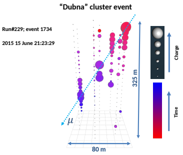
Introduction to Neutrino Physics

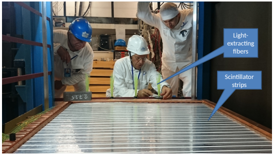
Dmitry V.Naumov

March 14, 2016

The XX International Scientific Conference of Young Scientists and Specialists

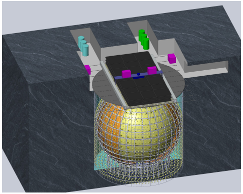


BAIKAL REAL EVENT



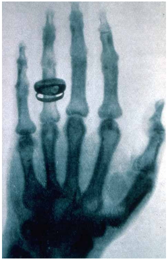
Mounting of the 1st section of the DANSS calorimeter (KNPP, 19.08.2015)

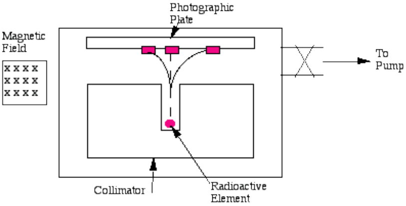
DANSS Calorimeter

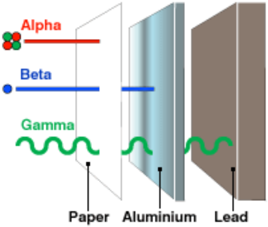


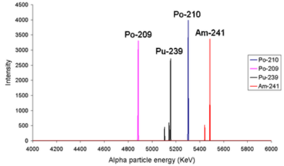
JUNO Project

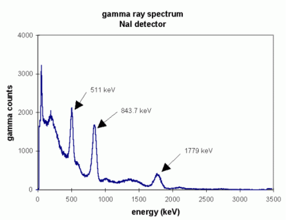
- 1895: Discovery of X-rays by Röntgen (**NP**: 1901)
- 1896: Discovery of radioactivity from uranium salts by Becquerel
- 1898: Discovery of two more radioactive nuclei: **polonium** and **radium** by Pierre and Marie Curie (**NP**: Becquerel and Pierre and Marie Curie: 1903)
- 1899: Rutherford coined a the terms **alpha** and **beta** rays and discover the concept of radioactive "half-life"
- 1902: Rutherford and Soddy "Theory of Atomic Disintegration" disproving an ancient idea of indivisible atoms
- 1903: Rutherford coined a term **gamma** ray. α, β, γ differ by their penetration power

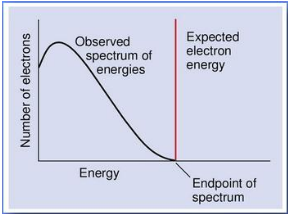






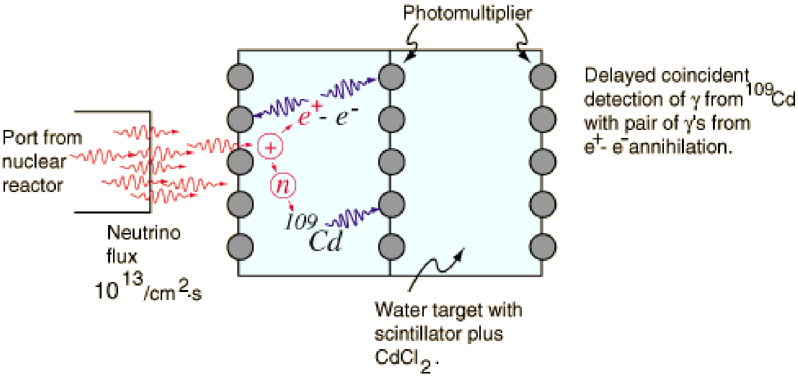






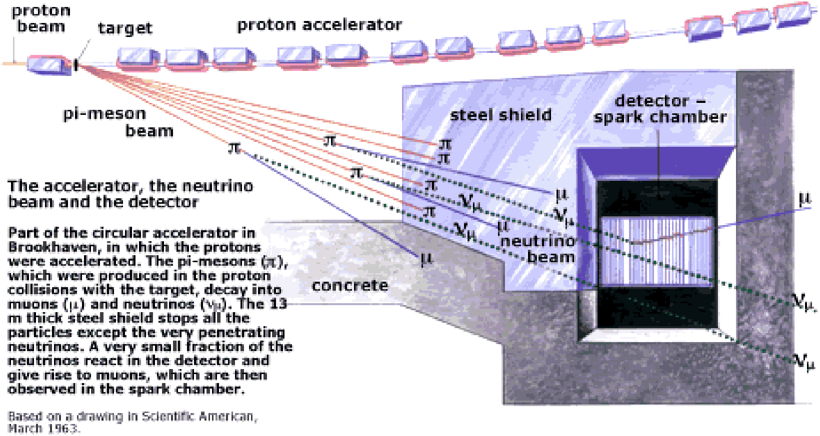
- Energy conservation dictates that energies of α, β, γ should be a difference between energy levels of initial and final nuclei
- α and γ radioactivity obey this law
  - Why γ spectrum has peaks and continuous parts?
- 1913: Chadwick discovered that β spectrum is continuous. Seems to be a violation of energy conservation law!
- Another problem of that times (not related to continuous β spectrum at first glance) **wrong statistics** of $^{14}_{7}N$ (and similarly of $^{6}_{3}Li$, etc):
  - Today: $7p + 7n = 14$ fermions (Bose statistics)
  - Old times: $14p + 7e = 21$ fermions (Fermi statistics)
  - The experiment: $^{14}_{7}N$ has Bose statistics. How?!

- 1930: Pauli hypothesized an existence of a *neutral light fermion with* $m_n < 0.01 m_p$ in nucleus. He called it **neutron**. Pauli attempted to solve both problems:
  - Continuous β spectrum: “neutron” is emitted together with electron sharing total allowed energy and momentum between them two.
  - Wrong statistics of $^{14}_{7}$N: $14p + 7n + 7e = 28$ fermions = Bose statistics
- The idea was brave (only e^-, p, γ existed at that times as elementary particles) but not fully correct:
  - Emitted “neutron” was actually another particle: **neutrino** (named by Fermi)
  - $^{14}_{7}$N nucleus was actually: $7p + 7n = 14$ fermions (Bose statistics) with **heavy neutron** $m_n > m_p$ discovered by Chadwick in 1932
- Pauli presented his hypothesis to public in 1933. Fermi formulated a quantum theory of β decay two months later
  - Fermi submitted a letter to *Nature*. It was rejected: *abstract speculations too far from physical reality to be of interest to the readers*
  - Fermi published his theory in Zeitschrift für Physik in 1934



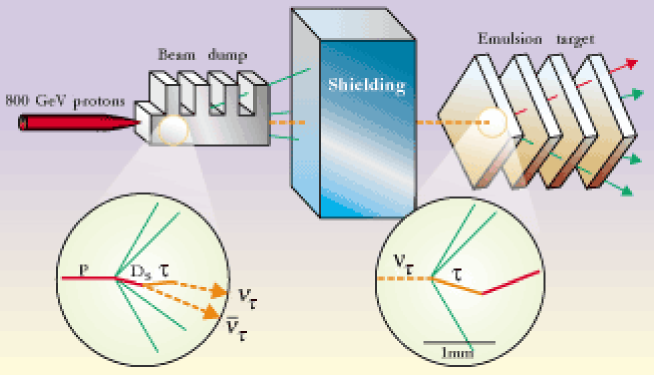
$\bar{\nu}_e$ discovery

- F. Reines and C. L. Cowan, Jr used *inverse beta decay reaction* to detect $\bar{\nu}_e$ from a nuclear reactor: $\bar{\nu}_e + p \to n + e^+$
- $e^+ + e^- \to \gamma\gamma$ and $n + {}^{108}\mathrm{Cd} \to {}^{109}\mathrm{Cd}^* \to {}^{109}\mathrm{Cd} + \gamma$
- 1956: published two papers about discovery.
- 1995: **NP** to F. Reines



ν_μ discovery

- 1962: L. M. Lederman, M. Schwartz and J. Steinberger discovered that there is **another type** of neutrino ν_μ produced in association with muon $\pi^+ \to \mu^+ + \nu_\mu$
- 1988: **NP** to L. M. Lederman, M. Schwartz and J. Steinberger



ν_τ discovery

- 2000: DONUT experiment discovered that there is **yet another type** of neutrino ν_τ produced in in association with tau lepton $D_s^+ \to \tau^+ + \nu_\tau$
- 4 ν_τ candidates in excess of the expected background (< 0.2 events)

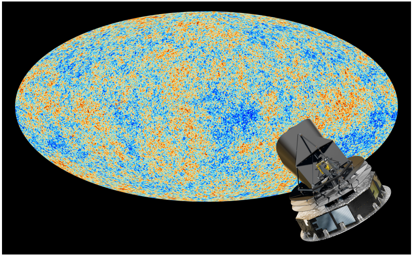
- Three flavours of neutrino are discovered. They are named: electron, muon and tau neutrino and are shortly written as ν_e, ν_μ, ν_τ.
- The flavour **seemed** to be conserved:
  - These are possible:

$$\nu_\mu + n \to \mu^- + p, \quad \tau^- \to \pi^- + \nu_\tau$$

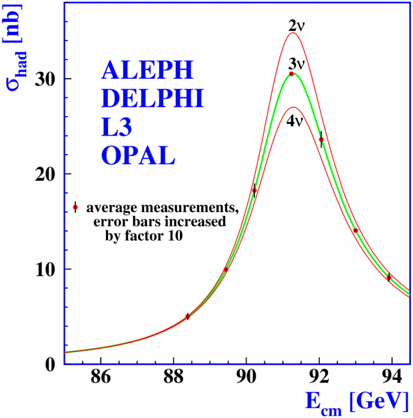
  - These are not possible

$$\nu_\mu + n \nrightarrow e^- + p, \quad \tau^- \nrightarrow \pi^- + \nu_\mu$$

- It was discovered later that flavour is not conserved. We will discuss it in what follows.



From cosmology. Planck 2015:
$N_\nu = 3.15 \pm 0.23$



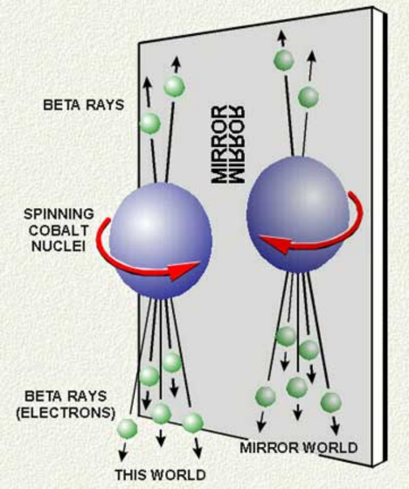
Invisible width of Z boson at LEP
$e^+ + e^- \to Z^0 \to \nu\bar{\nu}$ gives:
$N_\nu = 2.984 \pm 0.008$

Weak interactions violate parity

Physical laws in our world and in mirror world are different. How this can be seen?

Weak interactions violate parity

Weak interactions violate parity



- Wu discovered that electrons emitted in a direction opposite to ^{60}Co spin
- The same is seen differently in the mirror=Parity violation
- This was an important information to build the Standard Model

How to weigth neutrino?

- From particle's decays. The energy of decay products does depend on neutrino mass
  - From tritum decays $^3H \to {}^3He + e^- + \bar{\nu}_e$:
  $$m_{\nu_e} < 2.2 \text{ eV}$$
  - From pion decays $\pi^+ \to \mu^+ \nu_\mu$:
  $$m_{\nu_\mu} < 170 \text{ keV}$$
  - From tau lepton decays $\tau^- \to 2\pi^-\pi^+\nu_\tau$ and $\tau^- \to 3\pi^-2\pi^+\nu_\tau$:
  $$m_{\nu_\tau} < 18.2 \text{ MeV}$$
- From Cosmology:
  - Big Bang models predicts **fixed** ratio $n_\nu : n_\gamma$ in the Universe
  - If the total energy of all three types of neutrinos exceeded an average of 50 eV per neutrino, there would be so much mass in the universe that it would **collapse!**
  - Cosmology puts the strongest limit
  $$\sum_i m_i < 0.23 \text{ eV}$$

- It was found experimentally, that
  - This is possible:

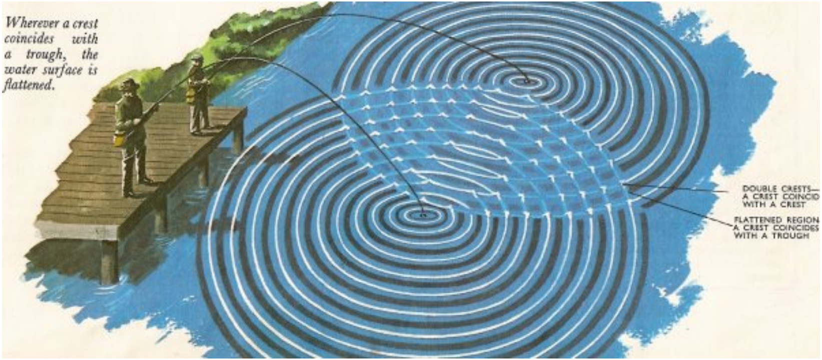
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\hookrightarrow \nu_\mu + n \to p + \mu^- \quad \text{flavour is conserved}$$

  - This is not possible:

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\hookrightarrow \nu_\mu + n \to p + e^- \quad \text{flavour is not conserved}$$

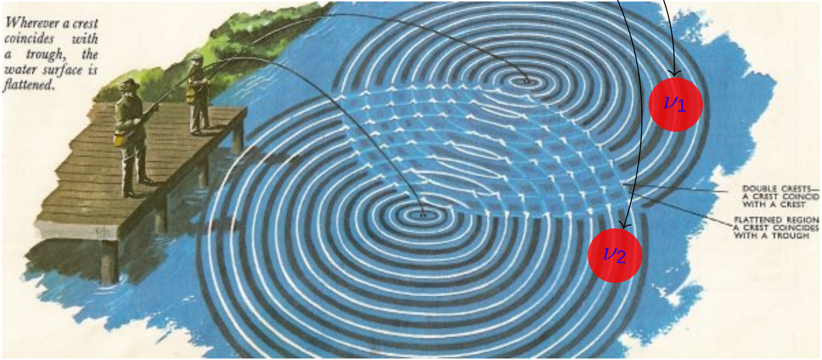
- Leaving out a very exciting history we can now state that the above picture is not correct:
  - Neutrino changes its flavour while it propagates! This change is to a good accuracy *periodic*
  - This is known as **neutrino oscillations**
  - The length of oscillations is proportional to $E_\nu/\Delta m^2_{ij}$ where $\Delta m^2_{ij} = m^2_i - m^2_j$
  - Flavour neutrinos ν_e, ν_μ, ν_τ do not have definite masses. Instead they are superpositions of states with definite masses. Quantum Mechanics in action!

$$\nu_e = U_{e1}\,\nu_1 + U_{e2}\,\nu_2$$



$$\nu_e = U_{e1}\,\nu_1 + U_{e2}\,\nu_2$$

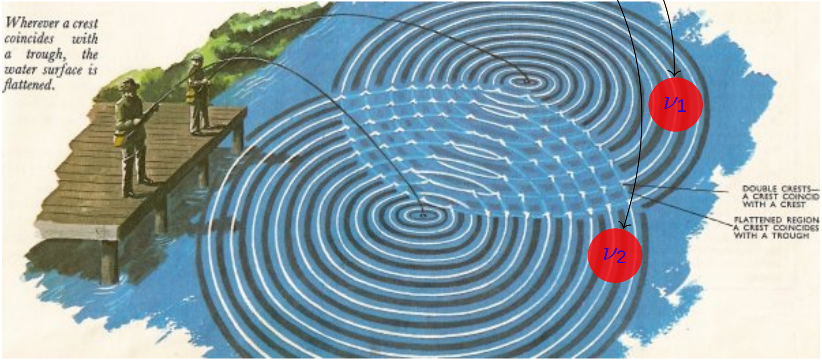
Waves ν_1 and ν_2 of different frequencies



$$\nu_e = U_{e1}\,\nu_1 + U_{e2}\,\nu_2$$

Amplitudes of ν_1 and ν_2

Waves ν_1 and ν_2 of different frequencies

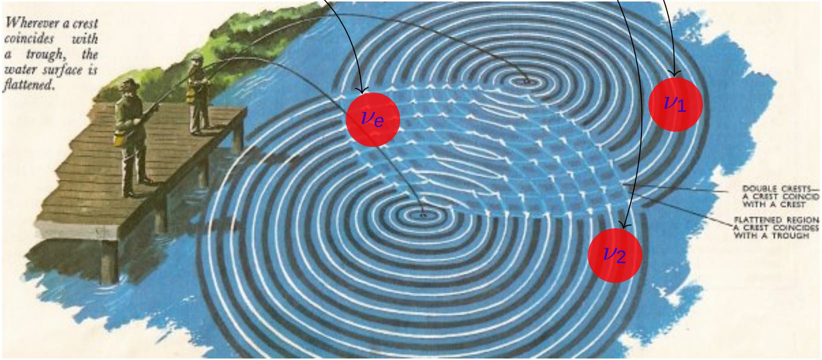


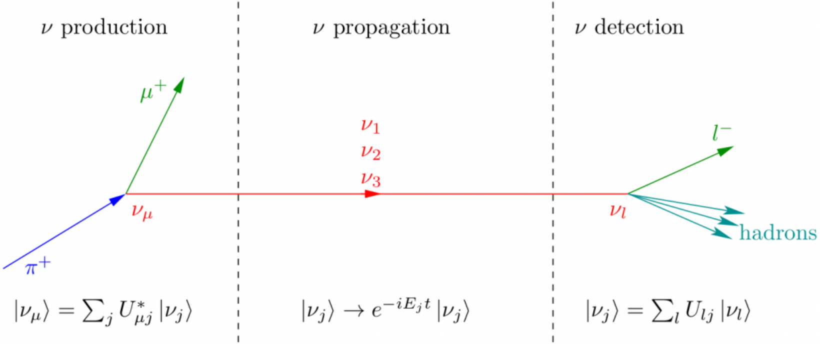
$$\nu_e = U_{e1}\,\nu_1 + U_{e2}\,\nu_2$$

Amplitudes of ν_1 and ν_2

Waves ν_1 and ν_2 of different frequencies

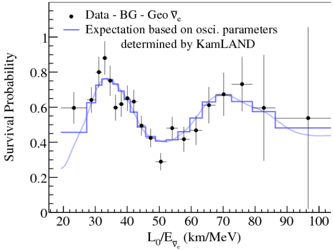
Interference picture



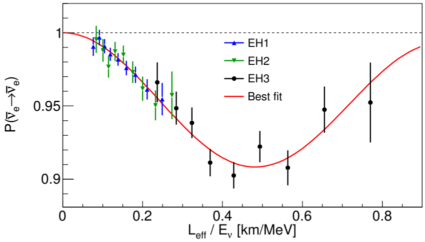


- The amplitudes U_{e1}, U_{e2} are part of neutrino mixing 3×3 matrix parametrized by 3 mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ and one phase δ

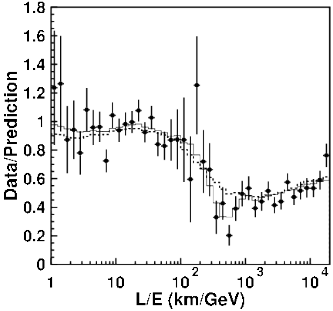
- Neutrino oscillations provides a sensitive tool to measure Δm^2_{ij} and mixing angles θ_{ij}
- Neutrino oscillations are observed experimentaly with atmospheric, solar, reactor, accelerator neutrinos



KamLAND: $\theta_{12}, \Delta m^2_{12}$



DayaBay: $\theta_{13}, \Delta m^2_{32}$



SuperKamikande: $\theta_{23}, \Delta m^2_{32}$

Re-thinking old limits + oscillation results

- From tritum decays
  $^3H \to {}^3He + e^- + \bar{\nu}_e$:

$$\sqrt{\sum_i |U_{ei}|^2 m_i^2} < 2.2 \text{ eV}$$

- From pion decays
  $\pi^+ \to \mu^+ \nu_\mu$:

$$\sqrt{\sum_i |U_{\mu i}|^2 m_i^2} < 170 \text{ keV}$$

- From tau lepton decays
  $\tau^- \to 2\pi^-\pi^+\nu_\tau$ and
  $\tau^- \to 3\pi^- 2\pi^+\nu_\tau$:

$$\sqrt{\sum_i |U_{\tau i}|^2 m_i^2} < 18.2 \text{ MeV}$$

- From Cosmology:

$$\sum_i m_i < 0.23 \text{ eV}$$

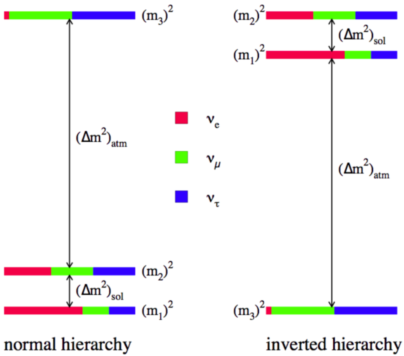
- From oscillations: neutrinos do have a definite non-zero mass (otherwise no oscillations possible)
- $|\Delta m^2_{31}| = 2.4 \cdot 10^{-3} \text{ eV}^2$

$$\hookrightarrow m_3 \geq \sqrt{\Delta m^2_{31}} = 0.05 \text{ eV}$$

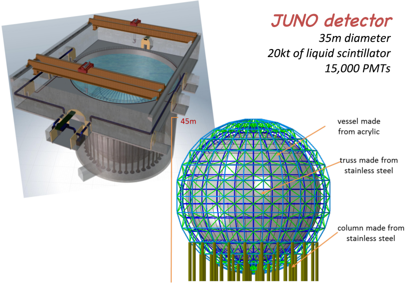
- $\Delta m^2_{21} = 7.5 \cdot 10^{-5} \text{ eV}^2$

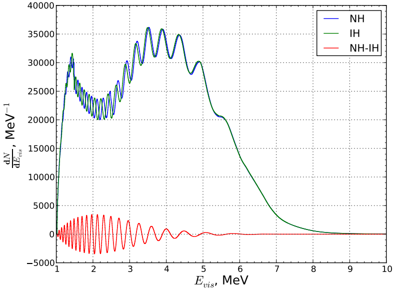
$$\hookrightarrow m_2 \geq \sqrt{\Delta m^2_{21}} = 0.009 \text{ eV} \qquad \text{NH}$$

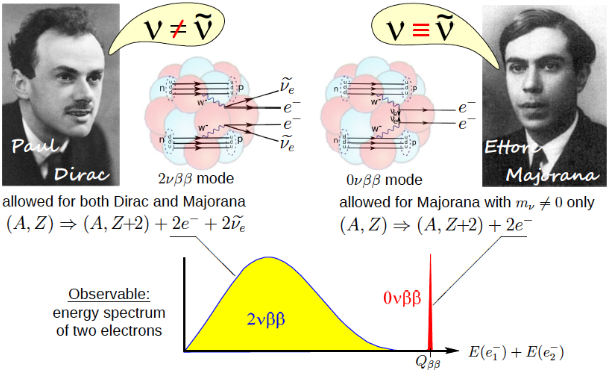
$$\hookrightarrow m_2 \geq \sqrt{\Delta m^2_{21}} + \sqrt{\Delta m^2_{31}} = 0.06 \text{ eV} \qquad \text{IH}$$



- What is heavier m_1 or m_3?
- Many experimental approaches (all using oscillations): accelerator neutrinos (T2K, NOVA, DUNE), reactor (JUNO), atmospheric (PINGU, BAIKAL GVD), cosmology

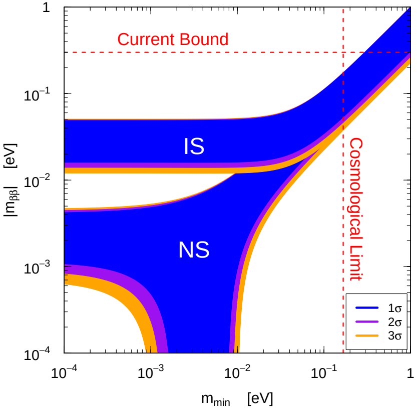






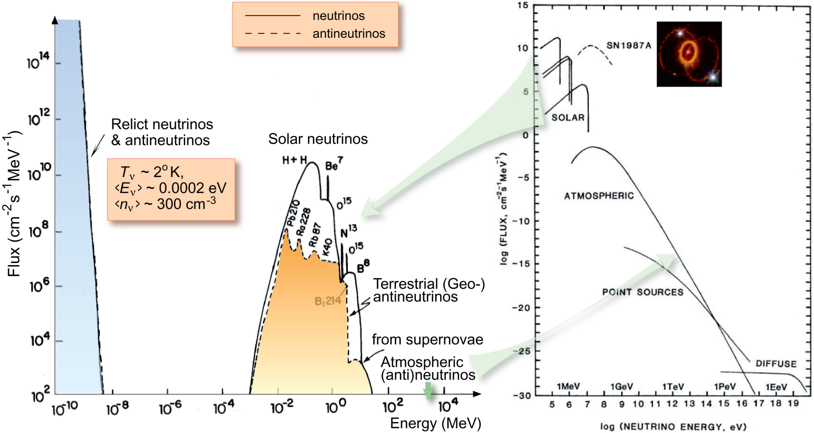
- Main question: If neutrino and anti-neutrino are the same particle or two different particles?
- A detection of $0\nu2\beta$ events will definitely say that neutrino is Majorana particle
- So far no $0\nu2\beta$ event is observed
- **Important:** Neutrinoless double beta decay experiments are sensitive to the absolute scale to neutrino masses unlike experiments with neutrino oscillations
- A very active field of research now

- Next generation of experiments will be sensitive to $m_{\beta\beta} \simeq 0.01$ eV and will be able to discover Majorana nature of neutrino if inverted hierarchy is right
- Next-to-next generation of experiments must be sensitive to $m_{\beta\beta} \simeq 0.001$ eV in order to be able to discover Majorana nature of neutrino if normal hierarchy is right
- **Important**: One should **not** infinitely increase sensitivity to $m_{\beta\beta}$. If Majorana nature of neutrino is not discovered with next and next-to-next generations of experiments = neutrino is a Dirac particle.

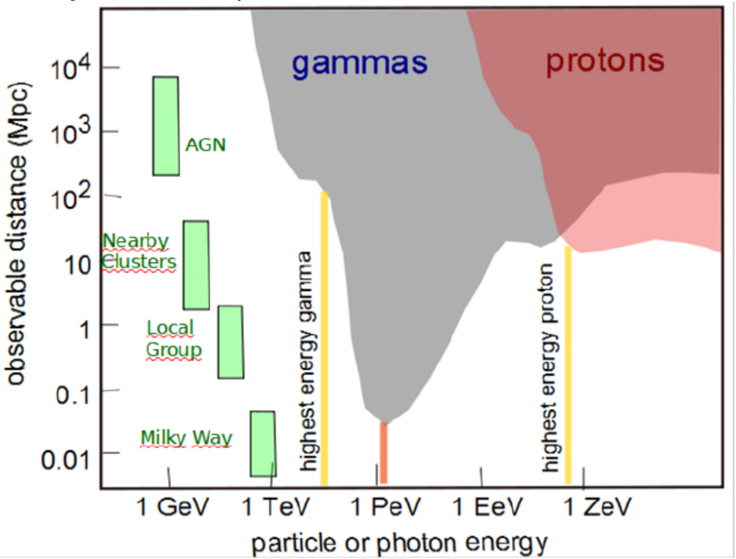


- Current limits are of the order of $m_{\beta\beta} \lesssim 0.2$ eV

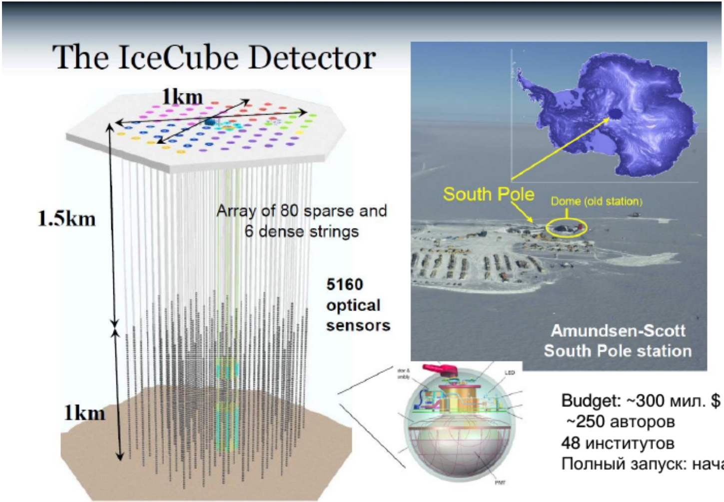
Neutrino fluxes



Visible sky in different particles

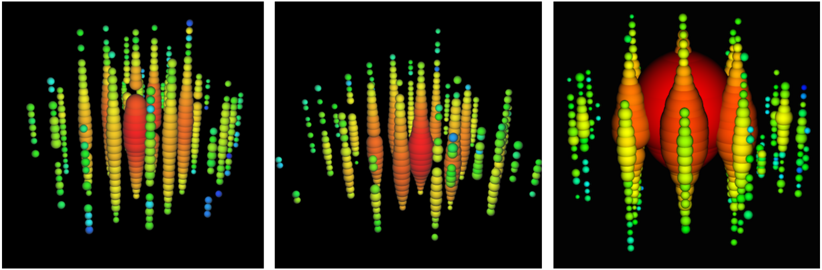


Revolution in Neutrino Astronomy



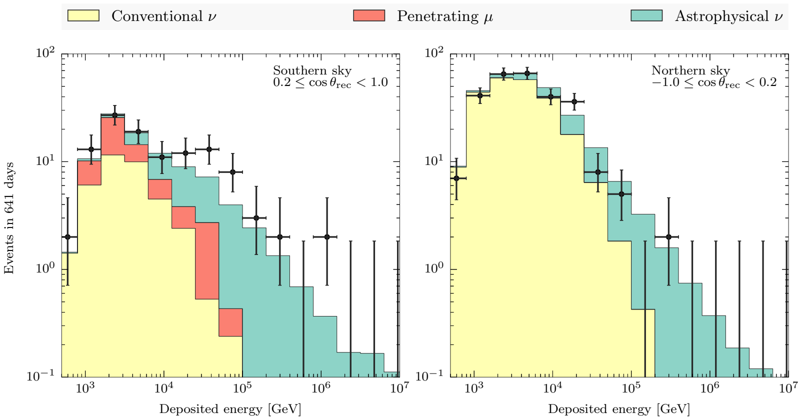
Budget: ~300 мил. $
~250 авторов
48 институтов
Полный запуск: начало 2011 г

- Long time astrophysical neutrino were a theory speculation. Nobody has seen them including IceCube.
- It was till a long waited **revolution!** came! IceCube observed neutrino of high energies of extra-terestial origin

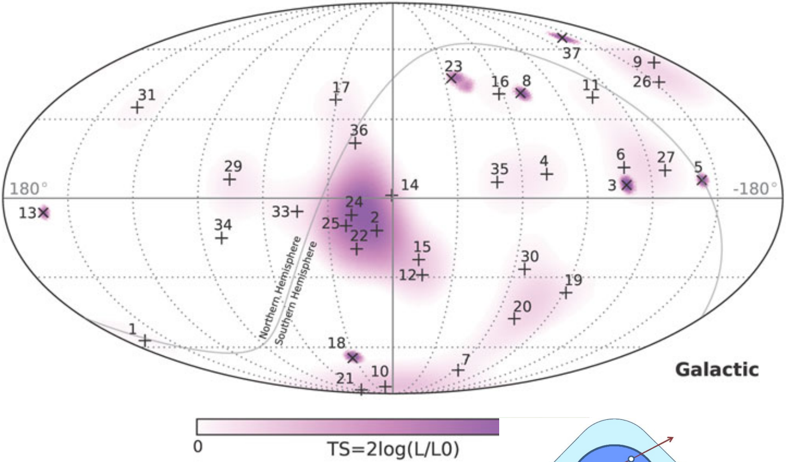


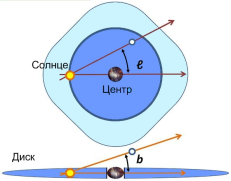
Bert, Ernie and Big Bird with energies 1.0, 1.1 and 2.2 PeV.

Current state: http://arxiv.org/pdf/1410.1749v2



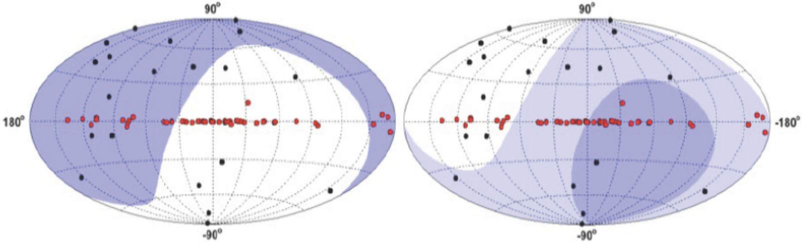
87^{+14}_{-10} **astrophysical neutrinos**





- Where neutrino come?
- Not clear

- Astrophysical neutrinos do exist (IceCube)
- Their sources are unknown.
- Direction accuracy reconstruction in IceCube is not good because of light rescattering in ice. We need a detector with good angular resolution
- BAIKAL GVD will have a good angular resolution. Baikal is the North Hemisphere thus will see South Hemisphere and Galactic Center



- Neutrino nucleus cross-sections measurements
- Precise measurements of solar neutrino fluxes
- Search for a sterile neutrino
- Monitoring of reactor fuel composition and power (nuclear non proliferation)
- Neutrino oscillations in matter
- Neutrino nucleus coherent scattering
- Measurement of CP-violation phase δ
- Study of loss of coherence effects in neutrino oscillations
- Observation of relic neutrinos (must be NP!)

JINR Neutrino Program widely covers major neutrino topics

- **NOVA:** Accelerator neutrino and antineutrino. Mass Hierarchy determination. Matter effects
- **OPERA:** Accelerator neutrino. $\theta_{23}, \Delta m^2_{32}, \nu_\tau$ appearance
- **BAIKAL GVD:** Astrophysical and atmospheric neutrino. Matter effects. $\theta_{23}, \Delta m^2_{32}$. Reach potential.
- **BOREXINO**: Solar, geo-neutrino, matter effects, $\theta_{12}, \Delta m^2_{21}$, rare processes
- **SOX**: Radioactive source. Sterile neutrino search.
- **SuperNEMO:** Dirac or Majorana vs $0\nu2\beta$
- **GERDA:** Dirac or Majorana vs $0\nu2\beta$
- **Daya Bay:** Reactor antineutrino. $\theta_{13}, \Delta m^2_{ee}$, sterile neutrino, reactor flux measurement
- **JUNO:** Reactor antineutrino. Mass Hierarchy determination. Precise (better than 1%) measurement of $\theta_{12}, \Delta m^2_{21}, \Delta m^2_{32}$, SN neutrinos, reach program.
- **DANSS:** Reactor antineutrino. Sterile neutrino. Reactor monitoring.
- **GEMMA-2:** Reactor antineutrino. μ_ν anomalous neutrino magnetic moment
- **νGEN:** Coherent Neutrino Germanium Nucleus Elastic Scattering

Brief Summary

- 1 km^3 scale by 2023
- Flexible structure (upgrade and re-arrangemenet)
- High accuracy in reconstruction of direction, good energy reconstruction and flavour decomposition
- 2304 PMTs
- Baikal was a pioneer in the field. Huge experience is accumulated
- New life began in 2014. A need for a 1 km^3 detector is clear to identify the sources.
- 27 astrophysical neutrinos to be detected by 2020.
- First cluster “Dubna” is installed in 2015

JINR contribution

- Assembly and test of deep water components.
- Continuous monitoring of the detector operation and remote control.
- Online and Offline
- Databases, DAQ
- Detector calibration and mass processing of data.
- Simulations, reconstruction, selection.
- Data analysis
- Additional 5.5M$/year for next 5 years are approved by JINR Directorate to build the detector.

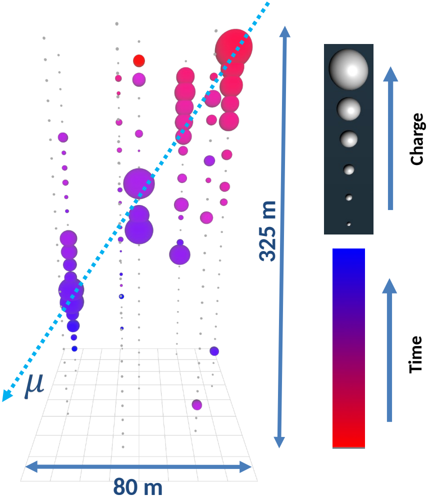
BAIKAL GVD Collaboration is now quickly expanding with Russian and Foreign Participants. Welcome to join us!

BAIKAL GVD. Current Status

"Dubna" cluster event

Run#229; event 1734

2015 15 June 21:23:29



BAIKAL GVD. Current Status

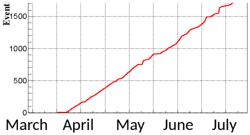
Cluster “DUBNA” (2015)

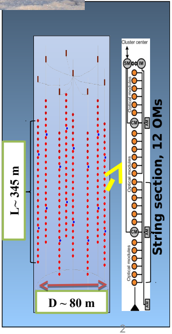
Status:

- ✓ The “DUBNA” cluster operates since April 2015 with 192 optical modules.
- ✓ Data analysis shows good consistency of experimental data with expected.
- ✓ New facility for long-term tests of the prepared parts of the array extensions is ready in Dubna.
- ✓ New production line of optical modules for the next detector extensions is ready to be started in Dubna.
- ✓ The place for the new data taking center at the array site is prepared for installation.
- ✓ Shore infrastructure has been expanded (transport and store facilities)

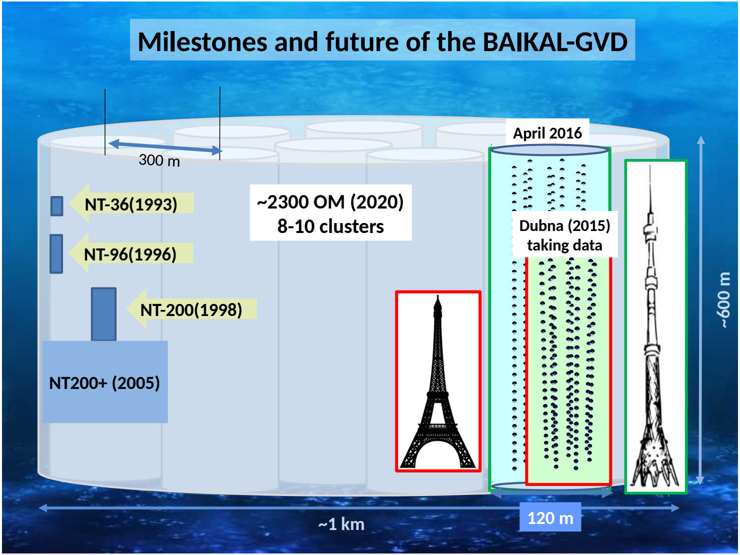
The demonstration cluster “DUBNA” has been put into operation

Integrated number of recorded events





BAIKAL GVD. Current Status



DLNP laboratory for PMT tests was created in 2014

An example: JUNO + NOVA young stars

We invite interested students and postdocs to work with us in the field of neutrino physics:

- R&D of detectors, methodology
- Theory of neutrino oscillations, neutrino-nucleus scattering
- within an exciting and world level physics program (BAIKAL GVD, DANSS, νGEN, JUNO, NOVA, etc)
- within enthusiastic and dedicated young teams
- within a modern and comfortable environment