JUNO-0νββ实验规划

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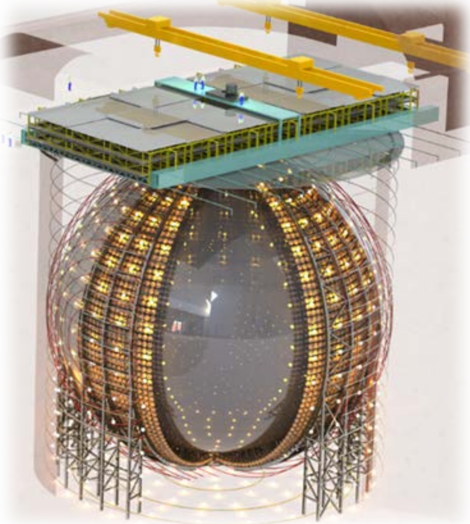
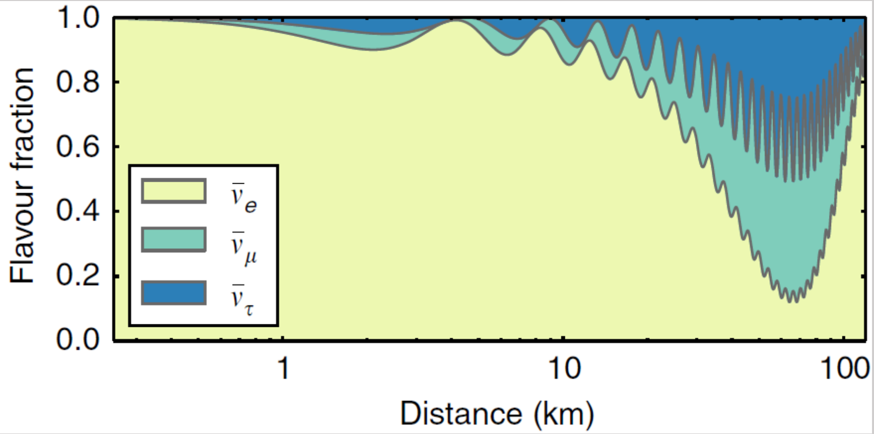
中国科学院高能物理研究所

2021年5月15日

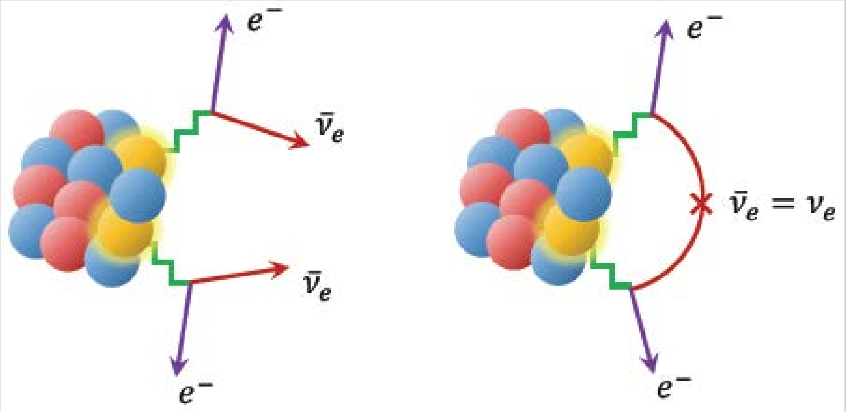


中微子质量



中微子质量是中微子研究的核心问题。实验上解决可“两步走”

- 中微子振荡实验 → 相对质量
- 双贝塔衰变实验 → 有效质量



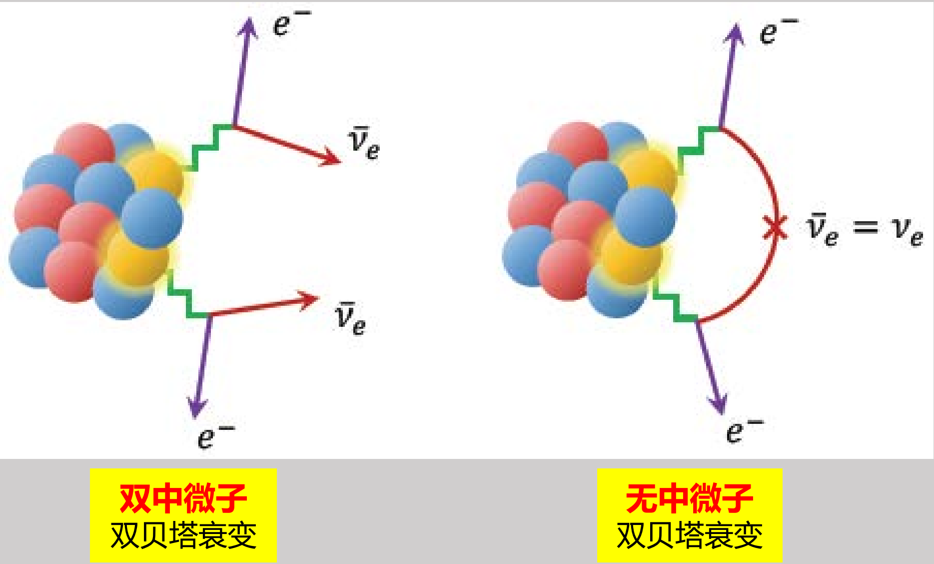
0νββ和中微子有效质量

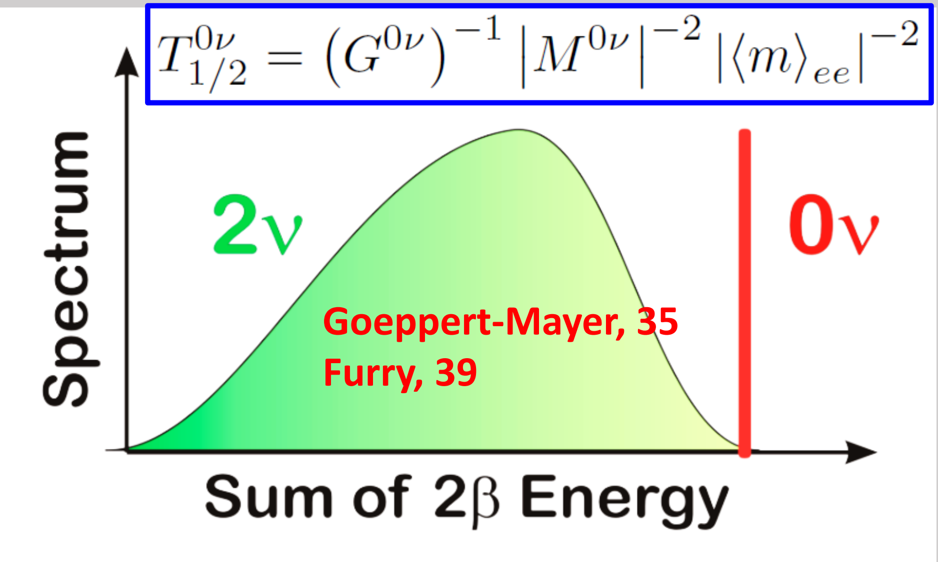
中微子是自身的反粒子吗?
——粒子物理的一个基本问题，
理论上倾向于“是”。

双贝塔衰变 (0νββ) 实验是
解决该问题的唯一可行方法

此外，

- 测量中微子有效质量
- 检验轻子数守恒
- 限制中微子的Majorana CP破坏相位



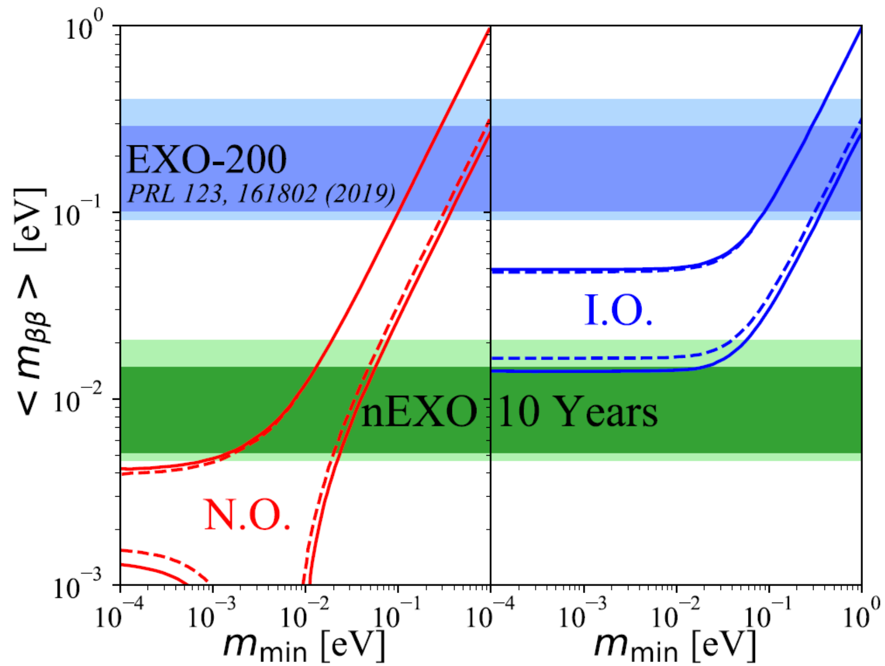


美国NLDBD Down Select启动

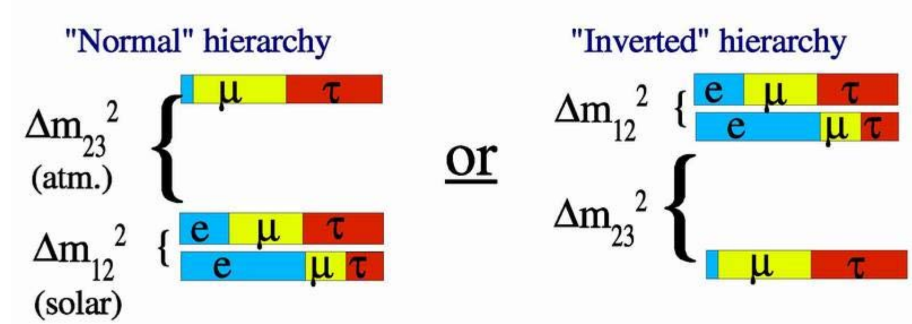
Ton Scale Neutrinoless Double Beta Decay Portfolio Review, July 13-16, 2021

To review CUPID, LEGEND-1000, and nEXO

- April 18th: This charge will be conveyed to the Team managers.
- June 1st: Proposal packages should be conveyed to the Office of Nuclear Physics.
- June 28th: Panel questions will be submitted to the Teams.
- July 13th-16th: Portfolio Review
  - Day 1: 90-minute presentations and Q&A
  - Day 2 and 3: Round-robin breakout sessions on Discovery Potential, Technical Maturity, Cost & Schedule, and Project Management.
  - Day 4: Panel Discussions and Conclusion



江门中微子实验

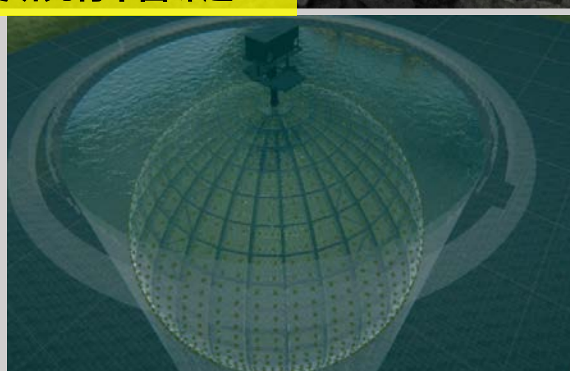


首要科学目标：

中微子质量顺序，
振荡参数精确测量

在天体中微子（超新星、太阳、地球、大气），质子衰变研究有丰富课题

国际最大
液闪探测器



江门中微子实验更远的未来

最灵敏的中微子绝对质量测量（~ meV）；

最灵敏地寻找0νββ衰变以确定中微子是Dirac 还是 Majorana 粒子

中微子振荡：确定质量顺序

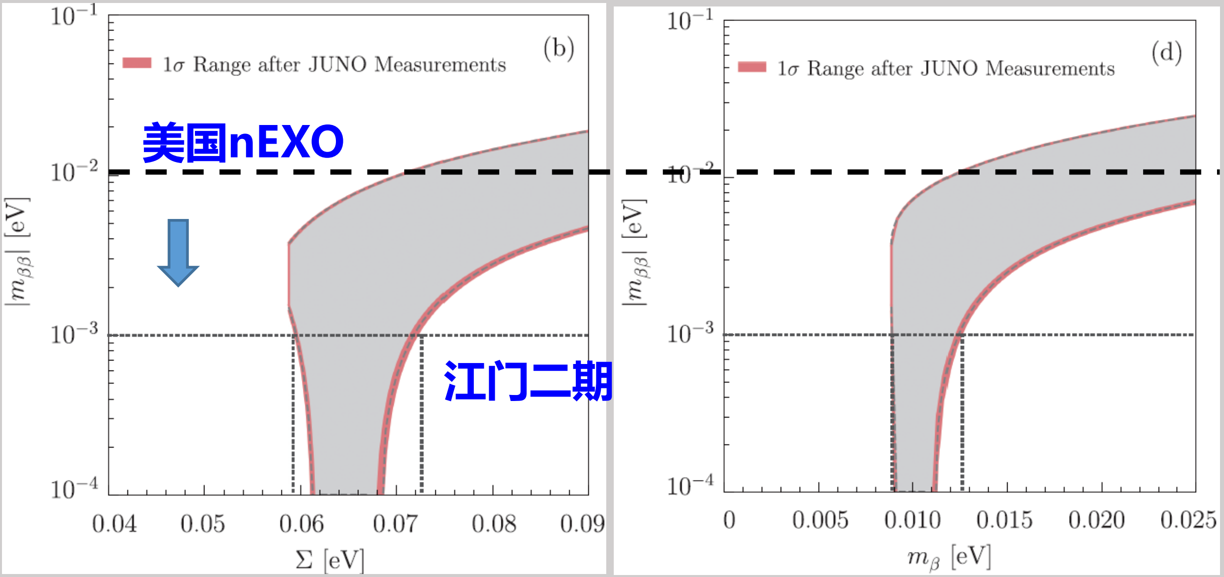
未来实验灵敏度

氚贝塔衰变： $m_\beta \leq 40$ meV

宇宙学： $\Sigma \leq 80$ meV

双贝塔衰变： $|m_{\beta\beta}| \approx 10$ meV **(美国nEXO)**

$|m_{\beta\beta}| \approx 1$ meV **(江门二期)**



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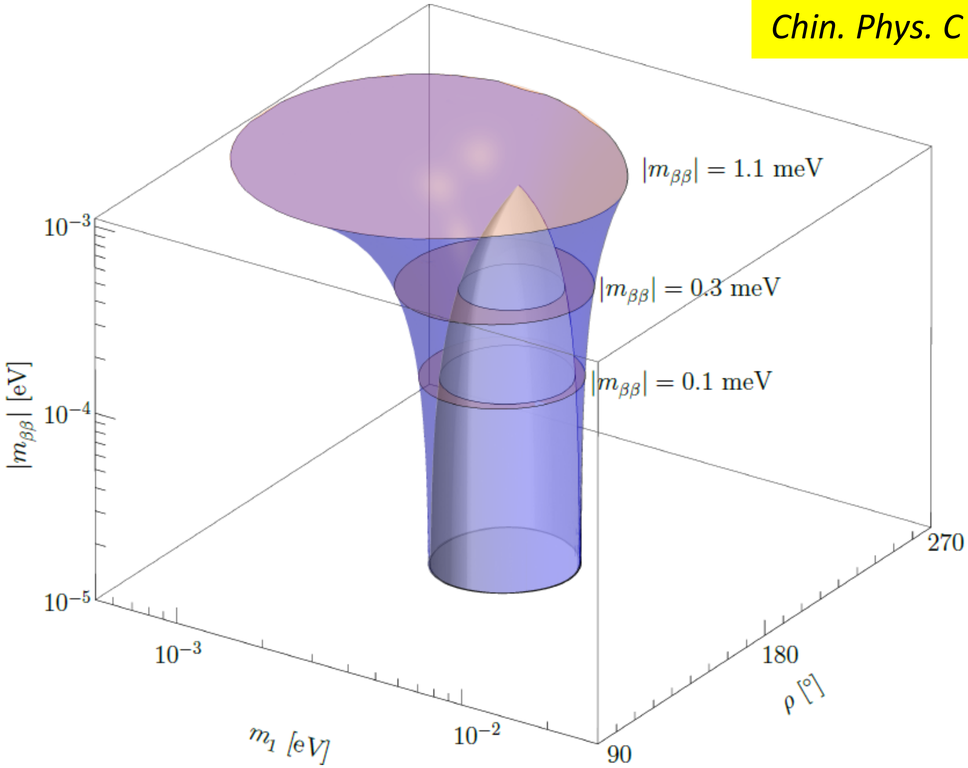
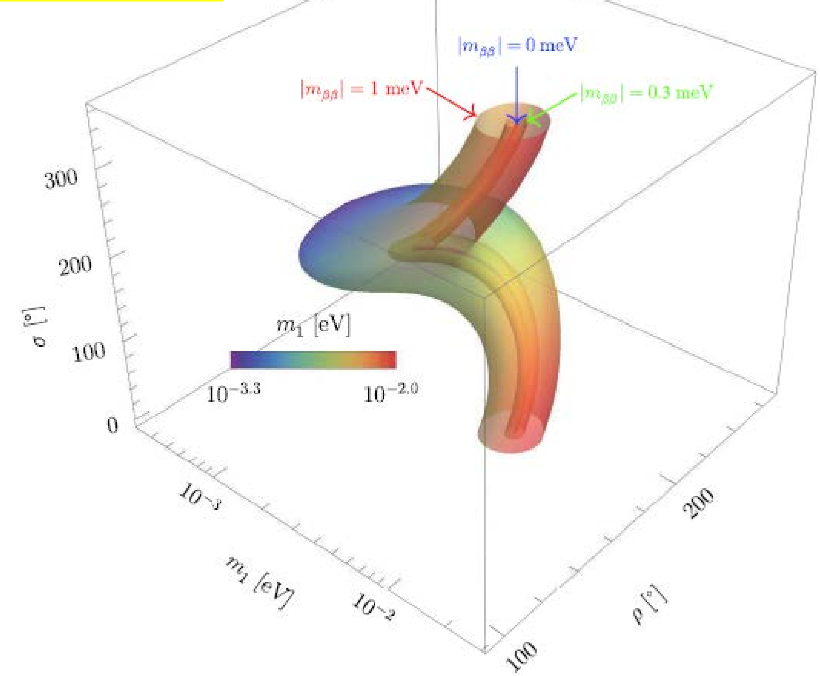
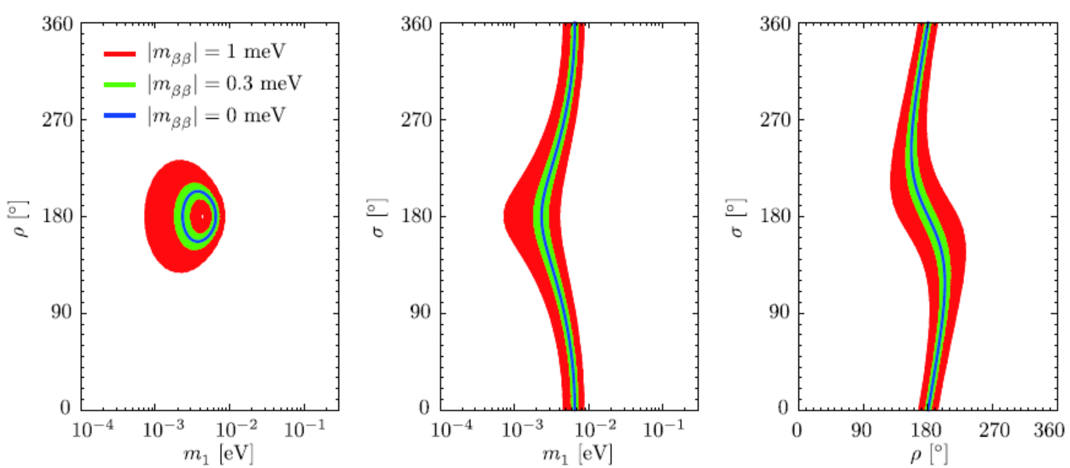






实验上追求 $|m_{\beta\beta}|$~meV的意义

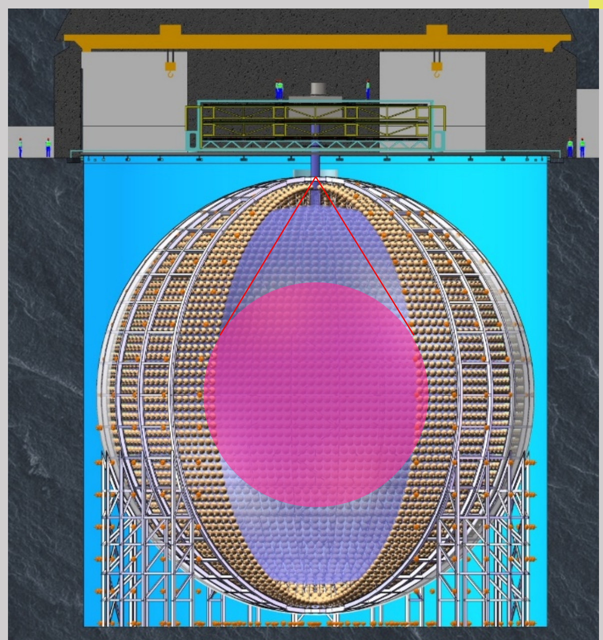
- 最轻中微子质量m_1、Majorana相位(ρ, σ)的参数空间被限制得很小
- 有望确定三代中微子质量谱

JUNO-ββ设想

	核素	质量(吨)	$<m_{\beta\beta}>$, meV
KamLAND-Zen	^{136}Xe	1	61-165
EXO-200	^{136}Xe	0.2	93-286
nEXO	^{136}Xe	5	7-22
GERDA	^{76}Ge	1	10-40
Majorana	^{76}Ge	1	10-40
SNO+	^{130}Te	8	19-46
JUNO-ββ	^{136}Xe	50	4-12
	^{130}Te	100-200	2-6 ?

Chin. Phys. C 41 (2017) 053001

在江门中微子探测器的中间置入一个气球，填充掺入^{130}Te的液体闪烁体(~2030年)



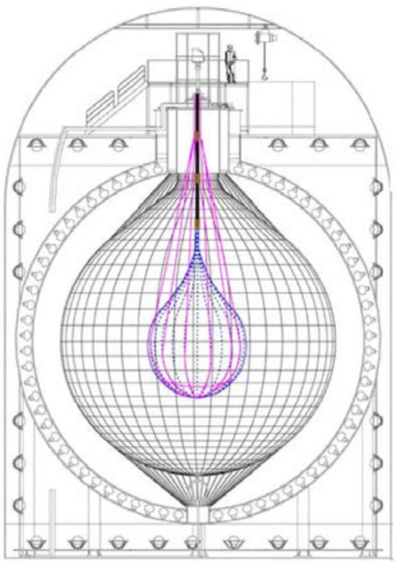
最大的靶质量

最好的液闪屏蔽

极好的能量分辨率(3%/√E)

极低本底

国际上基于液闪技术的0νββ实验



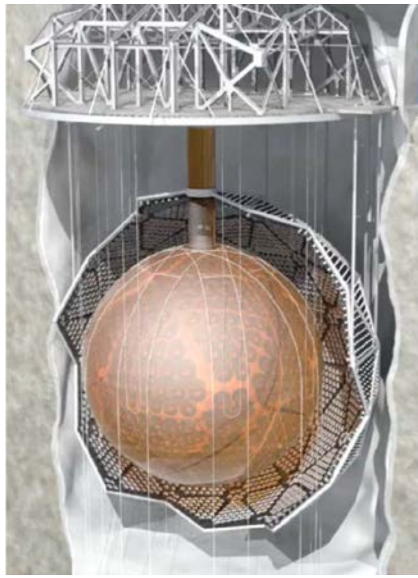
KamLAND-Zen

(~2700 m.w.e)

1千吨

~3% ^{enr}Xe

(2011 - Today)

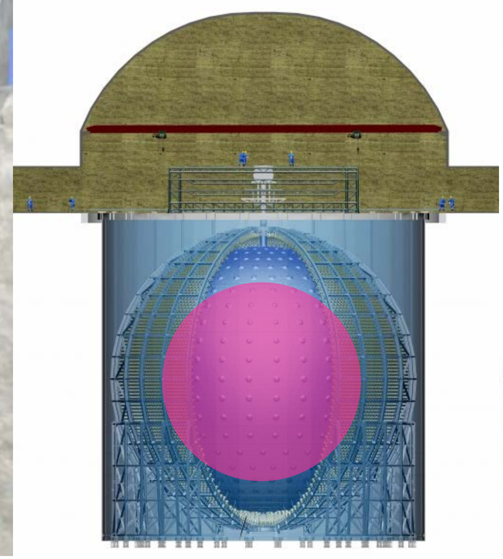


SNO+

(~6000 m.w.e)

780吨

^{nat}Te loading



JUNO-ββ

(~1800 m.w.e)

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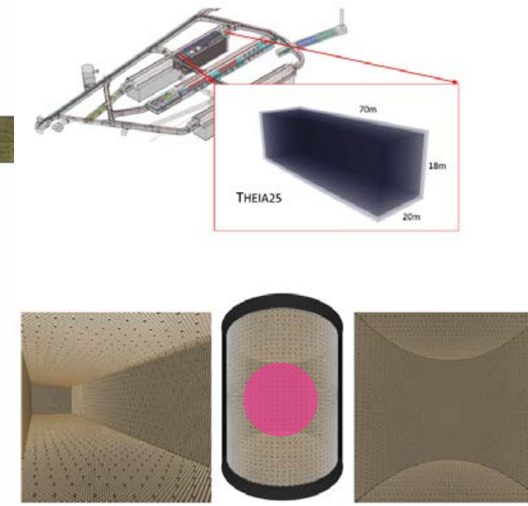
2万吨



THEIA

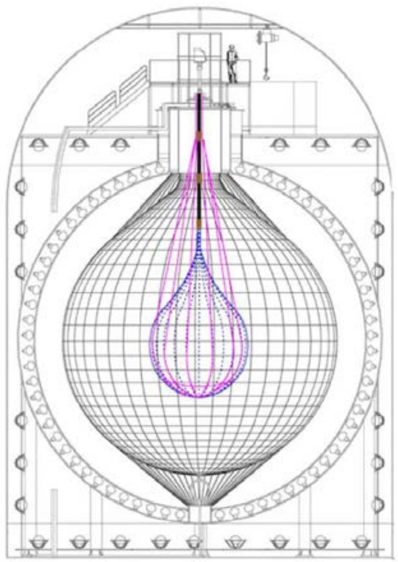
(4300 m.w.e)

Eur. Phys. J. C (2020) 80:416

THEIA-25(2.5万吨)探测器计划部署在DUNE四个洞室之一；

未来计划THEIA-100（10万吨）探测器

现在

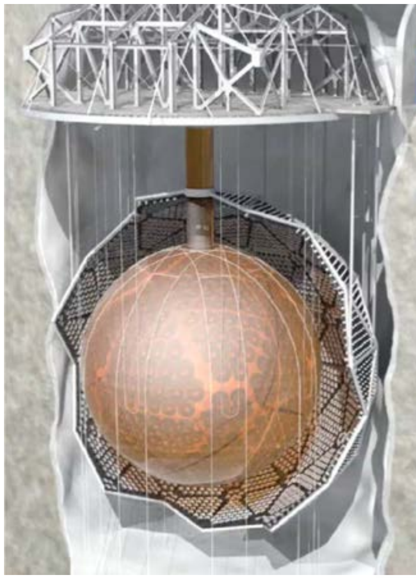


KamLAND-Zen

KLZ-800灵敏度(2020):
> 8×10^{25} yrs

KLZ-800 (5年):
> 5×10^{26} yrs

KamLAND2-Zen:
> 2×10^{27} yrs



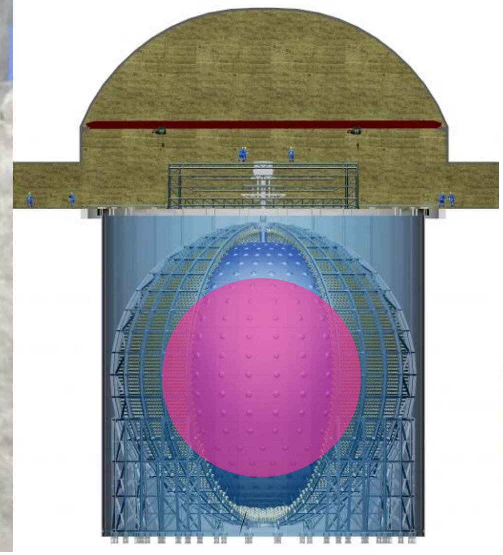
SNO+

试运行

0.5% loading (3年):
> 2×10^{26} yrs

2.5% loading (4年):
> 1×10^{27} yrs

未来



JUNO-ββ

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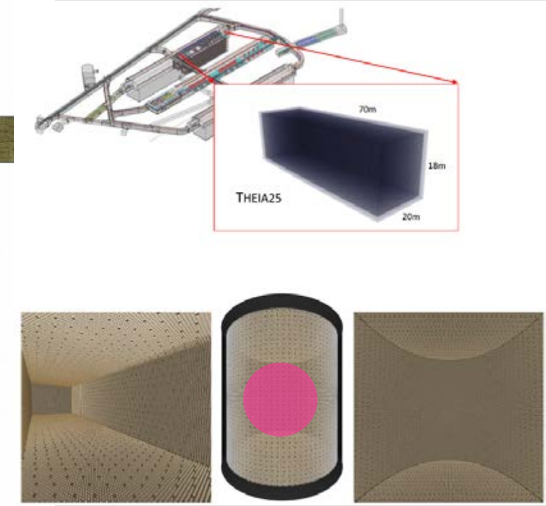
50吨^{136}Xe (5年):
> 1.8×10^{28} yrs

^{130}Te是候选，可容纳百吨，未做详细计算。



THEIA

(THEIA-25: 25 kton)
(THEIA-100: 100 kton)

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49.5吨^{136}Xe (10年):
> 2.0×10^{28} yrs

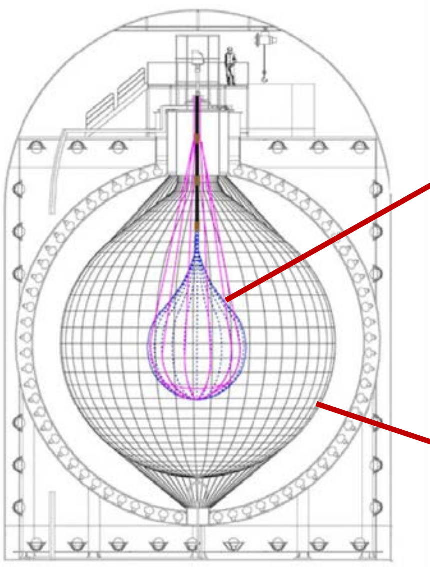
~31.4吨^{130}Te (10年):
> 1.1×10^{28} yrs

技术挑战：掺0νββ核素（Xe或Te）液闪及其纯化

		^{238}U (g/g)	^{232}Th (g/g)
	KamLAND (2002 osci. RPL)	~3.5 x 10^{-18}	~5.2 x 10^{-17}
	KamLAND (2005 thesis for PRL)	~3.4 x 10^{-18}	~8.7 x 10^{-17}
	KamLAND (2008 thesis for PRL)	~2.7 x 10^{-18}	~6.1 x 10^{-17}
	KamLAND (2015 solar)	5 x 10^{-18}	1.3 x 10^{-17}
1 kton	KamLAND-Zen (2013 PRL)	1.3 x 10^{-16}	1.8 x 10^{-15}
780 ton	SNO+ (2020)	10^{-15}	10^{-16}
20 kton	JUNO (baseline case)	10^{-15}	10^{-15}
太阳中微子、0νββ ←	JUNO (ideal case)	10^{-17}	10^{-17}
	THEIA (target)	10^{-17}	10^{-17}

References:
Phys. Rev. C. 85.045504, Phys. Rev. C 92, 055808 (2015), Phys. Rev. Lett.90.021802, Phys. Rev. Lett. 117.082503, Phys. Rev. C.84.035804, KamLAND Ph.D. theses, Eur. Phys. J. C (2020) 80:41, talks at NEUTRINO2020

技术挑战：制作干净的Balloon



Balloon film backgrounds:

^{238}U ~ 3 ×10^{-12} g/g
^{232}Th ~ 4 × 10^{-11} g/g

×10 reduction compared to KLZ 400 mini-balloon

R=1.9 m

KLZ-800制作的第一个Inner balloon（2014-2016）
有漏，拆除后重新做（2017.5-2018.4），2018.5安装

Azusa Gando @ Neutrino2018
Christopher Grant@ Neutrino2020

Outer balloon (R=6.5 m)

^{238}U ~ 18 ppt, ^{232}Th ~ 14 ppt

液袋方案曾是江门中心探测器备选方案之一（2015.7之前）。研制了直径12米的原型。

R=6 m

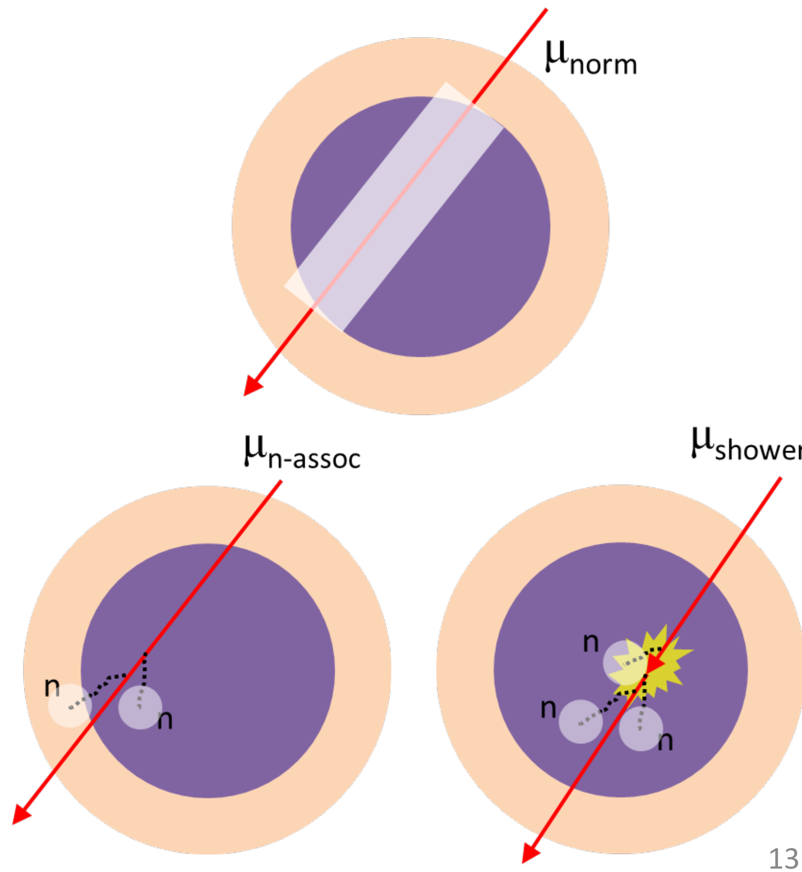
尽管JUNO探测器岩石覆盖 (~700 m) 不如Kamioka、SNOLab，但对宇宙线缪子有很强的Tracking能力，可实现精细的反符合判选去掉宇生本底

Table A9. The estimated rates for cosmogenic isotopes in JUNO LS by FLUKA simulation, in which the oxygen isotopes are neglected. The decay modes and Q values are from TUNL Nuclear Data Group [475].

Isotopes	Q (MeV)	$T_{1/2}$	Rate (per day)
^{3}H	0.0186 (β^-)	12.31 year	1.14×10^4
^{6}He	3.508 (β^-)	0.807 s	544
^{7}Be	$Q_{EC} = 0.862$ (10.4% γ, $E_\gamma = 0.478$)	53.22 d	5438
^{8}He	10.66 ($\beta^-\gamma$: 84%), 8.63 ($\beta^- n$: 16%)	0.119 s	11
^{8}Li	16.0 (β^-)	0.839 s	938
^{8}B	16.6 (β^+)	0.770 s	225
^{9}Li	13.6 (β^-: 49%), 11.94 ($\beta^- n$: 51%)	0.178 s	94
^{9}C	15.47 ($\beta^+ p$: 61.6%, $\beta^+\alpha$: 38.4%)	0.126 s	31
^{10}Be	0.556 (β^-)	1.51e6 year	1419
^{10}C	2.626 ($\beta^+\gamma$)	19.29 s	482
^{11}Li	20.55 ($\beta^- n$: 83%, $\beta^- 2n$: 4.1%)	0.00875 s	0.06
^{11}Be	11.51 ($\beta^-\gamma$: 96.9%), 2.85 ($\beta^-\alpha$: 3.1%)	13.76 s	24
^{11}C	0.960 (β^+)	20.36 min	1.62×10^4
^{12}Be	11.708 ($\beta^-\gamma$, $\beta^- n$: 0.5%)	0.0215 s	0.45
^{12}B	13.37 ($\beta^-\gamma$)	0.0202 s	966
^{12}N	16.316 ($\beta^+\gamma$)	0.0110 s	17
^{13}B	13.437 ($\beta^-\gamma$)	0.0174 s	12
^{13}N	1.198 (β^+)	9.965 min	19
^{14}B	20.644 ($\beta^-\gamma$, $\beta^- n$: 6.1%)	0.0126 s	0.021
^{14}C	0.156 (β^-)	5730 year	132
^{15}C	9.772 (β^-)	2.449 s	0.6
^{16}C	8.010 ($\beta^- n$: 99%)	0.747 s	0.012
^{16}N	10.42 ($\beta^-\gamma$)	7.130 s	13
^{17}N	8.680 ($\beta^-\gamma$: 5%), 4.536 ($\beta^- n$: 95%)	4.173 s	0.42
^{18}N	13.896 ($\beta^-\gamma$: 93%), 5.851 ($\beta^- n$: 7%)	0.620 s	0.009
Neutron			155 000

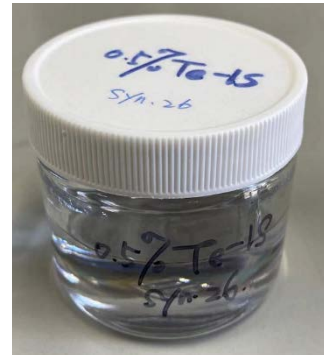
J. Phys. G43:030401 (2016)

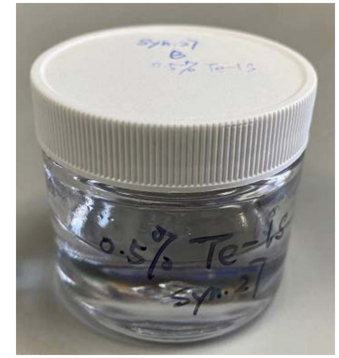
新的muon veto策略，
参见arXiv:2006.11760,
*CPC*45 (2021) 023004
(JUNO太阳中微子)

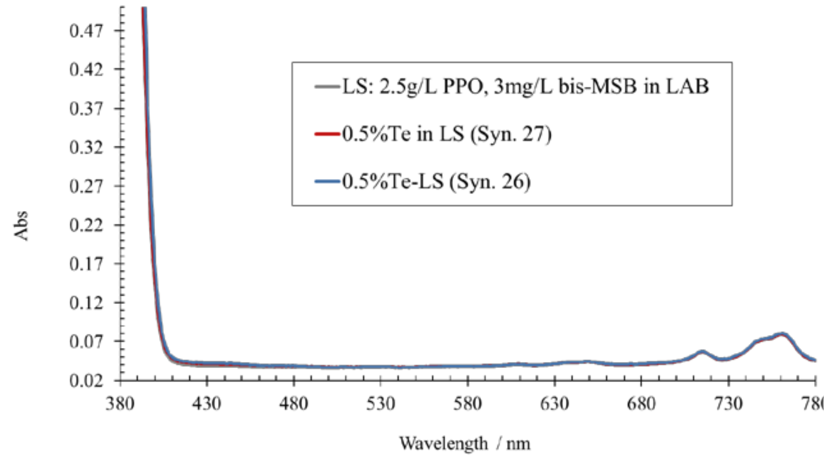


掺碲液闪

- **掺碲（Te）液闪是可行的方案，在国重实验室支持下已开展预研**
  - 研究新的Te-化合物合成方法
  - 实现一步将碲化合物溶入液闪→利于批量生产和纯化
- **目标：**
  - ^{nat}Te质量占比：3%
  - 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
- **研发规划：**
  - <2025年：完成掺碲液闪配方研究
  - <2028年：解决大规模生产工艺、光学纯化、放射性纯化工艺







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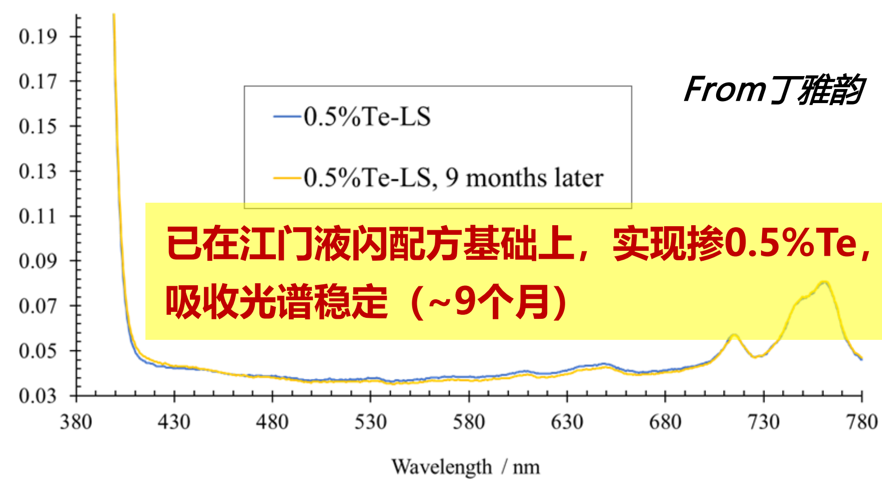

已在江门液闪配方基础上，实现掺0.5%Te，吸收光谱稳定（~9个月）

灵敏度 — 本底、靶质量、分辨率

For a none background-free experiment, use simple counting approach:

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

- Mt: Detector Exposure
- ϵ: Detector efficiency
- η: Isotope abundance
- b: Background in ROI

* For 90% C.L, α=1.64

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

Re-define Background Index (B.I.) and Detector Exposure

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

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

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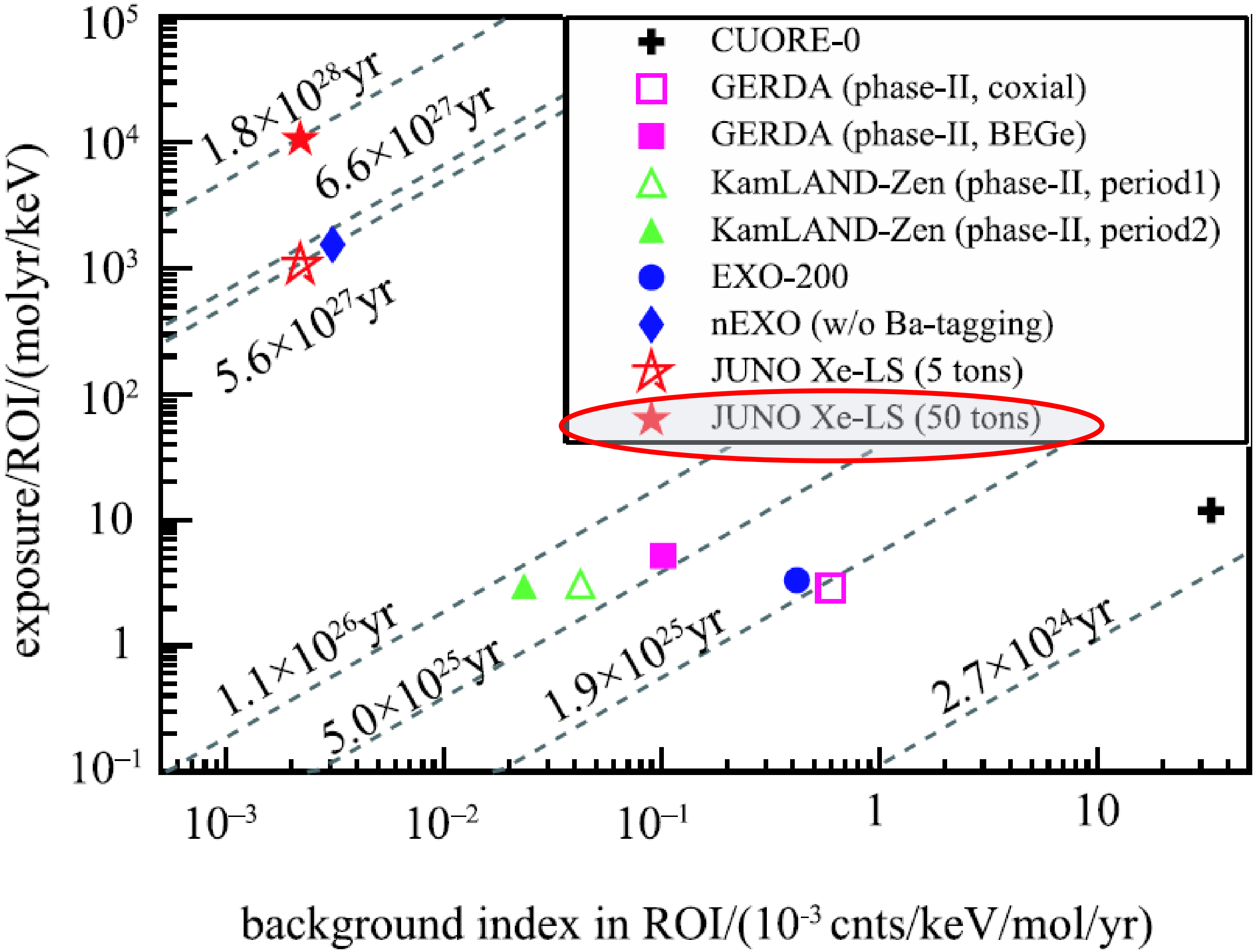
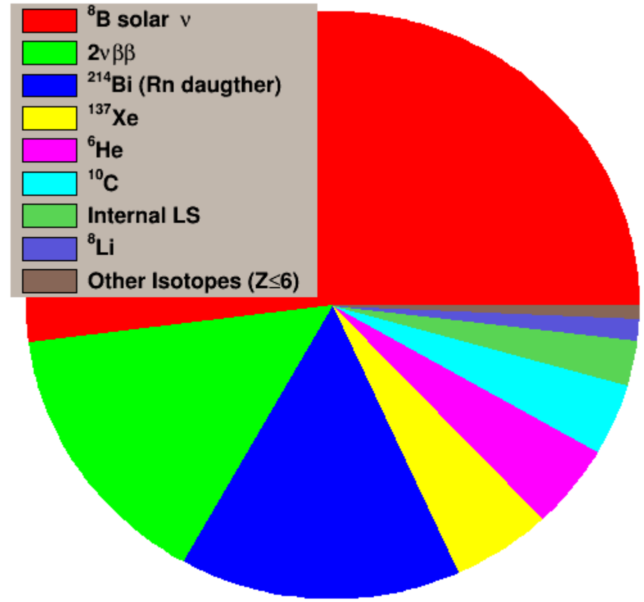


JUNO-ββ

	summary of backgrounds in 0νββ ROI [ROI·(ton ^{136}Xe)·yr]$^{-1}$		与THEIA比较
内禀本底	2νββ	0.2	~ x 2.0 与ROI选择相关
	^{8}B solar ν	0.7	~ x 1.9 THEIA假设50% ^{8}B可被去除
	Reactor $\bar{\nu}_e$-e	0.1	
	cosmogenic background		
宇生本底	^{10}C	0.053	~ x 3.2
	^{6}He	0.063	
	^{8}Li	0.016	
	^{12}B	3.8×10^{-4}	
	others ($Z \leqslant 6$)	0.01	
	^{137}Xe	0.07	
	internal LS radio-purity (10^{-17} g/g)		
放射性本底	^{214}Bi (^{238}U chain)	0.003	~ x 2.2
	^{208}Tl (^{232}Th chain)	—	
	^{212}Bi (^{232}Th chain)	0.03	
	external contamination		
	^{214}Bi (Rn daughter)	0.2	
	total	1.35	

ROI定义为FWHM：效率75.8%



Chin. Phys. C 41 (2017) 053001

2017年以^{136}Xe为例，计算了JUNO寻找0νββ的灵敏度。估算B.I.与THEIA发表结果相当，差别在ROI选择、放射性和宇生本底的去除能力

Background Index (B.I.)

~ 1.35 evts/FWHM/ (ton ^{136}Xe)/ yr

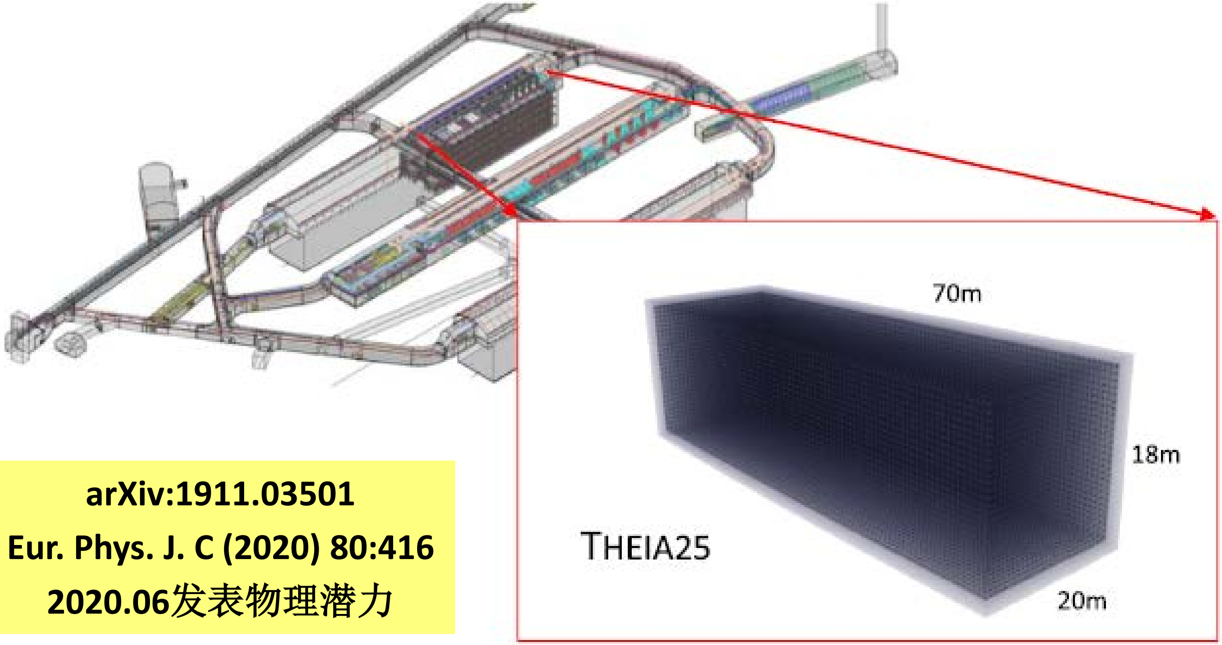
总结

- 液闪技术在0νββ舞台也有强的竞争力
  - 超大质量、极低本底
  - 够用的能量分辨率
- 至2030年，KamLAND/SNO+实验可能将 $T_{1/2}^{0\nu\beta\beta}$ 灵敏度提高至10^{27} 年
- **2030年**，计划将JUNO改造为0νββ实验，用**百吨量级^{130}Te**，将灵敏度再提高>20倍，**$|m_{\beta\beta}|$灵敏度逼近meV**
  - 技术路线明确，且极具挑战
  - 预期2025年左右解决Te-LS关键技术

谢谢！

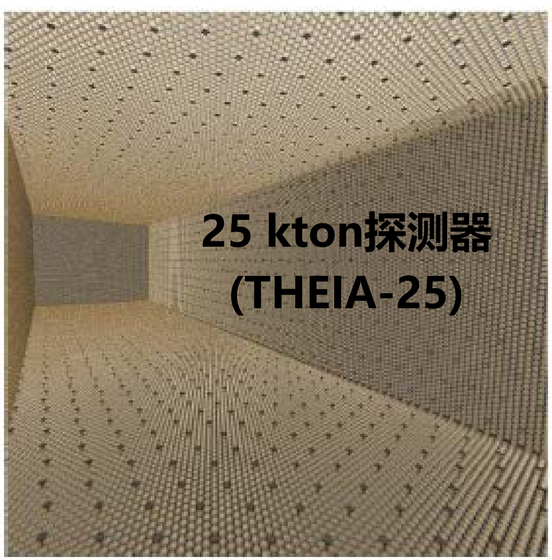
THEIA

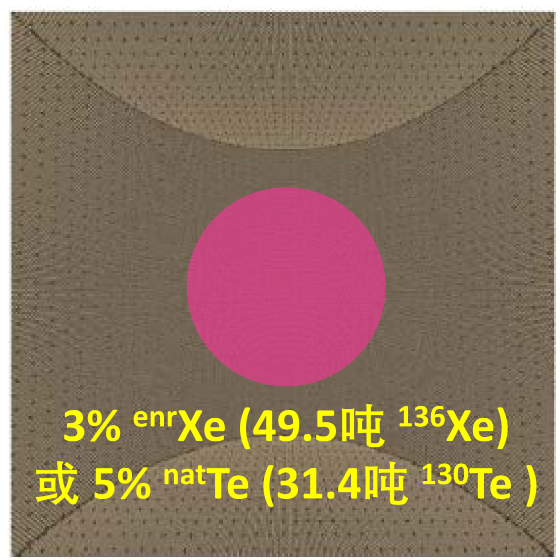
(水基液闪技术)



arXiv:1911.03501
Eur. Phys. J. C (2020) 80:416
2020.06发表物理潜力

为寻找0νββ的探测器配置：
90% PMT覆盖；
能量分辨3%/√E；
R=8m的Balloon, 盛装掺Xe或掺Te液闪；
LS纯度要求与JUNO一致





THEIA

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Table 7 Dominant background sources expected for the NLDBD search in THEIA. The assumed loading is 3% for Xe, for a ^{136}Xe mass of 49.5 t, and 5% for Te, for a ^{130}Te mass of 31.4 t. The events in the ROI/year are given for a fiducial volume of 7 m and an asymmetric energy range around the Q-value of the reaction (see text). A rejection factor of 92.5% is applied to ^{10}C, of 99.9% to ^{214}Bi, of 50% to the balloon backgrounds, and of 50% to the ^{8}B solar neutrinos

Source	Target level	Expected events/year	Events/ROI·year	
			5% ^{nat}Te	3% ^{enr}Xe
^{10}C		500	2.5	2.5
^{8}B neutrinos (flux from [124])		2950	13.8	13.8
^{130}I (Te target)		155 (30 from ^{8}B)	8.3	–
^{136}Cs (^{enr}Xe target)		478 (68 from ^{8}B)	–	0.06
$2\nu\beta\beta$ (Te, $T_{1/2}$ from [125])		1.2×10^{8}	8.0	–
$2\nu\beta\beta$ (^{enr}Xe, $T_{1/2}$ from [126,127])		7.1×10^{7}	–	3.8
Liquid scintillator	^{214}Bi: 10^{-17} g_U/g	7300	0.4	0.4
	^{208}Tl: 10^{-17} g_{Th}/g	870	–	–
Balloon	^{214}Bi: $< 10^{-12}$ g_U/g	$< 2\times10^{5}$	3.0	3.4
	^{208}Tl: $< 10^{-12}$ g_{Th}/g	$< 3\times10^{4}$	0.03	0.02

ROI定义 (-0.5 σ, 2 σ)：
效率66.9%

R=7 m FV cut：
效率67%

Background Index (B.I.)

~ 24 evts/(49.5 ton ^{136}Xe * 67%) =

0.72 evts/ROI/(ton ^{136}Xe)/yr