JUNO-0νββ实验规划

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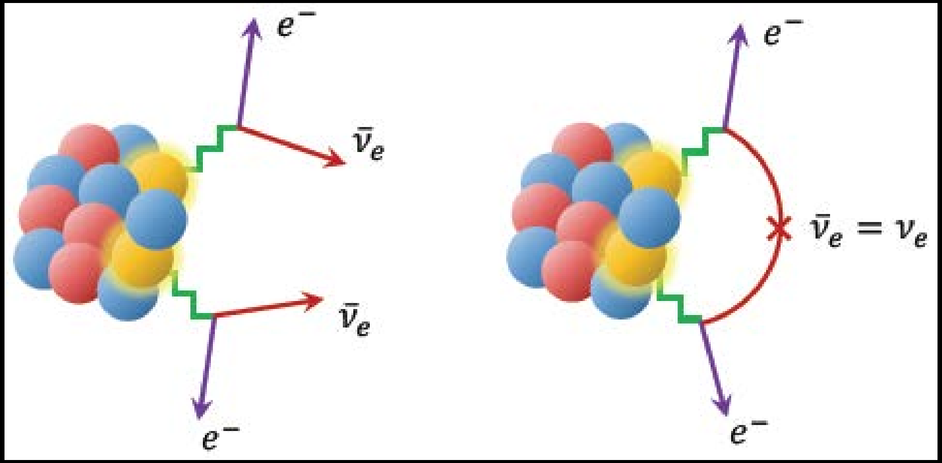
Neutrino-less Double Beta Decay

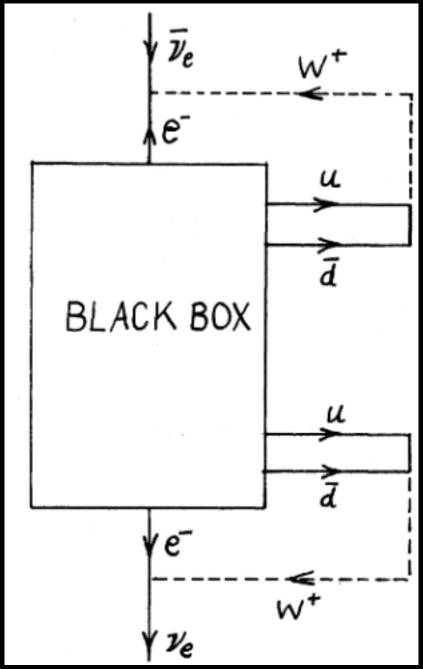
Determining the nature - Dirac or Majorana - of massive neutrinos is one of the most challenging and pressing problems in present day elementary particle physics

Schechter-Valle Theorem (1982) :
if a 0νββ decay happens, there must be an effective Majorana mass term (ν is of Majorana nature)



2νββ

0νββ



0νββ offers the most sensitive and only feasible probe to determine if neutrinos are Majorana neutrinos

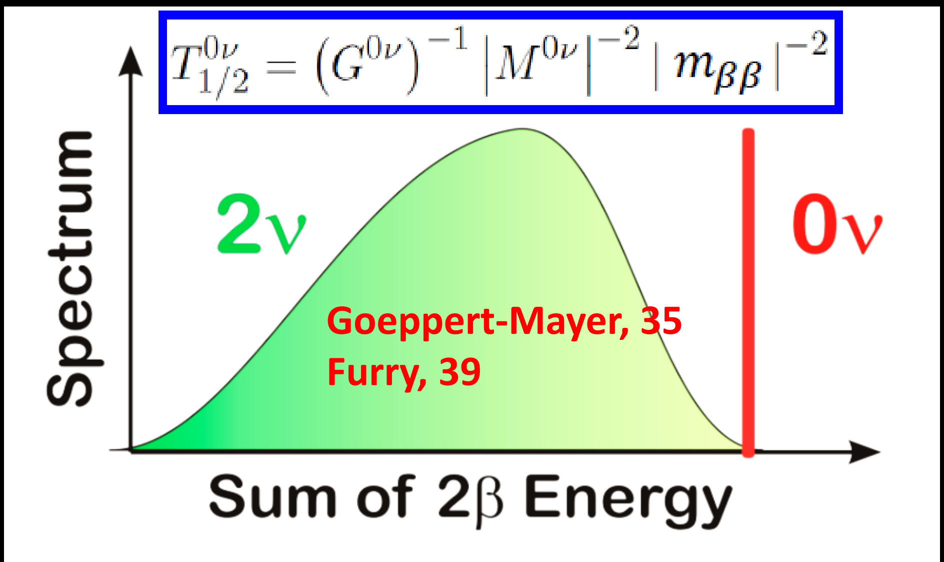
- Discovery of a new type of elementary particles
- Discovery of LNV: a guide for theorists
- MajoranaCP Phases

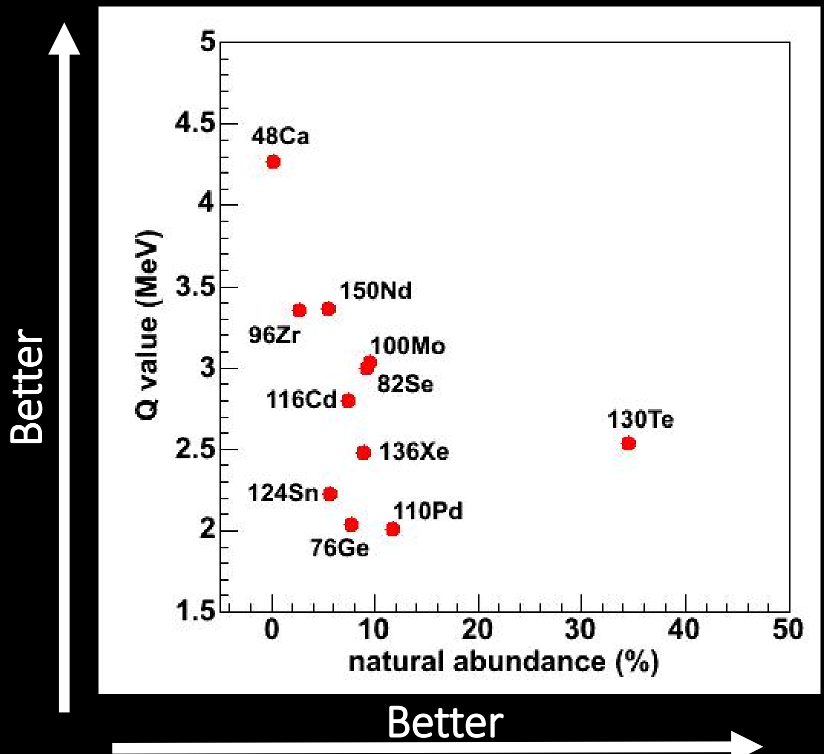
Effective Majorana mass $m_{\beta\beta}$

$$m_{\beta\beta} = m_1|U_{e1}|^2 e^{i\rho} + m_2|U_{e2}|^2 + m_3|U_{e3}|^2 e^{i\sigma}$$

Measure the $0\nu\beta\beta$ decay's lifetime, then convert it into the $|m_{\beta\beta}|$

The nuclear matrix element, $|M^{0\nu}|$, has large uncertainty





Different isotopes correspond to vastly different experimental techniques

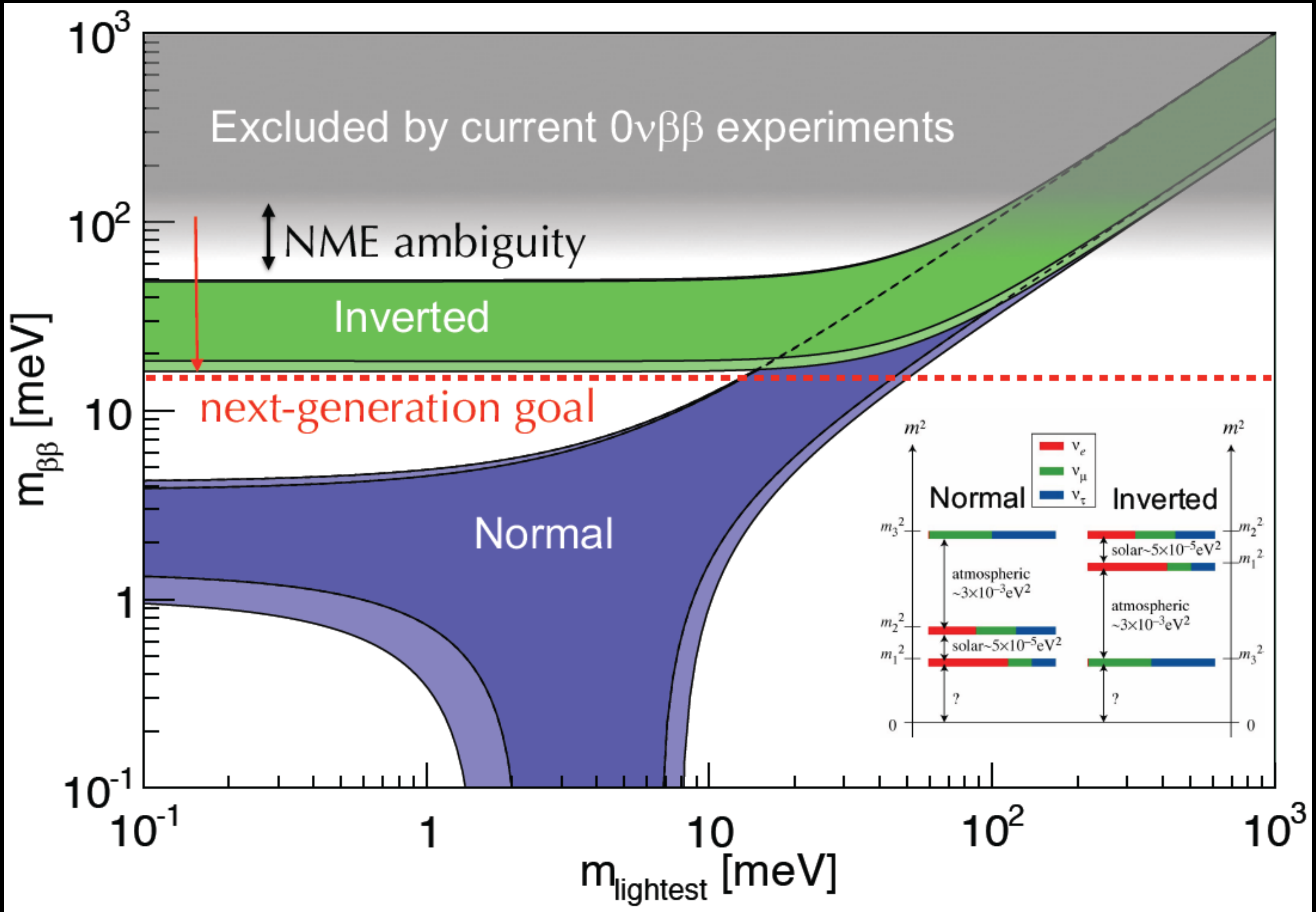
- Ultra-low external background
- Good energy resolution
- Large detector volume

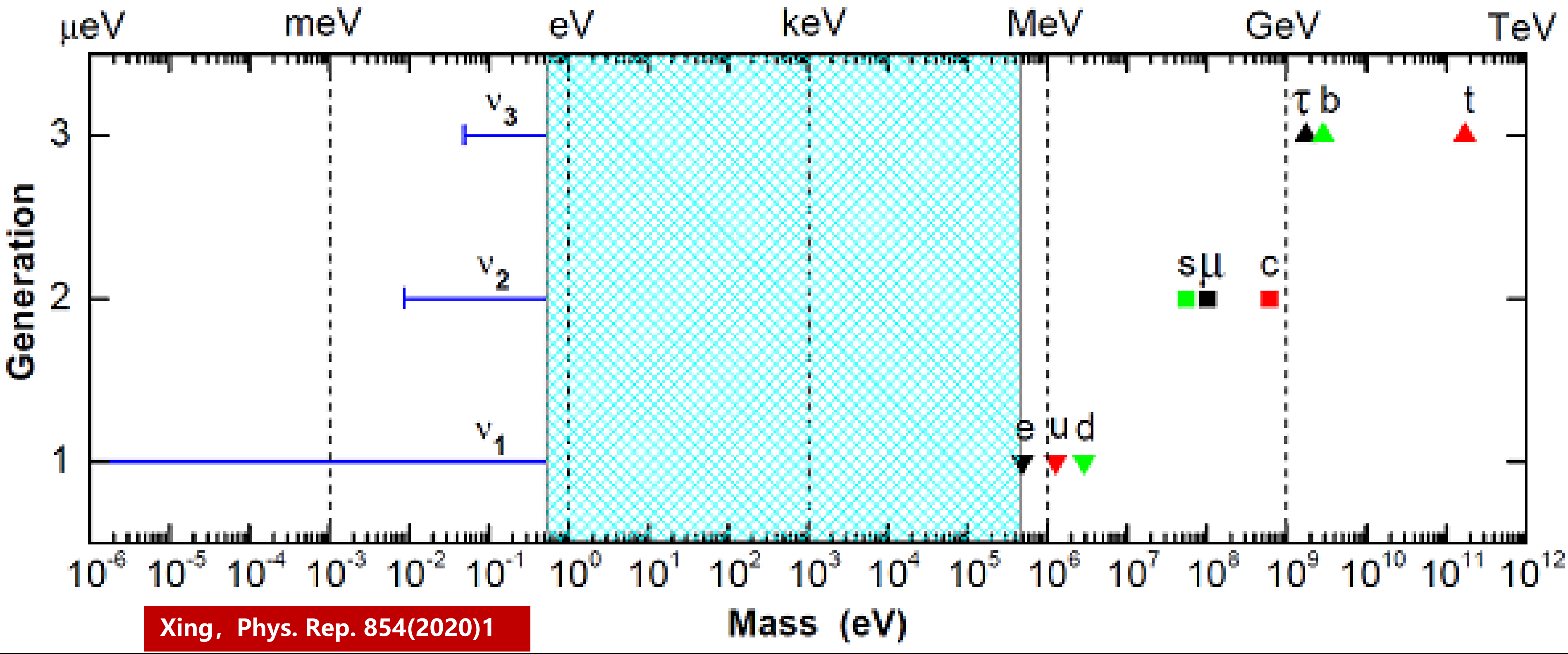
Present best Limits:

- ^{136}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
- ^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
- ^{130}Te (CUORE): $T_{1/2} > 3 \times 10^{25}$ yrs

Future goal:

- ~2 orders of magnitude improvement in $T_{1/2}$
- Covers Inverted ν-mass ordering region
- An aggressive experimental goal





Quark and Lepton Mass Spectra

0νββ is the most sensitive to determine neutrino masses

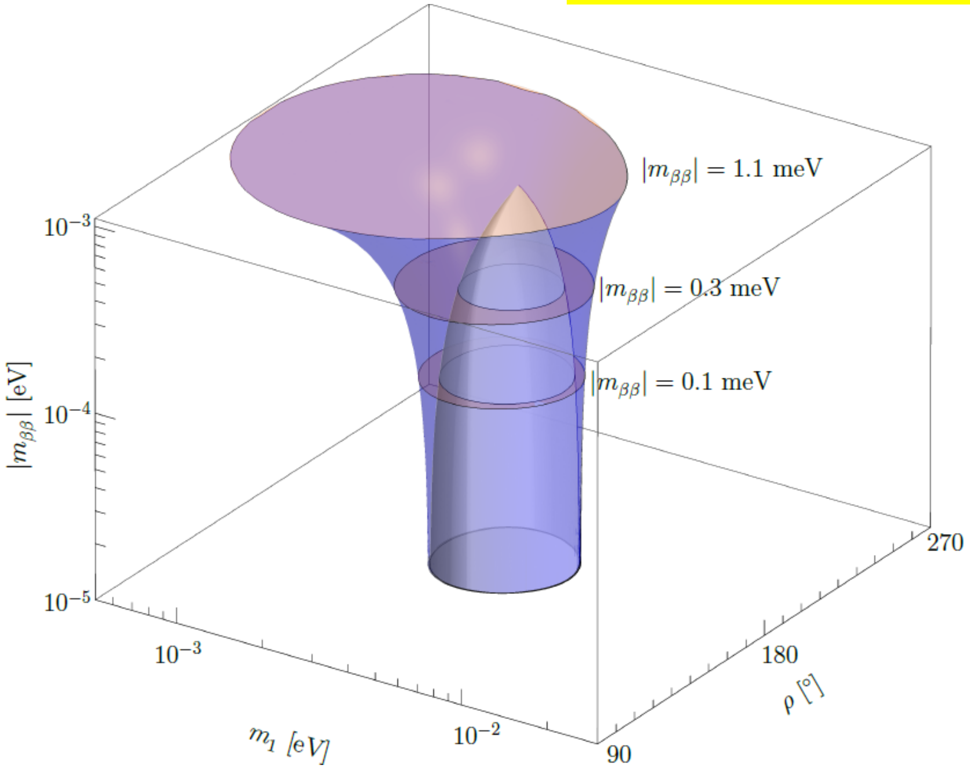
Osci. Expts : Determine ν mass ordering

^{3}H β-decay : $m_\beta \leq 40$ meV **(e.g. Project-8)**

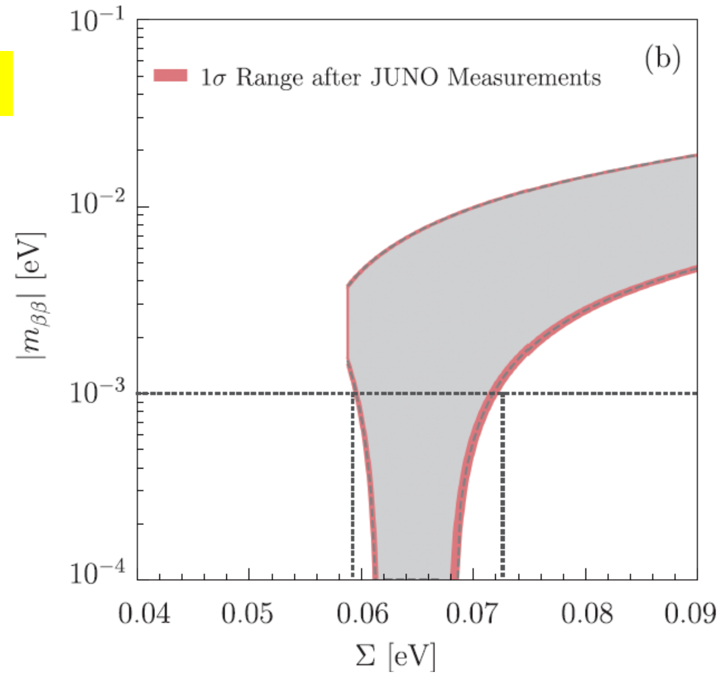
Cosmology : $\Sigma \leq 80$ meV

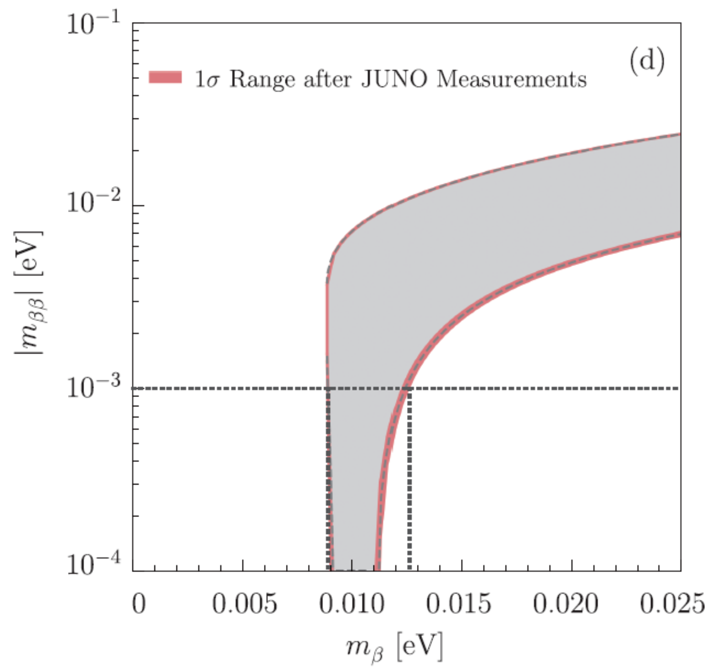
0νββ decay : $|m_{\beta\beta}| \approx 10$ meV **(e.g. nEXO)**

$|m_{\beta\beta}| \approx 1$ meV **(JUNO-ββ)**



Chin. Phys. C 44 (2020) 031001

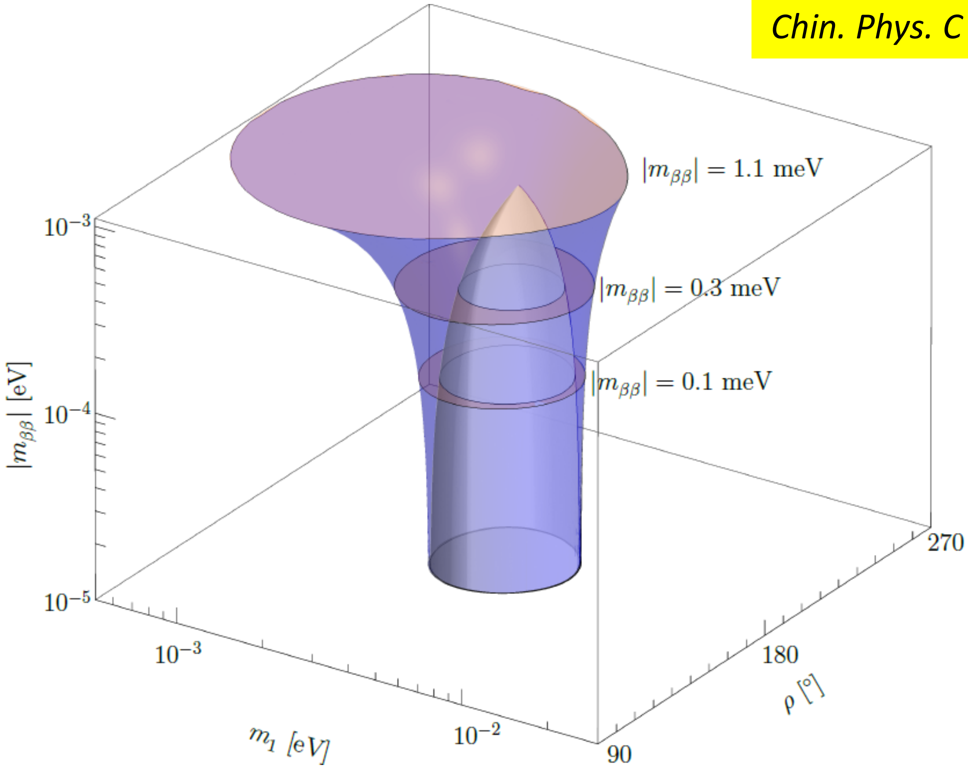


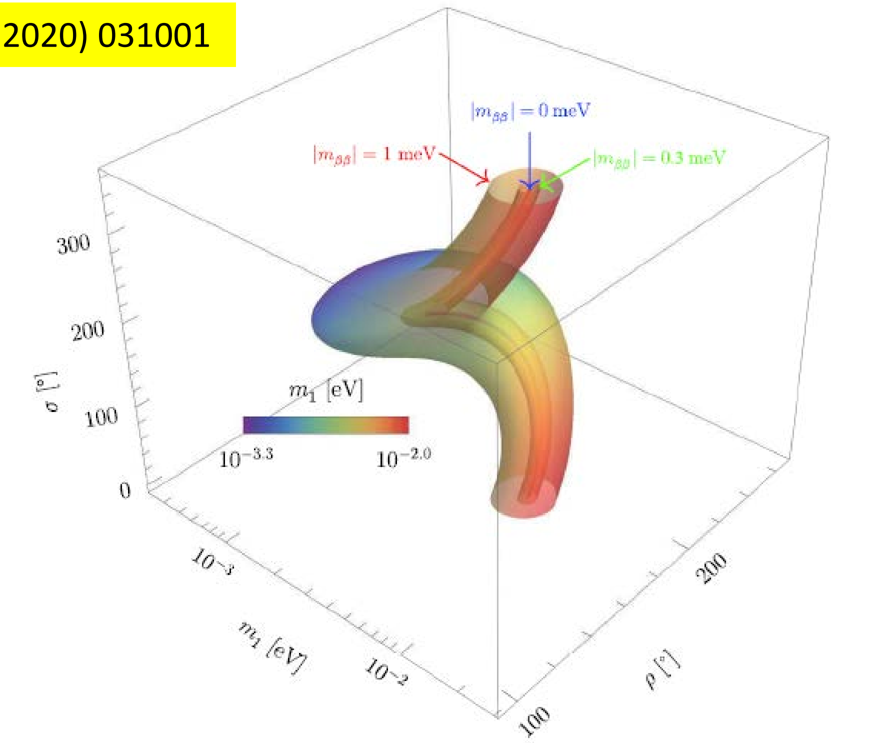


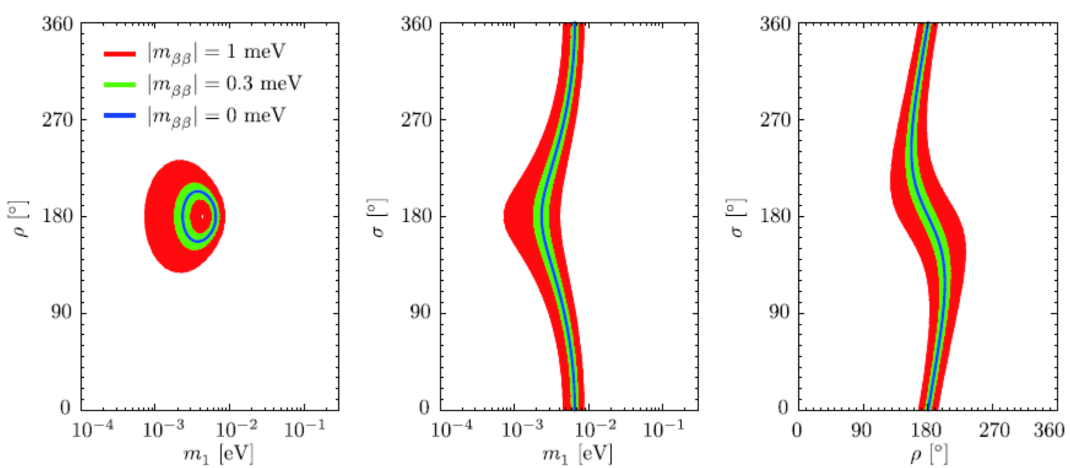
实验上追求 $|m_{\beta\beta}|$~meV的意义

- 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

Chin. Phys. C 44 (2020) 031001







实验上追求 $|m_{\beta\beta}|$~meV的意义

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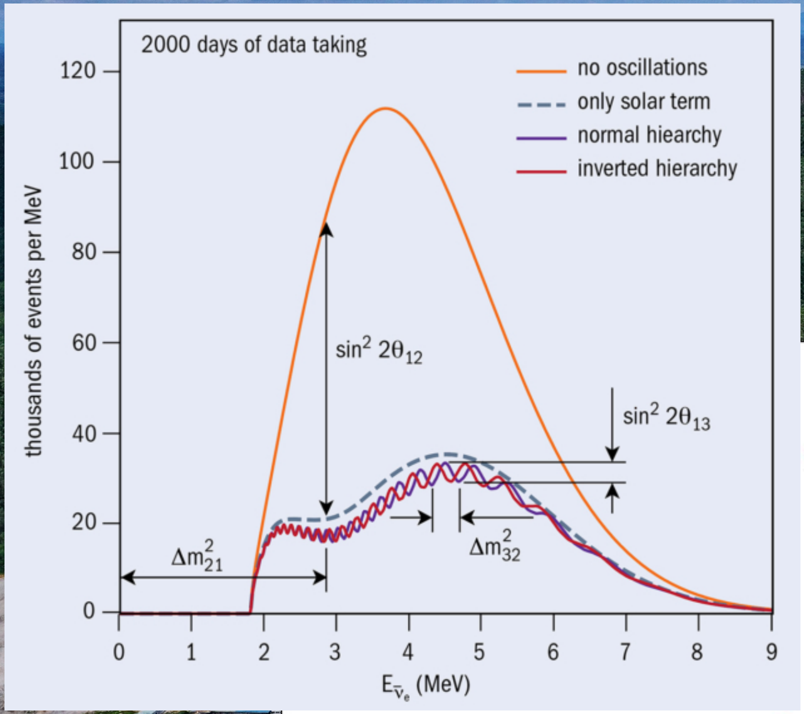
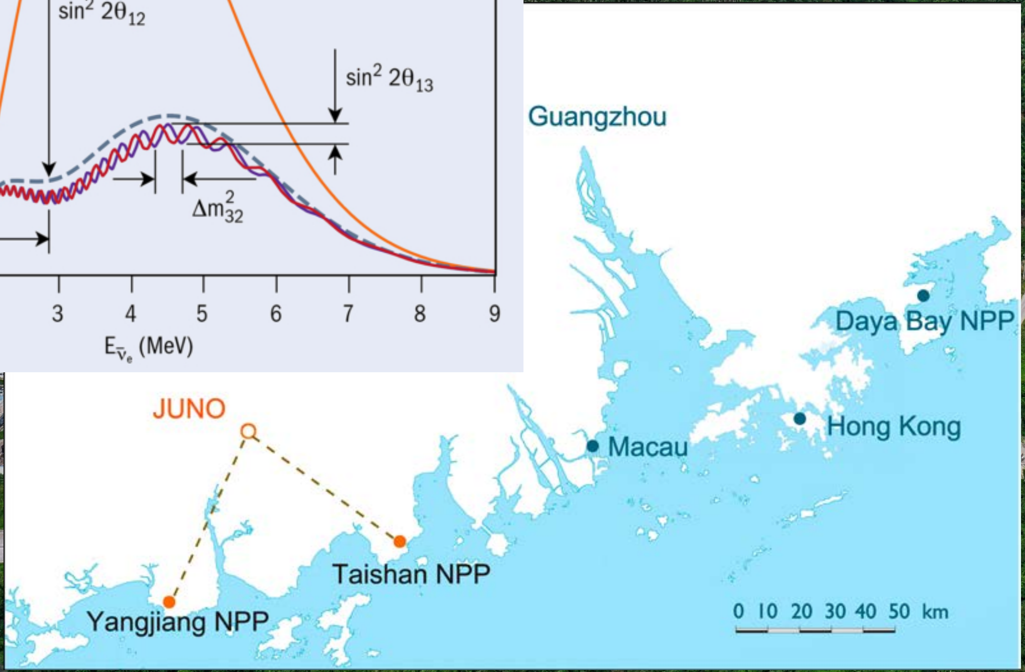
- 有望确定三代中微子质量谱

江门中微子实验



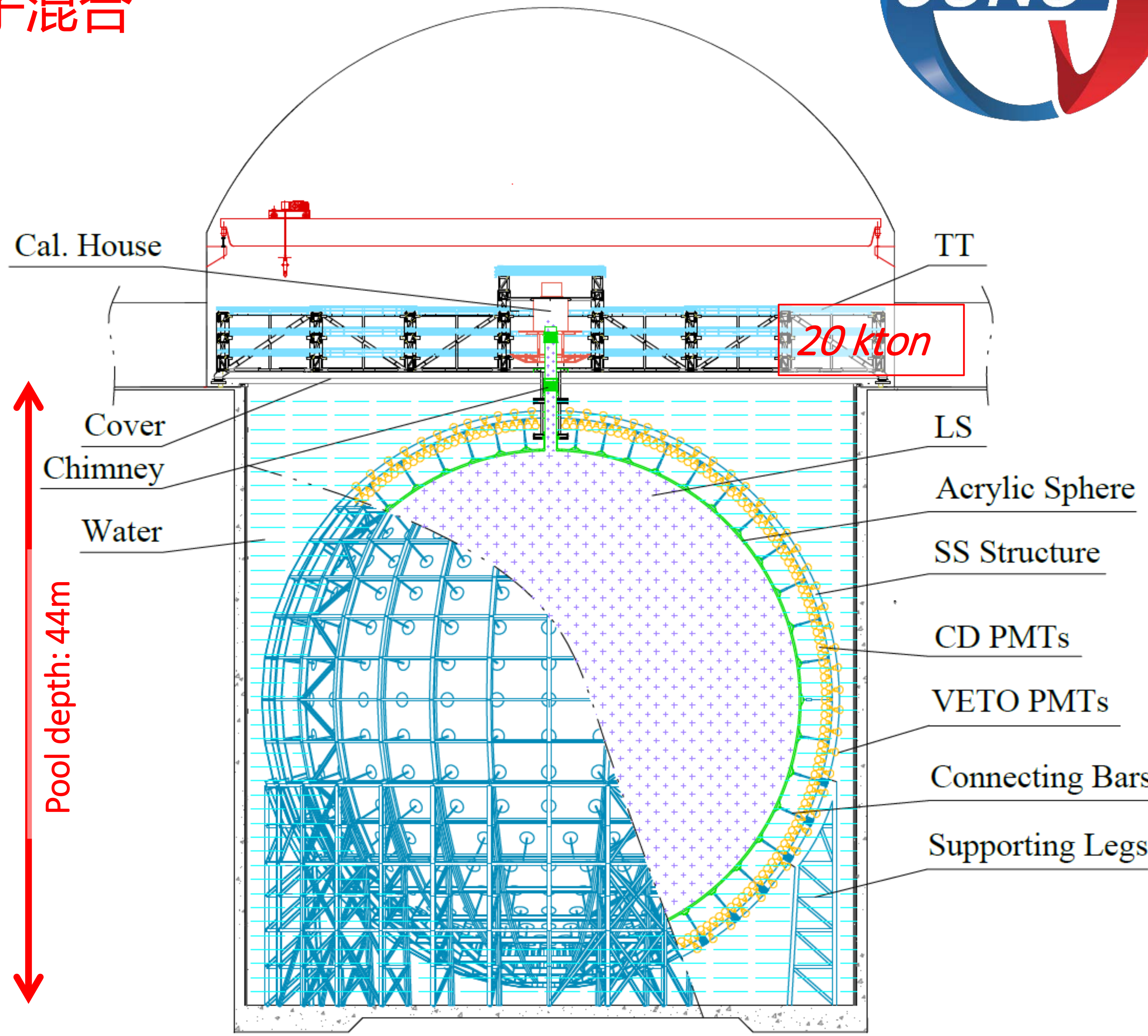
2000 days of data taking
no oscillations
only solar term
normal hiearchy
inverted hierarchy
thousands of events per MeV
$\sin^2 2\theta_{12}$
$\sin^2 2\theta_{13}$
Δm^2_{21}
Δm^2_{32}
0
20
40
60
80
100
120
0 1 2 3 4 5 6 7 8 9
$E_{\bar{\nu}_e}$ (MeV)



Guangzhou
Daya Bay NPP
JUNO
Hong Kong
Macau
Taishan NPP
Yangjiang NPP
0 10 20 30 40 50 km

江门中微子实验

- 中微子质量顺序
- 精确测量中微子混合
- 超新星中微子
- 地球中微子
- 太阳中微子
- 大气中微子
- 核子衰变
- 超预期发现?



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

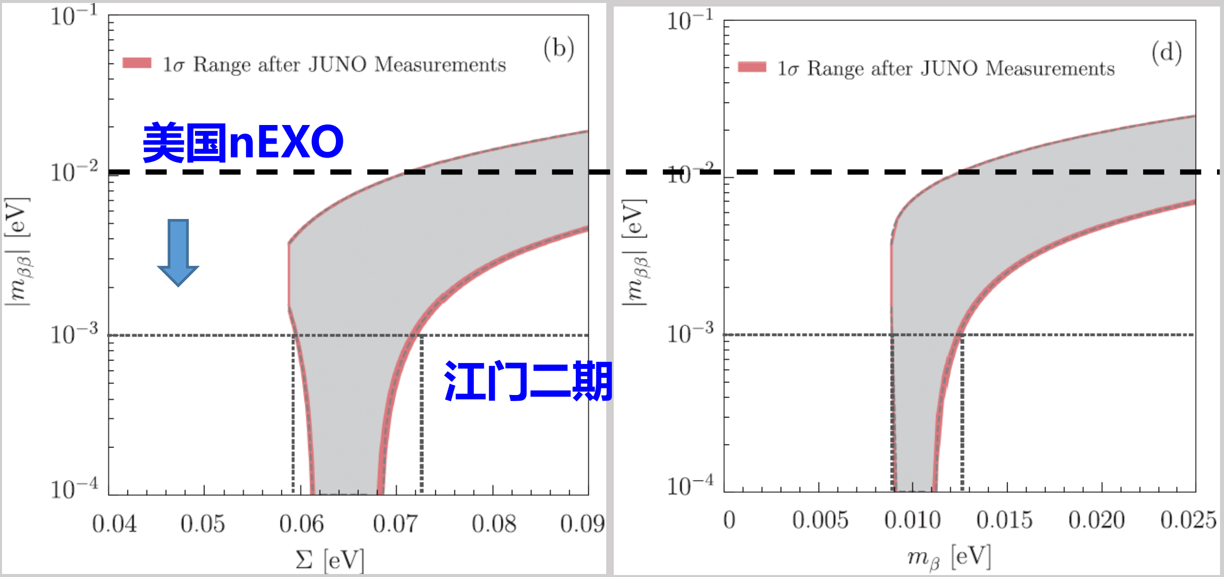
未来实验灵敏度

氚贝塔衰变：$m_\beta \lesssim 40$ meV

宇宙学：$\Sigma \lesssim 80$ 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)



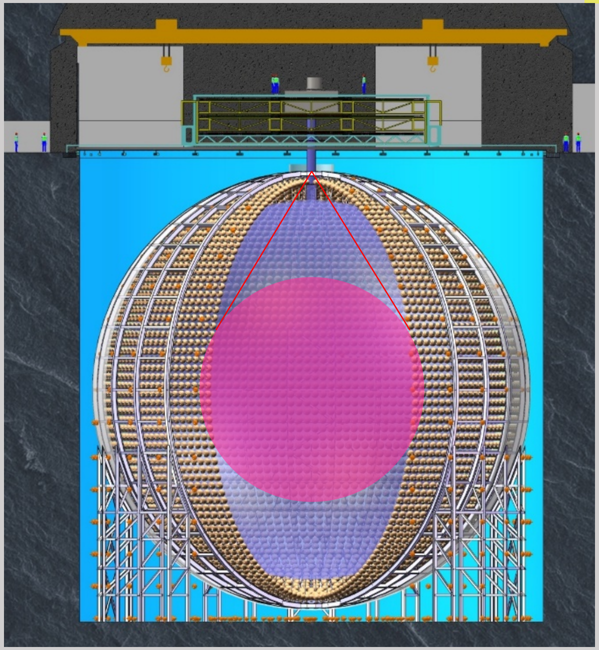
Chin. Phys. C 44 (2020) 031001

JUNO-ββ设想

	核素	质量(吨)	$\langle m_{\beta\beta} \rangle$, meV
KamLAND-Zen	^{136}Xe	1	61-165
EXO	^{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 ?

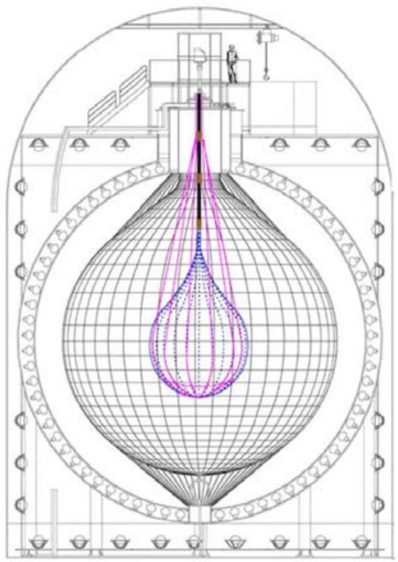
Chin. Phys. C 41 (2017) 053001

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

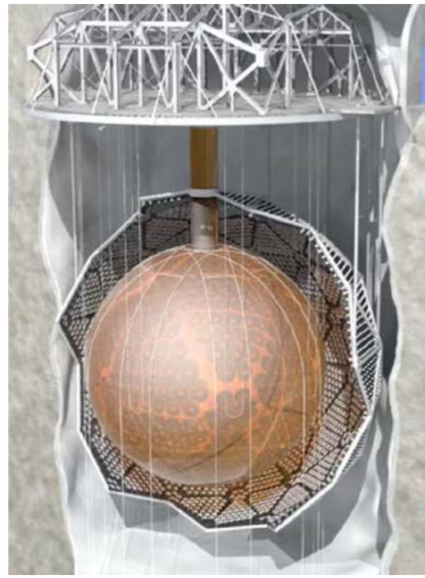
利用大型液闪探测器寻找0νββ



KamLAND-Zen

(~2700 m.w.e)

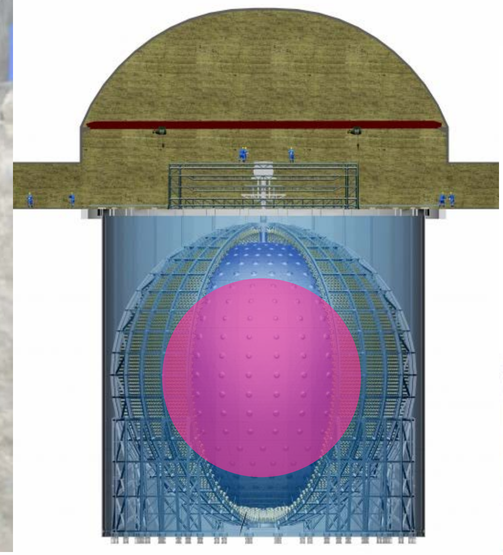
1千吨



SNO+

(~6000 m.w.e)

780吨

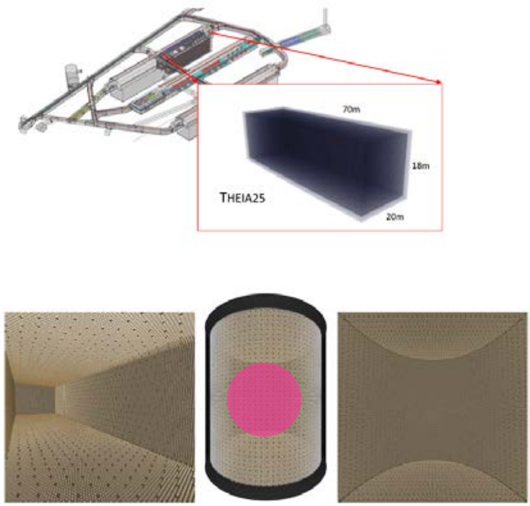


JUNO-ββ

(~1800 m.w.e)

Chin. Phys. C 41 (2017) 053001

2万吨



THEIA

(4300 m.w.e)

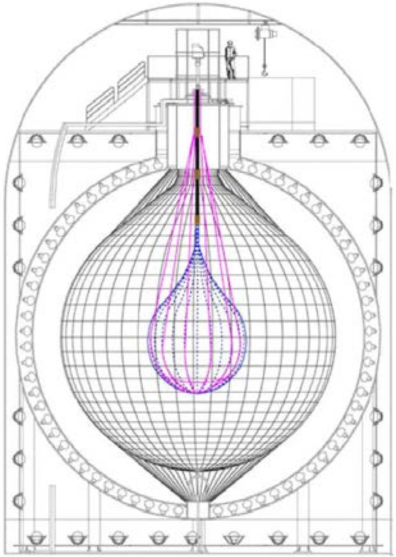
Eur. Phys. J. C (2020) 80:416

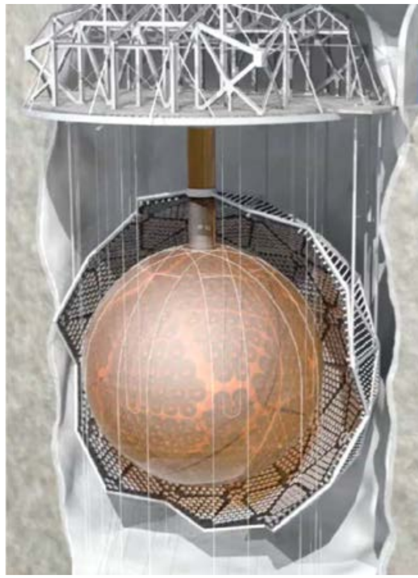
THEIA-25(2.5万吨)
探测器计划部署在
DUNE四个洞室之一;

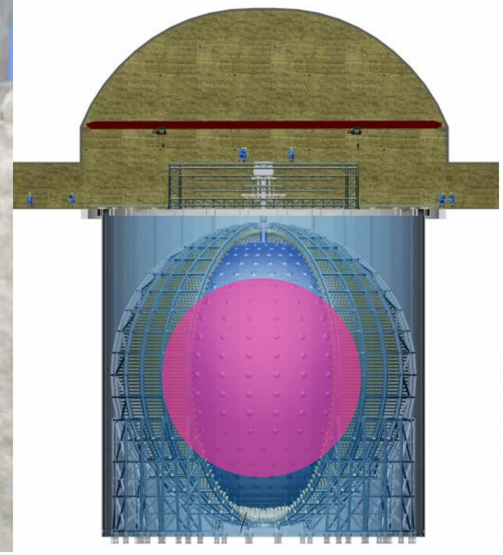
未来计划THEIA-100
(10万吨) 探测器

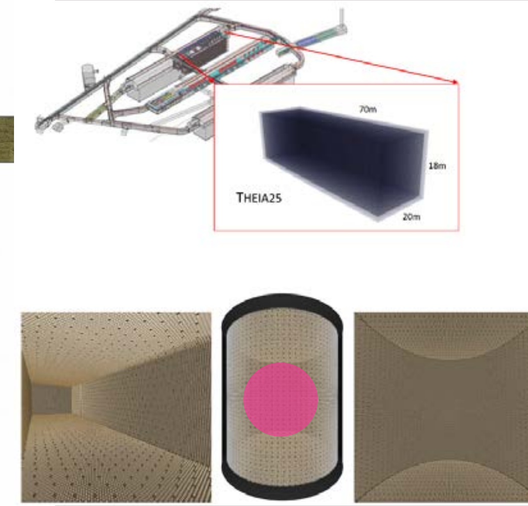
现在

未来









KamLAND-Zen

(~2700 m.w.e)

~3% ^{enr}Xe
(2011 - Today)

SNO+

(~6000 m.w.e)

0.5% ^{nat}Te (2020)
2.5% ^{nat}Te (2026)

JUNO-ββ

(~1800 m.w.e)

Chin. Phys. C 41 (2017) 053001

3% ^{enr}Xe
(~90% in ^{136}Xe)
OR 5% ^{nat}Te

THEIA

(4300 m.w.e)

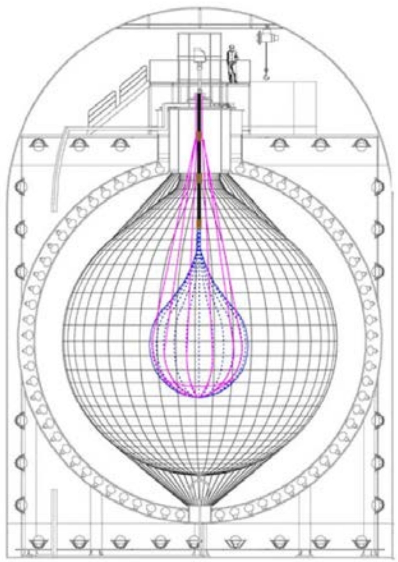
Eur. Phys. J. C (2020) 80:416

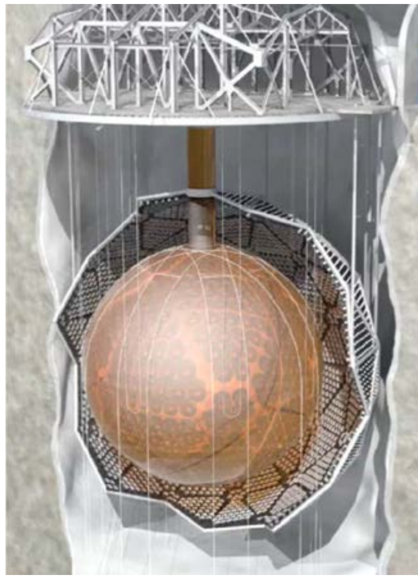
3% ^{enr}Xe
(89.5% in ^{136}Xe)
OR 5% ^{nat}Te

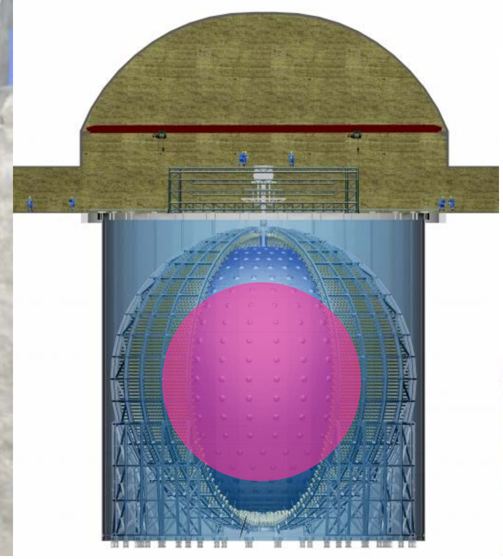
^{nat}Te: natural Tellurium (34.1% in ^{130}Te)
^{enr}Xe: enriched Xenon (~90% in ^{136}Xe，不同实验略有差别)

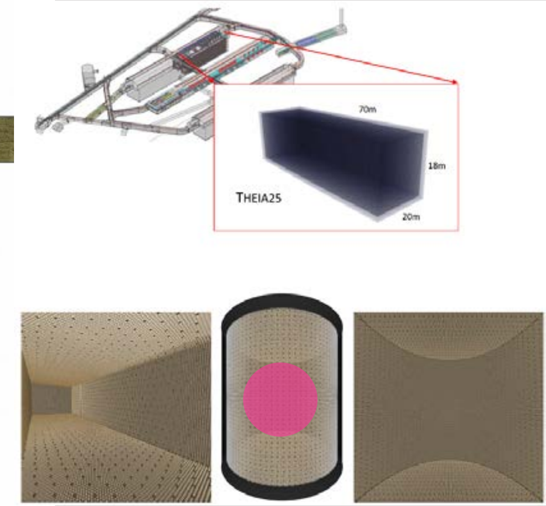
现在

未来









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
(47% full@2020.04)

0.5% loading (3年):
> 2×10^{26} yrs

2.5% loading (4年):
> 1×10^{27} yrs

JUNO-ββ

Chin. Phys. C 41 (2017) 053001

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)

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

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

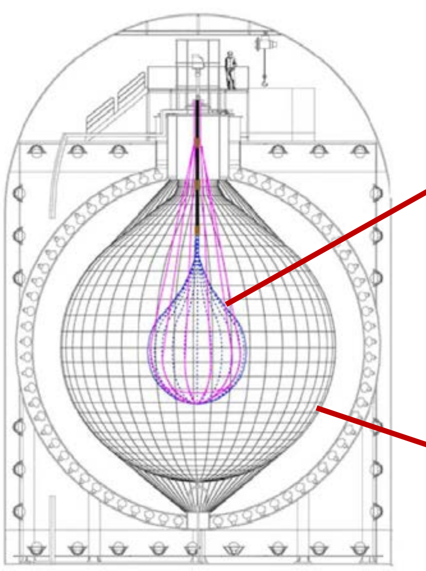
~31.4吨^{130}Te (10年):
> 1.1×10^{28} yrs

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。

尼龙薄膜球极易吸附灰尘。

R=6 m

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。

另一种可能性：全部20kton液闪掺入0νββ核素

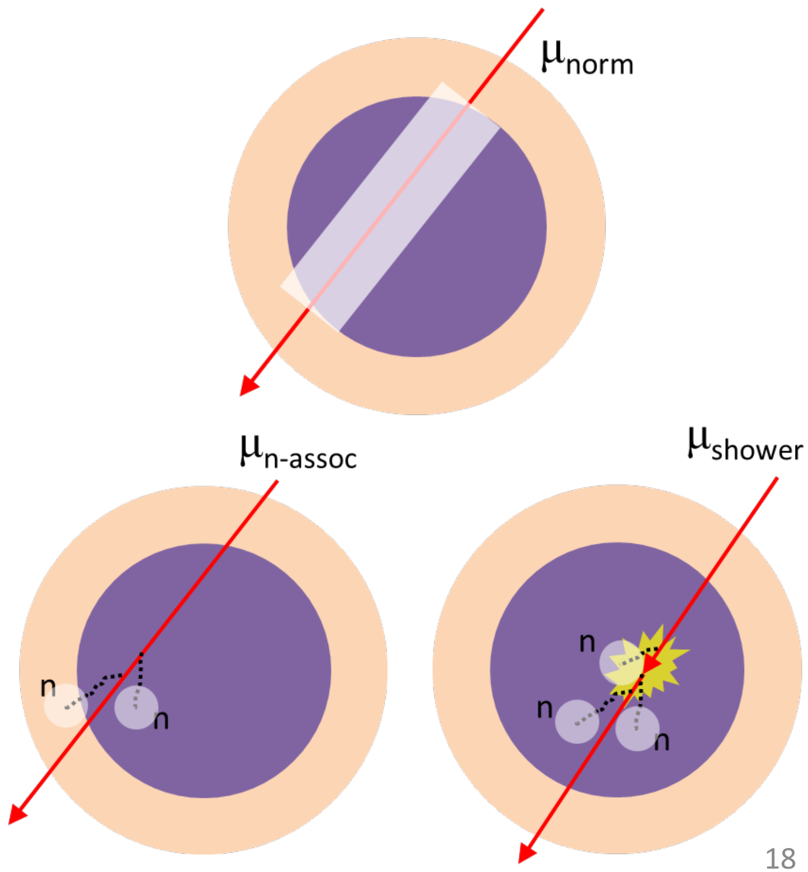
尽管JUNO探测器岩石覆盖 (~700 m) 不如Kamioka、SNOLab，但对宇宙线缪子有很强的Tracking能力，可实现精细的反符合判选去掉宇生本底

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 (β^-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 (β^-n: 51%)	0.178 s	94
^{9}C	15.47 (β^+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 (β^-n: 83%, β^-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 ($\beta^-\gamma$, β^-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 ($\beta^-\gamma$, β^-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 (β^-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 (β^-n: 95%)	4.173 s	0.42
^{18}N	13.896 ($\beta^-\gamma$: 93%), 5.851 (β^-n: 7%)	0.620 s	0.009
Neutron			155 000

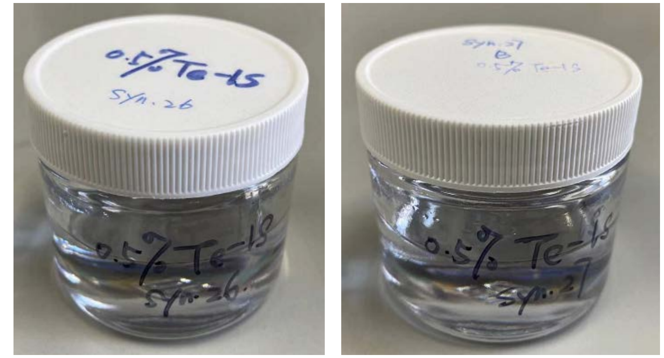
J. Phys. G43:030401 (2016)

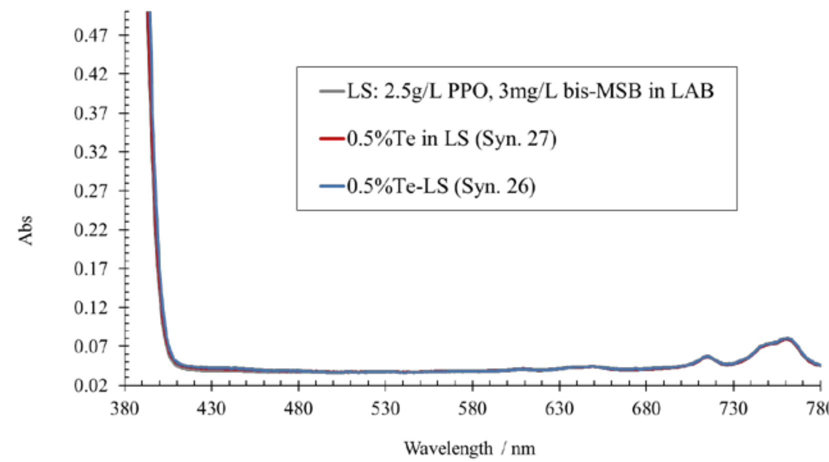
新的muon veto策略，
参见arXiv:2006.11760,
*CPC*45 (2021) 023004
(JUNO太阳中微子)

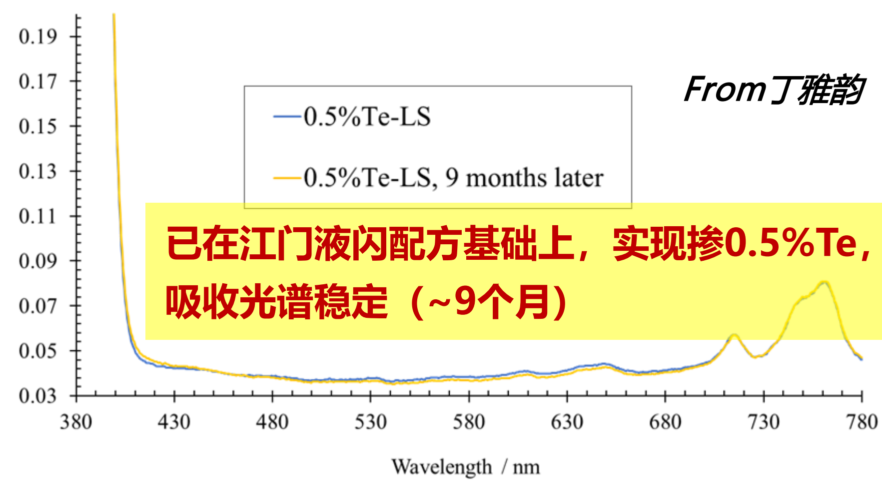


掺碲液闪

- **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







From丁雅韵

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:

Detector Exposure

Detector efficiency

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

Isotope abundance

Background in ROI

* For 90% C.L, α=1.64

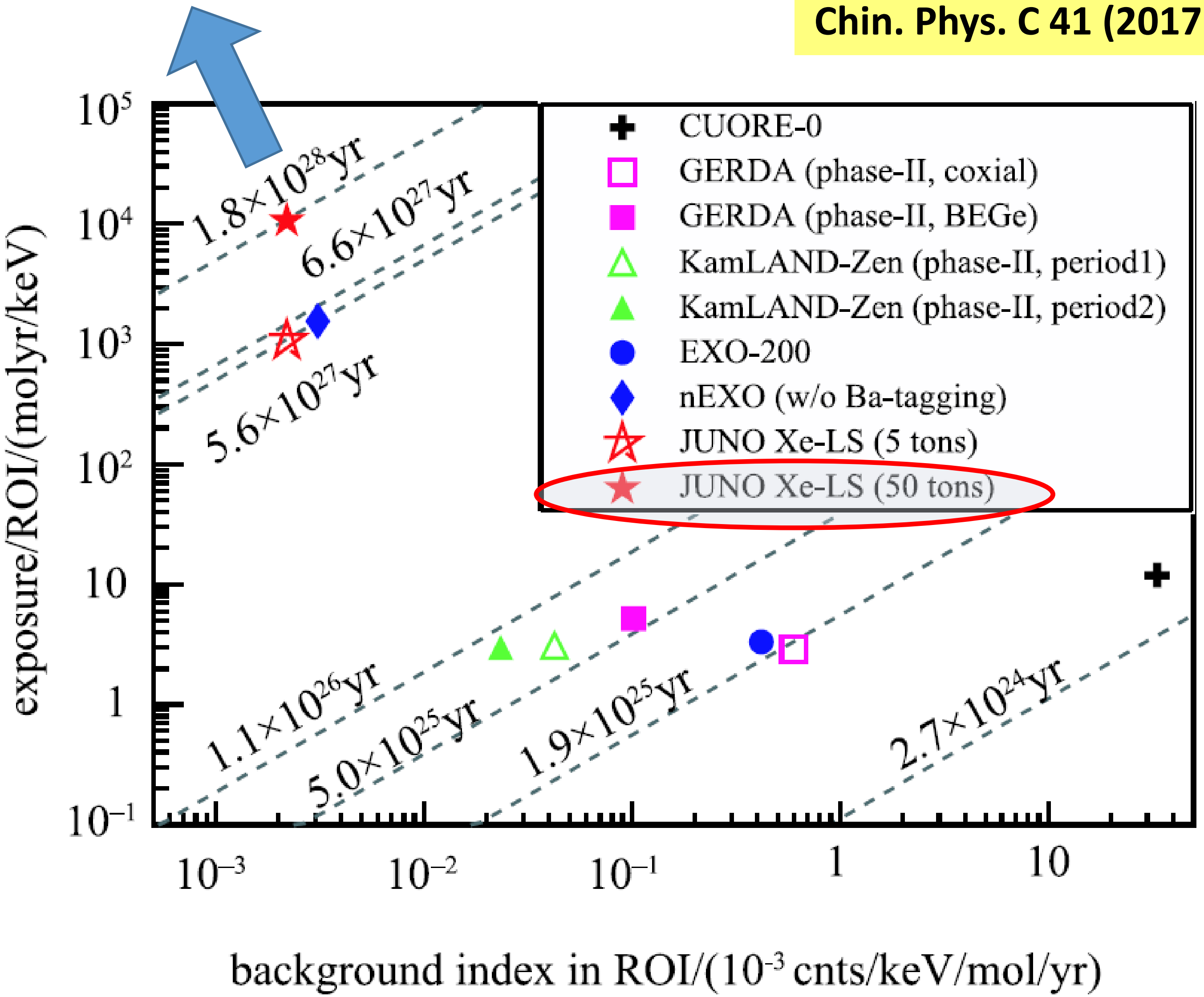
$$\left(\frac{T_{1/2}^{0\nu\beta\beta} \cdot \alpha}{\ln 2 \cdot N_A} \right)^2 = \frac{M_{\rm norm}}{B_{\rm I}}$$

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

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

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

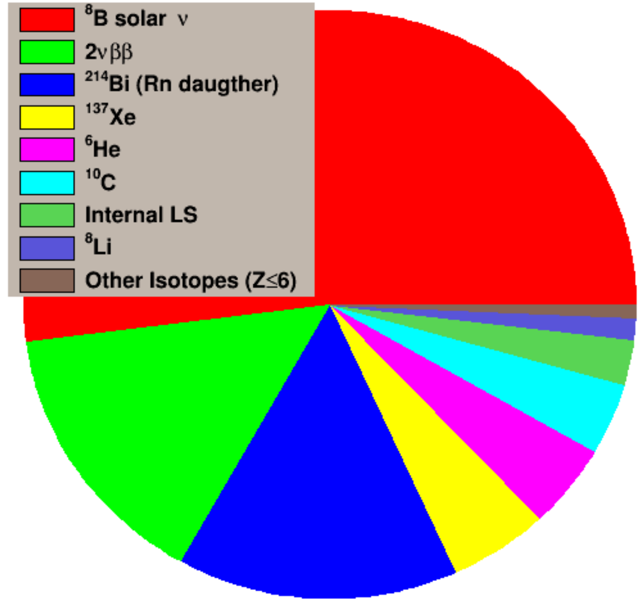
Chin. Phys. C 41 (2017) 053001



JUNO-ββ BKG Calc.

	summary of backgrounds in 0νββ ROI $[\mathrm{ROI}\cdot(\mathrm{ton}\ ^{136}\mathrm{Xe})\cdot\mathrm{yr}]^{-1}$		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 ($Z\leqslant6$)	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%



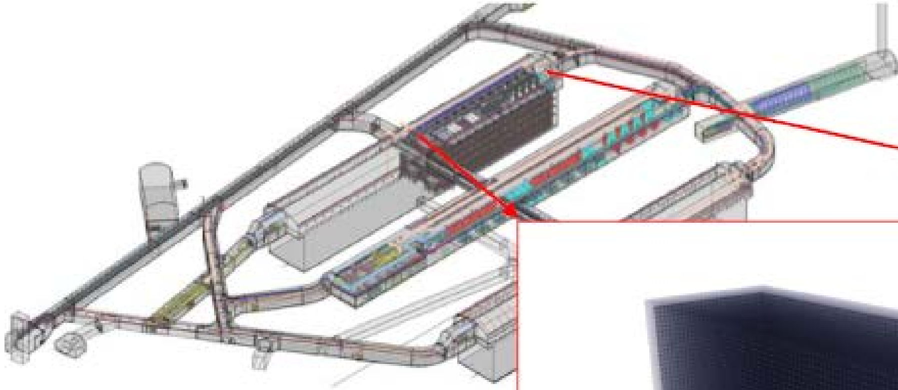
Chin. Phys. C 41 (2017) 053001

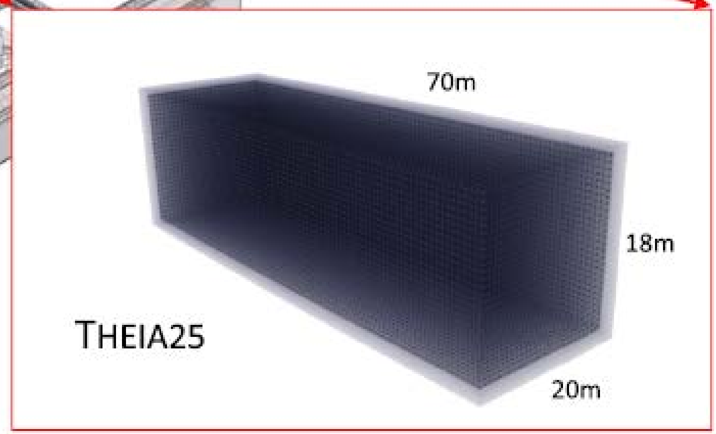
2017年以^{136}Xe为例，计算了JUNO寻找0νββ的灵敏度。

将系统计算掺碲液闪的本底，如Te的宇生本底；研究本底鉴别的新方法。

THEIA

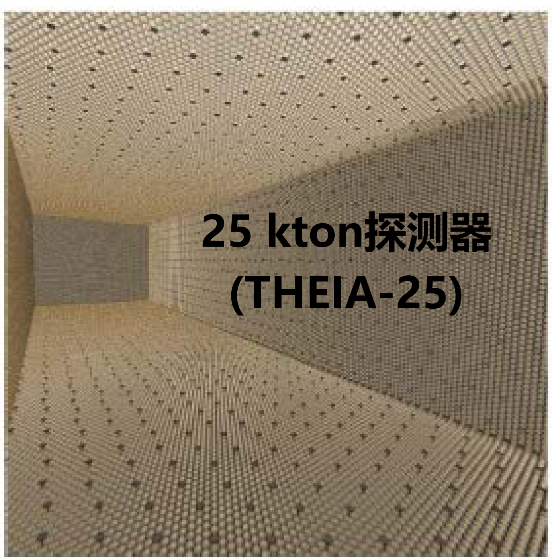
(水基液闪技术)

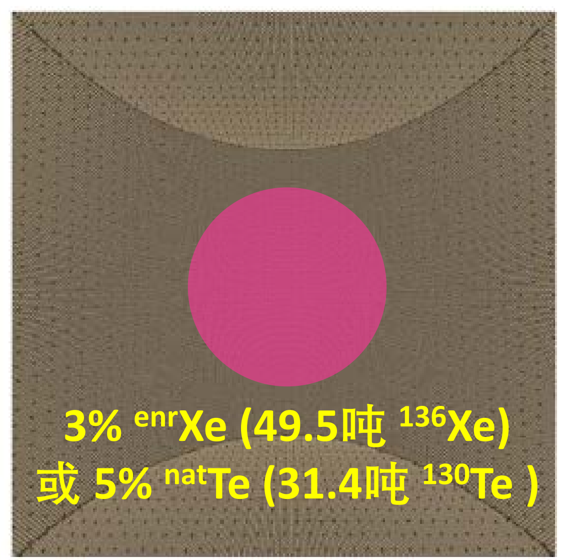




arXiv:1911.03501
Eur. Phys. J. C (2020) 80:416
2020.06发表物理潜力

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





总结

- **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！

KamLAND-Zen

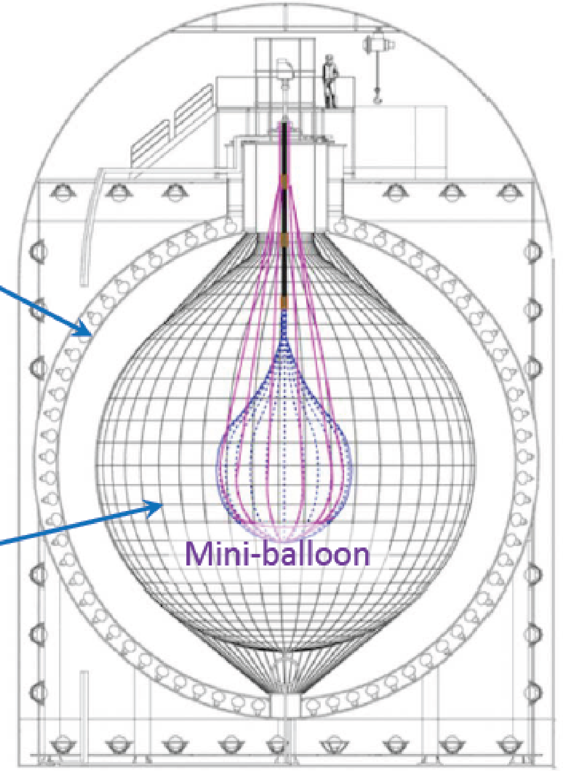
Mini-balloon:

- 25-μm-thick nylon film (durable)
- Fabricated in class-1 clean room
- Highly transparent (~99% at 400 nm)

Xenon loading:

- Chemically stable (noble gas)
- Good solubility (3.2% wt in LS)
- Removable from LS
- Purification is well-established

Located in Kamioka Mine at 2700 m.w.e.



91% enriched ^{136}Xe loaded in LS inside mini-balloon (Q value = 2.4578 MeV)

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Period	Concentration	Reduction (after / before)
Before 1st Purification	$(2.2 \pm 0.3) \times 10^{-18}$ g/g	-
After 1st Purification	$(2.2 \pm 0.5) \times 10^{-18}$ g/g	1.0 ± 0.3
After 2nd Purification	$(1.5 \pm 1.8) \times 10^{-19}$ g/g	15 ± 18

Table 7.5: Summary of ^{238}U concentration

Period	Concentration	Reduction (after / before)
Before 1st Purification	$(4.8 \pm 0.3) \times 10^{-17}$ g/g	-
After 1st Purification (top)	$(4.4 \pm 4.4) \times 10^{-18}$ g/g	10.9 ± 10.9
After 1st Purification (low)	$(2.2 \pm 0.2) \times 10^{-17}$ g/g	2.2 ± 0.2
After 2nd Purification	$(1.9 \pm 0.2) \times 10^{-17}$ g/g	2.5 ± 0.3

Table 7.8: Summary of ^{232}Th concentration

Period	Concentration	Reduction (after / before)
Before 1st Purification	$(2.2 \pm 0.2) \times 10^{-16}$ g/g	-
After 1st Purification	$(7.9 \pm 1.0) \times 10^{-17}$ g/g	2.8 ± 0.4
After 2nd Purification	$< 4.5 \times 10^{-18}$ g/g (90% C.L.)	> 49

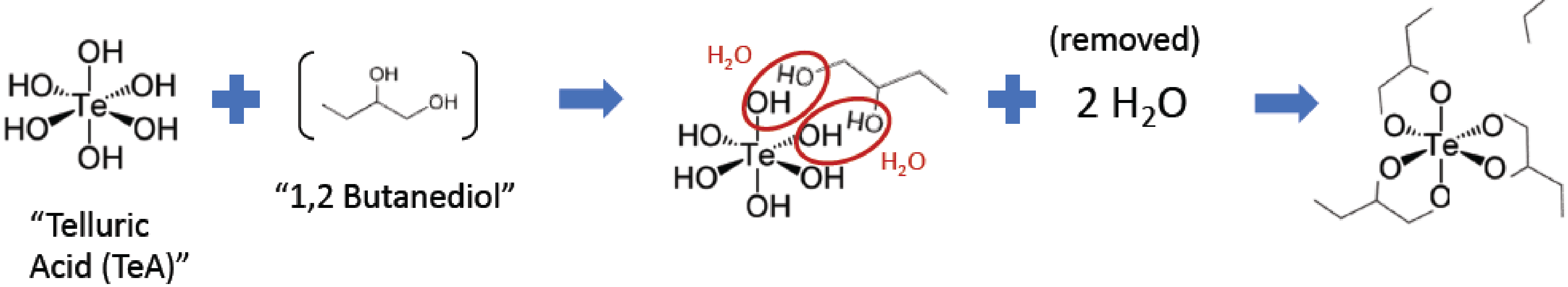
Table 7.9: Summary of ^{40}K concentration

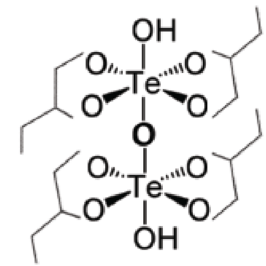
Kyohei Nakajima博士论文

^{130}Te Loading in Liquid Scintillator

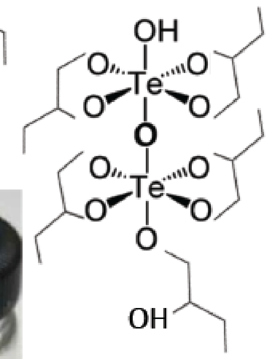
^{130}Te makes up 34% of the natural Te abundance (Q value = 2.5275 MeV)

Forming an organometallic compound from telluric acid and butanediol:

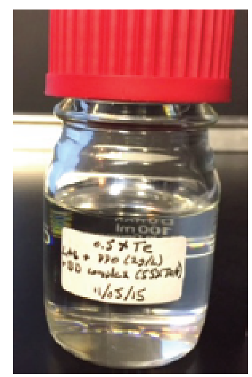


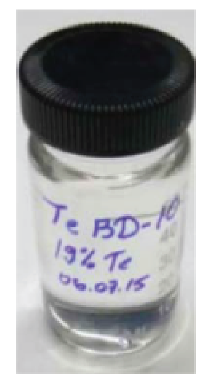


"TeDiol"



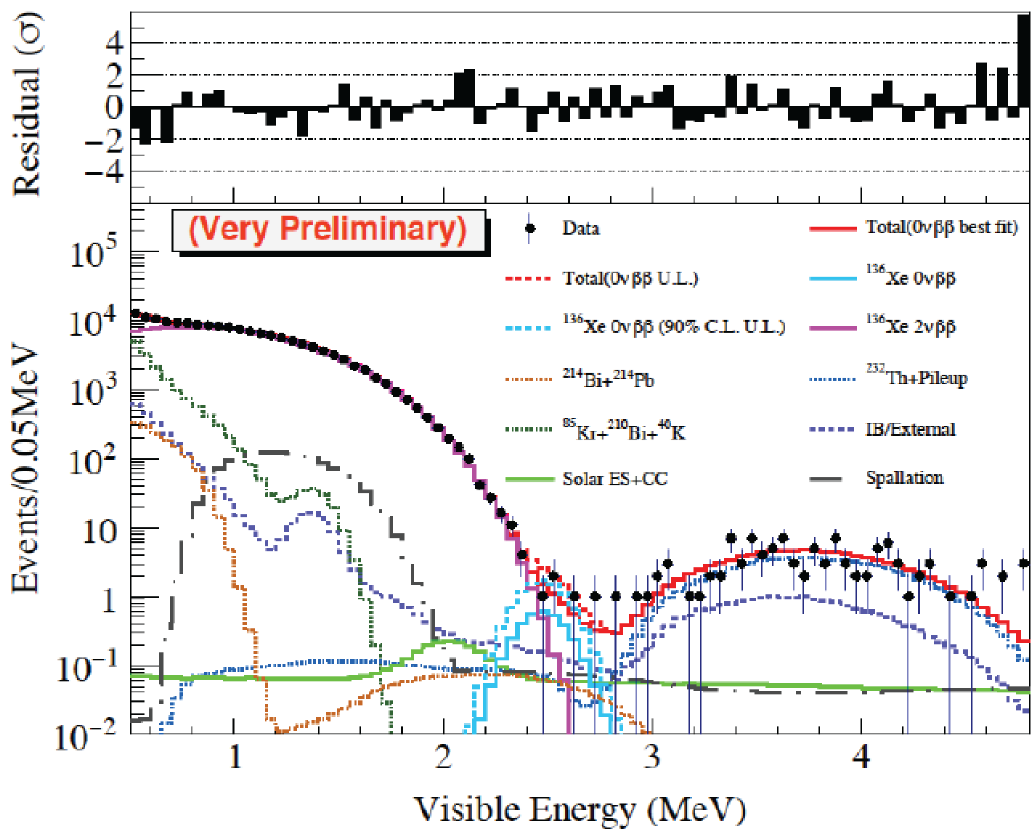
- TeDiol (TeBD) is mixed directly into SNO+ LS with 15 mg/L bis-MSB and a stabilizer called Dimethyldodecylamine (DDA)
- Optical transparency and light yield of the final Te-loaded LS cocktail are expected to produce ~ 460 p.e. / MeV in SNO+ for 0.5% ^{nat}Te loading by weight





Frequentist Fitting Results

*Data shown for r < 1.57 m



Summary for 246.1 kg-year of ^{136}Xe exposure

8 events observed in the ROI

$0\nu\beta\beta$ decay best-fit value:

2.8 events

Total ROI background best-fit value:

7.9 events

90% C.L. upper limit:

$T^{0\nu}_{1/2} > 4 \times 10^{25}$ years

Median Sensitivity

$T^{0\nu}_{1/2} > 8 \times 10^{25}$ years

Very Preliminary

KamLAND-Zen

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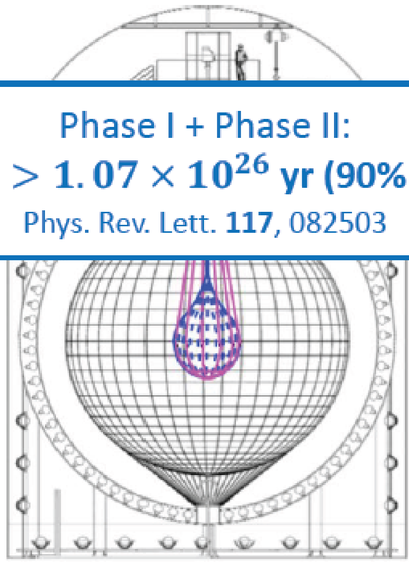
Evolution of KamLAND-Zen

"Future Neutrinoless Double Beta Decay Experiments"
Jason Detwiler (next Session)

Past

Phase I + Phase II:
$T_{1/2} > 1.07 \times 10^{26}$ yr (90% C.L.)
Phys. Rev. Lett. **117**, 082503



KamLAND-Zen 400

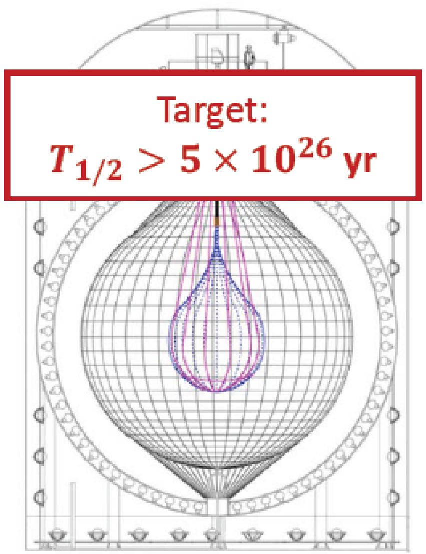
Mini-balloon Radius = 1.54 m

Xenon mass = 320 ~ 380 kg

2011 ~ 2015

Current

Target:
$T_{1/2} > 5 \times 10^{26}$ yr



KamLAND-Zen 800

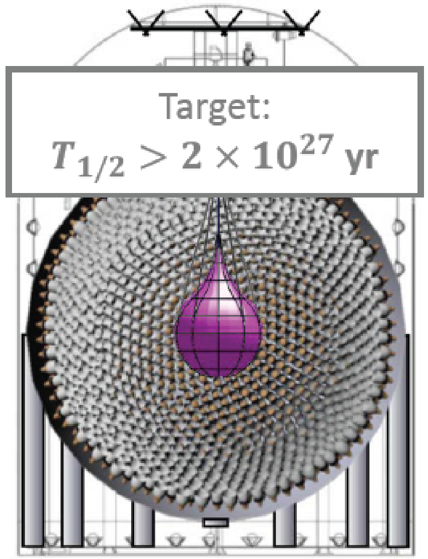
Mini-balloon Radius = 1.90 m

Xenon mass = 745 kg

Started January 2019

Future

Target:
$T_{1/2} > 2 \times 10^{27}$ yr



KamLAND2-Zen

Xenon mass ~ 1 ton

× 5 increase in light collection

Scintillation balloon film

KamLAND-Zen

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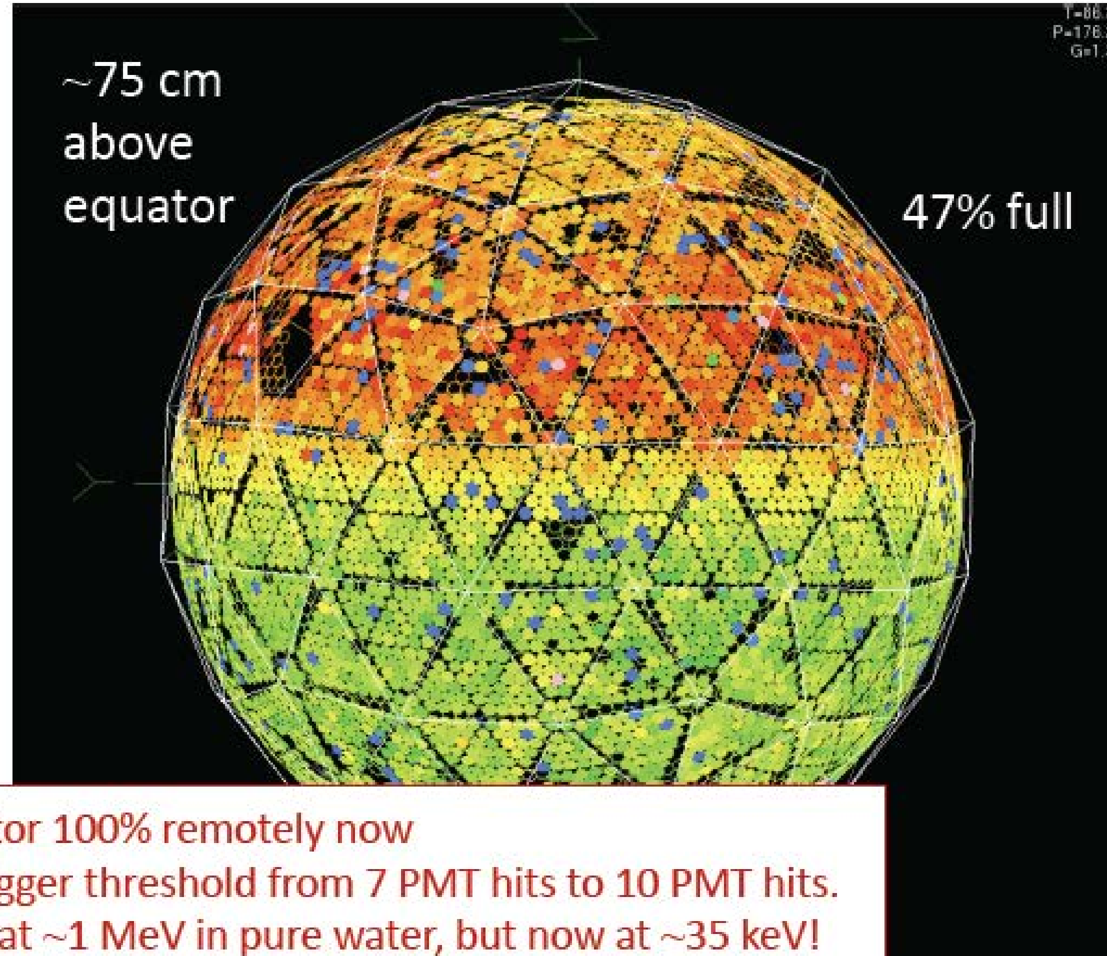
Nearly half-filled with LS since April 2020



- Operating the detector 100% remotely now
- Only changed the trigger threshold from 7 PMT hits to 10 PMT hits. Previously triggered at ~1 MeV in pure water, but now at ~35 keV!

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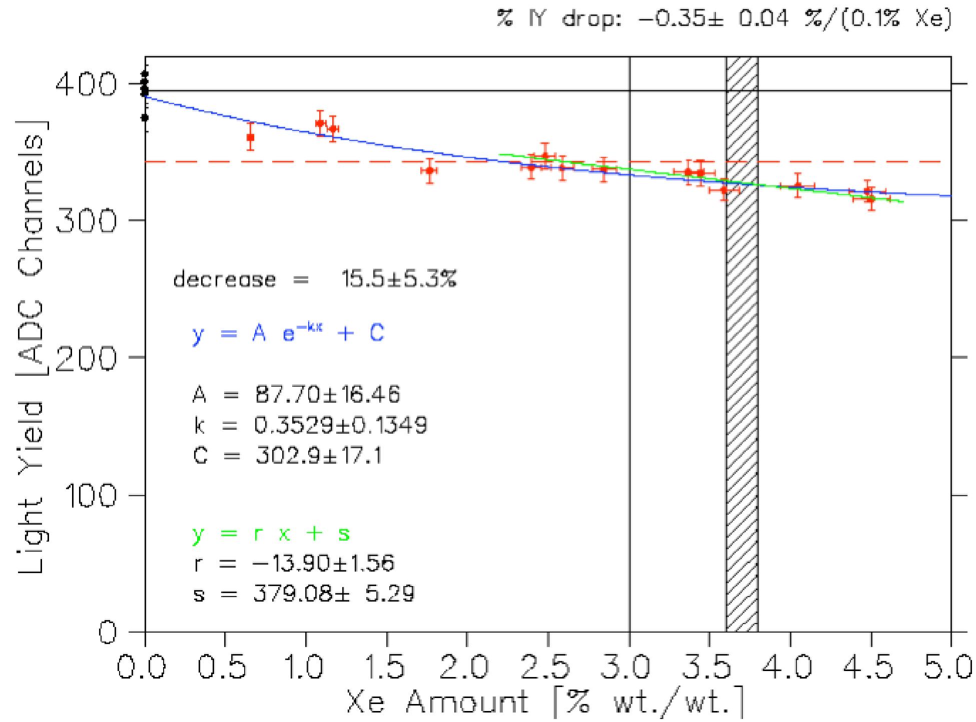
SNO+

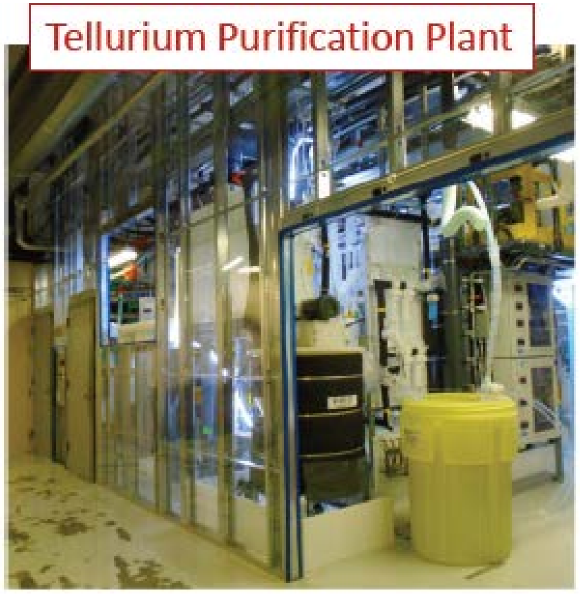


掺Xe液闪:

Limitations on max. doping;

^{136}Xe enrichment

From Y. Gando, 2011



~8 tons of telluric acid has been "cooling" underground for several years.

Ton-scale underground purification of telluric acid for further background reduction.

掺Te液闪:

Recipe

(light yield & max. doping)

Purification

(optical & radio-purity)

THEIA

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

Eur. Phys. J. C (2020) 80:416 Page 23 of 31 416

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