# Neutrino Oscillation at JUNO

…where calorimetry meets interferometry

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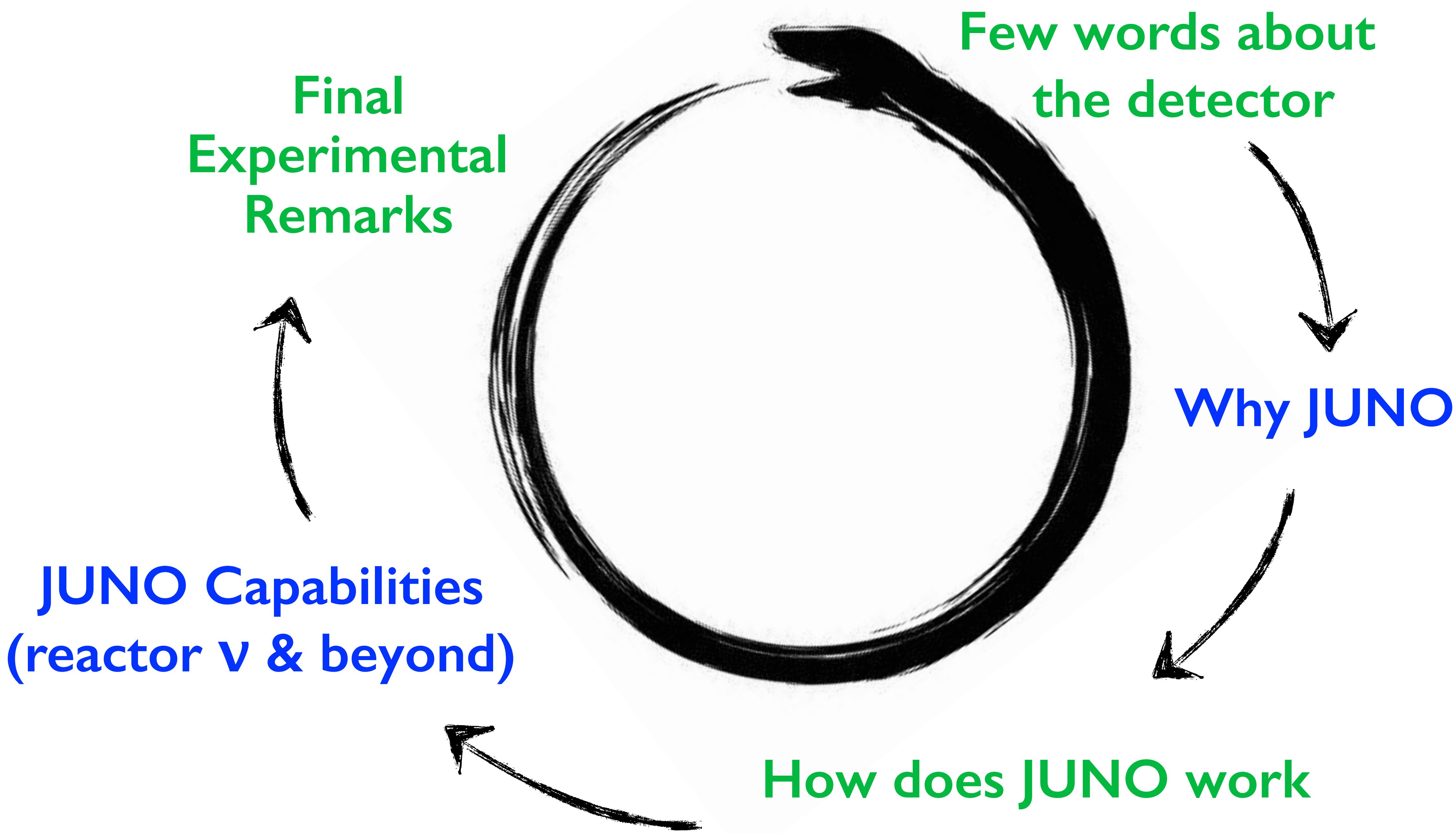
APC Laboratory - IN2P3

MARIE CURIE ACTIONS

# A Circular Presentation



# Jiangmen Underground Neutrino Observatory

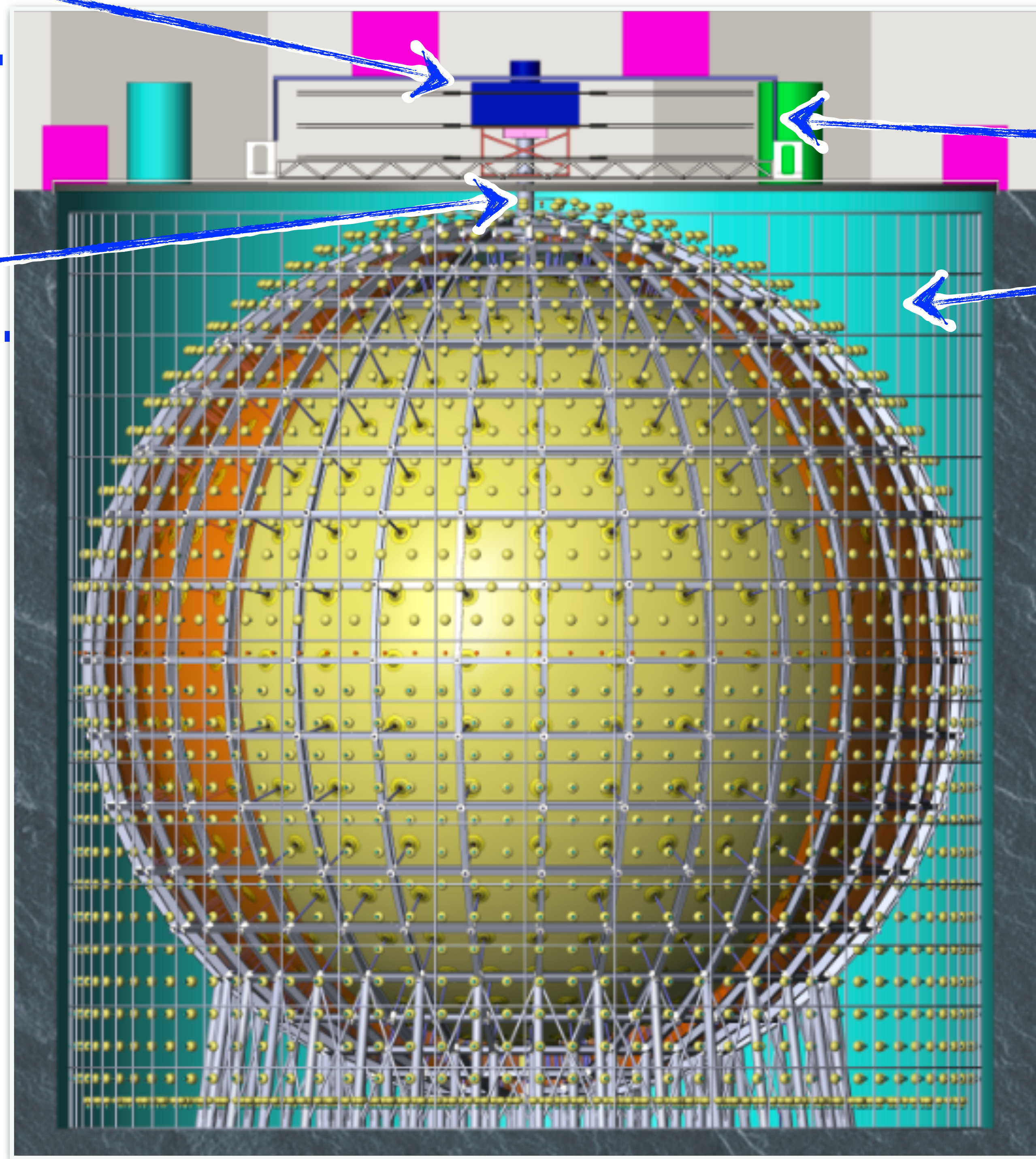
Calibration Room

**Muon Veto**

Chimney

Top Tracker

Water Pool



**Central Detector**

Steel Truss

Holding PMTs

~18000 x 20"

~25000 x 3"

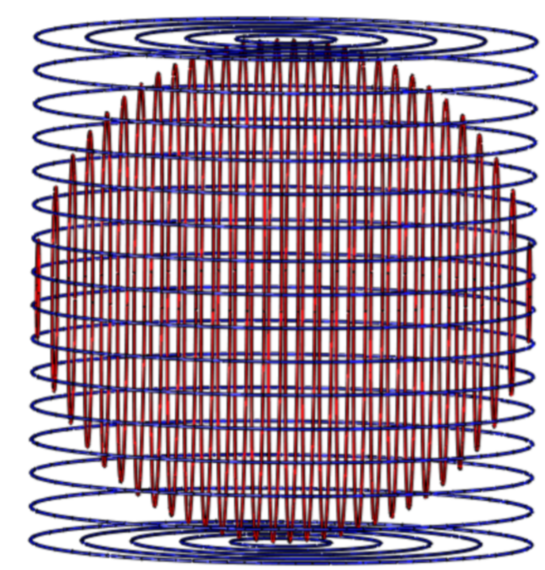
Acrylic Sphere

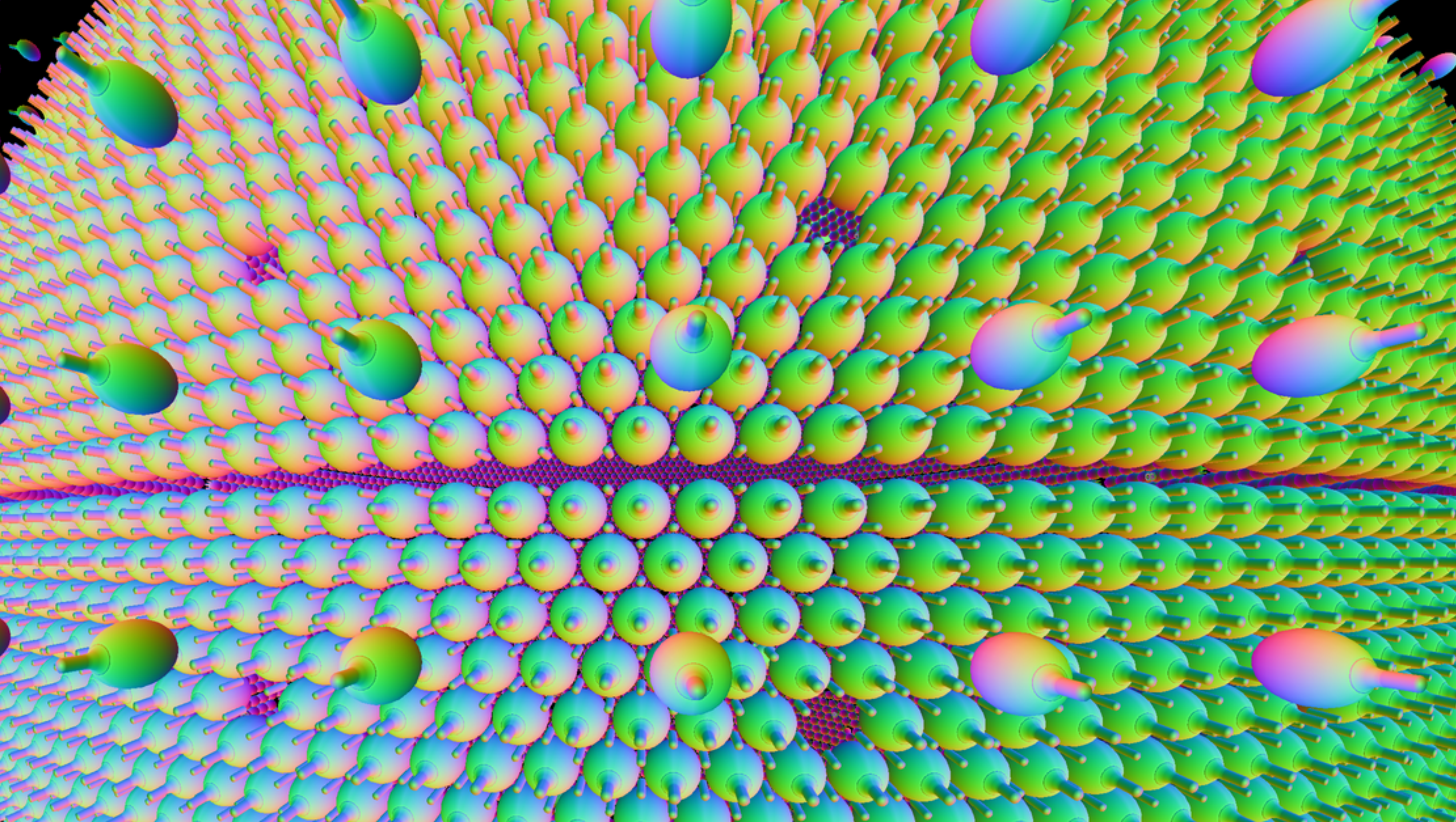
filled with

**Liquid Scintillator**

Magnetic Field

Compensating Coil





**Largest photocathode density ever built (~75% coverage)**

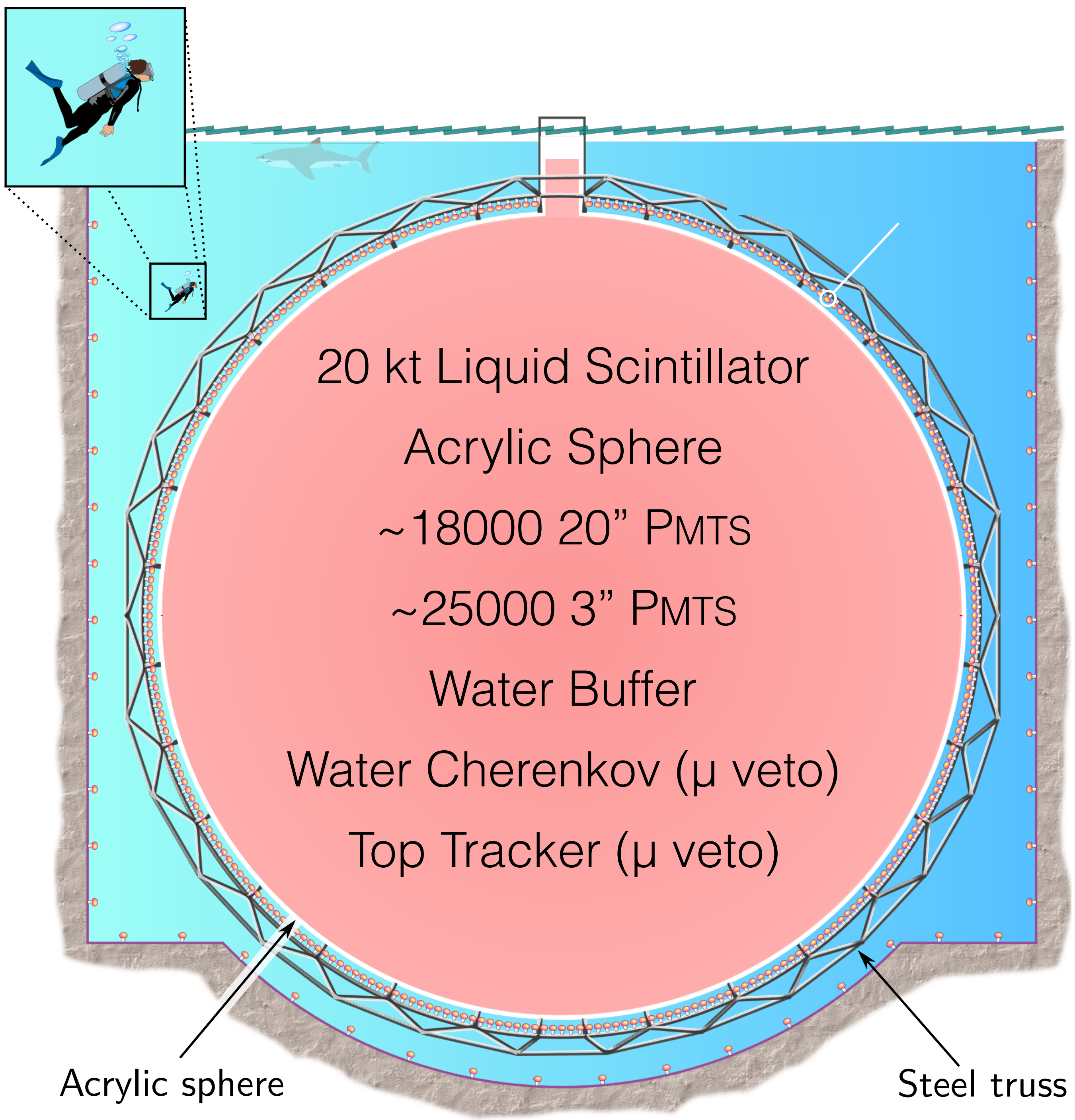
**Largest light level ever detected ~1200 pe/MeV**

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

**Highest precision calorimetry ever built**

# JUNO within the Global Neutrino Landscape

Liquid Scintillator (Anti)neutrino Detector

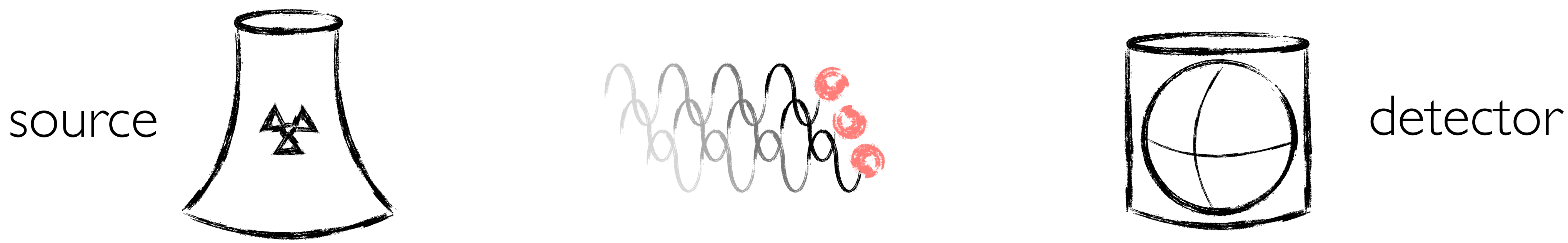


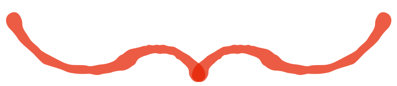

2 Key parameters:

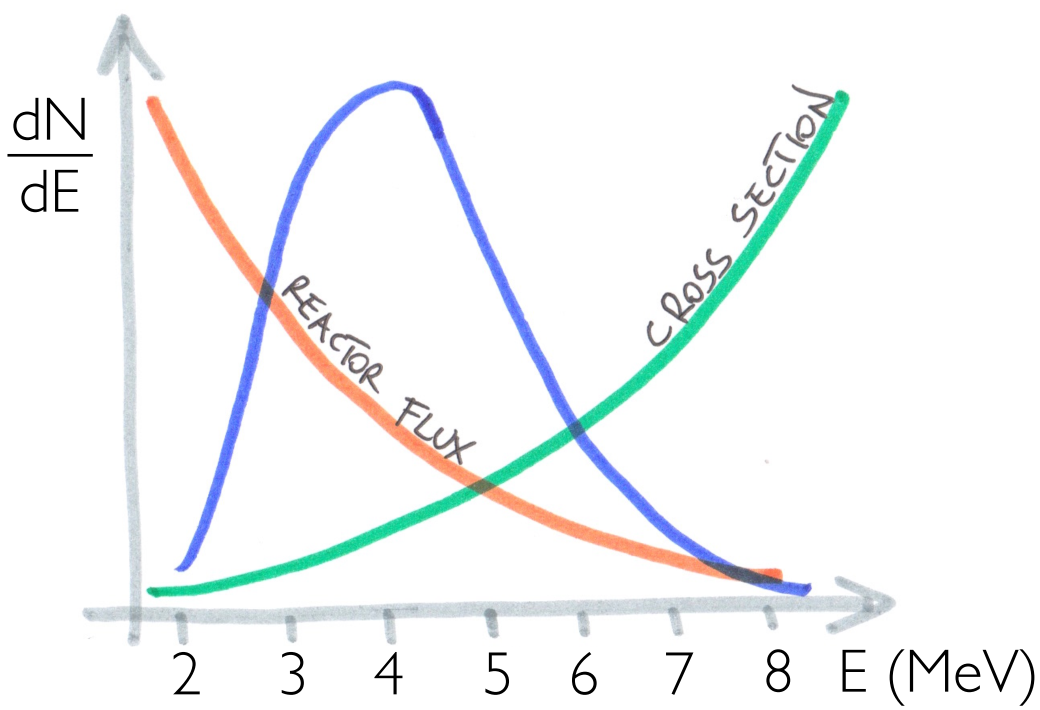
LARGE & PRECISE

| | 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 | $3\%/\sqrt{E}$ |

# Antineutrinos from Reactor






**Nuclear Power Plants**

Energy by breaking heavy nuclei

Fission fragments are unstable

Decaying through a cascade of beta decays

$(n \blacktriangleright p + e^- + \overline{\nu}_e)$

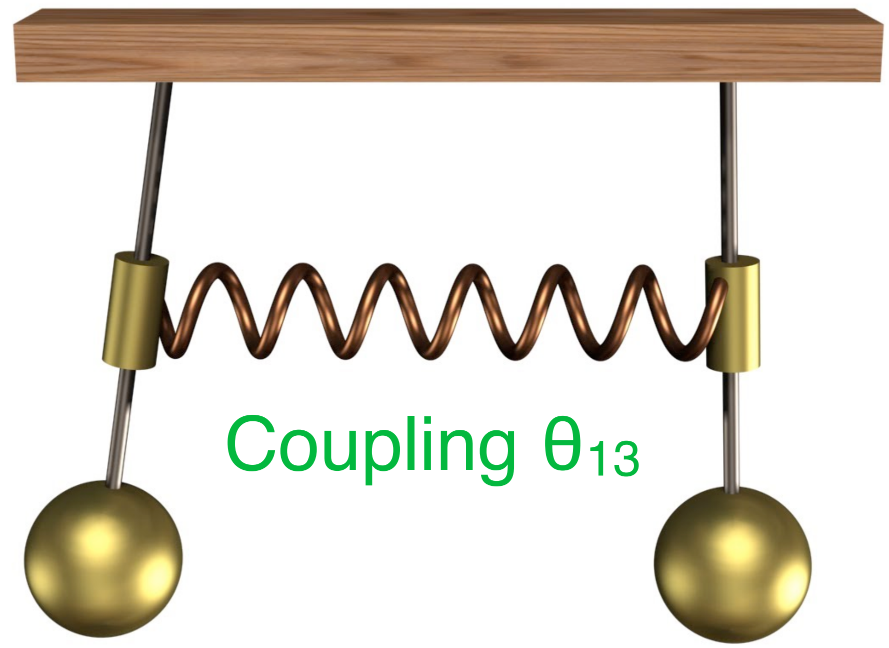
3 $GW_{th}$ reactor : $\sim 10^{20}\ \overline{\nu}_e$ / s

?

Why JUNO

# Neutrino Mixing

Three neutrino flavors ▸ **6 free parameters** (3 angles, 1 phase, 2 mass splittings)




**Atmospheric Oscillation**

Amplitude $\theta_{23}$

Frequency $\Delta m^2_{31}$

**Solar Oscillation**

Amplitude $\theta_{12}$

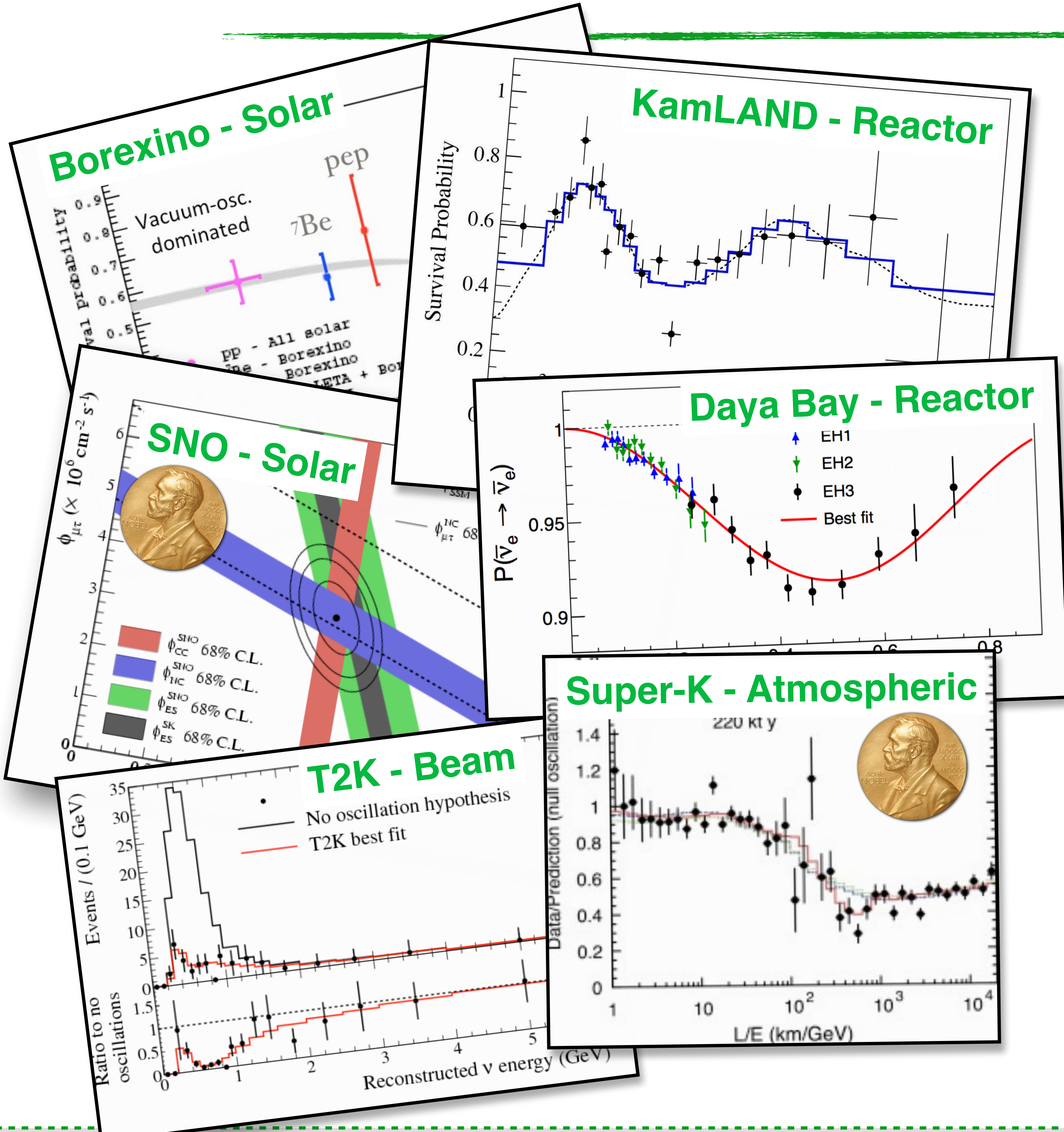
Frequency $\Delta m^2_{21}$

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

Atmospheric — Reactor (L~1km) — Solar

Credits: W.Winter

# State of the Art




Neutrino oscillation firmly **established**

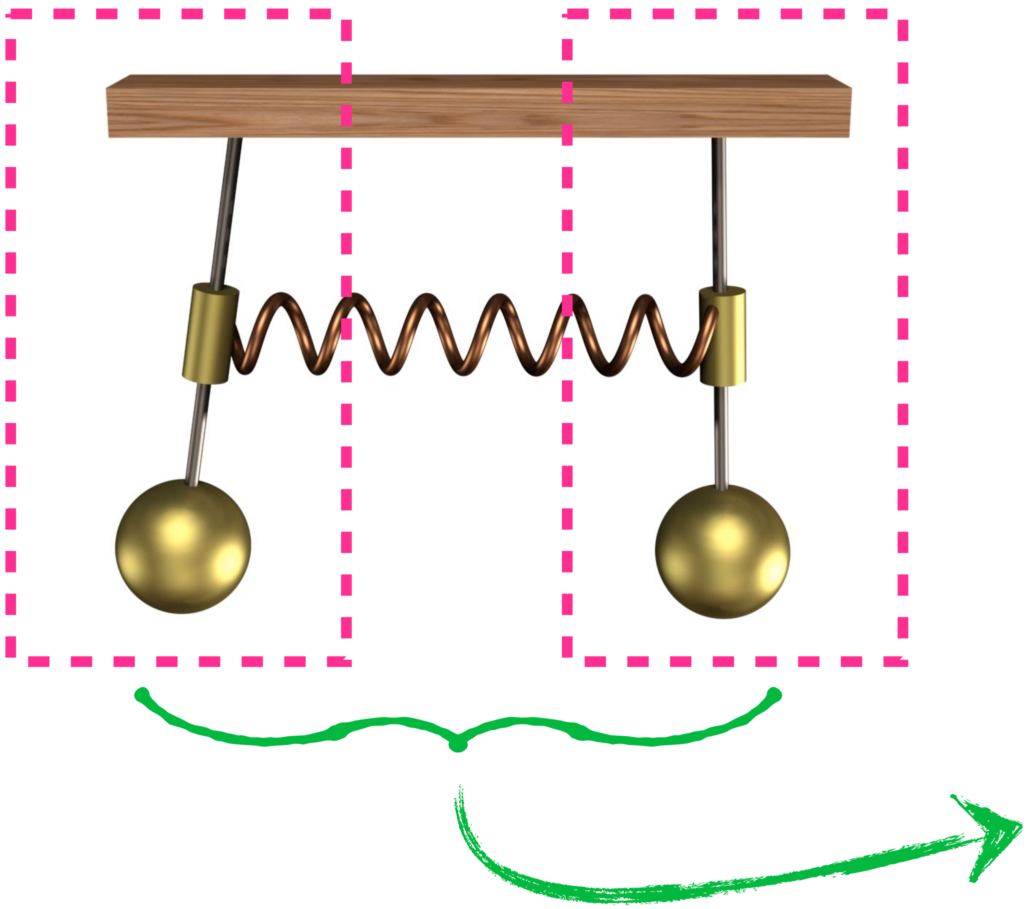
Great **variety** of sources, energies, baselines and experimental techniques

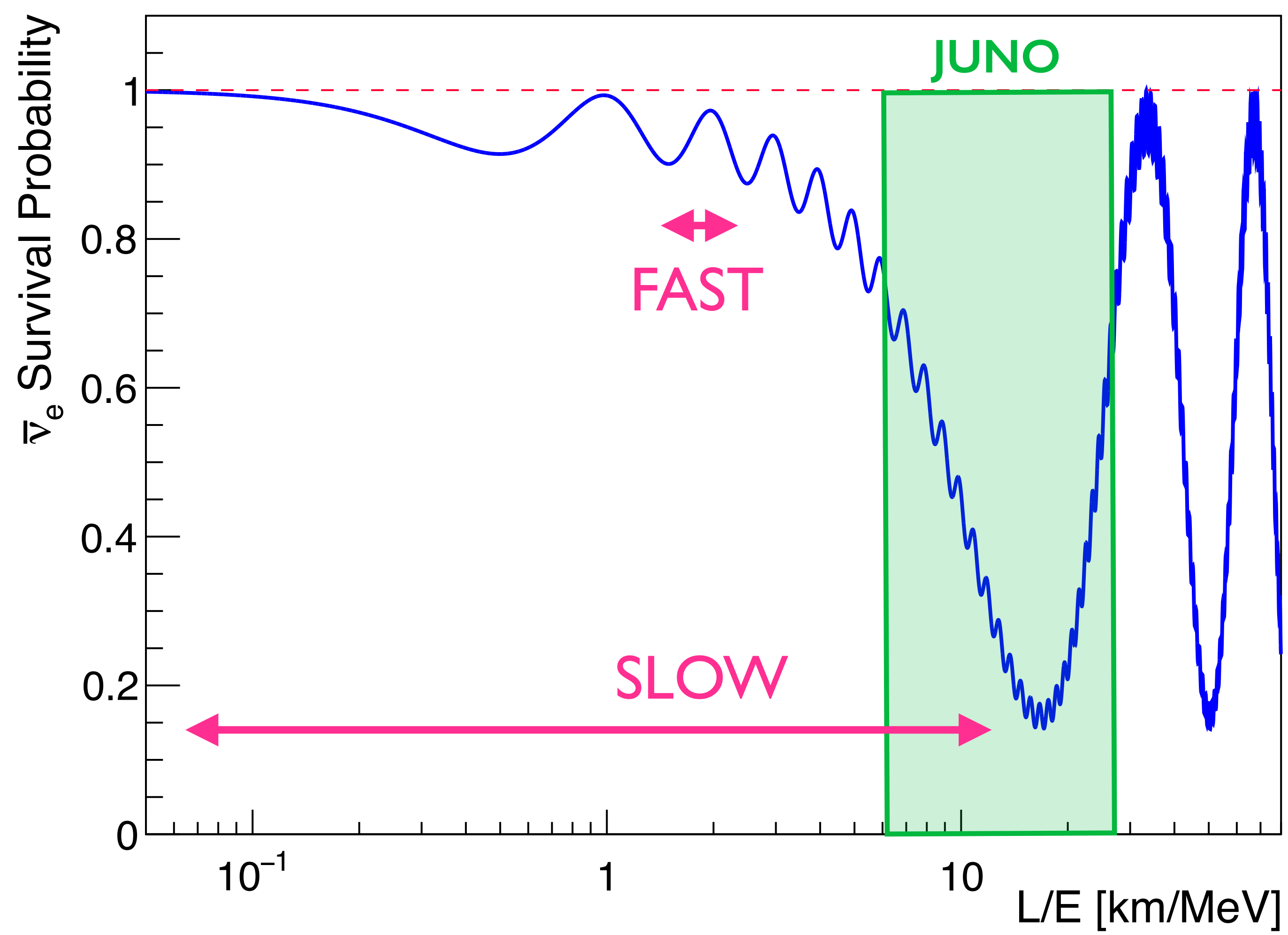
**Current precision**

| | |
|---|---|
| $\Delta m^2_{SOL}$ | 2.3% |
| $\Delta m^2_{ATM}$ | 1.6% |
| $\sin^2(\theta_{12})$ | 5.8% |
| $\sin^2(\theta_{13})$ | 4% |
| $\sin^2(\theta_{23})$ | ~9% |

[PRD 95, 096014 (2017)]

# Neutrino Oscillation at JUNO





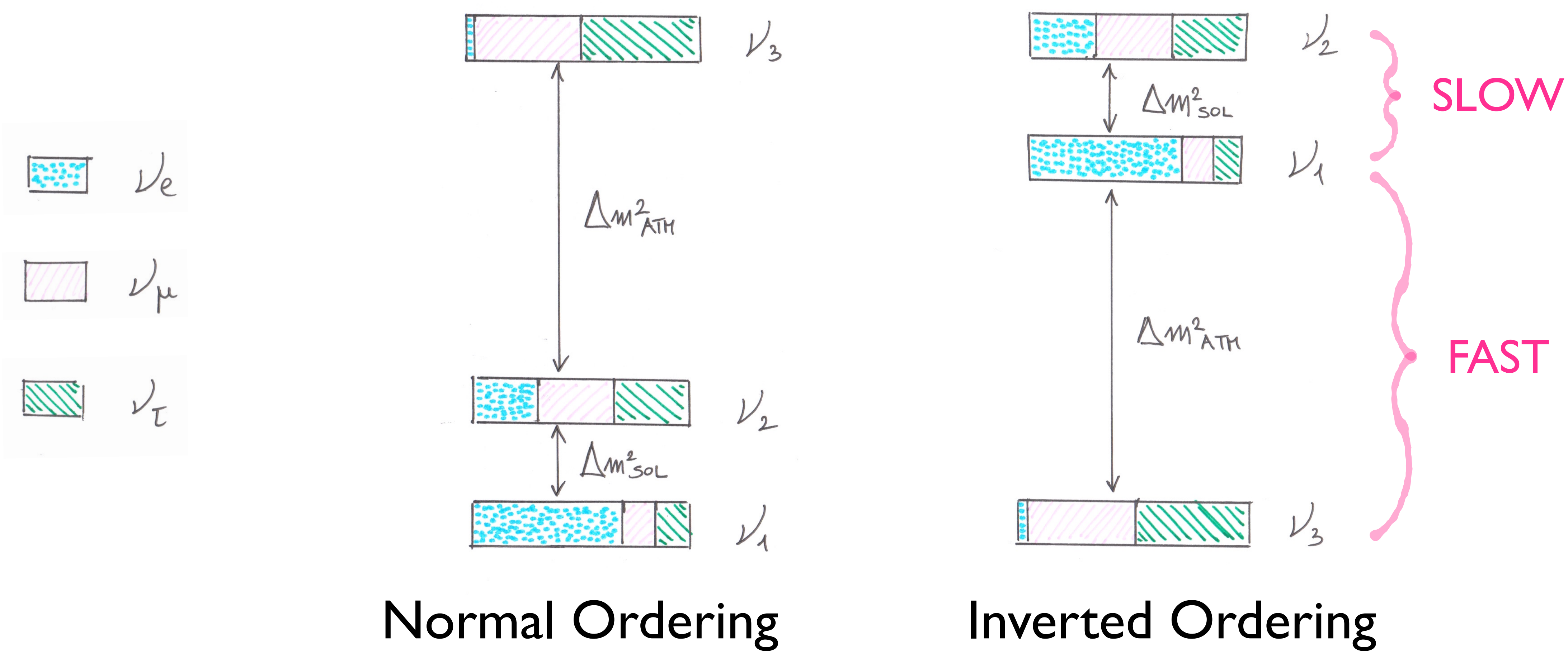

Experiments so far optimized to observe **only one oscillation** at a time

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

Powerful test of the 3-neutrino mixing model

Interference : proxy for determining **neutrino mass ordering** (Petcov&Piai 2002)

# Neutrino Mass Ordering




Two orders of magnitude between solar and atmospheric mass splittings

No experiment sensitive to sign($\Delta m^2_{ATM}$) so far

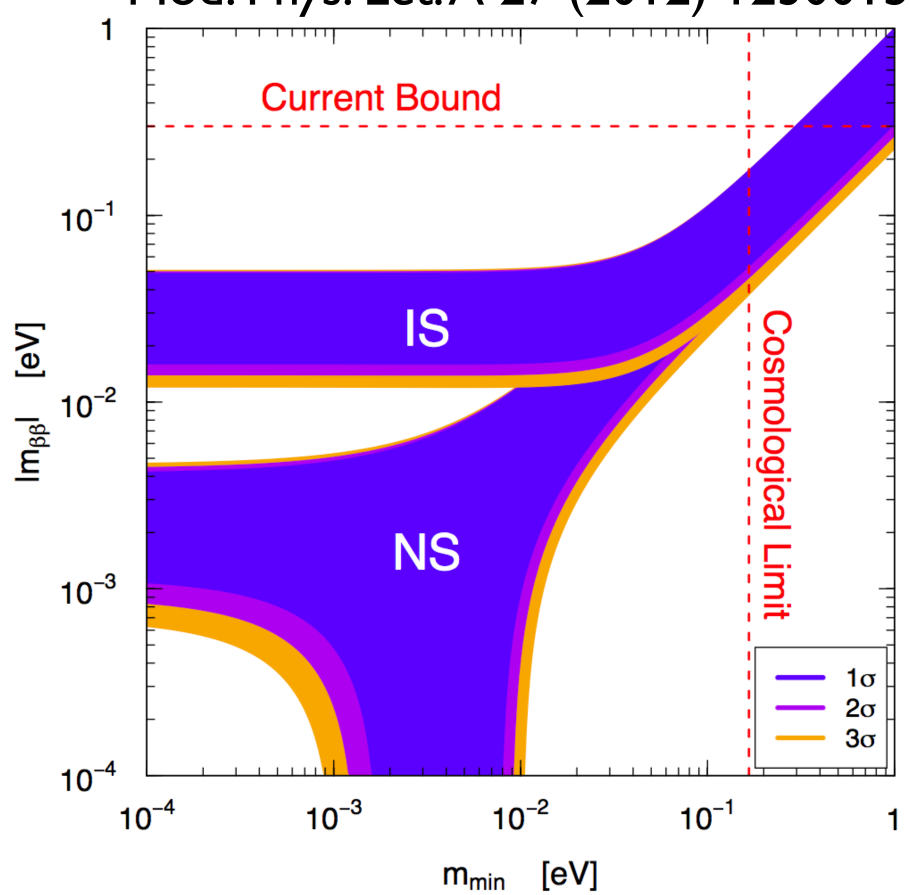
Ordering of mass eigenstates not constrained by theory

Need to be determined experimentally

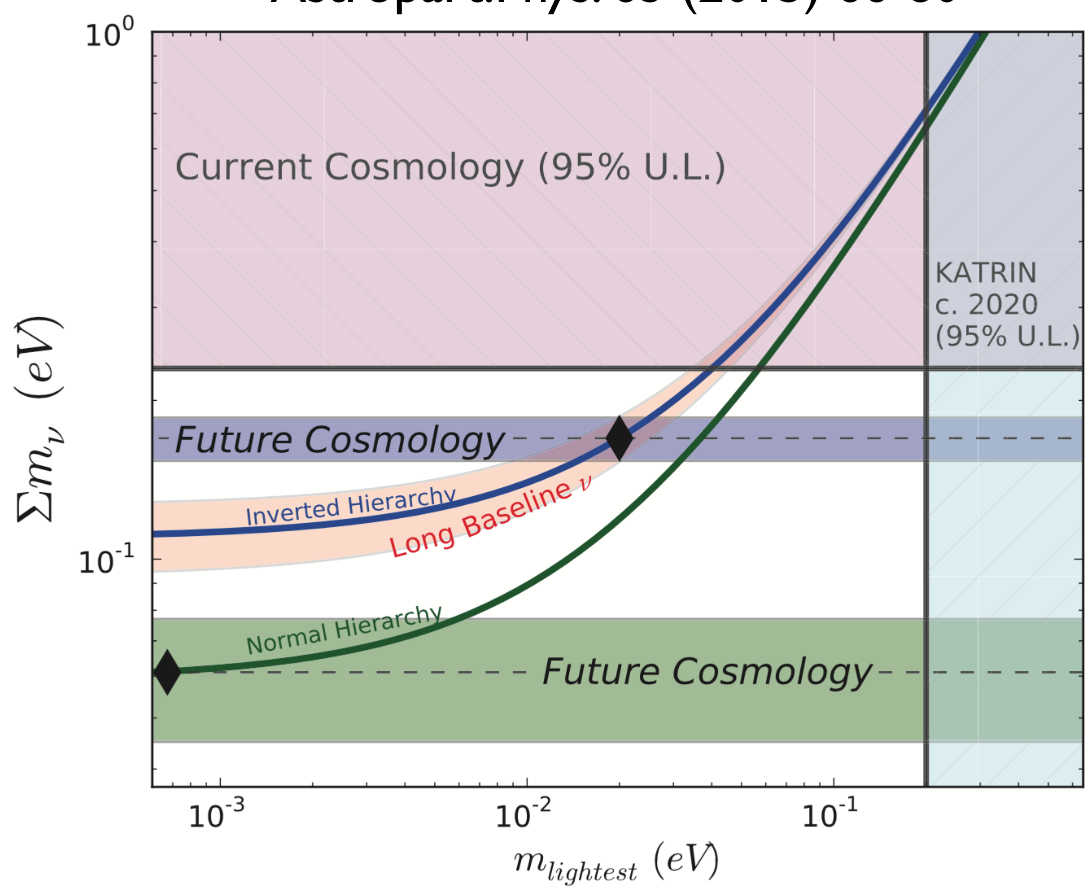
# Importance of Mass Ordering Determination

- **Fundamental parameter** that we did not manage to predict (so far)
- Help to understand what is the true nature of neutrinos (**Dirac** *vs* **Majorana**)
  - Define next generation of neutrino-less double beta decay experiments
- Help to use appearance data (neutrino beam) to constrain **CP-violation**
- Help to use cosmological measurements to constrain sum of **neutrino masses**

Mod. Phys. Let. A 27 (2012) 1230015

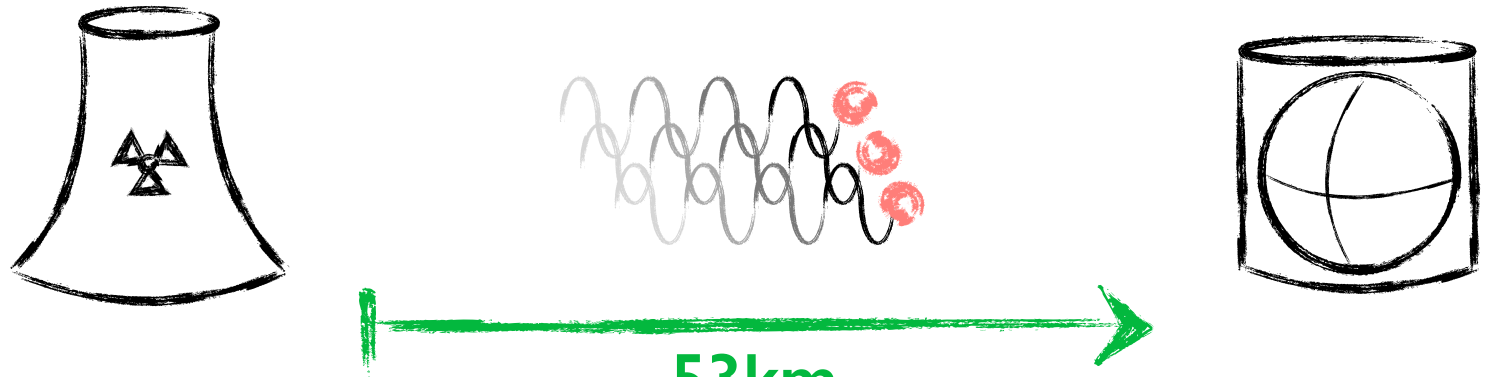



Astropart.Phys. 63 (2015) 66-80



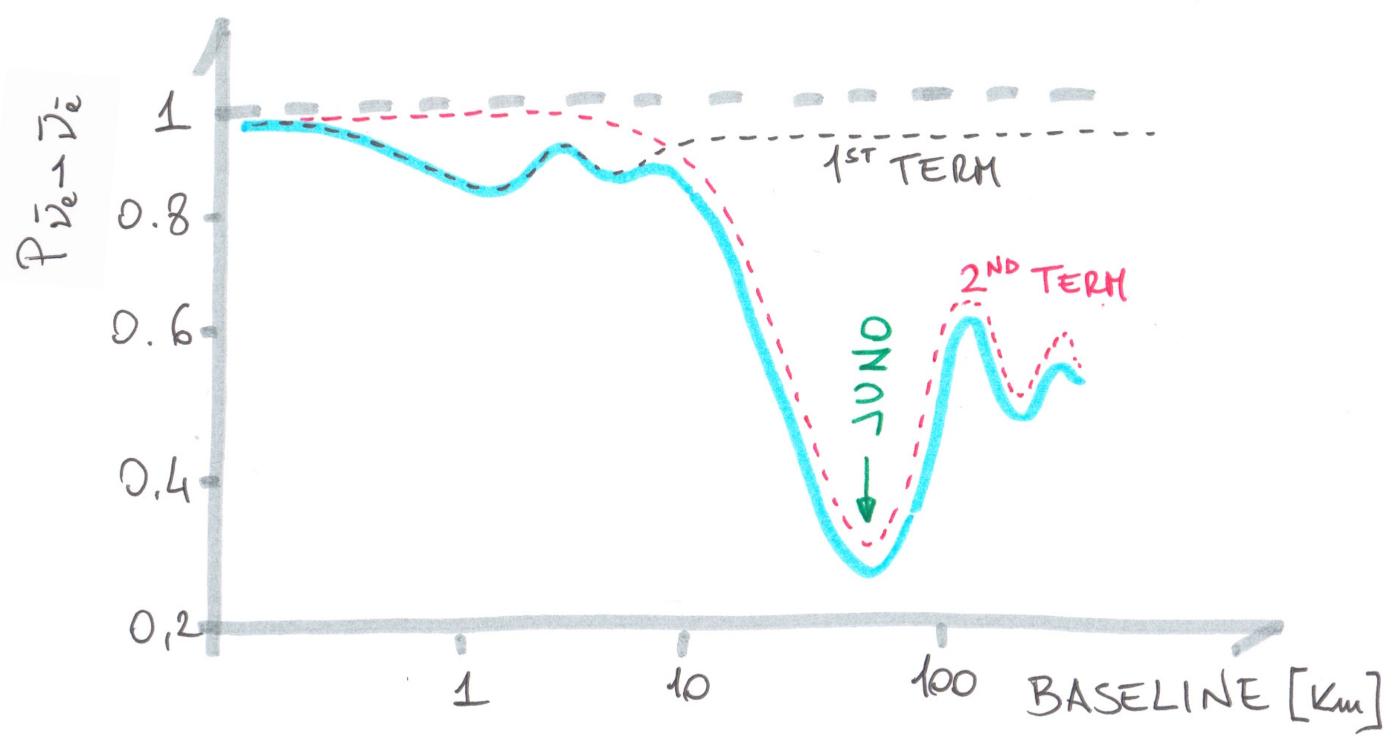

How does JUNO work

# Oscillation at 53 km Baseline




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

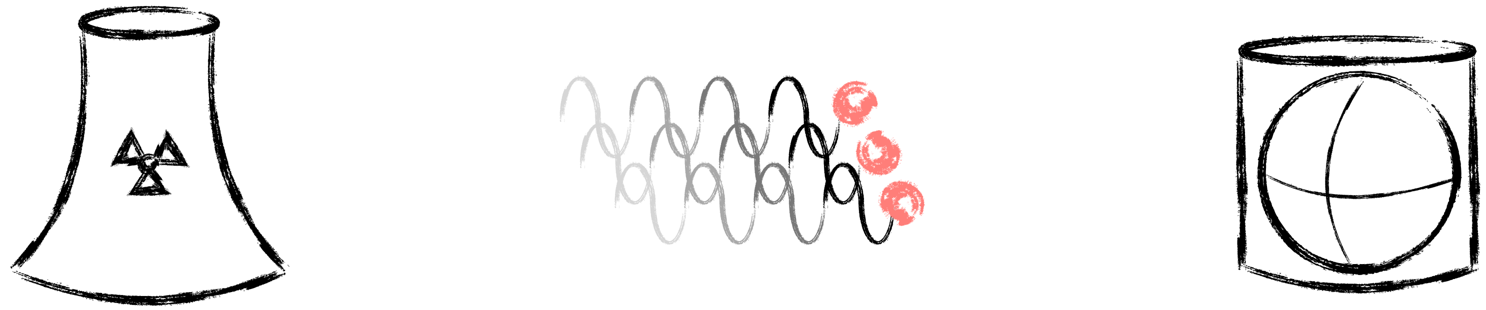
$$- \sin^2 2\vartheta_{12} \cos^4\vartheta_{13} \sin^2\Delta_{21}$$




$$\Delta_{ij} = \Delta m^2_{ij} \frac{L}{4E}$$

# Antineutrino Energy Spectrum at Detector

source



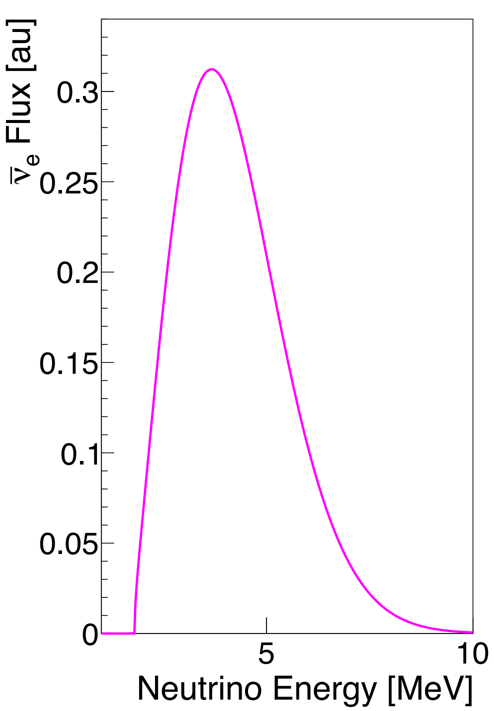
detector

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

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

$$\Delta_{ij} = \Delta m^2_{ij} \frac{L}{4E}$$

**Flux**

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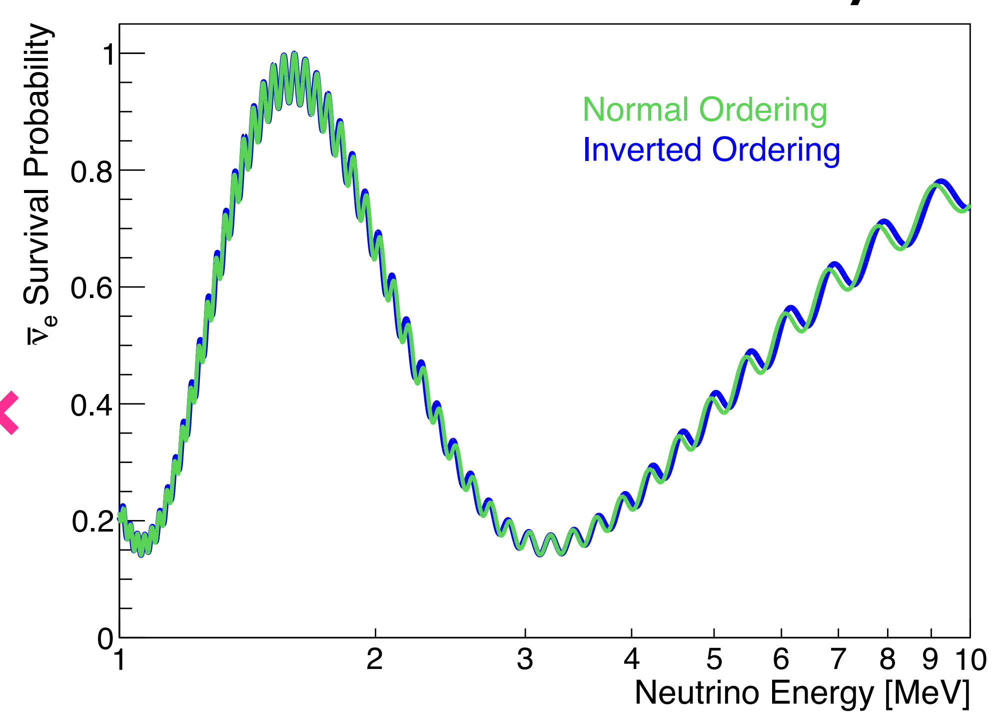
**Oscillation Probability**

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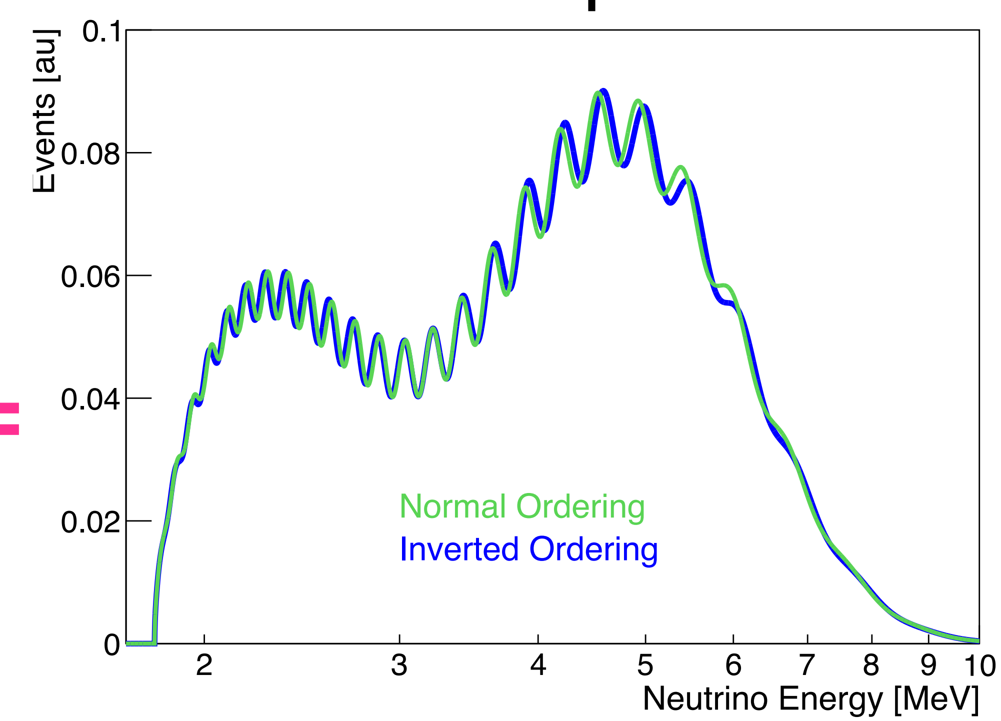
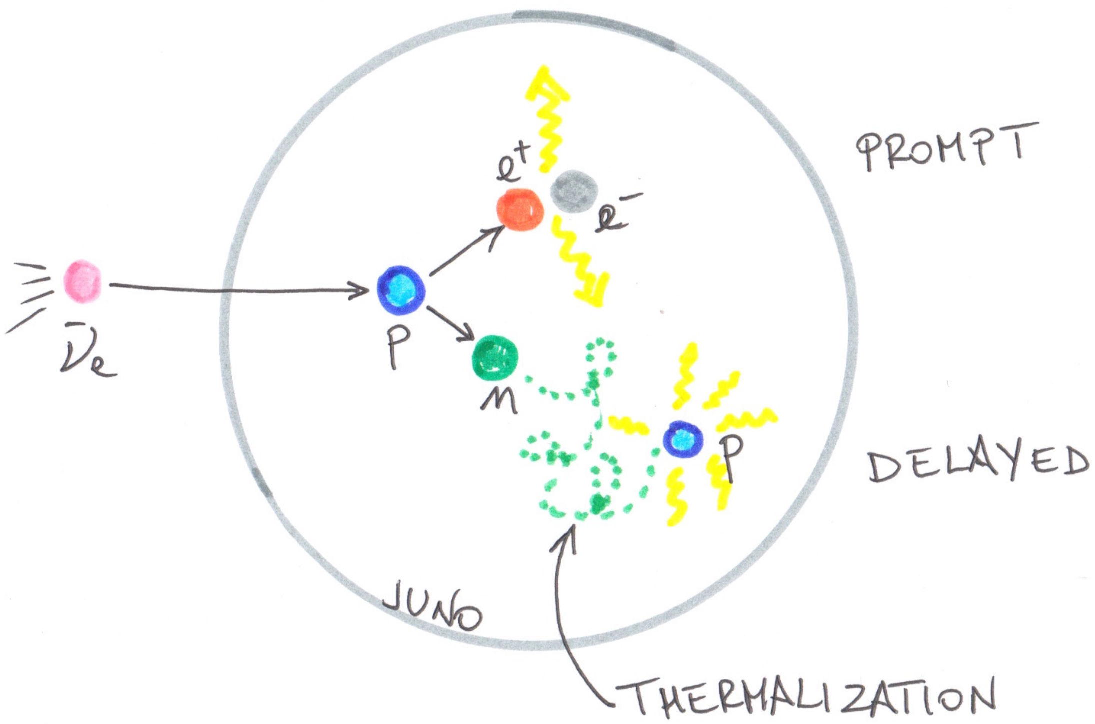
**Neutrino Spectrum**



# 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

60 IBD/day

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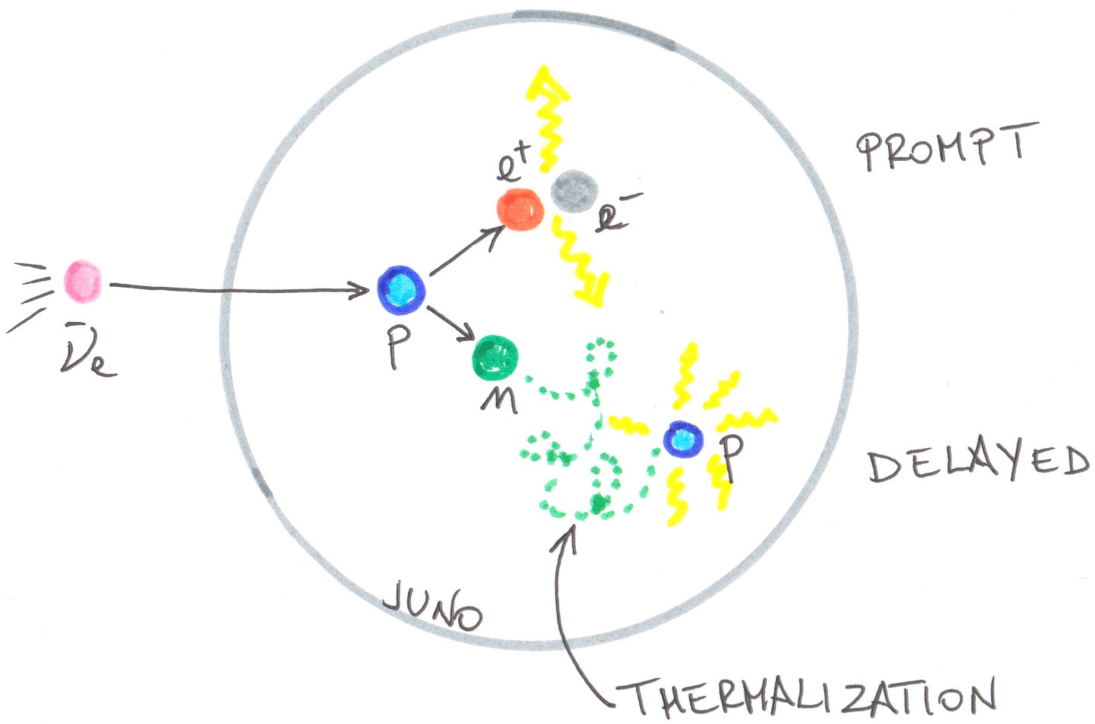


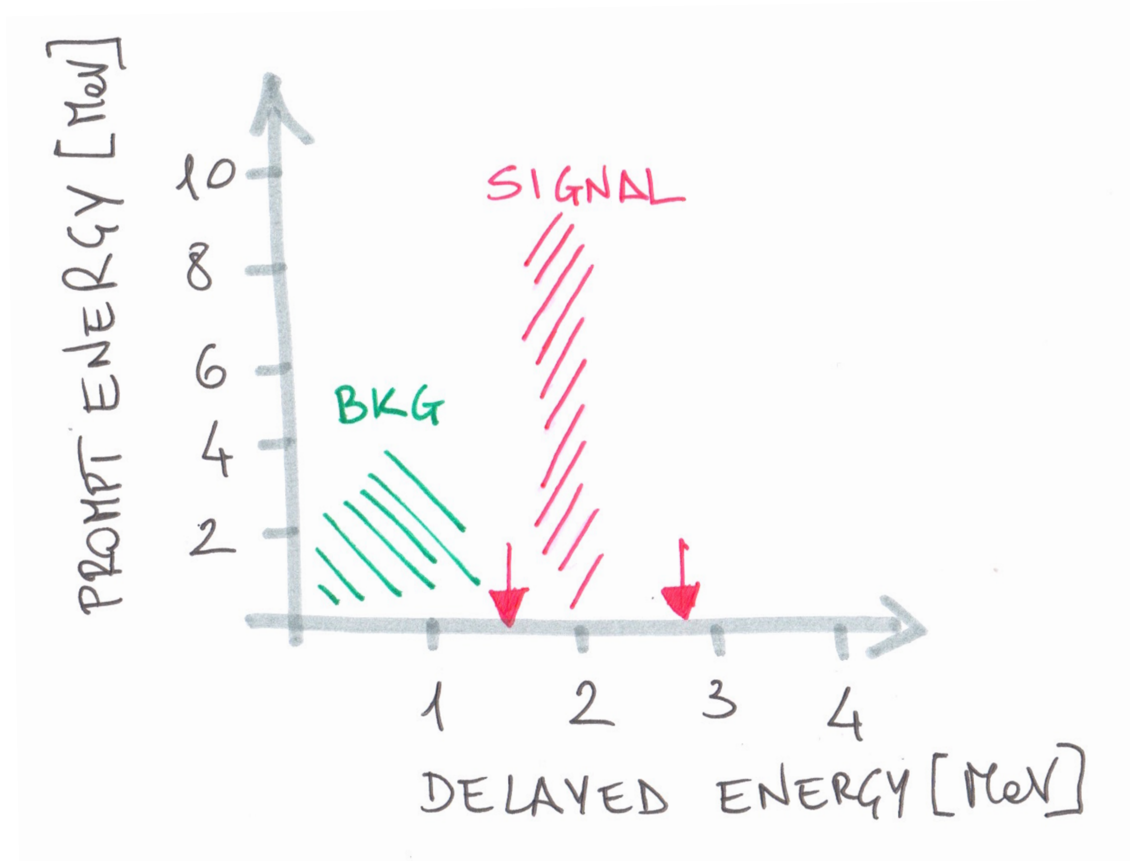


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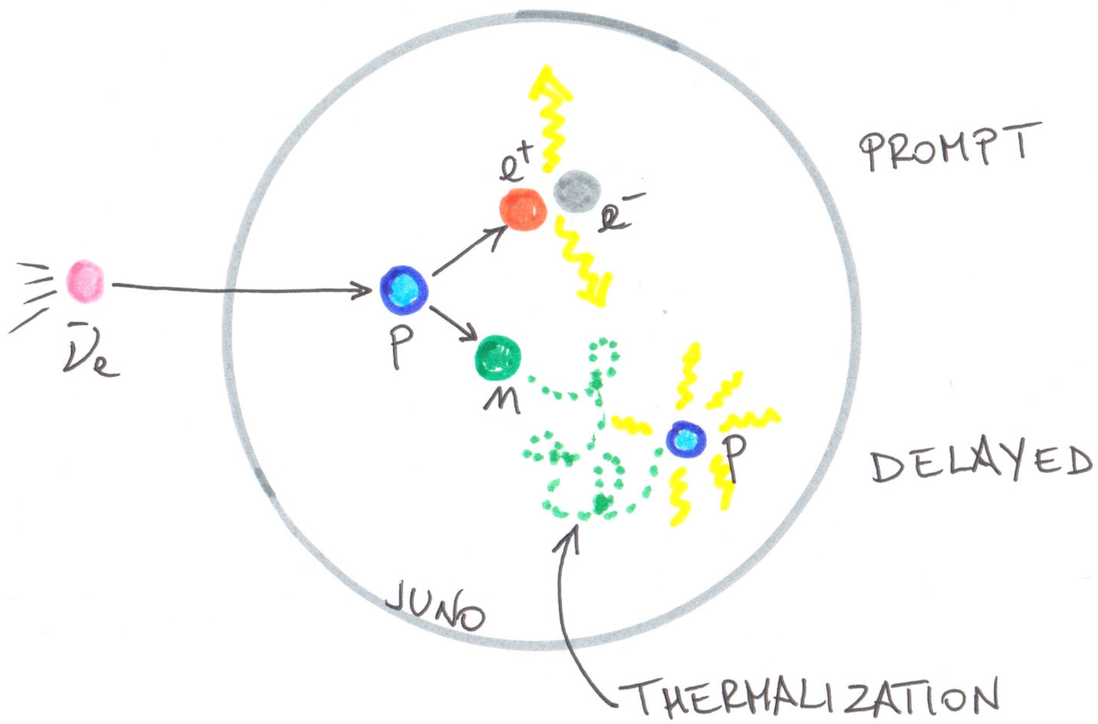


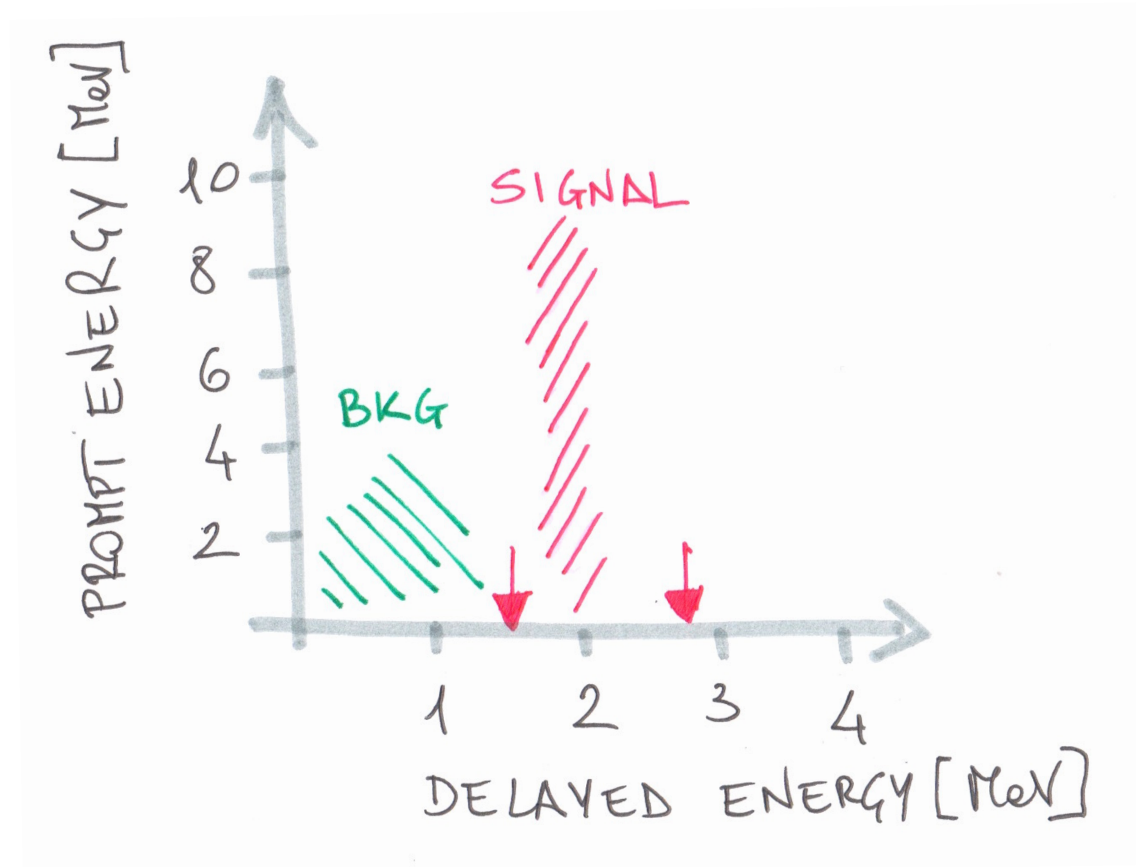


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$\bar{\nu}_e + p \longrightarrow e^+ + n$ Prompt

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

60 IBD/day

$$E(\bar{\nu}_e) = K(e^+) + K(n) - (m(n) - m(p)) + m(e^+) \sim K(e^+) + 1.8\ \text{MeV}$$

**Visible Energy**


JUNO Capabilities

# Physics Programme

## Reactor Neutrinos

- First combined observation of solar and atmospheric oscillation
- Mass ordering via solar-atmospheric interference
- Vacuum oscillation ▶ Not relying on matter enhancement (and related uncertainties)
- No $\theta_{23}$ octant or $\delta_{cp}$ ambiguities ▶ Complementary to NOvA, Pingu, DUNE
- Most precise measurement of solar parameters ($\theta_{12}$, $\Delta m^2_{12}$)

## Supernova Neutrinos

- Supernova burst likely to happen in the next 10 years
- Unique opportunity for Particle Physics and Astrophysics

## Geoneutrinos

- JUNO alone might detect more geo-ν than all the other world exps together

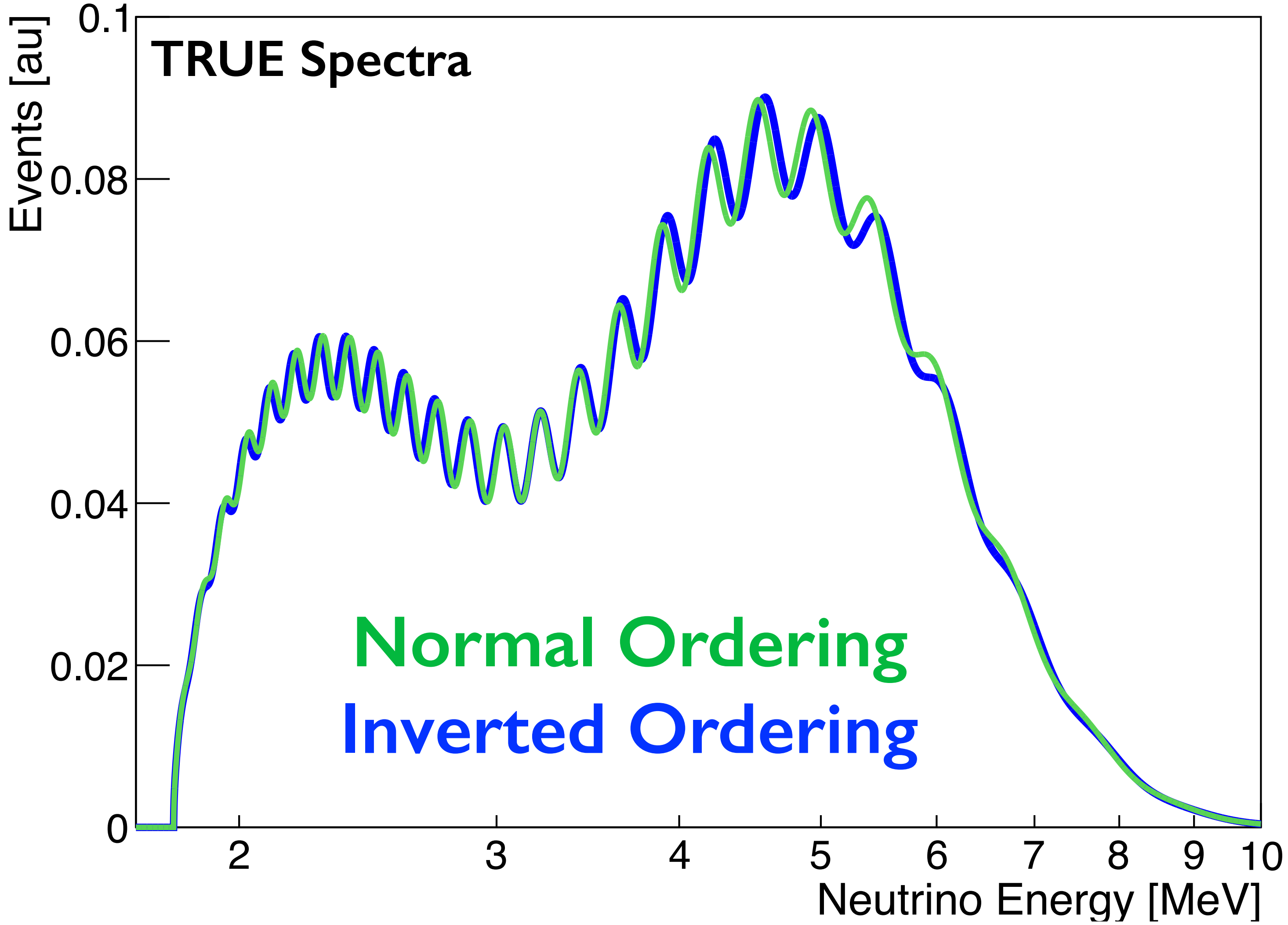
## Solar Neutrinos

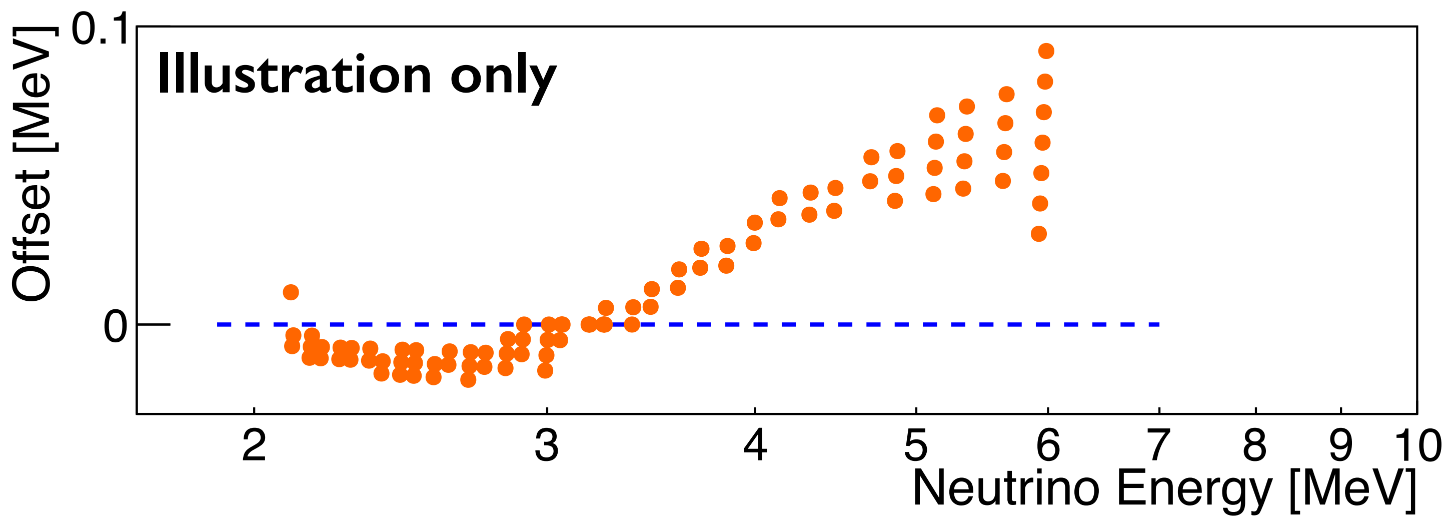
- Open issues in Solar physics (MSW turn on, Metallicity) could be addressed

## Much More

- Take a look at our Yellow Book: J.Phys. G43 (2016) no.3, 030401

# What Makes Mass Ordering Determination Possible




**Using oscillation parameters from latest "Bari" Global Fit PRD 95, 096014 (2017)**

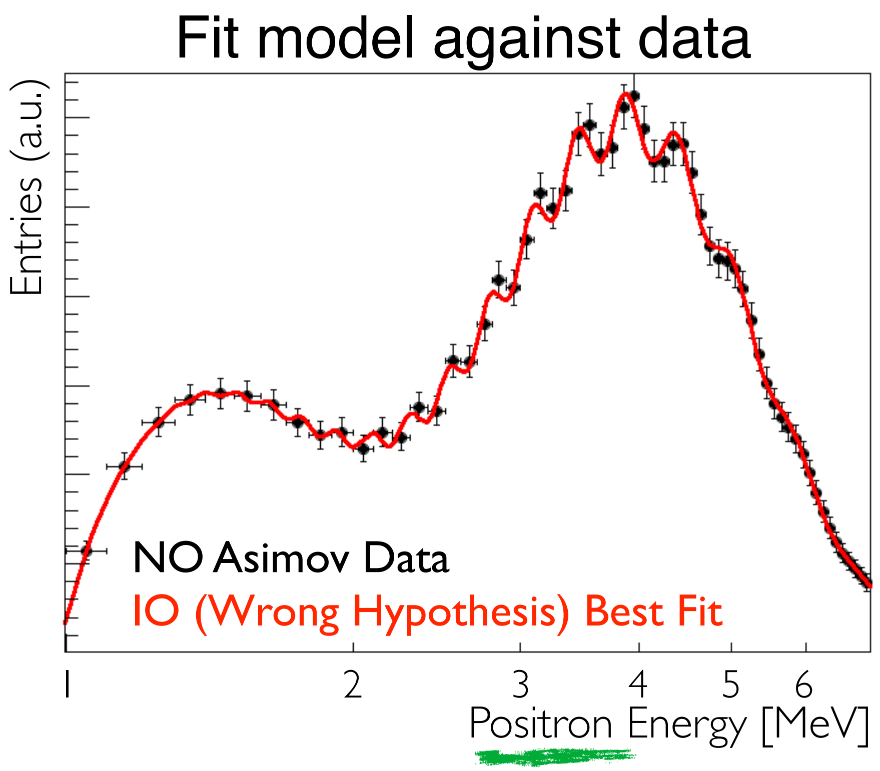
Below 3 MeV

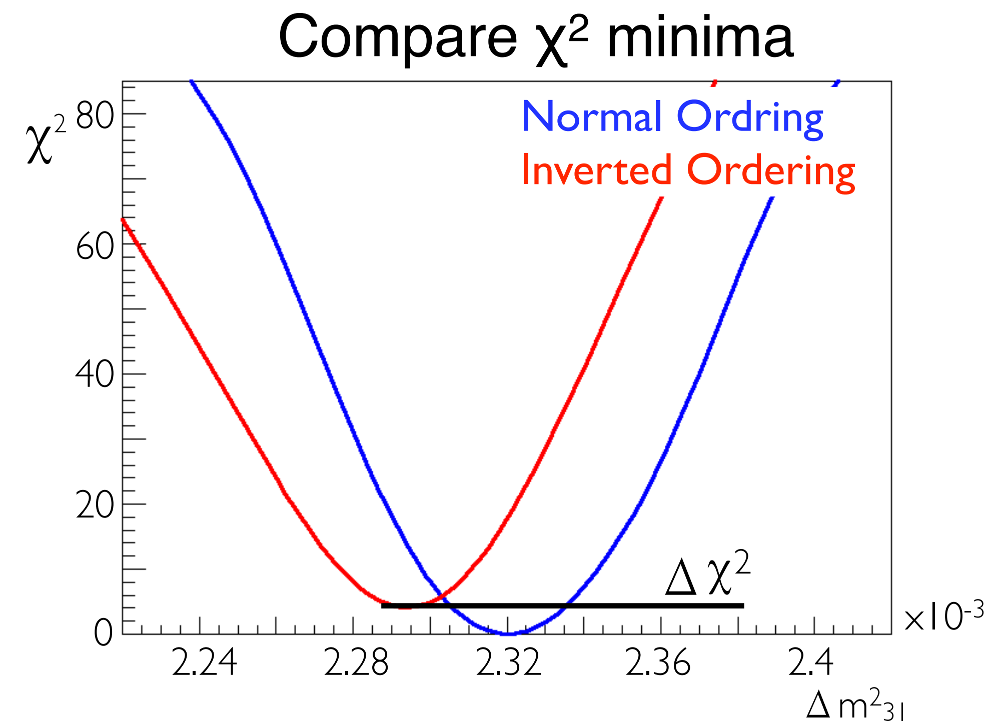
Around 3 MeV

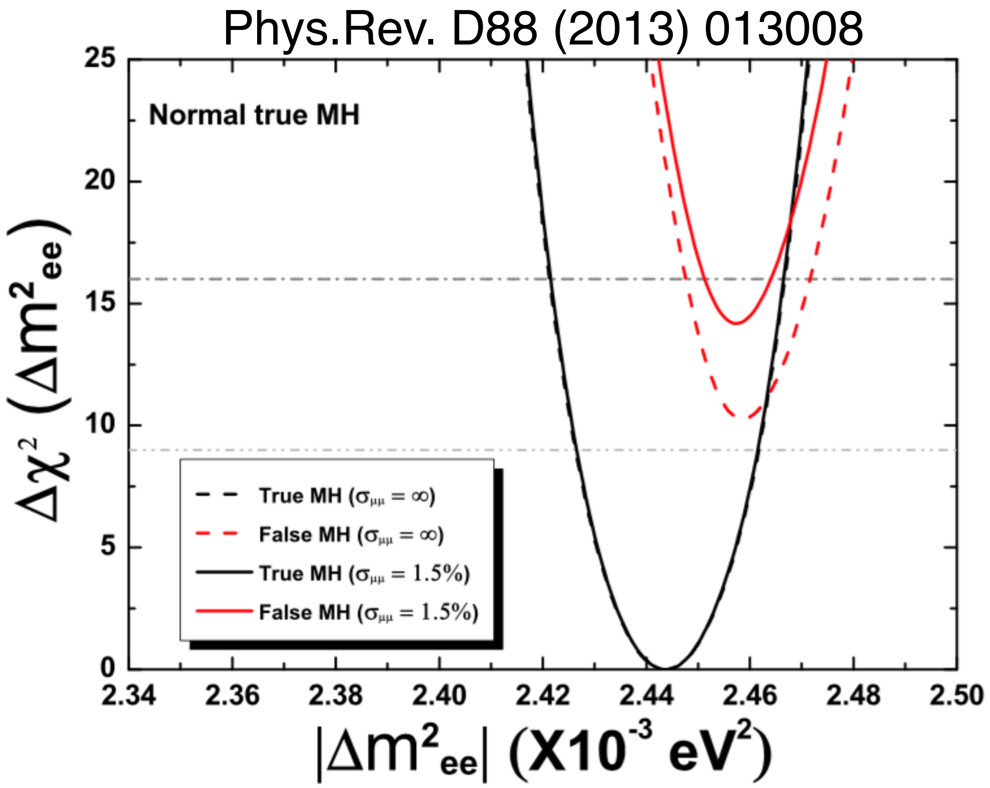
Above 3 MeV

Phase inversion around 3MeV not absorbable by $\Delta m^2_{ATM}$ tuning

# Mass Ordering Determination




**Mass Hierarchy Sensitivity**

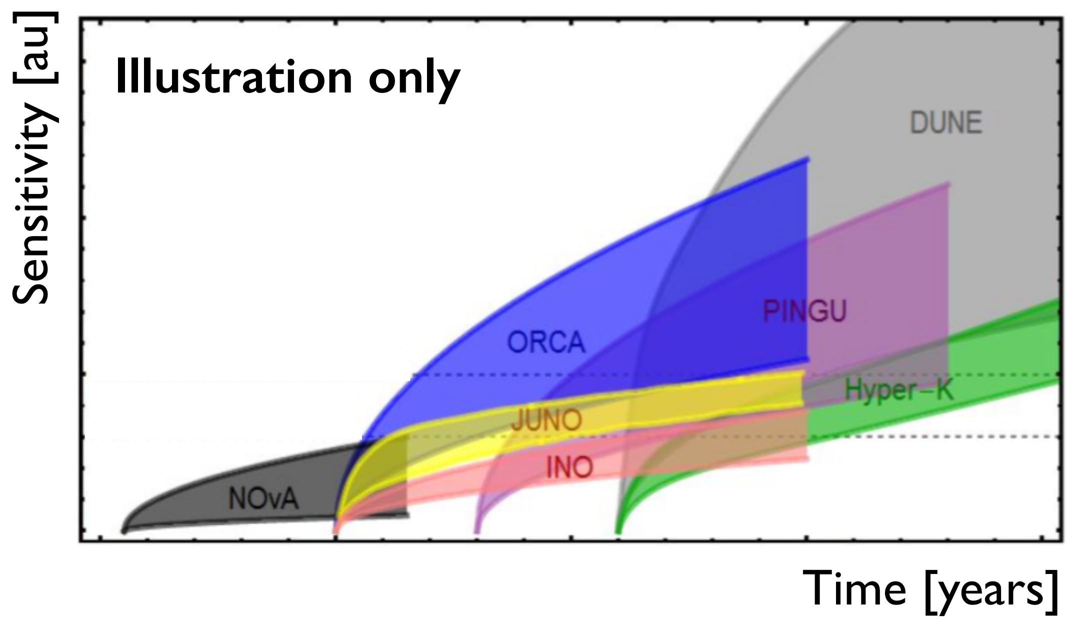
100k signal events (20kt x 36GW x 6 years)

$\Delta\chi^2$: 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 MO at JUNO




Many competing experiments ??

Many **complementary experiments** !!!

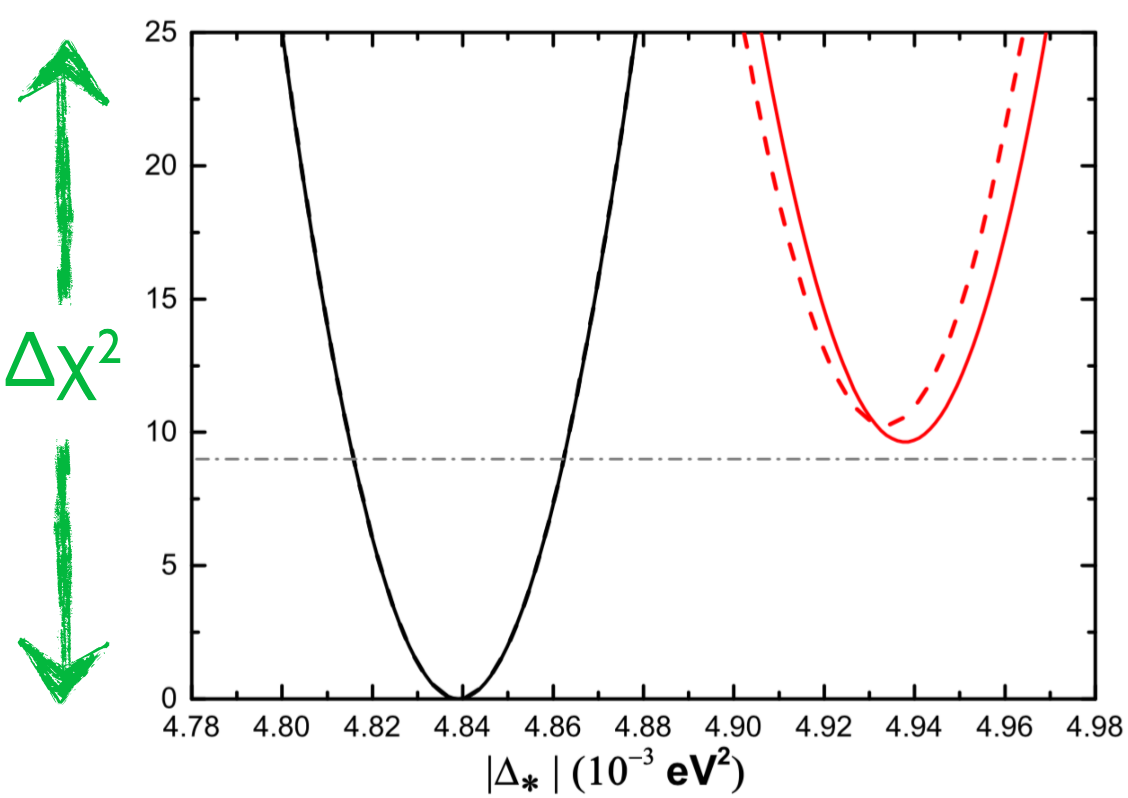
Similar time scales but

- different experimental techniques
- **different systematic uncertainties**

JUNO: only experiment exploiting **in-vacuum oscillation**

**No dependence from $\theta_{23}$ octant & CP phase**

**(Very) Little dependence from matter effects**




**arXiv: 1605.00900**

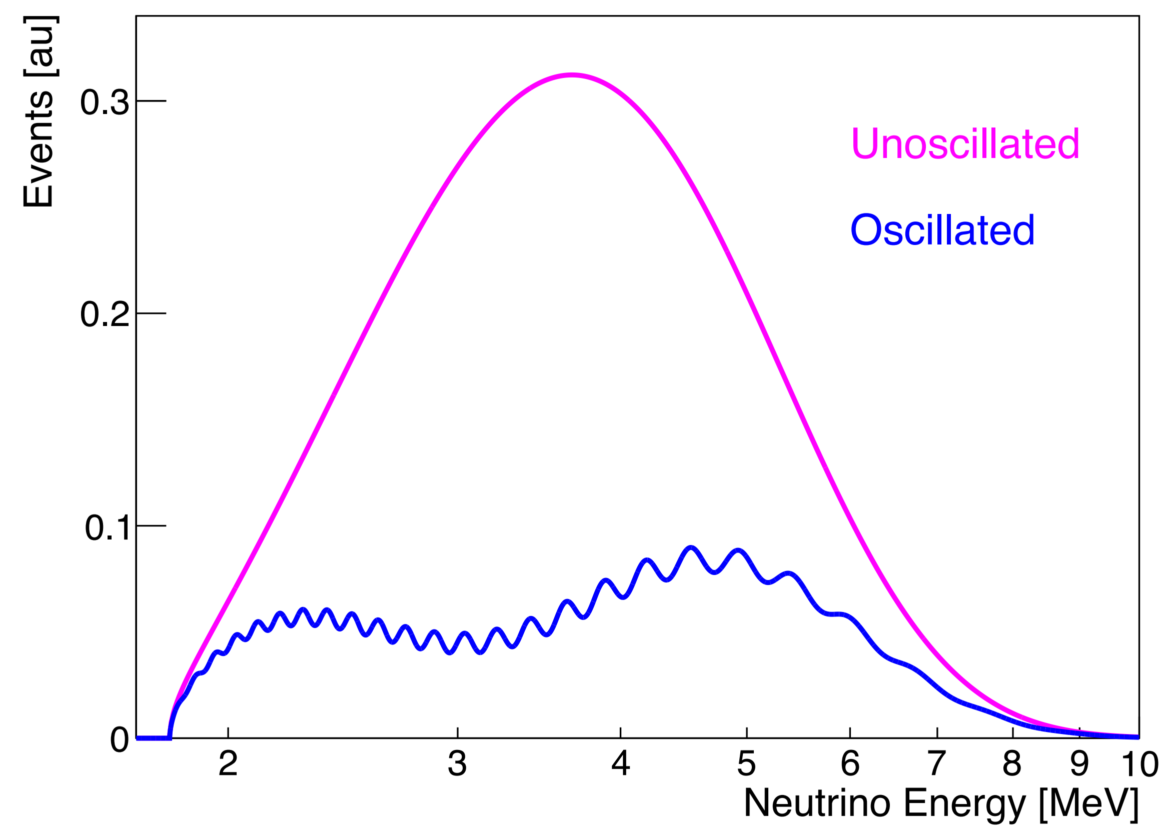
- - - - JUNO sensitivity w/o matter effects

——— JUNO sensitivity with matter effects

# Oscillation Parameters

Access to four oscillation parameters: $\theta_{13}$ , $\theta_{12}$ , $\Delta m^2_{21}$ , $|\Delta m^2_{ee}|$

Measurement of $\sin^2(2\theta_{12})$ , $\Delta m^2_{21}$ , $|\Delta m^2_{ee}|$ with better than 1% precision



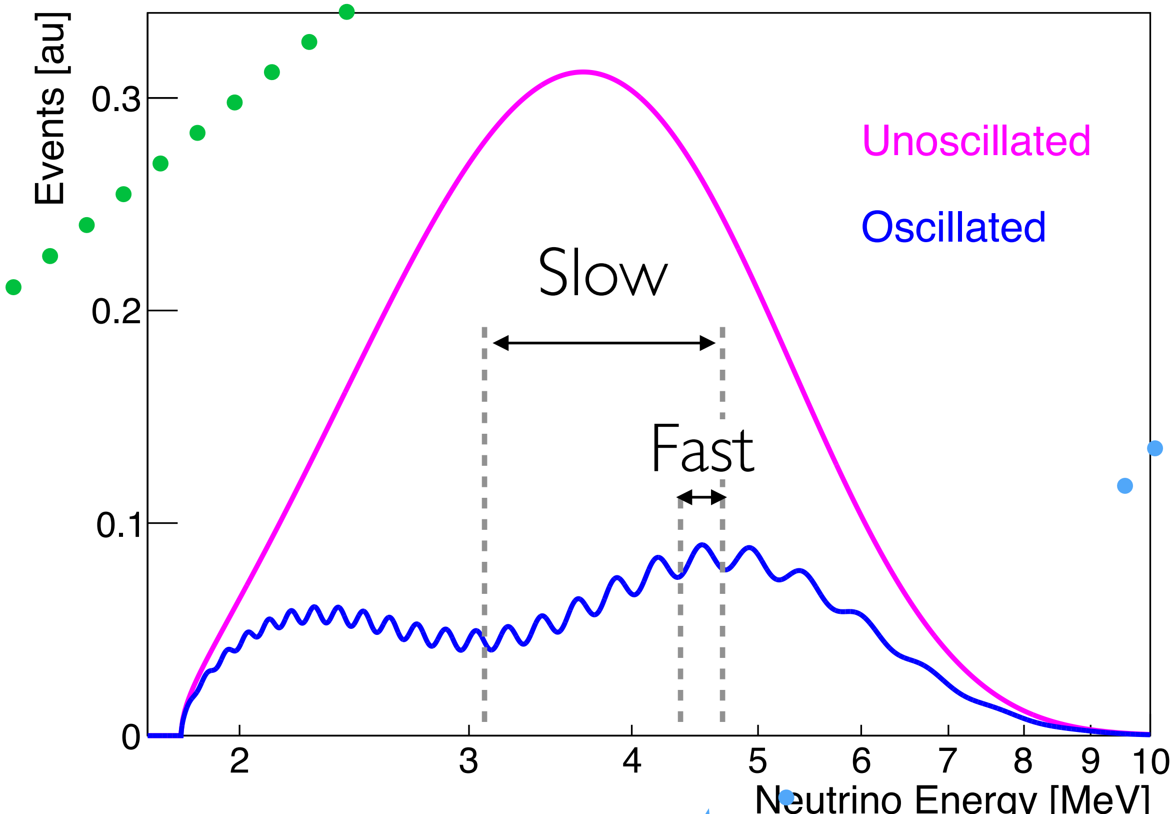

$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(\cos^2\theta_{12} \sin^2\Delta_{31} + \sin^2\theta_{12} \sin^2\Delta_{32}\right)$ Fast $\Delta m^2_{ATM}$

$- \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\Delta_{21}$ Slow $\Delta m^2_{SOL}$

# Mass Splittings

Access to four oscillation parameters: $\theta_{13}$ , $\theta_{12}$ , $\Delta m^2_{21}$ , $|\Delta m^2_{ee}|$

Measurement of $\sin^2(2\theta_{12})$ , $\Delta m^2_{21}$ $|\Delta m^2_{ee}|$ with better than 1% precision




$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \cdot \sin^2(\cos^2\theta_{12} \sin^2\Delta_{31} + \sin^2\theta_{12} \sin^2\Delta_{32}) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\Delta_{21}$$

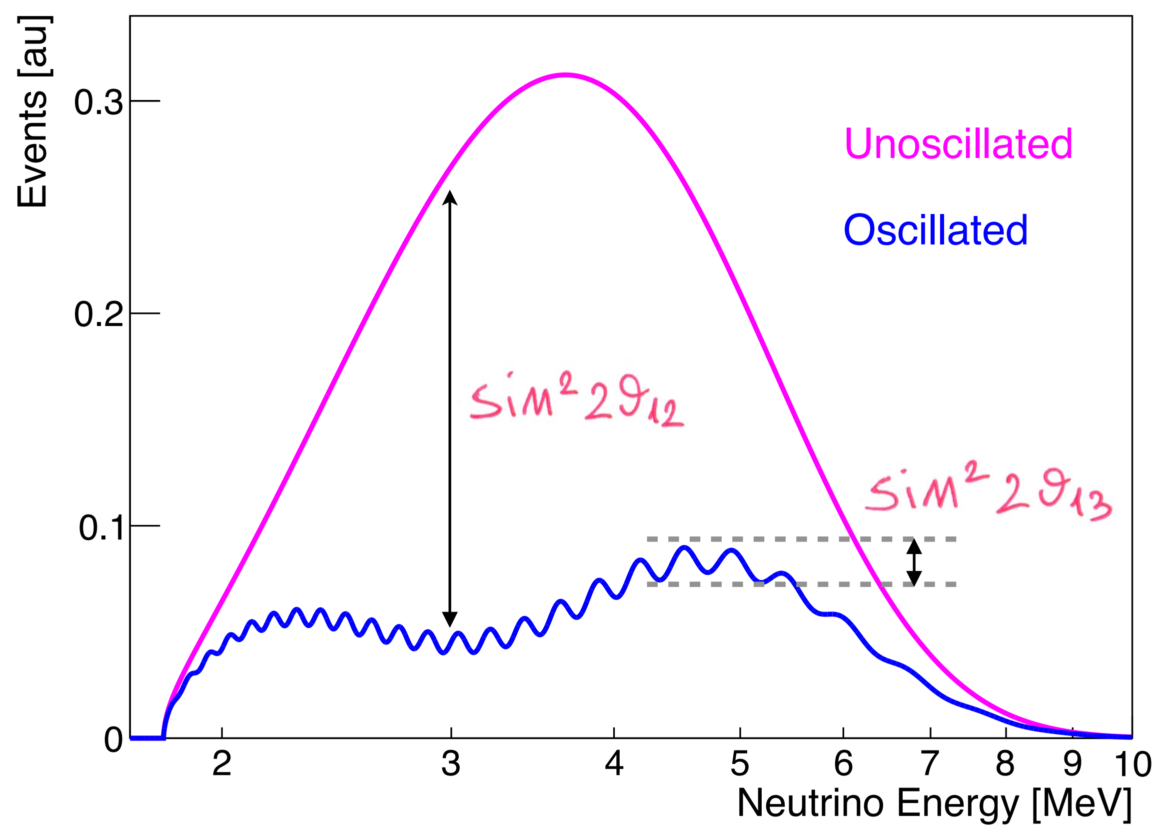
Fast $\Delta m^2_{ATM}$

Slow $\Delta m^2_{SOL}$

# Mixing Angles

Access to four oscillation parameters: $\theta_{13}$ , $\theta_{12}$ , $\Delta m^2_{21}$ , $|\Delta m^2_{ee}|$

Measurement of $\sin^2(2\theta_{12})$ , $\Delta m^2_{21}$ , $|\Delta m^2_{ee}|$ with better than 1% precision

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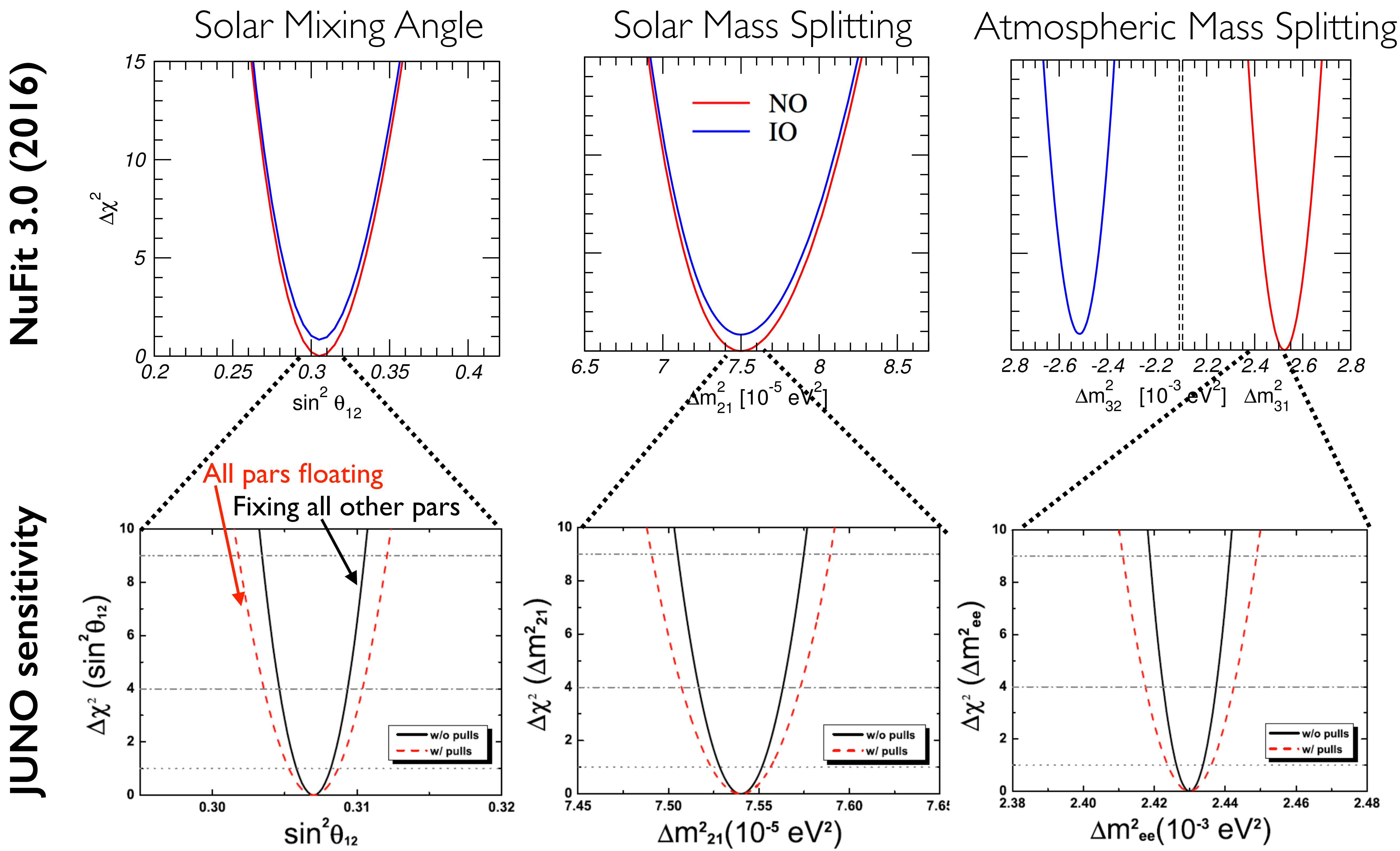
$$- \sin^2 2\theta_{12}\ \cos^4\theta_{13}\ \sin^2\Delta_{21}$$ Slow $\Delta m^2_{SOL}$

# Sensitivity To Oscillation Parameters (Direct Constraints)



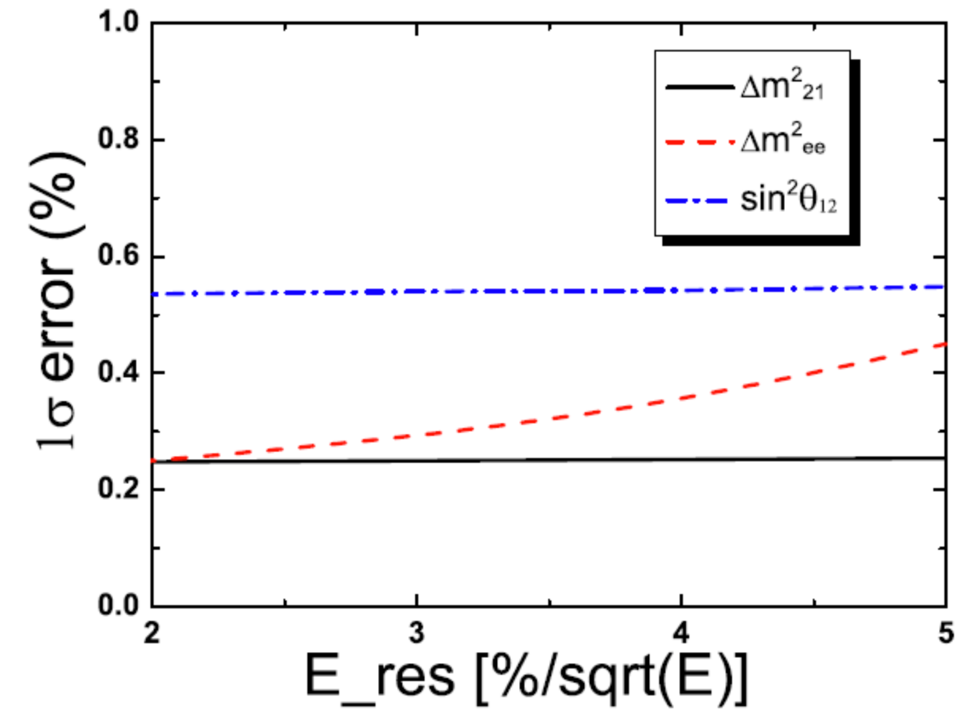

$\sin^2(\theta_{12})$: 0.54%

$\Delta m^2_{21}$: 0.24%

$\Delta m^2_{ee}$: 0.27%

# Oscillation Parameter Uncertainties

- $\Delta m^2_{ee}$ precision due to **multiple oscillation cycles**, each giving independent measurement
- Energy Resolution affects only $\Delta m^2_{ee}$ (fast oscillation)
- **High precision calorimetry needed only for atmospheric sector (amplitude & sign of mass splitting)**




**Considering background and systematics:**

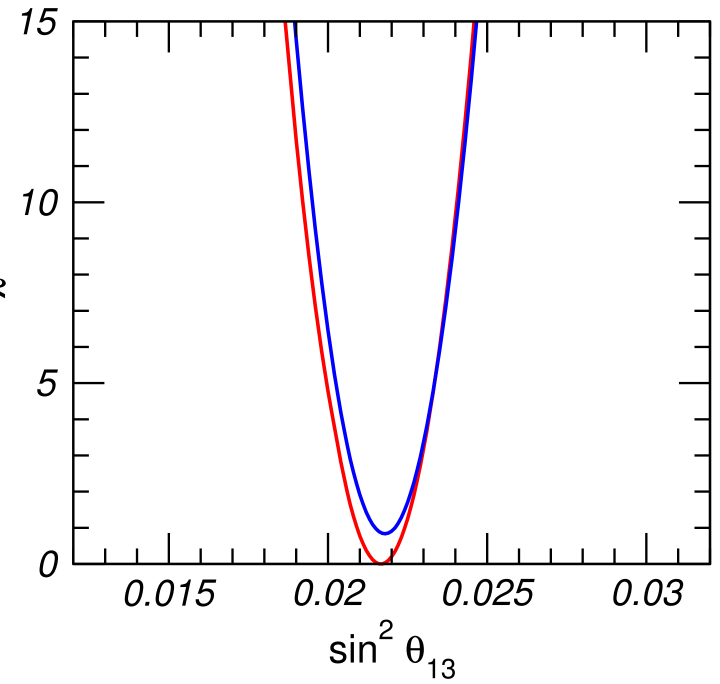
Cosmogenic Bkg (3% Norm + 10% Shape) → + BG
Bin-to-bin uncorrelated uncertainty → + B2B
Energy scale uncertainty → + EL
Energy non-linear uncertainty → + NL

| | Nominal | + B2B (1%) | + BG | + EL (1%) | + NL (1%) |
|---|---|---|---|---|---|
| $\sin^2\theta_{12}$ | 0.54% | 0.60% | 0.62% | 0.64% | 0.67% |
| $\Delta m^2_{21}$ | 0.24% | 0.27% | 0.29% | 0.44% | 0.59% |
| $\lvert\Delta m^2_{ee}\rvert$ | 0.27% | 0.31% | 0.31% | 0.35% | 0.44% |

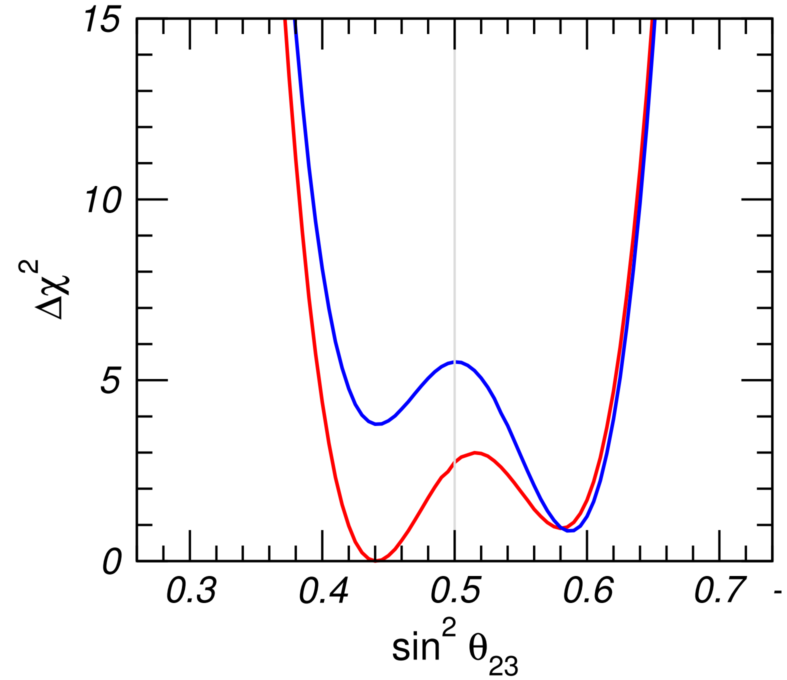
# Sensitivity To Oscillation Parameters (Indirect Constraints)

**NuFit 3.0 (2016)**

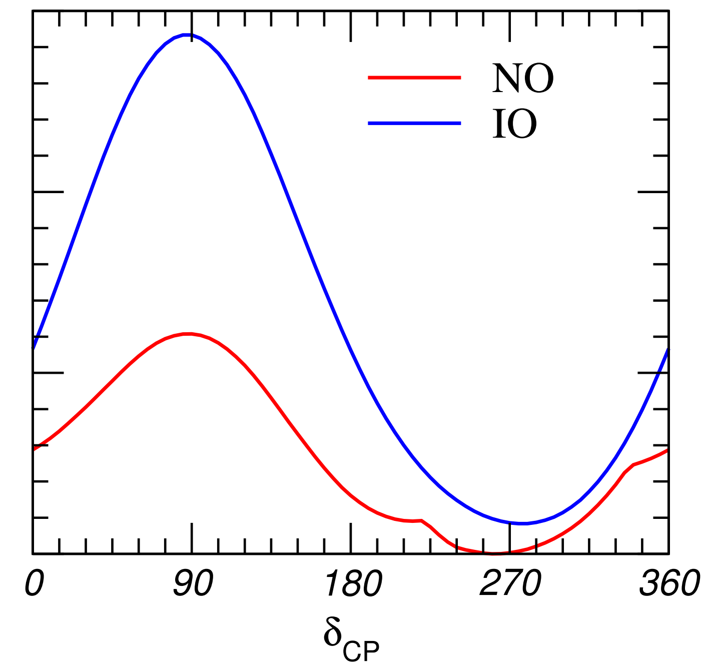
Reactor $\theta_{13}$




$\theta_{23}$ octant




CP Phase

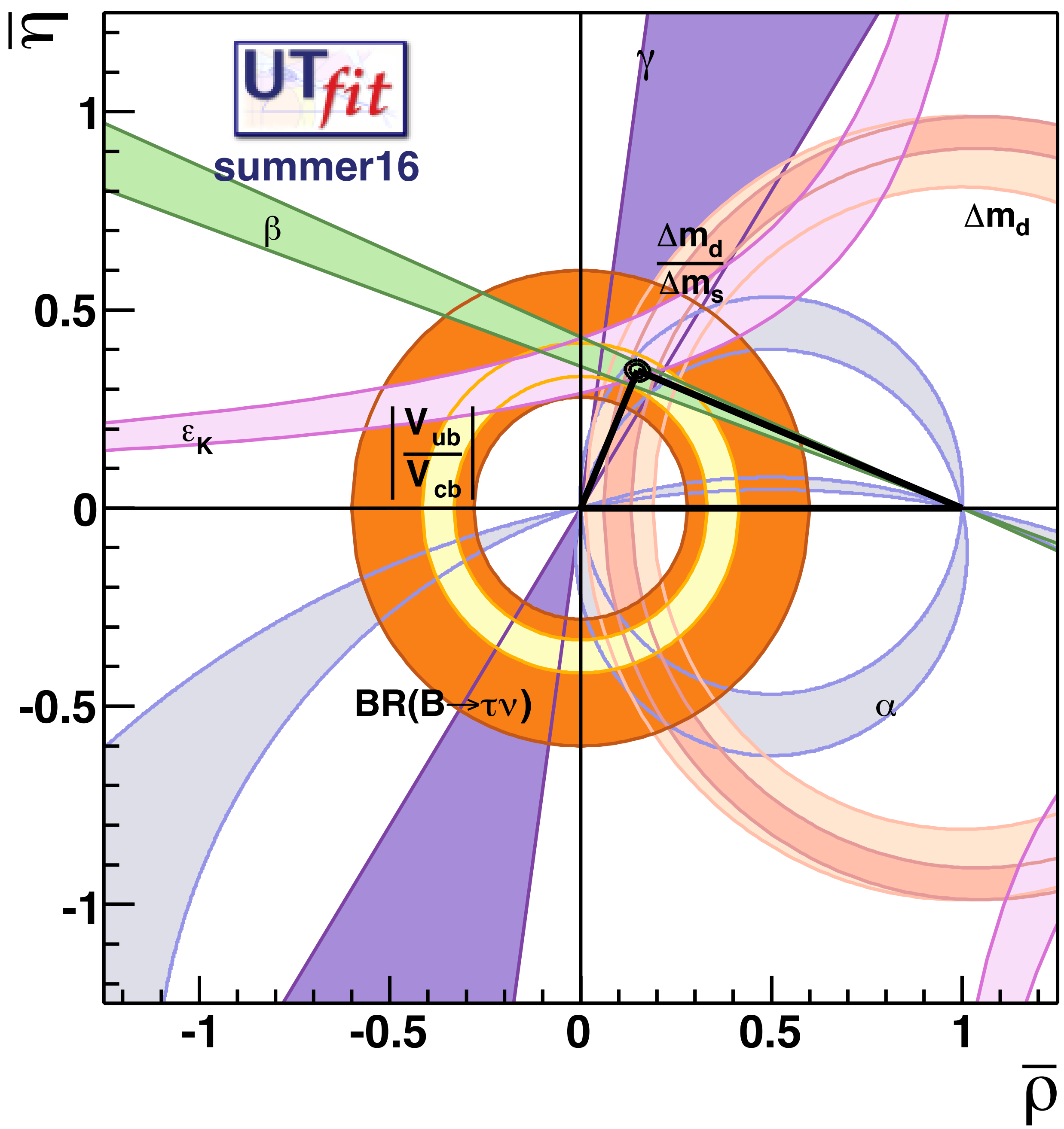



JUNO precision comparable to Double Chooz nowadays (~15 %)

Might be the only experiment to crosscheck $\theta_{13}$ accuracy

Both via Mass Hierarchy determination

# Unitarity Test




Neutrino longstanding quest for CKM-like precision

Test unitarity of the PMNS matrix

▸▸▸ Is the triangle closed?

Need extremely good precision in all mixing parameters

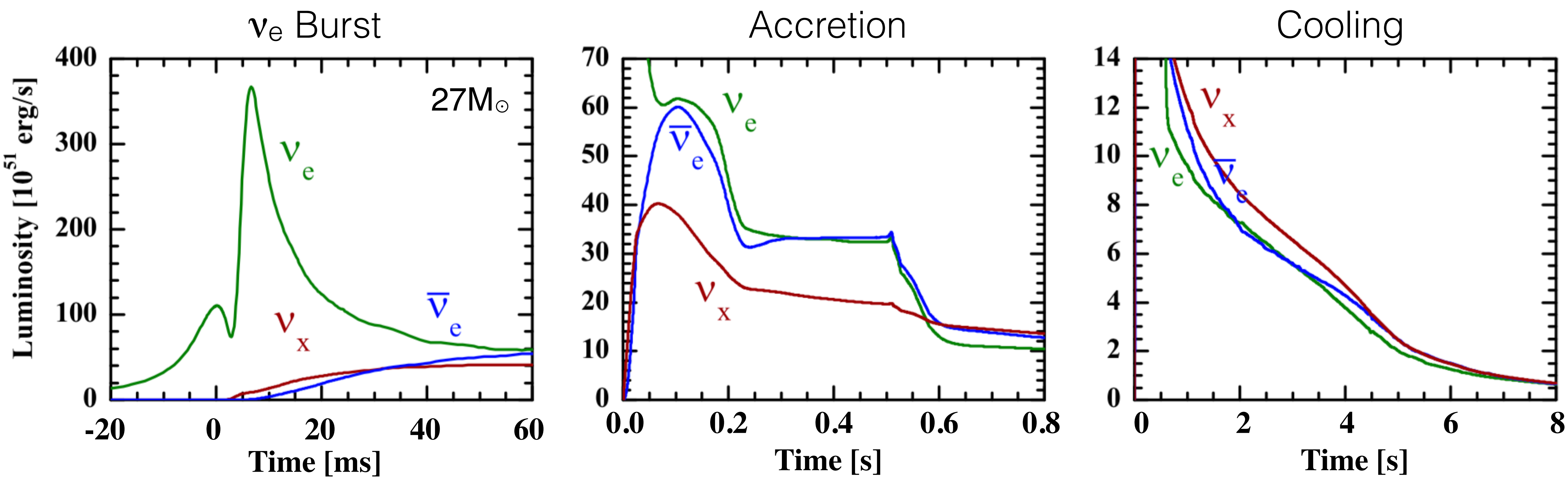
Synergy of many experiments

(eventually assessing CP violation, but that is a different story)

# Non-Reactor Neutrino Physics



# Supernova Neutrinos




- Huge amount of energy ($3\times10^{53}$erg) emitted in neutrinos (~0.2M⊙) over **long time range**
- 3 phases equally important ▶ 3 experiments teaching us about astro- and particle-physics

| Process | Type | Events ⟨$E_\nu$⟩=14MeV |
|---|---|---|
| $\bar{\nu}_e+p \rightarrow e^++n$ | CC | $5.0\times10^3$ |
| $\nu+p \rightarrow \nu+p$ | NC | $1.2\times10^3$ |
| $\nu+e \rightarrow \nu+e$ | ES | $3.6\times10^2$ |
| $\nu+{}^{12}C \rightarrow \nu+{}^{12}C^*$ | NC | $3.2\times10^2$ |
| $\nu_e+{}^{12}C \rightarrow e^-+{}^{12}N$ | CC | $0.9\times10^2$ |
| $\bar{\nu}_e+{}^{12}C \rightarrow e^++{}^{12}B$ | CC | $1.1\times10^2$ |
| *NB Other ⟨$E_\nu$⟩ values need to be considered to get complete picture.* | | |

Expected events in JUNO for a typical SN **distance of 10kpc**

We need to be able to handle Betelgeuse (d~0.2kpc) resulting in ~10MHz trigger rate

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

# Geoneutrinos

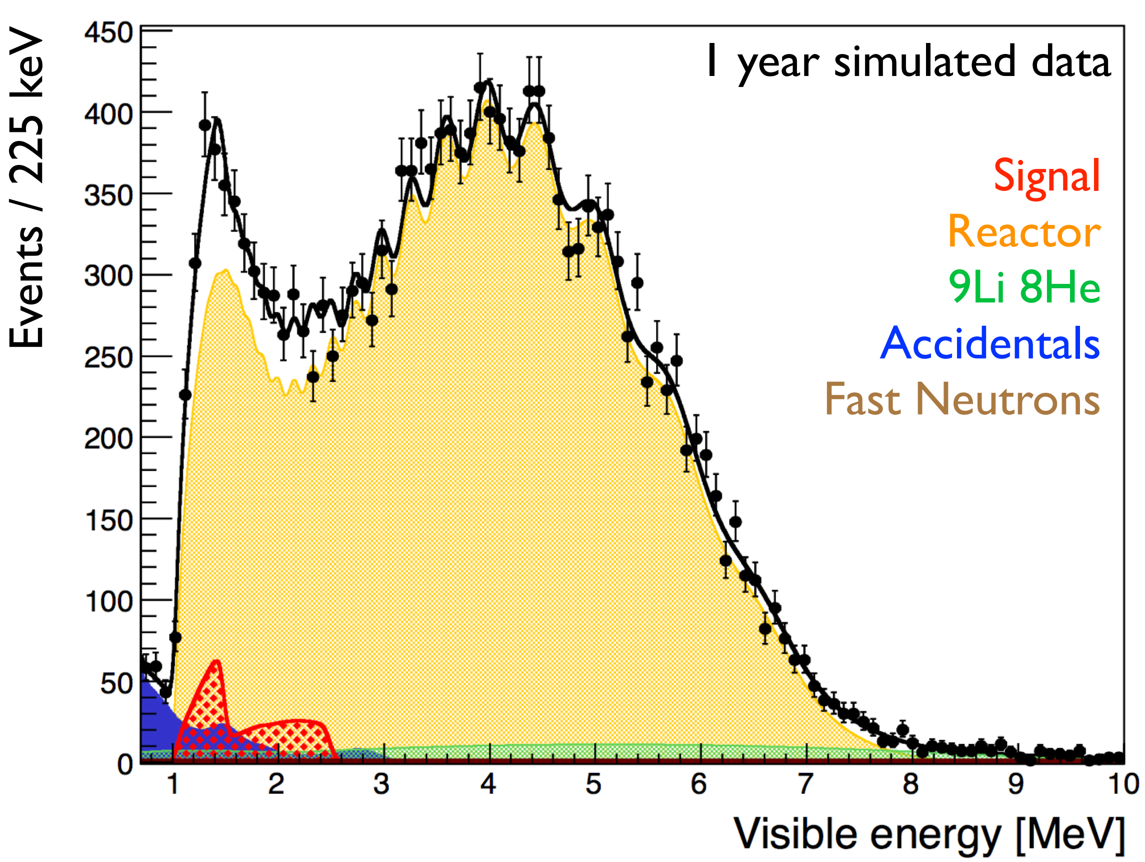
J.Phys. G43 (2016) no.3, 030401

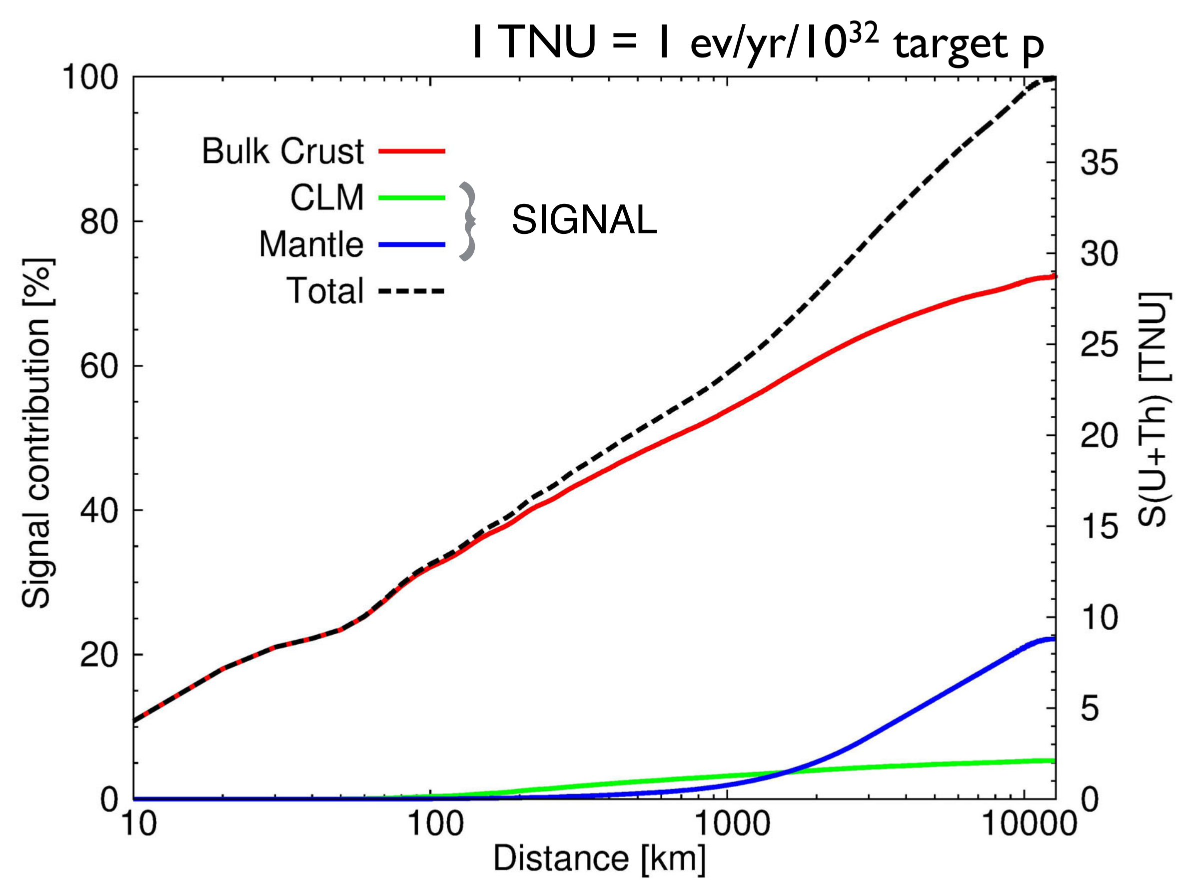
Earth's surface heat flow 46±3 TW. What fraction due to **primordial vs radioactive** sources?

Understanding of:

- **composition** of the Earth (chondritic meteorites that formed our Planet)
- chemical layering in the mantle and the nature of **mantle convection**
- energy needed to drive **plate tectonics**
- power source of the geodynamo, which powers the magnetosphere

Detect **electron antineutrinos from the $^{238}$U and $^{232}$Th** decay chains



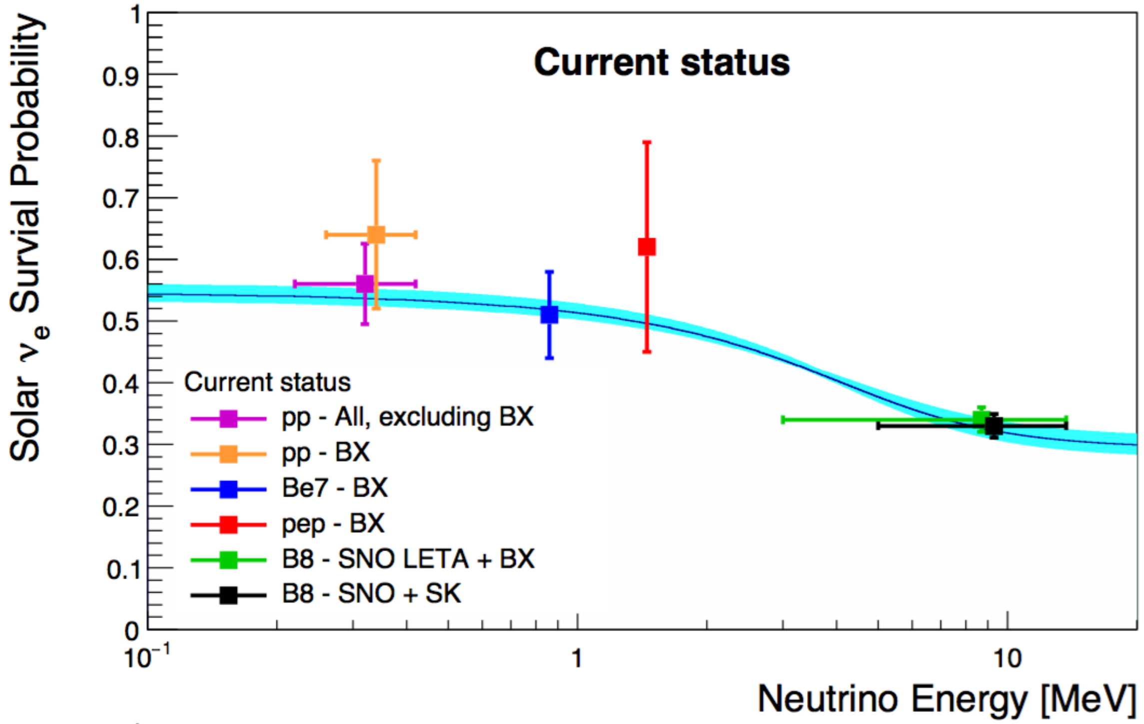
# Solar Neutrinos

Fusion reactions in solar core: powerful source of electron neutrinos O(1 MeV)

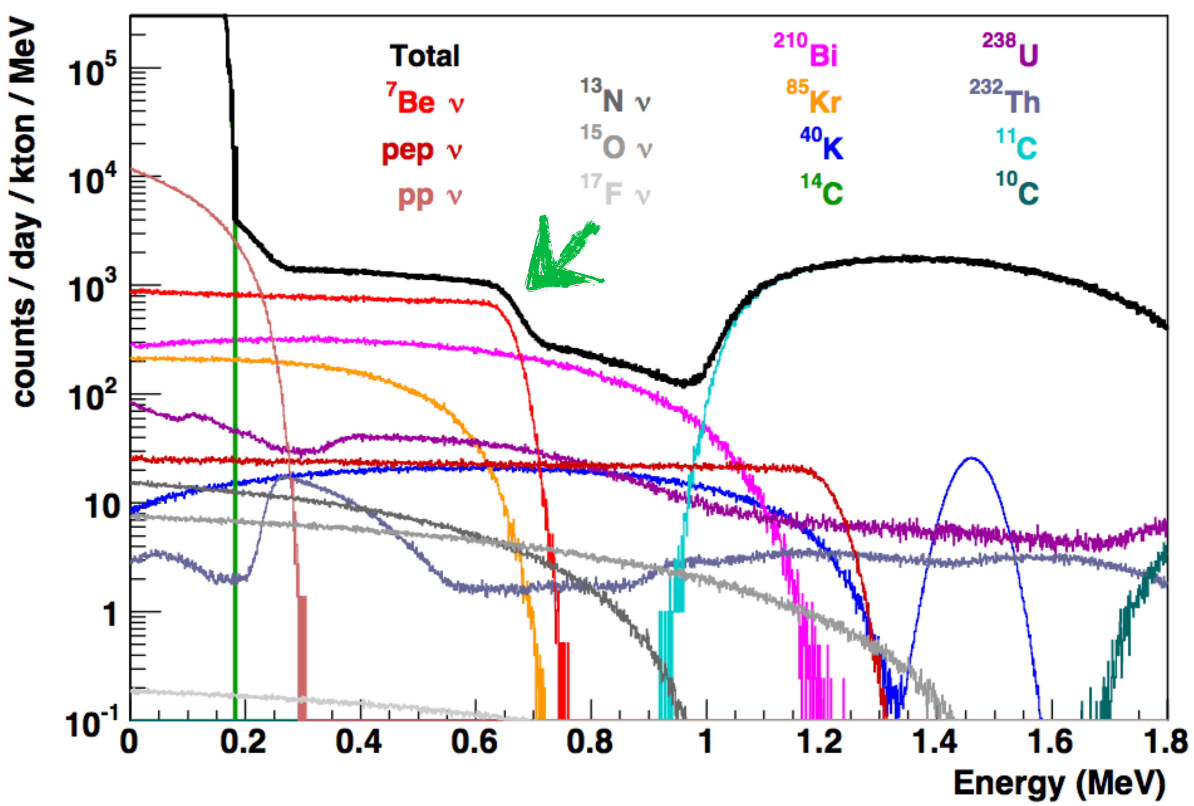
JUNO: neutrinos from **$^7$Be and $^8$B** chains

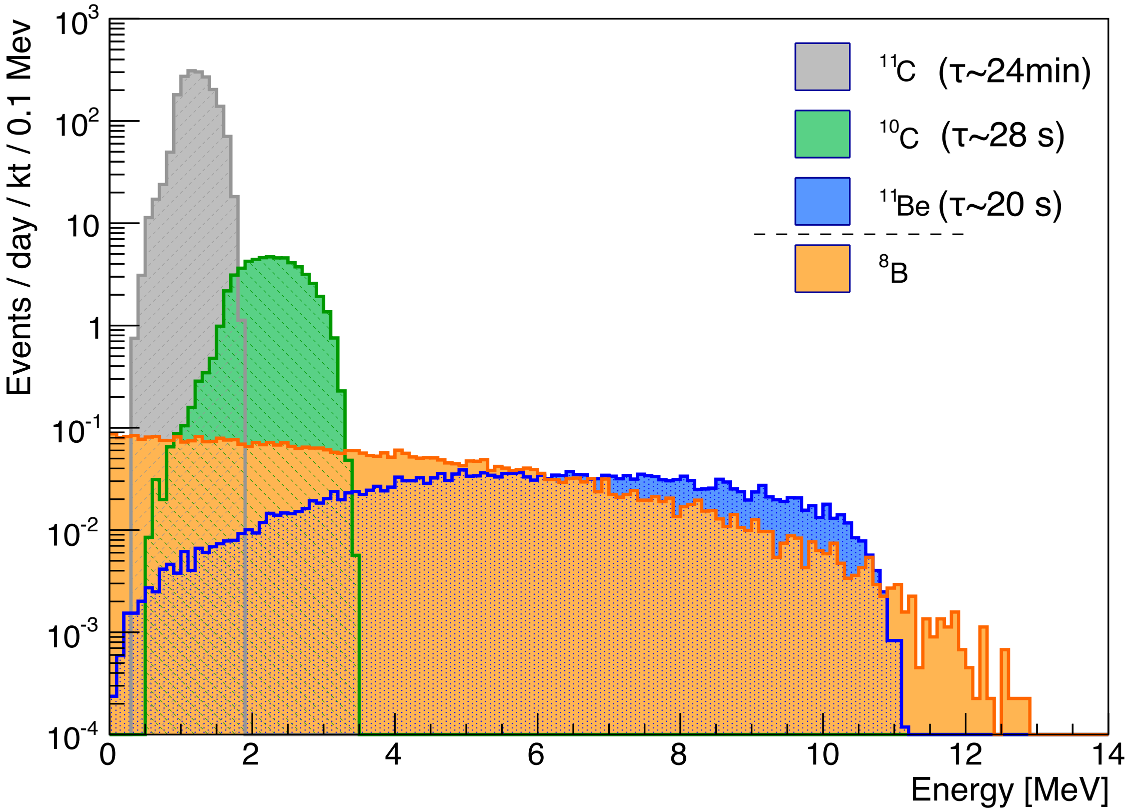
Investigate **MSW effect**: Transition between vacuum and matter dominated regimes

Constrain **Solar Metallicity** Problem: Neutrinos as proxy for Sun composition




arXiv 1602.01733

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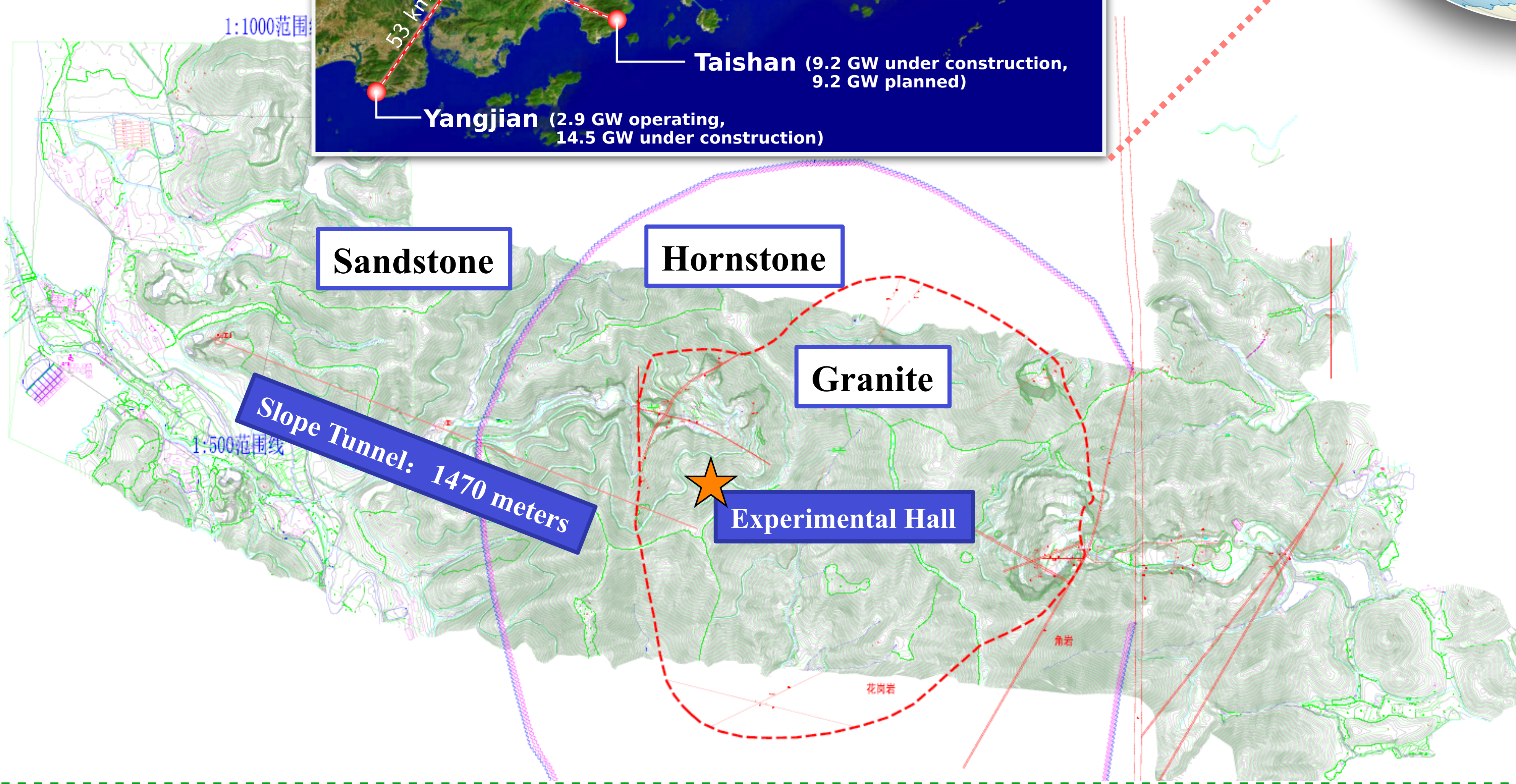
# Final Experimental Remarks

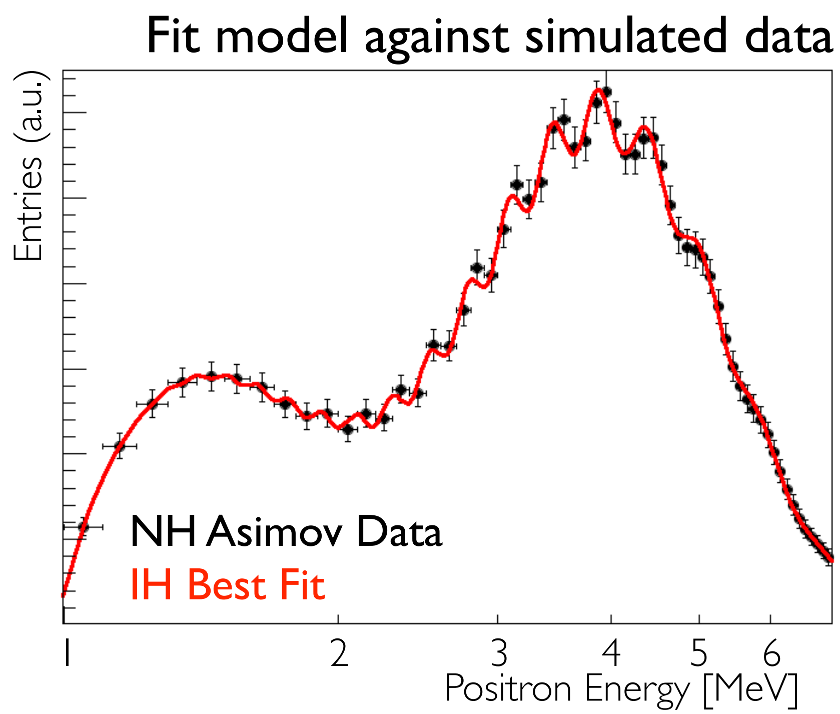
# A New Lab in the South of China

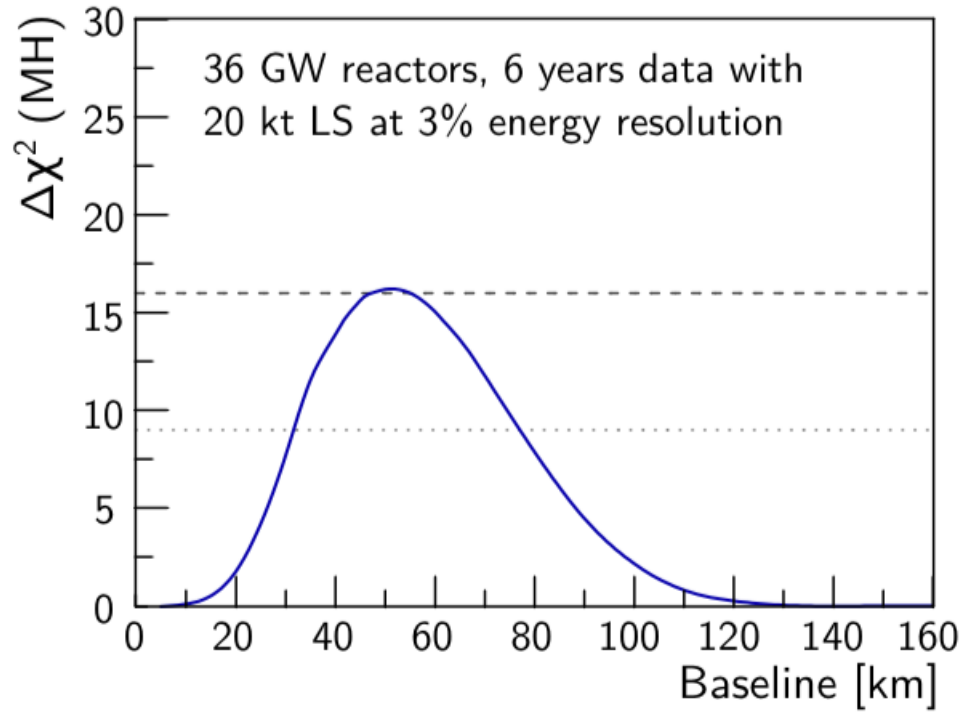




Nice granite structure at right distance from reactors (very lucky!)

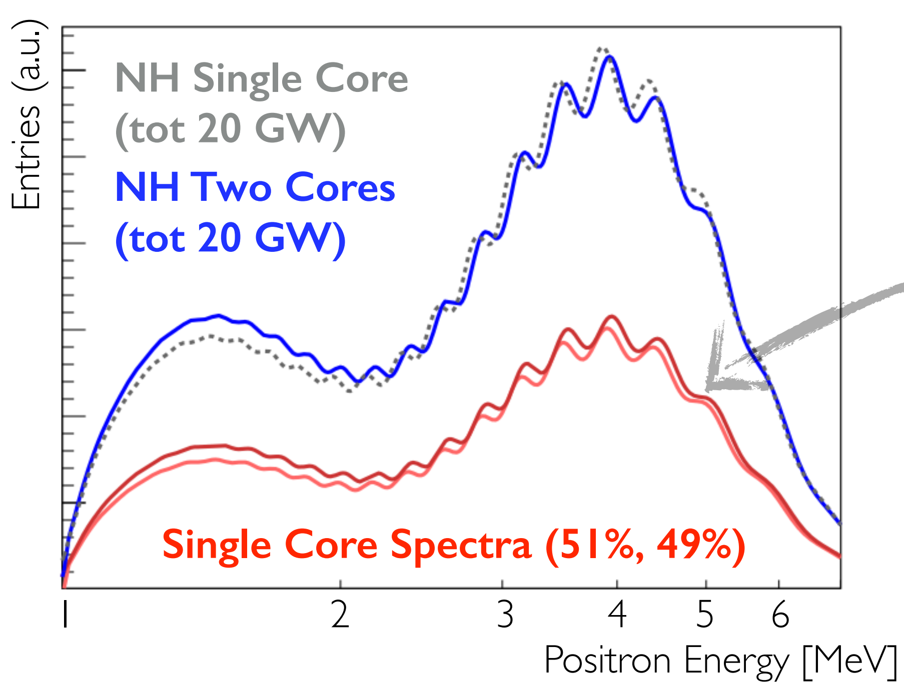
Jiangmen City
Guandong province

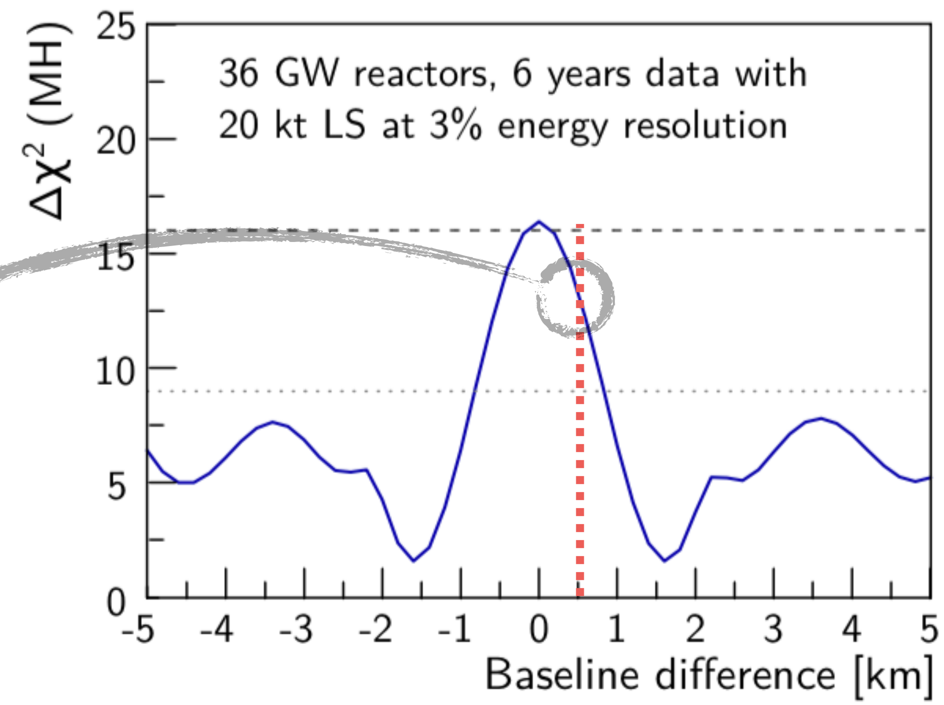
# Baseline Optimization




**~50 km**
optimal
baseline
for MH

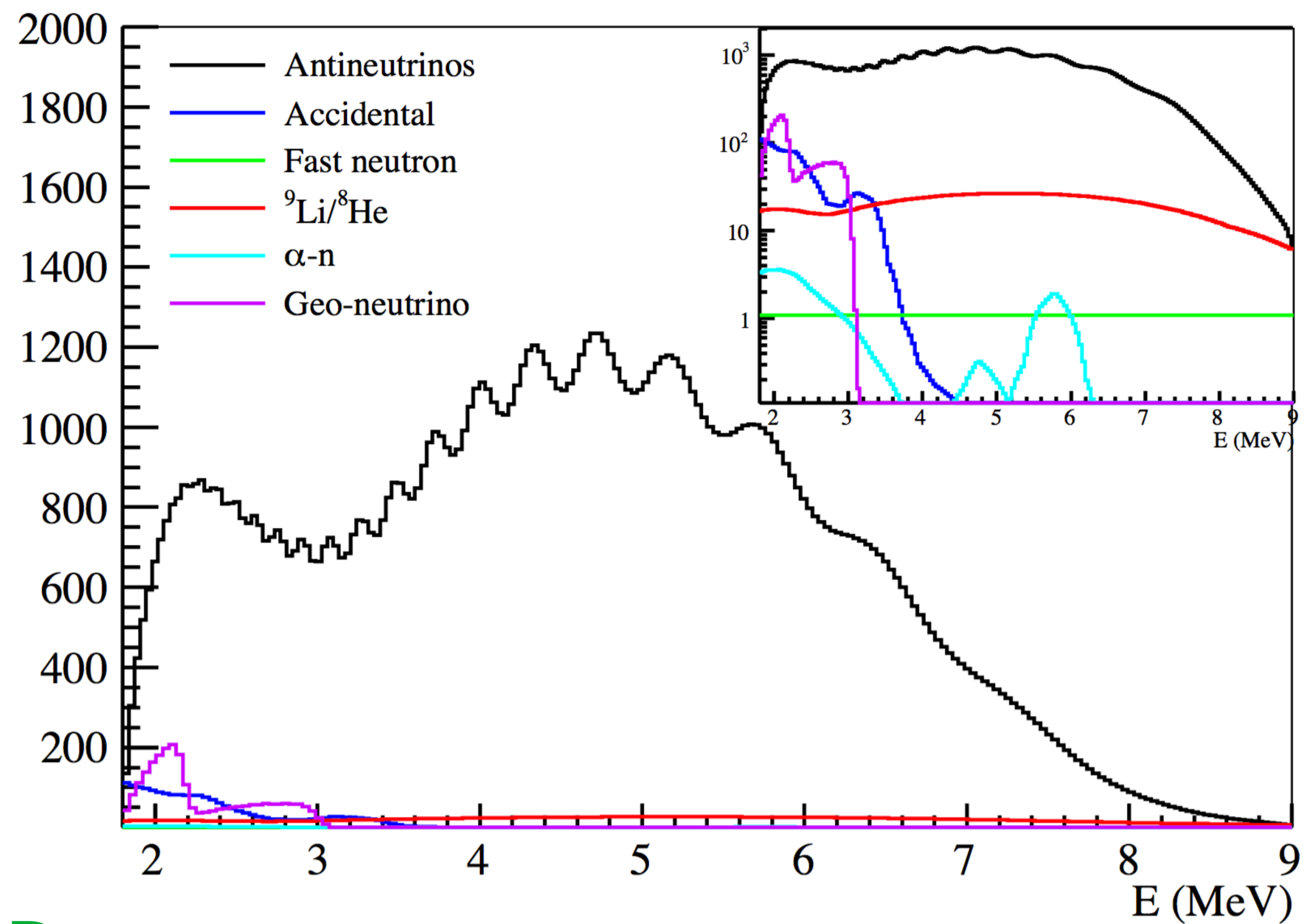



**~500m**
maximum
allowed
baseline
difference

# Almost 2 kmwe overburden to reduce cosmogenic background

# Background Summary After Selection




## Event Rate per Day

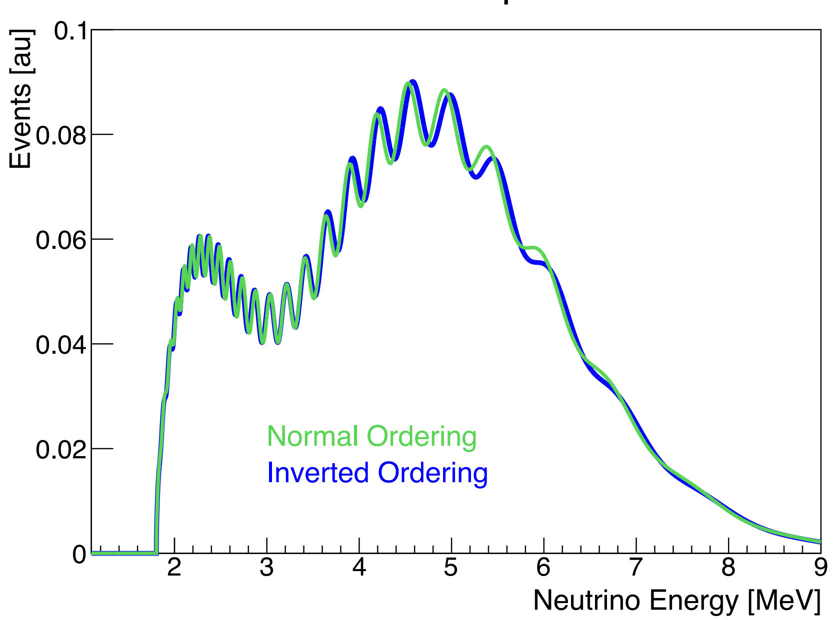
<table>
<tr><th>Selection</th><th>IBD efficiency</th><th>IBD</th><th>Geo-$\nu$s</th><th>Accidental</th><th>$^{9}$Li/$^{8}$He</th><th>Fast $n$</th><th>$(\alpha, n)$</th></tr>
<tr><td>-</td><td>-</td><td>83</td><td>1.5</td><td>$\sim 5.7 \times 10^{4}$</td><td>84</td><td>-</td><td>-</td></tr>
<tr><td>Fiducial volume</td><td>91.8%</td><td>76</td><td>1.4</td><td rowspan="3">410</td><td>77</td><td rowspan="5">0.1</td><td rowspan="5">0.05</td></tr>
<tr><td>Energy cut</td><td>97.8%</td><td rowspan="3">73</td><td rowspan="3">1.3</td><td rowspan="3">71</td></tr>
<tr><td>Time cut</td><td>99.1%</td></tr>
<tr><td>Vertex cut</td><td>98.7%</td><td>1.1</td></tr>
<tr><td>Muon veto</td><td>83%</td><td>60</td><td>1.1</td><td>0.9</td><td>1.6</td></tr>
<tr><td>Combined</td><td>73%</td><td>60</td><td colspan="5">3.8</td></tr>
</table>

# Detector Resolution

**Central Detector design optimized for Mass Ordering: "Precise & Large"**

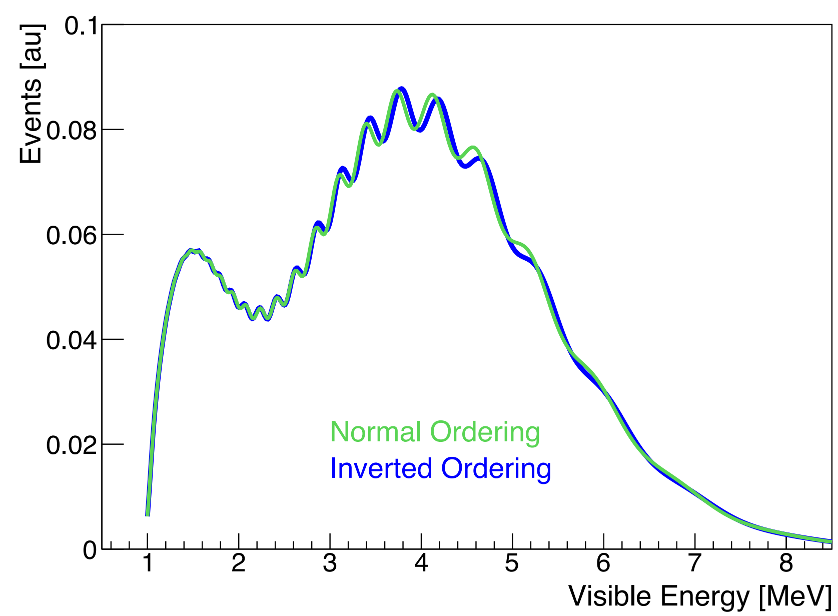
Detector Resolution: $\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma^2_{STOCH}}{E} + \sigma^2_{NON-STOCH}}$

Neutrino Spectrum



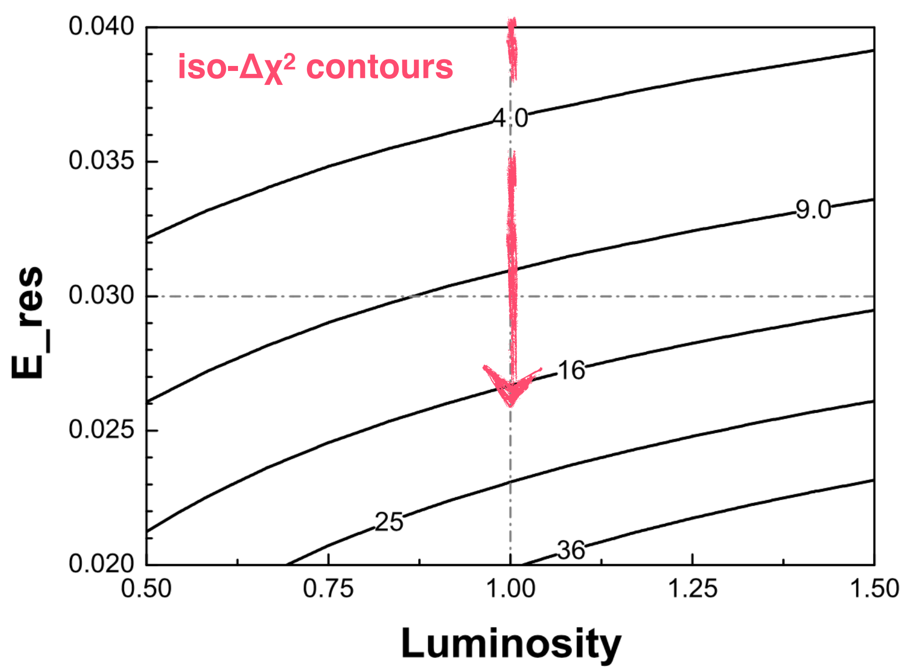

"True" Spectrum

Visible Spectrum




3% Energy Resolution

MH Sensitivity



# Detector Resolution

**Central Detector design optimised for Mass Hierarchy: "Precise & Large"**

Detector Resolution: $\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma^2_{STOCH}}{E} + \sigma^2_{NON-STOCH}}$

3% resolution at 1MeV is pivotal

- **stochastic term** → Maximise detected light → Large photocoverage, Transparent Scintillator
- **non-stochastic term** → Control of systematics → Small (3") PMTs, Calibration

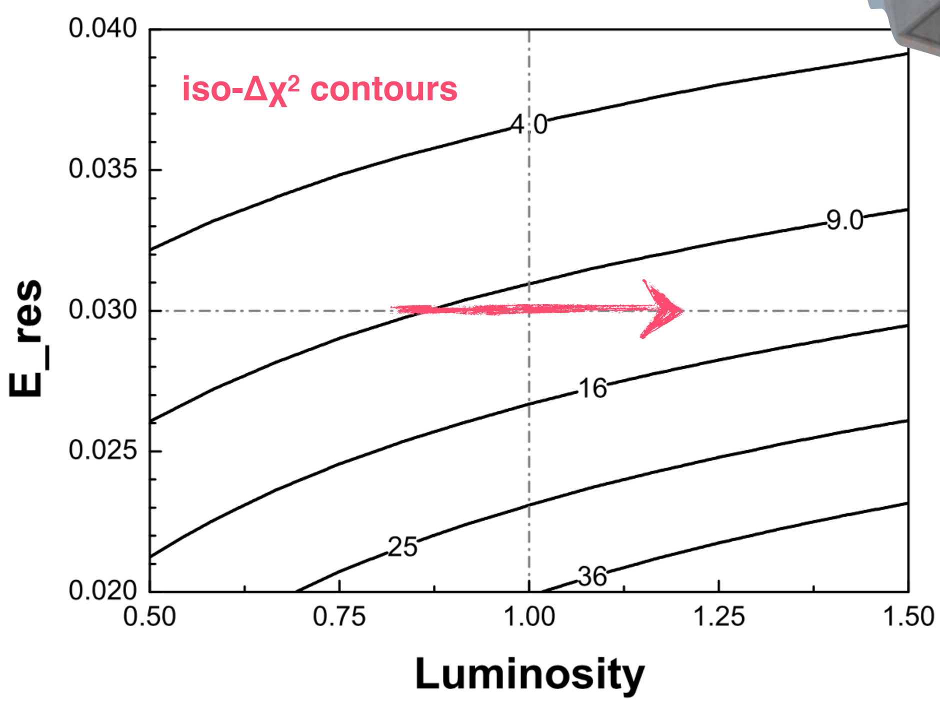
# Central Detector

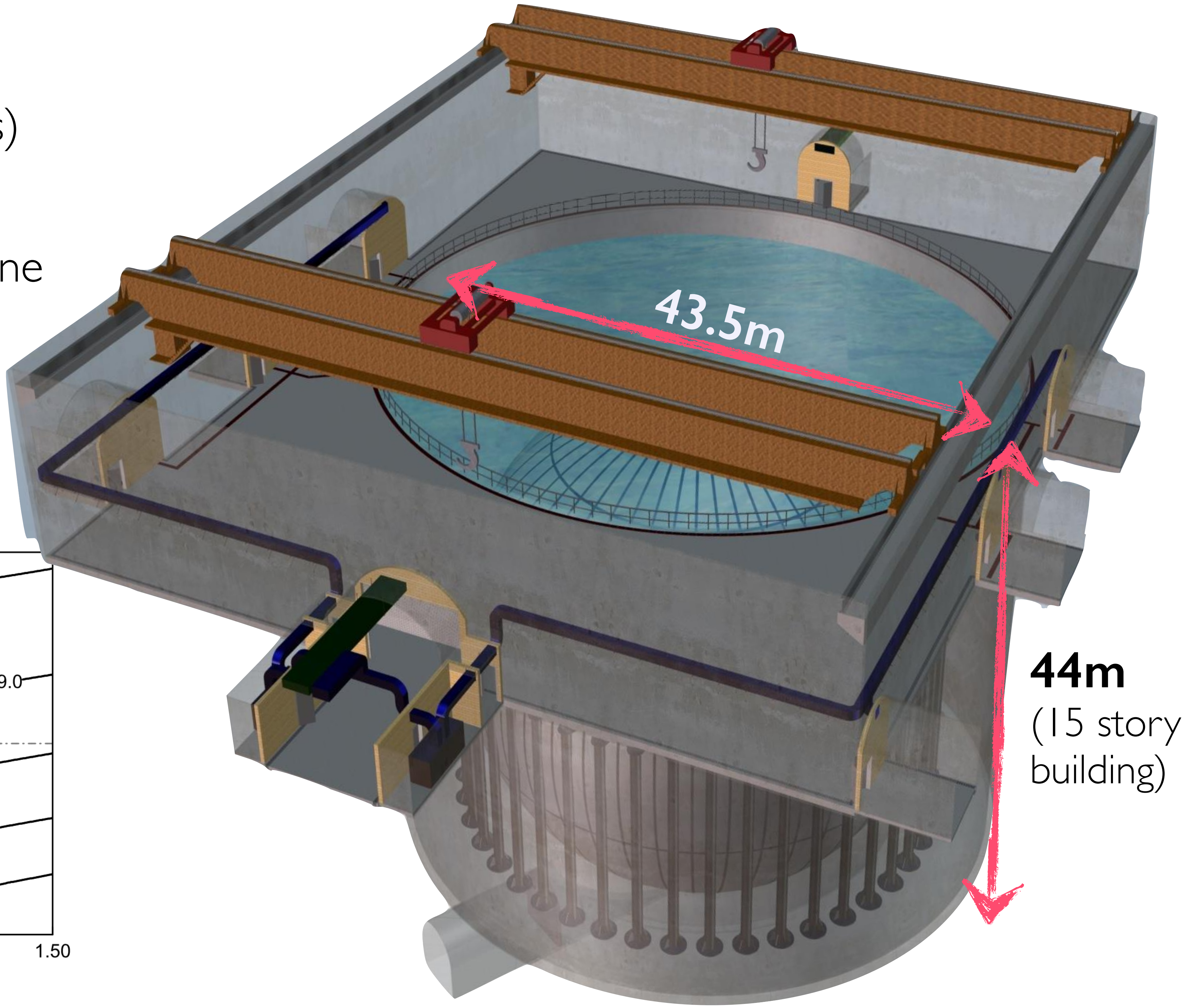
**Central Detector design optimized for Mass Hierarchy: "Precise & Large"**

Need high statistics
(looking for fine structures)

Need to recover
flux reduction due to baseline

Nominal Luminosity
100k events in 6 years



# CONCLUSIONS

- JUNO unprecedented **large & high precision-calorimetry** liquid scintillator detector
  - Requiring high light level (1200 pe/MeV) to reach **3% energy resolution** at 1MeV
- High precision neutrino oscillation with **reactor-ν**
  - SOLAR SECTOR : ≤1% precision in **solar terms**
  - ATMOSPHERIC SECTOR : **mass ordering through oscillation interference**
    (almost) insensitive to matter effects
    insensitive to δ(CP) and $\theta_{23}$

    } *Complementary to other experiments*
  - NON-REACTOR ν : leading physics capabilities (Supernova, Geoneutrinos, Solar neutrinos…)
- JUNO collaboration established in 2014 & funded ▸ **data taking slightly after 2020**