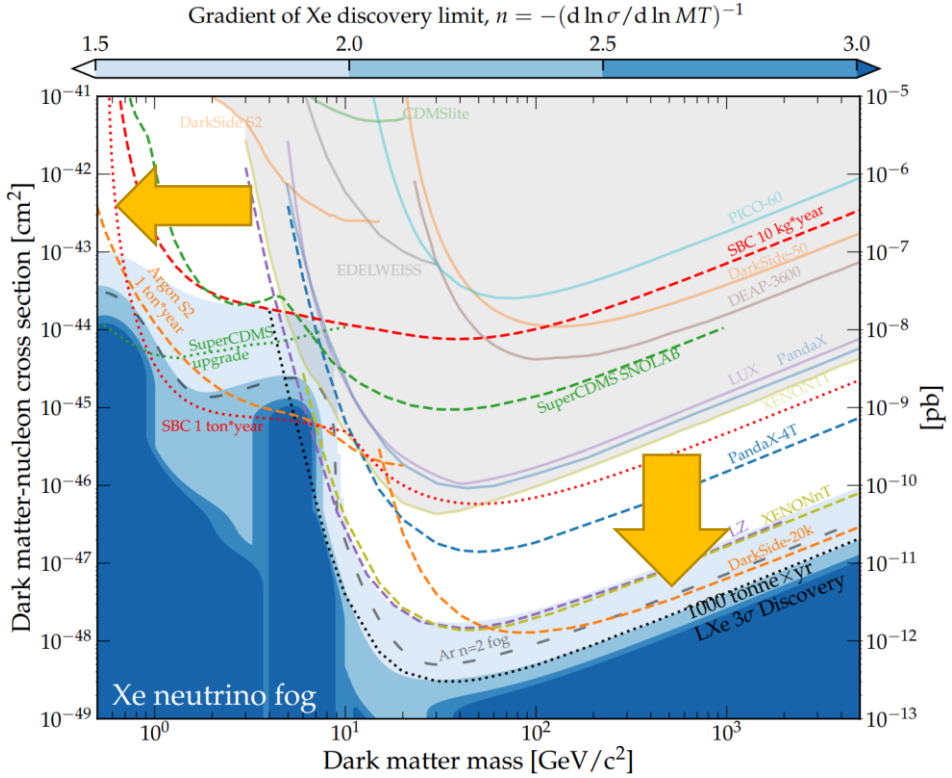
暗物质直接探测

- **Billions of DM may be passing through the Earth every second, but they interact very rarely.**
- **Direct detection experiments operate underground and search for DM via NR/ER.**





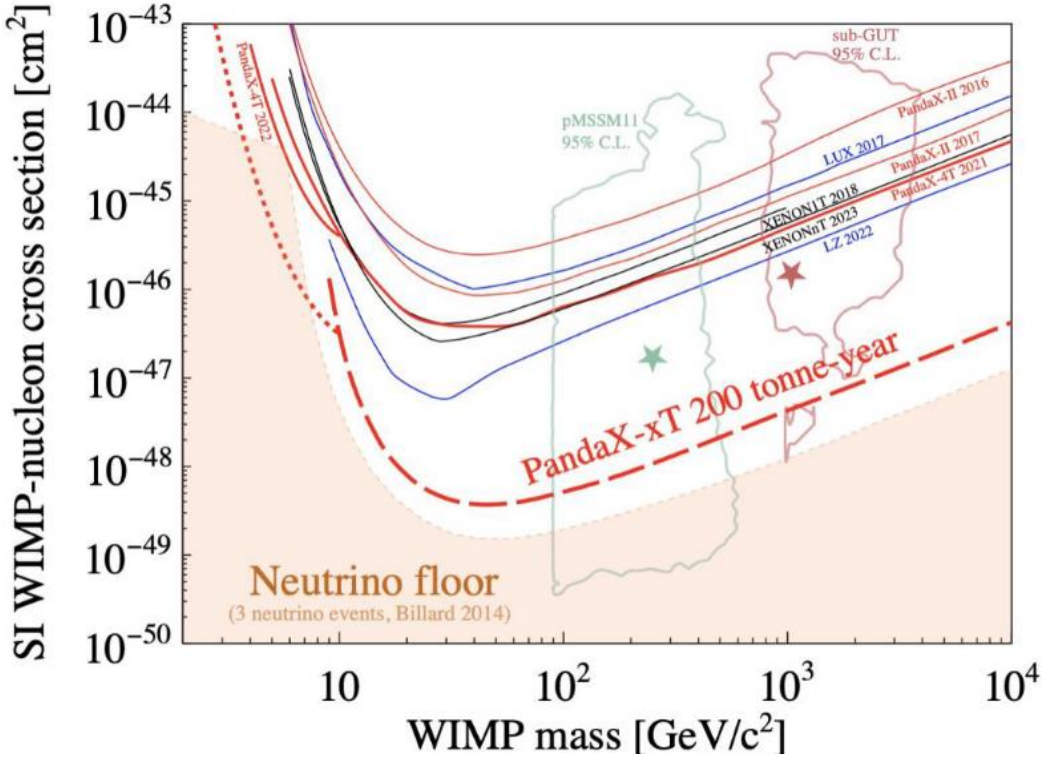
暗物质探测现状

Snowmass2021 Cosmic Frontier Dark Matter Direct Detection to the Neutrino Fog (2203.08084)

暗物质实验的发展趋势

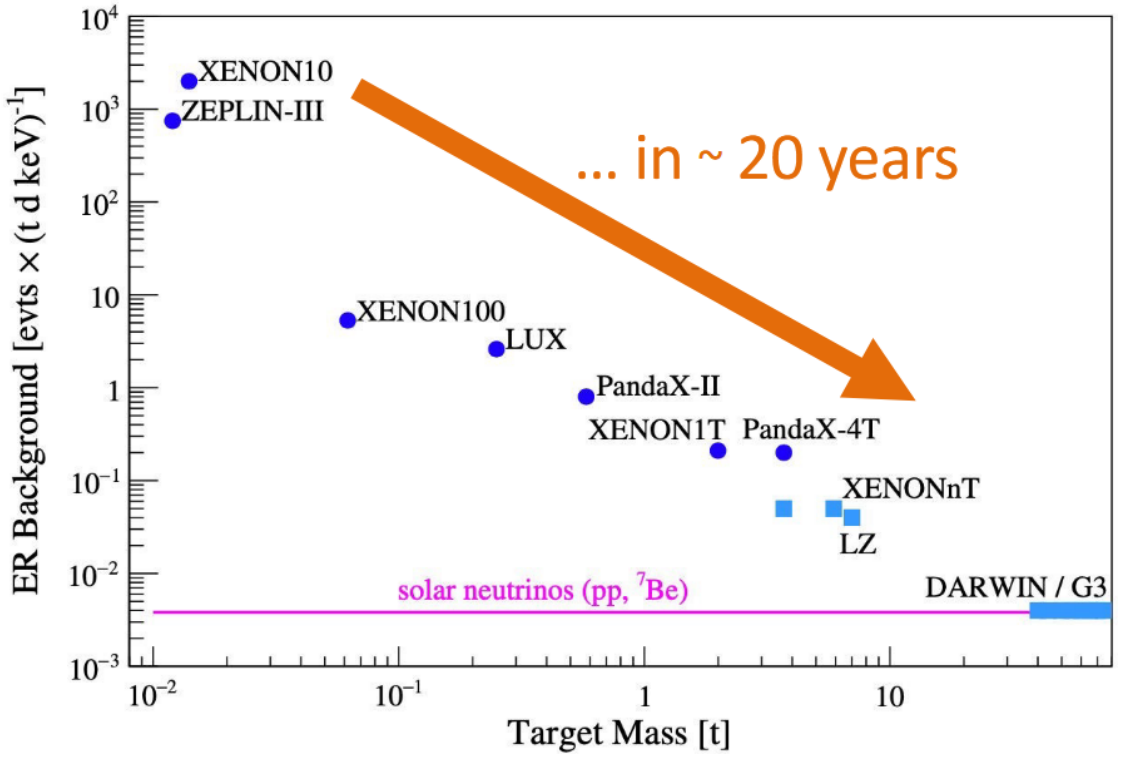
- 未来暗物质直接探测实验具有更高的灵敏度
- 未来实验探测器靶质量更大，本底更低

PandaX: status and future. Jianglai Liu's talk. PandaX collaboration.



我国PandaX未来实验探测暗物质的灵敏度

The DARWIN project. Julien Masbou's talk. DARWIN collaboration.



未来暗物质直接探测实验趋势

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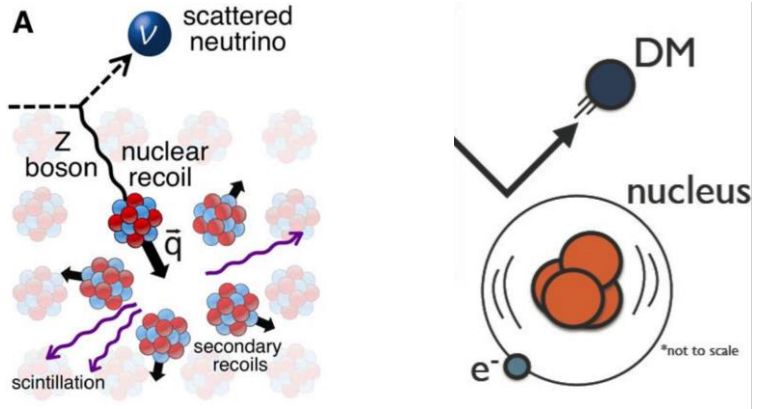
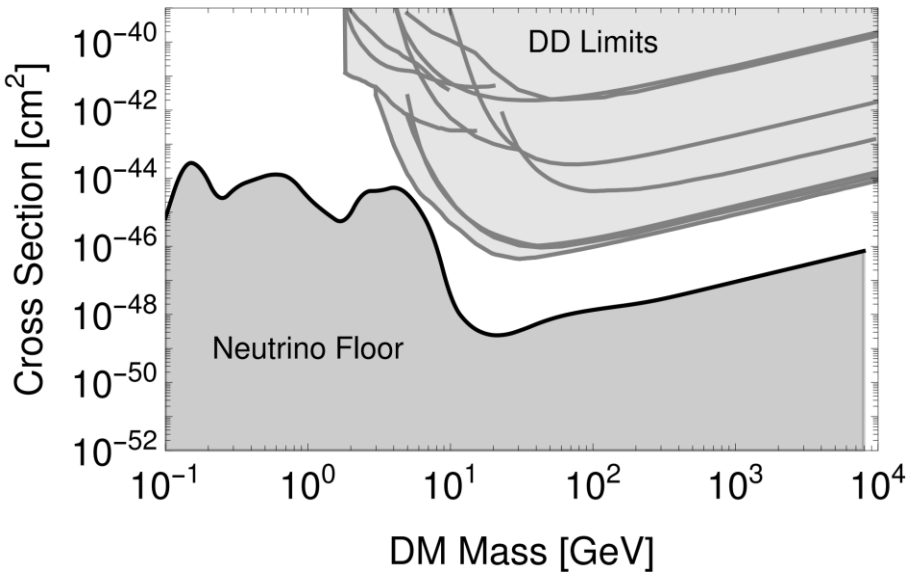
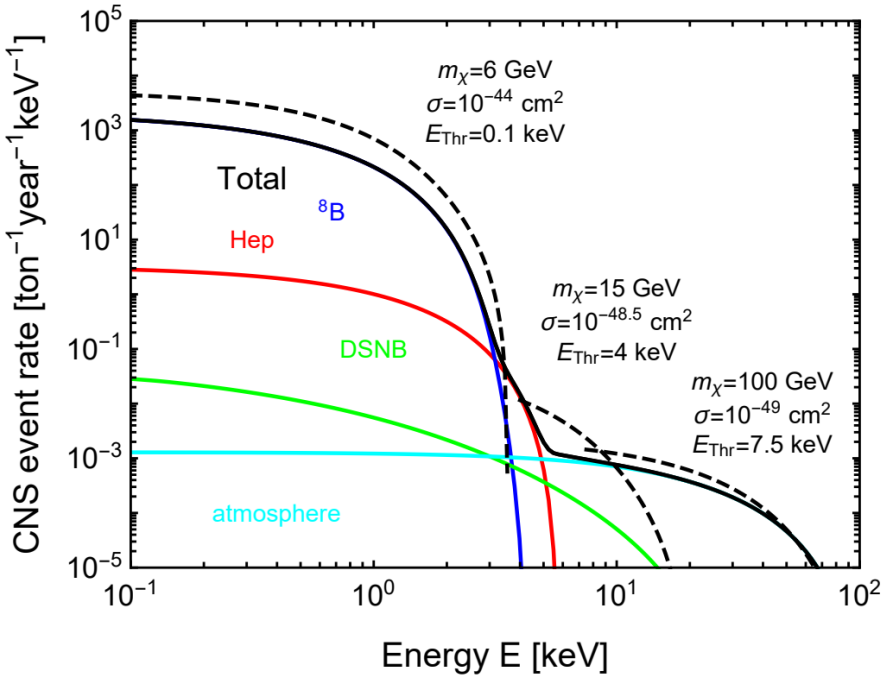
核反冲：暗物质 v.s 中微子

- 在暗物质探测器中，暗物质散射和**中微子核子散射**的响应非常接近
- **未来大型暗物质探测器**提高探测灵敏度将触及必然的中微子本底，从而出现**中微子迷雾**





中微子地板新定义—中微子迷雾



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内容概述

- 这些年，这些事儿
- 暗物质实验的机遇
- 暗物质探测和中微子散射
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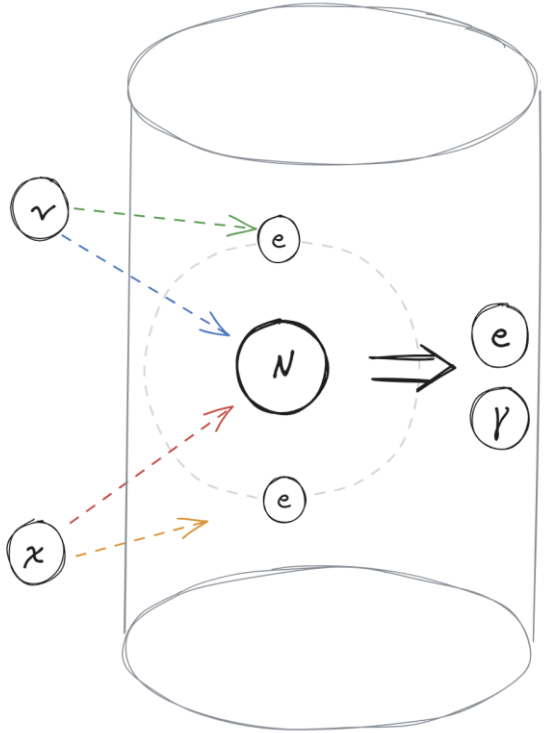
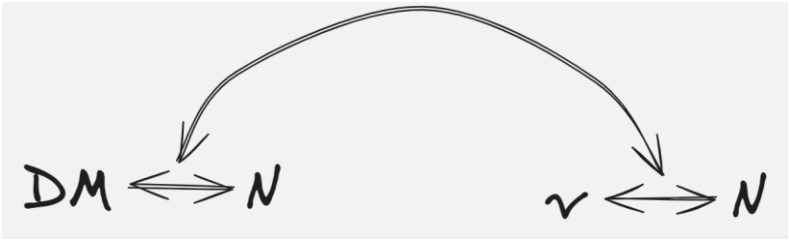
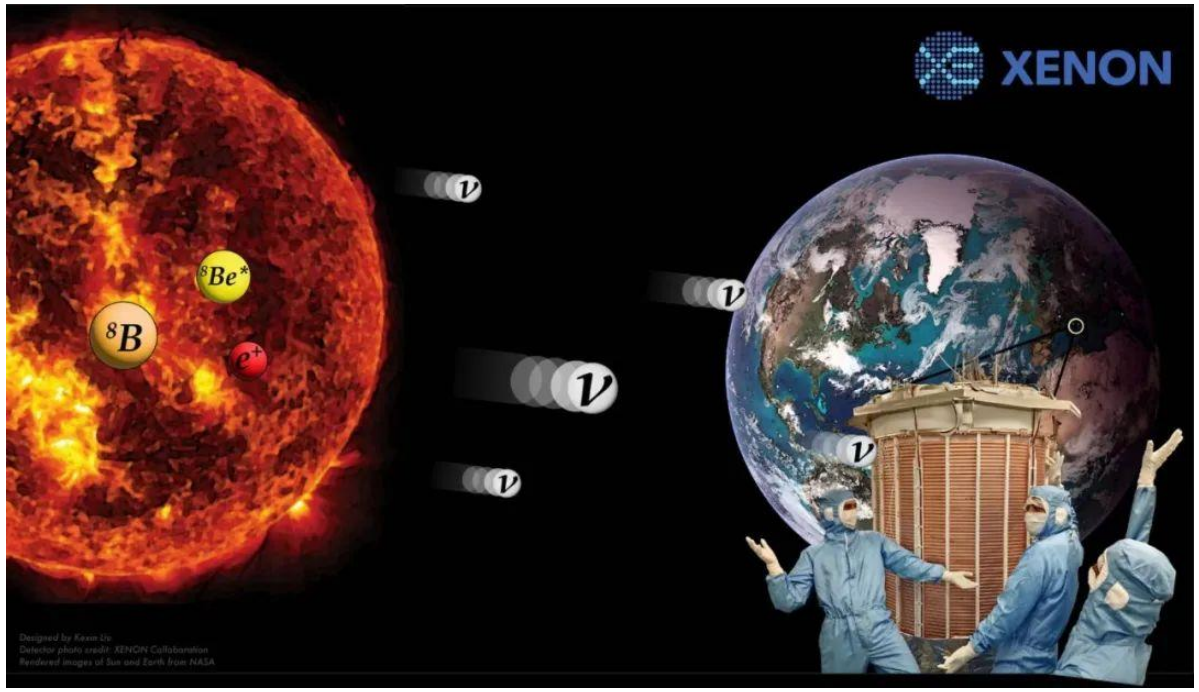
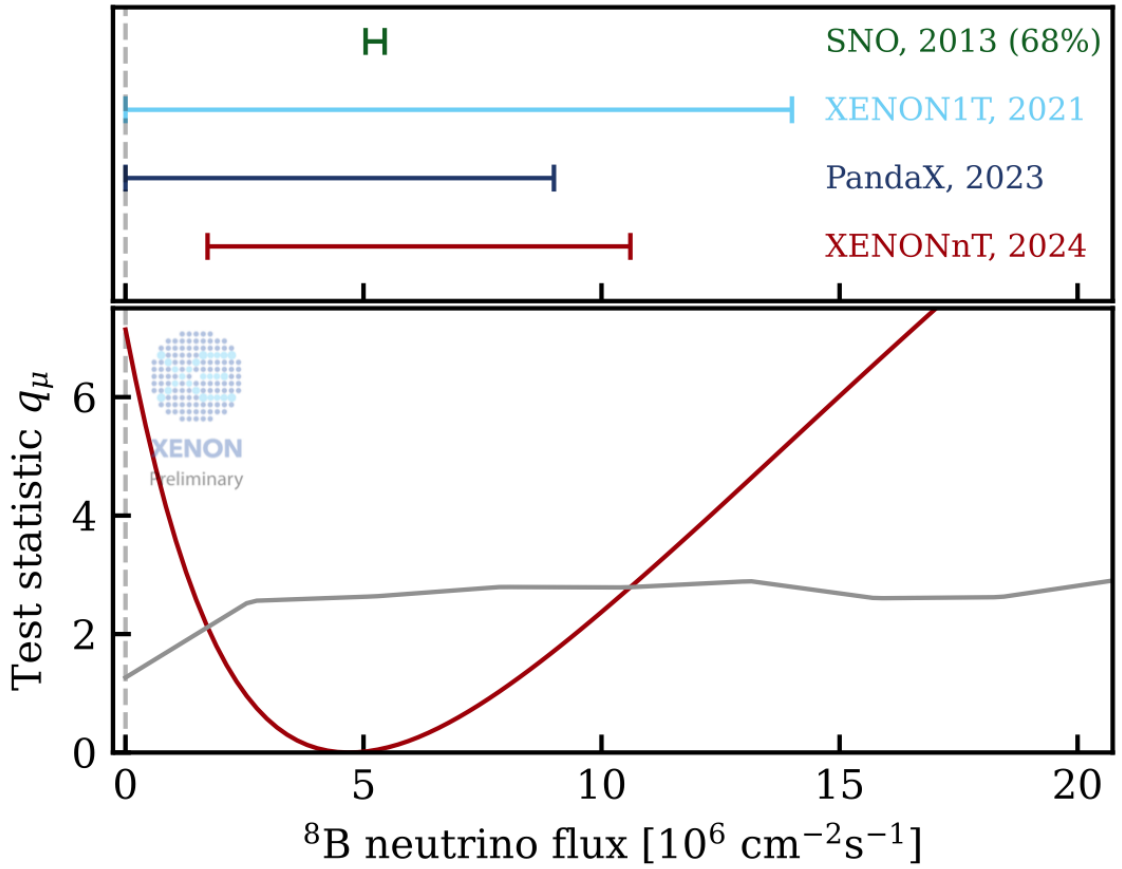




Neutrino physics at DM experiments

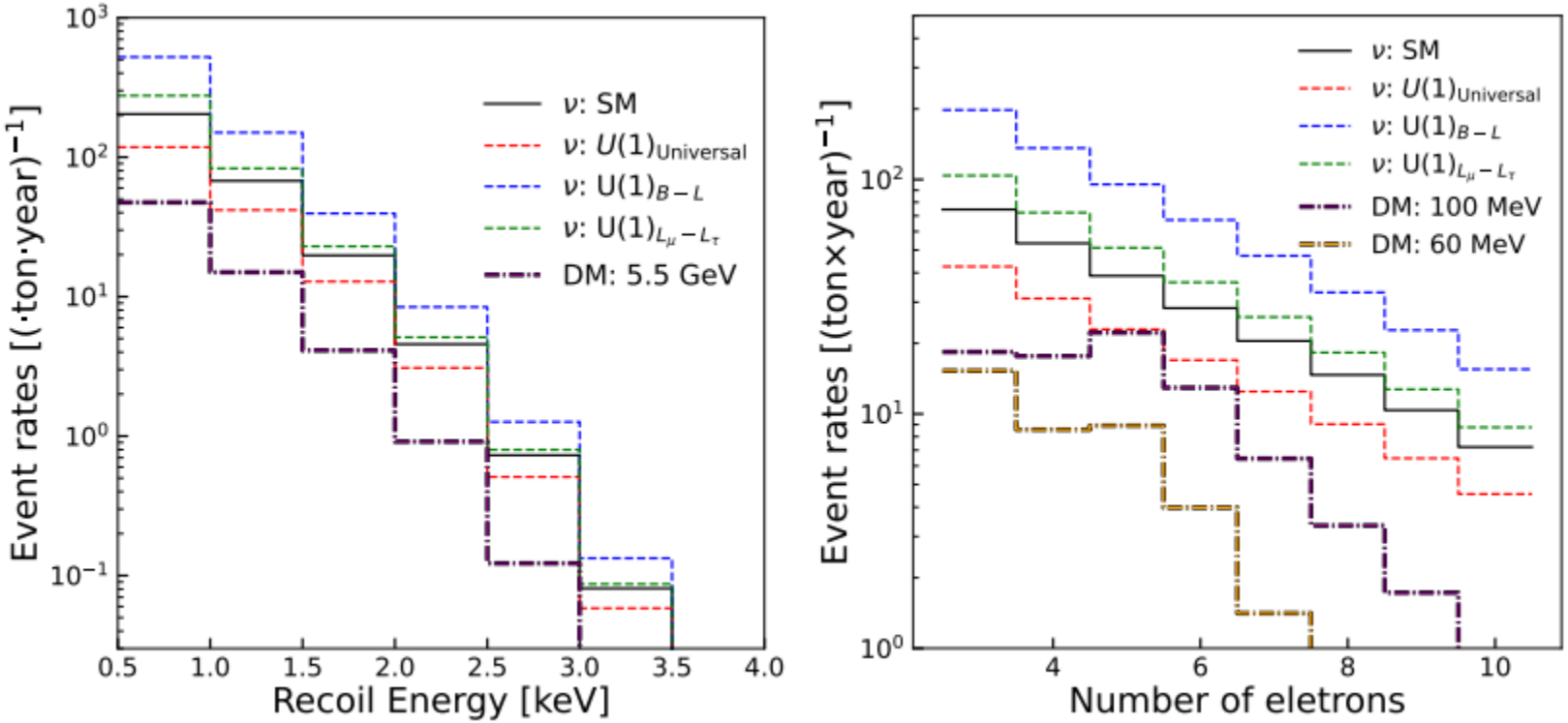




Ref: Fei Gao's talk@IDM2024

NR of neutrinos v.s DM

$$\frac{d\sigma}{dT} = \frac{1}{4\pi} G_F^2 Q_W^2 F^2\left(q^2\right) M\left(1 - \frac{MT}{2E_\nu^2}\right) \qquad \frac{dR}{dE_R} = \frac{n_0}{2\mu_N^2} \sigma_0^{SI} F_{SI}^2(E_R) \int_{v_{min}(E_R)} \frac{f(v, v_E)}{v} d^3v$$



***J. Tang**, B. L. Zhang, Phys.Rev.D 108 (2023) 6, 062004.*
arXiv: 2403.05819

Asymptotic analysis on binned likelihood

- Our method also provides a way to **select the most crucial source**, which can be utilized to reduce input parameters for **MC pseudo-experiments**

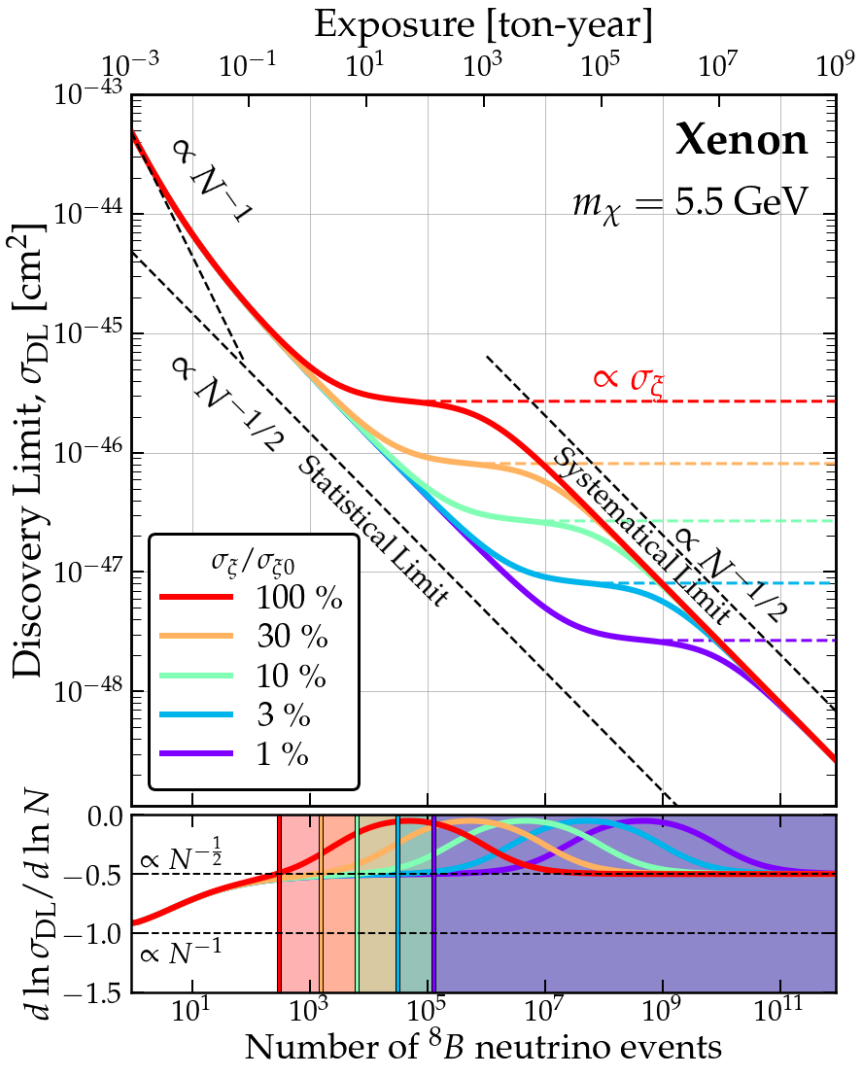
rank	source	contribution
0	8B	0.819
1	pep	0.021
2	150	0.006
3	Reactor	0.001
4	7Be2	0.001

$$\phi = \sum_i \frac{s_i^2}{v_i} - \left[\sum_i \frac{s_i b_i^j}{v_i}\right]_j \left[\sum_i \frac{b_i^j b_i^k}{v_i} + \frac{\delta_k^j}{\sigma_k^2}\right]^{-1}_{jk} \left[\sum_i \frac{s_i b_i^j}{v_i}\right]_k \Bigg|_{\boldsymbol{\theta}=1}$$

Only ^{8}B neutrino

$$\phi = \sum_i \frac{s_i^2}{s_i + b_i} - \frac{\left(\sum_i \frac{s_i b_i}{s_i + b_i}\right)^2}{\sum_i \frac{b_i^2}{s_i + b_i} + \frac{1}{\sigma_\nu^2}}$$

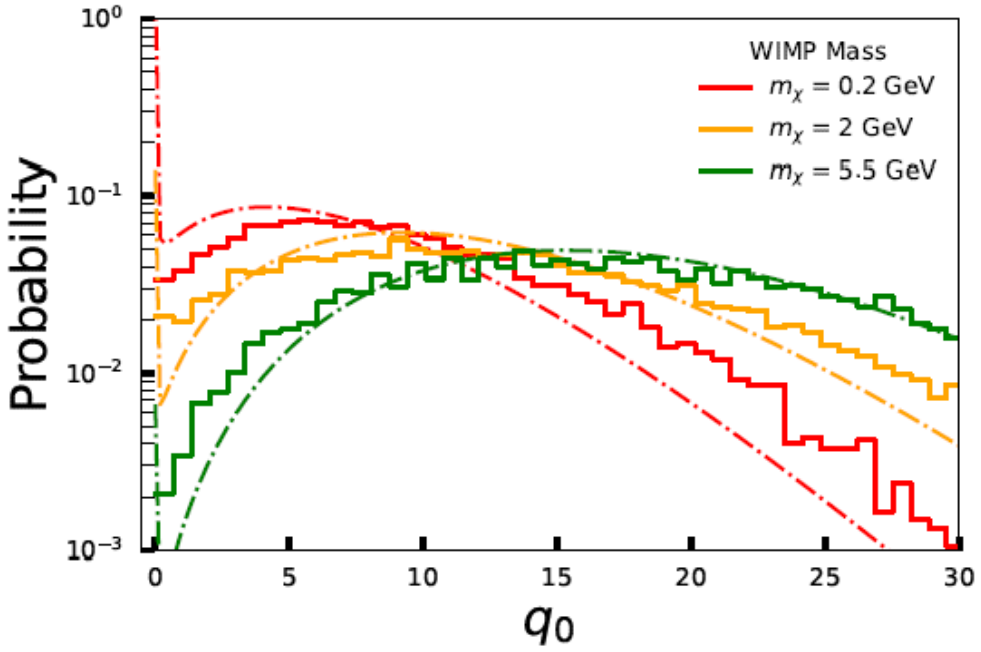
- It provides an **analytic** formula to describe the evolution

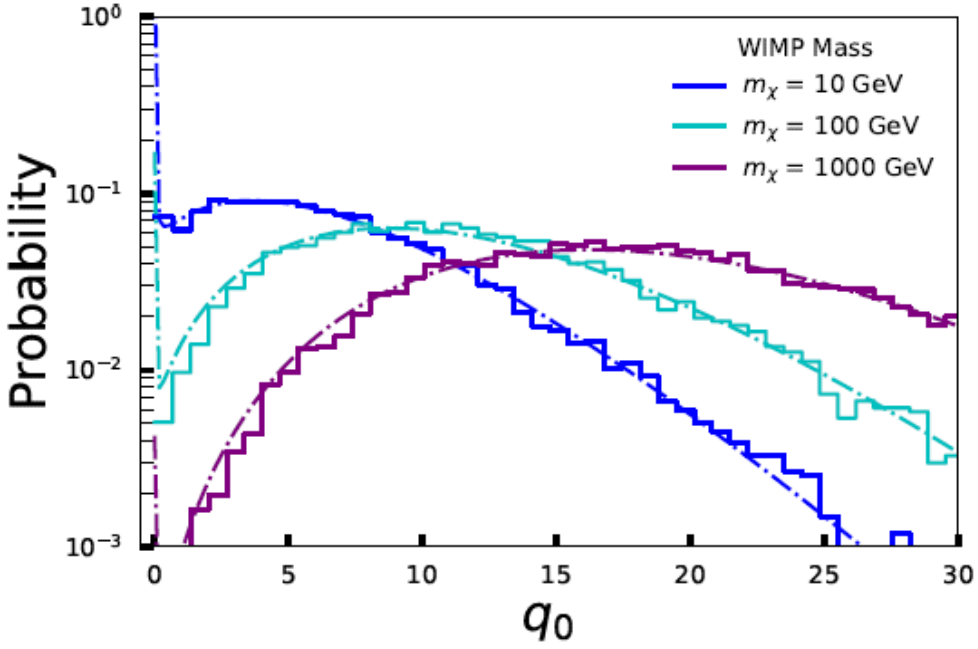


Evolution of the discovery limit cross section

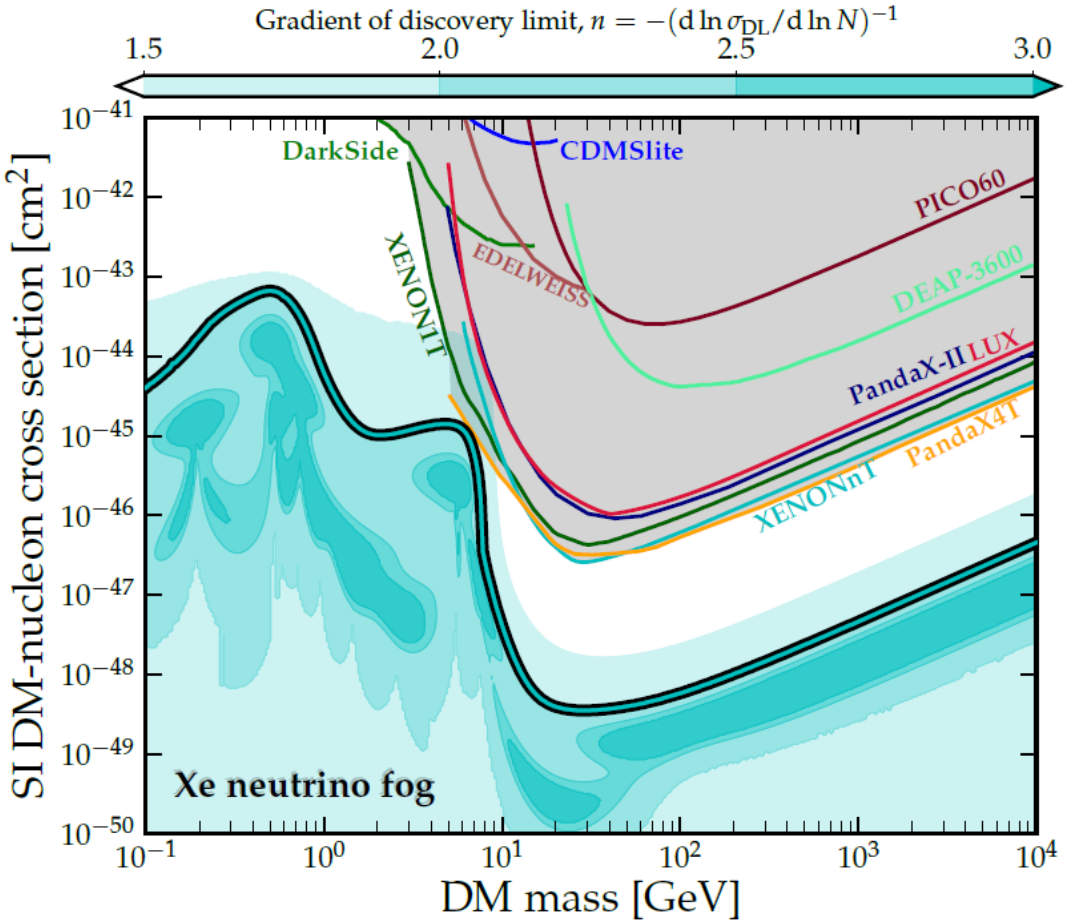
Asymptotic analysis on binned likelihood

	Speed	Accuracy	Extensible
Monte Carlo simulation	~1 day	✓	✓
Asimov dataset	~30 minutes	✓	sometimes ×
Asymptotic-Analytic Method	~10 seconds	✓ for big statistics	✓
Quasi-Asimov dataset	~10 seconds	✓	sometimes ×

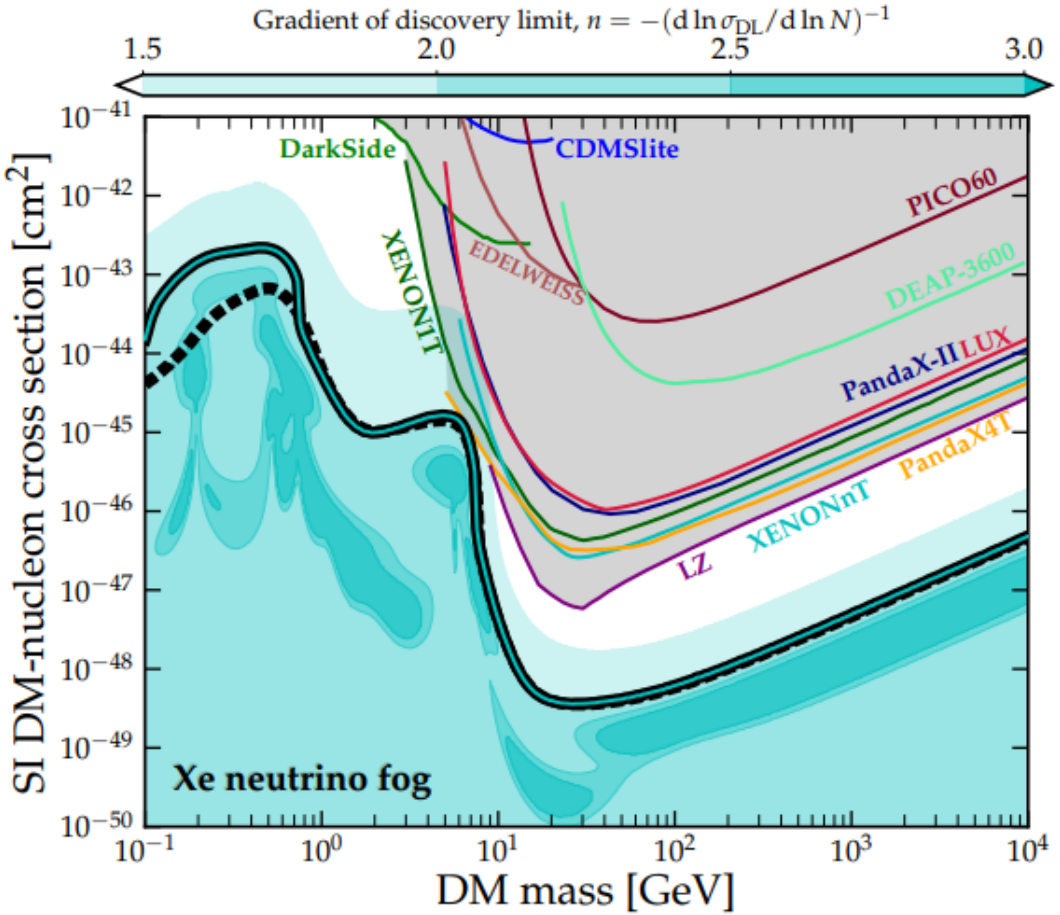




Asymptotic analysis for neutrino fogs



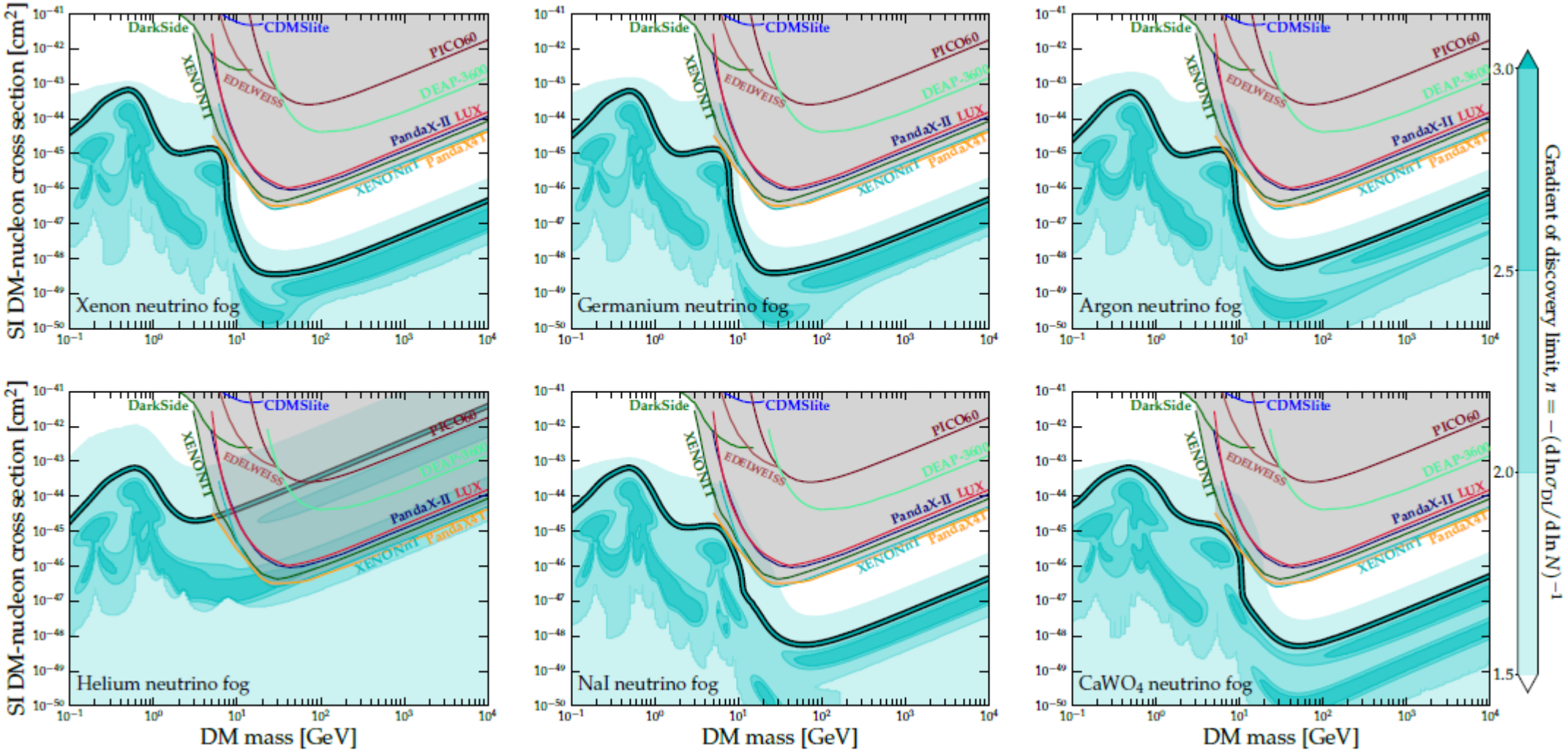
After considering the uncertainty of $\sin^2\theta_W$



Without considering the uncertainty of $\sin^2\theta_W$

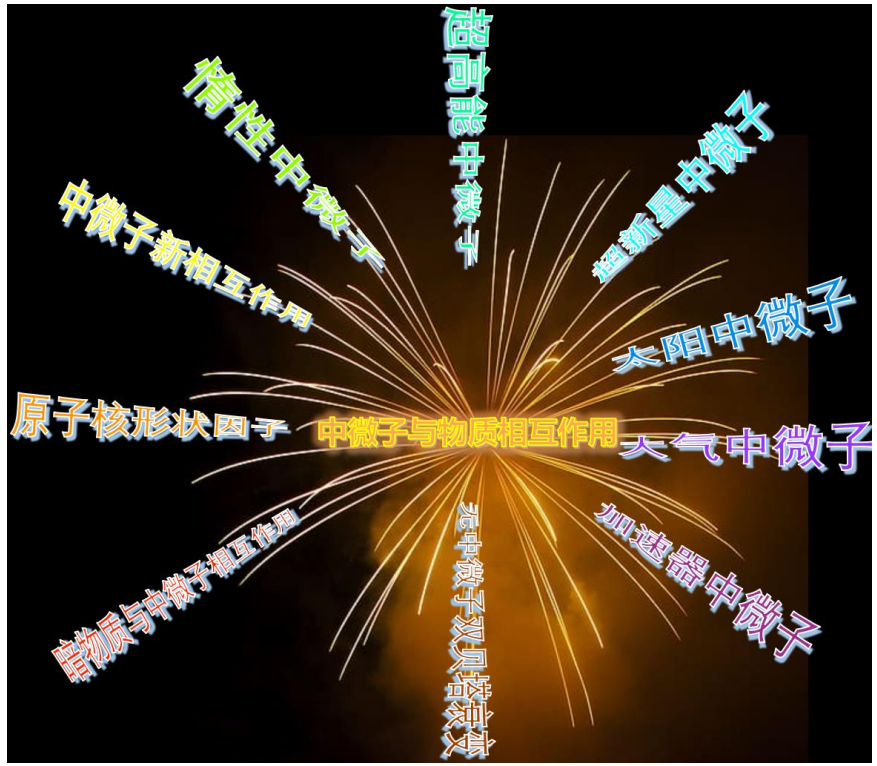
***J. Tang**, B. L. Zhang, Phys.Rev.D 108 (2023) 6, 062004*

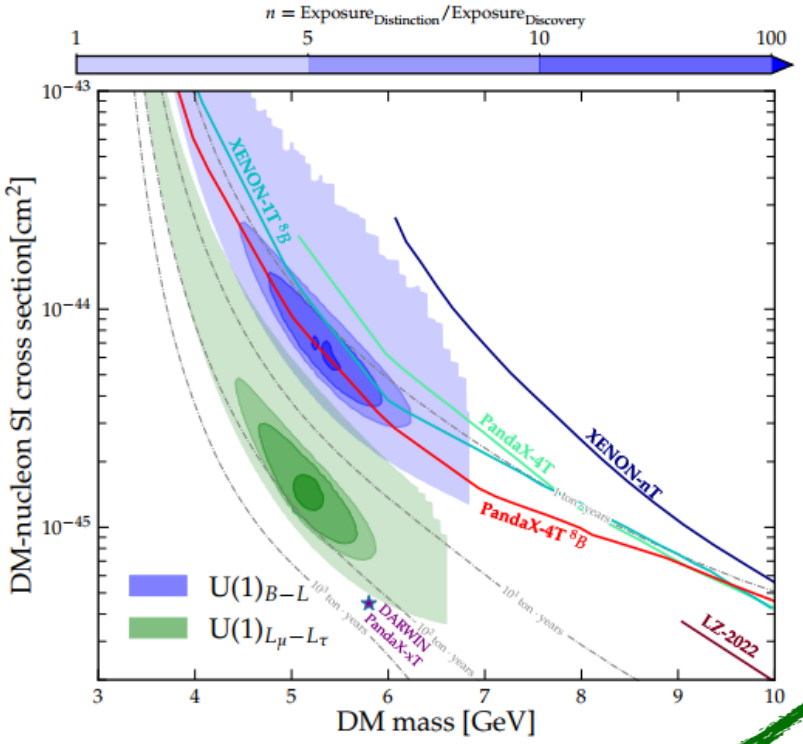
Neutrino fogs for different targets

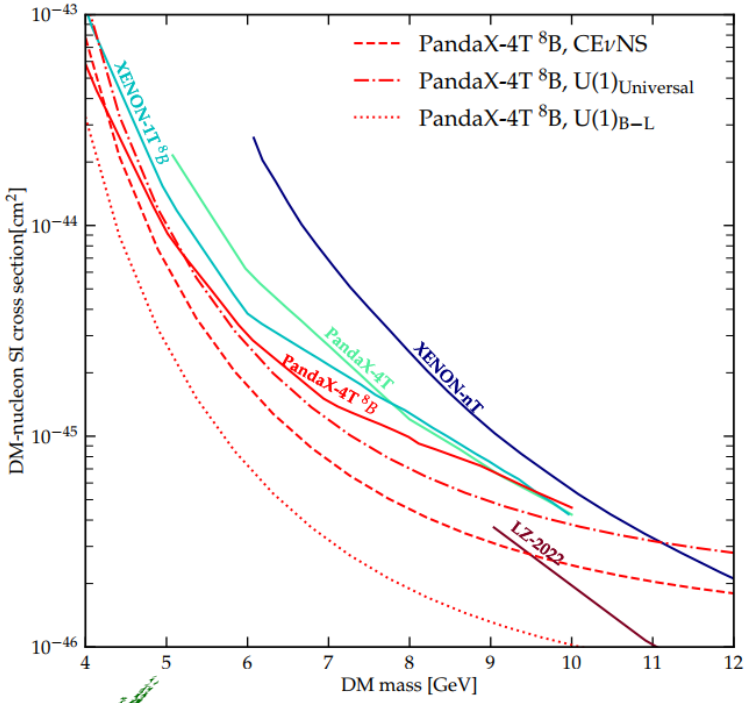


***J. Tang**, B. L. Zhang, Phys.Rev.D 108 (2023) 6, 062004*

利用中微子散射寻找新物理的统计方法



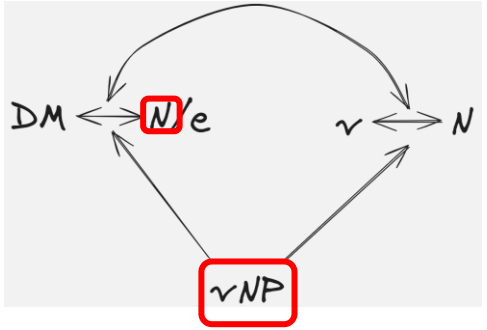




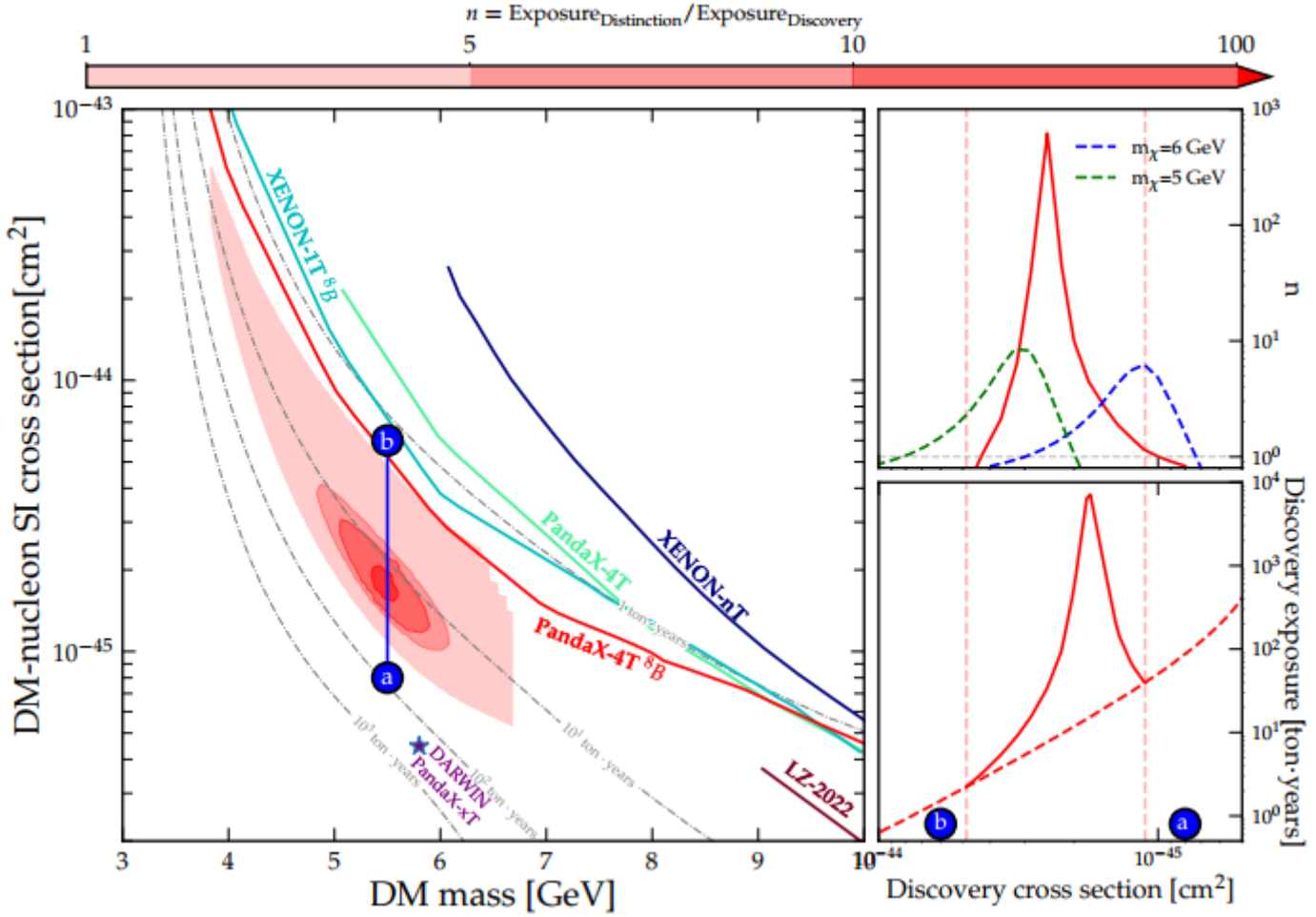
***J. Tang**, B. L. Zhang, Dark matter, CEvNS and neutrino new physics scrutinized by a statistical method in Xenon-based experiments,*

arXiv: 2403.05819, https://github.com/zhangblong/DistinctionLimit

中微子新物理影响暗物质的直接探测



- 中微子新物理+暗物质事例 v.s CEvNS事例
- 曝光量提高百倍才能从统计学上鉴别超出事例来自暗物质还是来自vNP

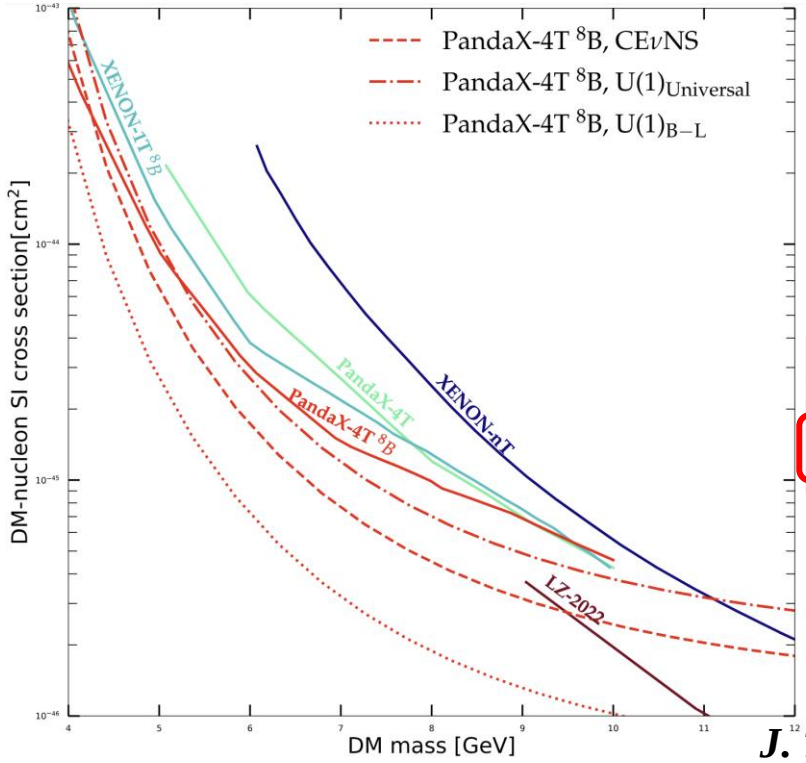


J. Tang, B. L. Zhang, arXiv: 2403.05819

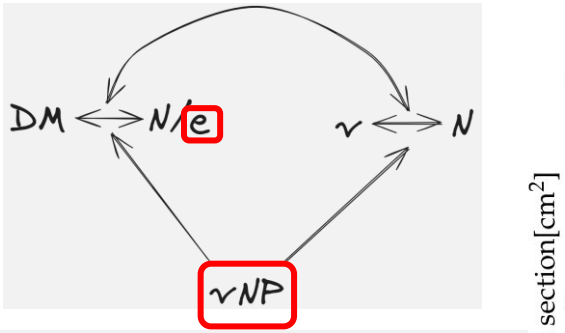
中微子新物理影响暗物质的直接探测

- **中微子新物理(vNP)**会对暗物质搜寻造成怎样的影响?
- vNP会**减弱**或增强中微子的贡献，从而对**目前暗物质的实验限制**具有可观的影响

- vNP减弱效应会让只存在标准模型相互作用和同时存在暗物质和vNP情形**无法区分**
- 推广至**暗物质-电子**相互作用

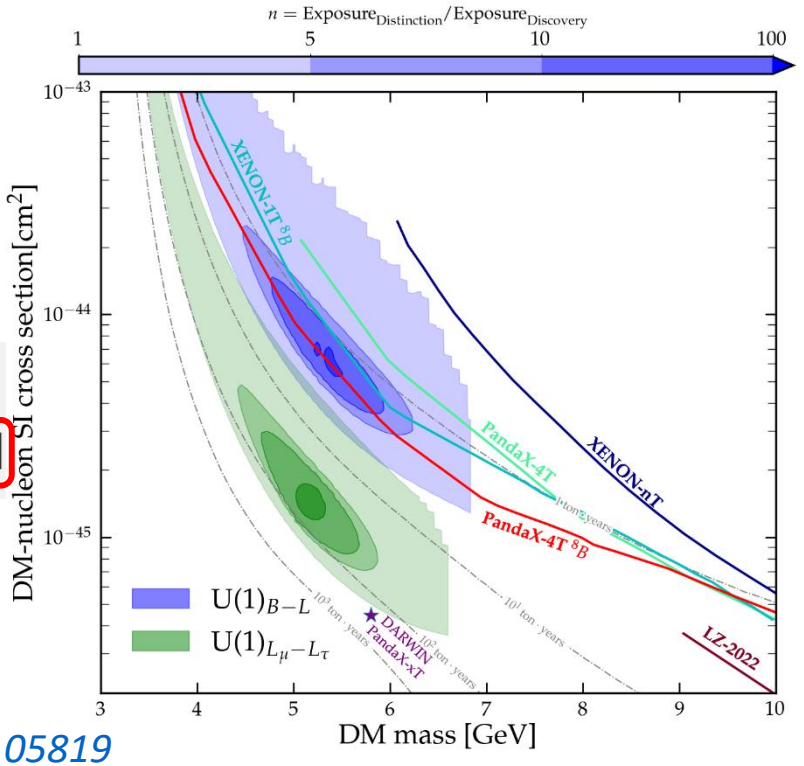


vNP会削弱或增强对暗物质的限制



增强：DM v.s. vNP

减弱：DM+vNP v.s. SM



需要近100倍曝光量去除vNP的影响

J. Tang, B. L. Zhang, arXiv: 2403.05819

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Summary and outlooks

- Neutrino floor is around the corner for the next-generation DM experiments. CEvNS might hinder DM discovery. Data mining?
- One stone for two birds: CEvNS and DM. Precision measurement of CEvNS is a probe of new physics.
- Further understanding of nuclear response?
- Discovery of new physics or exclusion limits in the new experiment.
- More are coming! Stay tuned…