Probing Neutrino Mass Ordering and Solar neutrinos with JUNO detector

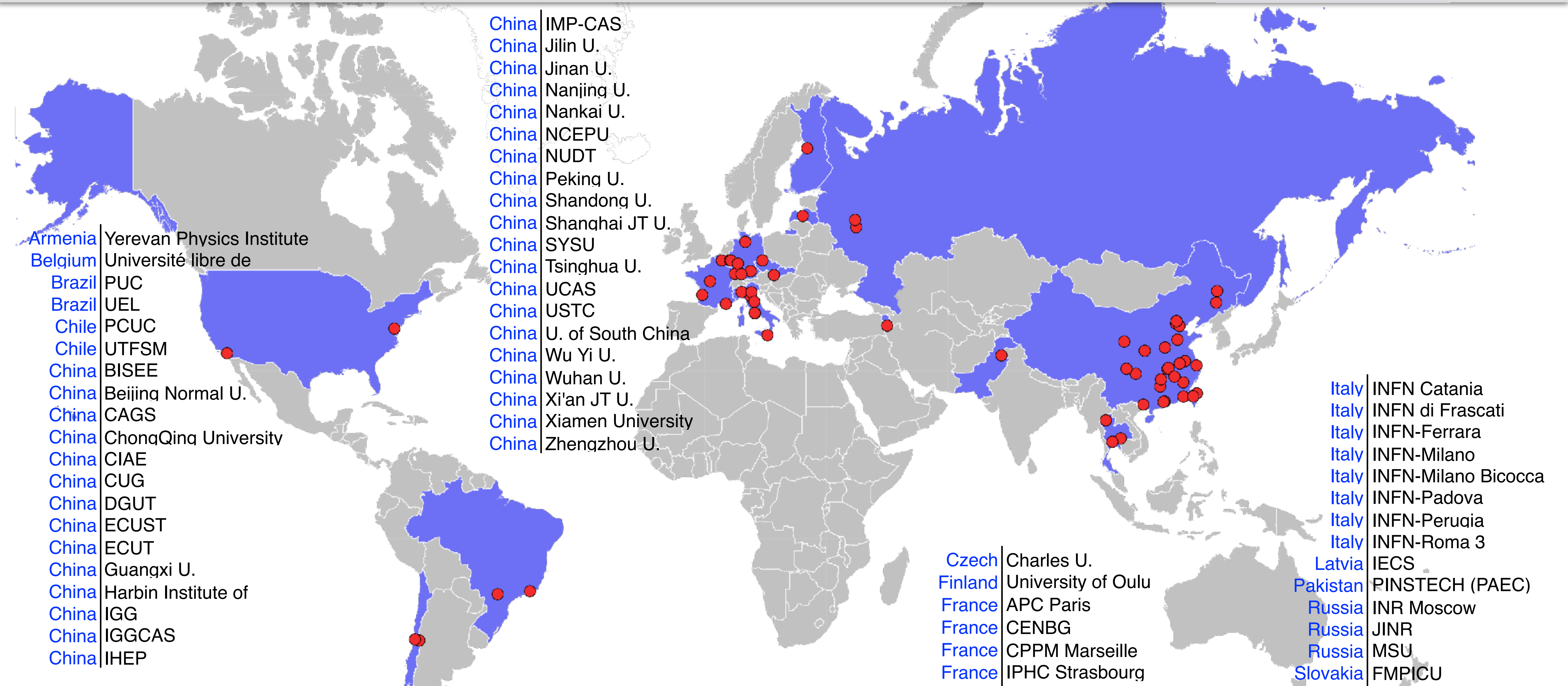
13 Aug 2018, 15 (Est) @Hahn N 130, 25'+5'

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

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

The 20th International Workshop on Neutrinos from Accelerators
@ Virginia Tech., Blacksburg, VA, U.S. 12–18 August 2018

JUNO collaboration



Armenia	Yerevan Physics Institute
Belgium	Université libre de
Brazil	PUC
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Chile	PCUC
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China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
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China	CUG
China	DGUT
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China	IGG
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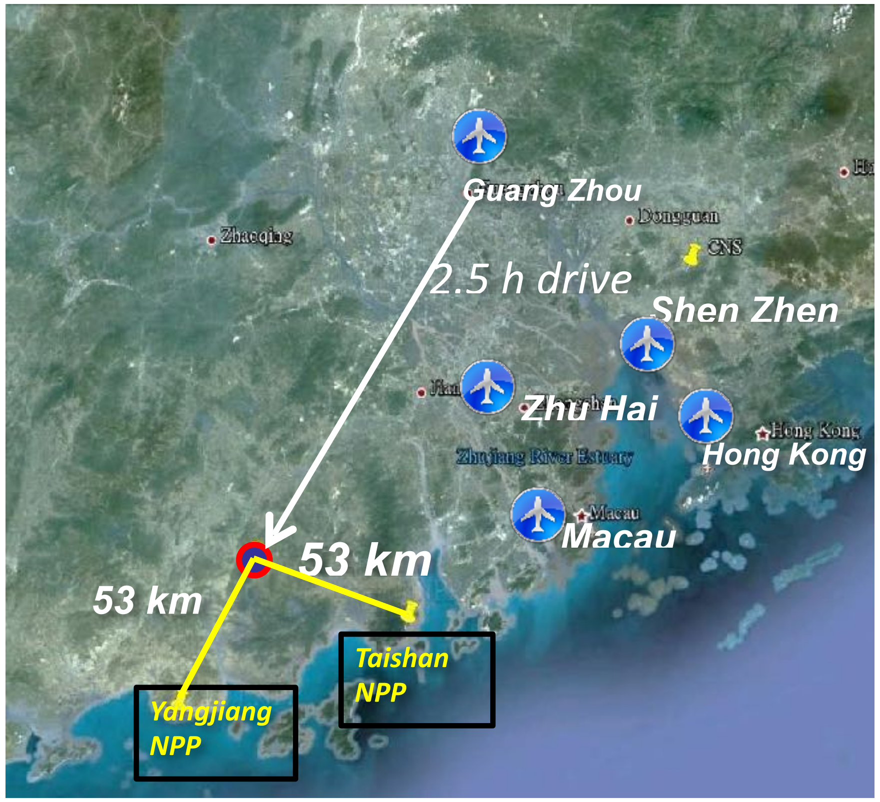
Italy	INFN-Milano
Italy	INFN-Milano Bicocca
Italy	INFN-Padova
Italy	INFN-Perugia
Italy	INFN-Roma 3
Latvia	IECS
Pakistan	PINSTECH (PAEC)
Russia	INR Moscow
Russia	JINR
Russia	MSU
Slovakia	FMPICU
Taiwan	National Chiao-Tung U.
Taiwan	National Taiwan U.
Taiwan	National United U.
Thailand	NARIT
Thailand	PPRLCU
Thailand	SUT
USA	UMD1
USA	UMD2
USA	UCI

Collaboration established on July 2014

Now 77 institutions ~600 collaborators

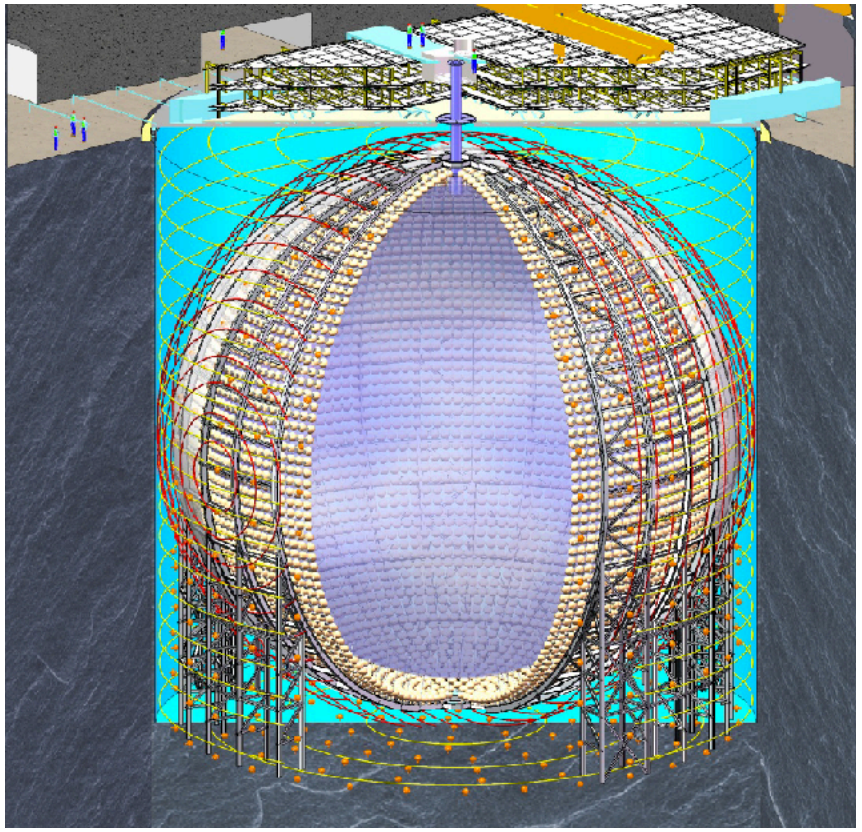
Outline

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

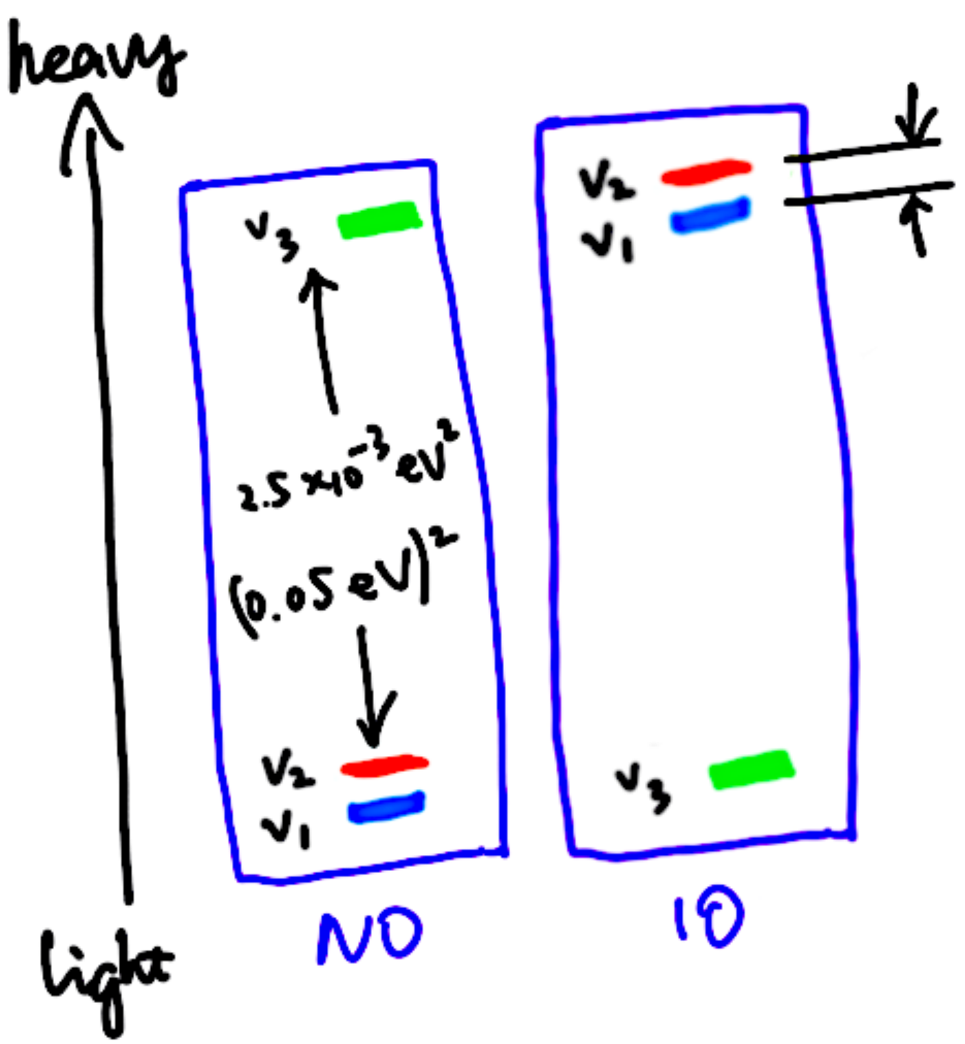


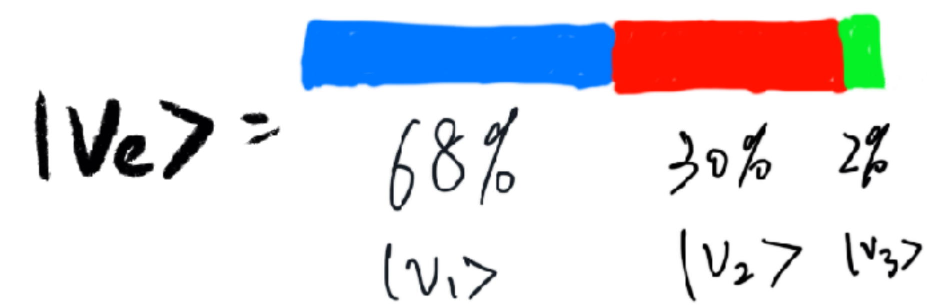
- Location: Kaiping, Jiangmen city, Guangdong province, China
- Reactor Anti-v: **36 GW** 27 GW by 2020

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



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, NO) than ν_2

Data from http://pdglive.lbl.gov/Particle.action?node=S067&init=0 on Aug. 7, 2018

NMO

neutrino mass ordering

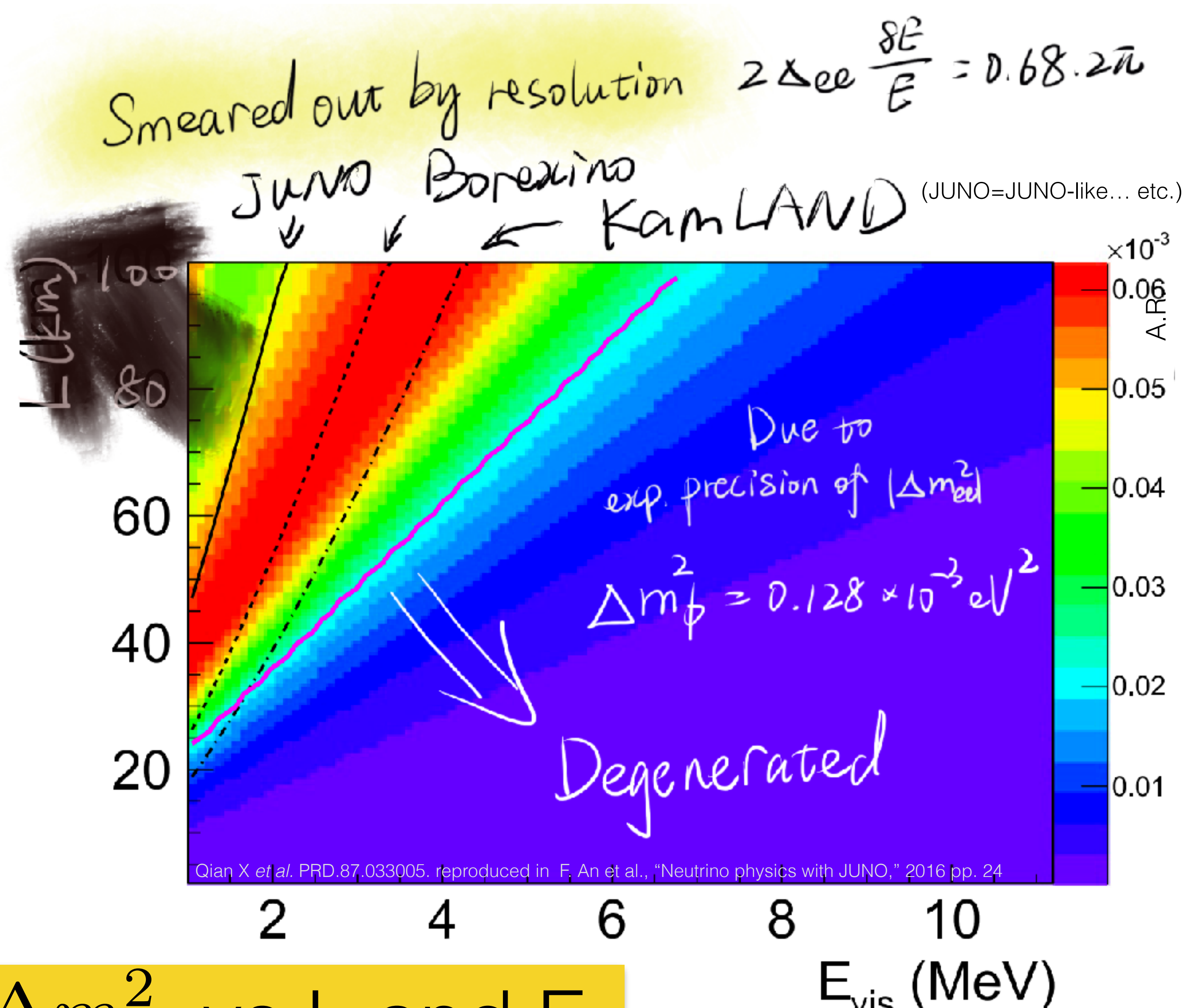
- Important step towards Generalized SM
- Reduce uncertainty on δ_{CP}
- Understand requirement for $0\nu\beta\beta$ experiment
- Help to understand core-collapse supernovae

3-ν Vacuum OSC. pattern

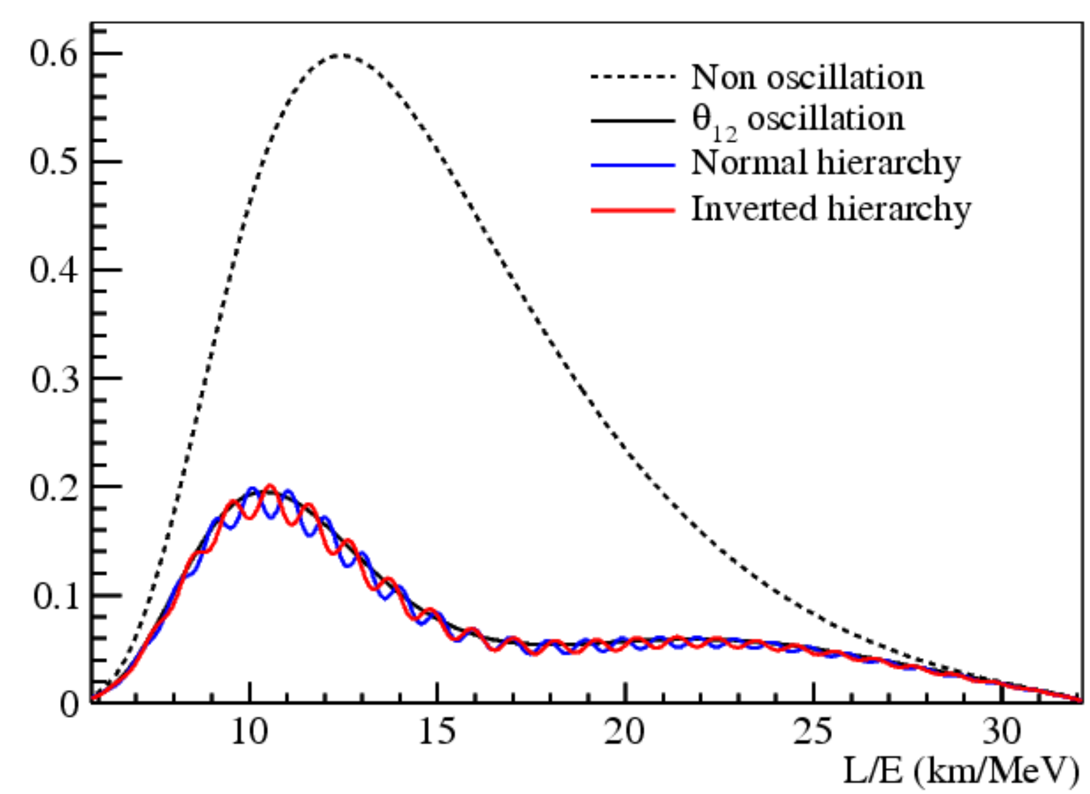
$$P_{ee} \sim 1 - 0.8\sin^2\left(2\pi\frac{L/E}{70}\right) + 0.04\cos^2\left(2\pi\frac{L/E}{70}\right)\cdot\sin^2\left(2\pi\frac{L/E}{1\pm\phi(L/E)}\right)$$

approx.: $4c_{12}^2 s_{12}^2=1$ +: NO, -: IO

$$P_{ee}(\xi) \overset{\xi=\frac{L\,(\mathrm{m})}{E\,(\mathrm{MeV})}}{=} a_0(\xi) + a_1(\xi)\cdot\sin^2 2\theta_{13}\cdot\cos\left[1.27\left(2\Delta m^2_{ee}\pm\Delta m^2_{\phi}\right)\cdot\xi\right]$$



Relative shape difference of Anti-ν flux



Zhan L *et al.* PRD 78 111103

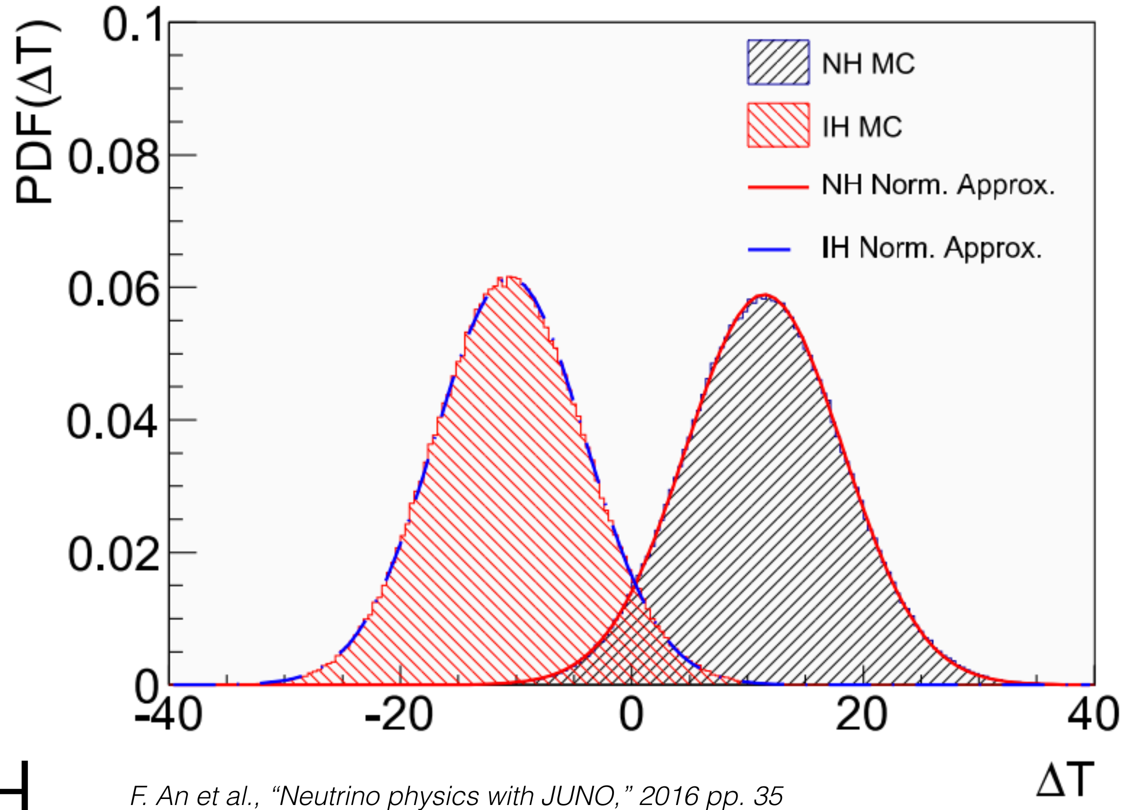
Δm^2_{ϕ} vs L and E

Statistical methods

$$\chi^2 = \chi^2_{\text{stat.}} + \chi^2_{\text{par.}} + \chi^2_{\text{sys.}}$$

$$T = \chi^2(\hat{\theta}_{\text{NH}}) - \chi^2(\hat{\theta}_{\text{IH}})$$

- Calculate *T* (data)
- Calculate p-value $\int_{T(\text{data})}^{+\infty} f(T;\text{IH})\text{d}T$
- It is the confidence level to reject IH.



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

- Without data -> report expected sensitivity
  - Median $(\beta = 0.5)$ sensitivity $p\text{–value}\,[T_{\text{med.}}(\text{NH})]$
  - Quick way: Asimov dataset $\sqrt{T(\text{Asimov}, \text{NH})}$

Cowan Eur. Phys. J. C (2011) 71: 1554

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 σ	3.3 σ	1.9 σ
Inverted MH	3.5 σ	3.4 σ	1.9 σ

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

Important factors

- Energy resolution Yellow Book
- Energy non-linearity Li Y.F. et al. PRD 88.013008
- Reactor spectrum uncertainty Zhan L. ESCAPE 2018
- Other factors

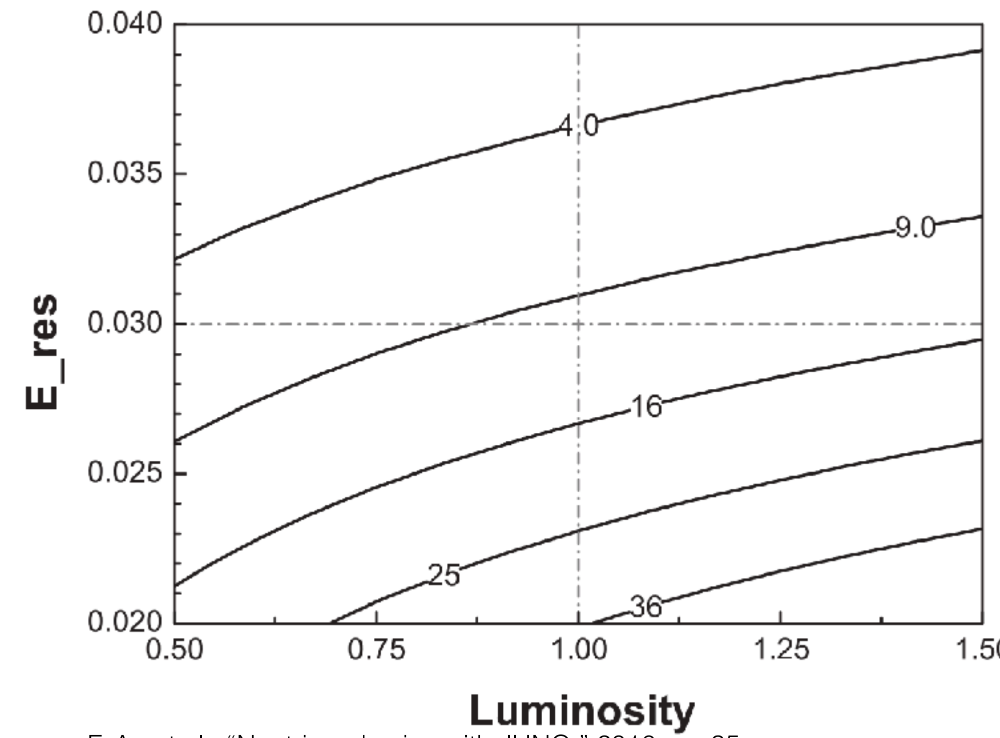
$$\mathrm{Var}[E_{\mathrm{rec.}}] = \sigma_0^2 + \sigma_1^2 \cdot \mu_{E_{\mathrm{rec.}}} + \sigma_2^2 \cdot \mu_{E_{\mathrm{rec.}}}^2$$

- 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

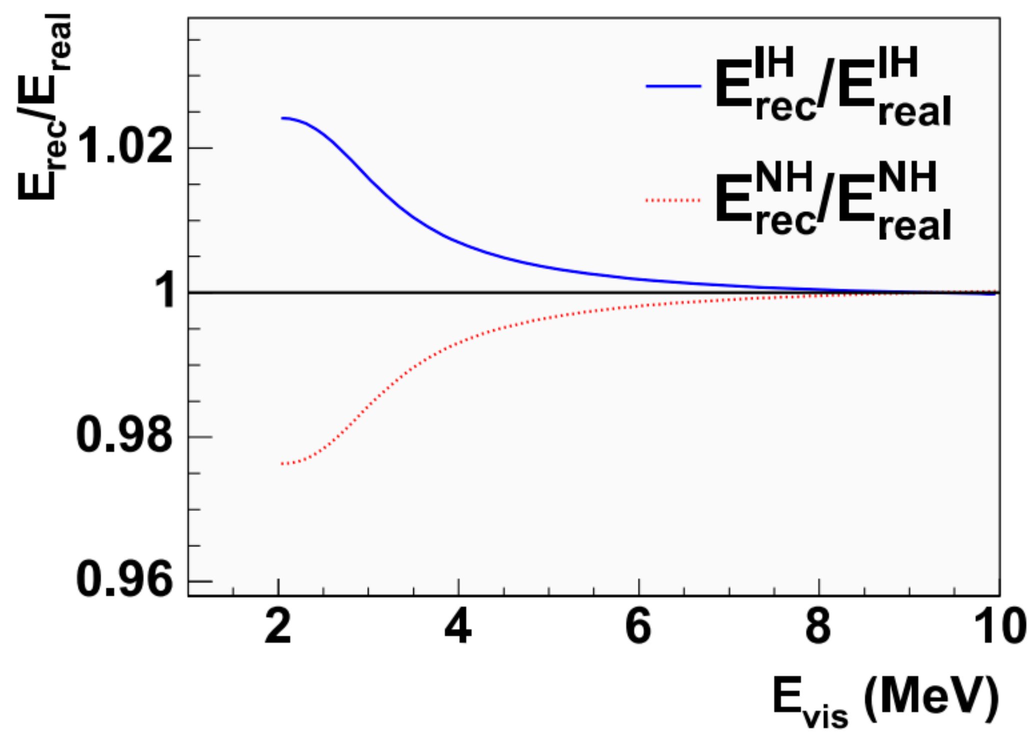
$$P_{ee} = a + b \cdot \sin^2\left(2\pi \cdot (\omega_0 \pm \omega(E)) \cdot E_{\mathrm{rec.}}^{-1}\right)$$

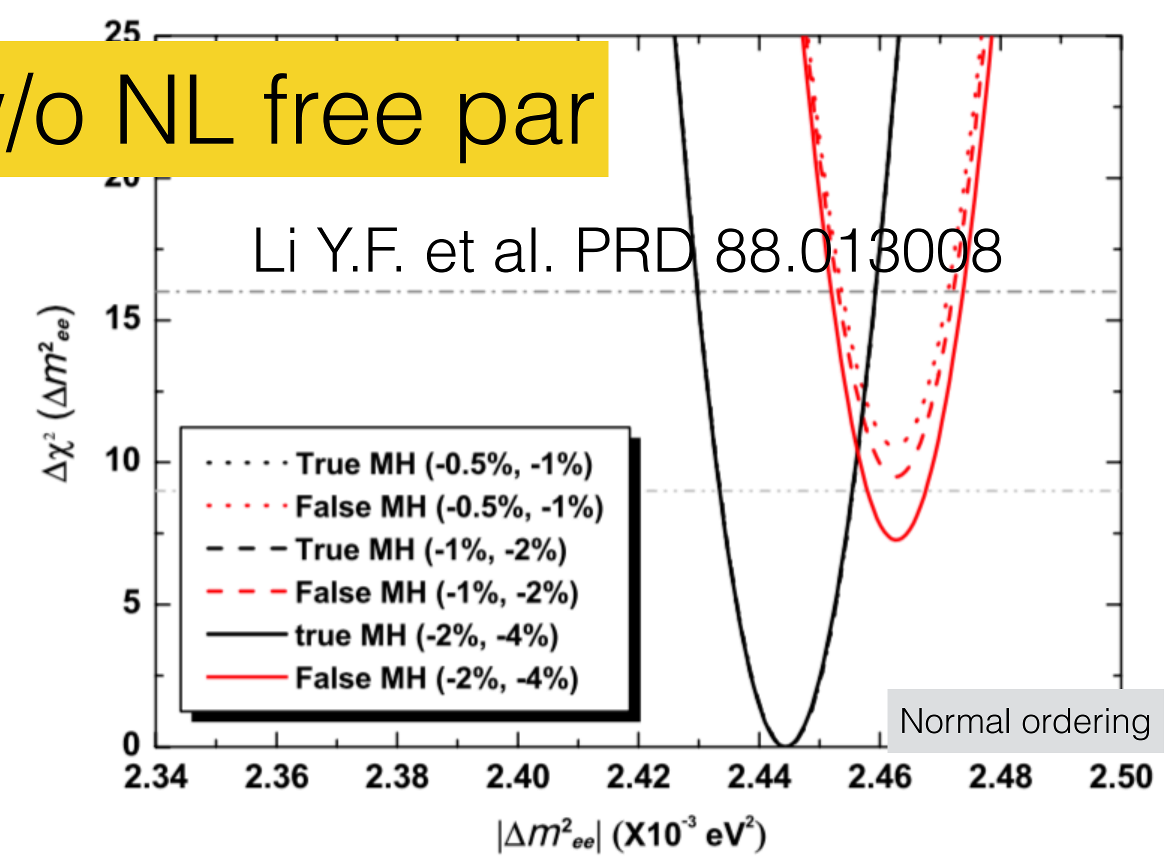
$$E_{\mathrm{rec.}} = \frac{\omega_0 + \omega(E)}{\omega_0 - \omega(E)} E_{\mathrm{real}}$$

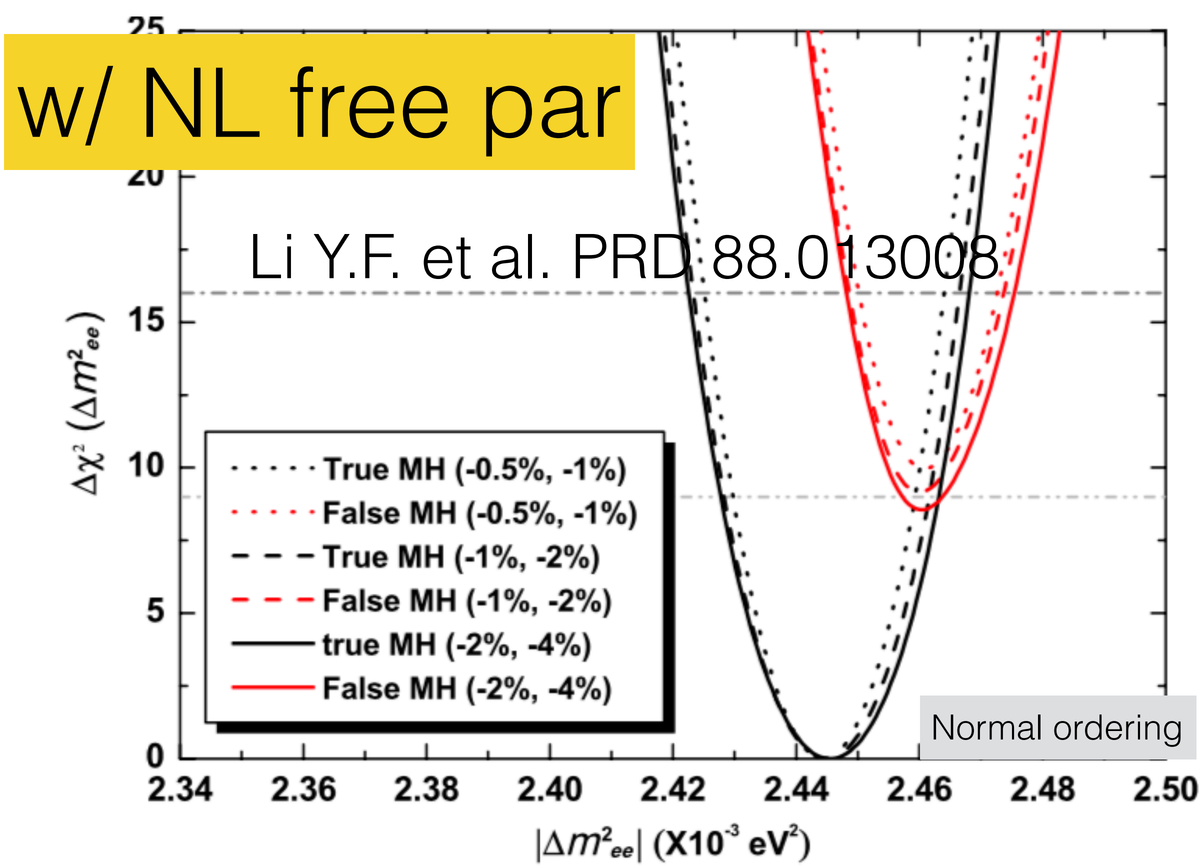
- **Special** residual NL can **invert** P_{ee}
- **Improved** by introducing **NL free par**
- **accurate NL**. DayaBay can do 0.5%

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

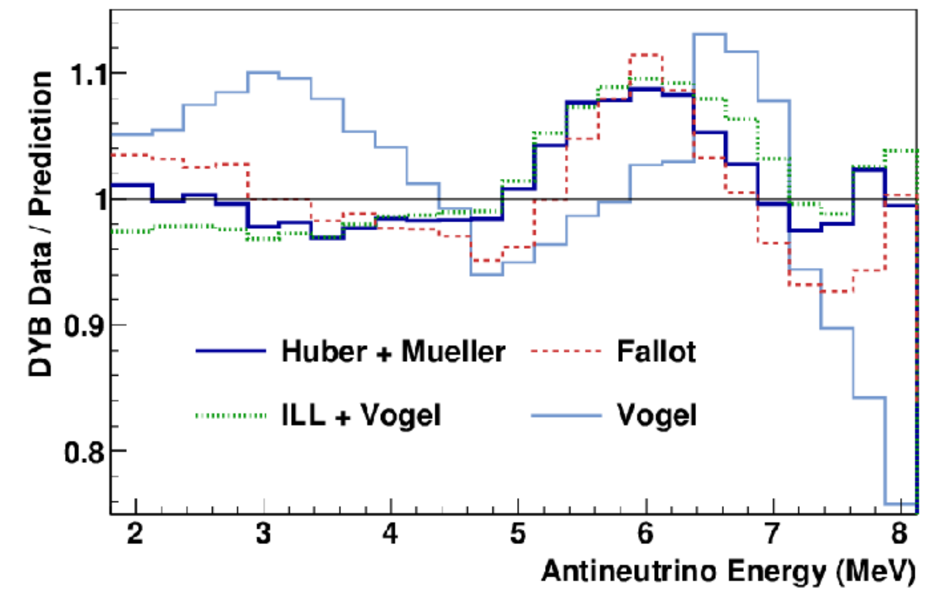






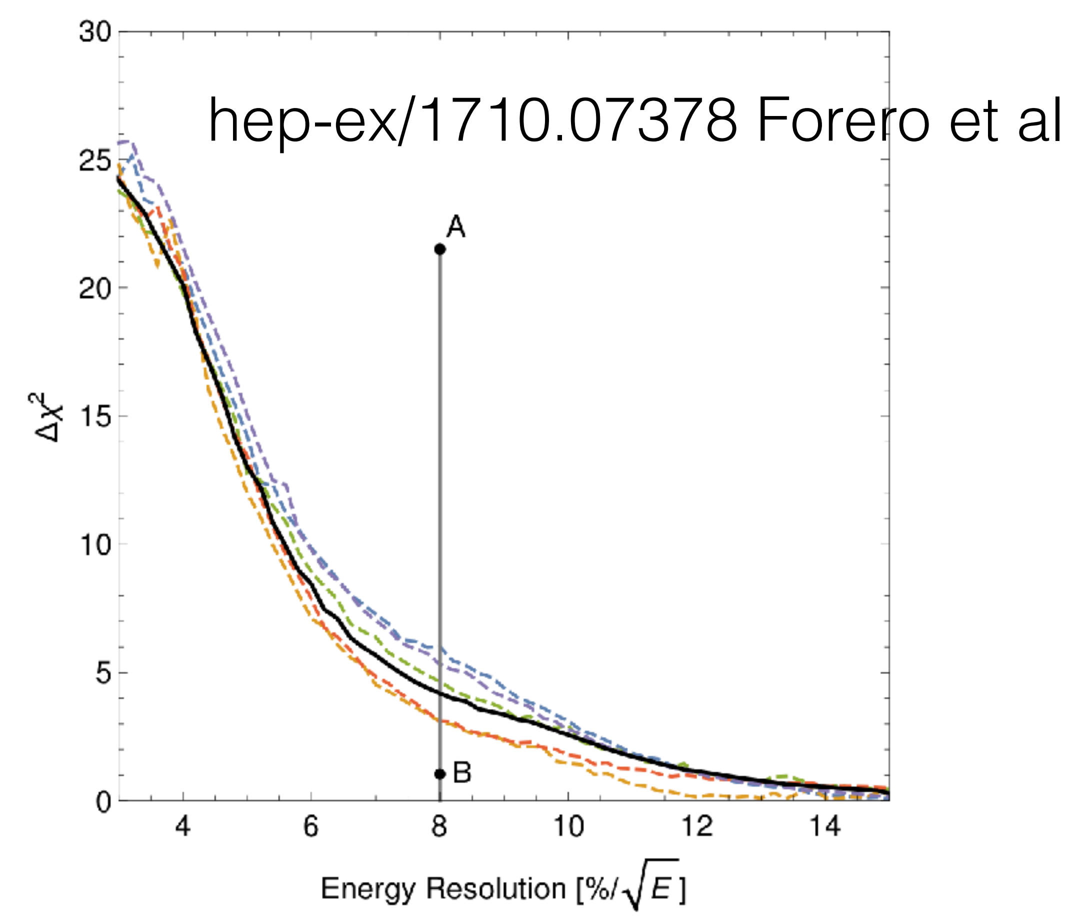
Reactor ν spectrum uncertainty

- Currently the predicted antineutrino spectrum have **discrepancy** (at 10% level) with respect to the observed antineutrino spectrum, also has unknown **uncertainty**
- **Known fine structure** does not hurt JUNO: Xin Qian took 6 spectra with fine local structure from Dan's 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



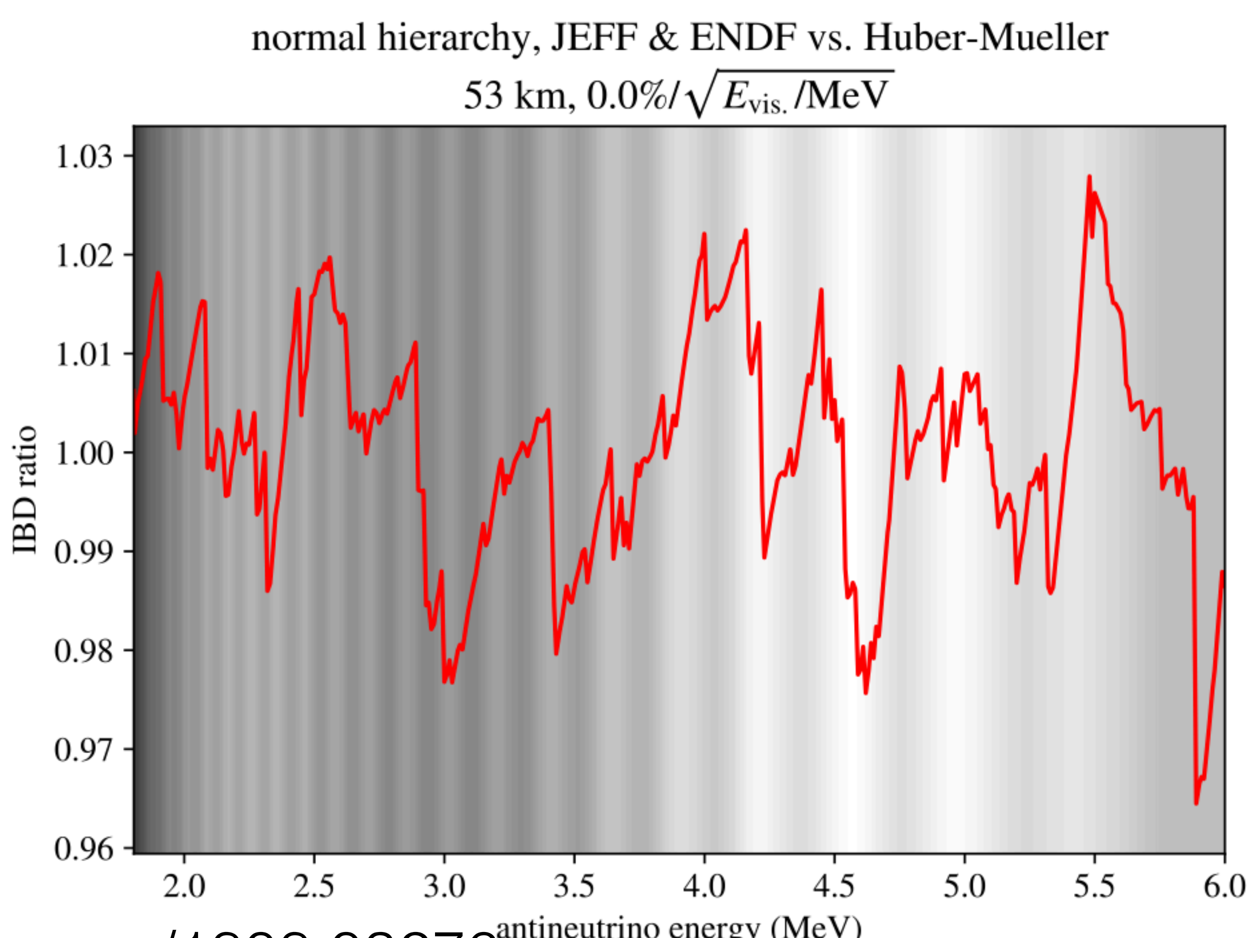
Reactor ν spectrum uncertainty

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

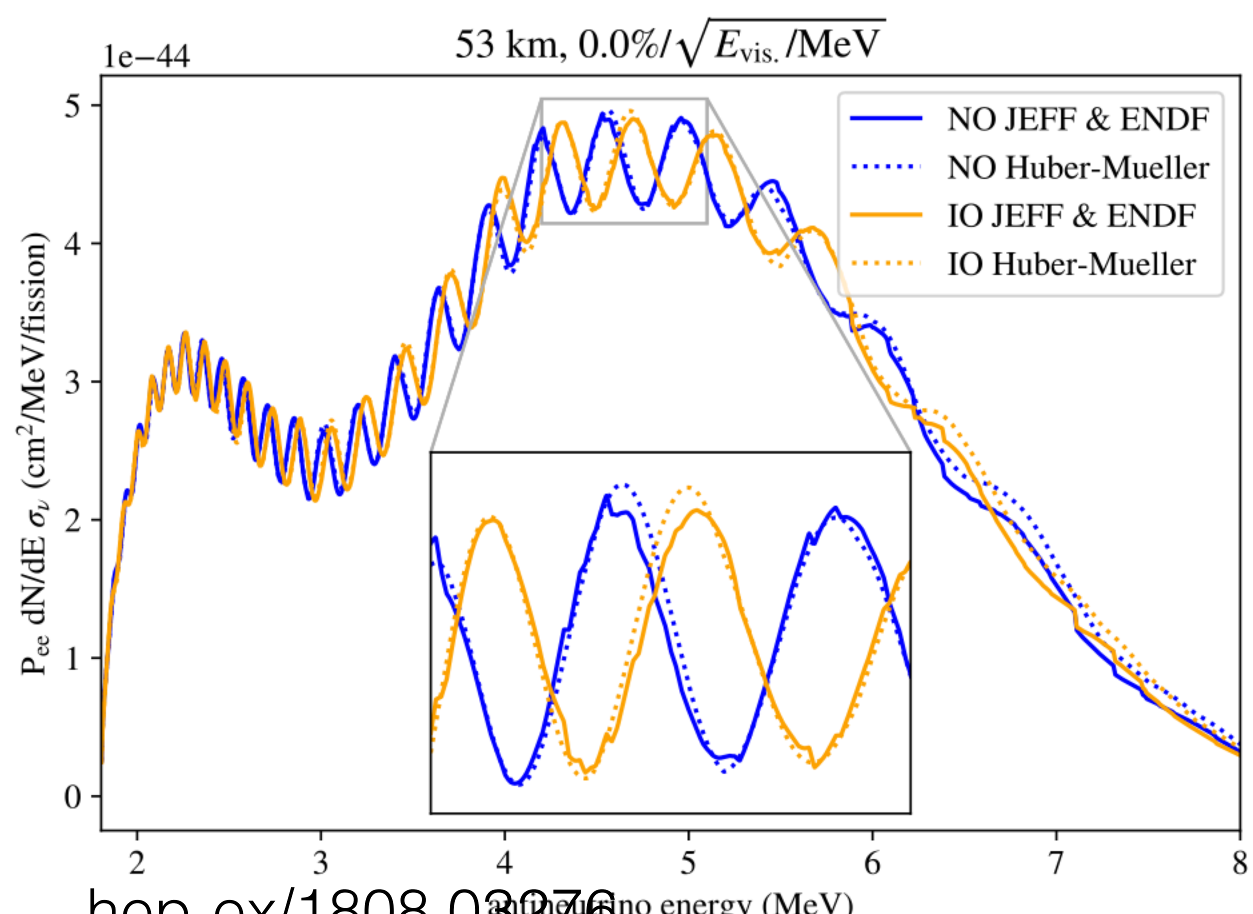
Reactor Neutrino Spectral Distortions Play Little Role in Mass Hierarchy Experiments

D. L. Danielson,[1,2] A. C. Hayes,[1] and G. T. Garvey[1,3]
[1] *Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2] *University of California at Davis, Davis, California 95616, USA*
[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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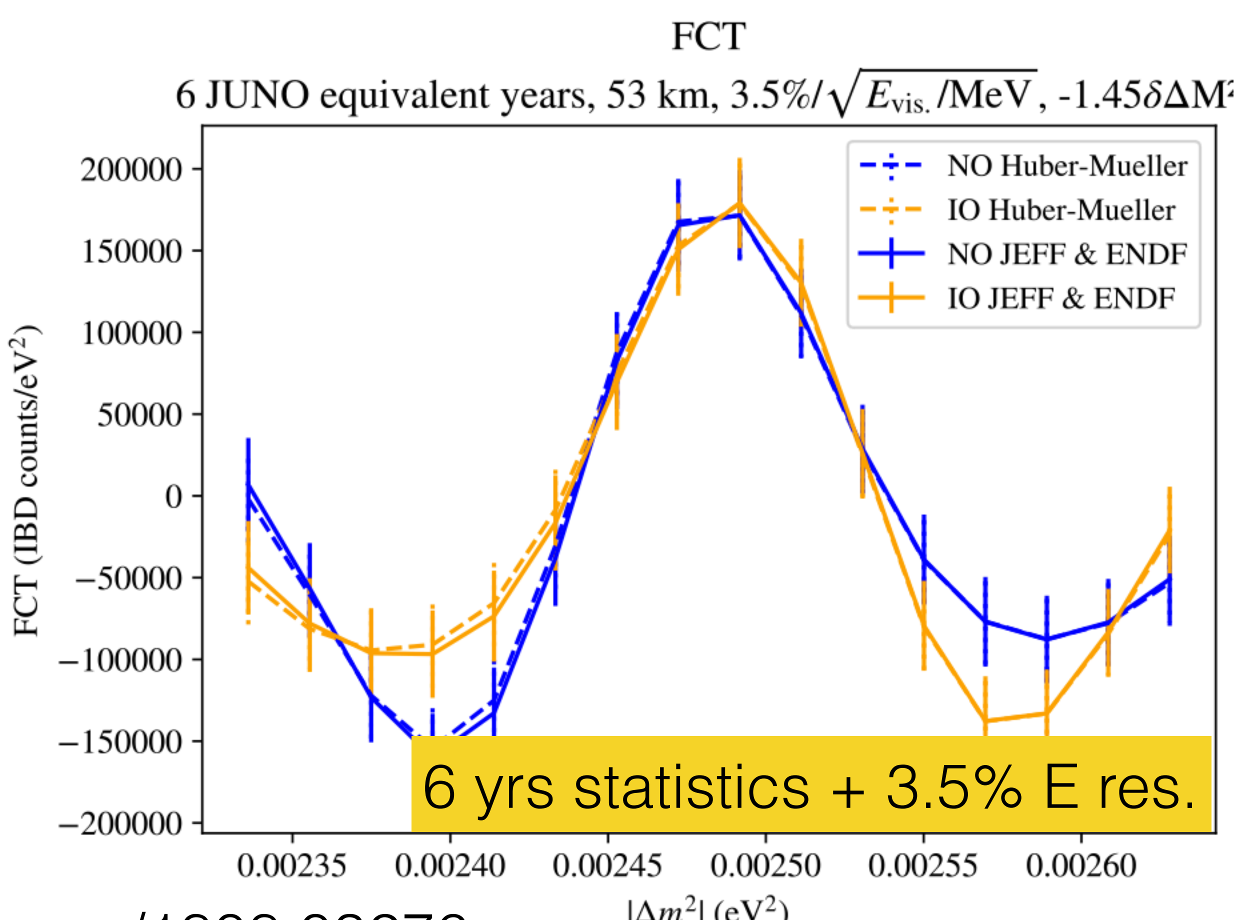

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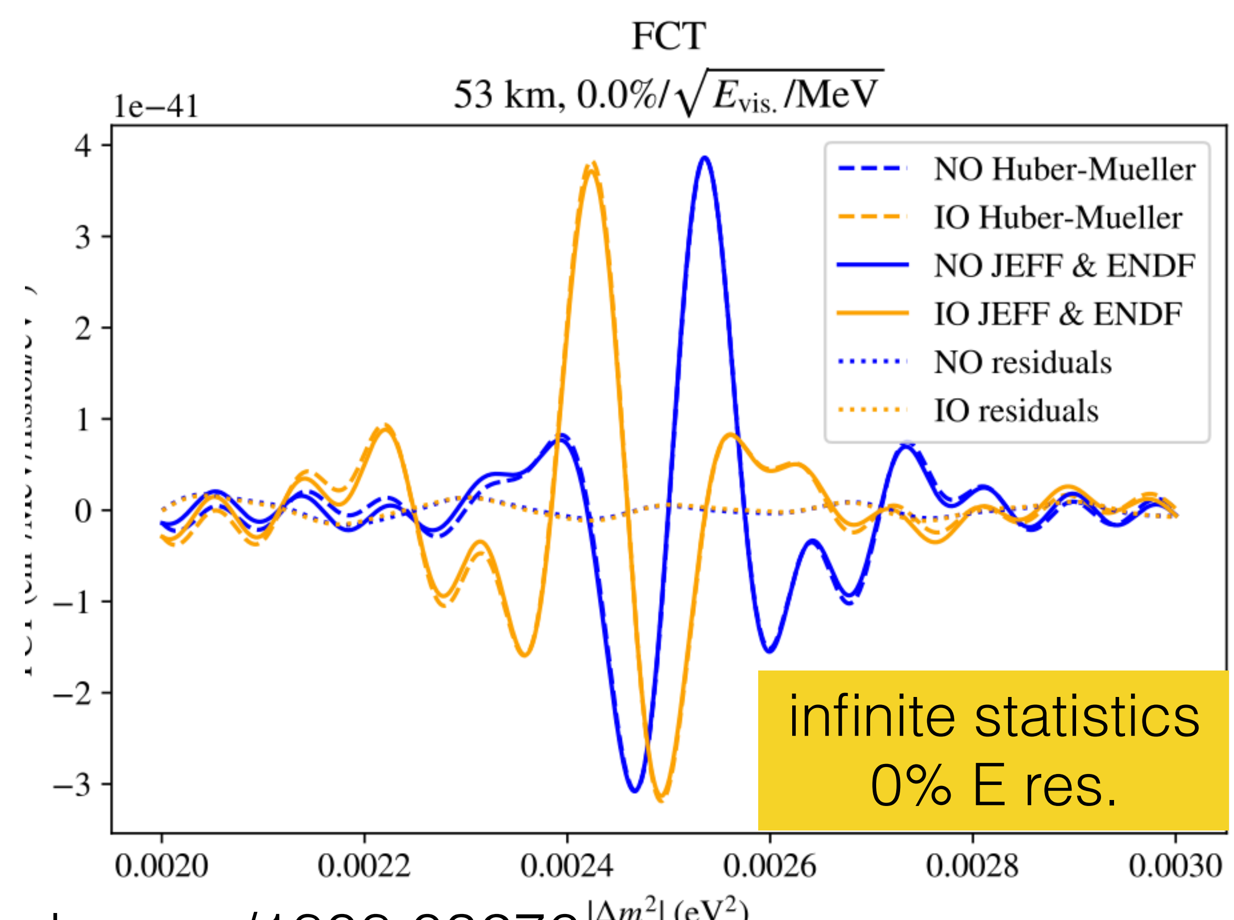


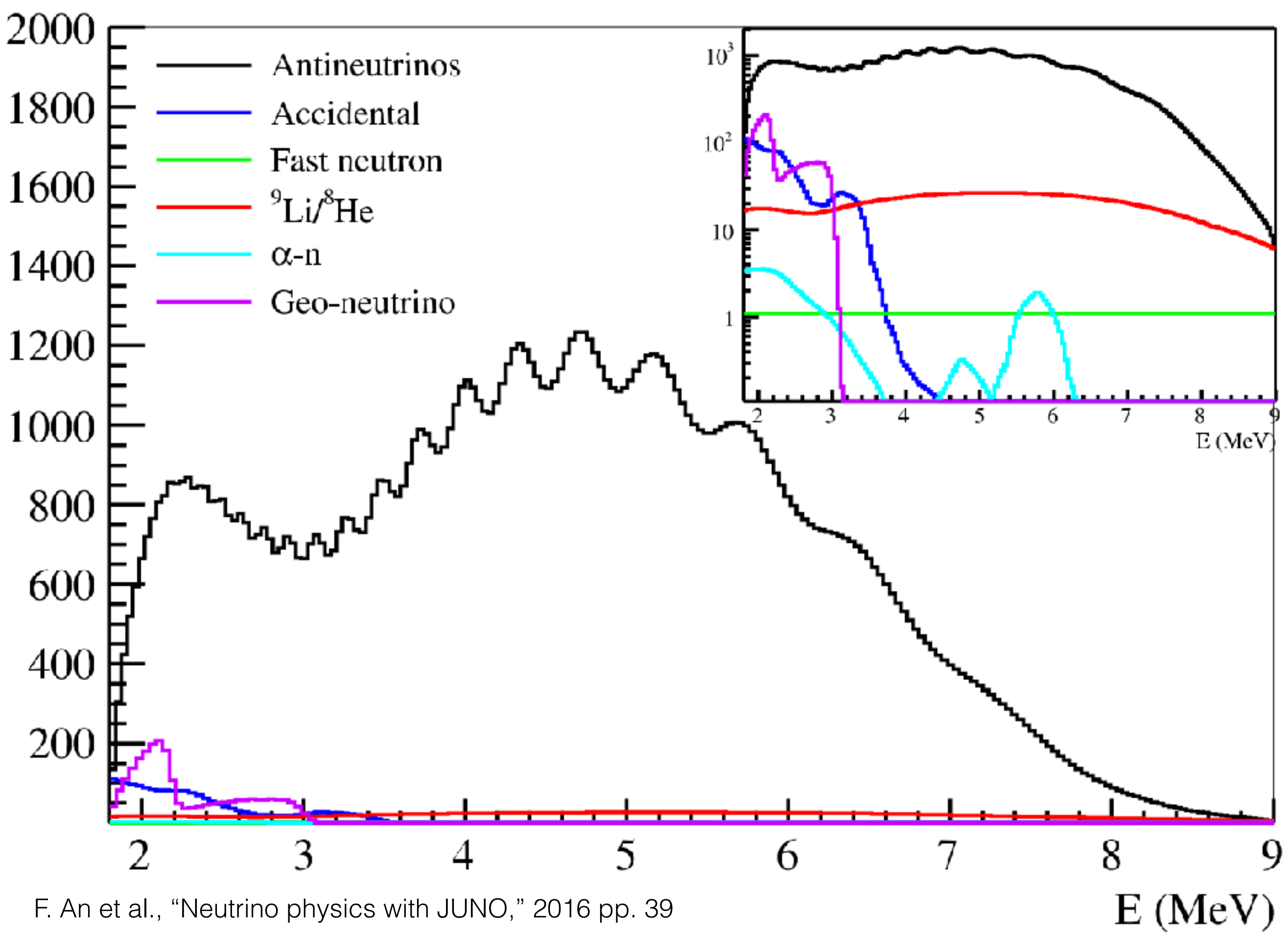
hep-ex/1808.03276

Other factors

	Stat.	Core dist.	DYB and HZ	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Table 2	Table 2%	1%	6.3%	0.4%	1%
$\Delta\chi^2_{\rm MH}$	+16	−3	−1.7	−1	−0.6	−0.1	+(4 − 12)

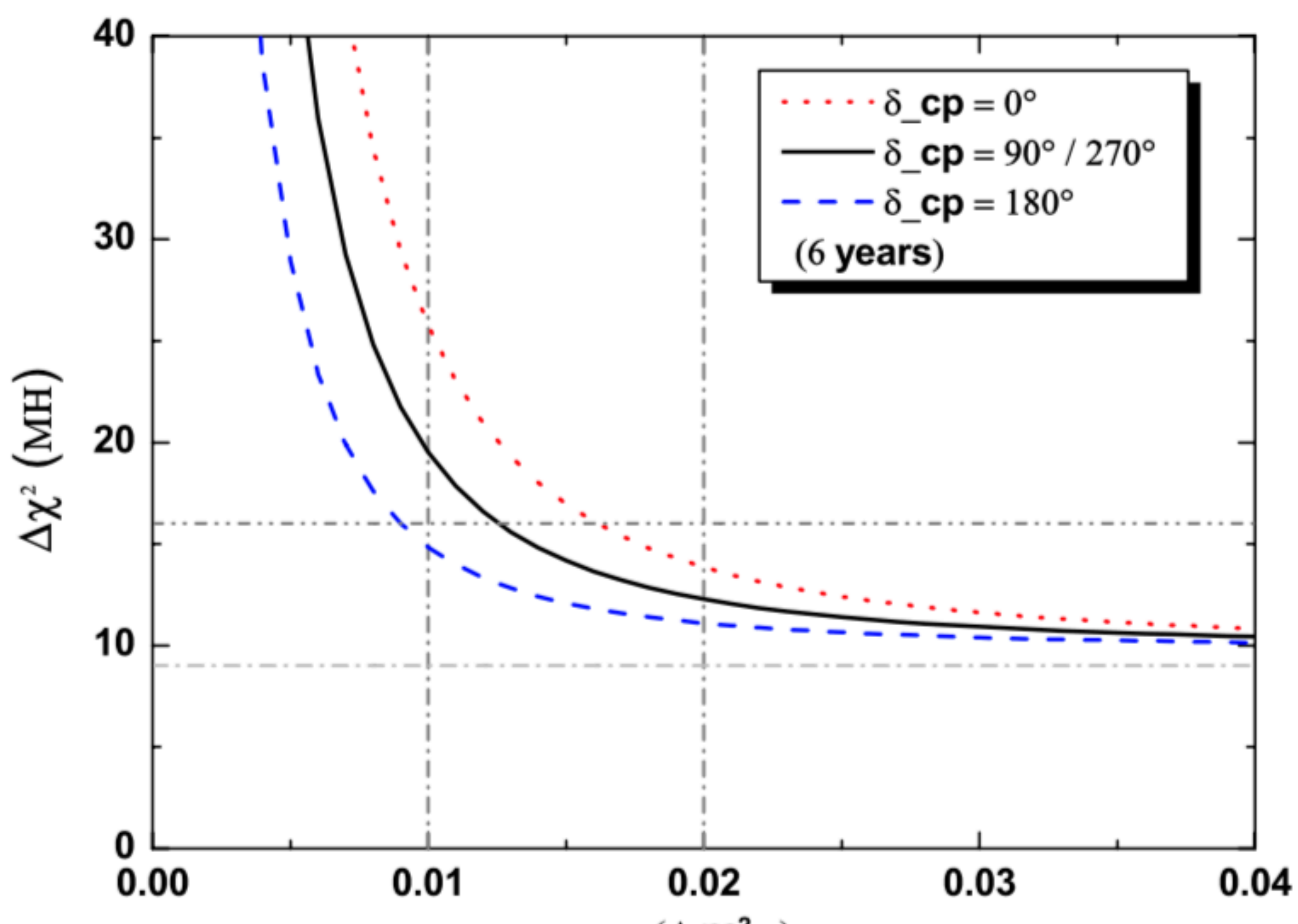
F. An et al., "Neutrino physics with JUNO," 2016 pp. 35

Signal-Background composition



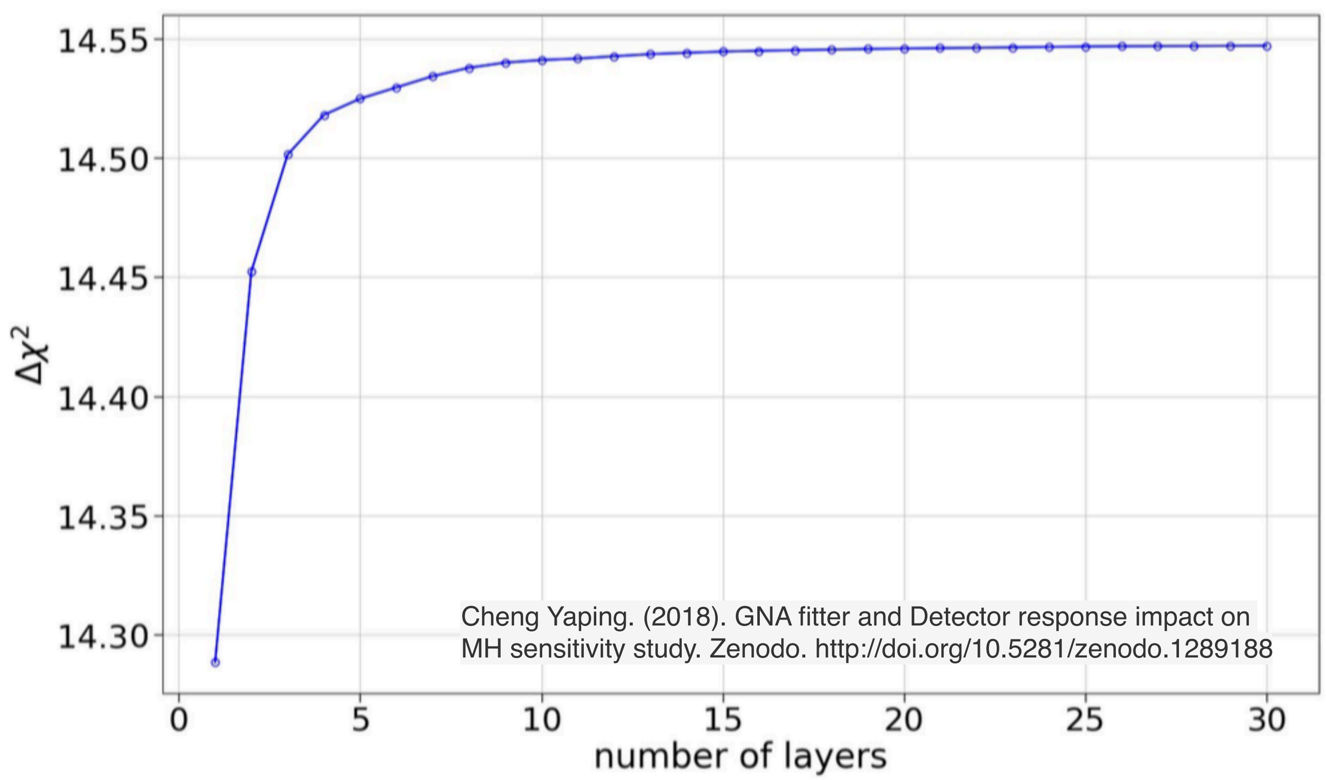
F. An et al., "Neutrino physics with JUNO," 2016 pp. 39

Constraint from acc.

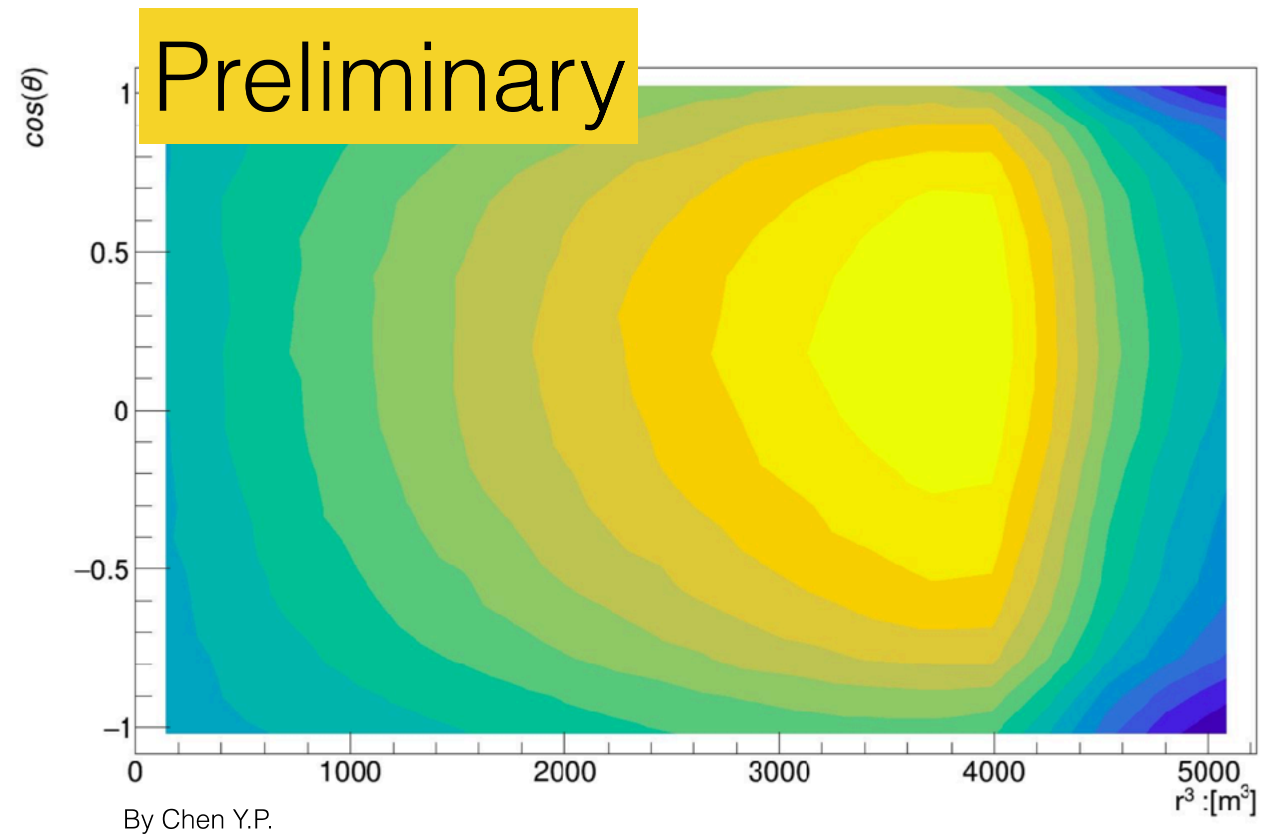


Li Y.F. et al. PRD 88.013008

Multivariate fit



E-r fit: Improvement vs $N_{r\text{-shells}}$

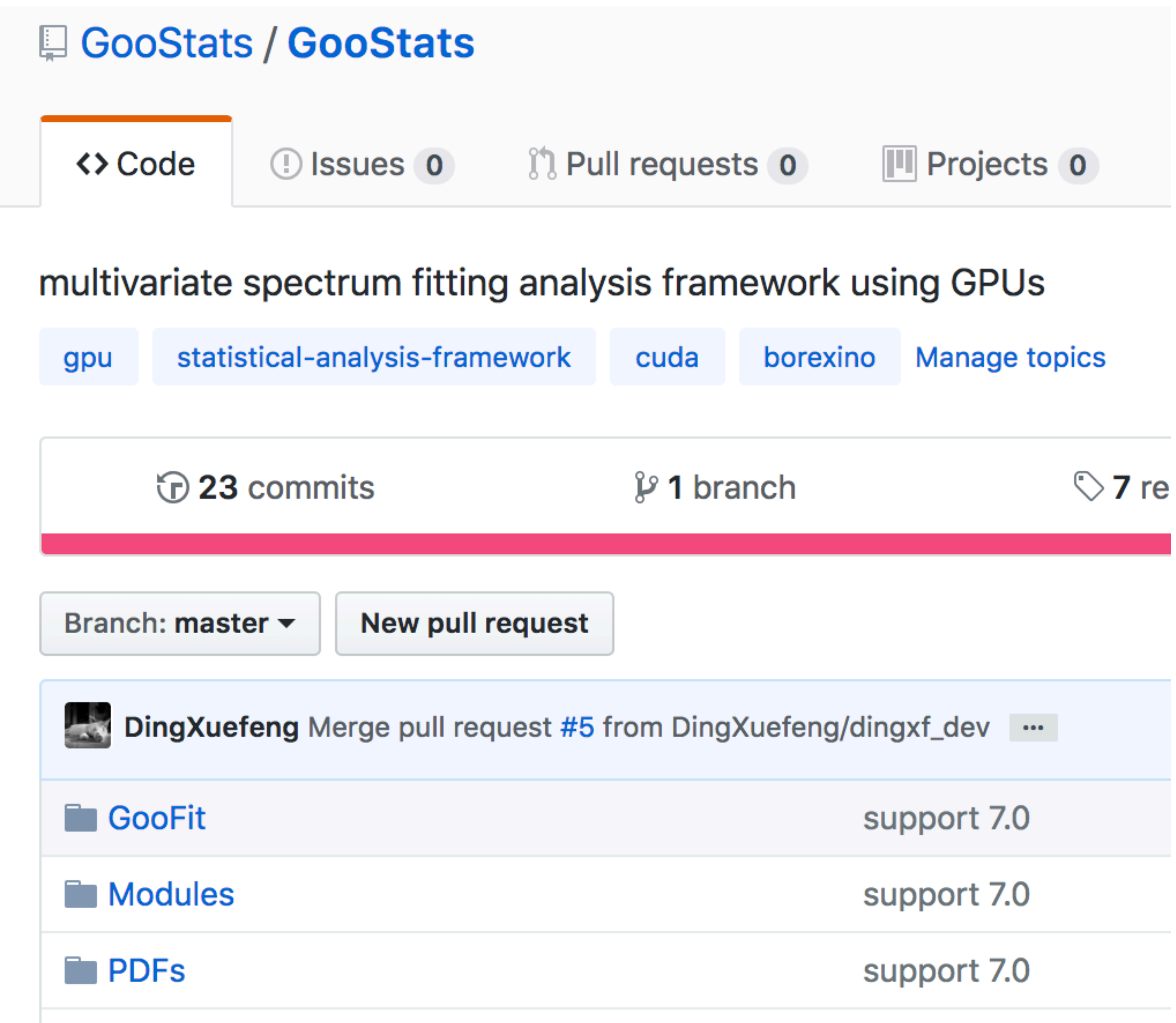


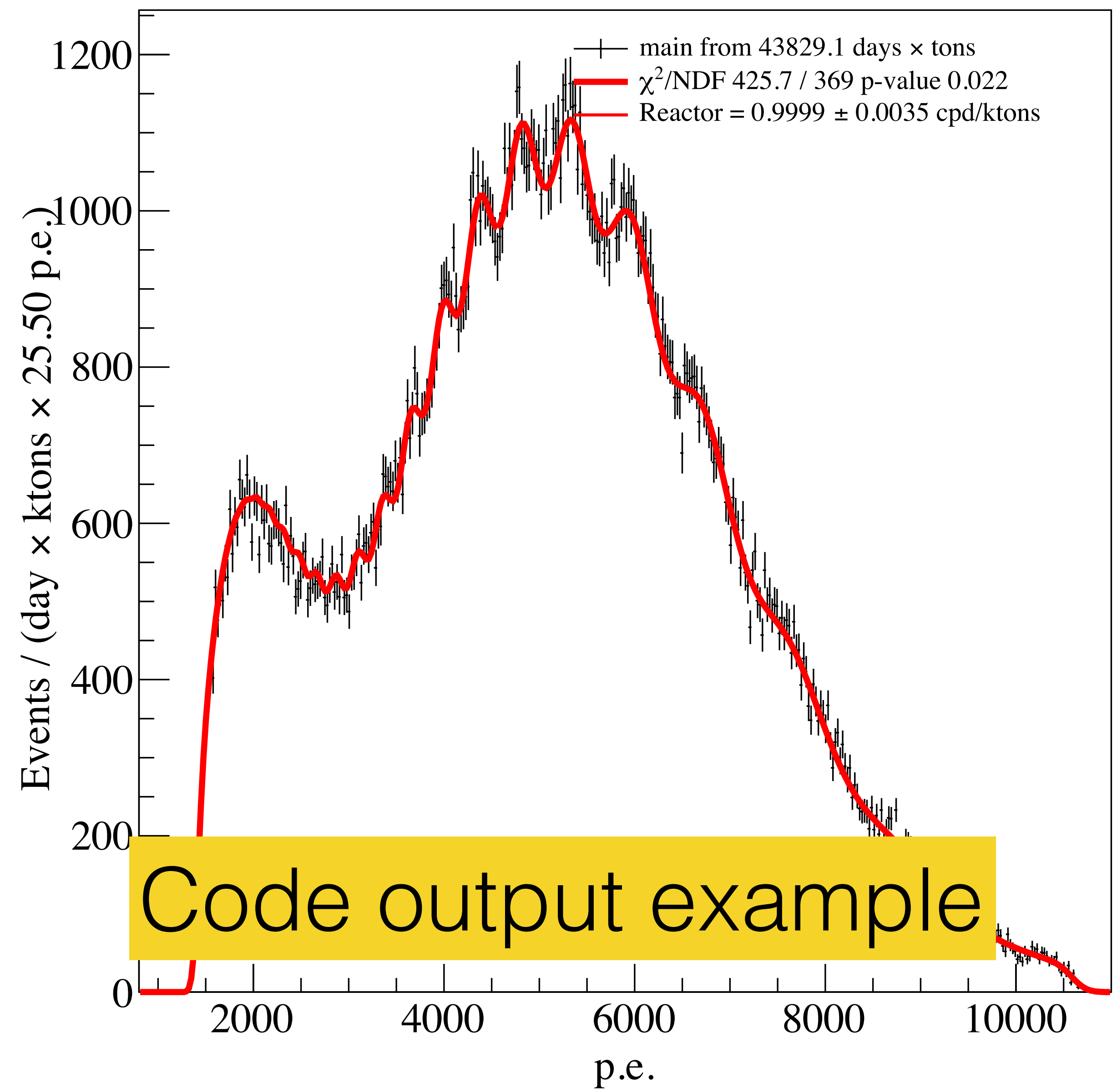
E non-uniformity over r-θ

- E-r, or E-r-θ fit: **high dimensional multivariate fit**
- Benefit: can improve $\Delta\chi^2$ and thus sensitivity
  - Remove non-uniformity: reduce constant term (σ_2)
  - utilize high local resolution.

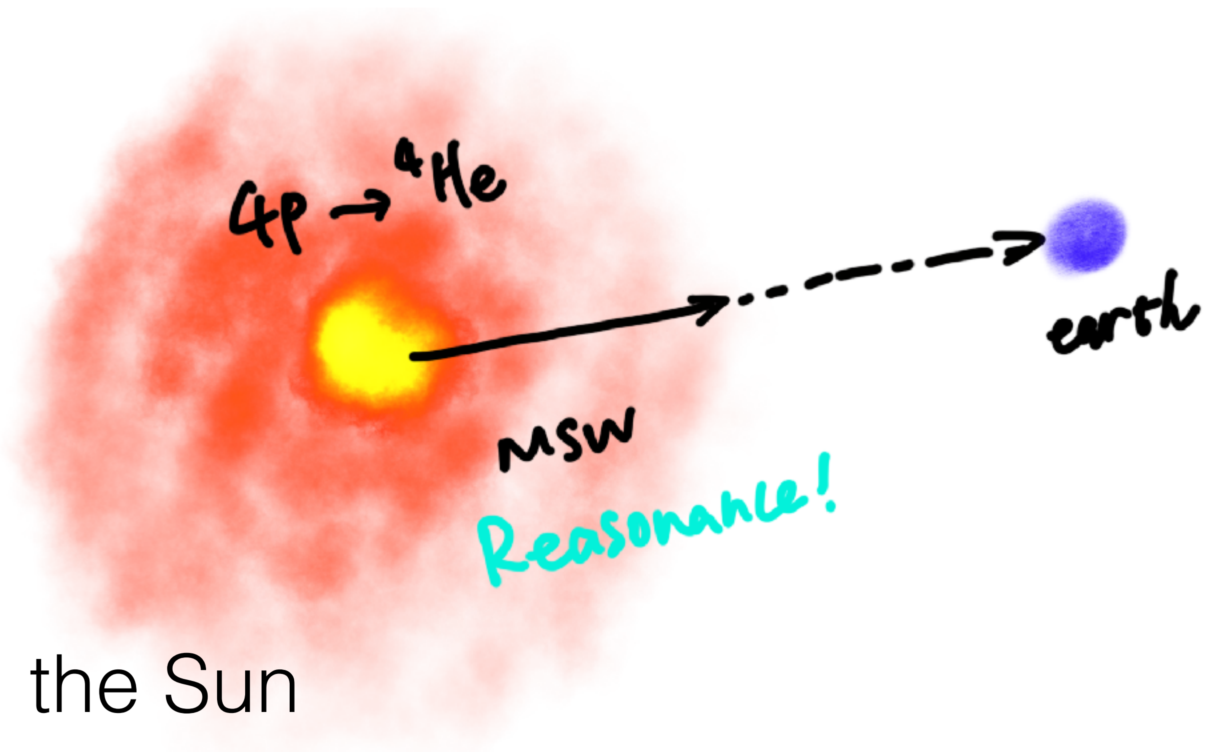
GPU accelerated fit

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



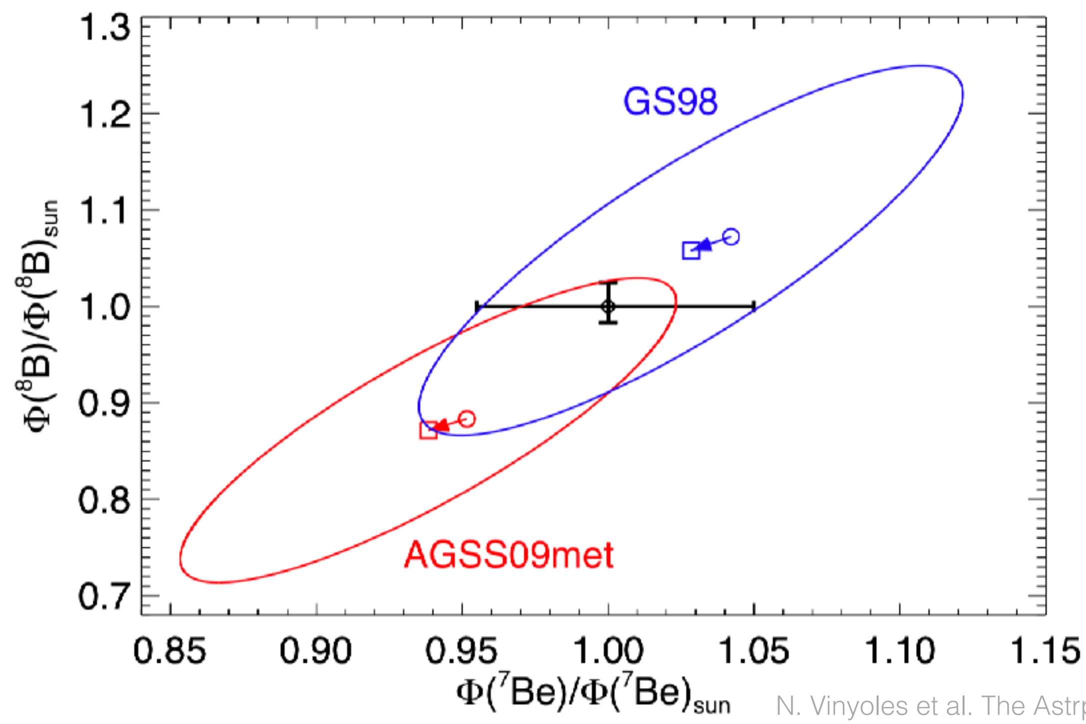


Ding, Xuefeng. (2018, May 19). GooStats, a multivariate spectrum fitting analysis package for particle physics accelerated by graphic processing units (Version v1.2.0). Zenodo. http://doi.org/10.5281/zenodo.1217007



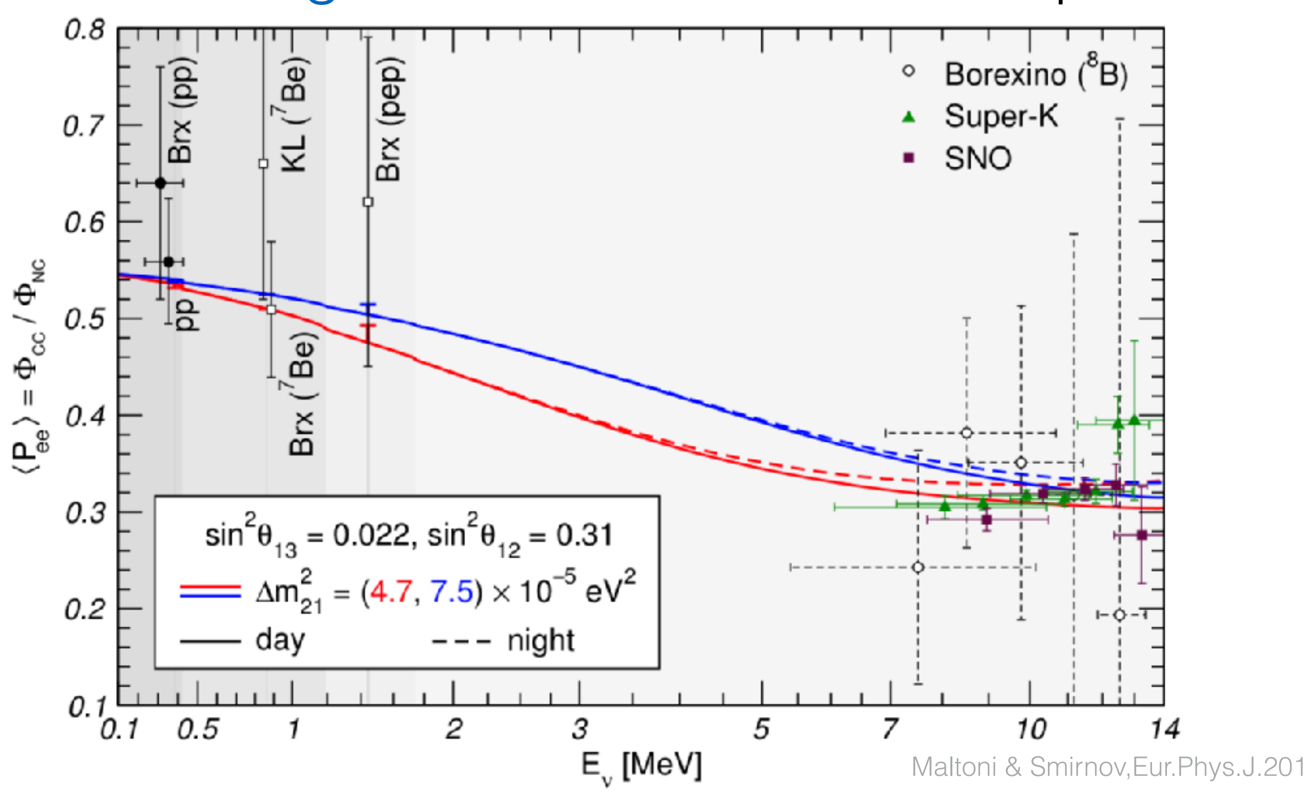
- Solar neutrino is produced in the **core region of the sun**. => study the core of the sun
- Solar neutrino propagate through **ultra-high-density region** and become **flavor-stable** => study MSW resonance (up turn, $\sin^2\theta_{12}$)

Two solar metallicity models

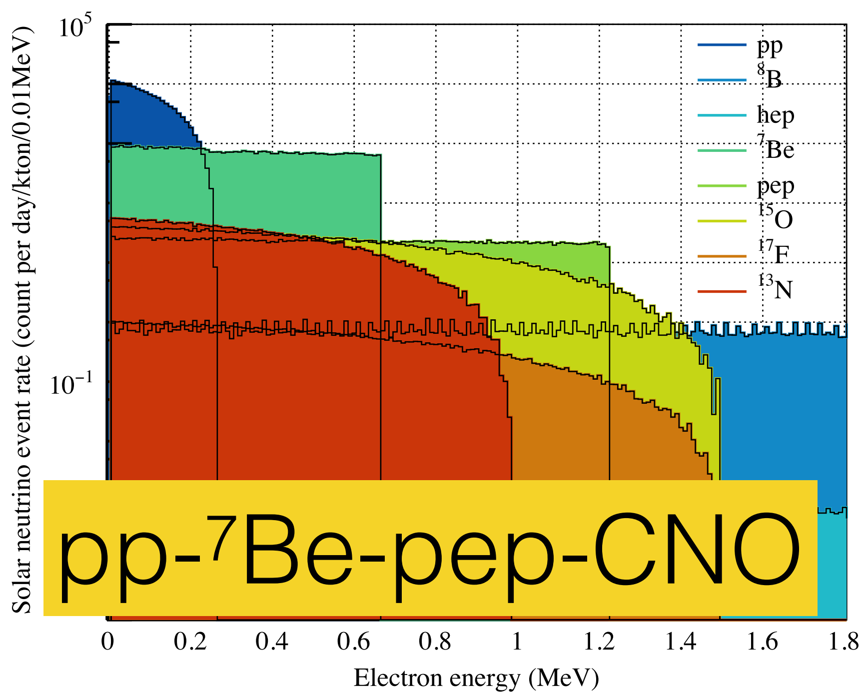


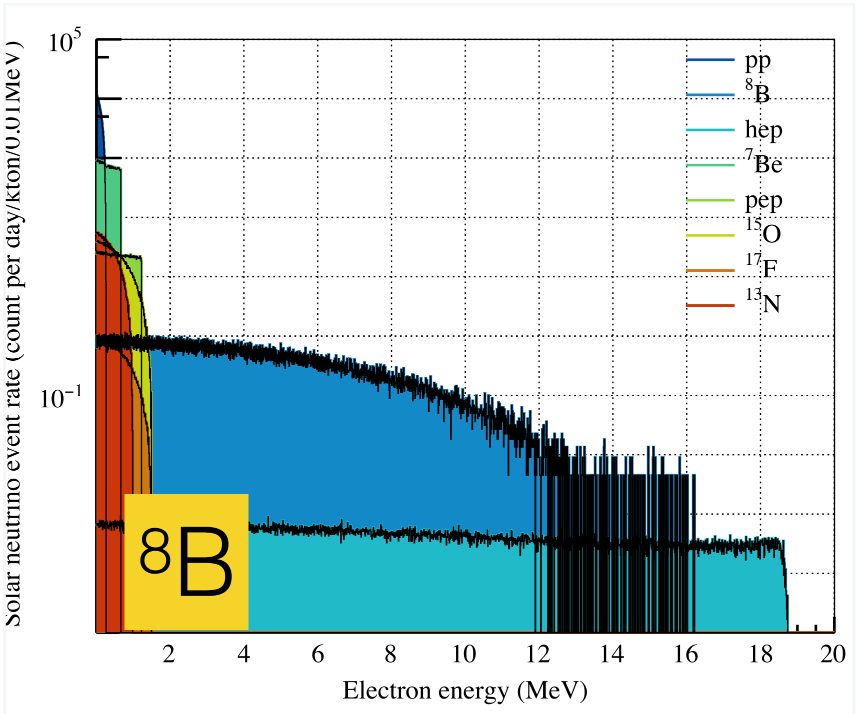
N. Vinyoles et al. The Astrph. Journ. 835 1 (2017) Improoved model

Solar vs global MSW-LMA survival prob.

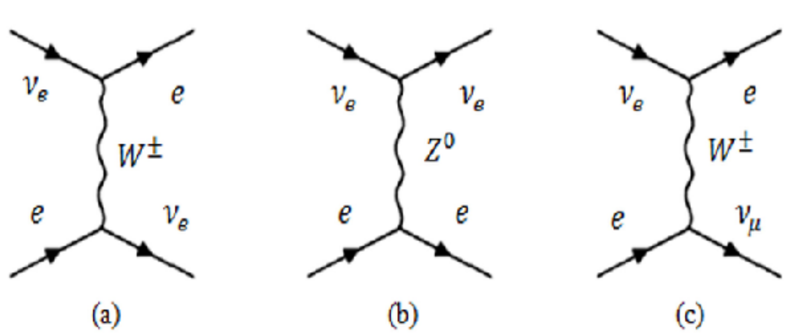


Maltoni & Smirnov,Eur.Phys.J.2016





what is rate? **is there upturn?**



- Signal: ES on electron
- Background:
  - Depend on energy range
- 2 group: **pp + ^{7}Be + pep + CNO**; **^{8}B**

pp-^{7}Be-pep-CNO LS bkg.

- LS ^{238}U chain, ^{232}Th chain 10^{-16} g/g, **^{210}Pb 5×10^{-24} g/g**
  - **Requirement for νMO** (with IBD signiture) **are weaker**: ^{238}U, ^{232}Th 10^{-15}g/g
- **nobel gas:** ^{85}Kr 500 cpd/kt, ^{39}Ar ~ O(1) cpd/kt
- **^{14}C** 10^{-17} g/g 1.65 kBq/kt
- Reactor ES. R_{ES} ~ 0.01 R_{IBD} = 0.04 cpd/kt, negligible

pp-^{7}Be-pep-CNO bkg. summary

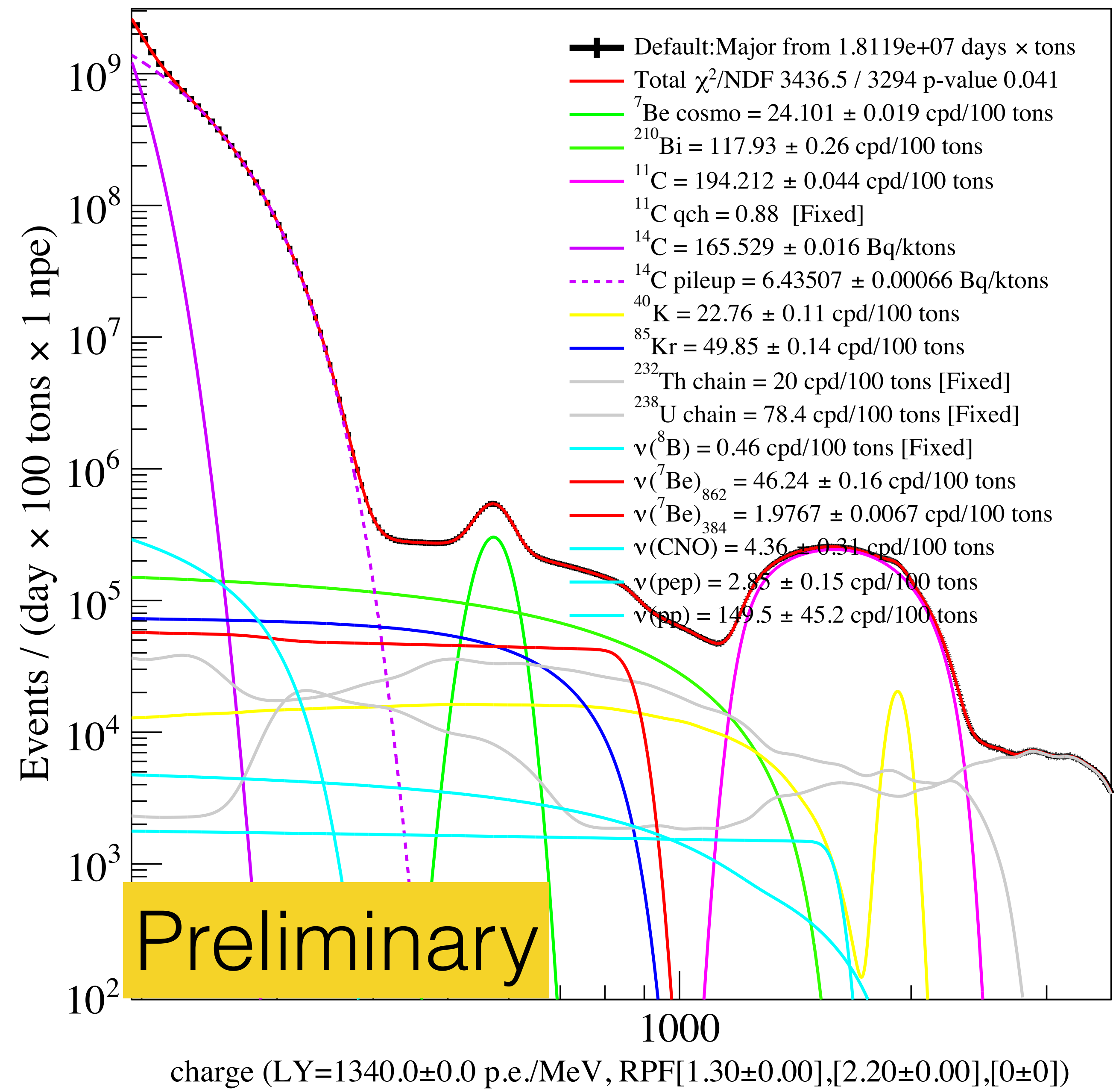
- 1.5 ms => to remove neutron, τ = 220 ns (>99.99%)
  - remove **μ (3 Hz), n (1.8 Hz)**
- TFC: μ + n, n2μ<3m && d2n<2m && t2d<111.2s, ~4% VT loss
  - removed **cosmogenic ^{10}C and ^{6}He**
- FV cut r<14 m (3.7 m buffer) (eff 49.5%)
  - **external γ** from ^{232}Th chain in **Acrylic** etc. 73 Hz Latt~0.167 m
- **Overall eff. 47.5%**
- assume **5.2 years** of data taking

pp-^{7}Be-pep-CNO precision

- 10^{-16} g/g ^{238}U/^{232}Th, 5×10^{-24} g/g ^{210}Pb, 10^{-17} g/g ^{14}C
- **stat**. precision: 0.4% ν(^{7}Be), 5% ν(pep), 7% ν(CNO)

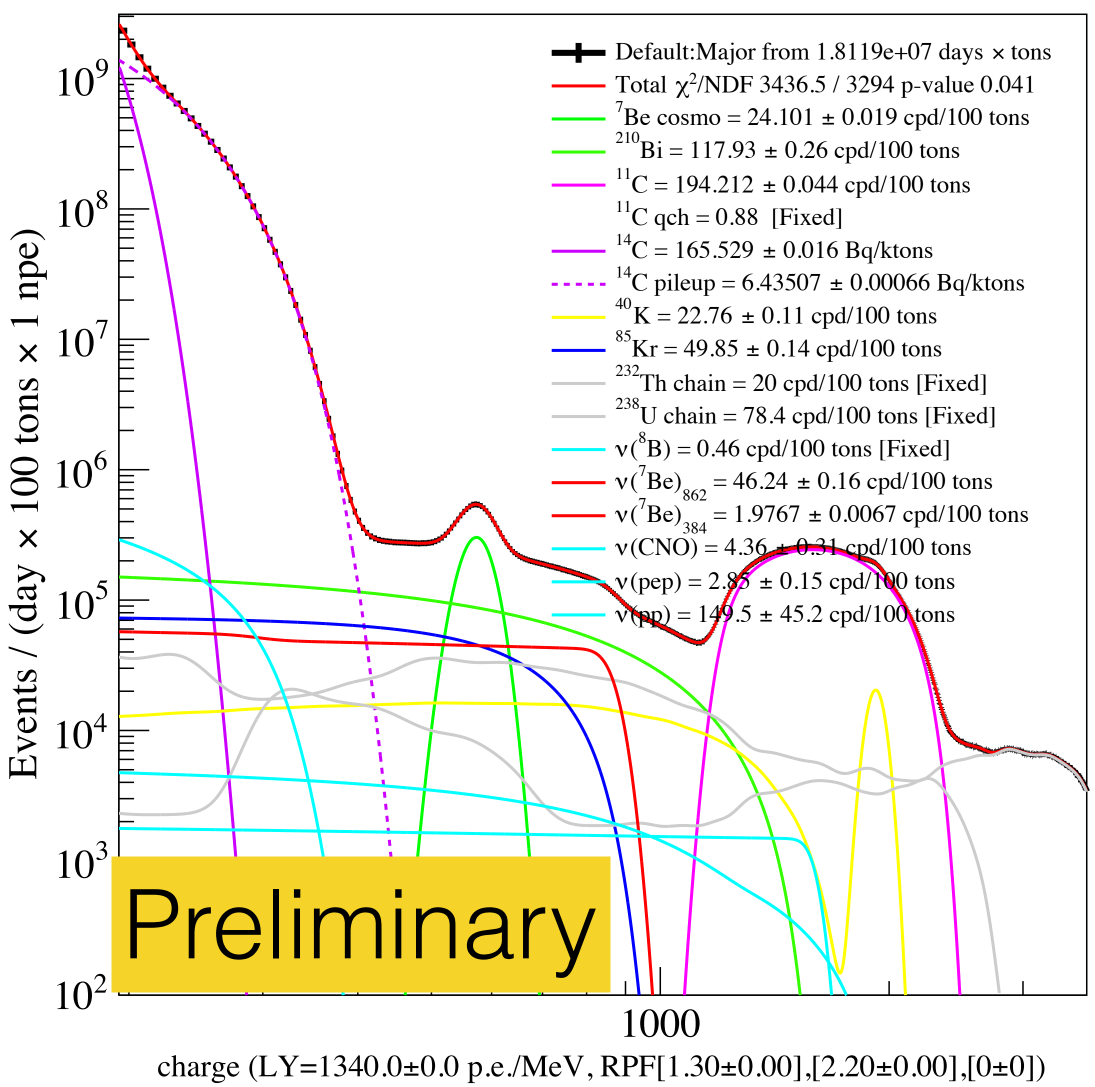
Shape systematics is important and will be studied next.

See also F. An et al., “Neutrino physics with JUNO,” 2016 pp. 90

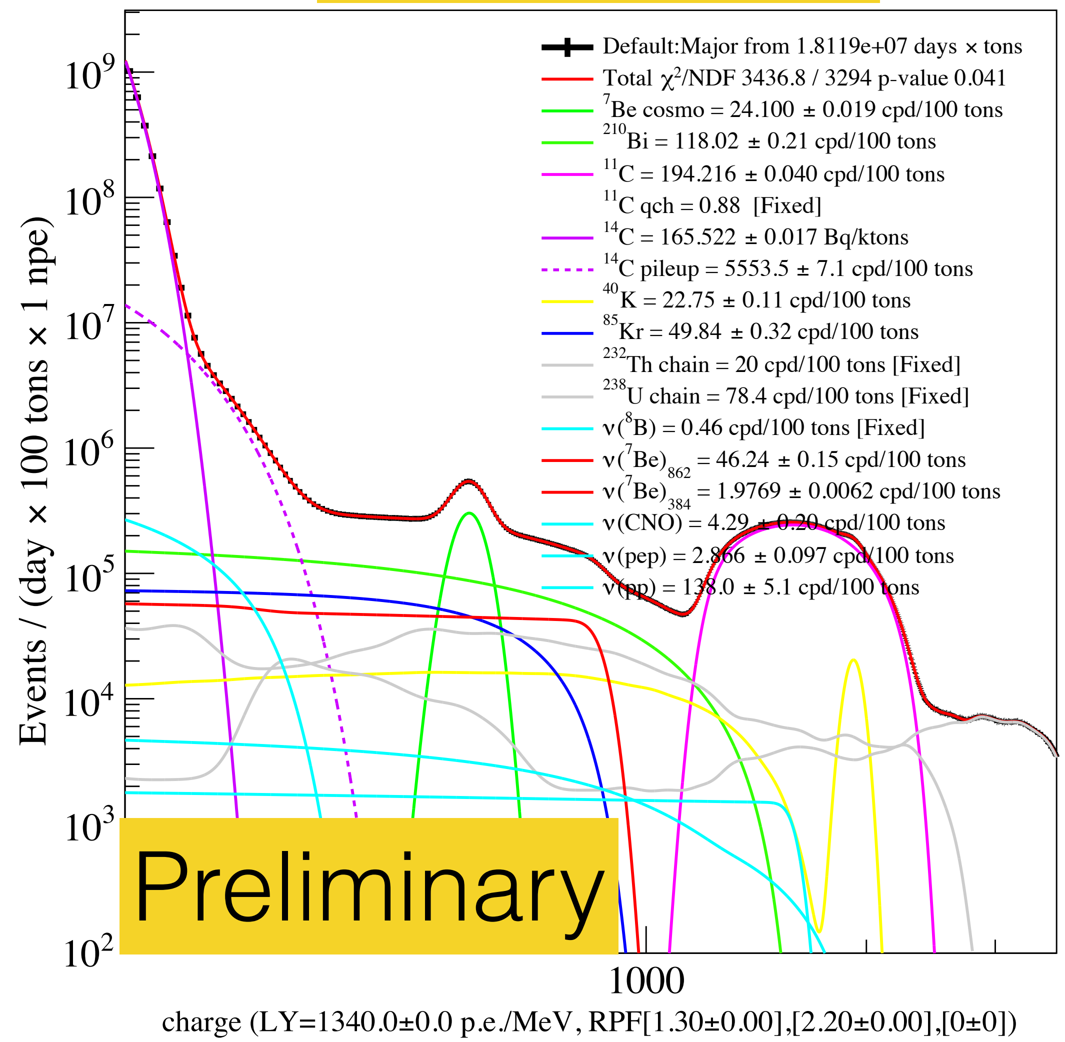


- Need to discriminate pile-up events
- 99% removal eff. for pile-up: **stat**. 4% ν(pp)

normal



pile-up x 1%

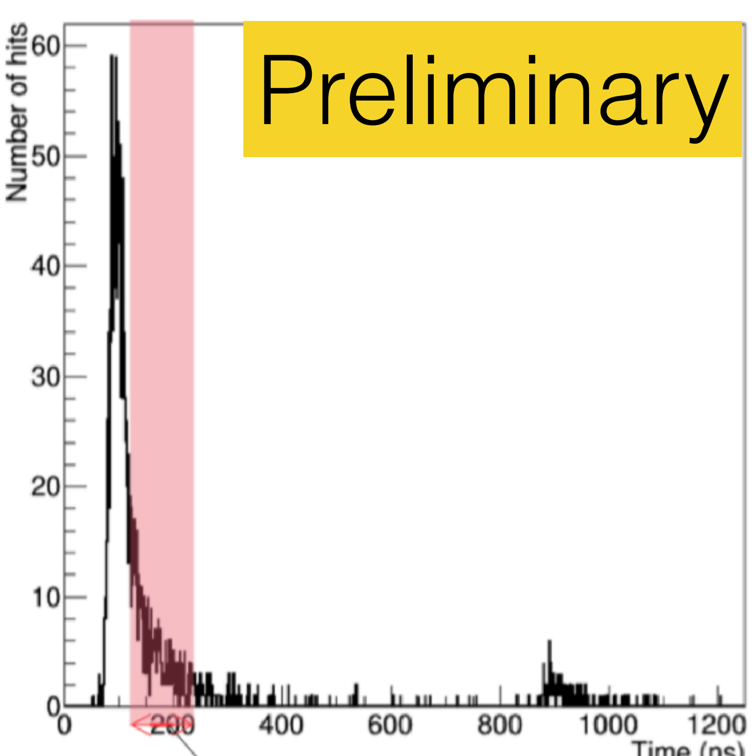


Removal of ^{14}C-^{14}C pile-up

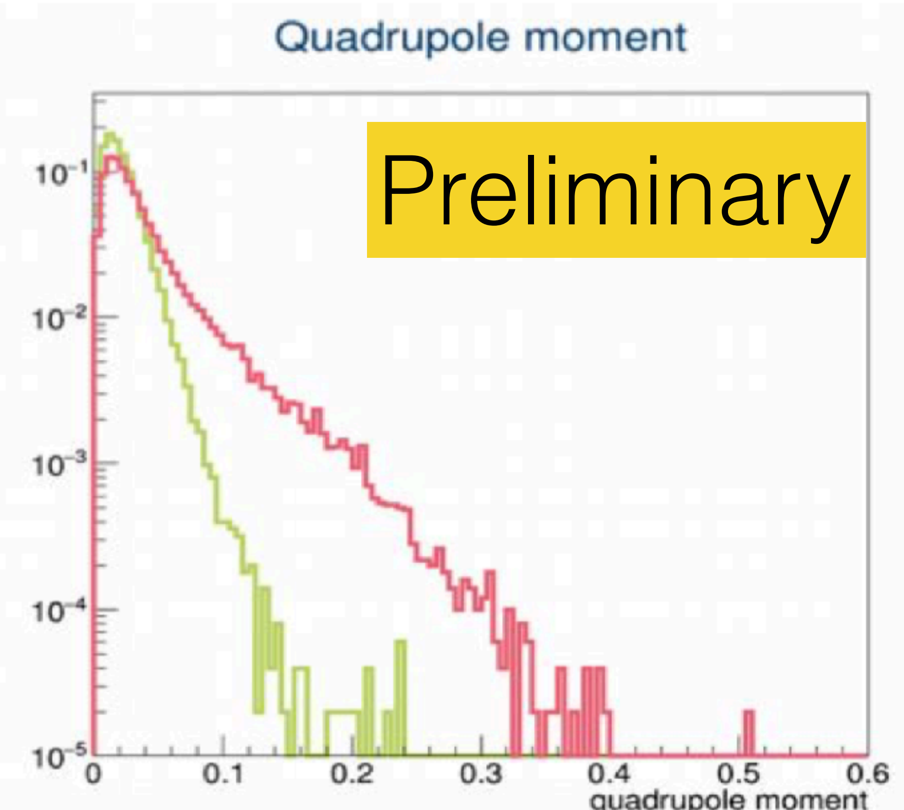
- From hit arrival time: two ^{14}C in the same DAQ window (1250 ns), two cluster of events, see *Ding Neutrino 2018*

DING, Xuefeng. (2018). Clusterization algorithm for sub-MeV events reconstruction in JUNO. Neutrino 2018, Zenodo. http://doi.org/10.5281/zenodo.1300976

- From hit spatial distribution (original vertex): two ^{14}C come at the same time, but far from each other



By PHILIPP KAMPMANN



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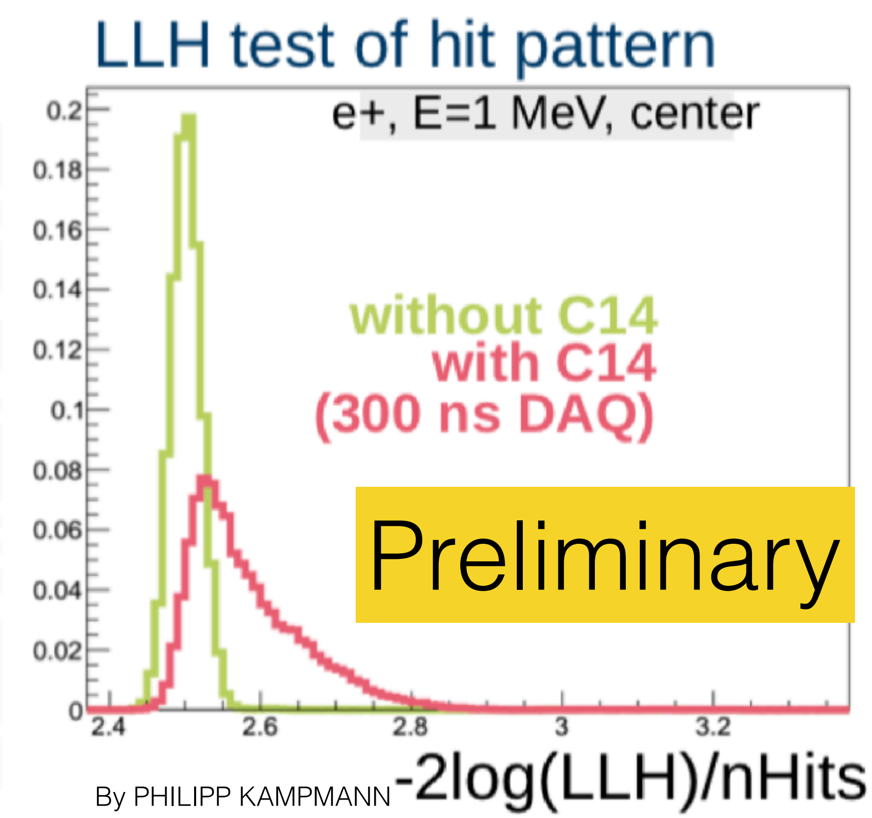
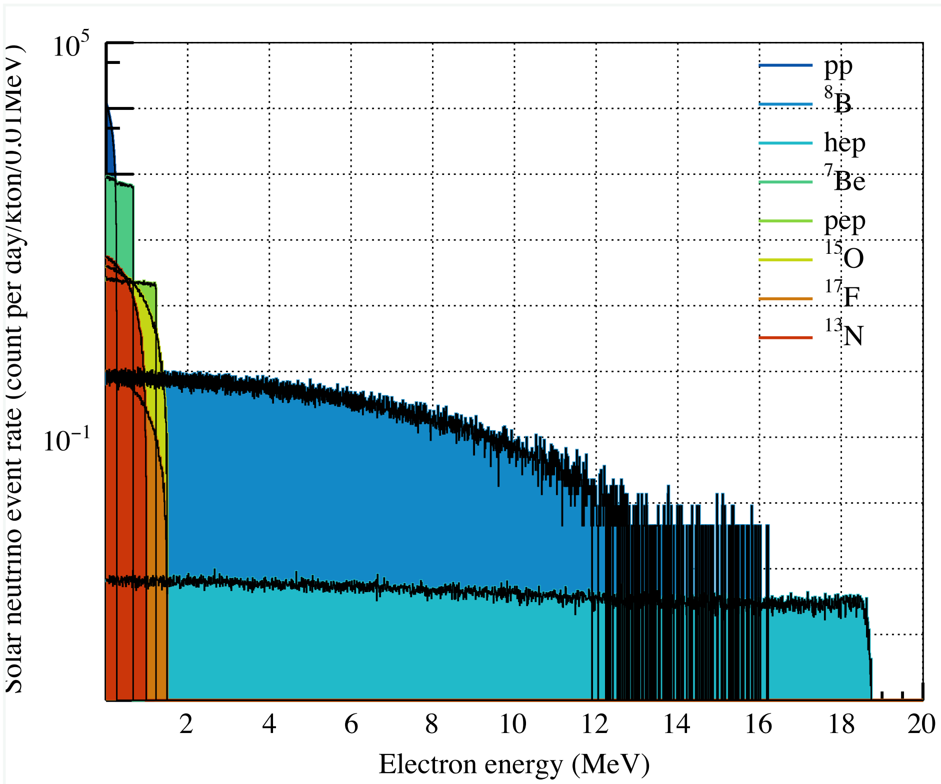
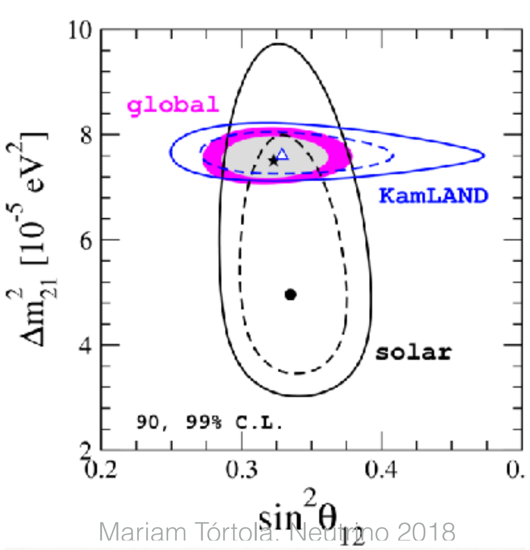


By PHILIPP KAMPMANN

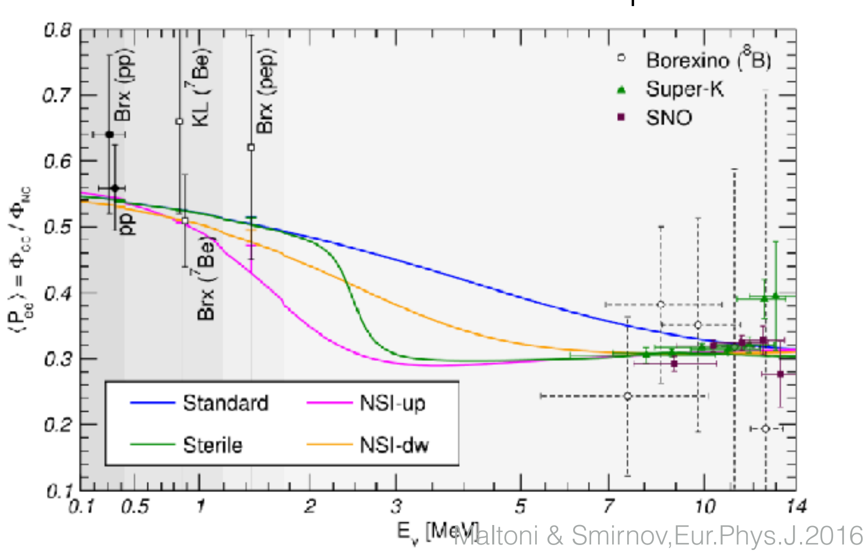
What and **Why** solar ^{8}B?



- Produced during ^{8}B β^{+}-decays
- Study the MSW in transition zone

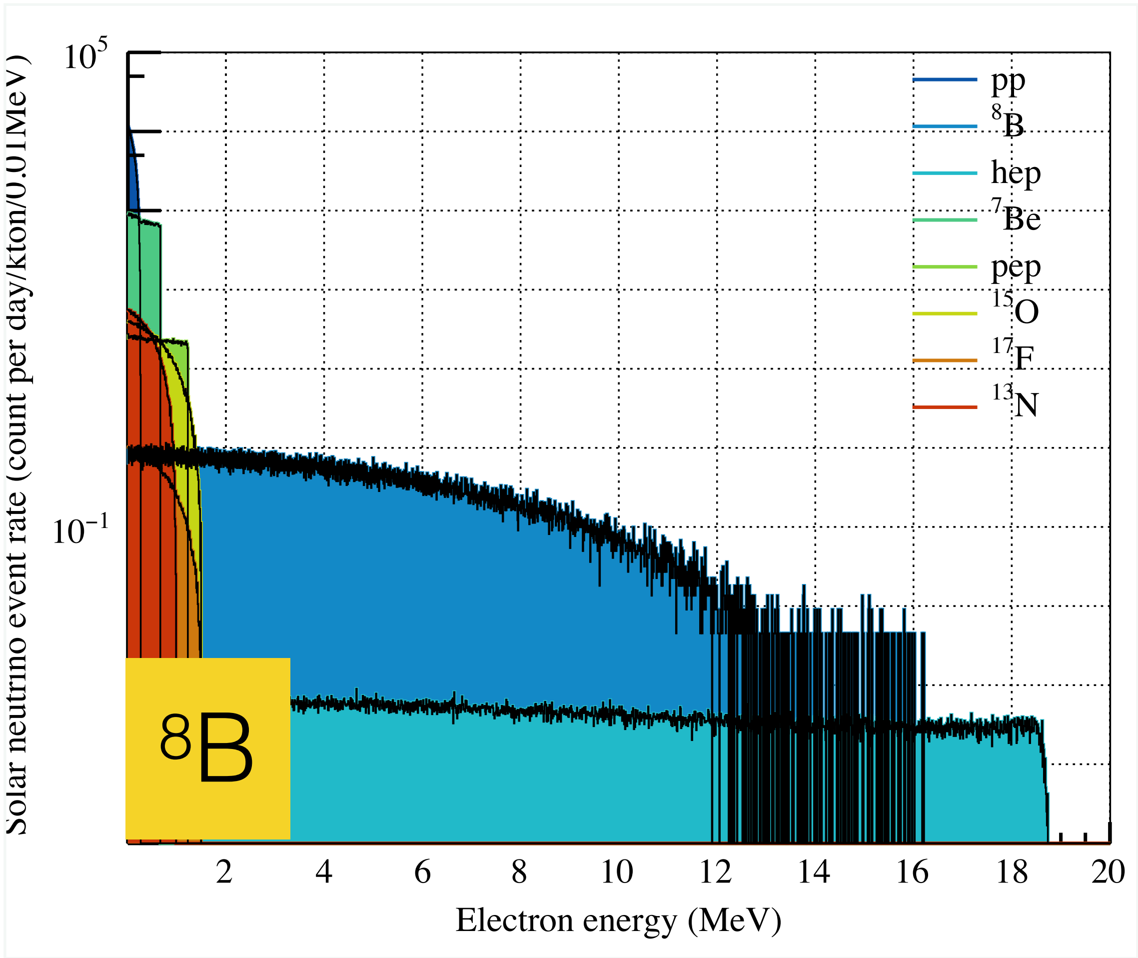


Various MSW-LMA survival prob.



- ~2σ discrepancy on Δm_{21}^2
- NSI and new physics can reconcile it
- Need P_{ee} in **transition zone**

ν(^{8}B) Signal and backgrounds



- Elastic scattering on e$^-$
- Need detection low threshold
- **~6000** ev. in **[2,2.5] MeV** in 6 yr.

backgrounds

main challenge

- External γs (FV cut)
- Cosmogenic
- Bulk ^{238}U/^{232}Th

ν(^{8}B) Cosmogenic

- 3.6 s x 3 m μ-track cylinder cut: 30% loss
- 112 s x 2 m neutron sphere cut: 4% loss
  - ^{10}C removal efficiency **better than 98% (Fluka)**
  - ^{11}Be can also be suppressed. see KL & BX

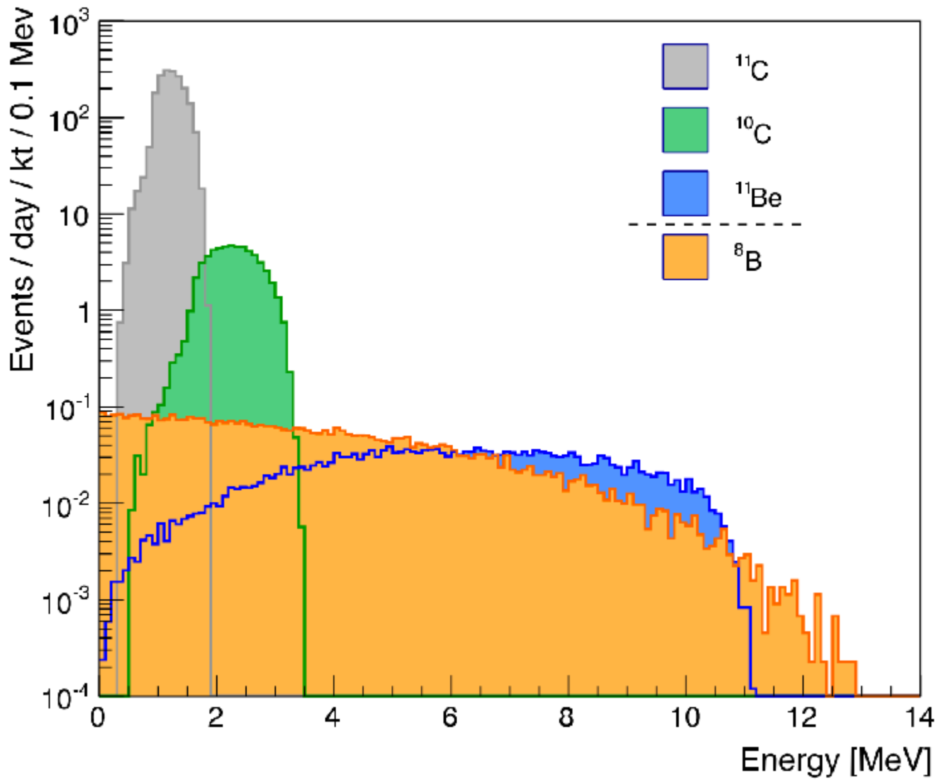
KamLAND PRC 81,2,025807, 2010

Borexino, 1709.00756

F. An et al., "Neutrino physics with JUNO," 2016 pp. 93 table 15, pp.175 table A9

	scale KL (cpd/kt)	Fluka (cpd/kt)	life time
^{11}C	1860	810	29.4 min
^{10}C	35	24.1	27.8 s
^{11}Be	2	1.2	19.9 s

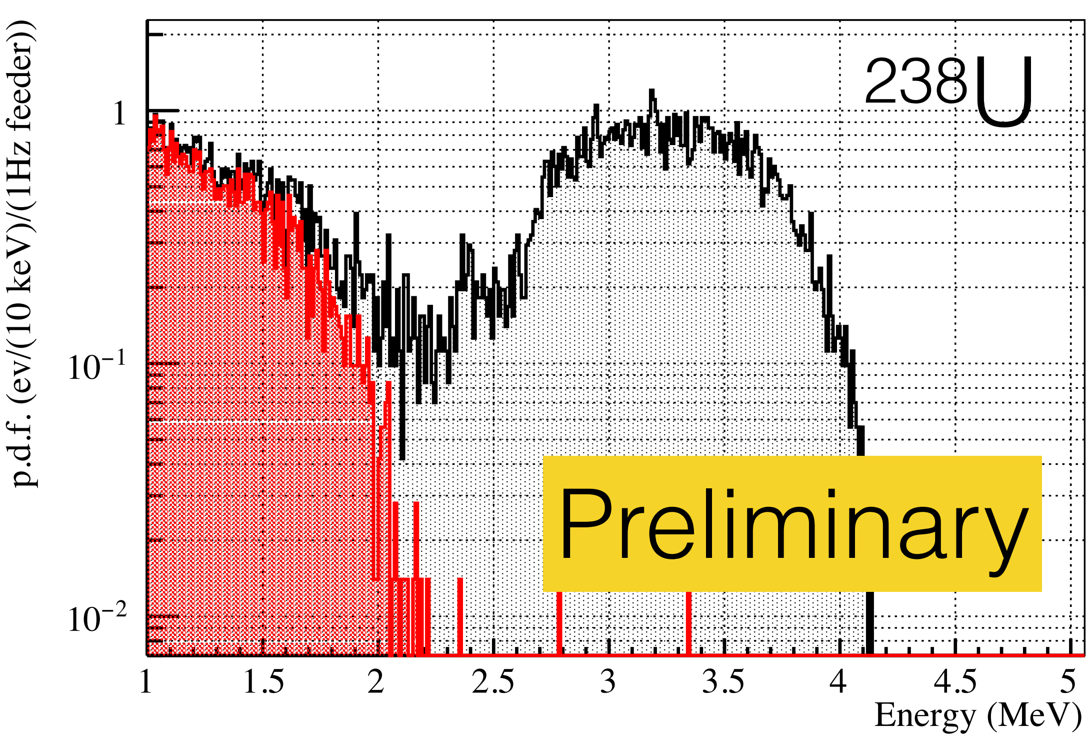
F. An et al., "Neutrino physics with JUNO," 2016 pp. 93

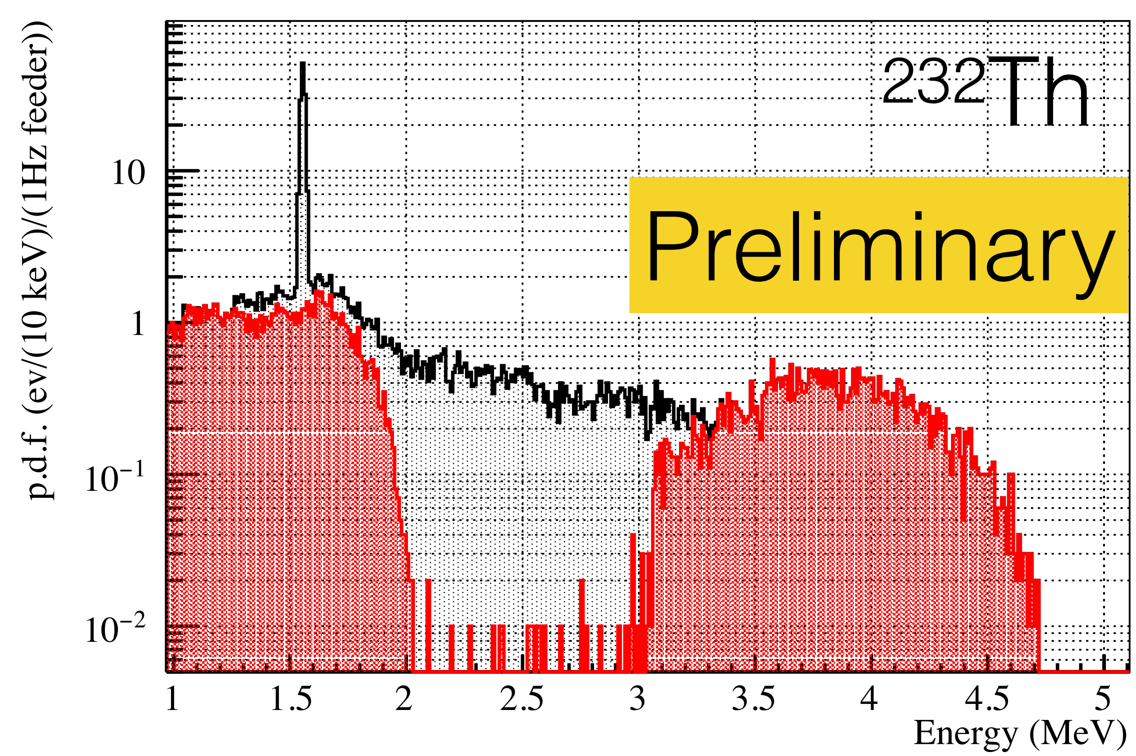


$\nu(^{8}B)$: Bulk $^{238}U/^{232}Th$

- Baseline 10^{-15} g/g (MH req.) 10^{-16} g/g (solar req.)
  - **Events with α decay can be vetoed**
  - Residual events can be subtracted with rate constrained to that measured through Bi-Po tagging

Black: with α. Red: w/o α. Non-linearity from LS not corrected.





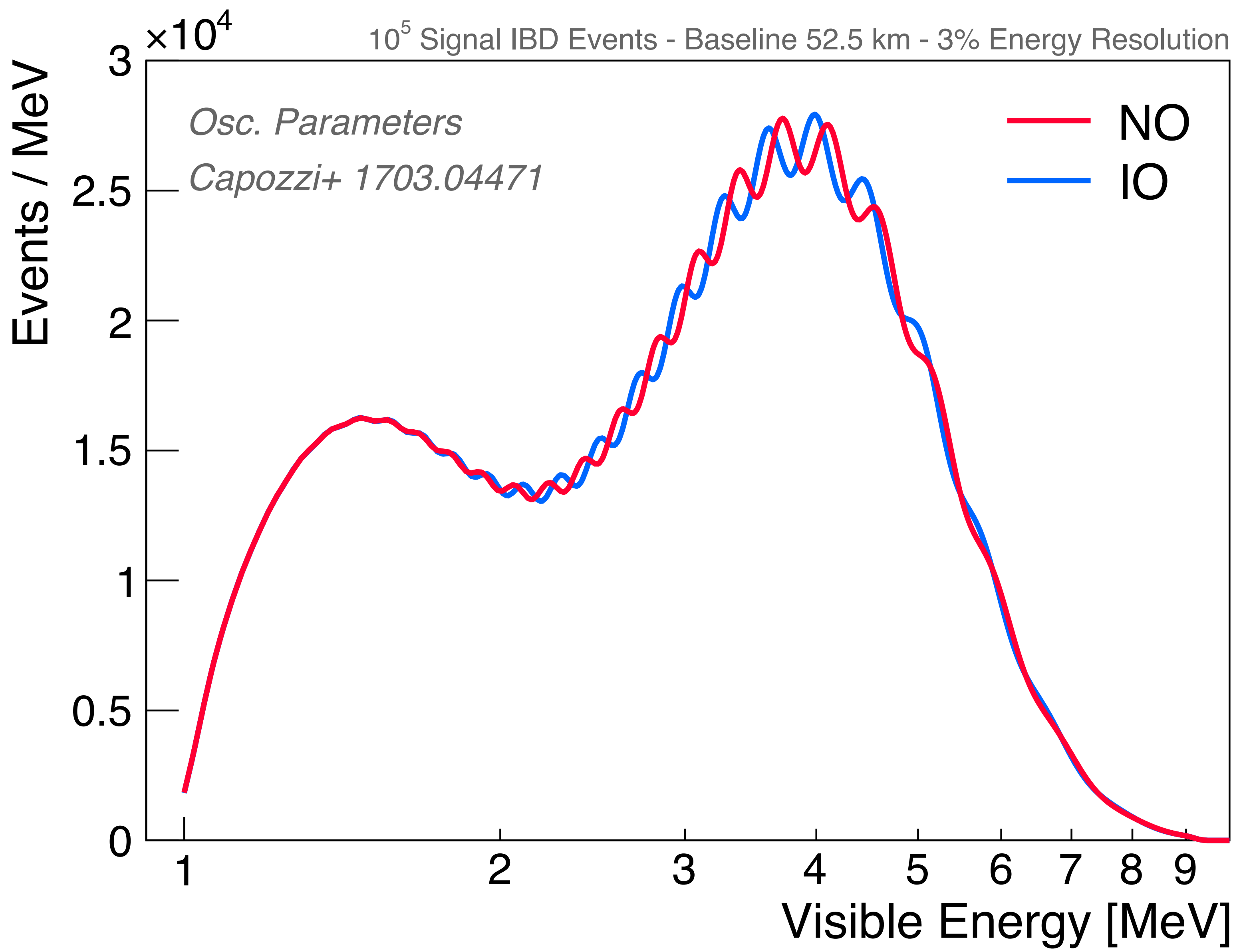
Conclusions

- JUNO's median sensitivity on determining **Neutrino Mass Ordering** is **~3.4σ with 6 years of data**
  - 3% energy resolution ($\frac{\sigma_0}{1.6} \oplus \sigma_1 \oplus 1.6\sigma_2 < 3\%$) is required.
  - Degeneration from residual NL removed by using free NL par.
  - Using multivariate fit can improve sensitivity
- **Expected precision on solar neutrinos** assuming 10^{-16} g/g ^{238}U etc. LS purity is at percent level. **Shape systematics** not included yet.
- **The S/B for solar ^{8}B neutrino** for JUNO depends on **the efficiency of removal of ^{10}C** with μ-n tagging algorithms
  - From Fluka it can reach 98%. Then **S/B ~ 1:1**
  - 6 yr 6000 ν ev. in [2,2.5] MeV: **touch transition zone**

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