Reactor Neutrino Experiments with km-scale baseline

PIC2022. Tbilisi

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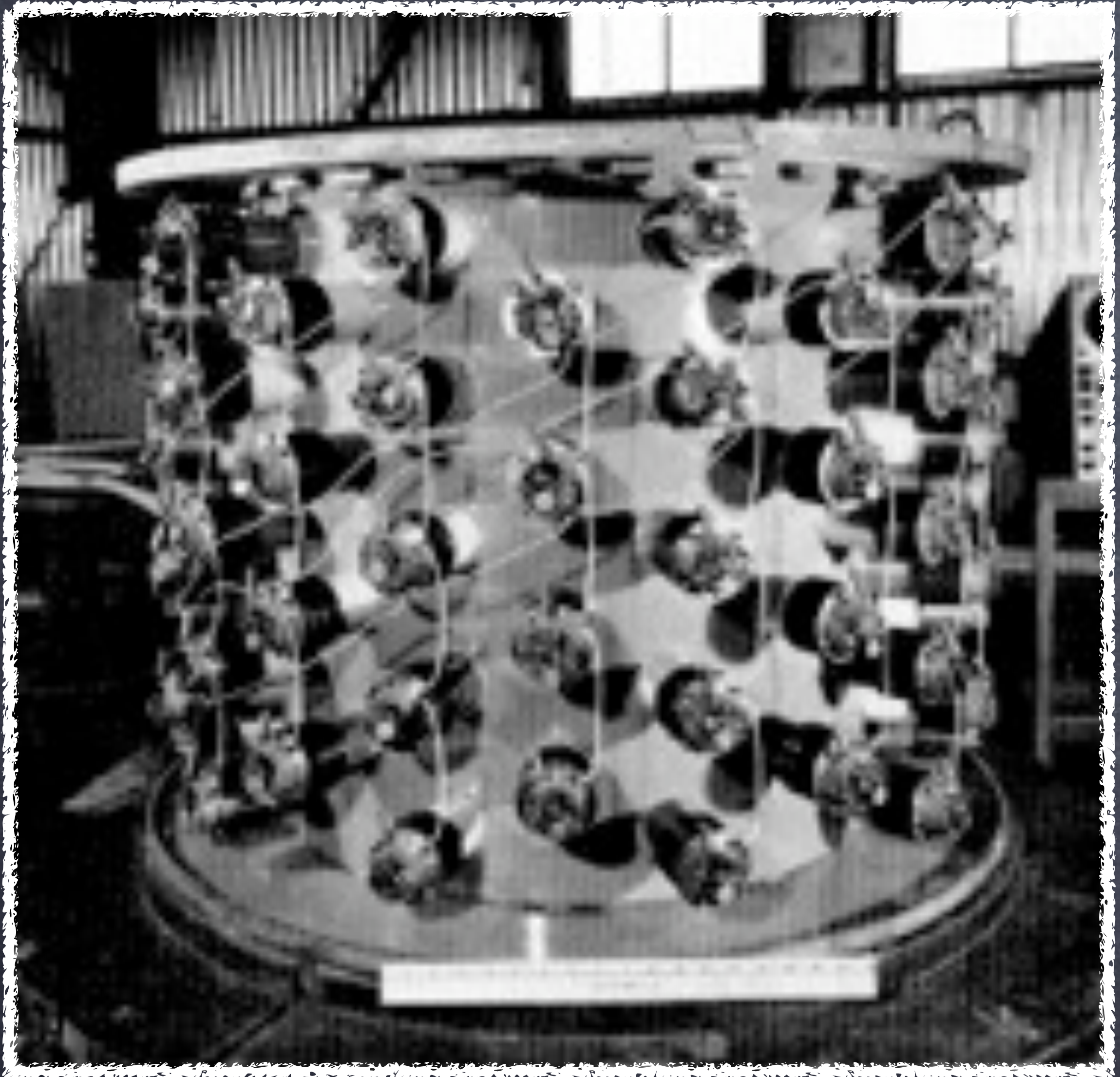
Outline

- Introduction: neutrino, nuclear reactors, physics case, top discoveries
- Status of $\theta_{13}, \Delta m^2_{31}$ measurements
- Reactor neutrino flux and spectrum: measurements, theory, anomalies
- Sterile neutrino searches
- Status of JUNO experiment
- New liquid scintillator technologies

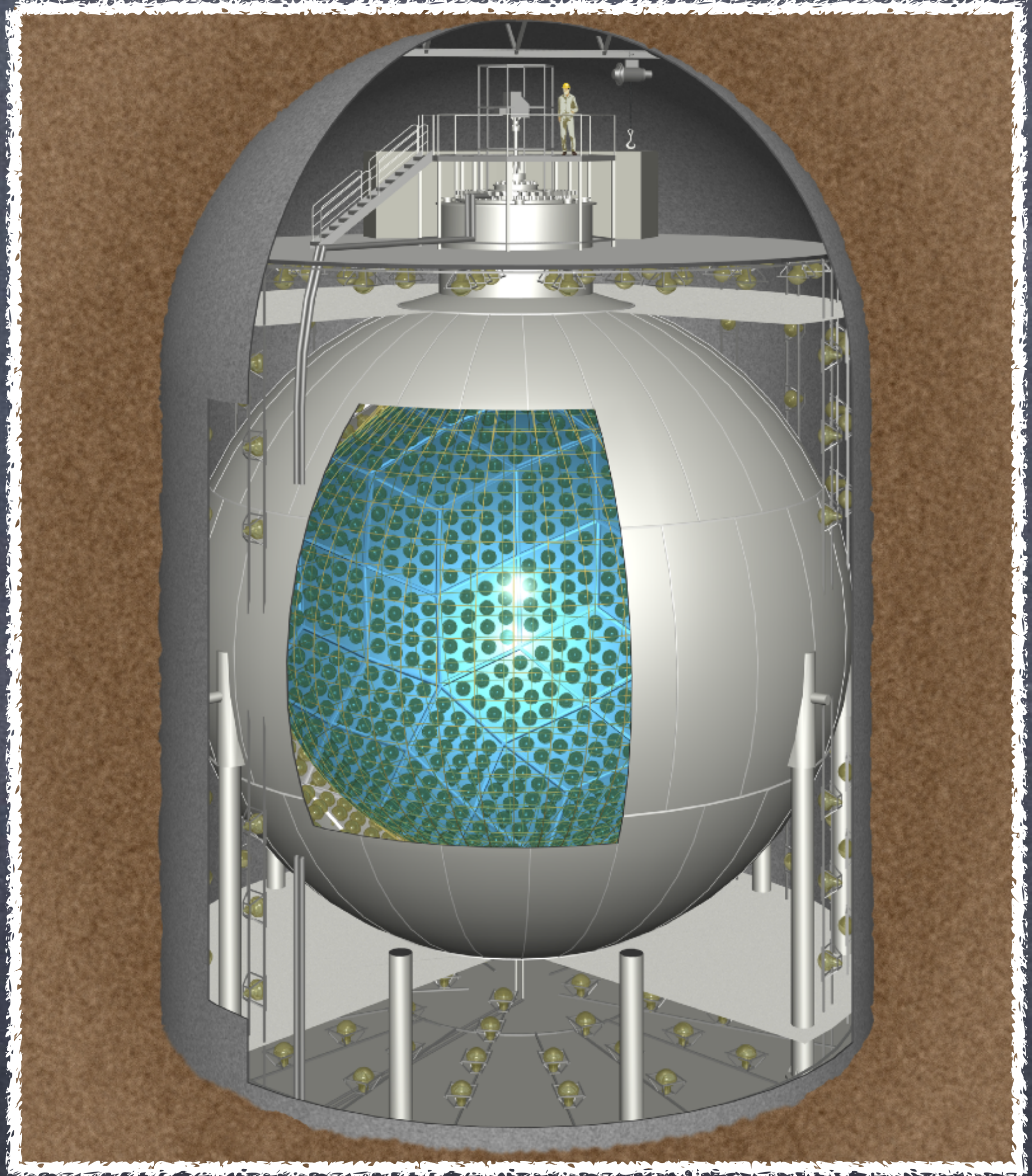
Top discoveries with reactor neutrino experiments

$\bar{\nu}_e$ discovery (Reines,Cowan)



1956

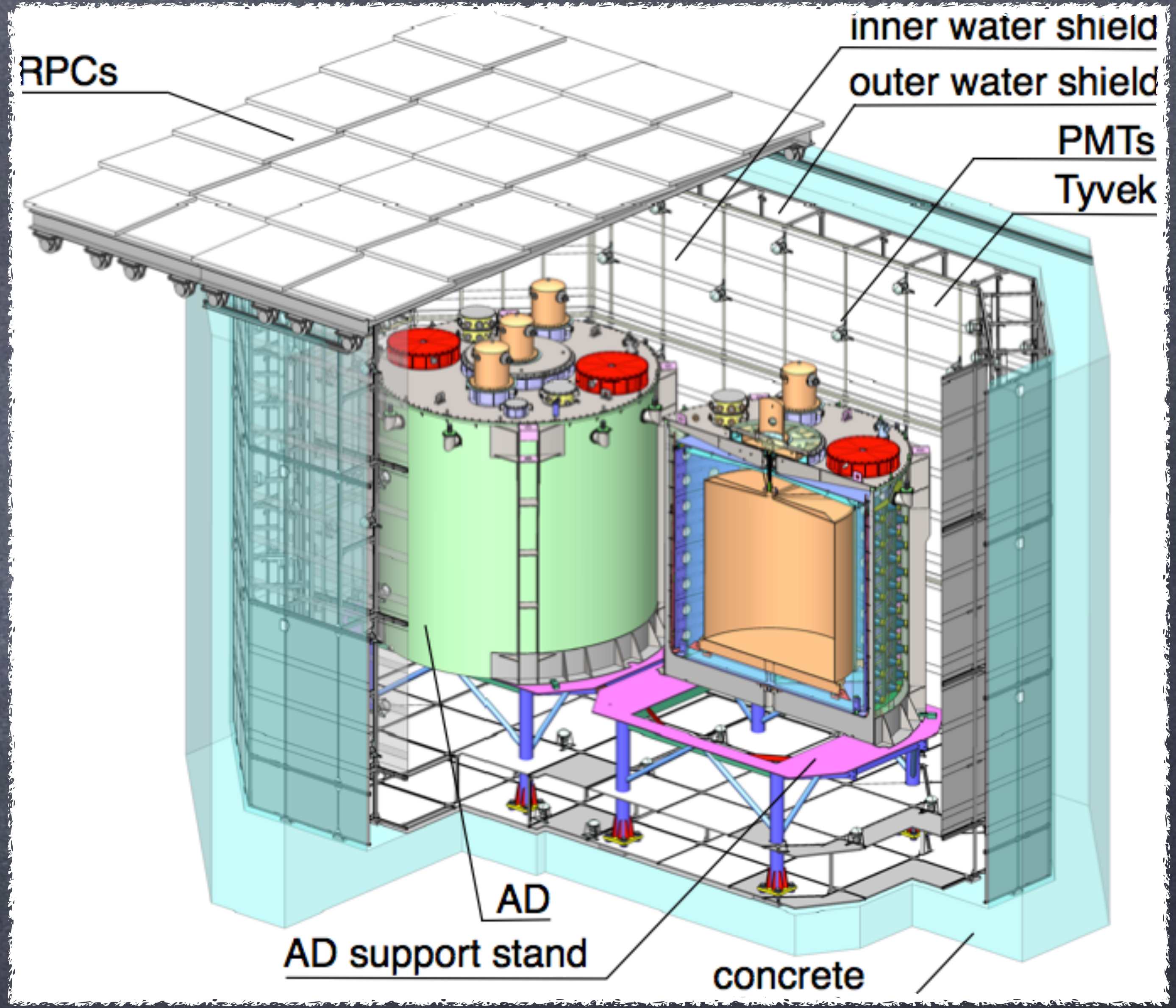
Discovery (+solar experiments) of neutrino oscillation due to Δm^2_{21}



Geo-neutrino discovery (+BOREXINO) (2010, 2013, 2015)

2005

Discovery (+accelerator experiments) of neutrino oscillation due to Δm^2_{32} and θ_{13}

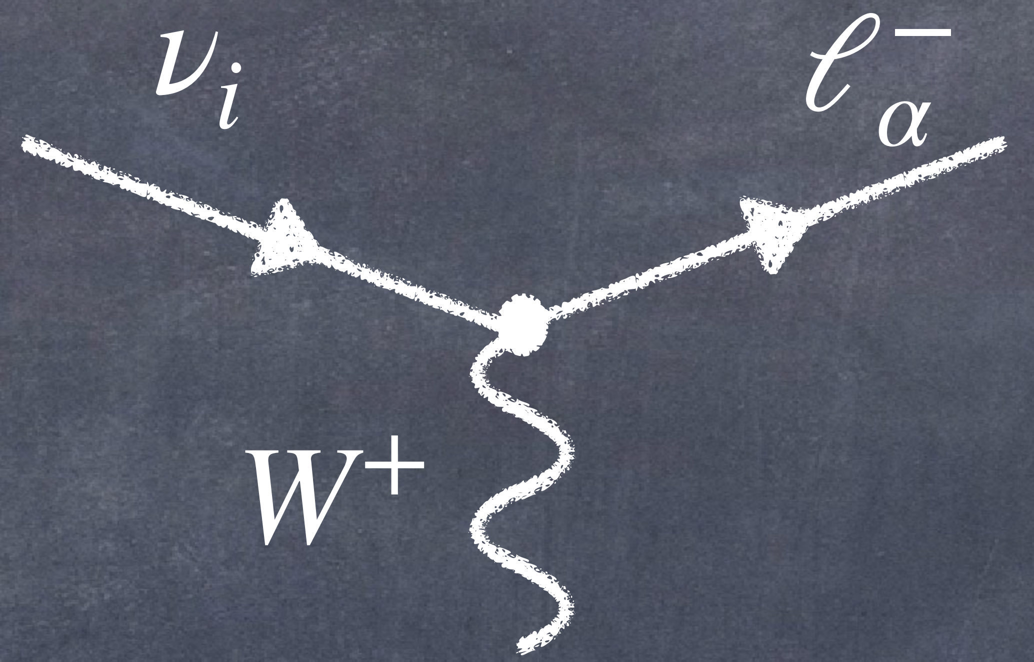


Discovery of non-zero value of θ_{13}

2012

Reactor Neutrino Experiments with km-scale baseline

- Neutral weakly interacting lepton
- Mix $(\theta_{13}, \theta_{12}, \theta_{23})$ with three families of charged leptons and $W^{\pm}$



$$\propto \frac{g}{2\sqrt{2}} V_{\alpha i}$$

- Three families: ν_1, ν_2, ν_3
  - $\Gamma_{W,Z}^{inv}$
  - Cosmology

$$V \approx \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.37 & 0.58 & 0.7 \\ 0.39 & 0.59 & 0.68 \end{pmatrix}$$

- Massive (meV):

$$\left.\begin{array}{l} m_2 \gtrsim 10 \\ m_{heavy} \gtrsim 50 \end{array}\right\}$$ Oscillations

$\sum_i m_i \lesssim 120$ Planck

$\overline{m}_{\nu_e} \lesssim 900$ KATRIN [2105.08533]

$\overline{m}_{\beta\beta} \lesssim 156$ KamLAND-ZEN [2203.02139]

$m_{light} \lesssim 500$

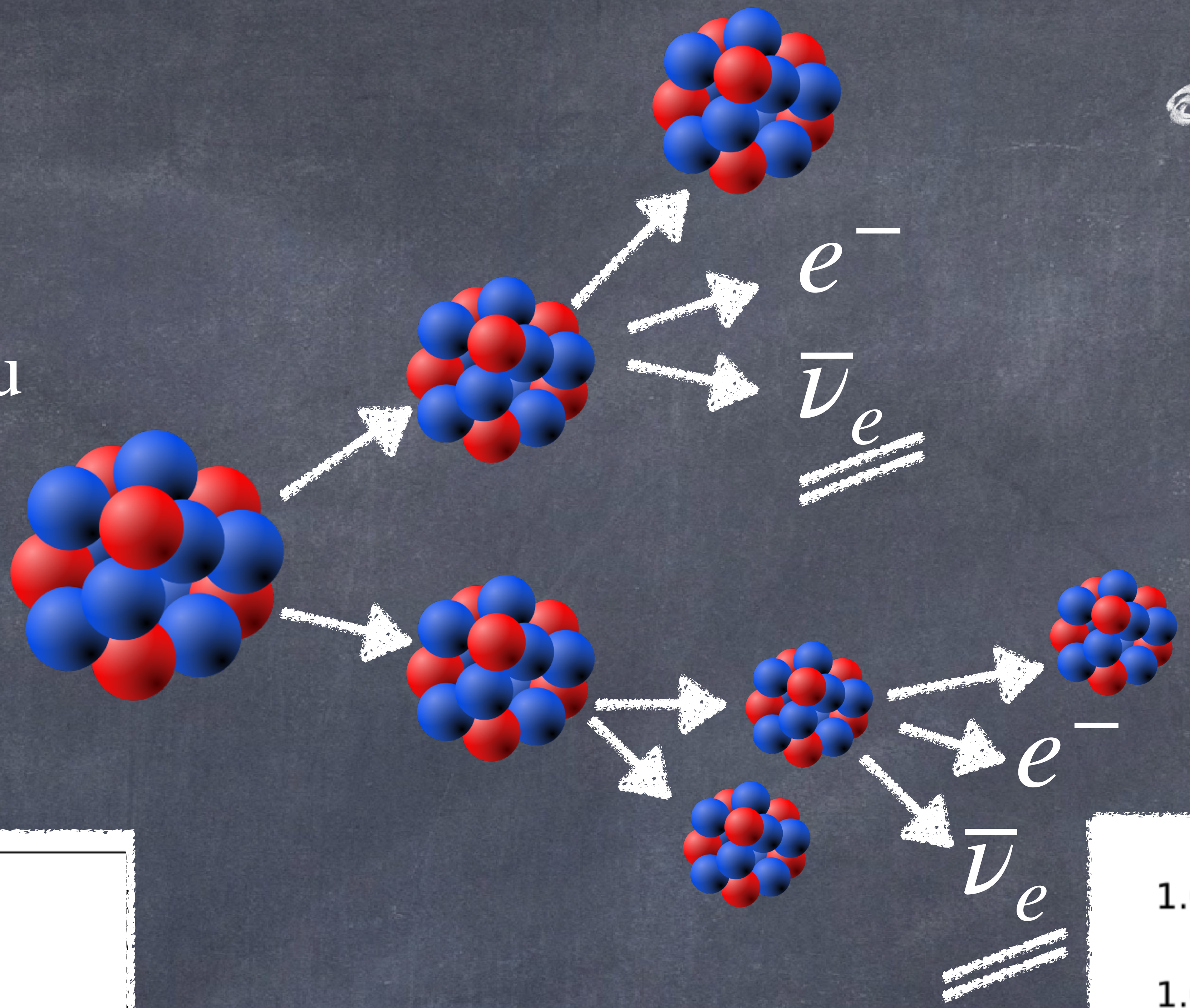
Unknowns

- Mass ordering $|\Delta m_{31}^2| \to \Delta m_{31}^2$
- $m_{light} = ?$
- Dirac or Majorana
- $\delta_{CP} = ?$
- V unitarity

Accessible @reactors

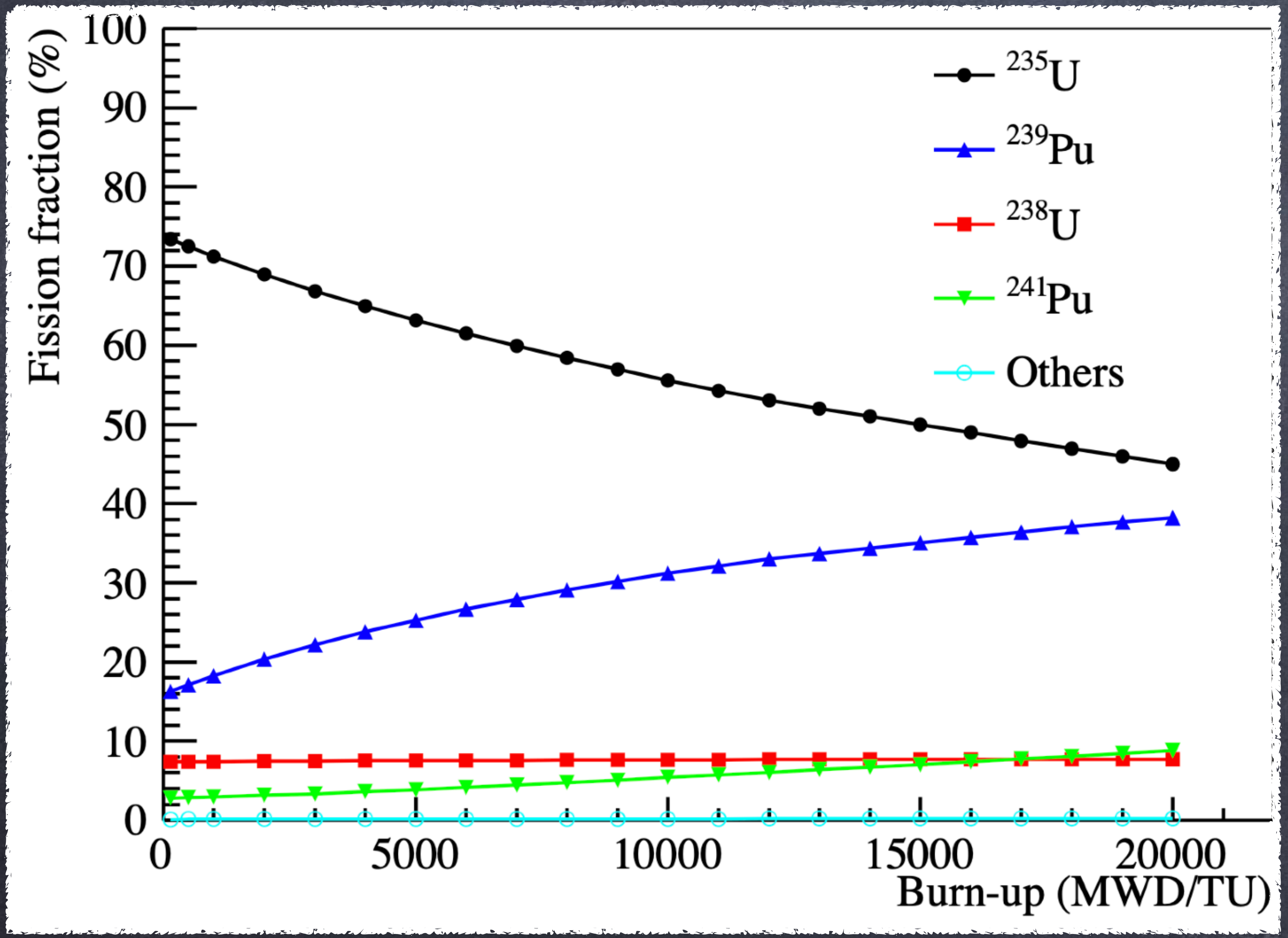
Reactor Neutrino Experiments with km-scale baseline

- Low Enriched Uranium (LEU)
  - 3-4 GW thermal power
  - Consumes ^{235}U. Produces ^{239,241}Pu
  - Refuel every 1.5-2 years
  - Extended core ⌀ few m
  - $6 \cdot 10^{20}\ \overline{\nu}/s\ @3GW_{th}$

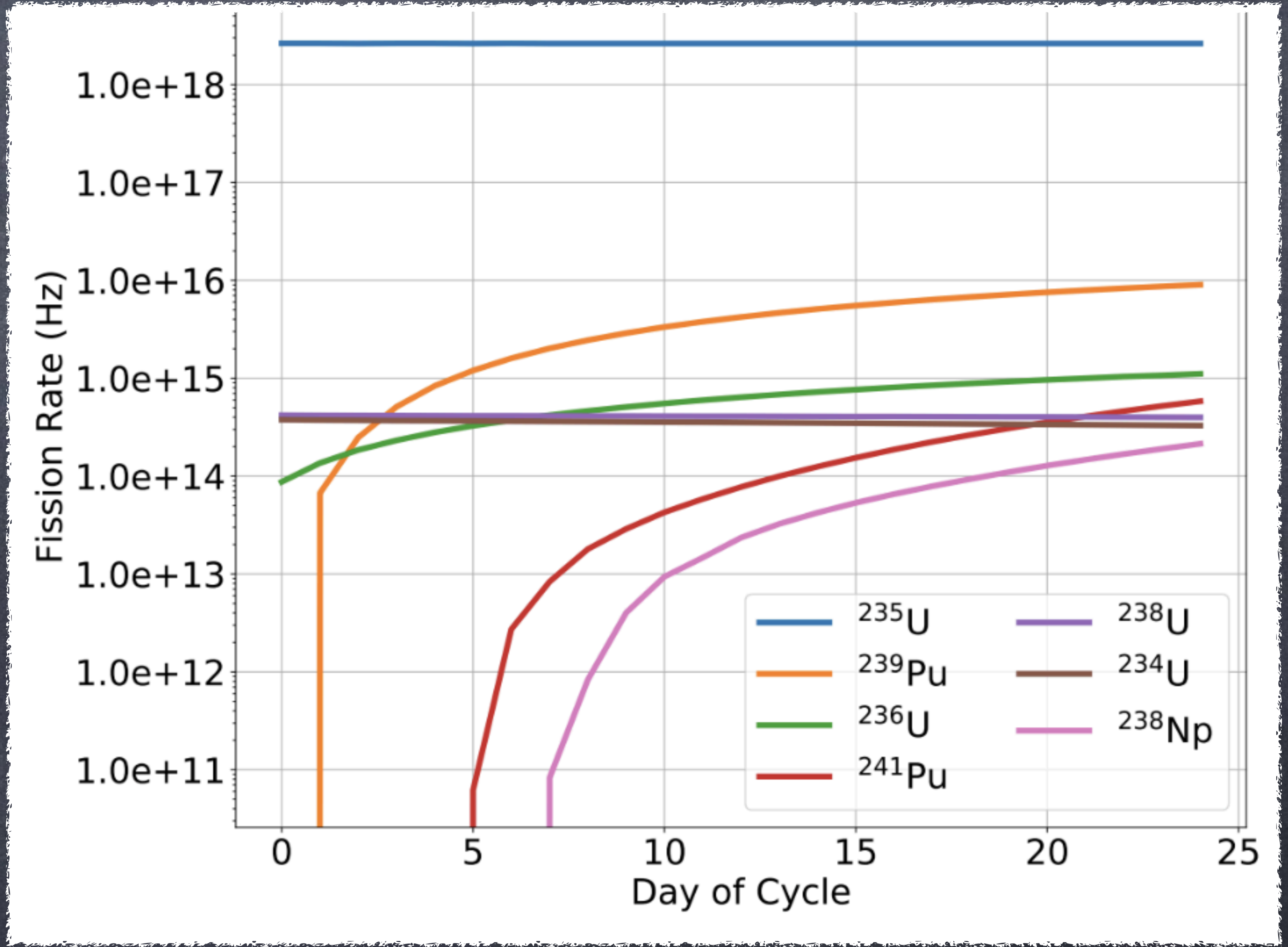


- 6ν/fission

- High Enriched Uranium (HEU)
  - 50-100 MW thermal power
  - Almost pure ^{235}U
  - Refuel every 1-3 months
  - Compact core ⌀ $\simeq 0.5$ m

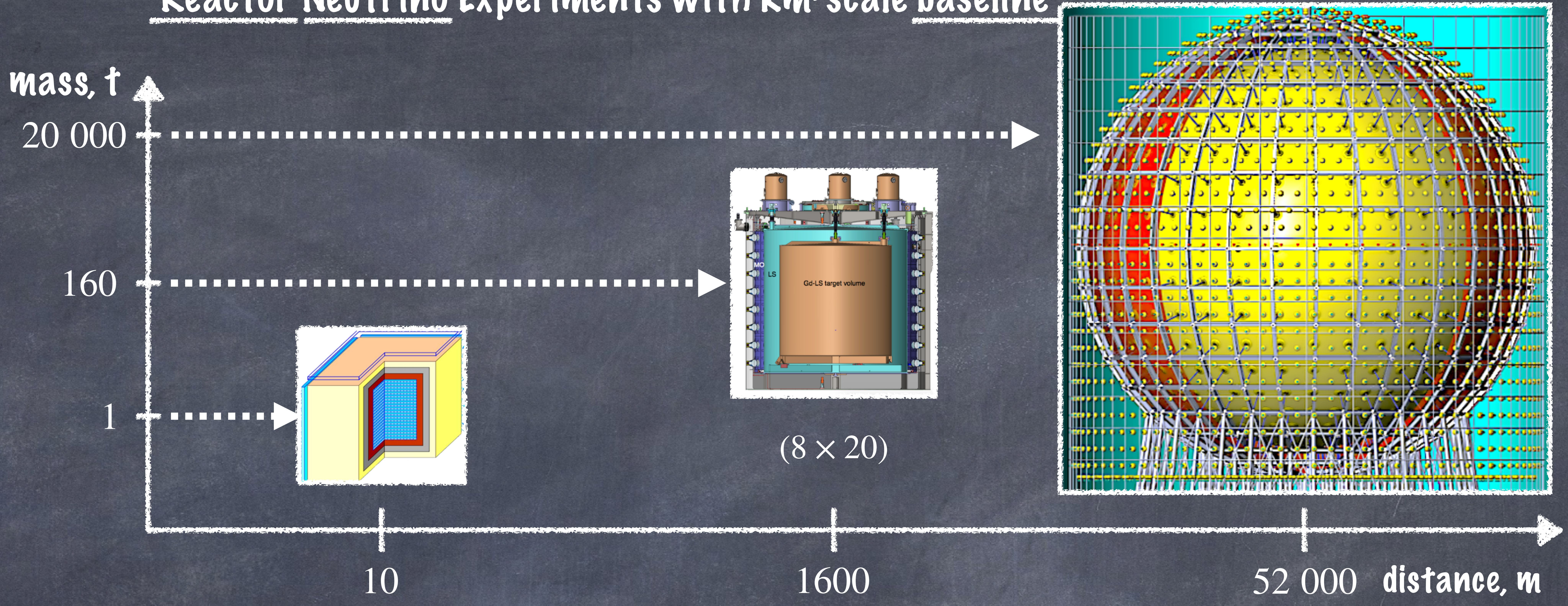


Fuel Evolution [2102.04614]



PROSPECT

Reactor Neutrino Experiments with km-scale baseline



Three neutrino mixing		$\theta_{13}, \Delta m^2_{31}$	$\Delta m^2_{31}, \Delta m^2_{21}, \theta_{21}, \theta_{13}$
Sterile neutrino: Δm^2_{41} (eV^2)	$\simeq (2 - 10)$	$\simeq (10^{-2} - 10^{-1})$	$\simeq (10^{-5} - 10^{-2})$
Spectrum @reactors	✓	✓	✓
Neutrino mass ordering			✓
Geo-, solar, atmospheric, Nucleon decay, SuperNova, DSNB neutrino			✓

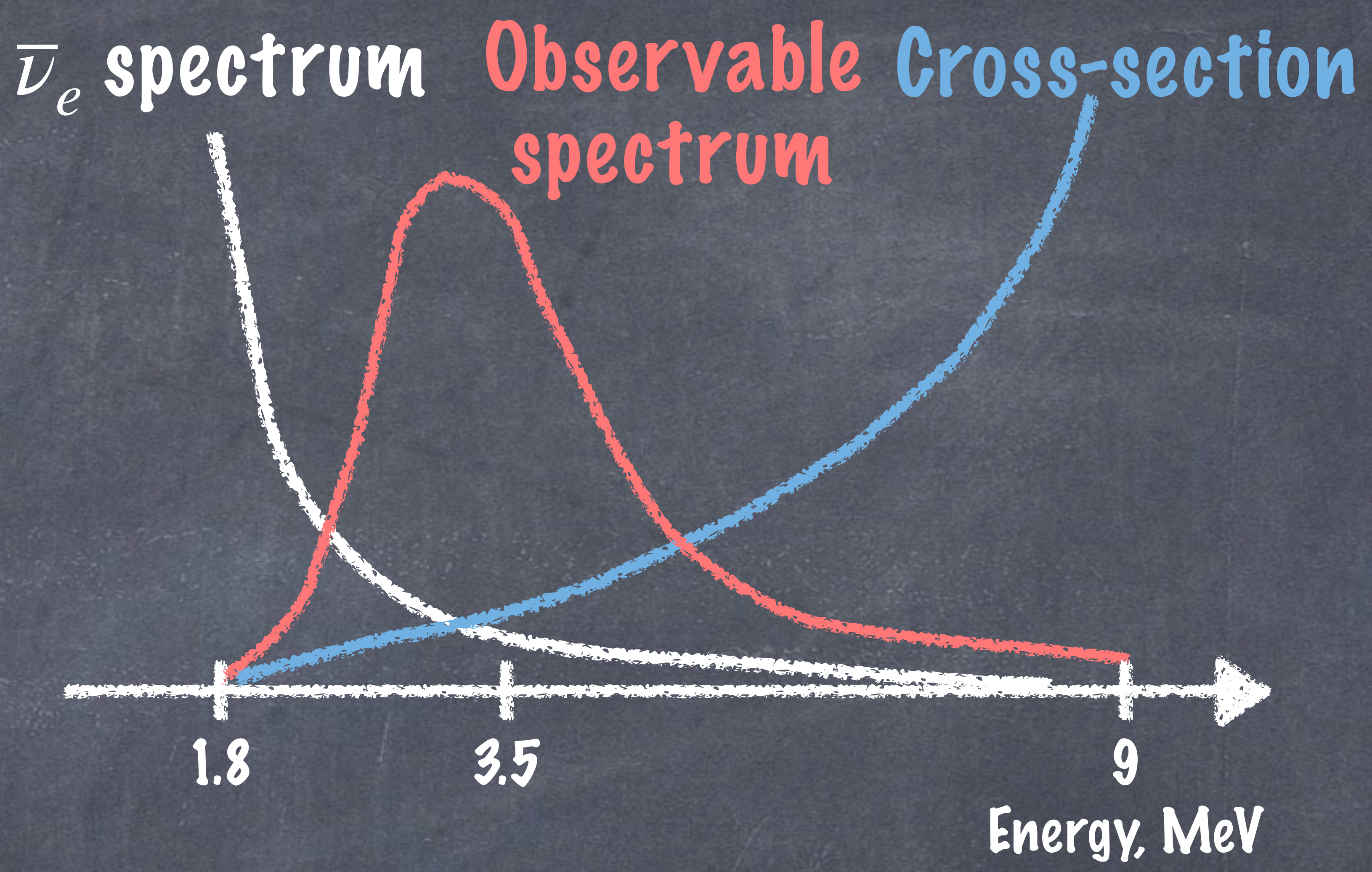
Reactor Neutrino Experiments with km-scale baseline

Detection: inverse β-decay (IBD) $\overline{\nu}_e + p \rightarrow e^+ + n$

Prompt = e^+ ionisation + $e^+e^- \rightarrow \gamma\gamma$

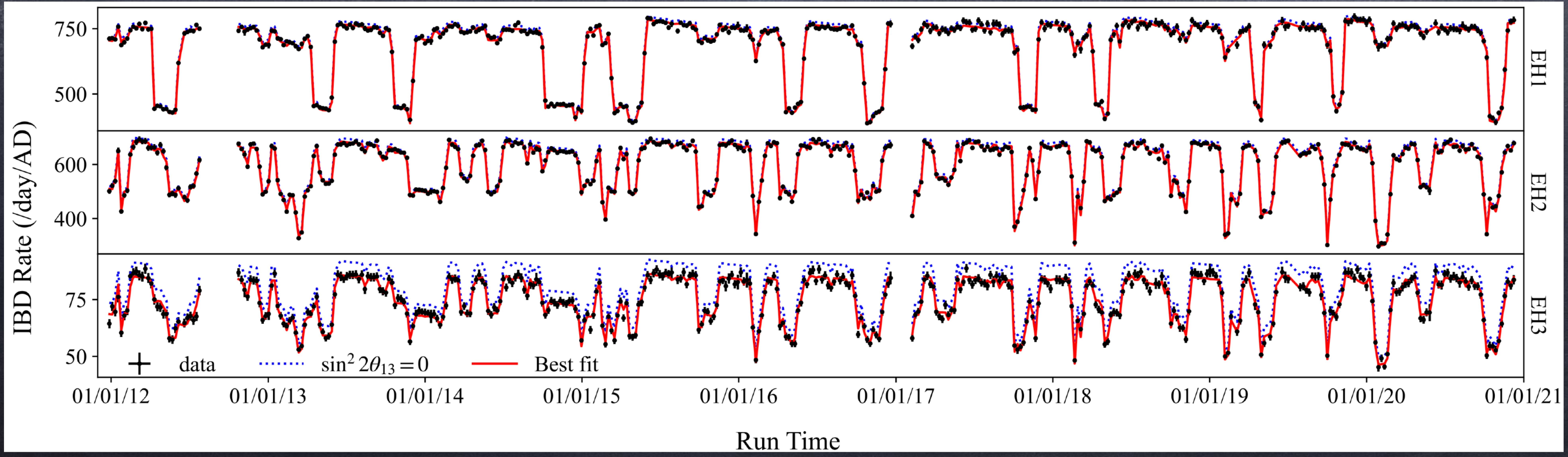
Delayed = n capture $\rightarrow \gamma(\gamma\ldots)$

} Event = prompt+delayed



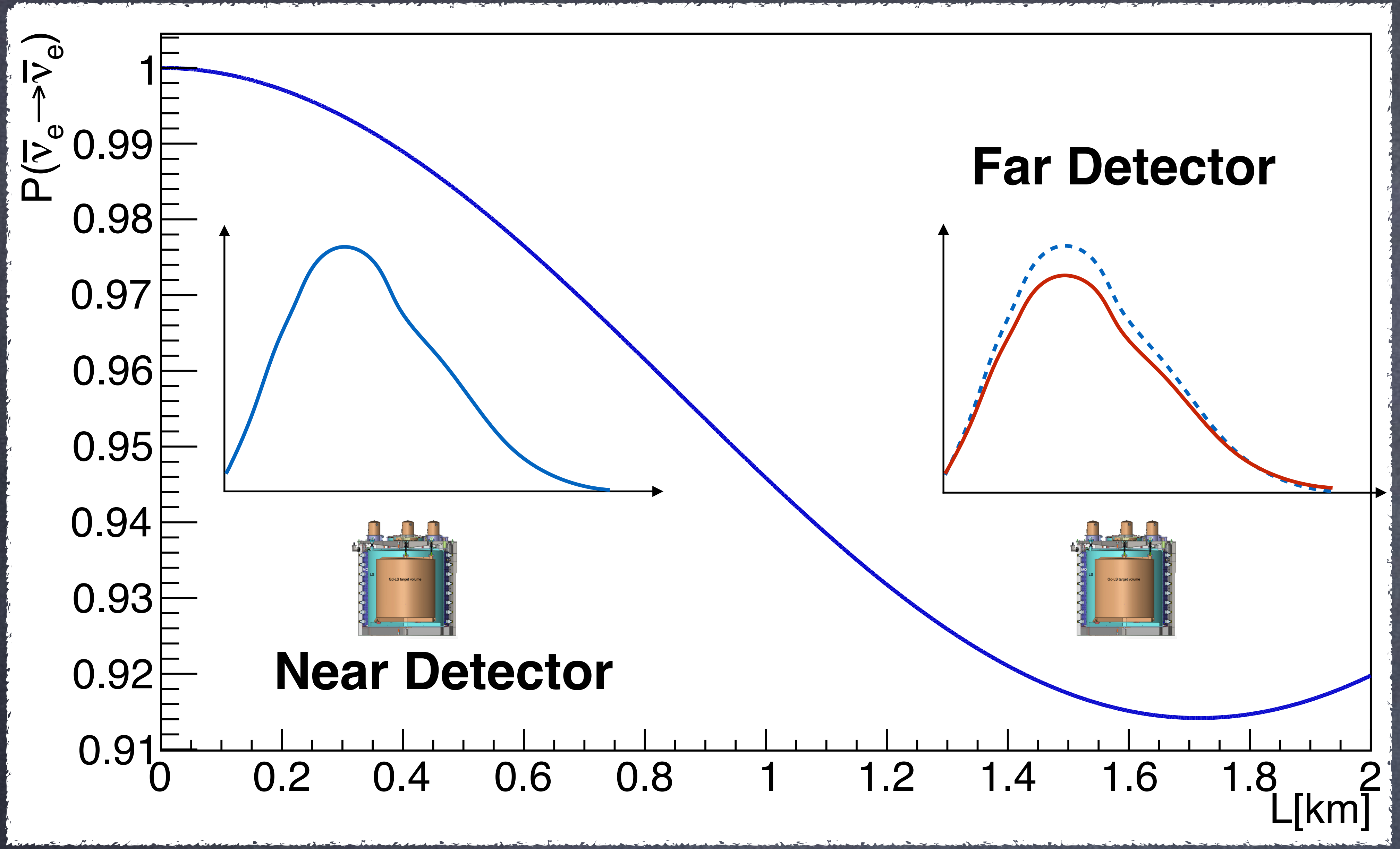
Reactor neutrino detectors = Precision Instruments

- Percent-level control of absolute detector efficiencies and energy scale (multiple calibration sources, cosmogenics)
- Excellent correlation with reactor power



Ex: Daya Bay

Reactor Neutrino Experiments with km-scale baseline



Ratio suppresses correlated uncertainties

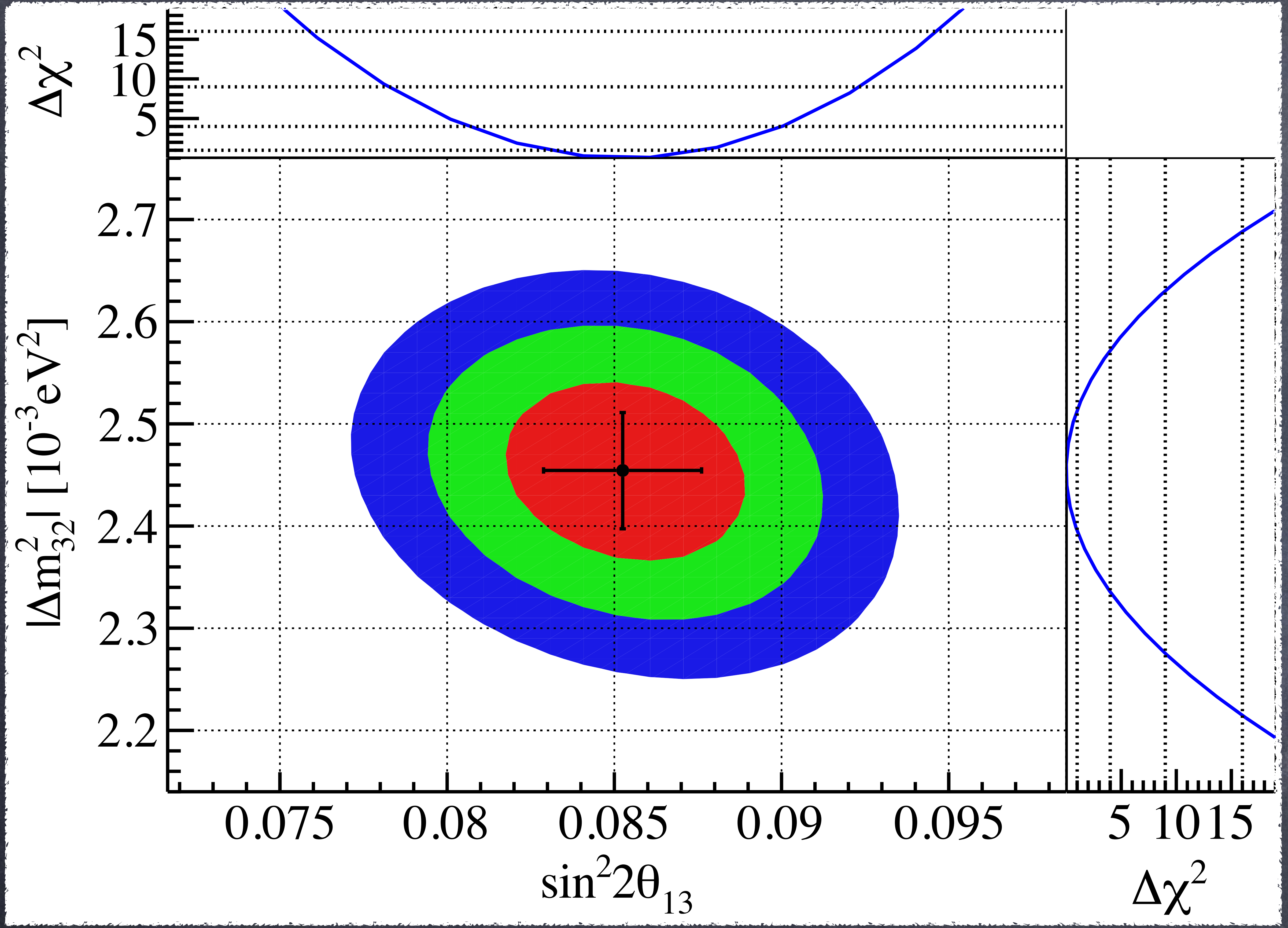
$$\frac{N_{far}(E)L^2_{far}}{N_{near}(E)L^2_{near}} \propto \cdot \frac{N^p_{far}}{N^p_{near}} \cdot \boxed{\frac{\varepsilon_{far}}{\varepsilon_{near}}} \cdot \frac{P_{osc}(L_{far}/E)}{P_{osc}(L_{near}/E)} \cancel{\frac{\sigma \cdot \Phi(E)}{\sigma \cdot \Phi(E)}}$$

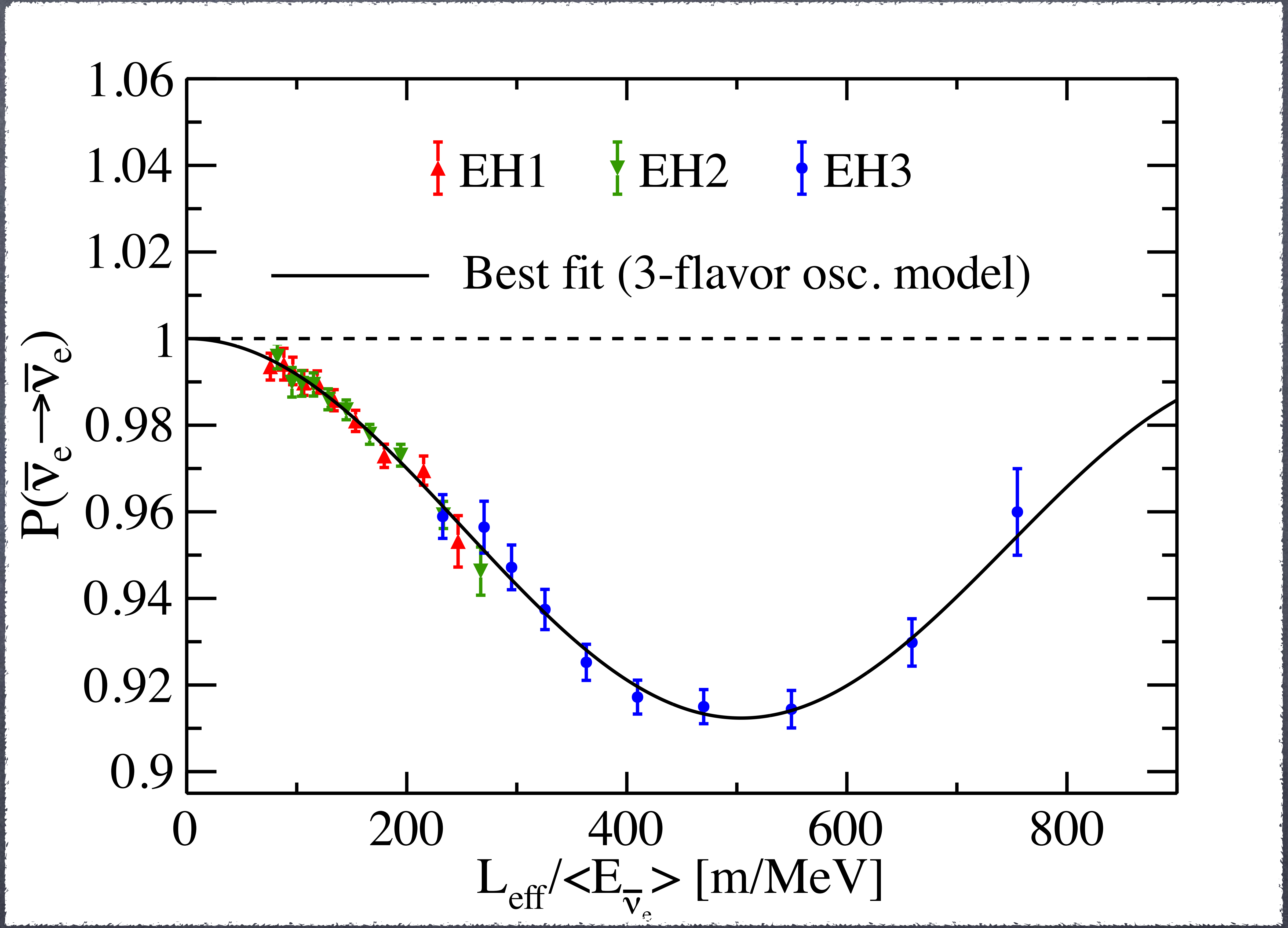
$$\sim 1 - \sin^2 2\theta_{13}$$

	Power $[GW_{th}]$	GdLS mass Near/ Far [t]	Distance Near/Far [m]	Overburden [mwe]	Running until	IBD detection correlated uncorrelated
Daya Bay	17.4	2×2×20 4×20	365, 490 1650	250 860	2020	1.2% 0.13%
Double Chooz	16.8	8 8	400 1050	120 300	Dec 2017	0.5% 0.2%
RENO	8.5	16 16	290 1380	120 450	2025	0.97% 0.13%

A decade of measurements

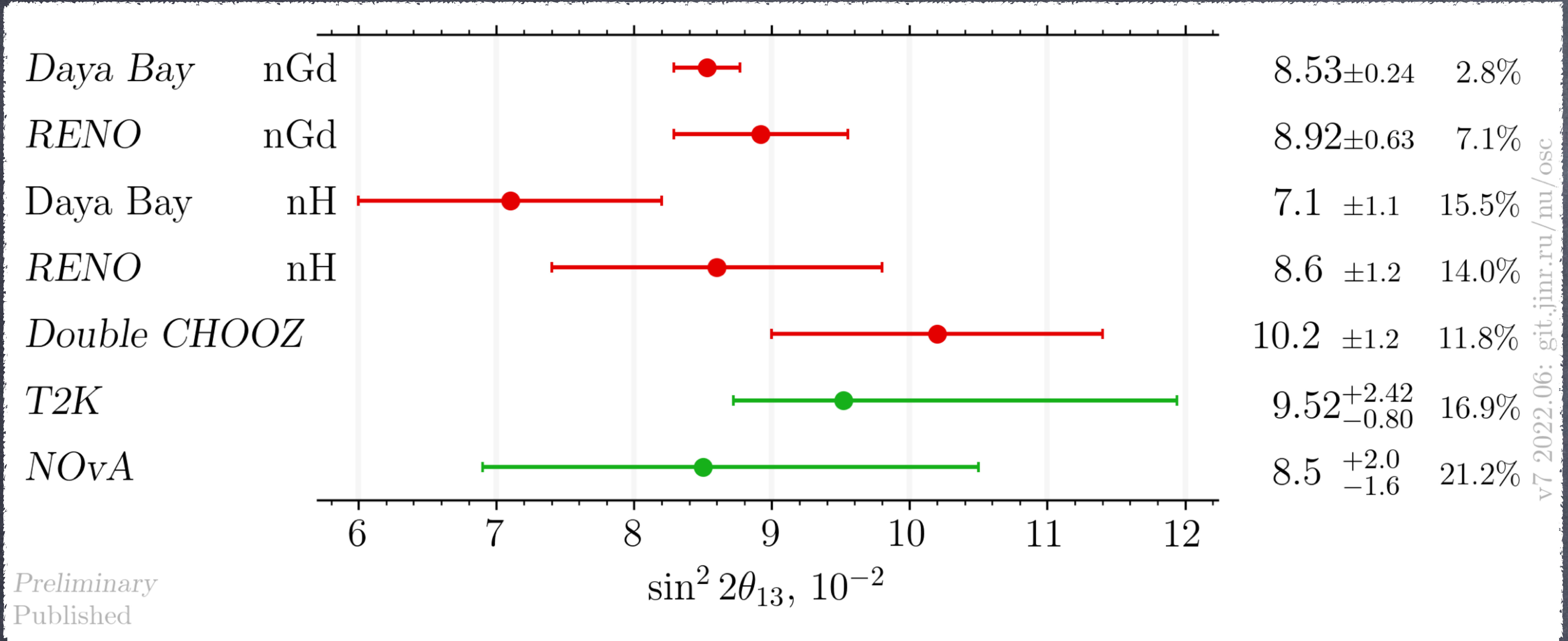
Three neutrino oscillation due to $\theta_{13}, \Delta m^2_{32}$

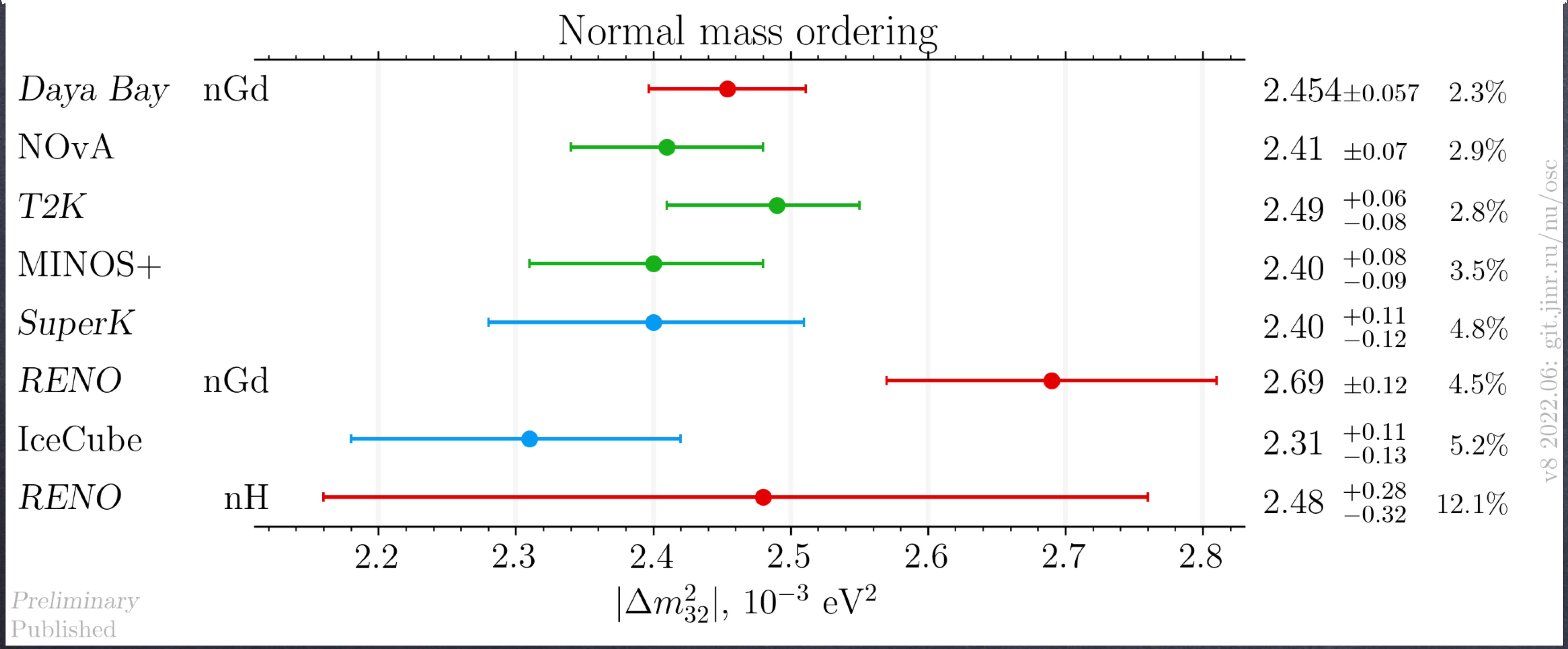




Daya Bay@Neutrino 2022

Three neutrino oscillation due to θ_{13}, Δm^2_{32}. Global picture





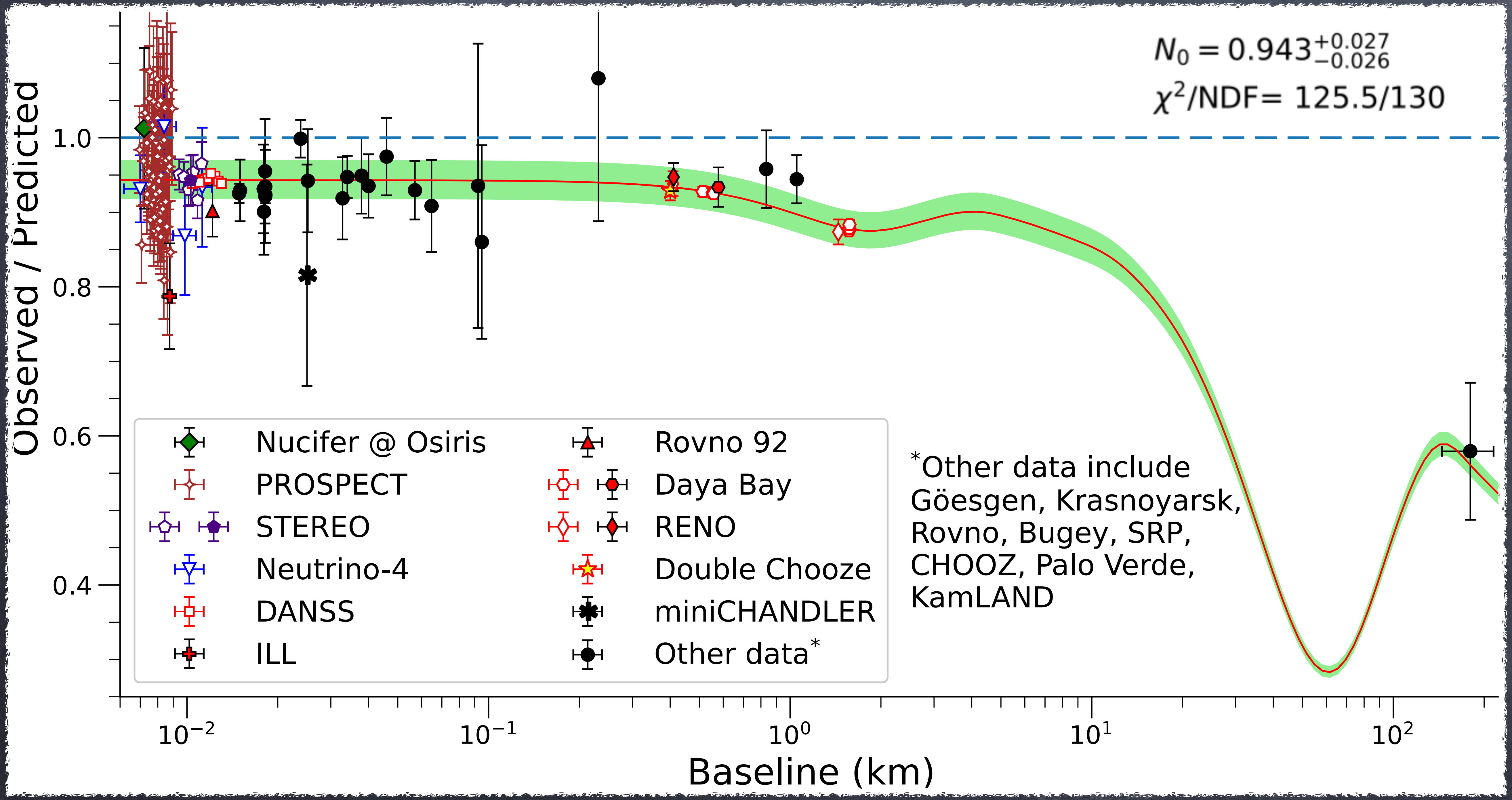
No running or planned experiment to surpass this precision

Reactor neutrino flux and spectrum

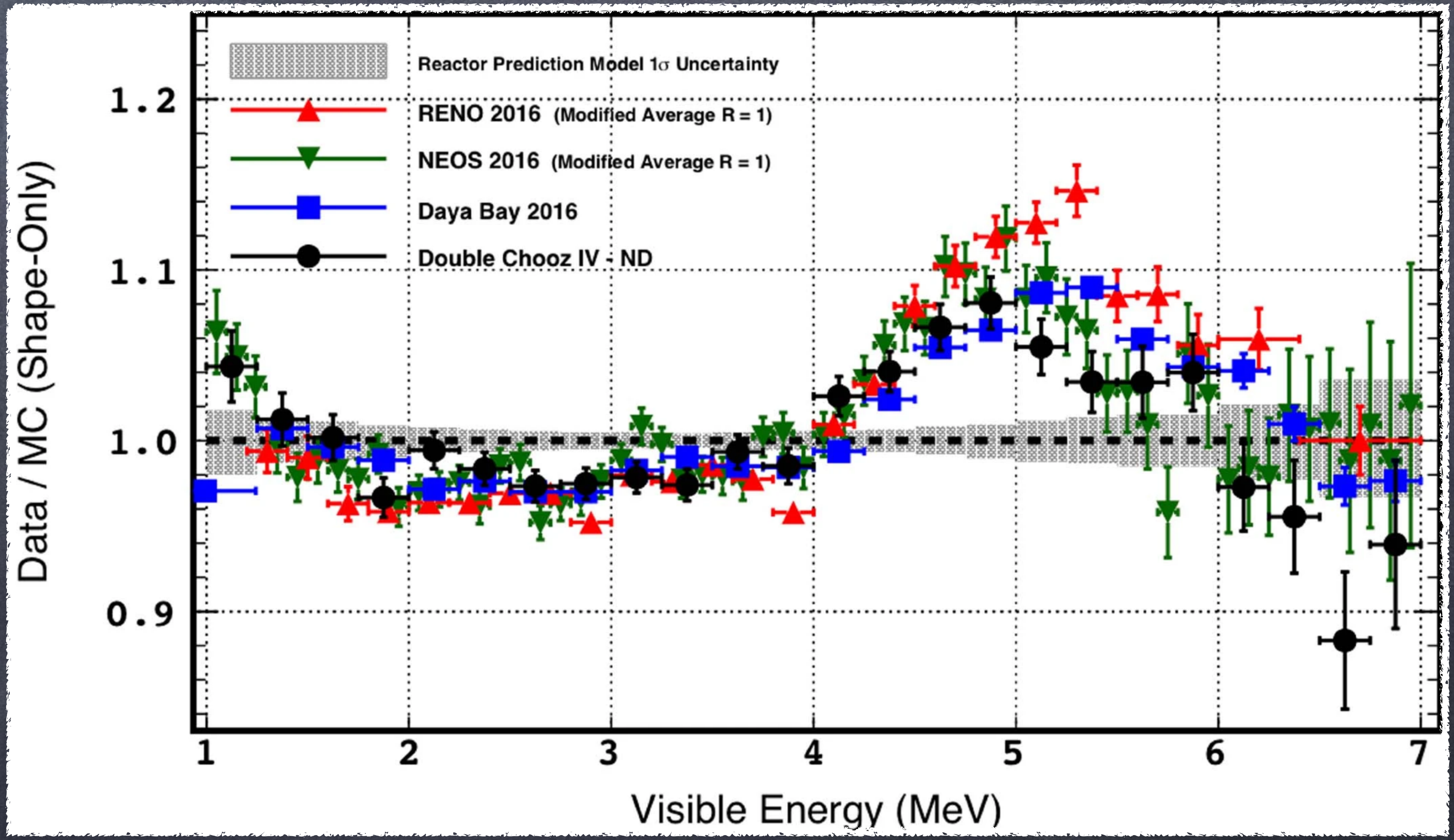
- Once θ_{13} determined (far/near cancelation), flux and energy spectrum are measured too

Mueller et al. 1101.2663
Huber 1106.0687

- Both have issues:
  1. The flux is about 6% below of a new HM model (=Reactor Antineutrino Anomaly, RAA)
  2. After 6% reduction the spectrum has a 'bump' @(4-6) MeV of prompt energy.



Universe 2021, 7(7), 246



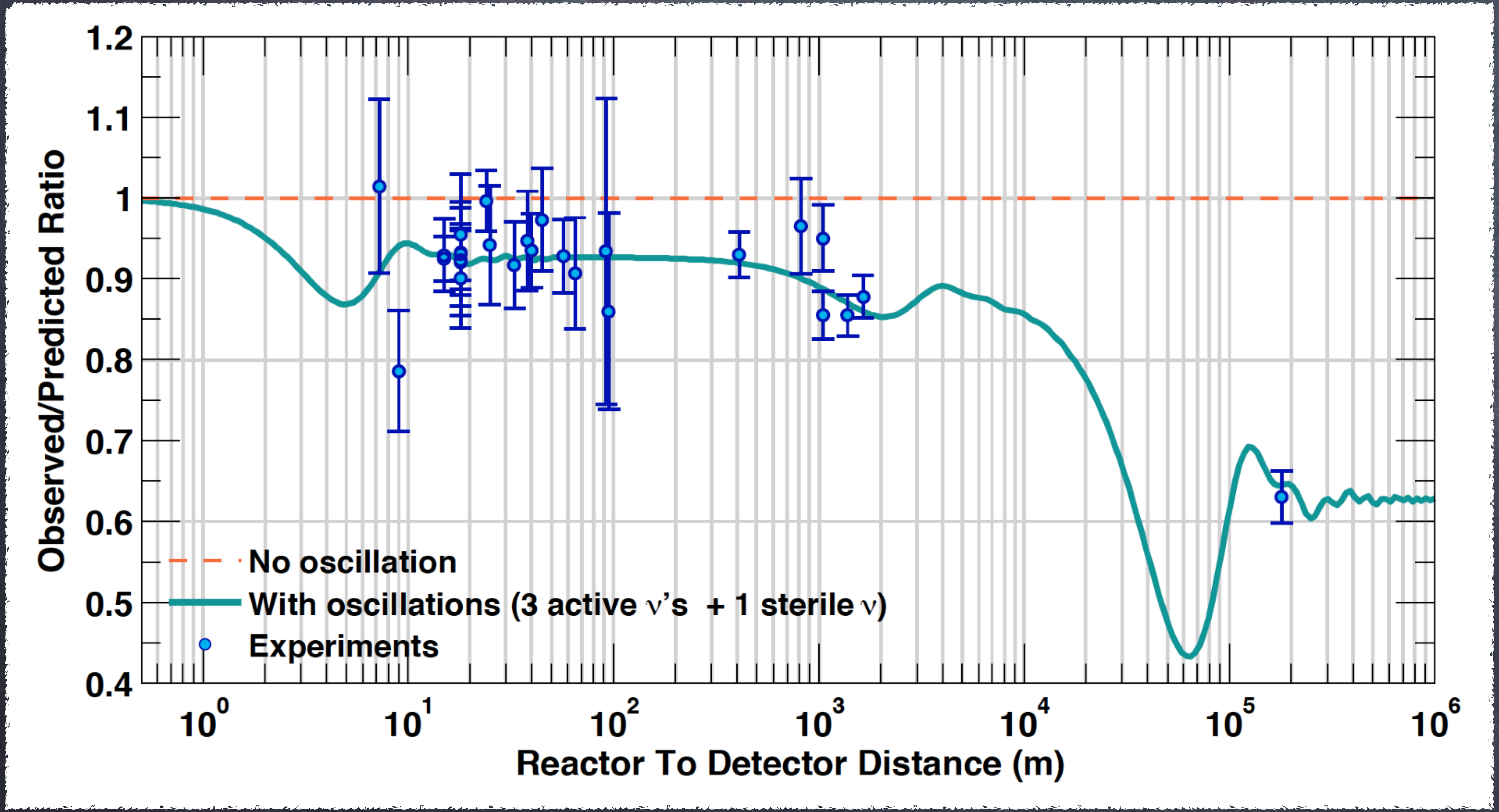
Double Chooz Nature Phys.16 (2020) 558

Lines of research to resolve the reactor neutrino anomalies

- Sterile neutrino state

3+1 ν model for the flux deficit

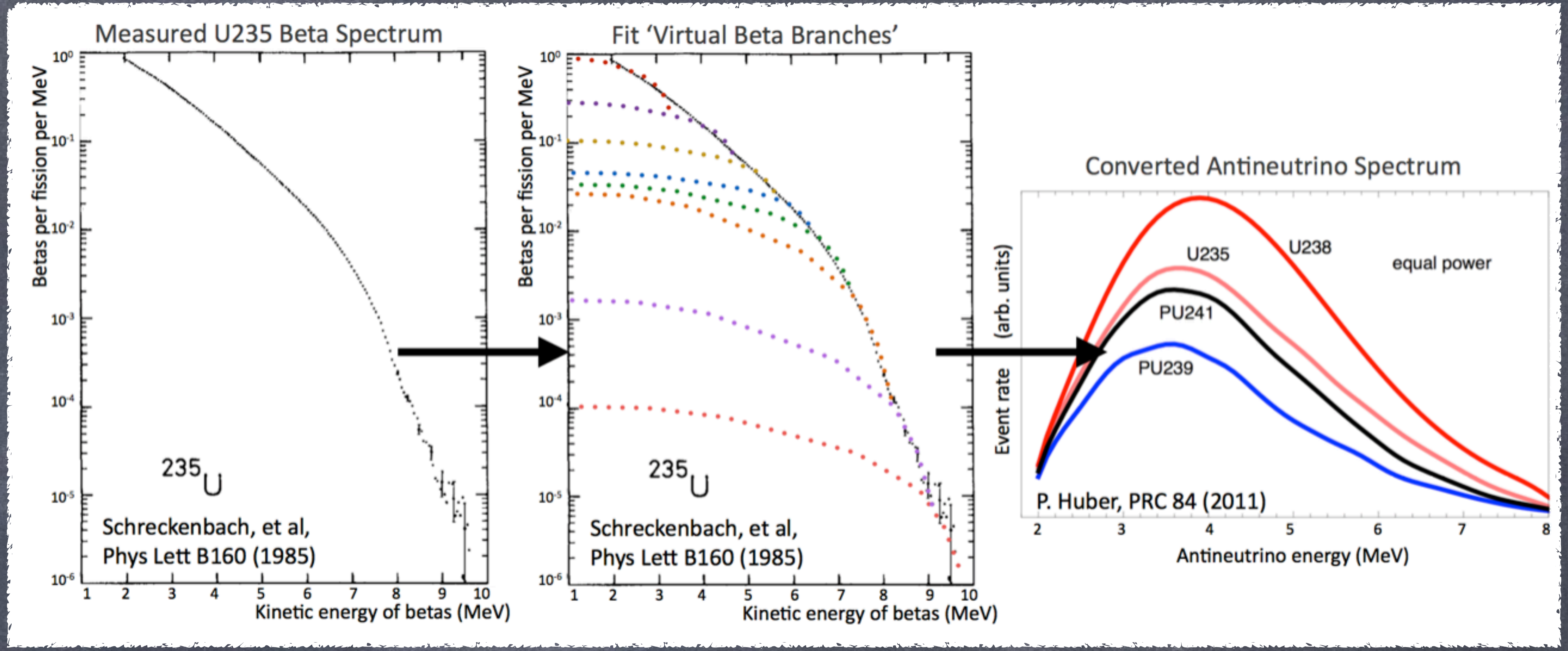
$$\Delta m^2 \approx 2\mathrm{eV}^2, \sin^2 2\theta \approx 0.1$$



PRD 83 073006

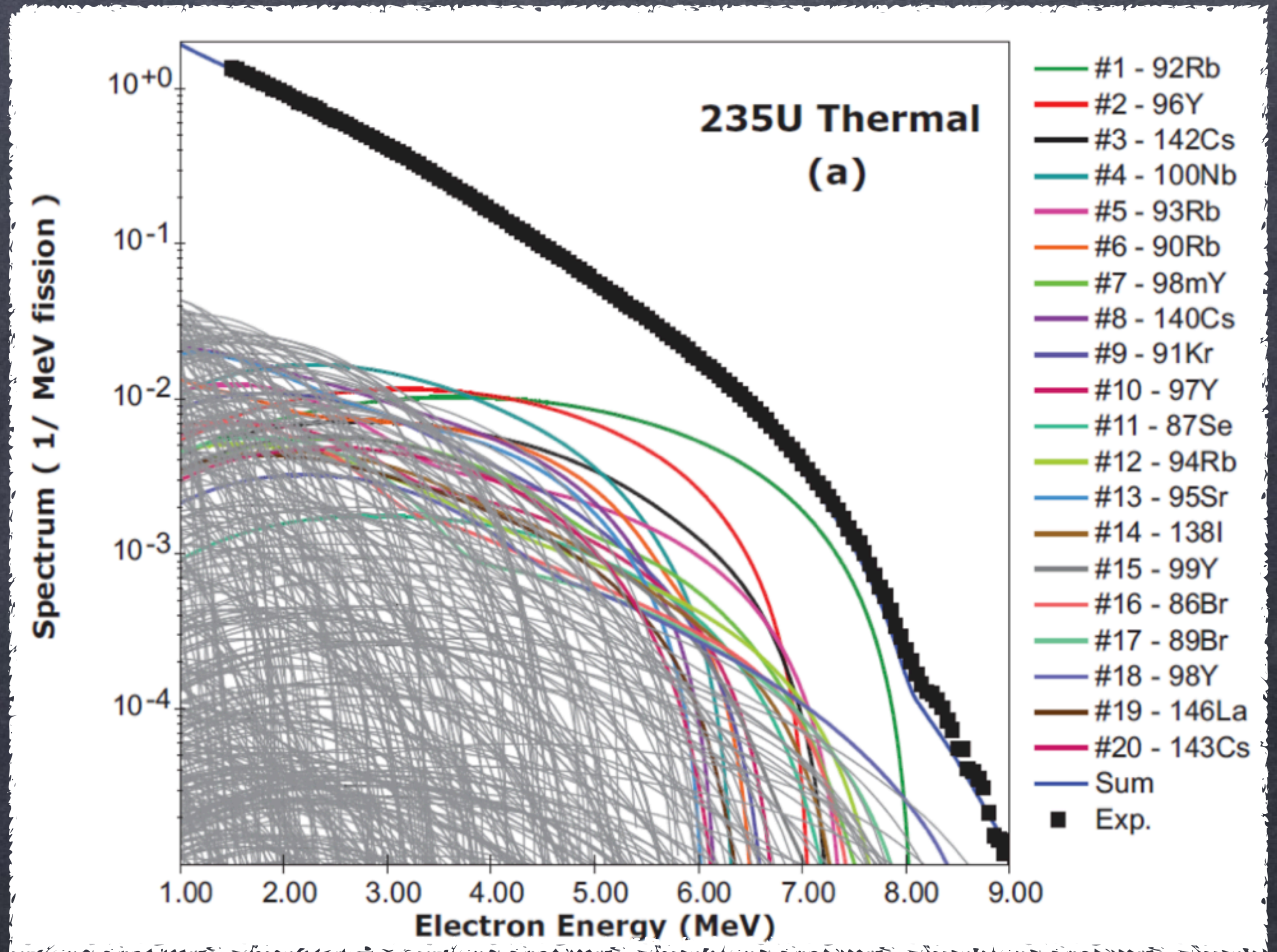
- Improve ν flux calculation method

A) Conversion method



- B) Summation method (SM) =Ab-initio

PRL 123, 022502



Sonzogni AAP2019

Why Sterile Neutrino?

- For $\overline{E}_\nu \approx 3.5$ MeV
  - $L_{\text{osc}} = \dfrac{4\pi E_\nu}{\Delta m^2_{32}} \approx 1.8\text{km}$
  - $L_{\text{osc}} = \dfrac{4\pi E_\nu}{\Delta m^2_{21}} \approx 59\text{km}$

- 3-neutrino oscillation can not explain the rate deficit at $L \ll 1\text{km}$
- 4 SM-neutrino excluded by Z lifetime and cosmology
- If oscillations wanted —> a smart idea is required

What is Sterile Neutrino?

- Sterile state = a coherent superposition of $\nu_1, \nu_2, \nu_3, \nu_4 \ldots$(similar to flavor) with vanishing interaction amplitude with W,Z
- NB! $\nu_1, \nu_2, \nu_3, \nu_4 \ldots$do interact with W,Z

pedagogical introduction 1901.00151

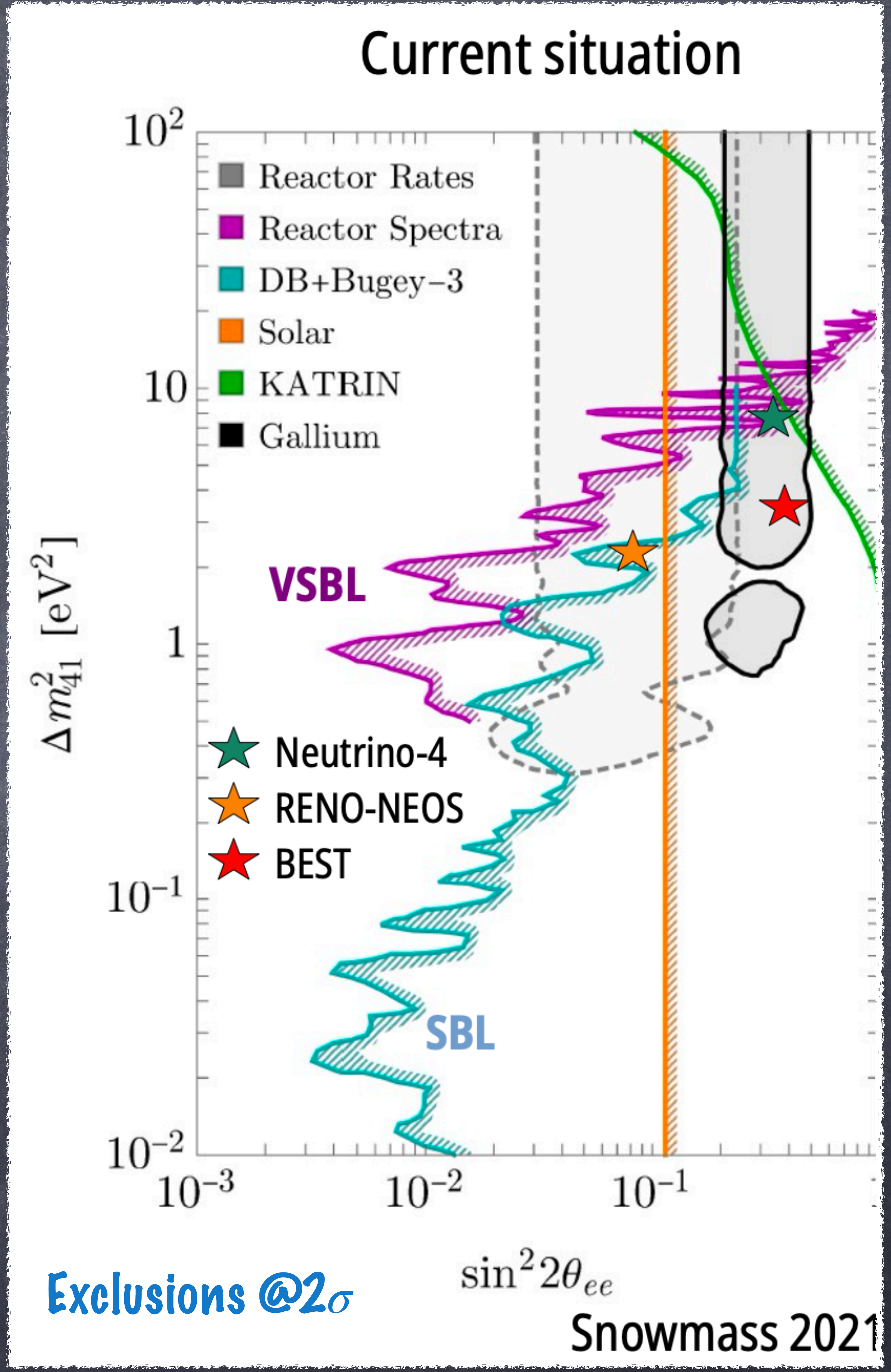
Lots of experimental searches for the Sterile Neutrino

- θ_{13} near detectors (Daya Bay, RENO, Double Chooz)
- SBL reactor experiments (NEOS (-II), STEREO, PROSPECT, DANSS, Neutrino-4, and more)
- Radioactive sources (BEST)

Current status

- No sterile neutrino state is discovered
- Neutrino-4, BEST and NEOS interpret their observations as evidence for sterile neutrino state
  - in strong tension with other experiments

Sterile neutrino hypothesis is unlikely



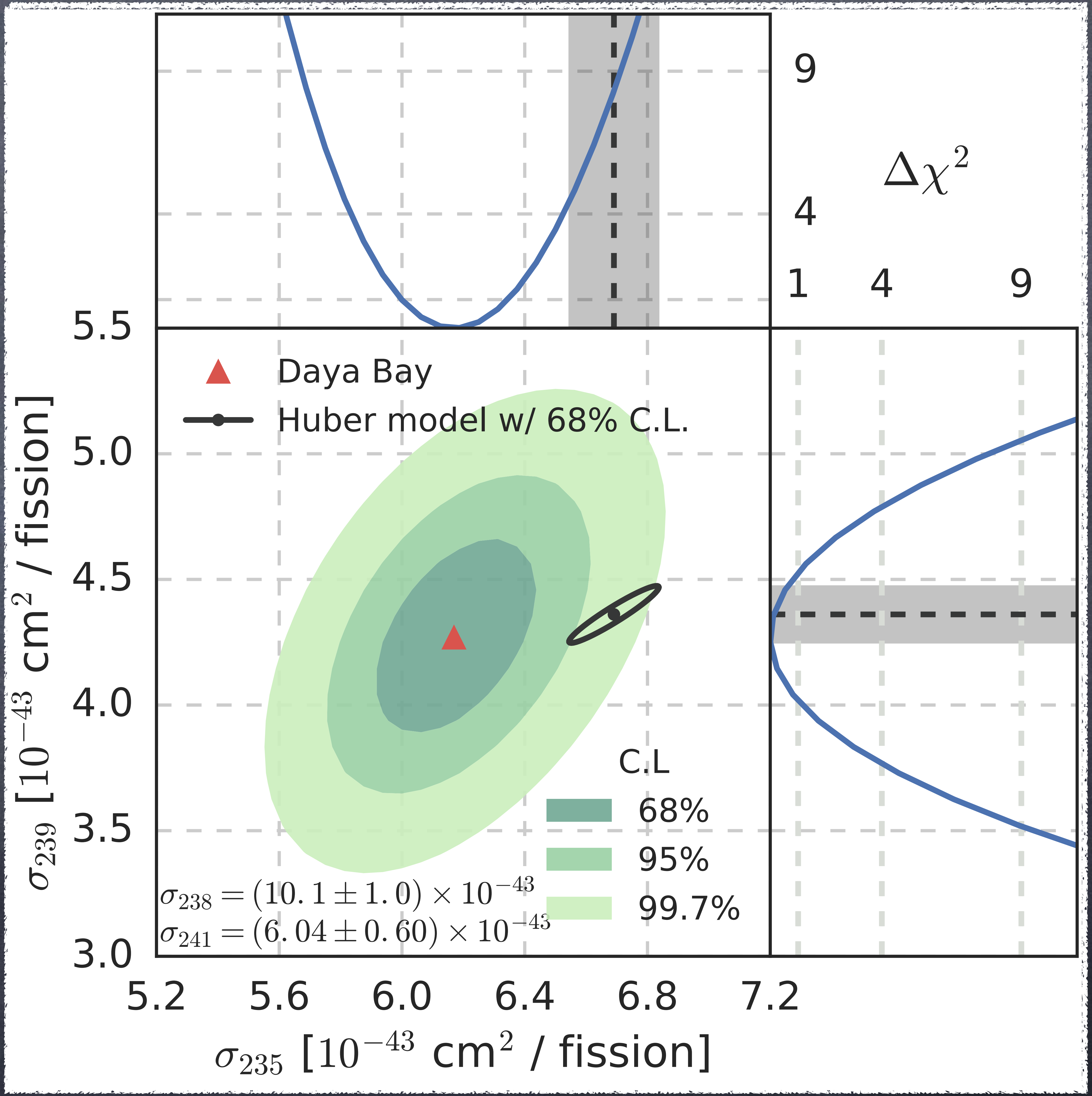
2203.07214

ν flux and spectrum

- U235 is $\sim 8\,\%$ smaller than HM expectation
  - Daya Bay, RENO, NEOSS-II, STEREO
  - Total Absorption Gamma Ray Spectroscopy (TAGS)
  - Kopeikin et al PRD 104, L071301

$$(S^e_{235}/S^e_{239})_{\mathrm{ILL}} = \underline{1.054}(S^e_{235}/S^e_{239})_{\mathrm{KI}}$$

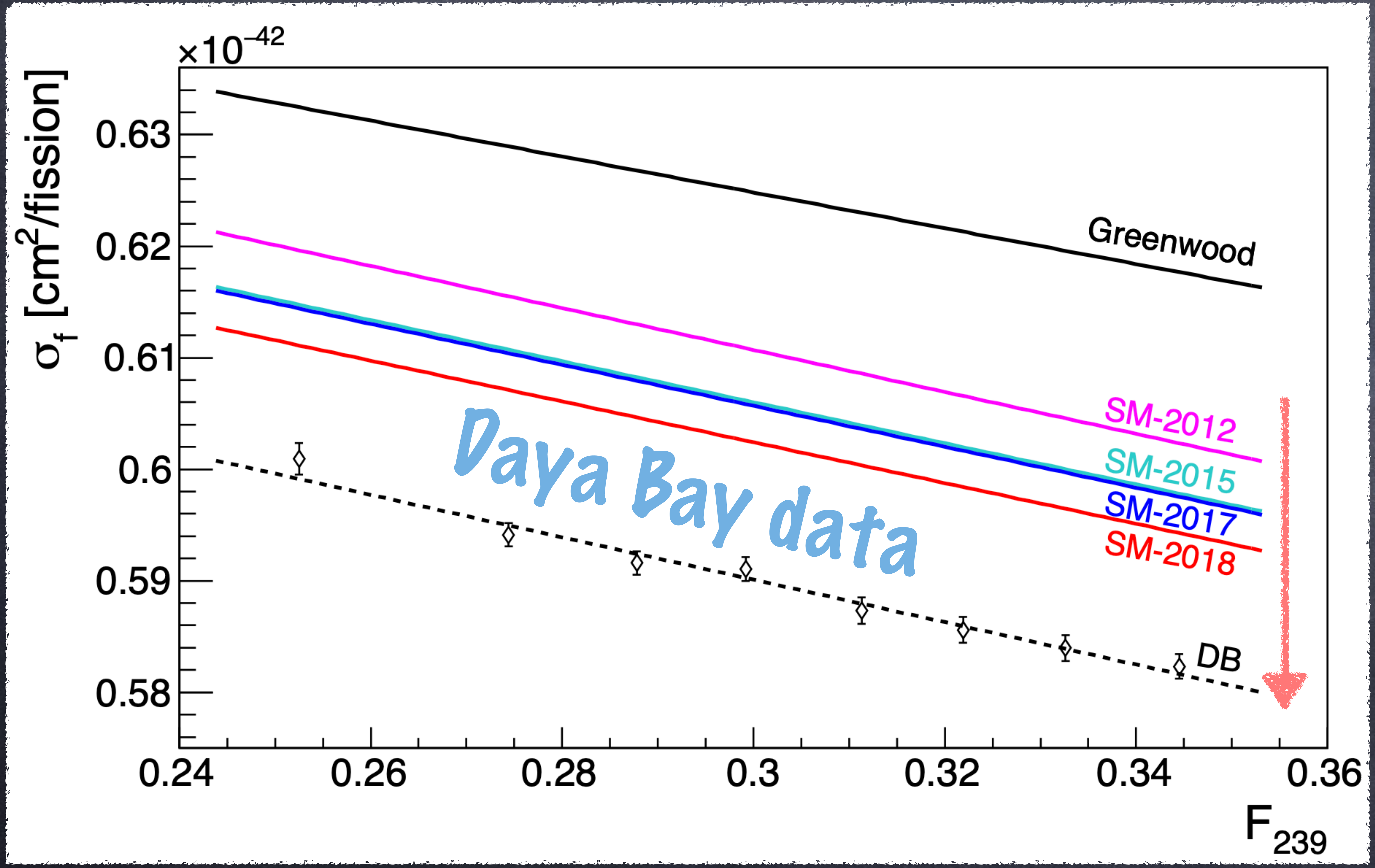
- Pu239 agrees with the HM model
- Disfavors the sterile neutrino hypothesis

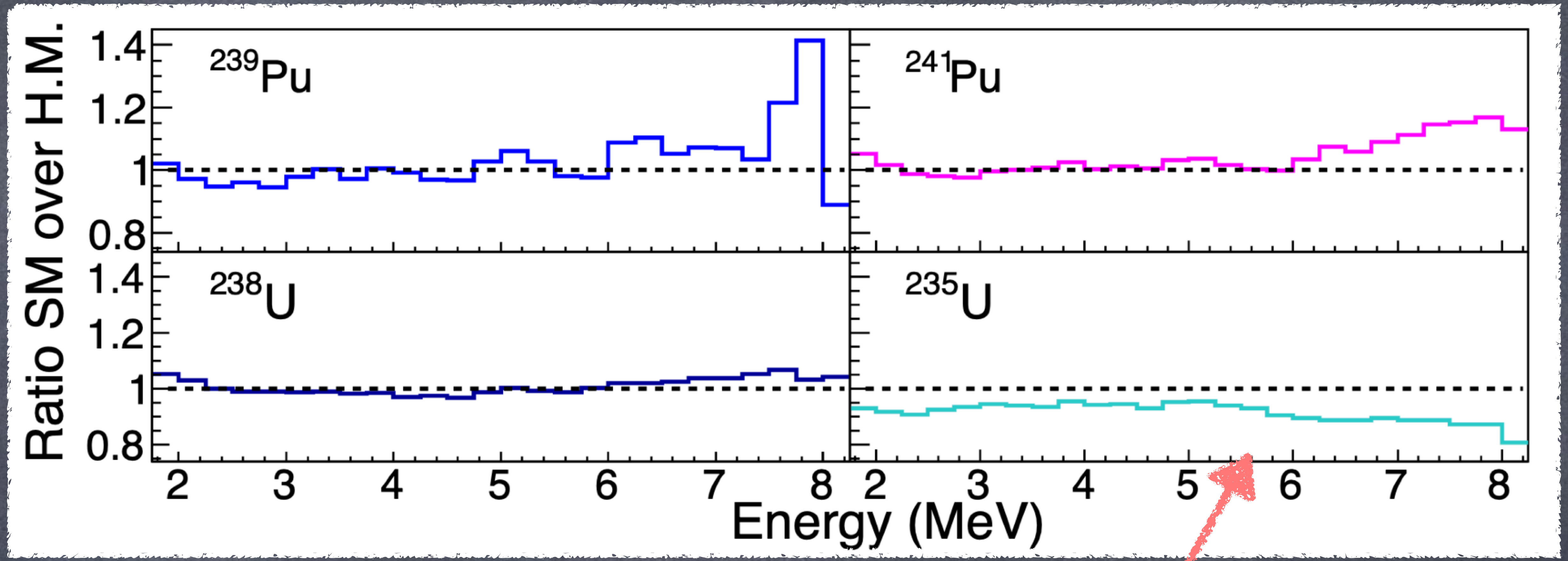


PRL 118, 251801

ν flux and spectrum

- Major effort to improve the nuclear data for summation method





^{235}U disagrees

RAA is gone

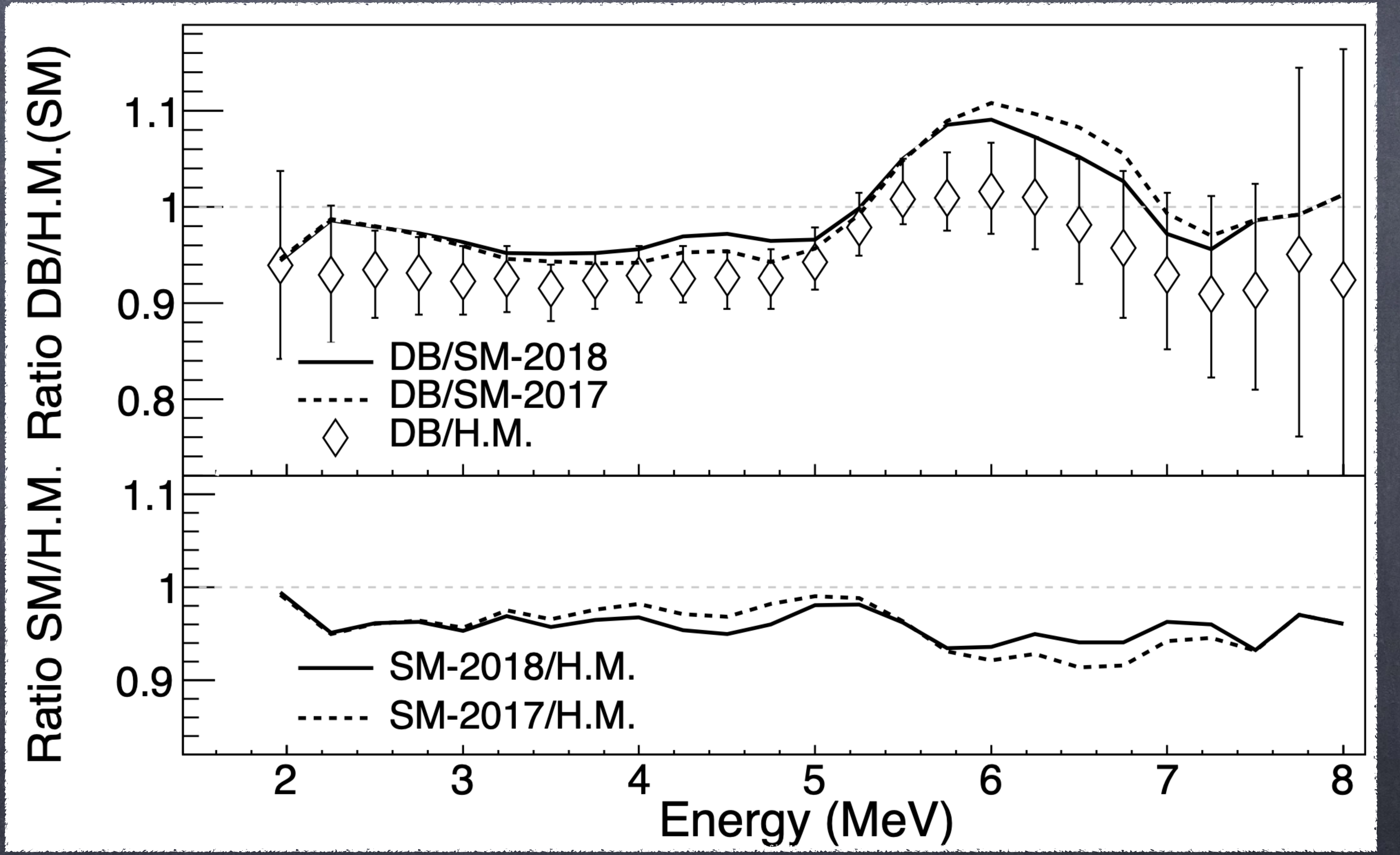
RAA reduced to <2%

PRL 123, 022502

ν flux and spectrum

- The bump is present in both ^{235}U and ^{239}Pu when compared to summation or conversion models

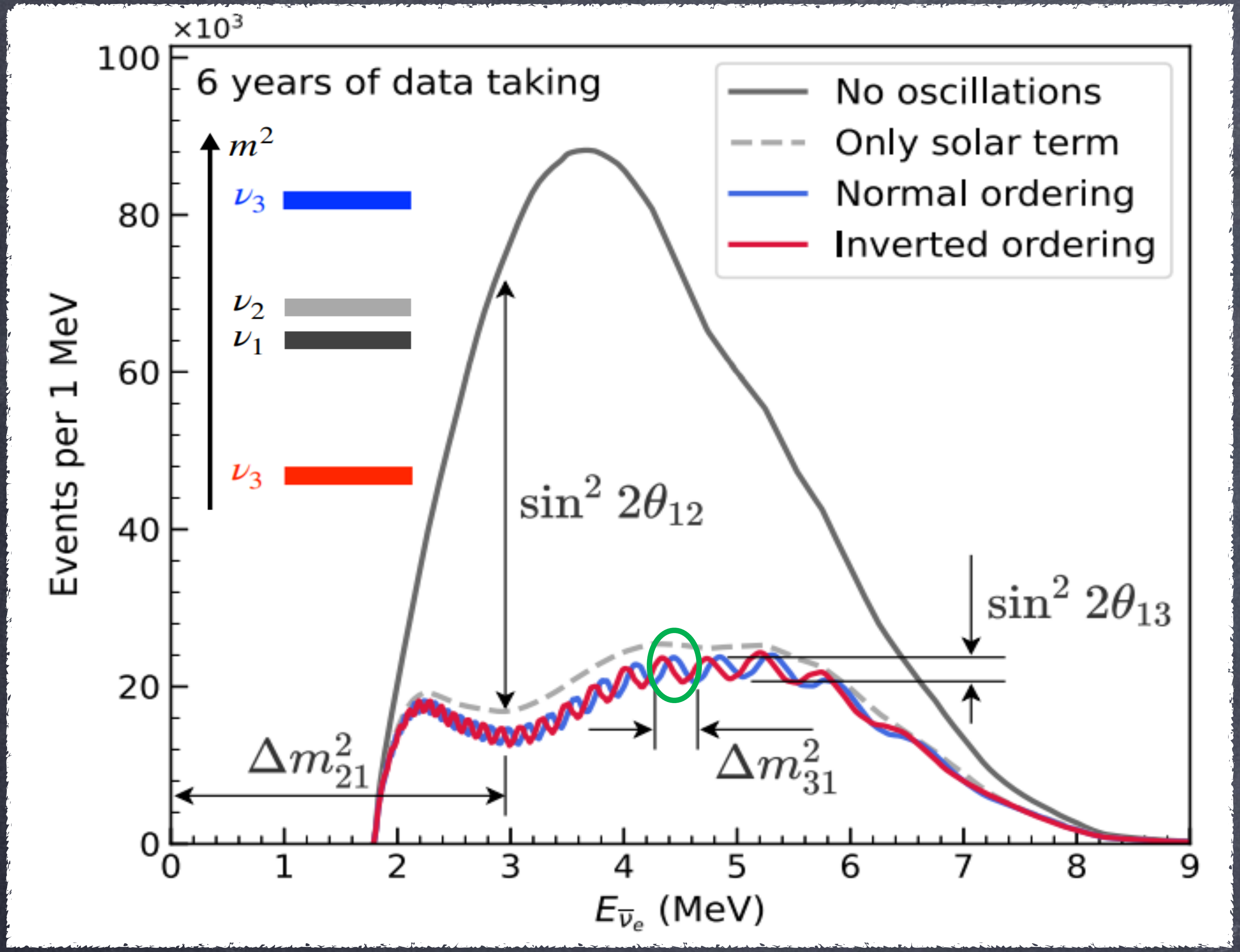
- This similarity suggests common origin or assumptions. The spectrum anomaly remains



PRL 123, 022505

JUNO experiment

The major mission: neutrino mass ordering determination



$\bar{\nu}_e$ spectrum @L=52 km

The requirements

- IBD statistics
  - 20 kt detector mass (LS)
  - 26.6 GWth nuclear reactors
- Background uncertainty
  - 650 m rock overburden
  - More than 99.5% muon veto efficiency
  - Material screening
  - Clean installation
- Energy scale/nonlinearity uncertainty < 1%
- Precision spectrum
  - TAO satellite detector
- Energy resolution $< 3\%/\sqrt{E}$
  - 78% PMT coverage
  - Transparent LS
  - 30% PDE of PMTs
  - Multiple calibrations

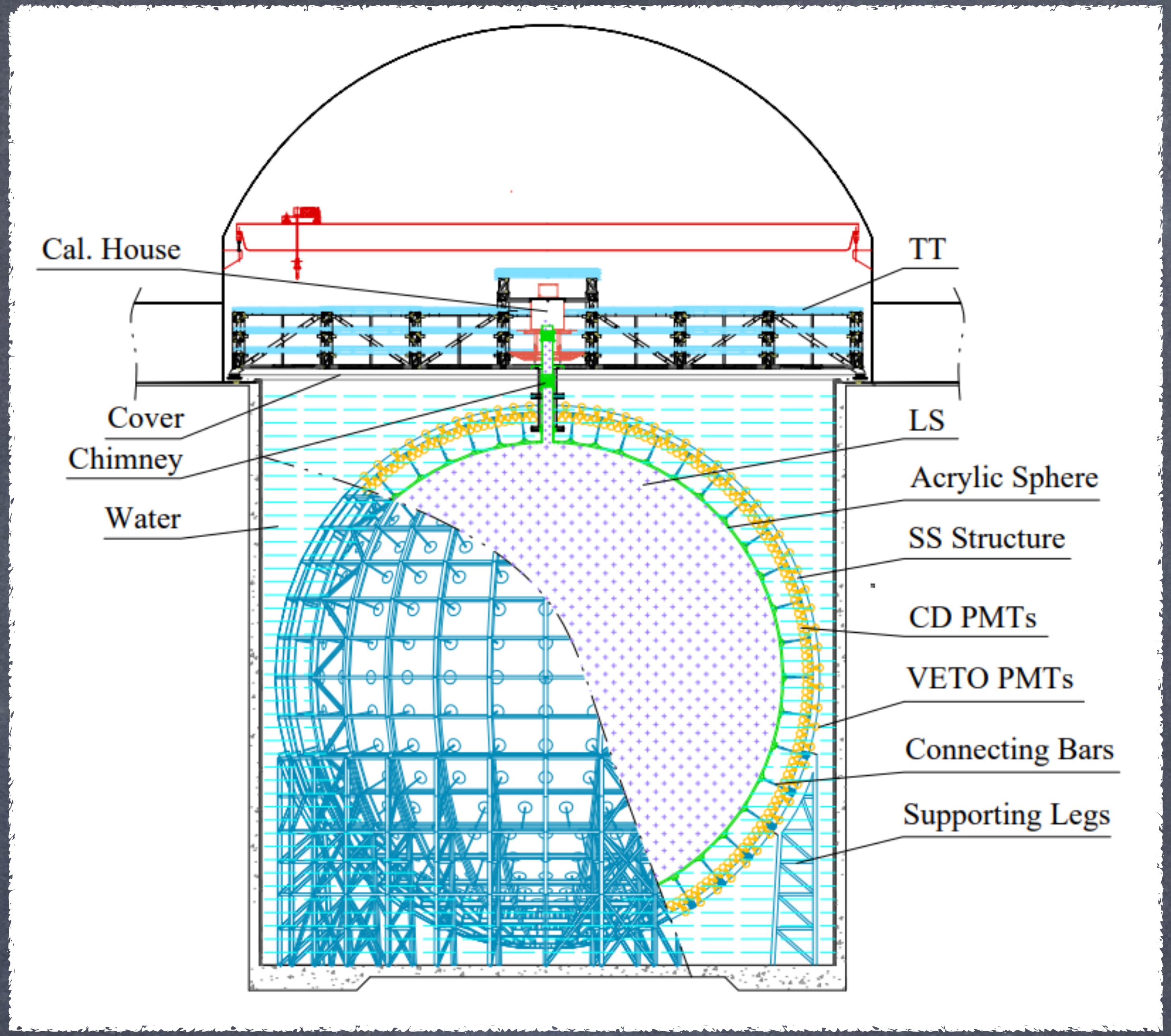
Solar neutrinos: 1-2 orders of magnitude higher requirements on radio purity


Slide from Jie Zhao @Neutrino 2022
JUNO
~52.5 km
Taishan NPP
2×4.6 GW$_{th}$
TAO
Yangjiang NPP
6×2.9 GW$_{th}$
736.0 m
252.5 m
8 reactors
26.6 GW$_{th}$
~700 m
~52.5 km
JUNO
Civil construction finished in Dec, 2021
Detector completion in 2023
Vertical tunnel:
563 m
Overburden:
~650 m
Slope tunnel: 1265 m @
slope of 42%

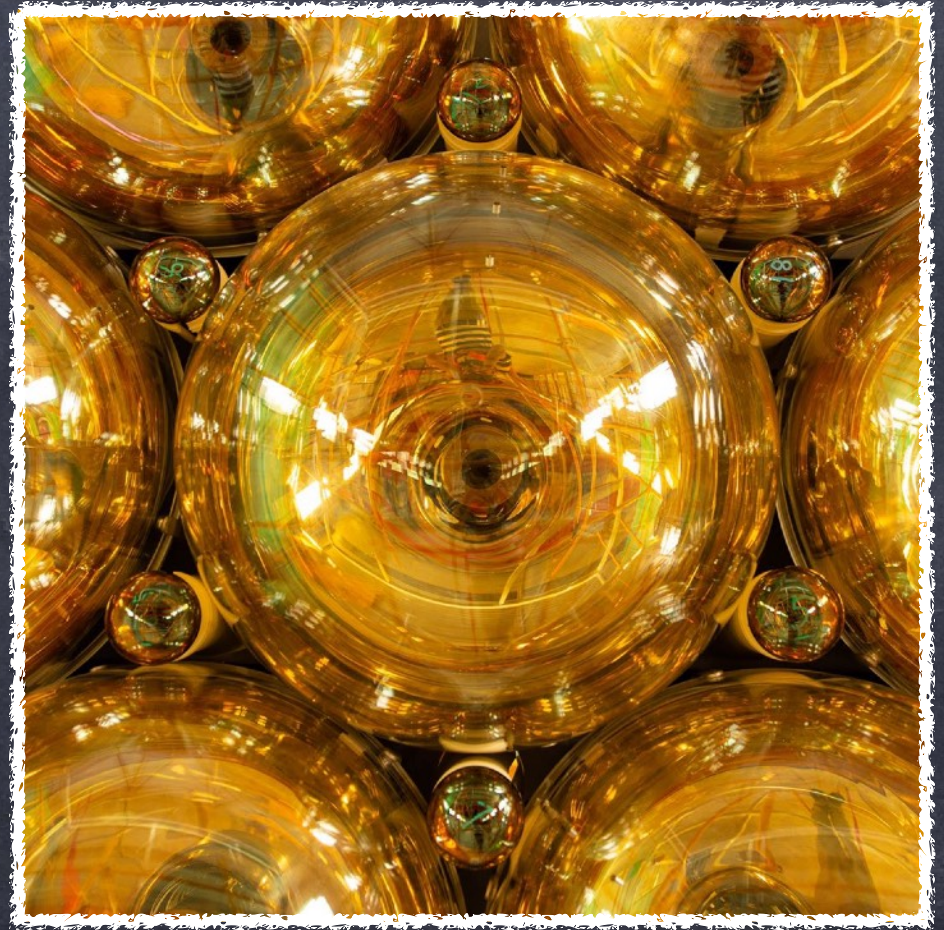
JUNO Central Detector

- Acrylic panels (220/265)

- Stainless Steel Structure (bottom half ready)

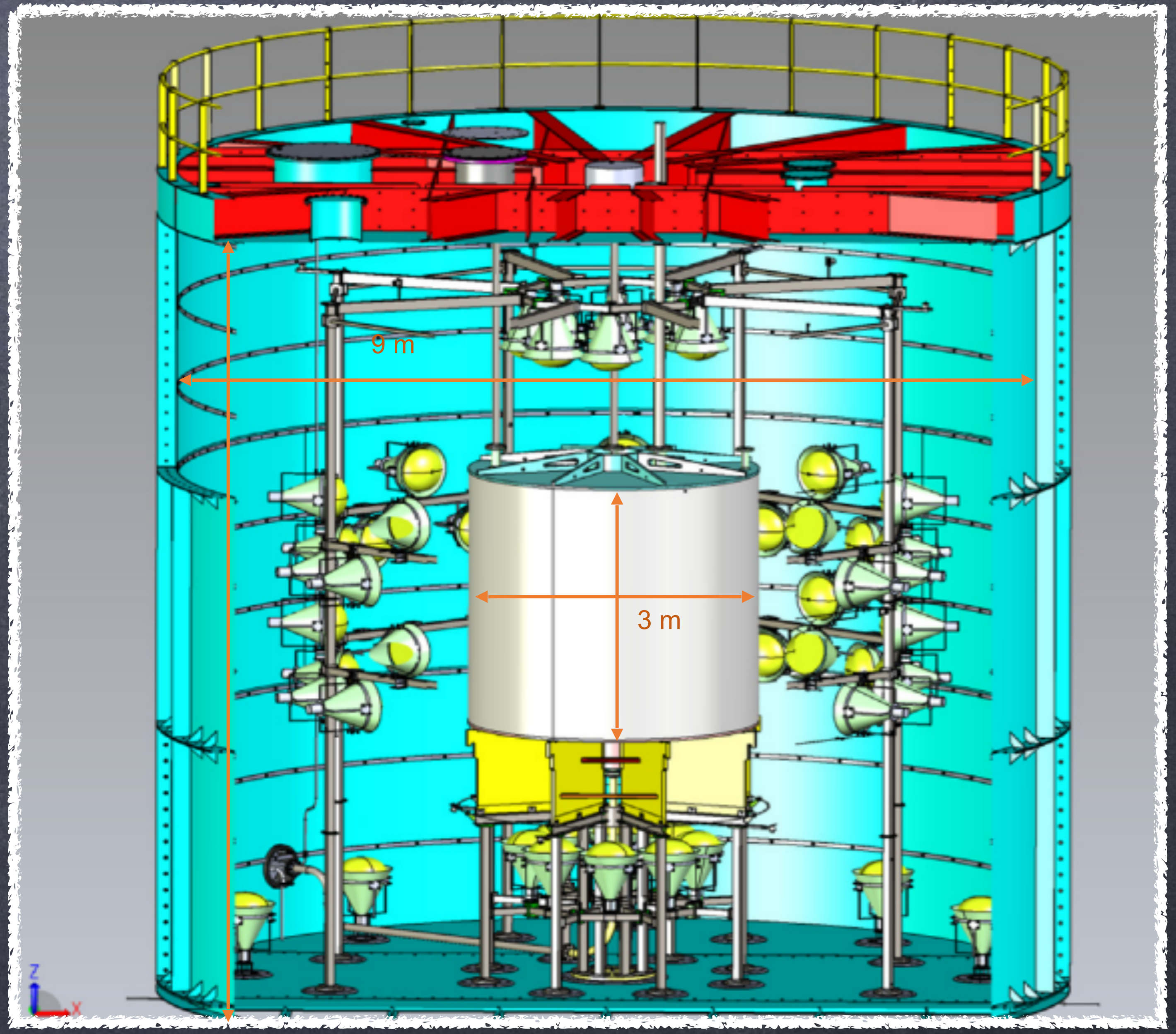


- 20'' PMTs:~18k (CD)+2.4k (WP)
- 3'' PMTs: 25.6k



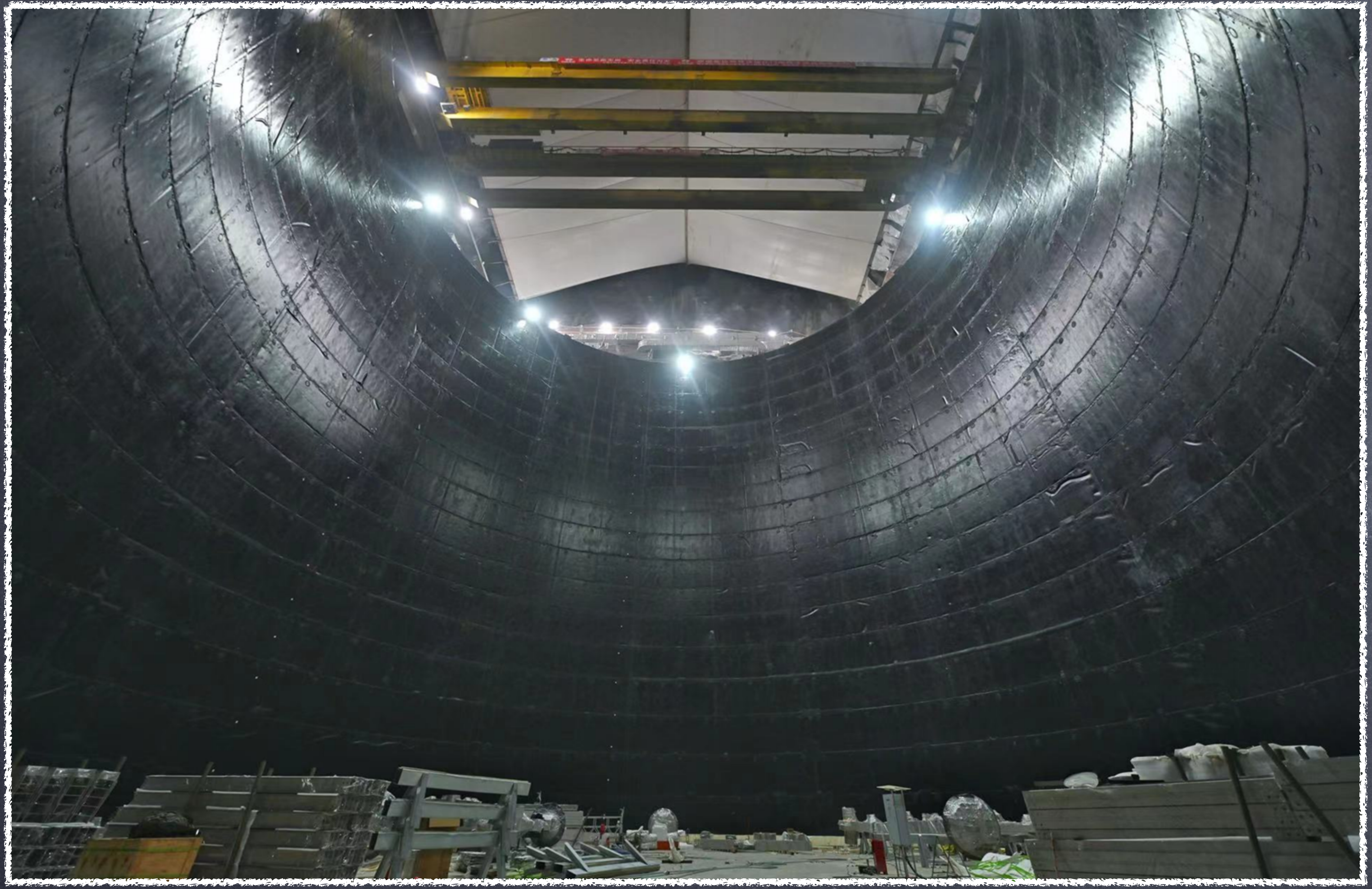
- production,
- performance tests,
- waterproof potting

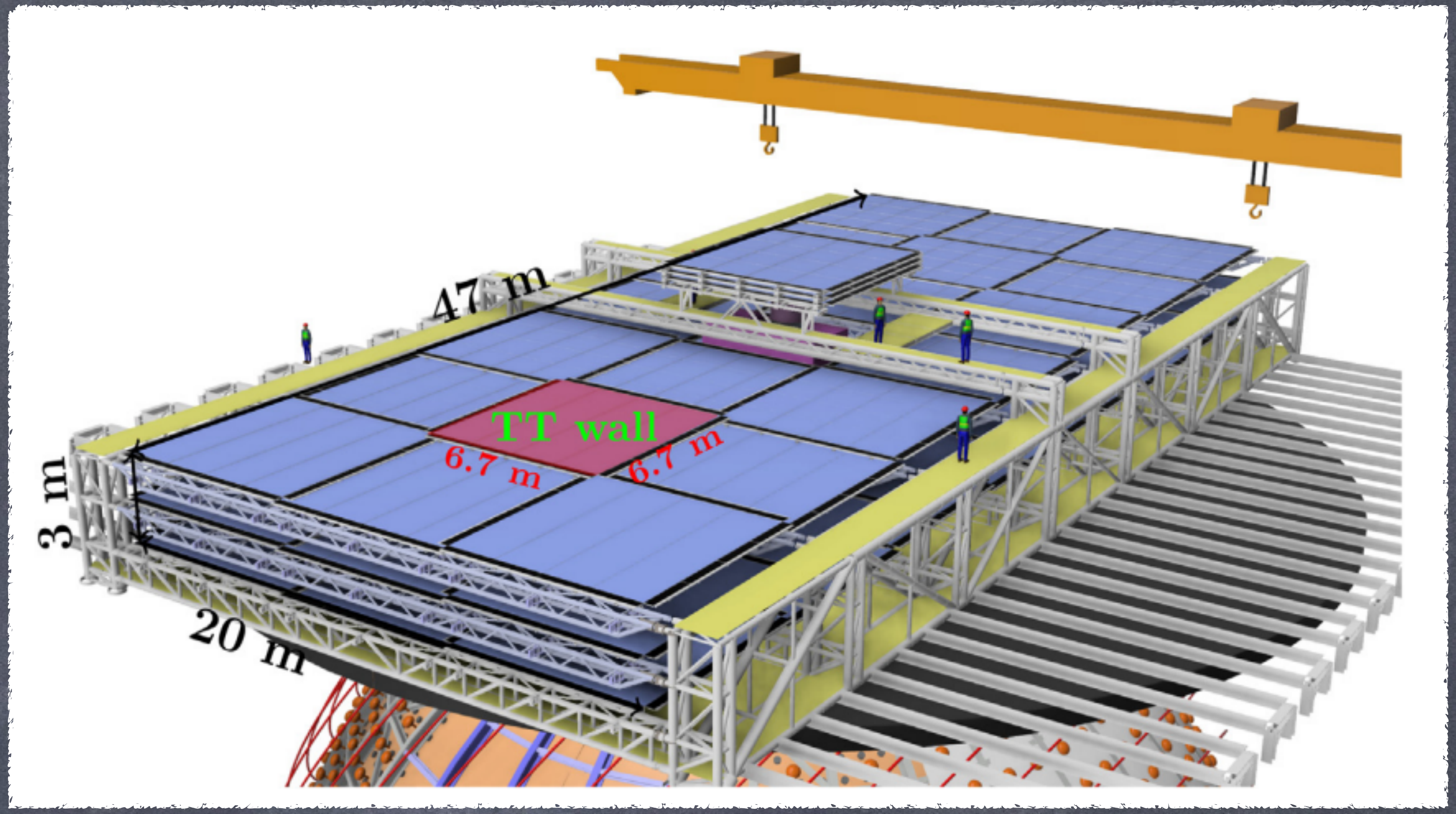
- Liquid scintillator
  - Four purification plants targeting U/Th @ $(10^{-17} - 10^{-16})$ g/g and 20 m attenuation length @430 nm
  - OSIRIS: 20t detector to monitor radio purity of LS before and during LS filling



Eur.Phys.J.C 81 (2021) 11, 973

JUNO Veto Detector





TOP tracker

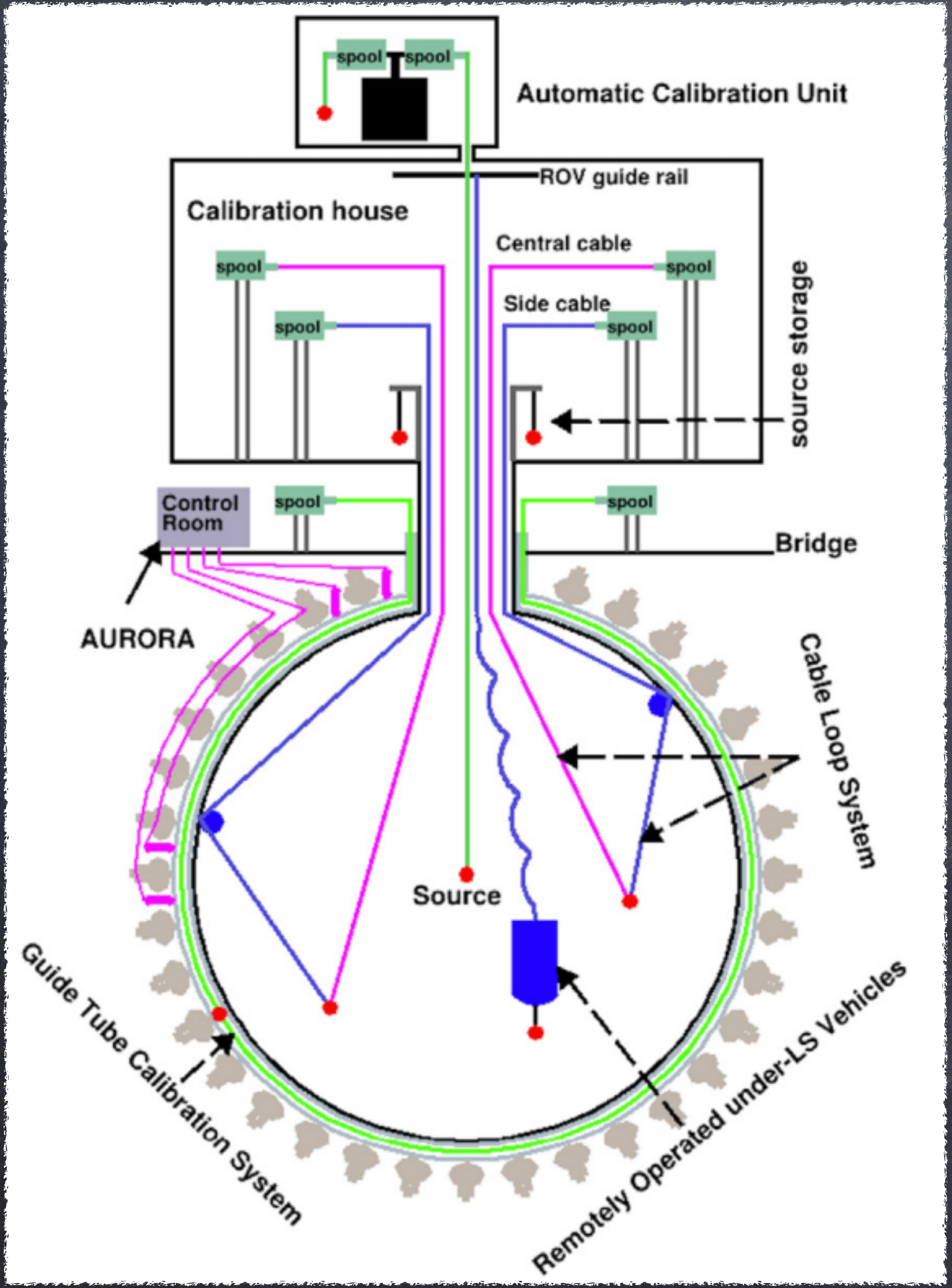
- Provide control muon samples to validate the track reconstruction and study cosmogenic backgrounds

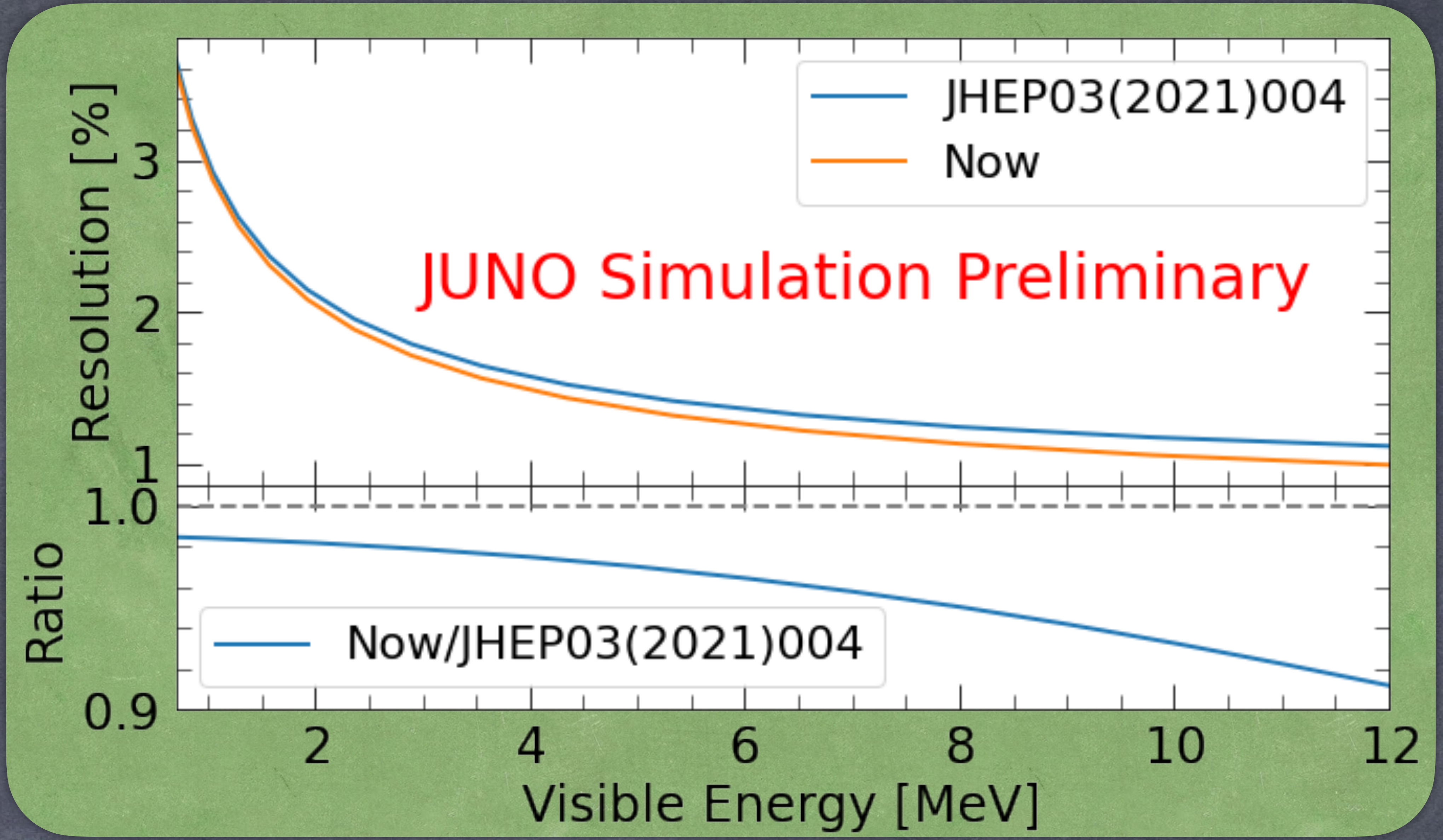
35 kton of ultrapure water serving as passive shield and water Cherenkov detector

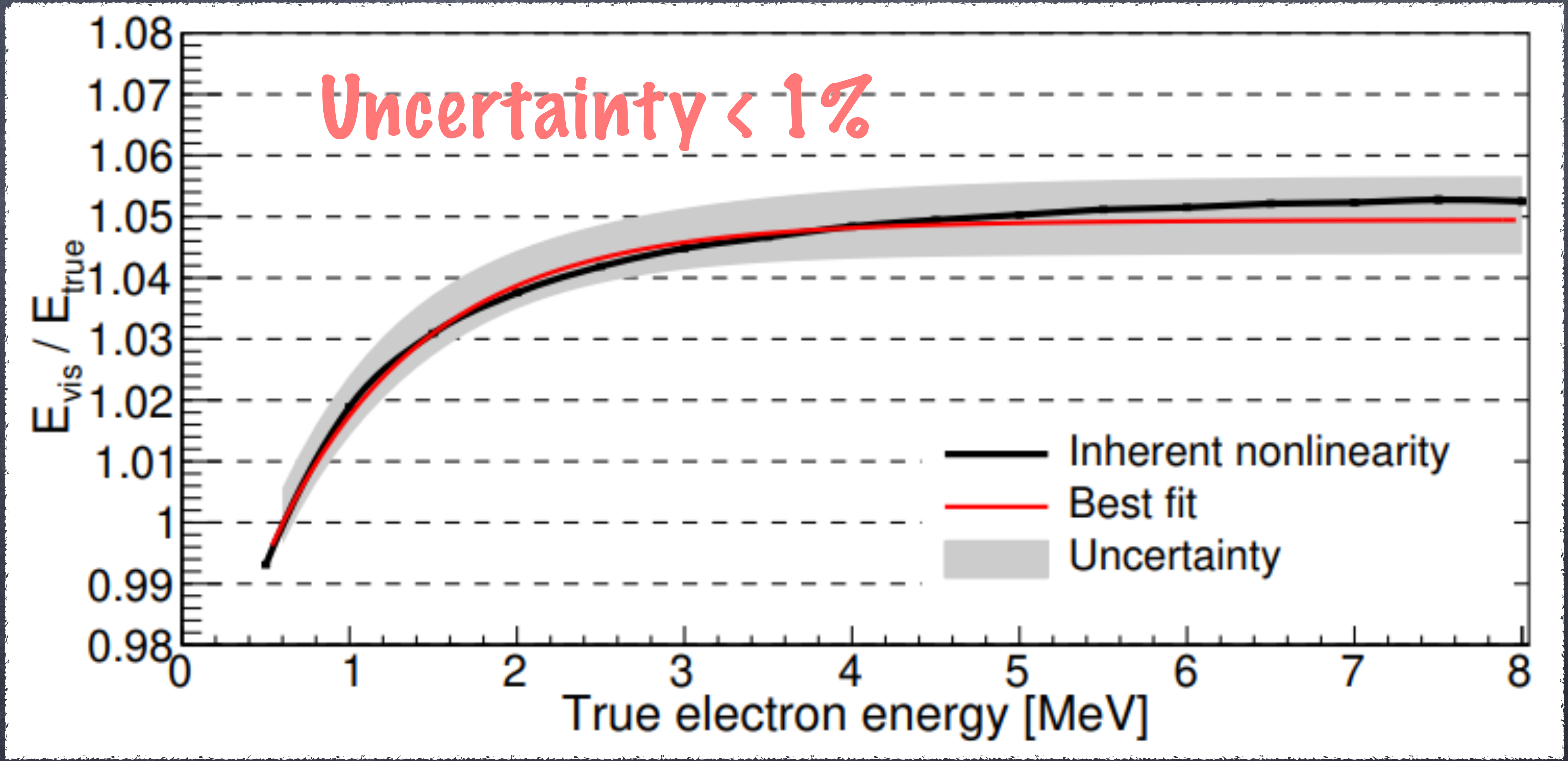
- 2400 20-inch MCP PMTs, detection efficiency of cosmic muons larger than 99.5%
- Keep the temperature uniformity 21°C±1°C
- Quality: ^{222}Rn < 10 mBq/m^3, attenuation length 30~40 m

JUNO Calibrations

- 1D, 2D, 3D scan systems with multiple calibration sources to control
  - the energy scale
  - detector response non-uniformity
  - < 1% energy non-linearity



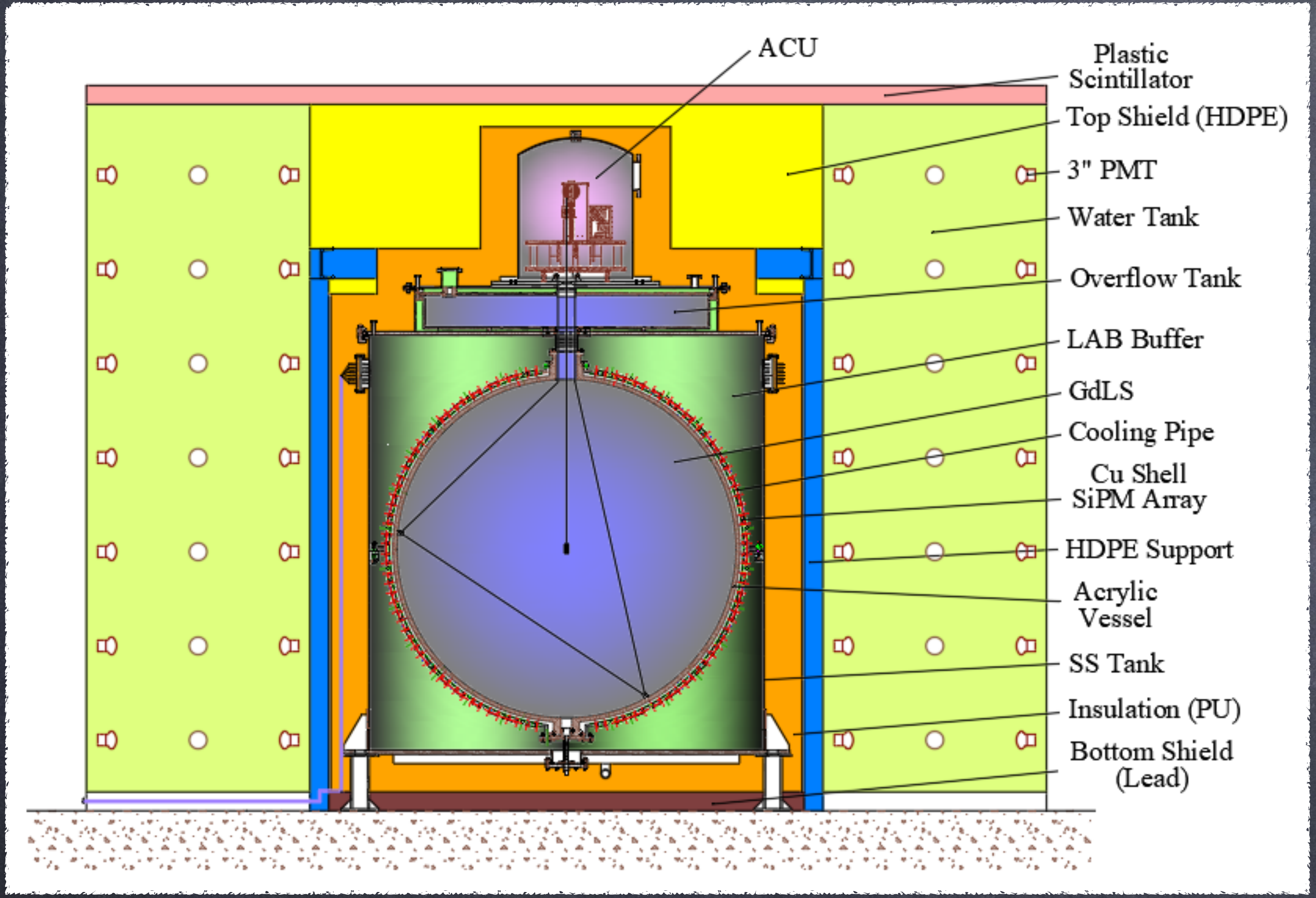




JHEP 03 (2021) 004

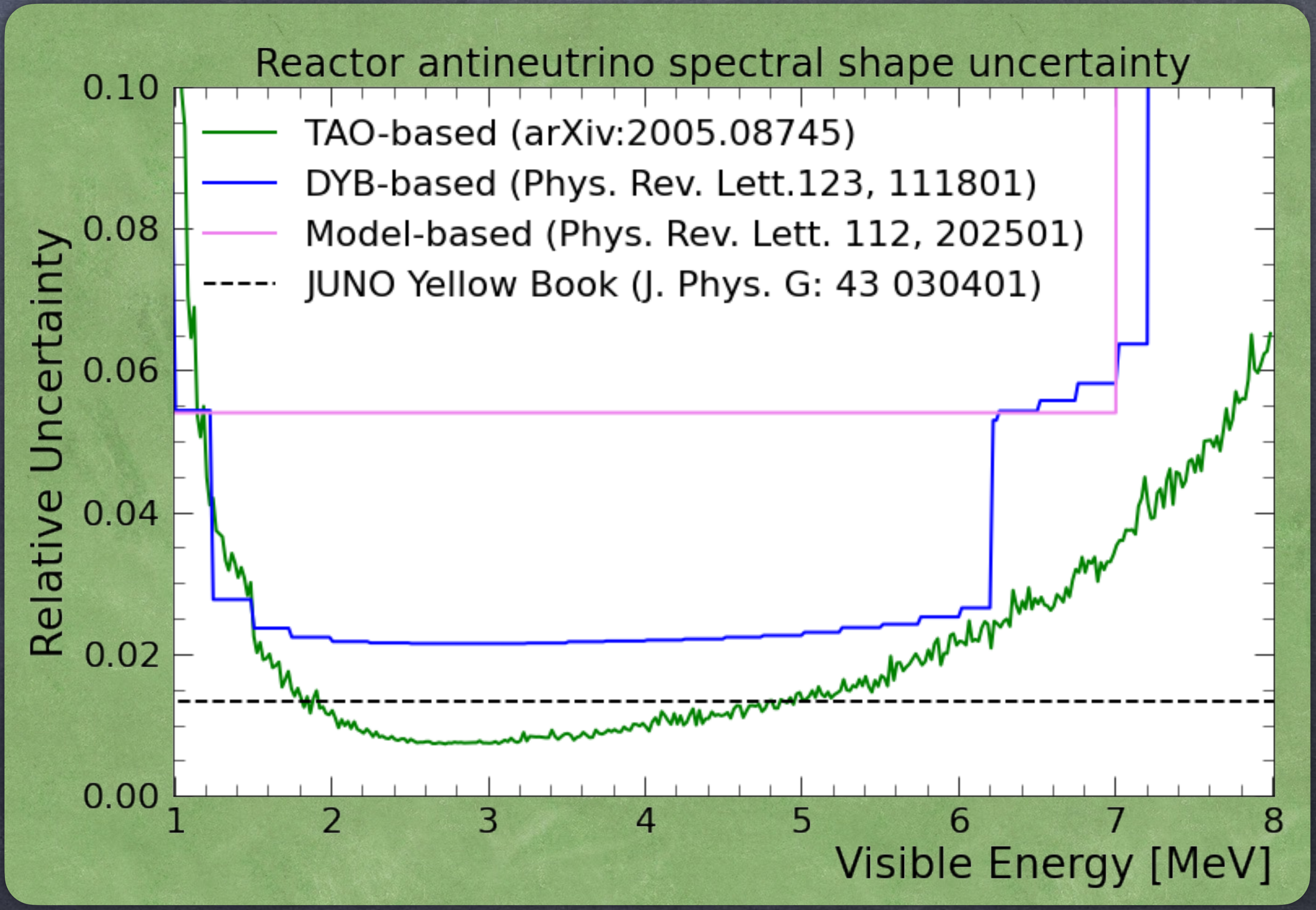
Taishan Antineutrino Observatory (TAO)

The major mission:
measure the reactor antineutrino spectrum at best accuracy ever



TAO CDR

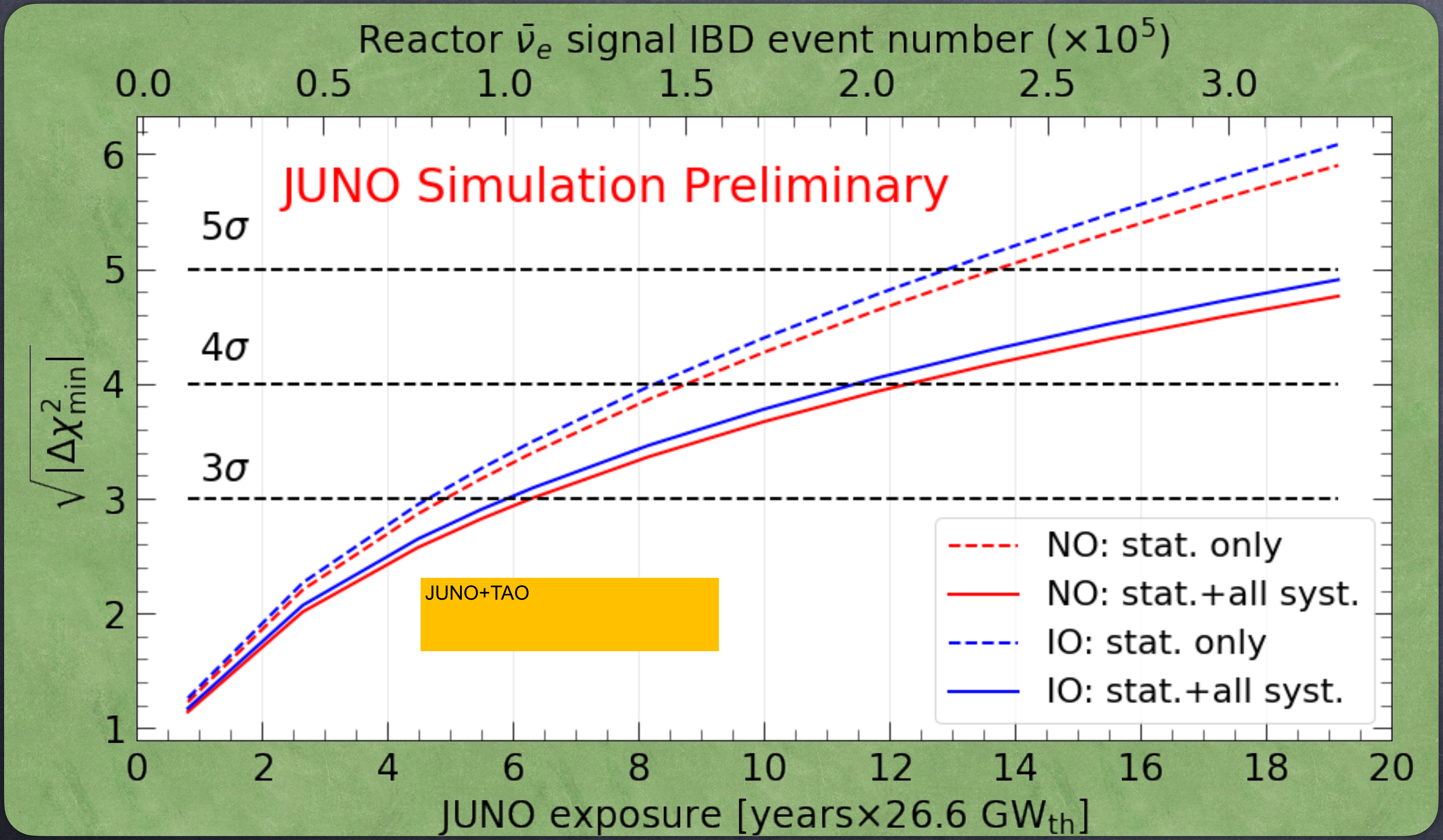
- SiPM with ~94% coverage
  - 4500 PEs/MeV
  - energy resolution < 2% @ 1 MeV
- Gd-LS at -50℃ to lower the dark noise of SiPM



2000 IBD/day @30m from the nearest reactor.

JUNO Physics Program

- **NMO:** 3σ@ 6yrs



- **Diffuse Supernova Neutrino Background:** 3σ@ 3yrs **and** 5σ@ 10yrs

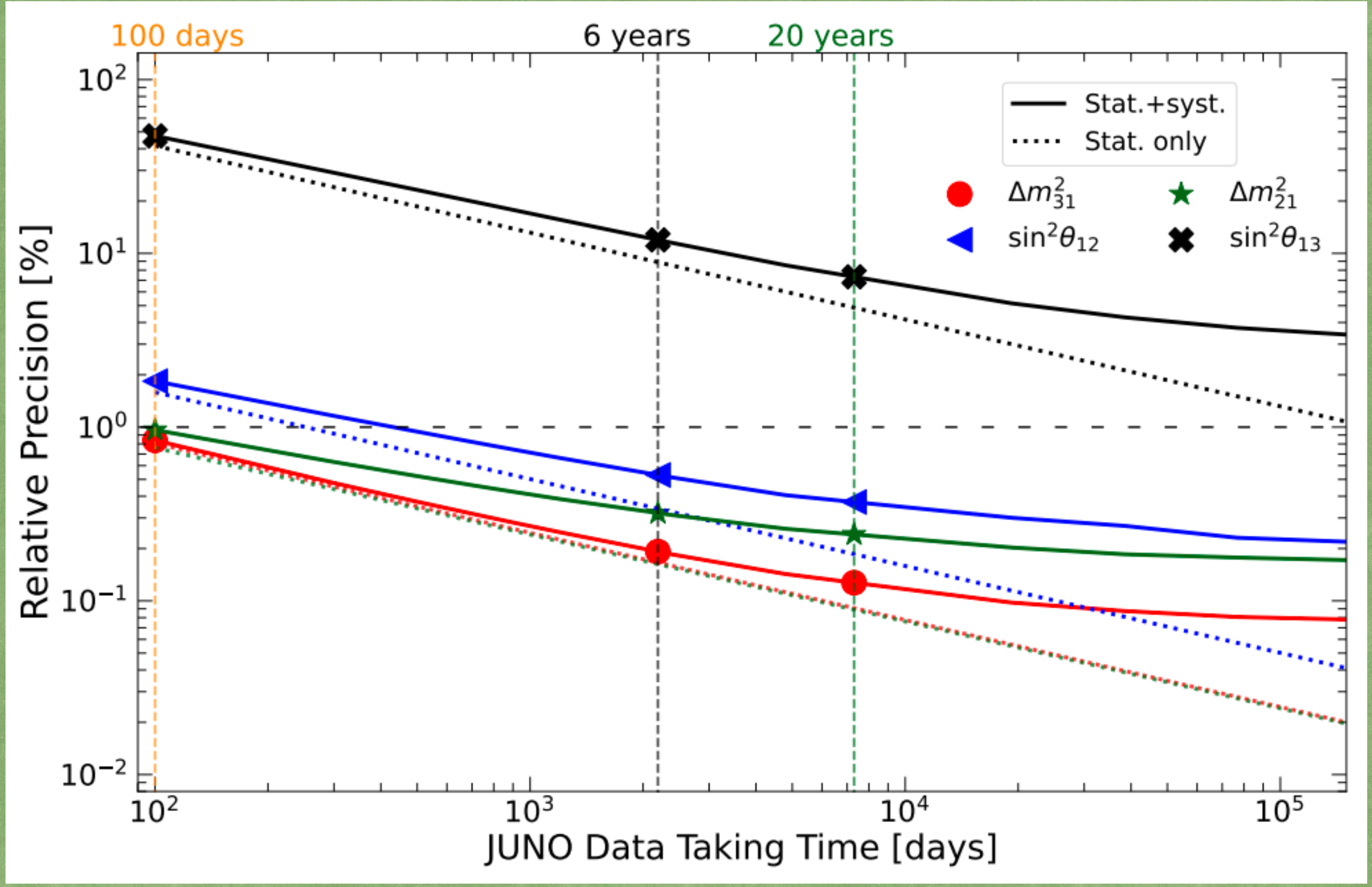
- **Nucleon decays:** $8.3 \cdot 10^{33}$ yrs in 10 yrs

JUNO Physics Program

- **Precision as for quarks:** $< 0.5\,\%$ for $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$

- **Improve meas. accuracy for solar** ^{7}Be, pep, CNO, ^{8}B

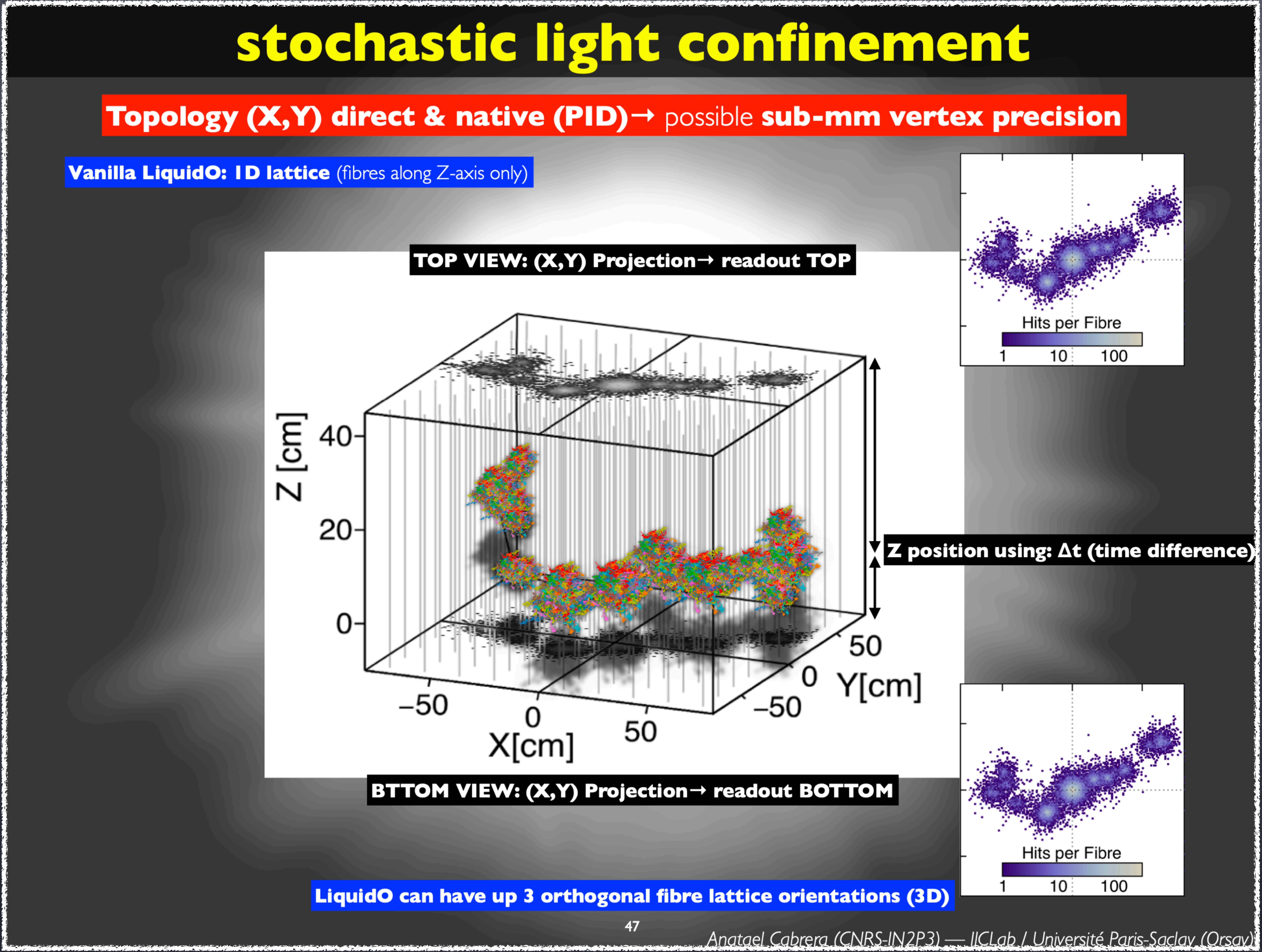
- **Geo-neutrino:**
400per year, 5 % in10 yrs



New detector technologies: opaque liquid scintillator

- What: medium with $\lambda_{scat} \sim 1\mathrm{mm}$ elastic scattering and minimal absorption
- Why: native self-segmentation
- Who: LIQUIDO Consortsium
- Benefits: good PID ($e^{\pm}, \gamma, n, p, \ldots$)

Opaque LS+fibres = highly segmented TPC

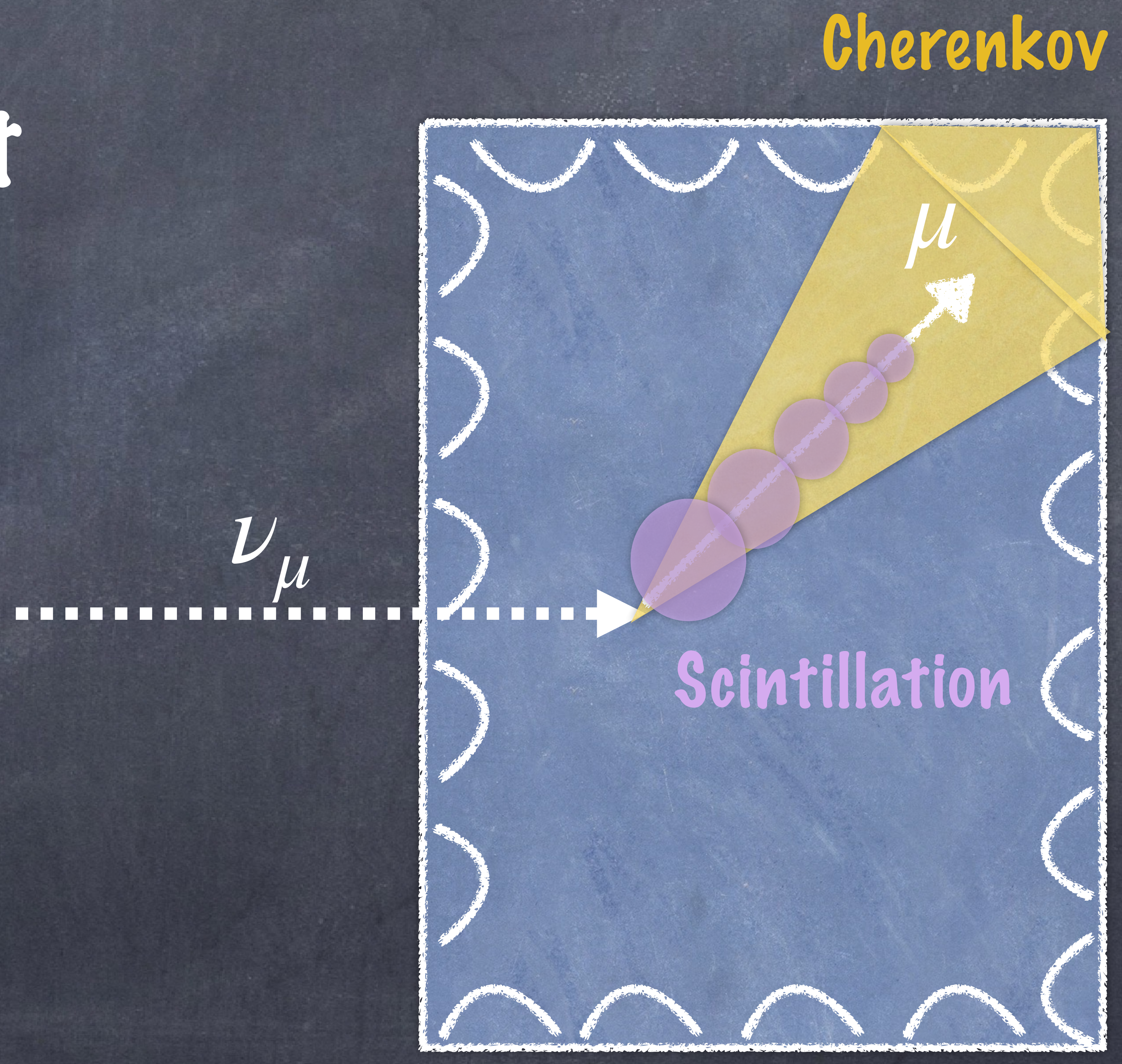


More details can be found in

A. Cabrera talk

New detector technologies: hybrid of Cherenkov and Scintiallor

- What: water based LS, slow scintillation light, fast PMT readout
- Why: add directionality
- Who: ANNIE, SANDI, EOS, Jinping 1T, ...



Neutrino experiments @nuclear reactors

- improved our knowledge about
  - Neutrino ($\theta_{13}, \theta_{21}, \Delta m^2_{31}, \Delta m^2_{12}$)
  - Nuclear physics (flux and spectrum measurements)
- provided new possibilities to search for physics BSM
- Are becoming very precise (sub-percent) instruments for further discoveries.