JUNO

Determination of the Neutrino Mass Hierarchy using Reactor Neutrinos

Björn Wonsak

Universität Hamburg

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

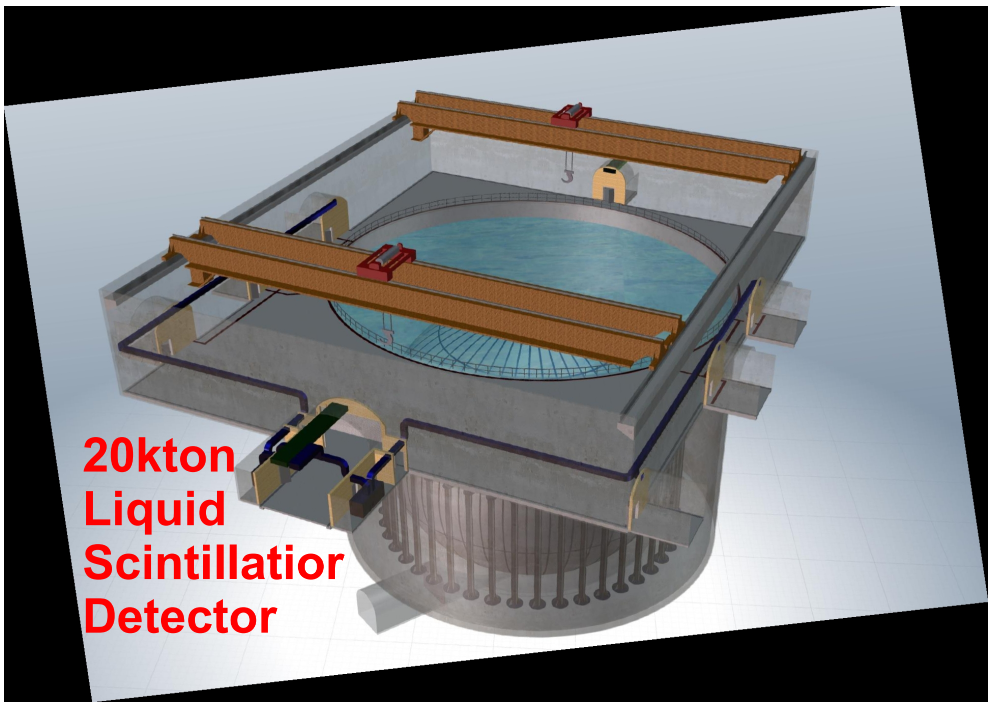
Overview

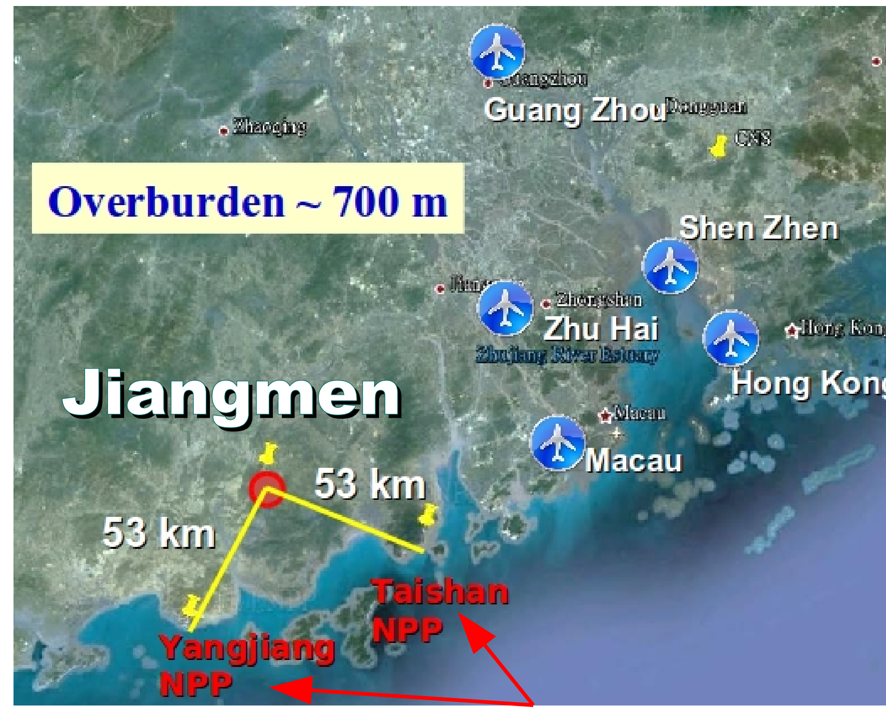
- Introduction
- Physics Motivation and Concept
- Detector Design and Project Status

JUNO

Jiangmen **U**nderground **N**eutrino **O**bservatory

Main goal: Mass Hierarchy (MH)

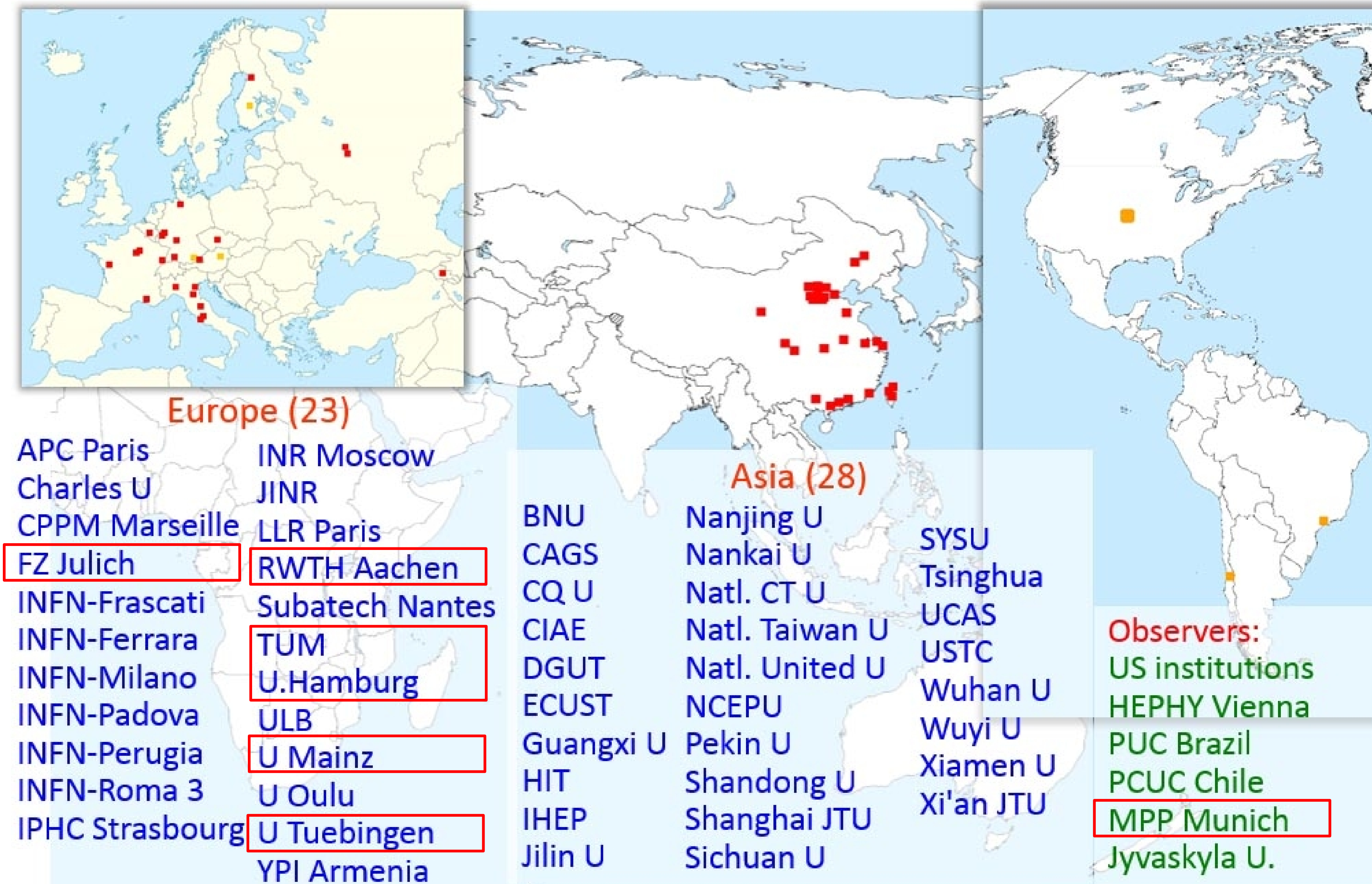




- Collaboration formed June 2014
- Start of civil engineering end 2014
- Begin data taking 2020

High power nuclear power plants (>17GW each)

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

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

Observers:

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

ν-Oscillation Mixing Parameters

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

$\theta_{23}=\theta_{atm}$ | $\theta_{13}=\theta_R, \delta$ | $\theta_{12}=\theta_{sol}$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\theta_{23} \approx 45°$ | $\theta_{13} \approx 9°, \delta$? | $\theta_{12} \approx 33°$

CP-violating phase δ_{CP}

Mass Hierarchy

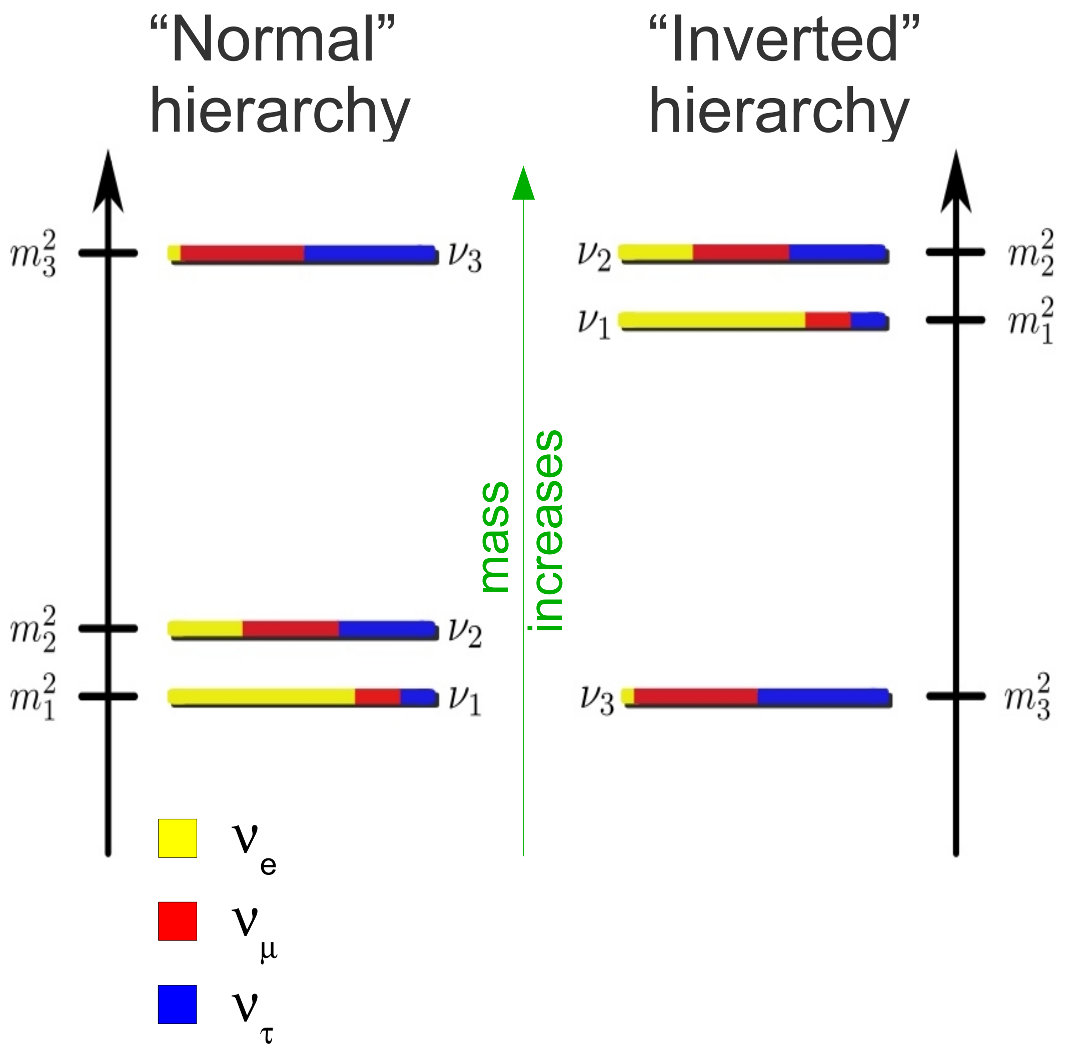
Two mass-differences:

$\Delta m^2_{solar} = \Delta m^2_{21} \approx 7.5\cdot10^{-5} eV^2$,

$|\Delta m^2_{atm}| = |\Delta m^2_{32}| \approx 2.5\cdot10^{-3} eV^2$

One sign unknown

→ Two mass orderings possible



How to Measure Mass Hierarchy

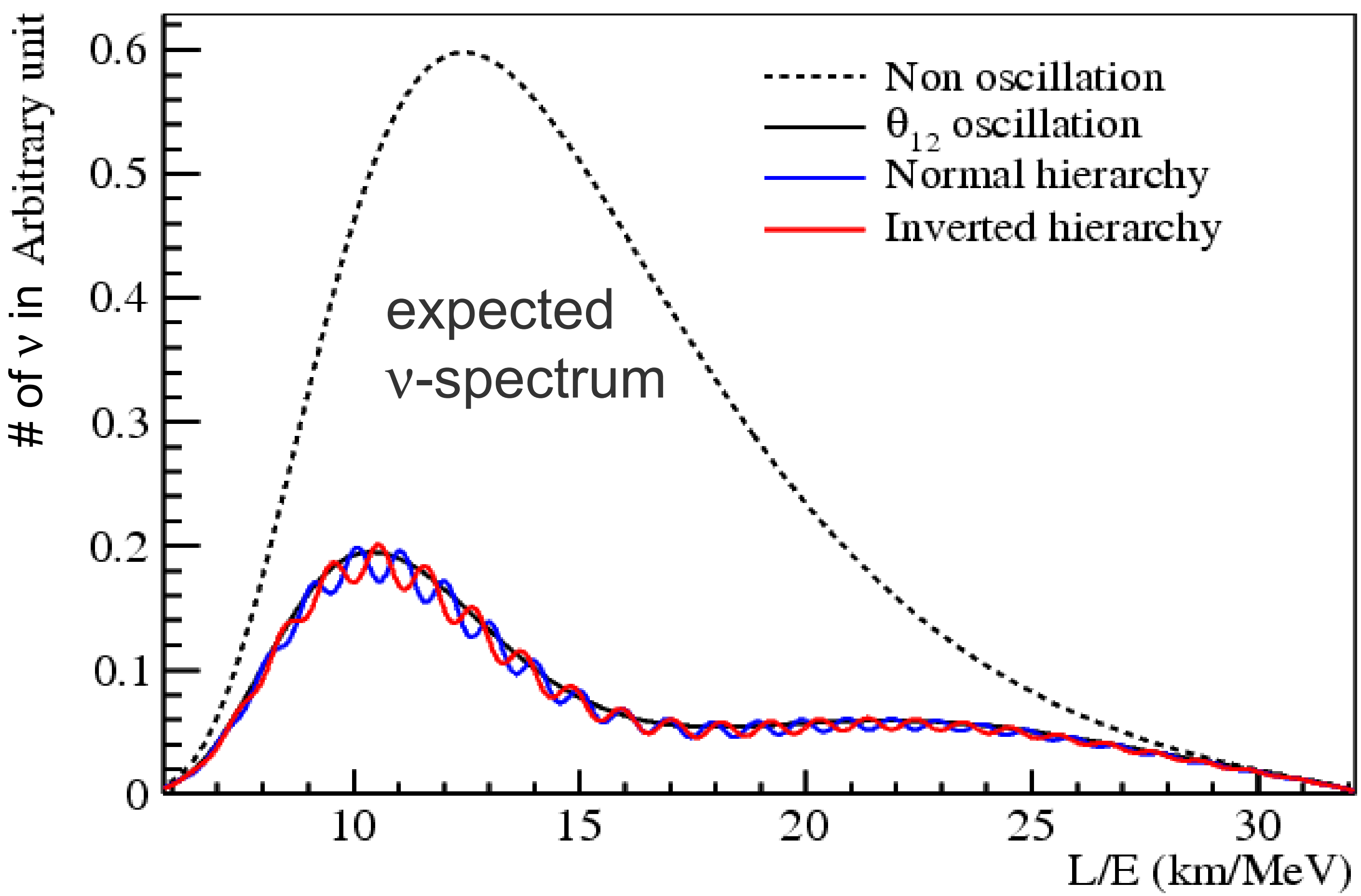
- **Matter effects:** **Long-baseline ν-exp., atmospheric ν, supernova ν**
  - Use oscillation between ν_e and ν_μ
  - Matter potential depends on sign of Δm^2_{13}
  - MSW resonance either for neutrinos or antineutrinos

- **Vacuum oscillation:** **Reactor ν at medium baseline**
  - Higher order terms of oscillation depend on Δm^2_{13}
  - Precision measurement of oscillation spectrum

Very different approaches → Complimentary
→ Nice synergy between both

Mass Hierarchy with Reactor Neutrinos

Idea: Put large (20kt) LS-detector at first maximum of solar oscillation



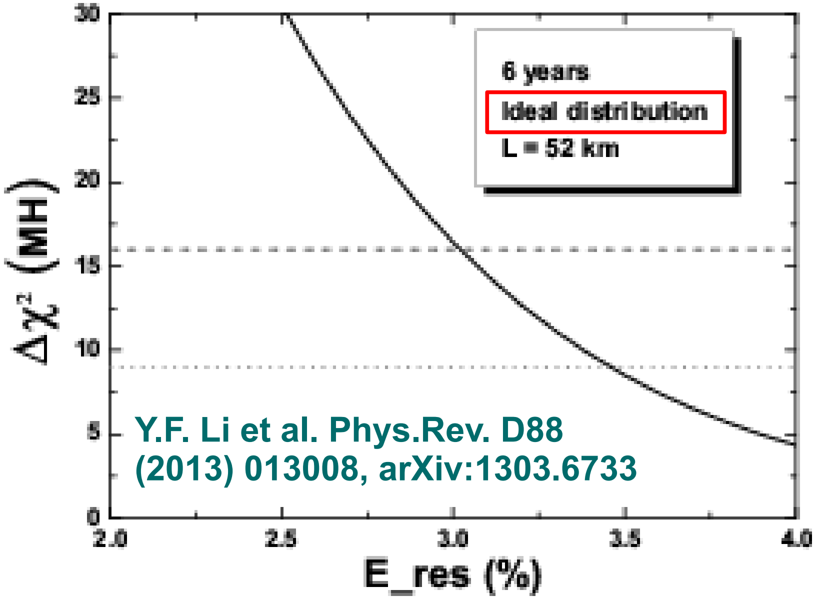
Different oscillation frequency of subdominant terms for the two hierarchies → Fourier-analysis

J. Learned et. al. hep-ex/0612022, L. Zhan et. al. 0807.3203

Requirements for Mass Hierarchy

- **Crucial point:** Need well defined L/E

- **Baseline L:**
  - Fixed by detector site to ~53 km
  - Difference btw. cores < 500 m



- **Energy resolution:**
  - Critical design parameter
  - $\Delta m^2_{Atm}/\Delta m^2_{Sol} \approx 33$
    $\rightarrow$ 3%/$\sqrt{E(\text{MeV})}$ required
    \+ non-stochastic term < 1%

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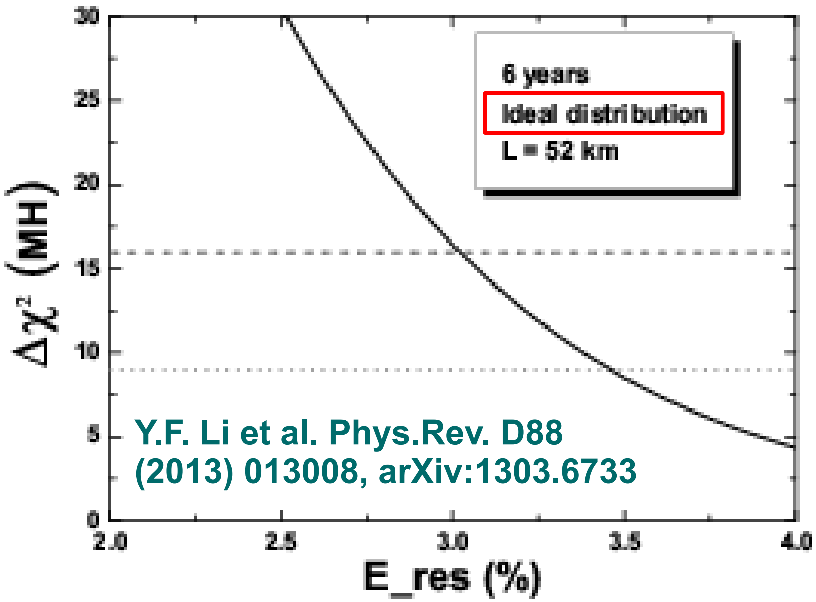


- **Energy resolution:**
  - Critical design parameter
  - $\Delta m^2_{Atm}/\Delta m^2_{Sol} \approx 33$

    → 3%/√E(MeV) required → High light yield

    + non-stochastic term < 1% → Calibrations

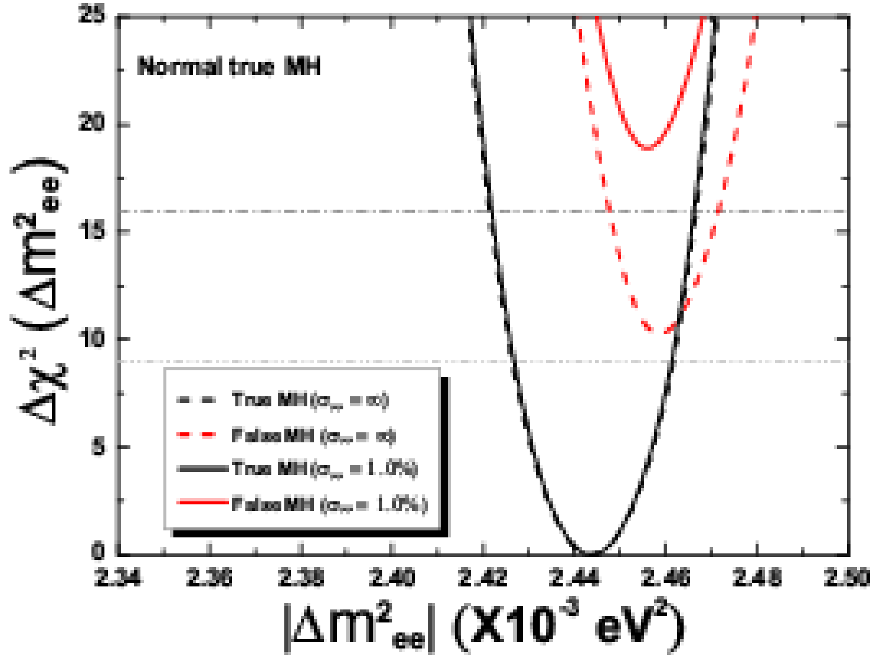
Addressed by:

High light yield

Calibrations

Mass Hierarchy Sensitivity

- **Measurement with or without constraint on $\Delta m^2_{\mu\mu}$**



Y.F. Li et al. Phys.Rev. D88 (2013) 013008, arXiv:1303.6733

- **Sensitivity after 6 years:**
  - No constraint: $\overline{\Delta\chi^2} > 9$ ⟶ relative measurement → self calibration of energy scale,

    Y.F. Li et al., Phys.Rev. D88 (2013) 013008
  - With 1% constraint: $\overline{\Delta\chi^2} > 16$

    Δm^2 @~1% by combined analysisT2K+NOvA [1312.1477]

Precision Measurement of Mixing Parameters

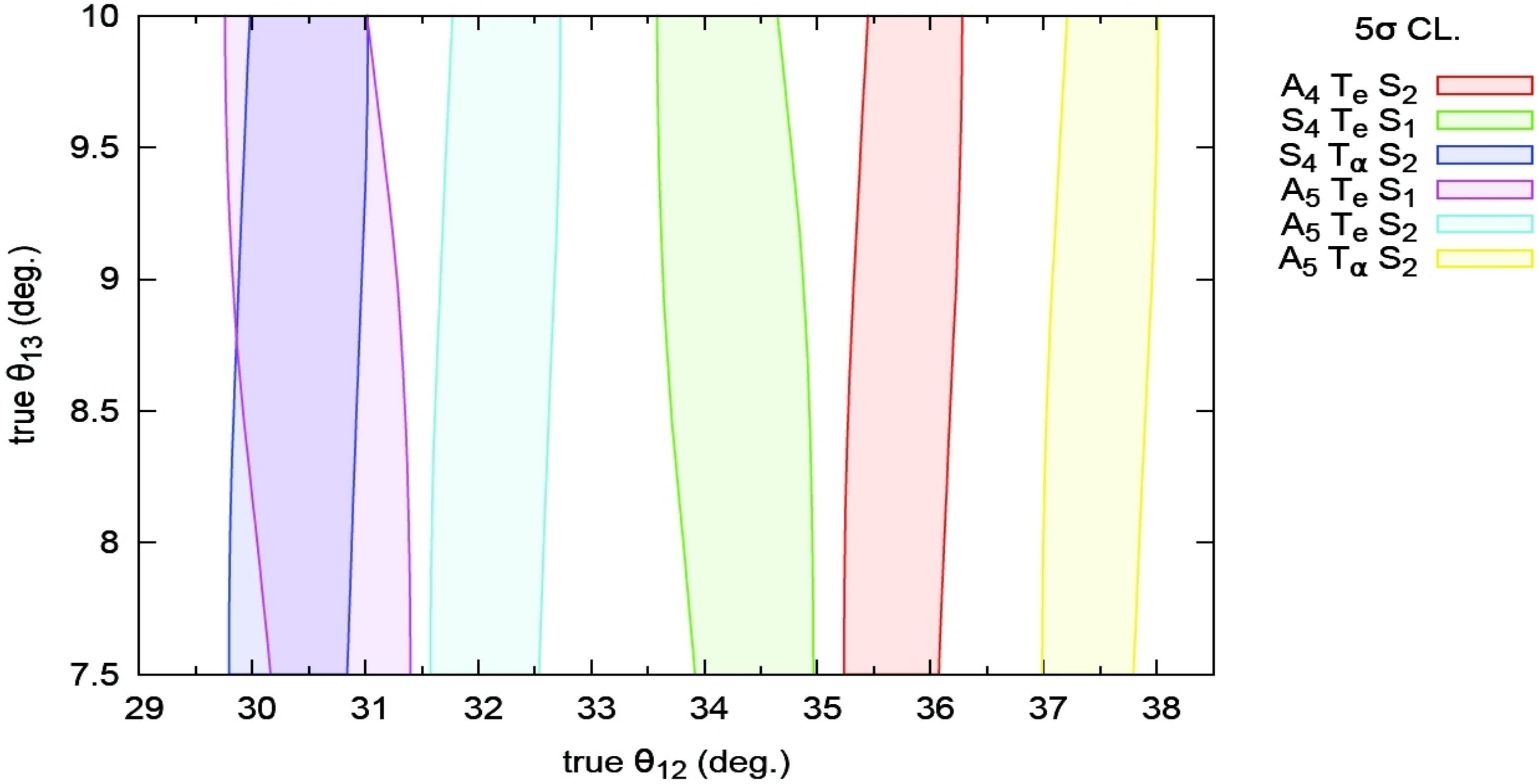
- Fundamental to the Standard Model and beyond
- Probing the unitarity of U_{PMNS} to ~1% level !
  - Uncertainty from other oscillation parameters and systematic errors, mainly energy scale, are included

	Current	JUNO
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	10%	N/A
$\sin^2\theta_{13}$	14% ➔ 4%	~ 15%

Will be more precise than CKM matrix elements !

Motivation for Precision

5σ allowed regions for solar predictions of JUNO (after 6 years)

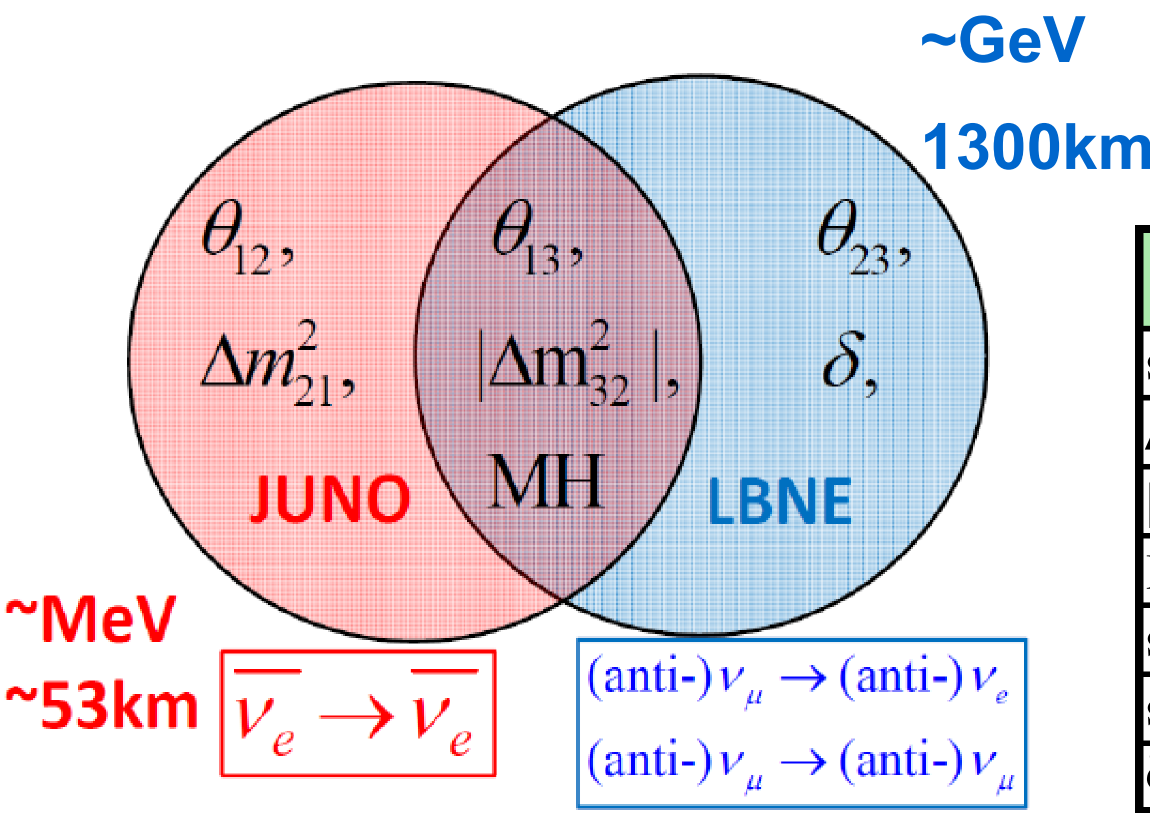


P. Ballet, S.F. King, C. Luhn, S. Pascoli and M.A. Schmidt: arXiv:1406.0308

Only one example!

Complimentarity to other Experiments

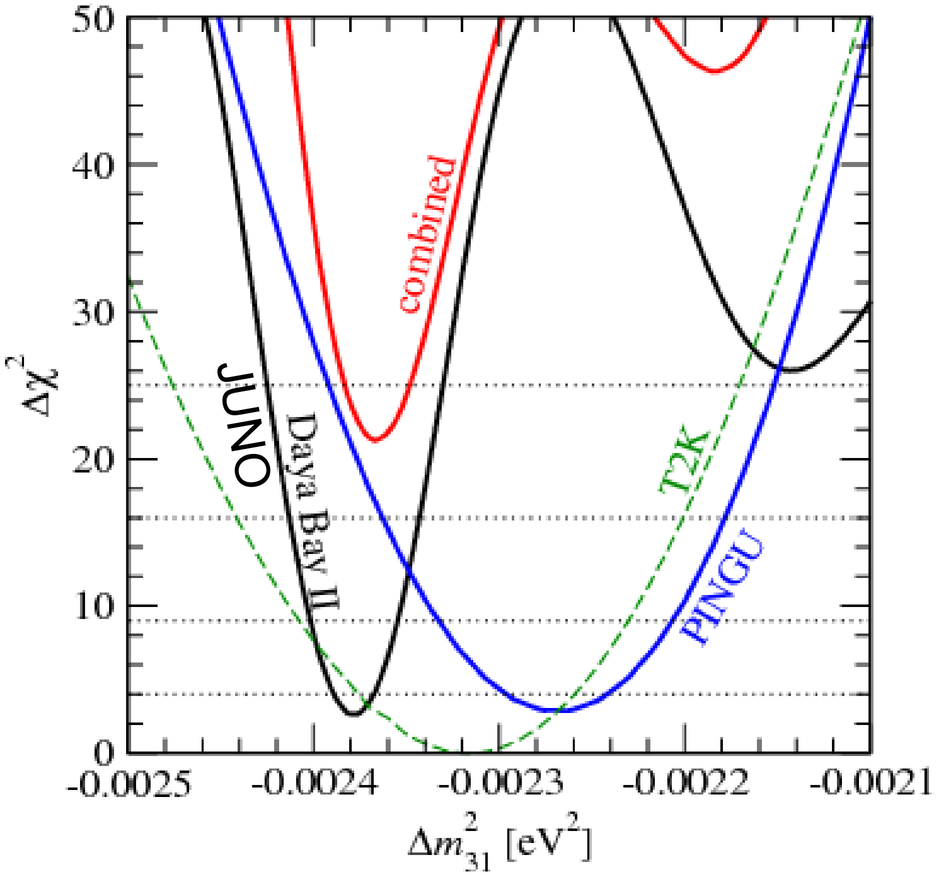
- **JUNO: Unique precision in the solar sector**
  - → Δm^2_{12} and θ_{12} enter long-baseline analysis
  - → will also affect δ_{CP} analysis



	JUNO	LBNE
$\sin^2 2\theta_{12}$	0.7%	
Δm^2_{21}	0.6%	
$\lvert\Delta m^2_{32}\rvert$	0.5%	0.3%
MH	3-4σ	>5σ
$\sin^2 2\theta_{13}$	14%	3%
$\sin^2 2\theta_{23}$		3%
δ_{CP}		10°

Complimentarity to other Experiments

- Different systematics compared to MH from matter effects
  → Combined analysis very effective



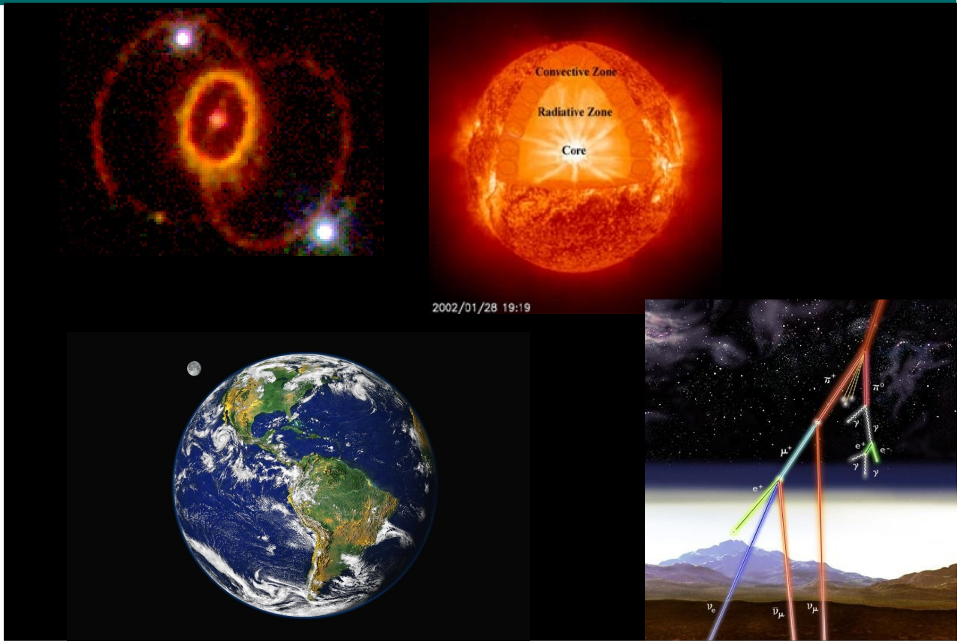
True: Normal hierarchy

Curves: Test for mass hierarchy
(for about 1 yr of data)

M. Blennow and T. Schwetz., JHEP 1309 (2013) 089

Other Physics at JUNO

- **Supernova ν**
  - Expected events (10kpc):
    IBD ~5000, other CC+NC+ES ~2000
  - Diffuse SN background
- **Geo-neutrinos**
  - Current results:
    KamLAND 30±7 TNU
    Borexino 38.8±12 TNU
  - JUNO expectation:
    ±10%(stat) ±10%(syst)
- **Atmospheric ν**
  - Possible aid to mass hierarchy?
- **Solar ν**
  - Only 700m overburden
  - Very demanding radiopurity control



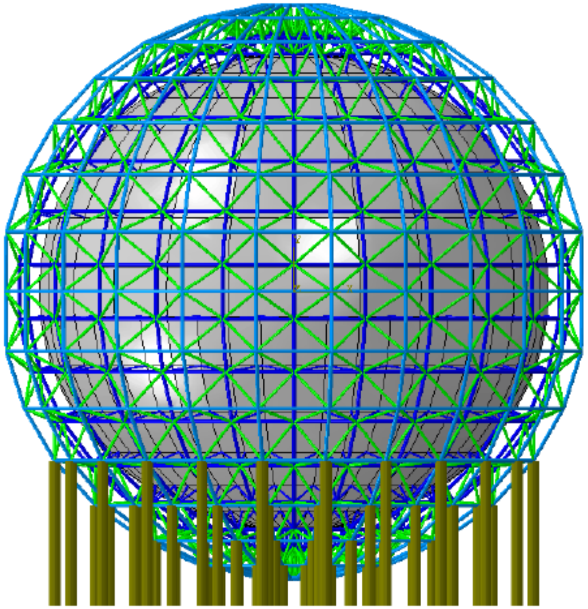
- **Proton Decay**
  - Example: p → K+ + anti-ν
    → $\tau > 1.9 \cdot 10^{34}$ yrs (90% C.L.)
- **New physics**
  - Light sterile neutrinos
  - Nonstandard interactions 1408.6301
  - Lorentz and CPT violation 1409.6970

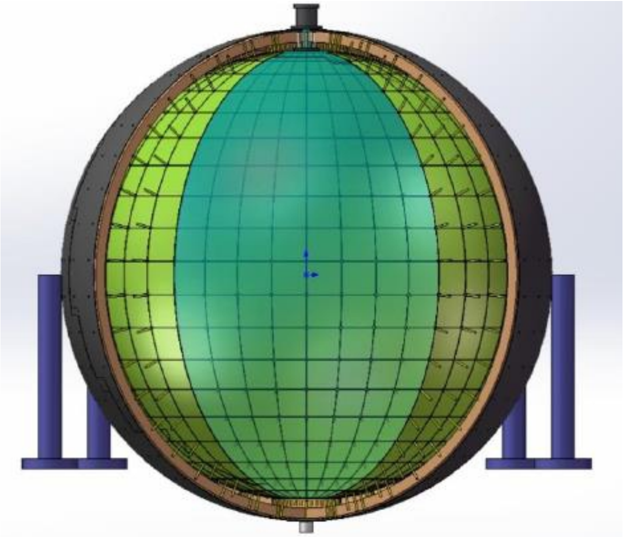
How to build such a detector?

	KamLAND	Borexino	Daya Bay	JUNO
Mass [t]	~1000	~300	~170	20000
Energy resolution	6%/√E	5%/√E	7.5%/√E	3%/√E
Light yield [p.e./MeV]	250	500	200	1200

Central Detector

- **Stainless steel sphere:**
  - 37.5 m diameter
  - ~ 17700 PMTs (20'')
    → ~75% coverage
- **Two options for inner vessel:**
  - Acrylic tank + stainless steel structure
  - Ballon + acrylic structure
- **Criterias are:**
  - Engineering: Safety, lifetime, stability
  - Physics: Radiopurity, light collection
  - Assembly and installation
- **Prototyp studies ongoing**





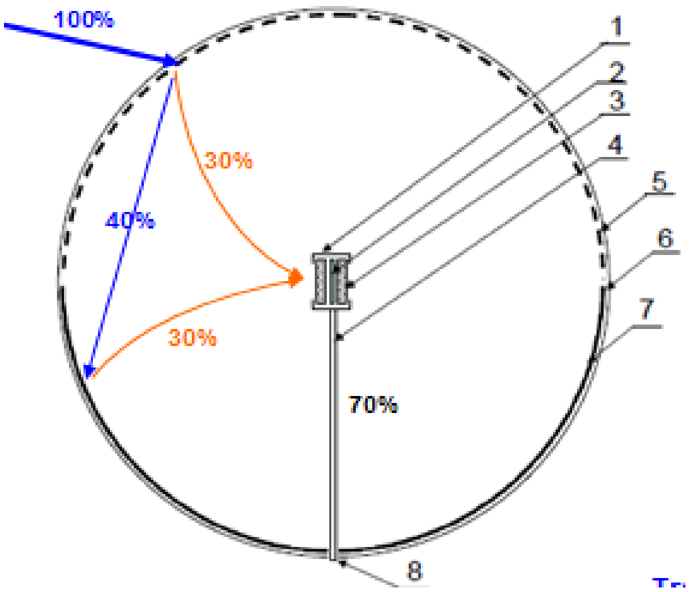
PMTs

- **Main requirement:**
  - High Quantenefficiency (QE)
  - Want to reach 35%

Current QE:

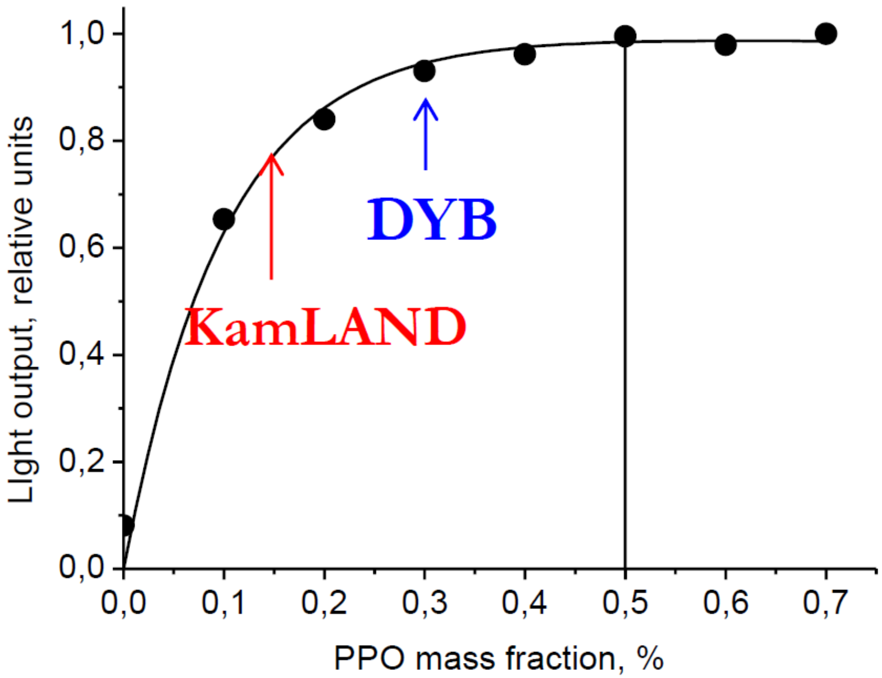
- **20” PMTs under discussion:**
  - New design: MCP-PMT (Chinese industry) — 30% (R+T)
  - Photonics-type Chinese PMT
  - New Hamamatsu PMT (SBA) — 32% (T)

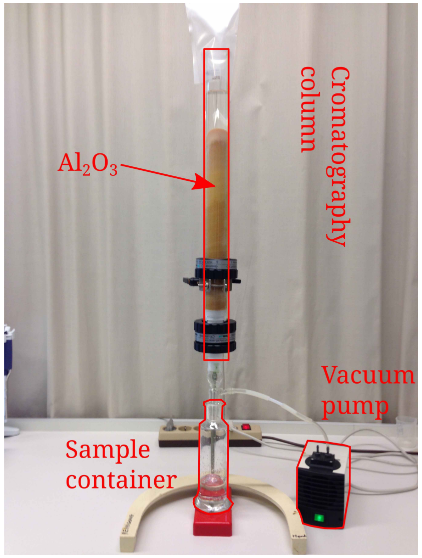
- **MCP-PMT development:**
  - Techincal issues mostly solved
  - Successful 8" prototypes
  - A few 20" prototypes



Liquid Scintillator

- **Recipe:**
  - LAB + PPO + bis-MSB
- **Key points:**
  - Attenuation: λ 15m → 30m
  - Light yield
  - Radiopurity
- **R&D efforts:**
  - Better raw materials
  - Improve production process
  - Purification: **(Borexino on board)**
    - Column purification (Al_2O_3 → λ = 25m)
    - Purification by charcoal
    - Vacuum distillation

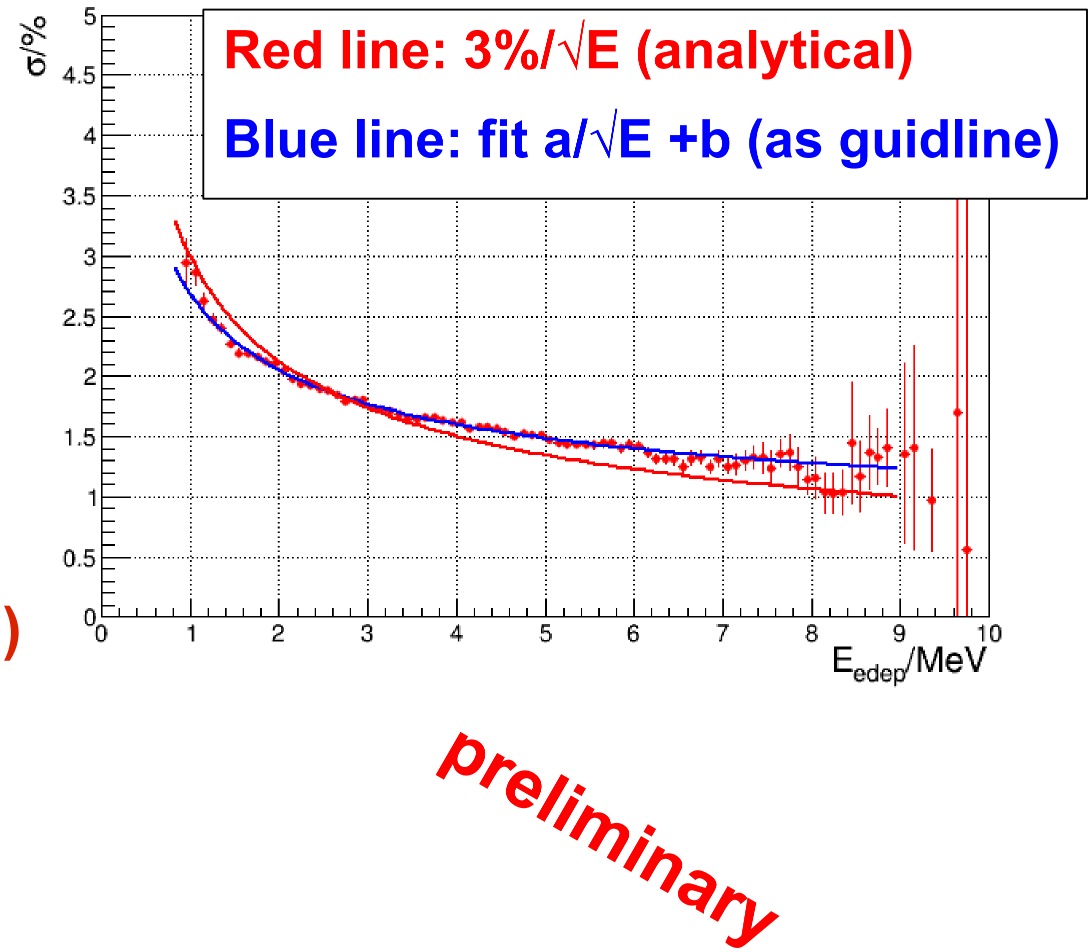




Detector Response MC Study

- **Optical model:**
  - QE = 35%
  - L.Y. = 10^4 γ/MeV,
  - λ_{Att} = 20m (@430nm)

- **Software status**
  - Full optical simulation
  - Full readout simulation **(soon)**
  - Full position-reconstruction
  - Full energy-reconstruction
  - Full calibration **(soon)**

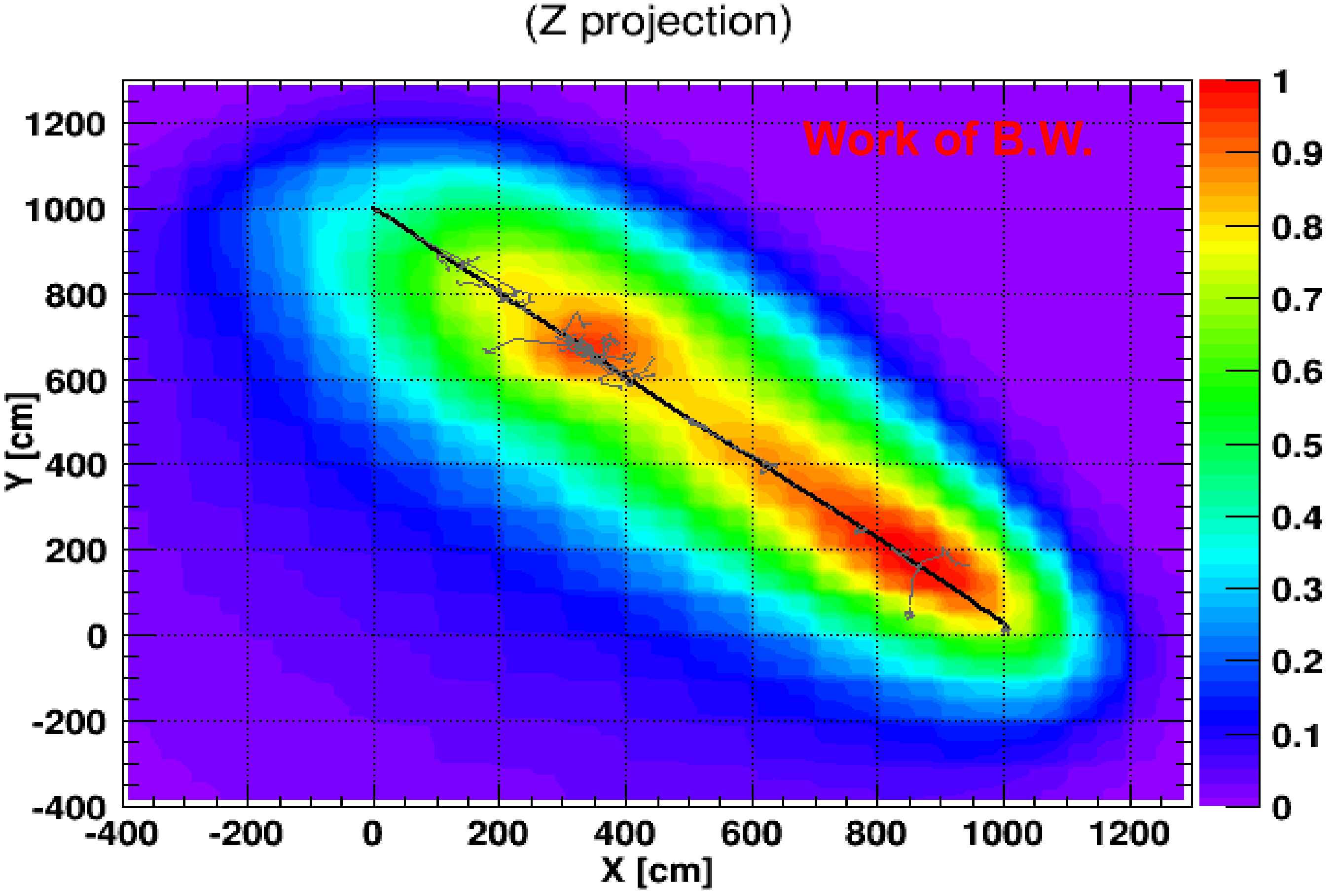


Both designs: Energy resolution is plausible

(enough light for 3% stochastical term, non-stochastical term under heavy investigation, but no showstopper yet)

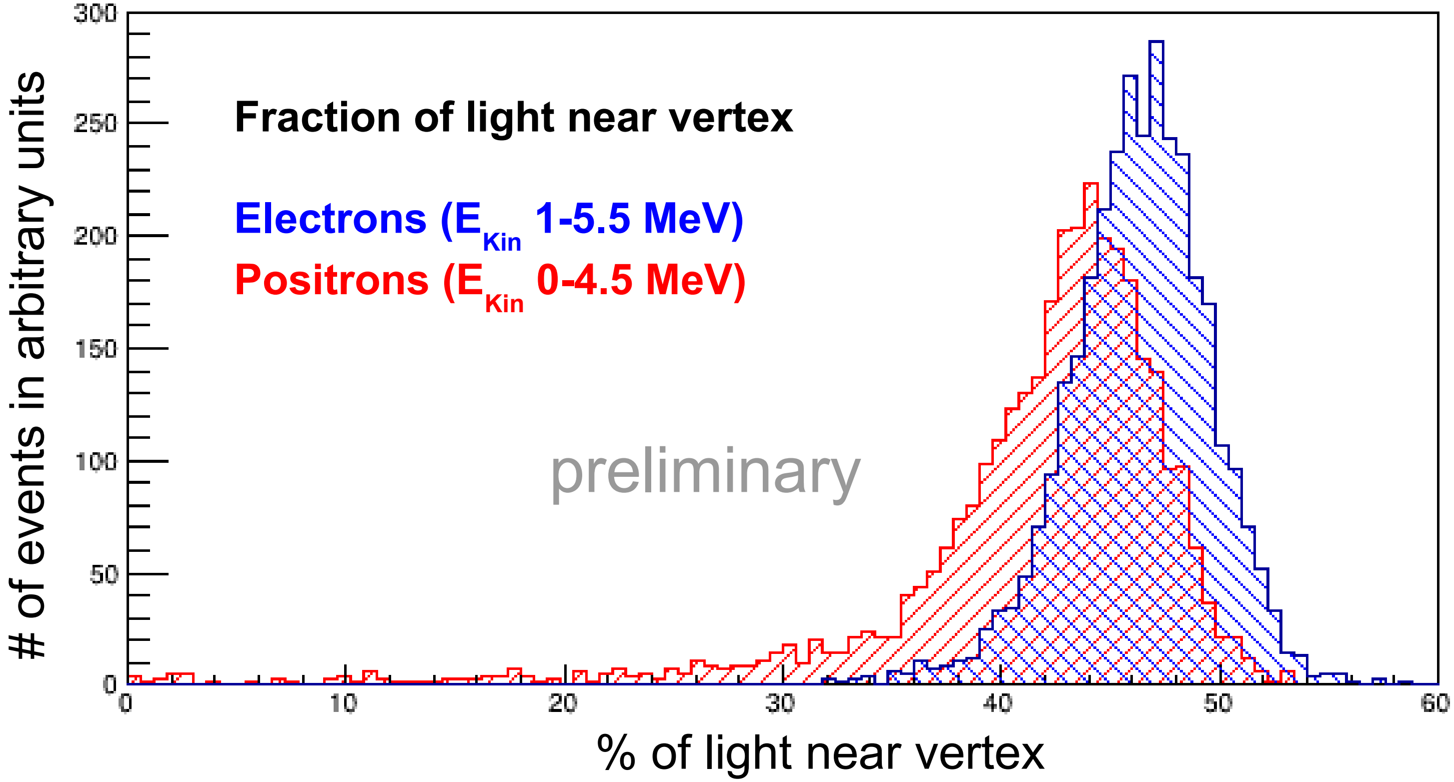
My Work: Tracking

- Developing **3d topological tracking**
- Only input: Vertex position and time
- dE/dx accessible



My Work: Topology at Low Energies (MeV)

- **Goal:** e^+/e^- discrimination



Other possible applications:

- Position reconstruction
- Energy reconstruction
- IBD directional reconstruction
- Stopping muon charge?

Conclusions: Physics Potential

- **JUNO → unprecedented physics instrument**
  - 20x larger, 2.5x more light yield
- **MH sensitivity:**
  - No constraint: $\overline{\Delta\chi^2}>9$
  - With 1% constraint: $\overline{\Delta\chi^2}>16$
  - **Challenge:** $\sigma_E \approx 3\%/\sqrt{E}$ (stat.) & < 1% (syst.)
  - Strong synergy with atmospheric ν program
- **Precision measurement of solar ν sector**
  - Probing the unitarity of U_{PMNS} to ~1% level
  - Complimentary to atmospheric ν program
- **Rich additional physics program**
  - Supernova ν and DSNB, geo-neutrinos, atmospheric & solar ν, proton decay, etc. ...

Summary: Project Status

- **International collaboration formed in 2014**
- **Civil construction started**

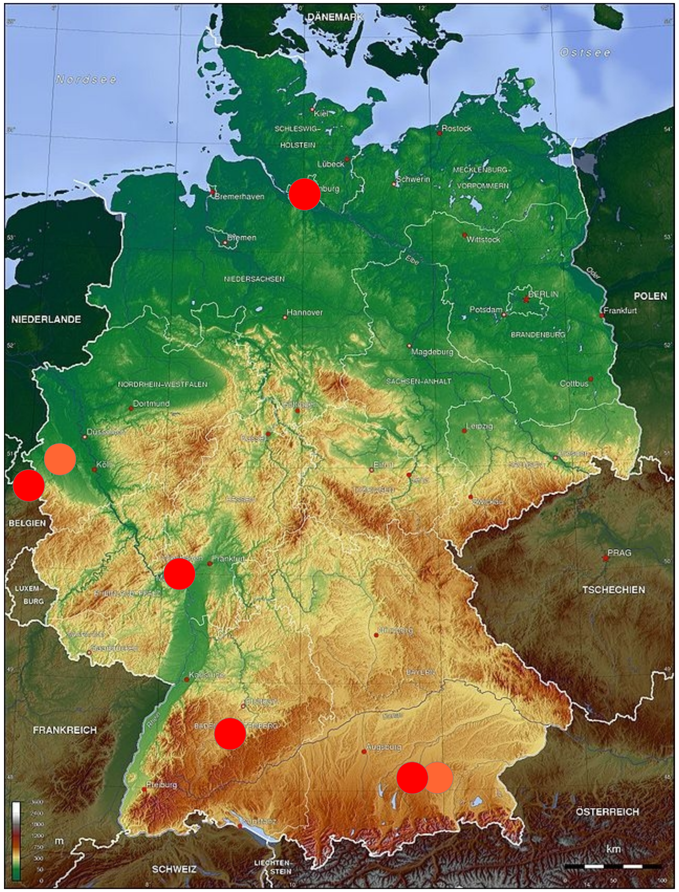
  Laboratory should be ready in about 3 years.
- **Detector optimization studies are ongoing**
- **Strong R&D program**
  - In particular on the liquid scintillator and PMTs
- **Data taking should start in 2020.**
- **Competitive schedule:**
  - En par with PINGU
  - One year before RENO-50

German Participation

- **Groups involved + main topic**
  - U. Hamburg: Reconstruction
  - RWTH Aachen: Electronics
  - JGU Mainz: Physics potential
  - U. Tübingen: WC-Veto
  - TU München: Liquid Scintillator

  - FZ Jülich: Electronics
  - MPP München: (Observer)

Chance for substantial contribution in key areas of the project!



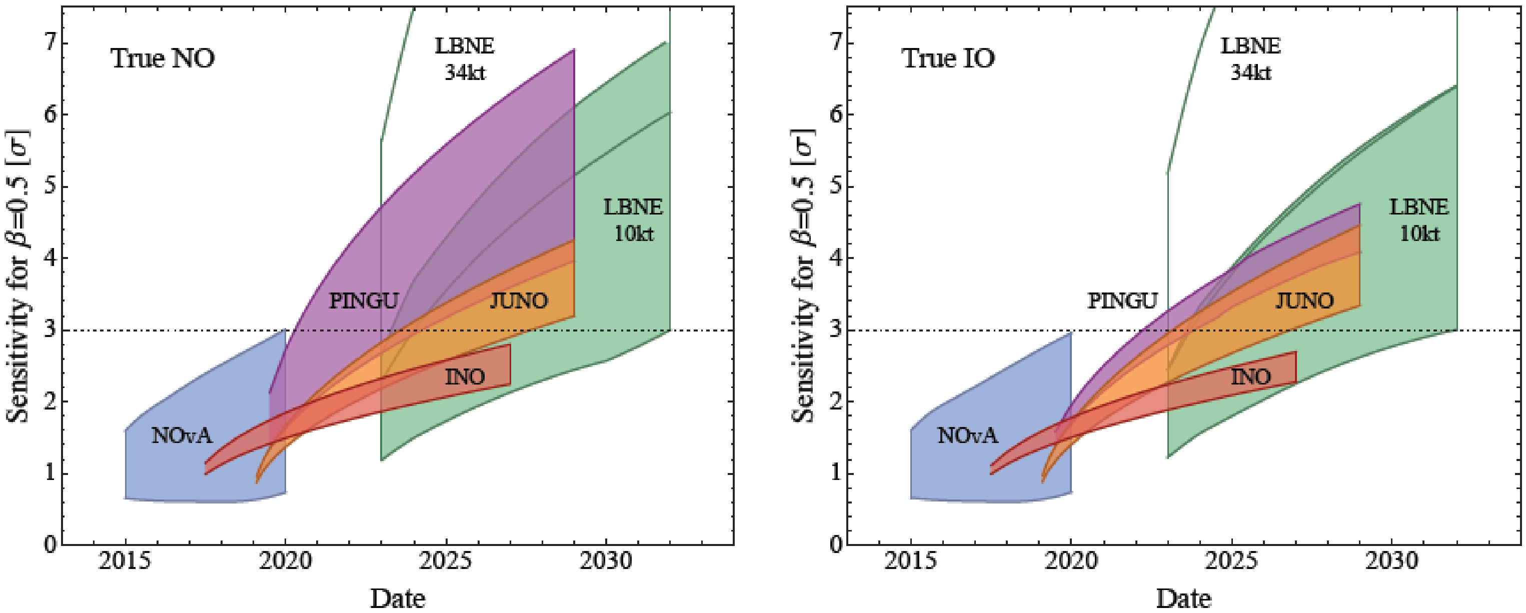
Other JUNO related Talks

- Di, 17:20 T 53.3 Gruppenbericht: The Jiangmen Underground Neutrino Observatory — •Sebastian Lorenz
- Di, 17:40 T 53.4 Determination of the neutrino mass hierarchy with atmospheric neutrinos in JUNO — •Michael Soiron
- Mi, 18:20 T 72.7 Studies on muon track reconstruction with the JUNO liquid scintillator neutrino detector — •Christoph Genster
- Mi, 18:05 T 72.6 Positron discrimination in large-volume liquid scintillator detectors using 3D topological reconstruction — •Björn Wonsak
- Mi, 18:35 T 72.8 Szintillatorreinigung mit Aluminiumoxid für den JUNO - Detektor — •Sabrina Prummer
- Do, 17:30 T 93.4 Towards a Design of Readout Electronics for the JUNO Detector — •Marcel Weifels

Backup Slides

Global Sensitivity Prospects MH

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



Different risks:

NOvA, LBNE: δ

PINGU, INO: θ_{23}=40-50°

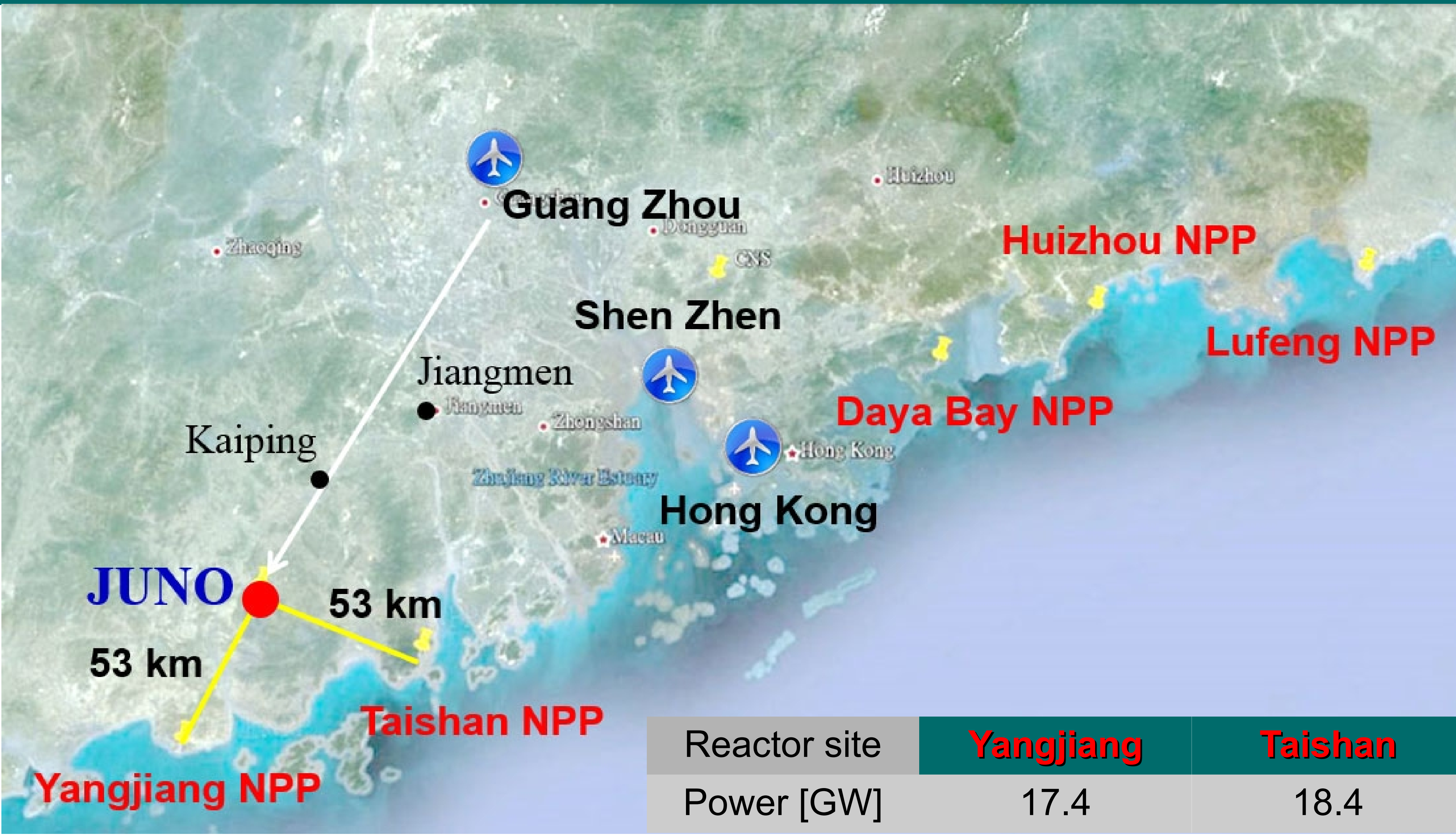
JUNO: 3%-3.5%

- **JUNO:**

Competitive measurement of MH using reactor neutrinos

  – **Independent of the yet-unknown CP phase and θ_{23}**

JUNO Site

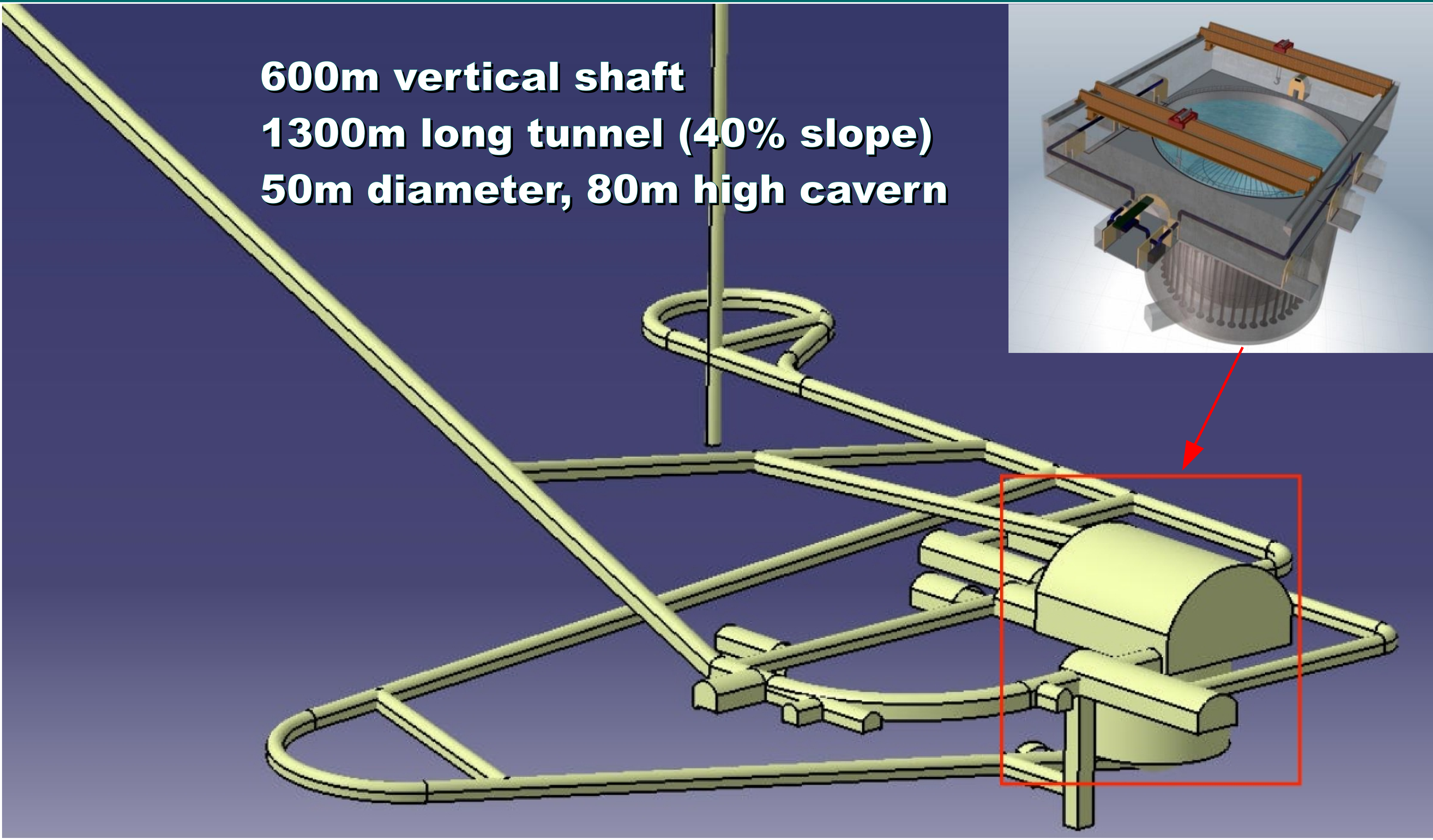


Reactor site	Yangjiang	Taishan
Power [GW]	17.4	18.4

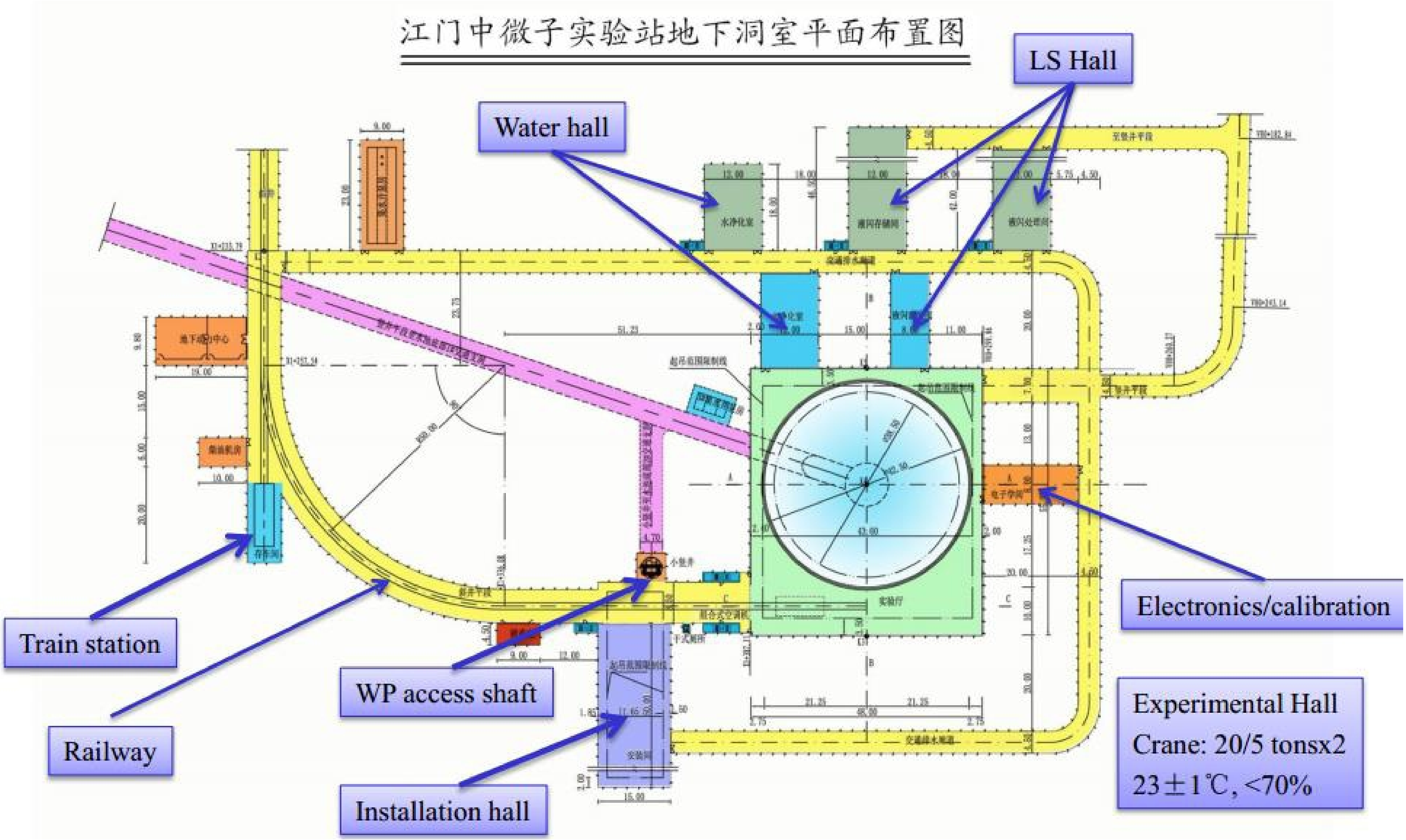
Civil Construction

Jiangmen Underground Laboratory

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



Detector Hall

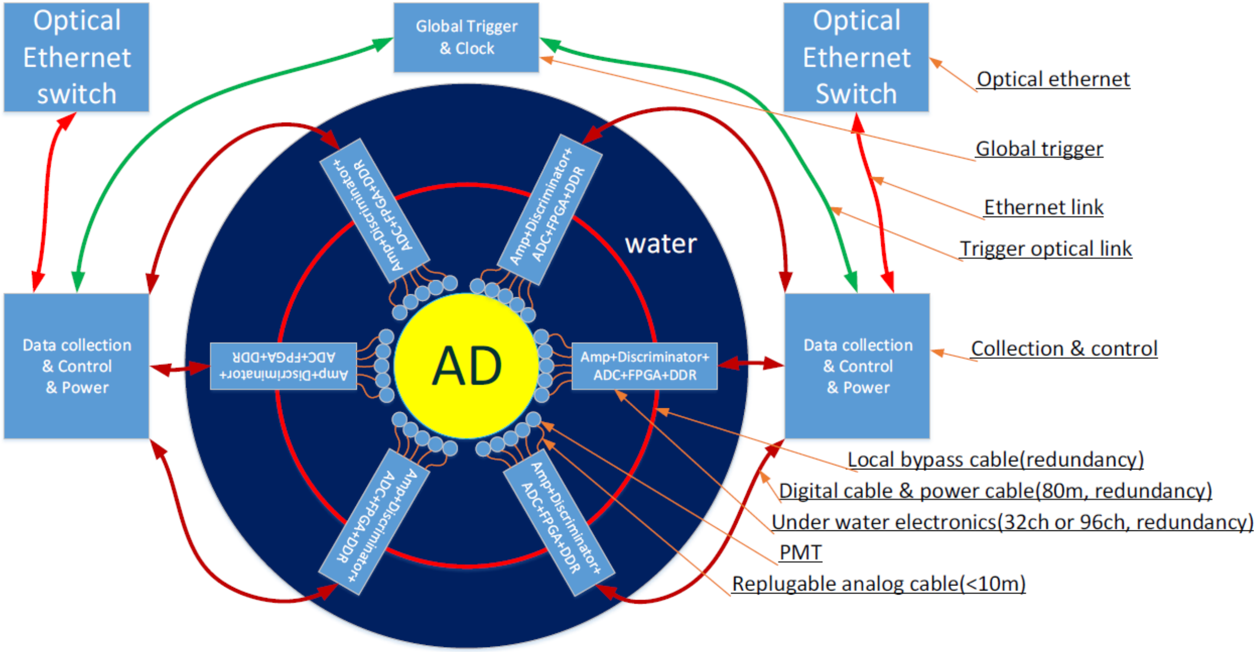


Schedule

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

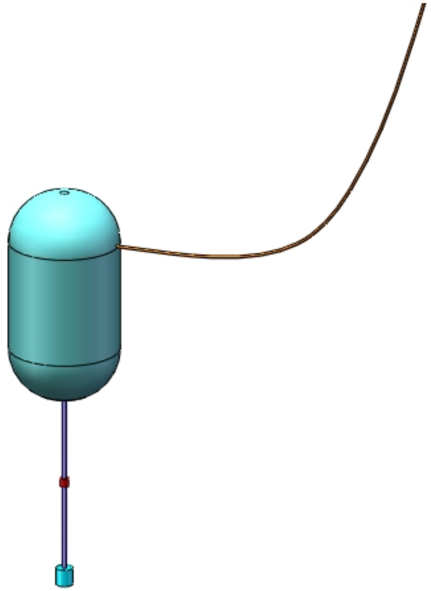
Electronics

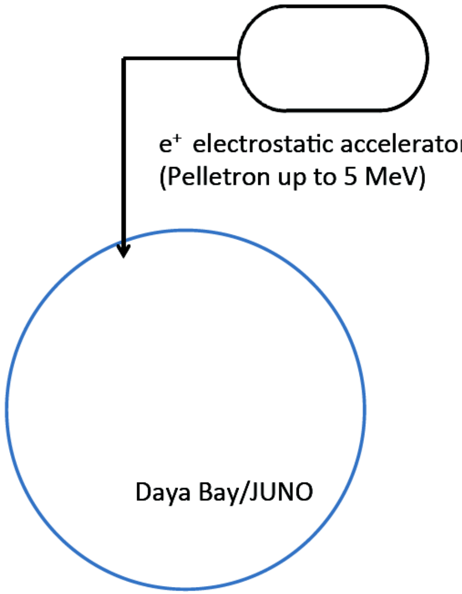
- **Full charge & time info from FADC**
  - 1GHz sampling rate
  - 20000 channels
  - Event rate: 50kHz
  - In water
  - Noise: 0.1 p.e.

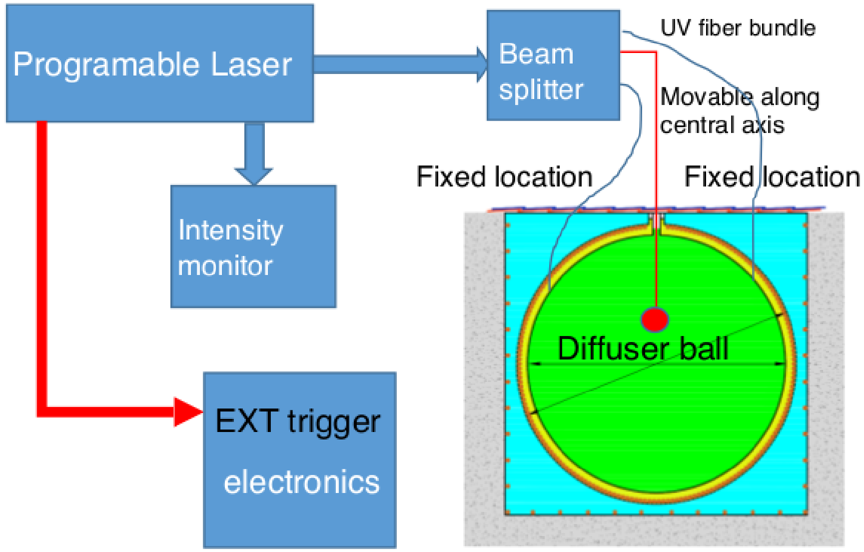


Calibration

- **high precision calorimetry**
  - critical validation & cross-check
  - redundancy & 4π coverage
  - natural calibration: fast-n captures (after μ)
  - excellent readout behaviour upon μ
  - H-n & C-n (all the time & everywhere)
  - external calibration source: [0,10]MeV
- **radioactive source calibration systems**
  - z-axis calibration with high precision
  - spherical symmetry of response (→chimney)
  - rope system (off-z-axis deployment)
  - consider versatile system
  - guide tube system (off-z-axis deployment)
  - boundaries and near boundary regions
- **short-lived diffusive radioactive sources**
  - full volume response map calibration
- **UV/blue laser systems**
  - readout & scintillator monitoring/calibration in situ

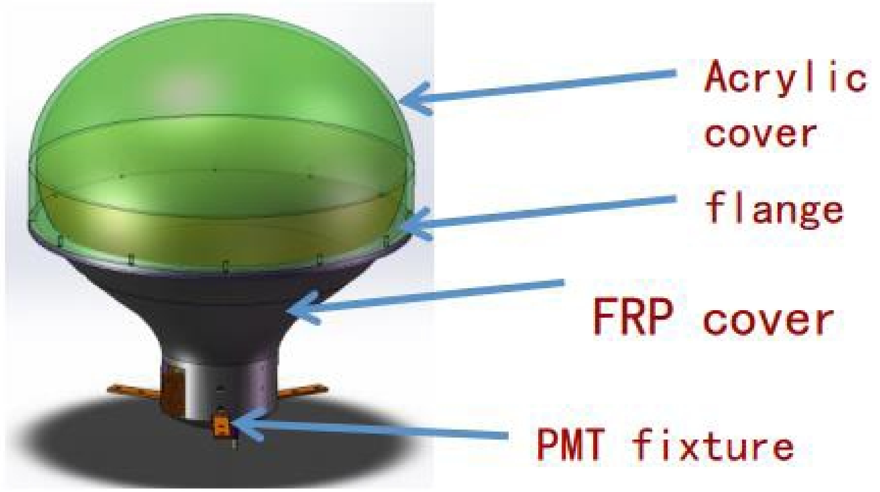






Implosion Protection

- Two groups working on the implosion prevention design
  - Calculation and experimentation (navy lab + university lab)
- Shock-wave calculation & comparison to data
- Chain reaction experimentation and iteration planed for this year (design & experiments)



Supernova Neutrinos

- Carbon reactions as additional channels compared to WC
- Help to pin down flavour content
- Most notable: Possibility to detect ν_e separately

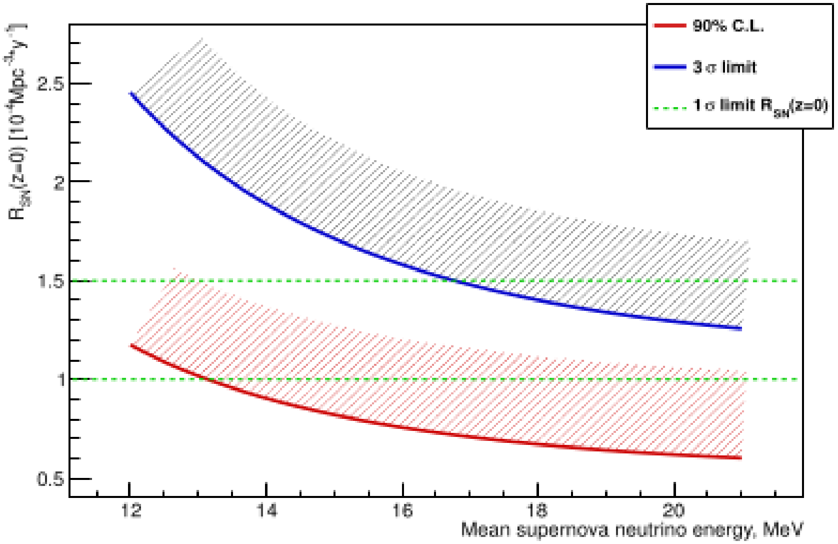
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$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

JUNO Yellow Book, in preparation

Diffuse Supernova ν Background

- Most important backgrounds:
  - Fast neutrons and atmospheric neutrino NC reactions
- Efficient pulse shape discrimination is crucial!

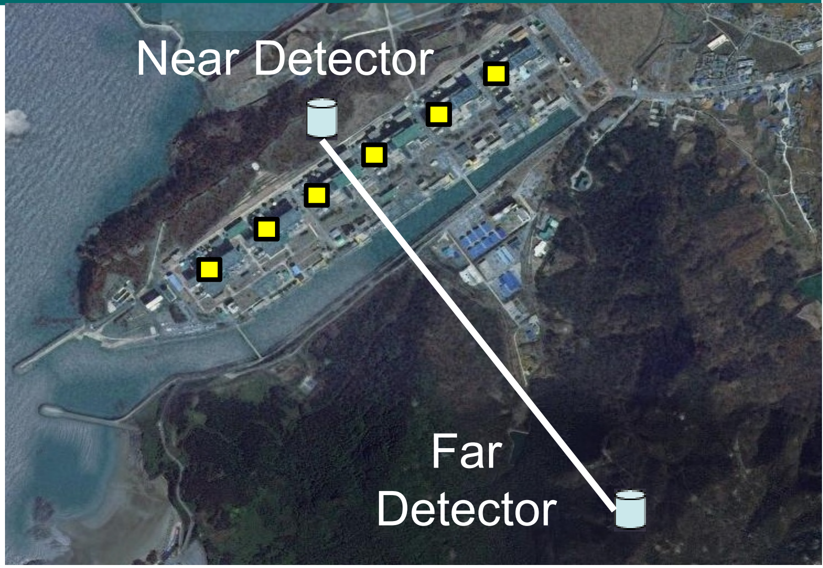
$\langle E_{\bar{\nu}_e} \rangle$	Detection significance [5 yrs]	Detection significance [10 yrs]
12 MeV	$1.2\,\sigma$	$1.7\,\sigma$
15 MeV	$1.7\,\sigma$	$2.8\,\sigma$
18 MeV	$2.2\,\sigma$	$3.1\,\sigma$
21 MeV	$2.7\,\sigma$	$3.8\,\sigma$



JUNO Yellow Book, in preparation

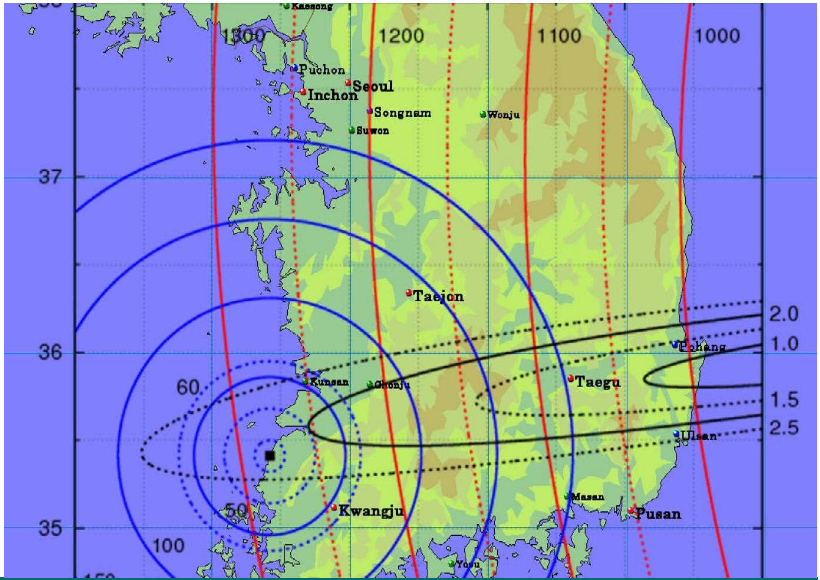
RENO-50

- **18 kton LS detector**
- **Proposed site:**
  - ~47 km from reactors
  - Under Mt. Guemseong (450 m)



- **Cylindric design**
- **In line with J-PARC ν beam**

- **Everything else very similar to JUNO**
- **Schedule approximately 1 yr behind JUNO**

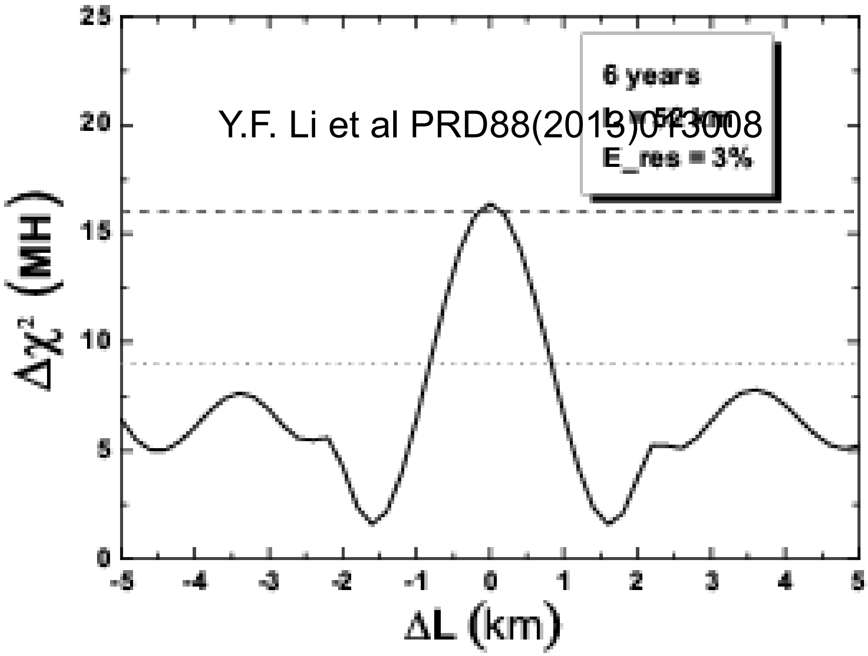


Baseline Optimisation

- Baseline varies between different reactor cores

- Shift of half an oscillation length
  → Oscillation cancels

- → optimisation of baseline
  → difference <= 500m



Y.F. Li et al PRD88(2013)013008

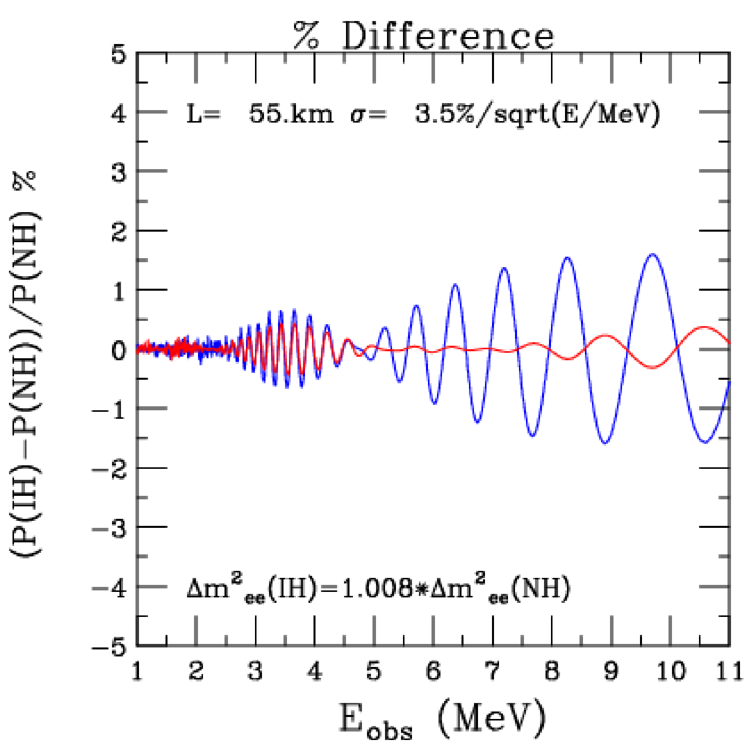
Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline(km)	52.75	52.84	52.42	52.51	52.12	52.21

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

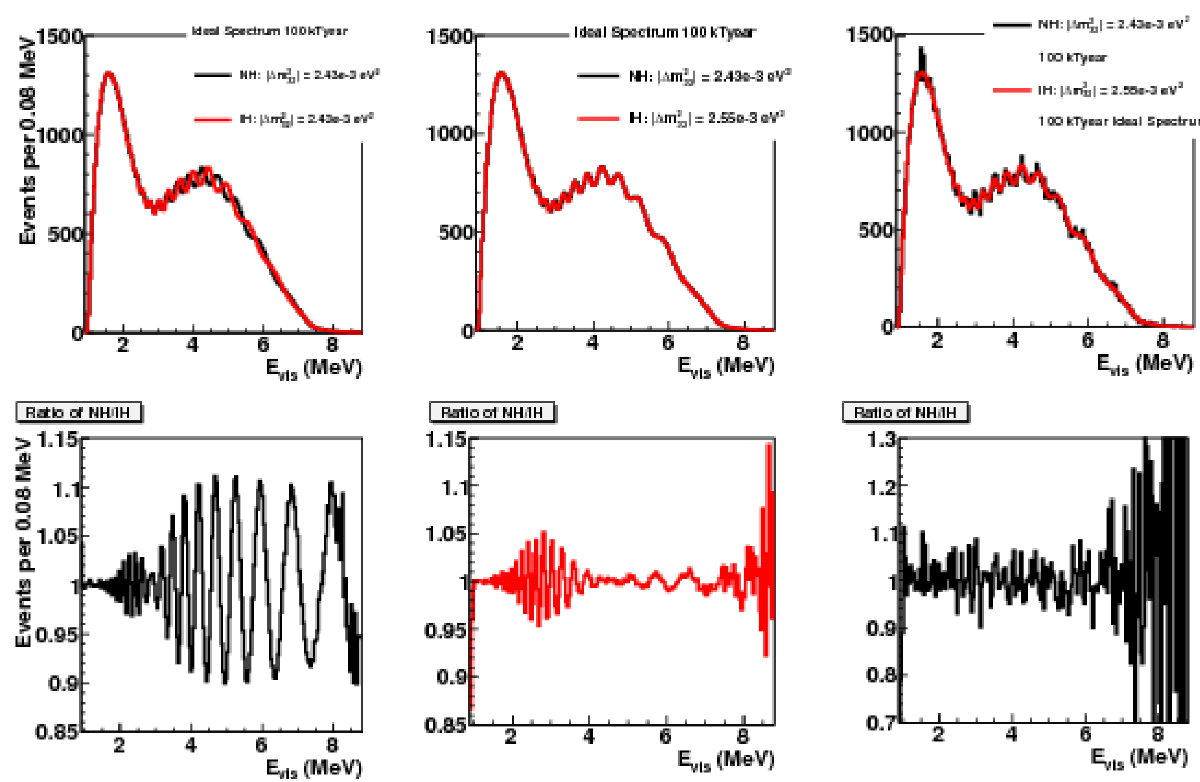
Non-Linearities

- **Energy reconstruction has bias or non-linearity residuals**
  → signals might disappear or wrong (solution)

- **Various studies show <= 1% uncertainty is needed**



S.J. Parke et al,
Nucl.Phys.Proc.Suppl. 188 (2009)

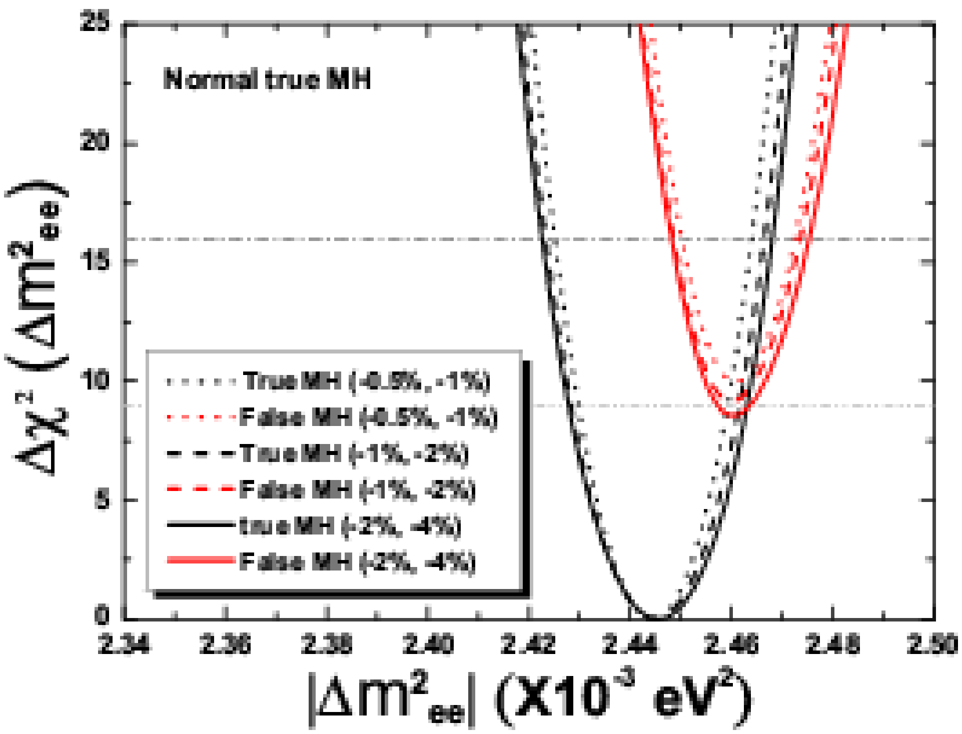


X. Qian et al, PRD87(2013)3, 033005

Energy Self-Calibration

- Based on Δm^2_{ee} periodic peaks
- Relatively insensitive to continuous backgrounds, non-periodic structures
- Daya-Bay non-linearity: 1%

Y.F. Li et al., arXiv:1303.6733



2% non-stochastic energy inaccuracy assumed

Effective Mass-Squared Differences

- ν_e and ν_μ disappearance experiments measure different effective atmospheric mass-squared Differences

$$\Delta m^2_{ee} \simeq \cos^2(\theta_{12}) \cdot \Delta m^2_{31} + \sin^2(\theta_{12}) \cdot \Delta m^2_{32}$$

$$\Delta m^2_{\mu\mu} \simeq \sin^2(\theta_{12}) \cdot \Delta m^2_{31} + \cos^2(\theta_{12}) \cdot \Delta m^2_{32} + \sin(2\theta_{12}) \sin(\theta_{13}) \tan(\theta_{23}) \cos(\delta) \cdot \Delta m^2_{21}$$

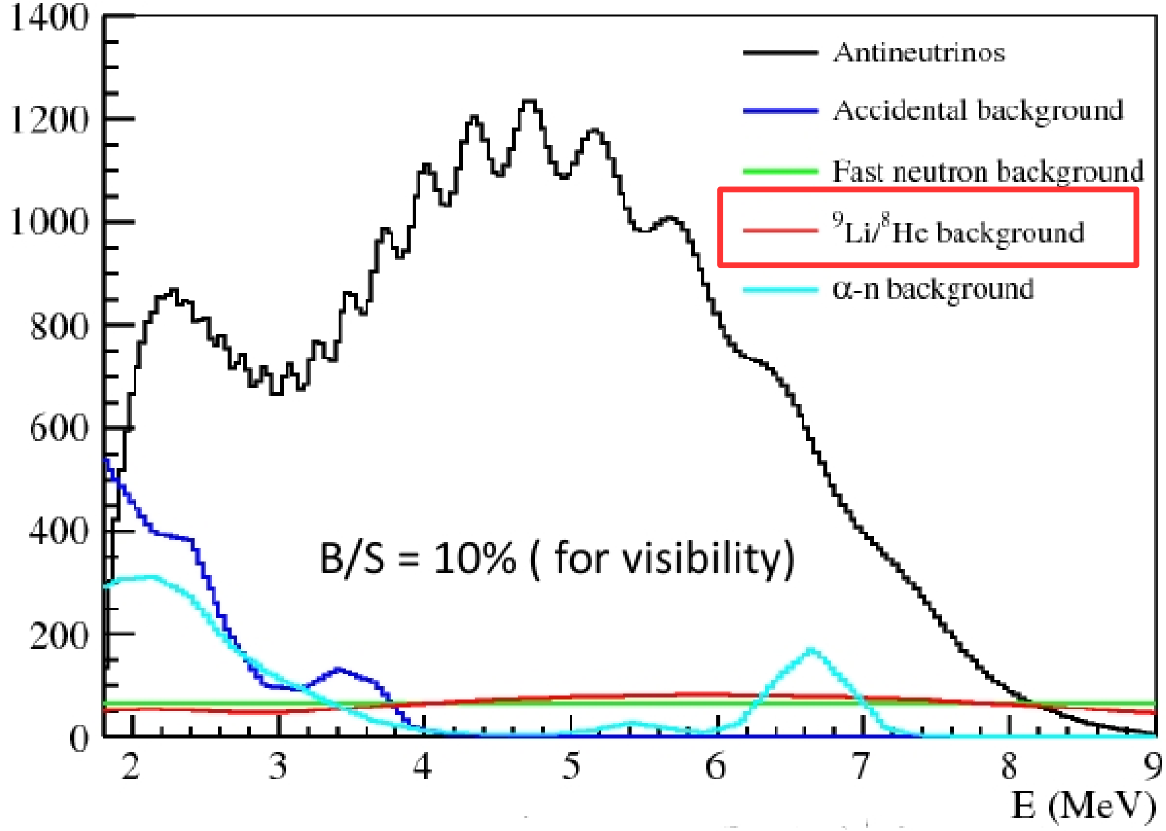
- With precision measurements of Δm^2_{ee} and $\Delta m^2_{\mu\mu}$, the difference

$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm \Delta m^2_{21} \cdot (\cos(2\theta_{12}) - \sin(2\theta_{12}) \sin(\theta_{13}) \tan(\theta_{23}) \cos(\delta))$$

(+: NH, -: IH) allows to determine the MH and possibly even $\cos\delta$ at high precision

H. Nunokawa et al, Phys.Rev. D72 (205) 013009

JUNO Background

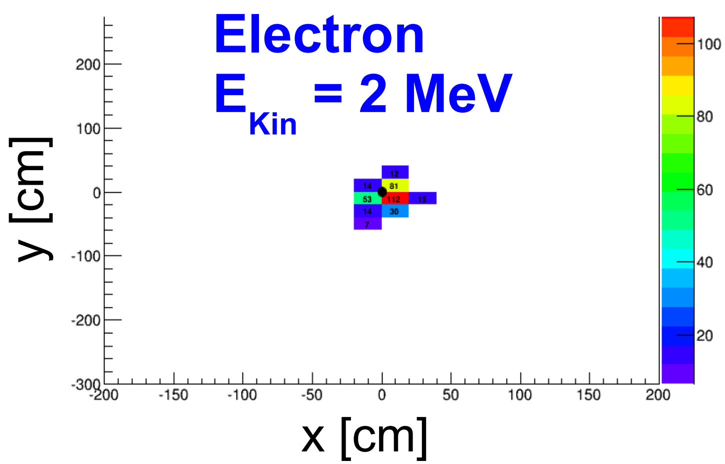


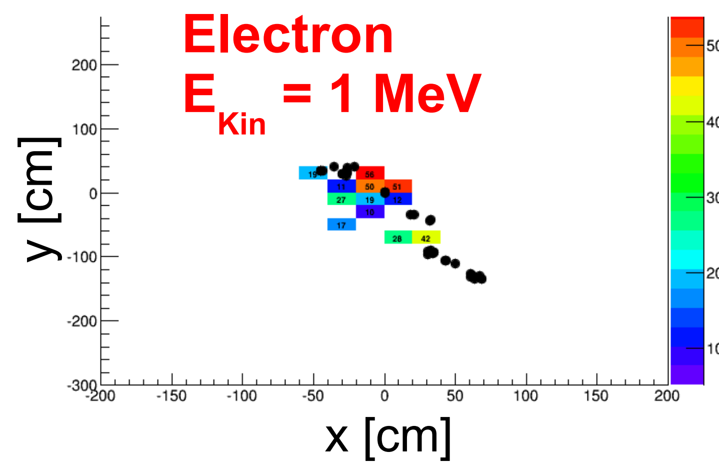
Assumes veto on cosmic muons!
→ 35-40% deadtime with old reconstruction methods.

25% caused by showers or muon bundels

My Work: Topology at Low Energies (MeV)

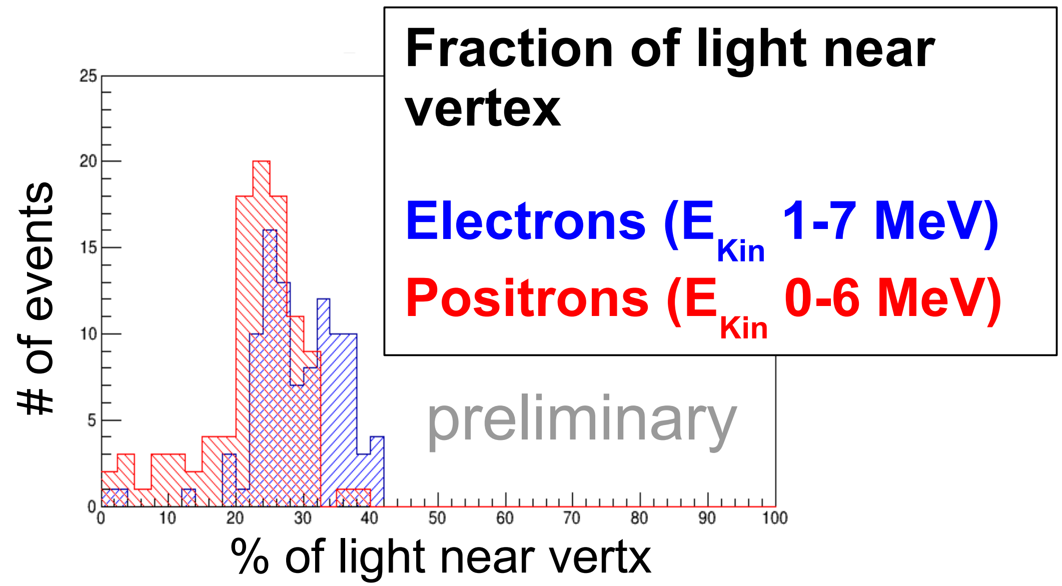
- **Goal:** e^+/e^- discrimination





Other possible applications:

- Position reconstruction
- Energy reconstruction
- IBD directional reconstruction
- Stopping muon charge?

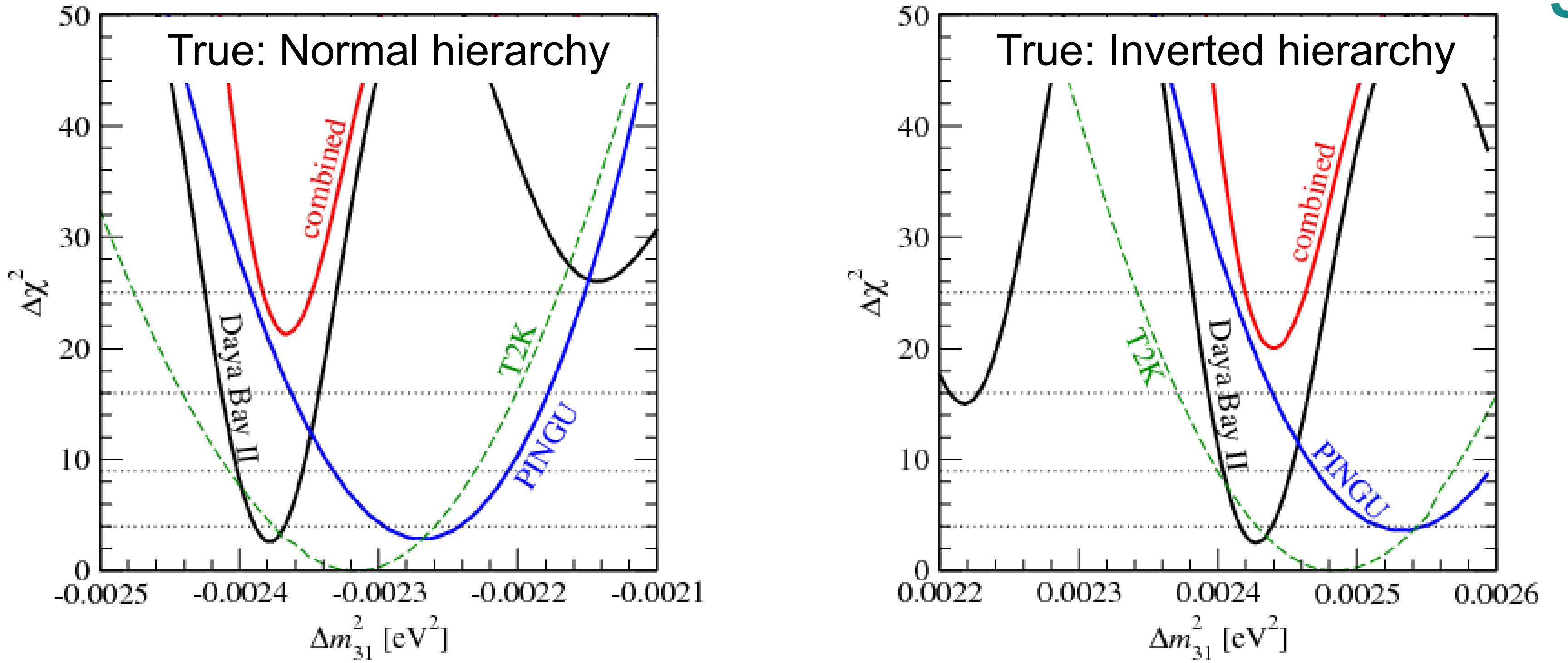


Complimentarity to other Experiments

- Different systematics compared to MH from matter effects
  → Combined analysis very effective

→ $$\Delta\chi^2_{Combined} \approx \Delta\chi^2_{JUNO,\,min} + \Delta\chi^2_{Atm,\,min} + \frac{\left(|\Delta m^2_{31,JUNO}| - |\Delta m^2_{31,Atm}|\right)}{\sigma^2_{JUNO} + \sigma^2_{Atm}}$$

Synergy term



M. Blennow and T. Schwetz., JHEP 1309 (2013) 089

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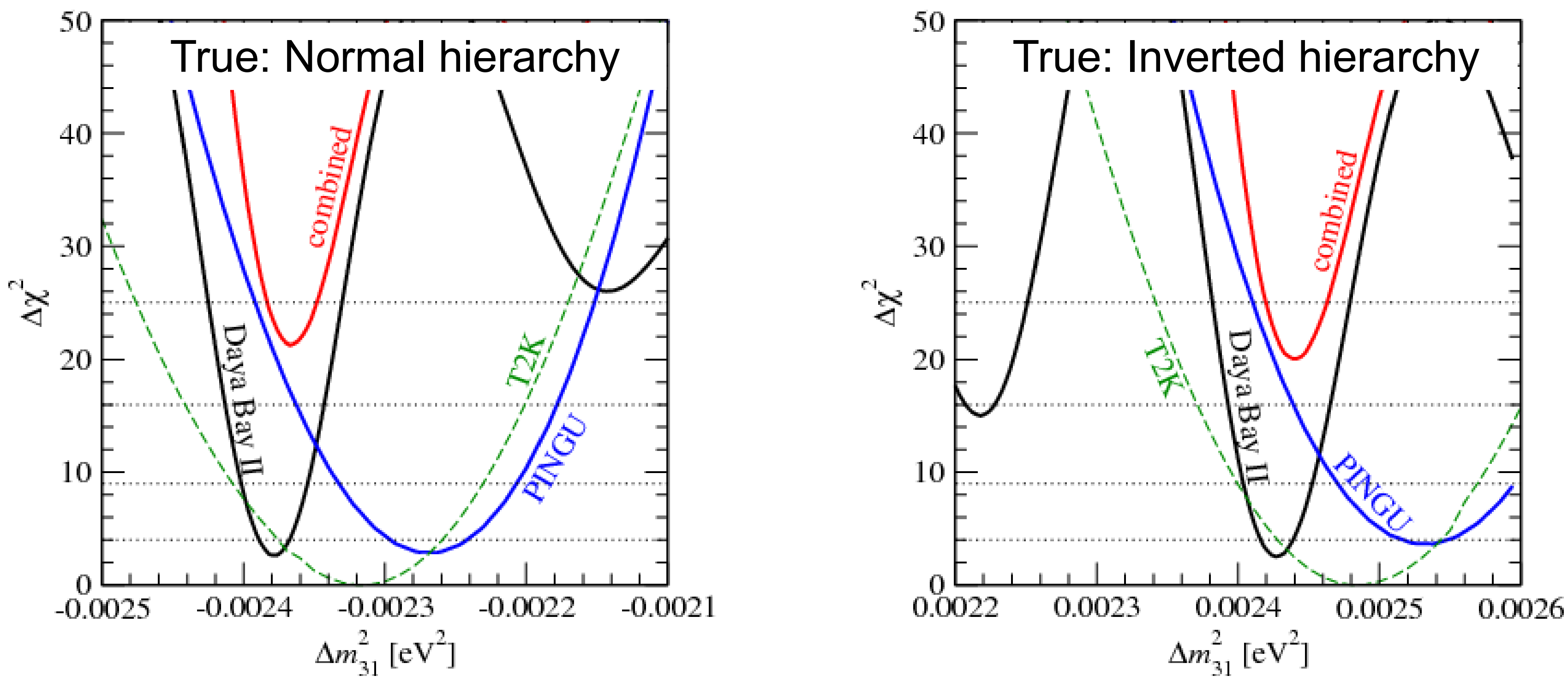
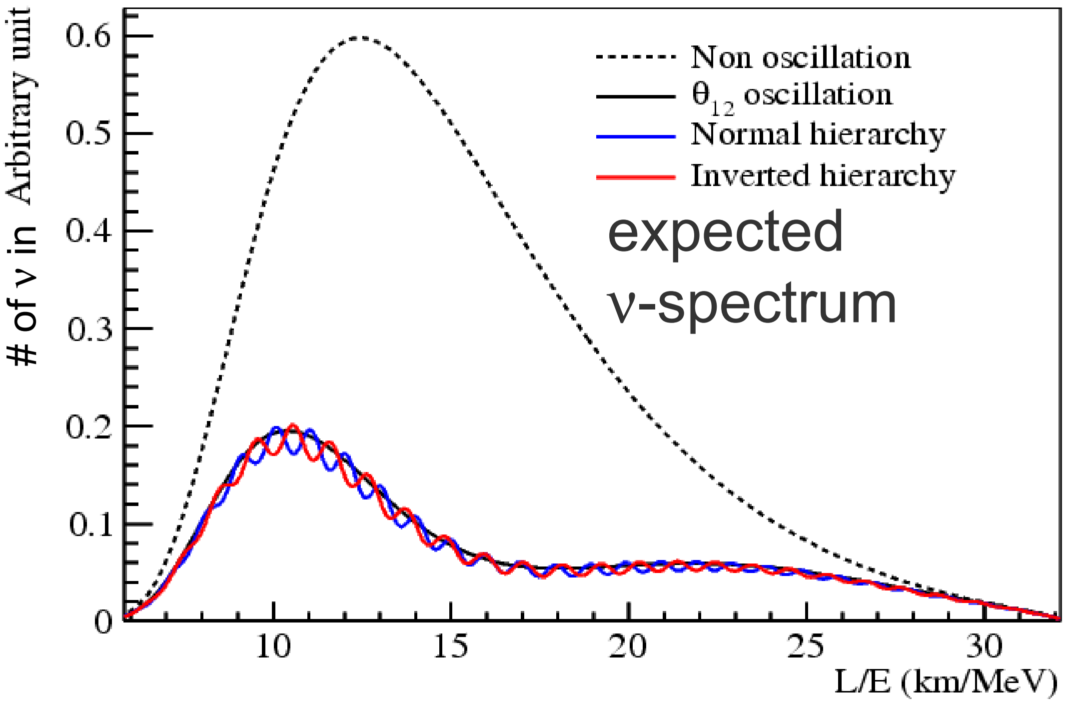
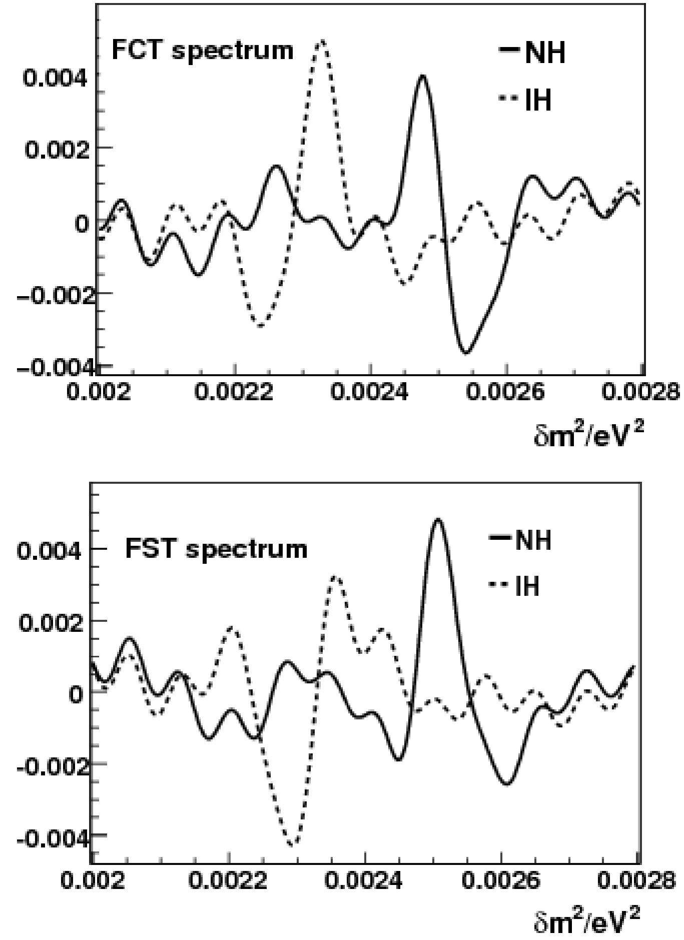


M. Blennow and T. Schwetz., JHEP 1309 (2013) 089

Mass Hierarchy with Reactor Neutrinos

Idea: Put large (20kt) LS-Detector at first maximum of solar oscillation





Different Oscillationfrequenzy of subdominant terms for the two hierarchies → Fourier-analysis

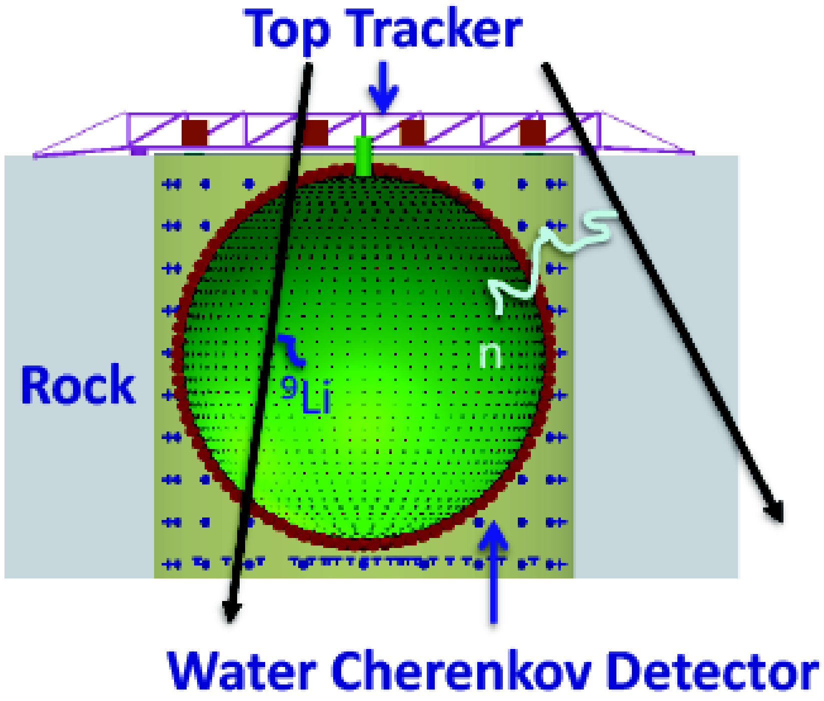
Phys.Rev. D78 (2008) 111103

J. Learned et. al. hep-ex/0612022
L. Zhan et. al. 0807.3203

Veto System

Goals:

- Cosmogenic isotope rejection
  (Muon track reconstruction defines veto region)
- Neutron background rejection (passive shielding and possible tagging)
- Gammas passive shielding



Water Cherenkov Pool:

- ~1500 PMTs
- 20-30kton ultrapure water with circulation system
- Earth magnetic field shielding
- Tyvek reflector film

Top Tracker:

- OPERA Target Tracker
- 2cm plastic scintillator strips
- Crosschecks on reconstruction

My Work: Topology at Low Energies (MeV)

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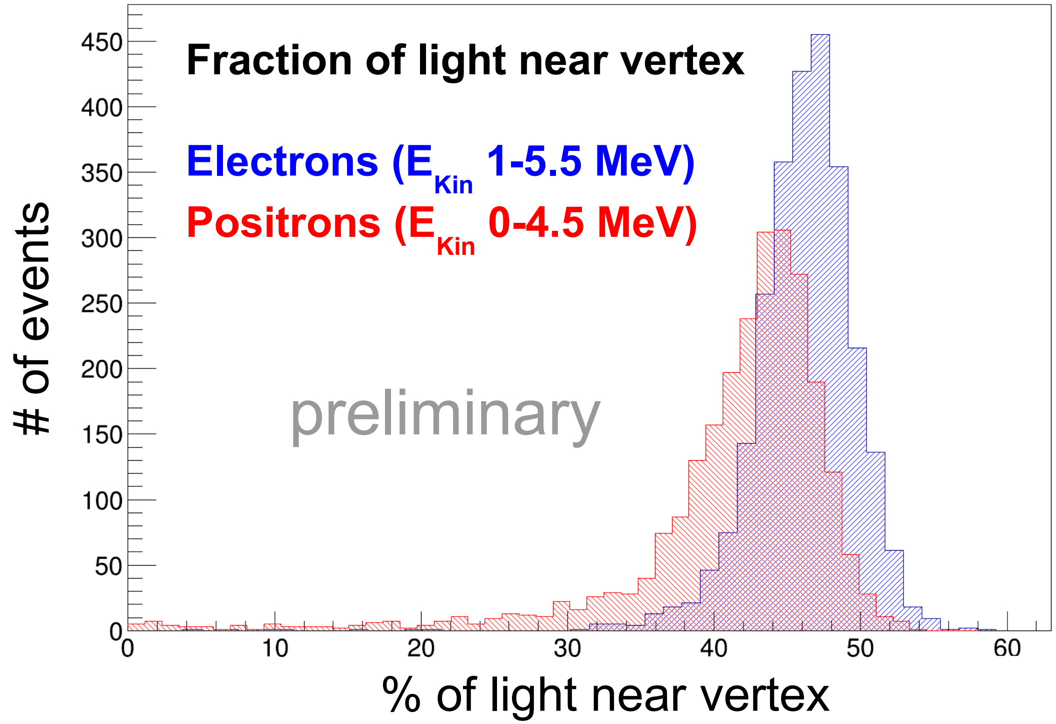

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