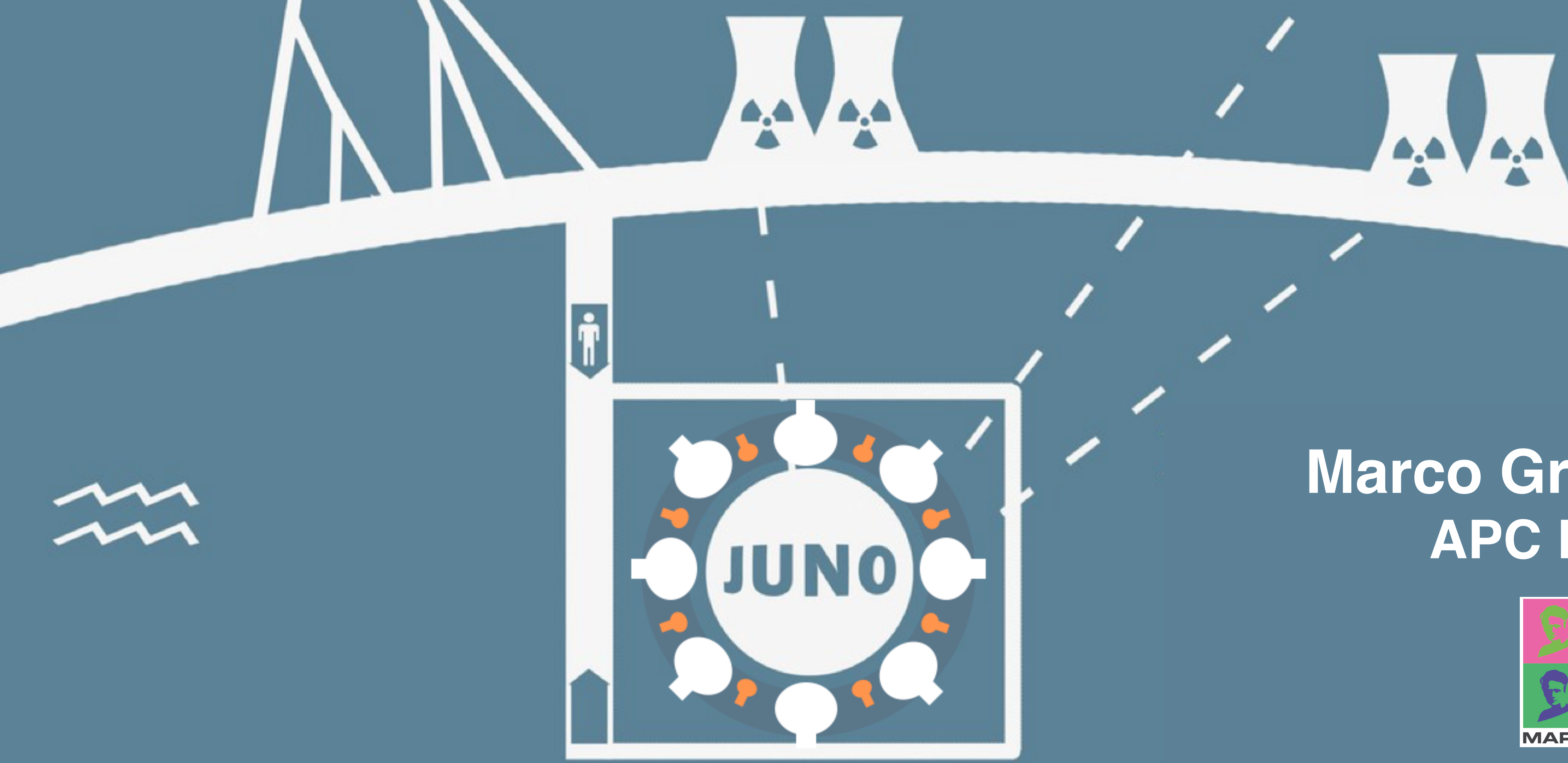
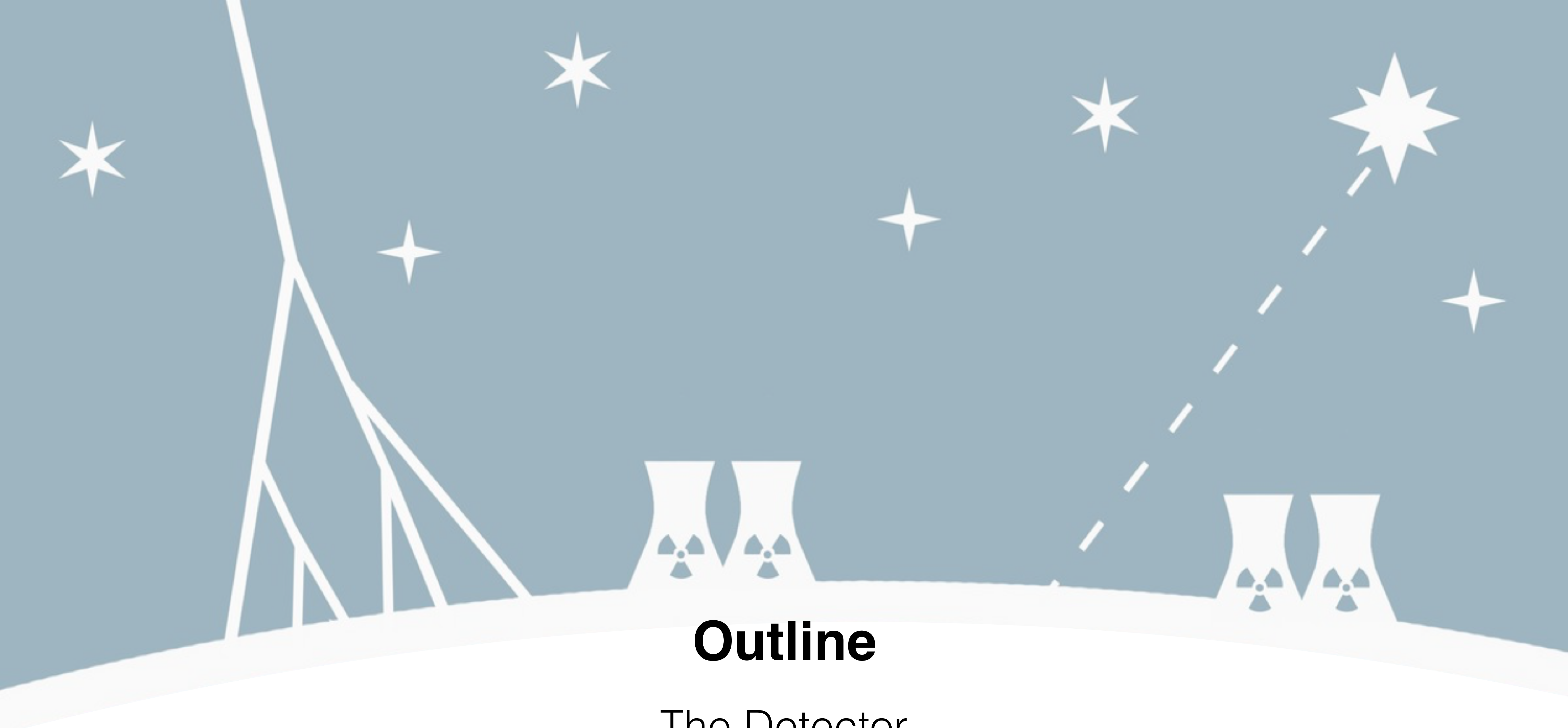
The Jiangmen Undergound Neutrino Observatory



Marco Grassi
APC Paris

MARIE CURIE ACTIONS



Outline

The Detector

Why JUNO

Reactor Neutrino Physics

Neutrinos Beyond Reactor
Supernova ✶ Geoneutrinos ✶ Solar Neutrinos

Project Status

The Detector at a Glance

a huge liquid scintillator detector…

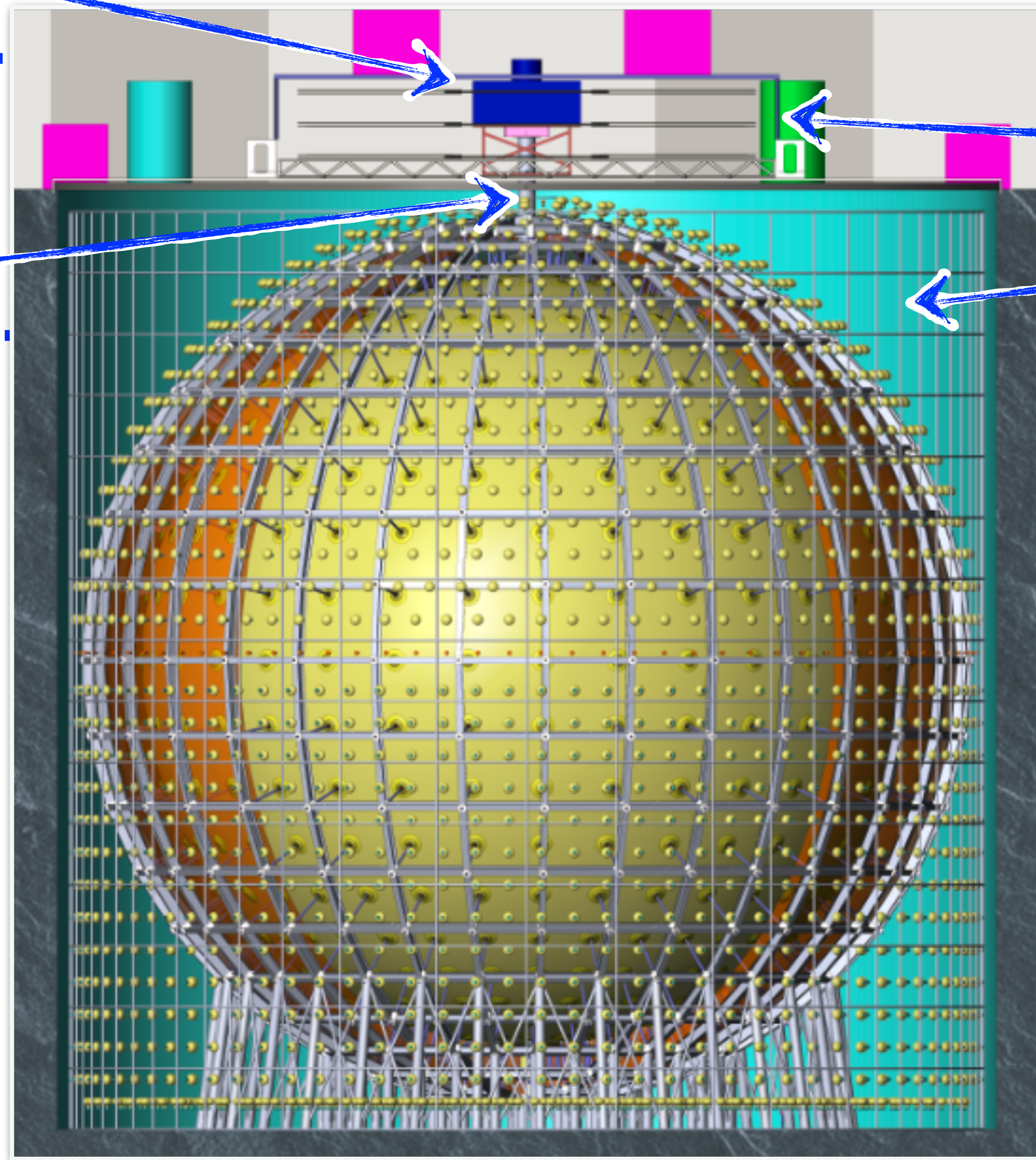
Calibration Room

Muon Veto

Chimney

Top Tracker

Water Pool



Central Detector

Steel Truss

Holding PMTs

18000 x 20''

25000 x 3''

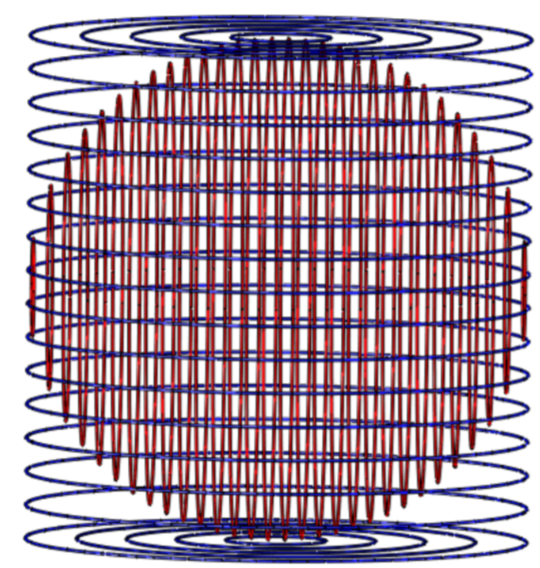
Acrylic Sphere

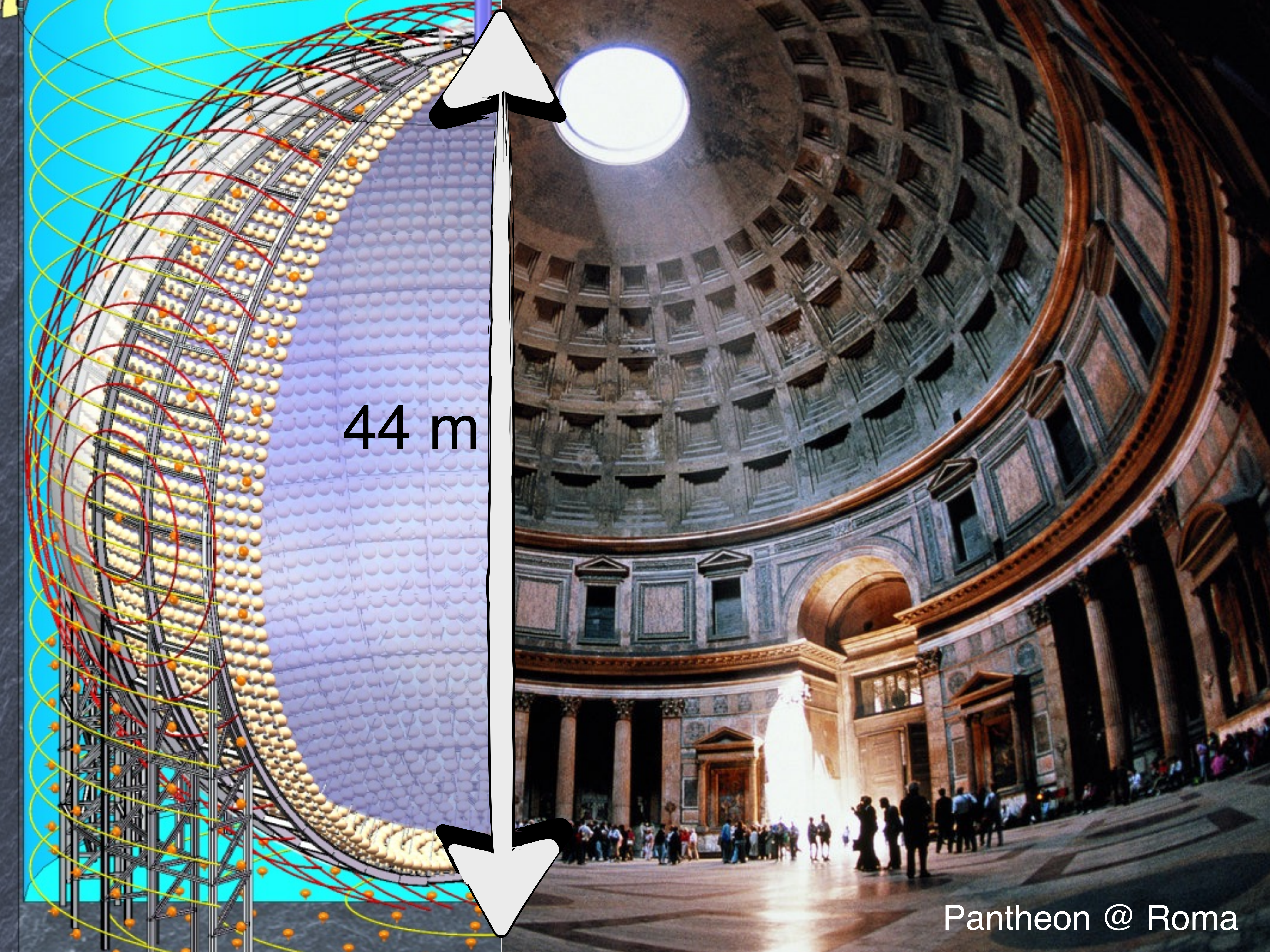
filled with

Liquid Scintillator

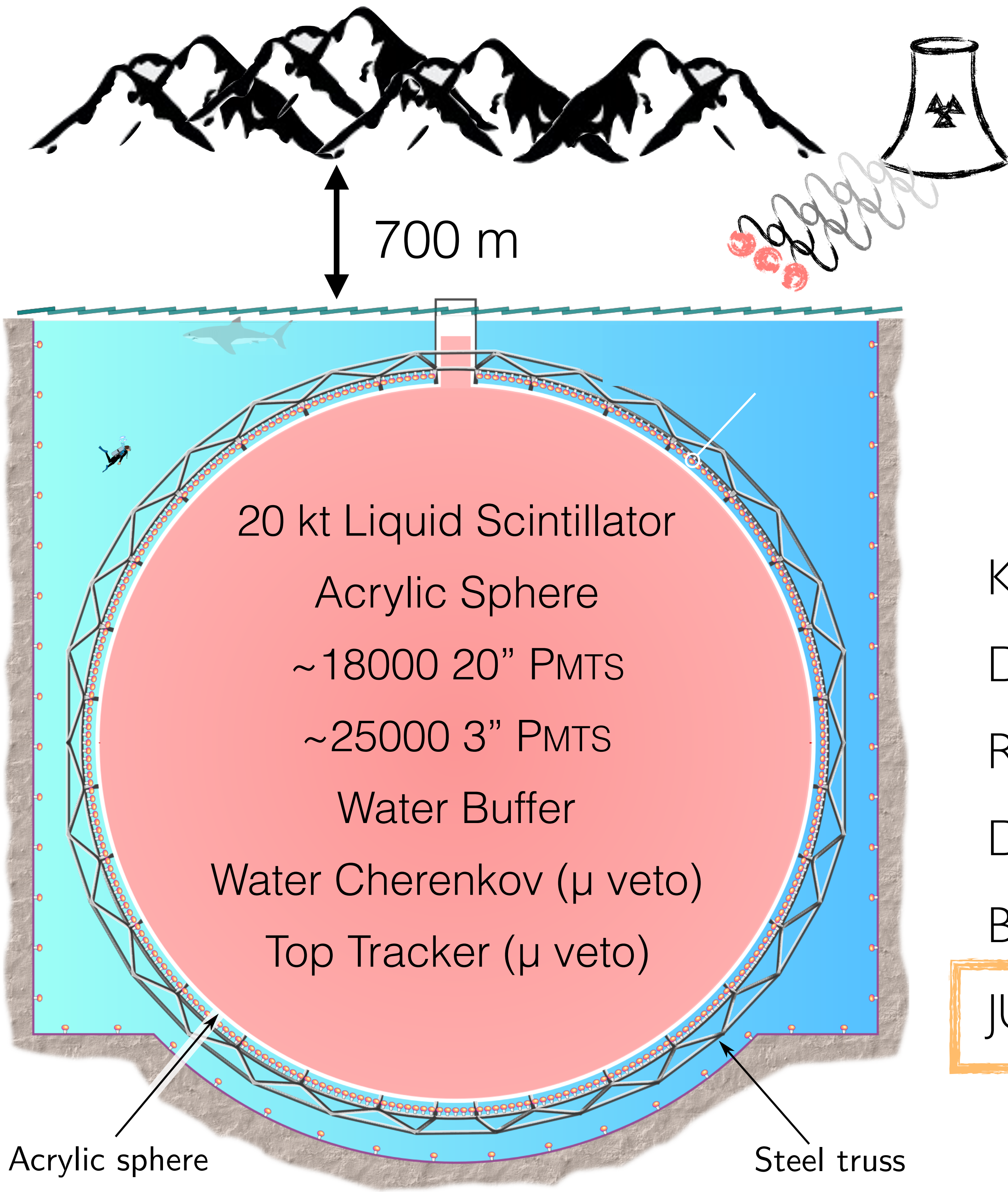
Magnetic Field

Compensating Coil




44 m
Pantheon @ Roma

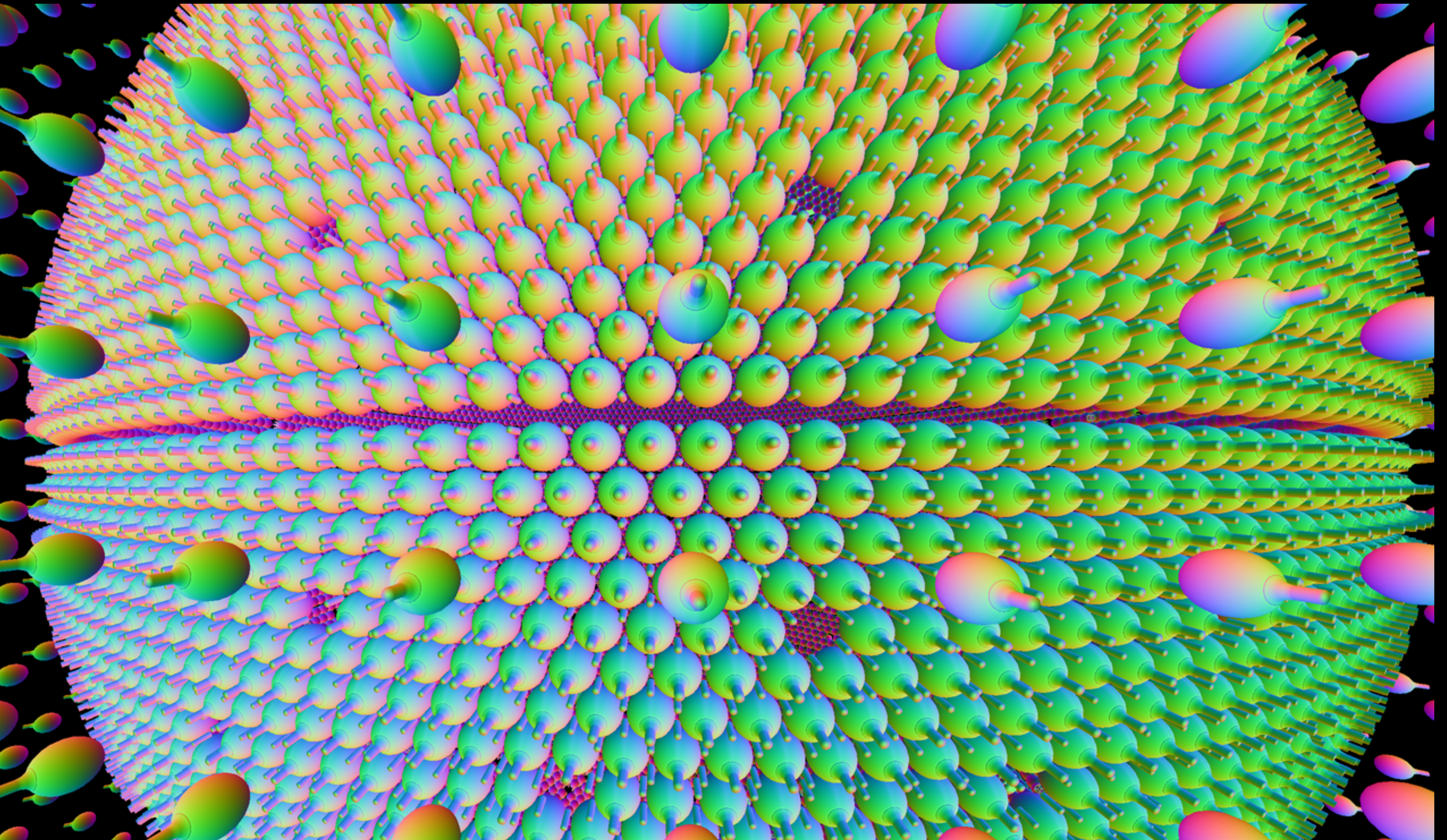
JUNO within the Global Experimental Landscape



2 Key parameters:

LARGE & PRECISE

	DETECTOR TARGET MASS	RESOLUTION
KamLAND	1000 t	$6\%/\sqrt{E}$
Double Chooz	8 t	$8\%/\sqrt{E}$
RENO	16 t	$8\%/\sqrt{E}$
Daya Bay	20 t	$8\%/\sqrt{E}$
Borexino	300 t	$5\%/\sqrt{E}$
JUNO	20000 t	$3\%/\sqrt{E}$



Largest photocathode density ever built: 78% coverage

Largest light level ever detected: 1200 pe/MeV

(Daya Bay 160 pe/MeV - Borexino 500 pe/MeV - KamLAND 250 pe/MeV)

Why JUNO?

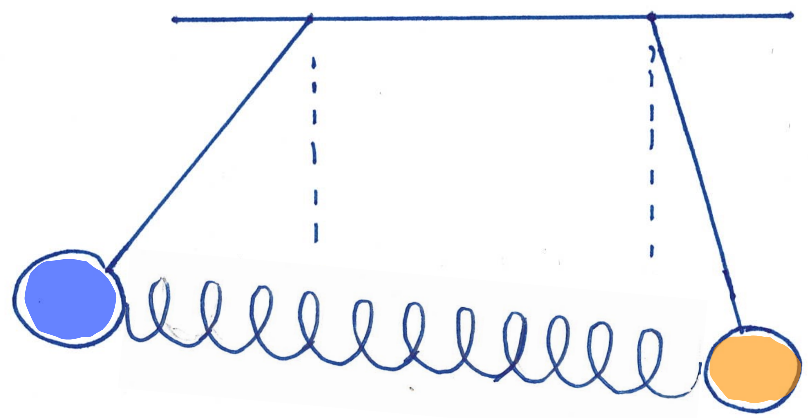
Neutrino Mixing

(non-zero) Neutrino Mass Eigenstates ≠ Interaction Eigenstates ▶ Oscillation

Atmospheric Oscillation

Amplitude: θ_{23}

Frequency: Δm^2_{31}



Coupling θ_{13}

Subleading: δ_{CP}

Solar Oscillation

Amplitude: θ_{12}

Frequency: Δm^2_{21}

Mixing described by the Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\vartheta_{23} & \sin\vartheta_{23} \\ 0 & -\sin\vartheta_{23} & \cos\vartheta_{23} \end{pmatrix} \begin{pmatrix} \cos\vartheta_{13} & 0 & \sin\vartheta_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\vartheta_{13}\, e^{i\delta} & 0 & \cos\vartheta_{13} \end{pmatrix} \begin{pmatrix} \cos\vartheta_{12} & \sin\vartheta_{12} & 0 \\ -\sin\vartheta_{12} & \cos\vartheta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric — Reactor (L~1km) — Solar

Credits: W.Winter

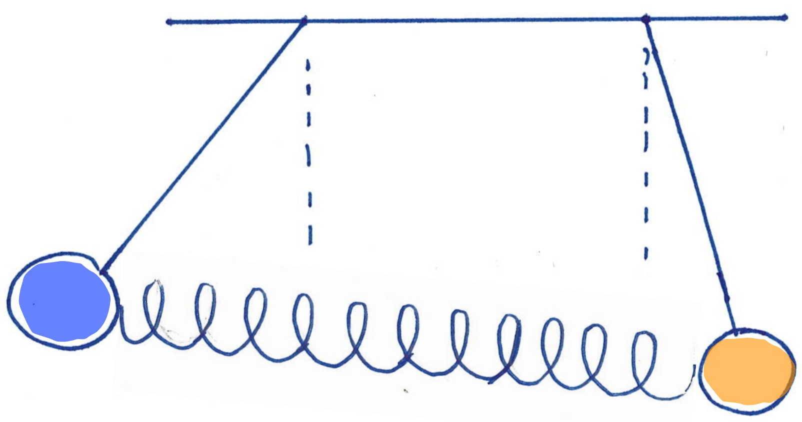
Neutrino Mixing at JUNO

(non-zero) Neutrino Mass Eigenstates ≠ Interaction Eigenstates ▶ Oscillation

Atmospheric Oscillation

Amplitude: θ_{23}

Frequency: Δm^2_{31}



Solar Oscillation

Amplitude: θ_{12}

Frequency: Δm^2_{21}

Coupling θ_{13}

Subleading: δ_{CP}

Experiments so far optimized to observe **only one oscillation** at a time

JUNO will see **interference pattern** resulting from both oscillations

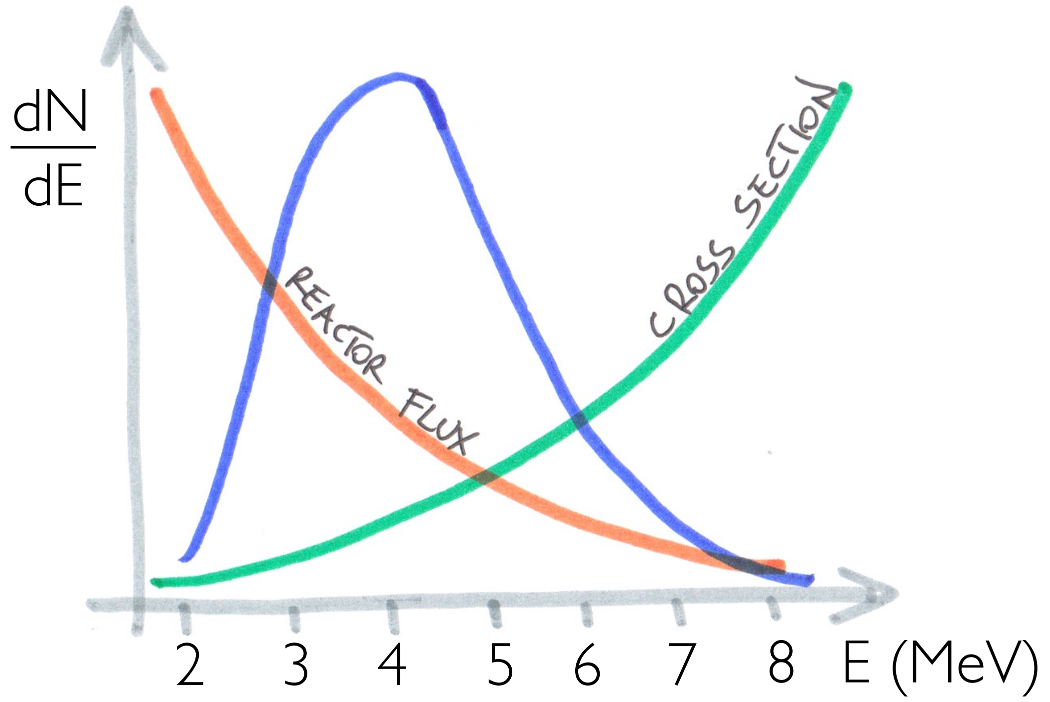
Δm^2_{21} / Δm^2_{31} ~ 3% ▶ Energy Resolution

Powerful test of the 3-neutrino mixing model

Interference allows to determine **neutrino mass ordering** (Petcov&Piai 2002)

Antineutrinos From Reactor

EMISSION SPECTRUM



Nuclear Power Plants

Energy by breaking heavy nuclei

Fission fragments are unstable

Cascade of beta decays

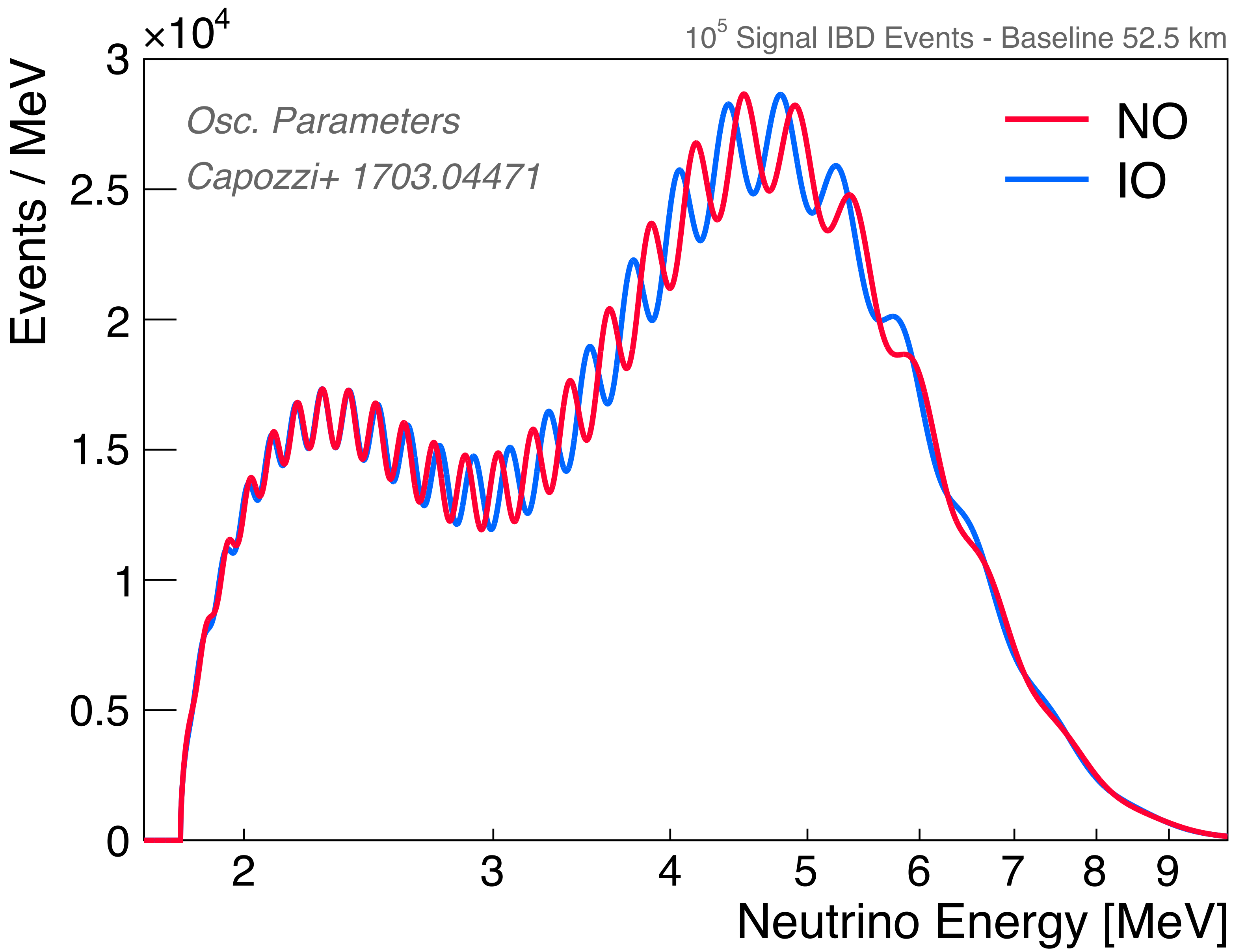
$$n \rightarrow p + e^- + \bar{\nu}_e$$

3 GW_{th} reactor : $\sim 10^{20}\ \bar{\nu}_e$ / s

Oscillated Antineutrino Spectrum

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\vartheta_{13} \cdot \sin^2\left(\cos^2\vartheta_{12}\,\sin^2\Delta_{31} + \sin^2\vartheta_{12}\,\sin^2\Delta_{32}\right)$$ Fast

$$- \sin^2 2\vartheta_{12}\,\cos^4\vartheta_{13}\,\sin^2\Delta_{21}$$ Slow



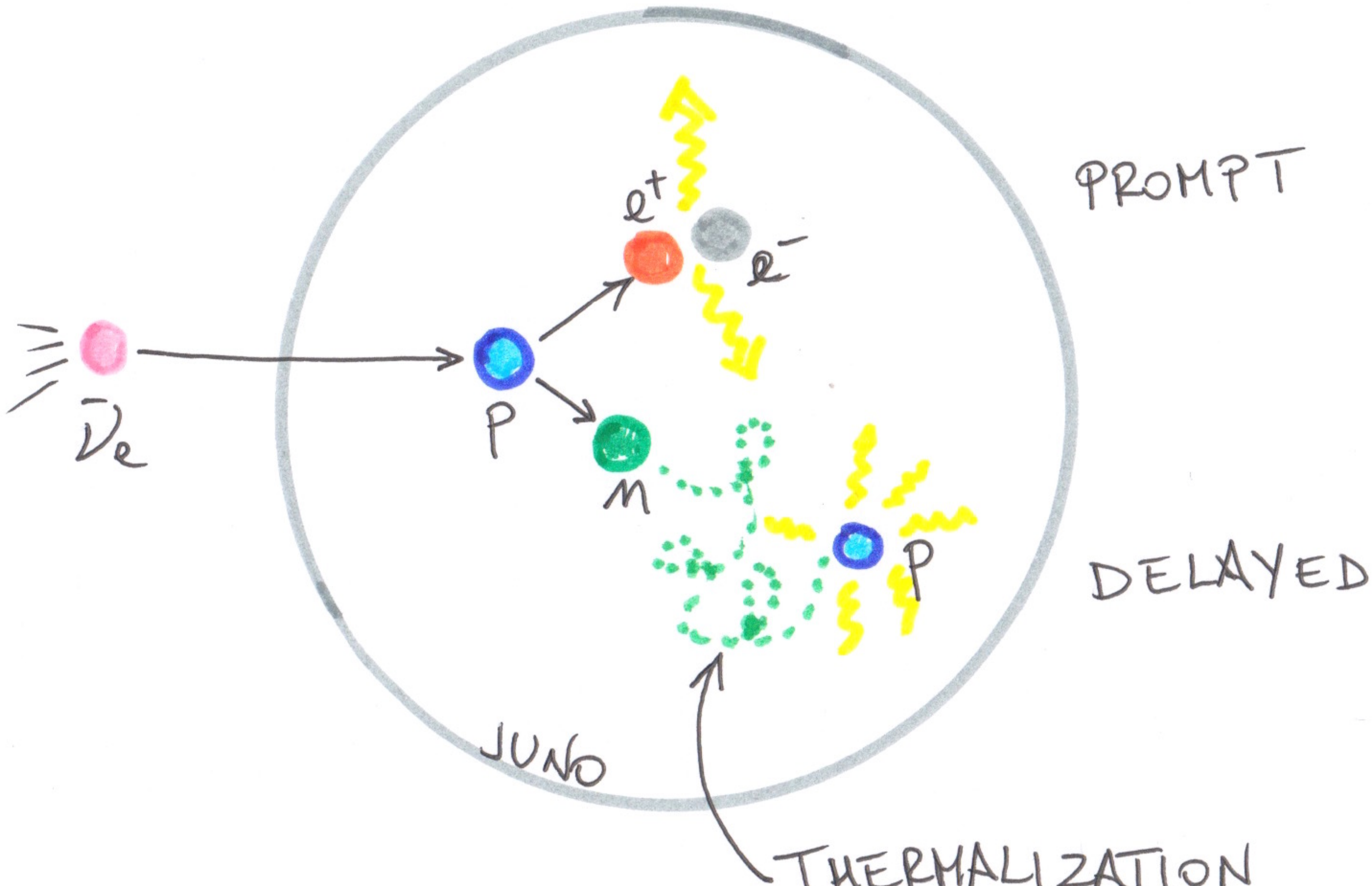
Goal: disentangle Blue/Red spectra

Need precise measurement of antineutrino energy

JUNO can be seen as an "Antineutrino Calorimeter"

Focus on antineutrino detection

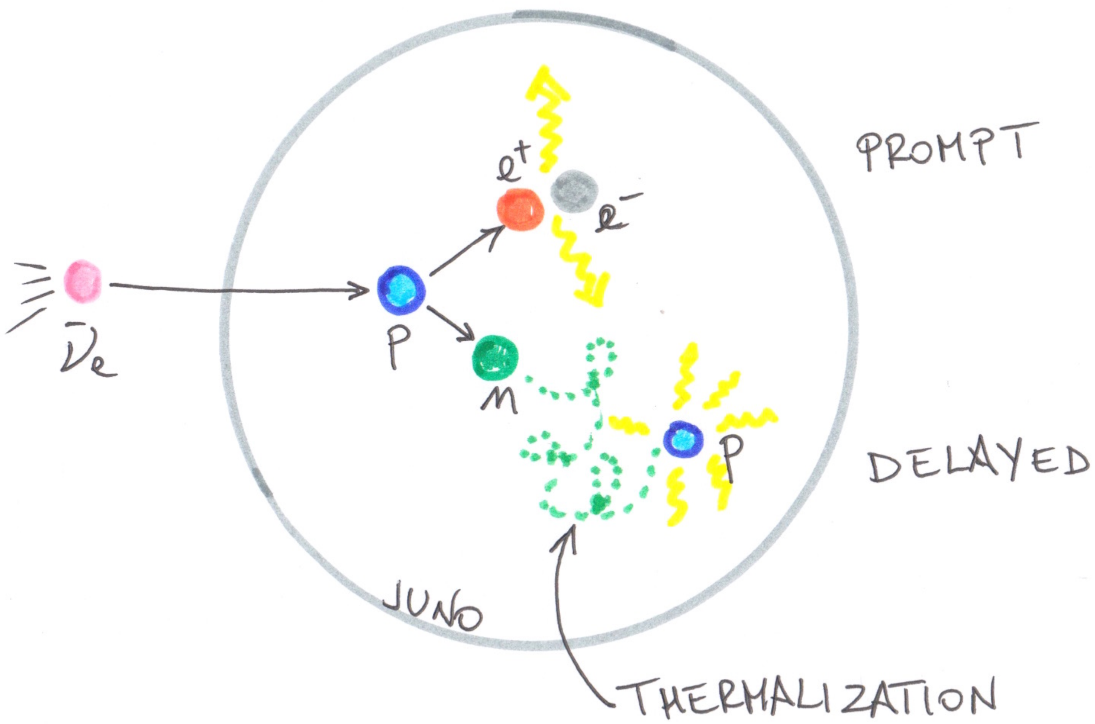
Signal Events: Antineutrino Detection

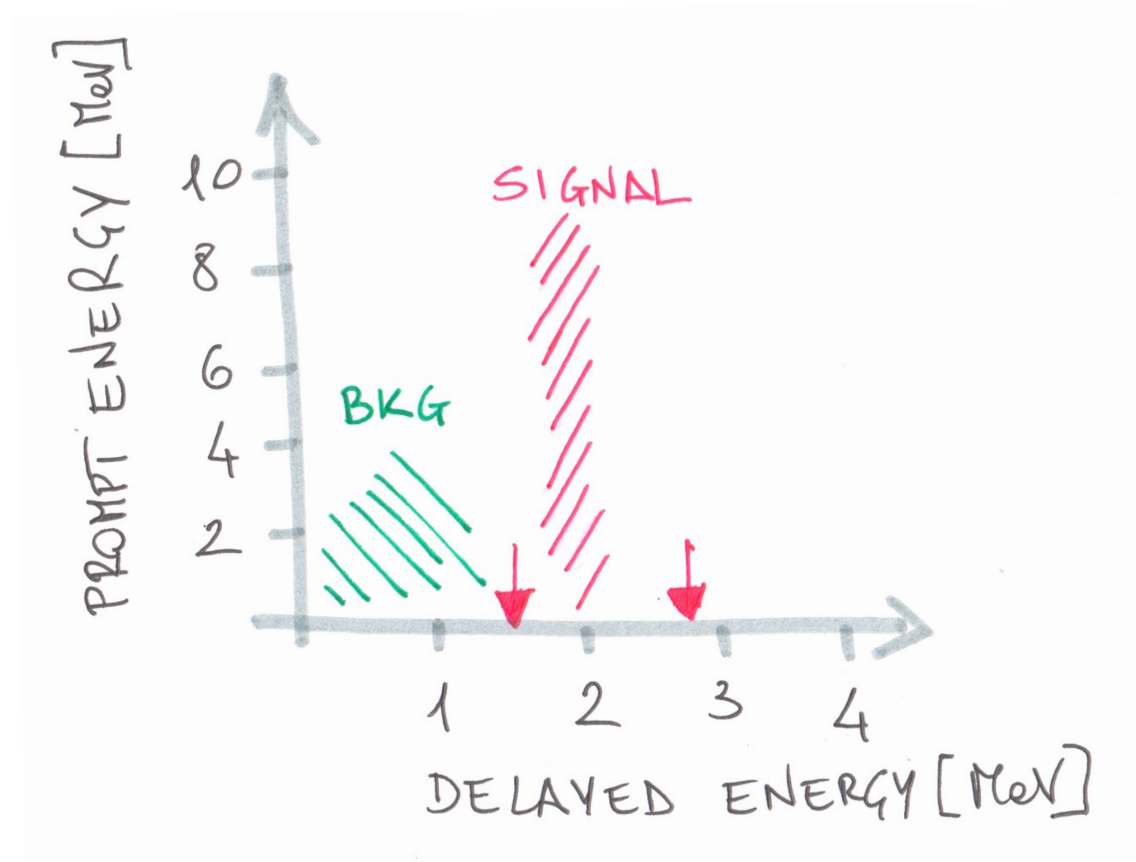


Inverse Beta Decay (IBD) :

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

Signal Events: Antineutrino Detection





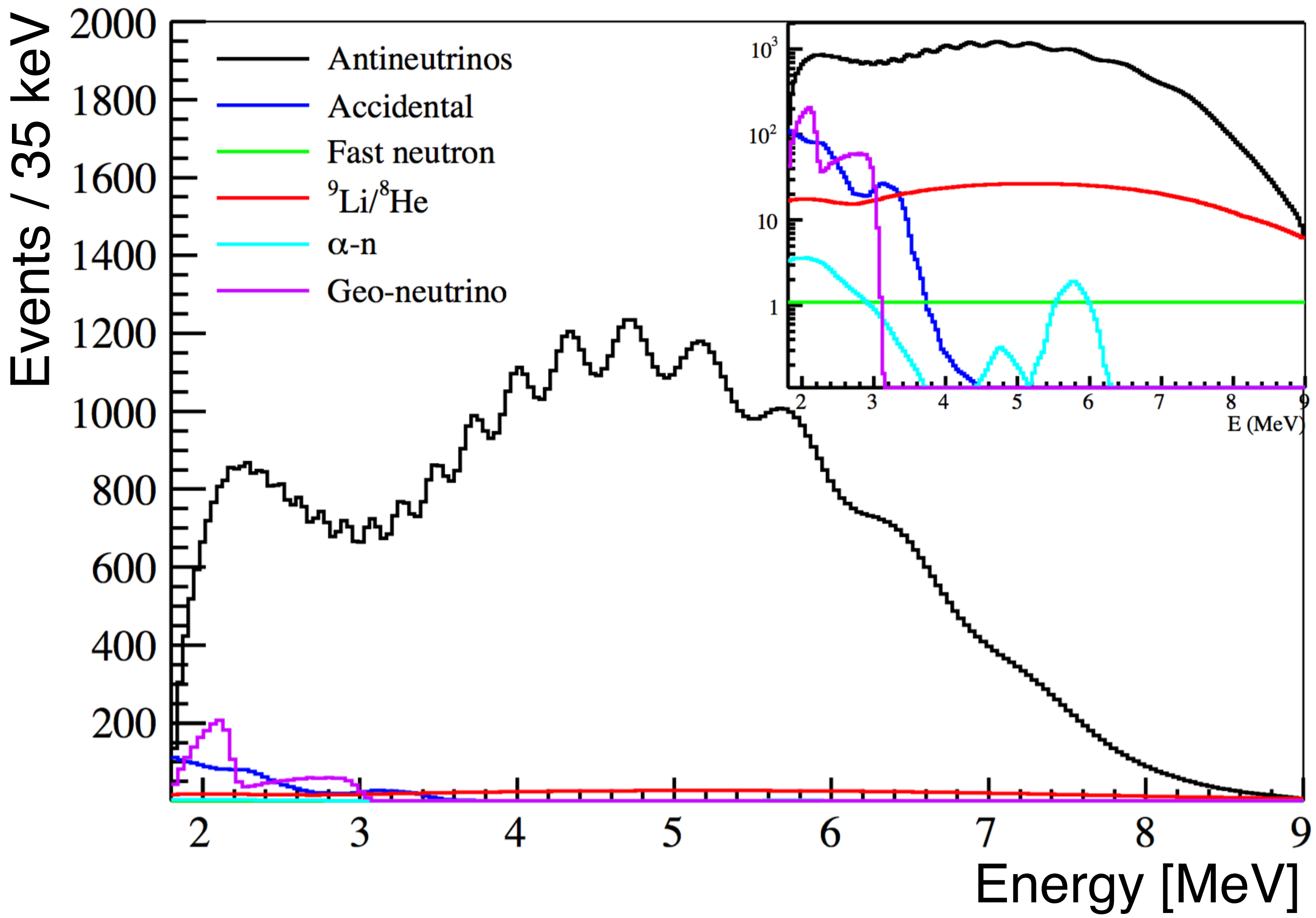
Inverse Beta Decay (IBD) :

$\bar{\nu}_e + p \longrightarrow e^+ + n$ Prompt

$n + p \xrightarrow{\tau \sim 200\,\mu s} D + \gamma\ (2.2\ \mathrm{MeV})$ Delayed

$E(\bar{\nu}_e) \sim K(e^+) + 1.8\ \mathrm{MeV}$ Prompt energy is a good proxy for $\bar{\nu}_e$ energy

Background Overview



Two Main Backgrounds

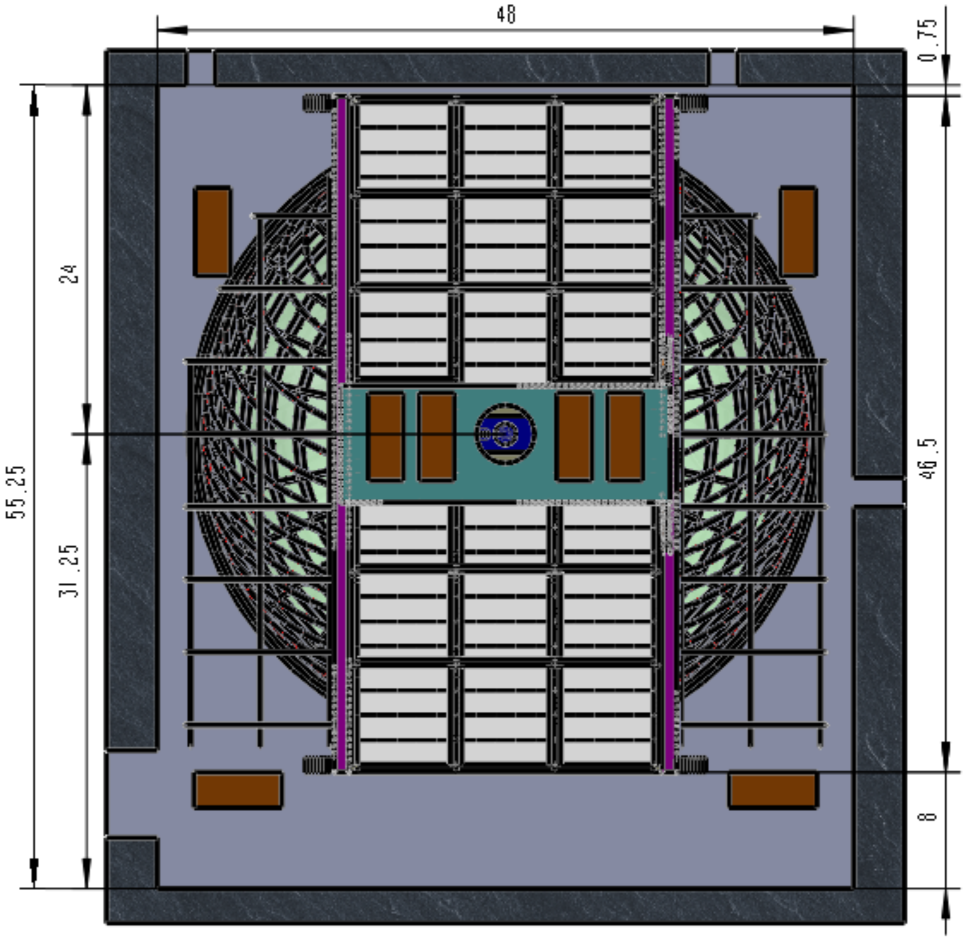
Random energy depositions from natural radioactivity

Unstable isotopes generated by muon spallation on liquid scintillator molecules

Event Rate per Day

Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	83	1.5	$\sim 5.7 \times 10^4$	84	-	-
Fiducial volume	91.8%	76	1.4		77	0.1	0.05
Energy cut	97.8%			410			
Time cut	99.1%	73	1.3		71		
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60		3.8			

Muon Veto



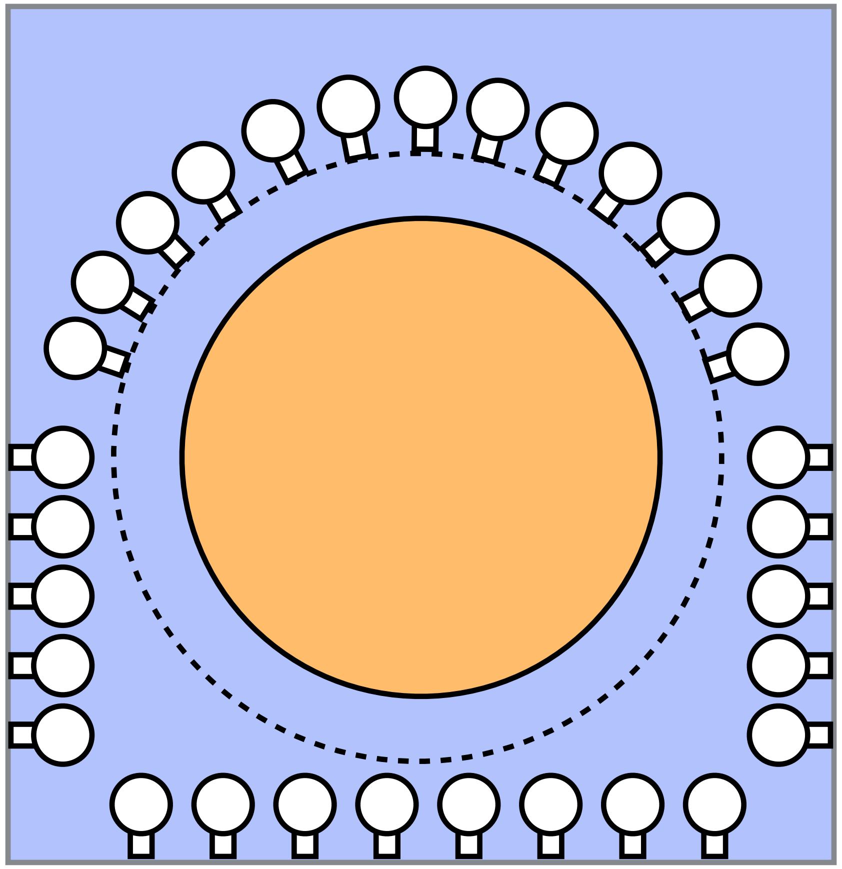
Top Tracker

OPERA plastic scintillator modules

Three overlapping layers

Partial coverage due to available modules

- Reject ~50% muons
- Provide tagged muon sample to study background rejection



Water Cherenkov

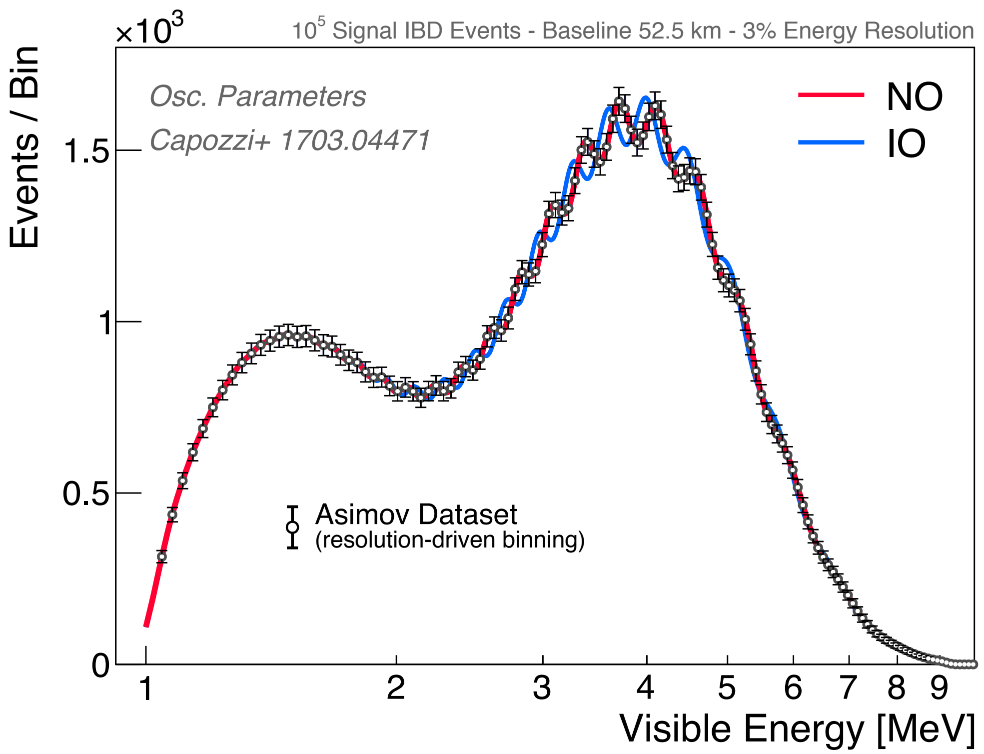
20~30kt ultra-pure water

Water acting as moderator &
pool instrumented to detect Cherenkov light

2000 20” PMTs located as in the picture

Maximize detection efficiency of Cherenkov light

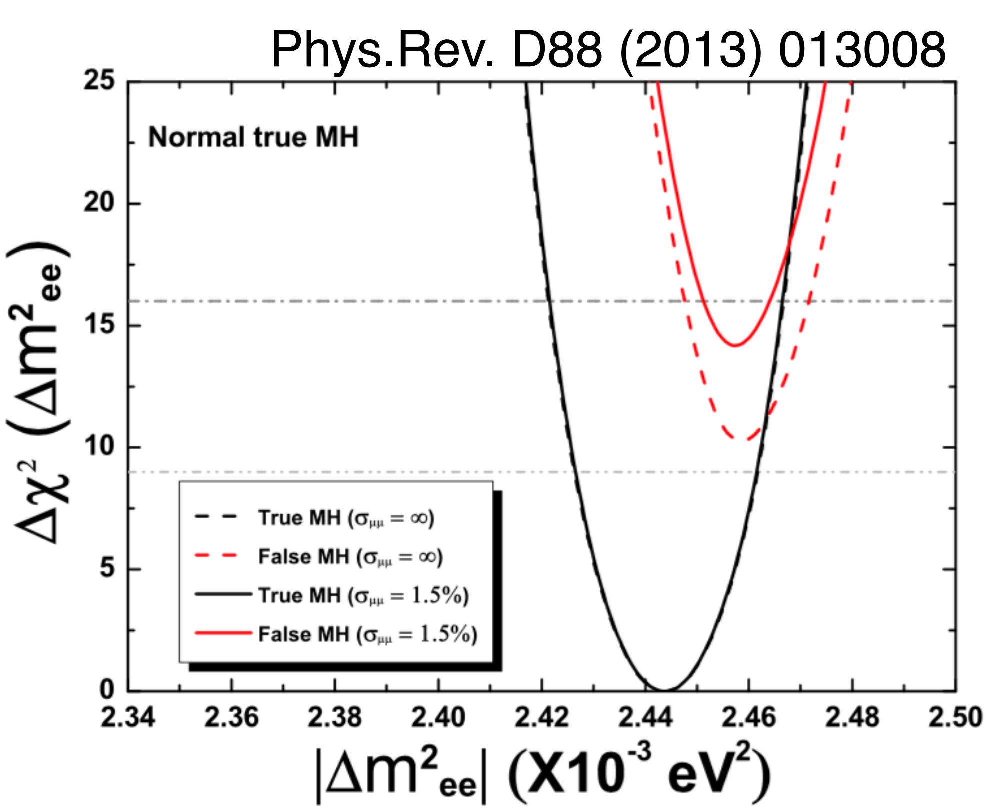
Mass Ordering Determination



Fit data against both models

Several experimental caveats

- Energy Resolution
- Energy Linearity
- Spatial distribution of reactor cores
- …



Mass Ordering Sensitivity

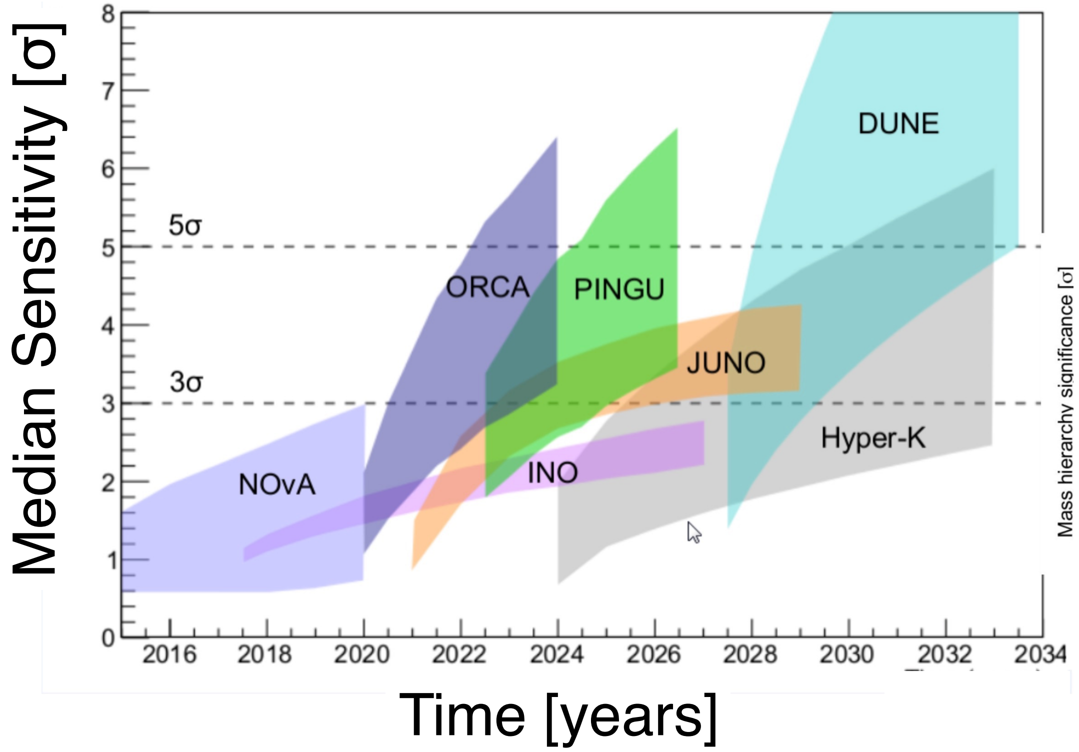
100k signal events (20kt x 36GW x 6 years)

$\Delta\chi^2$: Fitting wrong model - Fitting correct one

Unconstrained (JUNO only) $\Delta\chi^2 \sim 10$

Using external $\Delta m_{\mu\mu}$ (1.5% precision) from long baseline exps: $\Delta\chi^2 \sim 14$

What's Special About Mass Ordering at JUNO

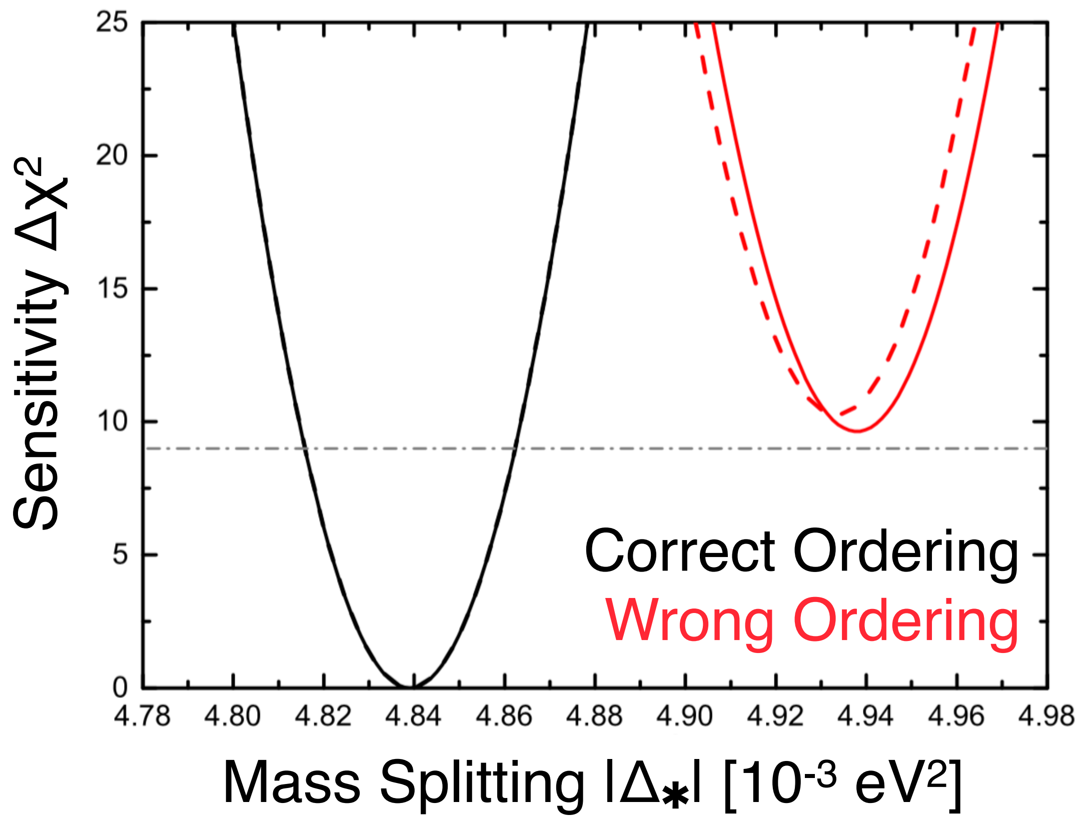


Many complementary experiments

Similar time scales but

- Different experimental techniques
- Different systematic uncertainties

JUNO only experiment exploiting disappearance in-vacuum oscillation



No dependence from θ_{23} or δ(CP)

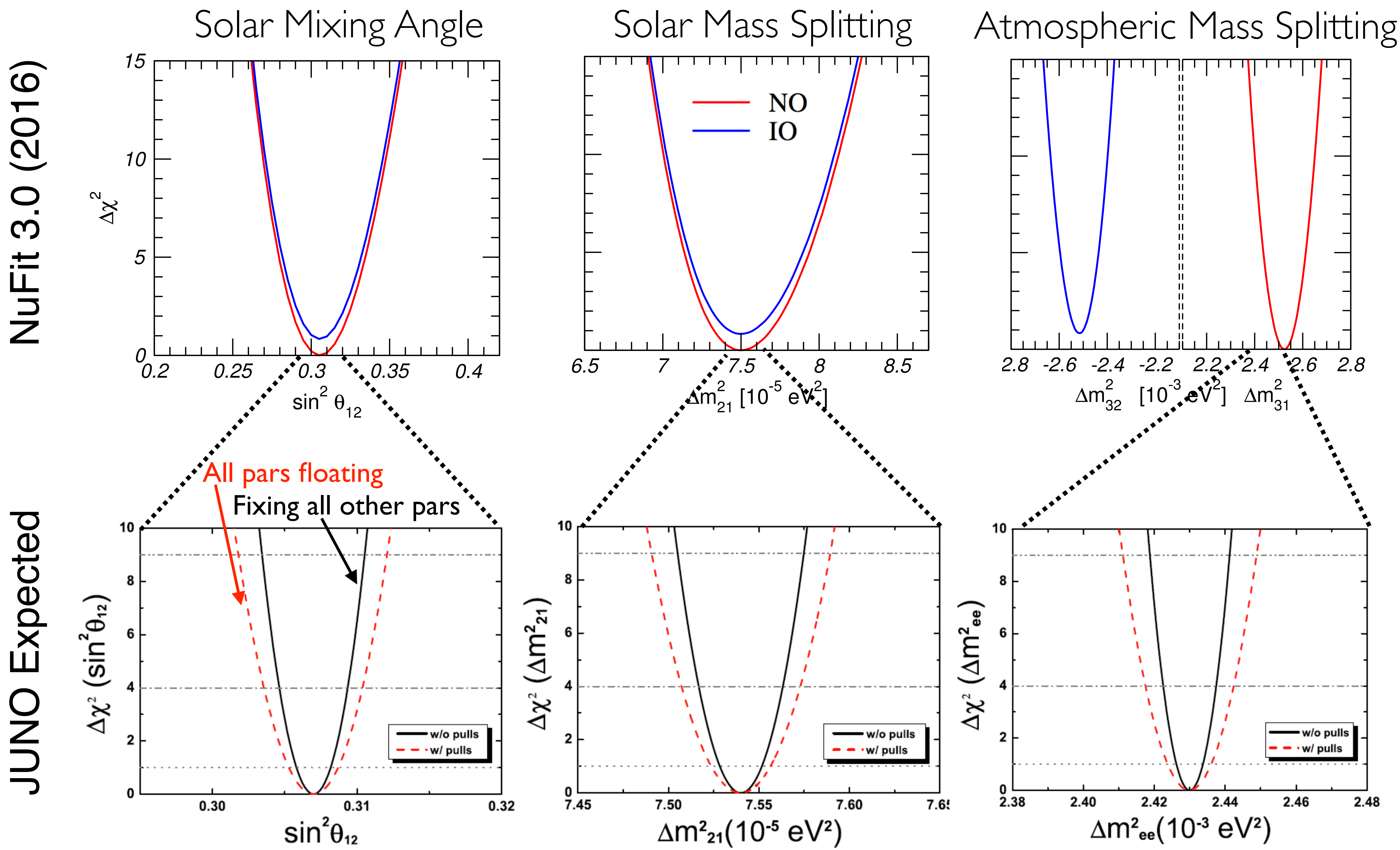
Very little dependence from matter effects

Chin.Phys. C40 (2016), 091001

- - - - JUNO sensitivity w/o matter effects

—— JUNO sensitivity with matter effects

Sensitivity To Oscillation Parameters



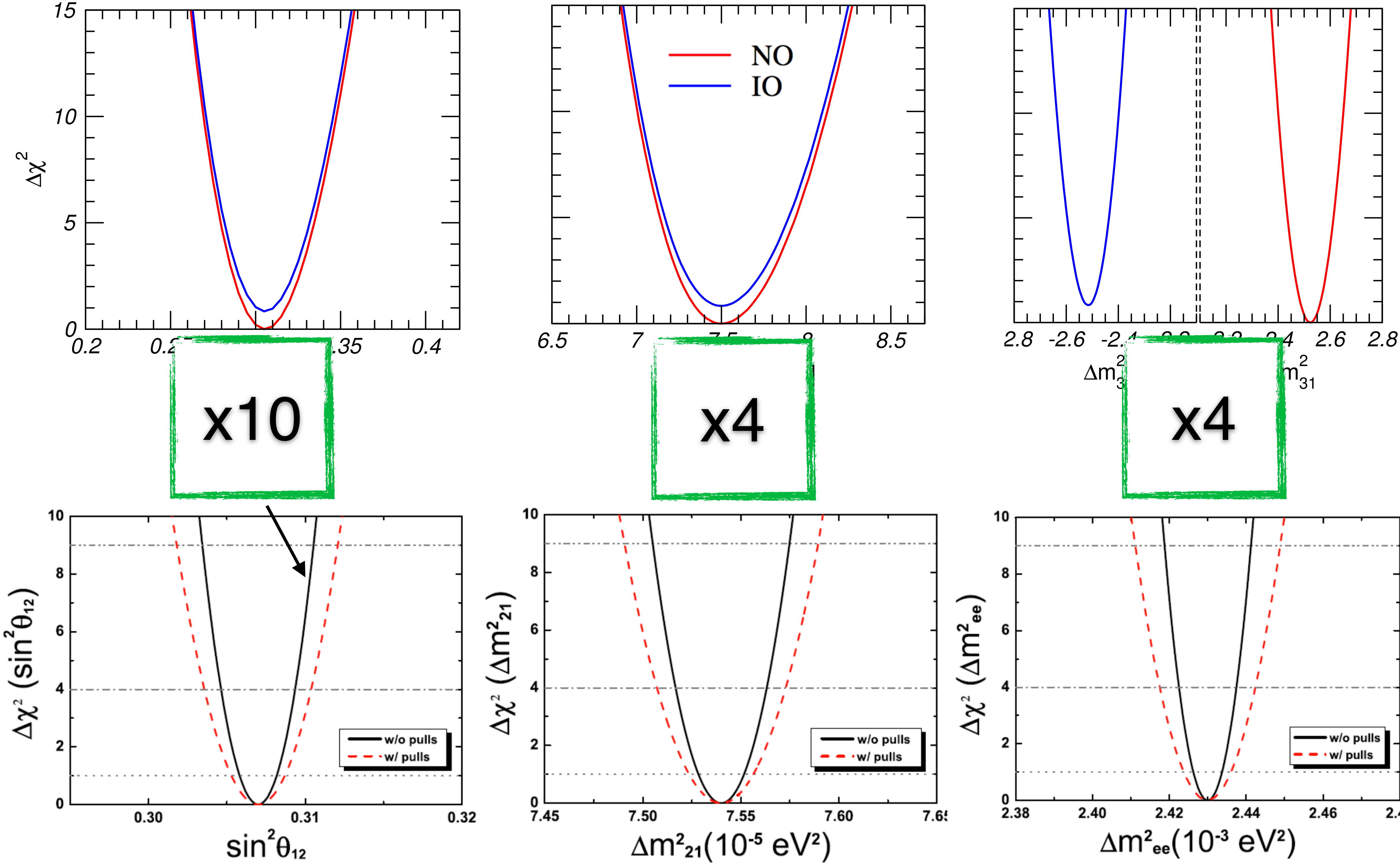
$\sin^2(\theta_{12})$: 0.67% **Δm^2_{21}: 0.59%** **Δm^2_{ee}: 0.44%**

Sensitivity To Oscillation Parameters

NuFit 3.0 (2016)

JUNO Expected

Solar Mixing Angle | Solar Mass Splitting | Atmospheric Mass Splitting



$\sin^2(\theta_{12})$: 0.67% | **Δm^2_{21}: 0.59%** | **Δm^2_{ee}: 0.44%**

Solar Oscillation Parameters: a Redundant Measurement

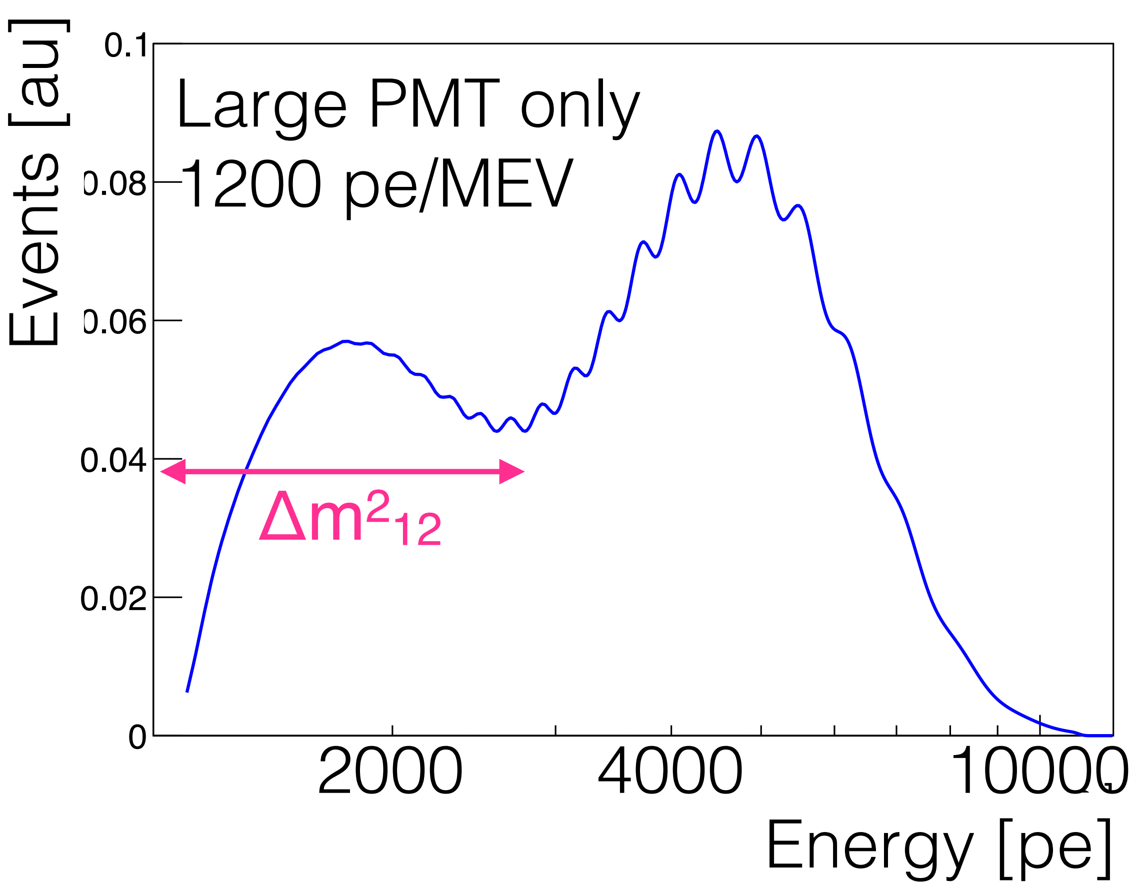
JUNO: a stereo-calorimetric detector

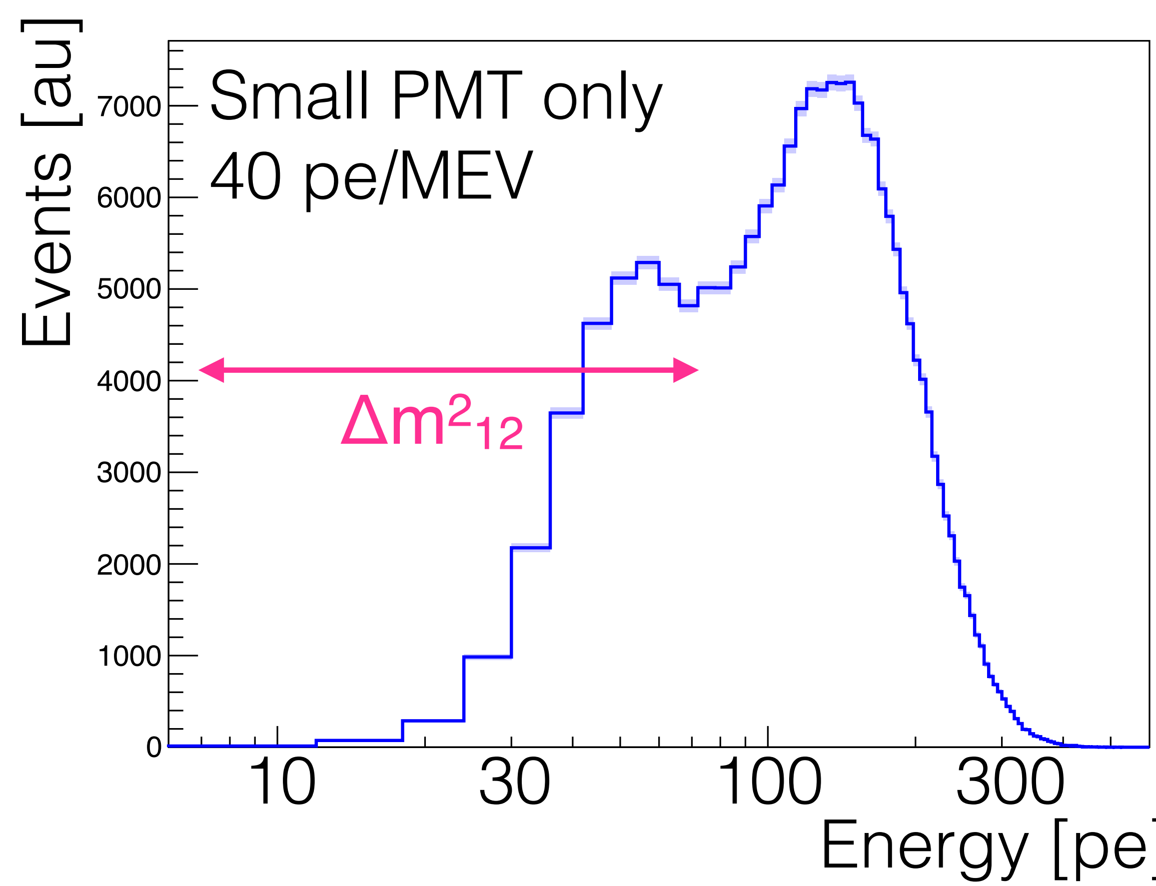
Two PMT systems looking at same event

- 20-inch: main calorimetry
- 3-inch: constrain energy systematics

Allow redundant solar par. measurement

Ensure accuracy!

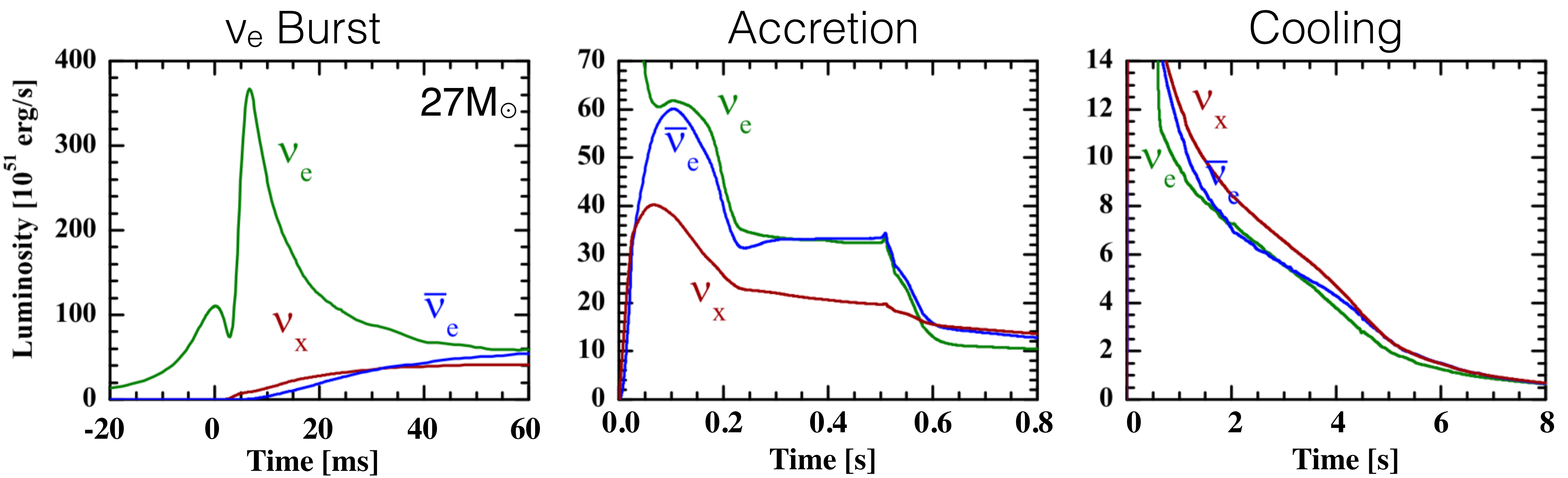




Beyond Reactor Neutrino Physics

Supernova Burst

99% of gravitational binding energy emitted as (anti)neutrinos



Process	Type	Events ⟨E_ν⟩=14MeV
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	5.0×10^3
$\nu + p \rightarrow \nu + p$	NC	1.2×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	NC	3.2×10^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	CC	0.9×10^2
$\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	1.1×10^2

NB Other ⟨E_ν⟩ values need to be considered to get complete picture.

Multiple detection channels

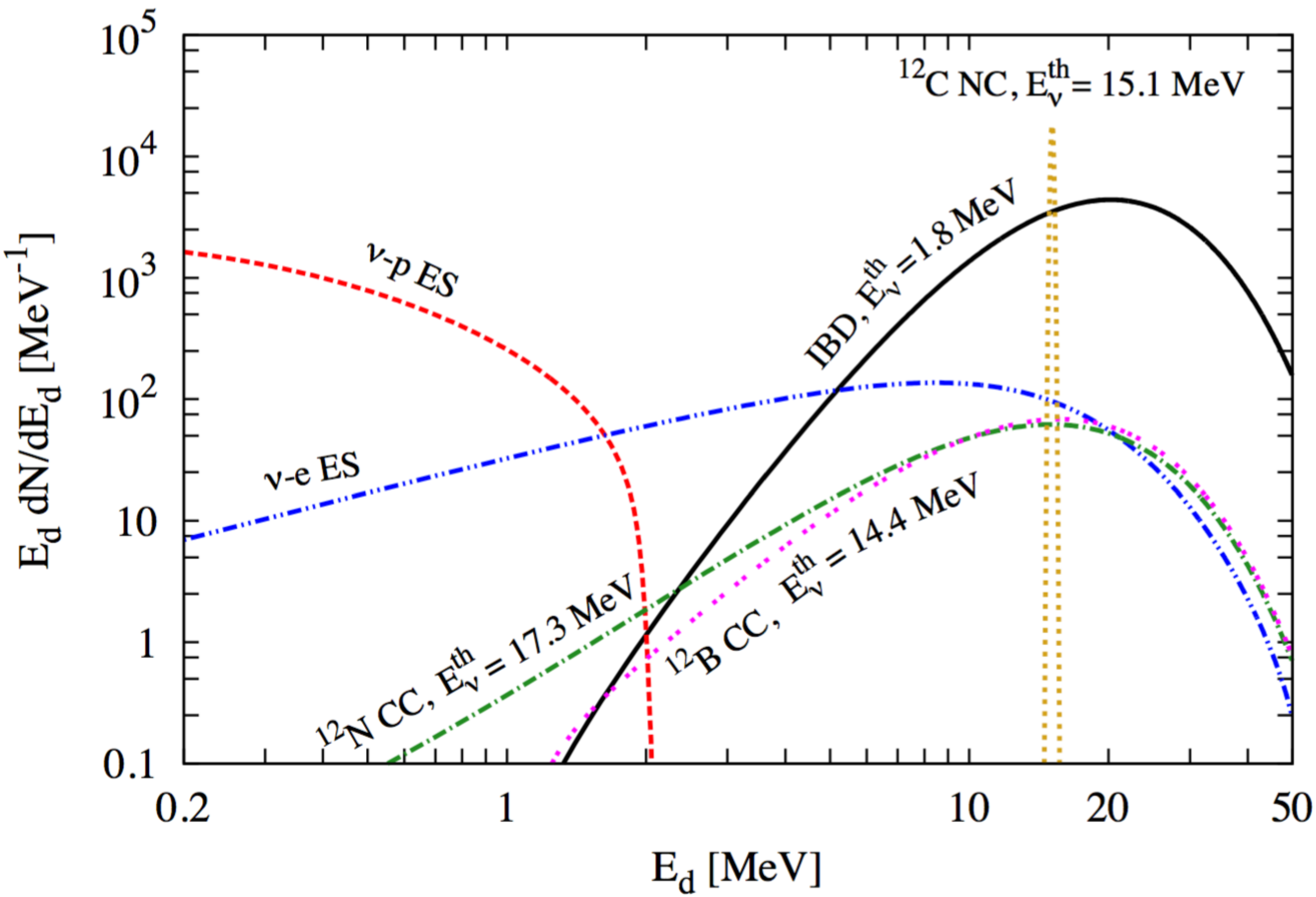
Expected events in JUNO for a typical supernova distance of 10kpc

J.Phys. G43 (2016) no.3, 030401

Supernova Neutrino - Detection Channels

Supernova at 10 kParsec

$$\langle E_{\nu_e} \rangle = 12 \text{ MeV}, \ \langle E_{\overline{\nu}_e} \rangle = 14 \text{ MeV and } \langle E_{\nu_x} \rangle = 16 \text{ MeV}.$$



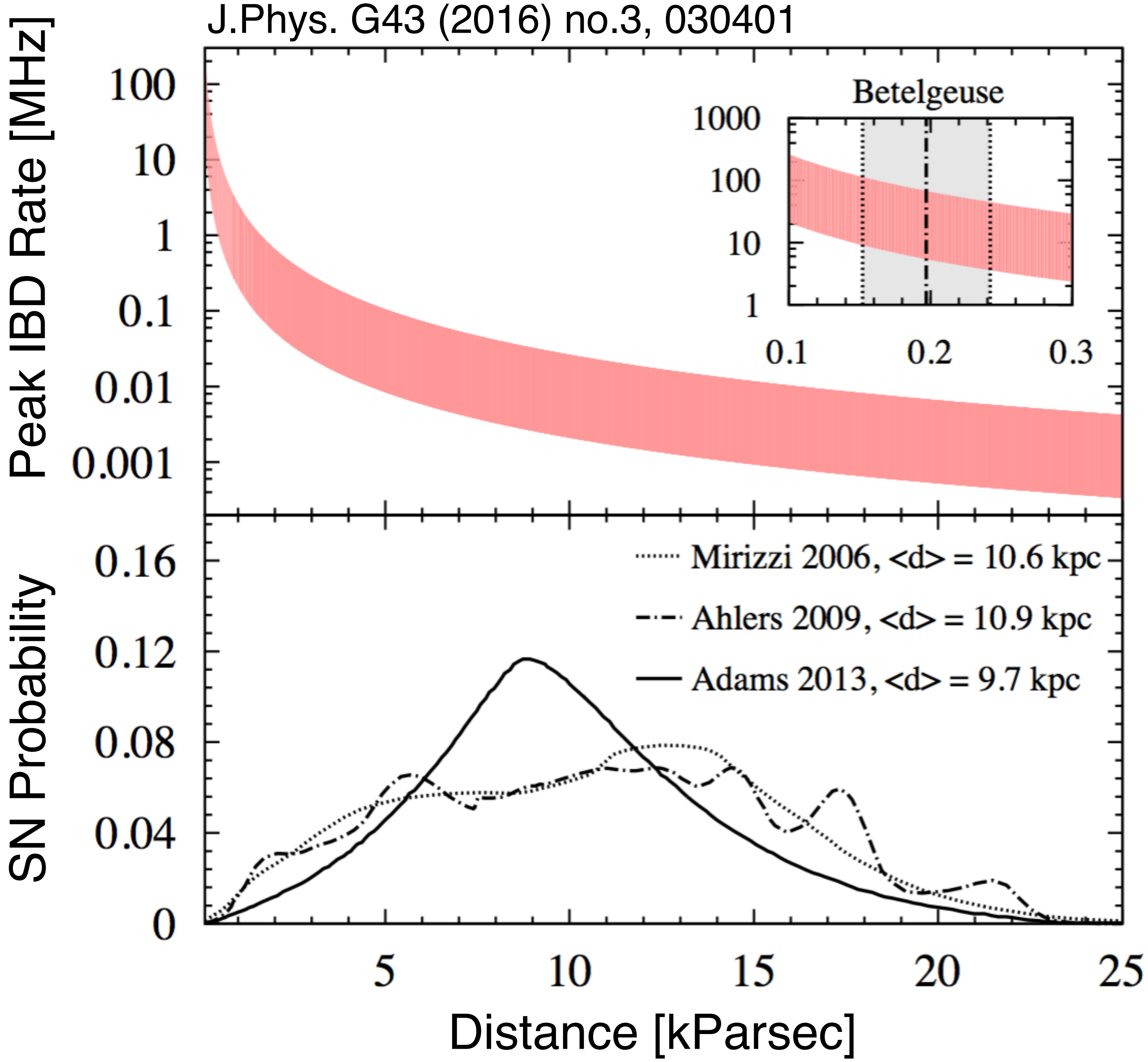
Visible Energy [MeV]

Challenges in Supernova Detection

The most difficult event to handle in JUNO's lifespan (if it will ever happen)

Electronics over-designed only to handle the data rate of such an event

J.Phys. G43 (2016) no.3, 030401



Both rate and energy need to be measured

Extreme pile-up condition
Hard to disentangle multiple energy depositions

Profit from 10s of PMT waveforms sampled at 1GHz

Profit from two redundant PMT systems with different readout electronics

Geoneutrinos

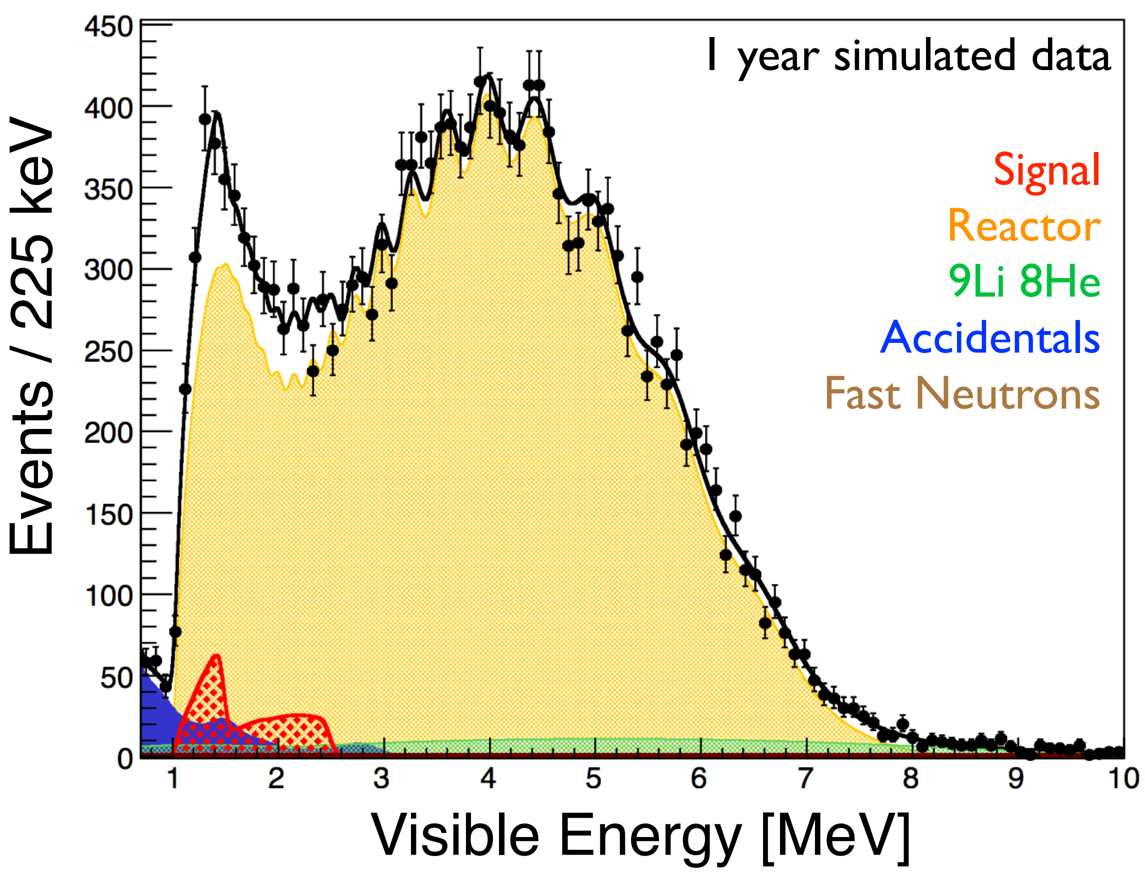
Earth's total heat flow is well measured: 46±3 TW.

Need to investigate its source: primordial vs radioactive

- Composition of the Earth (chondritic meteorites that formed our planet)
- Chemical layering of mantle & dynamics of mantle convection
- Energy needed to drive plate tectonics

What

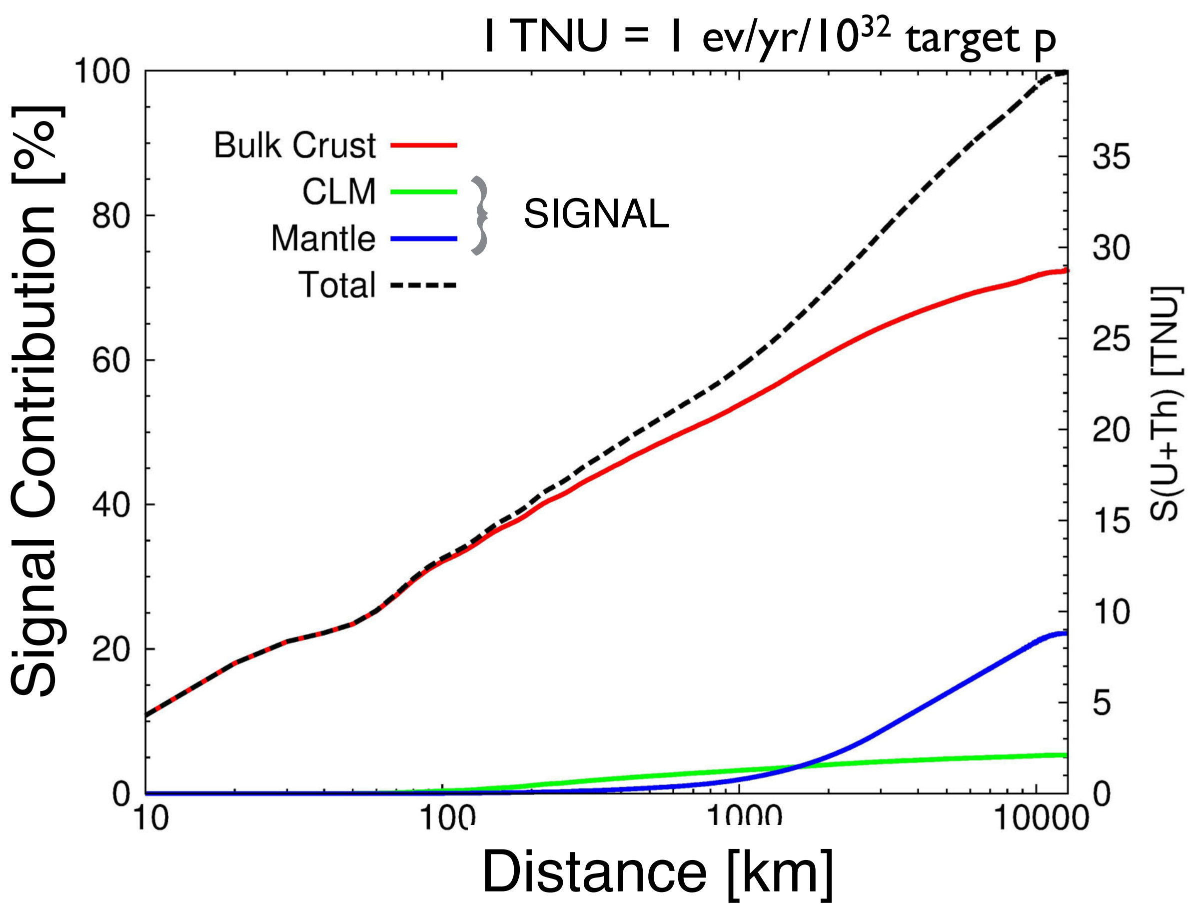
Detect $\bar{\nu}_e$ from the ^{238}U and ^{232}Th



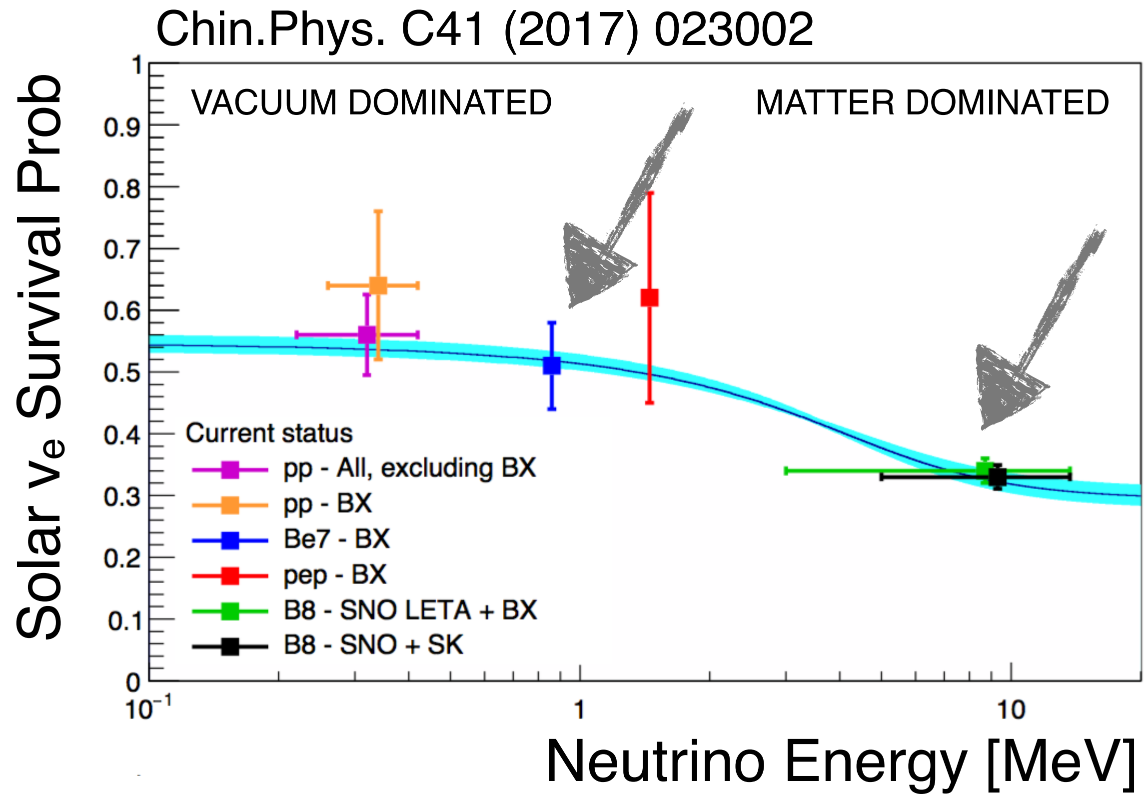
J.Phys. G43 (2016) no.3, 030401

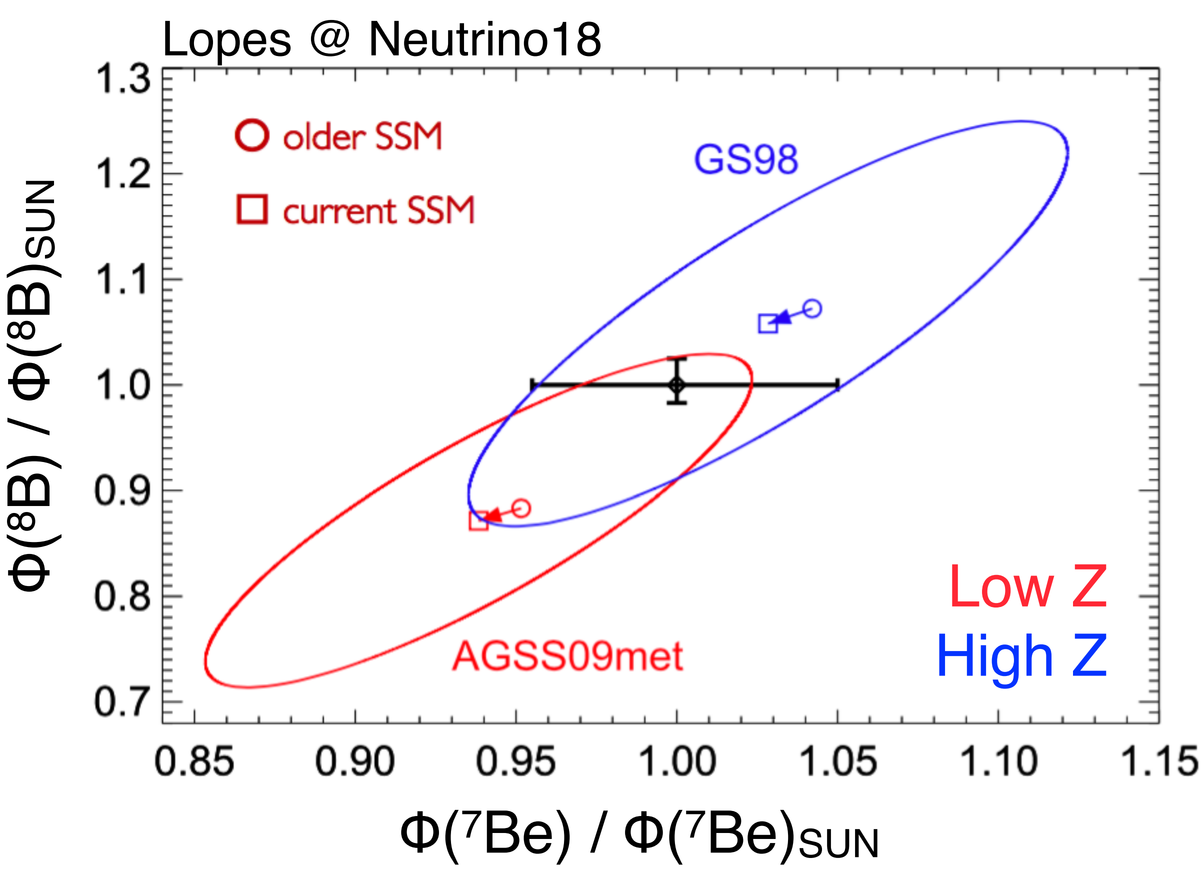
Challenge

Disentangle mantle contribution



Why Solar Neutrinos at JUNO





Sun fusion reactions: powerful source of electron neutrinos at O(1 MeV)

JUNO might detect neutrinos from ^{7}Be and ^{8}B chains

Investigate MSW effect: Transition between vacuum and matter dominated regimes

Constrain Solar Metallicity Problem: neutrinos as proxy for Sun composition

Challenges in Solar Neutrino Detection

Pros

20 kt detector
- Larger statistics than Borexino & SNO
- Aggressive fiducialization (external radioactivity)

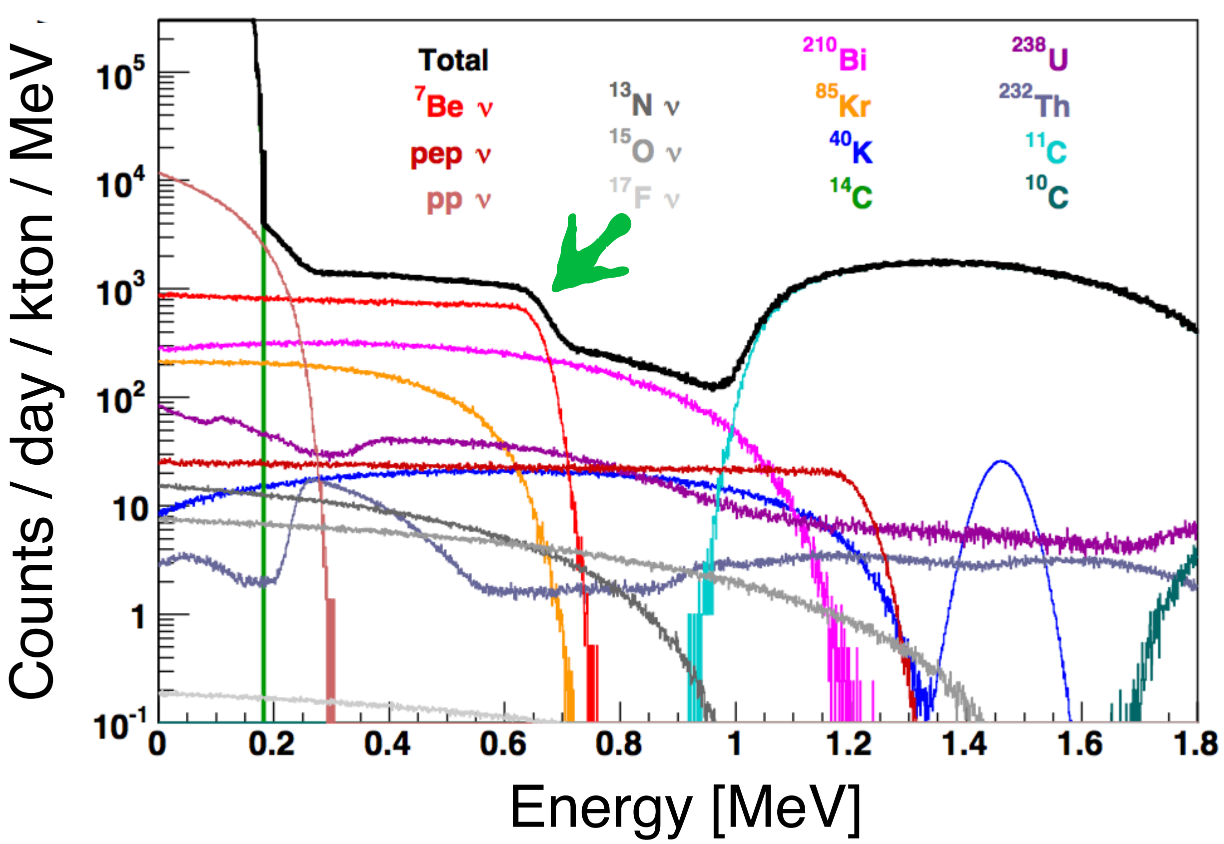
Challenges

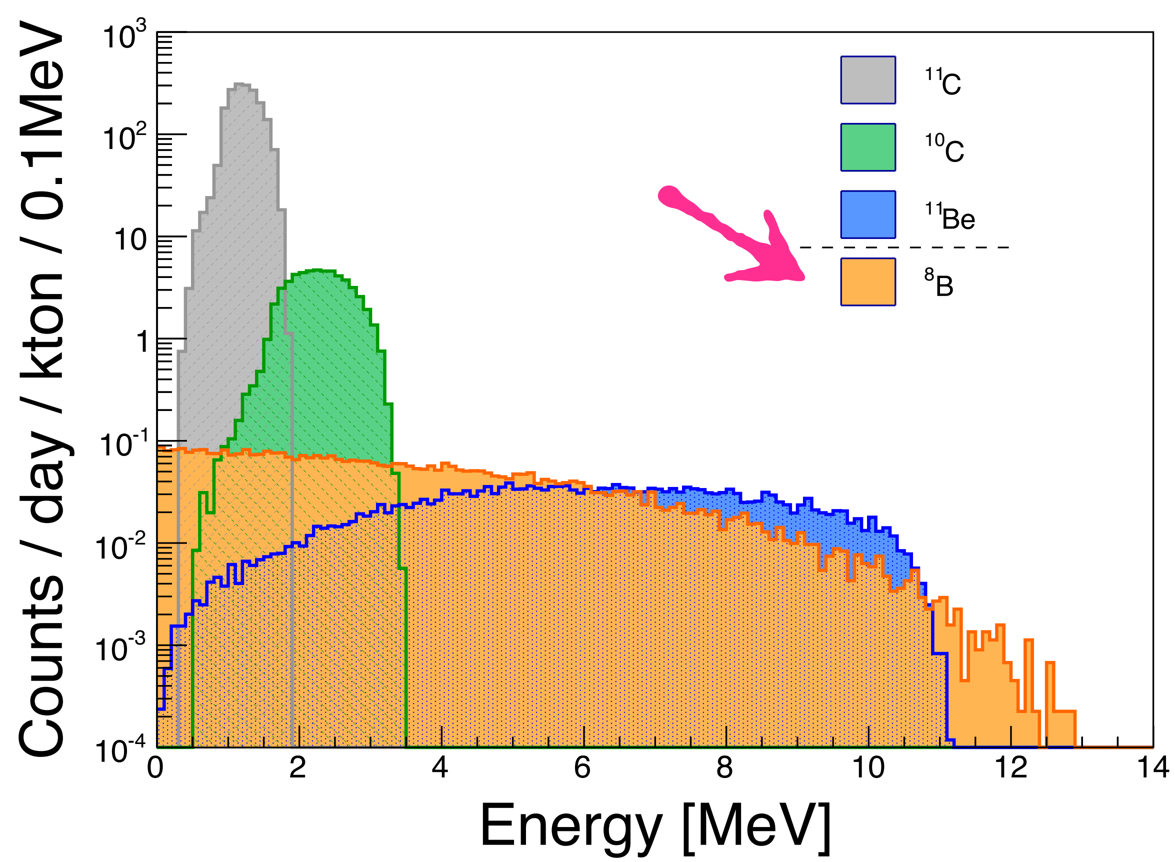
^{7}Be

- Detection through elastic scattering
- Prompt-delayed coincidence lost
- Swallowing scintillator radioactivity
- Rely on liquid scintillator purification

^{8}B

- Shallower wrt to other solar exps
- Considerable cosmogenic bkg
- Rely on statistical subtraction & 3-fold coincidence (n tagging)





Project Status

Prototypes

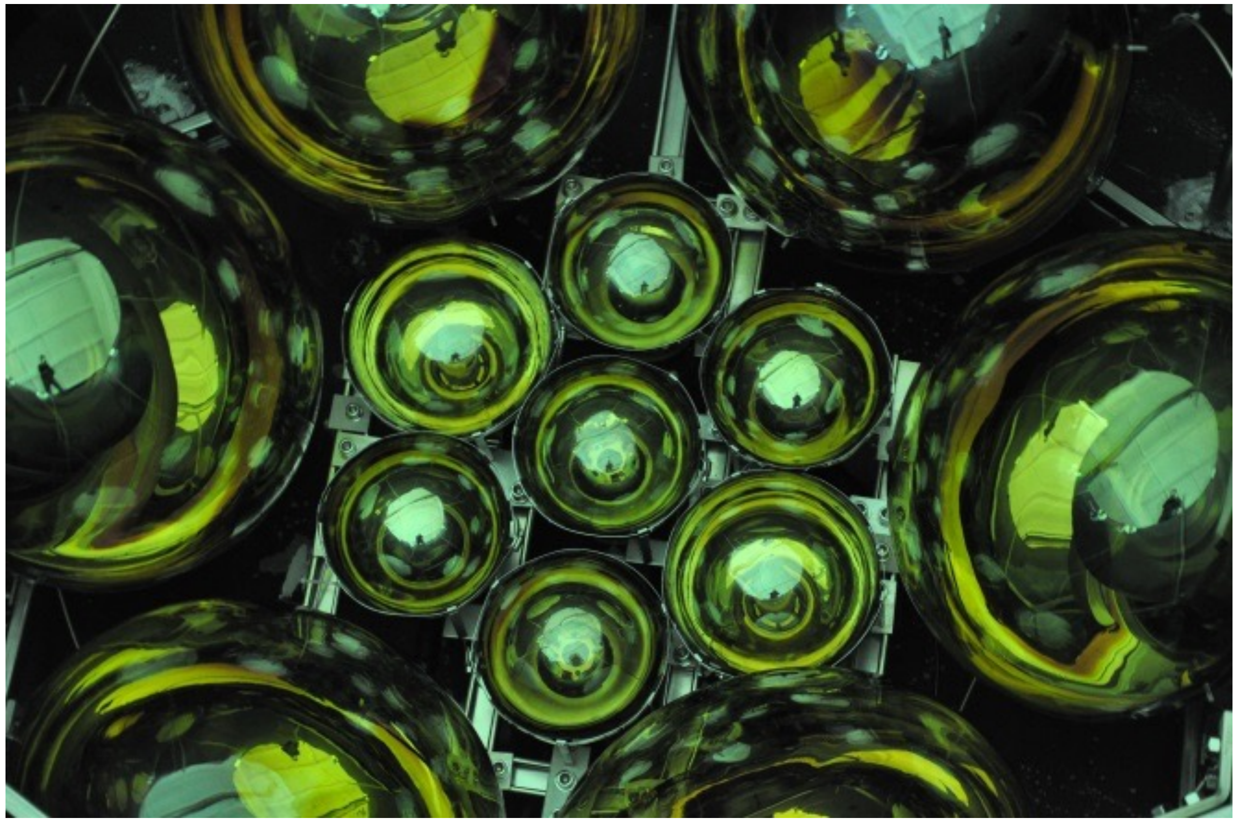
Acrylic bonding

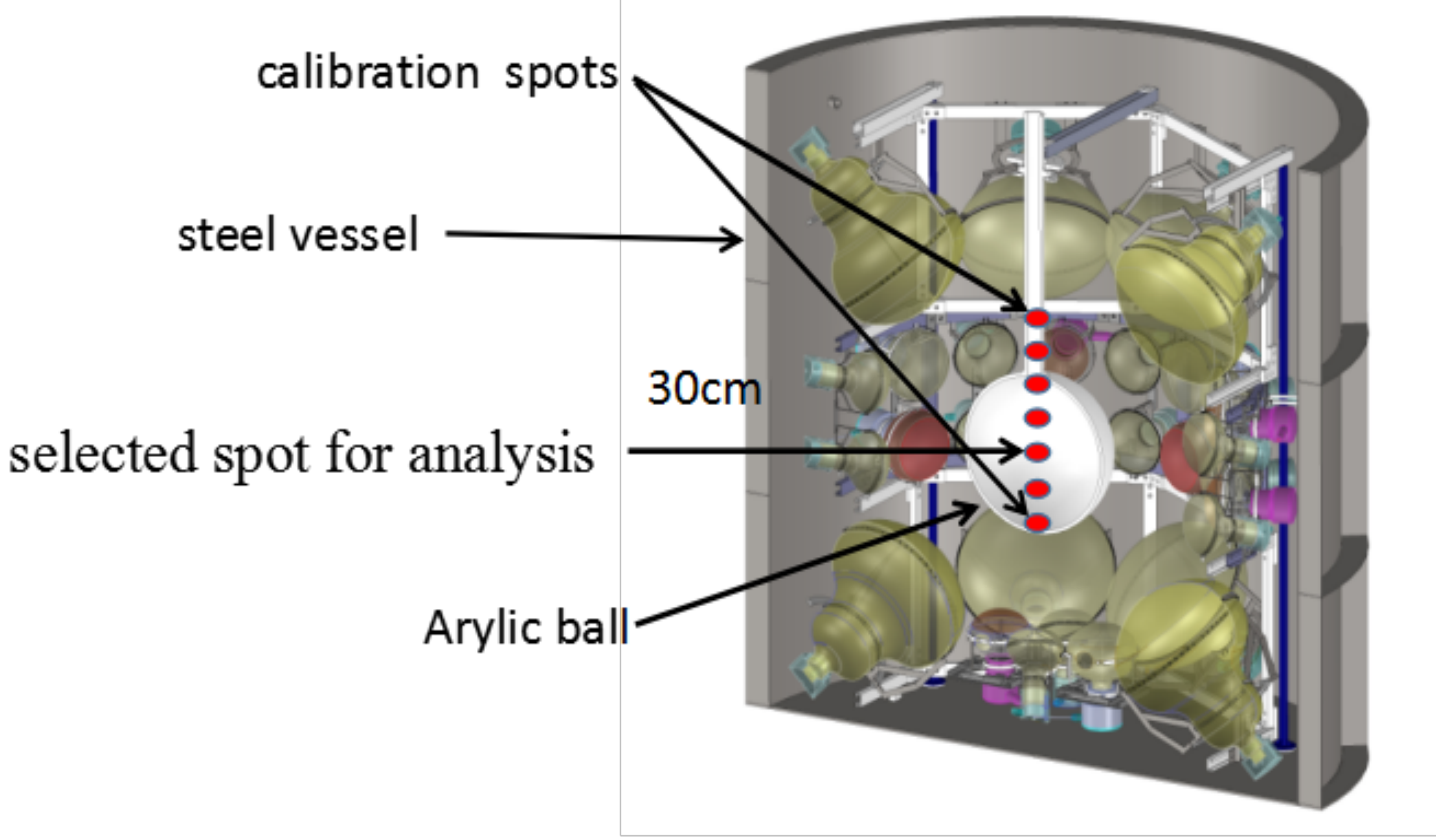
Steel Truss Structure

Electronics

Calibration

Small detector (integration)





Liquid Scintillator

One of Daya Bay detector dedicated to JUNO liquid scintillator R&D

Purification pilot plant now operational at Daya Bay underground site

Two main goals: transparency & radiopurity

Ongoing tests

- Optimization of LS formulation (PPO concentration. Bis-MSB needed?)
- ^{222}Rn Contamination
- Distillation (7000 liters/hour)
- Al_2O_3 purification
- Gas stripping
- Water extraction

23 m attenuation length reached!

Large Photomultipliers

15k MCP PMT (NNTV - China)
5k dynode PMT (Hamamatsu)

9000+ PMTs already delivered

Currently stored in warehouse close to experimental site

Being characterized by JUNO collaboration (heavy shift load)

Specifications (so far) meet our requirements

Small Photomultipliers

25000 units from HZC Photonics

Production rate: 2000/month

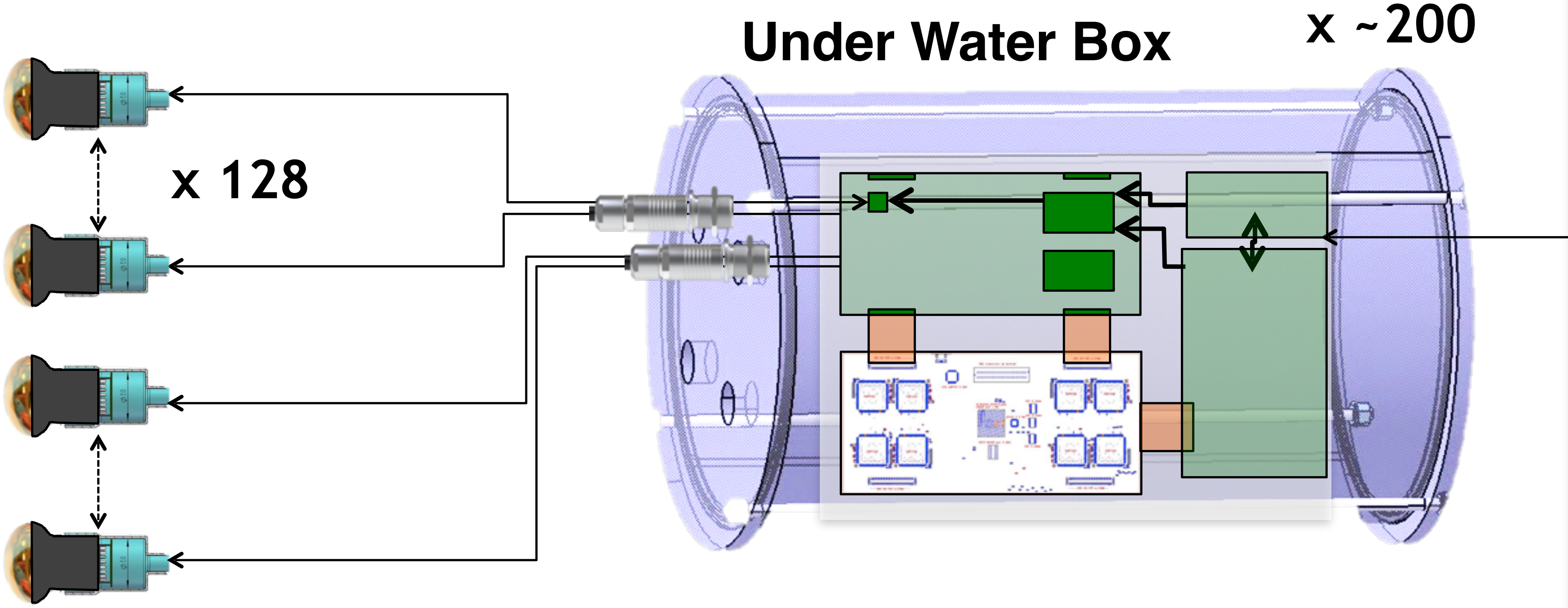
Gain (at JUNO): 3 10^6

QE x CE (at 420nm): 24%

SPE Resolution: 35%

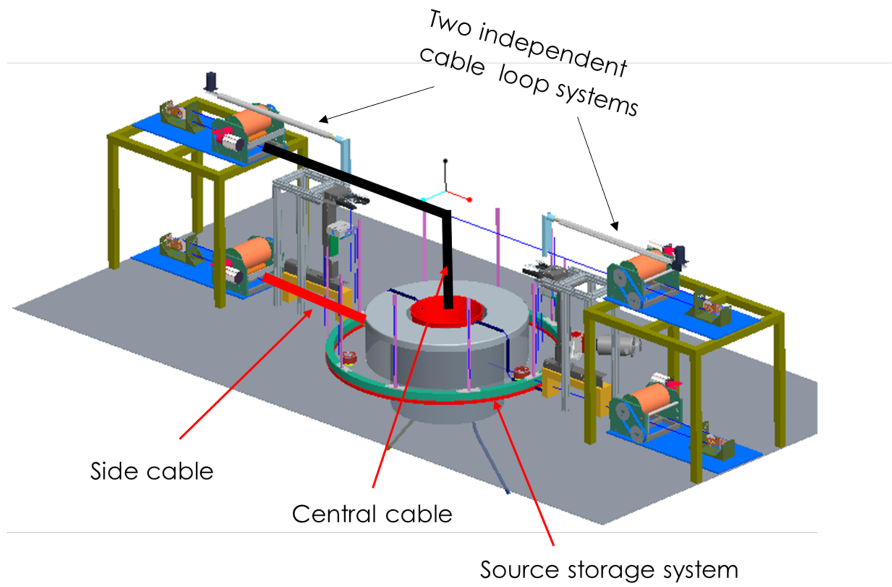
Dark Rate at 1/4 PE: 1kHz

Transit Time Spread: 5 ns

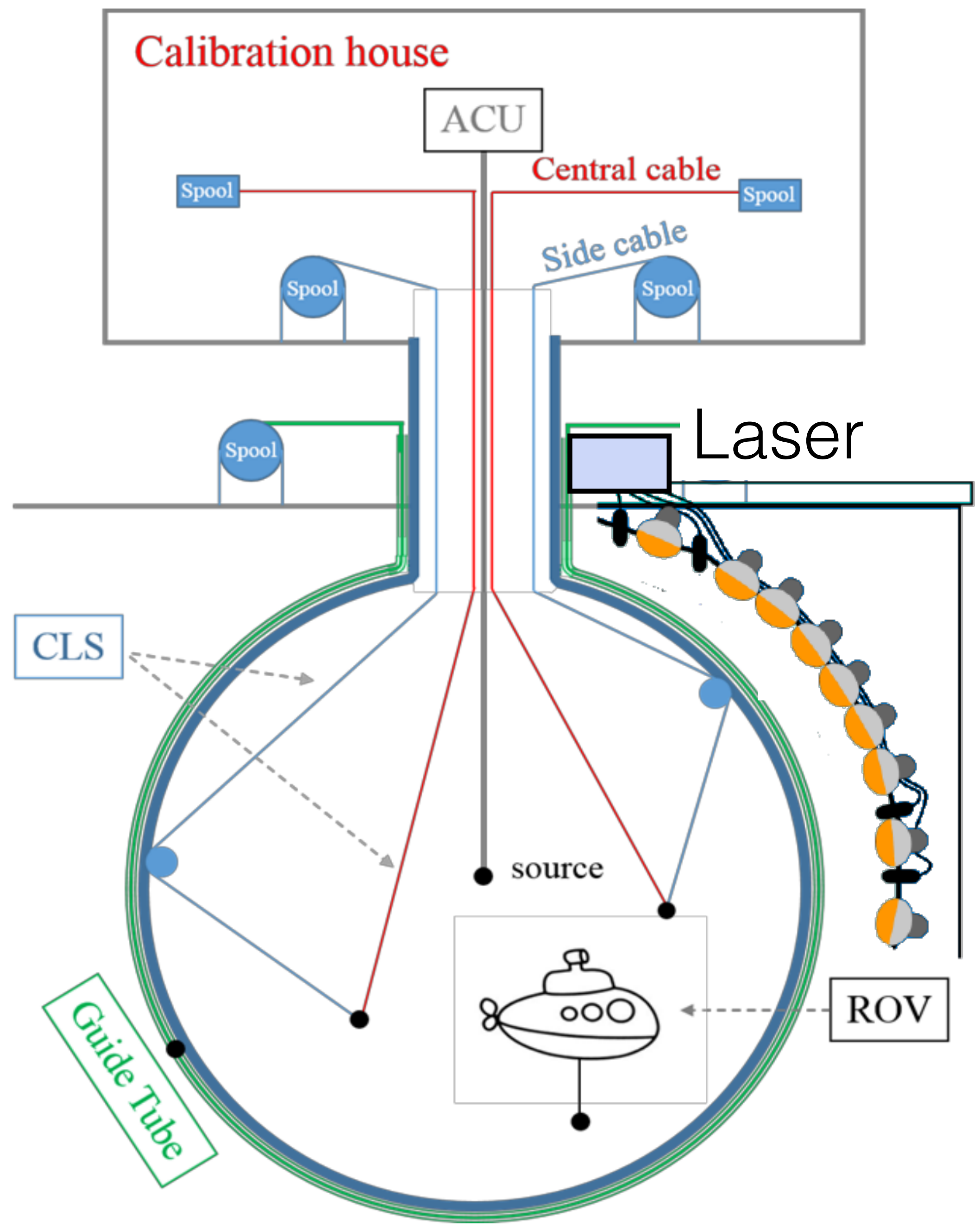


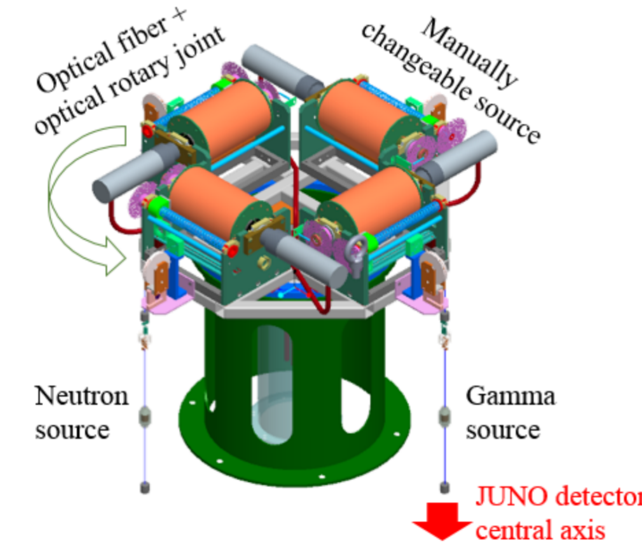
Calibration

Four complementary systems under development

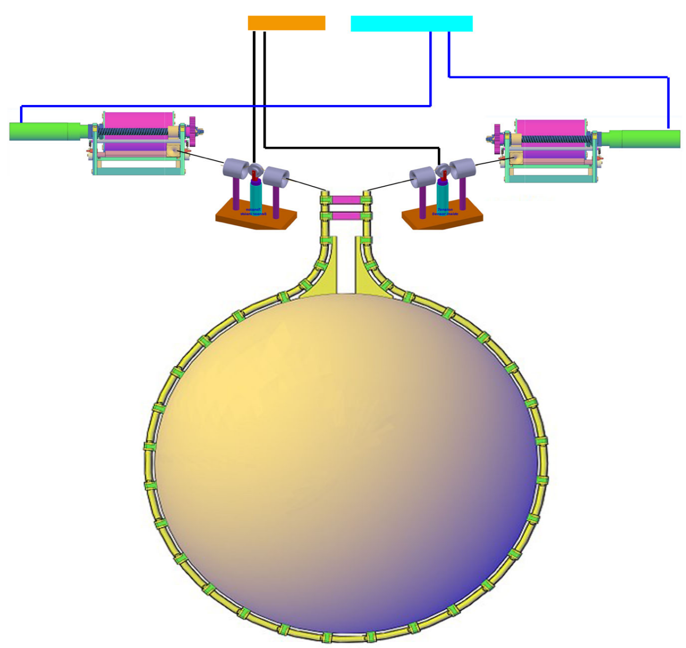


Cable Loop System

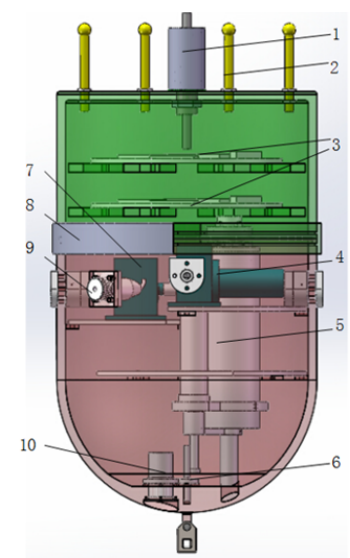




Automatic Calibration Unit

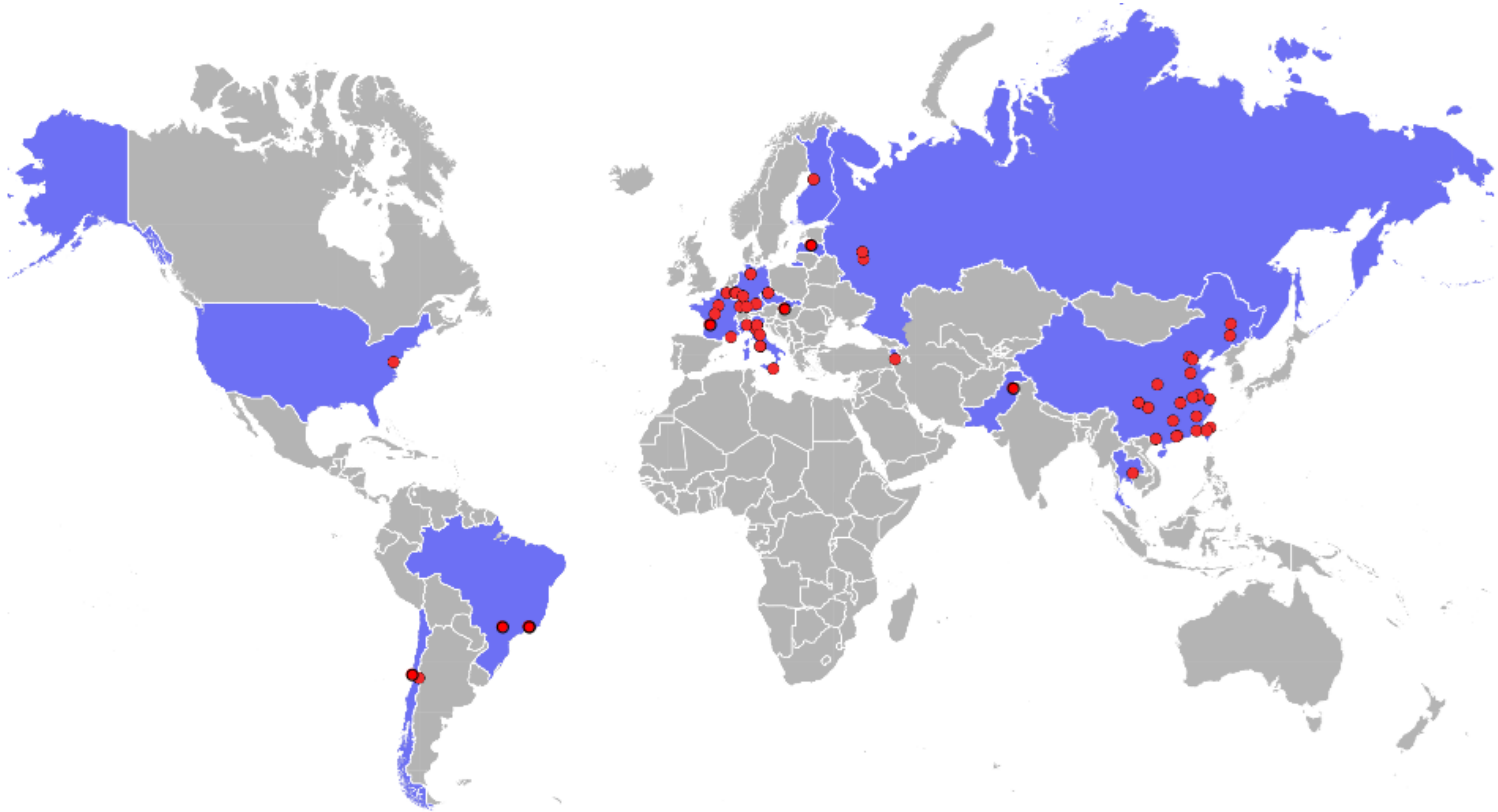


Guide Tube System



Remotely Operated Vehicle

Collaboration



More than 70 institutions from 17 countries, counting almost 600 scientists

Schedule

- **2014**: Conceptual design completed. Civil construction started
- **2015**: Setup of PMT production line
- **2016**: Bidding of detector components
- **2017**: Start PMT mass production. Electronics prototypes delivered
- **2018**: Electronics design finalized. PMT mass production & testing
- **2019**: PMT Potting, Electronics production & aging tests
- **2020**: PMT installation in central detector & veto
- **2021**: Detector filling. Start data taking

CONCLUSIONS

- JUNO is an **unprecedented** liquid scintillator detector (size & resolution)
    - 1200 pe/MeV required to reach 3% energy resolution at 1MeV
- High precision neutrino oscillation with reactor-ν
    - SOLAR SECTOR : $\leq$1% precision in solar terms
    - ATMOSPHERIC SECTOR : mass ordering through oscillation interference
      insensitive to matter effects, δ(CP) and θ_{23}
- NON-REACTOR ν : leading capabilities in Supernova, Geoneutrinos, Solar ν
- Collaboration est. in 2014 & project fully funded ▶ data taking in 2021