Prospects of neutrino mass ordering and solar neutrinos with JUNO

13 Feb 2019, 17:30 (MST) @Mt. Temple A, 12’+3’

Xuefeng Ding[1,2] on behalf of JUNO collaboration

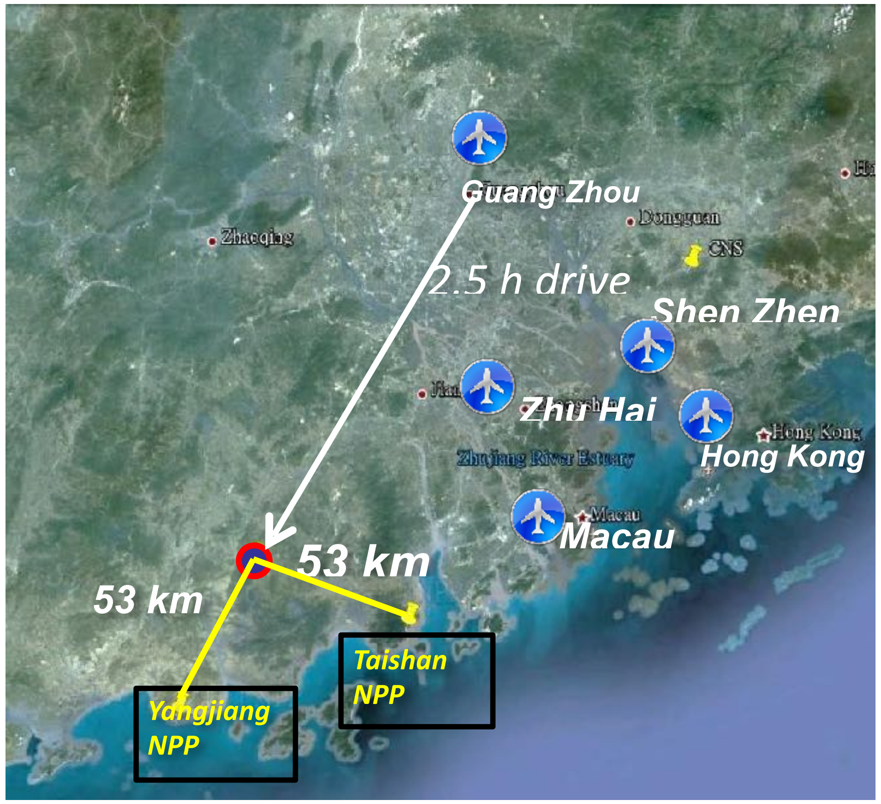
1. INFN Sezione di Milano, Milan, Italy
2. Gran Sasso Science Institute, L’Aquila, Italy

The Lake Louise Winter Institute 2019
@ Chateau Lake Louise, Edmonton, Alberta, Canada 10–16 February 2019

Outline

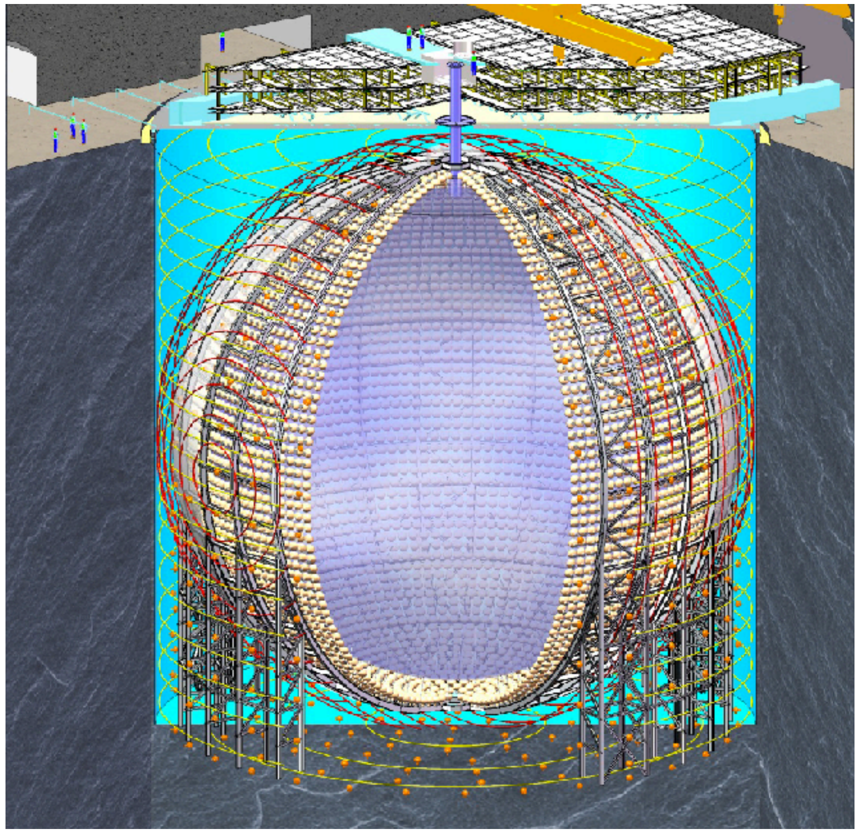
- JUNO project
- Neutrino mass ordering through Vacuum-Oscillation
- MSW resonance with solar neutrinos
- Conclusion

JUNO project

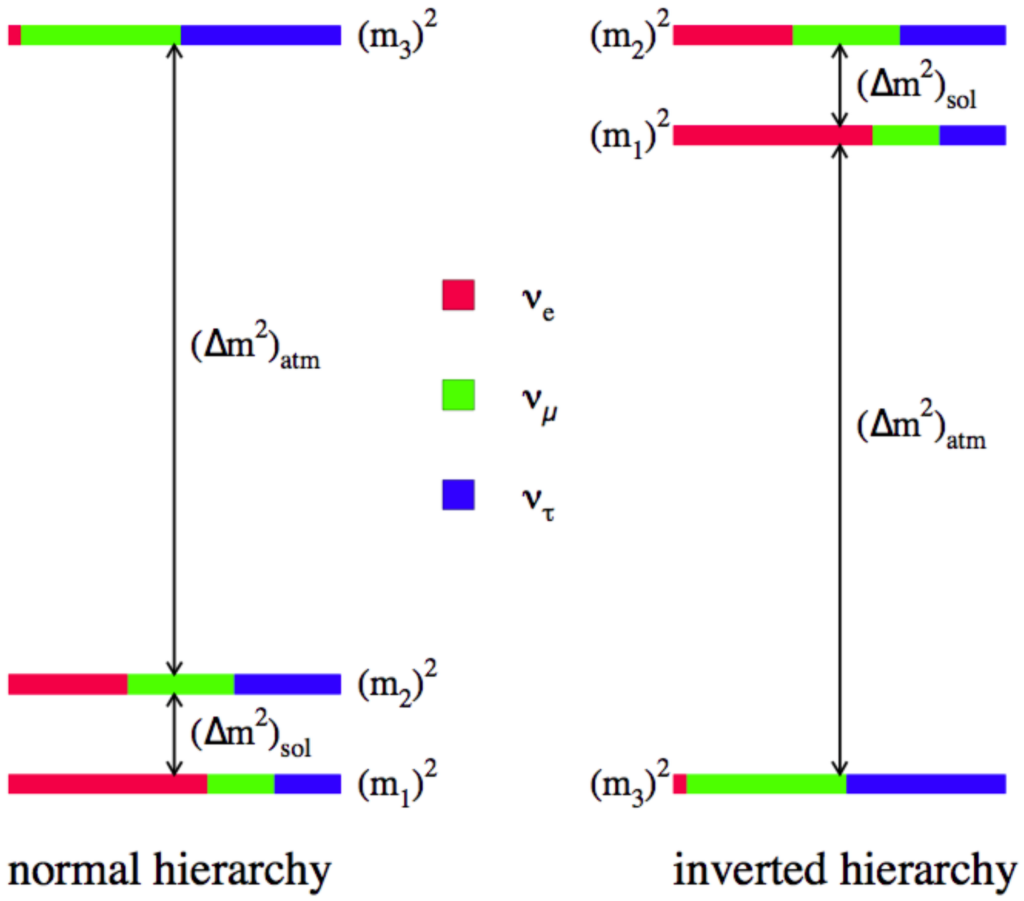


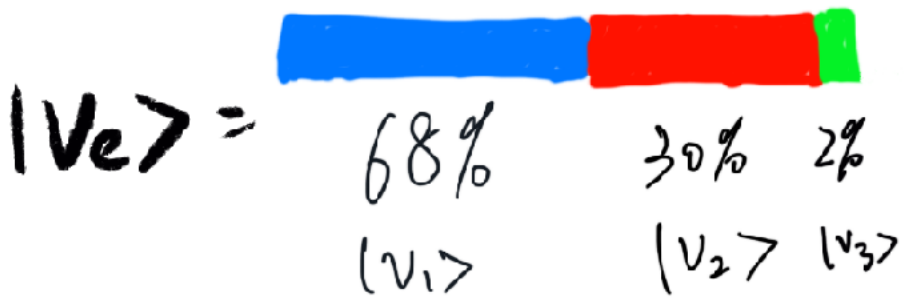
- Location: Kaiping, Jiangmen city, Guangdong province, China
- Reactor Anti-ν: **36 $\mathbf{GW_{th}}$** 27 GW_{th} by 2020

- Central detector: **20 kt** LS + **78%** PMT coverage
- Multi-purpose detector, optimized for **neutrino Mass Ordering** determination



What and **Why** mass ordering?





- ν_1, ν_2, ν_3 defined according to fraction in ν_e
- ν_2 is heavier than ν_1 (sun+MSW)
- we don't know if ν_3 is heavier (Normal ordering, NO) or lighter (Inverted ordering, IO) than ν_2

NMO

neutrino mass ordering

See F. An, et al., "Neutrino physics with JUNO," J. Phys. G Nucl. Part. Phys., vol. 43, no. 3, p. 030401, 2016. page 22

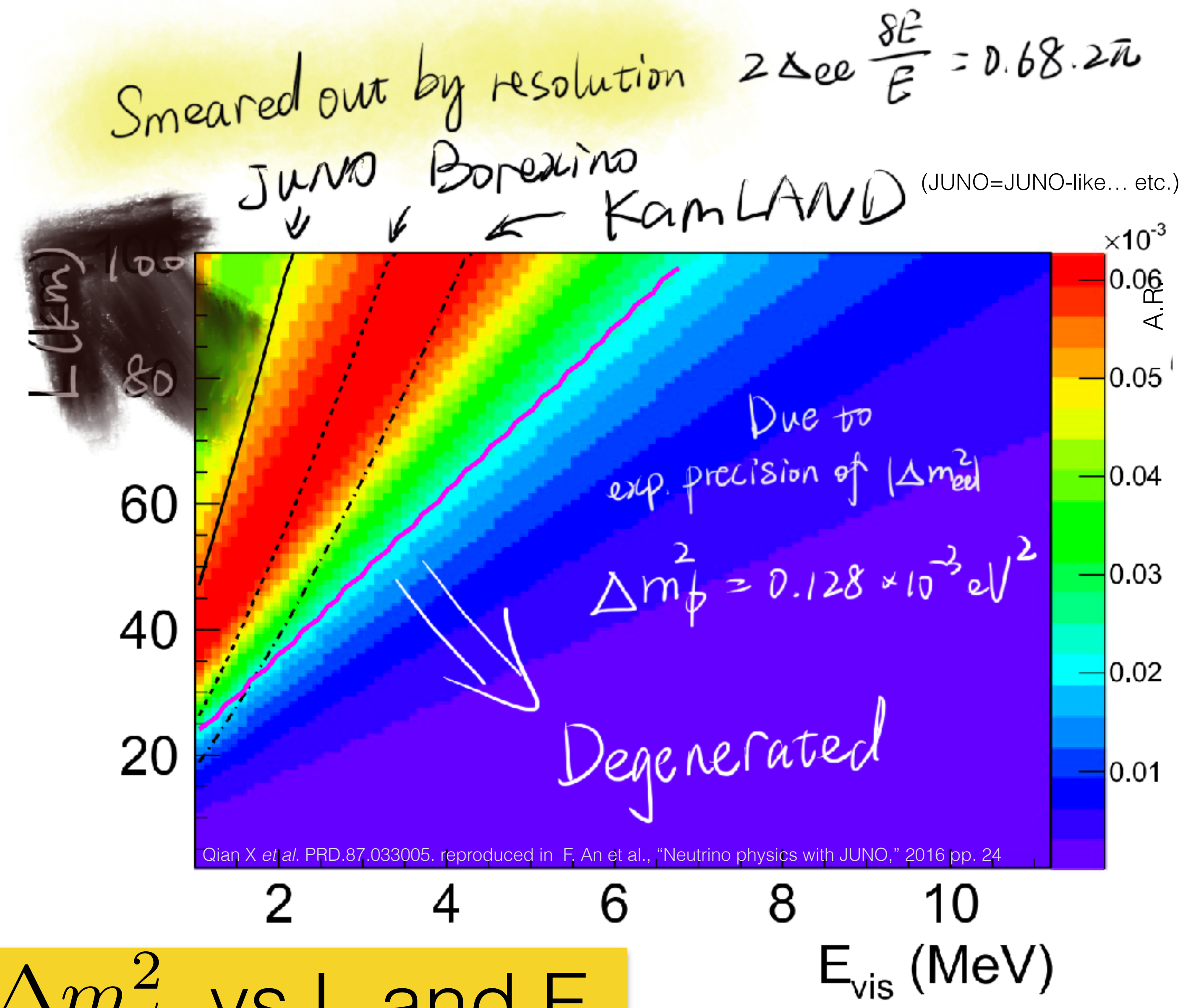
- Discriminators for models building ν mass
- Understand requirement for 0νββ experiment
- Reduce uncertainty on δ_{CP}
- Help to understand core-collapse supernovae
- Needed by absolute neutrino mass measurement

Medium-baseline reactor ν exp.

$$P_{ee}\left(\xi\right) = a_0\left(\xi\right) + a_1\left(\xi\right) \cdot {\color{blue}\sin^2 2\theta_{13}} \cdot \cos\left[1.27\left(2\Delta m_{ee}^2 {\color{red}\pm \Delta m_\phi^2}\right) \cdot \xi\right]$$

P_{ee}\left(\xi\right) = a_0\left(\xi\right) + a_1\left(\xi\right) \cdot {\color{blue} \sin^22\theta_{13}} \cdot \cos\left[1.27 \left(2\Delta m_{ee}^2 {\color{red}\pm \Delta m_\phi^2 }\right) \cdot \xi\right]

$$\xi = \frac{L\,(\mathrm{m})}{E\,(\mathrm{MeV})}$$



Smeared out by resolution $2\Delta_{ee}\frac{\delta E}{E} = 0.68\cdot 2\pi$

JUNO Borexino KamLAND

(JUNO=JUNO-like… etc.)

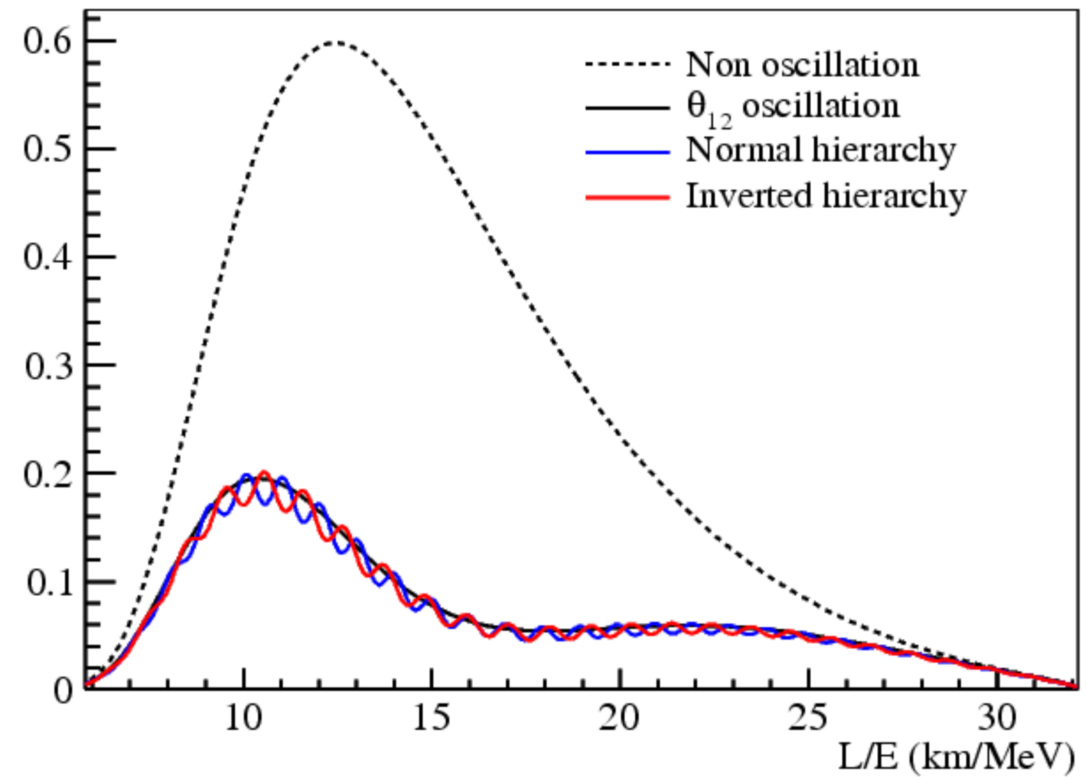
Due to exp. precision of $|\Delta m^2_{ee}|$

$\Delta m^2_\phi = 0.128\times 10^{-3}\,\mathrm{eV}^2$

Degenerated

Qian X *et al.* PRD.87.033005. reproduced in F. An et al., "Neutrino physics with JUNO," 2016 pp. 24

Relative shape difference of Anti-ν flux

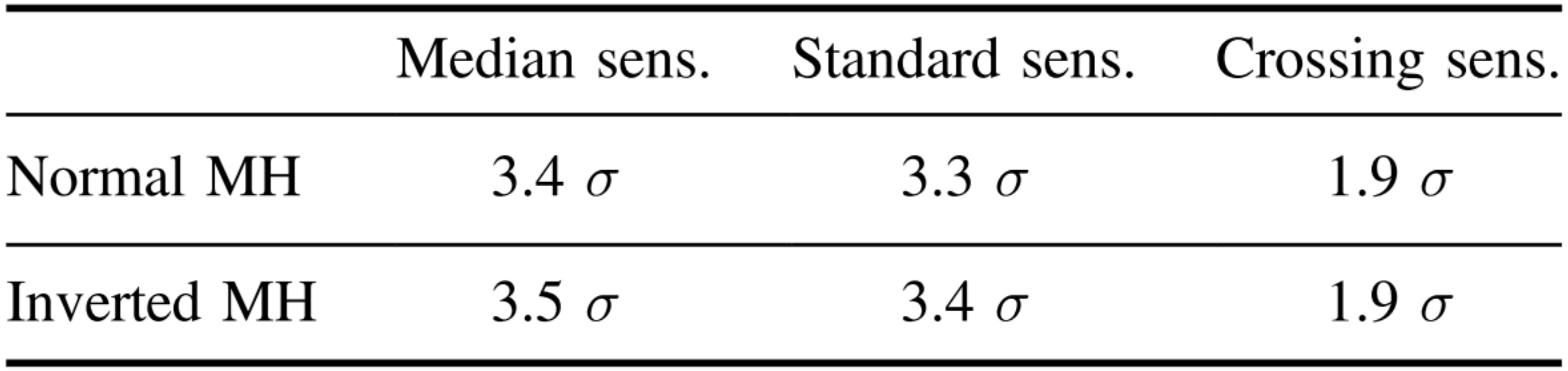


Zhan L *et al.* PRD 78 111103

Δm^2_ϕ vs L and E

Sensitivity and important factors

- 20 kt x 6 years x 73% efficiency, 36 GW_{th}



	Median sens.	Standard sens.	Crossing sens.
Normal MH	$3.4\ \sigma$	$3.3\ \sigma$	$1.9\ \sigma$
Inverted MH	$3.5\ \sigma$	$3.4\ \sigma$	$1.9\ \sigma$

F. An et al., “Neutrino physics with JUNO,” 2016 pp. 35

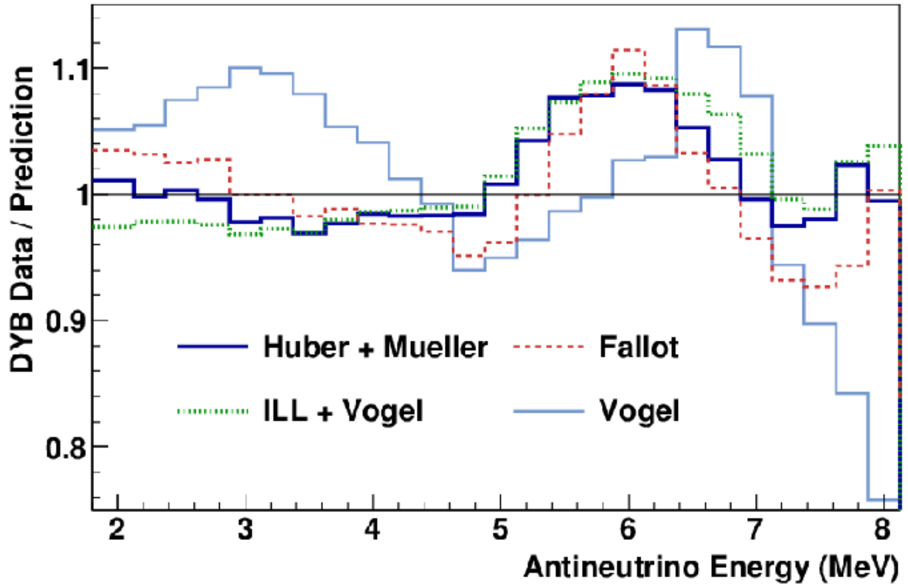
Important factors

- Energy resolution JUNO Yellow Book
  - High transparency LS (L_{att}>25 m)
  - High PDE PMT (~30%) & High coverage (18k PMT, 78%)
- Energy non-linearity Li Y.F. et al. PRD 88.013008
- Reactor spectrum uncertainty Zhan L. ESCAPE 2018
- Other factors

F. An, et al., “Neutrino physics with JUNO,” J. Phys. G Nucl. Part. Phys., vol. 43, no. 3, p. 030401, 2016

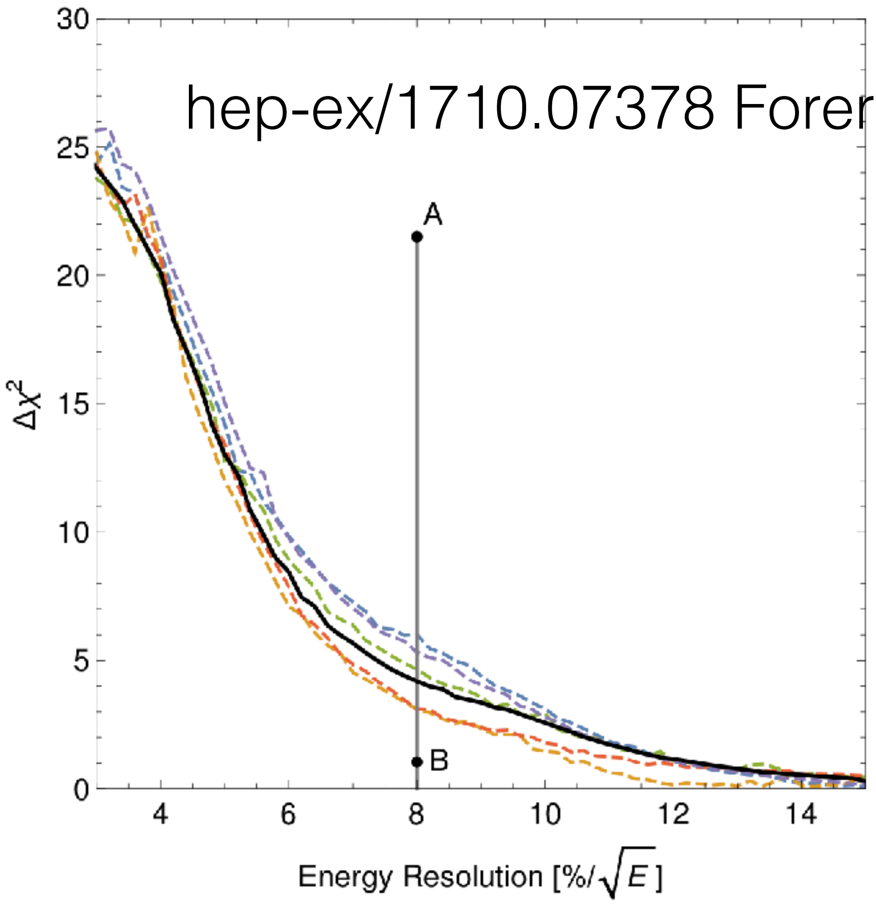
Reactor ν spectrum uncertainty

- Currently the predicted antineutrino spectrum have **discrepancy** (at 10% level) with respect to the observed antineutrino spectrum, also **fine structure** is missing in models
- **Known fine structure** does not hurt JUNO: Xin Qian took 6 spectra with fine local structure from ab initio calculation (PRL 114, 012502 (2015)), and fluctuate the spectra in JUNO sensitivity calculation => no major effect
- **Unknown fine structure** (infinite uncertainty) has larger impact (Huber)
- **Near detector** proposed to constrain



By An F.P.

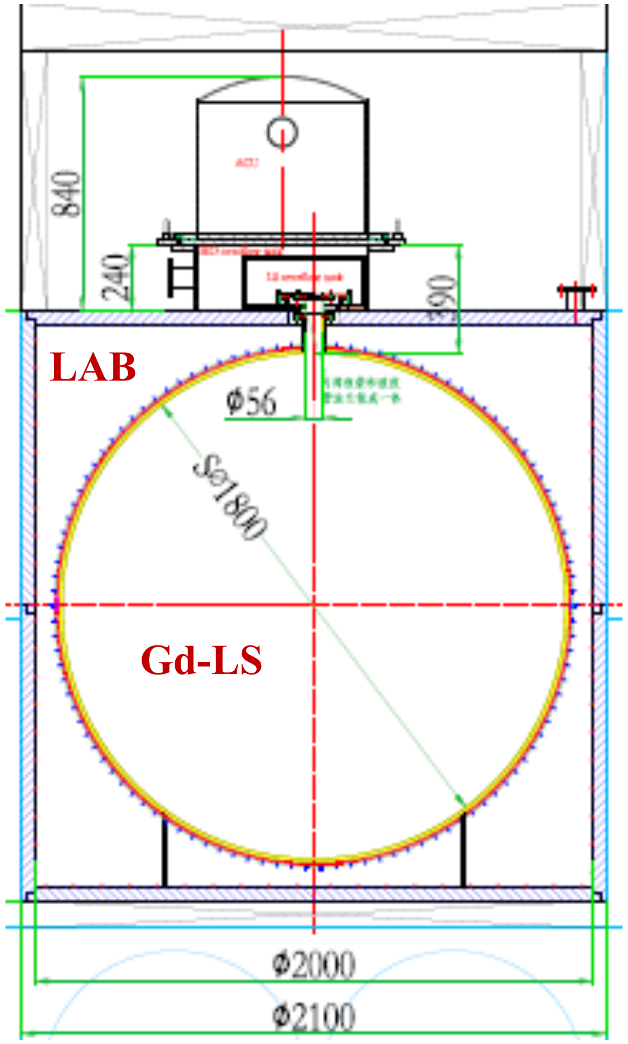
Zhan, Liang. (2018, June). Proposal of a Near Detector for JUNO Experiment. ESCAPE 2018



hep-ex/1710.07378 Forero et al.

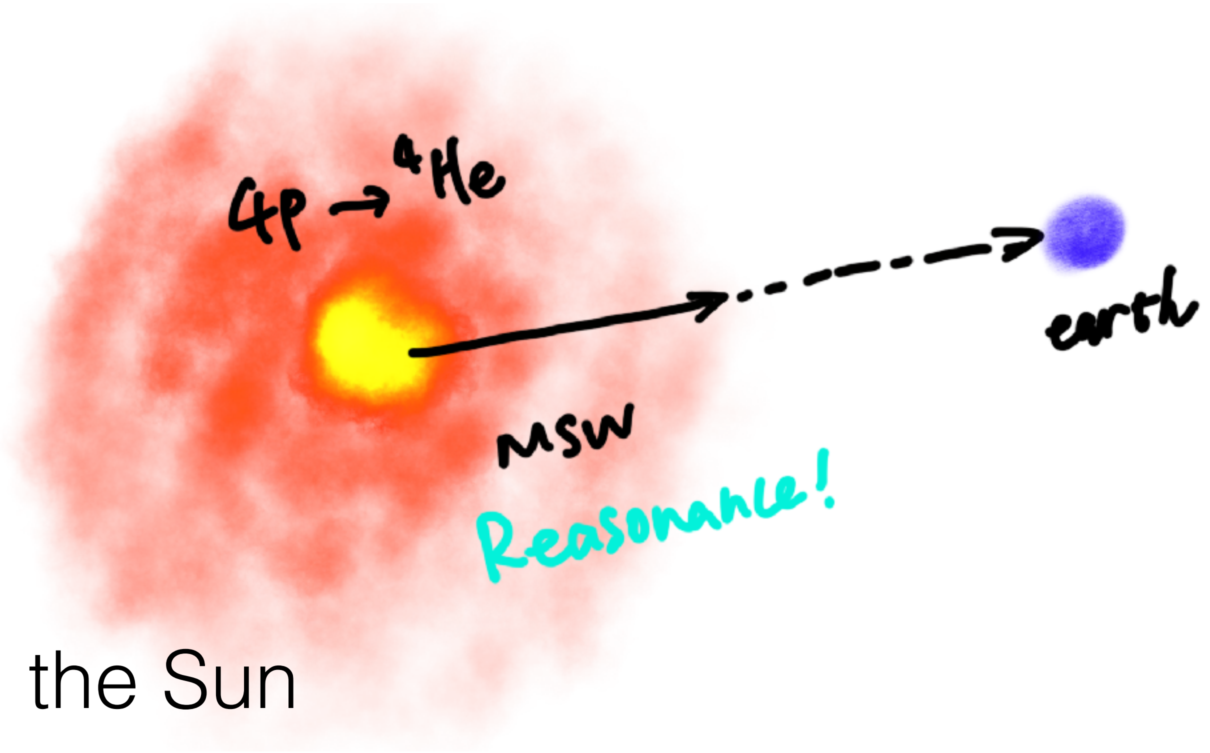
JUNO-TAO: “near detector”

- High resolution reactor anti-neutrino spectrum
- benchmark for investigation of nuclear database
- Search for sterile neutrino



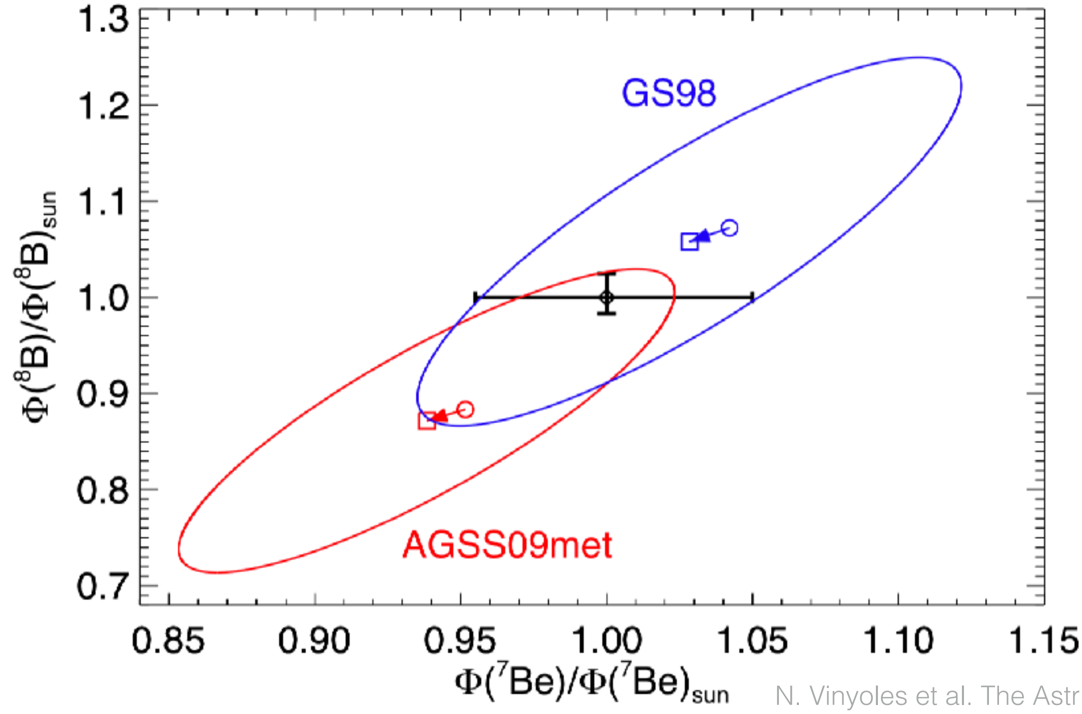
- Taishan Antineutrino Observatory (TAO)
- 1 ton fiducial mass @ 30 meters from core
  - 30 times JUNO event rate
- Full coverage 10 m^2 SiPM with 50% PDE
  - energy resolution of 1.7%/√E(MeV)
- R&D in progress
  - welcome new collaborators !

What and **Why** solar neutrino?



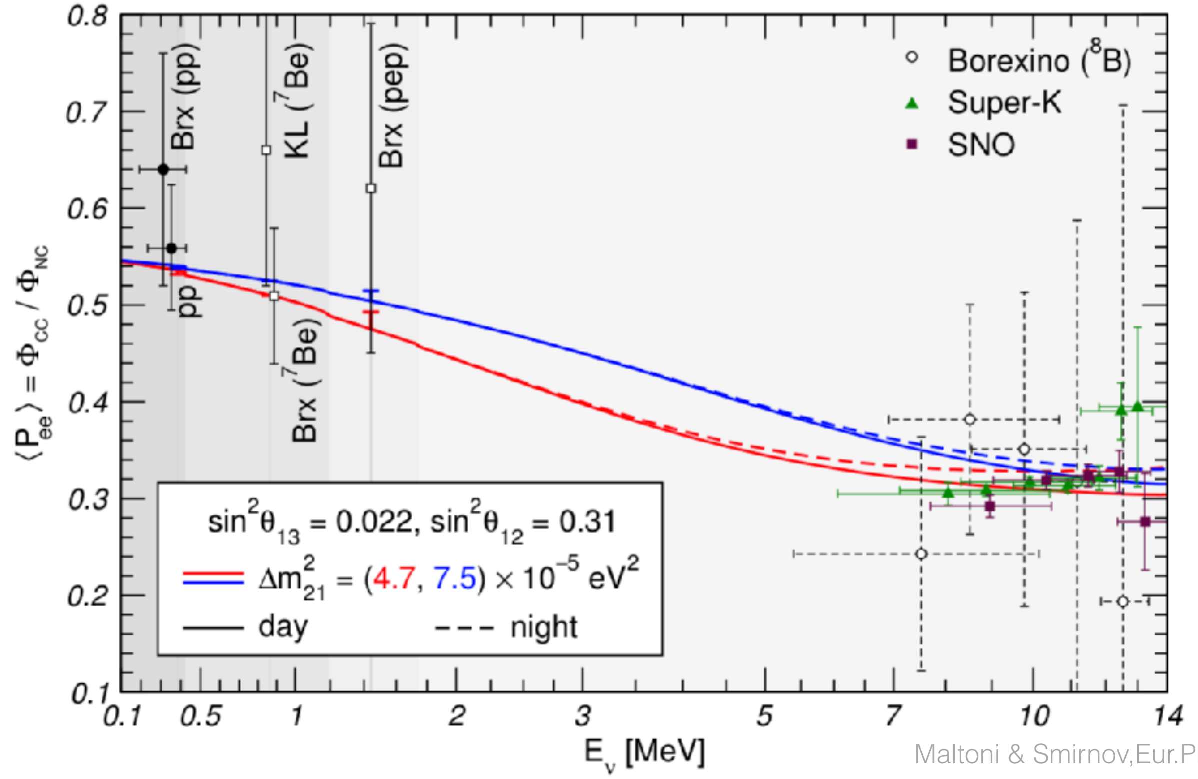
- Solar neutrino is produced in the **core region of the Sun**. => study the core of the Sun
- Solar neutrinos propagate through **ultra-high-density region** and become **flavor-stable** => study MSW resonance (up turn, $\sin^2\theta_{12}$)

Two solar metallicity models



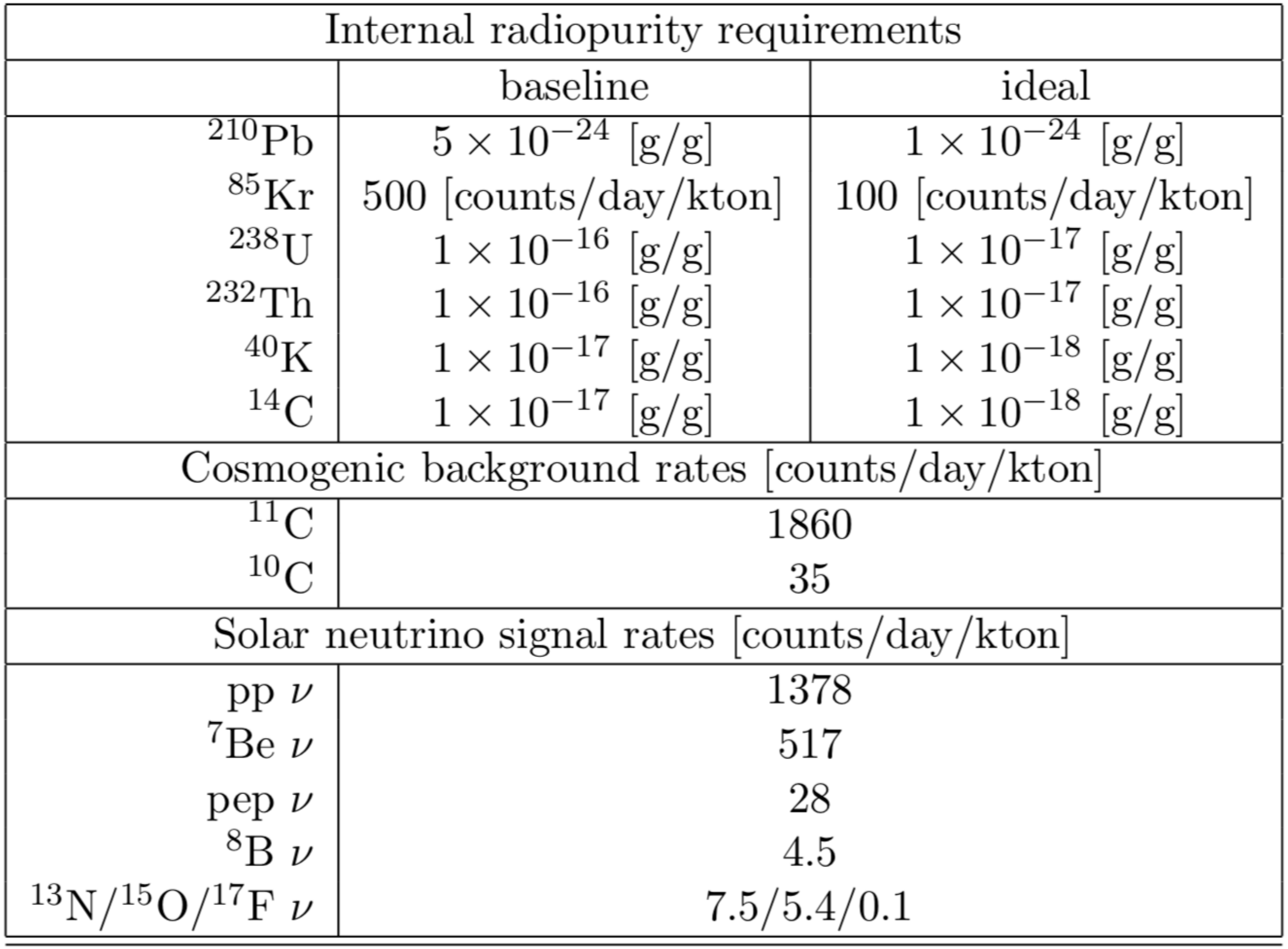
N. Vinyoles et al. The Astrph. Journ. 835 1 (2017) Improoved model

Solar vs global MSW-LMA survival prob.

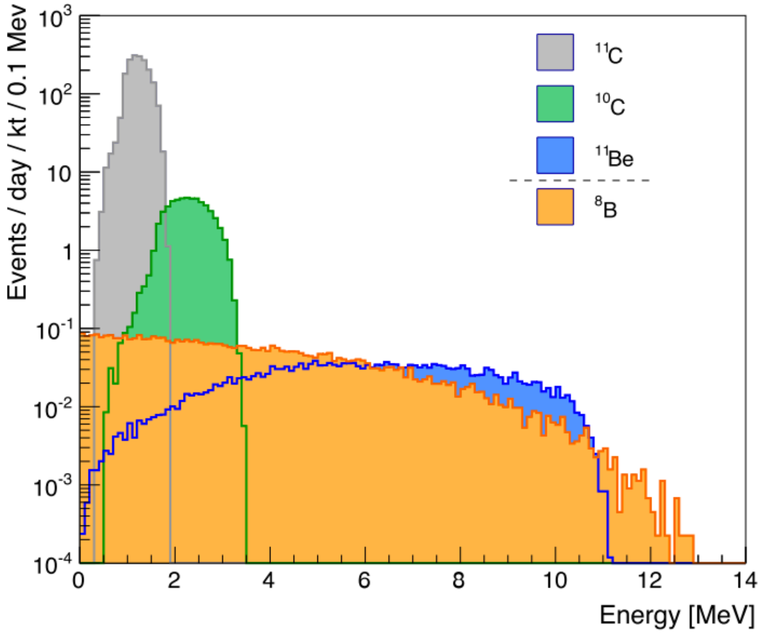


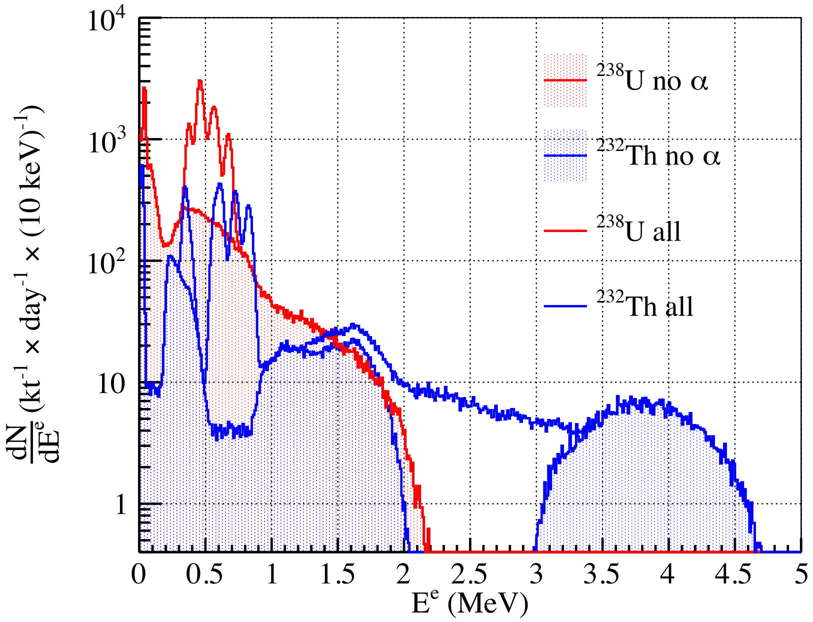
Maltoni & Smirnov,Eur.Phys.J.2016

solar neutrino challenge: backgrounds



Internal radiopurity requirements		
	baseline	ideal
^{210}Pb	5×10^{-24} [g/g]	1×10^{-24} [g/g]
^{85}Kr	500 [counts/day/kton]	100 [counts/day/kton]
^{238}U	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{232}Th	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{40}K	1×10^{-17} [g/g]	1×10^{-18} [g/g]
^{14}C	1×10^{-17} [g/g]	1×10^{-18} [g/g]
Cosmogenic background rates [counts/day/kton]		
^{11}C	1860	
^{10}C	35	
Solar neutrino signal rates [counts/day/kton]		
pp ν	1378	
^{7}Be ν	517	
pep ν	28	
^{8}B ν	4.5	
^{13}N/^{15}O/^{17}F ν	7.5/5.4/0.1	

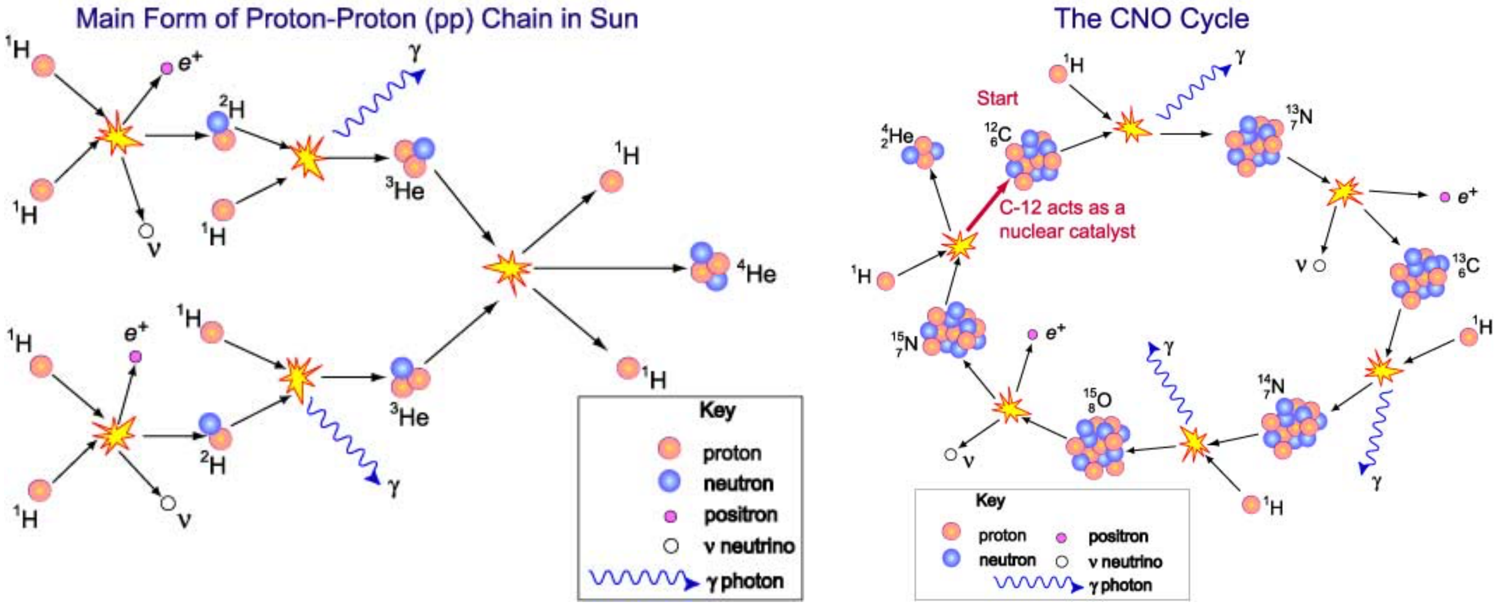


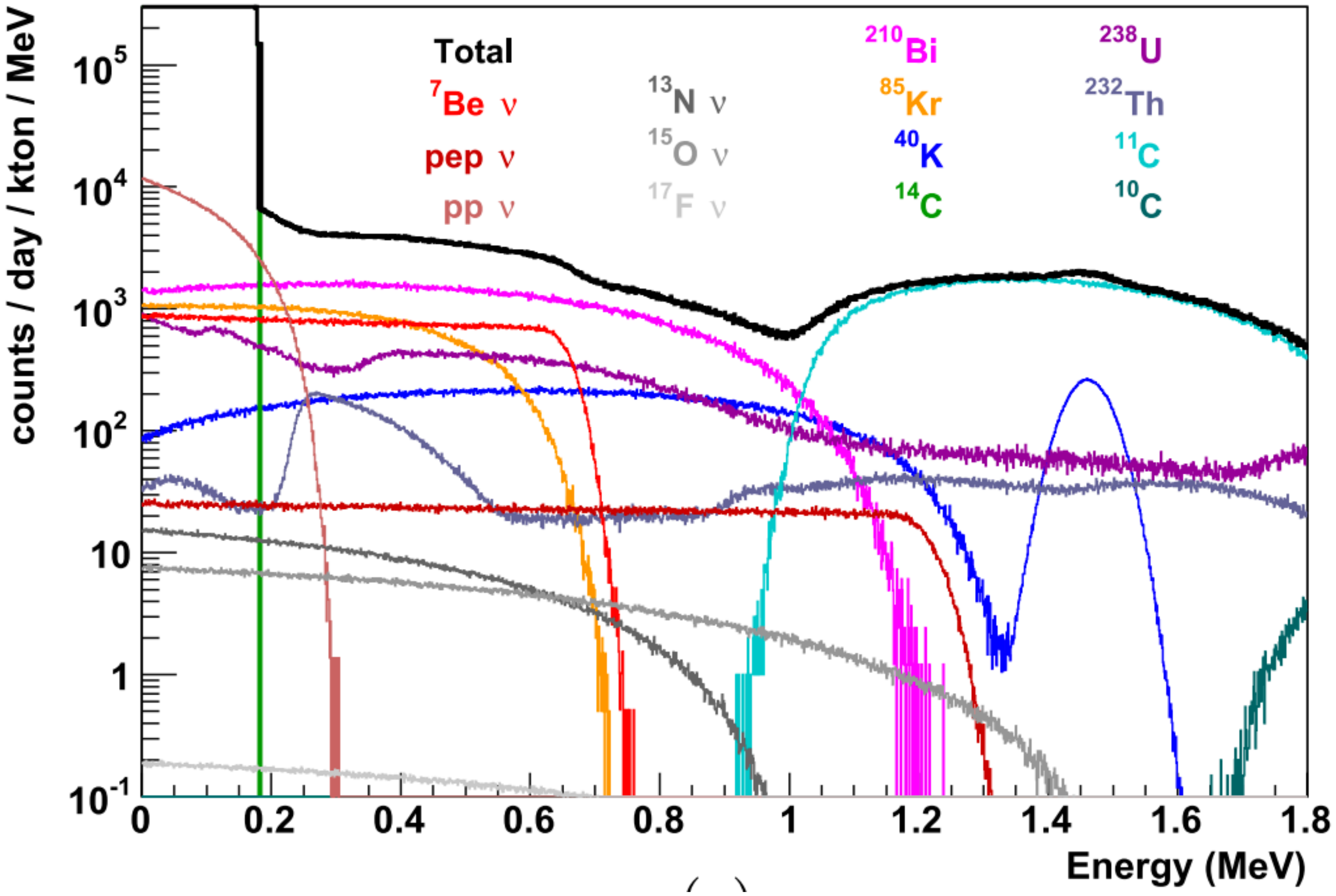


- Cosmogenic ^{10}C and ^{11}Be: produced by muon, can be suppressed using an algorithm tagging cosmogenic neutrons
- ^{238}U/^{232}Th: α related coincidence can be rejected by pulse shape discriminators

ν(^{7}Be) & ν(CNO)

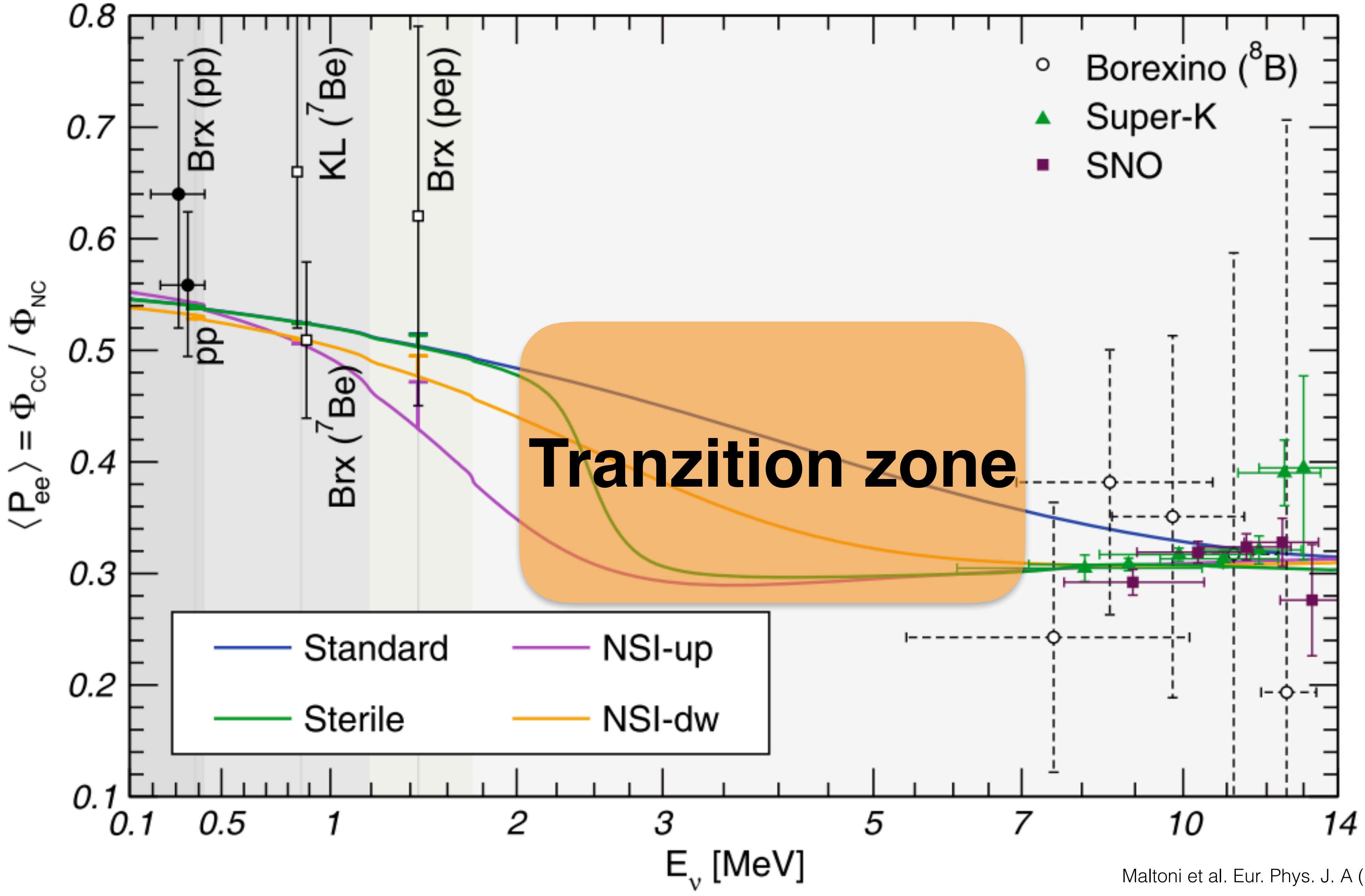
- Solar neutrino interaction rates extracted by fitting
- Dominated by systematic uncertainties
- Considering 0.5% energy scale precision, the ν(^{7}Be) precision can reach 7%, there is no sensitivity on ν(CNO).
- The sensitivity to ν(CNO) can be improved by improving energy scale precision and reducing ^{11}C





2 MeV ^{8}B

- Transition zone: space and indication of new physics

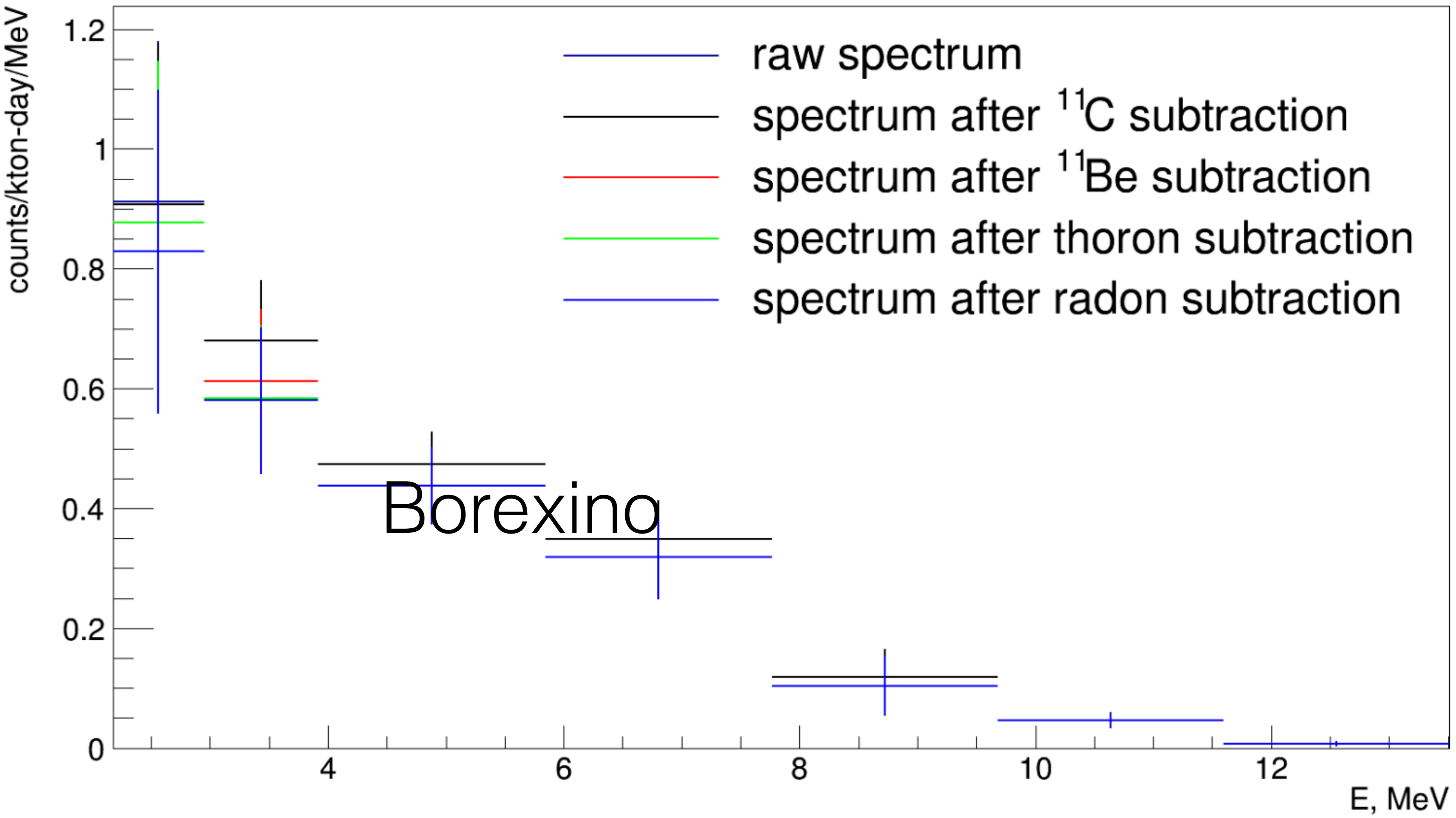


Maltoni et al. Eur. Phys. J. A (2016) 52:87

2 MeV threshold ^{8}B in JUNO

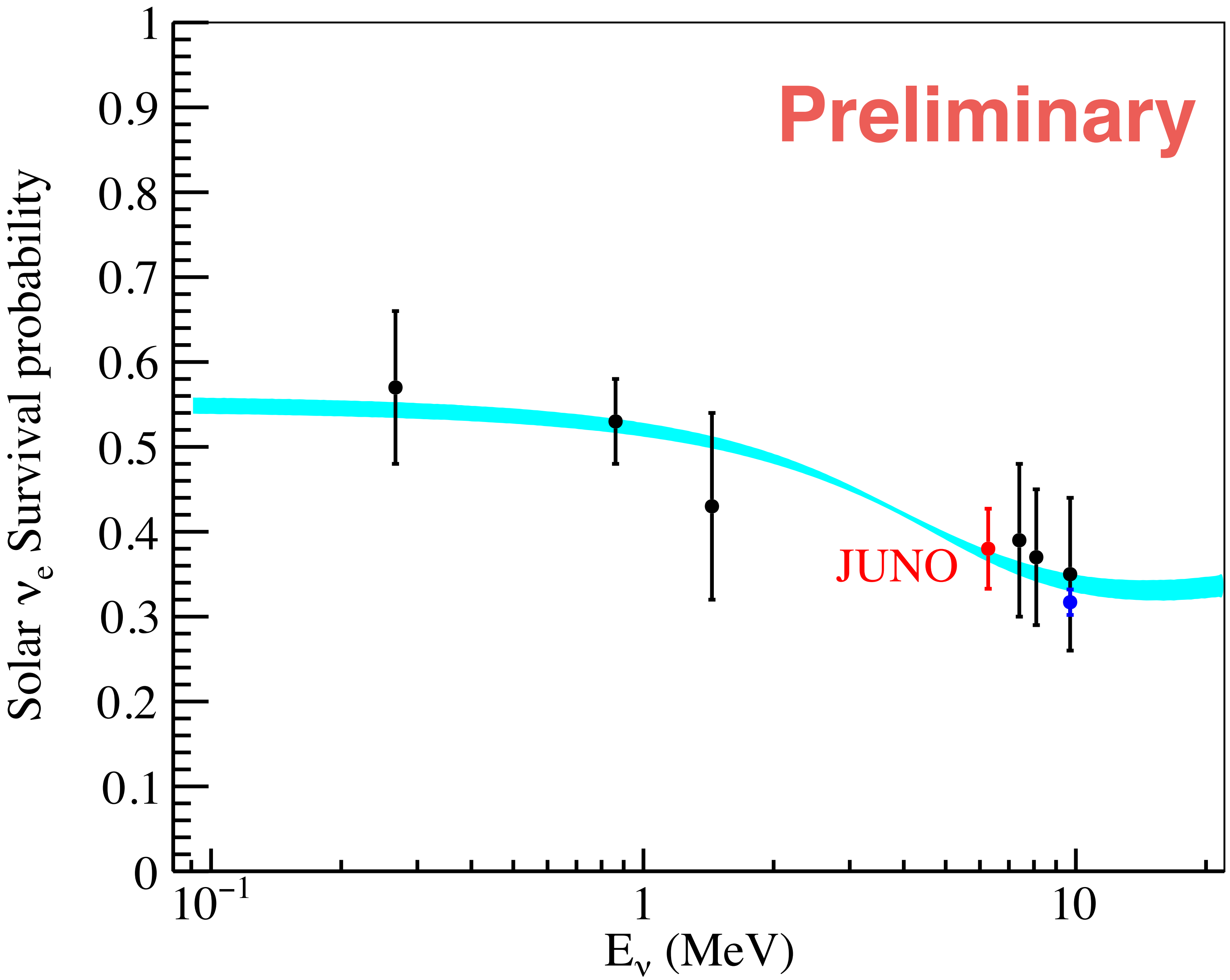
- Borexino: can reach 2.2 MeV visible energy threshold, but limited by size.

I. Drachnev, “New Spectral Analysis of Solar B Neutrino with the Borexino Detector,” Gran Sasso Science Institute, 2016.



solar ν(^{8}B) sensitivity

- JUNO: 2:1 S/B ratio in 2~3 MeV. ~ 10^3 ev/yr after all cuts
  - Average neutrino energy 7.09 MeV



Cyan: theoretical prediction. (PDG 2018)
Black: Borexino, Nature 2018
Blue: SNO & SuperK-IV
Red: this work. Including uncertainty on ν(^{8}B) flux

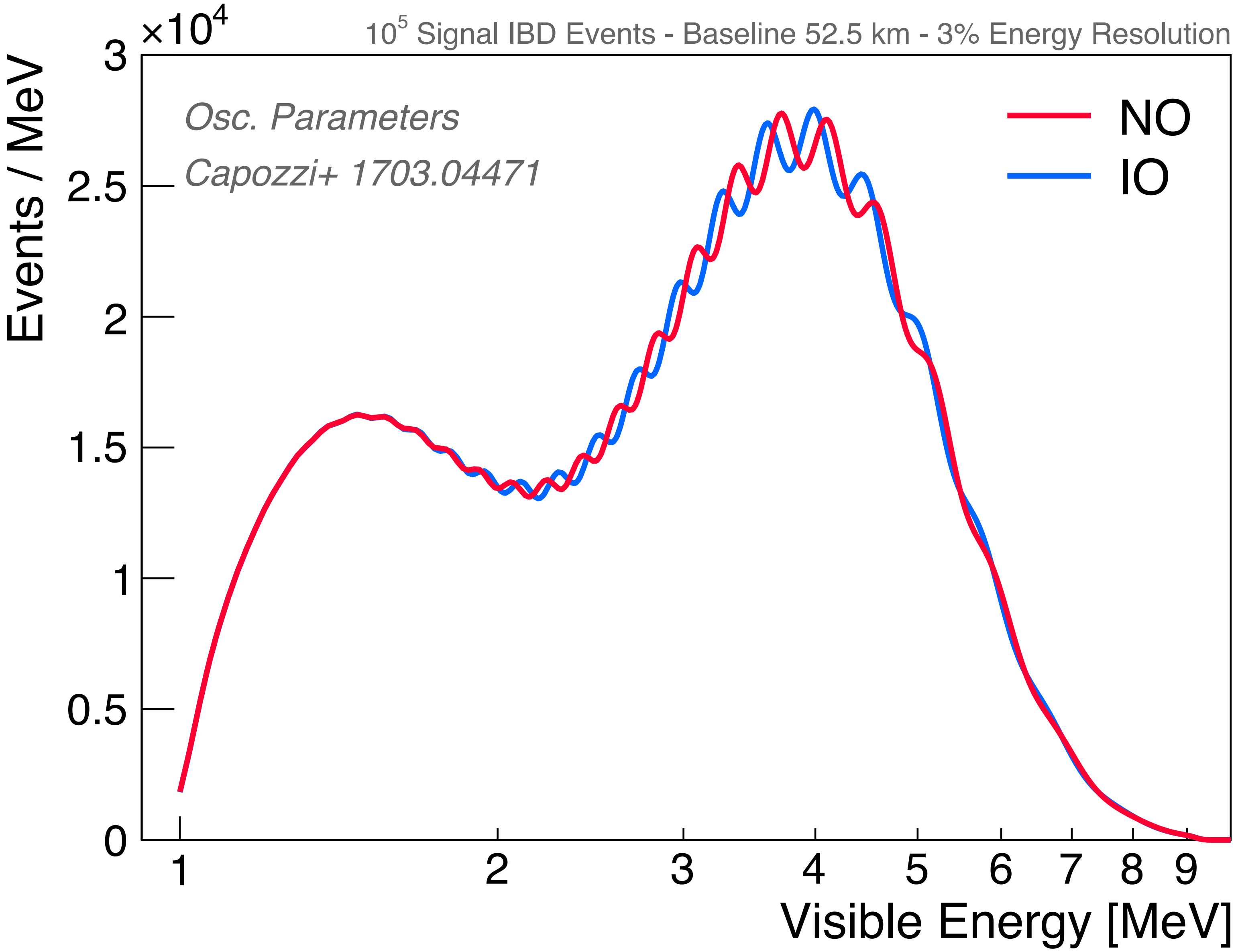
Conclusions

- JUNO's median sensitivity on determining Neutrino Mass Ordering is ~3.4σ with 6 years of data
  - The **fine structure** will not hurt the sensitivity.
  - R&D of **TAO** (Near detector) has started.
- Expected **statistical** uncertainty on **CNO is 2%**, and will be dominated by systematic uncertainty.
- **2:1 S/B in [2, 3] MeV** visible energy range for **ν(^{8}B)**.
  - average neutrino energy is 7 MeV, touching the transition zone and probing new physics

Backup

Smeared spectrum

- Example spectrum smeared with $\frac{\sigma_E}{E} = \sqrt{\left(\frac{1}{1200E}\right)^2 + (0.82\%)^2}$



pp-^{7}Be-pep-CNO external γ bkg.

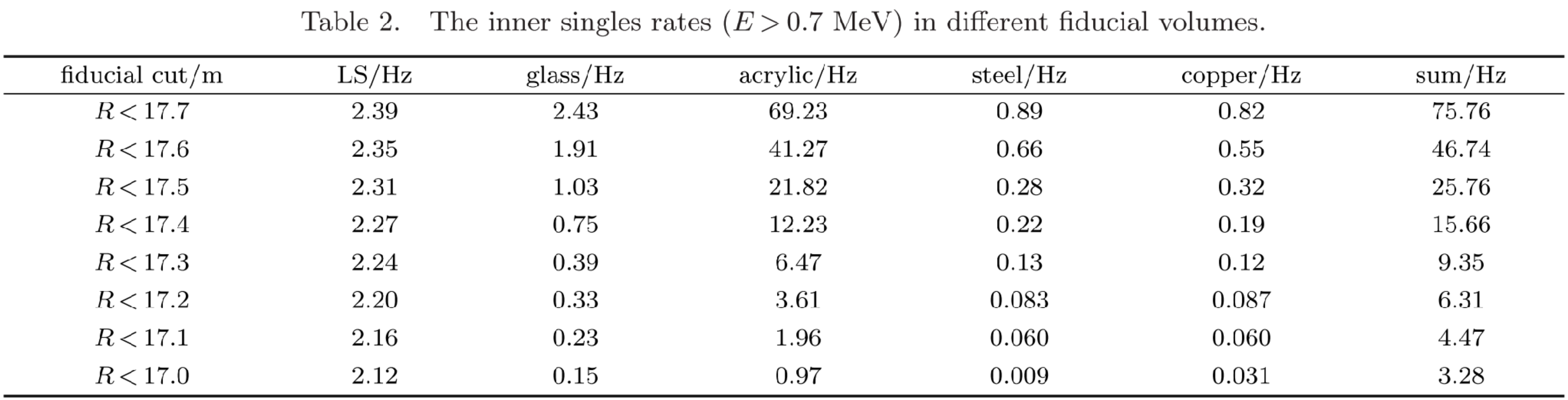


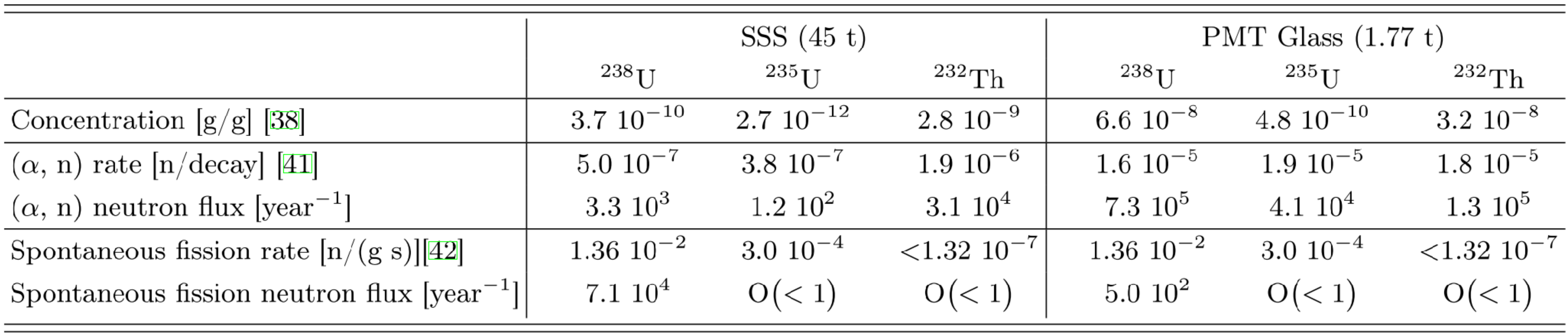
Table 2. The inner singles rates ($E > 0.7$ MeV) in different fiducial volumes.

fiducial cut/m	LS/Hz	glass/Hz	acrylic/Hz	steel/Hz	copper/Hz	sum/Hz
$R < 17.7$	2.39	2.43	69.23	0.89	0.82	75.76
$R < 17.6$	2.35	1.91	41.27	0.66	0.55	46.74
$R < 17.5$	2.31	1.03	21.82	0.28	0.32	25.76
$R < 17.4$	2.27	0.75	12.23	0.22	0.19	15.66
$R < 17.3$	2.24	0.39	6.47	0.13	0.12	9.35
$R < 17.2$	2.20	0.33	3.61	0.083	0.087	6.31
$R < 17.1$	2.16	0.23	1.96	0.060	0.060	4.47
$R < 17.0$	2.12	0.15	0.97	0.009	0.031	3.28

[1] X. Li, "Simulation of natural radioactivity backgrounds in the JUNO central detector *," vol. 026001.

pep(28 cpd/kt)

1/20 every 0.5m, R_0 = 74 Hz -> 1cpd/kt



	SSS (45 t)			PMT Glass (1.77 t)		
	^{238}U	^{235}U	^{232}Th	^{238}U	^{235}U	^{232}Th
Concentration [g/g] [38]	$3.7\ 10^{-10}$	$2.7\ 10^{-12}$	$2.8\ 10^{-9}$	$6.6\ 10^{-8}$	$4.8\ 10^{-10}$	$3.2\ 10^{-8}$
(α, n) rate [n/decay] [41]	$5.0\ 10^{-7}$	$3.8\ 10^{-7}$	$1.9\ 10^{-6}$	$1.6\ 10^{-5}$	$1.9\ 10^{-5}$	$1.8\ 10^{-5}$
(α, n) neutron flux [year^{-1}]	$3.3\ 10^{3}$	$1.2\ 10^{2}$	$3.1\ 10^{4}$	$7.3\ 10^{5}$	$4.1\ 10^{4}$	$1.3\ 10^{5}$
Spontaneous fission rate [n/(g s)][42]	$1.36\ 10^{-2}$	$3.0\ 10^{-4}$	$<1.32\ 10^{-7}$	$1.36\ 10^{-2}$	$3.0\ 10^{-4}$	$<1.32\ 10^{-7}$
Spontaneous fission neutron flux [year^{-1}]	$7.1\ 10^{4}$	O(<1)	O(<1)	$5.0\ 10^{2}$	O(<1)	O(<1)

JUNO: ~16 t SS, PMT: 177 t

^{8}B: 4.5 cpd/kt

BX 1.9 cpd/kt

JUNO 190 cpd/kt -> 0.1 cpd/kt

Systematics from **Energy NL**

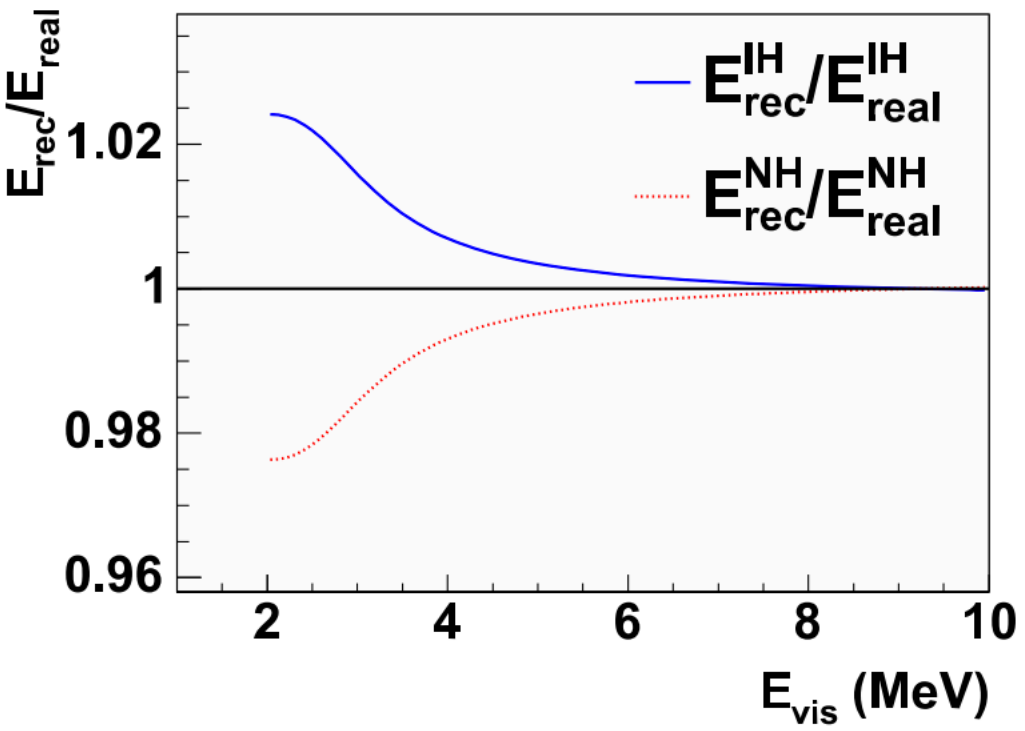
$$P_{ee} = a + b\cdot\sin^2\left(2\pi\cdot(\omega_0 \pm \omega(E))\cdot E_{\text{rec.}}^{-1}\right)$$

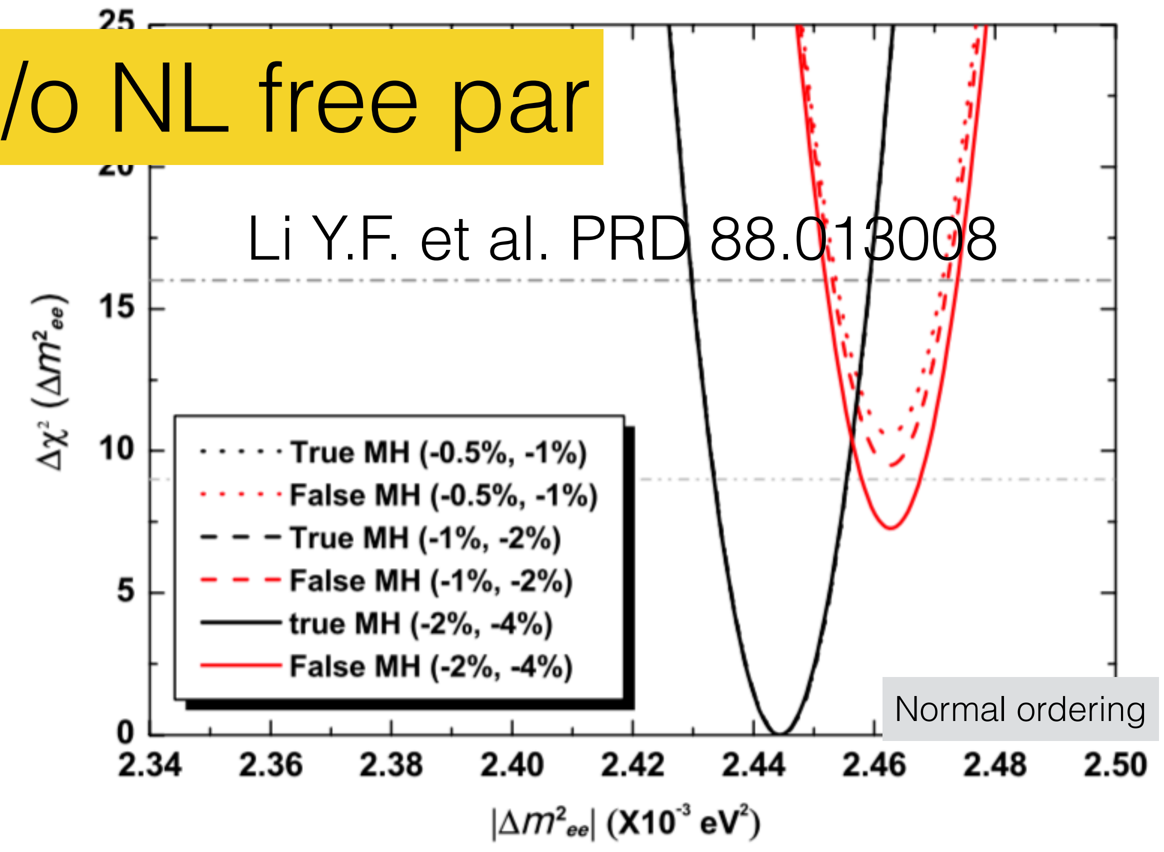
$$E_{\text{rec.}} = \frac{\omega_0+\omega(E)}{\omega_0-\omega(E)}E_{\text{real}}$$

- **Special** residual NL can **invert** P_{ee}
- **Improved** by introducing **NL free par**
- **accurate NL**. DayaBay can do 0.5%

Yu, Zeyuan. (2018, June). Calibration and Energy Scale in Daya Bay. Zenodo. http://doi.org/10.5281/zenodo.1314378

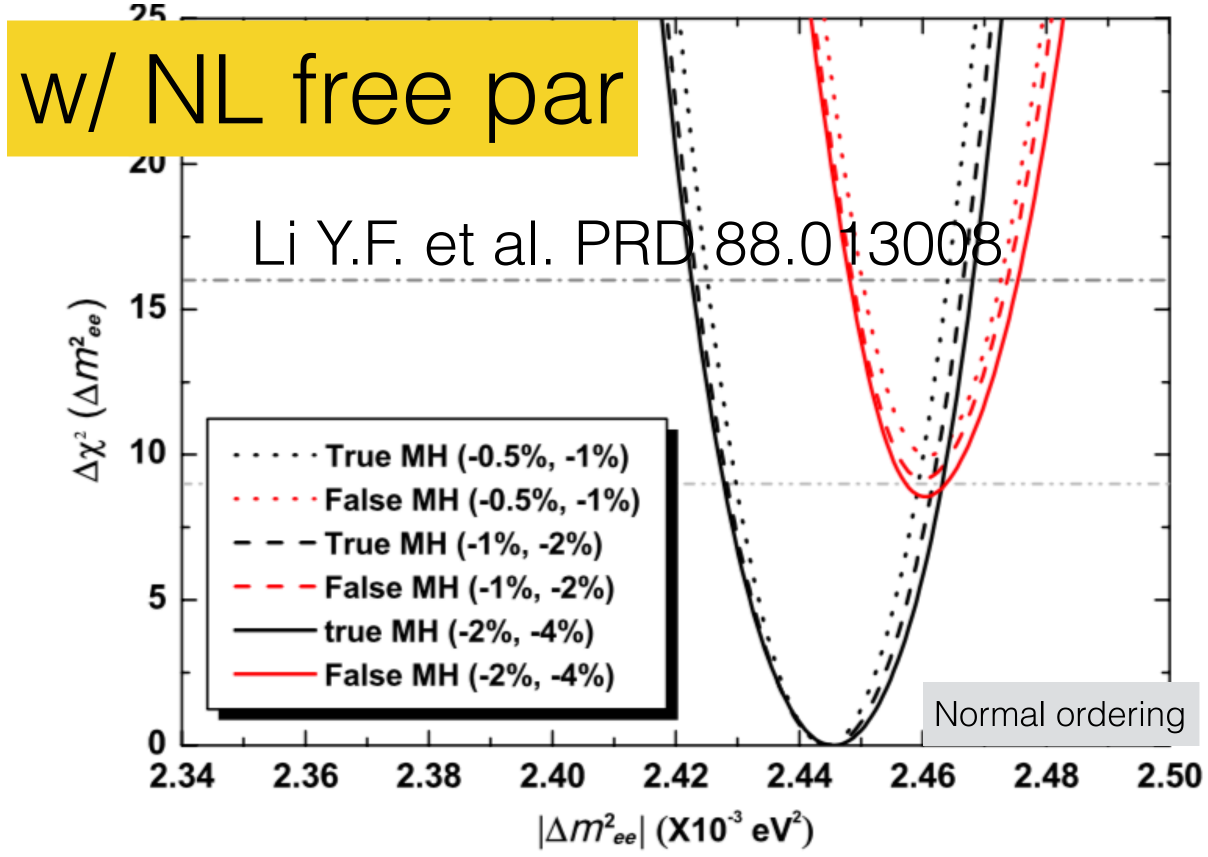
Qian X. et al. PRD.87.033005




w/o NL free par

Li Y.F. et al. PRD 88.013008

Normal ordering


w/ NL free par

Li Y.F. et al. PRD 88.013008

Normal ordering

“Constant term” in **Energy resolution**

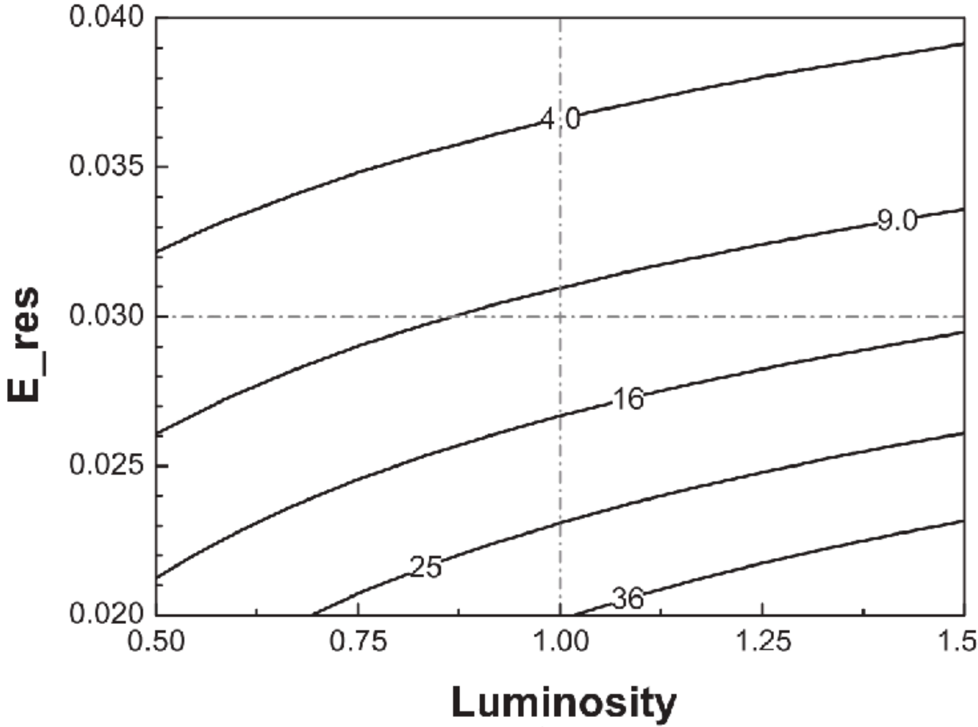
$$\mathrm{Var}[E_{\mathrm{rec.}}] = \sigma_0^2 + \sigma_1^2 \cdot \mu_{E_{\mathrm{rec.}}} + \sigma_2^2 \cdot \mu_{E_{\mathrm{rec.}}}^2$$

- σ_0: dark noise;
- σ_1: single p.e. charge resolution, light yield
- σ_2: history of dE/dx, quenching, residual non-uniformity

- **Importance to JUNO MO sensitivity**: $\frac{\sigma_0}{1.6} \sim \sigma_1 \sim 1.6 \cdot \sigma_2$

Requirement on energy resolution:

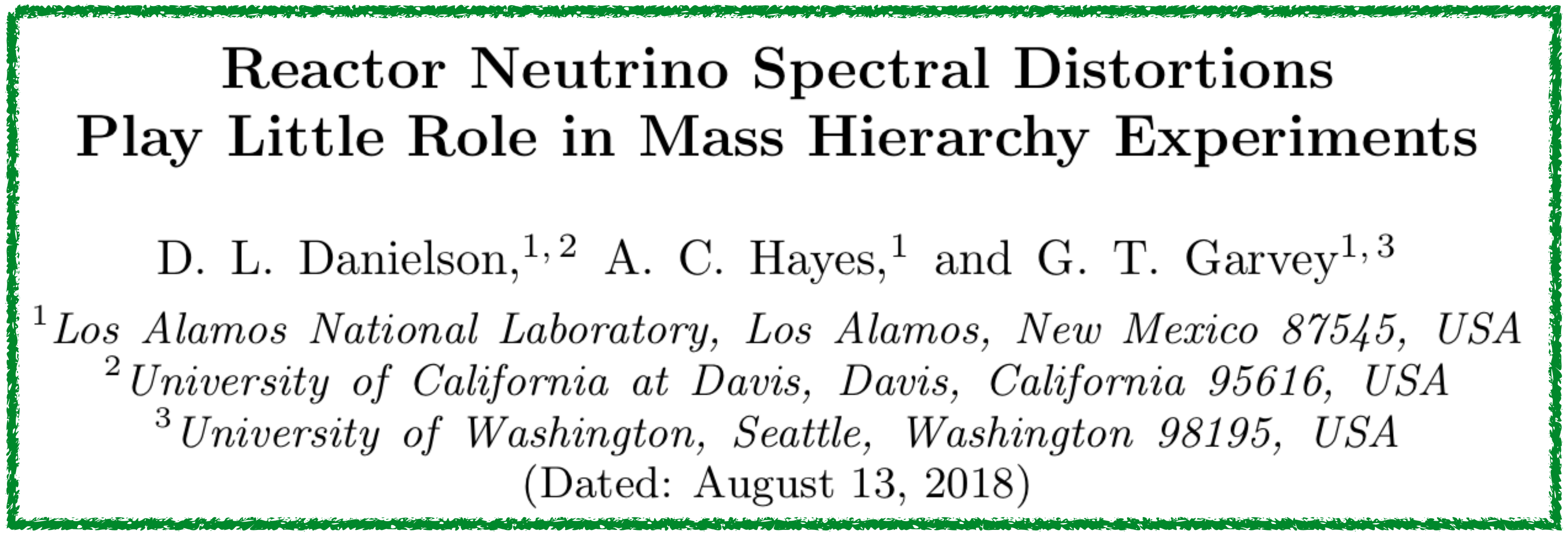
$$\frac{\sigma_0}{1.6} \oplus \sigma_1 \oplus 1.6\sigma_2 < 3\%$$



F. An et al., “Neutrino physics with JUNO,” 2016 pp. 35

Reactor ν spectrum uncertainty

- **LANL's respond** to "Unknown fine structure (**infinite uncertainty**) has larger impact (Huber)"



Reactor Neutrino Spectral Distortions Play Little Role in Mass Hierarchy Experiments

D. L. Danielson,[1,2] A. C. Hayes,[1] and G. T. Garvey[1,3]

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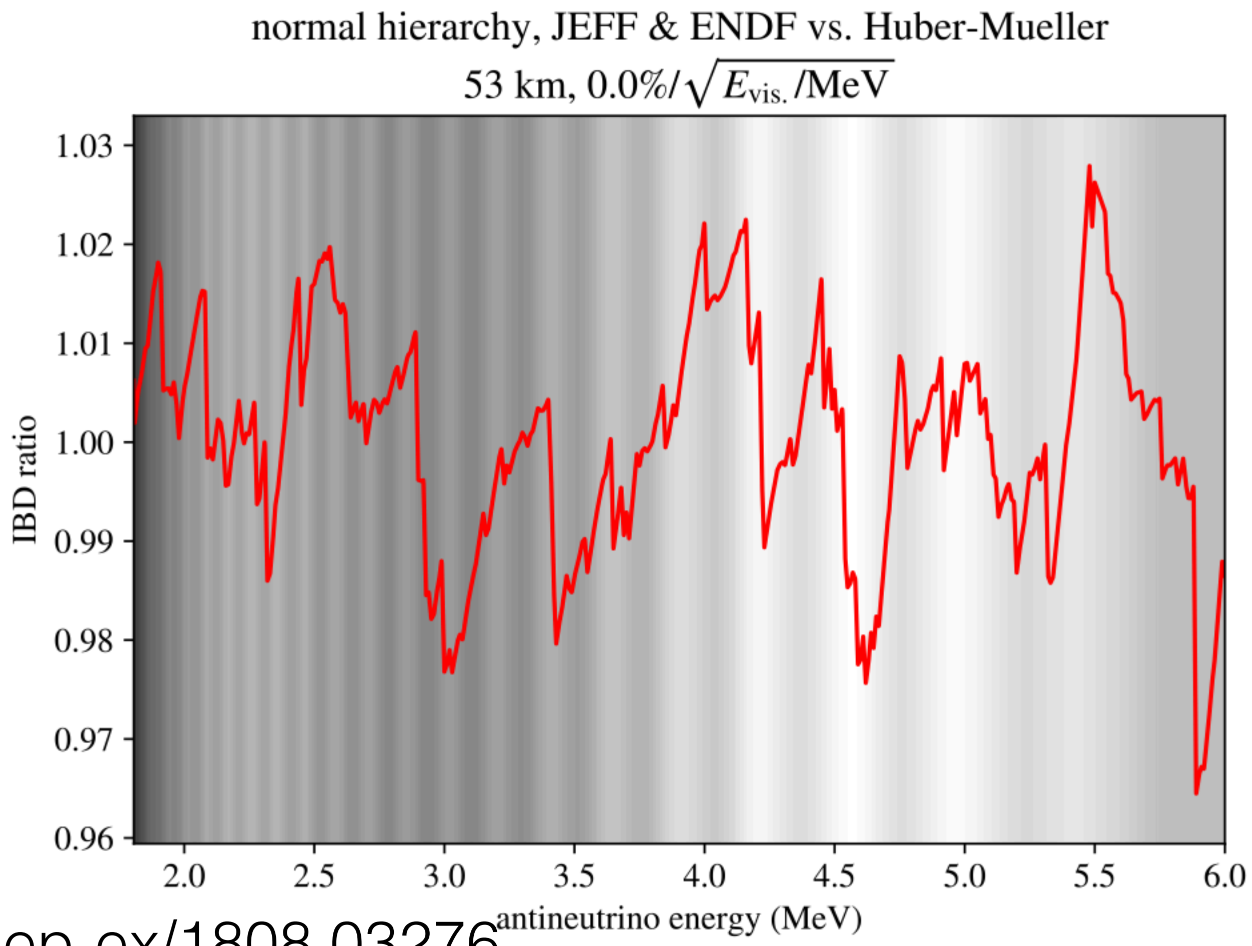
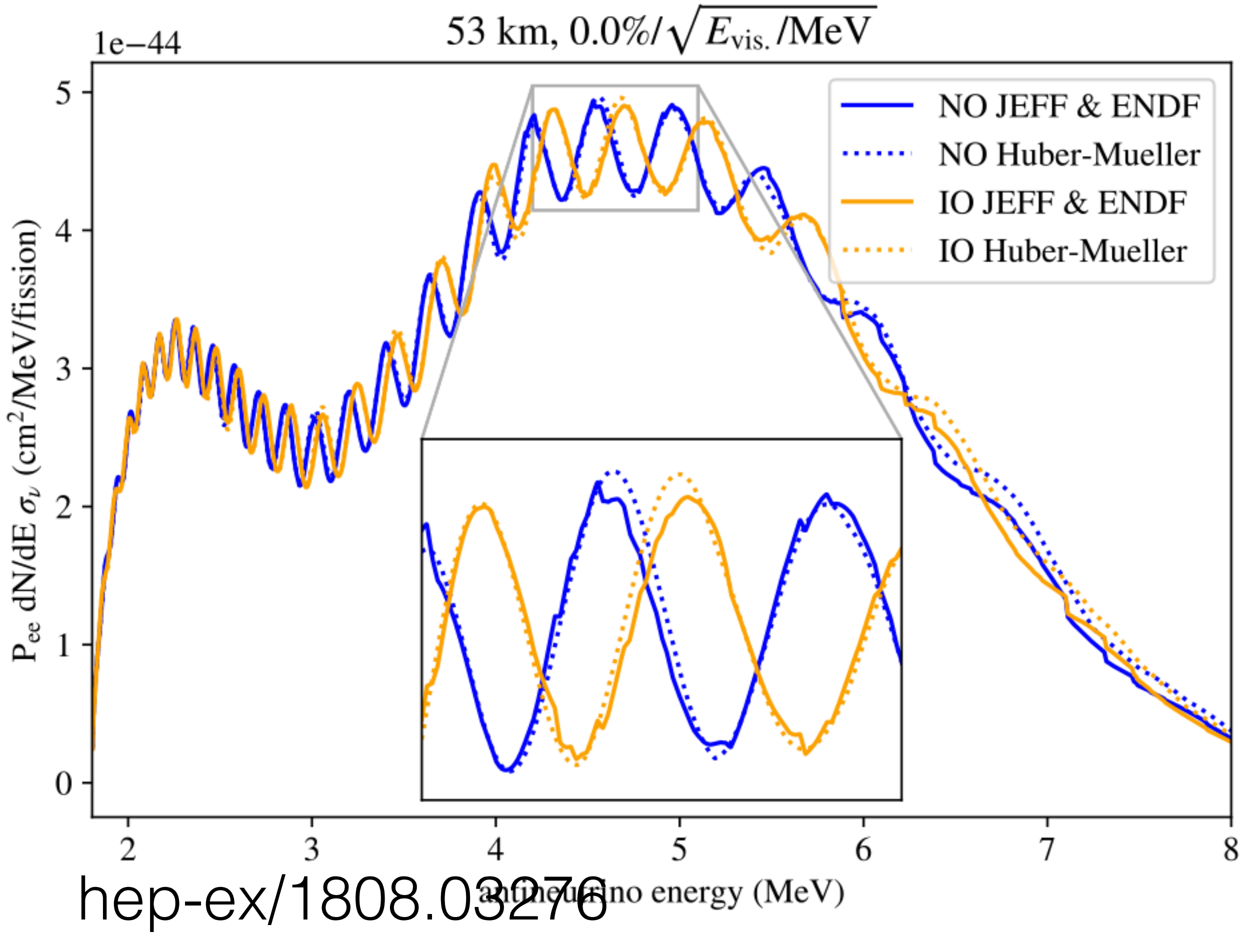
[3] *University of Washington, Seattle, Washington 98195, USA*
(Dated: August 13, 2018)

"Fine structure from JEFF&ENDF vs Huber: Magnitude **too small to be important**" (Danielson et al.)



hep-ex/1808.03276



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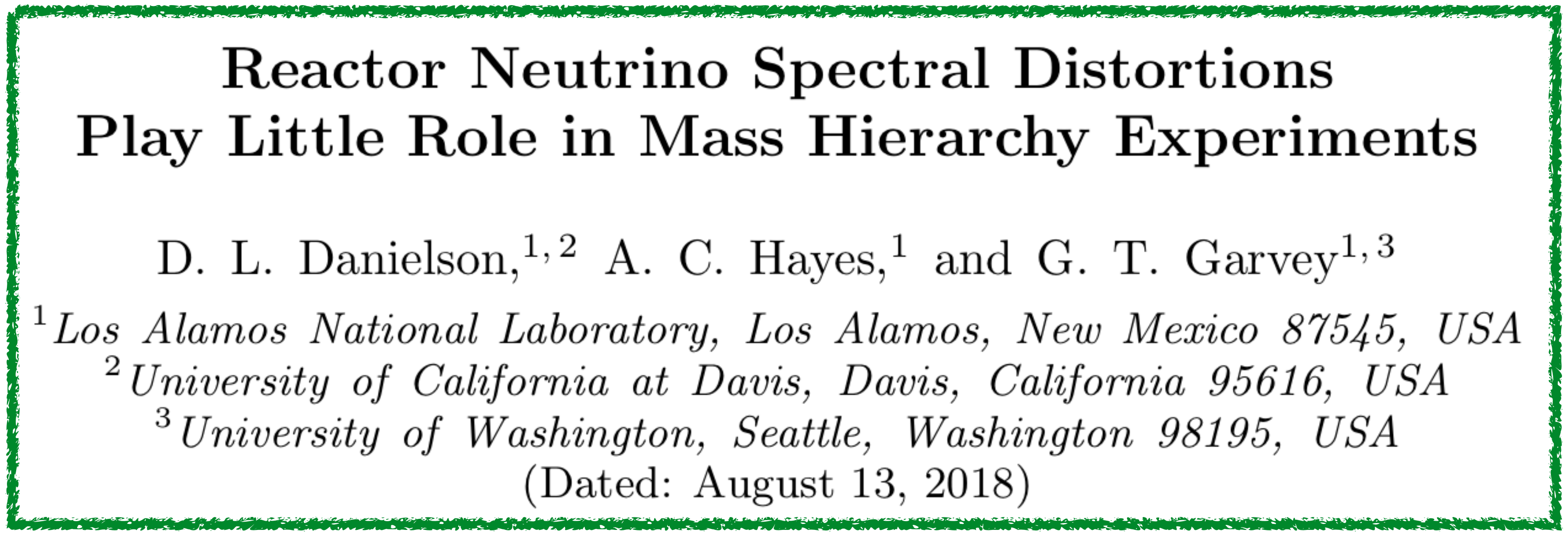

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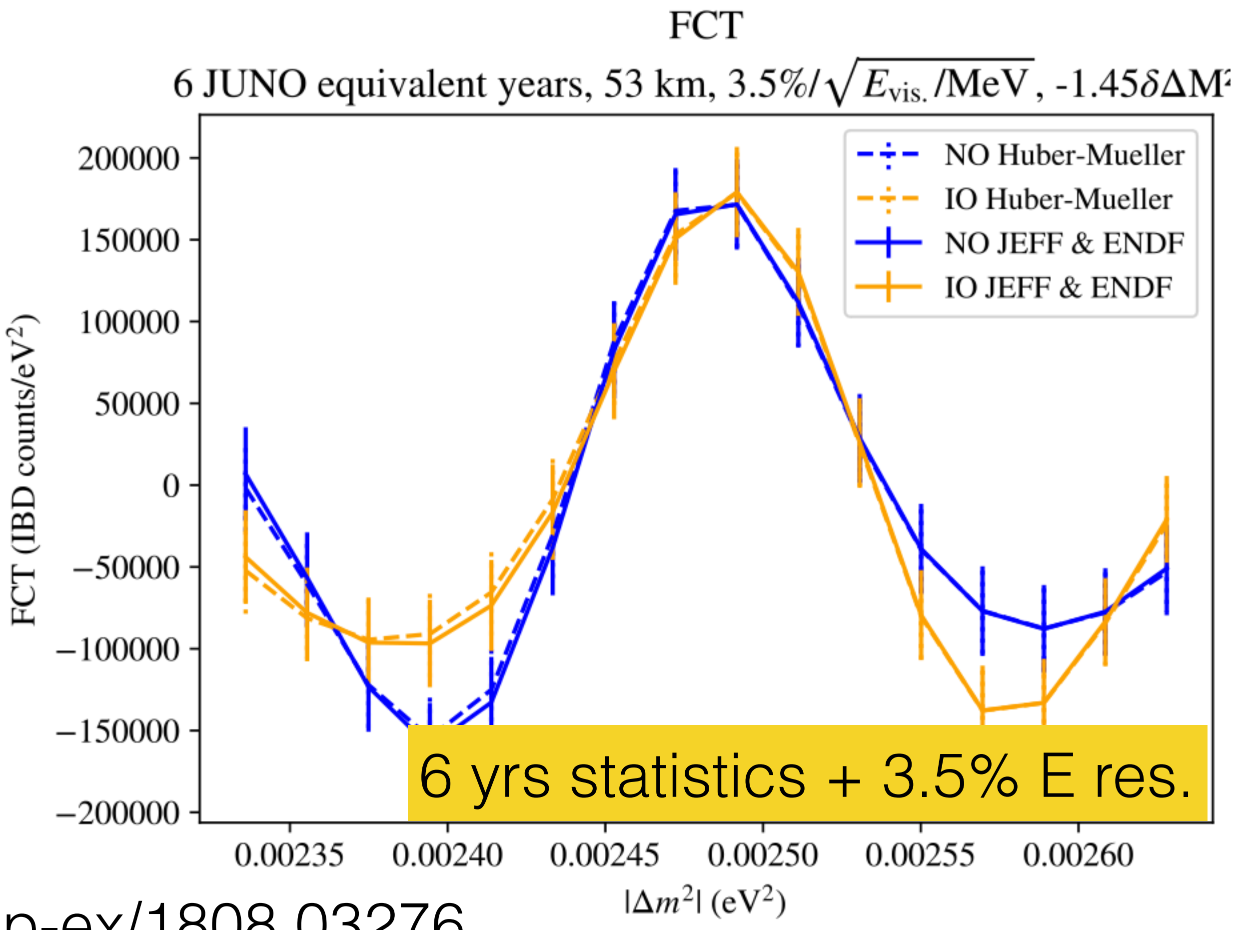
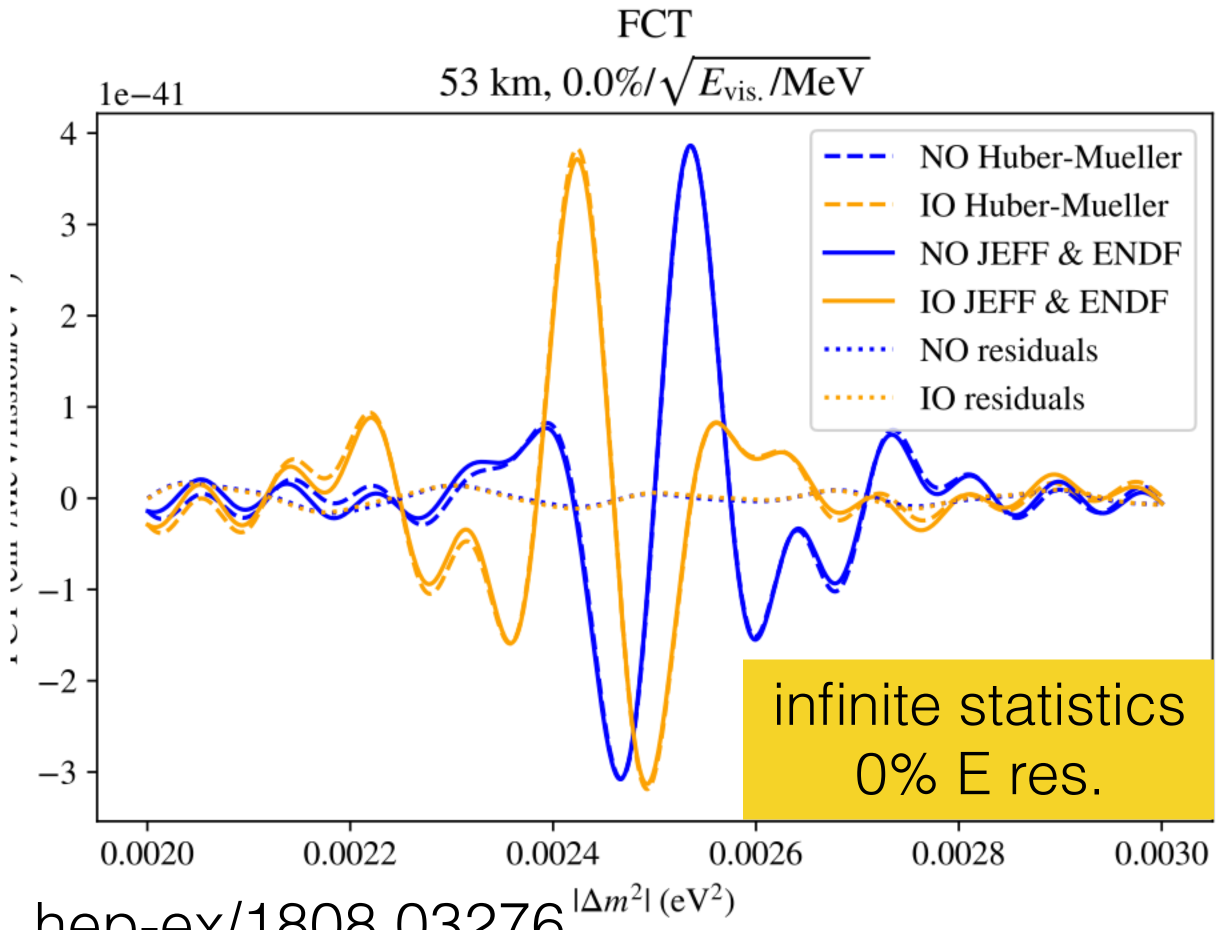


6 yrs statistics + 3.5% E res.

hep-ex/1808.03276

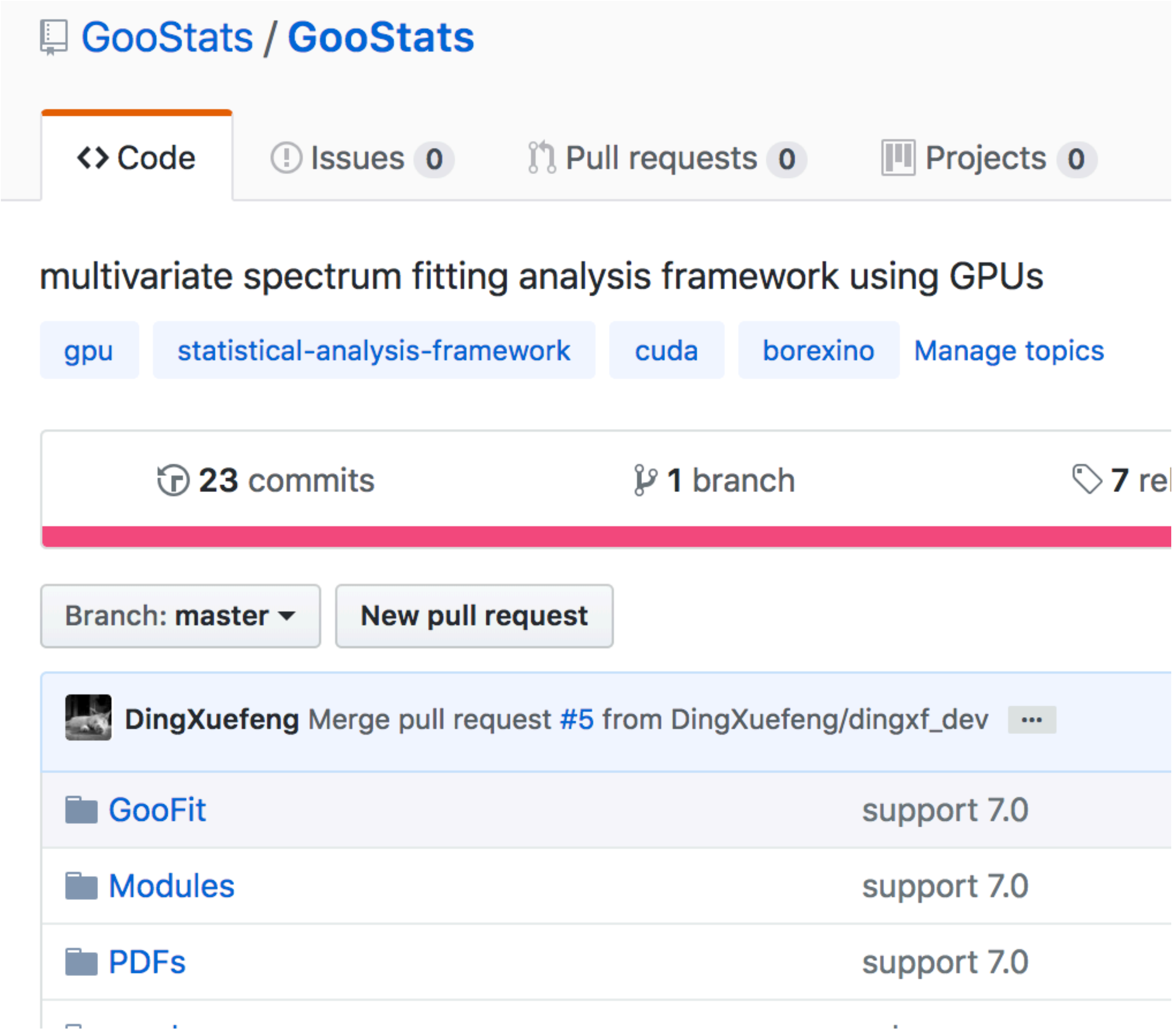


infinite statistics
0% E res.

hep-ex/1808.03276

GPU accelerated fit

git@gitHub.com:**GooStats/GooStats**



GooStats / GooStats

multivariate spectrum fitting analysis framework using GPUs

23 commits

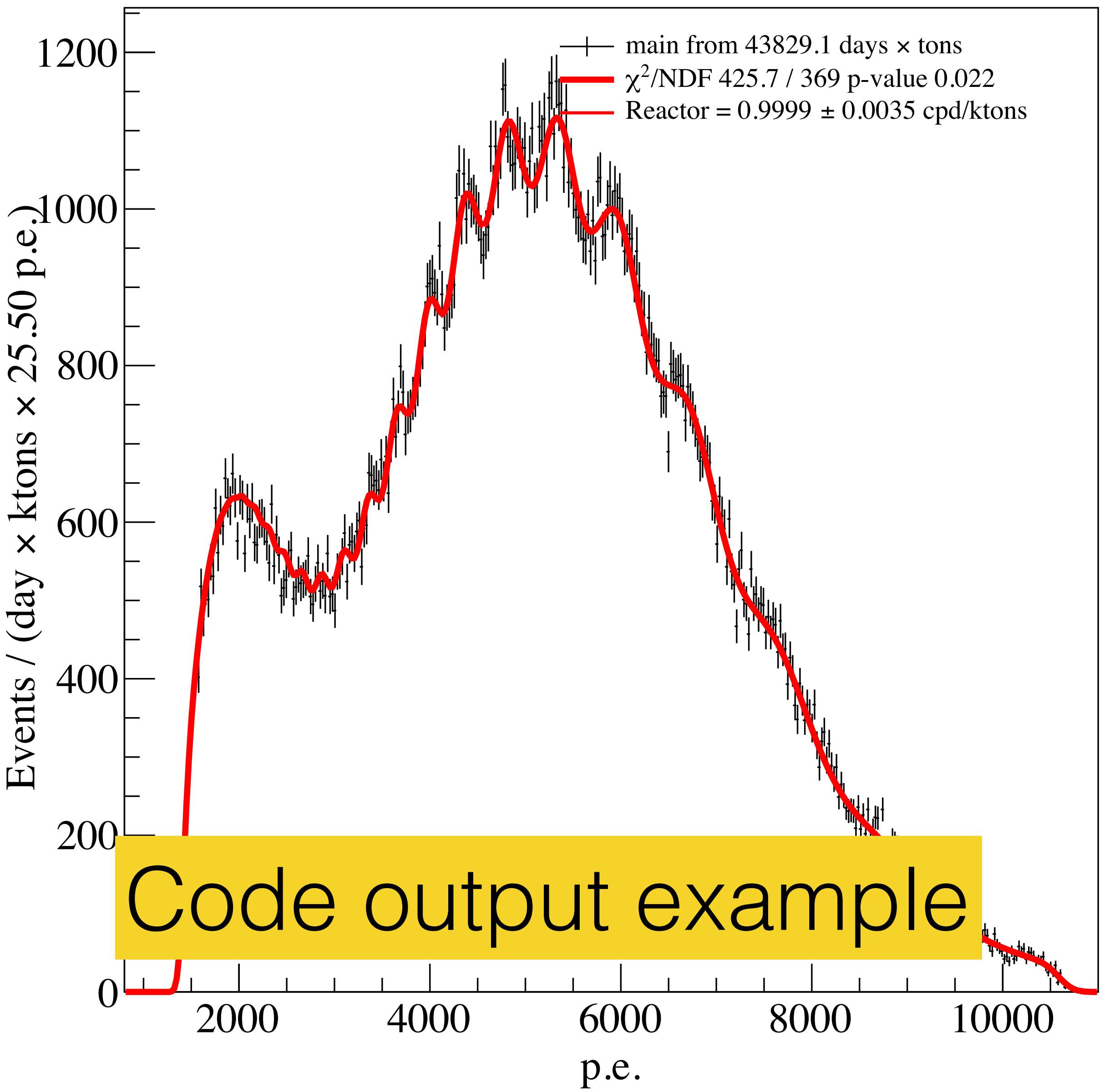
1 branch

7 rel

DingXuefeng Merge pull request #5 from DingXuefeng/dingxf_dev

GooFit	support 7.0
Modules	support 7.0
PDFs	support 7.0

GooStats: A GPU-based framework for multi-variate analysis in particle physics
JINST 2018 10.1088/1748-0221/13/12/P12018



Code output example

Ding, Xuefeng. (2018, May 19). GooStats, a multivariate spectrum fitting analysis package for particle physics accelerated by graphic processing units (Version v1.2.0). Zenodo. http://doi.org/10.5281/zenodo.1217007