Scintillator-based Detectors and Low Background Detectors

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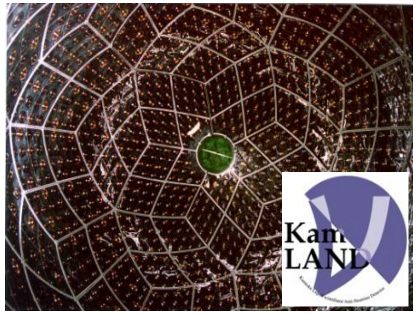
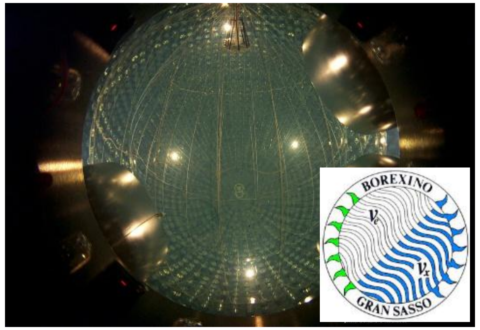
Workshop on Supernova Neutrino Observations: What Can We Learn? What Should We Do?
MITP, Mainz, 12.10.2017

Current & Future Scintillator-based Detectors

LVD, 1 kt

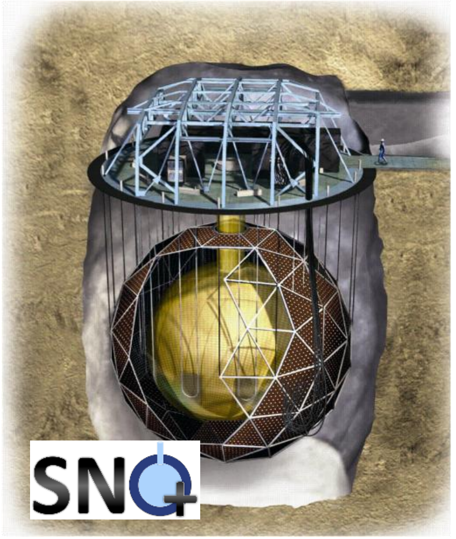


KamLAND, 1 kt

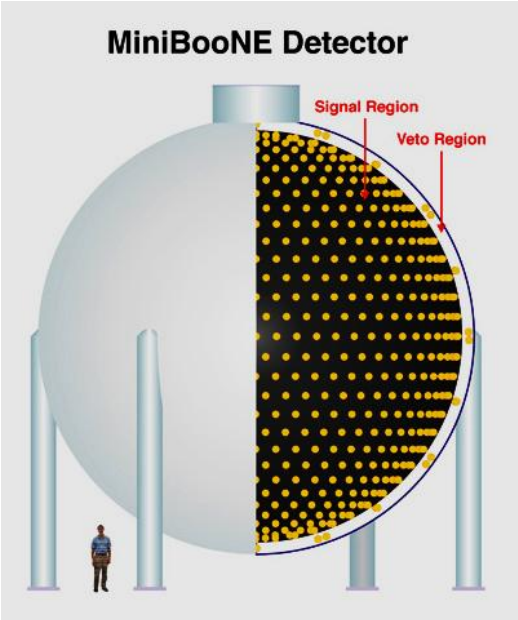


Borexino, 0.3 kt

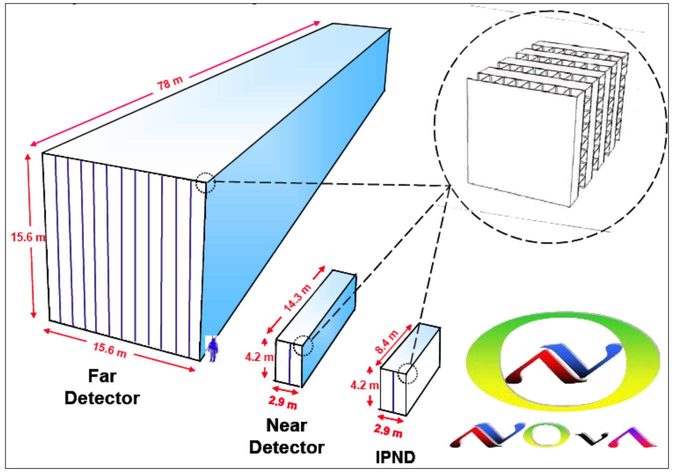
Daya Bay, 0.16 kt



SNO+, 1 kt



MiniBooNE, 0.7 kt

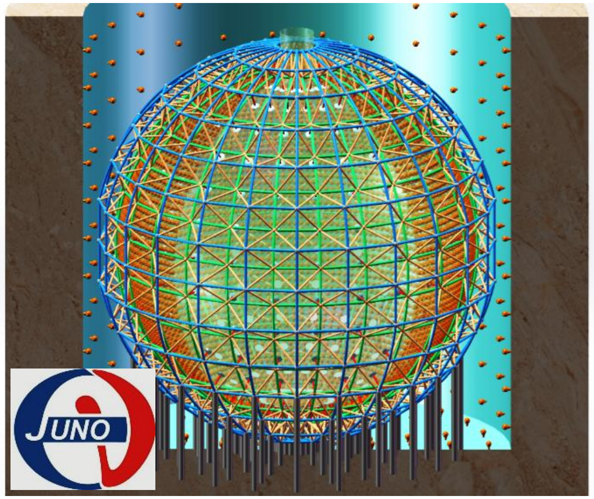


NOvA, 15 kt

Scholberg's review talk

Baksan, 0.33 kt

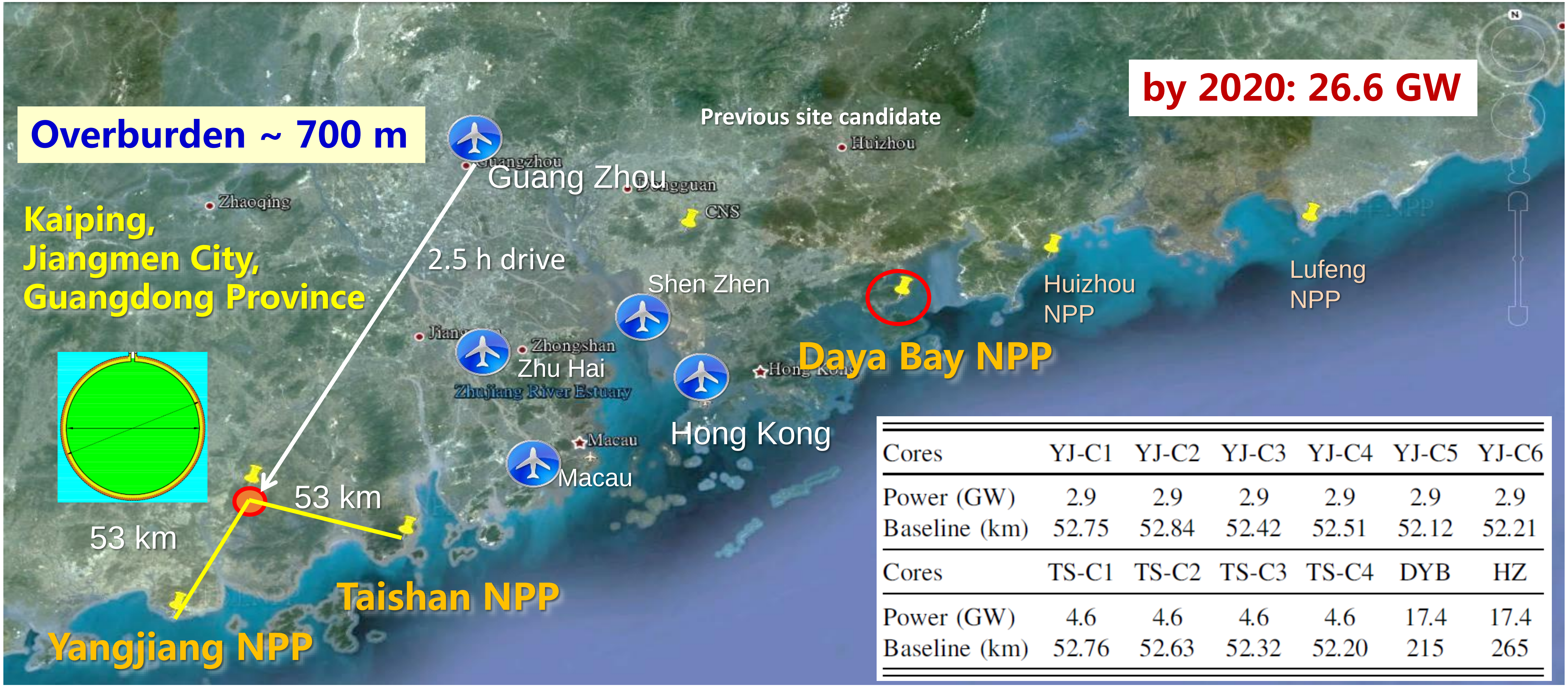
LENA, 50 kt



JUNO, 20 kt

The JUNO Experiment

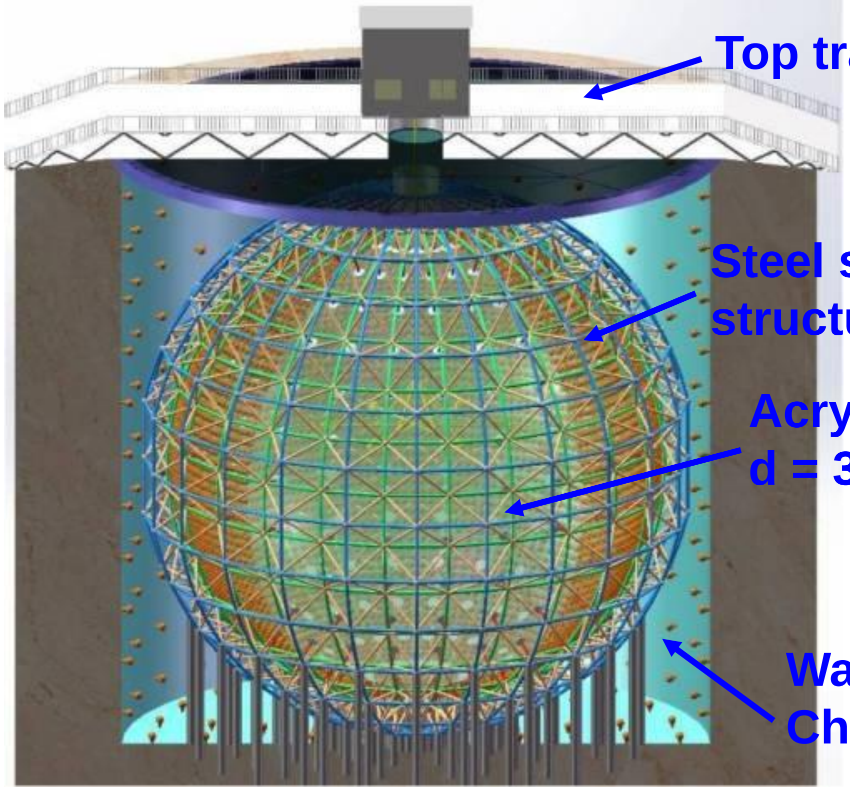
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

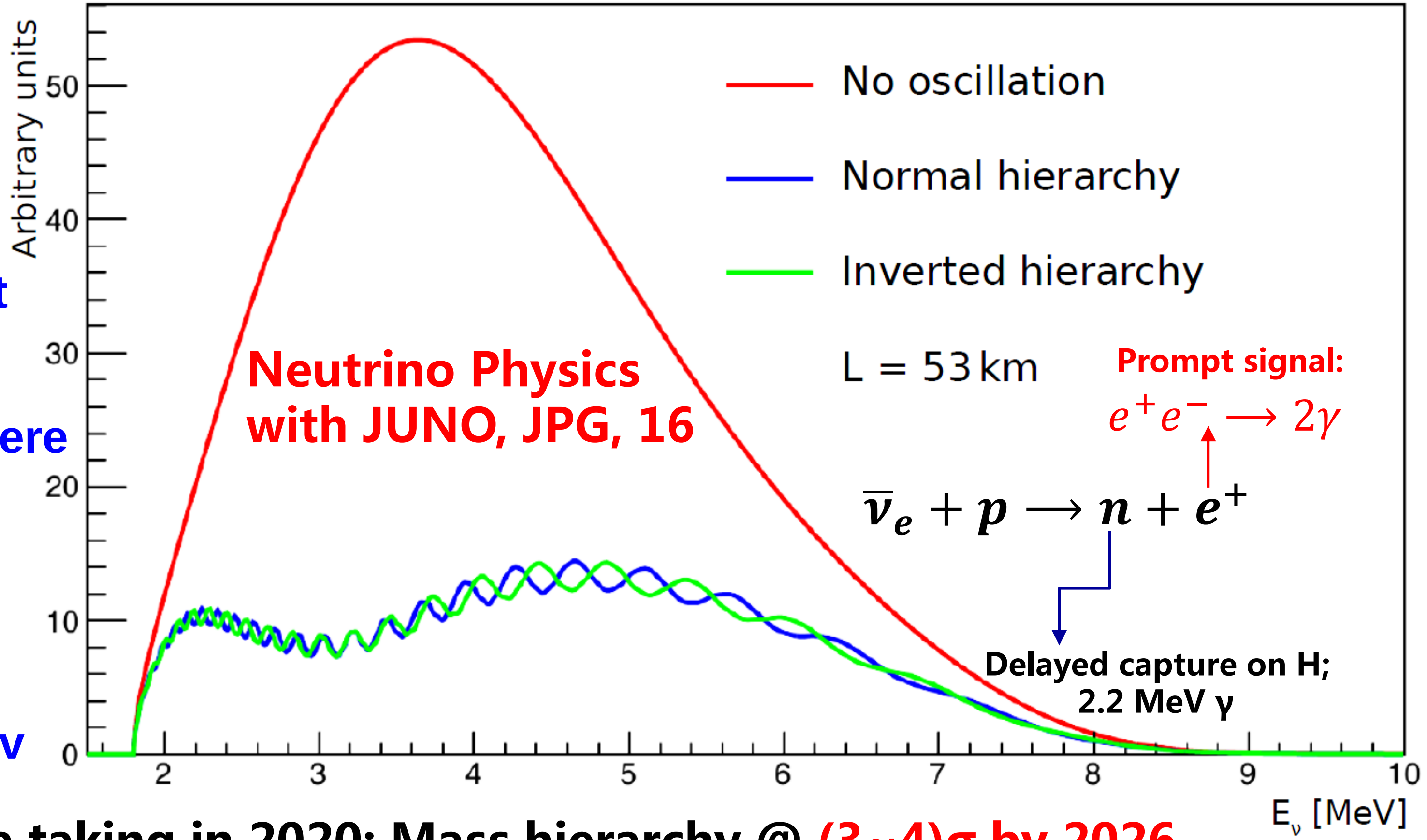


Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

The JUNO Experiment

Jiangmen **U**nderground **N**eutrino **O**bservatory





- 20 kiloton LS detector
- 3% energy resolution@ 1 MeV
- 700 m underground
- 18,000 20" +25,000 3" PMTs
- 53 km to the NPPs

Data taking in 2020; Mass hierarchy @ (3~4)σ by 2026

	KamLAND	Borexino	JUNO
LS mass	1 kt	0.3 kt	20 kt
Energy Resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

JUNO Collaboration

72 institutes
553 members

EUROPE(30)

Armenia (1)
YPI Erevan

Belgium (1)
ULB Brussels

Czech (1)
Charles U.

Finland (1)
U. Oulu

France (6)
APC Paris
CENBG France
CPPM Marseille
IPHC Strasbourg
LLR Paris
Subatech Nantes

Germany (7)
FZ Julich
RWTH Aachen
TUM Munich
U Hamburg
IKP FZI Jülich
U Mainz
U Tuebingen

Latvia (1)
IECS Riga

Italy (8)
INFN Catania
INFN-Frascati
INFN-Ferrara
INFN-Milano
INFN-Bicocca
INFN-Padova
INFN-Perugia
INFN-Roma3

Russia (3)
JINR Dubna
INR Moscow
MSU Moscow

Slovakia (1)
Comenius U

ASIA(37)

China (33)
BISEE
BNU
CAGS
CQU
CIAE
DGUT
ECUST
Guangxi
HIT
IHEP
IMP
CAS
Jilin U
Jinan U
Nanjing U
Nankai U
Natl. CT U
Natl. Taiwan U
Natl. United U
NCEPU
Pekin U
Shandong U
Shanghai JTU
Sichuan U
SUT
Tsinghua
SYSU
UCAS
USTC
U. of S. China
Wuhan
Wuyi
Xiamen U
Xi'an JTU

Thailand SUT
Thailand CU
Thailand NARIT
Pakistan PINST

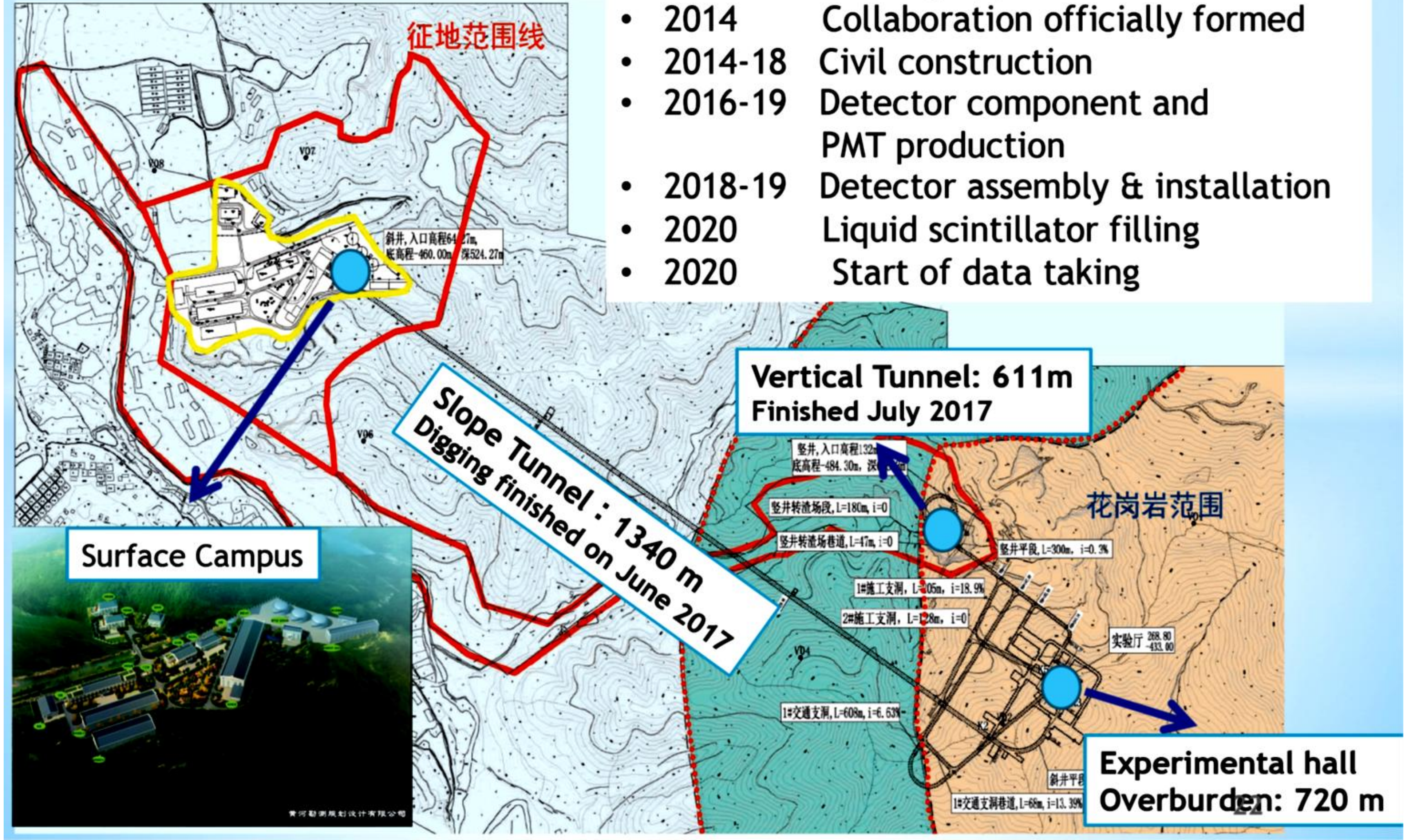
AMERICA (5)

PUCC Chile
UTFSM Chile
Maryland U
(2 groups)
UEL Brazil

B. Clerbaux
@NuFact17

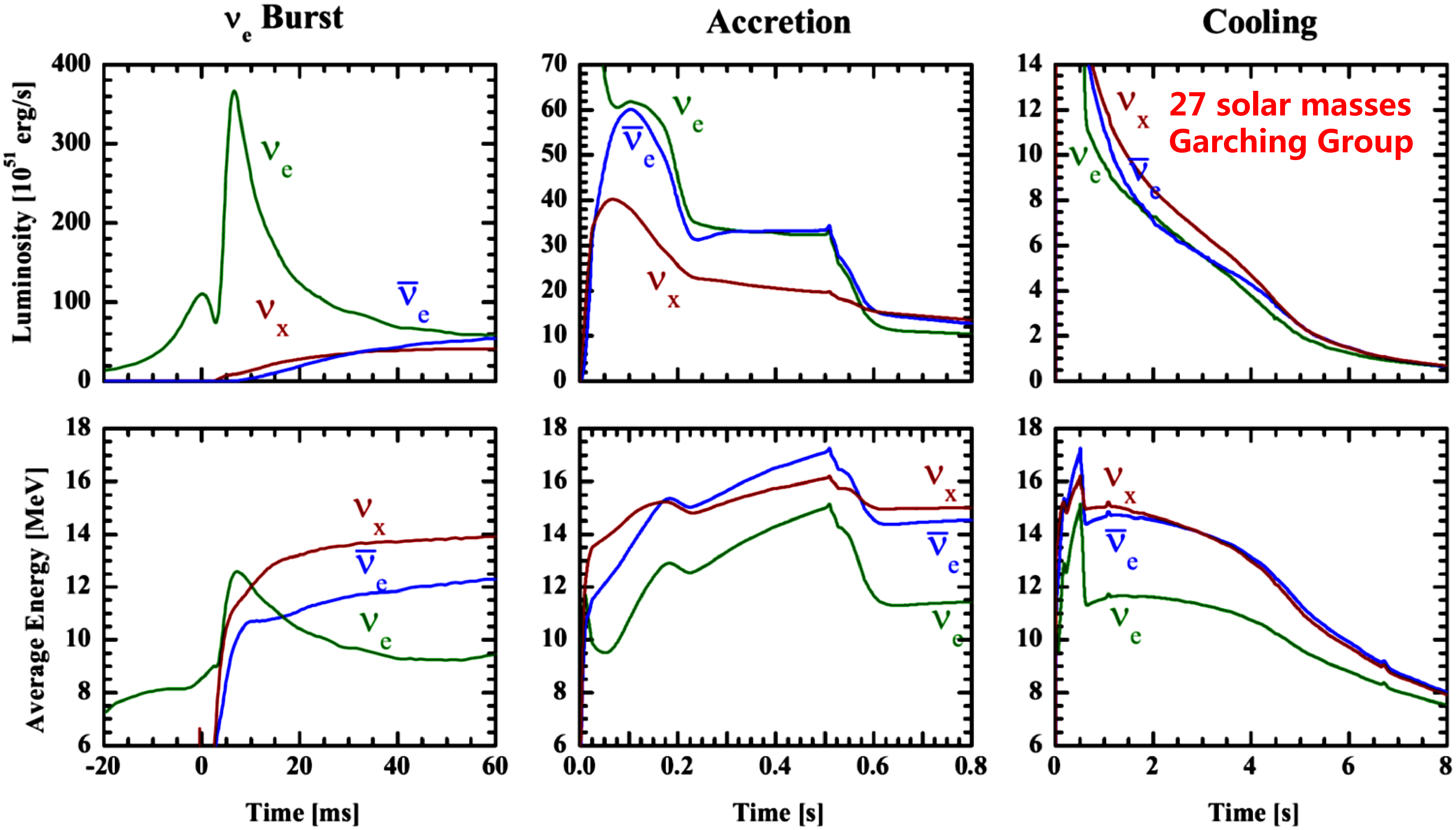
JUNO Timescale

- 2013 Funding approved
- 2014 Collaboration officially formed
- 2014-18 Civil construction
- 2016-19 Detector component and PMT production
- 2018-19 Detector assembly & installation
- 2020 Liquid scintillator filling
- 2020 Start of data taking

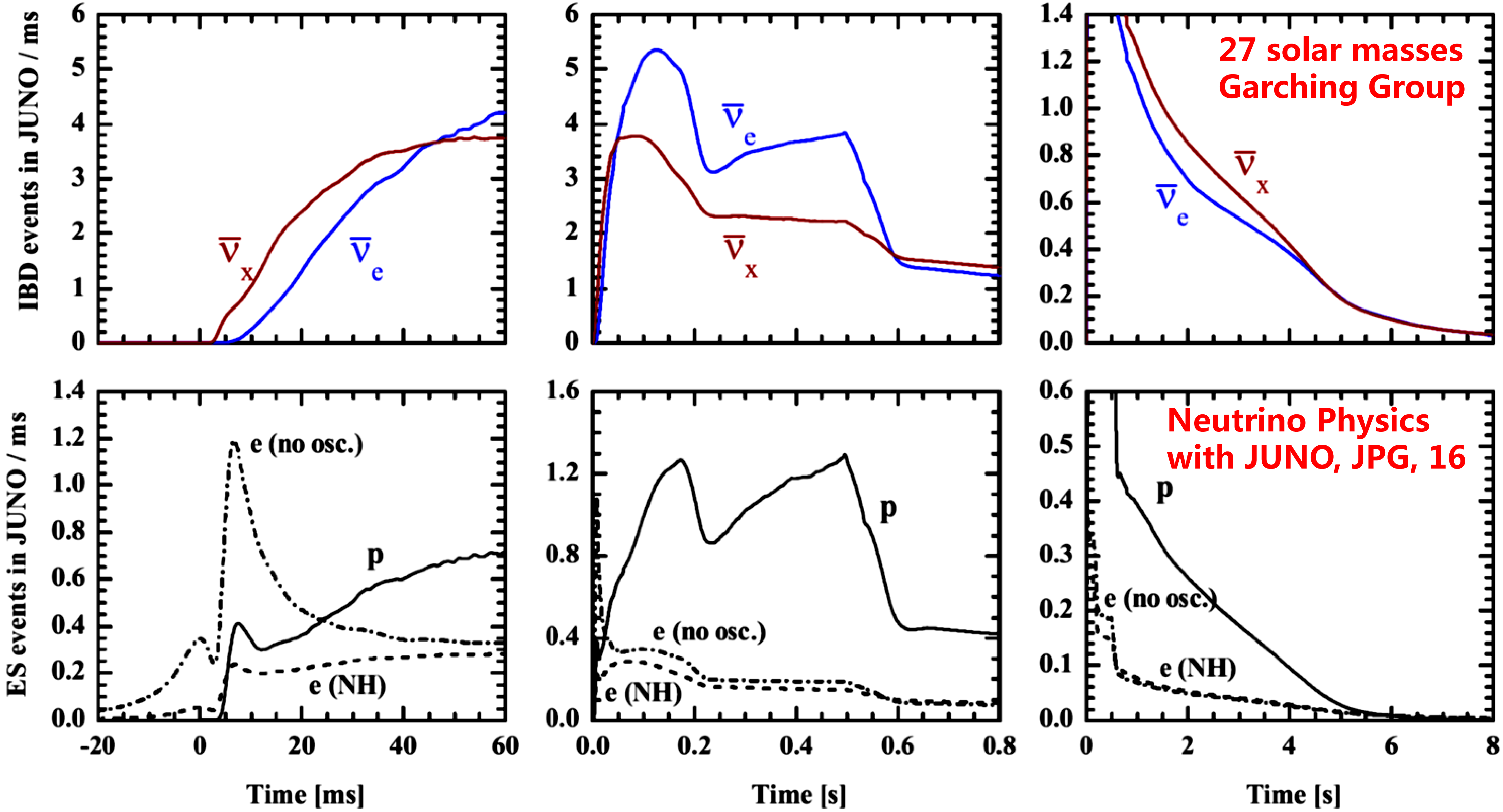


B. Clerbaux
@NuFact17

SN Models & Neutrino Spectra



SN Neutrino Event Rates



SN Neutrinos @ LS Detectors

Reaction channel	Interaction type	Sensitive to
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	$\overline{\nu}_e$
$\nu + p \rightarrow \nu + p$	NC	ν_x
$\nu + e^- \rightarrow \nu + e^-$	CC+NC	ν_e
$\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$ (14.39 MeV, 20 ms)	CC	$\overline{\nu}_e$
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$ (17.34 MeV, 11 ms)	CC	ν_e
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$	NC	ν_x

Natural abundance of $^{13}\mathrm{C}$ is about 1.1%

Fukugita *et al.*, PLB, 90; Suzuki *et al.*, PRD, 12

Reaction channel	Interaction type	Sensitive to
$\overline{\nu}_e + {}^{13}\mathrm{C} \rightarrow e^+ + {}^{13}\mathrm{B}$	CC	$\overline{\nu}_e$
$\nu_e + {}^{13}\mathrm{C} \rightarrow e^- + {}^{13}\mathrm{N}$	CC	ν_e
$\nu + {}^{13}\mathrm{C} \rightarrow \nu + {}^{13}\mathrm{C}^*$	NC	ν_x

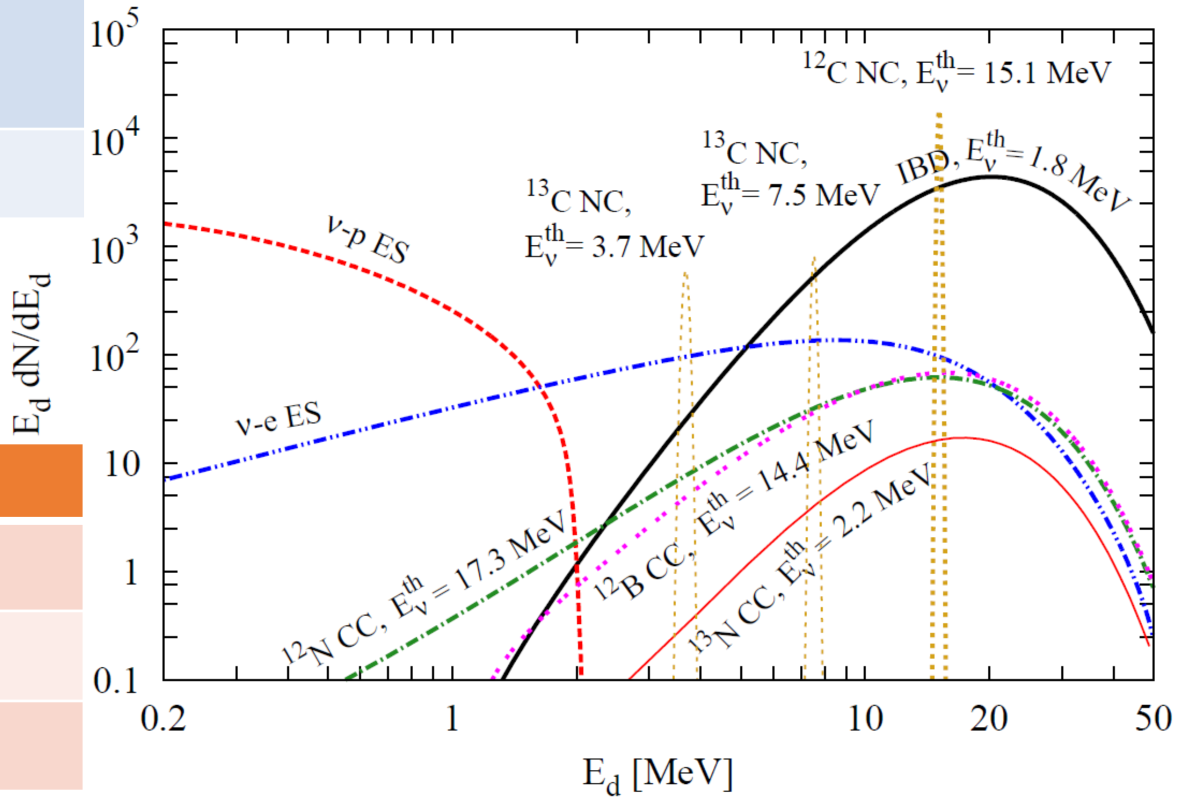
- **Elastic ν-p scattering important**
- **Advantage of LS: low threshold**

Beacom, Farr, Vogel, PRD, 02;
Dasgupta, Beacom, PRD, 11

Event spectra @ JUNO

Lu, Li, Zhou, PRD, 16

KRJ-para. with (12, 14, 16) MeV



SN Neutrinos @ LS Detectors

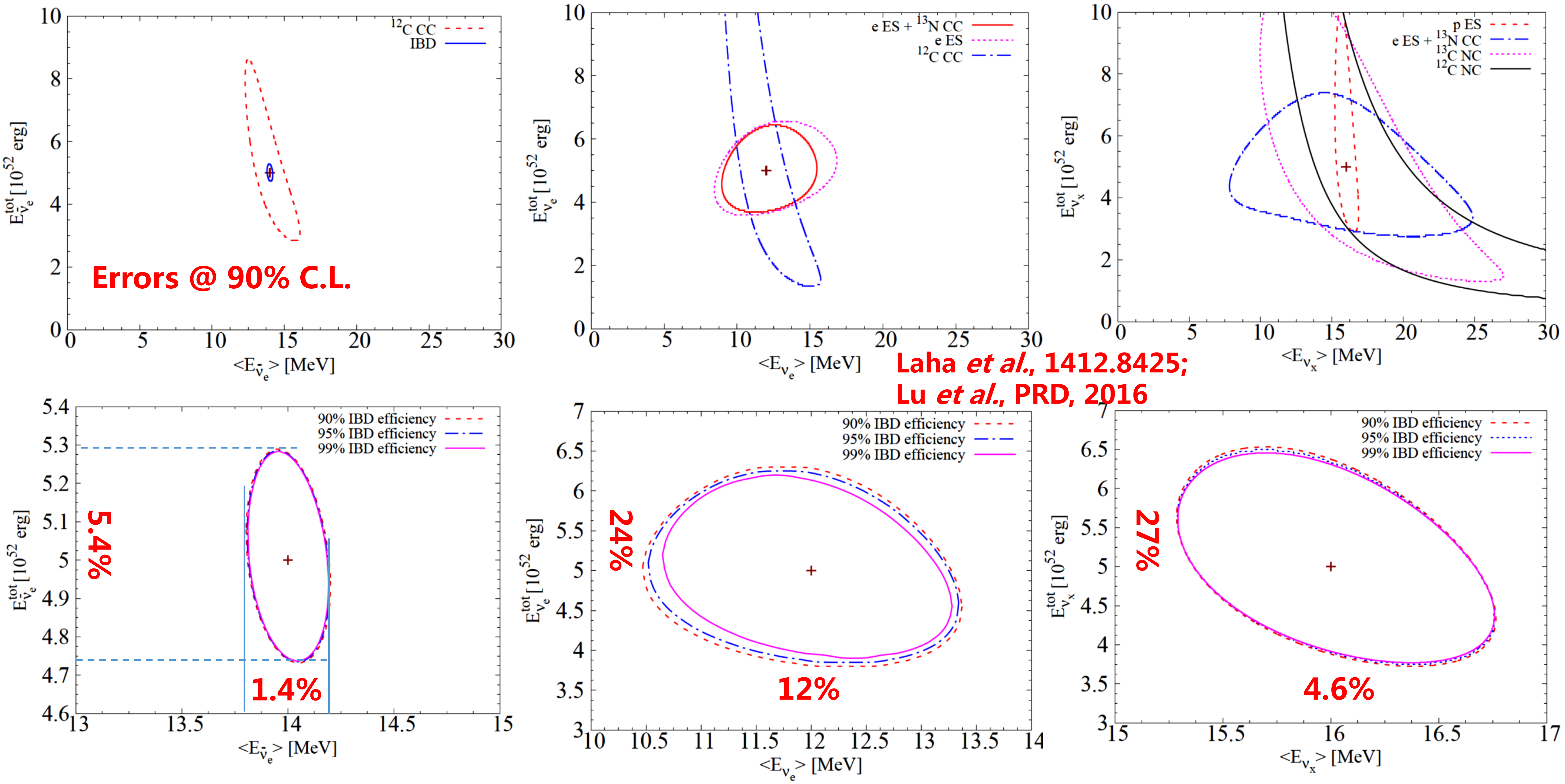
Channel	Type		No Oscillations	Normal Ordering	Inverted Ordering
			Number of SN Neutrino Events at JUNO		
$\overline{\nu}_e + p \to e^+ + n$	CC		4573	4775	5185
$\nu + p \to \nu + p$	ES		1578	1578	1578
		ν_e	107	354	278
		$\overline{\nu}_e$	179	214	292
		ν_x	1292	1010	1008
$\nu_e + e \to \nu_e + e$	ES		314	316	316
		ν_e	157	159	158
		$\overline{\nu}_e$	61	61	62
		ν_x	96	96	96
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC		43	134	106
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC		86	98	126
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC		352	352	352
		ν_e	27	76	61
		$\overline{\nu}_e$	43	50	65
		ν_x	282	226	226
$\nu_e + {}^{13}\mathrm{C} \to e^- + {}^{13}\mathrm{N}$	CC		19	29	26
$\nu + {}^{13}\mathrm{C} \to \nu + {}^{13}\mathrm{C}^*$	NC	$3/2^-(5/2^-)$	23(15)	23(15)	23(15)
		ν_e	3(1)	4(3)	4(2)
		$\overline{\nu}_e$	3(2)	4(2)	4(3)
		ν_x	17(12)	15(10)	15(10)

Detection channels	ν Flavors	Efficiency	Backgrounds	Systematics	
IBD	$\overline{\nu}_e$	95%	None	Detection	2%
^{12}C-CC	$\overline{\nu}_e$ and ν_e	90%	None	Detection	2%
pES	$\overline{\nu}_e$, ν_e and ν_x	99%	eES	Detection	2%
				Cross section	20%
				k_{B}	3%
eES	$\overline{\nu}_e$, ν_e and ν_x	99%	^{13}N-CC+IBD+pES	Detection	2%
^{13}N-CC	ν_e	100%	eES+IBD	Detection	2%
				Cross section	20%
^{12}C-NC	$\overline{\nu}_e$, ν_e and ν_x	100%	eES+IBD	Detection	2%
				Cross section	20%
^{13}C-NC	$\overline{\nu}_e$, ν_e and ν_x	100%	eES+IBD	Detection	2%
				Cross section	20%

- **IBD for $\overline{\nu}_e$ + sub-leading effects from ^{12}C CC**
- **Elastic ν-e scattering for ν_e + ^{12}C CC**
- **Elastic ν-p scattering for ν_x + eES**
- **A global analysis of all reaction channels?**

Laha *et al.*, 1412.8425; Lu *et al.*, PRD, 2016

SN Neutrinos @ LS Detectors

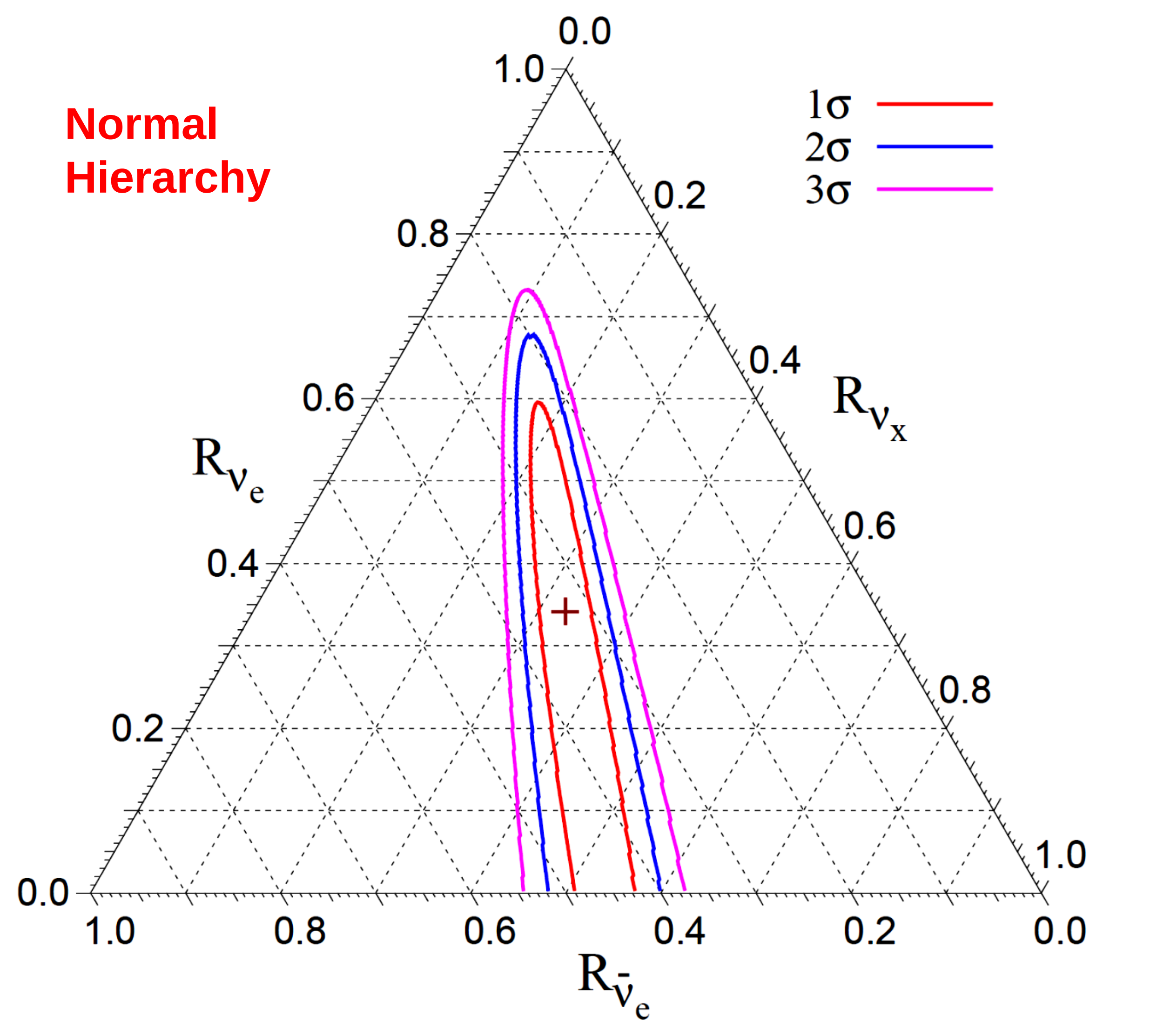


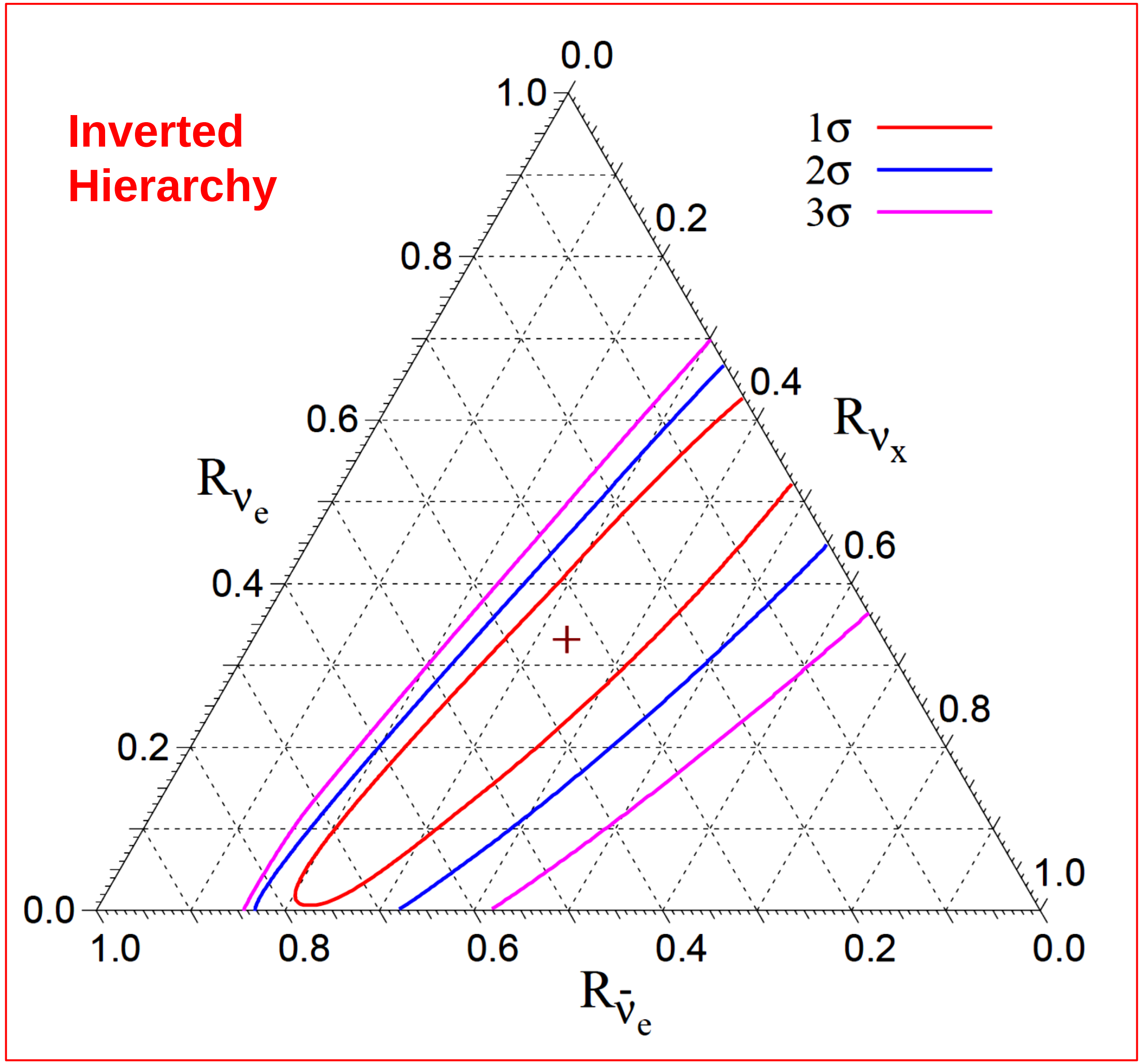
Laha *et al.*, 1412.8425;
Lu *et al.*, PRD, 2016

Test of Energy Equipartition Hypothesis

Including only the MSW matter effects in the SN

Lu, Li, Zhou *et al.*, PRD, 2016

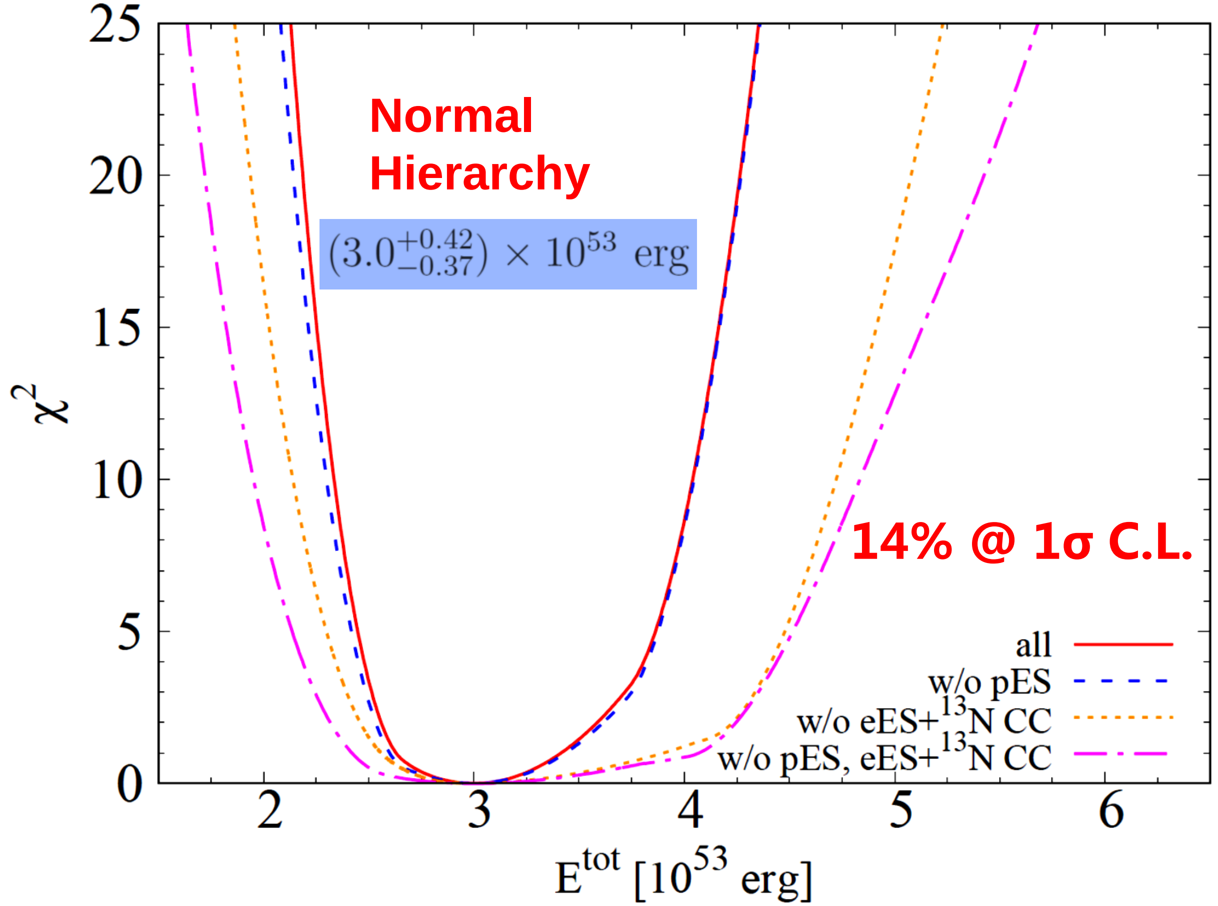


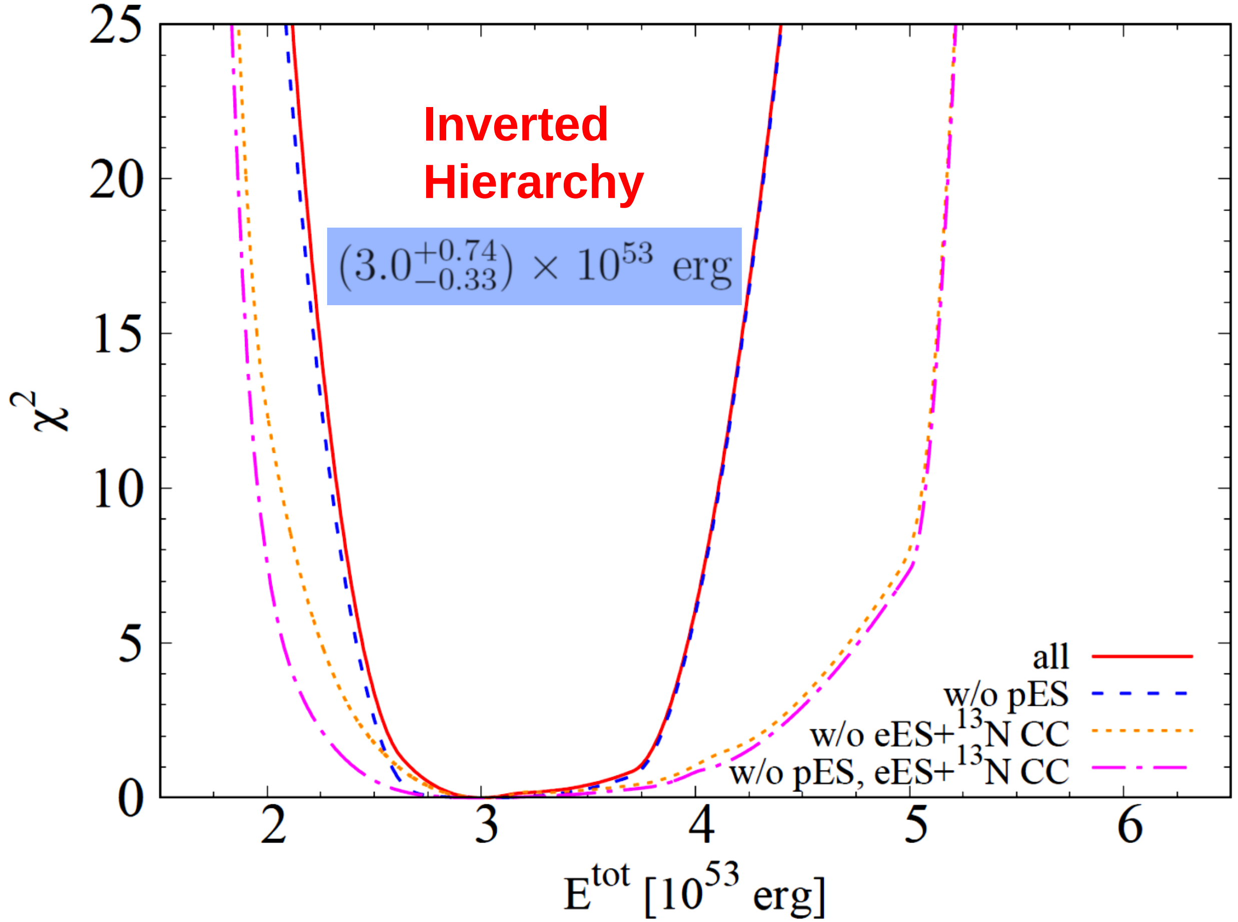


Total Gravitational Binding Energy

Including only the MSW effects in the SN, and fixing the spectral indices at γ =3

Lu, Li, Zhou *et al.*, PRD, 2016 [cf. Volpe's talk for SK]

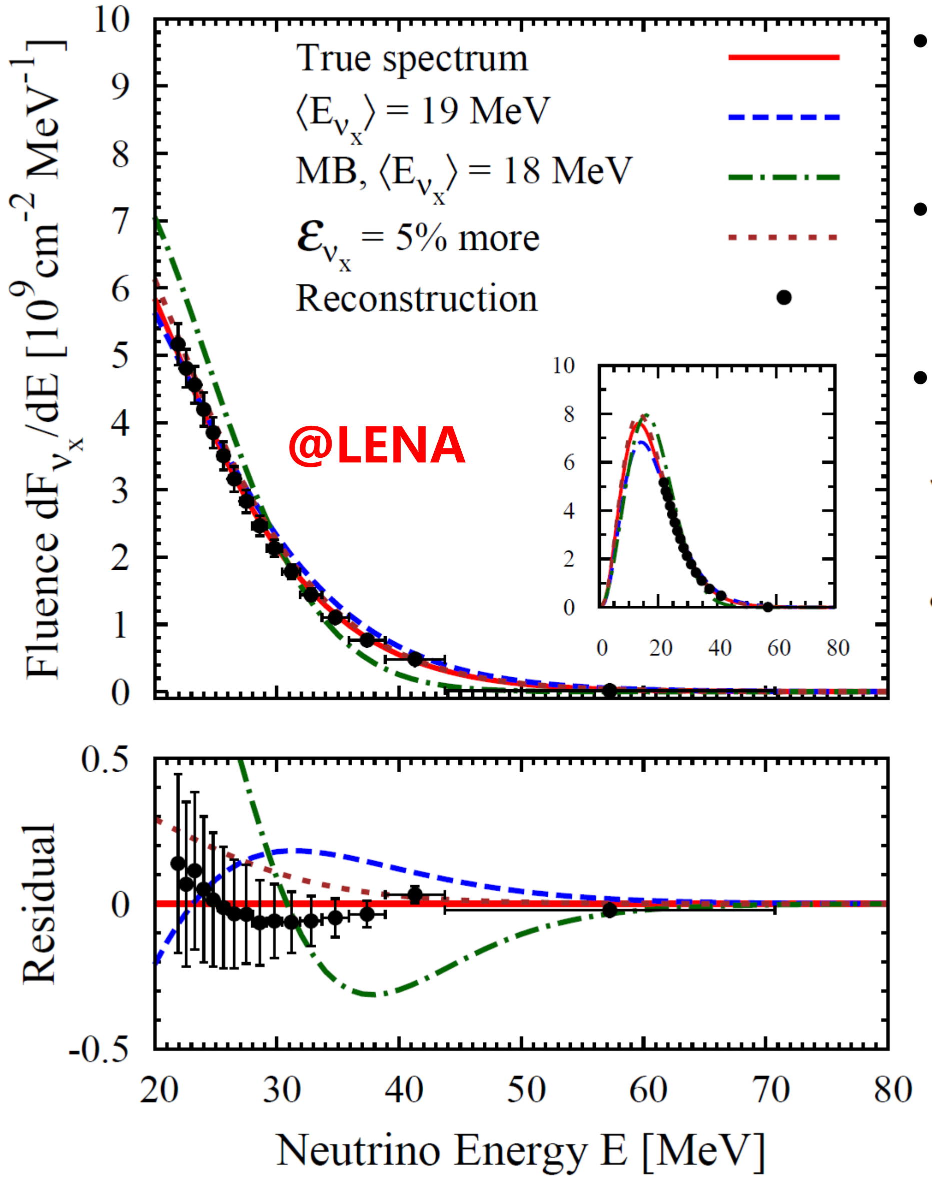




- **Conservatively assuming an uncertainty of 20% for the ν-p cross section (a few% ?)**
- **Possible to relax the constraint on the spectral index (important for <E>, not for E_{tot} ?)**

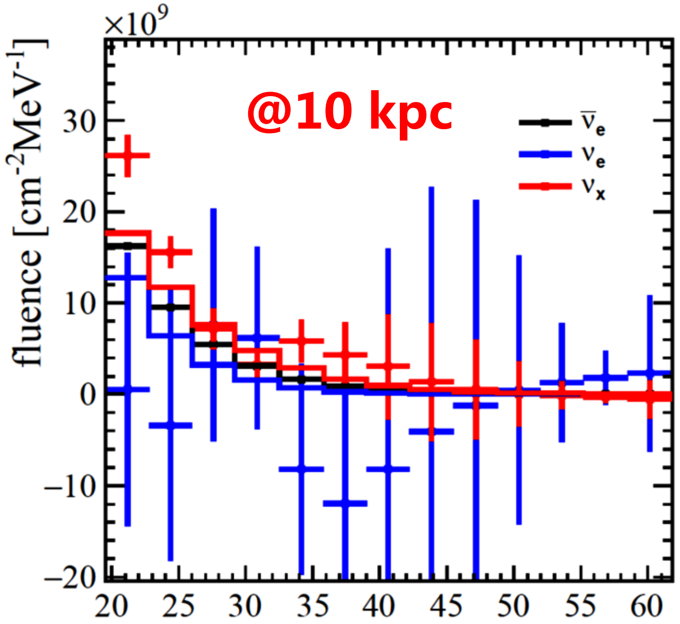
Unfolding of SN Neutrino Spectra

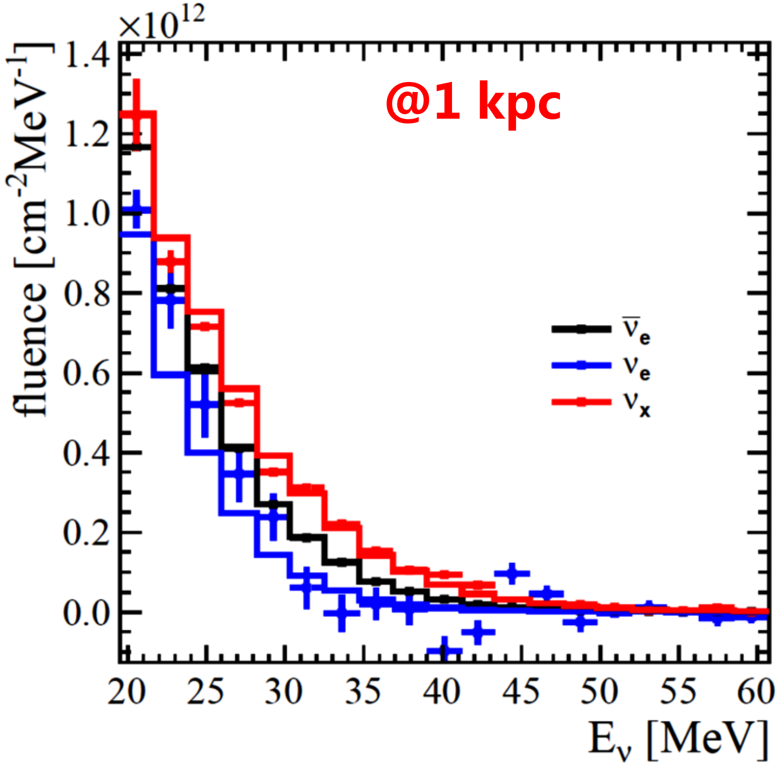
Dasgupta, Beacom, PRD, 11

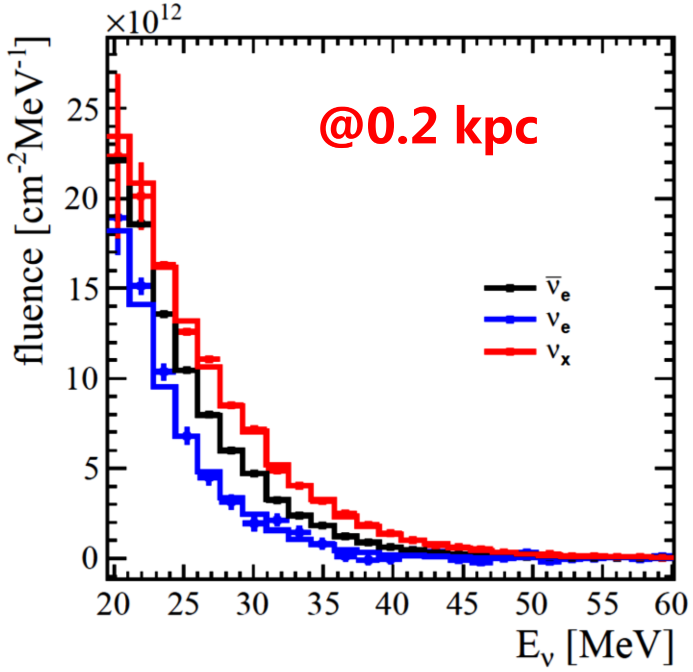


Li[2], Wen, Zhou, 17, to appear

- **Reconstruct all SN spectra in a single LS detector (JUNO)**
- **Full consideration of detector response (e.g., E resolution)**
- **SVD w. proper regularizations**





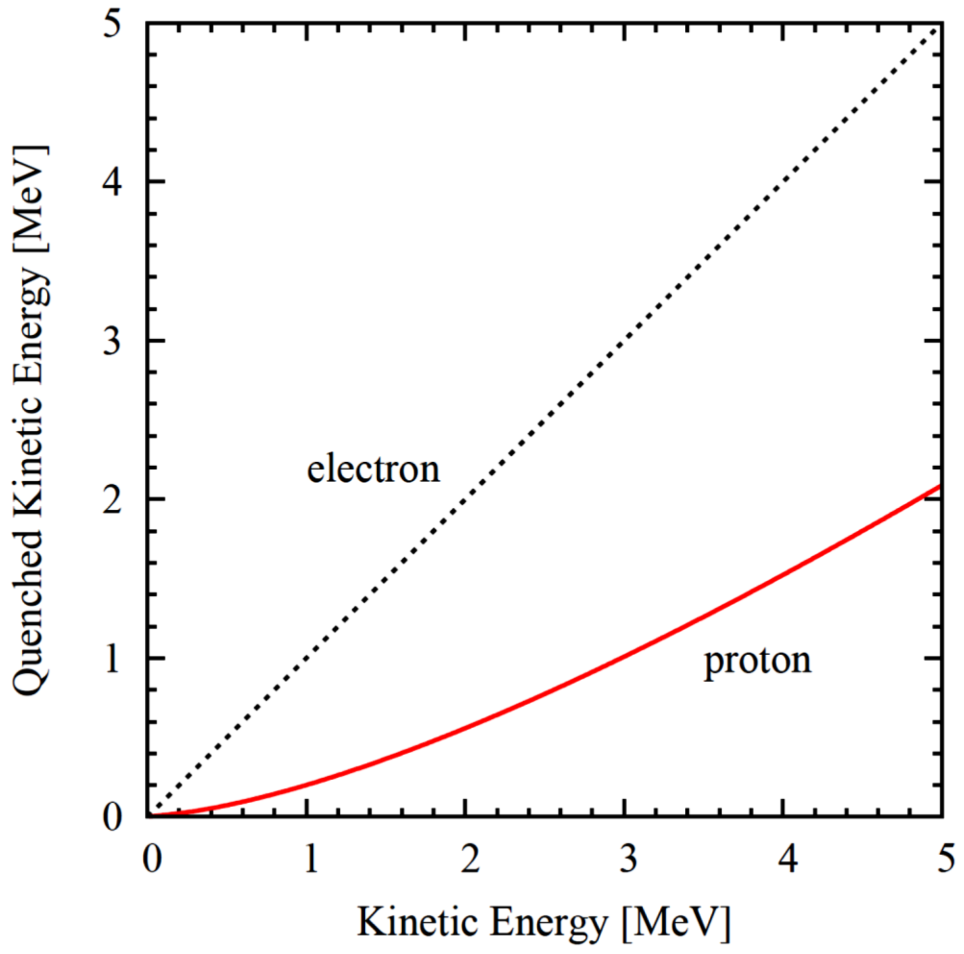


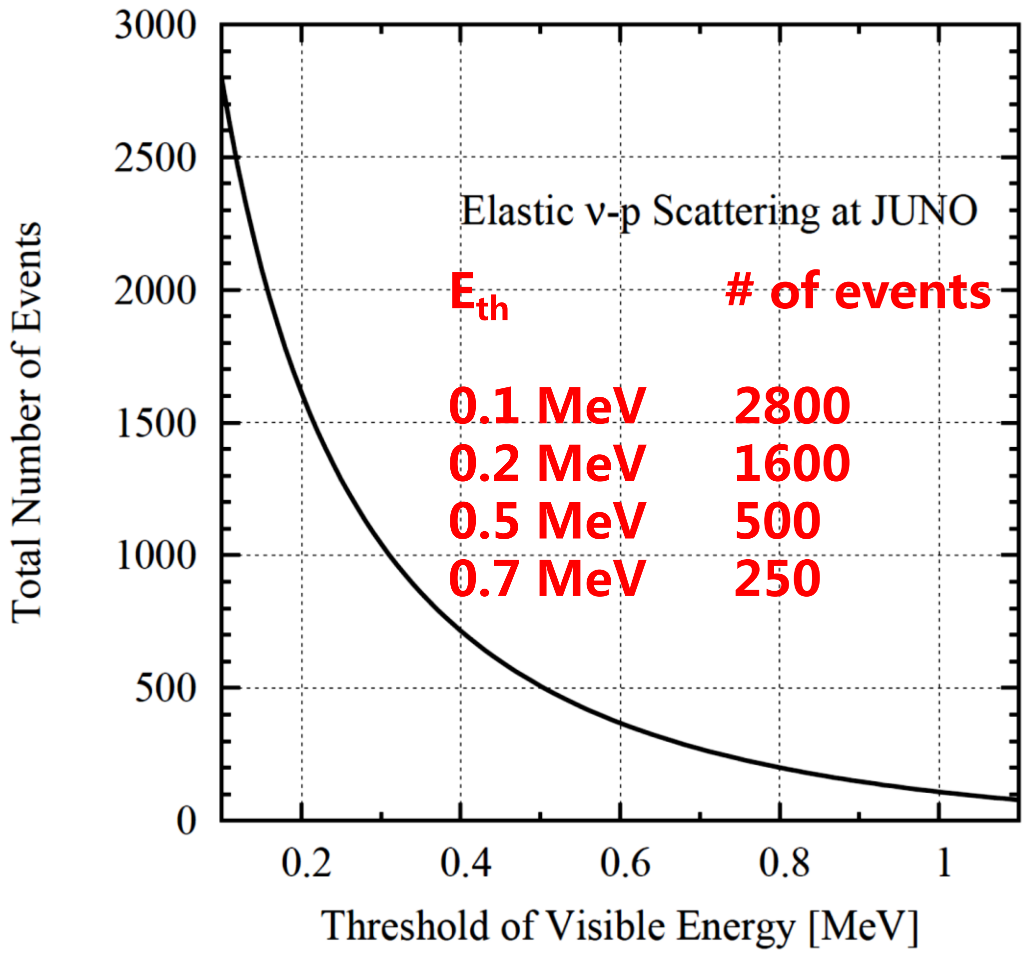
Elastic ν-p Scattering in LS Detectors

Beacom, Farr, Vogel, PRD, 02; Dasgupta, Beacom, PRD, 11; Lu, Li, Zhou, PRD, 16; Li et al., to appear

- **Elastic ν-p scattering important**
- **Advantage of LS: low threshold**

Quenching effects on the proton recoil energy $T_p \leq 2\ E^2/m_p$



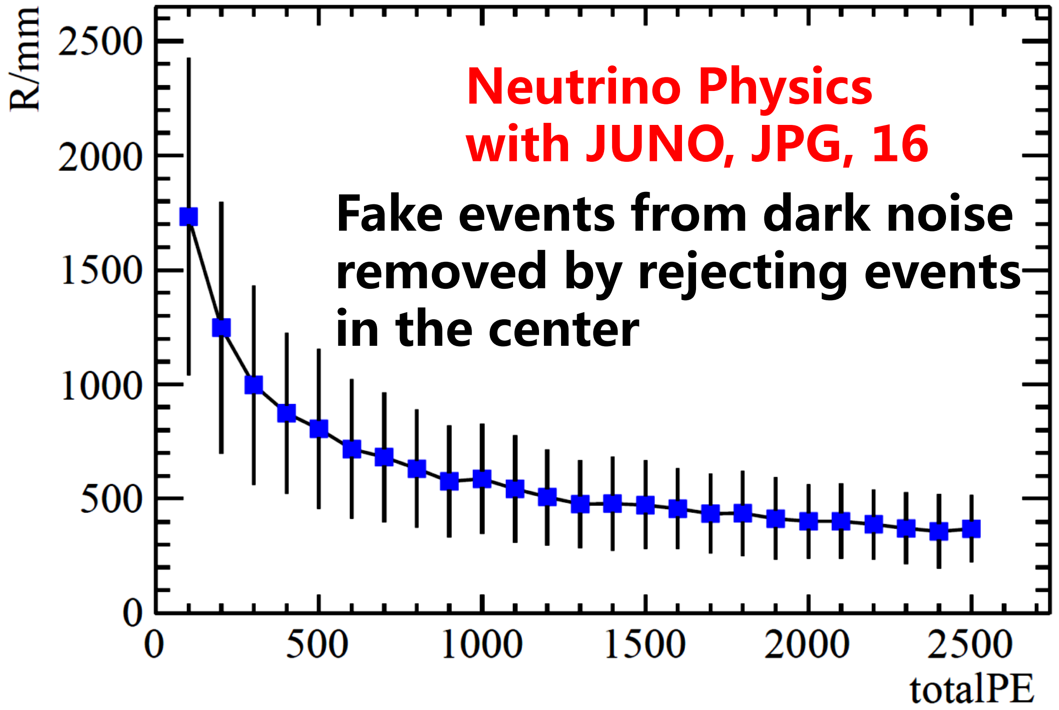


Borexino & JUNO: Radioactivity Backgrounds

A wonderful experience with Borexino

Isotope	Specification for LS	Achieved after filling (2007 - 2010)	After additional purification
^{238}U	$\leq 10^{-16}$ g/g	$(5.3 \pm 0.5)\cdot 10^{-18}$ g/g	$< 0.8\cdot 10^{-19}$ g/g
^{232}Th	$\leq 10^{-16}$ g/g	$(3.8 \pm 0.8)\cdot 10^{-18}$ g/g	$< 1.2\cdot 10^{-18}$ g/g
$^{14}C/^{12}C$	$\leq 10^{-18}$	$(2.69 \pm 0.06)\cdot 10^{-18}$ g/g	unchanged
^{40}K	$\leq 10^{-18}$ g/g	$\leq 0.4\cdot 10^{-18}$ g/g	unchanged
^{85}Kr	≤ 1 cpd/100 t	(30 ± 5) cpd/100 t	≤ 5 cpd/100 t
^{39}Ar	≤ 1 cpd/100 t	<< ^{85}Kr	<< ^{85}Kr
^{210}Po	not specified	~ (70) 1 dpd/100 t	unchanged
^{210}Bi	not specified	(20) 70 dpd/100 t	(20 ± 5) cpd/100 t

from Zuzel @ NNN 2016



Signals and Background for Reactor Neutrinos @JUNO

Selection	IBD efficiency	IBD	Geo-νs	Accidental	$^{9}Li/^{8}He$	Fast n	(α,n)
-	-	83	1.5	$\sim 5.7\times 10^{4}$	84	-	-
Fiducial volume	91.8%	76	1.4	410	77	0.1	0.05
Energy cut	97.8%	73	1.3		71		
Time cut	99.1%						
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60	3.8				

(per day)

Background > 0.2 MeV for SN @ 10 kpc

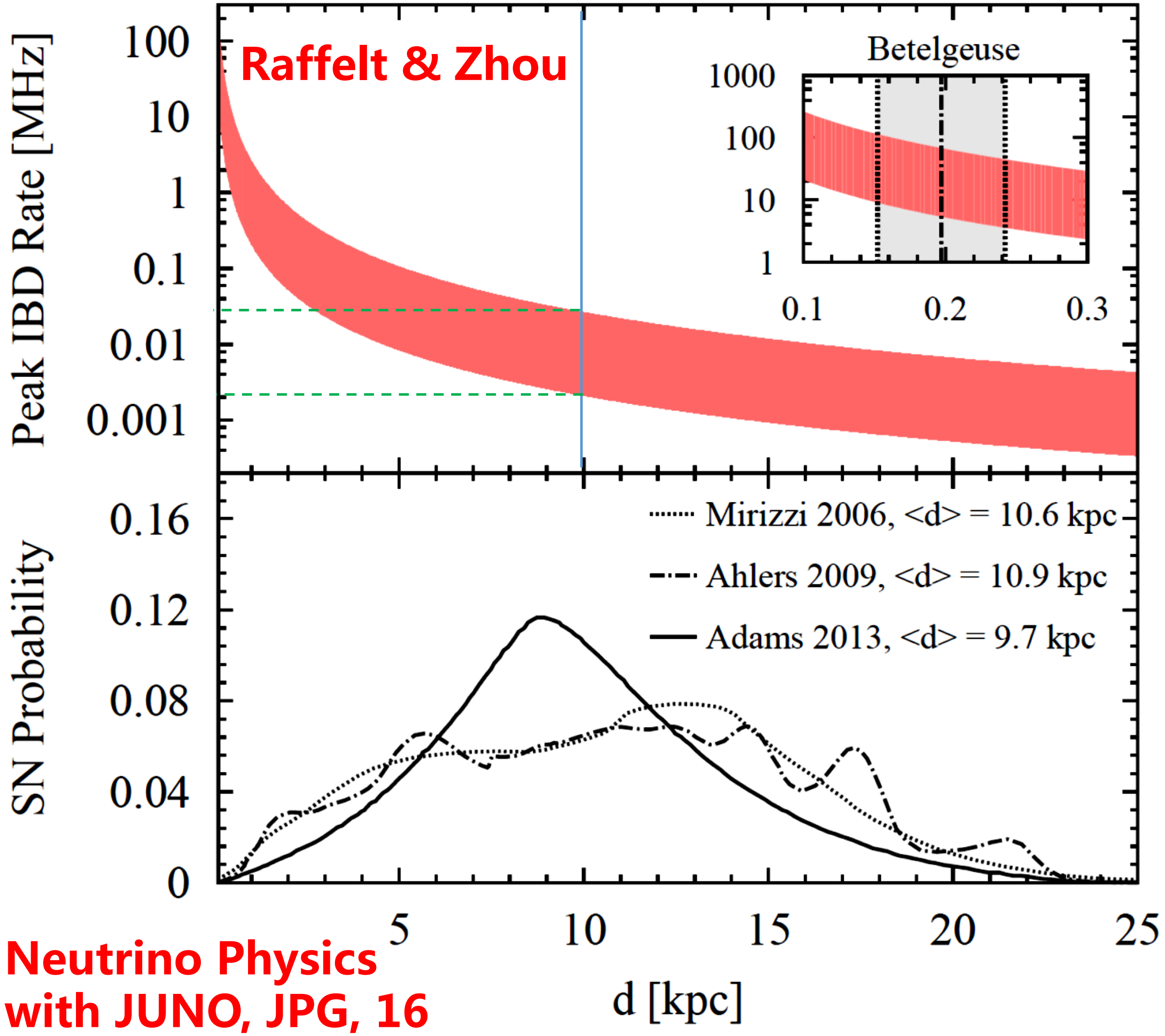
Channel	Reactor	Geo-Neutrino
IBD (10 s)	0.01	0.0002

Channel	^{85}Kr	^{210}Bi (^{210}Pb)
ePS (10 s)	10	70

Beta decays of ^{14}C dominate < 0.2 MeV

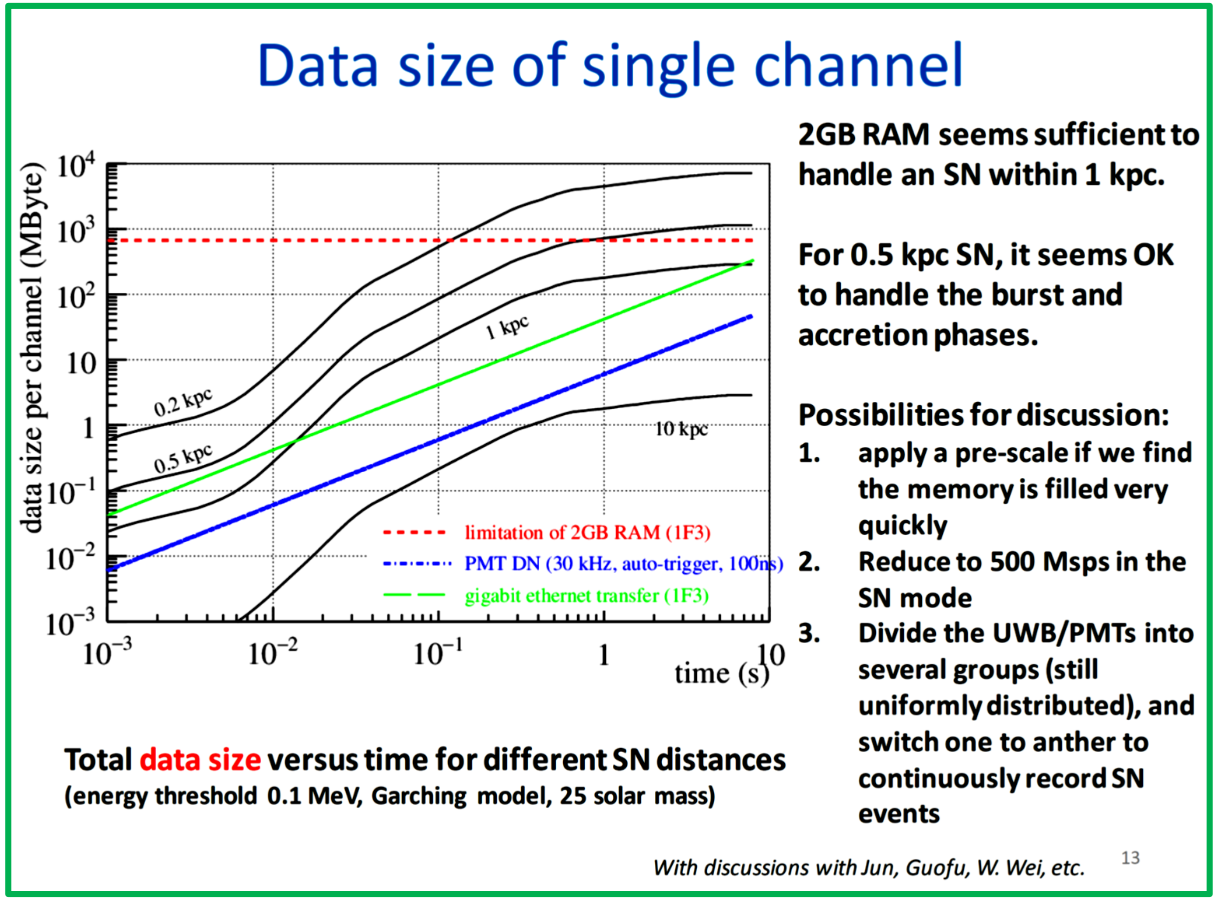
JUNO: SN Neutrino Trigger

Request for the DAQ @ JUNO



Neutrino Physics with JUNO, JPG, 16

A slide from L.J. Wen (in JUNO Collaboration)



- **For important physics, send requests to the JUNO collaboration**
- **Need a balance between cost and gain**

Further Discussions

- **Difficult to have a detector solely for the detection of SN neutrino burst, since we do not know when and where a star will explode (strong motivations from important physics?).**

- **Give the priority to DSNB (a topic for tomorrow), a guaranteed source of SN neutrinos. We have SK with Gd doping, but JUNO (available within 3 years) also has a good chance.**

Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e} \rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$2.3\,\sigma$	$2.5\,\sigma$	$2.0\,\sigma$	$2.3\,\sigma$
15 MeV	$3.5\,\sigma$	$3.7\,\sigma$	$3.2\,\sigma$	$3.3\,\sigma$
18 MeV	$4.6\,\sigma$	$4.8\,\sigma$	$4.1\,\sigma$	$4.3\,\sigma$
21 MeV	$5.5\,\sigma$	$5.8\,\sigma$	$4.9\,\sigma$	$5.1\,\sigma$

Neutrino Physics with JUNO, JPG, 16

- **Fine with detectors, which take SN neutrino detection as a second physics goal. For JUNO, neutrino mass ordering fixed within 6 yrs, precision measurements <1% within 3yrs. Then, what we should do with JUNO? (Neutrinoless Double-Beta Decays? Solar or SN neutrinos?)**

- **Dark matter detectors, which will never see any signals of DM, could be further used as SN neutrino detectors?**