

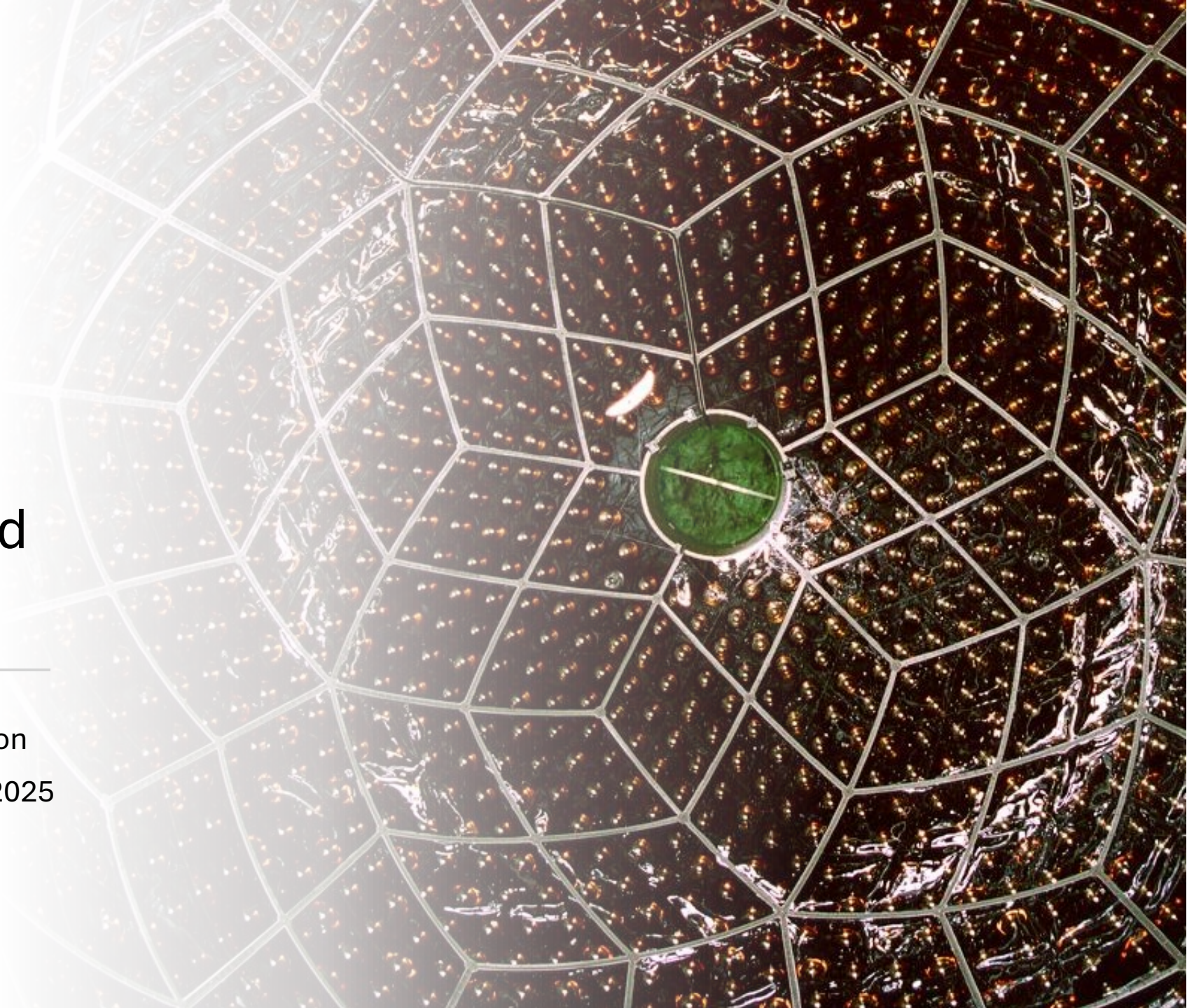


# Reactor Neutrino Oscillations

## Discovery with KamLAND, Status, and Future Outlook

---

Jason Detwiler, University of Washington  
LearnedFest '25, Honolulu HI, May 2, 2025

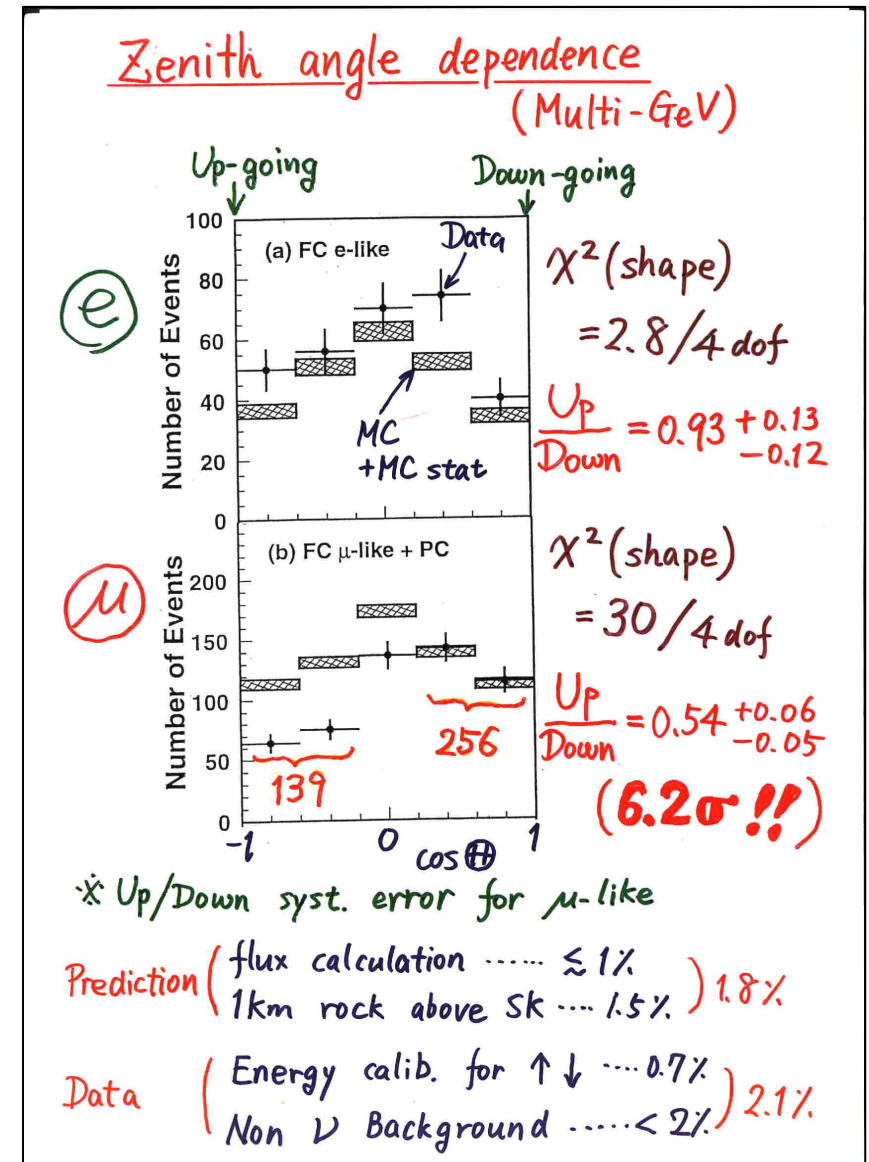






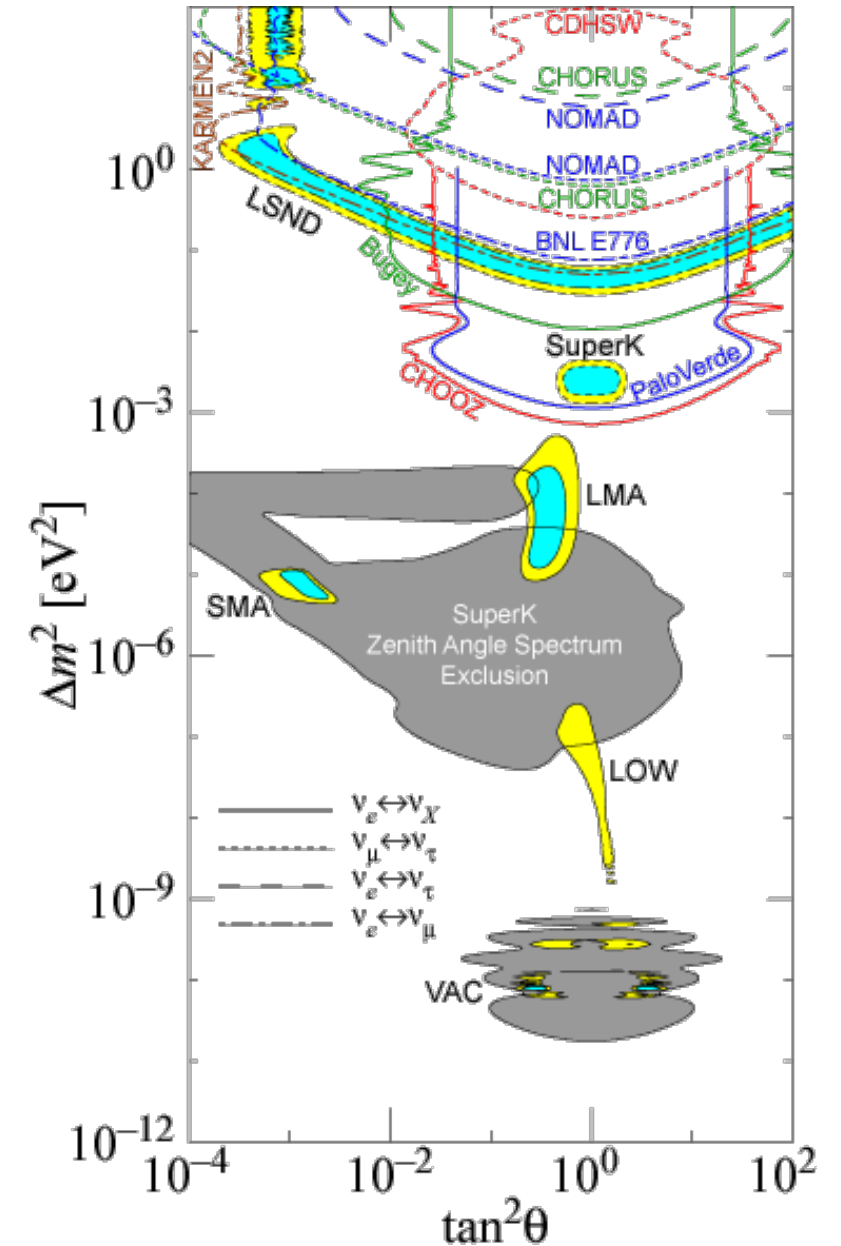
# Neutrino '98: SuperKamiokande!

- Kajita-sensei announced the first evidence of neutrino oscillation on June 5 at the Neutrino conference in Takayama.
- I was still an undergrad and was working at LANL that summer in condensed matter experiment. I remember this being the most exciting science news of that summer.
- I believe it was in 1999 I was presenting at the APS meeting in Atlanta and attended a session on neutrino oscillation where a young Giorgio Gratta mentioned this new reactor neutrino experiment in Japan during his presentation...



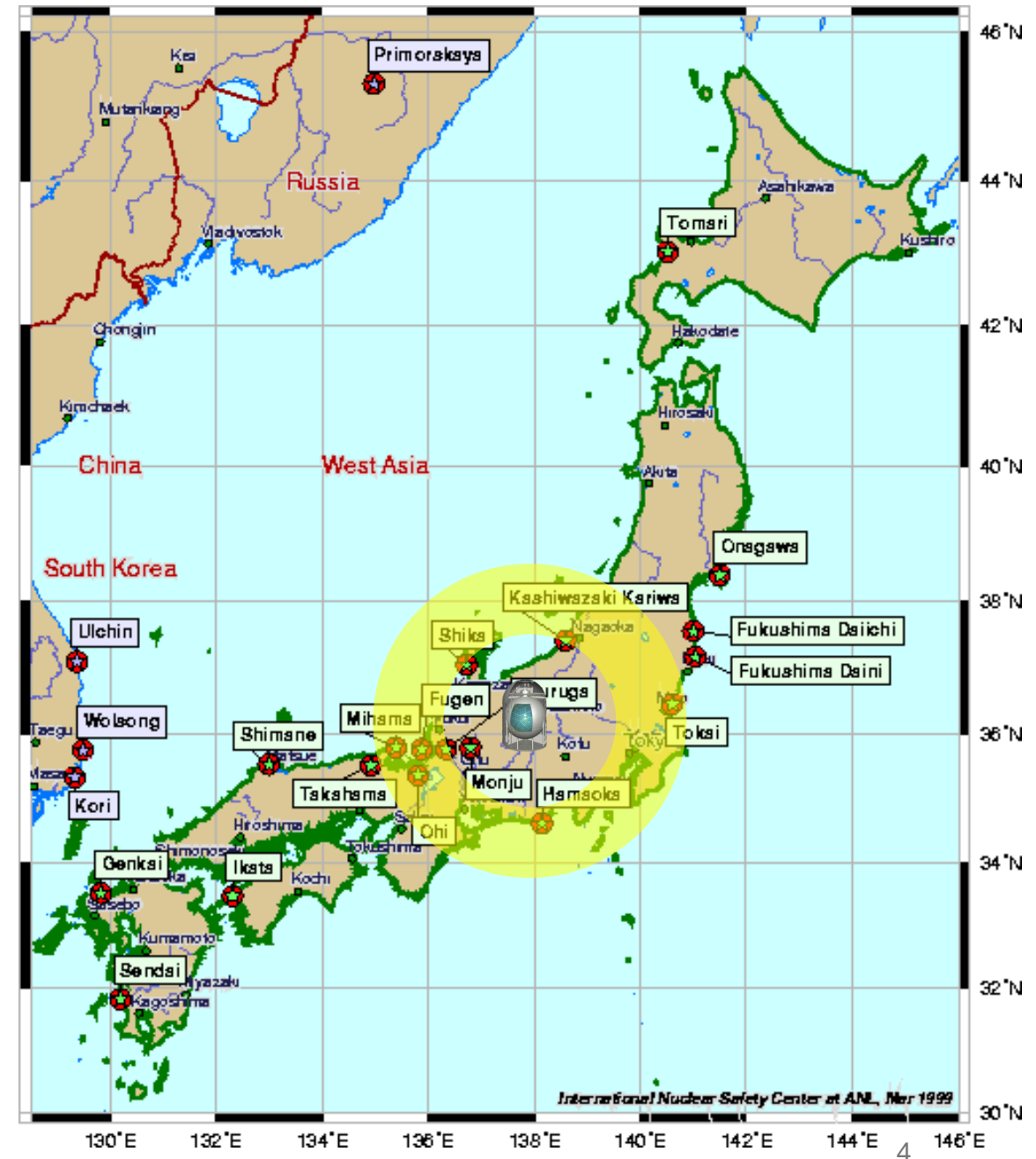
# Neutrino Oscillation Pre-KamLAND

- SuperK oscillations at  $\Delta m^2 \sim 10^{-3}$
- LSND hints at higher  $\Delta m^2$
- Solar neutrino problem solutions:
  - MSW flavor transformation
    - Small mixing angle
    - Large mixing angle
    - Low  $\Delta m^2$
  - Vacuum oscillations



# KamLAND Strategy

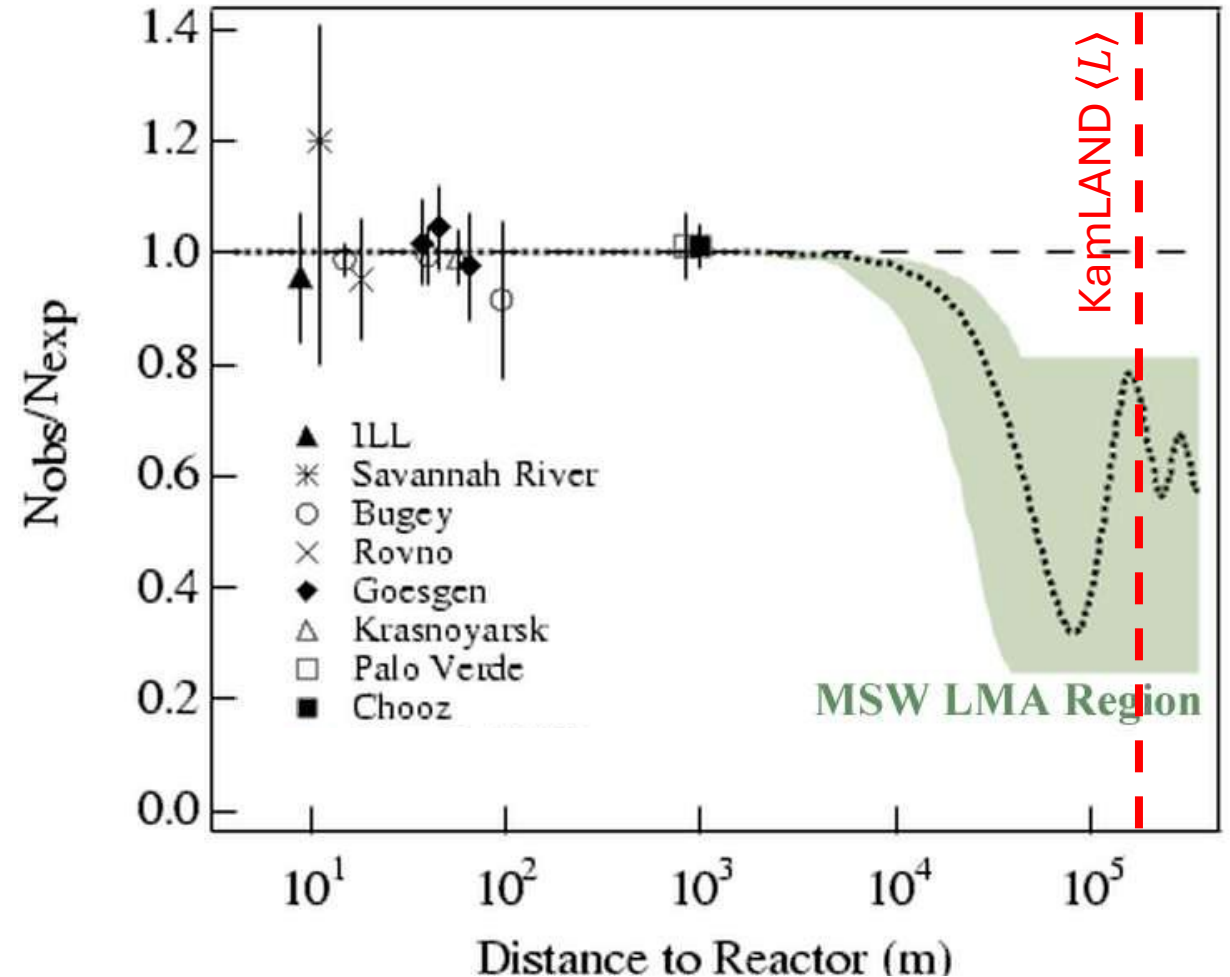
- Atsuto Suzuki: “let’s build a 1 kton LS detector in the old Kamiokande cavern”
- “Free beam” from the Japanese nuclear power industry, with convenient distribution
- Sensitive to LMA solution
  - Early ‘90’s theorists: “Don’t waste your time, it’s obviously SMA like the quarks...”





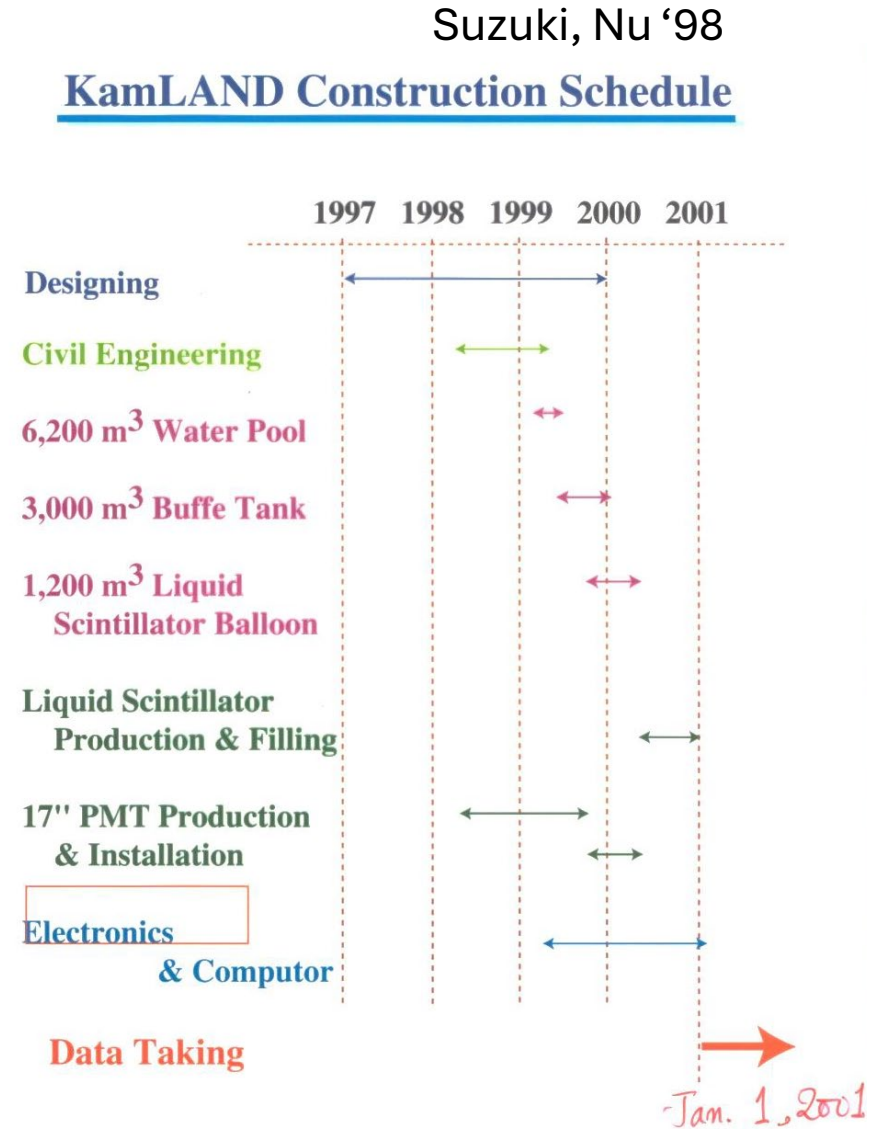
# KamLAND Strategy

- Atsuto Suzuki: “let’s build a 1 kton LS detector in the Kamiokande cavern”
- “Free beam” from the Japanese nuclear power industry, with convenient distribution
- Sensitive to LMA solution
  - Early ‘90’s theorists: “Don’t waste your time, it’s obviously SMA like the quarks...”



# KamLAND History

- '94: KamLAND proposal in Japanese
- '97: funded in Japan
- '98: Kamiokande dismantling/ PMT production  
US physicists express interest
- '99: major infrastructure construction  
DOE funding approval
- '00: PMT / balloon installation
- '01: filling, commissioning
- '02: start of data taking





# KamLAND History

- '94: KamLAND proposal in Japanese
- '97: funded in Japan
- '98: **Kamiokande dismantling/ PMT production**  
US physicists express interest
- '99: major infrastructure construction  
DOE funding approval
- '00: PMT / balloon installation
- '01: filling, commissioning
- '02: start of data taking



# KamLAND History

- '94: KamLAND proposal in Japanese
- '97: funded in Japan
- '98: Kamiokande dismantling/ PMT production  
US physicists express interest
- '99: **major infrastructure construction**  
DOE funding approval
- '00: PMT / balloon installation
- '01: filling, commissioning
- '02: start of data taking





# KamLAND History

- '94: KamLAND proposal in Japanese
- '97: funded in Japan
- '98: Kamiokande dismantling/ PMT production  
US physicists express interest
- '99: major infrastructure construction  
**DOE funding approval**
- '00: PMT / balloon installation
- '01: filling, commissioning
- '02: start of data taking

## KamLAND Collaboration Agreement Between the Collaborating Groups

### Purpose

The purpose of this document is to define the terms and conditions under which the collaborating groups (at present Japanese and American) agree to work together in building and operating a liquid scintillator anti-neutrino detector at the Kamioka mine. The experiment shall be known as KamLAND. The goals of the experiment include a search for reactor neutrino oscillations, solar neutrinos, geoneutrinos, and studies of searches for other astrophysical and particle physics phenomena. It is agreed that all collaborating groups are free to participate in all aspects of the experiment.

*Research Center for Neutrino Science, Tohoku University*

K. Furuno, J. Goldman, H. Hanada, K. Inoue, K. Ishihara, M. Kishimoto, M. Koga, T. Mitsui, M. Motoki, M. Nakajima, T. Nakajima, J. Shirai, F. Suekane, A. Suzuki, T. Takayama, K. Tamae

*University of Alabama*

J. Busenitz, A. Piepke

*Lawrence Berkeley National Laboratory, University of California, Berkeley*

B. Berger, R. N. Cahn, Y. D. Chan, X. Chen, S. J. Freedman, B. K. Fujikawa, L. Greiner, K. T. Lesko, K.-B. Luk, H. Murayama, D. R. Nygren, C. E. Okada, A. W. Poon, H. M. Steiner

*California Institute of Technology*

G. Horton-Smith, R. D. McKeown, V. Novikov, B. Tipton, P. Vogel

*Drexel University*

C. E. Lane

*Duke University, North Carolina State University, Triangle Universities Nuclear Laboratory*

L. DeBraekeleer, C. R. Gould, H. Karwowski, D. Markoff, K. Nakamura, R. Rohm, W. Tornow, A. Young

*University of Hawaii*

P. Gorham, J. Learned, S. Matsuno, S. Pakvasa

*Louisiana State University*

S. Dazeley, S. Hatakeyama, R. C. Svoboda

*University of New Mexico*

B. Dieterle, S. Riley

*Stanford University*

G. Gratta, Y. Uchida

*University of Tennessee*

S. Berridge, W. Bugg, H. Cohn, Yu. Efremenko, Yu. Kamyshkov



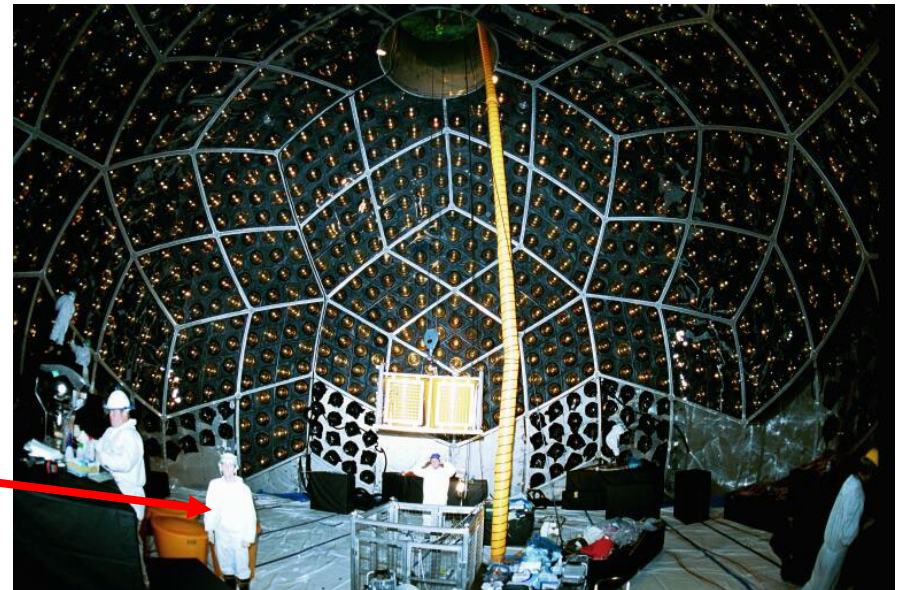
UH contribution: optical calibration system

# KamLAND History

- '94: KamLAND proposal in Japanese
- '97: funded in Japan
- '98: Kamiokande dismantling/ PMT production  
US physicists express interest
- '99: major infrastructure construction  
DOE funding approval
- '00: **PMT / balloon installation**
- '01: filling, commissioning
- '02: start of data taking



yours truly

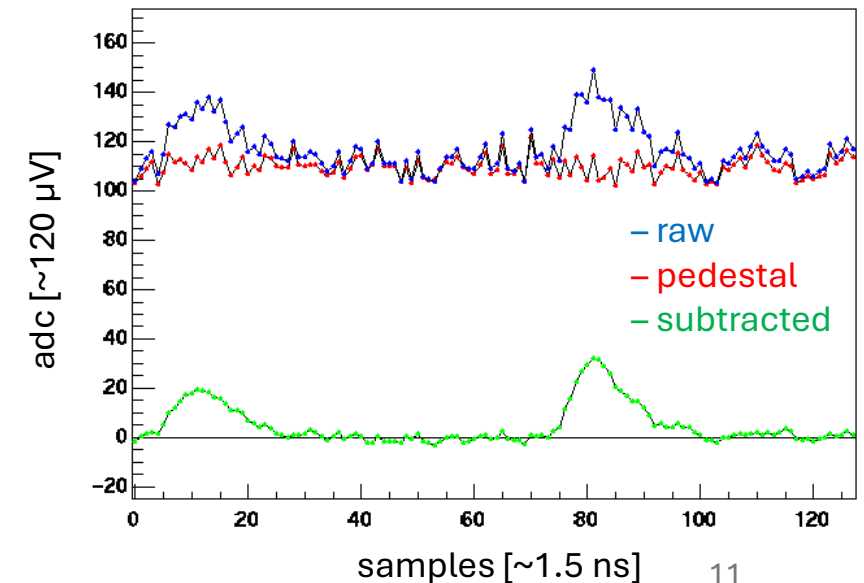
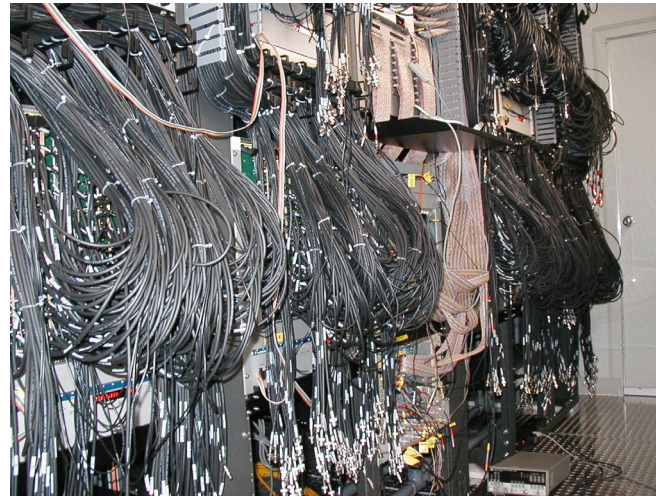
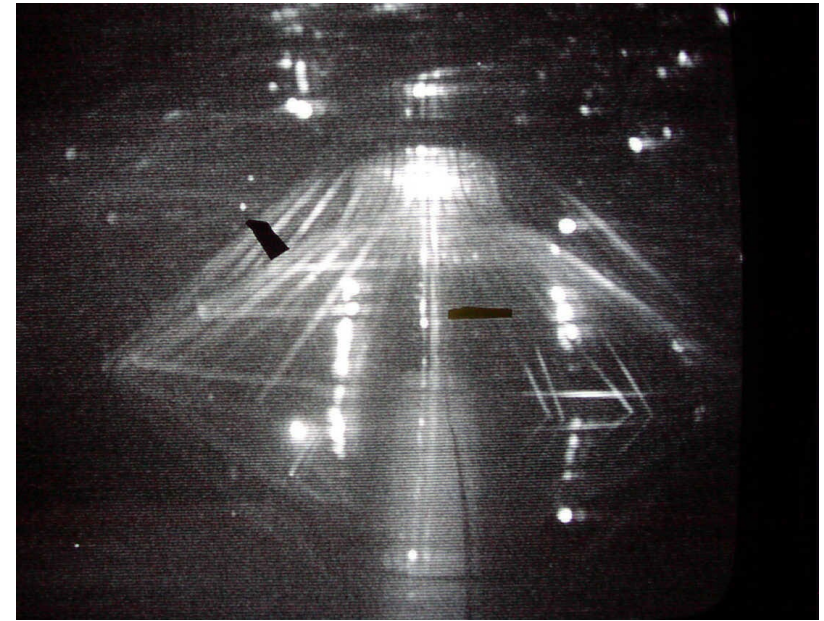


NASA Astro Pic of the Day, June 23 2023 <sup>10</sup>



# KamLAND History

- '94: KamLAND proposal in Japanese
- '97: funded in Japan
- '98: Kamiokande dismantling/ PMT production  
US physicists express interest
- '99: major infrastructure construction  
DOE funding approval
- '00: PMT / balloon installation
- **'01: filling, commissioning**
- '02: start of data taking



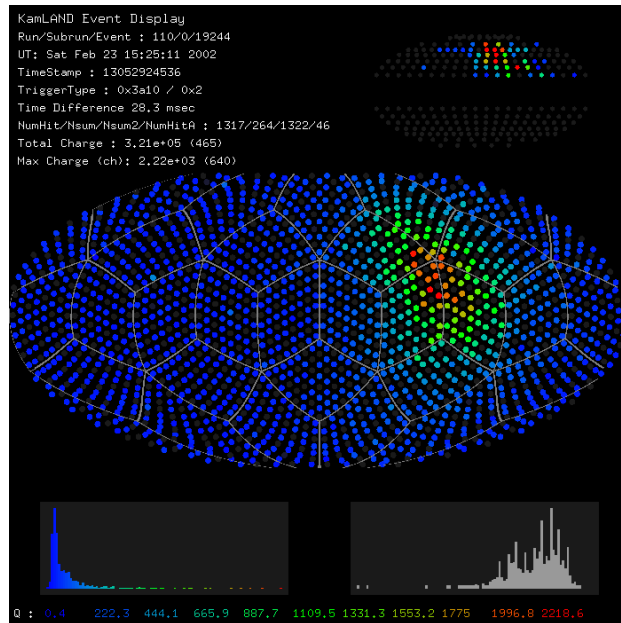
# KamLAND History

- '94: KamLAND proposal in Japanese
- '97: funded in Japan
- '98: Kamiokande dismantling/ PMT production  
US physicists express interest
- '99: major infrastructure construction  
DOE funding approval
- '00: PMT / balloon installation
- '01: filling, commissioning
- **'02: start of data taking!**

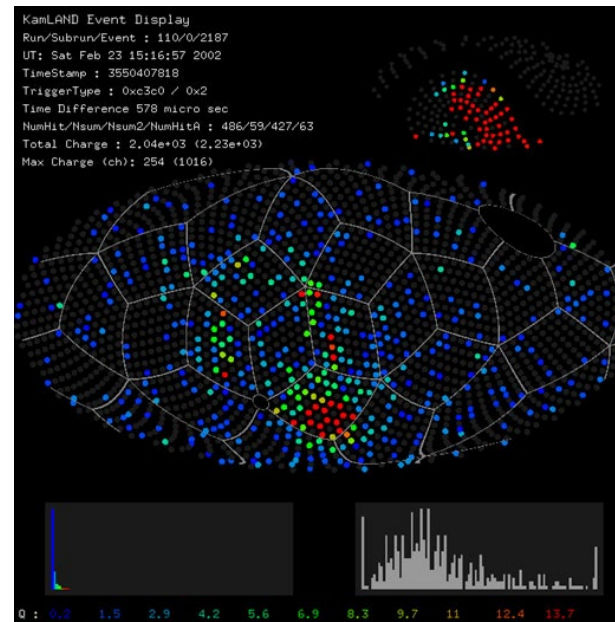




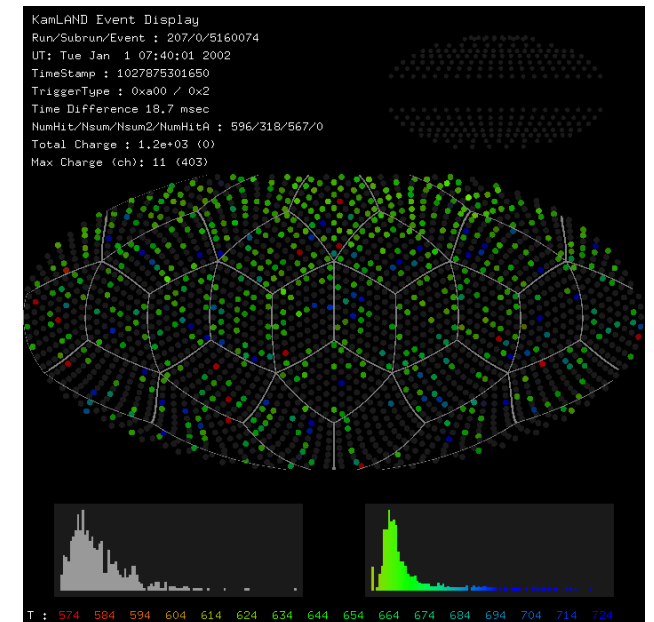
# First Data



stopping  $\mu$



buffer oil muon  
with Cherenkov ring



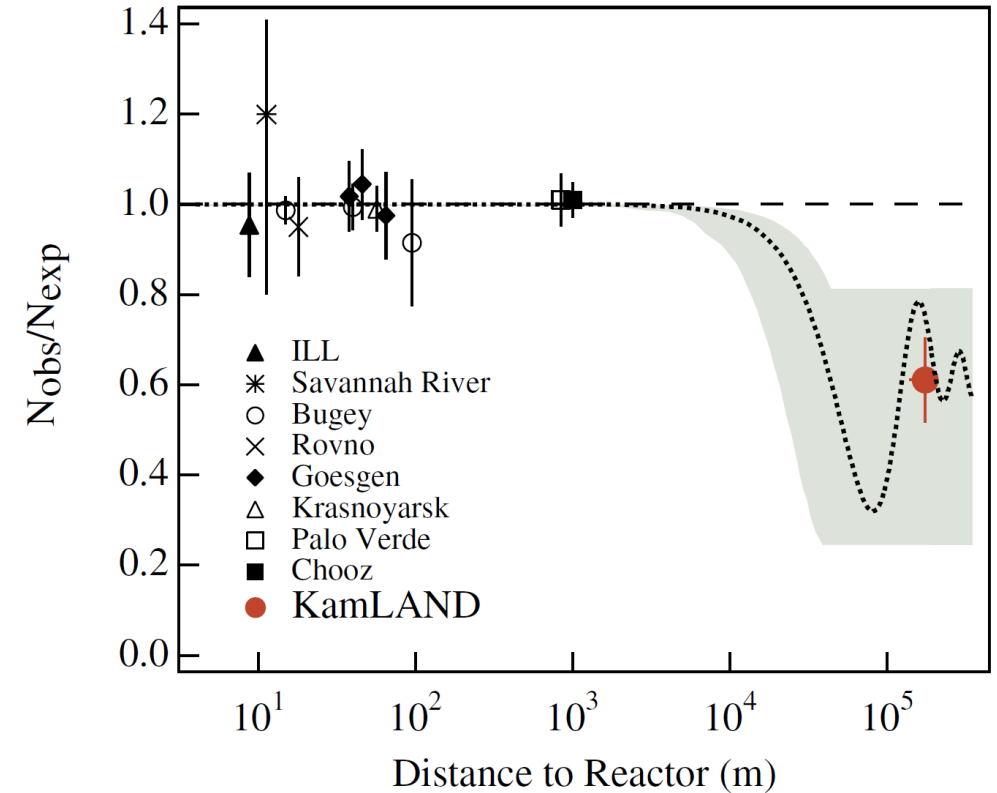
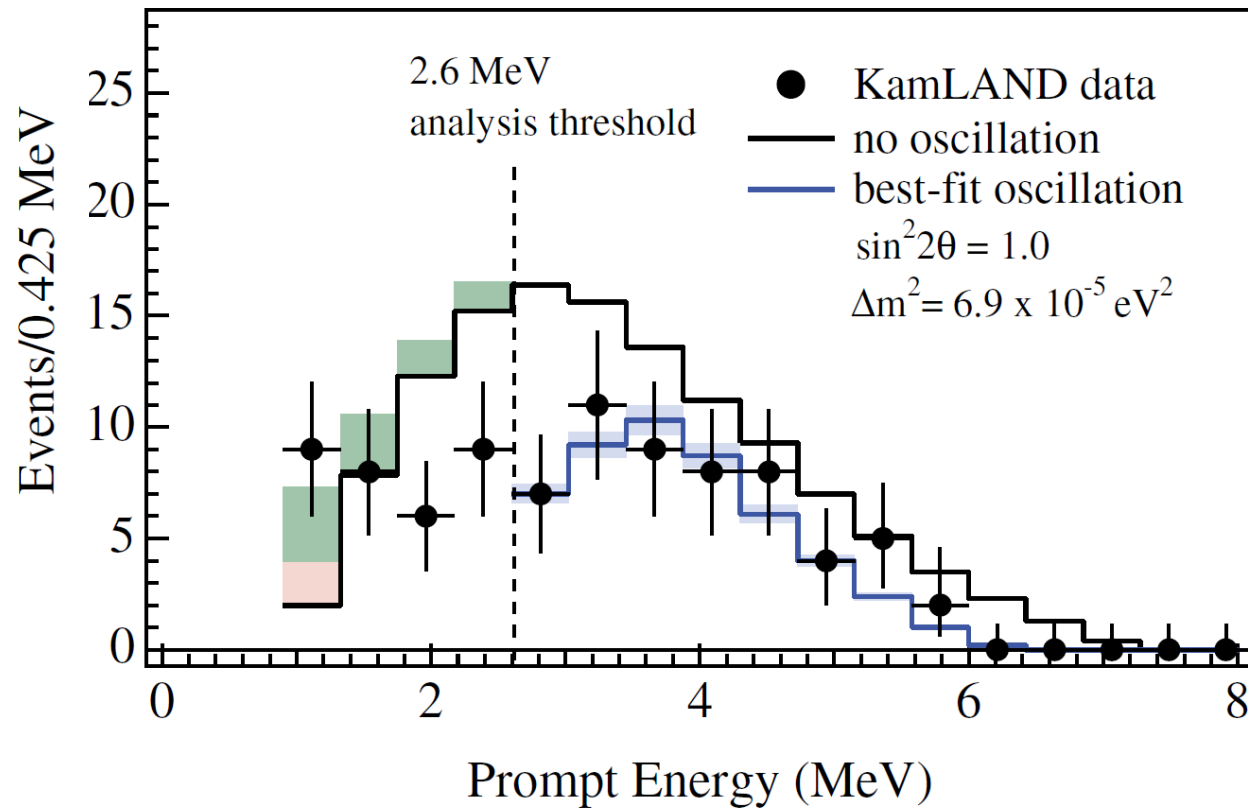
first antineutrino candidate



# Working in Japan

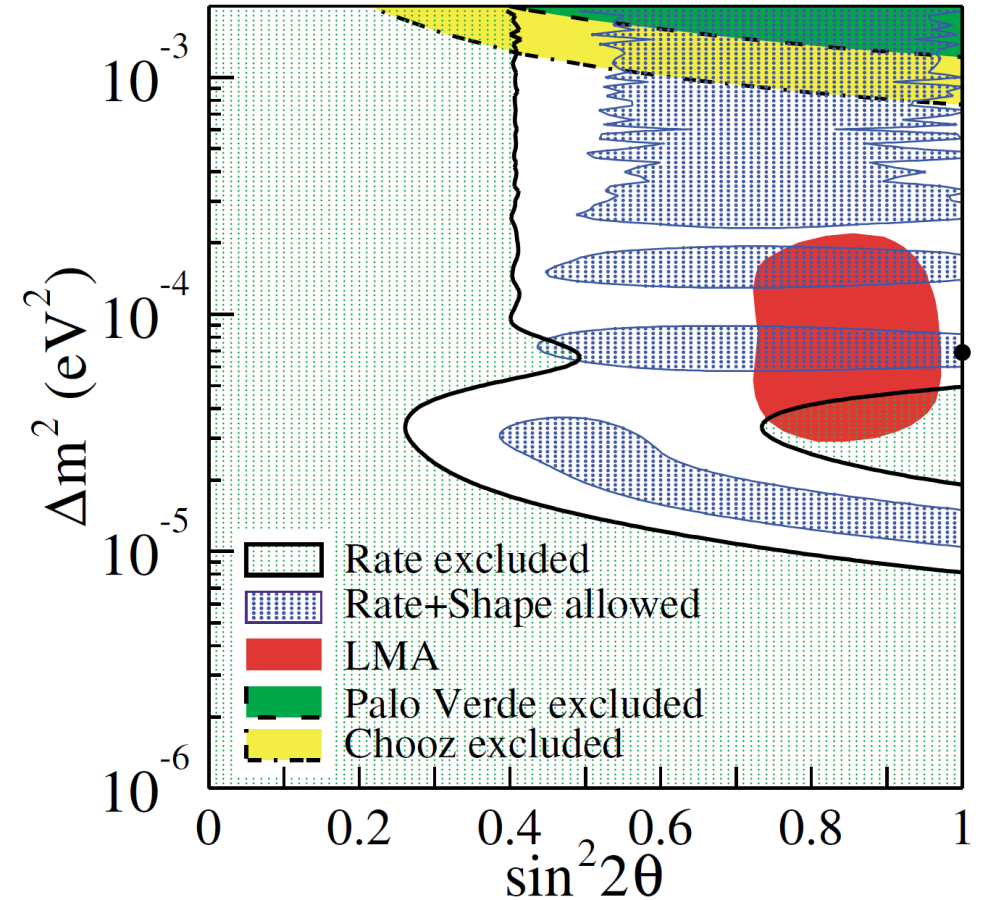
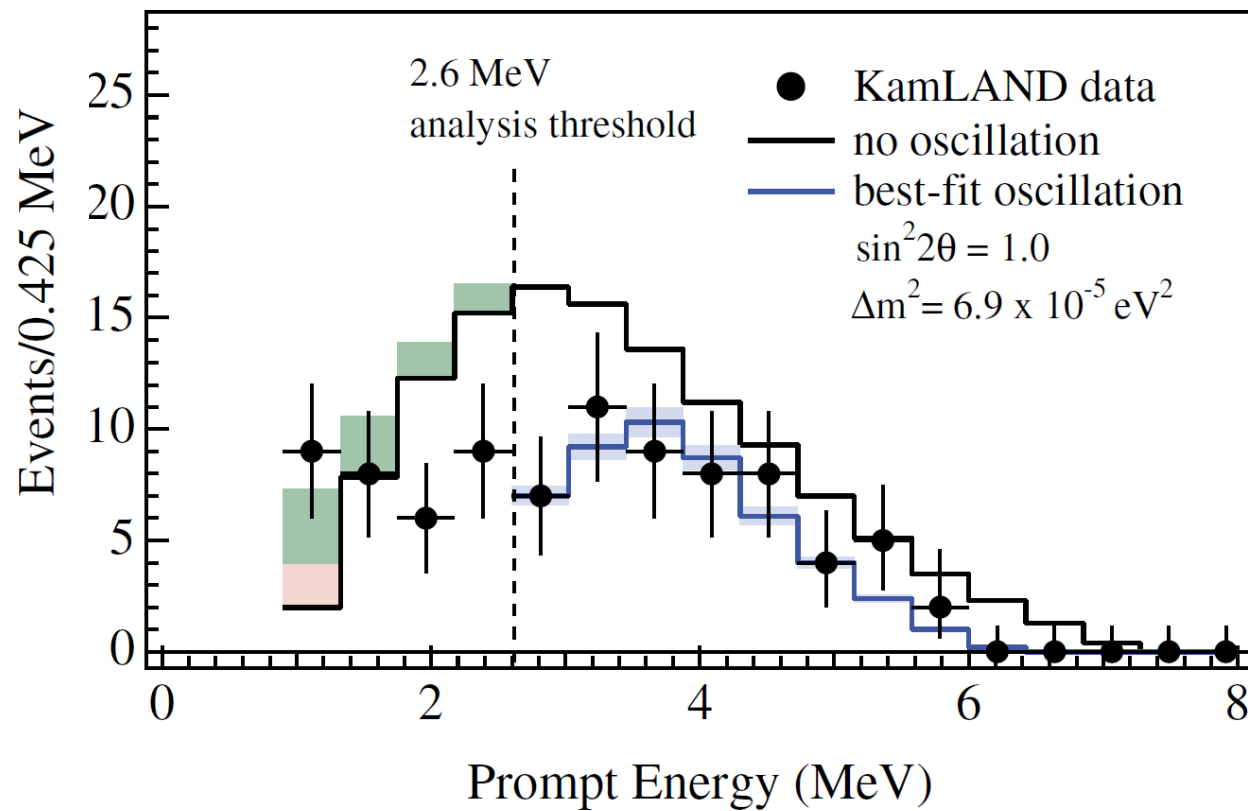


# First results: reactor neutrino disappearance

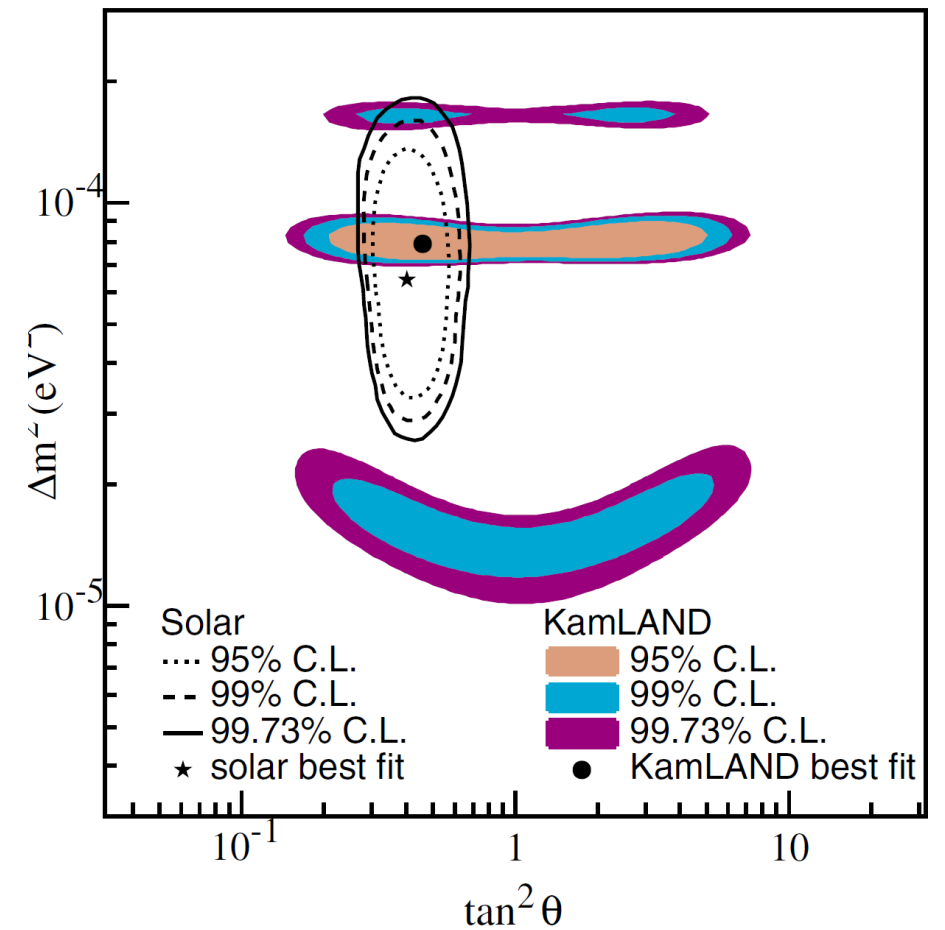
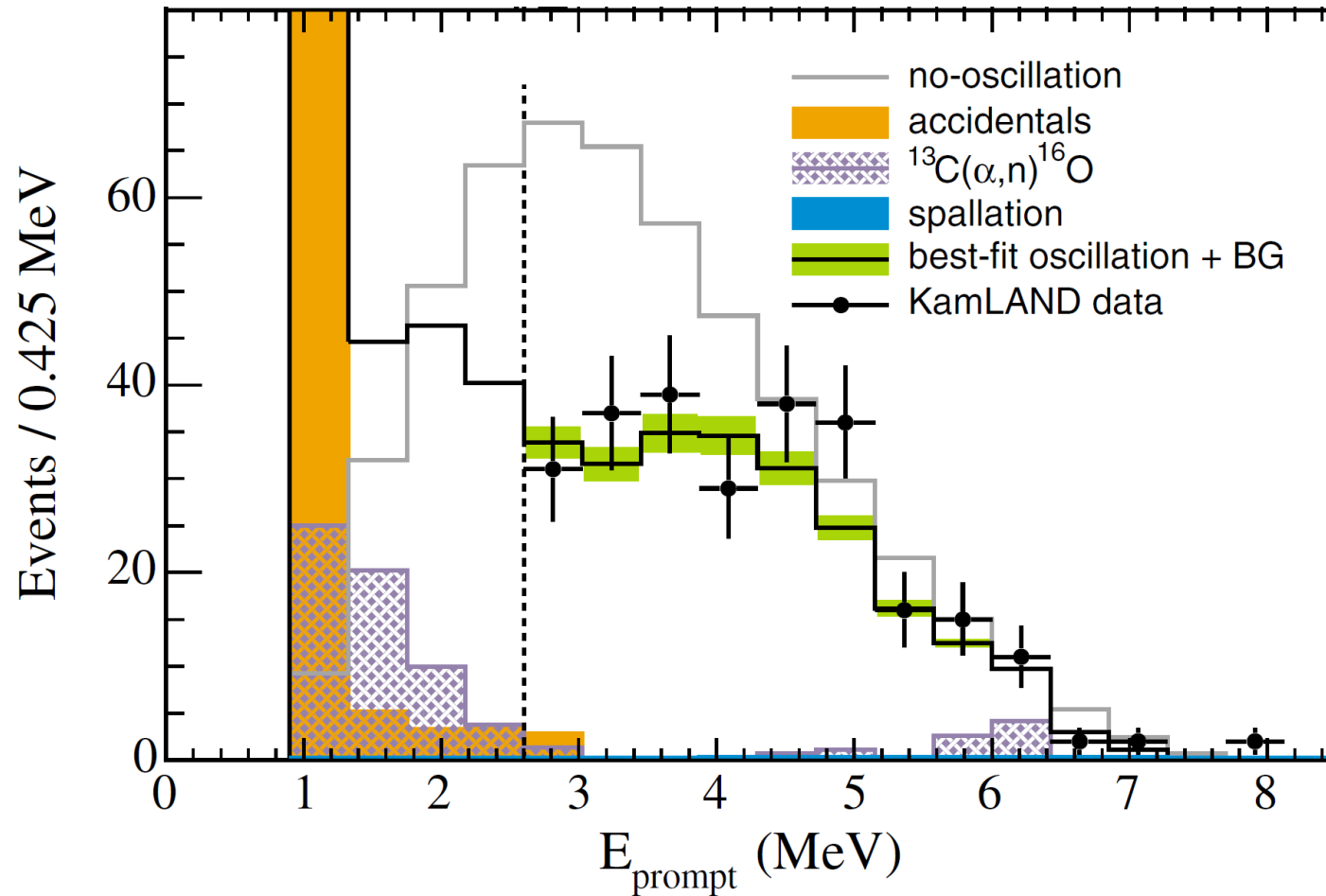




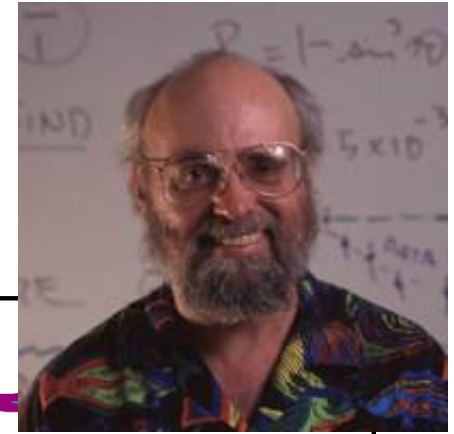
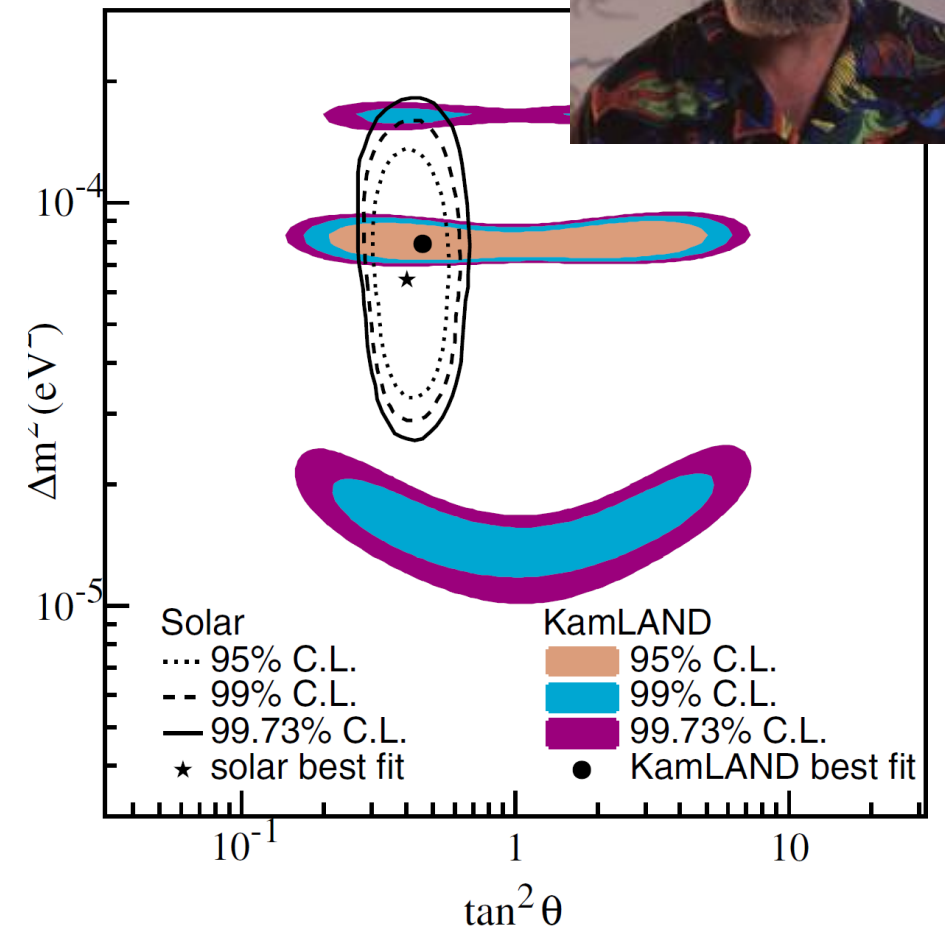
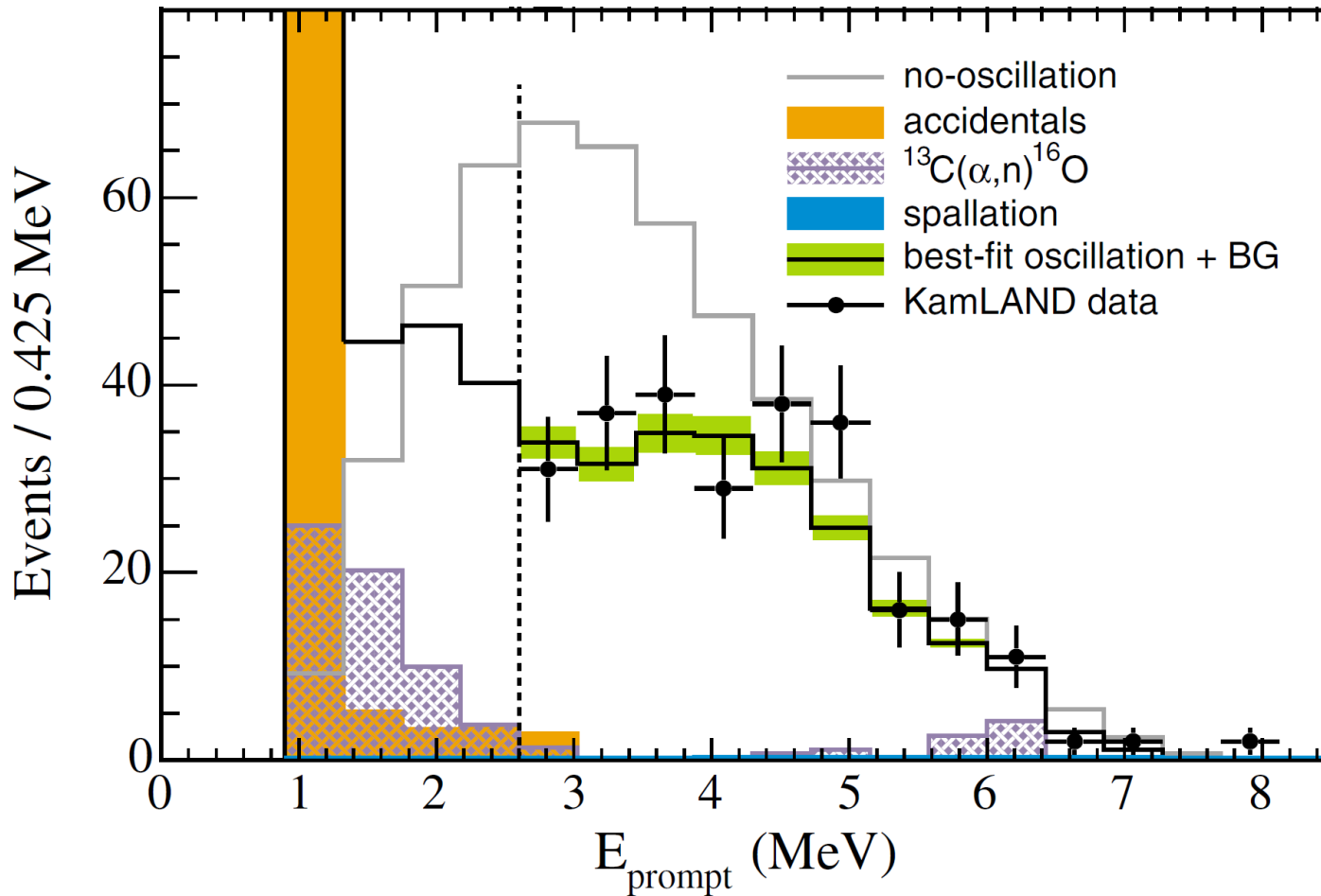
# First results: reactor neutrino disappearance



# Second Result: spectral distortion

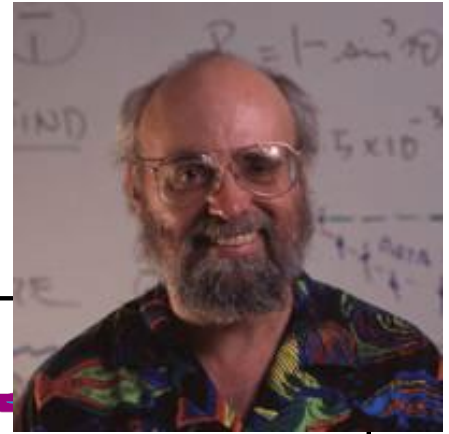
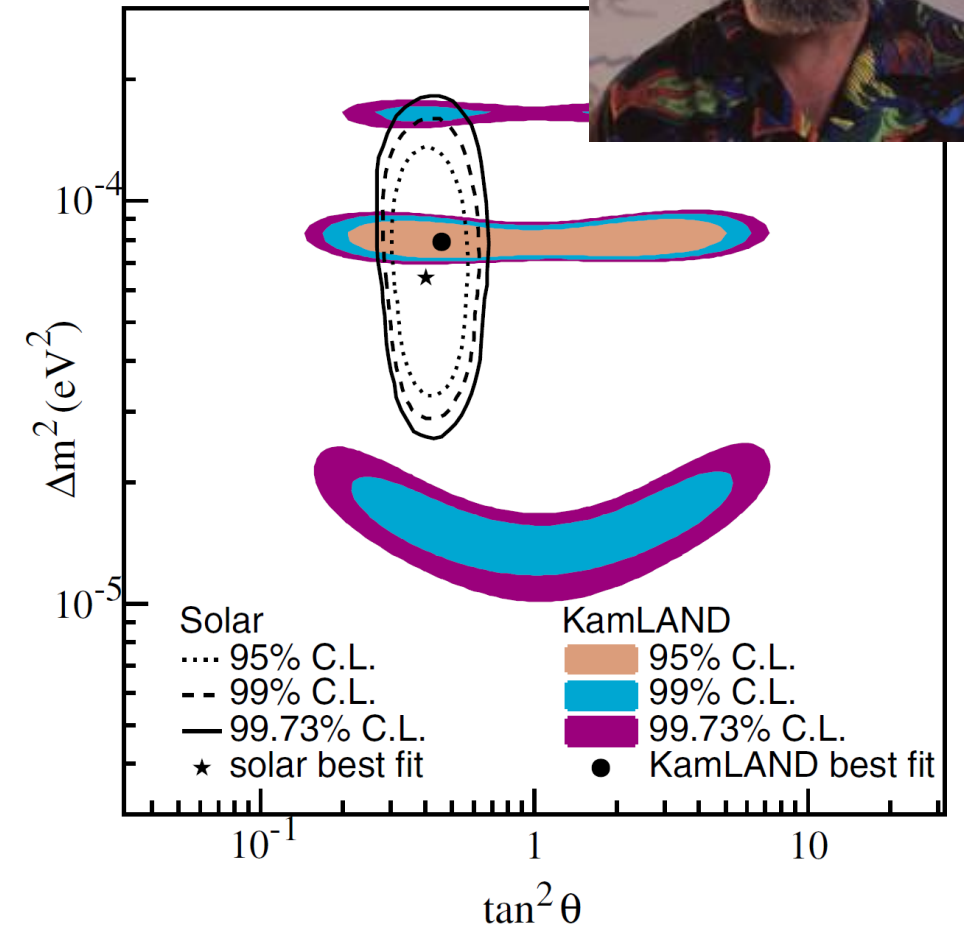
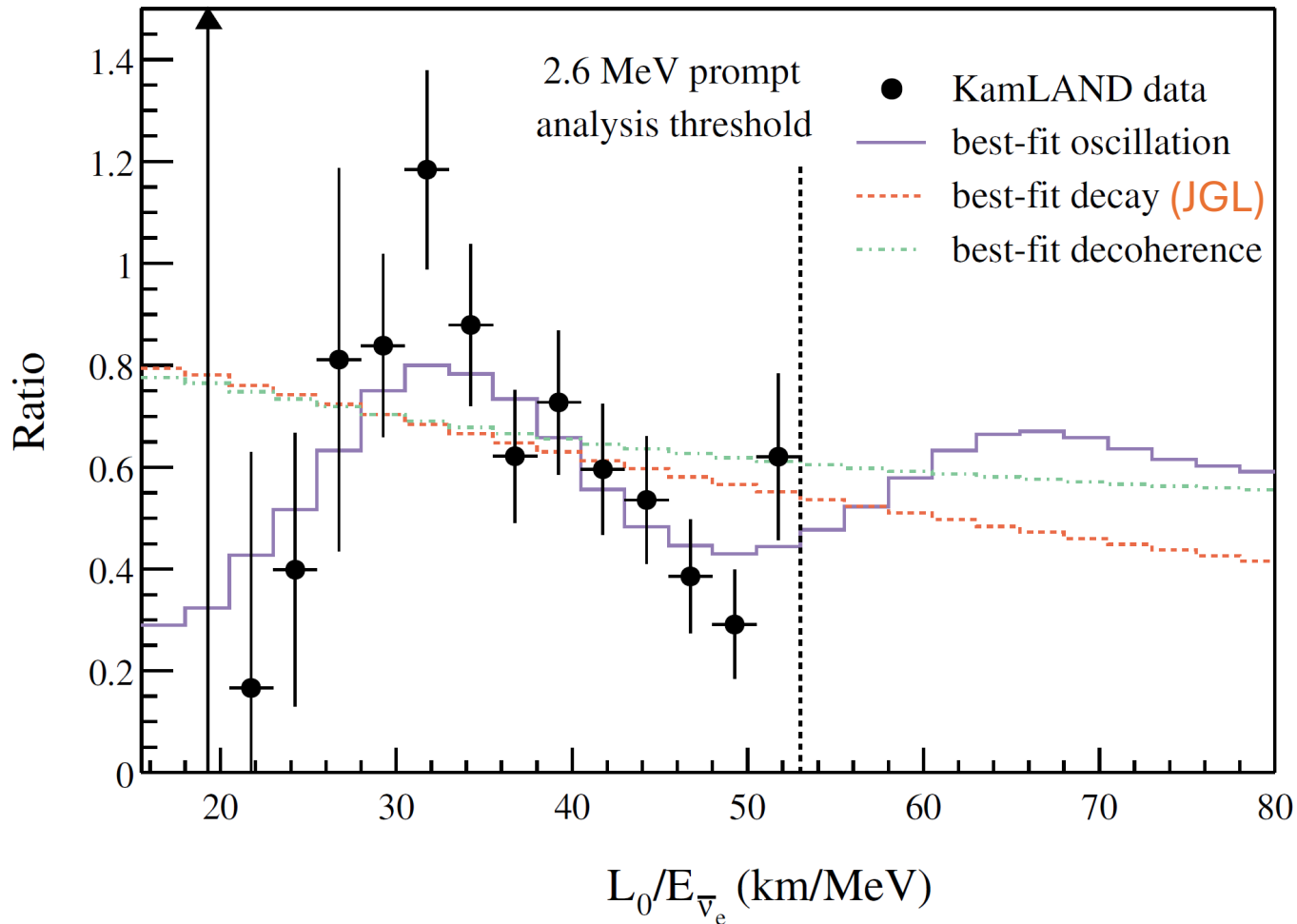


# Second Result: spectral distortion

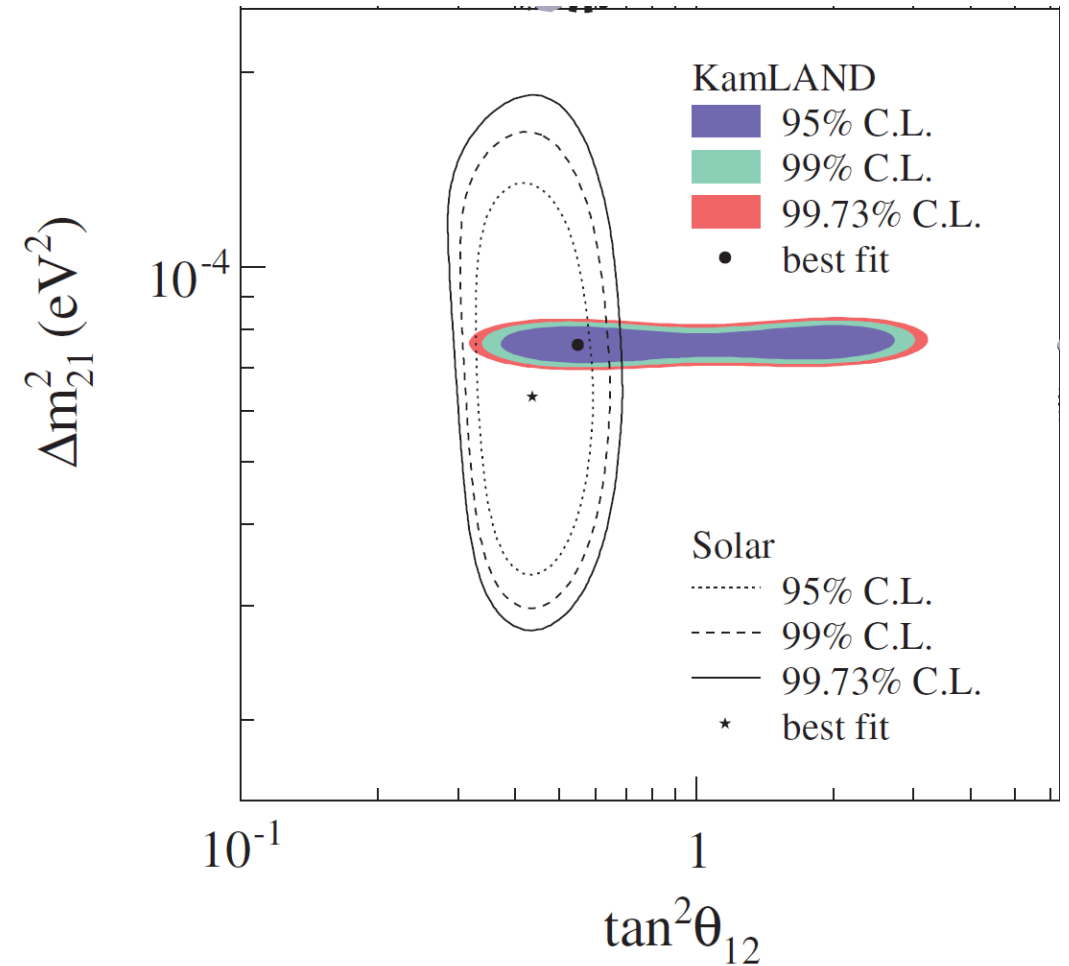
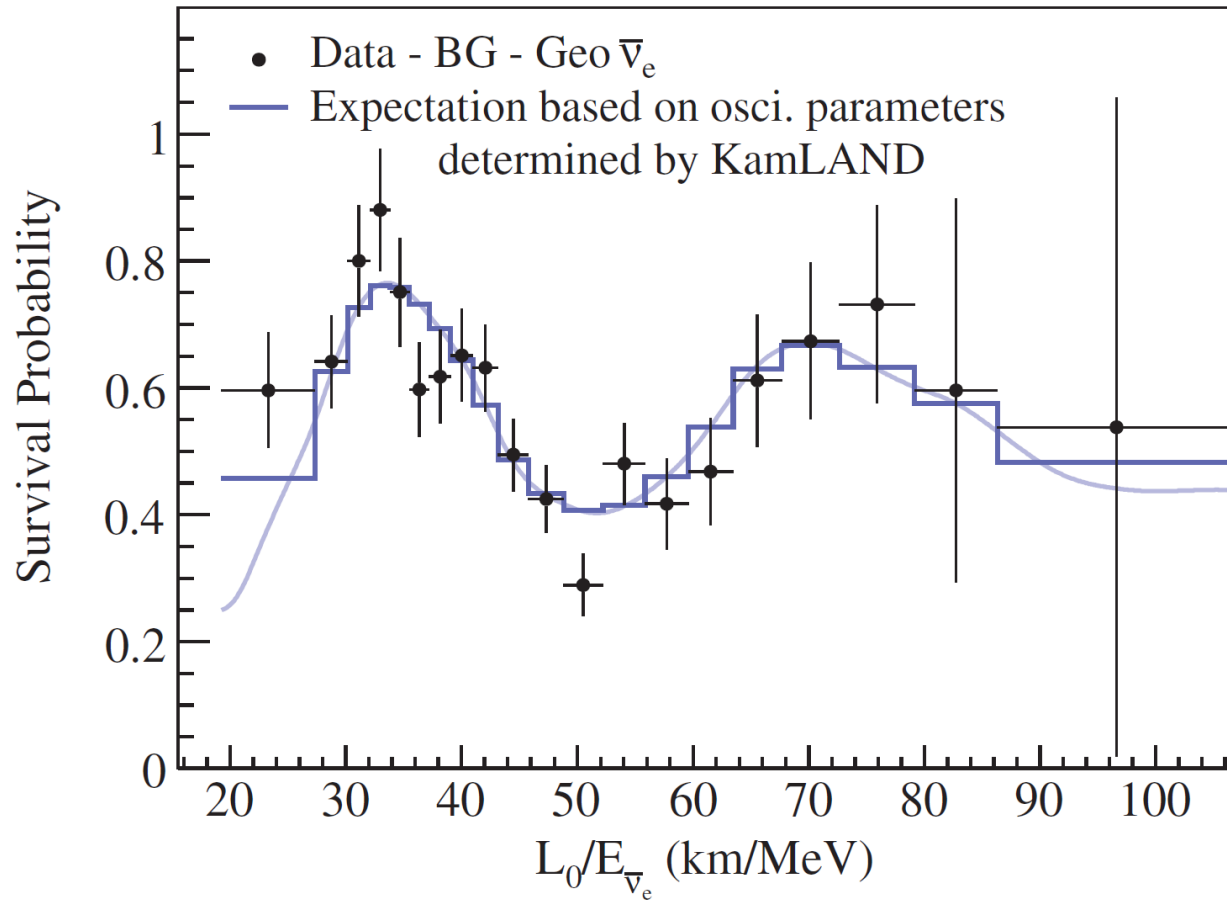




# Second Result: spectral distortion



# Third Result: precision oscillation



# Key Contributions





# Key Contributions





# Key Contributions





# Disaster Strikes...

From: kuni0\_in0ue@yahoo.co.jp  
Sent: Saturday, March 12, 2011 3:07 AM  
Subject: terrible earthquake

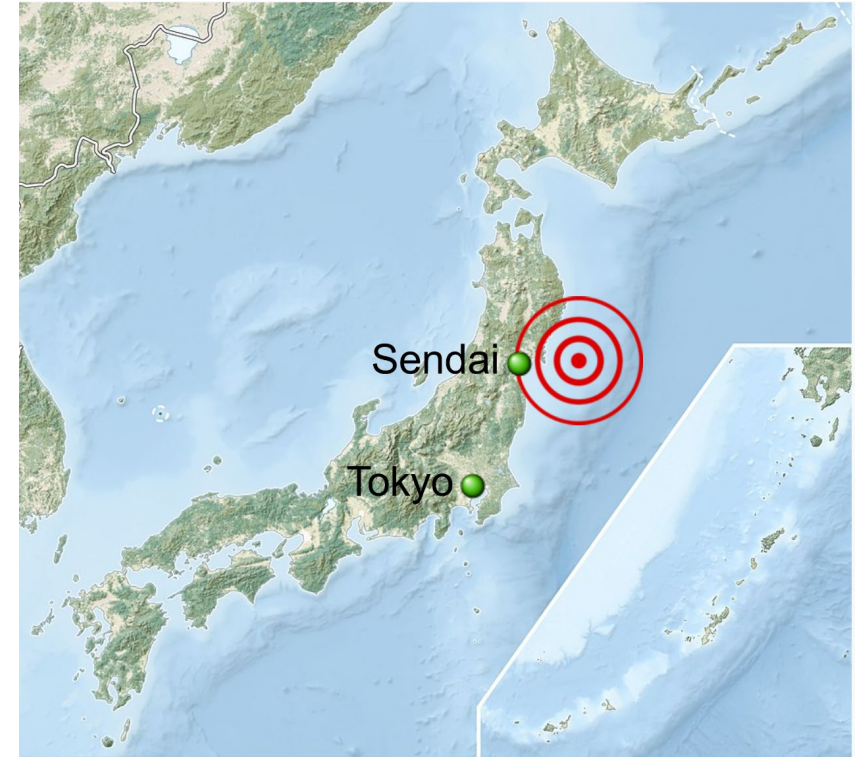
Dear colleagues,

We had really terrible earthquake yesterday.  
Electricity is not delivered yet. And we cannot send/receive e-mail  
with our usual account.  
I'm sending this with a battery and connection is very unstable.

However, as far as I know, No one was injured in RCNS.  
We are just waiting for a recovery of electricity.  
I think RCNS people in Kamioka cannot receive e-mail, but  
their telephone (81-578-85-0030) may be working.  
I cannot call them due to regulated use of the telephone line.  
Please inform them and our colleagues that  
we are OK, please ask them to maintain KamLAND safely.

Thank you very much for your help.

Best regards,  
Kunio Inoue





# Disaster Strikes...

From: kuni0\_in0ue@yahoo.co.jp  
Sent: Saturday, March 12, 2011 3:07 AM  
Subject: terrible earthquake

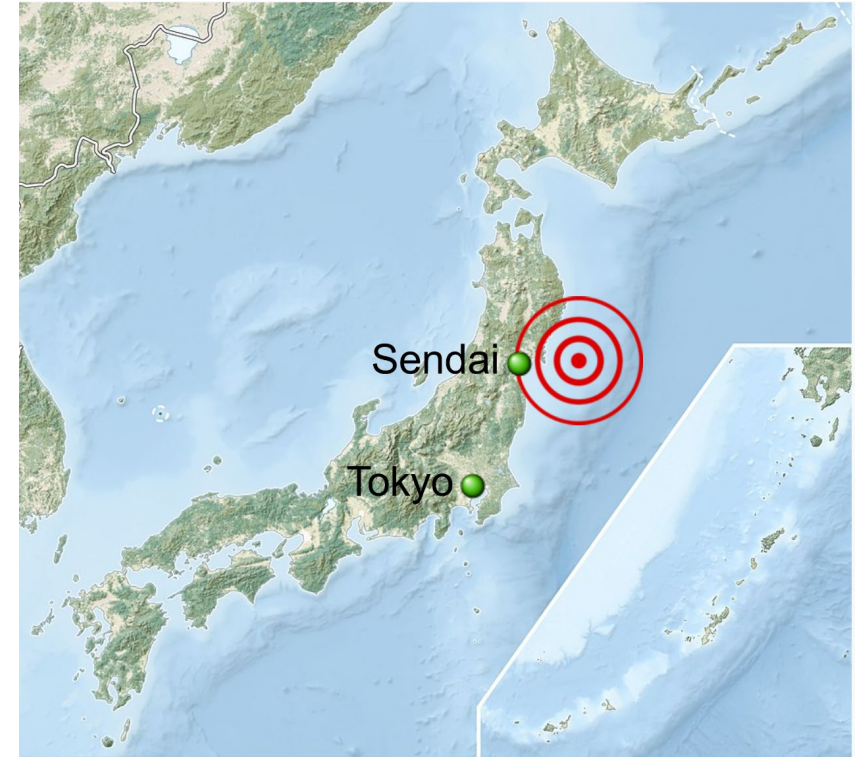
Dear colleagues,

We had really terrible earthquake yesterday.  
Electricity is not delivered yet. And we cannot send/receive e-mail  
with our usual account.  
I'm sending this with a battery and connection is very unstable.

However, as far as I know, No one was injured in RCNS.  
We are just waiting for a recovery of electricity.  
I think RCNS people in Kamioka cannot receive e-mail, but  
their telephone (81-578-85-0030) may be working.  
I cannot call them due to regulated use of the telephone line.  
Please inform them and our colleagues that  
we are OK, please ask them to maintain KamLAND safely.

Thank you very much for your help.

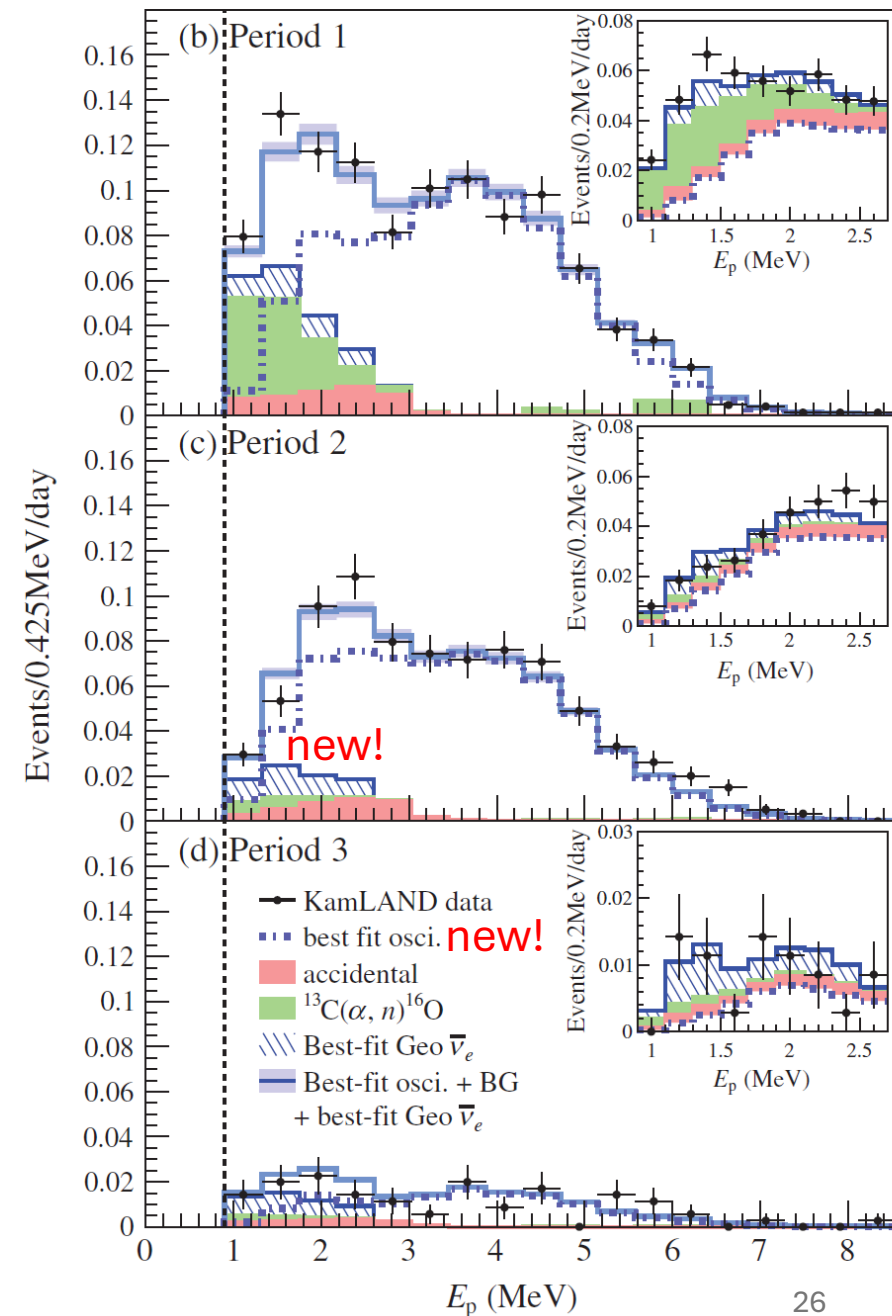
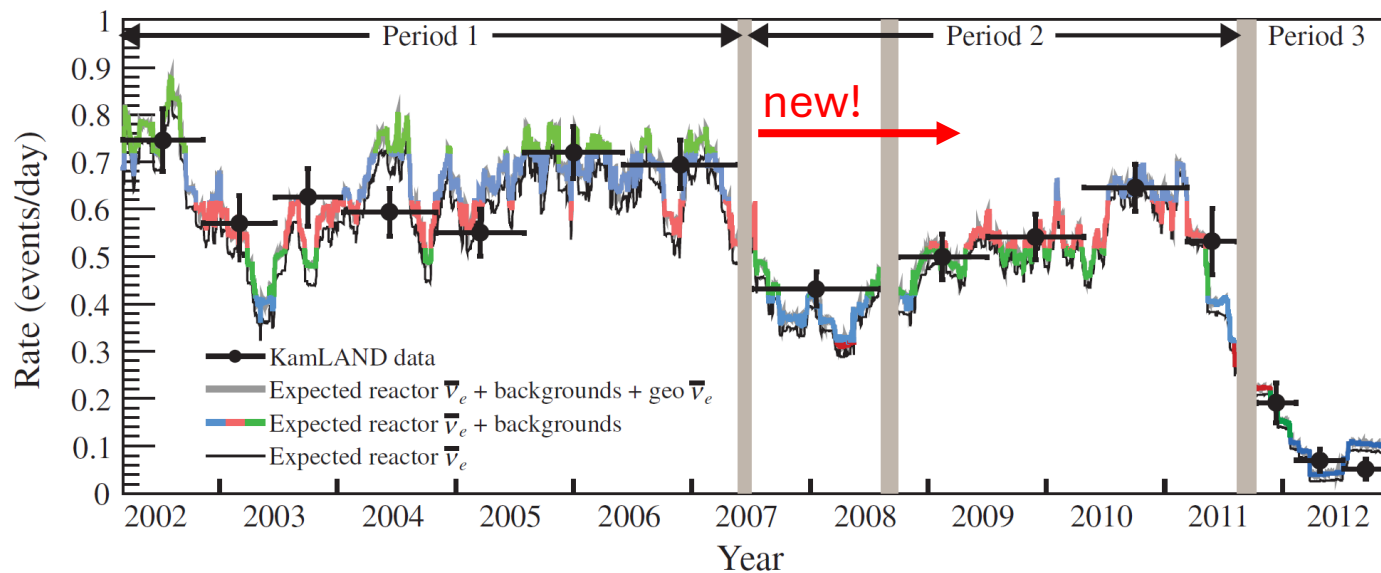
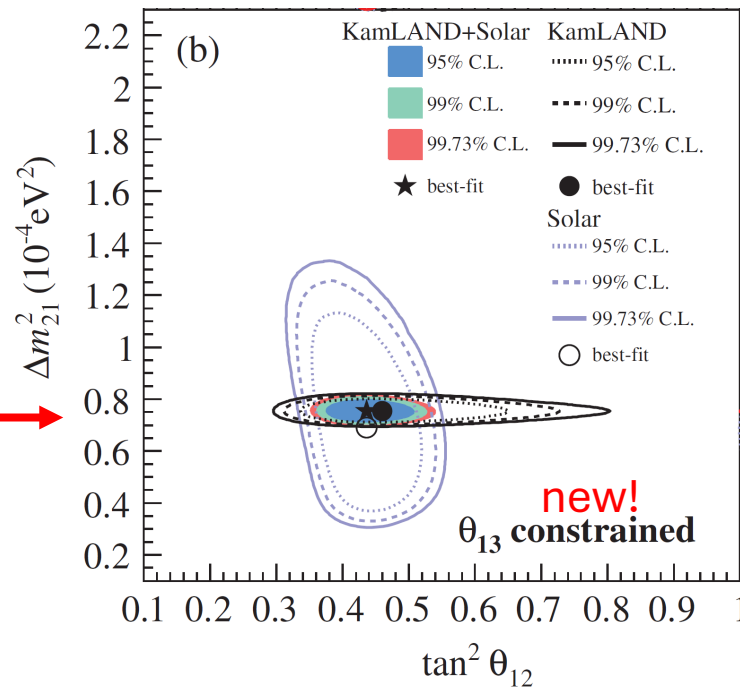
Best regards,  
Kunio Inoue



**My memory:** John was one of the most active on the collaboration in monitoring and communicating the situation, and in working to find ways to help!

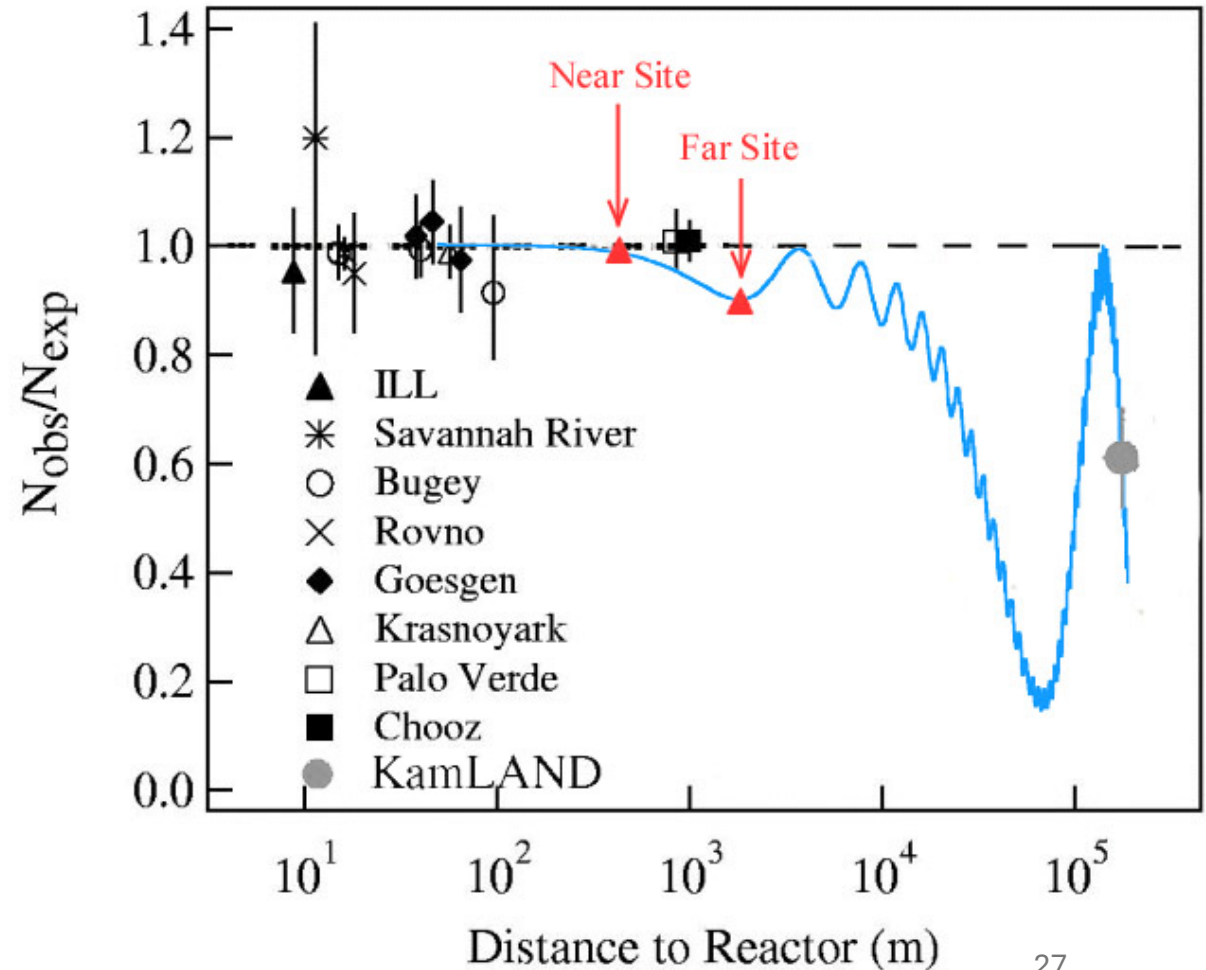
# Purification and Reactor-Off Data

PDG →



# The quest to measure $\theta_{13}$

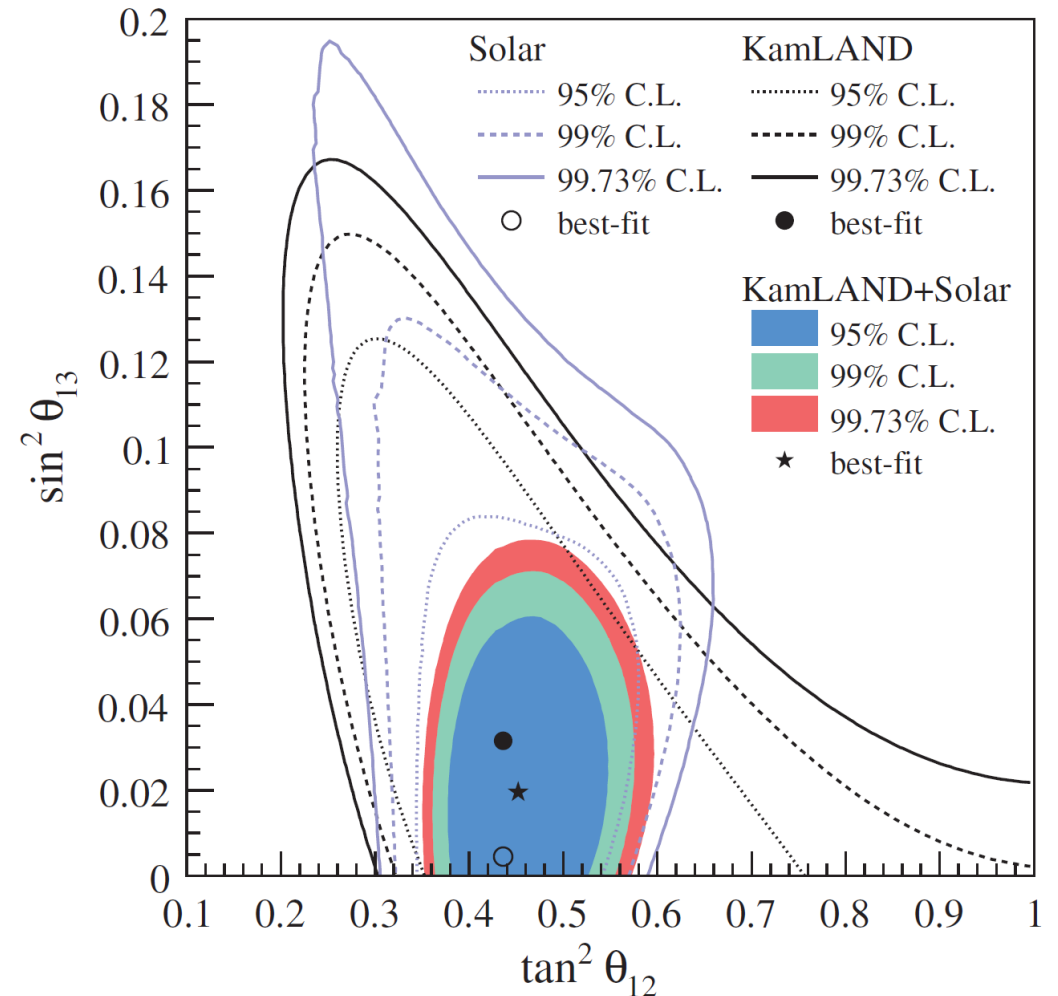
- Stringent CHOOZ limit: is  $\theta_{13}$  too small for CPV to be measured?





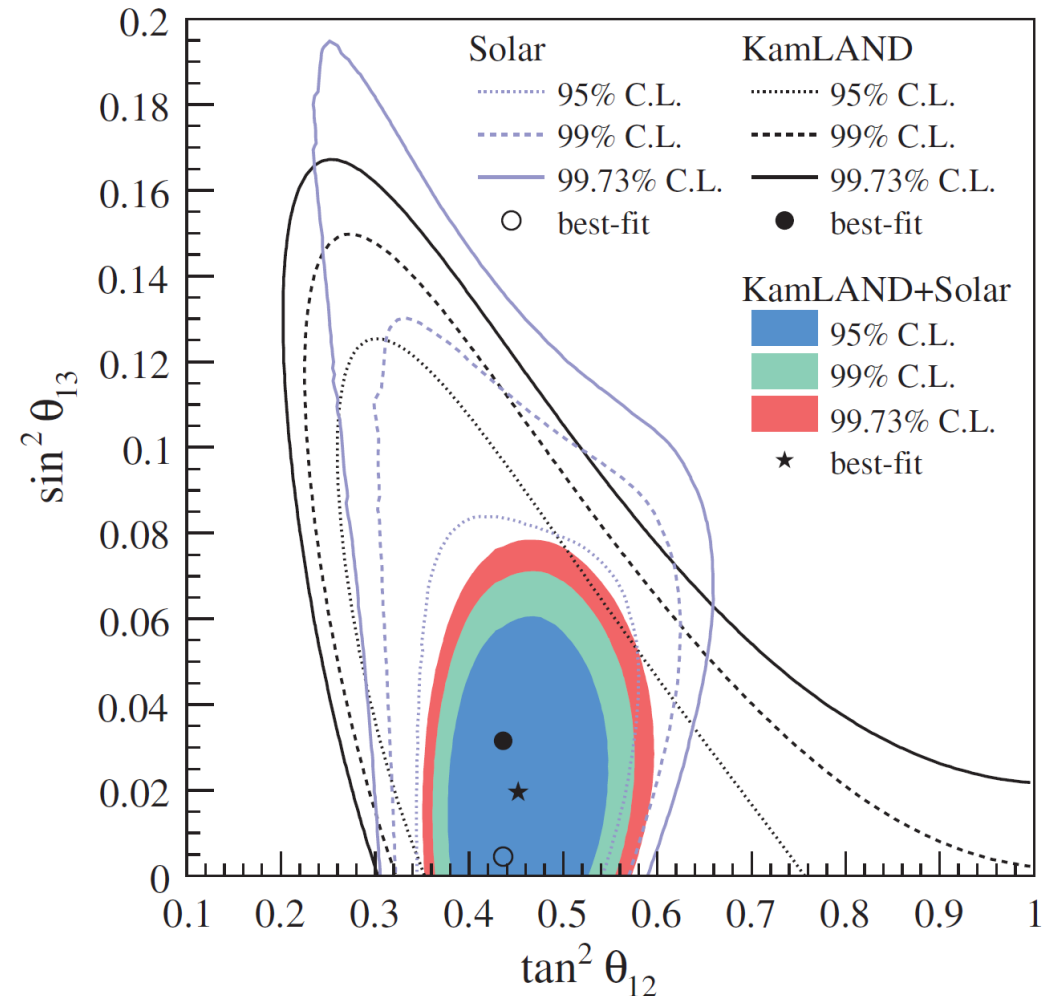
# The quest to measure $\theta_{13}$

- Stringent CHOOZ limit: is  $\theta_{13}$  too small for CPV to be measured?
- Non-zero  $\theta_{13}$  relieved tension between KamLAND & solar  $\theta_{12}$

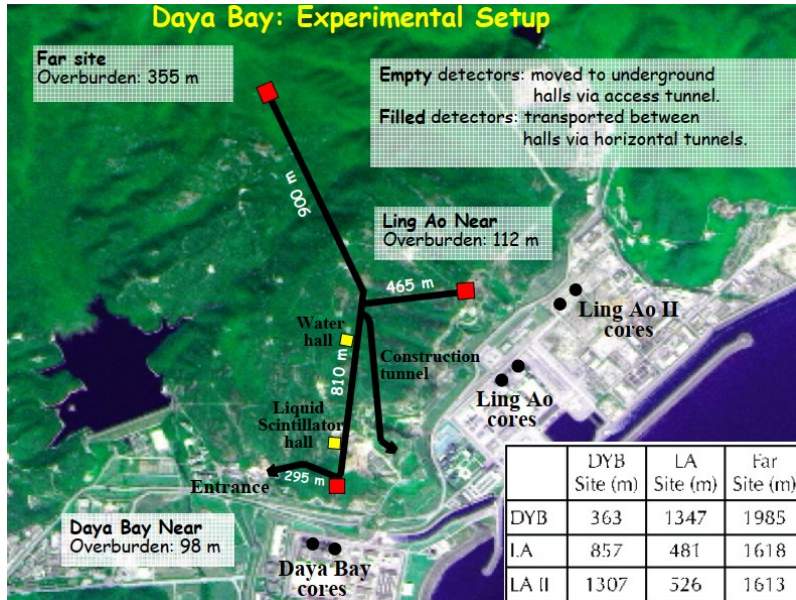


# The quest to measure $\theta_{13}$

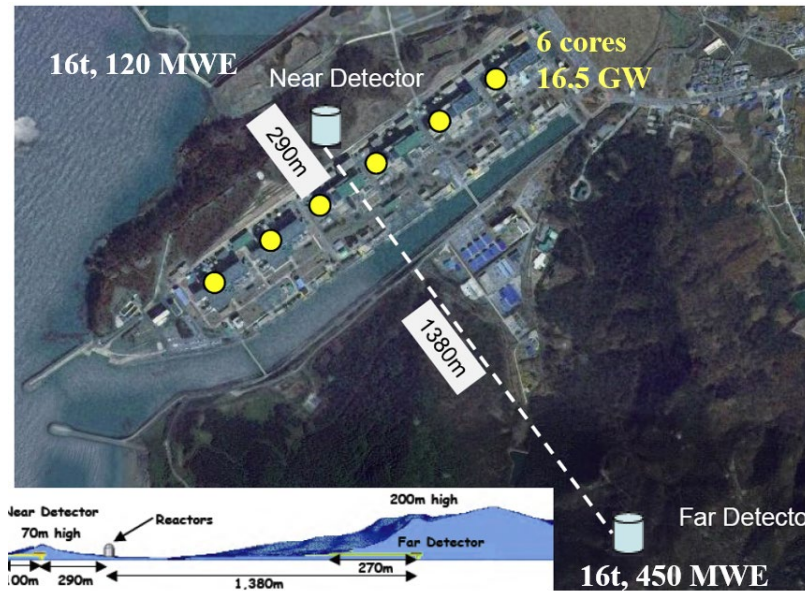
- Stringent CHOOZ limit: is  $\theta_{13}$  too small for CPV to be measured?
- Non-zero  $\theta_{13}$  relieved tension between KamLAND & solar  $\theta_{12}$
- Daya Bay, RENO, and Double-Chooz performed definitive measurements



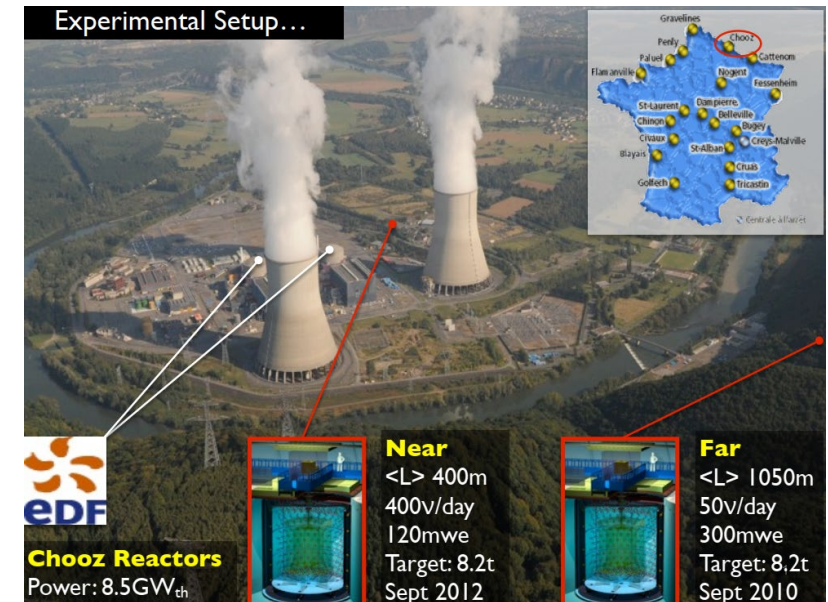
# The quest to measure $\theta_{13}$



Daya Bay



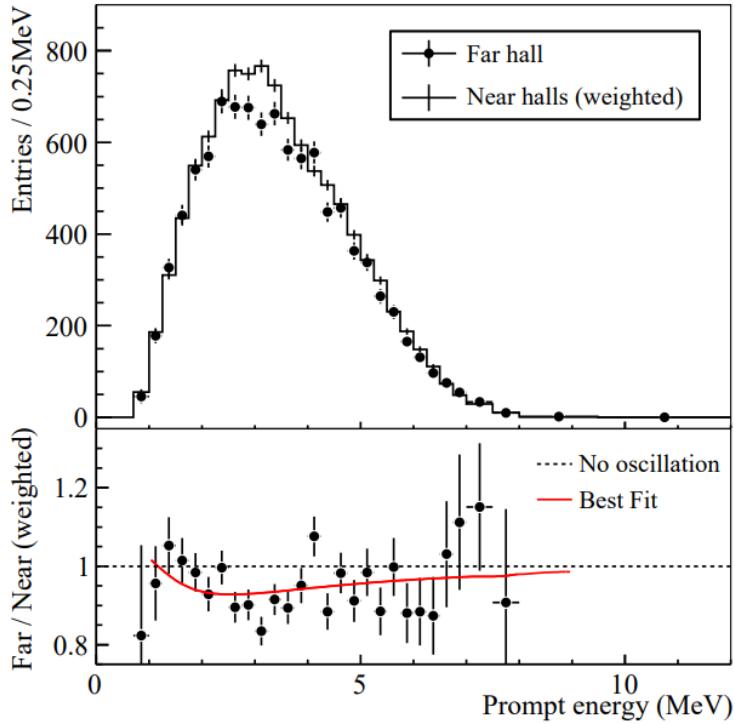
RENO



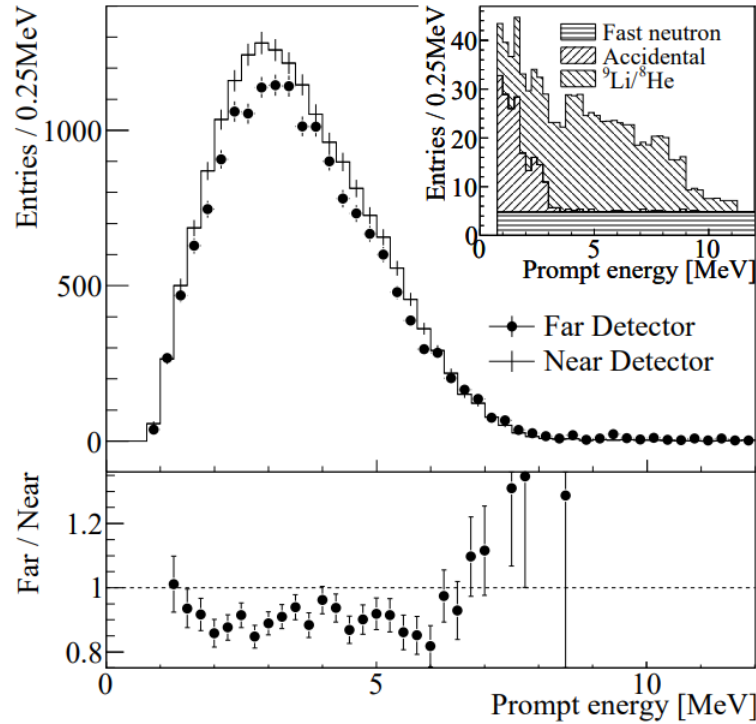
Double Chooz



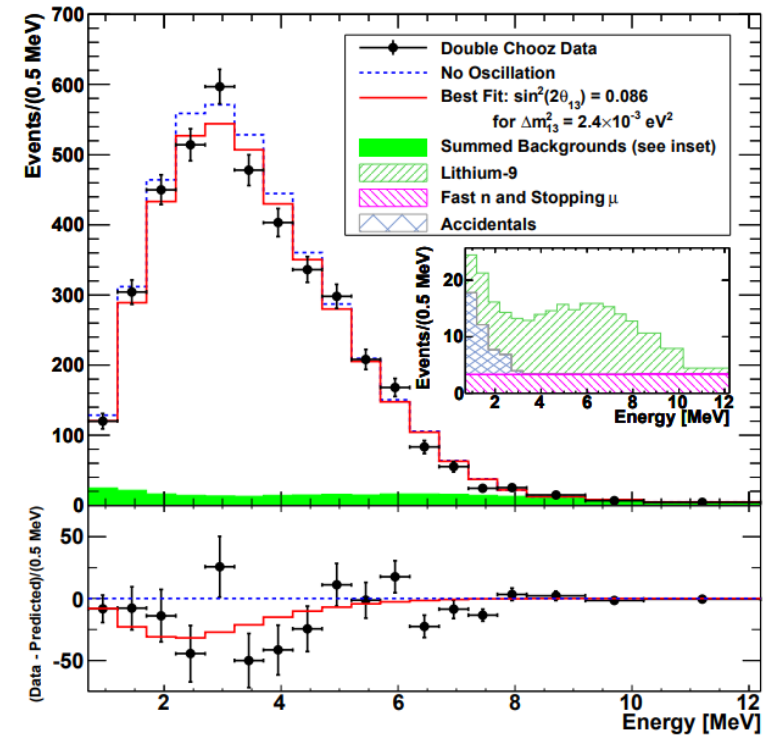
# The quest to measure $\theta_{13}$



Daya Bay  
PRL **108**, 171803 (2012)

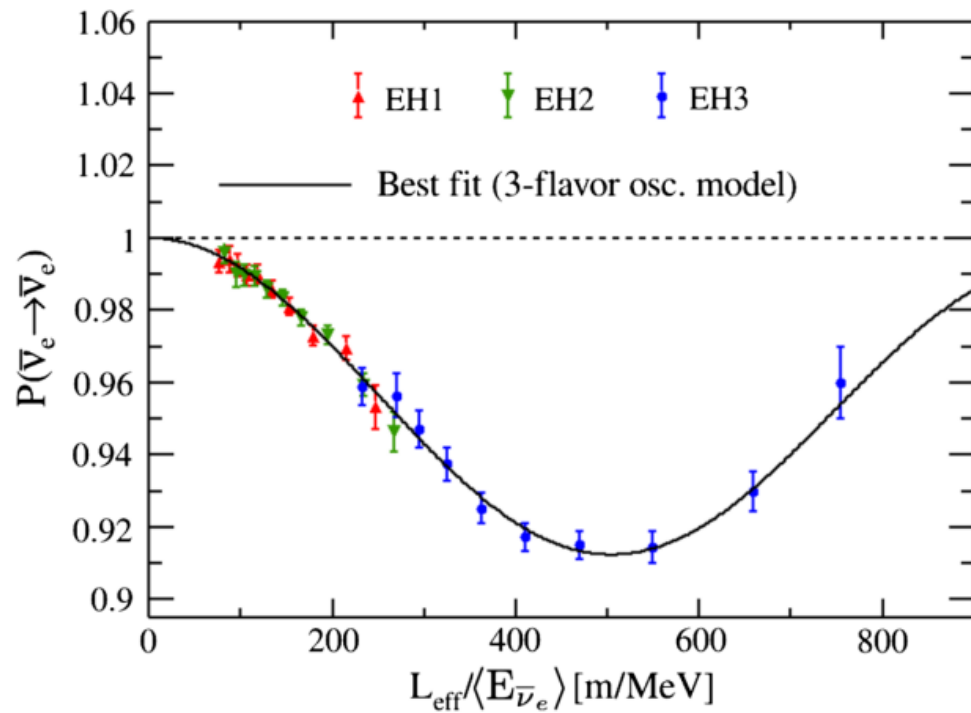


RENO  
PRL **108**, 191802 (2012)



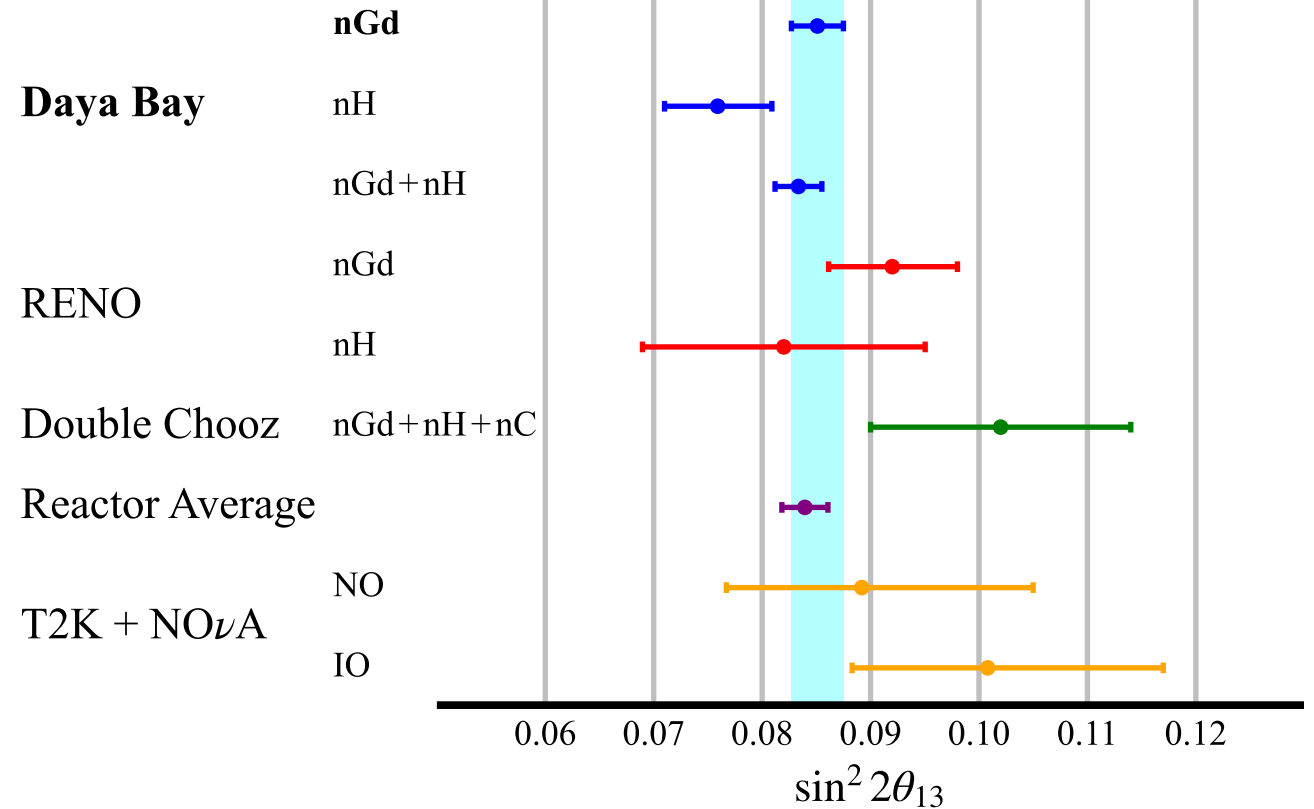
Double Chooz  
PRL **108**, 131801 (2012)

# The quest to measure $\theta_{13}$



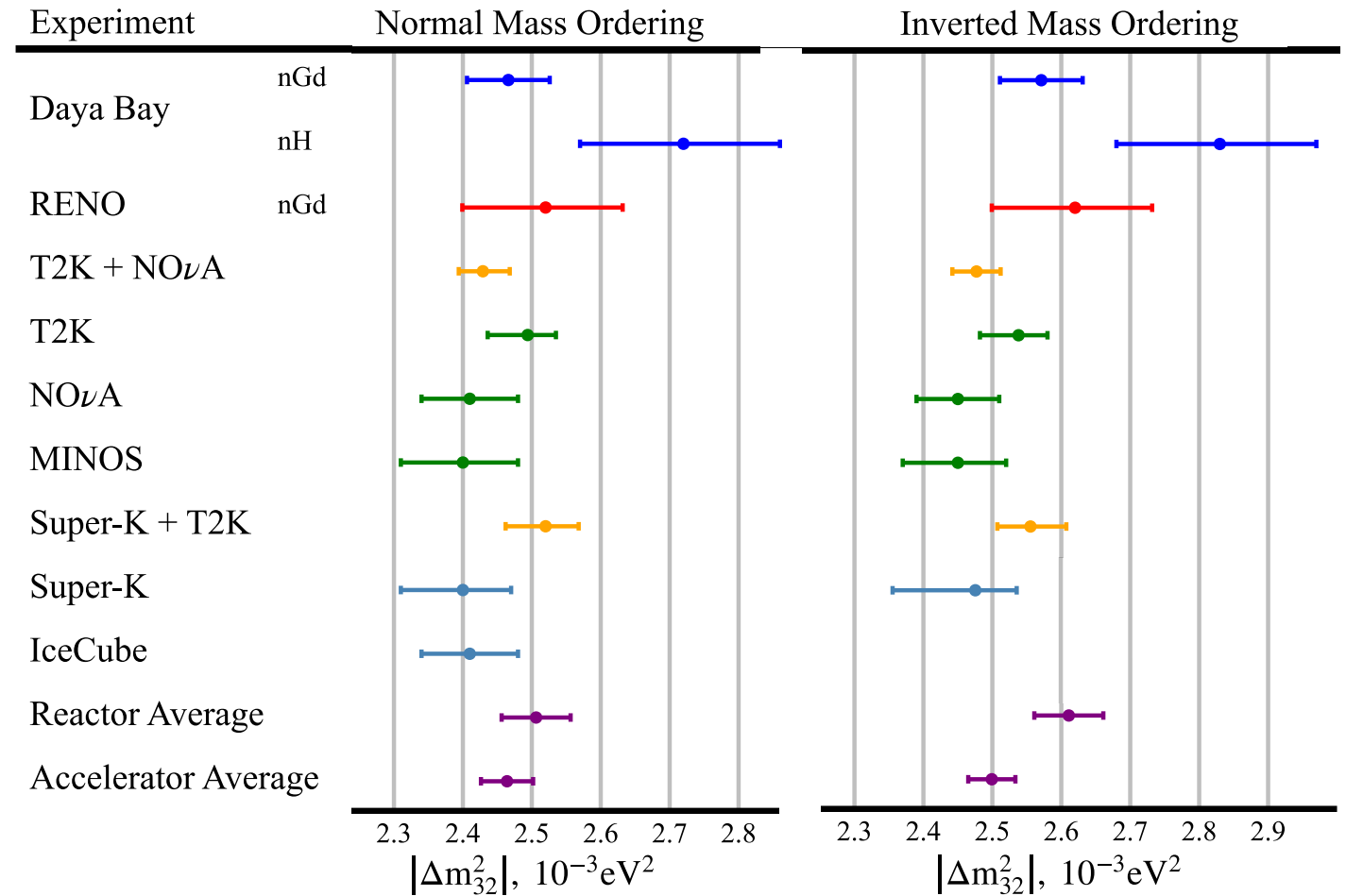
Experiment

Credit: H. Yu



# Neutrino Mass Hierarchy with Reactors

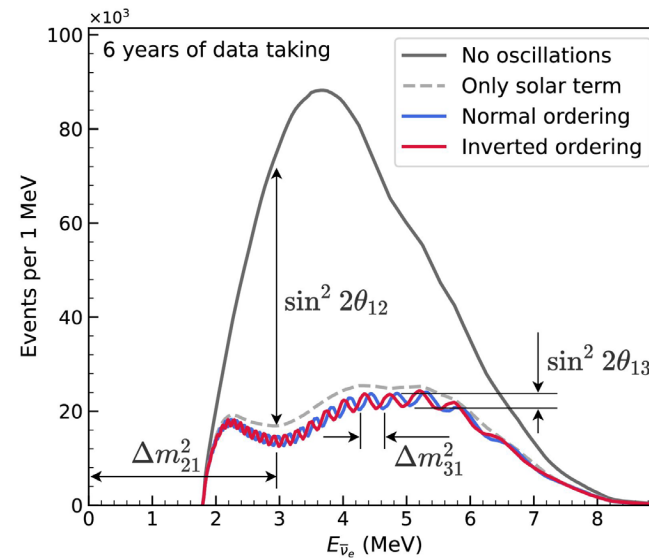
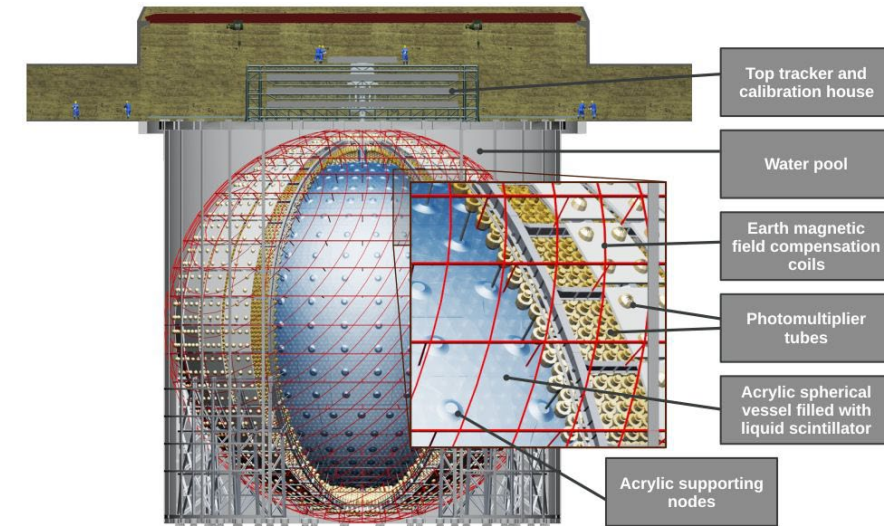
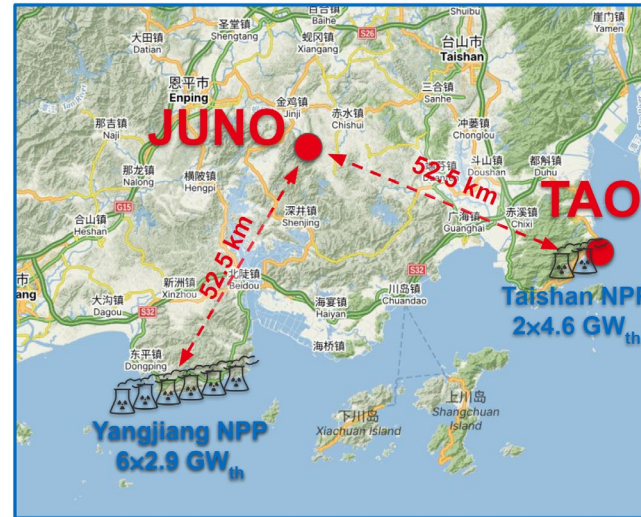
- Daya Bay + RENO gives a weak preference for the normal ordering when combined with accelerator and atmospheric measurements





# Neutrino Mass Hierarchy with Reactors

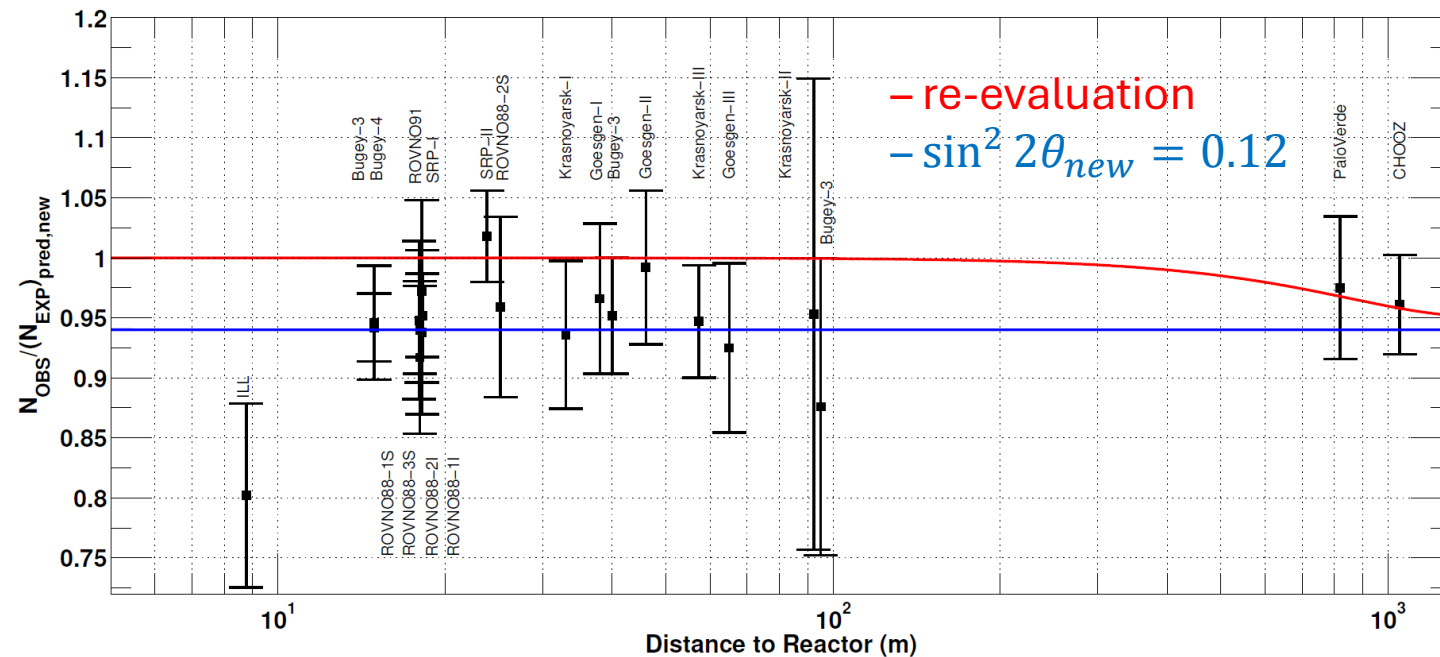
- Daya Bay + RENO gives a weak preference for the normal ordering when combined with accelerator and atmospheric measurements
- JUNO is mounting a definitive test with reactor neutrinos using a 20 kton (!) LS detector → requires x2 improvement in E scale systematic uncertainty over KamLAND
- JUNO will also make precision measurements of all oscillation parameters
- Currently in commissioning!



	PDG2023 [4]	JUNO 6 y
$\Delta m^2_{21}$	$7.53 \cdot 10^{-5} \text{ eV}^2 \pm 2.4\%$	<b>0.3%</b>
$\Delta m^2_{31}$	$2.5283 \cdot 10^{-3} \text{ eV}^2 \pm 1.3\%$	<b>0.2%</b>
$\sin^2 \theta_{12}$	$0.307 \pm 4.2\%$	<b>0.5%</b>
$\sin^2 \theta_{13}$	$0.022 \pm 3.2\%$	<b>12.1%</b>

# The Reactor Antineutrino Anomaly

- Re-evaluation of reactor antineutrino spectra combining global nuclear data with fission beta spectral measurements revealed a global suppression relative to expectations





# The Reactor Antineutrino Anomaly

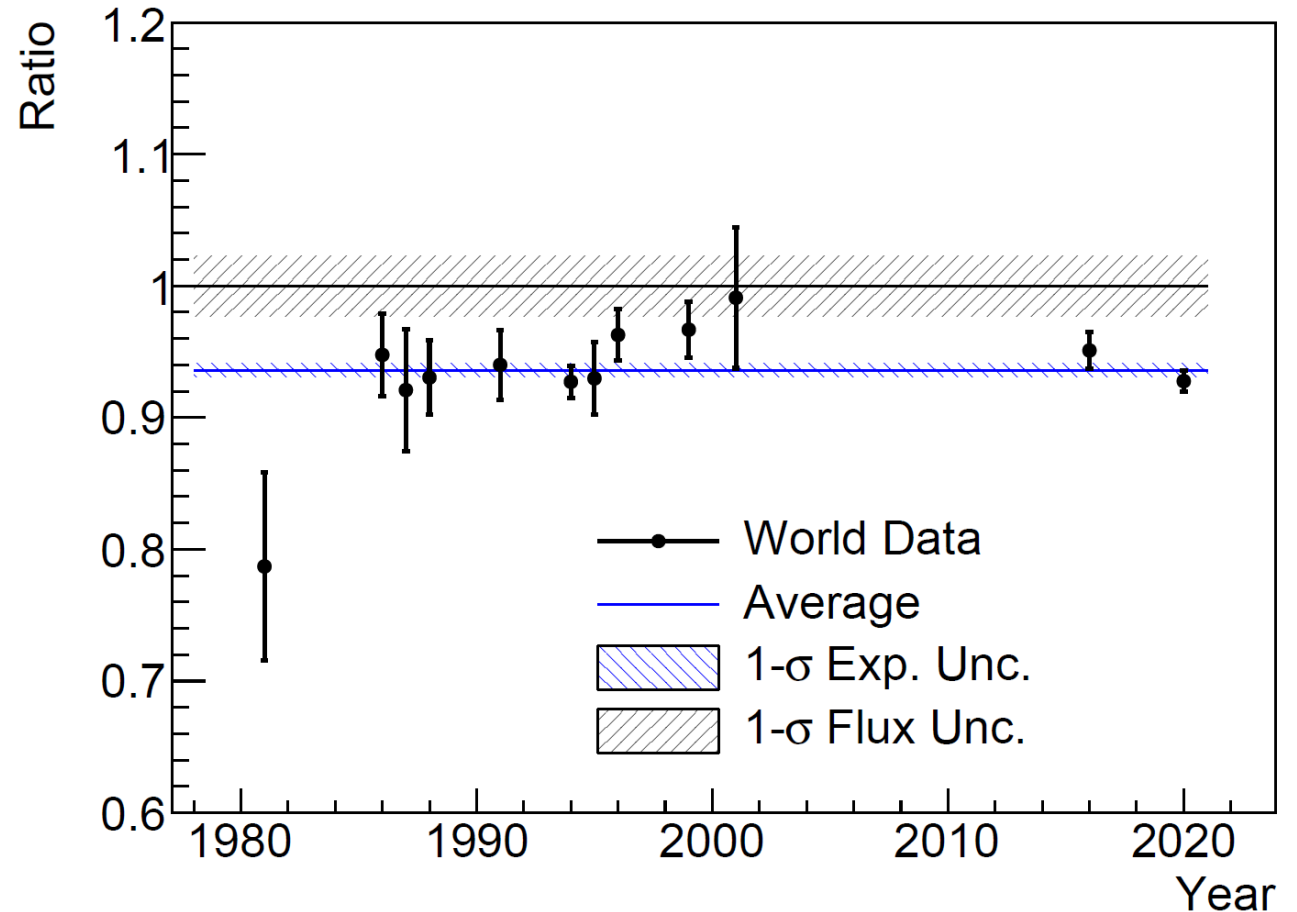
- Re-evaluation of reactor antineutrino spectra combining global nuclear data with fission beta spectral measurements revealed a global suppression relative to expectations
- Reactor antineutrino measurements?
- Nuclear data / nuclear theory?
- Beta spectrum measurements?
- Sterile neutrinos??

# The Reactor Antineutrino Anomaly

## • Reactor antineutrino measurements

- Nuclear data / nuclear theory?
- Beta spectrum measurements?
- Sterile neutrinos??

All reactor data is consistent with a global average with 0.5% uncertainty!

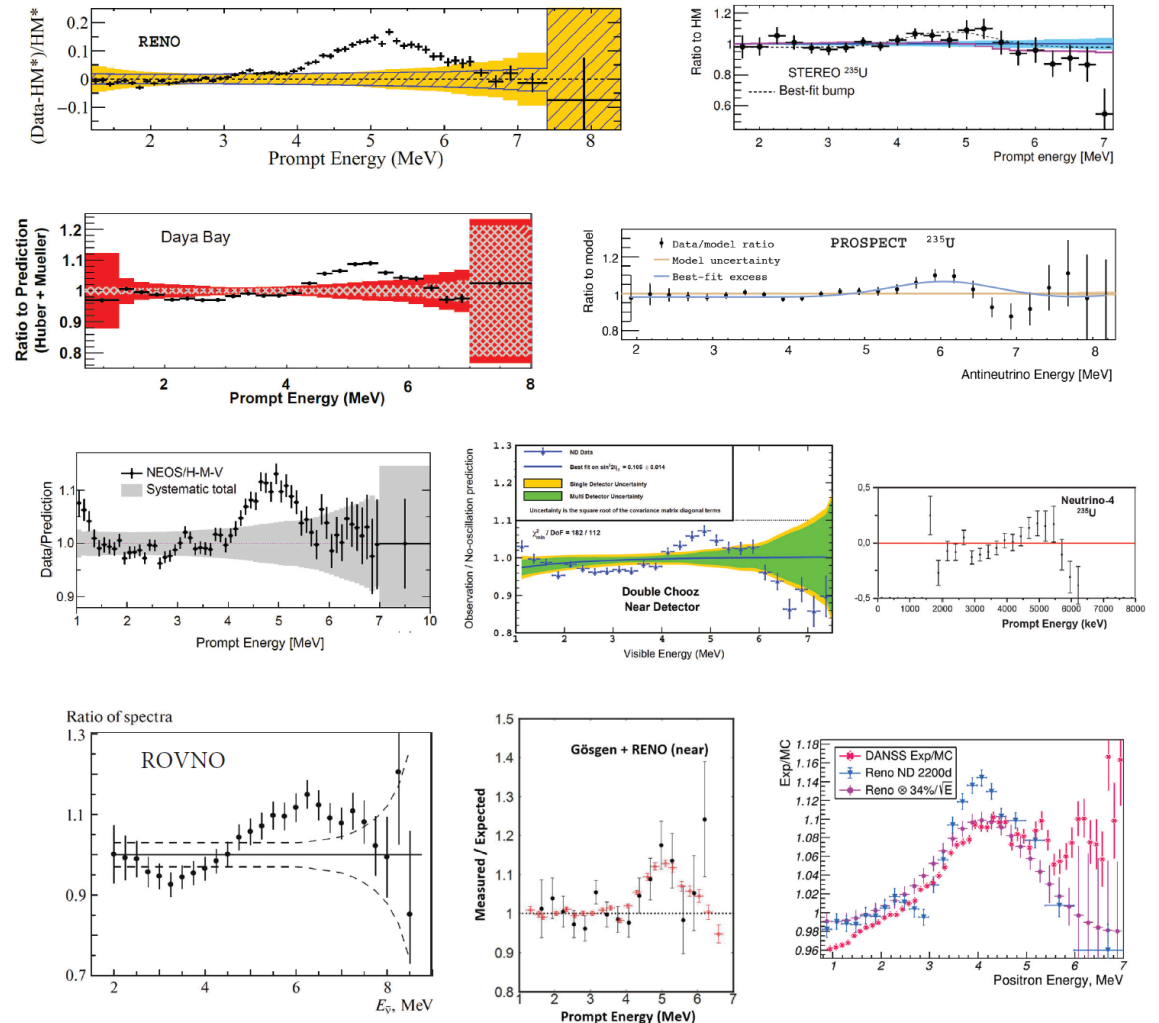


# The Reactor Antineutrino Anomaly

## Reactor antineutrino measurements

- Nuclear data / nuclear theory?
- Beta spectrum measurements?
- Sterile neutrinos??

Reactor experiments also consistently show a “6 MeV bump” not in the model, agreeing with each other within uncertainties



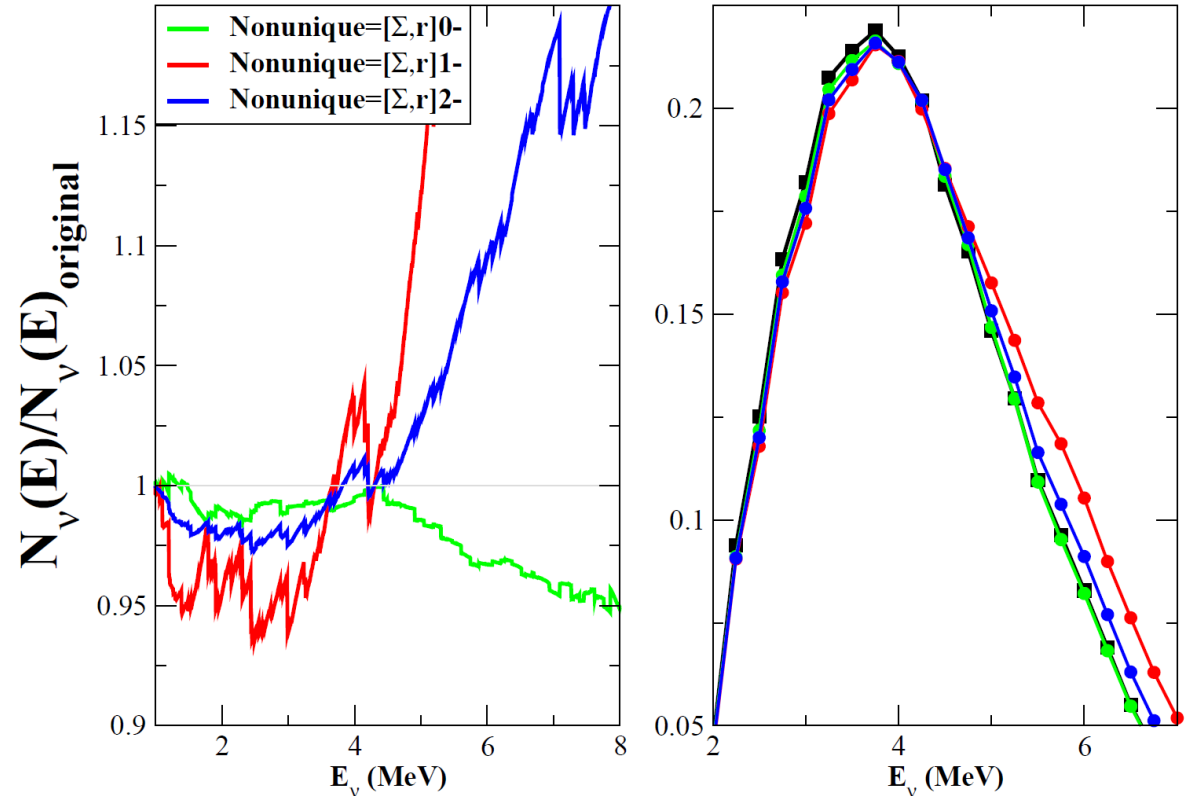


# The Reactor Antineutrino Anomaly

• ~~Reactor antineutrino measurements~~

- Nuclear data / nuclear theory?
- Beta spectrum measurements?
- Sterile neutrinos??

Theory uncertainties also appear to have been underestimated

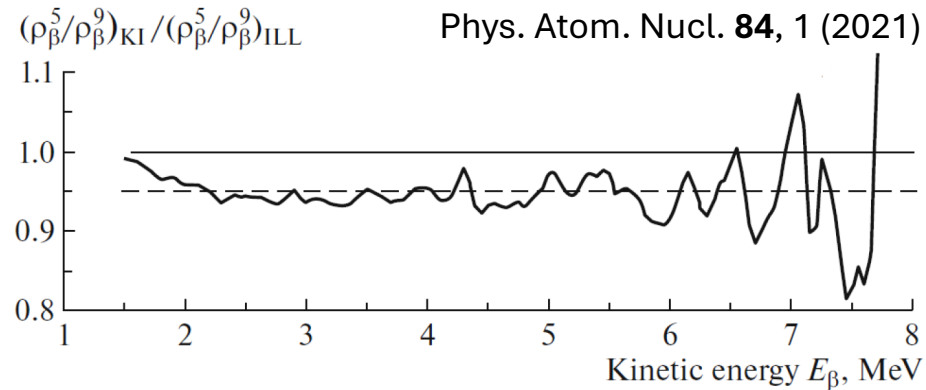


# The Reactor Antineutrino Anomaly

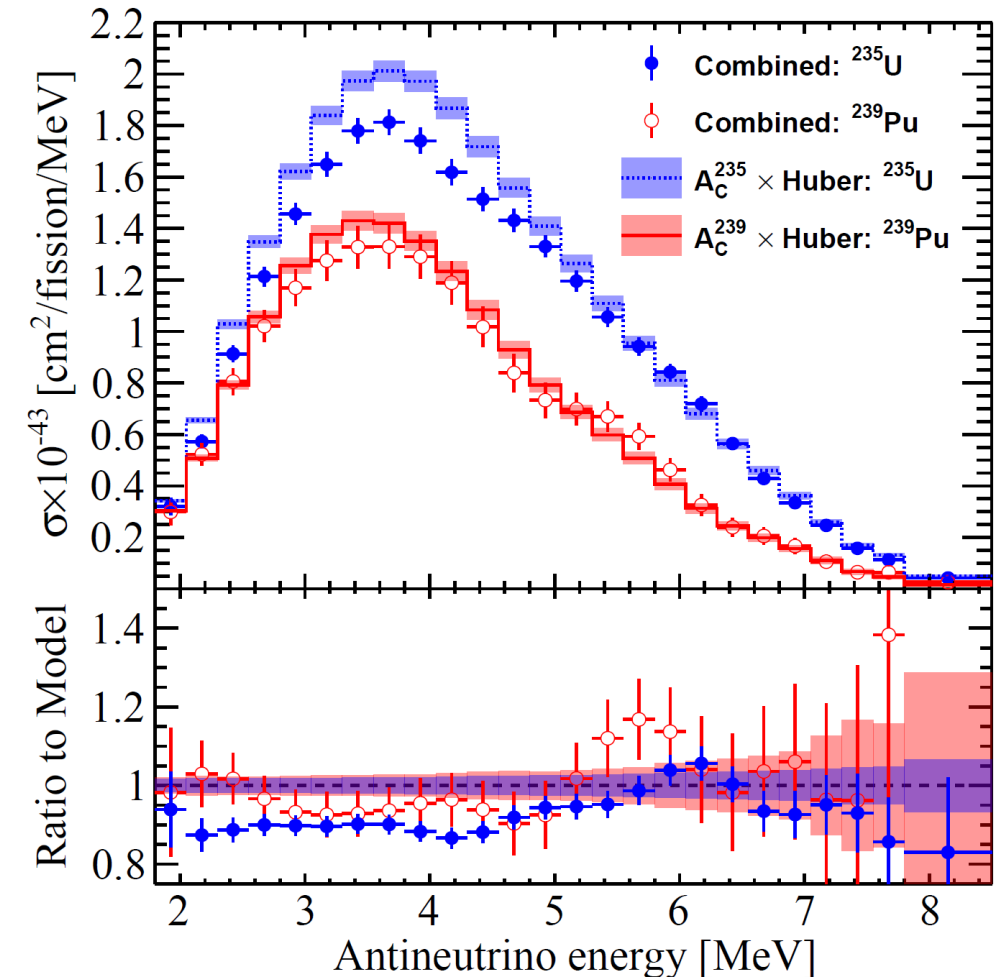
## Reactor antineutrino measurements

- Nuclear data / nuclear theory?
- Beta spectrum measurements?
- Sterile neutrinos??

The beta spectra also appear to be questionable, especially for  $^{235}\text{U}$



Daya Bay + PROSPECT, PRL **128**, 081801 (2022)

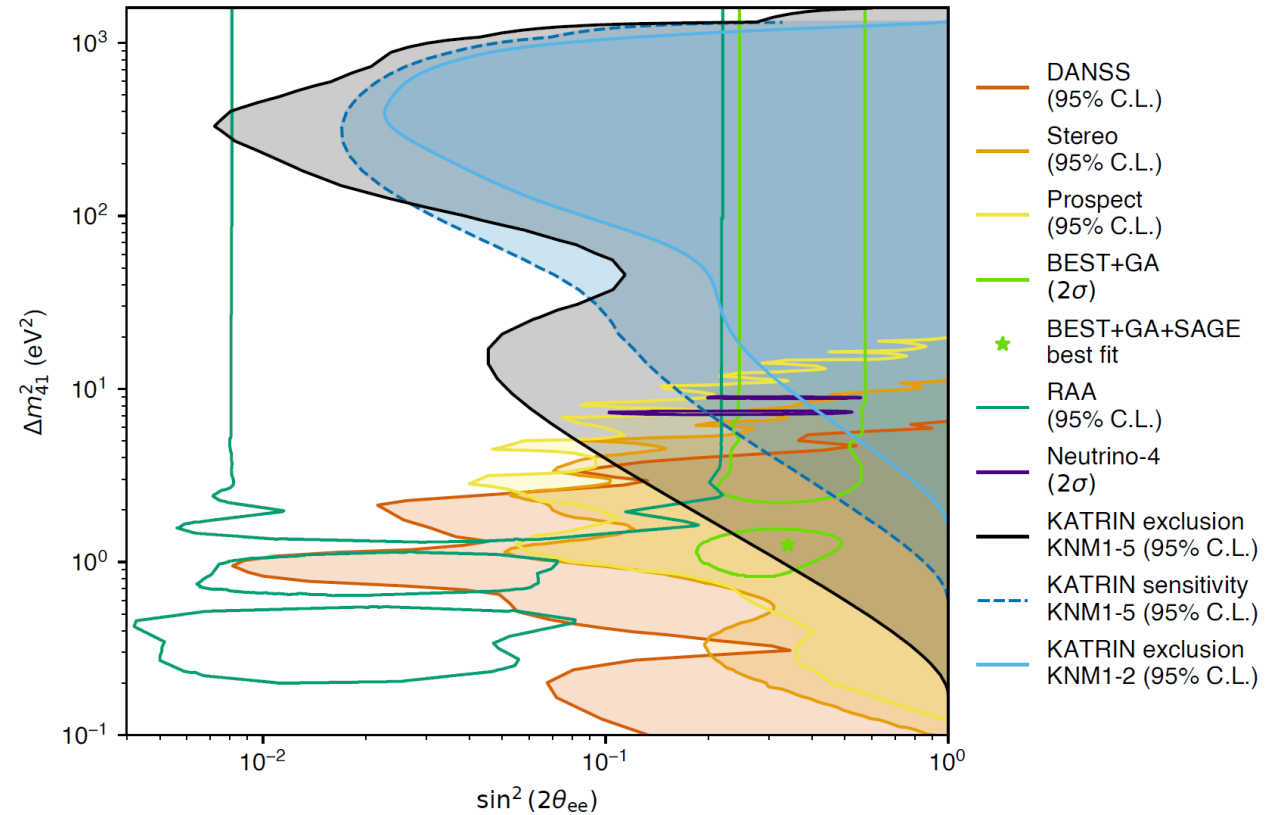


# The Reactor Antineutrino Anomaly

## Reactor antineutrino measurements

- Nuclear data / nuclear theory?
- Beta spectrum measurements?
- Sterile neutrinos??

Vigorous efforts to search for a neutrino-based solution remain inconclusive

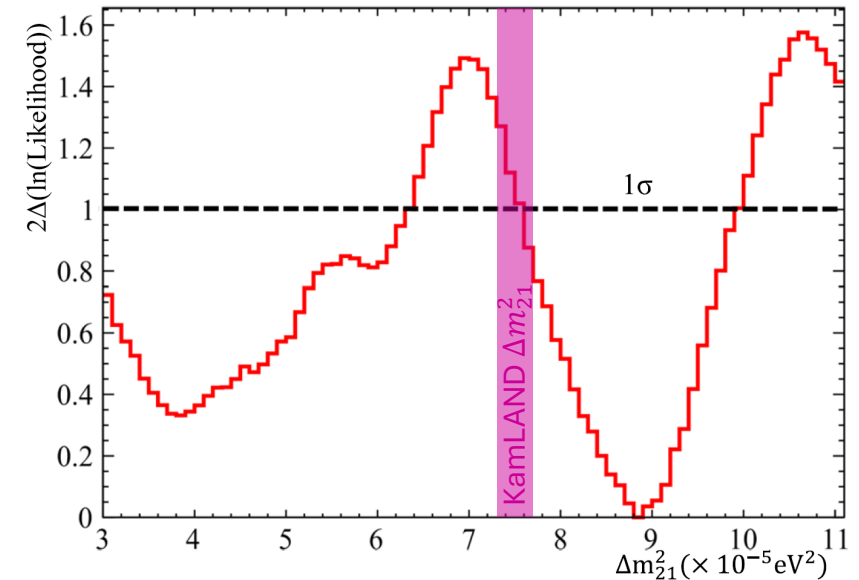
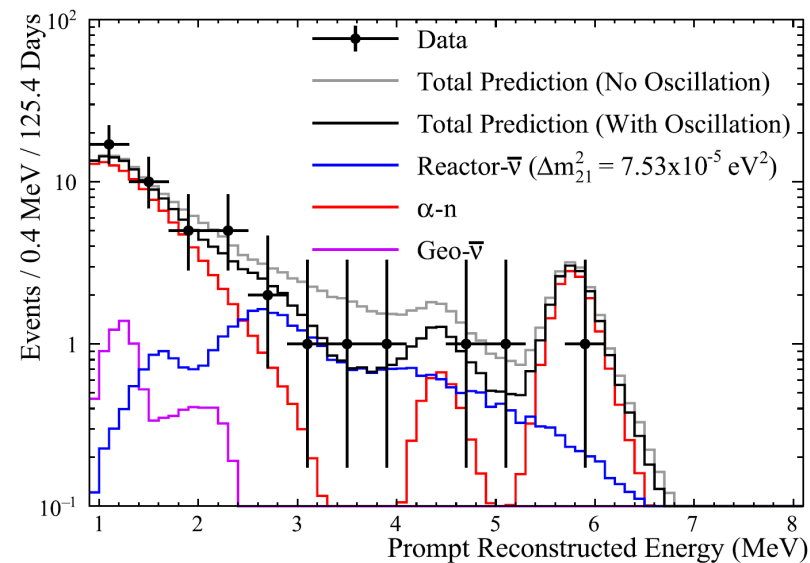
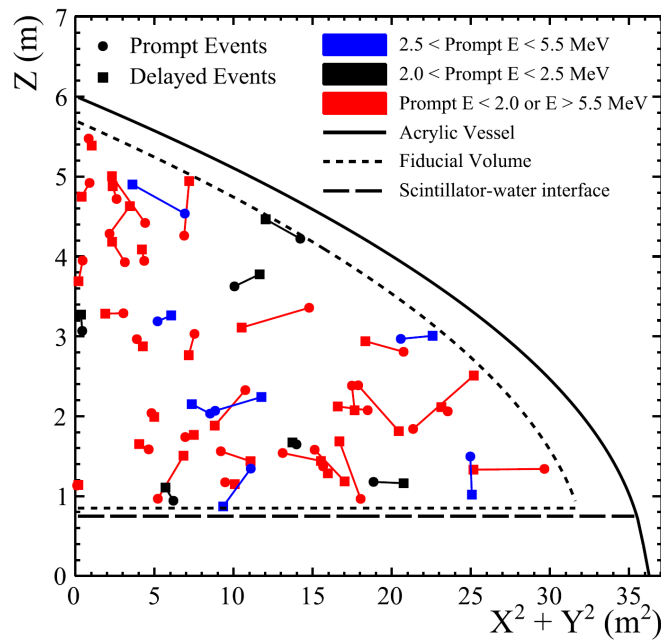




My biased list of other exciting reactor measurements in progress:

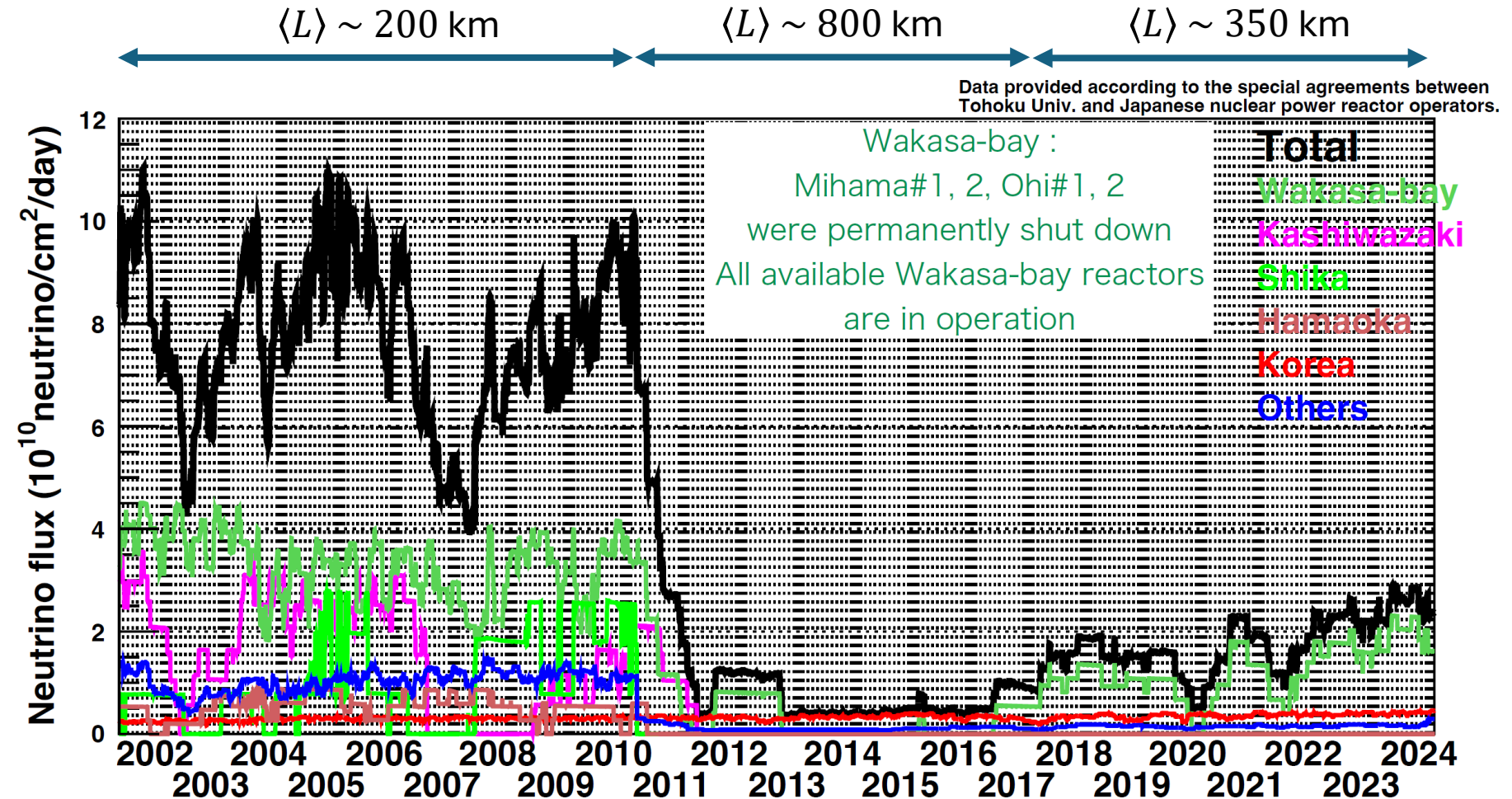
# My biased list of other exciting reactor measurements in progress:

- SNO+: first qualitative test of  $\Delta m_{21}^2$



# My biased list of other exciting reactor measurements in progress:

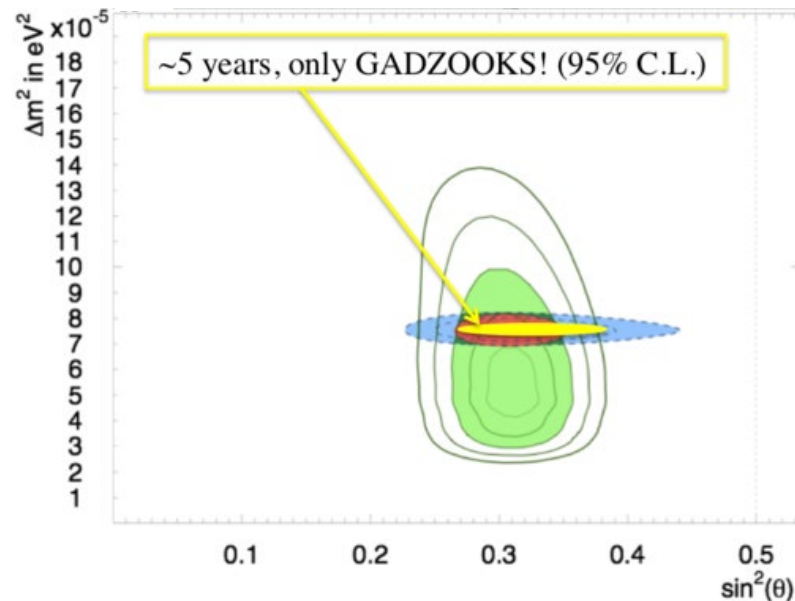
- SNO+
- KamLAND full-dataset:  
measure  $\Delta m_{21}^2$  at 3 effective baselines



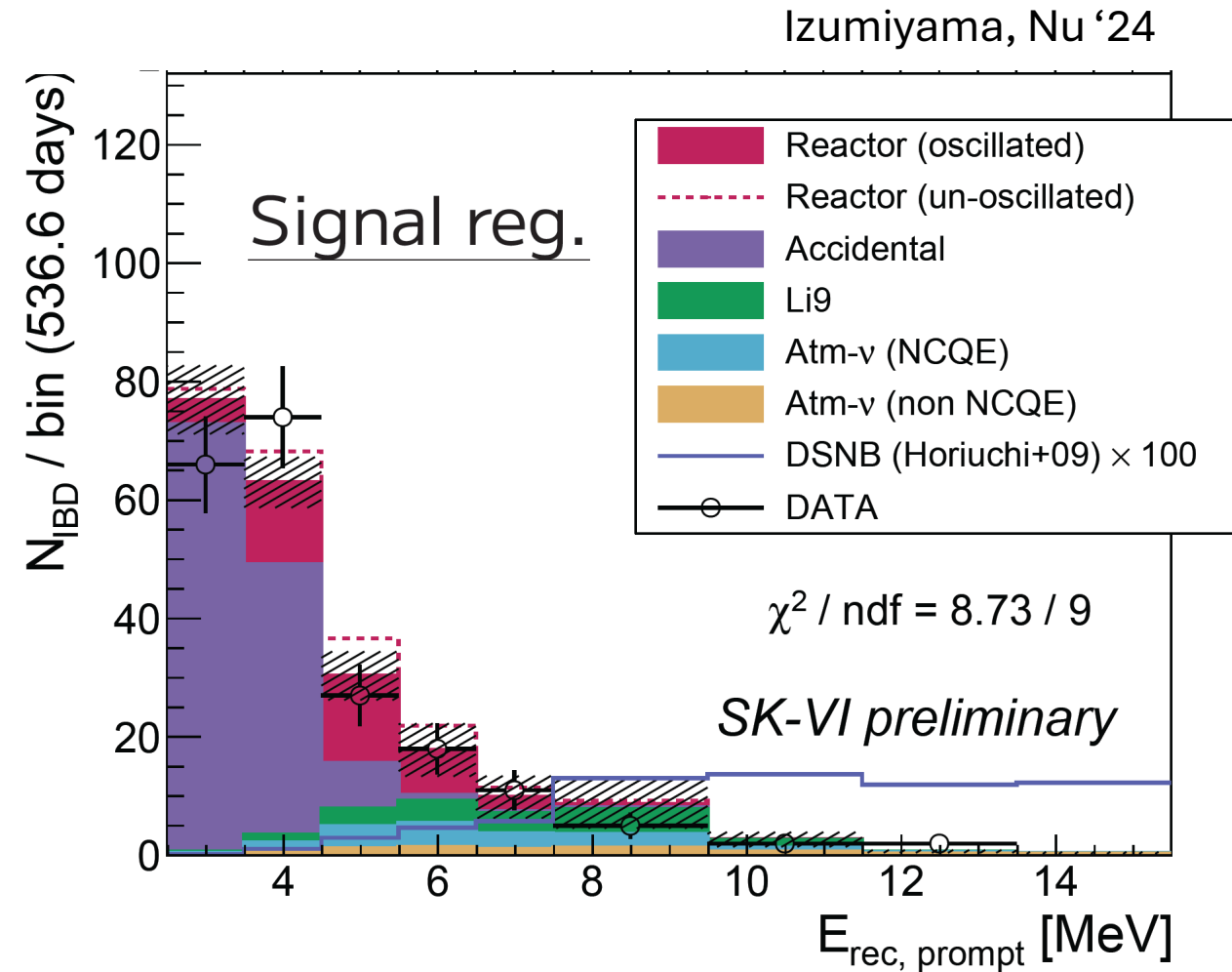


# My biased list of other exciting reactor measurements in progress:

- SNO+
- KamLAND full-dataset
- GADZOOKS! (SK-Gd)

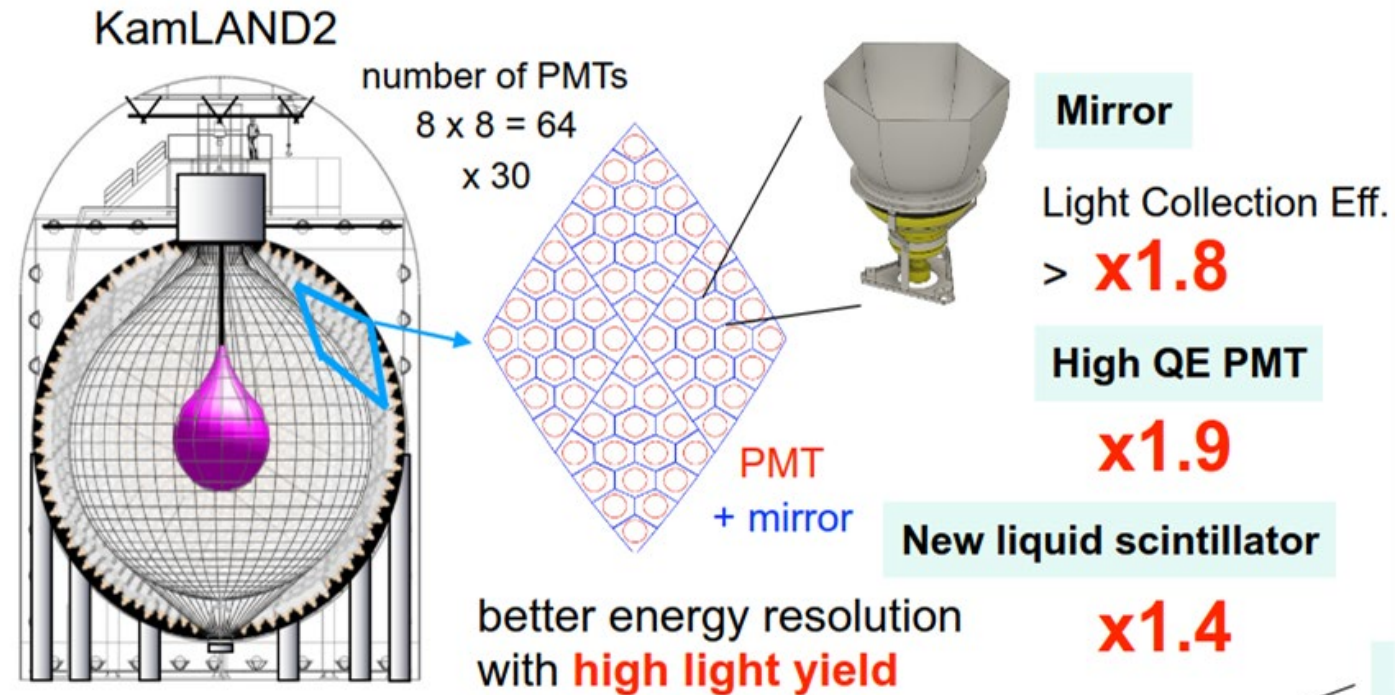


Nucl Part Phys Proc **273-275**, 353 (2016)



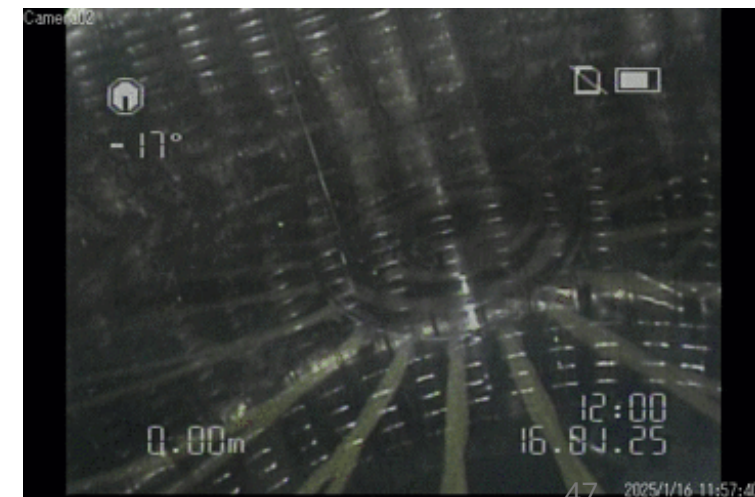
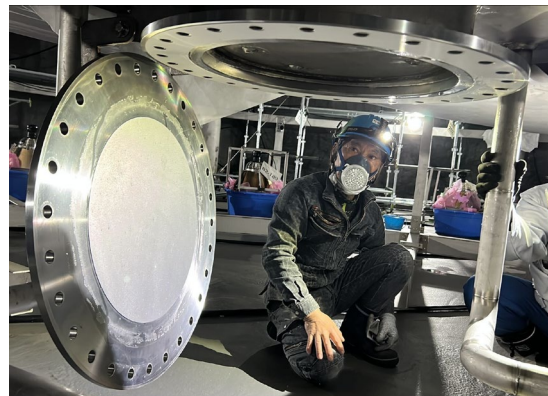
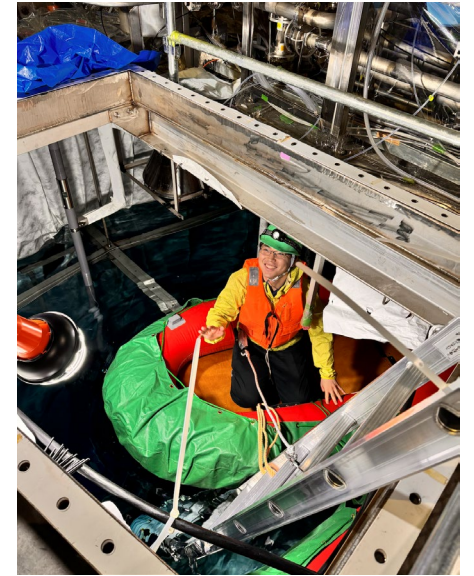
# My biased list of other exciting reactor measurements in progress:

- SNO+
- KamLAND full-dataset
- GADZOOKS! (SK-Gd)
- KamLAND2
- x2 resolution, lower bg, improved calibration (UH!)  
→ qualitatively better  $\Delta m^2$  measurement!
- Data taking start in 2027



# My biased list of other exciting reactor measurements in progress:

- SNO+
  - KamLAND full-dataset
  - GADZOOKS! (SK-Gd)
  - KamLAND2
- 
- x2 resolution, lower bg, improved calibration (UH!)  
→ qualitatively better  $\Delta m^2$  measurement!
  - Data taking start in 2027

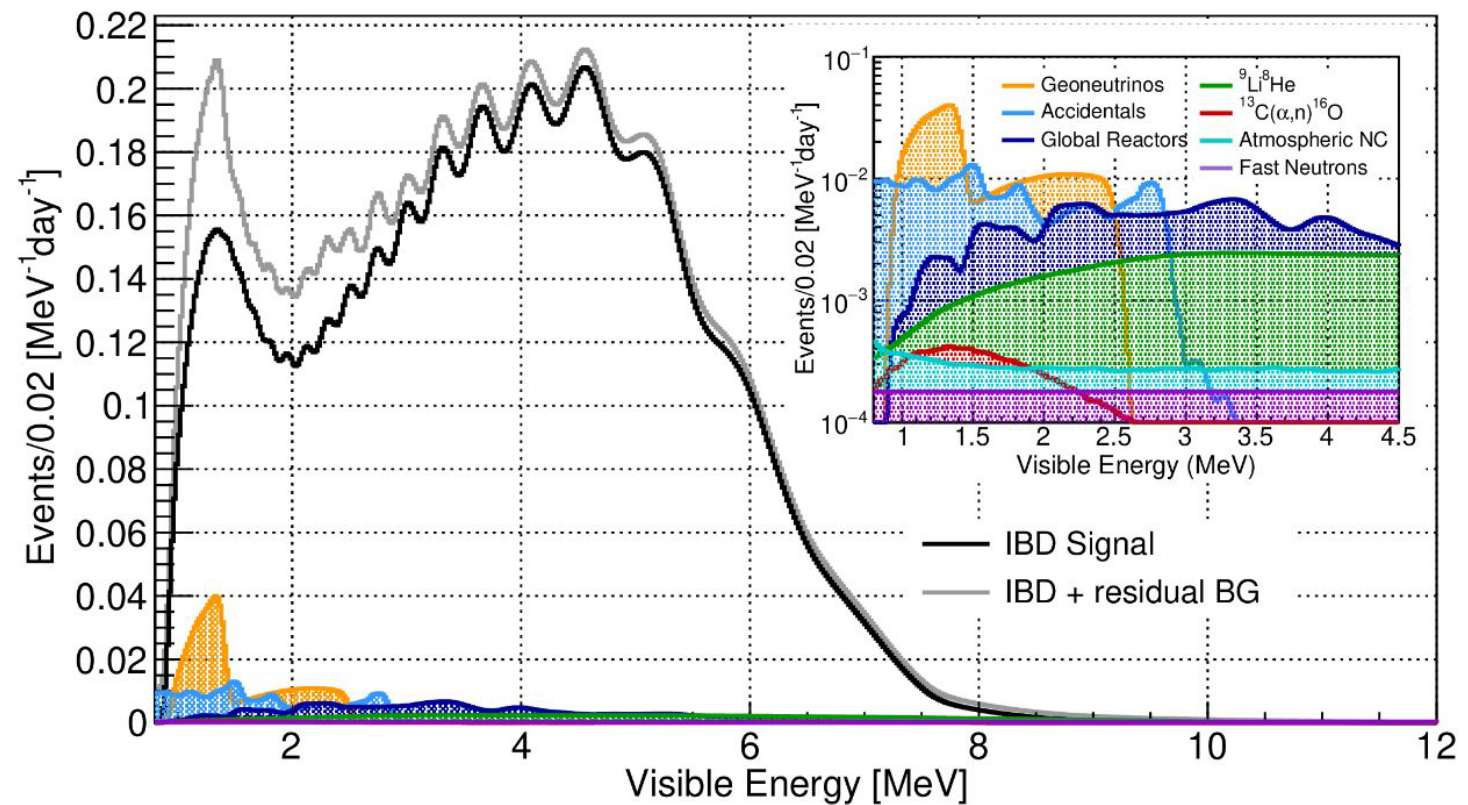




# My biased list of other exciting reactor measurements in progress:

- SNO+
- KamLAND full-dataset
- GADZOOKS! (SK-Gd)
- KamLAND2
- And of course: JUNO!  
(see Wei's and Benda's talks!)

Malyshkin, Nu '24



# Summary

- Reactors continue to reveal to us new secrets about the neutrino!
- A new generation of reactor experiments is poised to determine the mass ordering, measure neutrino oscillation with unprecedented precision, and reveal the source of the RAA
- Reactor neutrino measurement in general, and KamLAND in particular, rely on the techniques pioneered by John, and greatly benefitted from his contributions (including the non-technical ones!)



*Happy birthday to John, my respected colleague and friend !*



Special message to John  
from Atsuto Suzuki,  
speaking for all of us on  
KamLAND!