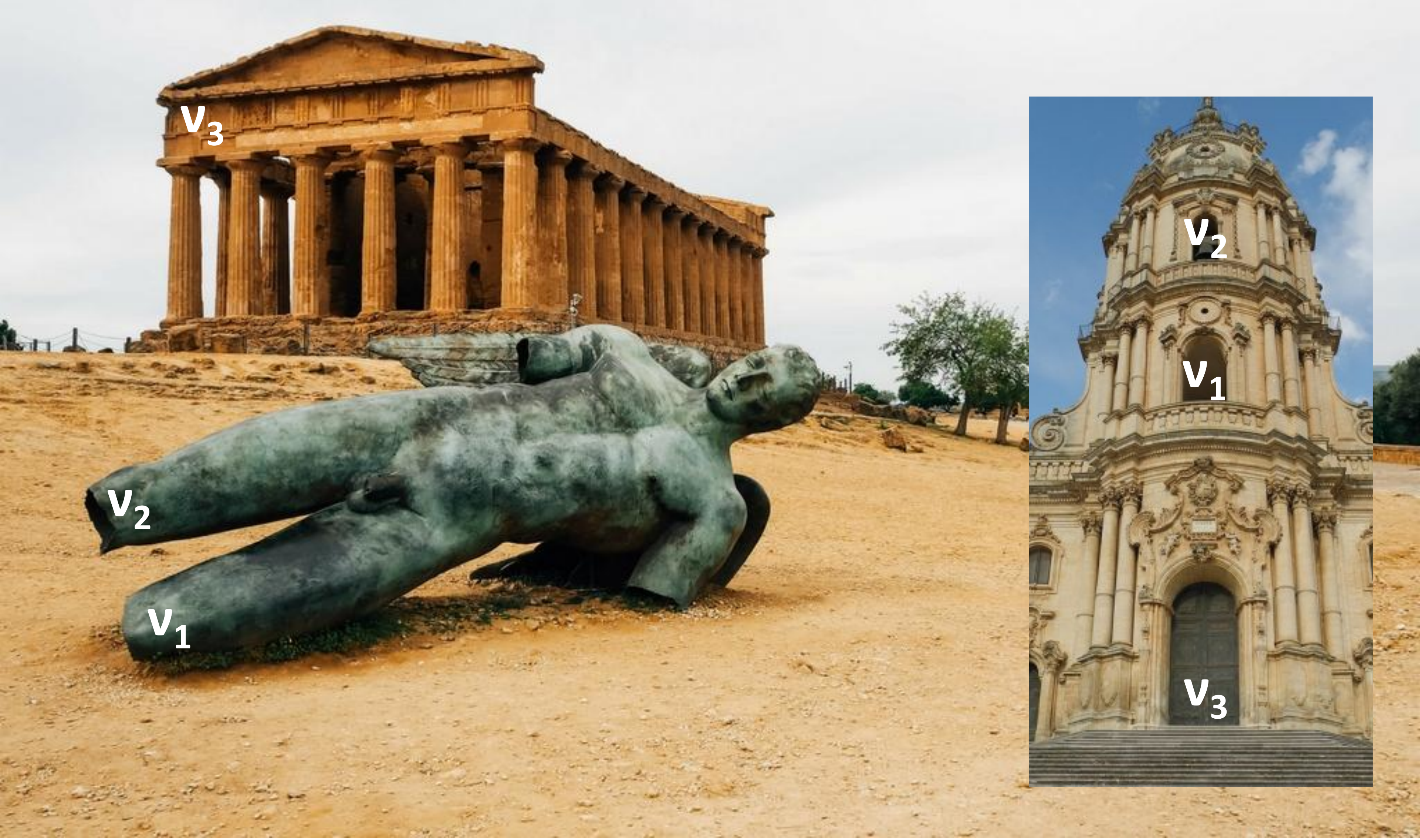
Measuring the Neutrino Mass Ordering in JUNO

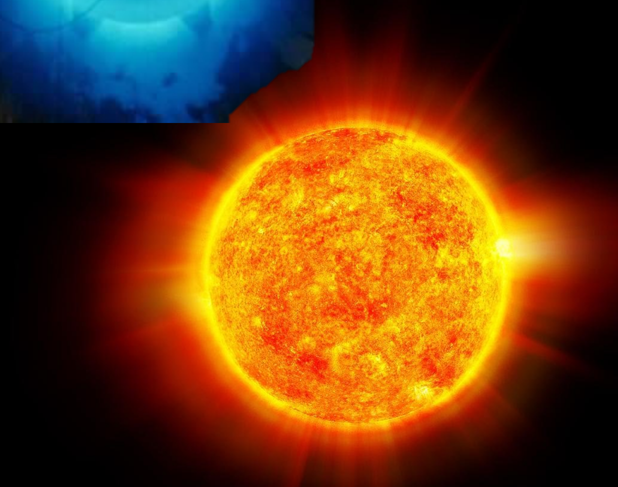


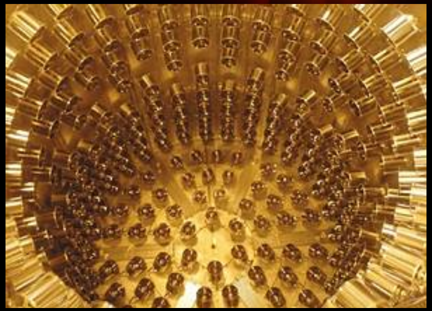
International School of Nuclear Physics
Erice, 16 Sep 2017

Michael Wurm
Uni Mainz

Outline

- **Neutrino mass ordering**
  - motivation
  - experimental methods
- **JUNO experiment**
  - signature of mass ordering
  - detector layout
  - systematic effects
  - other experimental inputs





Status of 3-flavor oscillations

$$\mathbf{U_{3\times3}} = \mathbf{U}_{\mathrm{PMNS}}$$

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

atmospheric mixing

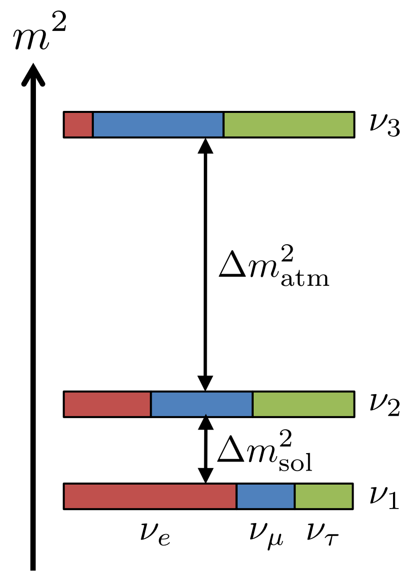
(maximal 45°?)

reactor mixing & CP violation

(small $\theta_{13}\approx 9°$, $\delta\approx -\pi$?)

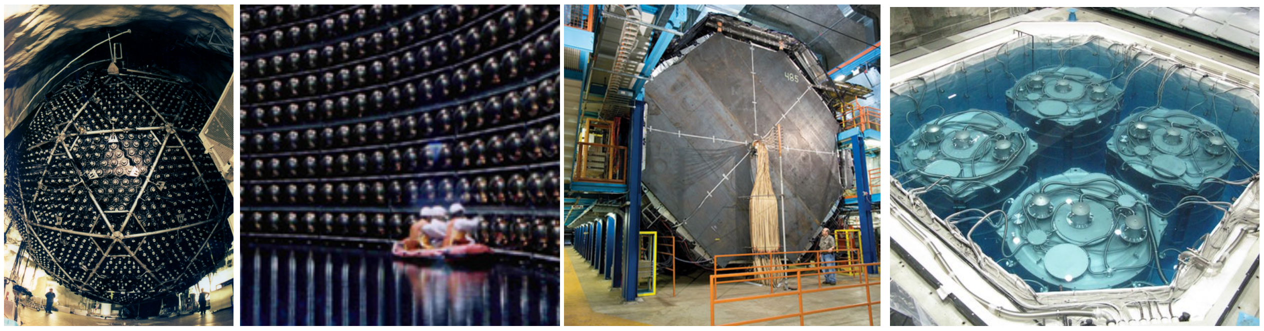
solar mixing

(large 33°)



mass squared differences :

- $\Delta m^2_{\mathrm{sol}} = \Delta m^2_{21}$ → *small splitting: +8x10^{-5} eV^2*
- $\Delta m^2_{\mathrm{atm}} = \Delta m^2_{32} \approx \Delta m^2_{31}$ → *large splitting: ±2.5x10^{-3} eV^2*



Open issues in 3-flavor mixing?

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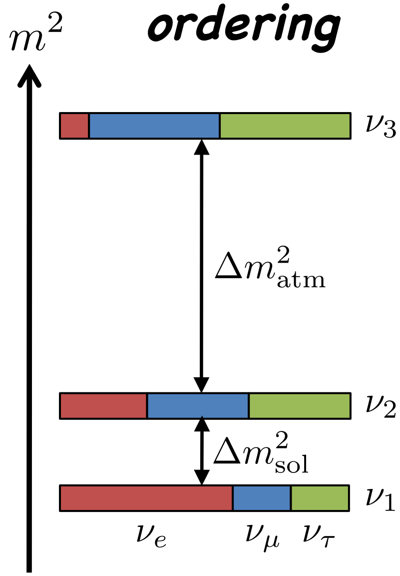
$$\mathbf{U_{3\times3}} = \mathbf{U}_{\mathrm{PMNS}}$$

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

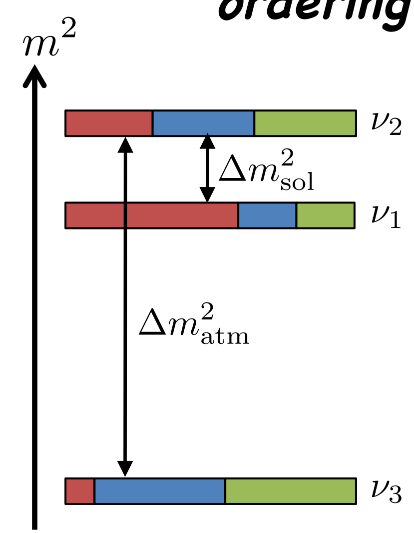
normal ordering



What is the

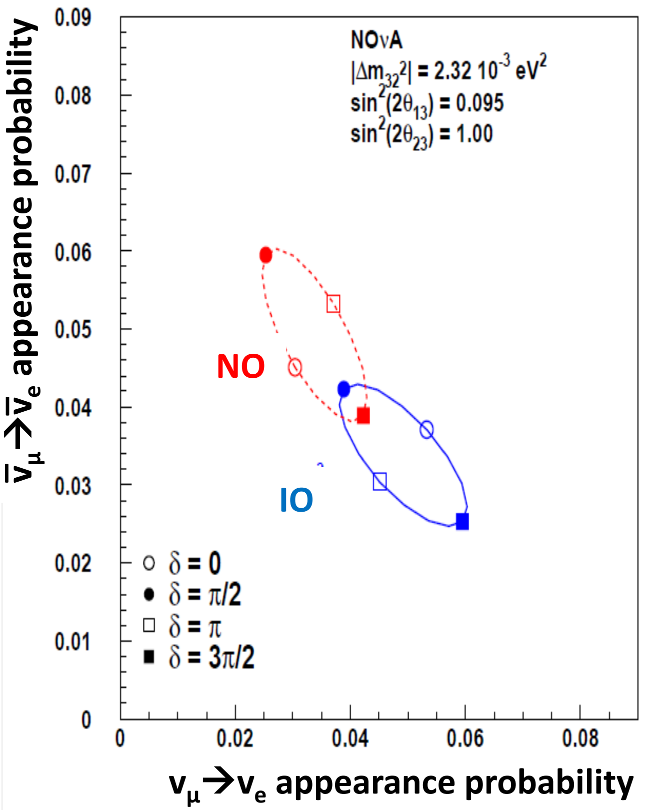
- **octant of θ_{23} ($\gtrless$45°)?**
- value of **CP-phase?**
- **mass ordering (MO)?** (sign of $\Delta m^2_{\mathrm{atm}}$)
- **unitarity of PMNS matrix** (sterile ν's)?

inverted ordering



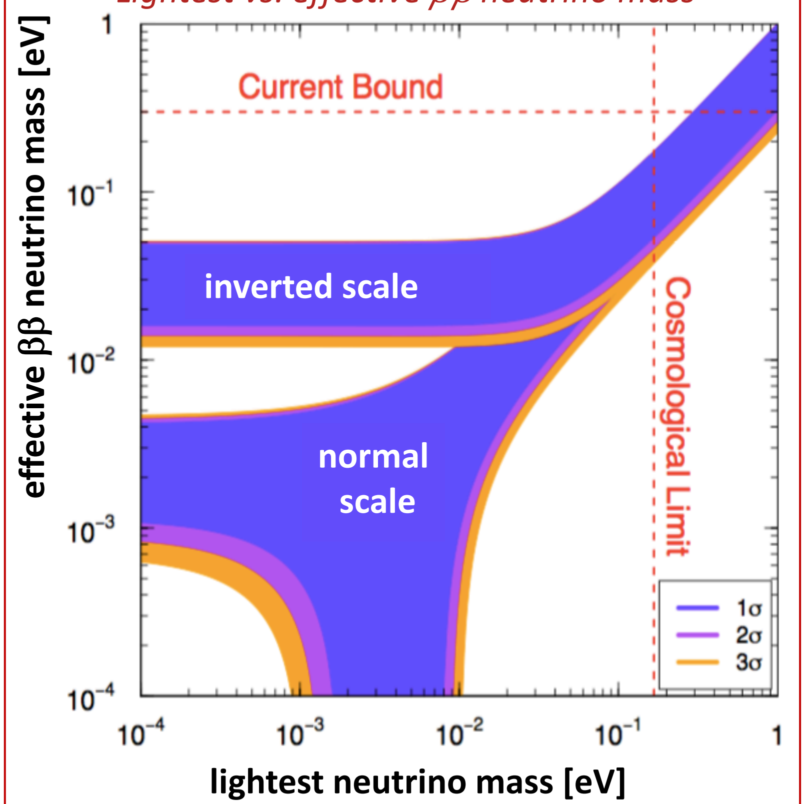
Implications of neutrino mass ordering

LBL: degeneracy of MO and δ_{CP}

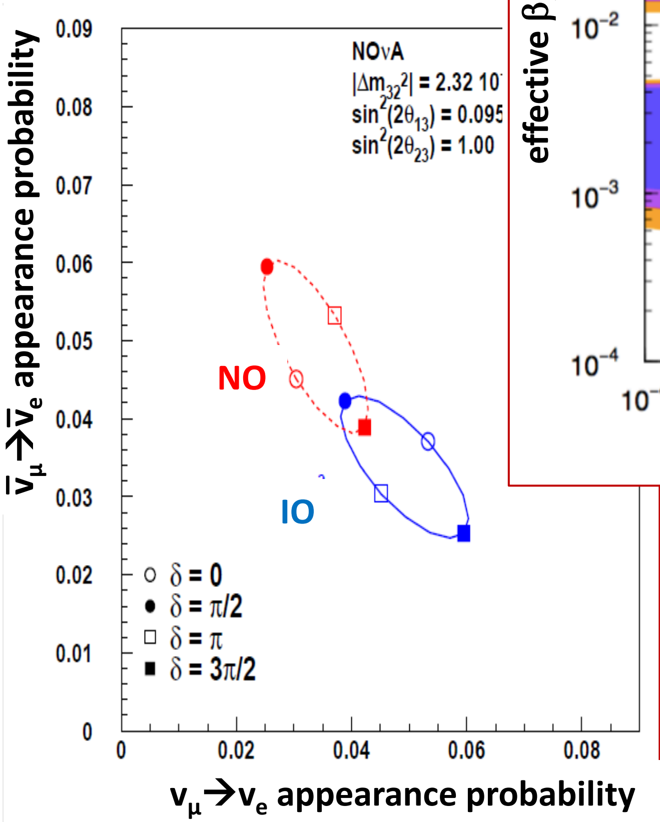


Implications of neutrino mass ordering

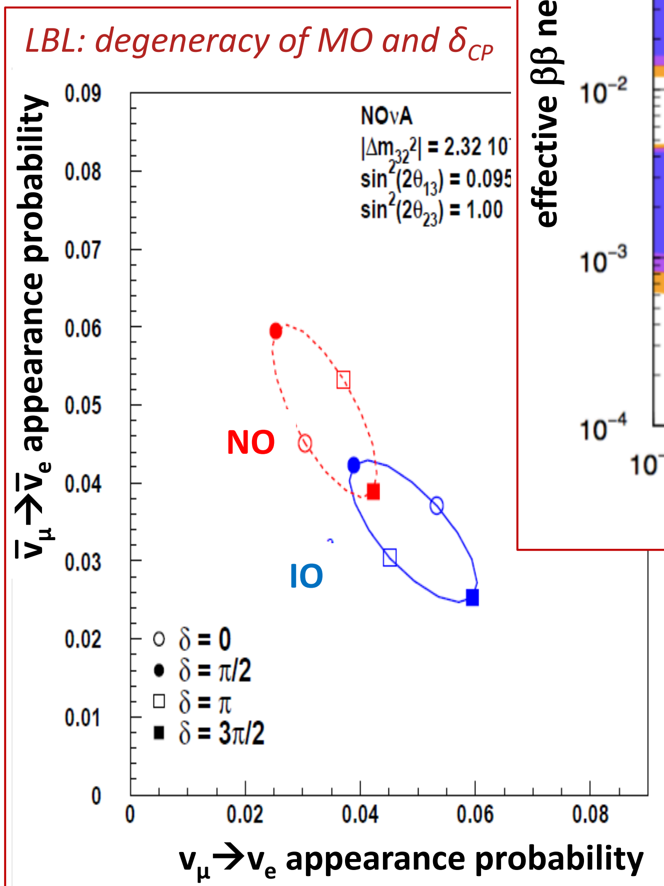
Lightest vs. effective $\beta\beta$ neutrino mass

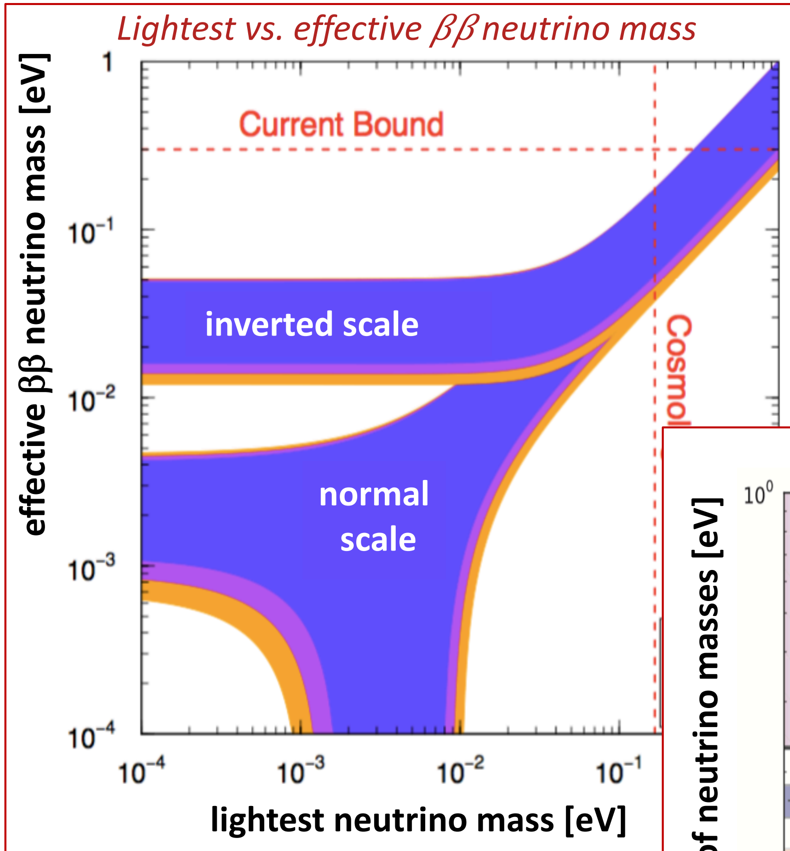


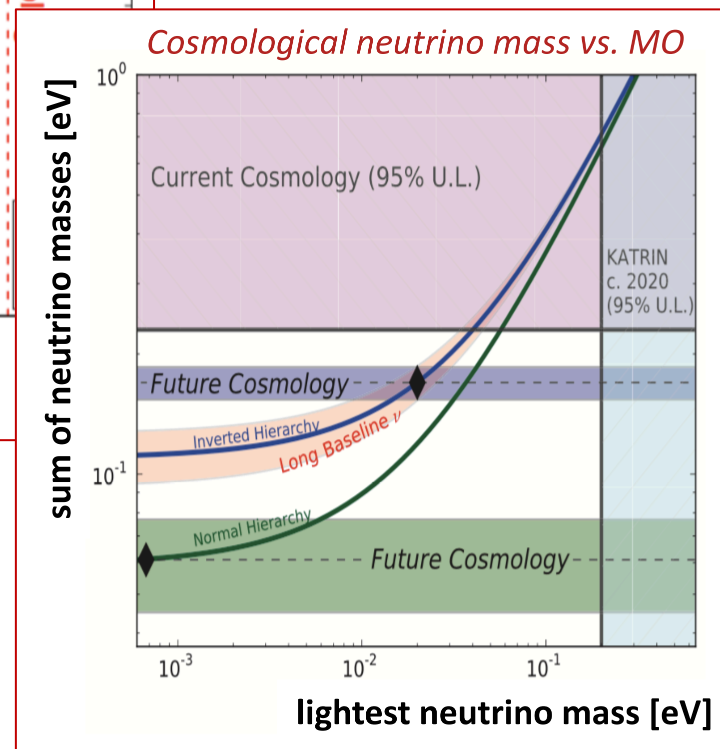
LBL: degeneracy of MO and δ_{CP}



Implications of neutrino mass ordering





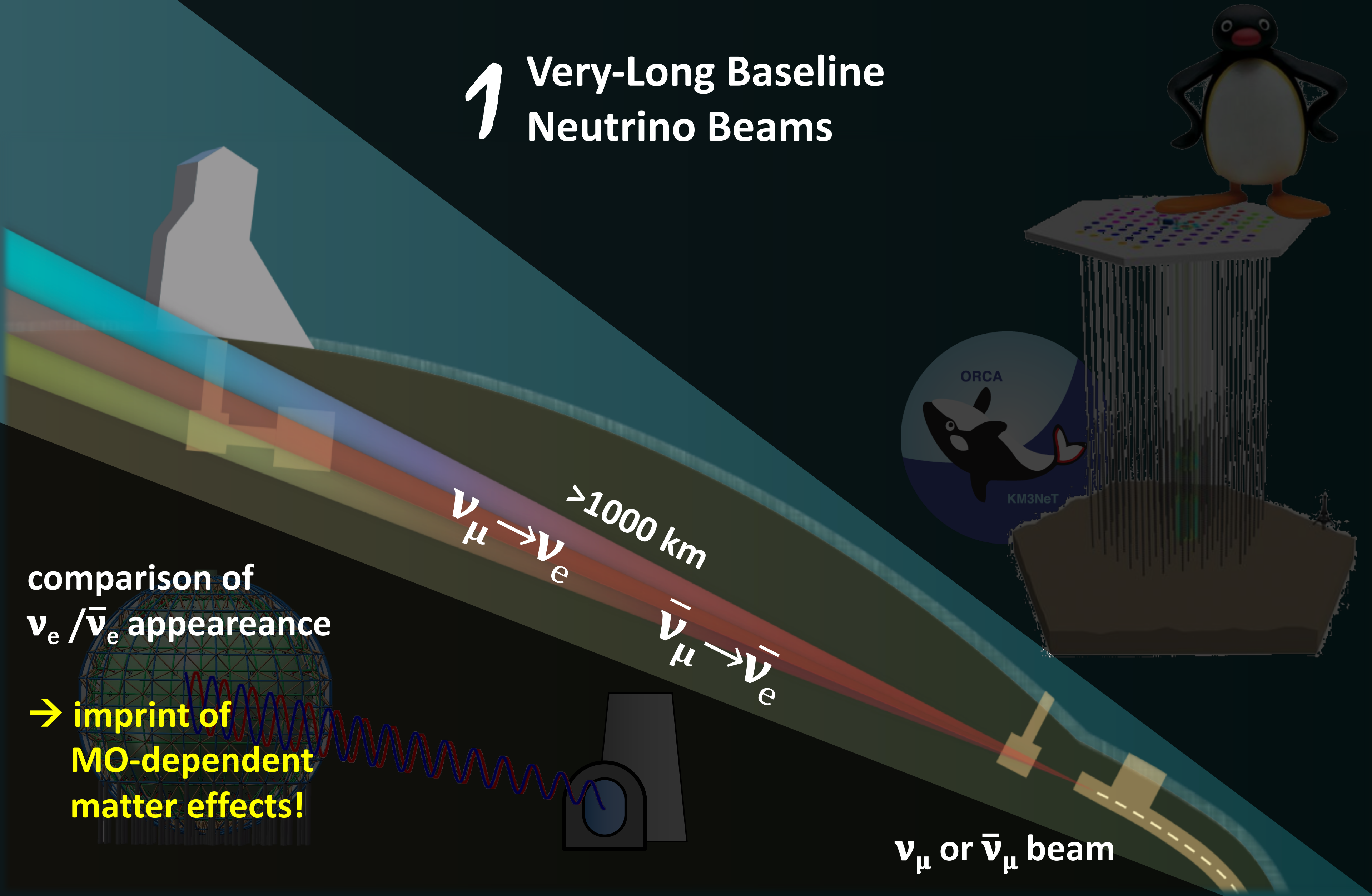


Concepts for MO measurement

1 Very-Long Baseline Neutrino Beams

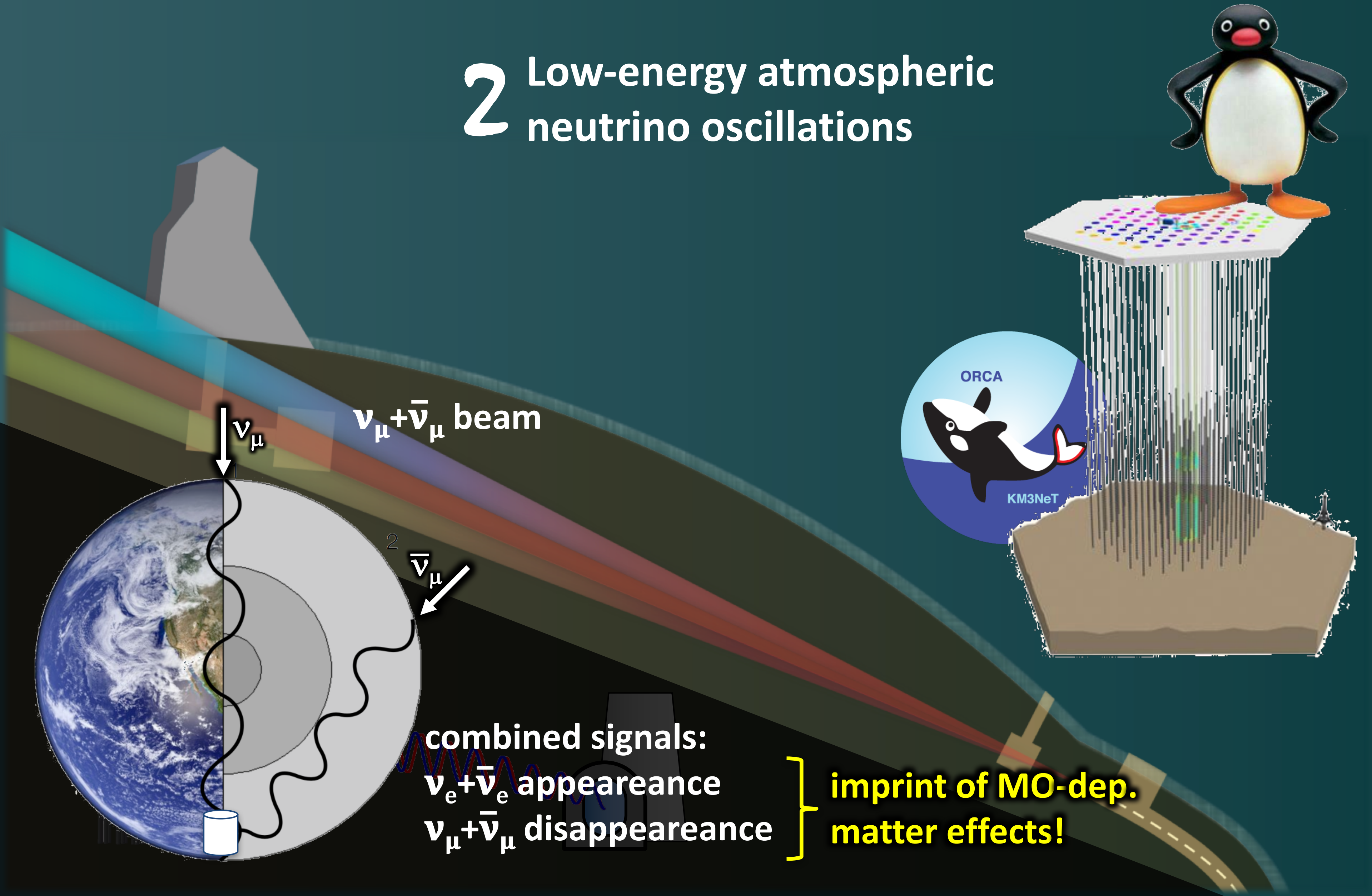
comparison of
ν_e / $\bar{\nu}_e$ appeareance

→ imprint of
MO-dependent
matter effects!



Concepts for MO measurement

2 Low-energy atmospheric neutrino oscillations

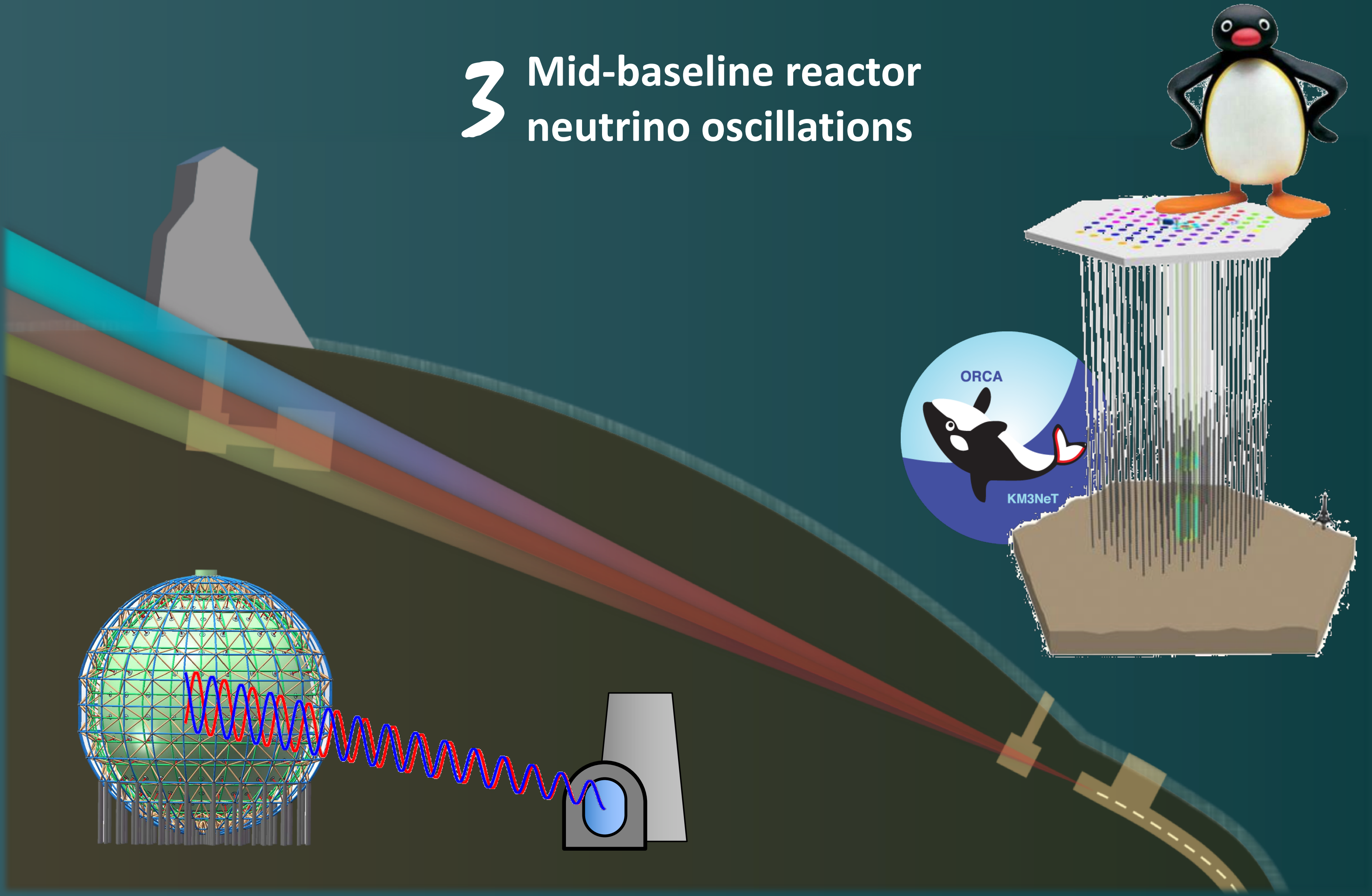


combined signals:
$\nu_e+\bar{\nu}_e$ appeareance
$\nu_\mu+\bar{\nu}_\mu$ disappeareance

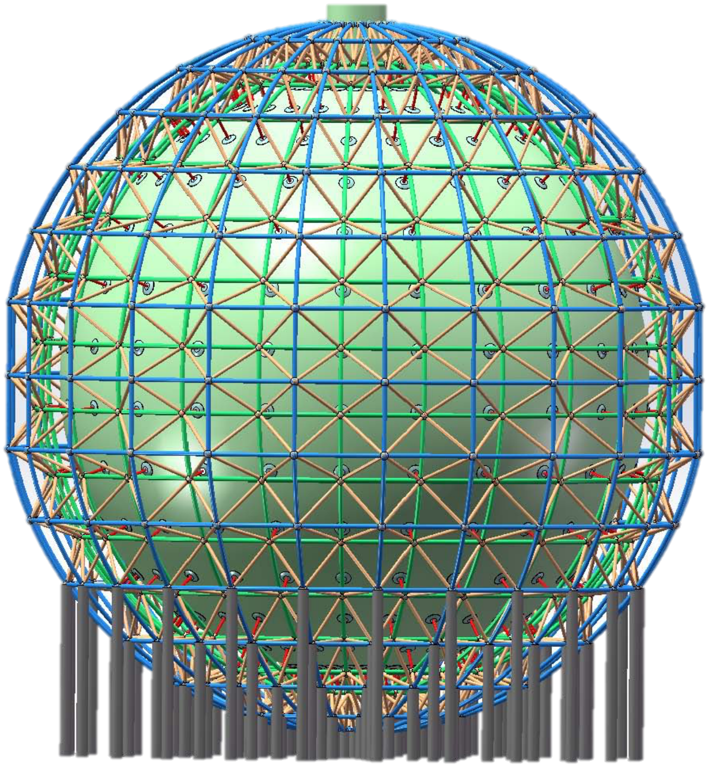
imprint of MO-dep. matter effects!

Concepts for MO measurement

3 Mid-baseline reactor neutrino oscillations



JUNO in a nutshell



JUNO characteristics

- liquid scintillator detector: 20ktons
- number of PMTs: 17,000 (20'')
- energy resolution: 3% at 1MeV
- rock overburden: 700m
- distance to reactors: 53km

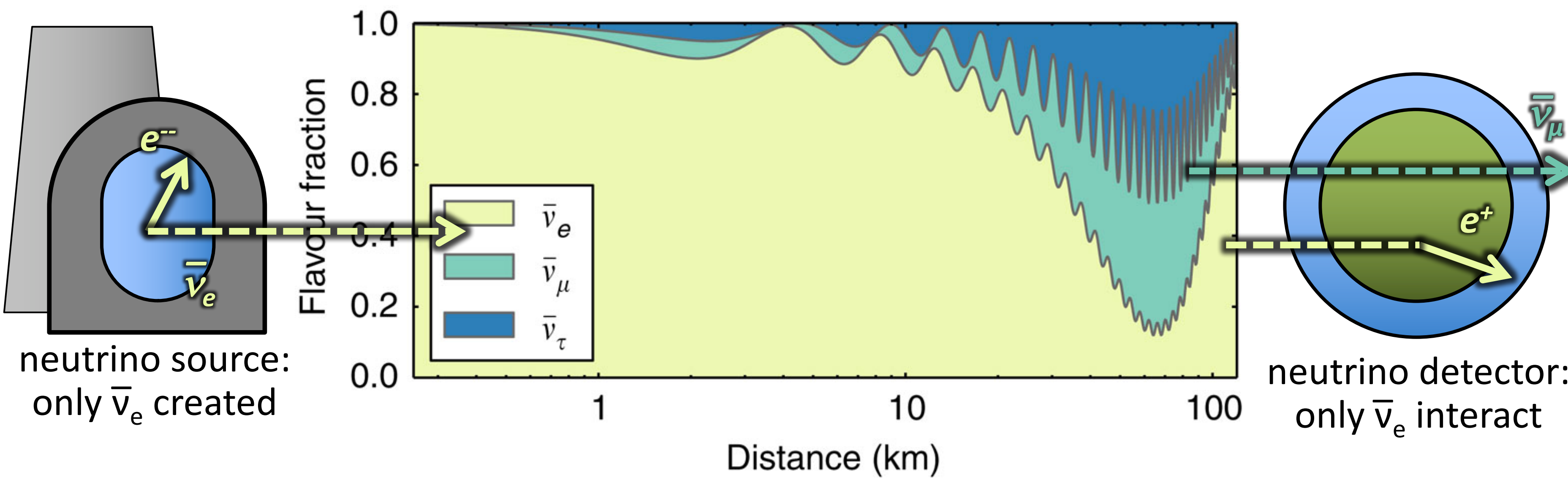
Physics objectives

- neutrino mass hierarchy
- sub-% measurement of solar oscillation parameters
- astrophysical neutrinos
- nucleon decay
- eV-scale sterile neutrinos

Reactor antineutrino oscillations

Common three-flavor reactor electron-antineutrino survival probability:

$$P_{ee} = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}}{4E}\right) - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}}{4E}\right)$$



neutrino source: only $\bar{\nu}_e$ created

neutrino detector: only $\bar{\nu}_e$ interact

→ oscillation parameters are extracted from **$\bar{\nu}_e$ disappearance pattern**

→ however, the formula above implicitly assumes $\Delta m^2_{31} = \Delta m^2_{32}$

Reactor $\bar{\nu}$ oscillations: full 3-flavor picture

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Survival probability

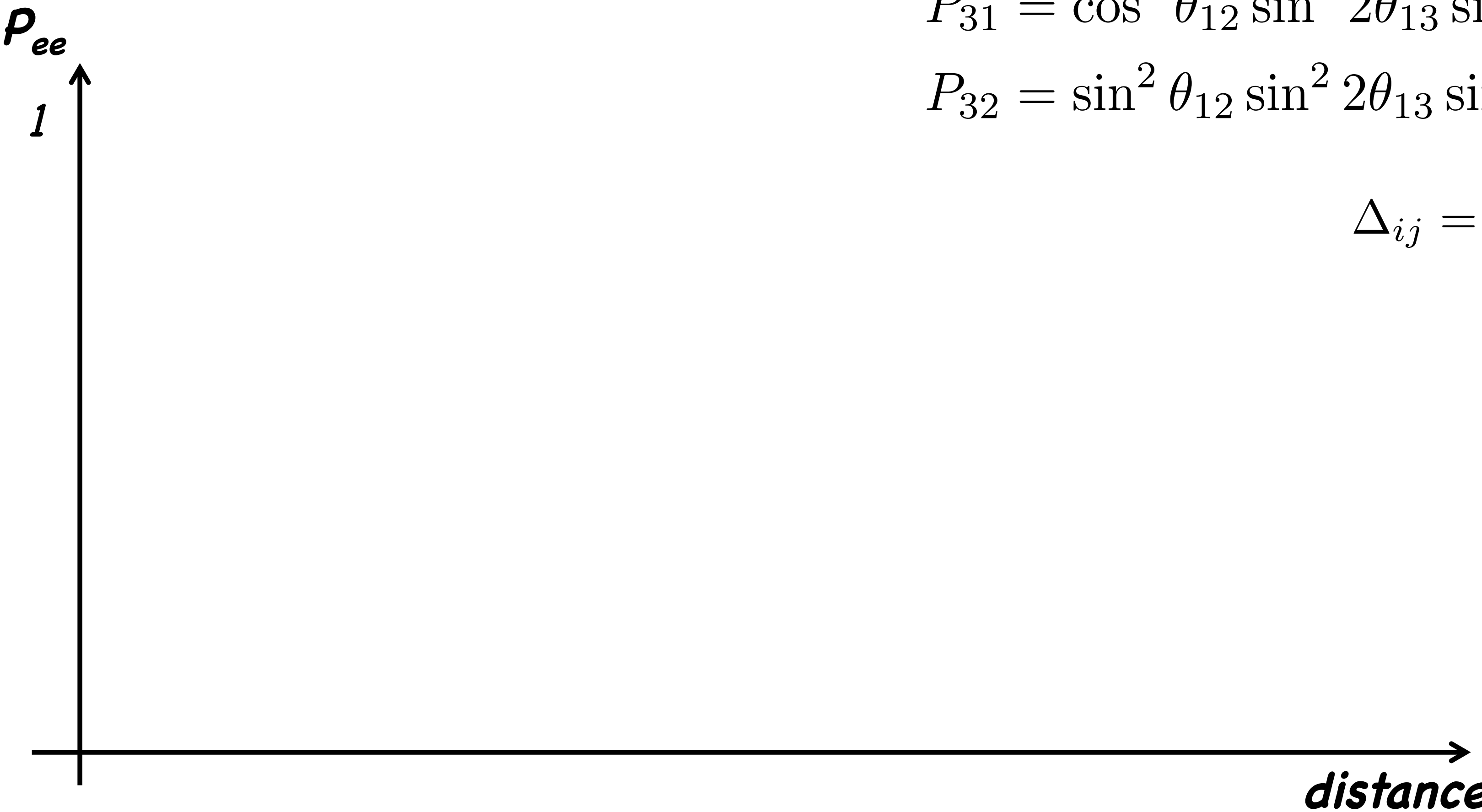
$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

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



Reactor $\bar{\nu}$ oscillations: full 3-flavor picture

JG|U

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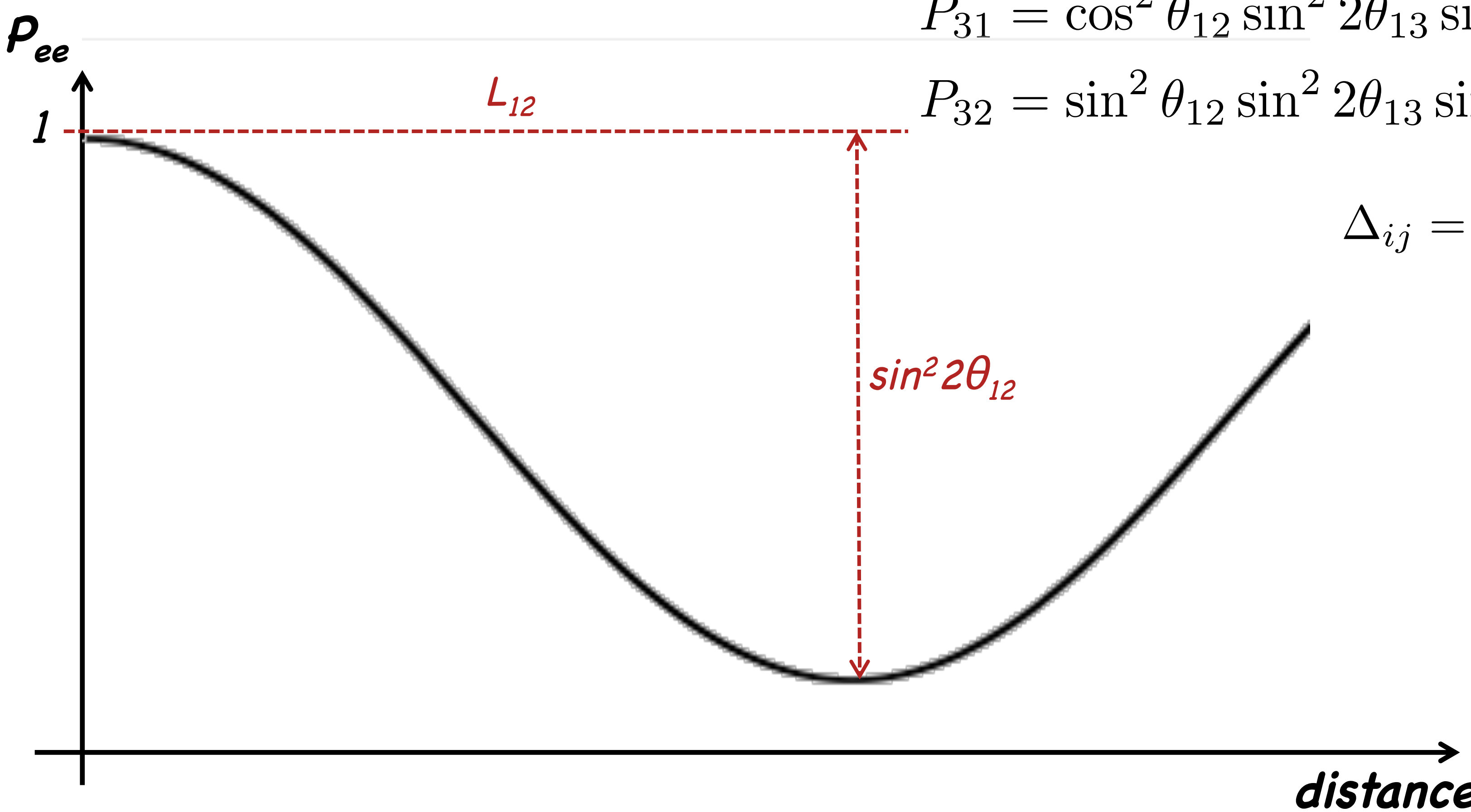

Reactor $\bar{\nu}$ oscillations: full 3-flavor picture

→ subdominant oscillation pattern depends on phase terms of P_{31}/P_{32}

→ depends on **relative sizes** of Δm^2_{32} and Δm^2_{31}

Survival probability

$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

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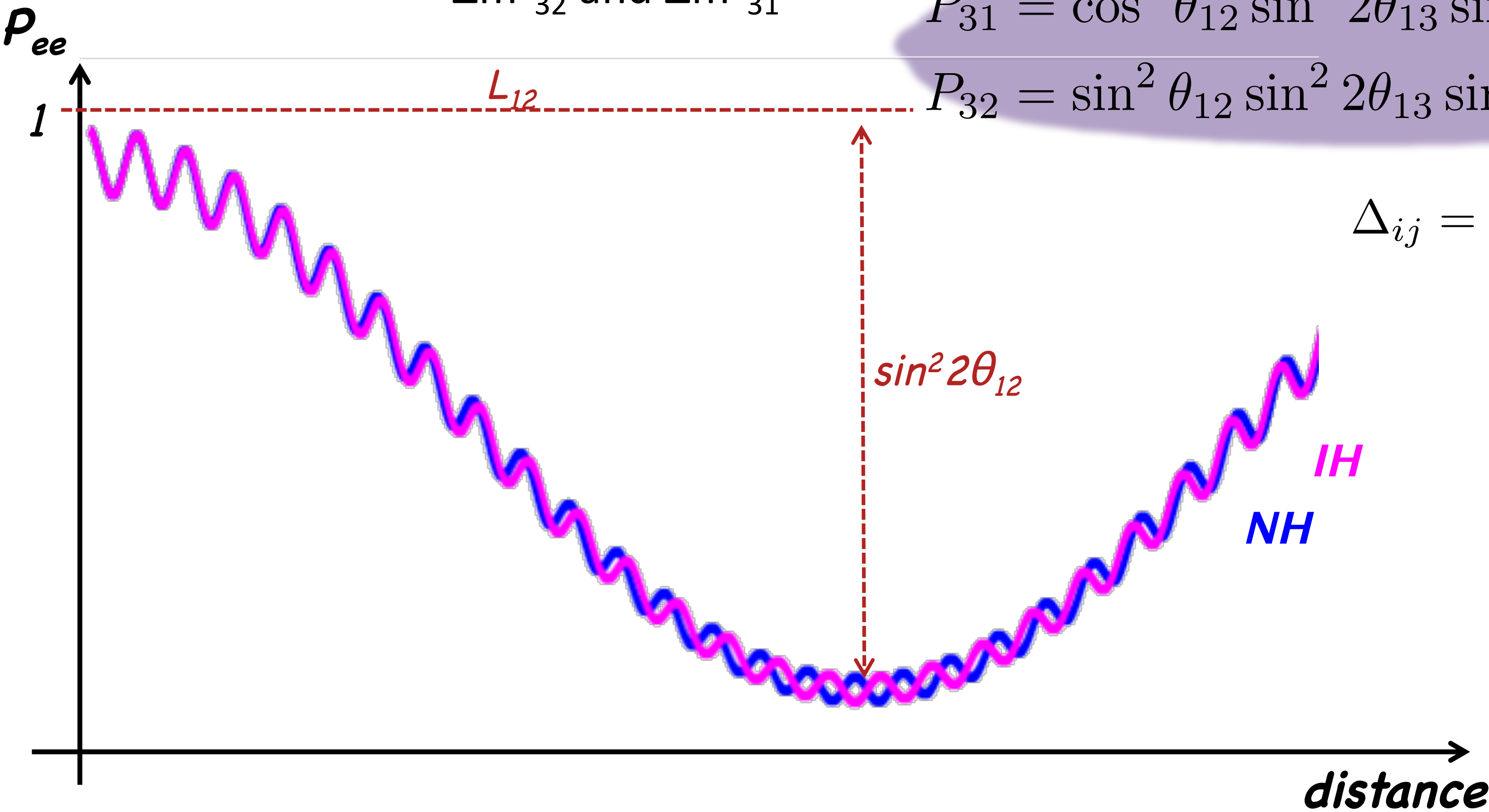
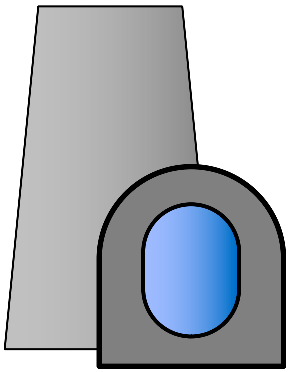
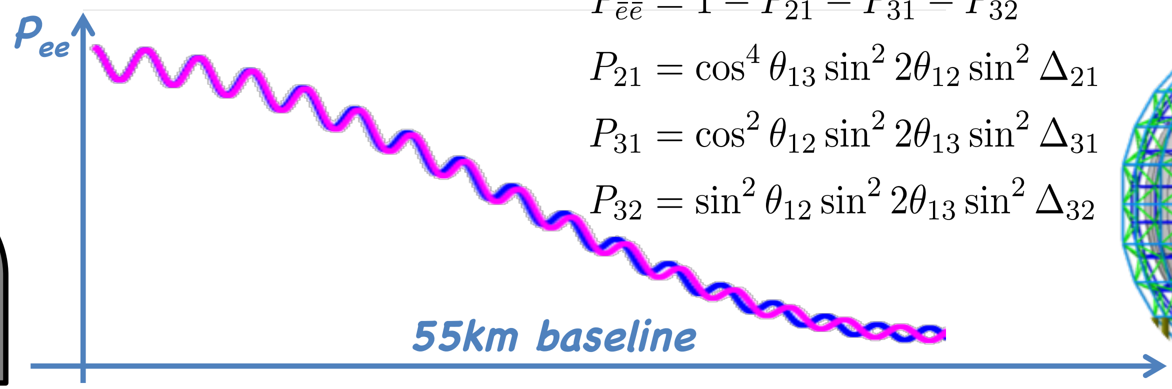


Oscillation pattern at 1st solar maximum





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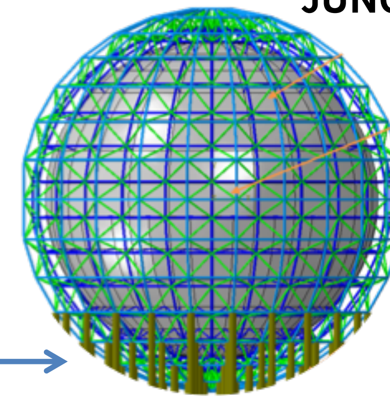
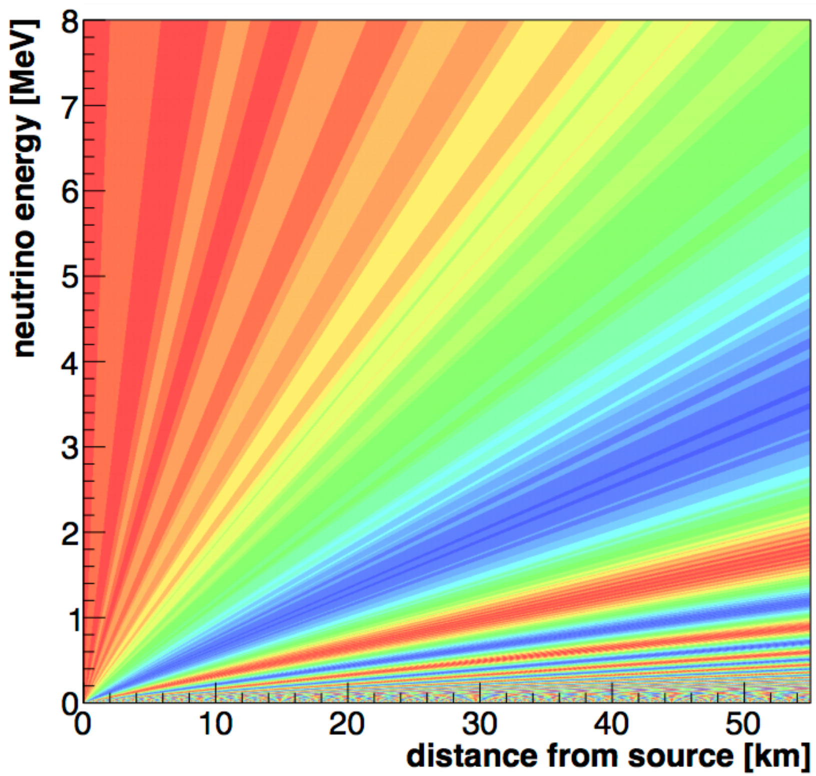
JUNO



Nuclear reactors at
- *Yangjiang*
- *Taishan*

(so. China)

Total power: (eventually) 38 GW



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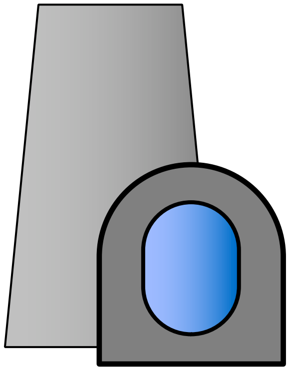

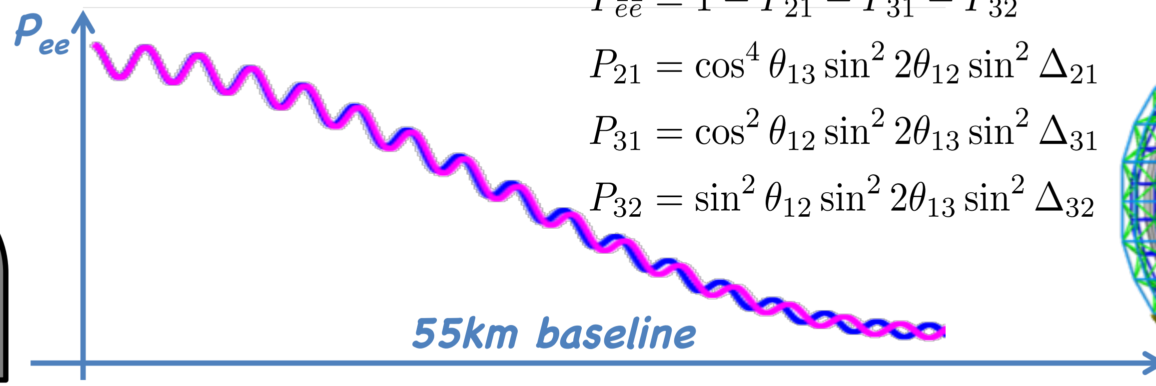

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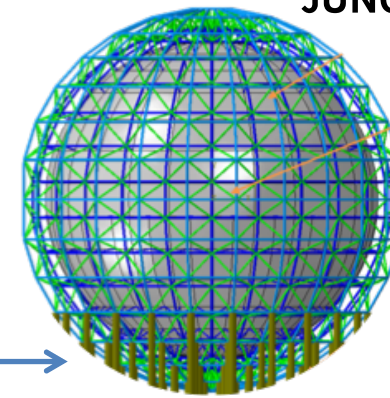

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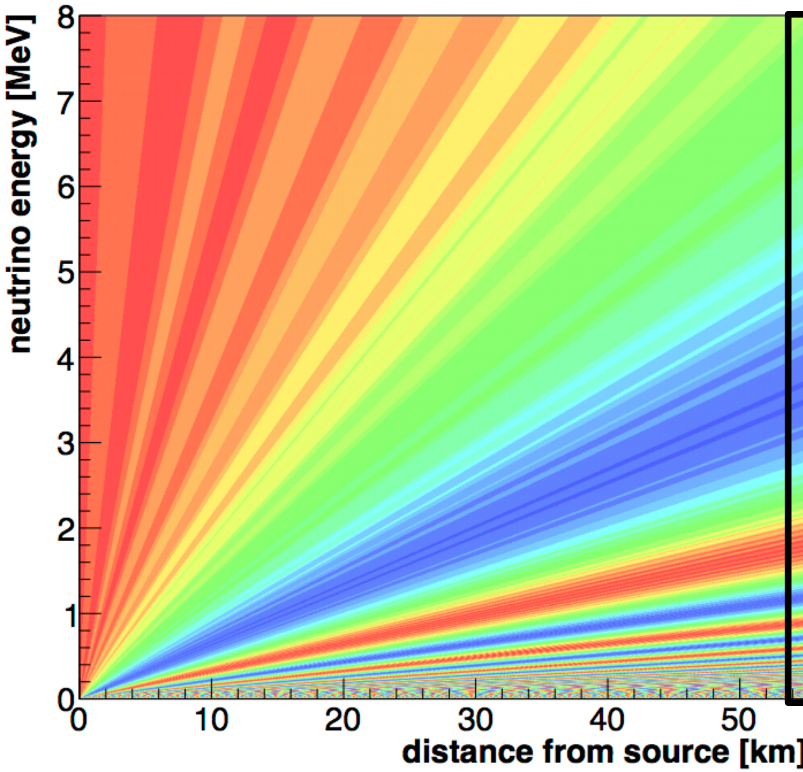

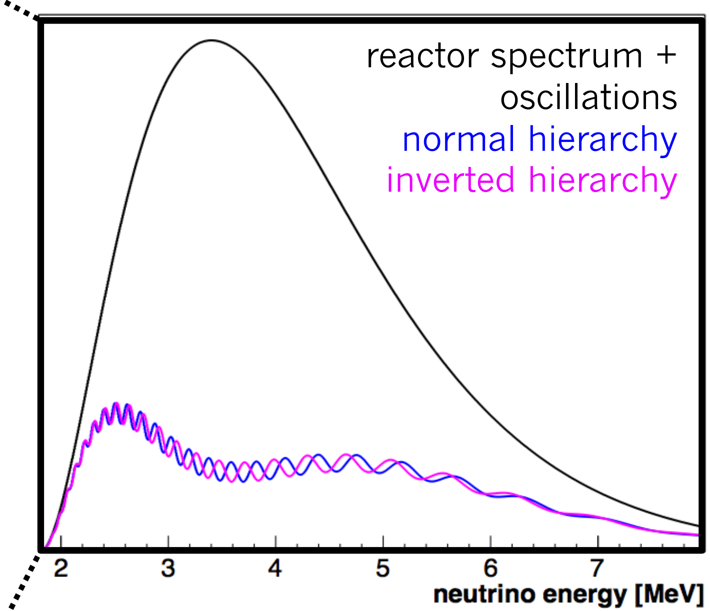

→ ***MH from spectral wiggles***

Basic detector requirements for JUNO

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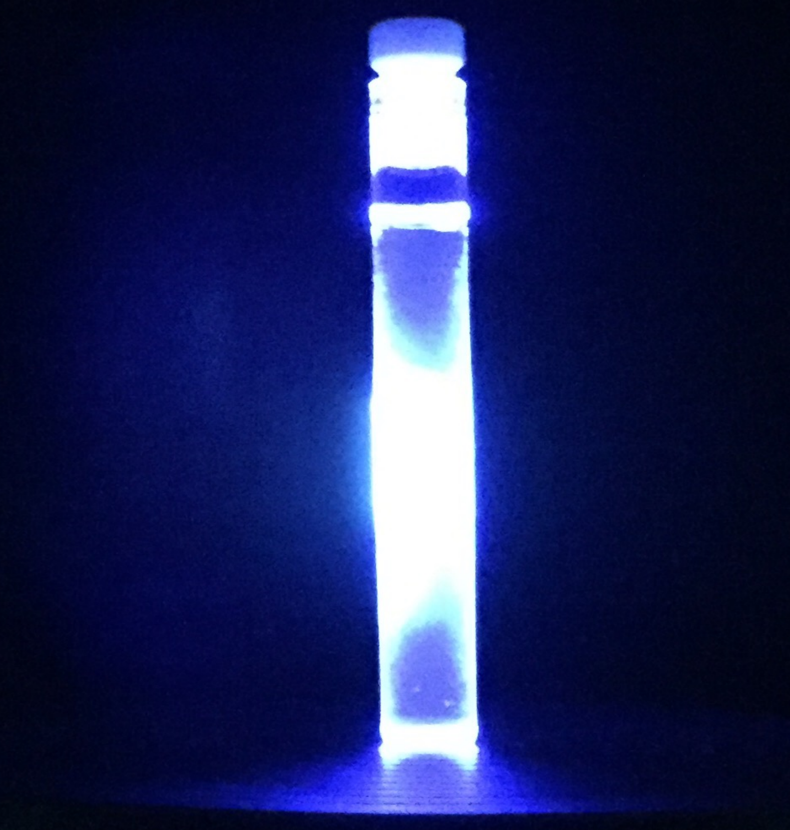
- reactor antineutrinos at MeV energies
  → **Liquid-scintillator detector**
  → Detection by inverse beta decay

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

- signature in position of spectral wiggles
  → **~3% energy resolution** at 1 MeV
  → photoelectron yield: **~1,100 pe/MeV**
- large distance to source and high-statistics measurement
  → large target mass: **20 kilotons of LAB**
- cosmogenic background
  → rock overburden of **~700 m**



JUNO Experimental Setup

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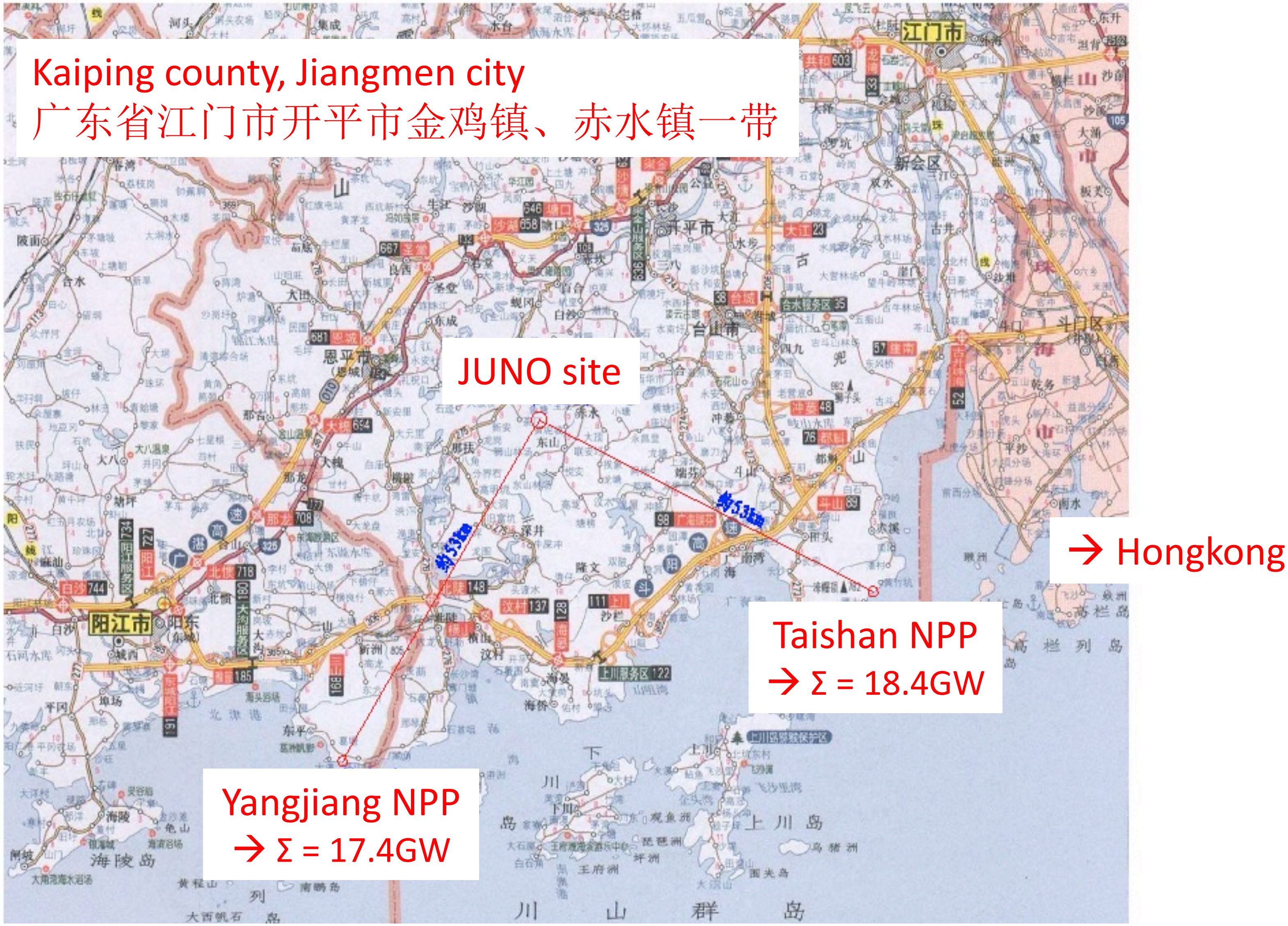
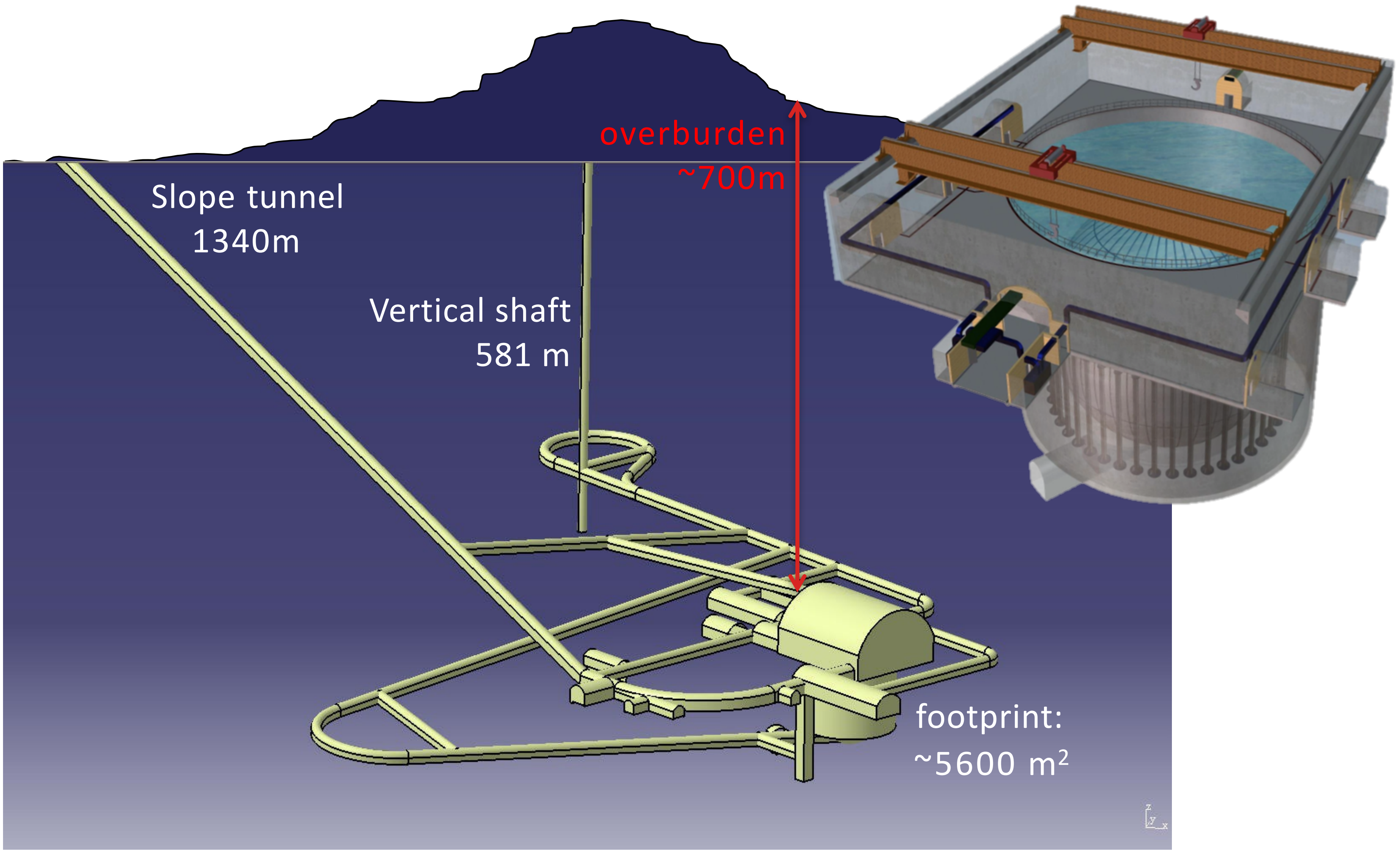
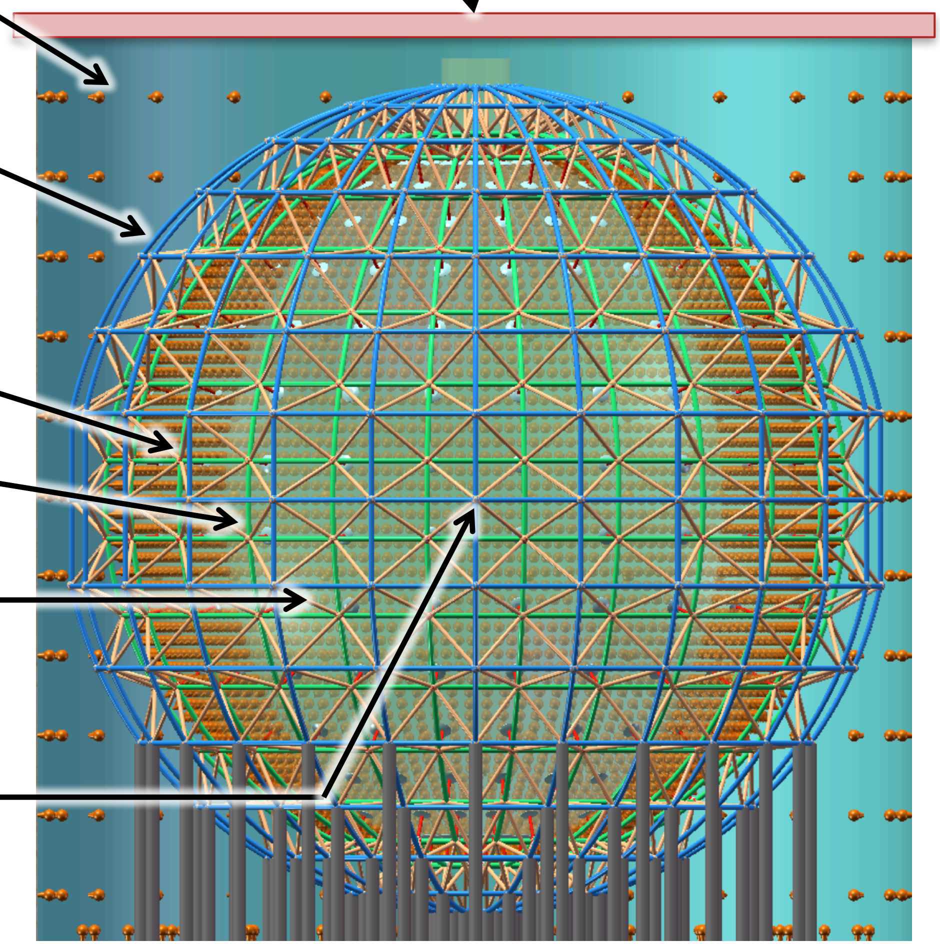


New underground laboratory



JUNO Detector layout



Outer water tank
Muon Cherenkov veto

Top muon veto
Scintillator panels

Steel support structure
optical separation

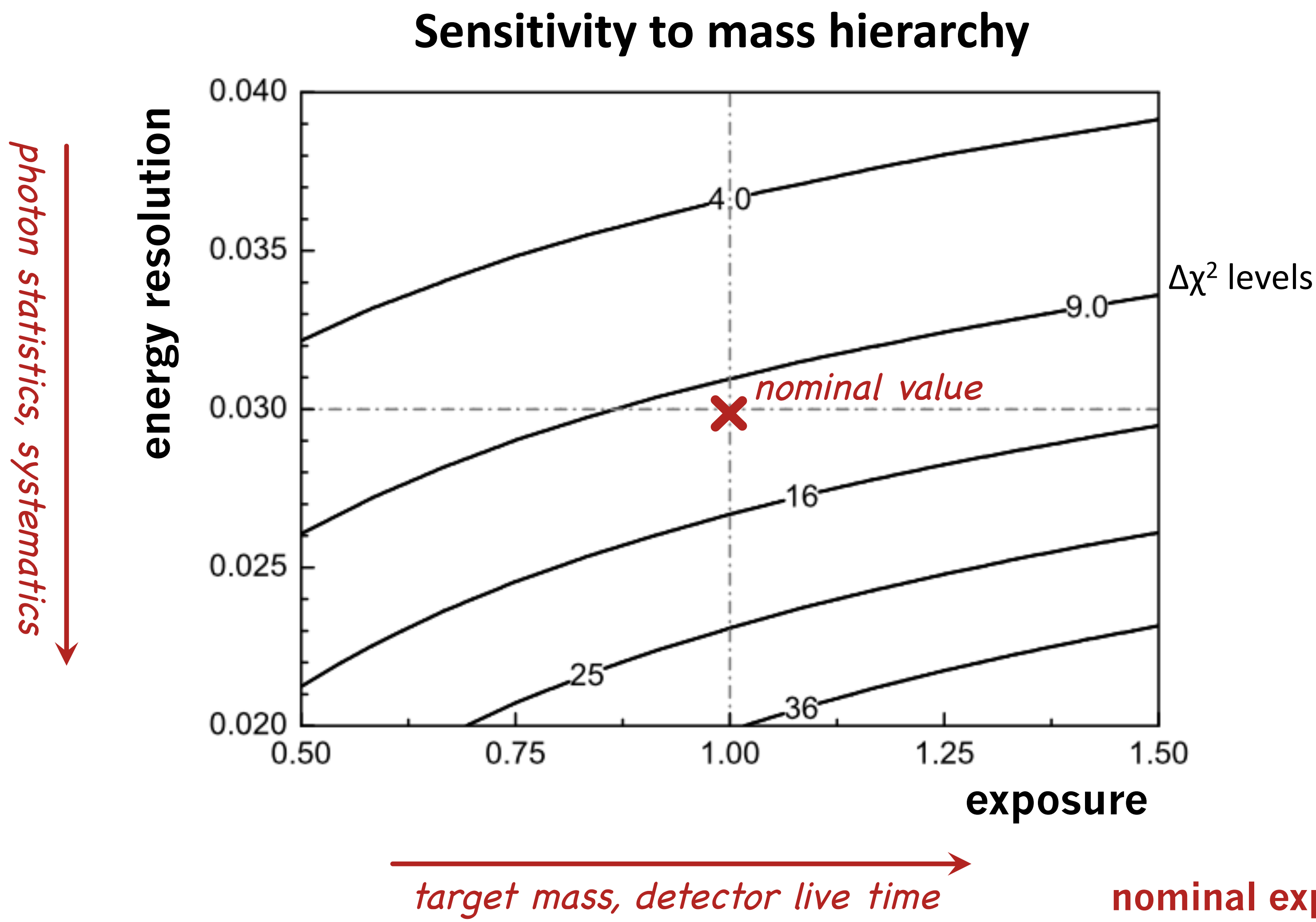
17,000 PMTs (20‘‘)

Water buffer

Acrylic sphere
diameter: 35.4m

Liquid scintillator
20 kt of LAB

Sensitivity to mass ordering [1]

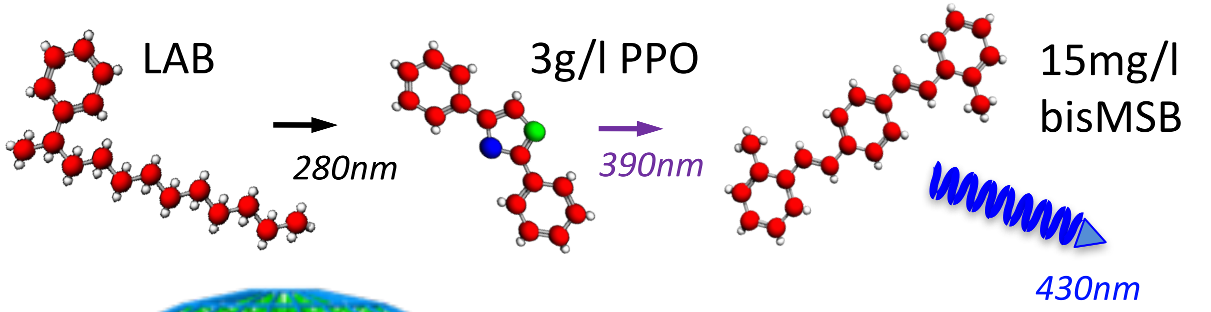


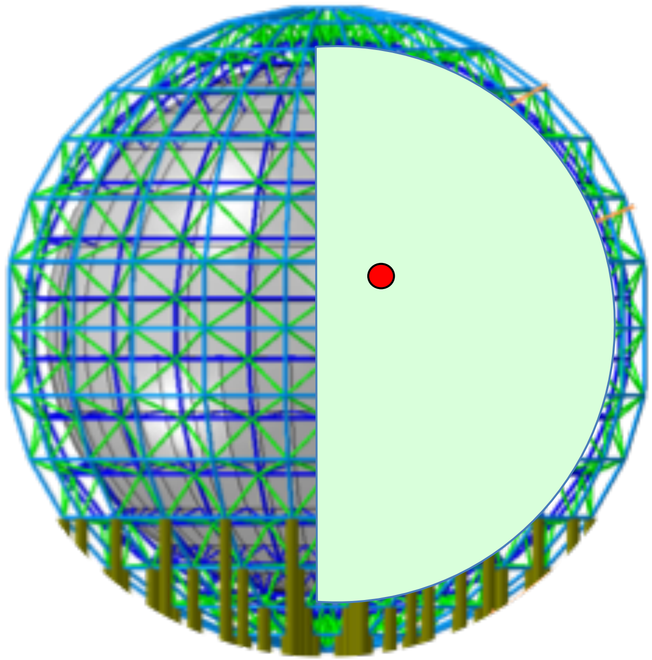
nominal exposure

- 36 GW x 6 years x 20kt
- 73% IBD efficiency

Energy resolution: Photon statistics

Scintillator light yield:
>10^4 photons per MeV





Energy resolution: Photon statistics

Scintillator light yield:
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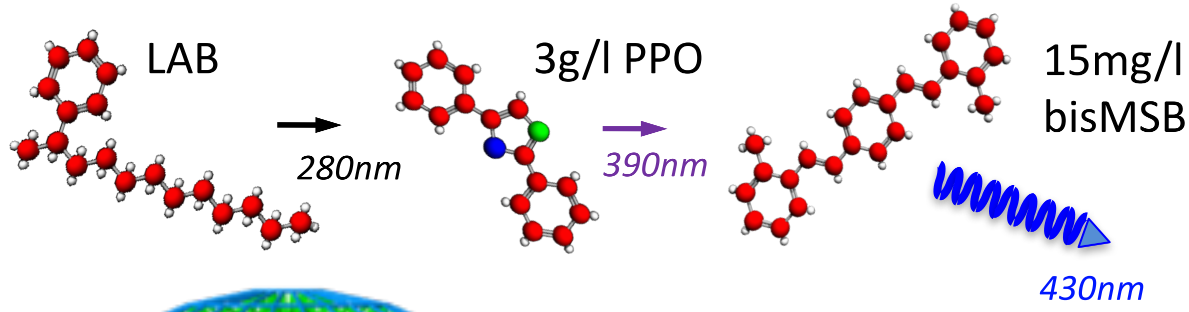
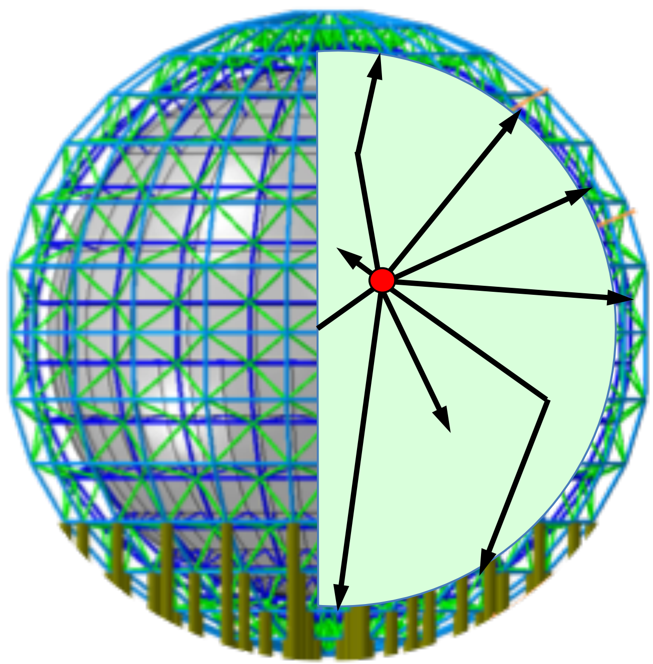
Light absorption in the liquid scintillator





Energy resolution: Photon statistics

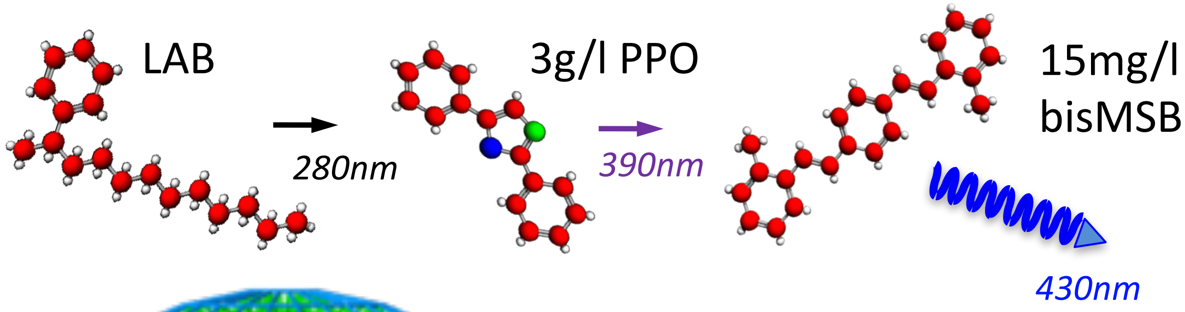
Scintillator light yield:
>10^4 photons per MeV

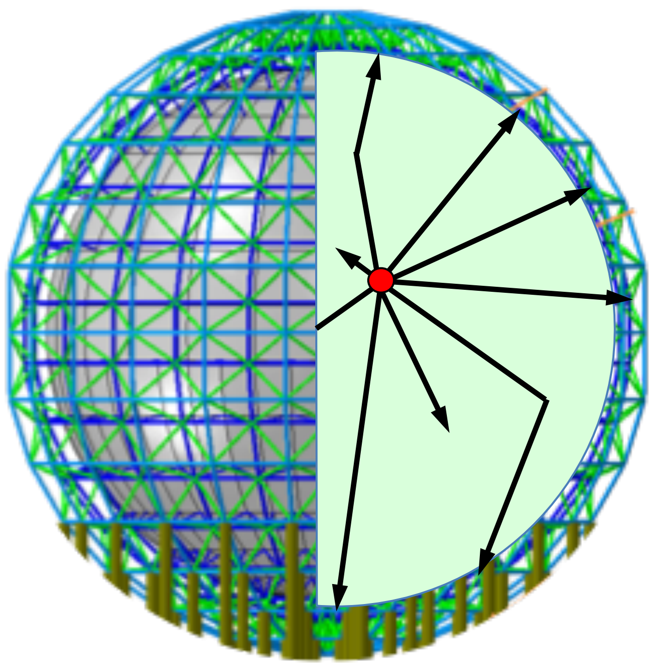
↓

Light absorption in the liquid scintillator

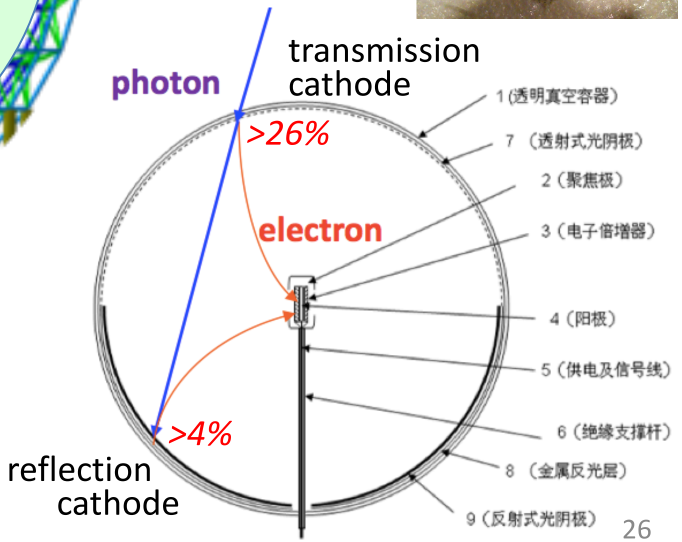
↓

PMT coverage (75%)
detection efficiency (>30%)





20'' MCP-PMT



Energy resolution: Photon statistics

Scintillator light yield:
>10[4] photons per MeV

↓

Light absorption in the liquid scintillator

↓

PMT coverage (75%)
detection efficiency (>30%)

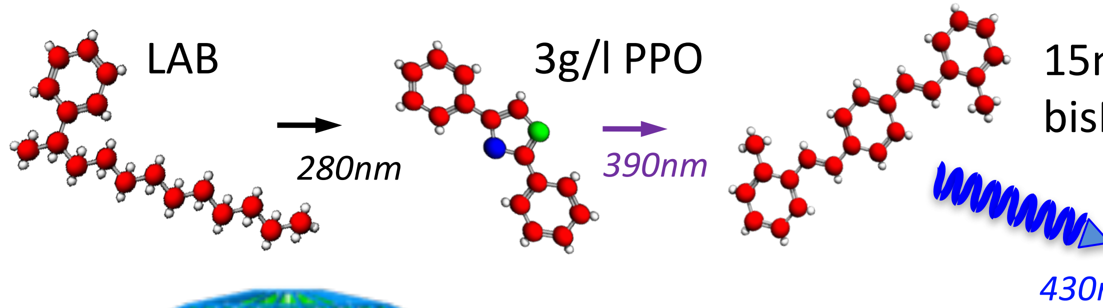
↓

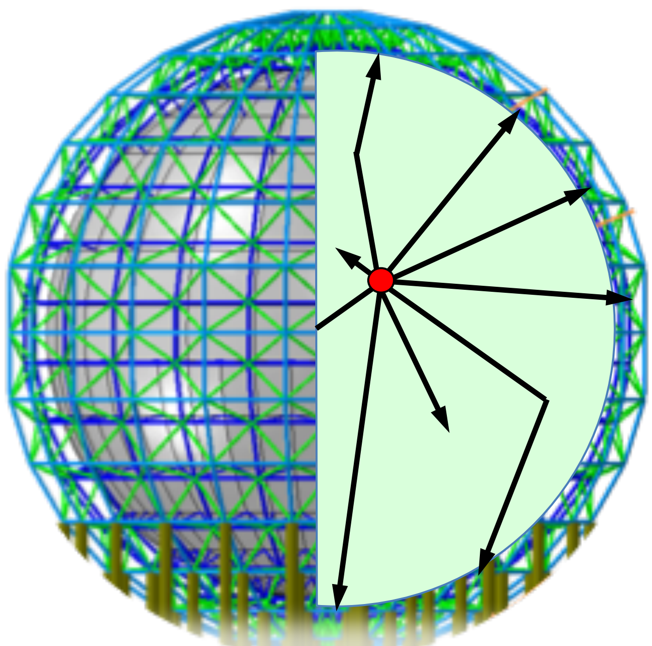
Photoelectron yield:
>1100 pe/MeV

→

Energy resolution:

$$\frac{\Delta E}{E} \sim \frac{1}{\sqrt{N_{pe}}} \leq \frac{3\%}{\sqrt{E_{[MeV]}}}$$





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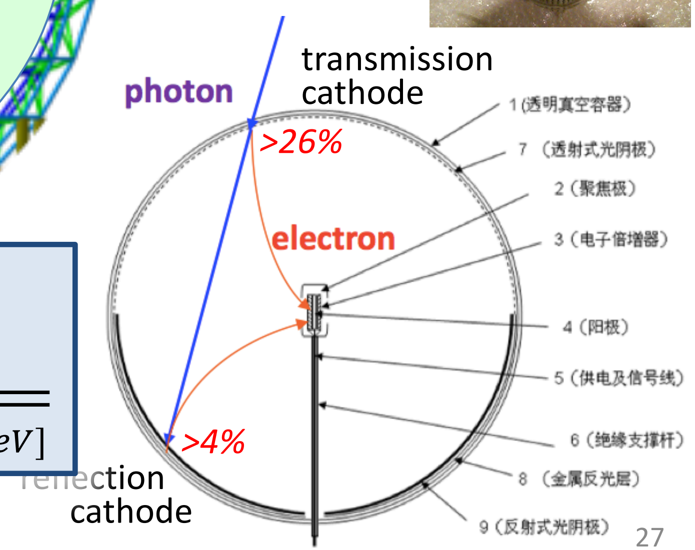

Energy resolution: Systematic effects

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Energy resolution function

$$\frac{\Delta E}{E} = \sqrt{\frac{a^2}{E} + b^2 + \frac{c^2}{E^2}}$$

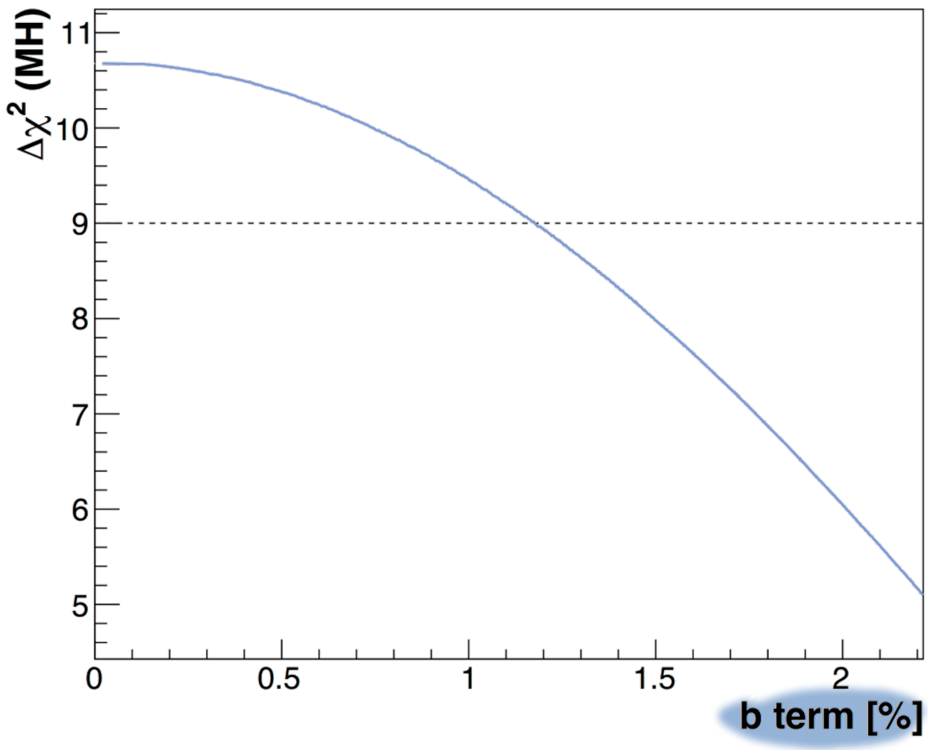
a term:

stochastic term (*photon statistics*)

b & c terms:

systematic contributions (*detector effects*)

- PMT dark noise
- linearity of electronics
- position reconstruction uncertainty
- ...



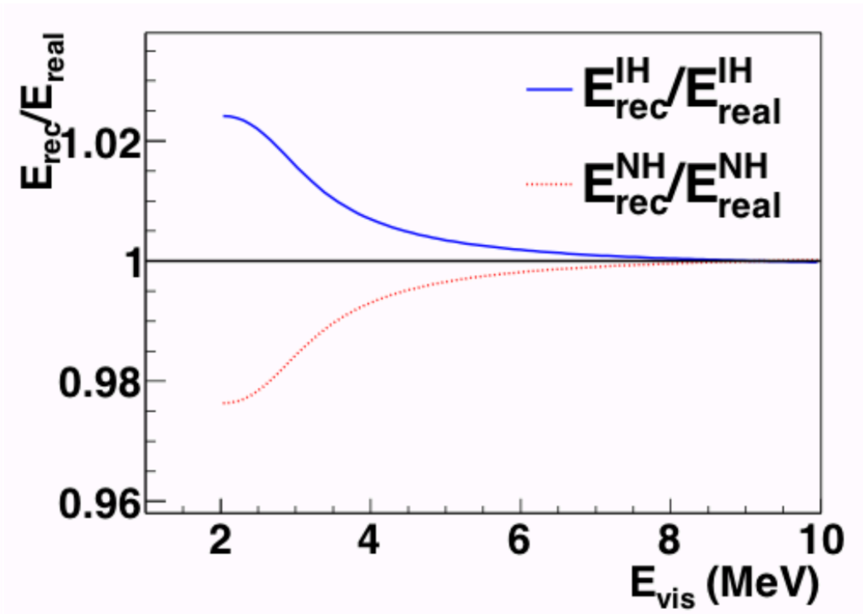
→ **calibrations** w/ radioactive sources deployed in LS (γ's, e^+, AmBe for n's etc.)

→ **multi-calorimetry** with small PMTs ...

Energy scale non-linearities

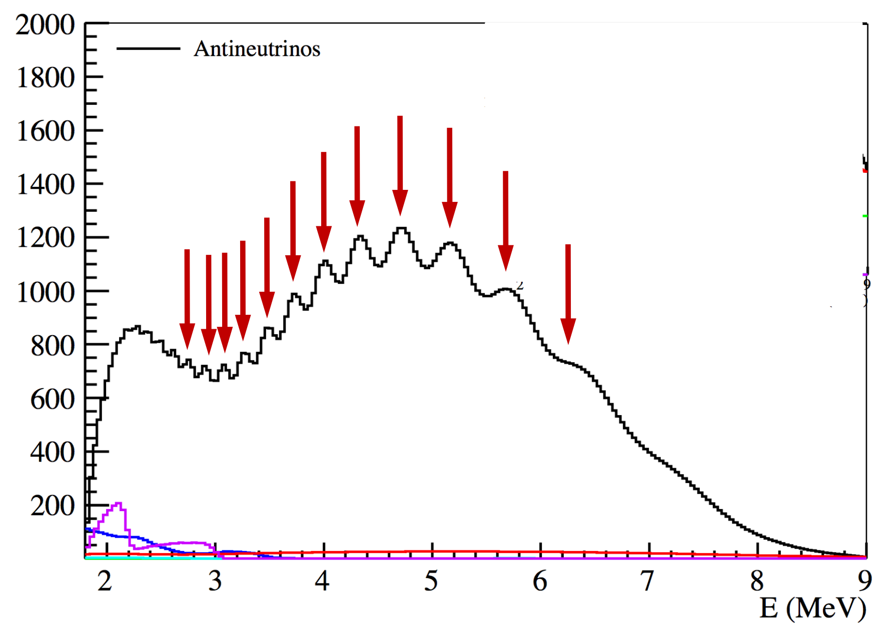
→ potentially very dangerous

example of non-linearity curves canceling the signature of MO



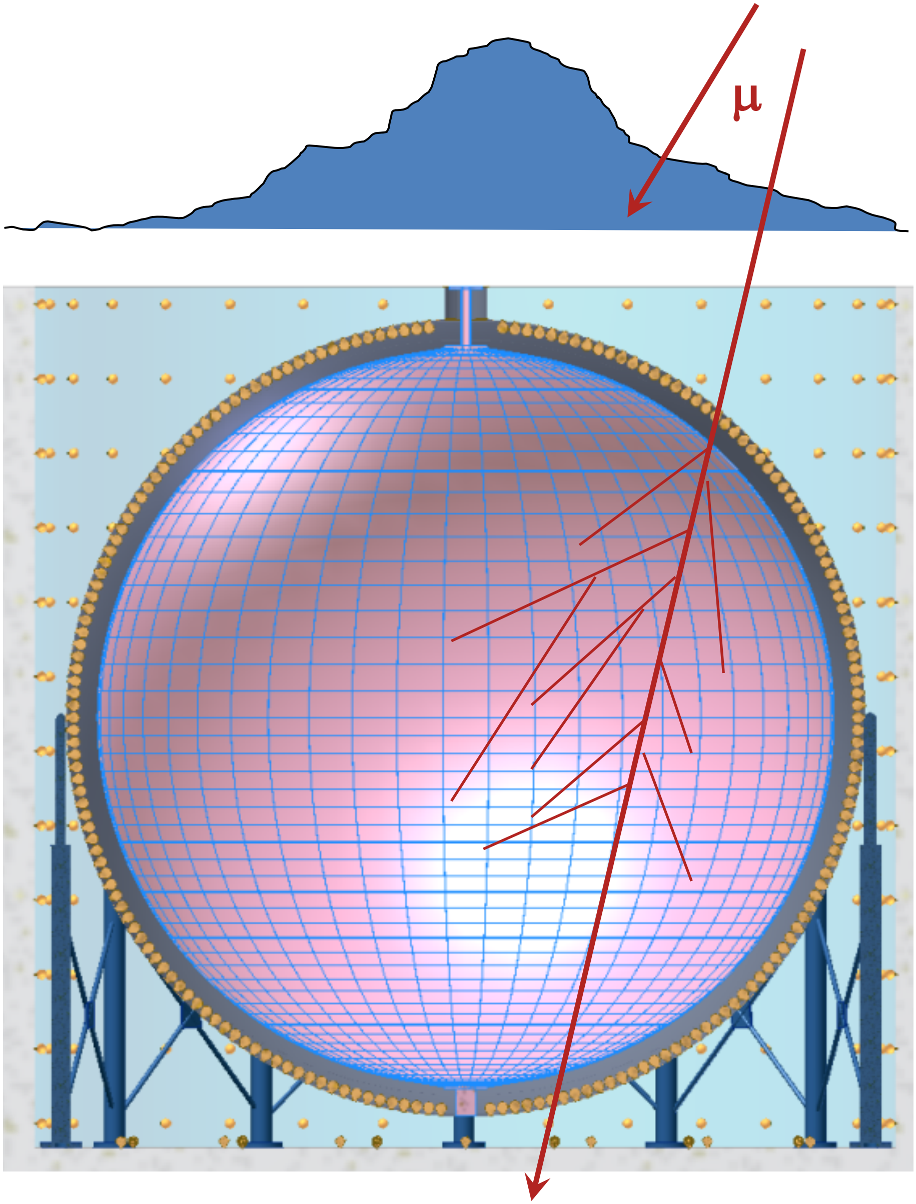
E_{rec} : reconstructed energy
E_{real} : true energy

however, relative position of peaks constrained by oscillation physics
→ active test for energy non-linearities



→ systematic studies show that effect can be largely avoided by **self-calibration**

Cosmogenic backgrounds [1]



Cosmic background levels

- rock shielding: 700 m
- μ rate in Central Detector: ~3 s^{-1}
- showering μ rate: ~0.5 s^{-1}

→ *radioisotopes from ^{12}C spallation*

Most dangerous: βn-emitters

- $^{9}Li \rightarrow {}^{9}Be + e^{-} + \nu_e$ [$\tau(^{9}Li)$~257ms]
  ↳ $2\alpha + n$

→ prompt electron signal
+ delayed neutron capture

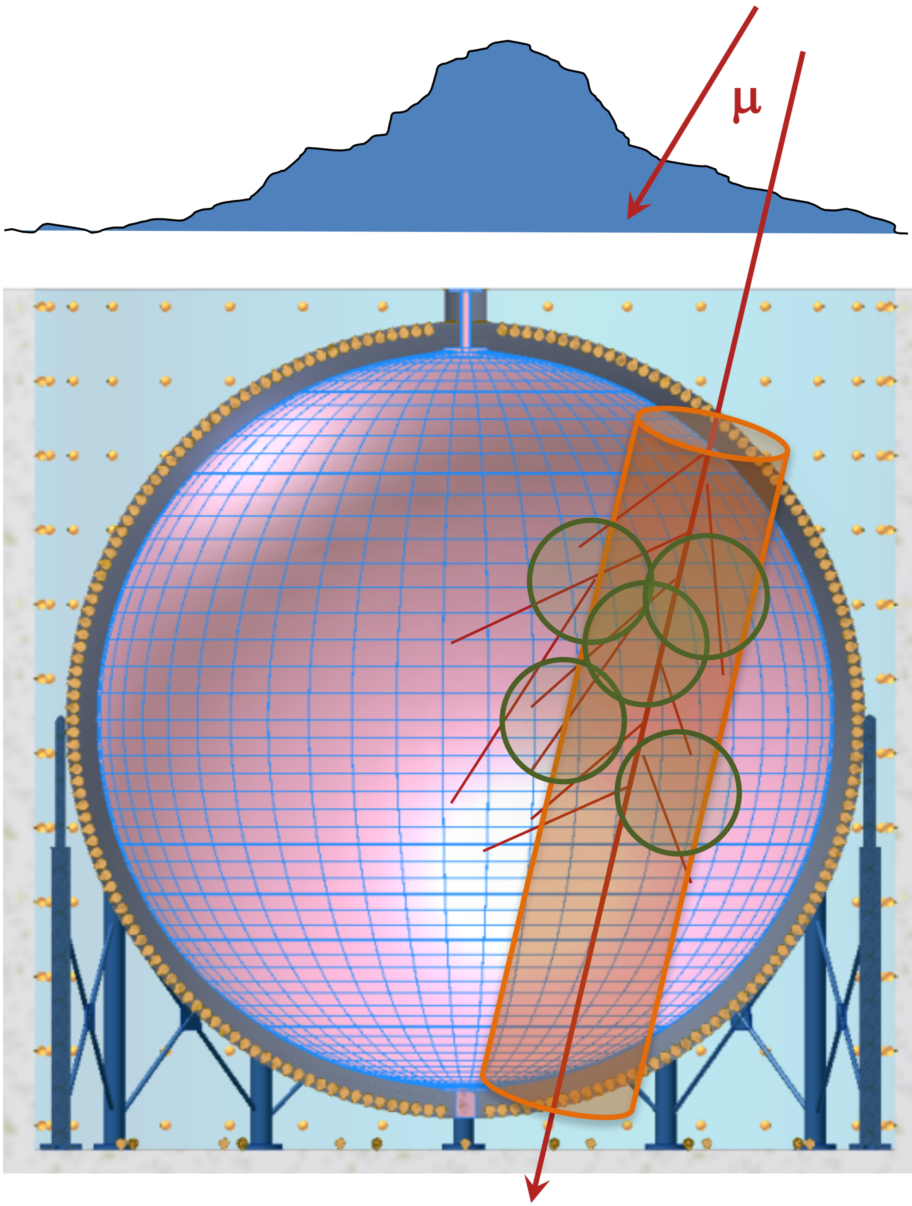
→ mimics neutrino (IBD) signature!

Expected ^{9}Li rate: ~80 d^{-1}

→ signal to background < 1:1

→ veto based on parent μ mandatory!

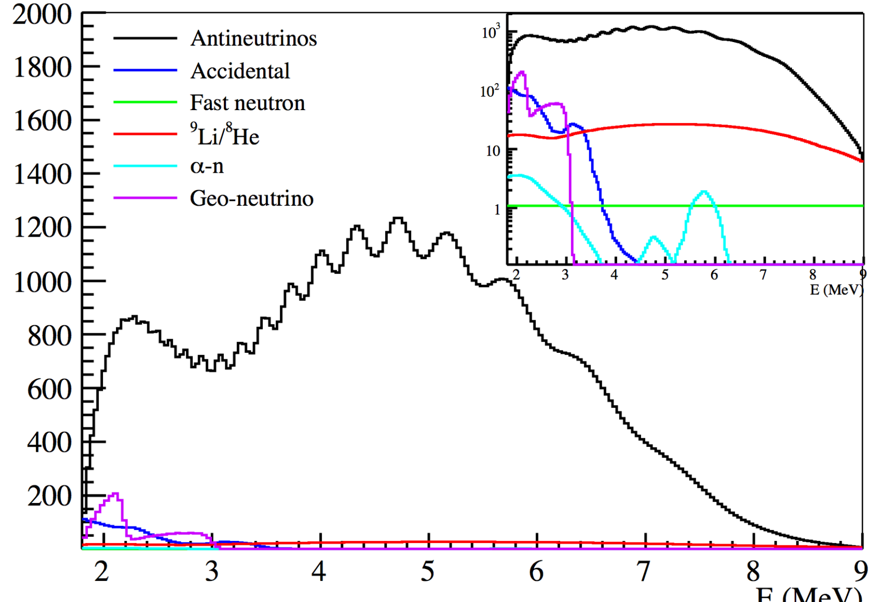
Cosmogenic backgrounds 2



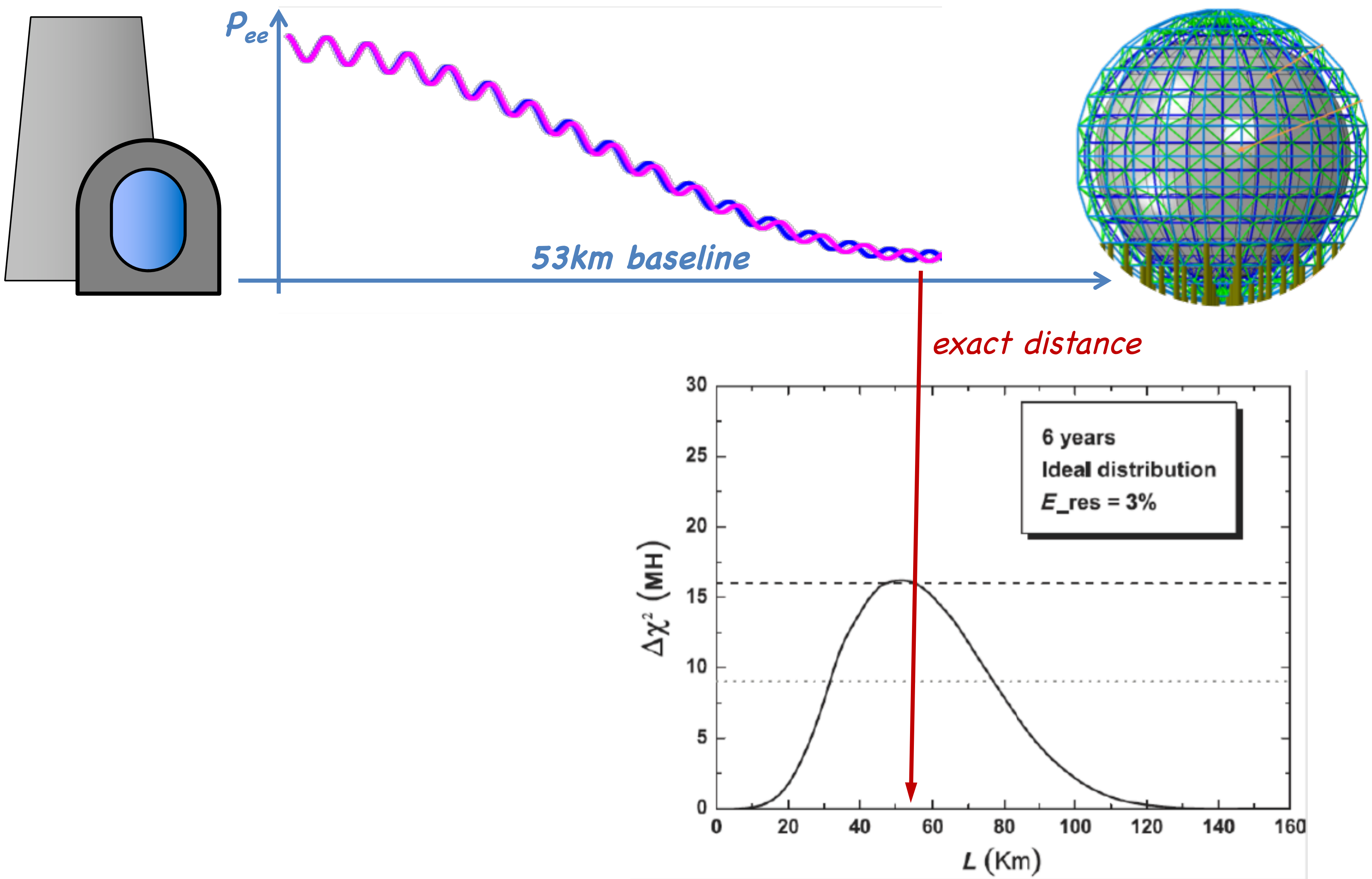
Possibilities for vetoing ^{9}Li

- radial cut around muon track
- identification of showering muons
  - cuts relative to neutron vertices
  - local (?) dE/dx of muons
  - ...

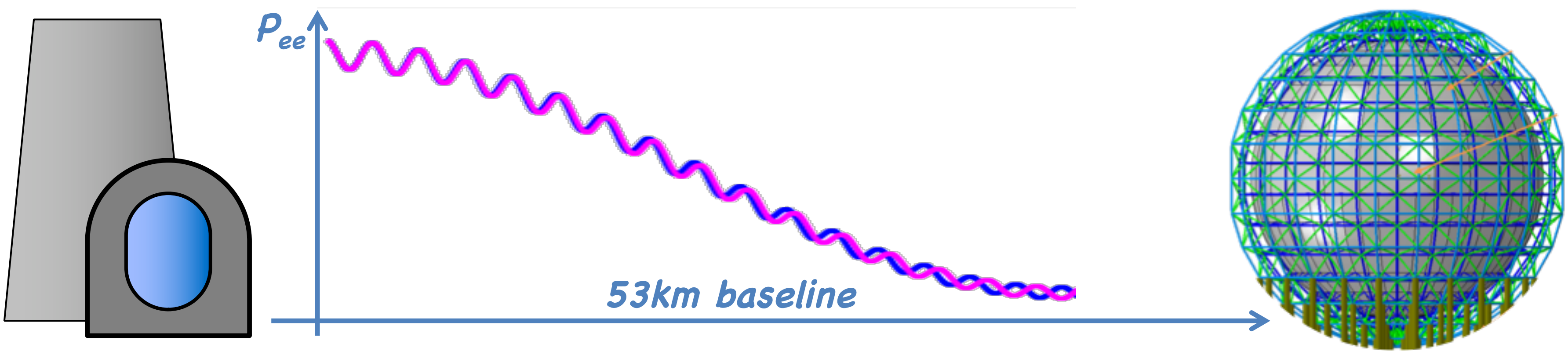
current veto: $^{9}Li/^{8}He$: $77 d^{-1} \rightarrow 1.6\ d^{-1}$
17% loss of exposure

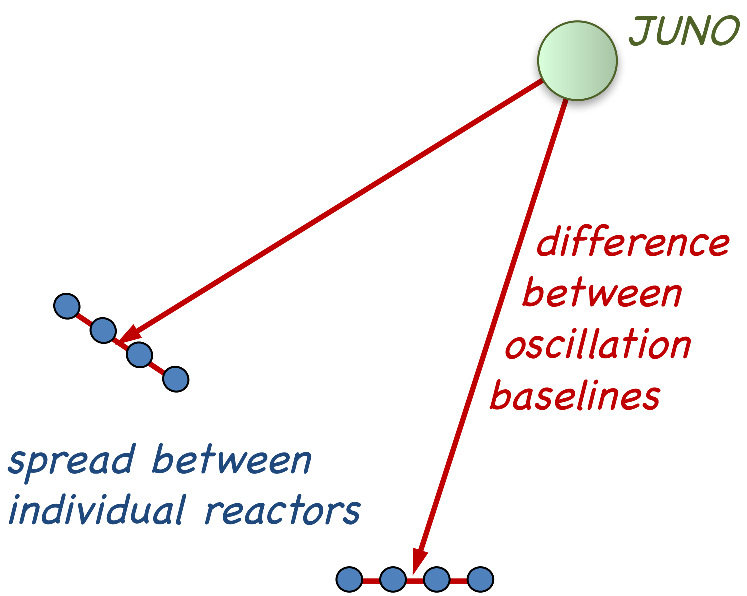


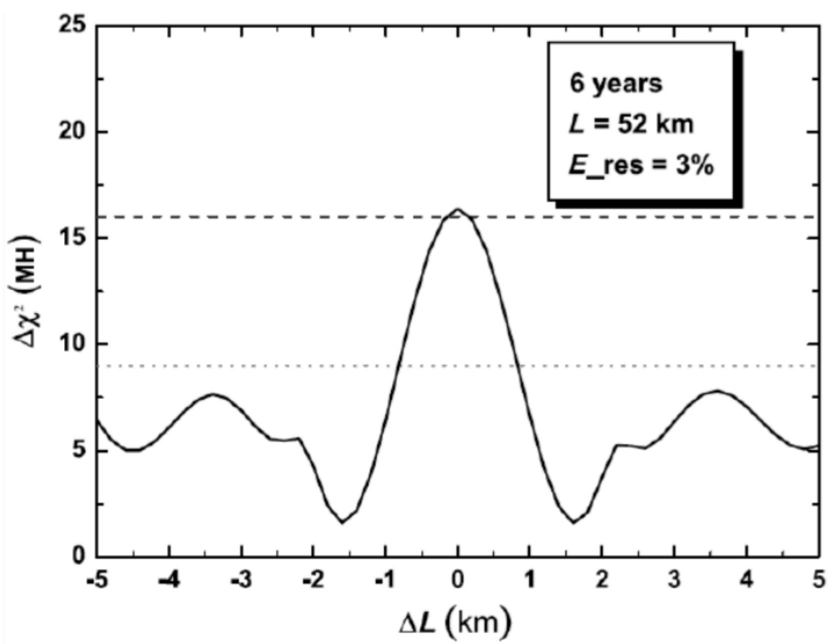
Systematics from oscillation baselines [1]



Systematics from oscillation baselines 2







Systematics from oscillation baselines [3]

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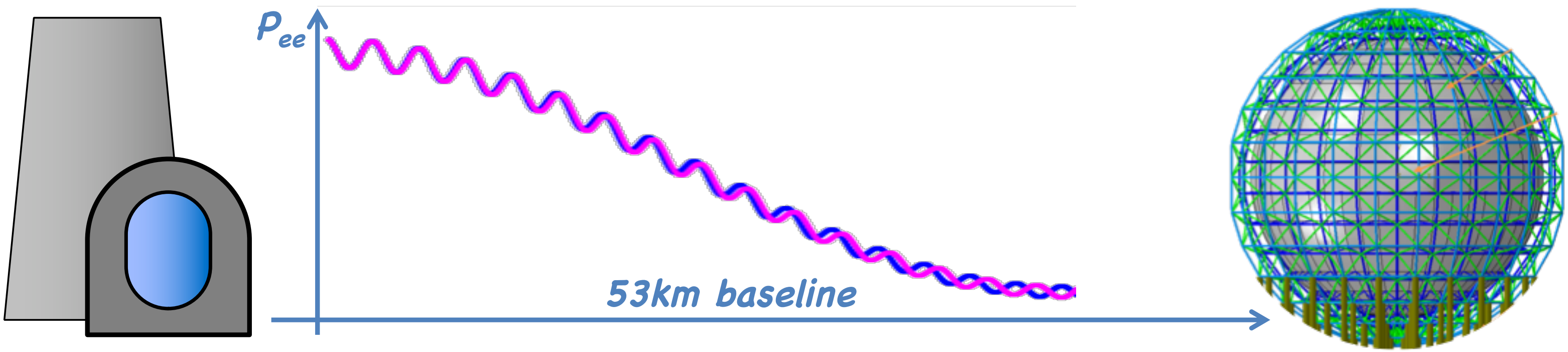
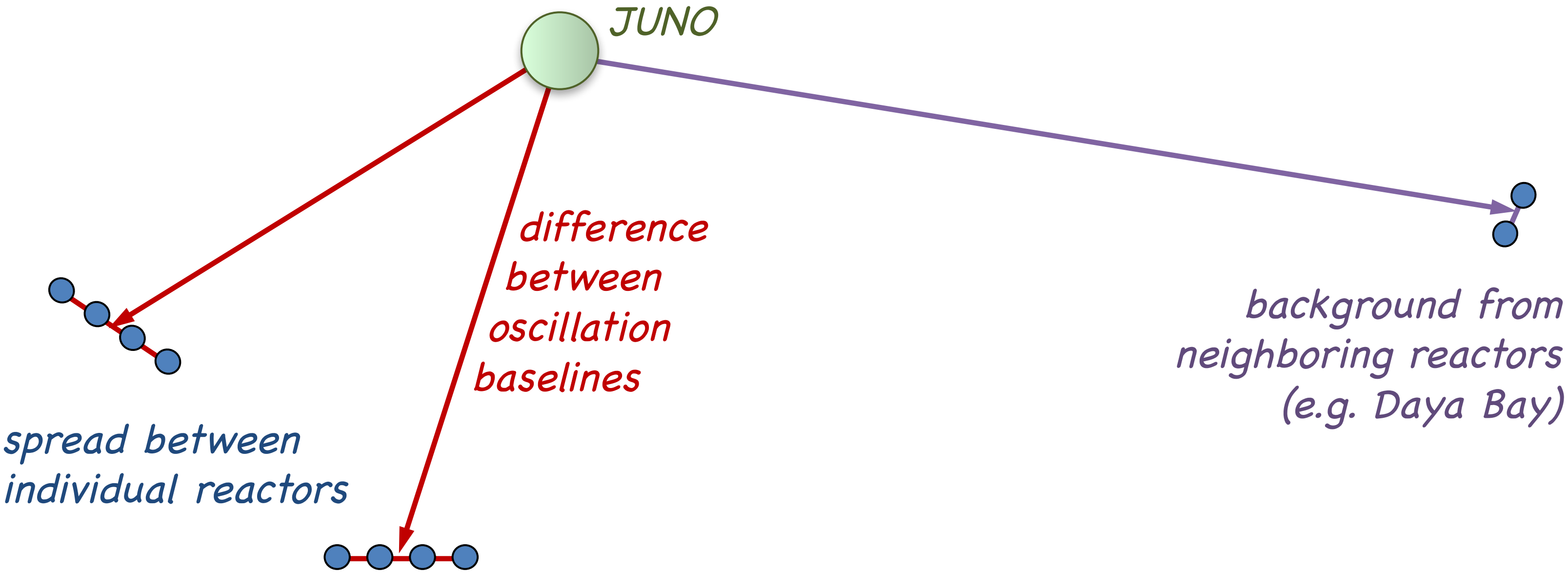
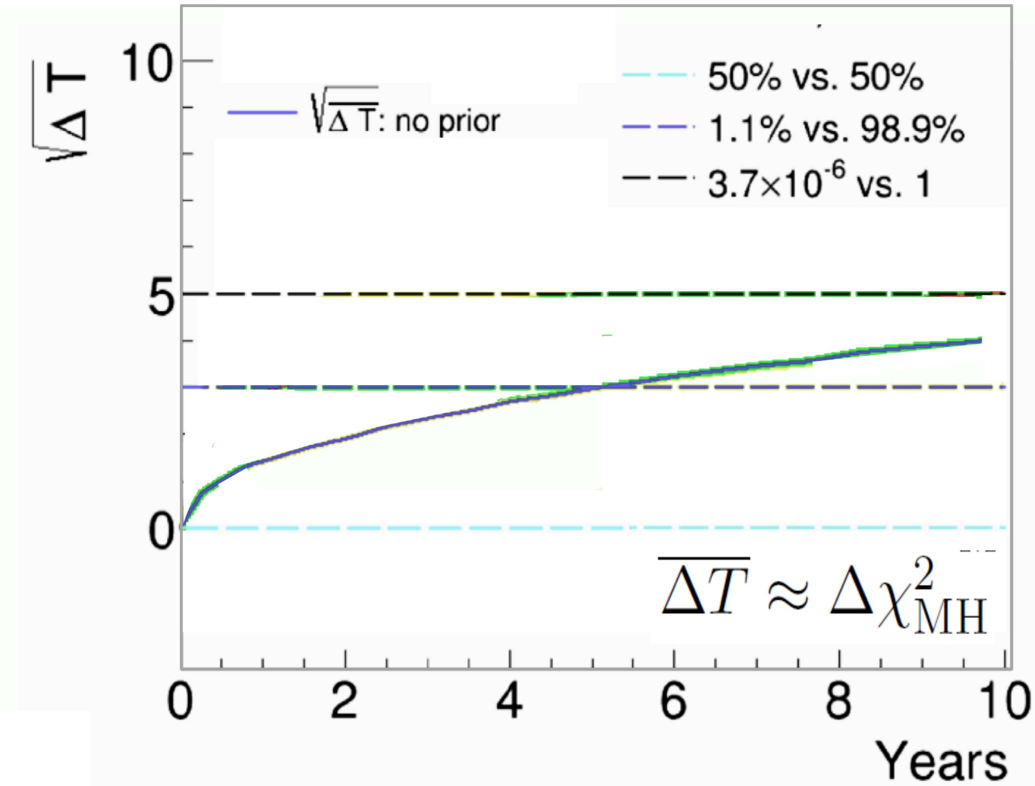




Sensitivity to mass ordering 2

JUNO, arXiv:1507.05613



defining factors:

- E resolution: 3% at 1MeV
- statistics: 100,000 ev

Sensitivity budget	$\Delta\chi^2$
Statistics only	+16
different core distances	-3
reactor background	-1.7
spectral shape	-1
S/B ratio (rate)	-0.6
S/B ratio (shape)	-0.1

JUNO's expected sensitivity level

*(assuming **3% energy resolution**)*

- JUNO alone based on 6 years: ~3σ

Input from accelerator/atmospheric ν's

JG|U

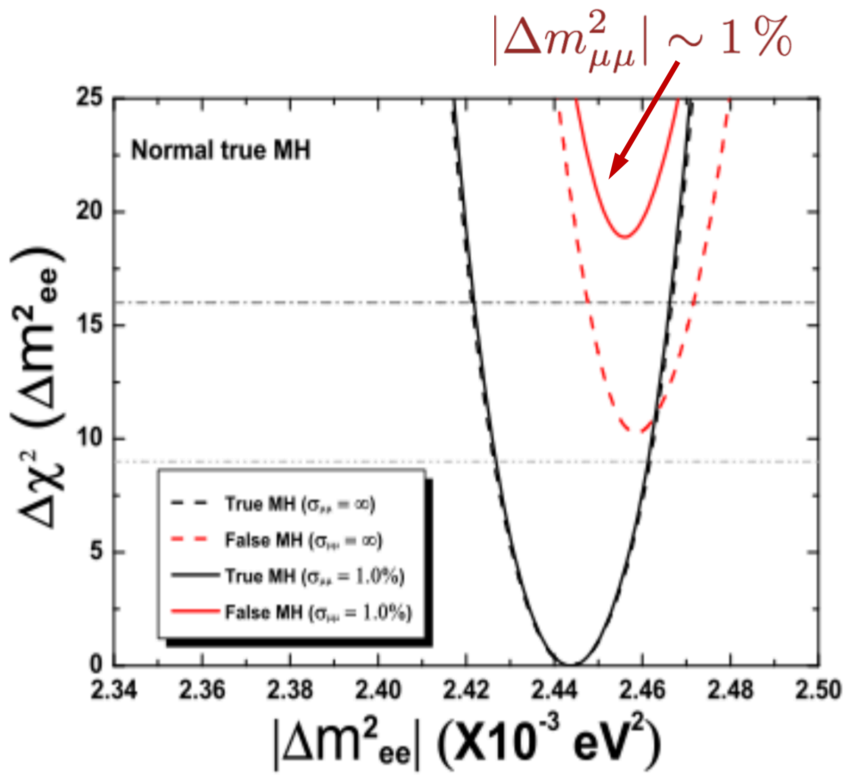
- JUNO measures reactor antineutrino disappearance $\bar{\nu}_e \rightarrow \bar{\nu}_e$ via effective

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

- Accelerator/atmospheric experiments measure $\nu_\mu \rightarrow \nu_\mu$ disappearance:

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

  - NOvA/T2K → $|\Delta m^2_{\mu\mu}| \sim 1\,\%$



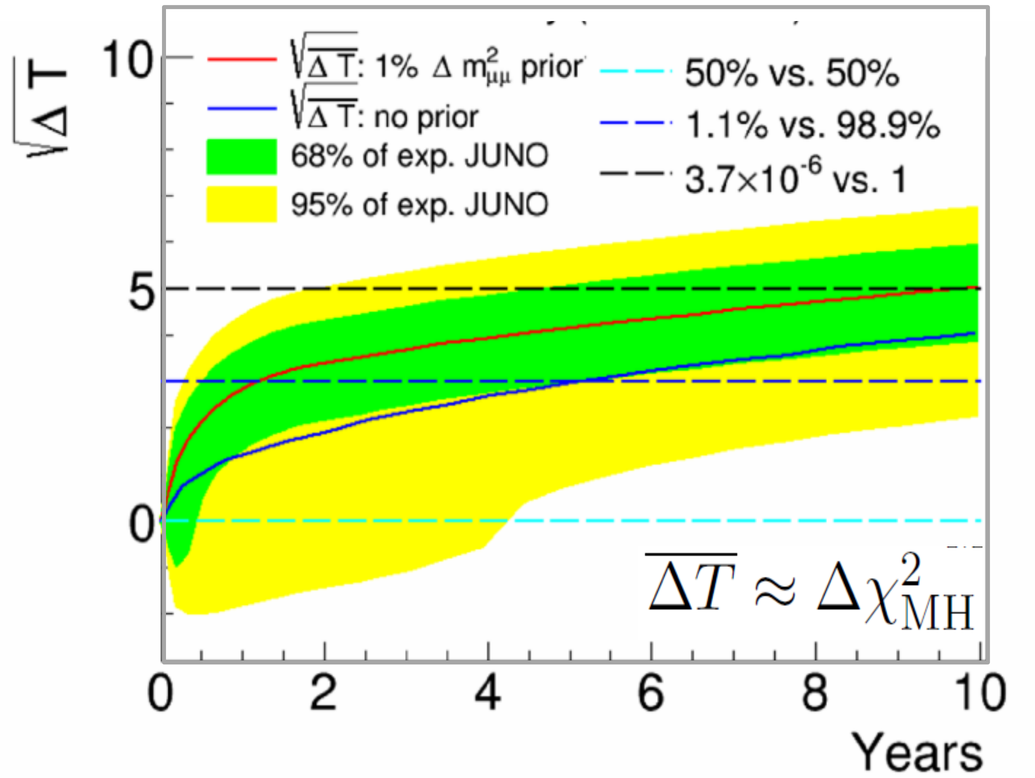
- **effective Δm² values** can be linked via

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

→ **inclusion of accurate measurement of $|\Delta m^2_{\mu\mu}|$ as prior in the analysis**

Sensitivity to mass ordering [3]

JUNO, arXiv:1507.05613



JUNO's expected sensitivity level

*(assuming **3% energy resolution**)*

- JUNO alone based on 6 years: ~3σ

\+ **precise data by T2K/NOvA on $\Delta m^2_{\mu\mu}$: 4σ**

defining factors:

- E resolution: 3% at 1MeV
- statistics: 100,000 ev

Sensitivity budget	**$\Delta\chi^2$**
Statistics only	+16
different core distances	-3
reactor background	-1.7
spectral shape	-1
S/B ratio (rate)	-0.6
S/B ratio (shape)	-0.1
information on $\Delta m^2_{\mu\mu}$	**+8**

Global effort on Mass Ordering

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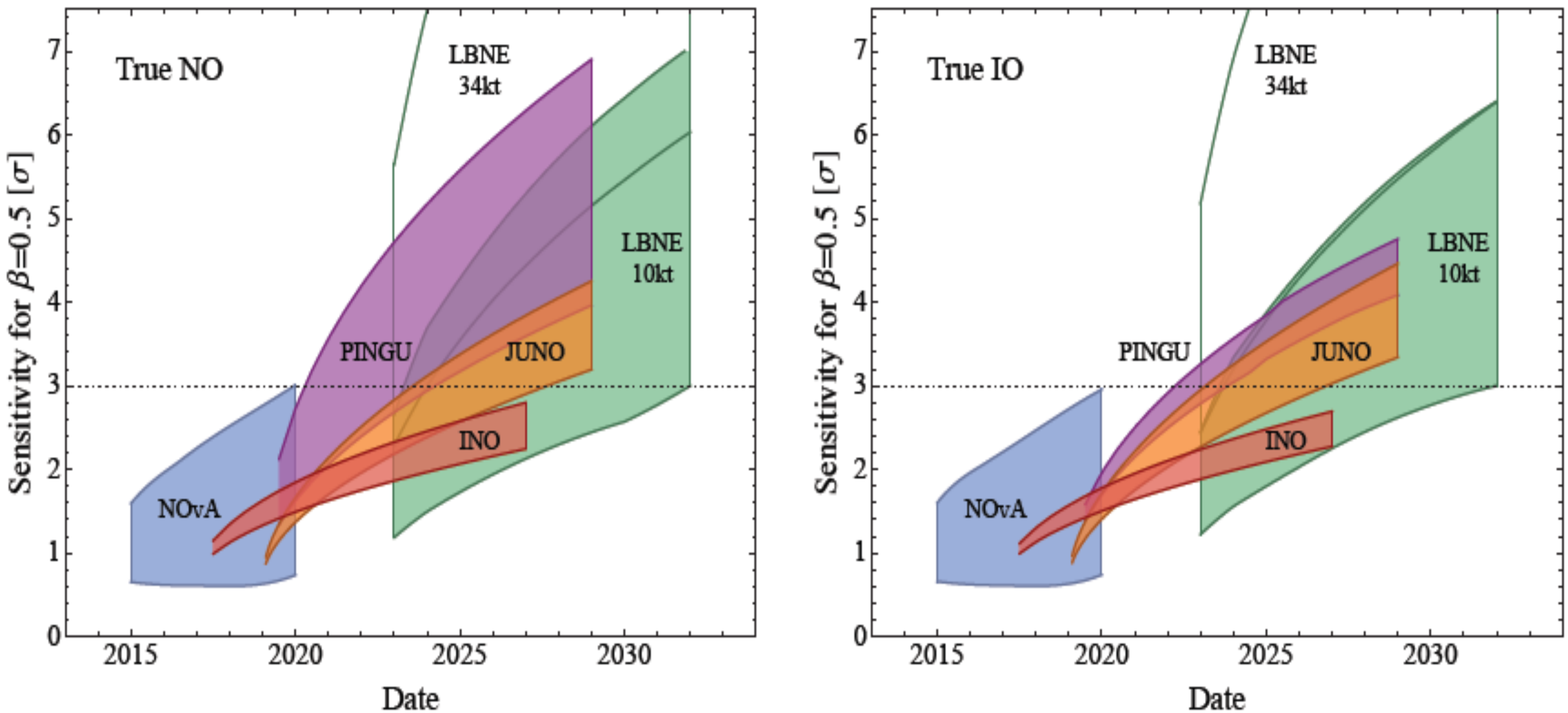

different techniques	mode	main uncertainties
▪ reactor neutrinos: JUNO	$\nu_e \rightarrow \nu_e$	energy res. (3-3.5%)
▪ atmospheric ν's: INO,PINGU,ORCA	$\nu_\mu \rightarrow \nu_\mu$	value of θ_{23}=40-50°
▪ long-baseline beam: LBNE→DUNE	$\nu_\mu \rightarrow \nu_e$	value of δ_{CP}

JUNO + future atmospheric ν results

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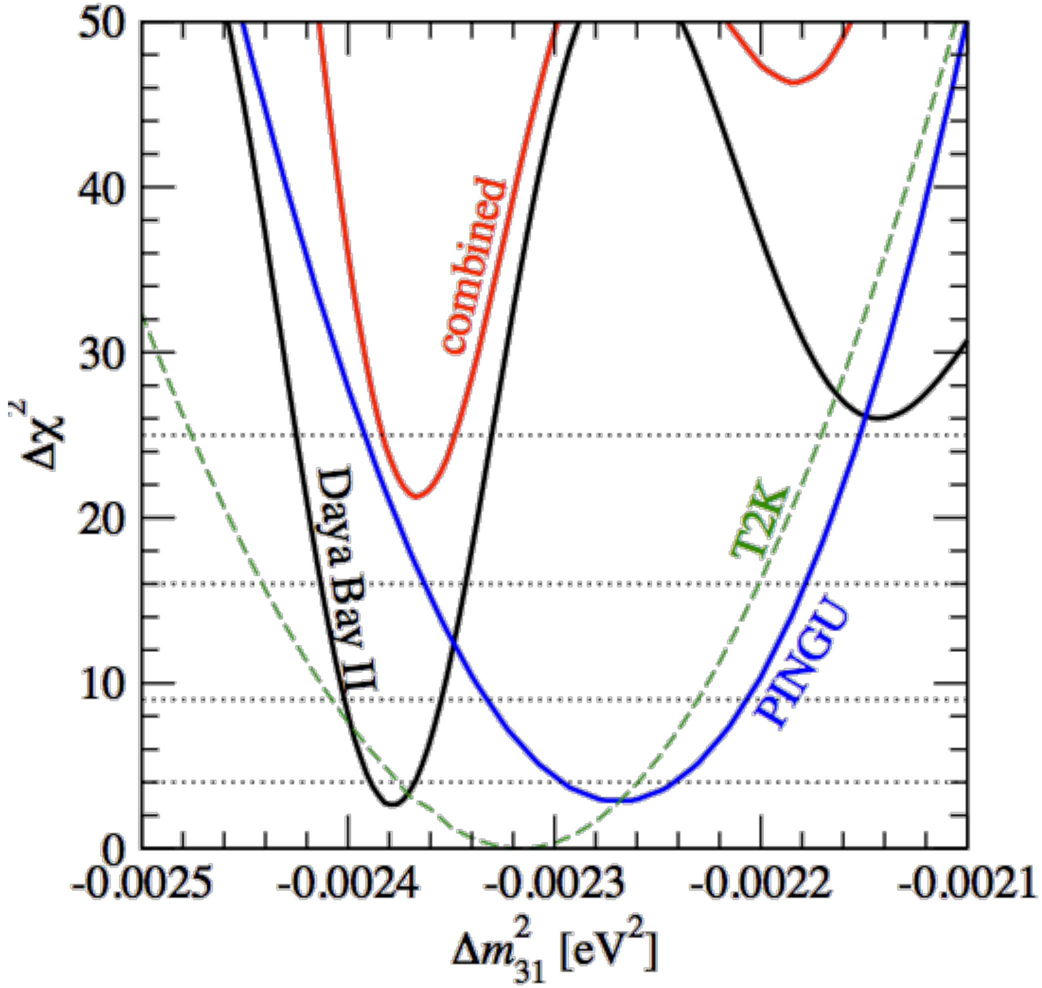
Blennow, Schwetz, arXiv:1306.3988

example assuming **very <u>poor</u> Δm^2 measurements**

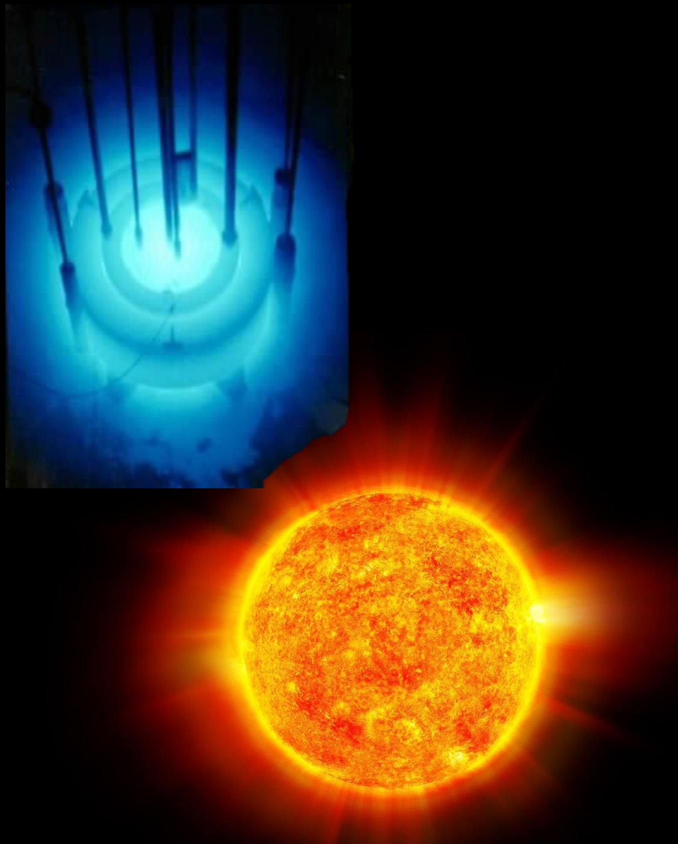


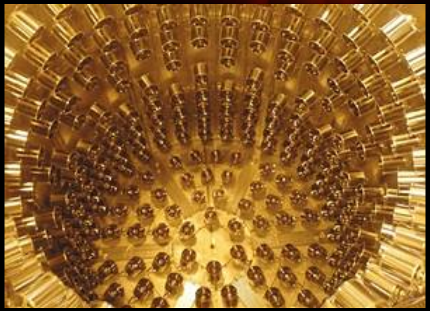
Conclusions

JUNO will offer a rich physics program!

→ *Yellow Book, arXiv:1507.05613*

- **Reactor neutrino oscillations**
  - mass ordering: 3σ → 4σ (with input on $\Delta m^2_{\mu\mu}$)
  - sub-% measurement of osc. parameters
- **Neutrinos from natural sources**
  - Galactic Supernova neutrinos
  - Diffuse Supernova Neutrino Background
  - Solar neutrinos
  - Geoneutrinos
  - Neutrinos from dark matter annihilation
  - Atmospheric neutrinos
- **Short-baseline oscillations** (sterile ν's)
- **Proton decay into $K^+\bar{\nu}$**





JUNO Collaboration

JG|U

553 collaborators from 72 institutions

Armenia, Belgium, Brazil, Chile, China, Czech Republic, Germany, Finland, France, Italy, Latvia, Pakistan, Russia, Slovakia, Thailand, Taiwan, and the United States

German institutes

RWTH AACHEN UNIVERSITY

UHH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

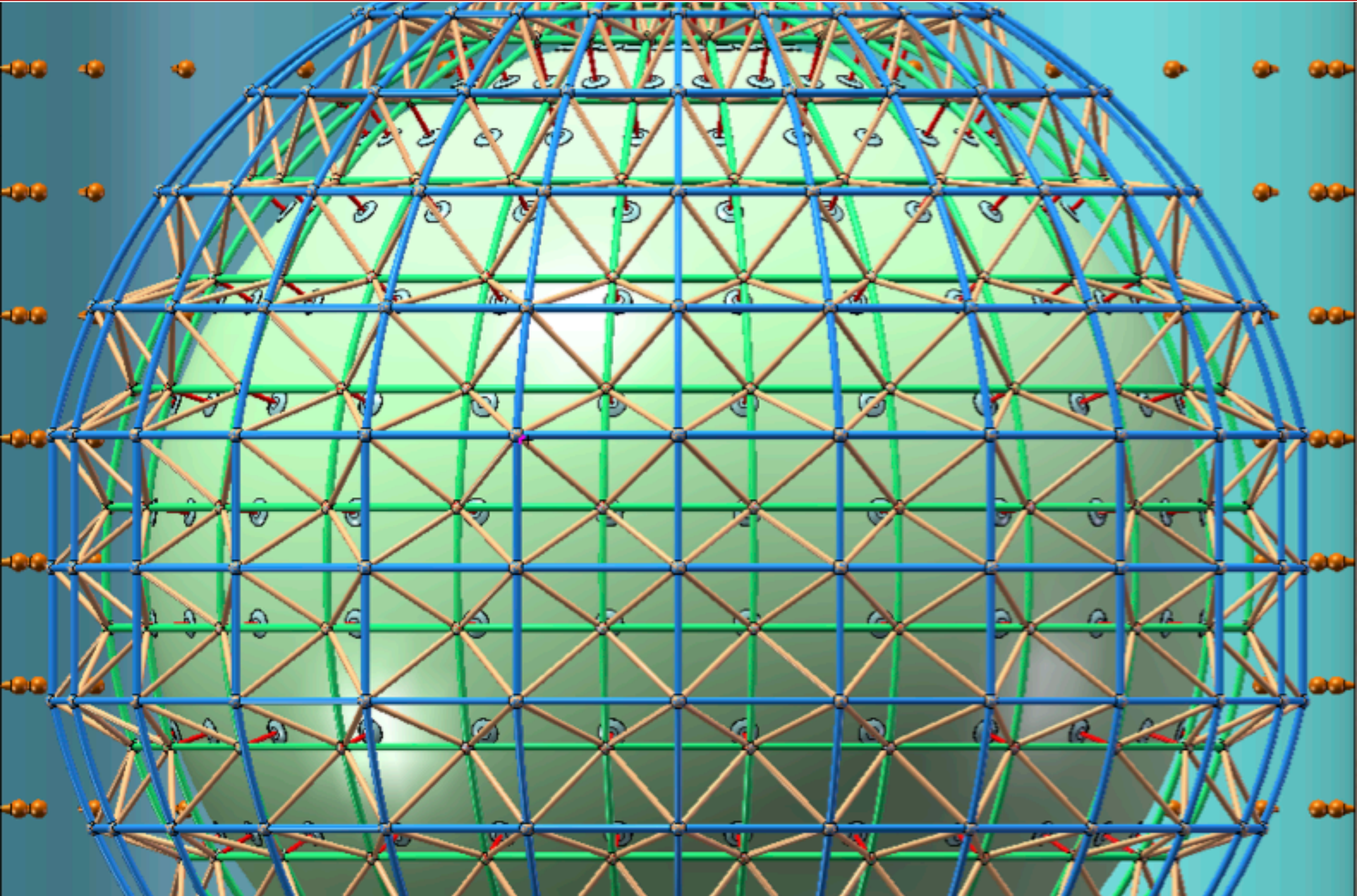
JÜLICH FORSCHUNGSZENTRUM

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

TUM Technische Universität München

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Backup slides



Matter effects, mass hierarchy, CP violation

Oscillation probability for ν_e appearance in a ν_μ neutrino beam:

effects of weak matter potential

atmospheric oscillations → T2K

$$P_{\mu e(\bar{\mu}\bar{e})} = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right)$$

solar oscillations

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right) \approx 0$$

leptonic CP violation

$$+J\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_\pm}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{B_\pm L}{2}\right)\cos\left(\mp\delta - \frac{\Delta_{13}L}{2}\right)$$

neutrino-antineutrino asymmetry term

$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

weak matter potential A

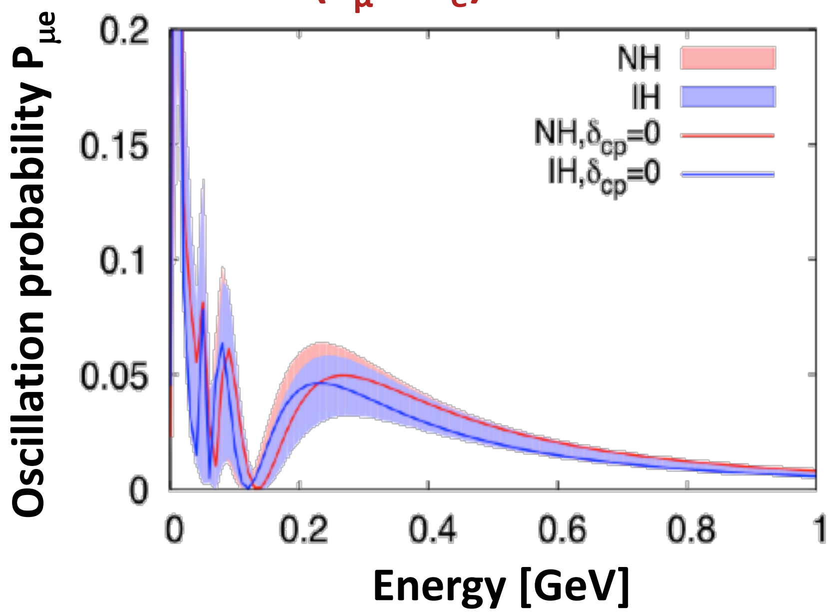
$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu} \qquad B_\pm = |A \pm \Delta_{13}| \qquad A = \sqrt{2}G_F N_e$$

→ $\nu \leftrightarrow \bar{\nu}$ asymmetry if $A \sim \Delta_{13}$!

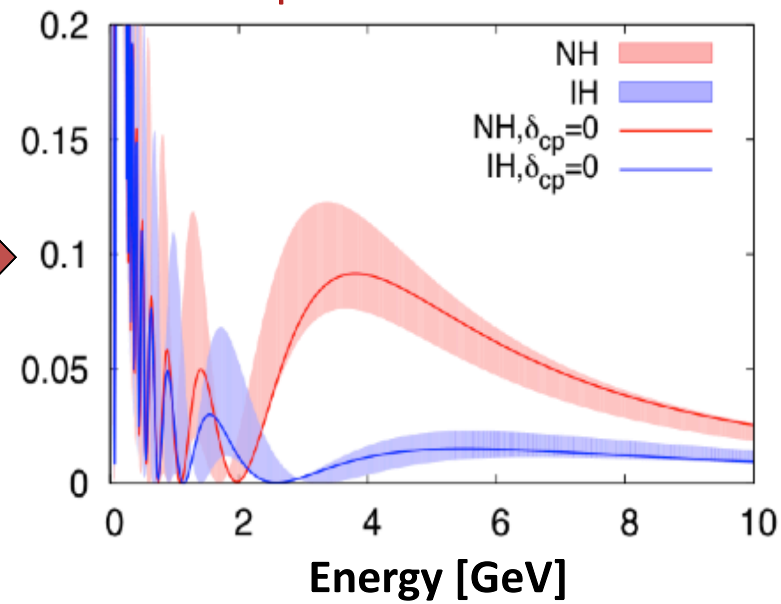
Oscillation patterns for long-baseline beams

- **Oscillation probabilities** differ for $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Enhanced electron-flavor appearance for: neutrinos → normal hierarchy; antineutrinos → inverted

P($\nu_\mu \rightarrow \nu_e$) for 130 km



P($\nu_\mu \rightarrow \nu_e$) for 2300 km



- **Far detector** at first atmospheric oscillation maximum:

  longer baseline → larger energy → larger matter effect!

MH from atmospheric neutrinos

D. Grant

Source: Atmospheric μ-neutrinos

- Energies: 2-20 GeV
- Baselines: 20-13000 km
- Matter potential: Earth core & mantle

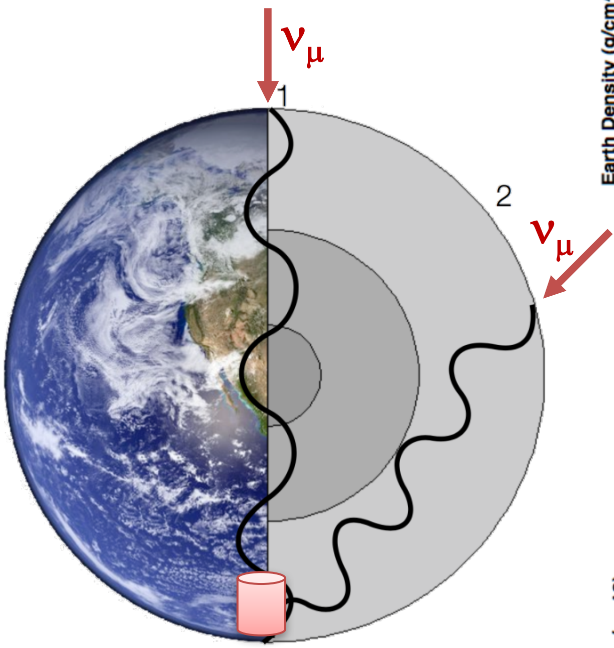
MH signature

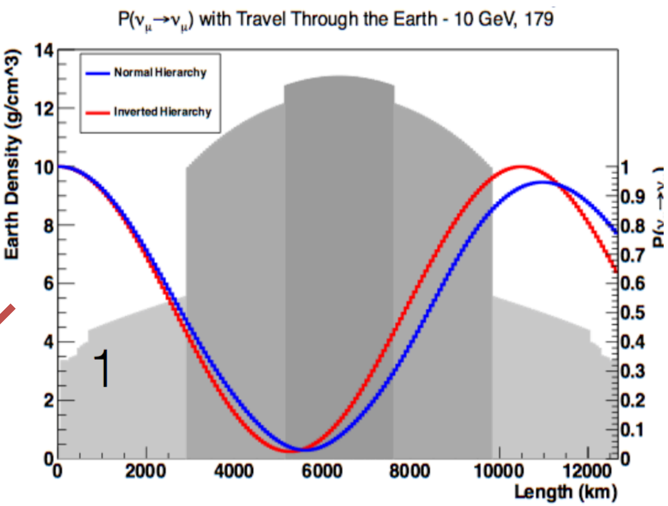
matter effects in

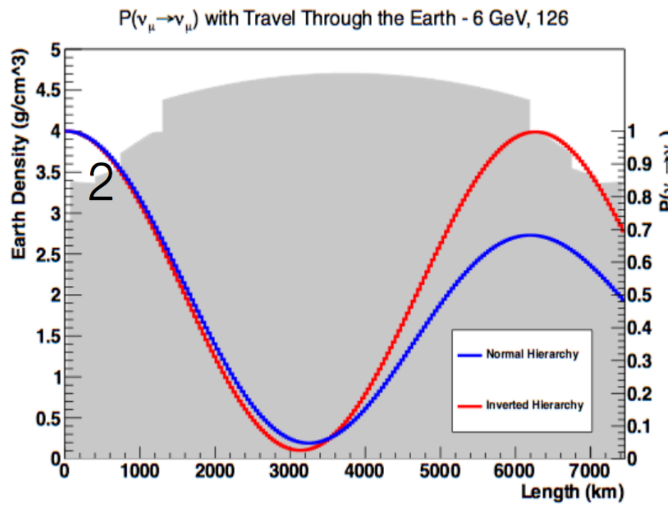
- $\nu_\mu \rightarrow \nu_\mu$ disappearance
- $\nu_\mu \rightarrow \nu_e$ appearance

Detector requirements

- relatively low energy threshold
- good angular resolution
- flavor identification
- nice to have: lepton charge ID ($\nu/\bar{\nu}$)







Atmospheric ν signal observed in PINGU

S.Böser

Event statistics

- ν_μ: $5.0\text{x}10^4$ yr^{-1}
- ν_e: $3.8\text{x}10^4$ yr^{-1}

→ detectable difference

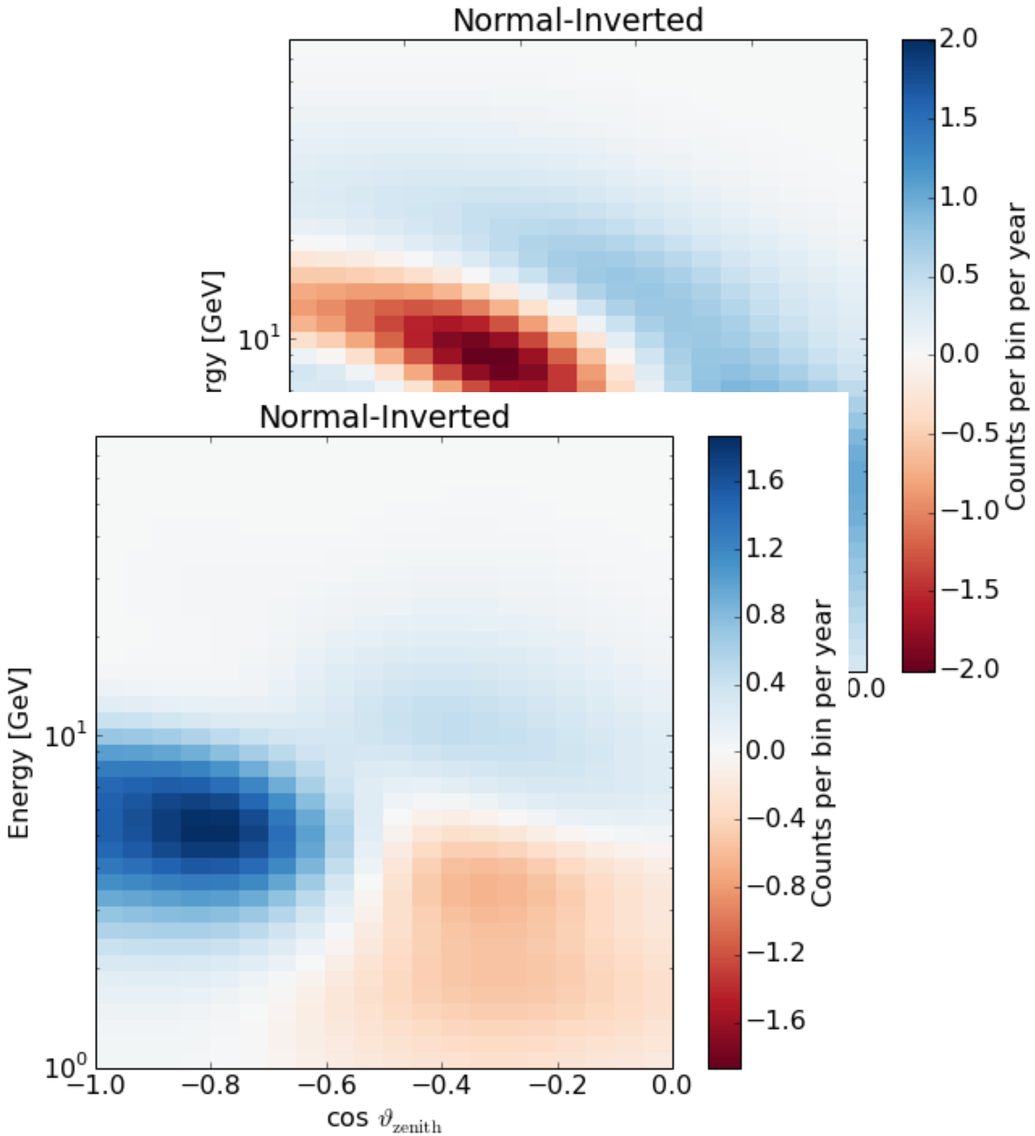
Detector resolution

- energy resolution: ~20% above 10 GeV
- directional resolution improving with energy

Particle identification

- ν_μ (CC): tracks
- ν_e (CC) + ν_x (NC): cascades

→ distinction of event types



JUNO's liquid scintillator

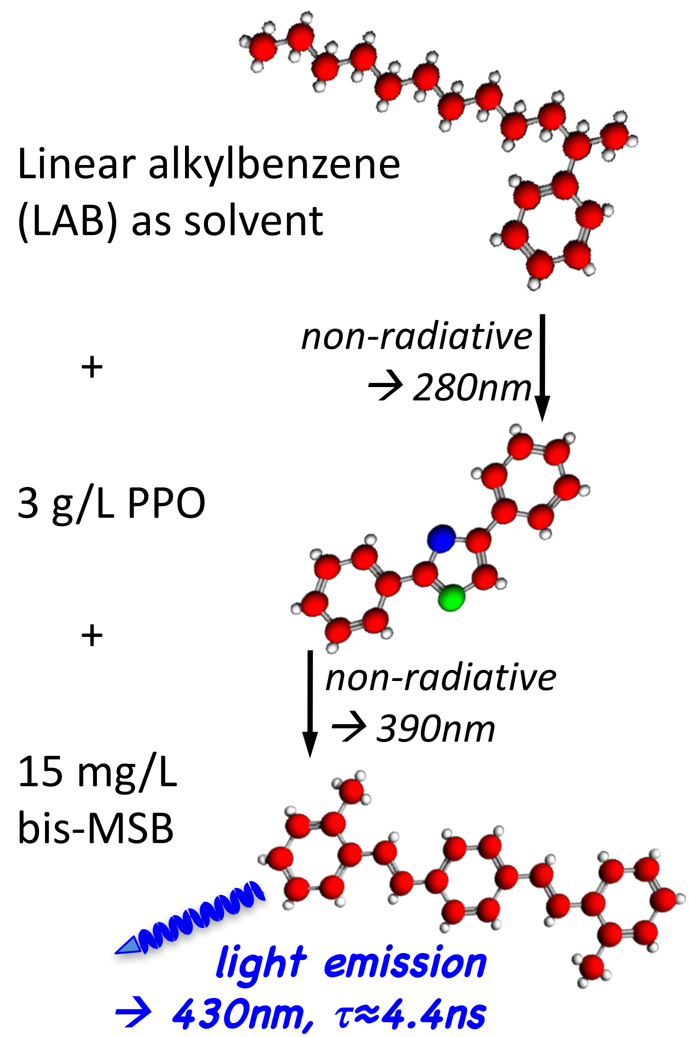
Required properties:

- Light transport over >17m
  → solvent LAB **very transparent**
  → no addition of gadolinium
  → Al_2O_3 column purification
- **High light yield**: >10^4 ph/MeV
  → pure LAB, no addition of paraffins
  → large fluor (PPO) concentration
- **Radiopurity**:
  → reactor neutrinos: $<10^{-15}$ g/g in U/Th
  → solar neutrinos: $<10^{-17}$ g/g
  → vacuum distillation

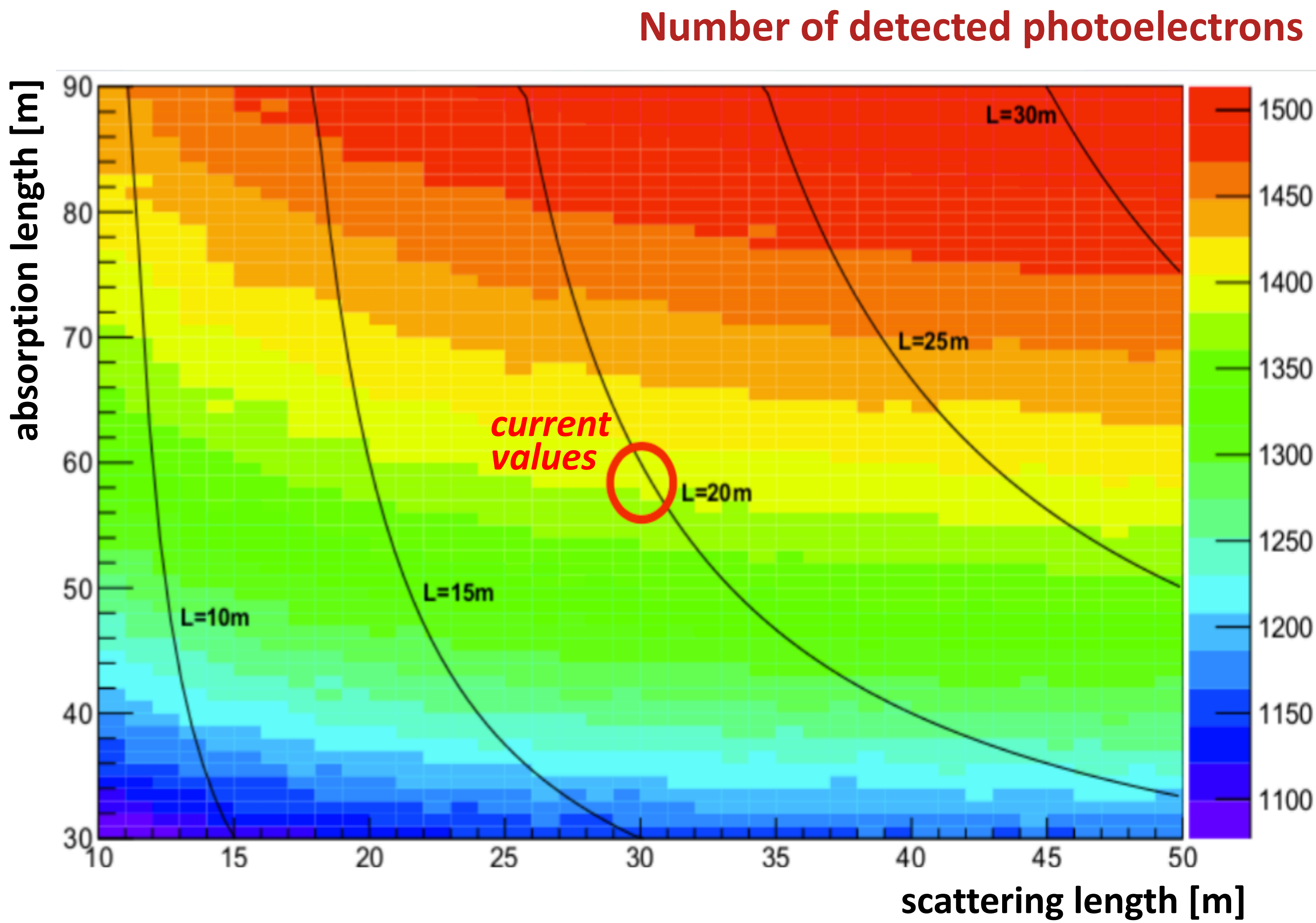
for free:

- Fast fluorescence times
  → **good spatial resolution**
- Good **pulse shaping** properties
  → background discrimination, e.g. e^+/e^-

LENA-style liquid scintillator



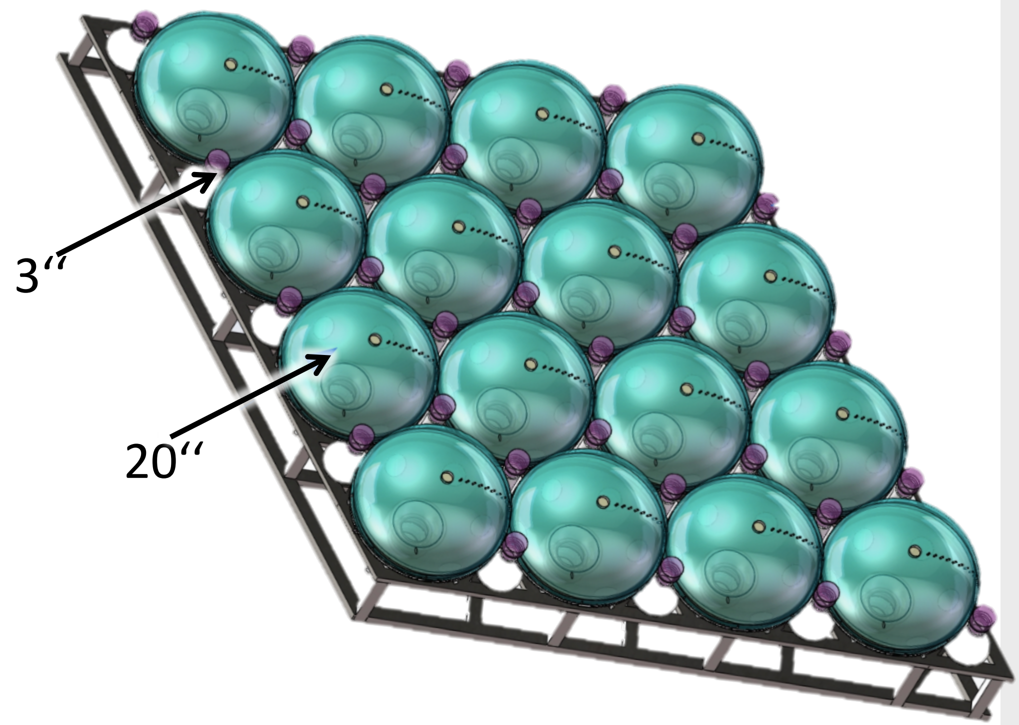
p.e. yield vs. scintillator transparency

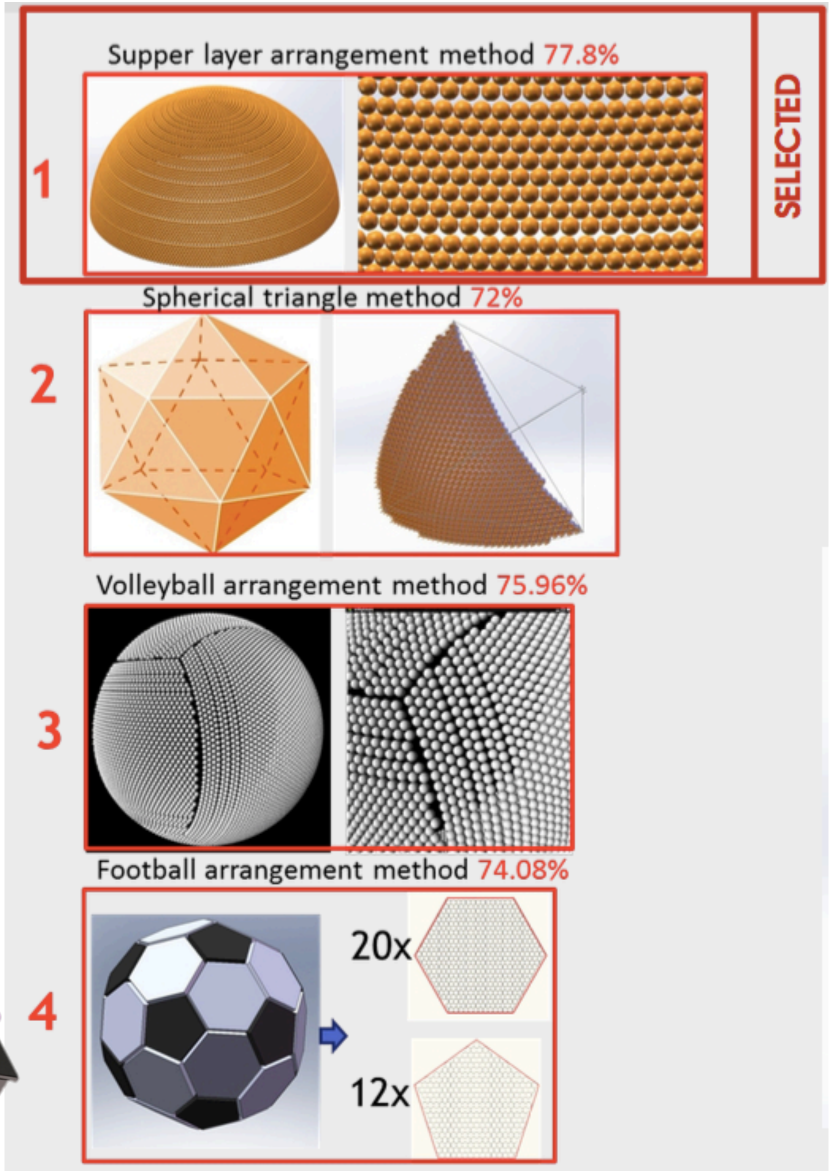


Light detection

Light collection required:

- optical coverage: 75%
  → 17,000 large PMTs (20‘‘)
  → additional small PMTs (3‘‘)
  (double calorimetry + timing)





Light detection

JG|U

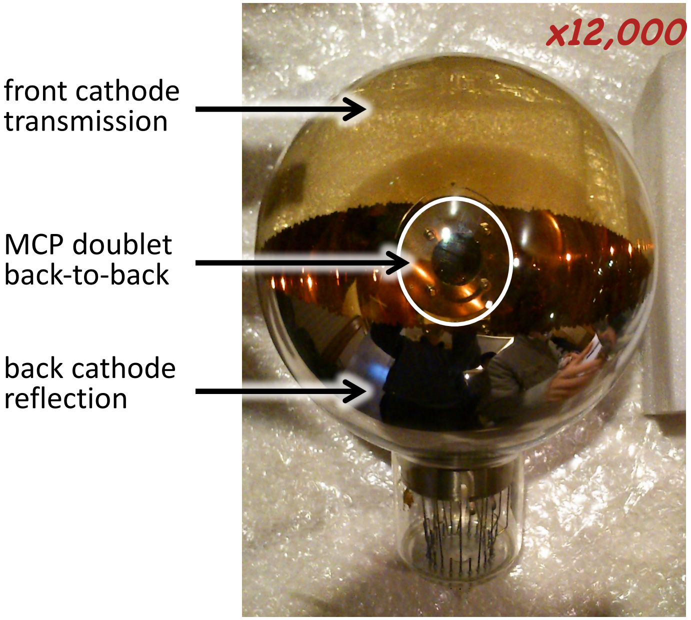
Light collection required:

- optical coverage: 75%
- quantum efficiency QE x collection efficiency CE = 35%

→ photons detected: ~26%

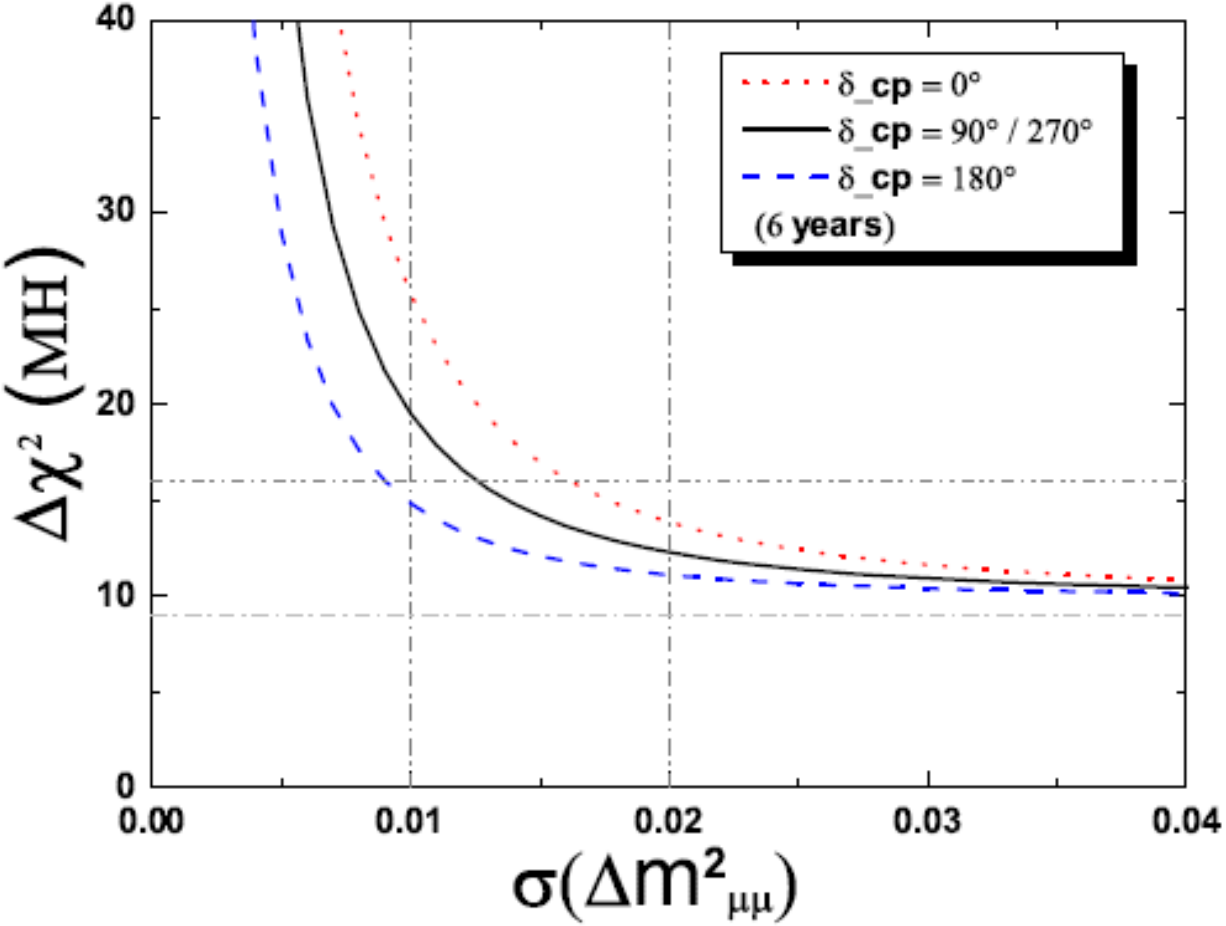
Parameter	Hamamatsu 20"	new MCP-PMT
Photocathode	transmission	transmission + reflection
QE (400nm)	30%(T)	26%(T) + 4%(R)
relative CE	100%	110%
peak-to-valley ratio	>3	>3
transit time spread	~3ns	~12ns
dark rate	~30kHz	~30kHz
afterpulsing	10%	3%

Hamamatsu R12860 (20"PMT)

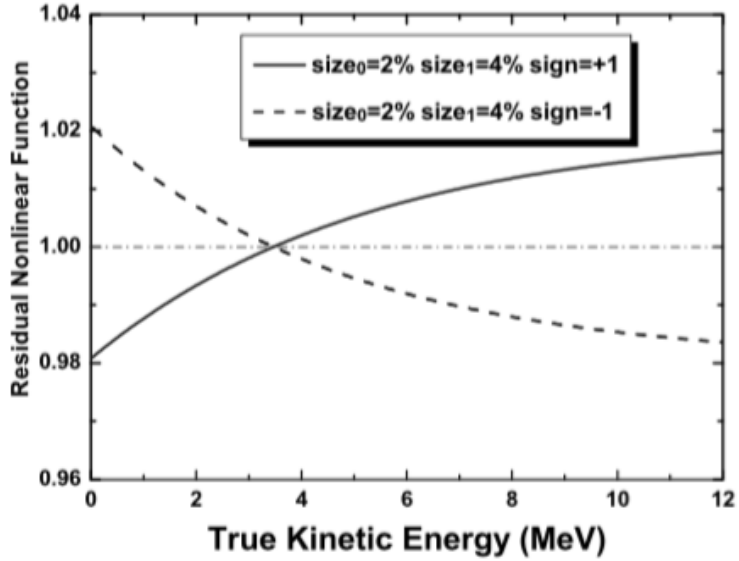


MCP-PMT 8" prototype

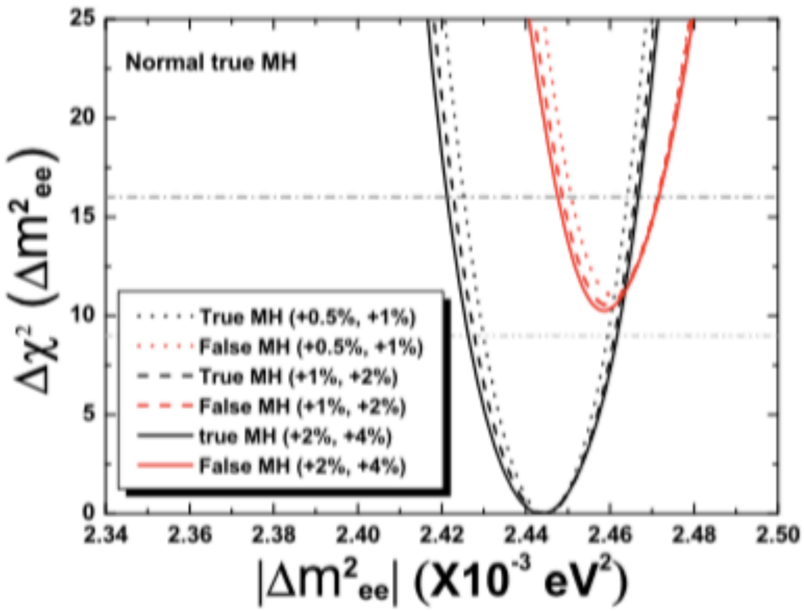
Influence of $\Delta m^2_{\mu\mu}$ accuracy



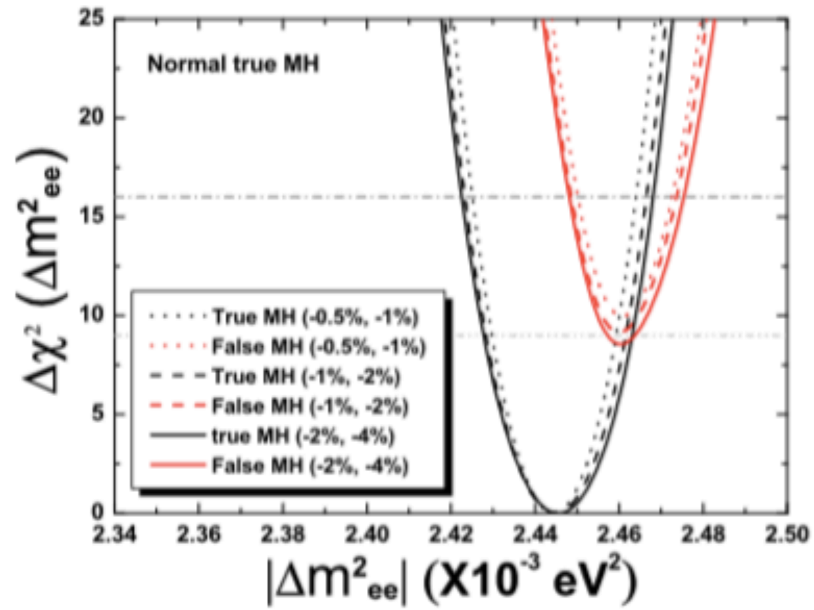
Influence of energy scale linearity



w/o self-calibration

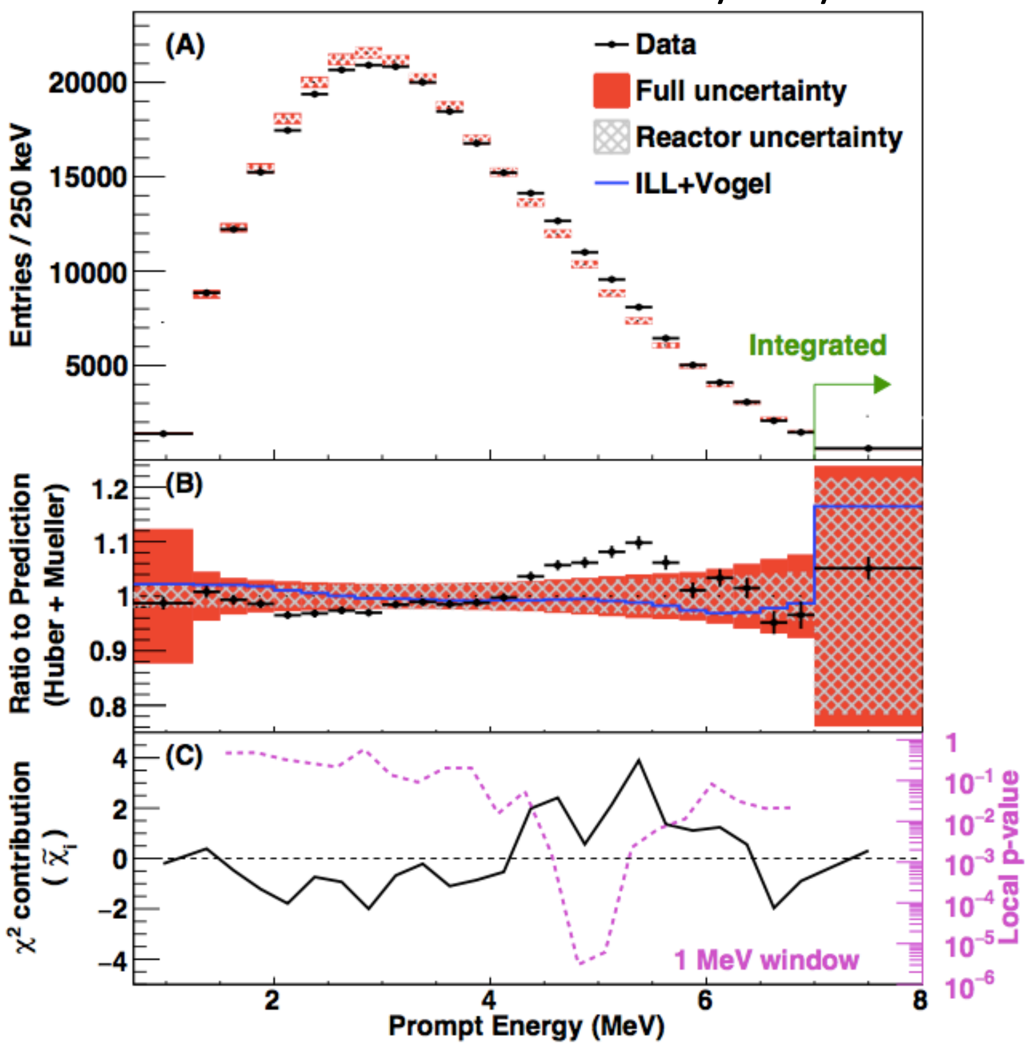


w/ self-calibration

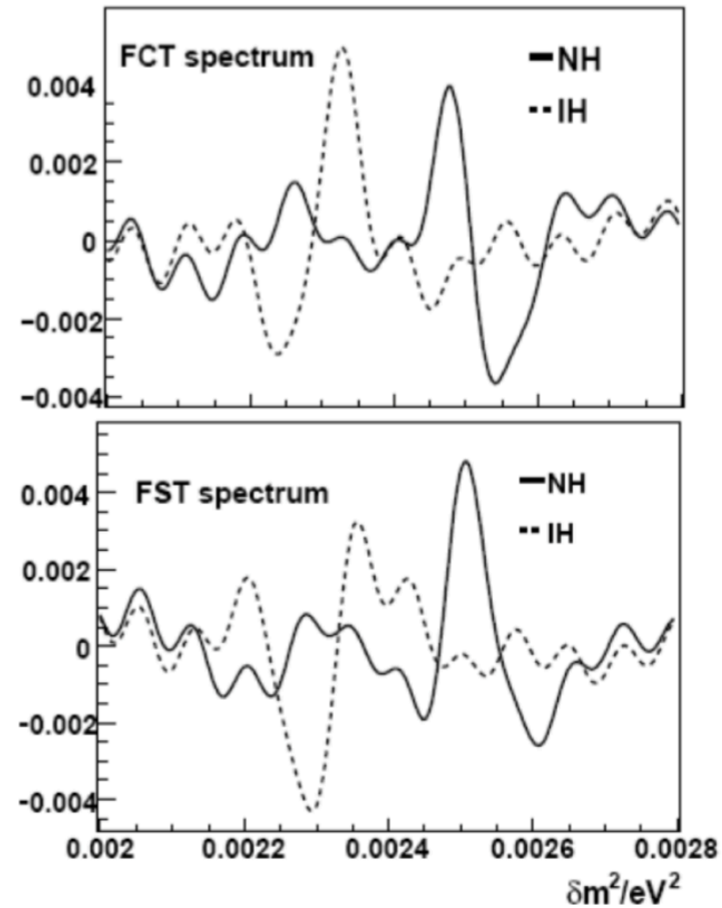


Reactor anomaly: 5 MeV bump

Daya Bay ND



MH Fourier analysis



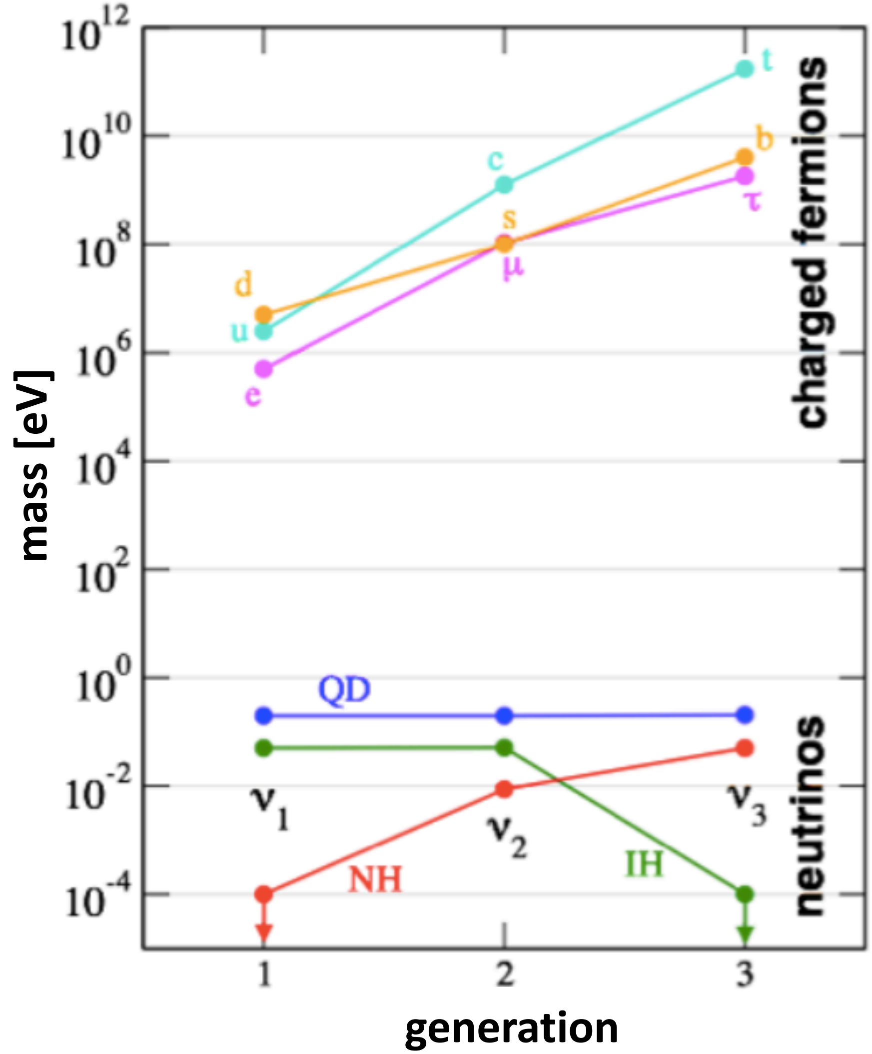
J. Learned et. al. Hep-ex/0612022

Implications of sgn(Δm^2_{32})

JG|U

- **Arrangement** of the neutrino masses
  - normal ordering: $m_1 < m_2 < m_3$
  - inverted ordering: $m_3 < m_1 < m_2$
  - quasi-degenerate: $m_1 \approx m_2 \approx m_3$
- resolving the **degeneracy in** the interpretation of **δ_{CP} measurements**
- target range for **sensitivity** of **0νββ decay** experiments
- combination with **cosmology** to resolve **neutrino masses**

Fermion families and masses



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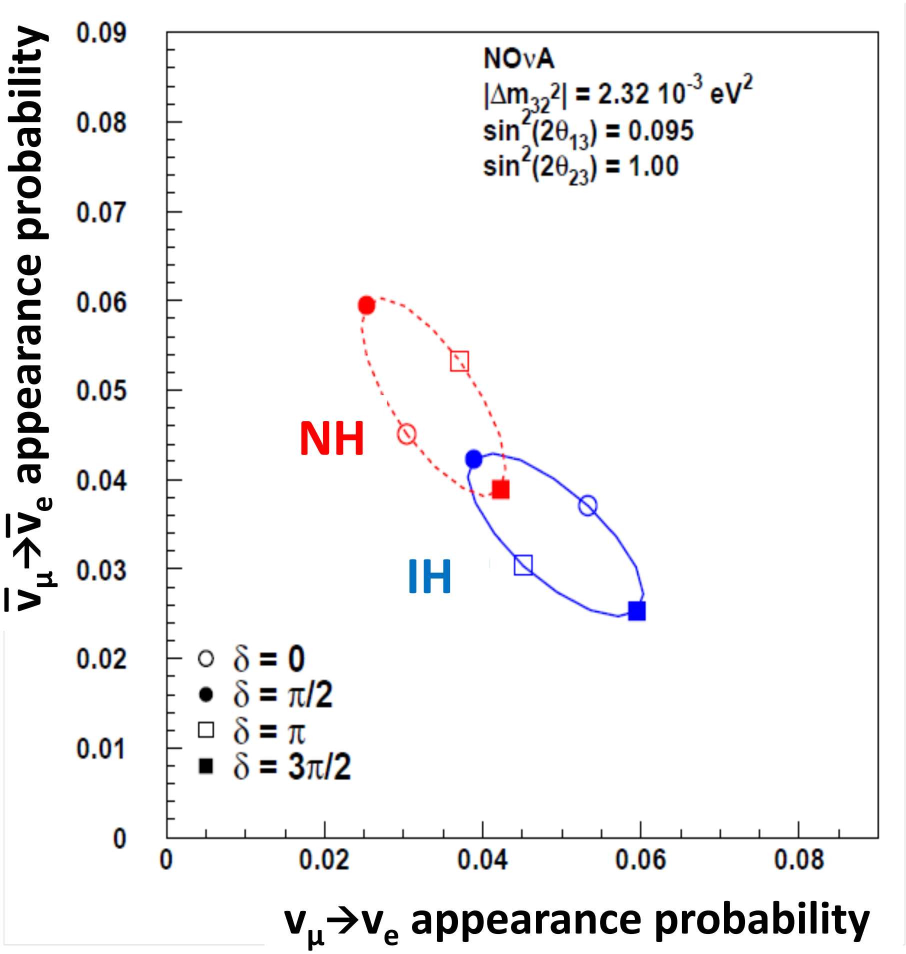
NOvA: degeneracy of MH and δ_{CP}



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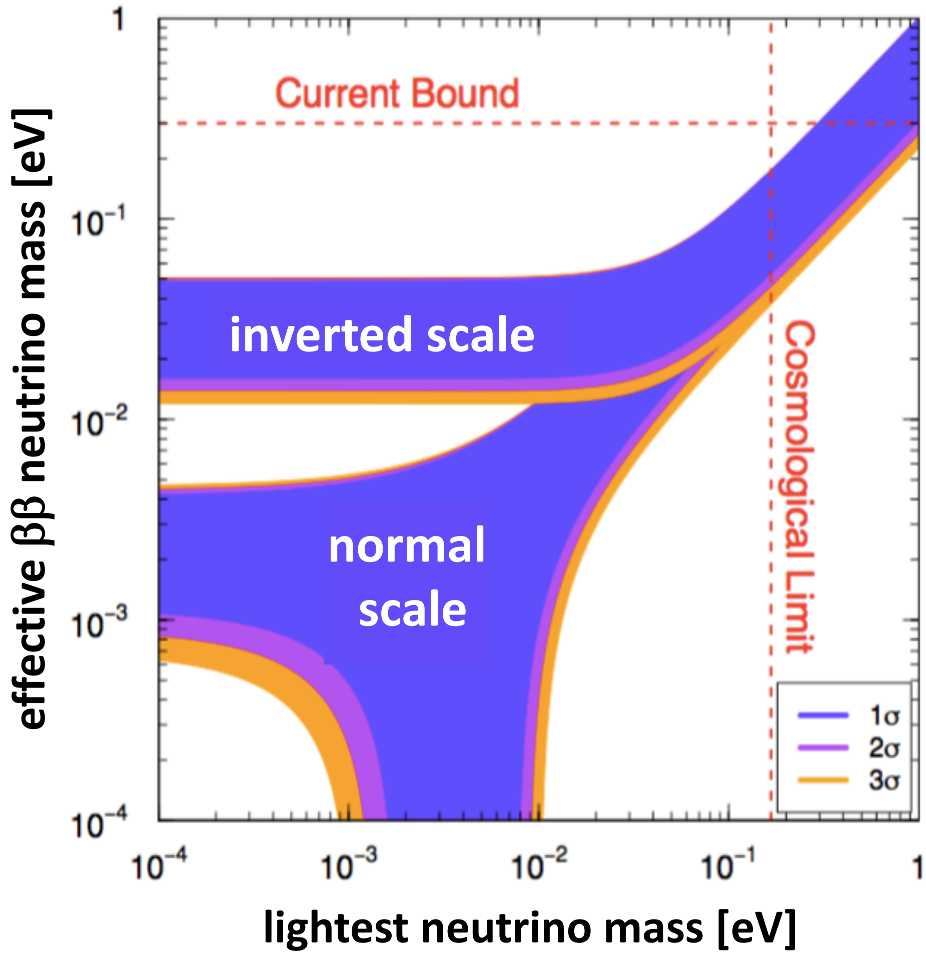
Lightest vs. effective ββ neutrino mass



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- combination with **cosmology** to resolve **neutrino masses**

Cosmological neutrino mass vs. MH