Project JUNO

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Our current knowledge of neutrino mixing matrix

$$V_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & \hat{s}_{13}^{*} \\ 0 & 1 & 0 \\ -\hat{s}_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} \equiv \cos\theta_{ij}, s_{ij} \equiv \sin\theta_{ij}, \hat{s}_{13} \equiv e^{+i\delta}\sin\theta_{13}$.

- $\sin^2\theta_{12} = 0.307 \pm 0.017$
- $\sin^2\theta_{23} = 0.398 \pm 0.03$
- $\sin^2\theta_{13} = 0.0228 \pm 0.0029$
- $\delta/\pi \approx 1.08 \pm 0.37$ Fogli et al. arxiv:1205.5254

2012

- Angle θ_{13} - is the discovery of 2012! (Daya Bay, Reno, Double Chooz, T2K, MINOS)
- Indication on non-zero value for $\delta_{\rm CP}$ from a global fit of the data

Neutrino mixing matrix:

$$|V_{\rm PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} .$$

is sharply different from the quark mixing matrix:

$$|V_{\rm CKM}| \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix} ,$$

This could be a guideline for theorists...

- Neutrino is massive!
- The mass of the heaviest is in quite narrow interval:

$$0.05 \text{ eV} < m_h < 0.36 \text{ eV}$$

- From neutrino oscillations:

$$\Delta m^2_{21} = (7.65^{+0.23}_{-0.20}) \times 10^{-5} \text{ eV}^2,$$
$$|\Delta m^2_{\mu\mu}| = (2.44^{+0.10}_{-0.10}) \times 10^{-3} \text{ eV}^2$$

- From tritium decays:

$$m_\beta = \left[\sum_i |V_{ei}|^2 m_i^2 \right]^{1/2} < 2.2 \text{ eV}$$

- From cosmology (model dependent):

$$\sum_i m_i < 0.36 \text{ eV}$$

- Dirac or Majorana?
- Neutrino mass hierarchy (MH)
- CP -violation phase δ
- Unitarity of neutrino mixing matrix or do exist sterile neutrinos?
- The mass of the lightest neutrino
- Presence of non standard interactions? (NSI)
- octant of θ_{23}

What is the mass hierarchy?

- Sometimes people erroneously say: "Just sign of $\Delta m^2_{31}, \Delta m^2_{31}$"
  - ↪ If this were right, then how to observe it? The survival probability is invariant under the change $\Delta m^2_{31} \to -\Delta m^2_{31}$, $\Delta m^2_{32} \to -\Delta m^2_{32}$

$$P_{ee} = 1 - 4 s^2_{13} c^2_{13} \left(c^2_{12} \sin^2 \Delta_{31} + s^2_{12} \sin^2 \Delta_{32} \right) - 4 c^4_{13} s^2_{12} c^2_{12} \sin^2 \Delta_{21},$$

where

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4 E_\nu}, \quad \Delta m^2_{ij} = m^2_i - m^2_j .$$

- Fortunately, the right answer would be: "Both the sign **and** the value of $\Delta m^2_{31}, \Delta m^2_{31}$ are different for normal (NH) and inverted (IH) hierarchies":

$$\begin{array}{lll} \text{NH:} & \Delta m^2_{31} \geq 0, \Delta m^2_{32} \geq 0, & |\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21} \\ \text{IH:} & \Delta m^2_{31} \leq 0, \Delta m^2_{32} \leq 0, & |\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21} . \end{array}$$

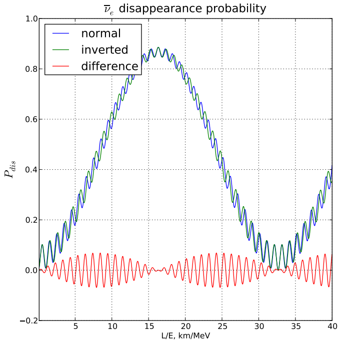
How the oscillation probability differs for two MH?

1. Assume what we have measured with accelerators and atmospheric neutrinos is Δm^2_{32}. Then,

$$P_{ee}^{NH} - P_{ee}^{IH} = -4 s^2_{13} c^2_{13} c^2_{12} \sin 2\Delta_{32} \sin 2\Delta_{21}$$

2. Assume what we have measured with accelerators and atmospheric neutrinos is Δm^2_{31}. Then,

$$P_{ee}^{NH} - P_{ee}^{IH} = +4 s^2_{13} c^2_{13} s^2_{12} \sin 2\Delta_{31} \sin 2\Delta_{21}$$



- The maximum is at $L/E \simeq 7.5$ km/MeV. Reactors with $\langle E \rangle \simeq 4$ MeV would need a baseline $L \simeq 30$ km

- Similar assumptions on what was measured (Δm^2_{31} or Δm^2_{32}) the "effect" is different: both sign and amplitude. This is disturbing...

What do we measure with accelerators, atmosphere and (recently) reactors like Daya Bay?

- Since $|\Delta m^2_{31,32}|/\Delta m^2_{21} \simeq 30$ all current neutrino oscillation experiments are degenerate in $\Delta m^2_{31,32}$ — can not measure Δm^2_{31} AND Δm^2_{32}
- What do they measure? They measure some effective values (H.Minokata et al. Phys.Rev.D76:053004,2007):

$$\begin{aligned}\Delta m^2_{\alpha\alpha} &\equiv \eta_\alpha \Delta m^2_{31} + (1-\eta_\alpha)\Delta m^2_{32} \\ &= \Delta m^2_{32} + \eta_\alpha \Delta m^2_{21} = \Delta m^2_{31} - (1-\eta_\alpha)\Delta m^2_{21},\end{aligned}$$

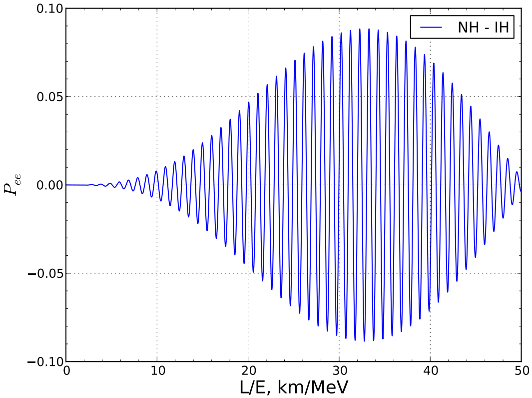
where

$$\eta_\alpha \simeq \frac{|V_{\alpha 1}|^2}{|V_{\alpha 1}|^2 + |V_{\alpha 2}|^2}$$

and thus

$$\begin{aligned}\Delta m^2_{ee} &\simeq c^2_{12}\Delta m^2_{31} + s^2_{12}\Delta m^2_{32} \\ \Delta m^2_{\mu\mu} &\simeq s^2_{12}\Delta m^2_{31} + c^2_{12}\Delta m^2_{32} + 2\Delta m^2_{21} s_{12}c_{12}s_{13}\tan\theta_{23}\cos\delta \\ \Delta m^2_{\tau\tau} &\simeq s^2_{12}\Delta m^2_{31} + c^2_{12}\Delta m^2_{32} - 2\Delta m^2_{21} s_{12}c_{12}s_{13}\cot\theta_{23}\cos\delta\end{aligned}$$

- $\Delta P_{\rm ee} = P_{\rm ee}^{NH} - P_{\rm ee}^{IH} = -4s_{13}^2 c_{13}^2 \sin^2 2\Delta_{\rm ee} \left(c_{12}^2 \sin 2s_{12}^2 \Delta_{21} - s_{12}^2 \sin 2c_{12}^2 \Delta_{21}\right)$
- If $c_{12}^2 = s_{12}^2$ — no way to measure MH with vaccuum oscillations
- For $\Delta m_{\rm ee}^2 = 2.44 \cdot 10^{-3}$ eV^2 the maximum of $\Delta P_{\rm ee}$ is at $L/E \simeq 10\pi$ km/MeV
  - ↪ $L = 60(120)$ km for $E = 2(4)$ MeV
  - ↪ The amplitude of the effect is $\sin^2 2\theta_{13} = 0.09$ (9% of amplitude modulation due to MH)



- With accelerators and $\langle E \rangle \simeq 1$ GeV one would need a baseline $L \simeq 30000$ km $\gg D_\oplus$ km in vacuum.
- However at long distances neutrino propagate in the matter (Earth). This changes a lot because of matter effect!

How matter matters?

- ν_e gets an additional phase shift relative to $\nu_{\mu,\tau}$ because of W exchange in reactions:

$$\nu_e + e \to \nu_e + e(W, Z), \quad \nu_{\mu,\tau} + e \to \nu_{\mu,\tau} + e(Z)$$

- The characteristic length in the Earth with $\rho \simeq 5.5 \mathrm{g/cm}^3$ is $L_m = (\sqrt{2} G_F n_e)^{-1} \simeq 1000$ km
- The effect is that ν_e becomes heavier in matter:

Normal Hierarchy	Inverted Hierarchy
$\nu_e \to \nu_3^m \to \nu_\tau$	$\nu_e \to \nu_2^m \to \nu_\mu$
$\nu_\tau \to \nu_2^m \to \nu_\mu$	$\nu_\mu \to \nu_1^m \to \nu_\tau$
$\nu_\mu \to \nu_1^m \to \nu_e$	$\nu_\tau \to \nu_3^m \to \nu_e$

- Due to matter effect $P_{\mu e}$ is enhanced for NH and suppressed for IH.
- The difference could be as large as 30% (!) for $E = 6$ GeV and $L = 6000$ km.

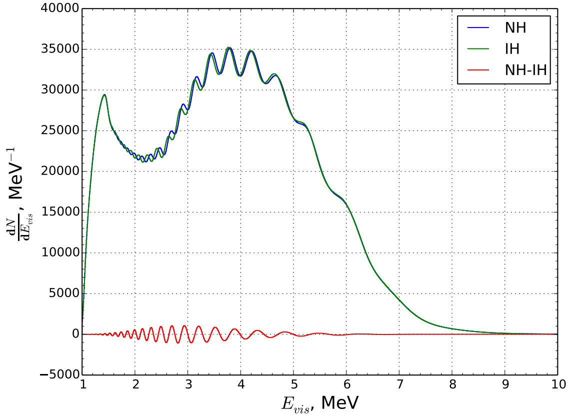
Therefore, a number of proposals:

Project	ν Source	Detector	Goal	Problem
Nova	LBL (810 km)	14 kt tracking calorimeter	2σ (2020)	Parameter degeneracy
JUNO	Reactor (58 km)	20 kt LS	3σ (2025)	Energy resolution
PINGU/ORCA	Atmosphere	1-10 Mt Ice	$3-5\sigma$ (?)	Energy resolution, systematics
INO	Atmosphere	50 kt mag. cal.	3σ (2030)	Low stat (10 years)
T2HK	LBL (295 km)	1 Mt water	3σ (2030)	Parameter degeneracy
LBNE	LBL (1300 km)	10 kt LAr	$2-5\sigma$ (2030)	Parameter degeneracy
LAGUNA/Glacier	LBL (2300 km)	20 kt LAr	5σ (2030)	Beam line from CERN
LAGUNA/LENA	LBL (2300 km)	50 kt LS	5σ (2030)	Beam line from CERN

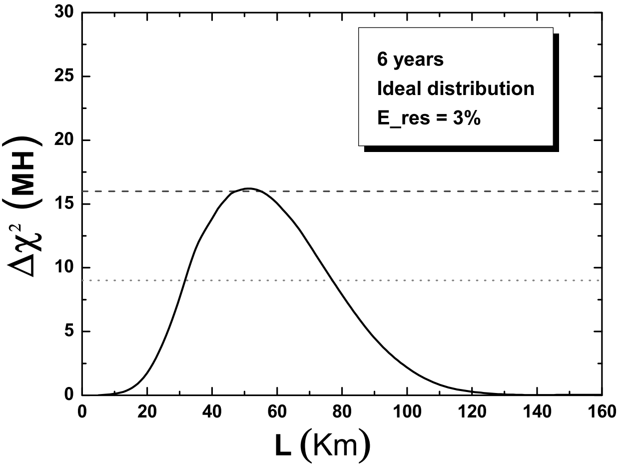
- Number of IBD events assuming no oscillations. For $P_{\rm th} = 35$ GWt and $L = 52$ km, assuming $m_{\rm H}/m_{\rm LS} = 0.12$ one gets

$$N_{\rm IBD} = 8.3 \cdot 10^4 \left(\frac{P_{\rm th}}{35\text{GWt}}\right) \left(\frac{m_{\rm det}}{20\text{ktons}}\right) \left(\frac{t}{\text{year}}\right) \left(\frac{52\text{km}}{L}\right)^2$$

- About 60 IBD events per day with energy spectrum (include geo-neutrinos) below

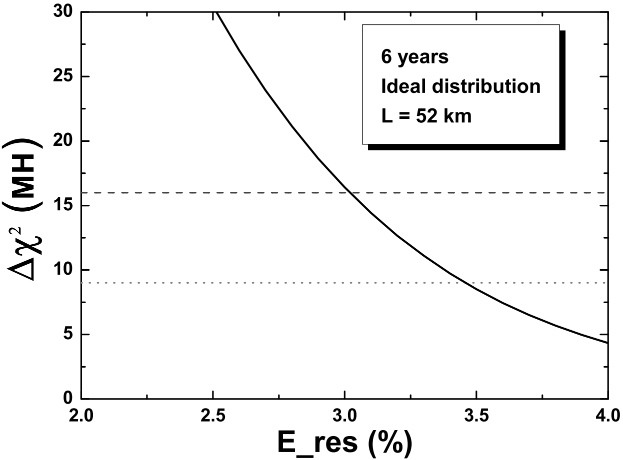


Distance optimization (Y.F. Li et al. PRD 88 (2013) 013008)



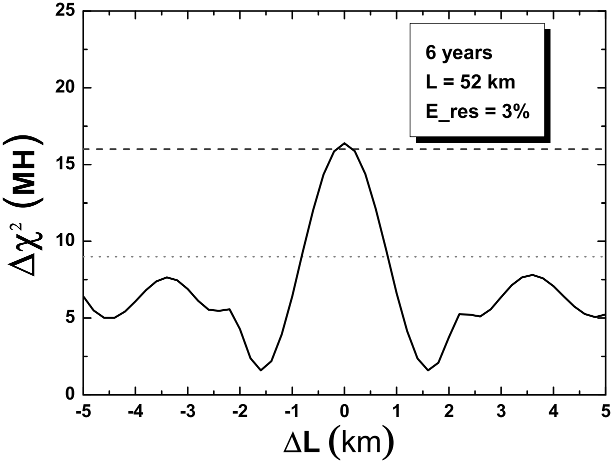
$\hookrightarrow L = 52$ km

Energy reconstruction (Y.F. Li et al. PRD 88 (2013) 013008)



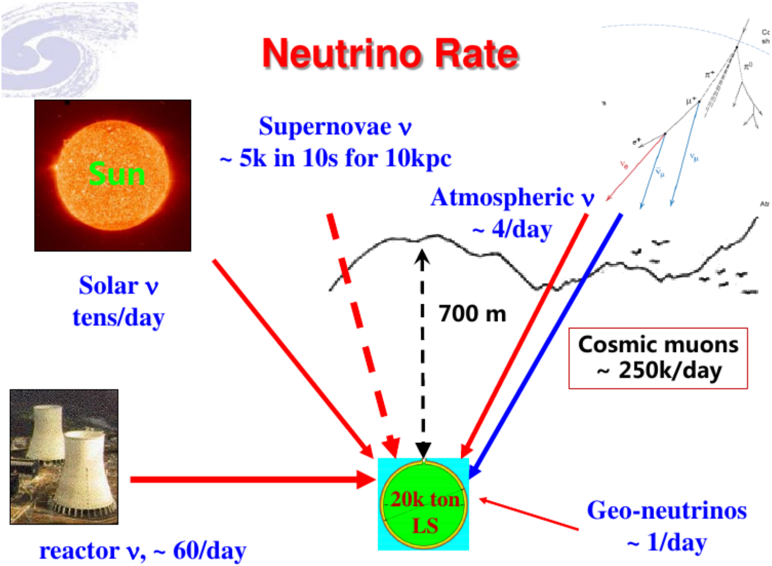
$\hookrightarrow \sigma_E = 3\%/\sqrt{E_{\text{vis}}} = (2.6\%/\sqrt{E_{\text{vis}}} + 0.3\%)$

Baseline requirements (Y.F. Li et al. PRD 88 (2013) 013008)

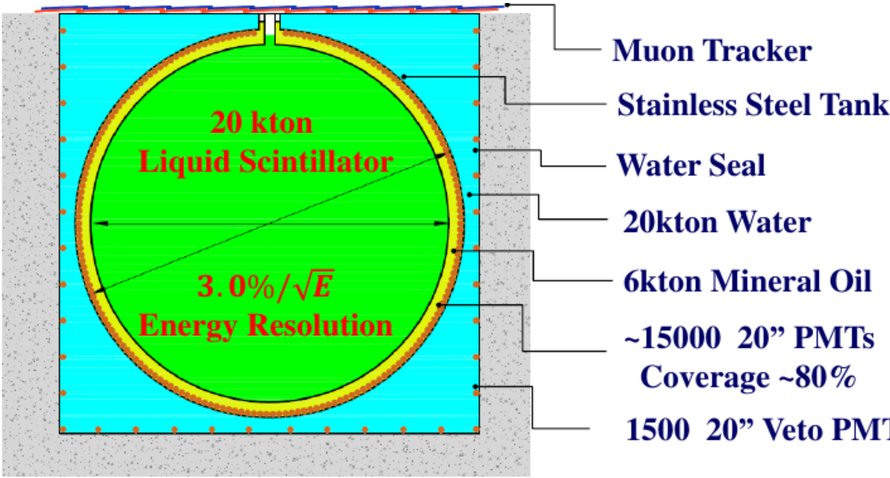


$\hookrightarrow \Delta L < 200$ m

IBD events and background (slide borrowed from J.Cao's talk)



Juno detector (current design) (slide borrowed from J.Cao's talk)



The mechanics of the ~40 m diameter detector is challenging. Many options are under consideration.

Challenges on 3% energy resolution

- JUNO geometry and 80% PMT coverage
  - ↪ 75-76% current engineering PMT layout
- High QE PMTs: from 25% to 35%
  - ↪ (a nontrivial) work in progress
- Increase light yield of LS by 13%
  - ↪ Could be tested in 2016 with Daya Bay
- LS attenuation length:
  - from 15 m = 24 m (absorption) + 40 m (Rayleigh) to 20 m = 40 m (absorption) + 40 m (Rayleigh)
    - ↪ Rayleigh scattering could be 27 m (further measurements ongoing)

Liquid Scintillator without Gd

- Better attenuation length $\rightarrow$ better energy resolution
- Less risk in synthesis and long-term stability
- Lower irreducible accidental backgrounds from LS, important for large detector. Without extensive purification:
  - With Gd: $\sim 10^{-12}$ g/g (Daya Bay Gd Cl_3 U/Th ~ 1 ppb)
  - Without Gd: $\sim 10^{-16}$ g/g

Default Recipe: LAB + 3g/L PPO + 15mg/L bis-MSB (Daya Bay: safe, very good transparency)

Background summary

Assumptions

- Overburden is 700 m
  - $E_\mu \simeq 211$ GeV, $R_\mu \simeq 3.8$ Hz
  - Single rates from LS and PMT are 5Hz, respectively
  - Good muon tracking
  - Similar muon efficiency as DYB

	DYB	JUNO
Mass (tons)	20	20k
E_μ (GeV)	57	211
L_μ (m)	1.3	23
R_μ (Hz)	21	3.8
$R_{singles}$ (Hz)	50	10

	B/S, % (DYB)	B/S, % (JUNO)	Techniques
Accidentals	1.4	10	Low PMT radioactivity; LS purification; prompt-delayed distance cut
Fast neutron	0.1	0.4	High muon detection efficiency (similar as DYB)
$^9Li/^8He$	0.4	0.8	Muon tracking; If good track, distance to muon track cut (<5m) and veto 2s; If shower muon, full volume veto 2s

Detector options (slide borrowed from J.Cao's talk)

Acrylic sphere in water
Grid for PMTs support
and Optical separation

Nylon (ETFE) balloon
in LAB in a stainless
steel sphere

LS in a stainless steel
sphere, PMTs in acrylic
modules in LAB or MO

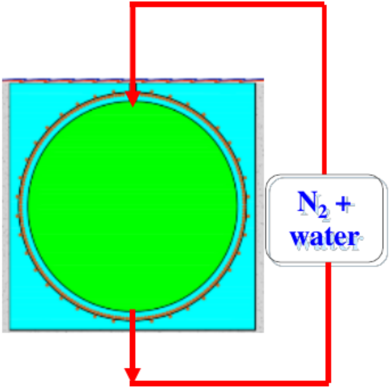
- Other variations: Balloon + module (sealed or not sealed); Steel tank only (high rate singles)
- 20 kton LS target → **diameter 35.4 m** (Fiducial Volume) LAB density 0.856 g/L, LS (w/ fluor) ~ 0.859
- The PMTs should be **~1.5 m away** from the FV, either by physical separation or by FV cut (estimated vertex resolution 5-10 cm). CD diameter **~39 m** (depends on PMT radioactivity)

Non trivial features of detector design (slide borrowed from J.Cao's talk)

- **Acrylic Sphere**
  - Transparency of thick acrylic (~12 cm)
  - Internal reflection (LS, acrylic 1.5, water 1.33. Hit pattern w/ dark zone?)
  - PMT potting (in water)
- **Balloon**
  - Transparency of nylon film
  - Haze (97% light in 2.5 degree cone)
  - Distortion of balloon between ropes
  - Radon/dust on balloon, radon from steel
  - Buffer layer: LAB scintillation? PE pollution to buffer LAB
- **Acrylic module (single or multiple PMTs)**
  - Radon from steel
  - Radioactivity between modules
  - Pollution to LS from steel and many materials

All need explosion proof for PMT

LS recycling (slide borrowed from J.Cao's talk)



- Online handling of LS
  - LS aging after years running?
  - Found high LS radioactivity after filling?
  - Pollution (optical and radioactivity e.g. Rn) from detector material
- Simulate the liquid flow → need **multiple ports**?
- Distillation? (power consumption, heat, LS transparency)

DAQ rate (slide borrowed from J.Cao's talk)

Can be < 100 Hz

Supernovea: >1k Hz

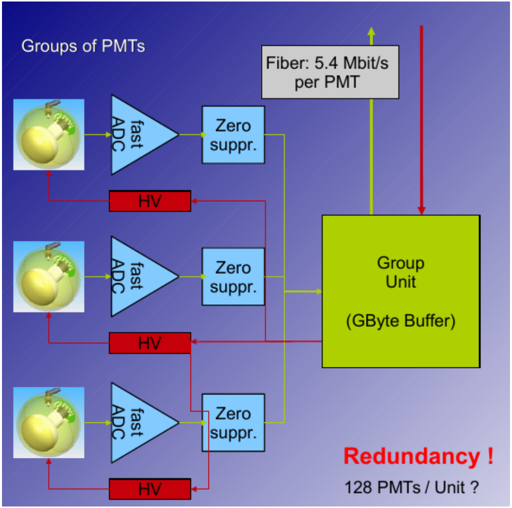
1k – 10k Hz

- Balloon need be in the middle of PMTs and FV to reject (α,n) from Rn
- Acrylic module can not be too high for mechanic reason

1M Hz, need consider event overlapping

Different requirements to electronics and DAQ

Electronics and trigger (slide borrowed from A.Stahl talk)



No hardware trigger. Write everything. Intelligent PMT

Other systems

- Veto system:
  - ↪ RPC planes?
  - ↪ OPERA plastic scintillators?
- Readout & trigger:
  - ↪ FADC for all PMTs
  - ↪ Need complicated trigger schemes for different physics (or software trigger)
- DAQ & slow control:
  - ↪ Handle KHz supernova events with 15K ch. FADC
- Offline software & computing
  - ↪ A new framework for neutrino exp. ?
- Calibration system
  - ↪ Sub-marine
  - ↪ 4π – robes
  - ↪ Others ?

- Time schedule:
  - end of 2014 — final decision
  - 2015 — engineering design, PMT production line manufacturing
  - 2016 — Start PMT production, detector production or bidding
  - 2017 — Complete civil construction, start detector construction
  - 2018 — Start LS production
  - 2019 — Complete detector assembly, installation, LS filling
  - 2020 — Start data taking
- in space (South of China, Kaiping county, Jiangmen city):

Brief summary of Daya Bay II (=JUNO) proposal (Demanding requirements but doable):

- 20 kt of LS (35.4 m diameter)
- Energy resolution $3\%/\sqrt{E}$
  - LAB based, non-doping liquid scintillator, attenuation length $>$ 20m (depends on Rayleigh scattering length)
  - PMT photocathode coverage $>$ 75%
  - PMT quantum efficiency $>$35%
- Thermal power 36 GWt
- Baseline 53 km, equal baselines
- Detector diameter 39m (depends on PMT radioactivity)
- Detector with recycling piping for online handling of LS
- LS radioactivity U/Th/K $< 10^{-15}$ g/g (for reactor ν). Total singles ($>$0.7 MeV) in fiducial volume $<$ 20 Hz
- Vertex and muon tracking (PMT timing requirements need be worked out)
- 60 neutrinos per day
- Sensitivity: $\simeq 3\sigma$ in 6 years

Rich physics goals

- measure CKM matrix to 1% level similar to the quark sector!

	Current	JUNO
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	7.5%	N/A
$\sin^2\theta_{13}$	10%$\rightarrow$ 4%	15%

- Supernova neutrinos (less than 20 events so far)
  - $\bar{\nu}_e + p \rightarrow n + e^+$, $\sim$ 3000 correlated events
  - $\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B}^* + e^+$, $\sim$ 10-100 correlated events
  - $\nu_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{N}^* + e^-$, $\sim$ 10-100 correlated events
  - $\nu_x + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^* + \nu_x$, $\sim$ 600 correlated events
  - $\nu_x + p \rightarrow \nu_x + p$, single events
  - $\nu_x + e^- \rightarrow \nu_x + e^-$, single events
- Geoneutrinos
  - 10 times more than recorderded by BOREXINO and KamLAND
  - Difficult on systematics
  - Background to reactor antineutrinos

Summary

- Mass hierarchy will likely be measured within next 10-15 years. Accelerator, atmosphere and reactor experiments will be crucial. None of them alone is able to unanimously discover it with a sensitivity better then 5σ. Join efforts are needed
- JUNO has a rich physics program: PMNS matrix and Δm^2_{ij} precision measurements (reaching the quark level precision within next 10 years)
- Collaborators are welcome!

Disclaimer: These are not official results (yet). This is a preliminary result from our study (D.Taichenachev, D.Naumov).

- The current design baseline seems to be nearly optimal for 20 ktons detector. But not optimal for free detector mass
- A better $3 \rightarrow 3.8\sigma$ sensitivity can be achieved at $L \simeq 85$ km. 20 ktons $\rightarrow \simeq 53$ ktons detector mass increase. FV diameter increases from 35.4 m to 49.1 m
- less strict energy resolution requirements
- New cite investigation...