

# **JUNO and RENO-50**

**Jun CAO**

**Institute of High Energy Physics**

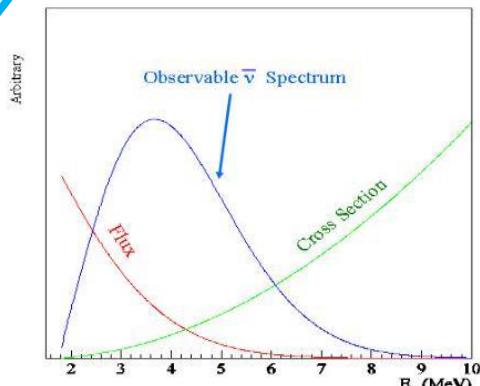
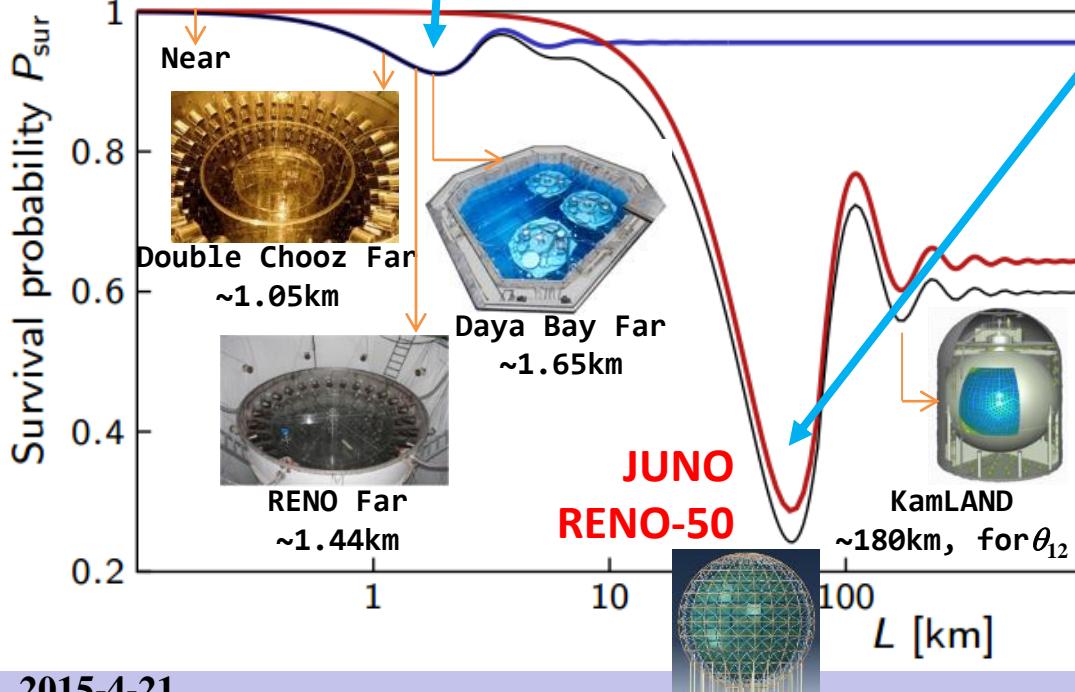
2<sup>nd</sup> International Meeting for Large Neutrino Infrastructures,  
Fermilab, Apr. 20-21, 2015

# Reactor Neutrinos

“Disappearance” experiments:  $\bar{\nu}_e \rightarrow \bar{\nu}_e$

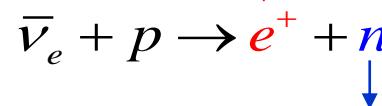
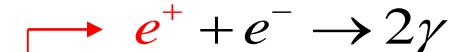
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left( \Delta m_{ee}^2 \frac{L}{4E} \right) - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \left( \Delta m_{21}^2 \frac{L}{4E} \right)$$

$$\Delta m_{ee}^2 \sim \cos^2 \theta_{12} \Delta m_{31}^2 + \sin^2 \theta_{12} \Delta m_{32}^2 \\ \sim 0.7 \Delta m_{31}^2 + 0.3 \Delta m_{32}^2$$



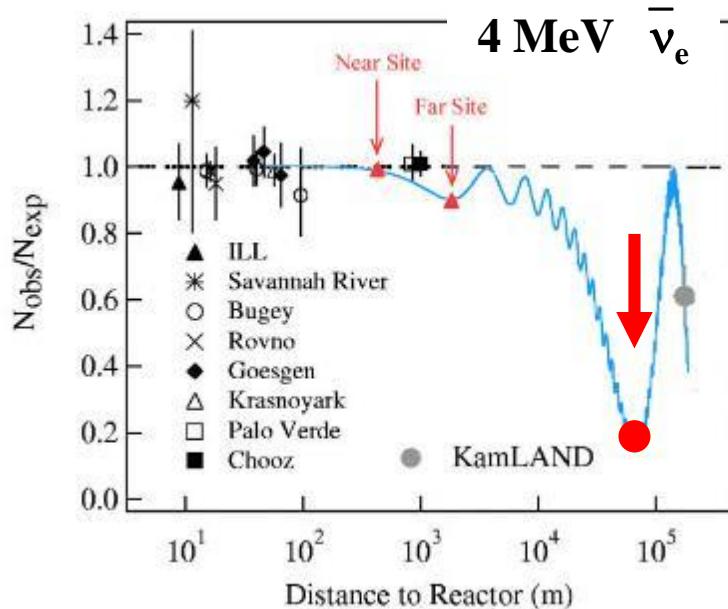
## ■ Inverse beta decay

Prompt signal



Capture on H or Gd,  
Delayed signal, 2.2 or 8 MeV

# Determine MH with Reactors

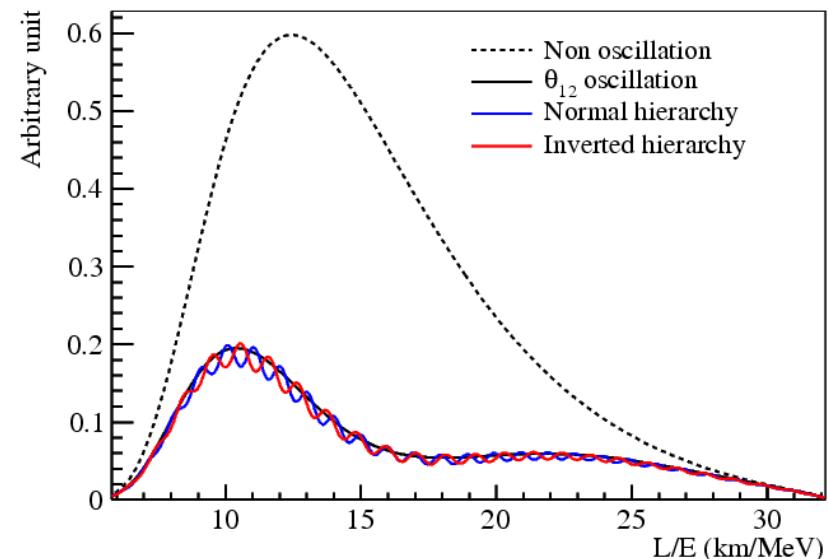


Precision energy spectrum measurement  
interference between  $P_{31}$  and  $P_{32}$   
→  $\phi$ : Relative measurement

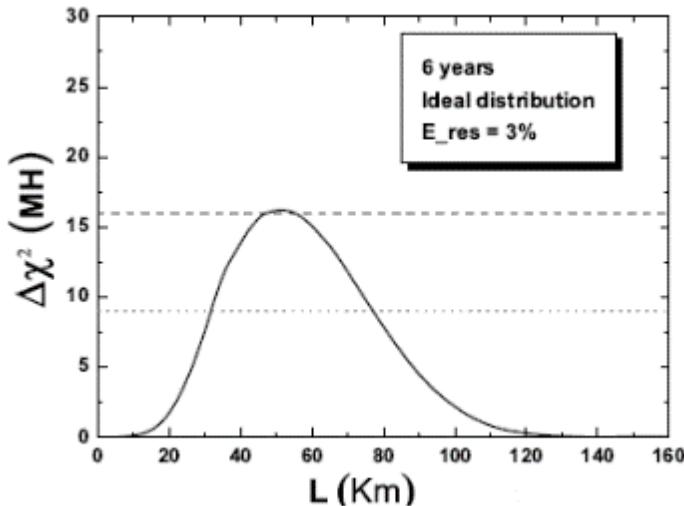
Further improvement with  $\Delta m_{\mu\mu}^2$   
measurement from accelerator exp.  
→  $\Delta m_{ee}^2$ : Absolute measurement

$$\begin{aligned}
 P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
 P_{21} &= \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \\
 P_{31} &= \underline{\cos^2(\theta_{12})} \sin^2(2\theta_{13}) \underline{\sin^2(\Delta_{31})} \\
 P_{32} &= \underline{\sin^2(\theta_{12})} \sin^2(2\theta_{13}) \underline{\sin^2(\Delta_{32})}
 \end{aligned}$$

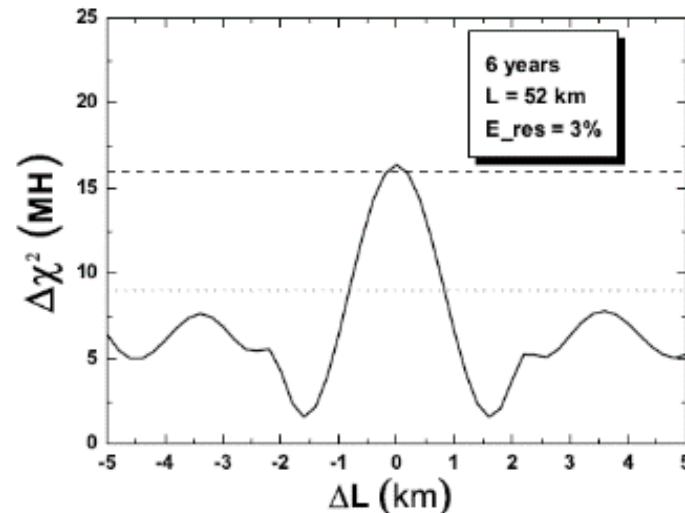
- $$\frac{1}{2} \sin^2 2\theta_{13} \left[ 1 - \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}} \cos(2|\Delta_{ee}| \pm \phi) \right]$$
- A fixed definition  $\Delta m_{ee}^2$
  - And an energy related phase shift  $\phi$



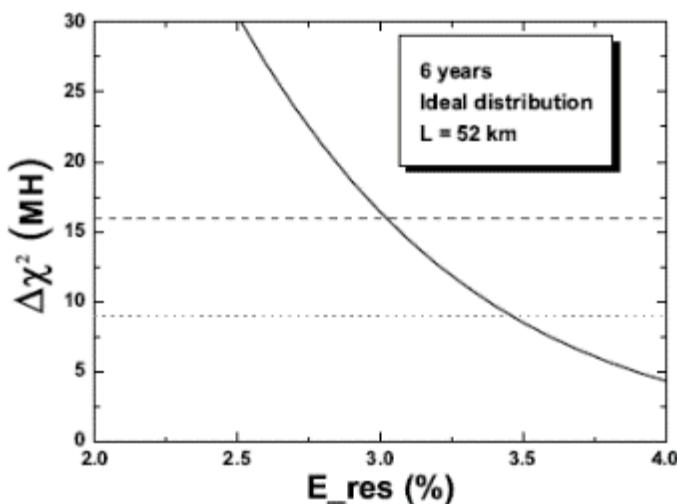
# Requirements



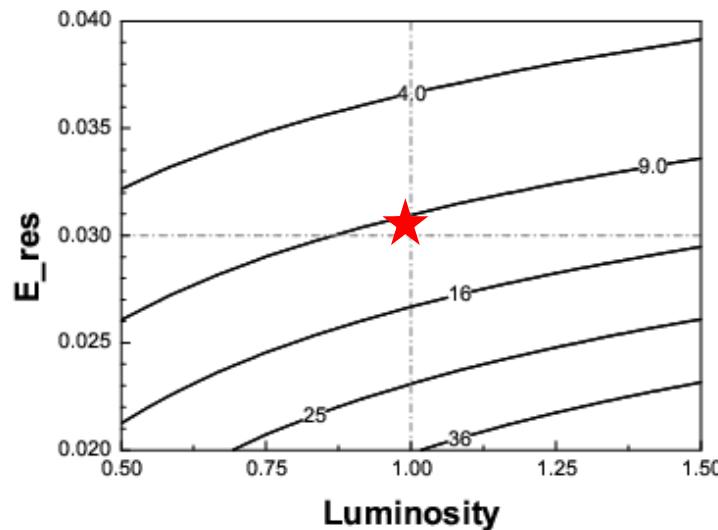
Proper baseline: 45-60 km



Equal baselines



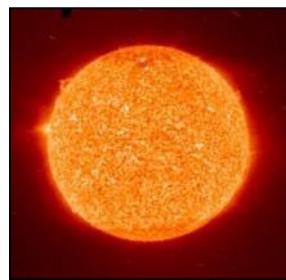
3% Energy resolution



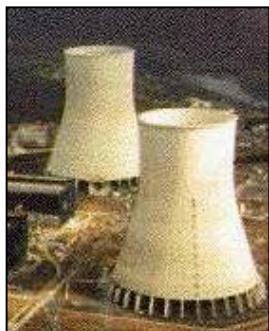
100k events=20 kton×35 GW×6 year



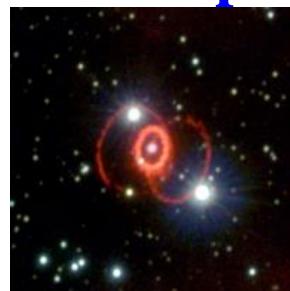
Supernova ν  
~ 5k in 10s for 10kpc



Solar ν  
(10s-1000s)/day

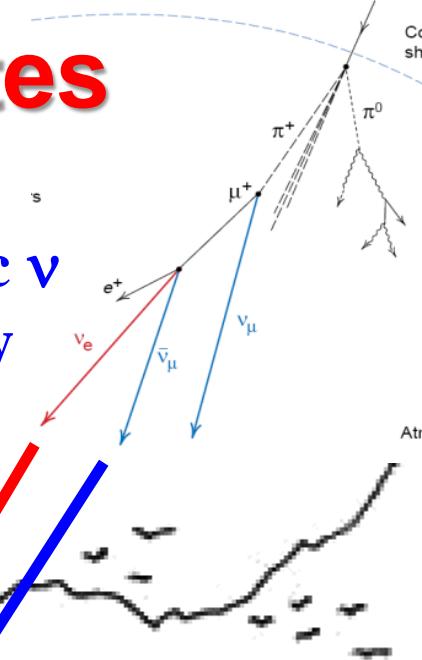


reactor ν, ~ 60/day



# Neutrino Rates

Atmospheric ν  
several/day



**Cosmic muons**  
~ 250k/day

0.003 Hz/m<sup>2</sup>

215 GeV

10% multiple-muon



**Geo-neutrinos**  
1-2/day

36 GW, 53 km

700 m

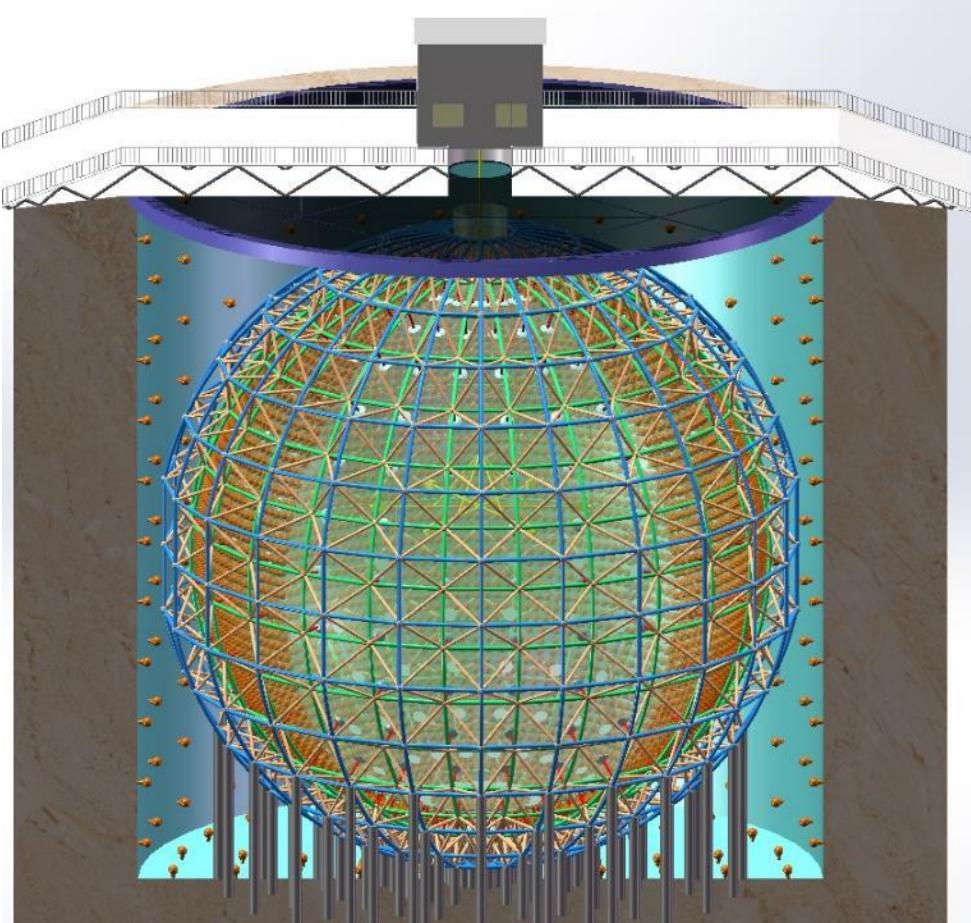
20k ton

LS



# The JUNO Experiment

- ◆ Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013. ~ 300 M\$.



- ◆ 20 kton LS detector
- ◆ 3% energy resolution
- ◆ 700 m underground
- ◆ Rich physics possibilities
  - ⇒ Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters
  - ⇒ Supernovae neutrino
  - ⇒ Geoneutrino
  - ⇒ Solar neutrino
  - ⇒ Atmospheric neutrino
  - ⇒ Exotic searches

Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011; by J. Cao at Nutel 2009, NuTurn 2012 ;  
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103, 2008; PRD79:073007, 2009



# Location of JUNO

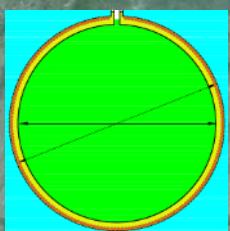


NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

## Overburden ~ 700 m

**by 2020: 26.6 GW**

# Kaiping, Jiang Men city, Guangdong Province



**53 km**

# Yangjiang NPP

2.5 h drive

# Guang Zhou

## Previous site candidate

**Lufeng  
NPP**

# Daya Bay NPP

# Hong Kong

Macau

• Zhongshan  
**Zhu Hai**  
Zhujiang River Estuary

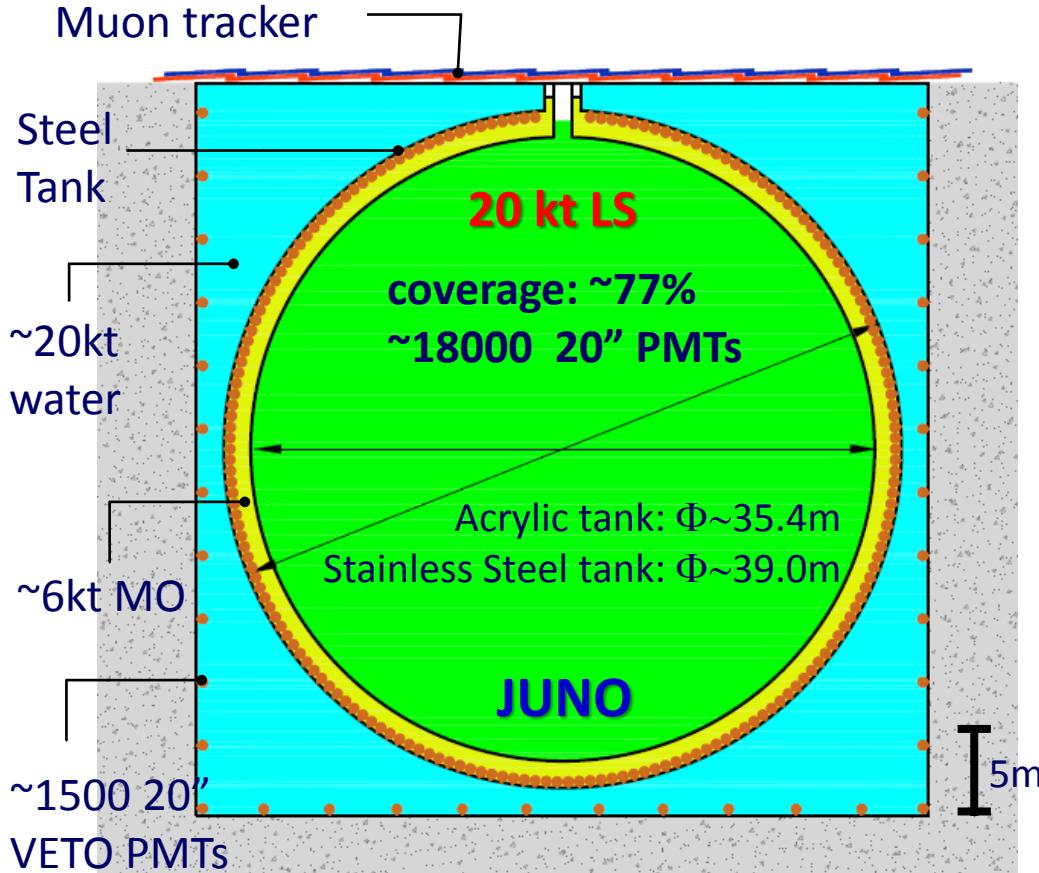
## Shen Zhen

# Hong Kong

**Huizhou  
NPP**

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

# High-precision, Giant LS detector



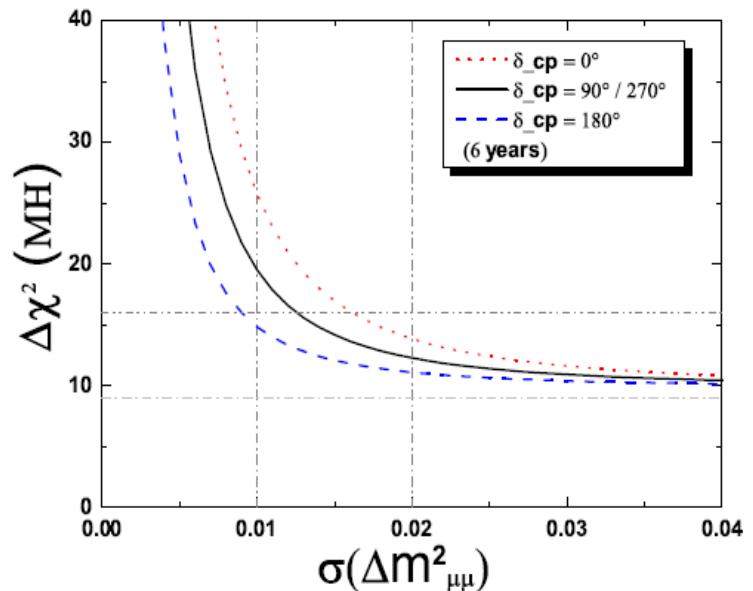
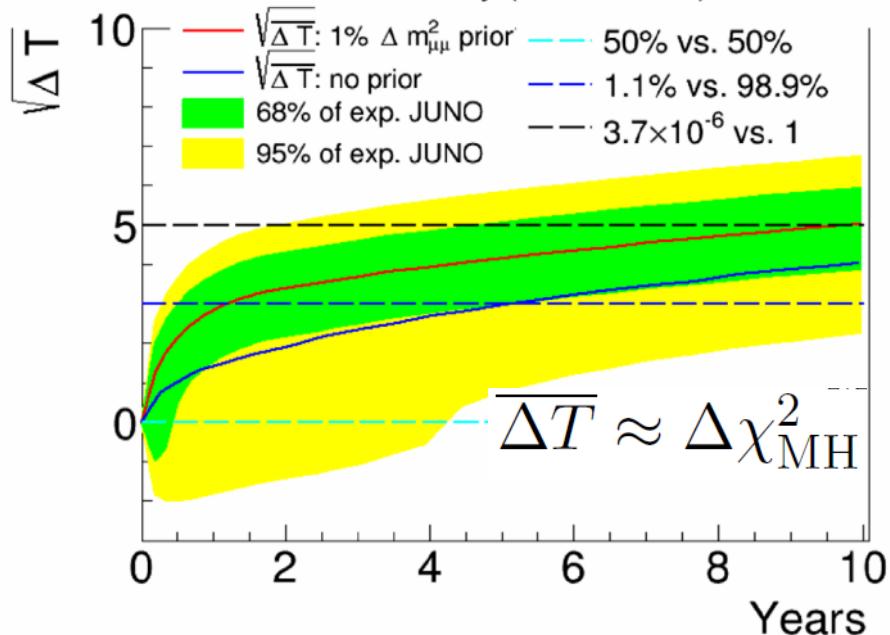
	KamLAND	BOREXINO	JUNO
LS mass	1 kt	0.5 kt	20 kt
Energy Resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV



# Sensitivity on MH

<i>PRD 88, 013008 (2013)</i>	Relative Meas.	Use absolute $\Delta m^2$
Statistics only	$4\sigma$	$5\sigma$
Realistic case	$3\sigma$	$4\sigma$

**JUNO MH  
sensitivity with  
6 years' data:**

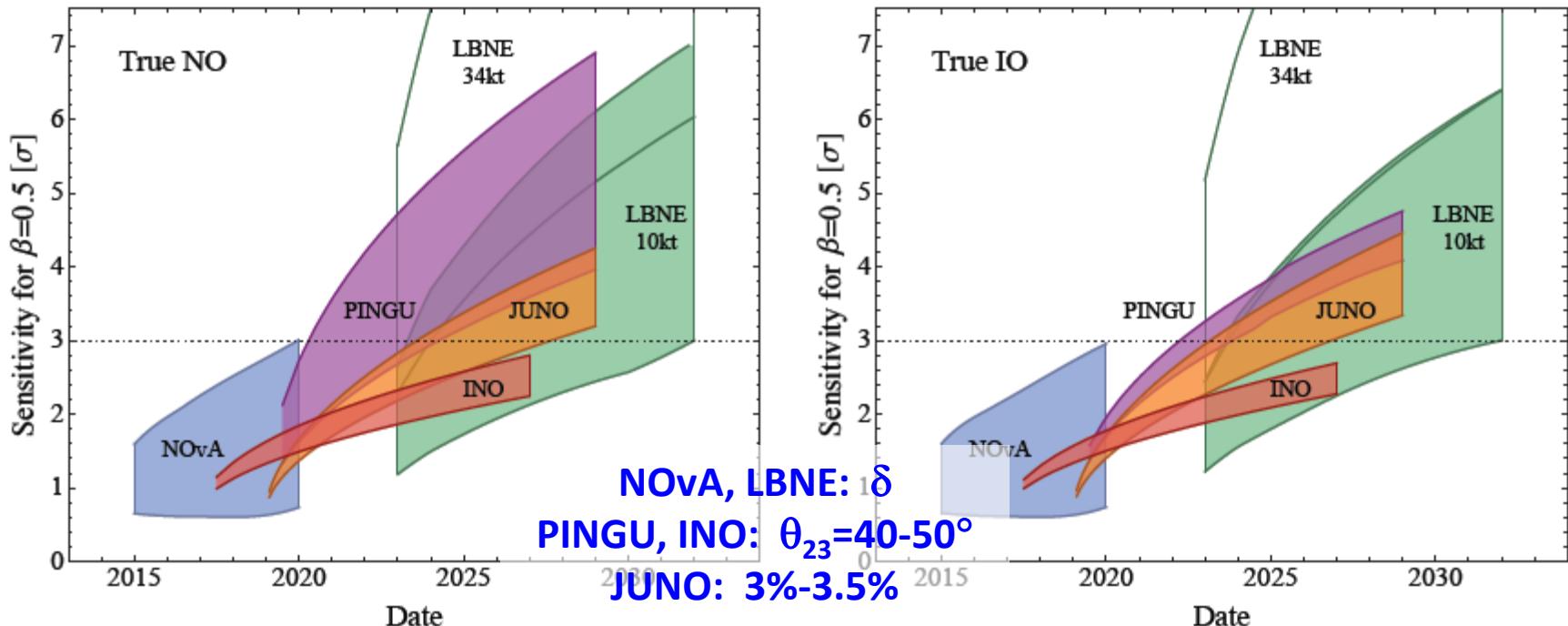


	Ideal	Core distr.	Shape	B/S (stat.)	B/S (shape)	$ \Delta m_{\mu\mu}^2 $
Size	52.5 km	Real	1%	4.5%	0.3%	1%
$\Delta \chi^2_{\text{MH}}$	+16	-4	-1	-0.5	-0.1	+8



# Other Exp/Proposals for MH

M. Blennow et al., JHEP 1403 (2014) 028



**JUNO: Competitive in schedule and Complementary in physics**

$\Delta m_{31}^2$  and  $\Delta m_{32}^2$   
Interference ( $\phi$ )

$\Delta m_{ee}^2$  and  $\Delta m_{\mu\mu}^2$   
difference

Matter Effect

Reactor



atmospheric

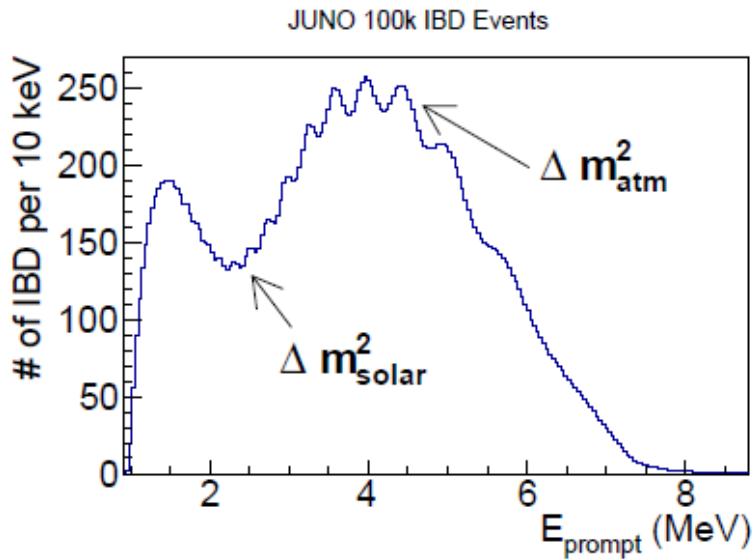


Accelerator

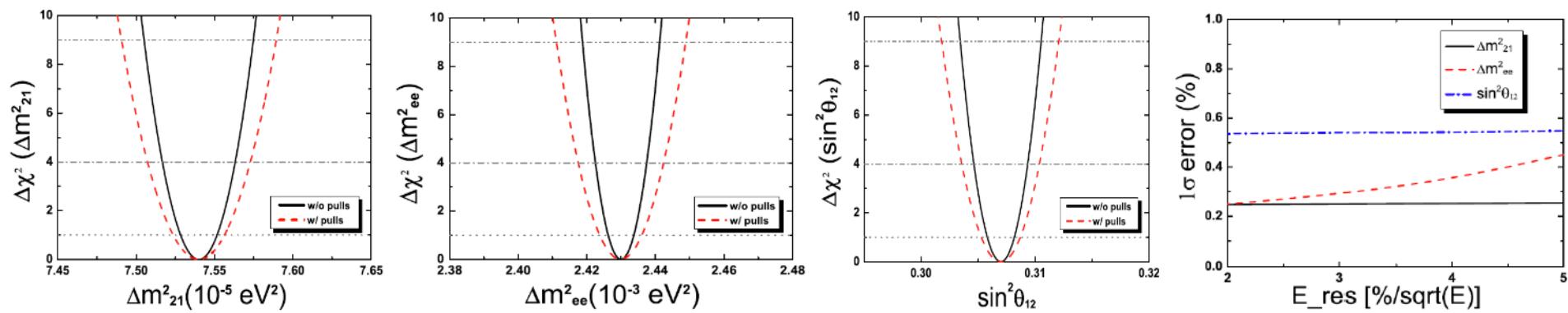


# Precision Measurements

Probing the unitarity of  $U_{\text{PMNS}}$  to  $\sim 1\%$   
more precise than CKM matrix elements !



Statistics	+BG	+1% b2b	+1% EScale	+1% EnonL
$\sin^2 \theta_{12}$	0.54%	0.67%		
$\Delta m^2_{21}$	0.24%	0.59%		
$\Delta m^2_{ee}$	0.27%	0.44%		



0.16% → 0.24%

0.16% → 0.27%

0.39% → 0.54%

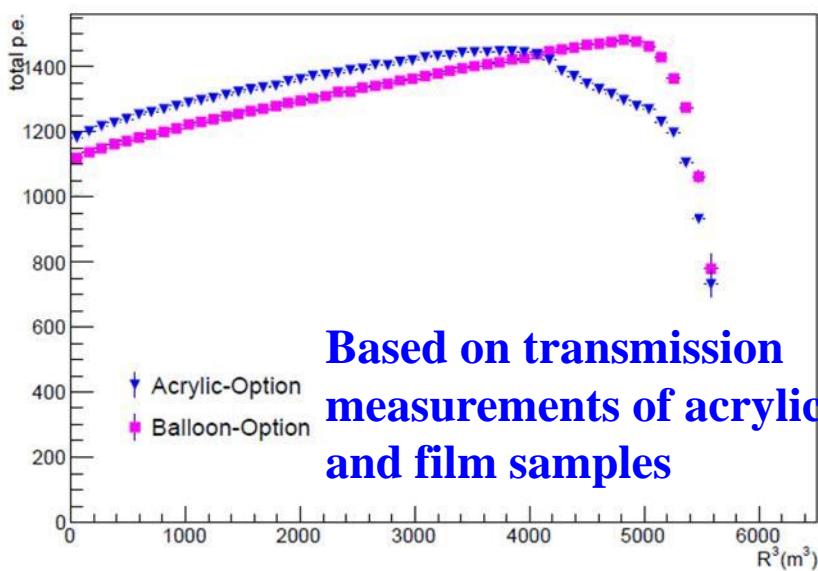
E resolution

Correlation among parameters



# Energy Resolution

- ◆ JUNO MC, based on DYB MC (p.e. tuned to data), except
  - ⇒ JUNO Geometry and 77% photocathode coverage
  - ⇒ High QE PMT: maxQE from 25% -> 35%
  - ⇒ LS attenuation length (1 m-tube measurement@430 nm)
    - from 15 m = absorption 30 m + Rayleigh scattering 30 m
    - to 20 m = absorption 60 m + Rayleigh scattering 30 m



## Photon Statistics

- ◆ 1200 p.e./MeV (center) → 2.89%/ $\sqrt{E}$
- ◆ 1400 p.e./MeV (edge) → 2.67%/ $\sqrt{E}$

## No significant contributions from (Toy MC)

- ◆ IBD neutron recoil, LS non-linearity, vertex smearing, vertex bias, non-uniformity
- ◆ PMT QE variation, QE non-uniformity, charge resolution, dark noise
- ◆ Electronic noise and non-linearity



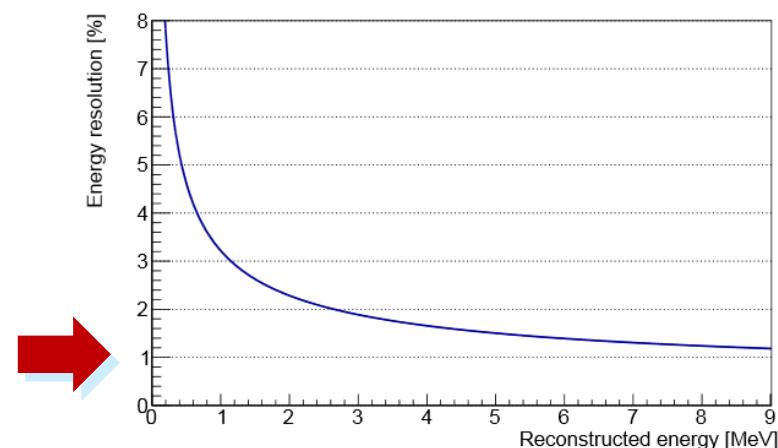
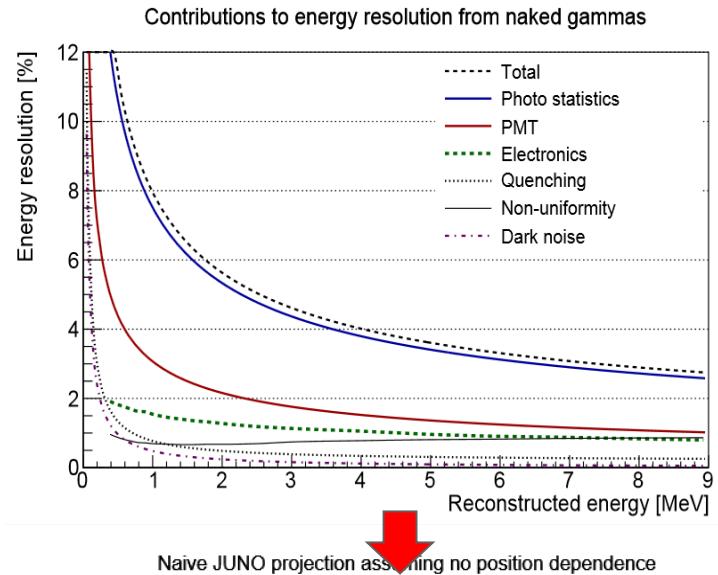
# Beyond Photo-statistics

$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

Impact to MH sensitivity

$$\approx \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{1.6 b}{\sqrt{E}}\right)^2 + \left(\frac{c}{1.6 \sqrt{E}}\right)^2}$$

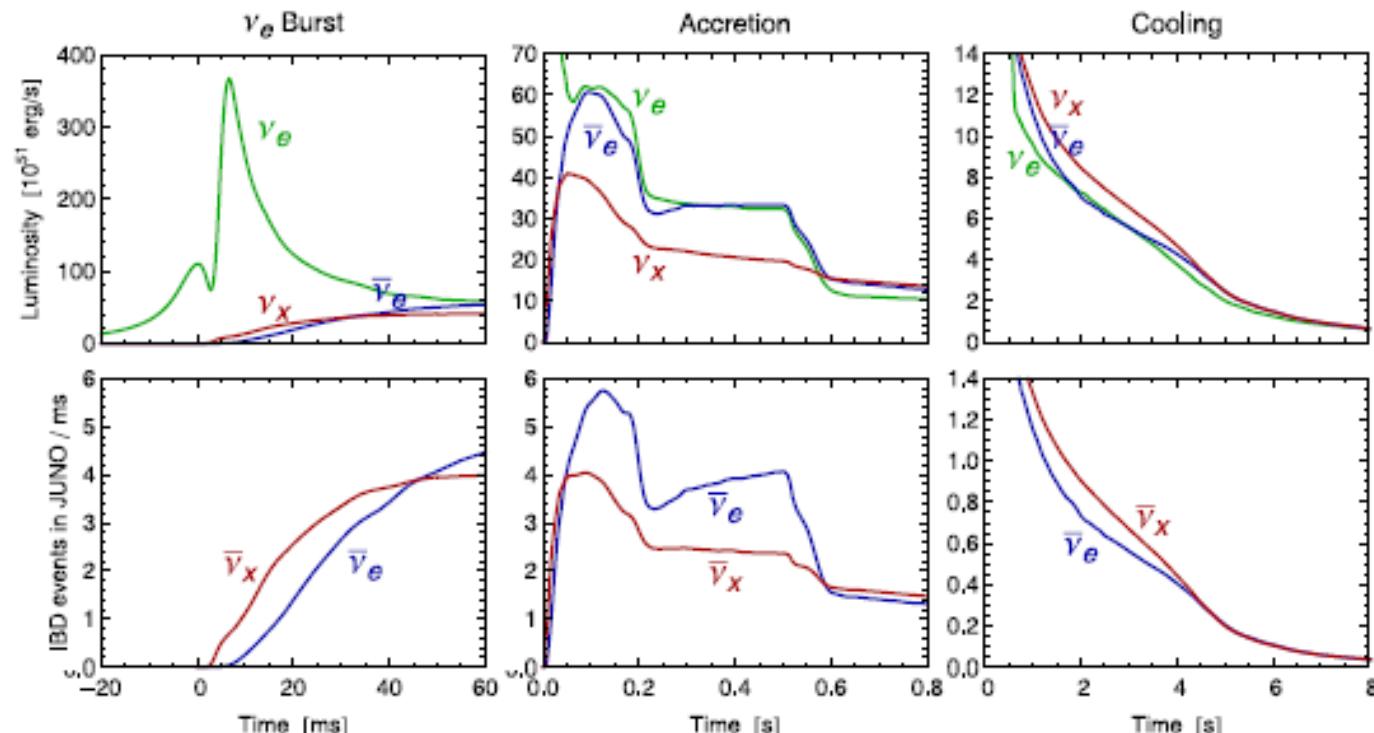
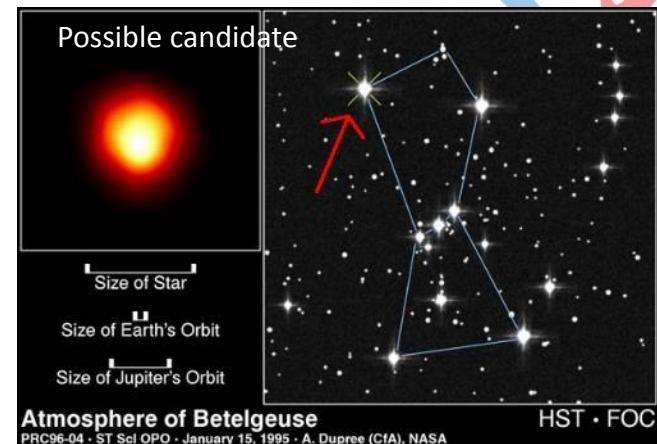
- ◆ Generic form of E resolution
  - ⇒ a: stochastic term
  - ⇒ b: constant term
  - ⇒ c: noise term
- ◆ Data validated Full MC (DYB & DC)
- ◆ Noise term dominated by PMT dark noise
- ◆ Constant term
  - ⇒ Residual non-uniformity
  - ⇒ Flaws in readout electronics
  - ⇒ Artifacts from resolution plotting
- ◆ No JUNO show stopper found in DYB model



# Supernova Neutrinos



- ◆ Less than 20 events observed so far
- ◆ Assumptions:
  - ⇒ Distance: 10 kpc (our Galaxy center)
  - ⇒ Energy:  $3 \times 10^{53}$  erg
  - ⇒  $L_\nu$  the same for all types





# Supernova Neutrinos

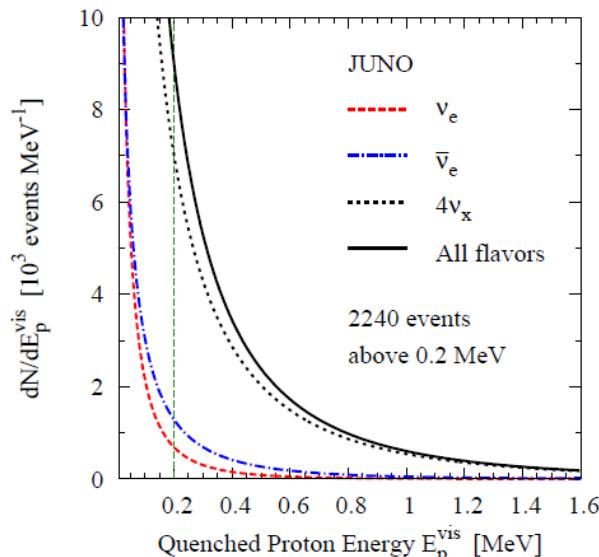


Estimated numbers of neutrino events in JUNO

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	$4.3 \times 10^3$	$5.0 \times 10^3$	$5.7 \times 10^3$
$\nu + p \rightarrow \nu + p$	NC	$6.0 \times 10^2$	$1.2 \times 10^3$	$2.0 \times 10^3$
$\nu + e \rightarrow \nu + e$	NC	$3.6 \times 10^2$	$3.6 \times 10^2$	$3.6 \times 10^2$
$\nu + {}^{12}\text{C} \rightarrow \nu + {}^{12}\text{C}^*$	NC	$1.7 \times 10^2$	$3.2 \times 10^2$	$5.2 \times 10^2$
$\nu_e + {}^{12}\text{C} \rightarrow e^- + {}^{12}\text{N}$	CC	$4.7 \times 10^1$	$9.4 \times 10^1$	$1.6 \times 10^2$
$\bar{\nu}_e + {}^{12}\text{C} \rightarrow e^+ + {}^{12}\text{B}$	CC	$6.0 \times 10^1$	$1.1 \times 10^2$	$1.6 \times 10^2$

LS detector vs. Water Cerenkov detectors: Neutral Current channels

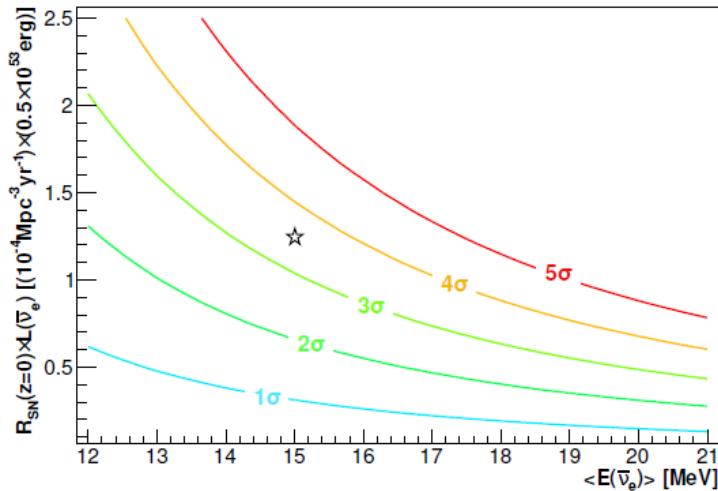
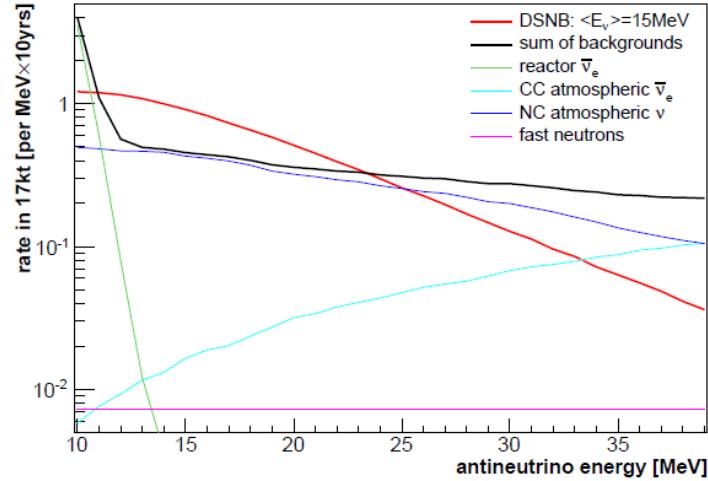
→ Measure energy spectra & fluxes of almost all types of neutrinos



- ◆  $\nu$  mass:  $< 0.83 \pm 0.24$  eV at 95% CL  
(arXiv:1412.7418)
- ◆ Locating the SN:  $\sim 9^\circ$
- ◆ Pre-SN  $\nu$  ( $> 1$  day)
- ◆ SN Nucleosynthesis via  $\nu_x$  spectra
- ◆ Collective  $\nu$  oscillation
- ◆ MH



# Diffuse Supernova Neutrino



- ◆ DSNB: Past core-collapse events
  - ⇒ Cosmic star-formation rate
  - ⇒ Core-collapse neutrino spectrum
  - ⇒ Rate of failed SNe

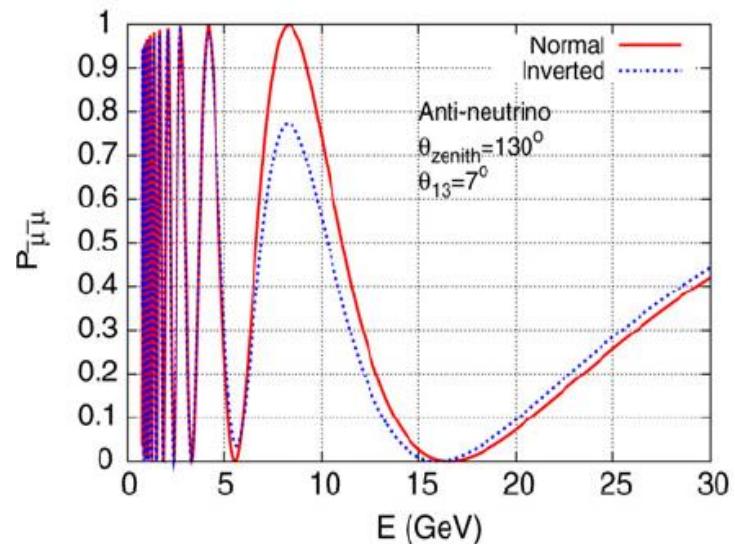
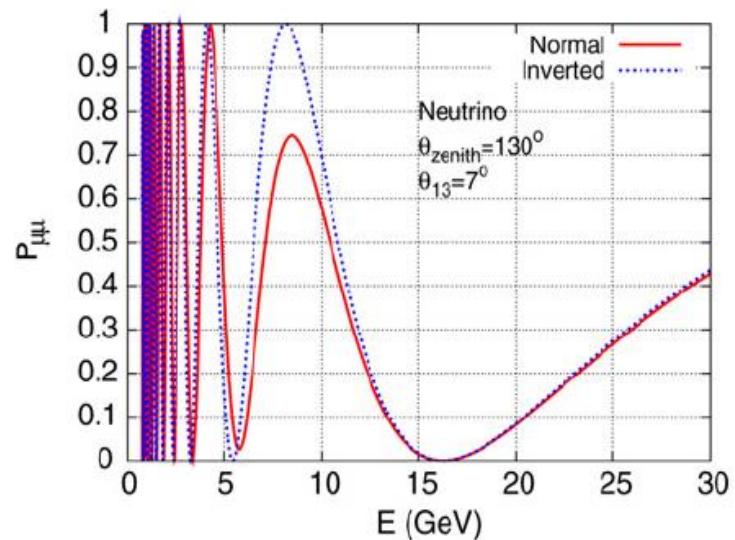
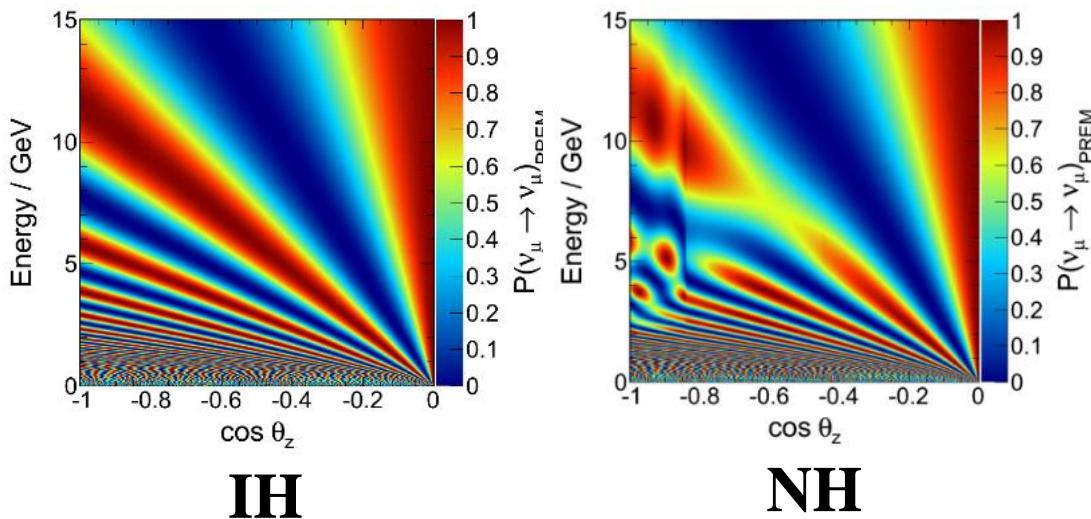
Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar{\nu}_e} \rangle = 12 \text{ MeV}$	12.2	$\varepsilon_{\bar{\nu}} = 50 \%$	6.1
	$\langle E_{\bar{\nu}_e} \rangle = 15 \text{ MeV}$	25.4		12.7
	$\langle E_{\bar{\nu}_e} \rangle = 18 \text{ MeV}$	42.4		21.2
	$\langle E_{\bar{\nu}_e} \rangle = 21 \text{ MeV}$	61.2		30.8
Background	reactor $\bar{\nu}_e$	1.6	$\varepsilon_{\bar{\nu}} = 50 \%$	0.8
	atm. CC	1.5	$\varepsilon_{\bar{\nu}} = 50 \%$	0.8
	atm. NC	716	$\varepsilon_{\text{NC}} = 1.1 \%$	7.5
	fast neutrons	12	$\varepsilon_{\text{FN}} = 1.3 \%$	0.15
		$\Sigma$		9.2

10 Years' sensitivity

Syst. uncertainty BG	5 %		20 %		
	$\langle E_{\bar{\nu}_e} \rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV		1.7 σ	1.9 σ	1.5 σ	1.7 σ
15 MeV		3.3 σ	3.5 σ	3.0 σ	3.2 σ
18 MeV		5.1 σ	5.4 σ	4.6 σ	4.7 σ
21 MeV		6.9 σ	7.3 σ	6.2 σ	6.4 σ

# Mass Hierarchy from Atmospheric

- ◆ Due to matter effect, oscillation probability of atmospheric muon neutrino when passing the Earth depends on mass hierarchy
- ◆ JUNO will have  $1-2\sigma$  sensitivity.
  - ⇒ Measure both lepton and hadron energy
  - ⇒ Good tracking and energy resolution





# Geo-neutrinos

## ◆ Geo-neutrinos

### ⇒ Current results

KamLAND:  $30 \pm 7$  TNU (*PRD 88 (2013) 033001*)

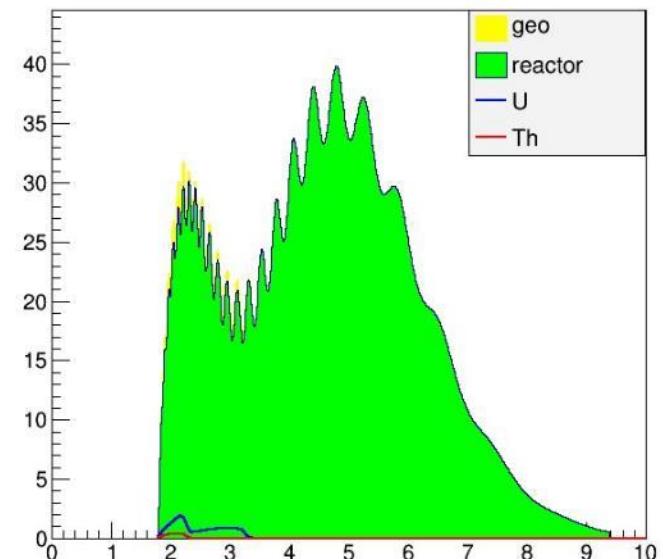
Borexino:  $38.8 \pm 12.2$  TNU (*PLB 722 (2013) 295*)

Statistics dominant

### ⇒ Desire to reach an error of 3 TNU

### ⇒ JUNO: 40 TNU, $\times 20$ statistics

- Huge reactor neutrino backgrounds
- Need accurate reactor spectra



Source	Events/year
Geoneutrinos	$408 \pm 60$
U chain	$311 \pm 55$
Th chain	$92 \pm 37$
Reactors	$16100 \pm 900$
Fast neutrons	$3.65 \pm 3.65$
$^9\text{Li} - ^8\text{He}$	$657 \pm 130$
$^{13}\text{C}(\alpha, n)^{16}\text{O}$	$18.2 \pm 9.1$
Accidental coincidences	$401 \pm 4$

## Combined shape fit of geo- $\nu$ and reactor- $\nu$

	Best fit	1 y	3 y	5 y	10 y
U+Th fix ratio	0.96	17%	10%	8%	6%
U (free)	1.03	32%	19%	15%	11%
Th (free)	0.80	66%	37%	30%	21%



# Solar and other Physics

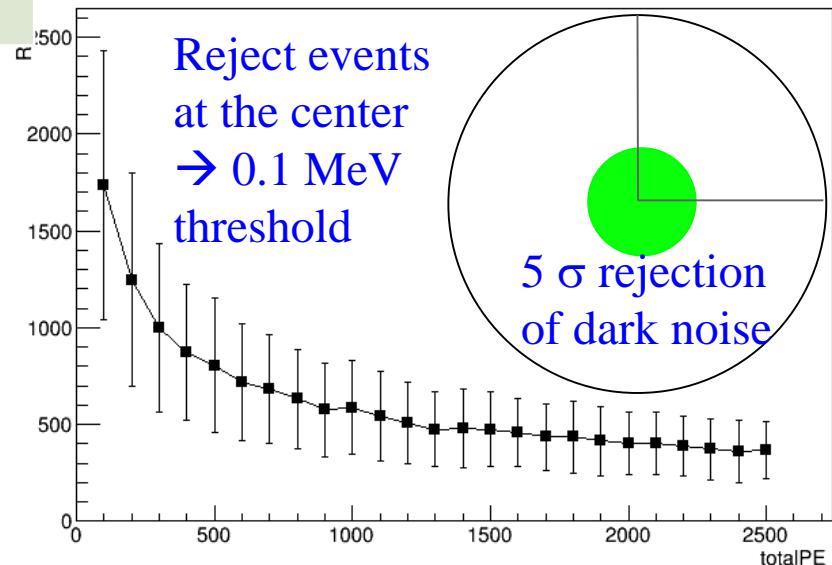
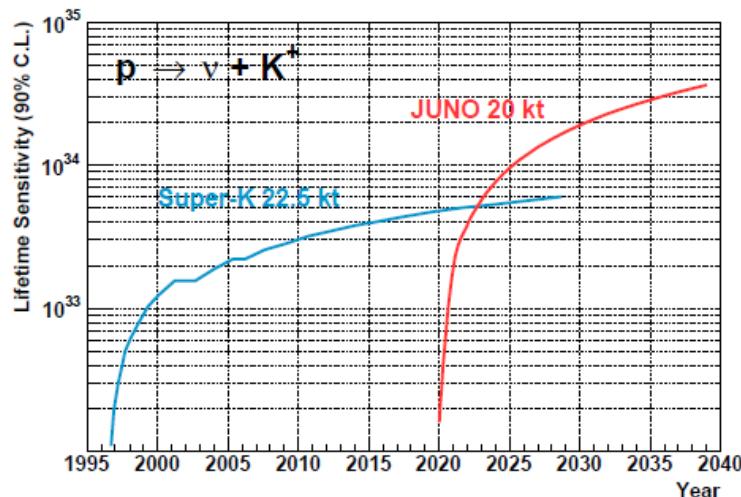
## ◆ Solar neutrino

- ⇒ Metallicity? Vacuum oscillation to MSW?
- ⇒  $^{7}\text{Be}$  and  $^{8}\text{B}$  at JUNO

Liquid Scintillator	U238	Th232	K40	Pb210 (Rn222)	Ref.
No Distillation	$10^{-15}$	$10^{-15}$	$10^{-16}$	$1.4 \cdot 10^{-22}$	Borexino CTF, KamLAND
After Distillation	$10^{-17}$	$10^{-17}$	$10^{-18}$	$10^{-24}$	

Source	Rate [cpd/1kt]
pp	1337
$^{7}\text{Be}$ [line 0.384 MeV]	19
$^{7}\text{Be}$ [line 0.862 MeV]	475
pep	28
$^{8}\text{B}$	4.5
$^{13}\text{N}$	25
$^{15}\text{O}$	28
$^{17}\text{F}$	0.7

## ◆ Proton Decay, sterile, dark matter, etc.



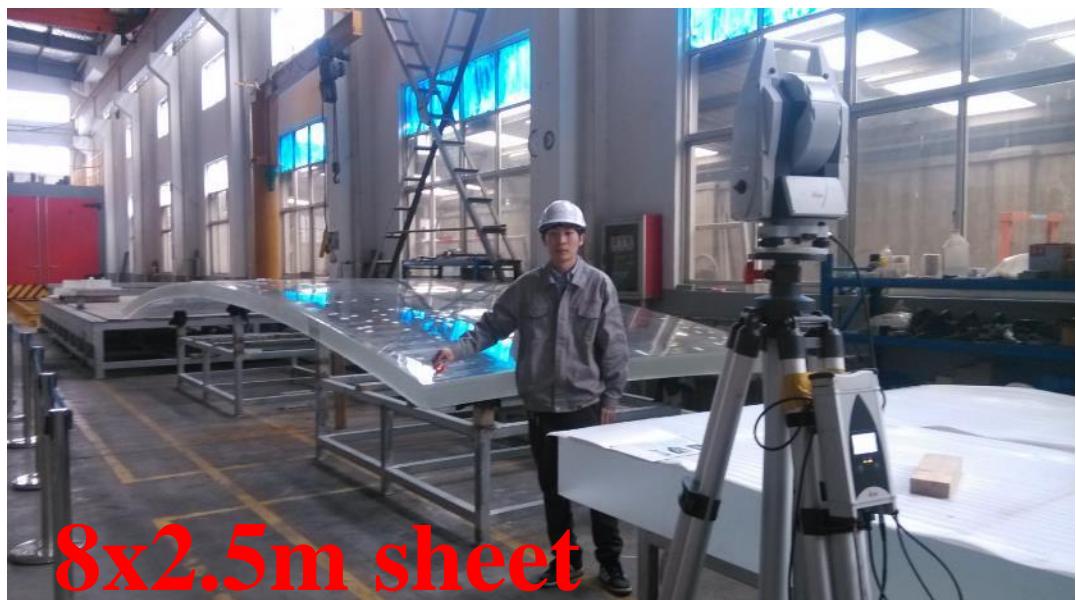
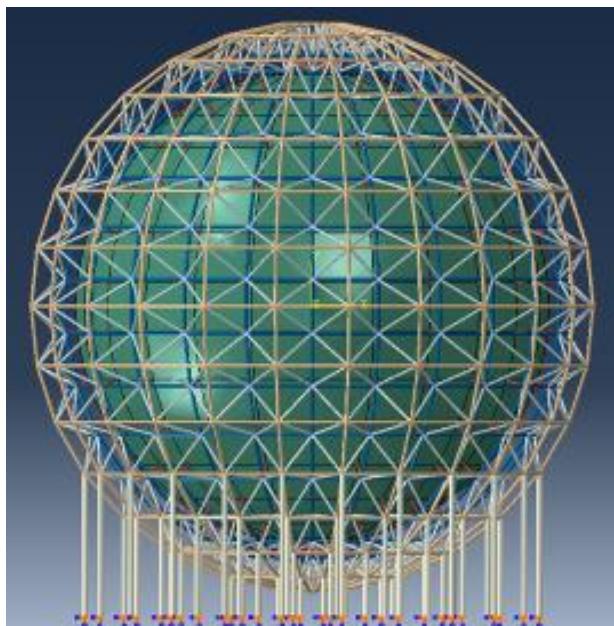
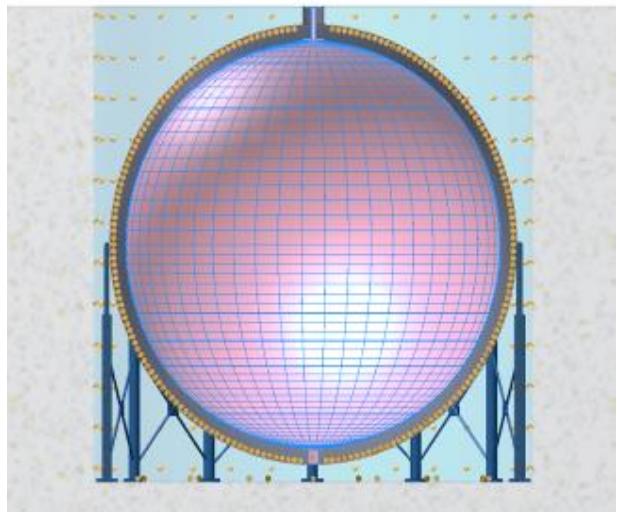


# JUNO Central Detector



## ◆ A huge detector in a water pool:

- ⇒ Default option: acrylic tank ( $D \sim 35\text{m}$ ) + SS truss
  - Sheet prototype and bonding test
- ⇒ Alternative option: SS tank ( $D \sim 39\text{m}$ ) + acrylic structure + balloon
  - 1/3 prototype underway



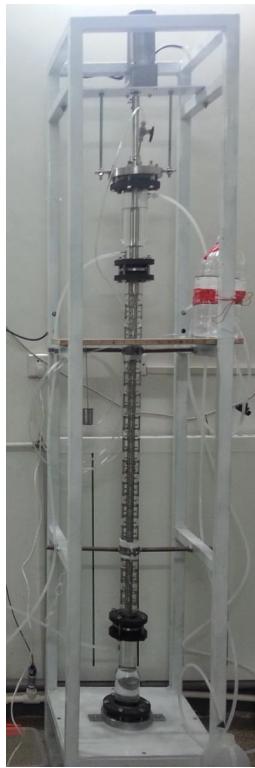
8x2.5m sheet



# Liquid Scintillator in JUNO



- ◆ Recipe
  - LAB+PPO+bisMSB (no Gd-loading)**
- ◆ Increase light yield
  - ⇒ Optimization of fluors concentration
- ◆ Increase transparency
  - ⇒ Good raw solvent LAB
    - Improve production processes
  - ⇒ Purification / Online handling
    - Distillation, Filtration, Water extraction,  
Nitrogen stripping
- ◆ Reduce radioactivity
  - ⇒ Less risk, since no Gd
  - ⇒ Intrinsic singles  
 $< 3 \text{ Hz}$  (above 0.7 MeV)  
if  ${}^{40}\text{K}/\text{U}/\text{Th} < 10^{-15} \text{ g/g}$  (TCF)



Linear Alky Benzene (LAB)	Atte. Length @ 430 nm
<b>RAW (specially made)</b>	<b>14.2 m</b>
<b>Vacuum distillation</b>	<b>19.5 m</b>
<b>SiO<sub>2</sub> coloum</b>	<b>18.6 m</b>
<b>Al<sub>2</sub>O<sub>3</sub> coloum</b>	<b>25 m</b>



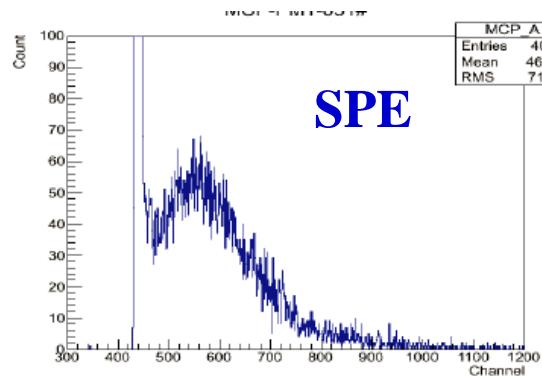
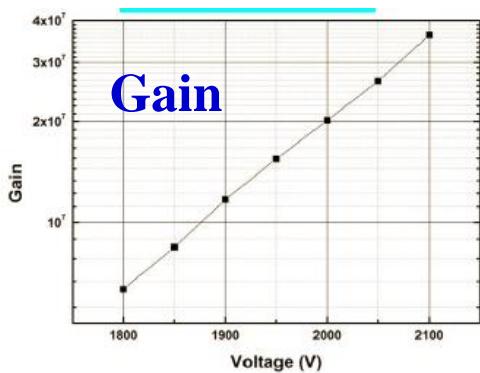
# High QE PMT Effort in JUNO



- ◆ High QE 20" PMTs under development:
  - ⇒ A new design using MCP: 4 $\pi$  collection
- ◆ MCP-PMT development:
  - ⇒ Technical issues mostly resolved
  - ⇒ Successful 8" prototypes
  - ⇒ Many 20" prototypes
- ◆ Alternative options:  
Hamamatsu or Photonics



20" and 8" MCP-PMTs



	R5912	R5912-100	MCP-PMT
QE@410nm	25%	35%	25%
Rise time	3 ns	3.4ns	5ns
Dark noise	1kHz	3.5kHz	2.2kHz
P/V of SPE	>2.5	>2.5	~2
TTS	5.5ns	1.5 ns	3.5 ns

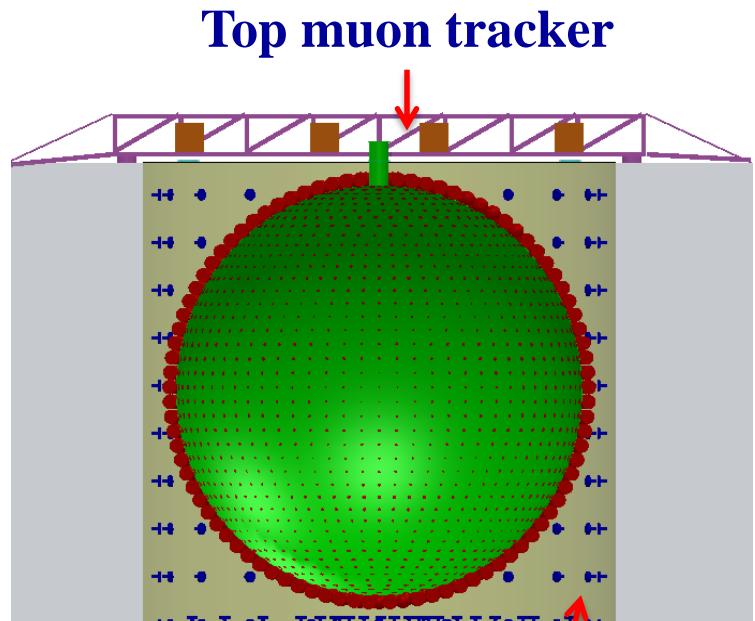


# Veto Detectors

- ◆ Cosmic muon flux
  - ⇒ Overburden : ~700 m
  - ⇒ Muon rate : **0.0031 Hz/m<sup>2</sup>**
  - ⇒ Average energy : 214 GeV
- ◆ Water Cherenkov Detector
  - ⇒ At least 2 m water shielding
  - ⇒ ~1500 20"PMTs
  - ⇒ 20~30 kton pure water
  - ⇒ Similar technology as Daya Bay  
**(99.8% efficiency)**
- ◆ Top muon tracker
  - ⇒ Muon track for cosmogenic bkg rejection
  - ⇒ Decommissioned OPERA plastic scintillator

## Muon multiplicity at JUNO

Multiplicity	1	2	3	4	5	6
Fraction	89.6%	7.7%	1.8%	0.6%	0.3%	0.07%



**Top muon tracker**  
**Water Cherenkov  
Detector**



# Project Plan and Progresses



First get-together meeting

Funding(2013-2014) review approved



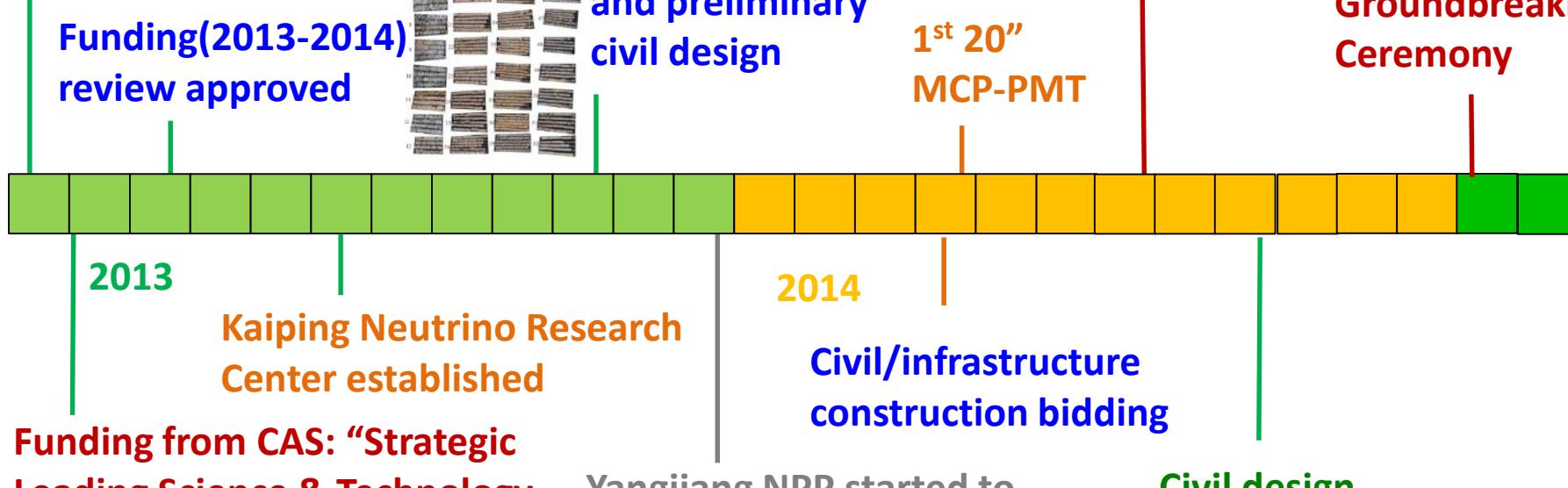
Geological survey and preliminary civil design



1<sup>st</sup> 20"  
MCP-PMT

Collaboration formed

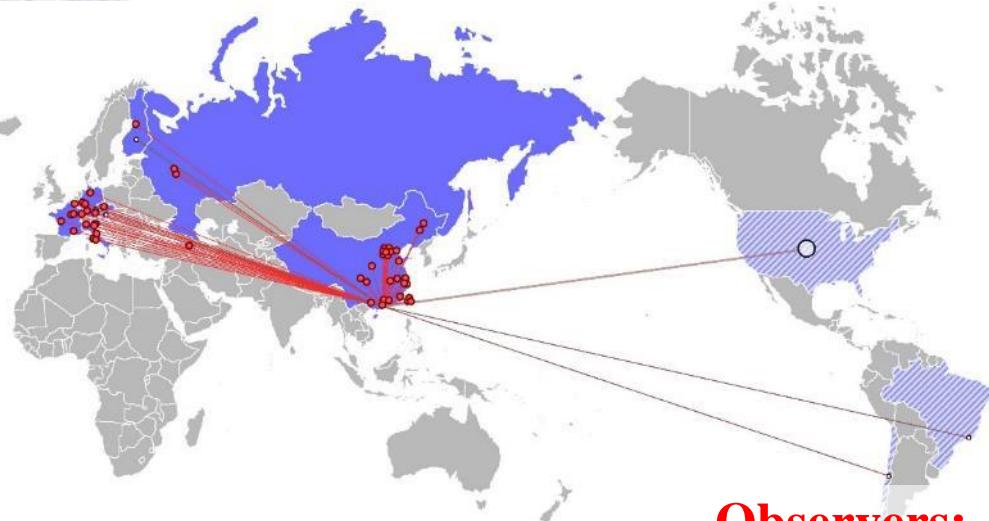
Groundbreaking Ceremony



- ◆ Civil construction : 2015-2017
- ◆ Detector component production : 2016-2017
- ◆ PMT production : 2016-2019
- ◆ Detector assembly & installation : 2018-2019
- ◆ Filling & data taking : 2020



# JUNO Collaboration



## Europe (23)

APC Paris  
Charles U  
CPPM Marseille  
FZ Julich  
INFN-Frascati  
INFN-Ferrara  
INFN-Milano  
INFN-Padova  
INFN-Perugia  
INFN-Roma 3  
IPHC Strasbourg

INR Moscow  
JINR  
LLR Paris  
RWTH Aachen  
Subatech Nantes  
TUM  
U.Hamburg  
ULB  
U Mainz  
U Oulu  
U Tuebingen  
YPI Armenia

**Observers:**  
US institutions  
HEPHY Vienna  
PUC Brazil  
PCUC Chile  
MPP Munich  
Jyvaskyla U.

## Asia (28)

BNU  
CAGS  
CQ U  
CIAE  
DGUT  
ECUST  
Guangxi U  
HIT  
IHEP  
Jilin U  
Nanjing U  
Nankai U  
Natl. CT U  
Natl. Taiwan U  
Natl. United U  
NCEPU  
Pekin U  
Shandong U  
Shanghai JTU  
Sichuan U  
SYSU  
Tsinghua  
UCAS  
USTC  
Wuhan U  
Wuyi U  
Xiamen U  
Xi'an JTU





# 江门中微子实验建设启动会

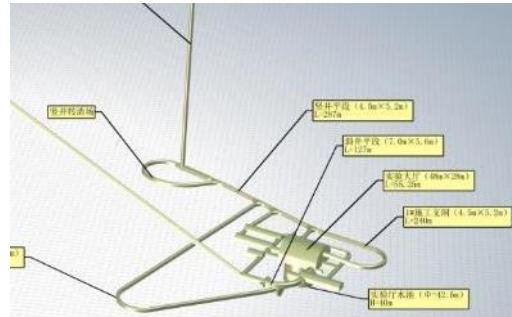
Jiangmen Underground Neutrino Observatory  
Construction Start-up Meeting



广东省·开平市·金鸡镇

2015-10-

Jan. 10, 2015

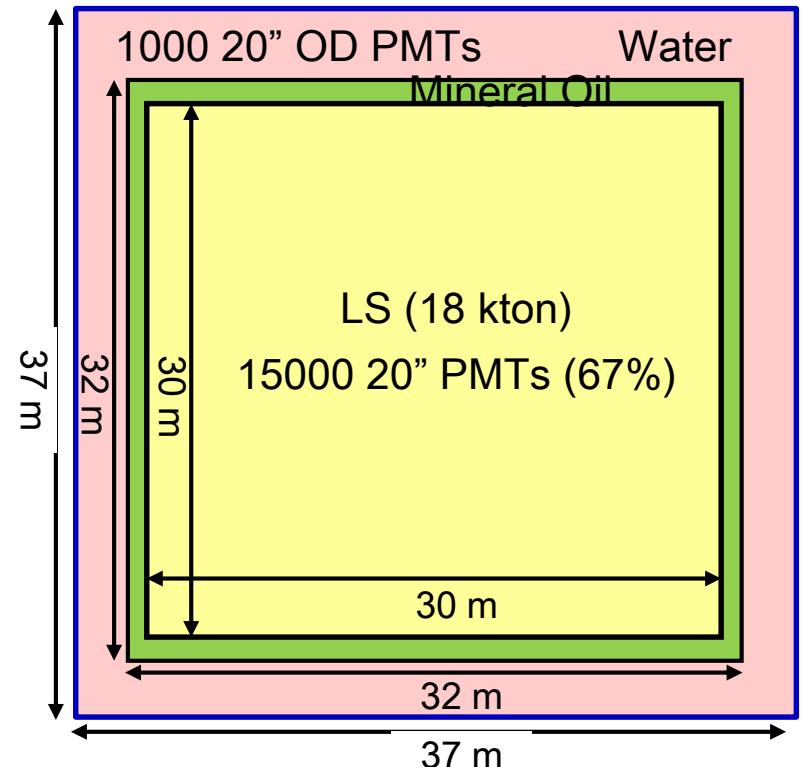


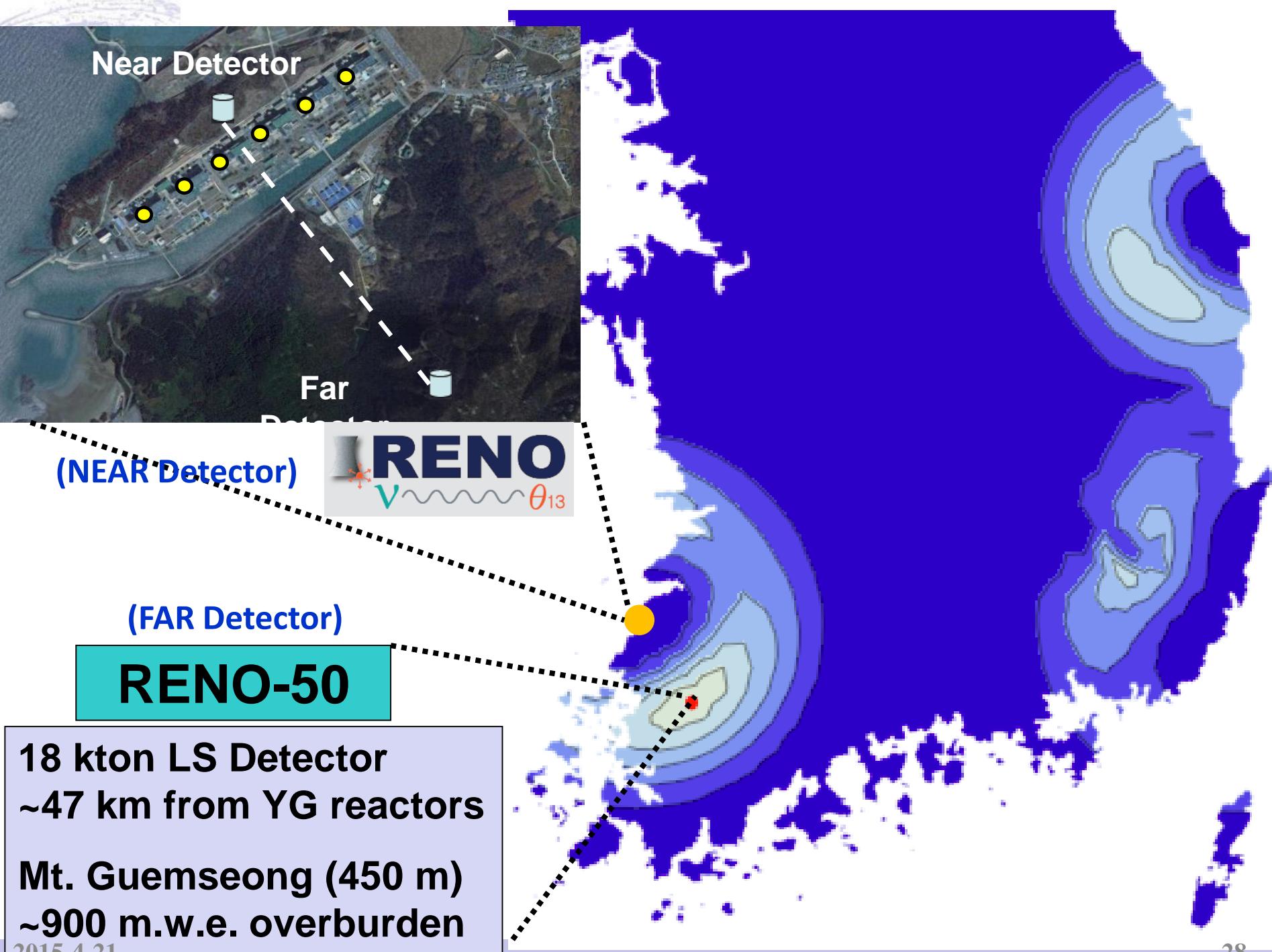
600 m vertical shaft  
1300-m long tunnel(40% slope)  
50-m diameter, 80-m high cavern



# RENO-50

- ◆ An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20" PMTs, at 50 km away from the Hanbit (Yonggwang) nuclear power plant
- ◆ Goals :
  - ⇒ Precision meas. of  $\theta_{12}$  and  $\Delta m^2_{21}$
  - ⇒ Determination of mass hierarchy
  - ⇒ Study neutrinos from reactors, (the Sun), the Earth, Supernova, and any possible stellar objects
- ◆ Budget : \$ 100M for 6 year(Civil engineering: \$ 15M, Detector: \$ 85M)
- ◆ Schedule
  - ⇒ 2014-2019: Facility and detector construction
  - ⇒ 2020~ Operation





# Additional Physics with RENO-50

- **Neutrino burst from a Supernova in our Galaxy**

- ~5,600 events (@8 kpc) (\* NC tag from 15 MeV deexcitation  $\gamma$ )
  - A long-term neutrino telescope

- **Geo-neutrinos : ~ 1,000 geo-neutrinos for 5 years**

- Study the heat generation mechanism inside the Earth

- **Solar neutrinos : with ultra low radioactivity**

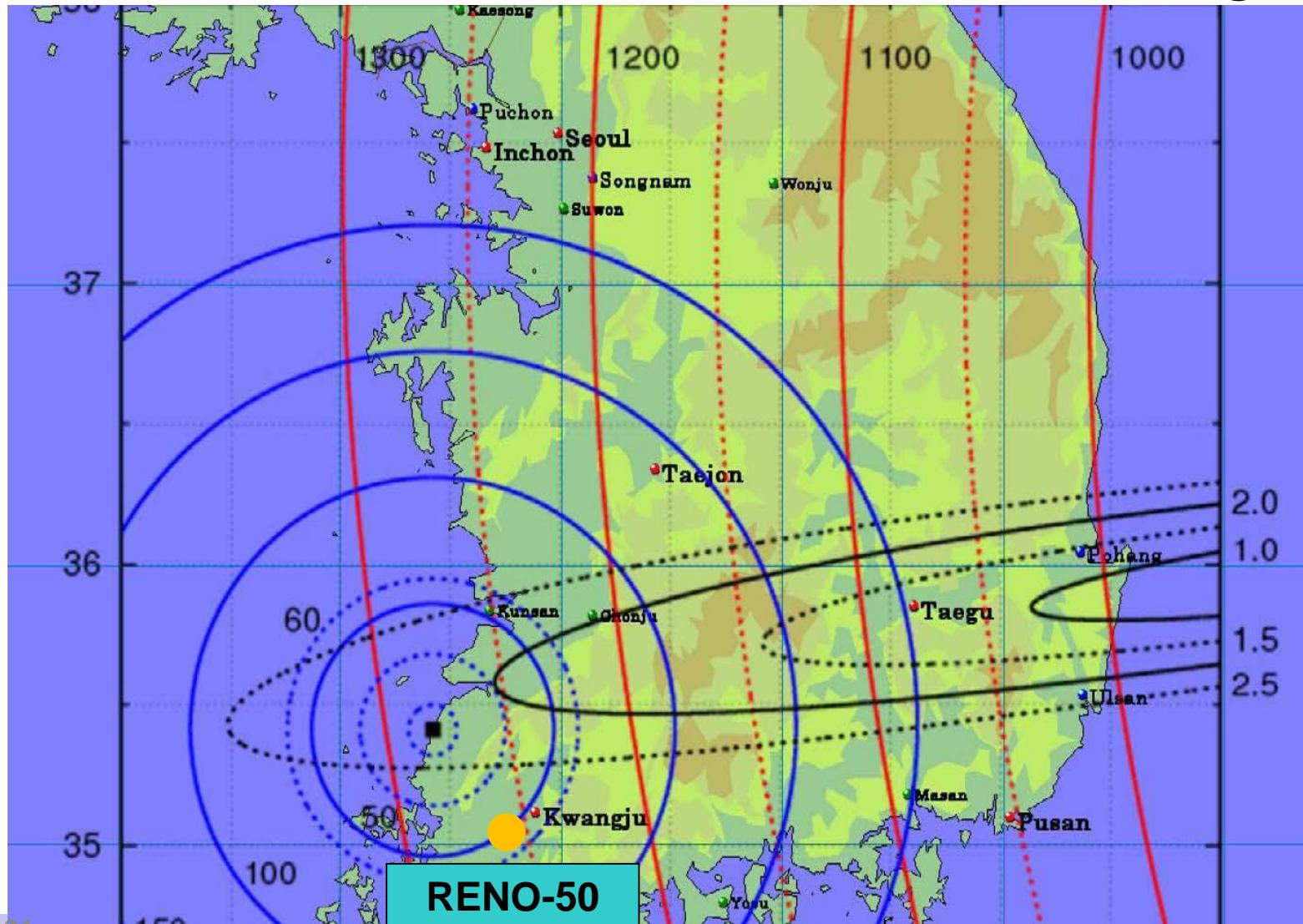
- MSW effect on neutrino oscillation
  - Probe the center of the Sun and test the solar models

- **Detection of J-PARC beam : ~200 events/year**

- **Neutrinoless double beta decay search : possible modification like KamLAND-Zen**

# J-PARC neutrino beam

Dr. Okamura & Prof. Hagiwara



RENO-50



# Summary

- ◆ 60-km baseline reactor experiment has unique role in determination of mass hierarchy and precision measurement of mixing parameters. Complementary to accelerator and Atmospheric exps.
- ◆ Very rich physics possibilities beyond reactor exp.
- ◆ JUNO was approved in Feb. 2013 w/ ~300 M\$ budget.
  - ⇒ Groundbreaking on Jan. 10, 2015. Civil construction will be completed in 3 years. Detector R&D progress well. Physics book and CDR in months.
  - ⇒ International collaboration formed.
- ◆ RENO-50 got 2M\$ R&D grant for 3 years (from Samsung)
  - ⇒ Liquid scintillator purification.
  - ⇒ High QE PMT performance to reach 3%.
- ◆ JUNO and RENO-50 aim at data taking in 2020.

# Thanks!