Reactor neutrino projects

FPCP 2017

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PRISMA

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

Outline

- **Upcoming short-baseline experiments**
  for eV-sterile neutrinos
  - doped liquid-scintillators:
    NEOS, Neutrino-4, **STÉRÉO**, **PROSPECT**
  - composite plastic scintillators:
    DANSS, **SoLiϑ**, CHANDLER

- **Medium-baseline experiments**
  for Neutrino Mass Hierarchy
  - **JUNO**, RENO-50

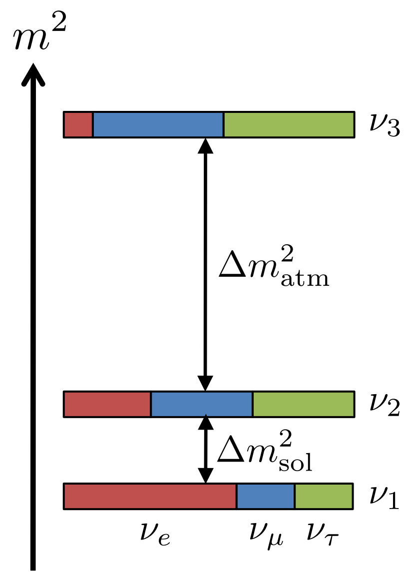
3-neutrino mixing parameters

cf. Qingmin Zhang's talk

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

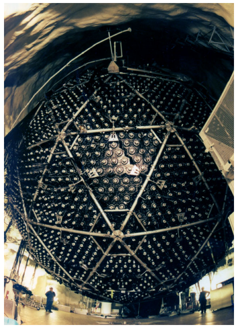
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} &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

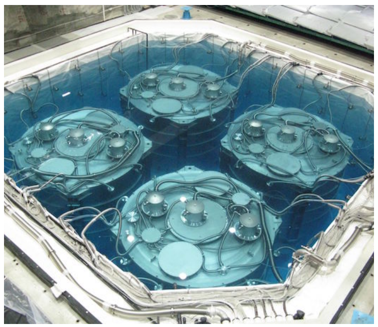
Super-Kamiokande	Daya Bay, RENO, DC	SK,SNO [KL,Bx]
atmospheric: $\theta_{23}\approx45°$?	reactors: $\theta_{13}\approx9°$, $\delta=-\pi$?	solar: $\theta_{12}\approx33°$



mass squared differences :

- $\Delta m^2_{\text{sol}} = \Delta m^2_{21}$ → *KamLAND+solar: +8x10^{-5} eV^2*
- $\Delta m^2_{\text{atm}} = \Delta m^2_{32} \approx \Delta m^2_{31}$ → *SK+acc+reactor: ±2.5x10^{-3} eV^2*



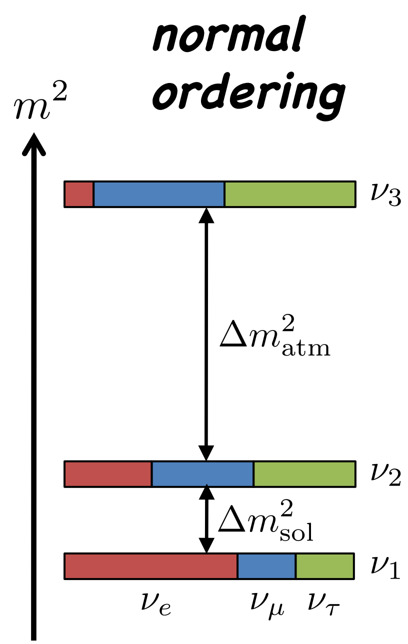



Open questions in neutrino oscillations

cf. Qingmin Zhang's talk

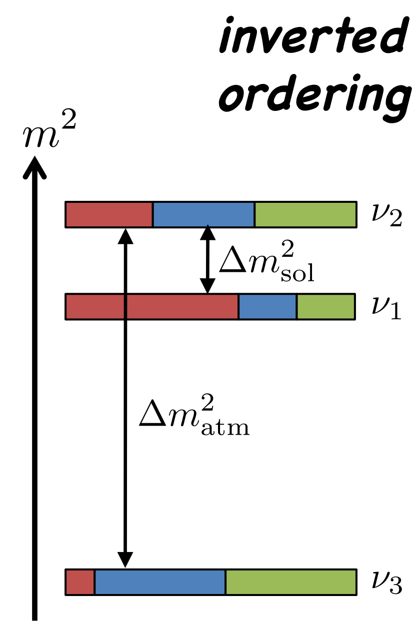
$$\mathbf{U_{3\times3}} = \mathbf{U}_{\text{PMNS}}$$

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



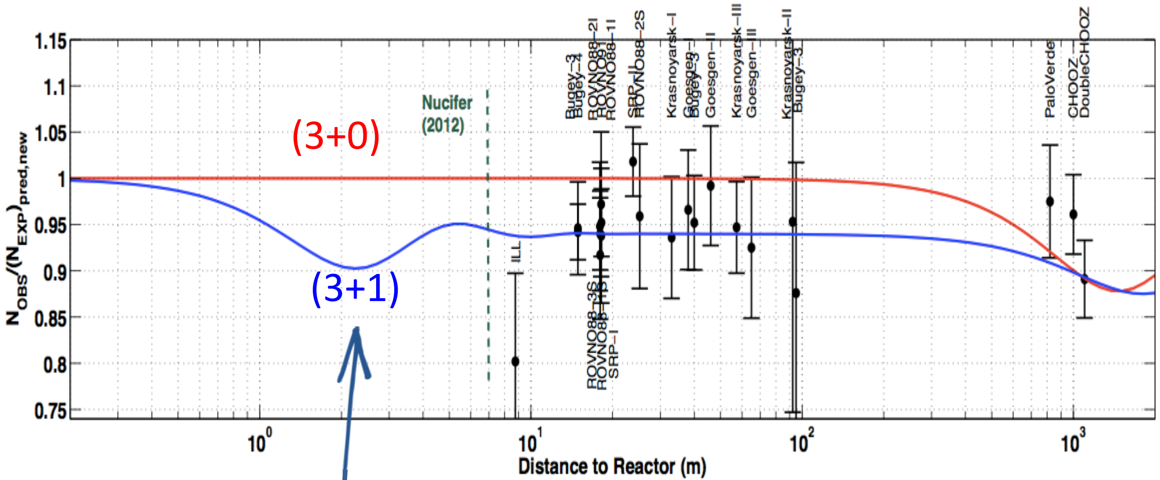
What is the

- **octant of θ_{23} ($\gtrless$ 45°)?**
- value of **CP-phase?**
- **mass hierarchy?** (sign of Δm^2_{atm})
- PMNS unitarity: **sterile neutrinos?**



Why very-short baseline (VSBL) experiments?

Electron neutrino disappearance anomalies:



- reactor experiments
  (7.3±2.3)% deficit in $\bar{\nu}_e$-rate at short distances (<100m)
- Gallium calibration data
  (14±5)% rate deficit close to a radioactive ν_e-source

→ *possible interpretation in terms of very short-baseline neutrino oscillations:*

$$P = 1 - \sin^2(2\theta_{new}) \sin^2\left(\frac{\Delta m^2_{new} L}{4E}\right)$$

→ *if so, new Δm^2 value on the order of 1eV²*

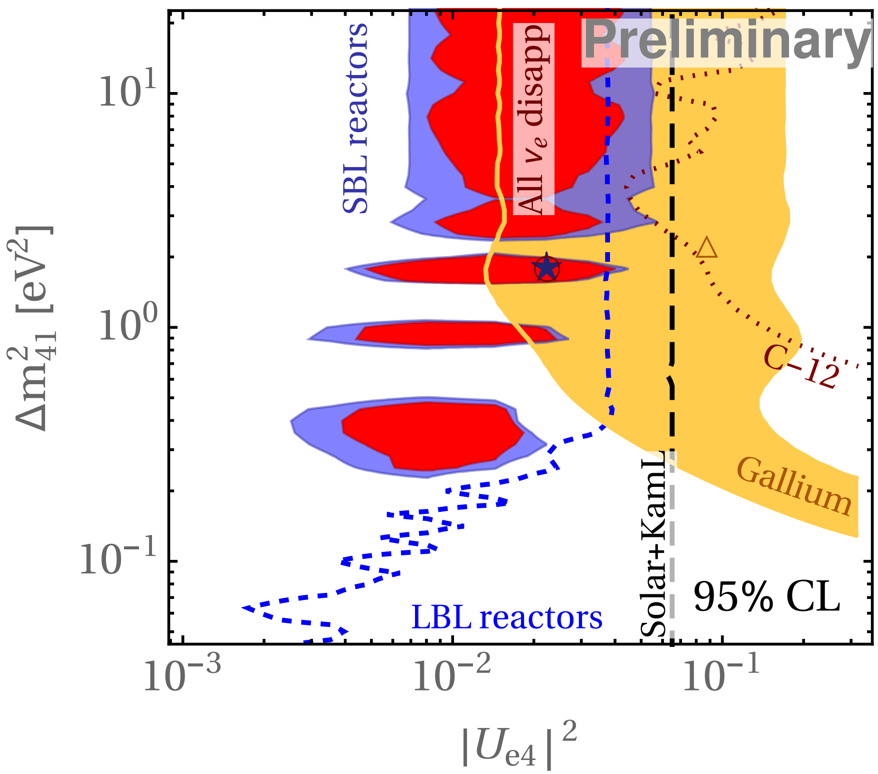
→ *if so, new flavor state must be sterile*

Mixing of (3+1) neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} & U_{14} \\ U_{21} & U_{22} & U_{23} & U_{24} \\ U_{31} & U_{32} & U_{33} & U_{34} \\ U_{41} & U_{42} & U_{43} & U_{44} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Sterile neutrino searches at reactors

$\nu_e \rightarrow \nu_s$ disappearance
from anomalies



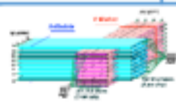
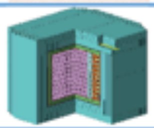
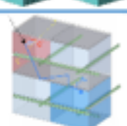
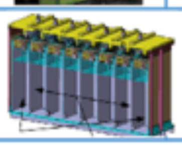
Dentler, Kopp, Machado, Maltoni, Martinez, Schwetz (2017)

→ **dedicated very short-baseline (VSBL) experiments at nuclear reactors**

- clear signature required
  → observe oscillation wave pattern!
- typical oscillation lengths ~10m
  → detectors close to reactor core
  → high background levels!
- favored option:
  compact segmented detectors!
  → enhanced spatial resolution
  → utilize event topologies for background discrimination

Overview of VSBL reactor experiments

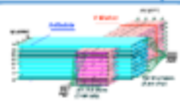
N. Bowden (Nu16)

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

Overview of VSBL reactor experiments

N. Bowden (Nu16)

SEGMENTED

Experiment		Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia)		3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
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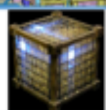
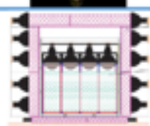
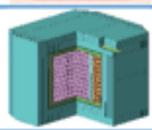
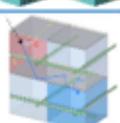
nuLat (USA)		40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia)		100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA)		85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US)		72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
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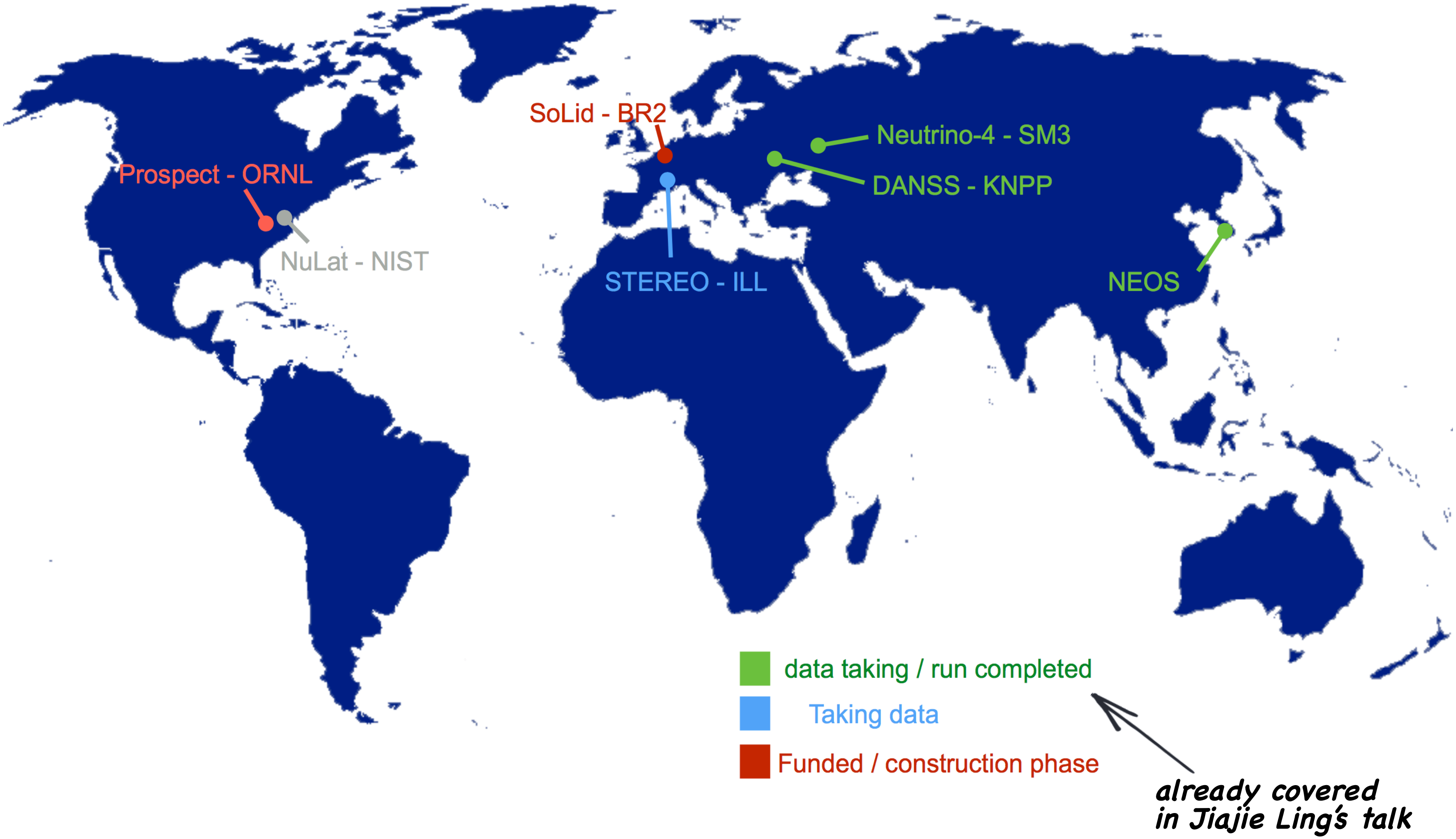
Stereo (France)		57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

Status of reactor VSBL experiments

A. Vacheret (NuTel17)

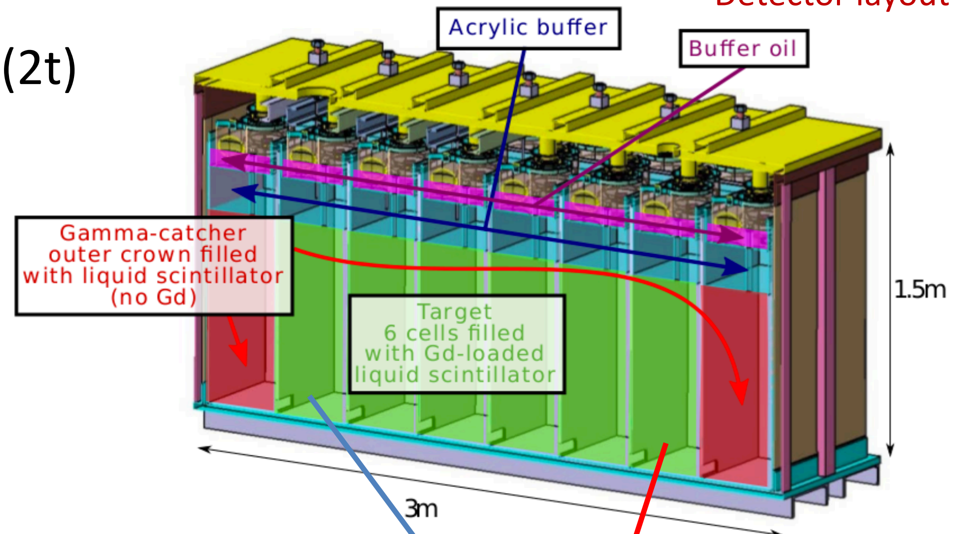


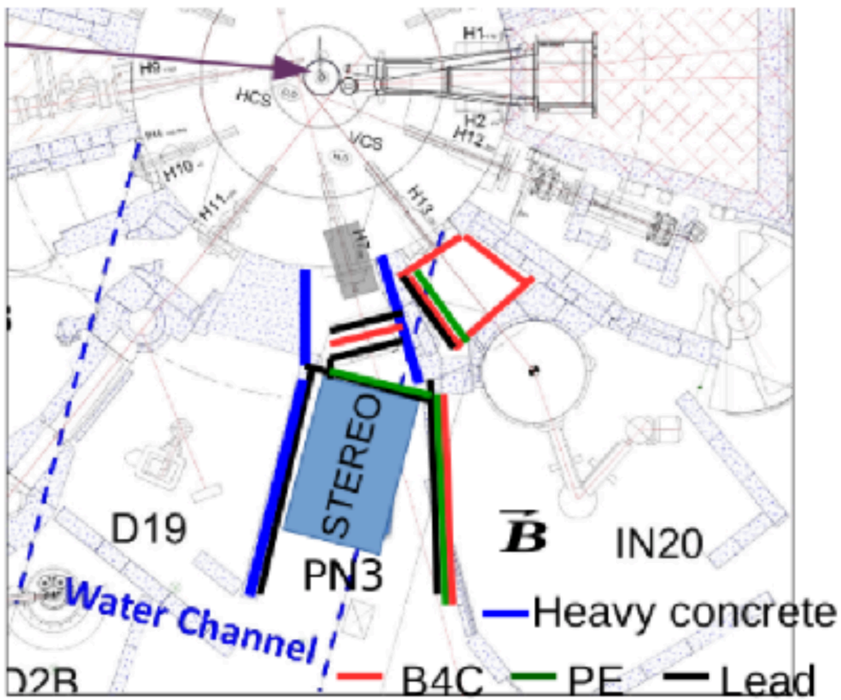
STÉRÉO at ILL reactor (Grenoble)

D. Lhuillier (15) & A. Vacheret (NuTel17)

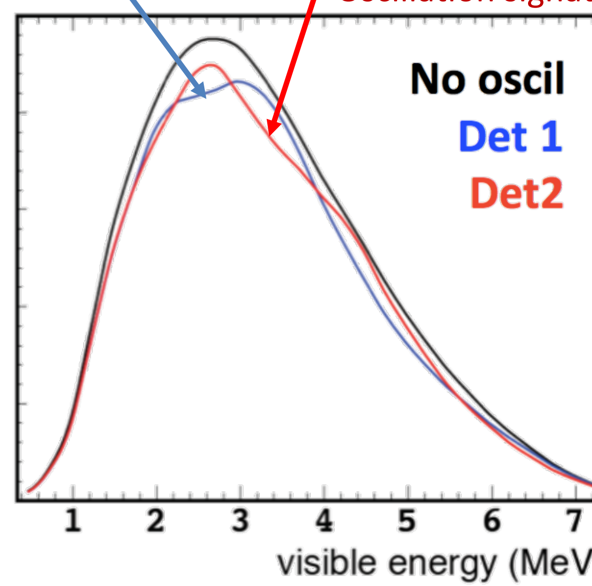
- 6 target cells w/ Gd-loaded scintillator (2t)
- variable baseline: **8.9m** - 11m from compact research reactor core

Detector layout





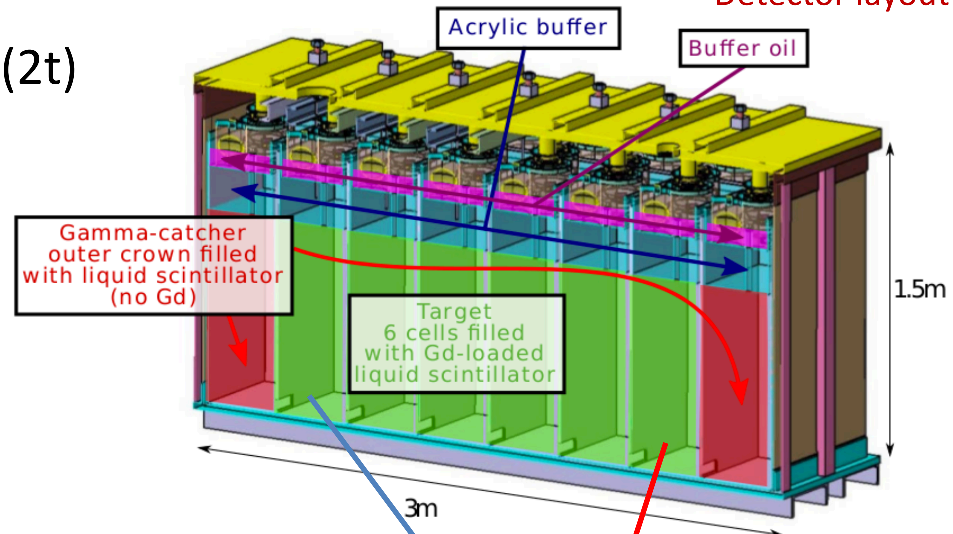
Oscillation signature

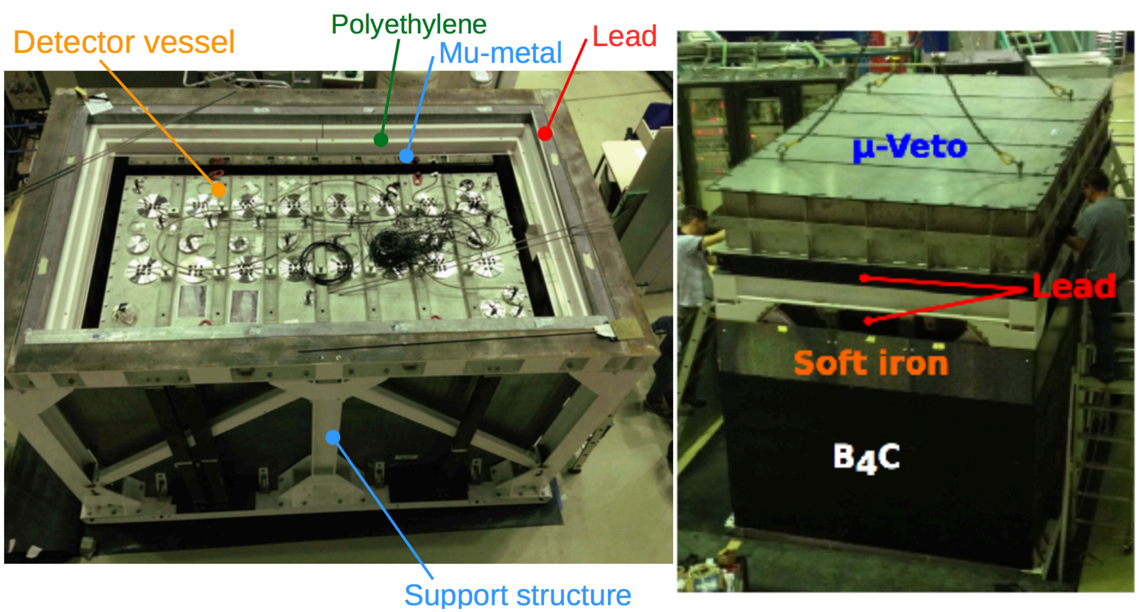


STÉRÉO at ILL reactor (Grenoble)

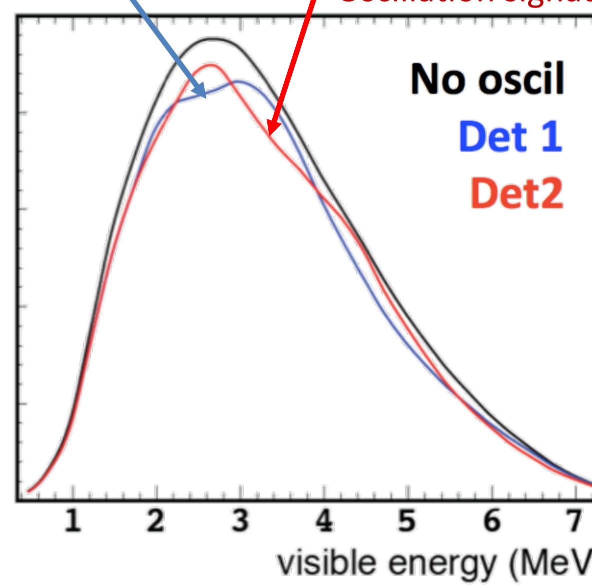
- 6 target cells w/ Gd-loaded scintillator (2t)
- variable baseline: 8.9m - 11m from compact research reactor core
- overburden: 15mwe + muon veto
- detector shielding against neutrons, γ-rays & magnetic fields

Detector layout



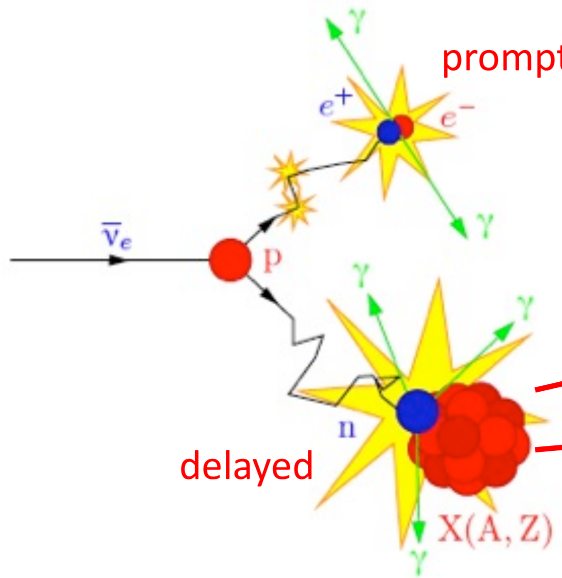


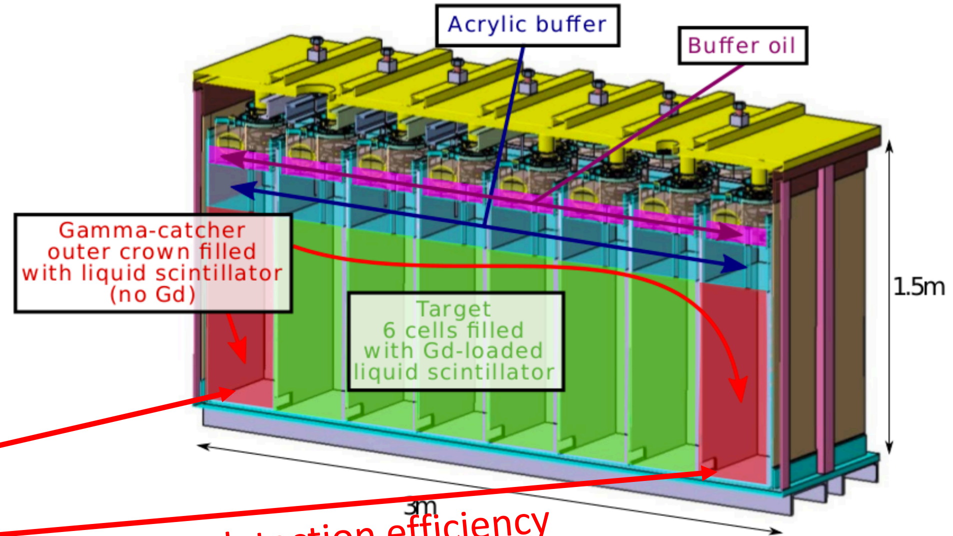
Oscillation signature



Antineutrino detection in STÉRÉO

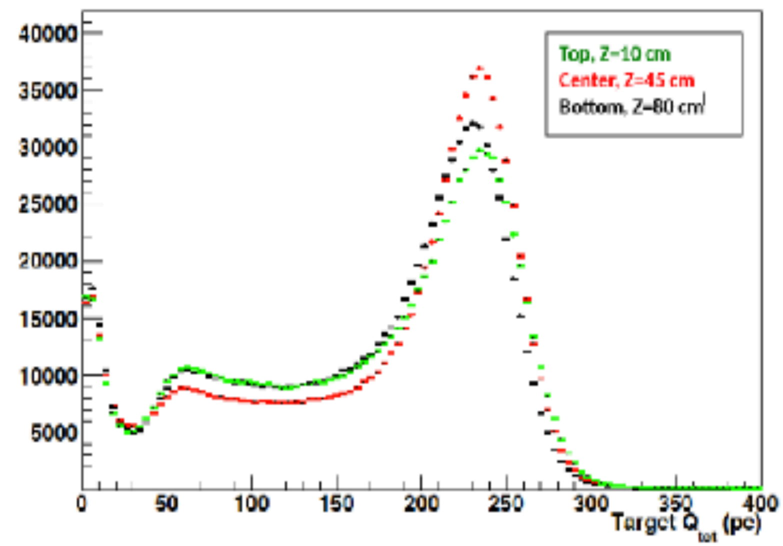
- $\bar{\nu}_e$-detection by inverse beta decay





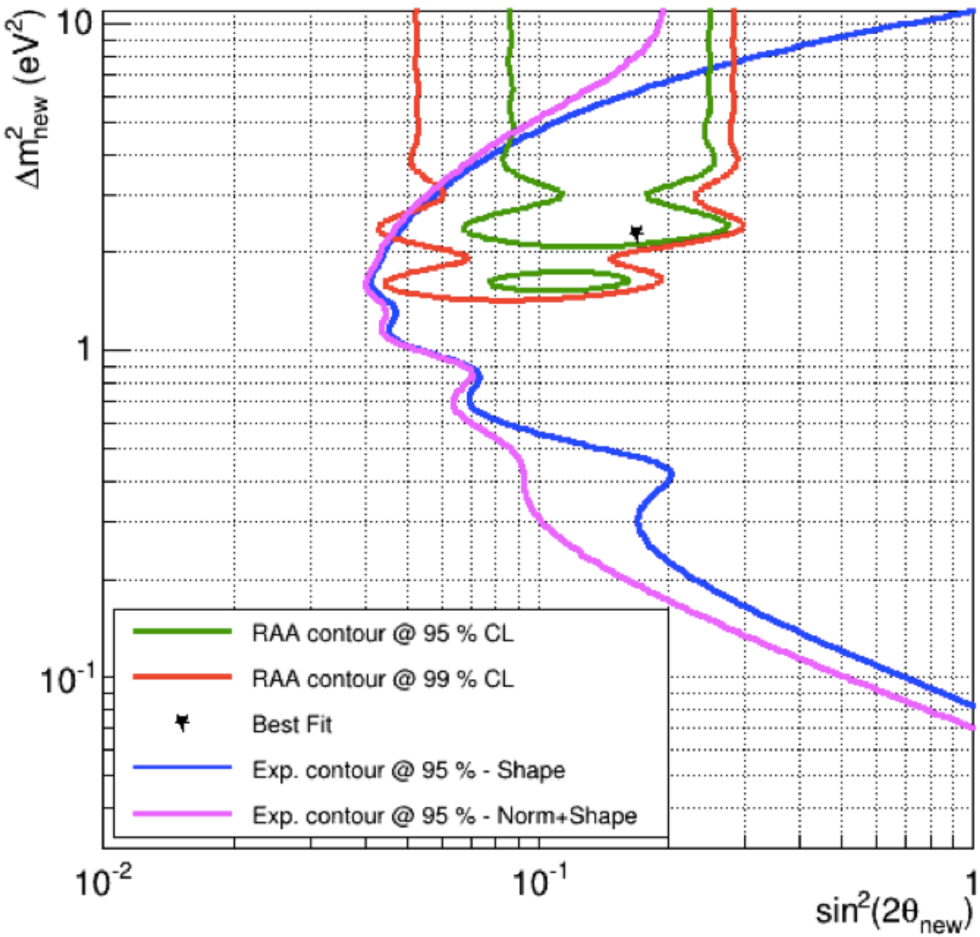
added for uniform γ-detection efficiency

- data taking started in November 2016:
  - rate in ν window (2-8 MeV): ~14 Hz
- source calibration data:
  - photoelectron yield: 290 pe/MeV
  - uniform light response within cells: ~2%



Expected sensitivity of STÉRÉO

D. Lhullier (2015)



Experimental parameters

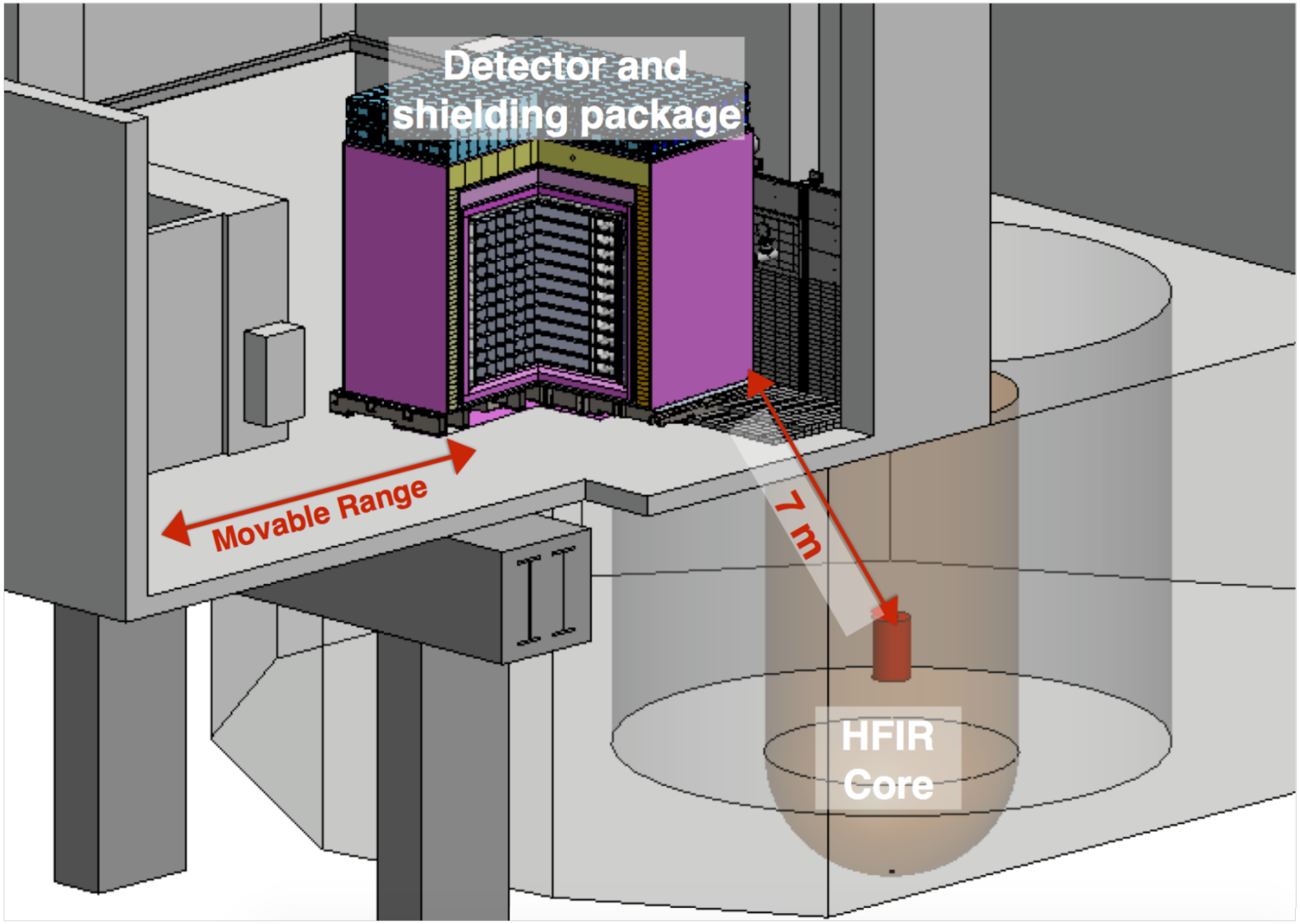
- 300 days, L_0 = 10 m
- E_{prompt}>2 MeV, $E_{delayed}$>5 MeV
- ~410ν_e/day
- δE_{scale} = 2%
- All syst. of predicted spectra
- S/B = 1.5, 1/E+flat model
- Norm 4%
- Start data taking in 2015

- data taking since November 2016, but intermission during this spring/summer

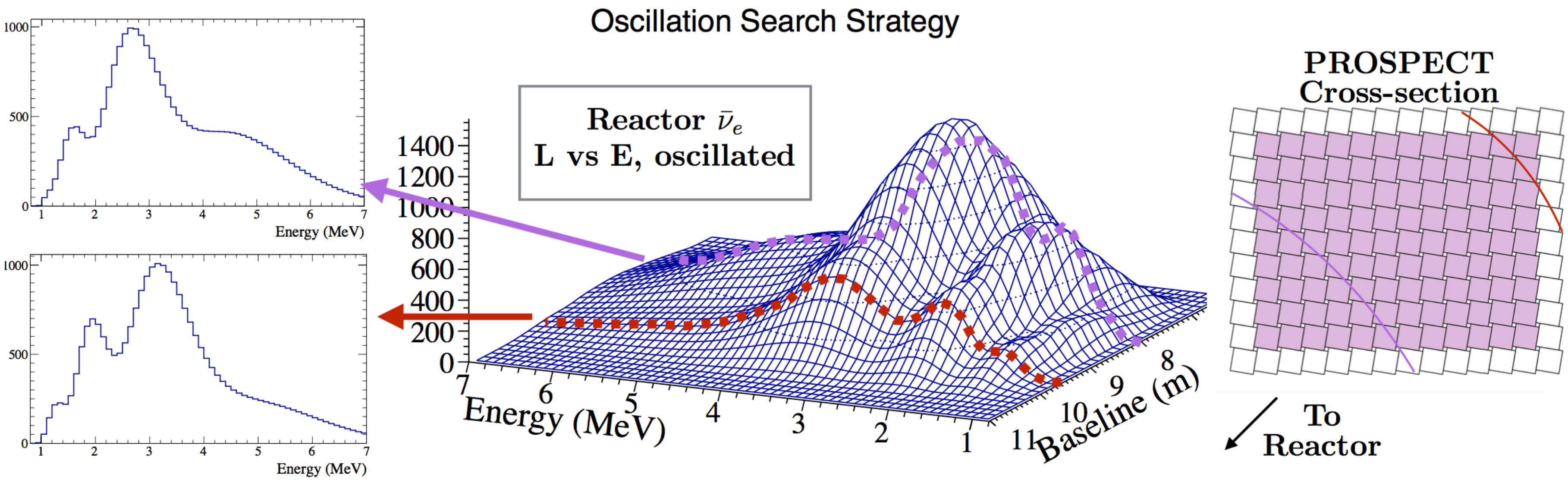
PROSPECT at Oak Ridge (US)

Surukuchi (IPA17)

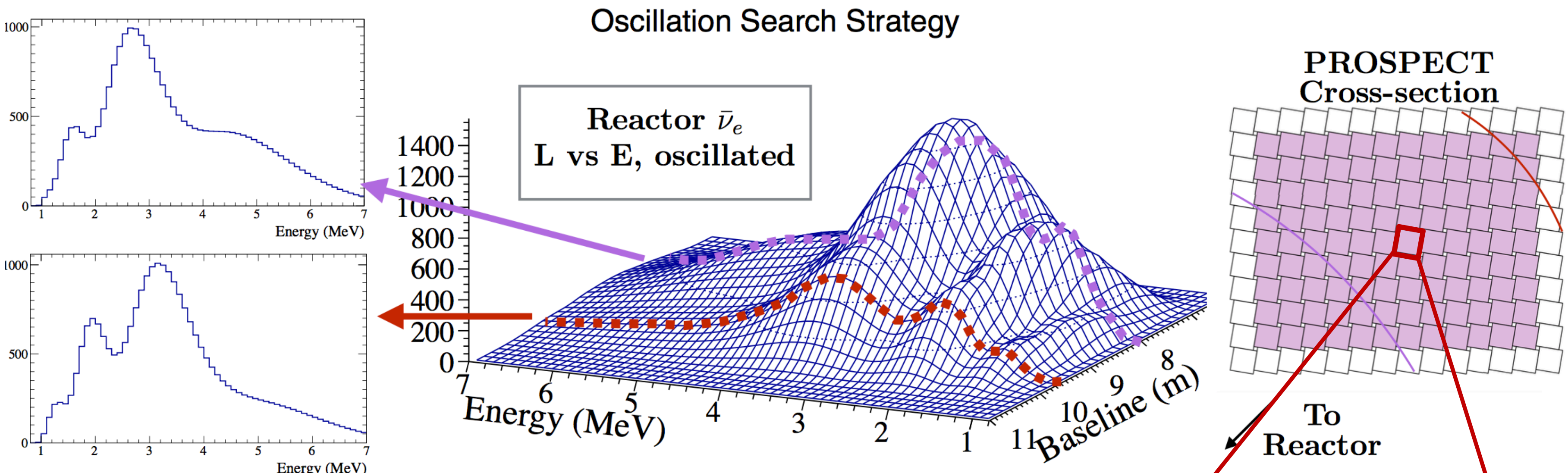
- highly segmented detector: ^{6}Li-loaded liquid scintillator (4ton)
- variable baseline: **7m**++ from very compact HFIR core (~0.5m)



Oscillation search

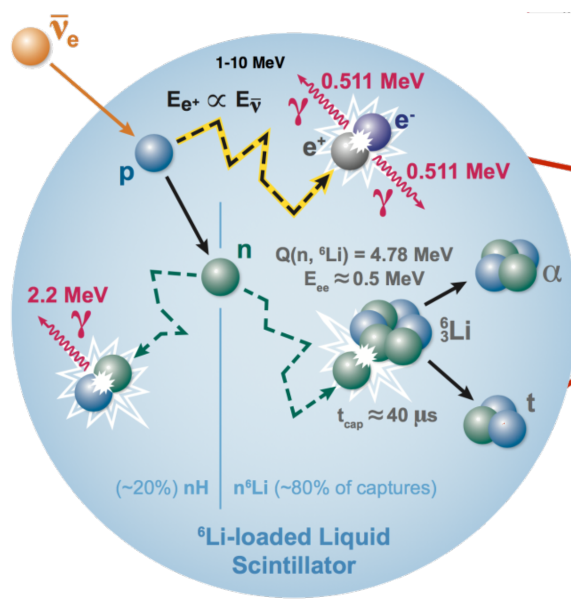


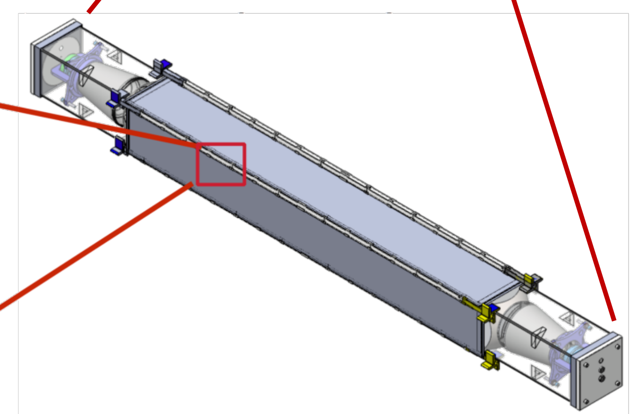
Segmented detector design



Target volume

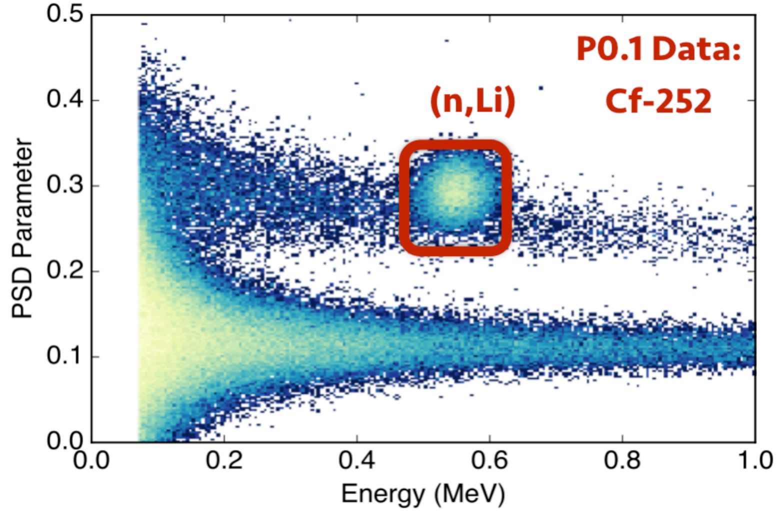
- 4 tons of Li-doped LS
- subdivided in 11x14 cells
- neutron capture on ^{6}Li: $n + {}^6Li \rightarrow {}^3H + {}^4He$

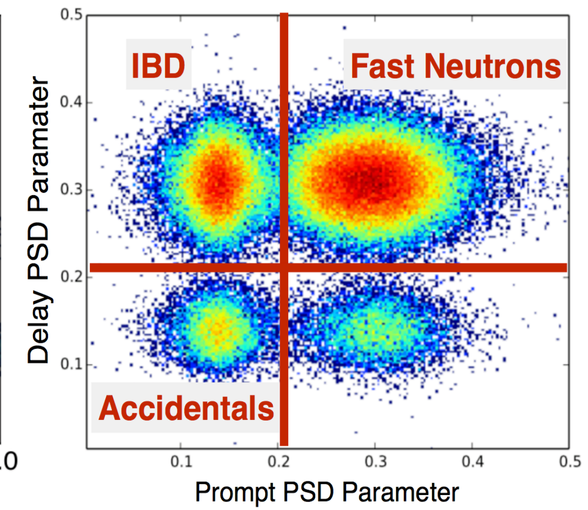


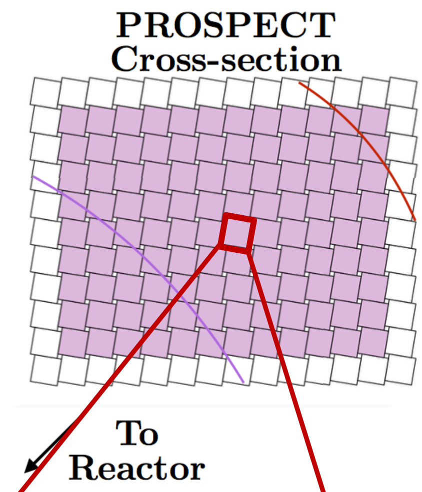


Segmented detector design

Pulse shape discrimination

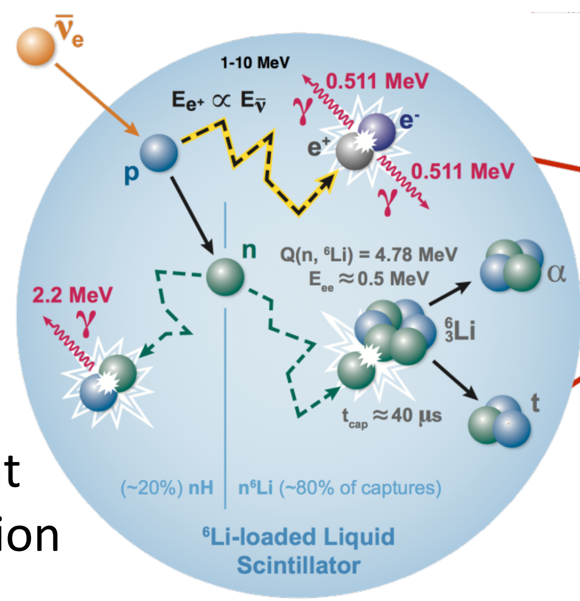


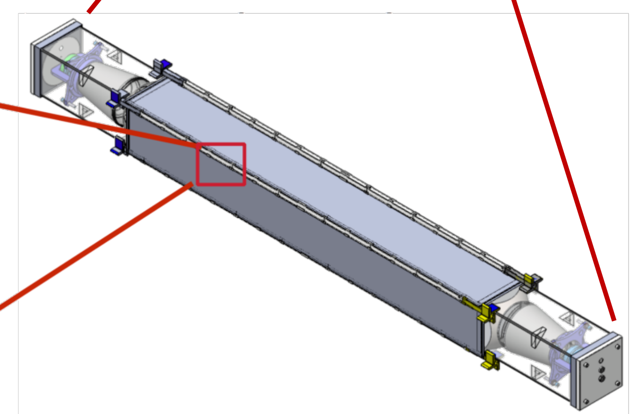




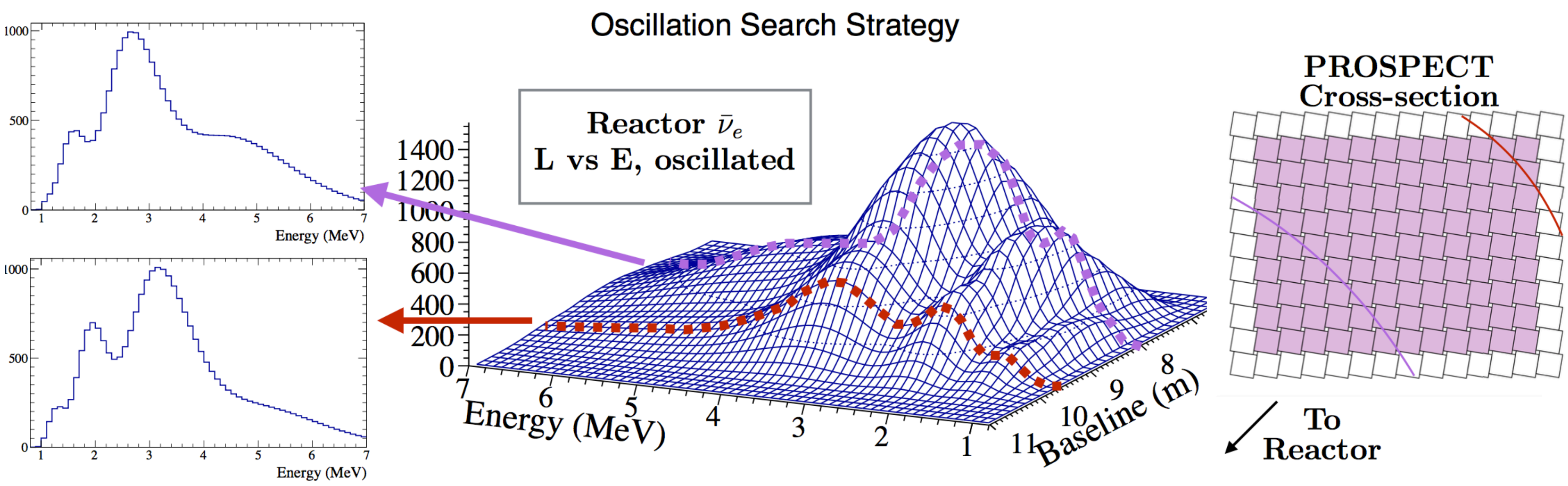
Target volume

- 4 tons of Li-doped LS
- subdivided in 11x14 cells
- neutron capture on ^{6}Li:
  $n + {}^6Li \rightarrow {}^3H + {}^4He$
- separation of delayed event by pulse shape discrimination





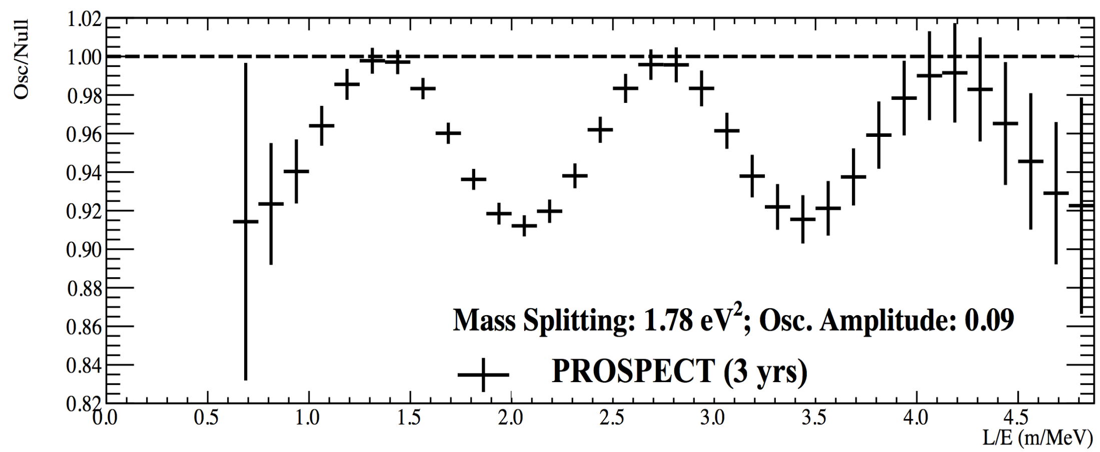
High-resolution measurement



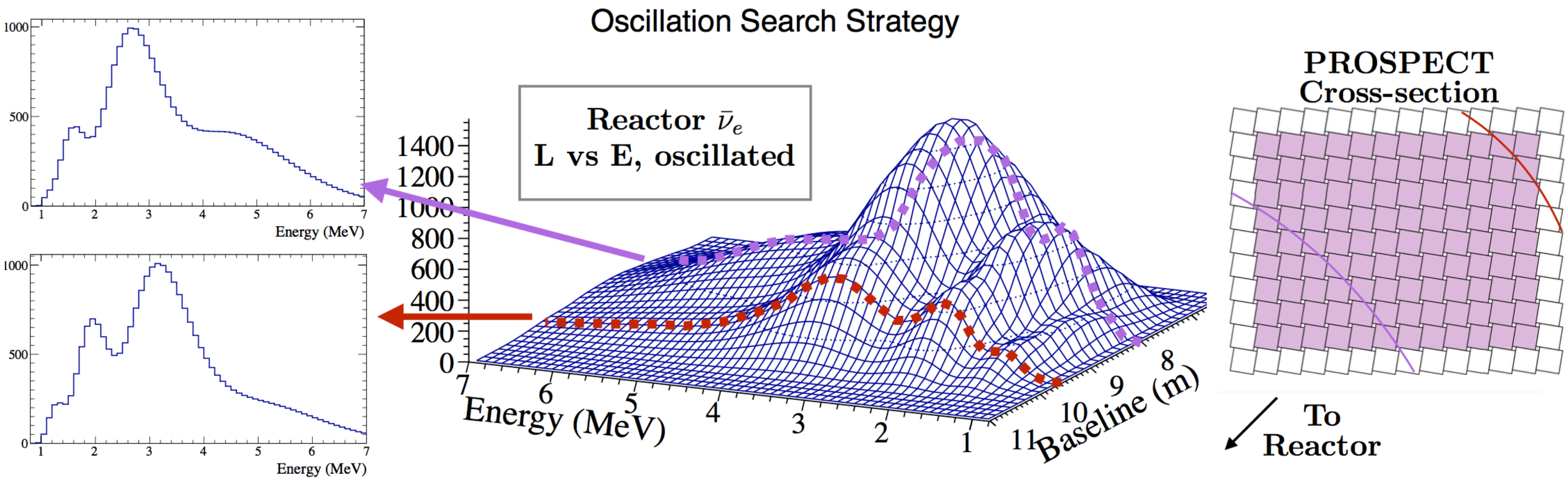
Experimental parameters:

- 160,000 events per year
- ΔE/E of 4.5% at 1MeV
- cell size: 14.4cm

→ fine-grained measurement of $\nu_e \rightarrow \nu_s$ oscillation signal



High-resolution measurement

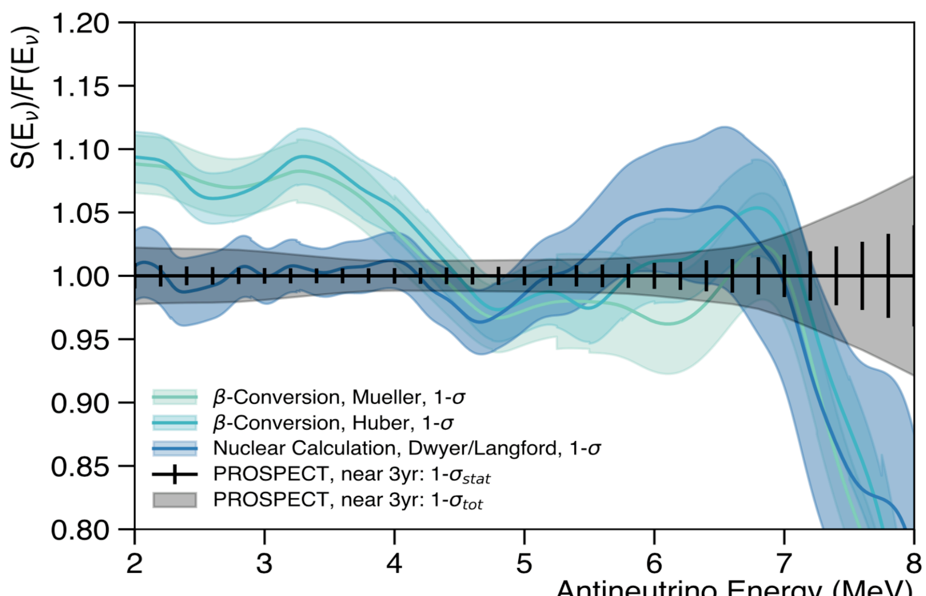


Experimental parameters:

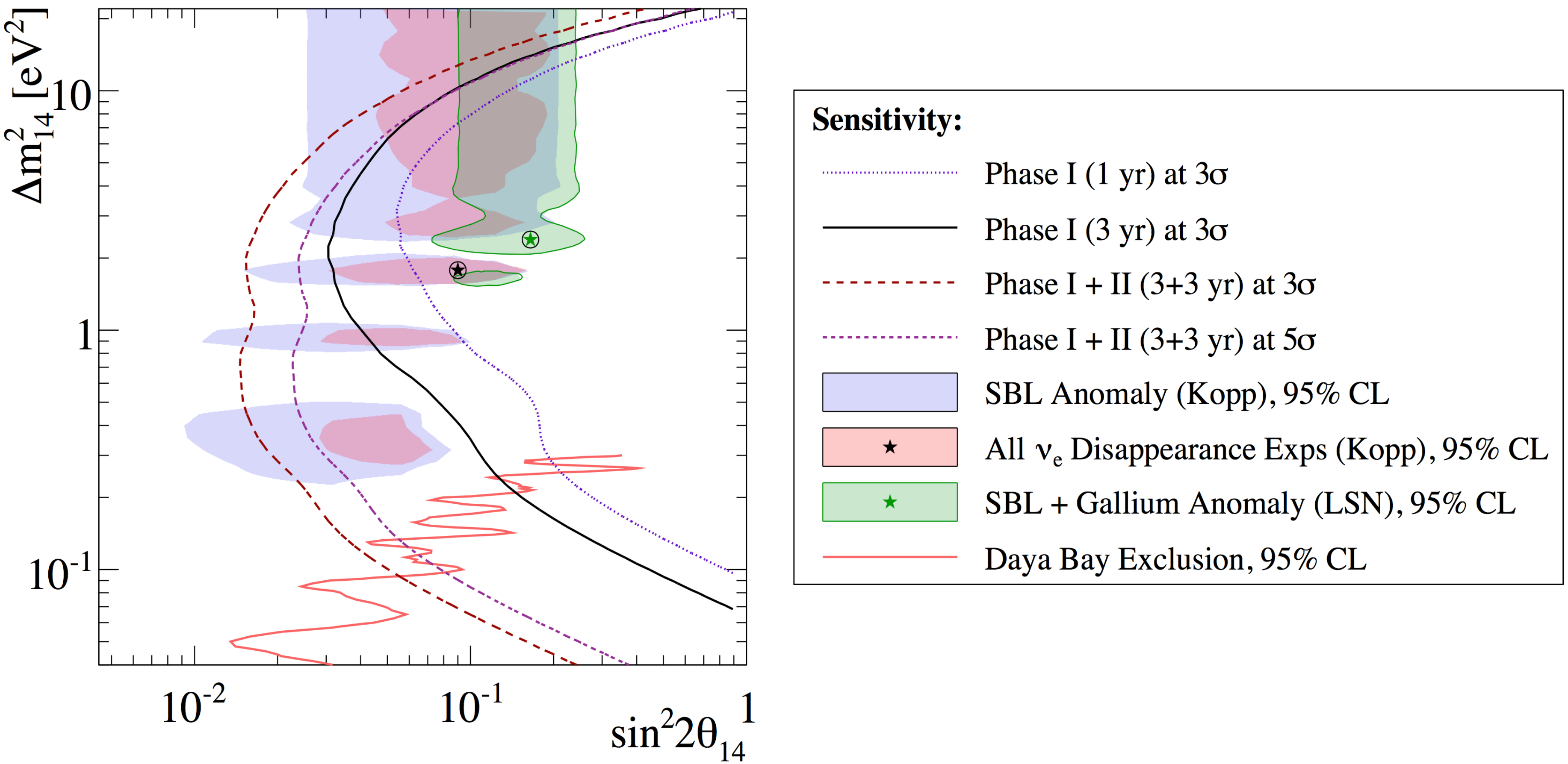
- 160,000 events per year
- ΔE/E of 4.5% at 1MeV
- cell size: 14.4cm

→ fine-grained measurement of $\nu_e \rightarrow \nu_s$ oscillation signal

→ precise measurement of ^{235}U ν-spectrum

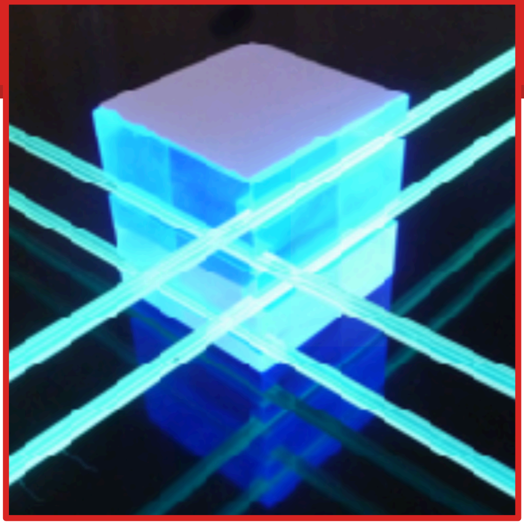


Projected Sensitivity



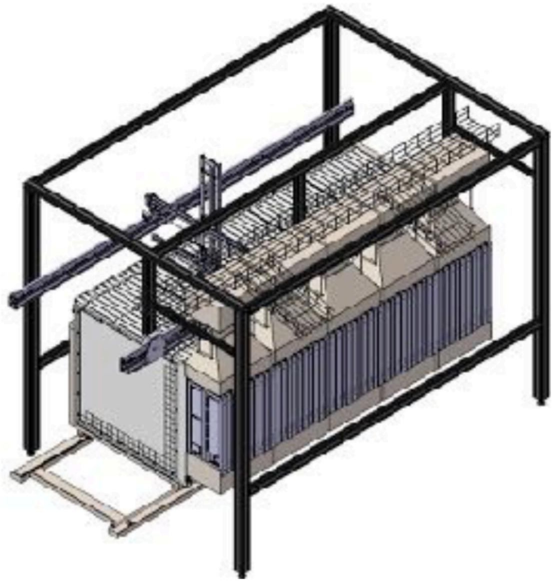
SoLið at BR2 (Belgium)

based on A. Vacheret's talk at NuTel17

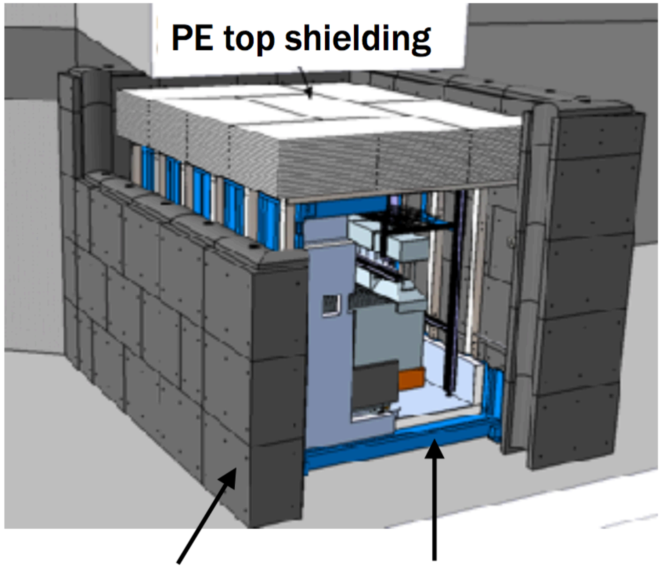


- composite detector (2t): plastic scintillator (PVC) cubes (5x5x5 cm^3) with intermittent ^{6}**Li**F:ZnS-layers
- variable baseline: **6-9m** from BR2 core
- CROSS calibration system (efficiency & energy at %-level)
- refrigerating container to limit SiPM dark noise
- external shielding enclosure for neutrons and γ-rays

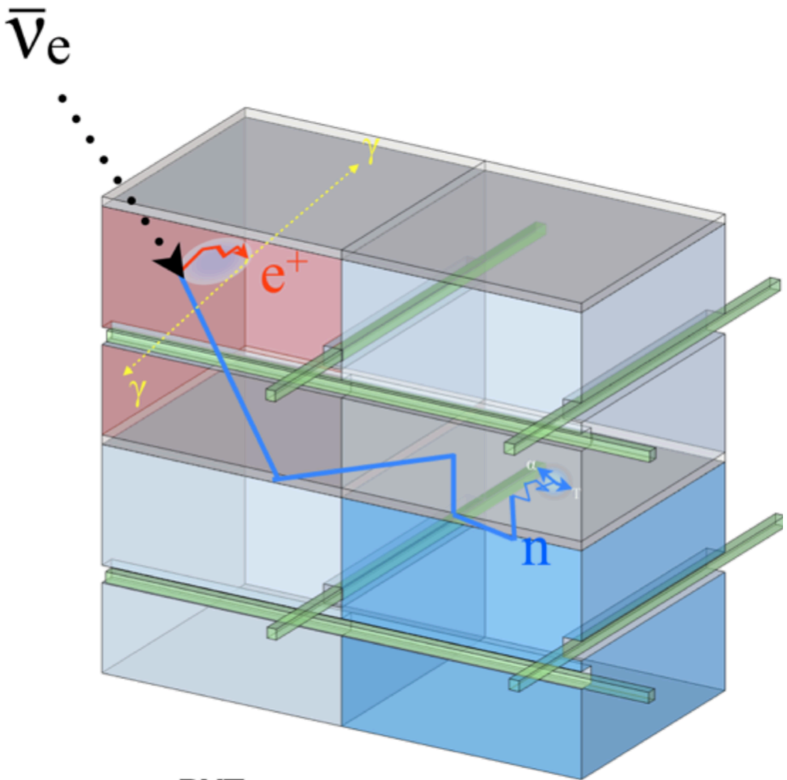
Geant4 model of SoLid at BR2

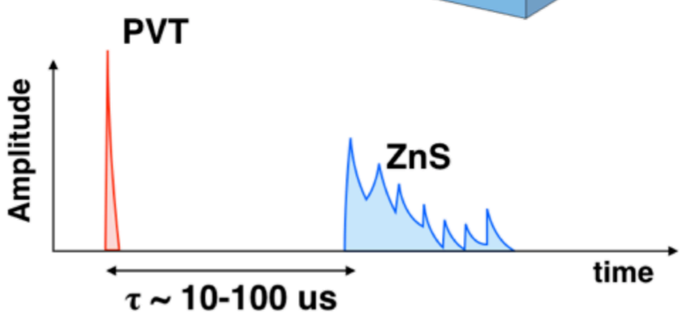


Detector Modules and rail CROSS source calibration robot



Antineutrino Detection in SoLiđ





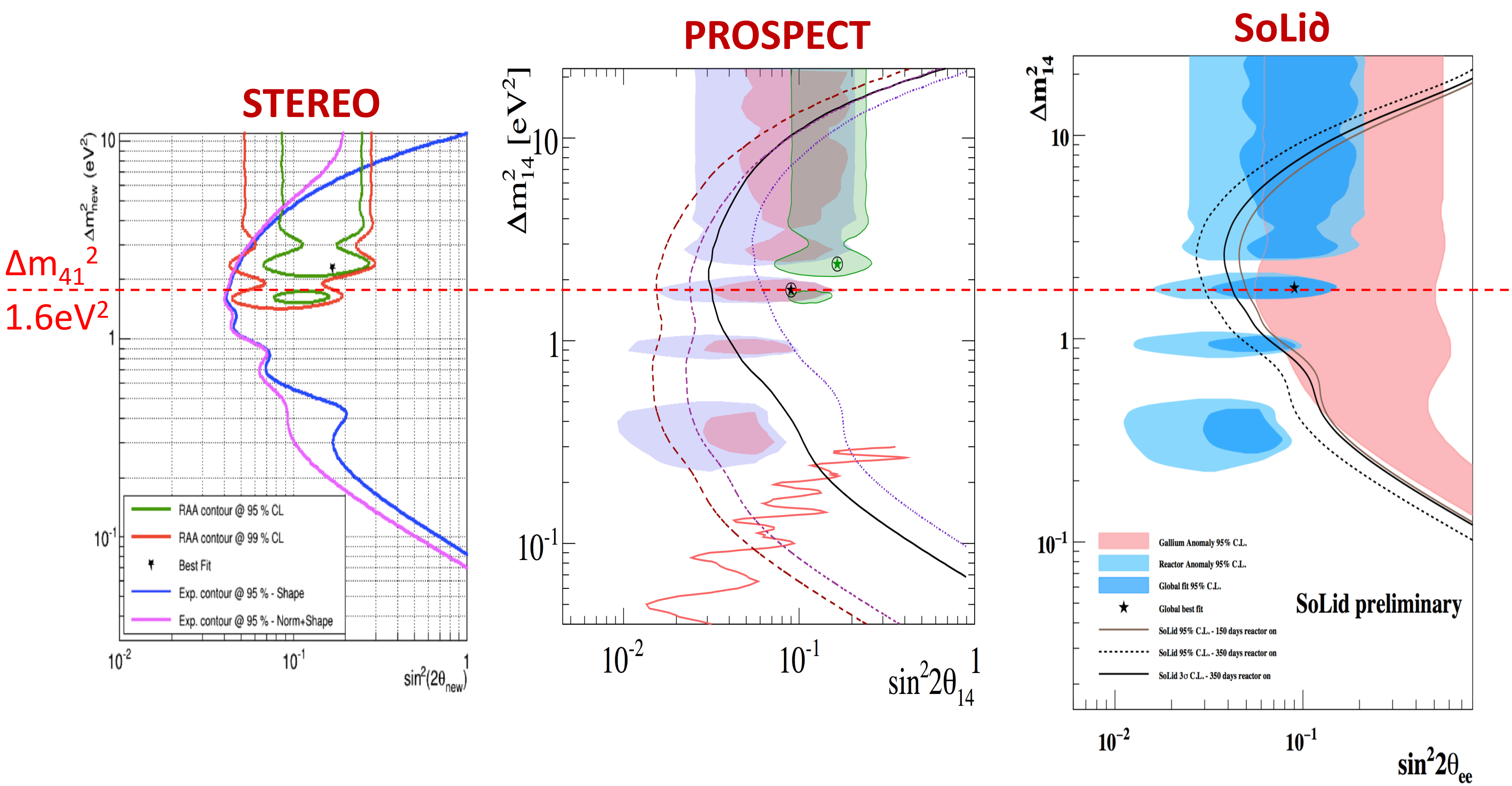
Detector configuration

- 3D detector with (5x5x5) cm^3 voxels
- optically separated by reflective foil
- light transport by wavelength-shifting fibers
- light read-out via SiPMs

detector construction on-going

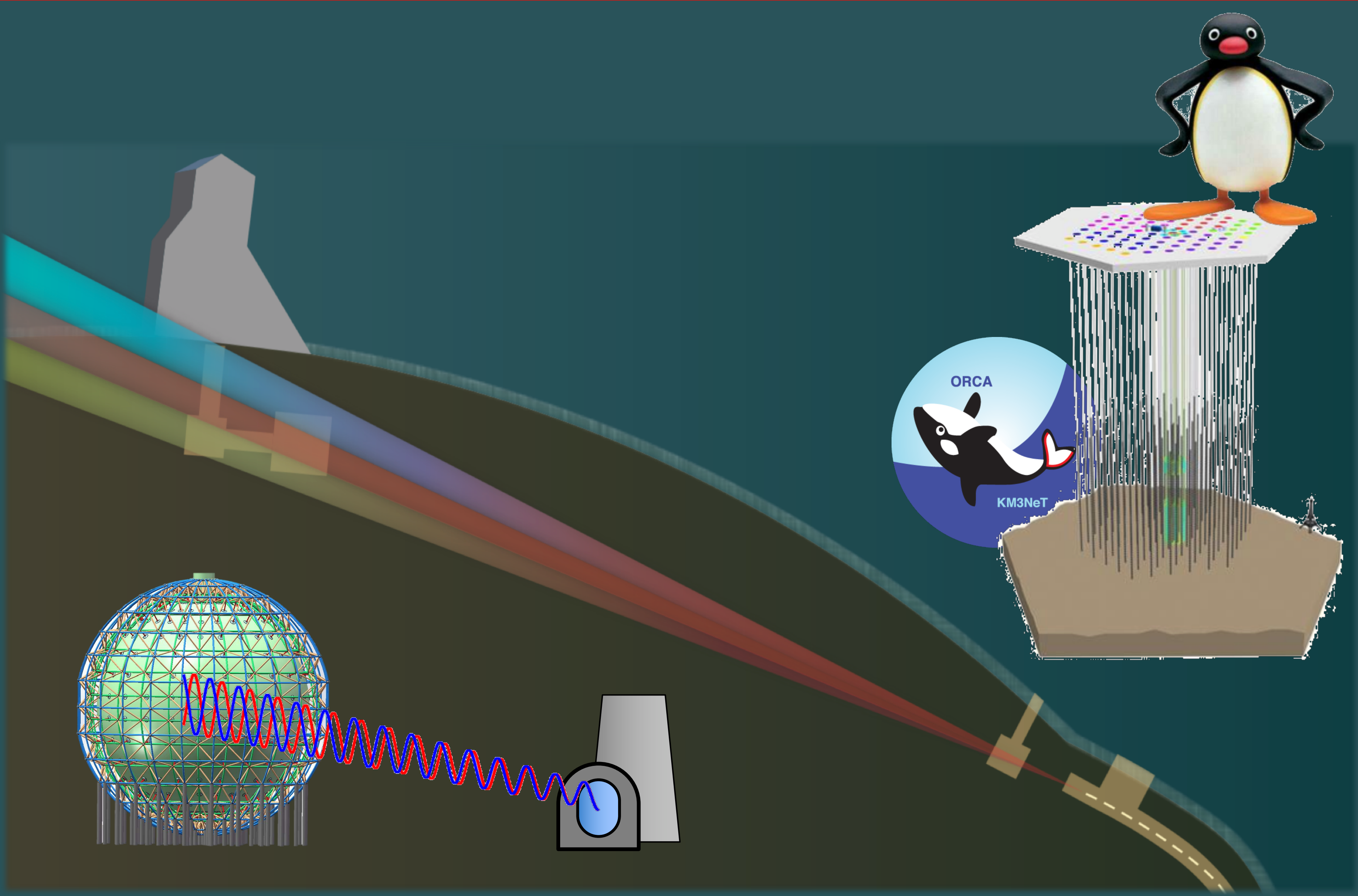
→ **data-taking expected this summer**

Projected sensitivities: STEREO, PROSPECT, SoLiđ



→ all three experiments feature excellent sensitivity in the preferred Δm^2 range

Concepts for MH measurement



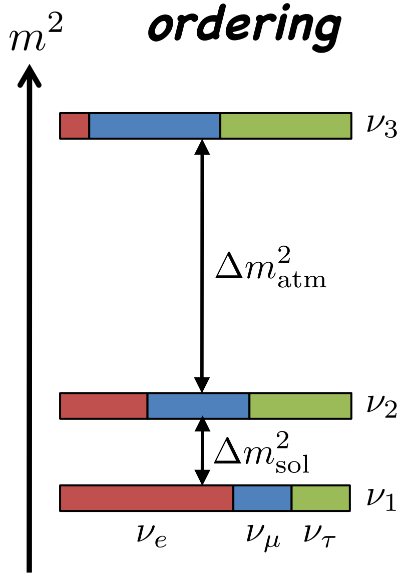
Open questions in neutrino oscillations

cf. Qingmin Zhang's talk

$$\mathbf{U_{3\times 3}} = \mathbf{U}_{\text{PMNS}}$$

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

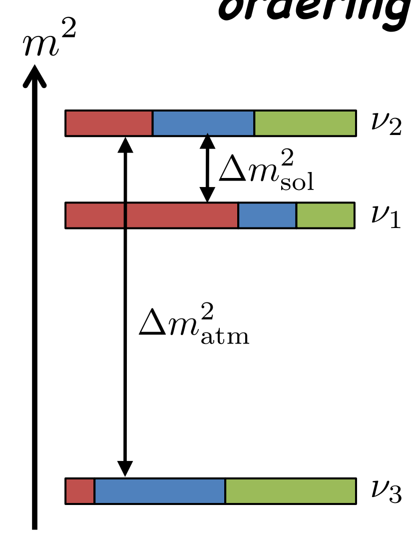
normal ordering



What is the

- **octant of θ_{23} ($\gtrless 45°$)?**
- value of **CP-phase?**
- **mass hierarchy?** (sign of Δm^2_{atm})
- PMNS unitarity: **sterile neutrinos?**

inverted ordering

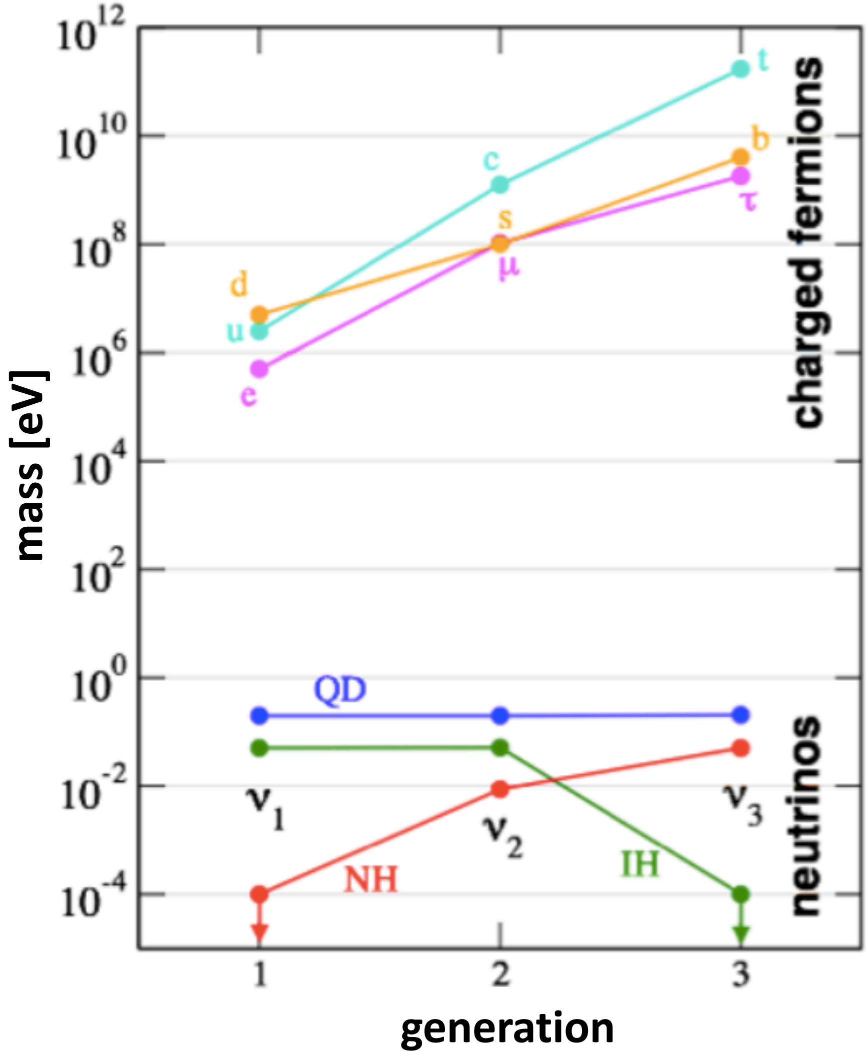


Why to measure mass hierarchy?

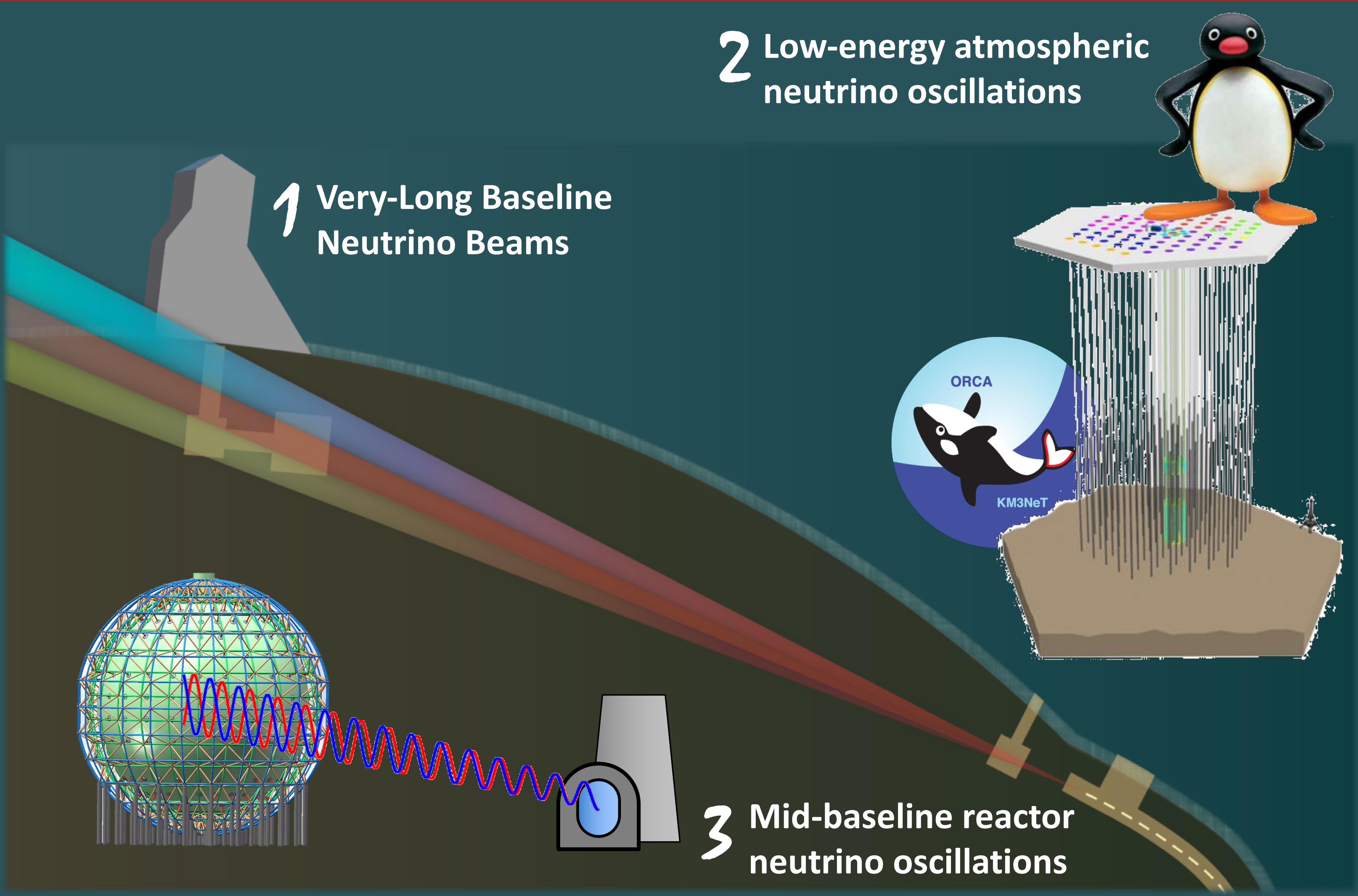
JG|U

- **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)
- Important preparatory step for future $\boldsymbol{\delta_{CP}}$ **measurements**
- target range for **sensitivity** of **0νββ decay** experiments
- combination with **cosmology** to find **lightest neutrino mass**

Fermion families and masses



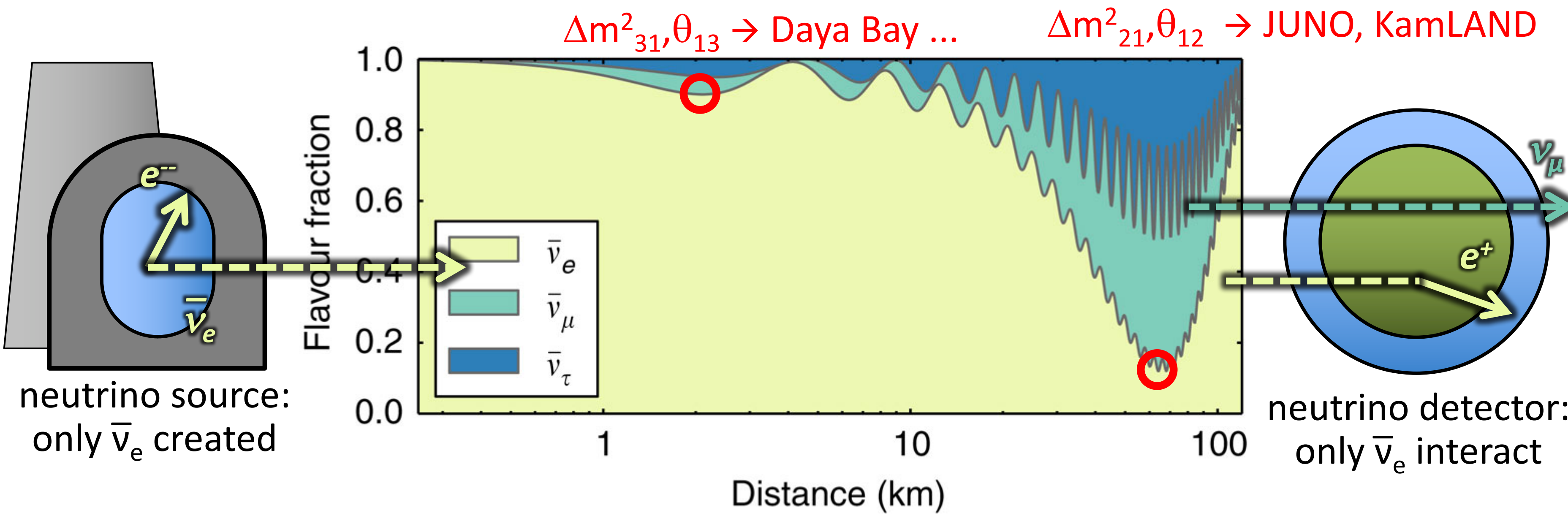
Neutrino Mass Hierarchy



Low-energy disappearance searches

Common three-flavor reactor electron-antineutrino survival probability:

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

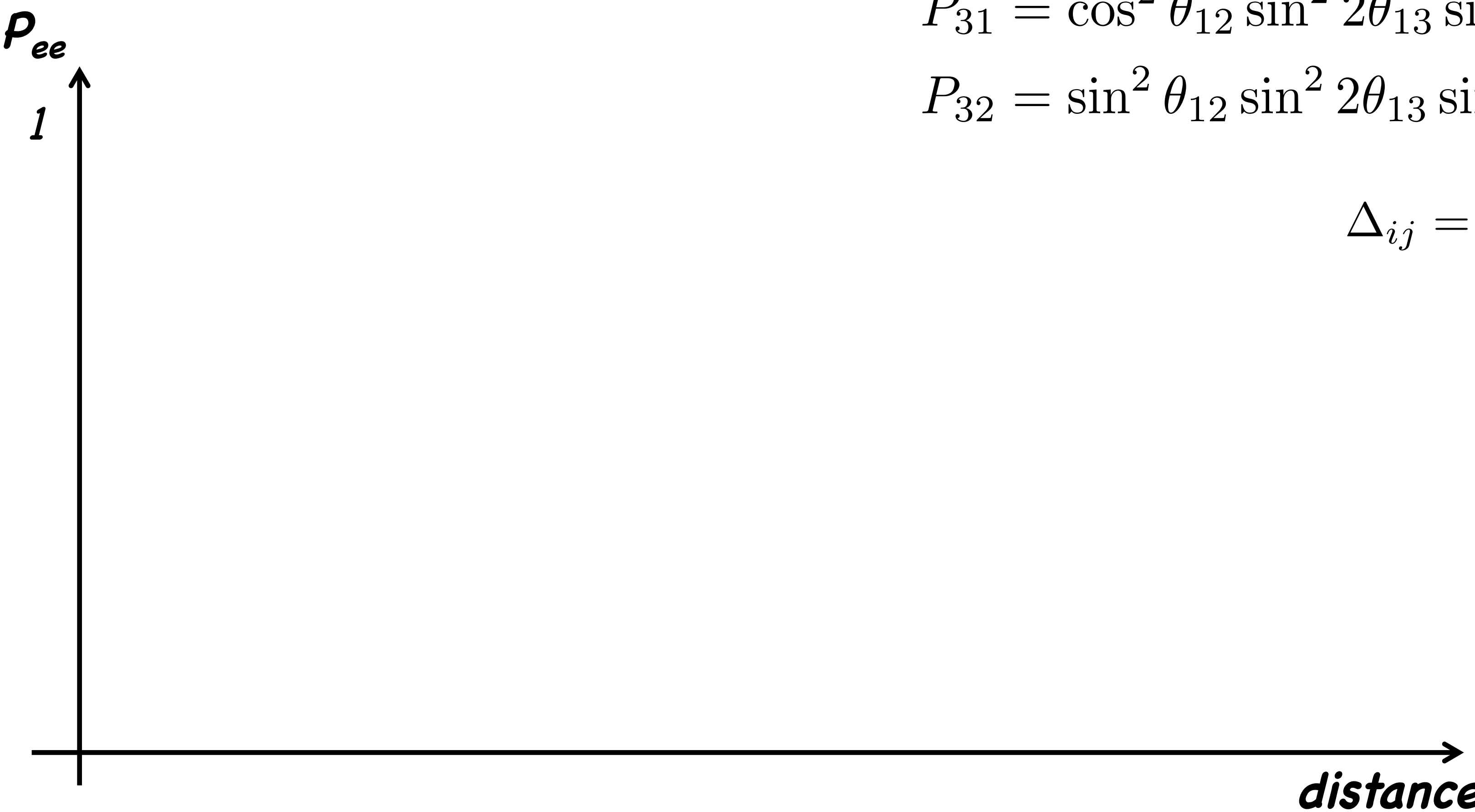


→ oscillation parameters are extracted from **$\bar{\nu}_e$ disappearance pattern**

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

Mass hierarchy with reactor neutrinos

[Petcov, Piai, hep-ph/0112074]



Survival probability

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

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

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

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

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

Mass hierarchy with reactor neutrinos

Survival probability

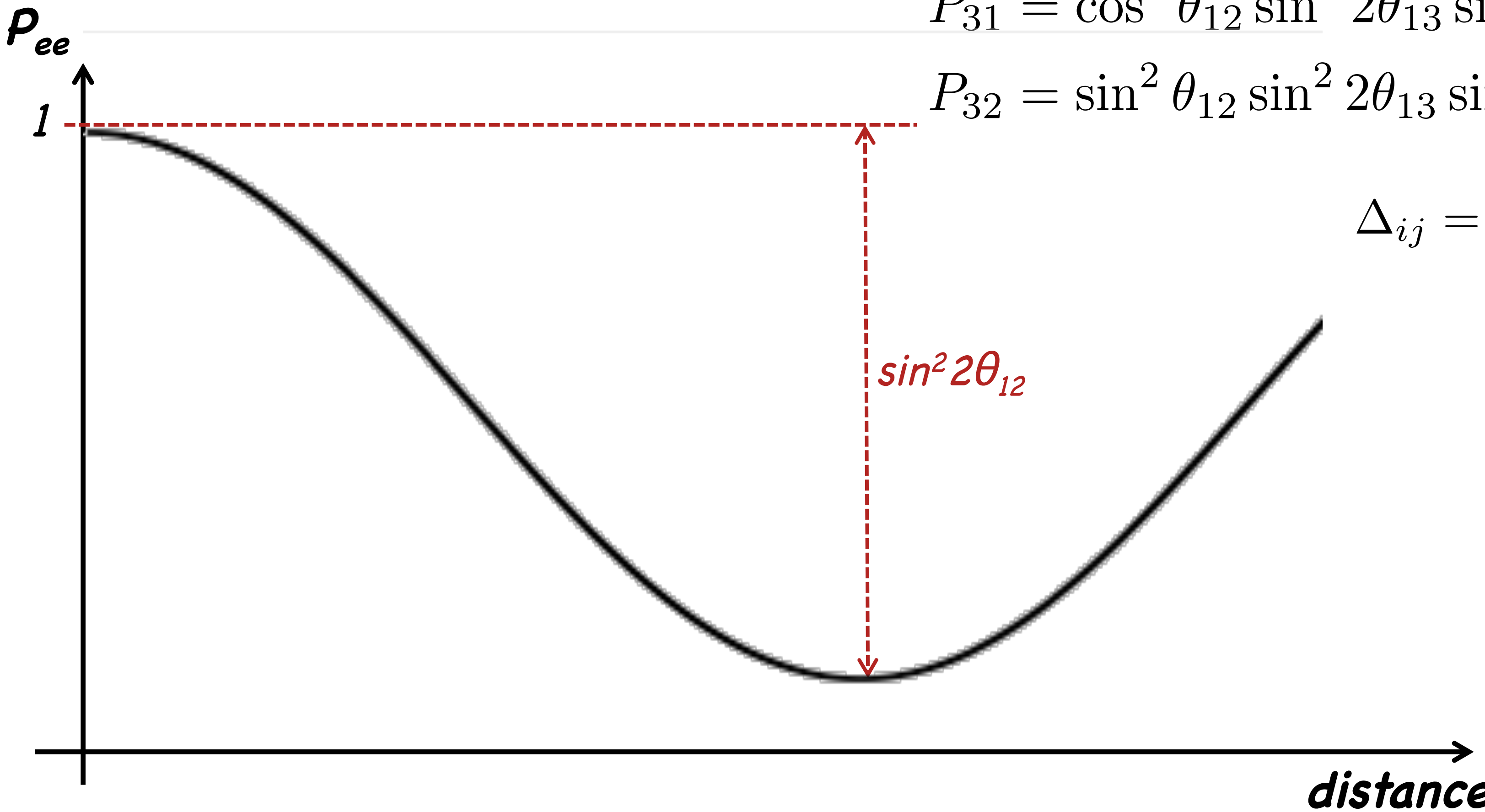
$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

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

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

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

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



Mass hierarchy with 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}

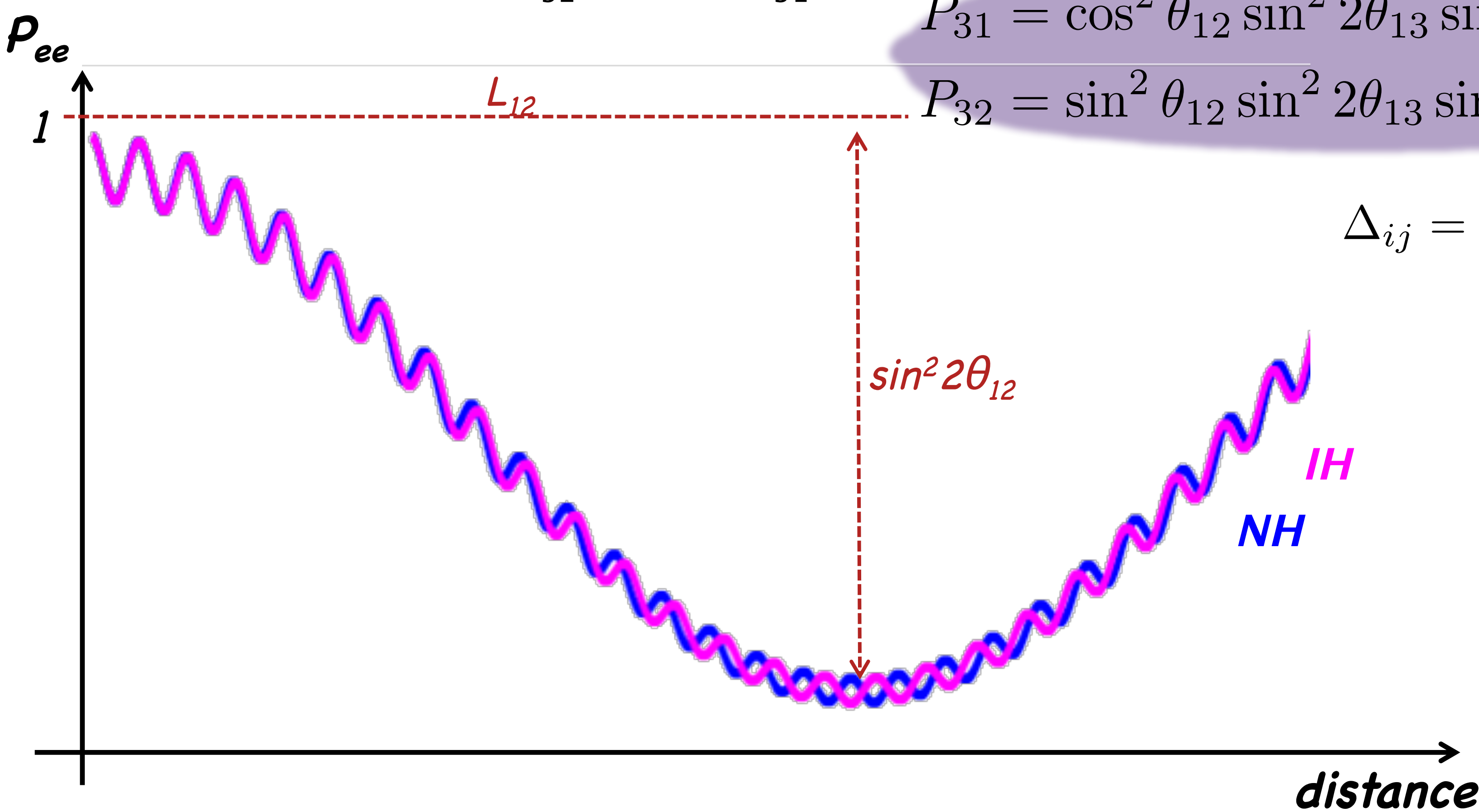
$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

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

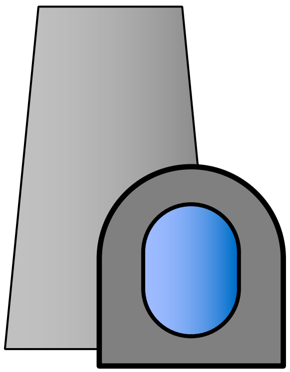
$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

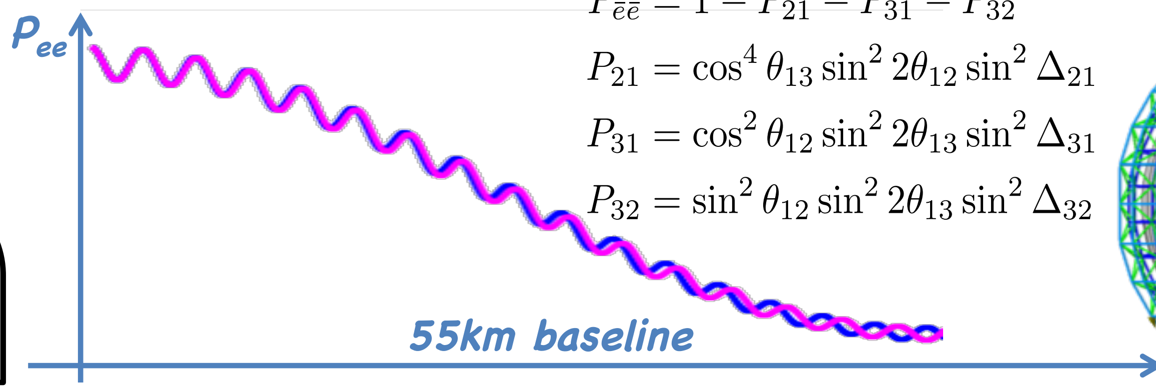
$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

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



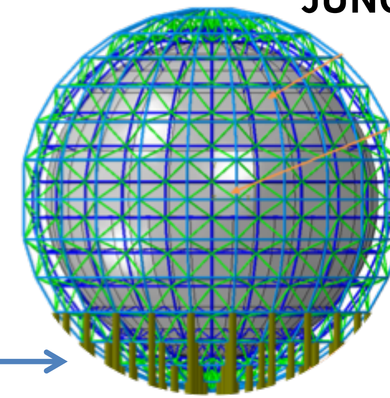
Mass hierarchy with reactor neutrinos





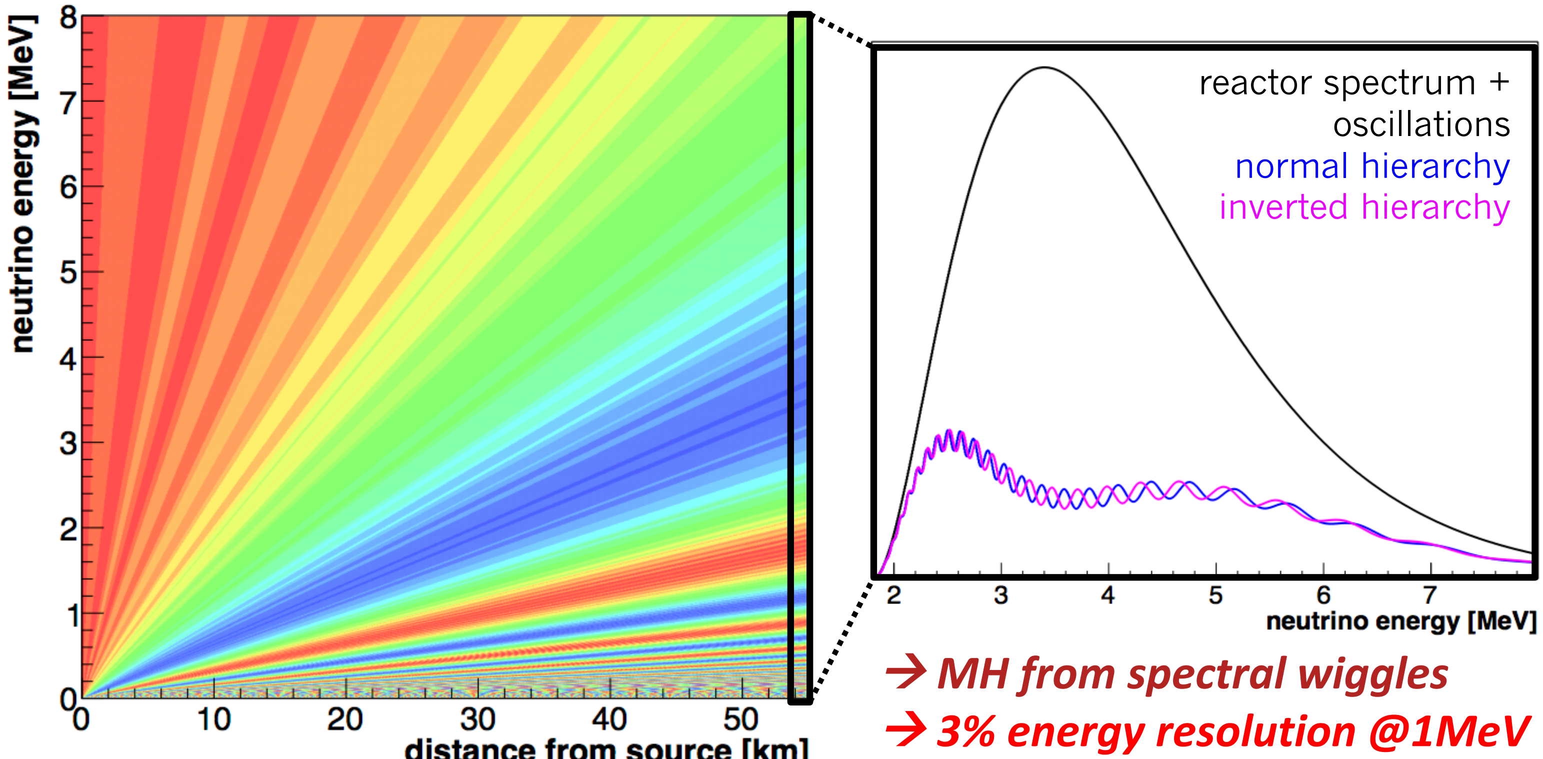
$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$
$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

JUNO



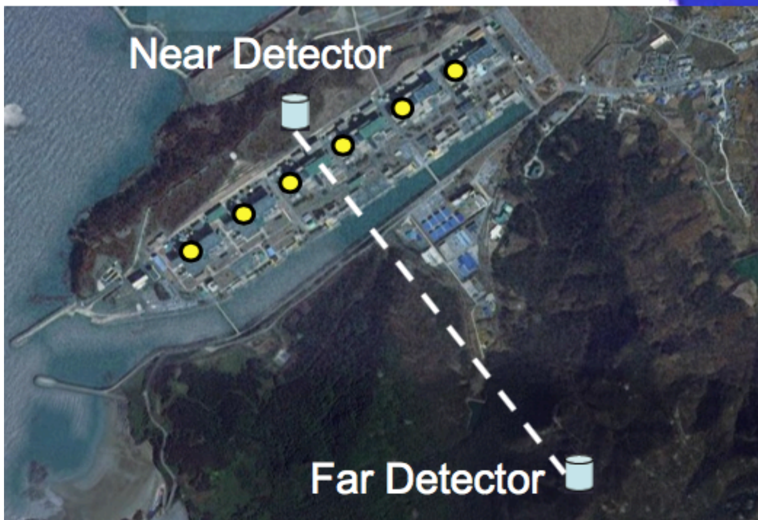
Nuclear reactors at
- *Yangjiang*
- *Taishan*
  (so. China)

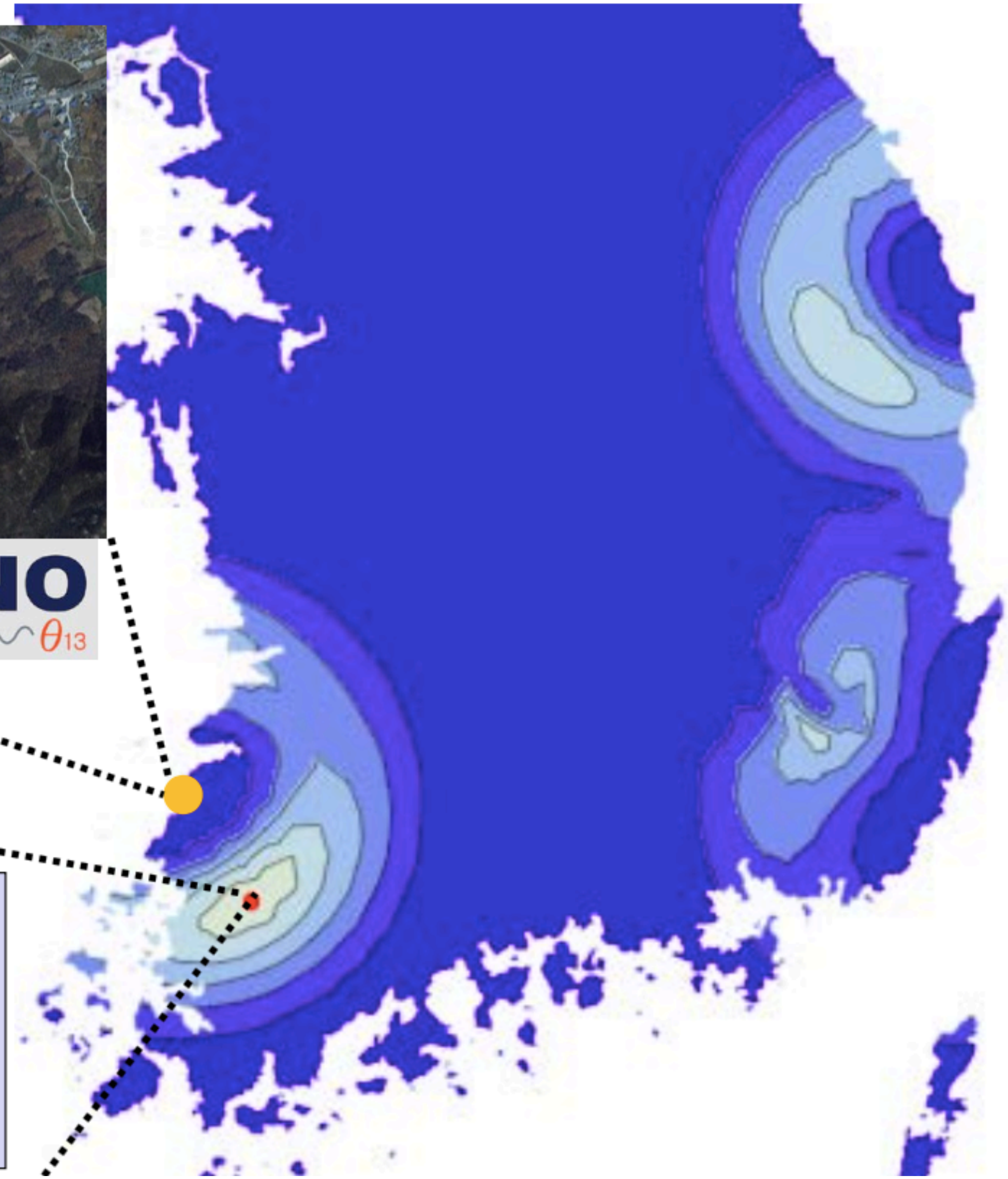
Total power:
38 GW



→ *MH from spectral wiggles*
→ *3% energy resolution @1MeV*

RENO-50 in South Korea



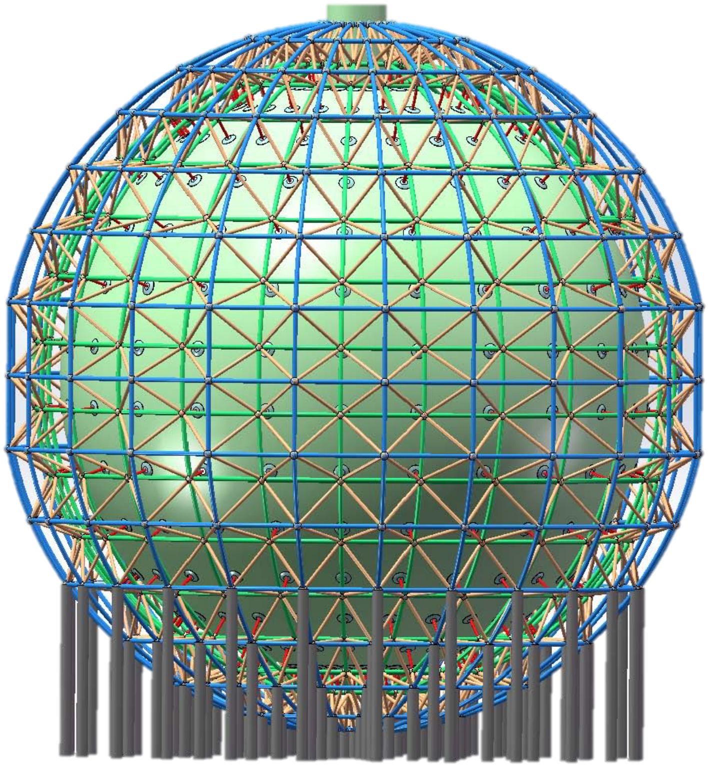


RENO-50

18 kton LS Detector
~47 km from YG reactors

Mt. Guemseong (450 m)
~900 m.w.e. overburden

JUNO in Jiangmen (China)



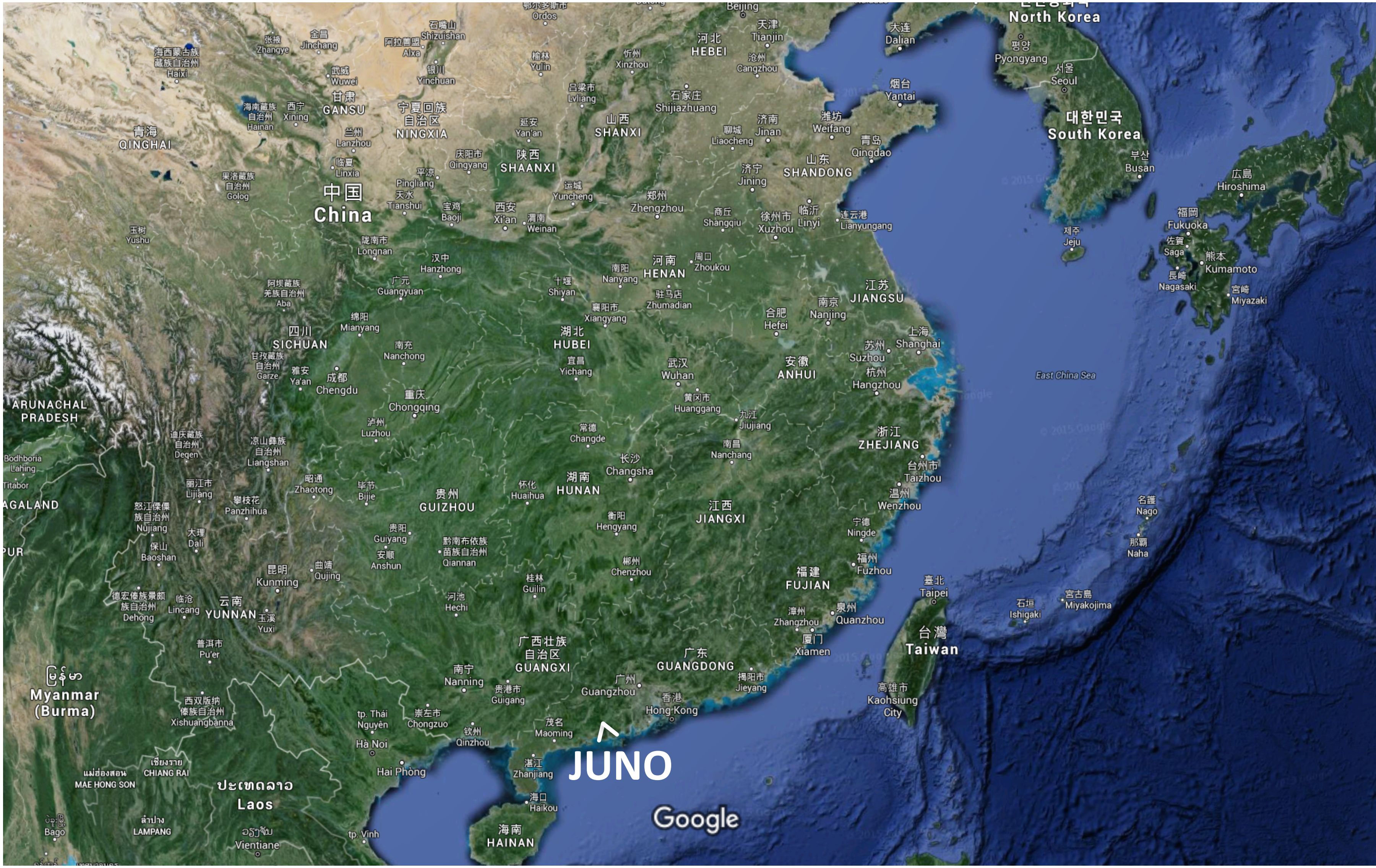
Physics objectives

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

JUNO characteristics

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

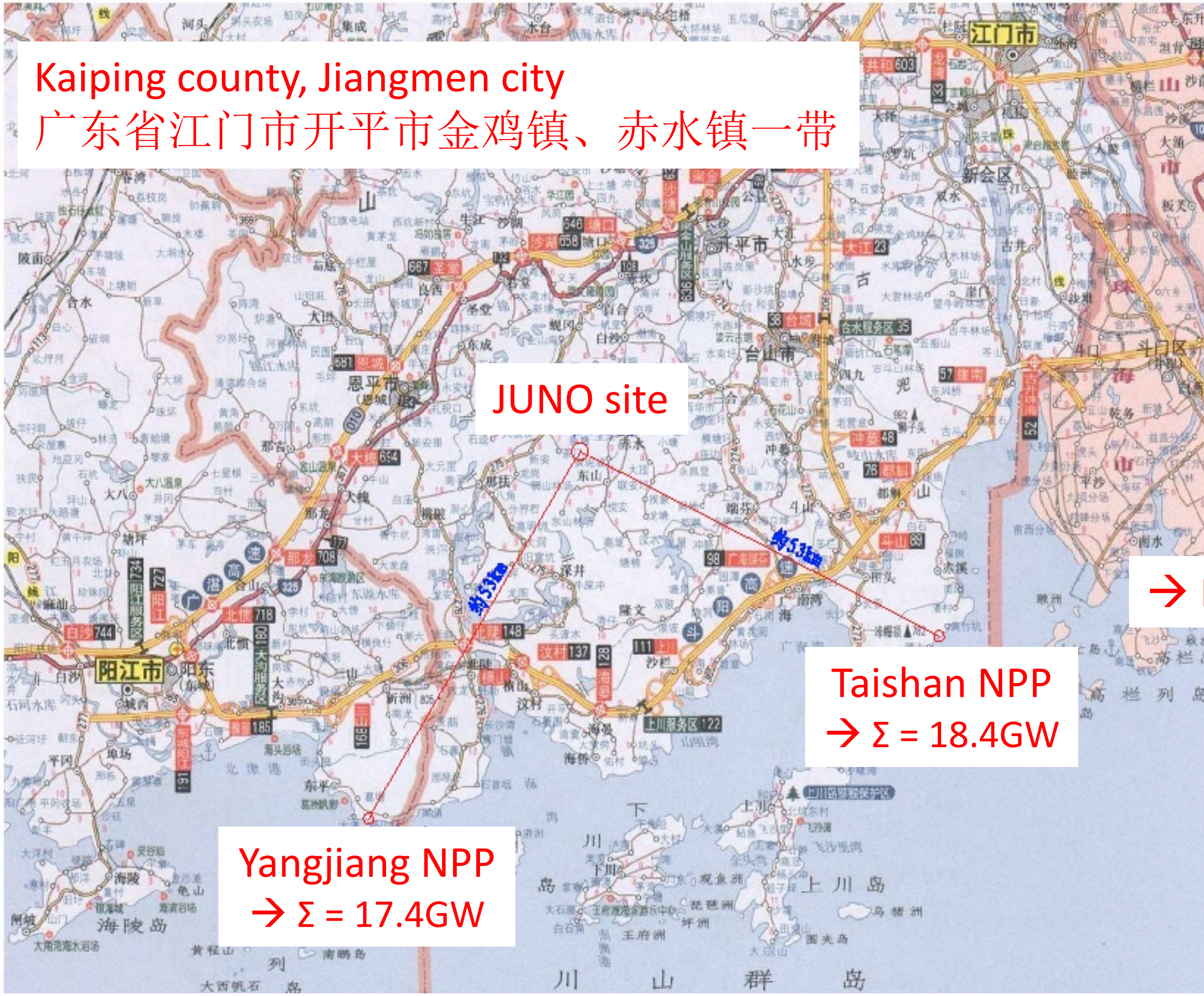
JUNO Experimental Location



Bilder © 2015 Landsat,Data SIO, NOAA, U.S. Navy, NGA, GEBCO,Kartendaten © 2015 Google,SK planet,ZENRIN 200 mi

JUNO Experimental Location

JUNO Experimental Location

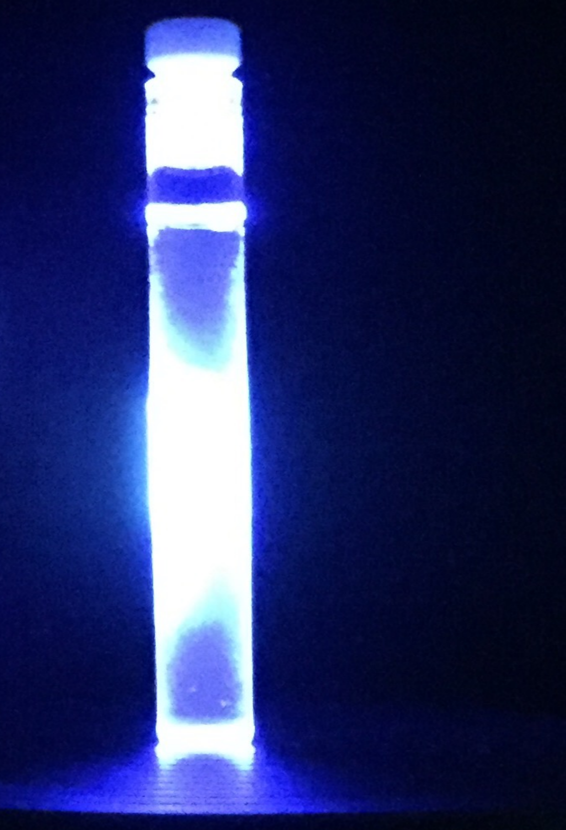


Basic detector requirements for JUNO

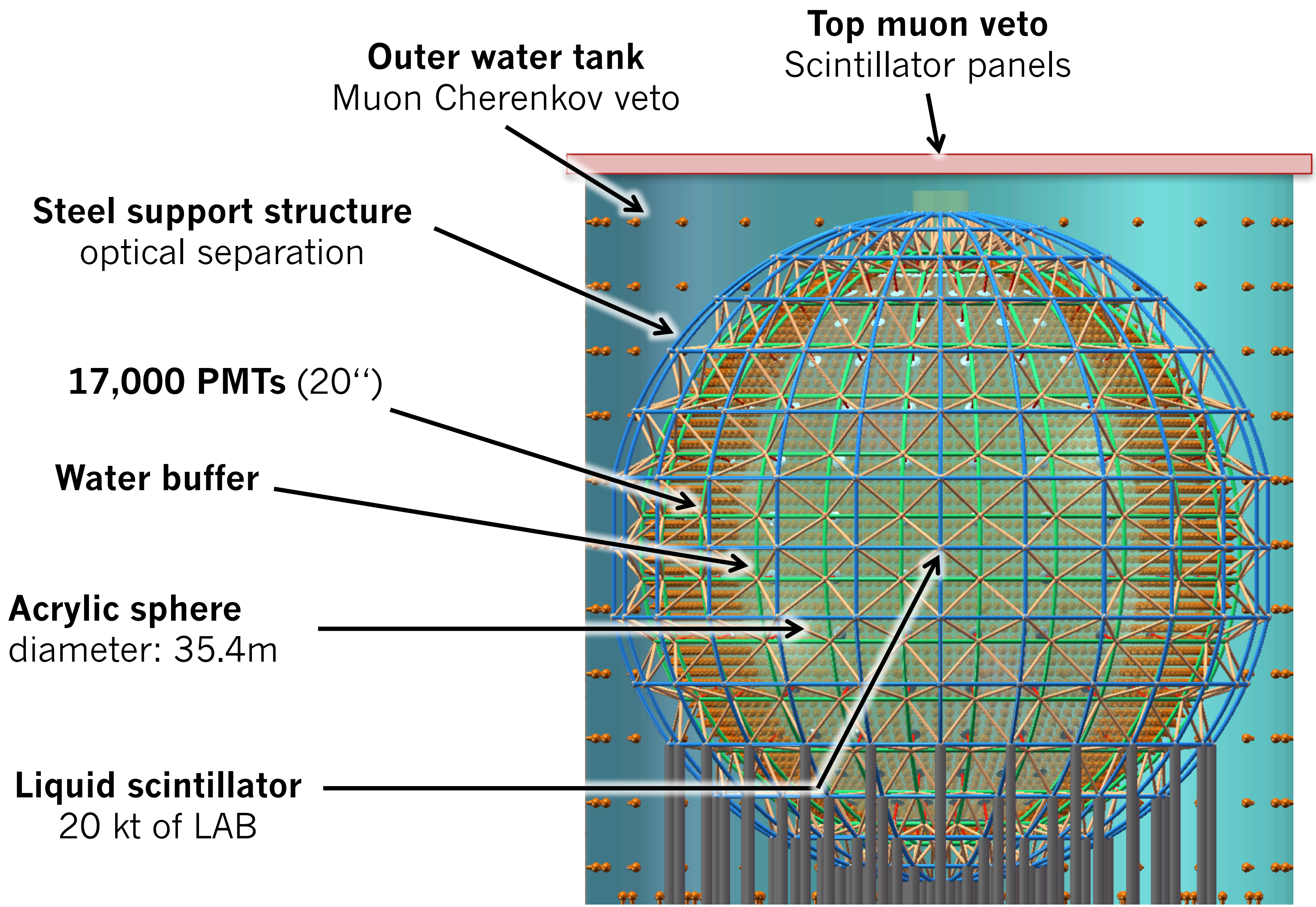
- reactor antineutrinos at MeV energies
  → **Liquid-scintillator detector**
  → Detection by inverse beta decay

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

- 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**



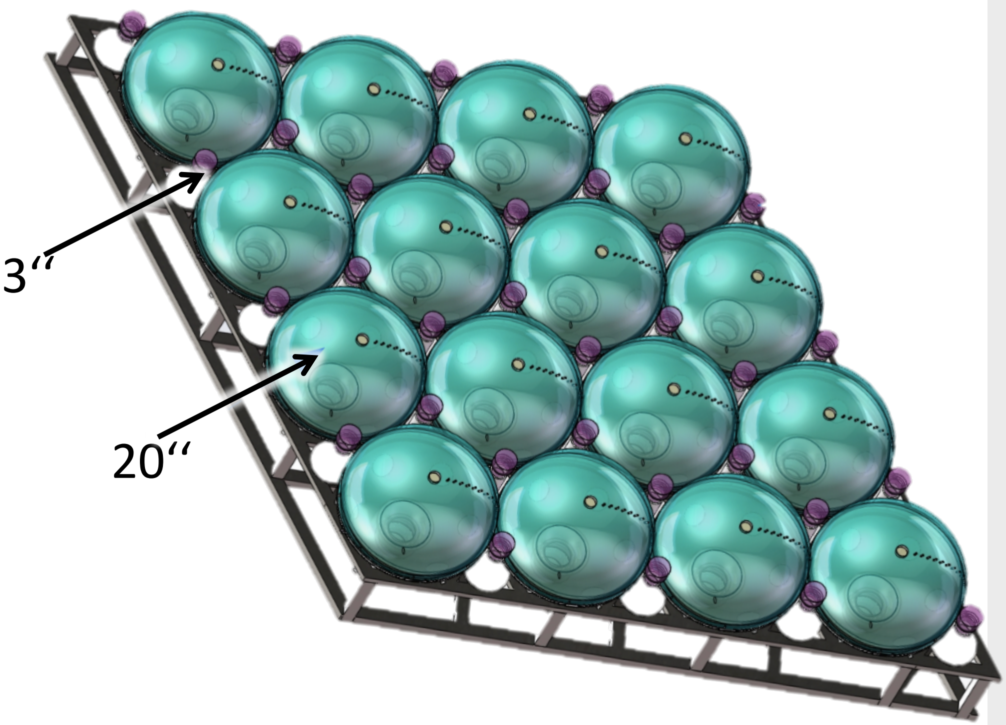
JUNO Detector Layout

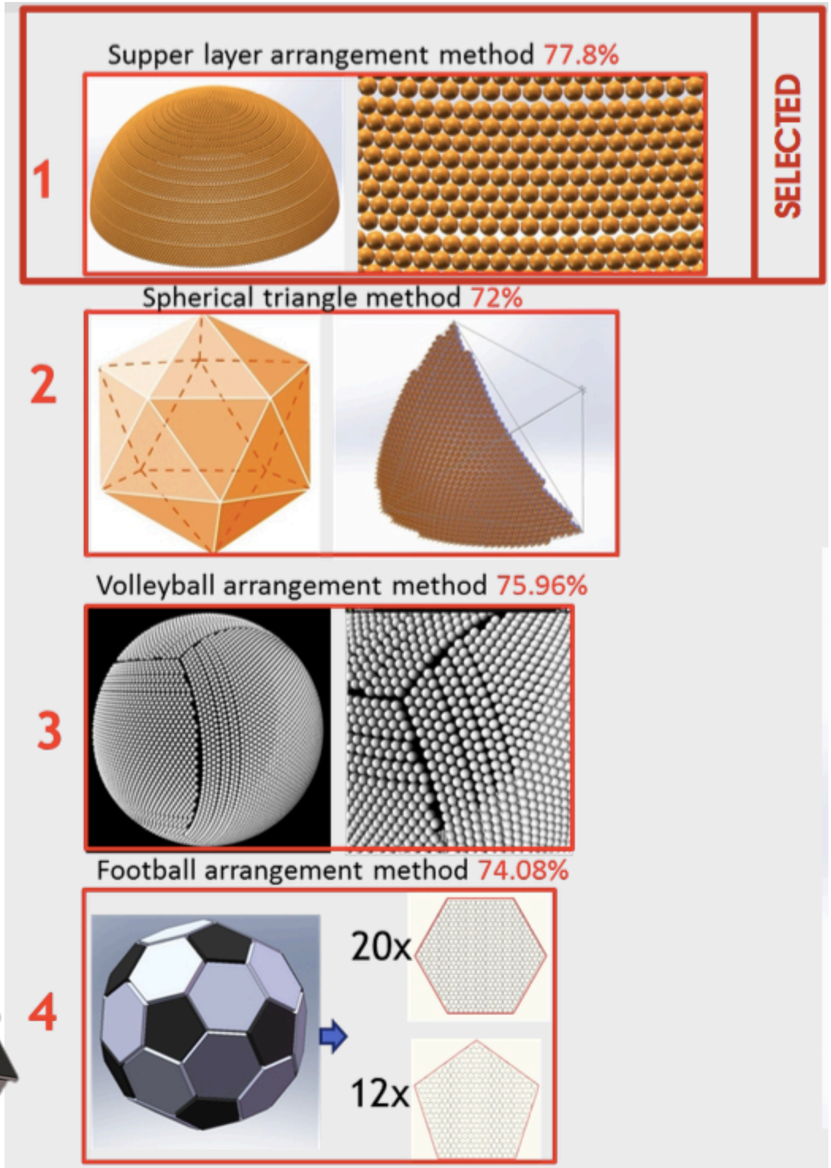


Light sensors: Photomultipliers

Optimize light collection:

- optical coverage: 78%
  → 17,000 large PMTs (20'') → 75%
  → additional small PMTs (3'') → 3%
  (double calorimetry + timing)





Light sensors: Photomultipliers

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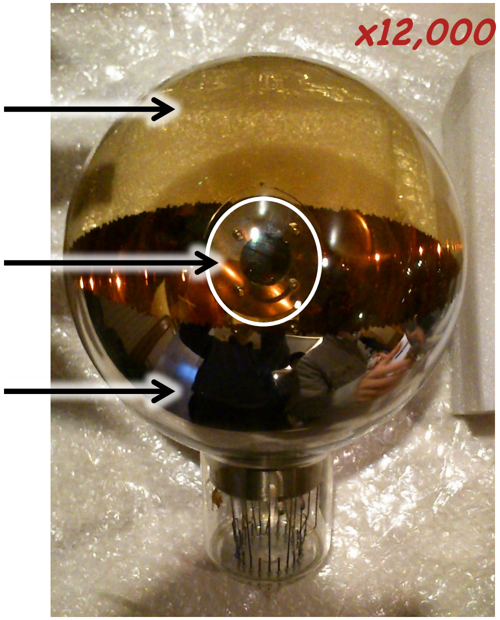
Optimize light collection:

- 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

JG|U

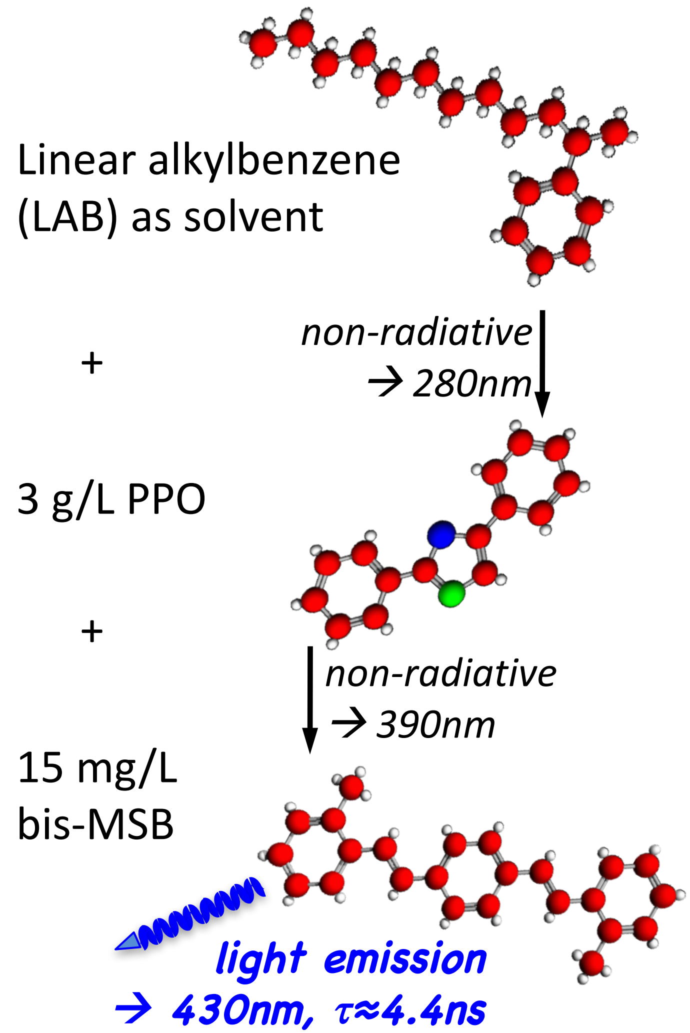
Required properties:

- 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:

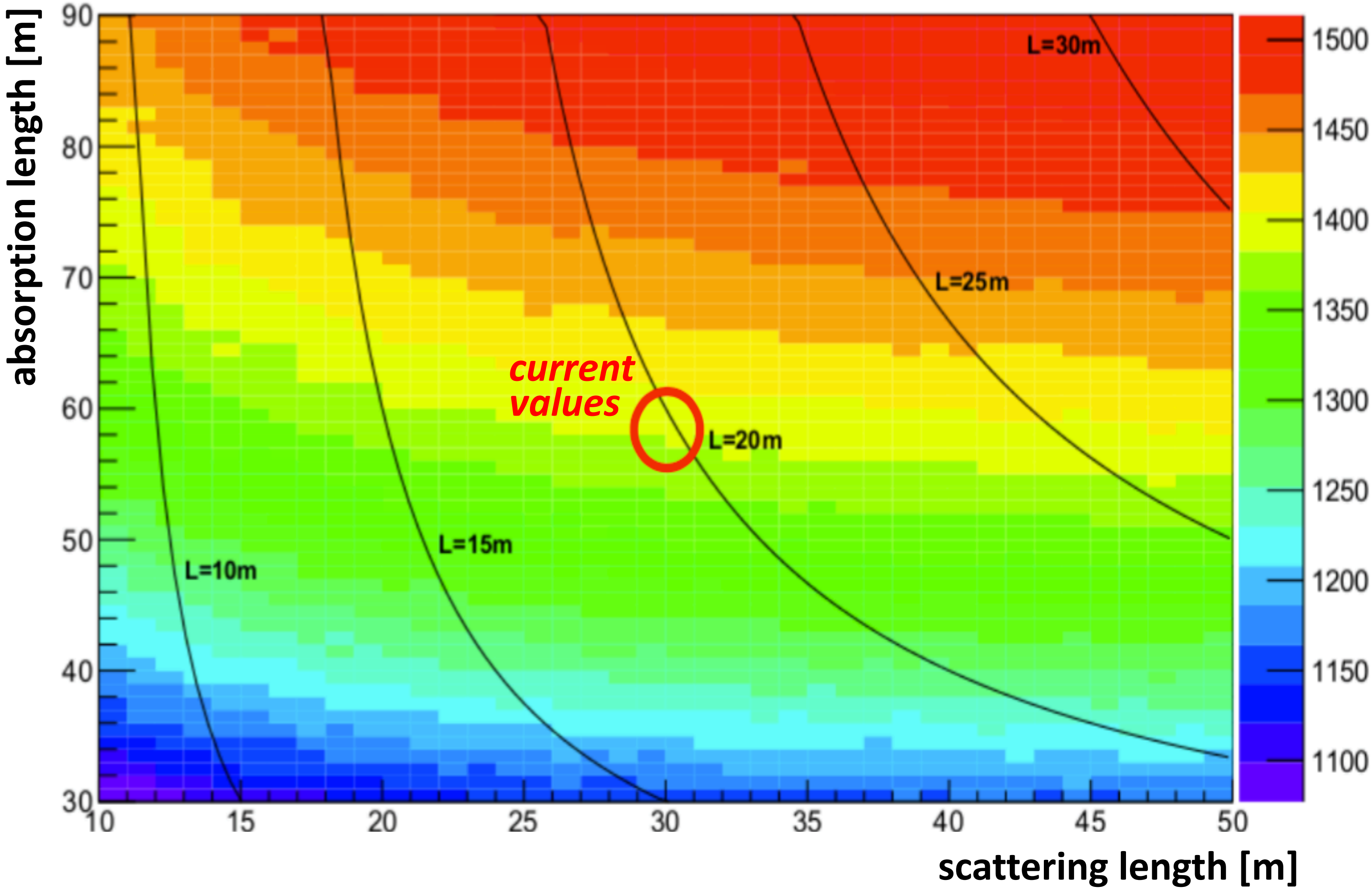
- Fast fluorescence times
  → **good spatial resolution**
- Good **pulse shaping** properties
  → background discrimination, e.g. e^+/e^-

LENA-style liquid scintillator



Photoelectron yield vs. LS transparency

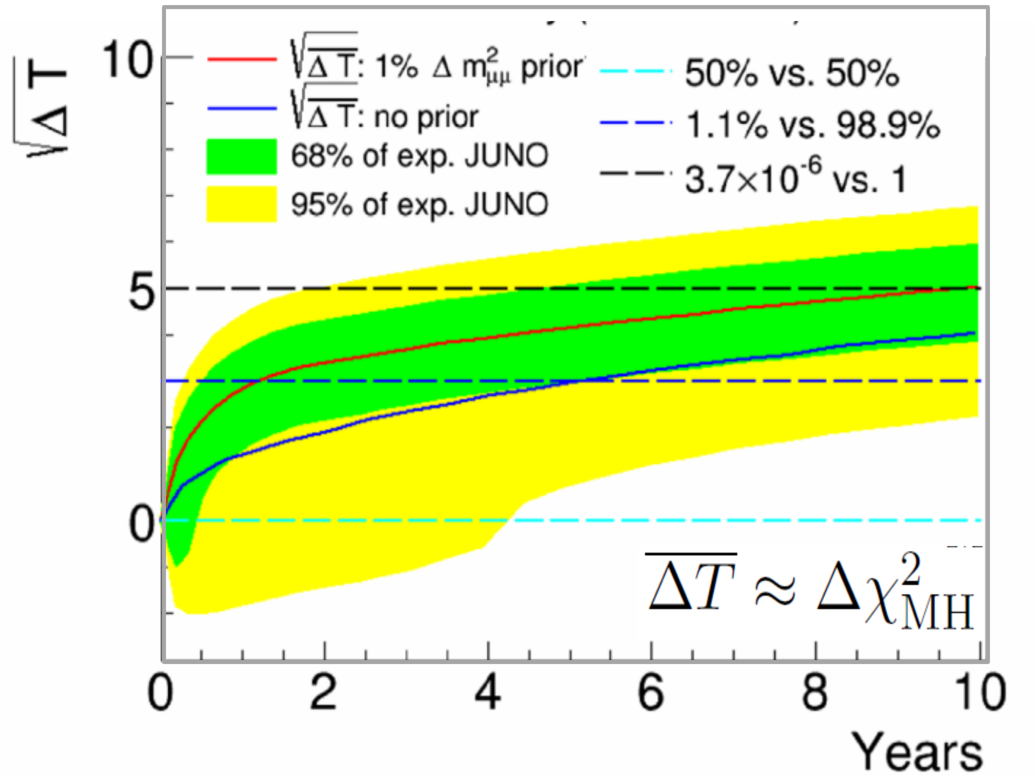
Number of detected photoelectrons



Sensitivity to mass hierarchy

JG|U

JUNO, arXiv:1507.05613



JUNO's expected sensitivity level

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

- JUNO alone based on 6 years: ~3σ

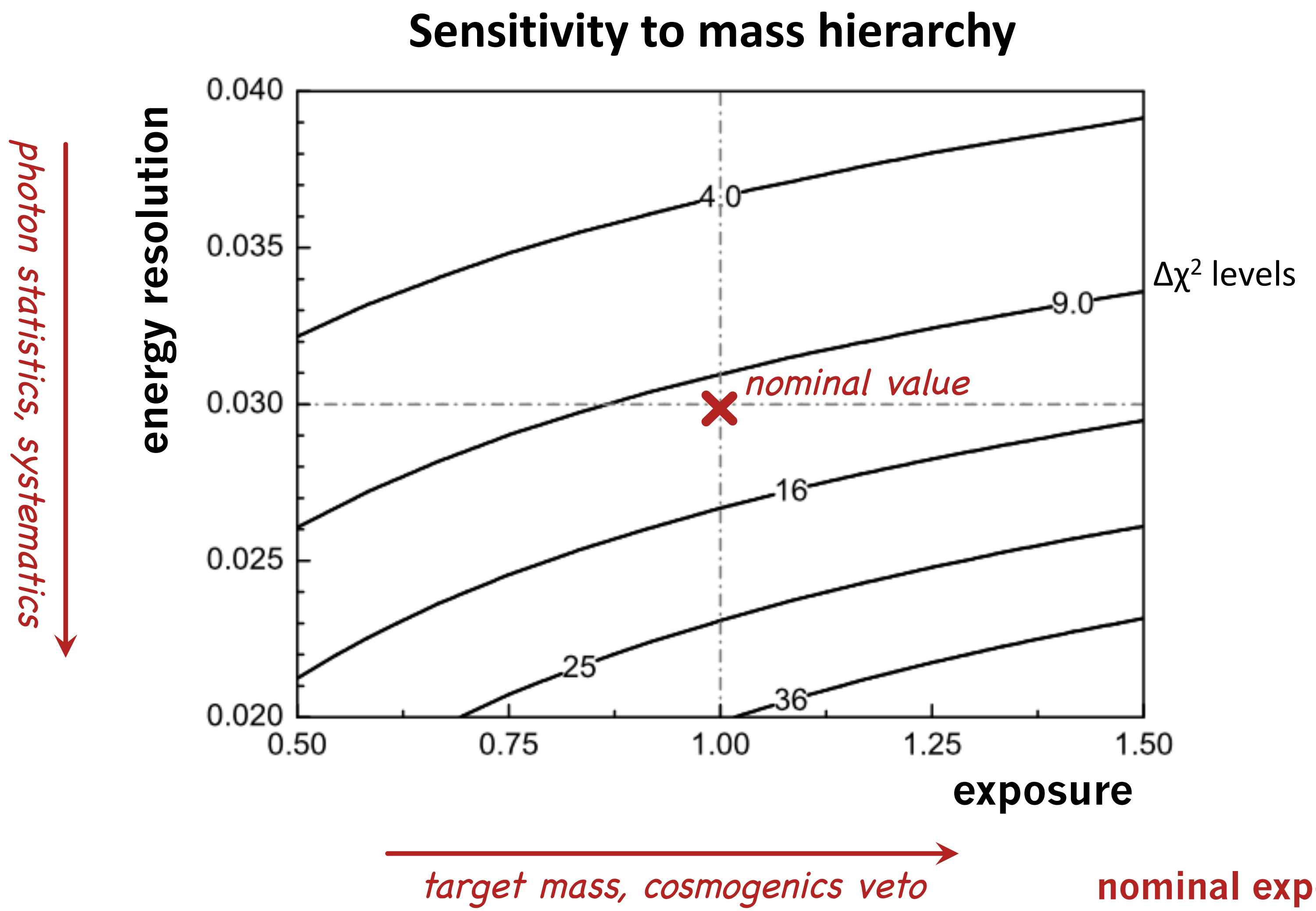
\+ precise data by T2K/NOvA on $\Delta m^2_{\mu\mu}$: **4σ**

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

Sensitivity vs. energy resolution

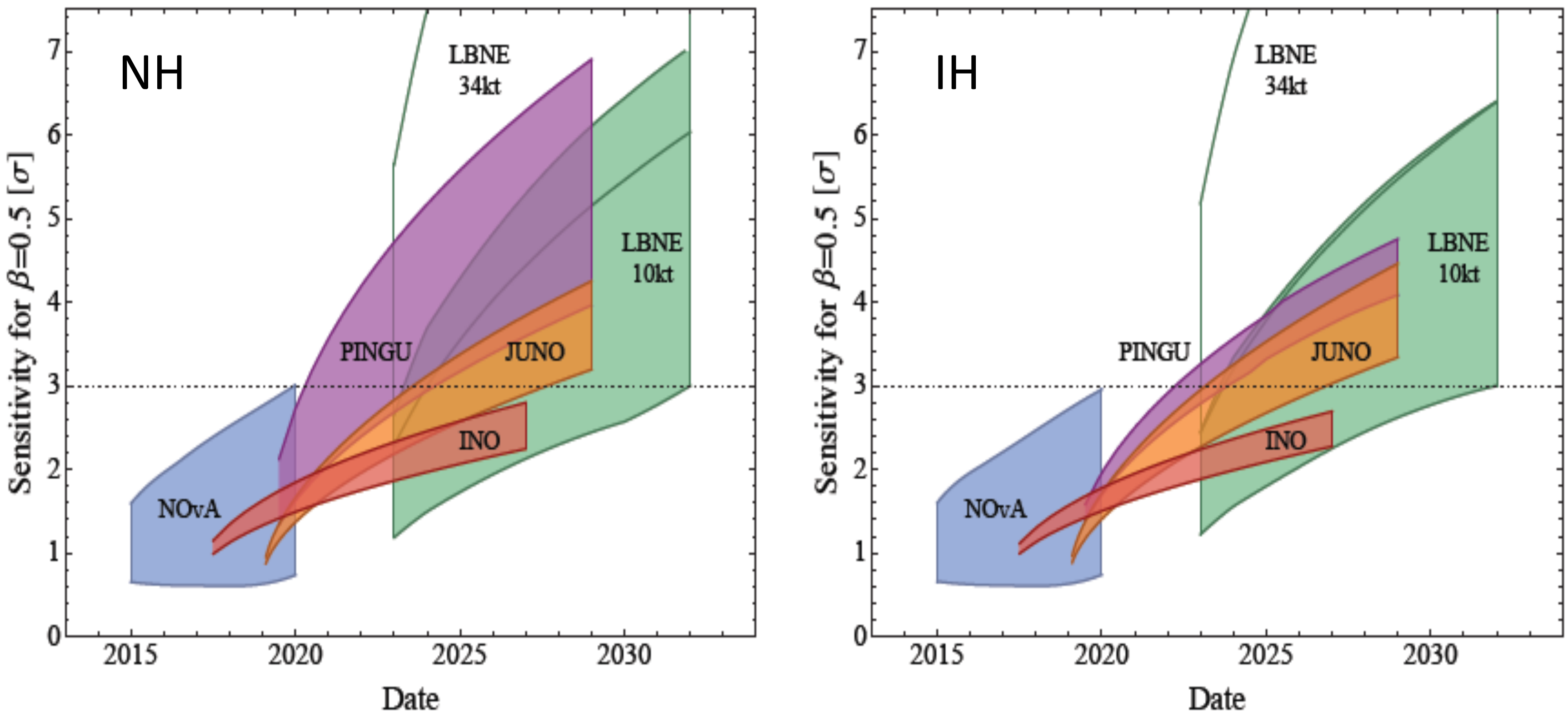


nominal exposure

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

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%)

Precision oscillation measurements

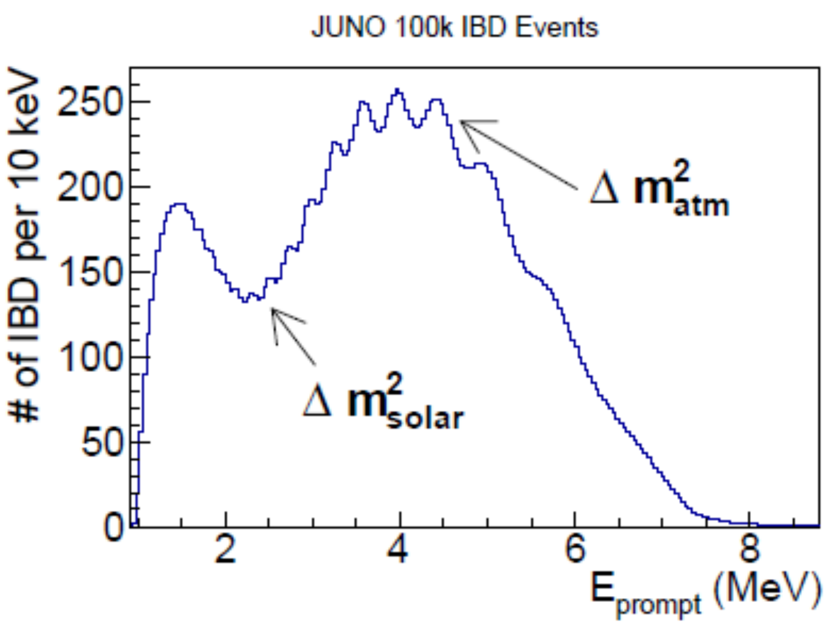
oscillation parameters	2015	2025?
	precision	
$\sin^2\theta_{12}$	5.4 %	0.67%
$\sin^2\theta_{23}$	~10 %	~7 %
$\sin^2 2\theta_{13}$	5.8 %	~3%
Δm^2_{21}	2.6 %	0.59%
$\lvert\Delta m^2_{ee}\rvert$	2.6 %	0.44%

+ inputs from other experiments

JUNO

atm., LBL

DB+DC+RENO



Precision tests!

- Mass sum rule:

$$\Delta m^2_{13} + \Delta m^2_{21} + \Delta m^2_{32} \stackrel{?}{=} 0$$

- Unitarity of mixing matrix

$$|UU^\dagger| \stackrel{?}{=} \mathbb{I}$$

→ ***are there more than three neutrino flavors?***

Physics reach of JUNO

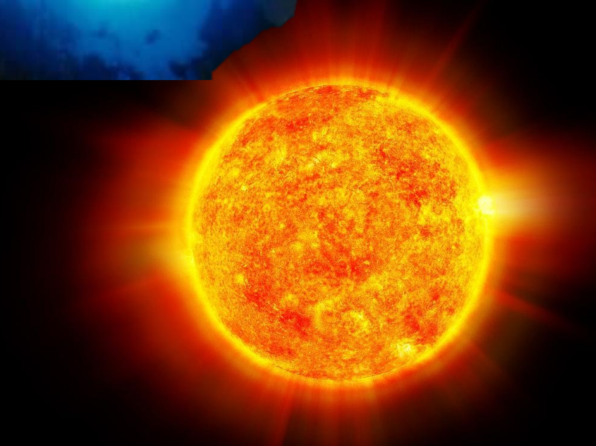
- **Reactor neutrino oscillations**
  - mass hierarchy
  - precise measurement of osc. parameters

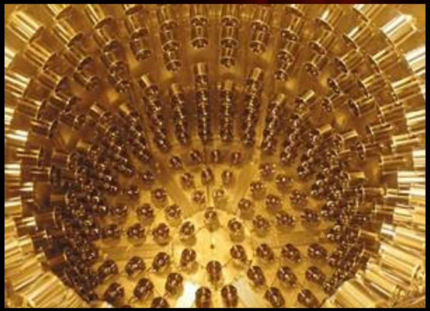
- **Neutrinos from natural sources**
  - Galactic Supernova neutrinos
  - Diffuse Supernova Neutrino Background
  - Solar neutrinos
  - Geoneutrinos
  - Neutrinos from dark matter annihilation
  - Atmospheric neutrinos

- **Short-baseline oscillations** (sterile ν's)

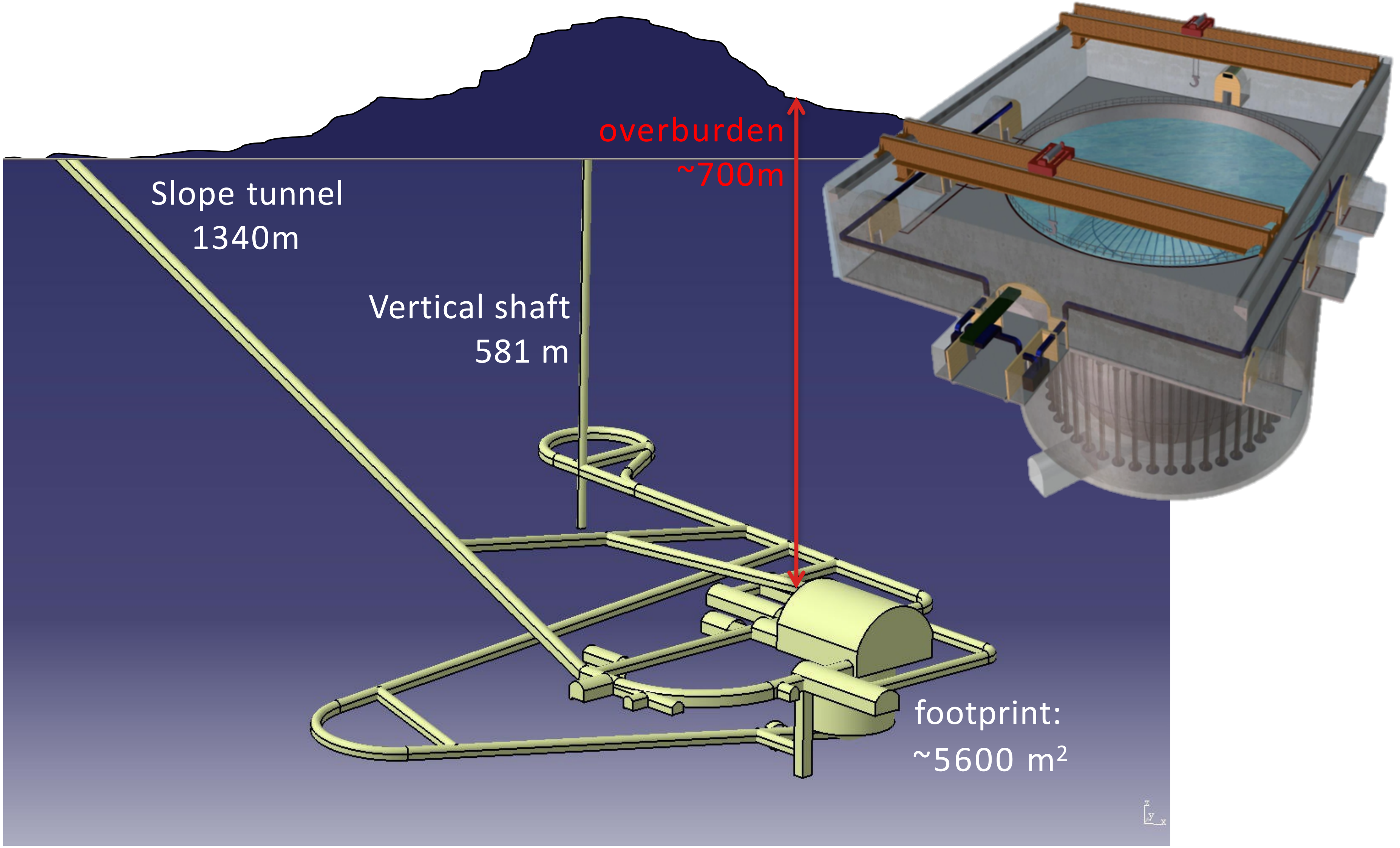
- **Nucleon decay,** esp. $p \rightarrow K^+\nu$

→ JUNO Yellow Book, arXiv:1507.05613



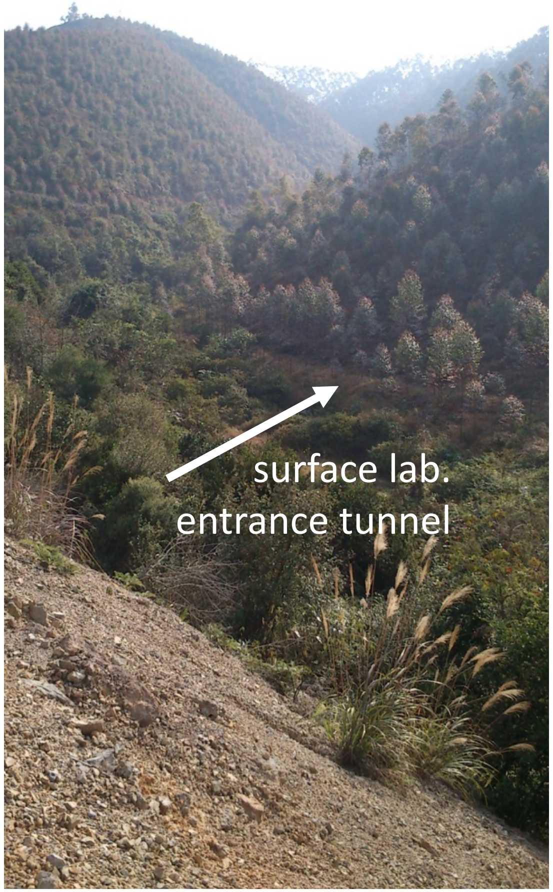


JUNO Underground Laboratory



Slope tunnel

Surface facilities

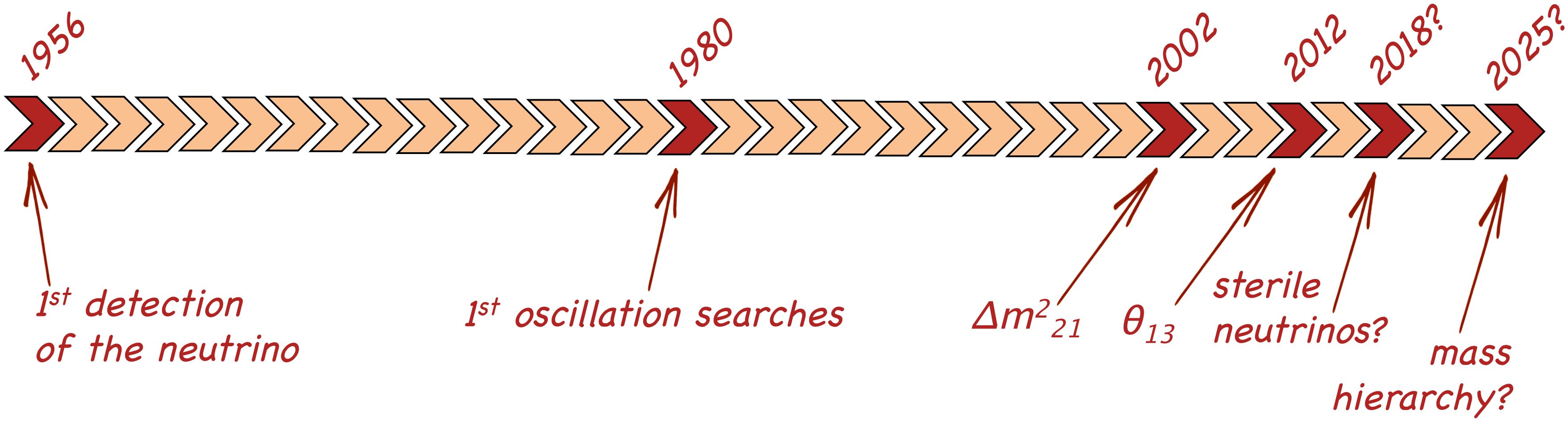


Surface facilities

Surface facilities

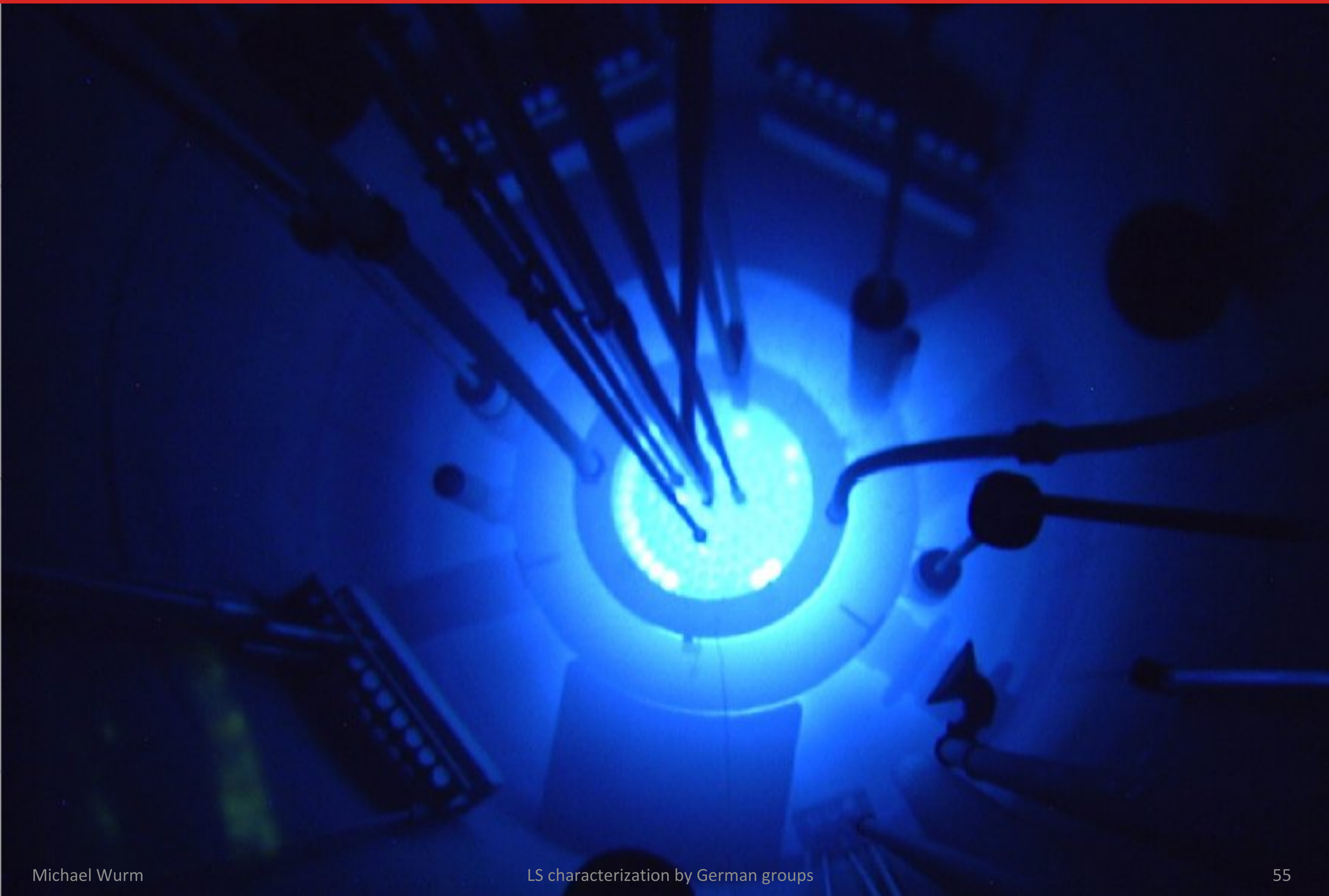
Conclusions

Timeline of reactor neutrino experiments:

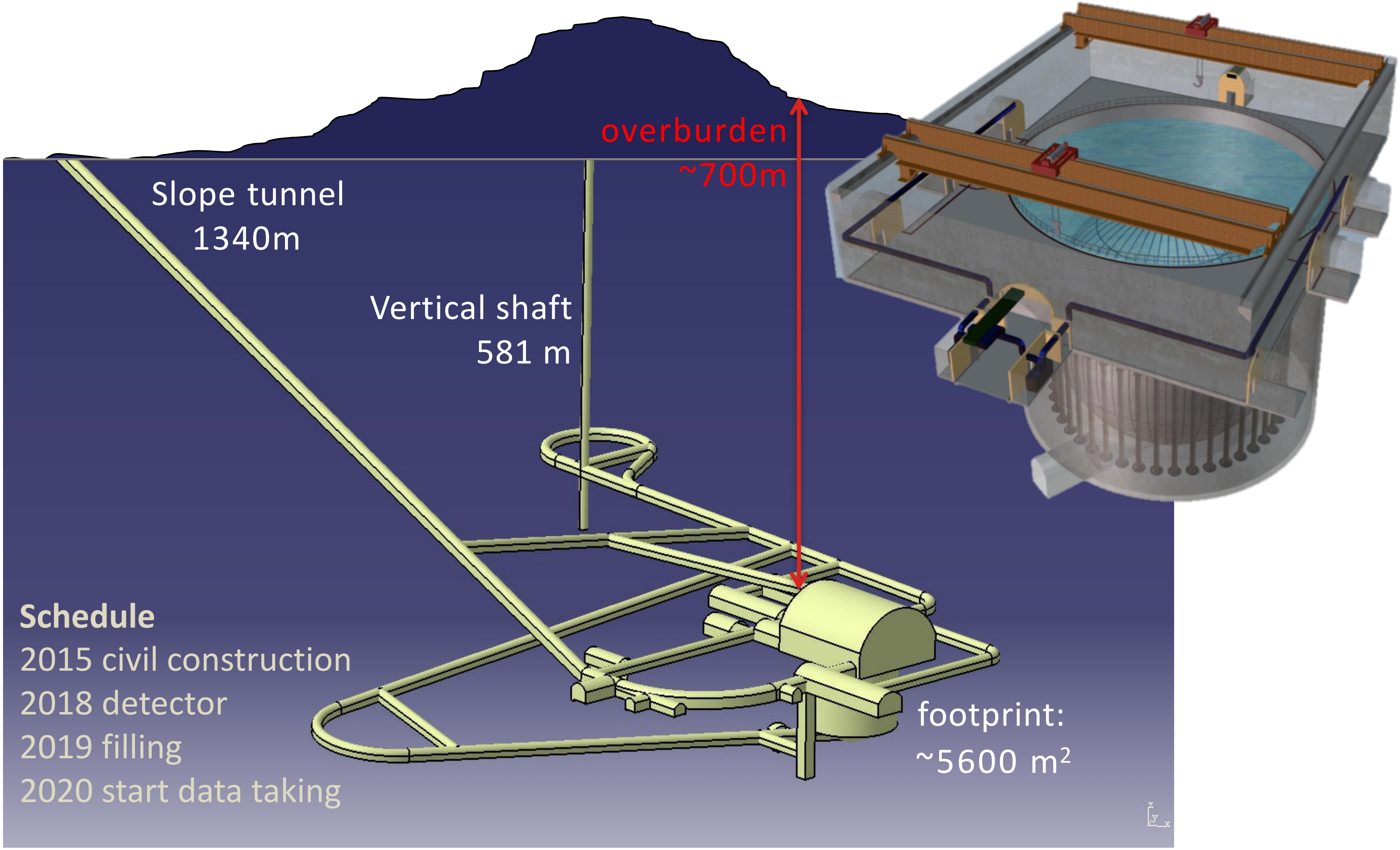


- → **reactor neutrino experiments** have made important contributions to neutrino oscillation searches
- → wealth of VSBL reactor experiments w/ highly segmented detectors: new results on **sterile neutrinos** are expected soon!
- → JUNO on its way to perform a first measurement of the **mass hierarchy**
- → **Stay tuned!**

Backup Slides



JUNO Underground Laboratory



Schedule
2015 civil construction
2018 detector
2019 filling
2020 start data taking

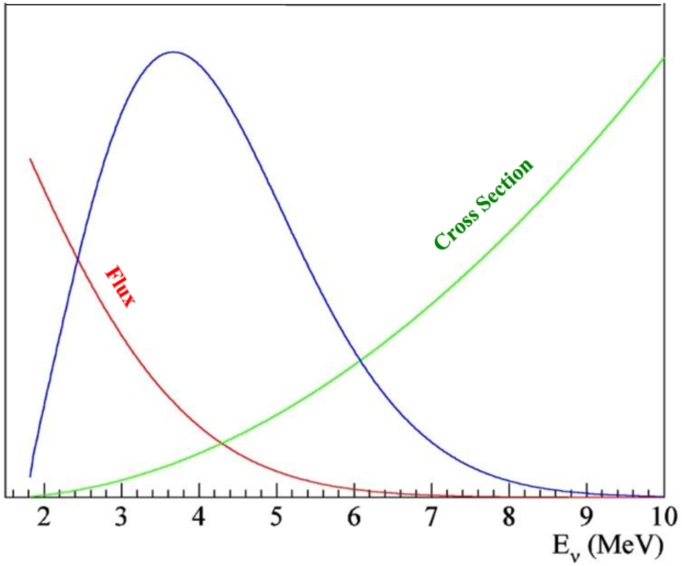
Re-evaluation of reactor ν spectrum

2011: **Mueller et al.** *[arXiv:1101.2663]*

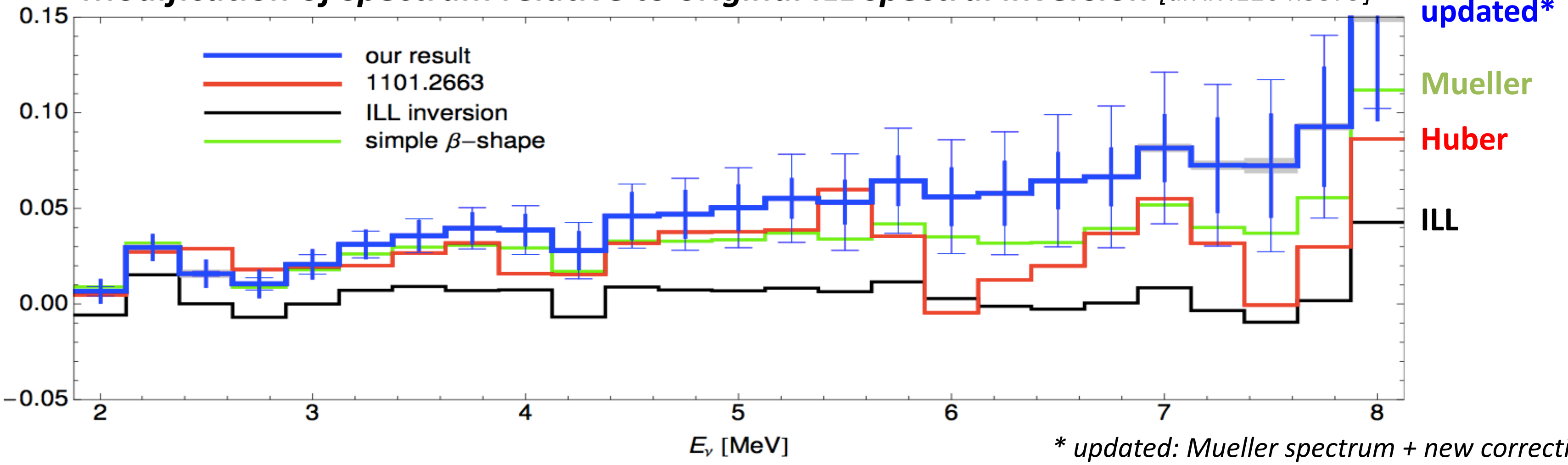
- revision of ILL spectral conversion:
  90% ab initio + 10% virtual branches
- other factors (weak magnetism, $\tau_{neutron}$)

→ **ν spectrum shifts to higher energies**

→ increase of expected rates by ~5% for all reactor neutrino experiments



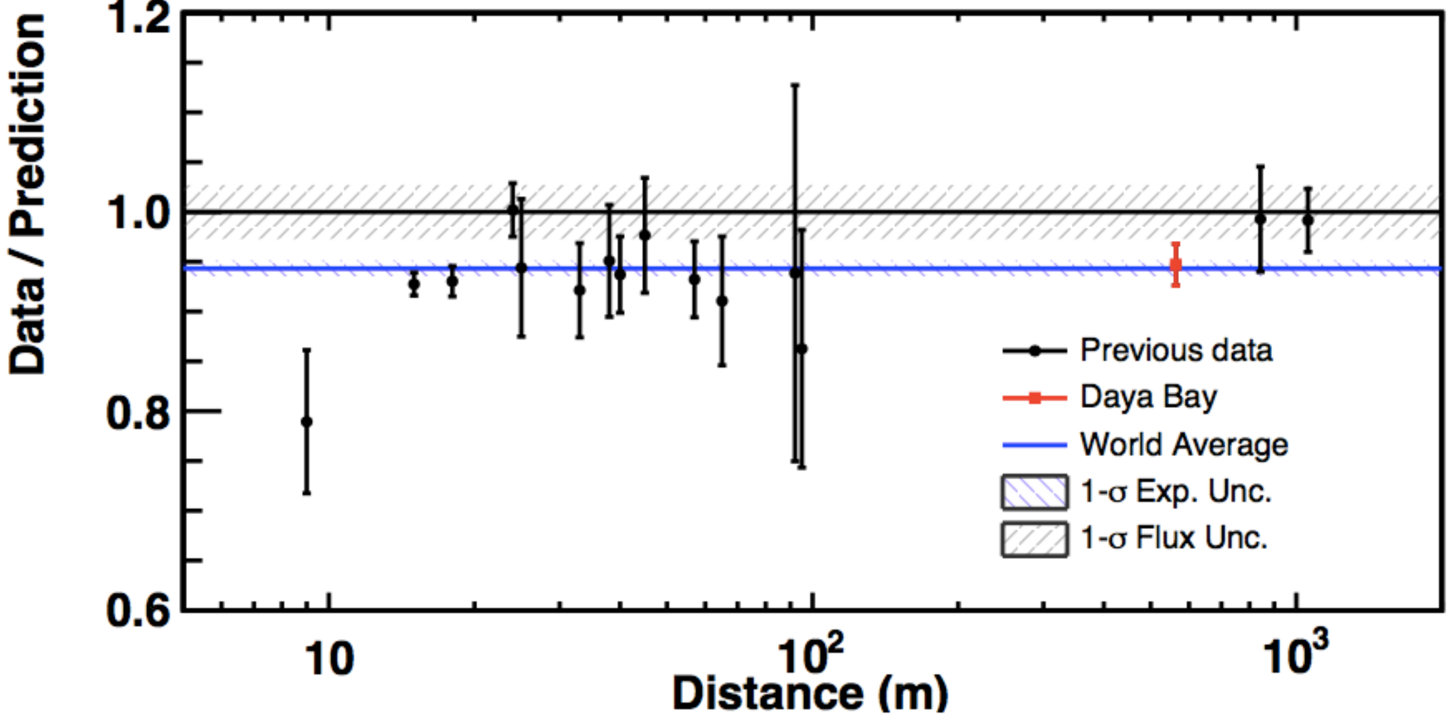
Modification of spectrum relative to original ILL spectral inversion *[arXiv:1204.5379]*



** updated: Mueller spectrum + new correction from Fermi theory (ν_s whitepaper)*

Reactor antineutrino anomaly

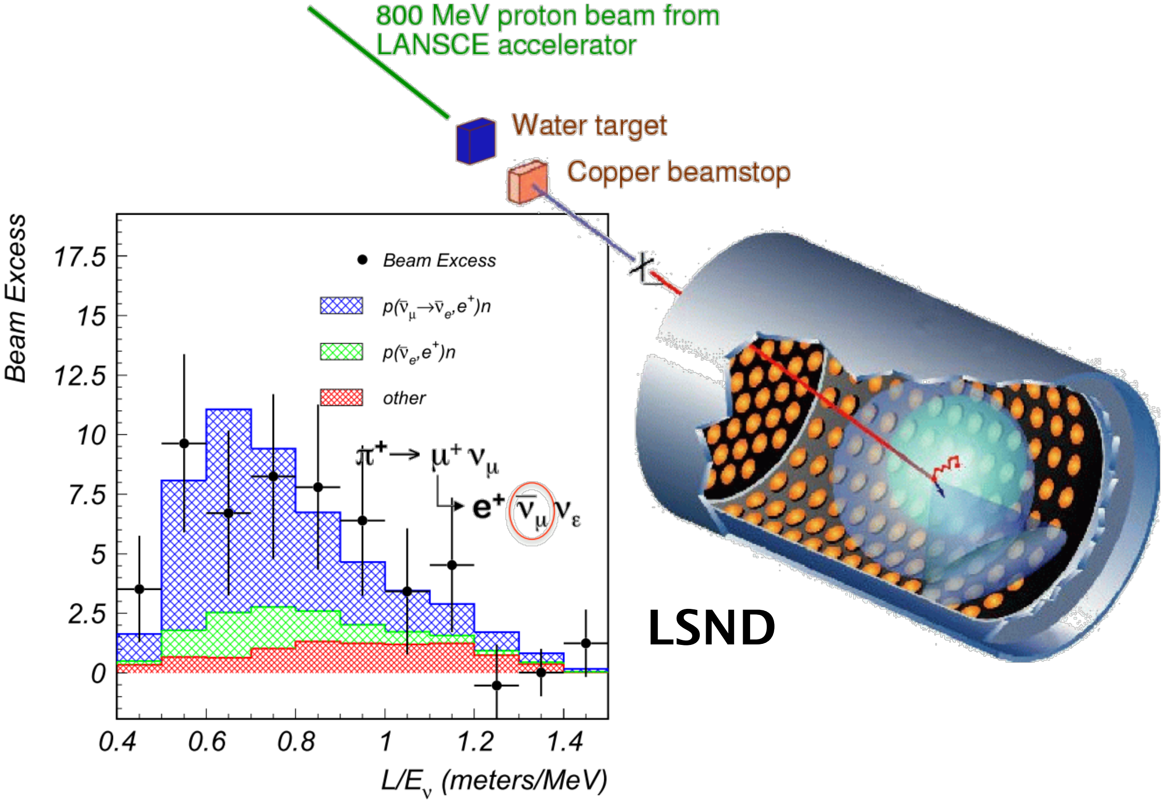
[Daya Bay coll., arXiv:1508.04233]

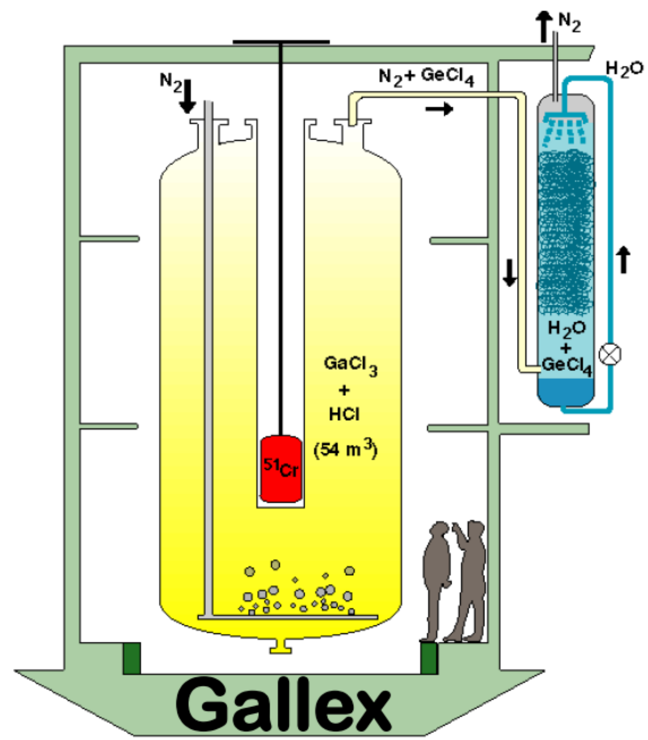


→ average rate of short-baseline (<1km) reactor neutrino experiments shows 6% deficit compared to expectation!

→ significance: ~3σ

Short baseline anomalies





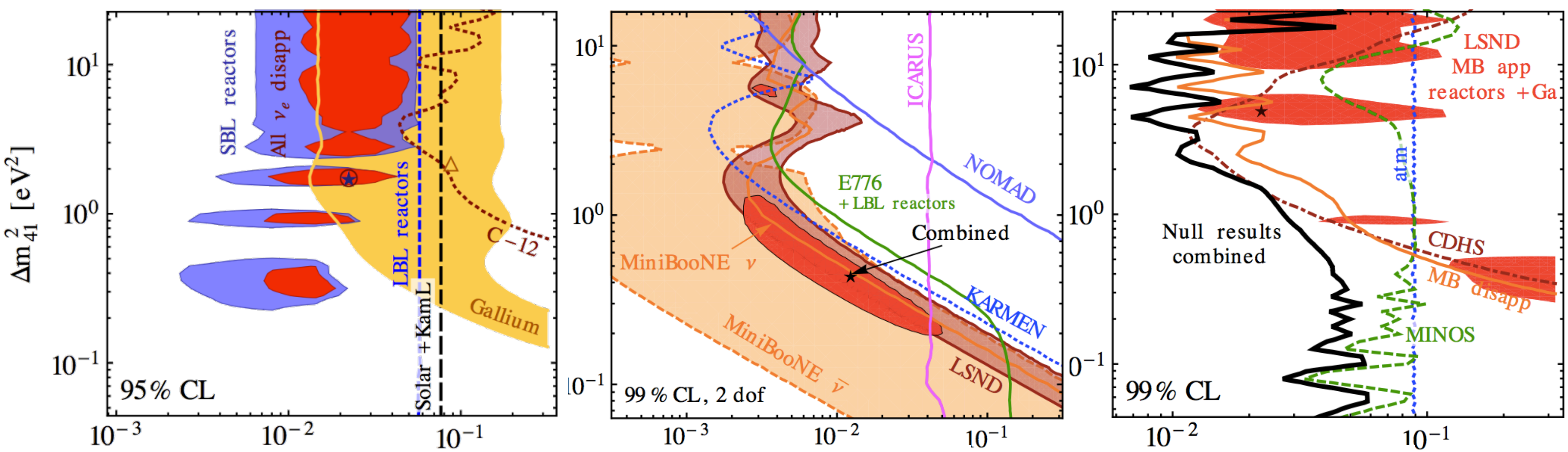
Short-baseline anomalies

- appearance: $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ LSND, MiniBOONE
- disappearance: $\nu_e \rightarrow \nu_e$ Gallium, **reactor anomalies**

→ point towards a 4th sterile neutrino state with mass ~1eV!

Sterile oscillations in global picture

$\nu_e \rightarrow \nu_s$ disappearance | $\nu_\mu \rightarrow \nu_e$ appearance | $\nu_\mu \rightarrow \nu_s$ disappearance



$|U_{e4}|^2$ | $\frac{1}{4}|U_{e4}|^2|U_{\mu 4}|^2$ | $|U_{\mu 4}|^2$

- in global scheme, no contradiction to $\nu_e \rightarrow \nu_s$ disappearance anomalies
- however, increasingly strong limits on $\nu_\mu \rightarrow \nu_s$ disappearance

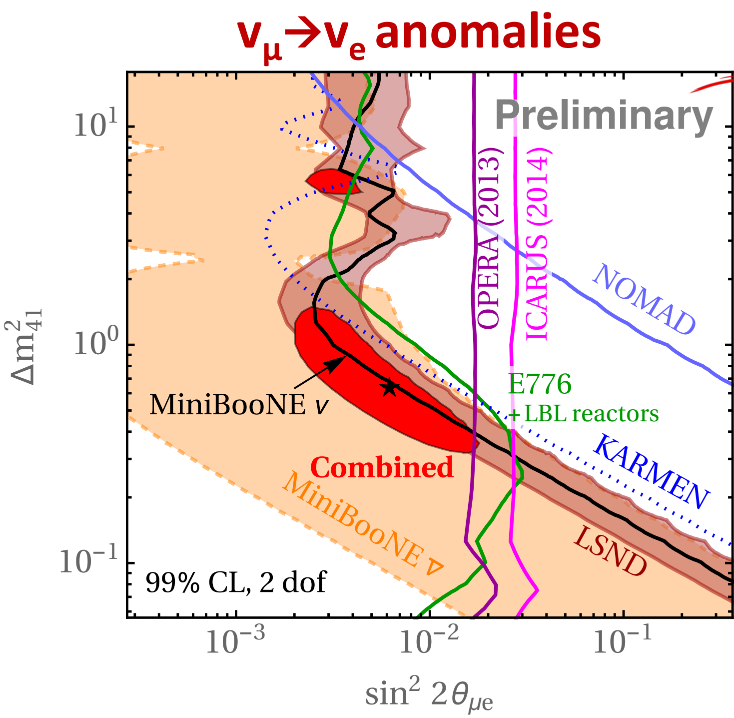
→ conflict with LSND/MiniBooNE results on $\nu_\mu \rightarrow \nu_e$ appearance

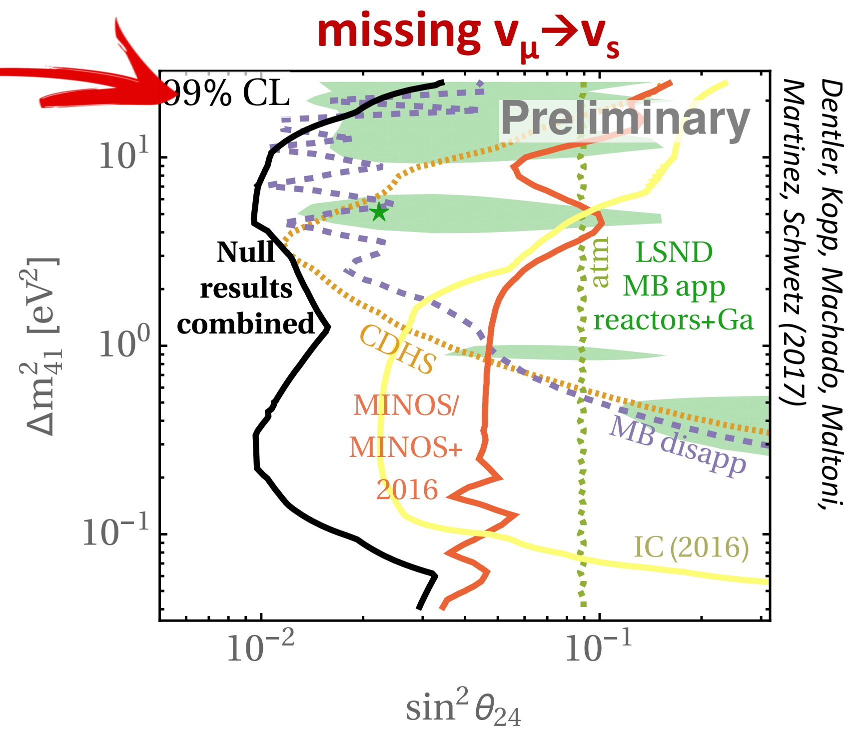
- eV-ν_s in strong tension with cosmological limits (N_{eff}, Σm_ν) if thermalized

Results on $\nu_\mu \rightarrow \nu_s$ disappearance 2/2

- **Note:** **Disappearance** $\sin^2\theta_{ee} = |U_{e4}|^2$, $\sin^2\theta_{\mu\mu} = |U_{\mu4}|^2$ ↔ and **appearance amplitudes** $\sin^2\theta_{\mu e} = |U_{e4}| \cdot |U_{\mu4}|$ are interlinked

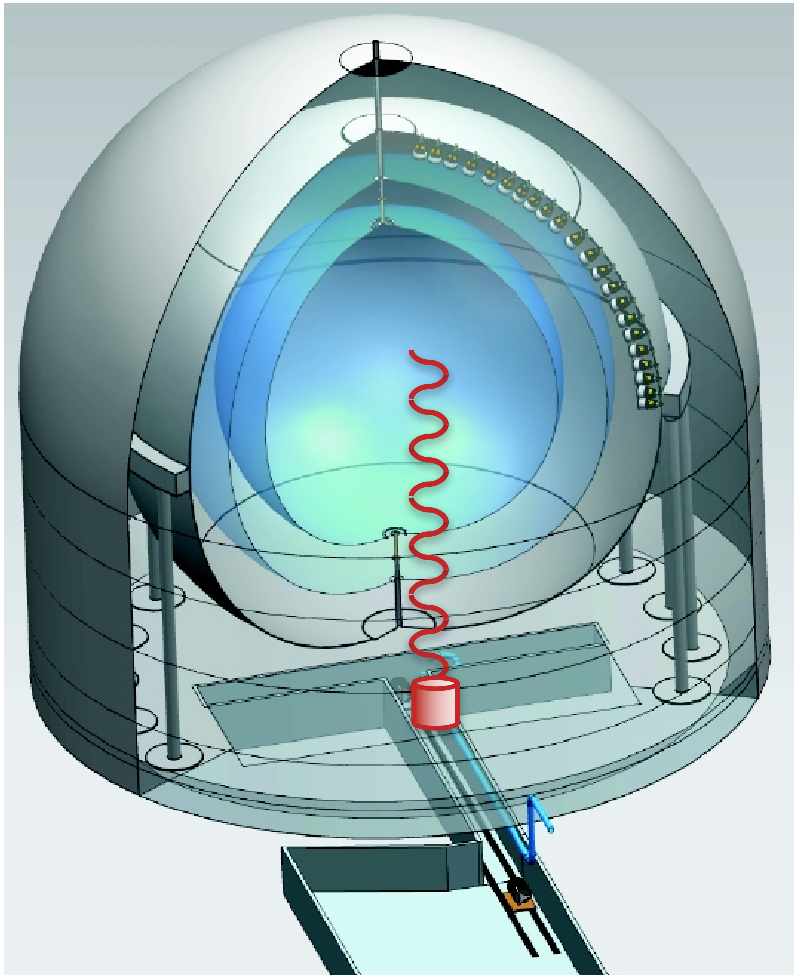
- Now, new results by **MINOS+/IceCube** on $\nu_\mu \rightarrow \nu_s$ further increased the tension:





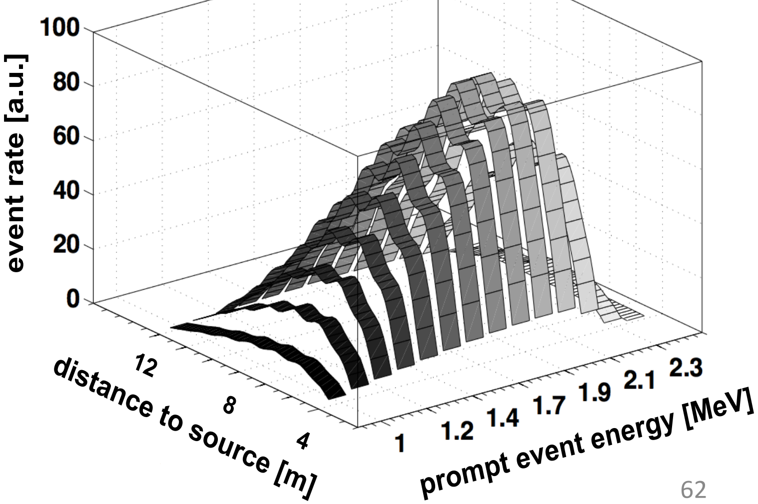
SOX: Radioactive source experiment

Schematic of SOX @ Borexino



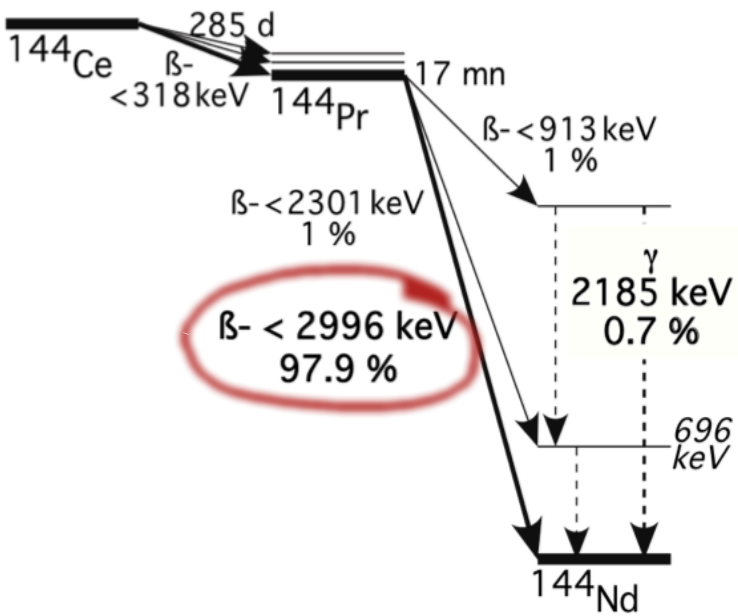
Start: March 2018 – duration: 1.5 yrs
German participation: Jülich, MZ, TUM, TÜ

- **radioactive antineutrino source** in pit below Borexino detector (L=8.5m)
- **source material: cerium** (100-150 kCi)
  $^{144}Ce \rightarrow {}^{144}Pr + e^- + \bar{\nu}_e$
  $^{144}Pr \rightarrow {}^{144}Nd + e^- + \bar{\nu}_e$ ($E_\nu \leq 3$MeV)
- signatures for $\bar{\nu}_e \rightarrow \bar{\nu}_s$ in 10^4 IBD events
  → $\bar{\nu}_e$ **rate deficit** (activity measurement)
  → **oscillation pattern** (inside LS target)



Antineutrino energy spectrum

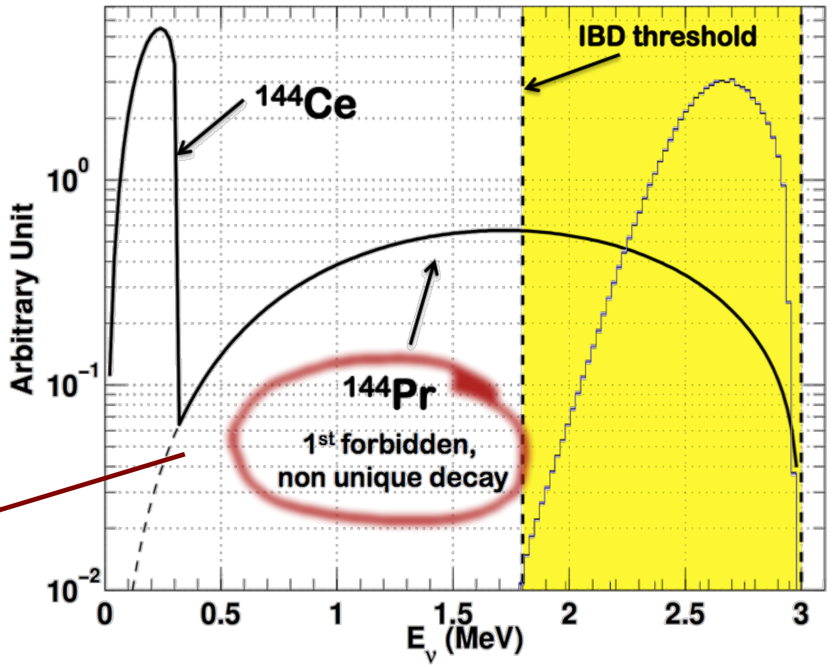
^{144}Ce-^{144}Pr decay scheme



IBD cross section:

$$\sigma_{\mathrm{IBD}} \approx 9.5 \cdot 10^{-45}\,\mathrm{cm}^2 \left(E - 1.8\,\mathrm{MeV}\right)^2$$

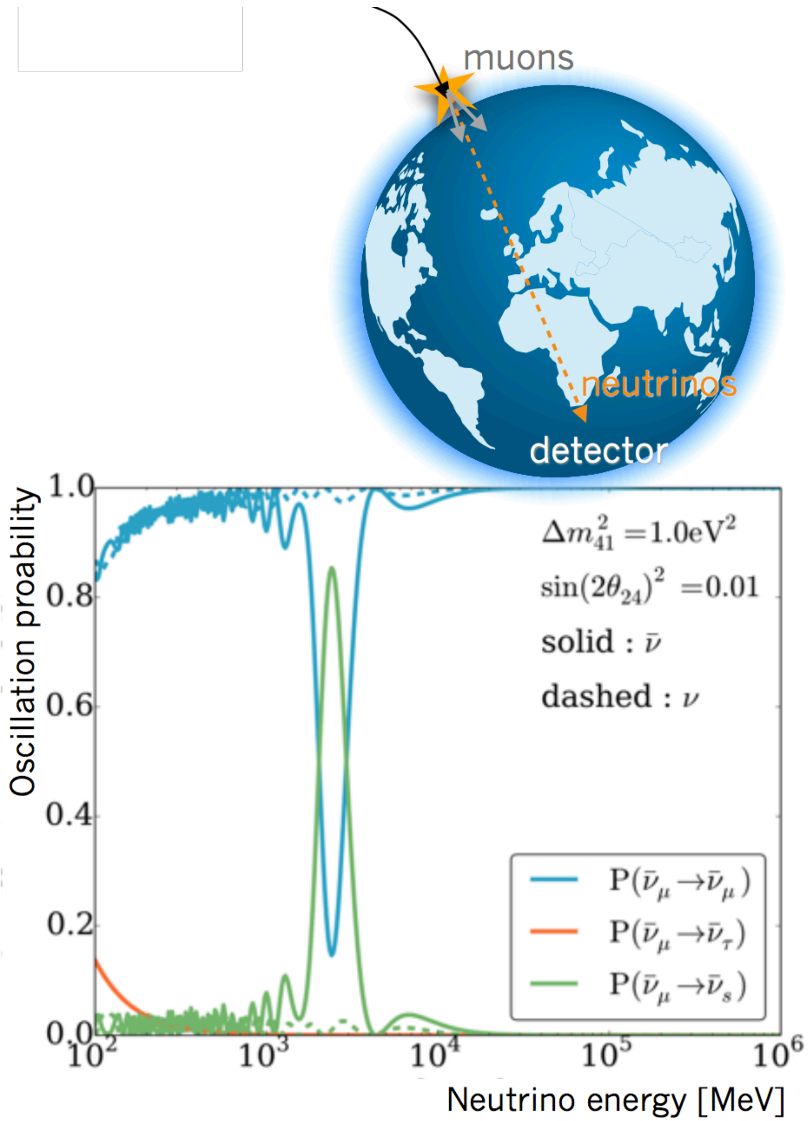
Expected energy spectrum



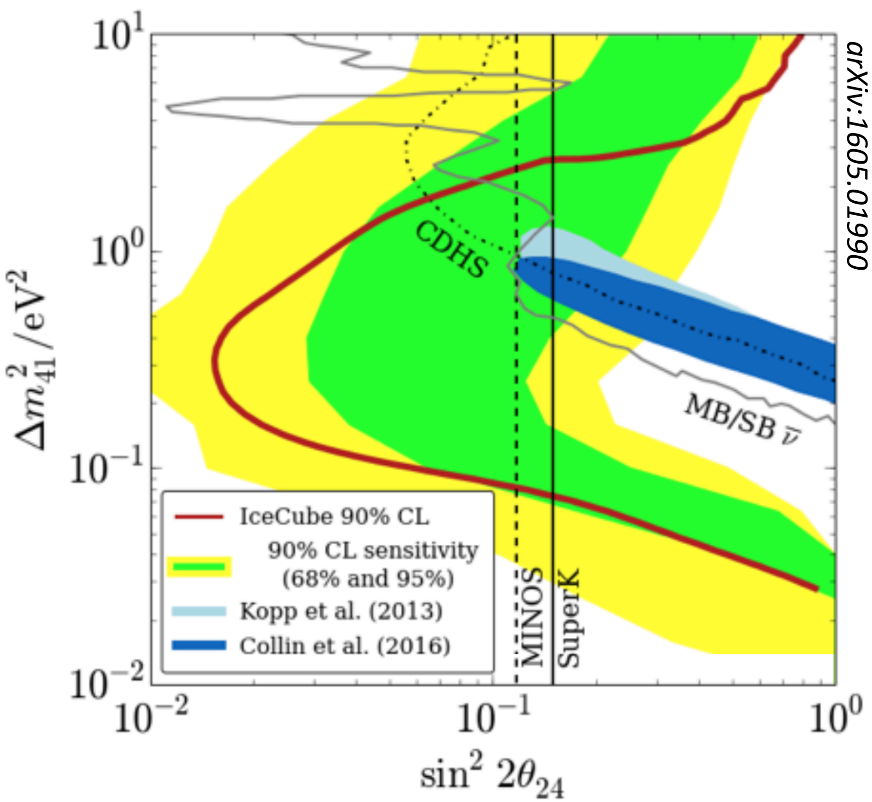
spectral shape is important!

→ lab measurements on-going

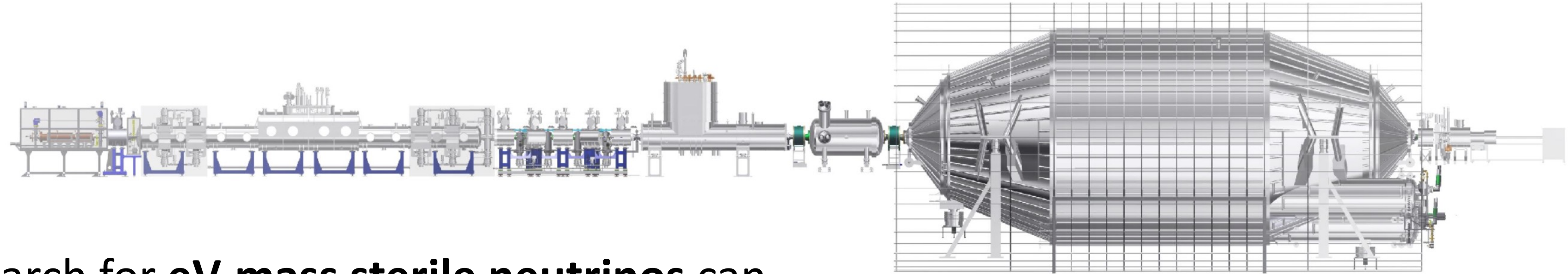
Recent IceCube result



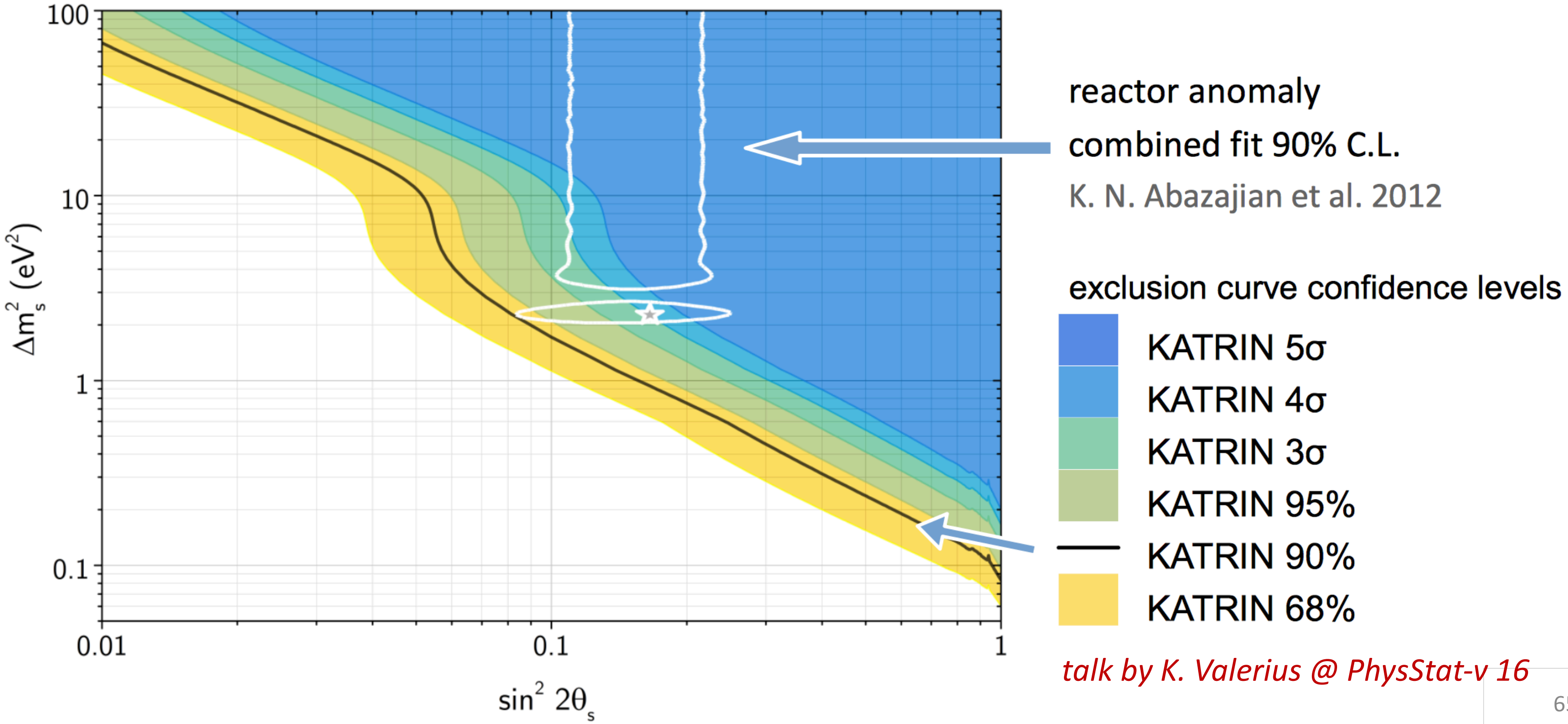
- Probe: **Atmospheric ν's** crossing the Earth
- **matter potential** affects only active ν's
- No resonant conversion of $\nu_\mu \to \nu_s$ found at TeV energies, i.e. $\Delta m^2_{41} \sim 1\mathrm{eV}^2$



eV-mass sterile neutrinos in KATRIN

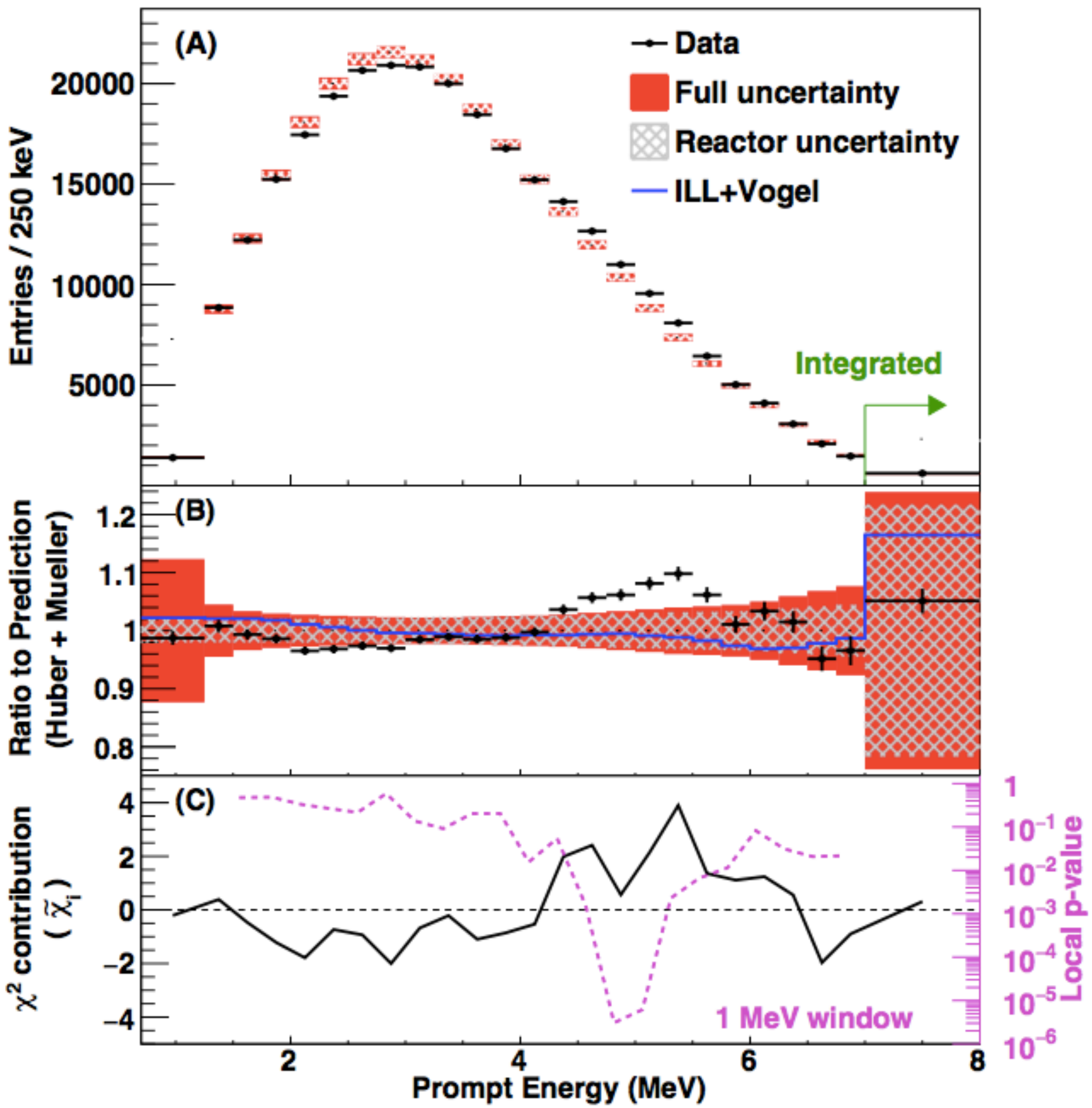


- search for **eV-mass sterile neutrinos** can be performed based on regular setup

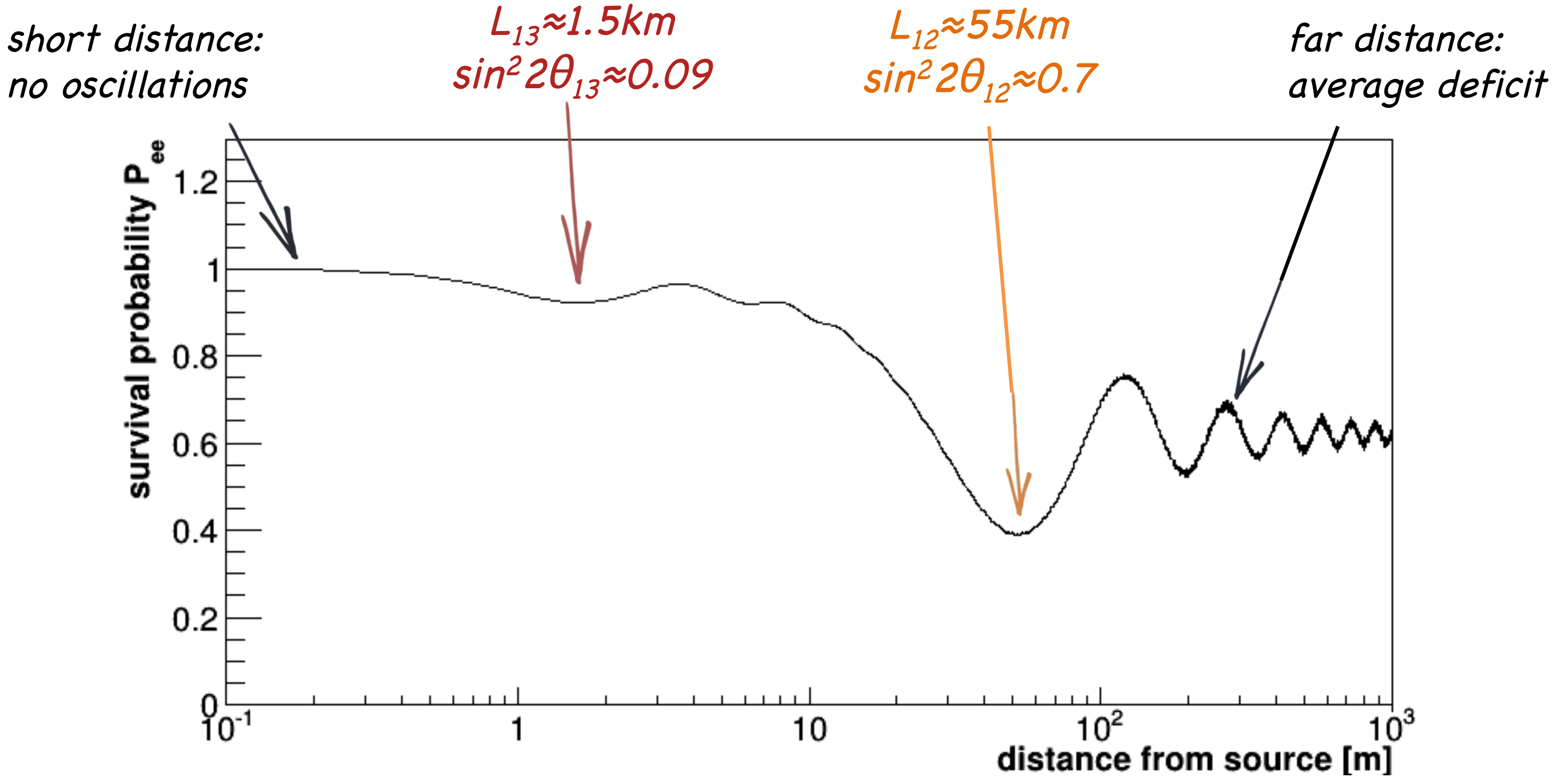


talk by K. Valerius @ PhysStat-ν 16

The 5-MeV bump



Reactor neutrino oscillation regimes

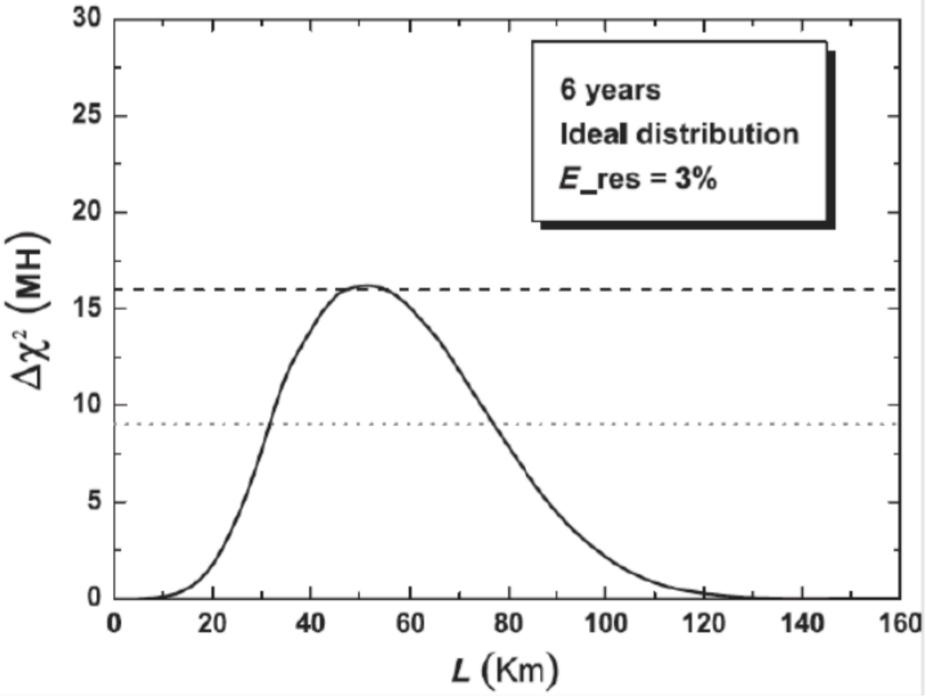


$$P_{\bar{e}\bar{e}} = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)$$

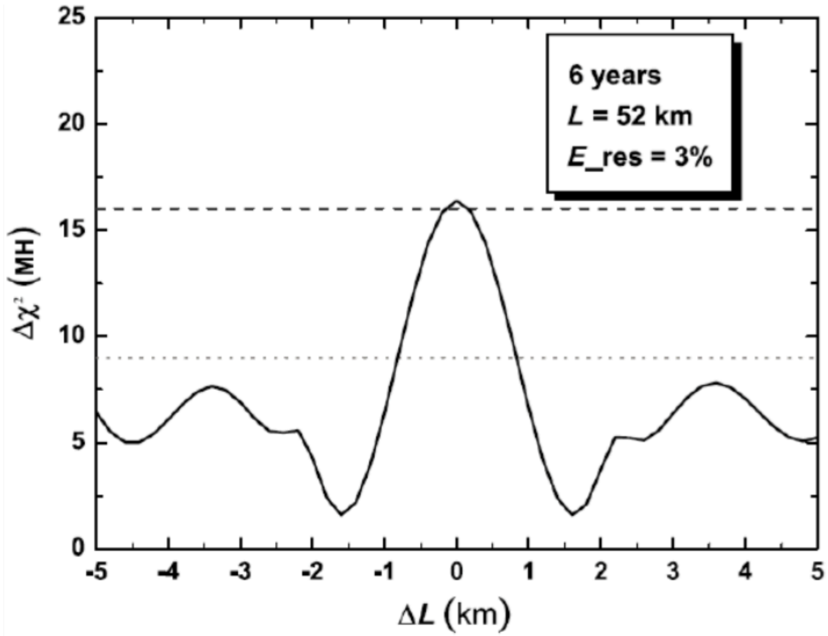
- good approximation by 2x 2-flavor-oscillations as $L_{13} << L_{12}$

Optimum baseline

Baseline optimization



Difference between baselines
to reactor complexes



Non-stochastic terms in E resolution

Energy resolution function

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

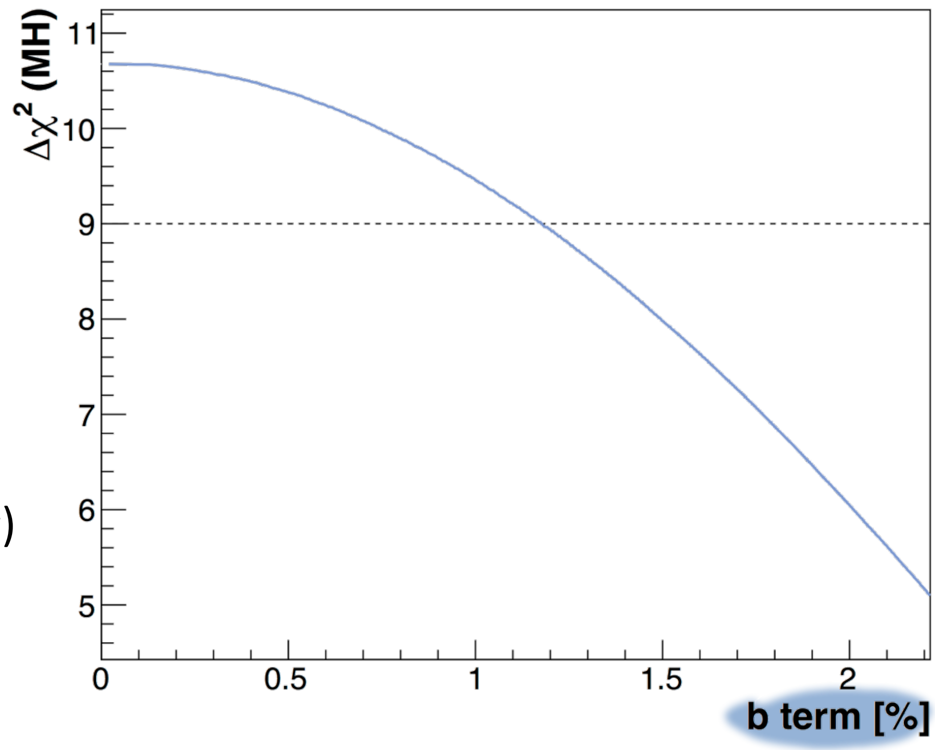
a term:

stochastic term (*photon statistics*)

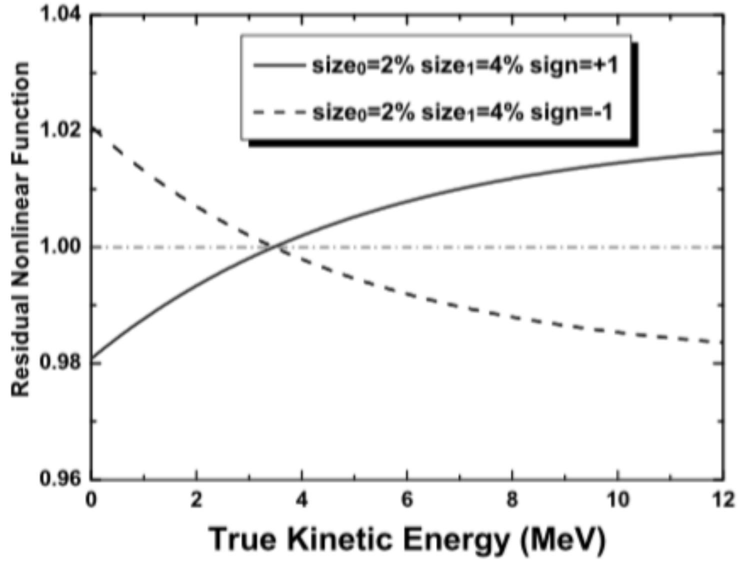
b & c terms:

systematic contributions (*detector effects*)

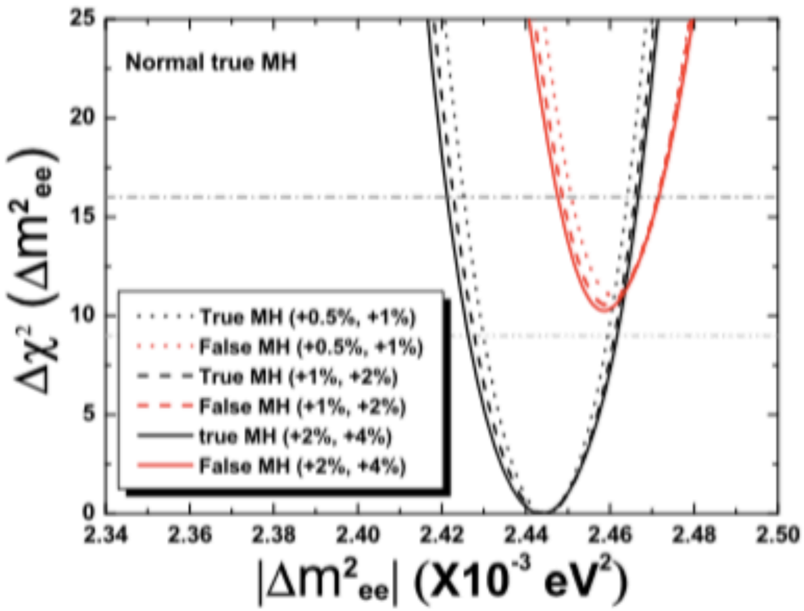
- PMT dark noise
- linearity of electronics
- position reconstruction uncertainty
- ...



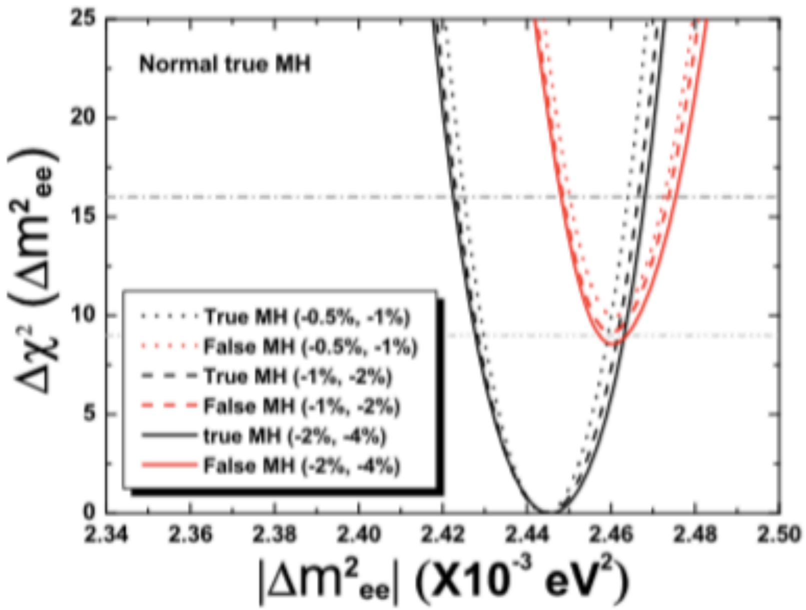
Influence of energy scale linearity



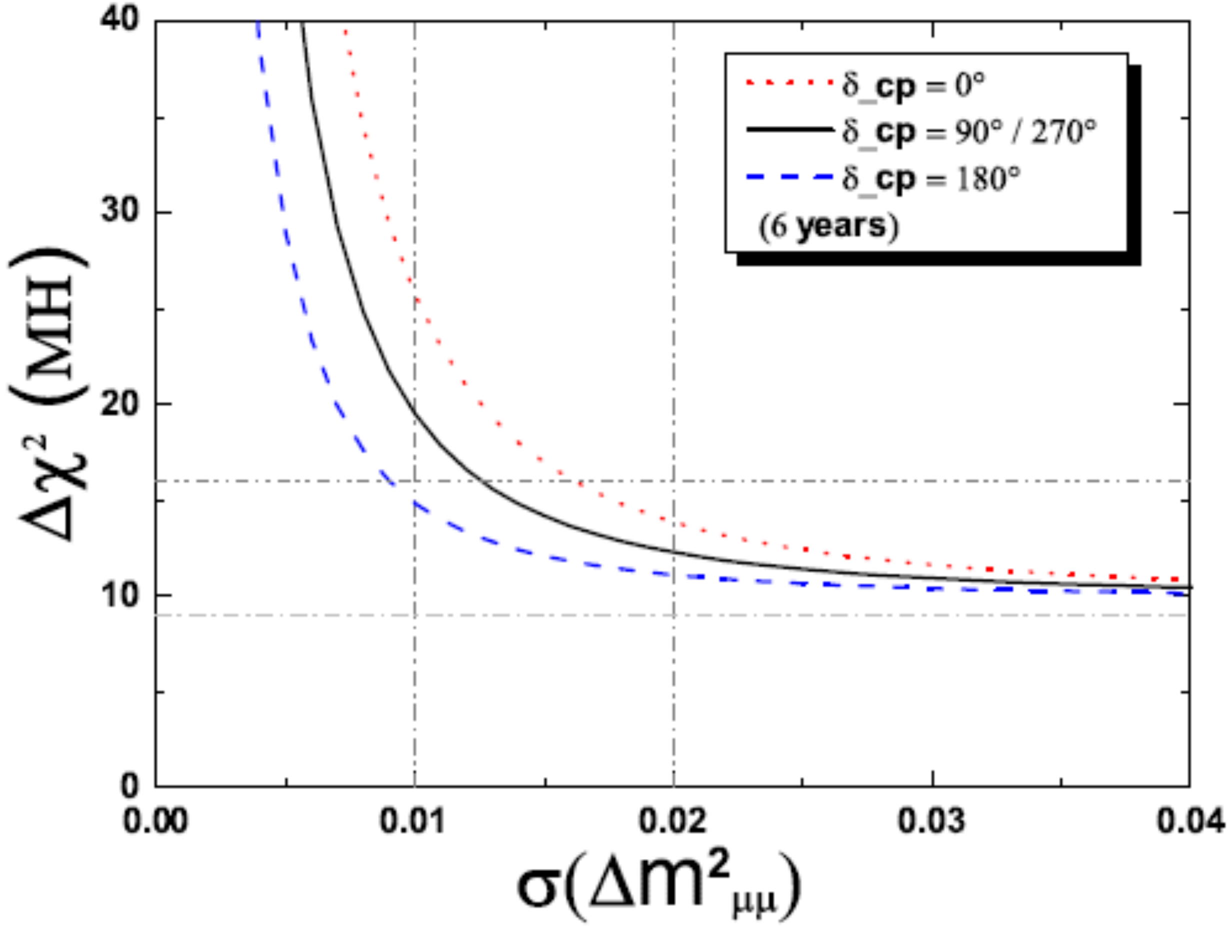
w/o self-calibration



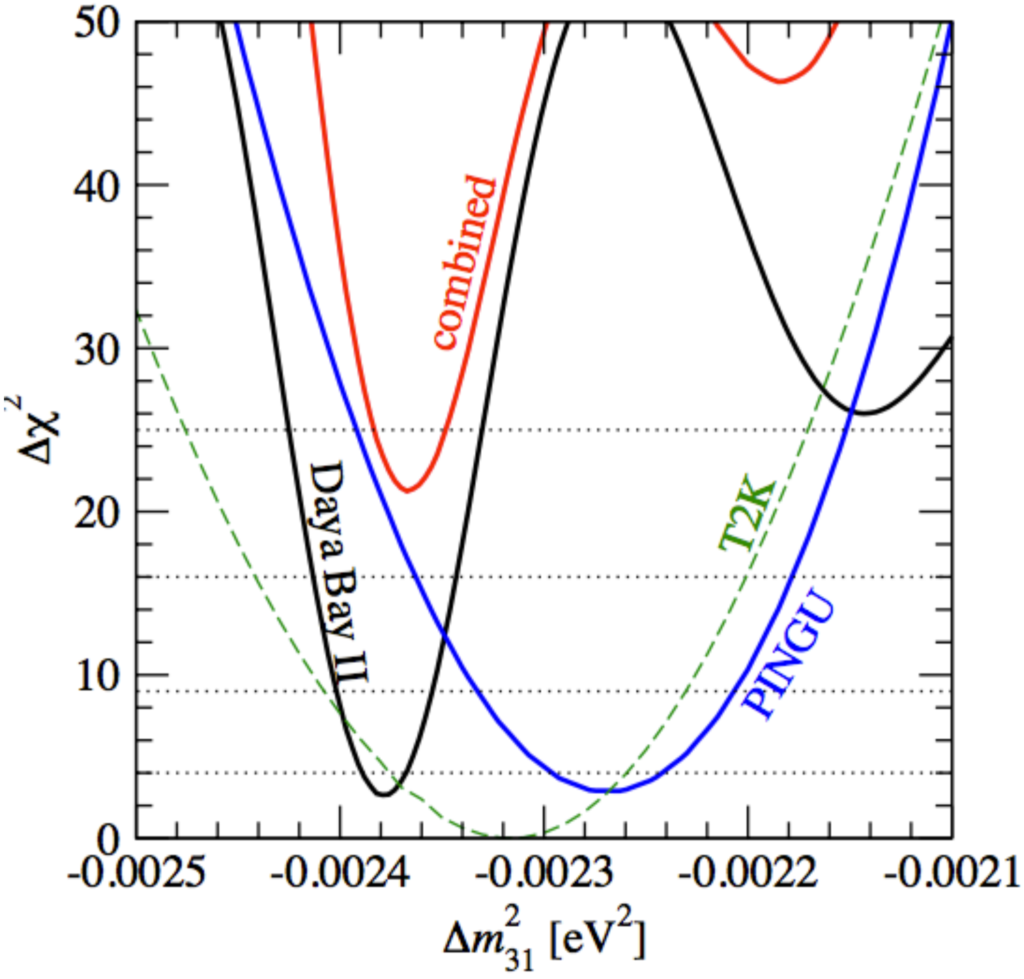
w/ self-calibration



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



Complementarity of MH experiments



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

Blennow, Schwetz, arXiv:1306.3988