Reactor Neutrino experiments

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JINR

Top discoveries with reactor experiments

- Discovery of anti-neutrino (1956) Reines & Cowan
- Discovery of neutrino oscillation due to Δm^2_{12}
- Discovery of geo-neutrino

KamLAND

- Discovery of neutrino oscillation due to Δm^2_{31} and measurement of θ_{13}

Daya Bay

Preparing for next breakthrough

Neutrino mass ordering	JUNO
Lepton mixing parameters with precision of quark sector	JUNO & Daya Bay
Precision coherent scattering	CONUS, RED-100, νGEN, TEXONO,...

Key facts

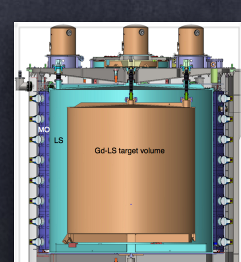
Energies of reactor $\overline{\nu}_e$ span in $\approx (1.8, 8)$ MeV for inverse beta decay (IBD) reaction

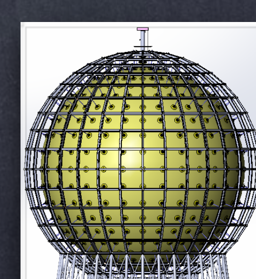
10^{-2} | 2 | 50 | L, km

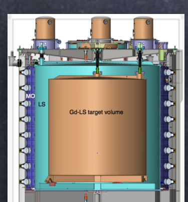
Sterile, Reactor flux

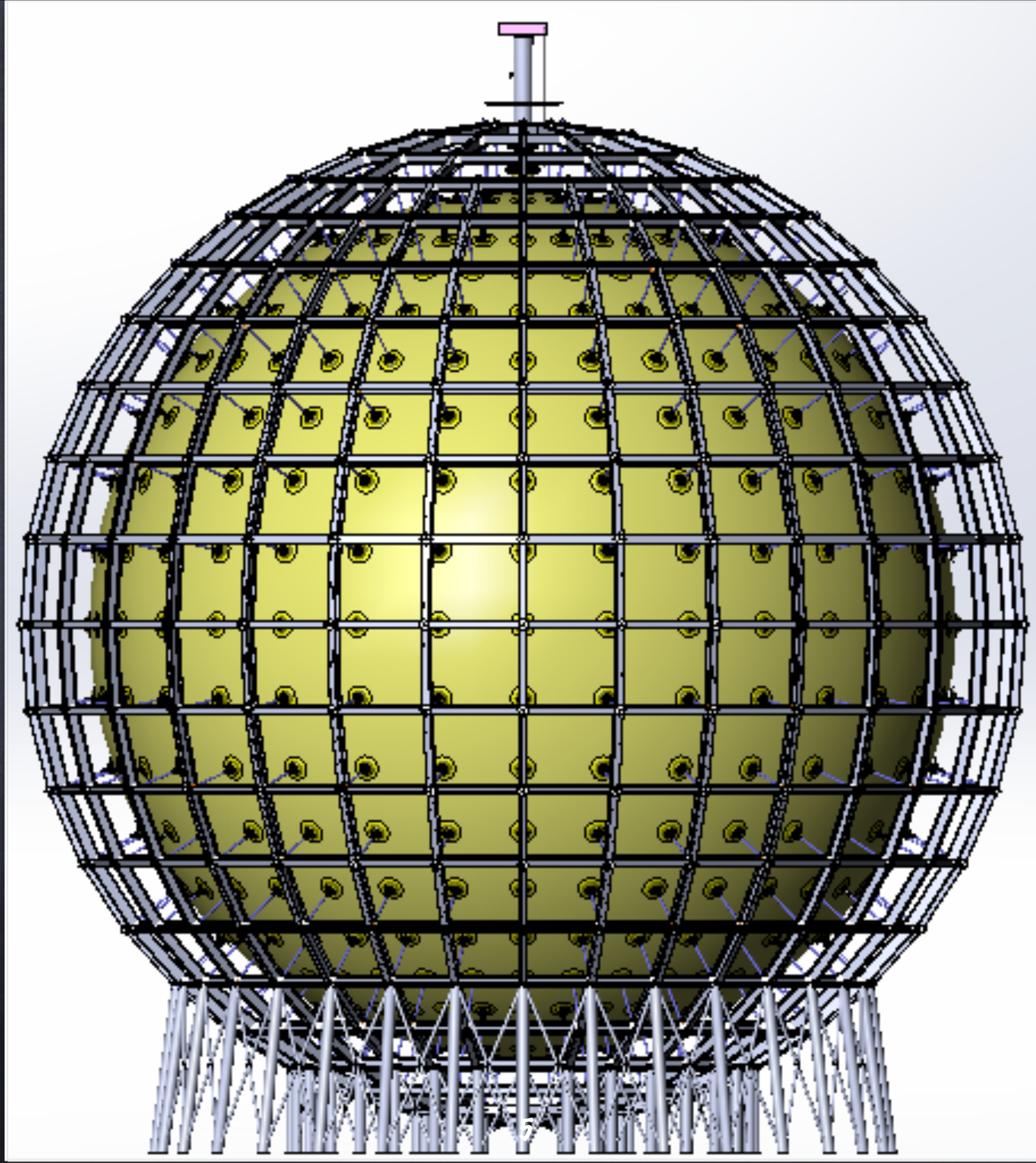
$\Delta m^2_{31}, \theta_{13}$

$\Delta m^2_{21}, \Delta m^2_{31}, \Delta m^2_{32}, \theta_{13}, \theta_{21}$

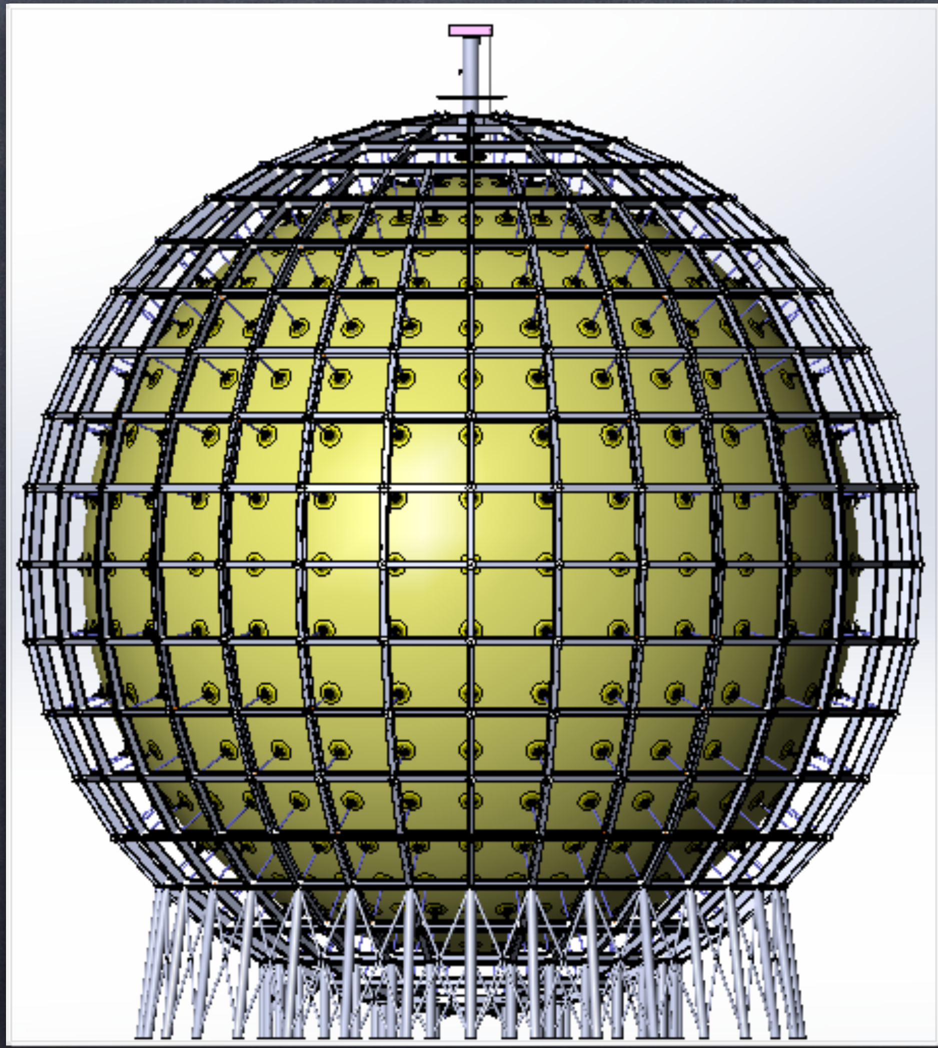
20 tons 

 20 000 tons



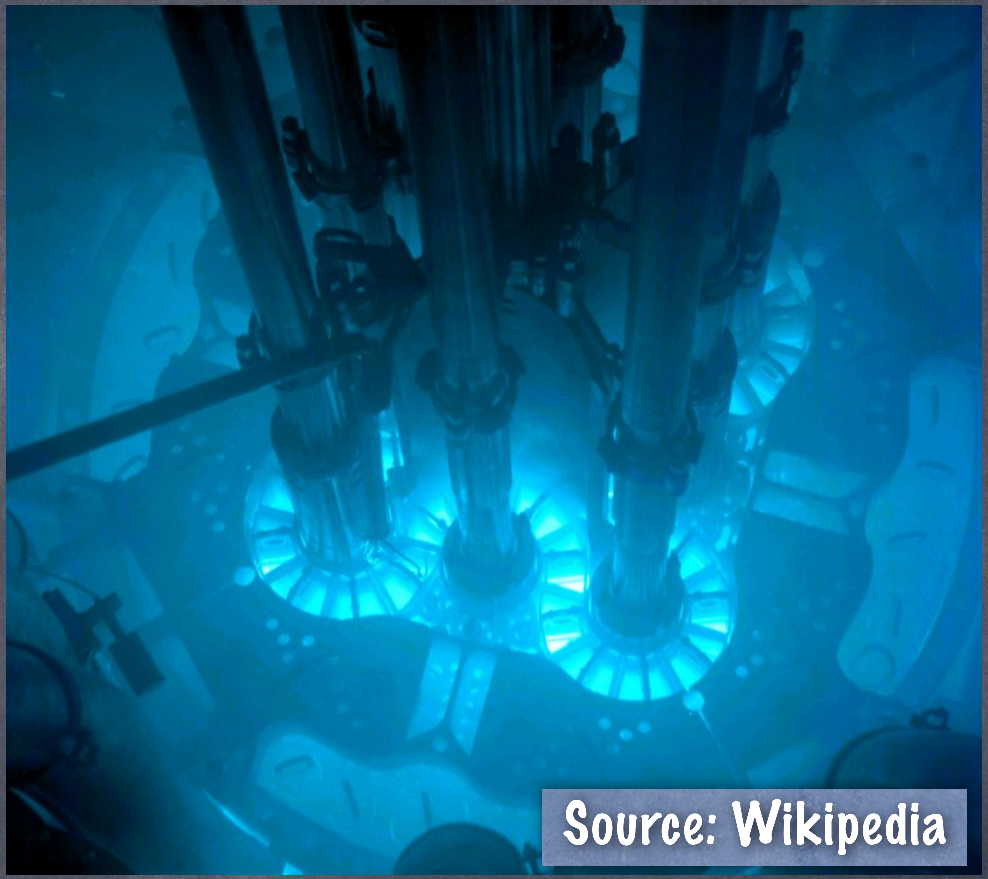


- Building up so huge detector is anyway expensive
- Therefore, the detector will be unique with a great performance
- Thus, it opens up a huge physics program beyond the main goal

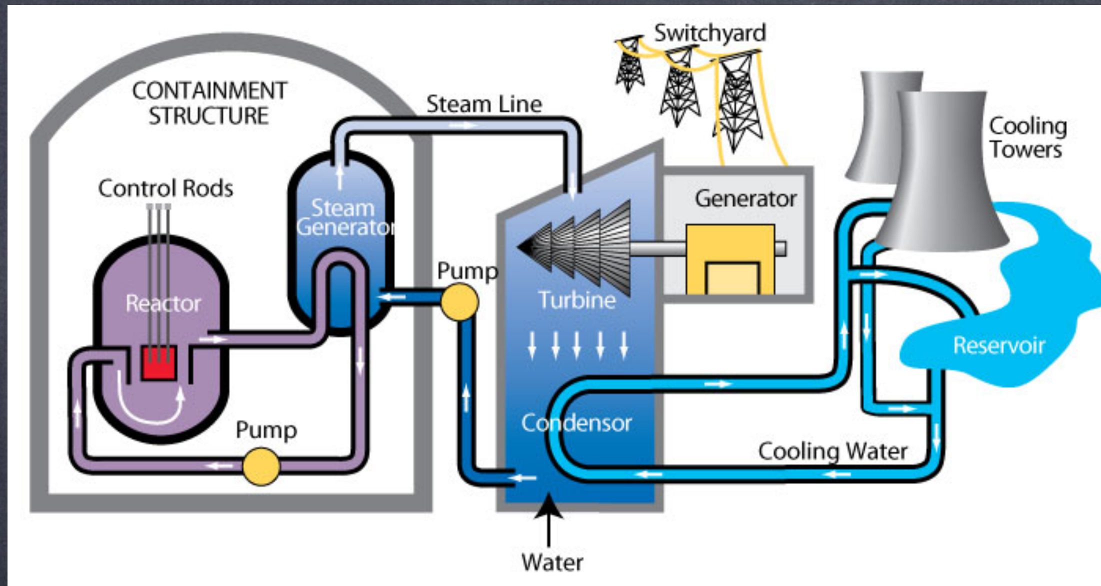


Nuclear Reactor. Basics

* Refer to A.Hayes lecture for more details



- Nuclear plant gets its energy via fissions of U and Pu isotopes
- About 11% of world energy is produced in reactors
- 437 nuclear power plants operating in 31 countries
- 200 MeV/fission, β decays and six $\overline{\nu}_e$



Source: Wikipedia

Source: wano.info

Source: Wikipedia

- Nuclear plant gets its energy via fissions of U and Pu isotopes
- About 11% of world energy is produced in reactors
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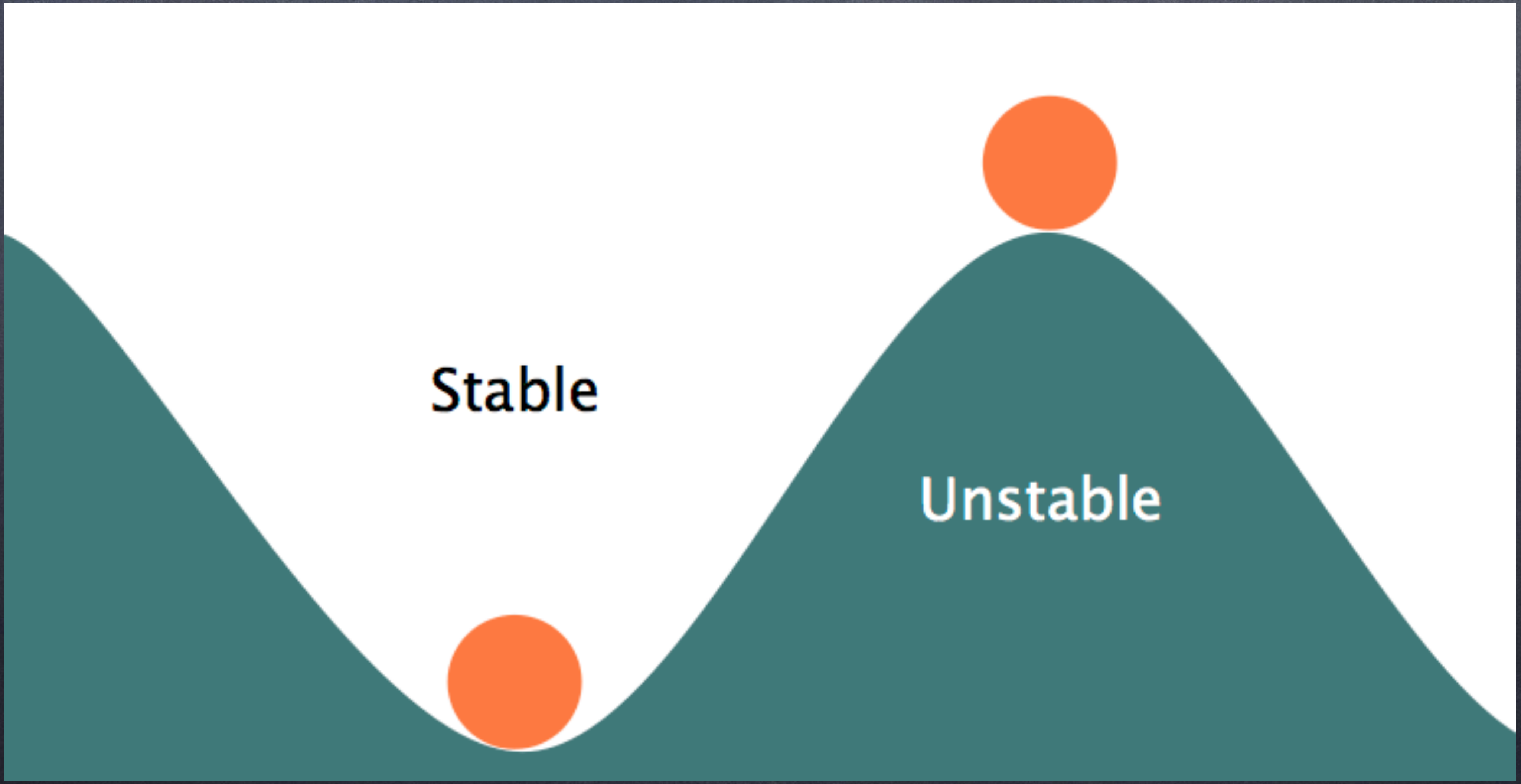
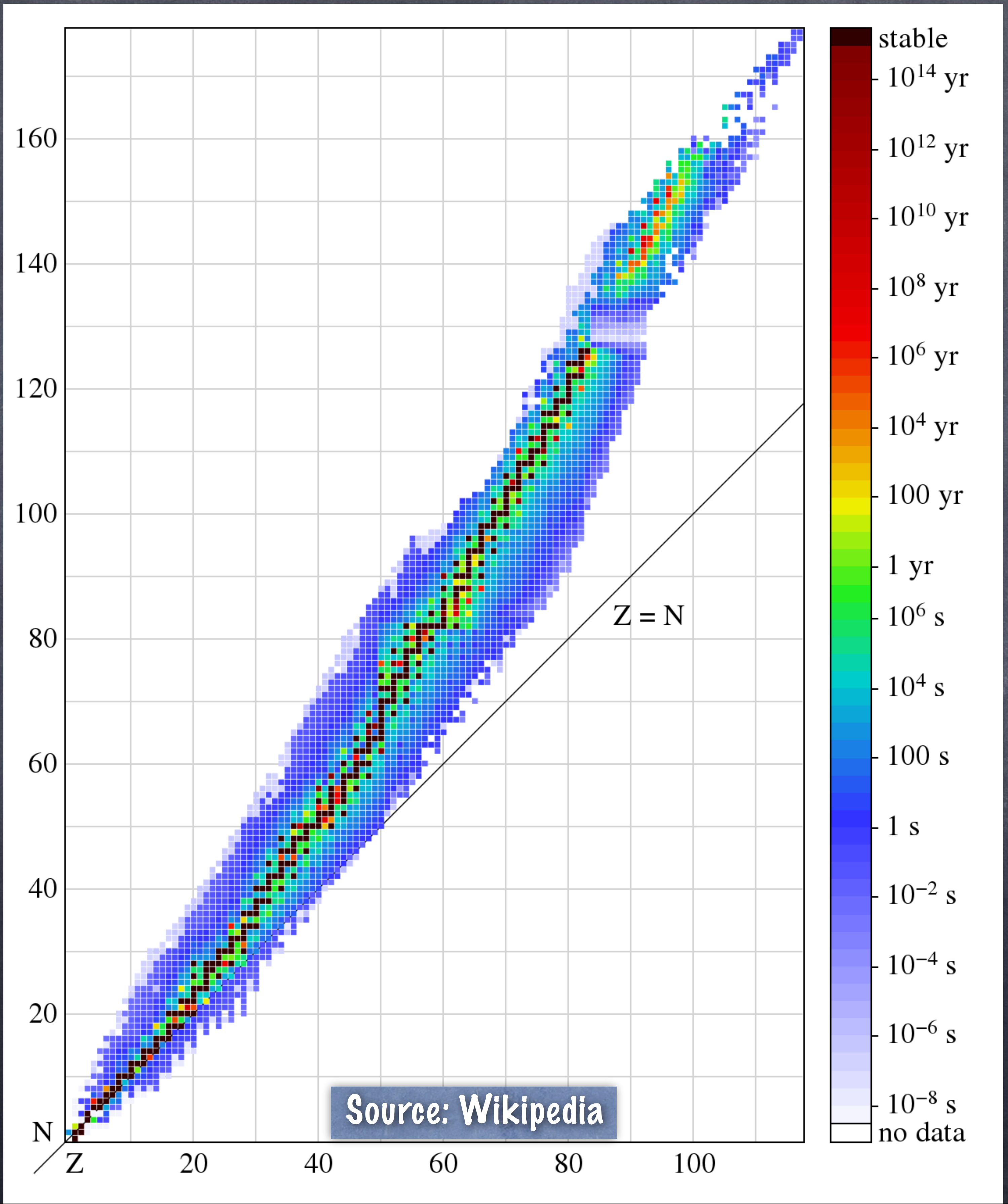
- 200 MeV/fission, β decays and six $\overline{\nu}_e$
- 3 GW reactor emits about $6 \cdot 10^{20}\ \overline{\nu}/s$

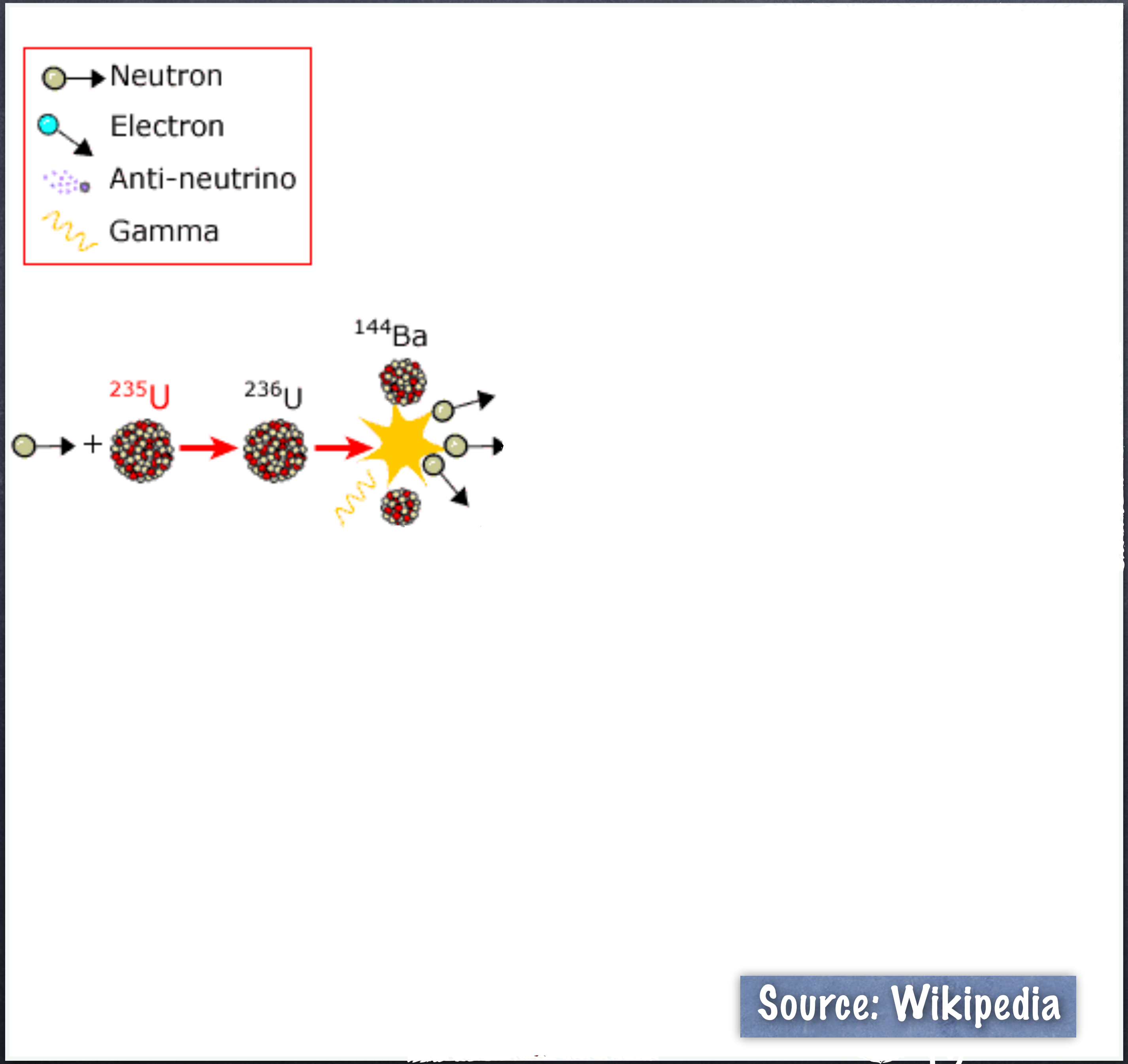
Stability and instability Of nuclei

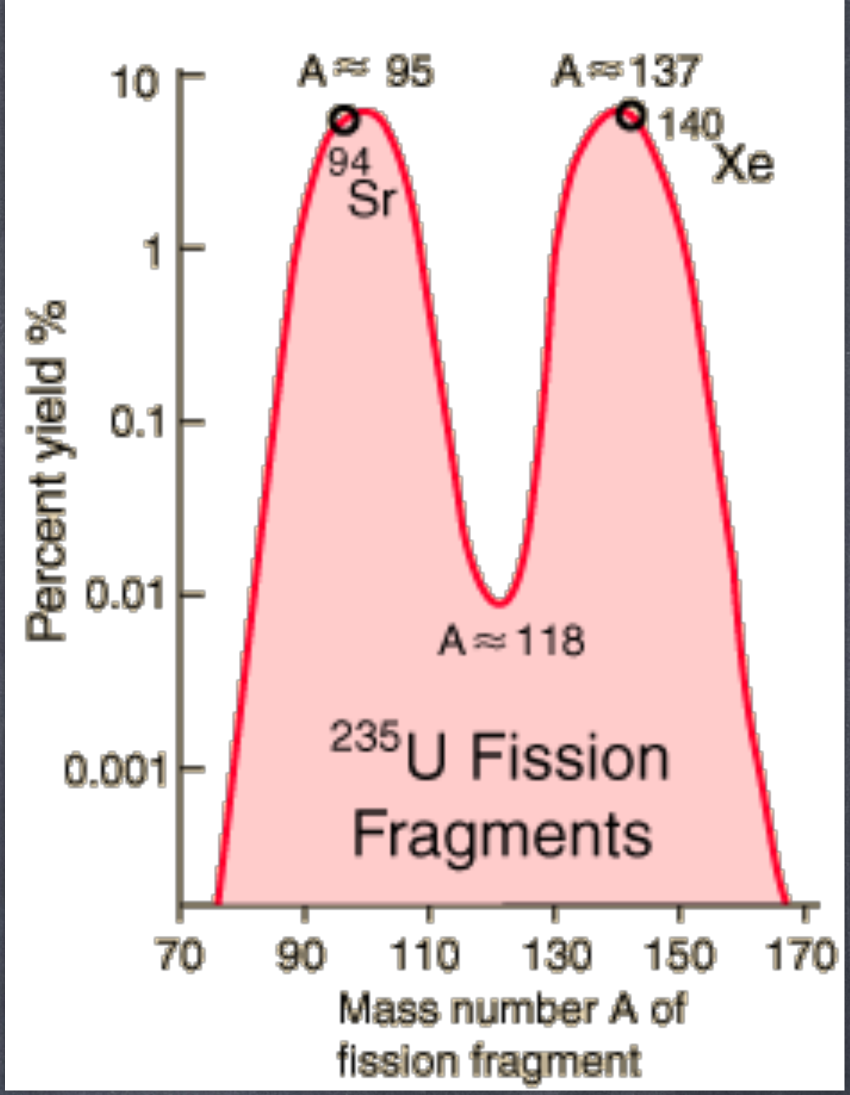


Isotopes off the stability valley are unstable



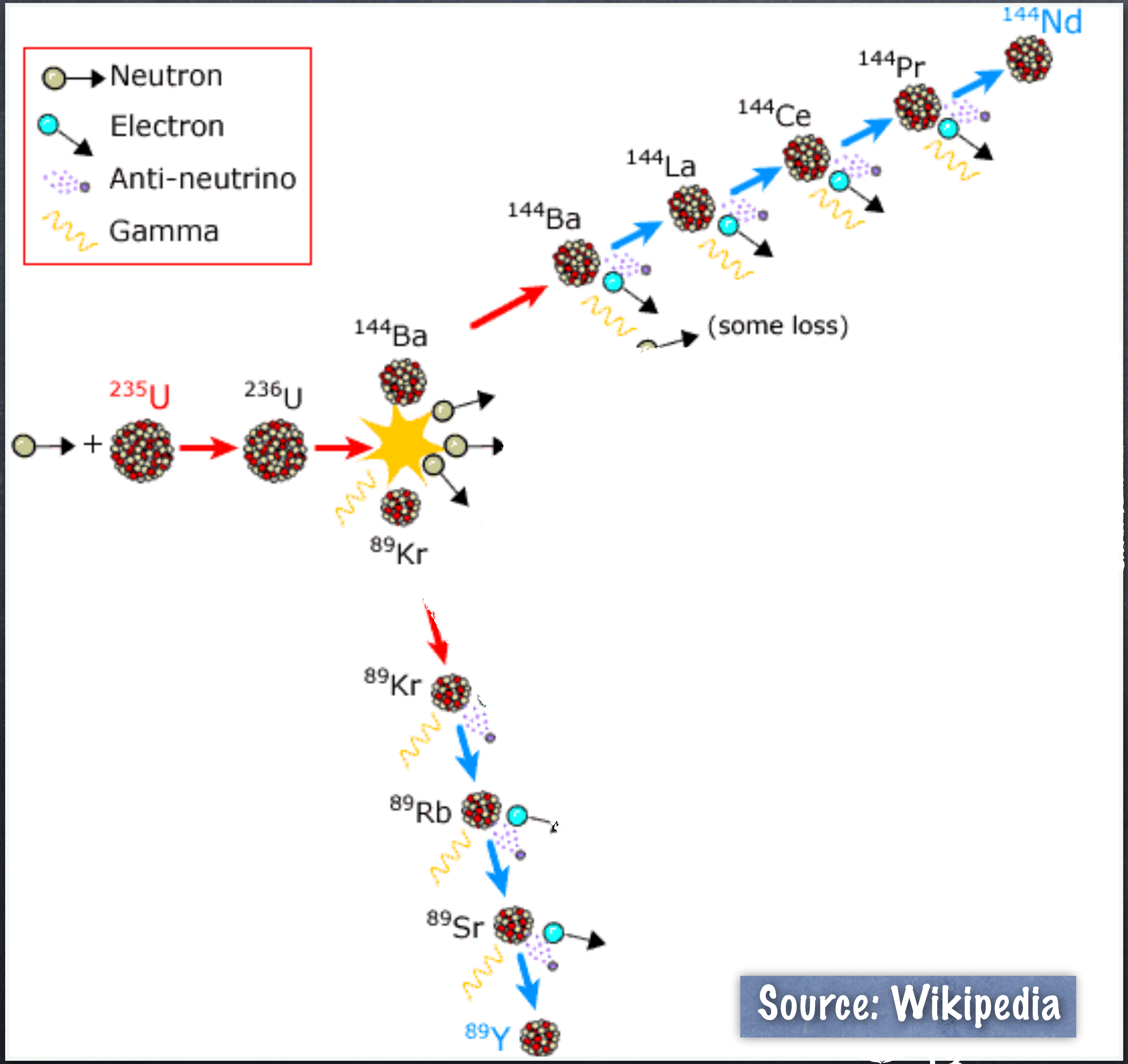
Chain reaction with ^{235}U

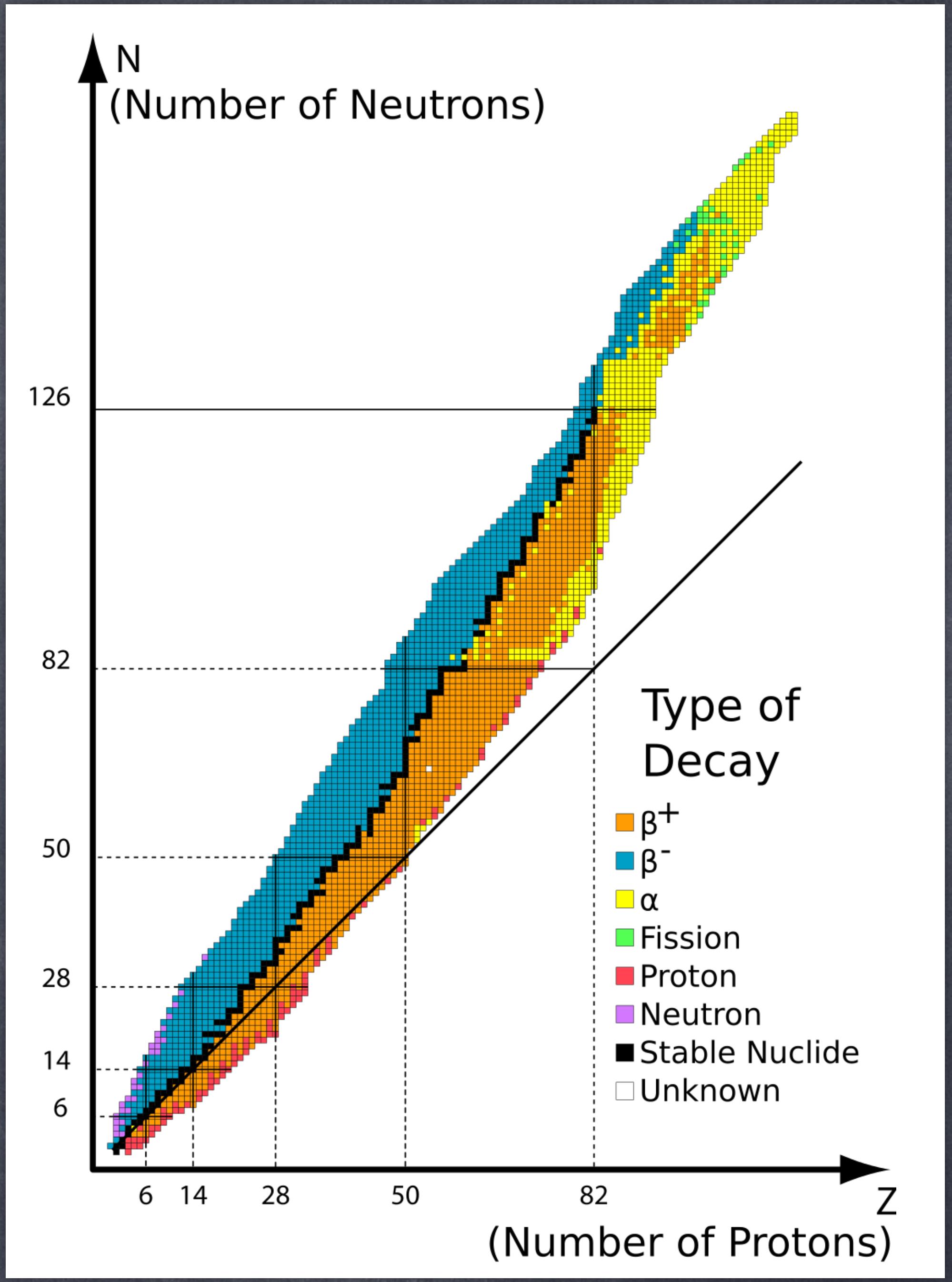




- Fissions are asymmetric

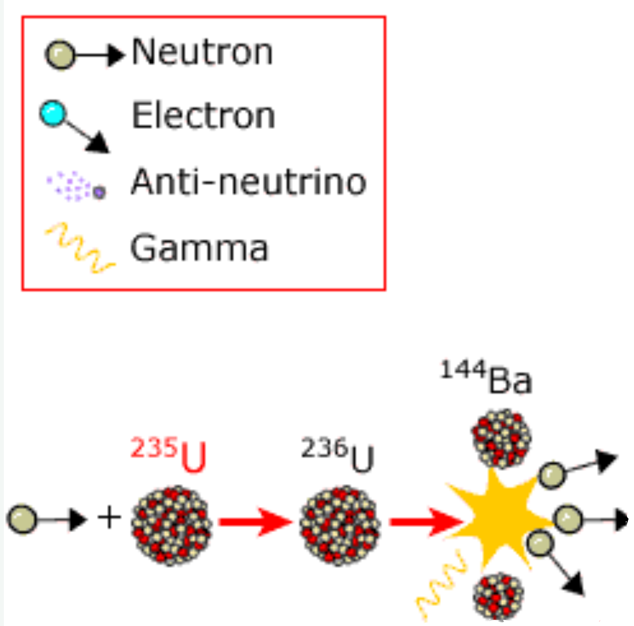
- Chain reaction with ^{235}U
- Neutron-rich isotopes β-decay

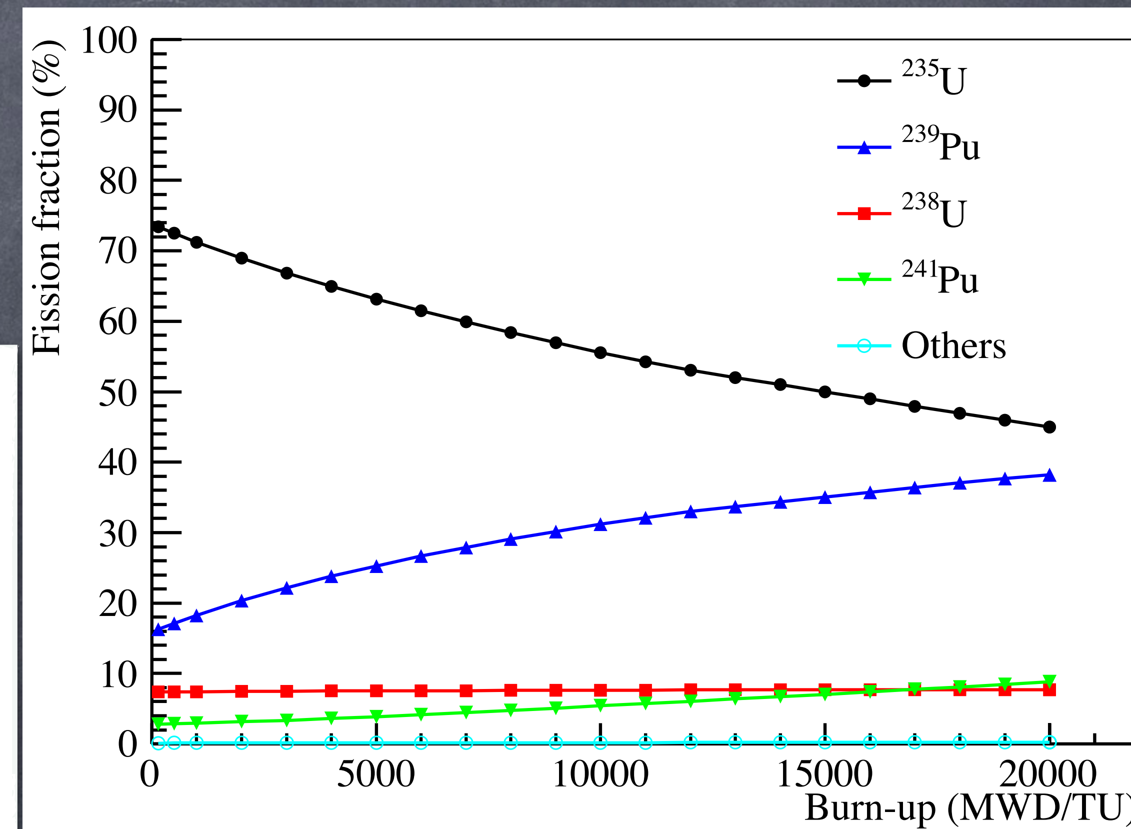




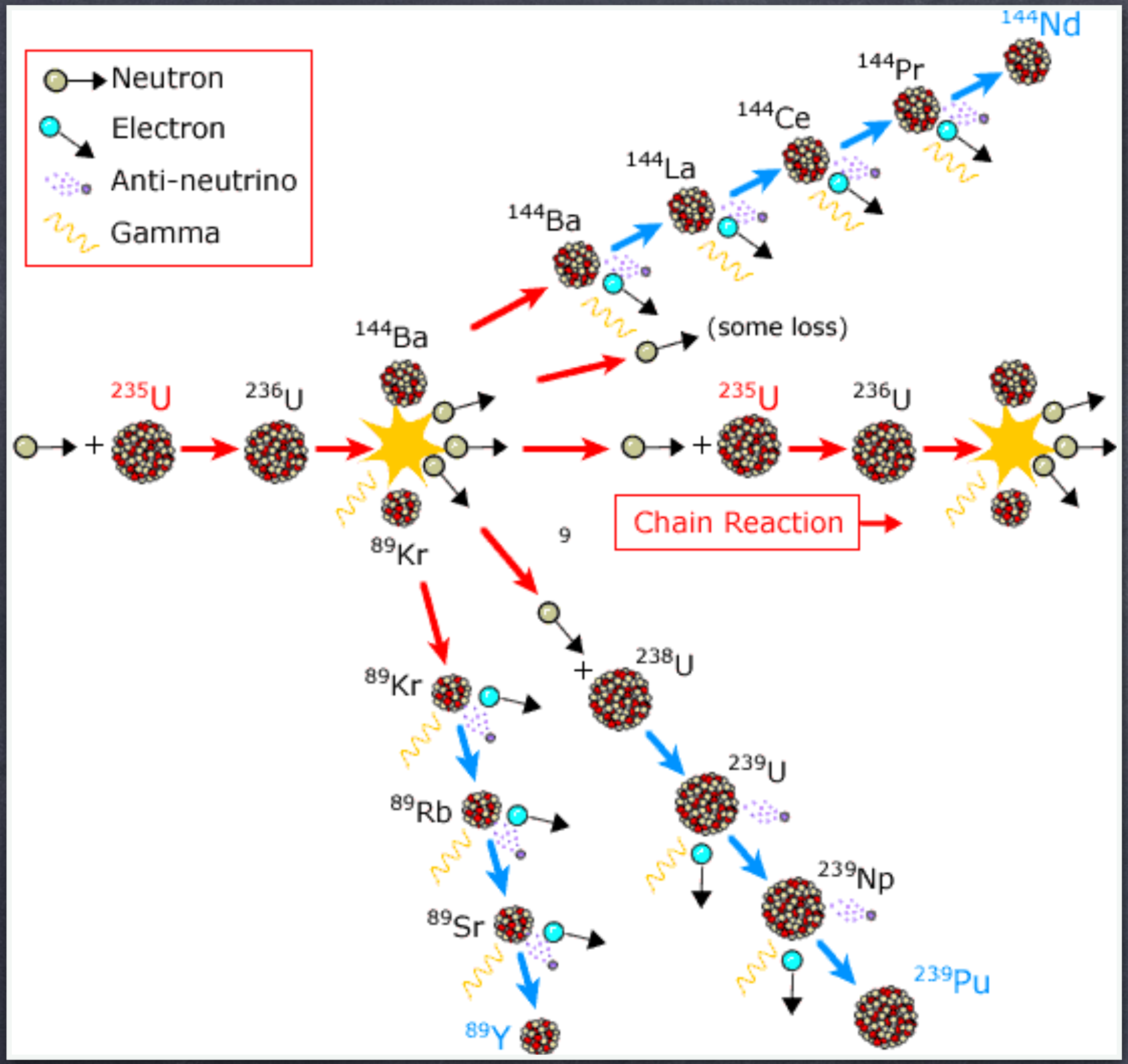
$$^{A}_{Z}\mathbf{X} \rightarrow {}^{A}_{Z+1}\mathbf{X'} + e^{-} + \overline{\nu}_e$$

- Chain reaction with ^{235}U
- Neutron-rich isotopes β-decay
- $\sim 6\,\overline{\nu}_e$ per fission

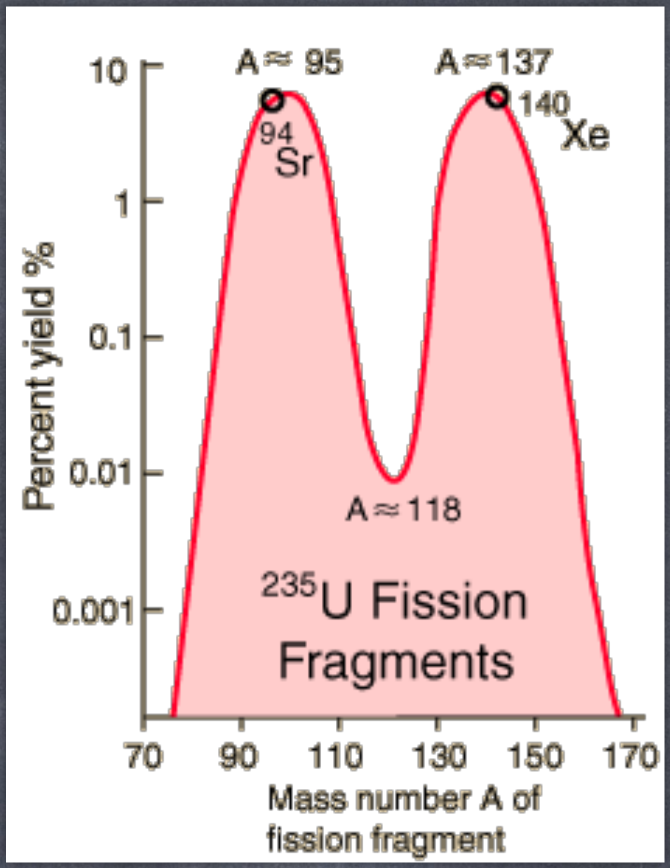




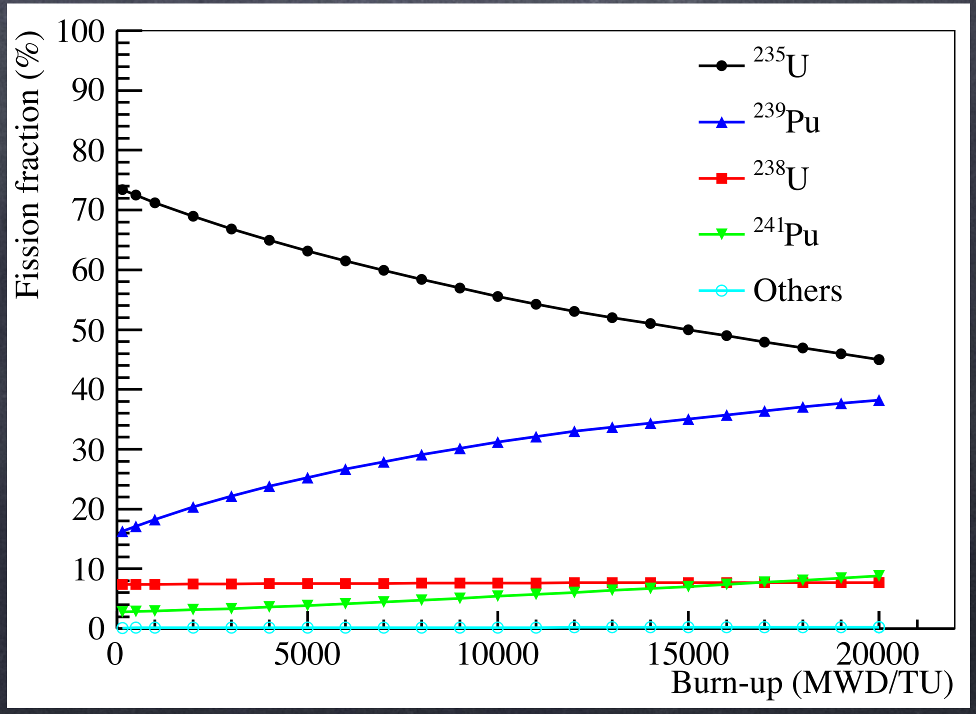
- ^{239}Pu production



- Chain reaction with ^{235}U



- Neutron-rich isotopes β-decay $\quad {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{X'} + e^{-} + \bar{\nu}_e$
- $\sim 6\,\bar{\nu}_e$ per fission
- ^{239}Pu production



Can we understand ≈ 6 antineutrinos per fission?

$m_A = m_N N + m_p Z - E_B$ <— Mass of a nucleus

Semi-empirical mass formula (Bethe-Weizcacker)

$$E_B = \underbrace{a_V A}_{volume} - \underbrace{a_S A^{2/3}}_{surface} - \boxed{\underbrace{a_C \frac{Z^2}{A^{1/3}}}_{Coulomb}} - \boxed{\underbrace{a_A \frac{(A-2Z)^2}{A}}_{asymmetry}} \underbrace{\pm \delta(A,Z)}_{pairing}$$

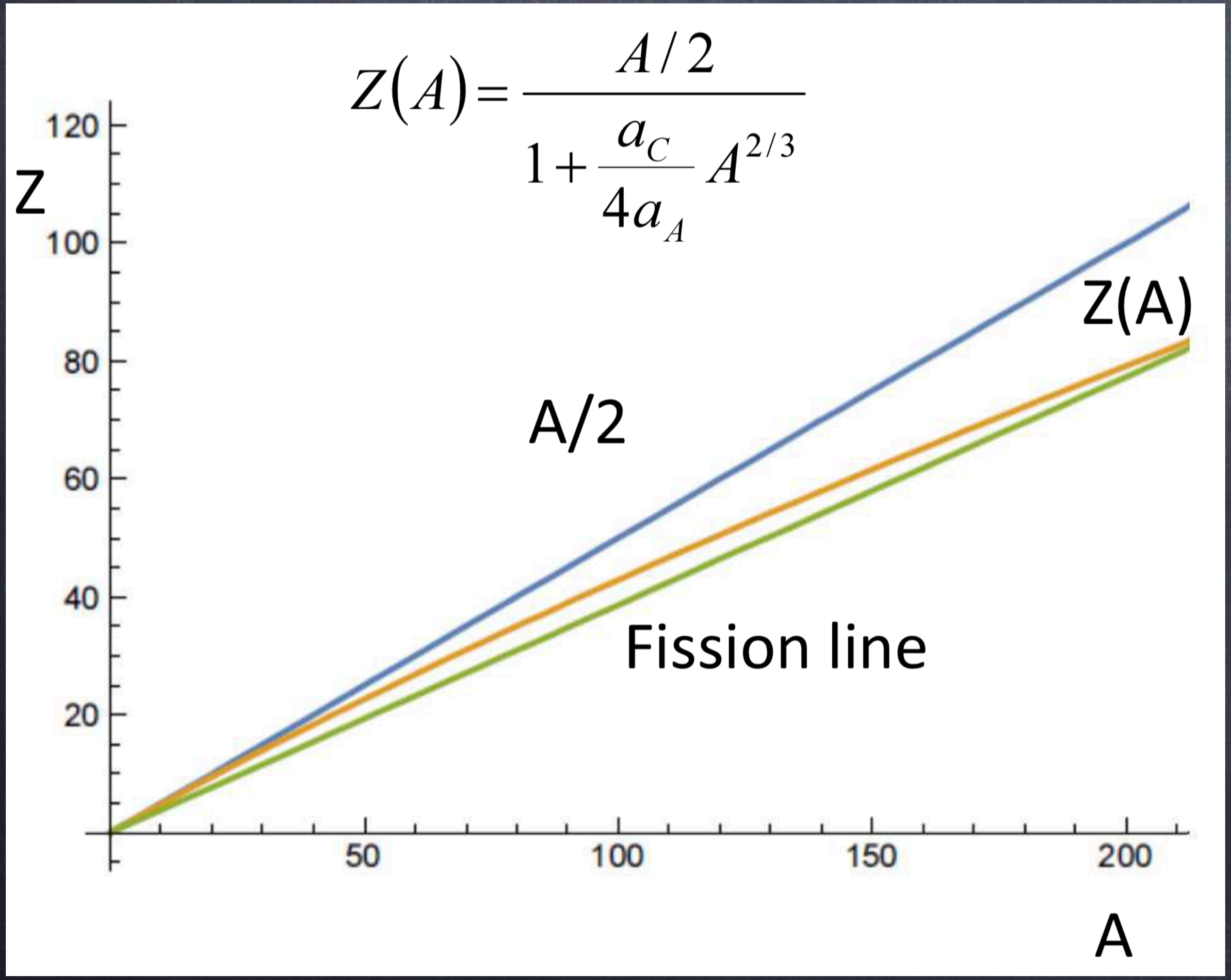
E_B increases if

$Z \to 0$ assuming $a_A = 0$

$Z \to N$ assuming $a_C = 0$

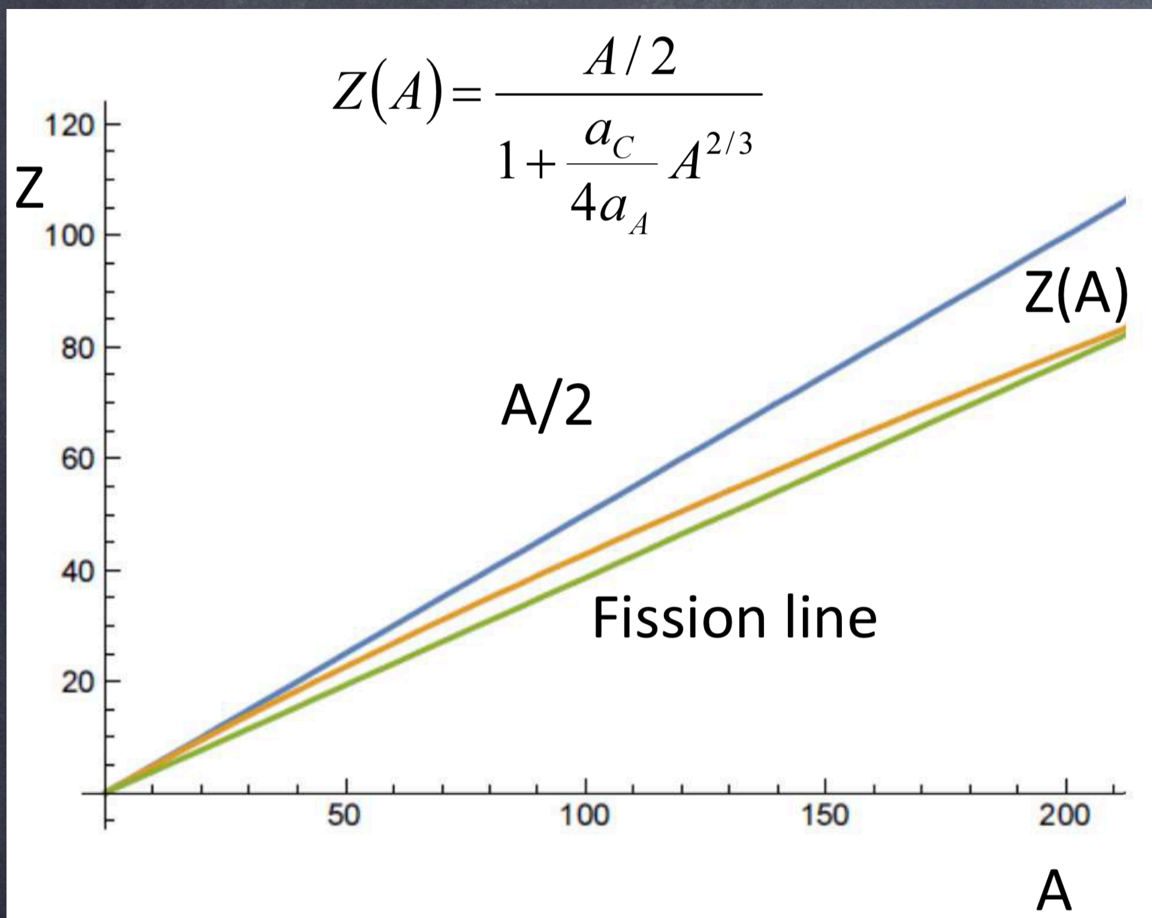
Can we understand ≈ 6 antineutrinos per fission?

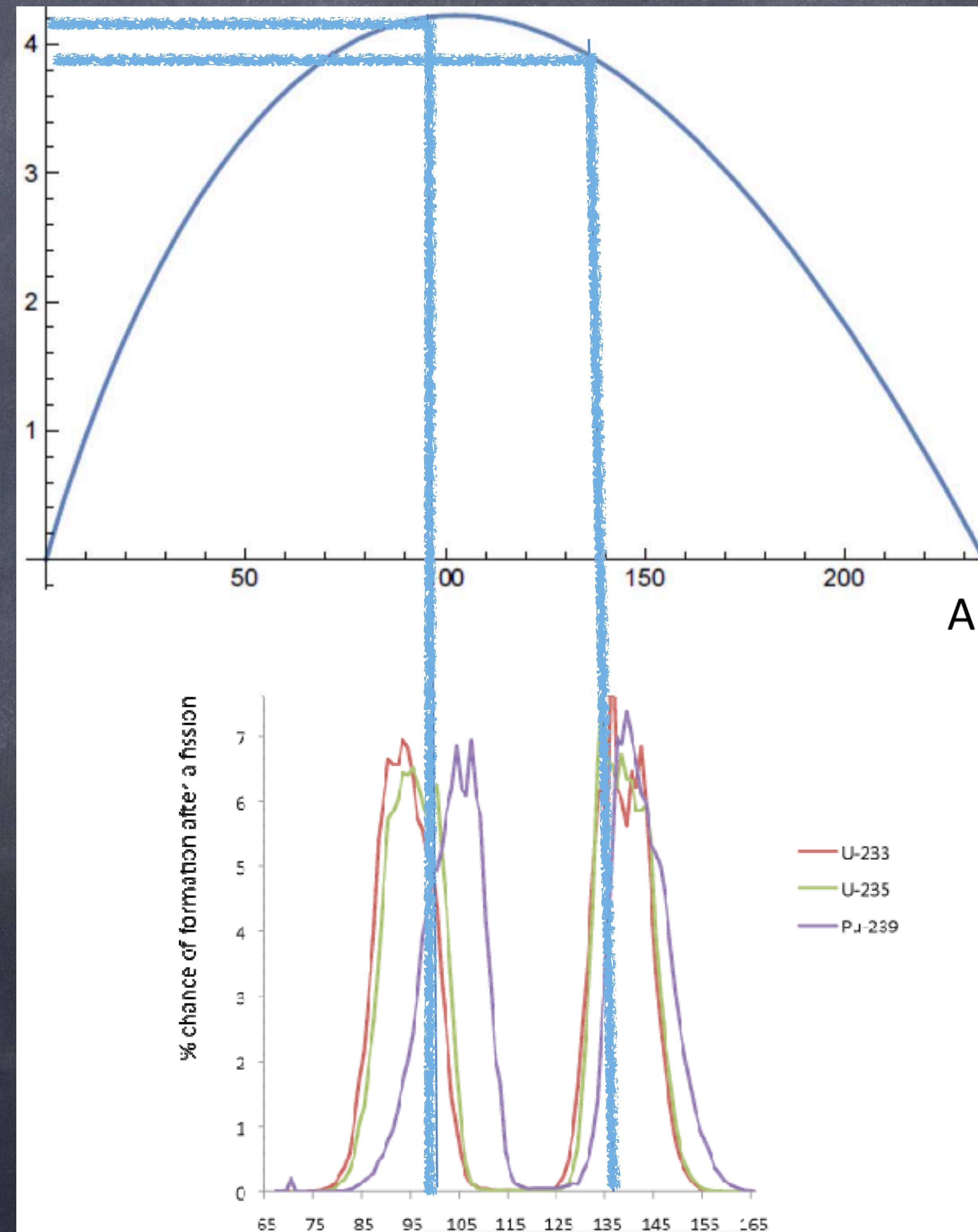
$$\frac{\partial}{\partial Z}\left(\underbrace{a_C\frac{Z^2}{A^{1/3}}}_{Coulomb}+\underbrace{a_A\frac{(A-2Z)^2}{A}}_{asymmetry}\right)=0 \quad \longrightarrow \quad Z(A)=\frac{A/2}{1+\frac{a_C}{4a_A}A^{2/3}}$$



- $Z(A)$ corresponds to most stable nucleus
- Fissions produce nuclei with (A,Z) following a «line»

Can we understand ≈ 6 antineutrinos per fission?

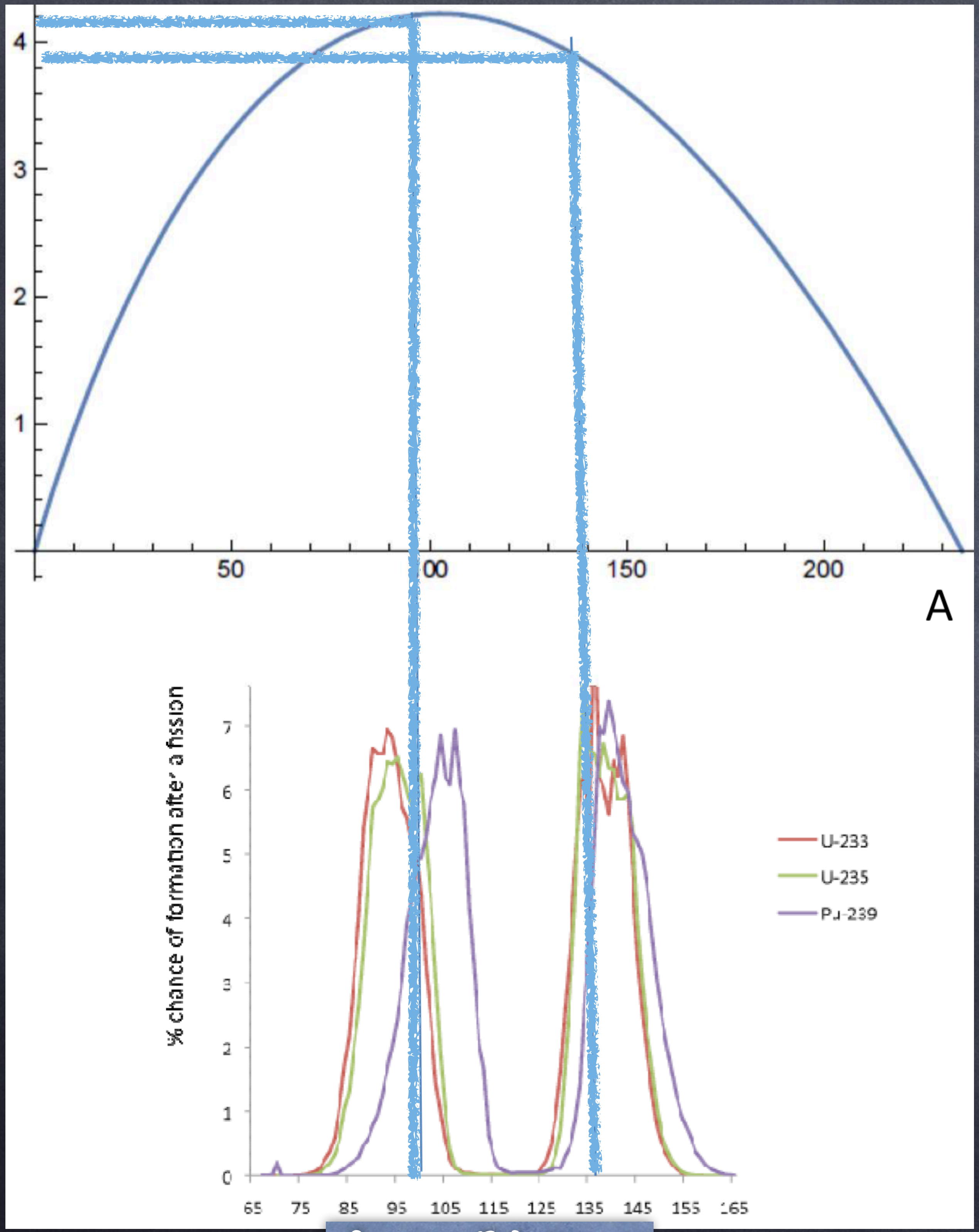




- $Z(A) -$ Fission line = number of β decays to reach the valley of stability

Source: R.Leitner

Can we understand ≈ 6 antineutrinos per fission?

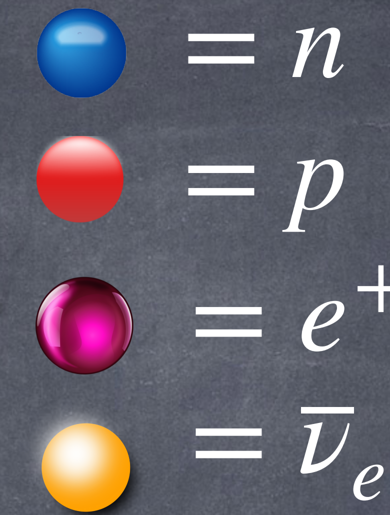


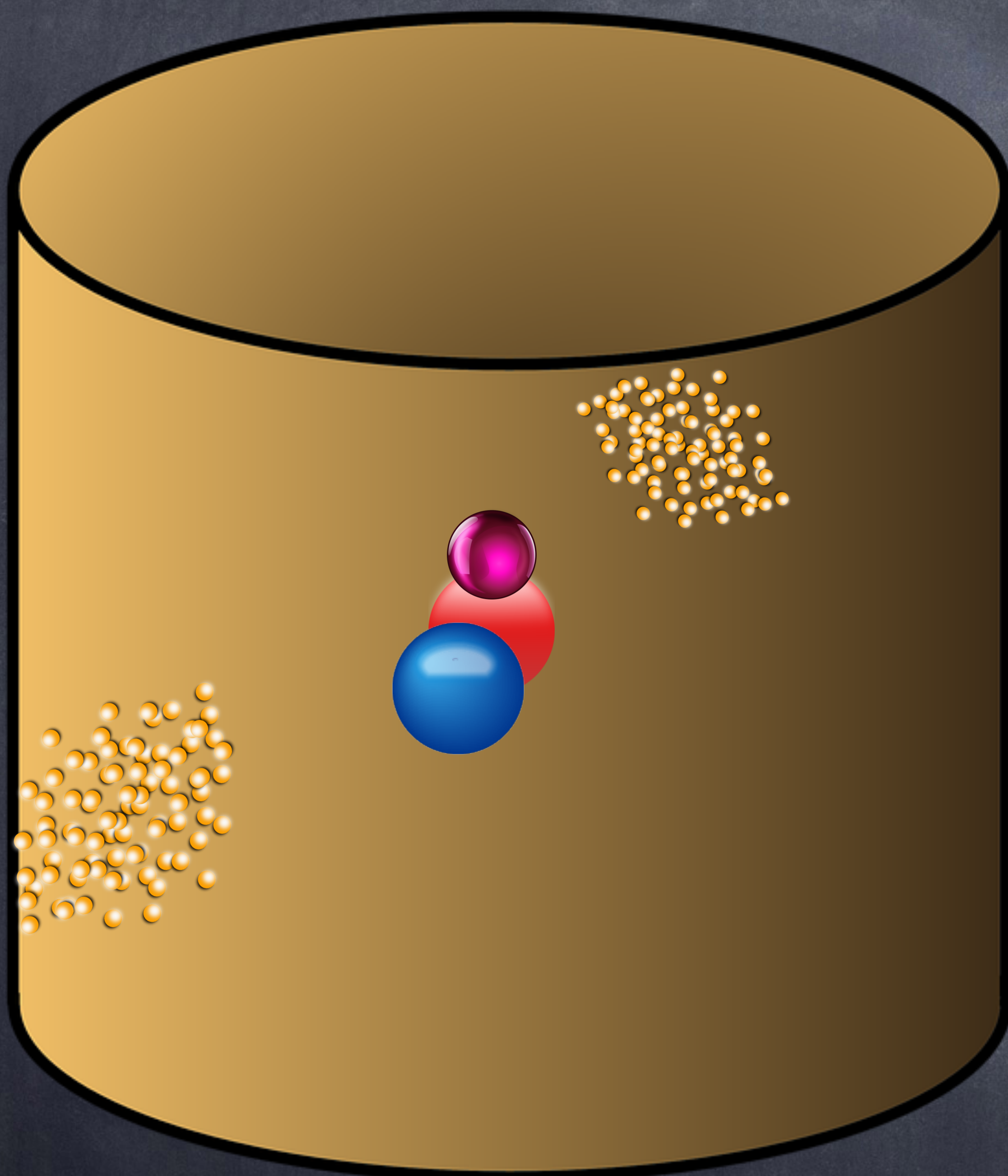
Source: R.Leitner

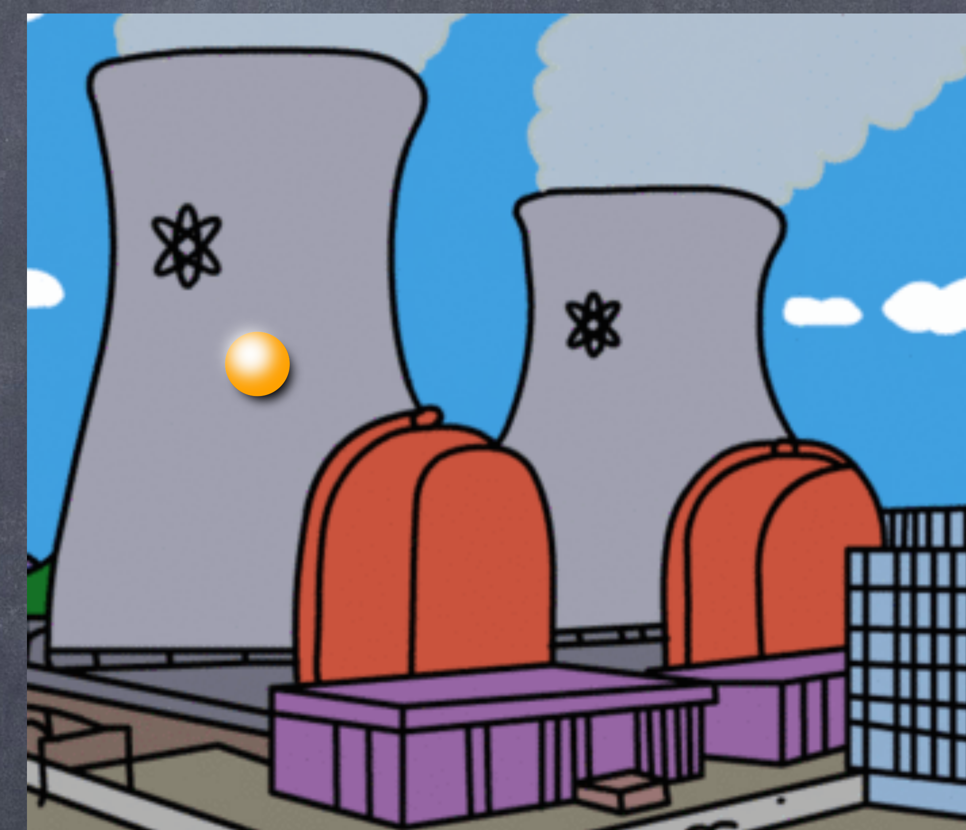
- Number of β decays $\approx 4.2 + 3.8 = 8$

Detection Method

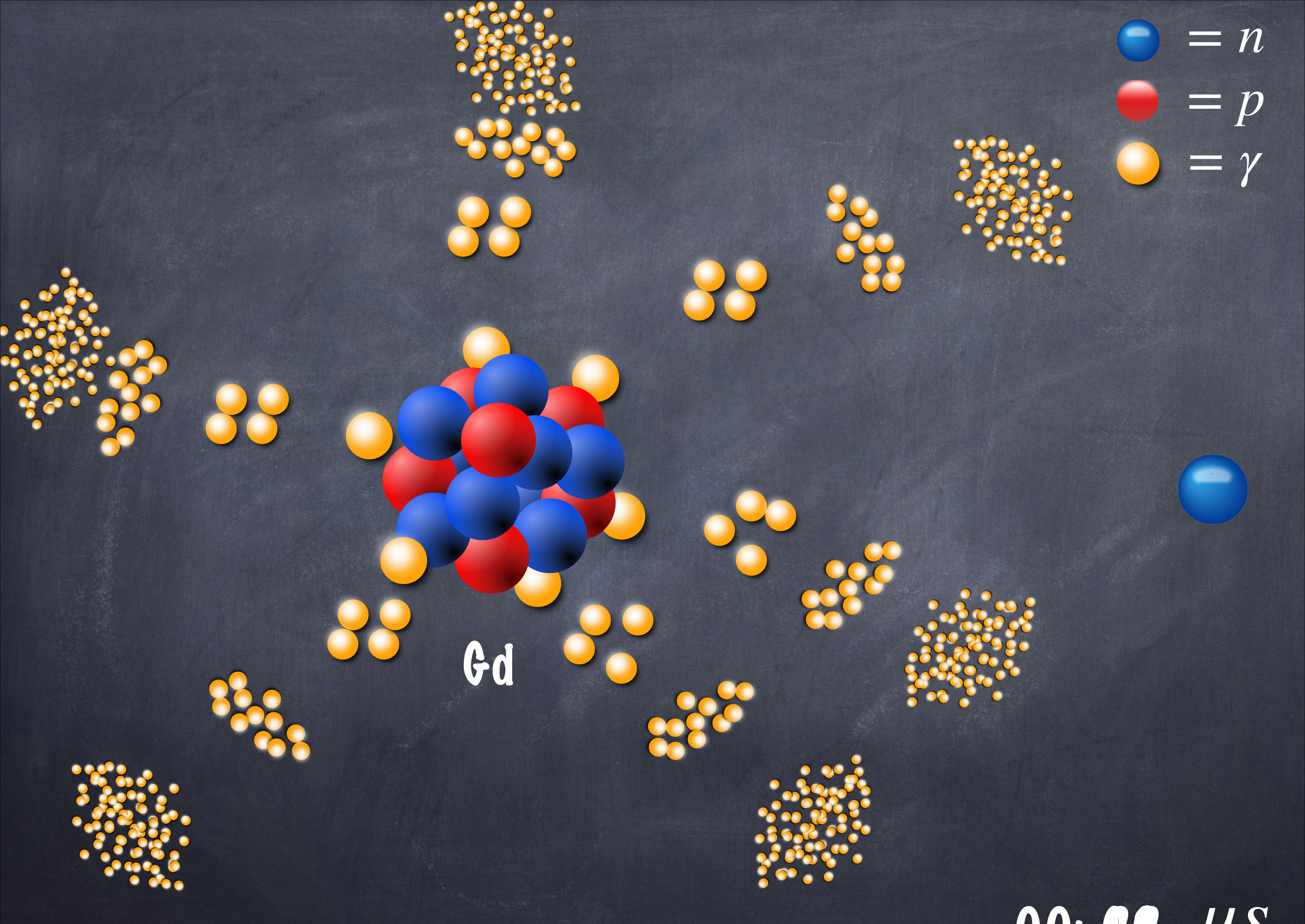
$$\overline{\nu}_e + p \rightarrow e^+ + n$$







00: [illegible] μs


$= n$
$= p$
$= \gamma$
Gd
00:
μs

Why Gd?
Can we understand $28\mu s$ @Daya Bay?

${}^{A}_{64}$Gd	$\sigma(n + {}^{A}_{64}\text{Gd} \to {}^{A+1}_{64}\text{Gd})$, [b]	Abundance, %
$A = 154$	85	2.18
$A = 155$	60900	14.80
$A = 156$	1.8	20.47
$A = 157$	254000	15.65
$A = 158$	2.2	24.84
$A = 160$	1.4	21.86

Can we understand 28μs @Daya Bay?

$$v_n = \sqrt{\frac{2kT}{m_n}} \approx 2.2\ km/s$$

$$\tau = \frac{1}{v_n \langle\sigma\rangle N_{Gd}}$$

$$N_{Gd} = 0.103\% \cdot \rho \cdot \frac{N_A}{\langle A \rangle}$$

$$= 0.00103 \cdot 0.86 g/cm^3 \cdot 6.022 \cdot 10^{23} / 157.25 g/cm^3$$

$$= 3.39 \cdot 10^{18} g/cm^3$$

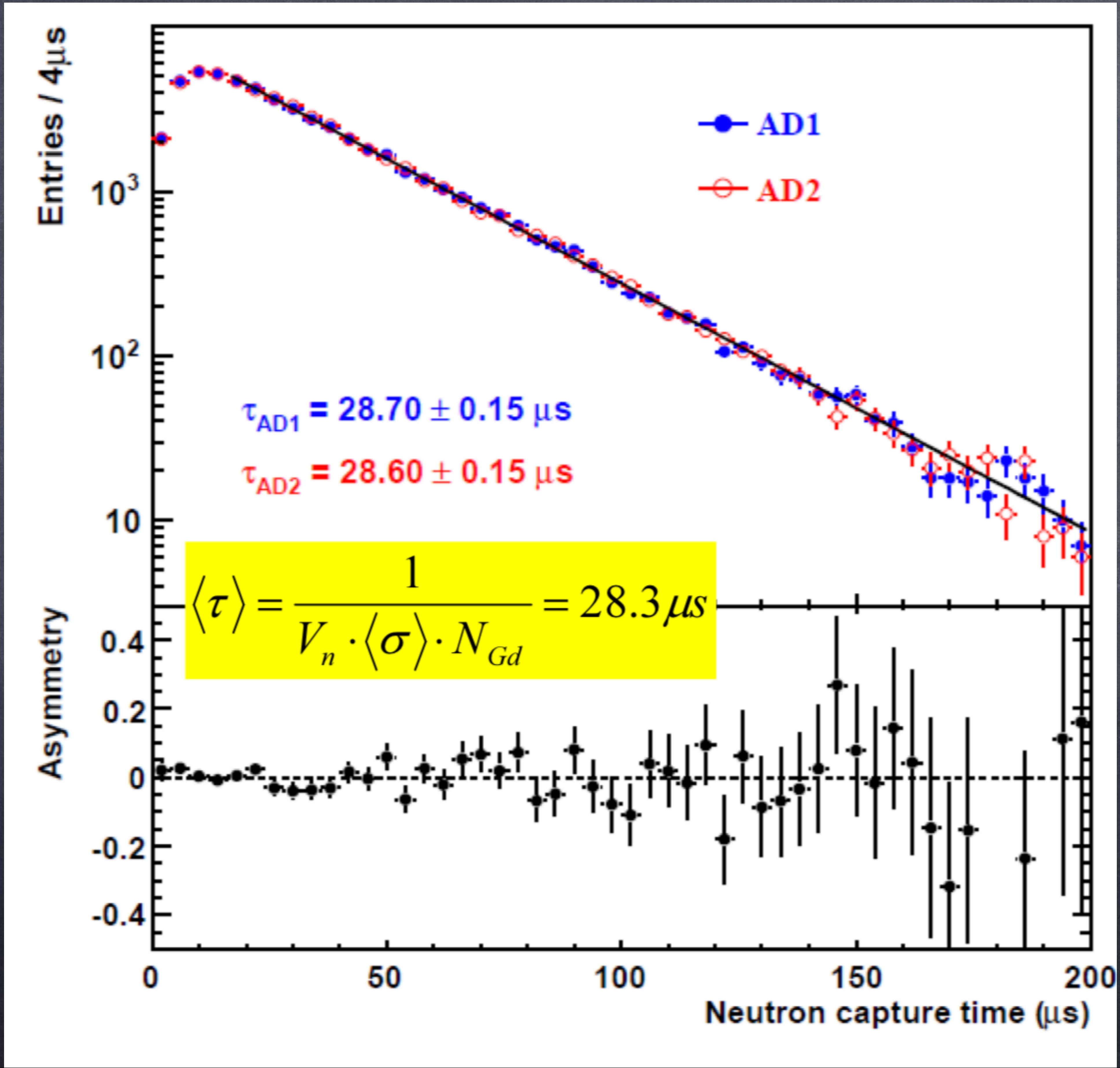
$$\langle\sigma\rangle = (0.148 \cdot 60900 + 0.1565 \cdot 254000) \cdot 10^{-24} cm^2$$

$$= 4.876 \cdot 10^{-22} cm^2$$

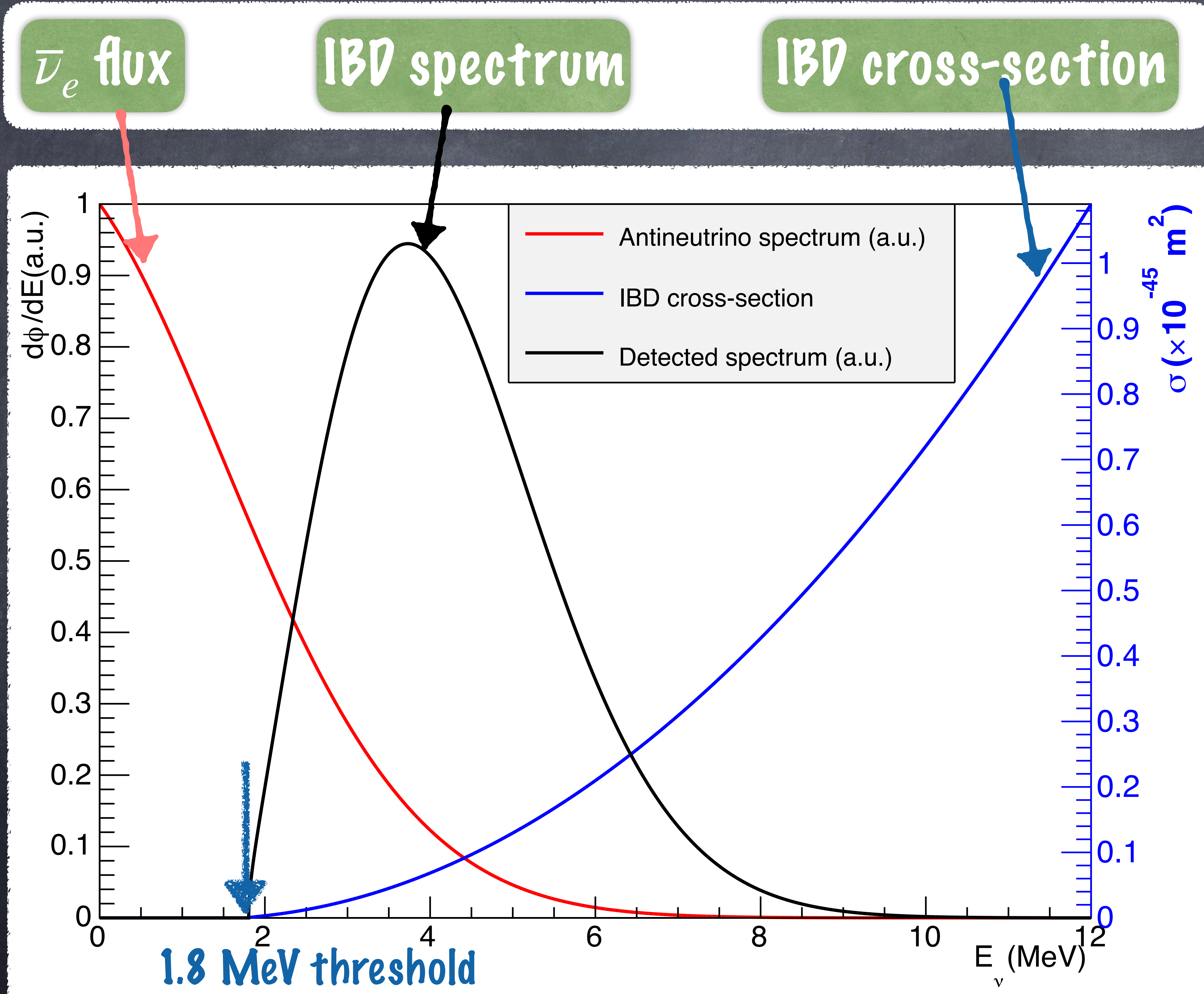
$$\boxed{\tau = \frac{1}{v_n \langle\sigma\rangle N_{Gd}} = 28.3\mu s}$$

Good agreement with observations

Neutron capture time @Daya Bay



IBD spectrum

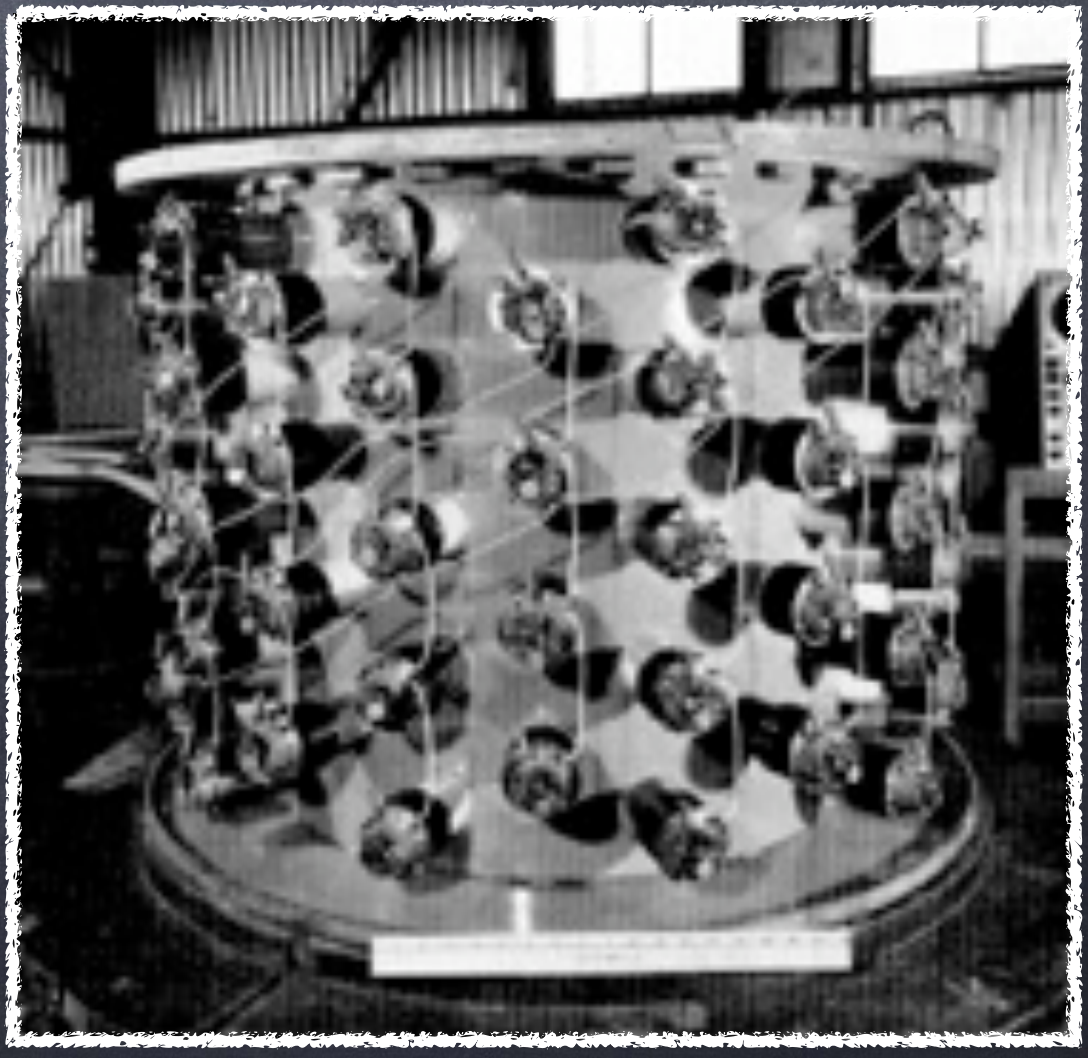


$\overline{\nu}_e$ flux
IBD spectrum
IBD cross-section
Antineutrino spectrum (a.u.)
IBD cross-section
Detected spectrum (a.u.)
dφ/dE(a.u.)
σ (×10^{-45} m^2)
E$_\nu$ (MeV)
1.8 MeV threshold

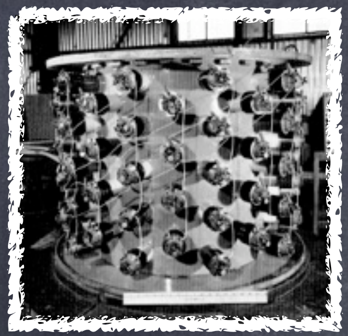
Short History
Of Reactor Neutrinos

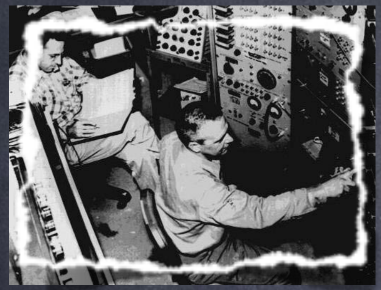
Reactor Neutrinos - Decades of Measurements

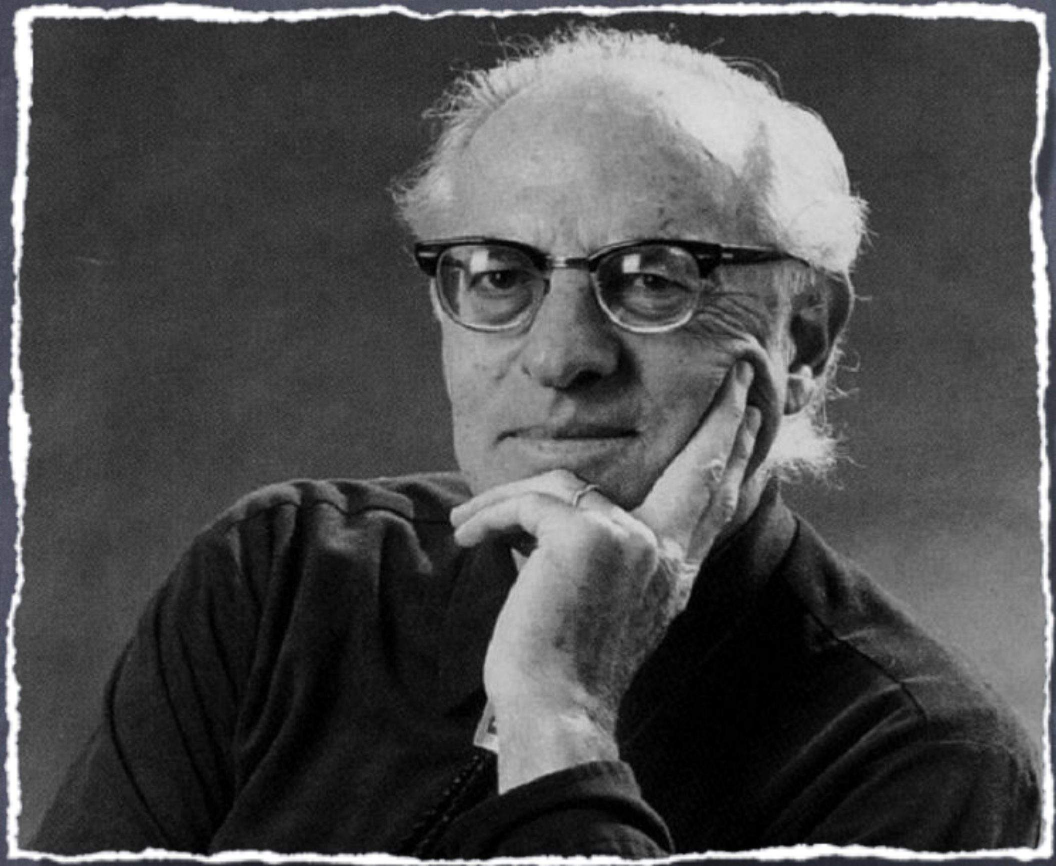
- F.Reines & C.Cowan. 1956 Discovery of $\overline{\nu}_e$
- The proposed detection method is now standard



Reactor Neutrinos - Decades of Measurements



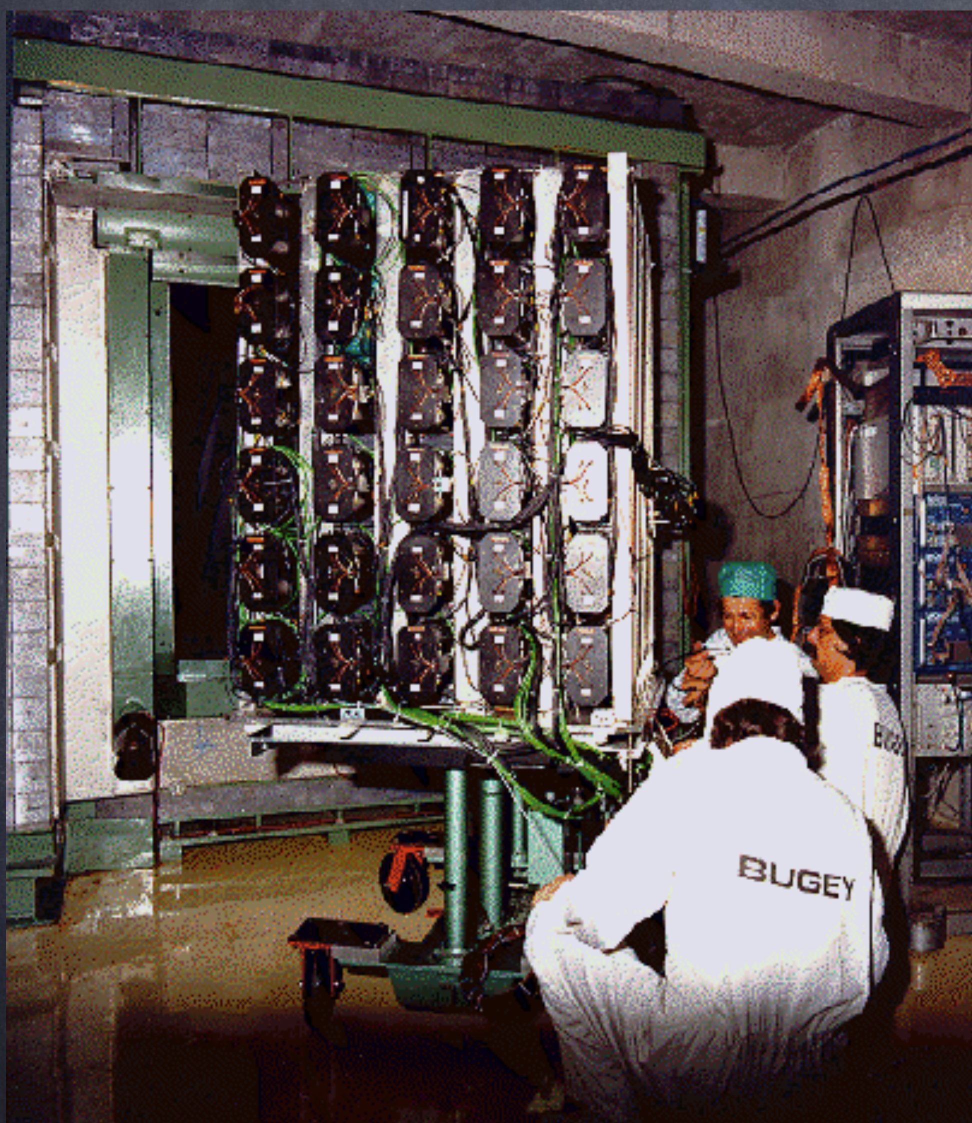


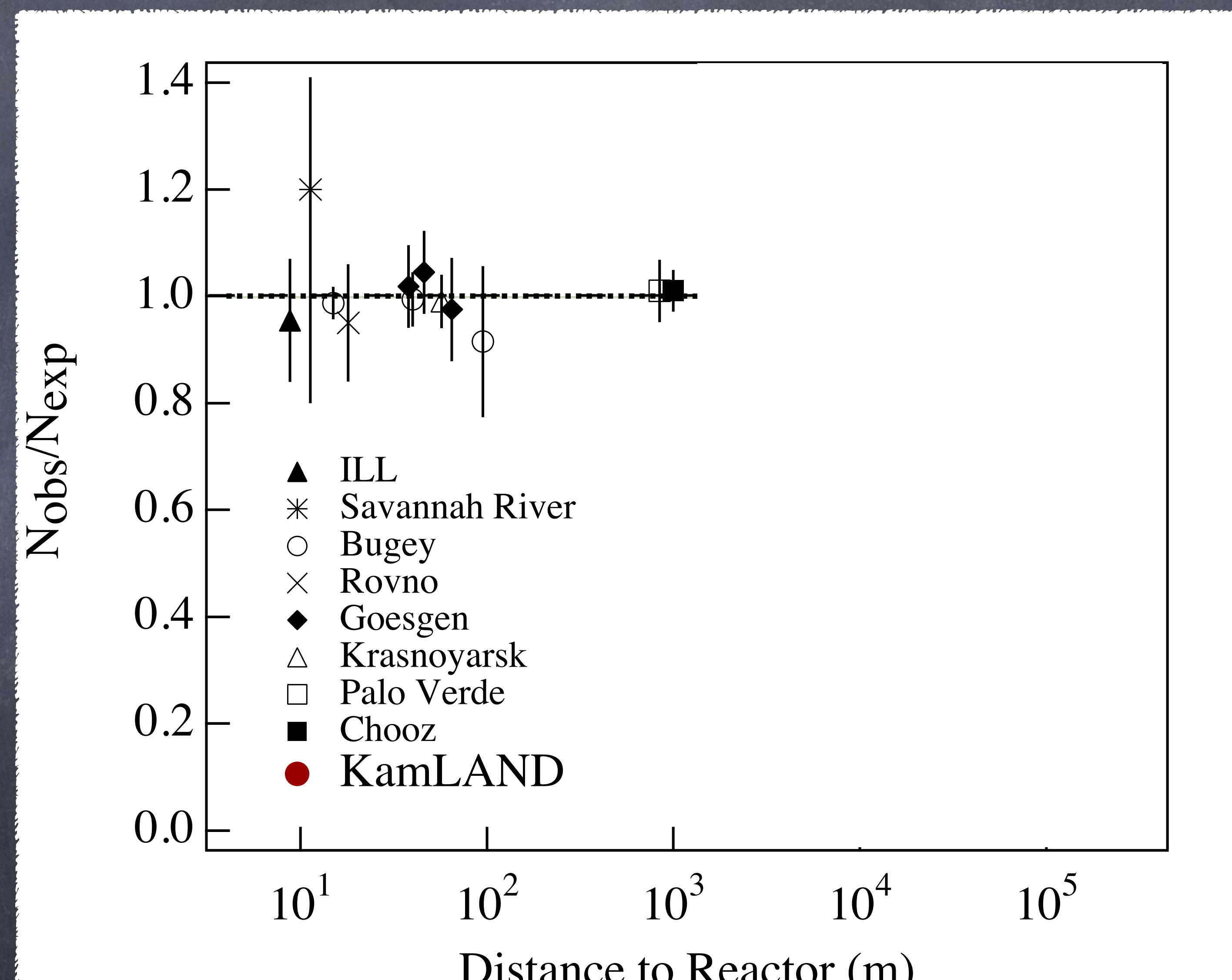


- F.Reines & C.Cowan. 1956 Discovery of $\overline{\nu}_e$
- The proposed detection method is now standard
- F.Reines lead the group which discovered atmospheric neutrinos in 1965
- F.Reines with IMB observed SN1987A in 1987
- NP to F.Reines in 1995

Reactor Neutrinos - Decades of Measurements

- BUGEY, ILL, ROVNO, ... flux measurements
- Good agreement with no oscillation model at short distances





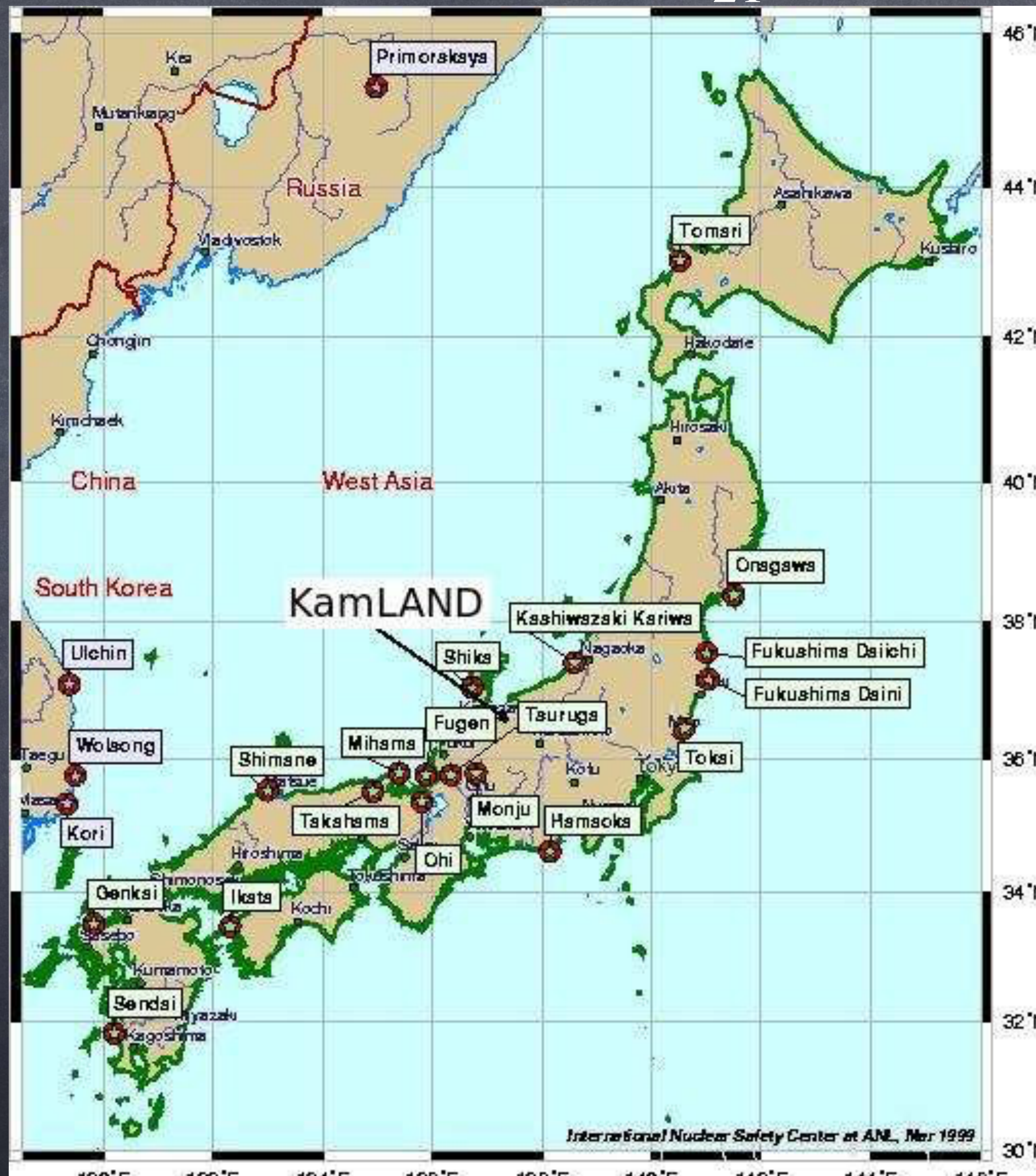
- No agreement at larger distances

Neutrino Oscillation

Δm^2_{21} driven

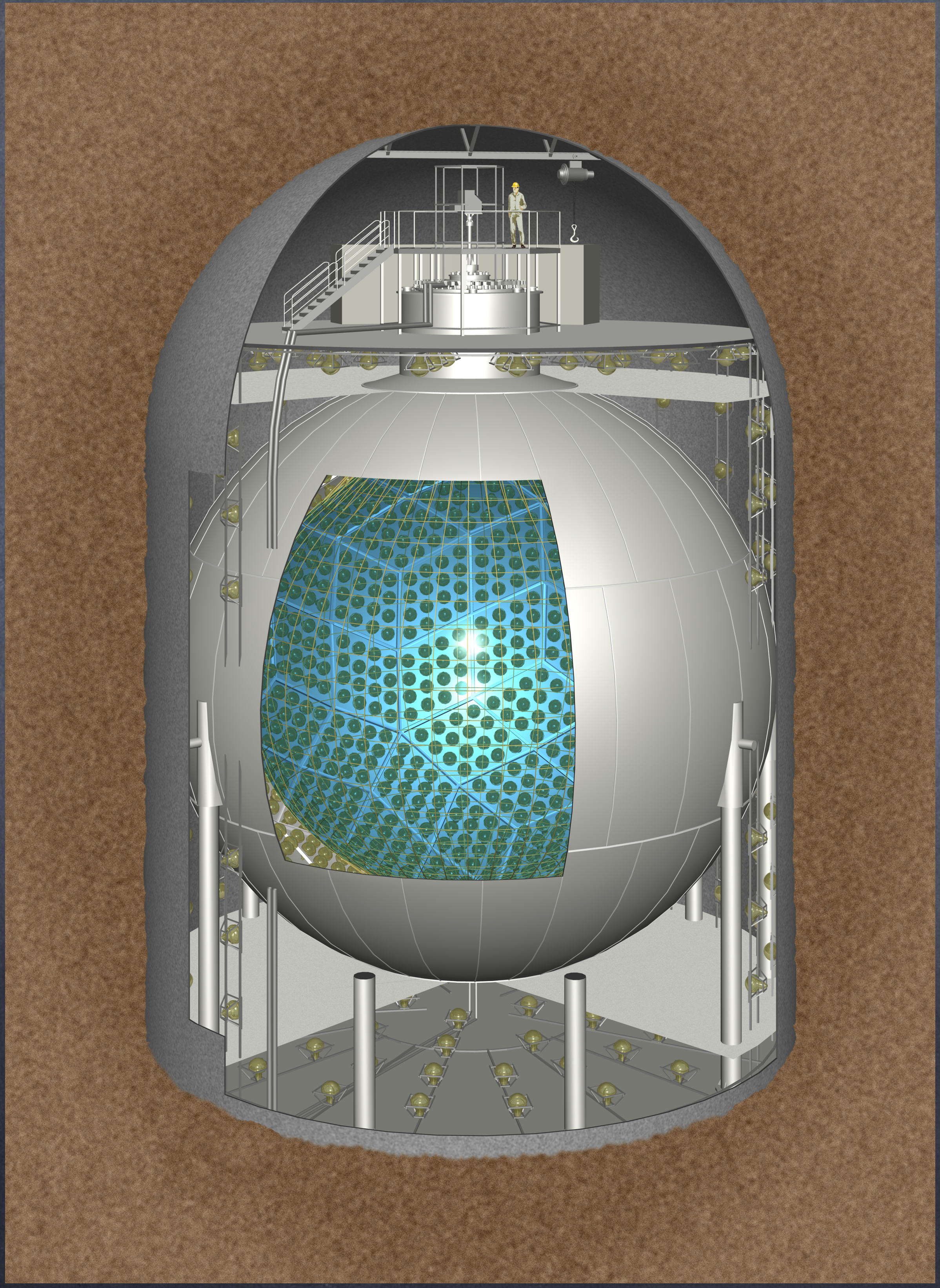
Reactor Neutrinos

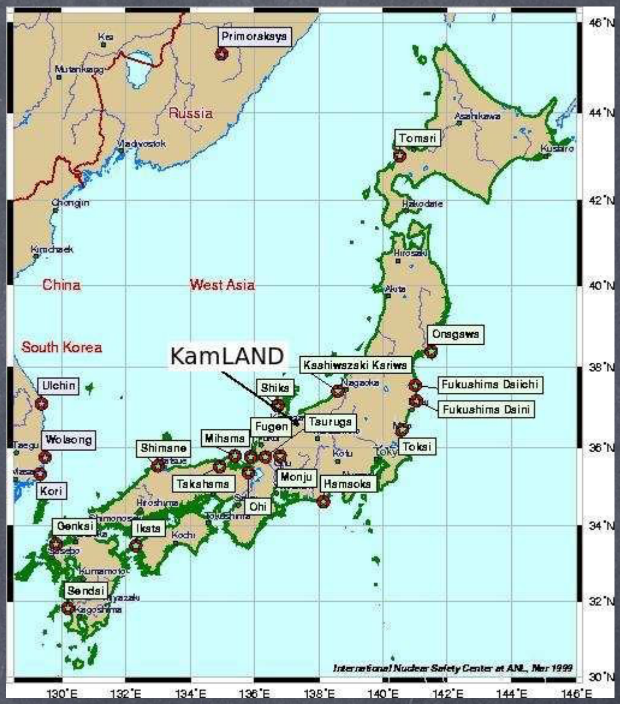
KamLAND: first evidence for Δm^2_{21} driven oscillation



More than 50 reactors around at $\langle L\rangle \approx 180$ km

Reactor Neutrinos
KamLAND: first evidence for Δm^2_{21} driven oscillation

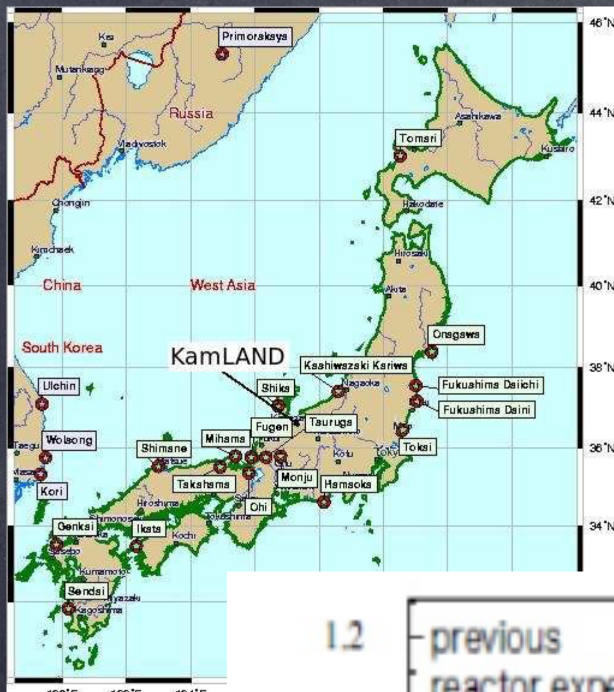


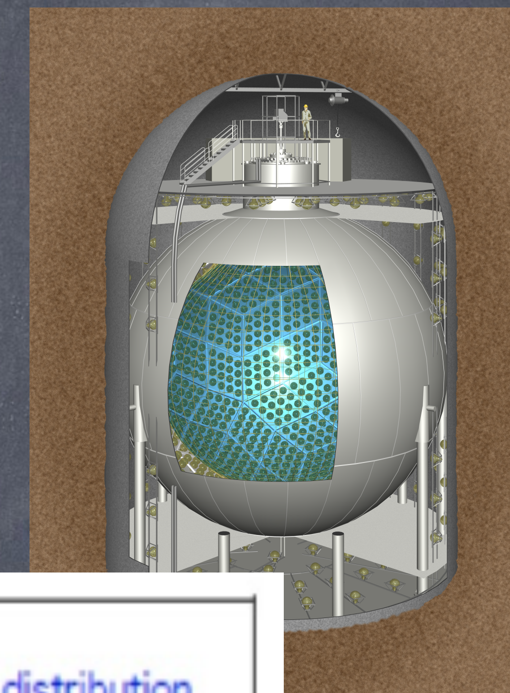


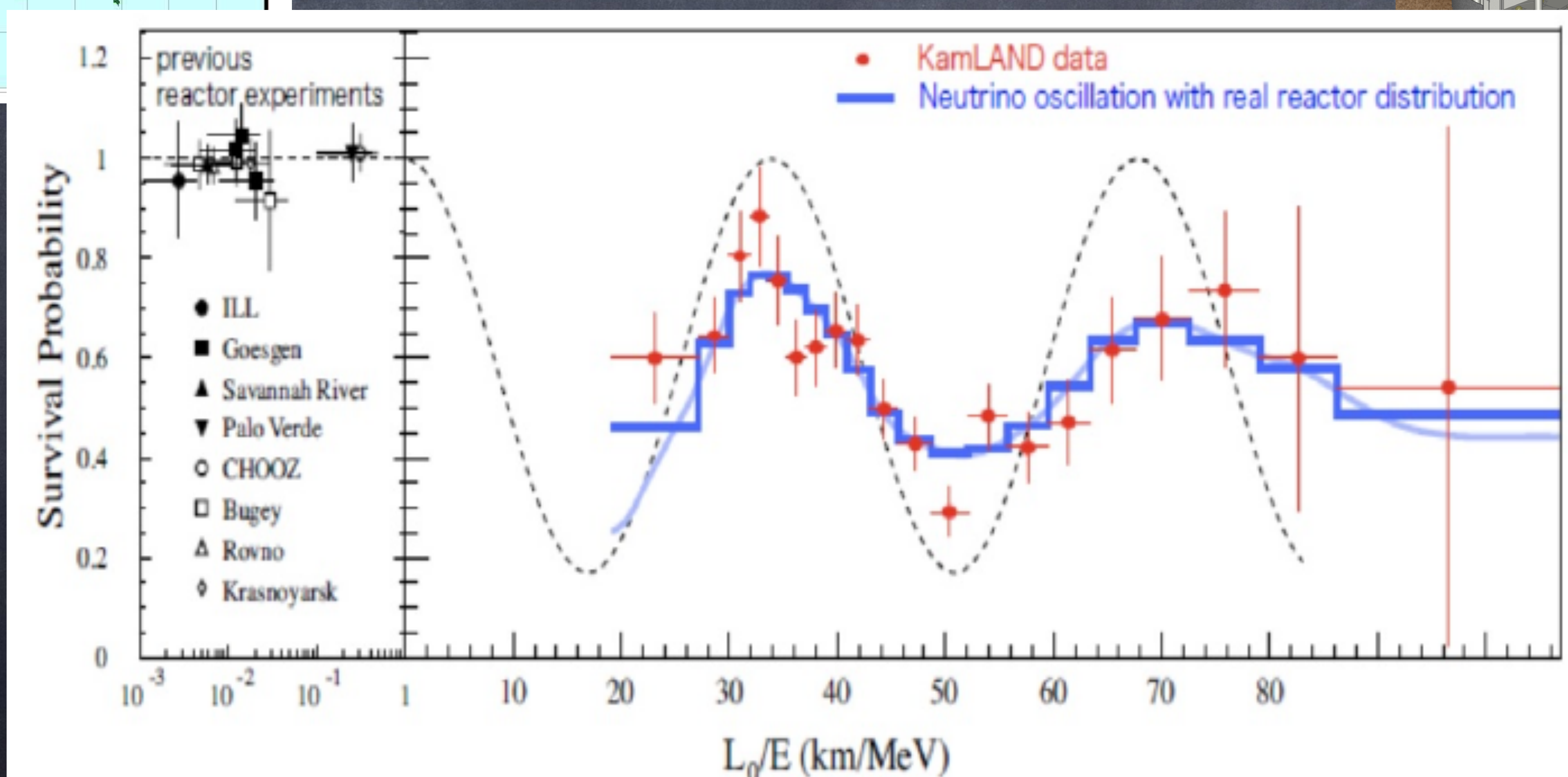
KamLAND LS detector

Reactor Neutrinos

KamLAND: first evidence for Δm^2_{21} driven oscillation







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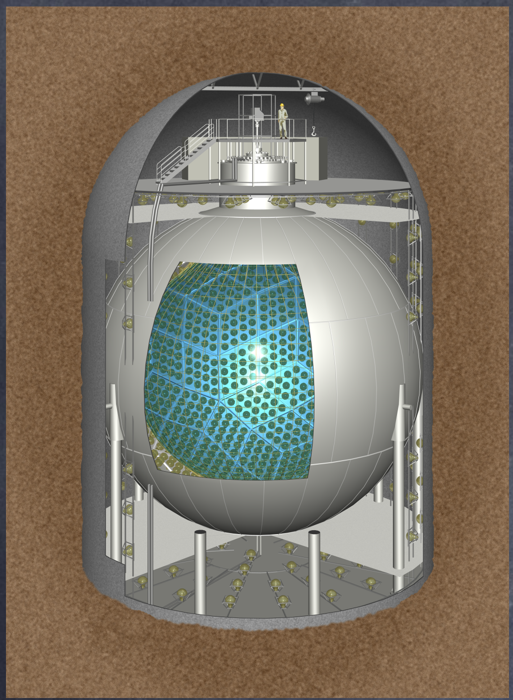
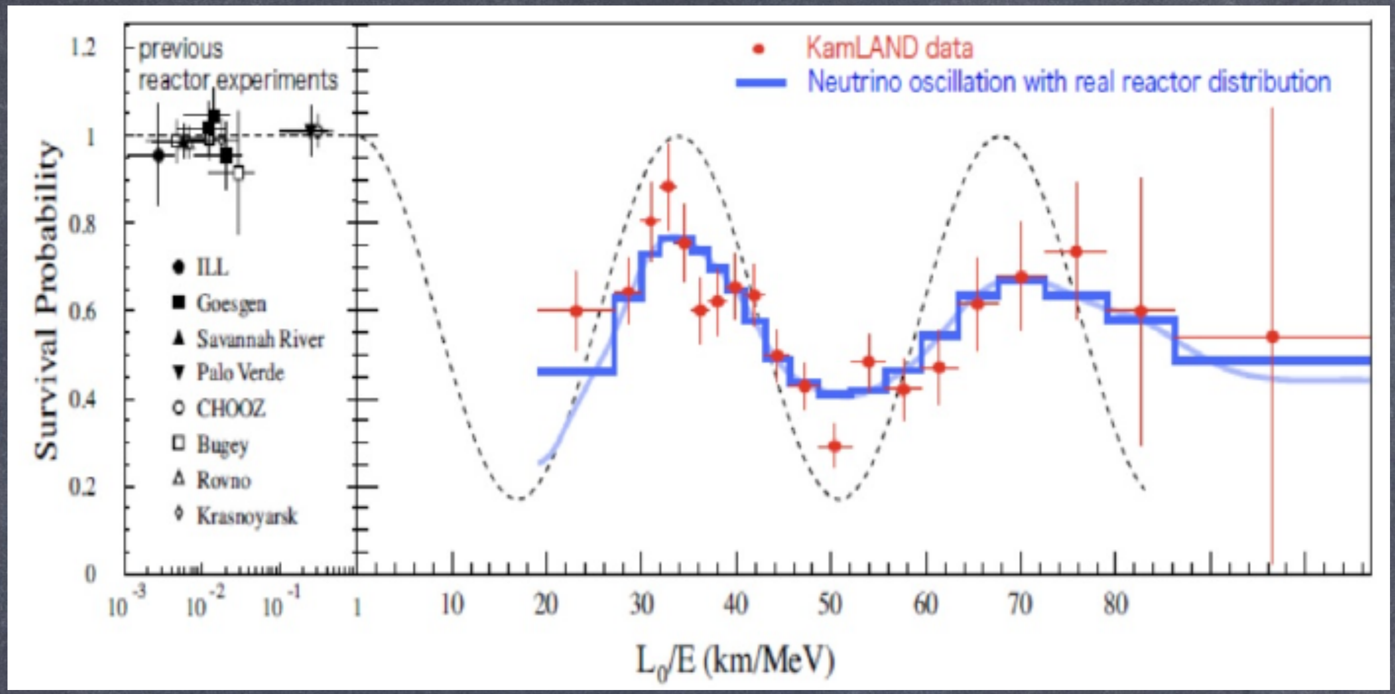
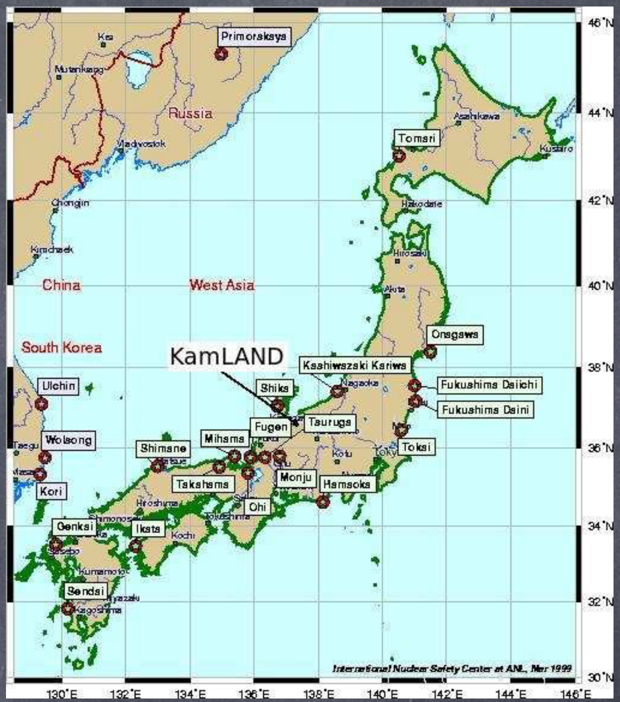
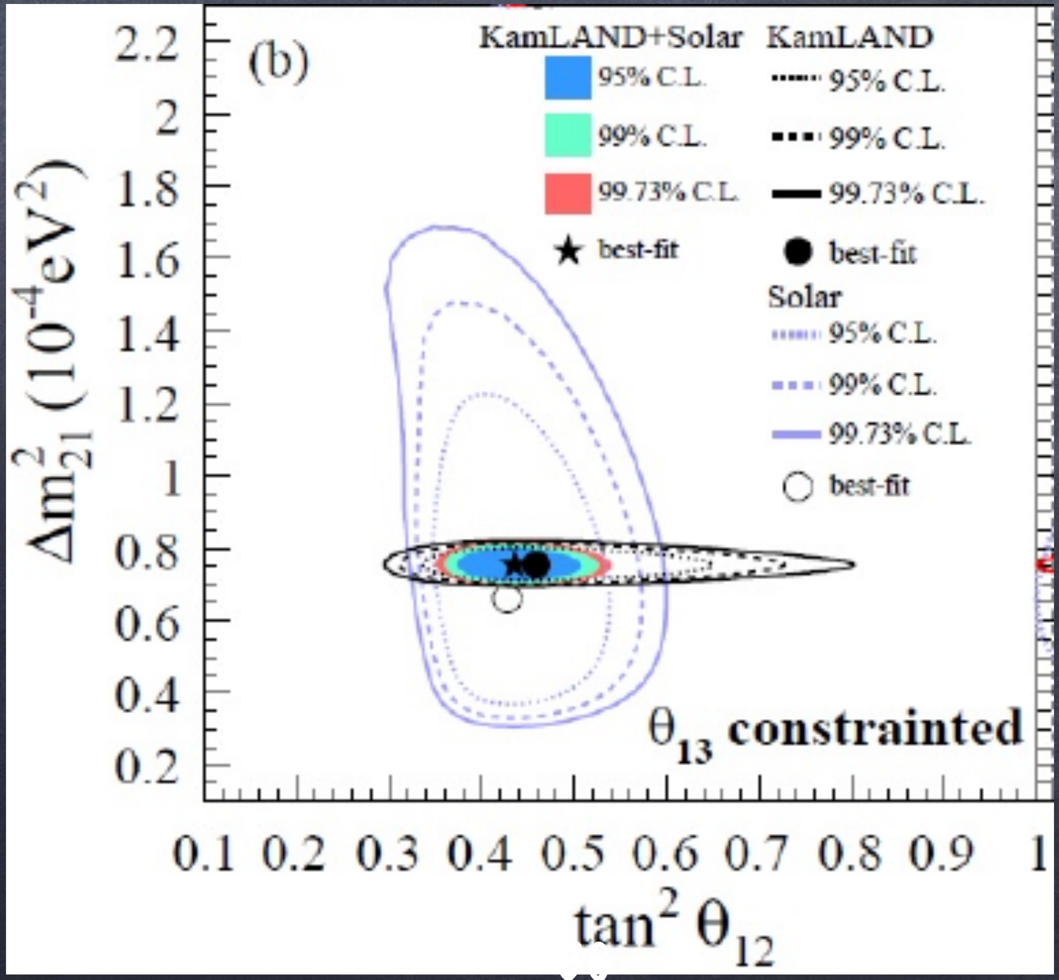
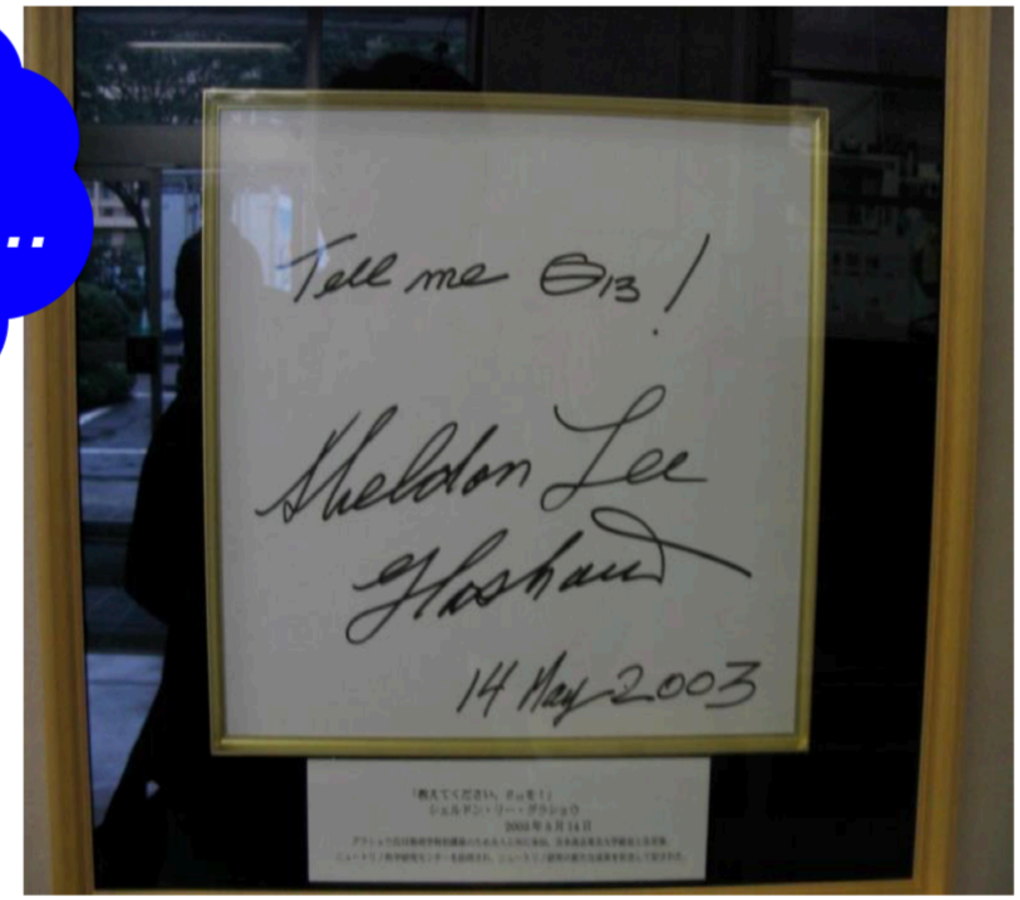








Neutrino Oscillation Race for θ_{13}



One of the Funders of the SM, Glashow, called for the measurement of θ_{13}

Photo **by Kam-Biu Luk**

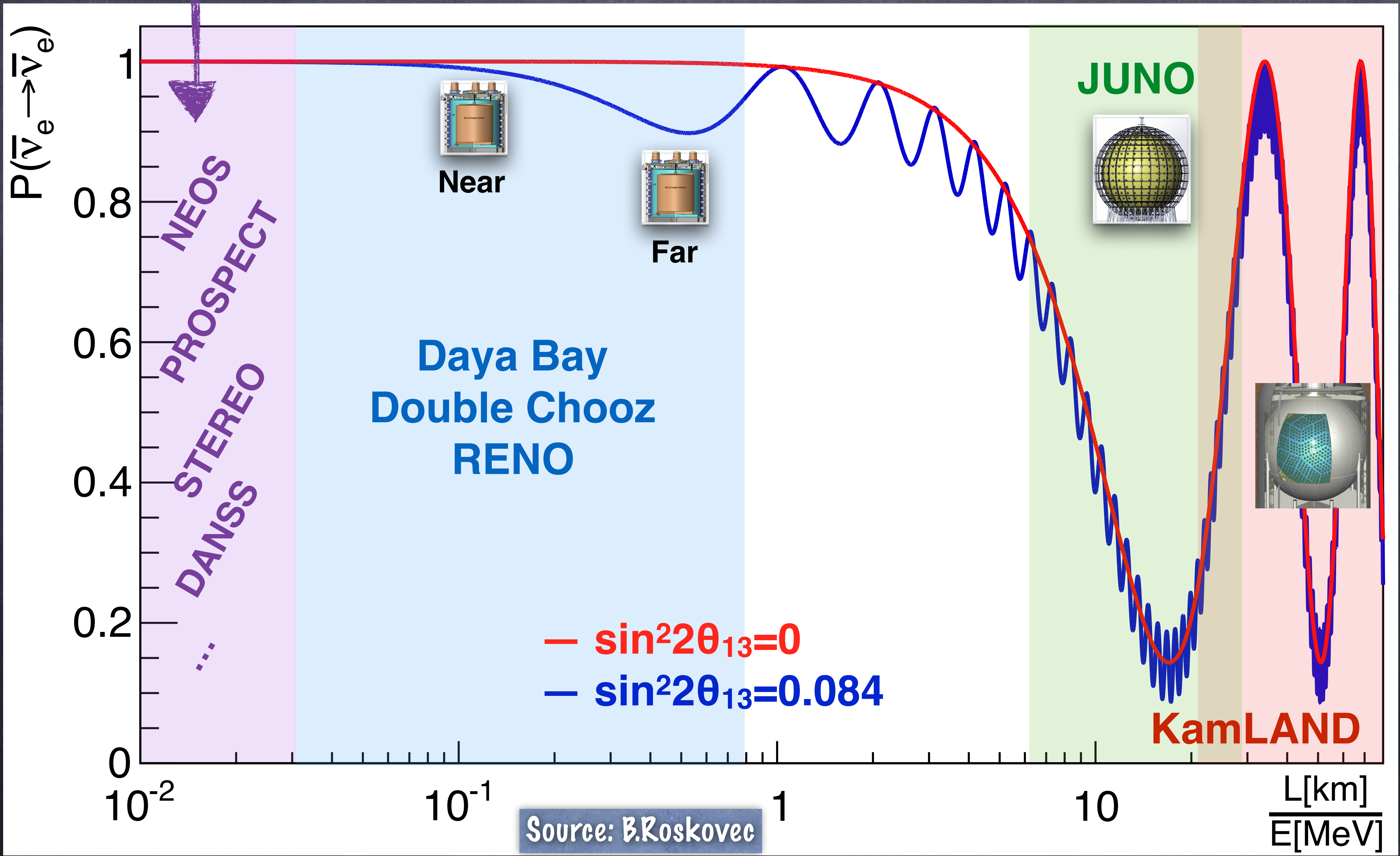
Two modes of oscillations

Is there 3rd mode?

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$$

Medium baseline

Short baseline



Source: B.Roskovec

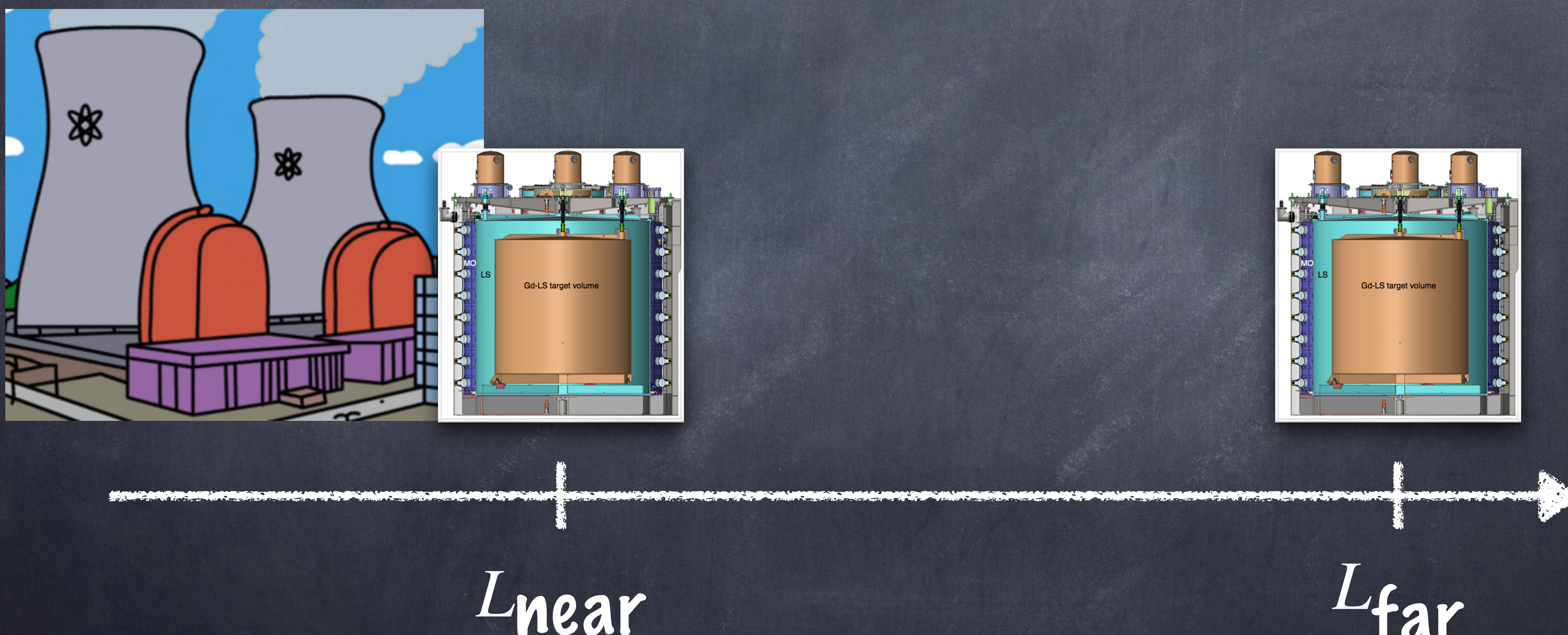
Why θ_{13} was not measured earlier?

- Upper limit by CHOOZ $\sin^2 2\theta_{13} < 0.15$
- Main limitations:
    - Uncertainty in the $\overline{\nu}_e$ flux
    - Uncertainty in the detection efficiency

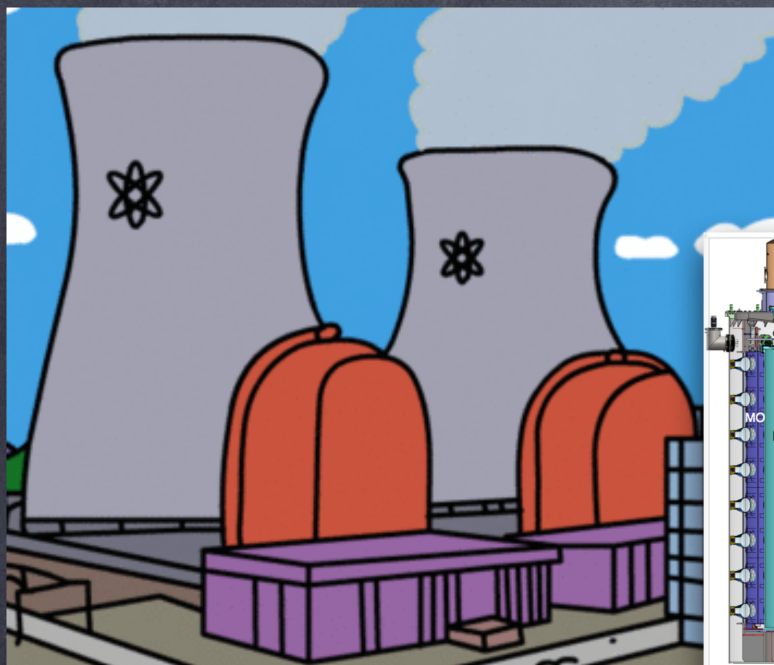
θ_{13} escaped detection

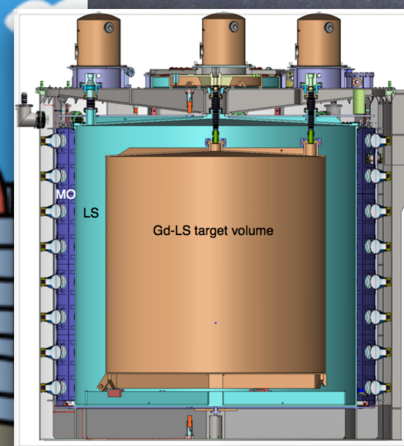
A receipt for θ_{13}

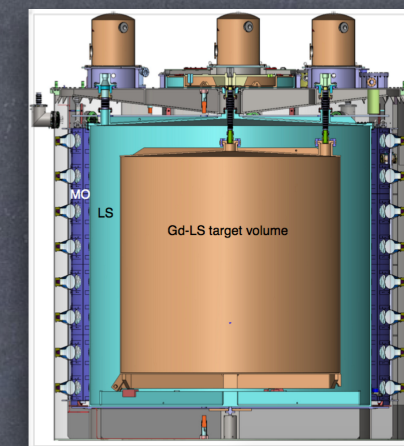
- The flux:
  - near and far detectors for relative measurements
  - Correlated systematics largely reduced
  - Proposal by Mikaelyan & Sinev



A receipt for θ_{13}







L_{near} L_{far}

$$N_{\text{near}}(E) \propto \frac{1}{L_{\text{near}}^2}\Phi(E) \cdot \sigma \cdot N_{\text{near}} \cdot \varepsilon \cdot P_{\text{osc}}(L_{\text{near}}/E)$$

$$N_{\text{far}}(E) \propto \frac{1}{L_{\text{far}}^2}\Phi(E) \cdot \sigma \cdot N_{\text{far}} \cdot \varepsilon \cdot P_{\text{osc}}(L_{\text{far}}/E)$$

A receipt for θ_{13}

$$N_{near}(E) \propto \frac{1}{L_{near}^2}\Phi(E) \cdot \sigma \cdot N_{near} \cdot \varepsilon \cdot P_{osc}(L_{near}/E)$$

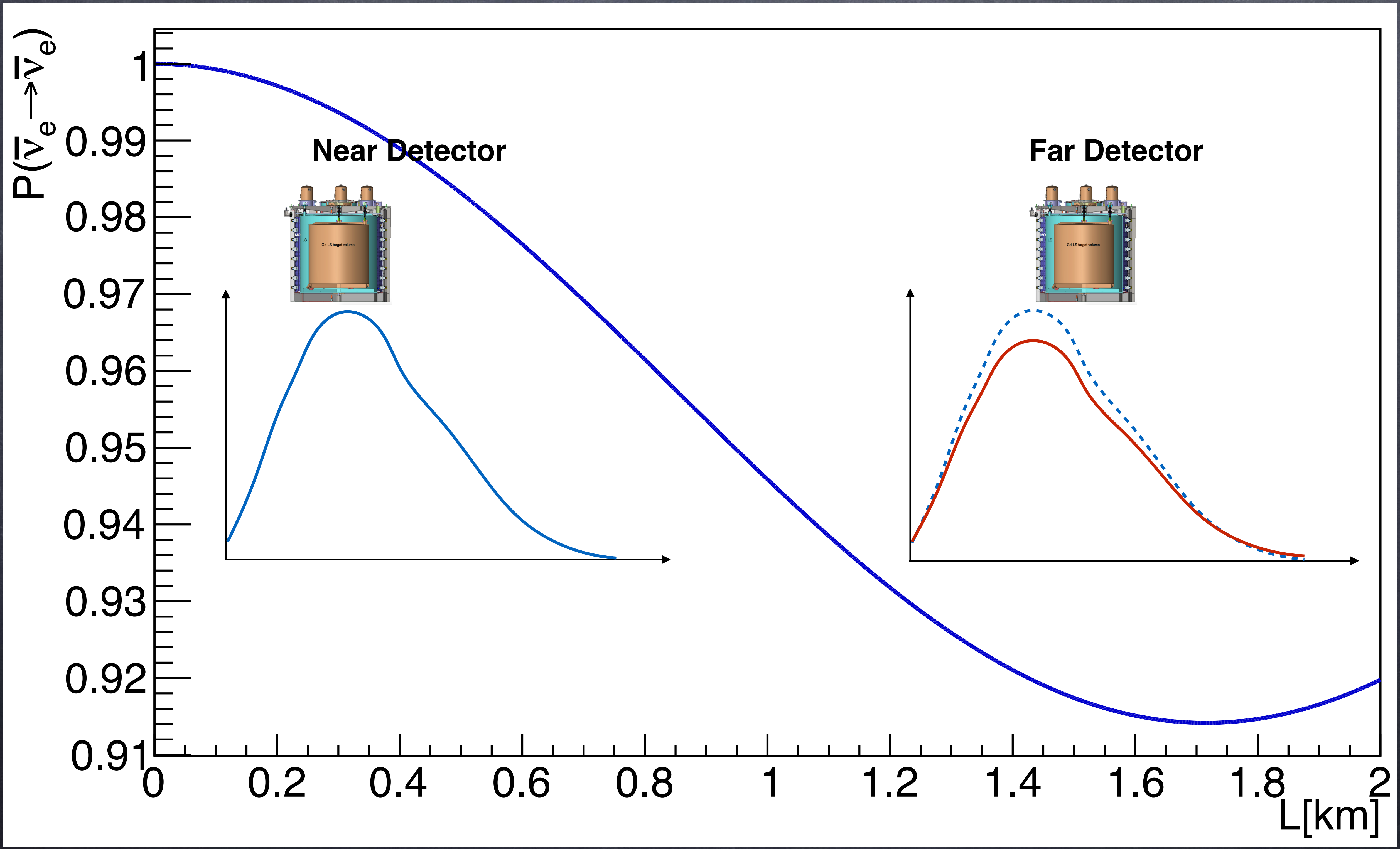
$$N_{far}(E) \propto \frac{1}{L_{far}^2}\Phi(E) \cdot \sigma \cdot N_{far} \cdot \varepsilon \cdot P_{osc}(L_{far}/E)$$

Ratio cancels correlated uncertainties

$$\frac{N_{near}(E)}{N_{far}(E)} \propto \frac{L_{far}^2}{L_{near}^2} \frac{N_{near} \cdot \varepsilon_{near}}{N_{far} \cdot \varepsilon_{far}} \cdot \frac{P_{osc}(L_{near}/E)}{P_{osc}(L_{far}/E)}$$

A receipt for θ_{13}

- The baseline optimization

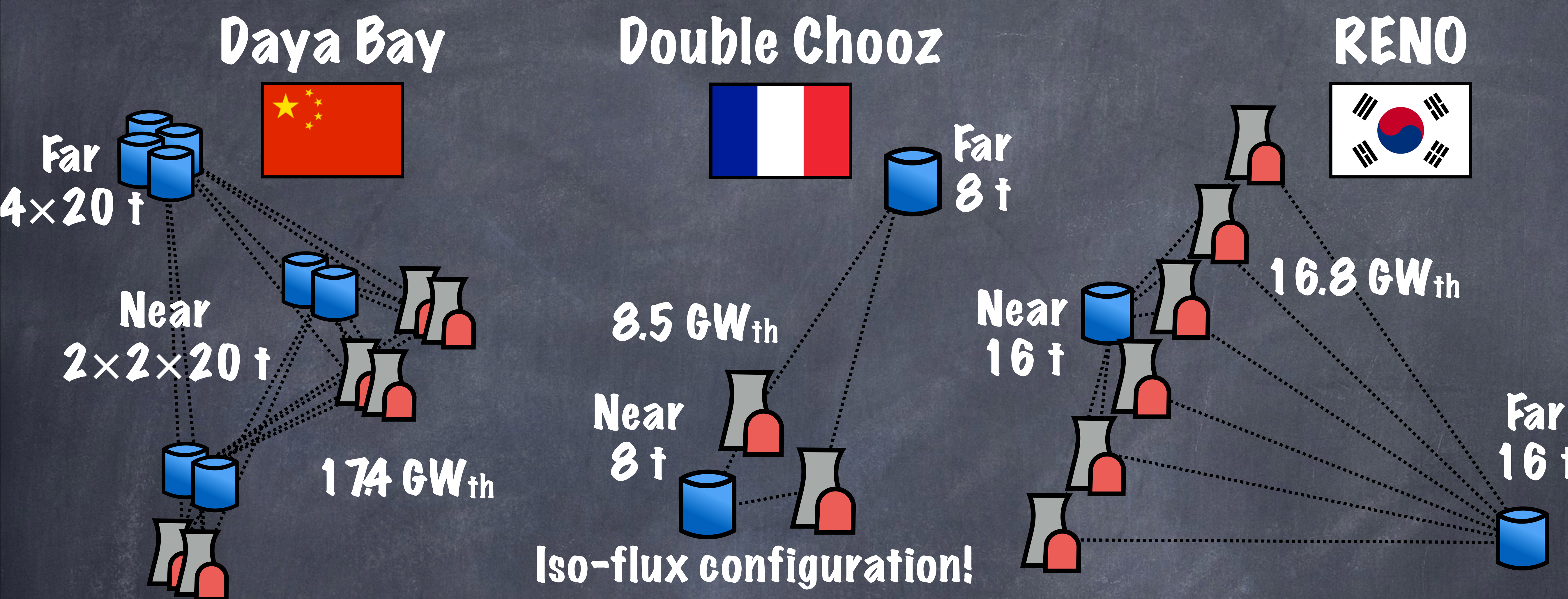


A receipt for θ_{13}

- The statistics:
  - Powerfull source
  - Large detector
- The background:
  - As low as possible
- Detector efficiency:
  - Calibrations

The big three

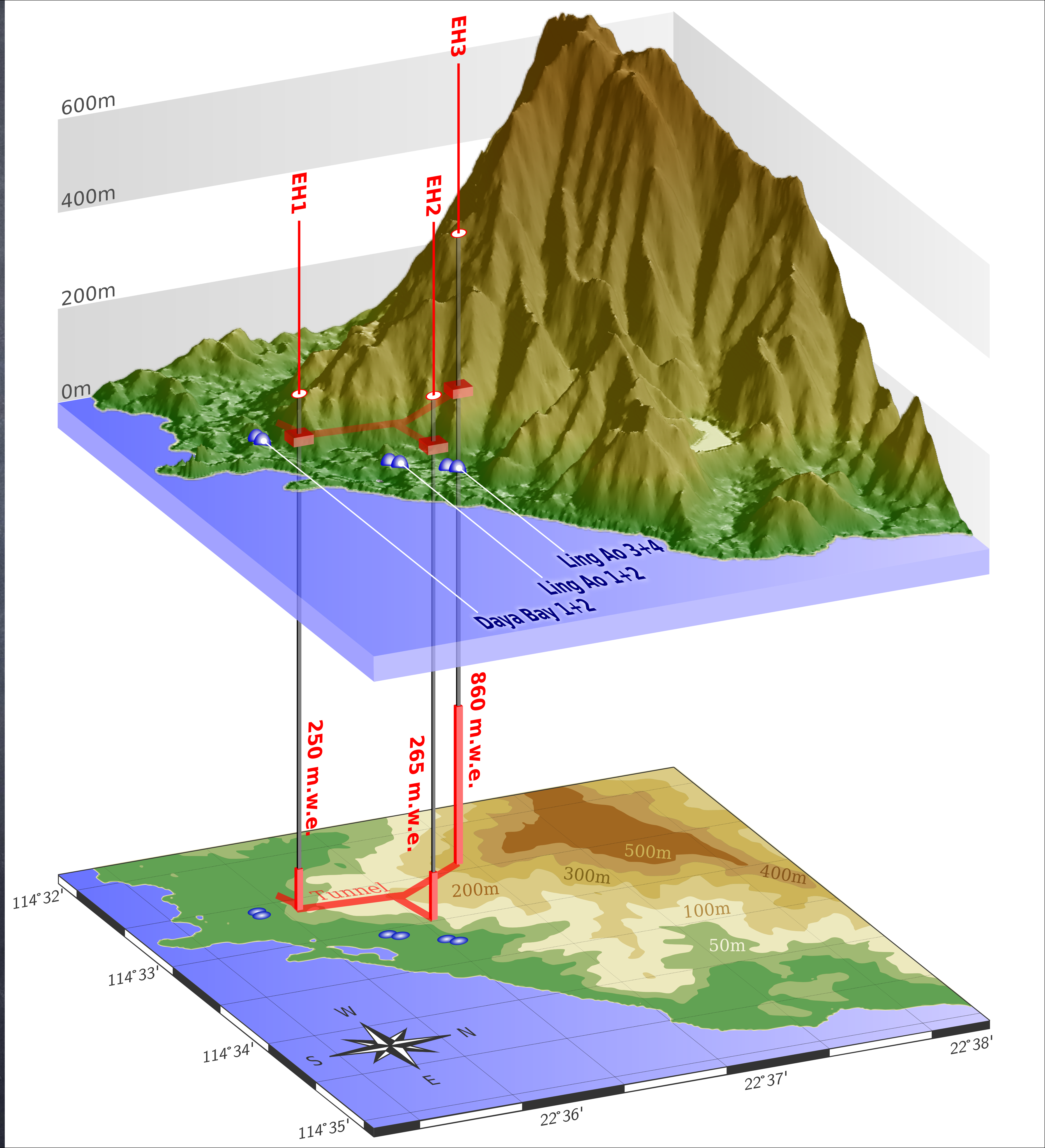
The Big Three



	Power [GW$_{th}$]	GdLS mass Near/Far [t]	Distance Near/Far [m]	Overburden [mwe]	Running until
Daya Bay	17.4	2×2×20 4×20	365, 490 1650	250 860	2020
Double Chooz	16.8	8 8	400 1050	120 300	Dec 2017 (Finished)
RENO	8.5	16 16	290 1380	120 450	2020-2021

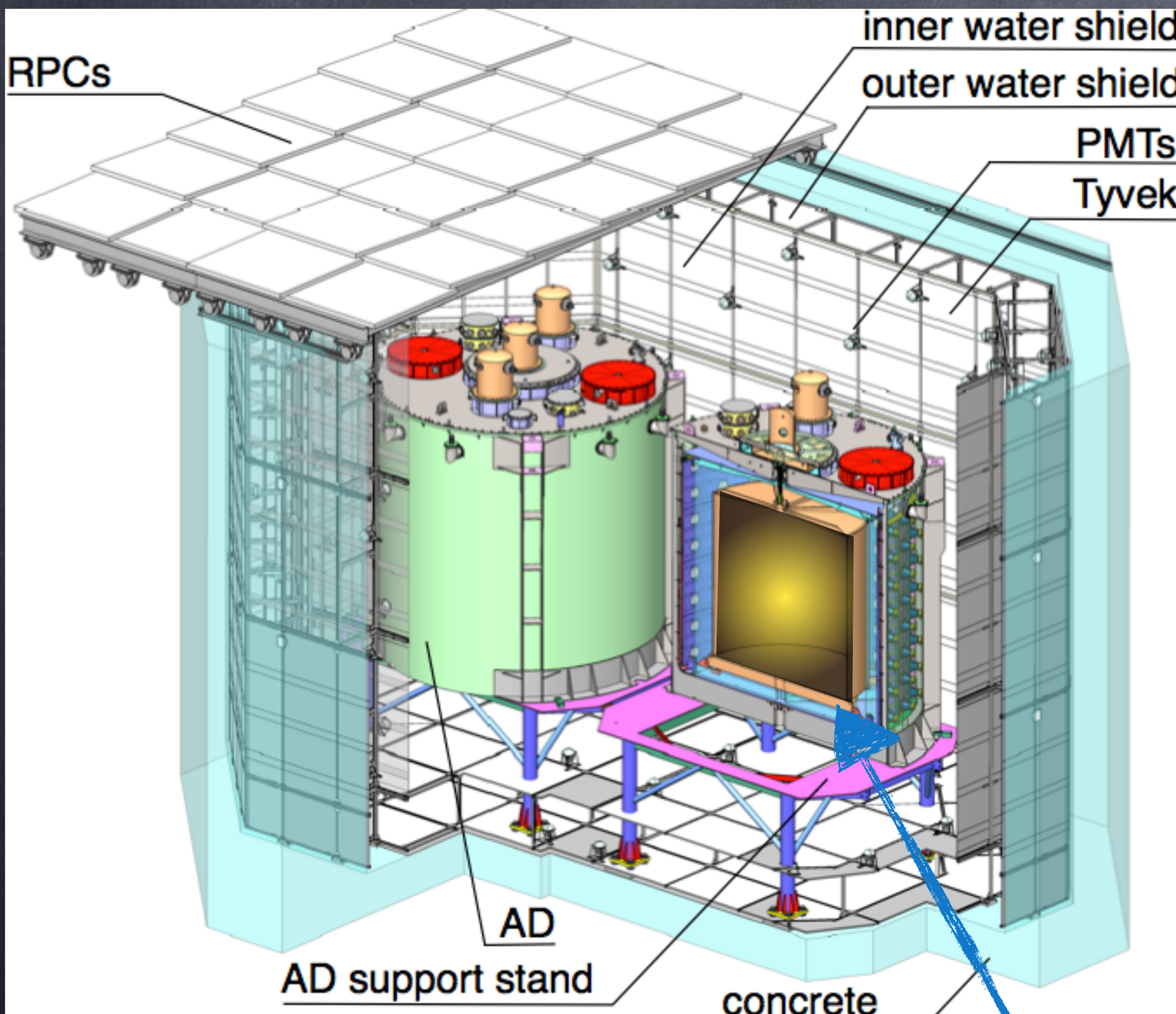
Source: B.Roskovec

3D Map of Daya Bay experiment

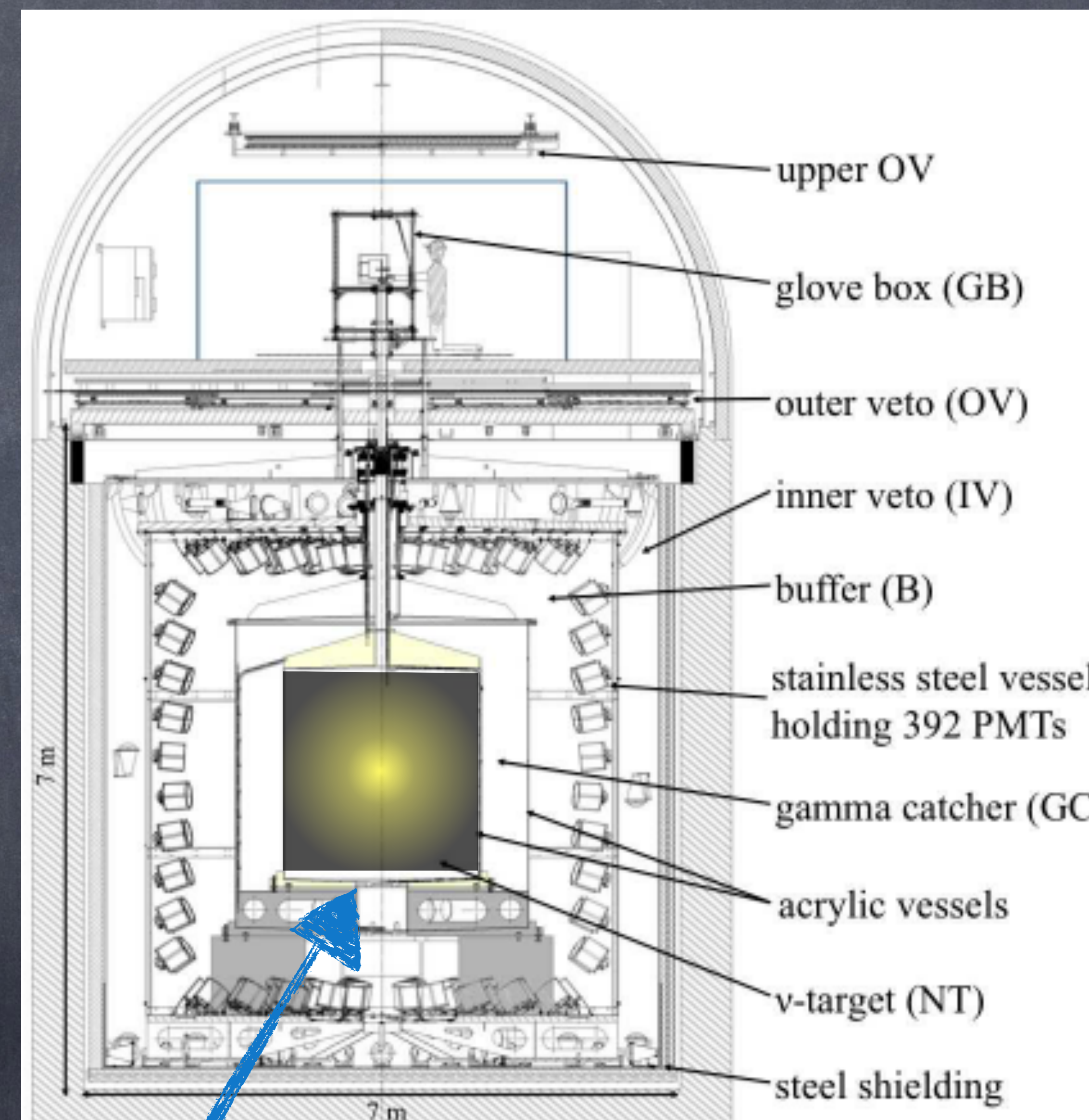


Detector design

Daya Bay & RENO



Double Chooz

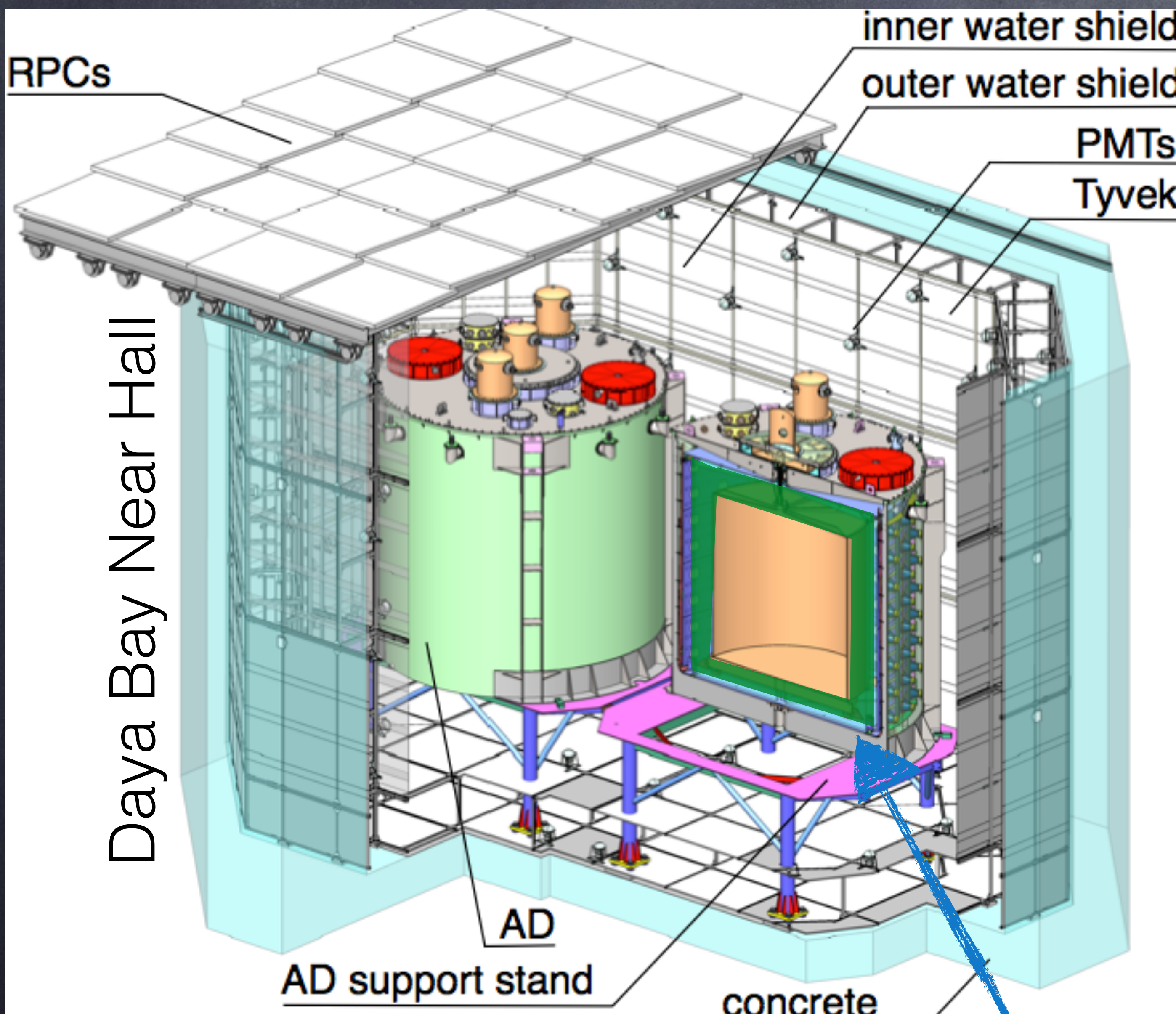


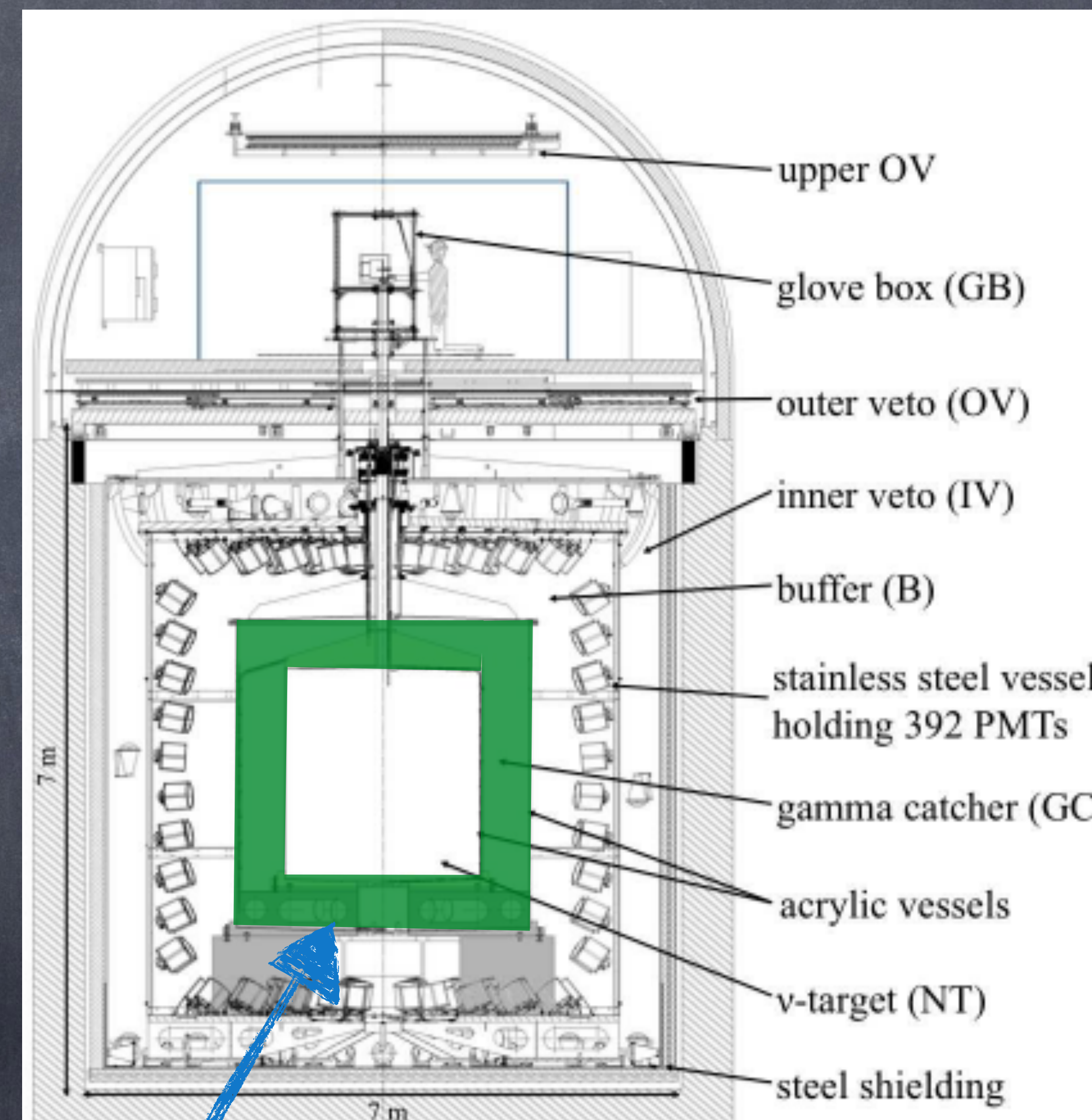
Gadolinium-doped liquid scintillator

Source: B.Roskovec

Daya Bay & RENO

Double Chooz

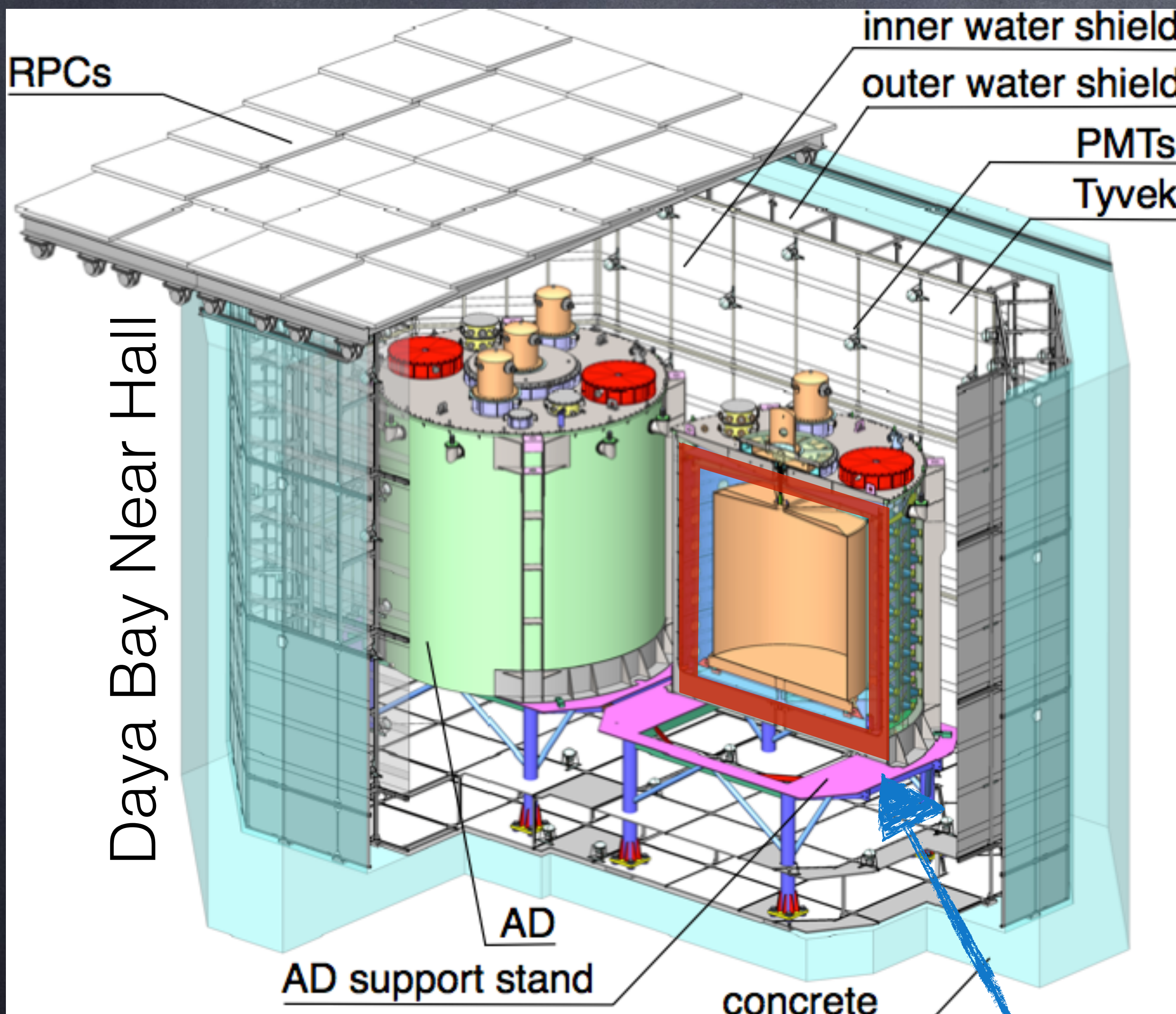




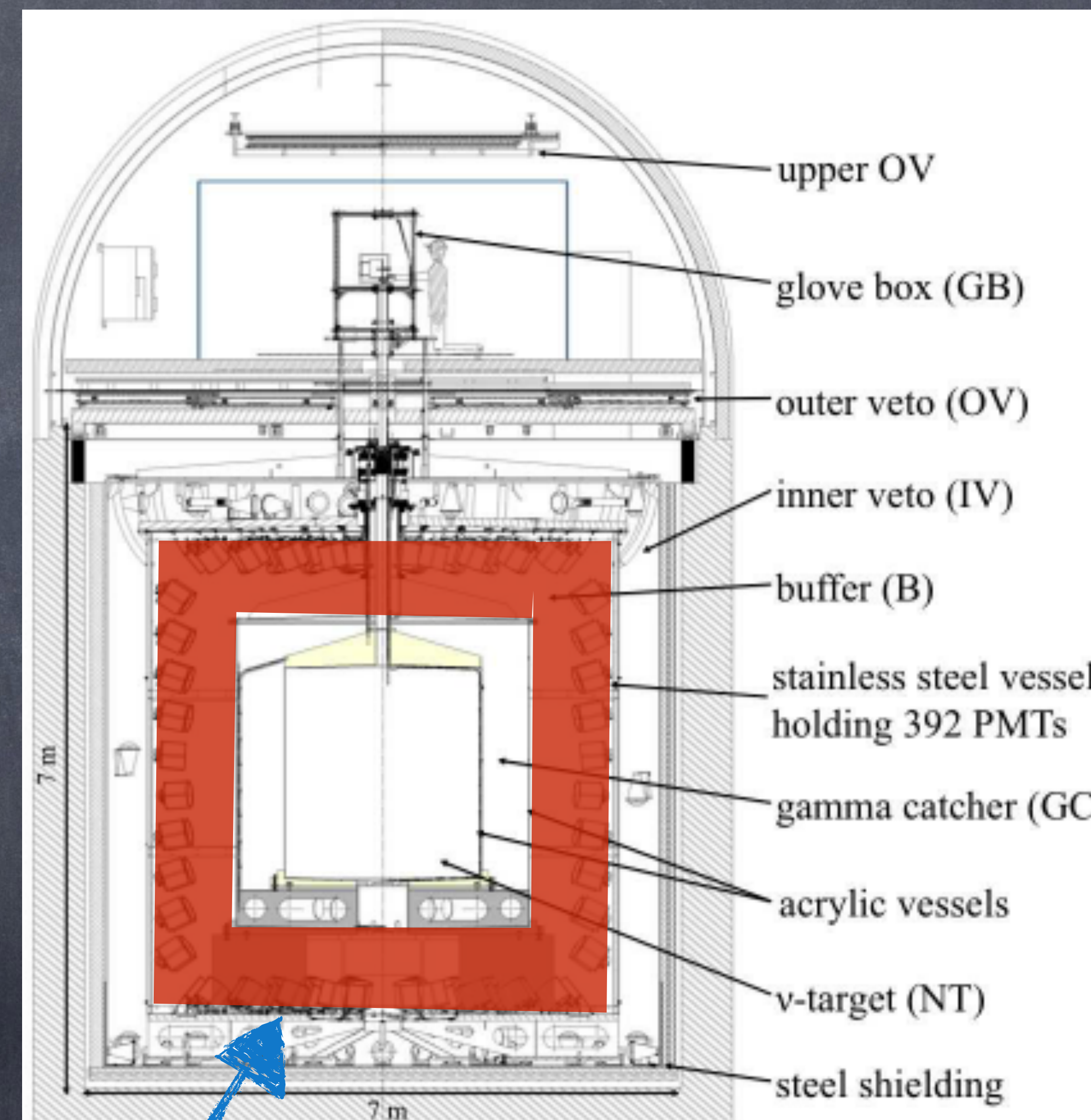
Liquid scintillator γ-catcher

Source: B.Roskovec

Daya Bay & RENO



Double Chooz

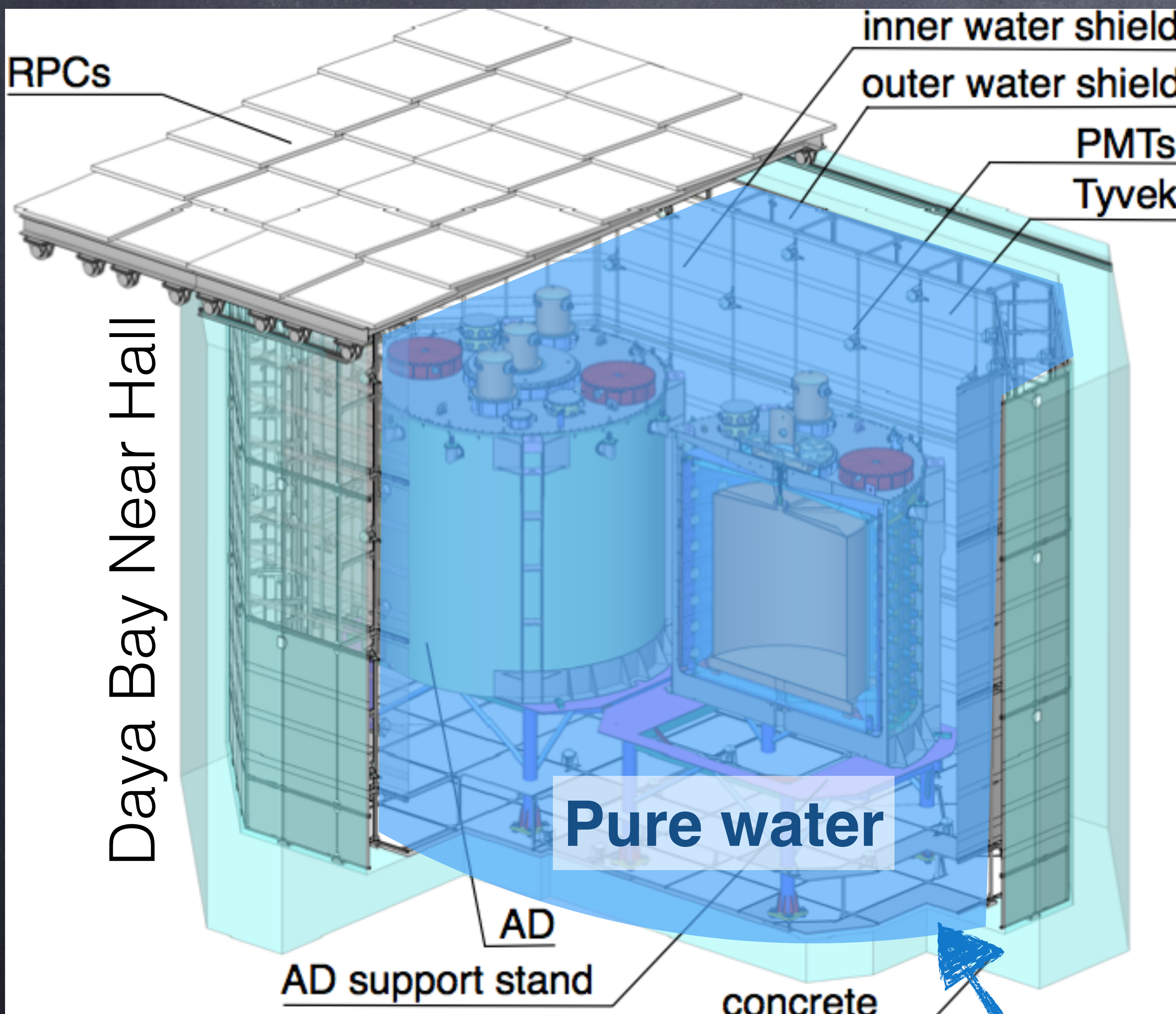


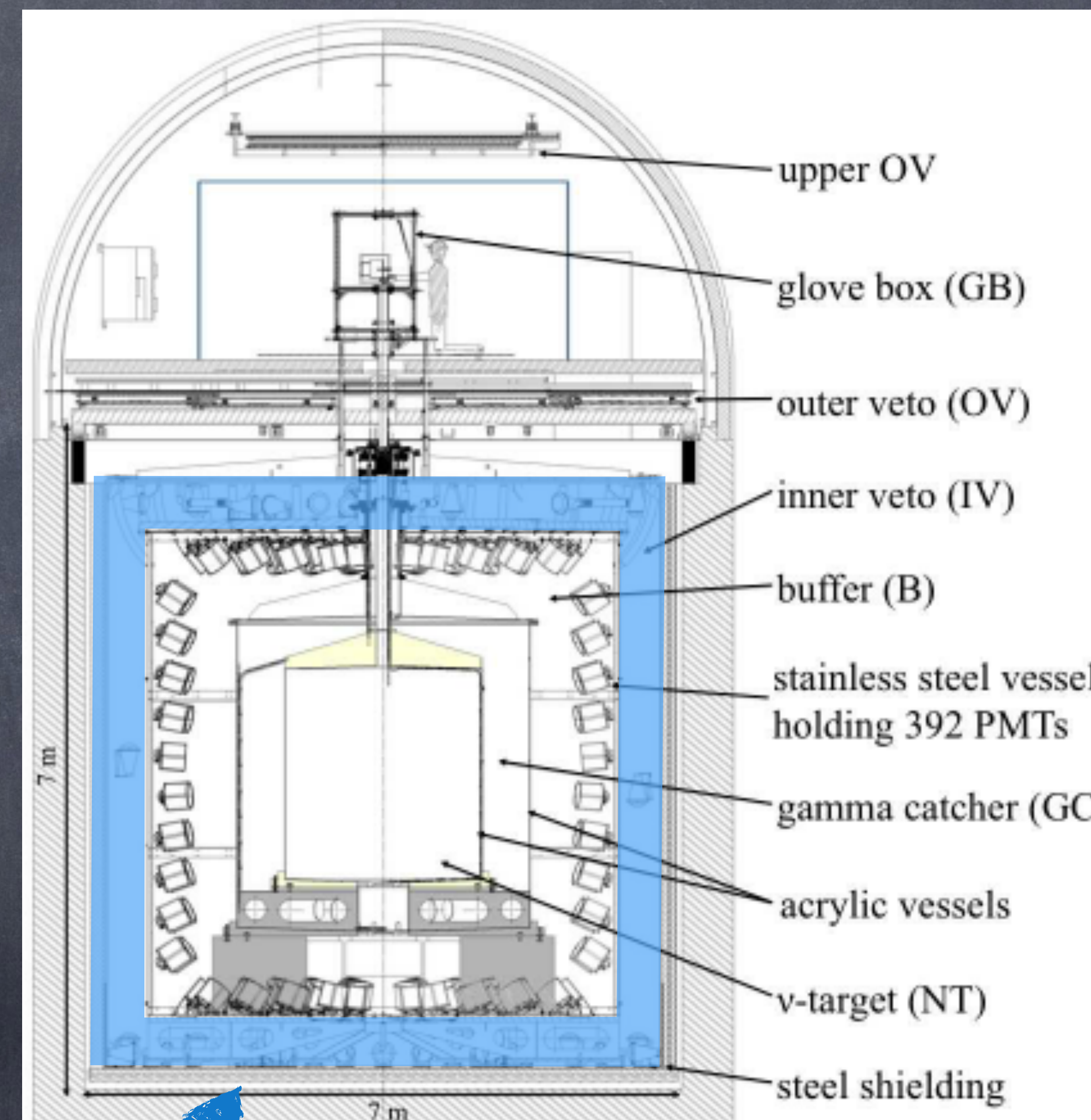
Non-scintillating transparent mineral oil with PMTs

Source: B.Roskovec

Daya Bay & RENO

Double Chooz





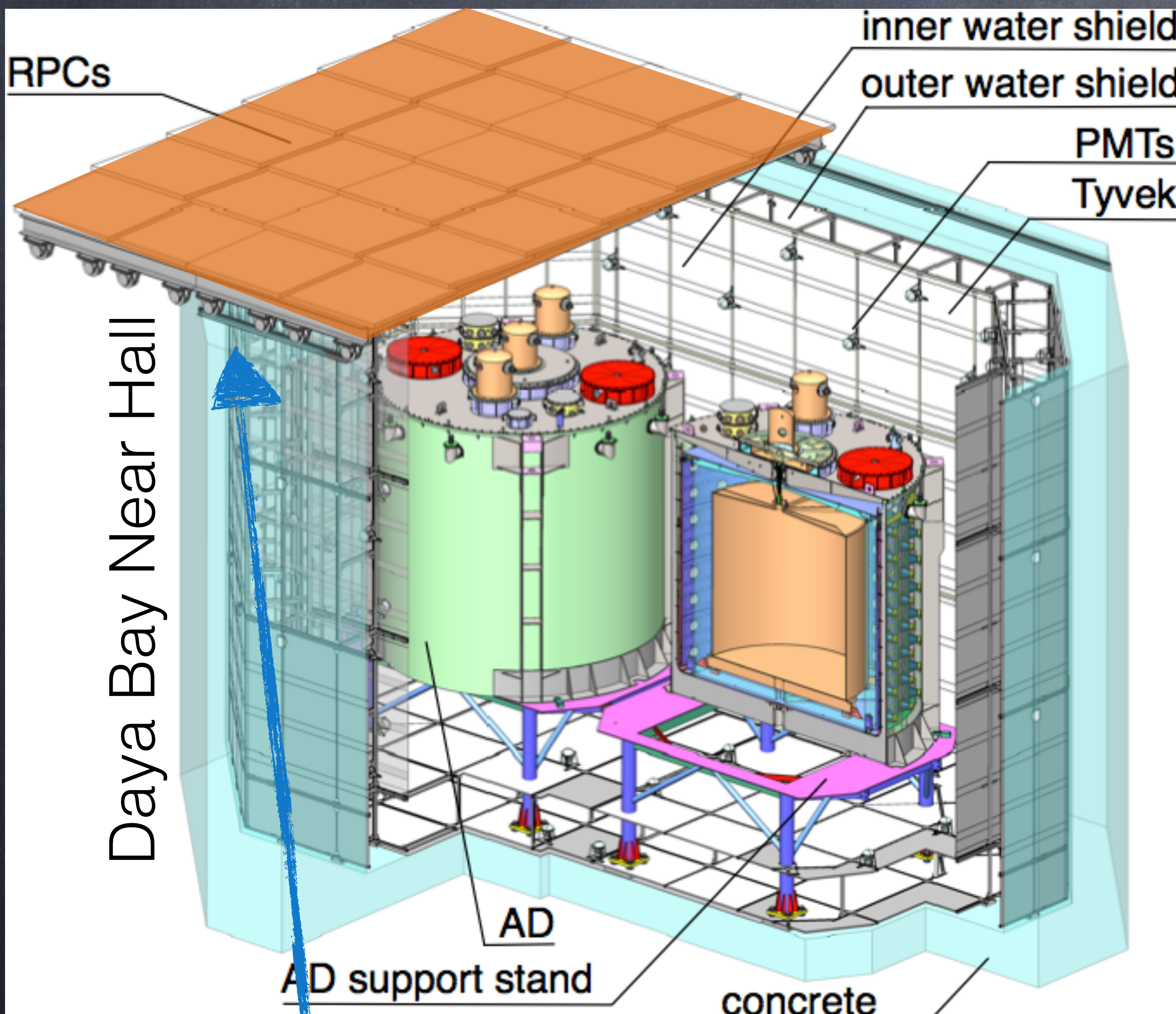
Liquid Scintillator

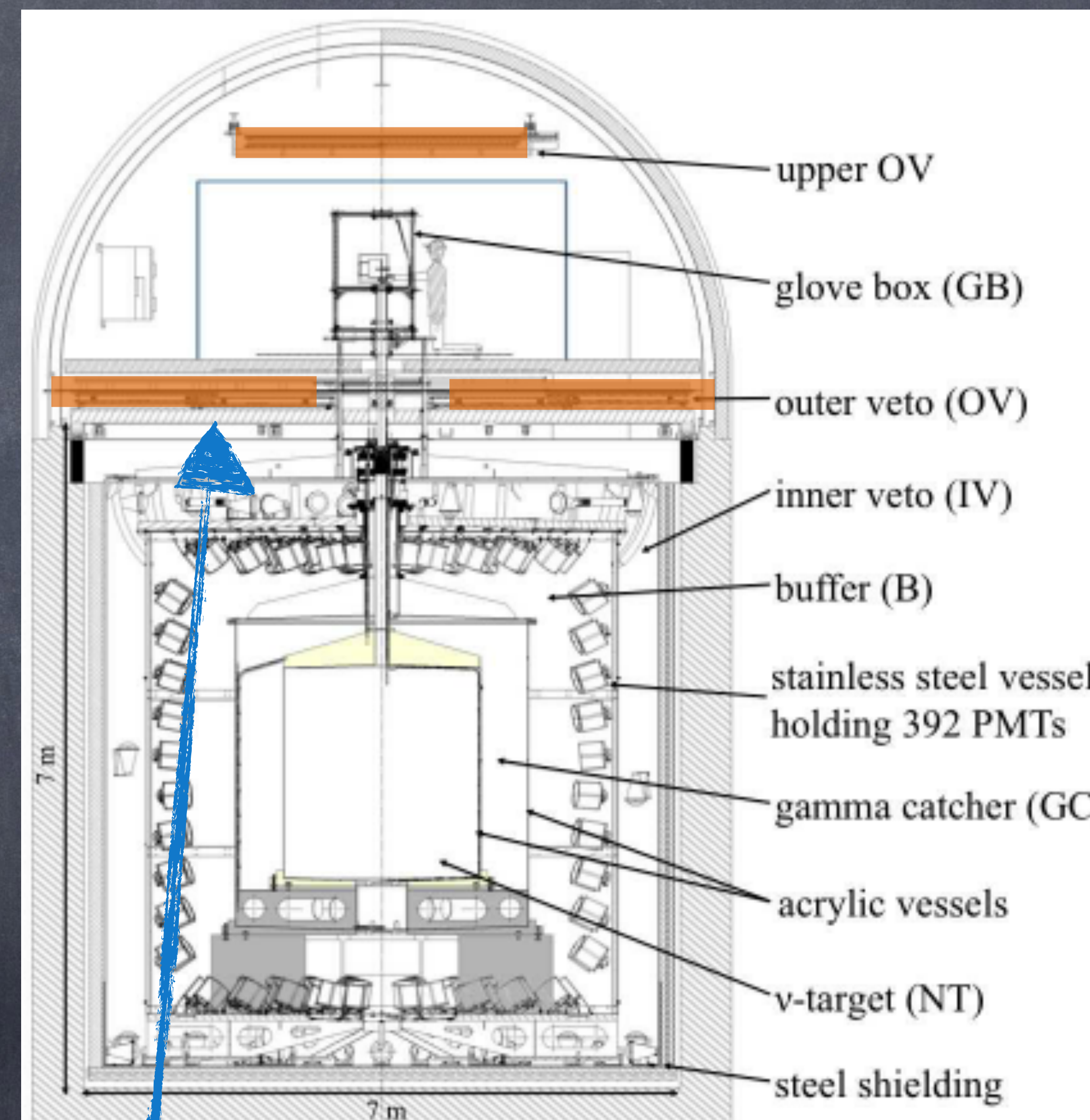
Cherenkov detector for shielding and cosmic muon detection

Source: B.Roskovec

Daya Bay

Double Chooz





4-layer RPC (Daya Bay)

Plastic scintillator for muons

Source: B.Roskovec

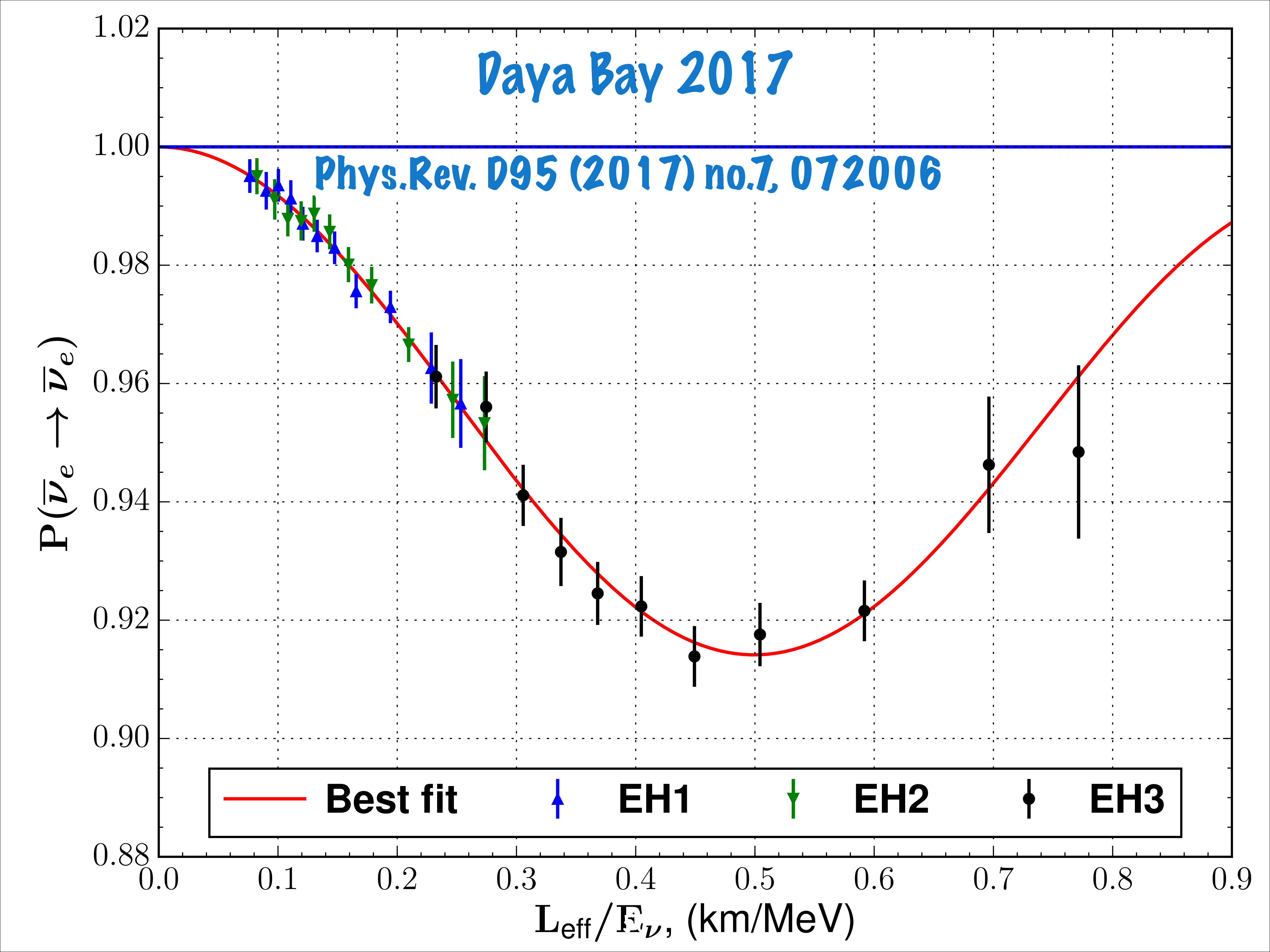
Importance of Relative Measurement

	Reactor flux		IBD detection	
	Correlated	Uncorrelated	Correlated	Uncorrelated
Daya Bay	1.5%	**0.2%**	1.2%	**0.13%**
Double Chooz	1.7%	**0.1%**	0.5%	**0.2%**
RENO	2.0%	**0.9%**	0.97%	**0.13%**

- Essentially only uncorrelated uncertainties matter for the relative far/near measurement
- Correlated uncertainties play role in absolute measurement of reactor neutrino flux and spectrum (see later)

Source: B.Roskovec

Non-zero θ_{13} discovered!

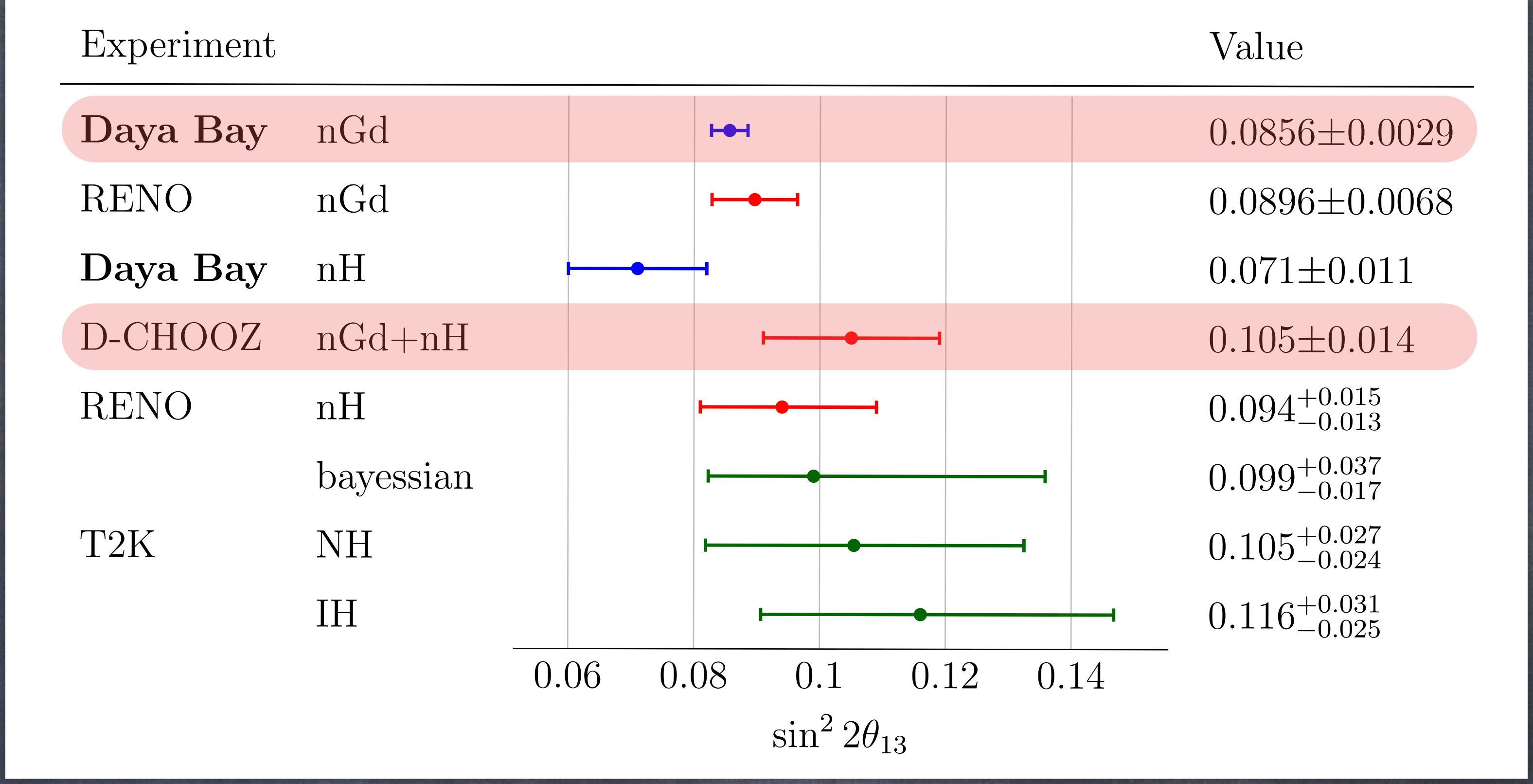


Daya Bay 2017
Phys.Rev. D95 (2017) no.7, 072006
$P(\overline{\nu}_e \to \overline{\nu}_e)$
L_{eff}/E_ν, (km/MeV)
Best fit
EH1
EH2
EH3
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Oscillation Results

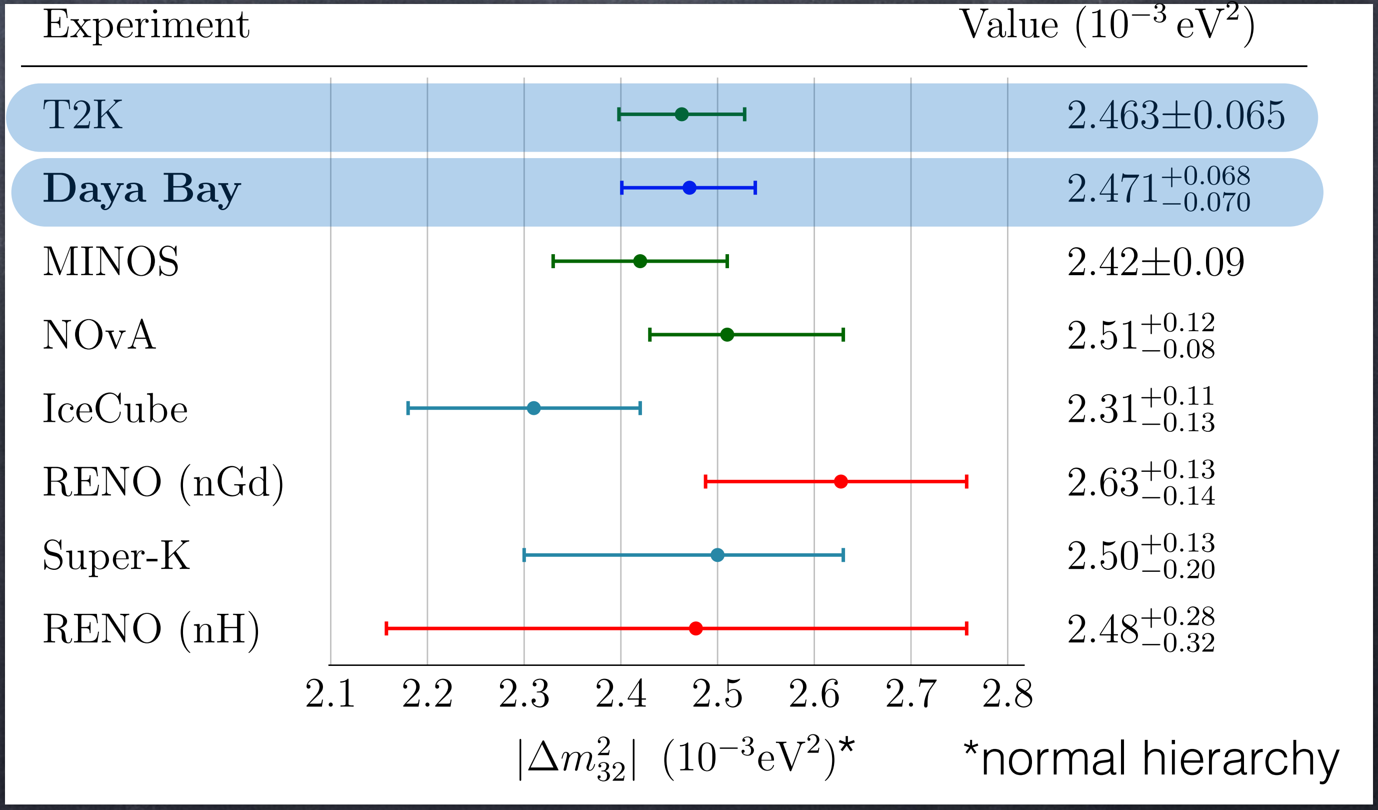
$\sin^2 2\theta_{13}$

- Daya Bay precision 3.4% - best known mixing angle
- 1σ tension between Daya Bay and Double Chooz



Δm^2_{32}

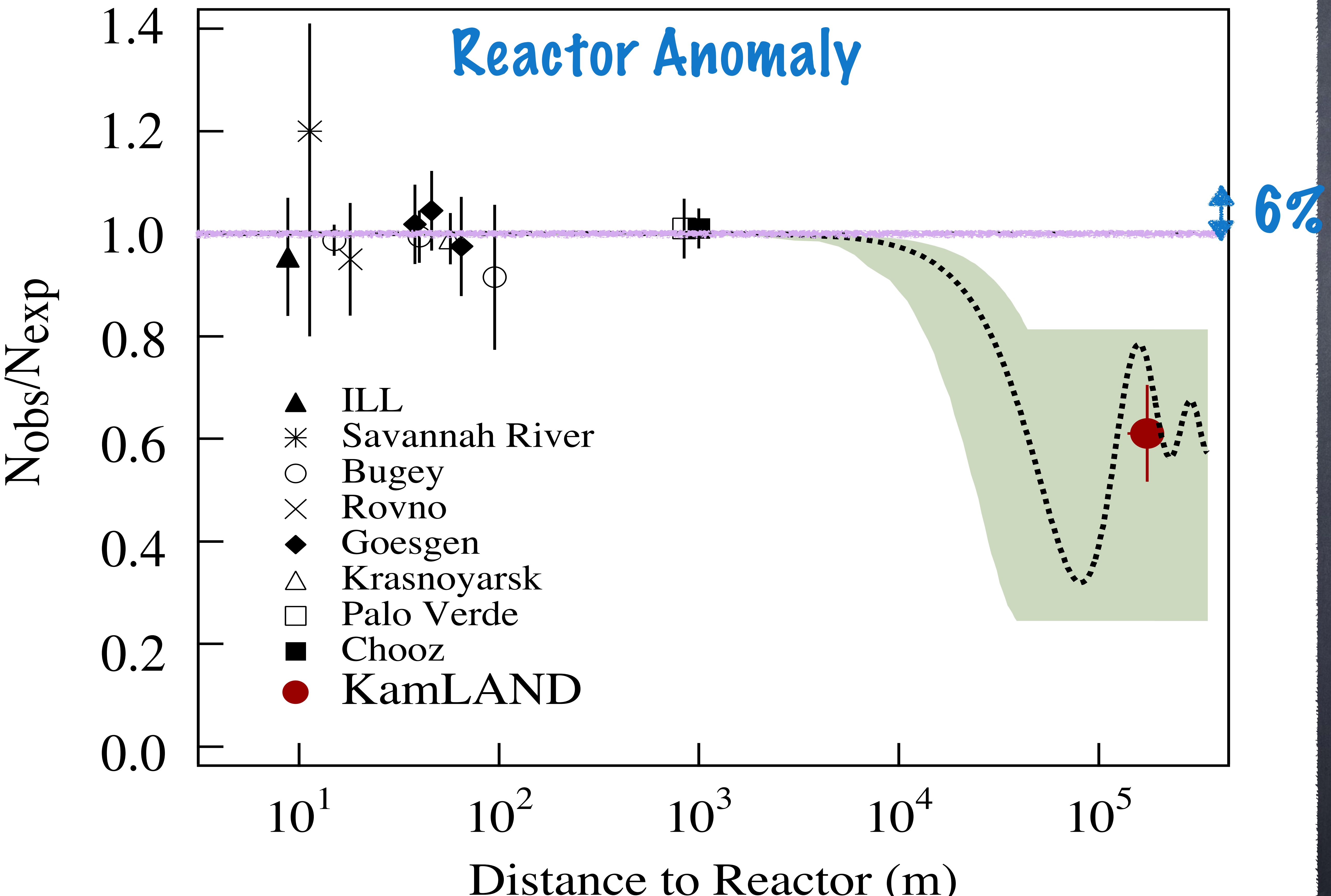
- Daya Bay's result is consistent and of comparable precision to that of accelerator experiments
- Further improvement by JUNO (see later)



The 2016 Breakthrough Prize in Fundamental Physics: SuperK, SNO, T2K, KamLAND & Daya Bay

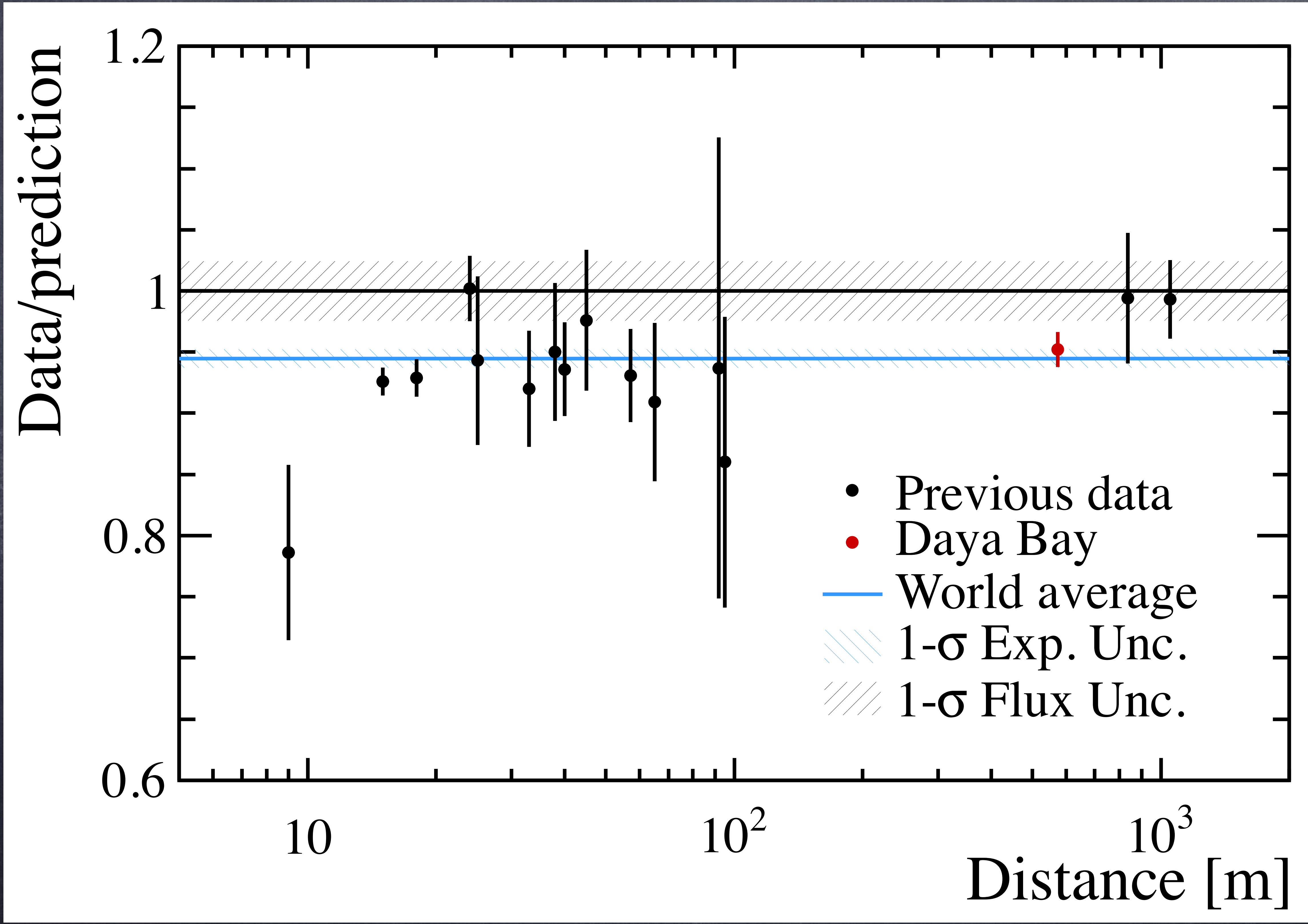
Source:Steve Jennings/Getty

Absolute measurements



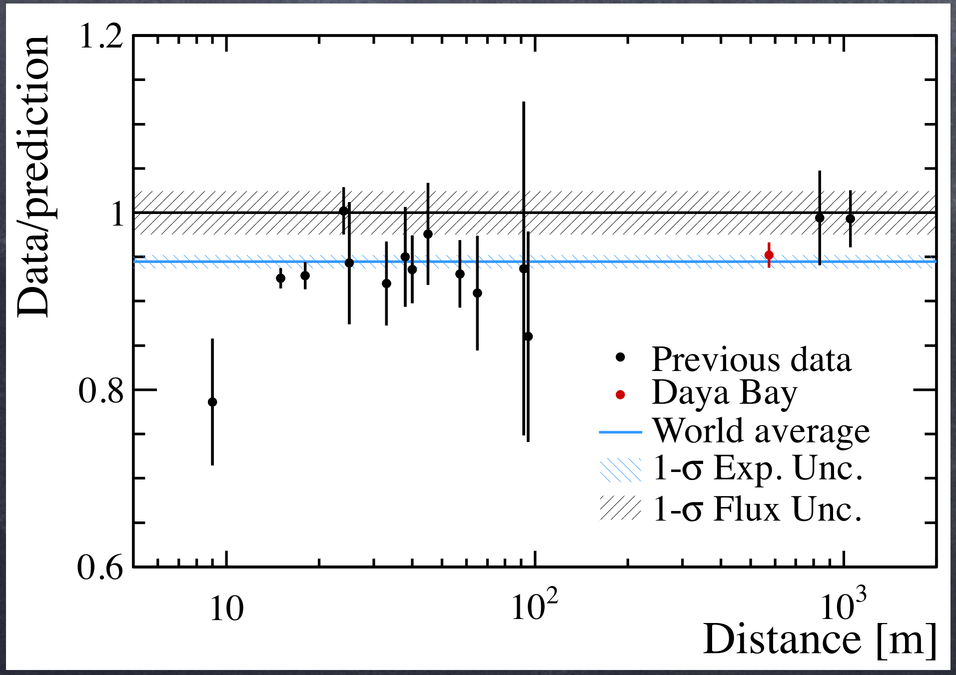
* Refer to A.Hayes lecture for more details

$$R = \frac{\text{data}}{\text{Huber+Muller}}$$



$$R = \frac{\text{data}}{\text{model}}$$

- Flux deficit observed w.r.t. Huber+Muller (new) model
  - Daya Bay R=0.952±0.014
  - Double Chooz R=0.945±0.008
  - RENO R=0.918±0.018
- No flux deficit w.r.t old model
  - Daya Bay R=1.001 ± 0.015 ± 0.027



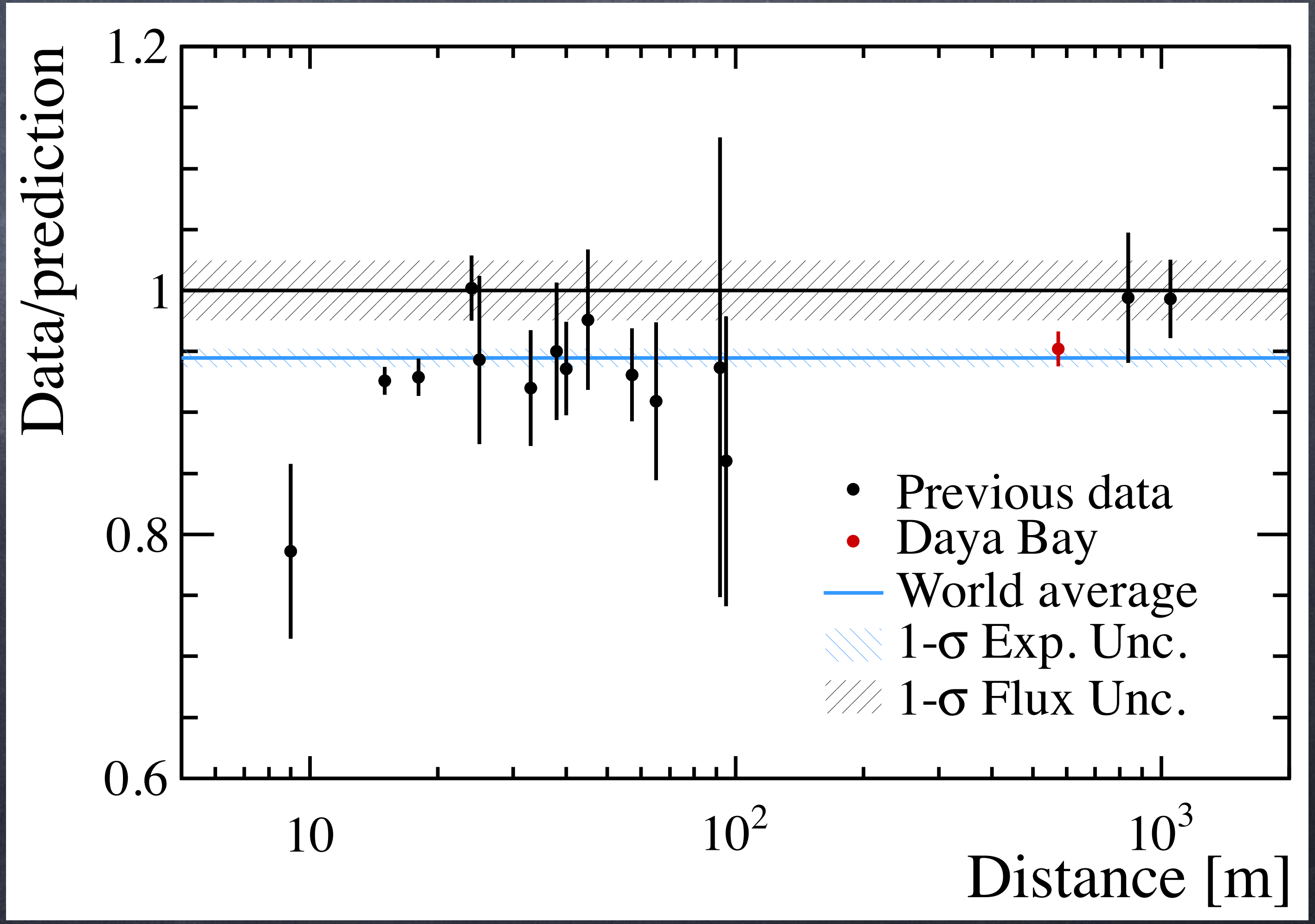
If new (Huber-Muller) model is correct?

YES

NO

- Sterile?
  - If yes, $\Delta m^2 \approx 1$ eV^2, $\sin^2 2\theta \approx 0.1$
- New phenomena?

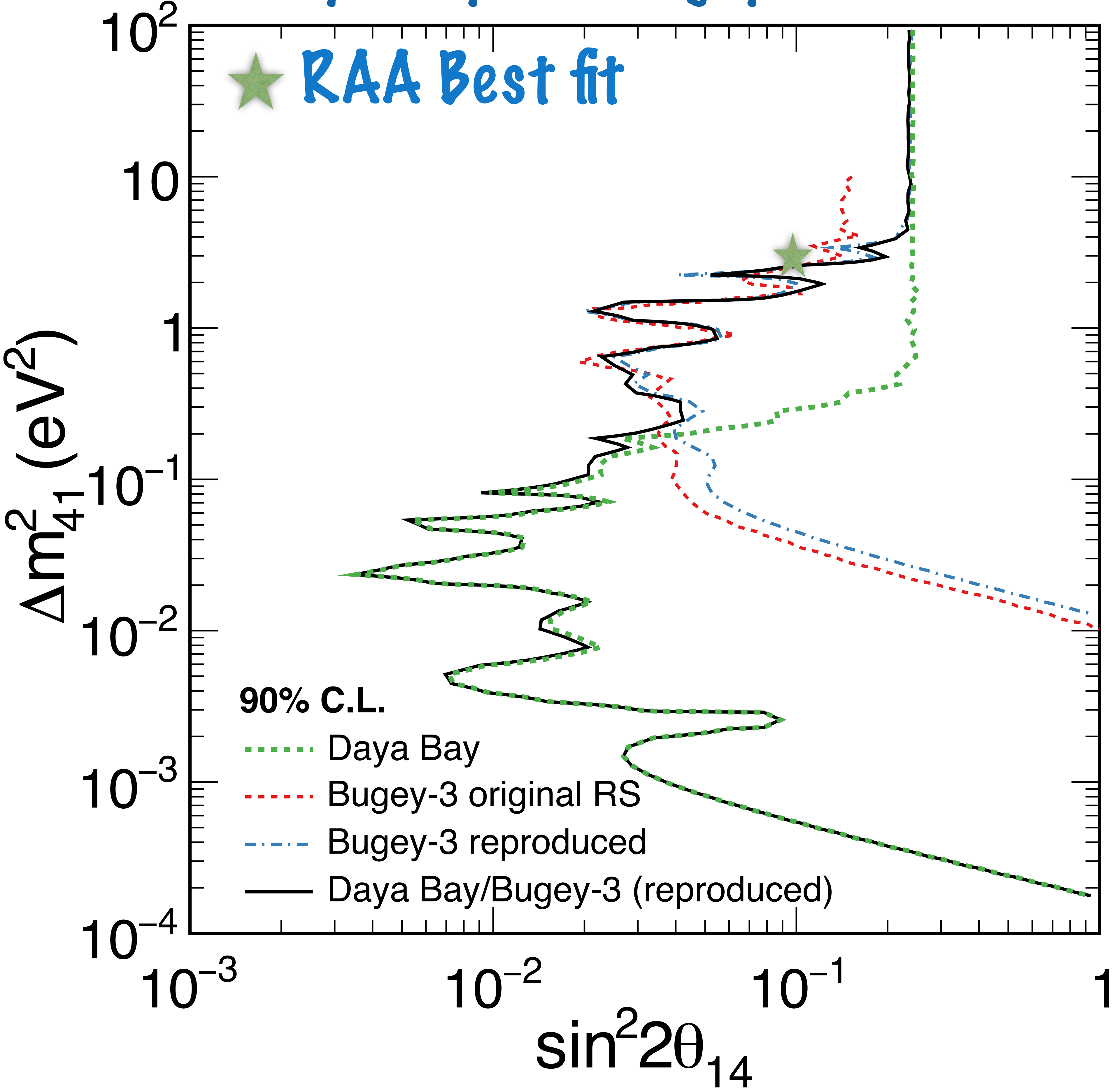
- Back to nuclear physics



Sterile Neutrino

* Refer to lectures of A.Hayes, C.Giunti, Yu.Shitov for more details

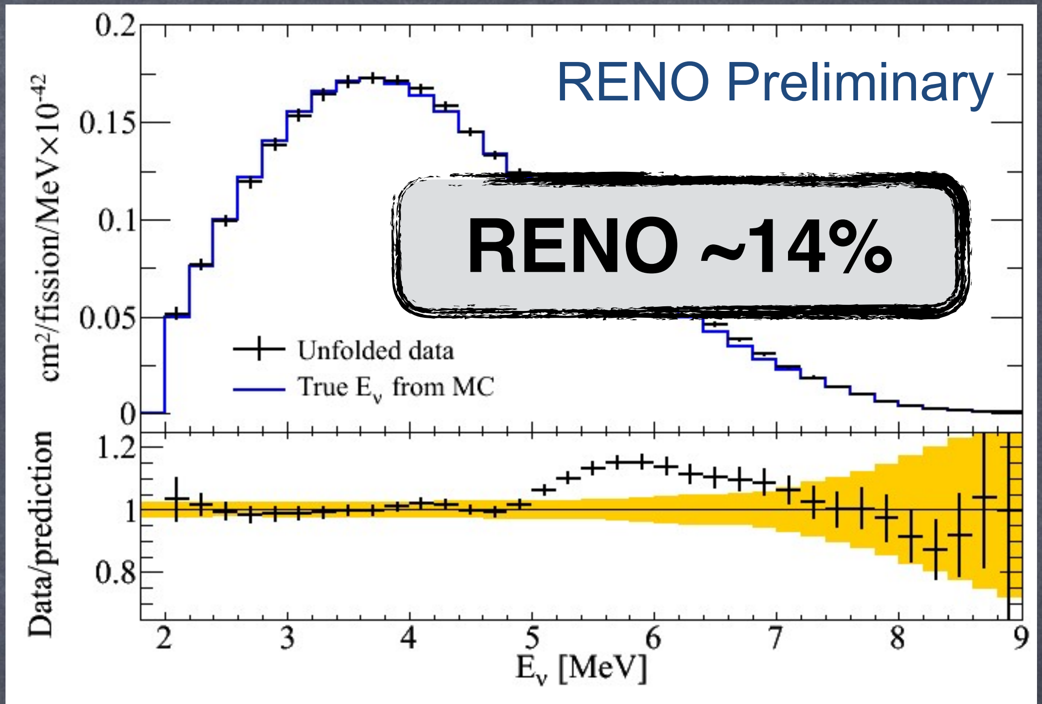
Daya Bay and Bugey-3 data

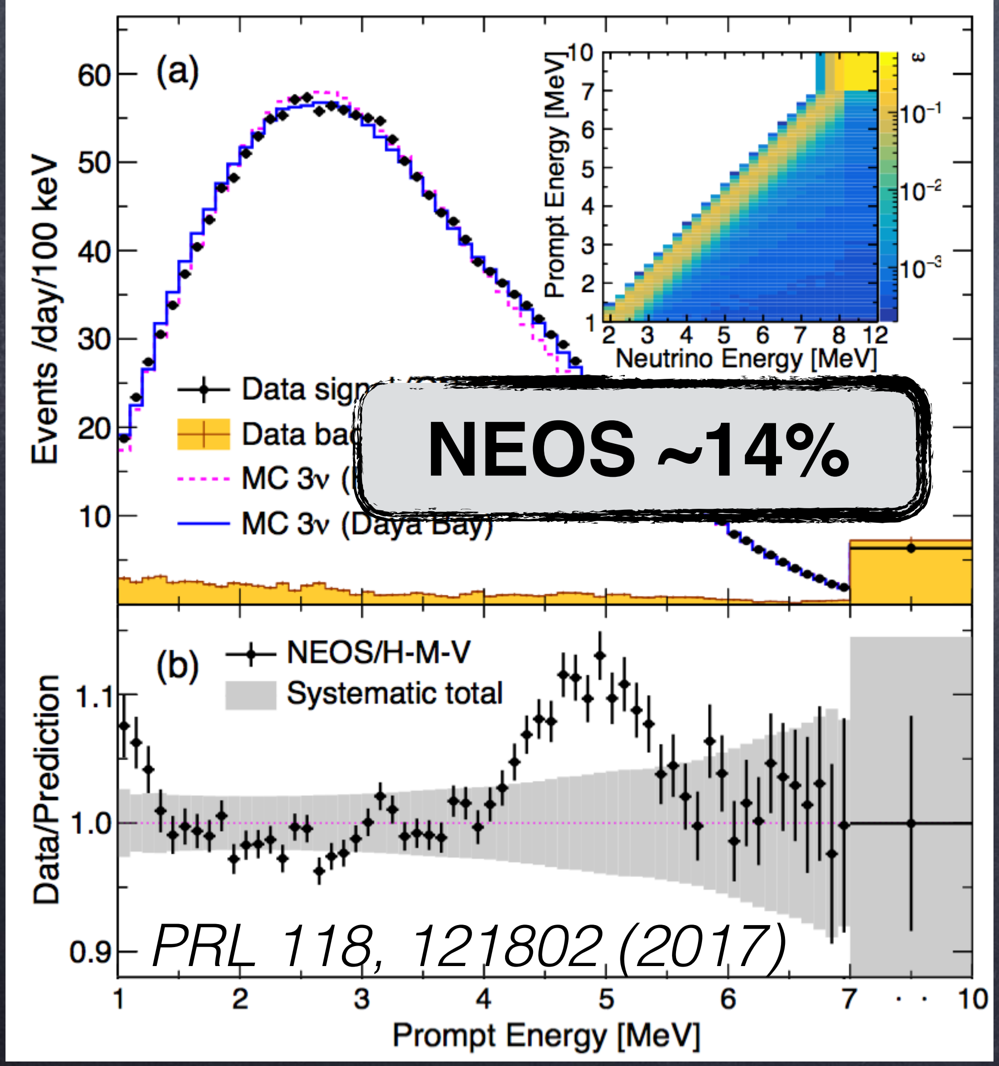


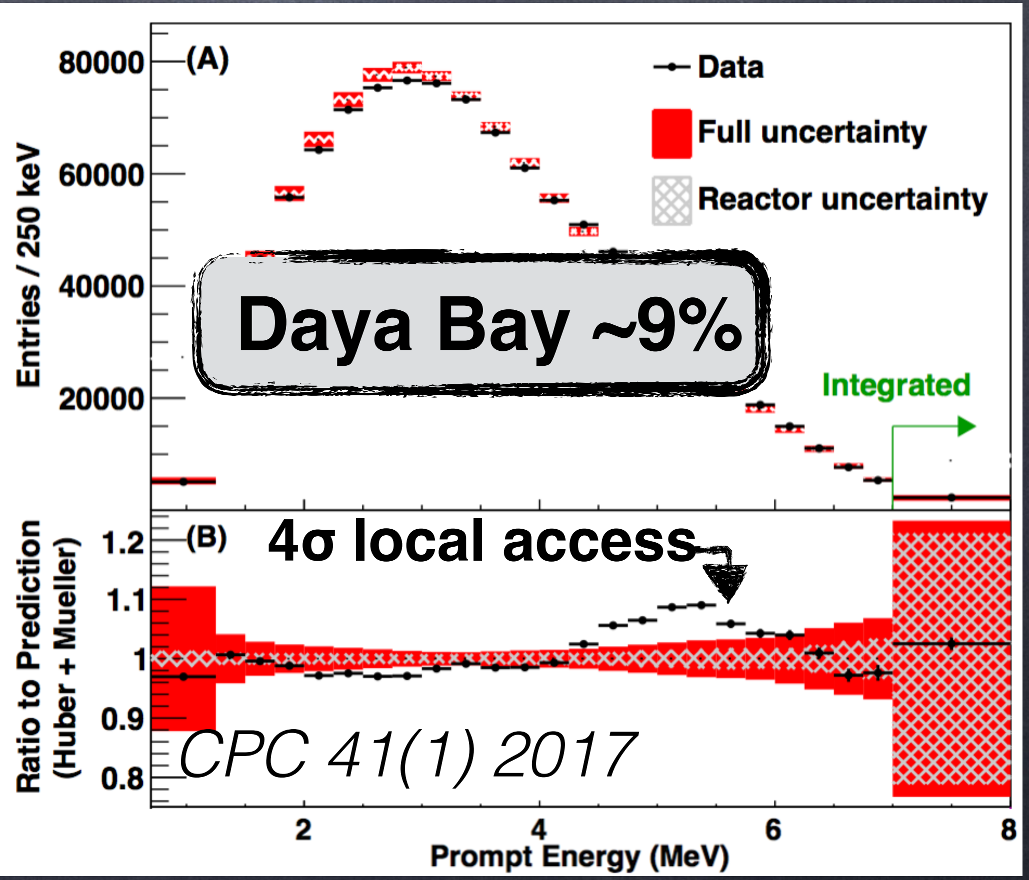
Spectrum measurement

Reactor Neutrino Spectrum Shape Anomaly

- Obvious discrepancy with model
  - Not a detector effect
  - Not due to sterile neutrinos
  - Could be prediction issues







Too many?
Are you tired?

You do not know what means to be tired

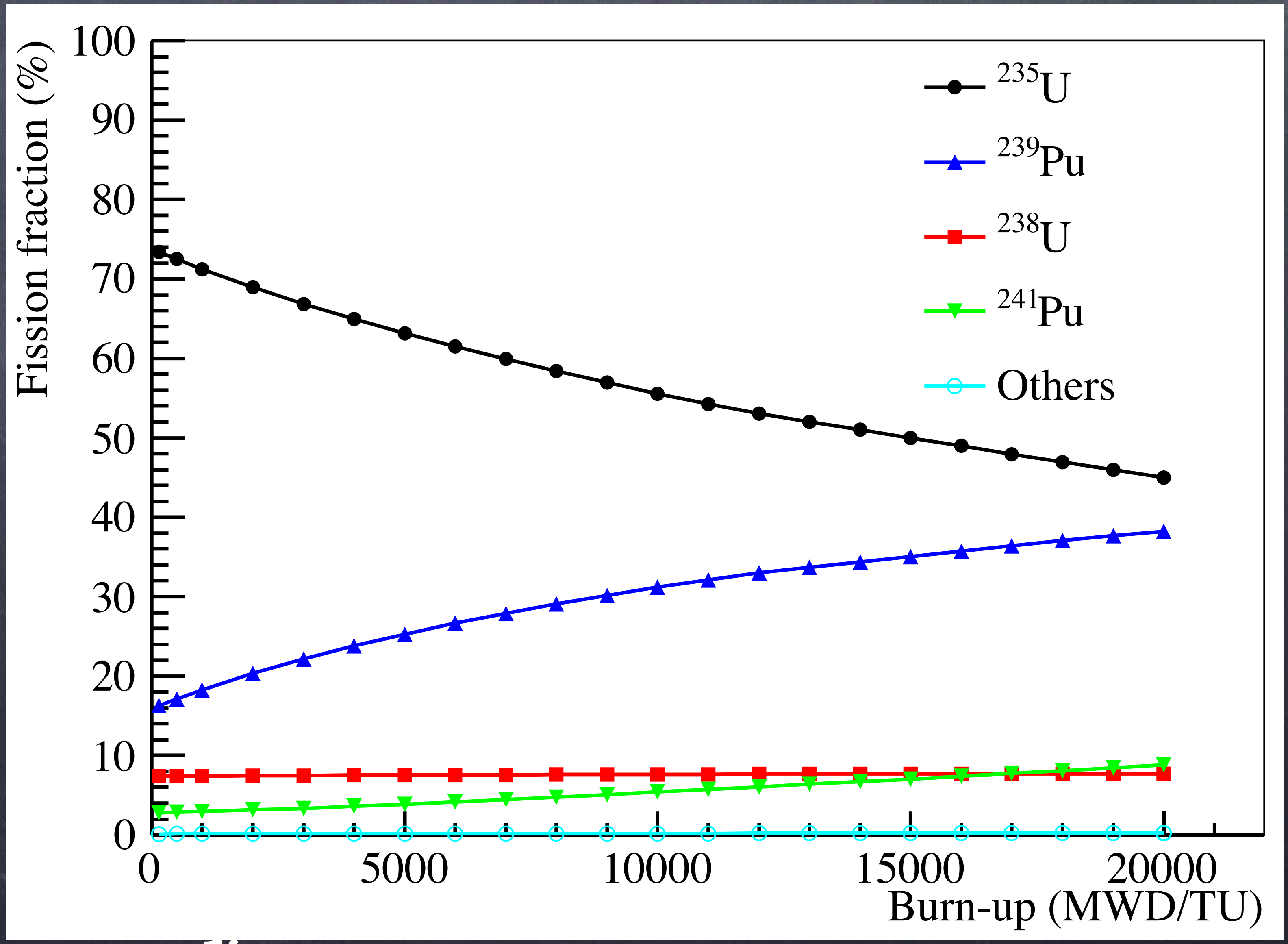
This is Kirill.
Kirill did not reach ...
He is tired a bit...

Measurement of neutrino spectrum from individual isotopes

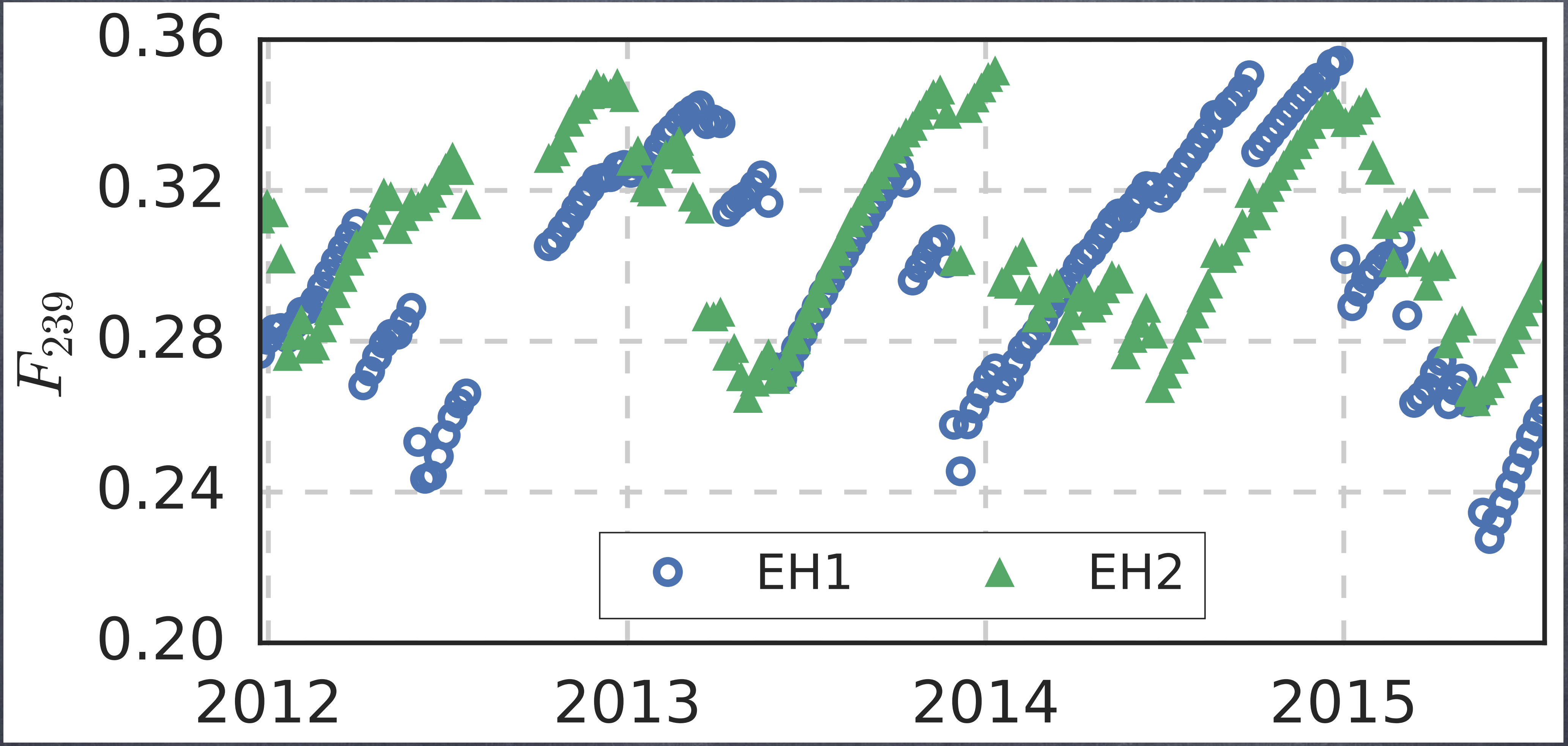
$$N_{IBD} \propto \sigma_{IBD} \sum_{i=isotopes} f_i \times S_i \equiv \sum_{i=isotopes} f_i \times \sigma_i$$

Spectrum of i-th isotope

Fission fractions evolve with time



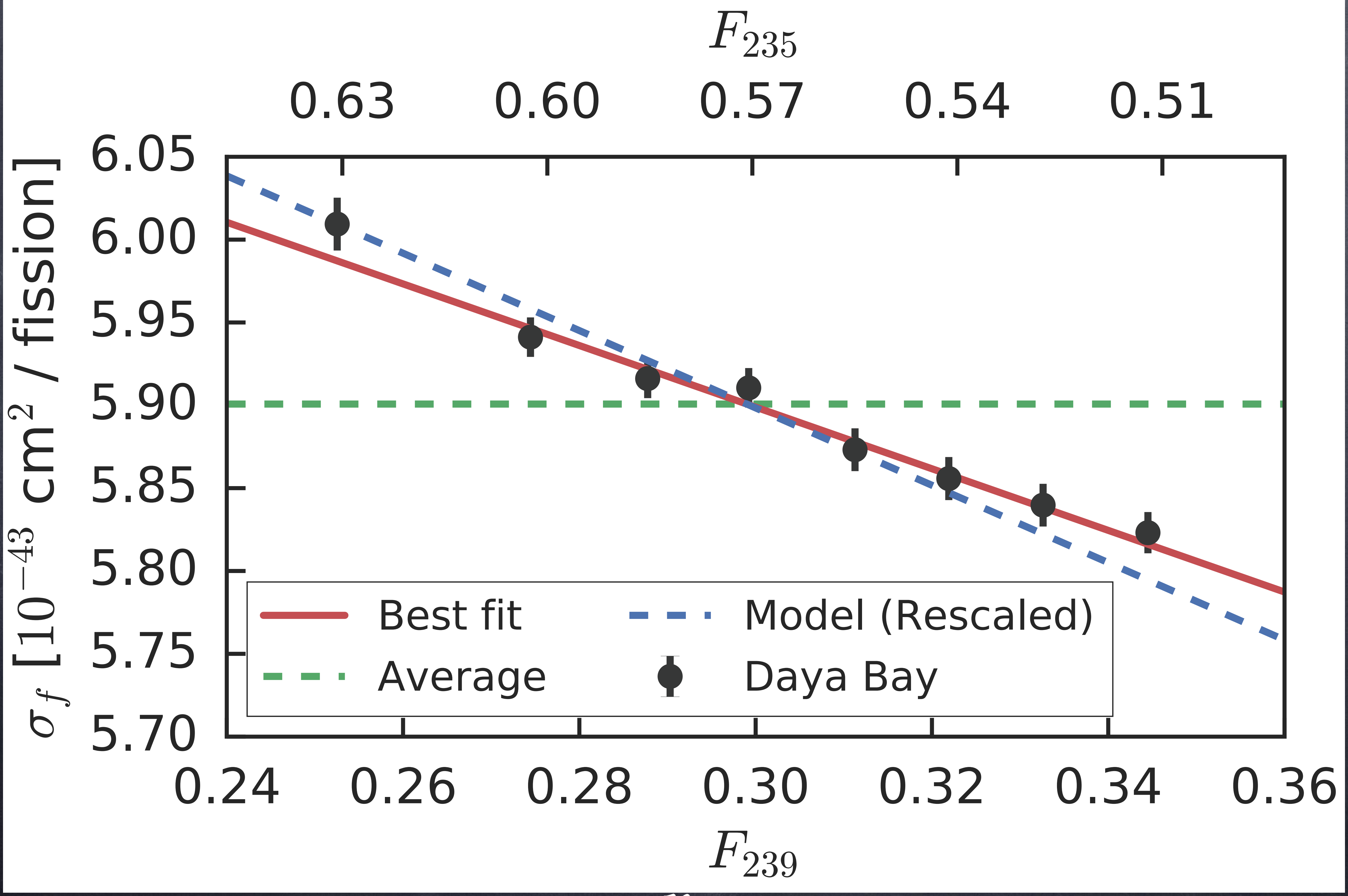
- Time evolution —> F_{239} evolution



- Observed N_{IBD}+ F_{239} evolutions —> individual isotopes

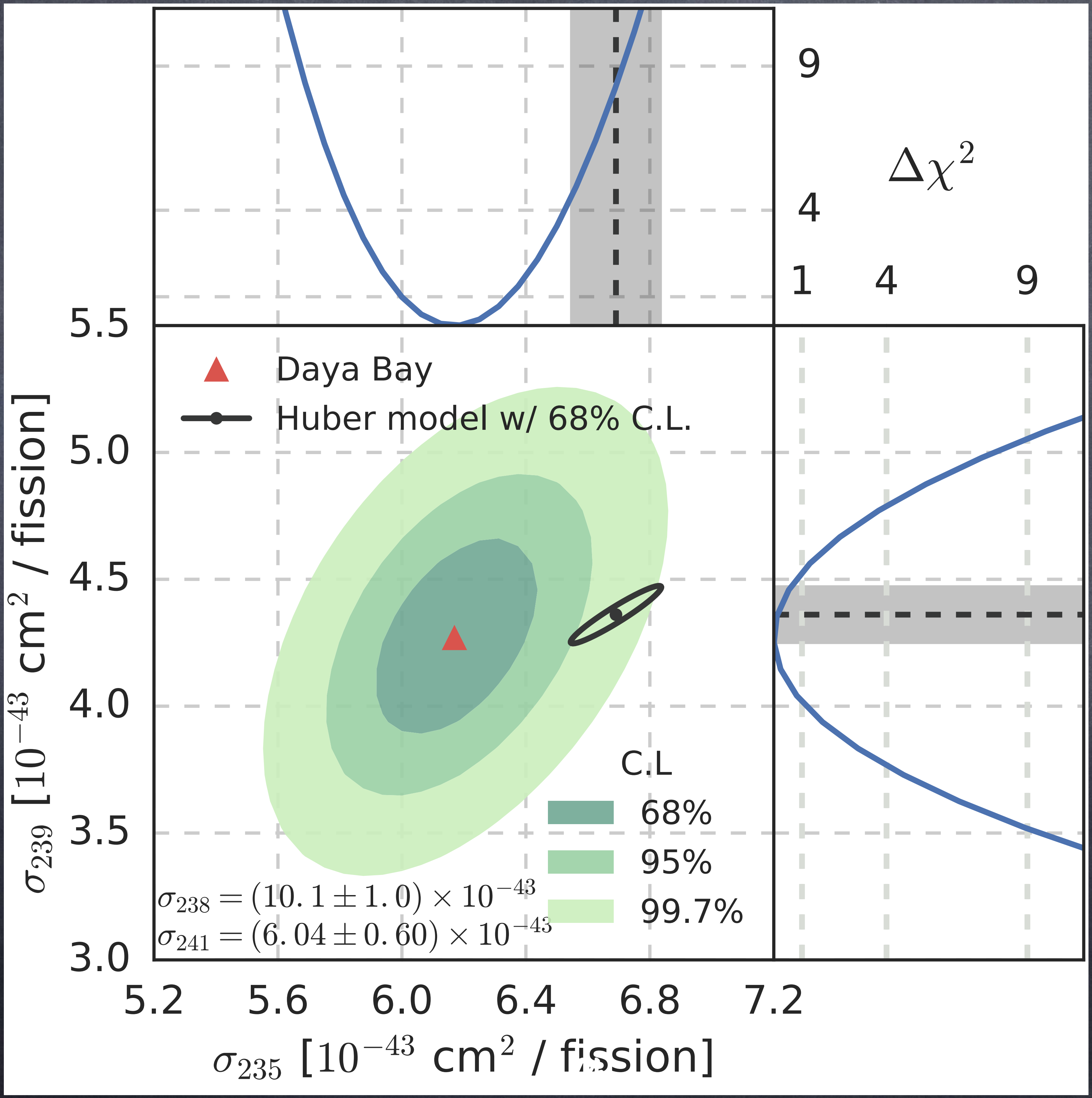
Fuel evolution measured by Daya Bay with unprecedented precision in 2017

PRL 118, 251801 (2017)



- U235 is off the HM model

PRL 118, 251801 (2017)



- Conclusions:
  - Wrong model for ^{235}U is behind most of the reactor flux anomaly
  - Explanation of flux anomaly purely by sterile neutrinos $\Longleftrightarrow$ equal deficit disfavored at 2.8σ

Reactor Flux Anomaly Cause	Suggests	$\Delta\chi^2$/NDF	Confidence level
^{235}U only	Prediction issues	0.17/1	Very probable
^{239}Pu only	Prediction issues	10.0/1	Disfavored at 3.2σ
All isotopes w/ equal deficit	Sterile neutrinos	7.9/1	Disfavored at 2.8σ

Nevertheless, Daya Bay did not rule out sterile neutrinos completely!
Composite model still possible

Coherent Scattering

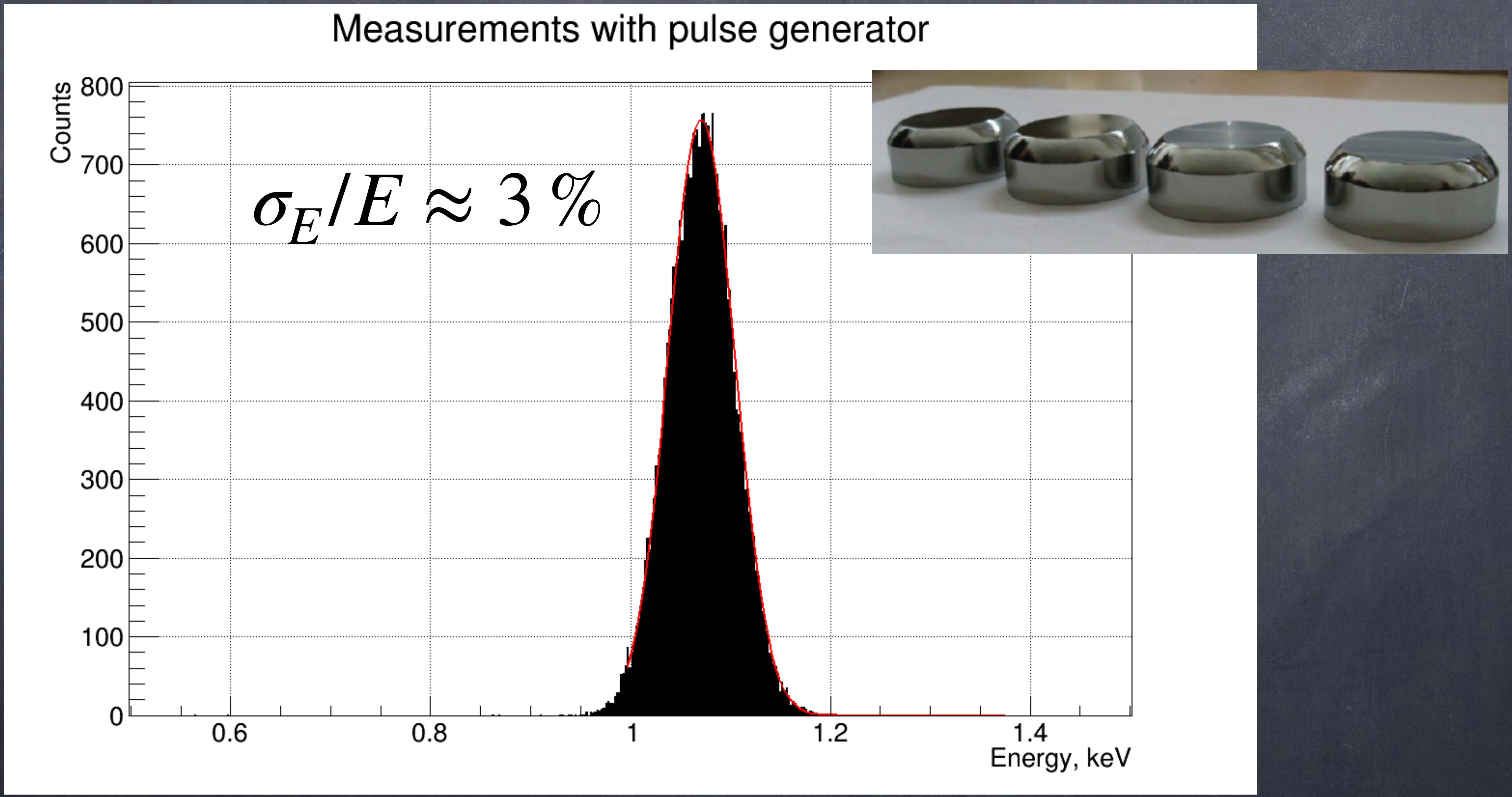
* Refer to lectures of H.Wong, Y.Sobczyk for more details

ν GEN @JINR

- JINR low threshold high purity Ge detectors

ν GEN @JINR

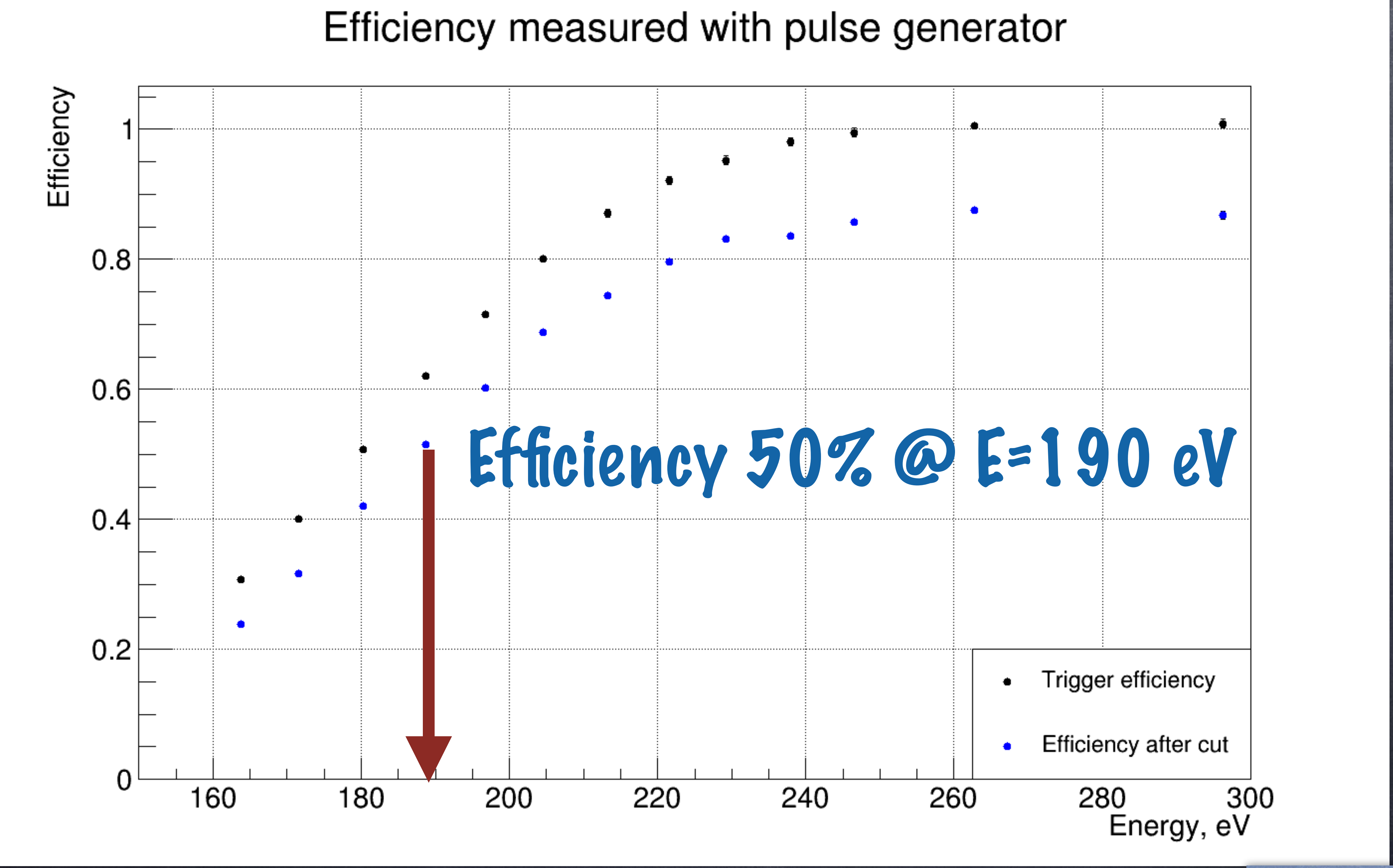
- Energy resolution (FWHM) = 78 eV



Source:A.Lubashevski

ν GEN @JINR

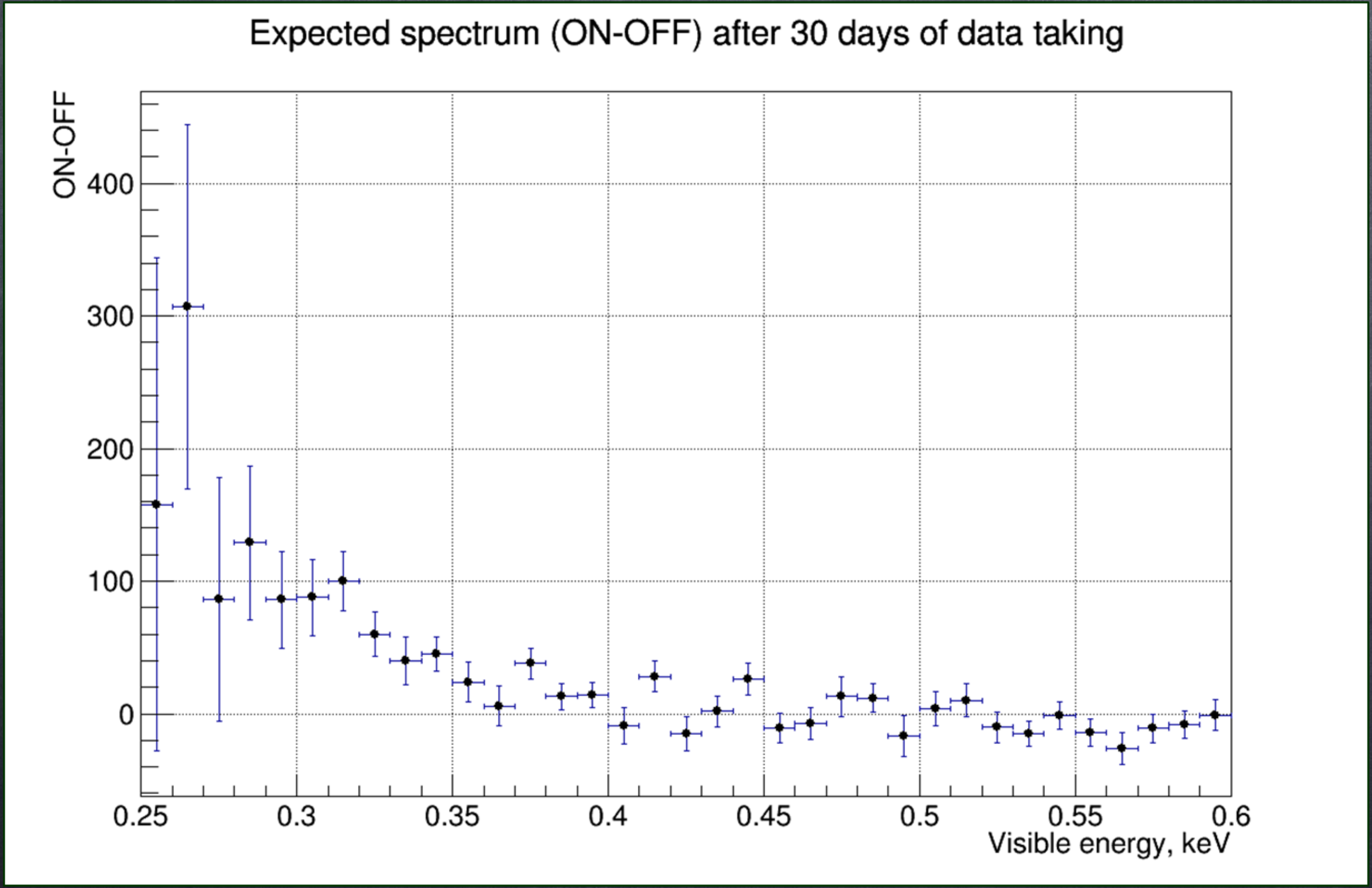
- Efficiency vs energy



Source:A.Lubashevski

ν GEN @JINR

- Expected spectrum in 30 days of data taking

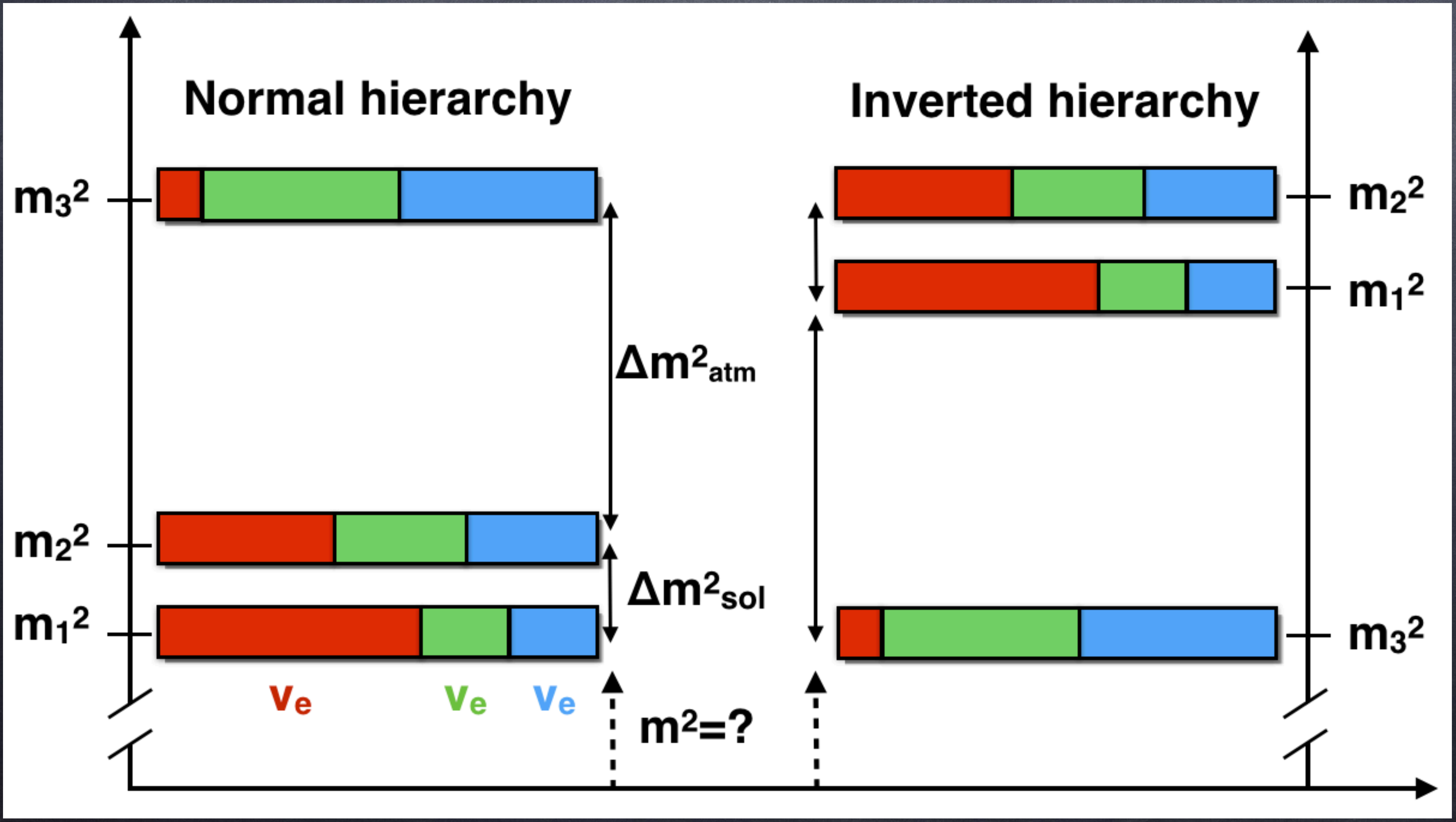


Source:A.Lubashevski

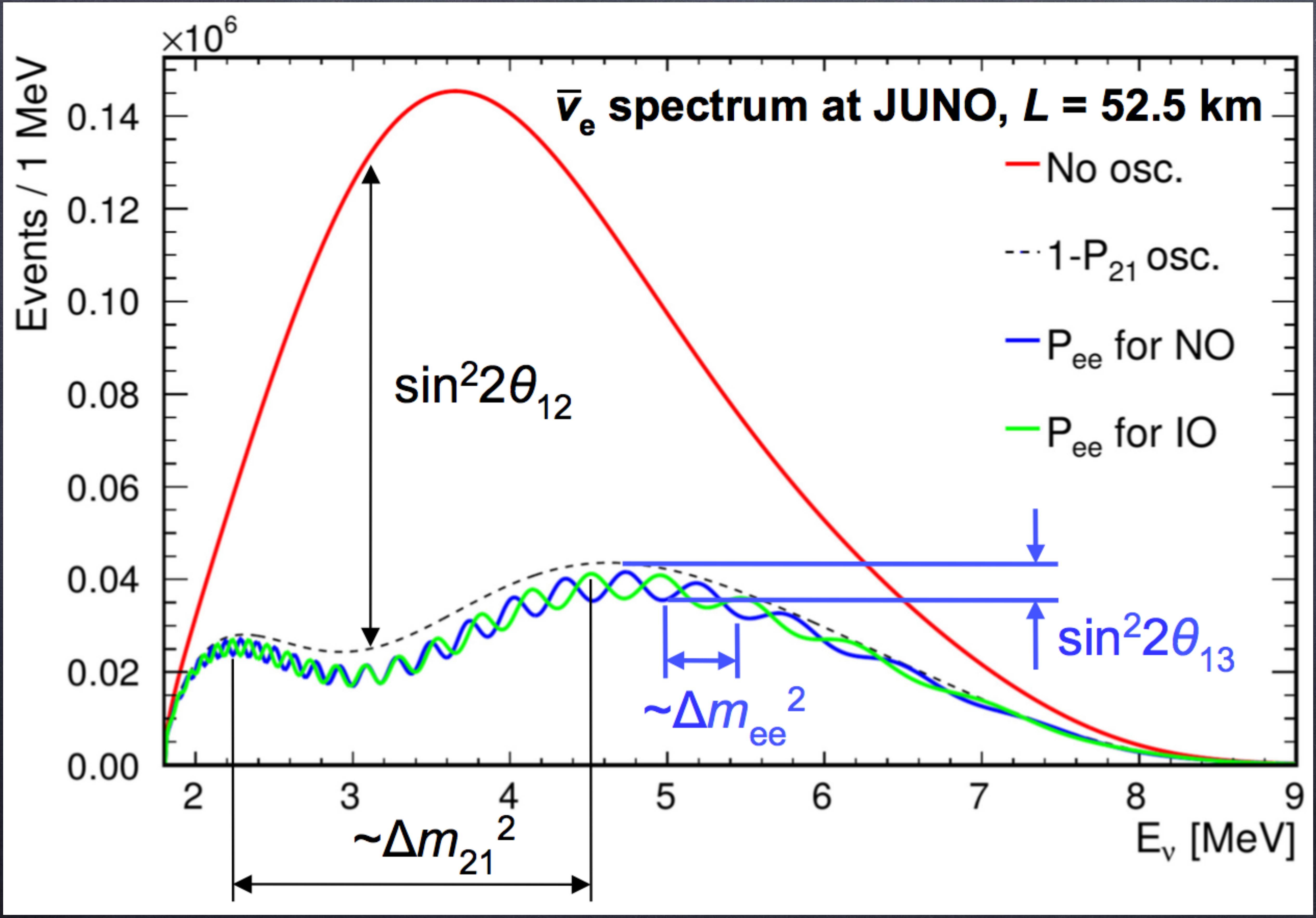
Mass Ordering

Neutrino Mass Ordering

Normal $m_3 > m_2\ (m_1)$ | **Inverted** $m_3 < m_1\ (m_2)$

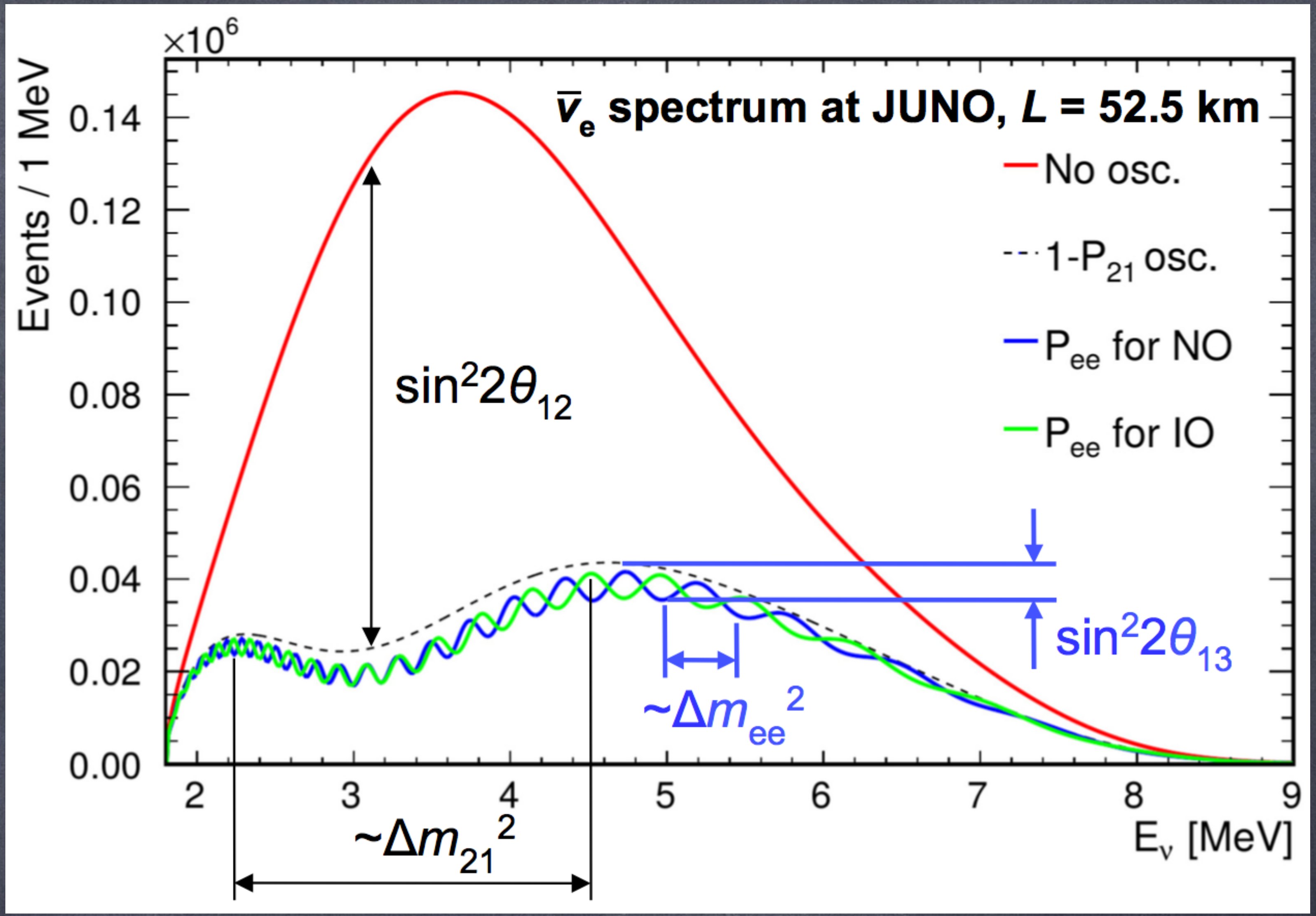


Expected signal



The requirements

- 20 ktons mass for detector
- $3\,\%/\sqrt{E}$ energy resolution
- Powerfull reactors (36 GW)

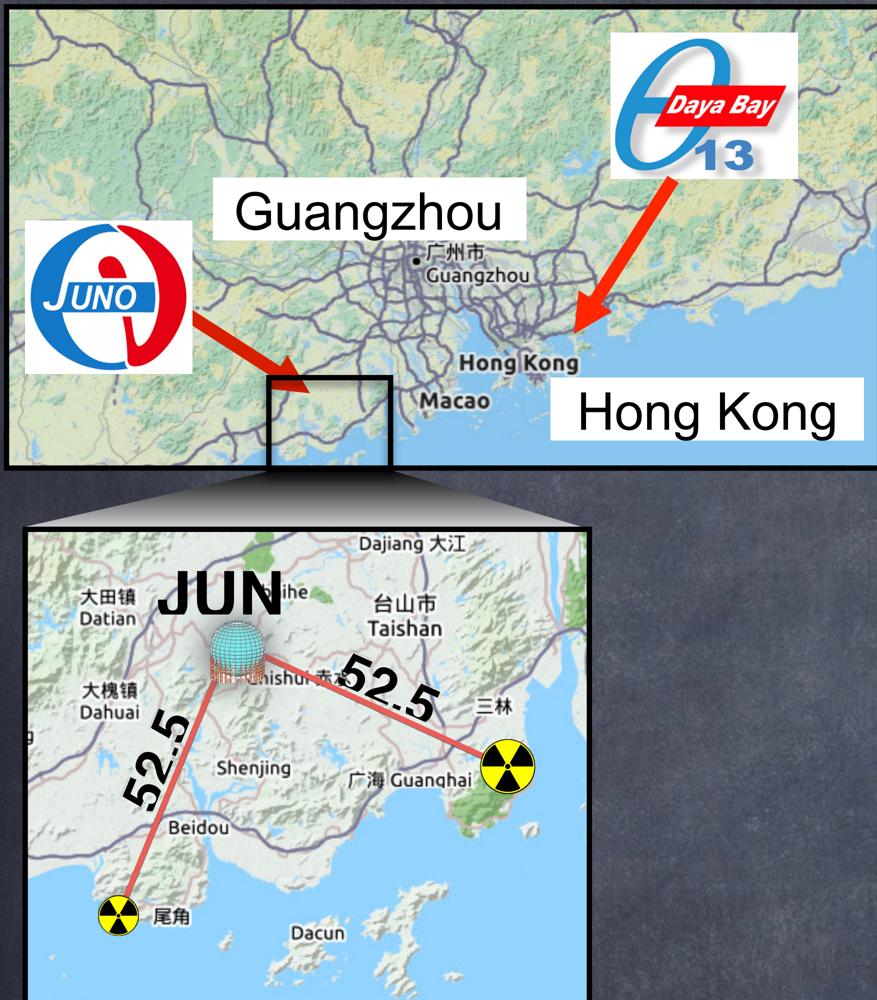


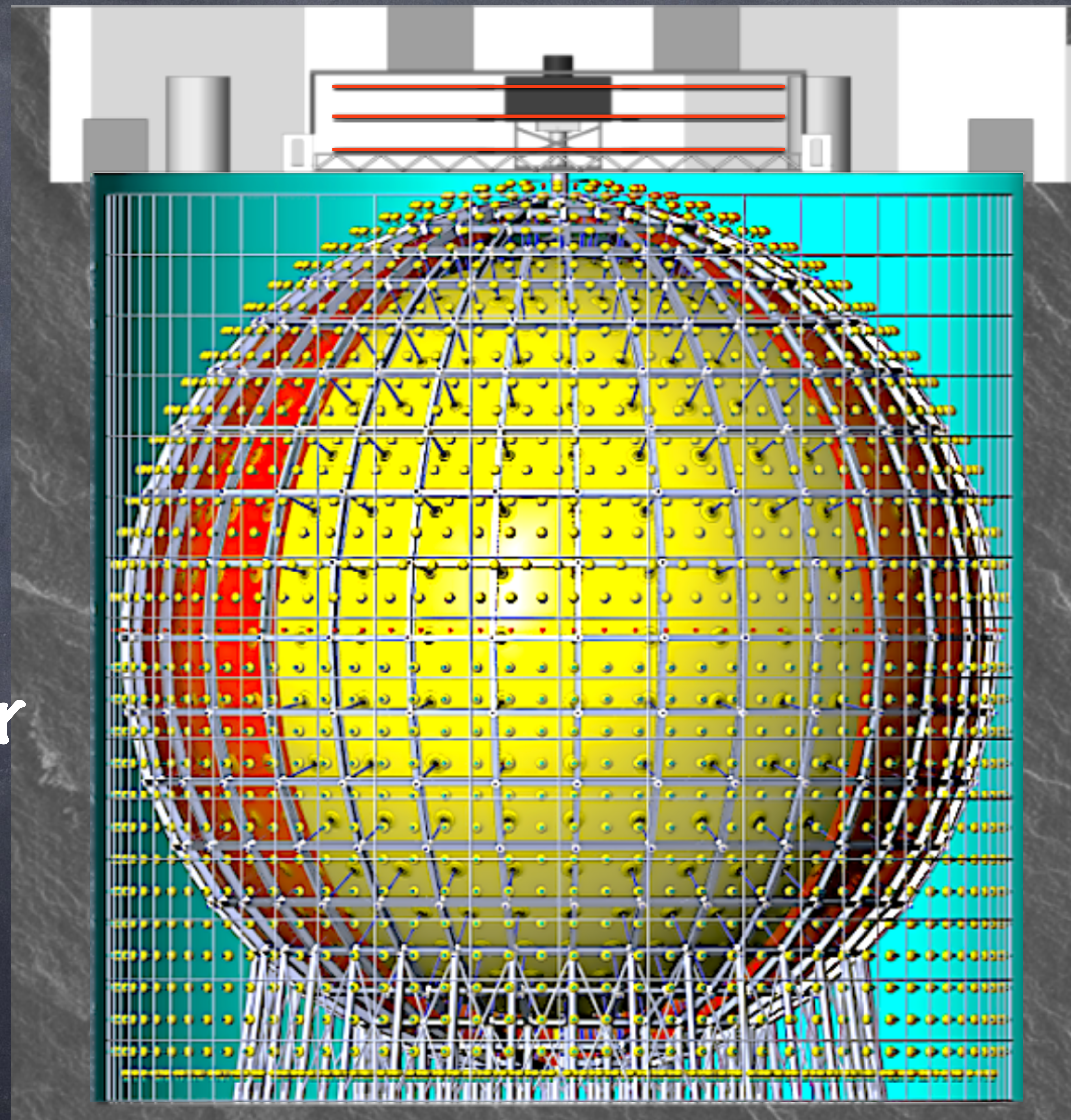
- JUNO is the first experiment to see both Δm^2

JUNO location

- Powerful source: 10 nuclear reactors (26.6 TW_{th} in 2021, later 35.8 GW_{th})
- Ideal baseline: 52.5 km
- Shielding: 700 m underground

JUNO central detector





- About 40 diameter
- 20 ktons
- 18k 20" PMTs
- 25k 3" PMTs
- 700 m shielding

JUNO Physics Program

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

JUNO Physics Program

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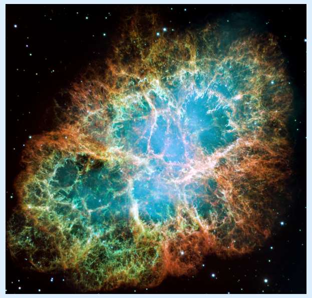
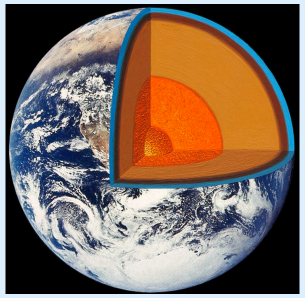
Δm_{31}^2	2.5% sign unknown	<0.5% sign determination

Other physics:

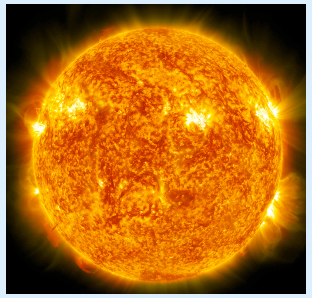
- **Supernova (SN) neutrinos**
  - 10^4 events from SN @ 10 kpc
  - Testing SN models
  - Possibility of independent determination of MH



- **Diffused SN neutrinos**
  - 1-4 events per year
  - Discovery if measured
- **Geoneutrinos**
  - From U/Th decays



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



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

Very short baseline experiments

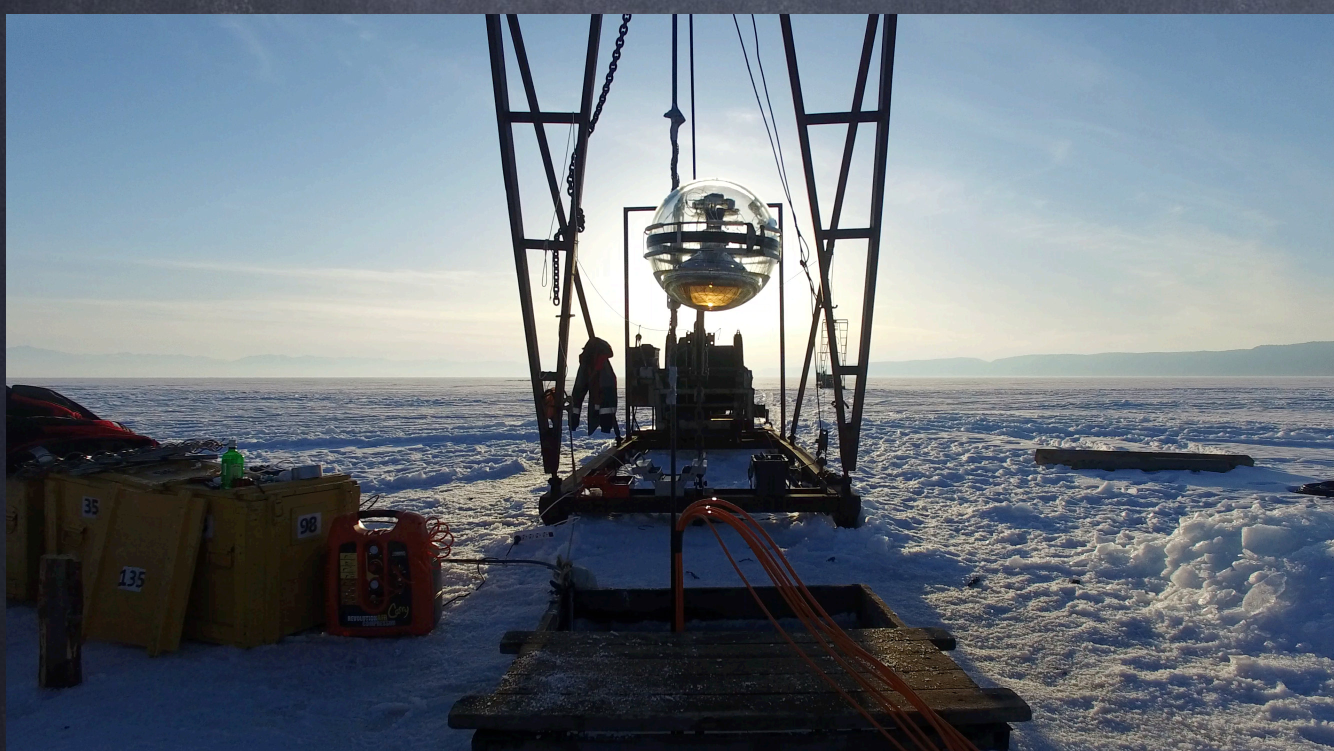
Experiment	Reactor power [MW_{th}]	Distance [m]	Target Mass [t]	Target type
NEOS	2700	25	1	GdLS
DANSS	3000	10-12	0.9	GdPS
STEREO	58	9-11	1.8	GdLS
PROSPECT	85	7-12	1	^{6}LiLS
SOLID	100	6-9	1.6	^{6}LiPS

LS=Liquid Scintillator PS=Plastic Scintillator

- Hunt for sterile neutrinos at ~1 eV scale $\Longleftrightarrow$ explanation of flux anomaly
- Precise measurement of reactor neutrino flux and energy spectrum for different fuel composition
  - Commercial reactors with mixture of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
  - Research reactors with mainly ^{235}U
- Challenge prediction models - measurement of ^{235}U yield&spectrum

Bonus
Jobs Offer @Dubna

https://inspirehep.net/record/1751642 Baikal GVD
https://inspirehep.net/record/1751641 Baikal GVD
https://inspirehep.net/record/1751640 Baikal & JUNO



* Why Baikal? Refer to lecture of N. Whitehorn