

“海铃计划”最新进展与未来展望

TRIDENT
The tRopical DEep-sea Neutrino Telescope

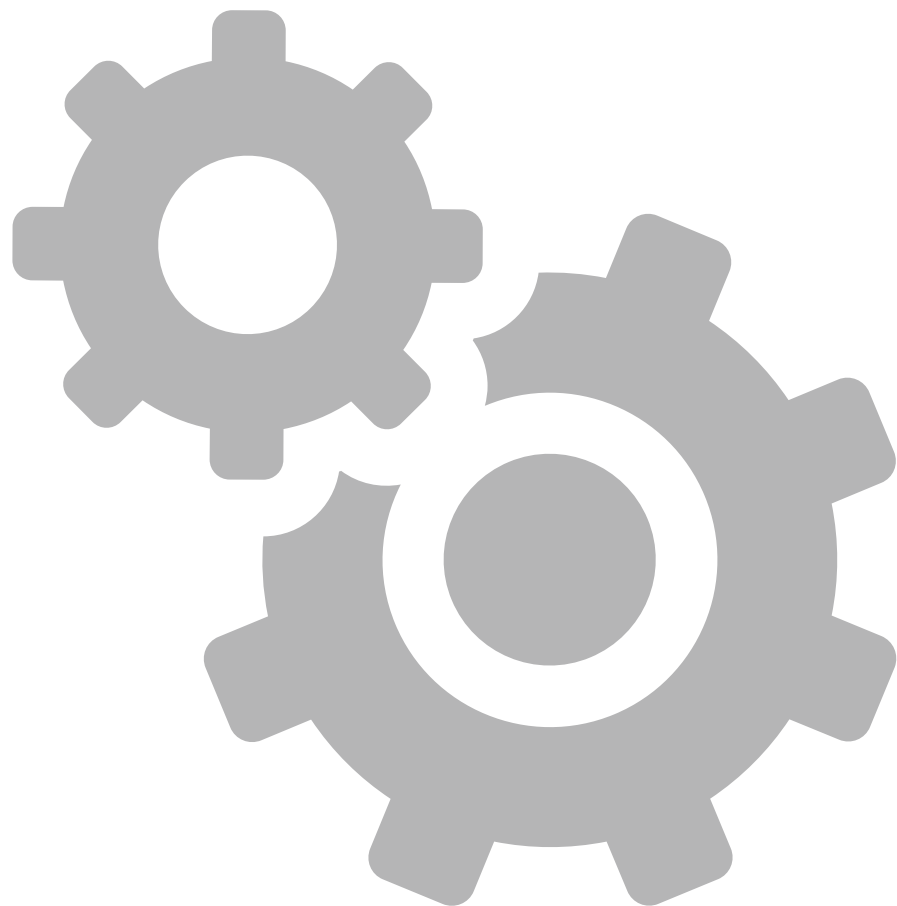
朱泰琳

on behalf of the TRIDENT Collaboration

上海交通大学李政道研究所

t.zhu@sjtu.edu.cn

2025年9月18-22日 | 中国地质大学 | 湖北·武汉



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中微子天文学简介

2

海铃计划背景介绍

3

海铃一期设计

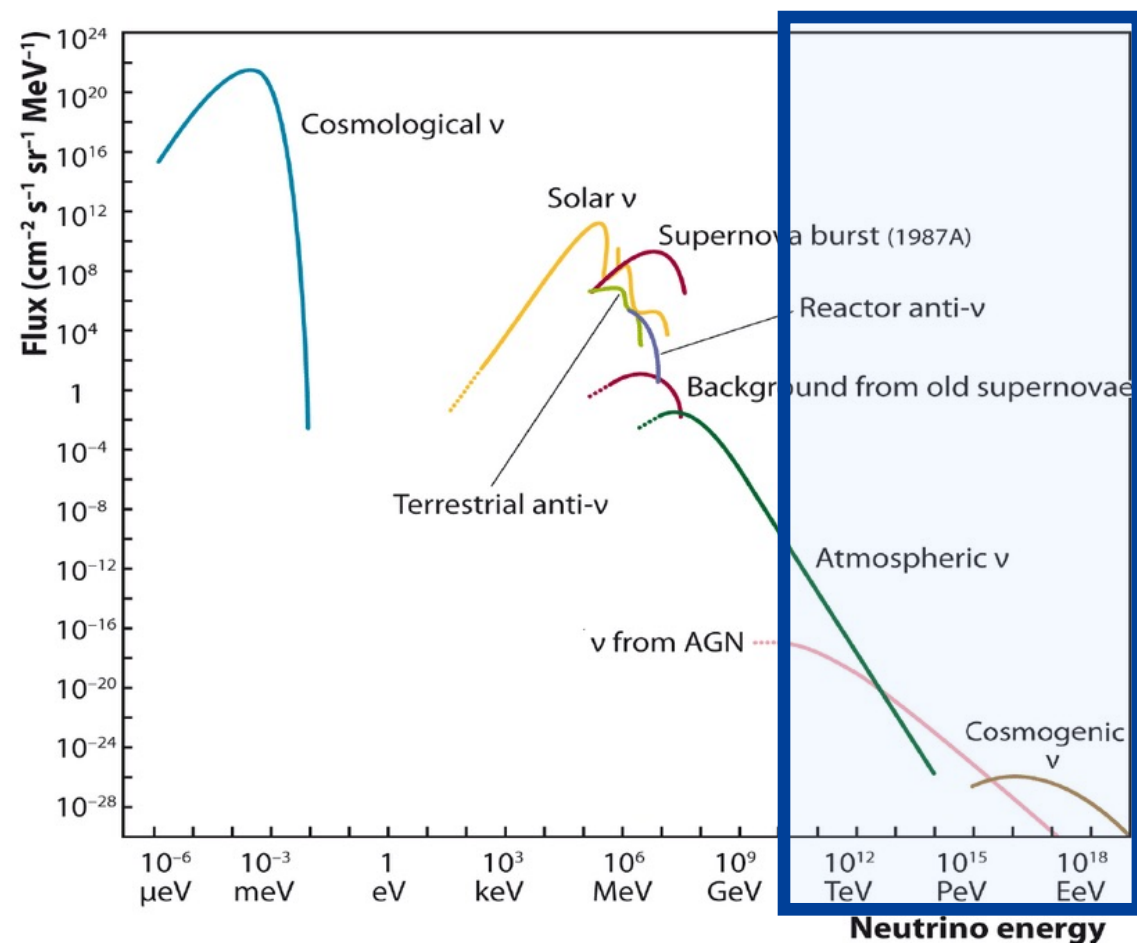
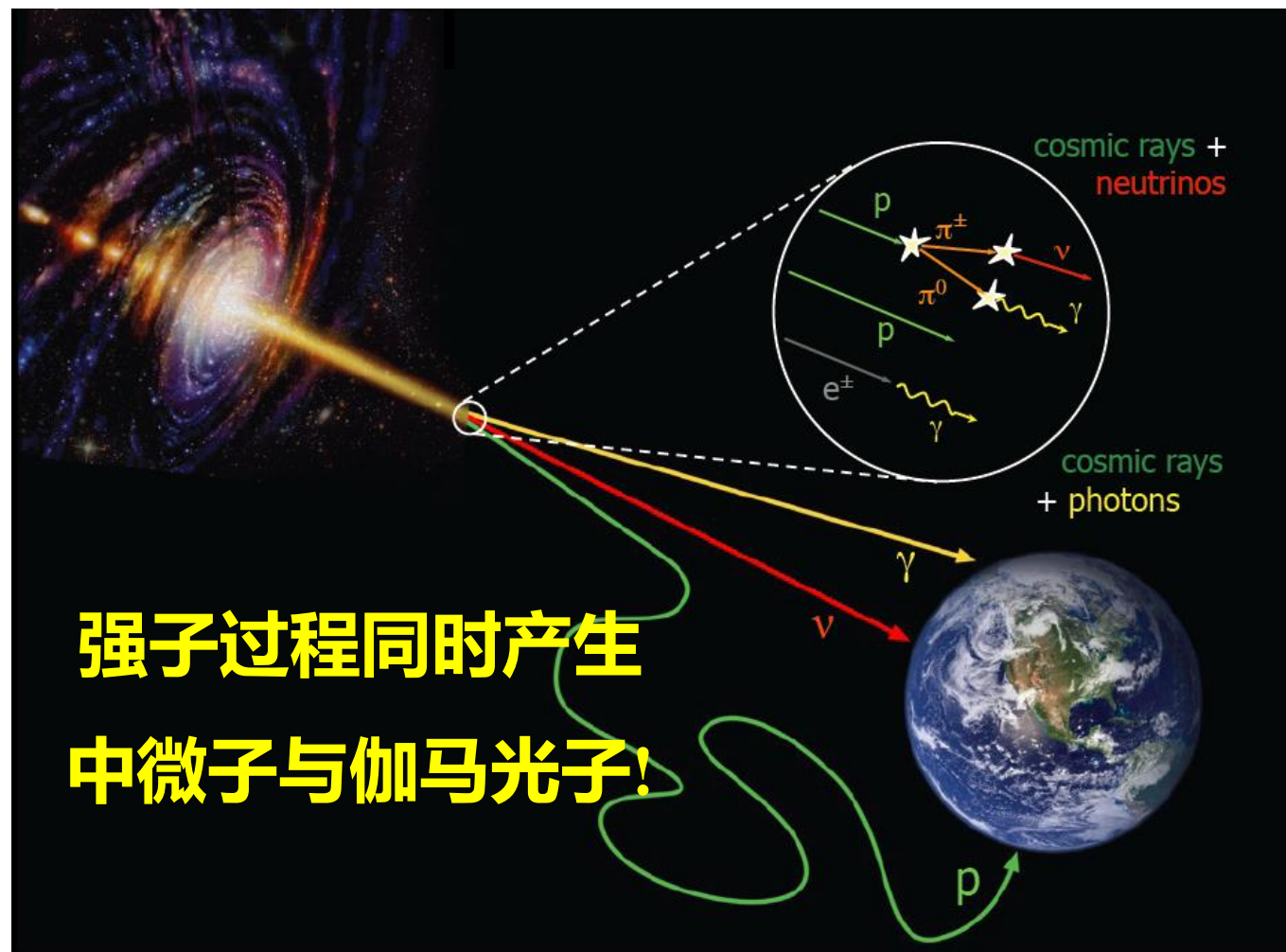
4

海铃未来展望

1. 宇宙射线起源？高能天体反应机制？



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中微子在传播过程中基本不发生偏转或衰减



保留完整源头指向性信息

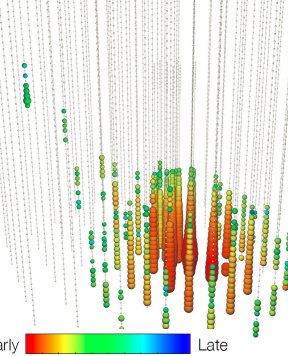
南极冰立方中微子望远镜：世界最大



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Science



Science



IceCube Lab

50 m

串列水平距离 ~125 m

探测球舱垂直距离 ~17m

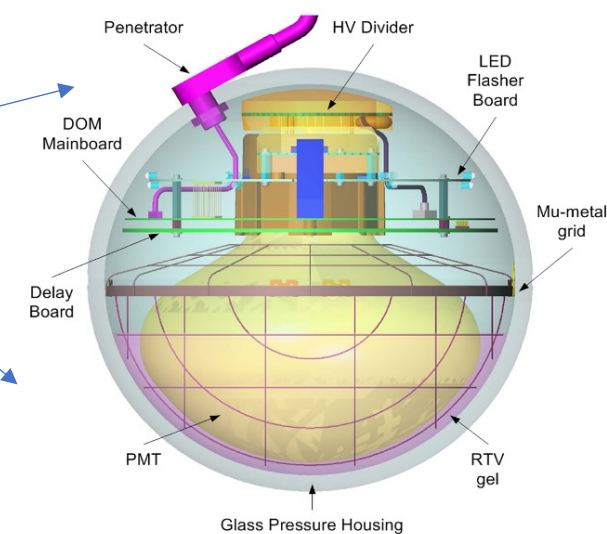
2010 竣工

1450 m

2450 m

2820 m

Deep Core



- Science 342, 6161 (2013)
- Science 361, eaat1378 (2018)
- Science 361, eaat2890 (2018)
- Nature 591, 220–224 (2021)
- Science 378, 538 (2022)
- Science 380, 1338–1343 (2023)

南极冰立方中微子望远镜：世界最大



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NGC 1068, 距地球 4700万光年

1) 无伴生伽马光子

2) 中微子辐射区离超级黑洞仅几十史瓦西半径

迄今, 人类探测到最高显著度
(4.2σ) 河外高能天体中微子源!

Science 342, 6161 (2013)

Science 361, eaat1378 (2018)

Science 361, eaat2890 (2018)

Nature 591, 220–224 (2021)

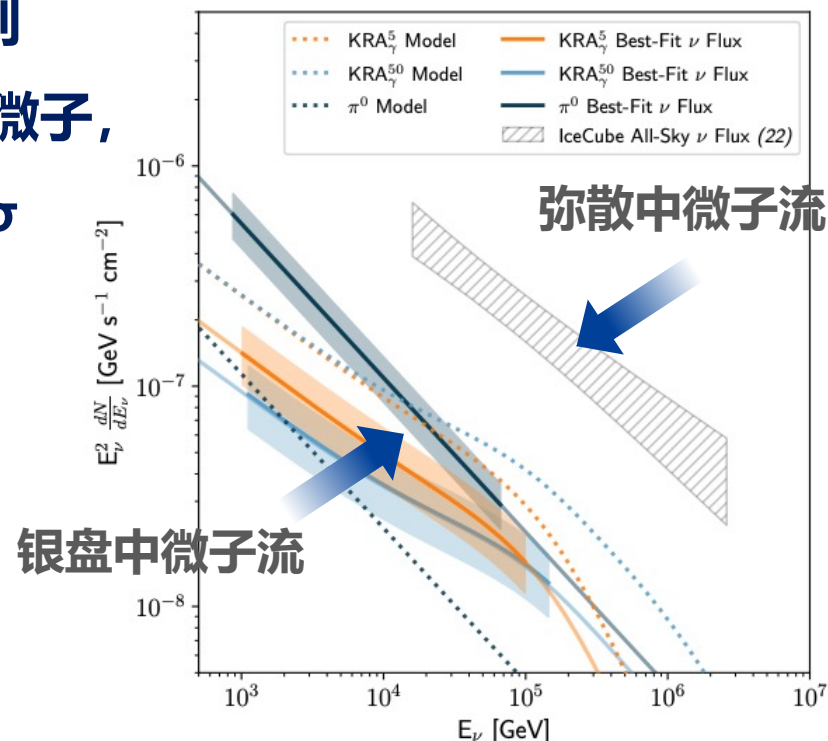
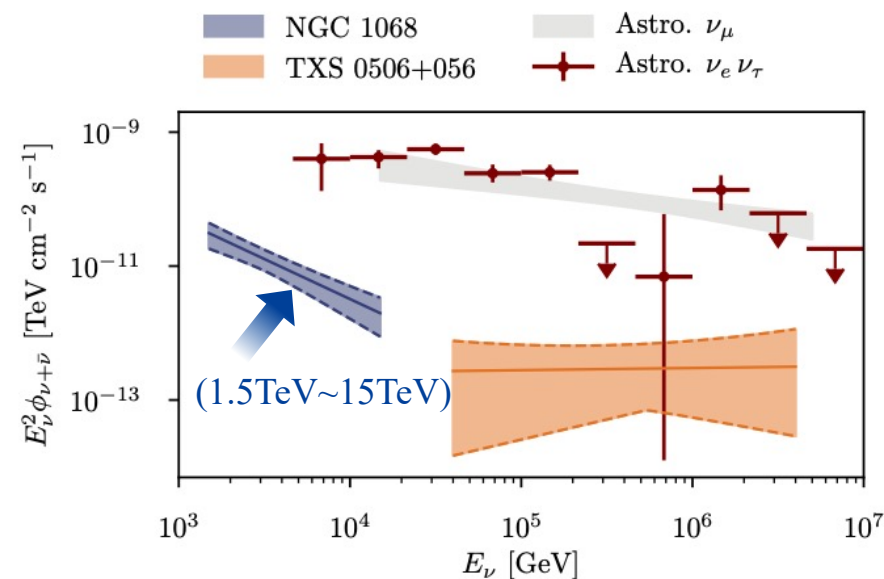
Science 378, 538 (2022)

Science 380, 1338–1343 (2023)

2023年, 观测到

>TeV级银盘中微子,

置信度高达 4.5σ



1) 至少有两类不同的天体中微子源

2) 弥散中微子流的起源大部分未知

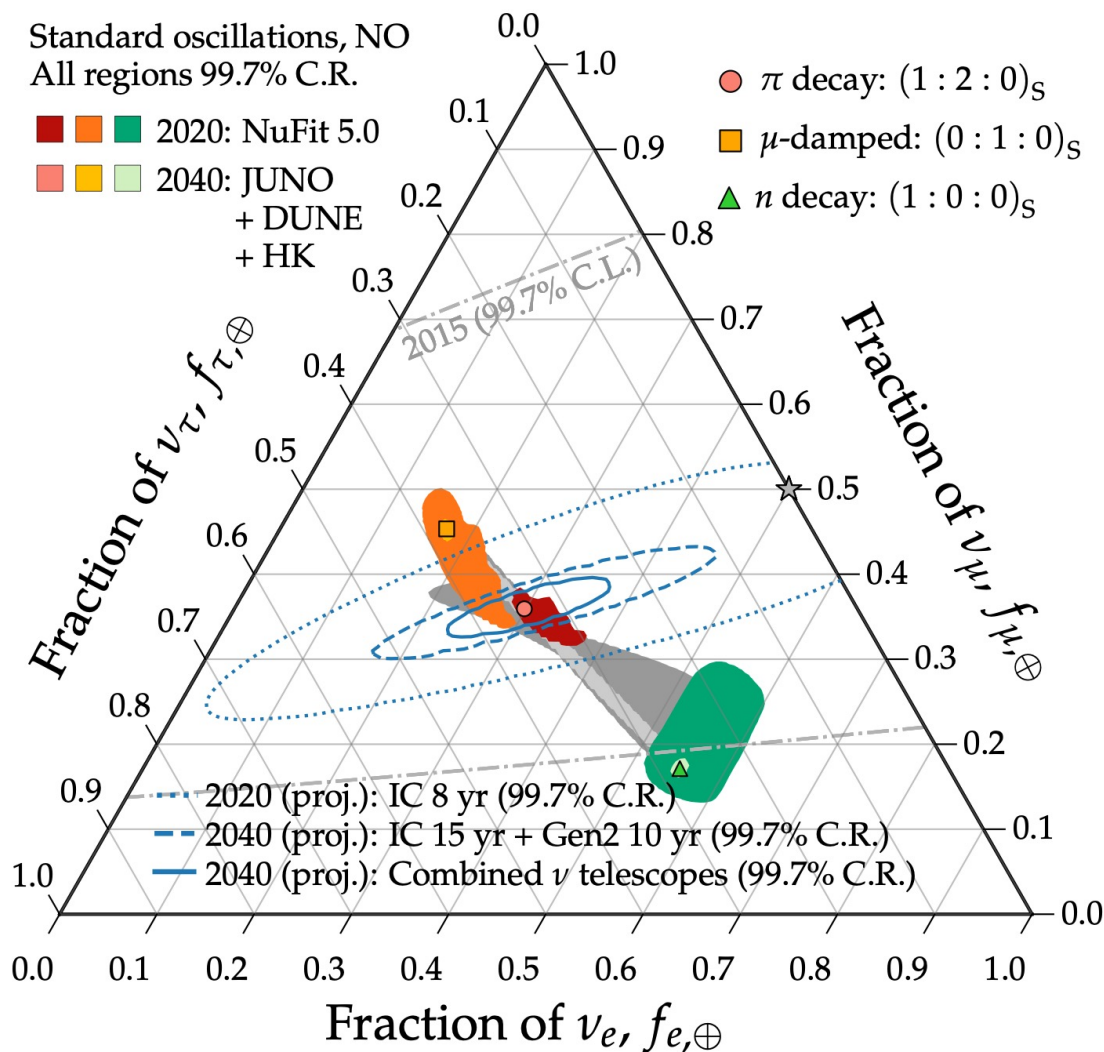
2. 通过天体中微子寻找新物理



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1) Lorentz broken? 寻找洛伦兹破缺



3) Dark matter? 间接探测暗物质

2) Quantum gravity? 寻找量子引力

4) Non-standard Oscillation? 寻找非标准模型振荡

IceCube Collab., Nat. Phys. 18, 1287-1292 (2022)

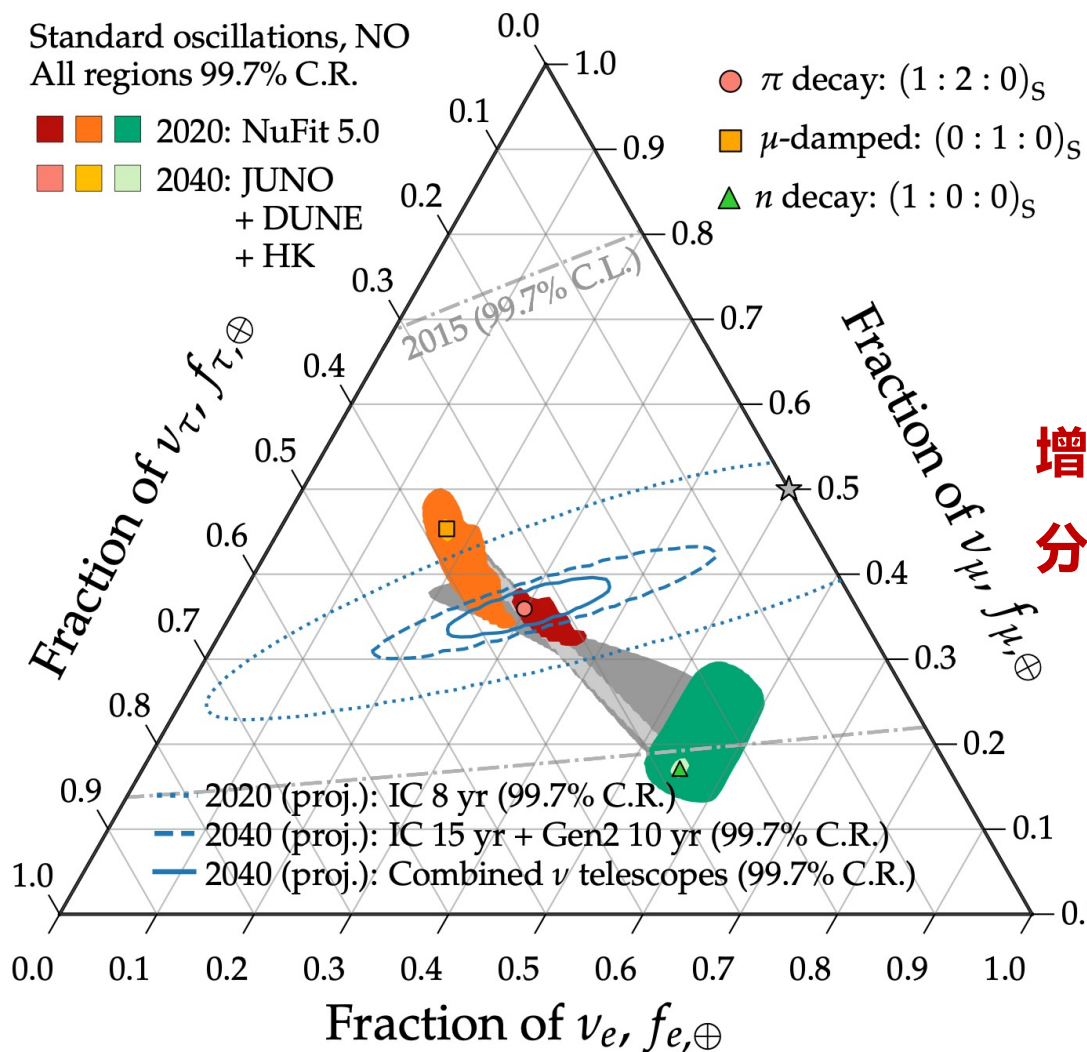
2. 通过天体中微子寻找新物理



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1) Lorentz broken? 寻找洛伦兹破缺



3) Dark matter? 间接探测暗物质

增加数据量、能量范围、提升角度
分辨能率与中微子味道甄别能力

→ 下一代中微子望远镜

2) Quantum gravity? 寻找量子引力

4) Non-standard Oscillation? 寻找非标准模型振荡

IceCube Collab., Nat. Phys. 18, 1287-1292 (2022)

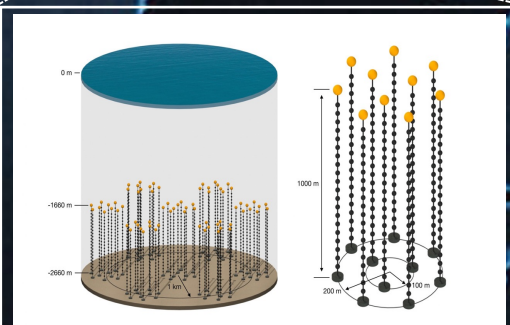
中微子天文学新时代



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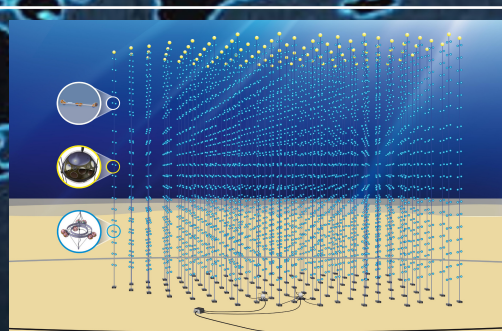


下一代中微子望远镜 (2030 era)



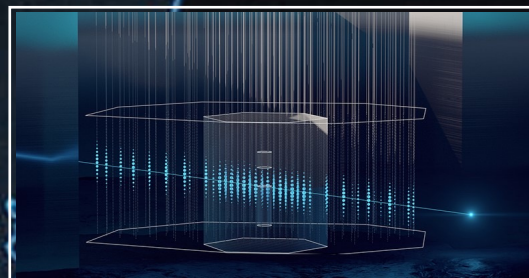
P-ONE (东太平洋)

深海 ~ 2.6 km,
体积 ~ 1 km^3 ,
规划 ~ 70根潜标



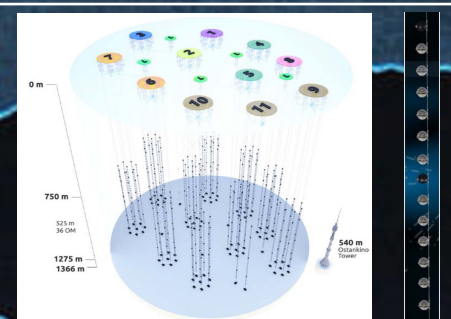
KM3NeT (地中海)

深海 ~ 3.5 km (ARCA),
体积 ~ 1 km^3 ,
规划 ~ 230根潜标



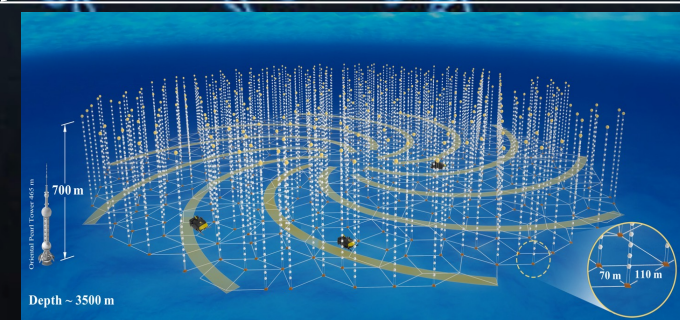
IceCube Gen-2 (南极)

冰川 ~ 2.5 km,
体积 ~ 8 km^3 ,
规划 ~ 210根潜标



Baikal-GVD (贝加尔湖)

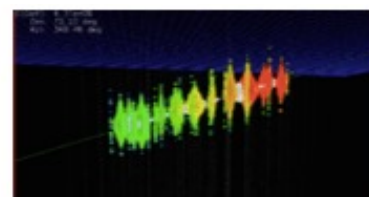
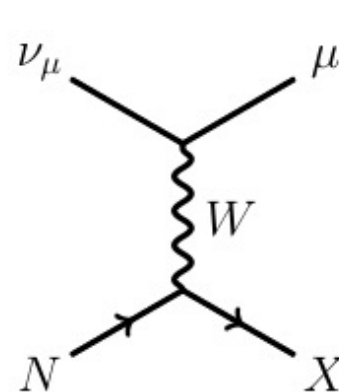
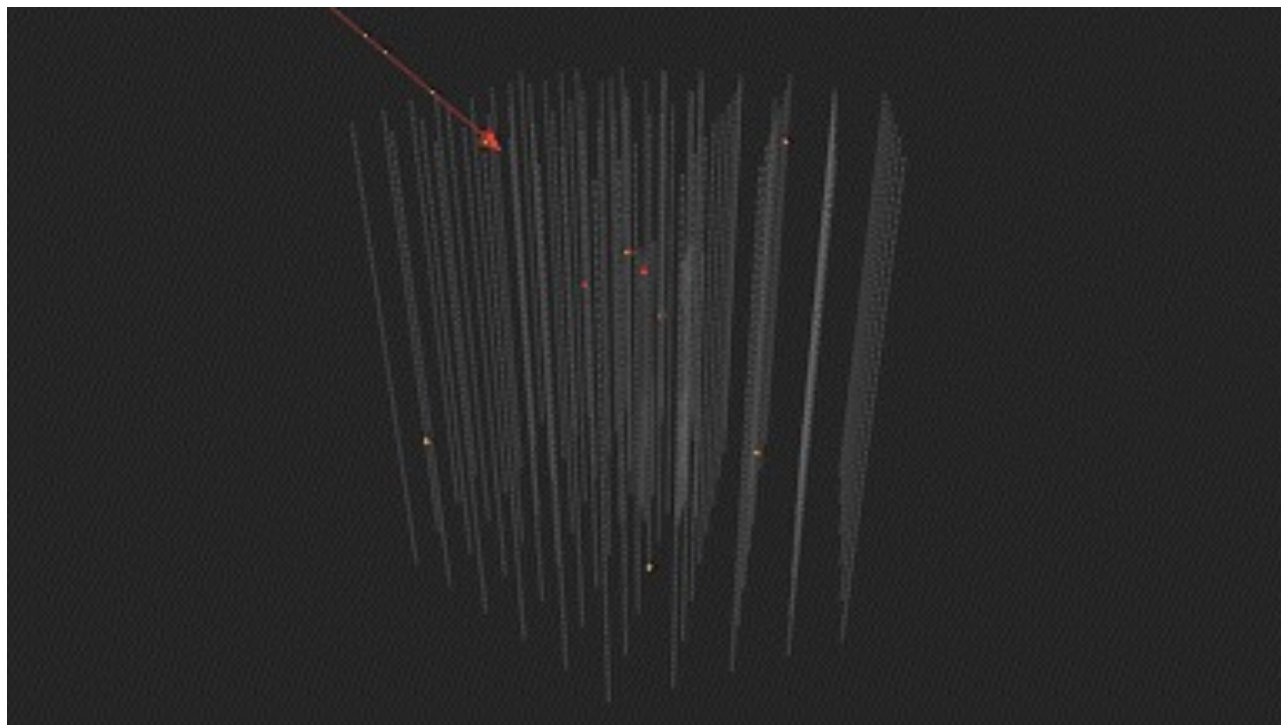
深海 ~ 1.4 km,
体积 ~ 1 km^3 ,
规划 ~ 140根潜标



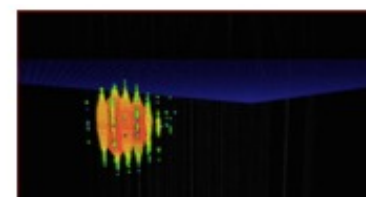
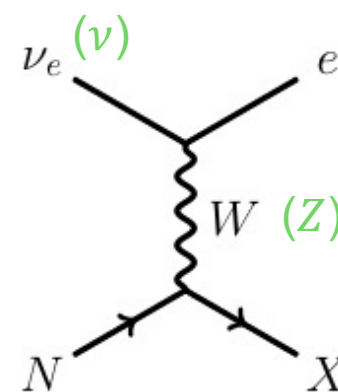
TRIDENT (中国南海)

深海 ~ 3.5 km,
体积 ~ 10 km^3 ,
规划 ~ 1200根潜标

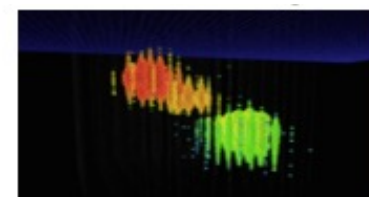
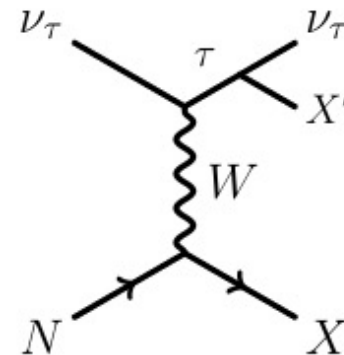
(HUNT, NEON)



Track
径迹事件



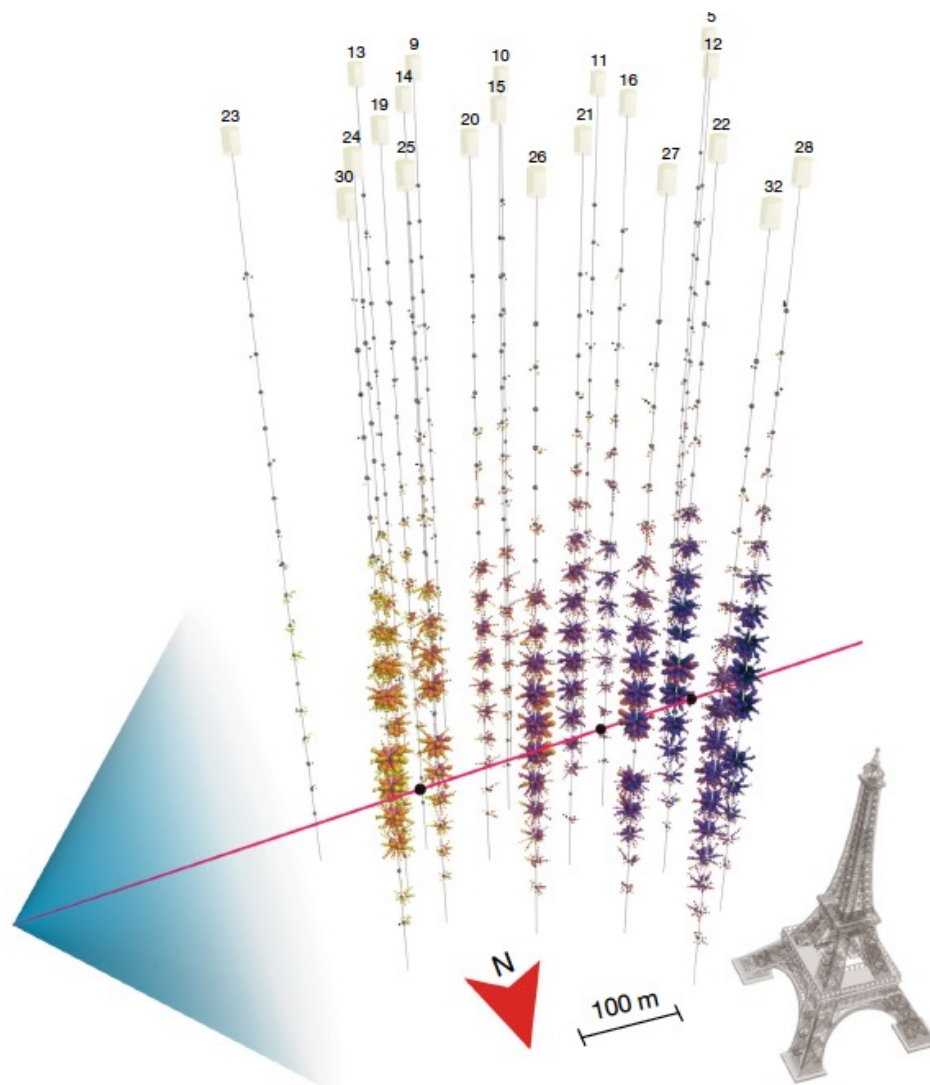
Cascade
级联事件



Double Cascade
双级联事件

- 中微子与海水反应，次级粒子产生切伦科夫光
- 通过探测切伦科夫光重构中微子信息
- 海水对光的散射、吸收特征 → 中微子望远镜选址的关键！

地中海中微子望远镜KM3NeT：220 PeV 事件



2025年，观测到迄今最高能的中微子事件（220 PeV）、仅用20多根潜标。
(KM3-230213A方向)

源头仍然未知！

最有可能：河外星系源？
AGN / GRBs

宇宙活动？
UHECR 与 CMB 相互作用
PBH蒸发
...

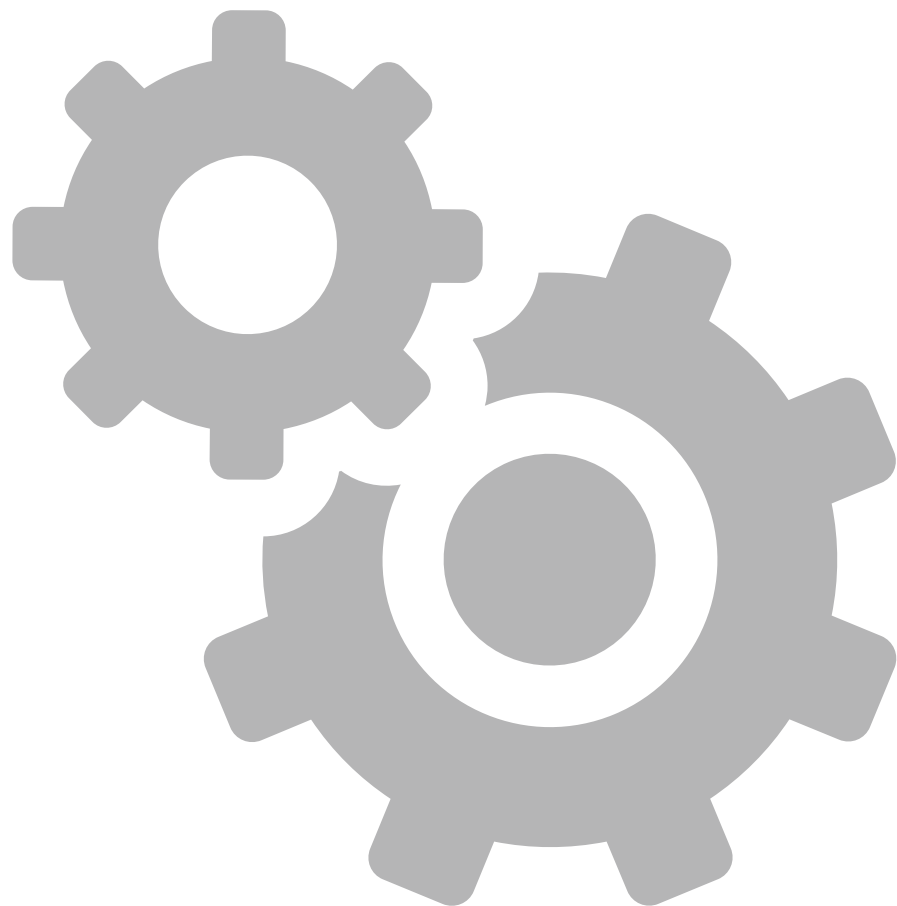
河内源？
尚无模型

arXiv:2502.08508

arXiv:2502.08484

arXiv:2502.08387

Nature 638, 376–382 (2025)



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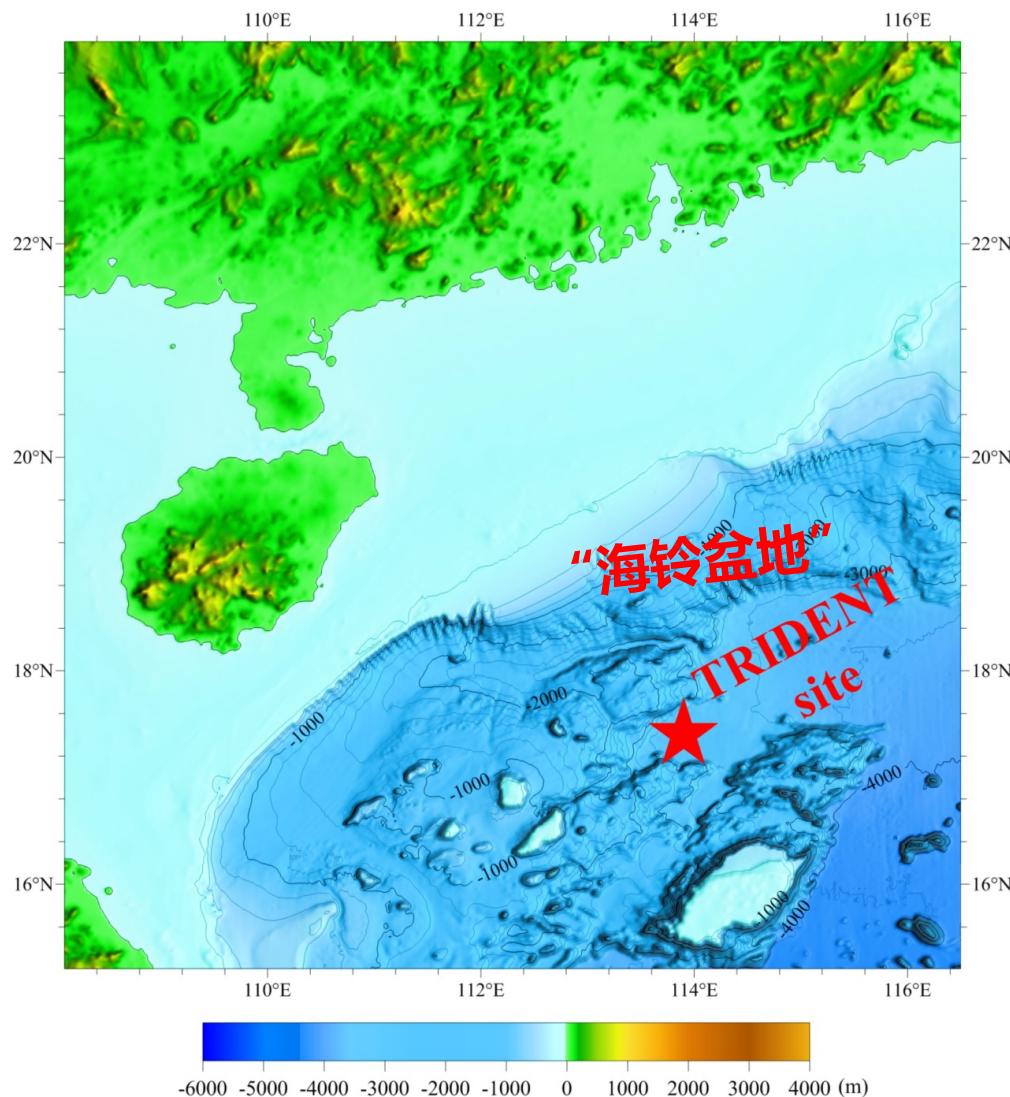
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海铃未来展望

海铃探路者 – 南海寻址



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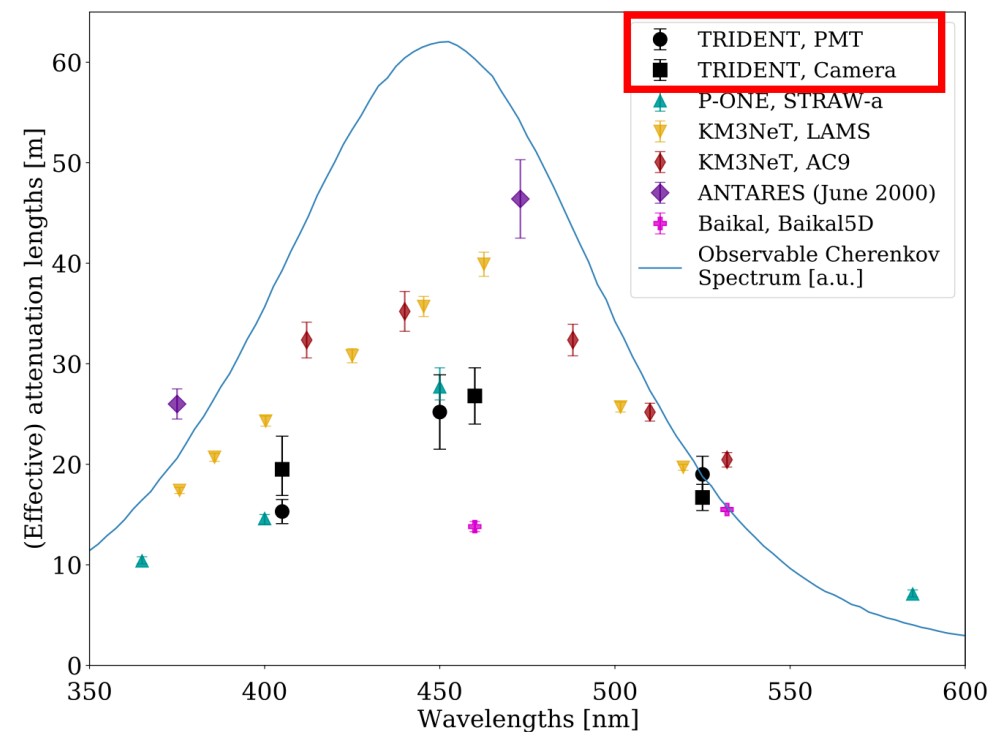
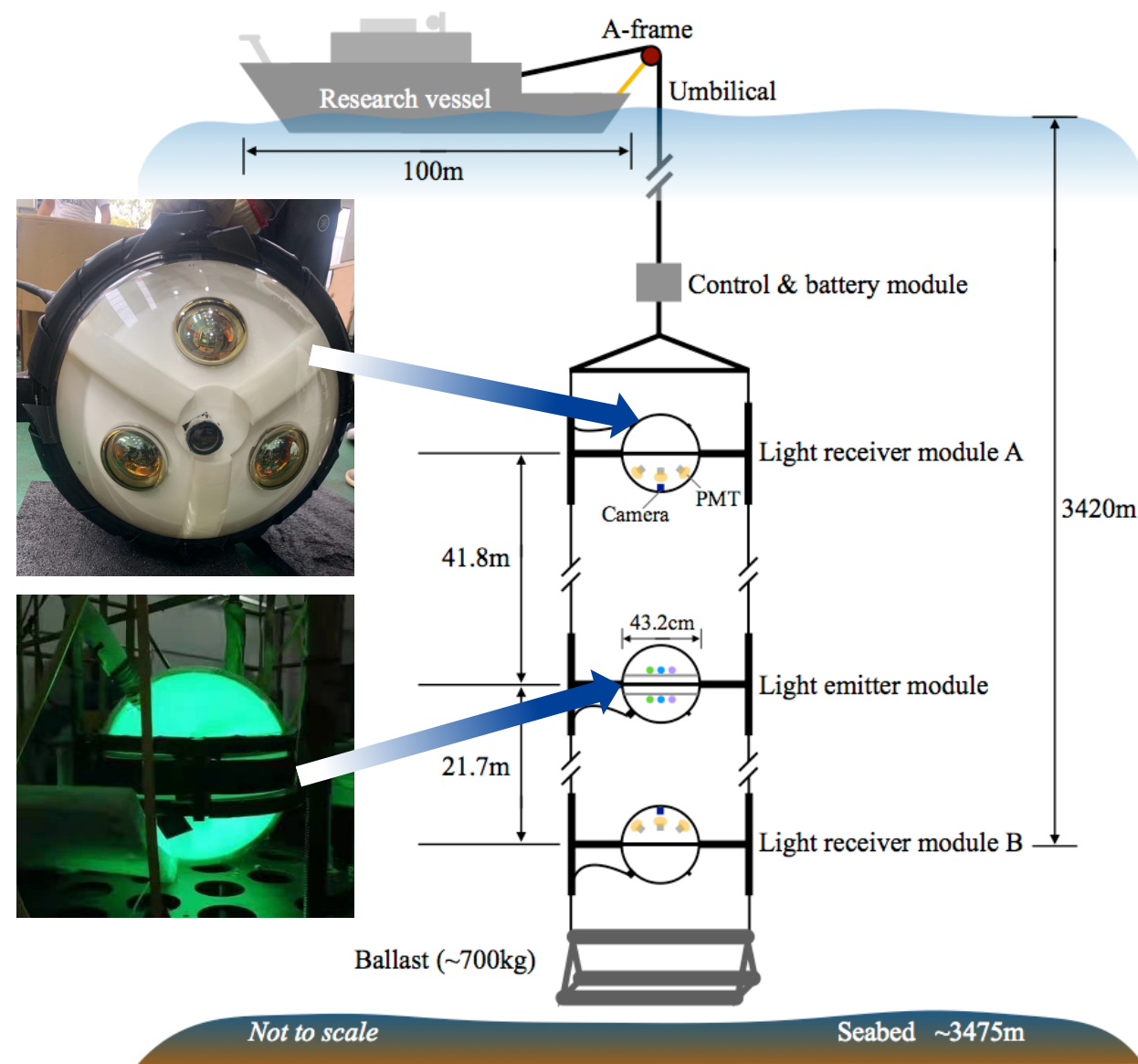


2021年9月，近80人组成的海铃团队赴南海选址科考

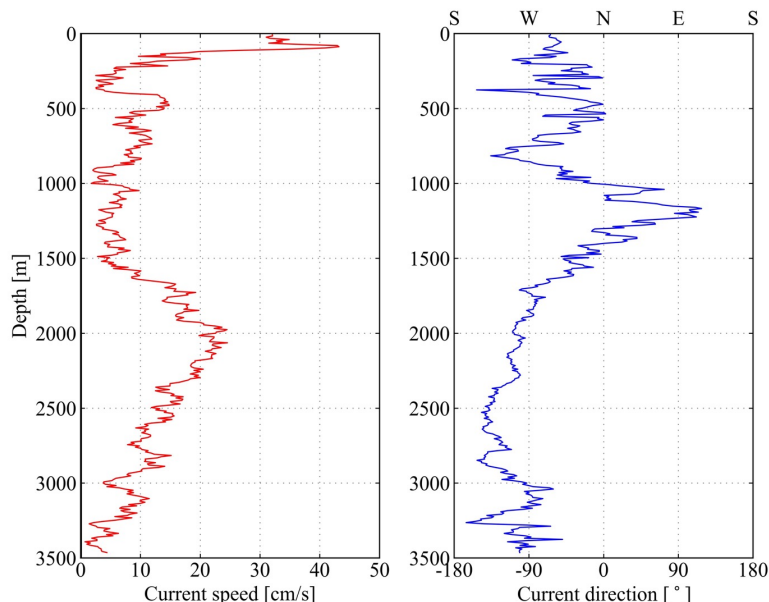


发现深3500m的深海开阔平坦盆地，生物活动少，适合建造大型科学设施

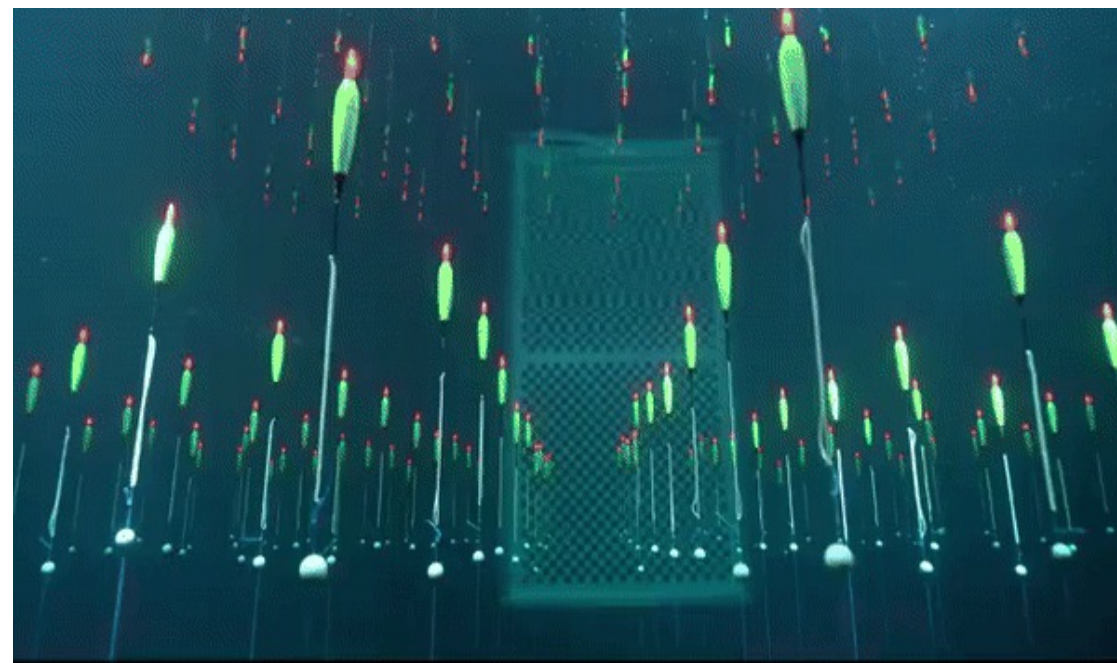
海水实测衰减强度与其他深海中微子实验台址相当，适合建造中微子望远镜！



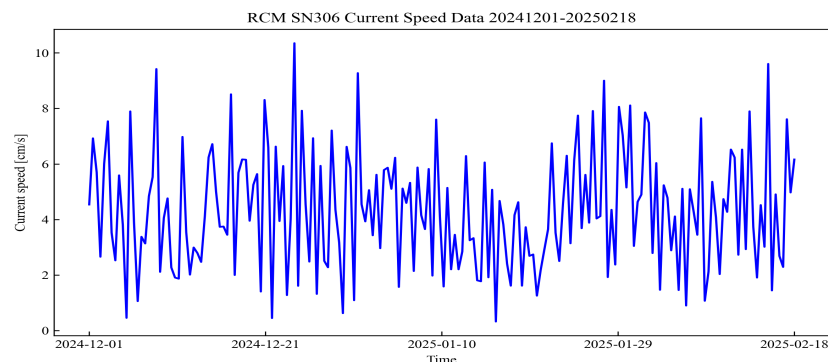
Current measured on Sep. 6, 2021 @ South China Sea



在上海交大船模拖曳水池 模拟探测器受洋流影响



Current measured during Dec 2024 – Feb 2025 @ South China Sea



F. Zhang (TAUP2025), TRIDENT
Prototype Testing

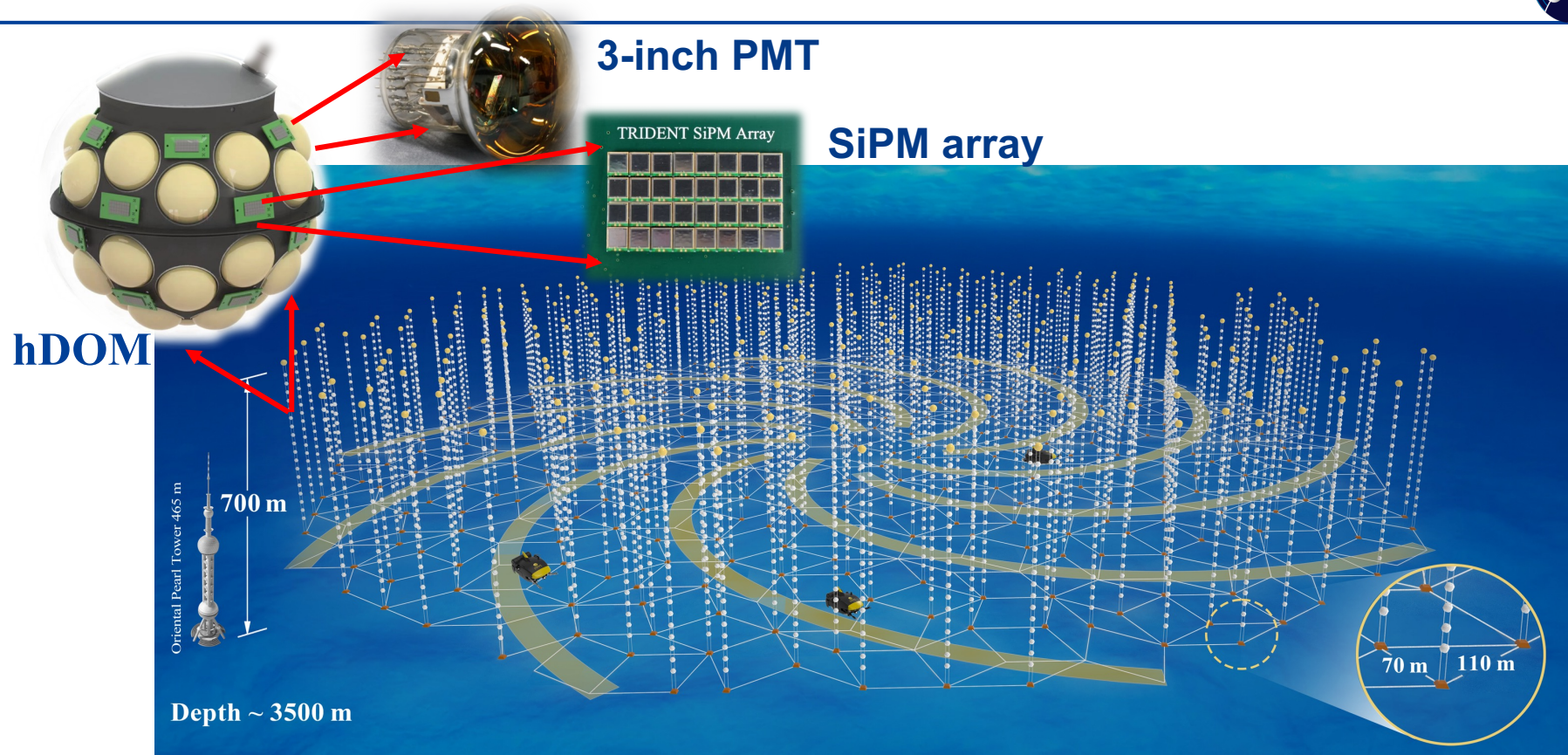
在海深 2800m 以下，洋流速度持续小于 10cm/s → 可稳定运行望远镜阵列

15

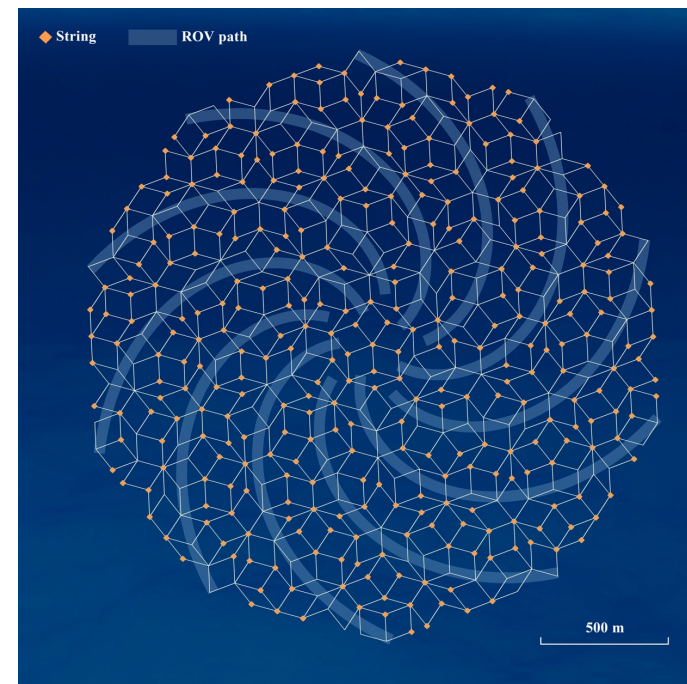
“海铃计划” 大阵列



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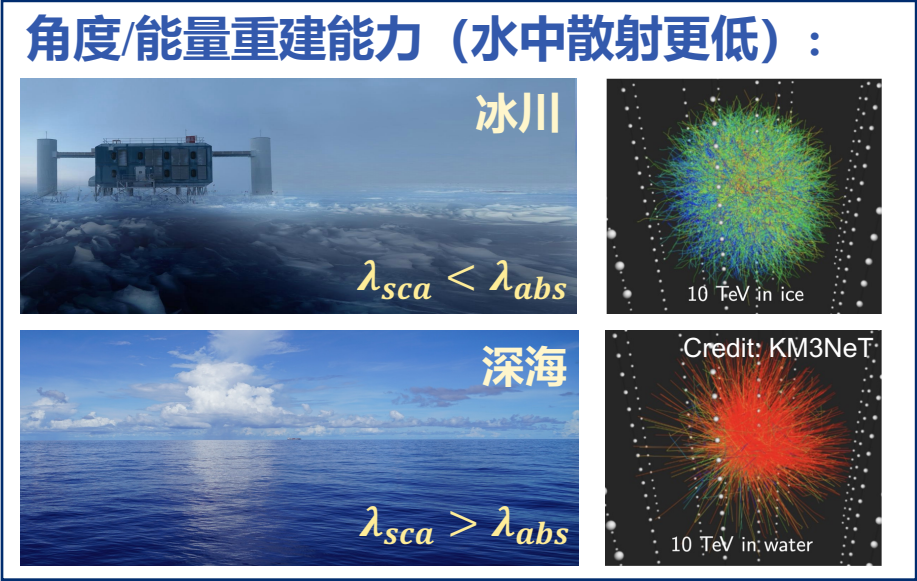
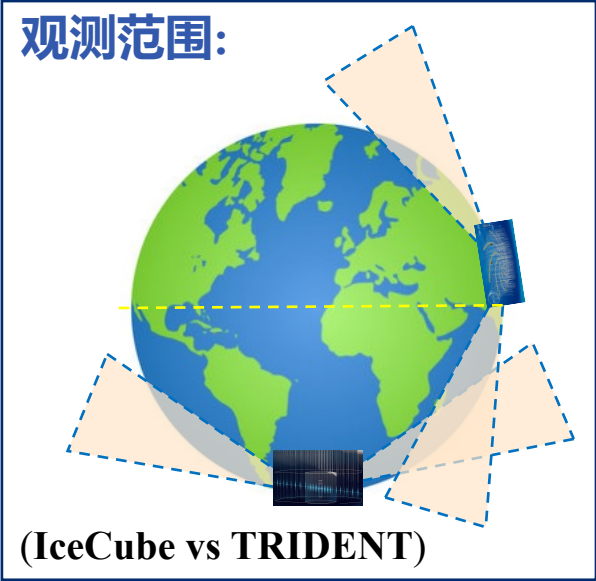


几何构型：Penrose 密铺

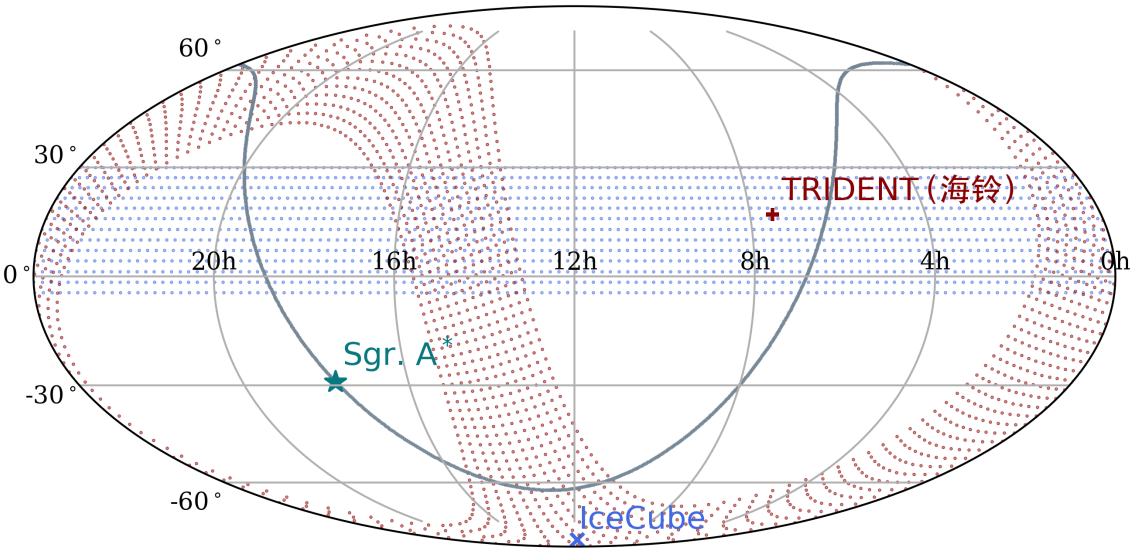
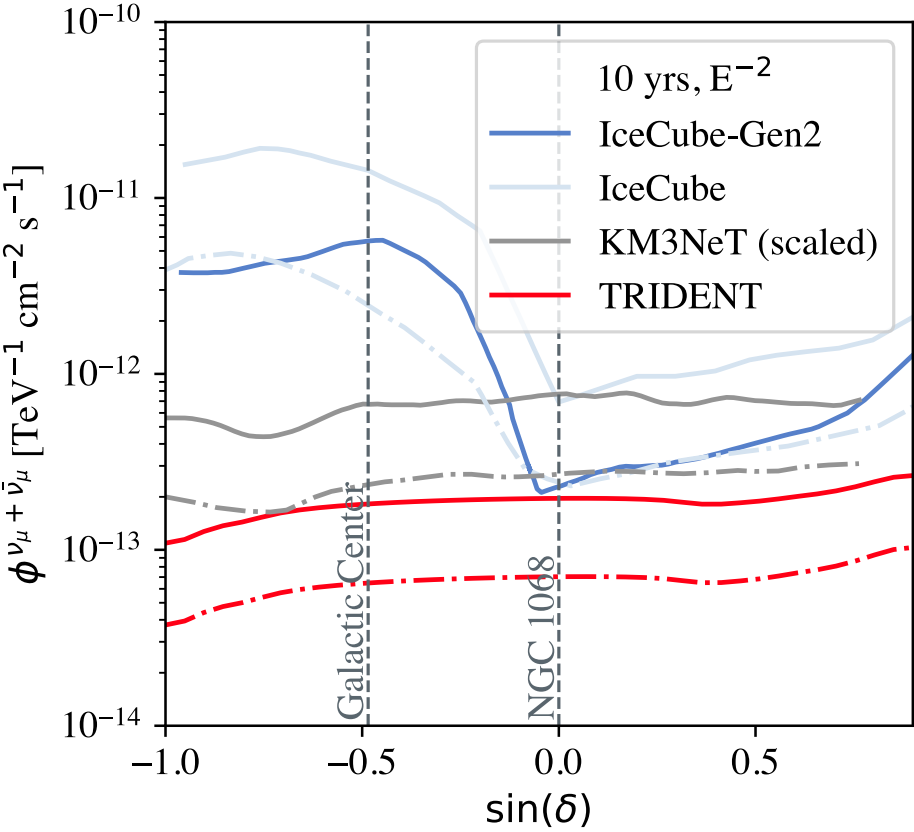


- **混合数字光学球舱 (hDOM) : 多 PMT + SiPM 设计, 增加角度分辨能力与光感应面积**
- **水平间距70m ~ 110m 不等; 竖直间距30m → 灵敏范围达到 sub TeV – EeV**
- **科学目标: 快速确认天文高能中微子源、高能中微子所有味道甄别**

海铃望远镜灵敏度



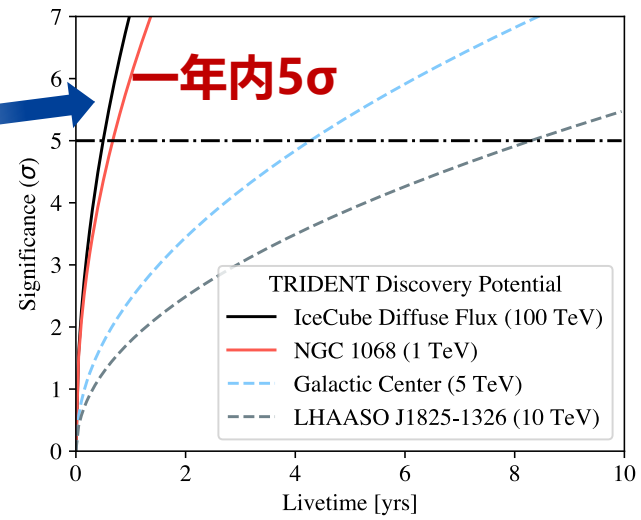
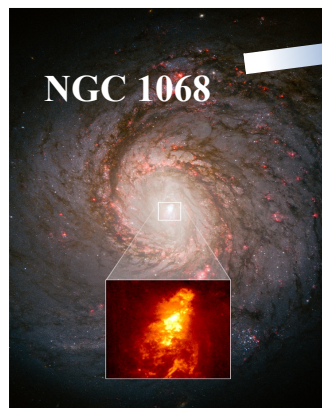
TRIDENT Collb., Nat. Astro. 7, 1497-1505 (2023)



南海台址位于地球低纬度

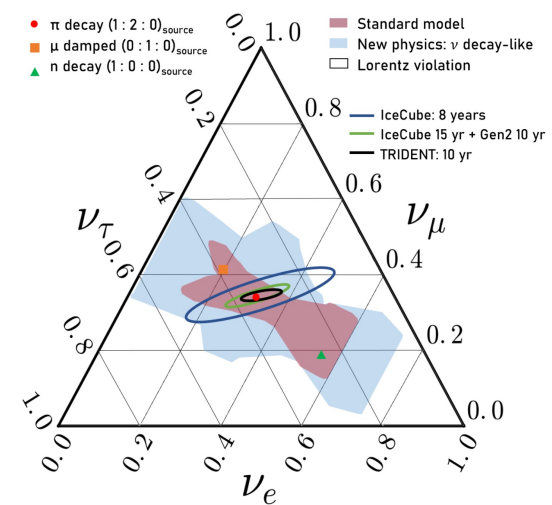
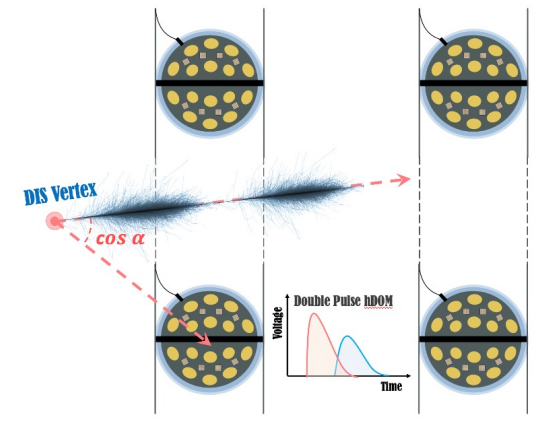
海铃可实现全灵敏度巡天!

寻找点源



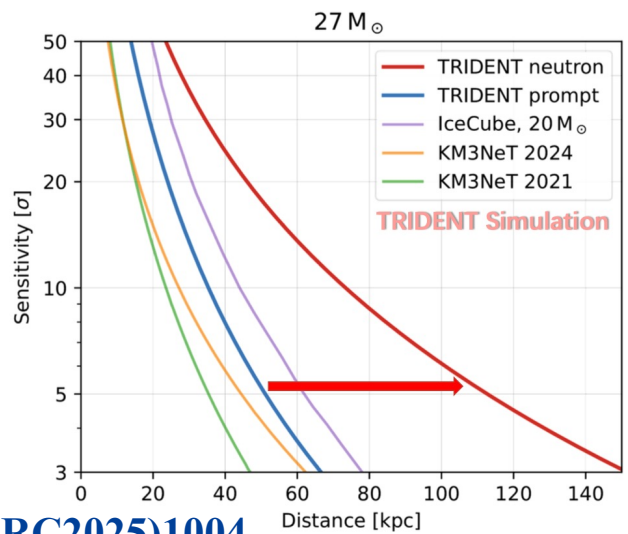
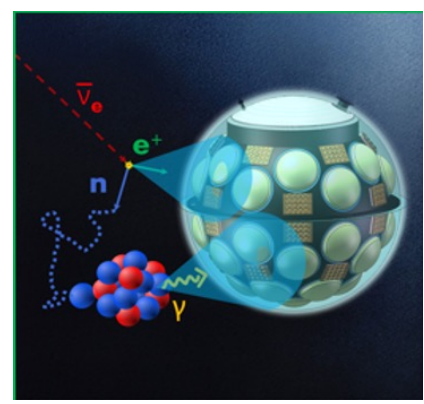
TRIDENT Collb., Nat. Astro. 7, 1497-1505 (2023)

天体中微子味道甄别



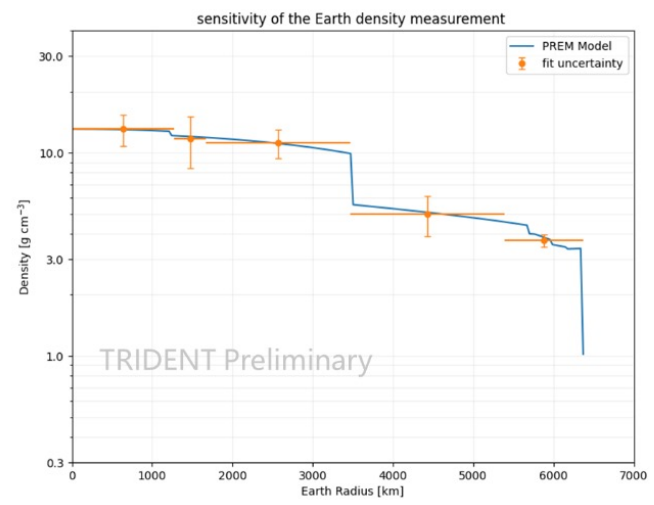
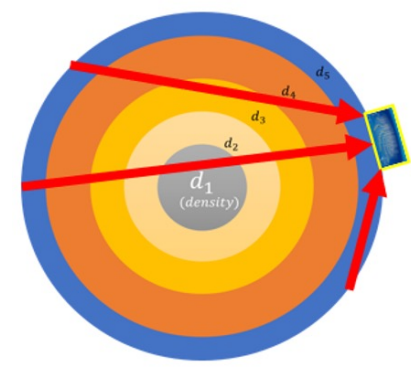
W. Tian (ICRC2025), Tau Neutrino Identification

河内核坍缩超新星探测

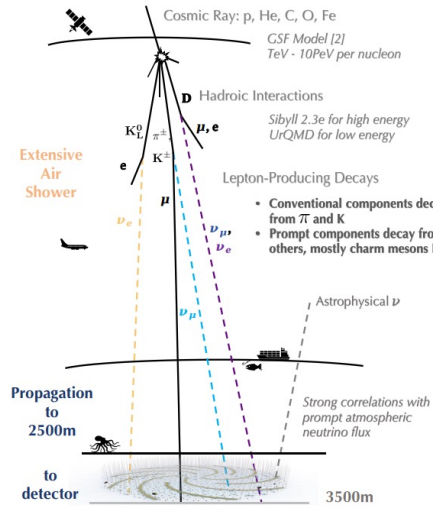
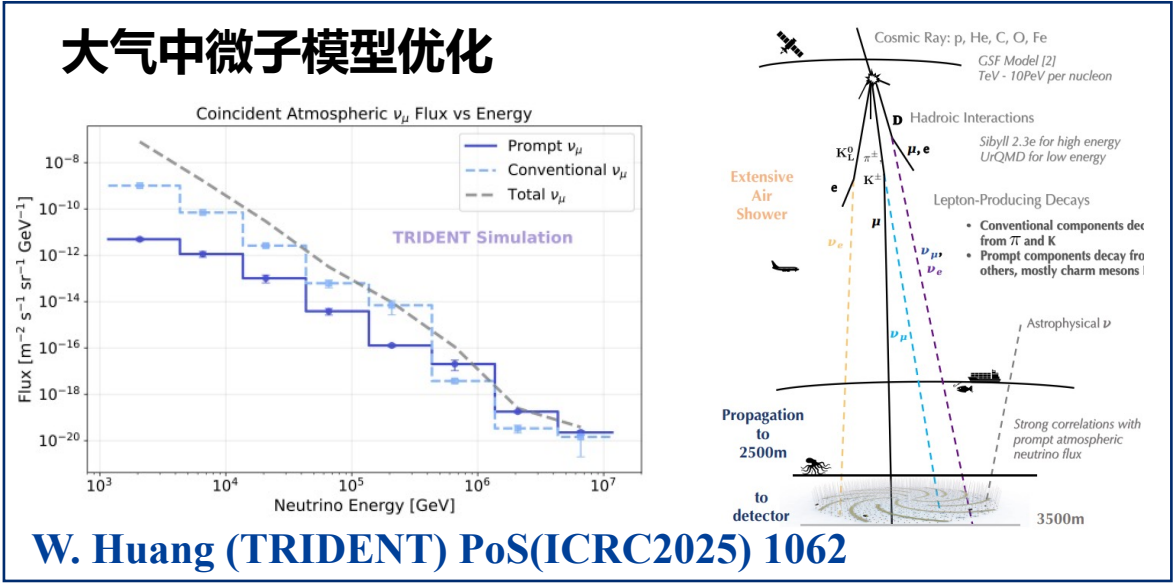
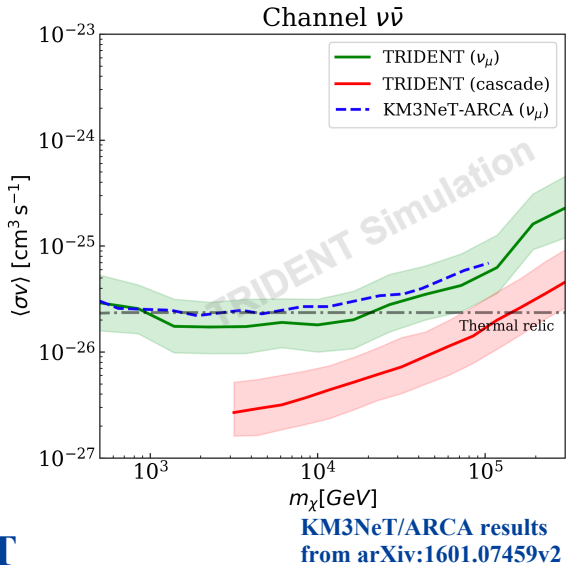
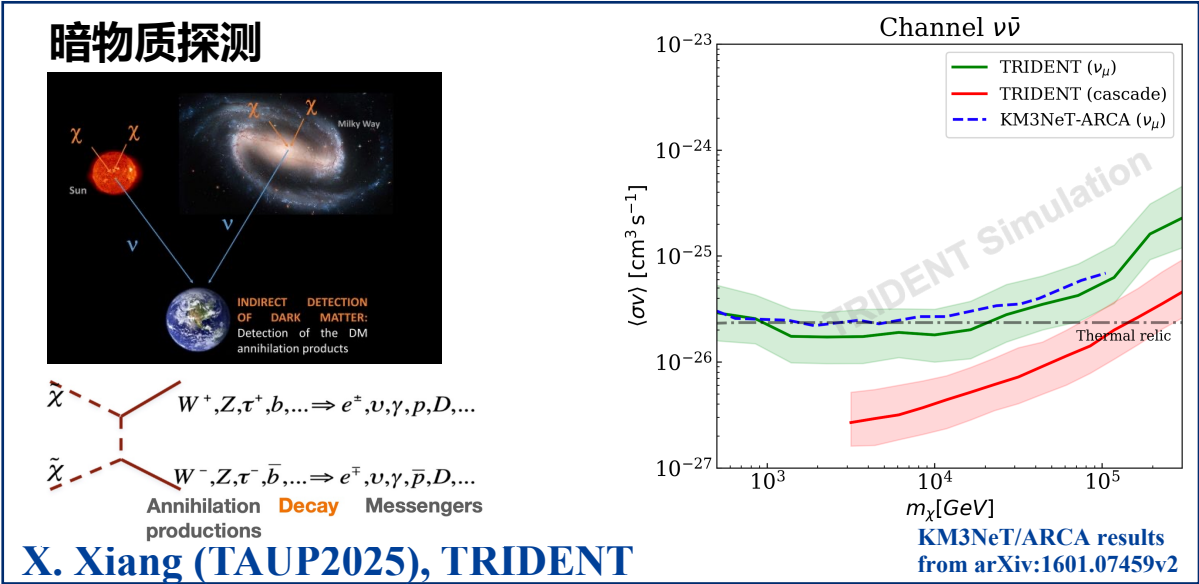


R. Cao (TRIDENT) PoS(ICRC2025)1004

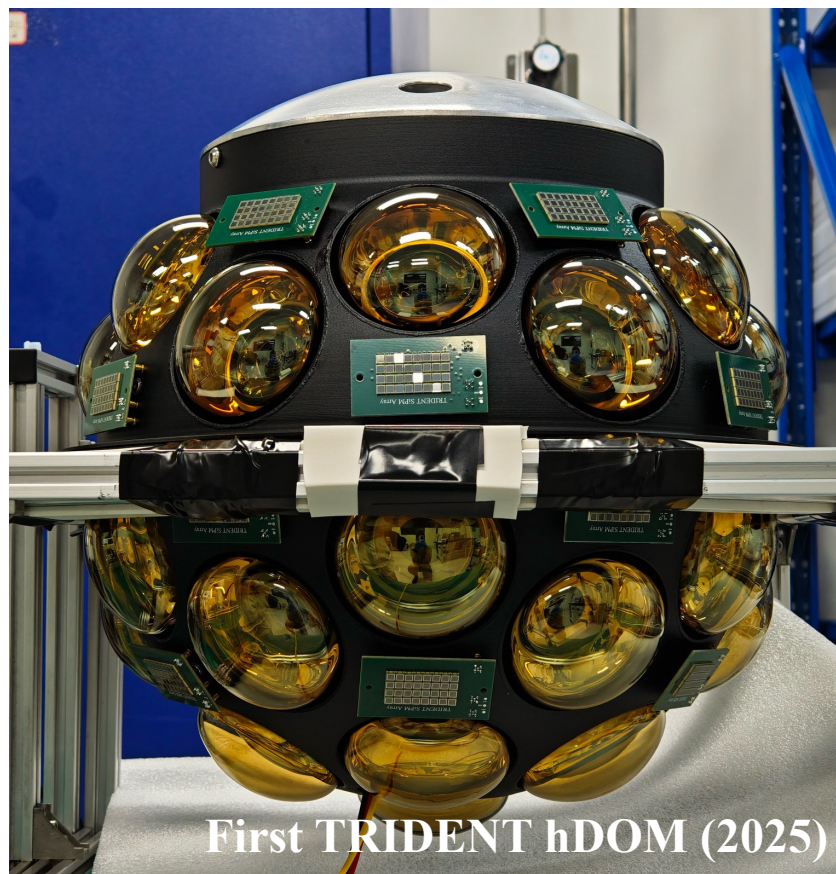
地球密度扫描



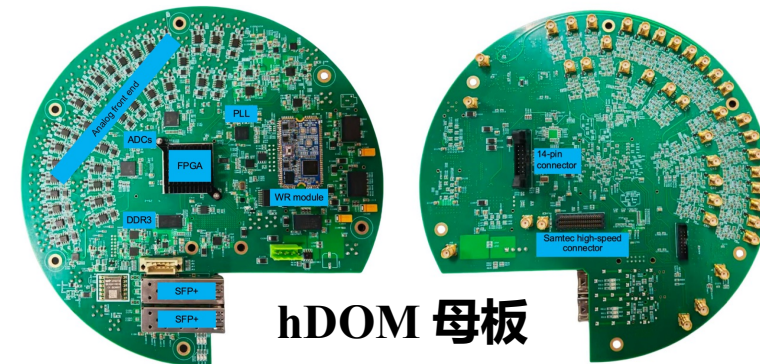
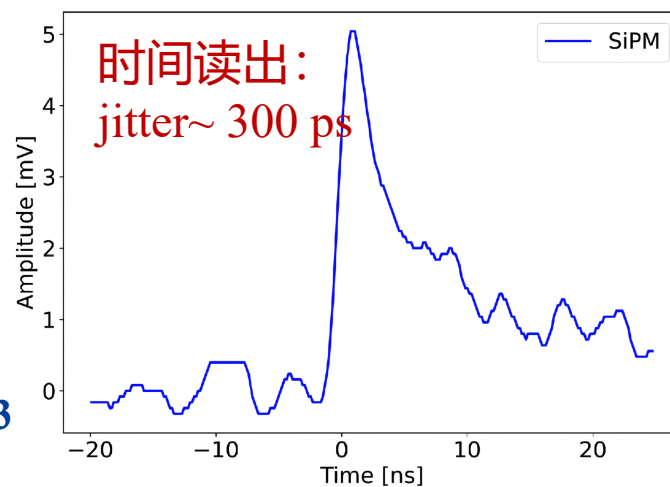
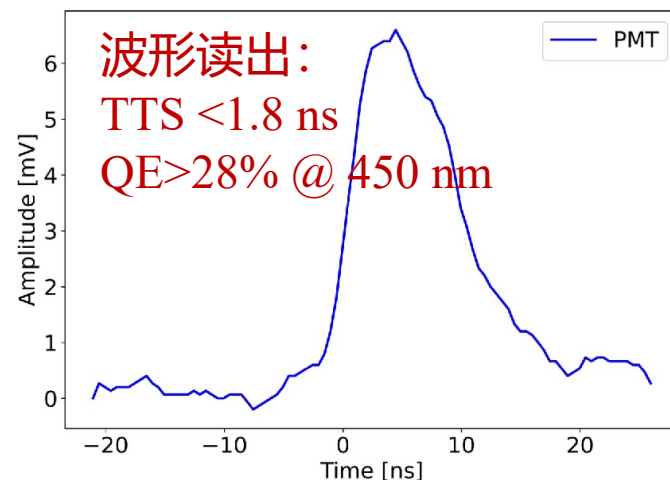
J. Huang (TRIDENT) PoS(ICRC2025)1059



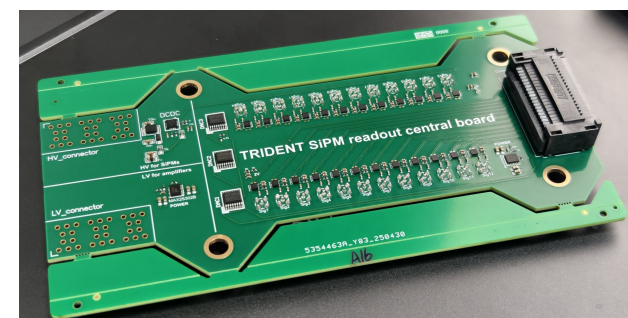
海铃探测球舱 hDOM 原创设计



W. Zhi et al (TRIDENT) PoS ICRC2023 (2023) 1213
F. Hu et al (TRIDENT) PoS ICRC2021 (2021) 1043



G. Zhang (TRIDENT) PoS (ICRC2025) 591



SiPM 子卡

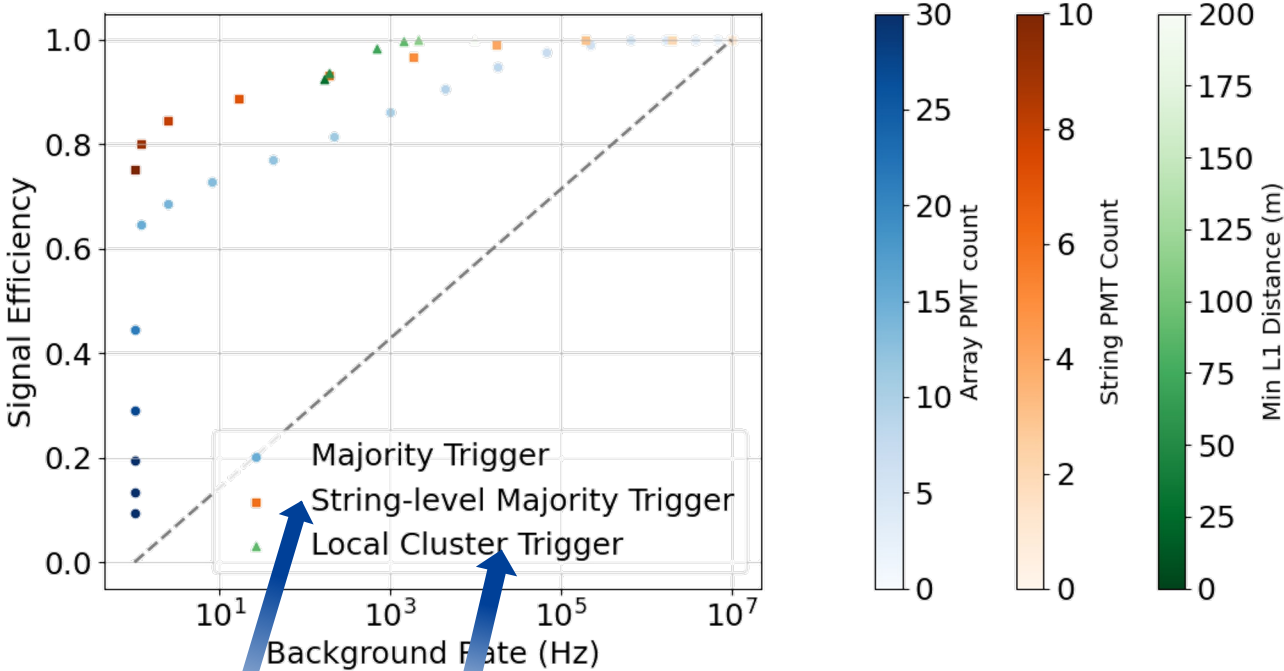
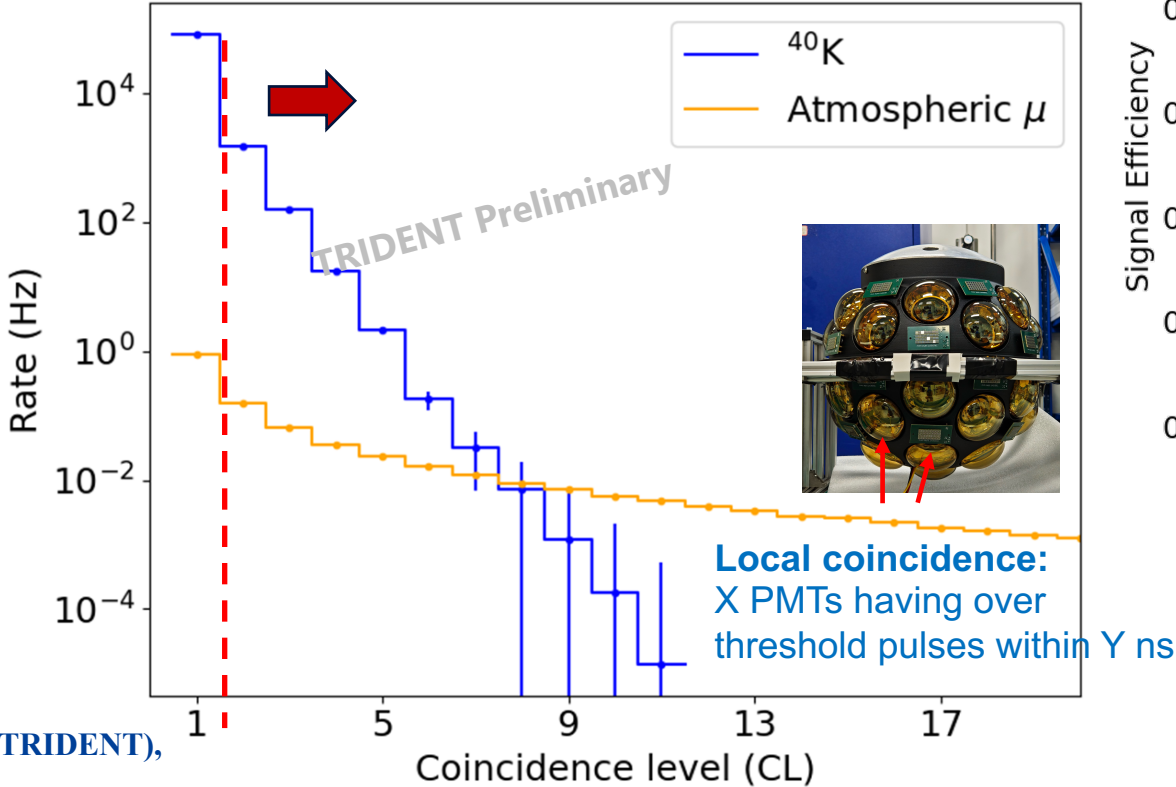
W. Zhi (TRIDENT) PoS (ICRC2025) 1055

基于 PMT+SiPM 的混合光学舱 (hDOM): 高光子收集面积 + 精准时间戳

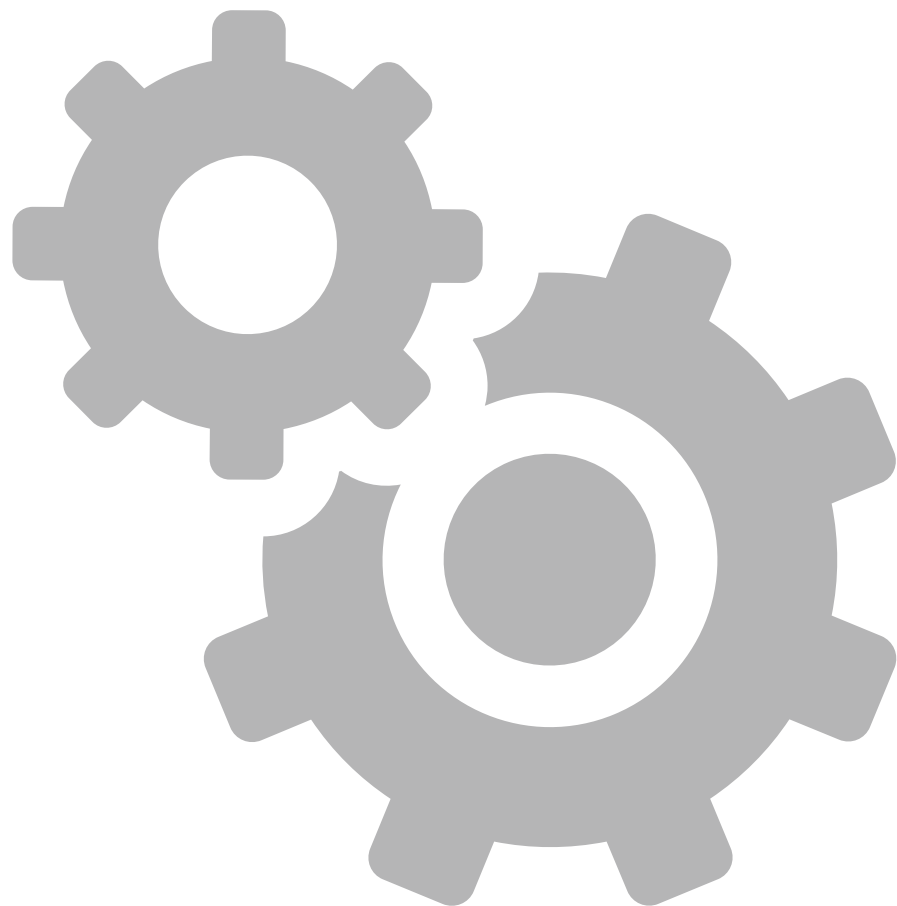
→ 径迹事件优于 0.1° ; 级联事件优于 2° @ 100TeV

海水中大量的**钾-40**是深海中微子望远镜的主要背景

主要背景	事例率
海水中钾-40 (K40)	$O(10^5)$ Hz / hDOM
大气缪子	$O(100)$ Hz / 10 strings



硬件与软件结合触发机制



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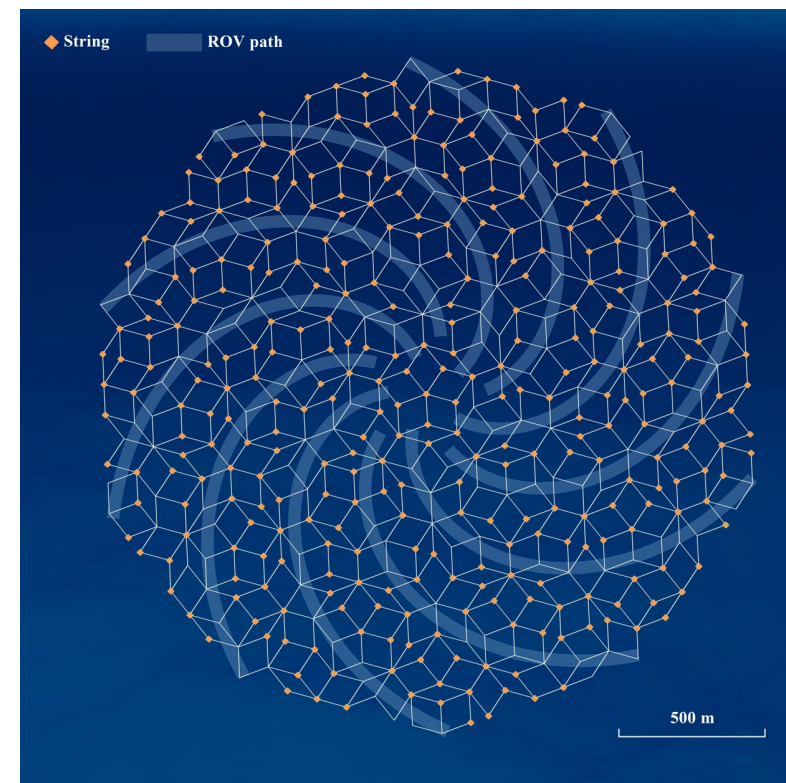
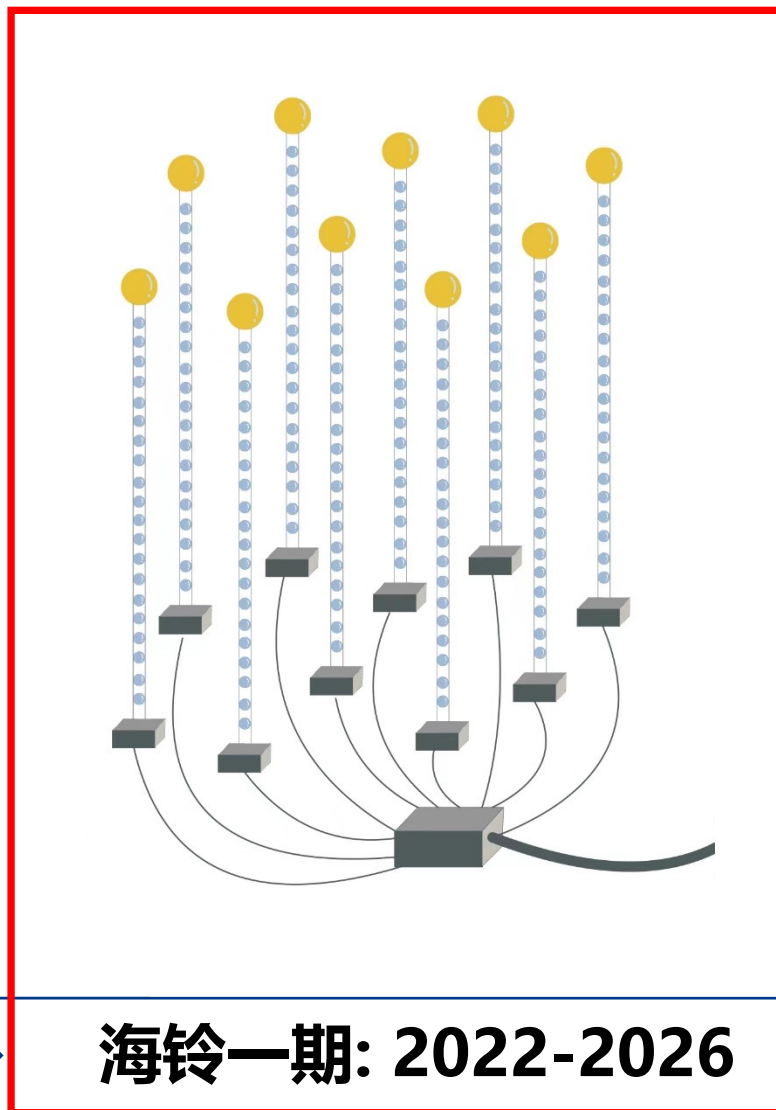
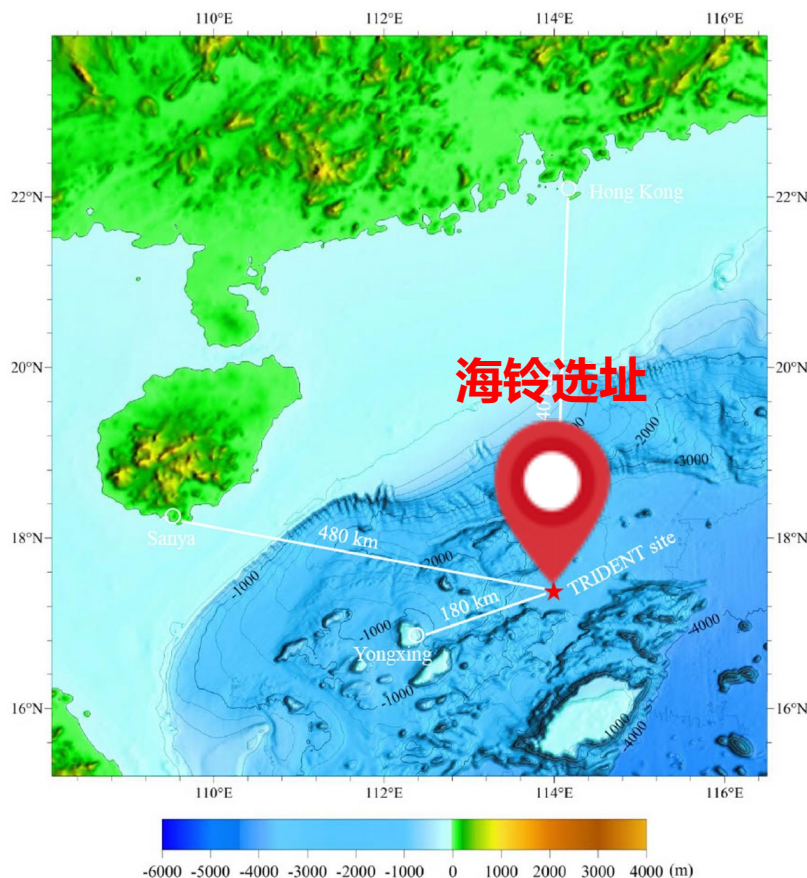
4

海铃未来展望

海铃建设路线



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海铃探路者: 2019-2022

海铃一期: 2022-2026

海铃大阵列: 2026-

“海铃一期” 研发进行时（整体规划）



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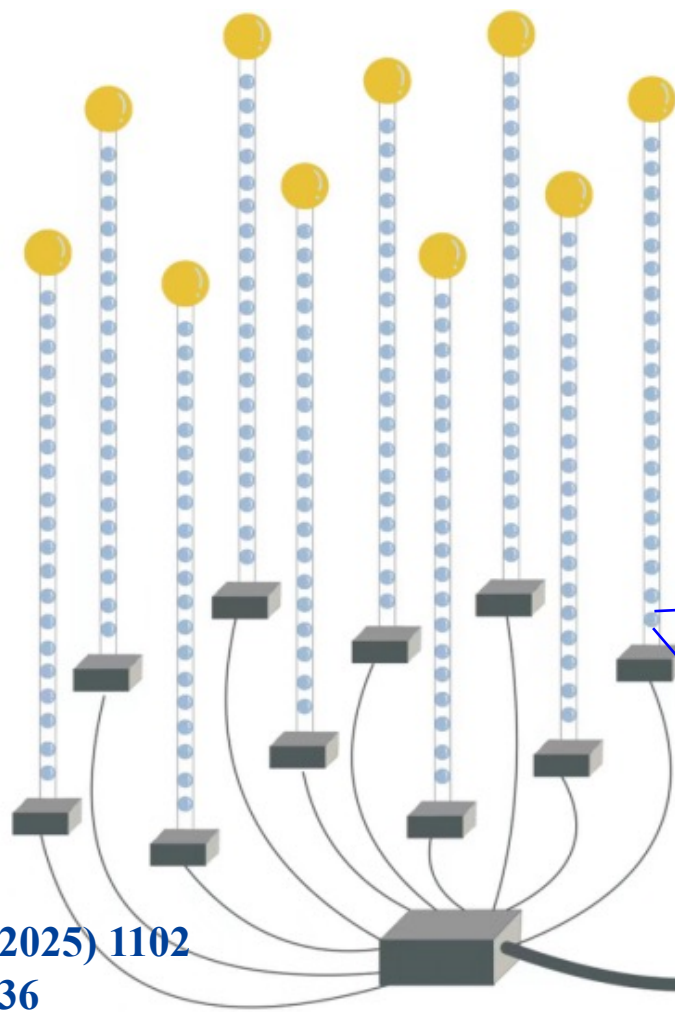


在科技部、上海市科委、上海交大的大力支持下，“海铃一期”于2022年启动

预计2026年，在海铃盆地布放**十根潜标**（每根20个hDOM）

搭载**亚纳秒级**的时钟同步系统与**20cm**精度的球舱定位系统

J. Liu (TRIDENT), PoS(ICRC2025) 1102
Y. Ye *et al* 2021 JINST 16 P11036



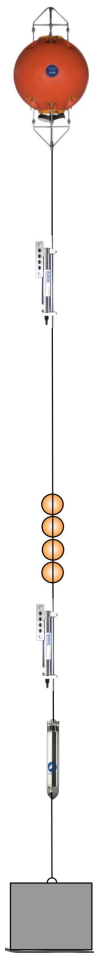
拟验证关键技术

- 光学舱对中微子信号的高精度探测
- 深海光电传输与耐压封装
- 串列的高效集成打包与精准布放
- 全阵列定位刻度与时钟同步
- 望远镜海量数据采集方案与处理策略

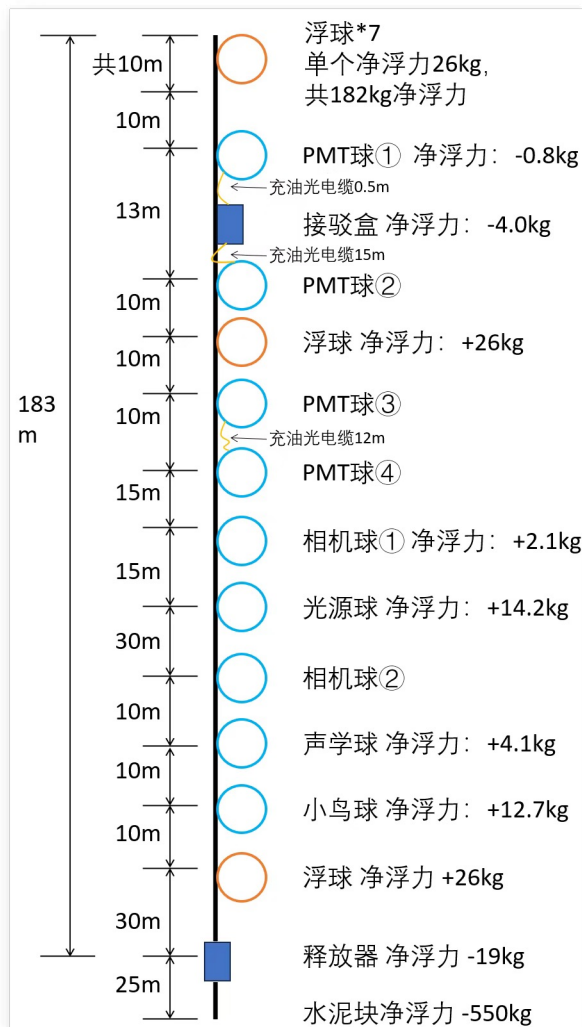


“海铃一期” 研发进行时（海试任务）

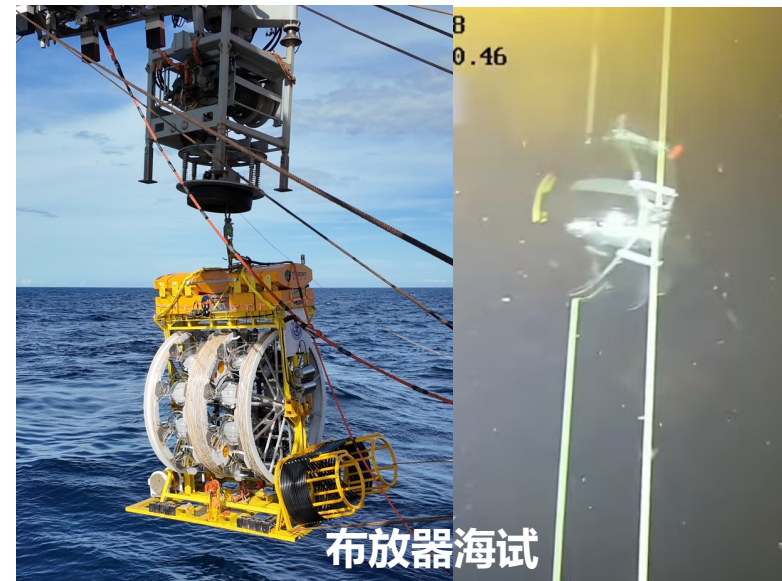
1) 环境流场与生物噪声监测



2) 中微子潜标串列样机海试



3) 望远镜串列打包与布放策略



“海铃一期” 研发进行时（技术验证）



TRIDENT
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交大拖拽水槽布放器1:4 模型测试

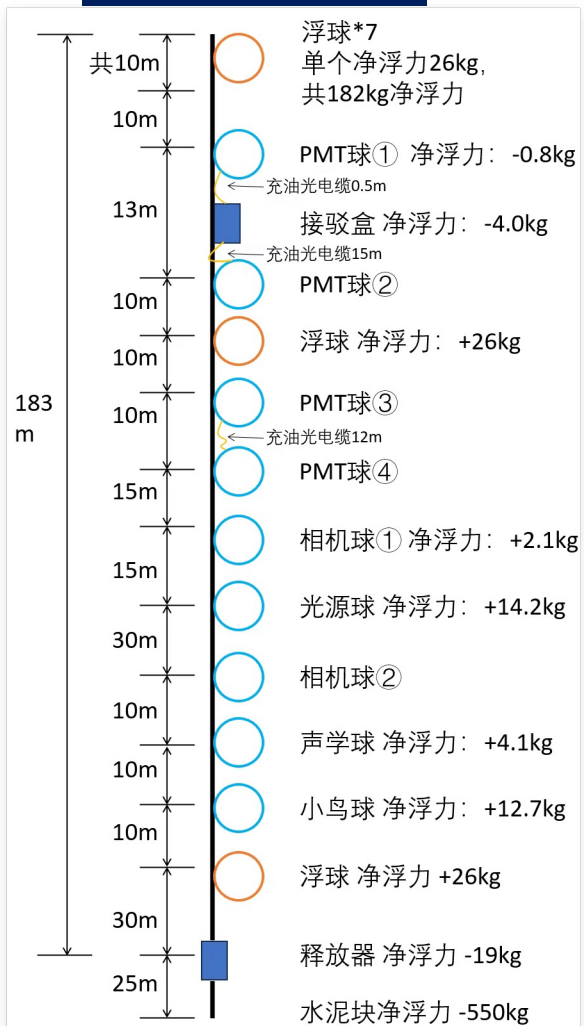
“海铃一期” 研发进行时（技术验证）



TRIDENT
海 | 铃 | 计 | 划



T-REX 2024



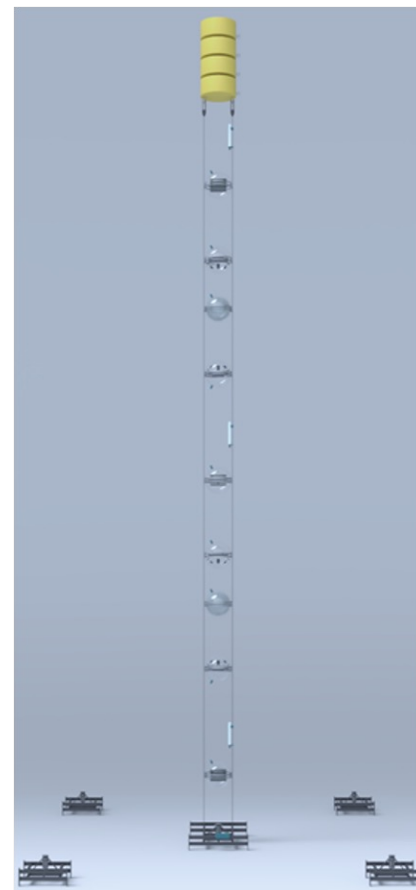
多目标自融式潜标

hDOM 小串 (2025)

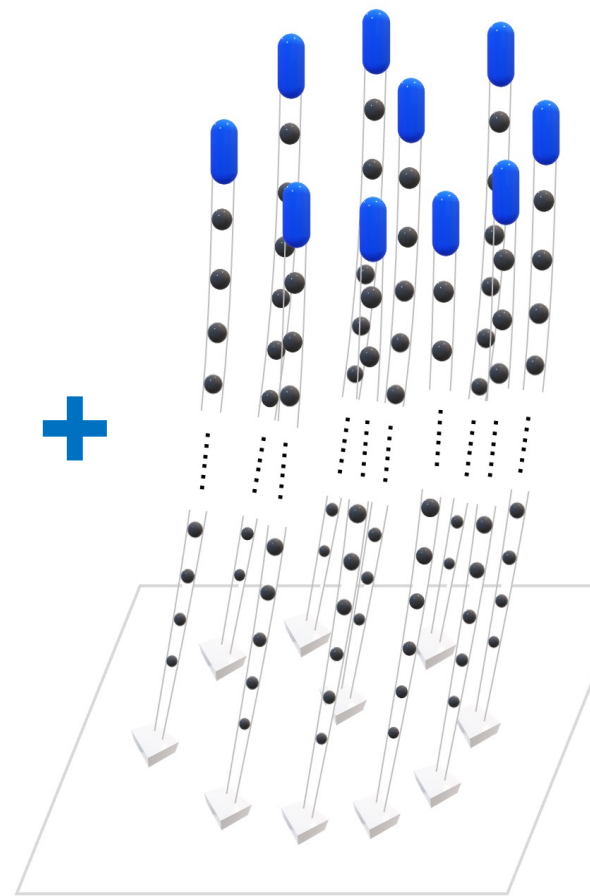


首个hDOM潜标, 装配测试中, 预计今年布放

一期布放 (2026)



刻度潜标 (研发中)

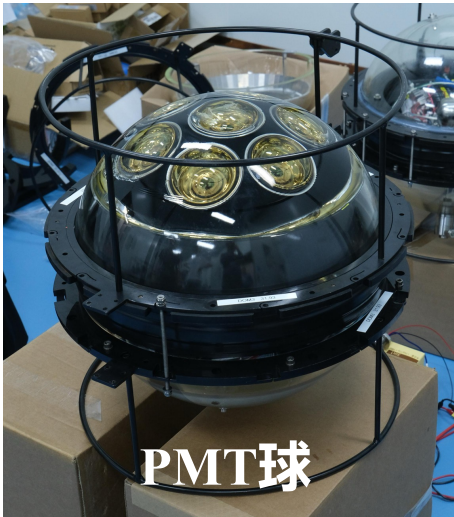
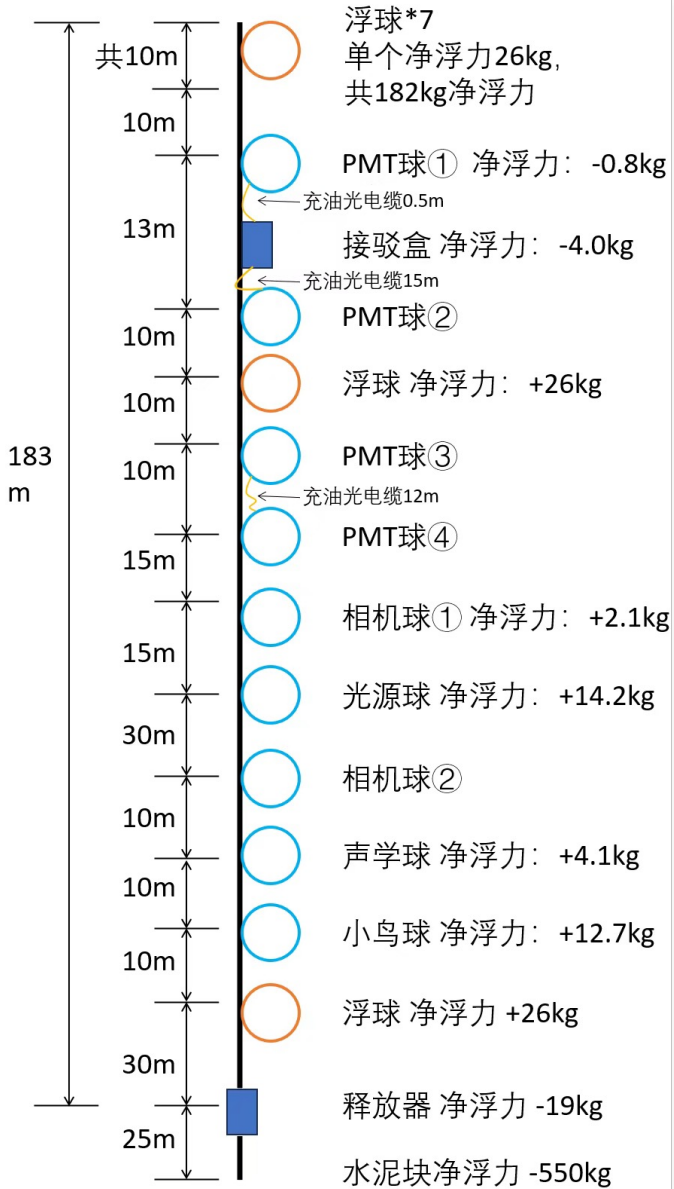


多根探测潜标

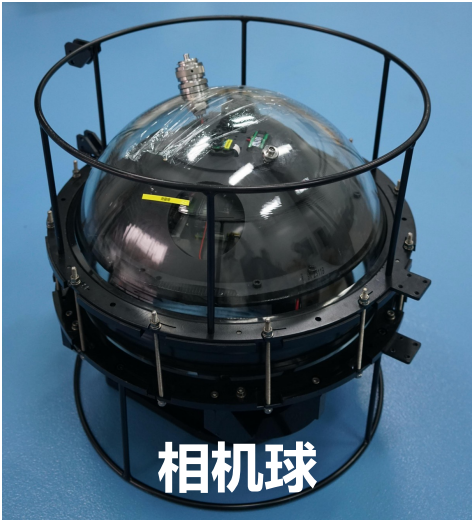
2024年海试 (T-REX 2024)



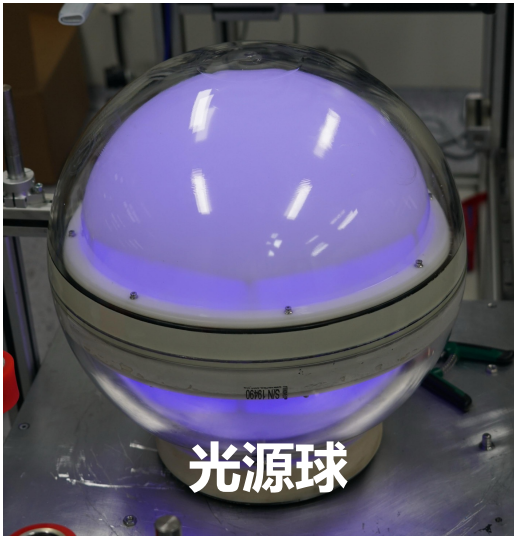
2024.12.01 – 2025.03.26布放于海铃盆地



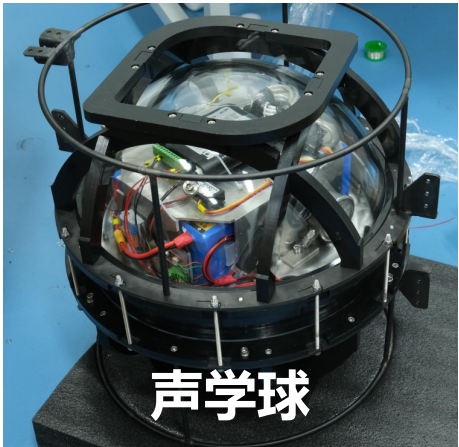
PMT球



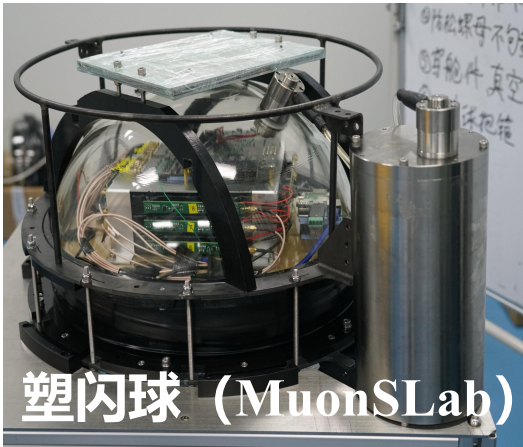
相机球



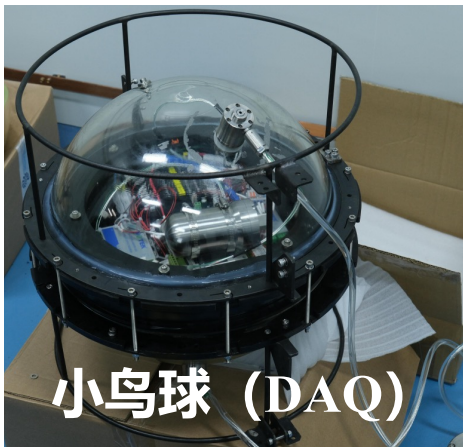
光源球



声学球



塑闪球 (MuonSLab)



小鸟球 (DAQ)

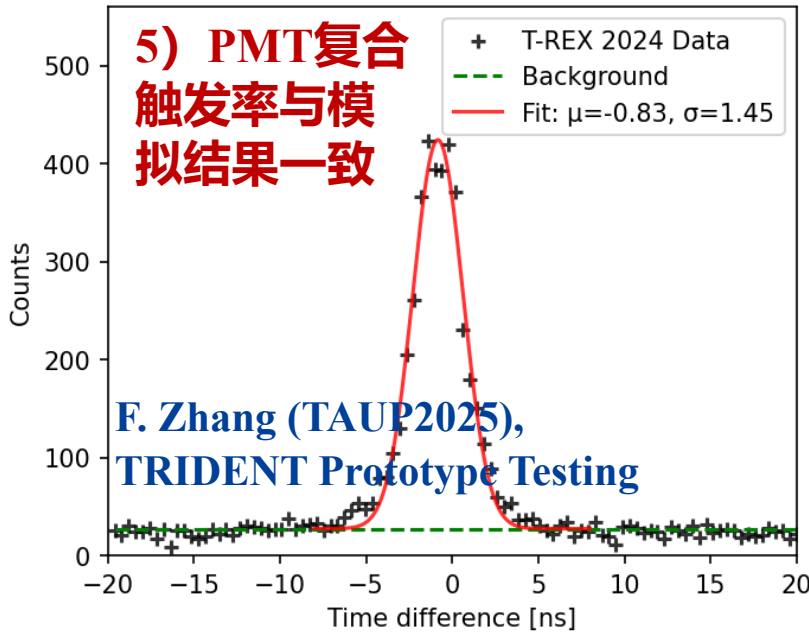
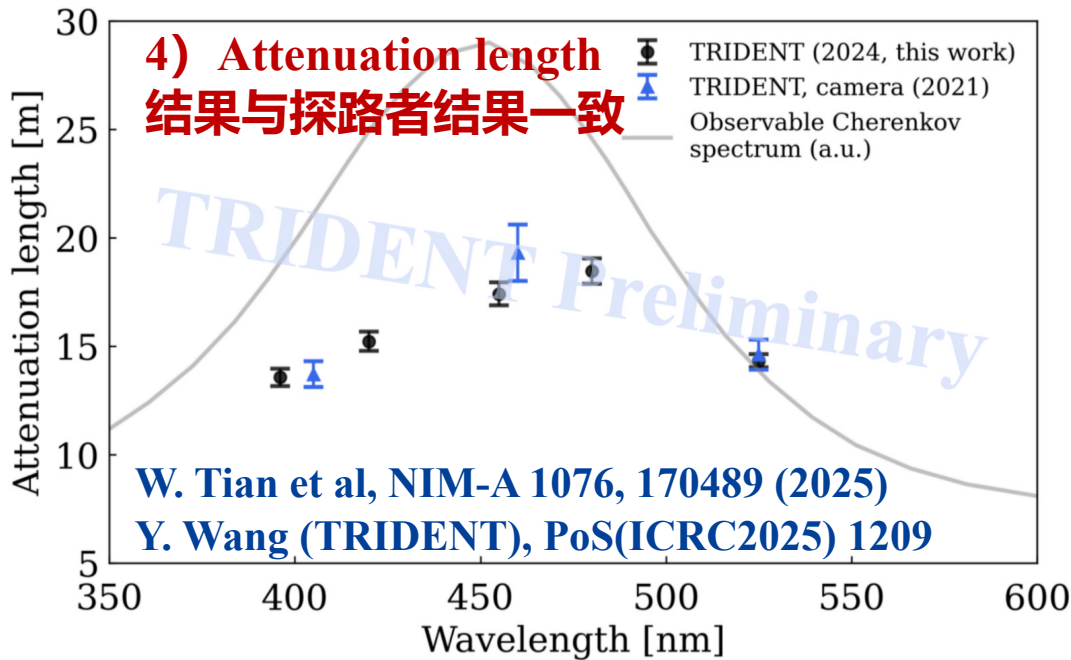
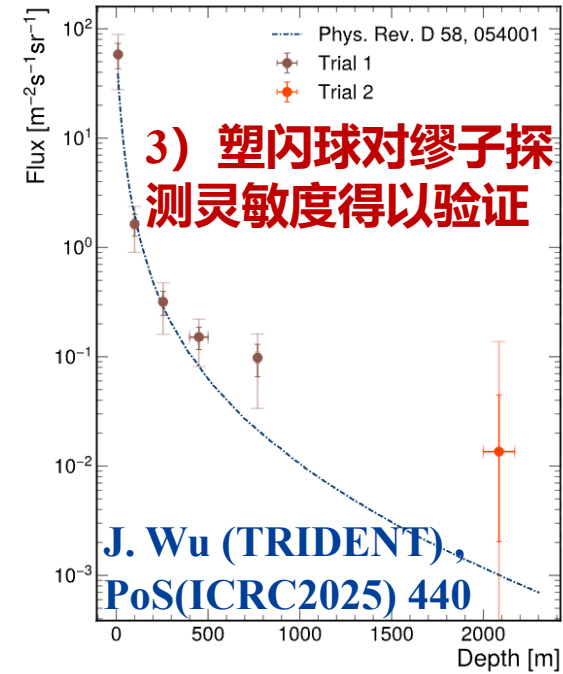
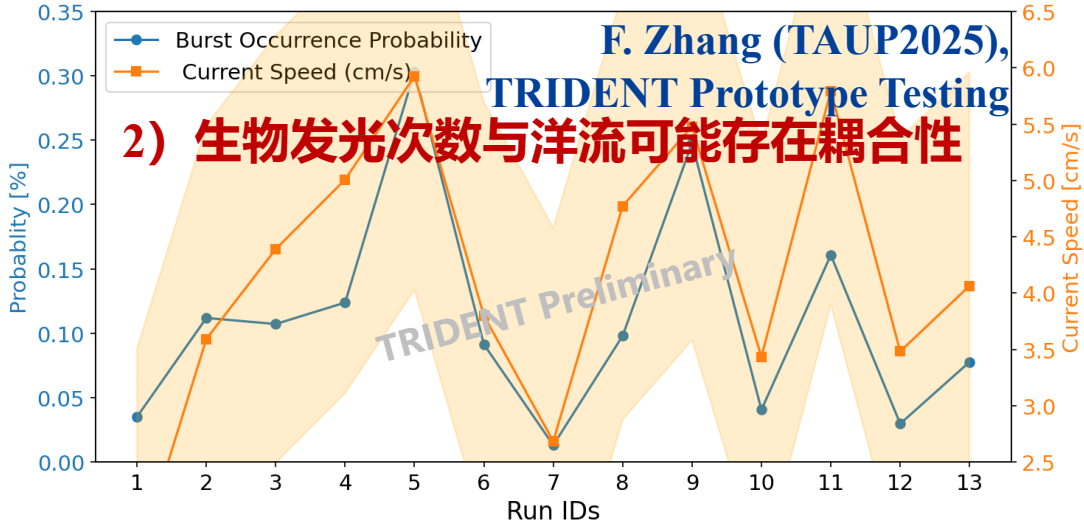
Y. Wang (TRIDENT), PoS(ICRC2025) 1209 ; J. Wu (TRIDENT) , PoS(ICRC2025) 440;
F. Zhang (TAUP2025), TRIDENT Prototype Testing

2024年海试初步结果



2025.3.26 回收

1) 4个月无可观测的生物附着



hDOM电子学读出 - FPGA



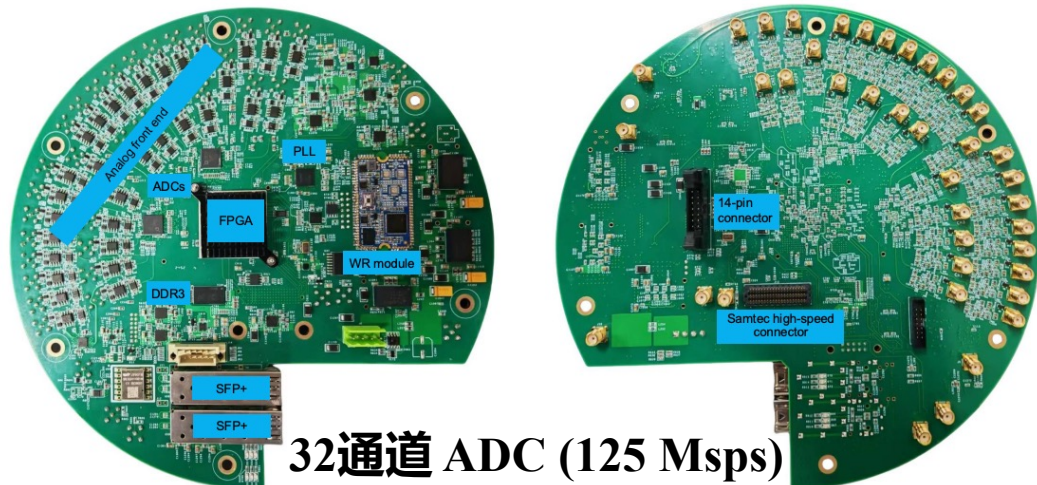
TRIDENT
海 | 铃 | 计 | 划



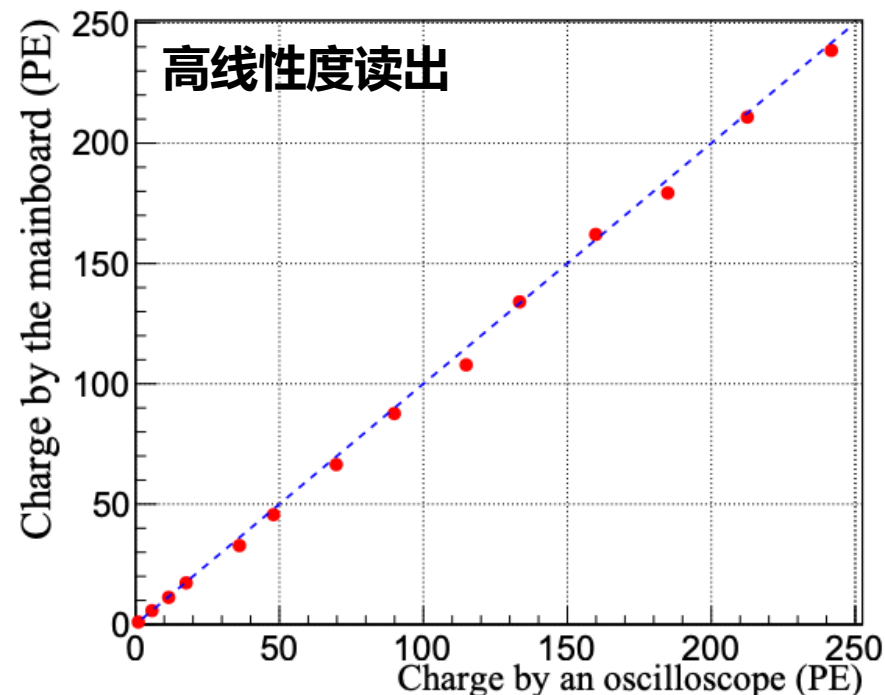
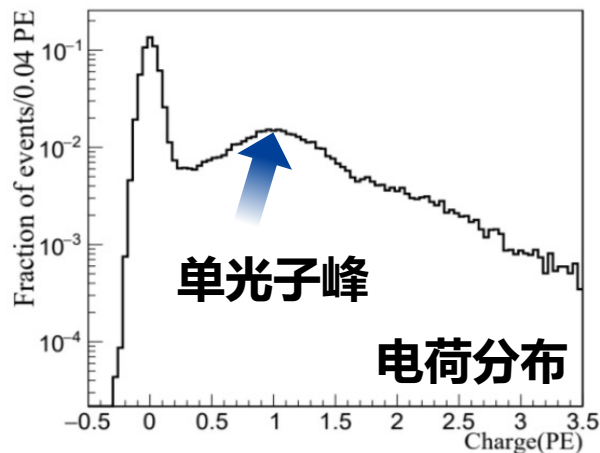
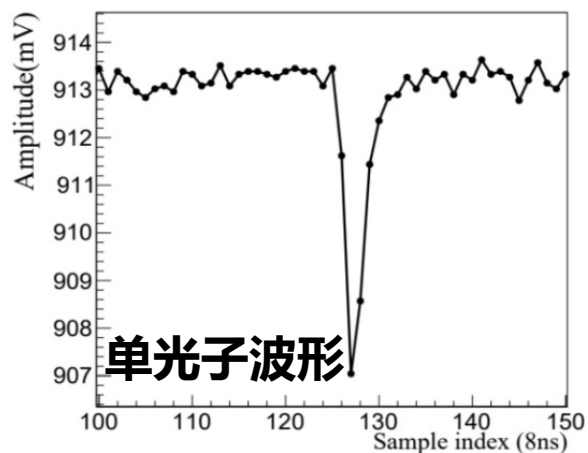
FPGA主板设计

Arxiv: 2507.00548v1

G. Zhang (TRIDENT) PoS (ICRC2025) 591



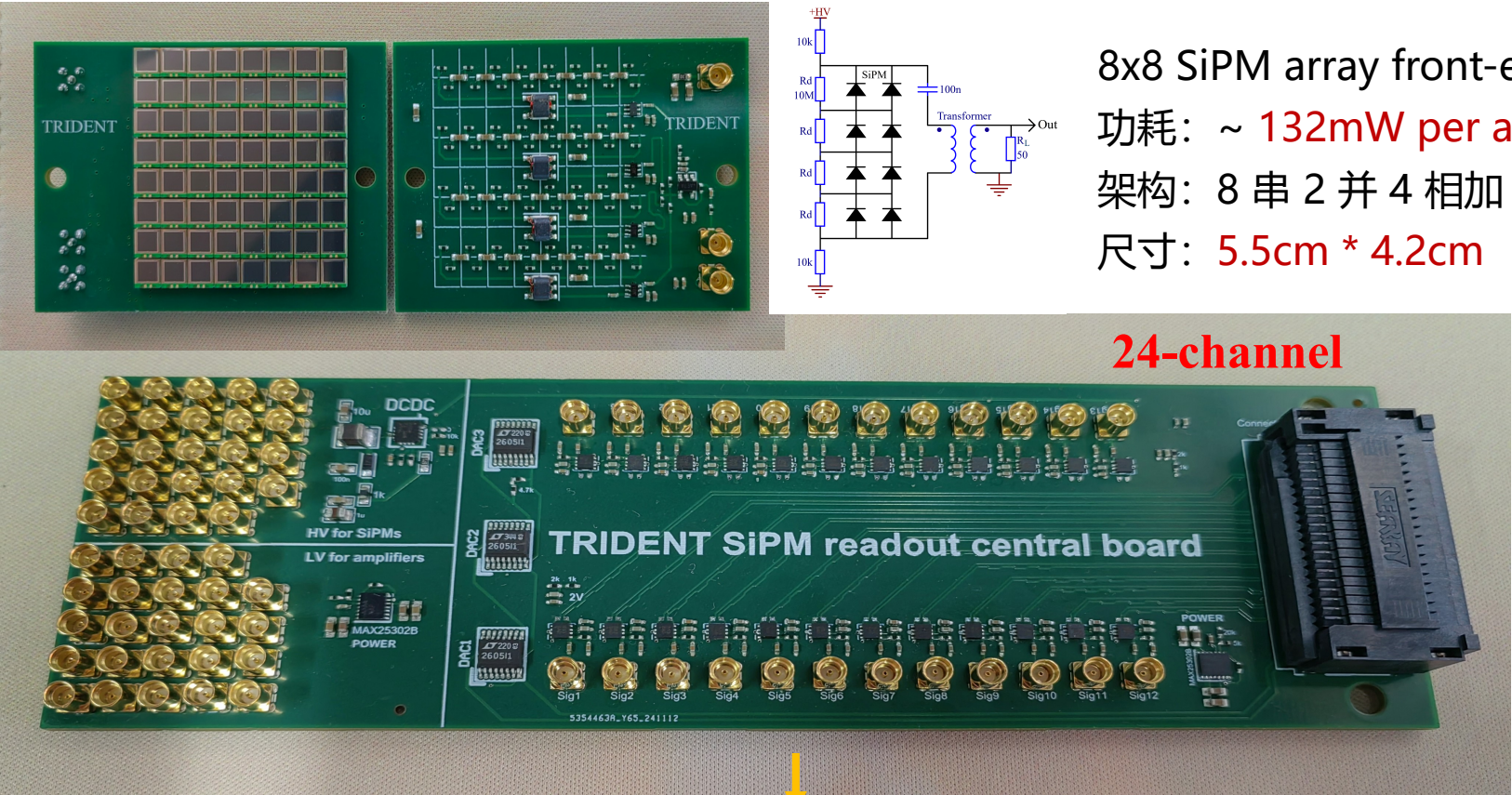
32通道 ADC (125 Msps)



- 嵌入式小白兔时钟同步系统，各hDOM间亚纳秒级同步
- 支持TDC读出，达到亚纳秒级TOT信号识别
- 嵌入式慢控系统

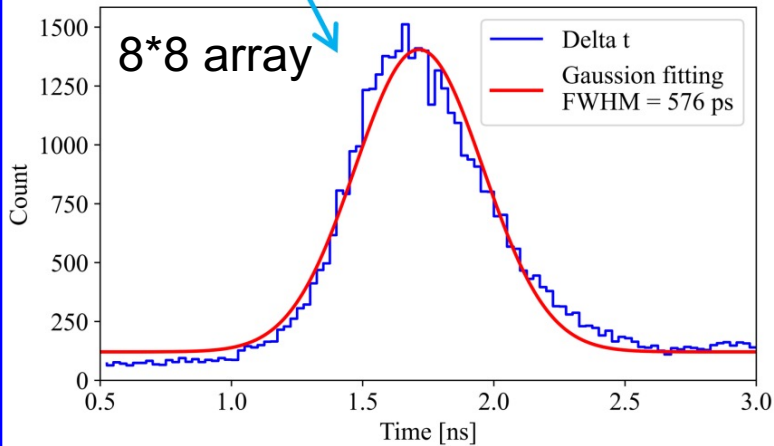
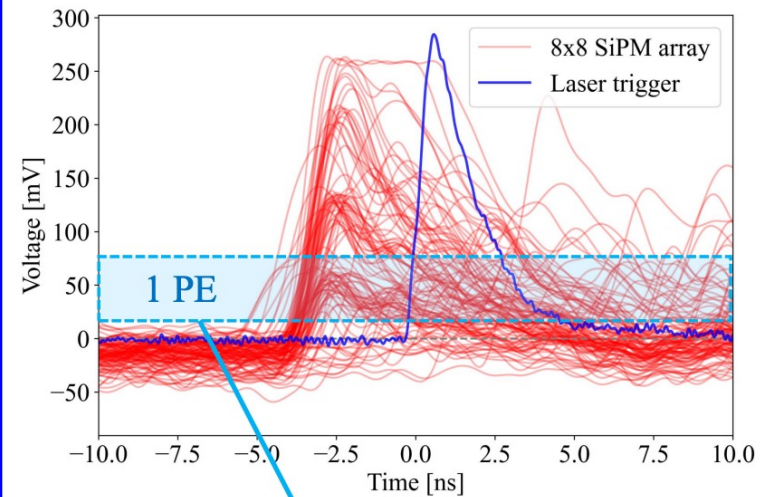
hDOM电子学读出 - SiPM

大面积的SiPM阵列可达高精度时间测分辨率（~ 500ps）：



8x8 SiPM array front-end
功耗：~ 132mW per array
架构：8 串 2 并 4 相加
尺寸：5.5cm * 4.2cm

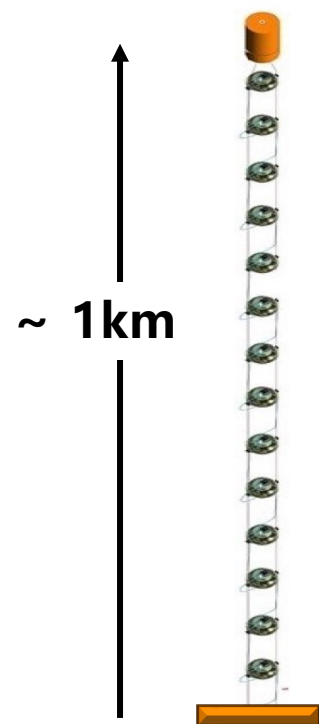
测试结果



W. Zhi (TRIDENT), PoS (ICRC 2025) 1055
W. Zhi et al 2024 JINST 19 P06011



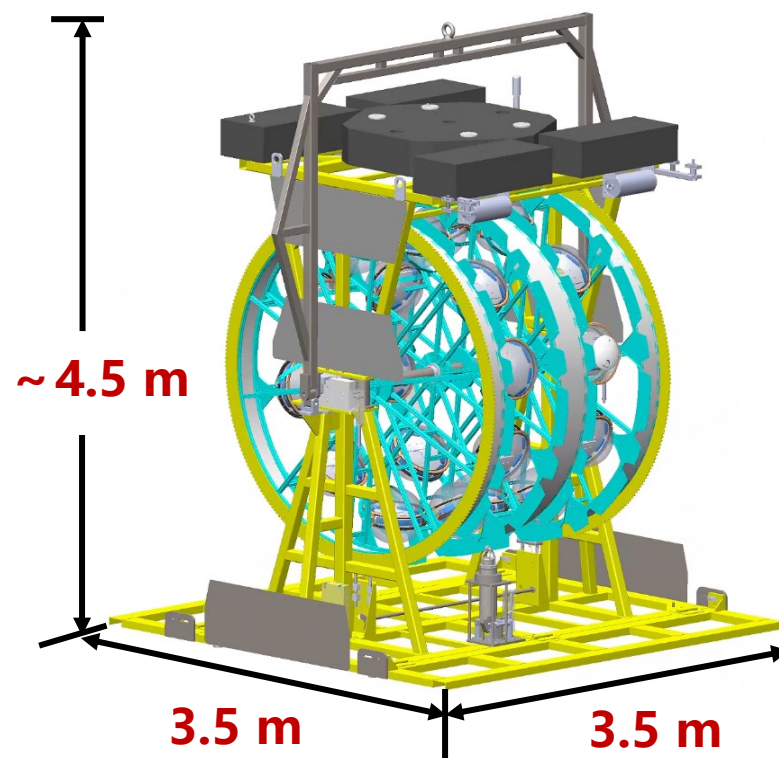
串列精准布放方案完成攻坚突破



中微子探测潜标



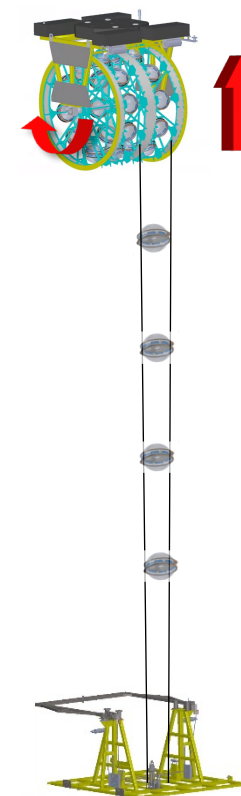
压缩



探测潜标集成布放器



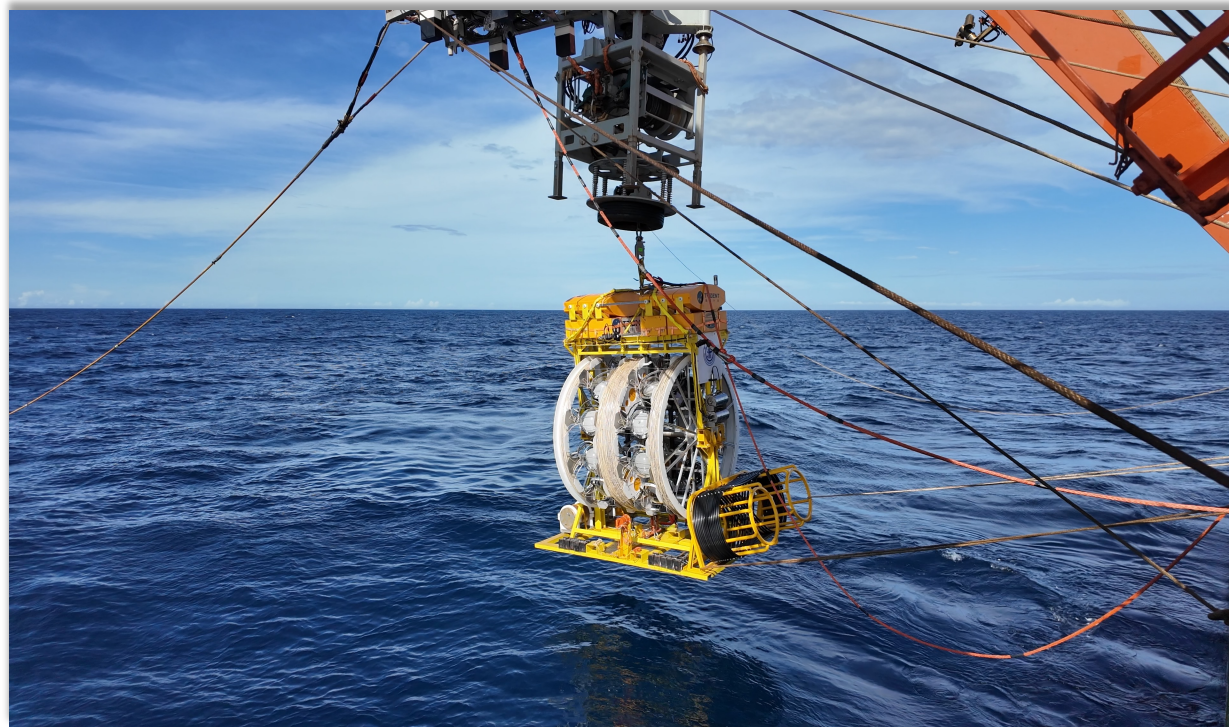
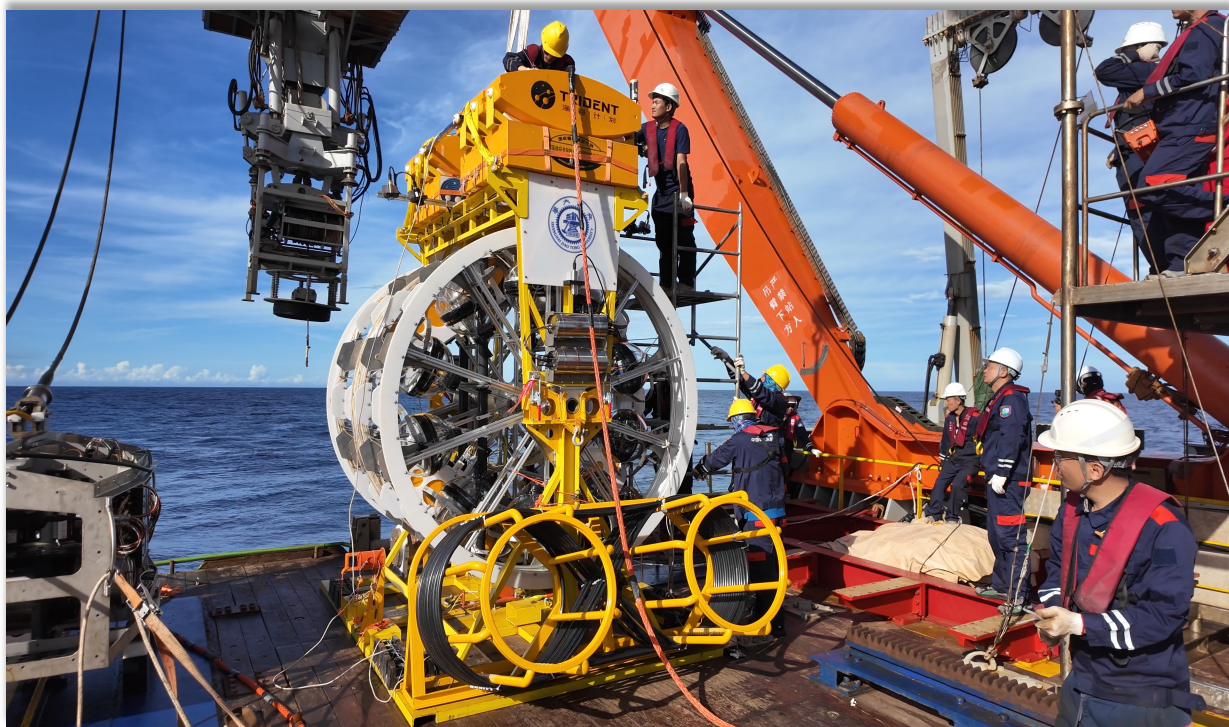
水下
展开



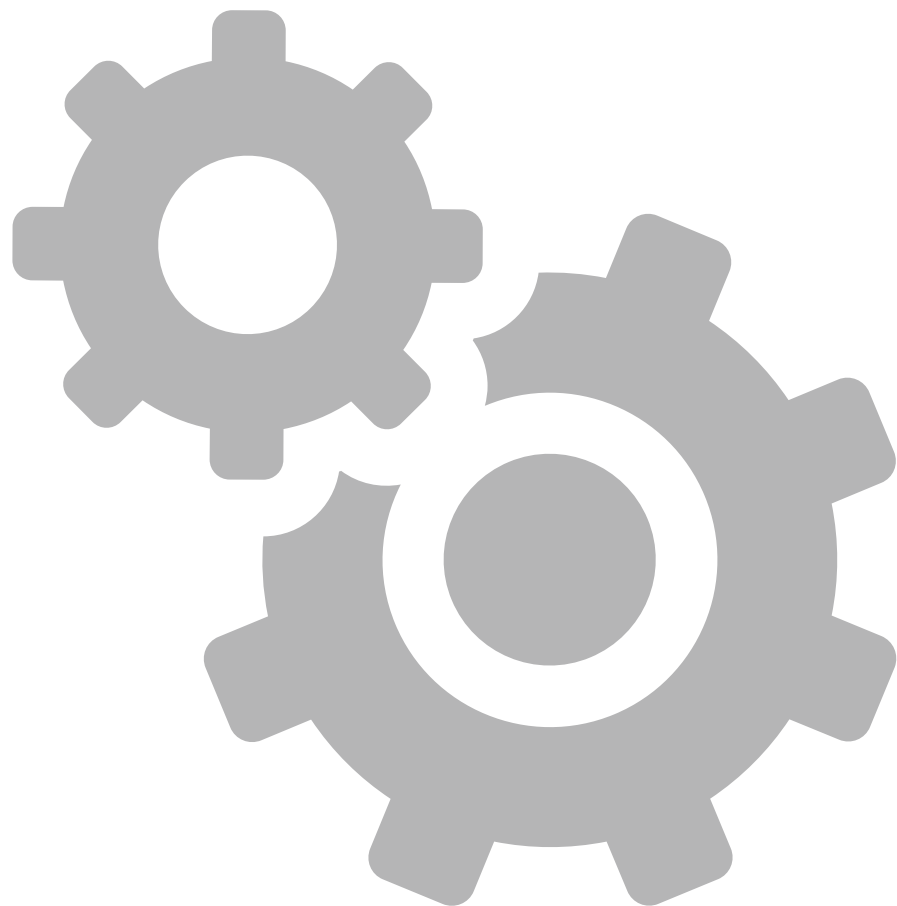
Y. Xue *et al*, Design and Lake Trial of a Deep-Sea Neutrino Detection Mooring Deployment System (in prep)

串列精准布放方案完成攻坚突破

- 创新设计了中微子“水车型”潜标布放装置，2025年8月完成两次海试布放验证



Y. Xue *et al*, Design and Lake Trial of a Deep-Sea Neutrino Detection Mooring Deployment System (in prep)



1

中微子天文学简介

2

海铃计划背景介绍

3

海铃一期设计

4

海铃未来展望

hDOM设计优化中

arXiv:2507.10256



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3-inch PMT hDOM

- 31 3" PMTs
- 24 SiPMs (4x8 array)



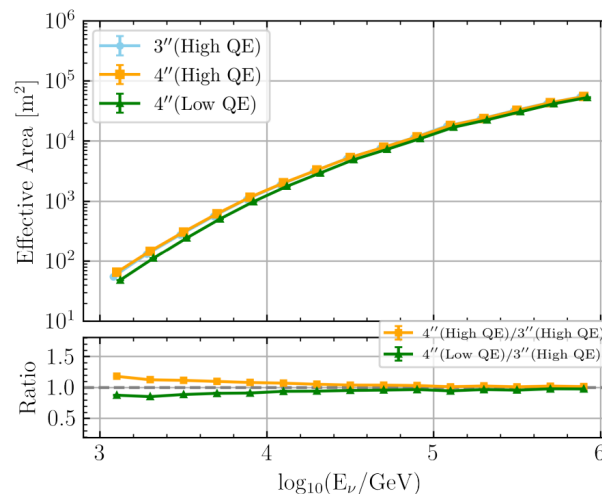
4-inch PMT hDOM

- 31 4" PMTs
- 5 SiPMs (8x8 array)

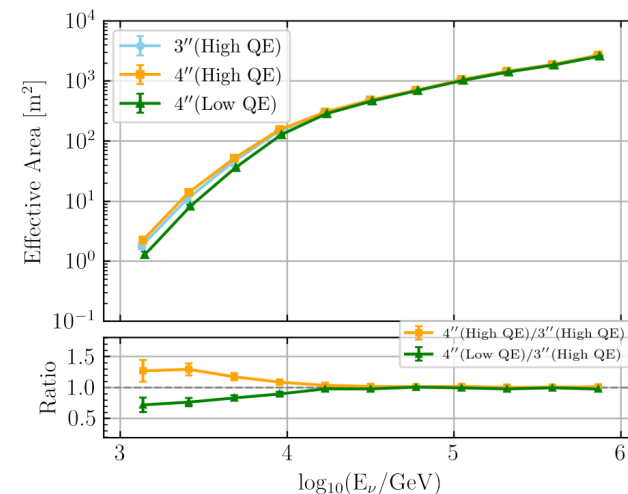


预算缩减,
性能不变!

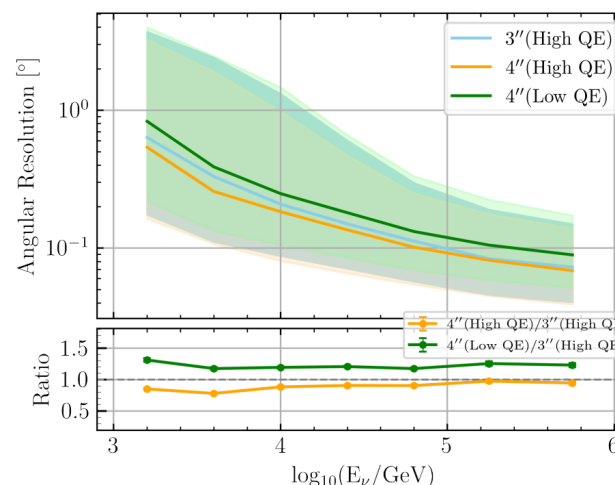
Effective Area (ν_μ - CC)



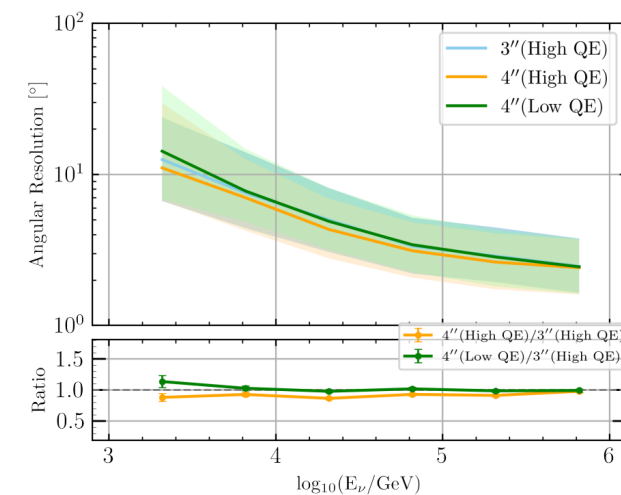
Effective Area (ν_e - CC)

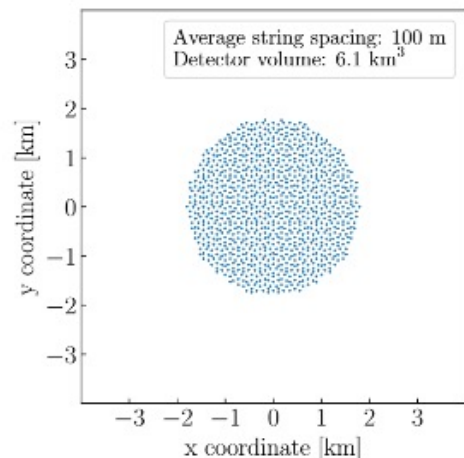
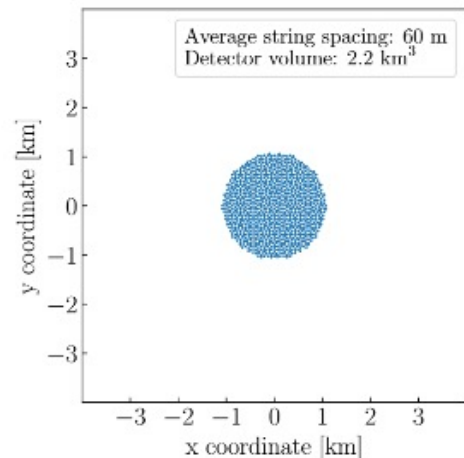


Angular Resolution (ν_μ - CC)



Angular Resolution (ν_e - CC)

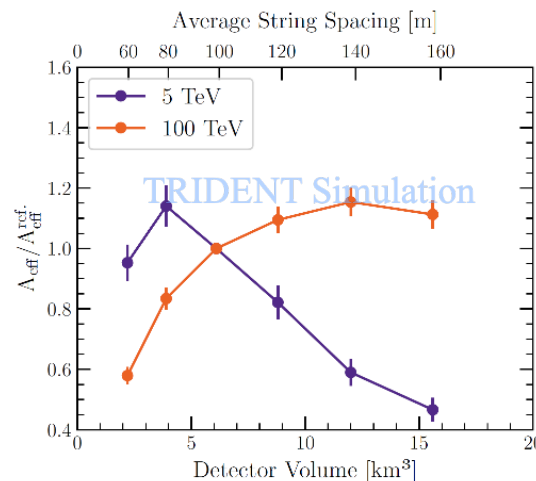




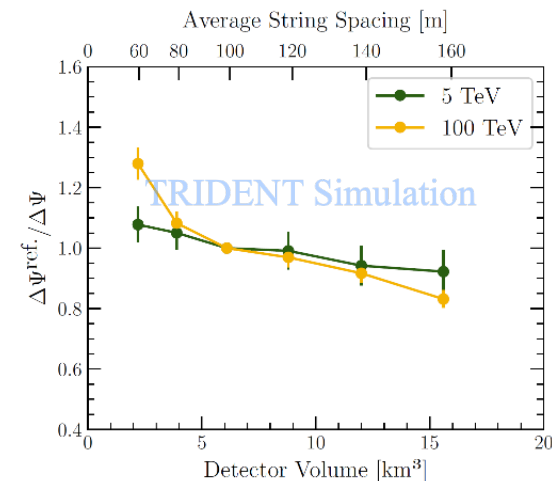
不同尺寸与间距下，
角度分辨率、有效面积、
探测能力的变化

$$\frac{dN}{dt} = \int d\Omega \int A_{\text{eff}}(E, \cos \theta) \times \Phi(E) dE$$

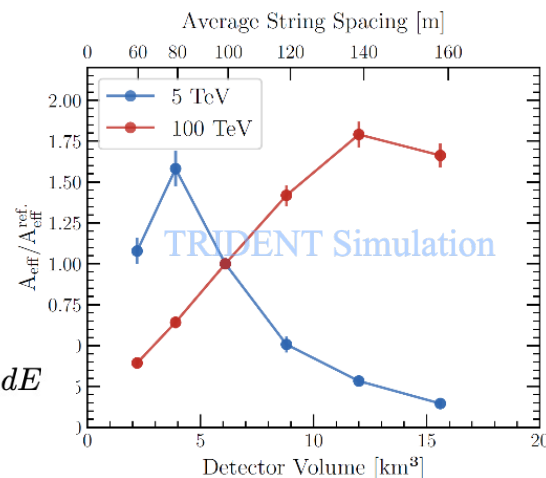
Effective Area vs String Spacing - Tracks



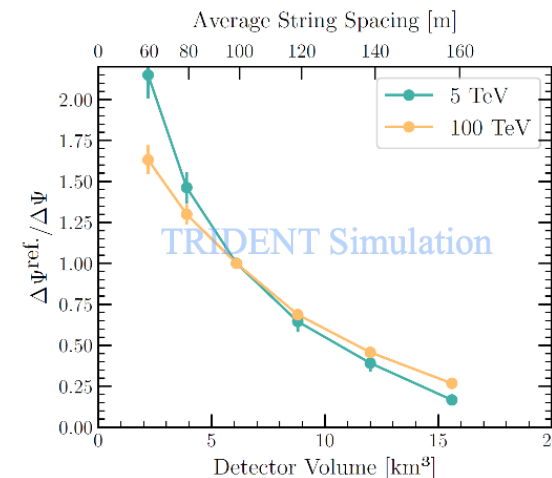
Angular Resolution vs String Spacing - Tracks



Effective Area vs String Spacing - Cascades



Angular Resolution vs String Spacing - Cascades



I. Morton-Blake *et al*, Optimising Underwater Neutrino
Telescopes for All-Flavour Point Source Sensitivity (in prep.)



- 工厂式1000平方米实验室建设中，位于三亚崖州湾
- 海铃一期200个hDOM和10根串列计划集中在此装配测试



~13 institutes, ~ 100 members



- **海铃大阵列建成后，将在多信使天文学研究和新物理探索等多领域达到国际领先水平**
- **"海铃计划"取得系列重要进展：**
 - **在南海海域选定理想台址，具备深海、光学性质优良、环境稳定等特点**
 - **通过多次海试，在探测球舱、刻度方案、通讯系统和布放技术等关键环节完成验证**
 - **计划2026年完成“海铃一期”建设，全面验证探测器性能**
 - **三亚基地建设稳步推进，国际合作网络持续拓展**

The logo for the TRIDENT telescope, featuring the word "TRIDENT" in a bold, white, sans-serif font. The background of the slide is a dark blue space scene with a large, glowing blue and white accretion disk around a black hole at the top. Below the black hole, a vertical beam of light contains several white neutrino symbols (ν_e). The entire scene is overlaid with a grid of vertical lines, each with a small blue sphere at the bottom, representing the telescope's detector modules.

TRIDENT

The tRopical DEep-sea Neutrino Telescope

谢谢!

诚邀各位同行关注、支持!



上海交通大学
SHANGHAI JIAO TONG UNIVERSITY



李政道研究所
TSUNG-DAO LEE INSTITUTE