Supernova Neutrinos @ JUNO

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The ECT* workshop on *SN Neutrinos at the Crossroads*, Trento, May 12 – 17, 2019

Neutrinos: Particle Physics and Astrophysics

Intrinsic Properties of Massive Neutrinos: Portal to NP beyond the SM

- Neutrino mass ordering
- Precision measurements
- Leptonic CP violation/CP phases
- Majorana vs. Dirac neutrinos

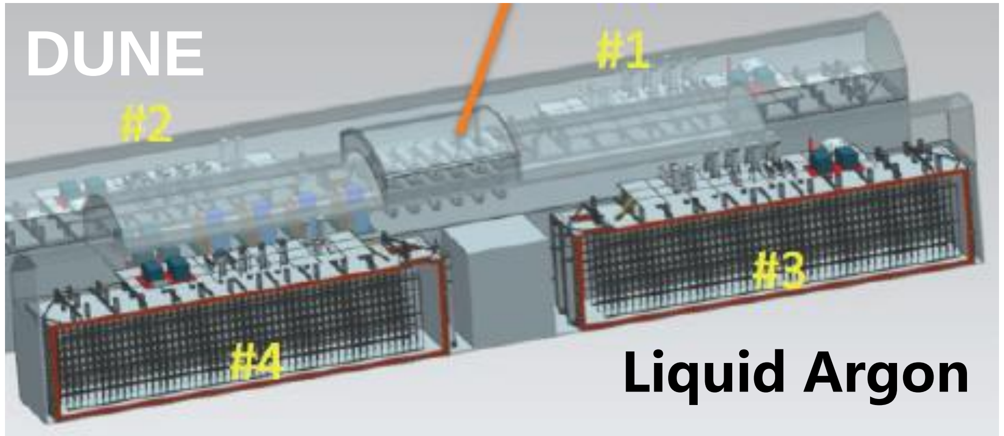
→

- Origin of neutrino masses
- Dynamics for flavor mixing
- Mechanism for CP violation

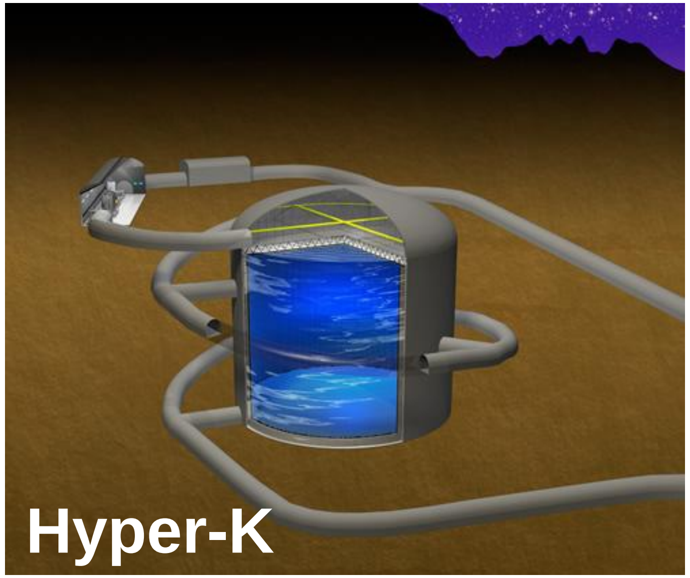
→ New Physics

Neutrinos as a Cosmic Messenger

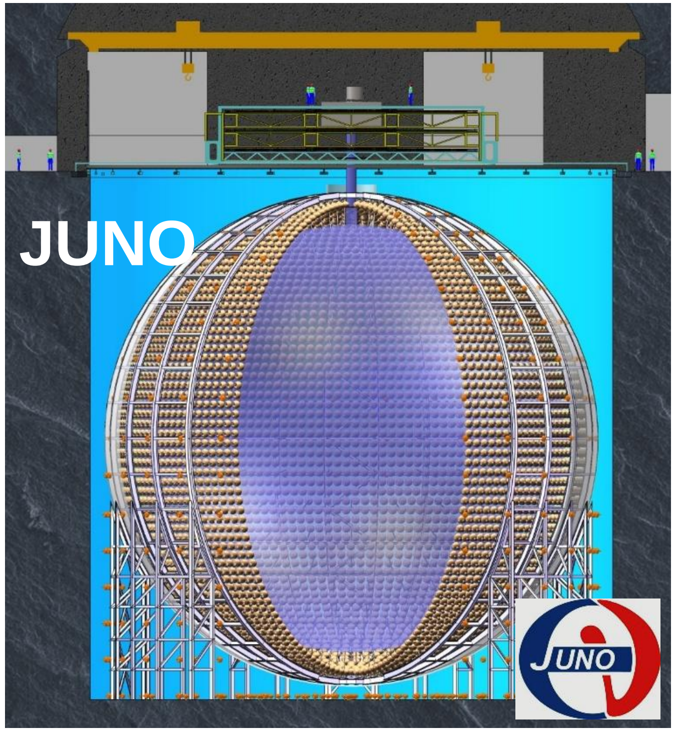
- Core-collapse supernovae
- Origin of high-energy cosmic rays
- Gamma rays & gravitational waves
- CνB & Matter-antimatter asymmetry



Water Cherenkov



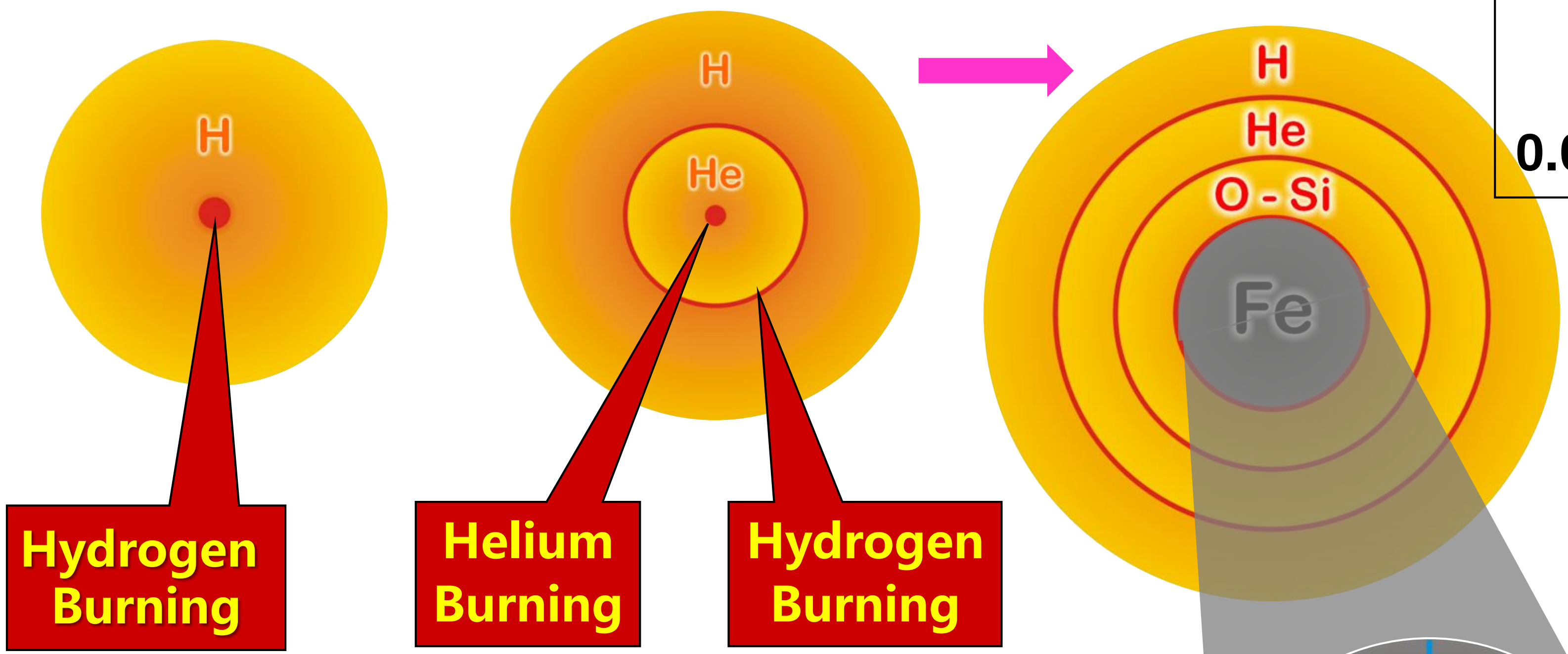
Liquid Scintillator



Multi-purpose Detectors

Core-Collapse Supernovae: the neutrino engine

Main-sequence star   Helium-burning star



Grav. binding energy $E_b \approx 3 \times 10^{53}$ erg

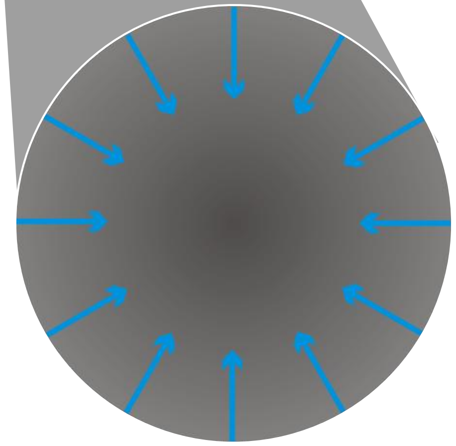
99%	Neutrinos
1%	Kinetic energy of explosion (1% of this into cosmic rays)
0.01%	Photons, outshine host galaxy

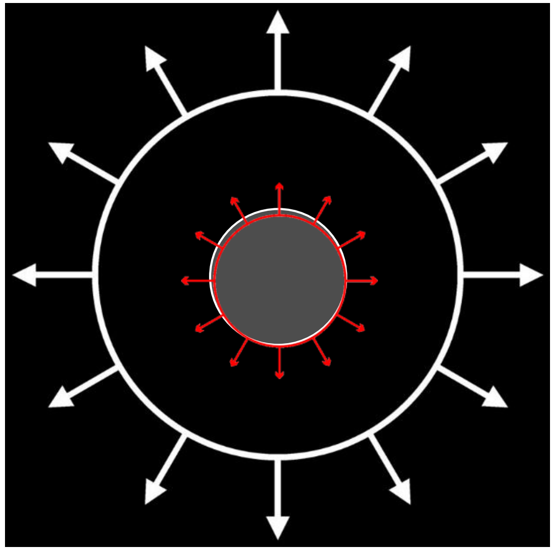
Reviews by H.-Th. Janka, 1702.08825, 1702.08713

0. > 8 Solar Masses
1. Collapse→Bounce
2. Shock wave halted
3. ν energy deposited
4. Final SN explosion

Degenerate iron core:

$\rho \approx 10^9$ g cm^{-3}
$T \approx 10^{10}$ K
$M_{Fe} \approx 1.5\ M_{sun}$
$R_{Fe} \approx 8000$ km

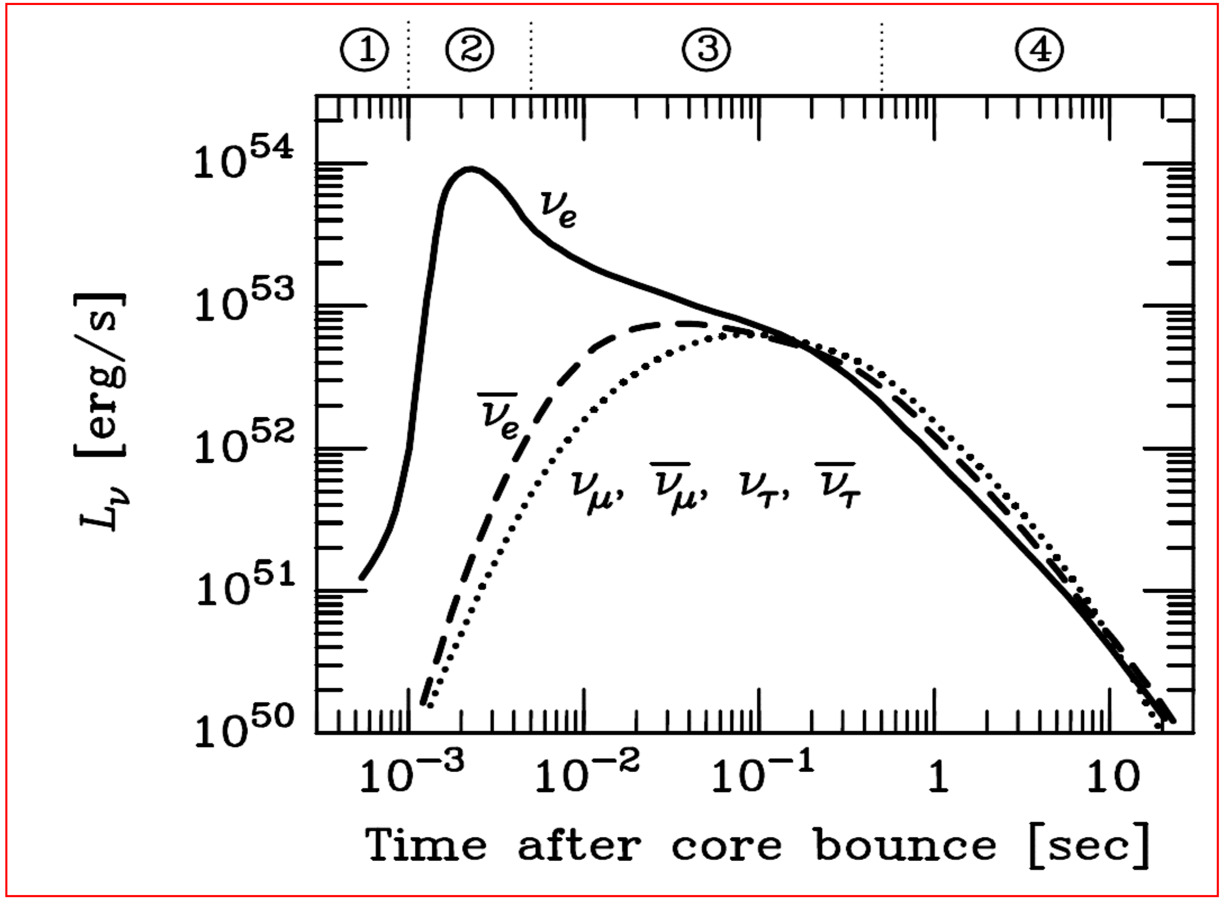




Proto-Neutron star:

$\rho \sim \rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}
$T \sim 30$ MeV

Supernova Neutrinos: flavors & spectra

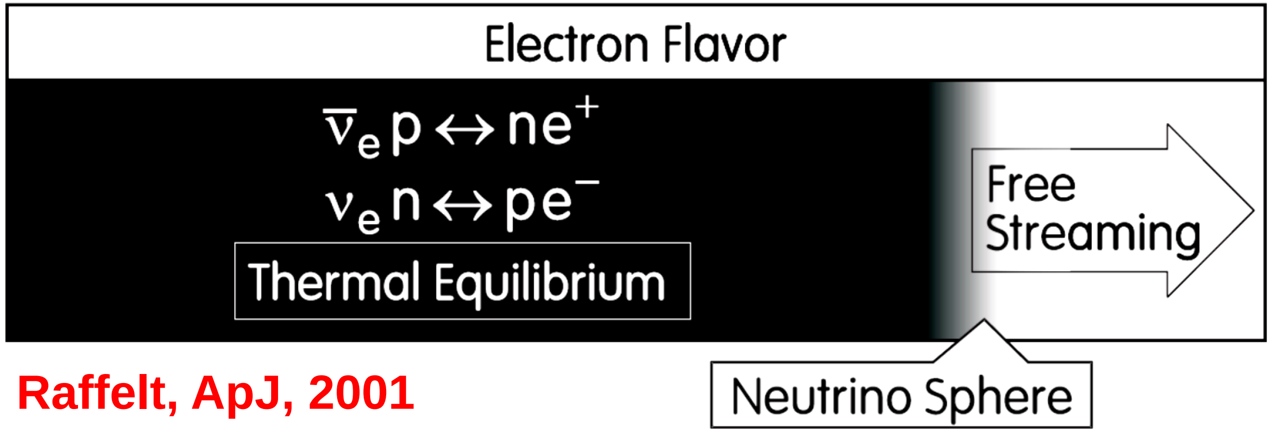


① **Collapse:** ν_e **production via** $e^- + p \longrightarrow \nu_e + n$

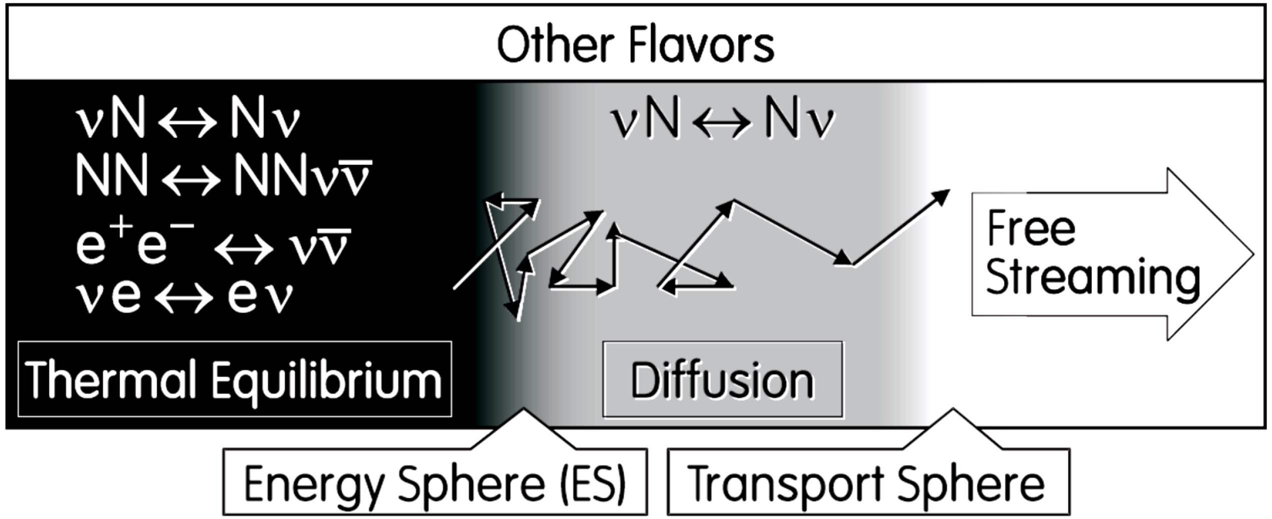
② **Neutronization ν_e burst:**
disintegration of heavy nuclei, capture on free p's, shock passing through ν-sphere

③ **Accretion:** **reduction of** $\mu_{\nu_e} \longrightarrow$ **neutrino pairs**

④ **Cooling:** **(anti)neutrinos of three flavors**

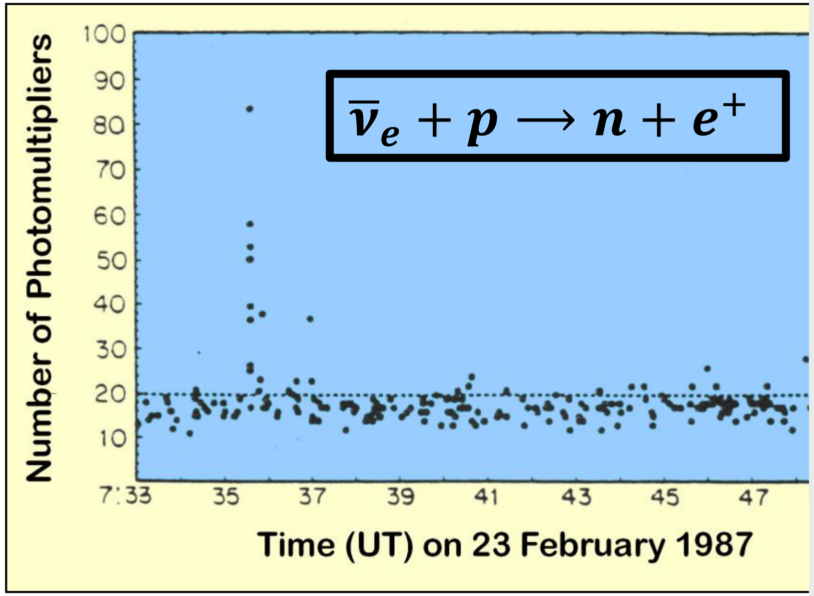


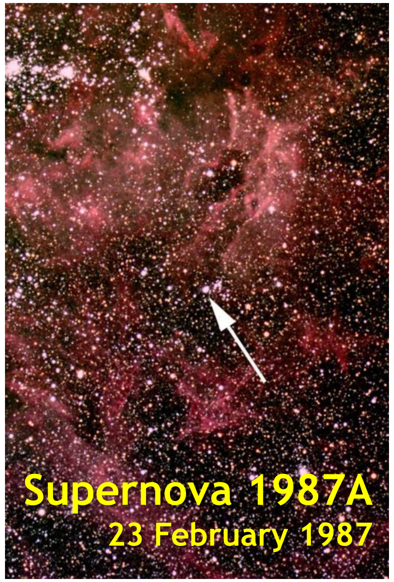
Raffelt, ApJ, 2001

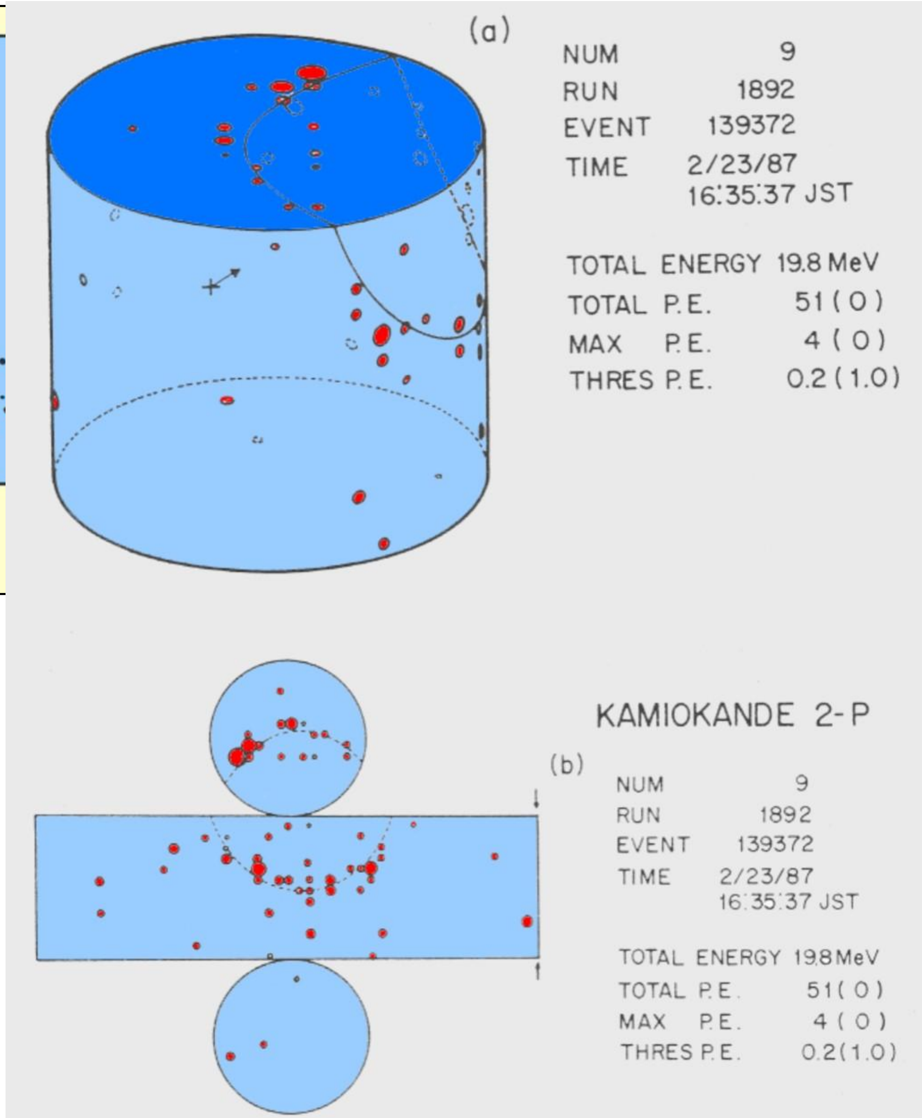


- **Neutrinos are close to thermal equilibrium**
- **Different flavors decouple at different radii**
- **SN neutrino fluxes are time dependent**
- **Keil-Raffelt-Janka (2003):** $F(E) \propto E^{\alpha}\, e^{-(\alpha+1)E/\overline{E}}$

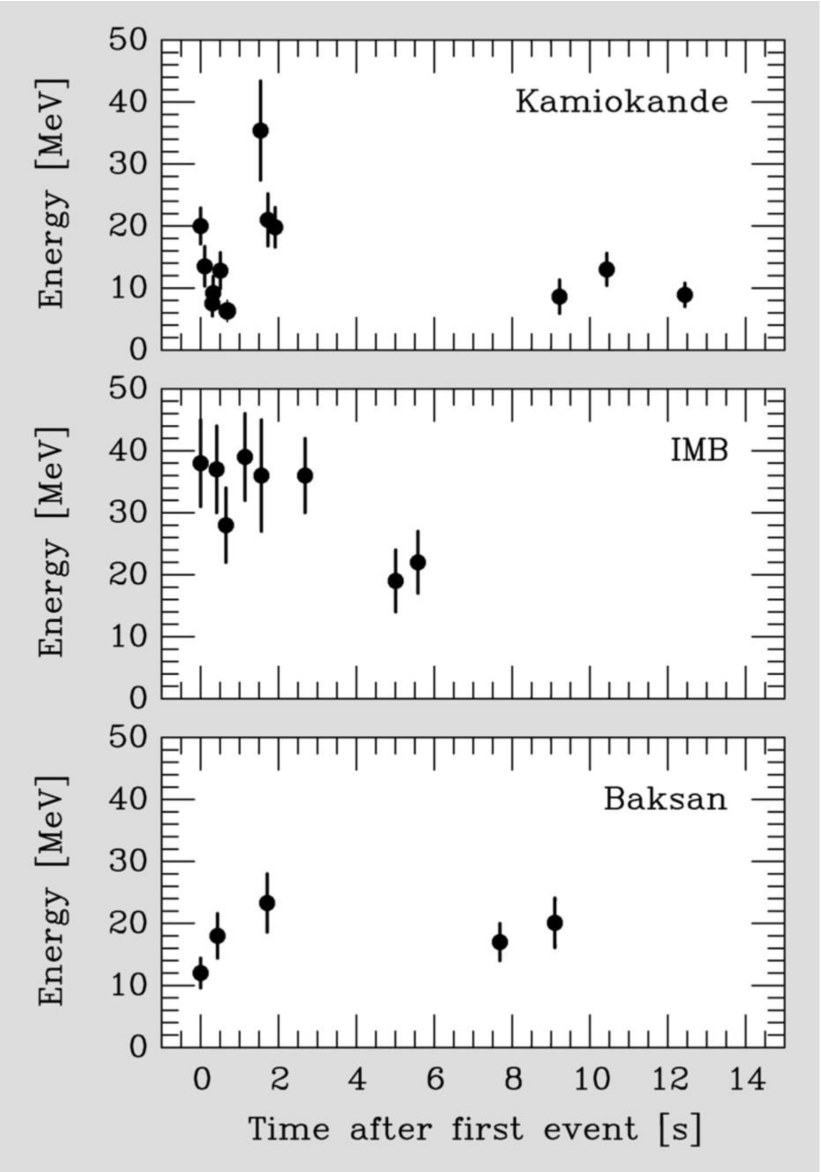
Detection of Supernova Neutrinos: SN 1987A







Hirata et al., PRD 38 (1988) 448

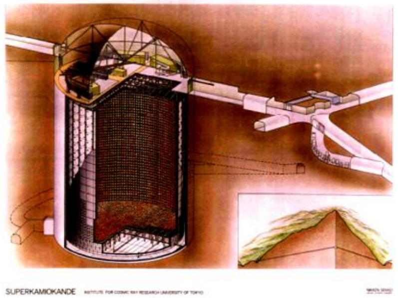


SN 1987A: Hirata et al., PRL 58 (1987) 1490; Bionta et al., PRL 58 (1987) 1494; Alekseev et al., PLB 205 (1988) 209

Detection of Supernova Neutrinos: opportunities

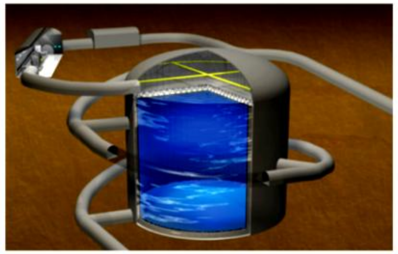
Supernova-relevant neutrino interactions © K. Scholberg

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$	$\nu_e + (N,Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N,Z) \rightarrow e^+ + (N+1, Z-1)$ Various possible ejecta and deexcitation products
Neutral current	Useful for pointing	Elastic scattering very low energy recoils	$\nu + A \rightarrow \nu + A^*$ $\nu + A \rightarrow \nu + A$ Coherent elastic (CEvNS)



Super-Kamiokande

Mozumi, Japan
22.5 kton fid. volume (32 kton total)
~5-10K events @ 10 kpc
(mostly anti-ν_e)
~5° pointing @ 10 kpc
Future: SK-Gd



Hyper-Kamiokande

- staged 2-module, 374-kton fid. water Cherenkov detector
- 1 module: 40% PMT coverage w/double efficiency

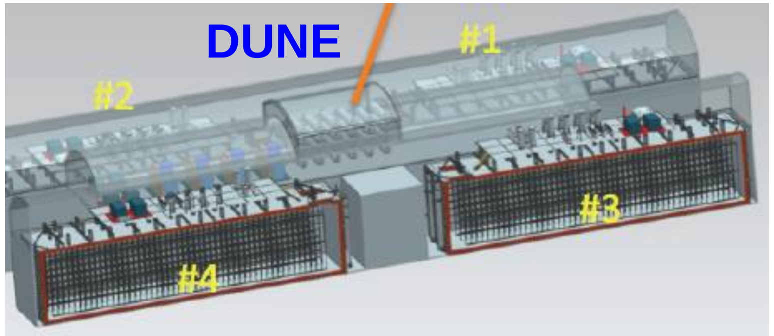
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC
↘ 1n, 2n emission

$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC
↘ 1n, 2n, γ emission

HALO

Relative 1n/2n rates sharply dependent on neutrino energy
⇒ spectral sensitivity

SNO ^{3}He counters + 79 t Pb
1~ 40 events @ 10 kpc

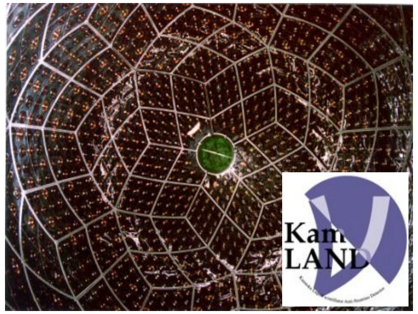


Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2720	3350
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770

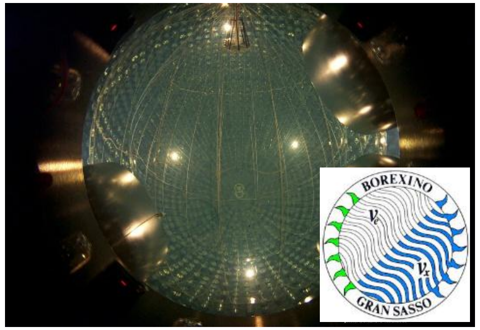
- **Water-Cherenkov: SK, HK**
- **LArTPC: ICARUS, DUNE**
- **Scintillator: NOvA, JUNO**

Current & Future Scintillator-based Detectors

LVD, 1 kt

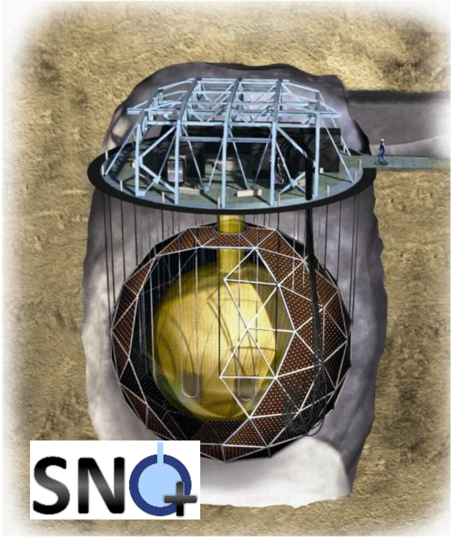


KamLAND, 1 kt

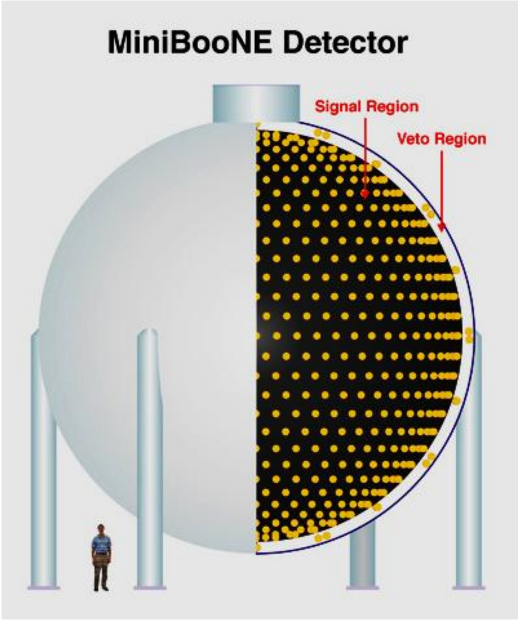


Borexino, 0.3 kt

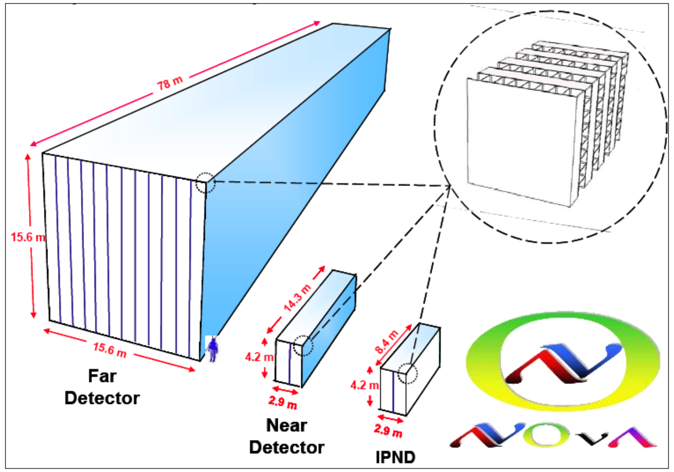
Daya Bay, 0.16 kt



SNO+, 1 kt



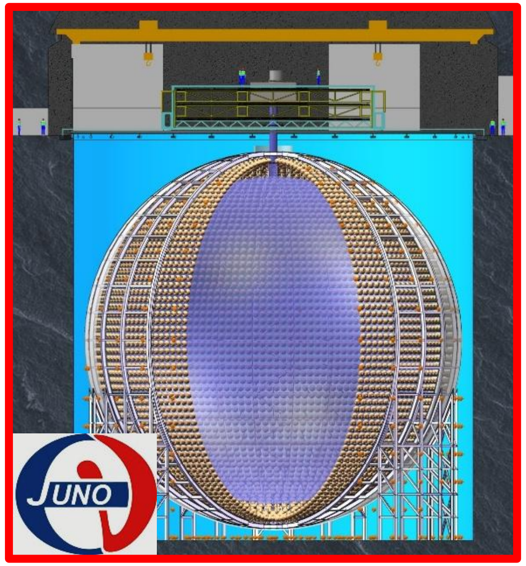
MiniBooNE, 0.7 kt



NOvA, 15 kt

Baksan, 0.33 kt

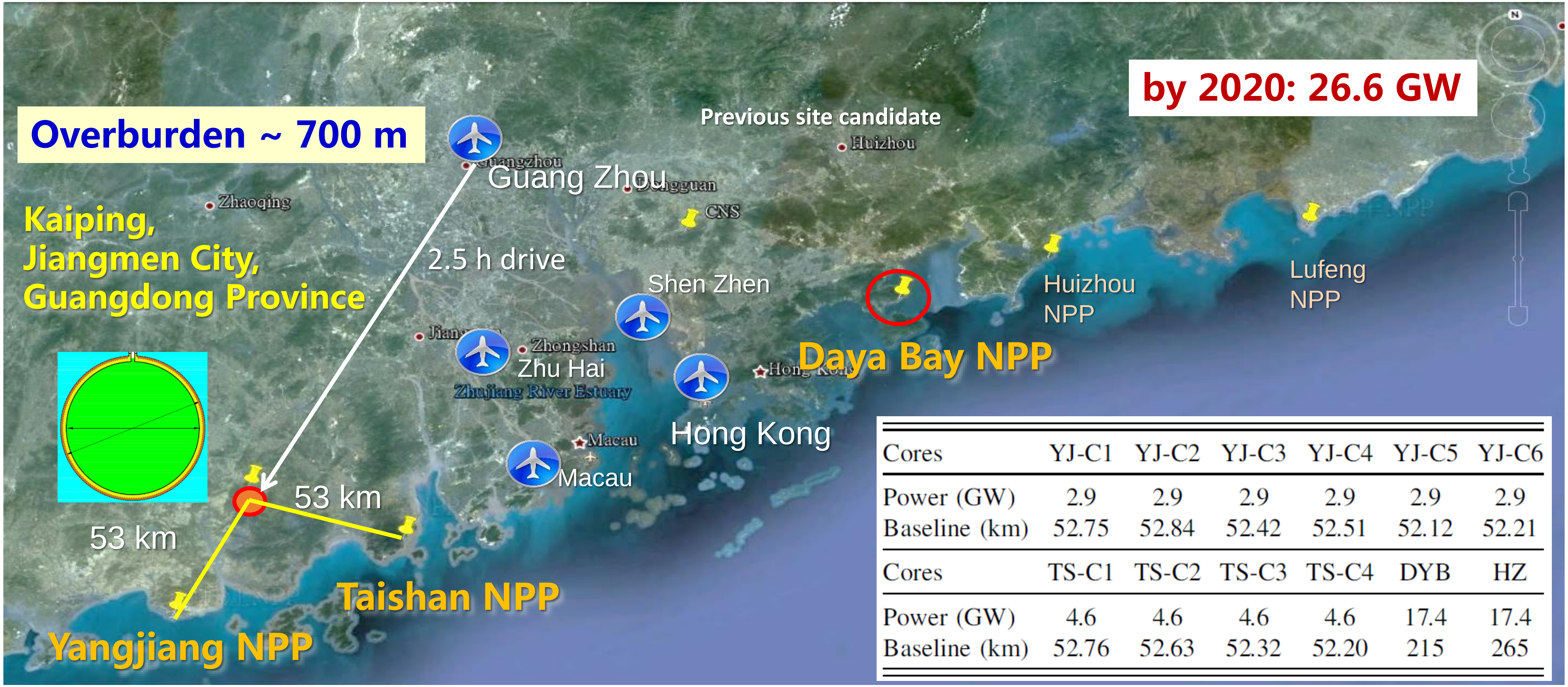
LENA, 50 kt



JUNO, 20 kt

The JUNO Experiment

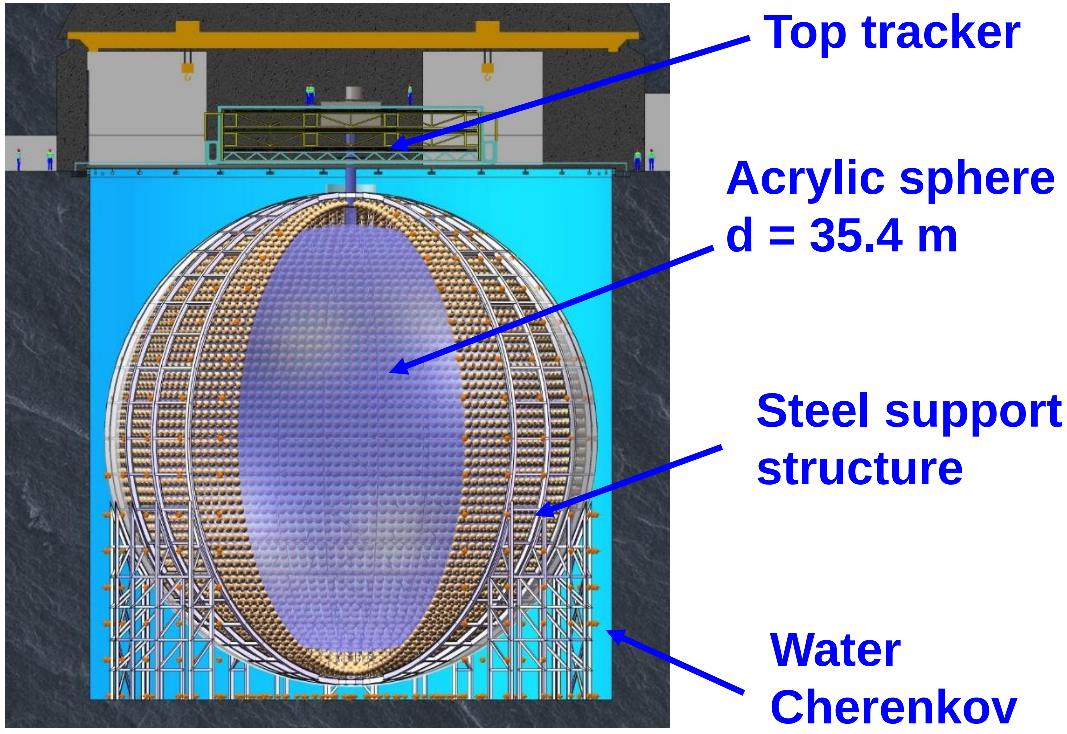
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

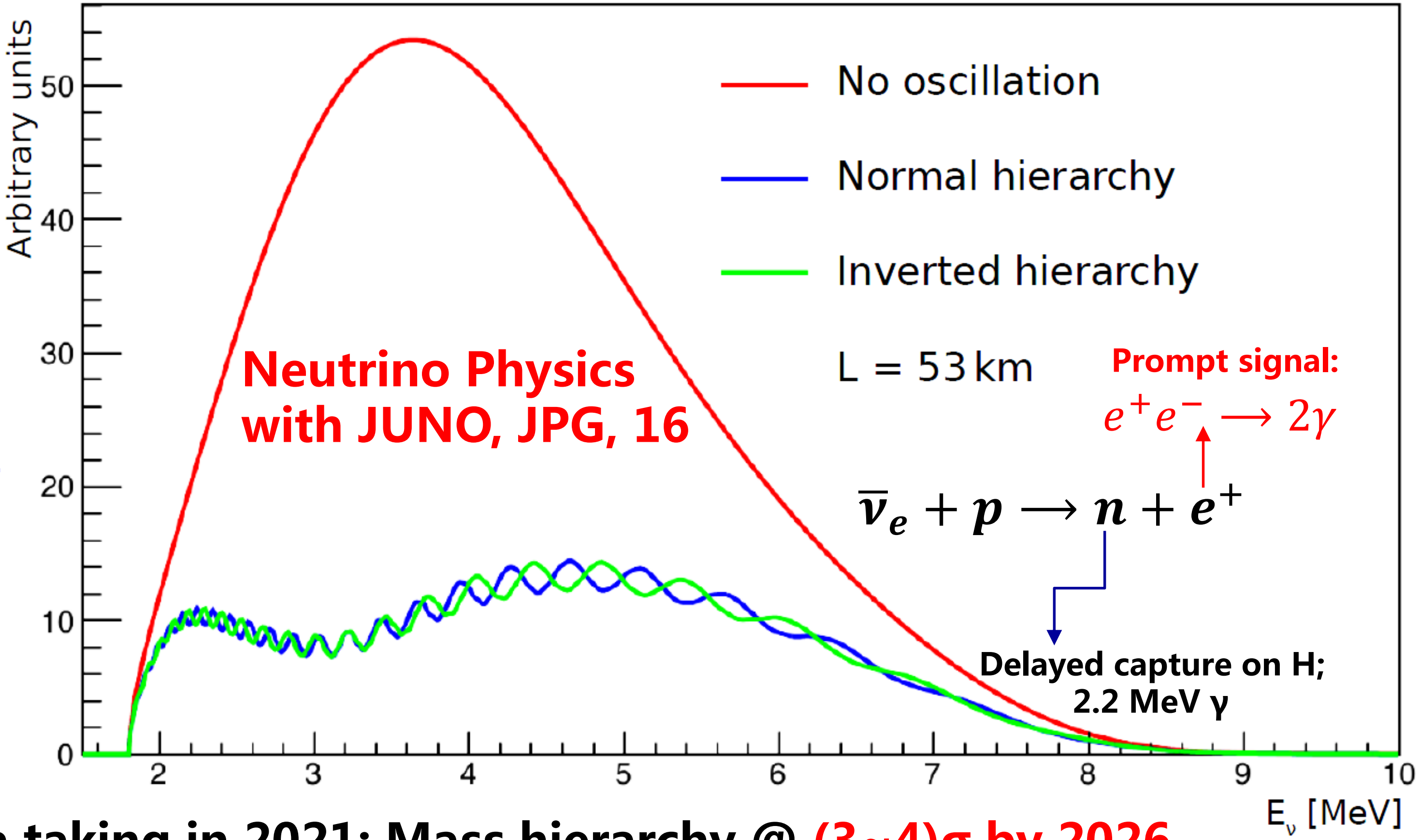


Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

The JUNO Experiment

Jiangmen Underground Neutrino Observatory





- **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 2021; Mass hierarchy @ (3~4)σ by 2026

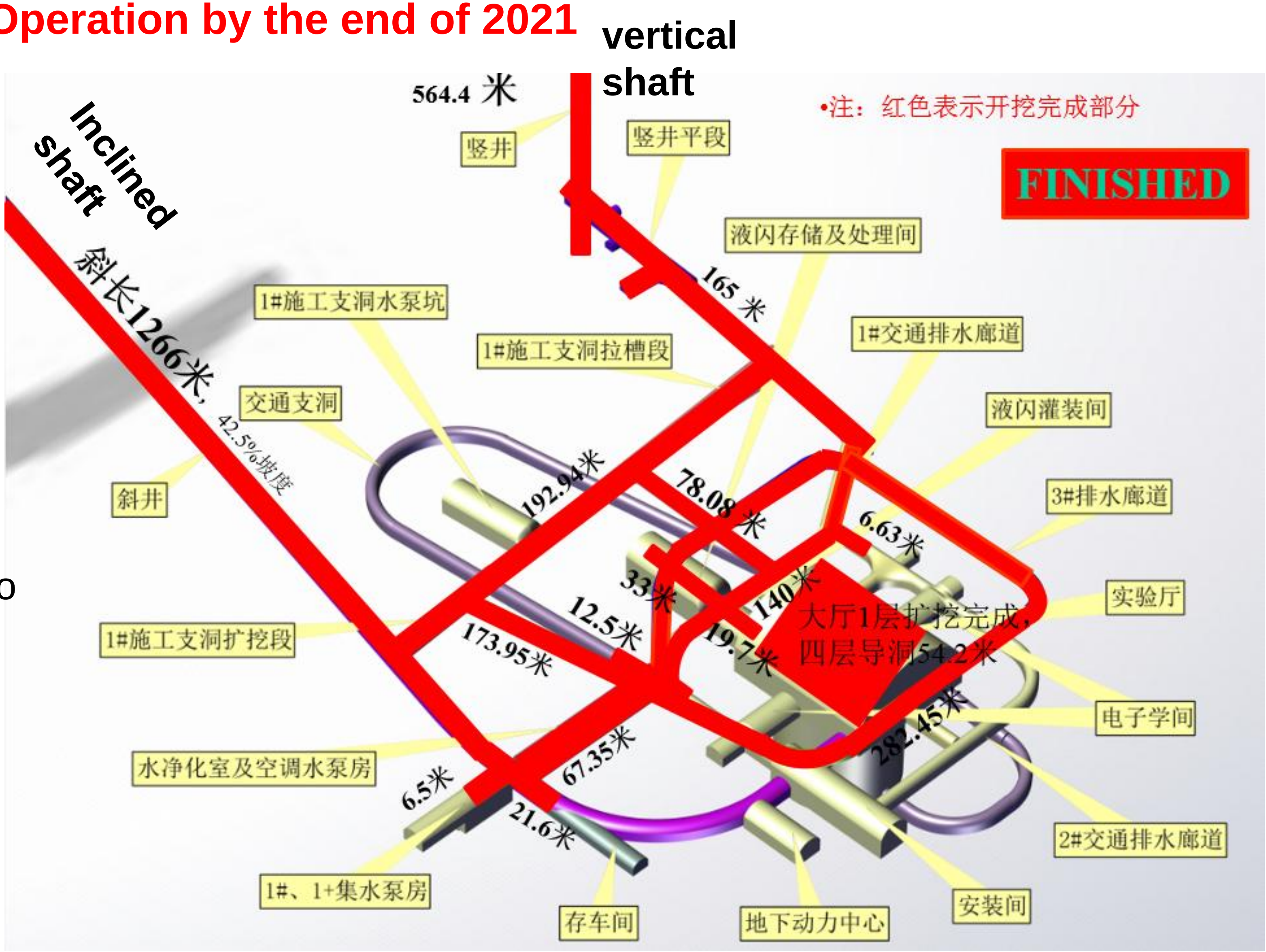
	KamLAND	Borexino	JUNO
LS mass	1 kt	0.3 kt	20 kt
Energy Resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

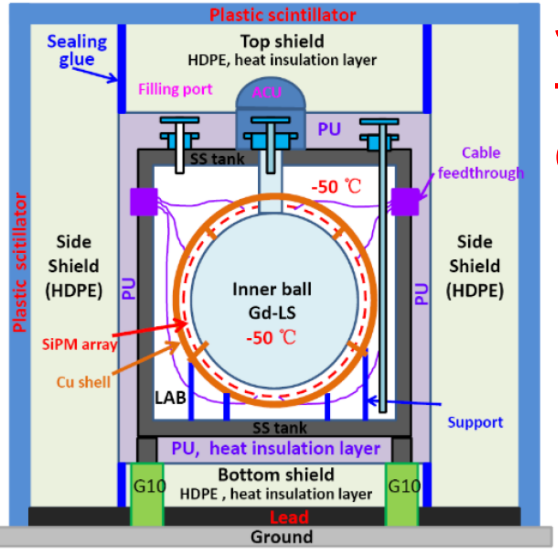
The JUNO Experiment: Progress and Status

- **Civil construction**: reached 700 m underground, exp. hall to be started
- **Central detector**: production of acrylic panels and stainless steel truss will start soon
- **PMT system**: receive 13,000 20-inch PMTs and 12,000 3-inch PMTs
- **Veto system**: top tracker delivered, water Cherenkov design completed
- **Liquid scintillator**: recipe optimized, pilot plant test nearly complete
- **Electronics**: all underwater, finalizing design, mass production starts soon

© M. He, "Prospects of JUNO" at Kavli IPMU, 2019-4-11

Operation by the end of 2021



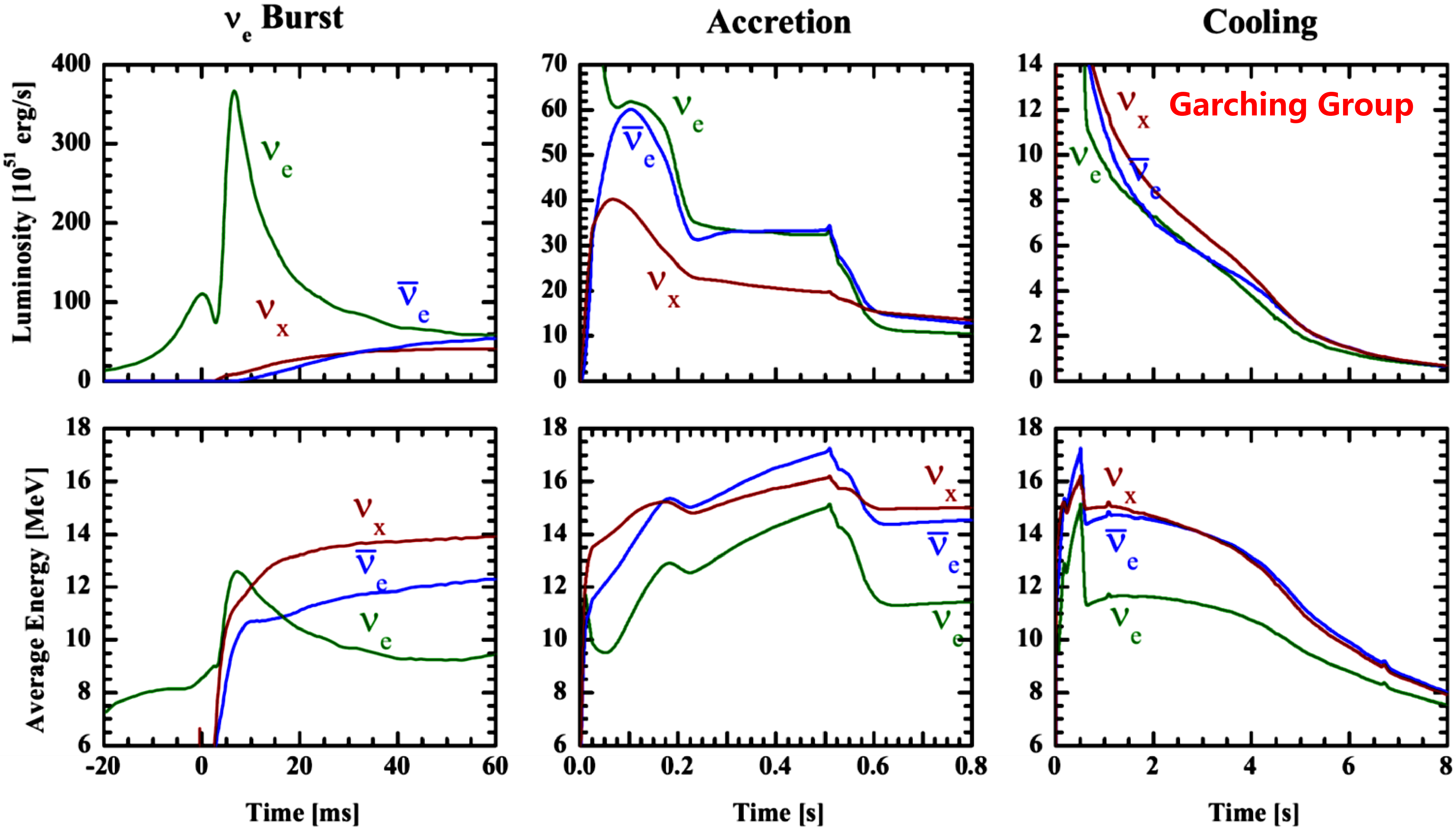


JUNO-TAO

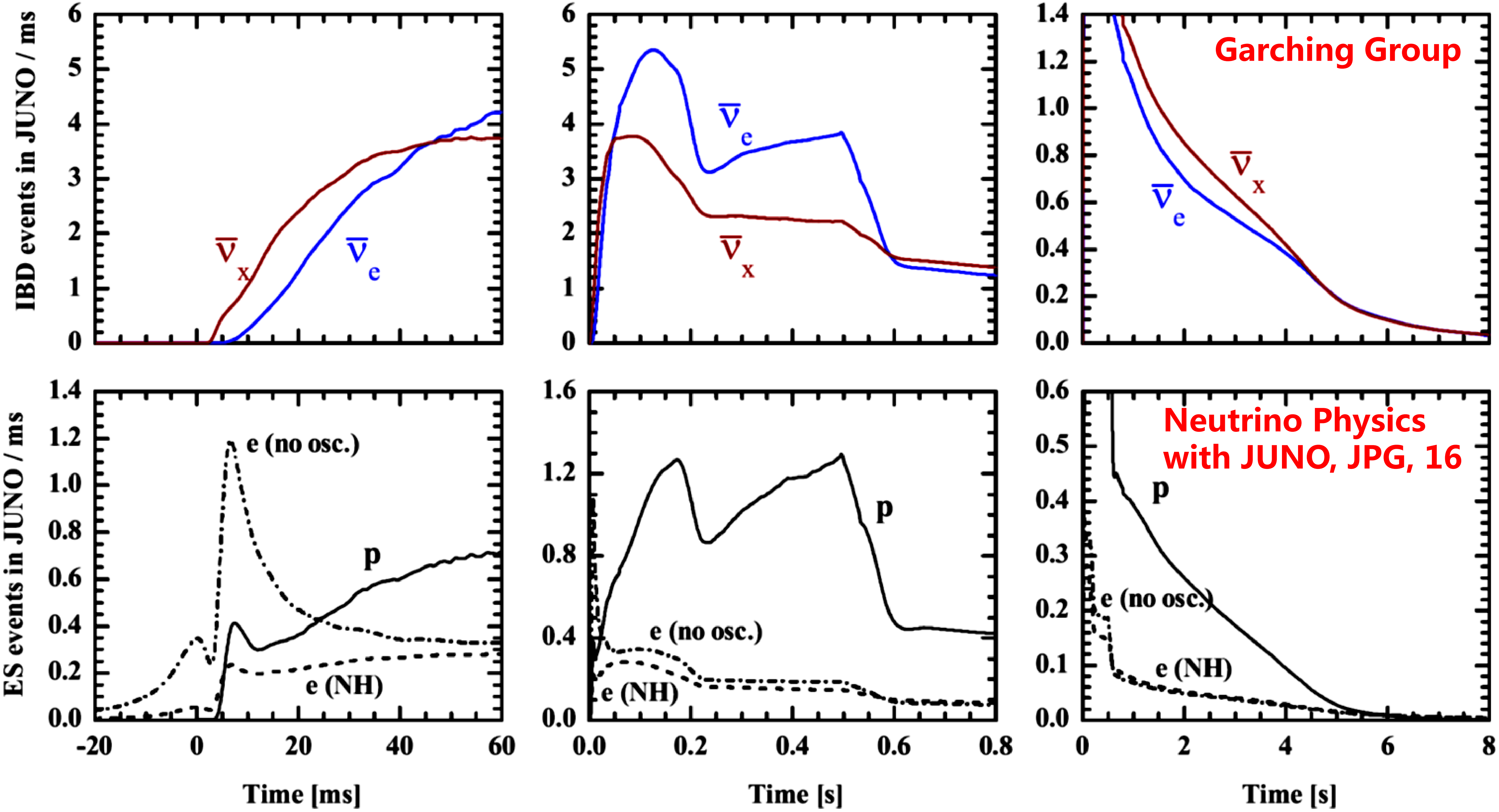
Taishan **A**ntineutrino **O**bservatory

- ~30 m to reactor (2000 IBD/day)
- 1.5% energy resolution@ 1 MeV
- SiPM 50% PDE
- Gd-LS@-50 °C

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}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

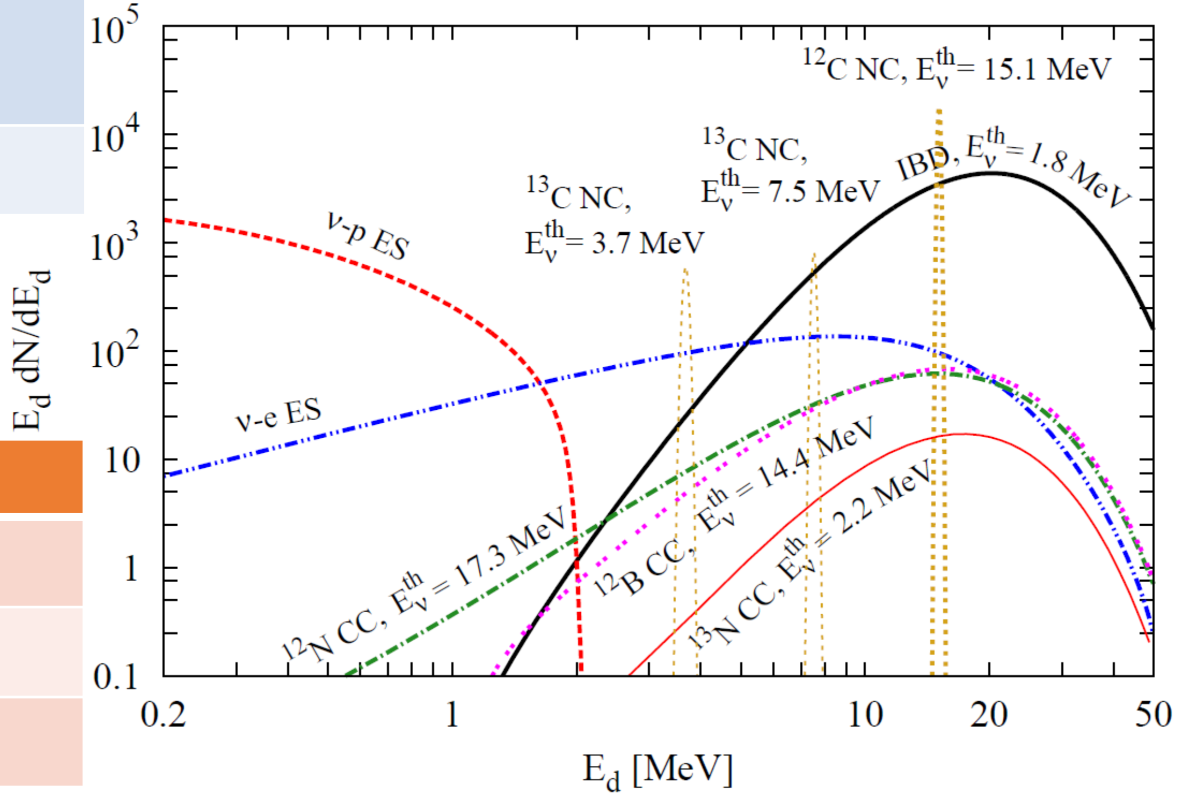
- **Elastic ν-p scattering important**
- **Advantage of LS: low threshold**

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

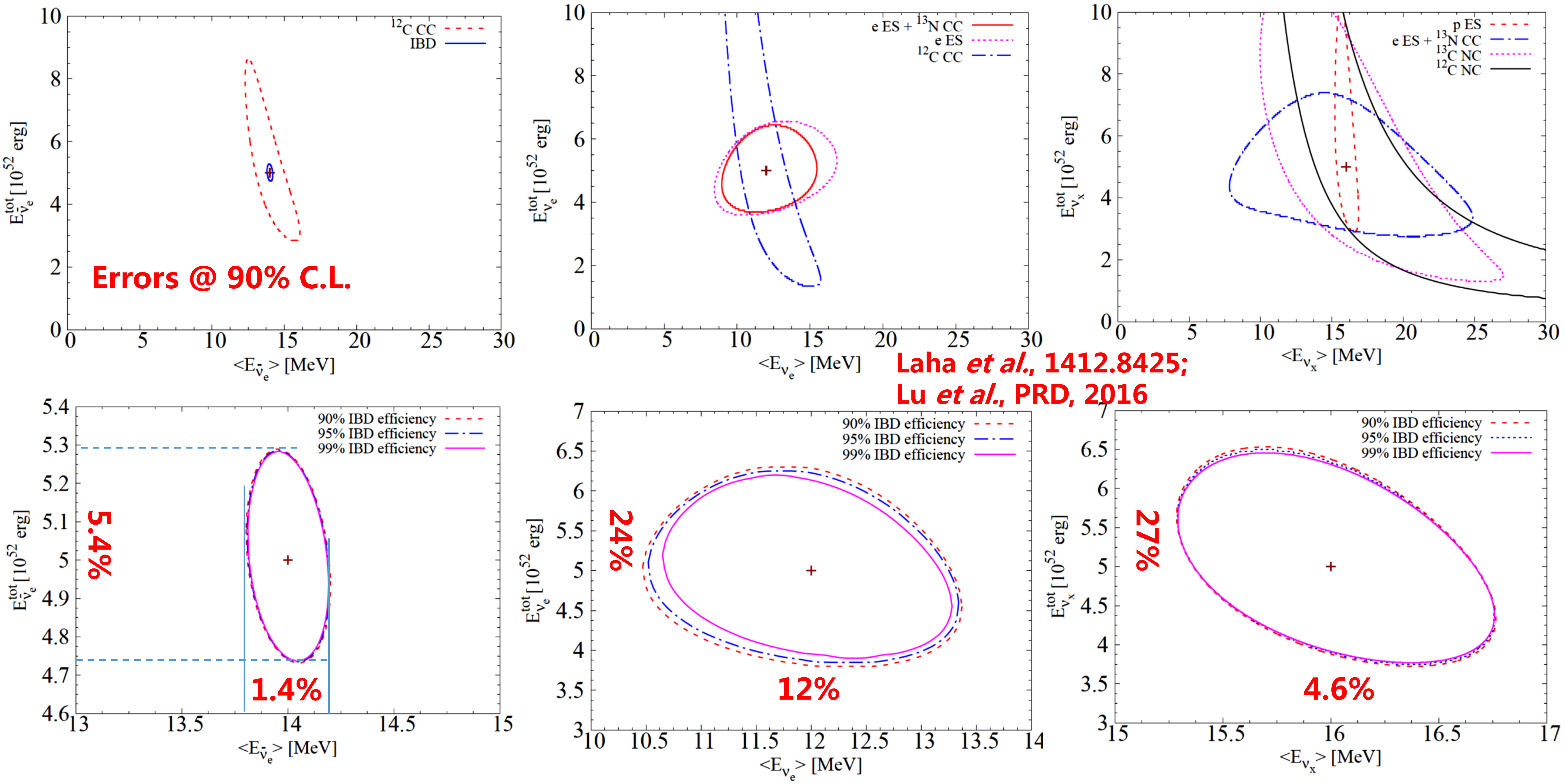
Channel	Type		Number of SN Neutrino Events at JUNO		
			No Oscillations	Normal Ordering	Inverted Ordering
$\overline{\nu}_e + p \to e^+ + n$	CC		4573	4775	5185
$\nu + p \to \nu + p$	ES		1578	1578	1578
		ν_e	107	354	278
		$\overline{\nu}_e$	179	214	292
		ν_x	1292	1010	1008
$\nu_e + e \to \nu_e + e$	ES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

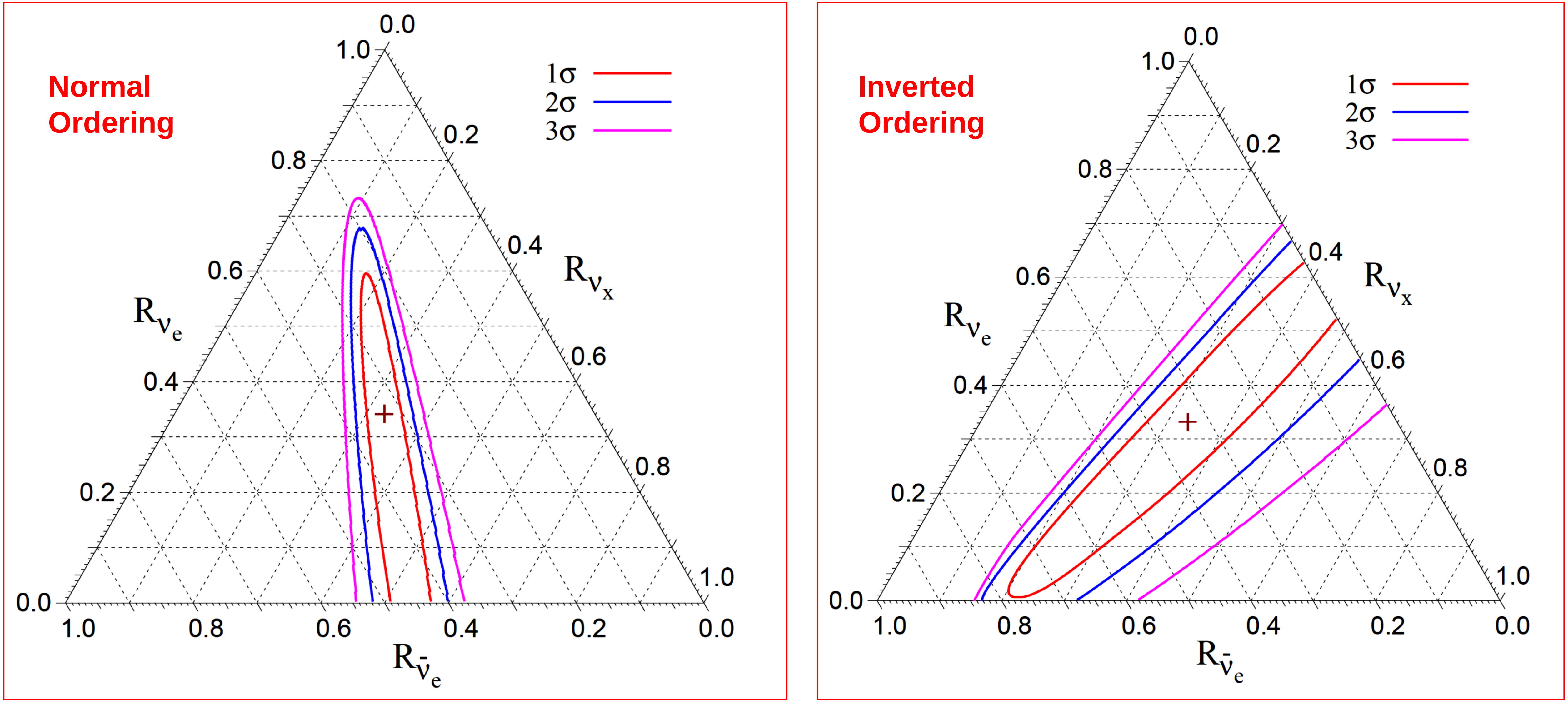


Laha *et al.*, 1412.8425;
Lu *et al.*, PRD, 2016

Test of Energy Equipartition Hypothesis

Including only the Mikheyev-Smirnov-Wolfenstein (MSW) matter effects

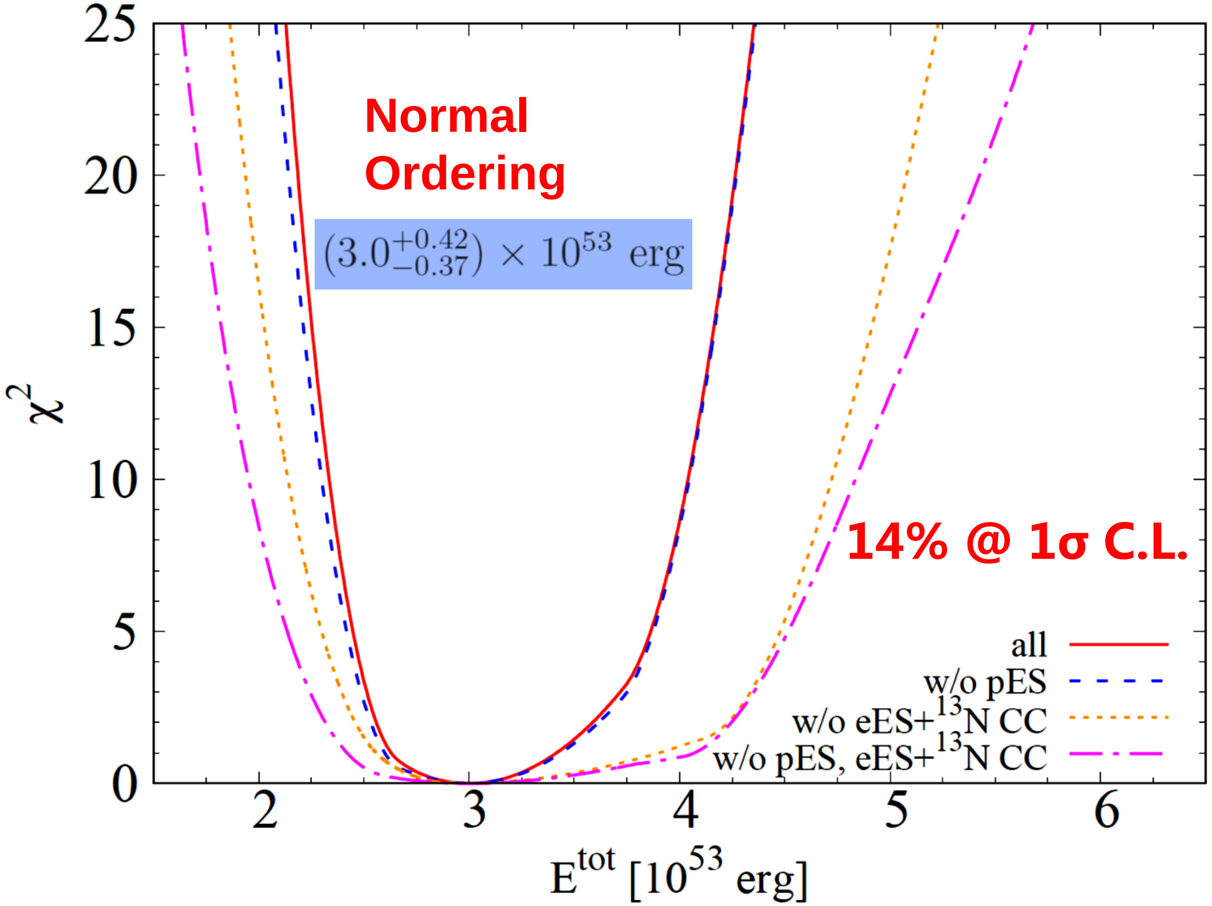
Lu, Li, Zhou, PRD, 2016

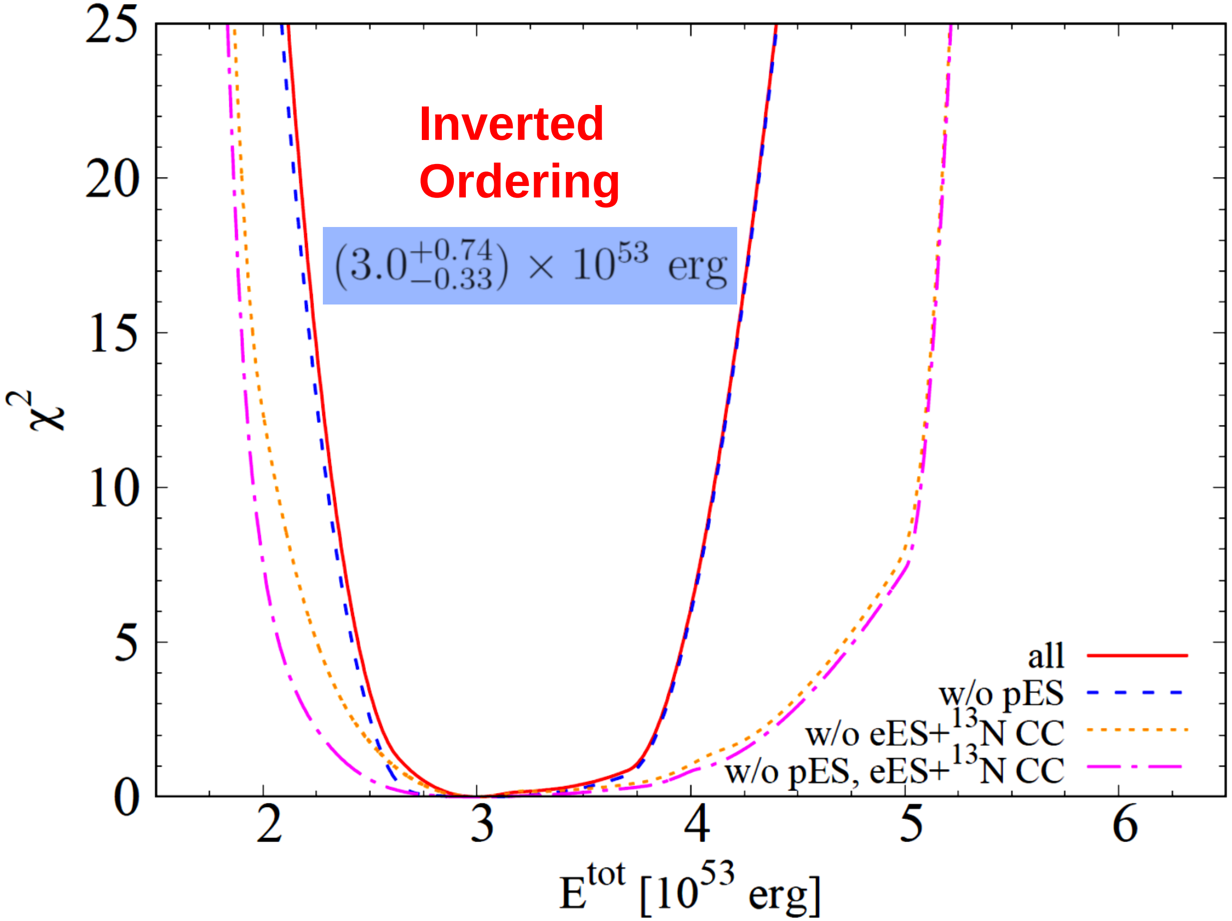


Total Gravitational Binding Energy

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

Lu, Li, Zhou, PRD, 2016; Gallo Rosso, Vissani, Volpe, JCAP, 2017

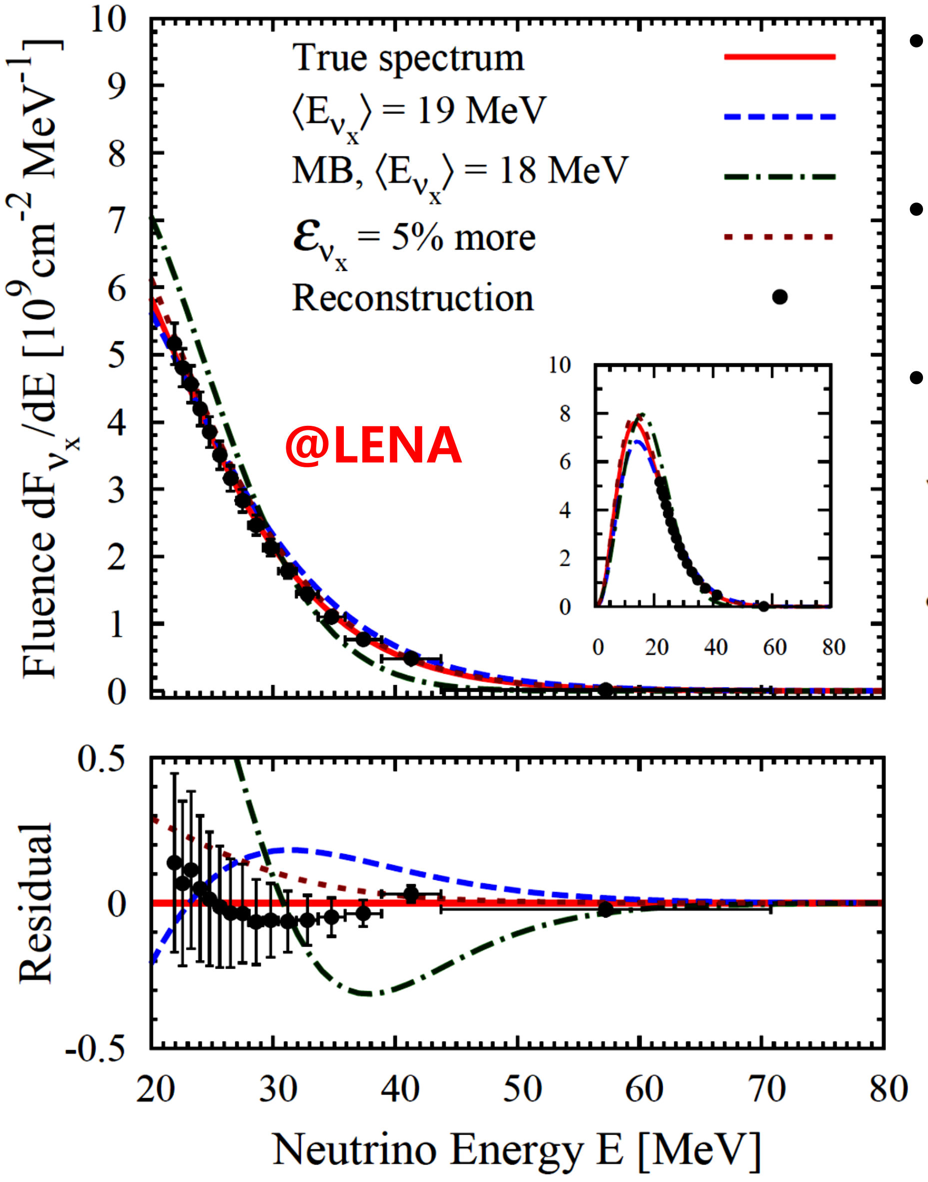




- **Conservatively assuming an uncertainty of 20% for the ν-p cross section (low as a few%)**
- **Possible to relax the constraint on the spectral index (important for <E>, but not for E_{tot})**

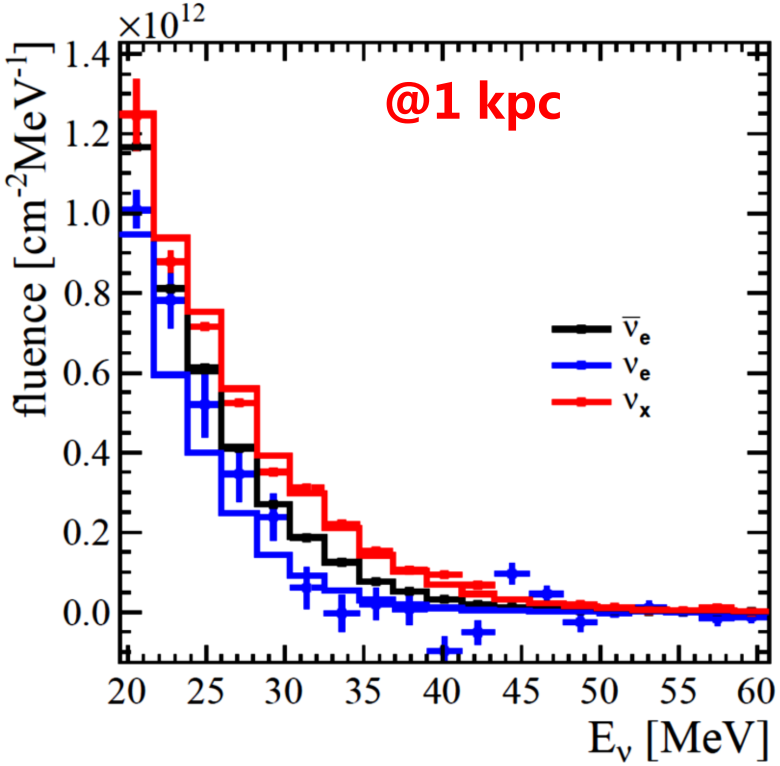
Unfolding of SN Neutrino Spectra

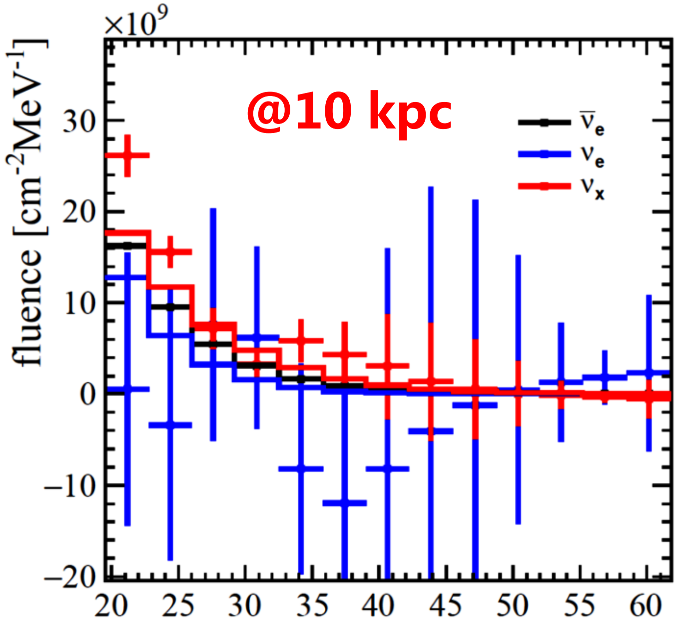
Dasgupta, Beacom, PRD, 11

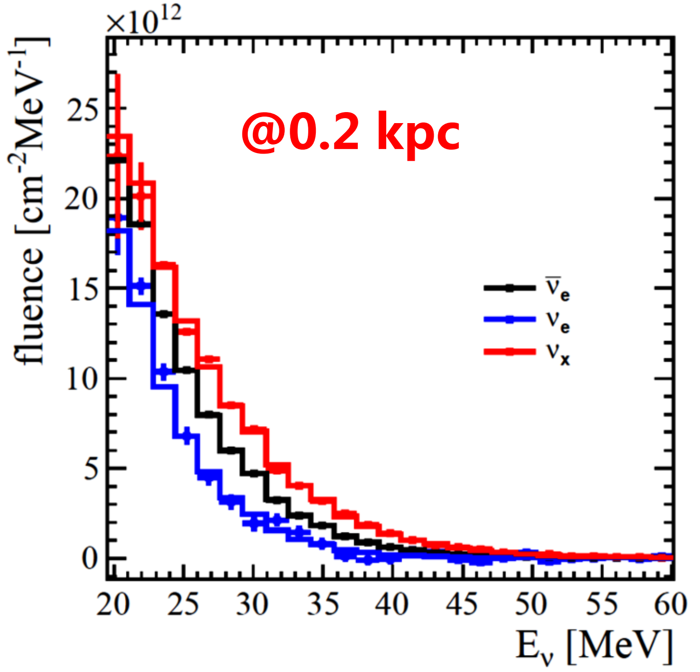


Li², Wang, Wen, Zhou, PRD, 18

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







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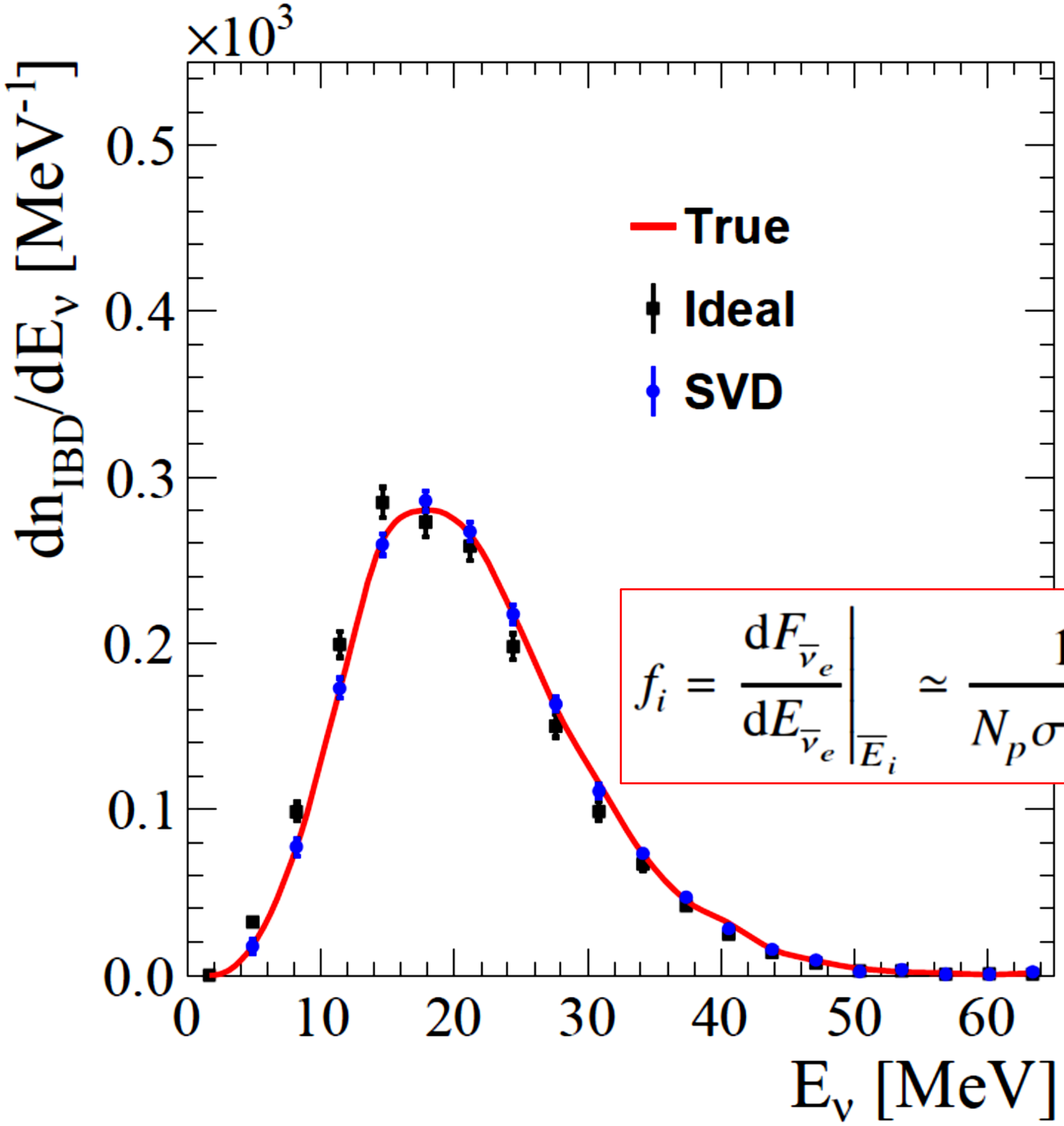
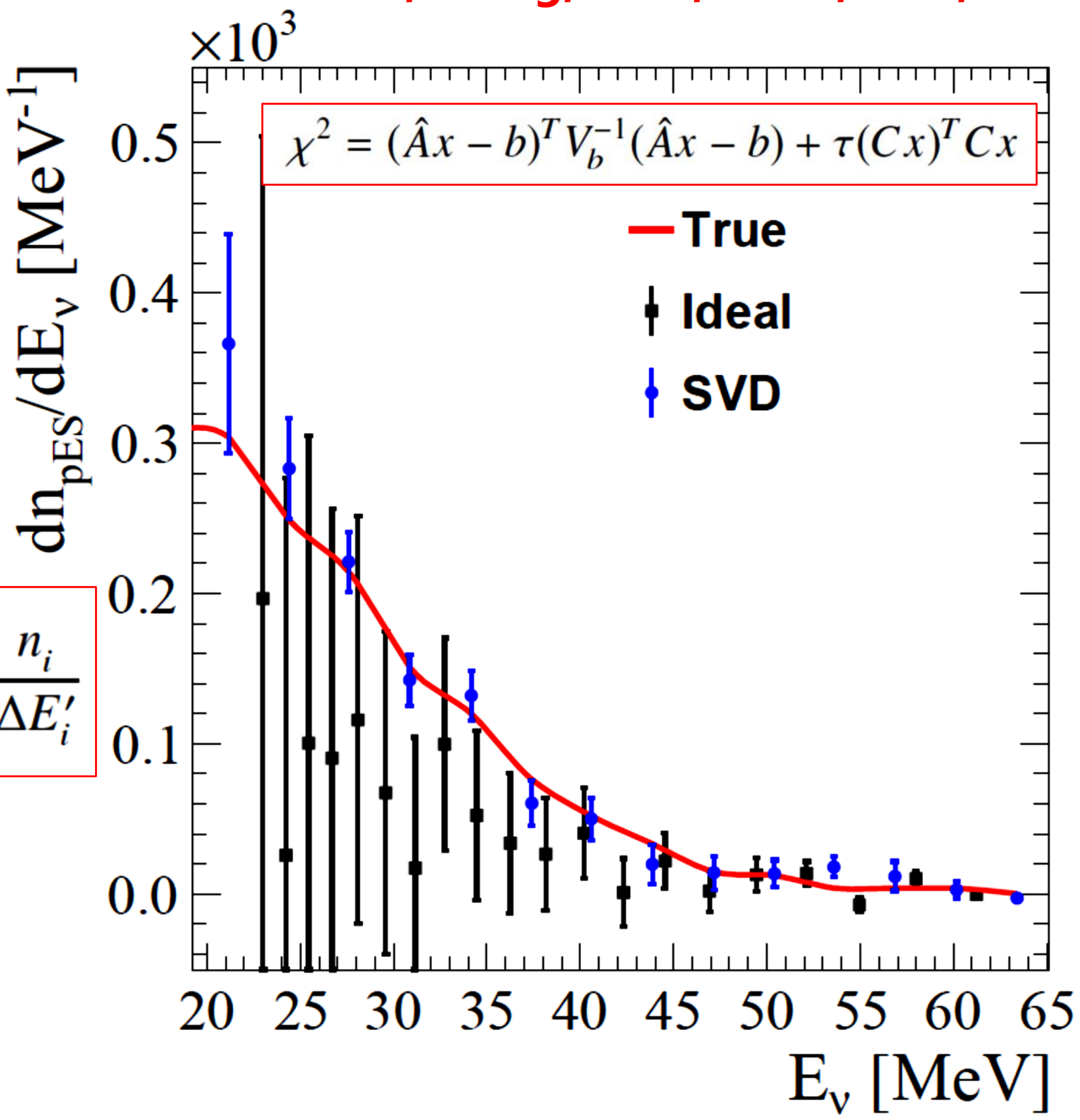


$$f_i = \left.\frac{\mathrm{d}F_{\overline{\nu}_e}}{\mathrm{d}E_{\overline{\nu}_e}}\right|_{\overline{E}_i} \simeq \frac{1}{N_p \sigma(\overline{E}_i)} \cdot \frac{n_i}{\Delta E'_i}$$

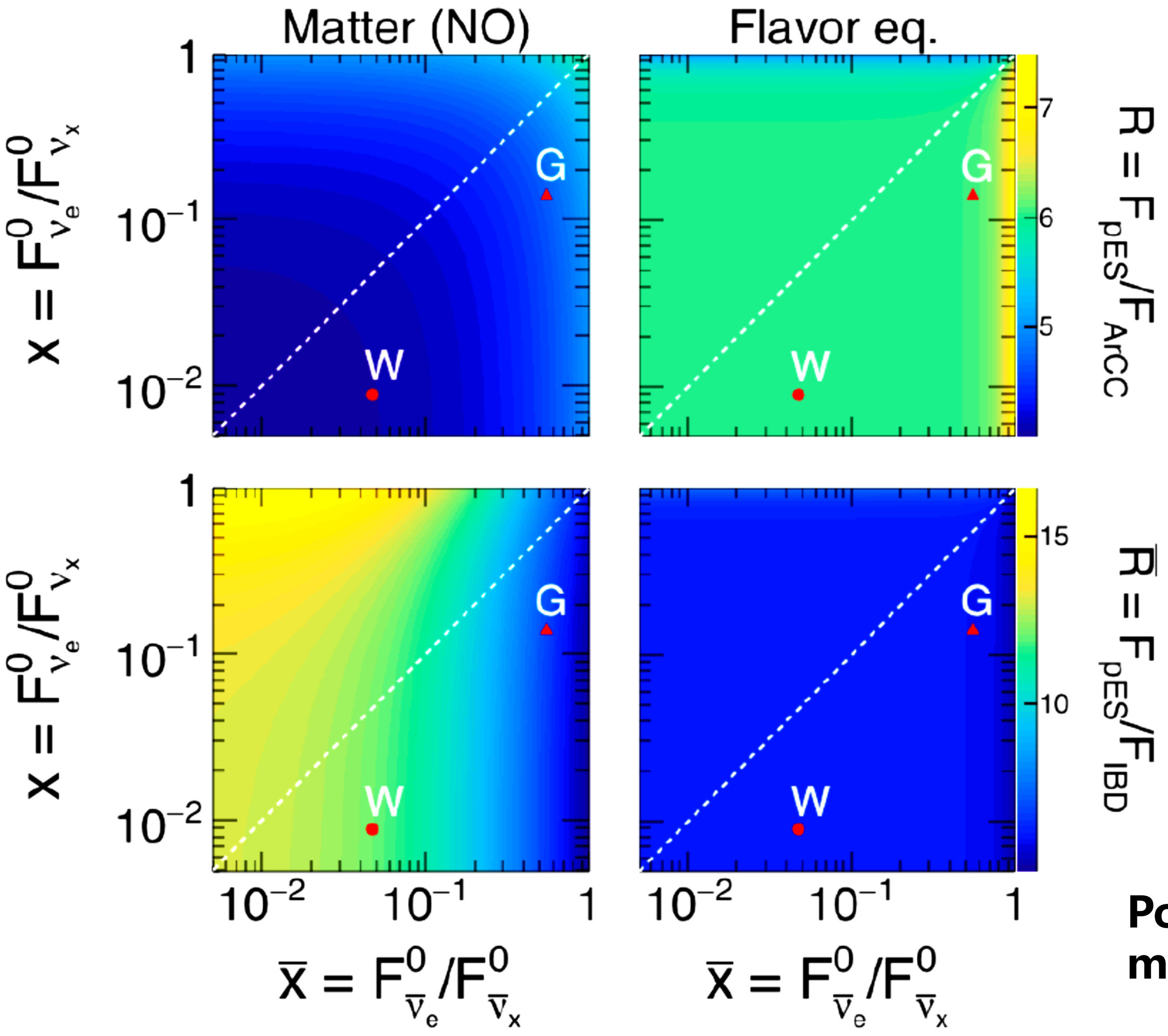
Li[2], Wang, Wen, Zhou, PRD, 18



$$\chi^2 = (\hat{A}x - b)^T V_b^{-1} (\hat{A}x - b) + \tau (Cx)^T Cx$$

Combined JUNO with HK and DUNE

Capozzi, Dasgupta, Mirizzi, PRD, 2018



Diagnosing the neutrino flavor equilibration

$$R = \frac{F_{\rm pES}}{F_{\rm ArCC}} = \frac{4 + x + \bar{x}}{P_{ee}x + (1 - P_{ee})} = \begin{cases} \frac{4}{1-P_{ee}} & x, \bar{x} \ll 1 \\ \frac{4+\bar{x}}{1-P_{ee}} & x \ll 1, \text{ and } \bar{x} \lesssim 1 \\ 6 & x \lesssim \bar{x} \lesssim 1 \end{cases}$$

$$\bar{R} = \frac{F_{\rm pES}}{F_{\rm IBD}} = \frac{4 + x + \bar{x}}{\bar{P}_{ee}\bar{x} + (1 - \bar{P}_{ee})} = \begin{cases} \frac{4}{1-\bar{P}_{ee}} & x, \bar{x} \ll 1 \\ \frac{4+\bar{x}}{\bar{P}_{ee}\bar{x}+1-\bar{P}_{ee}} & x \ll 1, \text{ and } \bar{x} \lesssim 1 \\ 6 & x \lesssim \bar{x} \lesssim 1 \end{cases}$$

Scenario	Mass Ordering	P_{ee}	$\bar{P}_{ee}$
ME	NO	0	$\cos^2\theta_{12} \simeq 0.7$
ME	IO	$\sin^2\theta_{12} \simeq 0.3$	0
FE	either	$1/3 \simeq 0.33$	$1/3 \simeq 0.33$

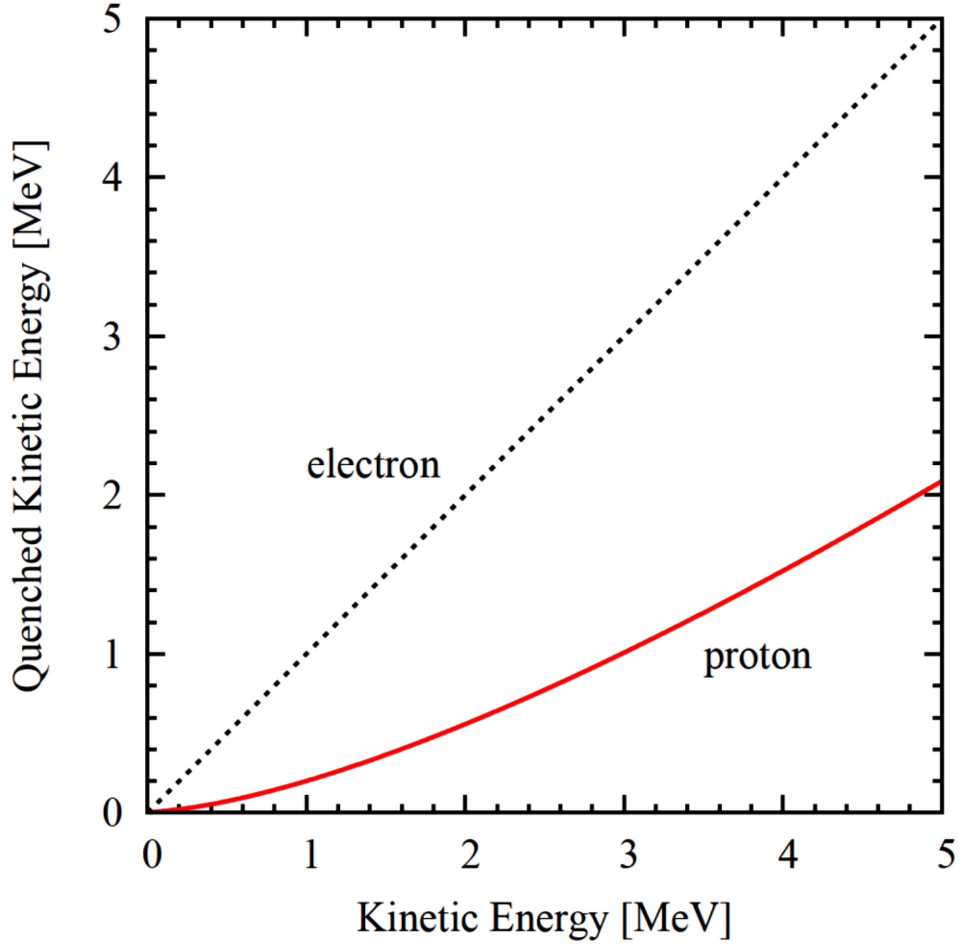
Possible to discriminate between the scenarios of matter effect (ME-NO) and flavor equilibration

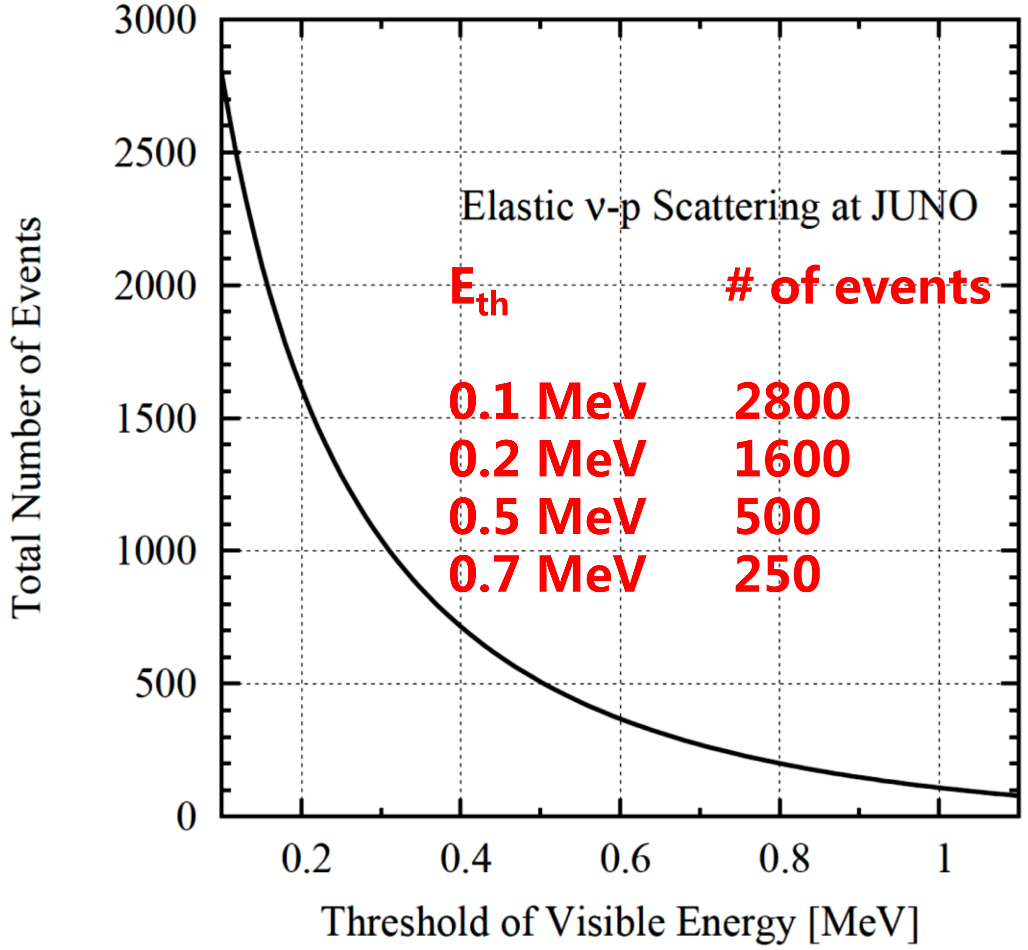
Elastic ν-p Scattering in LS Detectors

Beacom, Farr, Vogel, PRD, 02; Dasgupta, Beacom, PRD, 11; Lu, Li, Zhou, PRD, 16; Li et al., PRD, 18

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

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



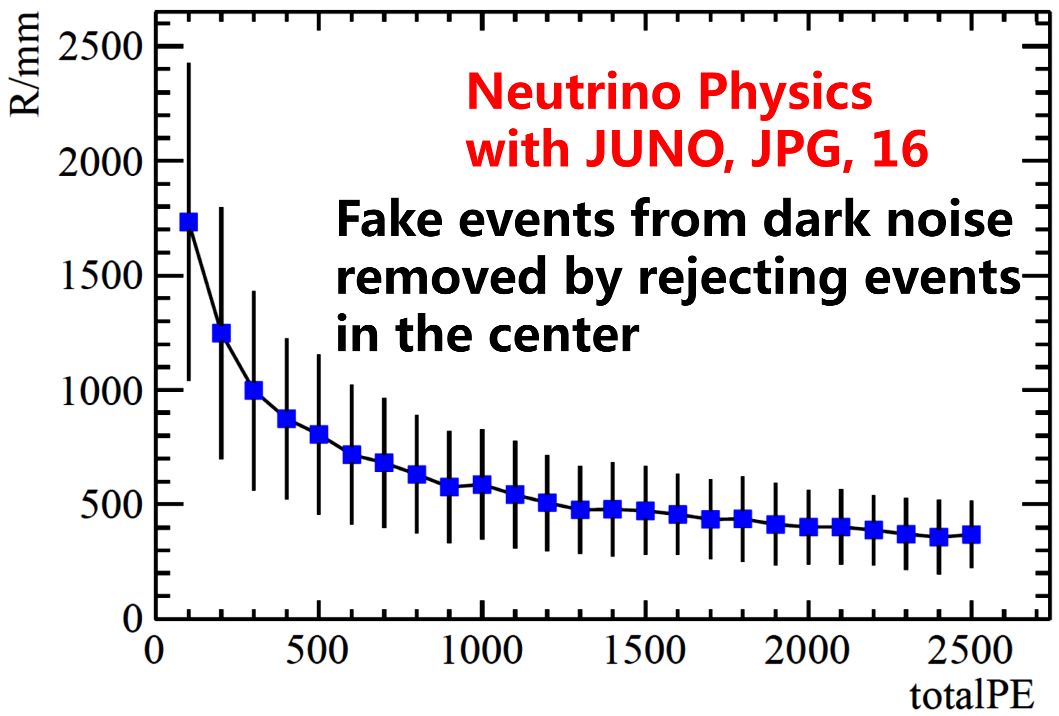


Borexino & JUNO: Radioactivity Backgrounds

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	$\leq$ 1 cpd/100 t	(30 ± 5) cpd/100 t	$\leq$ 5 cpd/100 t
^{39}Ar	$\leq$ 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		77	0.1	0.05
Energy cut	97.8%			410			
Time cut	99.1%	73	1.3		71		
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

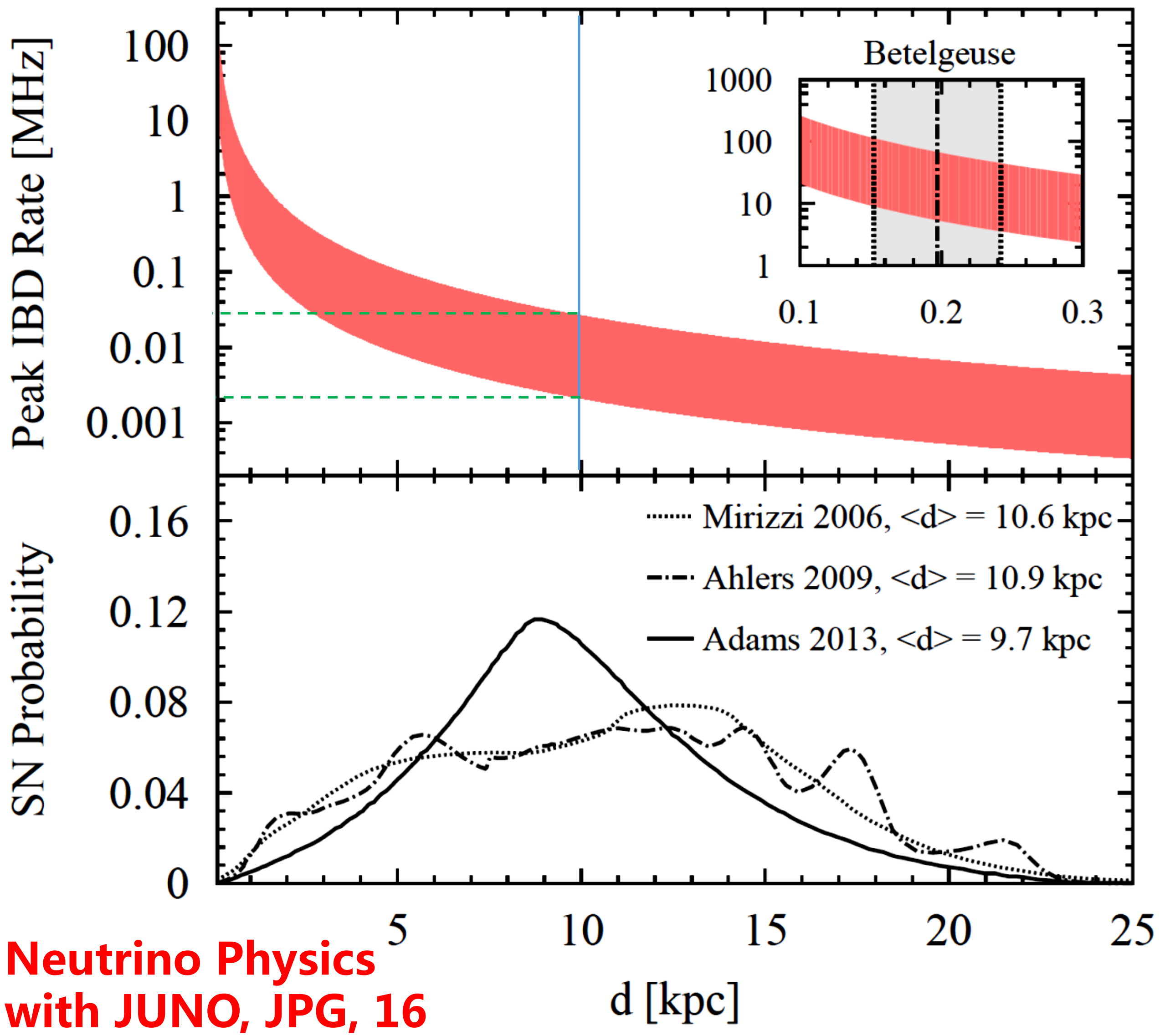
Channel	^{85}Kr	^{210}Bi (^{210}Pb)
ePS (10 s)	10	70

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

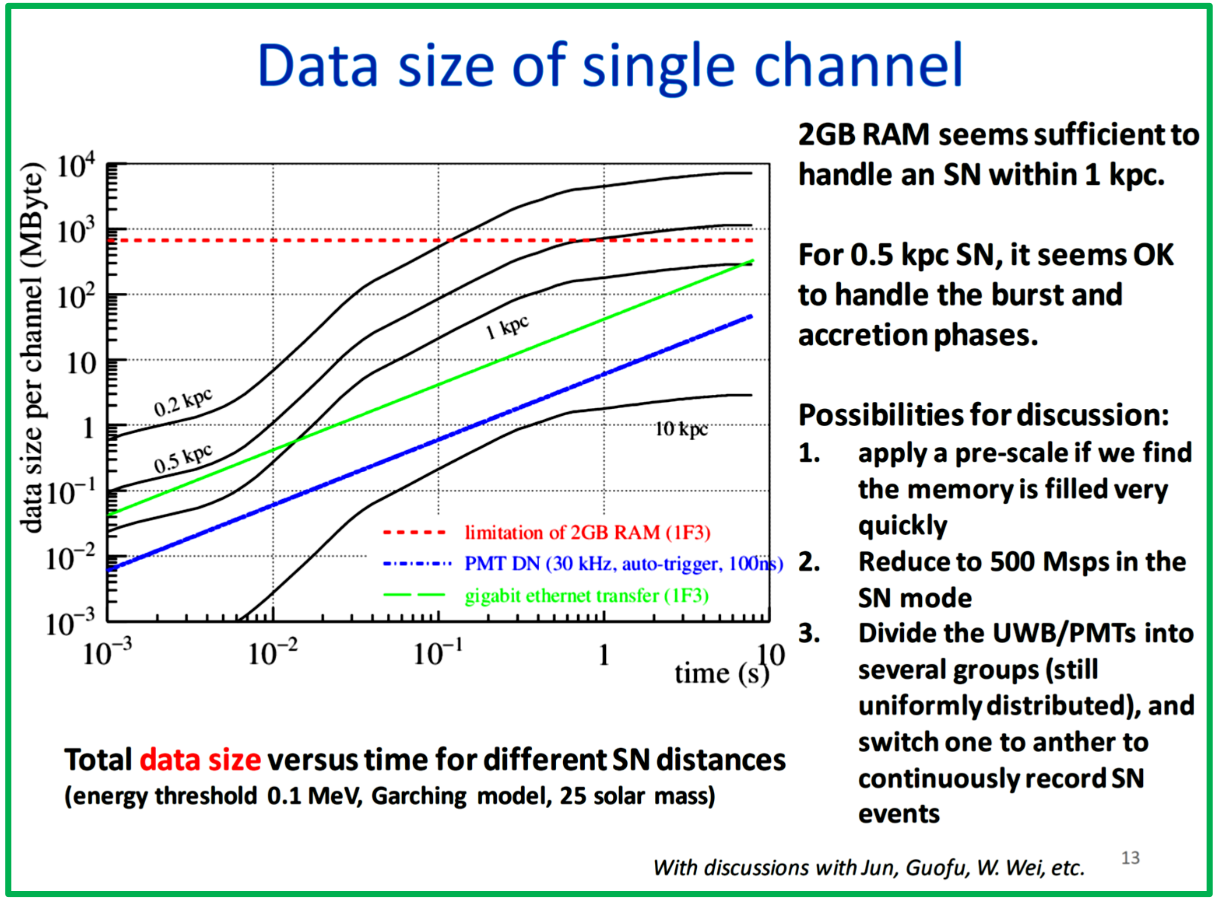
JUNO: SN Neutrino Trigger

Request for the DAQ @ JUNO

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

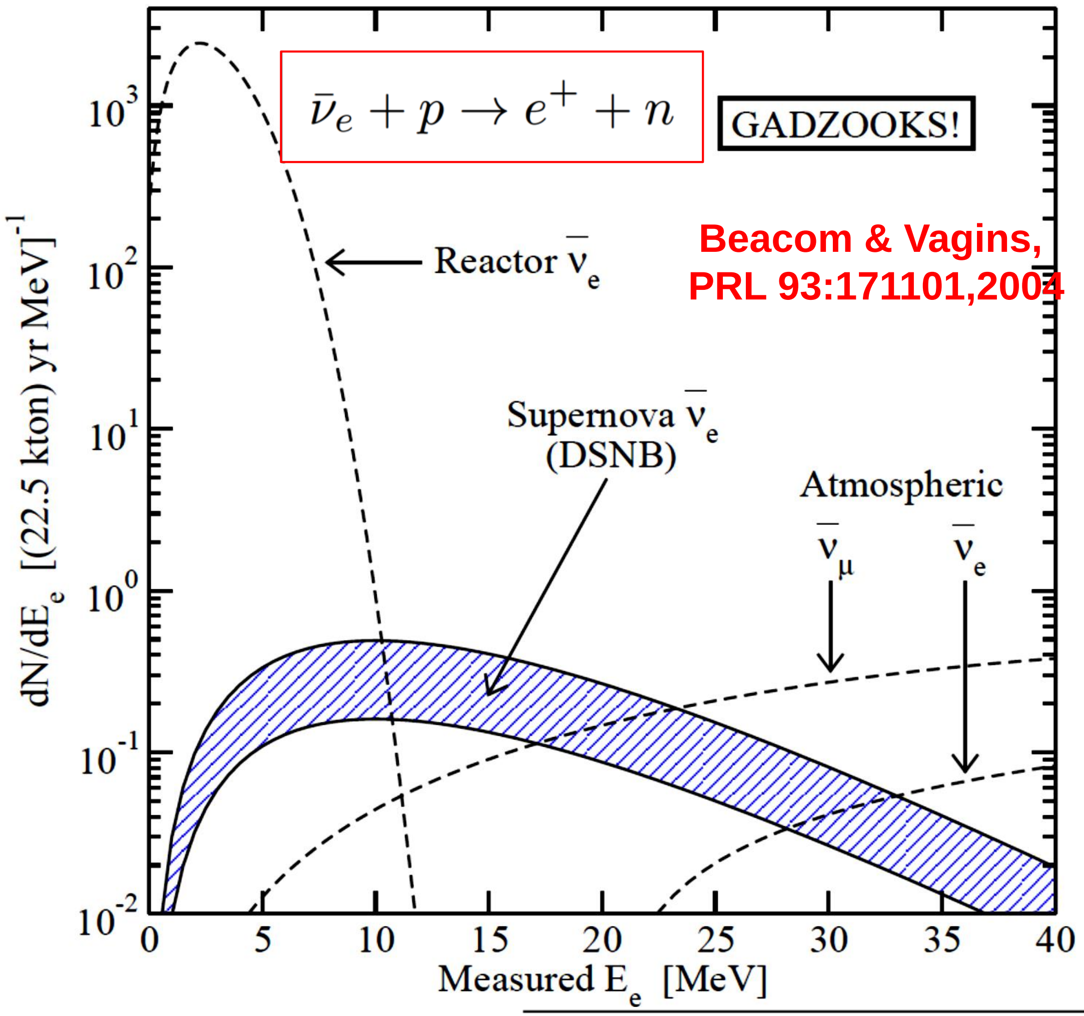


Neutrino Physics with JUNO, JPG, 16

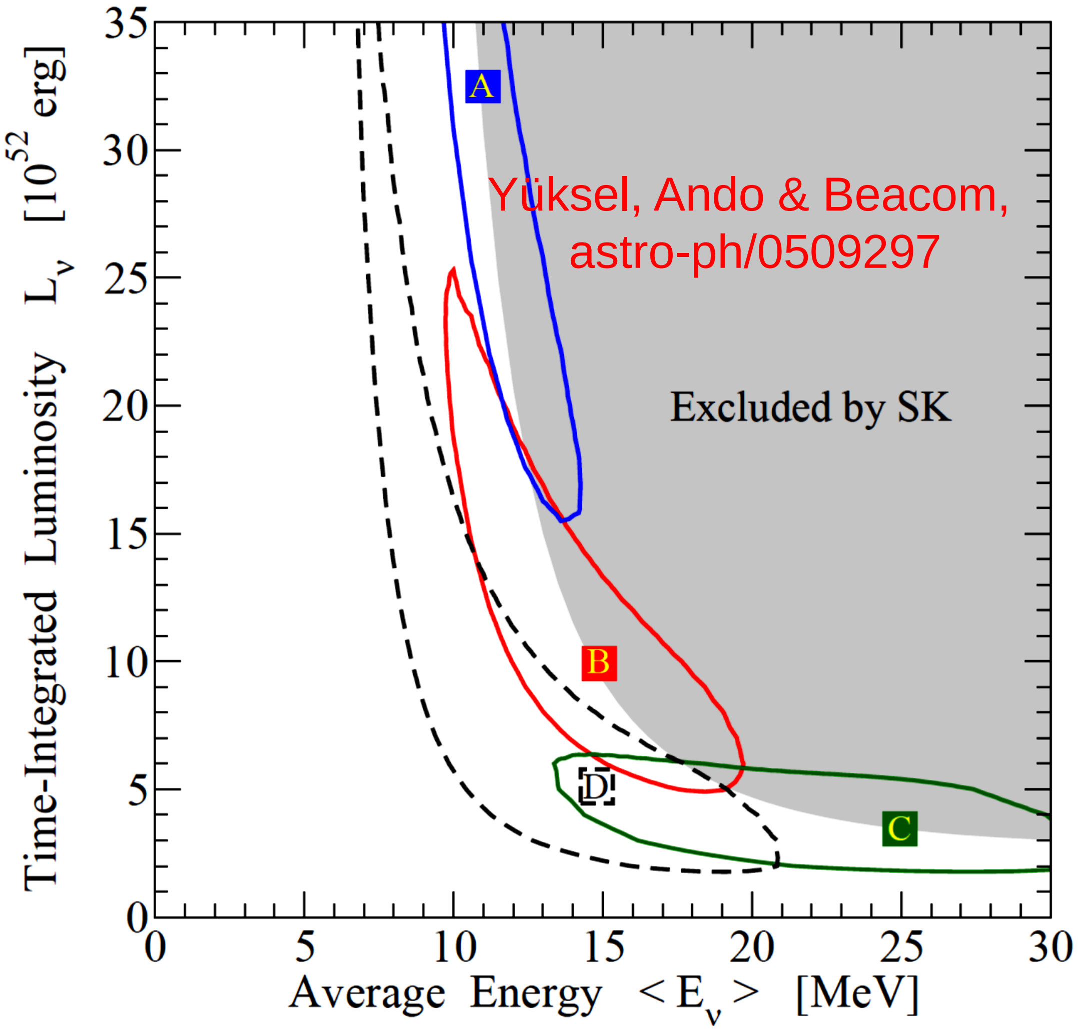


- **Trigger for SN neutrinos / Joining SNEWS**
- **Studies being carried out to store all the low-energy signals (even below 0.2 MeV)**

DSNB @ JUNO



Beacom & Vagins, PRL 93:171101,2004



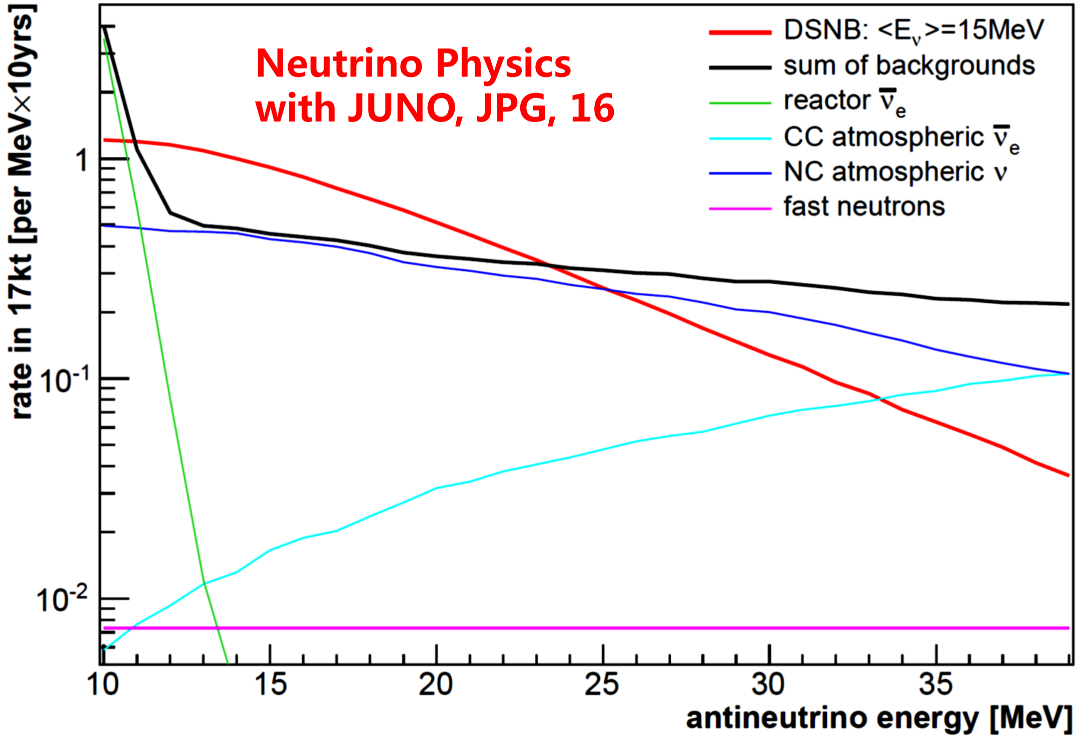
Yüksel, Ando & Beacom, astro-ph/0509297

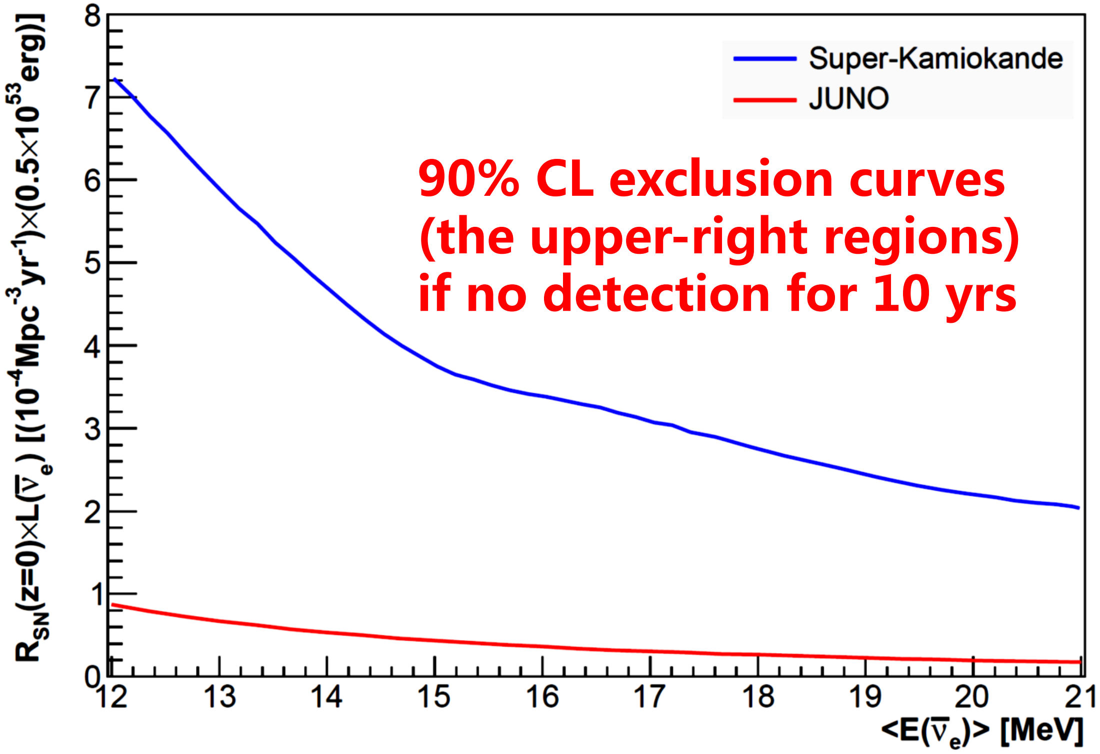
DSNB @ Gd-SK

Point	$\langle E_\nu \rangle$ [MeV]	L_ν [10^{52} erg]	Sensitivity
A	11	32	Average Energy
B	15	10	Both Variables
C	25	3.5	Integrated Luminosity
D	15	5	Lowered Sensitivity

90% CL sensitivity to average SN spectrum from DSNB after 5 years of Gd-Super-K

DSNB @ JUNO





Detailed calculations of atm. NC background

- **Atm. neutrino fluxes at the JUNO site (in collaboration with Honda)**
- **Simulations with GENIE/NuWro for ν-C interactions and TALYS for de-excitation**

J. Cheng et al., work in progress

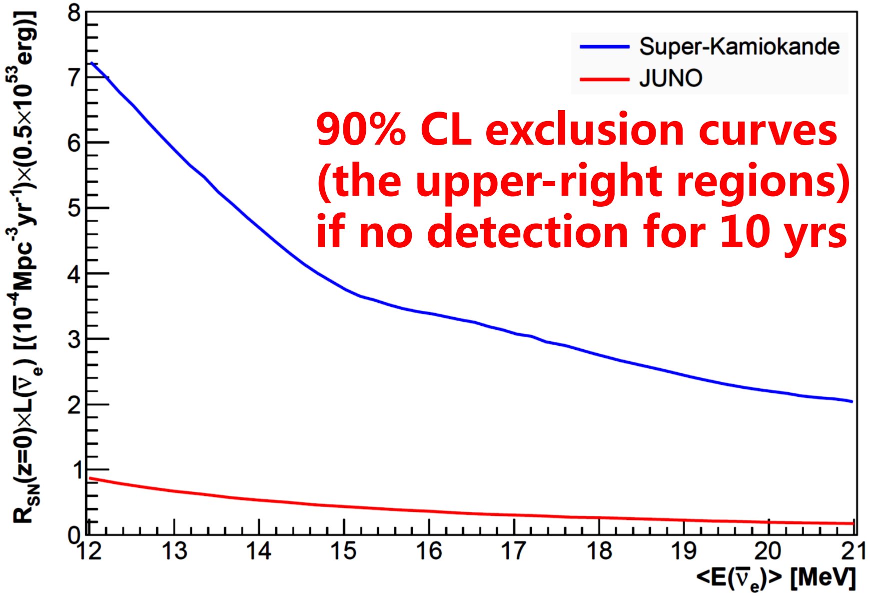
Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar\nu_e}\rangle = 12\,\mathrm{MeV}$	13	$\varepsilon_\nu = 50\,\%$	7
	$\langle E_{\bar\nu_e}\rangle = 15\,\mathrm{MeV}$	23		12
	$\langle E_{\bar\nu_e}\rangle = 18\,\mathrm{MeV}$	33		16
	$\langle E_{\bar\nu_e}\rangle = 21\,\mathrm{MeV}$	39		19
Background	reactor $\bar\nu_e$	0.3	$\varepsilon_\nu = 50\,\%$	0.13
	atm. CC	1.3	$\varepsilon_\nu = 50\,\%$	0.7
	atm. NC	$6 \cdot 10^2$	$\varepsilon_{\mathrm{NC}} = 1.1\,\%$	6.2
	fast neutrons	11	$\varepsilon_{\mathrm{FN}} = 1.3\,\%$	0.14
	Σ			7.1

Summary & Outlook

- **JUNO will provide a unique opportunity to detect SN ν_x neutrinos via pES, important for a lot of physics studies (independent of flavor conversions, total energy release, etc.)**
- **Give the priority to DSNB, a guaranteed source of SN neutrinos. We have the SK with Gd doping, and JUNO (available within 2 years) also has a very 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	$5.5\,\sigma$	$5.8\,\sigma$	$4.9\,\sigma$	$5.1\,\sigma$

- Observation window: 11 MeV < E_ν < 30 MeV
- PSD techniques for NC atmospheric ν
- Fast neutrons: r < 16.8 m (equiv. 17 kt mass)



- **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)**
- **Dark matter detectors probe SN neutrinos! (Lang et al., PRD, 2016)**

Thanks!