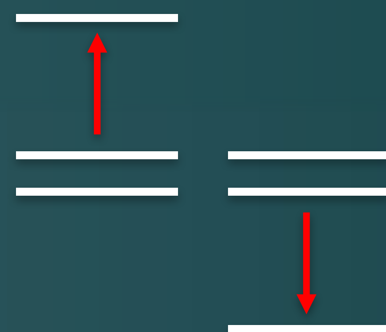
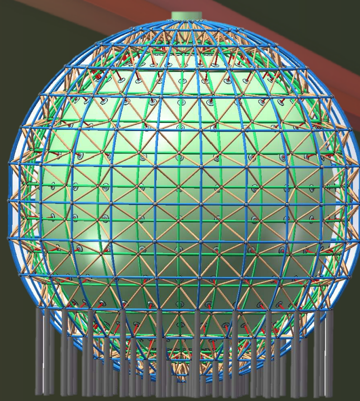
Neutrino Mass Hierarchy





KITP Nuclear Conference
Symmetry tests in nuclei and atoms
St. Barbara, 19 Sep 16

Michael Wurm

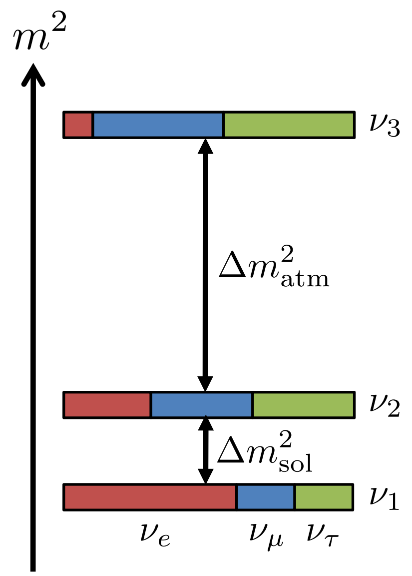
JG|U PRiSMA

Status of 3-flavor neutrino oscillations

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

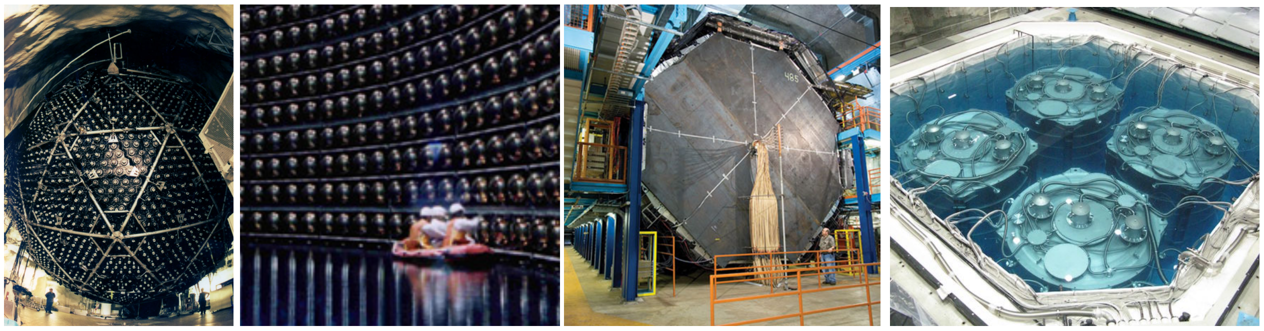
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} &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

atmospheric mixing	reactor mixing & CP violation	solar mixing
(maximal 45°?)	(small $\theta_{13}\approx 9°$, $\delta\neq 0$?)	(large 33°)



mass squared differences :

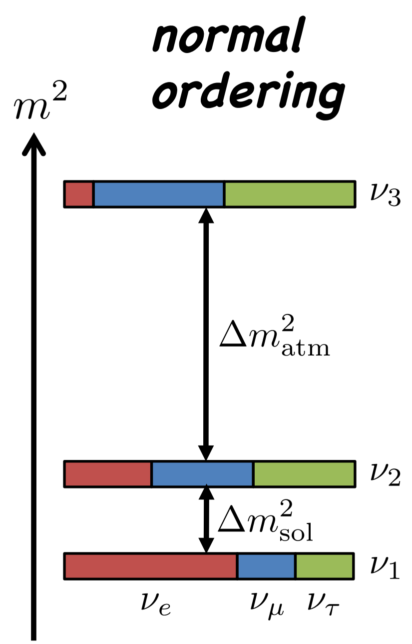
- $\Delta m^2_{\mathrm{sol}} = \Delta m^2_{21}$ → small splitting: $+8\mathrm{x}10^{-5}$ eV^2
- $\Delta m^2_{\mathrm{atm}} = \Delta m^2_{32} \approx \Delta m^2_{31}$ → large splitting: $\pm 2.5\mathrm{x}10^{-3}$ eV^2



Open issues in 3-flavor neutrino mixing

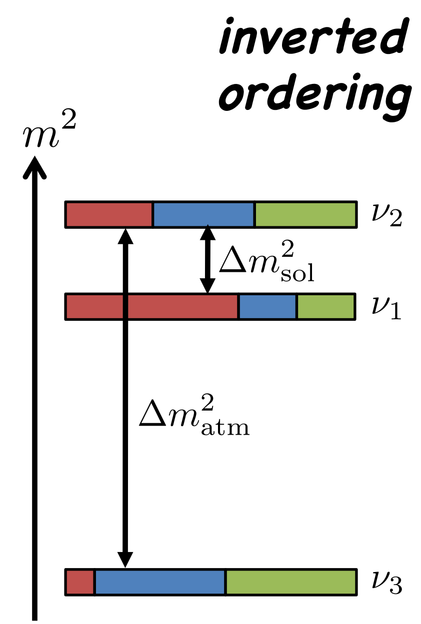
$$\mathbf{U_{3\times3}} = \mathbf{U}_{\mathrm{PMNS}}$$

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



What is the

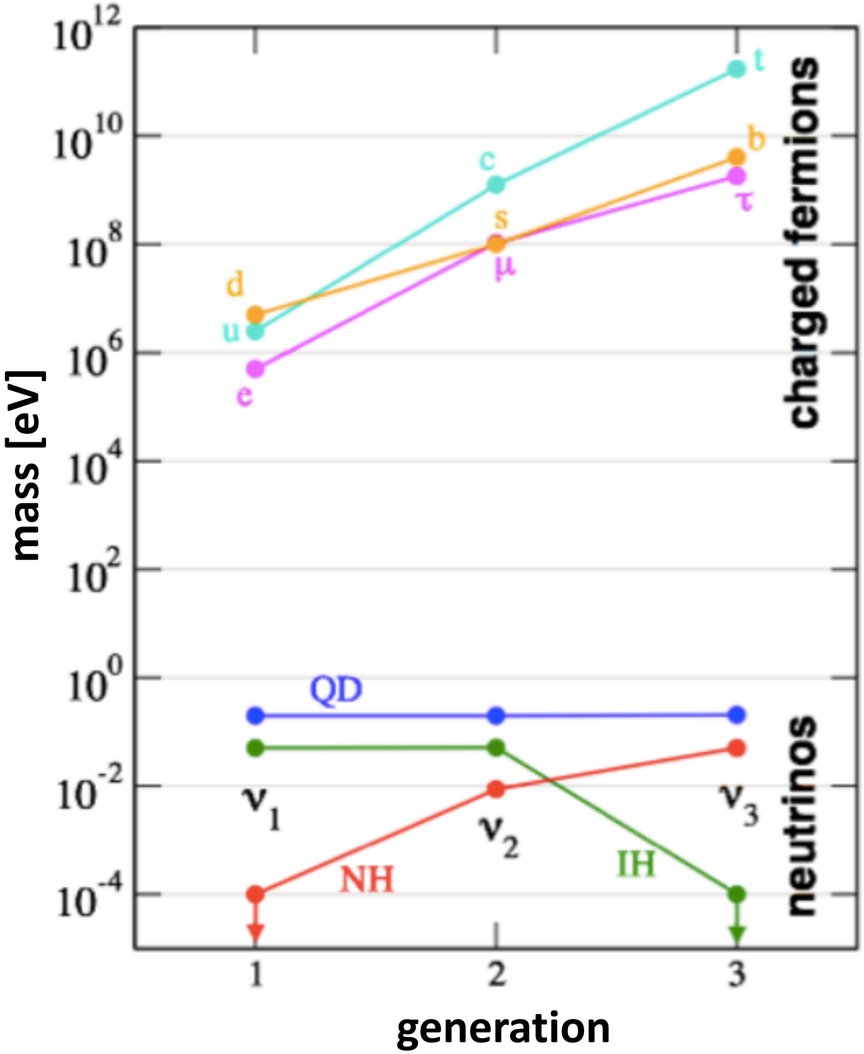
- **octant of θ_{23} ($\gtrless$ 45°)?**
- value of **CP-phase?**
- **mass hierarchy (MH)?** (sign of $\Delta m^2_{\mathrm{atm}}$)



MH: ‘Symmetries‘ in neutrino masses

- **Arrangement** of the neutrino masses
  - as in quark sector: $m_1 < m_2 < m_3$
    → normal hierarchy (NH)
  - opposed to it: $m_3 < m_1 < m_2$
    → inverted hierarchy (IH)
  - w/o clear ordering: $m_1 \approx m_2 \approx m_3$
    → quasi-degenerate (QD)

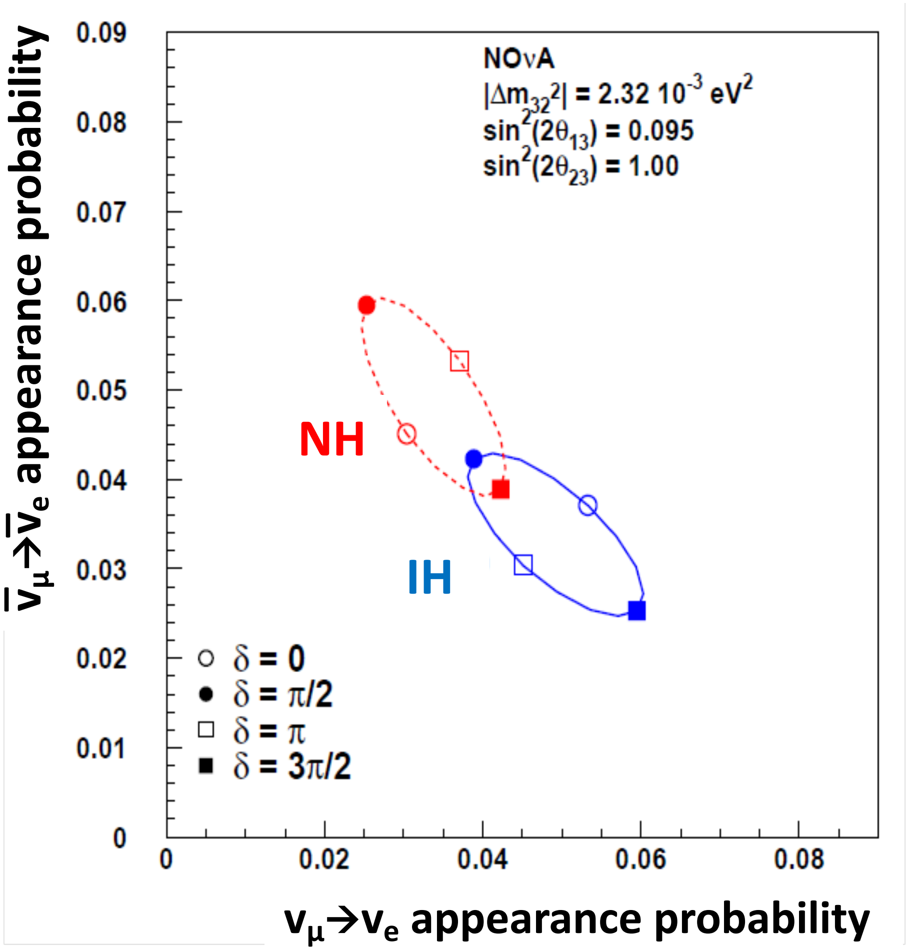
Fermion families and masses



MH: CP violation in the leptonic sector

- **Arrangement** of the neutrino masses
  - as in quark sector
    → normal hierarchy (NH)
  - opposed to it
    → inverted hierarchy (IH)
  - w/o clear ordering
    → quasi-degenerate (QD)
- resolving the **degeneracy in** the interpretation of **δ_{CP} measurements**

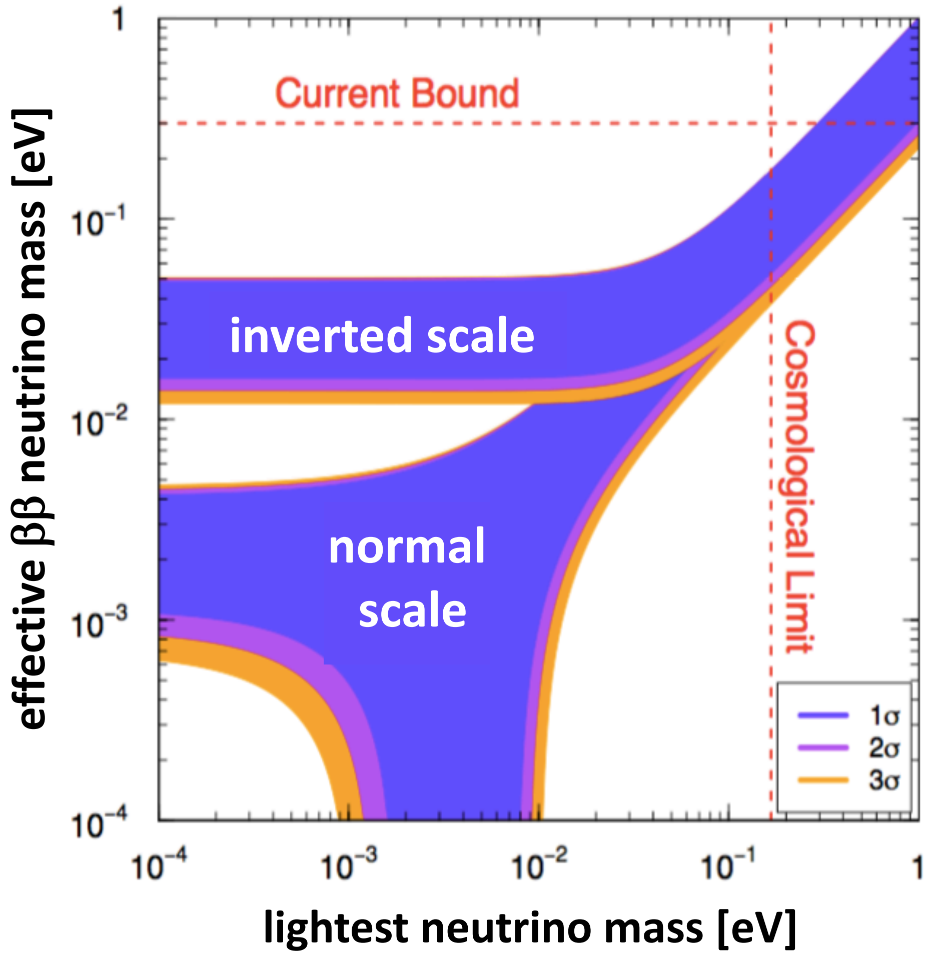
NOvA: degeneracy of MH and δ_{CP}



MH: Effective mass range of 0νββ decay

- **Arrangement** of the neutrino masses
  - as in quark sector
    → normal hierarchy (NH)
  - opposed to it
    → inverted hierarchy (IH)
  - w/o clear ordering
    → quasi-degenerate (QD)
- resolving the **degeneracy in** the interpretation of **δ_{CP} measurements**
- target range for **sensitivity** of **0νββ decay** experiments

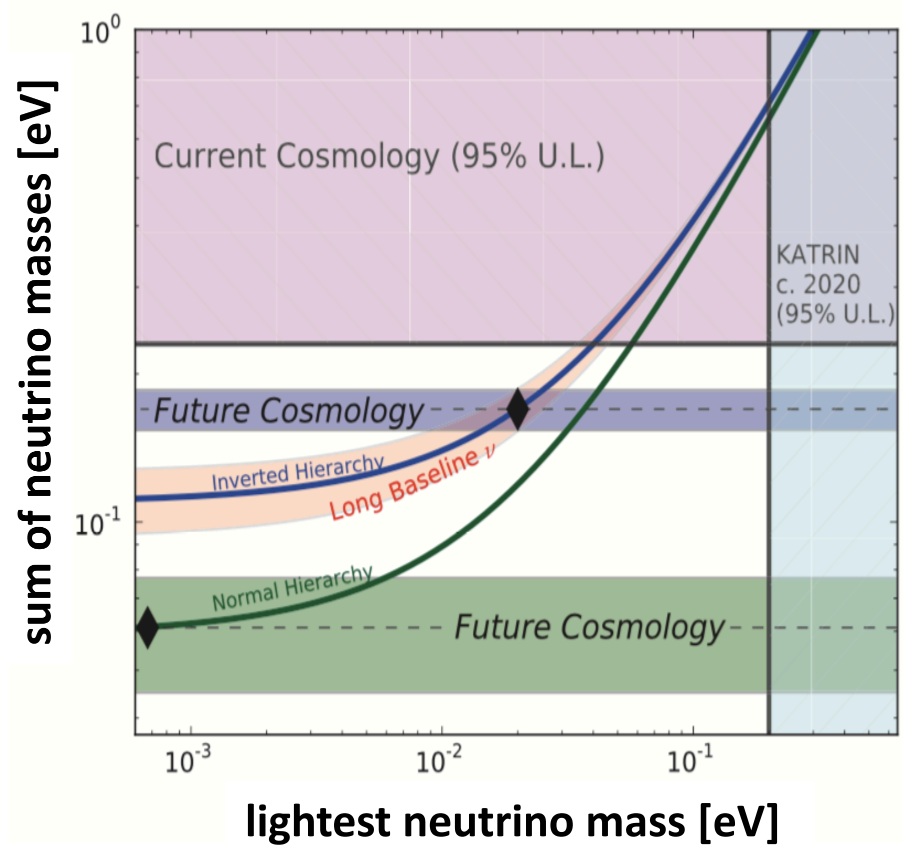
Lightest vs. effective ββ neutrino mass



MH: Absolute neutrino mass scale

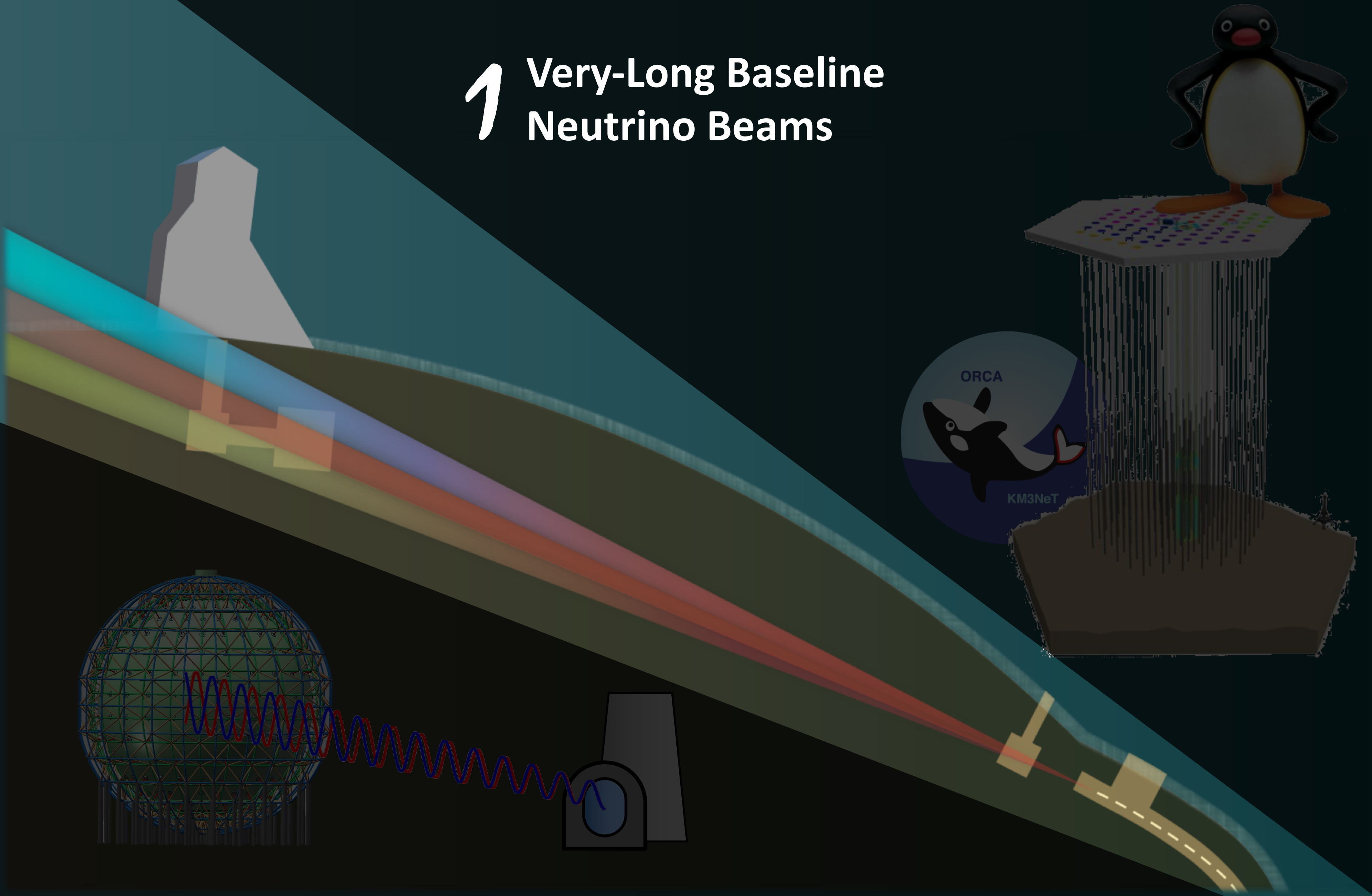
- **Arrangement** of the neutrino masses
  - as in quark sector
    → normal hierarchy (NH)
  - opposed to it
    → inverted hierarchy (IH)
  - w/o clear ordering
    → quasi-degenerate (QD)
- resolving the **degeneracy in** the interpretation of **δ_{CP} measurements**
- target range for **sensitivity** of **0νββ decay** experiments
- combination with **cosmology** to find **lightest neutrino mass**

Cosmological neutrino mass vs. MH



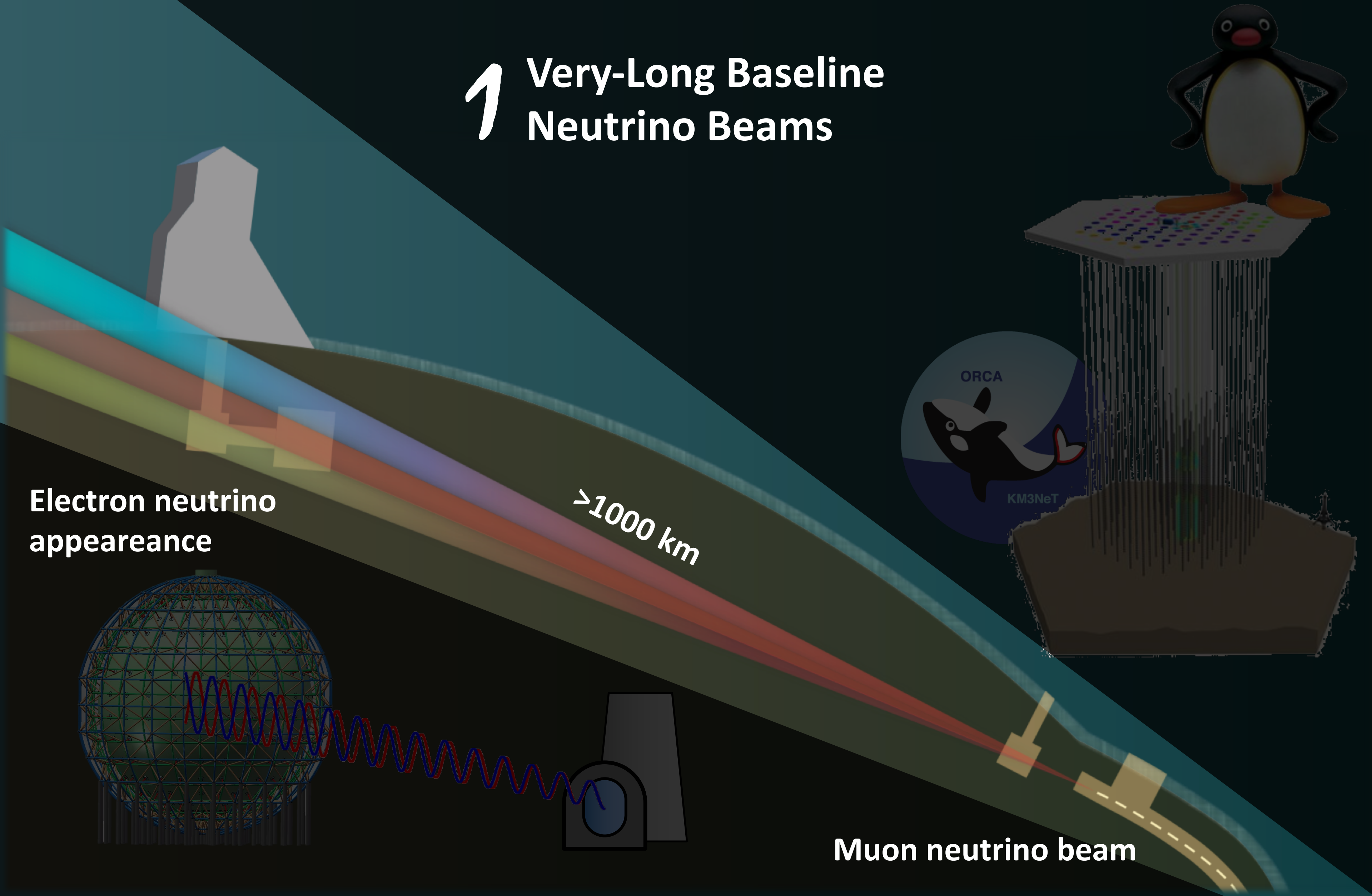
Concepts for MH measurement

1 Very-Long Baseline Neutrino Beams



Concepts for MH measurement

1 Very-Long Baseline Neutrino Beams



Long Baseline Beams: $\nu_\mu \rightarrow \nu_e$ appearance

Oscillation probability for ν_e appearance
in a ν_μ neutrino beam:

good approximation for 1st atmospheric oscillation maximum

$$P_{\mu e(\bar{\mu}\bar{e})} = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2\sin^2\left(\frac{B_\pm L}{2}\right)$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\left(\frac{AL}{2}\right)$$
$$+J\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_\pm}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{B_\pm L}{2}\right)\cos\left(\mp\delta-\frac{\Delta_{13}L}{2}\right)$$

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

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

Long Baseline Beams: $\nu_\mu \rightarrow \nu_e$ appearance

Oscillation probability for ν_e appearance
in a ν_μ neutrino beam:

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

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

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

neutrino-antineutrino asymmetry term

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

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

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

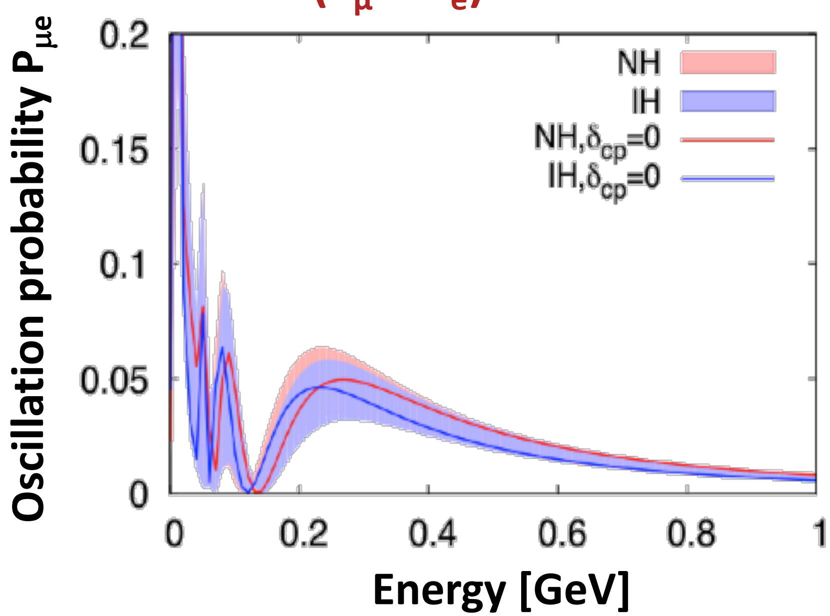
$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu} \qquad B_\pm = |A \pm \Delta_{13}| \qquad A = \sqrt{2}G_F N_e$$

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

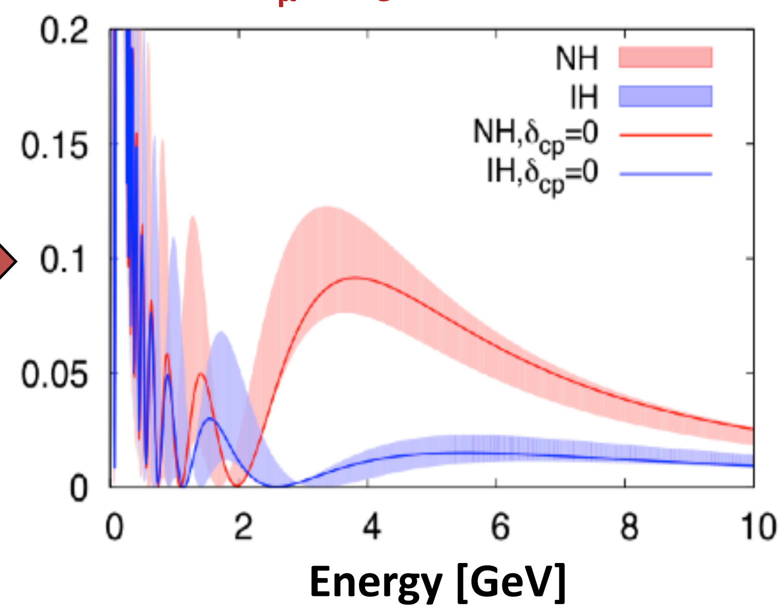
Oscillation patterns for long-baseline beam

- **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

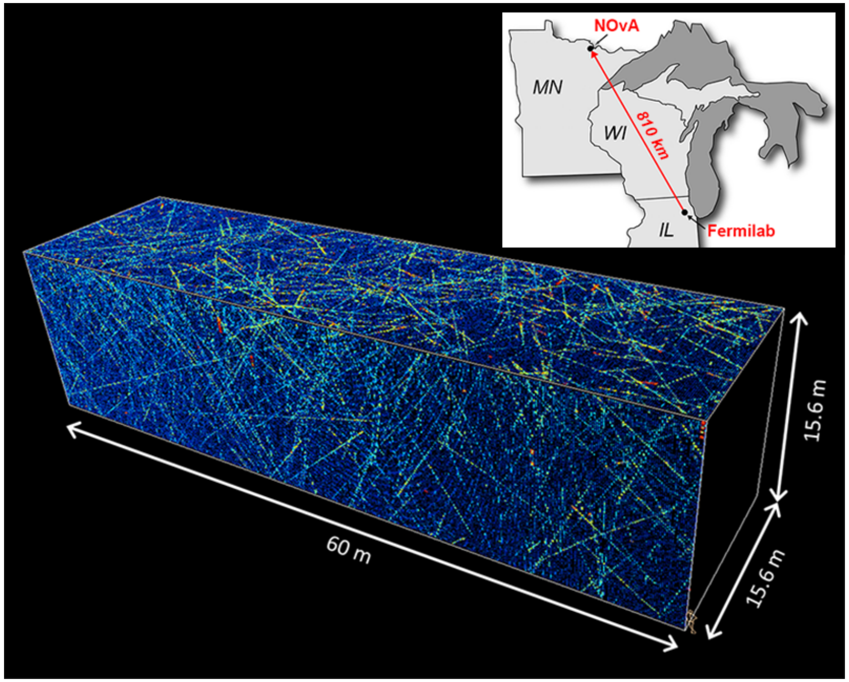


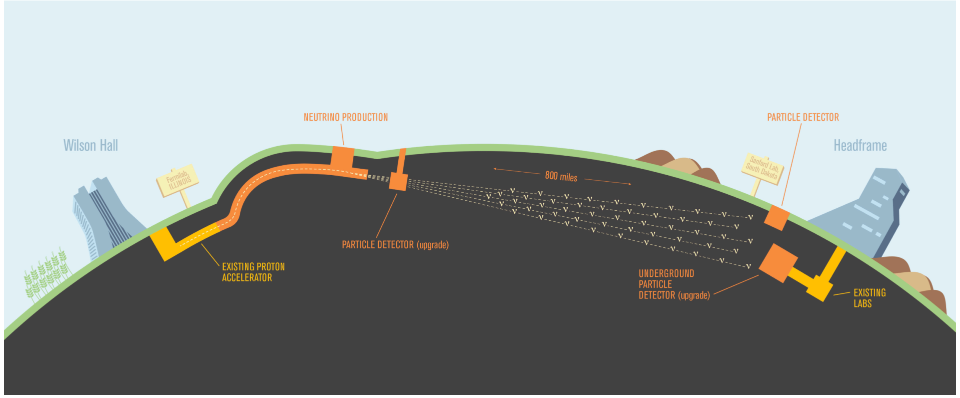
P($\nu_\mu \rightarrow \nu_e$) for 2300 km



- **Far detector** at first atmospheric oscillation maximum:
  longer baseline → larger energy → larger matter effect!

Long-baseline oscillation experiments





NOvA

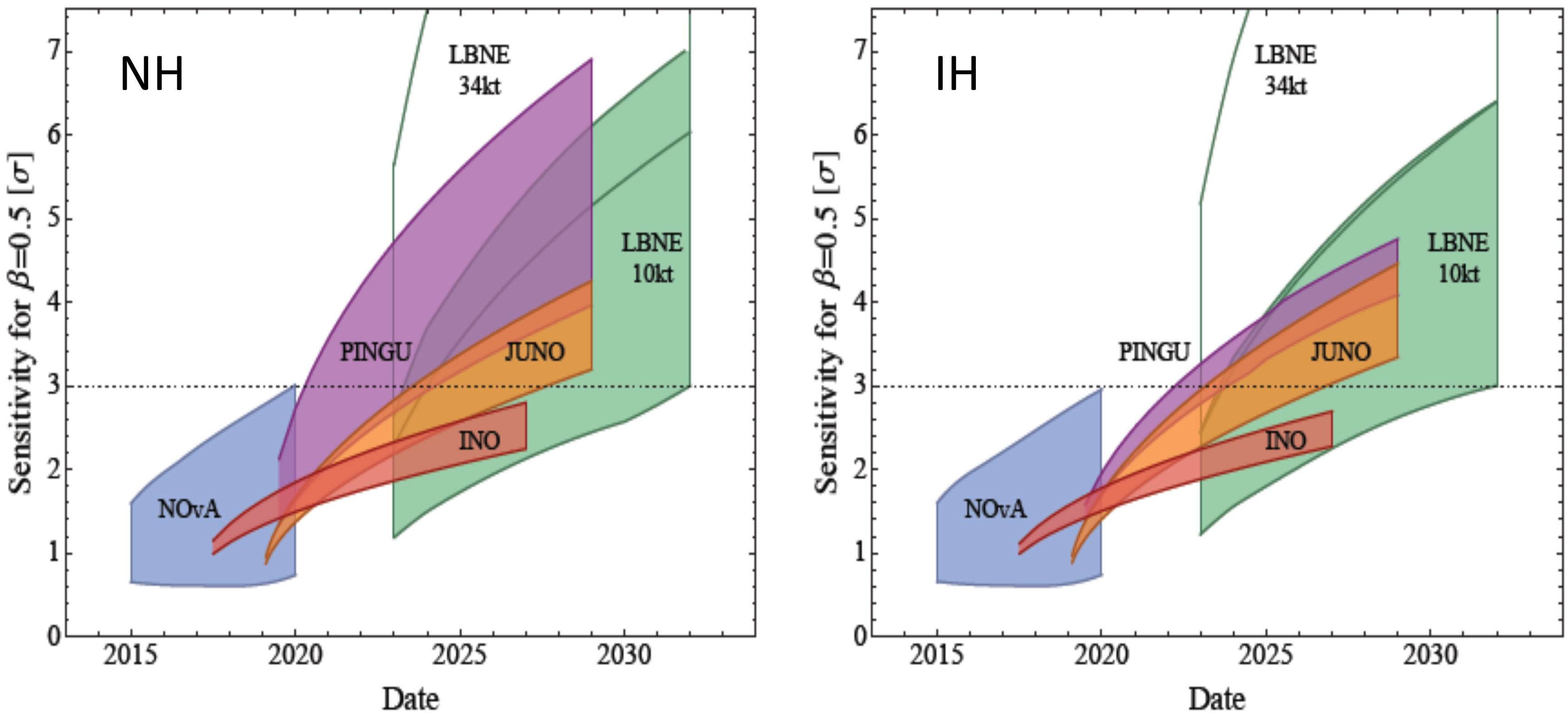
- baseline: 810km
- alignment: 16 mrad off-axis
- spectrum: (2±1) GeV
- beam power: 400kW
- detector: 14kt of segmented scintillator

LBNF/DUNE

- baseline: 1300km
- alignment: on-axis
- wide-band beam, 3.5 GeV
- beam power: 700kW
- detector: 4x10kt LAr TPC

Experimental sensitivities to MH

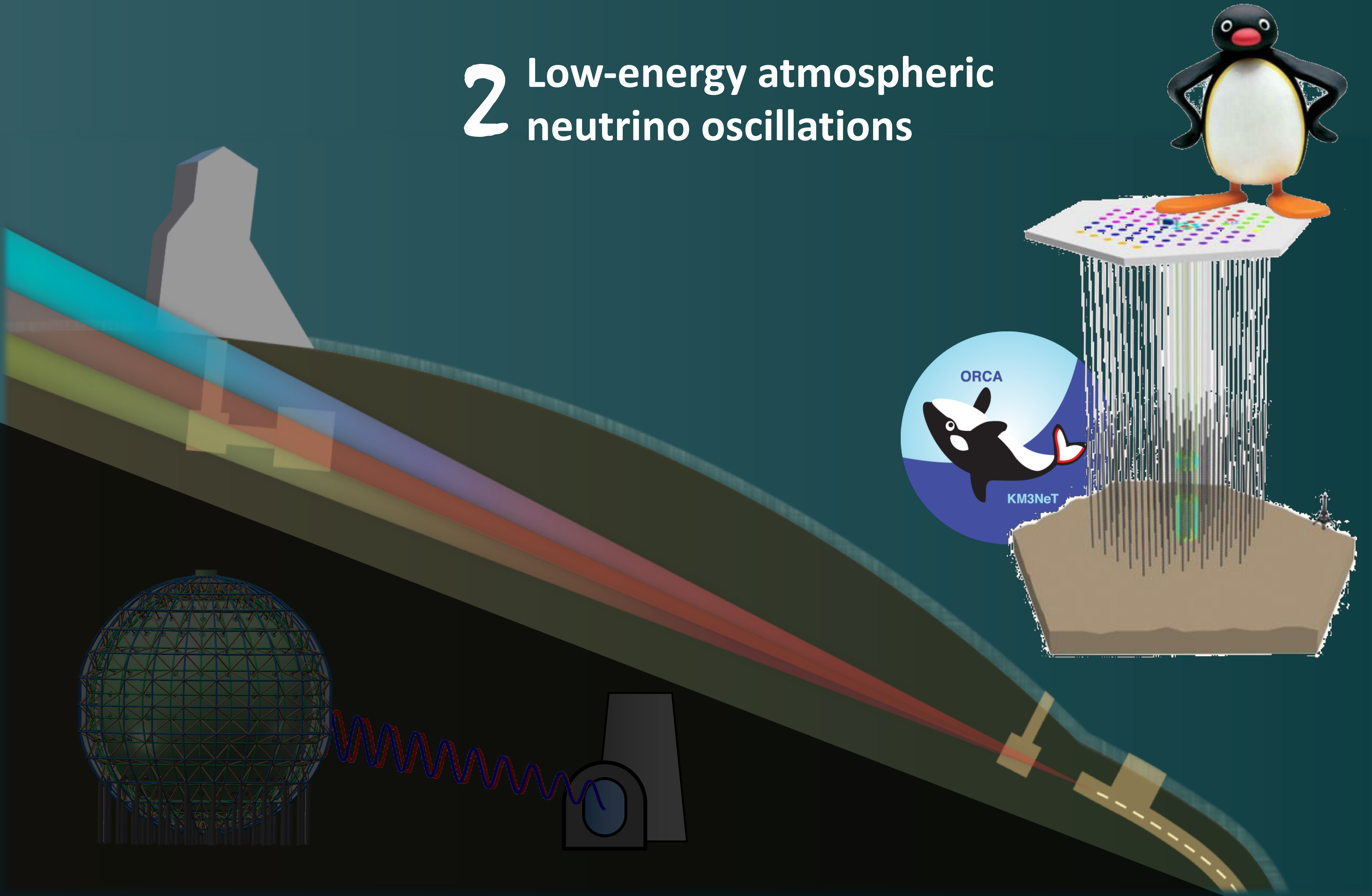
Blennow, Schwetz, arXiv:1311.1822



Experimental technique	Mode	Dominant factor
▪ long-baseline beams: NOvA, DUNE ...	$\nu_\mu \rightarrow \nu_e$	value of δ_{CP}
▪ atmospheric ν's: INO, PINGU, ORCA, HK ...	$\nu_\mu \rightarrow \nu_\mu$	value of θ_{23}=40-50°
▪ reactor neutrinos: JUNO, RENO-50 ...	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	energy res. (3-3.5%)

Concepts for MH measurement

2 Low-energy atmospheric neutrino oscillations



MH from atmospheric neutrinos

Source: Atmospheric μ-neutrinos

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

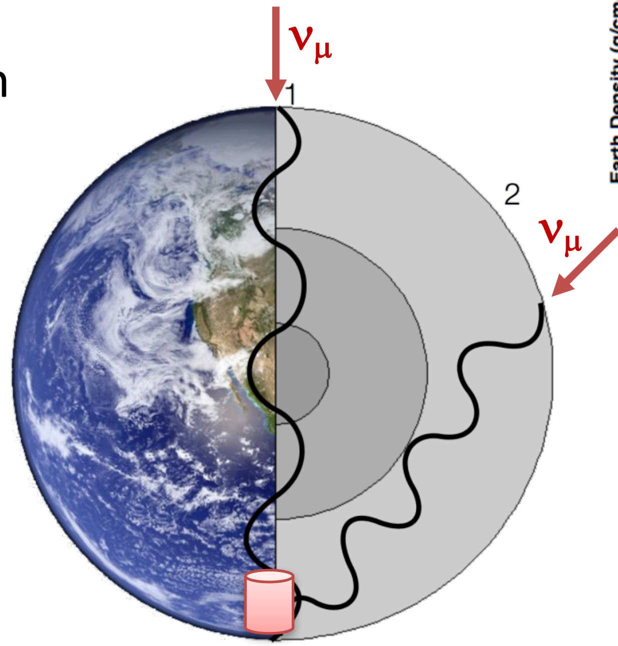
MH signature

matter effects in

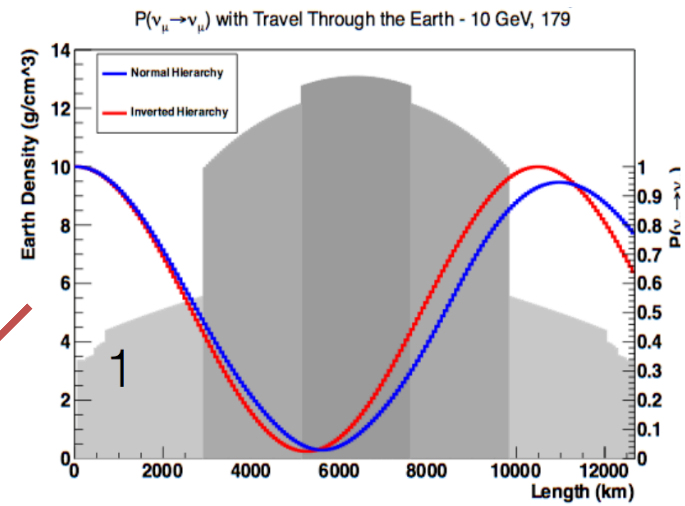
- $\nu_\mu \rightarrow \nu_\mu$ disappearance
- $\nu_\mu \rightarrow \nu_e$ appearance

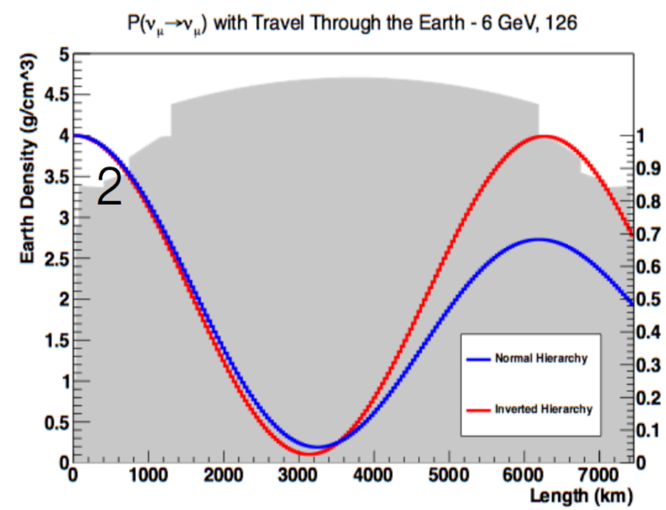
Detector requirements

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



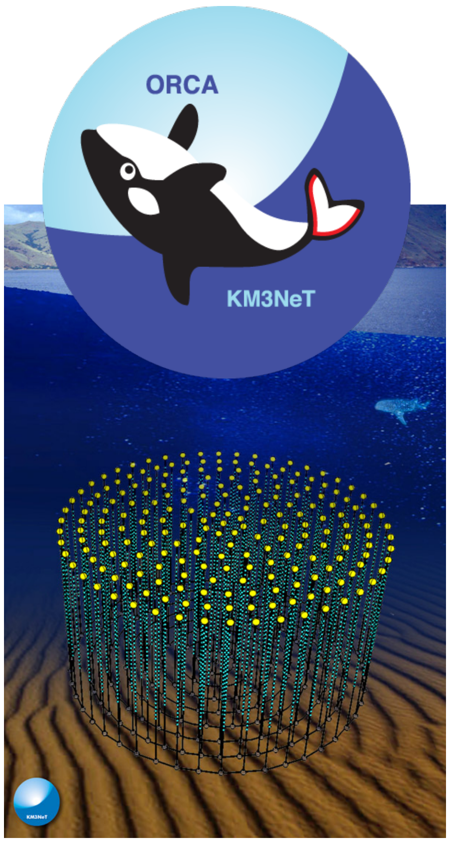
D. Grant

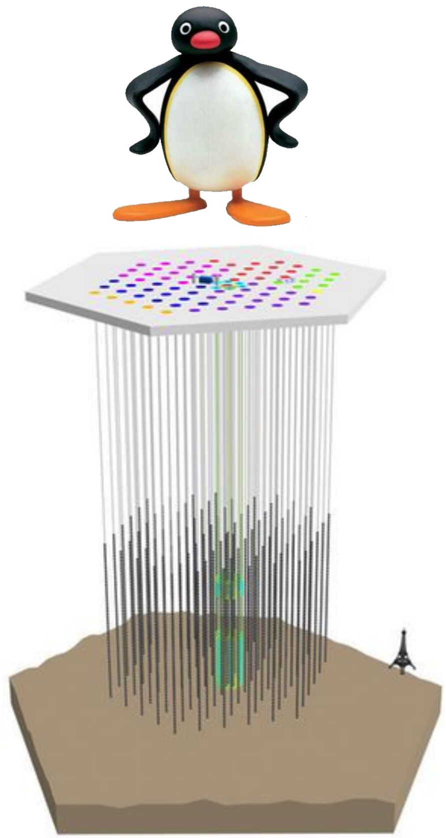




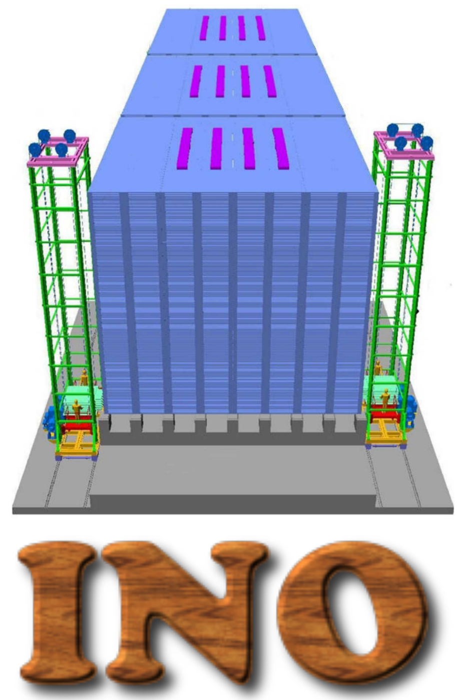
Projects with atmospheric MH sensitivity

Cosmic neutrino telescopes
→ low energy extensions

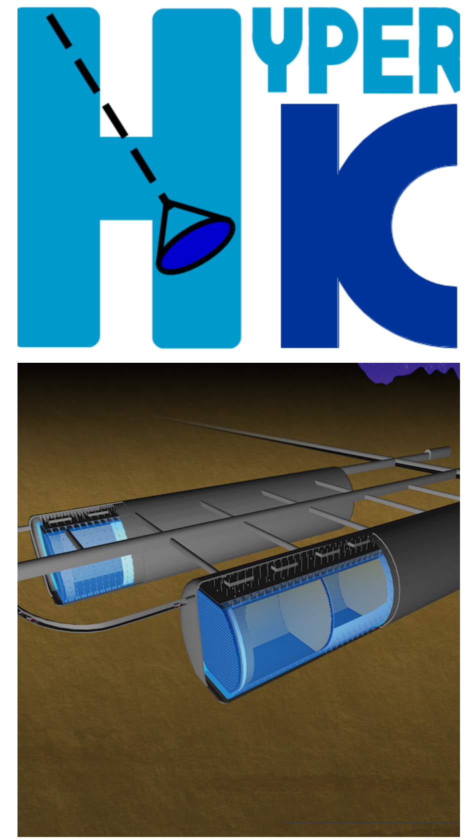




Magnetized Iron



Low-energy detectors
→ extended target size

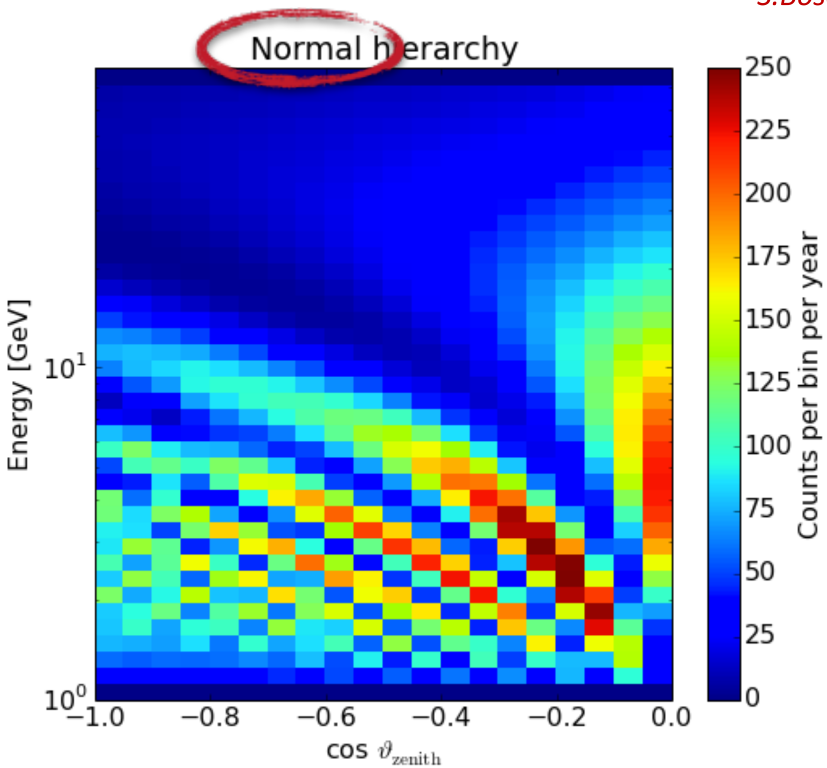


Atmospheric ν signal observed in PINGU

S.Böser

Event statistics

- ν_μ: 5.0x10^4 yr^{-1}
- ν_e: 3.8x10^4 yr^{-1}



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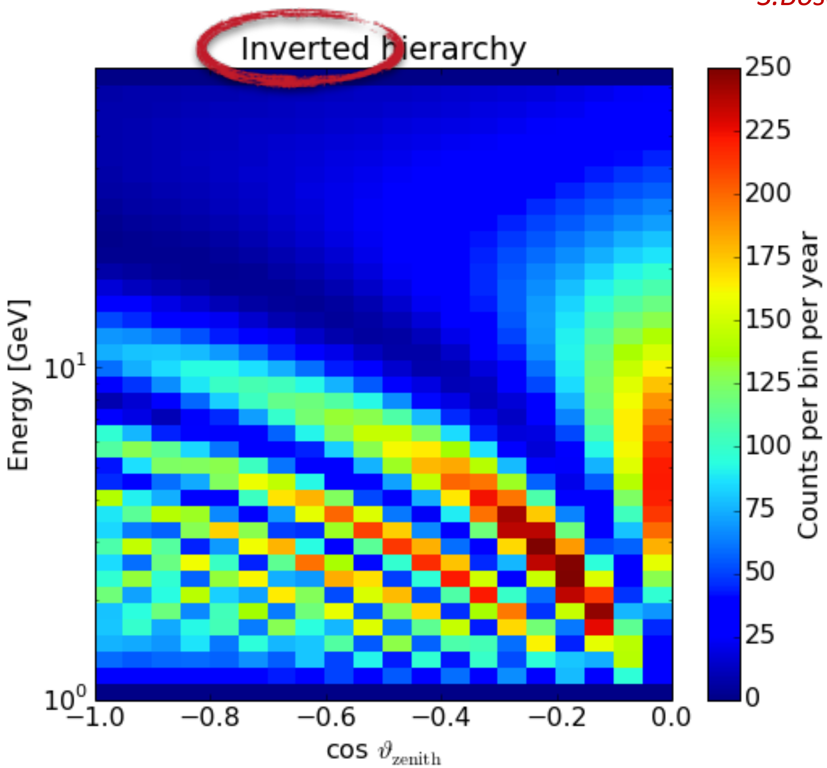

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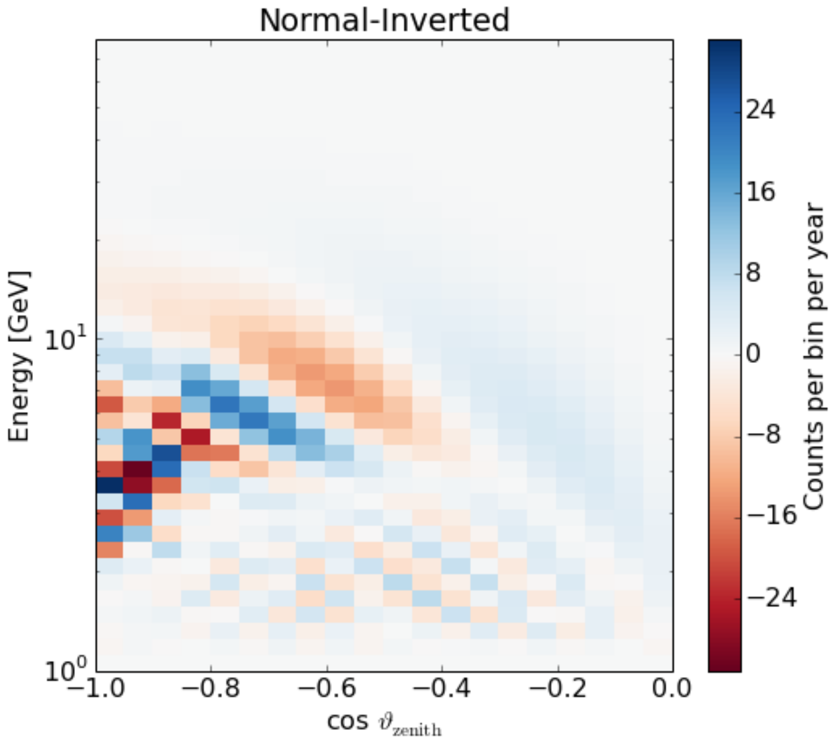
→ detectable difference



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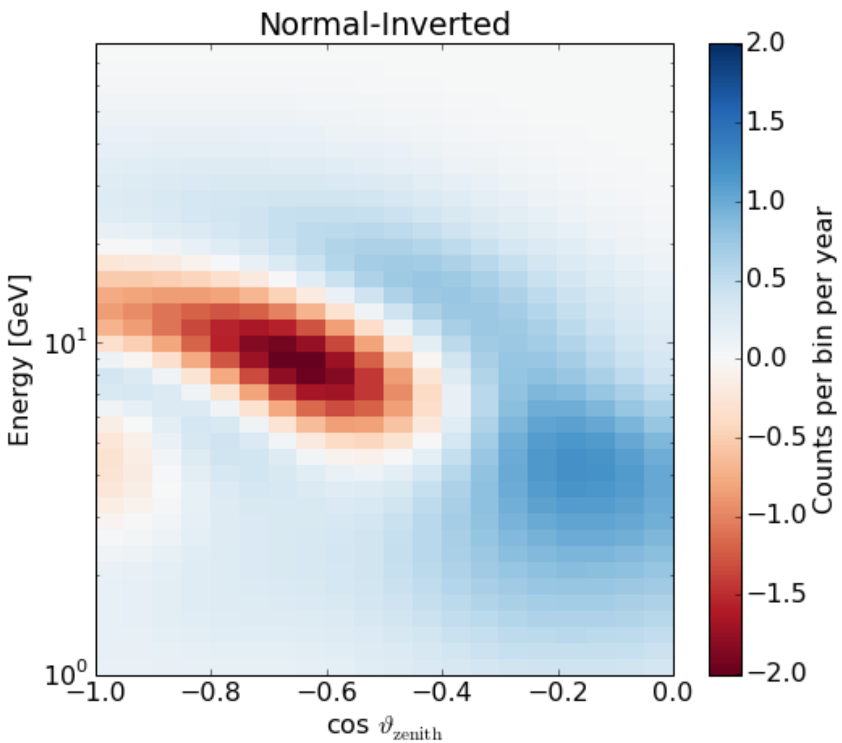
→ detectable difference

Detector resolution

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



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→ detectable difference

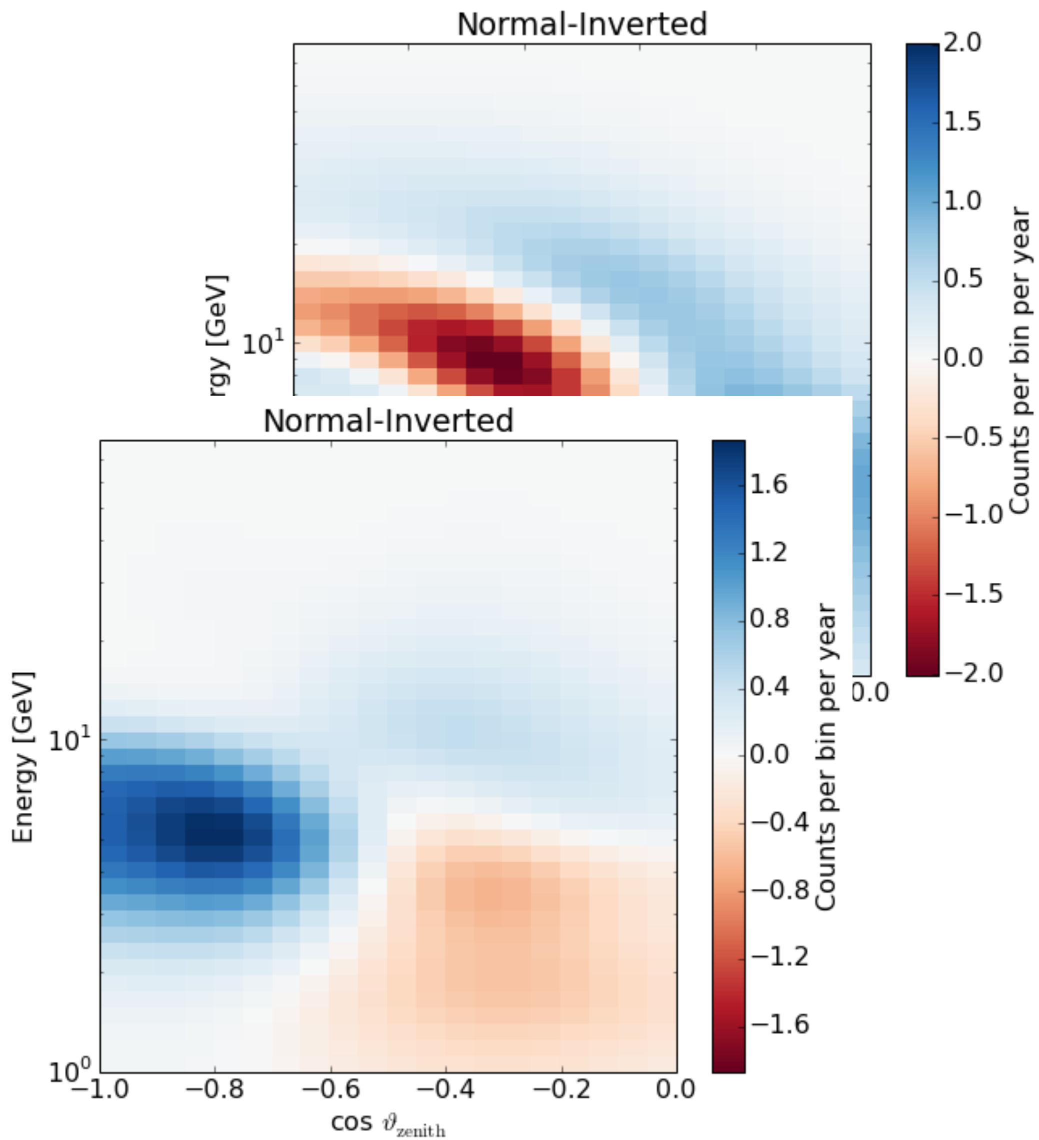
Detector resolution

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

Particle identification

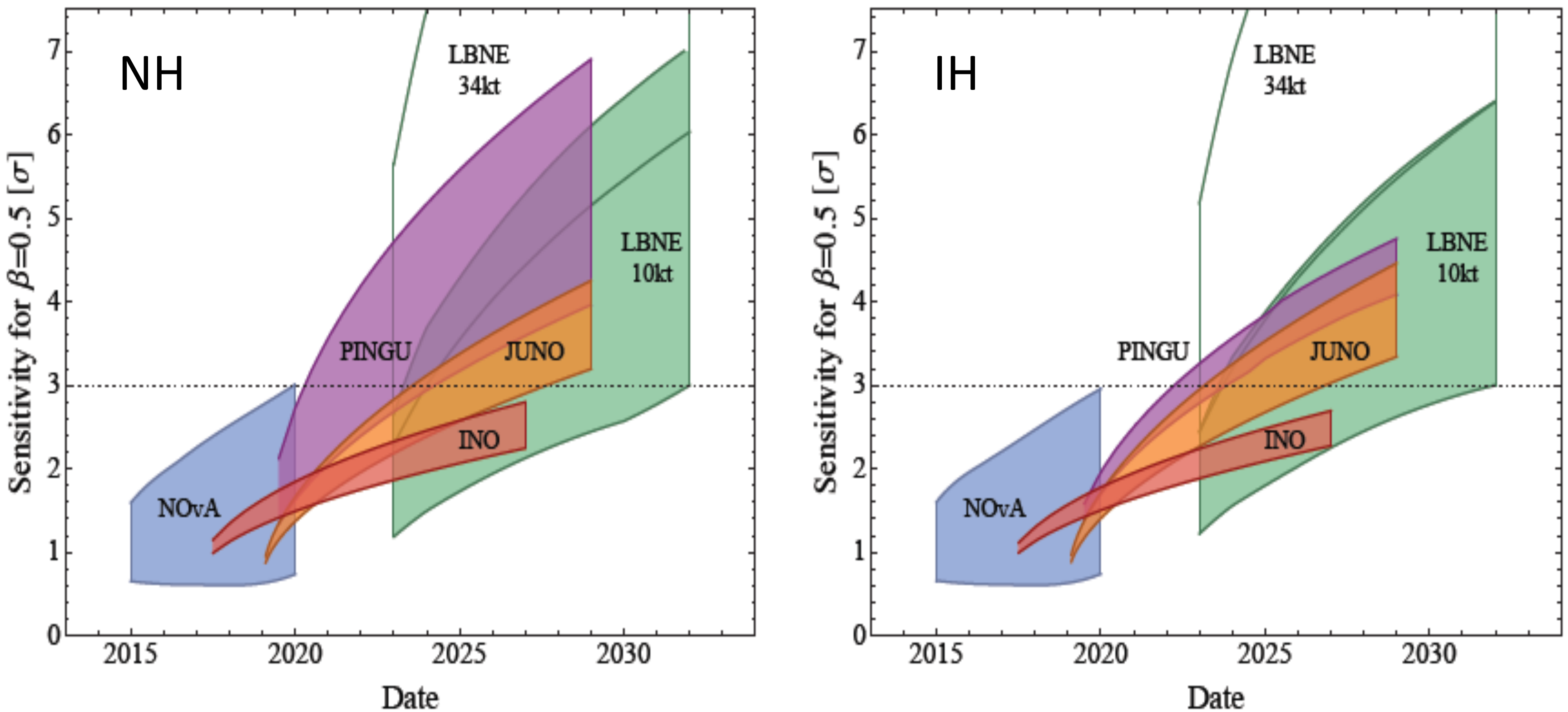
- ν_μ (CC): tracks
- ν_e (CC) + ν_x (NC): cascades

→ distinction of event types



Experimental sensitivities to MH

Blennow, Schwetz, arXiv:1311.1822



Experimental technique	Mode	Dominant factor
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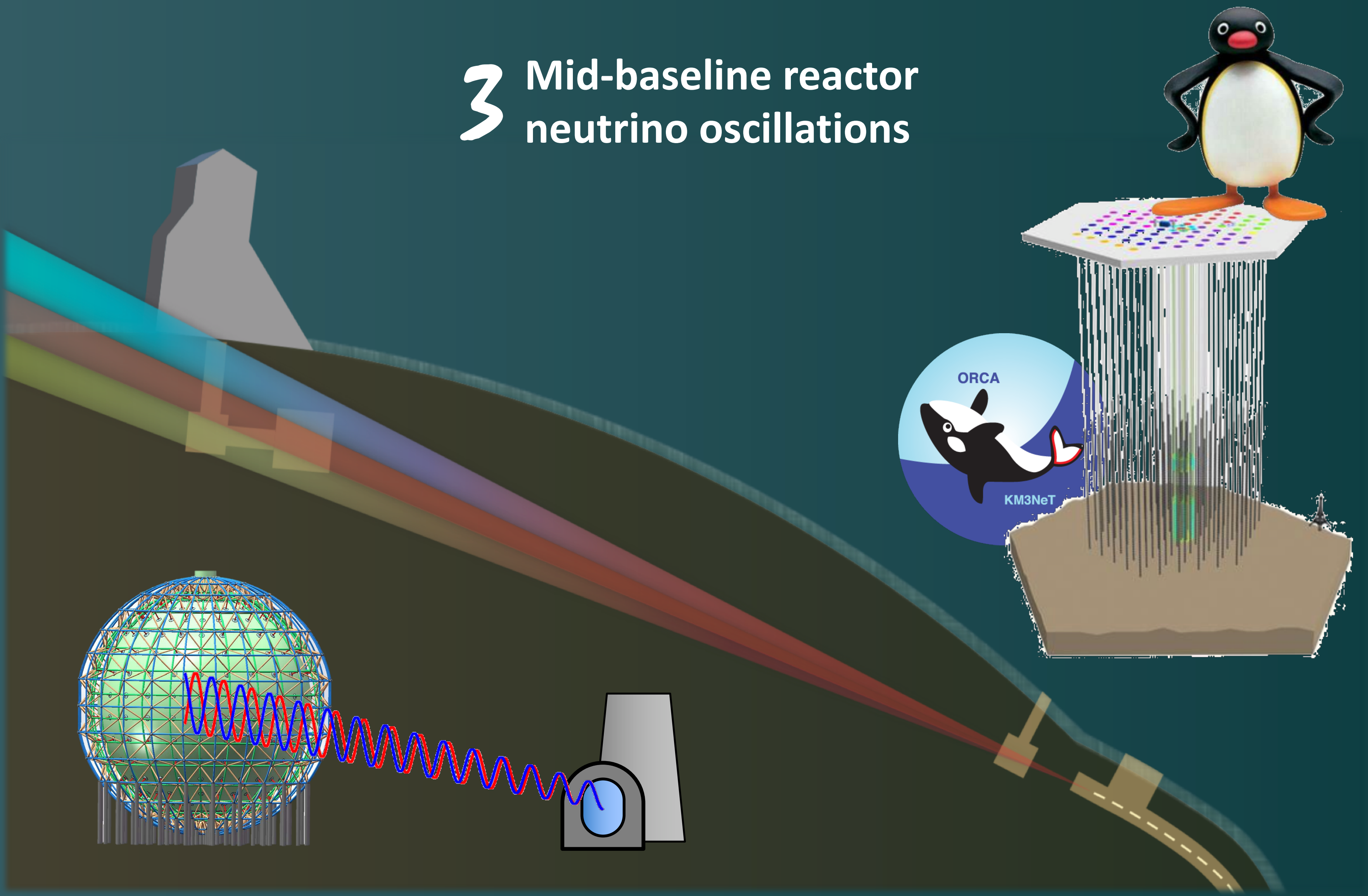
▪ atmospheric ν's: INO, PINGU, ORCA, HK ...	$\nu_\mu \rightarrow \nu_\mu$	value of θ_{23}=40-50°
▪ reactor neutrinos: JUNO, RENO-50 ...	$\overline{\nu}_e \rightarrow \overline{\nu}_e$	energy res. (3-3.5%)

Concepts for MH measurement

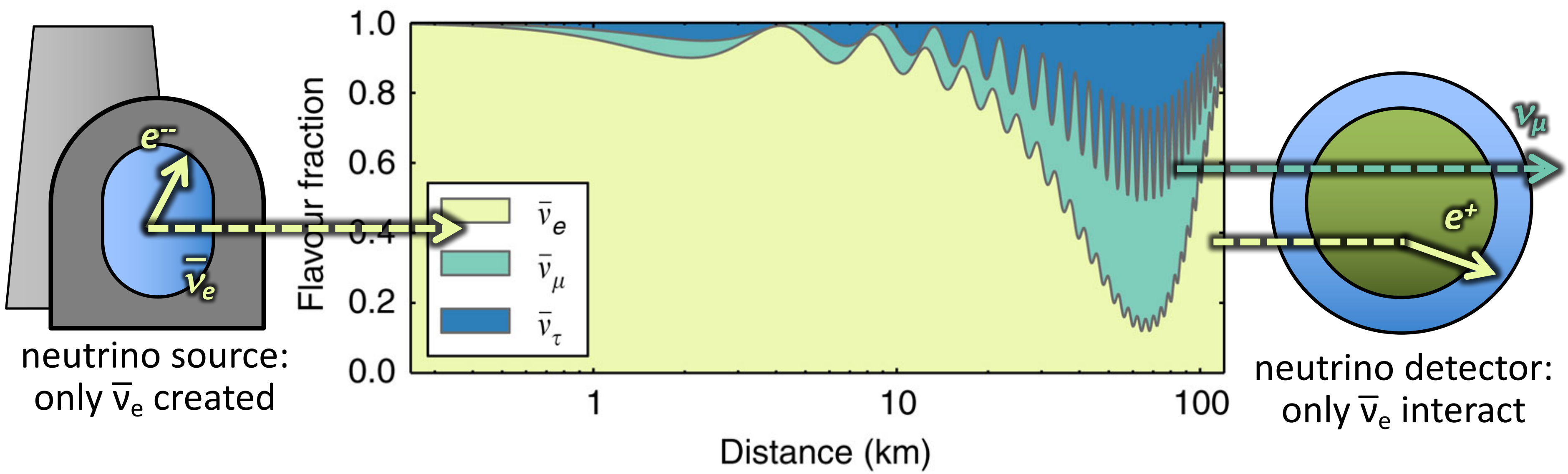
3 Mid-baseline reactor neutrino oscillations



Reactor neutrino oscillation experiments

Common three-flavor reactor electron-antineutrino survival probability:

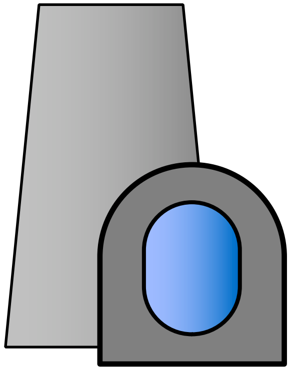
$$P_{ee} = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}}{4E}\right) - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}}{4E}\right)$$

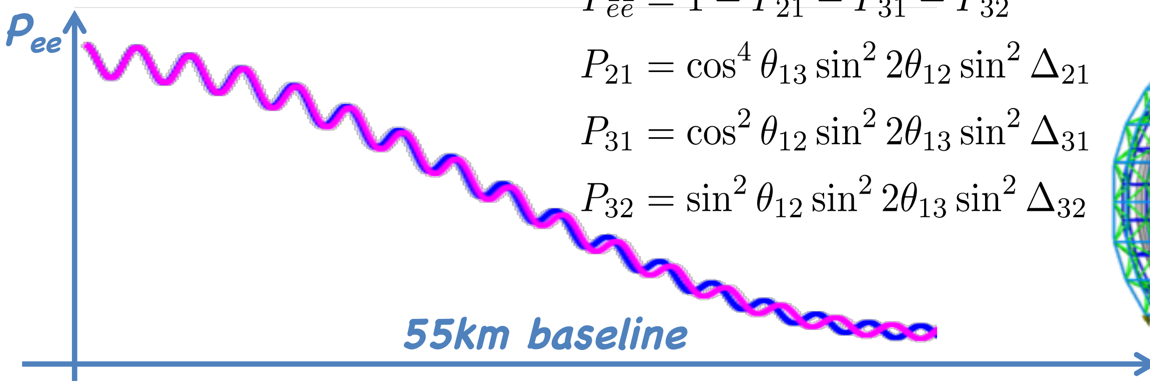


→ oscillation parameters are extracted from **$\bar{\nu}_e$ disappearance pattern**

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

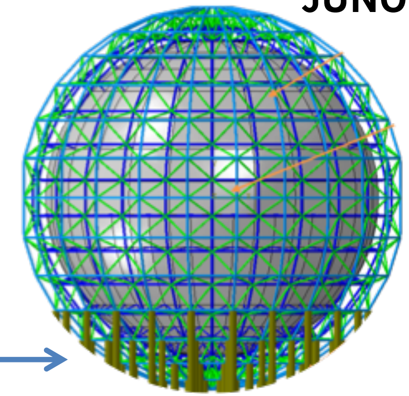
Reactor ν signal at 53km distance





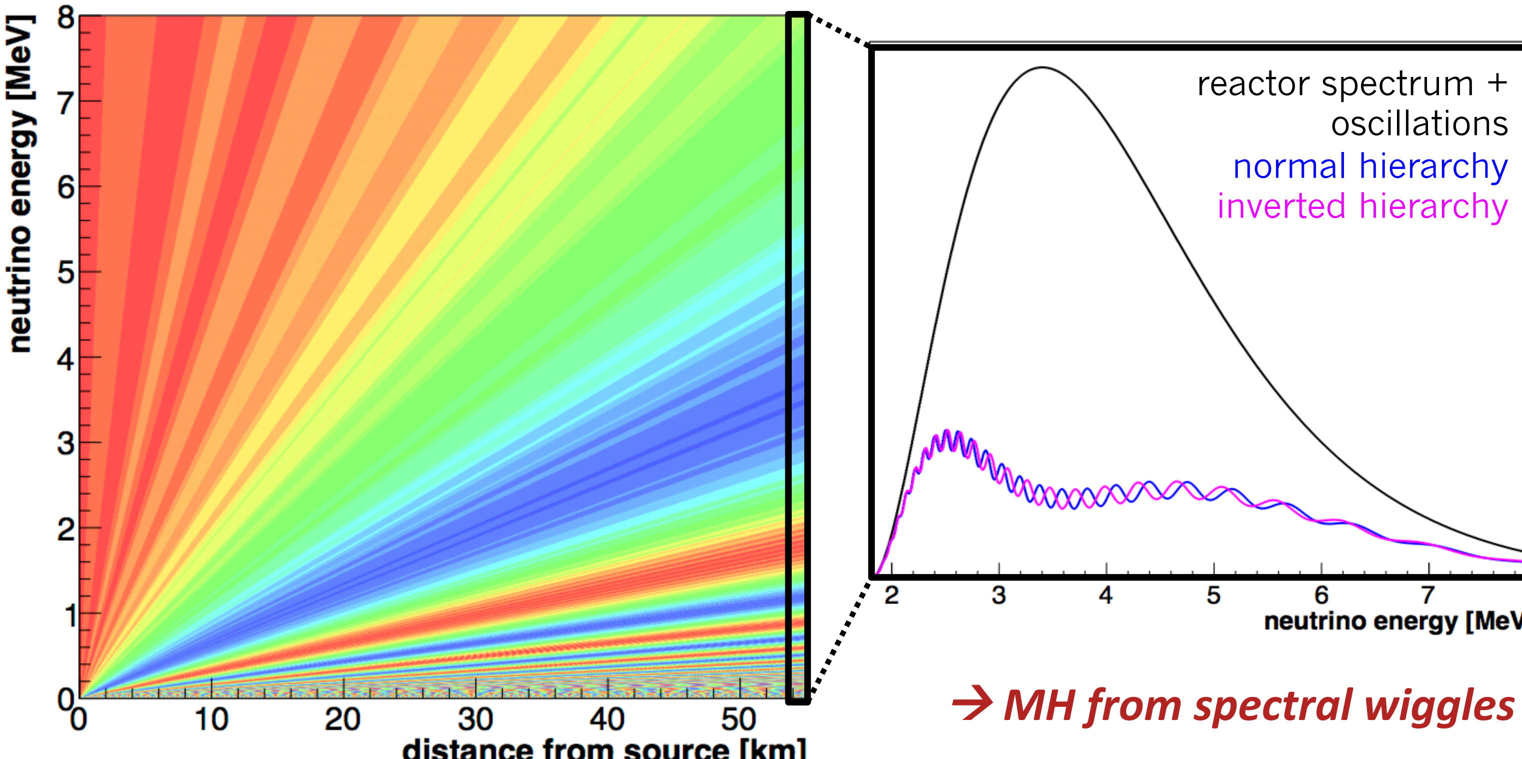
$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$
$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

JUNO



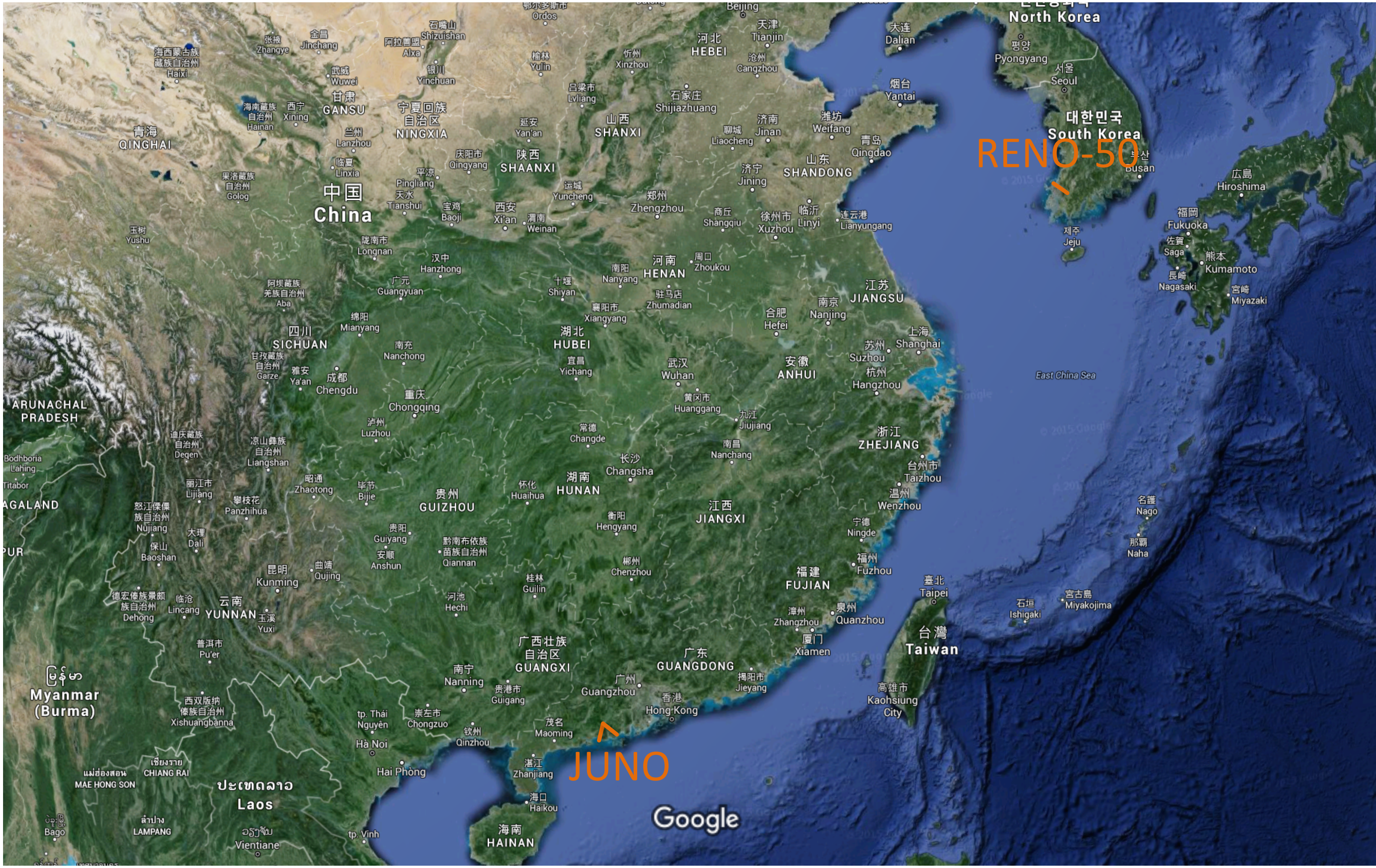
Nuclear reactors at
- *Yangjiang*
- *Taishan*
  (so. China)

Total power:
38 GW



→ MH from spectral wiggles

Reactor experiments for MH



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Basic detector requirements for JUNO

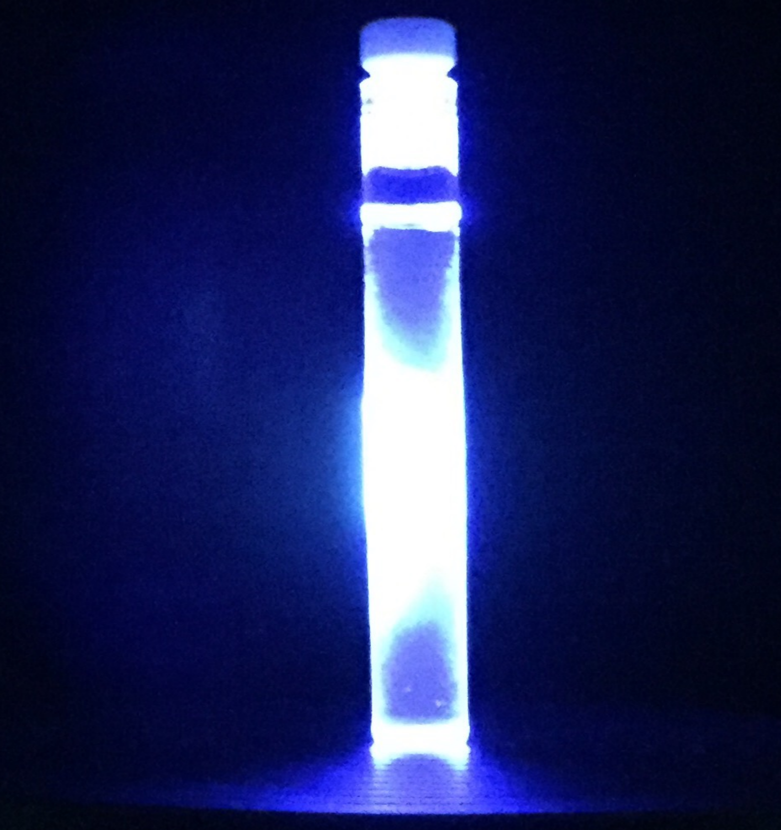
- reactor antineutrinos at MeV energies
  → **Liquid-scintillator detector**
  → Detection by inverse beta decay

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

- 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 detector layout

Outer water tank
Muon Cherenkov veto

Top muon veto
Scintillator panels

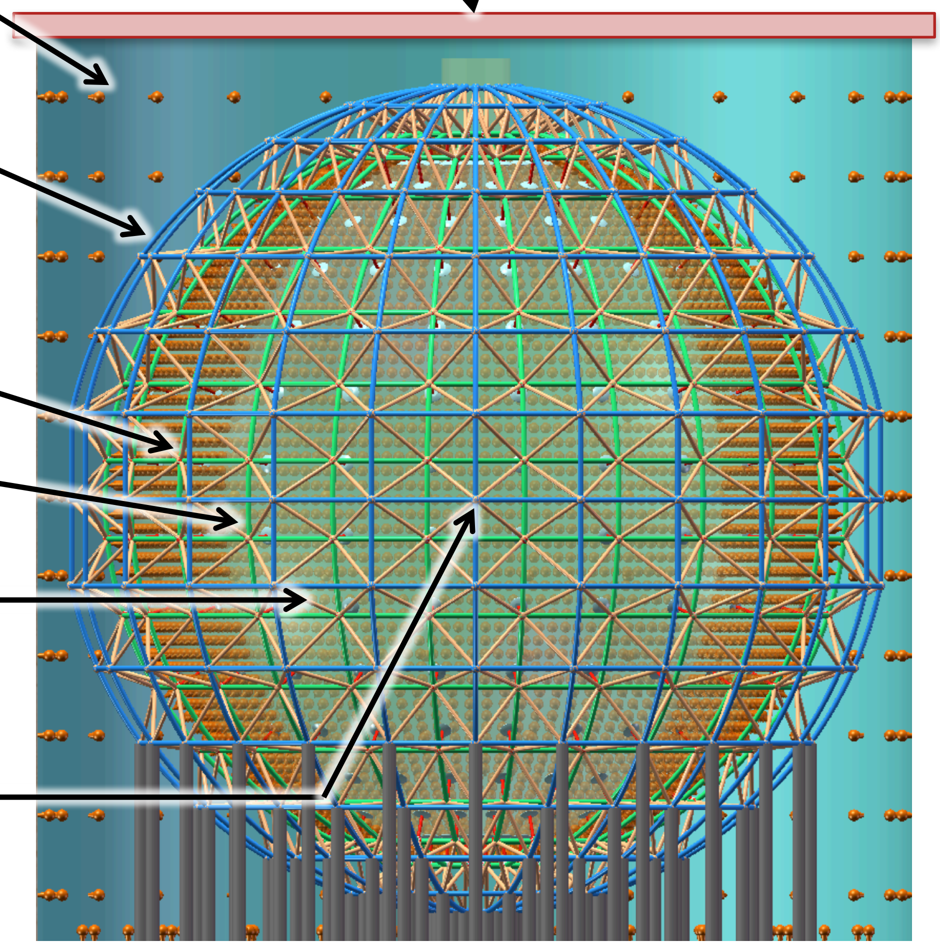
Steel support structure
optical separation

17,000 PMTs (20‘‘)

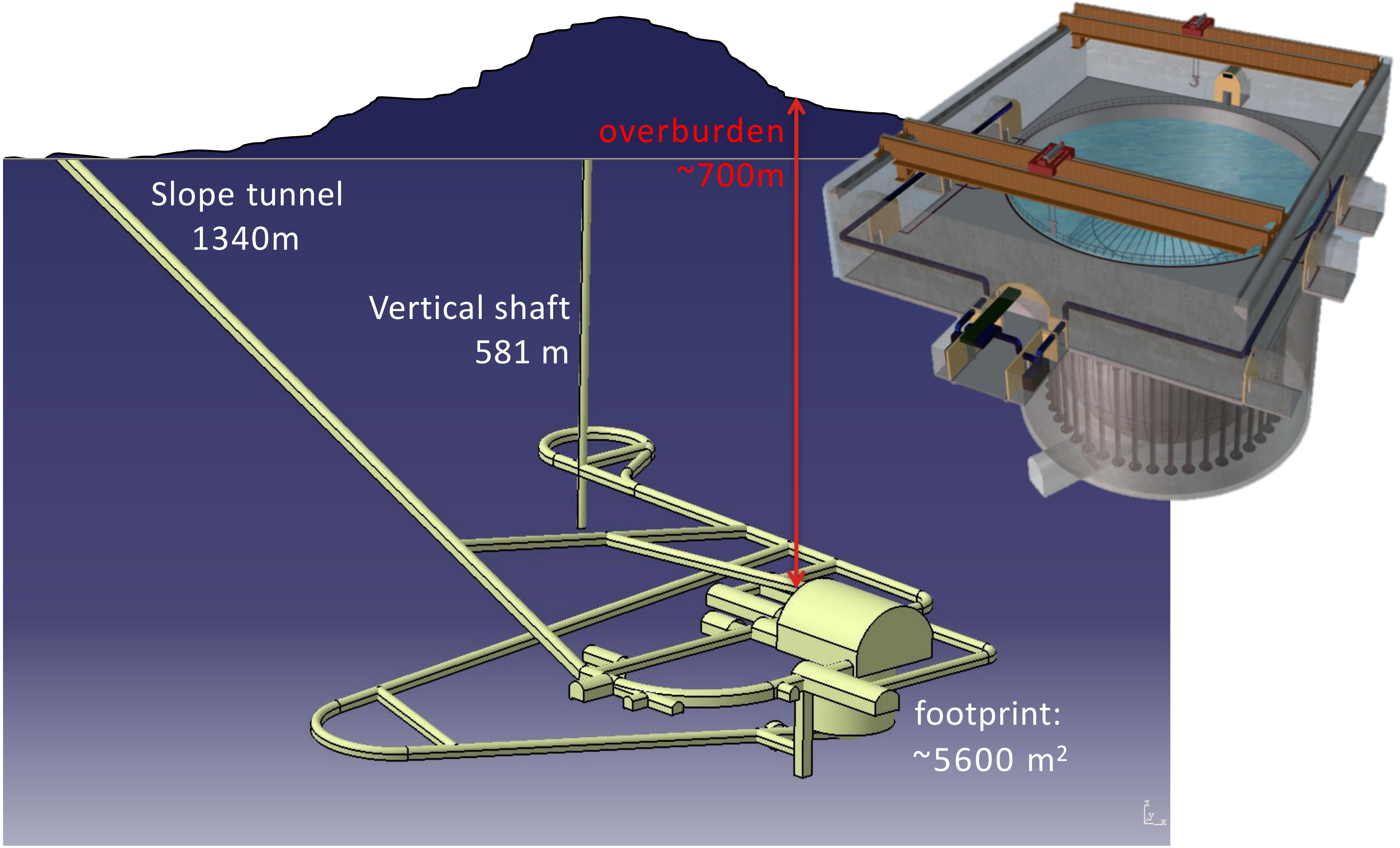
Water buffer

Acrylic sphere
diameter: 35.4m

Liquid scintillator
20 kt of LAB

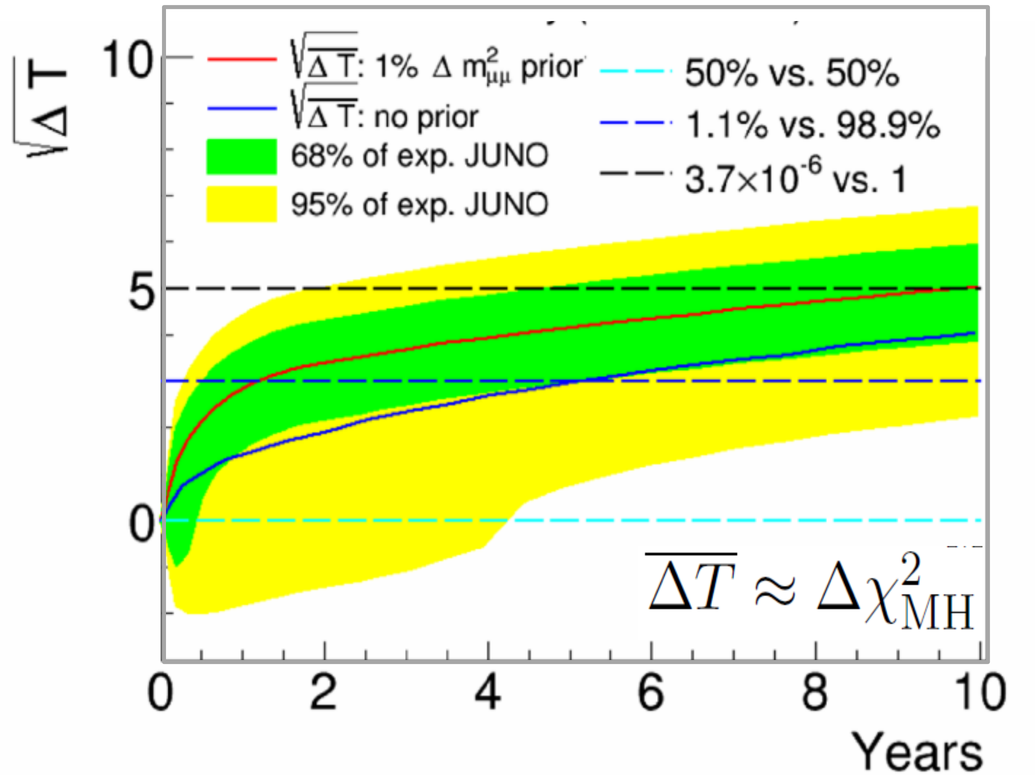


Underground laboratory



Sensitivity to mass hierarchy

JUNO, arXiv:1507.05613



JUNO's expected sensitivity level

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

- JUNO alone based on 6 years: ~3σ

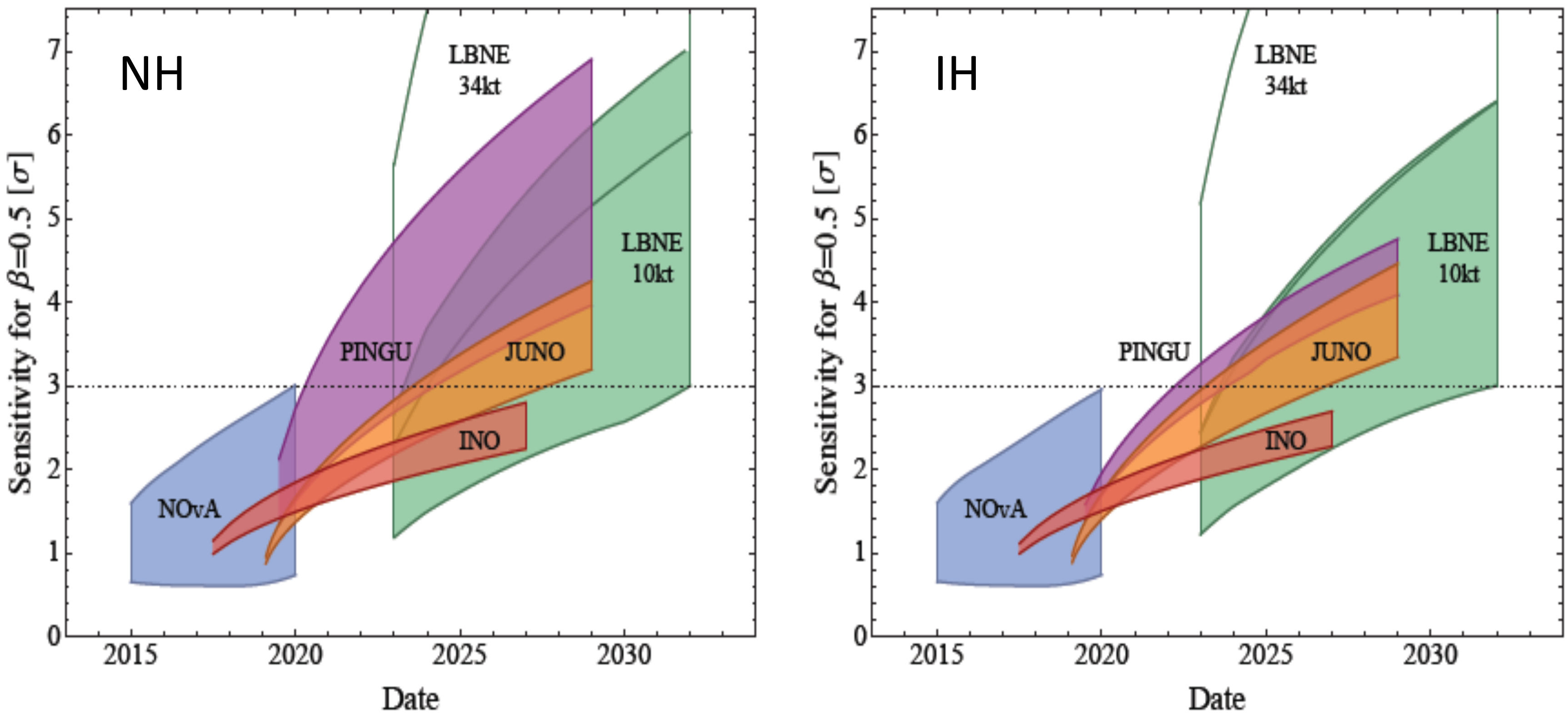
\+ precise data by T2K/NOvA on $\Delta m^2_{\mu\mu}$: **4σ**

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

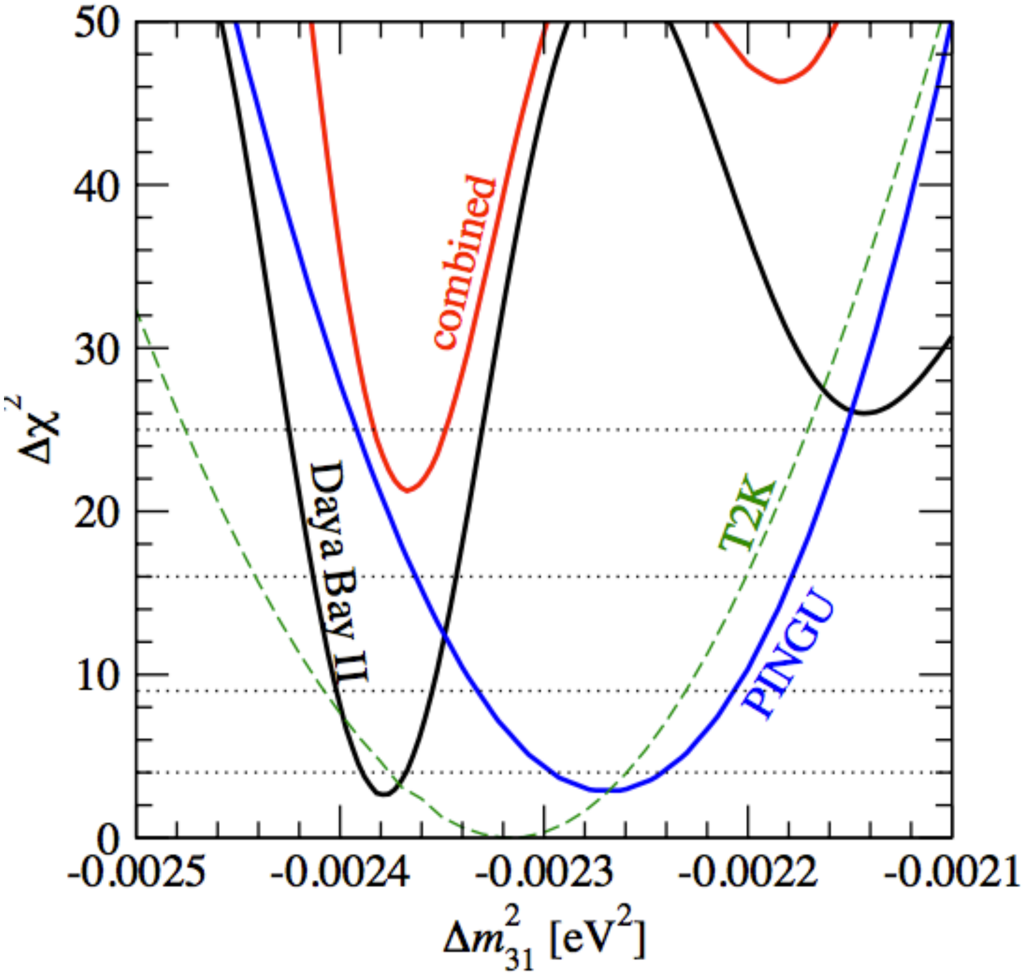
Experimental sensitivities to MH

Blennow, Schwetz, arXiv:1311.1822



Experimental technique	**Mode**	**Dominant factor**
▪ long-baseline beams: NOvA, DUNE ...	$\nu_\mu \to \nu_e$	value of δ_{CP}
▪ atmospheric ν's: INO, PINGU, ORCA, HK ...	$\nu_\mu \to \nu_\mu$	value of θ_{23}=40-50°
▪ reactor neutrinos: JUNO, RENO-50 ...	$\bar{\nu}_e \to \bar{\nu}_e$	energy res. (3-3.5%)

Complementarity of MH experiments



combine measurements of $|\Delta m^2_{31}|$ from PINGU and JUNO

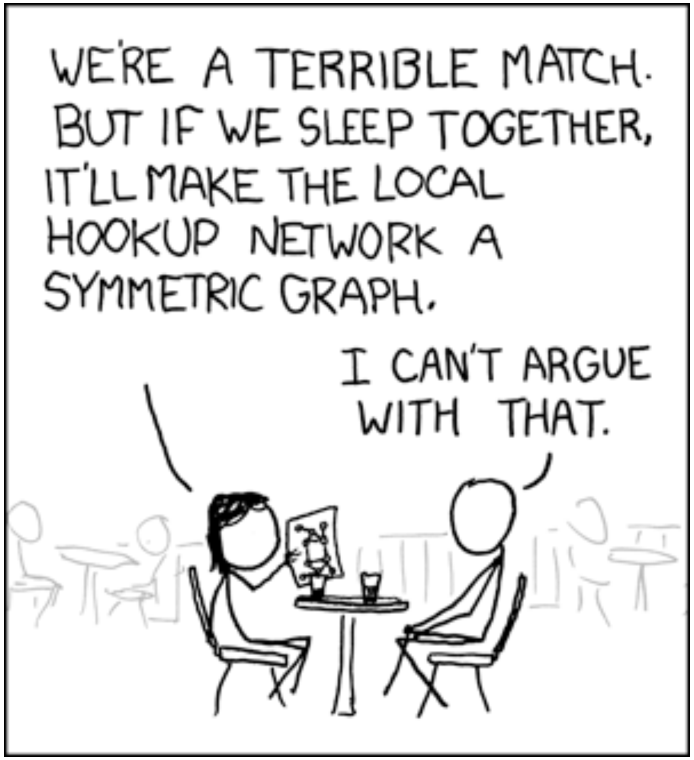
Blennow, Schwetz, arXiv:1306.3988

Conclusions

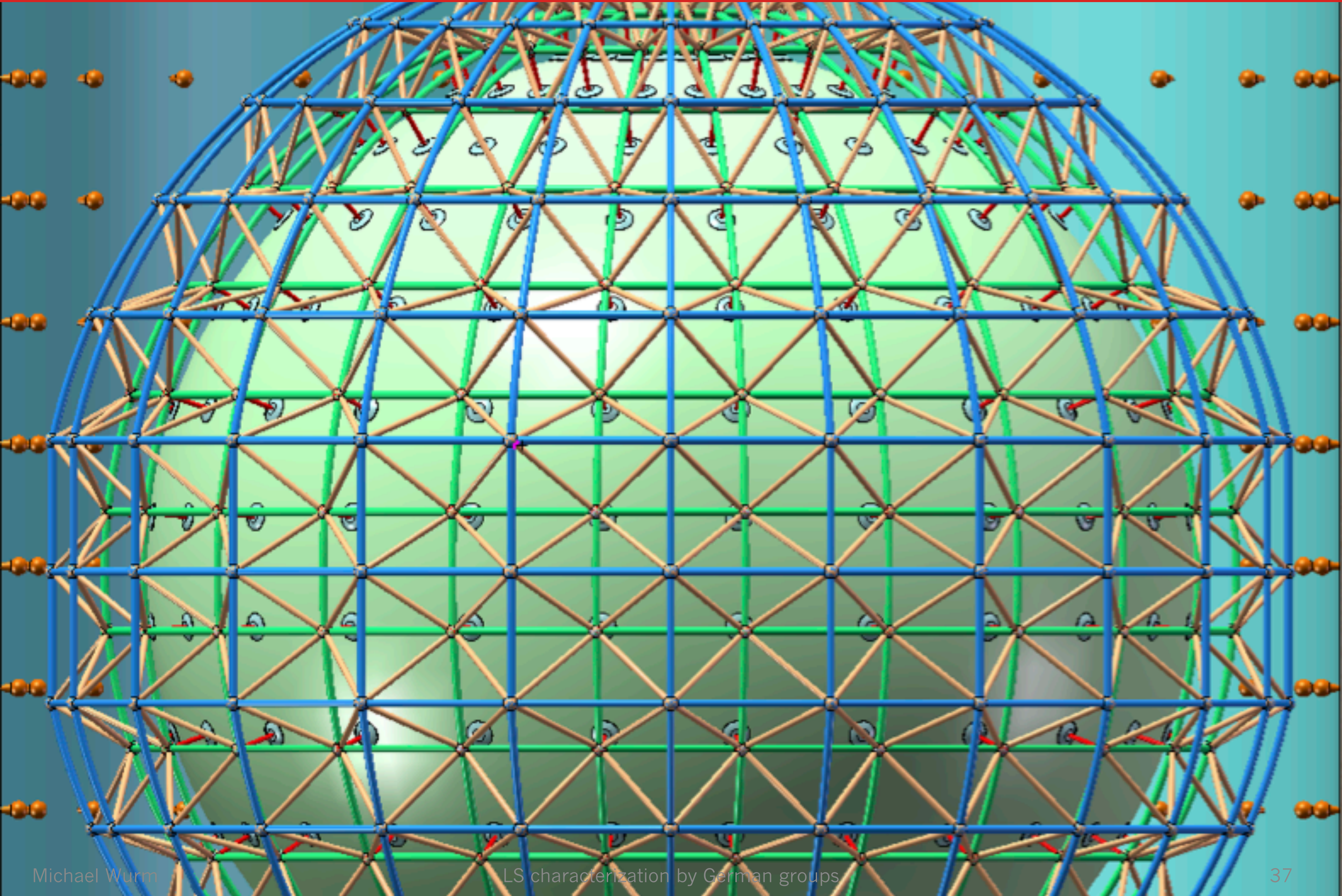
- While not a classic ‘symmetry‘ itself, mass hierarchy is of consequence for other aspects of symmetry in the neutrino sector:
  - fermionic mass ordering, leptonic CP, $0\nu\beta\beta$ sensitivity ...
- Three major approaches to measuring MH:
  - long-baseline neutrino beams
  - low-energy atmospheric-ν detectors
  - mid-baseline reactor neutrino experiments
- Techniques are subject to different systematics/boundary conditions

→ combination will bring sufficient sensitivity for a MH discovery!

Thank you!


WE'RE A TERRIBLE MATCH. BUT IF WE SLEEP TOGETHER, IT'LL MAKE THE LOCAL HOOKUP NETWORK A SYMMETRIC GRAPH.
I CAN'T ARGUE WITH THAT.

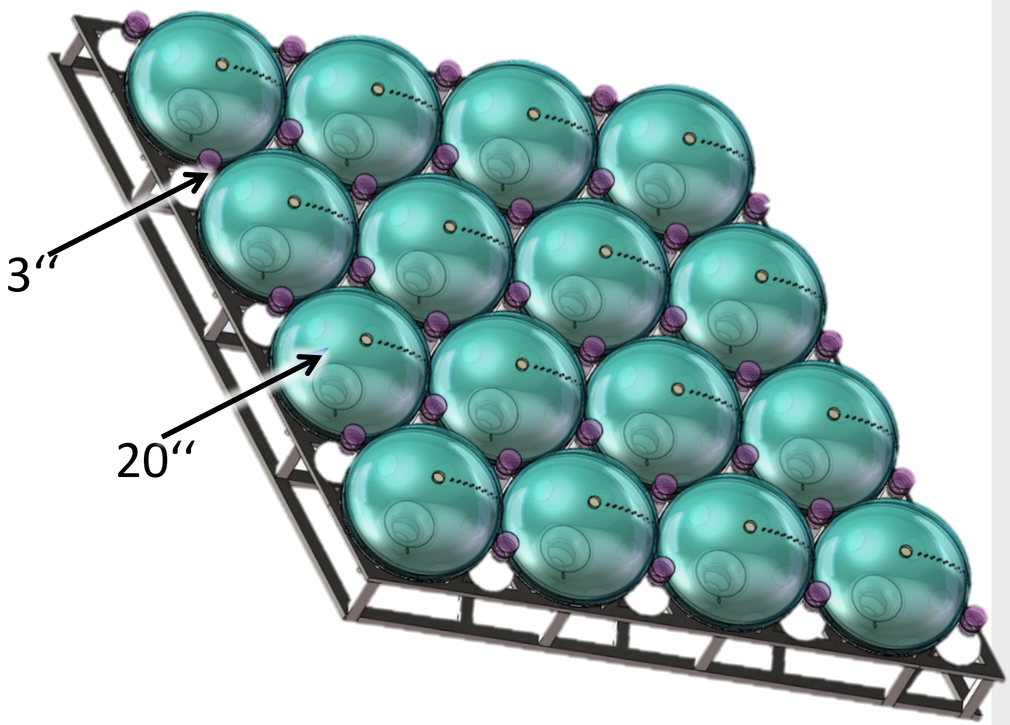
Backup Slides

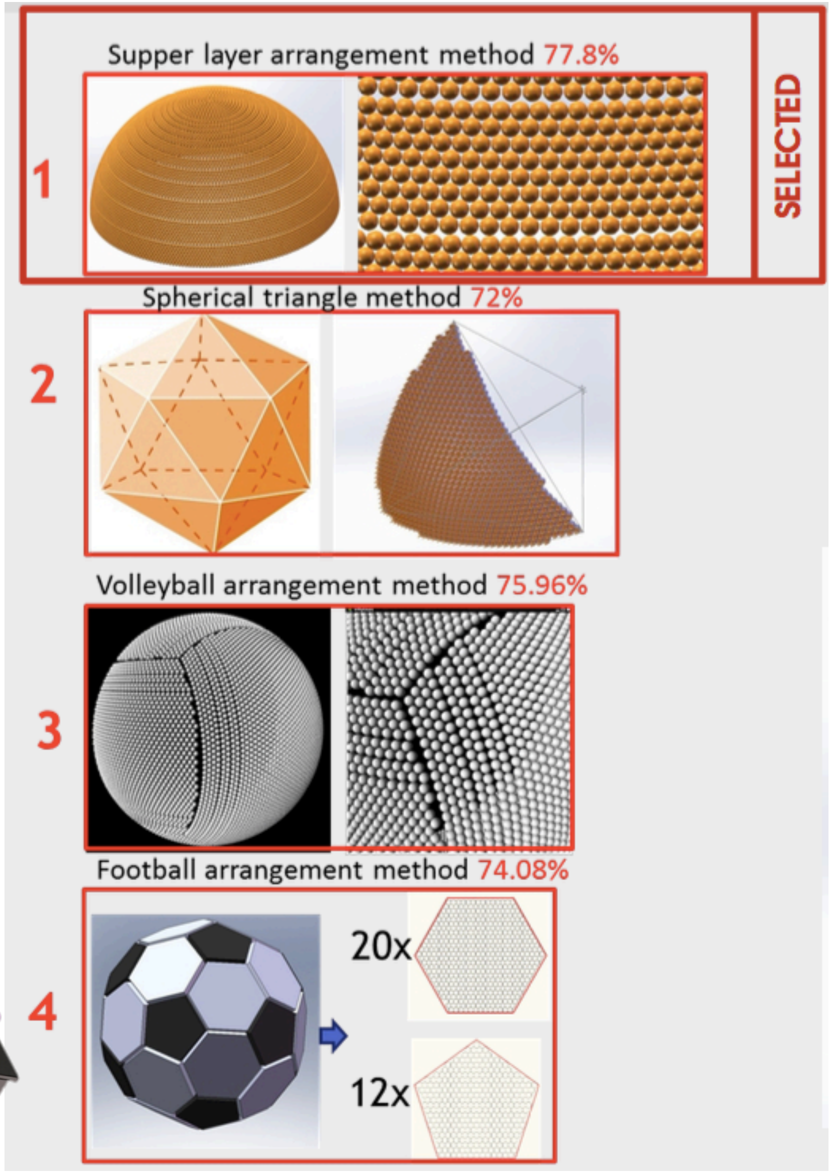


Light detection

Light collection required:

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





Light detection

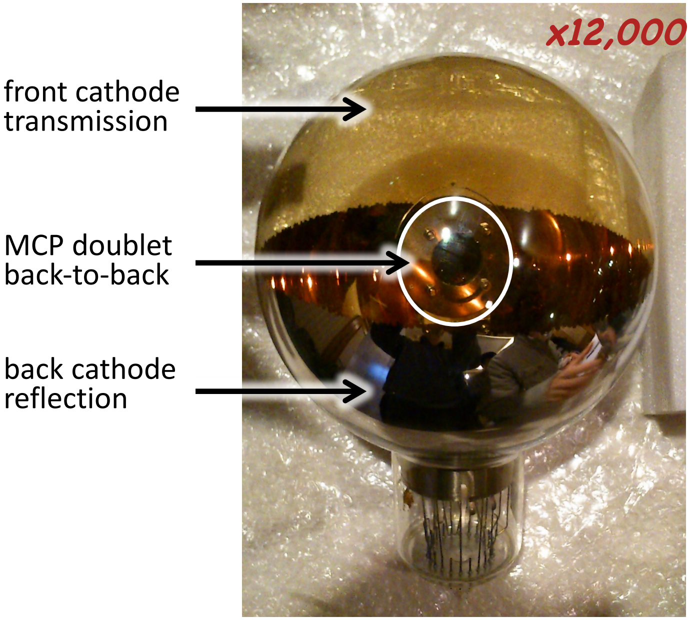
Light collection required:

- 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

JUNO's liquid scintillator

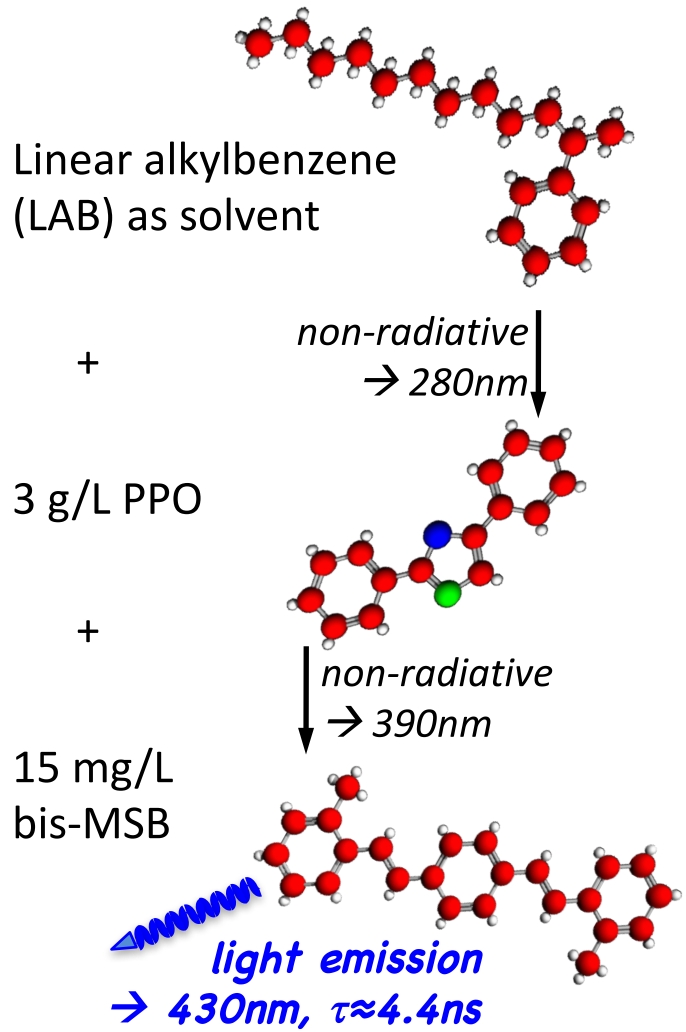
Required properties:

- 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

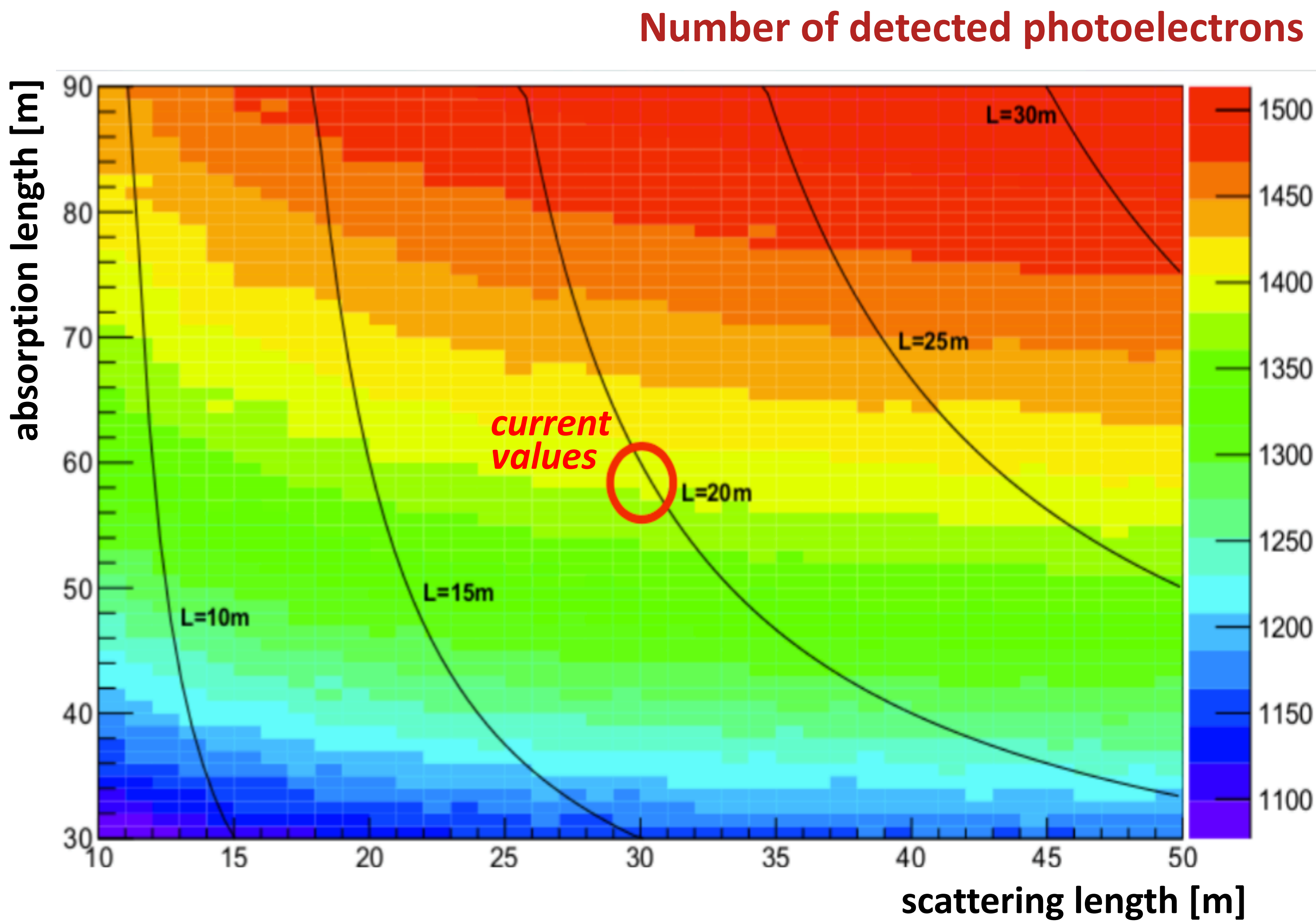
for free:

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

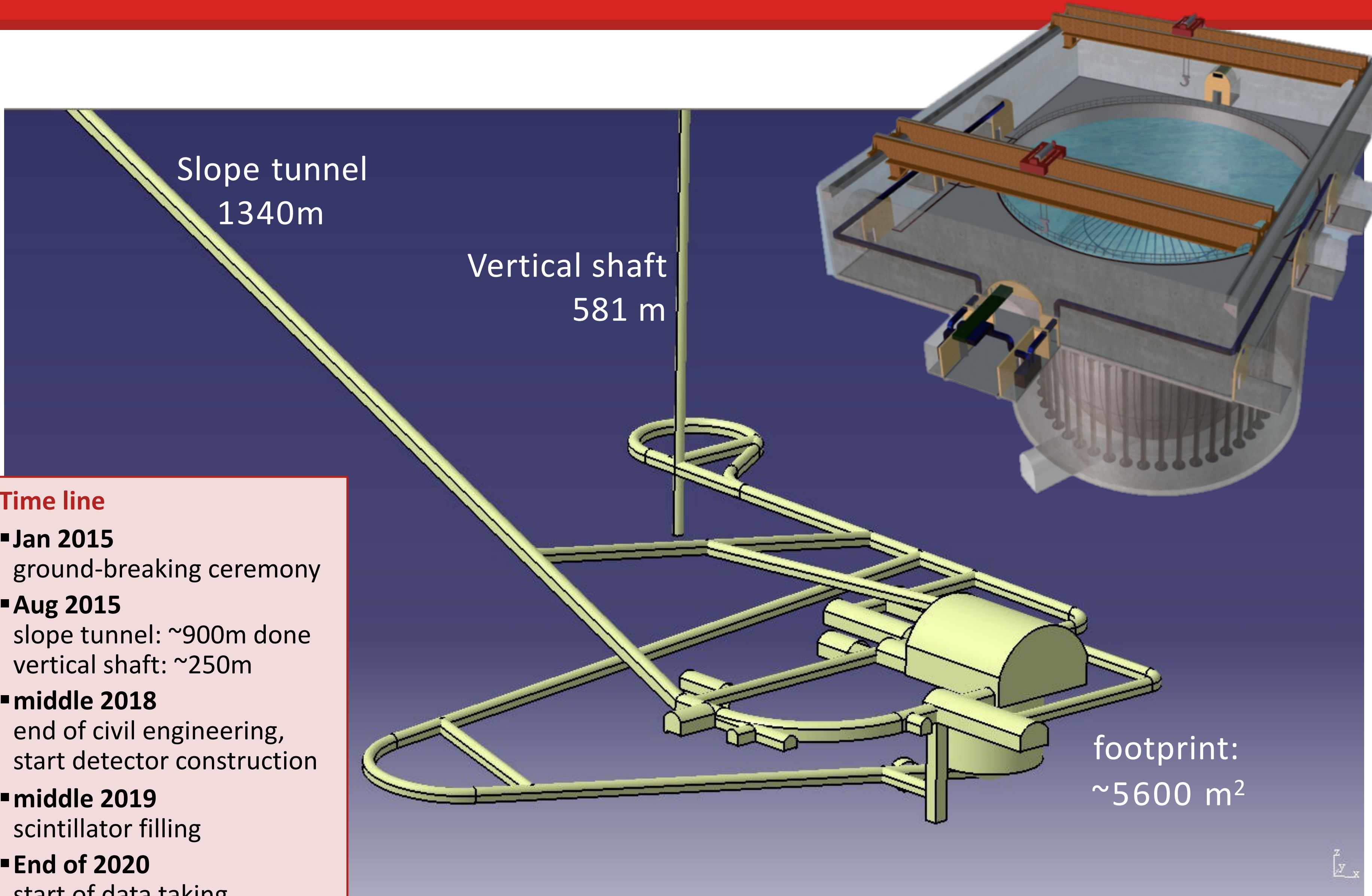
LENA-style liquid scintillator



p.e. yield vs. scintillator transparency



Schedule



Time line

- **Jan 2015**
  ground-breaking ceremony
- **Aug 2015**
  slope tunnel: ~900m done
  vertical shaft: ~250m
- **middle 2018**
  end of civil engineering,
  start detector construction
- **middle 2019**
  scintillator filling
- **End of 2020**
  start of data taking

How to measure MH? – Reactor neutrinos

[Petcov, Piai, hep-ph/0112074]

Survival probability

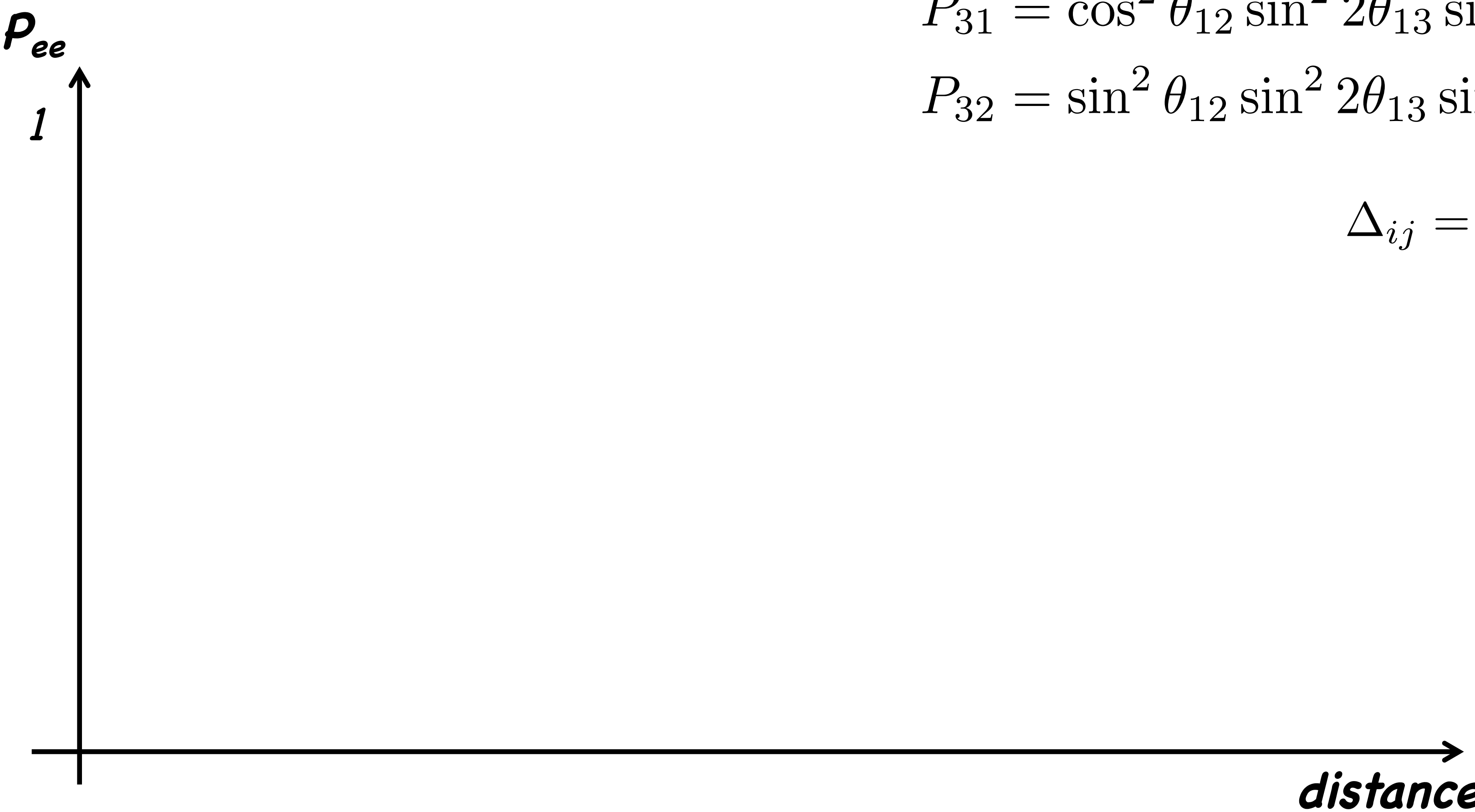
$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

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

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

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

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



How to measure MH? – Reactor neutrinos

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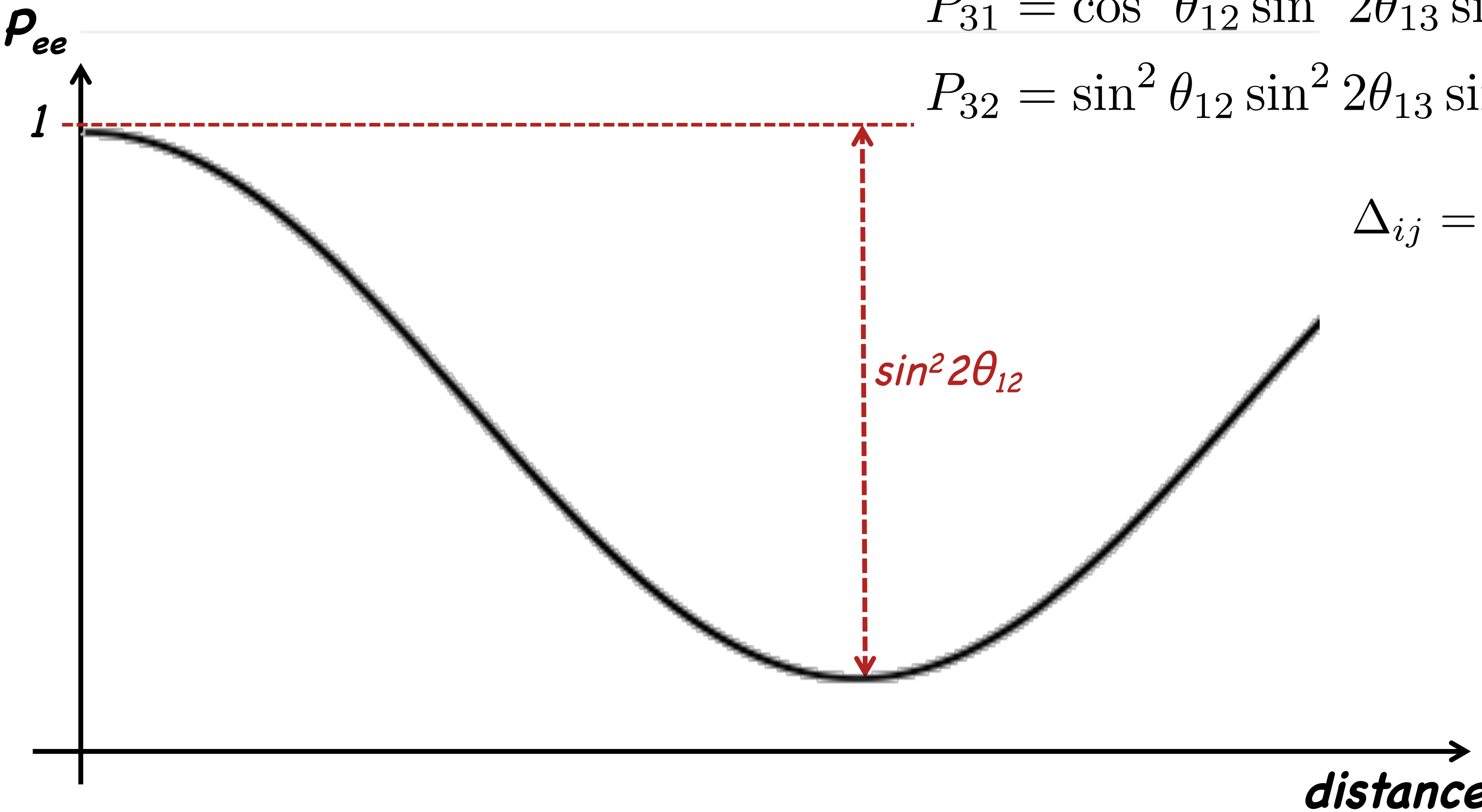

How to measure MH? – Reactor neutrinos

→ 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

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

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

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

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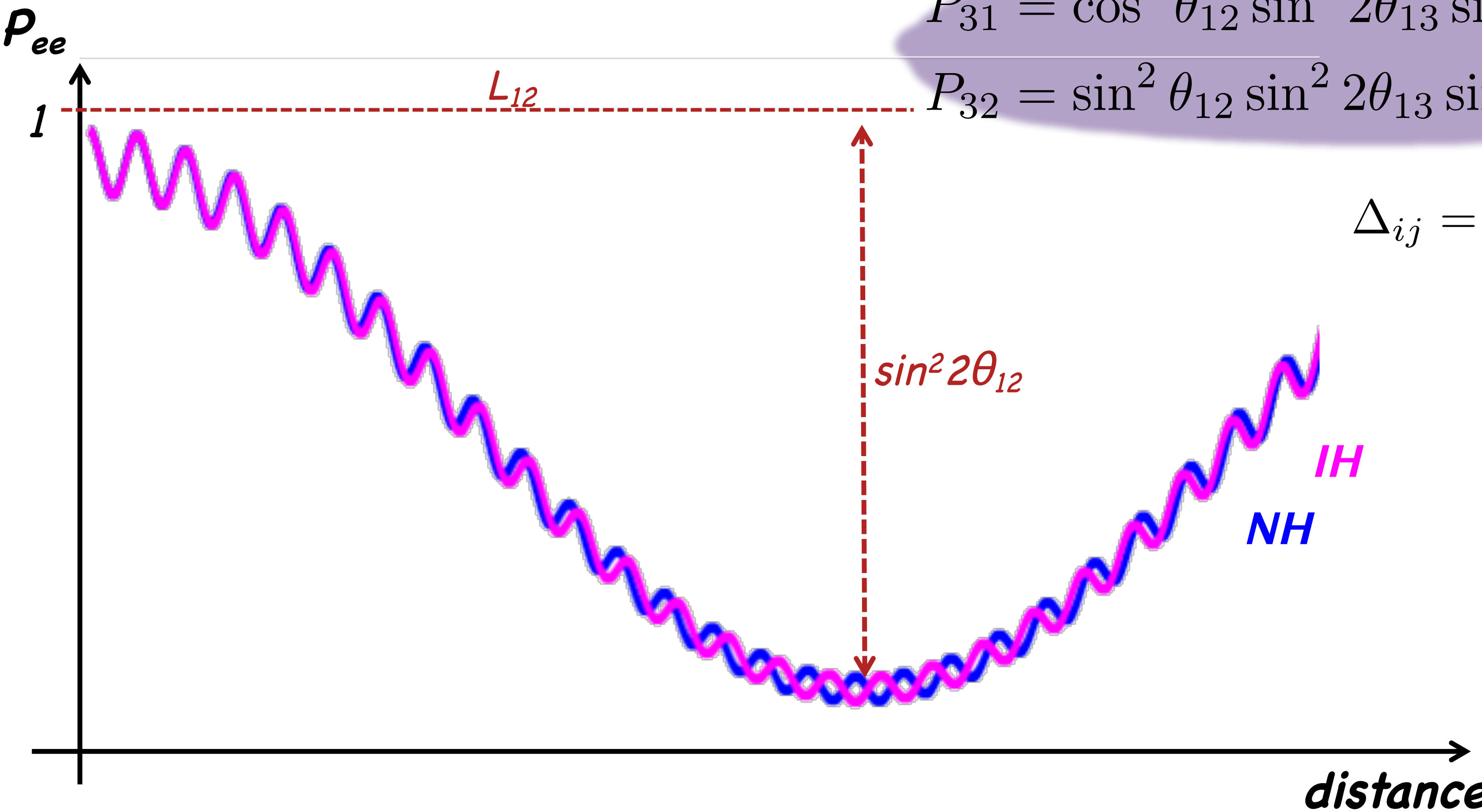
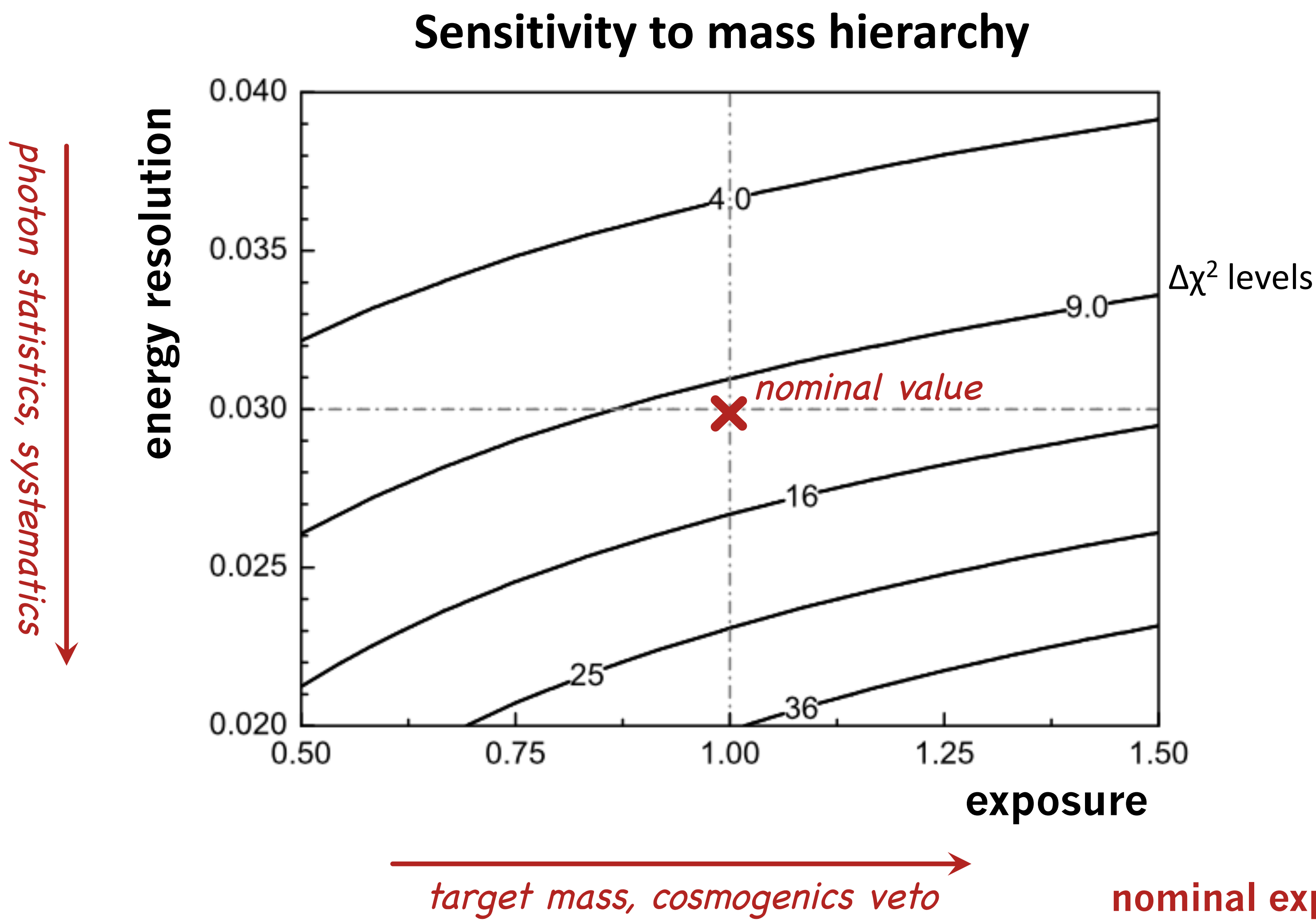


Sensitivity vs. energy resolution

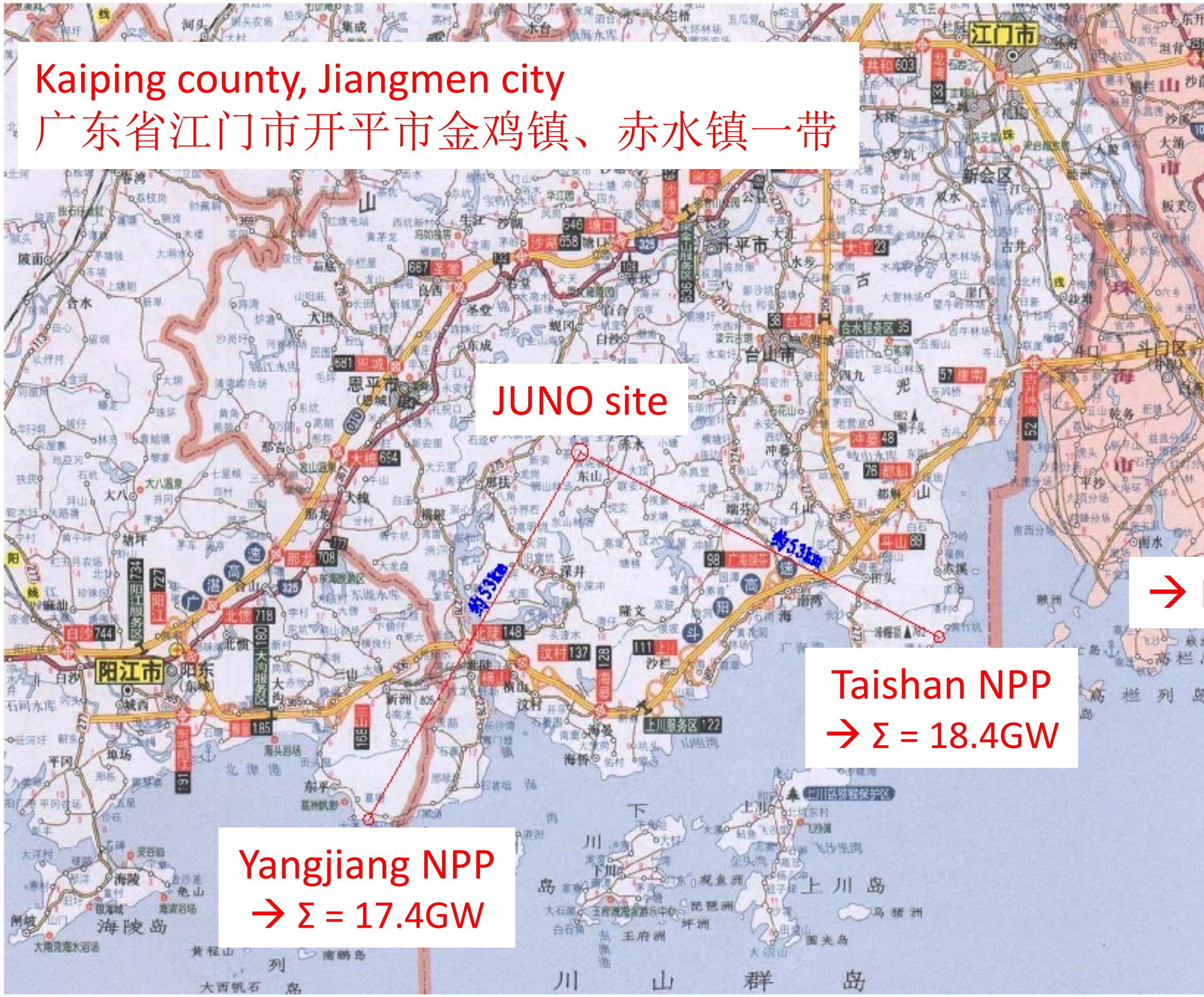


nominal exposure

- 36 GW x 6 years x 20kt
- 80% IBD efficiency

Experimental setup for reactor neutrinos

Experimental setup for reactor neutrinos



JUNO Collaboration

380 scientists, 60 institutions, 1/3 from Europe

Armenia, Austria, Belgium, Brazil, Chile, Chinese Republic, Czech Republic, Germany, Finland, France, Italy, Japan, Korea, Russia, Taiwan, and the United States

German institutes

RWTH AACHEN UNIVERSITY

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

JÜLICH FORSCHUNGSZENTRUM

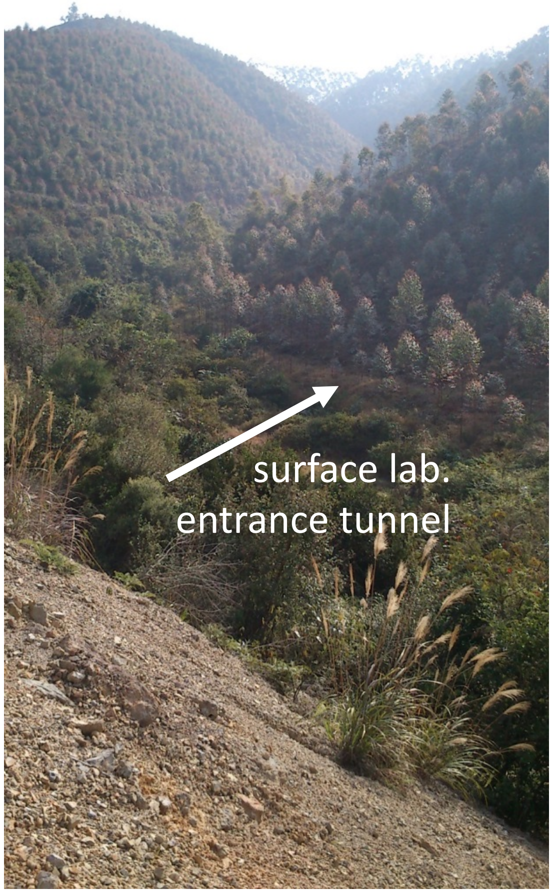
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Technische Universität München

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Slope tunnel

Surface facilities

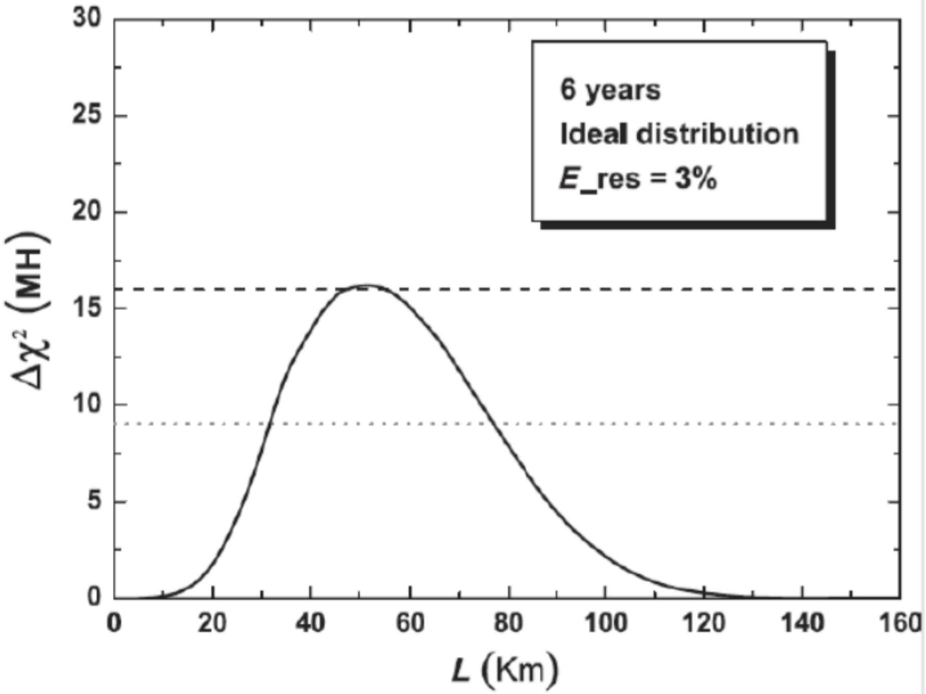


Surface facilities

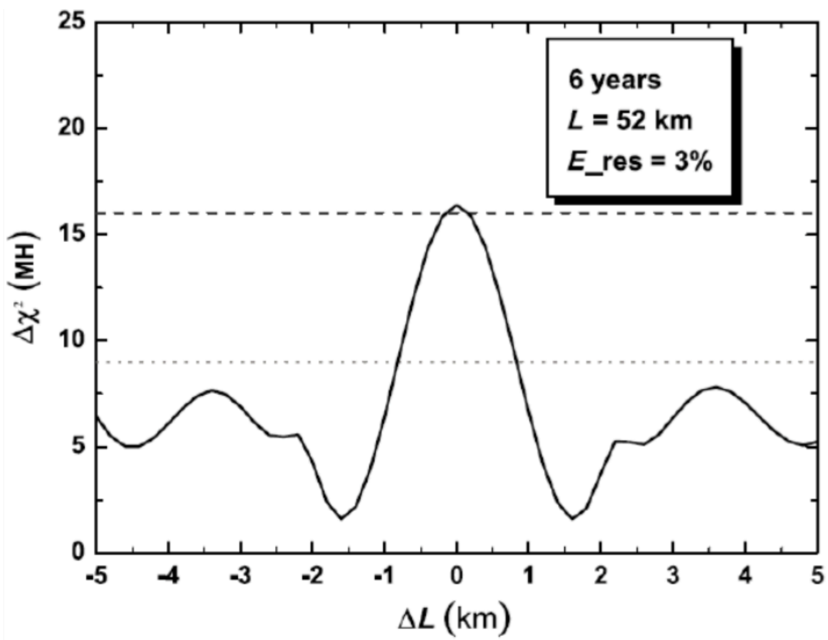
Surface facilities

Optimum baseline

Baseline optimization



Difference between baselines
to reactor complexes



Non-stochastic terms in E resolution

Energy resolution function

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

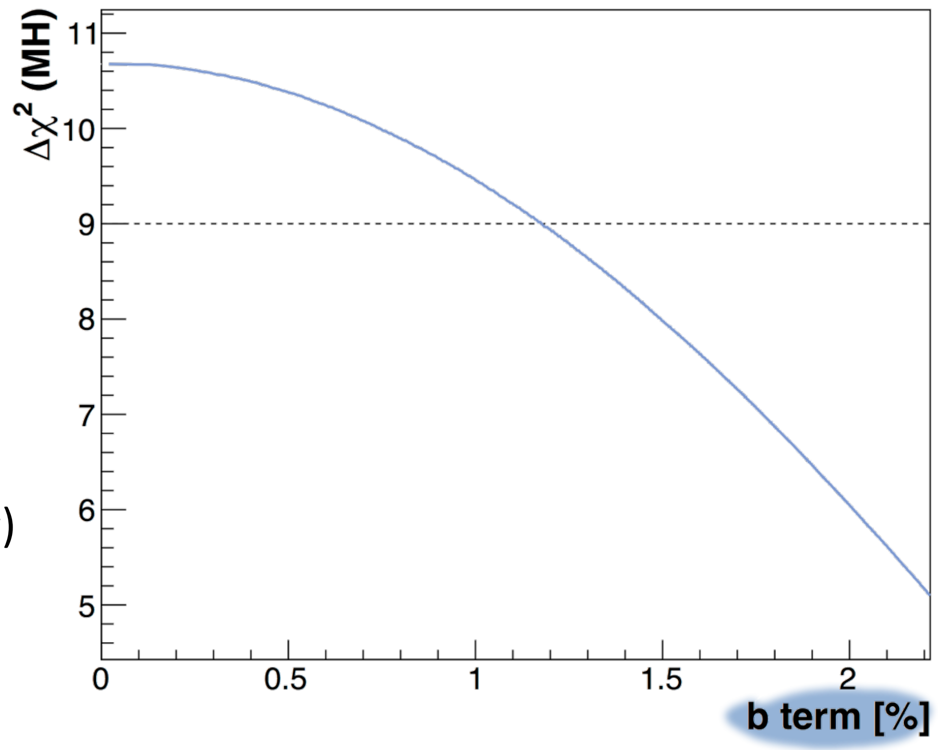
a term:

stochastic term (*photon statistics*)

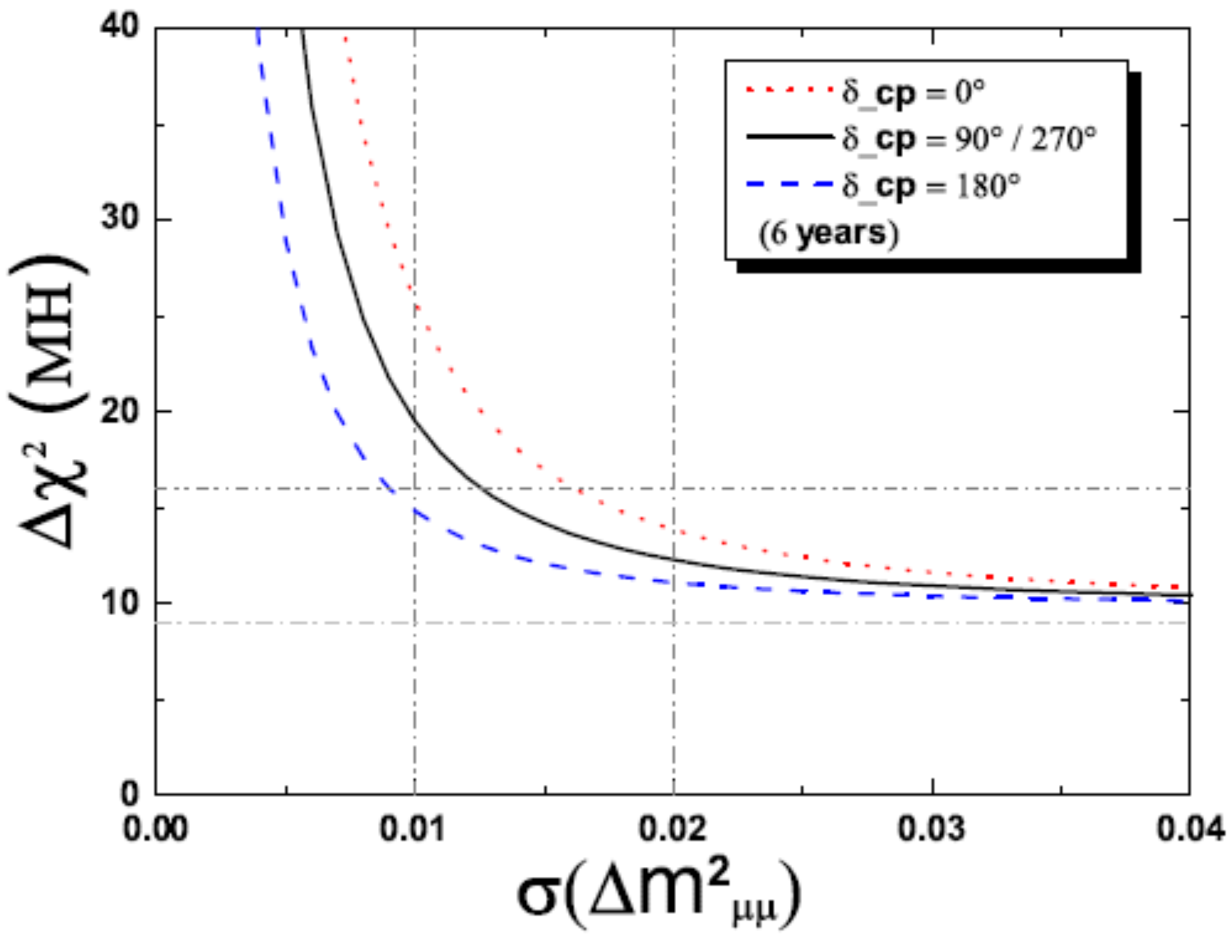
b & c terms:

systematic contributions (*detector effects*)

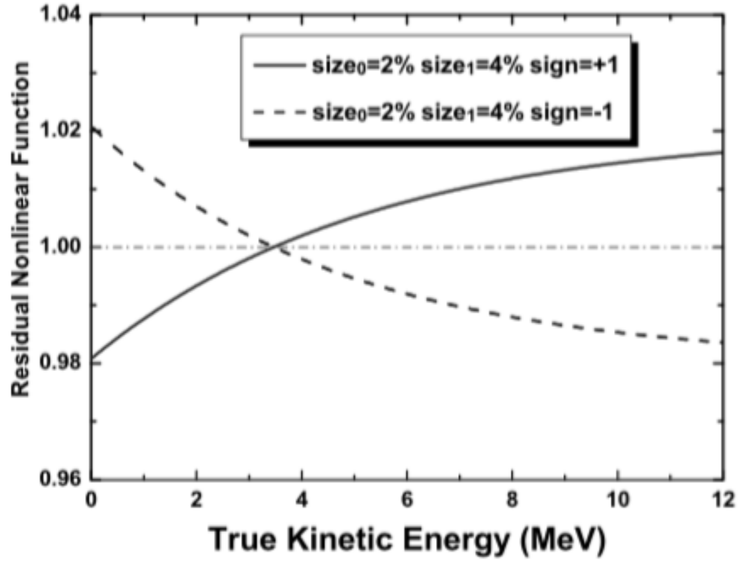
- PMT dark noise
- linearity of electronics
- position reconstruction uncertainty
- ...



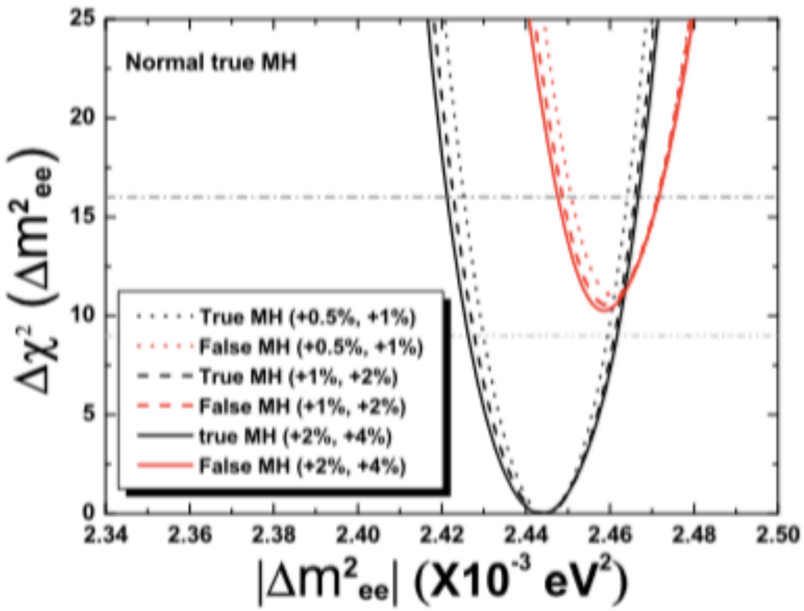
Influence of $\Delta m^2_{\mu\mu}$ accuracy



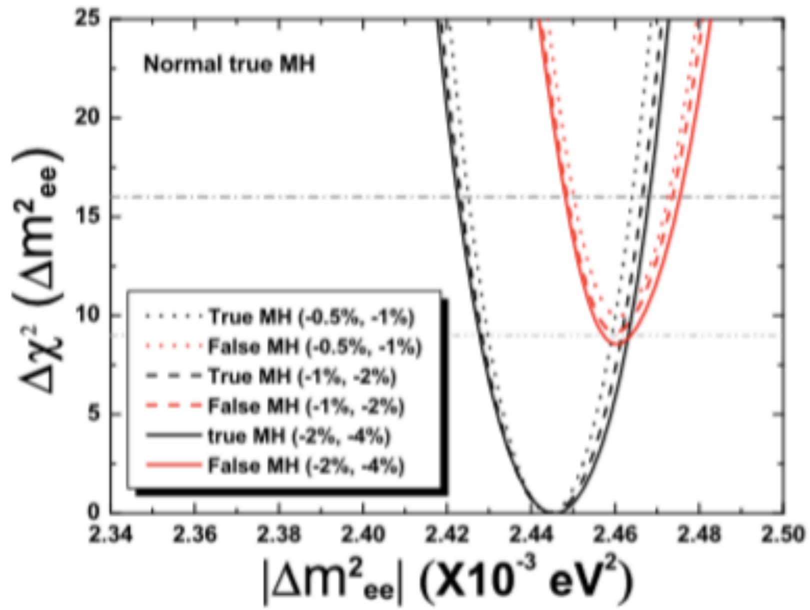
Influence of energy scale linearity



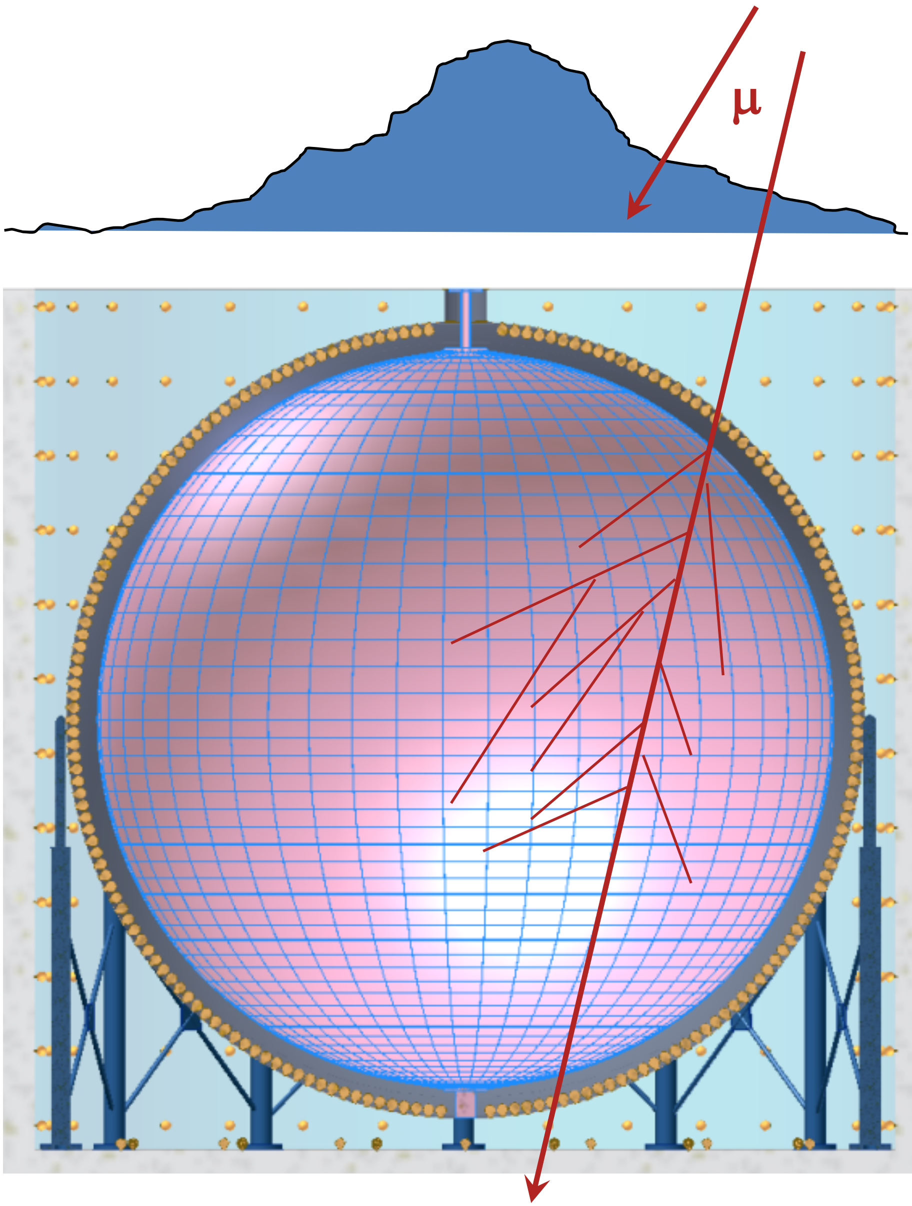
w/o self-calibration



w/ self-calibration



Cosmogenic backgrounds



Cosmic background level

- 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

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

→ prompt electron signal
+ delayed neutron capture

→ mimics neutrino (IBD) signature!

Expected ^{9}Li rate: ~70 d^{-1}

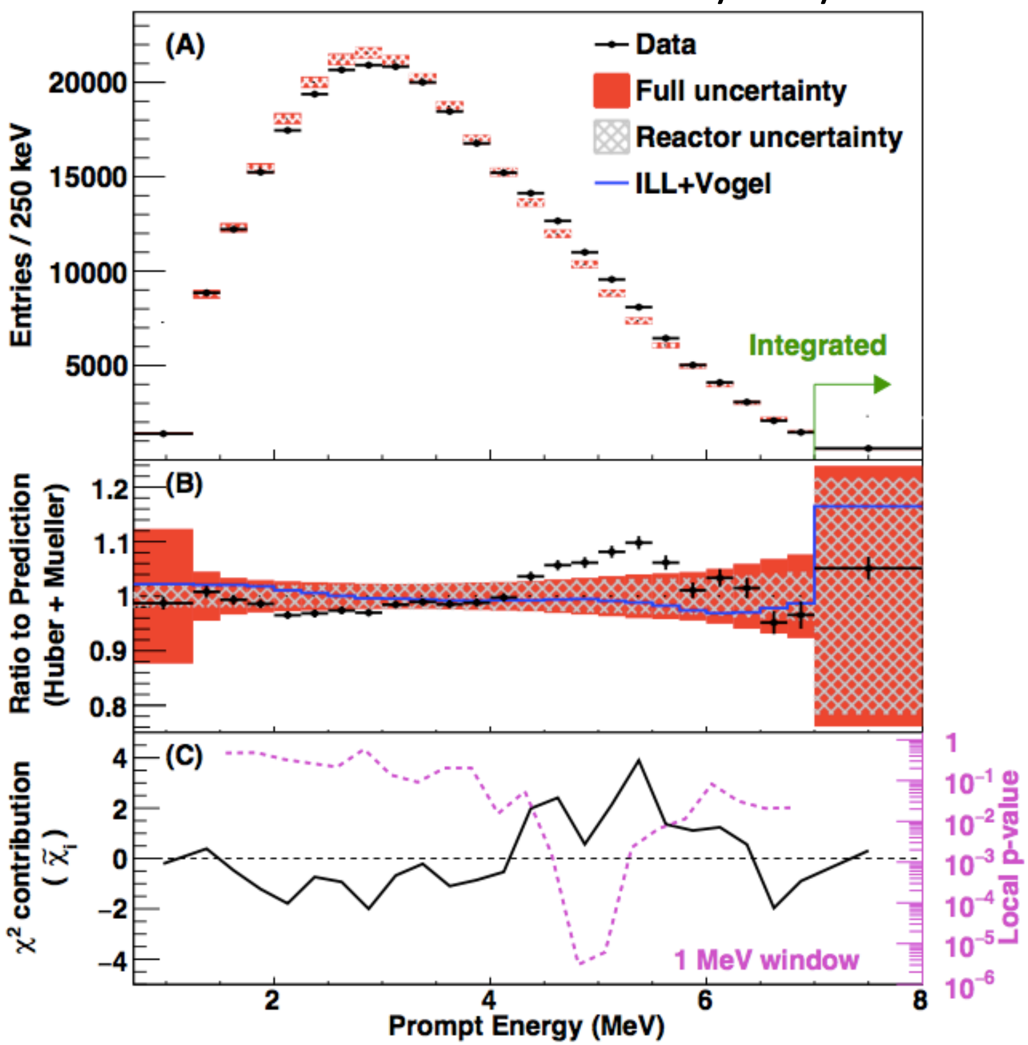
→ signal to background ~1:1

→ veto based on parent μ mandatory!

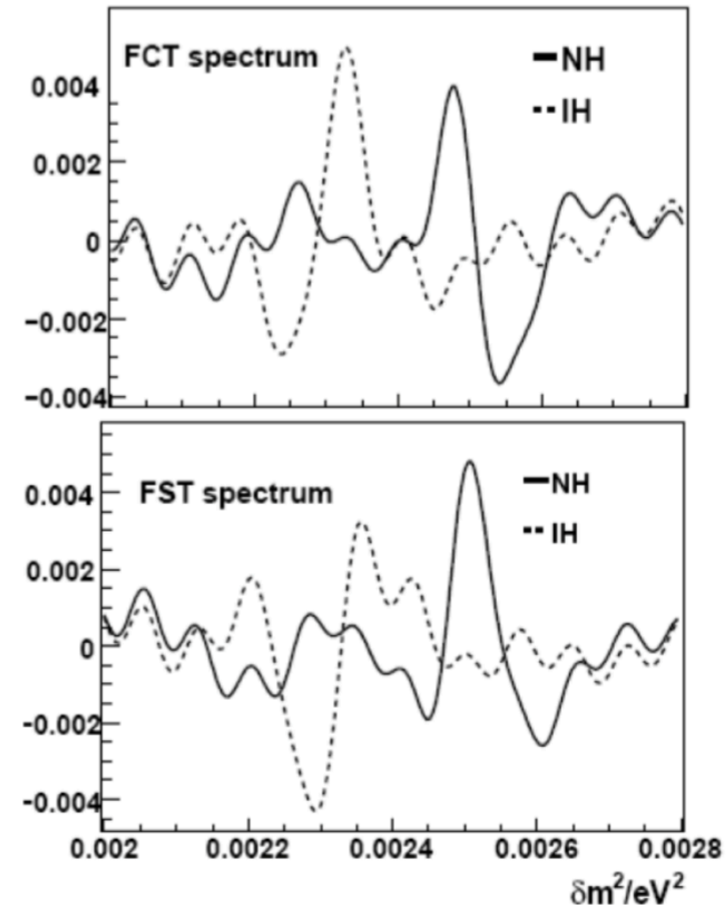
→ dead time introduced: ~20%

Reactor anomaly: 5 MeV bump

Daya Bay ND

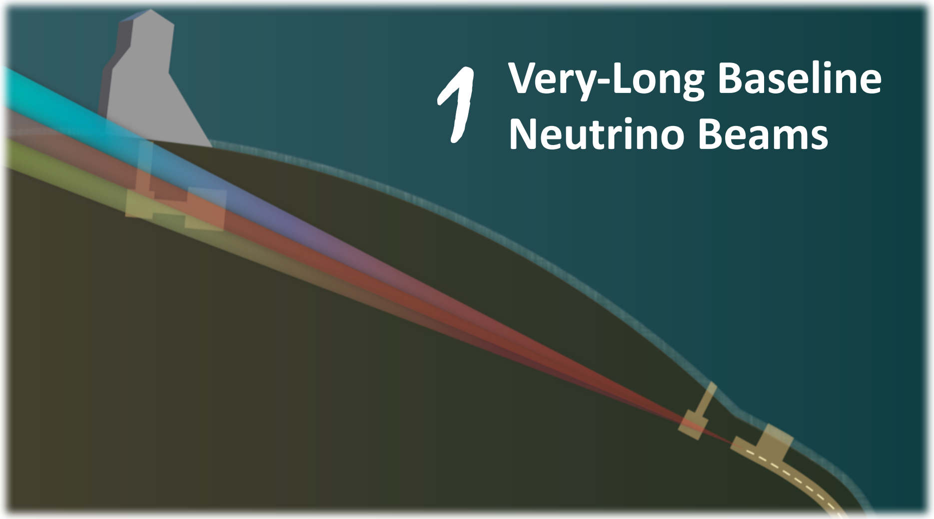


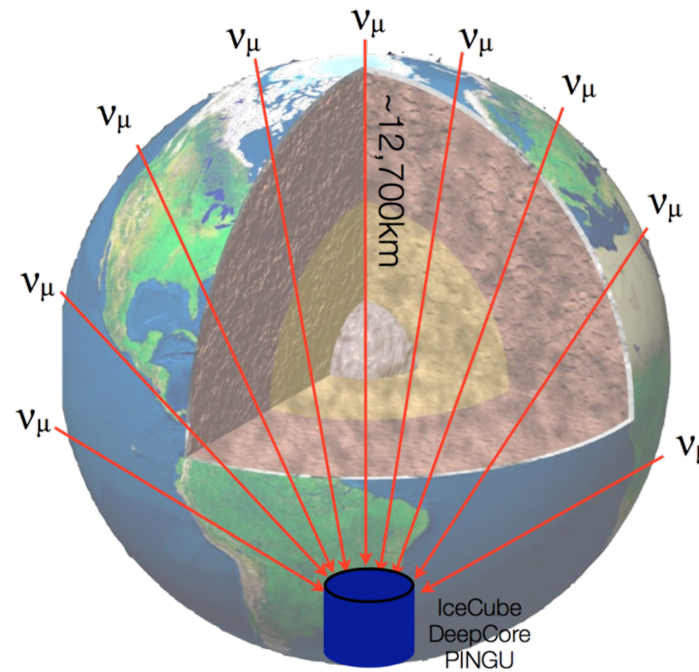
MH Fourier analysis



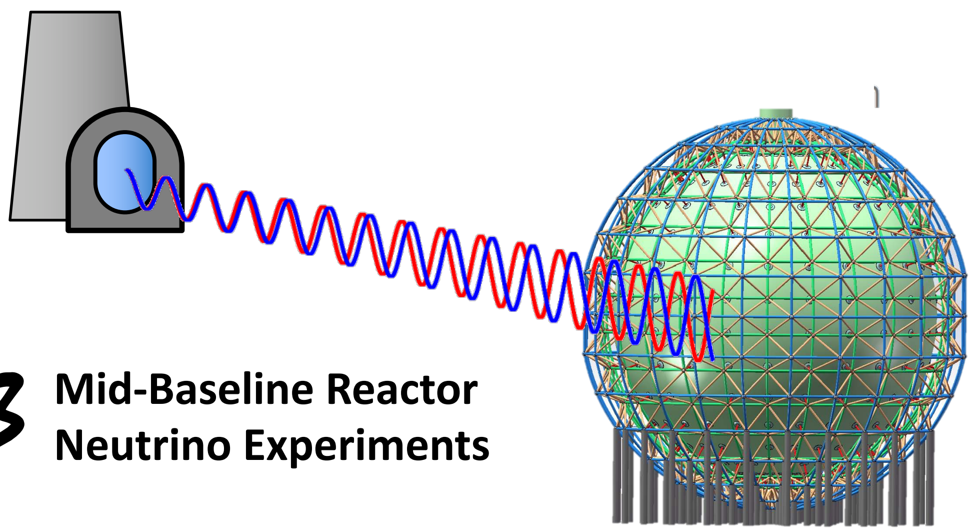
J. Learned et. al. Hep-ex/0612022

Concepts for MH measurement



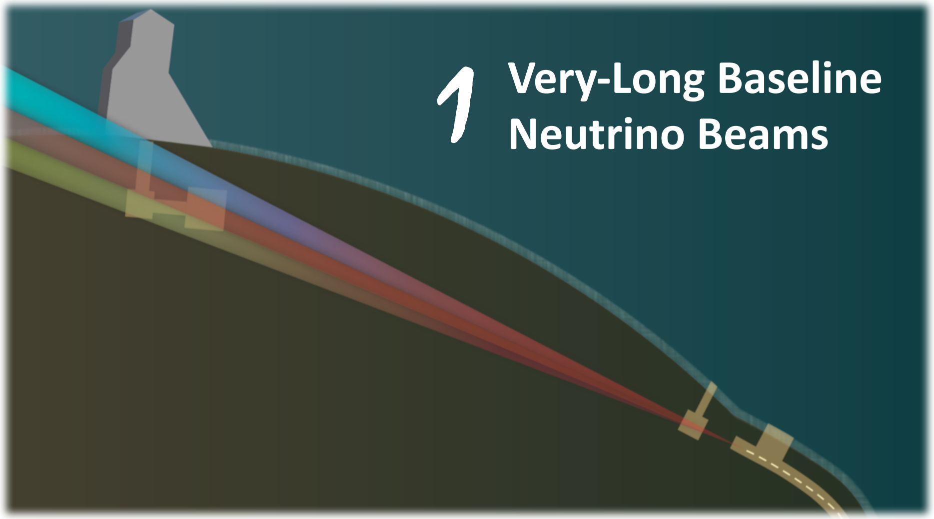


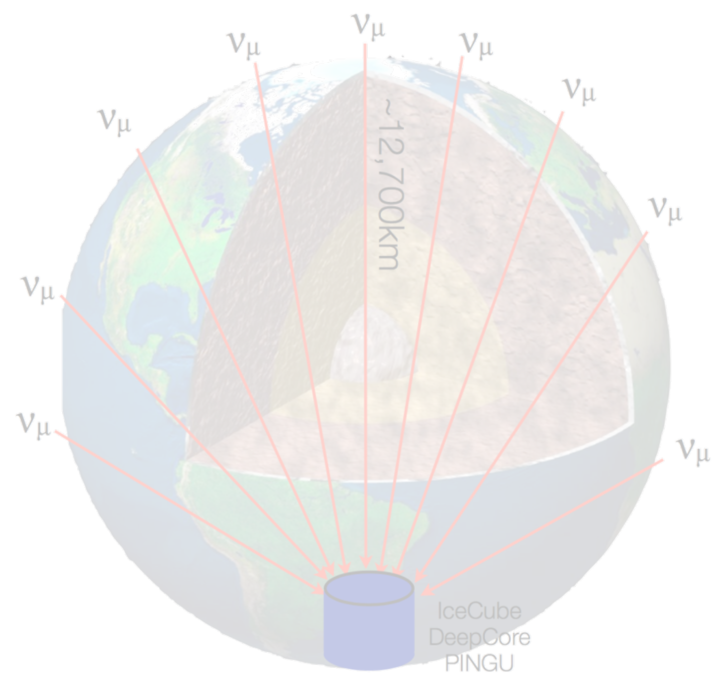
2 Atmospheric Neutrino Experiments



3 Mid-Baseline Reactor Neutrino Experiments

Concepts for MH measurement





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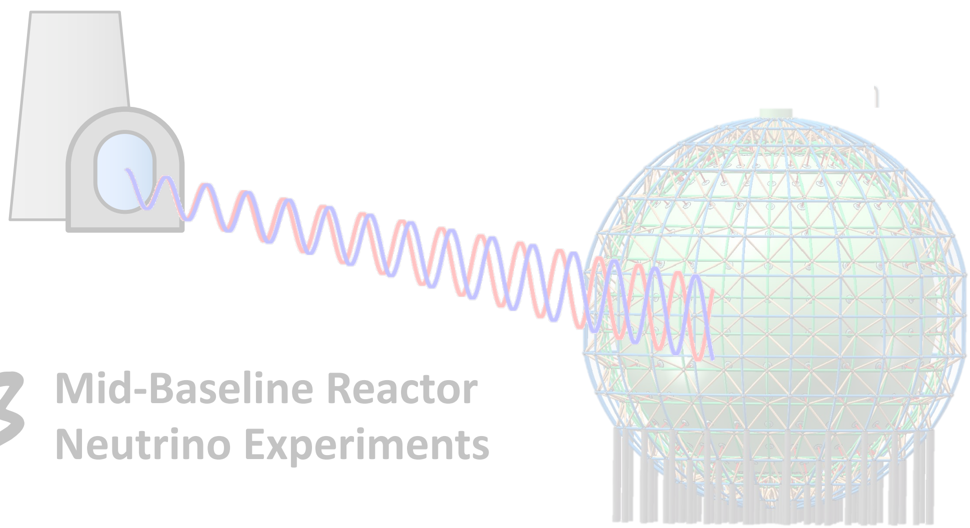

3 Mid-Baseline Reactor Neutrino Experiments