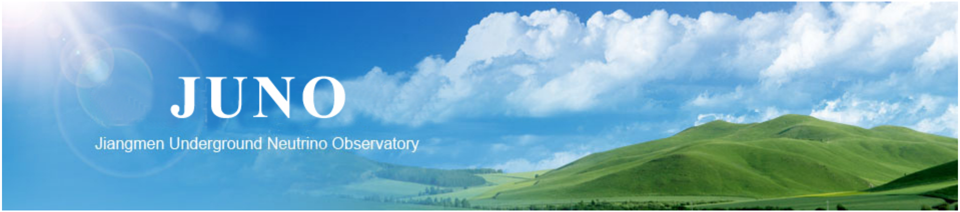


A. Garfagnini

Padova University and INFN

June 30, 2014

Neutrino Oscillations and Mass Hierarchy

Pontecorvo (1957) Maki, Nakagawa and Sakata (1962) Pontecorvo and Gribov (1969)

$$U = U_{MNS} \cdot \Gamma = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times diag(1, e^{i\beta}, e^{i\gamma})$$

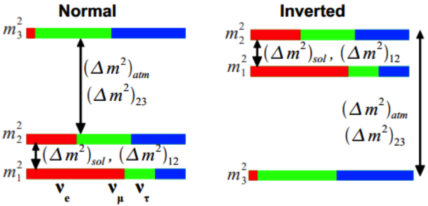
Atm + accel ν

Next generation experiments

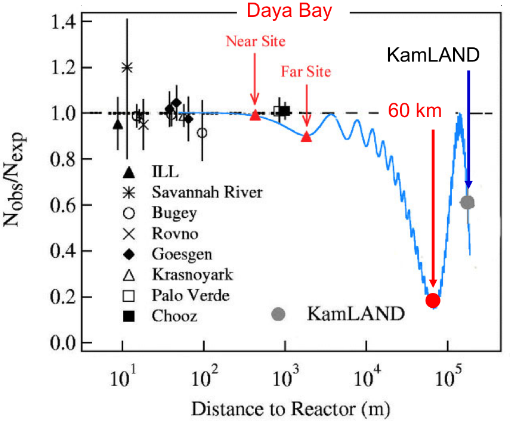
solar + long baseline reactors

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

$$\begin{aligned} \Delta^2_{31} &= \Delta^2_{32} + \Delta^2_{21} \\ NH : |\Delta^2_{31}| &= |\Delta^2_{32}| + |\Delta^2_{21}| \\ IH : |\Delta^2_{31}| &= |\Delta^2_{32}| - |\Delta^2_{21}| \end{aligned}$$



A Next Generation Reactor νs Experiment



- ✓ Rich ν physics possibilities
  - ✓ Mass Hierarchy
  - ✓ Precision measurement of mixing parameters
  - ✓ Geo neutrinos
  - ✓ Supernovae neutrinos
  - ✓ Atmospheric neutrinos
  - ✓ Sterile neutrinos
  - ✓ Exotic searches

Recent talk on reactor νs:
Lianjian Wen, Neutrino 2014

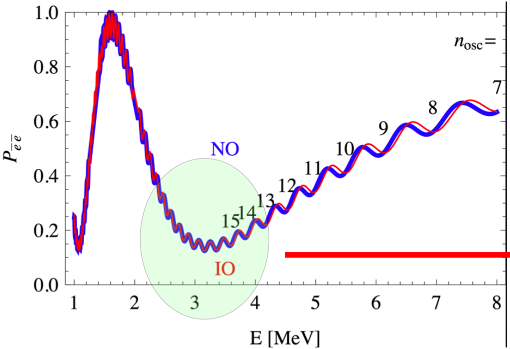
✓ Large large fiducial volume (20 kt) needed

Talks: Y.F. Wang at ICFA seminar 2008, Neutel 2011; J. Cao at Neutel 2009, NuTurn 2012;
Papers: L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103 (2008); PRD79:073007 (2009).

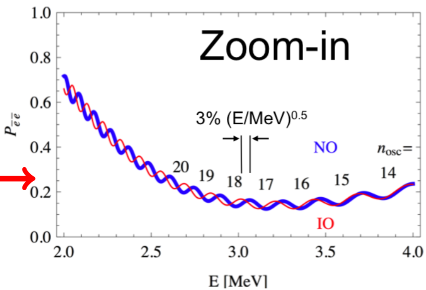
ν Mass Hierarchy At Reactors

- Mass Hierarchy accessible thanks to large θ_{13} $\rightarrow$ exploit L/E spectrum
- S.T. Petcov et al., PLB533(2002)94; S.Choubey et al., PRD68(2003)113006

- High precision energy measurement required
- Look for the interference between solar and atmospheric oscillations
- Independent of CP phase and θ_{23}



Energy resolution is a Key Component

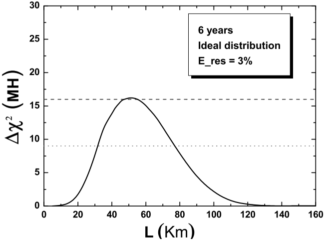


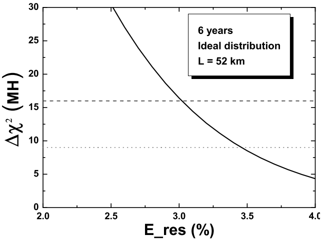
W. Winter, Neutrino 2014

ν Mass Hierarchy in JUNO

- Oscillation probability is different for the two mass hierarchies
- Energy resolution is a key component

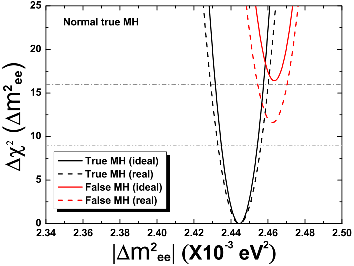
Yu-Feng Li, et al, ar.Xiv:1303.6733





Detector size: 20 kt
Energy resolution: $3\%/\sqrt{E}$
Thermal Power: 36 GW
Exposure: 120 kt yr (6 years)
The relative measurement can reach a 4 σ sensitivity (5 σ with $\Delta_{\mu\mu} \sim 1\%$)

Due to reactor core distributions, a relative measurement can reach a 3 σ sensitivity



Measurements of Mixing Parameters in JUNO

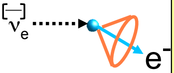
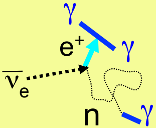
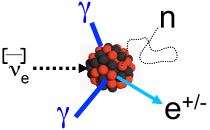
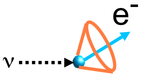
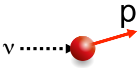
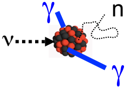
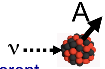
- Probing the unitarity of U_{PMNS} to 1% level

	Current Error	Juno
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
Δm^2_{13}	?	N/A
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	20%	N/A
$\sin^2\theta_{13}$	14% $\rightarrow$ 4%	$\sim$ 15%

The PMNS will be more precise than the CKM matrix.

Detection of Supernova Neutrinos

K. Scholberg, Neutrino 2014

	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 (CENNS)

IBD (electron antineutrinos) dominates for current detectors

Detection of Supernova Neutrinos in JUNO

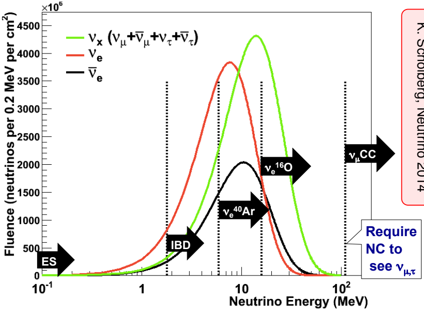
- Less than 20 events observed so far
- Assumptions:

✓ Distance: 10 kpc (our Galaxy center)

✓ Energy: 3×10^{53} erg

✓ Neutrino energies and temp:

- $< E_{\nu_e} >= 11$ MeV, $T_{\nu_e} = 3.5$ MeV
- $< E_{\overline{\nu_e}} >= 16$ MeV, $T_{\nu_e} = 5$ MeV
- $< E_{\nu_x} >= 25$ MeV, $T_{\nu_e} = 8$ MeV



K. Scholberg, Neutrino 2014

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
$\nu + e \to \nu + e$	NC	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

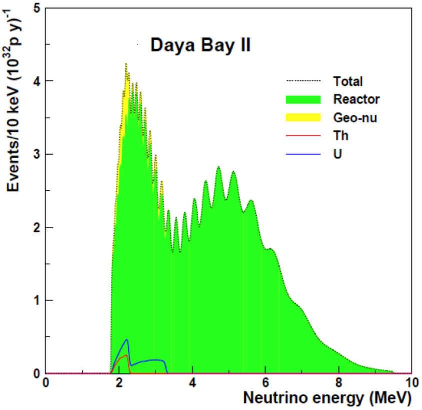
Lianjian Wen, Neutrino 2014

Correlated events.

Better detection in LS than in Water

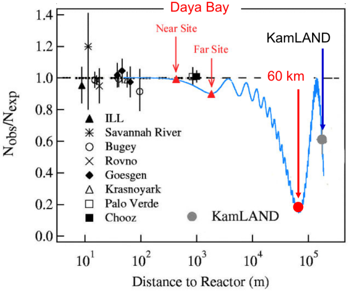
Detection of Geo Neutrinos in JUNO

- State of the art on Terrestrial Neutrino measurements:
  - ✓ Borexino: $64 \pm 25 \pm 2$ TNU
  - ✓ KamLAND: $40 \pm 10 \pm 11$ TNU
- Efforts to reach an error of 3 TNU $\rightarrow$ statistically dominant
- JUNO shall have $\times 10$ statistics, but systematics will be an issue
- Expected rates:
  - ✓ Borexino: $\sim$ 1 event/70 days
  - ✓ KamLAND: $\sim$ 1 event/30 days
  - ✓ JUNO: $\sim$ 1.5 event/day



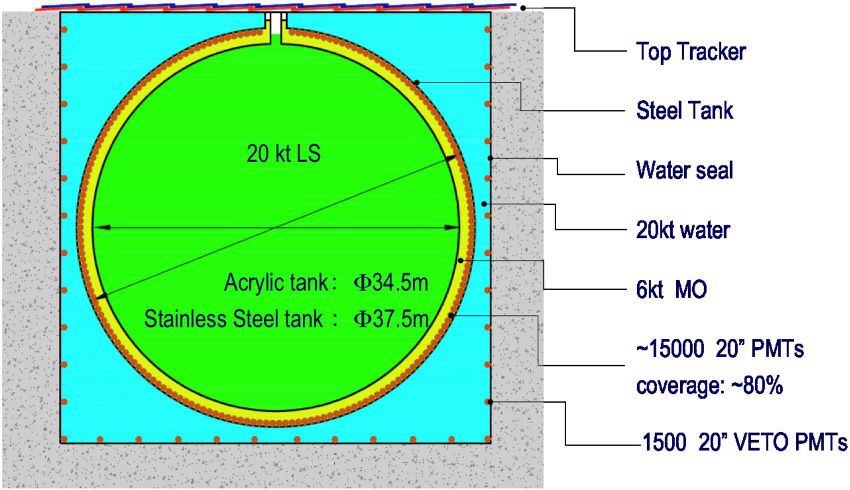
Detector Design Requirements

- ✓ large 20 kton fiducial volume (35.4 m diameter)
- ✓ 39 m detector diameter (driven by PMTs radioactivity)
- ✓ 3% energy resolution:
  - Linear Akyl Benzene (LAB) liquid scintillator, non Gd doped, attenuation length > 20 m
  - PMT photocatode coverage > 75%
  - PMT quantum efficiency > 35%
- ✓ online handling of LS with recycling piping system
- ✓ very low LS radioactivity: U/Th/K < 10^{-15}g/g (for reactor $\overline{\nu}_e$). Total single rates in FV < 20 Hz (E > 700 keV)



- ✓ Vertex and muon tracking (PMT timing requirements under discussion)
- ✓ 20 years life time: no aging, stable running conditions, earthquake 0.1 g resistant

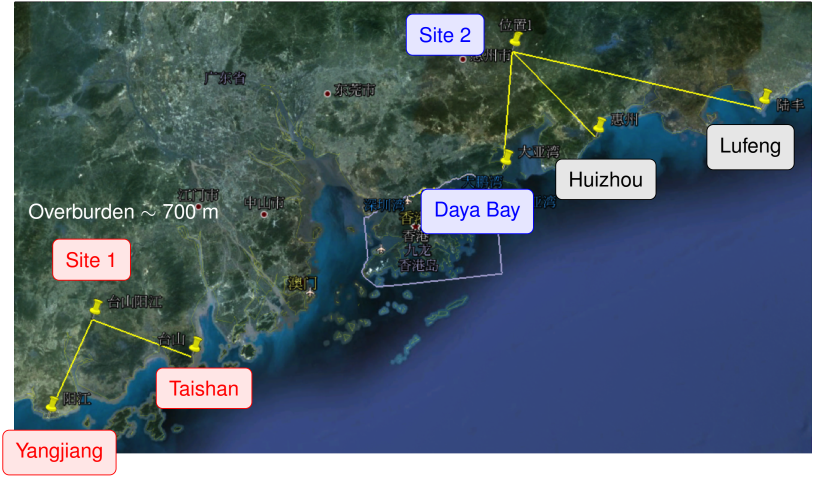
The JUNO Detector Concept Design



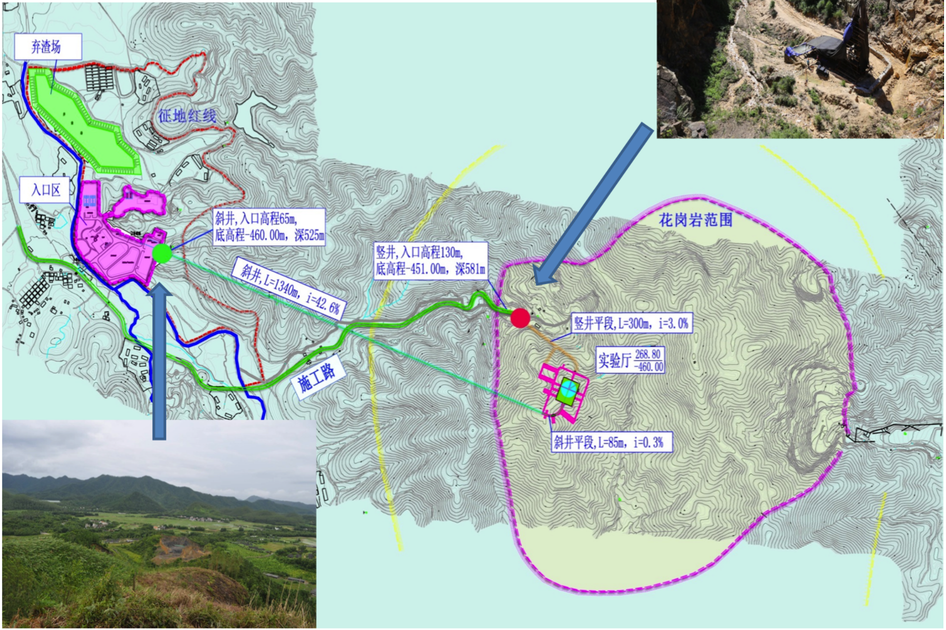
The mechanics of a 40 m diameter detector is challenging: many options are being considere by the Collaboration

The Experimental Site and The Reactors

	Yuanhjiang	Taishan	Daya Bay	Huizhou	Lufeng
Status	Under Constr.	Under Constr.	Operational	Planned	Planned
Power	17.4 GW	18.4 GW, (9.2 GW by 2020)	17.4 GW	17.4 GW	17.4 GW

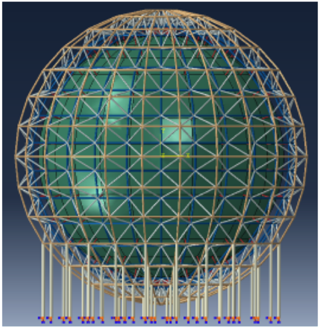


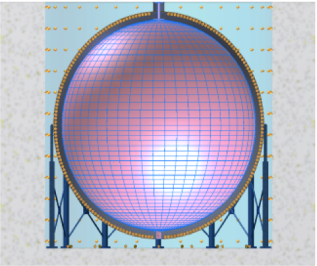
Experimental Site Layout



The Central Detector

- A huge detector in a water pool
- Two open options:
  - ✓ Default option: acrylic tank (⌀ ~ 35 m) + Stainless Steel structure
  - ✓ Backup option: Stainless Steel tank (⌀ ~ 38 m) + acrylic structure + balloon
- Important issues:
  - ✓ engineering (mechanics, safety, . . .)
  - ✓ physics (cleanliness, light collection, . . .)
  - ✓ assembly and installation

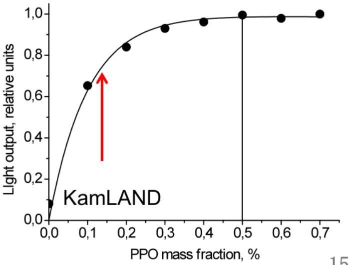




The Liquid Scintillator

- Scintillator base: Linear Alkyl Benzene
- Current mixture: LAB + PPO + BisMSB
- Requirements:
  - ✓ Long attenuation length
  - ✓ Improved production process
  - ✓ High purified material (process: distillation, filtration, water extraction, nitrogen stripping, . . .)
  - ✓ Highest Light Yield: optimizaion of flourine concentration
- Othe important requirements:
  - ✓ Controlling energy non-linearity
  - ✓ Aging
  - ✓ Engineering issue: treatment of 20 ktons
  - ✓ Raw material selection: background & purity issues

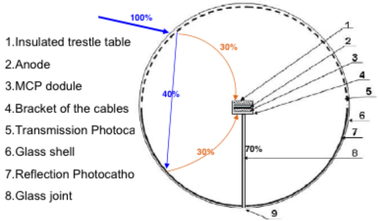
Linear Alky Benzene	Atte. L(m) @ 430 nm
RAW	14.2
Vacuum distillation	19.5
SiO_2 coloum	18.6
Al_2O_3 coloum	22.3
LAB from Nanjing, Raw	20
Al_2O_3 coloum	25

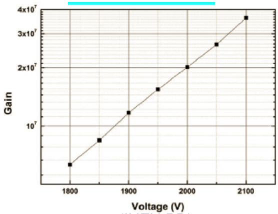


High QE PMT

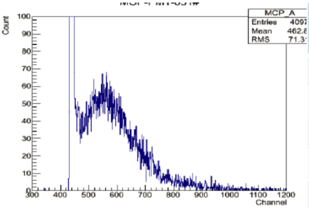
- Three types of high quantum efficiency PMTs are under development:
  - ✓ Hamamtsu R5912-100 with Super Bialkaly photocathode
  - ✓ Photonis PMT
  - ✓ A new design using Micro Channel Plates: 4π collection efficiency

- MCP-PMT development:
  - ✓ technical issues mostly solved
  - ✓ successful 8" prototypes produced/tested
  - ✓ few 20" prototypes produced





(INFN PD)

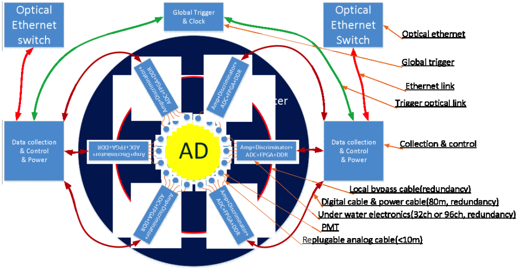


	R5912	R5912-100	MCP-PMT
QE@410nm	25%	35%	25%
Rise time	3 ns	3.4ns	5ns
SPE Amp.	17mV	18mV	17mV
P/V of SPE	>2.5	>2.5	`2
TTS	5.5ns	1.5 ns	3.5 ns

Trigger and Readout Electronics

- Charge and timing info (1 GHz FADC)

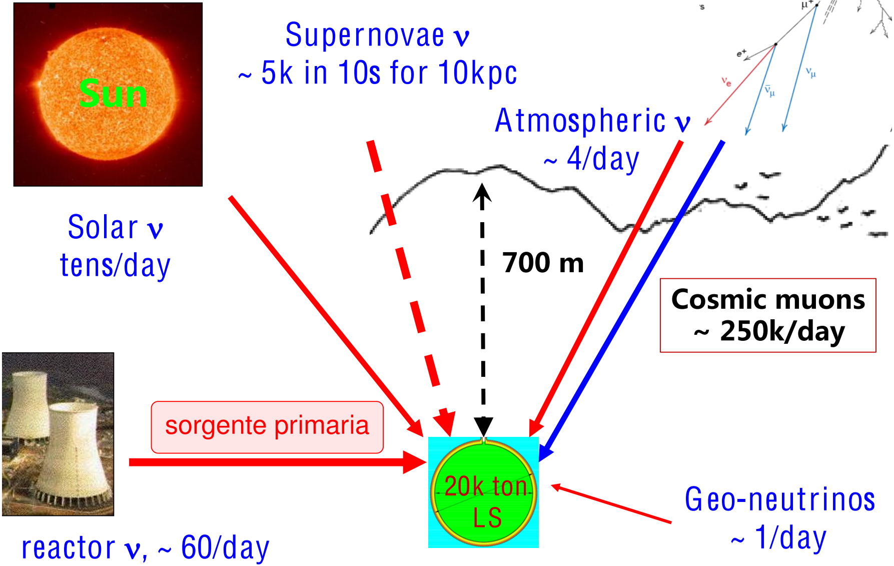
Number of Channels	20000
Event Rate	$\sim$ 50 kHz
Charge precision	1-100 p.e.: 0.1-1 p.e.; 100-4000 p.e.: 1-40 p.e.
Noise	0.1 p.e.
Timing	$0 - 2\ \mu$s: $\sim$ 100 ps



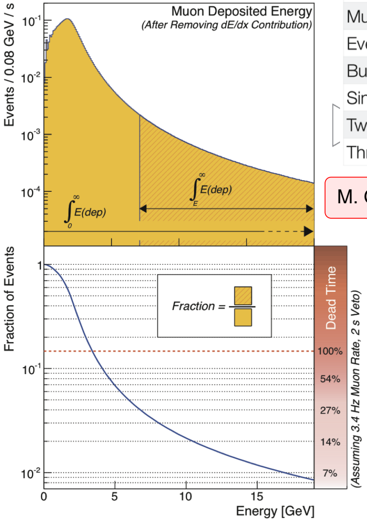
Baseline: dry electronics
Option: in-water electronics

In case of in-water electronics:
✓group PMT per 100 ch
✓global trigger on surface

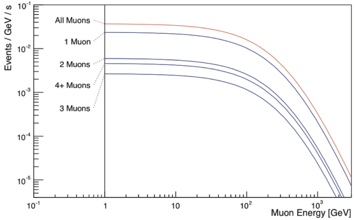
Neutrino Rate



Cosmic Muons in JUNO



	[Hz]
Muon Rate	5.4 ± 1.2
Event Rate	4.1 ± 0.9
Bundle Rate	0.69 ± 0.16
Single μ rate	3.4 ± 0.7
Two μ rate	0.43 ± 0.10
Three μ rate	0.13 ± 0.03



M. Grassi, Neutrino 2014

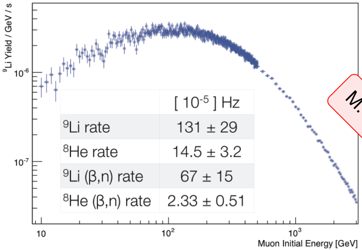
JUNO granite overburden 750 m ($\sim$ 2000 mwe)
muon bundles play an important role

Kamland Rejection Scheme:

✓select events w/ $E_{shower} - E_{thr}$
✓veto the whole detector
✓... long enough to allow all the isotopes to decay

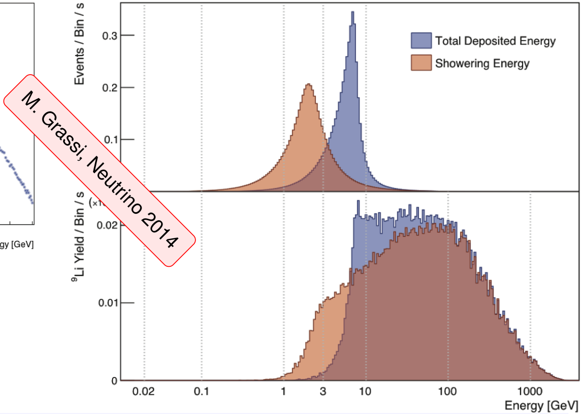
With a 2 s veto, the deadtime goes to 100%

^{9}Li Background in JUNO



	$[10^{-5}]$ Hz
^{9}Li rate	131 ± 29
^{8}He rate	14.5 ± 3.2
^{9}Li (β,n) rate	67 ± 15
^{8}He (β,n) rate	2.33 ± 0.51

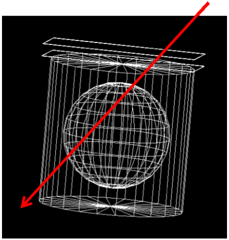
The Top Tracker may play a significant role



^{9}Li is one of the most important backgrounds in JUNO

The Kamland veto scheme to showering muon events brings a 100% deadtime
New rejection schemes must be studied according to JUNO muon tracking capabilities

The JUNO Top Tracker

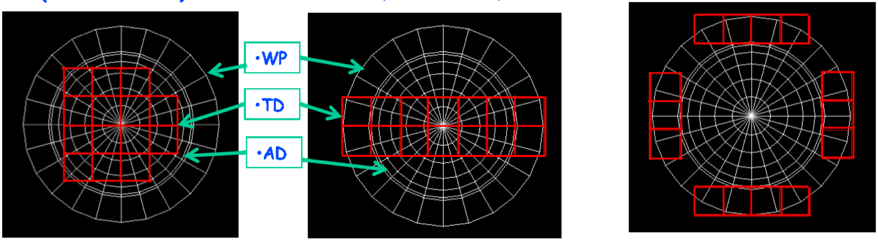


- Possibility to reuse the OPERA Target Tracker for JUNO
- 62 planes, sensitive area: 6.7×6.7 m^2
- with x-y readout coordinates (read from both sides)
- A first attempt to optimize the existing TT planes has been performed: the 4XY Rectangle option is preferred
- investigation on how to improve the Top Tracker coverage is under investigation

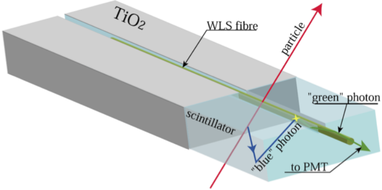
•4XY Middle (Mid)
•(3×4+2 modules)

•4XY Rectangle(Rtg)
•(2×7 modules)

•4XY Around("O")
•(2×4+2×3 modules)



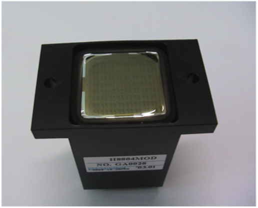
The OPERA Target Tracker



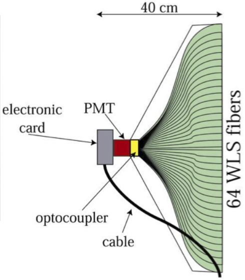
detection technique: polystyrene scintillating strips (plastic)

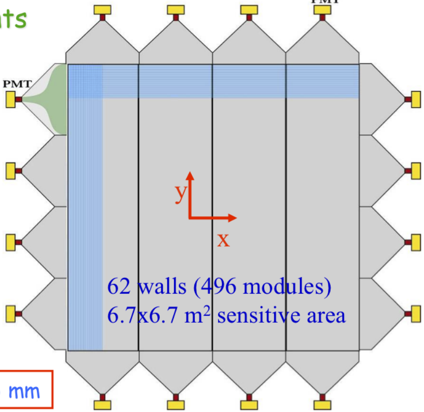
role:

- find the "good" Pb/emulsion brick
- calorimetric information on neutrino events



Hamamatsu MA-PMT (64 channels) 3x3 cm^2





62 walls (496 modules)

6.7x6.7 m^2 sensitive area

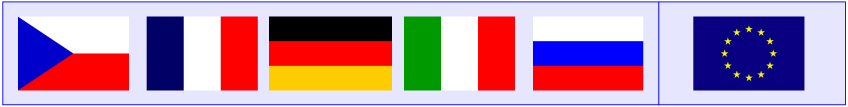
TT wall thickness<36 mm

La collaborazione - JUNO

- Una proto collaborazione esiste dal 2013
- La Collab. sarà definita al prossimo meeting (Pechino, 28-30 Luglio 2014)

La collaborazione - JUNO Europa

- Items di interesse comuni:
  - ✓ Top Tracker (FR+IT), PMT electronics (DE), LAB purification (IT+DE), . . .
- Prossimo meeting JUNO-Europa a Milano (9 luglio)



Praha	Parigi 7 (APC)	Aachen (RWTH)	Ferrara	Dubna (JINR)
	Strasburgo	Julich	Frascati	
		Monaco (TUM)	Milano	
		Tubinga	Perugia	
			Padova	

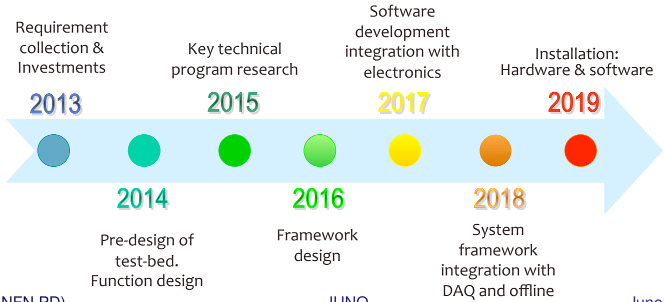
Bologna (?), Roma3 (?)

JUNO Status

- The project has been approved by CAS for R&D and design
- Geological survey completed:
  - ✓ Granite rock, little water, $T \sim 31$ °C
- EPC contract signed:
  - ✓ Engineering design by July 2014
  - ✓ Construction work starting in November 2014

Task Sharing will be defined by the end of 2014

- The collaboration is preparing a CDR and a Yellow Book on JUNO Physics



JUNO a Padova

- Persone interessate:

✓ Brugnera, Dusini, Garfagnini, Lippi, Mezzetto, Sirignano, Stanco

✓ a breve decideremo le percentuali e le richieste finanziarie per il 2015 (in accordo con gli altri gruppi italiani)

✓ forte sinergia in divenire con i gruppi italiani (per esempio LNF per TT) ed europei

- Argomenti di possibile interesse (dipende da $\sum$FTE):

✓ Top Tracker (elettronica e rivelatore)

✓ DAQ (globale) ed elettronica dei PMT

✓ test dei PMT da 8" (insieme a Milano)

- Richieste alla Sezione per il 2015:

✓ supporto da officina elettronica per Top Tracker (da definire dopo il 9 luglio)

✓ supporto da ufficio tecnico (da definire dopo il 9 luglio)