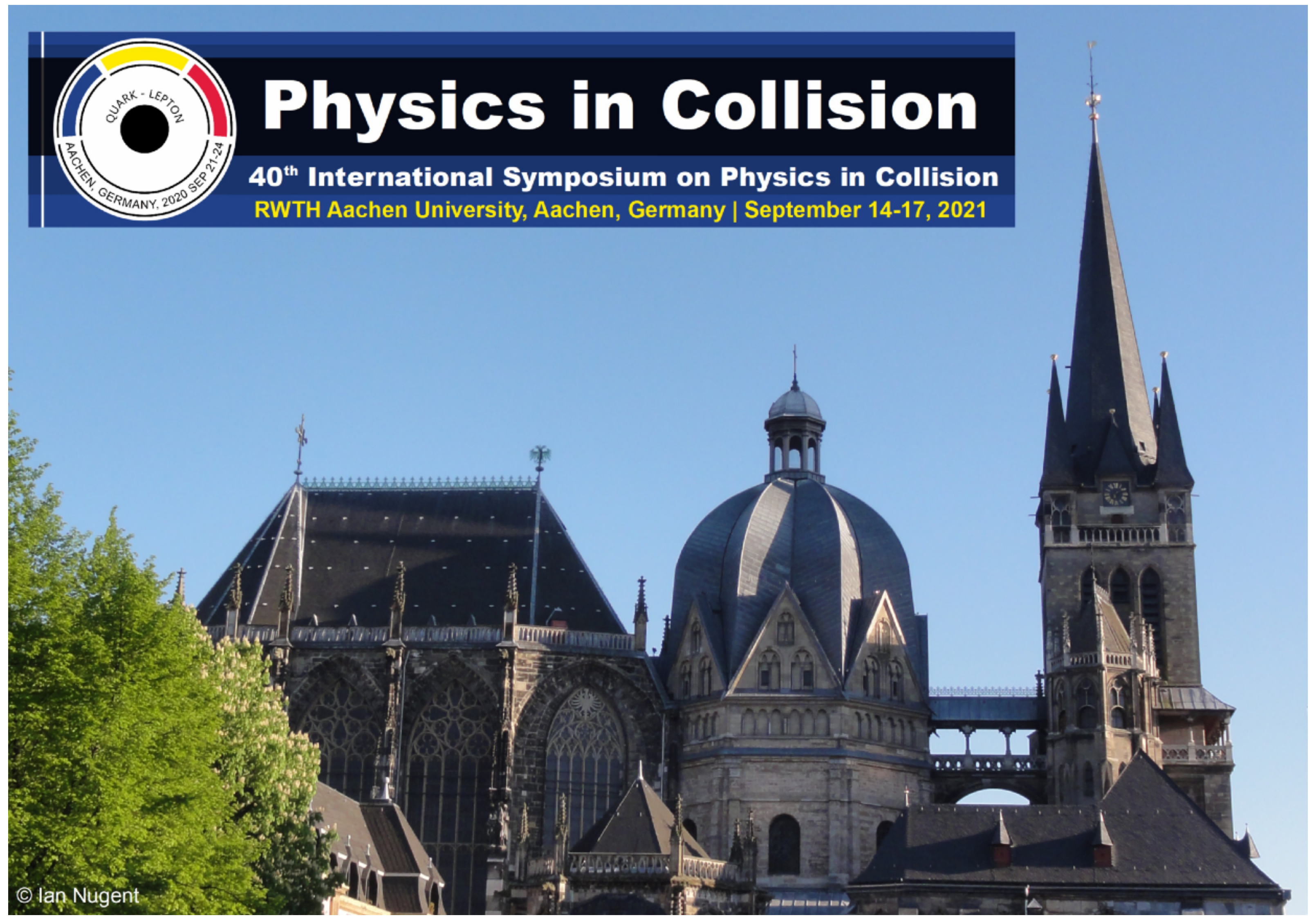
RWTH AACHEN UNIVERSITY

Reactor Neutrino Experiments with km-Scale Baseline

40th International Symposium on Physics in Collision 2021

Philipp Soldin*
16.09.2021



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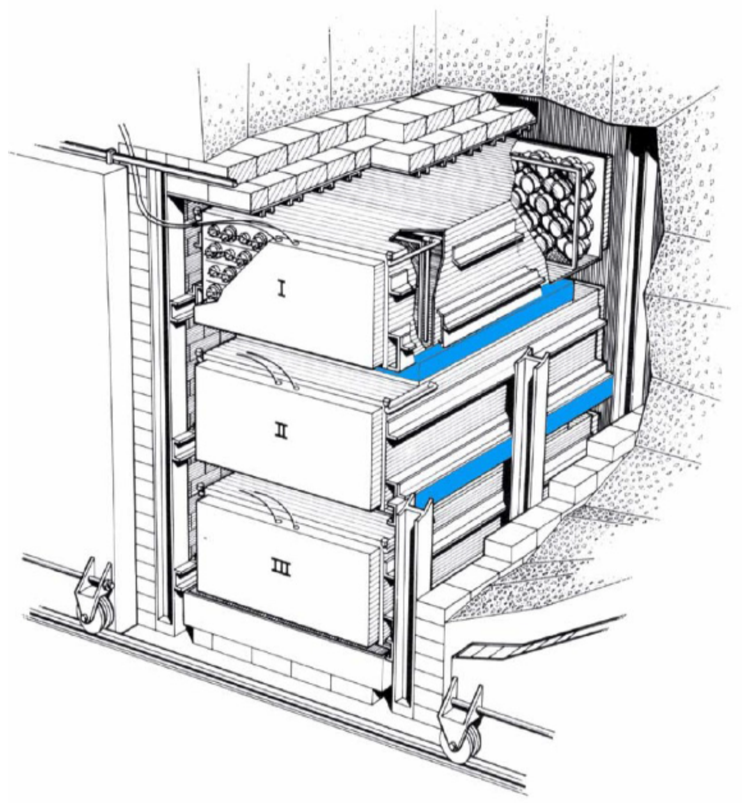
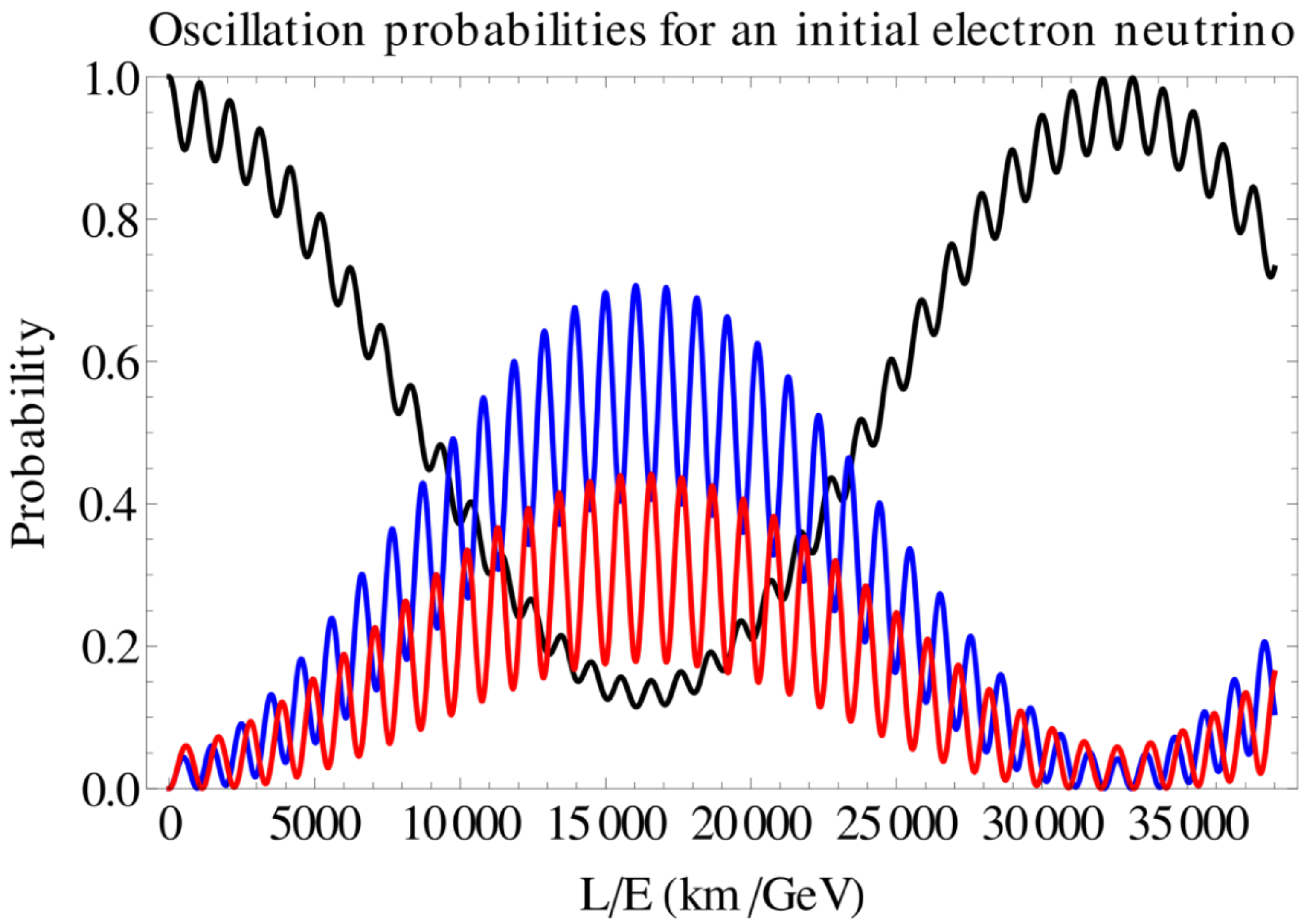
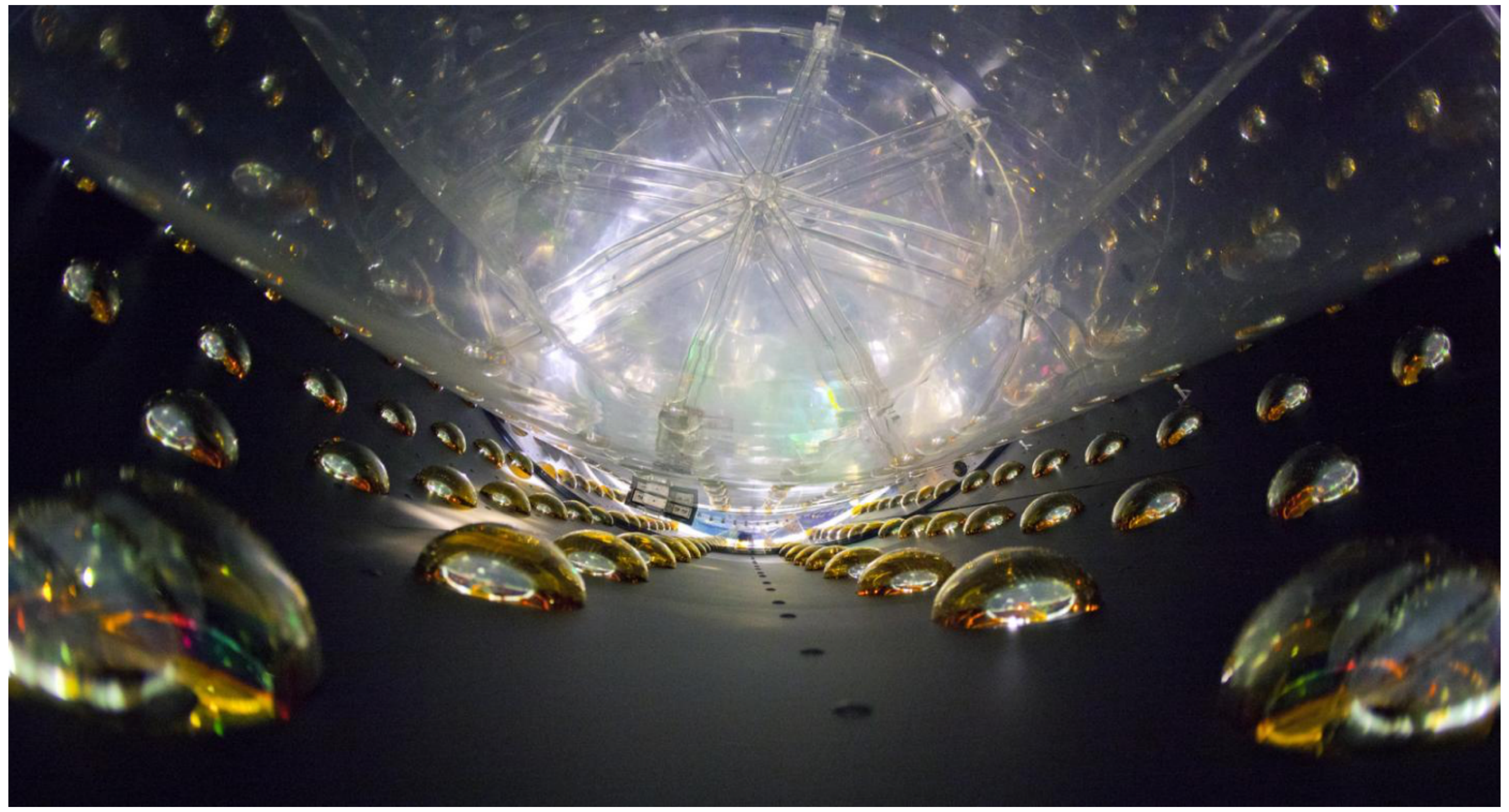
*part of the Double Chooz Collaboration

Outlook

- Reactor Neutrinos
  - Production & IBD Detection
  - Neutrino Oscillation
- Measurement of the θ_{13} mixing angle
  - Reactor Neutrino Experiments
  - Results
- Anomaly Measurements
  - Sterile Neutrinos
  - Energy spectrum distortion
  - Fuel measurements
  - Reactor Antineutrino Anomaly

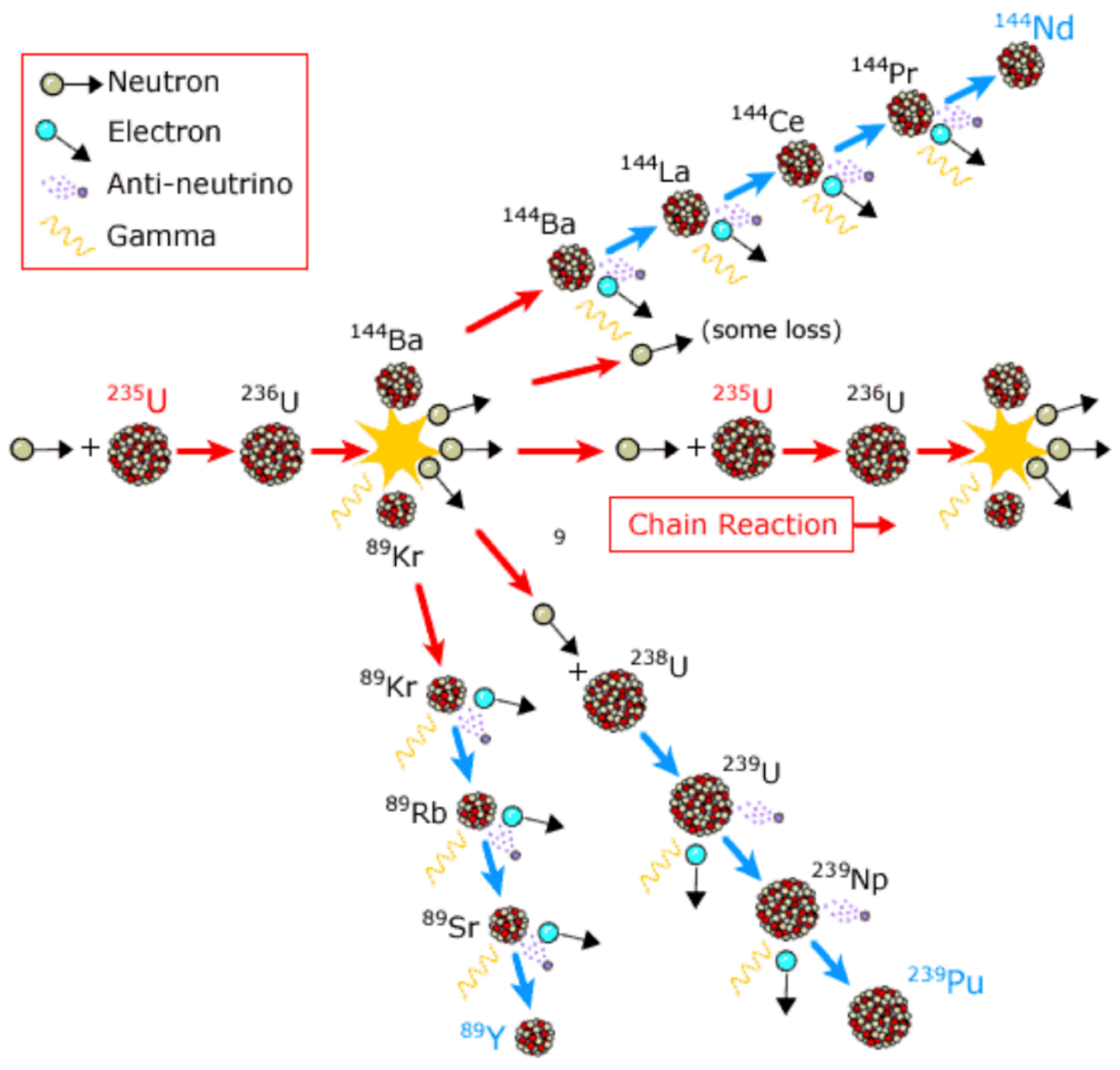


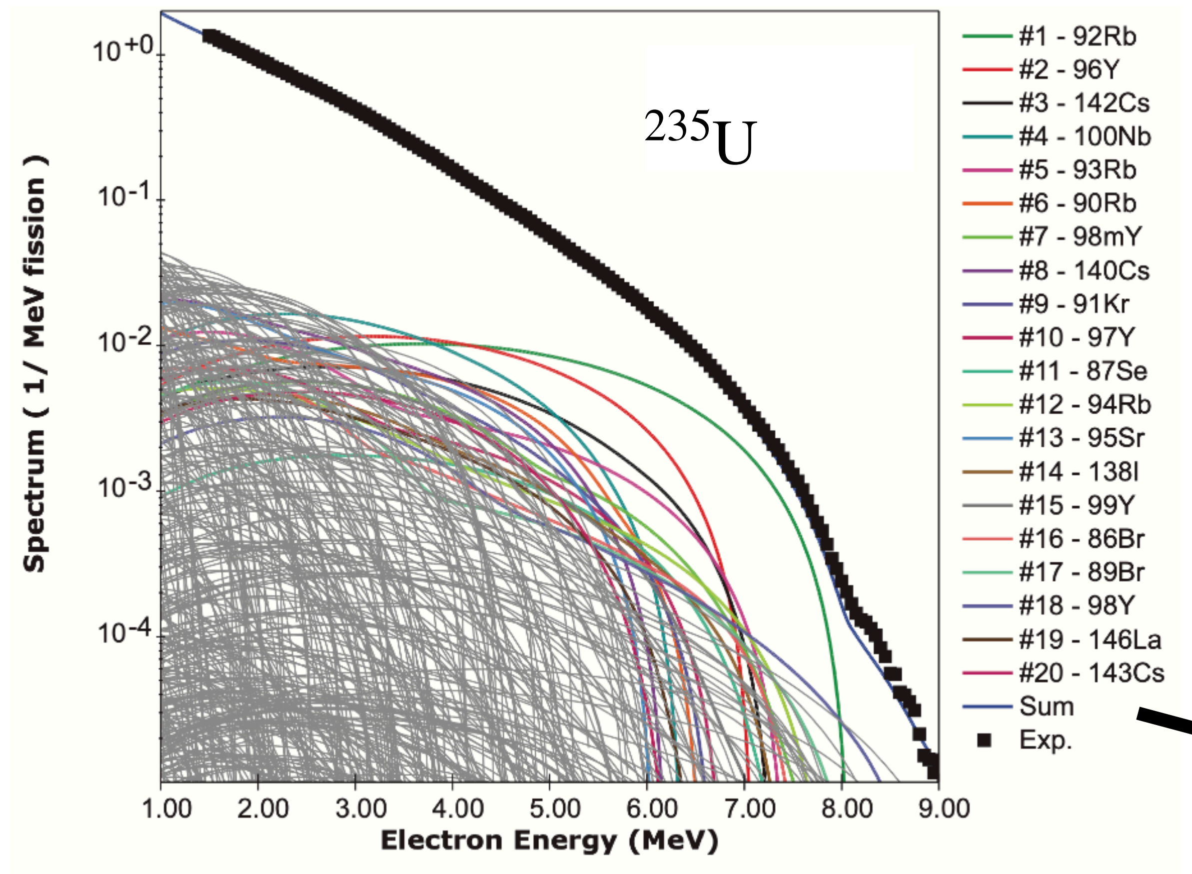




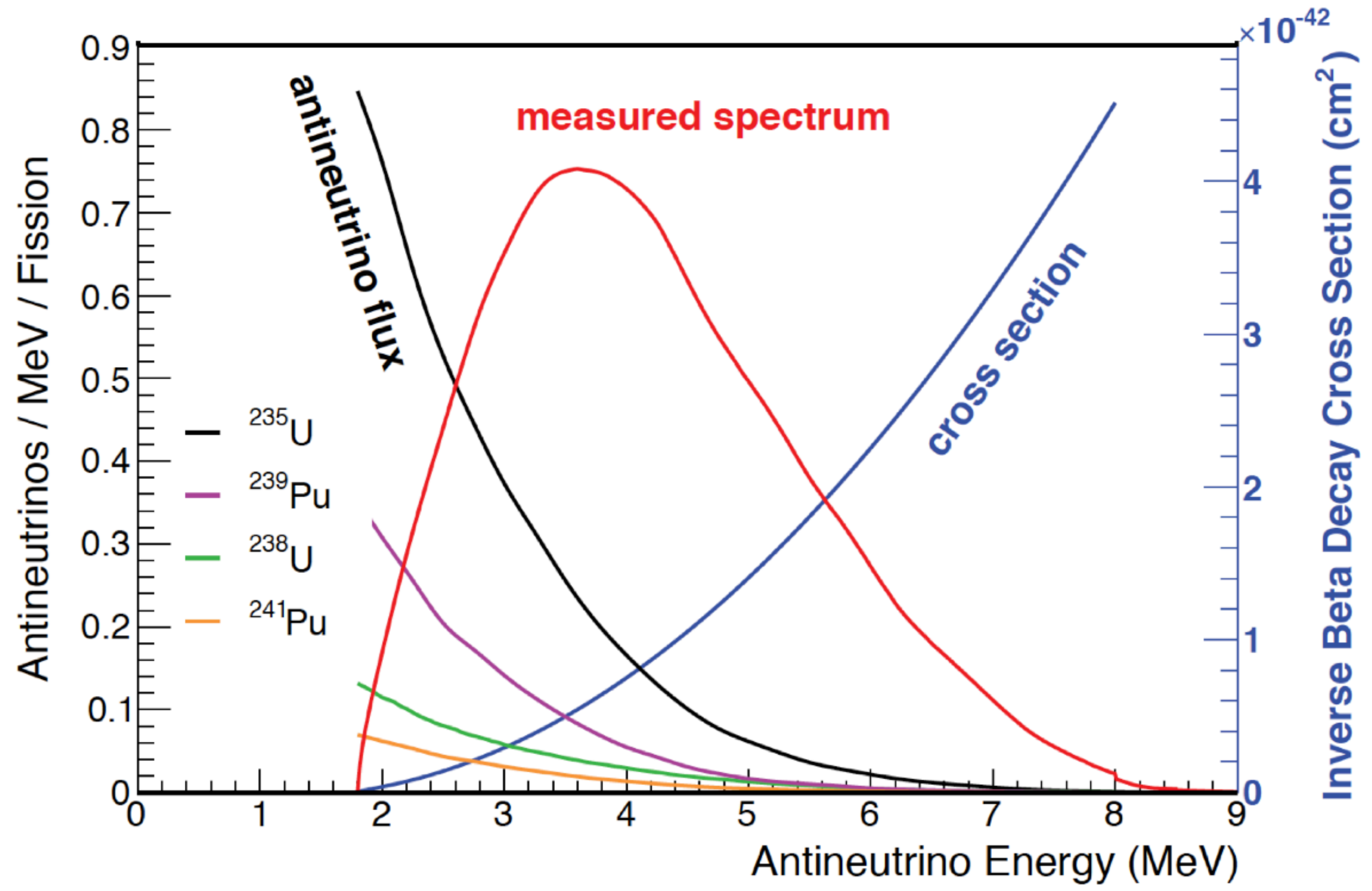
Reactor Neutrino Production

$^{235}\mathrm{U}$ fission chain





- Four main isotopes $^{235}\mathrm{U}, ^{238}\mathrm{U}, ^{239}\mathrm{Pu}, ^{241}\mathrm{Pu}$
- Total reactor prediction based on thousands of fission contributions
- Calculation heavy, use conversion method by Huber+Mueller with β-spectra from ILL
- Final spectrum depends on individual reactor cores and time dependent fuel composition



- Nuclear reactors are a strong source for neutrinos via beta decay

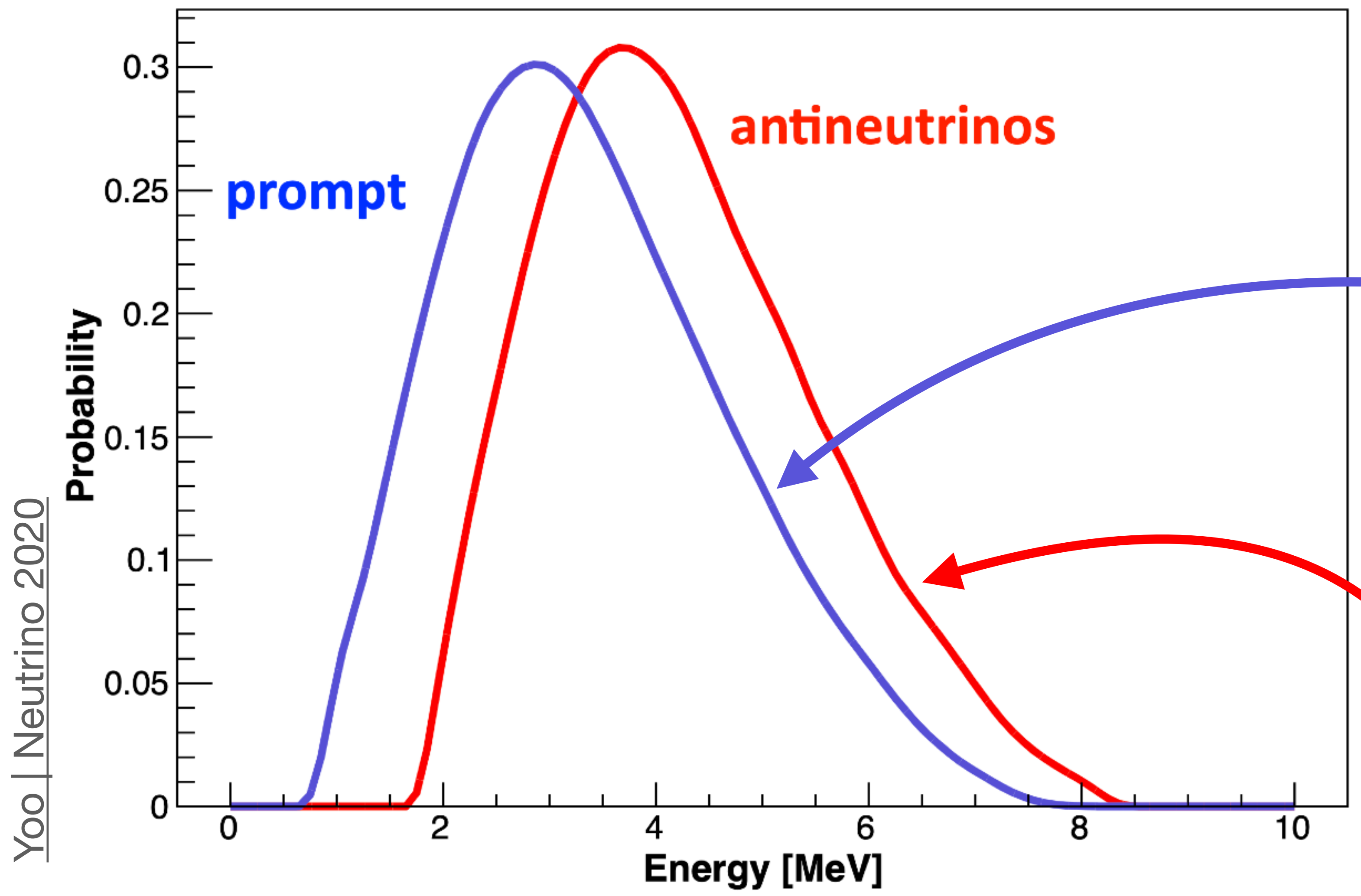
$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}X' + e^- + \bar{\nu}_e$$

- $\sim 6\ \bar{\nu}_e$ per fission process
- $2 \cdot 10^{20}\ \bar{\nu}_e\ \left[\mathrm{s}^{-1}\mathrm{GW}^{-1}\right]$ produced

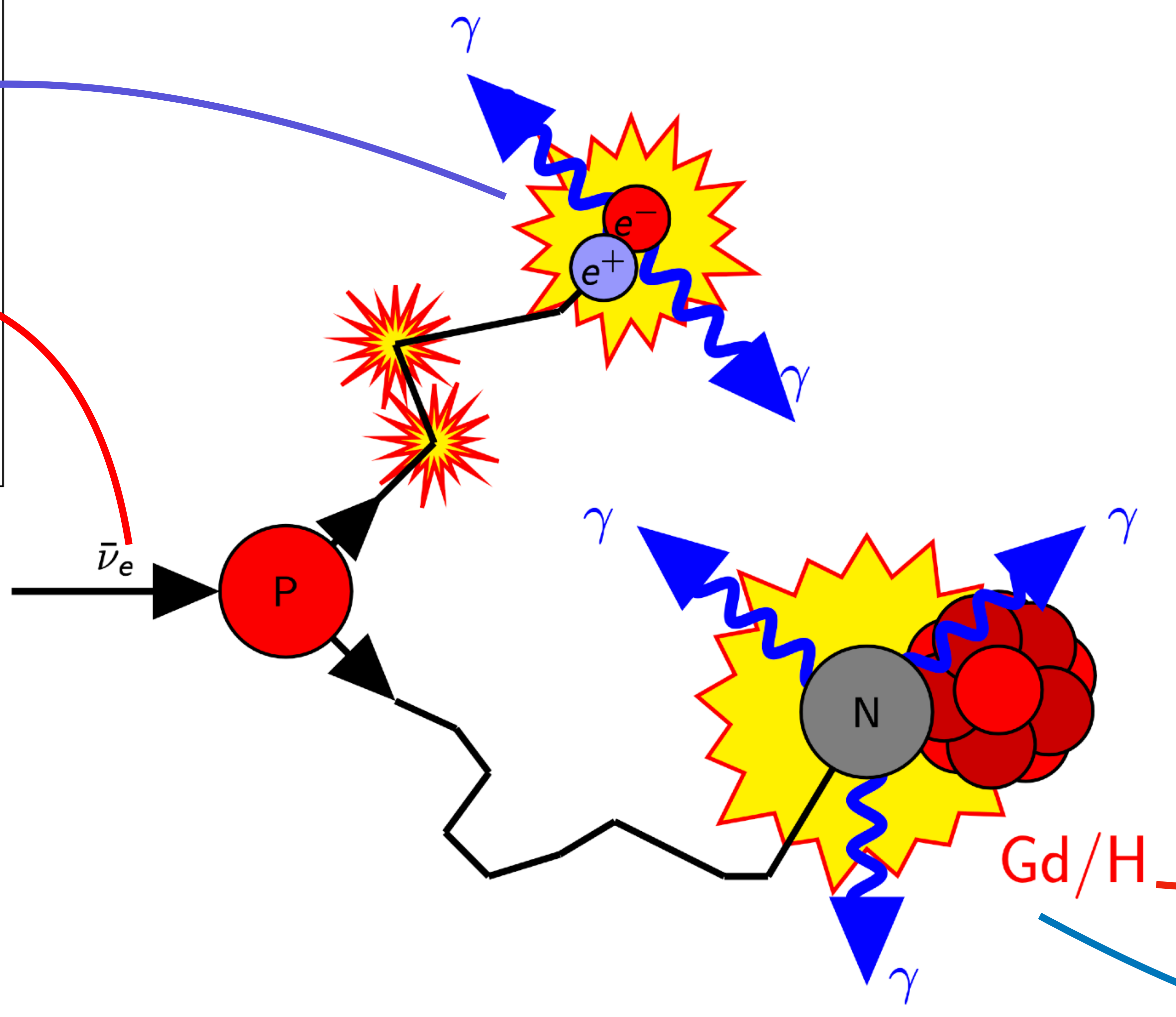
Reactor Neutrino Detection

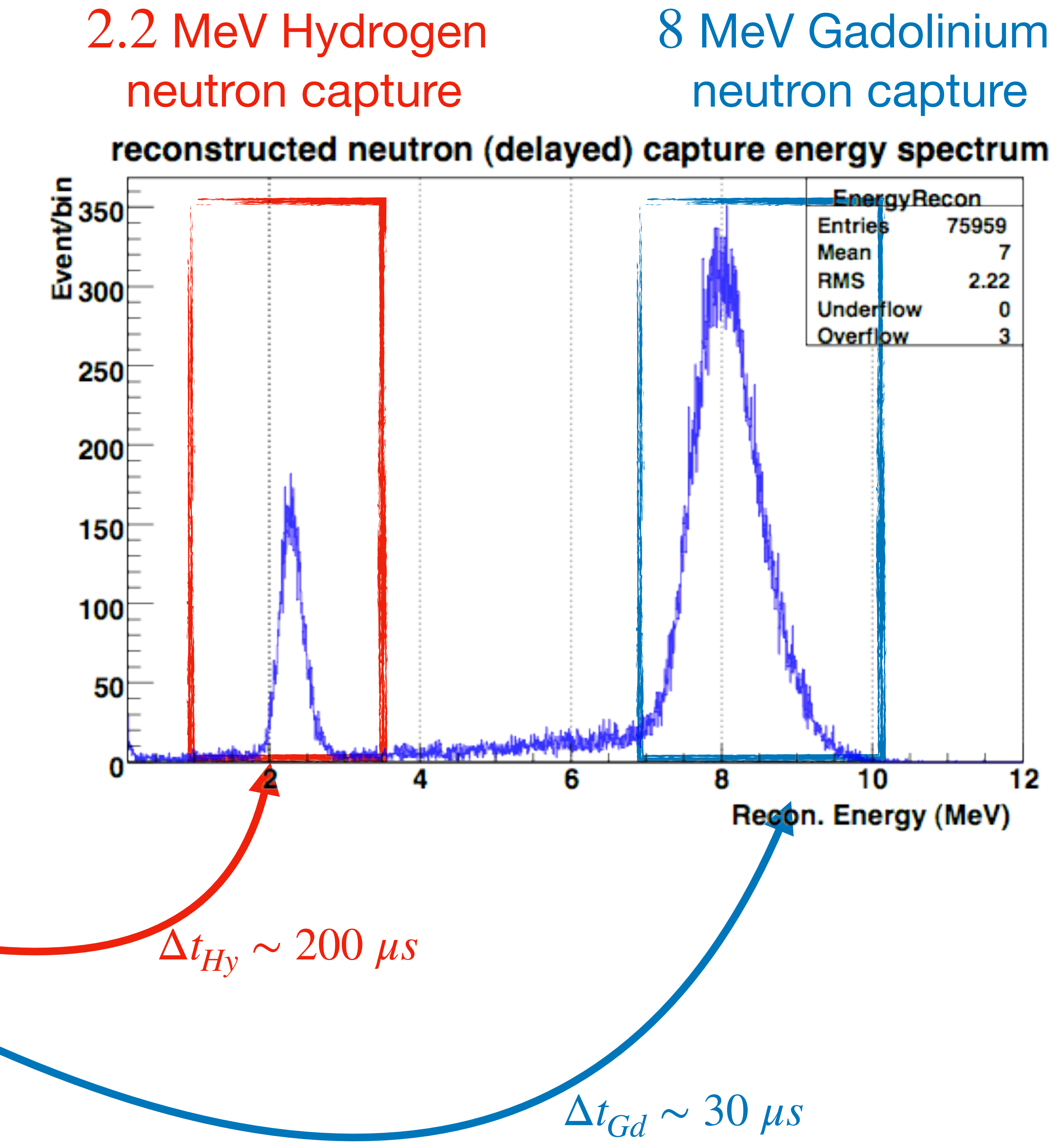
- $\bar{\nu}_e$ Detection via Inverse Beta Decay (IBD)

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



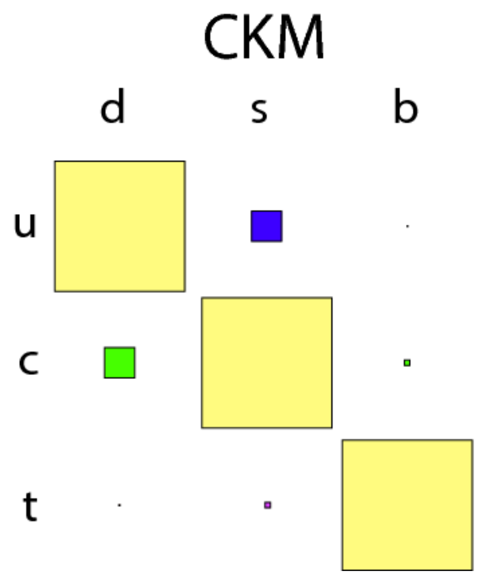
Yoo | Neutrino 2020

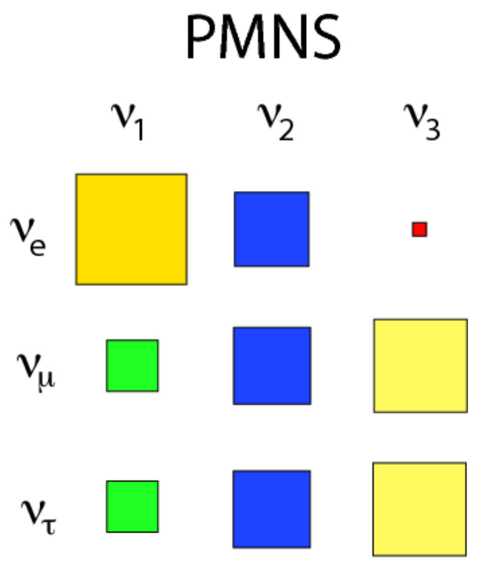




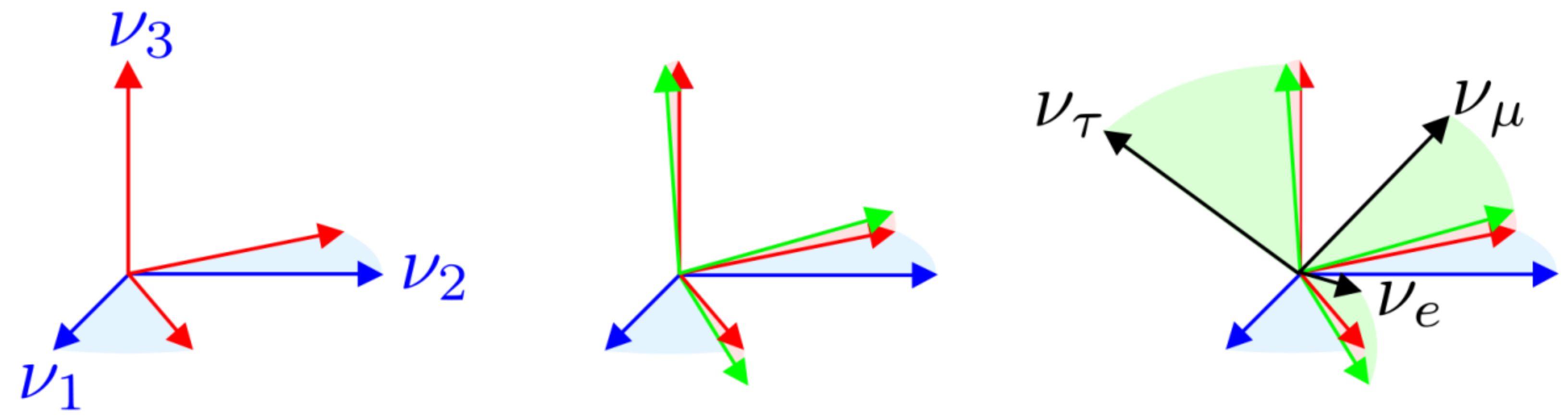
- 1.8 MeV threshold for IBD process
  - $E_{\text{prompt}} \approx E_{\nu} - 0.8$ MeV
- Distinct event signature
- Low background due to double signal
- Relatively high cross section

Theory of Neutrino Oscillation





$$\overbrace{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}}^{\text{Flavour Eigenstate}} = \underbrace{\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}}_{U_{\text{PMNS}}} \overbrace{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}^{\text{Mass Eigenstate}}$$



$$\overbrace{\underbrace{\overbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}^{\substack{\text{Atmospheric}\\ P(\nu_\mu\to\nu_\mu)}}}_{\theta_{23}\sim 45^\circ} \underbrace{\overbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}^{\substack{\text{Reactor and Accelerator}\\ P(\nu_e\to\nu_e)\ \&\ P(\nu_\mu\to\nu_e)}}}_{\theta_{13}\ \&\ \delta_{\text{CP}}} \underbrace{\overbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}^{\substack{\text{Solar}\\ P(\nu_e\to\nu_x)}}}_{\theta_{12}\sim 33^\circ}}^{U_{\text{PMNS}}}$$

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

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

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

$$\boxed{P(\bar\nu_e\to\bar\nu_e) = |\langle\bar\nu_e|\bar\nu_e\rangle|^2 = \left|\sum_i U^*_{ei}U_{ei}\exp\left(-i\frac{m_i^2 L}{2E}\right)\right|^2 = \ldots \approx 1 - \sin^2(2\theta_{13})\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\Delta_{21}}$$

- Neutrinos travel as Mass eigenstate
- Flavor Eigenstates are superposition of Mass eigenstates
- Unitary U_{PMNS} describes rotation between these two Eigenbases
- Described by three independent Euler angles and a free δ_{CP} phase associated with θ_{13}

Theory of Neutrino Oscillation

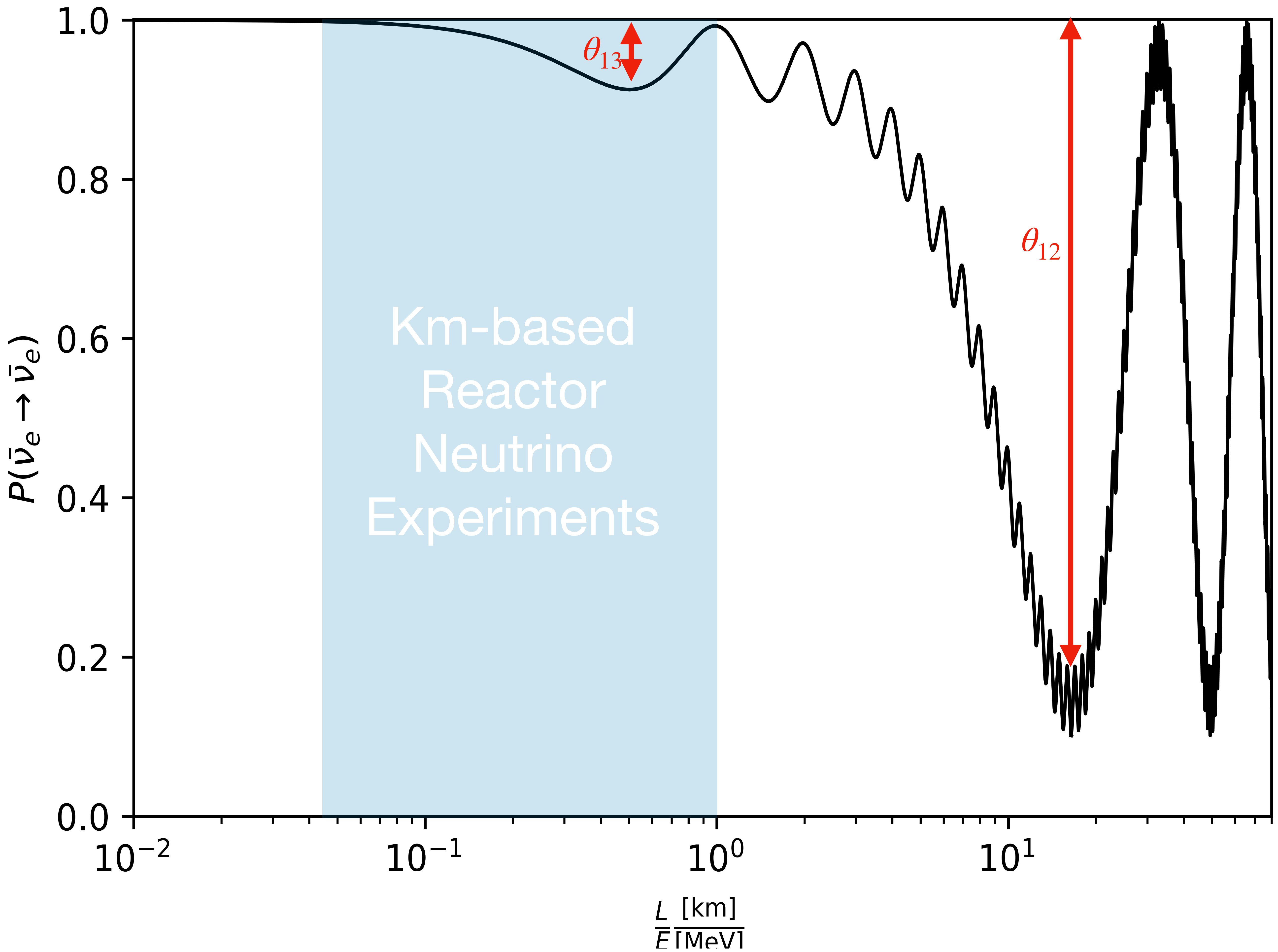
$$\Delta_{ij} \equiv \Delta m^2_{ij} \frac{L}{4E}$$

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

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13})\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\Delta_{21}$$

- θ_{13} is oscillation amplitude
- Δm^2_{ee} is oscillation frequency
- Higher θ_{13} means fewer measured neutrinos
- Near/Far approach cancels almost all systematics
- Main uncertainties are detection efficiency and number of target protons

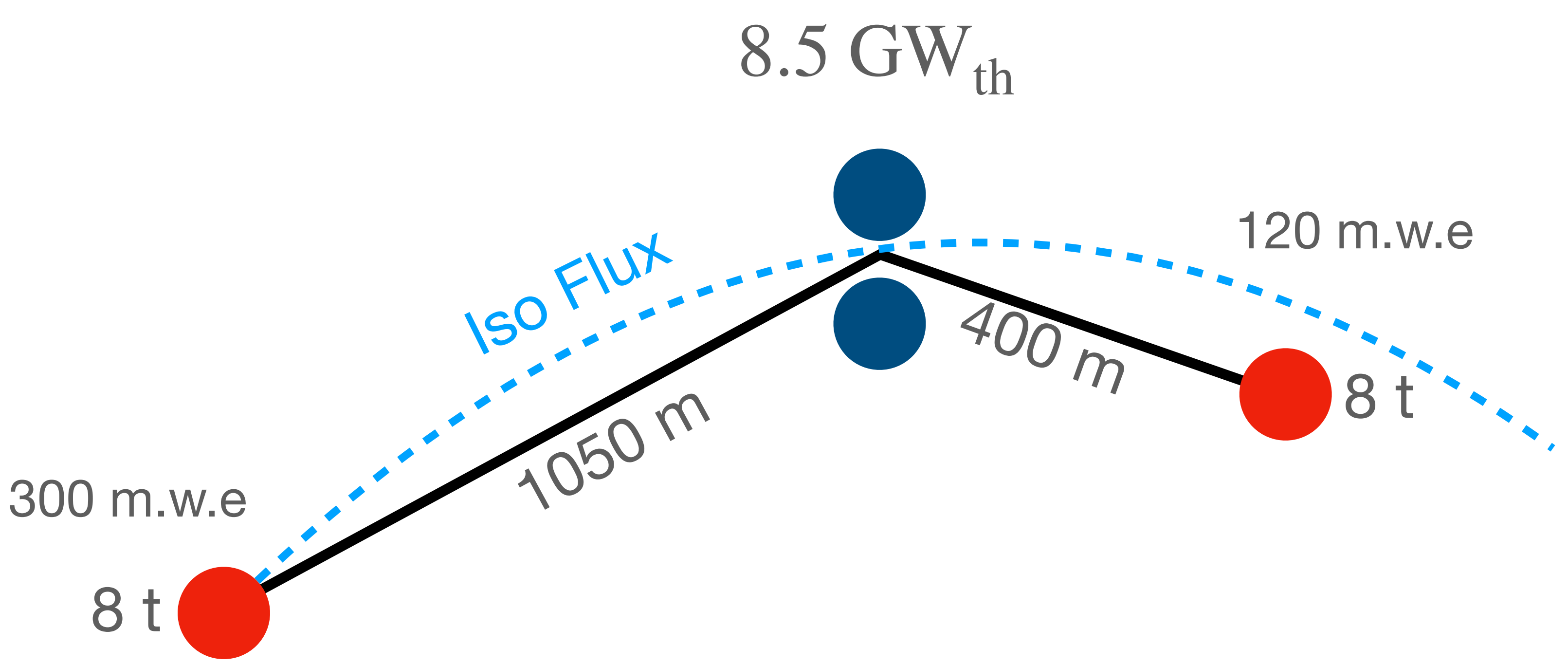
$$\frac{R_{\text{far}}}{R_{\text{near}}} = \overset{\text{Distance}}{\frac{L^2_{\text{near}}}{L^2_{\text{far}}}} \cdot \overset{\text{Target Mass}}{\frac{N_{\text{far}}}{N_{\text{near}}}} \cdot \overset{\text{Detector Efficiency}}{\frac{\epsilon_{\text{far}}}{\epsilon_{\text{near}}}} \cdot \overset{\text{Survival Probability}}{\frac{P_{\text{far}}(\bar{\nu}_e \to \bar{\nu}_e)}{P_{\text{near}}(\bar{\nu}_e \to \bar{\nu}_e)}}$$



Experimental Setups

Double Chooz

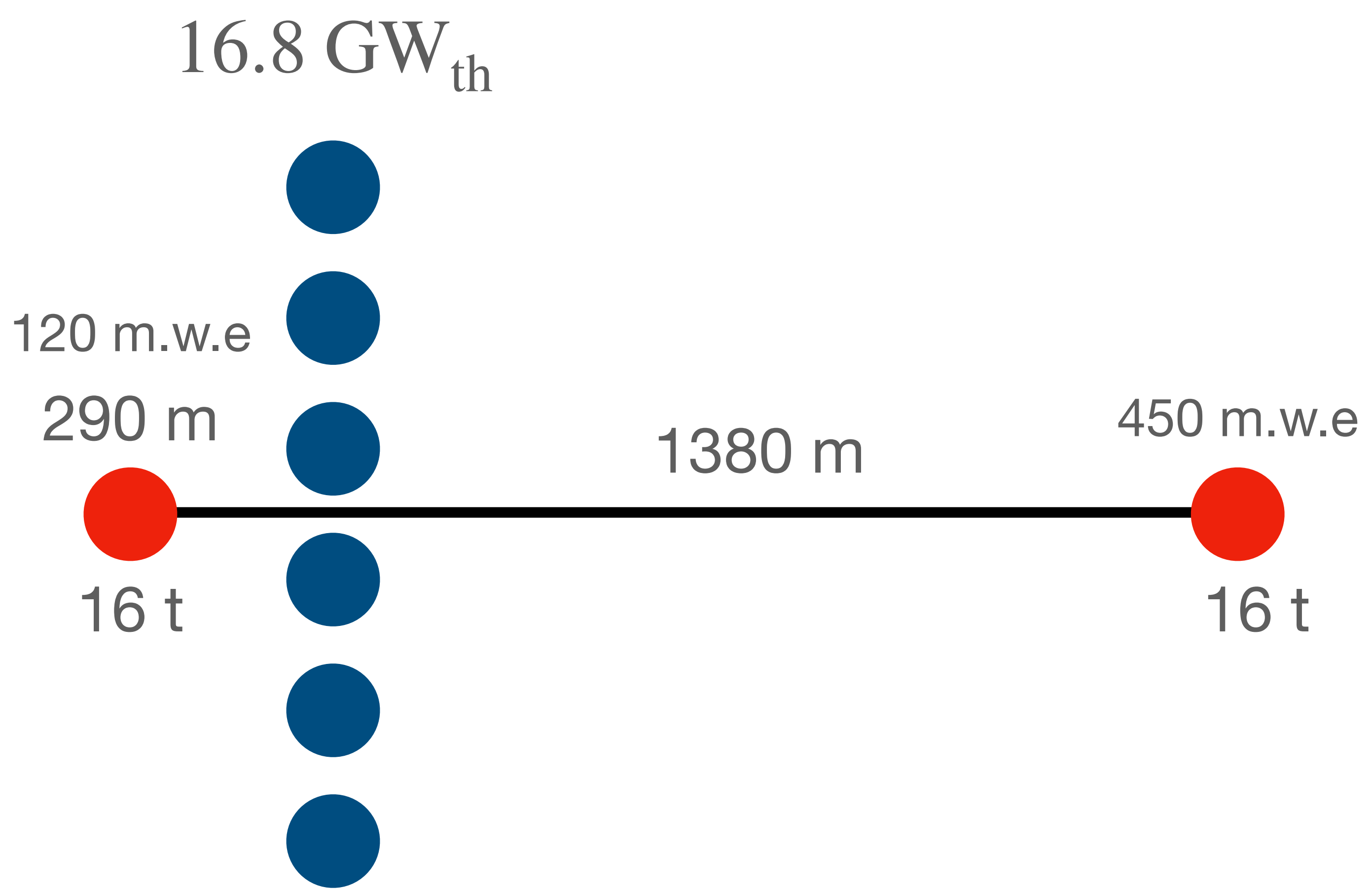
France



periods with
no signal „off-off“

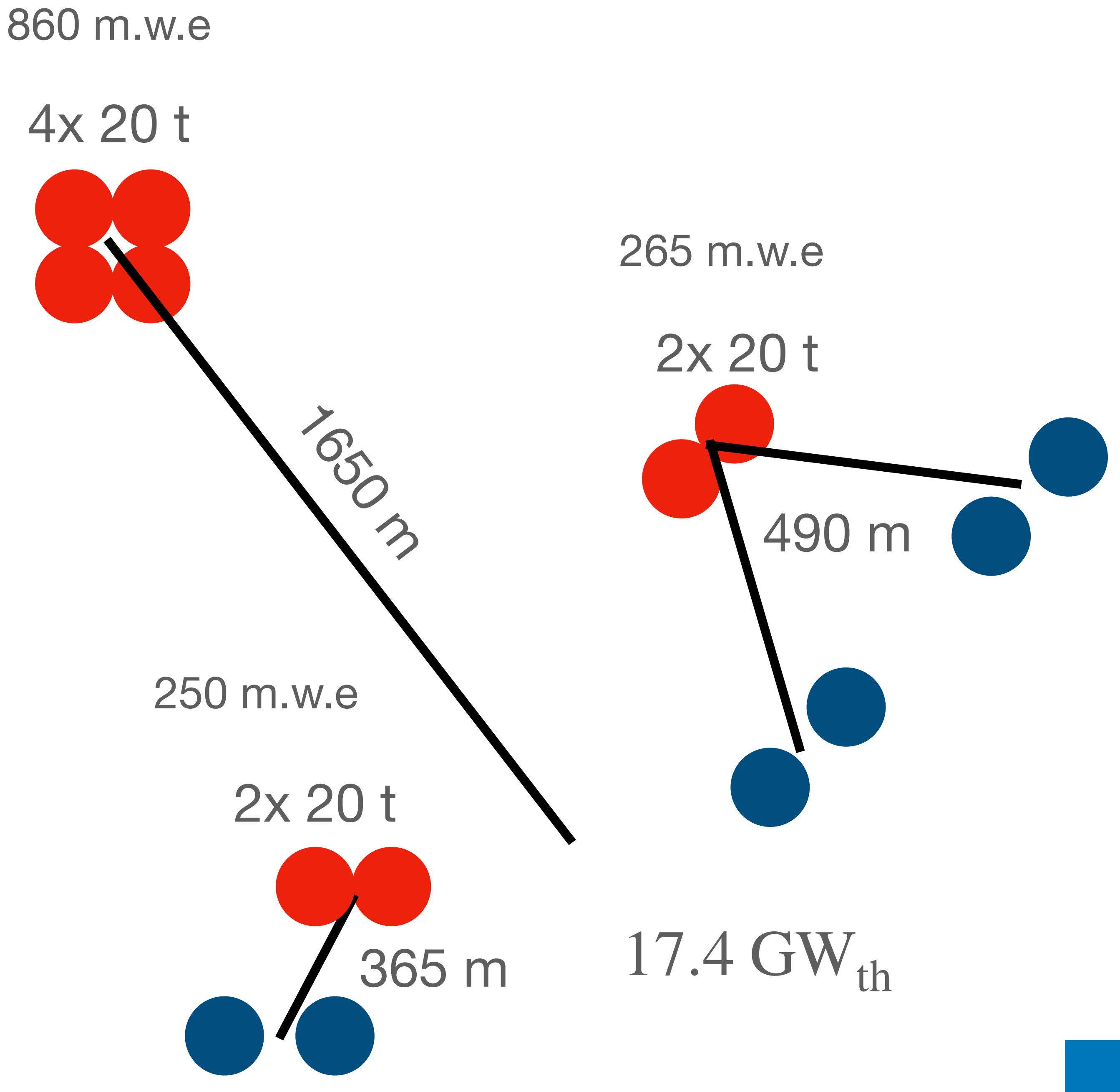
RENO

South Korea

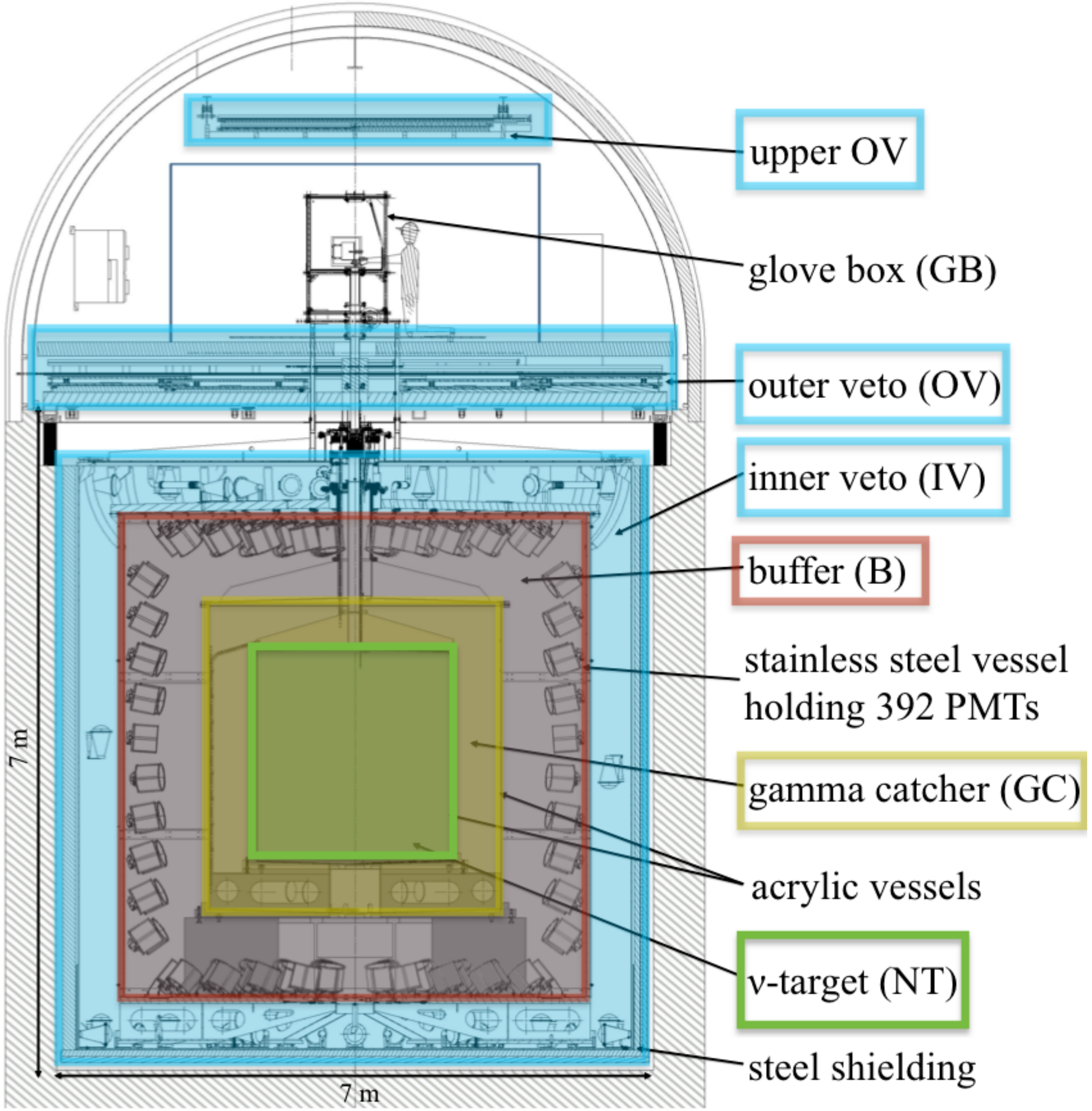


Daya Bay

China



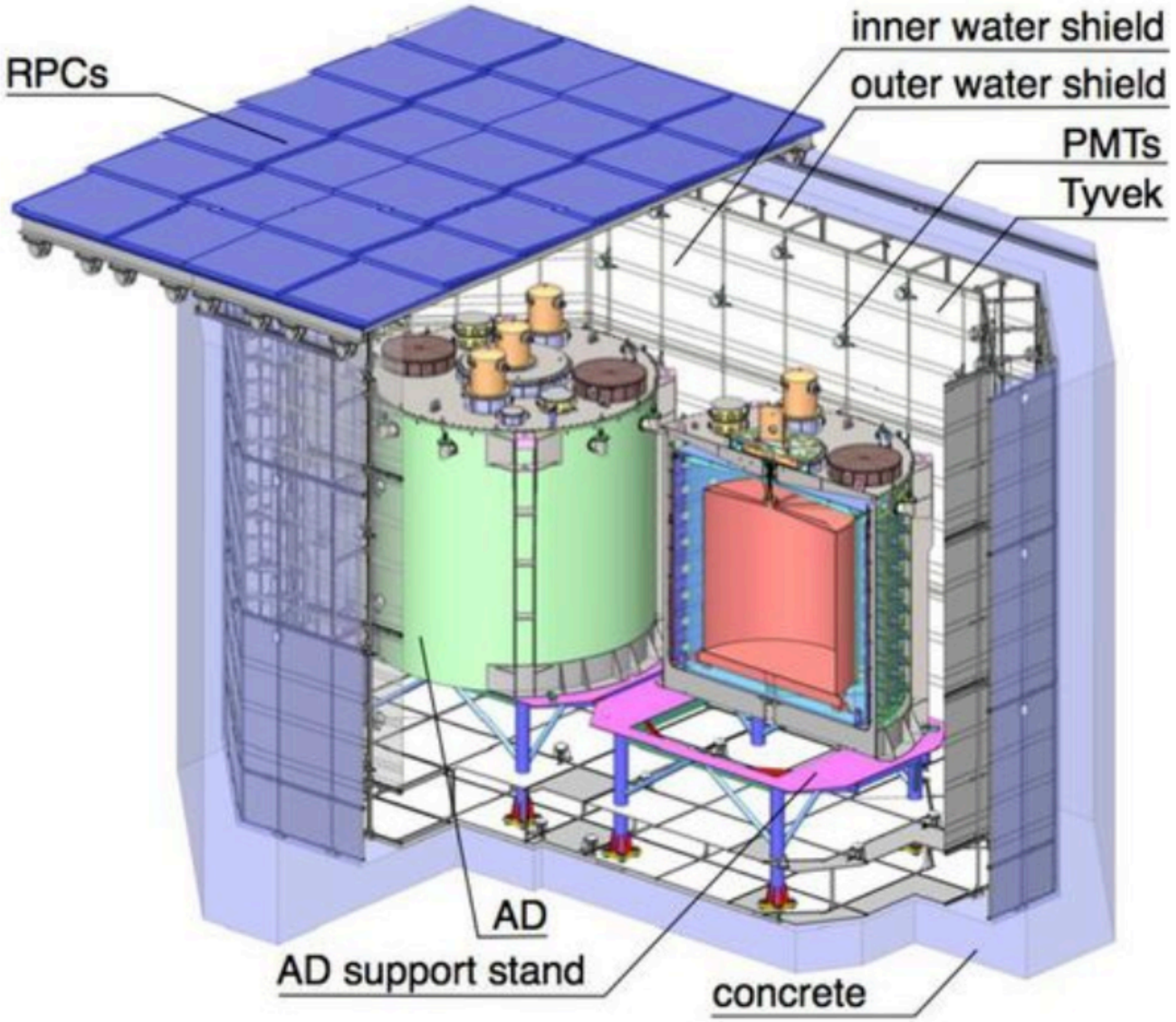
Neutrino Detectors



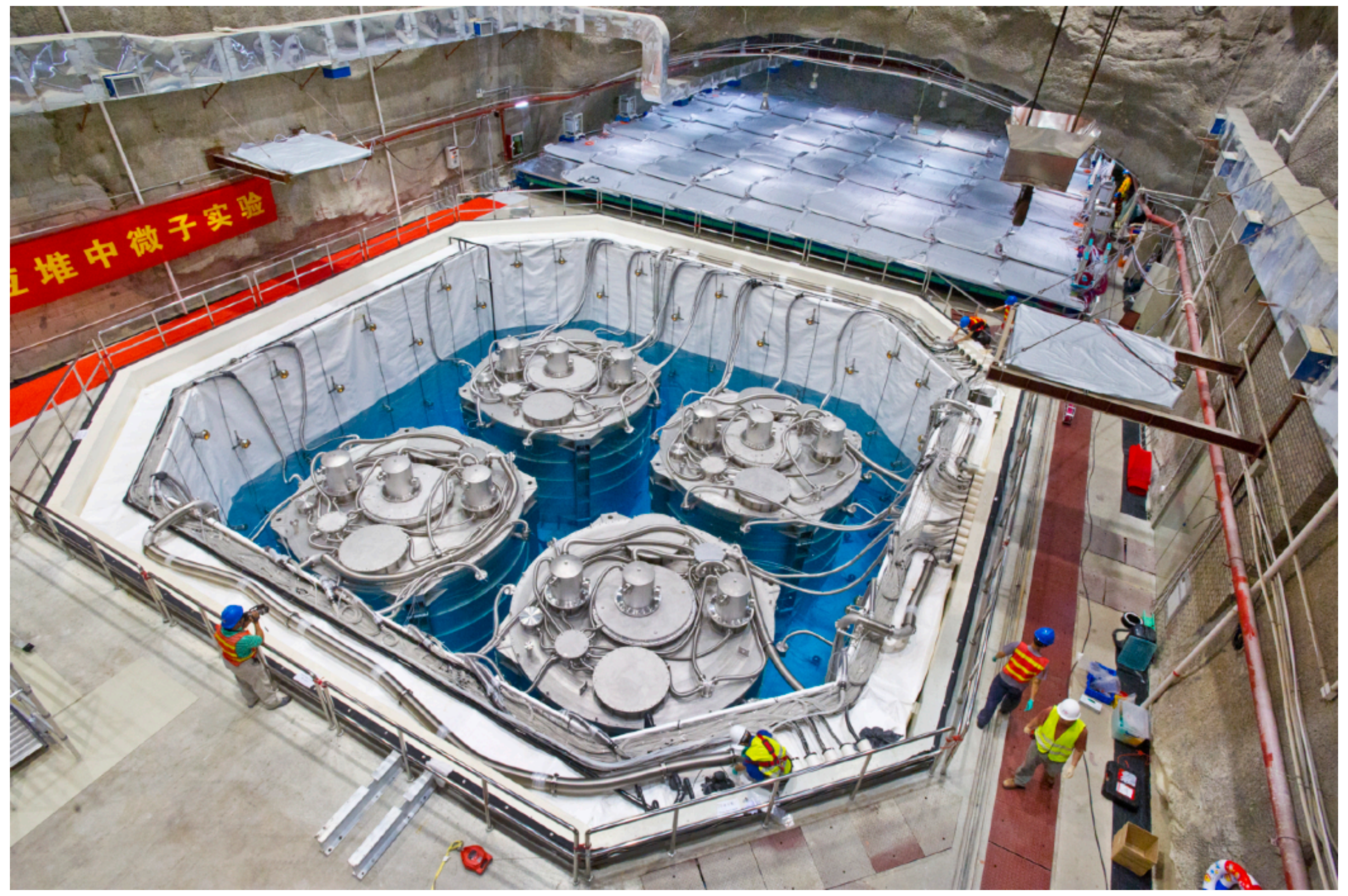
Double Chooz Detector

- Detector Designs for Daya Bay, Reno and Double Chooz all similar
- **Neutrino Target (NT)**
  - $1 \mathrm{g l}^{-1}$ Gd doped LS
- **Gamma Catcher (GC)**
  - Undoped LS
  - Measures γ's, that leave the NT
- **Buffer (GC)**
  - Non scintillating mineral oil
  - PMT Locations
- **Muon Veto**
  - Shielded LS (DC) / Water (DB, RENO) with PMTs
  - Used for atmospheric muon veto

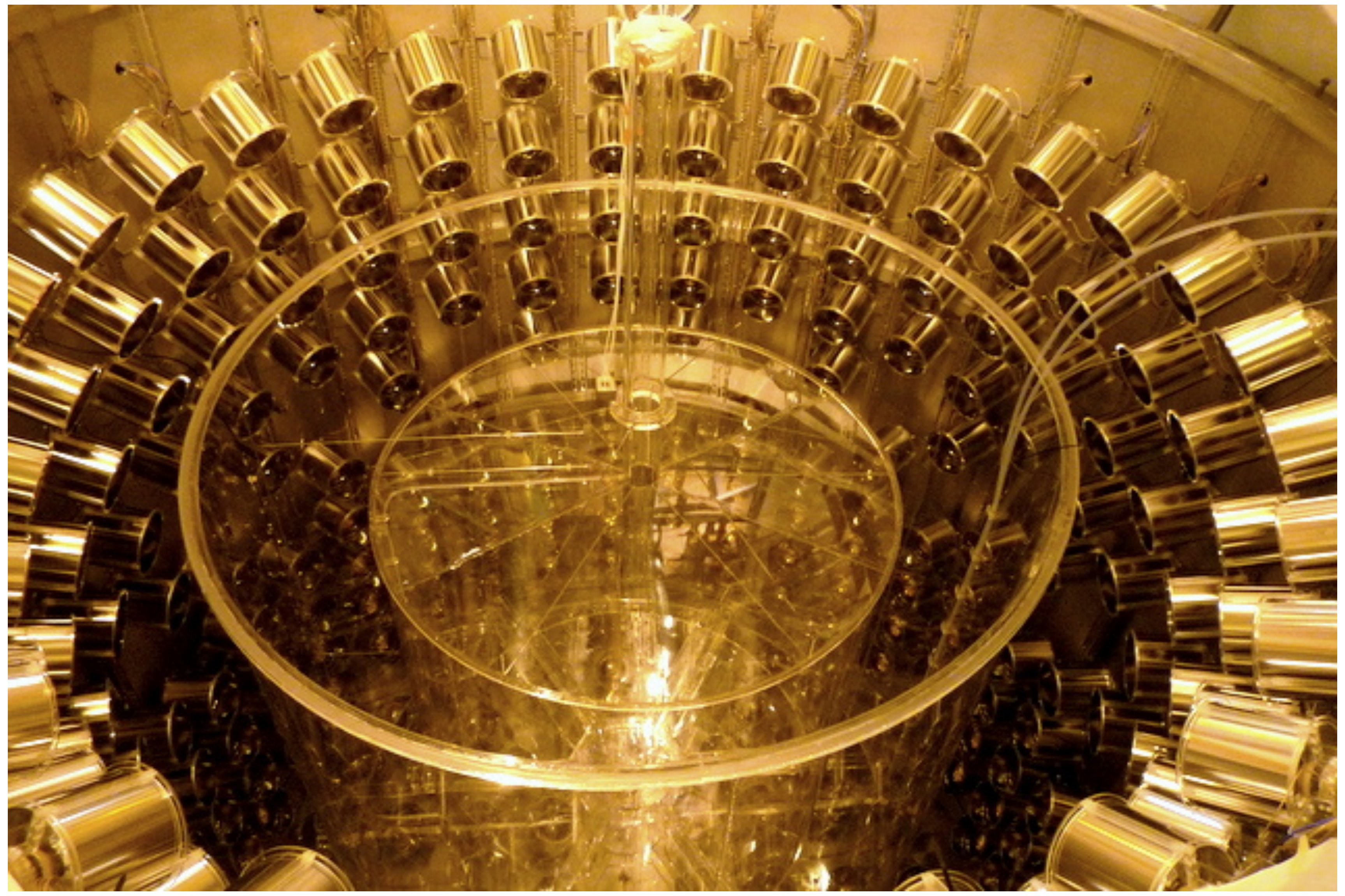
Neutrino Detectors



Daya Bay Near Detector Schematics



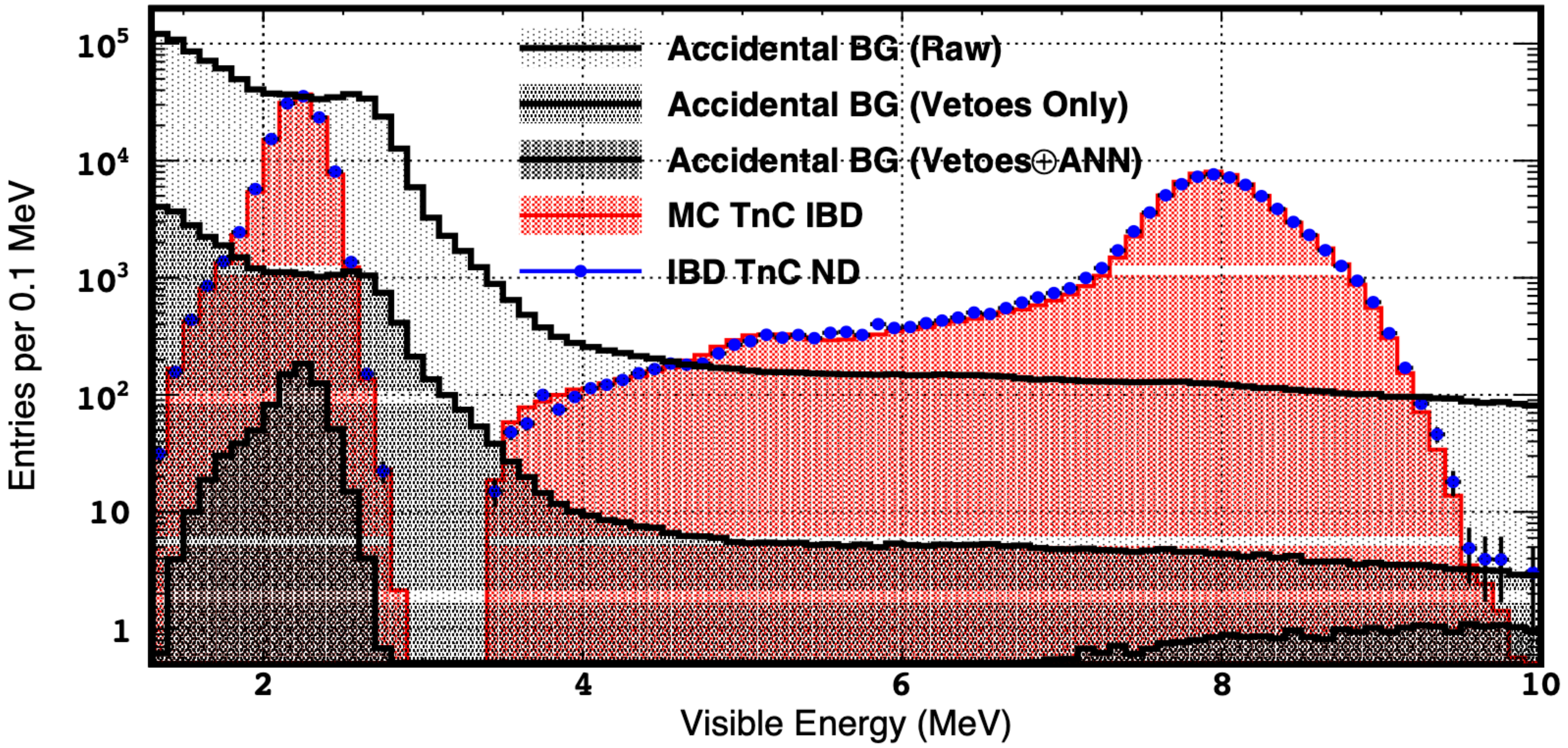
Daya Bay Far Detector

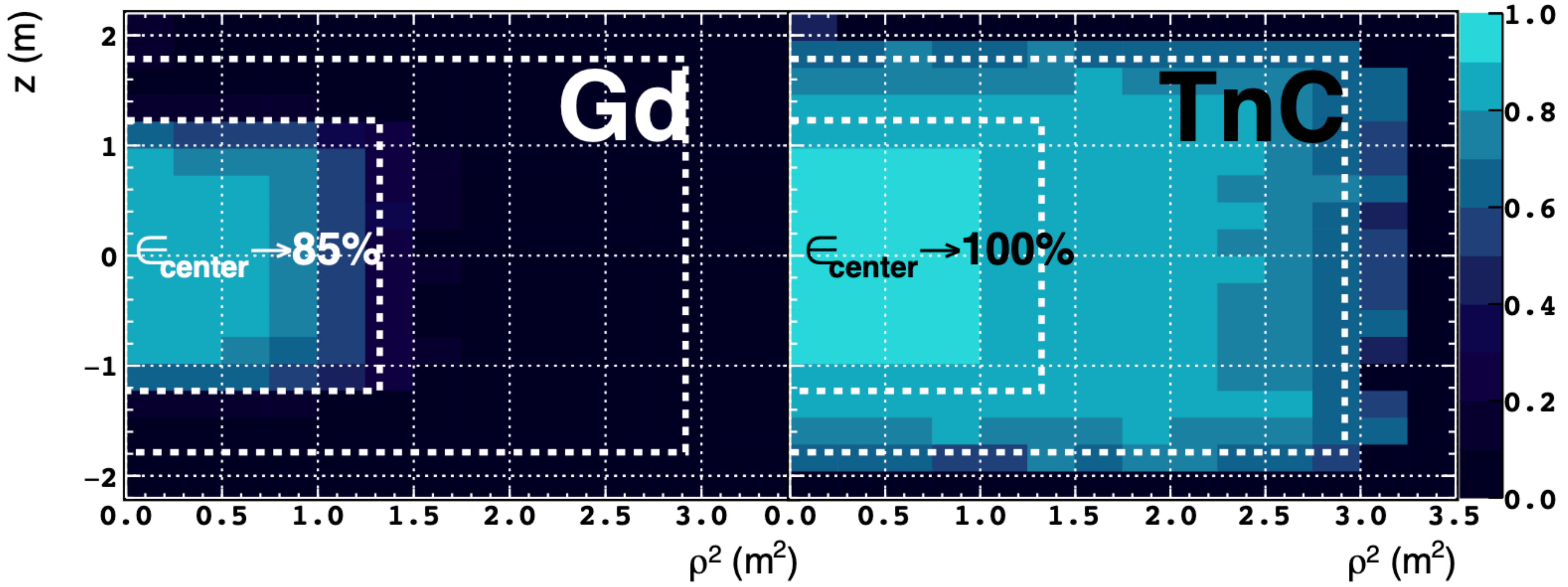


Double Chooz

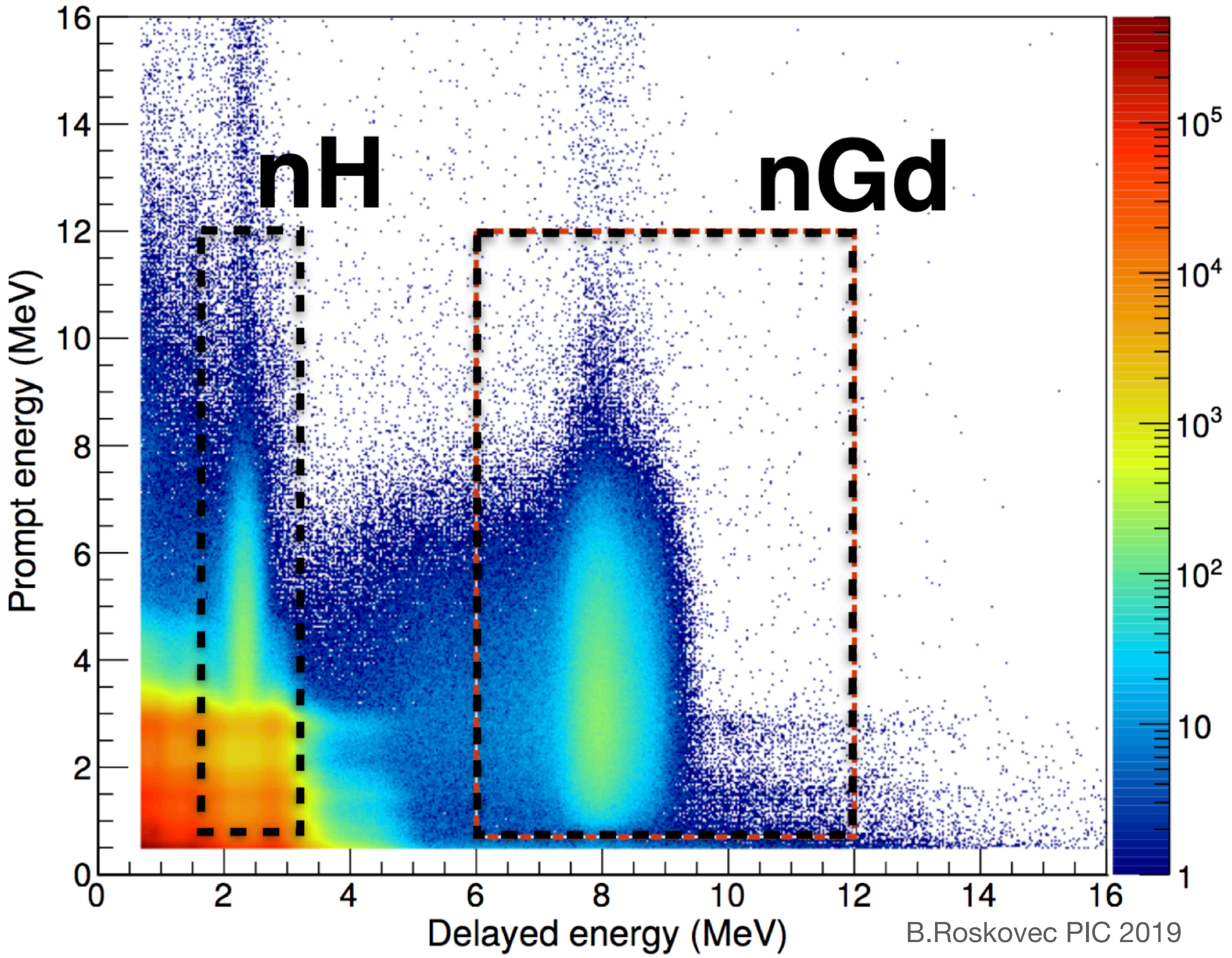
IBD Measurement (Selection)

- Double Chooz uses Gd+H+C neutron capture (TnC)





- Daya Bay and Reno use cut based analysis with Gd only / Hy only
    - Based on energy, time, spacial information and μ-veto



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IBD Measurement (Backgrounds)

Uncorrelated:

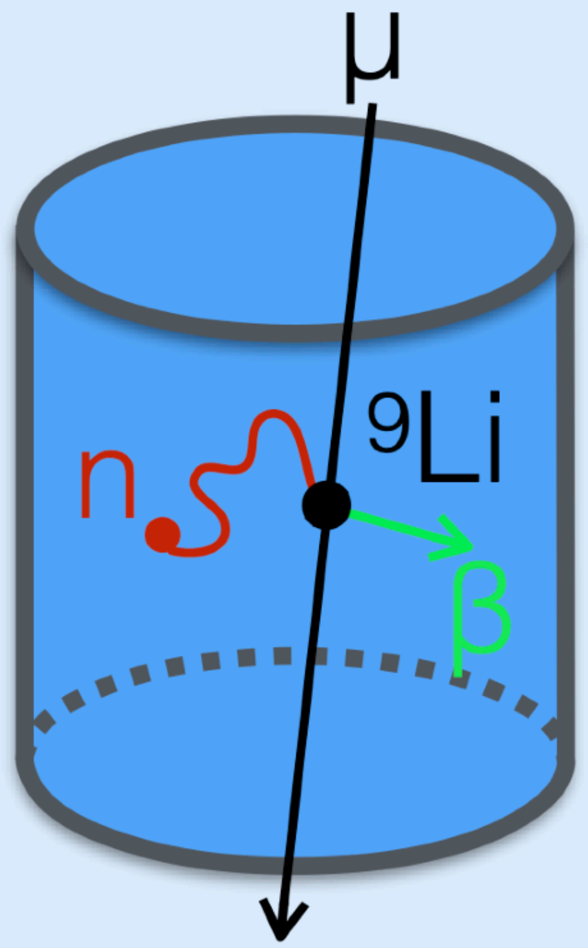
Accidental coincidence

Radioactivity γ

+

High-energy β decay

Correlated from cosmic muons:

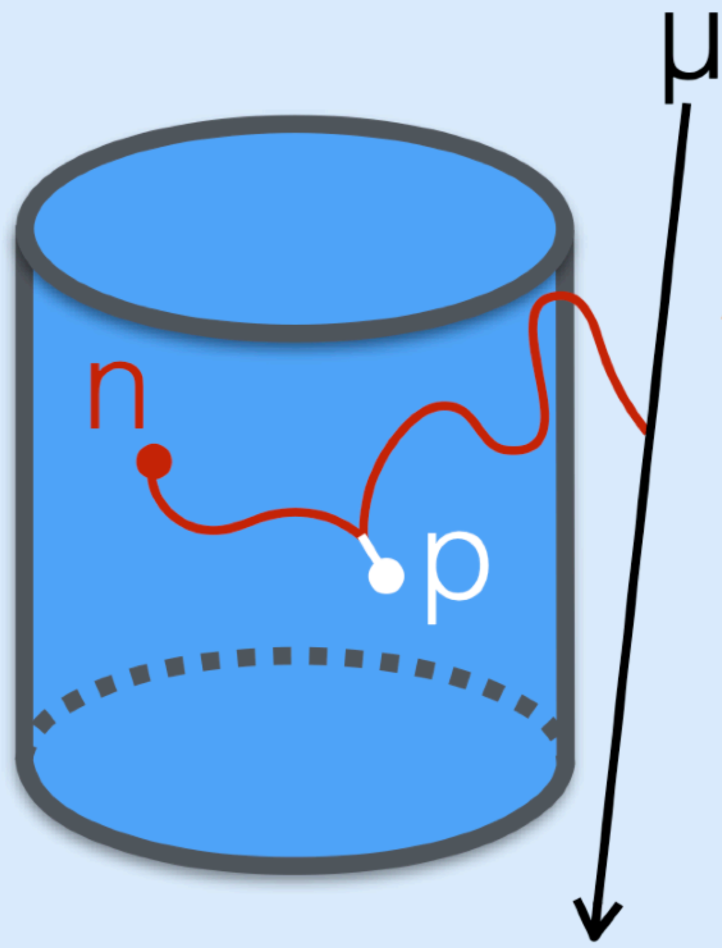


^{9}Li/^{8}He Isotopes

β decay

+

n capture

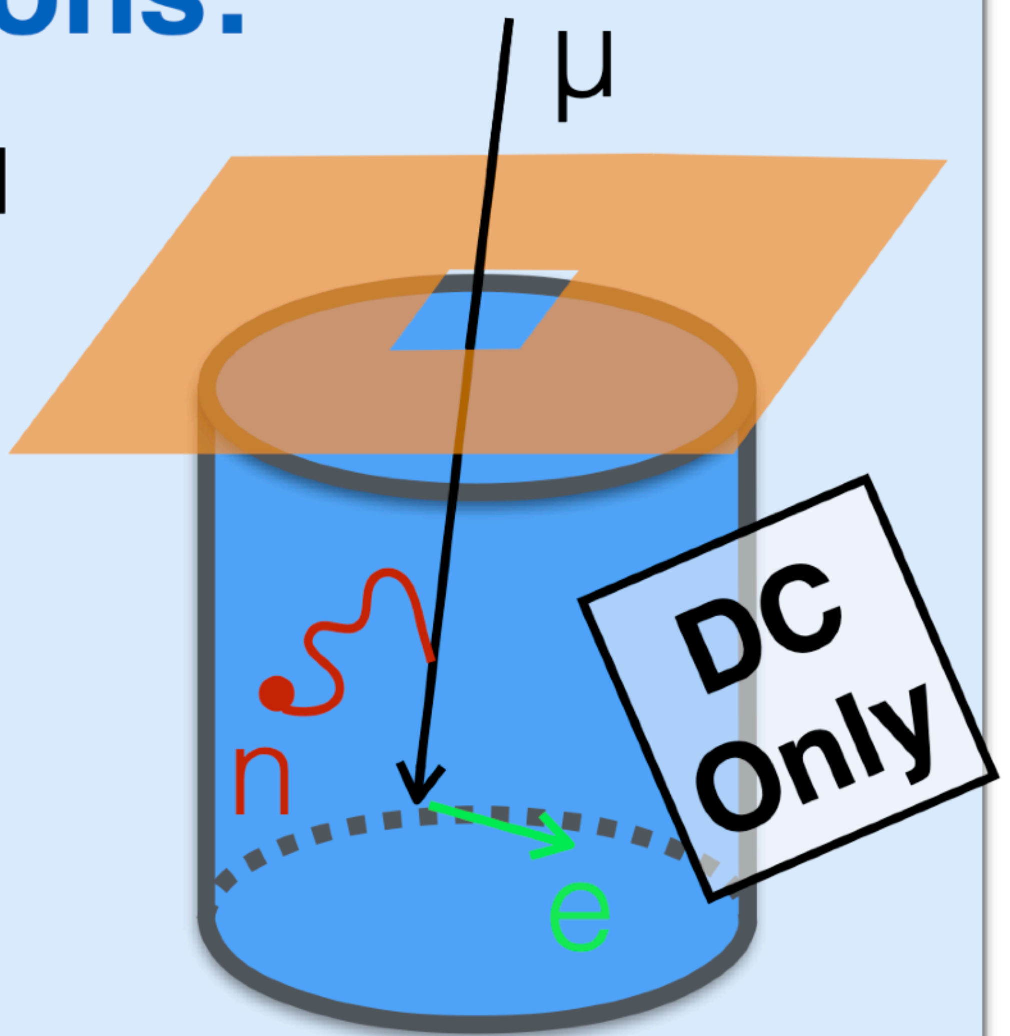


Fast neutrons

Recoil on p

+

n capture



Unvetoed muons

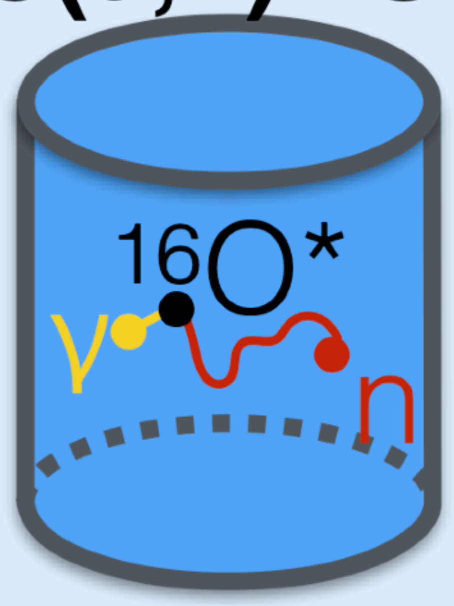
Muon ionization

+

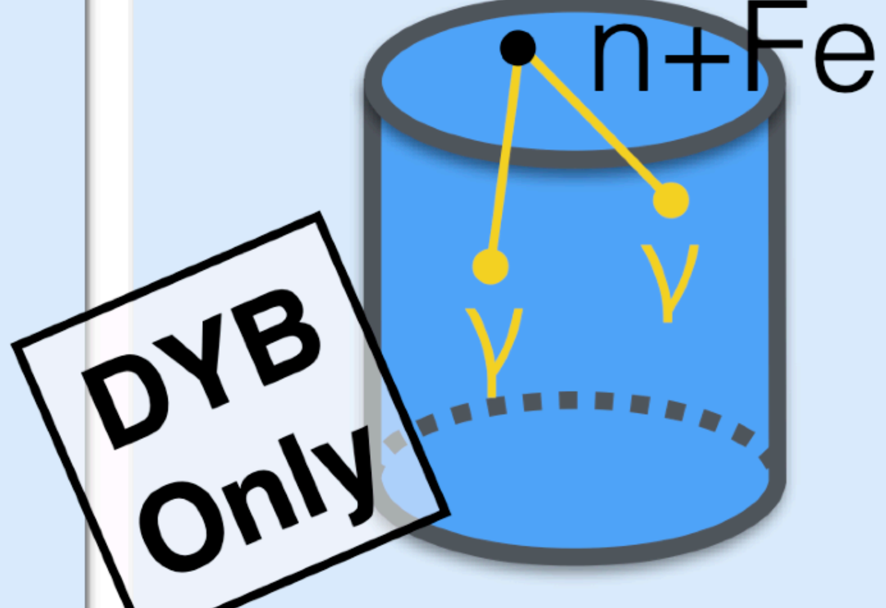
n capture/ muon decay

Others:

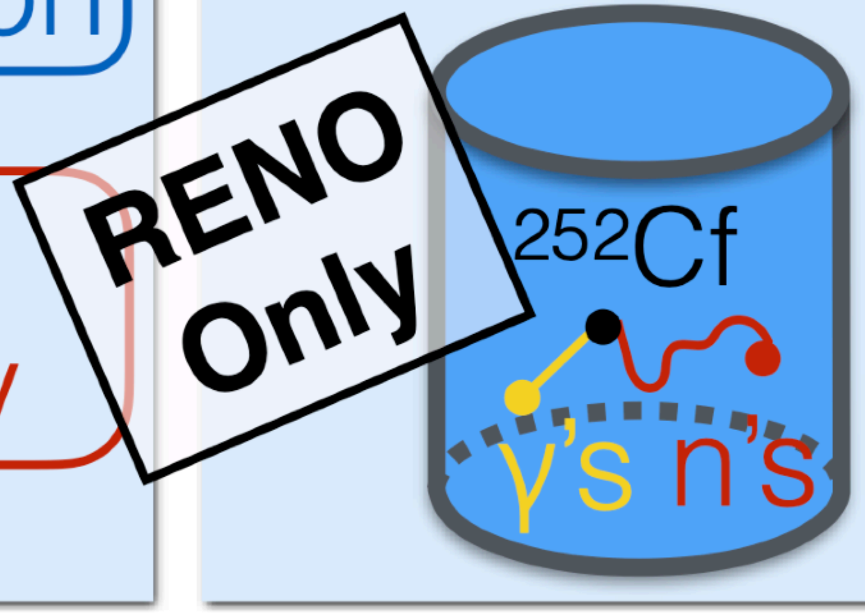
$^{13}C(\alpha,n)^{16}O$



^{241}Am-^{13}C



^{252}Cf decay



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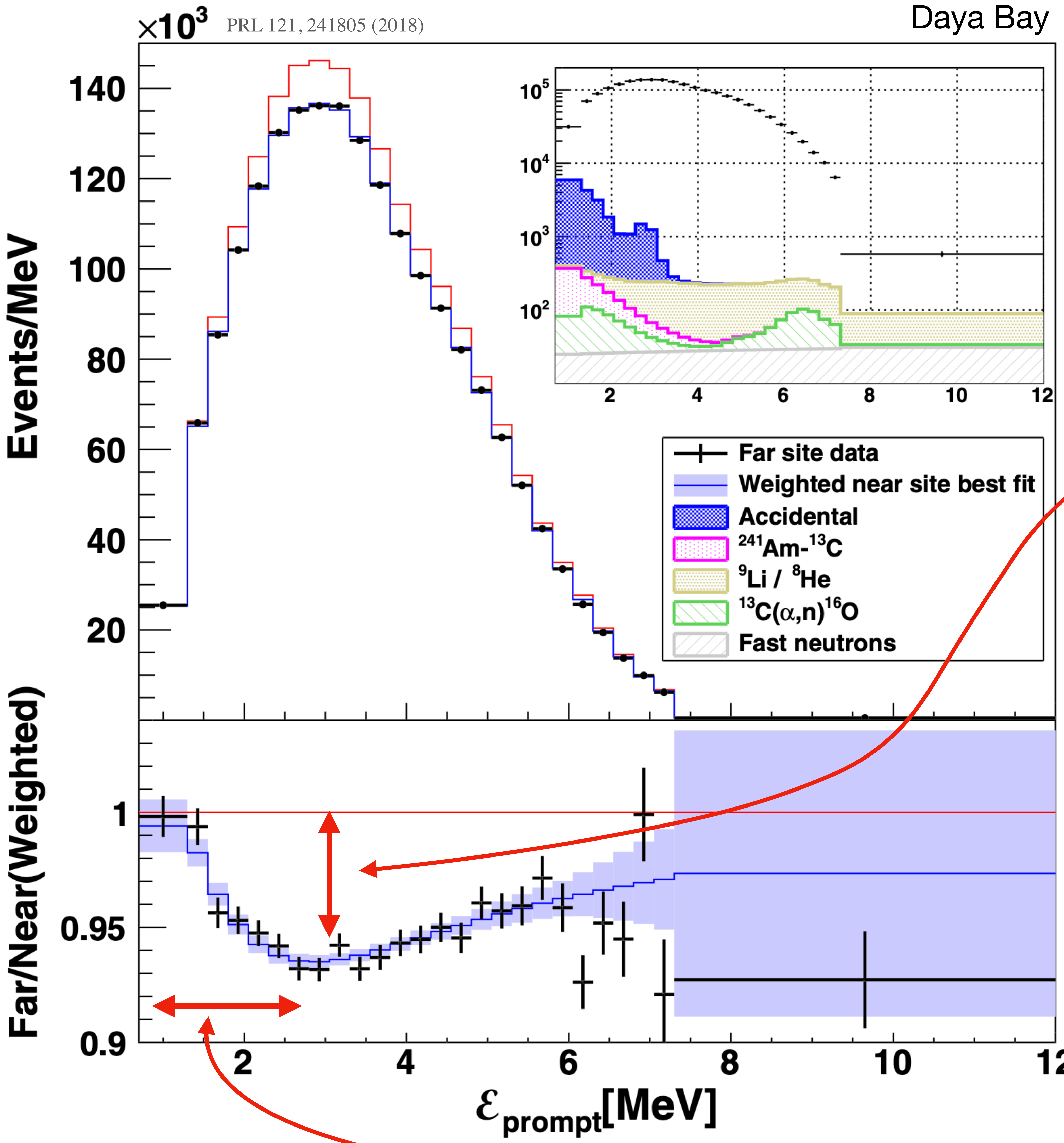
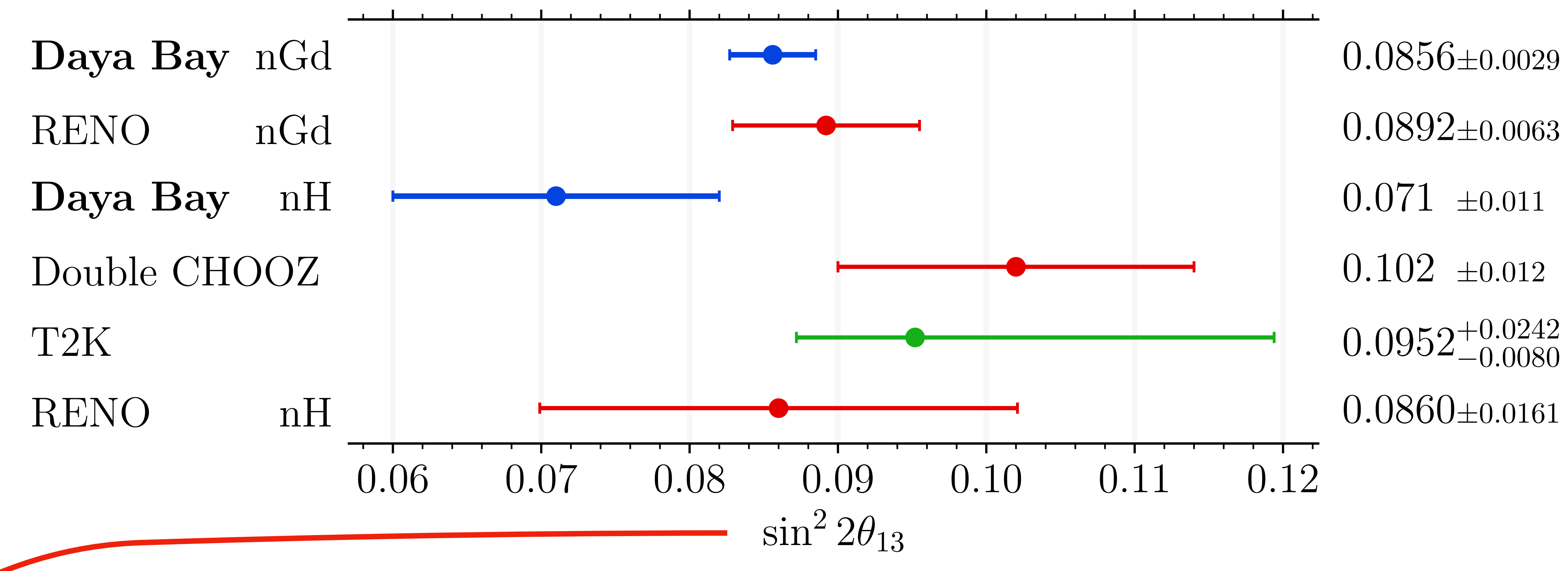
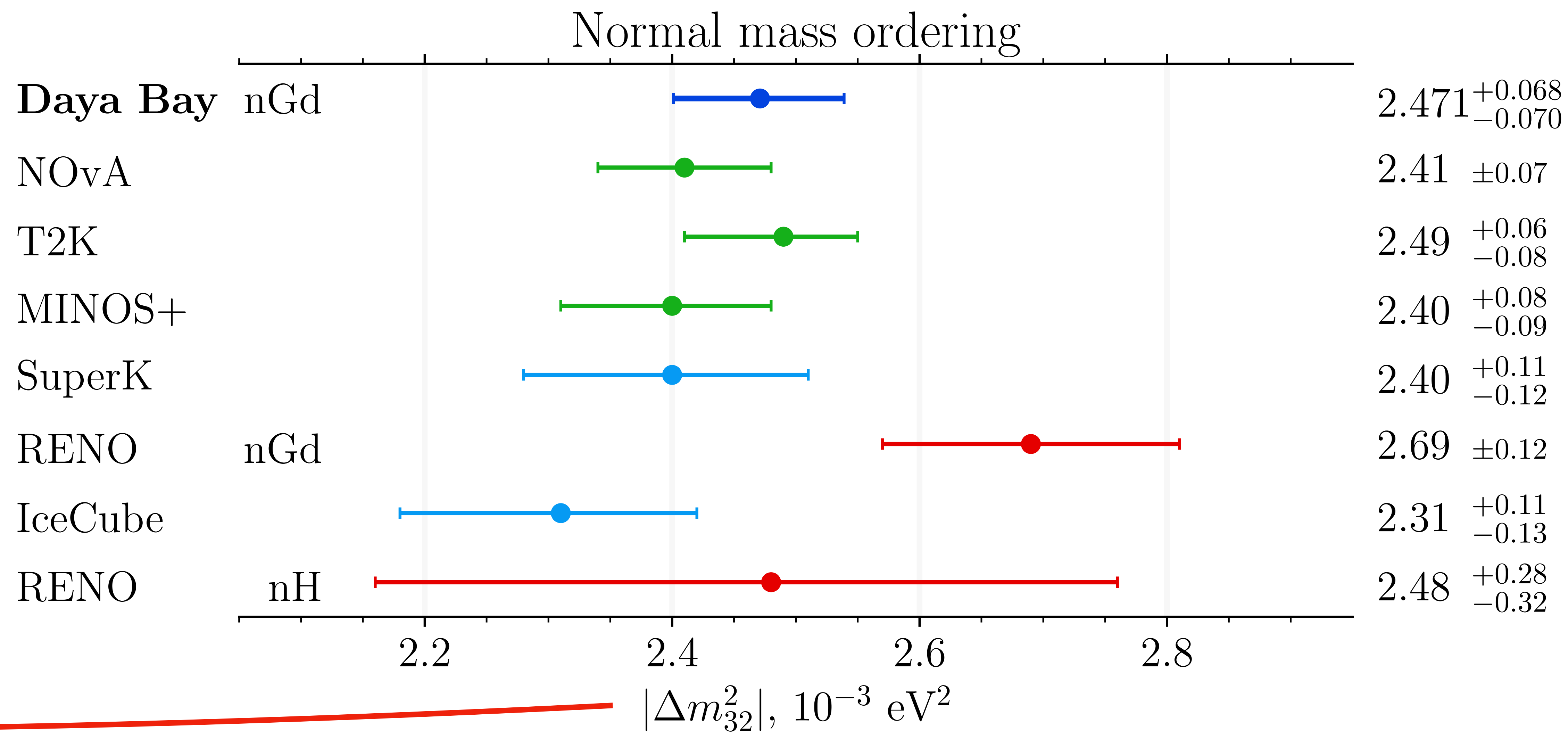
Measurement Results





- Most precise measurement by Daya Bay with $\sin^2(2\theta_{13}) = 0.0856 \pm 0.0029$ ($\pm 3.4\,\%$)

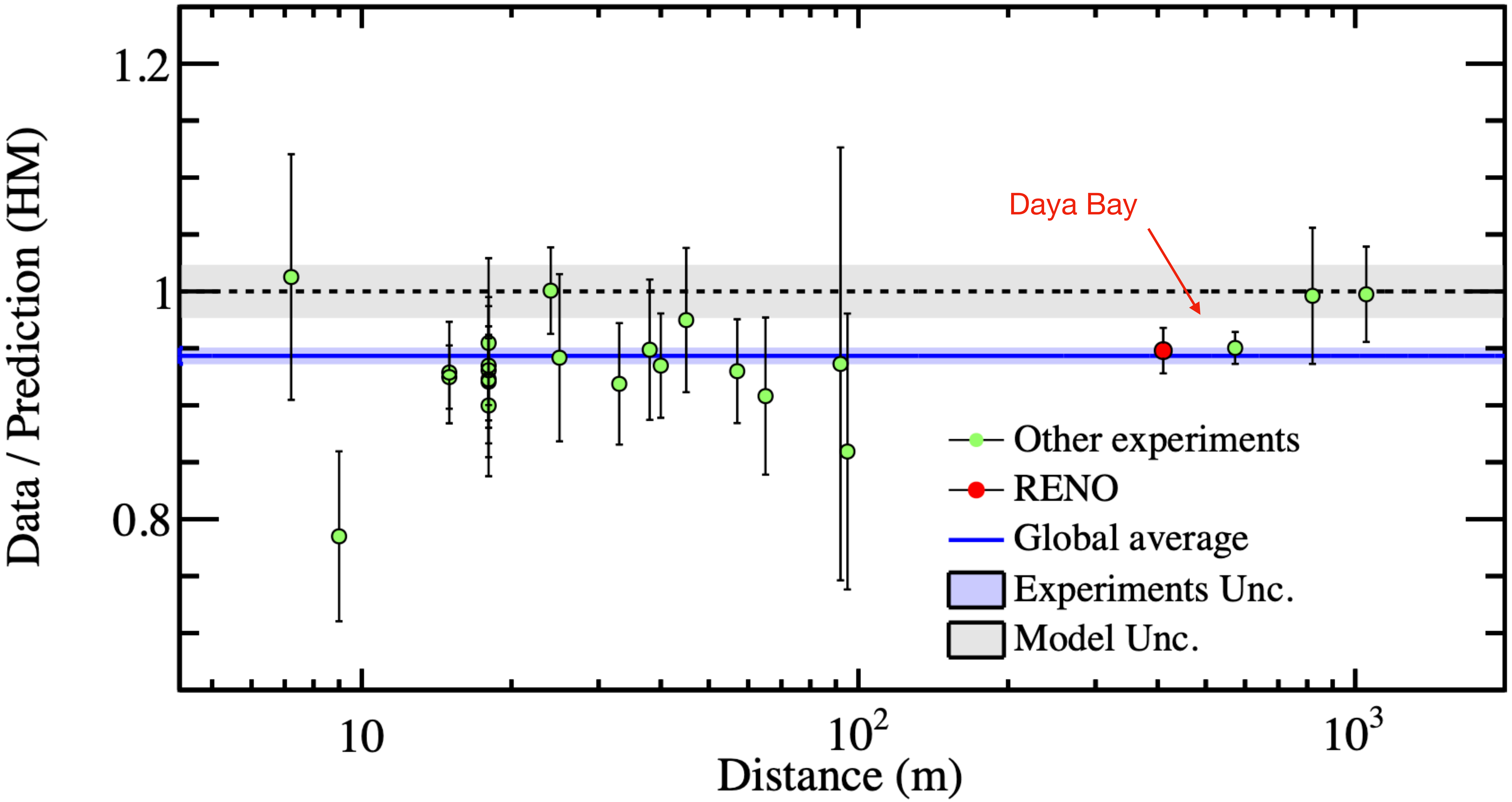
- Tension between Daya Bay and Double Chooz $> 1\sigma$



v4.1 2020.08: git.jinr.ru/nu/osc

Reactor Antineutrino Anomaly

Different experiments observe the same global deficit to the Huber-Muller prediction with different reactors and different baselines



A possible solution for this reactor antineutrino anomaly is a fourth (BSM) sterile neutrino flavor with $\Delta m^2 \gtrsim 1$ MeV

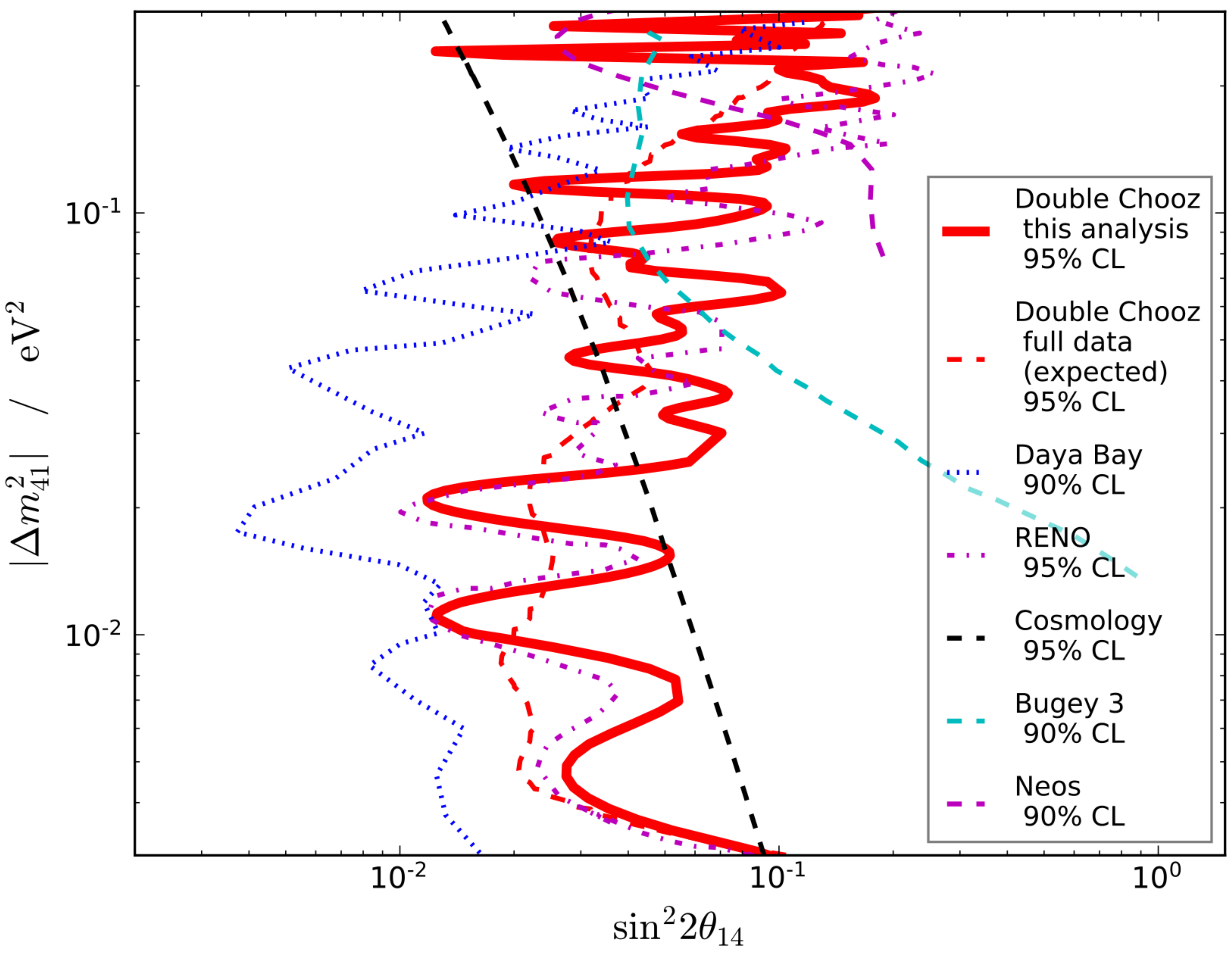
Sterile Neutrinos

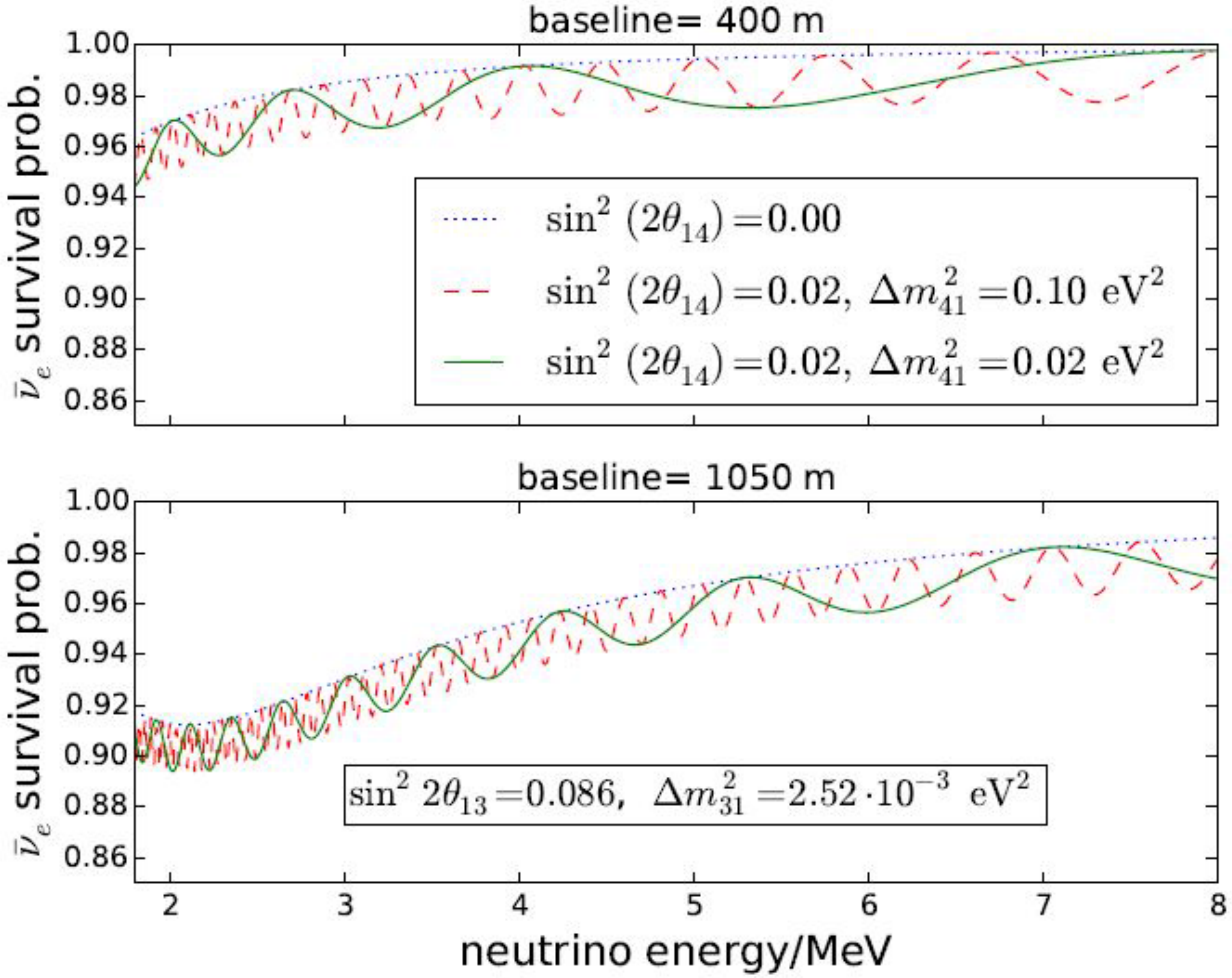
See Talk by Pranava Surukuchi

2 ν flavour approximation

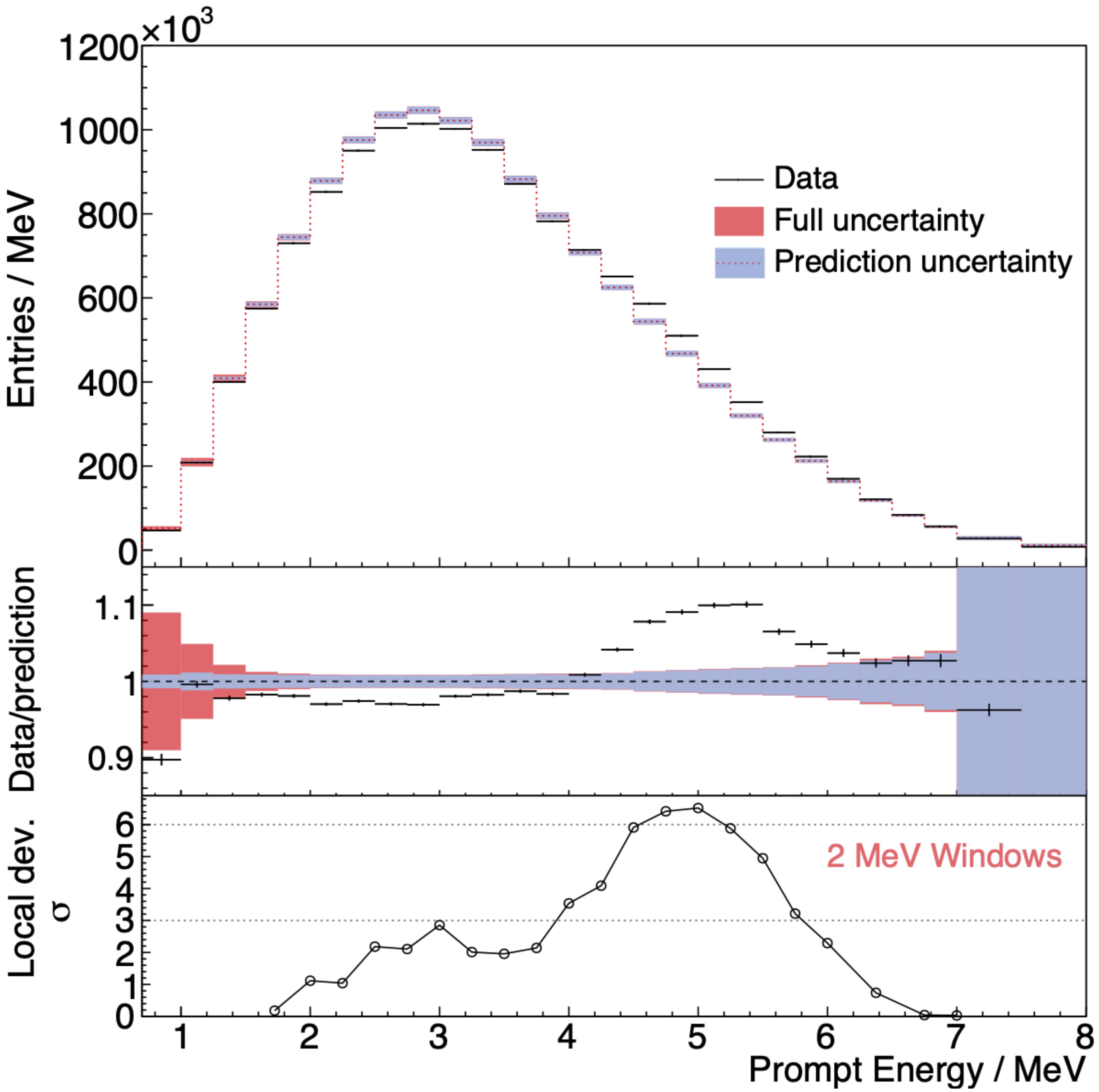
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{ee}L}{4E}\right) - \sin^2(2\theta_{14})\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

θ_{14} oscillation is always a deficit from θ_{13} oscillation



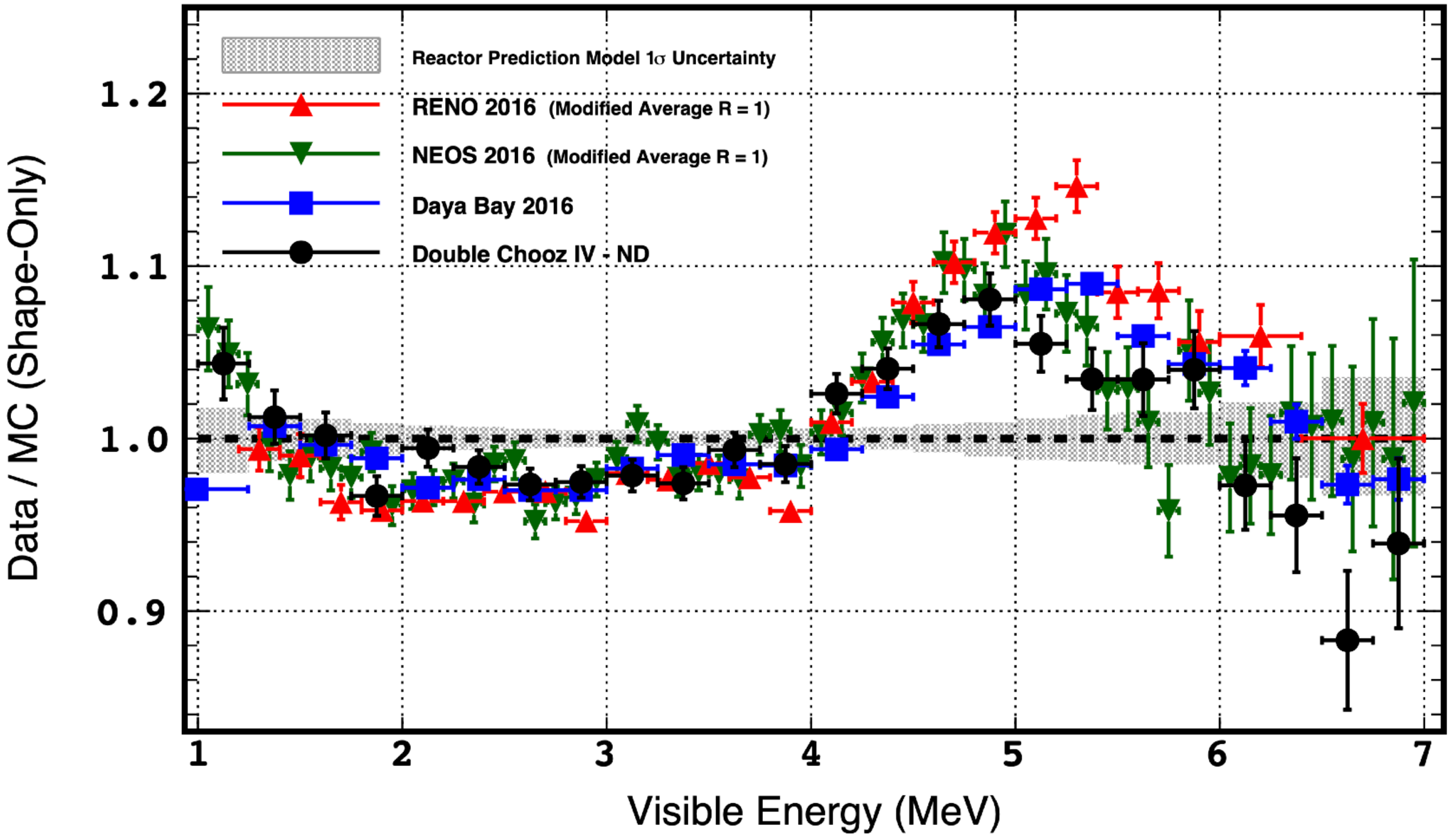


Energy Spectrum Distortion



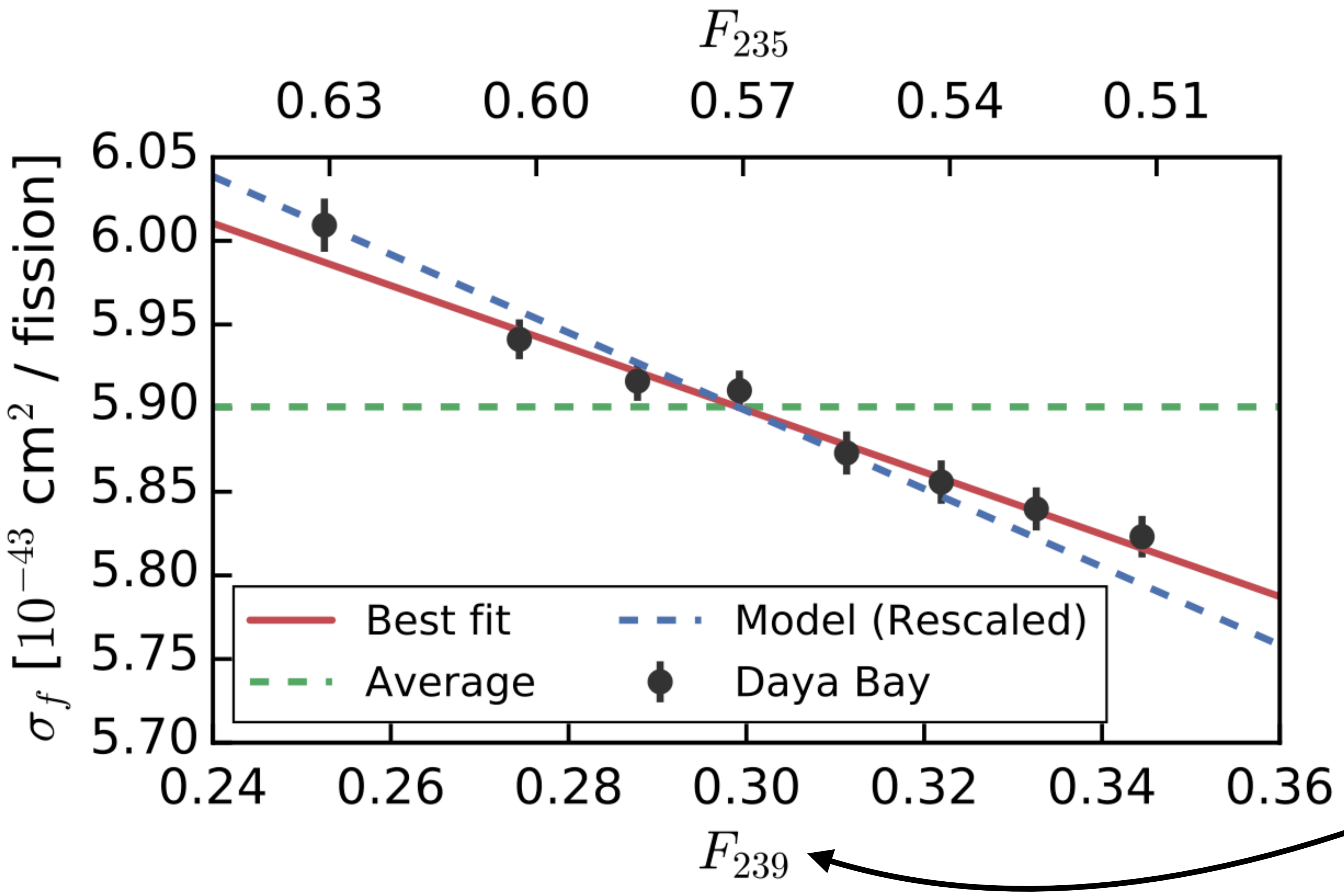
arXiv: 1904.07812

- Measured reactor neutrinos have a clear „Bump“ around 5 MeV with respect to the Huber+Müller expectation
    - consistently for near and far detectors
    - consistently for different experiments
- Double Chooz suggests a shape more complex than a simple gaussian (empirical)
- Daya Bay reports deviation from model prediction up to $6\ \sigma$
- θ_{13} measurement is robust against this distortion — near-far cancellation



arXiv:1901.09445

Energy Spectrum Distortion (Rate)



PhysRevLett.118.251801

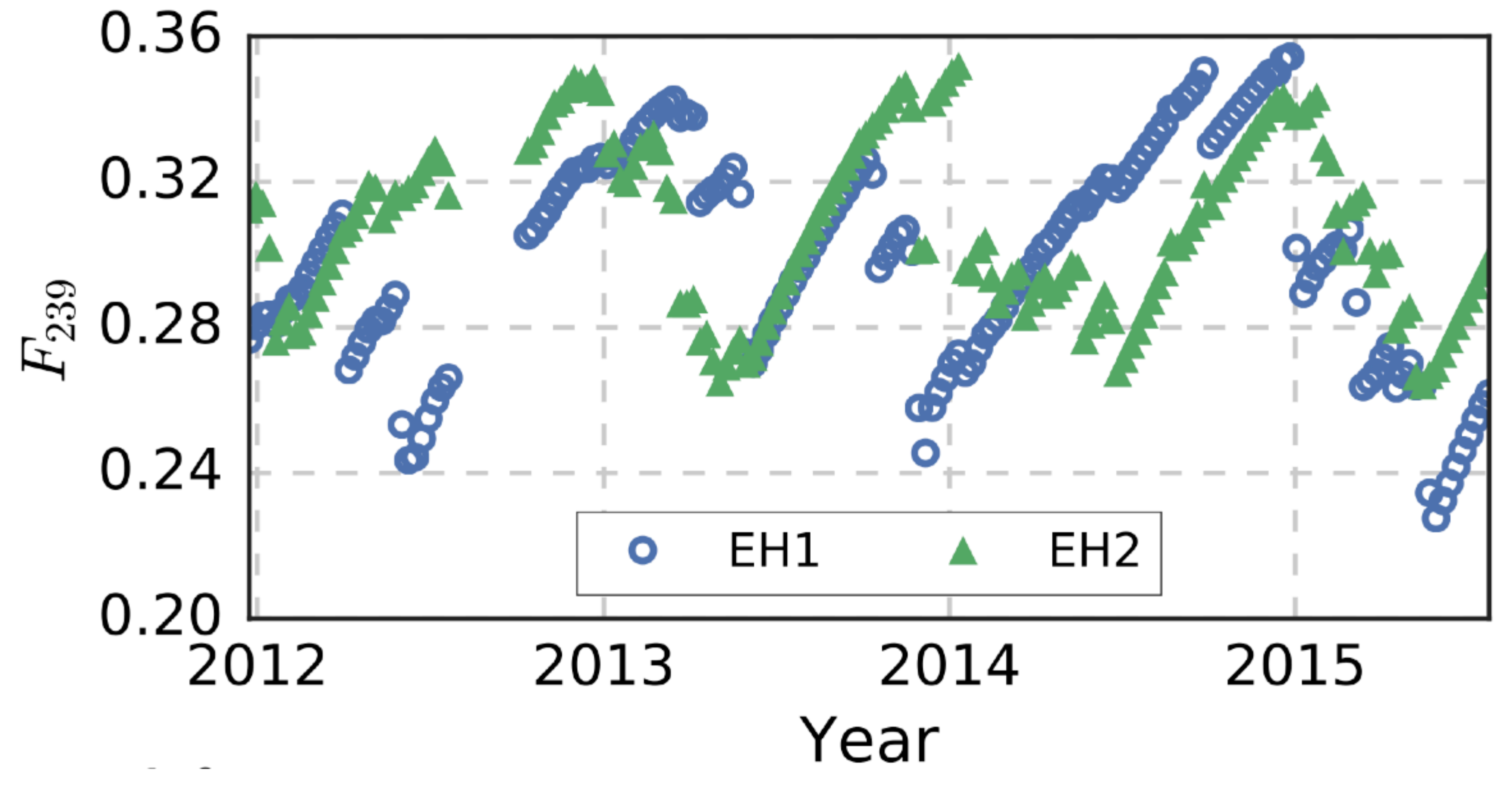
$$\sigma_f = \sum_i F_i \sigma_i$$

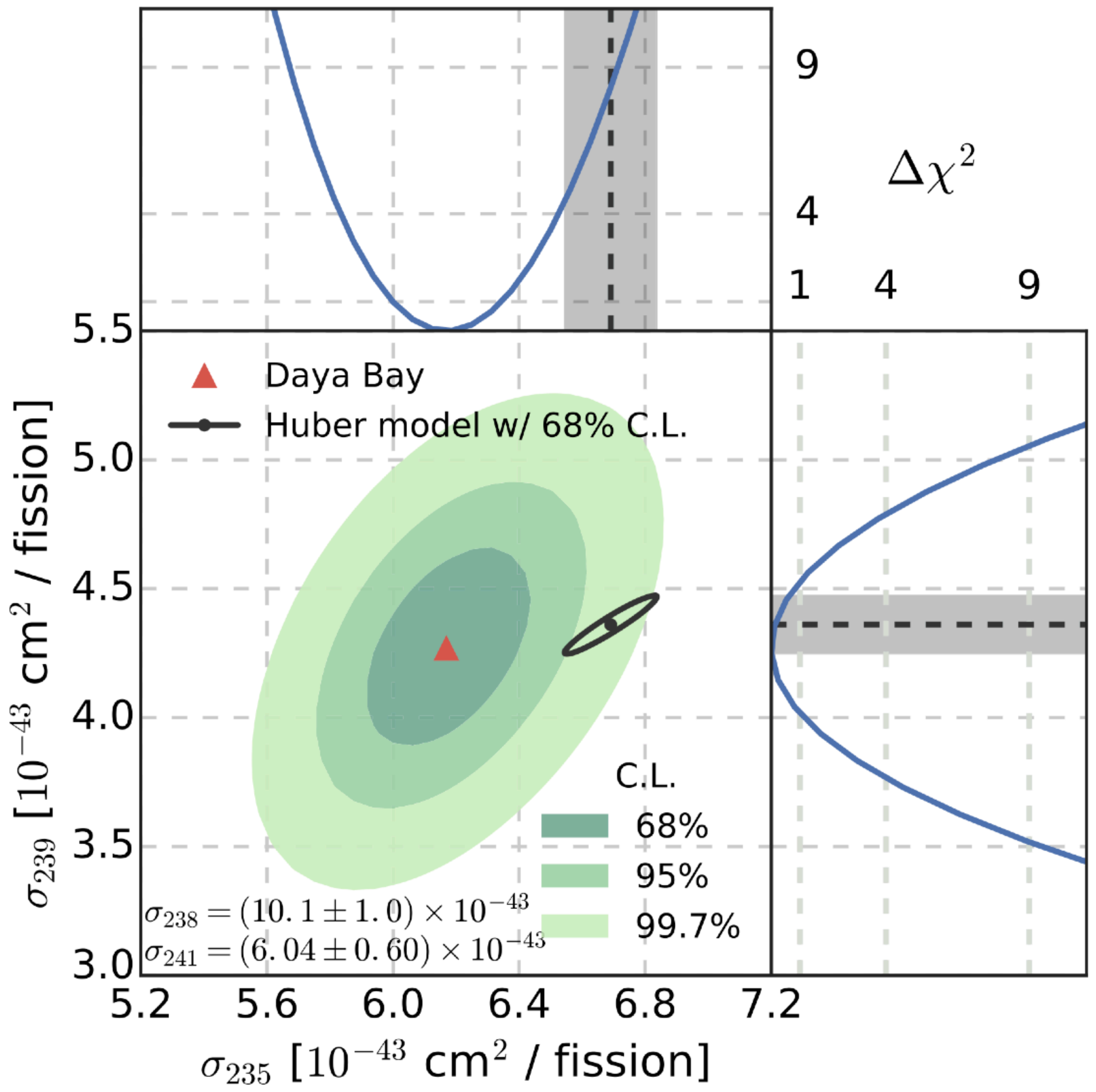
Total IBD yield

Isotope IBD yield

Isotope Fission Fraction

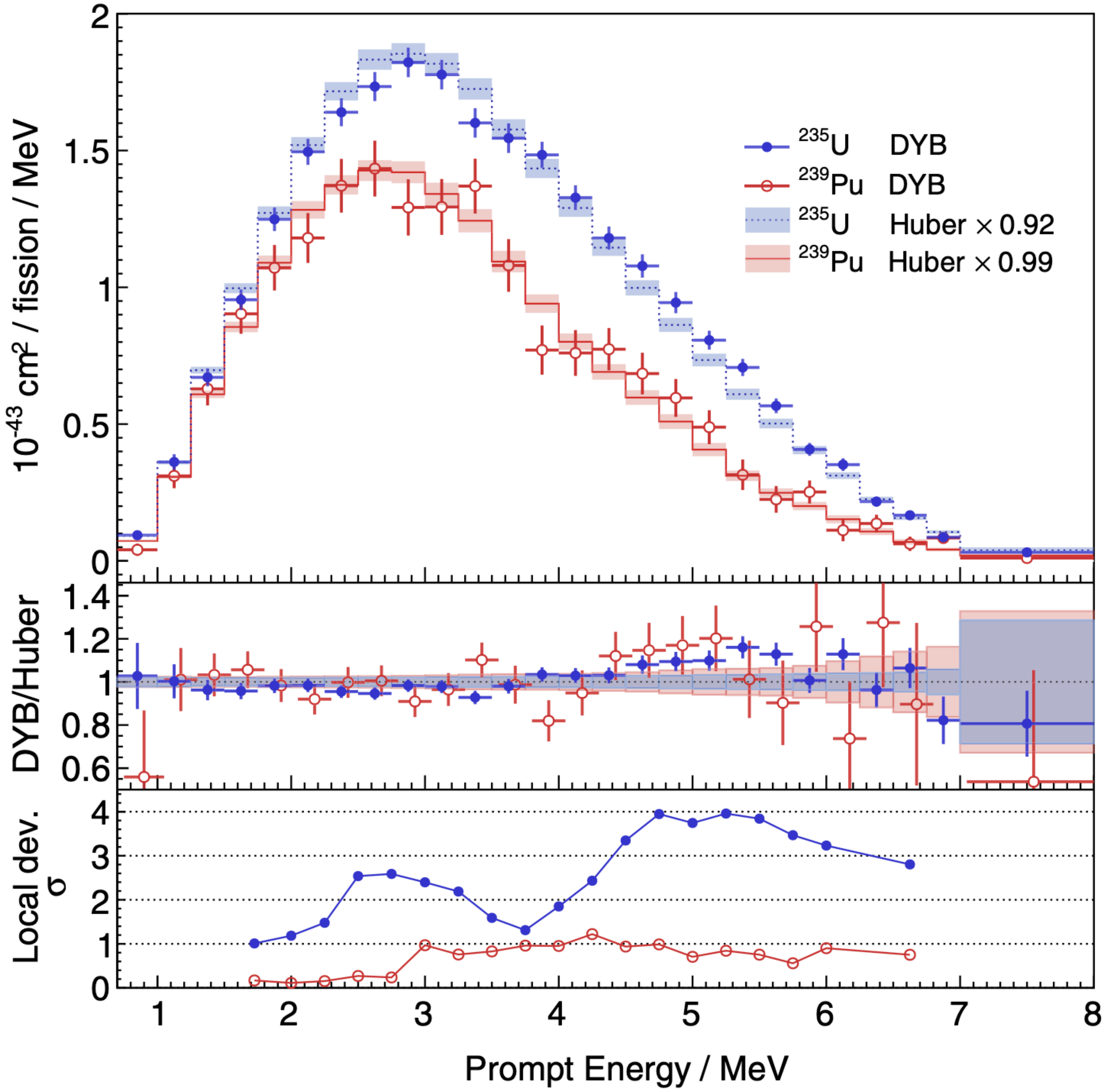
^{239}Pu





- Daya Bay measured the reactor fuel composition by observing the relative isotope fission fraction change over time
- Observed deficit of $7.8\,\%$ for ^{235}U ← indicates issue with isotope prediction for ^{235}U
- Assumption that all isotopes show the same deficit (basis of sterile neutrino assumption) is disfavored by $2.8\,\sigma$
- Measurement confirmed by RENO, also disfavors no-correlation between Bump and ^{235}U with $2.9\,\sigma$

Energy Spectrum Distortion (Shape)



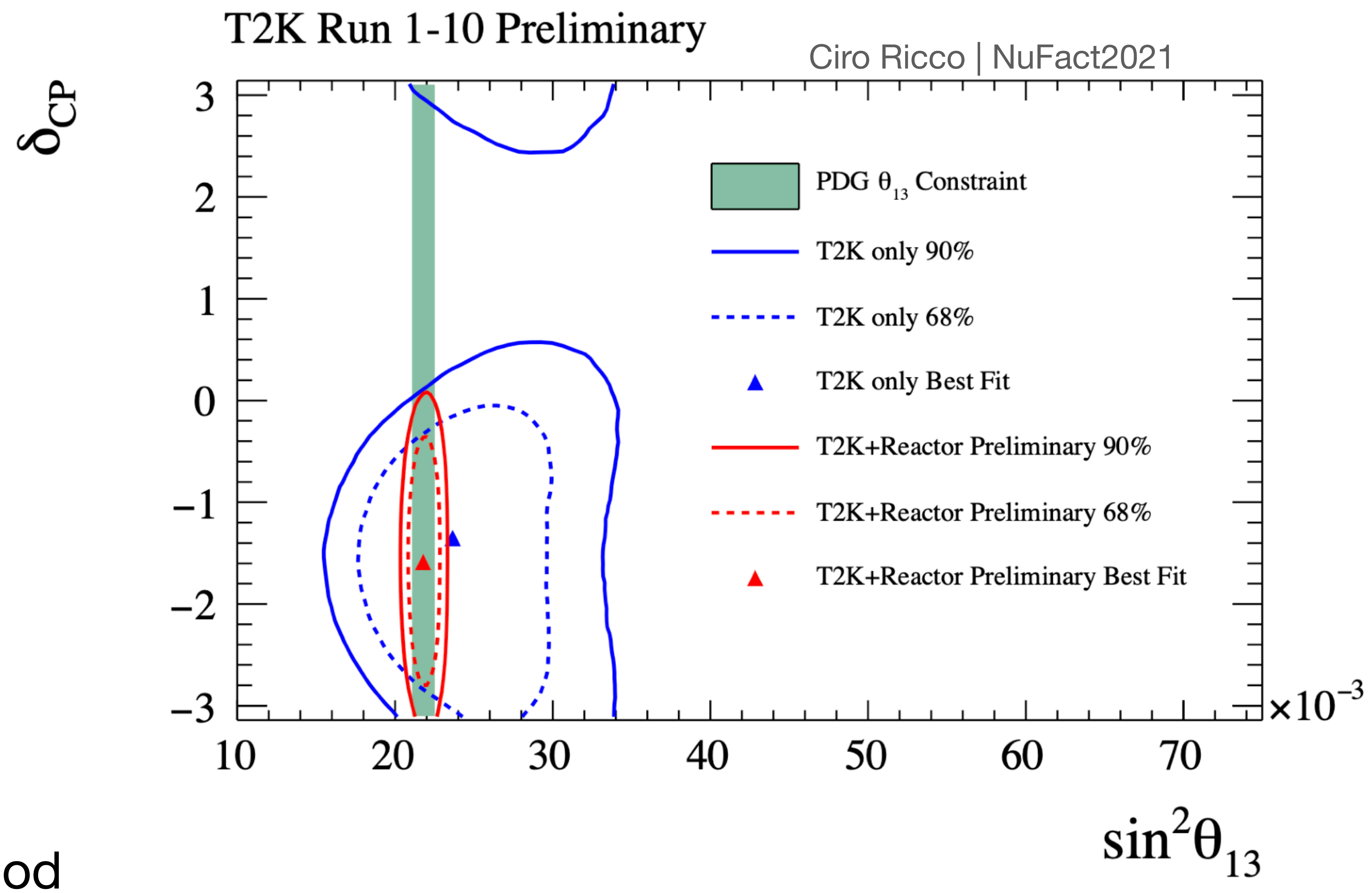
- Daya Bay also reports extraction of spectra from $^{235}\mathrm{U}$ and $^{239}\mathrm{Pu}$ fission
- Fit to relative differences between spectra with different fission fraction allows individual spectrum extraction from full IBD prompt spectrum
- Both spectra show an excess at $[4,6]\ \mathrm{MeV}$ with up to 1.2 σ for $^{239}\mathrm{Pu}$ and up to 4 σ for $^{235}\mathrm{U}$
- This confirms the rate only analysis and indicates an incorrect spectrum prediction in the Huber-Mueller model

Importance of a precise θ_{13} measurement

$$\overbrace{\begin{pmatrix}\nu_e\\\nu_\mu\\\nu_\tau\end{pmatrix}}^{\text{Flavour Eigenstate}} = \underbrace{\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}}_{U_{\text{PMNS}}} \overbrace{\begin{pmatrix}\nu_1\\\nu_2\\\nu_3\end{pmatrix}}^{\text{Mass Eigenstate}}$$

$$\overbrace{\underbrace{\overbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}^{\substack{\text{Atmospheric}\\ P(\nu_\mu\to\nu_\mu)}}}_{\theta_{23}\sim 45^\circ} \underbrace{\overbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}^{\substack{\text{Reactor and Accelerator}\\ P(\nu_e\to\nu_e)\ \&\ P(\nu_\mu\to\nu_e)}}}_{\theta_{13}\ \&\ \delta_{\text{CP}}} \underbrace{\overbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}^{\substack{\text{Solar}\\ P(\nu_e\to\nu_x)}}}_{\theta_{12}\sim 33^\circ}}$$

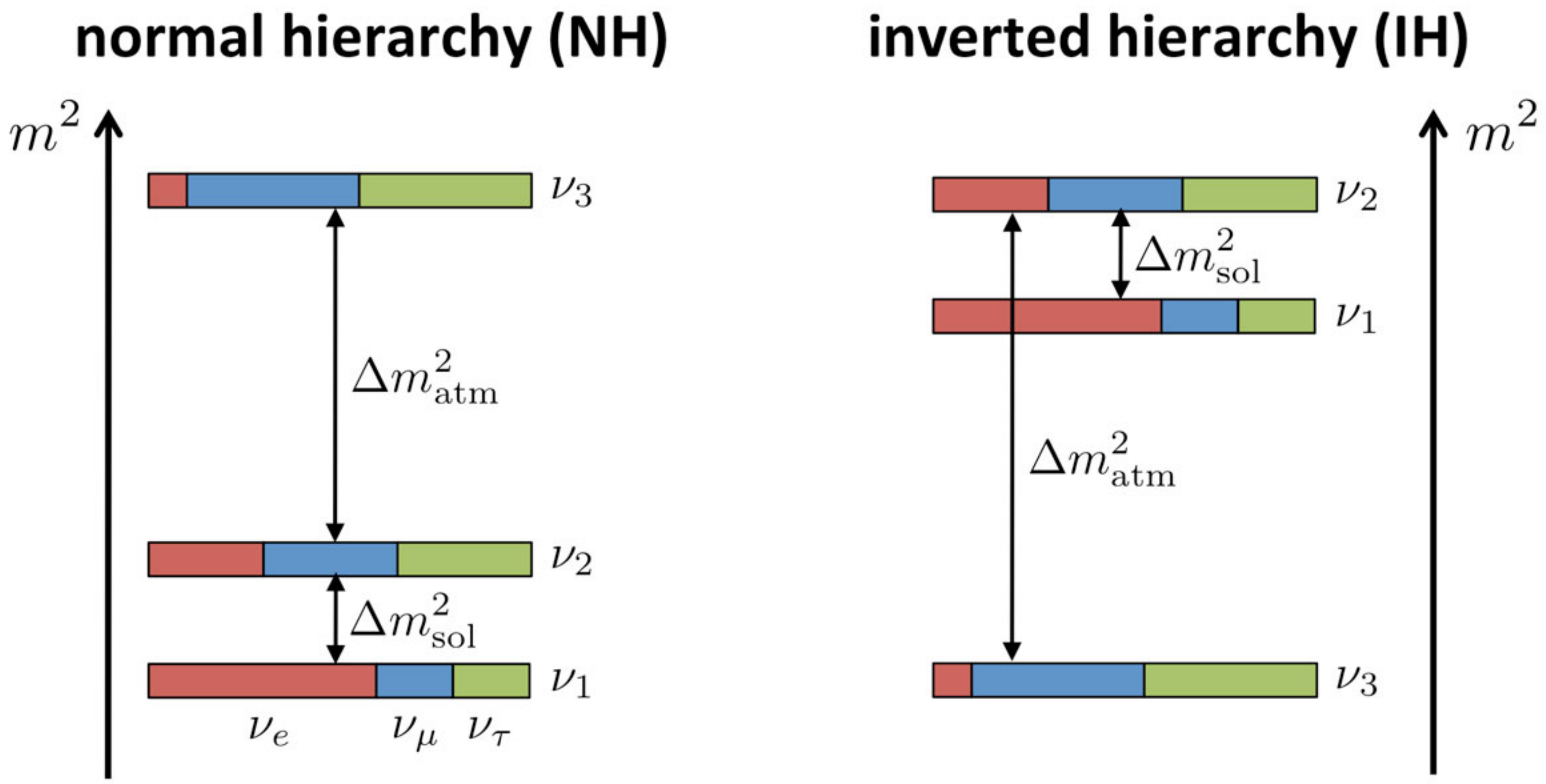
- CP violation is measured in the T2K experiment
- A more precise measurement of θ_{13} allows for a stronger constraint towards δ_{CP}
  - Tension between Daya Bay and Double Chooz needs to be understood
- Understanding θ_{13} means a better understanding of reactor fission processes

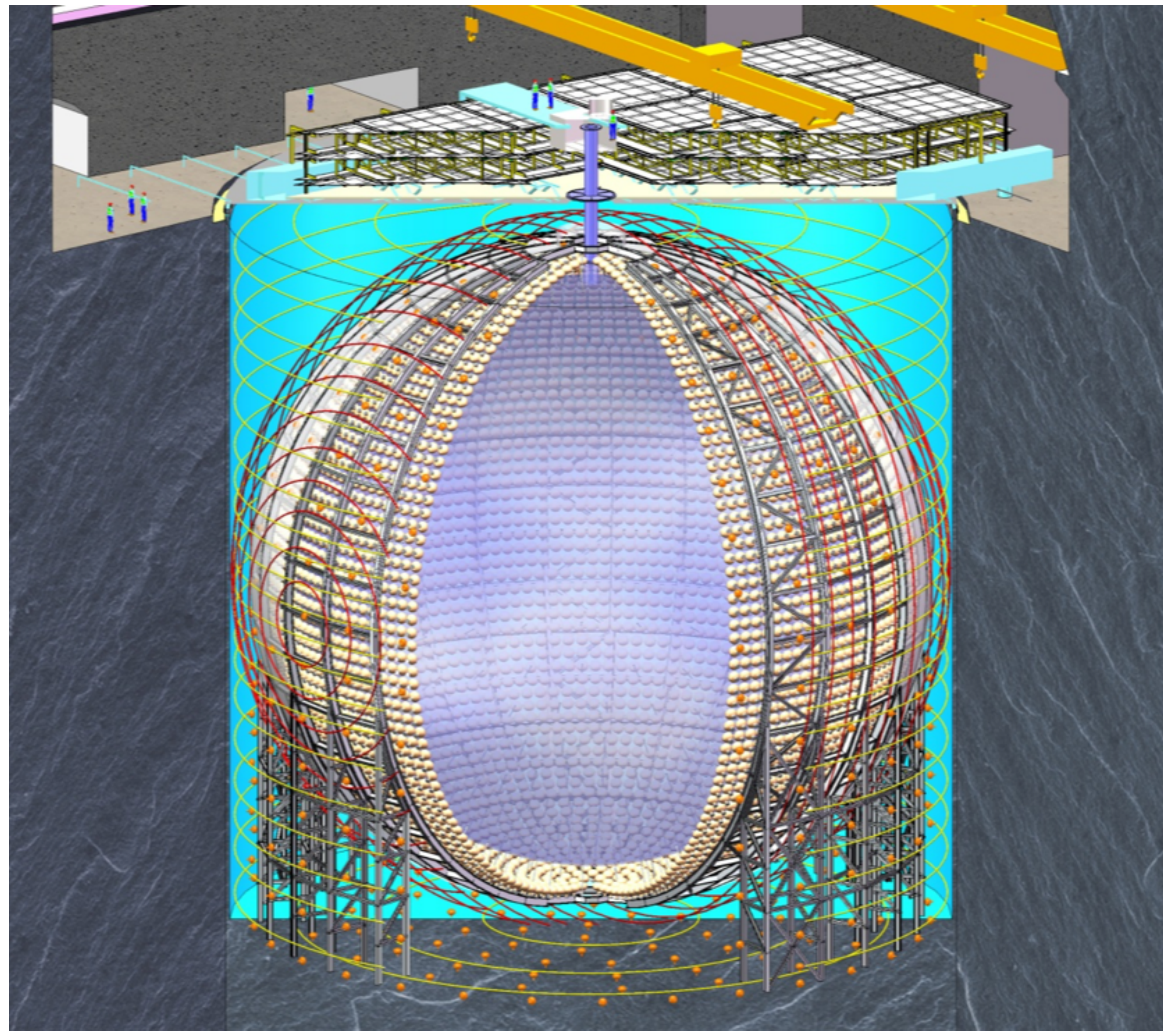


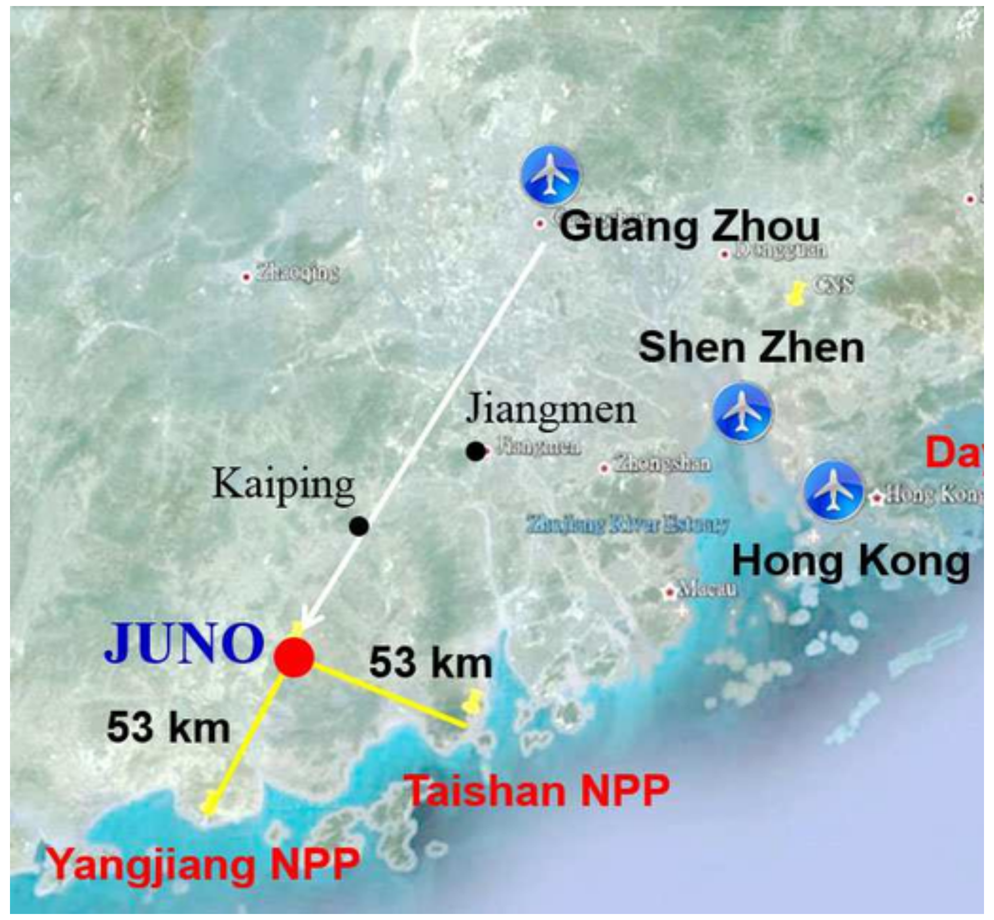
Ciro Ricco | NuFact2021

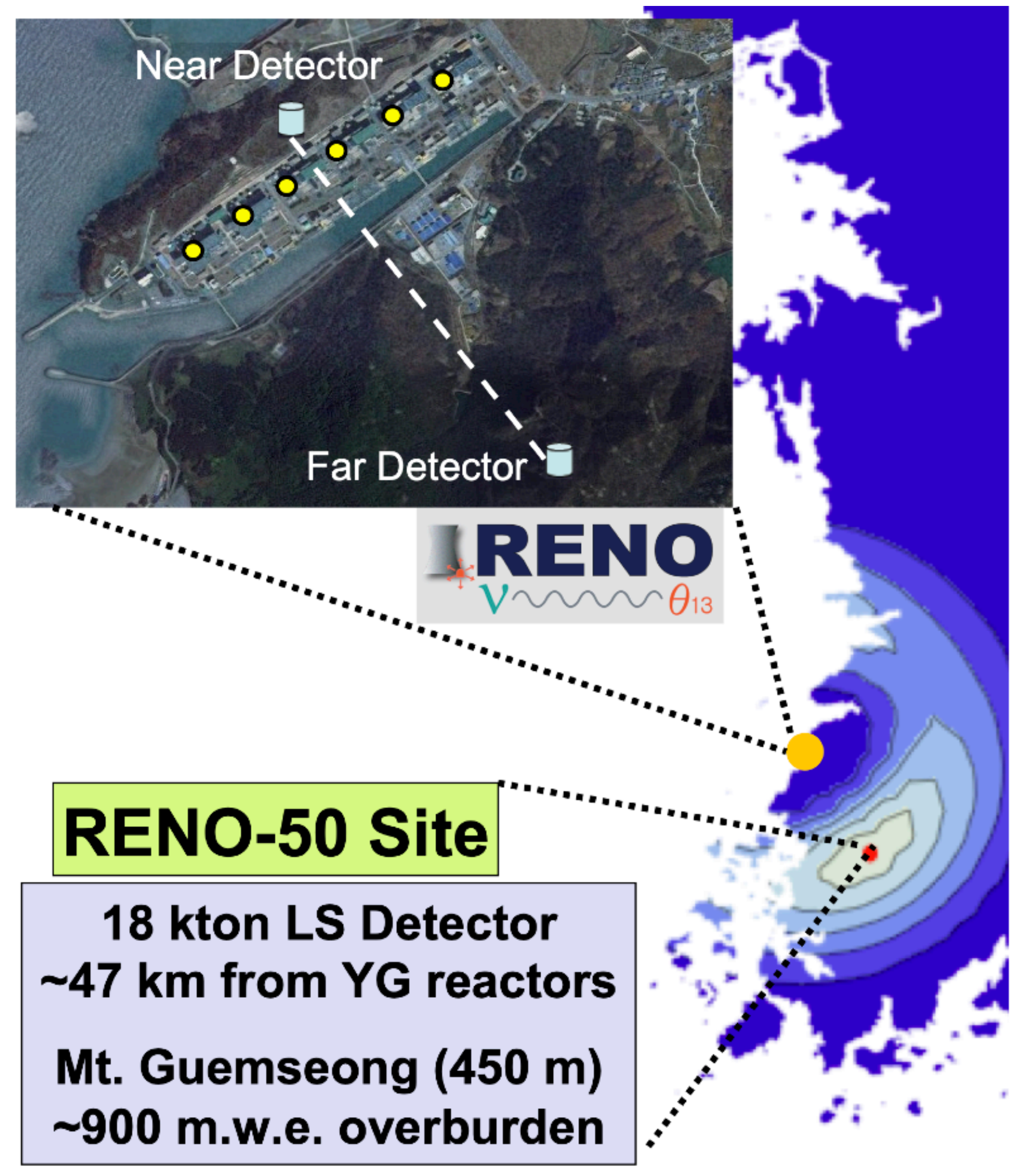
Future Neutrino Experiments

- Next generation of neutrino experiments will measure, among other things, the neutrino mass hierarchy
  - New experiment in china JUNO
  - Extension of RENO→RENO-50









RENO-50 Site

18 kton LS Detector
~47 km from YG reactors

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

Seon-Hee Seo | EPS 2015

Conclusion

- Precise measurement of the neutrino mixing angle θ_{13} with $3.4\,\%$ uncertainty by Daya Bay

$$\sin^2(2\theta_{13}) = 0.0856 \pm 0.0029$$

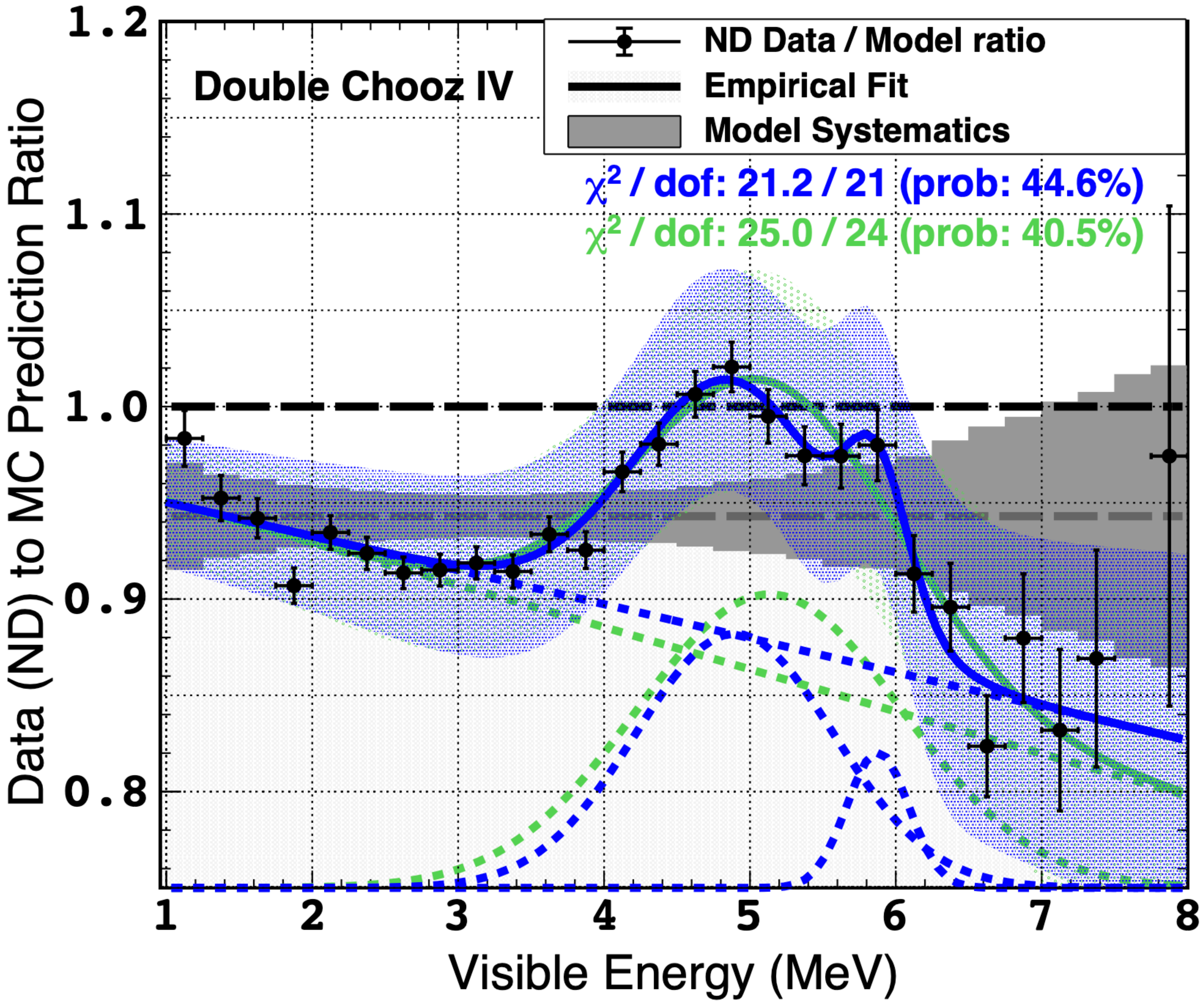
- Observed tension between Double Chooz and Daya Bay needs to be understood
- Impressive progress towards the investigation of the rate and shape differences to the prediction
  - Suggestion that the model prediction is incorrect

- Daya Bay stopped data taking at the end of 2020 → last final $\sin^2(2\theta_{13})$ result expected in 2022 with $2.7\,\%$ uncertainty
- Double Chooz stopped data taking at the end of 2018
- Future neutrino reactor experiments are currently being build

More exiting reactor neutrino physics is coming! Stay tuned!

Backup

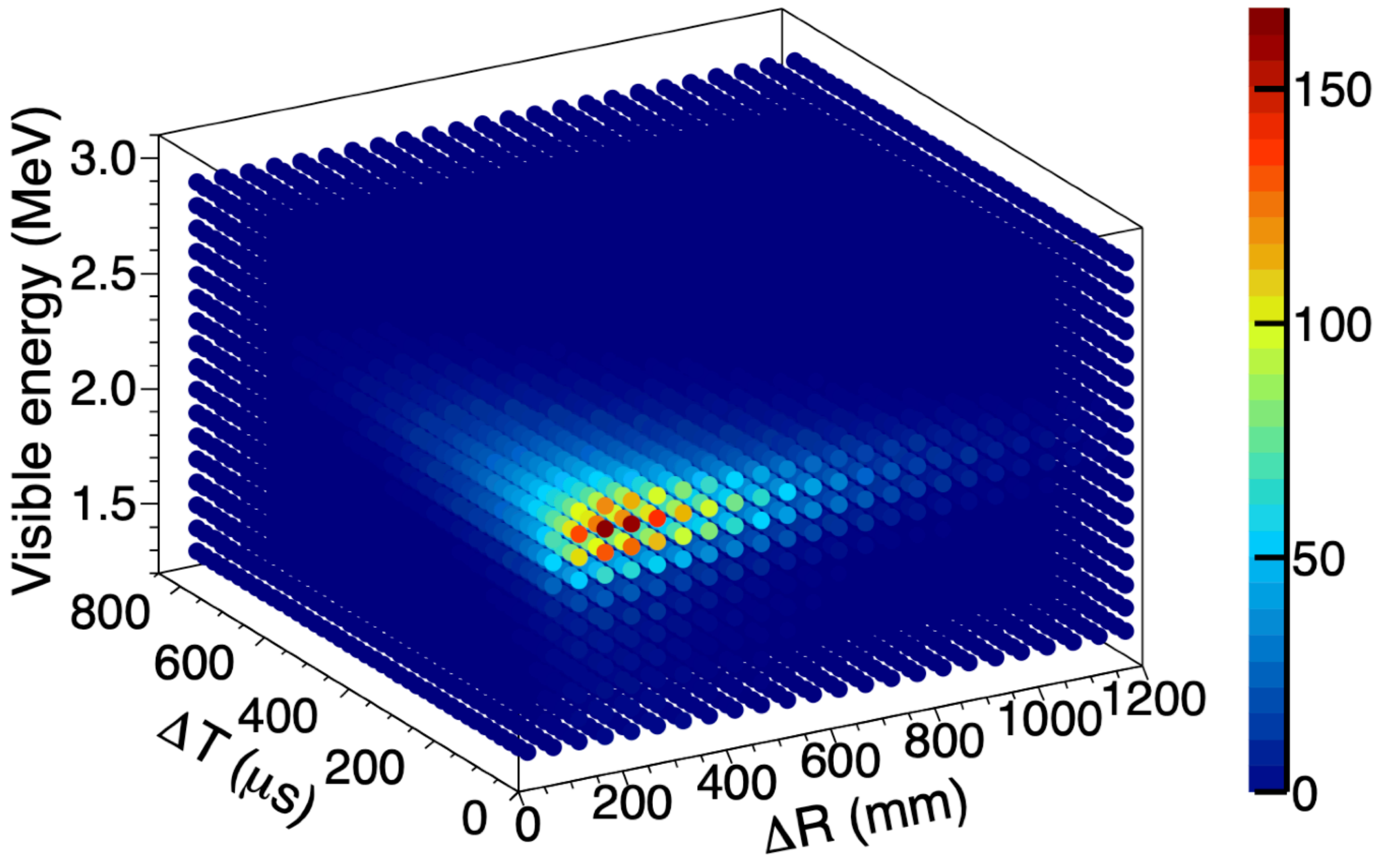
Empirical Bump Structure

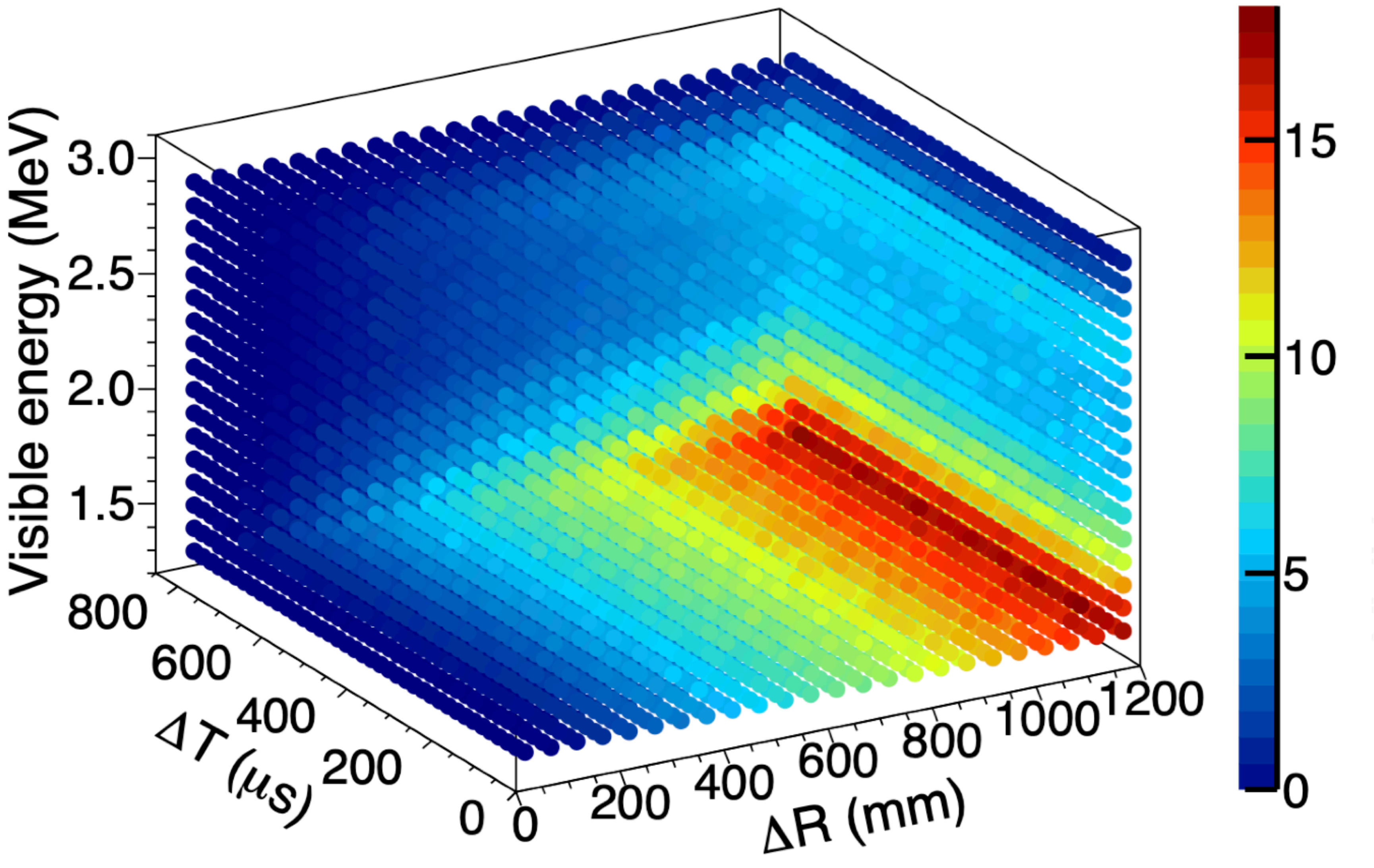


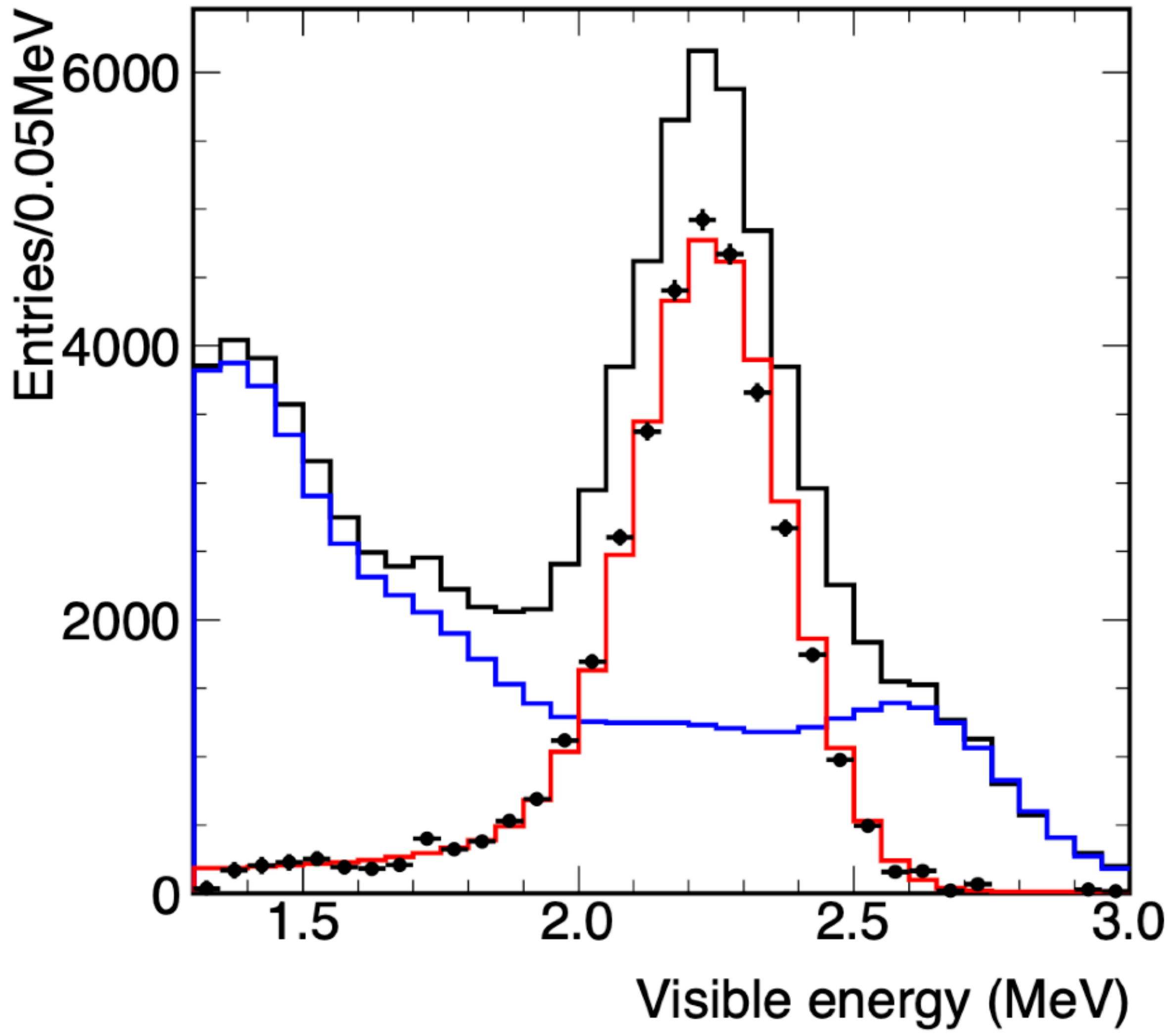
arXiv:1510.08937

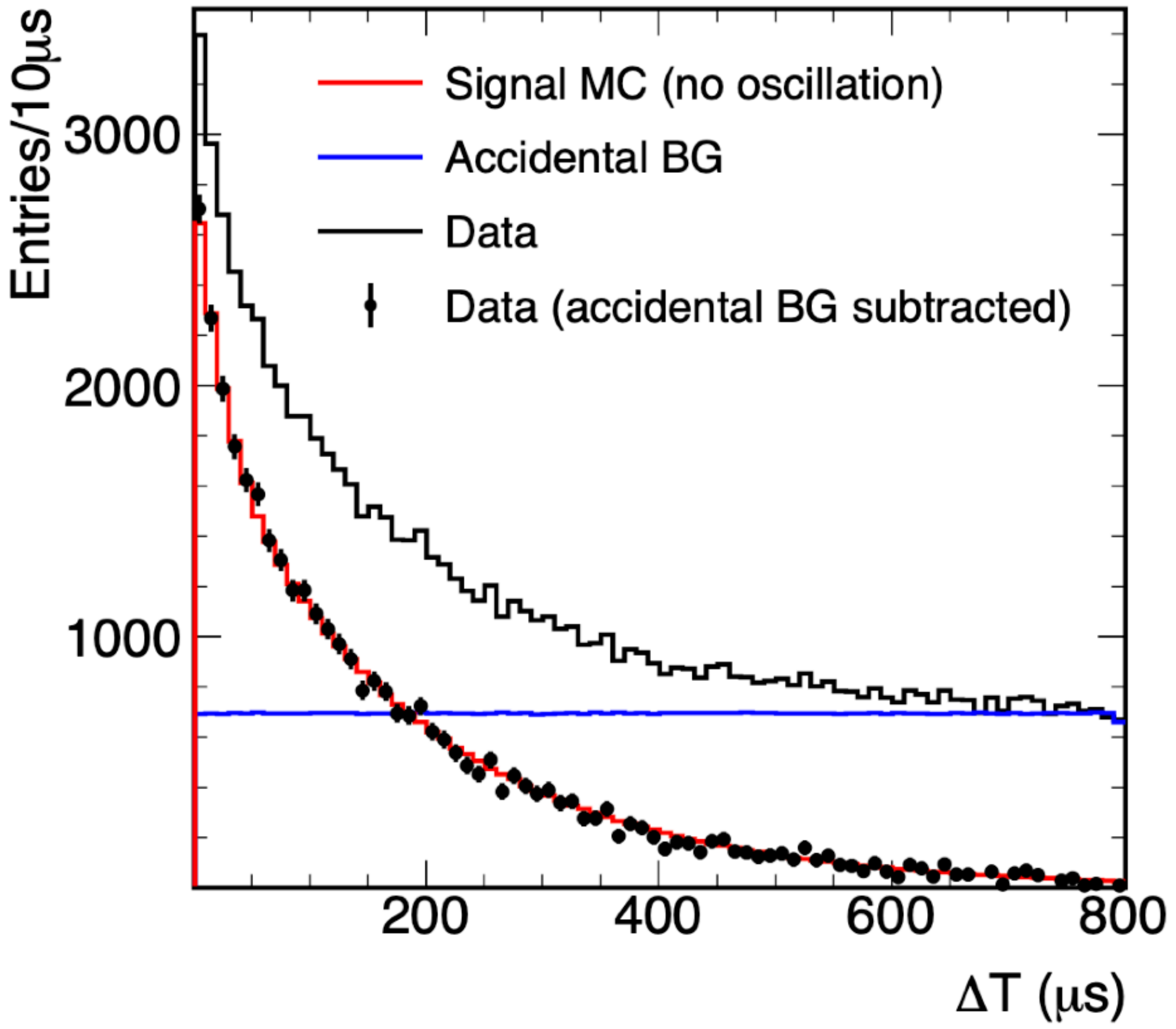
Double Chooz ANN

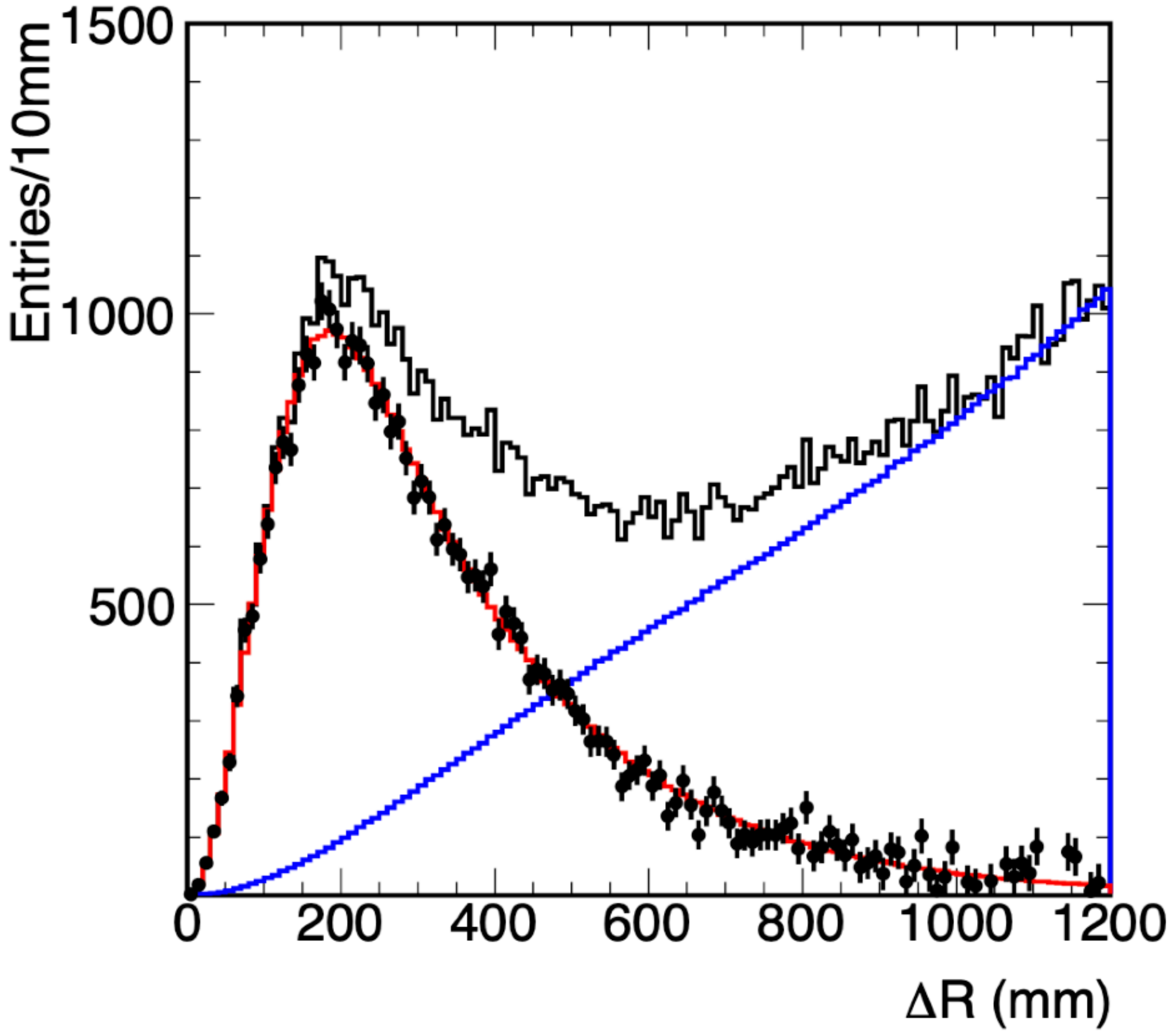
- IBD selection via neural network ($\Delta t, \Delta R, E_{\mathrm{delayed}}$) + μ-veto





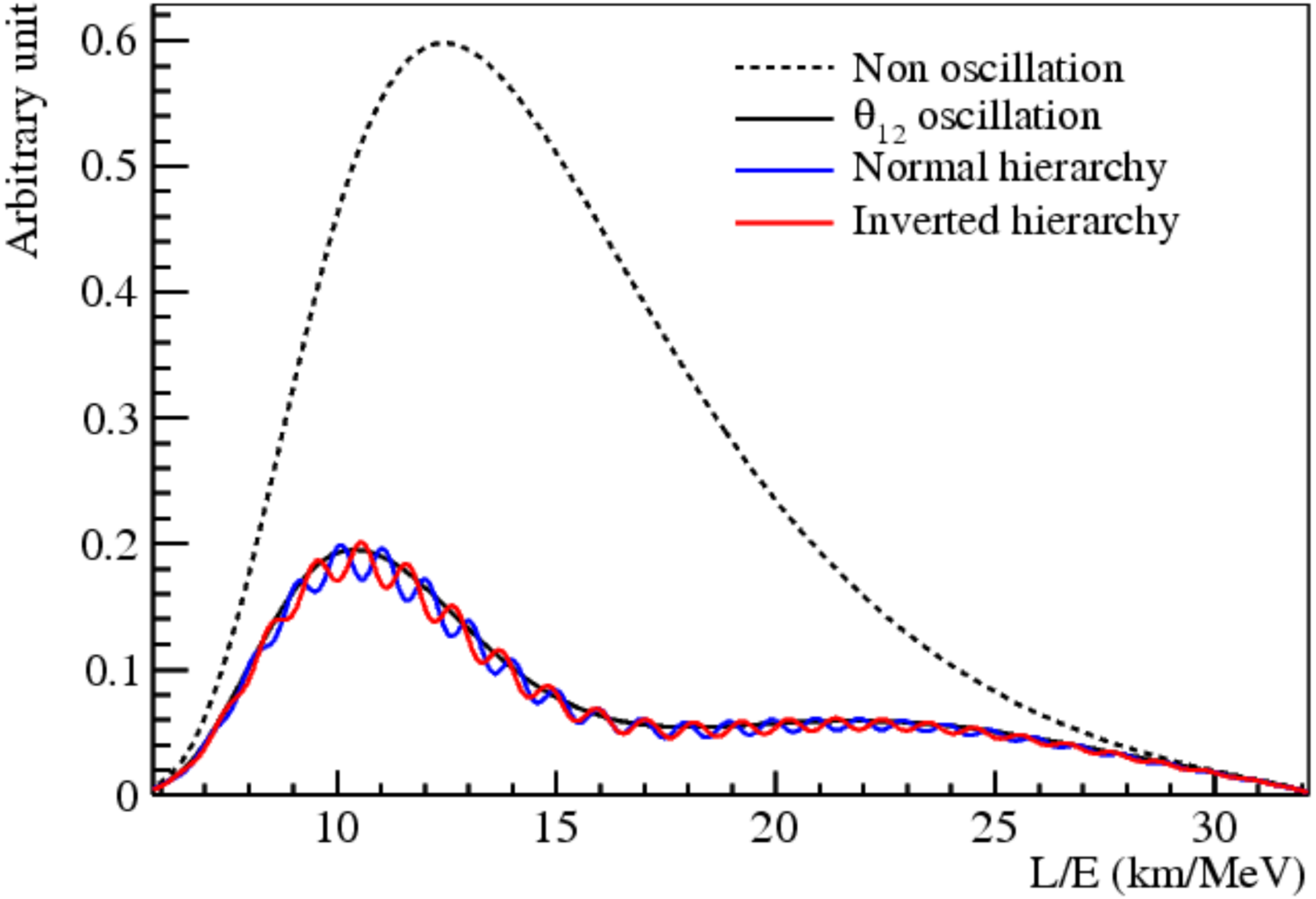






arXiv:1510.08937

Conclusion



Arbitrary unit
0.6
0.5
0.4
0.3
0.2
0.1
0
10
15
20
25
30
L/E (km/MeV)
Non oscillation
θ_{12} oscillation
Normal hierarchy
Inverted hierarchy