Neutrino Physics with Nuclear Reactors

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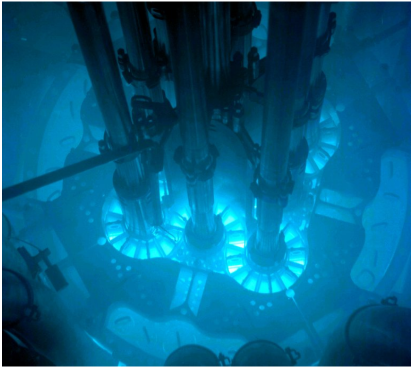
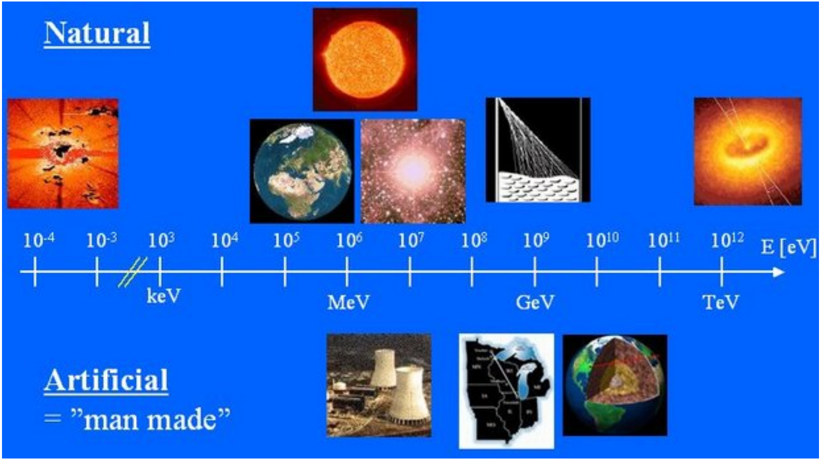
JINR

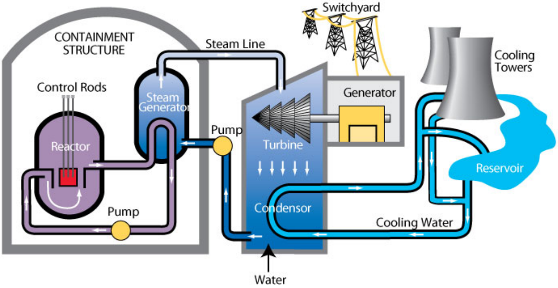
Mini-Workshop In Framework of the 72nd Board Meeting of the EPS Nuclear Physics Division
September, 27 2016

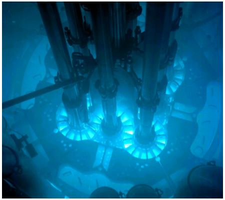


- Generations of quarks and leptons with definite mass do not mix in interactions with γ, Z^0
- They do mix in interactions with $W^{\pm}$
- The mixing is governed by unitary matrices V_{CKM} for quarks and V_{PMNS} for leptons
- $V_{3\times3}$ mixing matrix is parametrized by 3 mixing angles θ_{ij}, 1 CP-violating phase δ (2 more phase for Majorana neutrinos only)

- What do we want to learn?
  - $\hookrightarrow$ θ_{ij}, δ and neutrino masses m_i
- How can we learn it?
  - $\hookrightarrow$ Measurements of "neutrino mass": $m_\alpha^{\mathrm{eff}} = \sum_i |V_{\alpha i}|^2 m_i$
  - $\hookrightarrow$ Search for $0\nu2\beta$ decays: $m_{\beta\beta} = |V_{ei}^2 m_i|$
  - $\hookrightarrow$ Flavour appearance and disappearance in neutrino oscillations: $\theta_{ij}, \delta, \Delta m_{ij}^2$
  - $\hookrightarrow$ Cosmology and deep sky surveys limit $\sum_i m_i$

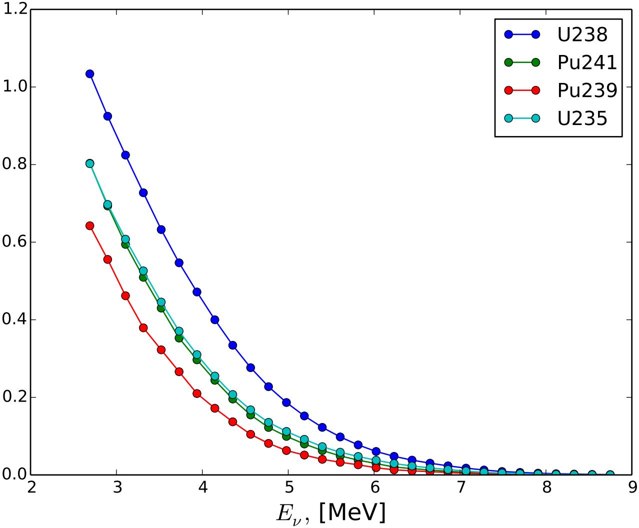

Natural
10^{-4} 10^{-3} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} E [eV]
keV
MeV
GeV
TeV
Artificial
= "man made"

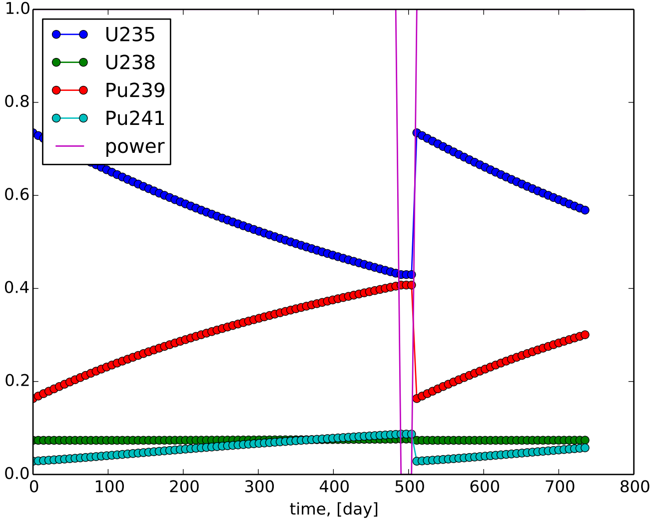


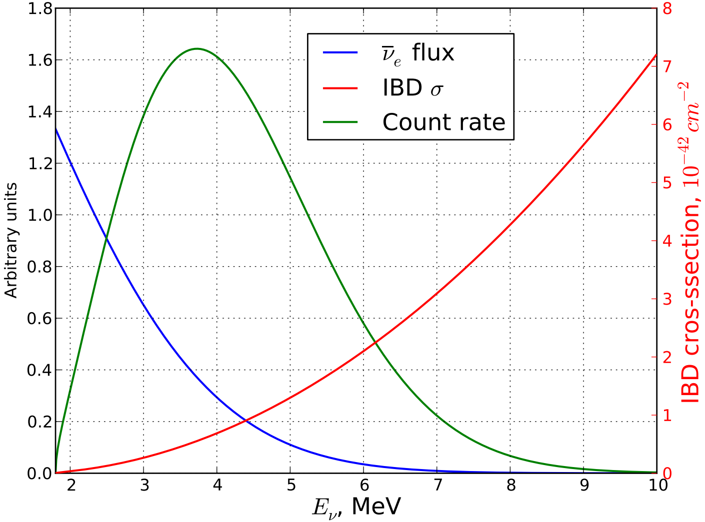


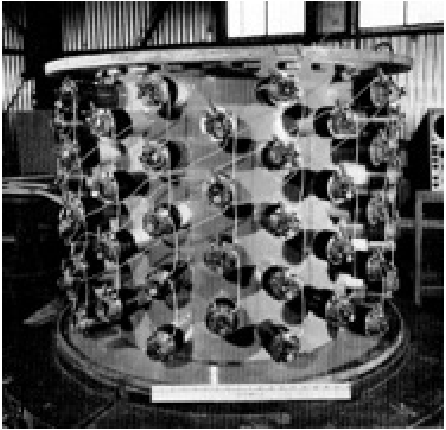
Inside of a Nuclear Reactor

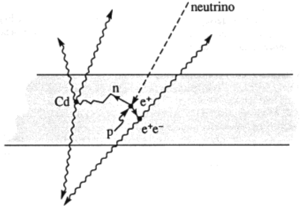
- Nuclear plant gets its power via fission of uranium and plutonium isotopes.
- About 11% of world energy is produced in reactors.
- 437 nuclear power reactors operating in 31 countries
- Each fission releases about 200 MeV of energy and six antineutrino.
- Typical $3\mathrm{GW}_{\mathrm{th}}$ reactor emits $6 \cdot 10^{20} \bar{\nu}_e/\mathrm{s}$.


1.2
1.0
0.8
0.6
0.4
0.2
0.0
2
3
4
5
6
7
8
9
E_ν, [MeV]
U238
Pu241
Pu239
U235

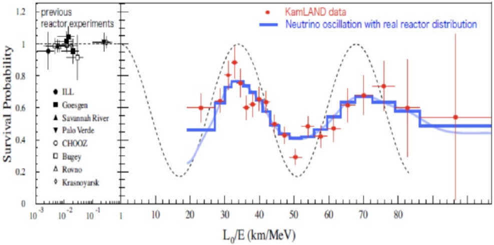

U235
U238
Pu239
Pu241
power
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
600
700
800
time, [day]

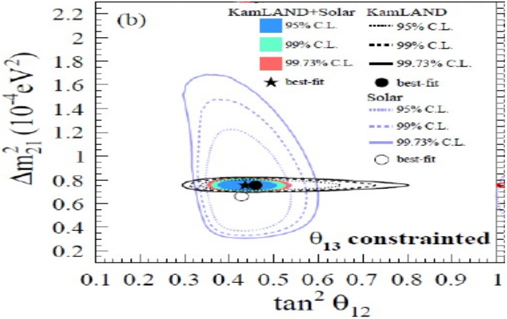

$\overline{\nu}_e$ flux
IBD σ
Count rate
Arbitrary units
IBD cros-ssection, $10^{-42} cm^{-2}$
E_ν, MeV
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
2
3
4
5
6
7
8
9
10
8
7
6
5
4
3
2
1
0

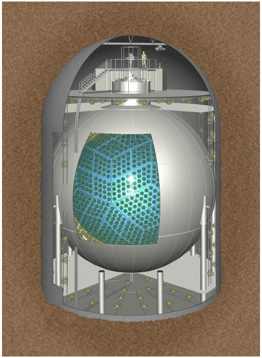




- F.Reines and C.Cowan, $\bar{\nu}_e$ discovery in 1956
- The proposed method is now the standard in all reactor neutrino experiments
- Nobel Prize to F.Reines in 1995.







KamLand + solar data yield

$$\sin^2\theta_{12} = 0.307^{+0.018}_{-0.016},$$

$$\Delta m^2_{21} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\text{eV}^2.$$

Figures from [1409.4515]

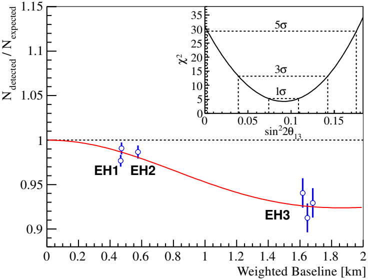
First indications

- $\sin^2 2\theta_{13} < 0.15$ by Chooz. Phys.Lett.B466:415-430,1999
- First hints in 2011 (but no results $\gtrsim 3\,\sigma$ for $\theta_{13} > 0$):
  - Tensions between solar, reactor oscillations suggest $\theta_{13} > 0$. G.L. Fogli *et al.*, Phys. Rev. D84, 053007 (2011)
  - MINOS, T2K, Double Chooz indicated $\theta_{13} > 0$

Discovery (2012)

Two reactor experiments Daya Bay (5.2σ) and RENO (4.9σ) observed a clear deficit in the event rate at far site:

$$\sin^2 2\theta_{13} = \begin{cases} 0.092 \pm 0.017 \text{ Daya Bay} \\ 0.113 \pm 0.023 \text{ RENO} \end{cases}$$



The Breakthrough Prize in Fundamental Physics 2016

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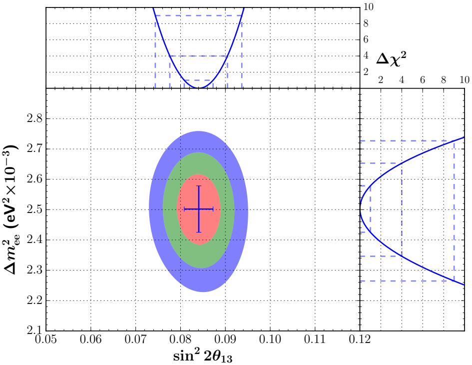


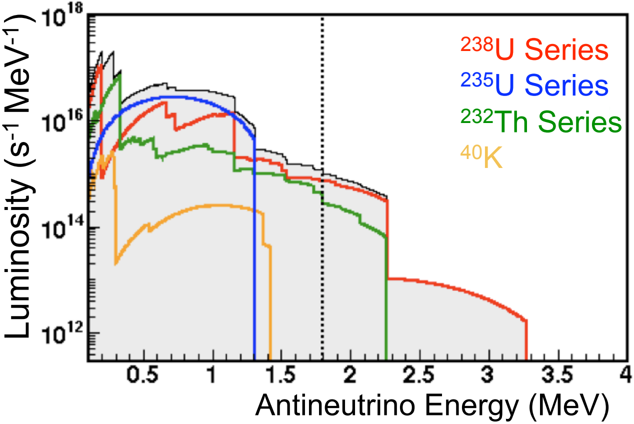
Current result (2016 based on 1230 days)
Daya Bay provides the most accurate measurement of $\sin^2 2\theta_{13}$ (25σ) and of Δm^2_{ee}:

$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(\text{stat.}) \pm 0.0019(\text{syst.})$$

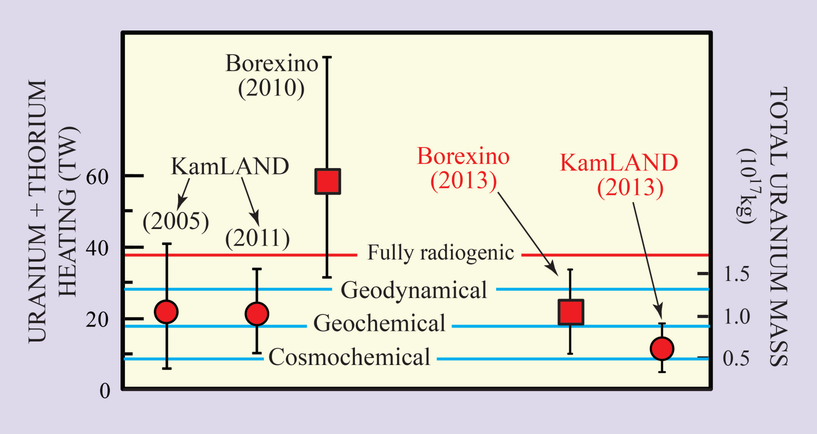
$$\Delta m^2_{ee} = (2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})) \cdot 10^{-3}\ \text{eV}^2$$

The Breakthrough Prize in Fundamental Physics 2016

- The main question: origin of heat in the Earth interior?
- Two main possible contributions (how much for each?):
  1. Primordial heat
  2. Decays of radioactive nuclei
     - Is there a geo-reactor?



- Primordial and radiogenic contributions are about the same



- Old reactor neutrino experiments yield data/theory $= 0.976 \pm 0.024$
- New theoretical calculation predicts theory by 3% lower thus leading to a *reactor anomaly* with data/theory $= 0.943 \pm 0.023$ [hep-ex/1101.2755], Phys.Rev.D83:073006,2011
- If interpreted in terms of neutrino oscillations one needs $\Delta m^2_{\mathbf{new}} \simeq 1\mathrm{eV}^2 \neq \Delta m^2_{21,31,32}$ and $\sin^2 2\theta_{\mathbf{new}} \simeq 0.1$
  - ✓ Since $\Gamma_{\mathbf{inv}}(Z^0) = 3\Gamma_{\nu\bar{\nu}}(Z^0) \hookrightarrow$ new neutrino should be *a sterile state=coherent superposition of 4 ν_i*

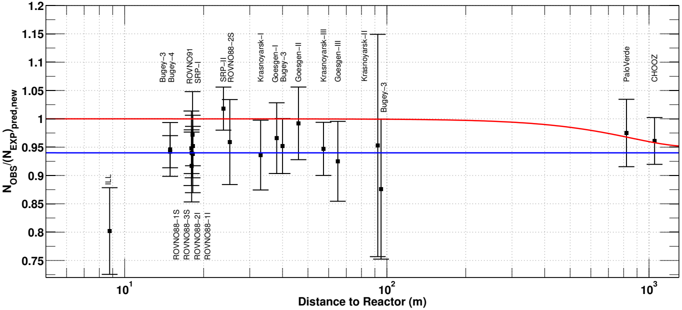


Figure from [hep-ex/1101.2755]

- The mixing of leptons is governed by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

- where $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$ are mixing angles, and $e^{-i\delta}$ is the CP-violating factor.

Parameter	best fit value ($\pm 1\sigma$)
$\sin^2\theta_{12}$	$0.307^{+0.018}_{-0.016}$
$\sin^2\theta_{23}$	$0.386^{+0.024}_{-0.021}$
$\sin^2\theta_{13}$	$0.024^{+0.0025}_{-0.0025}$

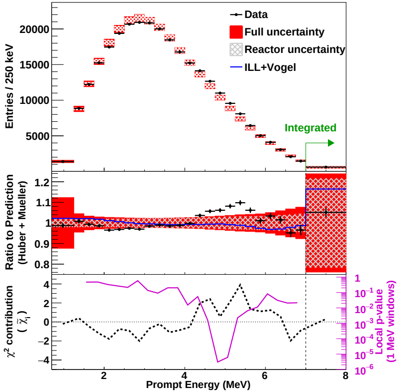
The summary of neutrino mixing angle parameters

Parameter	best fit value ($\pm 1\sigma$)
Δm^2_{21}	$7.54^{+0.26}_{-0.22} \times 10^{-5}\text{eV}^2$
$\lvert\Delta m^2_{\mu\mu}\rvert$	$2.43^{+0.06}_{-0.10} \times 10^{-3}\text{eV}^2$
m_e	< 2.05 eV
$\sum_i m_i$	< 0.66 eV
$m_{\beta\beta}$	$< (0.2 - 0.4)$ eV

The summary of neutrino mass parameters

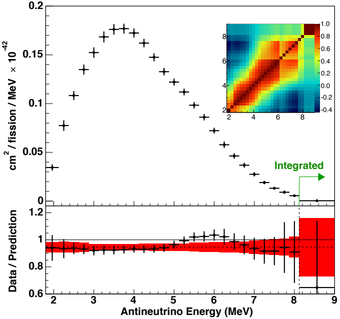
- **Mass hierarchy.**
  - $m_3 > m_1$ or $m_3 < m_1$.
  - accelerator (NOVA, T2HK, LBNE, LBNO), atmospheric (PINGU/ORCA, INO) and reactor neutrinos (JUNO, RENO-50)
- **CP violation.**
  - $\delta = ?$
  - T2HK, NOVA and LBNE, LBNO
- **Mixing matrix unitarity.**
  - $VV^\dagger \stackrel{?}{=} 1$
  - Do sterile neutrinos exist?
  - A long list of experimental proposals on the market.
- **Dirac vs. Majorana**
  - $\nu \stackrel{?}{=} \bar{\nu}$
  - GERDA, CUORE, KamLand-Zen, EXO, SuperNEMO

Observed positron spectrum



- Bump feature around 5–6 MeV.
- Consistent with other experiments.
- Seen for both Huber+Mueller/ILL+Vogel.

Extracted antineutrino spectrum



- **Global significance: 2.6σ.**
- **Local significance: 4σ.**

Claimed theoretical uncertainty of $2-2.7\%$ does not look reasonable

- One needs to measure the spectra due to each isotope
- This is a hard task and one may need several experiments to measure 235^{U} independently (PROSPECT) on ^{238}U, ^{239}Pu, ^{241}Pu.
- There is an ongoing work of JINR group in Daya Bay
- Other experiments with good energy resolution and large statistics are welcome

- Monitor the reactor power (first proposal by Borovoi and Mikaelyan).
  - ↪ Strong correlation between $\bar{\nu}_e$ rate and reactor power is found
- Monitor the Pu content
  - ↪ Change of $\bar{\nu}_e$ spectrum with time
  - ↪ Needs good energy resolution detector
  - ↪ Needs to understand how the reactor actually work (spectra)
- Develop a detector technology
  - ↪ Minimal overburden
  - ↪ Close to a reactor
  - ↪ Minimal shielding

Detection Coherent **N**eutrino–**Ge** **N**ucleus Elastic Scattering (KNPP).

Brief Summary

- $\nu + A \to \nu + A$ **Coherent Neutrino Nucleus Scattering** (CNNS)
- Recoil energy < 1 keV. JINR **low-threshold HPGe detectors** with energy threshold of **350 eV**.

- The background $\simeq$ 0.5 events/kg/keV/day.
- 10m from reactor core = 10 events per day.

JINR contribution

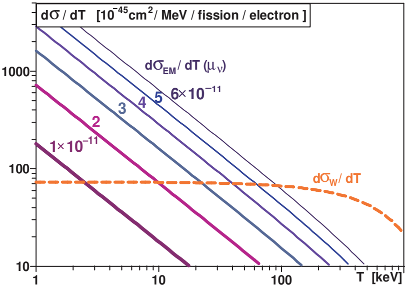
- Expertise in the production of unique low-threshold HPGe detectors

- This is JINR proposal
- Unique experience in conducting low-background $0\nu2\beta$-search experiments and low-threshold experiments (search for neutrino magnetic moment) at the KNPP.

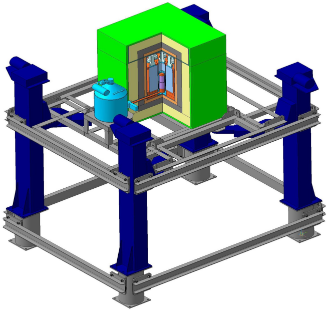
Expects to detect the coherent neutrino-nucleus scattering and measure CNNS cross-section in Ge during the nearest 3–5 years.

GEMMA = **G**ermanium **E**xperiment Searching for **M**agnetic **M**oment of **A**ntineutrino

- Standard Model: $\mu_\nu = 10^{-19} \frac{m_\nu}{\text{eV}} \mu_B$
- Extensions of SM: $\mu_\nu = 10^{-11 \div 12} \mu_B$ (Majorana) and $\mu_\nu < 10^{-14} \mu_B$ (Dirac)
- An observation of the $\mu_\nu > 10^{-14} \mu_B$ = New Physics + Majorana.



- Kalinin Nuclear Power Plant
- GEMMA result: $\mu_\nu < 2.9 \cdot 10^{-11} \mu_B$
- GEMMA-2 sensitivity: $\mu_\nu = 1.0 \cdot 10^{-11} \mu_B$
- Movable platform



Run by JINR and ITEP

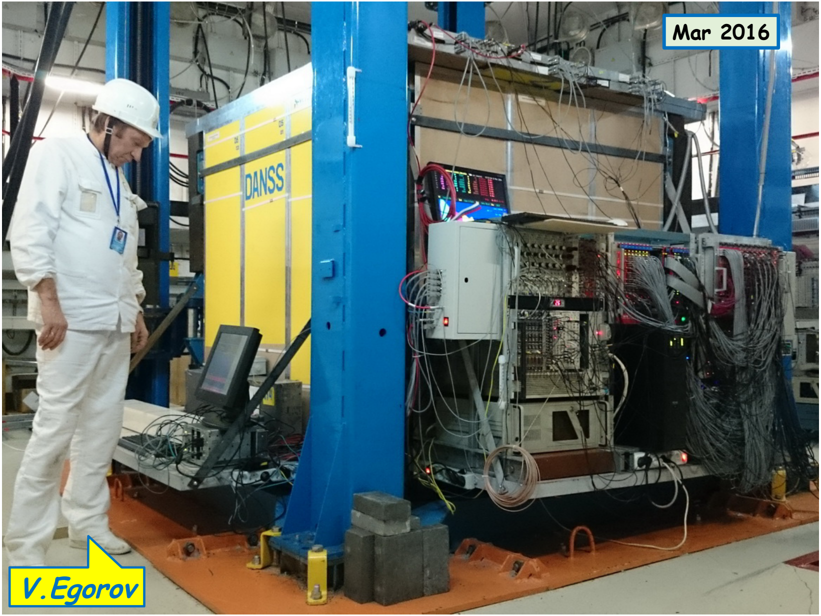
	Power (MW_{th})	Baseline (m)	Mass (ton)	Dopant	Seg.
PROSPECT (US)	85	6–20	1&10	^{6}Li	Y
NuLat (US)	1500	3–8	1	^{10}B& ^{6}Li	Y
NUCIFER (FR)	70	$\simeq 7$	0.7	Gd	N
STEREO (FR)	57	$\simeq 10$	1.8	Gd	N
DANSS (RU)	3000	9–12	0.9	Gd	Y
NEUTRINO-4 (RU)	100	6–12	1.5	Gd	N
POSEIDON (RU)	100	5–8	1.3	Gd	N
SOLID (UK)	45–80	6.8	2.9	Gd, ^{6}Li	Y
HANARO (SK)	30	6	1	Gd	Y

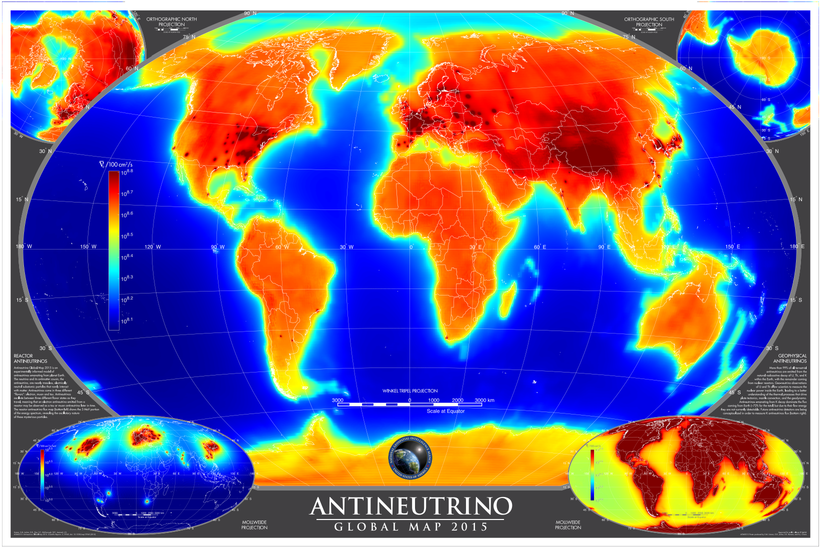
Challenges:

- Background suppression
- Calibrations

Advantages:

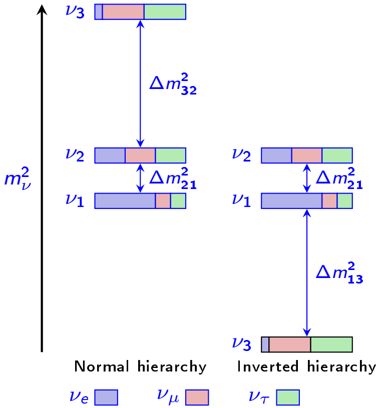
- $6\mathrm{Li}(n,\alpha)^3\mathrm{He}$ – localization of the delayed signal, better reduction of γ background
- Segmentation reduces the background


Mar 2016
DANSS
V.Egorov


ANTINEUTRINO
GLOBAL MAP 2015
WINKEL TRIPEL PROJECTION
ORTHOGRAPHIC NORTH PROJECTION
ORTHOGRAPHIC SOUTH PROJECTION
REACTOR ANTINEUTRINOS
GEOPHYSICAL ANTINEUTRINOS
MOLLWEIDE PROJECTION
MOLLWEIDE PROJECTION
Scale at Equator

- JUNO, RENO-50

Neutrino mass



Mixing defined by angles: $\theta_{12}, \theta_{23}, \theta_{13}$.

Neutrino mass

- Neutrinos are massive
- Neutrino mass was never measured
- $\sum m_\nu \lesssim 1$ eV (cosmology)
- $m_e < 2.2$ eV (direct)
- $\langle m_{\beta\beta} \rangle < 0.25$ eV ($0\nu\beta\beta$)

Mass splitting

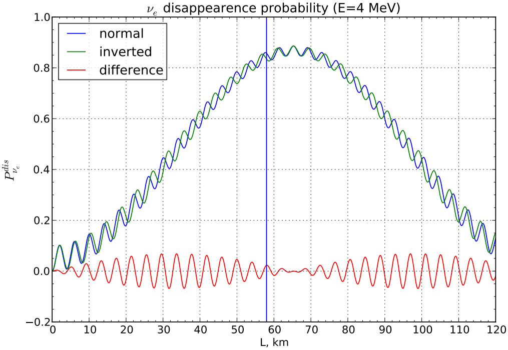
From oscillation experiments:

- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
- $\left|\Delta m^2_{32}\right| = (2.42 \pm 0.06) \times 10^{-3}$ eV^2
- $\left|\Delta m^2_{32}\right| / \Delta m^2_{21} \sim 32$

Mass hierarchy

Which neutrino is the lightest one: ν_1 or ν_3?

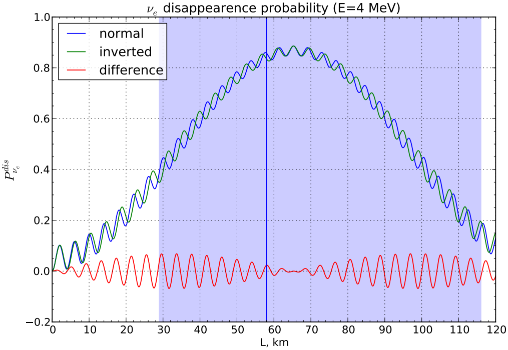
Neutrino mass hierarchy in reactor experiments (JUNO and RENO-50)



$$P_{\text{dis}} = \sin^2 2\theta_{13} \left(\sin^2 \theta_{12} \sin^2 \Delta_{32} + \cos^2 \theta_{12} \sin^2 \Delta_{31}\right) + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

$$\Delta_{jk} = 1267 \cdot \frac{\Delta m_{jk}^2}{\text{eV}^2} \ \frac{L}{E} \ \left[\frac{\text{MeV}}{\text{km}}\right]$$

Neutrino mass hierarchy in reactor experiments (JUNO and RENO-50)



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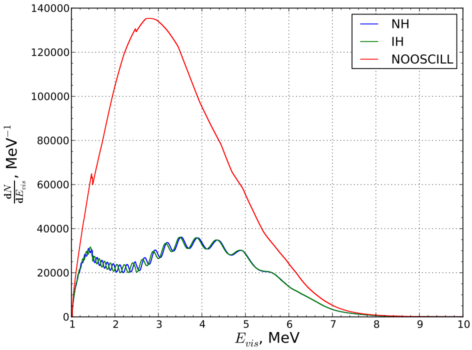
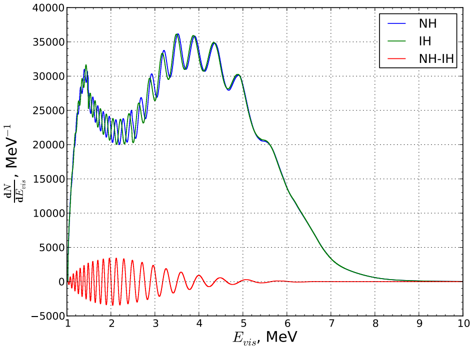
$$\Delta_{jk} = 1267\cdot\frac{\Delta m^2_{jk}}{\text{eV}^2}\;\frac{L}{E}\;\left[\frac{\text{MeV}}{\text{km}}\right]$$

Neutrino mass hierarchy in reactor experiments (JUNO and RENO-50)



- Picture: ideal energy resolution.
- Sensitivity to: θ_{12}, Δm^2_{21}, θ_{13}, Δm^2_{32}.
- Required energy resolution $\lesssim 3\%$.

Neutrino mass hierarchy in reactor experiments (JUNO and RENO-50)



- Picture: ideal energy resolution.
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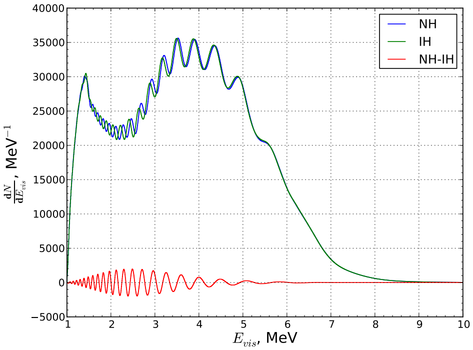
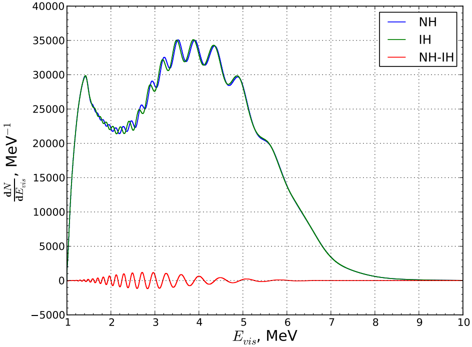
Neutrino mass hierarchy in reactor experiments (JUNO and RENO-50)



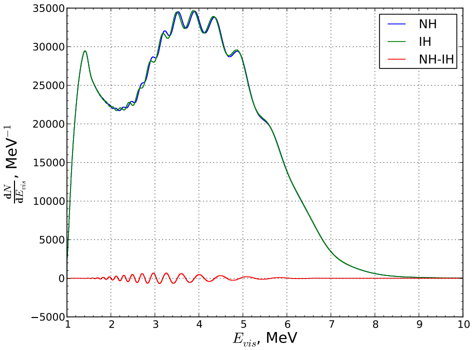
- Picture: energy resolution 2%.
- Sensitivity to: θ_{12}, Δm^2_{21}, θ_{13}, Δm^2_{32}.
- Required energy resolution $\lesssim 3\%$.

Neutrino mass hierarchy in reactor experiments (JUNO and RENO-50)



- Picture: energy resolution 3%.
- Sensitivity to: θ_{12}, Δm^2_{21}, θ_{13}, Δm^2_{32}.
- Required energy resolution $\lesssim 3\%$.

Neutrino mass hierarchy in reactor experiments (JUNO and RENO-50)



- Picture: energy resolution 4%.
- Sensitivity to: θ_{12}, Δm^2_{21}, θ_{13}, Δm^2_{32}.
- Required energy resolution $\lesssim 3\%$.

- Several important discoveries were made with reactor antineutrino:
  - $\overline{\nu}_e$
  - θ_{12}, θ_{13}, Δm^2_{21}
  - Geo-neutrinos
  - Precise measurement of Δm^2_{32}
- Amazing hints:
  - Sterile neutrino
- Near terms discoveries are expected:
  - Neutrino mass hierarchy
  - Coherent neutrino-nucleus scattering
  - Constrain mixing parameters to help in measurement of δ CP violation phase with accelerators and atmospheric neutrinos
- Possible discoveries
  - New physics and neutrino nature (ν magnetic moments)
- Applied science
  - non-proliferation
  - reactor power independent monitoring

Nuclear physics is a key ingredient to make this program possible