Daya Bay and JUNO Reactor Neutrino Experiments: Results and Prospects

(on behalf of the Daya Bay and JUNO Collaborations)

+

Geoneutrinos at ANDES 3 kt Liquid Scintillator Detector

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Neutrino Mixing and Oscillations

atmospheric, accelerator

solar, reactor L~60 km

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

reactor L~2 km, accelerator

$$\mathcal{P}_{\nu_\alpha\to\nu_\beta}(L) = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}\left(U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right)\sin^2\left[\frac{\Delta m^2_{ij}L}{4E}\right]$$

$$+ 2\sum_{i>j}\mathrm{Im}\left(U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right)\sin\left[\frac{\Delta m^2_{ij}L}{2E}\right]$$

6 Oscillation-driving Parameters
(in case of 3-neutrino framework):

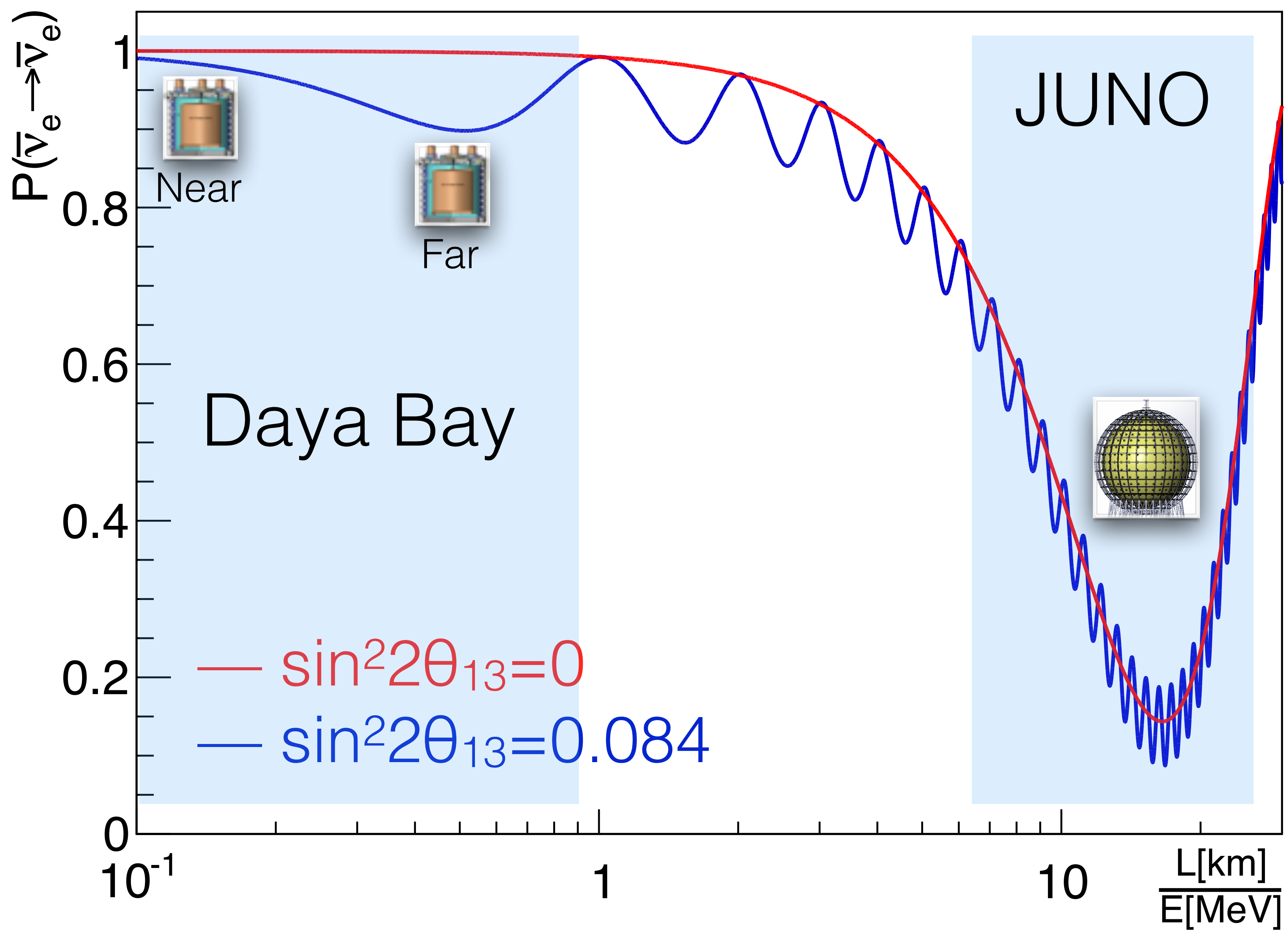
- Two mass splittings $\mathbf{\Delta m_{21}^2}$, $\mathbf{\Delta m_{31}^2}$ ($\Delta m_{32}^2=\Delta m_{31}^2-\Delta m_{21}^2$)
- Mixing angles $\boldsymbol{\theta_{12}}$, $\boldsymbol{\theta_{23}}$, $\boldsymbol{\theta_{13}}$
- CP-violation phase $\boldsymbol{\delta_{CP}}$

Unknown before 2012
Measured first by Daya Bay

Reactor Antineutrino Oscillations

Two modes of oscillations: $P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$ Medium baseline

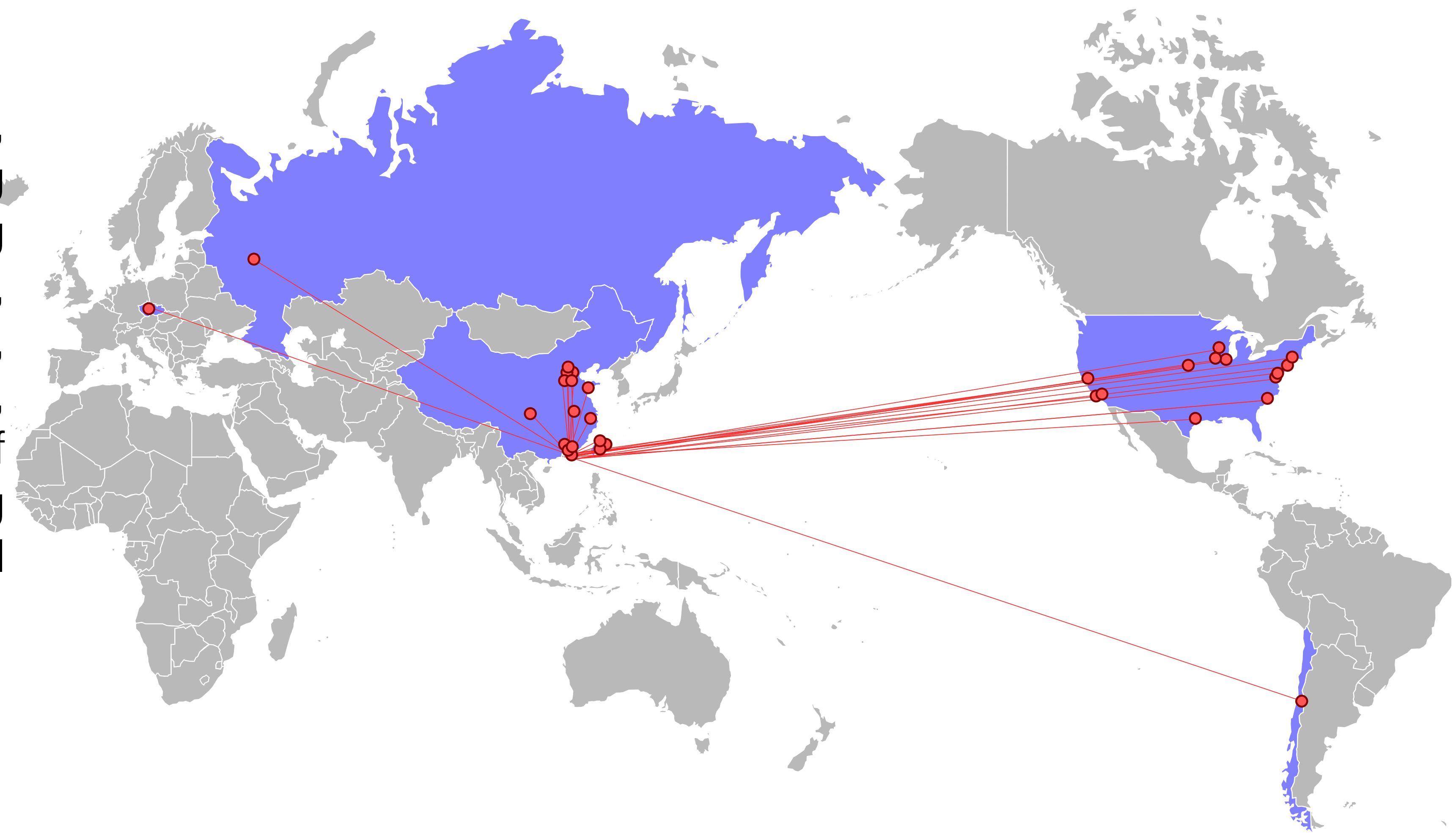
$- \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$ Short baseline



Daya Bay Experiment Collaboration

Asia (23)

Beijing Normal Univ., CGNPG, CIAE, Dongguan Univ. Tech., IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiaotong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Xi'an Jiaotong Univ, NUDT, ECUST, Congqing Univ, Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.



North America (16)

BNL, Iowa State Univ., Illinois Inst. Tech., LBNL, Princeton, RPI, Siena, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin-Madison, Univ. of Illinois-Urbana-Champaign, Virginia Tech., William & Mary, Yale

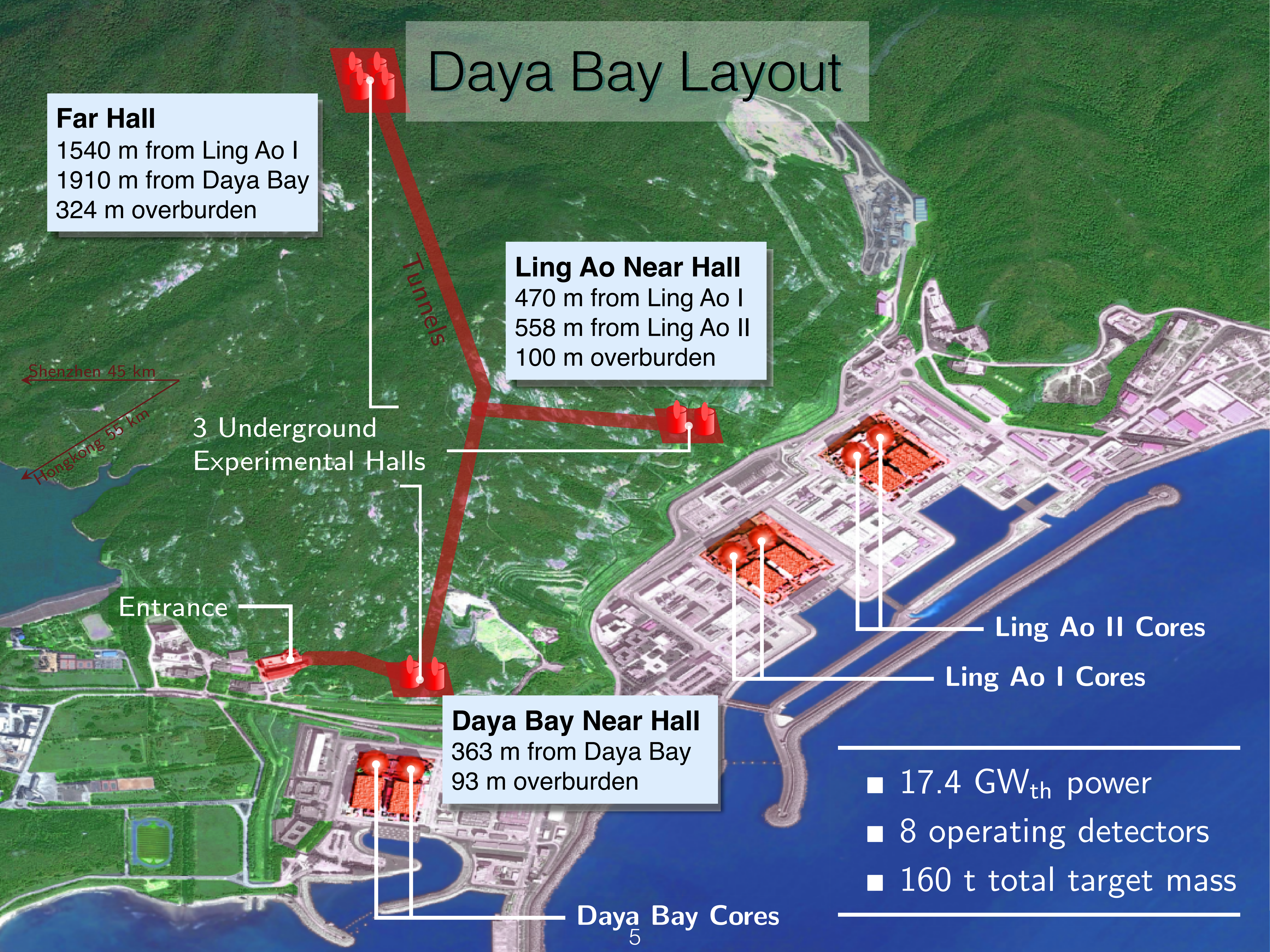
Europe (2)

Charles University, Czech Republic
JINR, Dubna, Russia

South America (1)

Catholic University of Chile

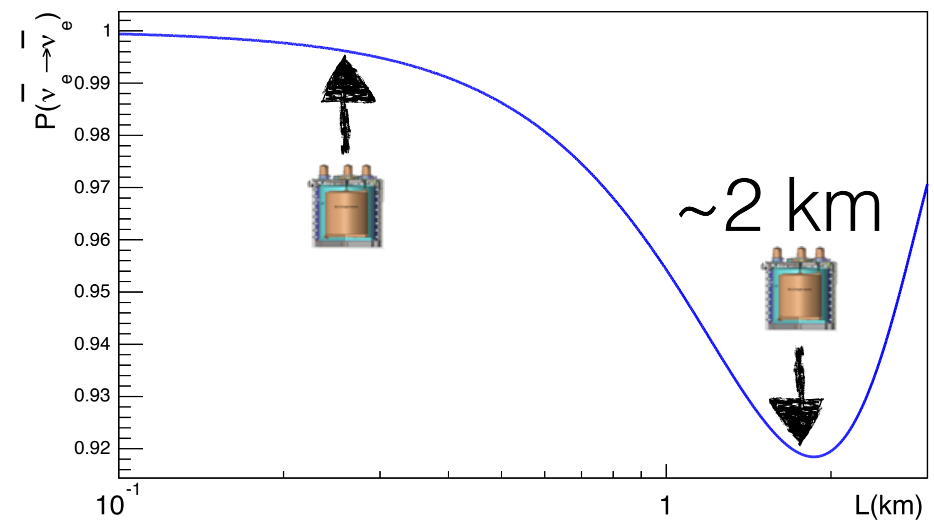
Daya Bay Layout



- 17.4 GW_{th} power
- 8 operating detectors
- 160 t total target mass

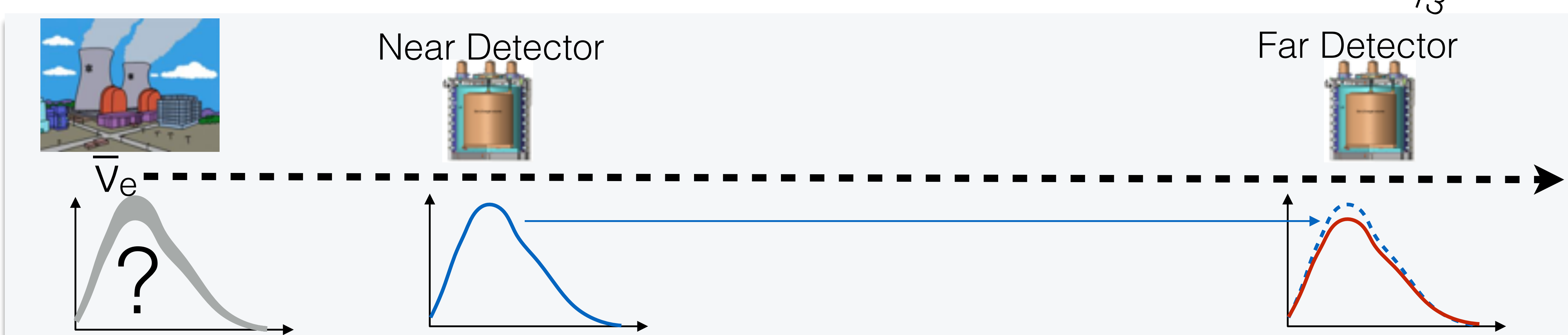
Keys to Precise Measurement

- High statistics - powerful source, large detectors
- Reduction of systematics - Near&Far functionally identical detectors
- Ideal baseline
- Low background



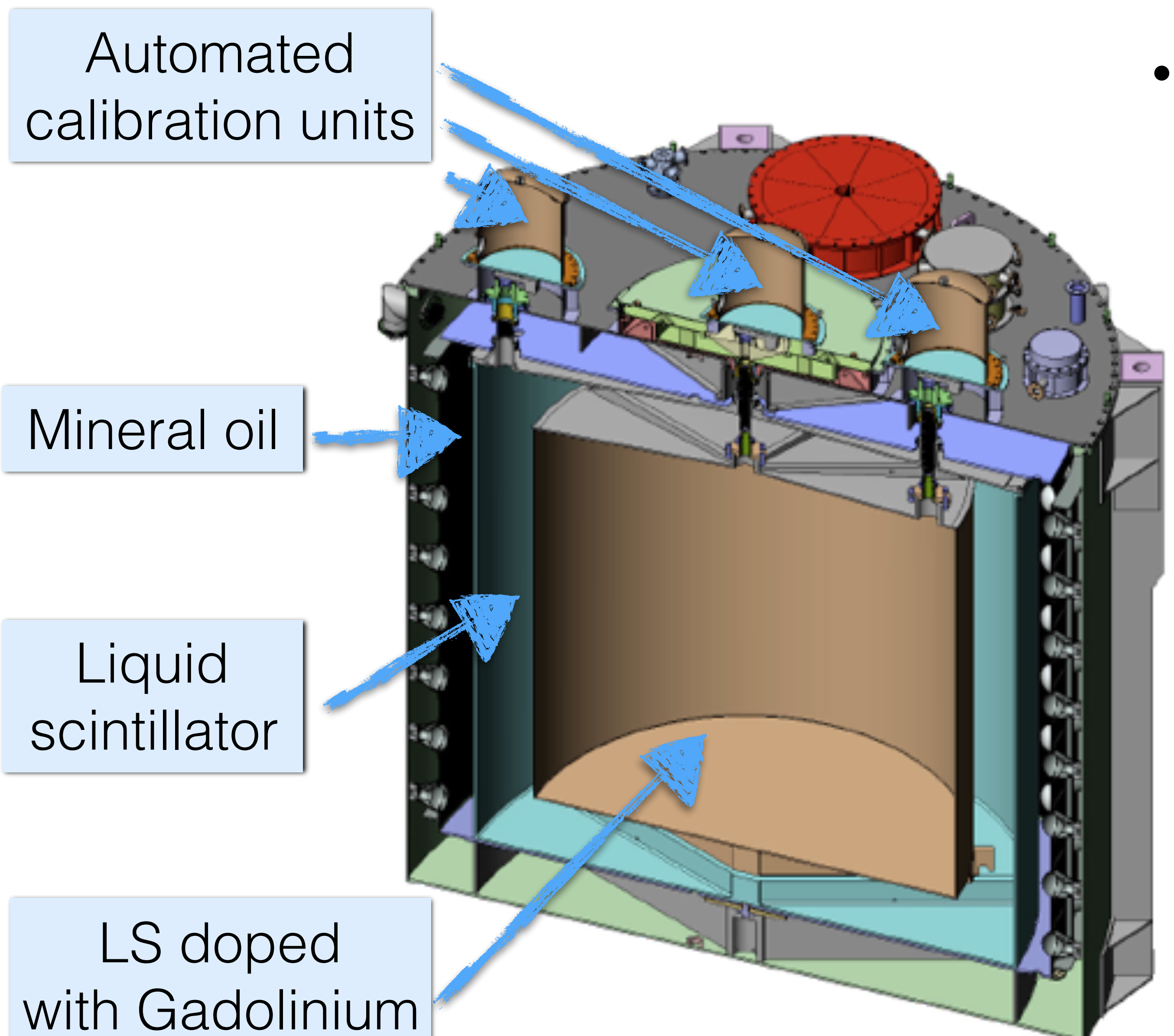
$$\frac{R_{Far}}{R_{Near}} = \left(\frac{L_{Near}}{L_{Far}}\right)^2 \left(\frac{N_{Far}}{N_{Near}}\right)\left(\frac{\varepsilon_{Far}}{\varepsilon_{Near}}\right)\left(\frac{P_{Far}(L_{Far})}{P_{Near}(L_{Near})}\right)$$

- Measured flux
- $1/r^2$
- Number of targets
- Detection efficiency
- Probability function of θ_{13}

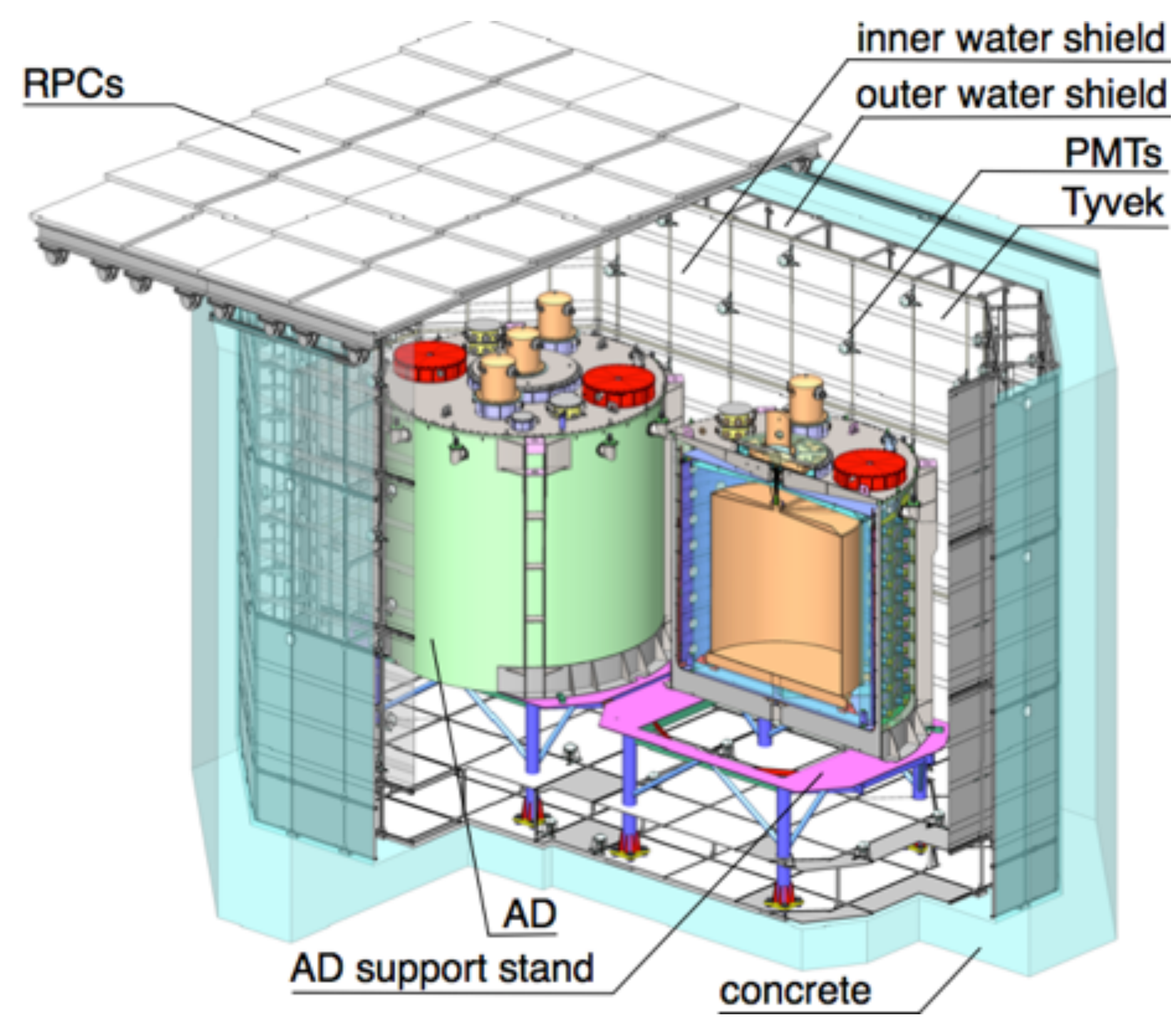


Antineutrino Detector and Muon Tagging System

- Antineutrino detector (AD)
  - 3 separated regions - GdLS, LS, MO
  - 192x8” PMT
  - 3 ACUs with radioactive sources and LEDs for weekly energy calibration



- Muon tagging system
  - ADs submerged in the water pool - passive shielding from n and γ; active muon detector
  - Inner and outer optically separated regions of the pool - two independent water Cherenkov detectors
  - 4-layer resistive plate chamber array



Detection Method - Inverse Beta Decay

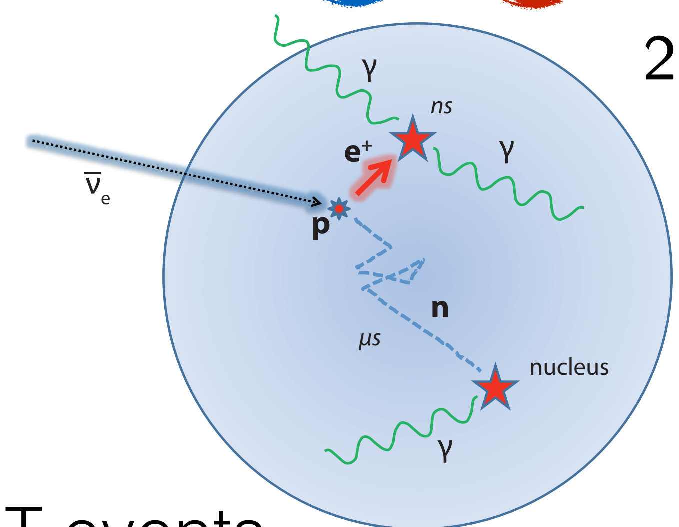
Coincidence

Prompt signal — Delayed signal

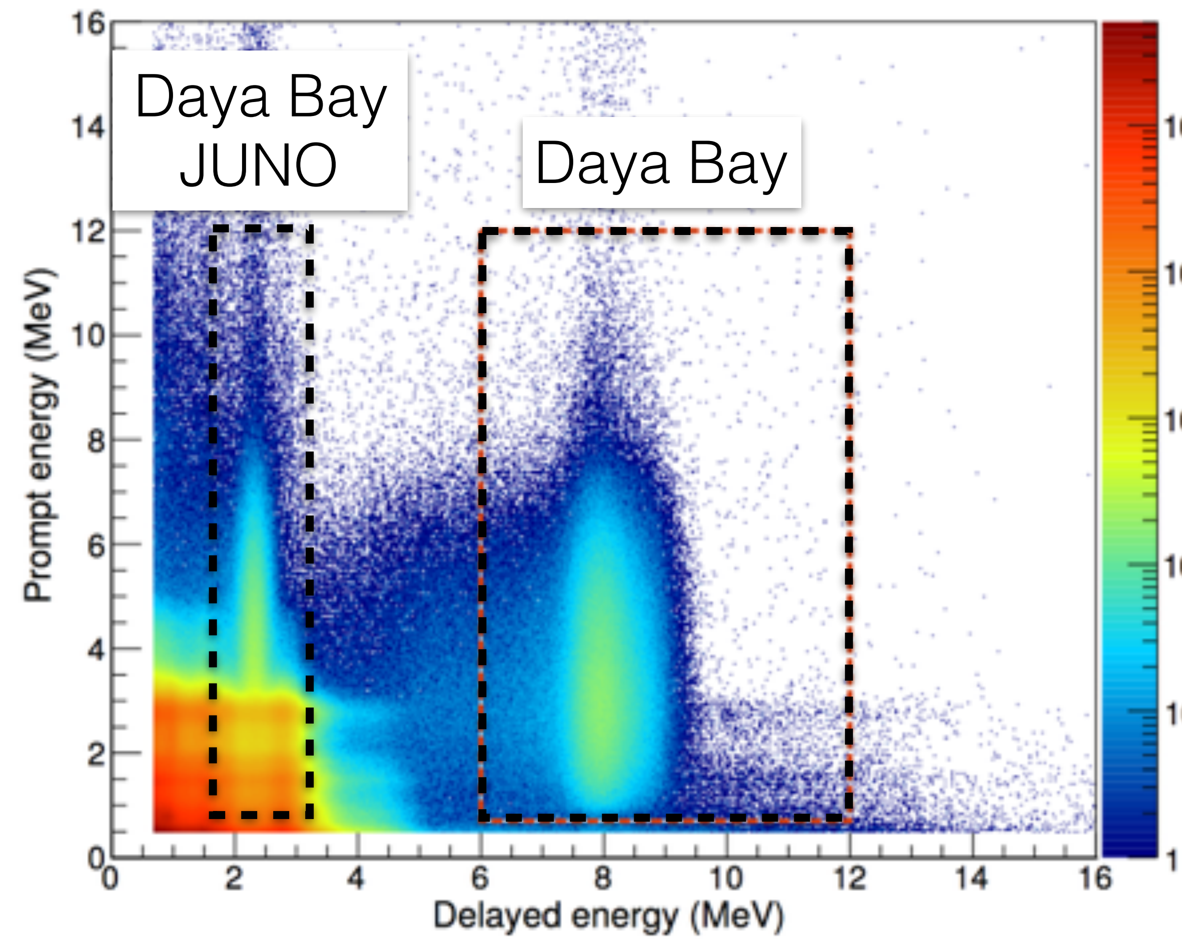
Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

$30\ \mu s \rightsquigarrow n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma s\ (8\ \text{MeV})$ — Daya Bay

$200\ \mu s \rightsquigarrow n + H \rightarrow D + \gamma\ (2.22\ \text{MeV})$ — Daya Bay+JUNO



- IBD selection
  - Remove flashing PMT events
  - Prompt energy cut: 0.7 MeV<E_p<12 MeV
  - Delayed energy cut: 6 MeV<E_p<12 MeV
  - Coincidence time: 1 μs<dt<200 μs
  - Selection of isolated prompt-delayed pair
  - Veto after tagged muon for the background reduction



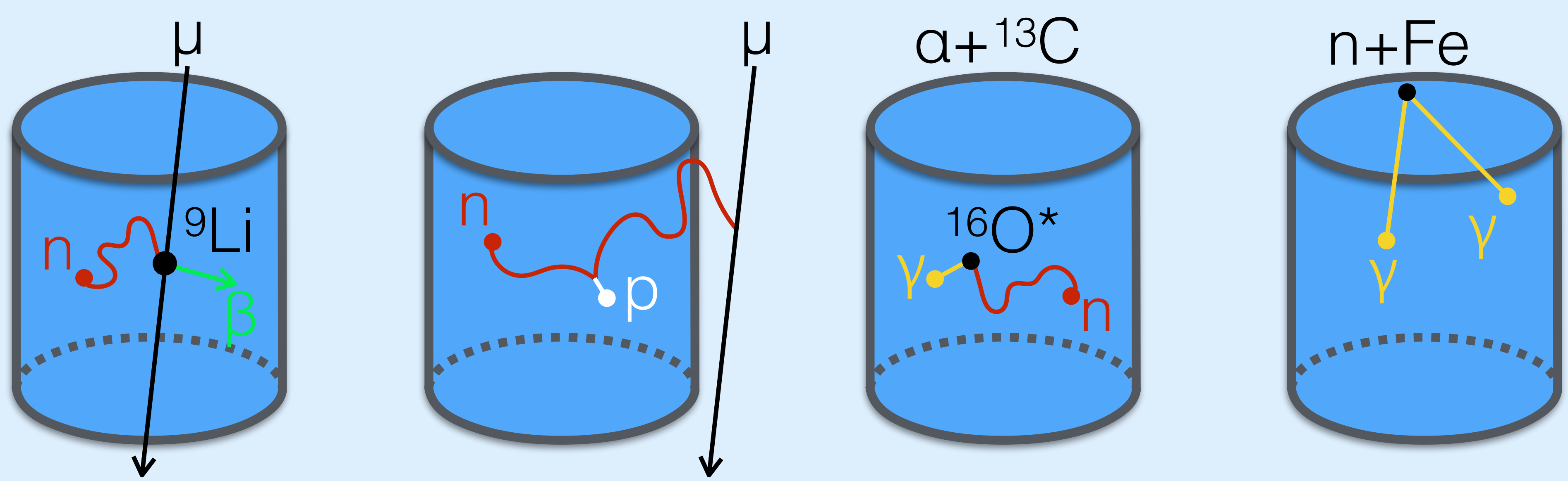
IBD Backgrounds

- IBD background at Daya Bay (Mostly common for all LS experiments)
  - Low background experiment with B/S ~2.0% at Far Hall
  - Precise measurement - background uncertainties well under control

Uncorrelated:

Accidental coincidence
of two independent events

Correlated:



^{9}Li/^{8}He
Unstable spallation products induced by cosmic muons

Fast neutrons
Induced by untagged cosmic muons

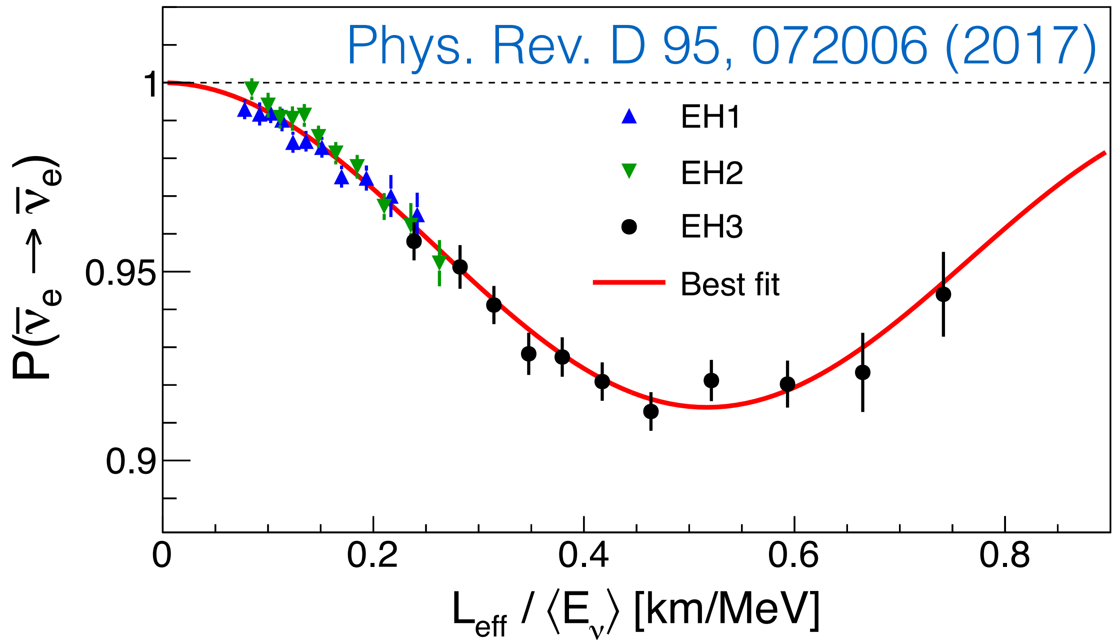
13C(α,n)16O
Induced by α interacting on carbon atoms

^{241}Am-^{13}C
Correlated signal from calibration n source in ACUs

Neutrino Oscillations at Daya Bay

Three neutrino framework:

$$\sin^2 2\theta_{13} = (8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})) \times 10^{-2}$$
$$|\Delta m^2_{ee}| = (2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})) \times 10^{-3}\ \text{eV}^2$$



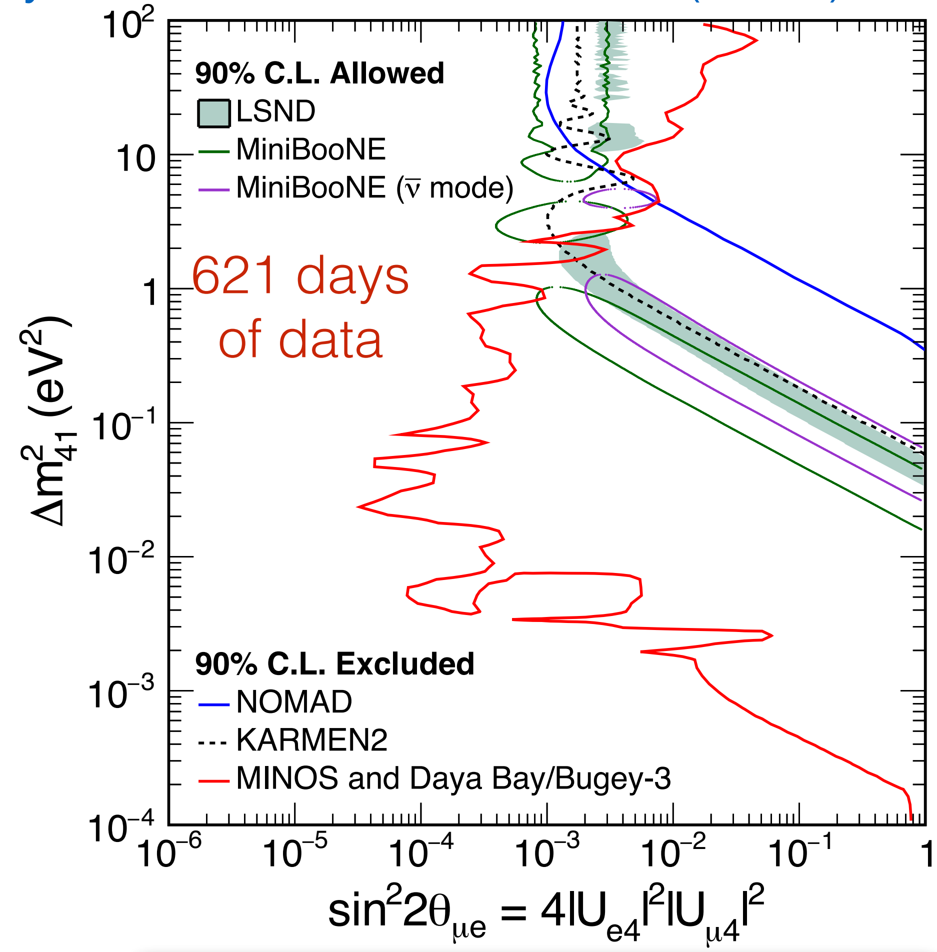
- $\sin^2 2\theta_{13}$ measurement
  - Most precise measurement up to date
  - Precision 4% → 3% by the end of 2017
  - Crucial for experiments searching for CP-violation in lepton sector
- $|\Delta m^2_{ee}|$ measurement
  - Comparable precision with long baseline accelerator experiments

Sterile neutrinos (3+1):

- Daya Bay measurement:
  - No hint of light sterile neutrino observed
  - Most stringent limit for $|\Delta m^2_{41}|<0.2\ \text{eV}^2$

  Phys. Rev. Lett. 117, 151802 (2016)
- Combined result with MINOS and Bugey-3

  Phys. Rev. Lett. 117, 151801 (2016)

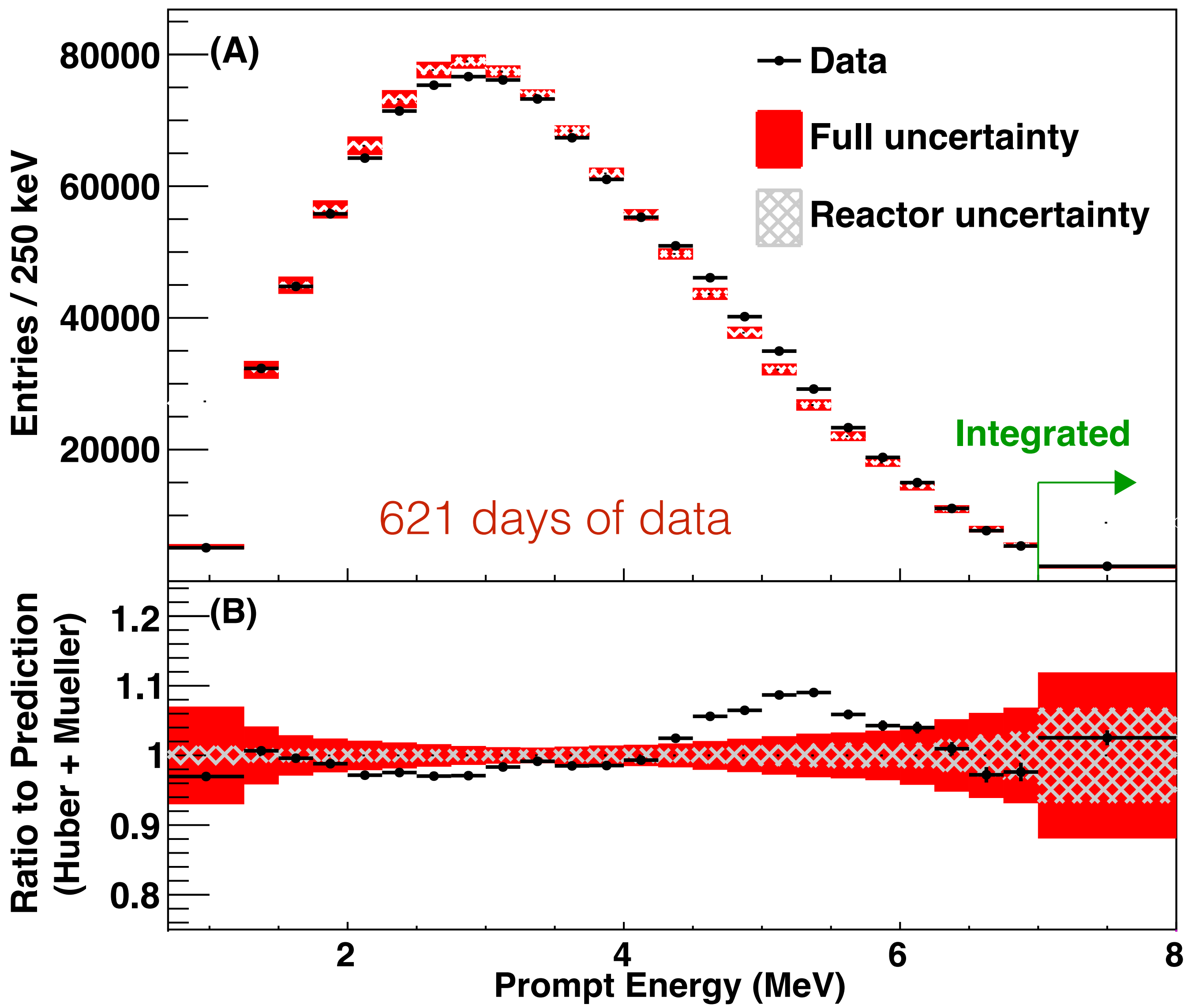


LSND=Daya Bay⊕MINOS

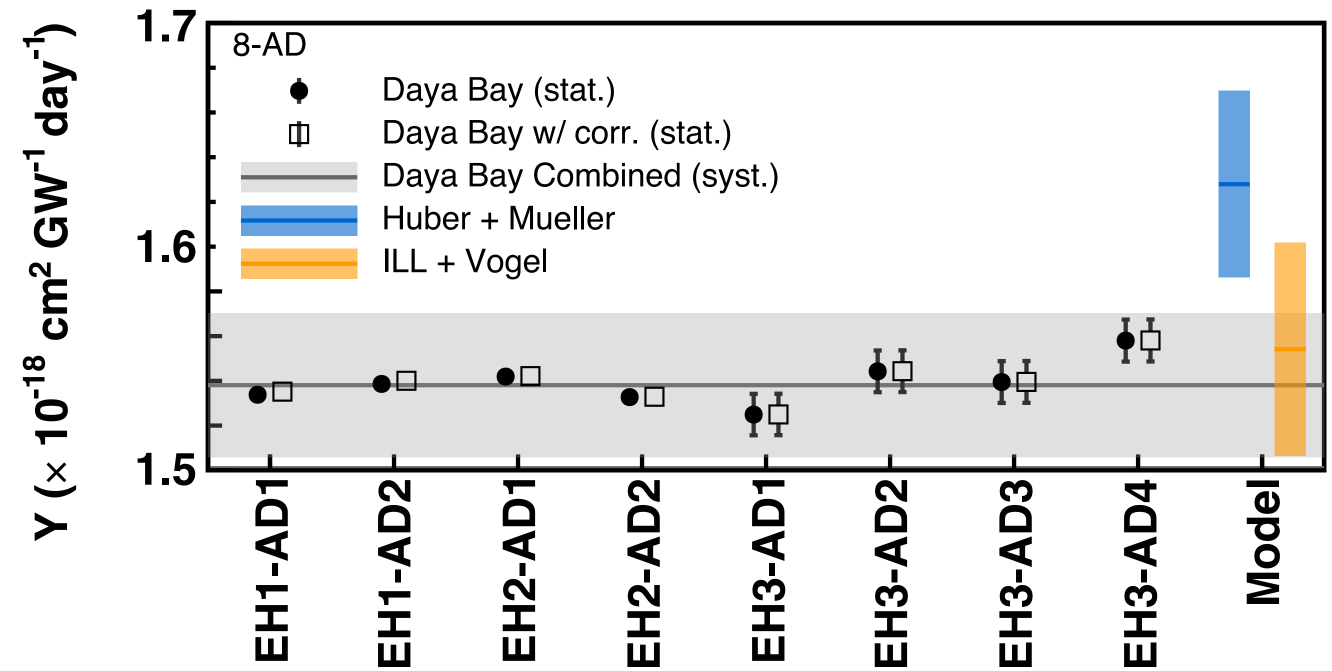
$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$

Reactor Antineutrino Energy Spectrum and Absolute Flux

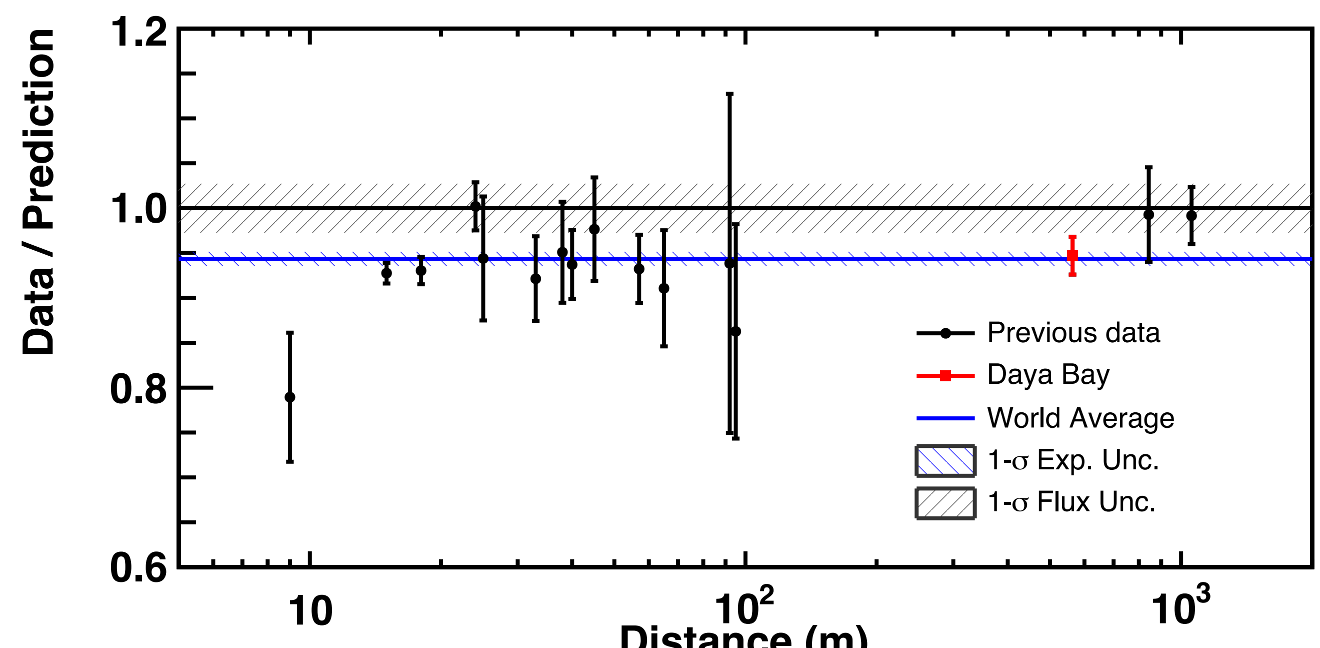
Spectral shape



Absolute flux



- Data lower than the prediction models
  - Huber+Mueller: 0.946±0.020
  - ILL+Vogel: 0.992±0.021

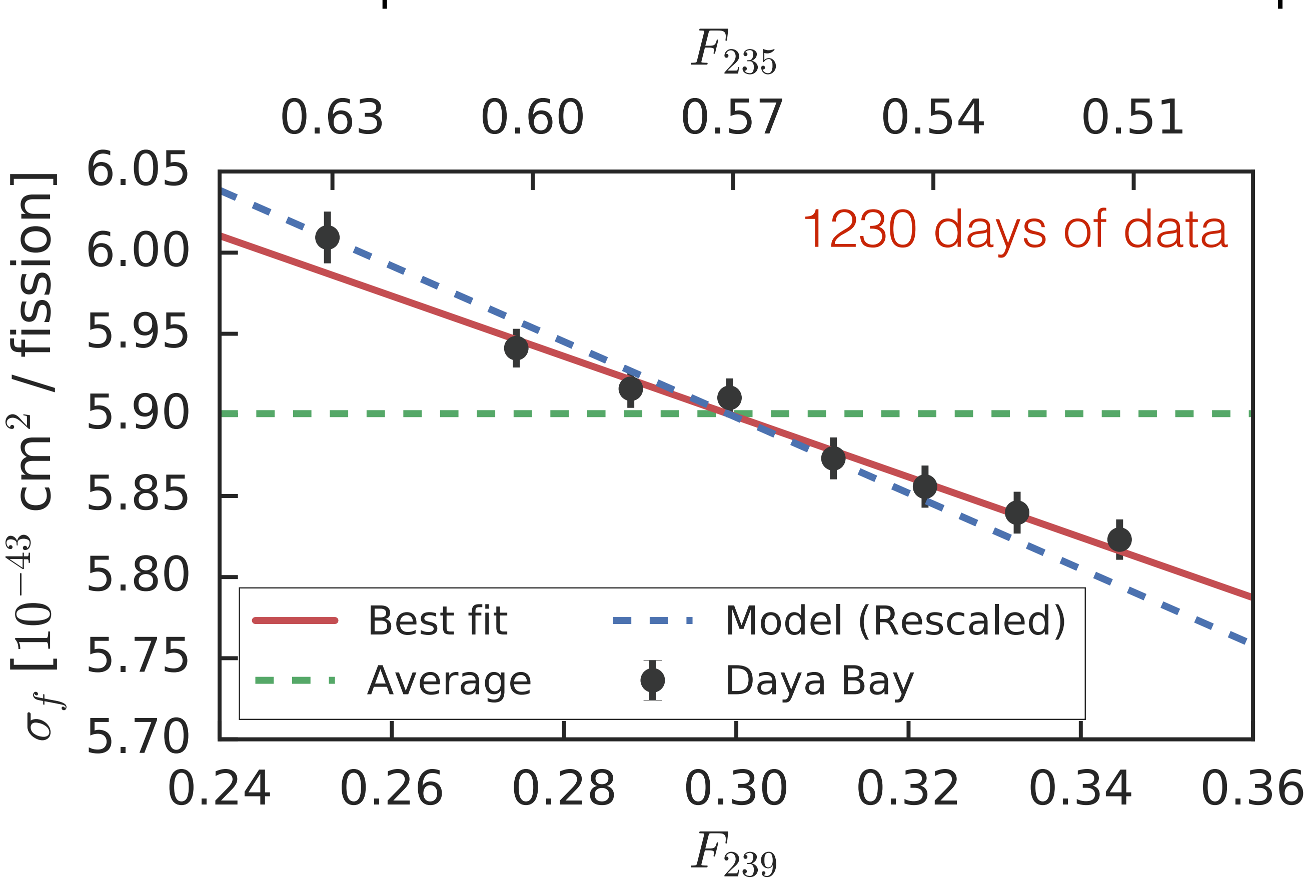


- Inconsistent with the traditional predictions based on β^- spectrum conversion

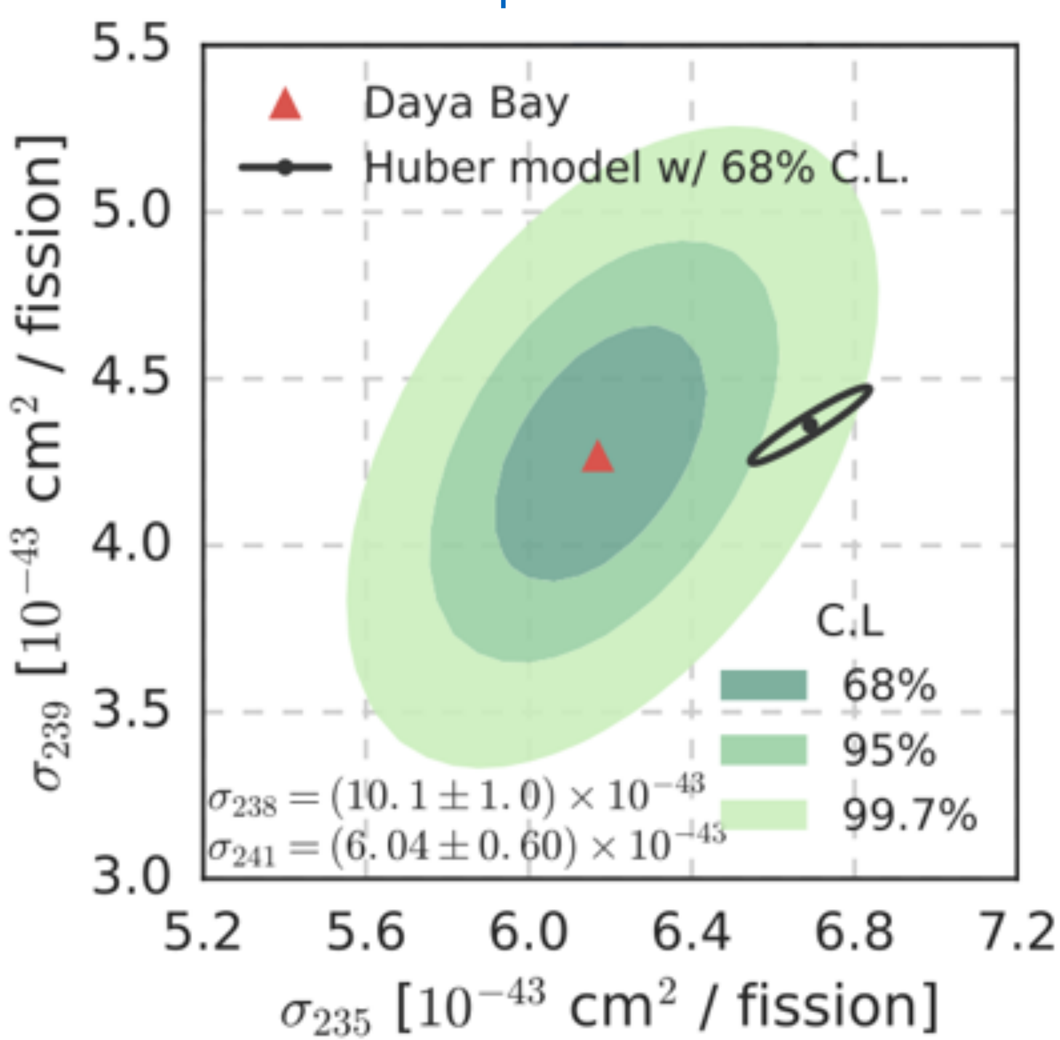
Chinese Physics C, 2017, 41(1): 13002-013002

First Measurement of Fuel Evolution

- Antineutrino flux from ^{235}U,^{238}U,^{239}Pu,^{241}Pu fissions not constant over time (^{235}U->^{239}Pu)
- Daya Bay is first to measured this evolution
- Constant flux ruled out on more than 10σ
- Equal deficit hypothesis excluded 2.6σ
- ^{235}U is suspected to cause the discrepancy



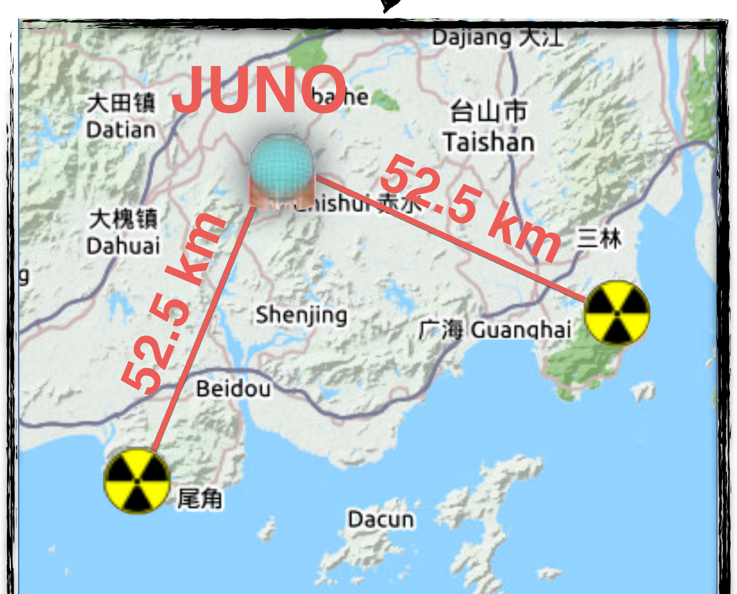
^{235}U is suspected element

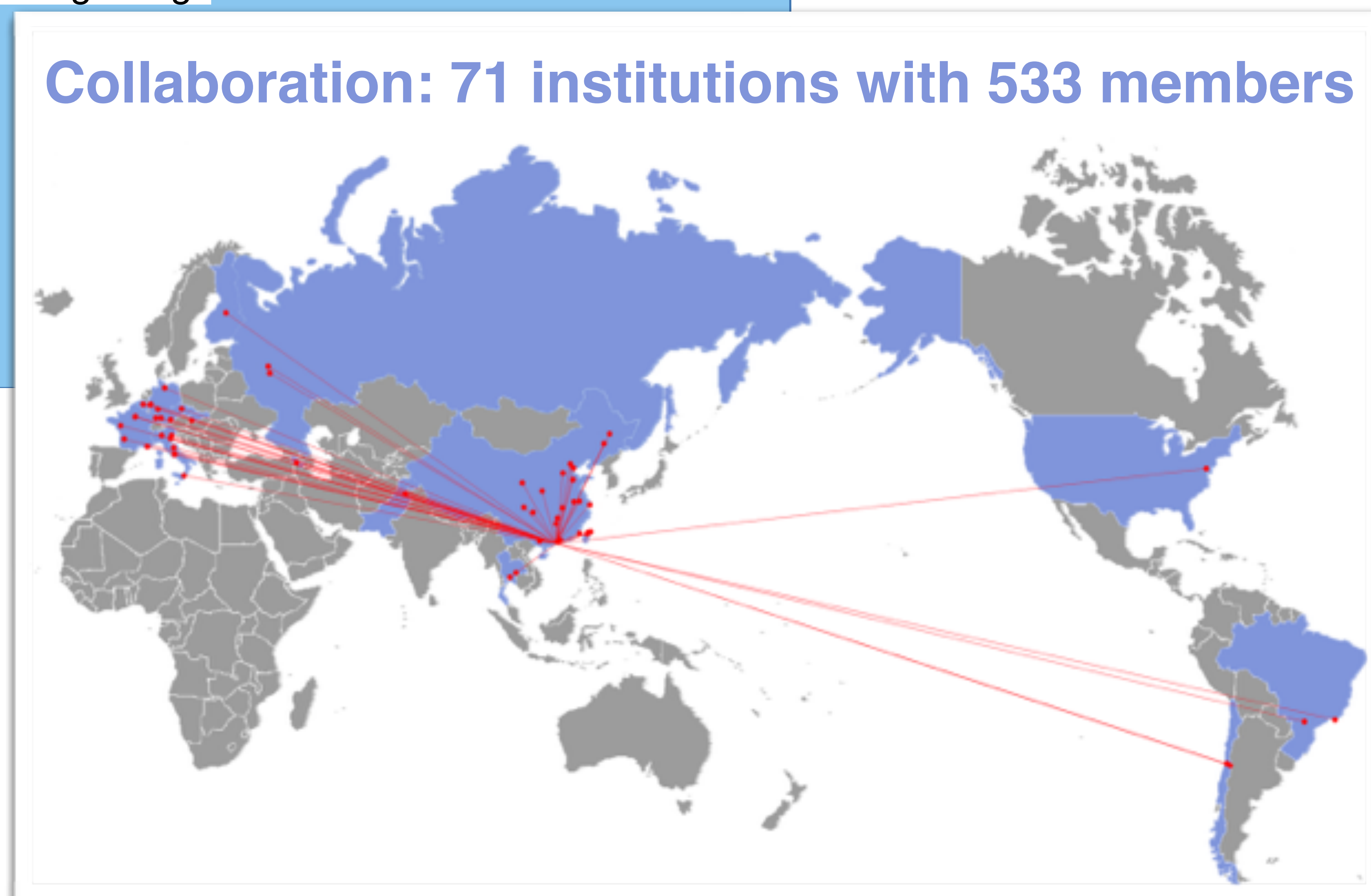


Message: Prediction models very likely need revision to be able to explain observations

Phys. Rev. Lett, 118, 251801 (2017)

JUNO Location & Collaboration



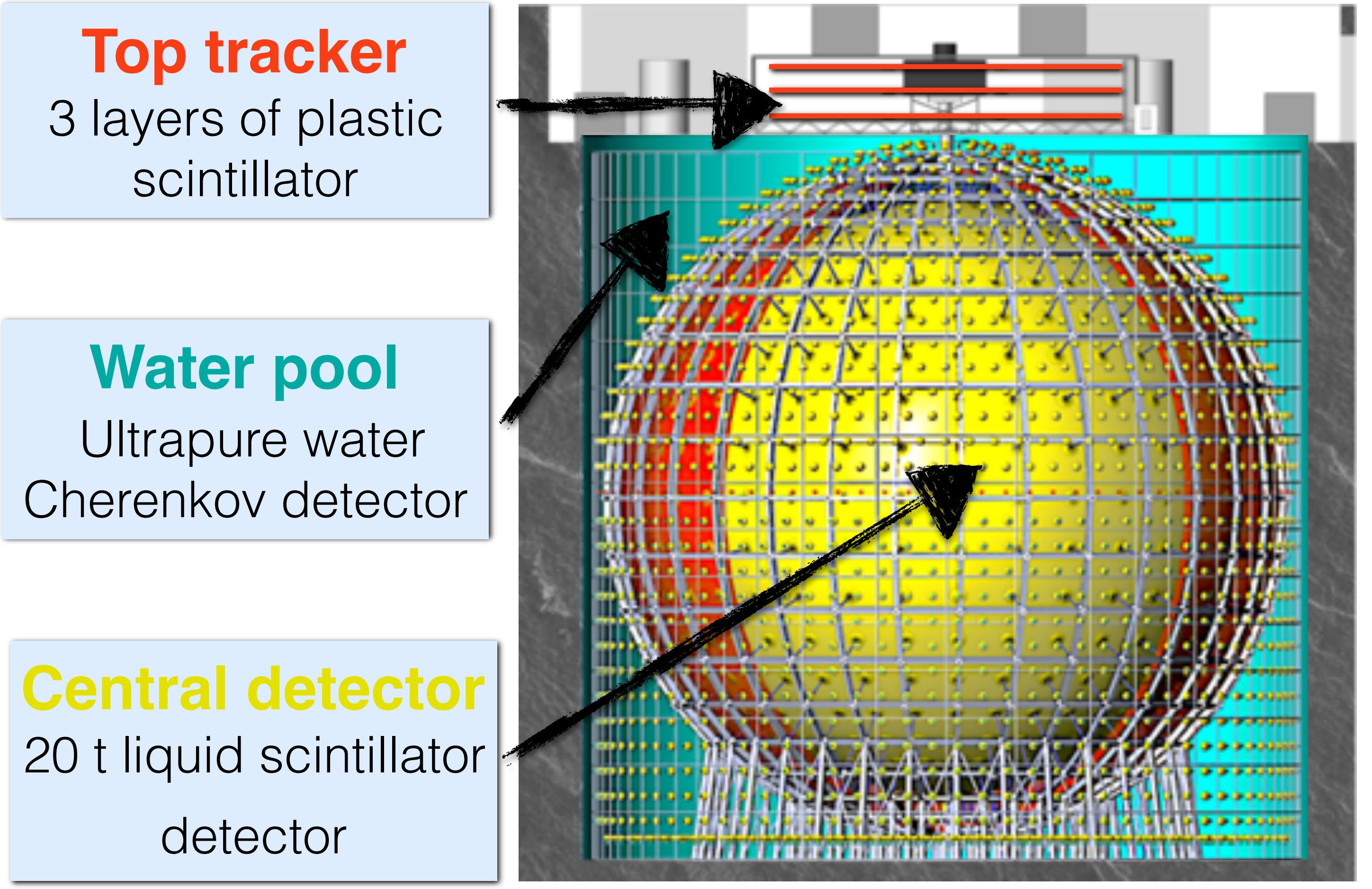


JUNO Experiment

- Multipurpose experiment with primary goal to determine neutrino mass hierarchy (MH)
- Using reactor neutrino oscillations on medium baseline
- First experiment to measure two neutrino oscillation modes simultaneously

Keys to Precise Measurement:

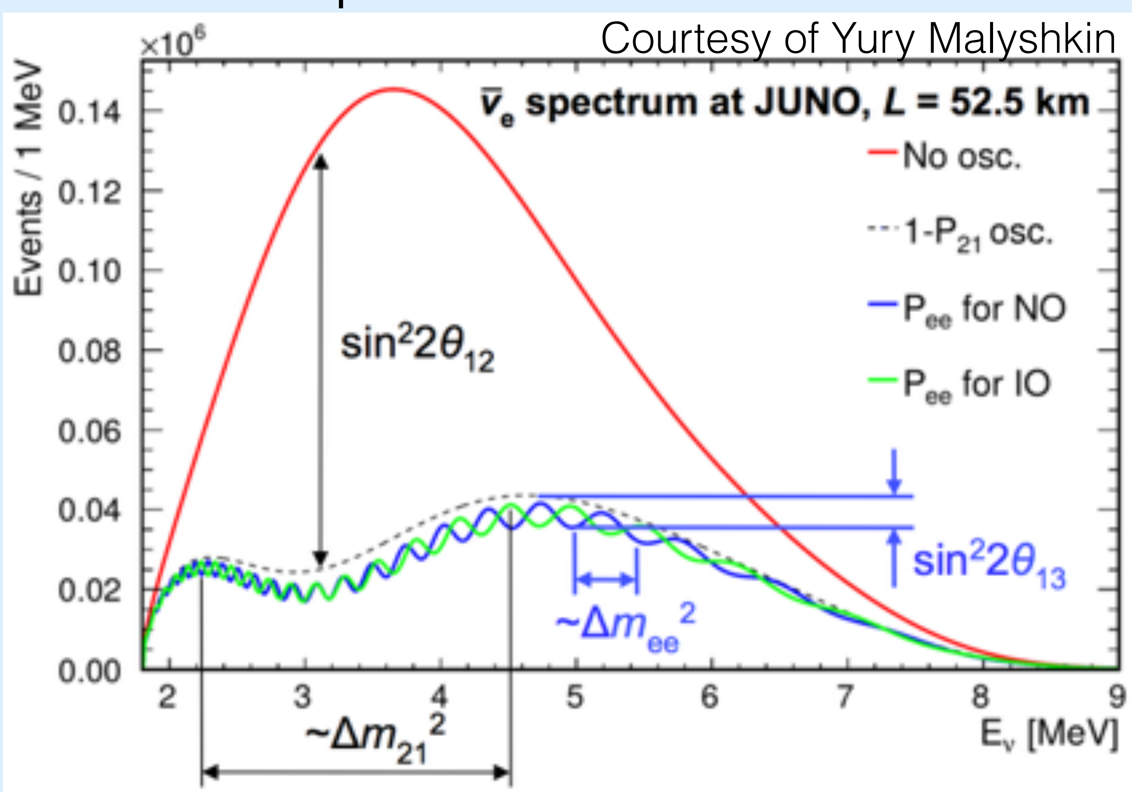
- **Powerful source:** 10 nuclear reactors ($26.6\ TW_{th}$ in 2020, later $35.7\ GW_{th}$)
- **Ideal baseline:** 52.5 km
- **Shielding:** 700 m underground
- **Huge target mass:** Single 20 kt LS detector
  - $\sim 10^5$ events in 6 years detected via IBD
- **Superb energy resolution:** 3%@1 MeV
  - High-yield scintillator
  - 75% photo coverage
- **Systematics suppression:**
  - Unique combination of two sets of PMTs: 17k 20-inch PMTs + 25k 3-inch PMTs



JUNO Physics Program

Reactor neutrino oscillations:

- Mass hierarchy determination
- Precise measurement of particular oscillation parameters

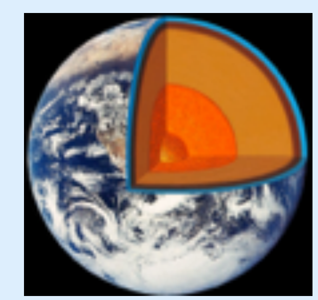


Parameter	Current precision (1σ)	Improvement by JUNO
$\sin^2 2\theta_{12}$	5%	<0.7%
Δm_{21}^2	2.3%	<0.6%
Δm_{31}^2	2.5% sign unknown	<0.5% sign determination

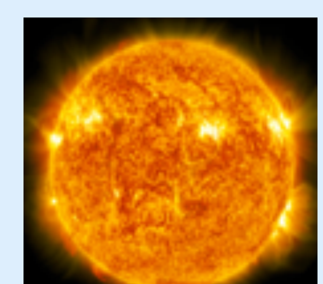
Other physics:

- **Supernova (SN) neutrinos**
  - 10^4 events from SN @ 10 kpc
  - Testing SN models
  - Possibility of independent determination of MH

- **Diffused SN neutrinos**
  - 1-4 events per year
  - Discovery if measured
- **Geoneutrinos**
  - see next slide



- **Solar neutrinos**
  - ^{7}Be neutrinos detected via elastic scattering



- **Proton decay**
  - $p \to K^+ + \nu$
- **…and more**

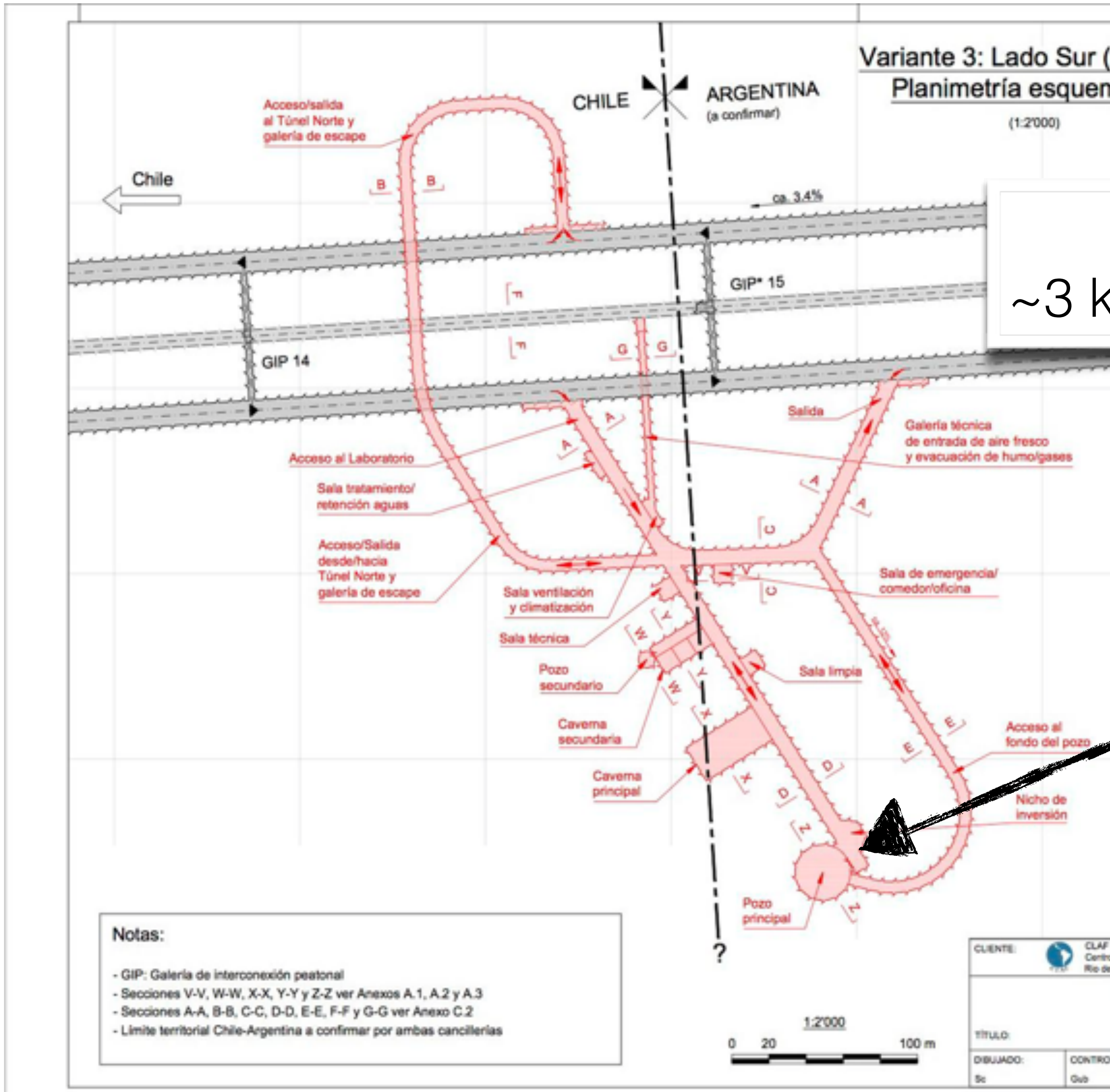
Summary of Daya Bay&JUNO

- Daya Bay experiment
  - Provided most precise measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$

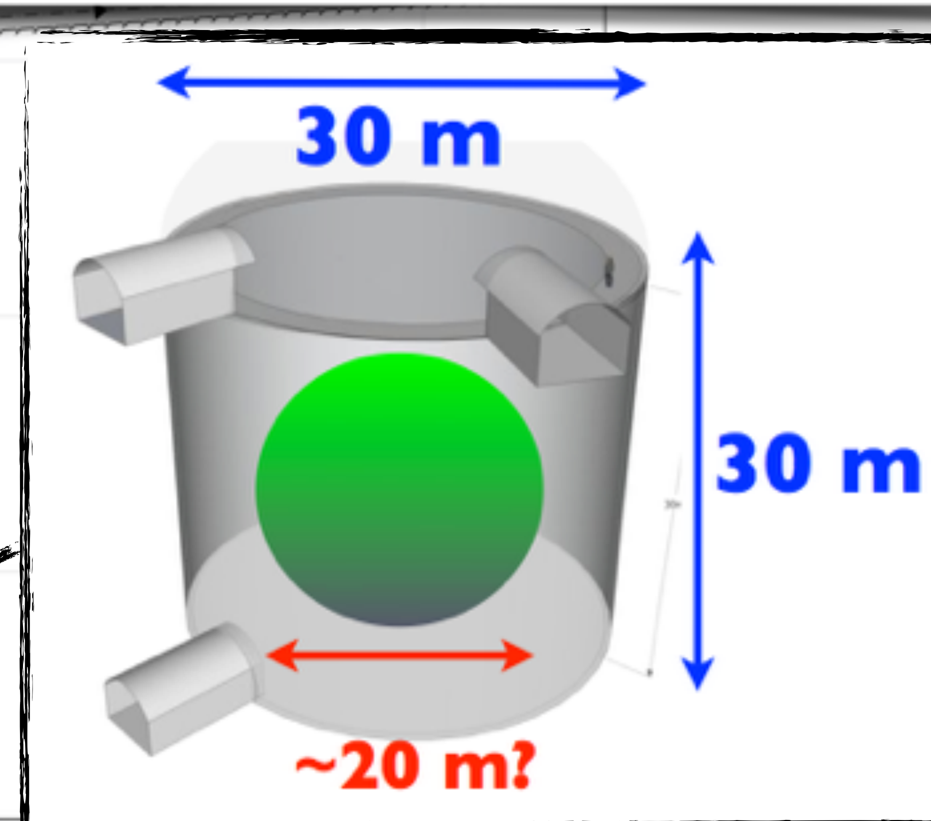
$$\sin^2 2\theta_{13} = \big(8.41 \pm 0.27(\mathrm{stat.}) \pm 0.19(\mathrm{syst.})\big) \times 10^{-2}$$
$$|\Delta m^2_{ee}| = \big(2.50 \pm 0.06(\mathrm{stat.}) \pm 0.06(\mathrm{syst.})\big) \times 10^{-3}\,\mathrm{eV}^2$$

  - Searched for sterile neutrinos itself as well as joined analysis with MINOS
  - Measured reactor neutrino properties: Spectrum shape, absolute flux, fuel evolution -> Predictions do not correspond to the data
  - Run until 2020 - Precision of $\sin^2 2\theta_{13}$ <3% by then
- JUNO experiment
  - Start data taking 2020
  - Broad physics program including:
    - Neutrino mass hierarchy determination
    - Reduction of the uncertainty of particular oscillation parameters
    - Measurement of neutrinos from various sources

ANDES 3 kt Liquid Scintillator Detector



Cavern can accommodate
~3 kt liquid scintillator (LS) detector



The Earth Dynamics

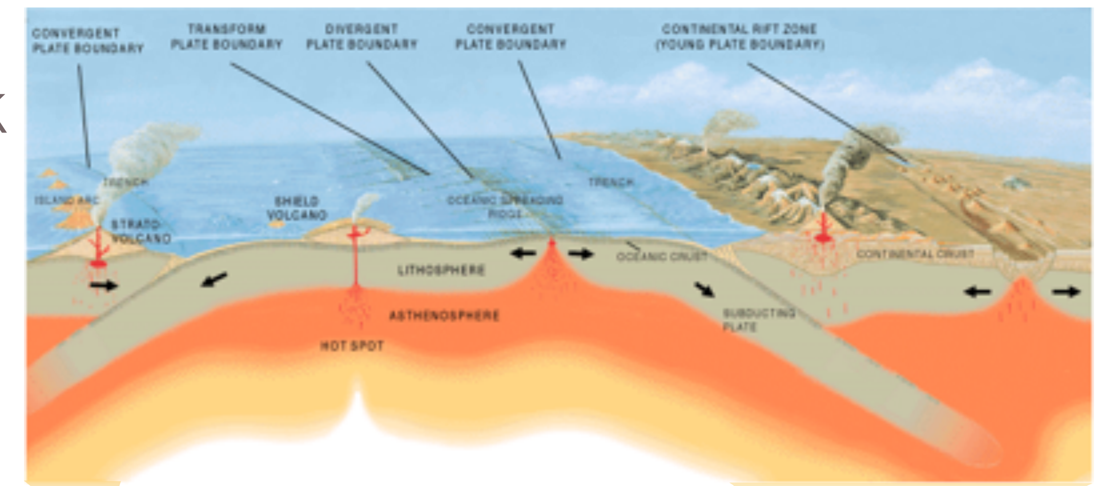
Crust - Lower density silicate rock

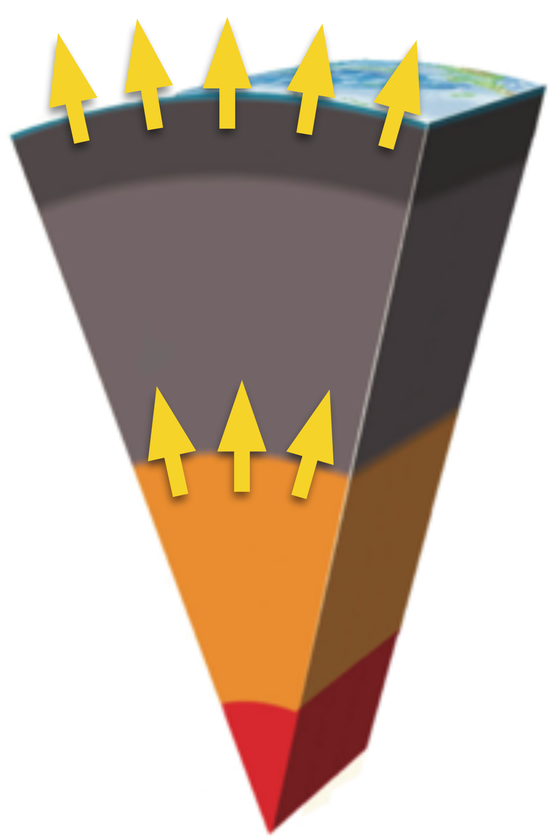
Upper and lower mantle
Solid but viscous silicate rock

Outer core - Molten metal

Inner core - Solid metal

Plate tectonics





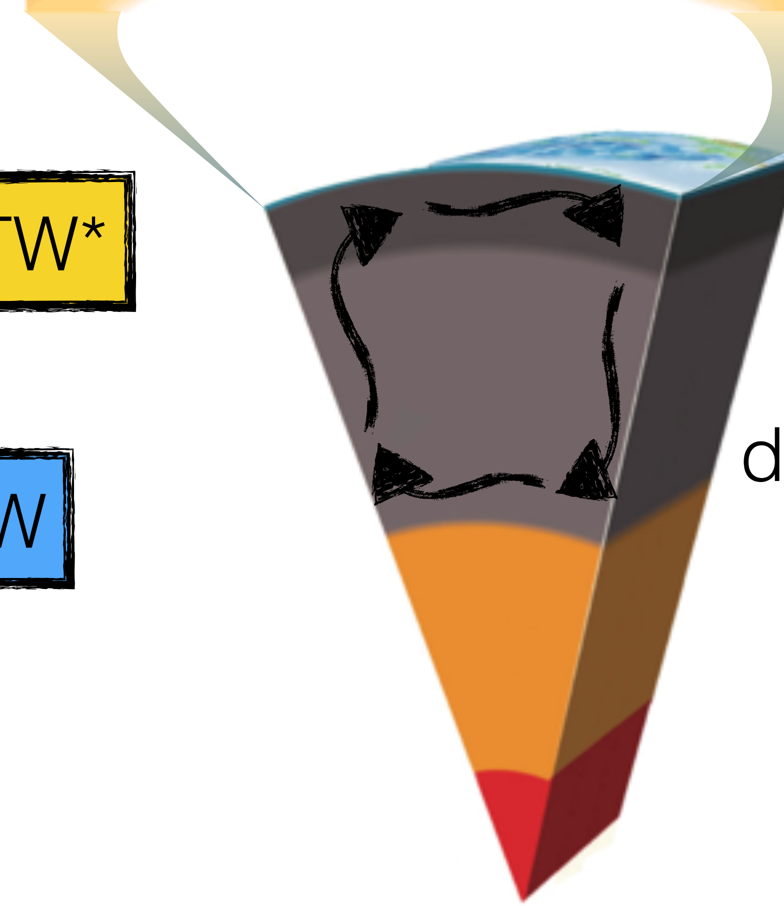
Surface heat flow: (46±3) TW*

=

Cooling of the interior: ? TW

+

Heat sources: ? TW



Earth dynamics

*Jaupart et al. (2007)

Heat Sources - Radioactivity

- Radionuclides in the Earth:

$$^{238}_{92}\mathrm{U} \longrightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6\mathrm{e}^- + 6\bar{\nu}_e + \boxed{51.689\ \mathrm{MeV}}$$

$$^{235}_{92}\mathrm{U} \longrightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 7\mathrm{e}^- + 7\bar{\nu}_e + \boxed{46.402\ \mathrm{MeV}}$$

$$^{232}_{90}\mathrm{Th} \longrightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4\mathrm{e}^- + 4\bar{\nu}_e + \boxed{42.652\ \mathrm{MeV}}$$

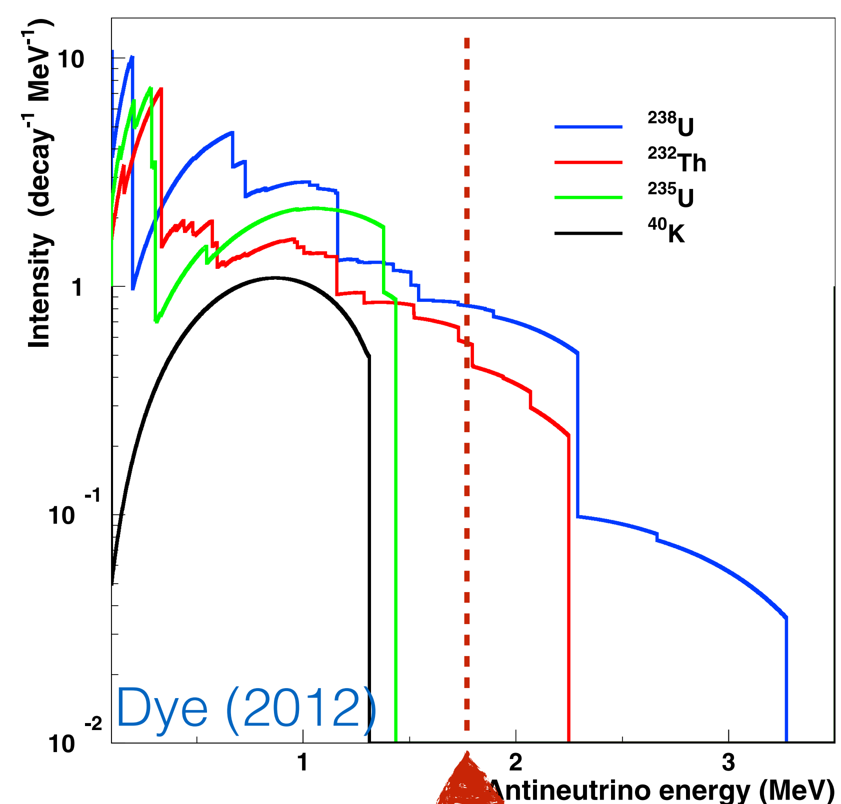
$$^{40}_{19}\mathrm{K} \xrightarrow{89.3\%} {}^{40}_{20}\mathrm{Ca} + \mathrm{e}^- + \bar{\nu}_e + \boxed{1.311\ \mathrm{MeV}}$$

$$^{40}_{19}\mathrm{K} + \mathrm{e}^- \xrightarrow{10.7\%} {}^{40}_{18}\mathrm{Ar} + \nu_e + \boxed{1.505\ \mathrm{MeV}}$$

Geoneutrinos:
Mostly electron antineutrinos

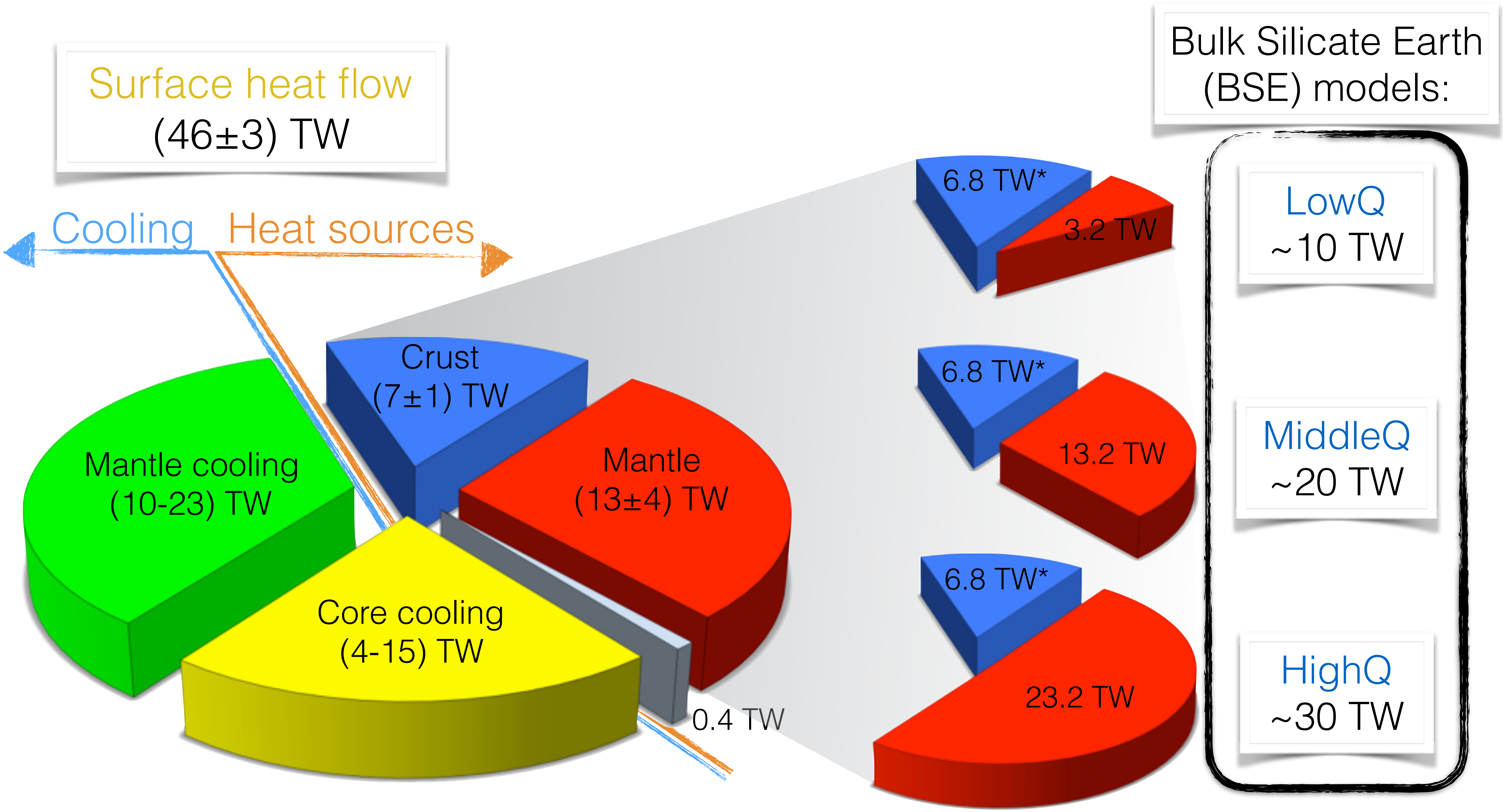
Radiogenic heat breakdown:
^{238}U: ~40%
^{232}Th: ~40%
^{40}K: ~20%

Energy per decay chain
Part carried away by geoneutrinos
Rest is converted to heat



Geoneutrino energy above IBD threshold

Breakdown of the Heat Balance

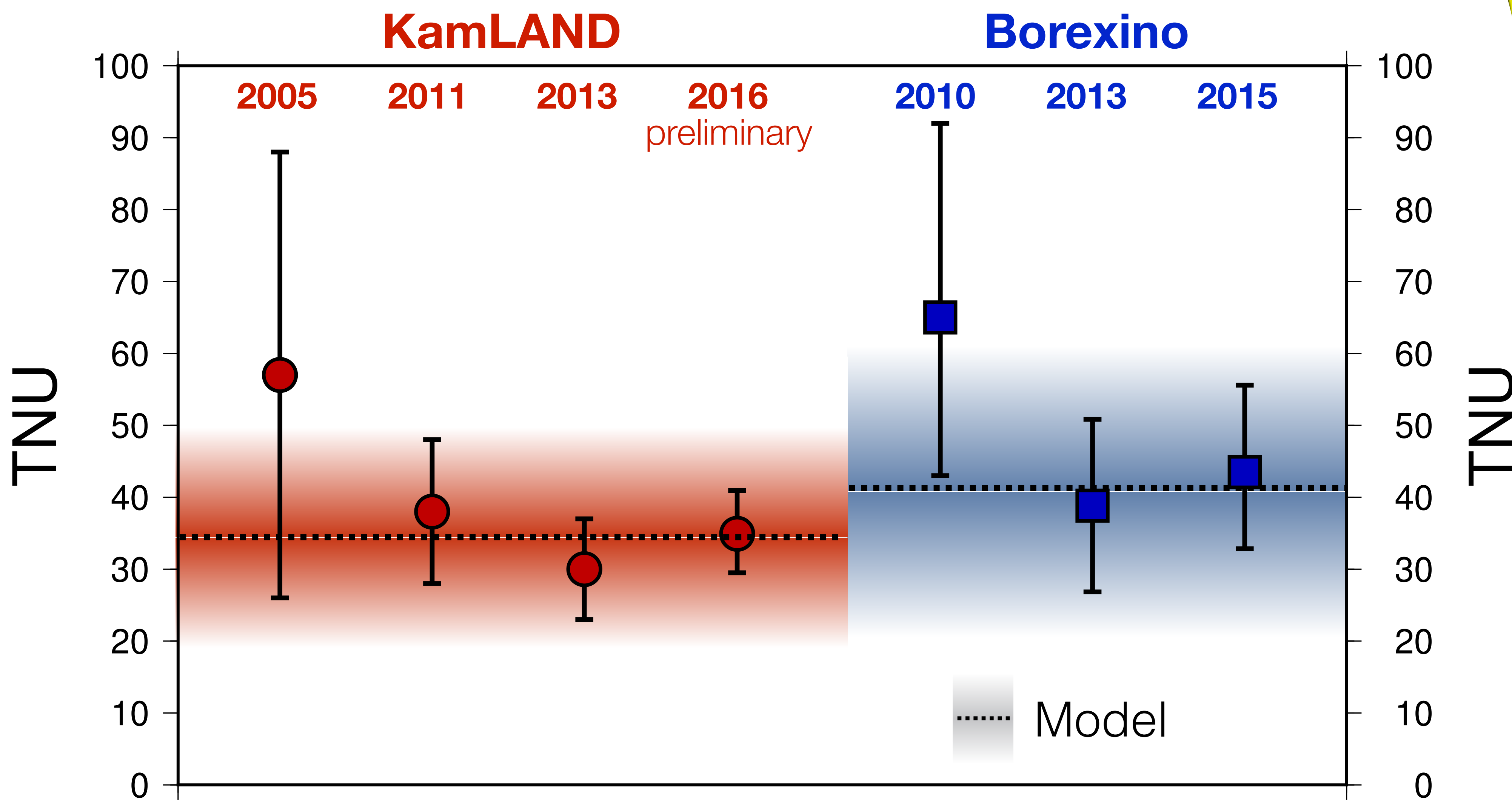


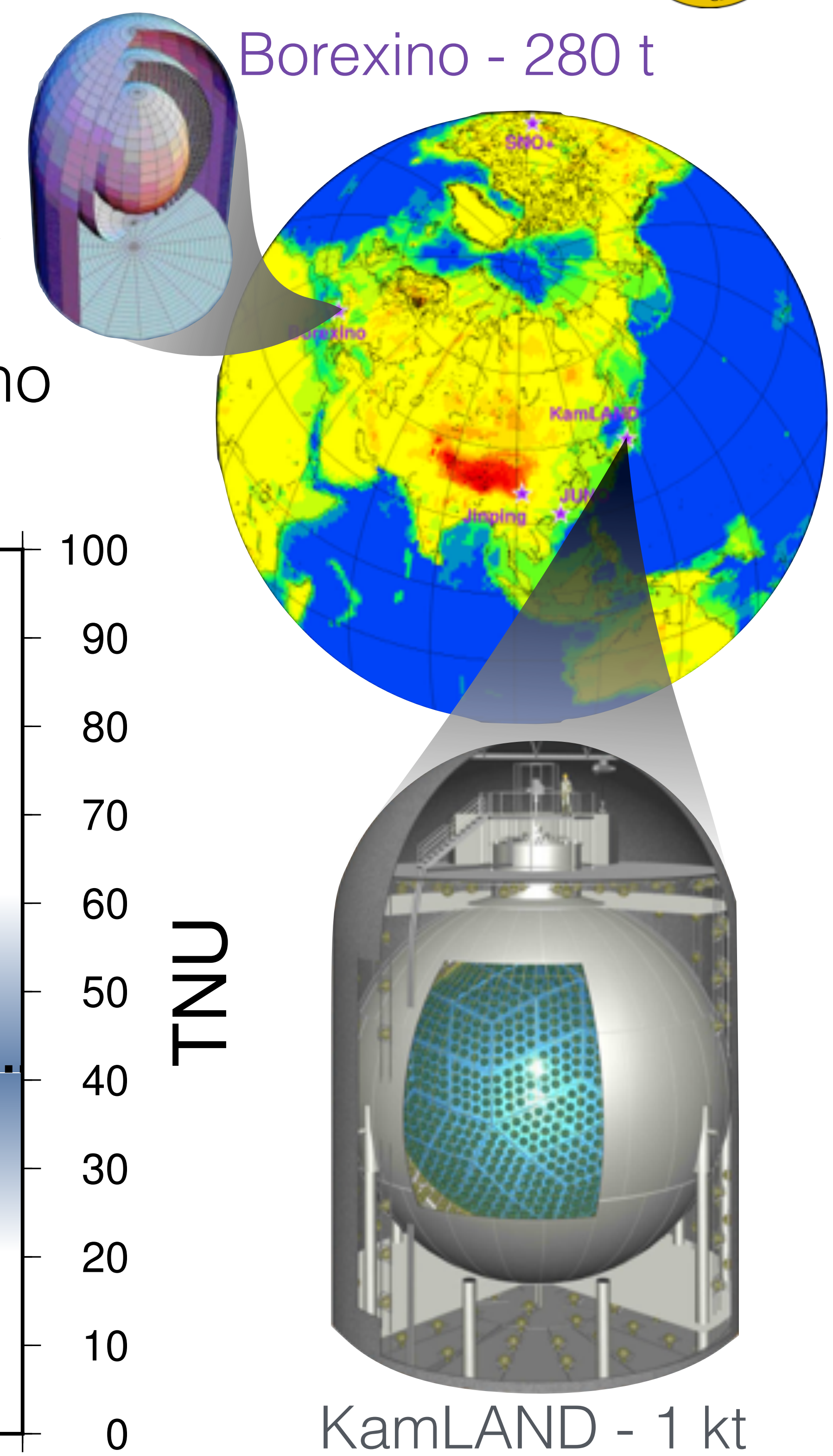
BSE: (20±4) TW**

*Huang et al. (2013)
**McDonough&Sun (1995)

Geoneutrino Measurements so far

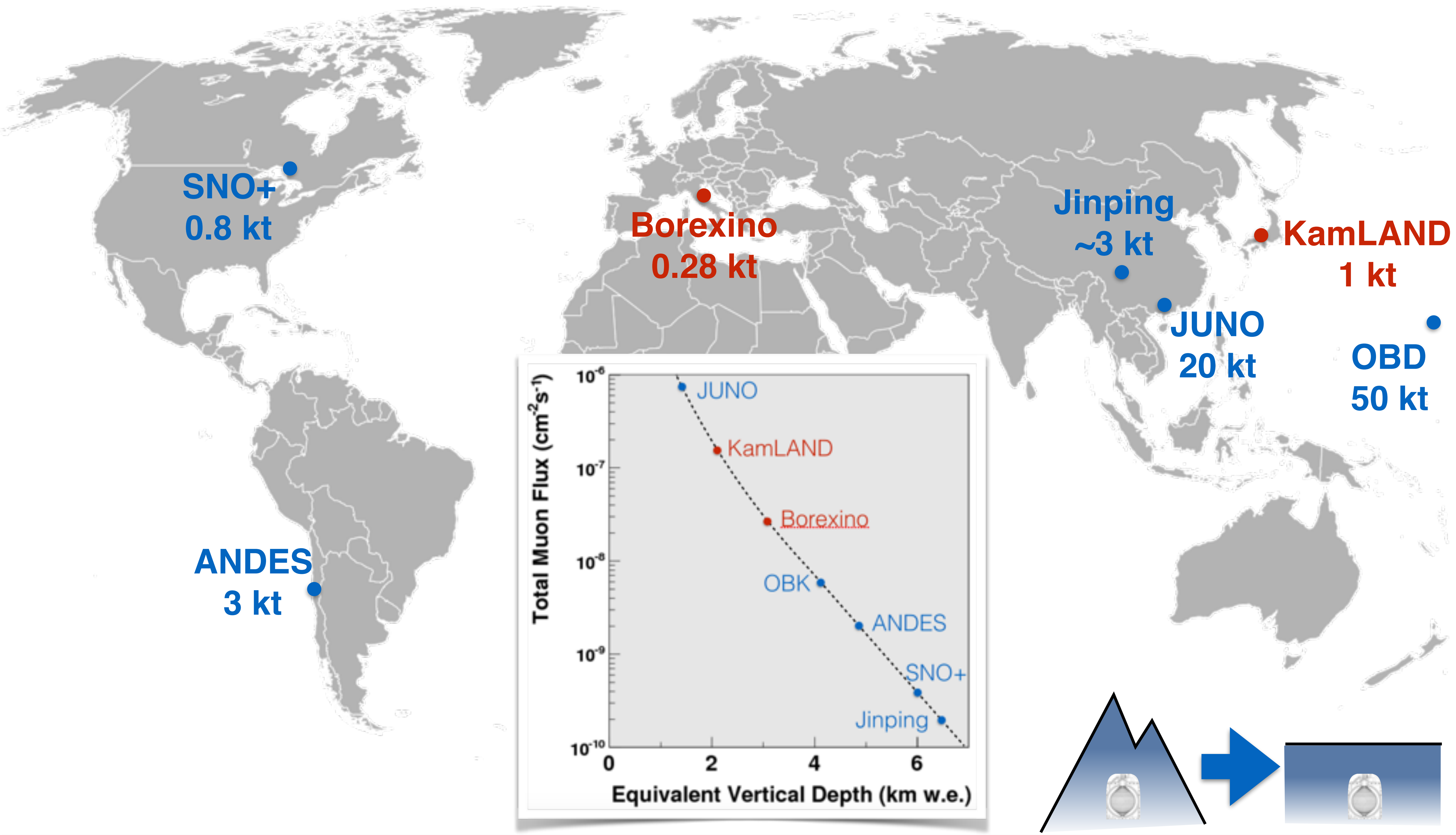
- 2005 - KamLAND - first to measure geo-ν's
- 2016 - KamLAND - best precision - 17% uncertainty
- Only two experiments so far: KamLAND and Borexino





1 TNU (Terrestrial Neutrino Unit) = 1 event detected by IBD per year on 10^{32} protons

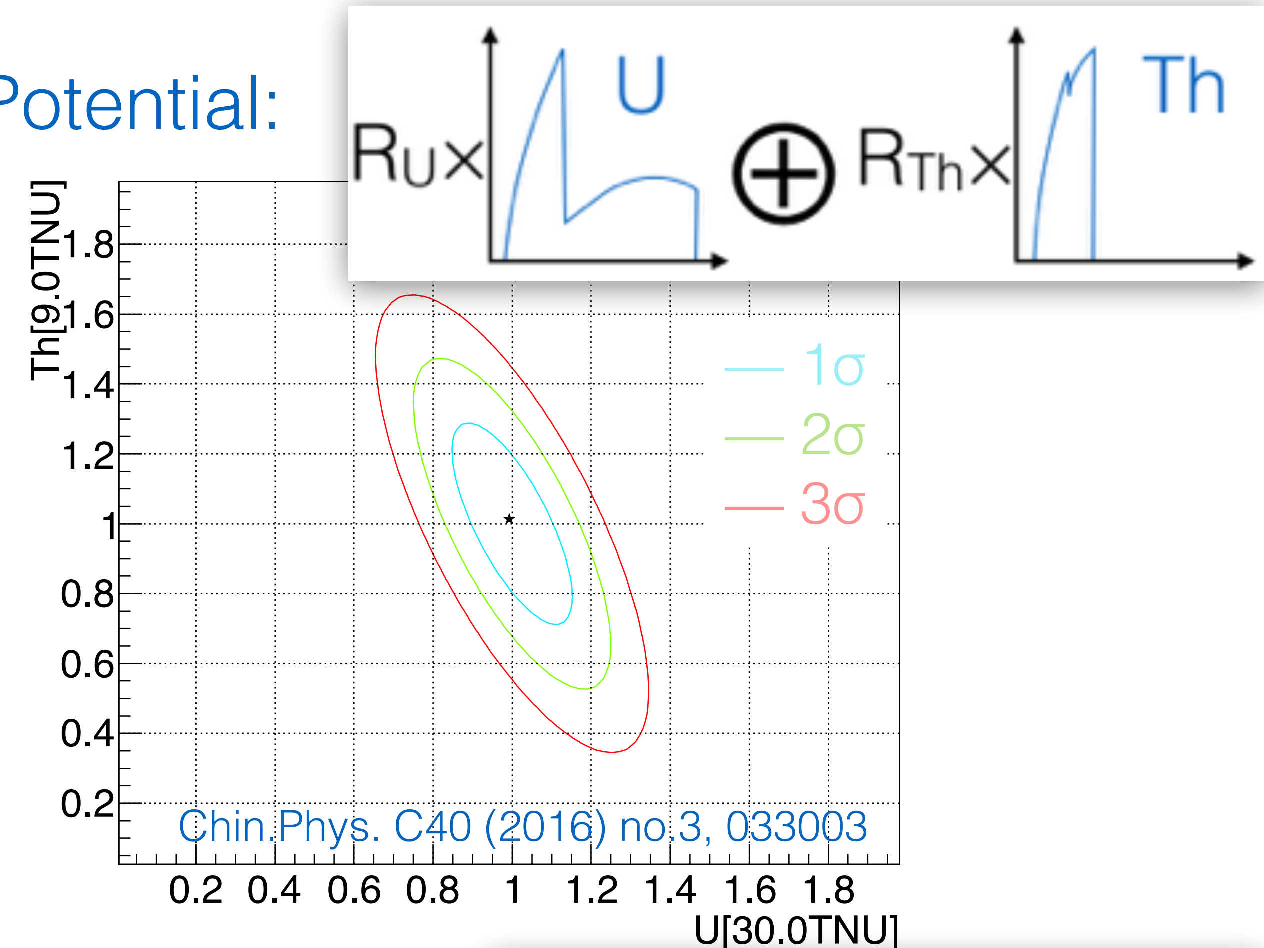
Upcoming Experiments



Geoneutrino Measurement at JUNO

- JUNO geo-ν advantage
  - High statistics
  - In 1 year - highest sample of geo-ν's
- JUNO geo-ν limitation
  - Huge reactor background
  - Large cosmic-ray muon induced background

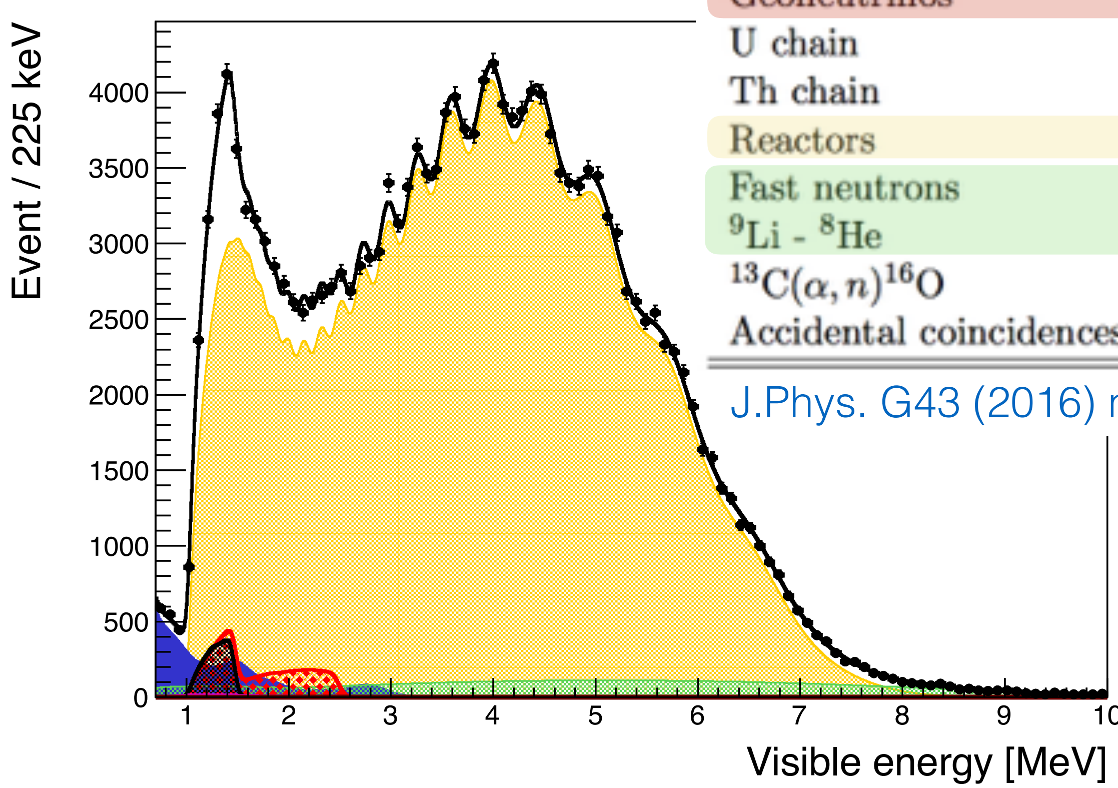
Potential:

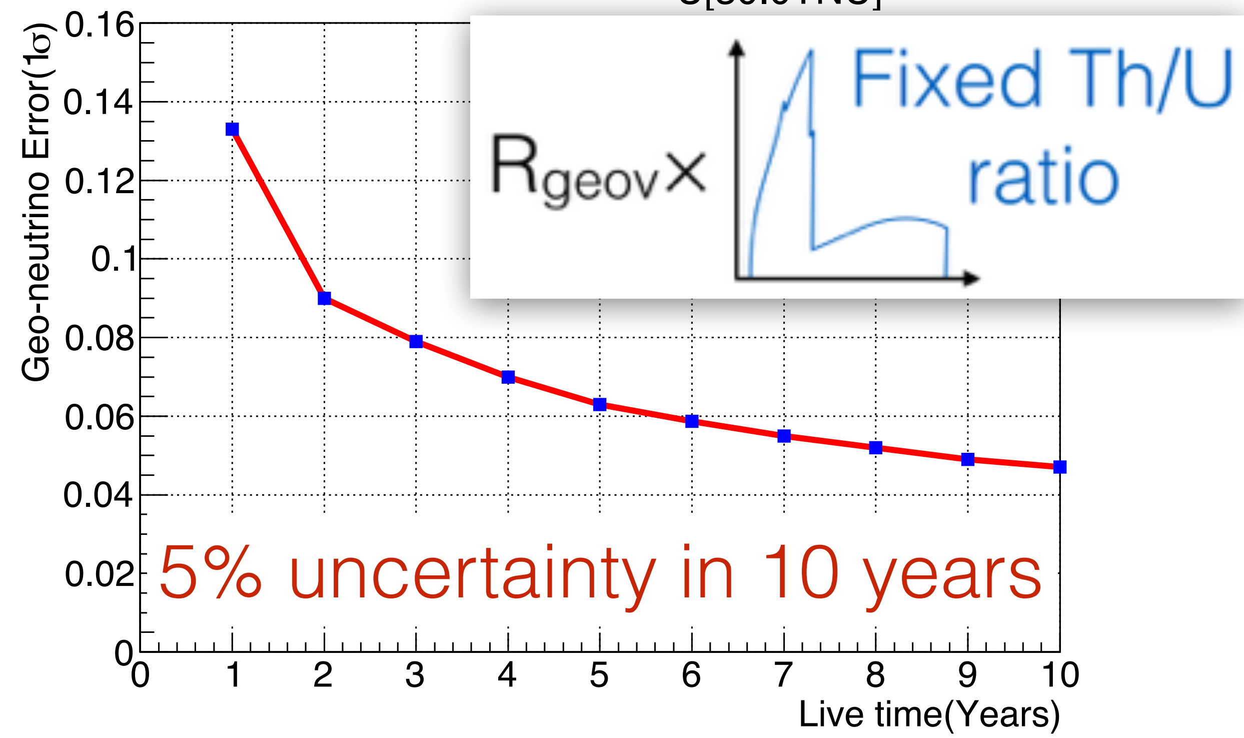


Chin.Phys. C40 (2016) no.3, 033003

Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	36.5 ± 36.5
^{9}Li - ^{8}He	657 ± 130
$^{13}C(\alpha, n)^{16}O$	18.2 ± 9.1
Accidental coincidences	401 ± 4

J.Phys. G43 (2016) no.3, 030401





Geoneutrino Measurement at ANDES

Investe beta decay (IBD):

Time coincidence

prompt signal | delayed signal

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

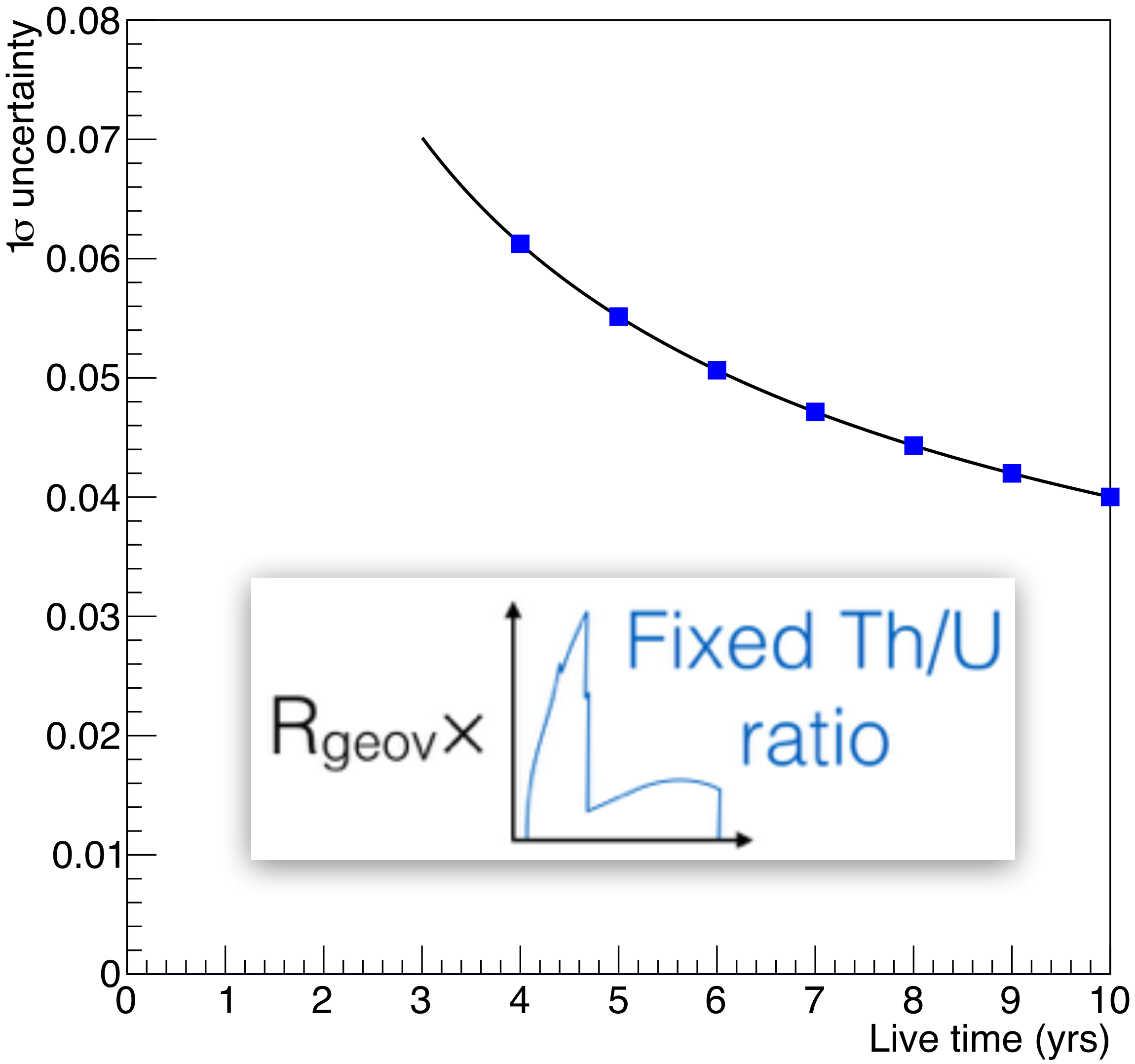
Only ^{238}U and ^{232}Th geo-ν's can be detected

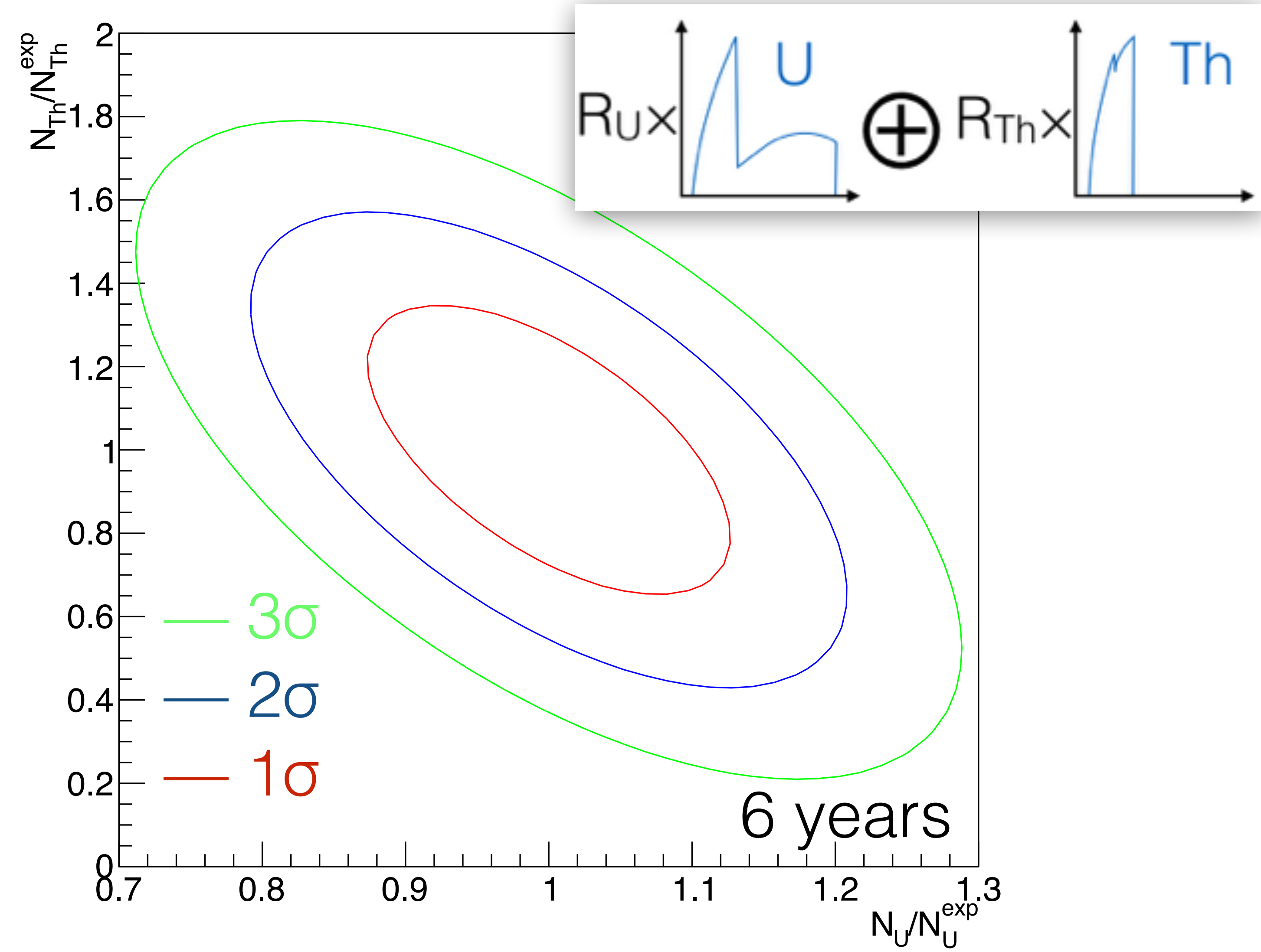
Event rates at ANDES 3 kt liquid scintillator detector

	Events (/year/3 kt)	Comment
Geo-ν's	75	41.8 TNU; ε=0.85; 0.73×10^{32} p/kt
Reactor ν's	5.5± Daya Bay rate&shape	3.6 TNU (geoneutrinos.org- 2015 database)
Accidentals	20.0±0.2	Number depends on many factors
Fast neutrons	0.50±0.15	10×Jinping ⇐ 10×higher muon flux
9Li/^{8}He	7.0±2.1	10×Jinping ⇐ 10×higher muon flux
^{13}C(α,n)^{16}O	3.0±0.9	JUNO-like scintillator

ANDES Preliminary Sensitivity

- For fixed $R_{Th/U} \simeq 4$
  - $\sigma_{geo\text{-}\nu}$=5.1%[4.7% stat. only] in 6 years of data
  - $\sigma_{geo\text{-}\nu}$=4.0% in 10 years
- For free $R_{Th/U}$:
  - Rule out zero Th flux on ~4σ in 6 years of data (>5σ in 10 years)

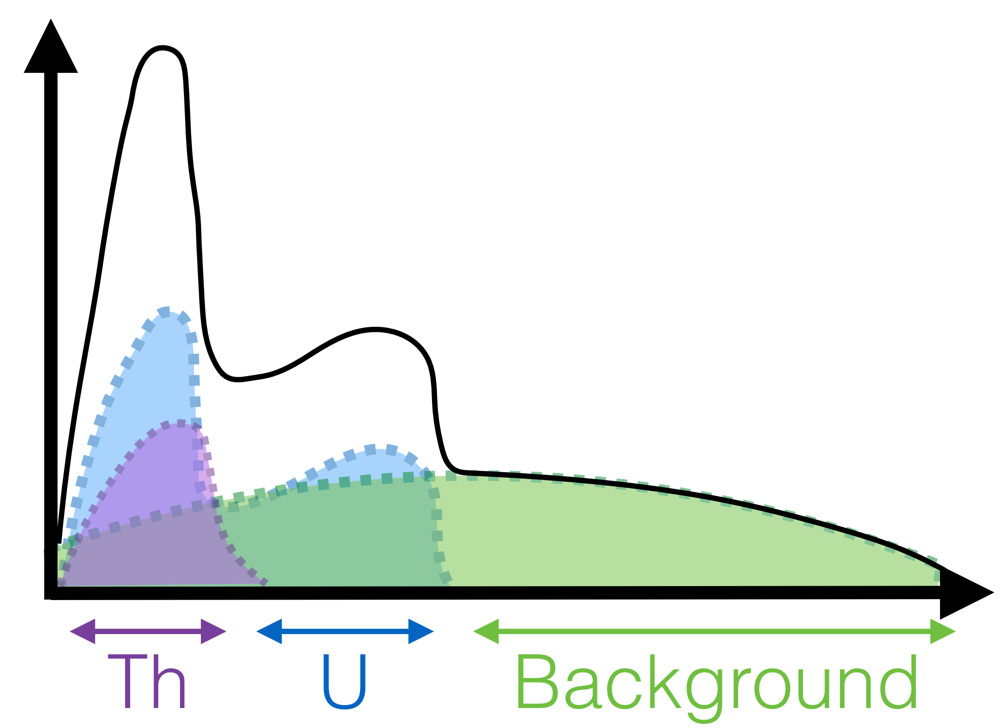




Design: What Matters for Geoneutrinos

- What is needed to perform good geo-ν measurement?
  - Low cosmic ray muon flux-> Be underground ANDES✓
  - Low reactor antineutrino flux -> Be far from reactors ANDES✓
  - Low radioactivity -> Purified liquid scintillator ANDES✓
  - High statistics -> Large detector (3 kt?) ANDES±

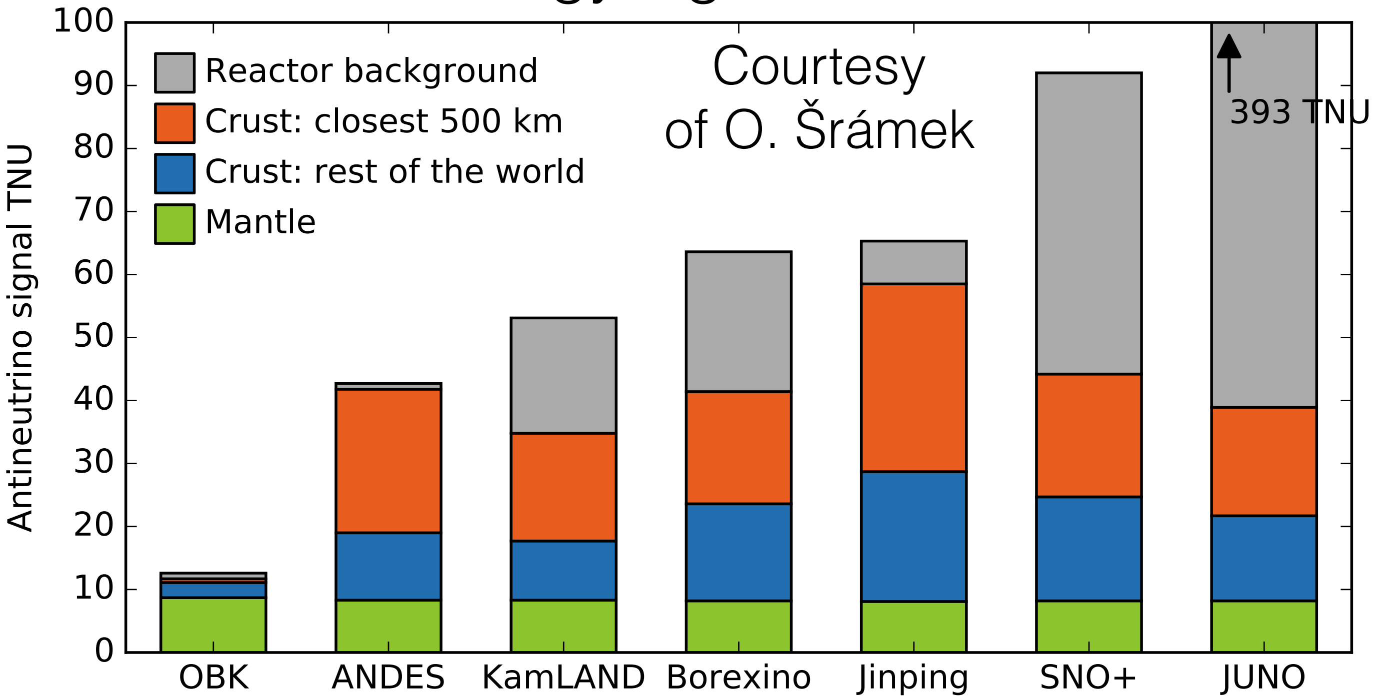
- What does not matter that much
  - No need for superb energy resolution
  - Even ~10%@1 MeV is enough



Reactor Neutrino Background

- Daya Bay shown that predictions of the reactor neutrino flux does not match measured data
- Daya Bay has measured the generic antineutrino spectrum
- We use it as the best description of this background we currently have

Antineutrino flux in geo-ν energy signal window



Predictions do not agree with data->
Using Daya Bay Reactor Neutrino Spectrum:

	Reactor signal in geo-ν window	1σ uncertainty (10 years)
JUNO	355 TNU	5->8%
Jinping	6.8+ TNU	3.3->?%
ANDES	0.9 TNU	4.0%

Information from Geoneutrino Measurements

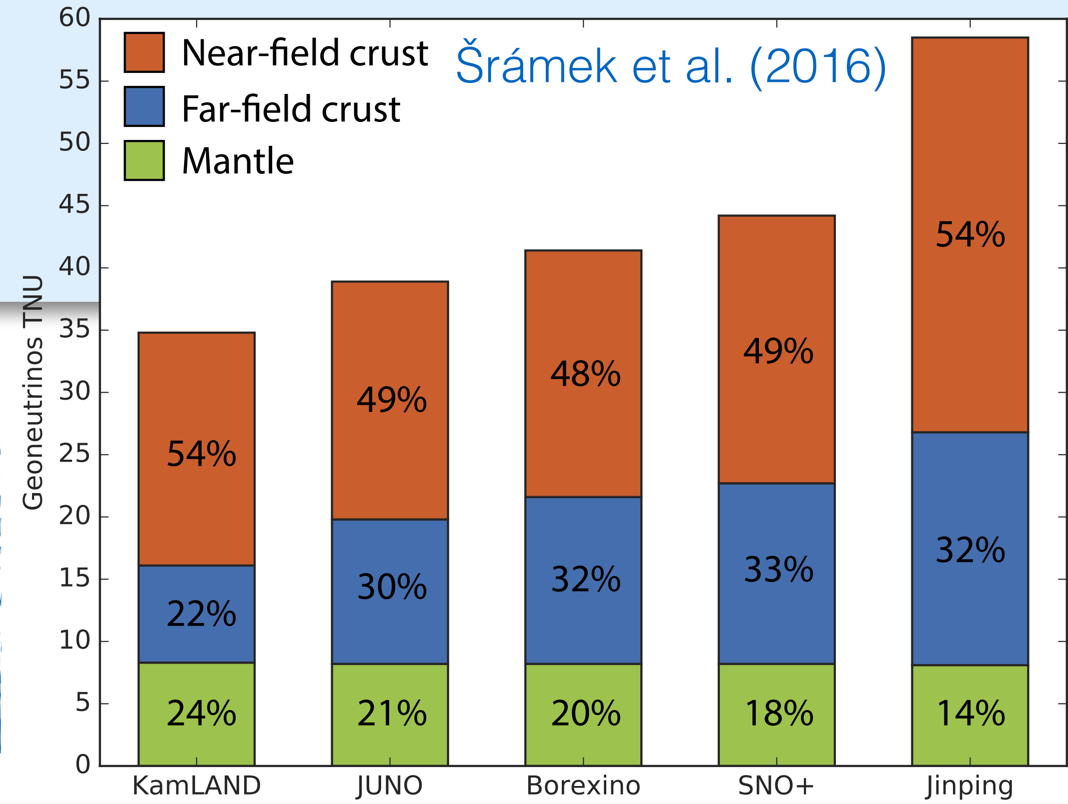
- Geoneutrinos can reveal the contribution of cooling/heat sources to the drive of Earth dynamics -> depends on radionuclides in the mantle

Today

Prediction:

Current prediction:
~13% uncertainty

Local crust model
(L≲300 km):
Input from various
geophysicist fields



Measurement:

Current measurements:
>17% uncertainty

Tomorrow

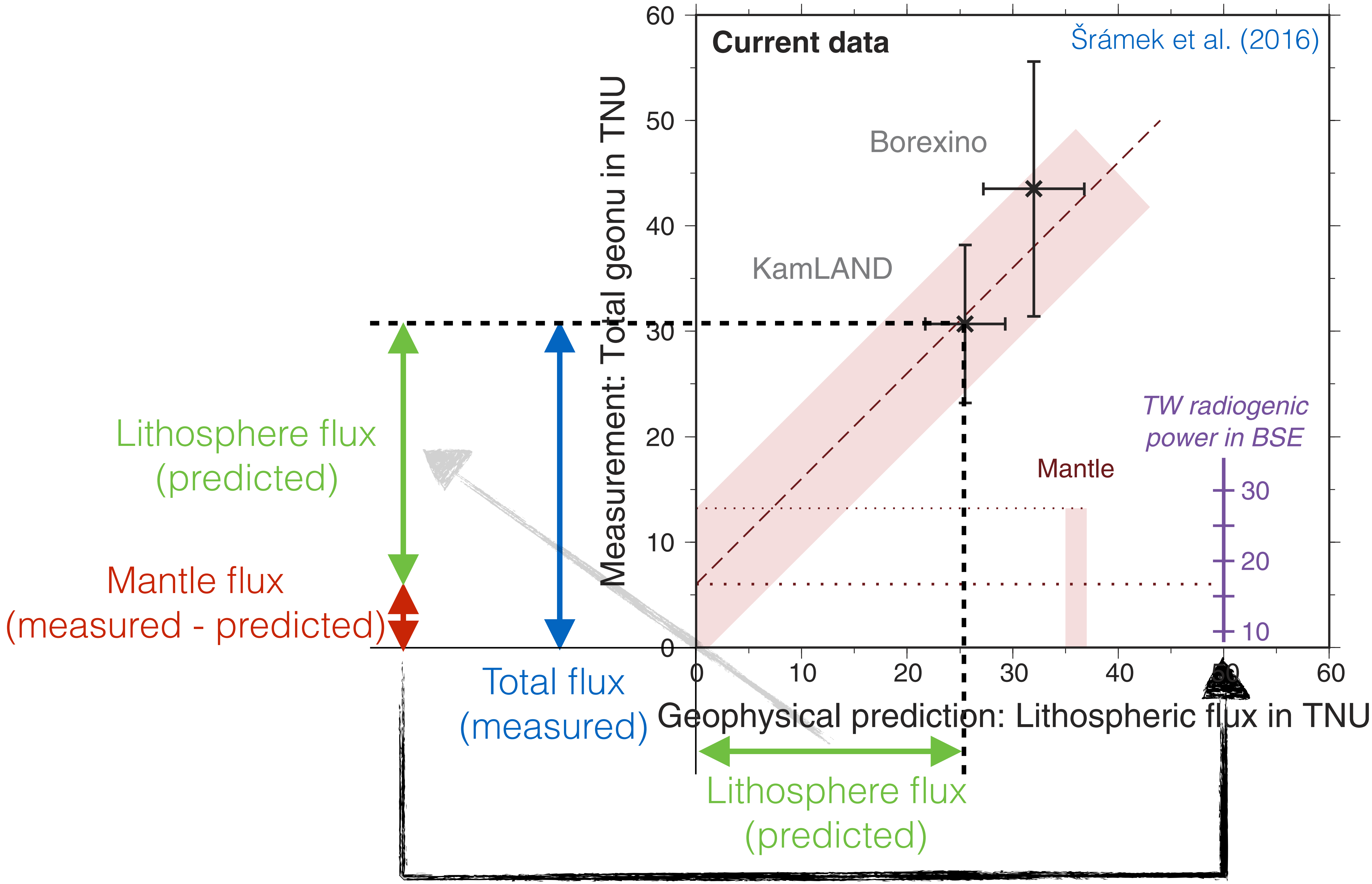
Future prediction:
~7% uncertainty

Even single measurement
can improve the model

Future measurements:
~5% uncertainty

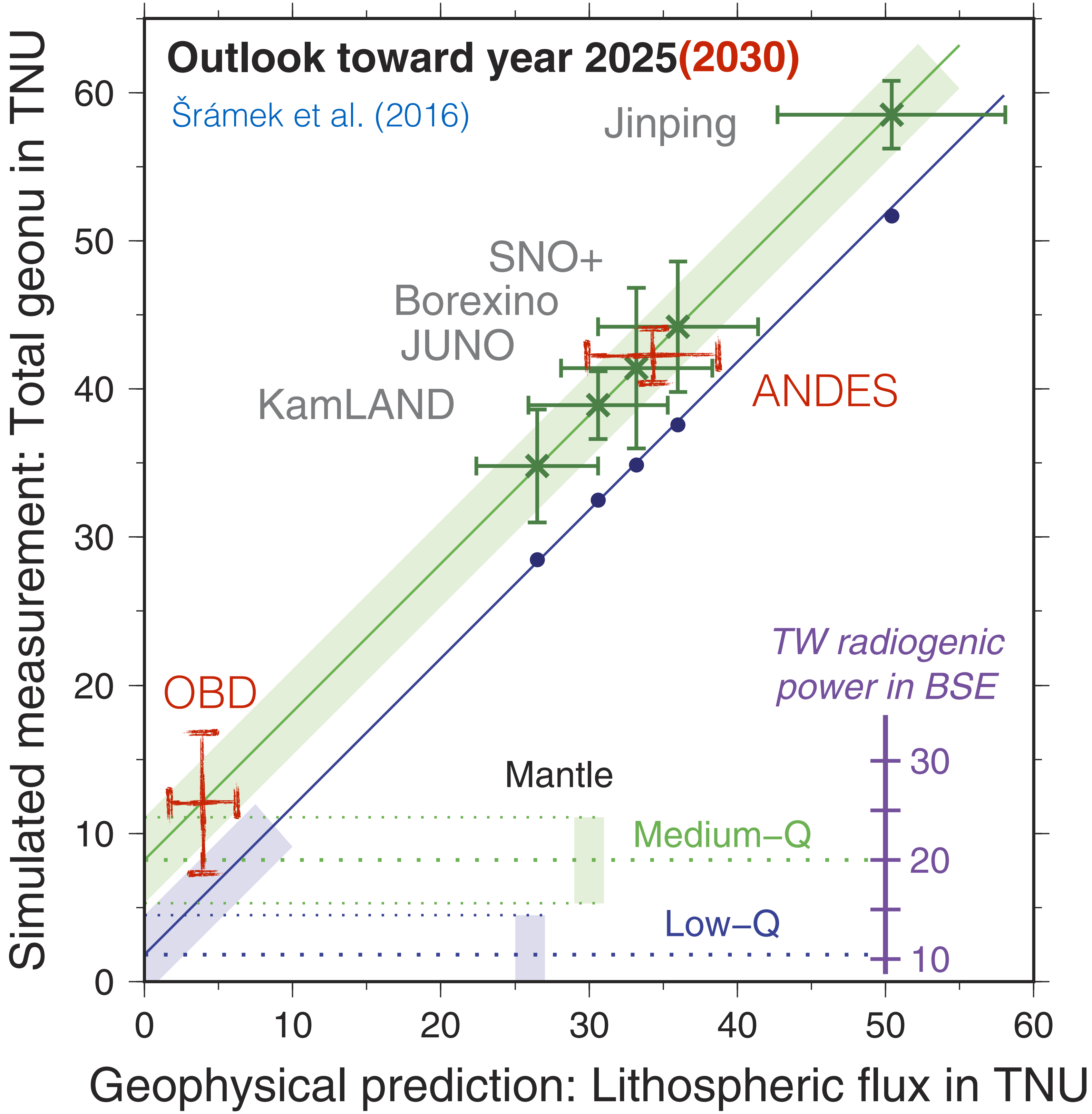
Combination of prediction
and measurements:
Mantle heat production

Constraining Mantle with Several Measurements



Comparison with LowQ/MiddleQ/High! models

Including Future Measurements



Summary of ANDES 3 kt LS Detector

- Geoneutrino physics:
  - ANDES the third deepest underground laboratory - Low muon flux
  - The lowest reactor background among continental experiments
  - Measurement in the location with one of the thickest crust (D>60 km)
  - The only detector in a convergent margin tectonic setting, where oceanic plate is subducted beneath continental crust
  - First deep underground laboratory in southern hemisphere
  - Potentially the most precise geo-ν measurement
- Propaganda:
  - Opportunity for physicists from Latin America
  - Investment to the future - LS detectors has demonstrated long lifetime full of interesting results: KamLAND (since 2002), SNO (since 1999), SuperKamiokande (since1996)