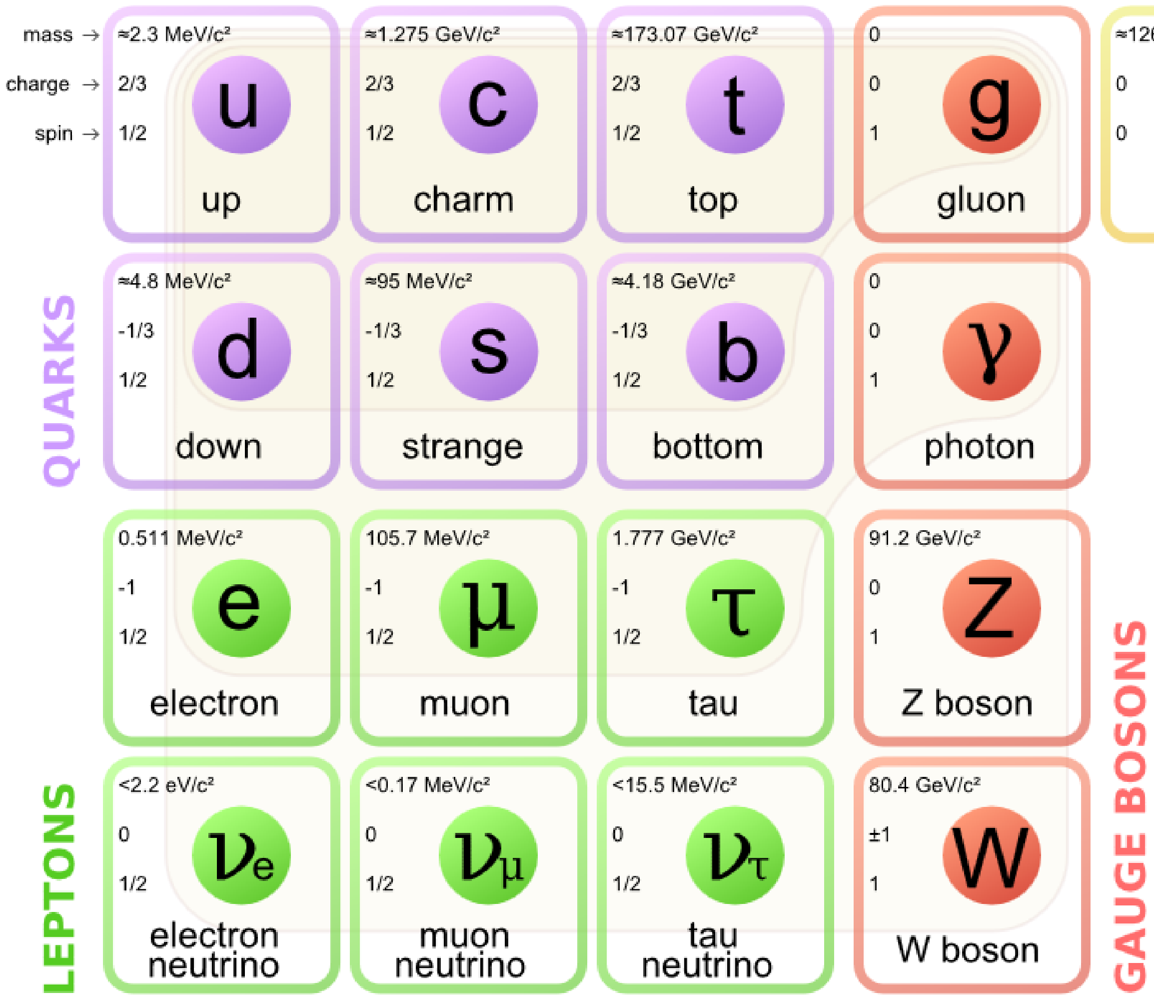
Overview of the JUNO experiment

Liangjian Wen

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Continental margin in South China workshop, Jul 21-23, 2017

Neutrino as fundamental particles



Standard Model of Elementary Particles:

a) Three generations of quarks and leptons

b) Gauge bosons as force carriers:

strong interaction (8 gluons)

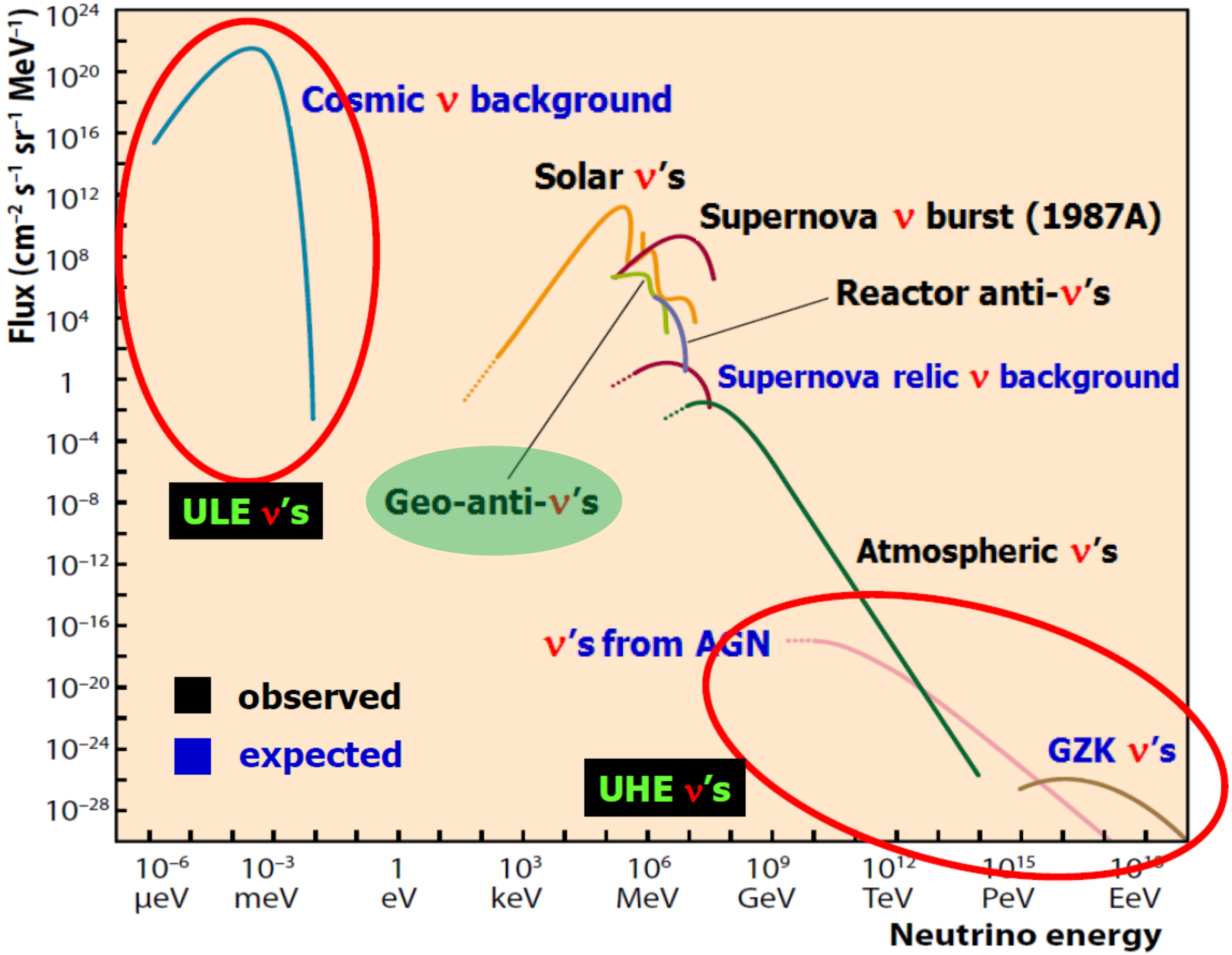
Weak interaction (W & Z)

Electromagnetic interaction (γ)

Gravitation (Graviton?)

Massive neutrinos are already the Physics beyond the Standard Model

Neutrinos as comic messengers



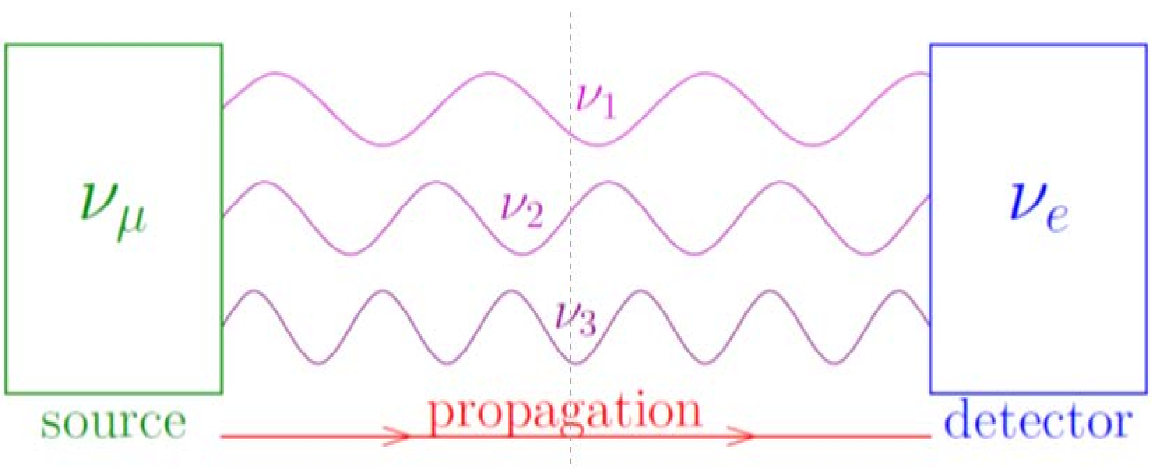
Neutrino Oscillation Theory

Two-flavor mixing $\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$

Pontecorvo, 1957; Maki, Nakagawa, Sakata, 1962

PMNS matrix describes the neutrino mixing

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



$$\sum_{k>j} \mathrm{Re}\left[U_{ek} U^*_{\mu k} U^*_{ej} U_{\mu j}\right] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)$$

Neutrino Oscillations: quantum phenomena of massive neutrinos at the macroscopic distances

Future Neutrino Puzzles

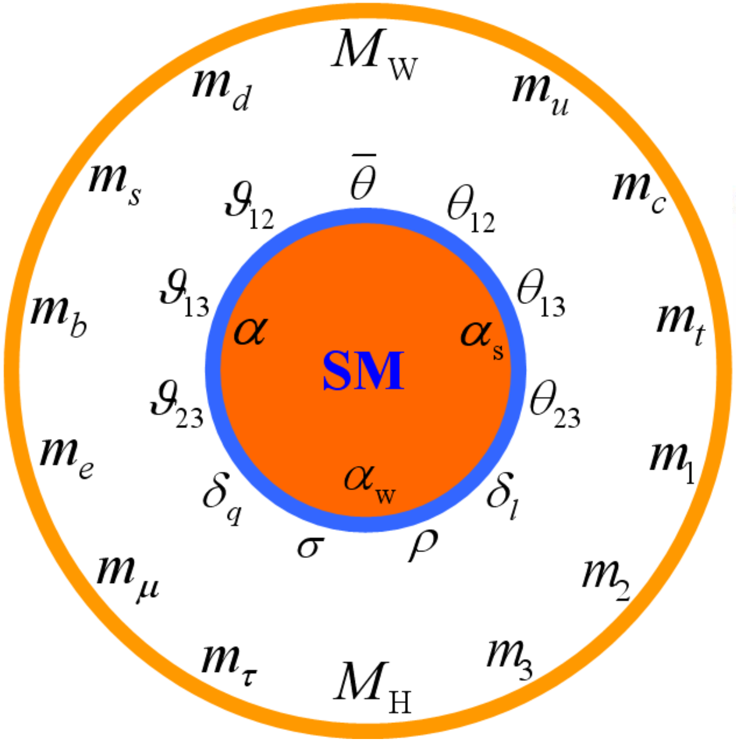
$\Delta m^2_{31} > 0$?

δ_{CP} ?

$\nu = \bar{\nu}$?

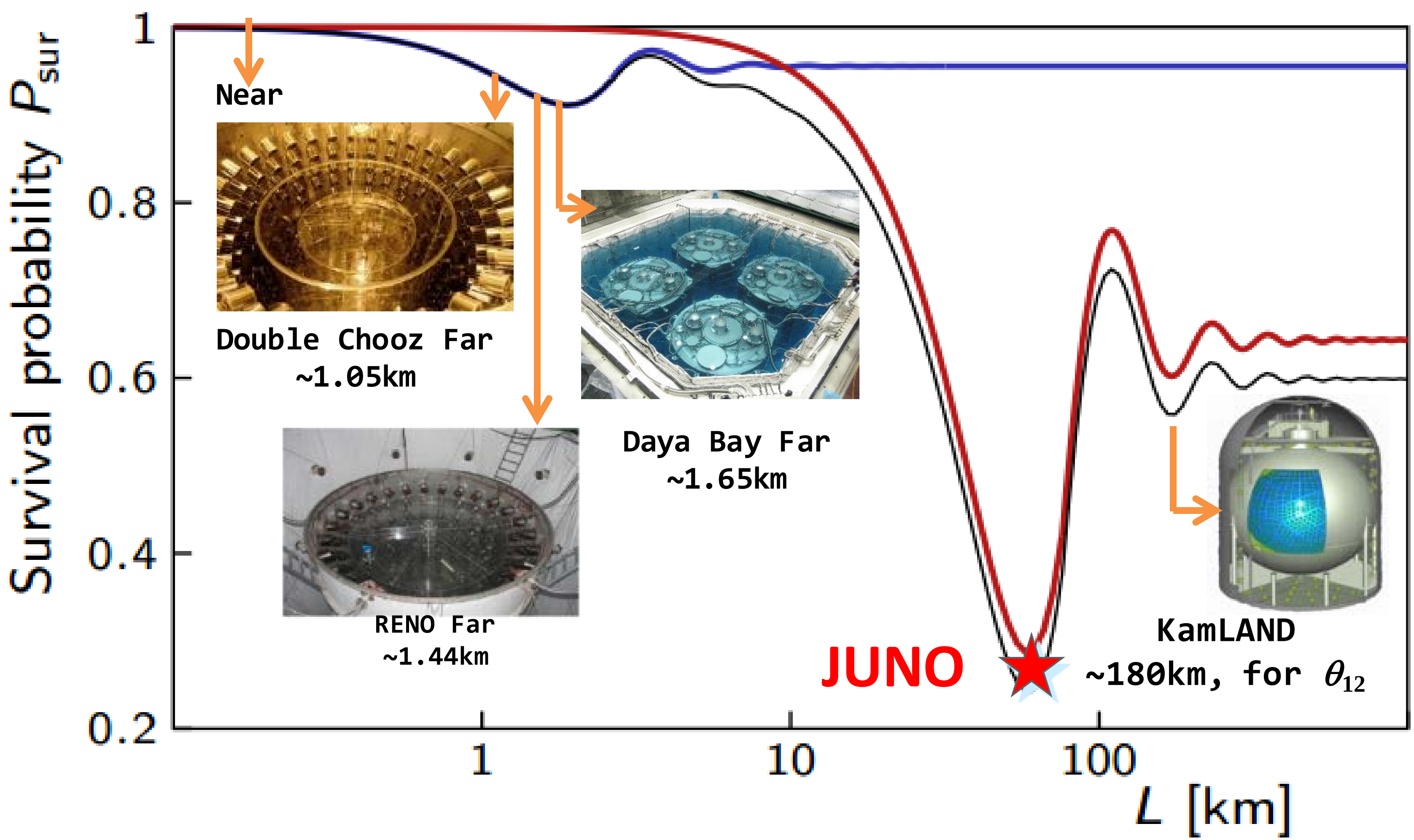
$U_{PMNS} U^{+}_{PMNS} = I$?

...

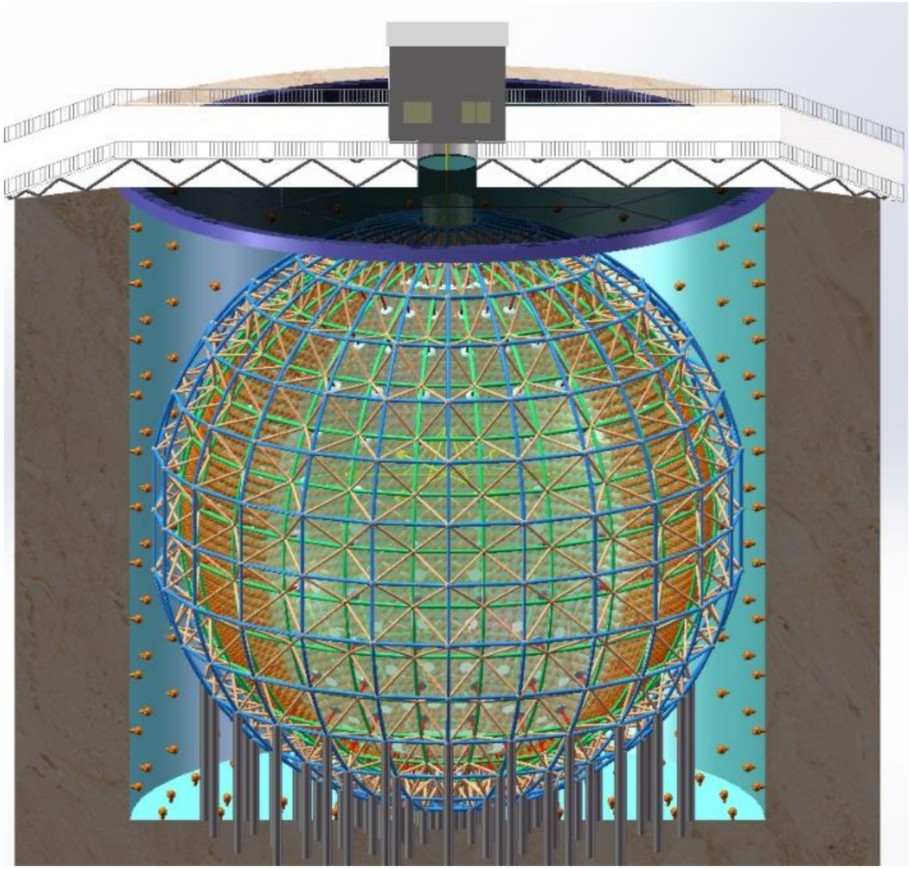


Fritzsch-Xing Plot

Reactor Neutrino Oscillation



Jiangmen Underground Neutrino Observatory



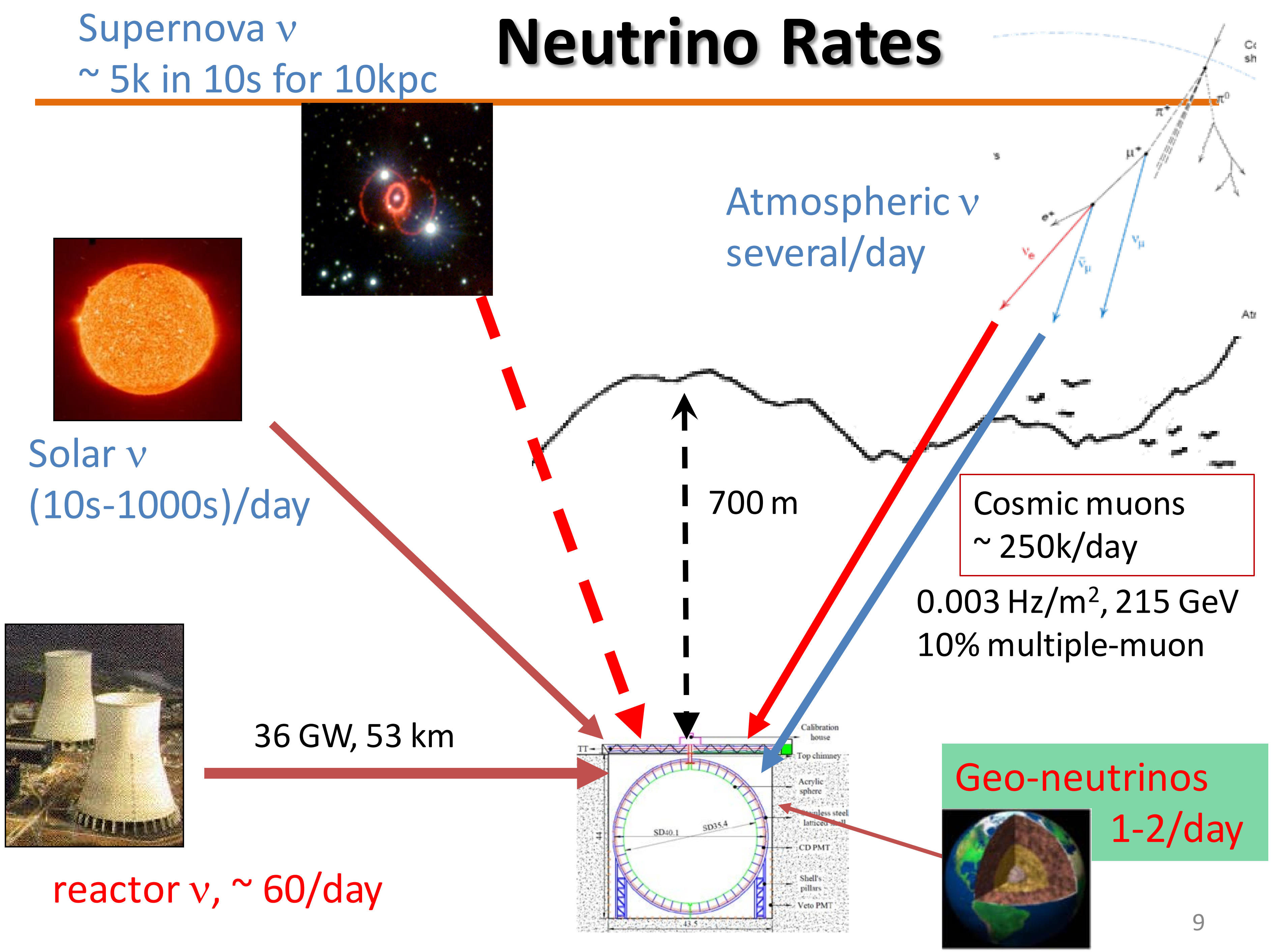
JUNO has been approved in Feb. 2013.
~ 300 M$ by China

- 20 kton LS detector
- 3%/sqrt(E) energy resolution
- 700 m underground
- Rich physics possibilities
  - Reactor neutrino for Mass hierarchy
  - Precision measurement of oscillation parameters
  - Supernovae neutrino
  - Geoneutrino
  - Solar neutrino
  - Atmospheric neutrino
  - Exotic searches including proton decay, dark matter

Neutrino Physics with JUNO, J. Phys. G 43, 030401 (2016)

The JUNO Experimental Site

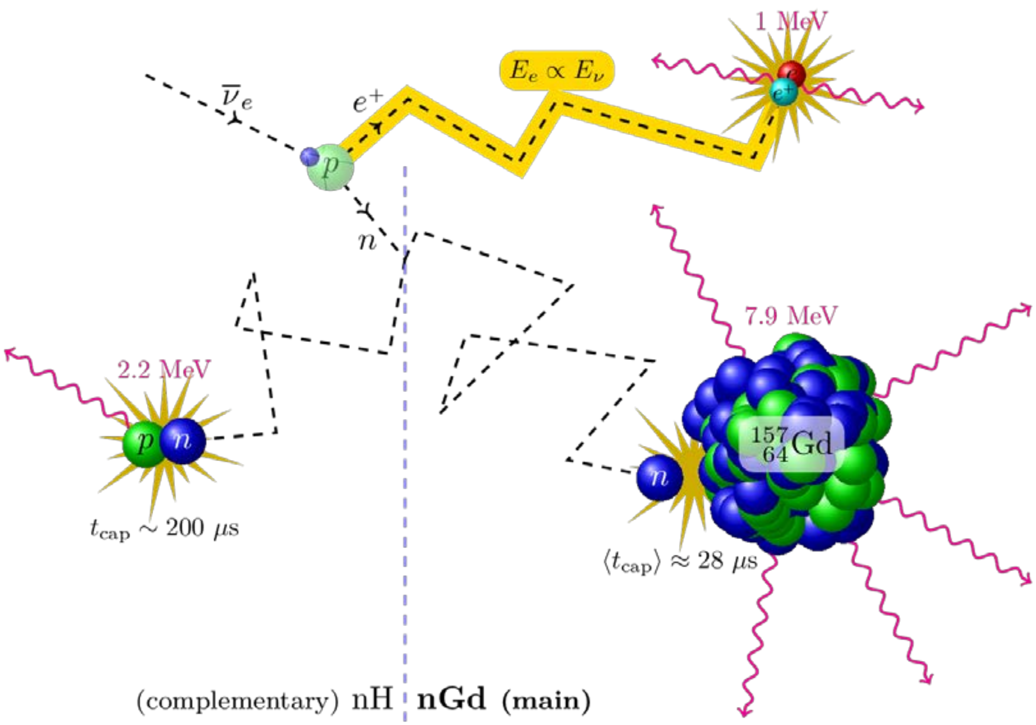
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

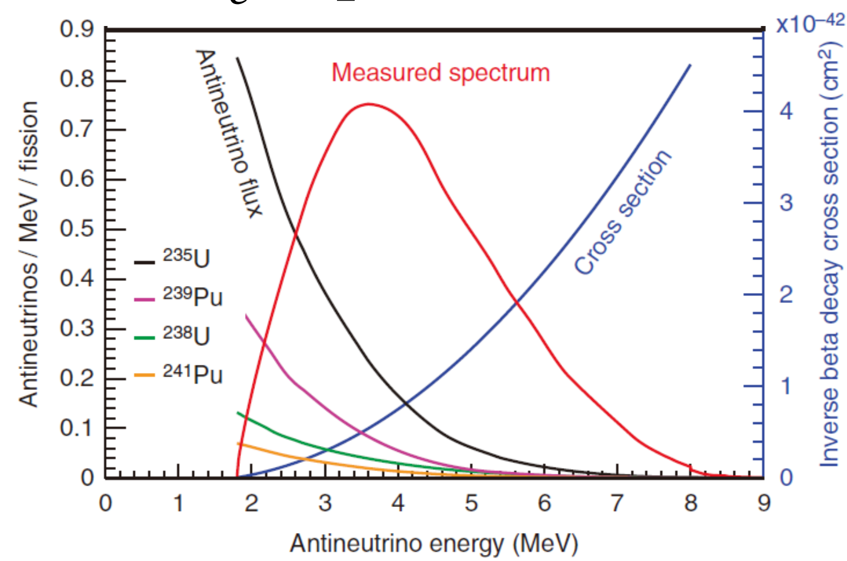

Neutrino Rates
Supernova ν
~ 5k in 10s for 10kpc
Atmospheric ν
several/day
Solar ν
(10s-1000s)/day
700 m
Cosmic muons
~ 250k/day
0.003 Hz/m², 215 GeV
10% multiple-muon
36 GW, 53 km
Calibration house
Top chimney
Acrylic sphere
CD PMT
Shell's pillars
Veto PMT
SD40.1
SD35.4
43.5
Geo-neutrinos
1-2/day
reactor ν, ~ 60/day

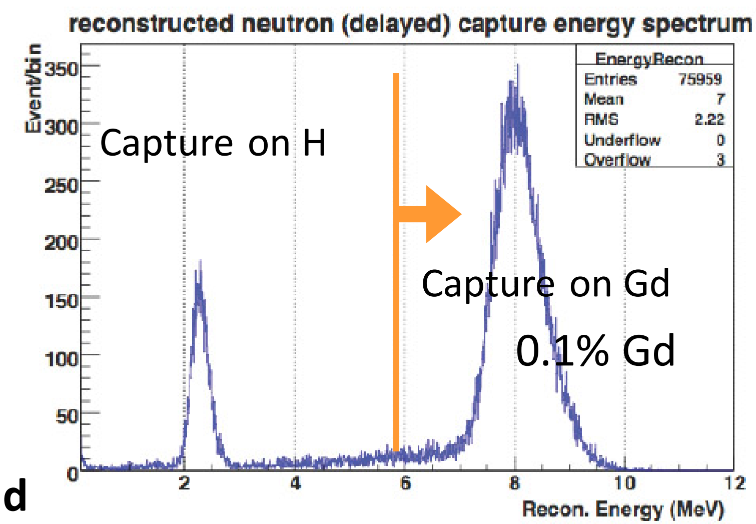
Reactor $\bar{\nu}$ Detection

- Inverse-β reaction (IBD)
- Liquid scintillator technology

$$\overline{\nu}_e + p \rightarrow e^+ + n$$



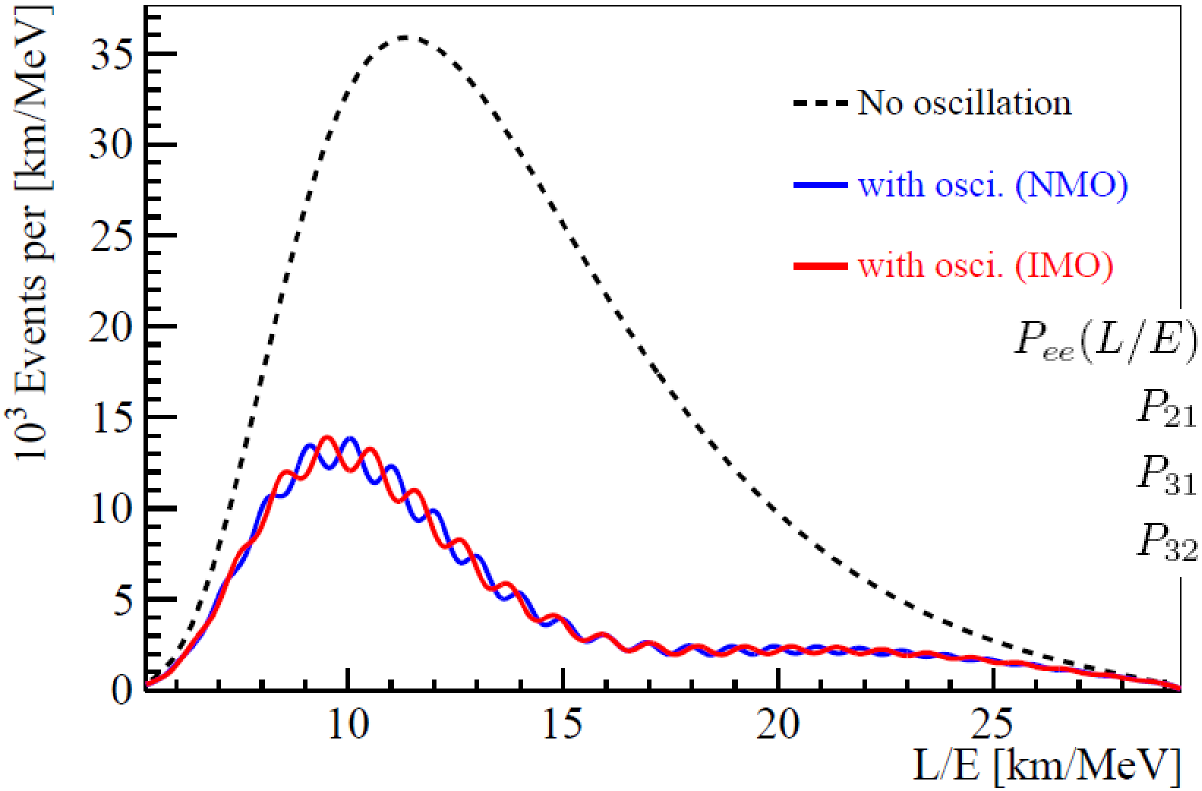




$$E_{\overline{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

10-40 keV (T_n) ***1.8 MeV:*** **Threshold**

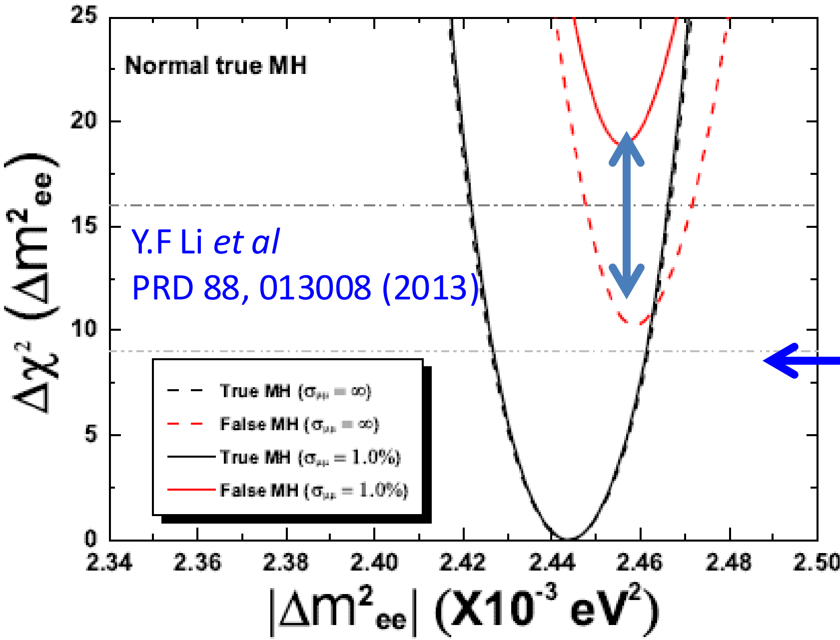
Principle to Determine NMO



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

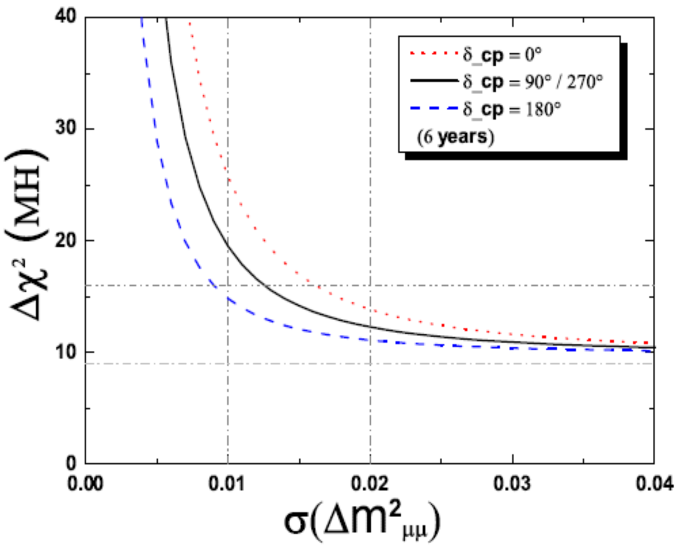
Independent on CP phase and θ_{23} (Acc. & Atm. do)
Energy Resolution is the key

Sensitivity on Neutrino Mass Ordering



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

$\sqrt{\Delta\chi^2}$	Relative Meas.	[a]Use absolute $\Delta m_{\mu\mu}^2$
Ideal case	4	5
[b]Realistic case	3	4



[a] If accelerator experiments, e.g NOvA, T2K, can measure $\Delta M^2_{\mu\mu}$ to ~1% level

[b] Take into account multiple reactor cores, uncertainties from energy non-linearity, etc

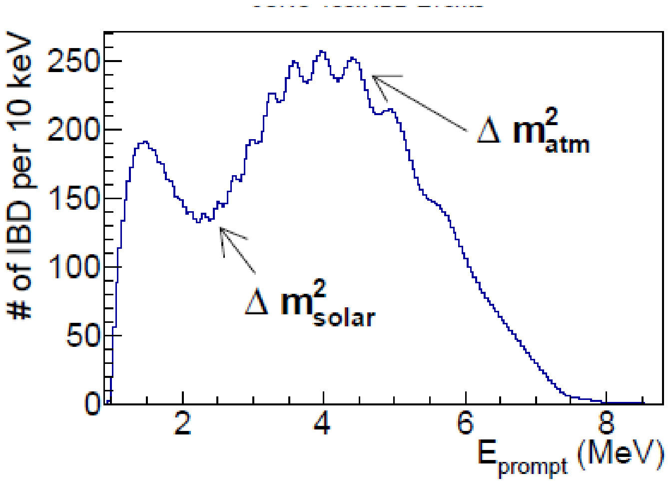
	Ideal	Core distr.	DYB & HZ	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Real	Real	1%	6.3%	0.4%	1%
$\Delta\chi^2_{MH}$	+16	- 3	-1	- 1	- 0.6	- 0.1	+ (4-12)

Precision Measurement

Current precision

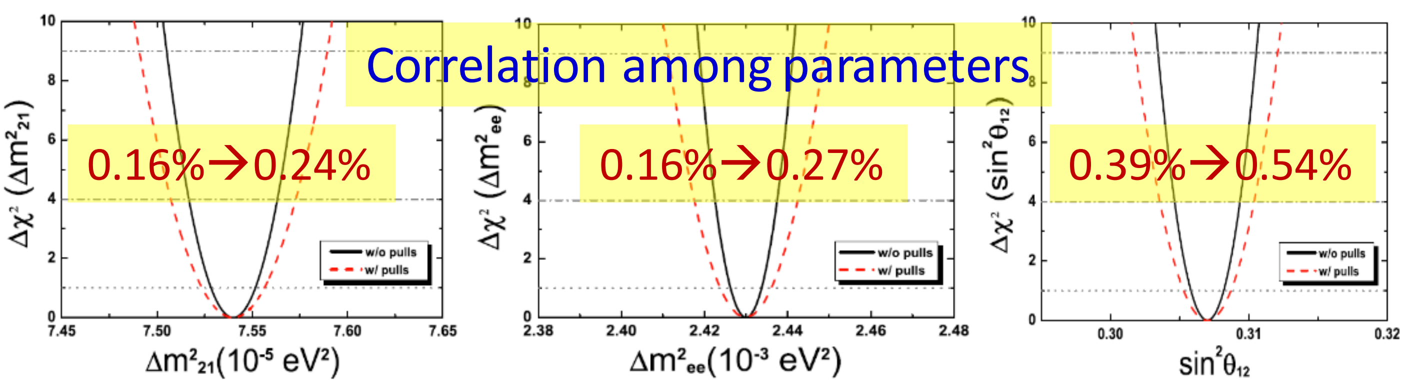
	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant Exps.	KamLAND	MINOS	SNO	Daya Bay	SK/T2K
Individual 1σ	2.7% [20]	4.1% [25]	6.7% [6]	10% [21]	14% [23, 24]
Global 1σ	2.6%	2.7%	4.1%	8.6%	11%

Probing the unitarity of U_{PMNS} to ~1%, more precise than CKM matrix elements!



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

J. Phys. G43:030401 (2016)

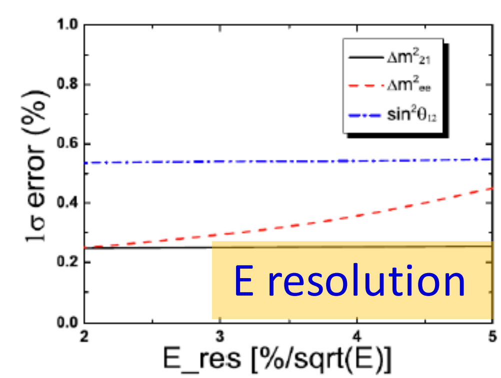


Correlation among parameters

0.16%→0.24%

0.16%→0.27%

0.39%→0.54%



E resolution

Supernova neutrinos at JUNO

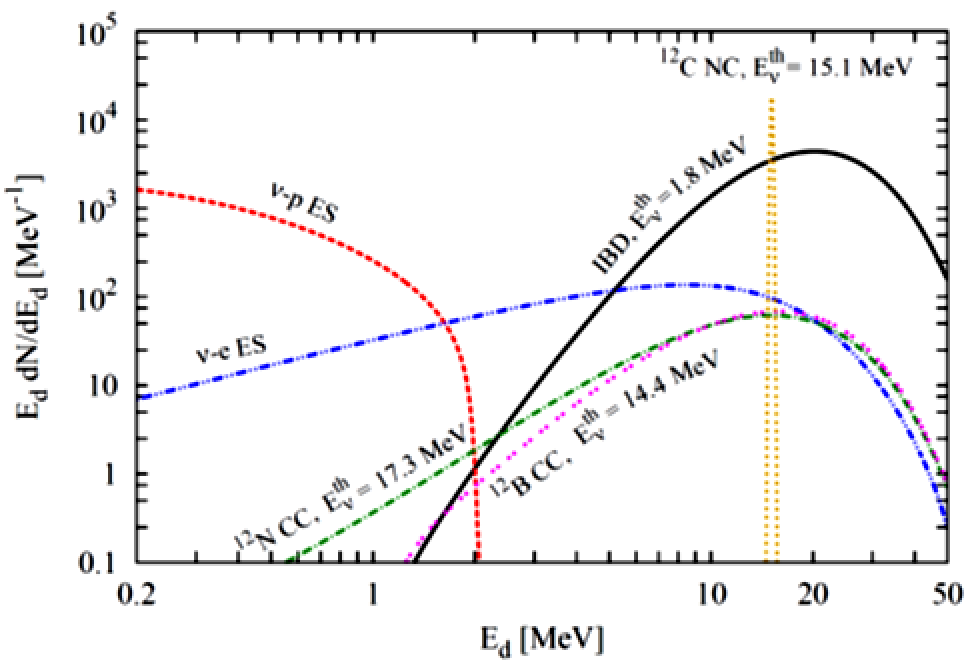
Measure energy spectra & fluxes of almost all types of neutrinos

Typical galactic SN assumptions: 10 kpc galactic distance, 3×10^{53} erg, L_ν the same for all types

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

Correlated events.
Better detection in LS than in Water

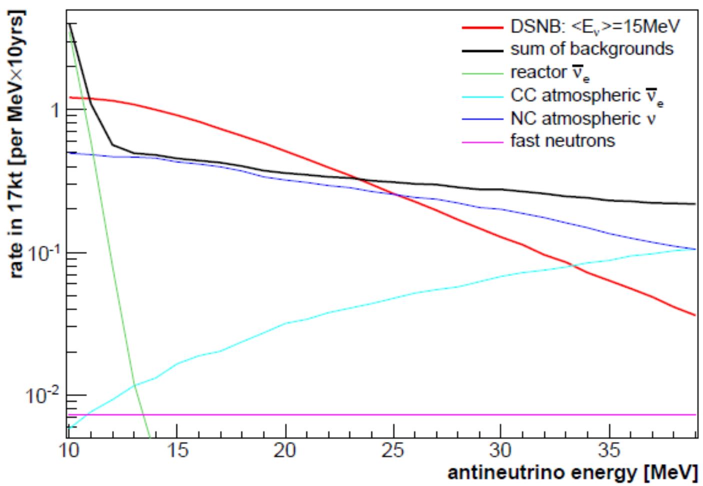
J. Phys. G43:030401 (2016)

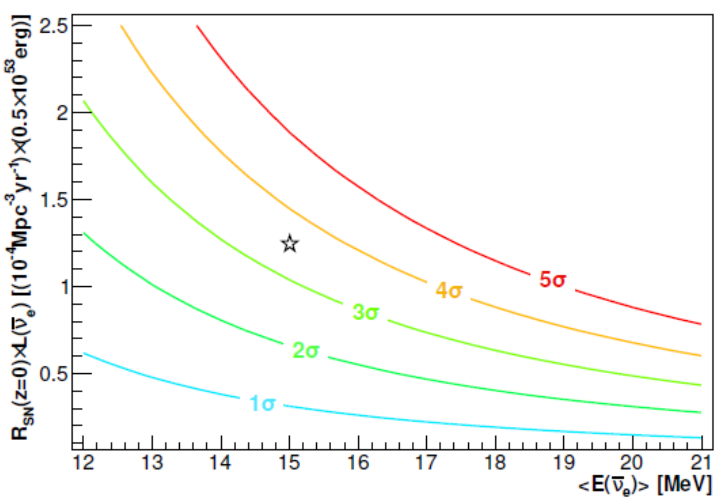


Supernova-ν researches at JUNO

- NMO sensitivity
- Absolute ν mass
- SN direction
- flux/spectra meas. & recon.
- time evolution
- test various SN models
- …

Diffuse Supernova Neutrino Background





J. Phys. G43:030401 (2016)

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

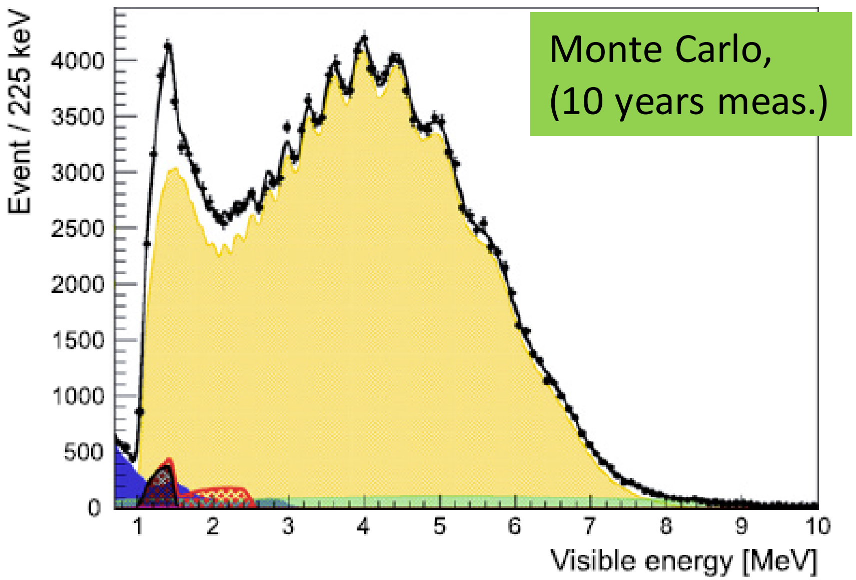
Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar{\nu}_e}\rangle = 12\,\mathrm{MeV}$	12.2	$\varepsilon_\nu = 50\,\%$	6.1
	$\langle E_{\bar{\nu}_e}\rangle = 15\,\mathrm{MeV}$	25.4		12.7
	$\langle E_{\bar{\nu}_e}\rangle = 18\,\mathrm{MeV}$	42.4		21.2
	$\langle E_{\bar{\nu}_e}\rangle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

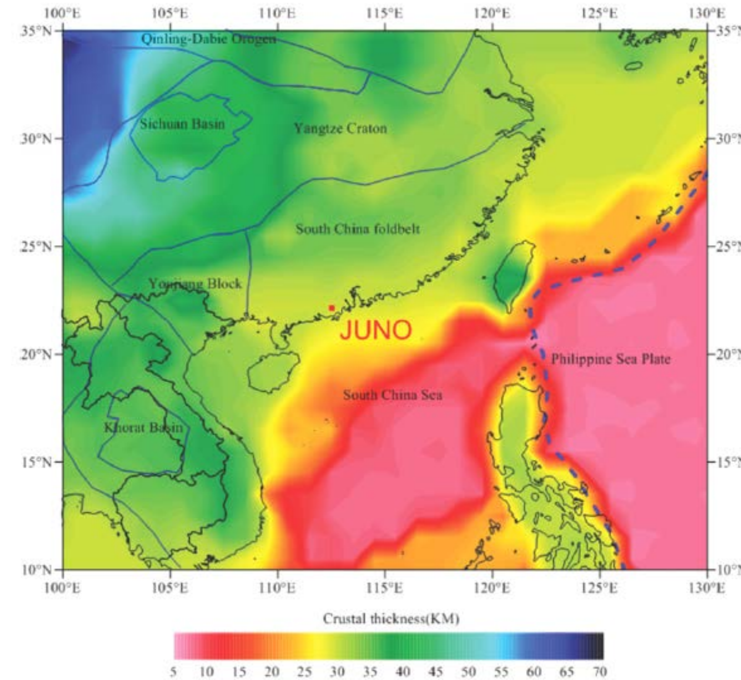
10 Years' sensitivity

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

Other Physics Topics

- Geo-ν measurement at JUNO
  - Huge reactor neutrino backgrounds
  - Need accurate reactor spectra





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

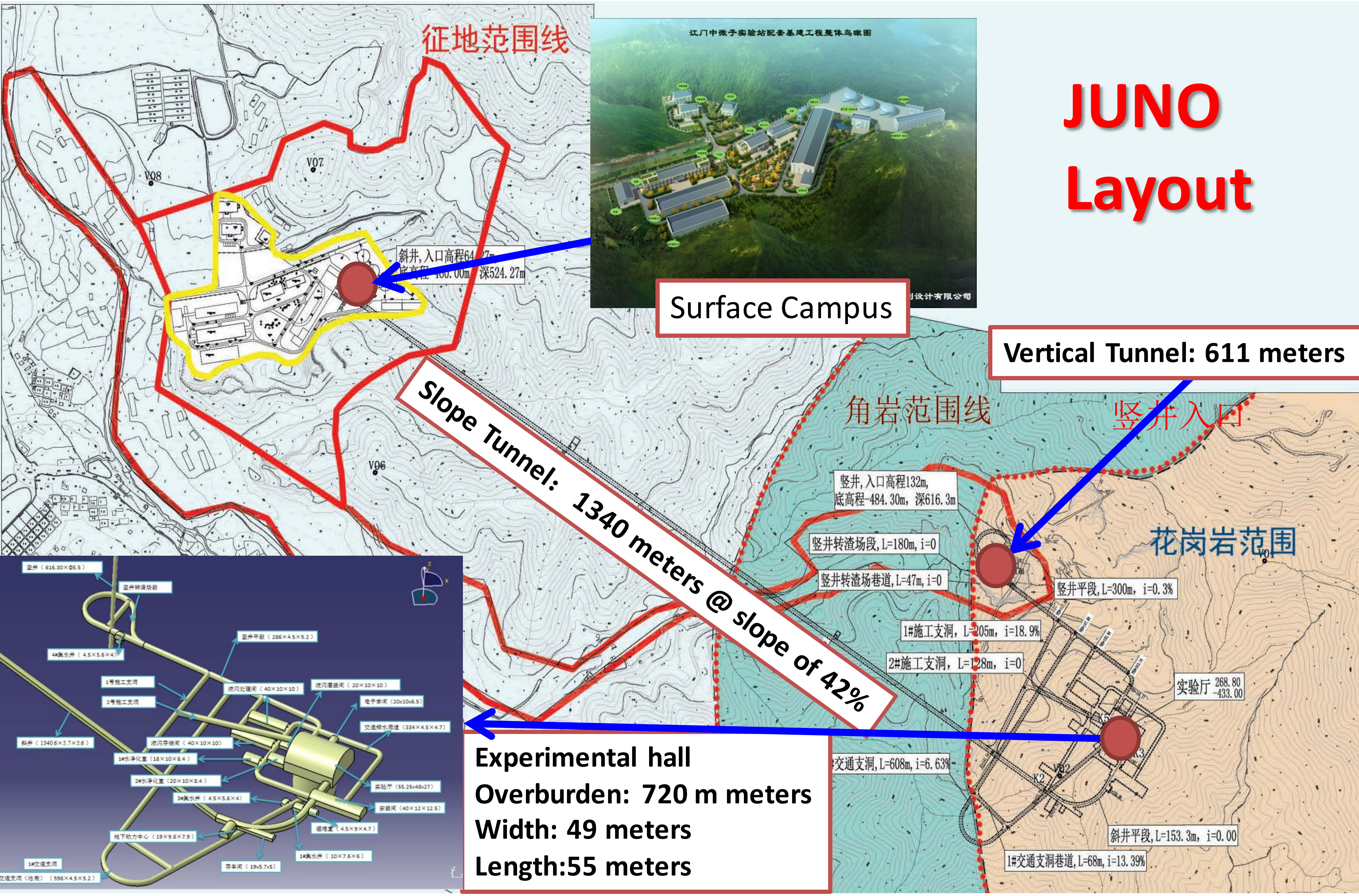
  - 20 x statistics than previous meas.

KamLAND: 30±7 TNU ***(PRD 88 (2013) 033001)***

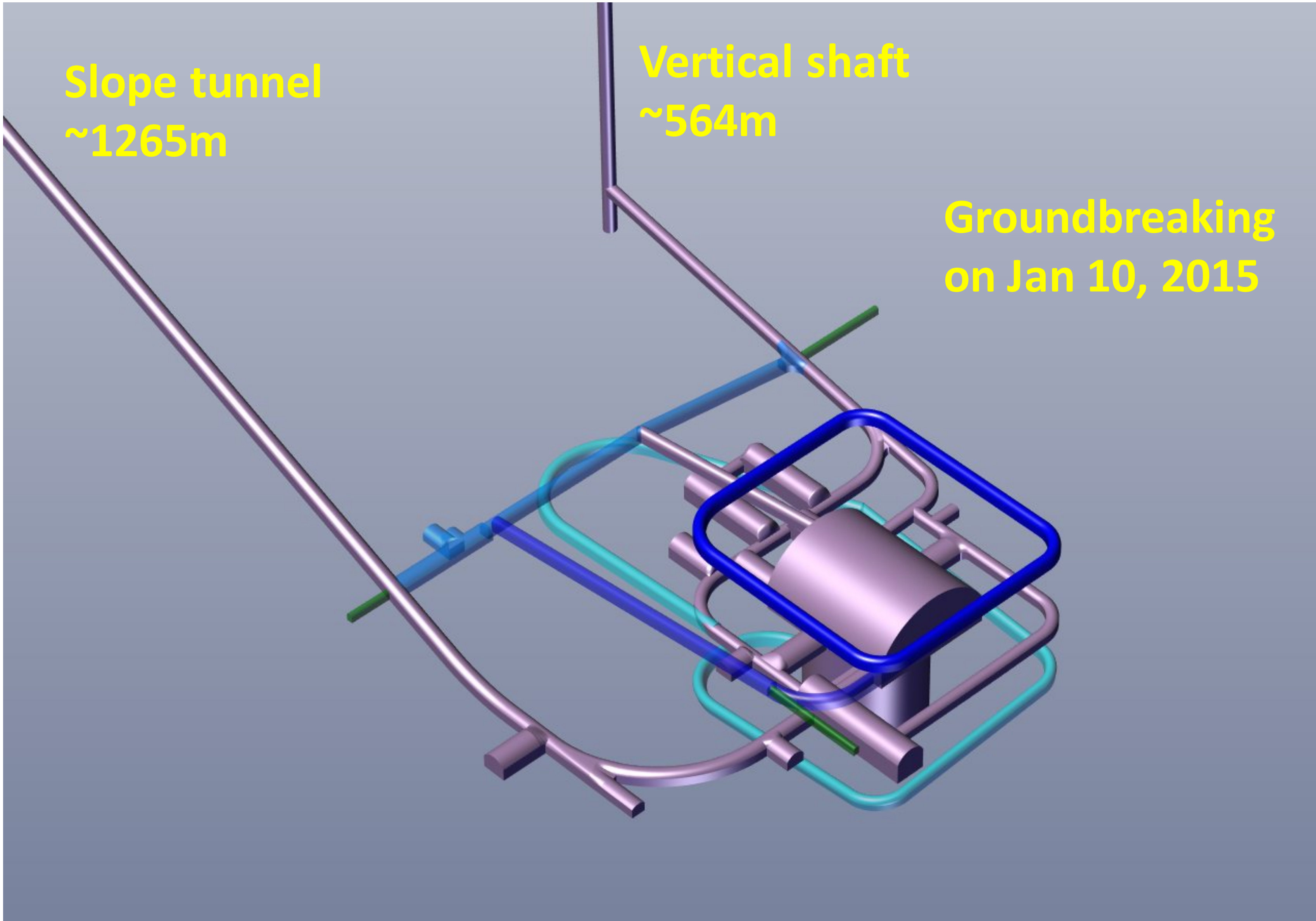
Borexino: 38.8±12.2 TNU ***(PLB 722 (2013) 295)***

Others (atmospheric neutrinos, sterile neutrinos, proton decay, neutrinos from dark matter… etc) were not included in this talk

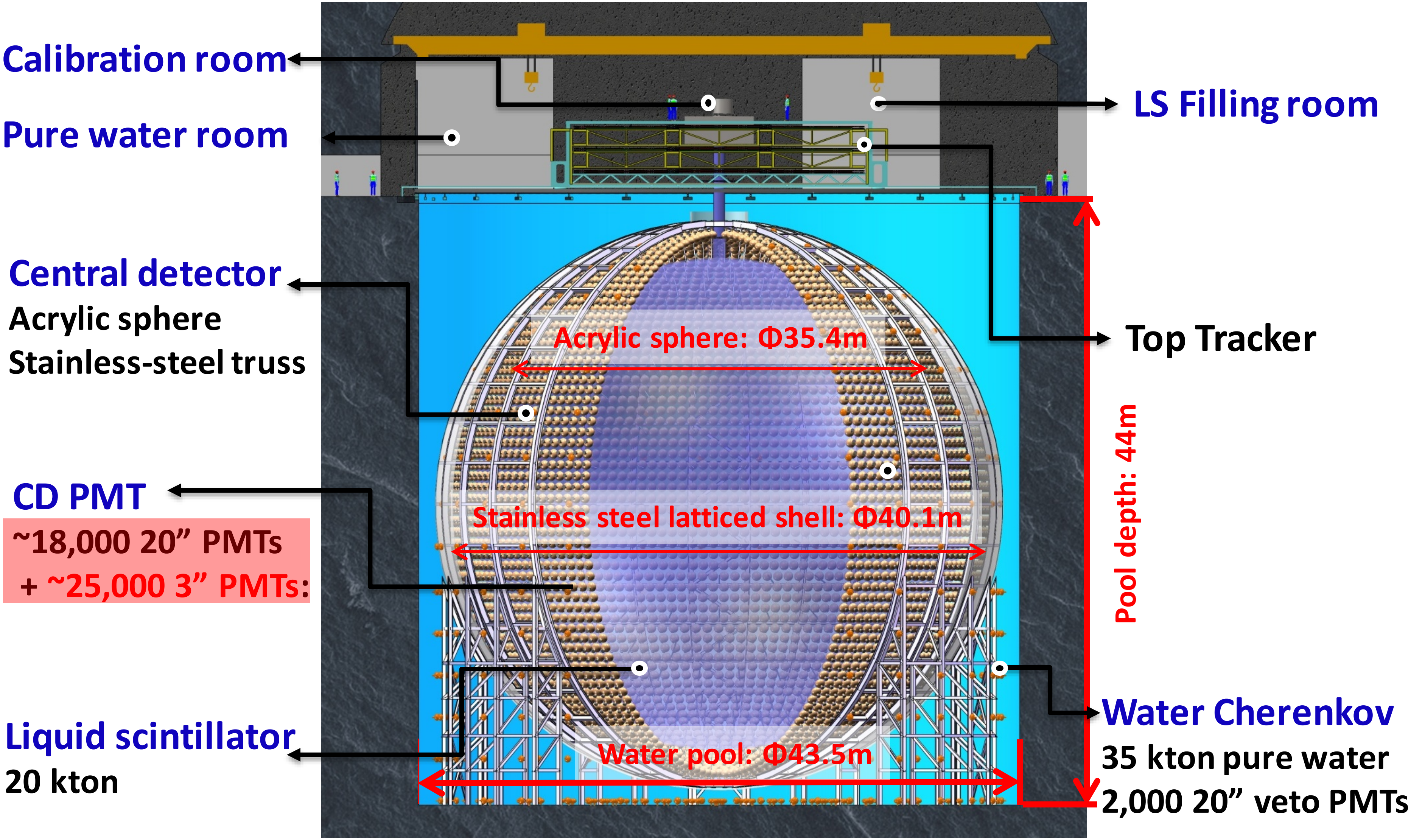
JUNO Layout

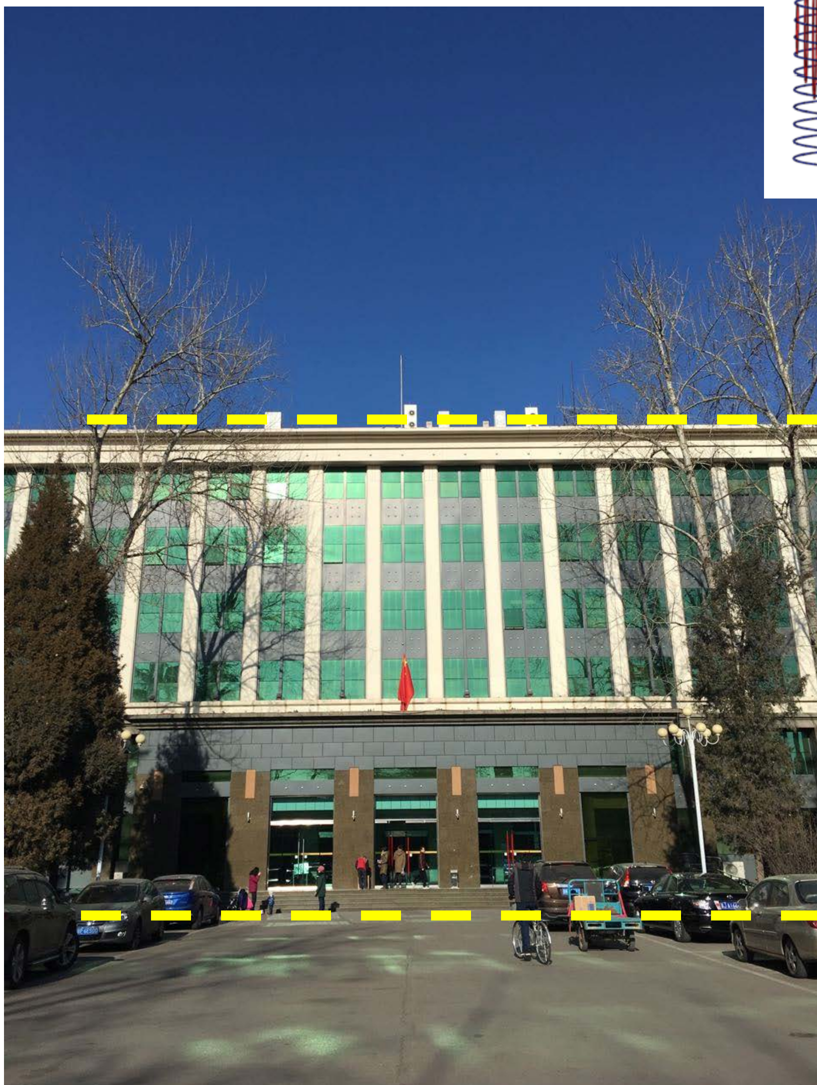

征地范围线
江门中微子实验站配套基建工程整体鸟瞰图
Surface Campus
Vertical Tunnel: 611 meters
Slope Tunnel: 1340 meters @ slope of 42%
V08
V07
V06
角岩范围线
竖井入口
花岗岩范围
竖井,入口高程132m,
底高程-484.30m，深616.3m
竖井转渣场段,L=180m, i=0
竖井转渣场巷道,L=47m, i=0
竖井平段,L=300m, i=0.3%
1#施工支洞，L=205m, i=18.9%
2#施工支洞，L=128m, i=0
实验厅 268.80 -433.00
交通支洞,L=608m, i=6.63%
斜井平段,L=153.3m, i=0.00
1#交通支洞巷道,L=68m, i=13.39%
Experimental hall
Overburden: 720 m meters
Width: 49 meters
Length:55 meters

JUNO Underground Laboratory

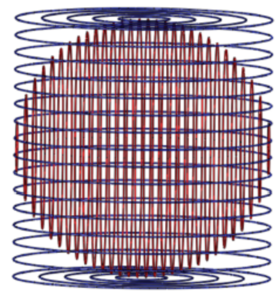


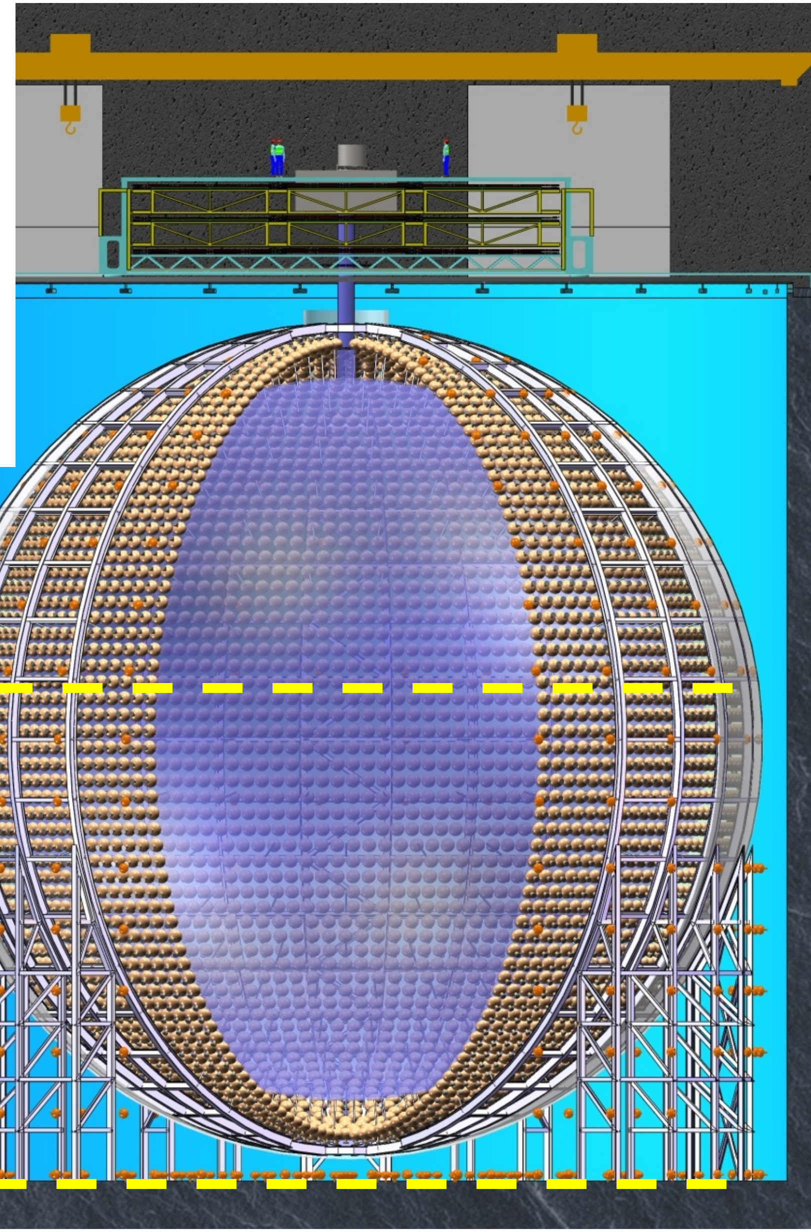
JUNO Detector



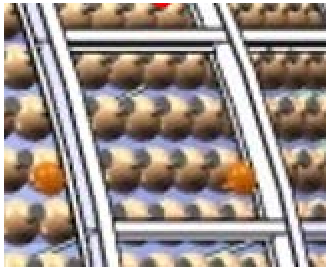


Magnetic Field Compensating Coil





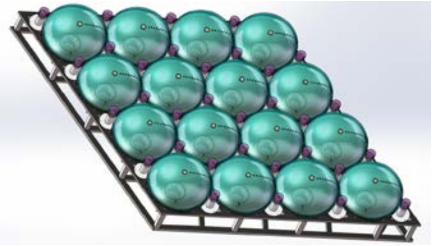
Overview of JUNO PMT systems

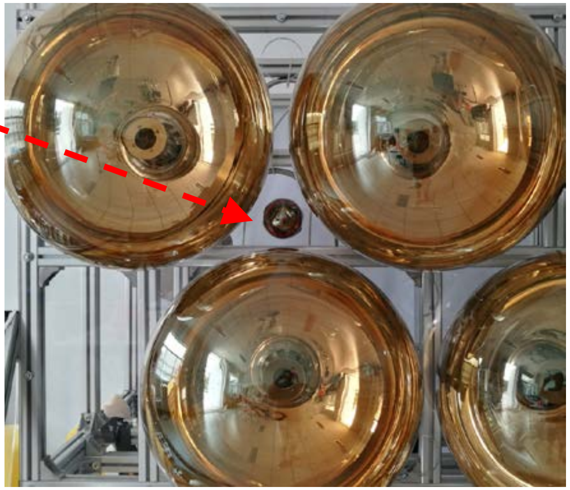


20” PMT
(~75% photo-coverage)

3” PMT
(~2% photo-coverage)

3” PMT





A Demo for the PMT module

20” MCP-PMT
15,000

20” Dynode-PMT
5,000

3.1” PMT
25,000

JUNO 20-inch PMTs

Successful 20-inch MCP-PMT

Project Team

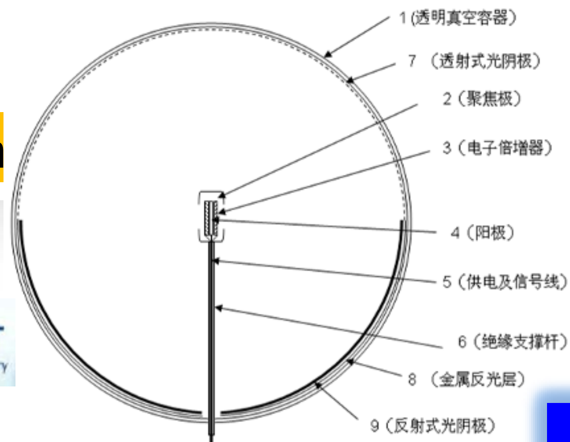
中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

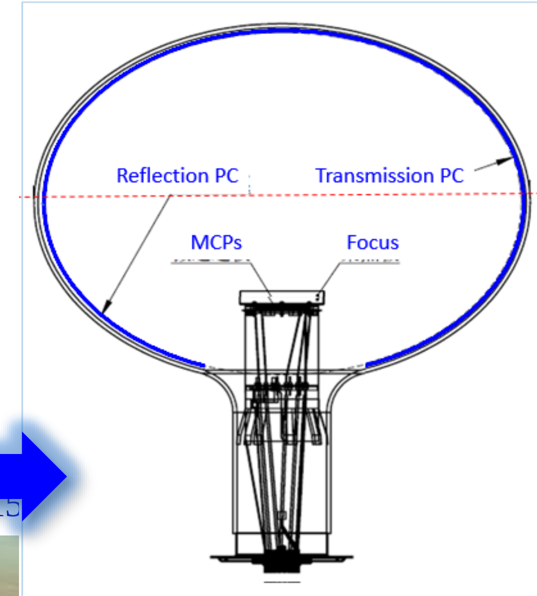
南京大学

北方夜视技术股份有限公司
NORTH NIGHT VISION TECHNOLOGY CO.,LTD

中核（北京）核仪器厂
CNNC Beijing Nuclear Instrument Factory

中国科学院西安光学精密机械研究所
XIAN INSTITUTE OF OPTICS AND PRECISION MECHANICS OF CAS





Characteristics	unit	MCP-PMT（NNVC）	R12860（Hamamatsu）
Detection Efficiency (QE*CE*area)	%	27%, > 24%	27%, > 24%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2, F~12	R~5,F~9
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40

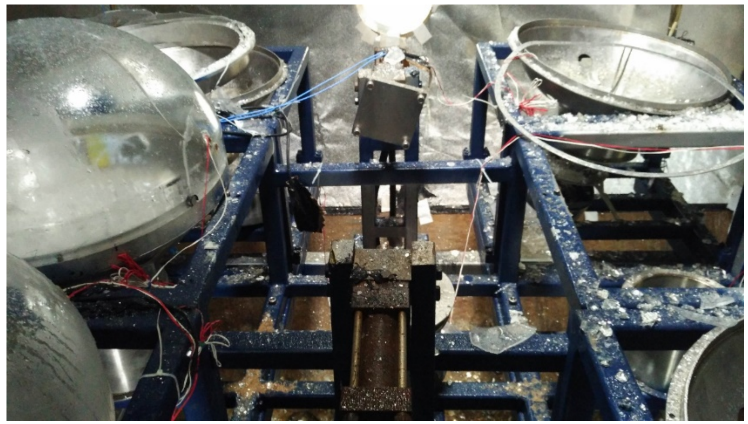
15k MCP-PMT (75%) from NNVT
5k Dynode(25%) from Hamamatsu

Underwater implosion tests

6 times of protection tests under 0.5MPa water since 2016, a baseline solution has been found

1st test

2nd test

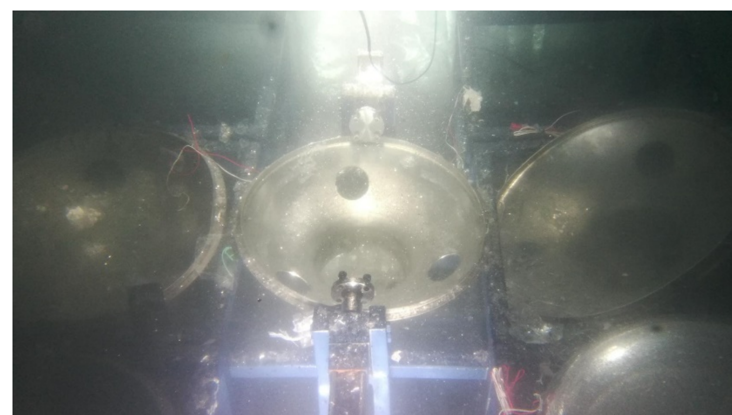


3rd test

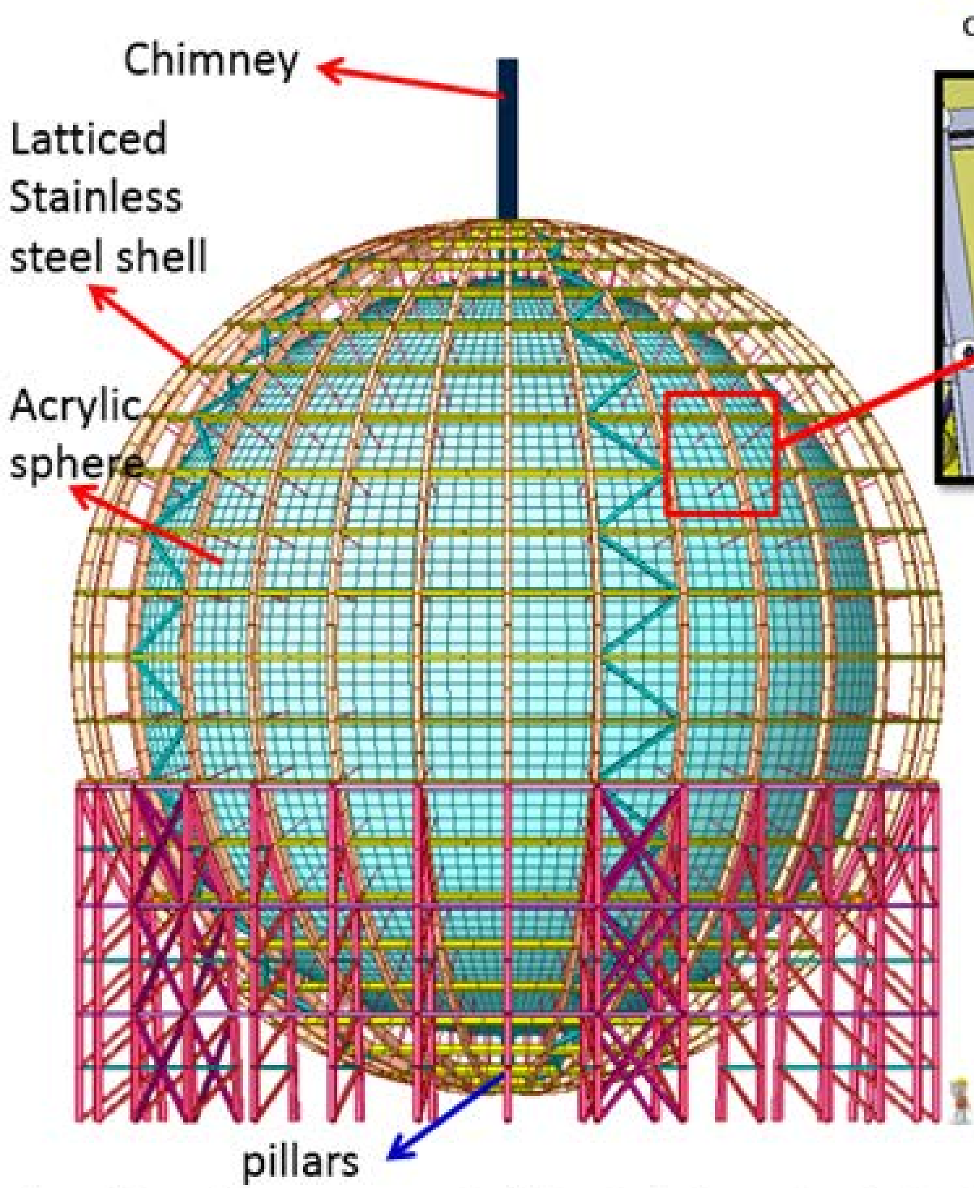
4th test

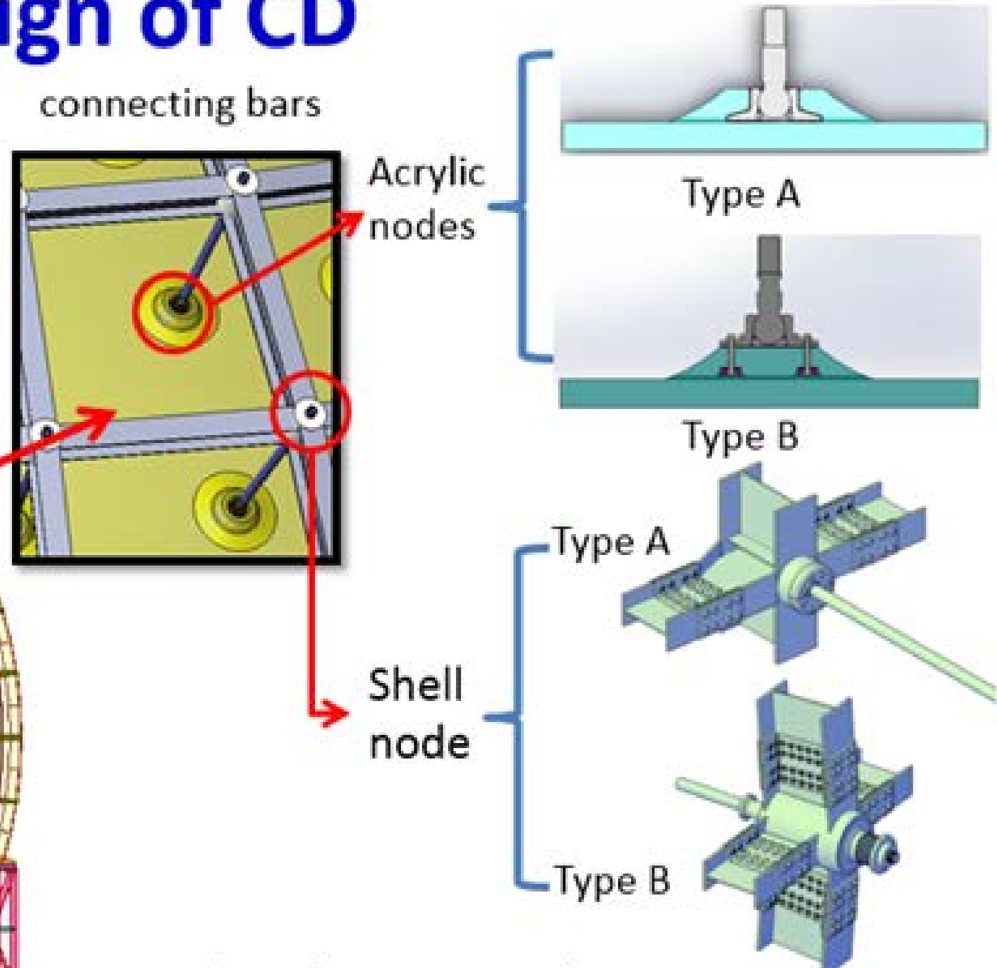
5th test

6th test



Latest design of CD

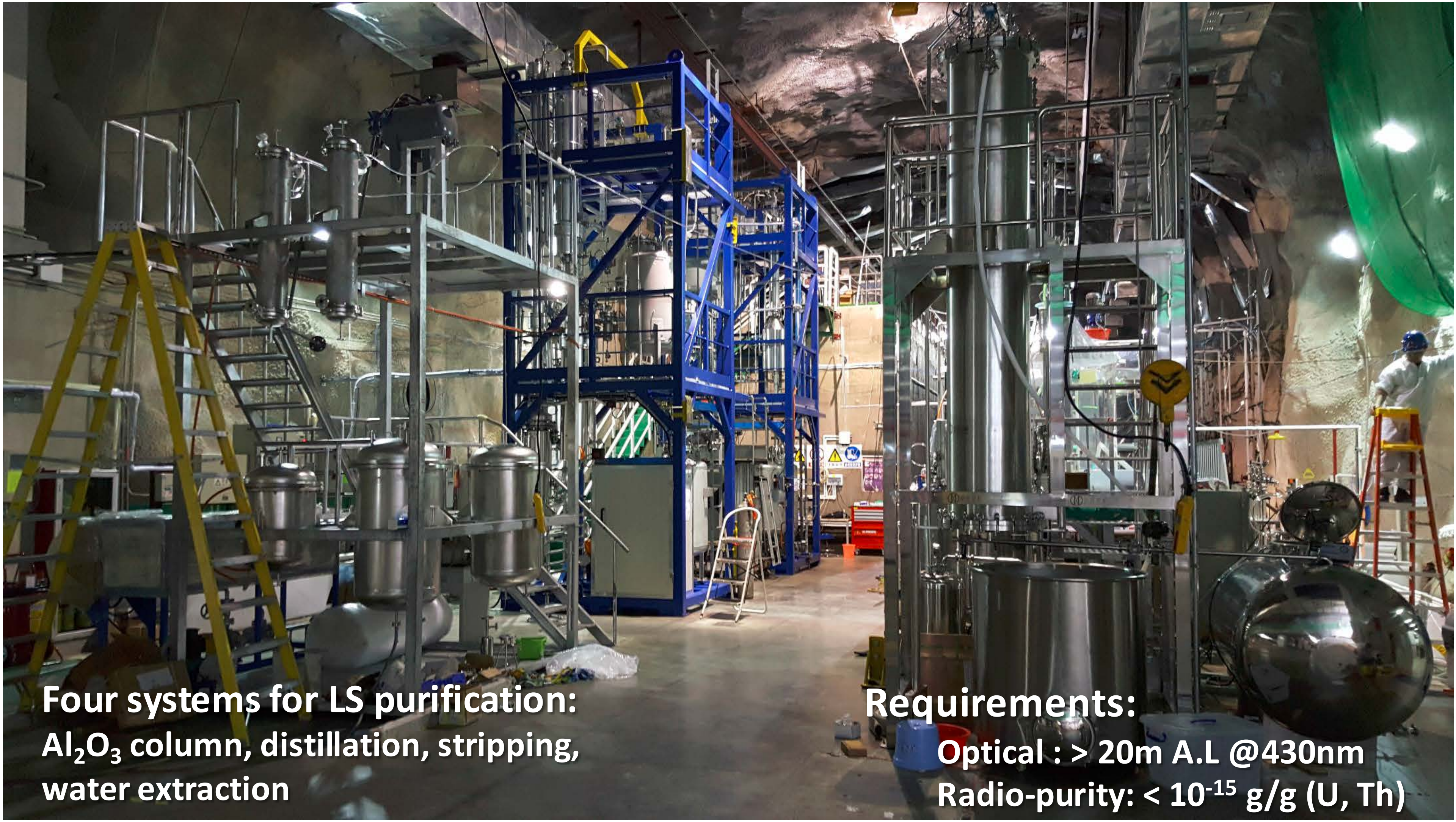




Acrylic sphere supported by stainless steel shell

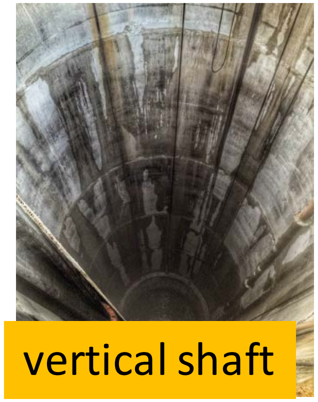
- Acrylic sphere: Inner diameter 35.4m. thickness: 120mm.
- Stainless shell: Inner diameter 40.1m. Divided into 30 longitudes and 23 layers.
- Weight of acrylic sphere: ~600t.
- Weight of shell: ~590 t.
- No. of connecting bars: 590

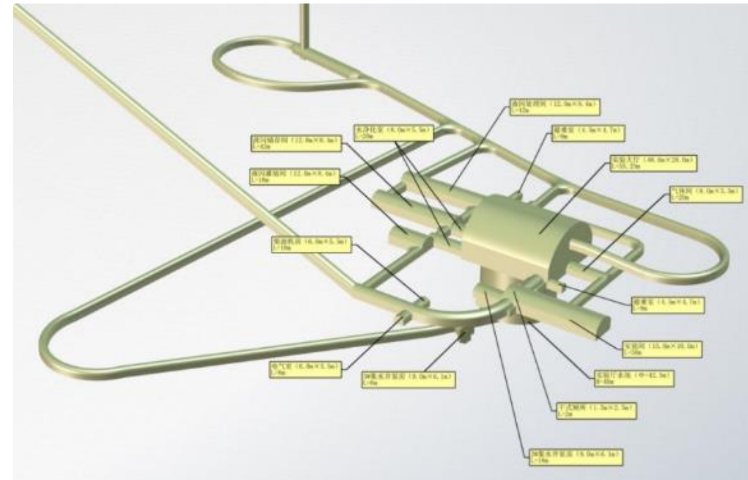
JUNO-LS Pilot plant



Full systems tested in Daya Bay LS hall.
A new batch of purified LS was produced and filled into DYB-AD1.

JUNO Schedule



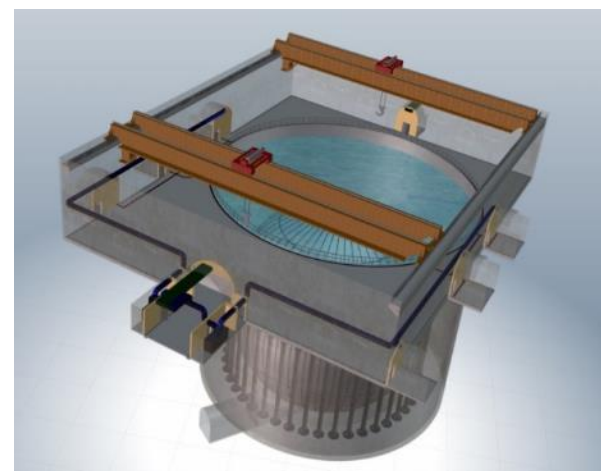


Schedule:

- Civil preparation： 2013-2014
- Civil construction： 2014-2018
- Detector component production： 2016-2017
- Detector assembly & installation： 2018-2019
- Filling & data taking： 2020-2021

Future Plan

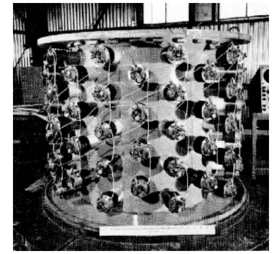
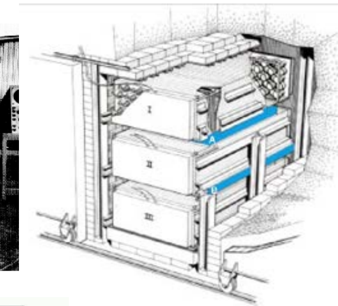
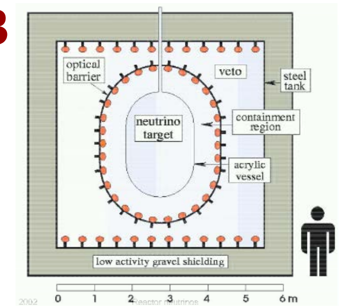
- **Run for 20-30 years**
- **Likely, double beta decay experiment in 2030**

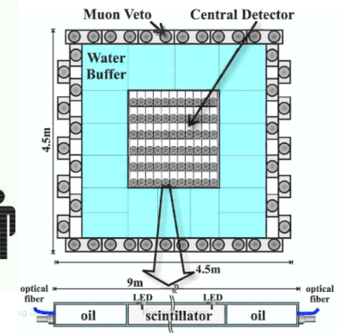


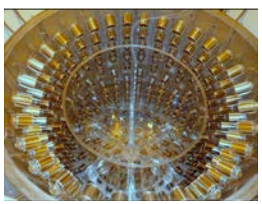
Thanks!

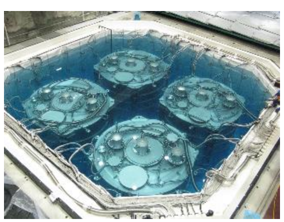
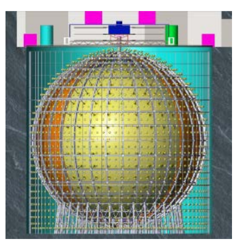
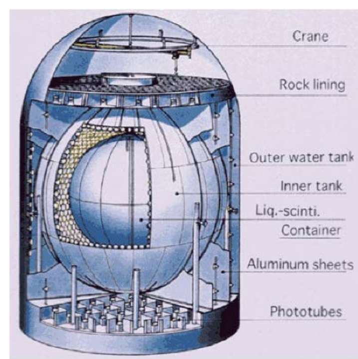
Reactor Neutrinos

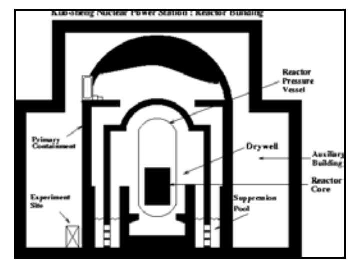
- Discovery of neutrino in 1956
- Early search for oscillation 70's-80's
- Small θ_{13} in 1990s
- limit on neutrino magnetic moment (00's)
- Observation of reactor $\overline{\nu_e}$ disappearance in 2003
- Discovery of non-zero θ_{13} in 2012
- Mass hierarchy and precision measurements
- Sterile neutrinos, Magnetic moment, …

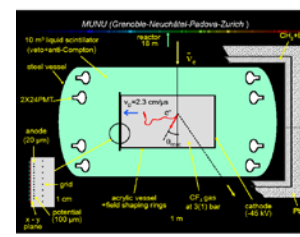




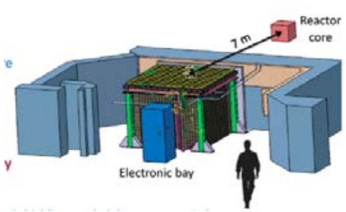


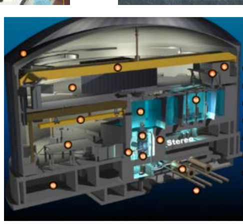
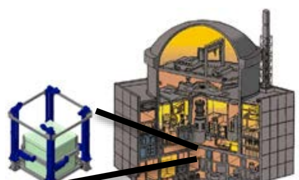




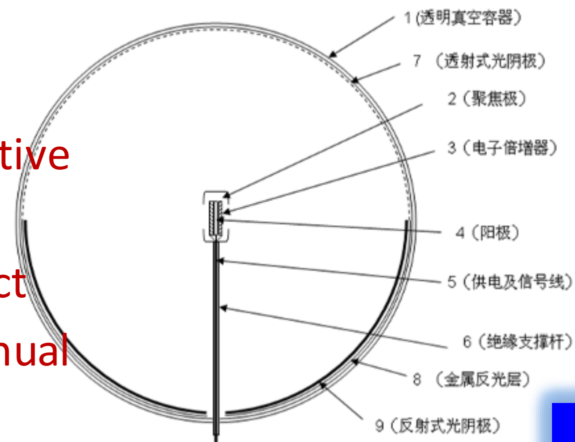


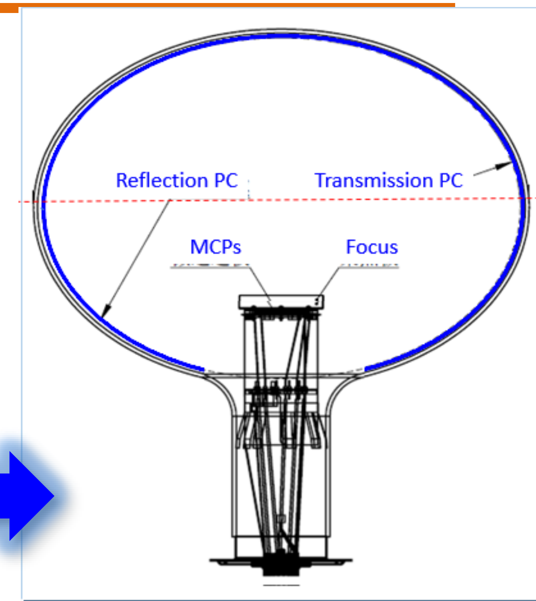


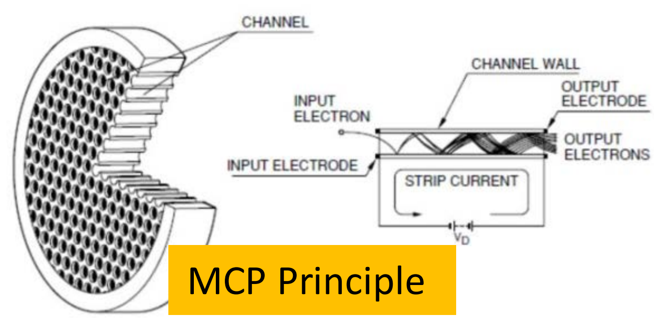

R&D of 20” MCP-PMT

- Advantages:
  - Higher QE: transmissive photocathode at top + reflective photocathode at bottom
  - High CE: less shadowing effect
  - Easy for production: less manual operation and steps

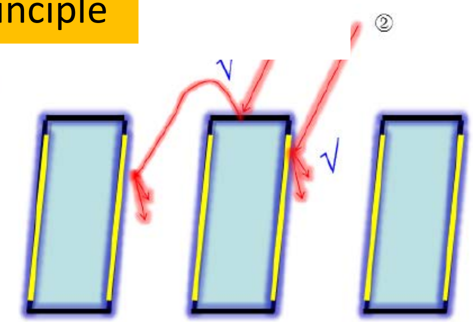




Project Team



MCP Principle



Design — 2009

5”(8”) Prototype — 2010~2013

20” Prototype — 2013~2015

Production — 2016~2019