Neutrino Experiments at Nuclear Reactors

Past, Present, and Future

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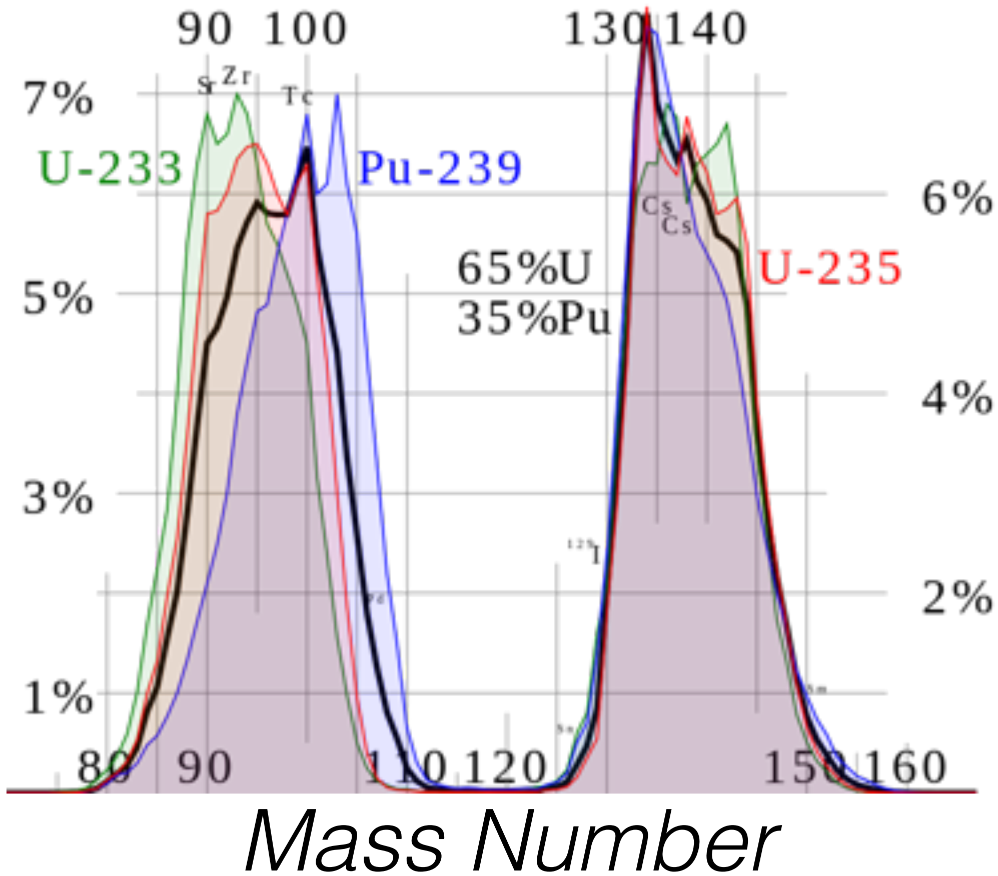
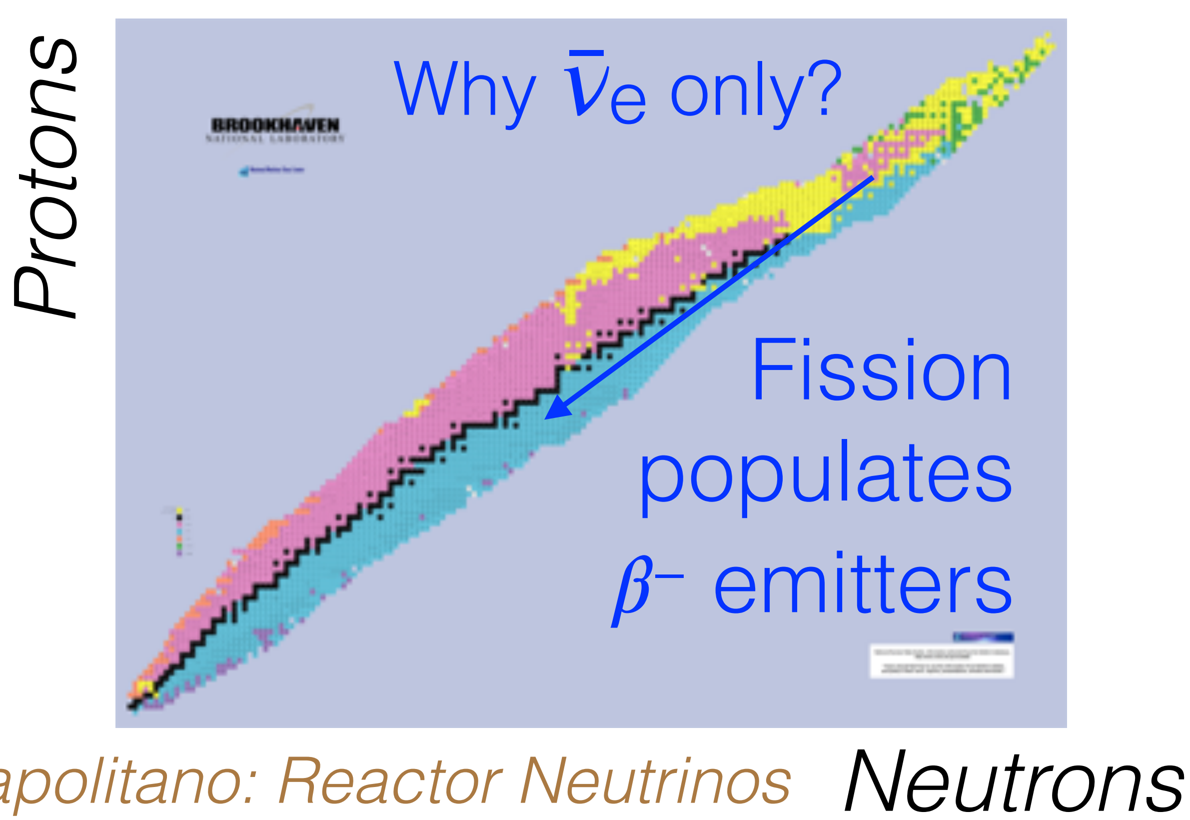
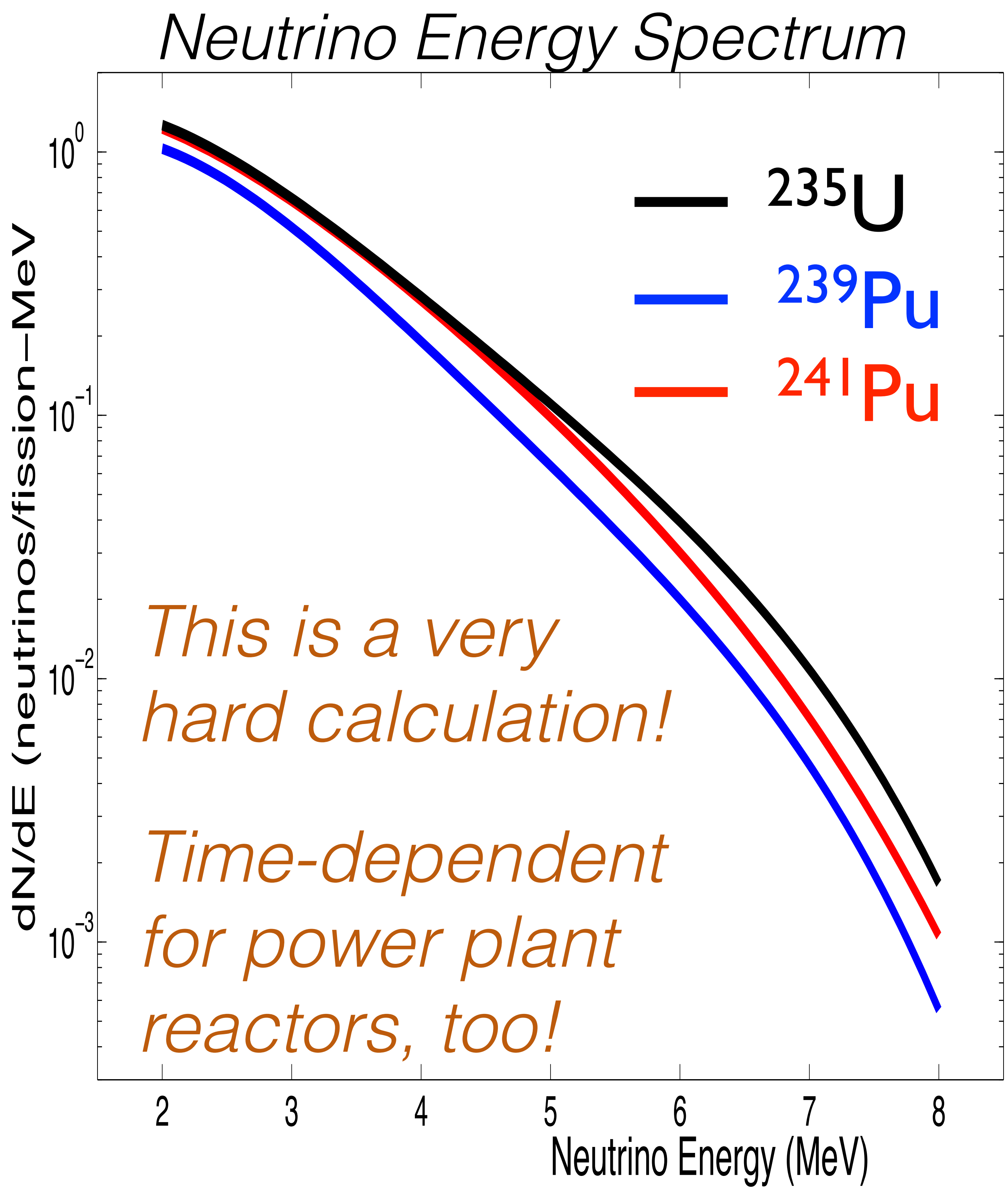
for the Daya Bay and PROSPECT Collaborations

FPCP 2016 Caltech
6-9 June 2016

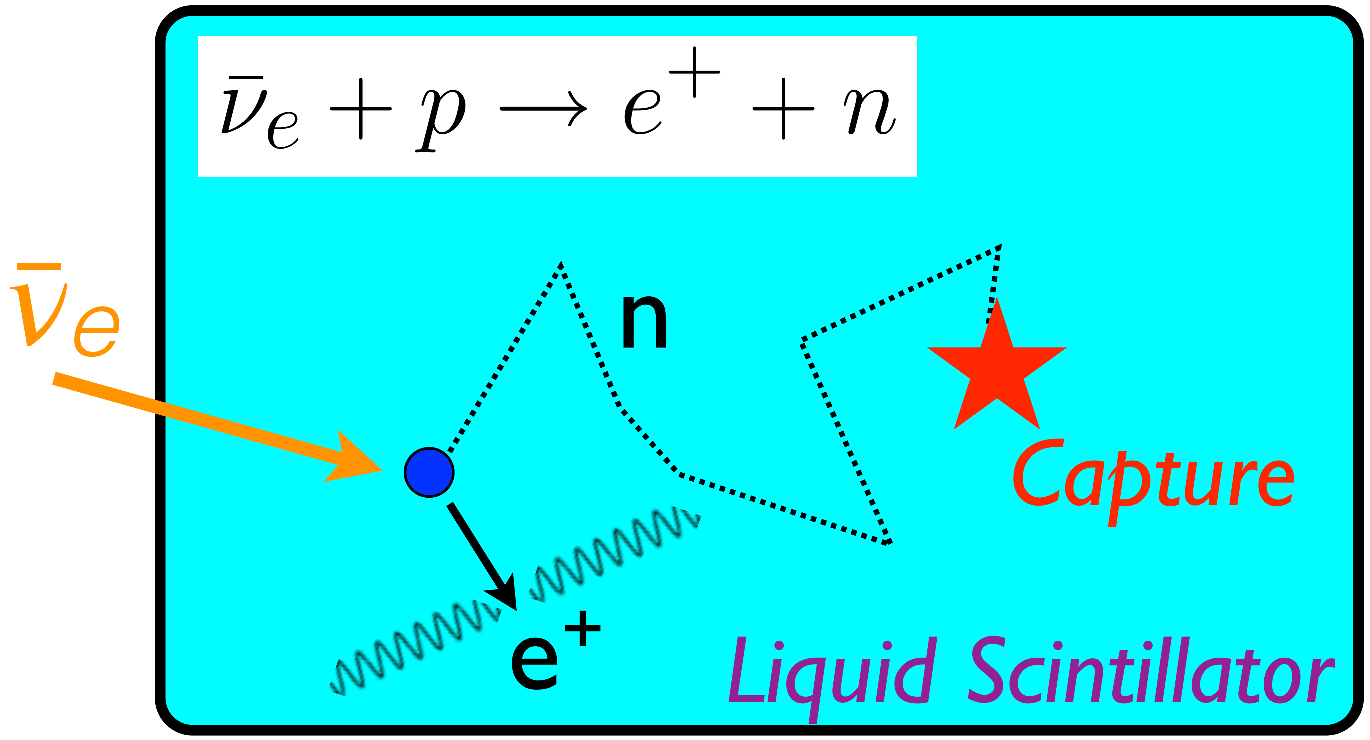
Reactors Produce $\bar{\nu}_e$ Only

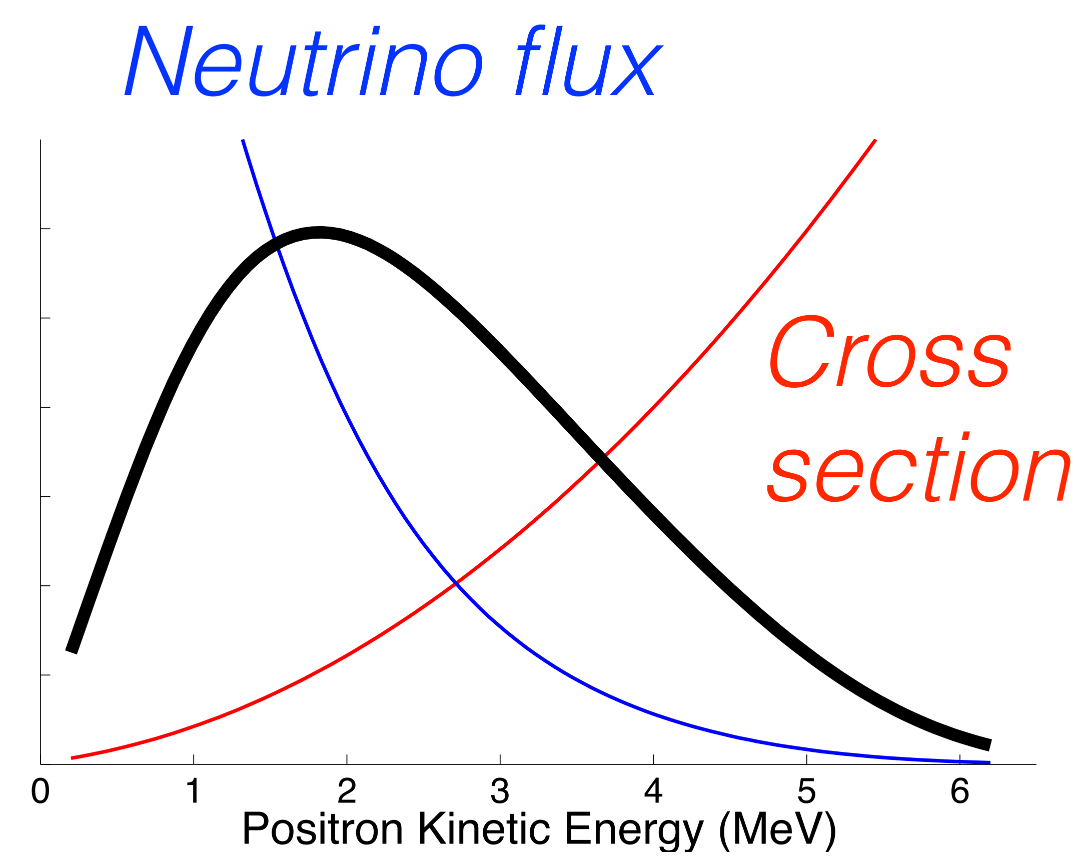






Detecting $\bar{\nu}_e$ at MeV Energies





- Get neutrino energy from **"prompt"** signal of positron plus annihilation energy (1.022 MeV)
- Neutron gives **"delayed"** signal via capture reaction
- Different capture options: *p*, *^{3}He*, *^{6}Li*, *Cd*, *Gd*

Primary Physics Topics

- Neutrino Oscillations: "Three Angles and a Phase"

PHYSICAL REVIEW D **78,** 071302(R) (2008)

$$P_{ee} = 1 - \{\cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) + \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) + \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})\},$$

$$\Delta_{ij} = 1.27(|\delta m^2{}_{ji}|L)/E_\nu$$

$$\delta m^2{}_{ji} \equiv m_j^2 - m_i^2$$

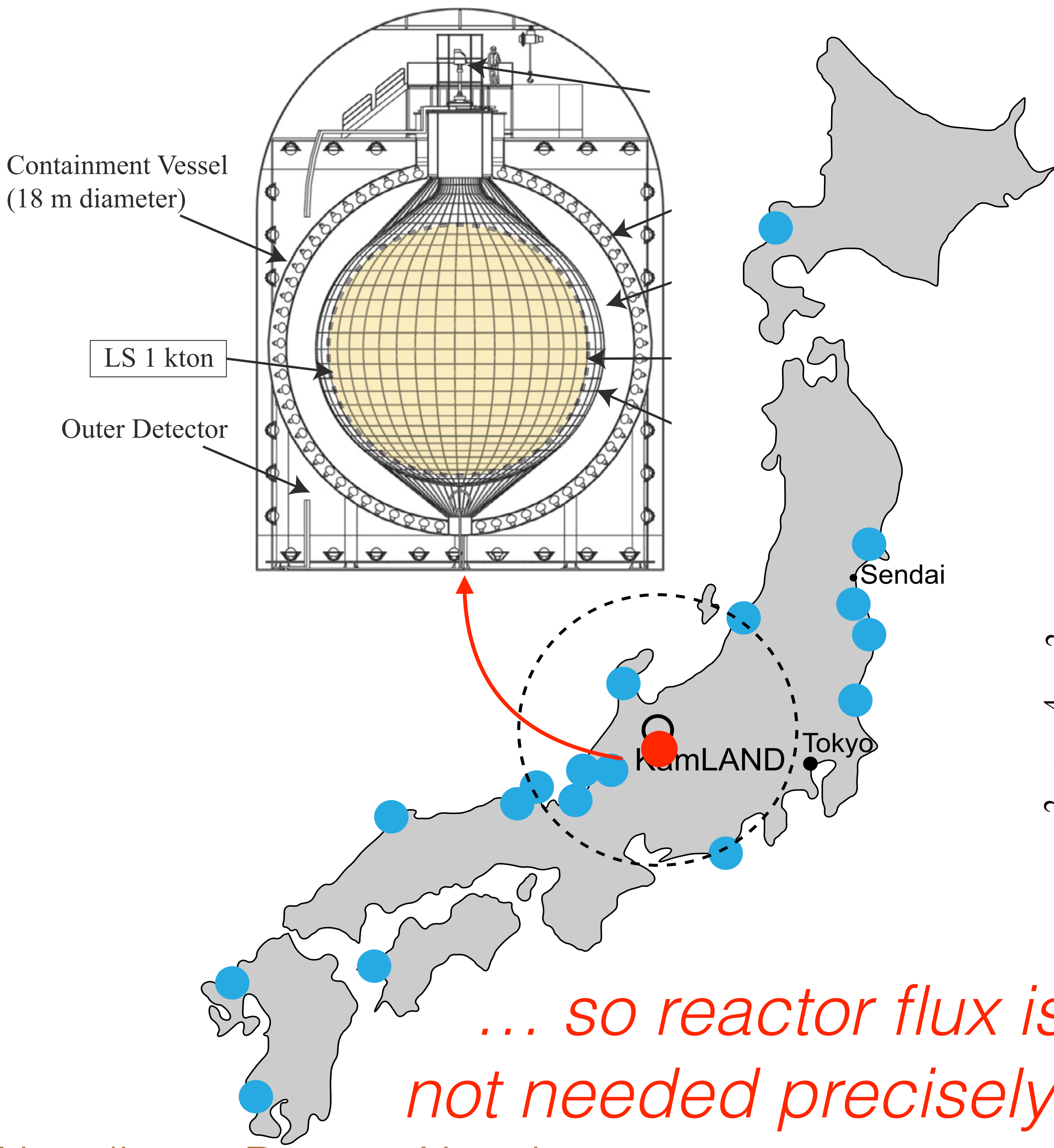
☛ Neutrino Disappearance at Different Distances

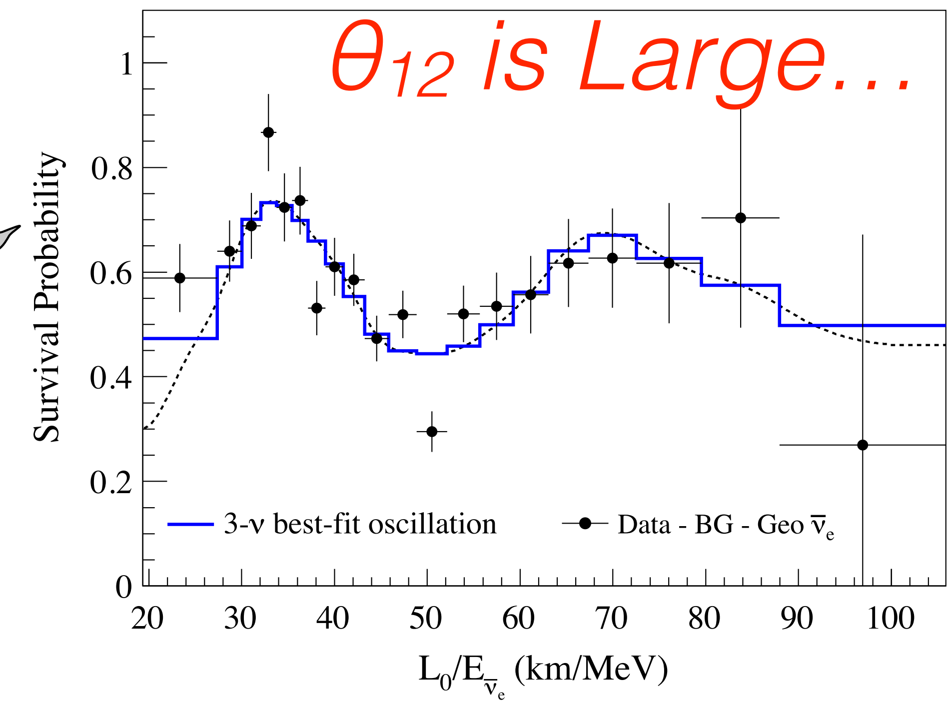
Measure θ_{12}: KamLAND, JUNO
Measure θ_{13}: Daya Bay, RENO, Double Chooz
Mass Hierarchy via θ_{12} vs θ_{13} Interference: JUNO

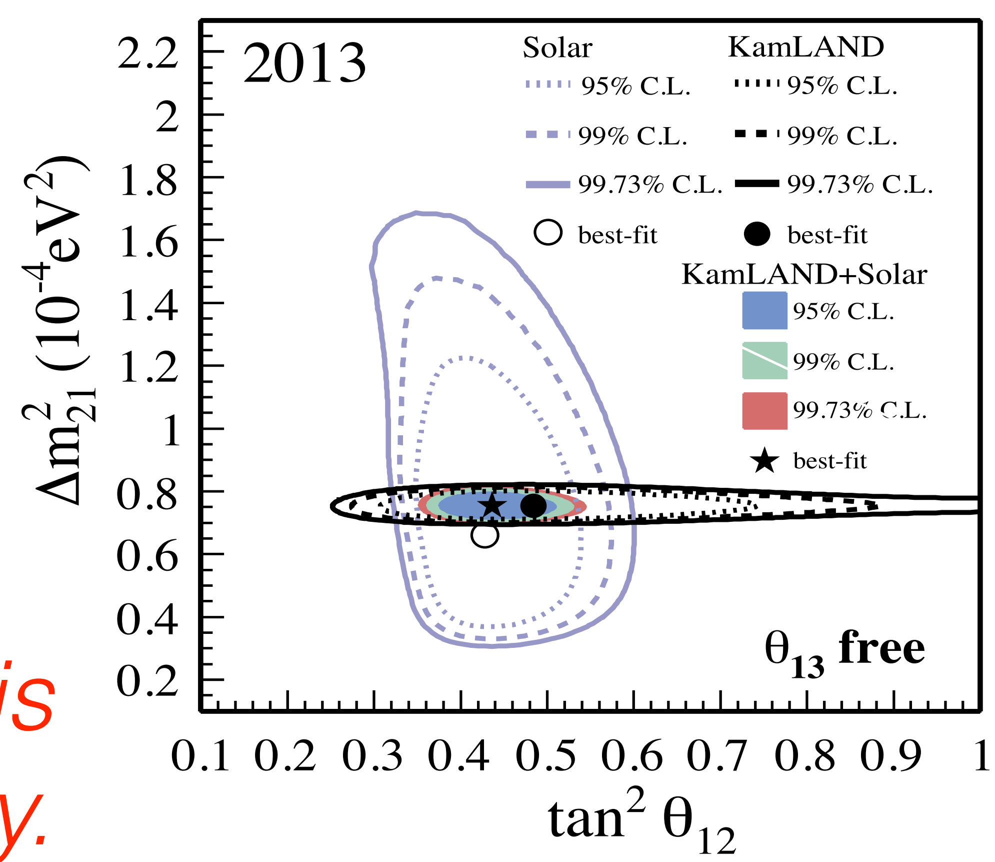
- Reactor Neutrino Flux and Spectrum Measurements
- Search for Sterile Neutrinos and other *BSM* physics

KamLAND: Measuring θ_{12}

Nuclear Physics B 908 (2016) 52–61







… so reactor flux is not needed precisely.

Mid 2000's: We Needed θ_{13}

Is there *CP* violation in the neutrino sector?

- ☛ Maybe, if the mixing matrix is really 3×3

However, ≈2005 we knew that θ_{12} and θ_{23} were large, and that θ_{13} was small ($\sin^2 2\theta_{13} \leq 0.15$)

- ☛ Cannot have *CP* violation if $\theta_{13}=0$

How to measure a very small value of θ_{13}?

- Appearance of ν_e in a ν_μ beam *(Next talk)*
- ★ Disappearance of ν_e from a reactor

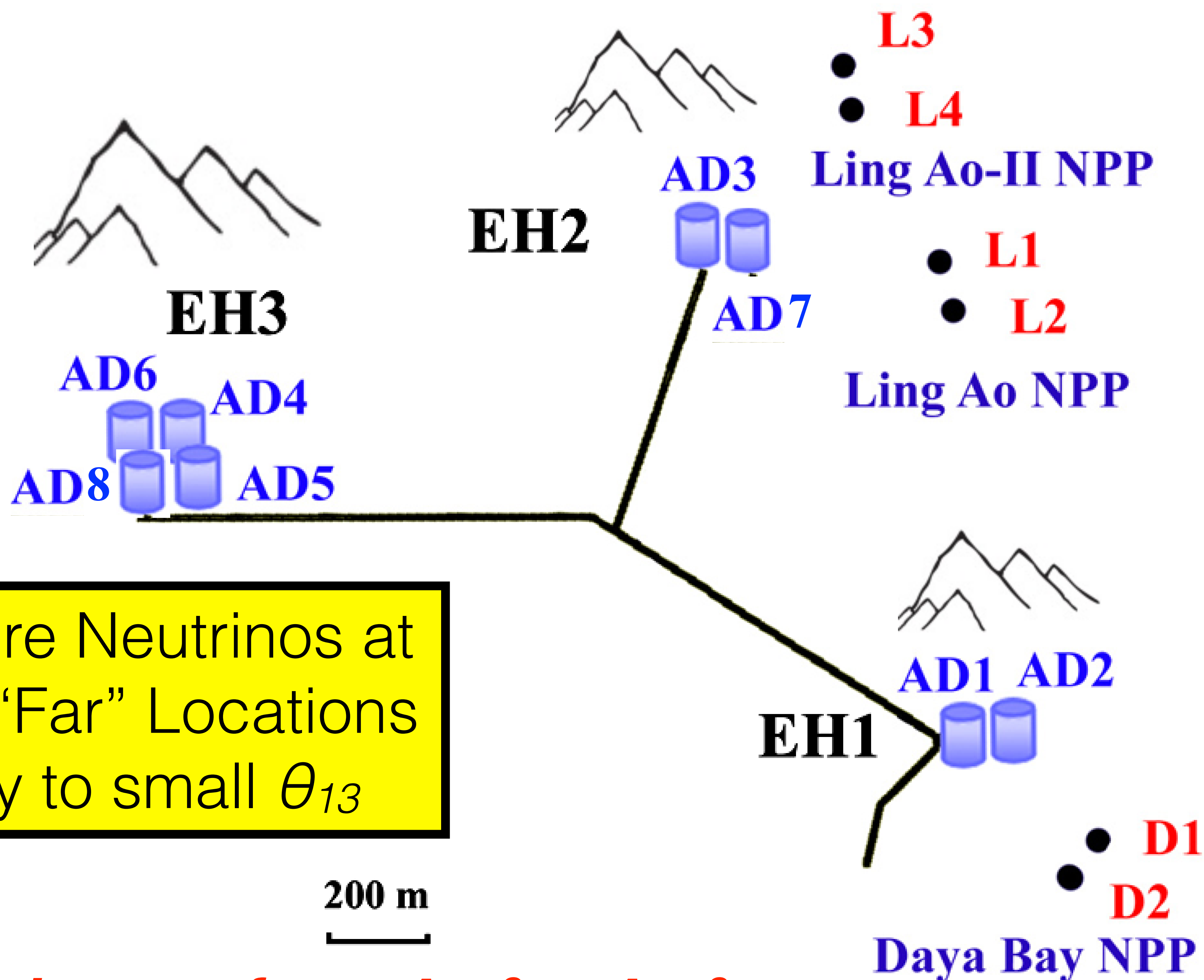
Reactor neutrino disappearance is difficult!

<u>Remember</u>: Calculating the neutrino flux is hard!

Experiments: Daya Bay, RENO, and Double Chooz

Daya Bay: Precision $\bar{\nu}_e$ Physics

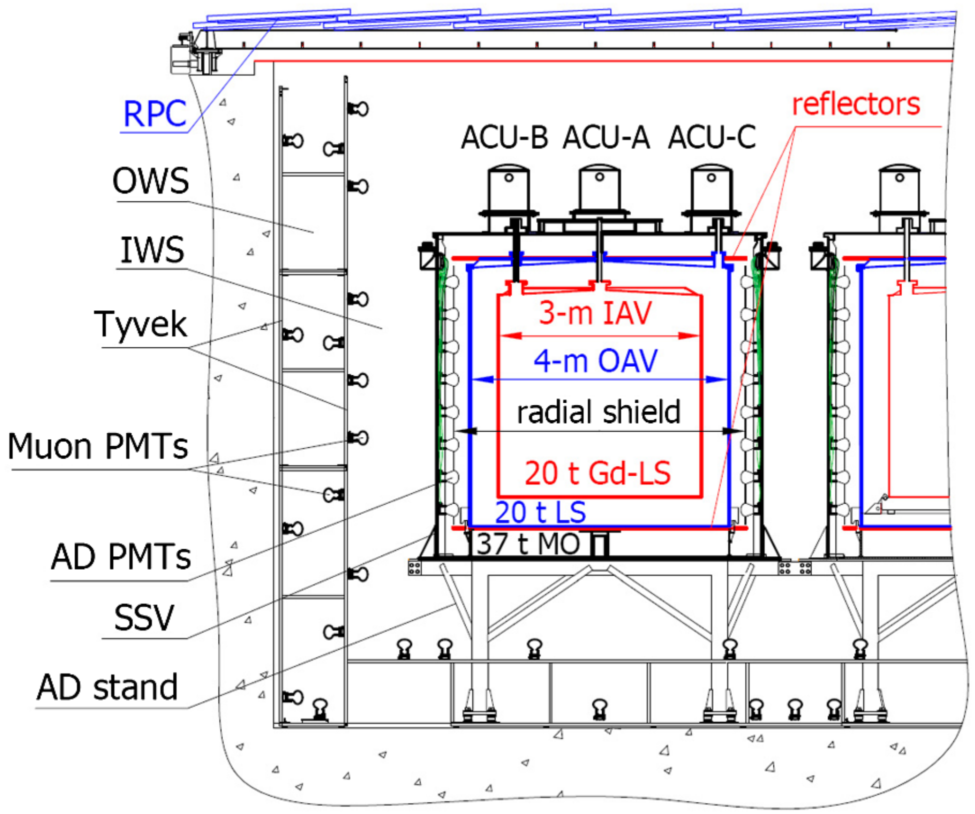
Detectors under granite "mountains"

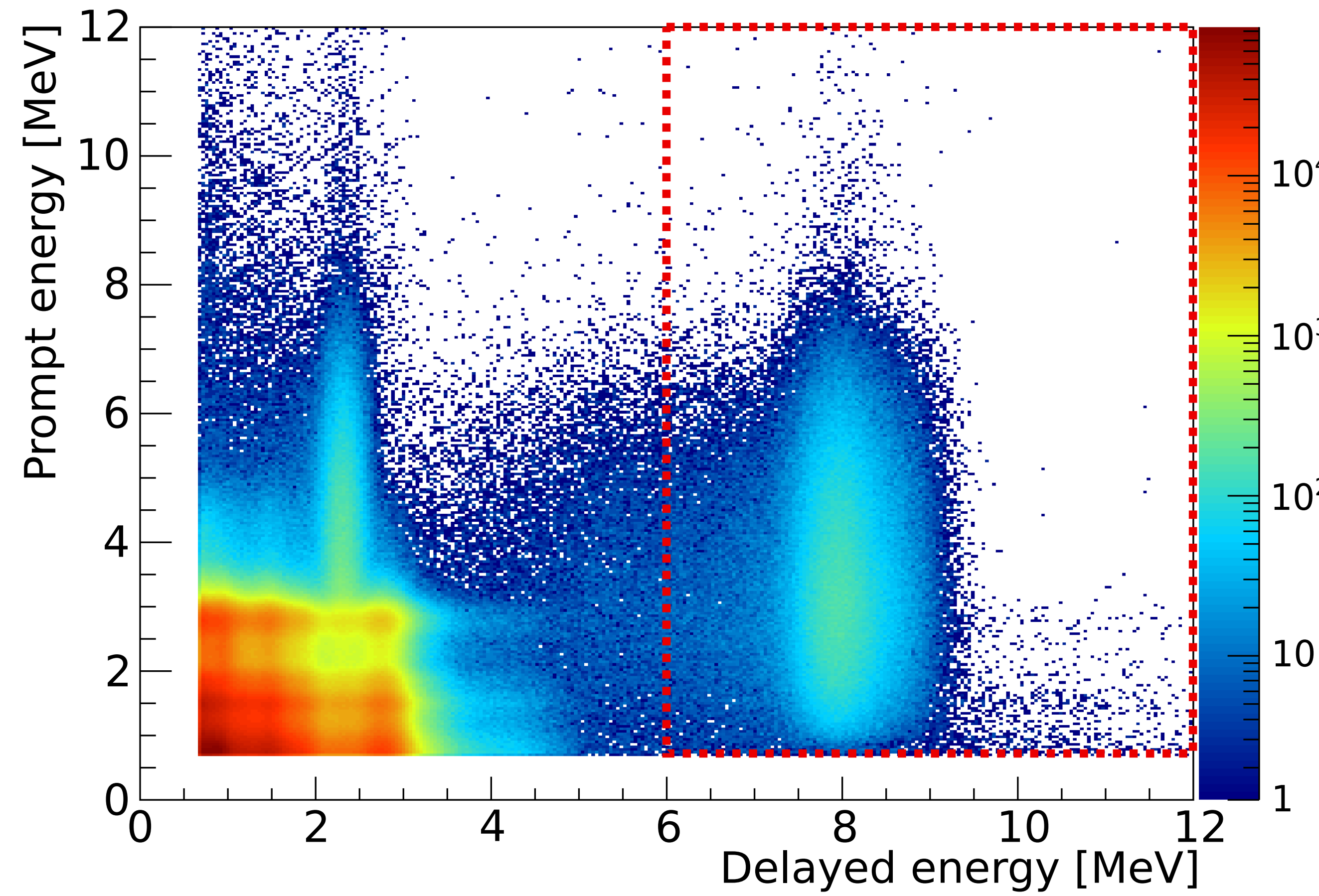


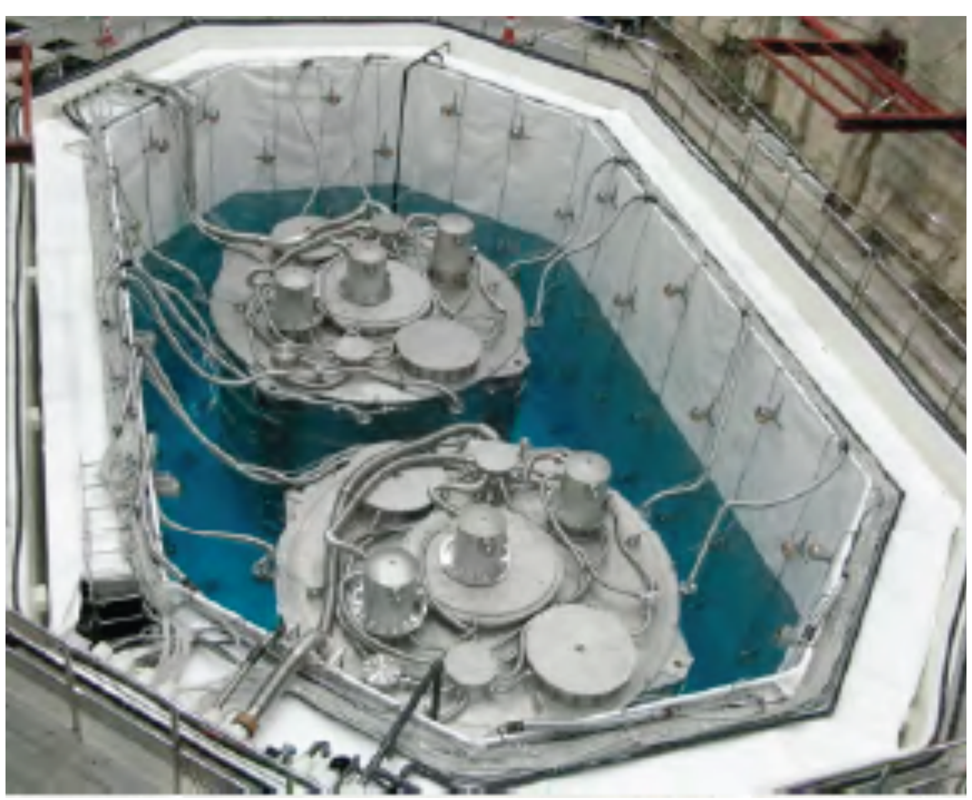
Must Measure Neutrinos at "Near" and "Far" Locations for sensitivity to small θ_{13}

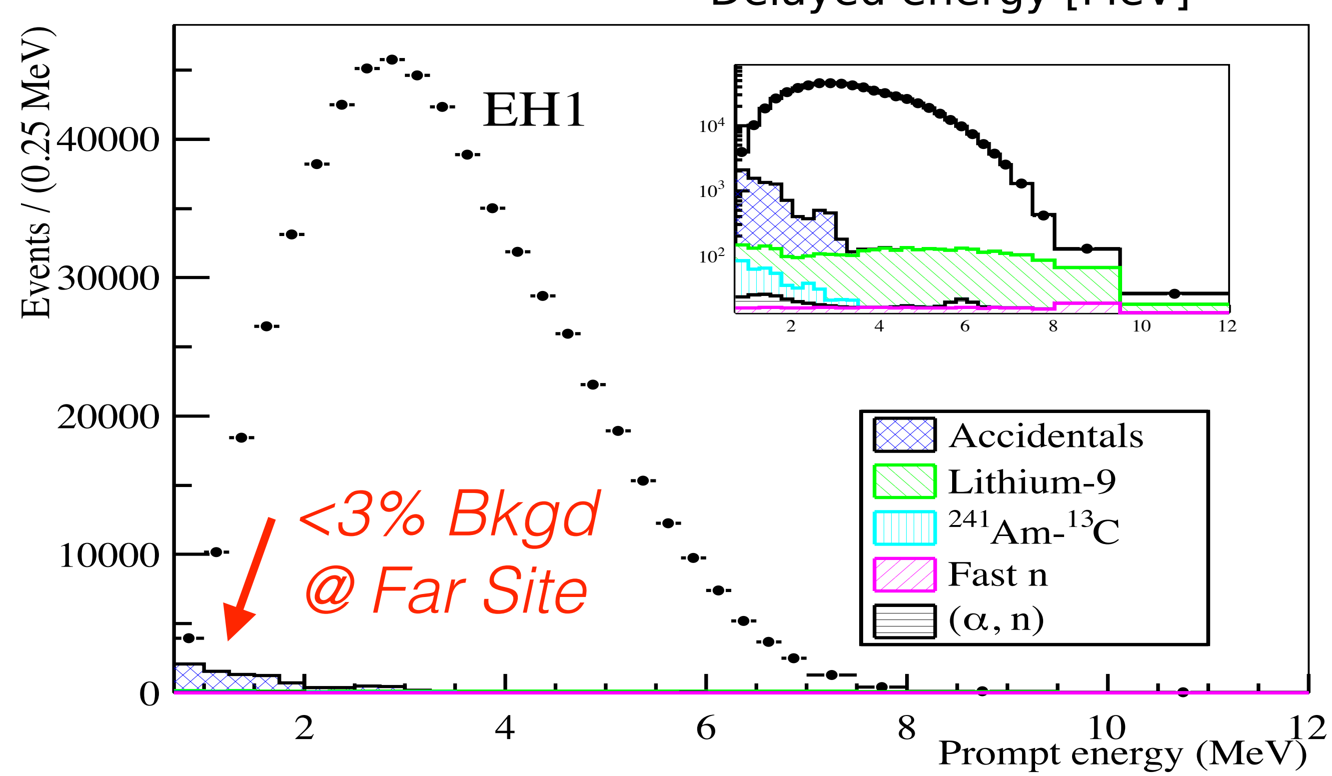
Far location known from $\Delta m^2_{23} \approx \Delta m^2_{13}$

Daya Bay: Quick Details





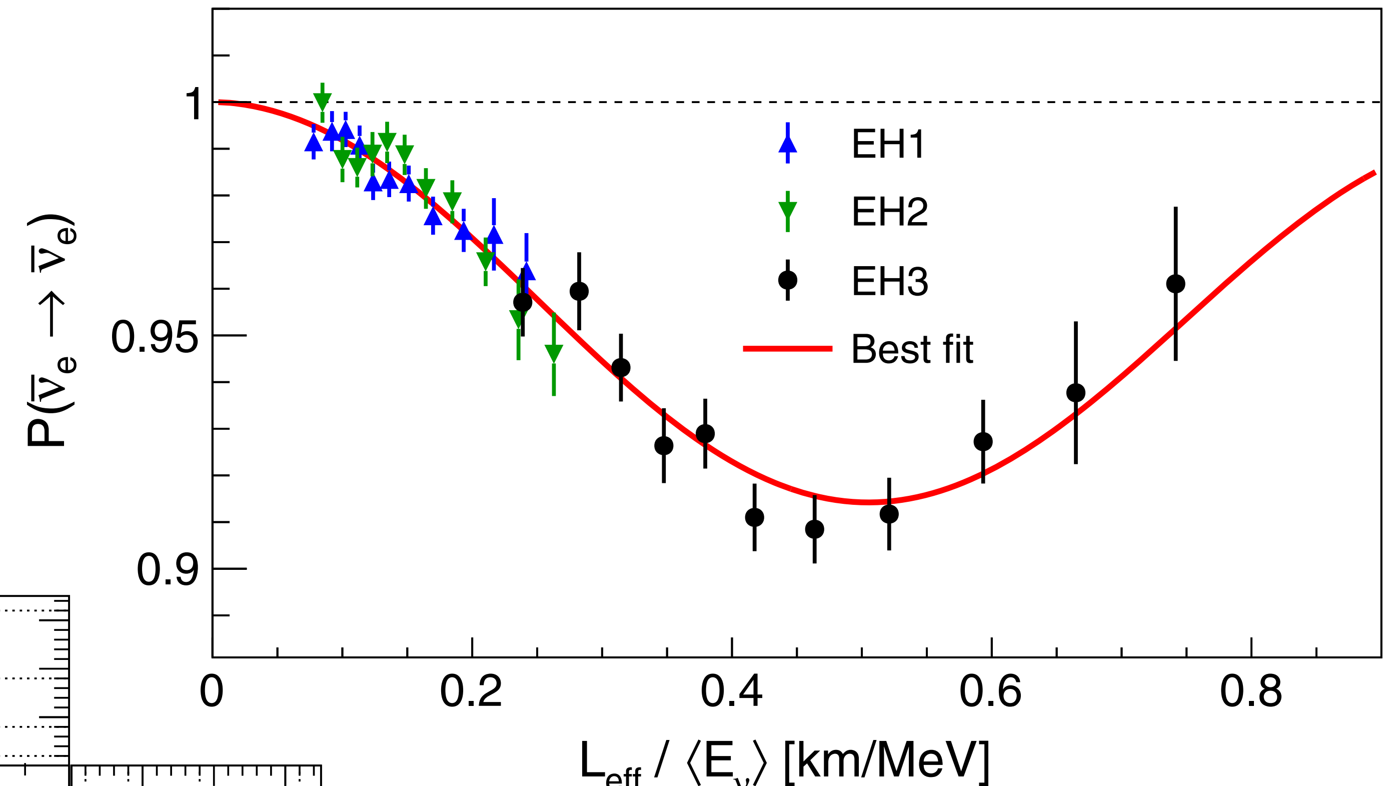


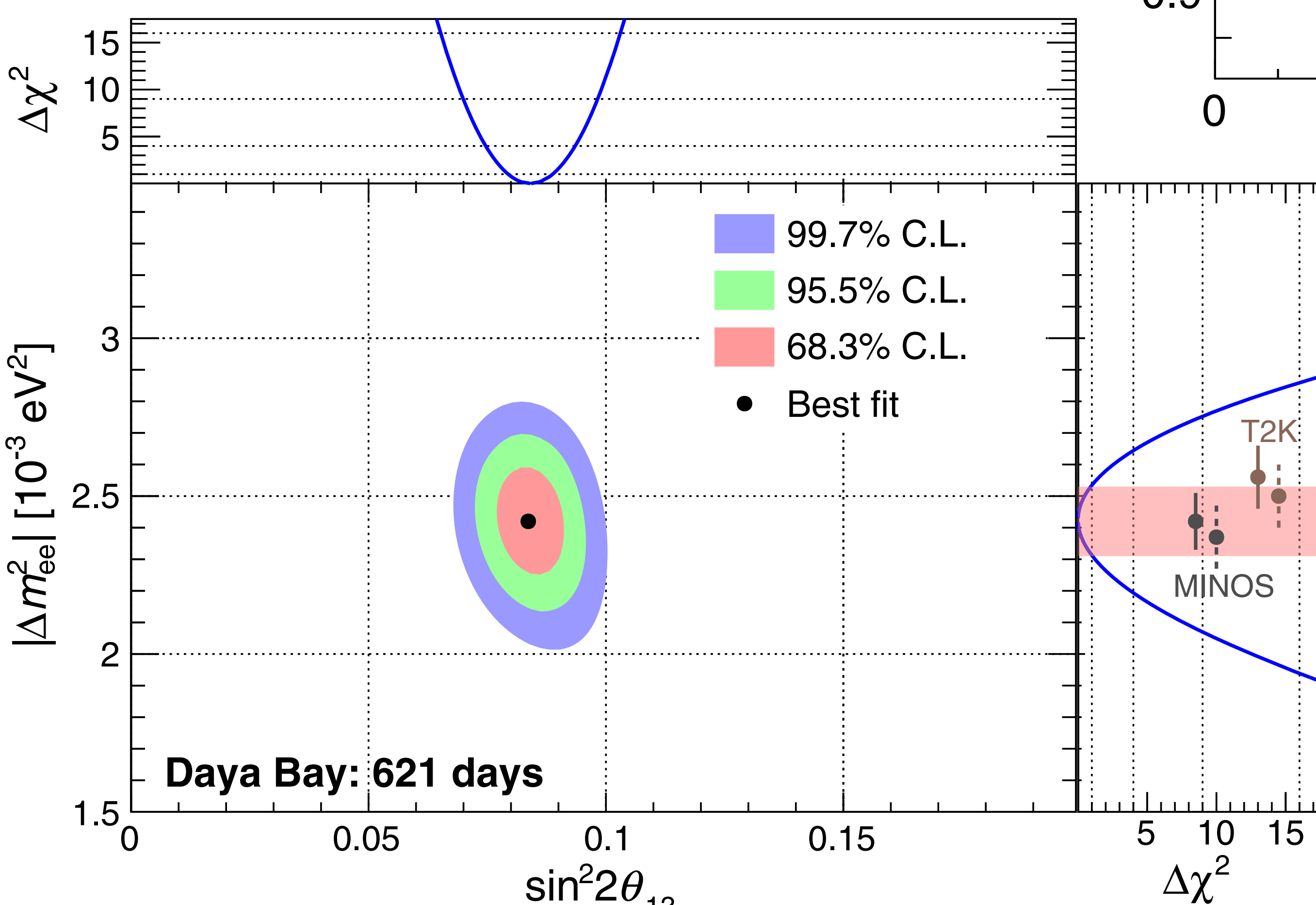


Daya Bay: θ_{13} Oscillations

PRL **115**, 111802 (2015)

Full fit with eight 20-Ton detectors and six reactors, each ≈2.9 GW_{th}





Best fit plotted as disappearance probability:

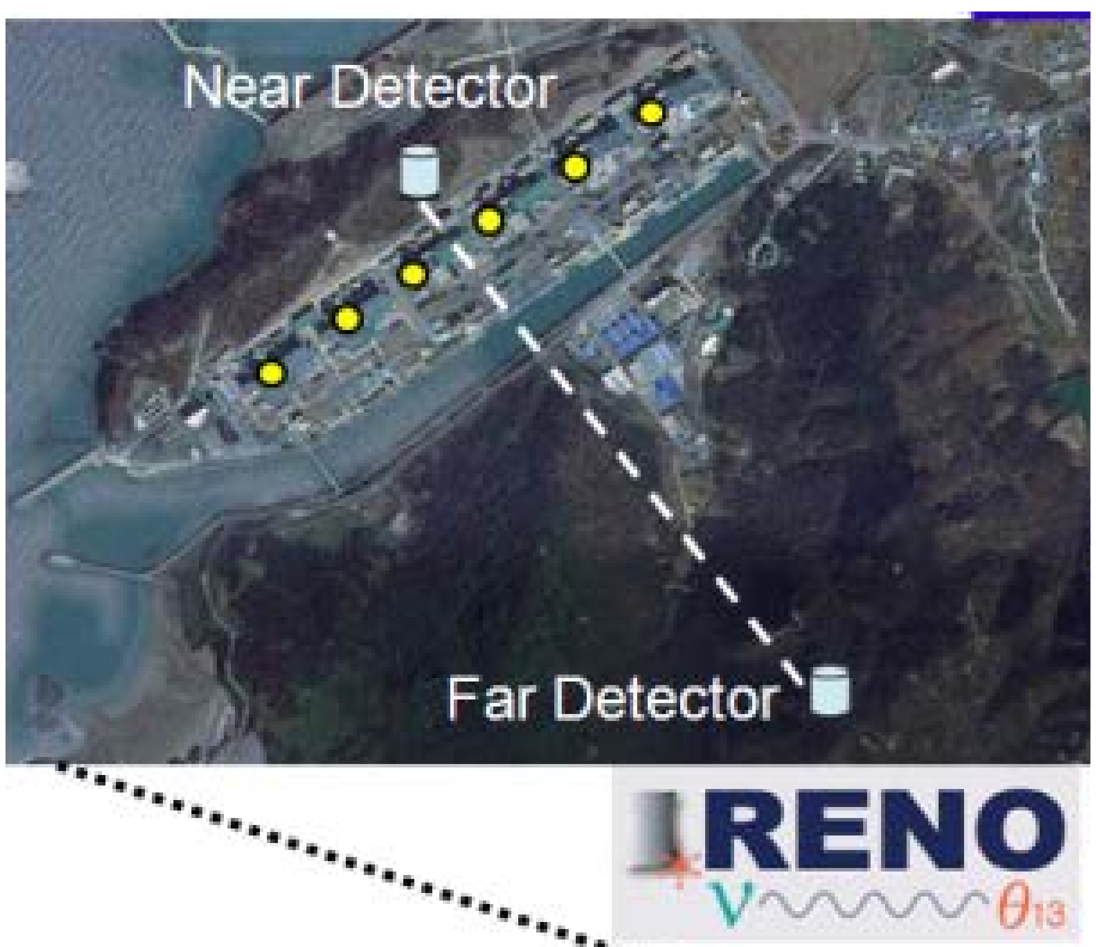
$\sin^2 2\theta_{13} = 0.085 \pm 0.005$

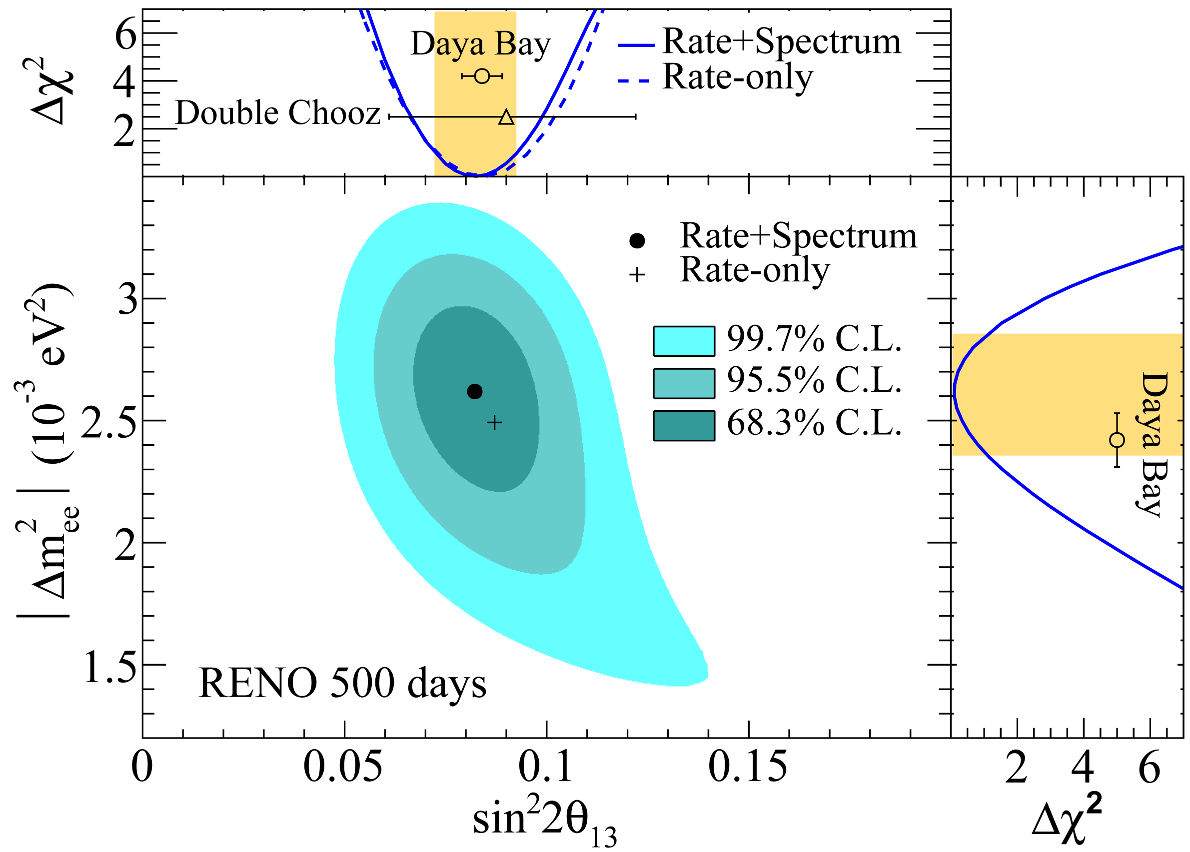
$\Delta m^2_{ee} = (2.42 \pm 0.11) \times 10^{-3}$ eV^2

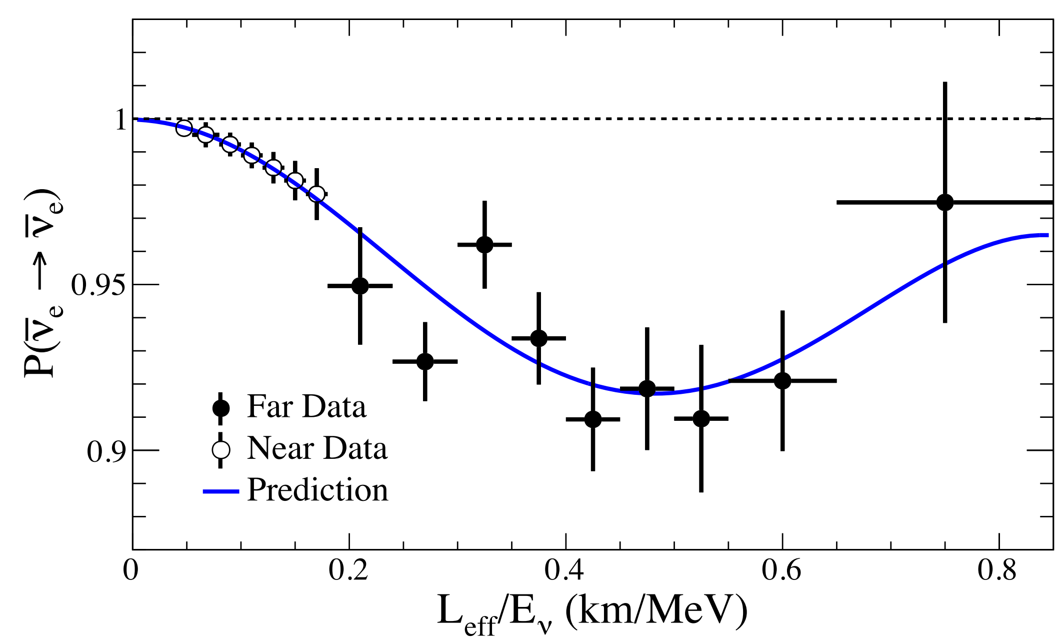
RENO: θ_{13} Oscillations

PRL **116,** 211801 (2016)

Six reactors on a line, two detectors on the bisector.

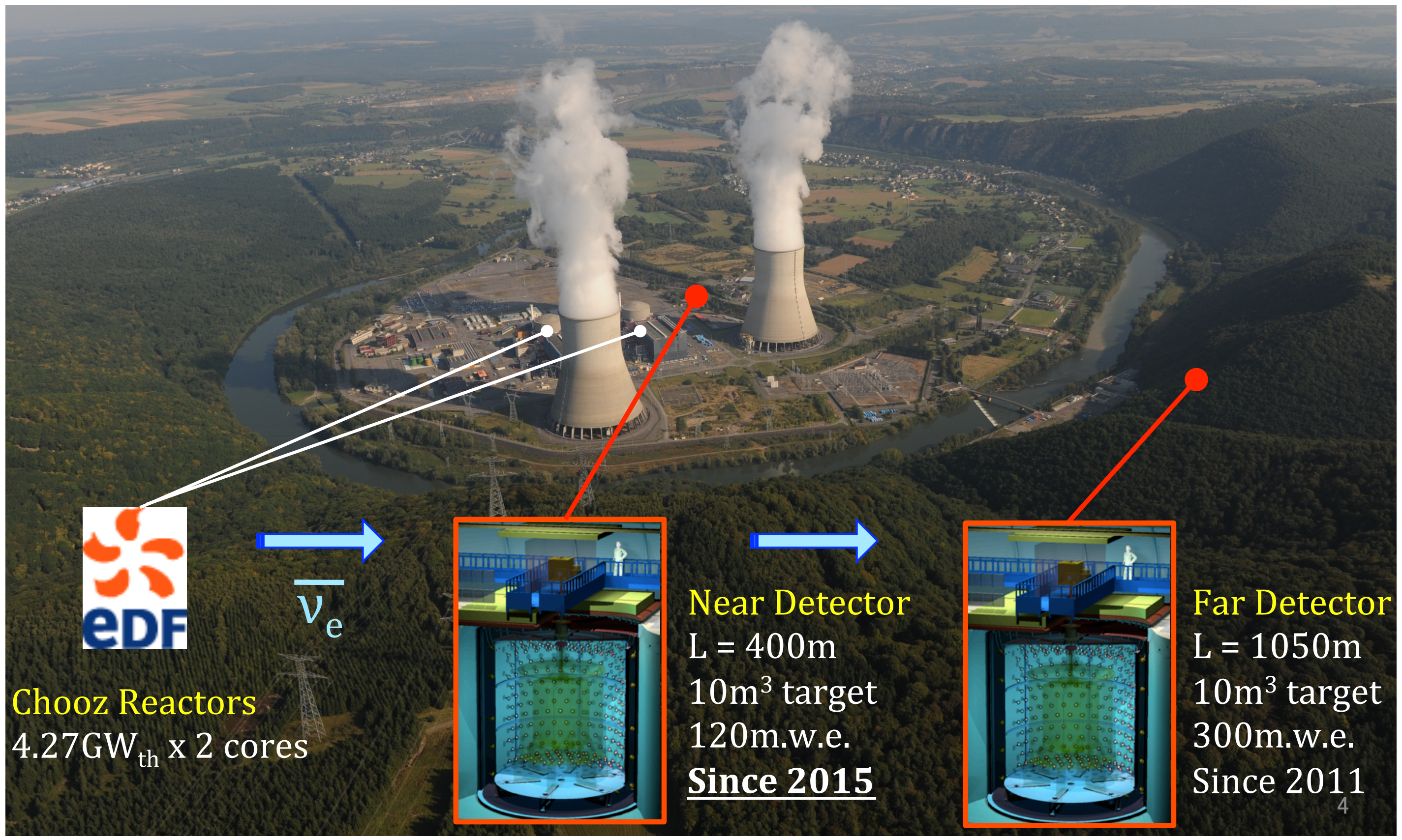






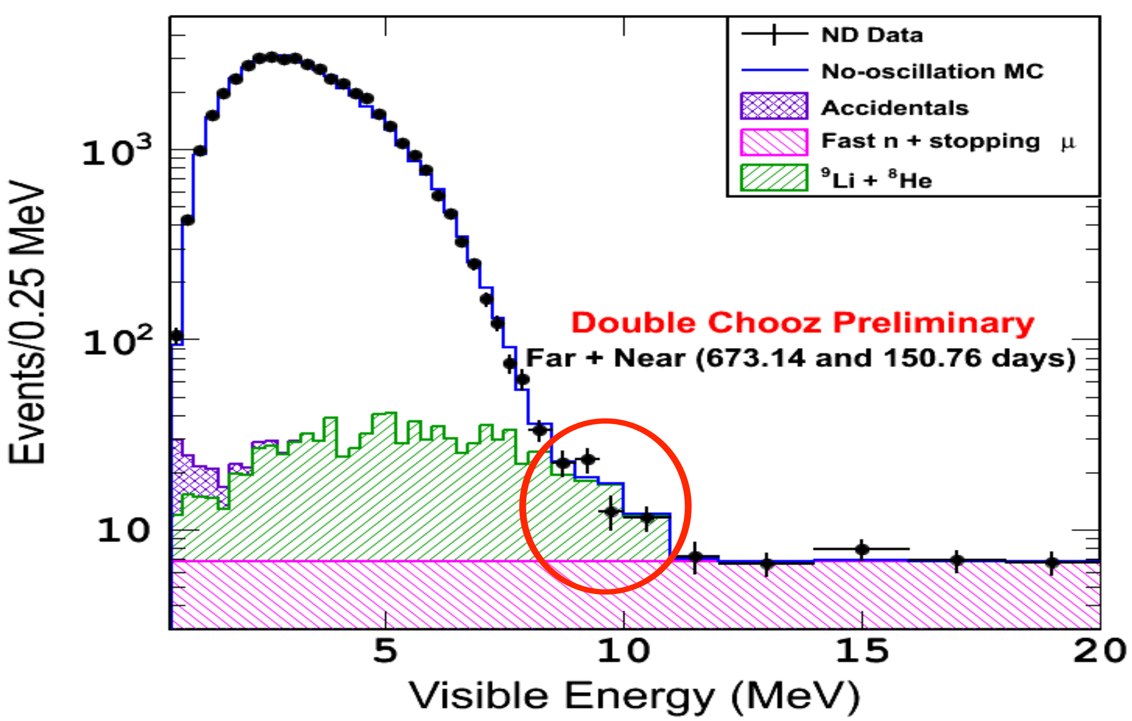
Double Chooz: θ_{13} Oscillations

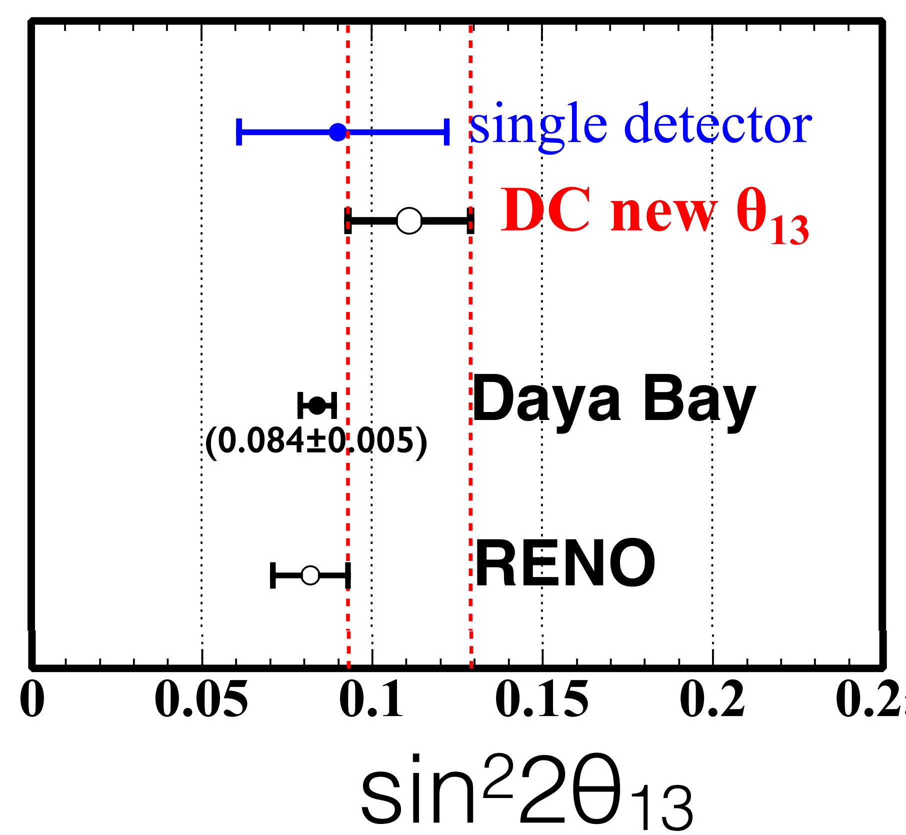
http://theory.fnal.gov/jetp/talks/DCIV@FNAL_Anatael_160315.pdf



Two reactors, detectors at 0.4 km and 1.1 km, rate-only analysis:

$\sin^2 2\theta_{13}=0.111\pm0.018$





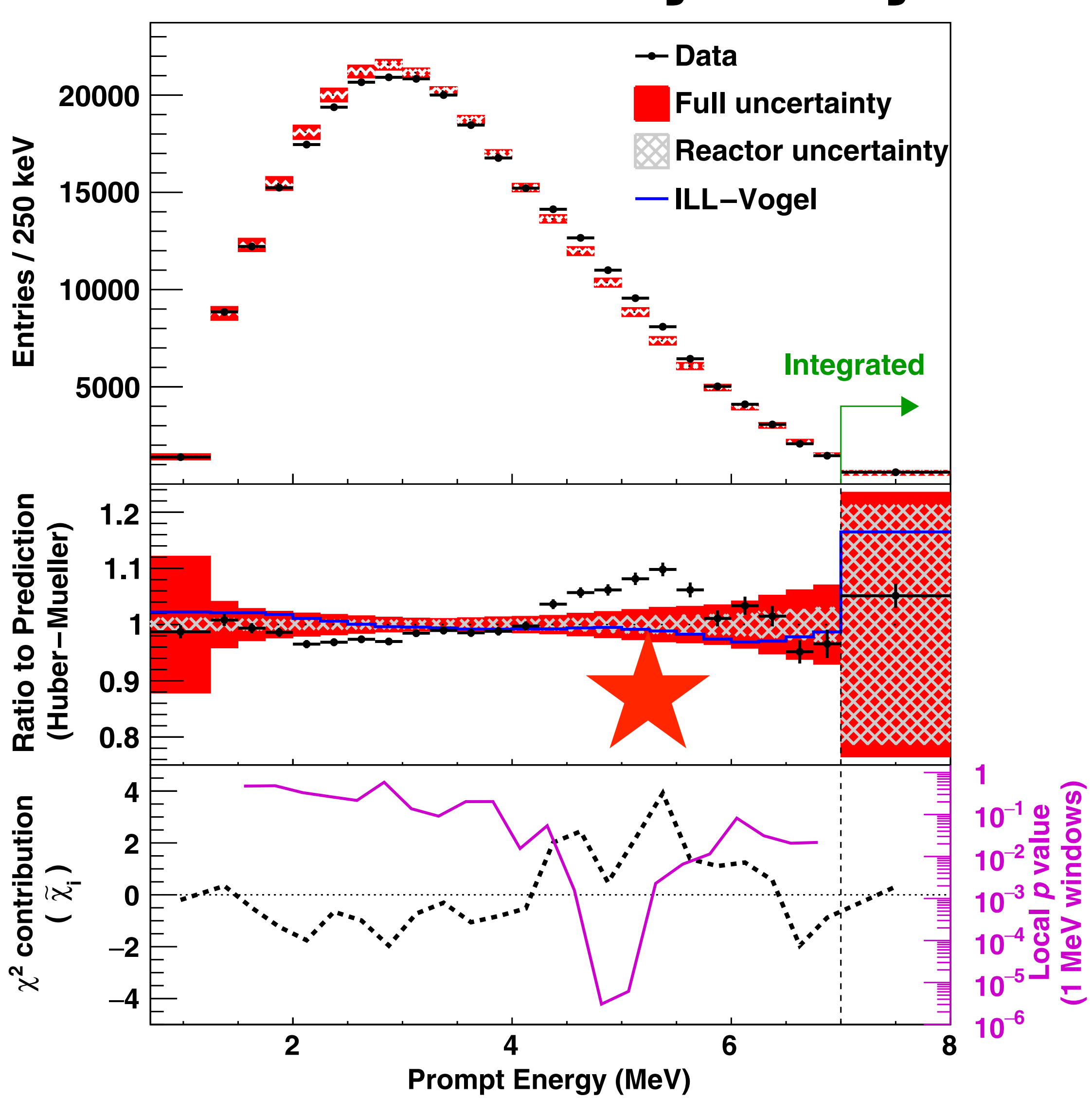
Detected $\bar{\nu}_e$ Spectra

High statistics leads to some surprises

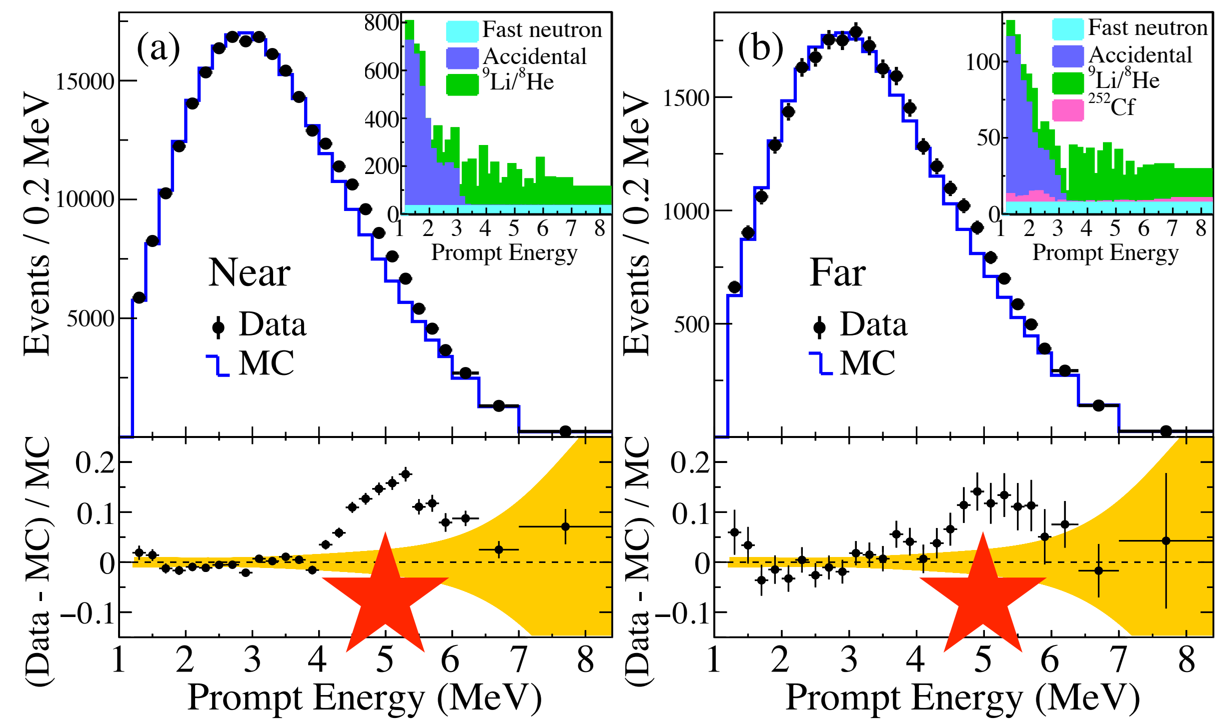
★ The "Bump"

Recall: Hard Calculation!

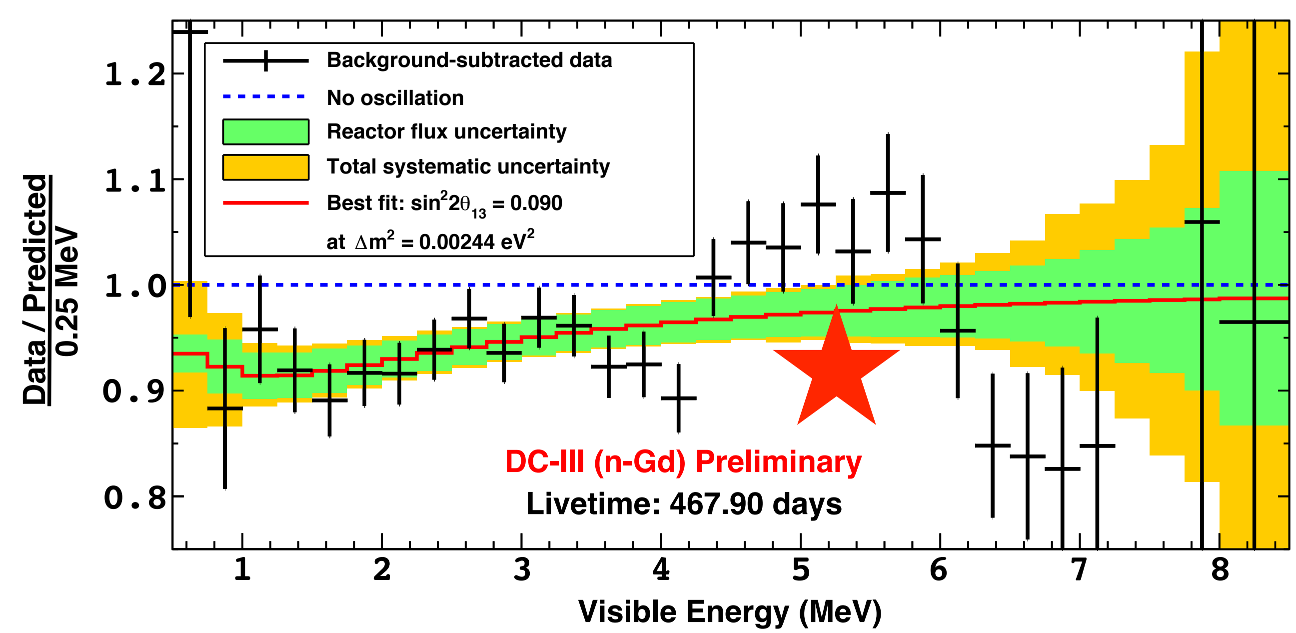
Daya Bay



RENO

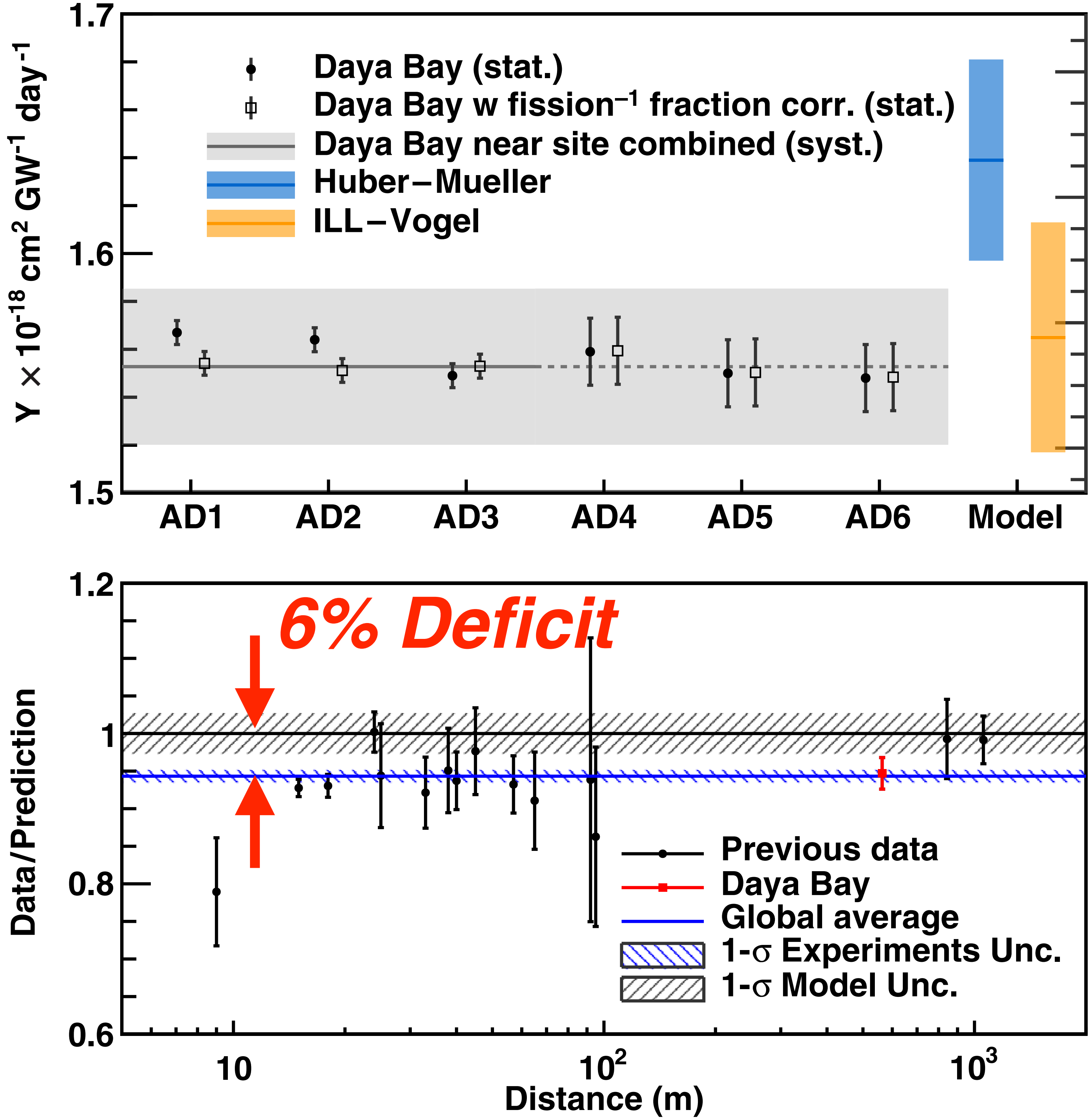


Double Chooz



Reactor Neutrino Anomaly

PRL **116**, 061801 (2016)



Missing neutrinos?

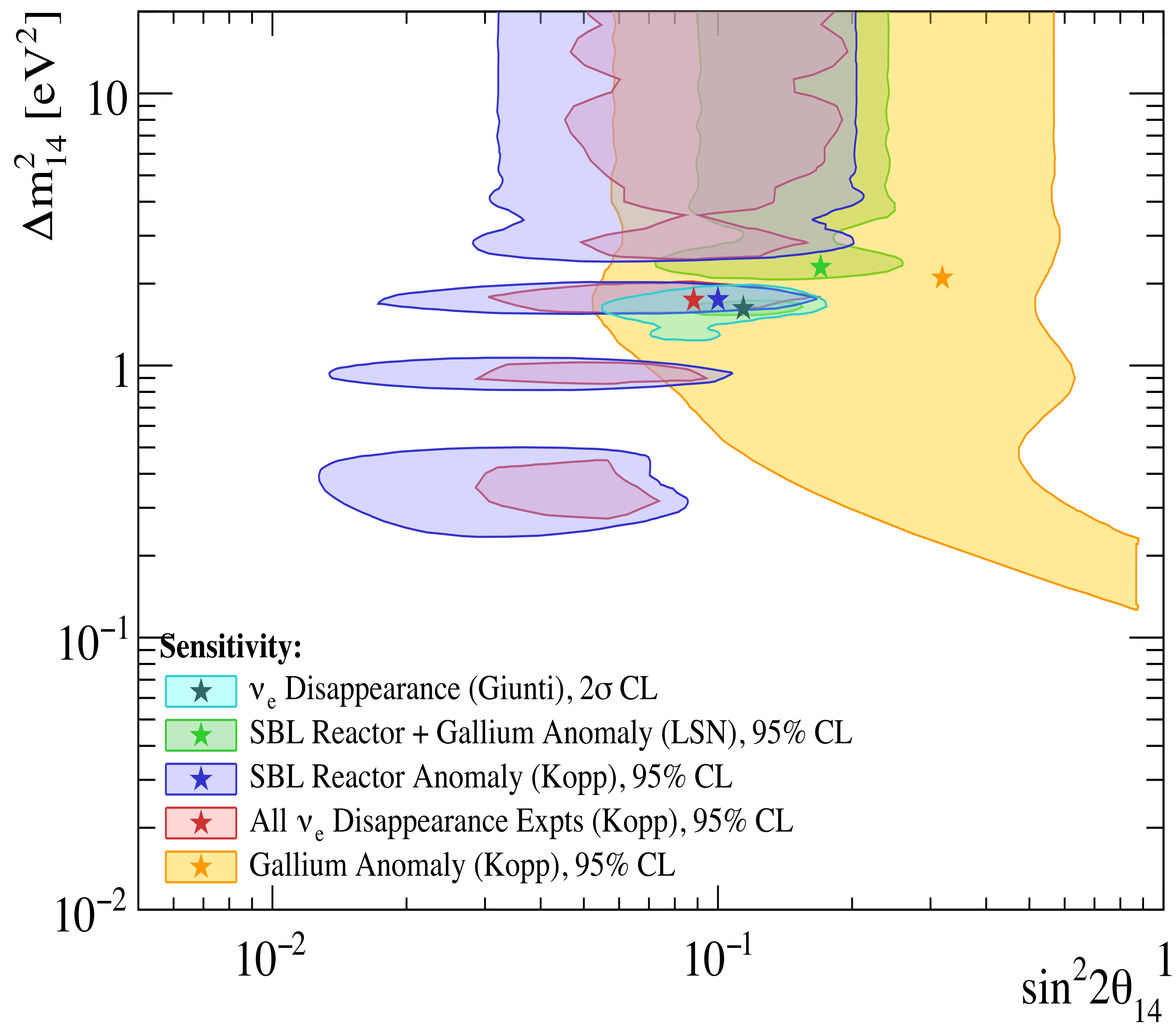
How well can we predict the reactor neutrino spectrum?

Special problems for power plants (time dependence)

<u>New review paper</u>:
Hayes and Vogel
arXiv:1605.02047
(For Ann. Rev.)

Sterile Neutrinos (?)

Are there disappearance oscillations with wavelength ~meters (Δm^2~eV^2)?



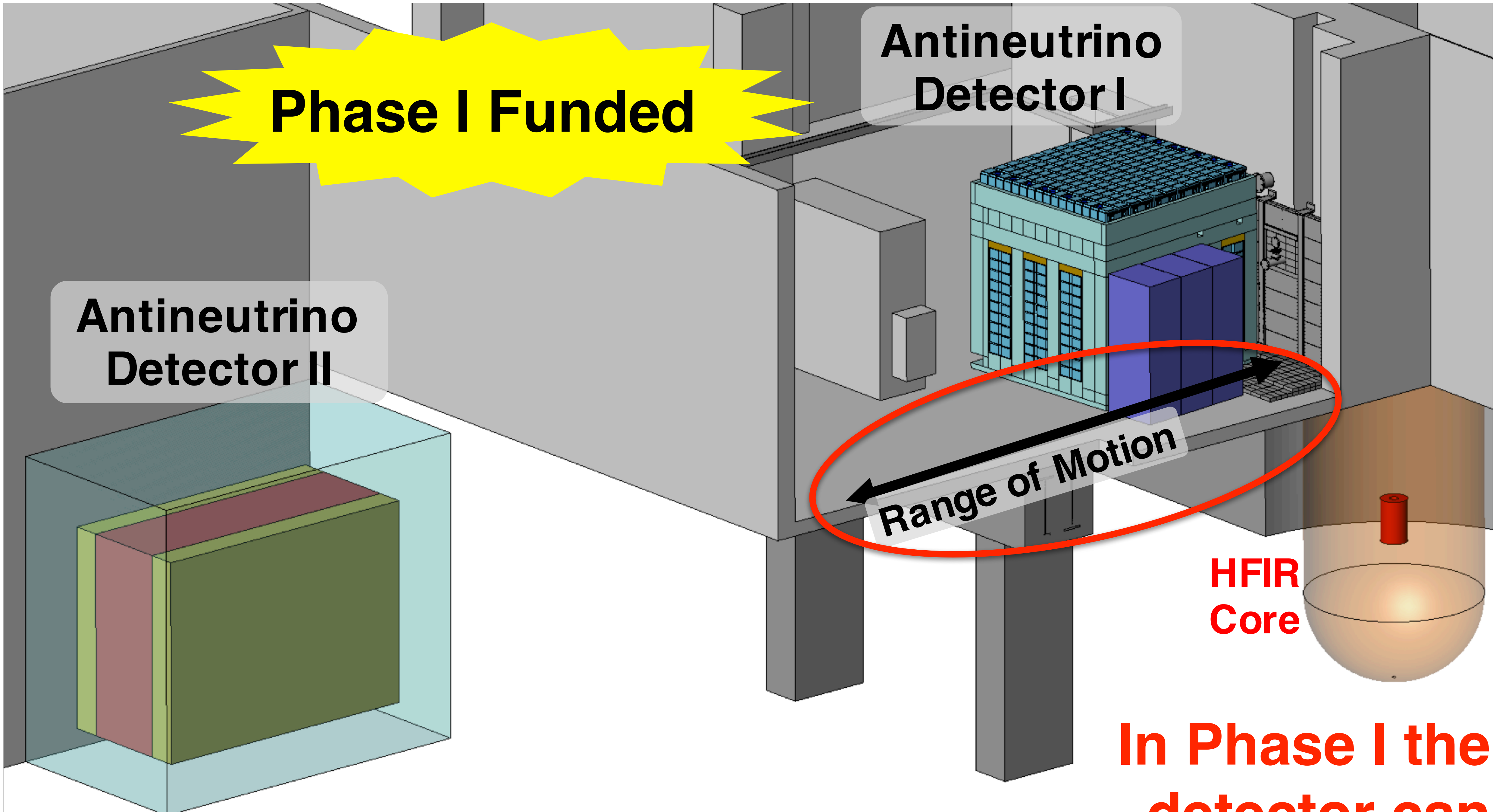
References

Gallium
PRC 83(2011)065504

BOONE, MiniBOONE
AnnRev 63(2013)45

Global fits
JHEP 1305(2013)050
PRD 88(2013)073008

PROSPECT @ HFIR

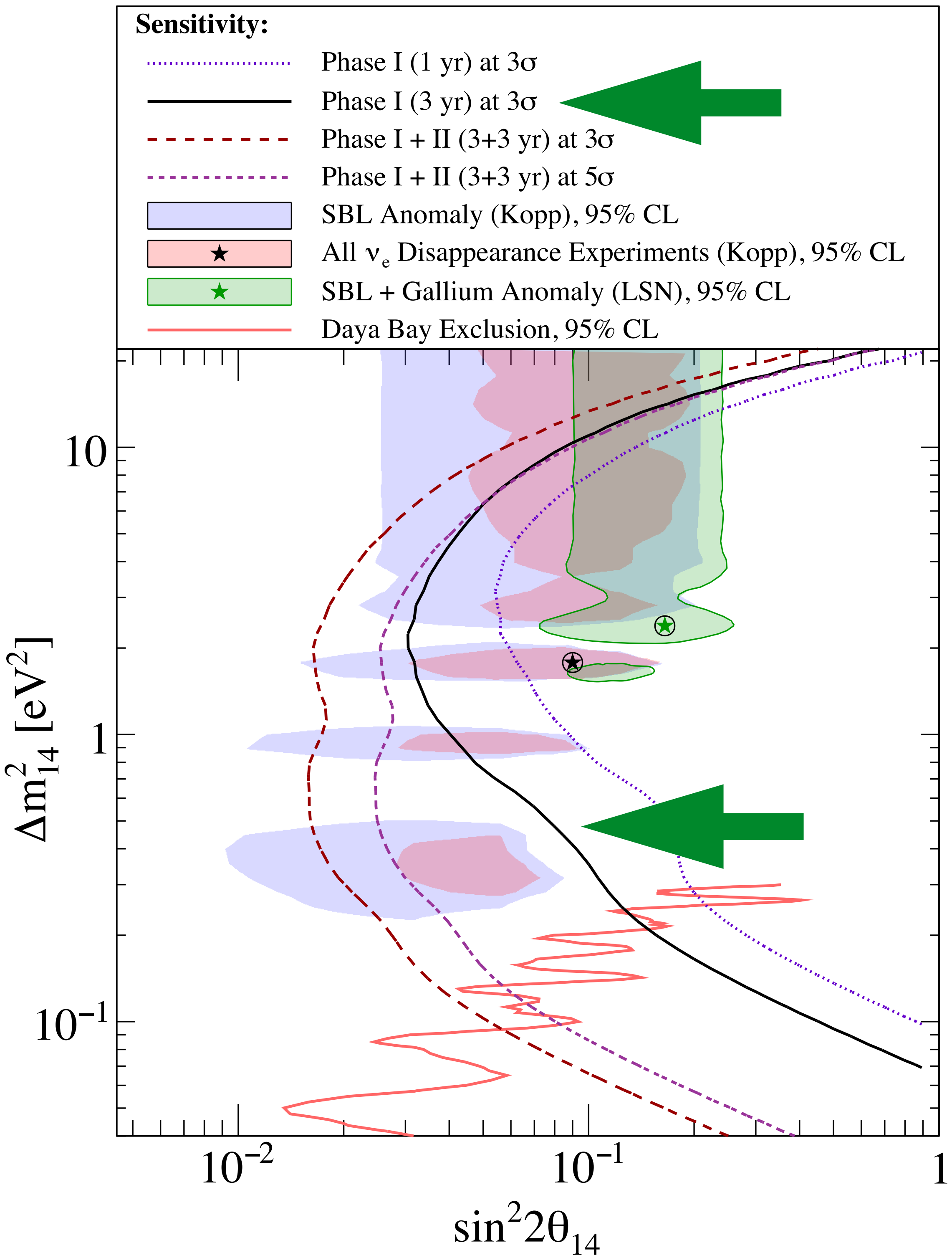


In Phase I the detector can move ≈3m

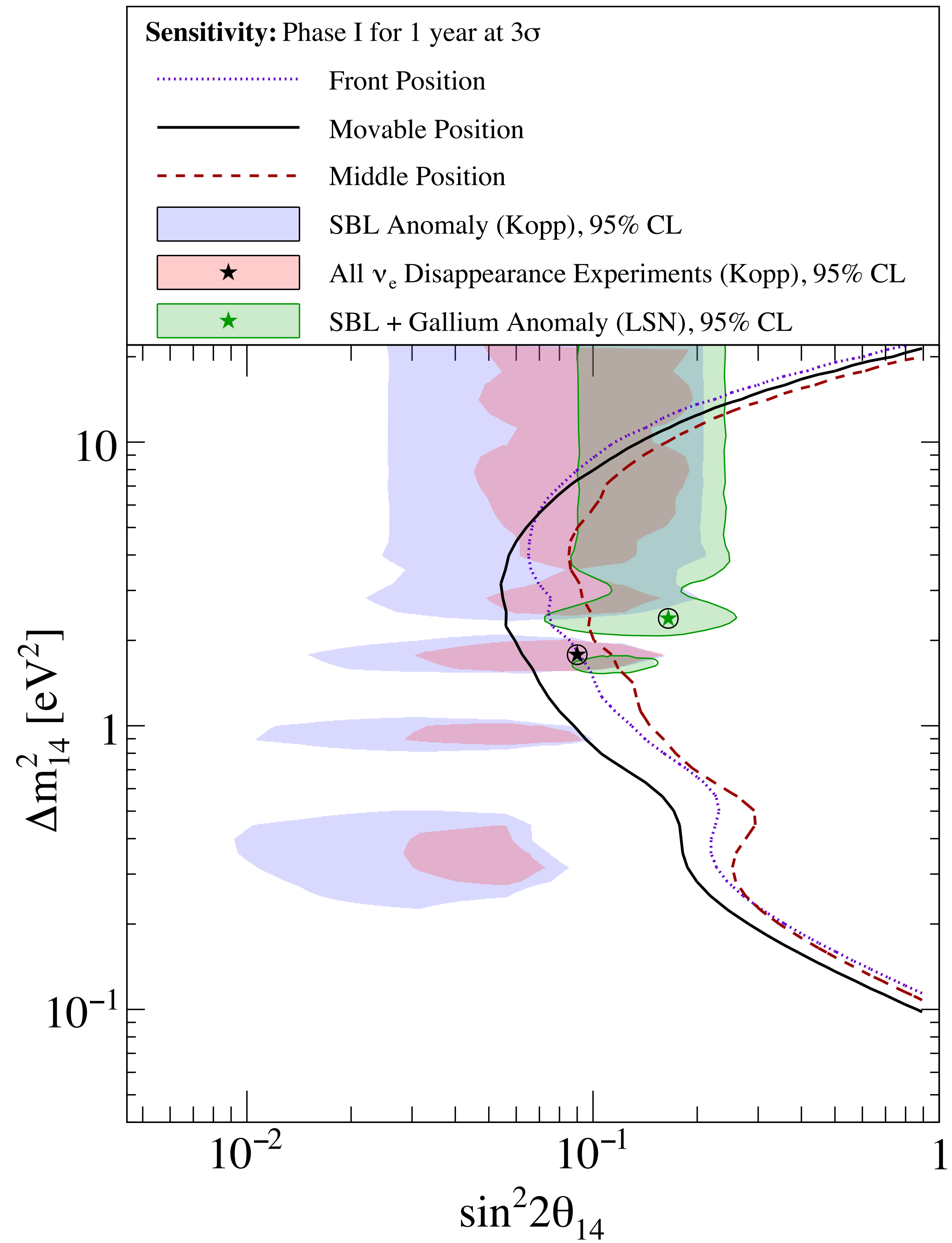
Second detector for greater coverage in Phase II

PROSPECT Sensitivity

Phase I and Phase II

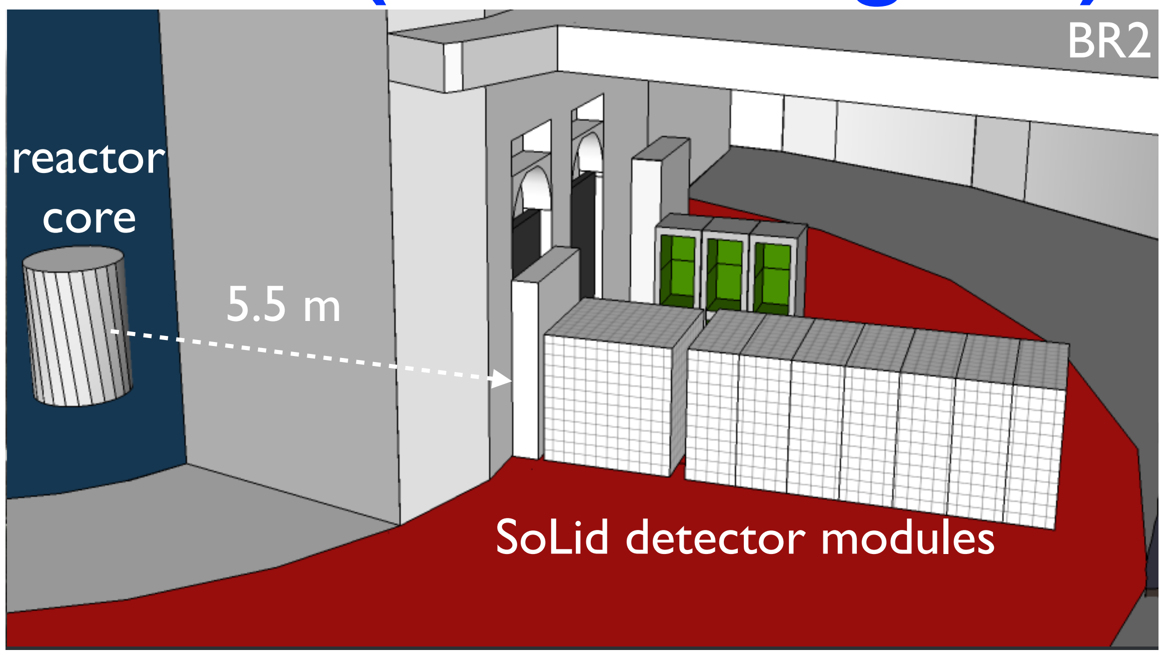


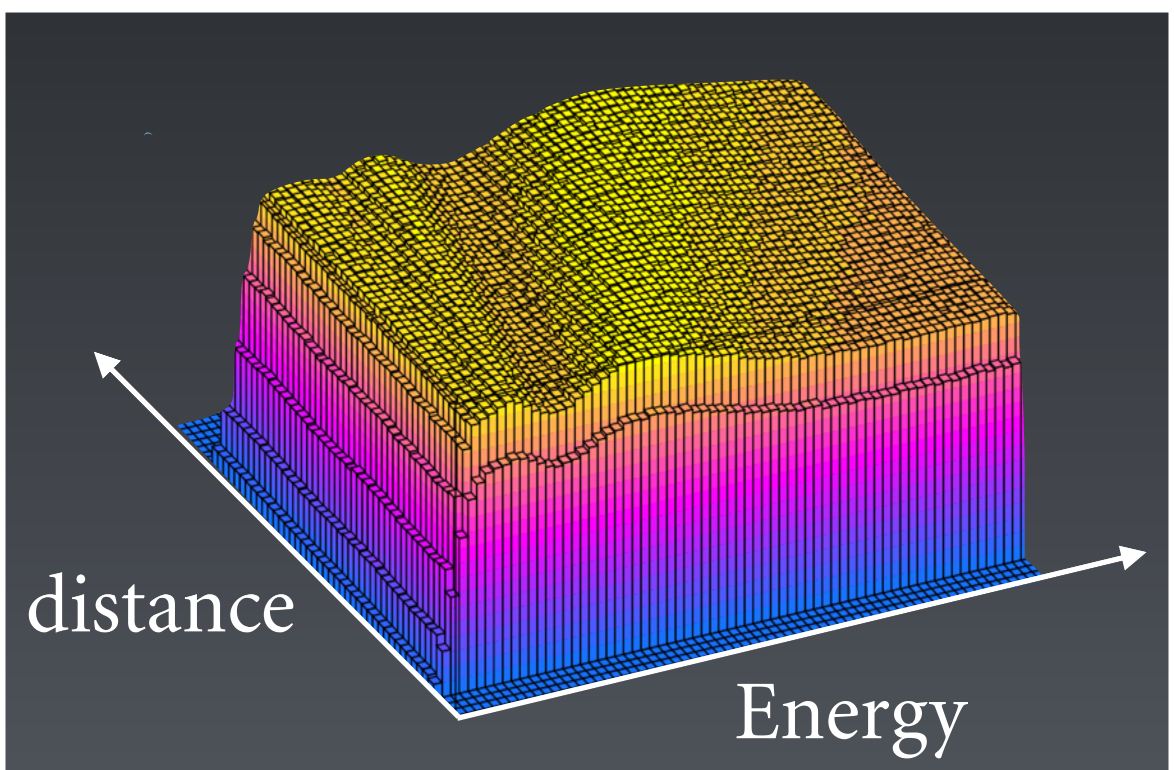
Phase I with Positioning



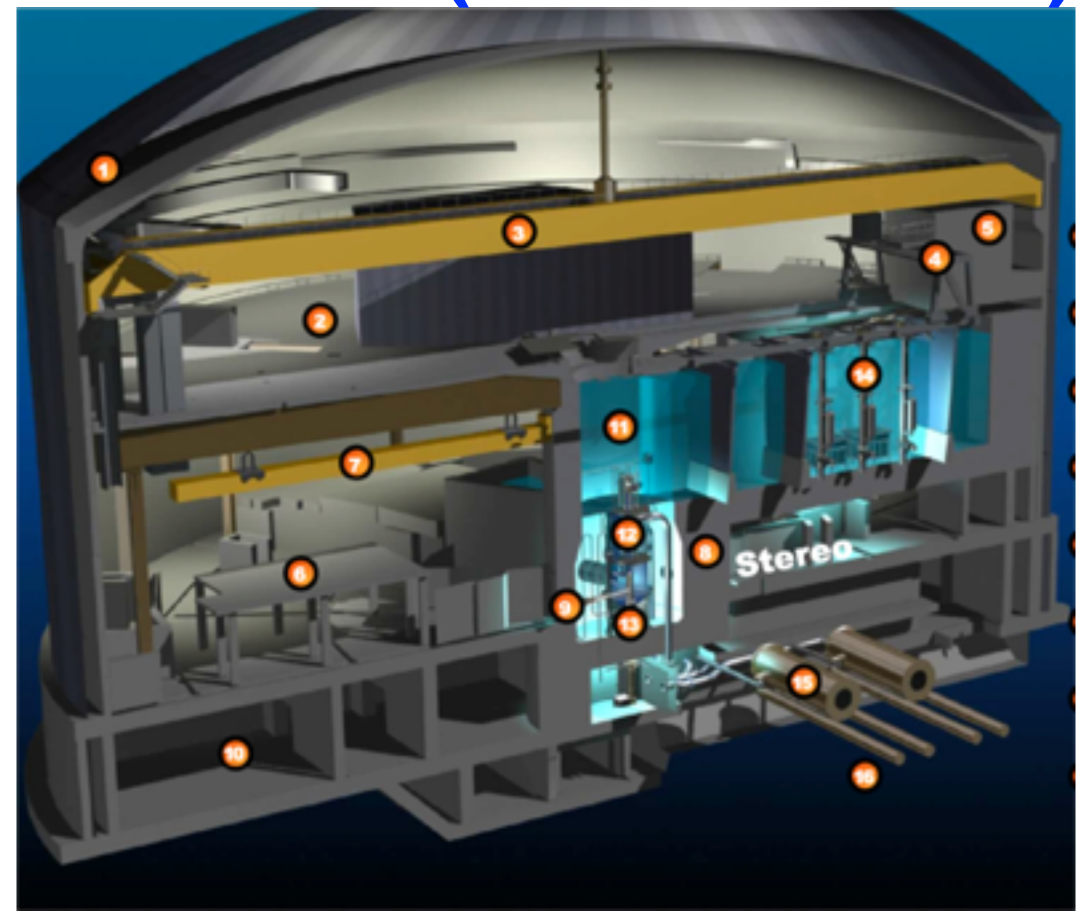
Other VSBL Experiments

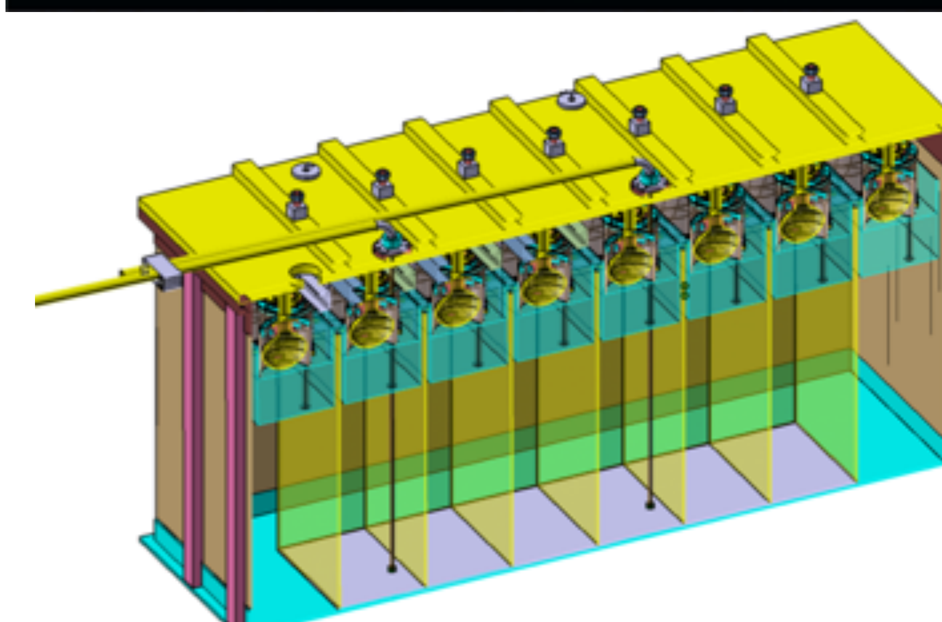
SoLiD (@BR2 Belgium)



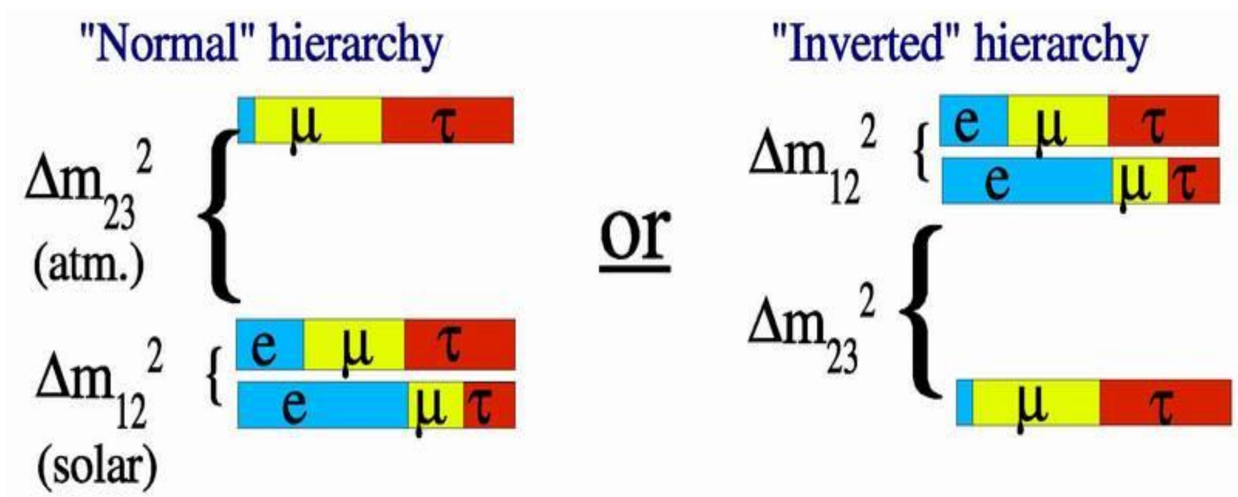


STEREO (@ILL France)

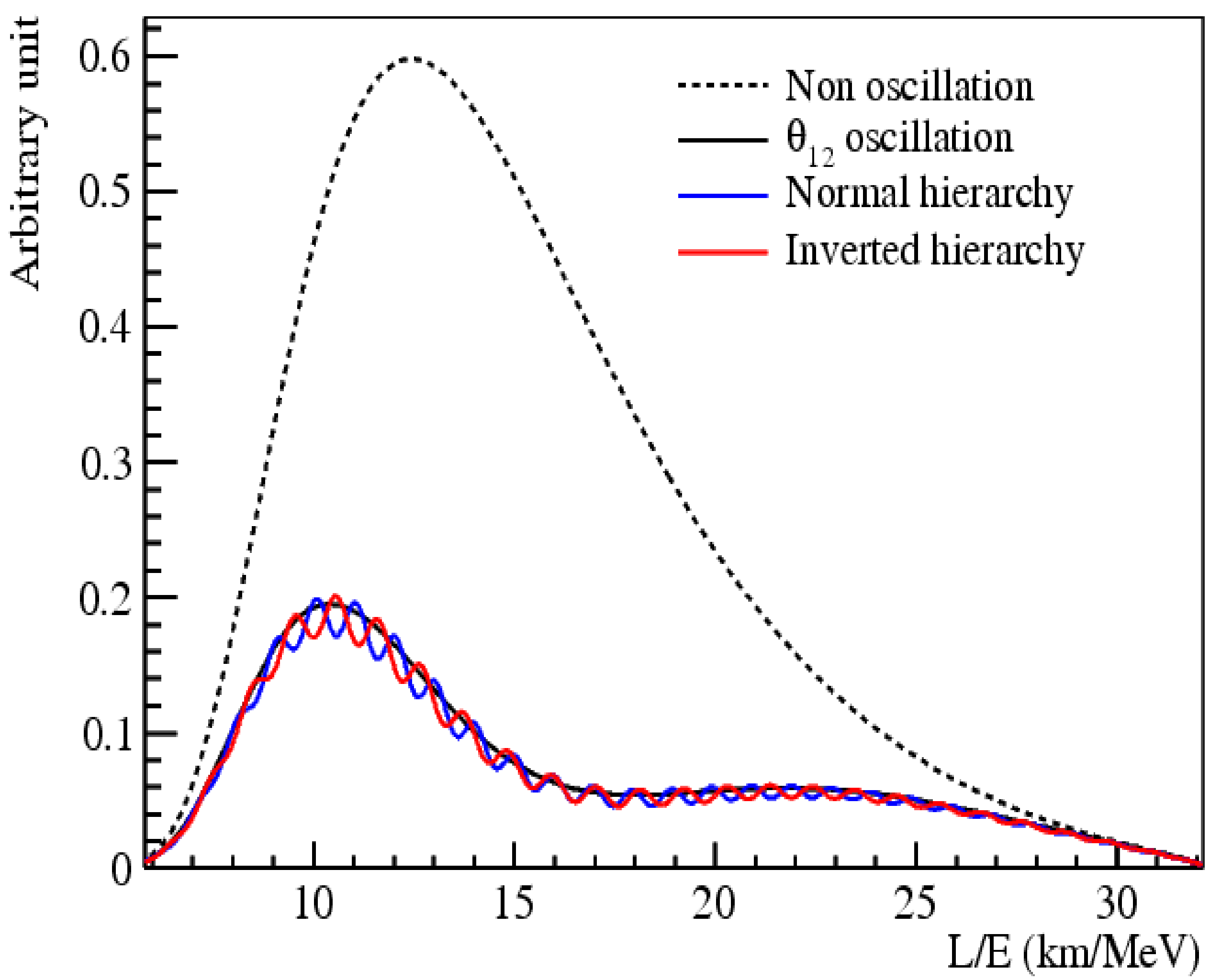




Mass Hierarchy: θ_{12} and θ_{13}



$$\Delta m_{31}^2 = \Delta m_{32}^2 + \Delta m_{21}^2$$
$$\text{NH}: \ |\Delta m_{31}^2| = |\Delta m_{32}^2| + |\Delta m_{21}^2|$$
$$\text{IH}: \ |\Delta m_{31}^2| = |\Delta m_{32}^2| - |\Delta m_{21}^2|$$

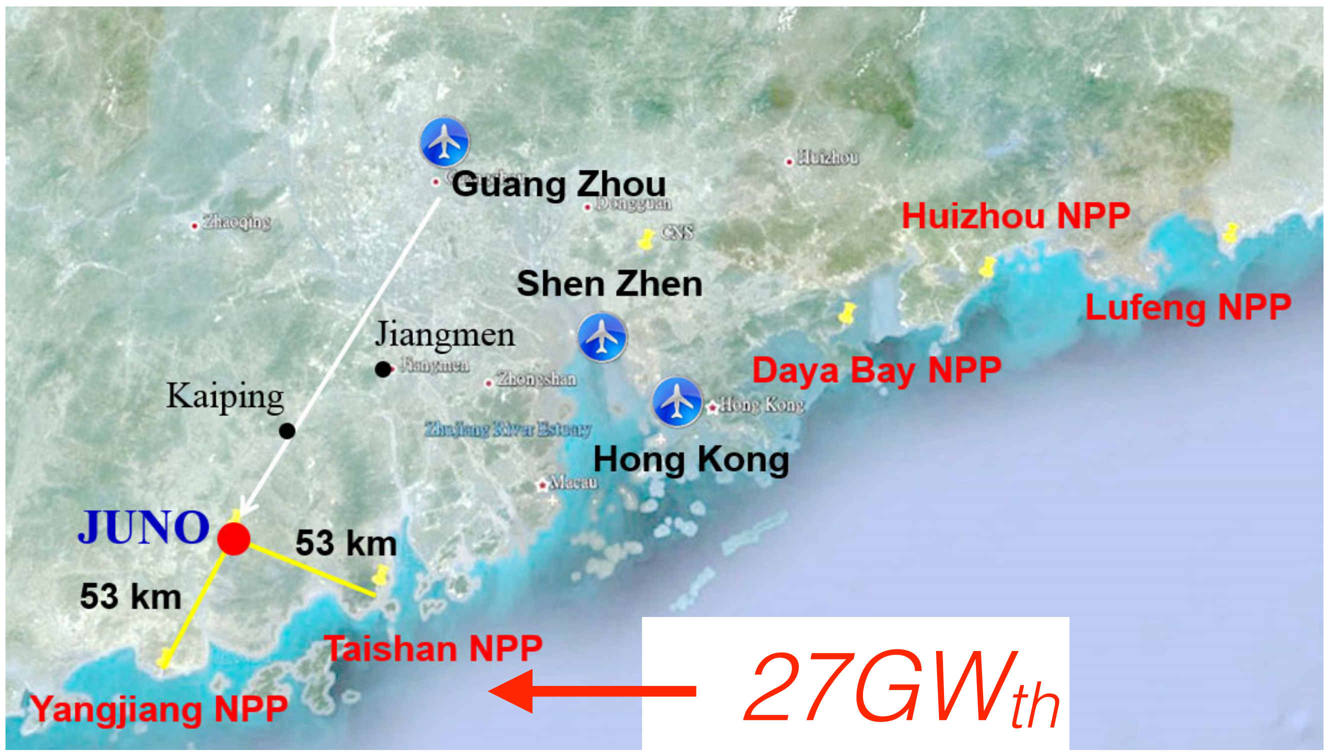


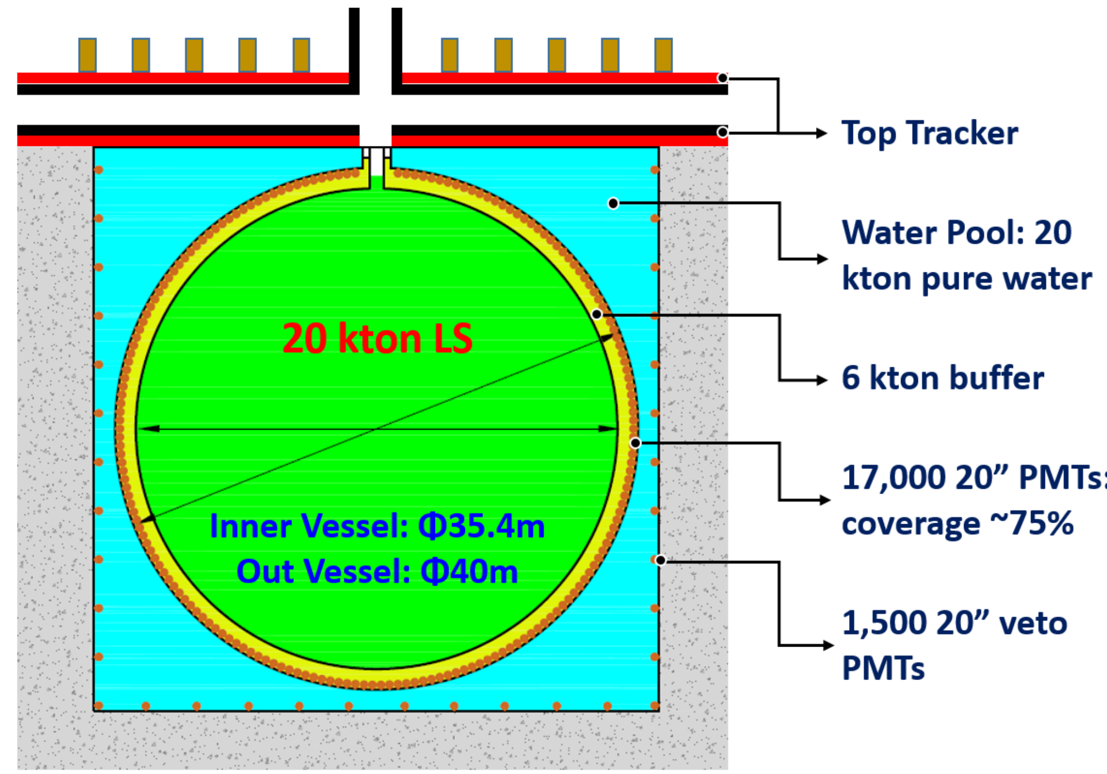
$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$

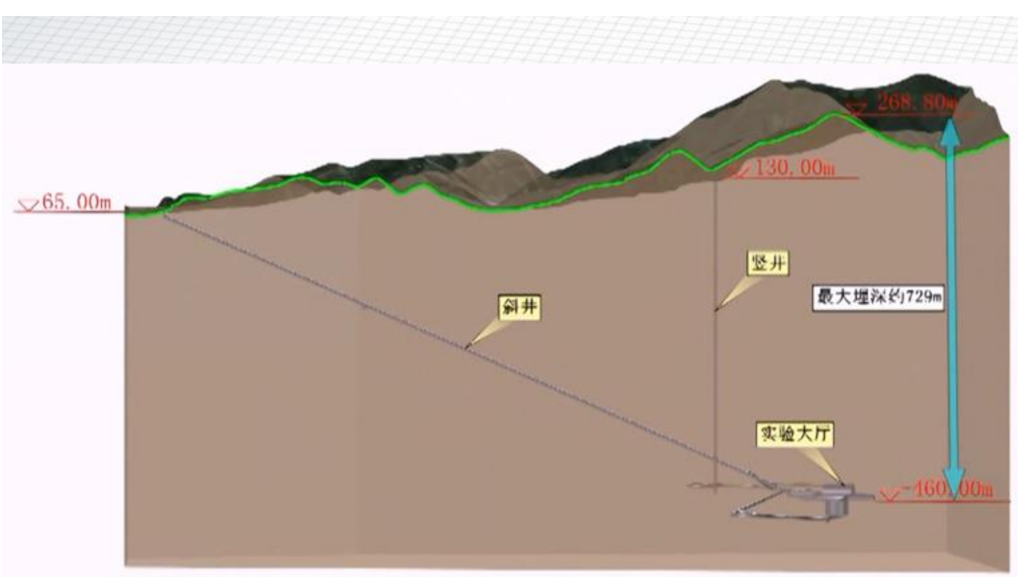
Interference between θ_{12} (e.g. KamLAND) and θ_{13} (e.g. Daya Bay) distinguishes ordering.

JUNO Jiangmen Underground Neutrino Observatory

See arXiv:1508.07166 (CDR)







A 600m vertical shaft
A 1300m long tunnel(40% slope)
A 50 m diameter, 70 m high cavern

Conclusions

Neutrino experiments at nuclear reactors remain critical contributors to fundamental physics.

Nuclear power plants are strong sources but not so well understood, so “near detectors” are crucial.

Research reactors are not so powerful, but offer more control over interpretation of results.

New results (sterile neutrinos, mass hierarchy) will be coming out within the next five years.

Thank You!

… and Thanks to Caltech Physics!

Populating the Field for Reactor Neutrino Physics

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Pedro Ochoa-Ricoux, Michael Mendenhall