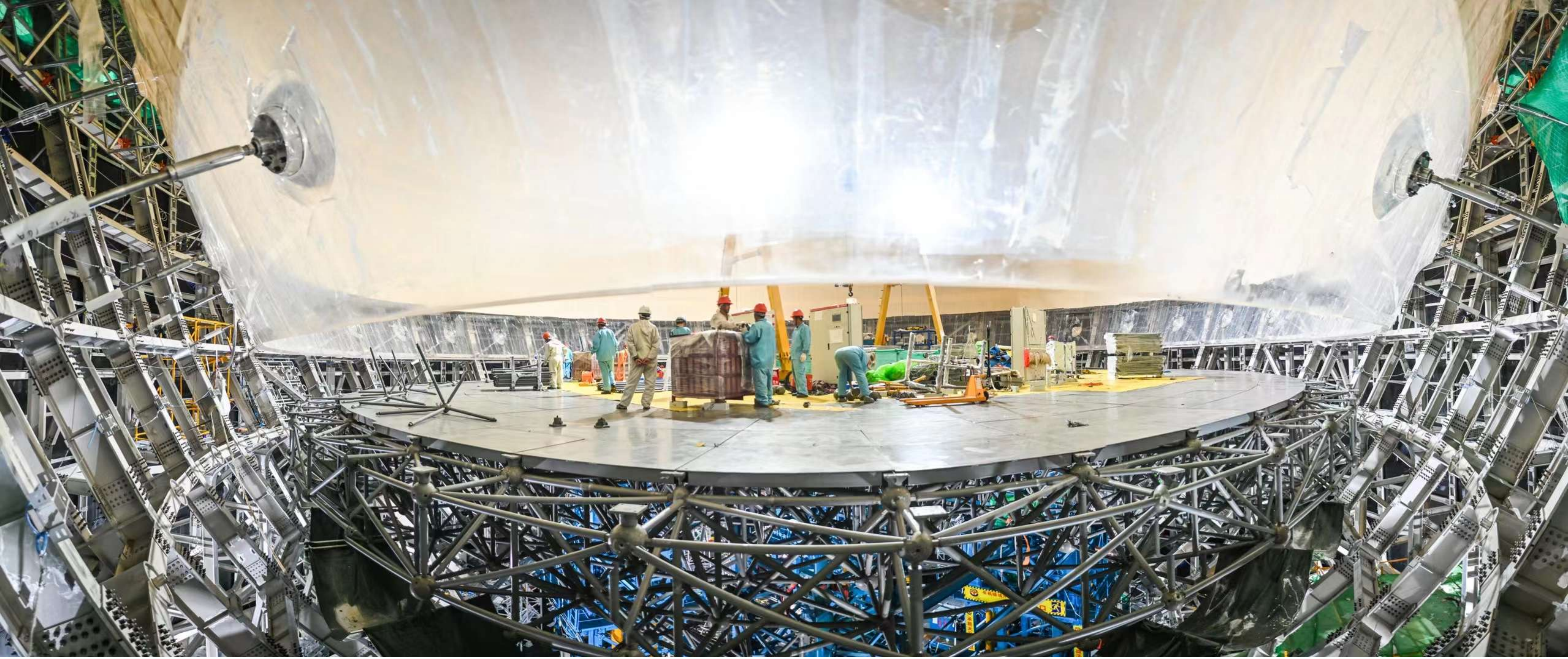
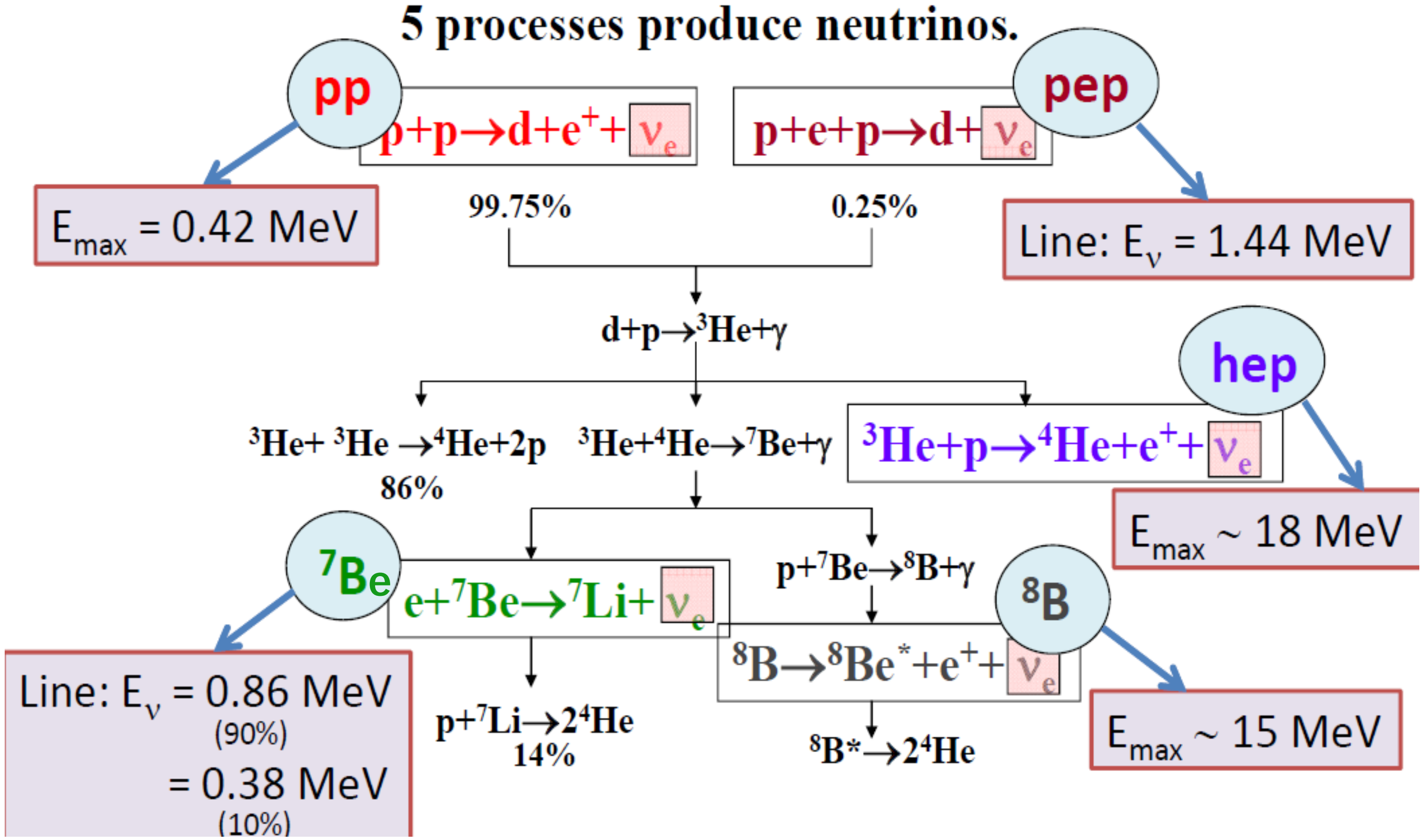


JUNO探测太阳中微子的潜力

崔晨阳（代表JUNO合作组）

pp-chain



5 processes produce neutrinos.

pp: $p+p \rightarrow d+e^+ + \nu_e$ (99.75%)

E_{max} = 0.42 MeV

pep: $p+e+p \rightarrow d + \nu_e$ (0.25%)

Line: E_ν = 1.44 MeV

$d+p \rightarrow {}^3He+\gamma$

${}^3He + {}^3He \rightarrow {}^4He+2p$ (86%)

${}^3He+{}^4He \rightarrow {}^7Be+\gamma$

hep: ${}^3He+p \rightarrow {}^4He+e^+ + \nu_e$

E_{max} ~ 18 MeV

^{7}Be: $e+{}^7Be \rightarrow {}^7Li + \nu_e$

Line: E_ν = 0.86 MeV (90%)

= 0.38 MeV (10%)

$p+{}^7Li \rightarrow 2\,{}^4He$ (14%)

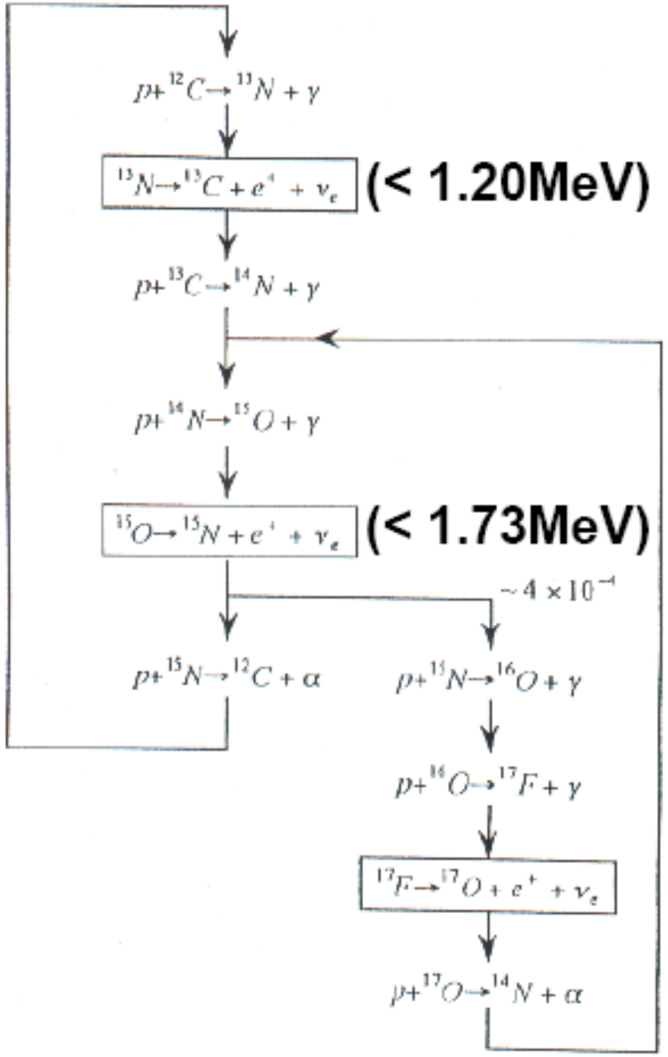
$p+{}^7Be \rightarrow {}^8B+\gamma$

^{8}B: ${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

E_{max} ~ 15 MeV

${}^8B^* \rightarrow 2\,{}^4He$

CNO-chain



$p+{}^{12}C \rightarrow {}^{13}N+\gamma$

${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$ (< 1.20MeV)

$p+{}^{13}C \rightarrow {}^{14}N+\gamma$

$p+{}^{14}N \rightarrow {}^{15}O+\gamma$

${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$ (< 1.73MeV)

$\sim 4 \times 10^{-4}$

$p+{}^{15}N \rightarrow {}^{12}C+\alpha$

$p+{}^{15}N \rightarrow {}^{16}O+\gamma$

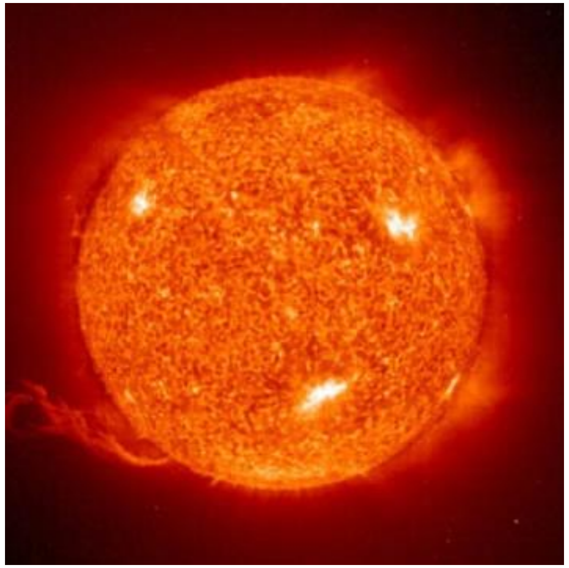
$p+{}^{16}O \rightarrow {}^{17}F+\gamma$

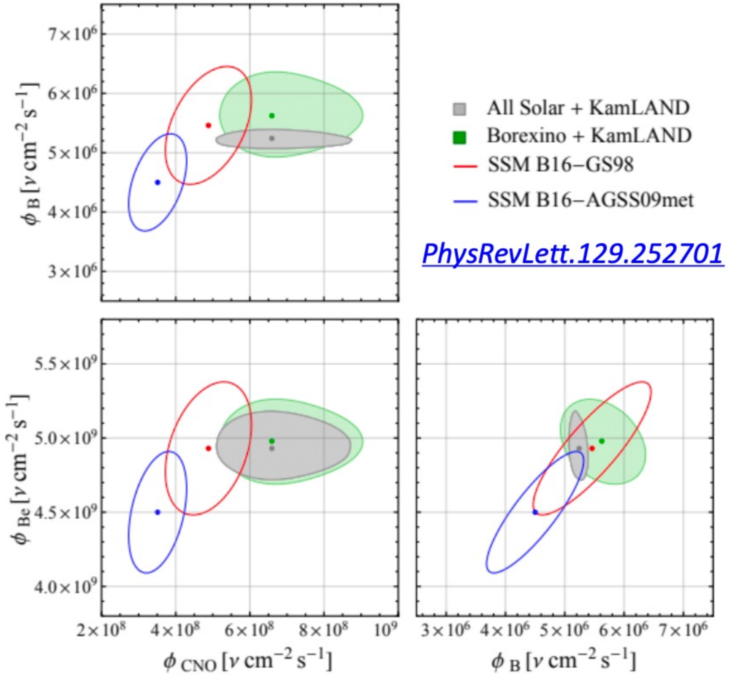
${}^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$

$p+{}^{17}O \rightarrow {}^{14}N+\alpha$

□ 太阳金属丰度问题

	FLUX	Dependence on T	SSM-/HZ (1) SSM B16-GS98	SSM-/LZ(2) SSM B16-AGSS09met	DIFF. (HZ-LZ)/HZ
pp chain	pp (10^{10} cm^{-2} s^{-1})	$T^{-0.9}$	5.98(1±0.006)	6.03(1±0.005)	-0.8%
	pep (10^{8} cm^{-2} s^{-1})	$T^{-1.4}$	1.44(1±0.01)	1.46(1±0.009)	-1.4%
	^{7}Be (10^{9} cm^{-2} s^{-1})	T^{11}	4.94(1±0.06)	4.50(1±0.06)	8.9%
	^{8}B (10^{6} cm^{-2} s^{-1})	T^{24}	5.46(1±0.12)	4.50(1±0.12)	17.6%
CNO cycle	^{13}N (10^{8} cm^{-2} s^{-1})	T^{18}	2.78(1±0.15)	2.04(1±0.14)	26.6%
	^{15}O (10^{8} cm^{-2} s^{-1})	T^{20}	2.05(1±0.17)	1.44(1±0.16)	29.7%

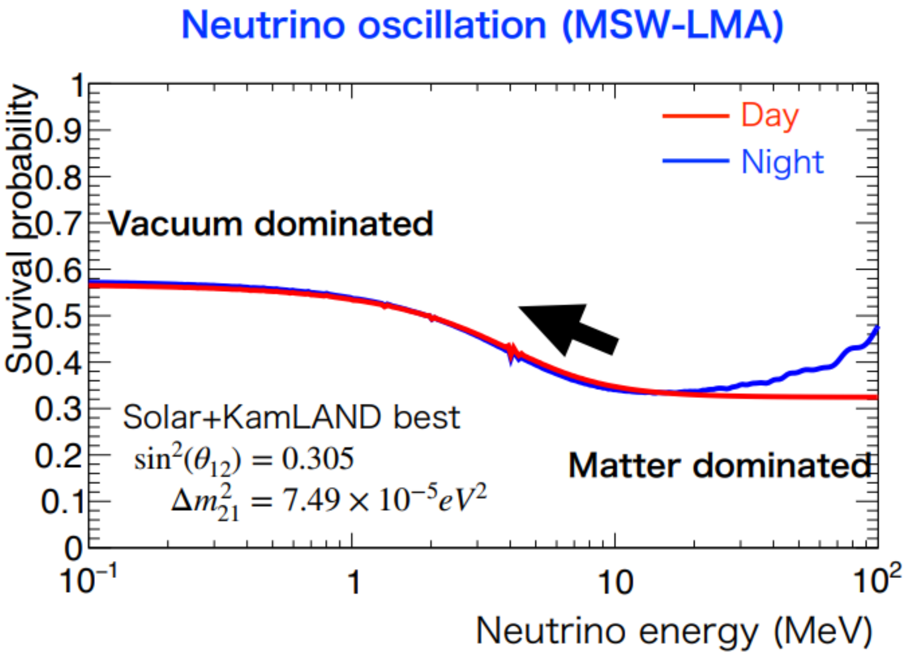


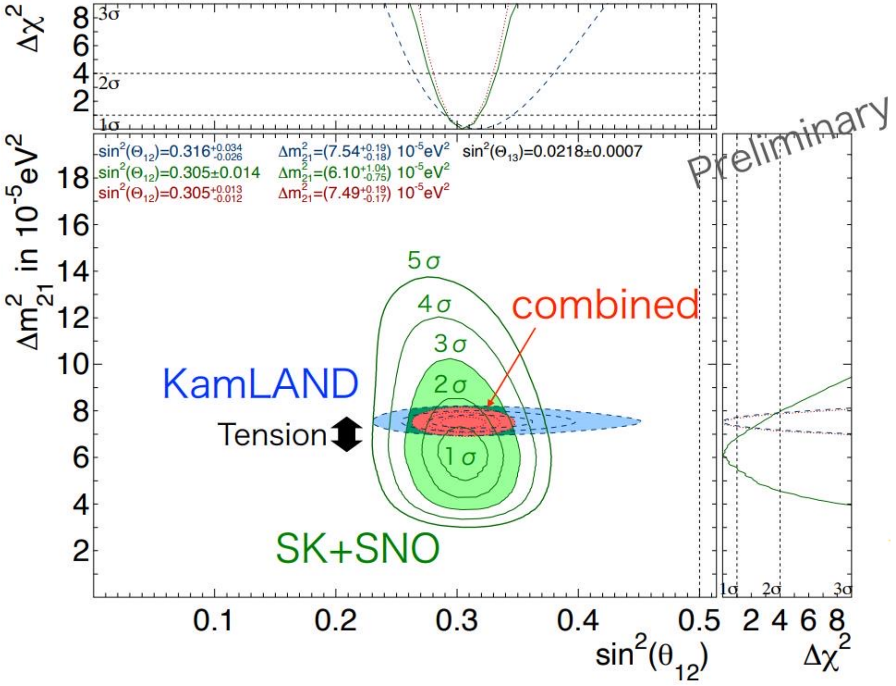


PhysRevLett.129.252701

- Borexino在3.1σ C.L 上偏好高金属丰度的GS98模型
- 与B16-AGSS09 有~2σ 的偏差

□ 振荡物理





JUNO collaboration, Chin. Phys. C 46, 123001 (2022)

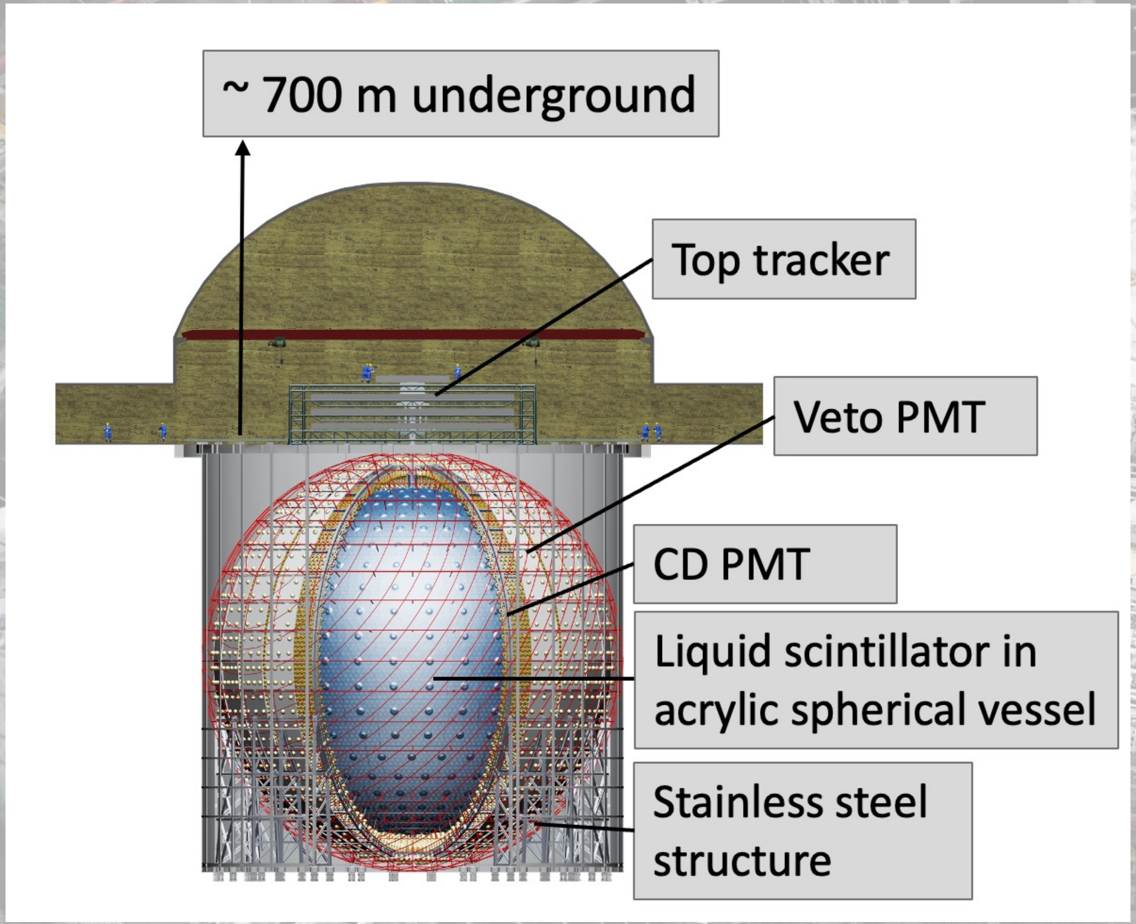
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

- Upturn: 高能段的物质振荡与低能区真空振荡的过渡区域
- 振荡参数的测量：太阳和反应堆的Tension ~ 1.5σ
- 日夜效应：中微子的振荡概率会被地球调制10%左右(flux)

JUNO可用同一探测器，不同中微子源（太阳，反应堆）独立测量Δm^2_{21}以检验此偏差

✓ 其中，反应堆中微子可测量<1%

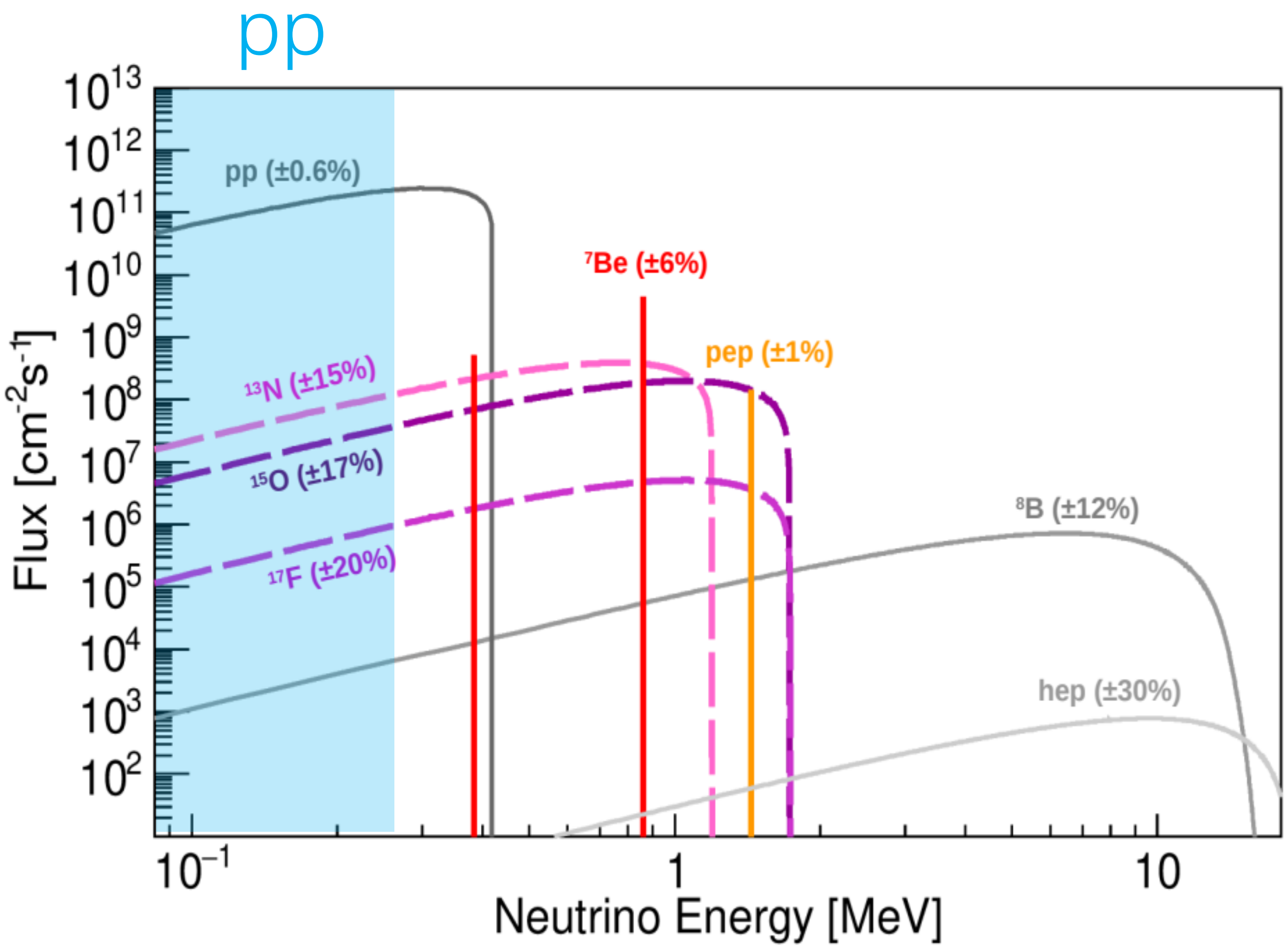

江門中微子實驗
Jiangmen Underground Neutrino Observatory



20 kt 液体闪烁体 → Borexino的70倍
3%/$\sqrt{E}$ 能量分辨 → 好于Borexino (5%)

能量阈值 → 好于水切伦科夫探测器SuperK
天然放射性本底 → 达到Borexino初期水平

适合开展太阳中微子所有产生链的流强探测

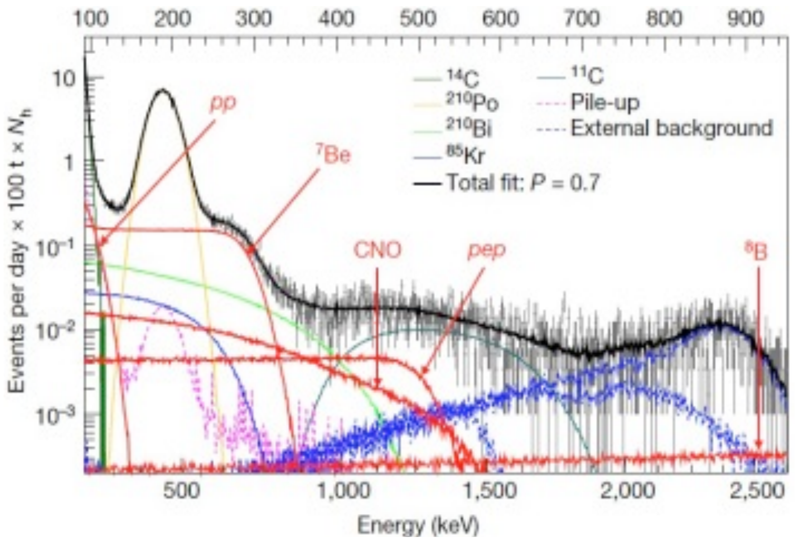


pp分析能区[0.15, 0.25] MeV

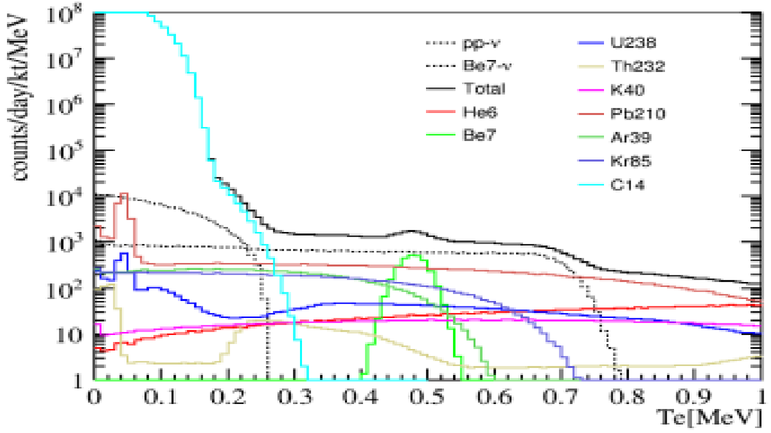
pp-v → 太阳亮度，θ_{12}

- 太阳99%的能量来源于pp链
  - 太阳SSM预言不确定度: ~0.6%
  - 测量不确定度: ~10% (Borexino)
  - 高流强，真空主导振荡
- pp中微子探测挑战
  - 低阈值和触发（暗噪声）
  - 本底分析
    - ^{14}C pile-up
  - sub-MeV的能量刻度
  - 系统不确定度
    - Trigger, PID and 探测器响应

Borexino *Nature* **562**, 505–510 (2018)



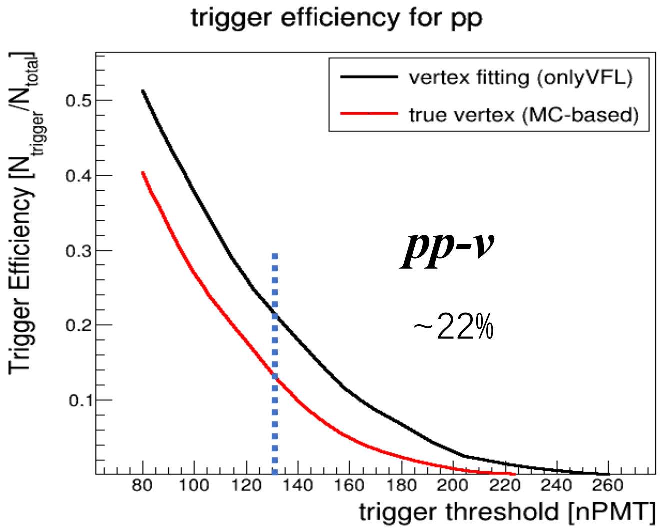
JUNO at ^{14}C 10^{-18}g/g

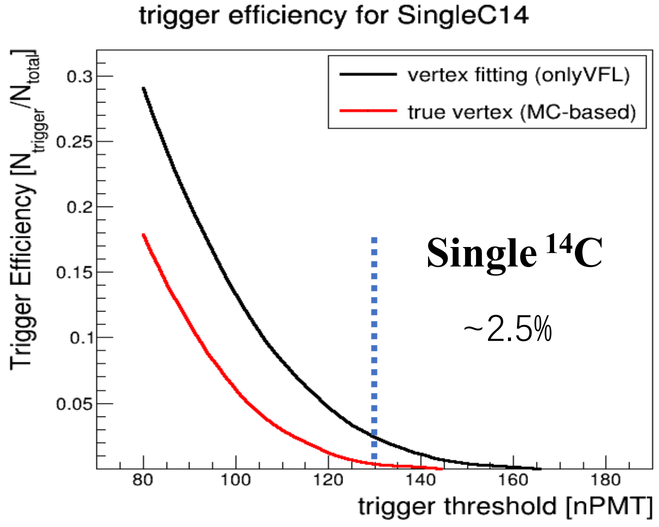


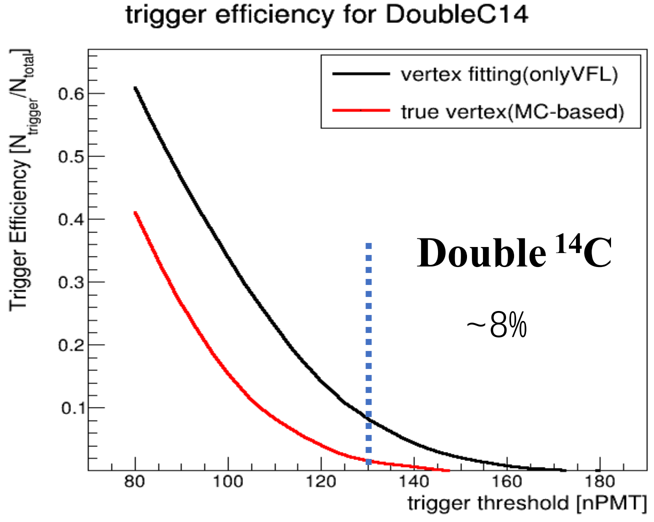
观测 pp-ν 的技术难点

ES：1240 cpd/kt $\xrightarrow[\text{Bkg cut}]{\text{Trigger}}$ 10 cpd/kt (0.08-0.25MeV)

- 低阈值、低触发 → 需要优化触发算法（目前：onlyVFL，130 nPMTs触发阈值）







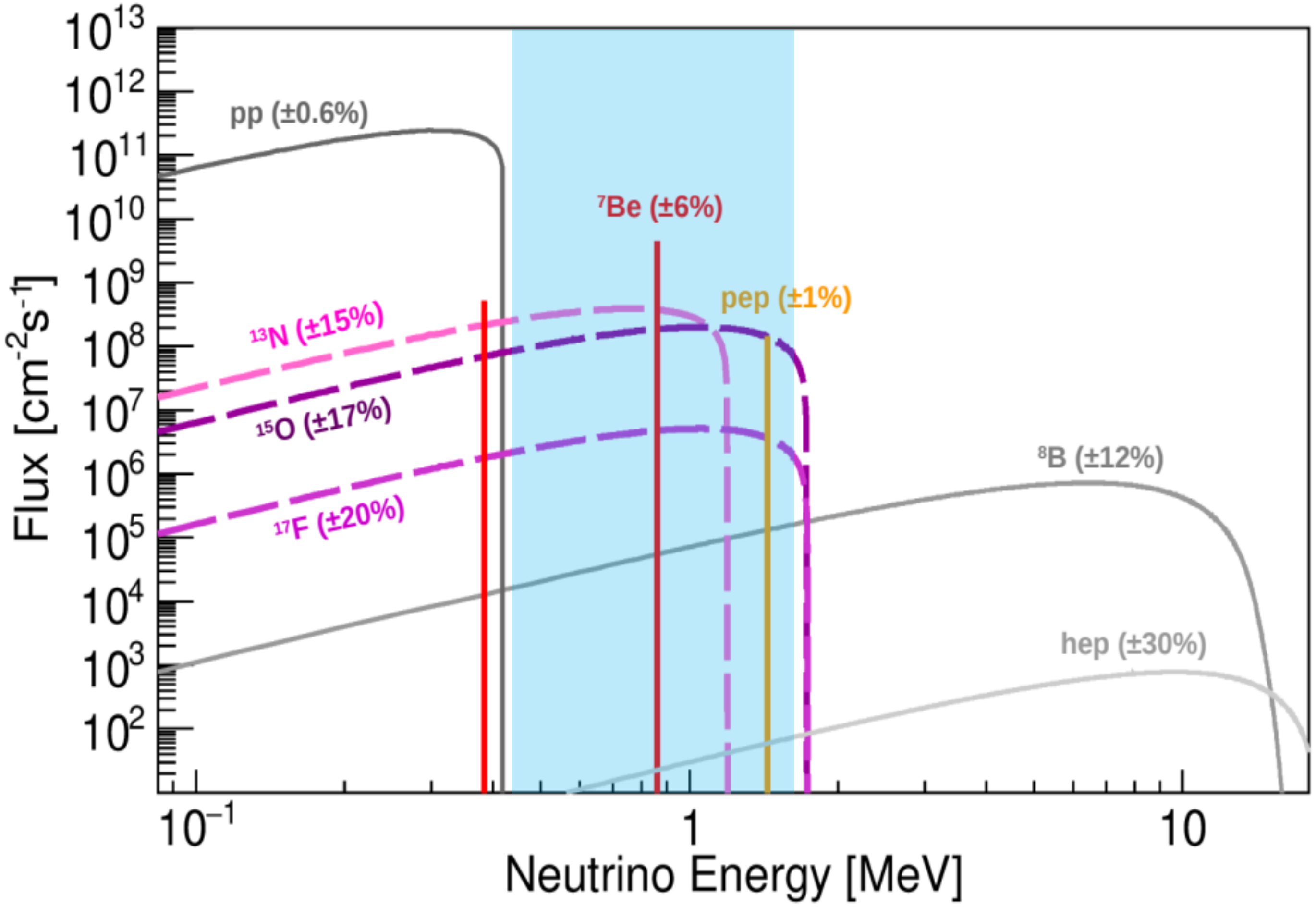
^{14}C：

10^{-17} g/g

- 本底控制 → 开发算法鉴别^{14}C pile-up
  - *pp-ν*: single cluster
    - $\nu_e + e^- \rightarrow \nu_e + e^-$
  - ^{14}C pileup event: more than one cluster
    - $^{14}\text{C} \rightarrow {}^{14}\text{N} + \nu_e + e^-$
    - Multiple ^{14}C events in the same time window

Preliminary

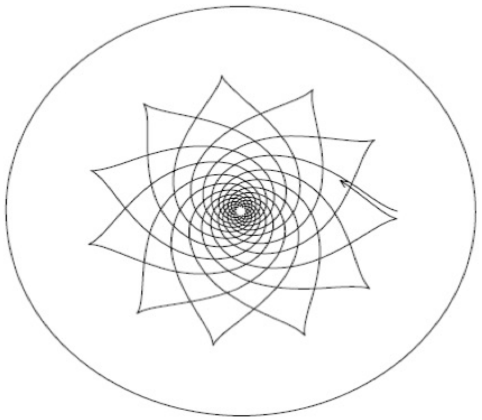
		Sig efficiency	Bkg efficiency	S/B (10^{-17} [g/g])
raw		--	--	1/1727
After trigger		22%	8%	1/626.5
After PID	TMVA (BDTG)	1.1% (22%×5%)	0.008% (8%×0.1%)	1/12.56
	VGG16-1D	3.3% (22%×15%)	0.008% (8%×0.1%)	1/4.2
	VGG16-2D	4% (22%×18%)	0.008% (8%×0.1%)	1/3.5



^{7}Be, pep, CNO分析能区[0.45, 1.6] MeV

研究意义:

- Be7-ν → g-mode
  - ➢ 可以通过太阳中微子流量探测 g- 模式振动（小时量级周期）
  - ➢ 意义：太阳内核, 调制CNO 中微子flux


g 模式振动的传播

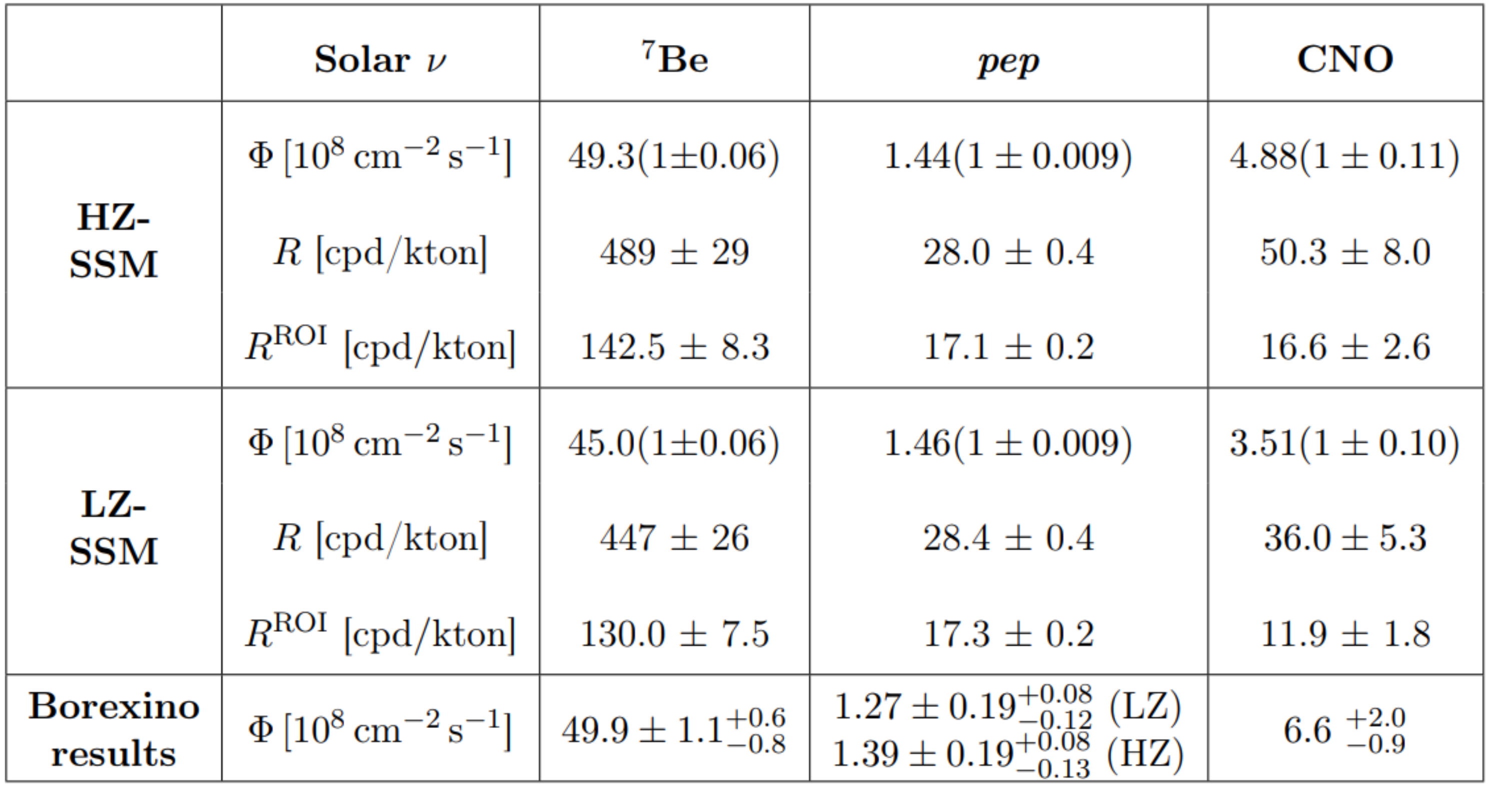
- CNO → 太阳金属丰度问题

	GS98	SSM09Ne	TWA	the Sun
pp/10^{10}	5.96 (0.5%)	5.99 (0.5%)	5.98 (0.5%)	5.97 (0.5%)
pep/10^{8}	1.45 (0.9%)	1.46 (0.9%)	1.47 (0.9%)	1.45 (0.9%)
^{7}Be/10^{9}	4.91 (6%)	4.70 (6%)	4.84 (6%)	4.80 (5%)
^{8}B/10^{6}	5.35 (12%)	4.89 (12%)	5.13 (12%)	5.16 (2%)
CNO/10^{8}	5.15 (12)	3.87 (15%)	3.88 (15%)	6.6 (5.7-8.6)

🧐 新增问题:CNO 中微子流量低于观测

Be7, pep, CNO-v 预期rate

LZ-SSM HZ-SSM对三类中微子的流强预测和在JUNO 反应rate



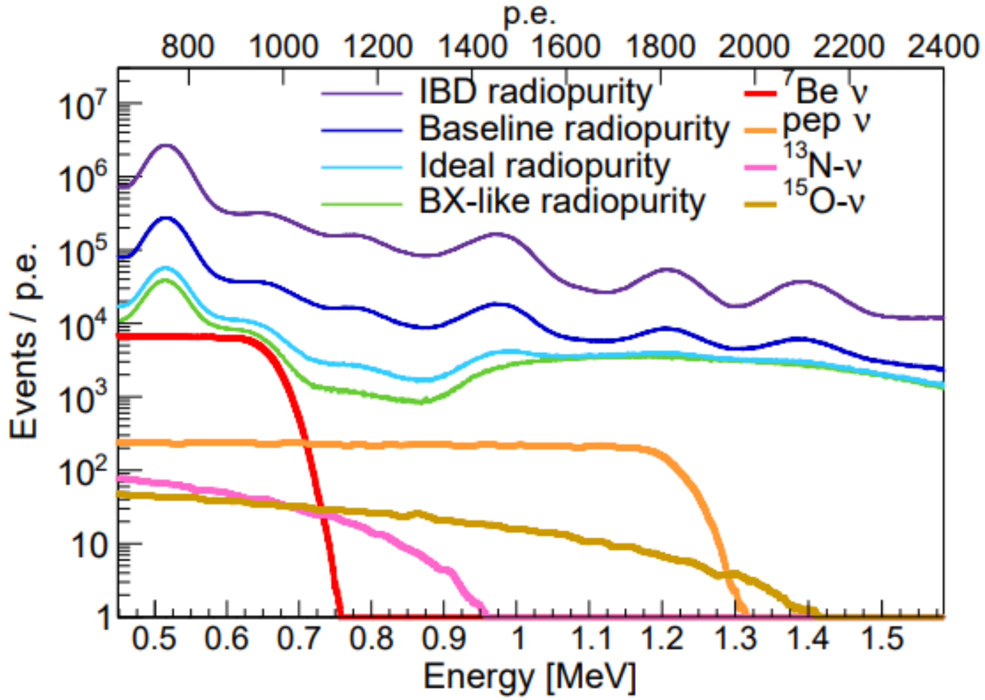
	Solar ν	**^{7}Be**	***pep***	**CNO**
HZ-SSM	$\Phi\ [10^8\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	$49.3(1{\pm}0.06)$	$1.44(1 \pm 0.009)$	$4.88(1 \pm 0.11)$
	R [cpd/kton]	489 ± 29	28.0 ± 0.4	50.3 ± 8.0
	R^{ROI} [cpd/kton]	142.5 ± 8.3	17.1 ± 0.2	16.6 ± 2.6
LZ-SSM	$\Phi\ [10^8\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	$45.0(1{\pm}0.06)$	$1.46(1 \pm 0.009)$	$3.51(1 \pm 0.10)$
	R [cpd/kton]	447 ± 26	28.4 ± 0.4	36.0 ± 5.3
	R^{ROI} [cpd/kton]	130.0 ± 7.5	17.3 ± 0.2	11.9 ± 1.8
Borexino results	$\Phi\ [10^8\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	$49.9 \pm 1.1^{+0.6}_{-0.8}$	$1.27 \pm 0.19^{+0.08}_{-0.12}$ (LZ) $1.39 \pm 0.19^{+0.08}_{-0.13}$ (HZ)	$6.6\ ^{+2.0}_{-0.9}$

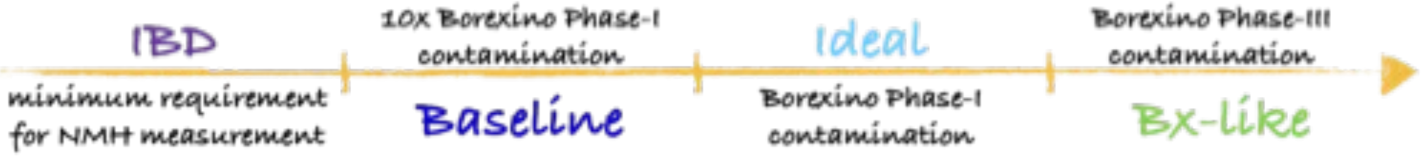
JUNO本底分析

- 液闪中的天然放射性　　假定不同的放射性纯度下的液闪

Radio-purity Scenario		^{40}K	^{85}Kr	^{232}Th-chain	^{238}U-chain	^{210}Pb/ ^{210}Bi	^{210}Po
IBD	$c\ [\frac{g}{g}]$	1×10^{-16}	-	1×10^{-15}	1×10^{-15}	5×10^{-23}	-
	$R\ [\frac{cpd}{kt}]$	2289	5000	3508	15047	12031	12211
Baseline	$c\ [\frac{g}{g}]$	1×10^{-17}	-	1×10^{-16}	1×10^{-16}	5×10^{-24}	-
	$R\ [\frac{cpd}{kt}]$	229	500	351	1505	1203	1221
Ideal	$c\ [\frac{g}{g}]$	1×10^{-18}	-	1×10^{-17}	1×10^{-17}	1×10^{-24}	-
	$R\ [\frac{cpd}{kt}]$	23	100	35	150	241	244
Borexino	$c\ [\frac{g}{g}]$	-	-	$<5.7\times10^{-19}$	$<9.4\times10^{-20}$	-	-
	$R\ [\frac{cpd}{kt}]$	4.2	100	1.4	2	115	446.9

NOTE: Contribution from pileup and reactor neutrinos found negligible in the ROI




IBD

minimum requirement for NMH measurement

10x Borexino Phase-I contamination

Baseline

Ideal

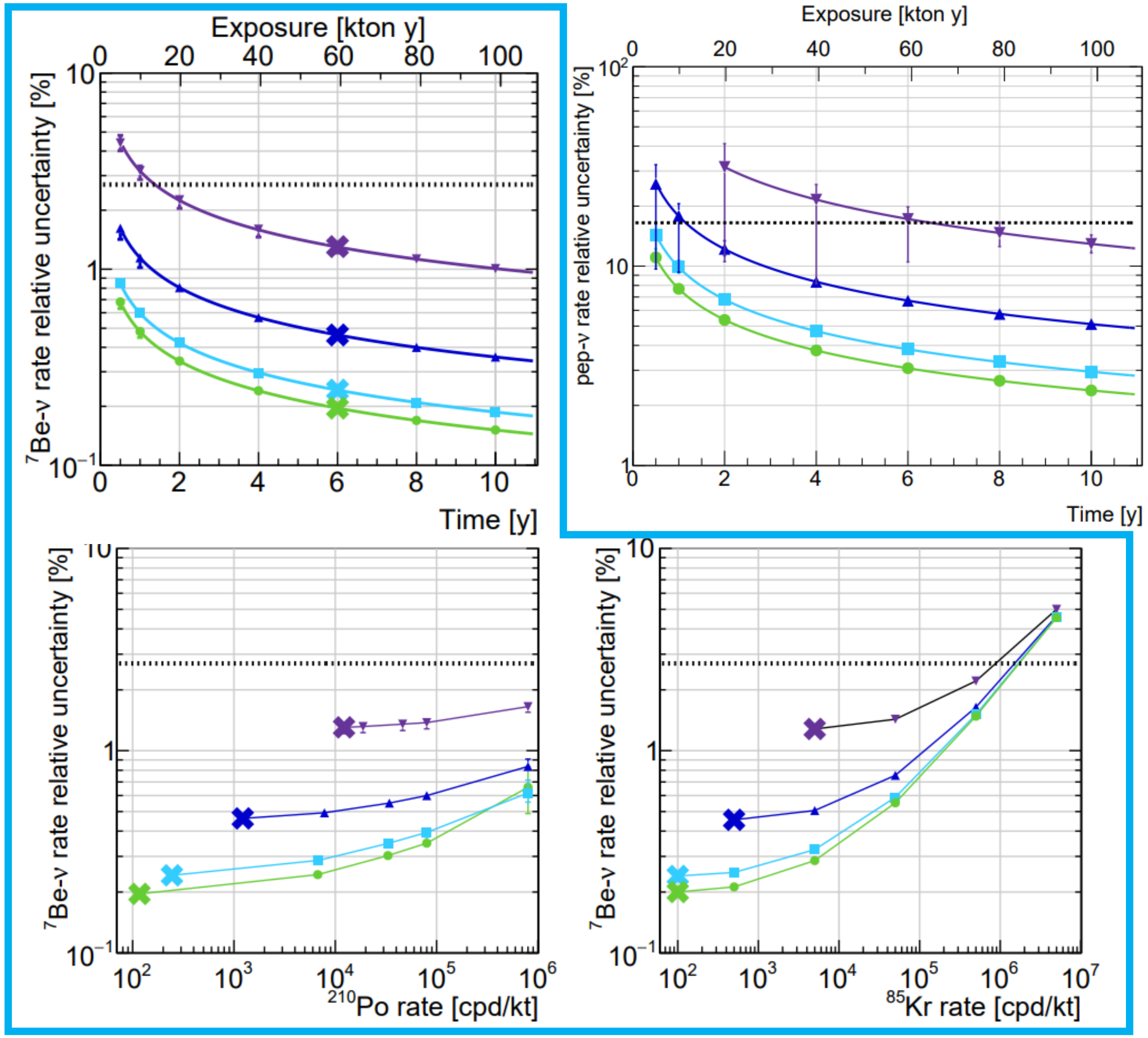
Borexino Phase-I contamination

Borexino Phase-III contamination

Bx-like

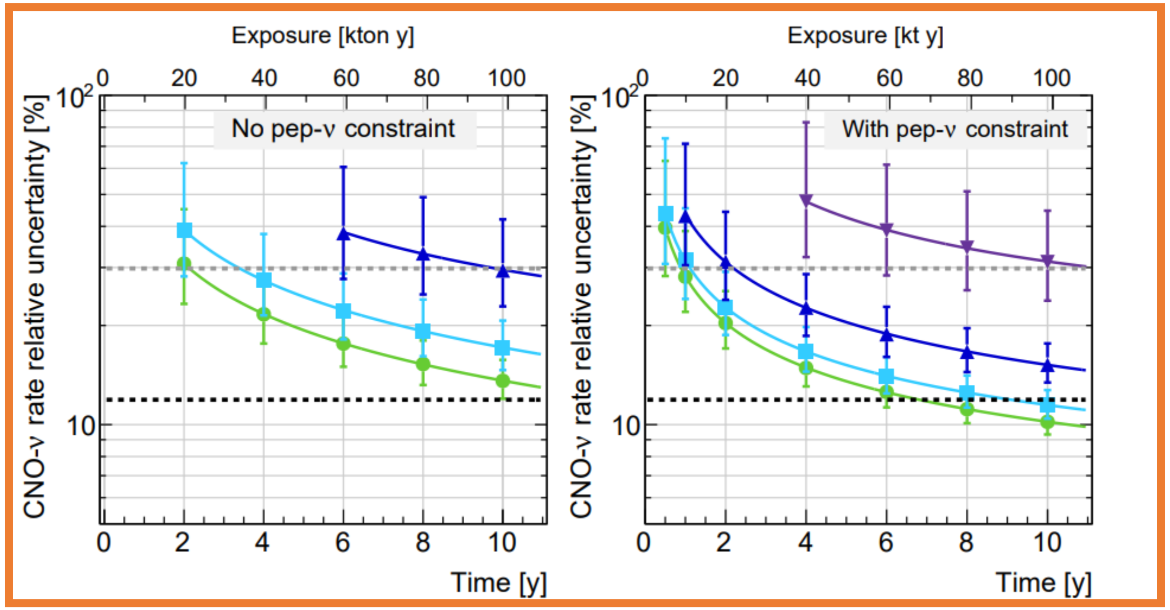
JUNO观测^{7}Be, pep, CNO中微子流强灵敏度

BX-like　Ideal　Baseline　IBD　BX result



^{7}Be

CNO

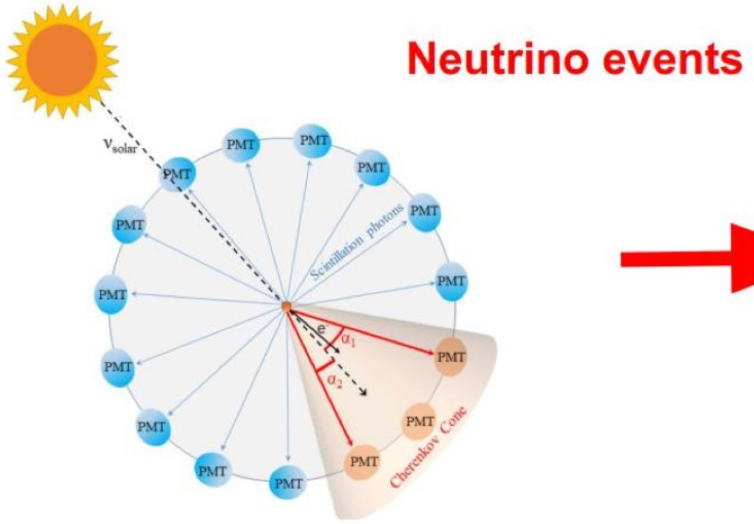


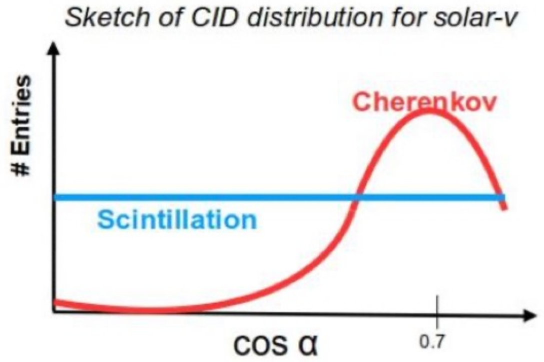
	^{7}Be	pep	CNO	
			无pep约束	有pep约束
Borexino	2.7%	17%	-12%, +30%	
6年数据	0.25%-0.5%	4%-7%	20%-40%	15%-18%
10年数据	0.2%-0.35%	3%-5%	16%-30%	12%-16%

精度范围对应Baseline-ideal scenarios，分析未加入系统误差

JCAP 10 (2023) 022

CID方法(Correlated Integrated Directionality)





The cos α distribution for Cherenkov photons is peaked ~ 0.7.

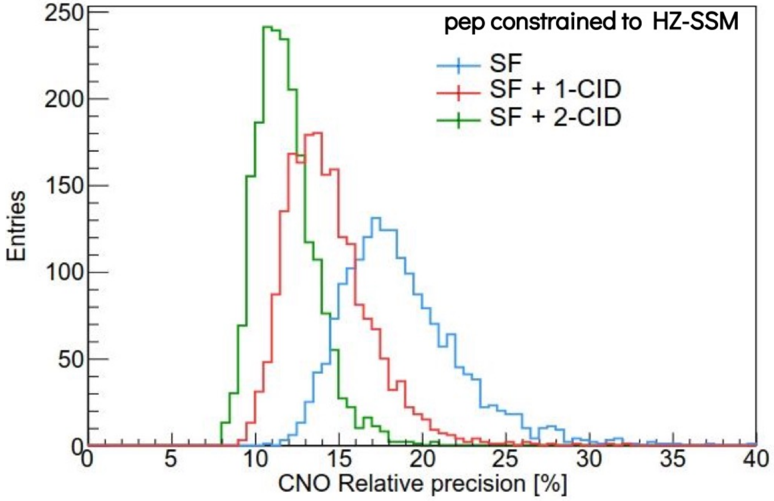
The CID technique exploits the **directionality of Cherenkov light** to separate neutrino events from the background.

The cos α distribution is flat for scintillation photons.

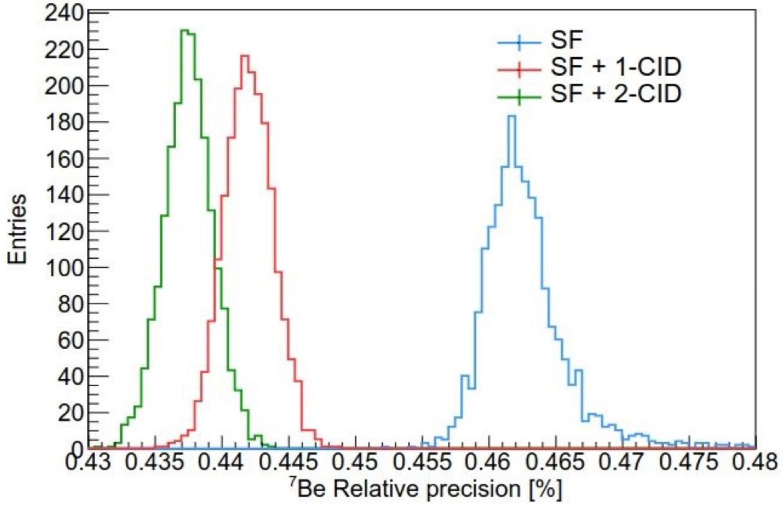
利用切伦科夫光的方向性可以提高CNO, 7Be中微子测量的灵敏度

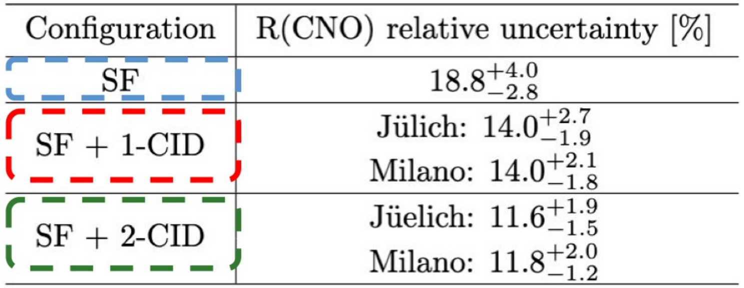
CID--status:

CNO neutrinos

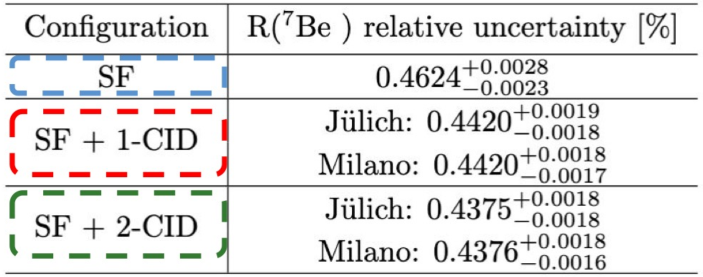


^{7}Be neutrinos





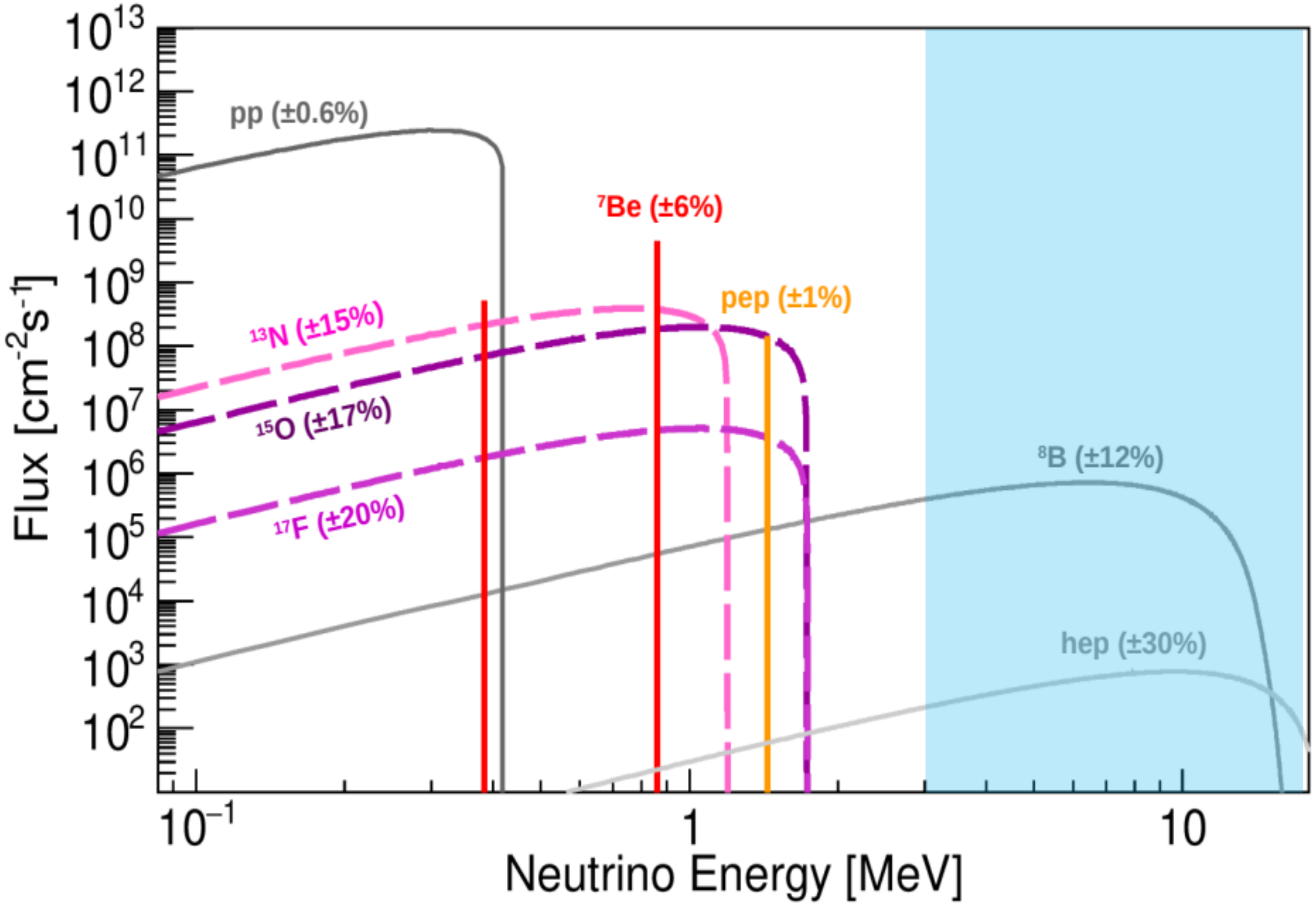
Configuration	R(CNO) relative uncertainty [%]
SF	$18.8^{+4.0}_{-2.8}$
SF + 1-CID	Jülich: $14.0^{+2.7}_{-1.9}$ Milano: $14.0^{+2.1}_{-1.8}$
SF + 2-CID	Jüelich: $11.6^{+1.9}_{-1.5}$ Milano: $11.8^{+2.0}_{-1.2}$



Configuration	R(^{7}Be) relative uncertainty [%]
SF	$0.4624^{+0.0028}_{-0.0023}$
SF + 1-CID	Jülich: $0.4420^{+0.0019}_{-0.0018}$ Milano: $0.4420^{+0.0018}_{-0.0017}$
SF + 2-CID	Jülich: $0.4375^{+0.0018}_{-0.0018}$ Milano: $0.4376^{+0.0018}_{-0.0016}$

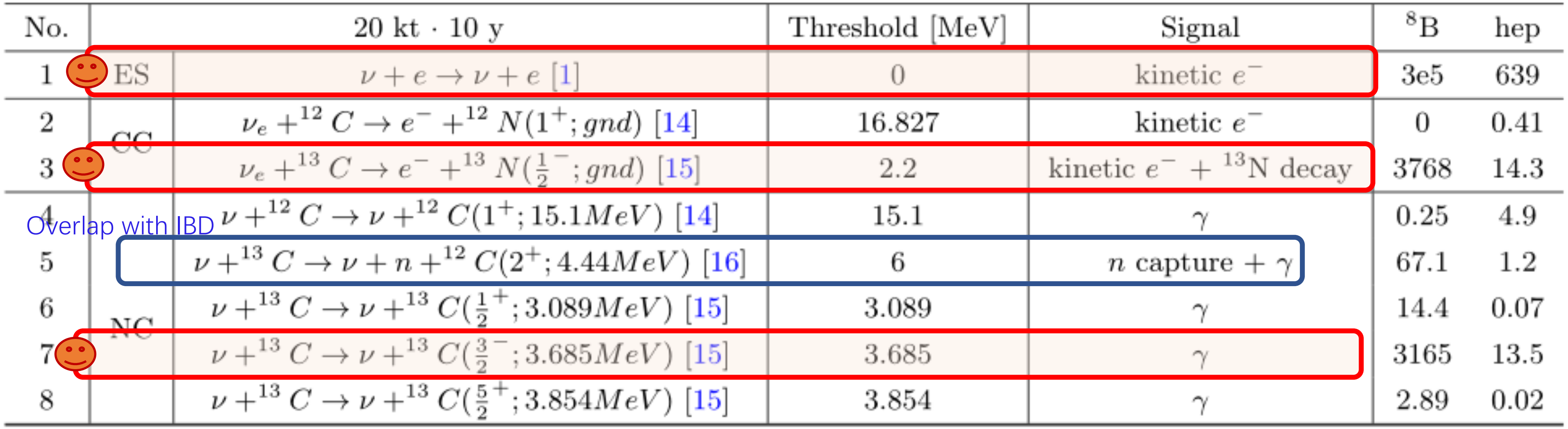
Warning

- 目前的结果基于toy MC，下一步要基于full MC模拟进行分析



^{8}B分析能区[2, 16] MeV

反应道



No.	20 kt · 10 y		Threshold [MeV]	Signal	^{8}B	hep
☺ 1	ES	$\nu + e \rightarrow \nu + e$ [1]	0	kinetic e^-	3e5	639
2	CC	$\nu_e +^{12}C \rightarrow e^- +^{12}N(1^+; gnd)$ [14]	16.827	kinetic e^-	0	0.41
☺ 3		$\nu_e +^{13}C \rightarrow e^- +^{13}N(\frac{1}{2}^-; gnd)$ [15]	2.2	kinetic e^- + ^{13}N decay	3768	14.3
4	NC	$\nu +^{12}C \rightarrow \nu +^{12}C(1^+; 15.1MeV)$ [14]	15.1	γ	0.25	4.9
5		$\nu +^{13}C \rightarrow \nu + n +^{12}C(2^+; 4.44MeV)$ [16]	6	n capture + γ	67.1	1.2
6		$\nu +^{13}C \rightarrow \nu +^{13}C(\frac{1}{2}^+; 3.089MeV)$ [15]	3.089	γ	14.4	0.07
☺ 7		$\nu +^{13}C \rightarrow \nu +^{13}C(\frac{3}{2}^-; 3.685MeV)$ [15]	3.685	γ	3165	13.5
8		$\nu +^{13}C \rightarrow \nu +^{13}C(\frac{5}{2}^+; 3.854MeV)$ [15]	3.854	γ	2.89	0.02

Overlap with IBD

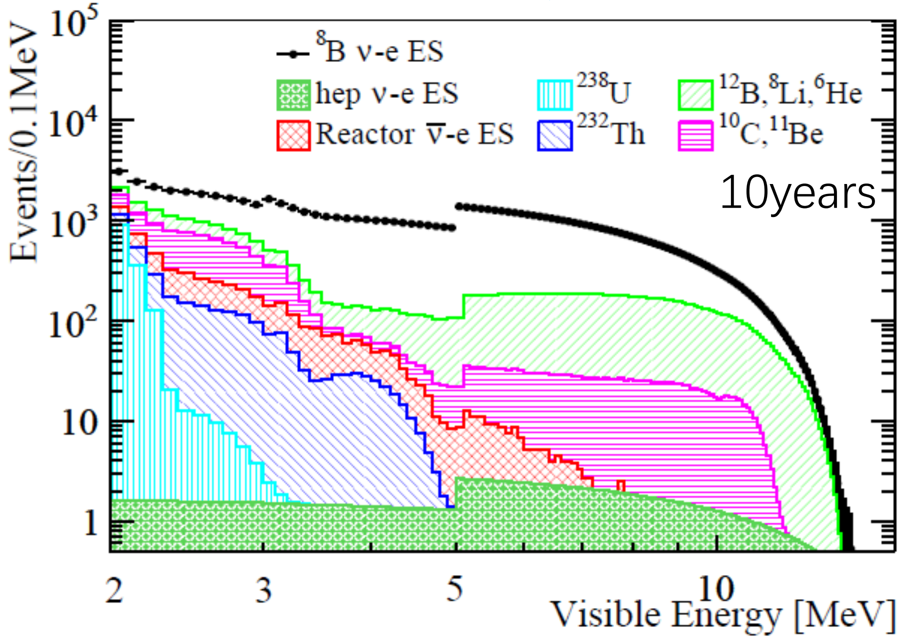
^{8}B太阳中微子ES&NC反应道本底和信号小结

- 信号特征： 单信号
- ^{8}B事例挑选效率：
  - ✓ Muon反符合效率: 52%
  - ✓ (3, 5) MeV: 52% (muon veto) * 80% (^{212}Bi-^{208}Tl cut)
- 其他系统误差
  - ✓ FV cut: 1%, refer to Borexino

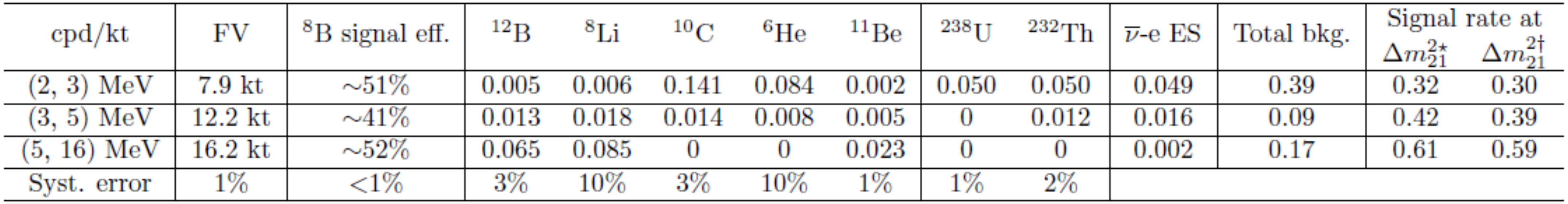
    (Phys. Rev. D, 101(6):062001, 2020).
  - ✓ Detector energy scale: 0.3%, refer to Daya Bay

    (Nucl. Instrum. Meth. A, 940:230-242, 2019.)

3 MeV和 5 MeV的跳变来自不同 FV cut



$\Delta m^{2\star}_{21} = 4.8 \times 10^{-5}$ eV^2, and $\Delta m^{2\dagger}_{21} = 7.5 \times 10^{-5}$ eV^2

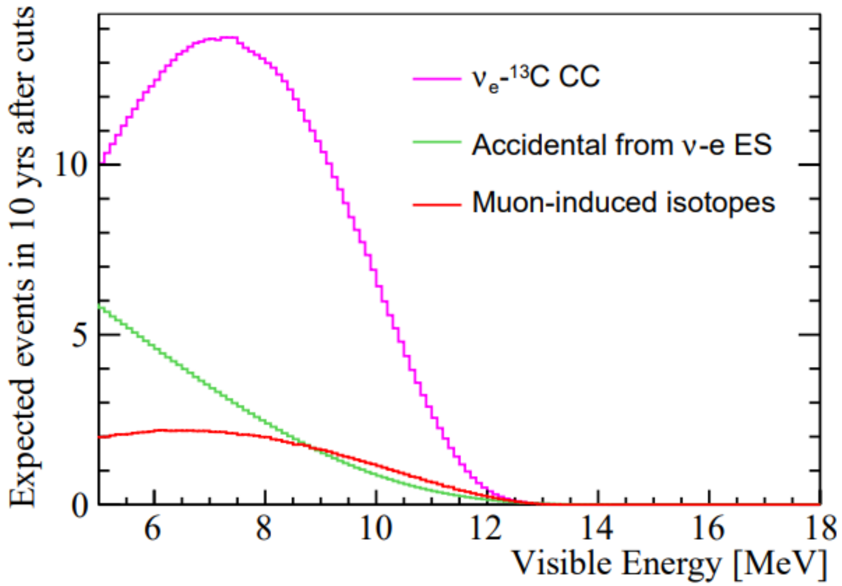


cpd/kt	FV	^{8}B signal eff.	^{12}B	^{8}Li	^{10}C	^{6}He	^{11}Be	^{238}U	^{232}Th	$\overline{\nu}$-e ES	Total bkg.	Signal rate at $\Delta m^{2\star}_{21}$	Signal rate at $\Delta m^{2\dagger}_{21}$
(2, 3) MeV	7.9 kt	~51%	0.005	0.006	0.141	0.084	0.002	0.050	0.050	0.049	0.39	0.32	0.30
(3, 5) MeV	12.2 kt	~41%	0.013	0.018	0.014	0.008	0.005	0	0.012	0.016	0.09	0.42	0.39
(5, 16) MeV	16.2 kt	~52%	0.065	0.085	0	0	0.023	0	0	0.002	0.17	0.61	0.59
Syst. error	1%	<1%	3%	10%	3%	10%	1%	1%	2%				

^{8}B太阳中微子CC道探测

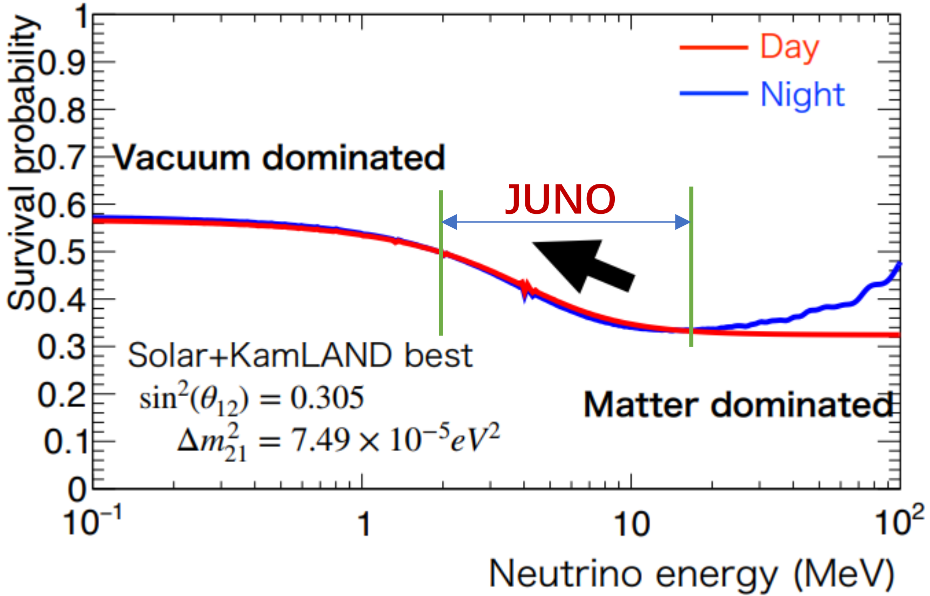
$$\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N(\frac{1}{2}^-)$$

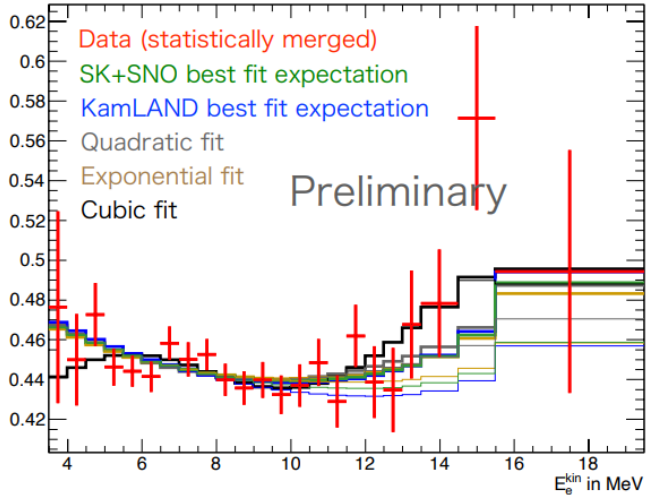
- 信号特征：快慢符合信号
  - 快信号：电子动能
  - 慢信号：^{13}N衰变 (β^+, τ = 863 s)
- 优化事例挑选条件

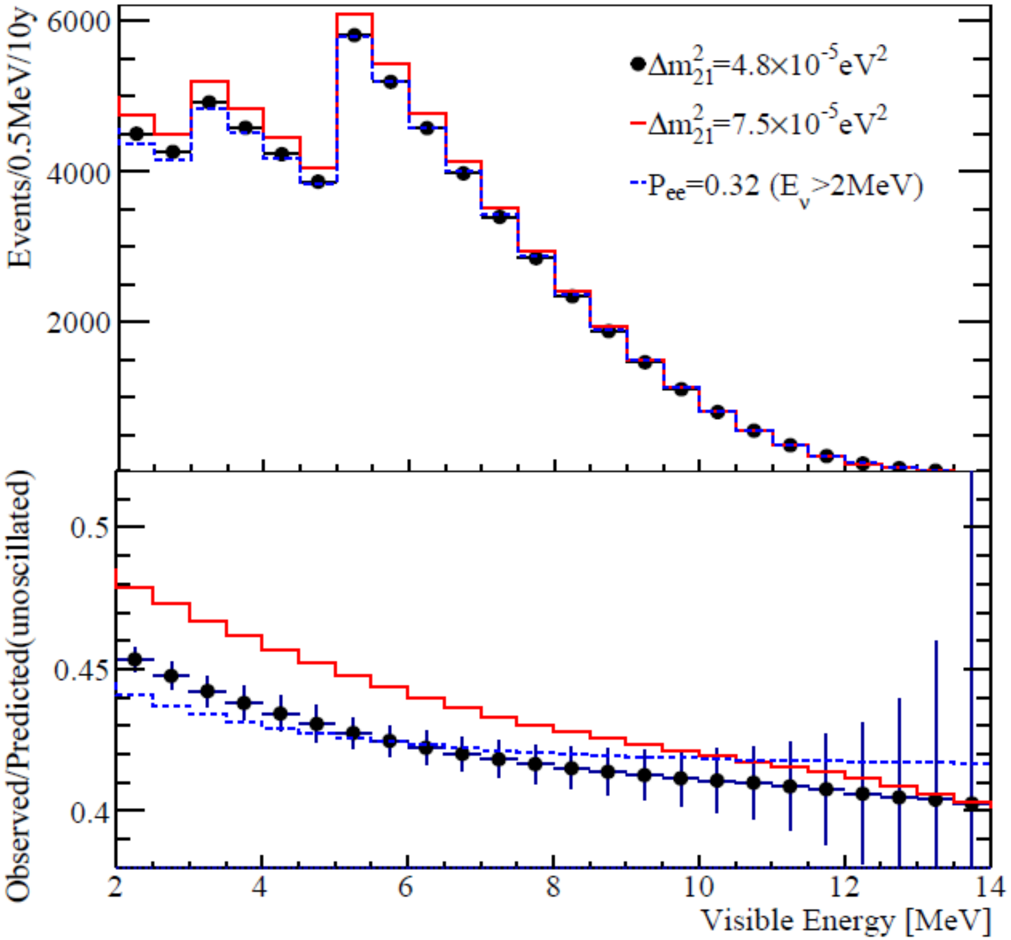


	Cuts	CC signal efficiency	CC signal	Background for CC channel		
				Solar ES	Muon-induced isotopes	
				Accidental	Accidental	Correlated
–	–	–	3929	–	–	–
Time cut	$\Delta T < 900$ s	65%	2554	10^{10}	10^{13}	10^{12}
Energy cut	5 MeV $< E_p <$14 MeV 1 MeV $< E_d <$ 2 MeV	79% 91%	1836	10^9	10^{10}	10^9
Fiducial volume Cut	$R < 16.5$ m [30]	81%	1487	10^7	10^7	10^8
Vertex cut	$\Delta d < 0.47$ m	87%	1293	328	10^5	10^6
Muon veto	Muon and TFC veto [30]	50%	647	164	53	58
Combined	–	17%	647	275		

B8-ν: upturn

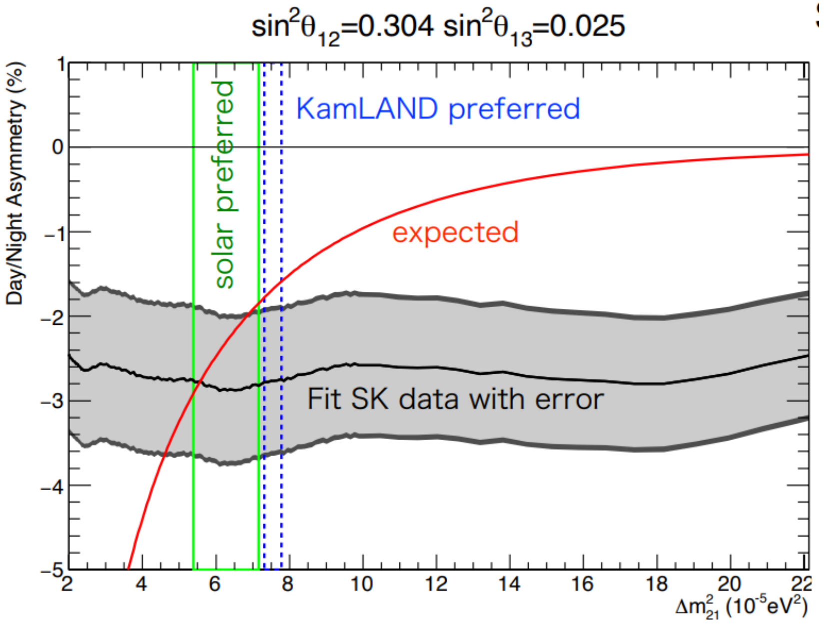

Neutrino oscillation (MSW-LMA)


Neutrino 2022 SK-I/II/III/IV Recoil Electron Spectrum



✓排除平的P_{ee}: 2.7 σ with Δm^2_{21}=7.5×10^{-5}eV^2

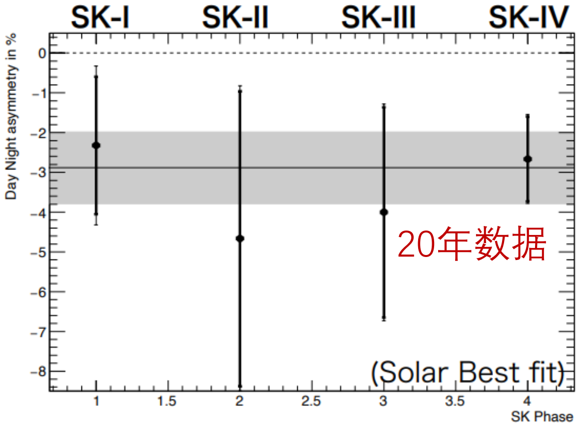
B8-v: 日夜效应



Significance of D/N asymmetry:

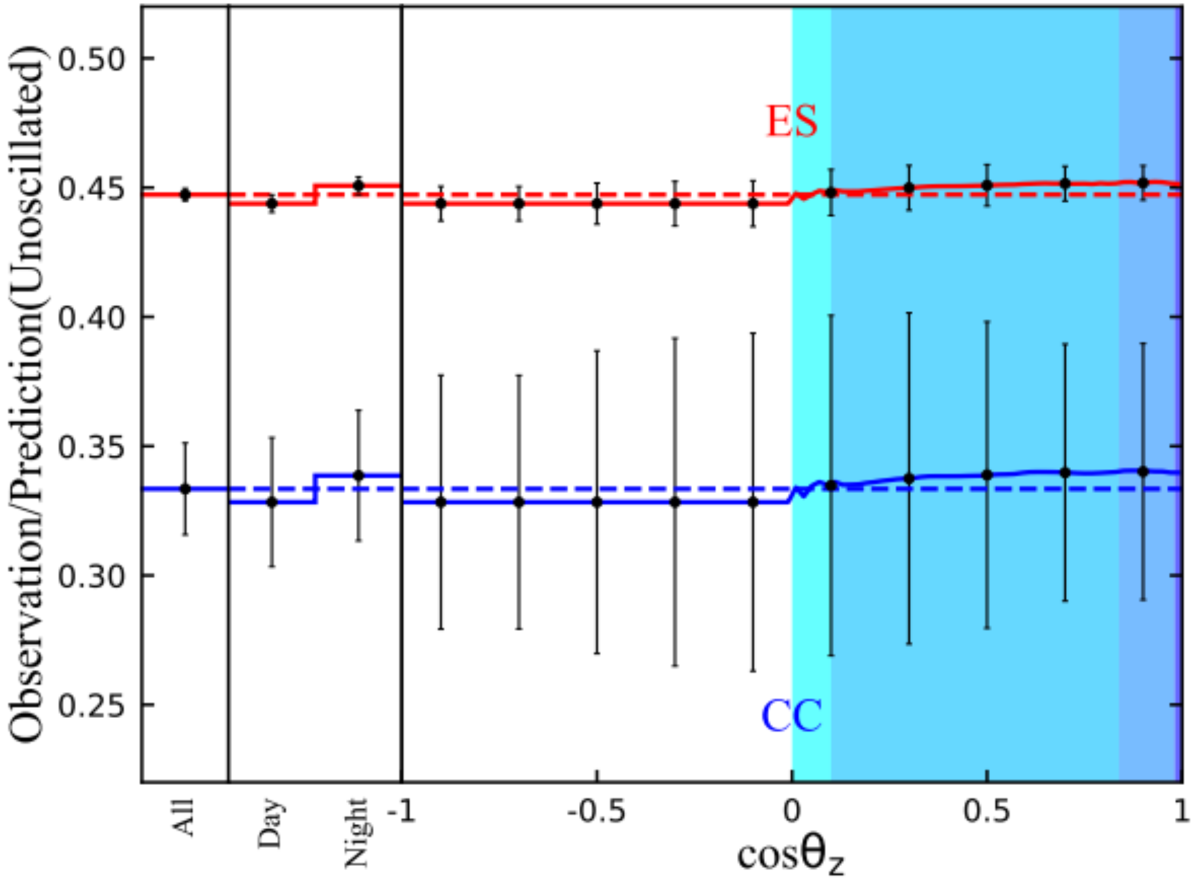
3.2σ for Solar Best fit

3.1σ for Global Best fit



20年数据

(Solar Best fit)

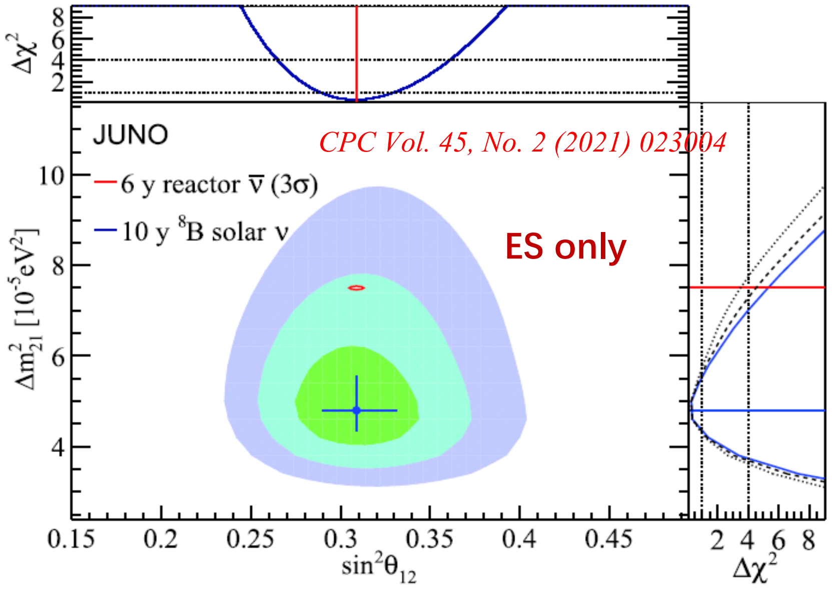


■JUNO测量日夜效应精度:

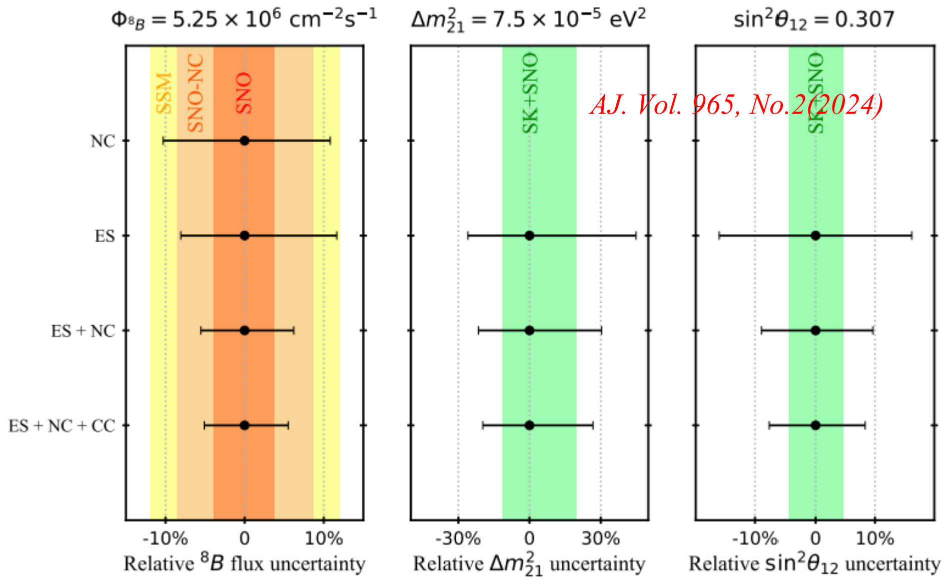
- ✓10年数据：(-2.9±0.9)% for Δm^2_{21}=7.5×10^{-5} eV^2
- ✓主要灵敏度来自ES反应道，因其大统计量

B8-ν: 模型无关的测量

- 利用ES, NC, CC三个反应道
  - ✓可模型无关的测量^{8}B太阳中微子流强(5%), 和振荡参数$\sin^2\theta_{12}$(8%)和Δm^2_{21}(20%)
  - ✓如果联合SNO-NC结果，可获得世界上最高的^{8}B中微子流强精度3%



CPC Vol. 45, No. 2 (2021) 023004



AJ. Vol. 965, No.2(2024)

Without ^{210}Po reduction , dashed line in the right panel

^{238}U/^{232}Th ~ 10^{-15} g/g, E_{thr} > 5 MeV, dotted line in the right panel

总结

◆JUNO探测器优势

✓ 最大的液闪靶体积(20 kt)，低能量阈值(0.1 MeV)、低天然放射性本底(U/Th~10^{-17} g/g)、高能量分辨率(3%/$\sqrt{E}$)

◆太阳中微子流强和振荡测量

□ ^{7}Be → g-modes， CNO中微子 → 太阳金属丰度模型

	^{7}Be	pep	CNO	
			无pep约束	有pep约束
Borexino	2.7%	17%	-12%， +30%	
6年数据	0.25%-0.5%	4%-7%	20%-40%	15%-18%
10年数据	0.2%-0.35%	3%-5%	16%-30%	12%-16%

相关合作组文章：

1. *CPC Vol. 45, No.2 (2021) 023004*
2. *AJ. Vol. 965, No.2(2024)*
3. *JCAP 10 (2023) 022*

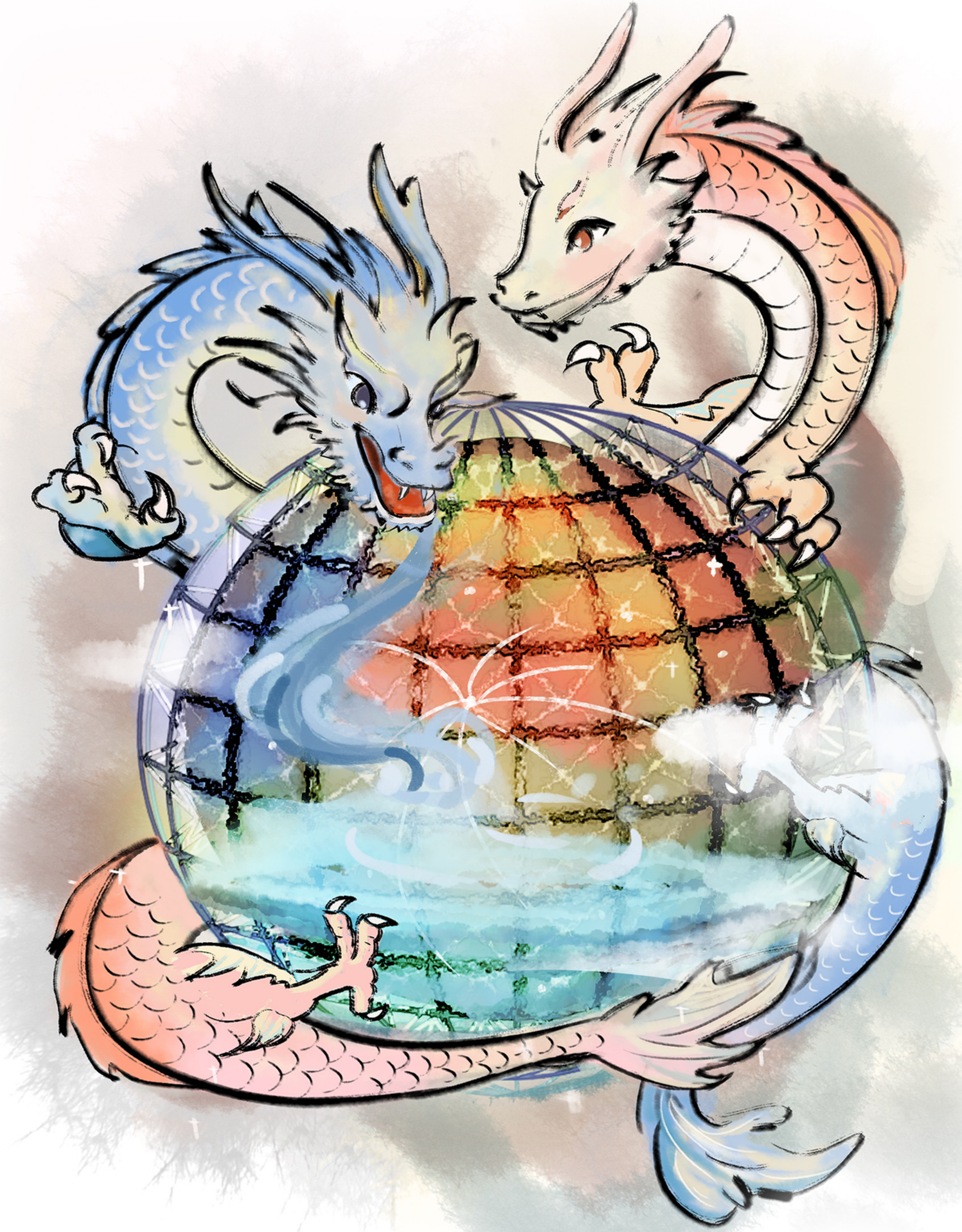
□ ^{8}B中微子：10年数据，流强5%，$\sin^2\theta_{12}$ 8%和Δm^2_{21} 20%，太阳金属丰度

- ➢ SuperK和Borexino实验只能观测 B8太阳中微子ES道，因此受振荡参数影响无法独立确定^{8}B太阳中微子总流强
- ➢ JUNO将在国际上首次探测到太阳中微子和^{13}C的NC和CC反应道，且不需要太阳模型和其他实验测量结果的输入独立测量^{8}B太阳中微子流强和振荡参数

□ ^{8}B中微子：进一步检验标准振荡模型，比如日夜效应和中微子存活几率upturn等

- ➢ 日夜效应：10年(-2.9±0.9)% for Δm^2_{21}=7.5×10^{-5} eV^2， 和SuperK 20年数据结果相当
- ➢ Upturn：分析能区[2,16] MeV，阈值低于SuperK的3.5 MeV，几乎完全覆盖upturn能区

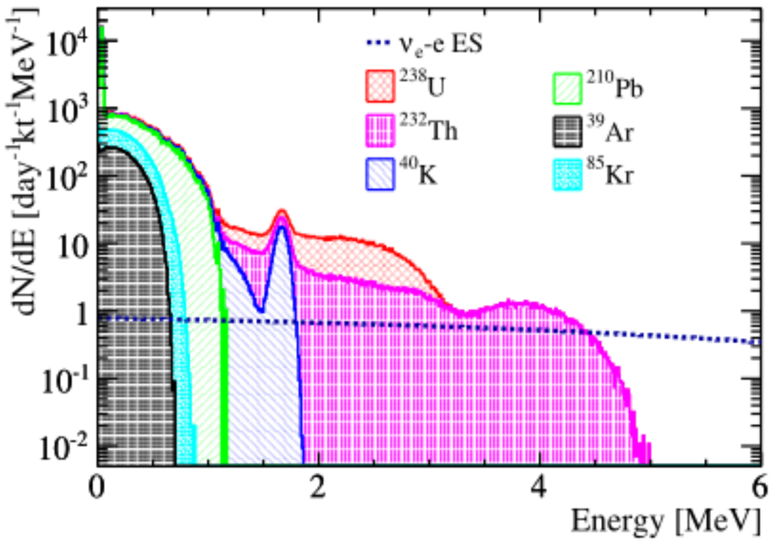
□ pp和hep中微子：进行中



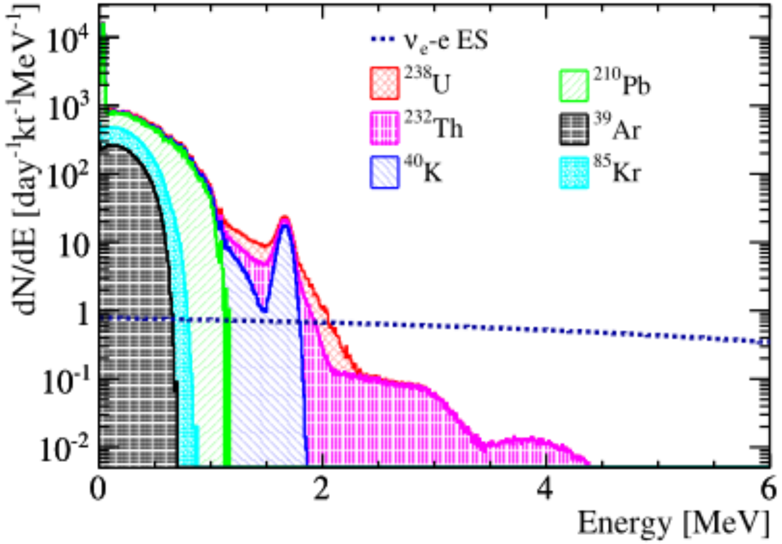
谢谢！

B8-本底分析--液闪中本底

^{238}U: 10^{-17} g/g
^{232}Th: 10^{-17} g/g
^{40}K: 10^{-18} g/g
^{210}Pb: 10^{-24} g/g
^{14}C: 10^{-17} g/g
^{39}Ar/^{85}Kr: 1 μBq/m^3
^{210}Po: 2600 cpd/kt

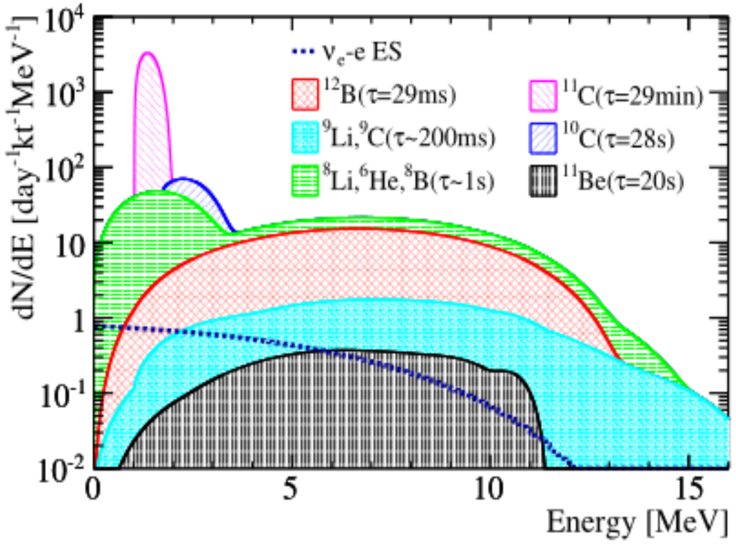


Bi-Po/Tl reduction

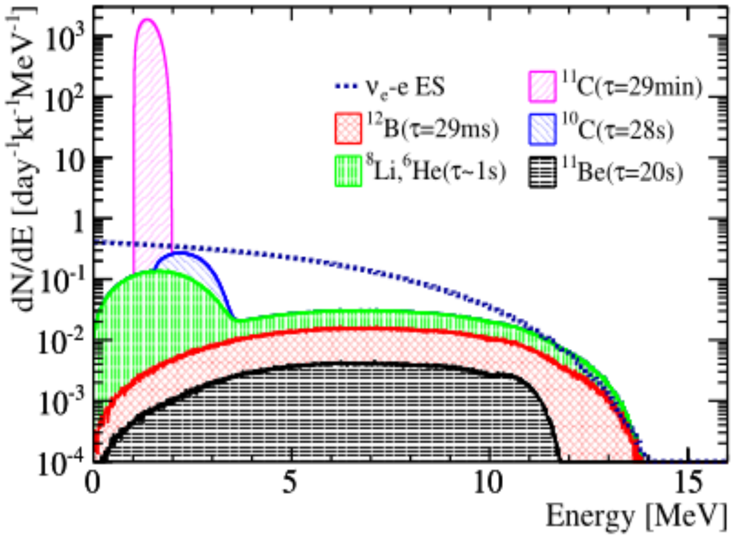


μ flux: 0.004 Hz/m^2
Rate in LS: 3.6 Hz
Rate in water: 10 Hz

将来in-situ可测量：
宇生同位素产额、距离muon径迹的分布、伴随产生中子的比例



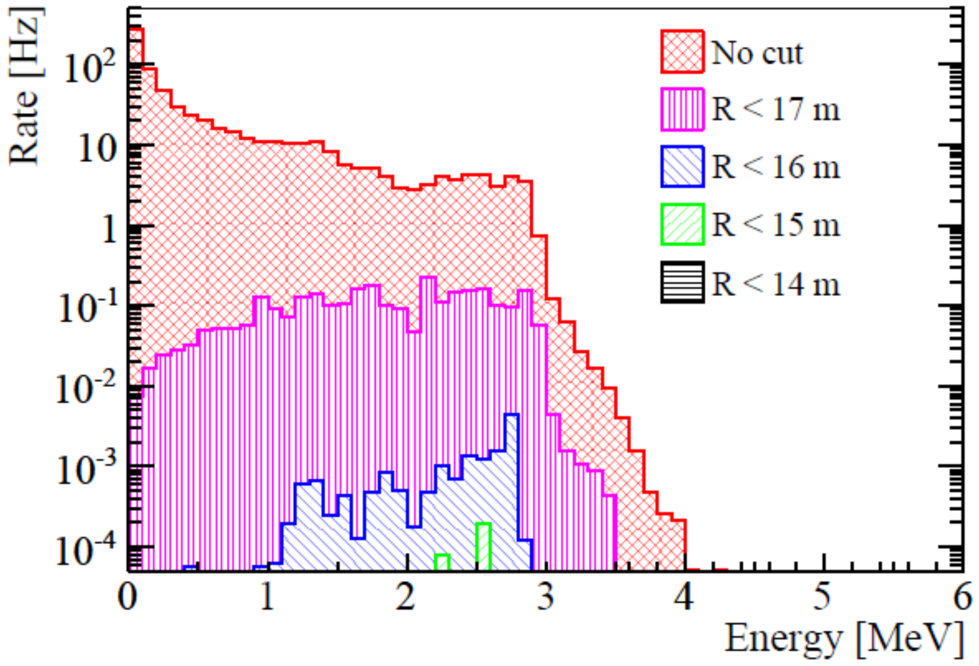
μ track + TFC reduction



B8-本底分析--外部天然放射性本底

外部材料本底

主材料	U/Th含量	参考
有机玻璃	< 1 ppt	Ref: NIMA1004 (2021) 165377
不锈钢网架	< 1 ppb	Same supplier with Daya Bay
PMT玻璃	~200 ppb	Ref: NIMA 898 (2018) 67–71
超纯水	Radon < 0.1 Bq/m^3	Ref: RDTM (2018) 2:48
岩石	10~30 ppm	4 m水层，5 mm HDPE隔离



中子(radiogenic)在外部材料上的俘获

- 高能gamma： 中子在金属、PMT玻璃和有机玻璃上的俘获产生
- 残留本底： < 0.001 cpd with R < 16.5 m

Fiducial volume cut的优化

- 本底压低到0.5%, 信号在高能区达到最大值

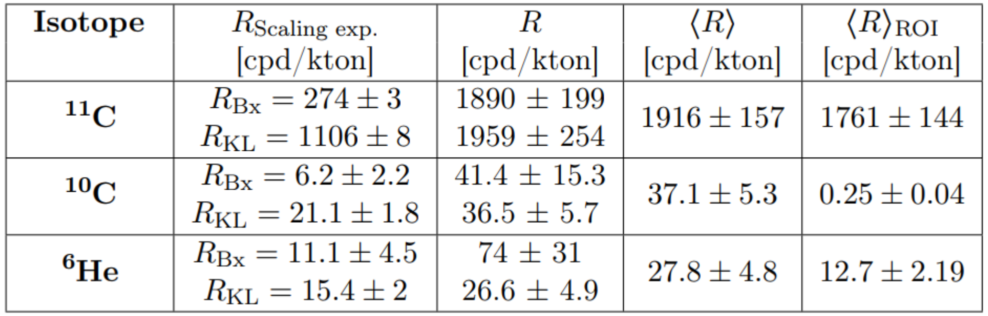
	R<16.5m	R<15m	R<13m	R<14m
Energy (MeV)	> 5	(3, 5)	(2, 3)	<2
靶质量 (kt)	16.2	12.2	7.9	9.9

CNO-宇生同位素本底

- ✓ ^{11}C (τ=29min), ^{10}C (τ=27.8s), ^{6}He (τ=1.16s)是此能区主要本底

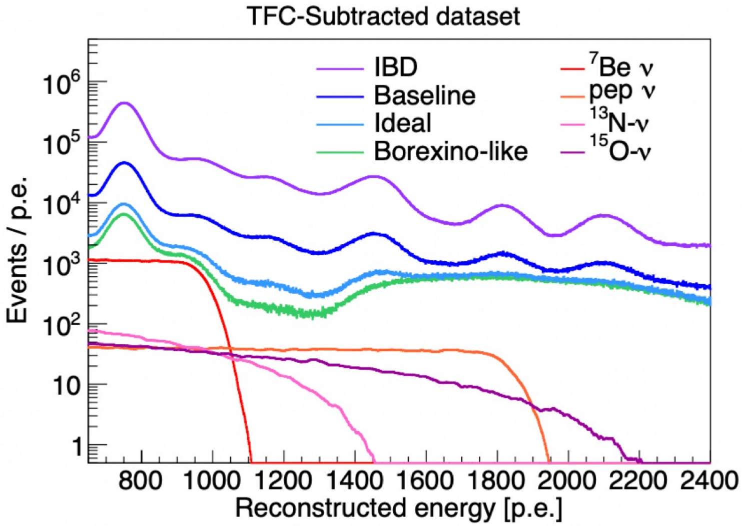
$$R^{\mathrm{JUNO}} = R^{\mathrm{ref}} \cdot \left(\frac{\bar{E}_\mu^{\mathrm{JUNO}}}{\bar{E}_\mu^{\mathrm{ref}}} \right)^{\alpha} \cdot \frac{\Phi(\mu)^{\mathrm{JUNO}}}{\Phi(\mu)^{\mathrm{ref}}} \cdot \frac{\epsilon_C^{\mathrm{JUNO}}}{\epsilon_C^{\mathrm{ref}}};$$

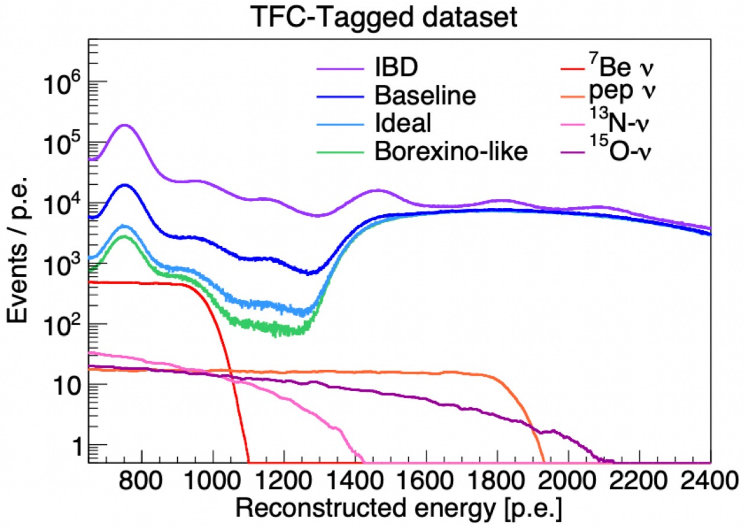
- ✓ ^{11}C半衰期很长，很难通过简单muon反符合策略去除



Isotope	$R_{\text{Scaling exp.}}$ [cpd/kton]	R [cpd/kton]	$\langle R \rangle$ [cpd/kton]	$\langle R \rangle_{\text{ROI}}$ [cpd/kton]
^{11}C	$R_{\text{Bx}} = 274 \pm 3$ $R_{\text{KL}} = 1106 \pm 8$	1890 ± 199 1959 ± 254	1916 ± 157	1761 ± 144
^{10}C	$R_{\text{Bx}} = 6.2 \pm 2.2$ $R_{\text{KL}} = 21.1 \pm 1.8$	41.4 ± 15.3 36.5 ± 5.7	37.1 ± 5.3	0.25 ± 0.04
^{6}He	$R_{\text{Bx}} = 11.1 \pm 4.5$ $R_{\text{KL}} = 15.4 \pm 2$	74 ± 31 26.6 ± 4.9	27.8 ± 4.8	12.7 ± 2.19

- ✓ 用TFC(Three-Fold-Coincidence)方法，将数据分成TFC-subtracted和TFC-tagged，在fitter中同时做拟合


TFC-Subtracted dataset


TFC-Tagged dataset