中微子物理和天文学

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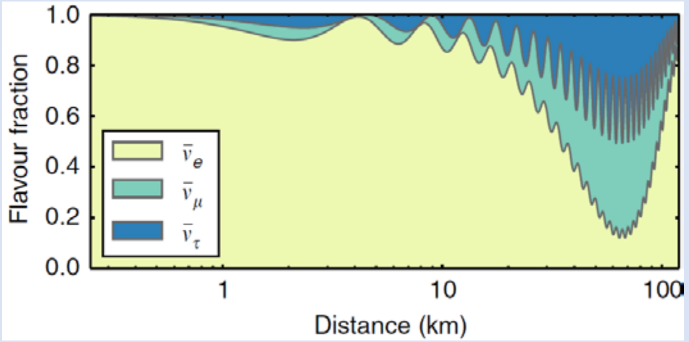
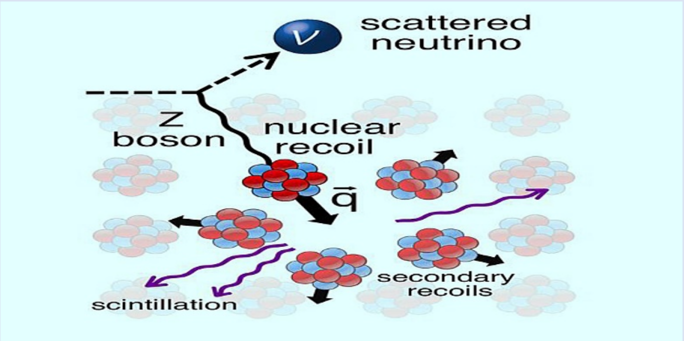
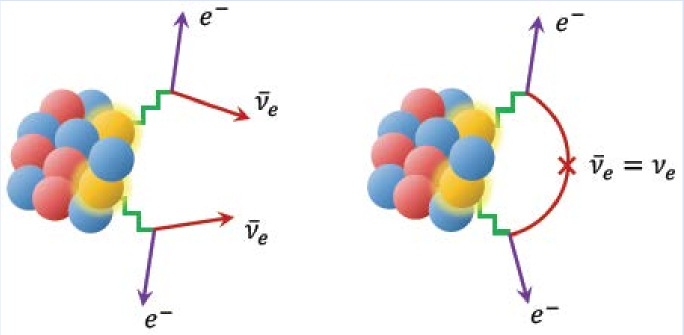
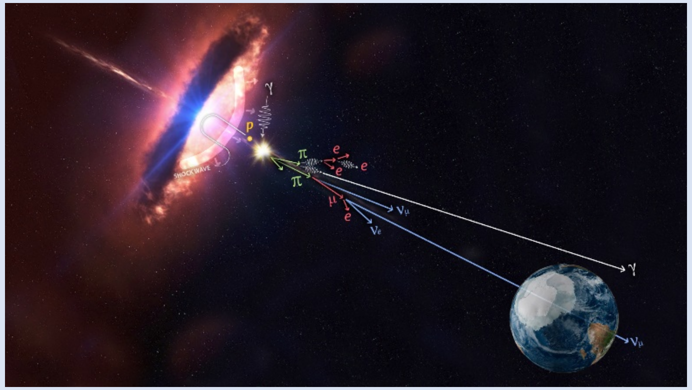
中国物理学会高能物理分会2021年战略研讨会，2021.10.11-12









拟讨论的科学问题

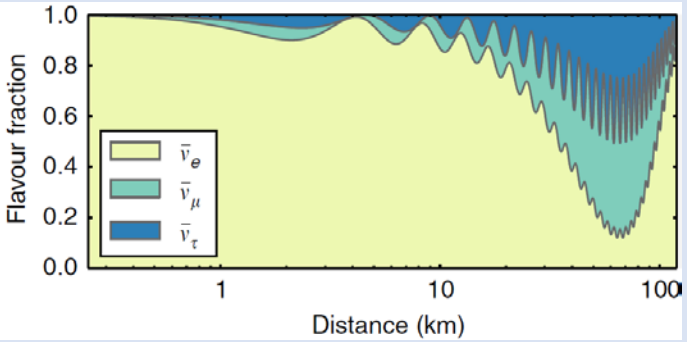
粒子物理

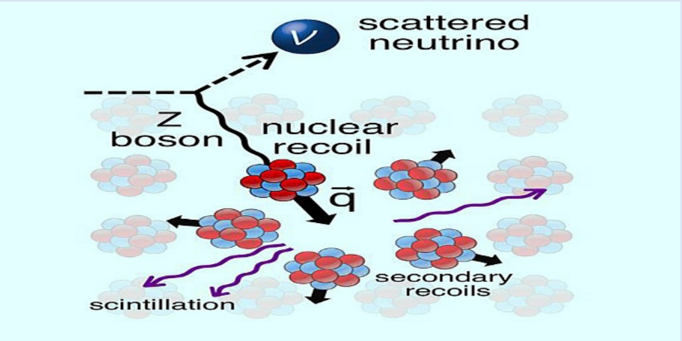
- 中微子质量顺序、轻子CP破坏 ← 中微子振荡
- Majorana属性，绝对质量 ← 无中微子双β衰变
- 中微子-核子相干散射 ← 多种类型的中微子探测器

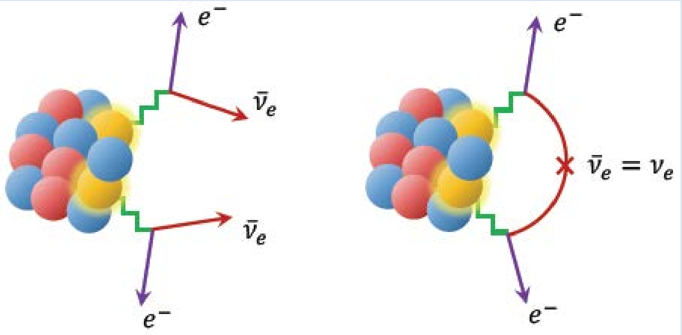
天文学

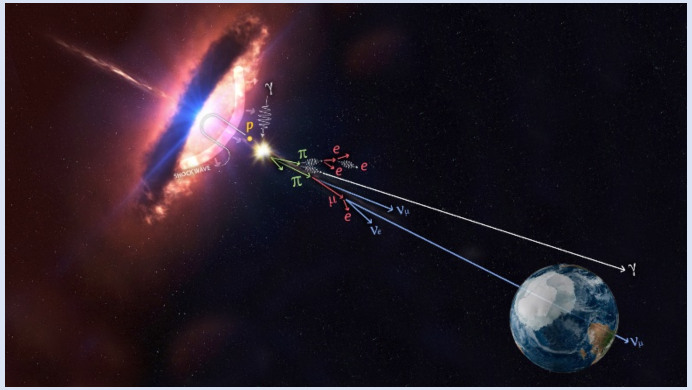
- 高能宇宙中微子起源 ← 中微子望远镜
- 中低能天体中微子 ← 多种类型的中微子探测器
  - 太阳、地球、超新星、极端天文现象伴随的中微子

注：本报告中，国内相关进展摘自“高能物理分会非加速器物理研讨会（2021.05）”



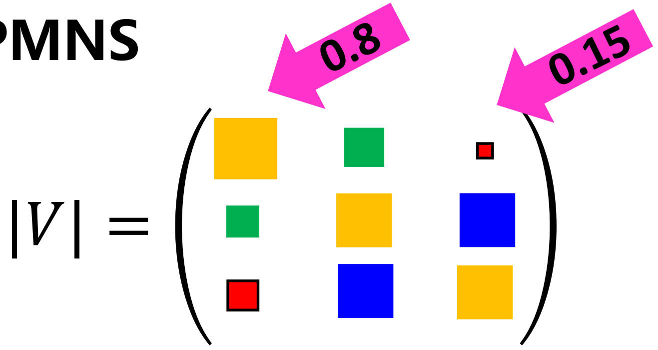






中微子振荡 – 现状

PMNS

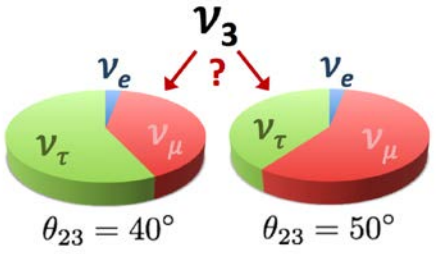


Approximate μ-τ symmetry?

$\theta_{23} \sim 45^\circ$ $|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$

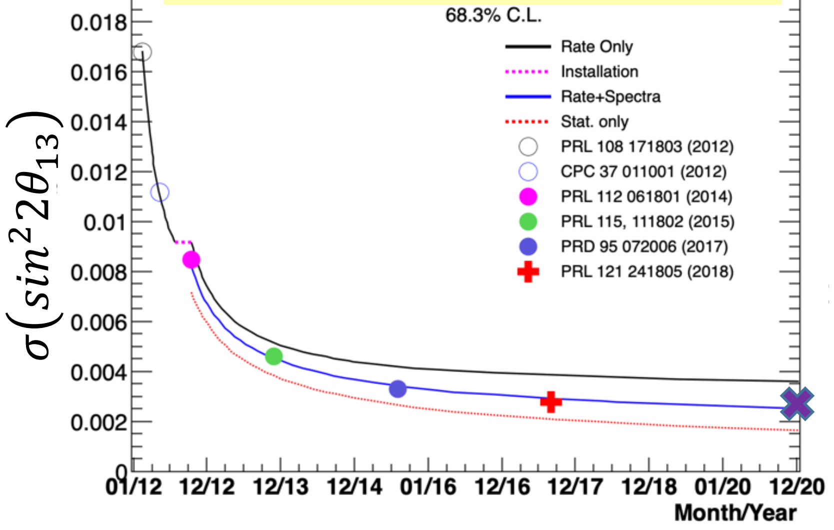
$\theta_{12} \sim 34^\circ$ $\Delta m^2_{21} \sim 7.5 \times 10^{-5}\ \mathrm{eV}^2$

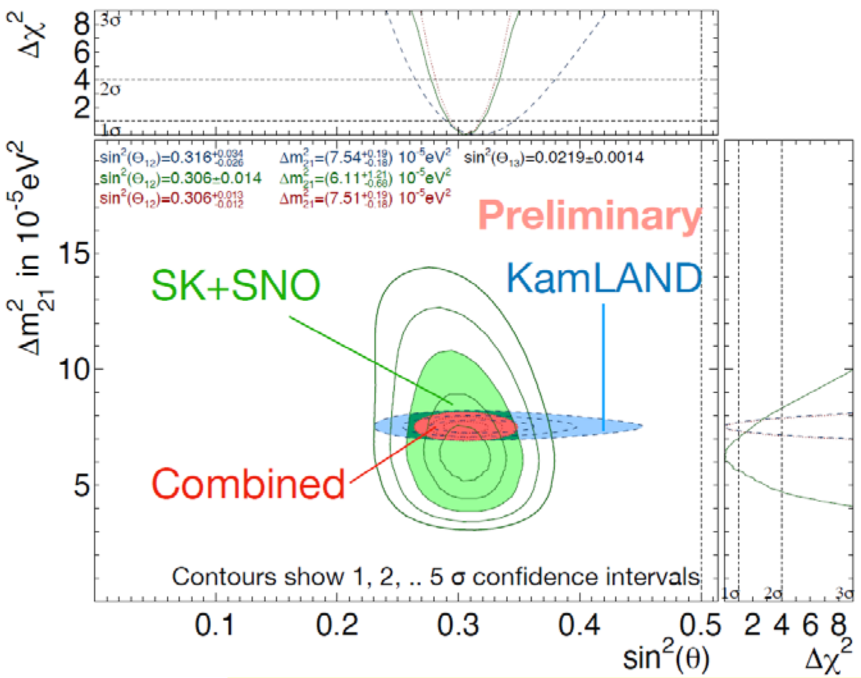
$\theta_{13} \sim 8.4^\circ$



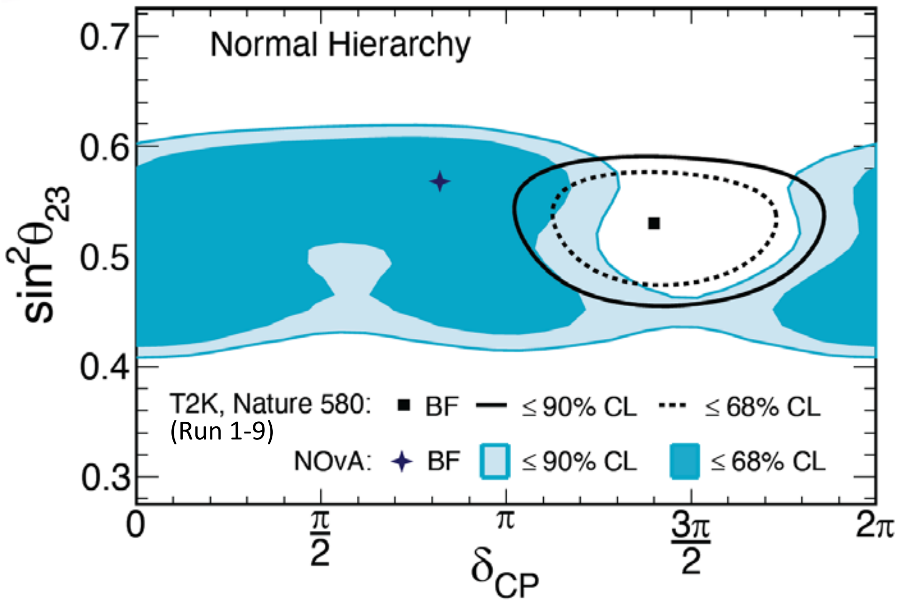
θ_{23} Octant?

大亚湾实验装置于2020.12退役





太阳和大气中微子实验对Δm^2_{21}测量差别从~2 σ减小到~1.4 σ



T2K、NOvA都倾向于正序，但δ_{CP} 的best-fit值存在Tension

未来中微子振荡实验目标：

- Δm^2_{31} 符号
- δ_{CP} 大小
- 振荡参数精确测量

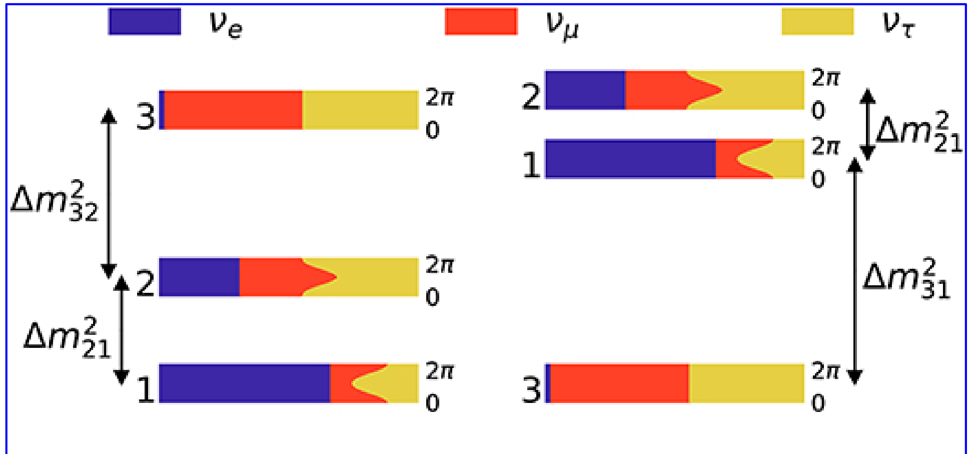
中微子振荡 – 中微子质量顺序 & 精确测量

- 是中微子的基本属性，影响轻子的味结构
- 所有模型必须面对的问题，是新一轮的科学前沿热点和竞争焦点
- 精确测量振荡参数：检验中微子混合幺正性

	当前直接测量	江门实验
Δm^2_{21}	2.5%	<0.6%
$\Delta m^2_{31}/\Delta m^2_{32}$	2.8% (大亚湾/T2K/NOvA)	<0.6%
$\sin^2\theta_{12}$	4.7% （SNO)	< 0.6%
$\sin^2 2\theta_{13}$	3.2% → 2.7% (大亚湾)	~ 10%

中微子源	国际中微子实验	时间
加速器	美国 DUNE	2026? (2029*)
	日本 Hyper-K	2027
宇宙线	地中海 ORCA 南极 PINGU	尚未获得 全部支持
反应堆	中国 JUNO	2023

* https://www.science.org/content/article/costs-balloon-u-s-particle-physics-megaproject



正序（$m_3>m_2>m_1$）

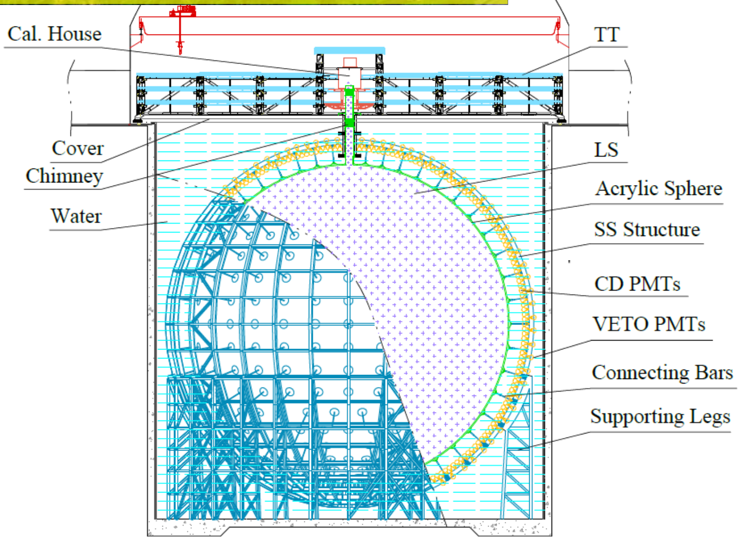
逆序（$m_2>m_1>m_3$）

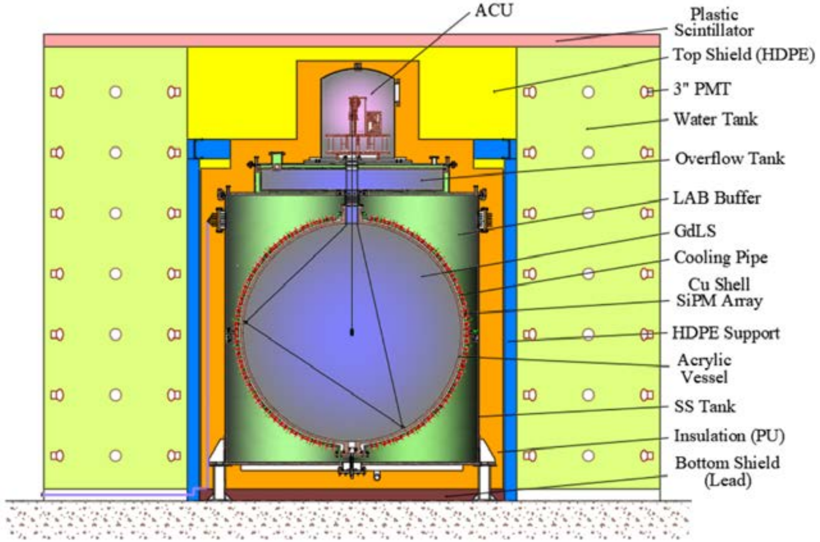
中微子振荡 – 江门中微子实验

JUNO Physics and Detector, arXiv:2104.02565

- 2020.12实验大厅挖掘完成
- 土建即将全部完成，探测器安装已部分开始
- 预期2022年底完成JUNO探测器建设

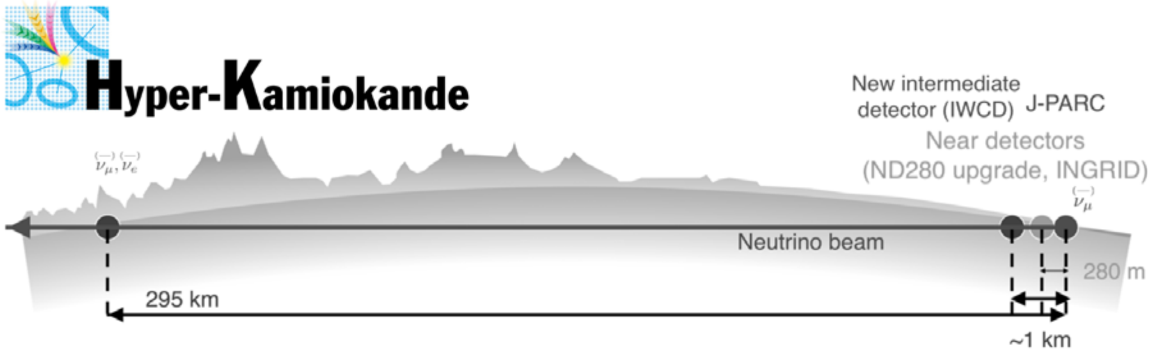
- JUNO-TAO探测器设计建设中
  - 近距离精确测量反应堆中微子能谱
  - 高精度、低温液闪技术：10m^2 SiPM (50% PDE) + 2.8 t GdLS (-50 °C) → 4500p.e./MeV

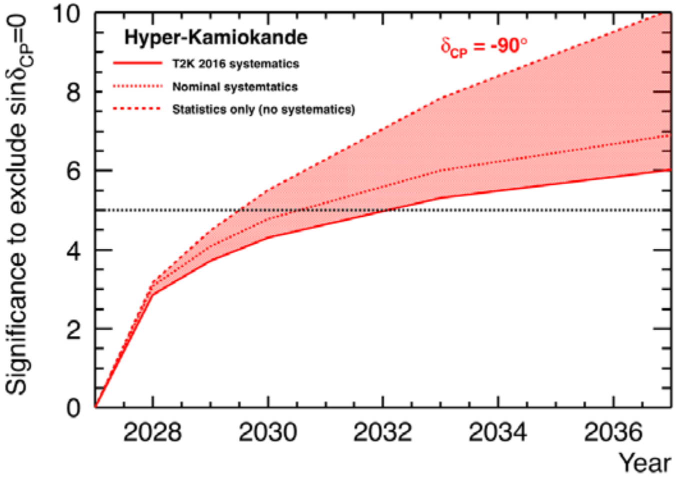


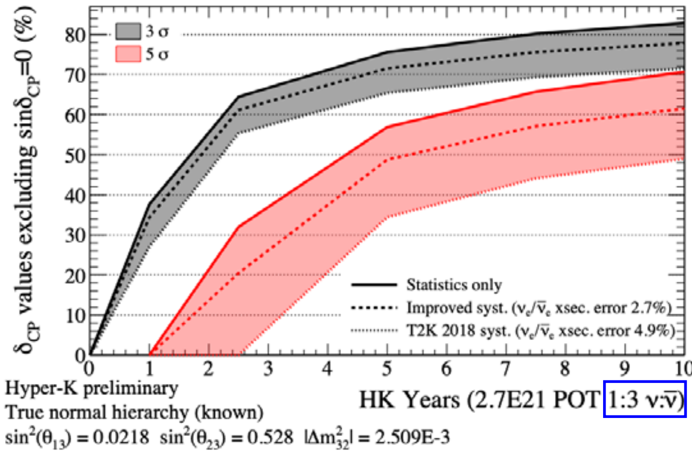


中微子振荡 – 国际竞争

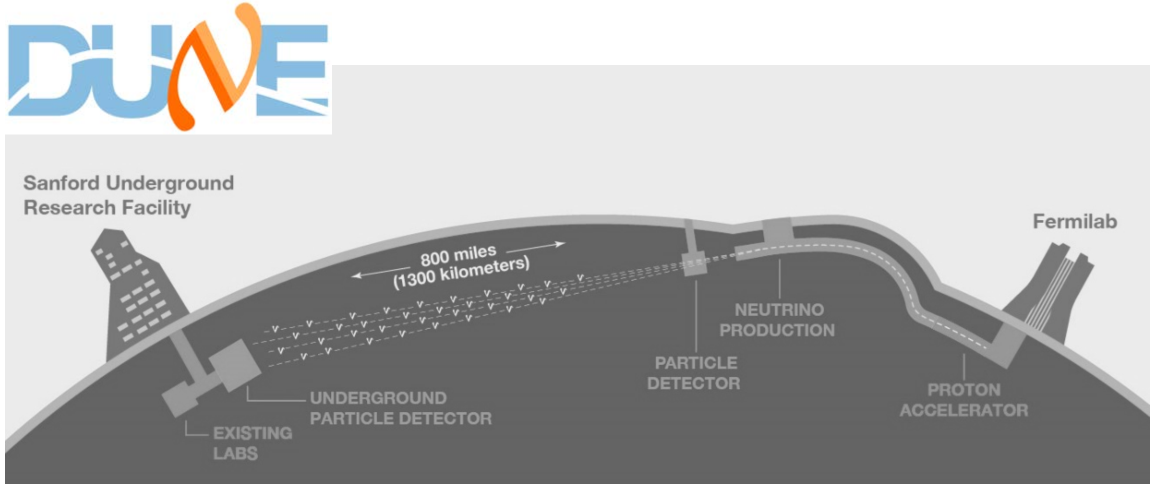
CP破坏灵敏度

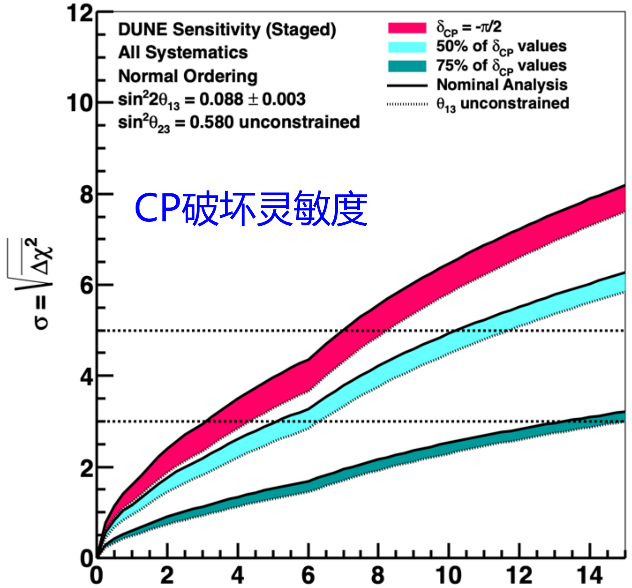


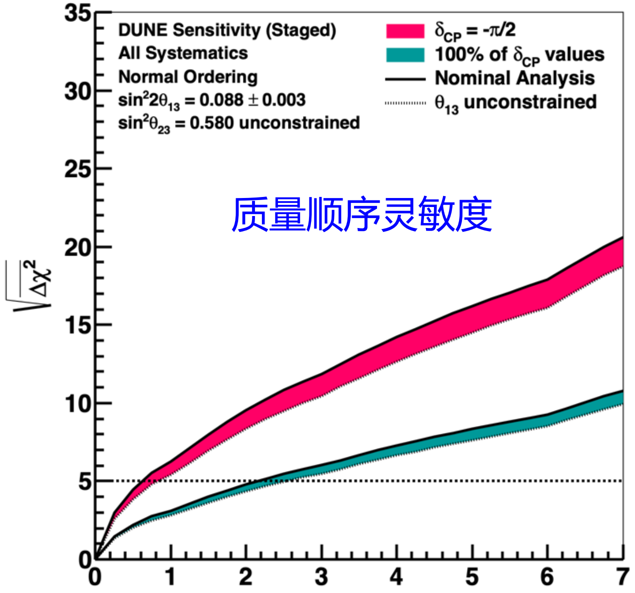




ν:ν̄ = 1:3

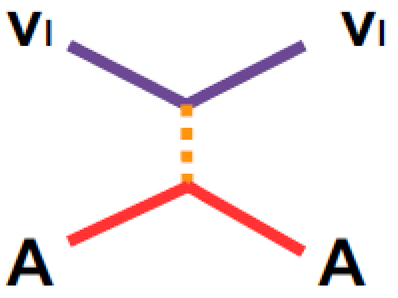






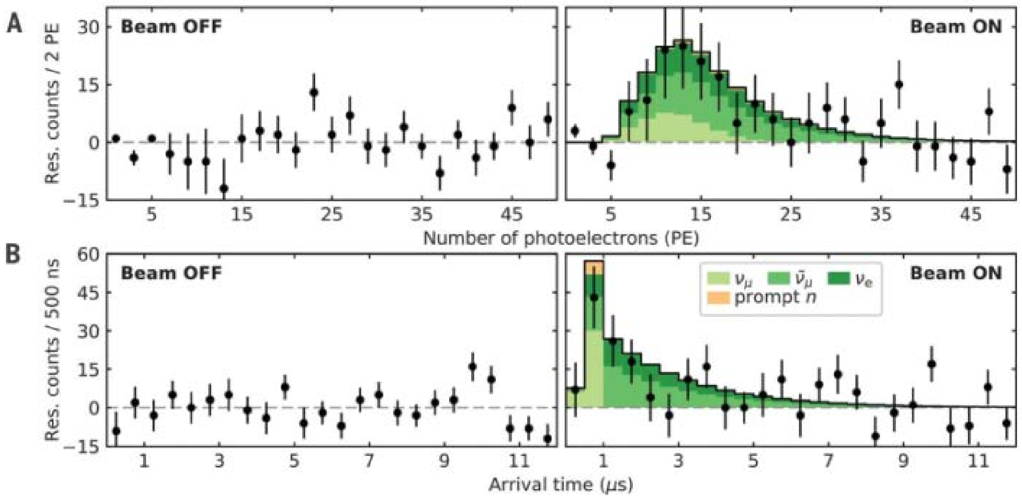
ν:ν̄ = 1:1

中微子相干散射（CEvNS）



截面 ∝ N^2

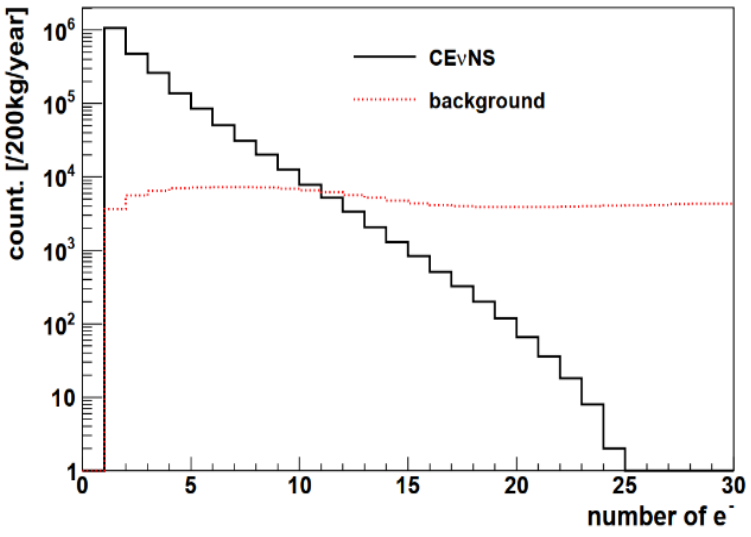
- **寻找新物理的探针**
  - 核结构、中子形状因子、θ_W、中微子电磁性质、惰性中微子、…
- **对天体物理、宇宙学研究很重要**
  - 太阳中微子流强、超新星中微子、DM实验中的ν floor、….

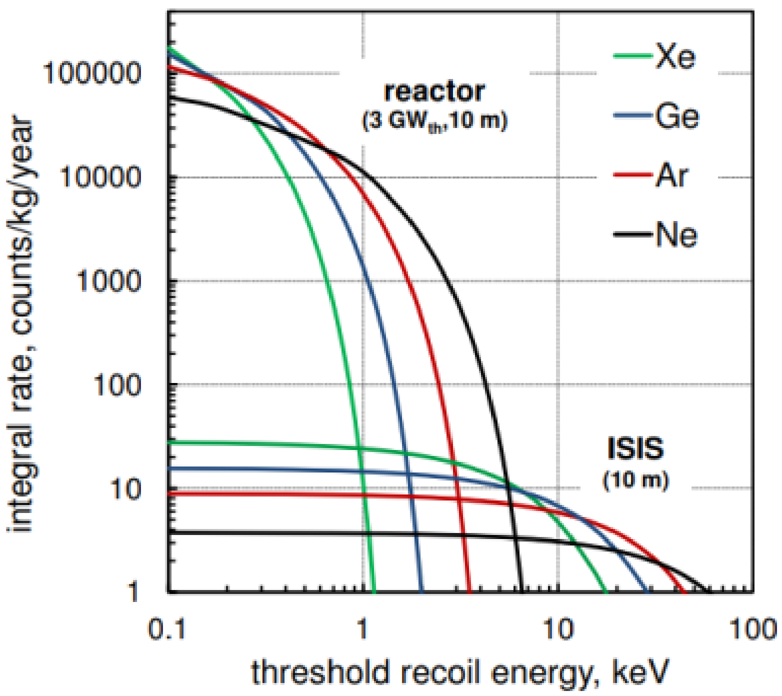


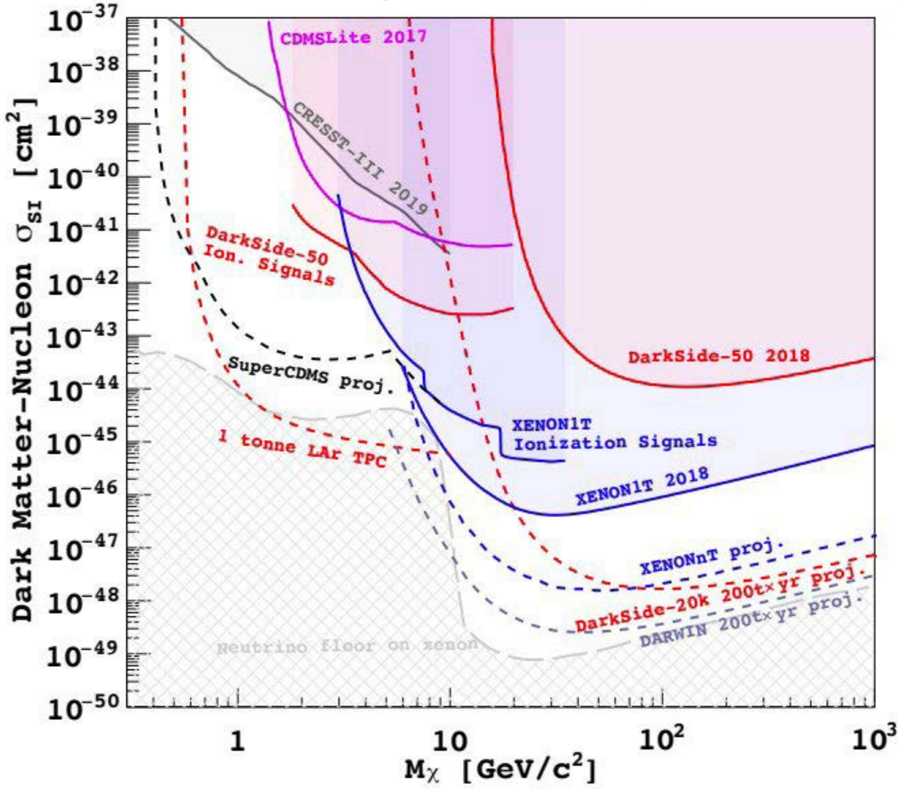
- 反应堆中微子源（未观测到）
  - CONNIE, CONUS, MINER, Nu-CLEUS, RICOCHET, TEXONO, RED-100, nuGEN, ...
- SNS中微子源（COHERENT观测到）

中微子相干散射（CEvNS）

- 研发极低阈值的两相TPC探测器，探索中微子探测器小型化技术
  - 先实现0.5 keV_{nr} 阈值, 最终目标0.1 keV_{nr}
- 百公斤级探测器应用：测量反应堆中微子的CEvNS @ 台山反应堆
  - E.g., 100 kg 贫氩 @ 35 m，0.5 keV_{nr}，~400 evts/d，S/B ~ 3:1
- 其他可能性：吨量级LAr两相TPC @ CJPL-II，测^{8}B 的CEvNS，寻找轻质量暗物质







无中微子双β衰变（NLDBD）

- 解决“中微子是否自身的反粒子”问题
- 测量中微子绝对质量
- 检验轻子数守恒
- 限制中微子的Majorana CP破坏相位

中微子质量灵敏度

中微子振荡：确定质量顺序

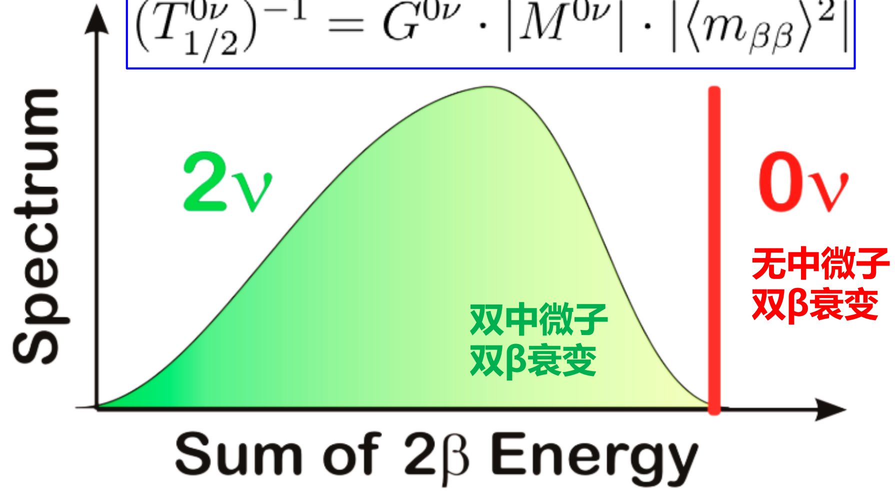
氚贝塔衰变：$m_\beta \lesssim 40$ meV

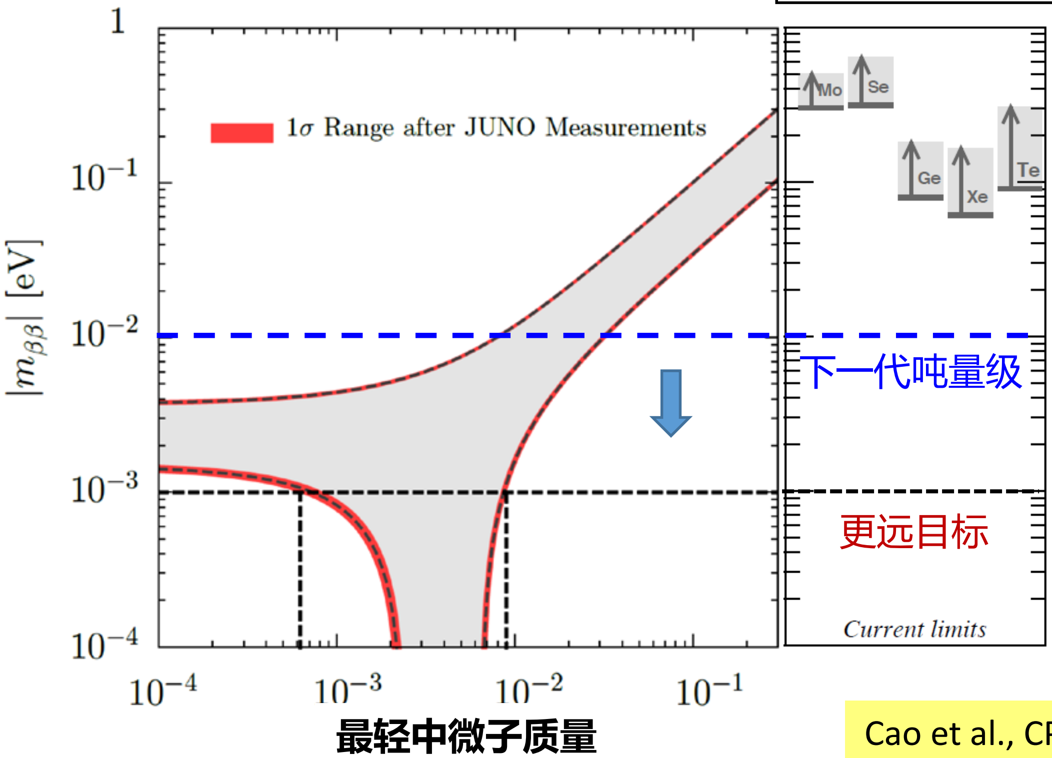
宇宙学：$\Sigma \lesssim 80$ meV

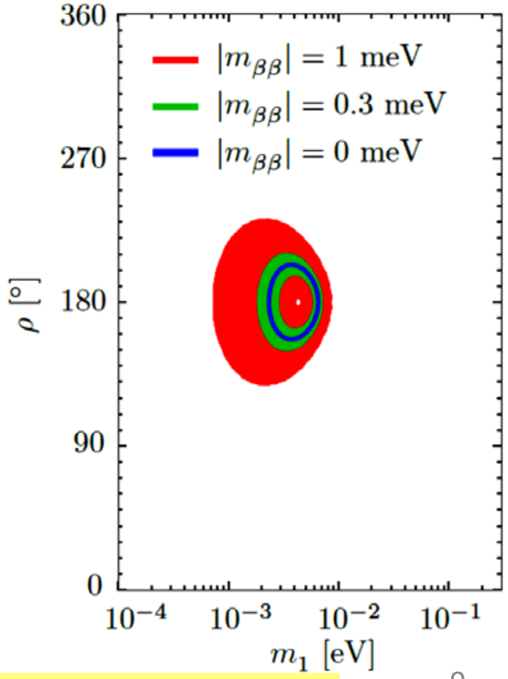
双贝塔衰变：$|m_{\beta\beta}| \approx 10$ meV

$m_{\beta\beta} = \left|\Sigma_i U_{ei}^2 m_i\right|$ [eV]

$$\boxed{(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot |M^{0\nu}| \cdot |\langle m_{\beta\beta}\rangle^2|}$$







Cao et al., CPC 44 (2020) 031001

无中微子双β衰变（NLDBD）

Detector Exposure

Detector efficiency

$$T_{1/2}^{0\nu\beta\beta} = \frac{\ln 2 \cdot N_A}{M_{isotope}} \cdot \frac{\boxed{Mt} \cdot \epsilon \cdot \eta}{\alpha \cdot \sqrt{b}}$$

Isotope abundance

Background in ROI

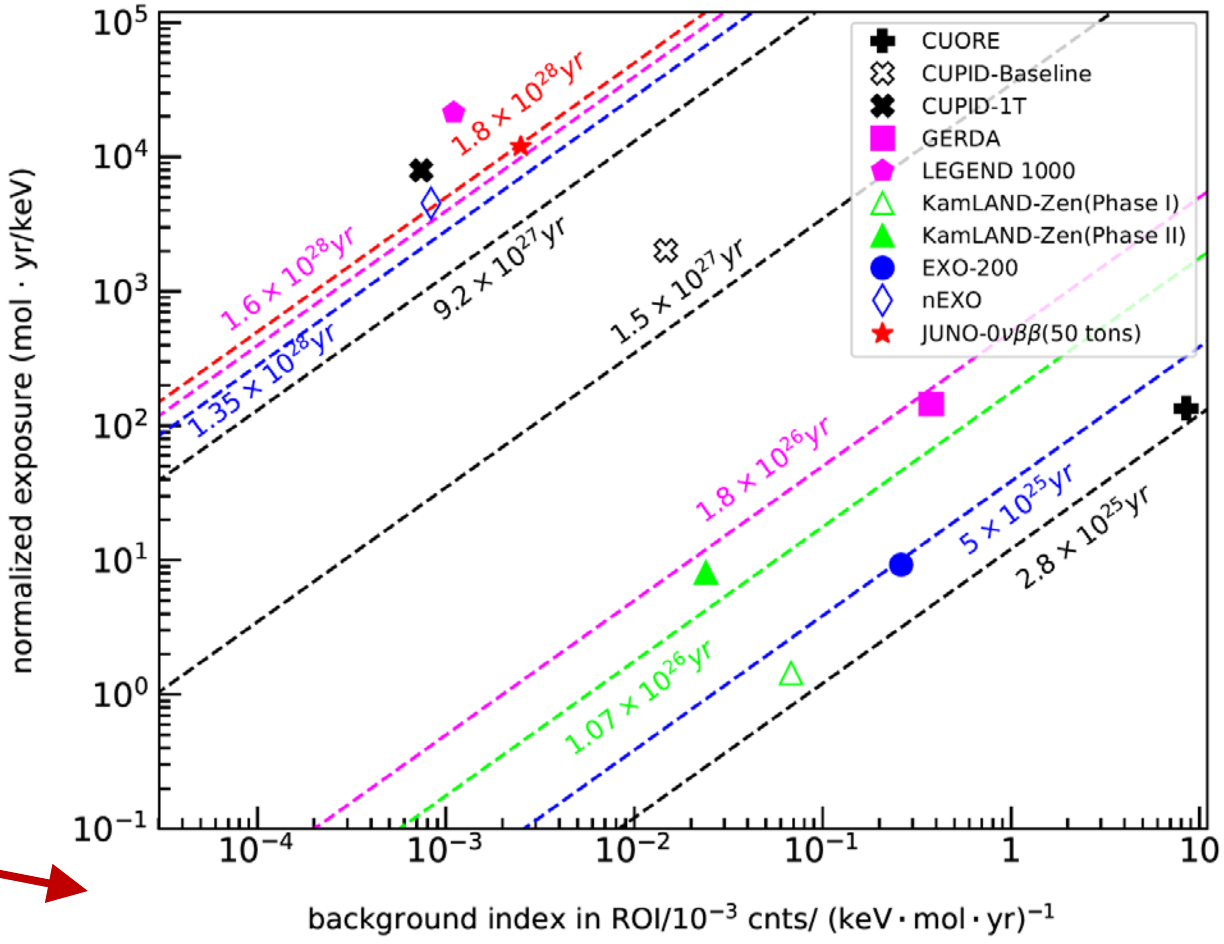
* For 90% C.L, α=1.64

$$\left(\frac{T_{1/2}^{0\nu\beta\beta} \cdot \alpha}{\ln 2 \cdot N_A}\right)^2 = \frac{M_{\mathrm{norm}}}{B_{\mathrm{I}}}$$

$$\boxed{M_{norm} = \frac{M\epsilon\eta \cdot t}{\mathrm{ROI} \cdot M_{isotope}}}$$

$$\boxed{B_I = \frac{b}{(M\epsilon\eta \cdot t / M_{isotope}) \cdot \mathrm{ROI}}}$$

Courtesy: Yasheng Fu, remade from CPC 41 (2017) 053001



实验的决定性因素

- 靶质量
- 能量分辨率、本底水平

无中微子双β衰变（NLDBD） – 国际形势

美国Down Select启动

吨量级NLDBD实验，Portfolio Review, July 13-16, 2021

CUPID, LEGEND-1000, and nEXO

DoE尚未发布Report of the portfolio review.

In US, the large (and rather contentious) infrastructure bill being argued in Congress does include over 200M$ for ton-scale double beta decay

北美 – 欧洲 workshop

https://agenda.infn.it/event/27143/

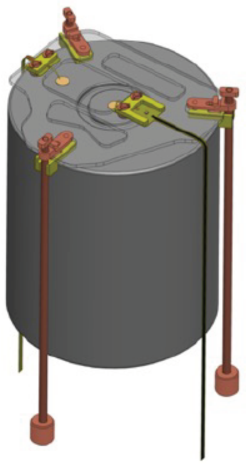
未来灵敏度到10^{28} yrs的NLDBD实验，Sep 29 – Oct. 1, 2021

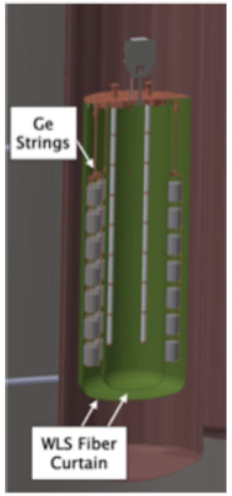
CUPID, LEGEND-1000, nEXO and NEXT

The Majorana nature of neutrino and the possible contribution of neutrinos to explain the matter-antimatter asymmetry in the universe are among the most challenging physics goals in the next decade. The purpose of the North America-Europe workshop on Double Beta Decay is to **stimulate the discussion between the North American and European double beta decay community and the corresponding funding agencies to consolidate a strategy and define a path to the discovery of Majorana neutrinos**. The discussion will focus on the upcoming generation of **high sensitivity projects**, their discovery potentials and the underground infrastructures.

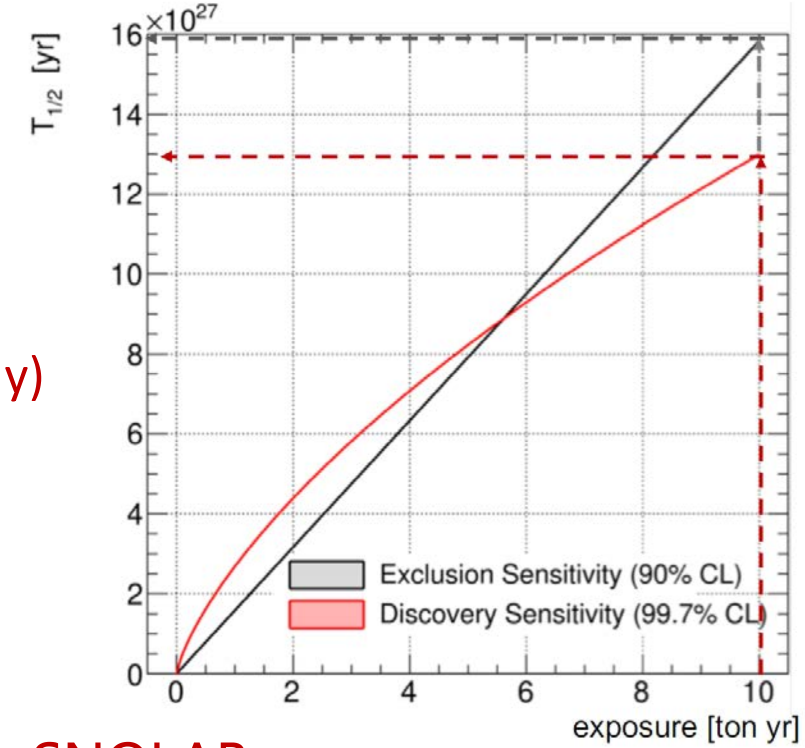
无中微子双β衰变 – ^{76}Ge

90% CL exclusion sensitivity @ 10 ton-yr	1.6 10^{28} yr
3σ discovery sensitivity @ 10 ton-yr	1.3 10^{28} yr





- GERDA： > 1.8 x 10^{26} yrs
- LEGEND-1000： > 10^{28} yrs
  - Pre-CDR: 2107.11462
  - BKG: 0.025 counts/(FWHM t y)



ICPC detector assembly:

- 2.6 kg average mass
- EFCu
- PEN
- ASIC front end
- Flat flex cables

Detector arrays:

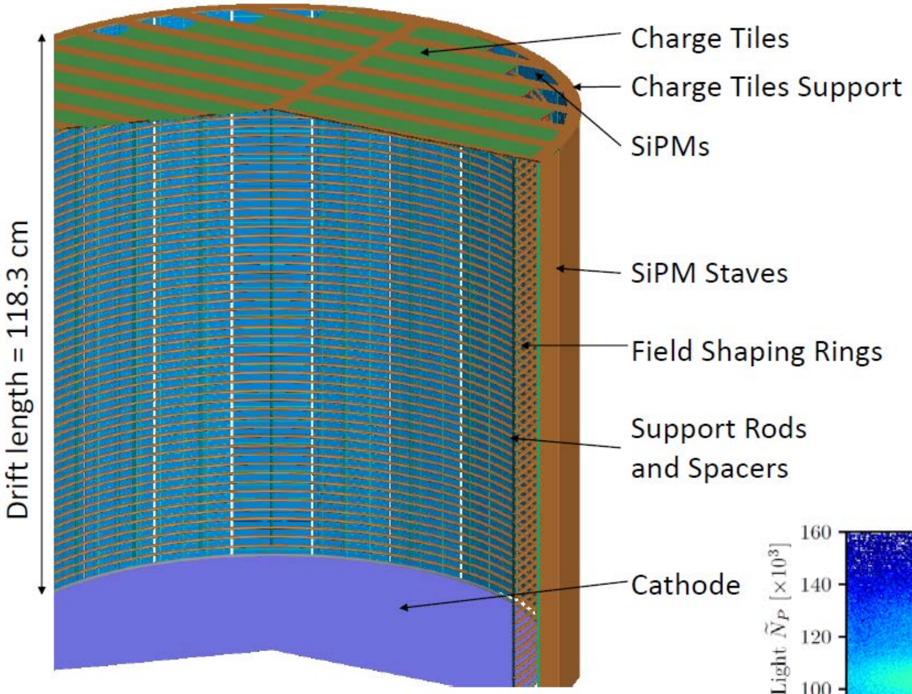
- 4 arrays
- 100 ICPCs / array
- 1000 kg total mass
- 0.12% FWHM (0.05% σ) at $Q_{\beta\beta}$
- Double-barrel LAr instrumentation
- Underground argon
- Reentrant tubes

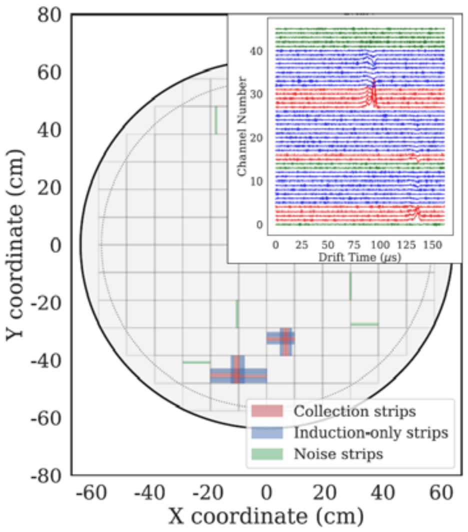
- Baseline选址：SNOLAB
  - 宇宙线本底占比：0.6%
  - 启动：2022，Module 1完成：2028
  - Module 4完成：97–133个月
- 备选选址：LNGS
  - 宇宙线本底占比：20-50% → 10% w/ 中子标记
  - Module 1完成：2027

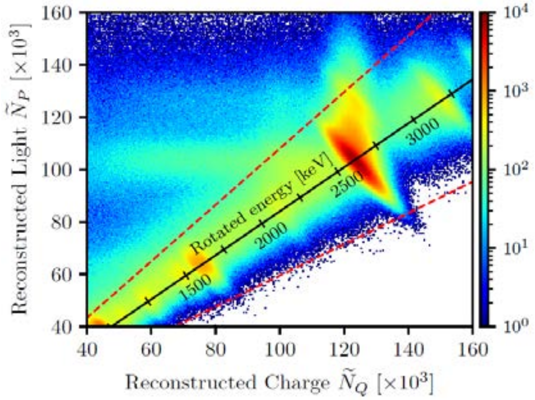
LEGEND

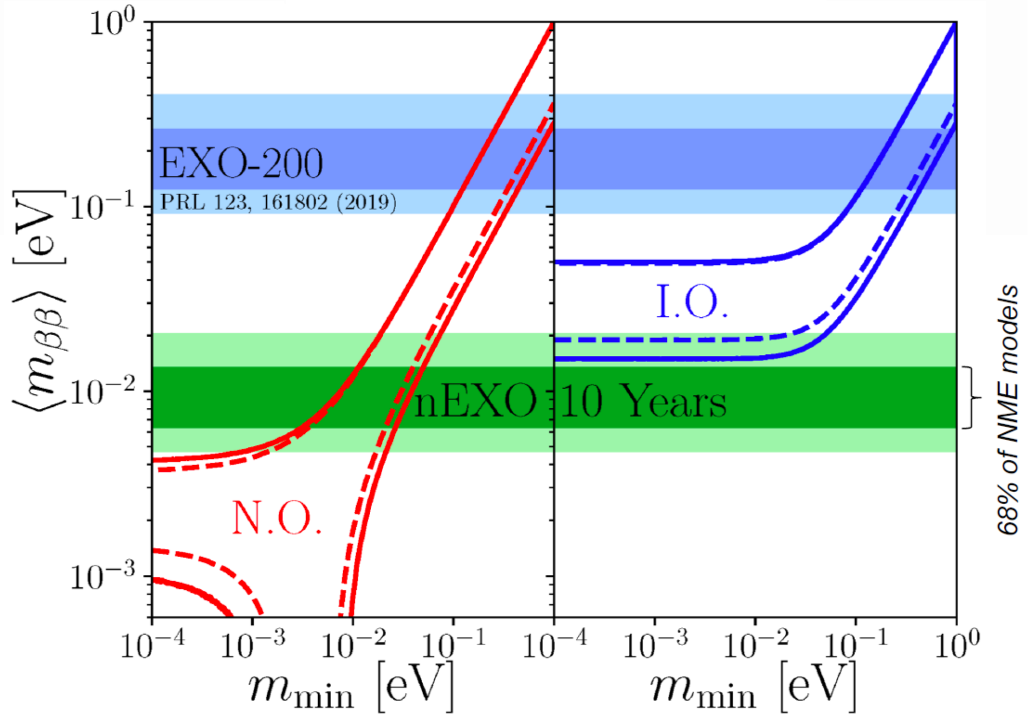
From Stefan Schönert

无中微子双β衰变 – ^{136}Xe (Liquid)









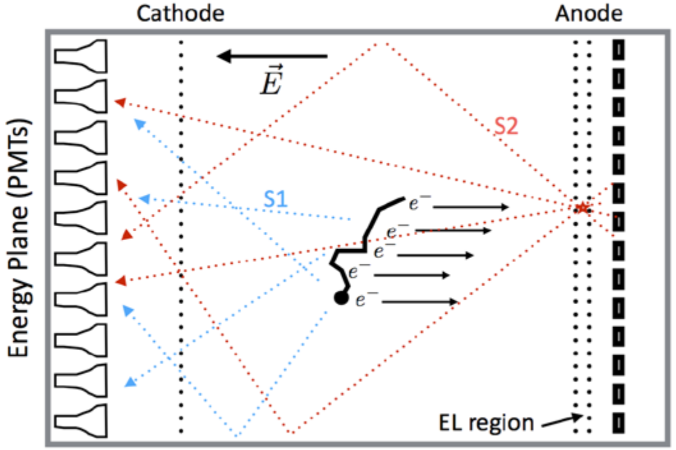
nEXO

From Giorgio Gratta

- EXO-200： > 3.5 x 10^{25} yrs (90% C.L.)
- KamLAND-Zen： > 1.06 x 10^{26} yrs (90% C.L.)
- nEXO： > 10^{28} yrs @ 6.5 yrs (90% C.L.)
  - Pre-CDR: 1805.11142， Sensitivity: 2106.16243
  - BKG: 0.07 counts/(FWHM t y)
  - Resolution: < 1% (σ) @ Q-value

- Baseline选址：SNOLAB Cryopit
  - 启动：2022
  - 运行：2028

无中微子双β衰变 – ^{136}Xe (Gas)



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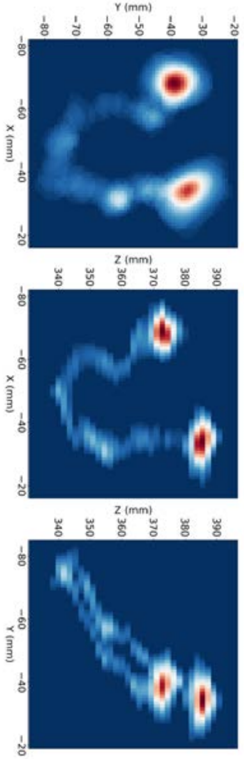
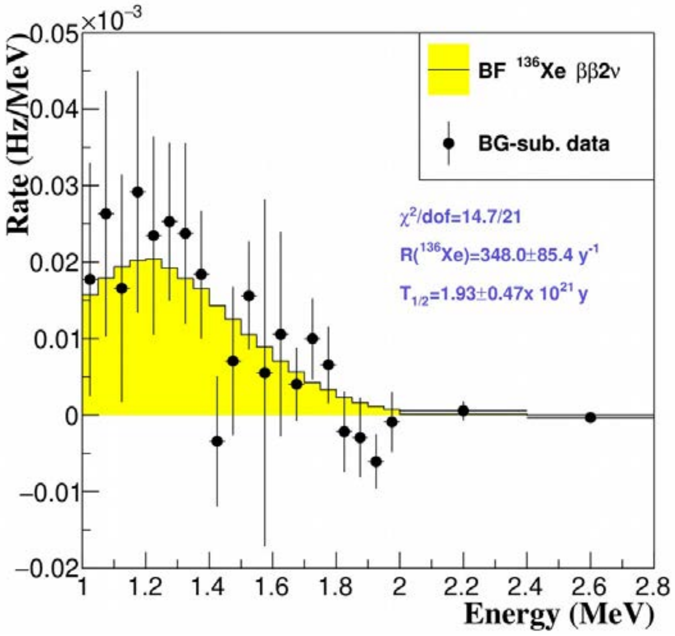
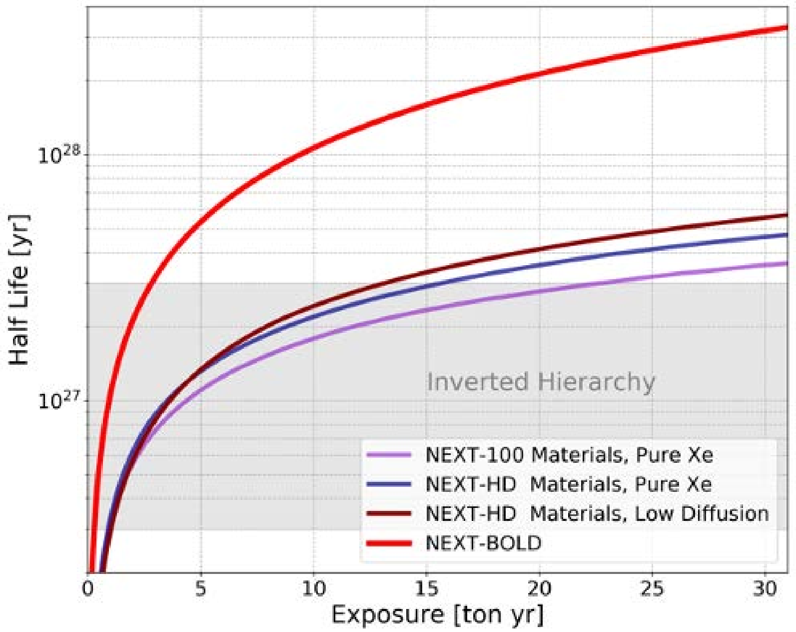


From J.J. Gómez-Cadenas

- Baseline选址：LNGS or SNOLab
    - Demonstration at LSC (**Canfranc Underground Laboratory**)





- NEXT-White (5 kg)： technology demonstration
    - Resolution <1% FWHM
- NEXT-100： ~ 10^{26} yrs (90% C.L.), operation in 2022
- NEXT-HD (1 ton): ~ 10^{27} yrs (90% C.L., 5 ton*yrs), Op. in 2026
    - BKG: 0.061 counts/(ROI t y) ~ 0.044 counts/(FWHM t y)
- NEXT-BOLD: ~ 10^{28} yrs (90% C.L., 5 ton*yrs), Op. in 2029
    - 1 ton, w/ Ba-tagging

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无中微子双β衰变 – ^{130}Te、^{100}Mo

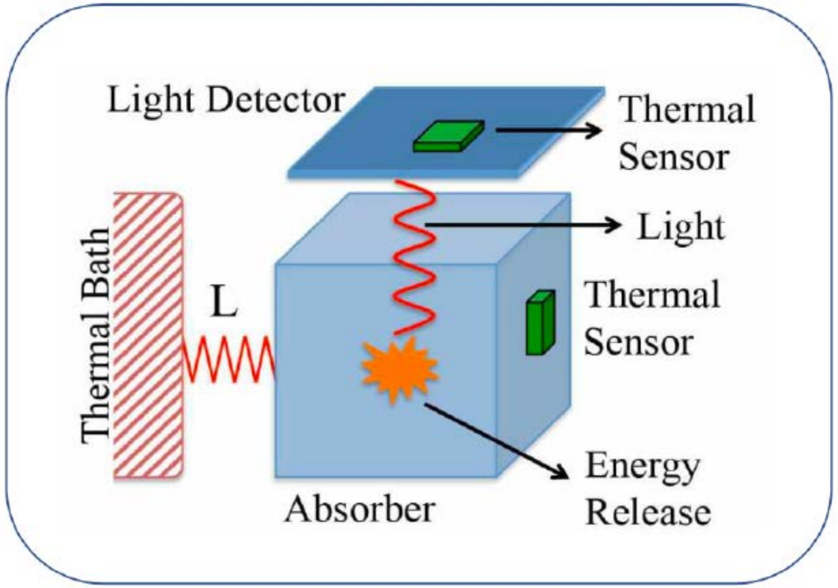
Te

- CUORE： > 3.2 x 10^{25} yrs (90% C.L.)
- SNO+： 试运行
  - 0.5% loading： > 2 x 10^{26} yrs (90% C.L., 3 yrs)
  - 2.5% loading： > 1 x 10^{27} yrs (90% C.L., 4 yrs)

Mo

- CUPID： > 1.1 x 10^{27} yrs @ 10 yrs (3σ)
  - Pre-CDR: 1907.09376
  - LNGS scientific approval in 2020.9
  - BKG: 0.5 counts/(FWHM t y)
  - Energy: 5 keV FWHM
- CUPID-1T： > 8 x 10^{27} yrs @ 10 yrs (3σ)
- 选址：LNGS
  - 启动：2022 （CUORE 2024结束）
  - 运行：2028

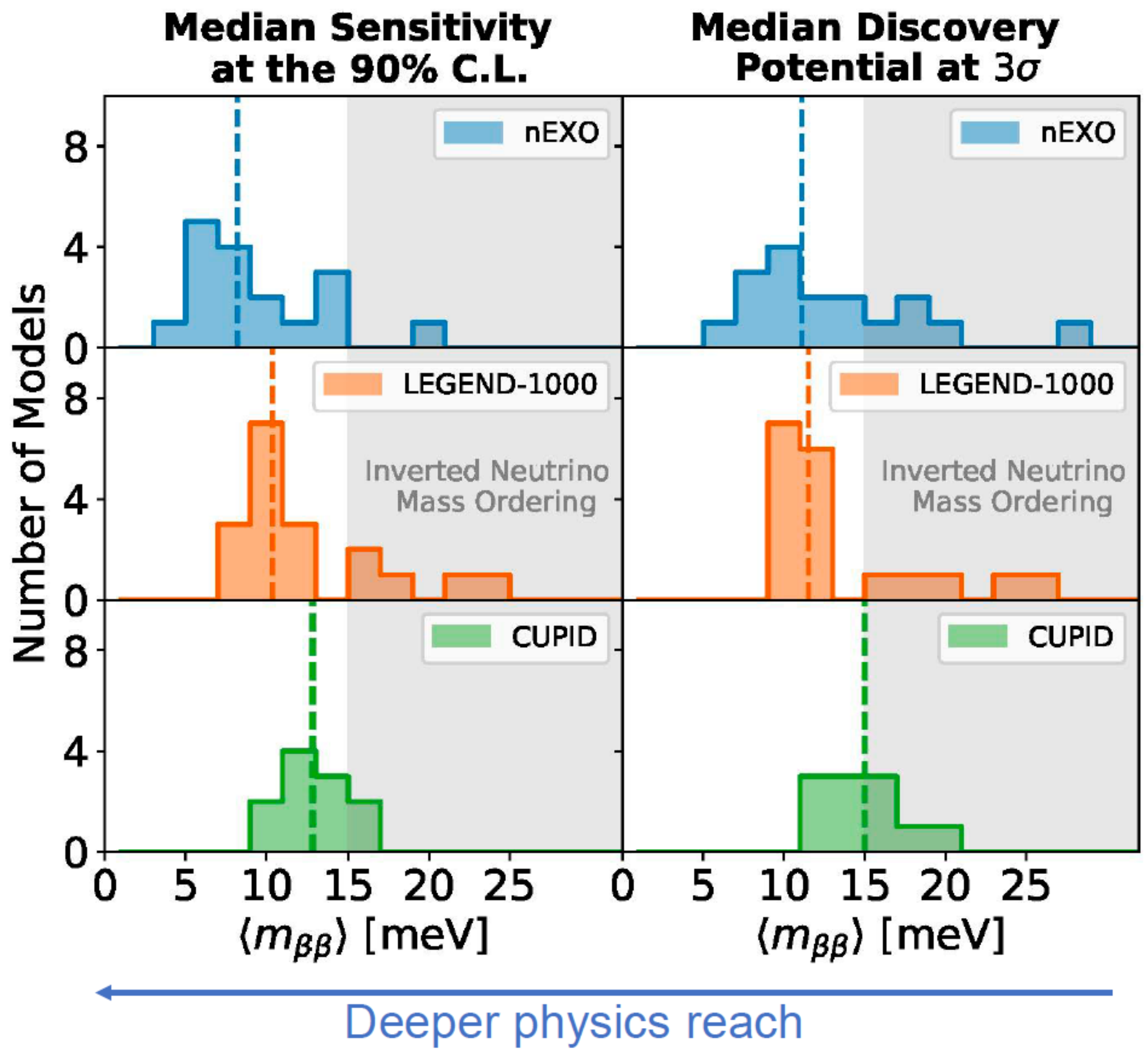
CUPID ^{100}Mo
heat + light
(scintillating bolometer)



CUPID: 472 kg $Li_2{}^{100}MoO_4$, >95% in ^{100}Mo, 240 kg ^{100}Mo
CUPID-1T: 1000 kg of ^{100}Mo

From K. Heeger and M. Pavan

无中微子双β衰变 – 国际实验比较



	$m_{\beta\beta}$ [meV], (*median NME*)	
	90% excl. sens.	3σ discov. potential
nEXO	8.2	11.1
LEGEND	10.4	11.5
CUPID	12.9	15.0

$T_{1/2}$ values used [x10^{28} yr]:

nEXO: 1.35 (90% sens.), 0.74 (3σ discov.)

LEGEND: 1.6 (90% sens.), 1.3 (3σ discov.)

CUPID: 0.15 (90% sens.), 0.11 (3σ discov.)

From Giorgio Gratta

Closed session statement

北美 – 欧洲 workshop

- Neutrino-less double beta decay search is recognised as very compelling science capable of reshaping current understanding of nature
- The international stakeholders in neutrino-less double beta decay research do agree in principle that the best chance for success is an international campaign with more than one large ton-scale experiment implemented in the next decade, with one ton scale experiment in Europe and the other in North America.
- The international stakeholders in neutrino-less double beta decay are interested in exploring whether a more formal structure for international coordination on this research would be beneficial, not only for experiments of the next decade but also for future multi-ton and/or multi-site experiments.

实验	预算
nEXO	~ 250 M$ (sub-total) + ~ 100 M$ (contingency)
LEGEND	Unknown
CUPID	~ 30 M$ (Italy) + ~ 20 M$ (U.S.)
NEXT-HD	20 – 30 M€

See https://agenda.infn.it/event/27143/

无中微子双β衰变（NLDBD） – 国内研究

第268期双清论坛
“深地前沿物理研讨会”，2020.11

- 低温晶体量热器（^{100}Mo）
- 高压气体TPC （^{82}Se，^{136}Xe）
- 高纯锗（^{76}Ge）
- 液体闪烁体（^{130}Te）

CJPL

JUNO

国内实验结果$T_{1/2}^{0\nu}$ (90% C.L.)

- PandaX-II *(2019, CPC)*:
  > 2.1 x 10²³ yrs
- CDEX *(2017, Sci.China)*：
  > 6.4 x 10²² yrs

基金委“无中微子双贝塔衰变物理和关键探测技术研究”专项项目指南，2021.09.29发布

研究期限：2022年1月1日-2025年12月31日

无中微子双贝塔衰变物理的理论研究；高纯度富集钼酸锂晶体研制和富集原料提纯技术；新型TES光热探测读出系统研制和压低双中微子双贝塔衰变的本底效应；能量刻度技术研发和新物理探索；掺碲液体闪烁体探测技术。

掌握下一代实验实现10meV甚至meV量级中微子有效质量测量灵敏度的关键技术，为建设具有国际竞争力的无中微子双贝塔衰变大型实验装置提供技术支撑和培养科研队伍。

“大科学装置前沿研究”重点专项指南

1.3 无中微子双贝塔衰变和太阳中微子实验关键技术研究

研究内容：依托中国锦屏地下实验室，开展寻找无中微子双贝塔衰变、太阳中微子探测实验的关键技术和方法研究，并初步建立相关实验装置开展实验探测。

考核指标：在无中微子双贝塔衰变实验领域开展先进高纯锗半导体探测器、极低温晶体量能器、基于 Topmetal 技术的高气压时间投影室等实验技术研究，确定具有中微子双贝塔衰变有效质量小于 10meV 灵敏度的探测器技术方案；建设百吨级太阳中微子探测平台，实现太阳 B8 中微子的探测，重建出太阳中微子方向，5MeV 能量区间，太阳角重建的角度分辨为 35 度（68%的置信区间）。

无中微子双β衰变（NLDBD） – 国内研究

CUPID-CJPL

地面/地下晶体测试
(2021-2022)
6-12自然丰度晶体

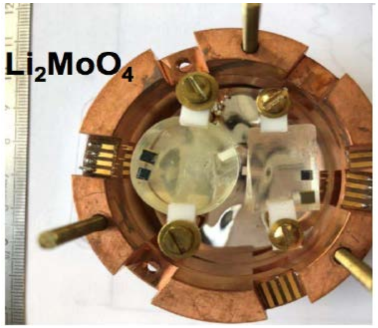
↓

CUPID-CJPL-Demo样机实验
(2022-2024)
10 kg, 36块富集晶体

↓

CUPID-CJPL-200
(2024+)
>1000块富集晶体

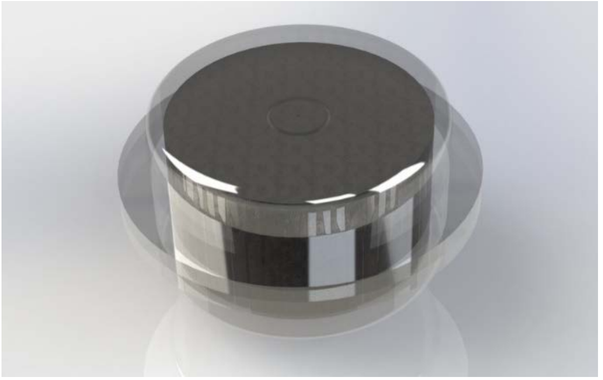
45×45×45 mm³ high purity LMO crystal



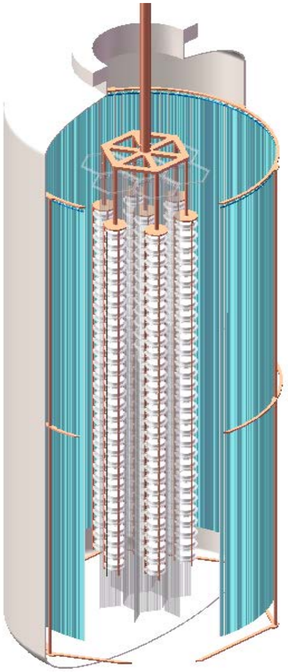
Sens: 9 x 10^{26} yrs @ 5 yrs

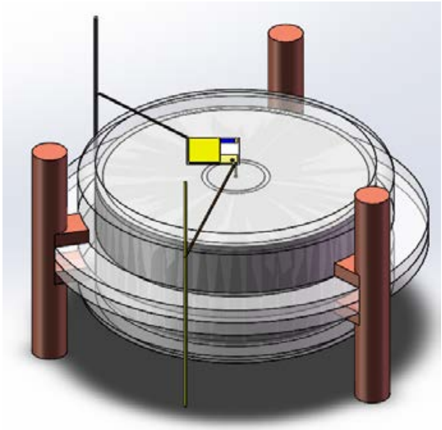
CDEX-300ν

- BEGe和ICPC探测器自主研制
- 富集Ge探测器研制，首批2021底到CJPL



BEGe + LAr active shielding





From 高能物理分会非加速器物理研讨会报告，2021.05

无中微子双β衰变（NLDBD） – 国内研究

PandaX-III

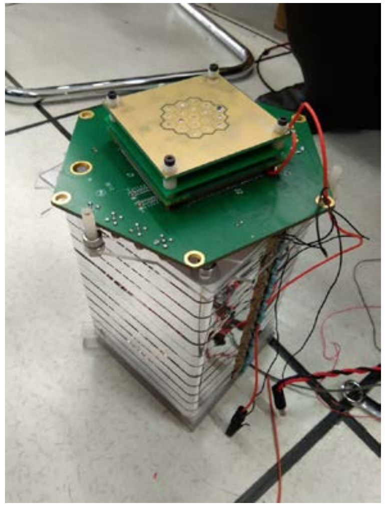
- 高压气氙TPC，原型探测器验证阶段
- 灵敏度分析: 2.7 x 10^{26} yrs (90% CL, 140 kg*5 yrs)

JHEP 06 (2021) 106

- PandaX-4T暗物质探测器也可寻找0νββ，预期灵敏度 10^{25} yrs水平

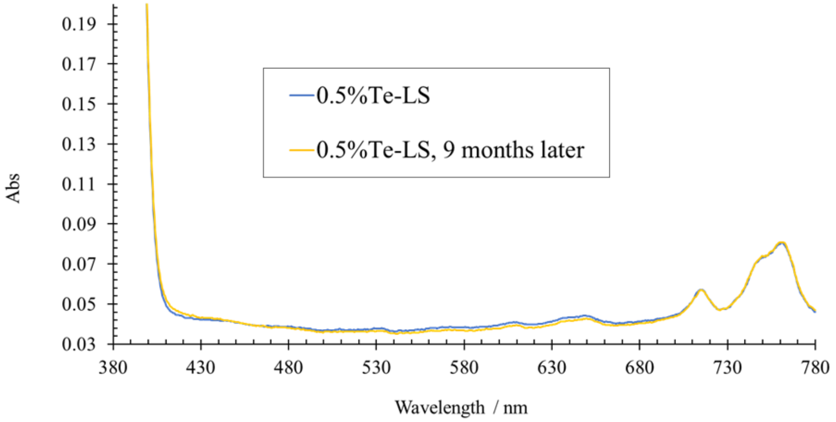
NνDEx

- 关键技术：Topmetal-S芯片
  - 目标：30 e-
  - 实测：~ 50 e-
- 100 kg样机 (2022)



Te-LS

- 新的Te化合物合成方法
- 研究Te-LS配方和工艺，力争2025年实现
  - 高^{nat}Te质量占比
  - 极低放射性：~10^{-17} g/g
  - 光产额、透明度与现有液闪相当
  - 长期稳定性：>10年



From 高能物理分会非加速器物理研讨会报告，2021.05

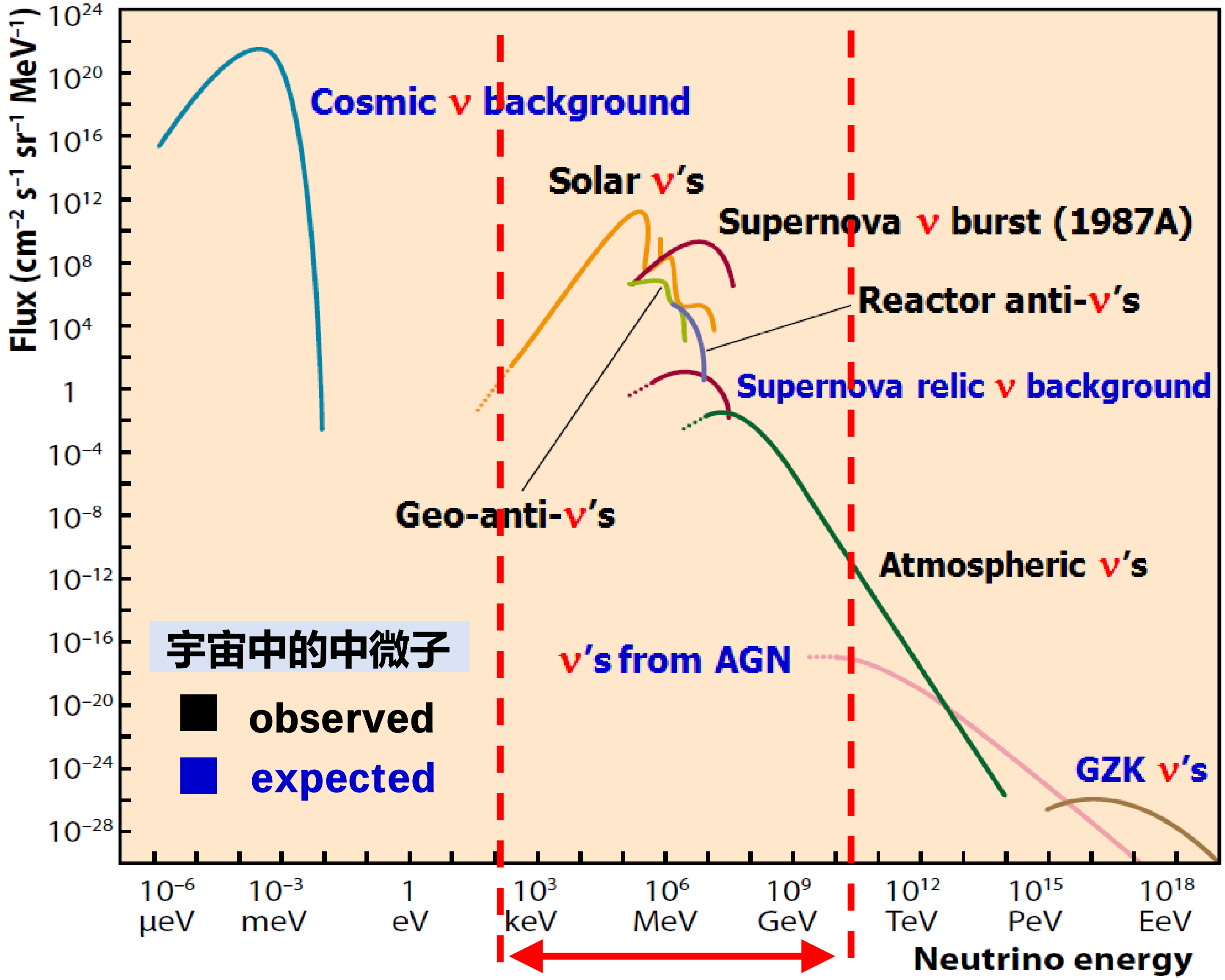
无中微子双β衰变（NLDBD） – 战略讨论

- North American – European workshop上未考虑中国CJPL、日本Kamioka的实验
- nEXO、LEGEND极有可能分别落户SNOLab、LNGS
- CUPID使用CUORE的基础设施，极有可能仍在LNGS

- 我们怎么做?
  - 研发关键技术，做好准备
  - 参与国际合作 vs. 自己干， “以我为主”也需要国际合作

- 0νββ国际合作现状
  - CUPID-preCDR (1907.09376)：复旦、中科大、上海交大
  - LEGND pre-CDR (2107.11462)：无国内单位署名
  - nEXO pre-CDR (1805.11142)：高能所、微电子所
  - JUNO-0νββ计划：以合作组名义向Snowmass提交了LOI

宇宙中的中微子



江门探测器观测能力

超新星爆发中微子（CCSNe）

（人类历史上仅一次观测）

SN1987A，2002年诺贝尔奖

超新星遗迹中微子（DSNB）

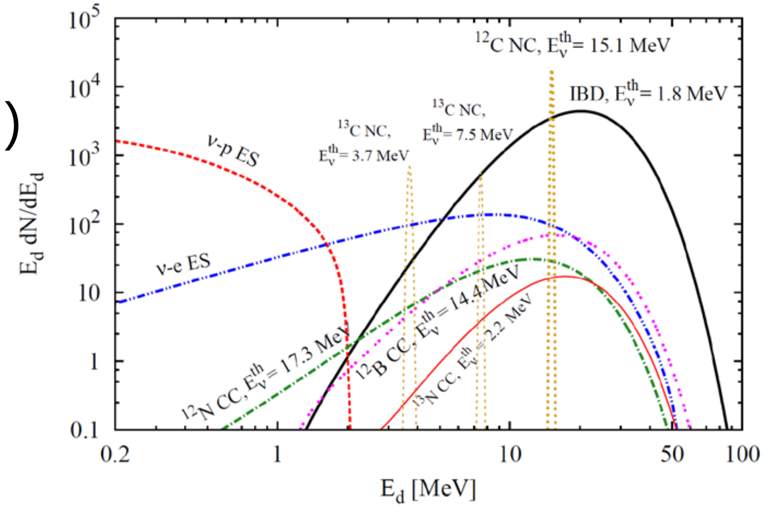
（人类尚未观测到）

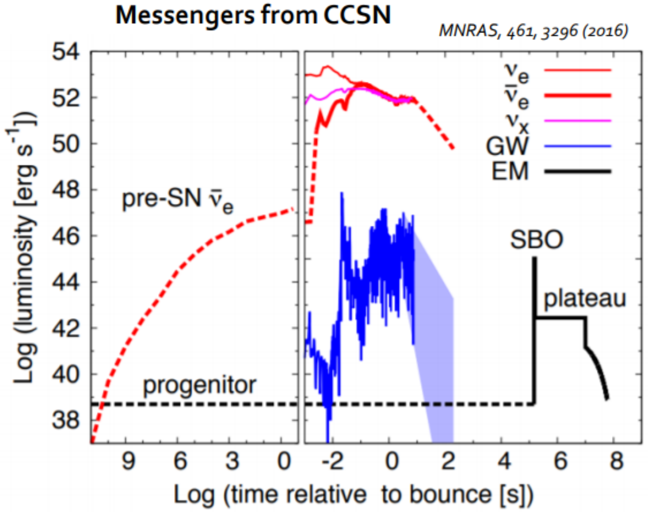
宇宙演化至今所有爆发成功的超新星中微子形成的遗迹

宇宙高能中微子望远镜

中微子天文学 — 中低能天体中微子

- **JUNO**
  - **CCSNe**：全味道探测（IBD、eES、pES）
  - **多信使天文学**：专用Multi-messenger trigger系统
  - **DSNB**：IBD
  - **太阳中微子**： ν-e ES， ν-^{13}C NC、CC
  - **地球中微子**：IBD



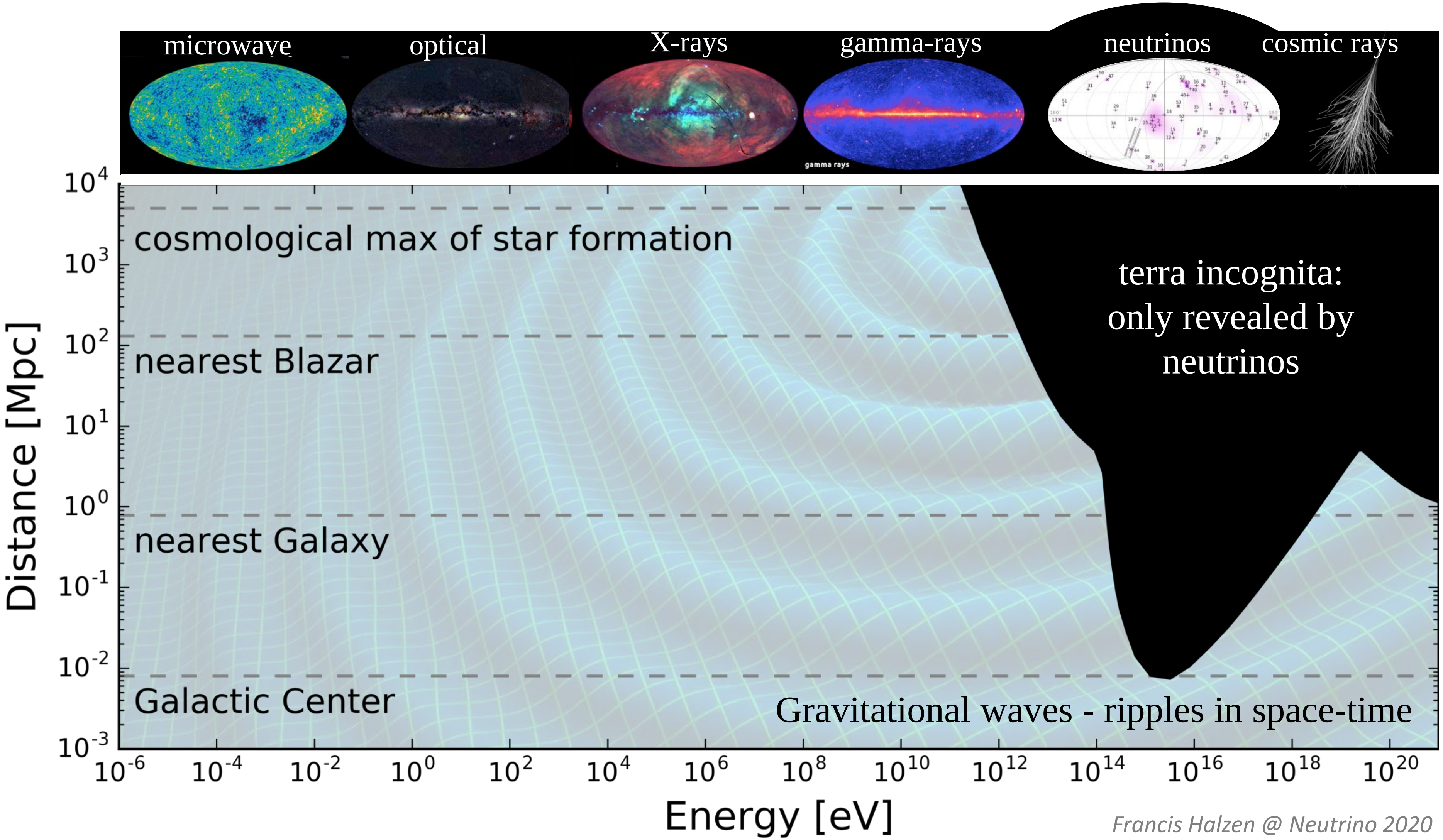


- **锦屏中微子实验（LiCl液闪）**
  - **太阳中微子**：$\nu_e(^7Li, ^7Be)e^-$, $\nu_e(^7Li, ^7Li^*)\gamma$
  - **地球中微子**：IBD

	主要科学目标
太阳 ν	ν 振荡物质效应、太阳金属丰度问题
地球 ν	判别地球物理模型
超新星 ν	理解超新星爆发机制
DSNB	发现超新星遗迹中微子，帮助理解宇宙演化
多信使	寻找极端天文现象伴随的中微子

- **PandaX-4T**
  - **太阳中微子**： ν-e ES、 ν-Xe CEνNS
  - **CCSN**： ν-Xe CEνNS

中微子天文学 — 宇宙高能中微子



Francis Halzen @ Neutrino 2020

IceCube	IceCube-Gen2
Deep ice	Deep ice
1 km^3	~10 km^3
2011 –	Projected, 1st phase imminent

ANTARES
Deep water
0.01 km^3
2008 – 2019

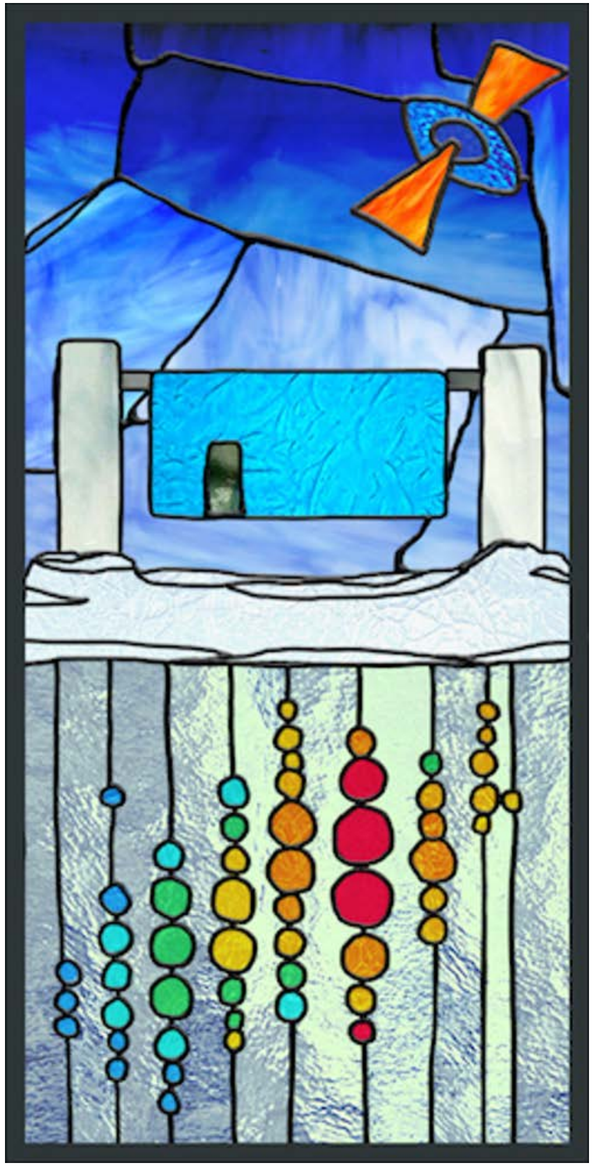
KM3NeT
Deep water
1 + 0.006 km^3
Construction

Baikal/GVD
Deep water
~1 km^3
Construction

P-ONE

Universe is opaque above **~100 TeV** energy

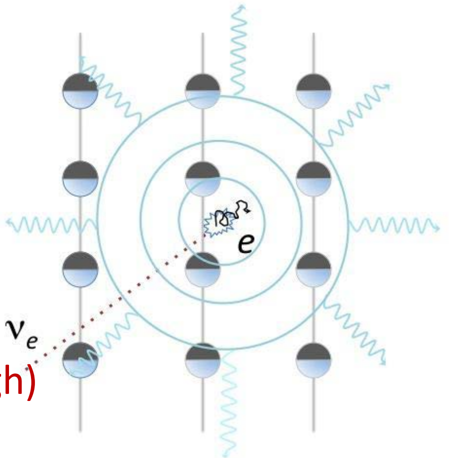
高能中微子望远镜



Francis Halzen @ Neutrino 2020

- **科学问题：高能宇宙中微子的起源是什么？宇宙射线的起源是什么？**
- **手段：用中微子望远镜寻找、研究天体中微子源**
- **关键：源的方向重建、能量阈值**

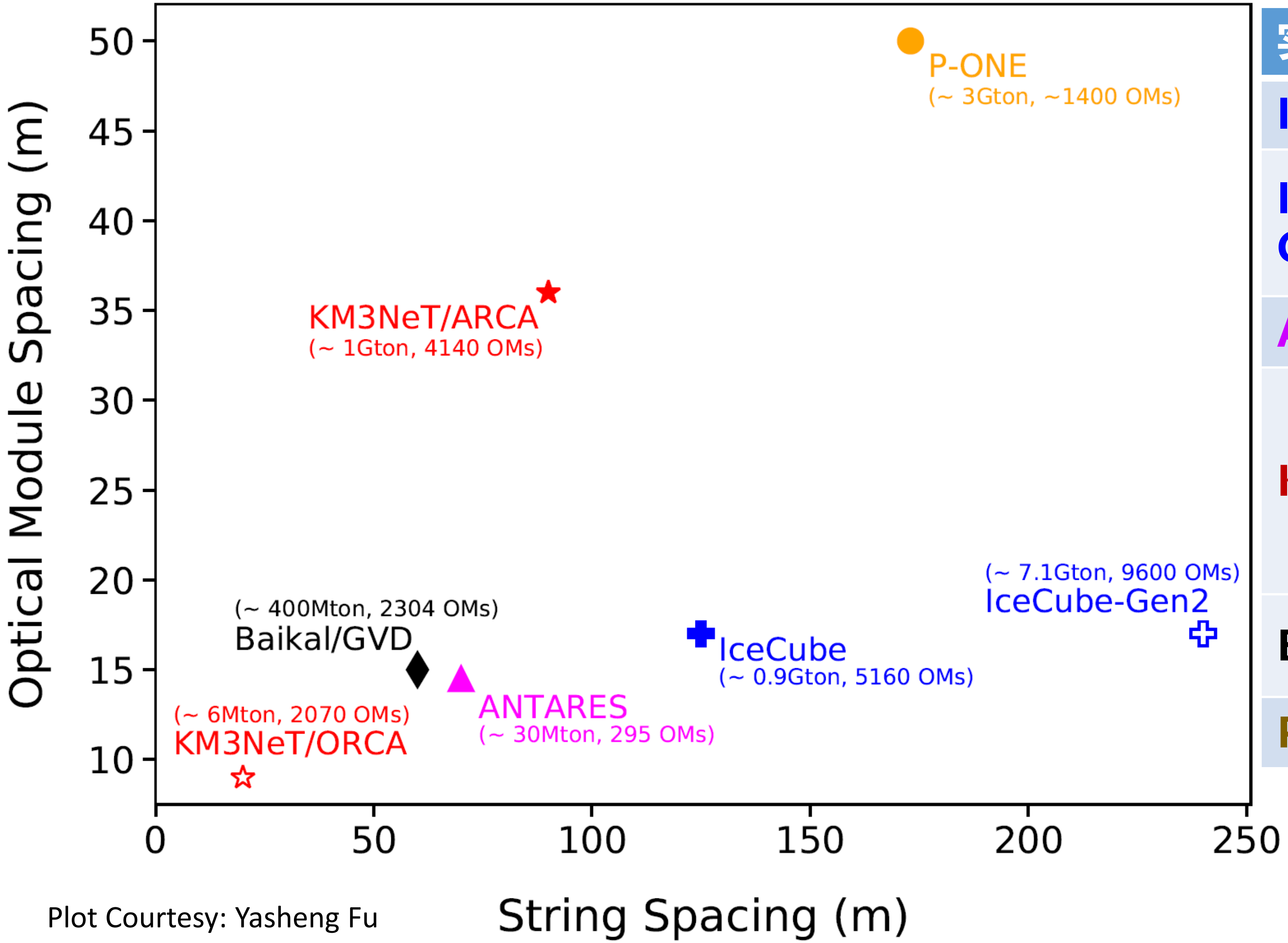
- 1 – 10 km^3 量级 水 或 冰
  - 南极冰： L_{abs} : 100 ~ 200 m, L_s^{eff} : ~25 m (Mie scat.)
  - 贝加尔湖水： L_{abs}: 22±2 m, L_s^{eff} : ~ 300-500 m (Rayleigh)
  - 地中海海水： L_{abs} : ~ 25 m, L_s^{eff} : >100 m (Rayleigh)
  - 南海海水：
- PMT阵列
  - 纵向（光学模块间距 D_{OM}）： 10 ~ 50 m
  - 横向（String间距 D_S）： 20 ~ 240 m



PeV ν_e and ν_τ showers:

- 10 m long
- volume ~ 5 m^3
- isotropic after 25~50 m

高能中微子望远镜 – 国际计划



实验	能量阈值	High-E能力
IceCube	~ 100 GeV	~ PeV
IceCube-Gen2	core : GeV optical : TeV	0.1 - 1 TeV 100 PeV
ANTARES	~ 100 GeV	~ 100 TeV
KM3NeT	ORCA: 3 GeV	~ 0.1 TeV
	ARCA: ~TeV	~ PeV
Baikal/GVD	~ TeV	~ PeV
P-ONE		

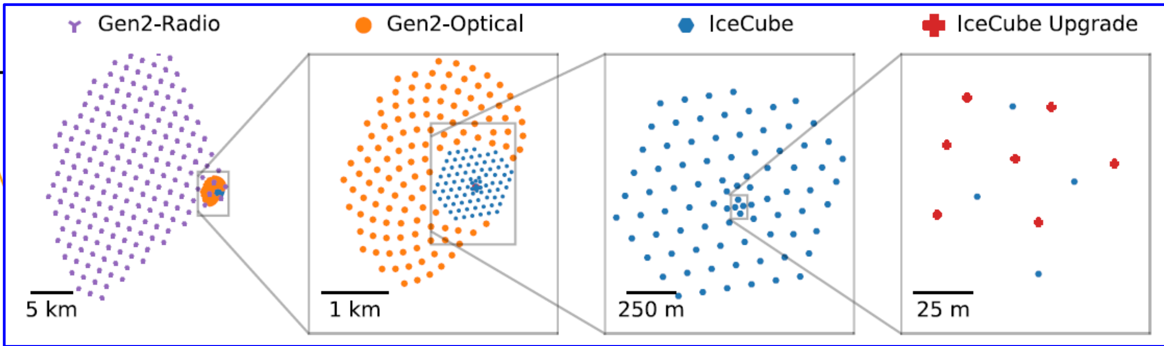
Plot Courtesy: Yasheng Fu

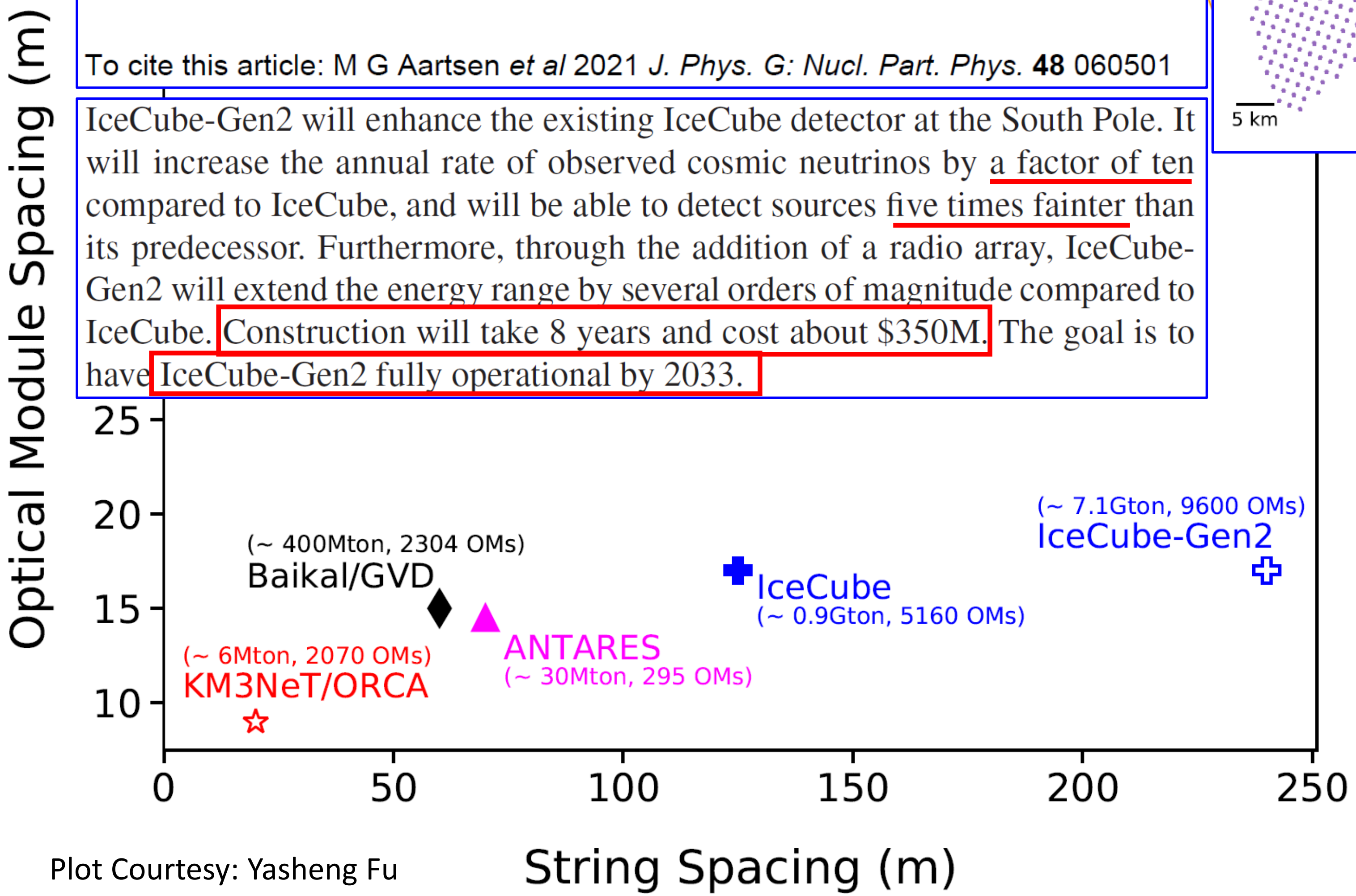
高能中微子望远镜 – 国际计划

IceCube-Gen2: the window to the extreme Universe

To cite this article: M G Aartsen *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* **48** 060501

IceCube-Gen2 will enhance the existing IceCube detector at the South Pole. It will increase the annual rate of observed cosmic neutrinos by a factor of ten compared to IceCube, and will be able to detect sources five times fainter than its predecessor. Furthermore, through the addition of a radio array, IceCube-Gen2 will extend the energy range by several orders of magnitude compared to IceCube. Construction will take 8 years and cost about \$350M. The goal is to have IceCube-Gen2 fully operational by 2033.

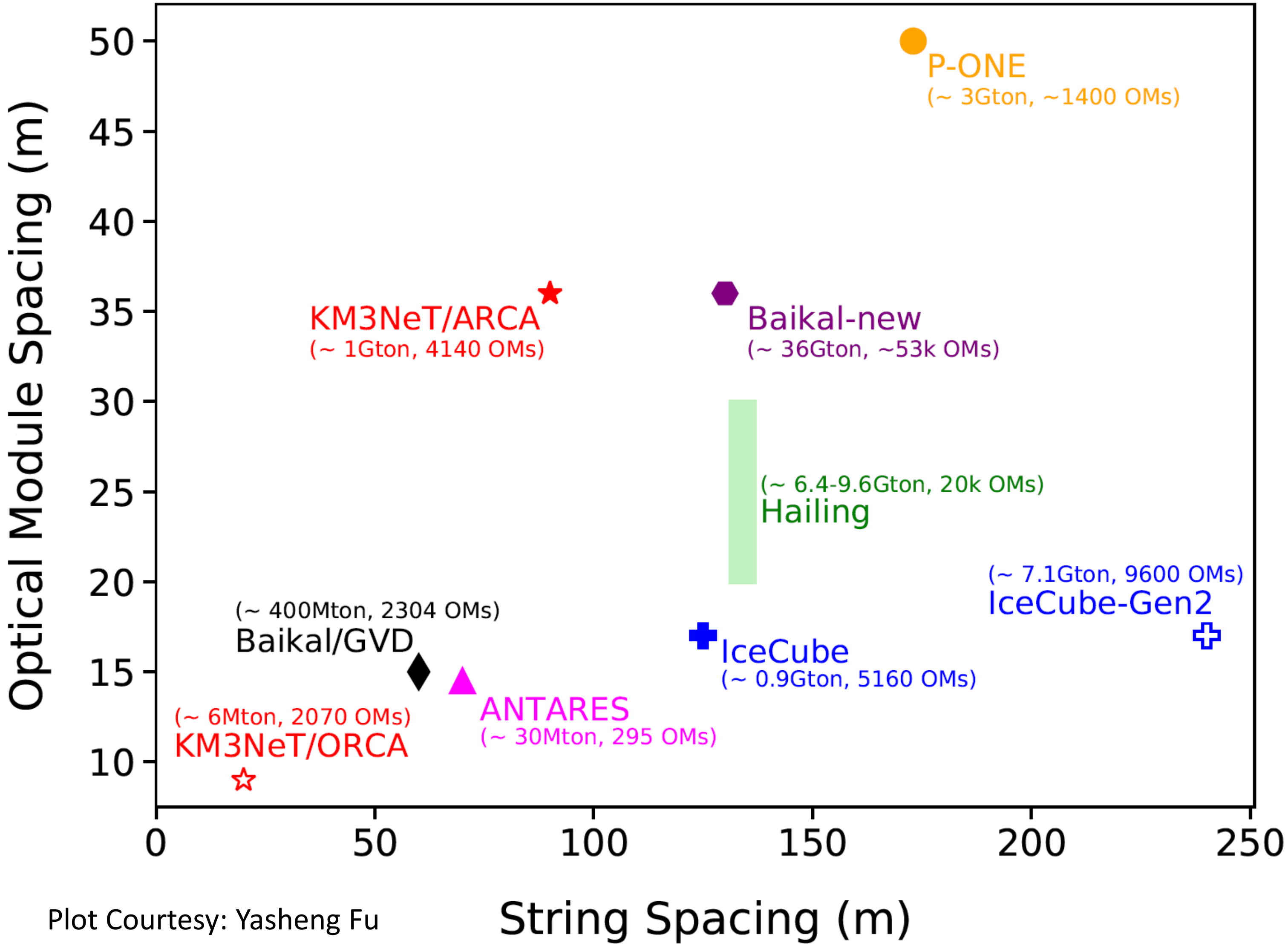




Plot Courtesy: Yasheng Fu

- D_S、D_{OM}、N_{OM}的选择，决定于
  - ☐ E_ν 阈值 → 探测能力
  - ☐ 靶质量 → 统计量
- 关键技术 & 成本因素：
  - ☐ PMT module + 电子学
  - ☐ Deployment（PMT、电缆）
  - ☐ 水体环境
  - ☐ PMT定位

高能中微子望远镜 – 国内计划



Plot Courtesy: Yasheng Fu

- “海铃”计划
  - ~ 4 x 4 x 1 km^3
  - ~ 20 k OMs

PoS (ICRC2021) 1043

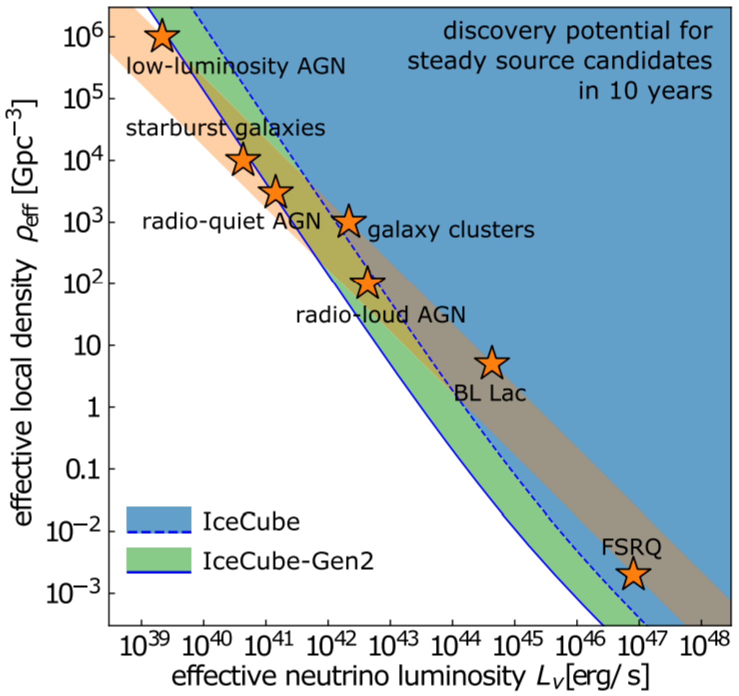
hDOM概念设计：
31 PMTs (XP72B20) +
20 SiPM (PA3325-WB-0808)

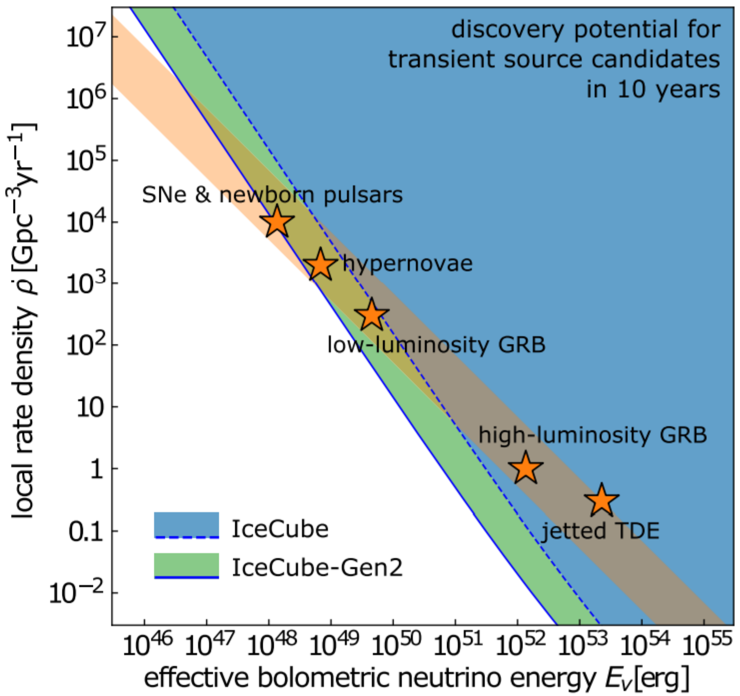
→ **< 0.1° angular resolution**

- “新”Baikal计划
  - ~ 6 x 6 x 0.9 km^3, E>100 TeV
  - ~ 53 k OMs
    - e.g., 20-in PMT per OM

高能中微子望远镜 – 国内计划

建造10x ~ 40x IceCube
规模的高能中微子望远镜





2008.04323

- 优化D_S、D_{OM}、N_{OM}的选择
  - E_ν 阈值、靶质量
- OM设计
  - 如何以低造价实现< 0.1° 角分辨
    - Single PMTs : Upward-looking 20-in PMT (?)
    - Multi-PMTs : 4 pi view
    - Hybrid : small PMTs + SiPM arrays
  - 10万/OM（含光电器件+机械电子学+电缆+海/湖中安装），~2万 OMs → ~20亿量级

总结

- **中微子振荡**
  - 规划明确，稳步进行
- **无中微子双贝塔衰变**
  - 国际吨量级实验形势渐明，LEGEND/nEXO/CUPID将吸引大量国际合作者
  - 国内部署了关键技术预研，未来1-2年需思考：国际合作 vs. 自己干
- **高能中微子望远镜**
  - 进一步明确科学目标，研发更灵敏、造价便宜的光探测模块，能实现 ≫10x IceCube规模
- **中微子相干散射**
  - 技术先行，应用于粒子物理研究（中微子、暗物质）、或监测

谢谢！

未来中微子振荡实验

Primary goals: ν mass ordering (NMO) and CP violation

NMO: fundamental ν property, imply different flavor structure, a model discriminator
Strategy: Complementary NMO determination in neutrino oscillations

Δm^2_{31} and Δm^2_{32} interference (ϕ)	Δm^2_{ee} and $\Delta m^2_{\mu\mu}$ difference	Matter Effect

Reactor

Atmospheric

Accelerator

Effective Parameters

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

$$\Delta m^2_{\mu\mu} = \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \cos\delta\,\sin\theta_{13}\,\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}$$

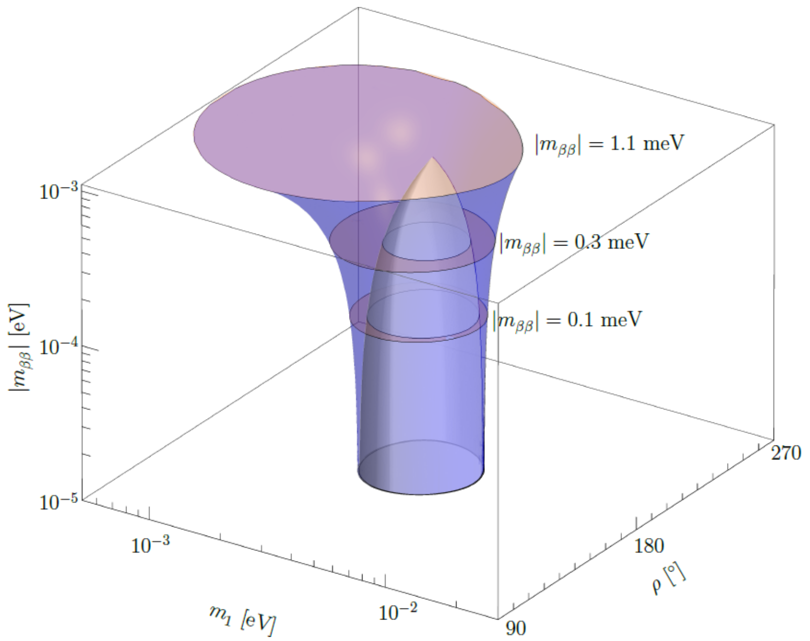
$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm\Delta m^2_{21}(\cos 2\theta_{12} - \cos\delta\,\sin\theta_{13}\,\sin 2\theta_{12}\tan\theta_{23})$$

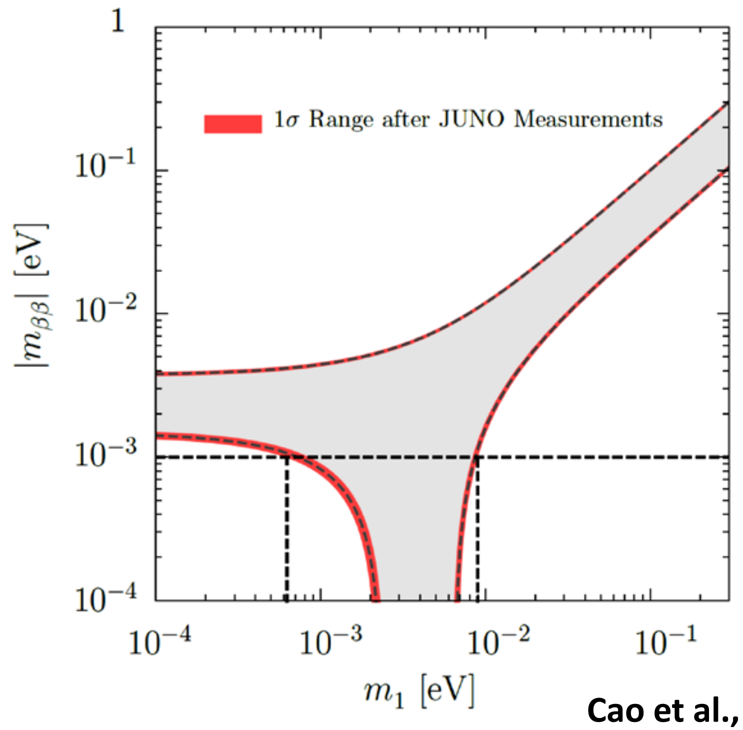
DUNE

Hyper-Kamiokande

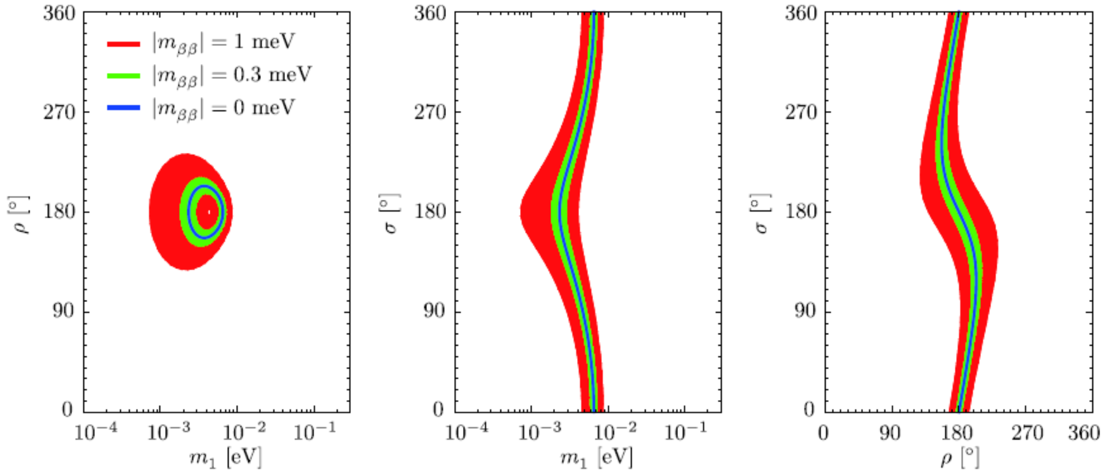
δ_{CP} : matter-antimatter asymmetry
Strategy: Compare $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at Acc.

未来：1 meV sensitivity of $|m_{\beta\beta}|$





Cao et al., CPC 44 (2020) 031001



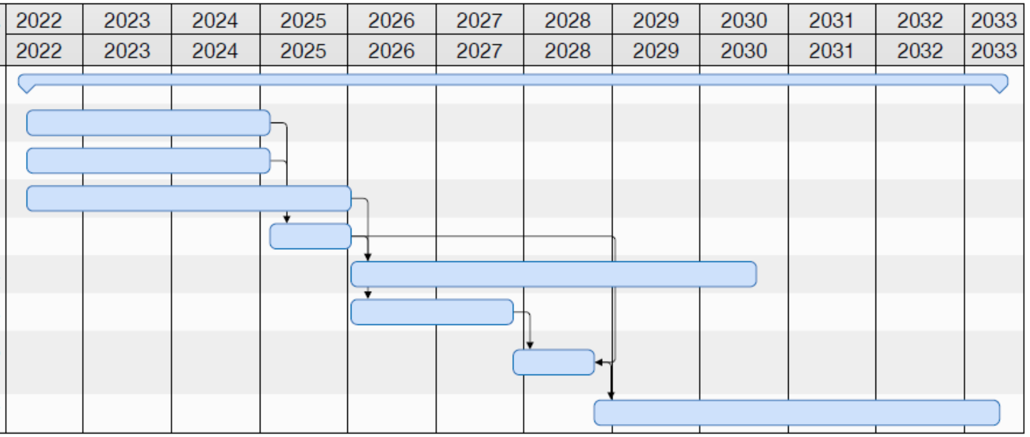
- 最灵敏地确定最轻中微子质量

$$\boxed{m_1 \in [0.7, 8]\ \text{meV}}$$

- 将 (m_1, ρ, σ)约束到很小的参数空间

The project

#	Traits	Title	Given Work	Given Earliest Start	Resources	Predecessors
0		**NEXT-Project**		**12/05/2022**		
1		NEXT-100 Operation	3 years			
2		NEXT-HD R&D	3 years			
3		NEXT-BOLD R&D	4 years			
4		NEXT-HD (LSC)/ construction	1 year			1; 2
5		NEXT-HD-LSC operation	5 years			4
6		BOLD Demonstrators	2 years			3
7		BOLD/HD module 2 construction	1 year			4EE; 6
8		BOLD/HD (2) operation	5 years			7



- Operation of NEXT-100 runs in parallel with R&D for NEXT-HD and NEXT-BOLD from 2021 to 2025
- Preparation of infrastructures (water tank, gas, pressure vessel, inner copper shielding) proceeds as soon as NEXT-100 is in operation. **LSC, which enters as new group in NEXT will lead this activity.**
- Procurement of ~200 kg per year of Xe-136 from 2021 to 2026 (LSC).
- **NEXT-HD can begin operation at intermediate mass (and lower pressure) and scale up as more xenon becomes available.**

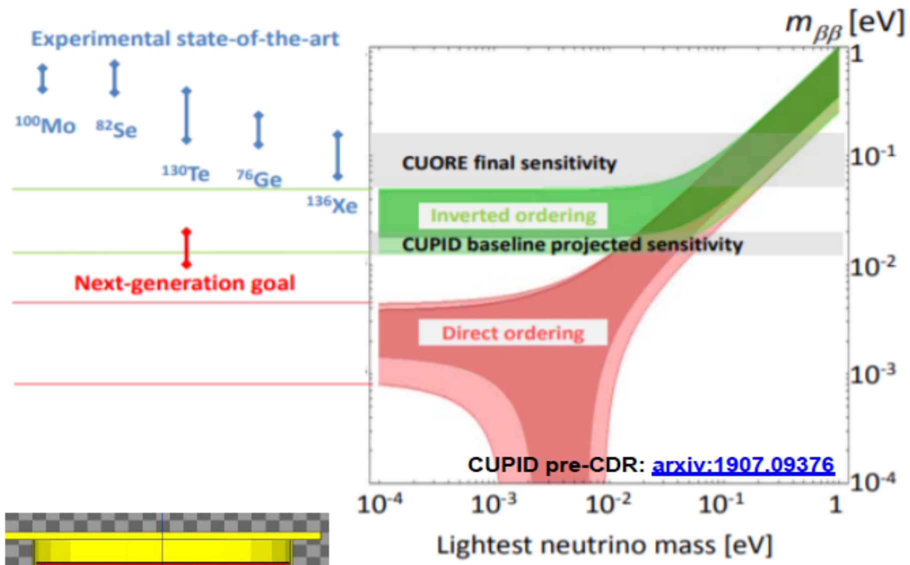
Backups: CUPID-1T experiment

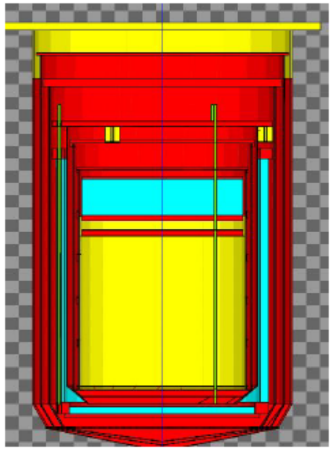
CUPID-1T: HALLMARKS

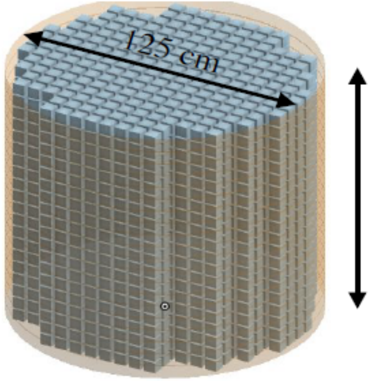
- 1000 kg of ^{100}Mo in a new cryostat or multiple facilities world wide
- Sensitivity: $m_{\beta\beta}$<10 meV (NH)

POTENTIAL EXPANSIONS

- Large volume cryogenic facilities in multiple Underground Labs worldwide
- ~1900 kg of LMO







Build a large-size CUPID-CJPL detector as a part of CUPID network detectors to achieve ultimate ton-scale sensitivity for Mo-100

Towards CUPID-1T. Snowmass 2021 Planning workshop

Backups: Sensitivity projection

基本参数	CUPID-CJPL Demonstrator		CUPID-CJPL 200
晶体材料	Li_2MoO_4	Li_2MoO_4	Li_2MoO_4
晶体总质量（kg）	10	30	200
有效同位素富集度	85%	85%	95%
有效同位素质量（kg）	5	15	106
能量分辨率（FWHM，keV）	10	10	5
本底水平（cts/keV/kg/yr)	0.001	0.001	0.0001
半衰期灵敏度（5yr, yr）	$3.5\text{x}10^{25}$	$6.0\text{x}10^{25}$	$9\text{x}10^{26}$
有效质量灵敏度（5yr, meV）	70-130	41-75	12-22
预算估计（人民币百万元）	20	50	200

CUPID-CJPL不同规模实验半衰期和有效马约拉纳质量测量灵敏度预测

Journal of Physics G: Nuclear and Particle Physics

MAJOR REPORT

IceCube-Gen2: the window to the extreme Universe

To cite this article: M G Aartsen *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* **48** 060501

Abstract

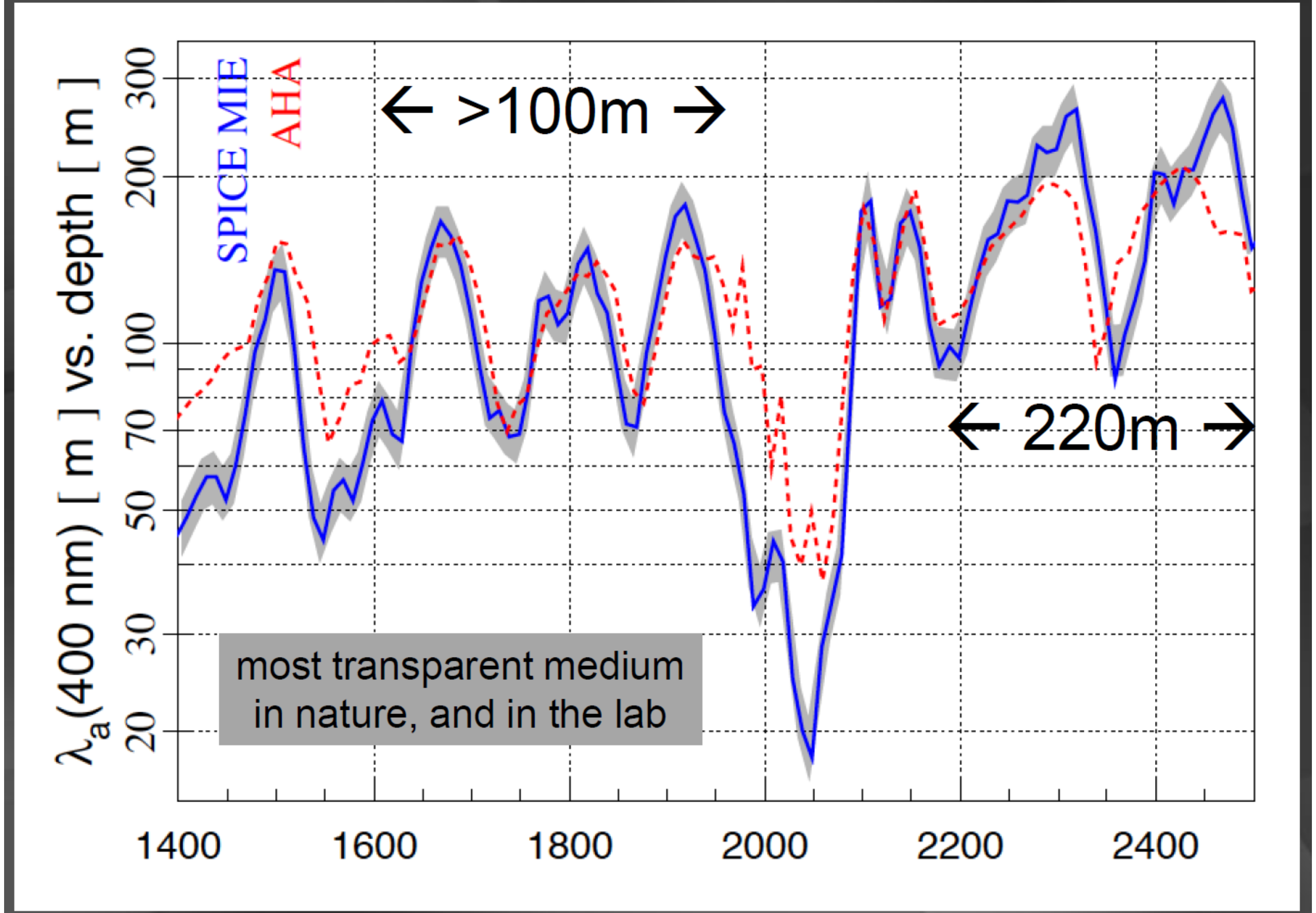
The observation of electromagnetic radiation from radio to γ-ray wavelengths has provided a wealth of information about the Universe. However, at PeV (10^{15} eV) energies and above, most of the Universe is impenetrable to photons. New messengers, namely cosmic neutrinos, are needed to explore the most extreme environments of the Universe where black holes, neutron stars, and stellar explosions transform gravitational energy into non-thermal cosmic rays. These energetic particles have millions of times higher energies than those produced in the most powerful particle accelerators on Earth. As neutrinos can escape from regions otherwise opaque to radiation, they allow an unique view deep into exploding stars and the vicinity of the event horizons of black holes. The discovery of cosmic neutrinos with IceCube has opened this new window on the Universe. IceCube has been successful in finding first evidence for cosmic particle acceleration in the jet of an active galactic nucleus. Yet, ultimately, its sensitivity is too limited to detect even the brightest neutrino sources with high significance, or to detect populations of less luminous sources. In this white paper, we present an overview of a next-generation instrument, IceCube-Gen2, which will sharpen our understanding of the processes and environments that govern the Universe at the highest energies. IceCube-Gen2 is designed to:

(a) Resolve the high-energy neutrino sky from TeV to EeV energies
(b) Investigate cosmic particle acceleration through multi-messenger observations
(c) Reveal the sources and propagation of the highest energy particles in the Universe
(d) Probe fundamental physics with high-energy neutrinos

IceCube-Gen2 will enhance the existing IceCube detector at the South Pole. It will increase the annual rate of observed cosmic neutrinos by a factor of ten compared to IceCube, and will be able to detect sources five times fainter than its predecessor. Furthermore, through the addition of a radio array, IceCube-Gen2 will extend the energy range by several orders of magnitude compared to IceCube. Construction will take 8 years and cost about \$350M. The goal is to have IceCube-Gen2 fully operational by 2033.

IceCube-Gen2 will play an essential role in shaping the new era of multi-messenger astronomy, fundamentally advancing our knowledge of the high-energy Universe. This challenging mission can be fully addressed only through the combination of the information from the neutrino, electromagnetic, and gravitational wave emission of high-energy sources, in concert with the new survey instruments across the electromagnetic spectrum and gravitational wave detectors which will be available in the coming years.

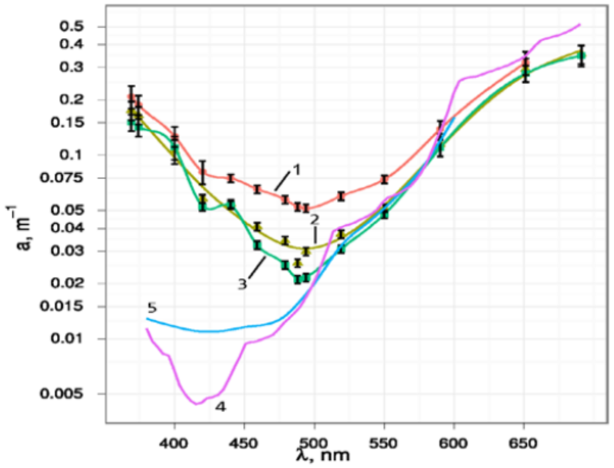
absorption length of Cherenkov light

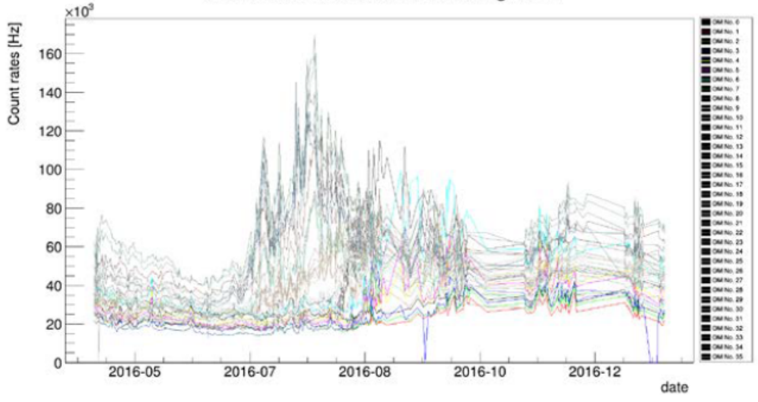


IceCube	IceCube-Gen2
Deep ice	Deep ice
1 km^3	~10 km^3
2011 –	Projected, 1st phase imminent

Baikal/GVD
Deep water
~1 km^3
Construction

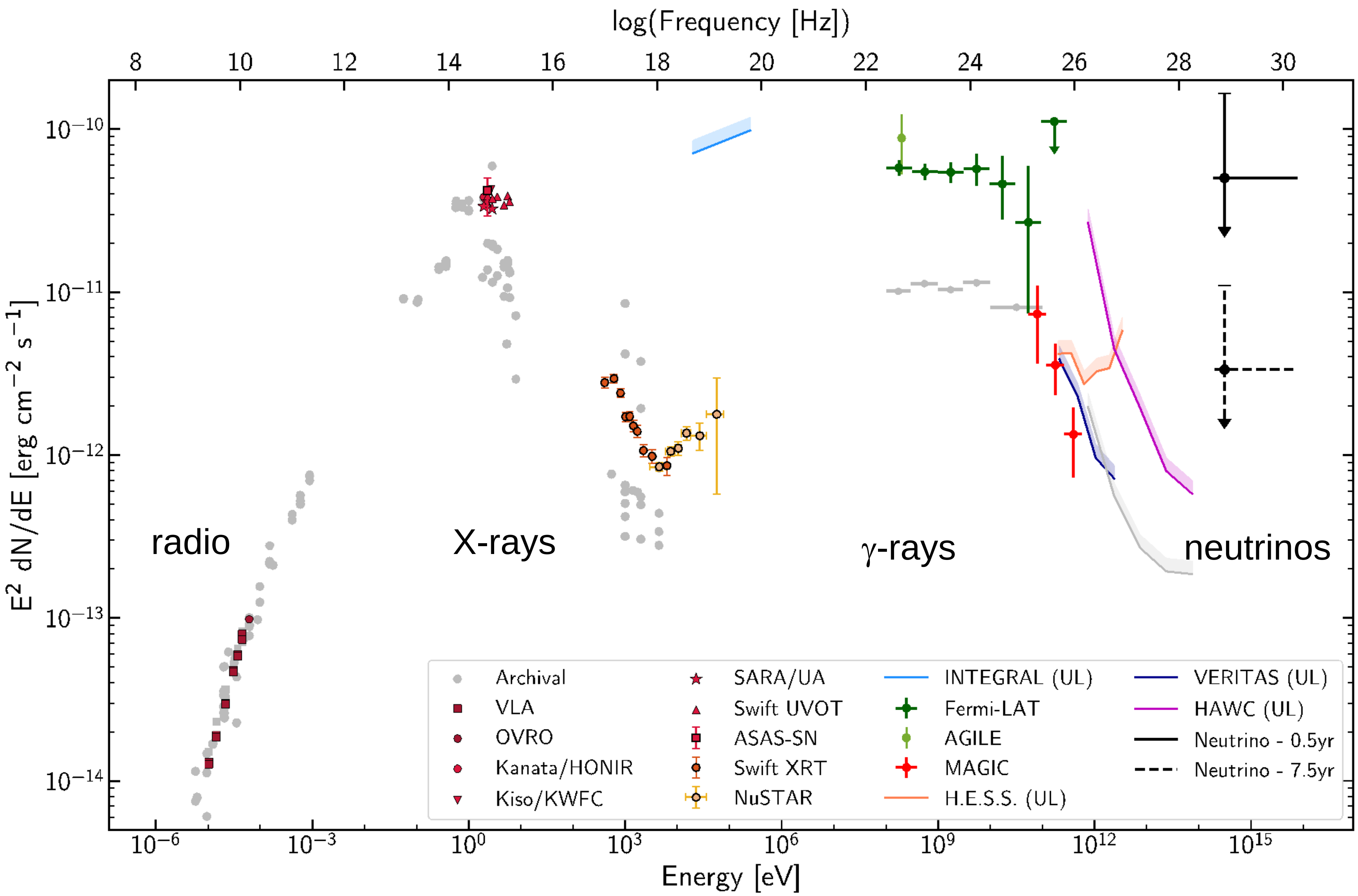
- Water properties





- **Absorption length: ~ 22-24 m**
- **Scattering length: L_s ~ 30-50 m**
  $L_{eff} = L_s /(1- \langle\cos\theta\rangle)$ ~ 300-500 m
- **Strongly anisotropic phase function: $\langle\cos\theta\rangle \sim 0.9$**
- **Moderately low background in fresh water:**

  15 – 40 kHz (R7081HQE)
  absence of high luminosity bursts from biology and K^{40} background.



we know that this cosmic accelerator is a cosmic ray source