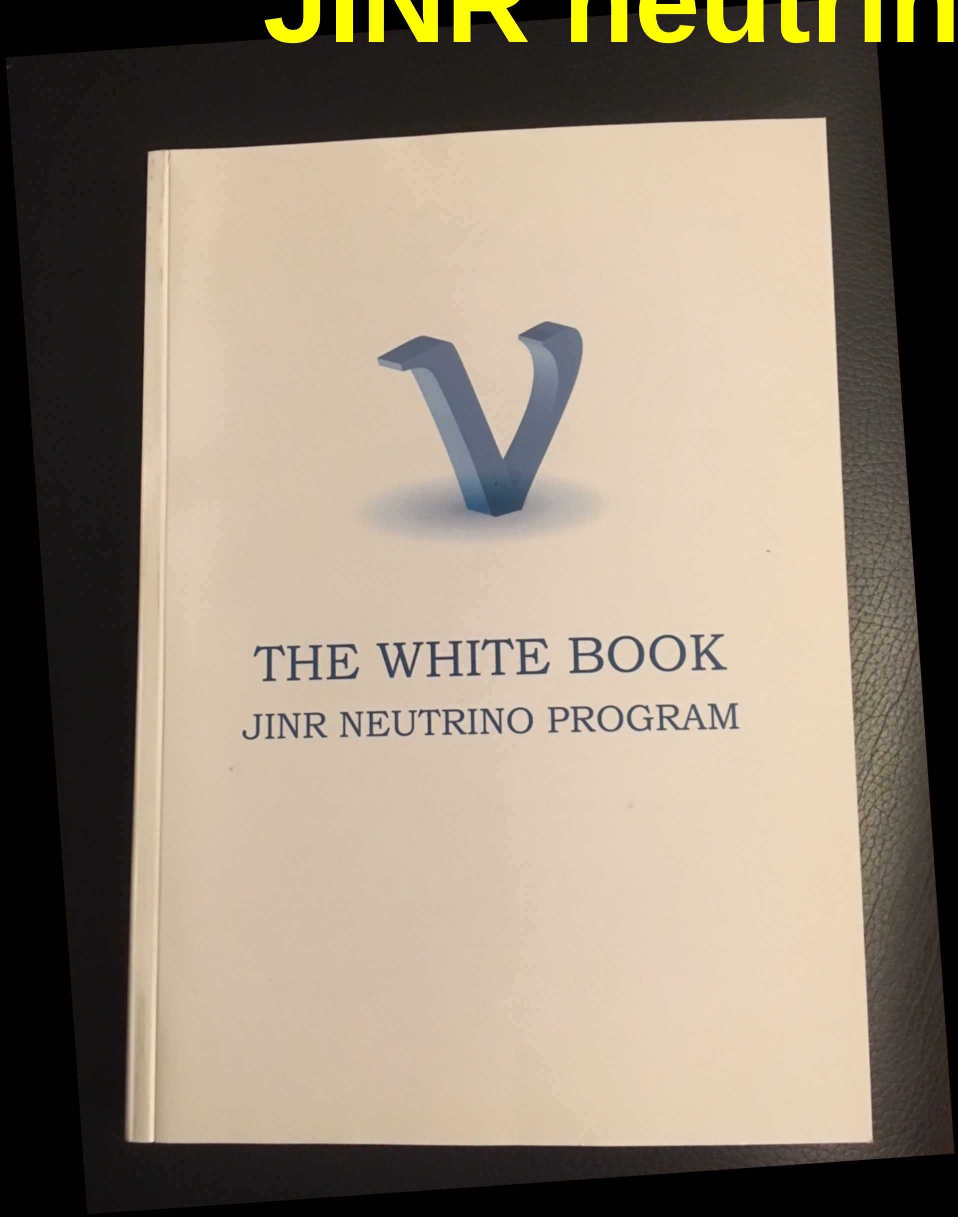
# JINR neutrino program




*Oleg Smirnov*
**(DLNP)**

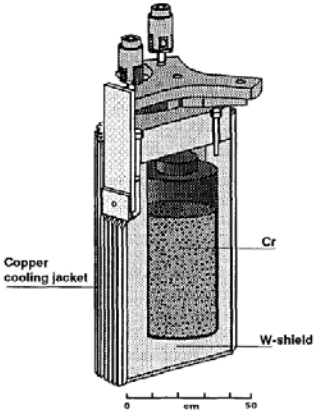
**The XXII International Scientific Conference of Young Scientists and Specialists (AYSS-2018)**

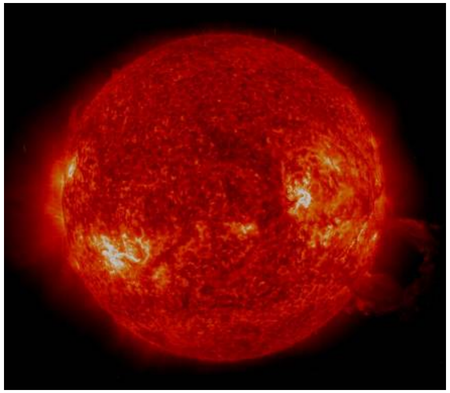
# JINR neutrino program

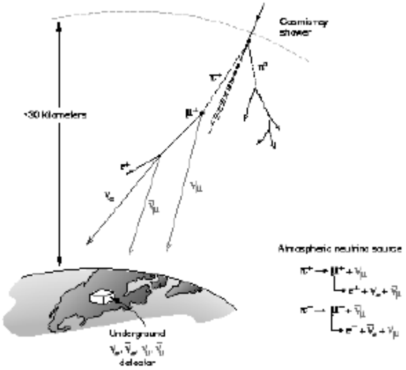
- “White book” published in 2014: 11 neutrino experiments with JINR participation
- 1. BAIKAL (Deep water detector of muons and neutrino in Baikal lake)
- 2. BOREXINO (LS Solar neutrino detector at LNGS)
- 3. Проект νGeN  (Experiment at Kalininskaya nuclear power plan on coherent neutrino scattering on Ge nucei)
- 3. DANSS (Detector of the Reactor AntiNeutrino based on Solid Scintillator)
- 4. Daya Bay Experiment (reactor antineutrino experiment)
- 5. GEMMA (Germanium Experiment Searching for Magnetic Moment of Antineutrino)
- 6. GERDA (double beta-decay)
- 7. JUNO  (new generation reactor experiment)
- 8. NOVA (new generation accelerator experiment)
- 9. OPERA (accelerator experiment on neutrino oscillations)
- 10. SuperNEMO (Search for neutrinoless double beta decay with NEMO-3 and the next generation double beta decay experiment SuperNEMO)
- 11. EDELWEISS (Experience pour DEtecter Les Wimps En Site Souterrain.)

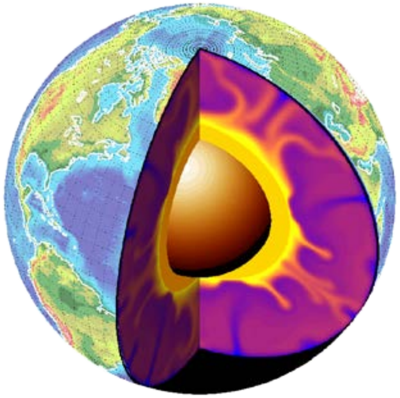
# Neutrino sources

- Artificial:
  - Accelerators
  - Reactors
  - Isotopes sources
- Natural
  - Solar
  - Atmospheric
  - Natural radioactive isotopes in the Earth (geo-neutrino)
  - Supernovae

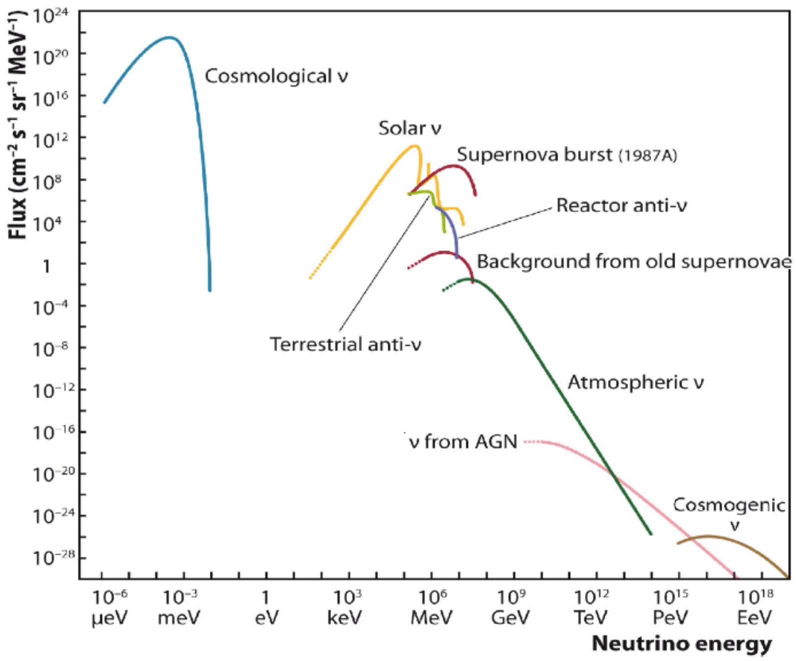


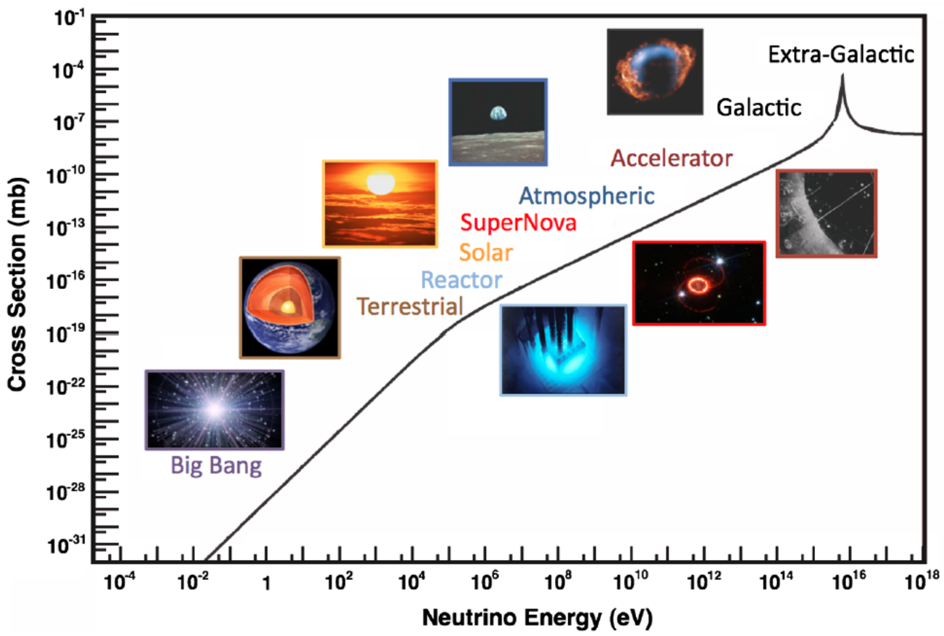





# Neutrino sources



# Neutrino

3 flavour states of neutrino ($\boldsymbol{v_e, v_\mu, v_\tau}$) -
are a mixure of 3 mass states : $\boldsymbol{v_1, v_2, v_3}$ with masses $\boldsymbol{m_1, m_2, m_3}$

$$\begin{pmatrix} \boldsymbol{v_e} \\ \boldsymbol{v_\mu} \\ \boldsymbol{v_\tau} \end{pmatrix} = \boldsymbol{U_{PMNS}(3 \times 3)} \begin{pmatrix} \boldsymbol{v_1} \\ \boldsymbol{v_2} \\ \boldsymbol{v_3} \end{pmatrix}$$

PMNS : (unitary) matrix, proposed in 1962 by 1962 Ziro Maki, Masami Nakagawa and Shoichi Sakata to explain neutrino oscillations predicted by Bruno Pontecorvo

# Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} =$$

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

atmospheric ν
+ K2K, MINOS
**$\Delta m^2_{23} = 2.4 \cdot 10^{-3}$ eV²**
**$\Theta_{23} \sim 42°$**

reactor ν
DC, DB, RENO, T2K
**$\Delta m^2_{31} \approx \Delta m^2_{atm}$**
**$\Theta_{13} \sim 9°$**

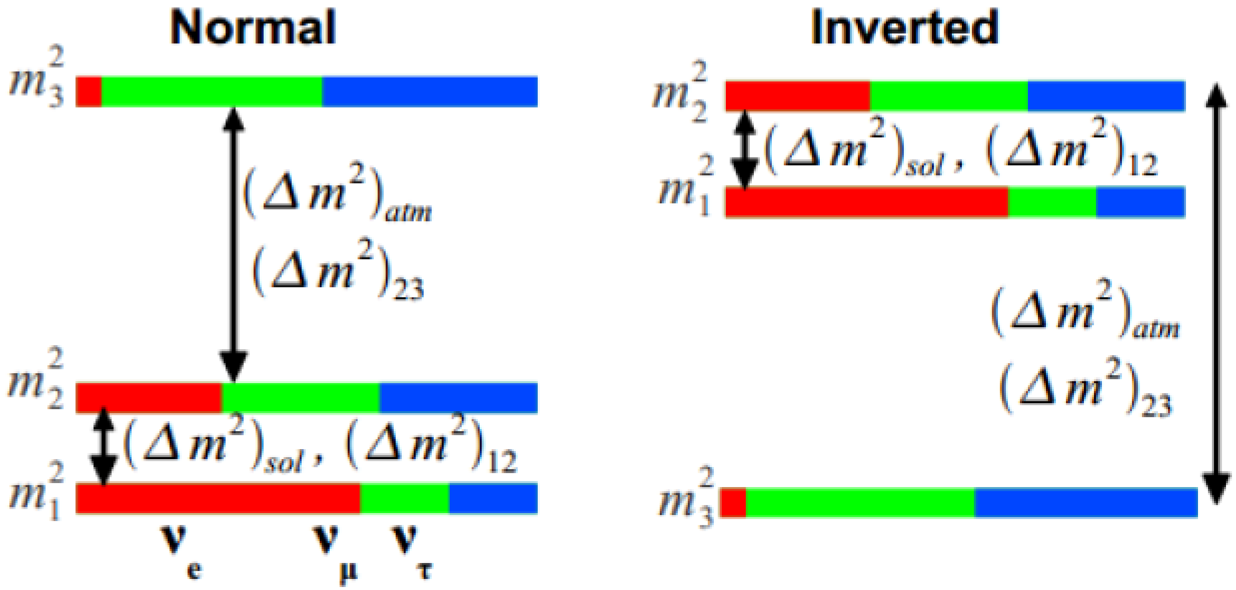
solar ν
+ KamLAND
**$\Delta m^2_{12} = 7.6 \cdot 10^{-5}$ eV²**
**$\theta_{12} = (34 \pm 3)°$**

$c_{ij} \equiv \cos\Theta_{ij}$, $s_{ij} \equiv \sin\Theta_{ij}$, $\delta$ – CP violating phase

$P_\nu \equiv diag\{e^{i\rho}, \quad e^{i\sigma}, \quad 1\}$ - Majorana phases

# Open questions in neutrino physics

- Mass hierarchy (**NOvA**, T2K, **JUNO**): $\Delta m^2_{31} = m^2_3 - m^2_1 > 0$ or $< 0$
- CP-violating phase (**NOvA**, T2K)
- Dirac or Majorana (EXO-200, KamLand-Zen, **GERDA**)

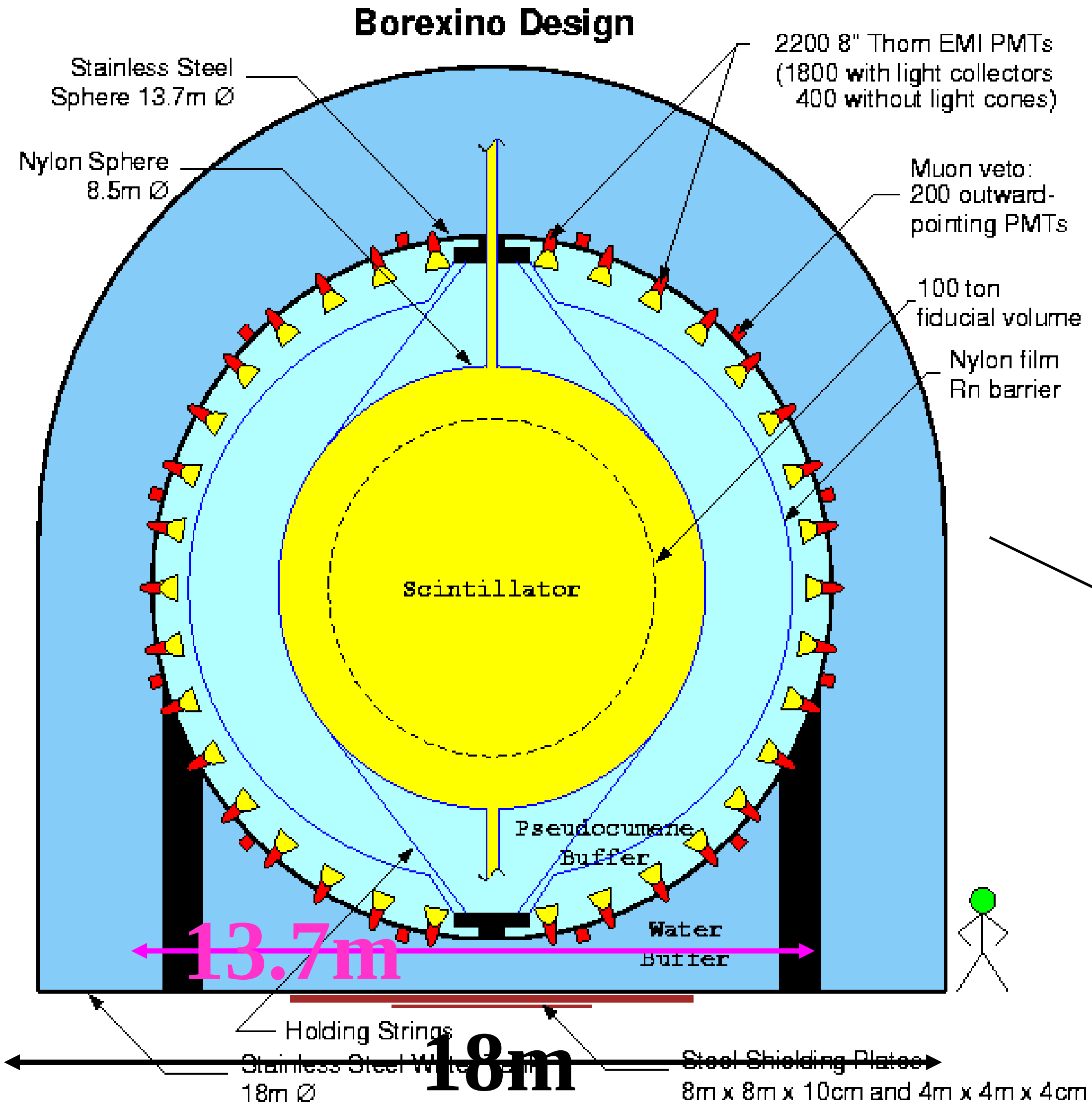


# Sensitivity of different oscillation experiments.

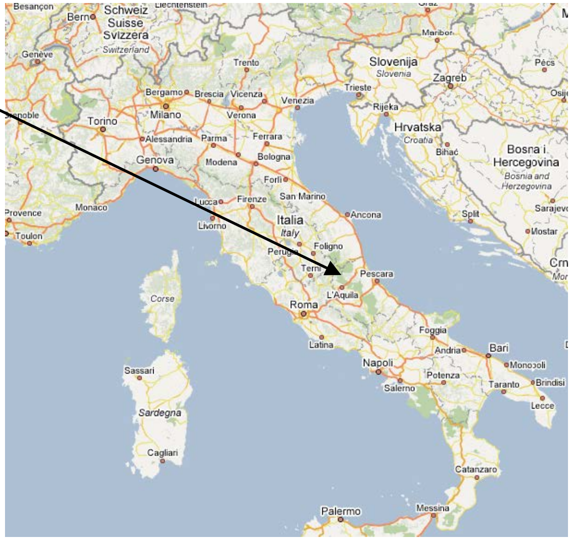
- $S\left(\frac{L}{E}\right) = \sin^2 1.27\Delta m^2[eV]\frac{L[km]}{E[GeV]}$

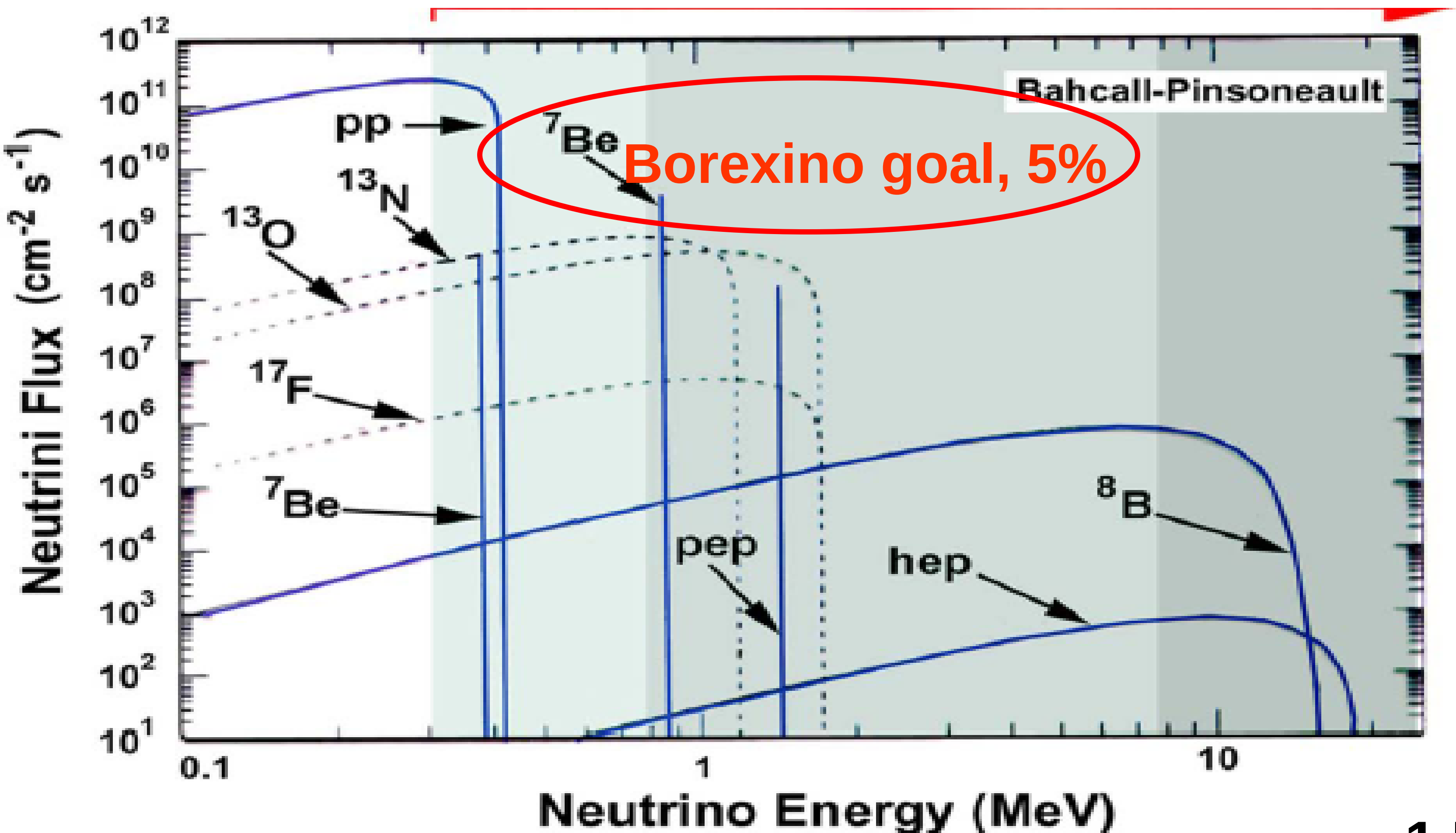
| Source | Type of $\nu$ | $\overline{E}$[MeV] | $L$[km] | $\min(\Delta m^2)$[eV$^2$] |
|---|---|---|---|---|
| Reactor | $\overline{\nu}_e$ | $\sim 1$ | 1 | $\sim 10^{-3}$ |
| Reactor | $\overline{\nu}_e$ | $\sim 1$ | 100 | $\sim 10^{-5}$ |
| Accelerator | $\nu_\mu, \overline{\nu}_\mu$ | $\sim 10^3$ | 1 | $\sim 1$ |
| Accelerator | $\nu_\mu, \overline{\nu}_\mu$ | $\sim 10^3$ | 1000 | $\sim 10^{-3}$ |
| Atmospheric $\nu$'s | $\nu_{\mu,e}, \overline{\nu}_{\mu,e}$ | $\sim 10^3$ | $10^4$ | $\sim 10^{-4}$ |
| Sun | $\nu_e$ | $\sim 1$ | $1.5 \times 10^8$ | $\sim 10^{-11}$ |

# BOREXINO




- 278 t of liquid organic scintillator PC + PPO (1.5 g/l)
- (ν,e)-scattering with 200 keV threshold
- Outer muon detector



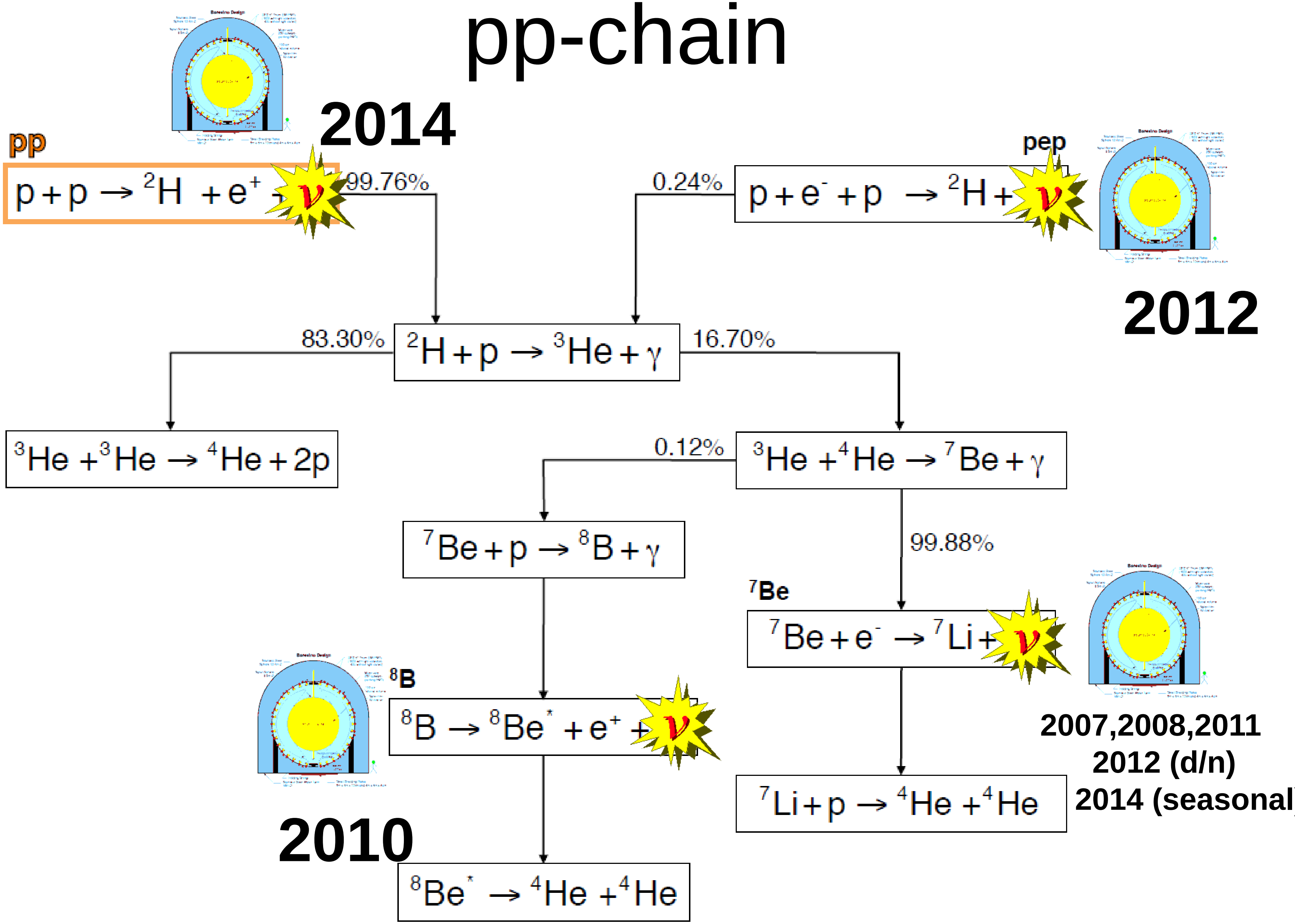



**~1 Bq**

**50 events/d/100t expected ($\nu_e$ and $\nu_{\mu,\tau}$ elastic scattering on $e^-$) or $5 \cdot 10^{-9}$ Bq/kg (typically: drinking water ~10 Bq/kg; human body in $^{40}K$: 5 kBq)**

Low energy->no Cherenkov light->No directionality,
no other tags-> extremely pure scintillator is needed

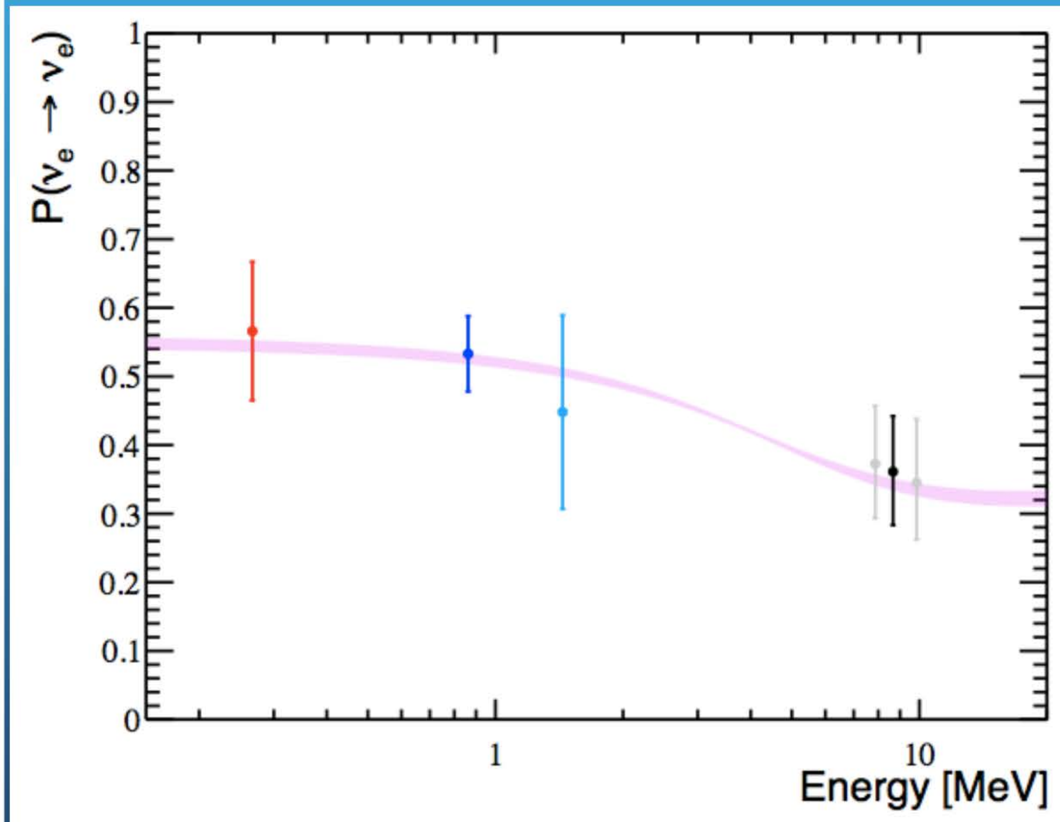
# pp-chain



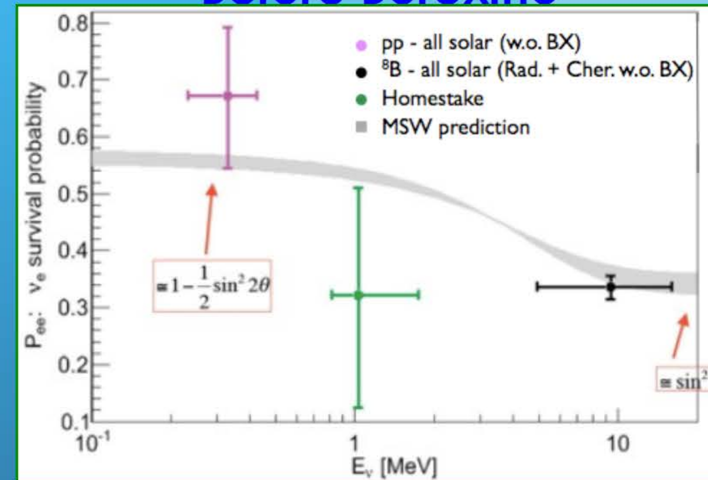
pp
2014
$p + p \rightarrow {}^2H + e^+ + \nu$
99.76%
0.24%
pep
$p + e^- + p \rightarrow {}^2H + \nu$
2012
83.30%
$^2H + p \rightarrow {}^3He + \gamma$
16.70%
$^3He + {}^3He \rightarrow {}^4He + 2p$
0.12%
$^3He + {}^4He \rightarrow {}^7Be + \gamma$
$^7Be + p \rightarrow {}^8B + \gamma$
99.88%
$^7$Be
$^7Be + e^- \rightarrow {}^7Li + \nu$
$^8$B
$^8B \rightarrow {}^8Be^* + e^+ + \nu$
2007,2008,2011
2012 (d/n)
2014 (seasonal)
$^7Li + p \rightarrow {}^4He + {}^4He$
2010
$^8Be^* \rightarrow {}^4He + {}^4He$

# $P_{ee}$: Borexino impact

Borexino now




Before Borexino

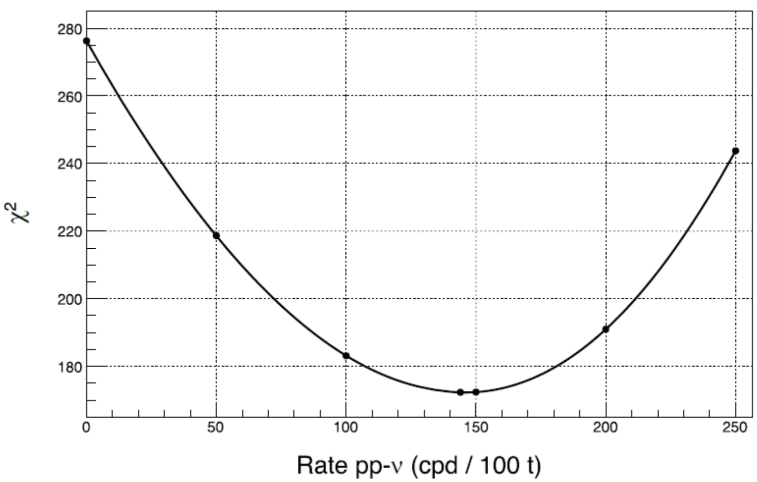



From the measured interacton rates and assuming HZ-SSM fluxes we get:

- $P_{ee}(pp)=0.57\pm0.10$
- $P_{ee}(^7Be,862keV)=0.53\pm0.05$
- $P_{ee}(pep)=0.43\pm0.11$
- $P_{ee}(^8B)= 0.36\pm0.08$ $<E_\nu>=8.7$ MeV

# First real-time measurement of pp-neutrino flux (~11% precision )

pp = 144 ± 13 (stat) ± 10 (syst) cpd/100 t
compared to expected (MSW/LMA,HM)
131±2 cpd/100 t


**pp neutrino flux:**

$(6.6 \pm 0.7) \cdot 10^{10}$ $cm^{-2}s^{-1}$

vs

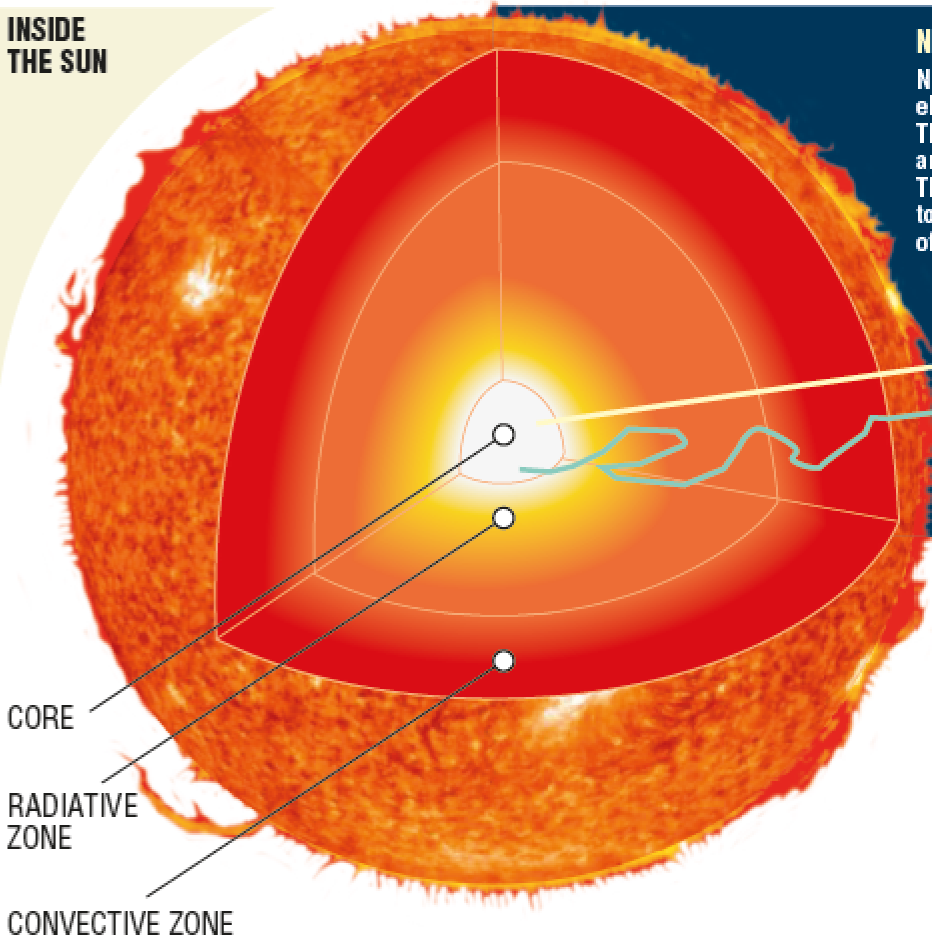
$(5.98 \pm 0.04) \cdot 10^{10}$ $cm^{-2}s^{-1}$


Zero pp count is excluded at 10σ level

**“Neutrinos from the primary proton–proton fusion process in the Sun”**
**Nature, Vol. 512 (2014) pp.383-386**

# THE SUN AS BOREXINO SEES IT IN REAL TIM

## INSIDE THE SUN

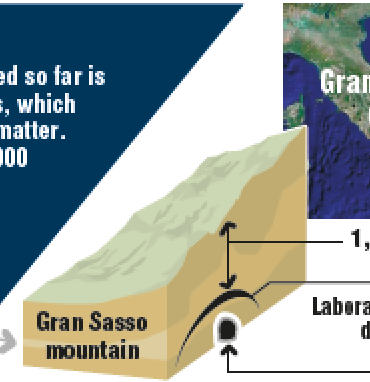



### NEUTRINOS

Neutrinos are particles with no electric charge and a tiny mass. They rarely interact with matter and may cross it undisturbed. That's why they take 8 minutes to get there from the core of the Sun to the Earth.

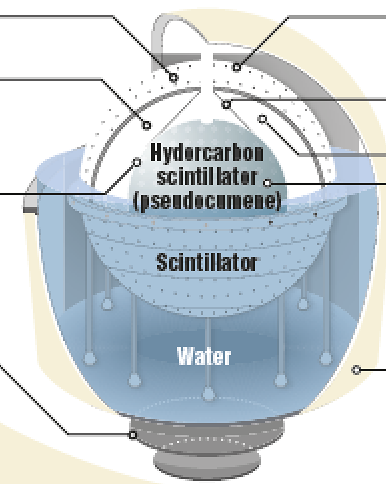
### PHOTONS

The radiation studied so far is made up of photons, which interact with solar matter. It takes about 100.000 years for it to reach the Sun's surface and reach Earth.




**By analyzing P-P neutrino emissi Borexino has shown that the ene produced today in the Sun's core to that produced 100.000 years a**

## THE BOREXINO DETECTOR: HOW IT WORKS



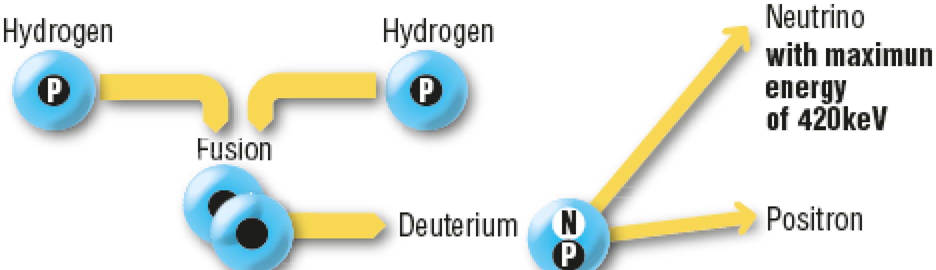

Borexino displays a russian doll structure. Surrounded by 2.400 tons of highly purified water, a stainless steel sphere contains 1.000 tons of a liquid hydrocarbon (pseudocumene). At its center, within a smaller nylon sphere, are 300 tons of scintillating liquid.

Within this innermost sphere neutrinos interact with the liquid scintillator producing small flashes of light.

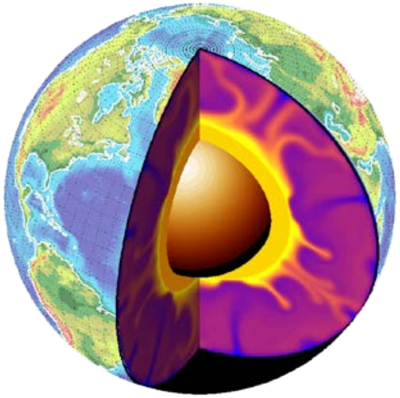
The photomultiplier tubes, acting as ultra-sensitive artificial eyes, detect and record the light flashes produced by the neutrinos.

Borexino observes dozens of these signals every day.

## THE THERMONUCLEAR FUSION REACTION THAT PRODUCES THE P-P NEUTRINOS RECENTLY STUDIED BY BOREXINO



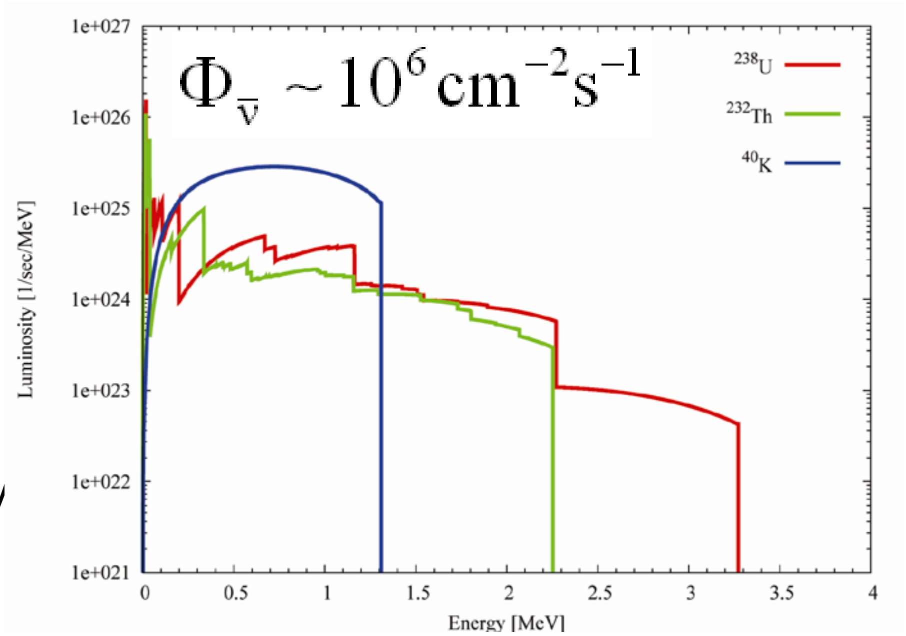
# Geo-neutrinos: anti-neutrinos from β-decays of radioactive elements in the Earth



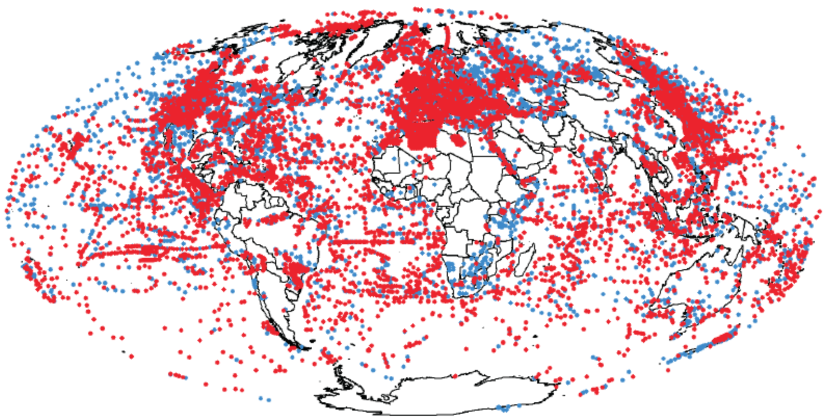
**$^{238}$U, $^{232}$Th and $^{40}$K ($^{87}$Rb,$^{235}$U) release heat together with antineutrinos**

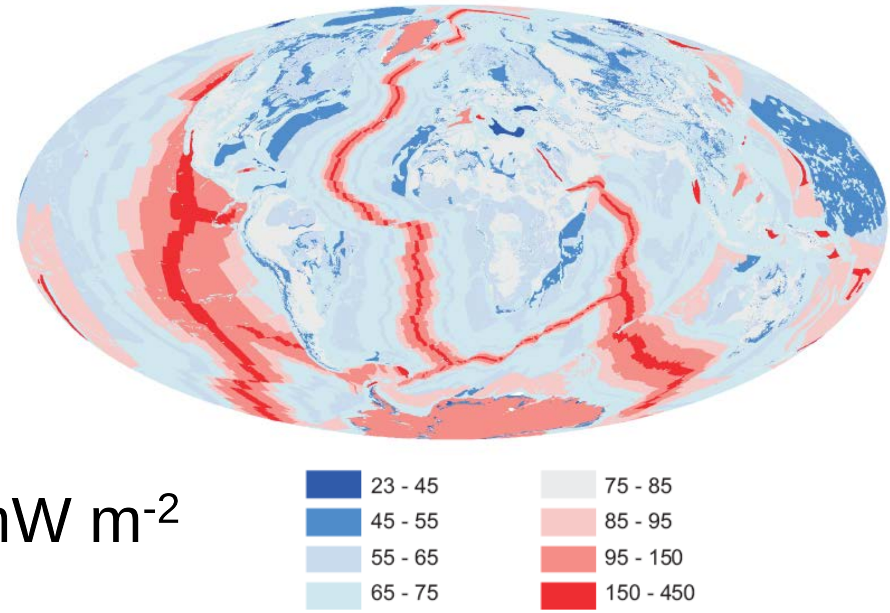
| Decay | $T_{1/2}$ [$10^9$ yr] | $E_{\max}$ [MeV] | $Q$ [MeV] | $\varepsilon_{\bar\nu}$ [$\mathrm{kg^{-1}s^{-1}}$] | $\varepsilon_H$ [W/kg] |
|---|---|---|---|---|---|
| $^{238}\mathrm{U} \to {}^{206}\mathrm{Pb} + 8\,{}^4\mathrm{He} + 6e + 6\bar\nu$ | 4.47 | 3.26 | 51.7 | $7.46 \times 10^7$ | $0.95 \times 10^{-4}$ |
| $^{232}\mathrm{Th} \to {}^{208}\mathrm{Pb} + 6\,{}^4\mathrm{He} + 4e + 4\bar\nu$ | 14.0 | 2.25 | 42.7 | $1.62 \times 10^7$ | $0.27 \times 10^{-4}$ |
| $^{40}\mathrm{K} \to {}^{40}\mathrm{Ca} + e + \bar\nu$ (89%) | 1.28 | 1.311 | 1.311 | $2.32 \times 10^8$ | $0.22 \times 10^{-4}$ |

- Earth emits (mainly) antineutrinos whereas Sun shines in neutrinos.
- A fraction of geo-neutrinos from U and Th are above threshold for inverse β on protons: 1.8 MeV
- Different components can be distinguished due to different energy spectra: e. g. anti-ν with highest energy are from Uranium.



# Heat flow through the surface of the Earth






“Earth’s surface heat flux”, J. H. Davies and D. R. Davies (2010)

mW $m^{-2}$

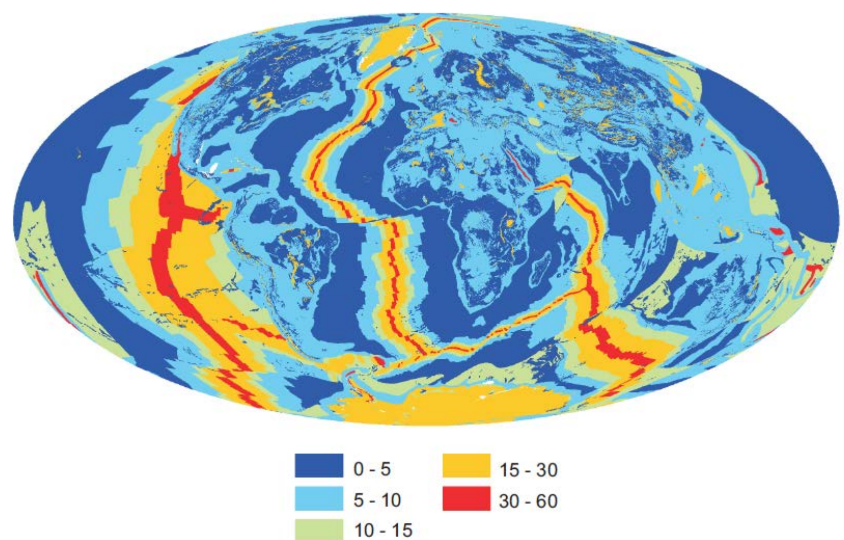
47±2 TW

38 347 measurements of the thermal flux

In agreement with previous estimations based on incomplete set of the same data

46±3 TW[Jaupart et al., 2007] and

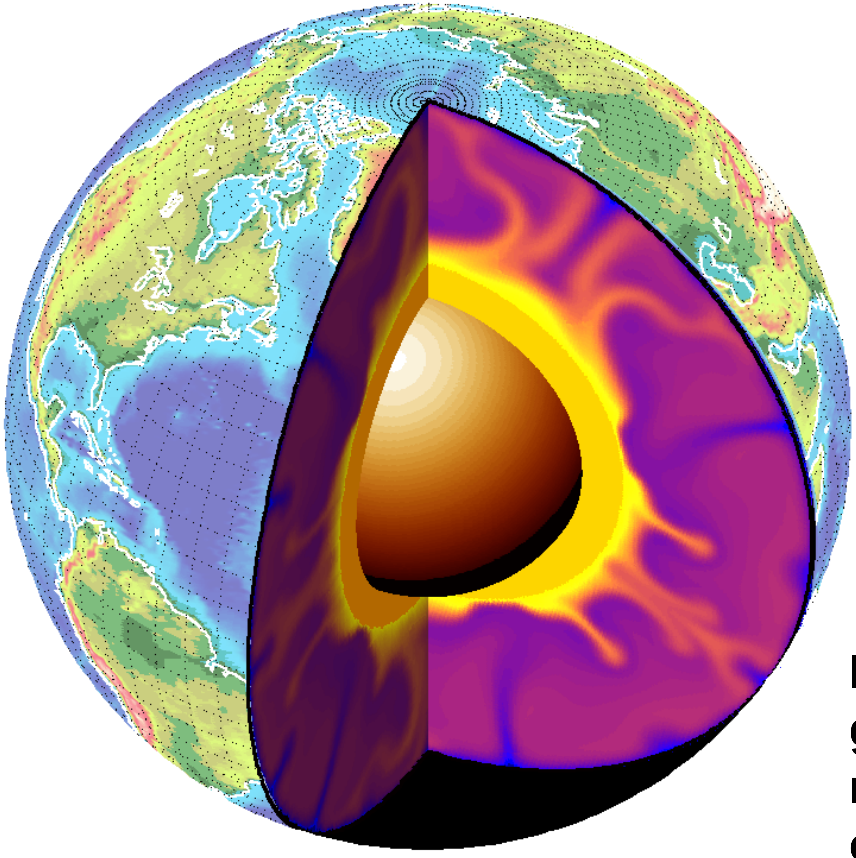
44±1 TW [Pollack et al., 1993]



# Open questions on the natural radioactivity in the Earth

What is the radiogenic contribution to terrestrial heat production?

What is hidden in the Earth's core? (geo-reactor, $^{40}K$, …)?

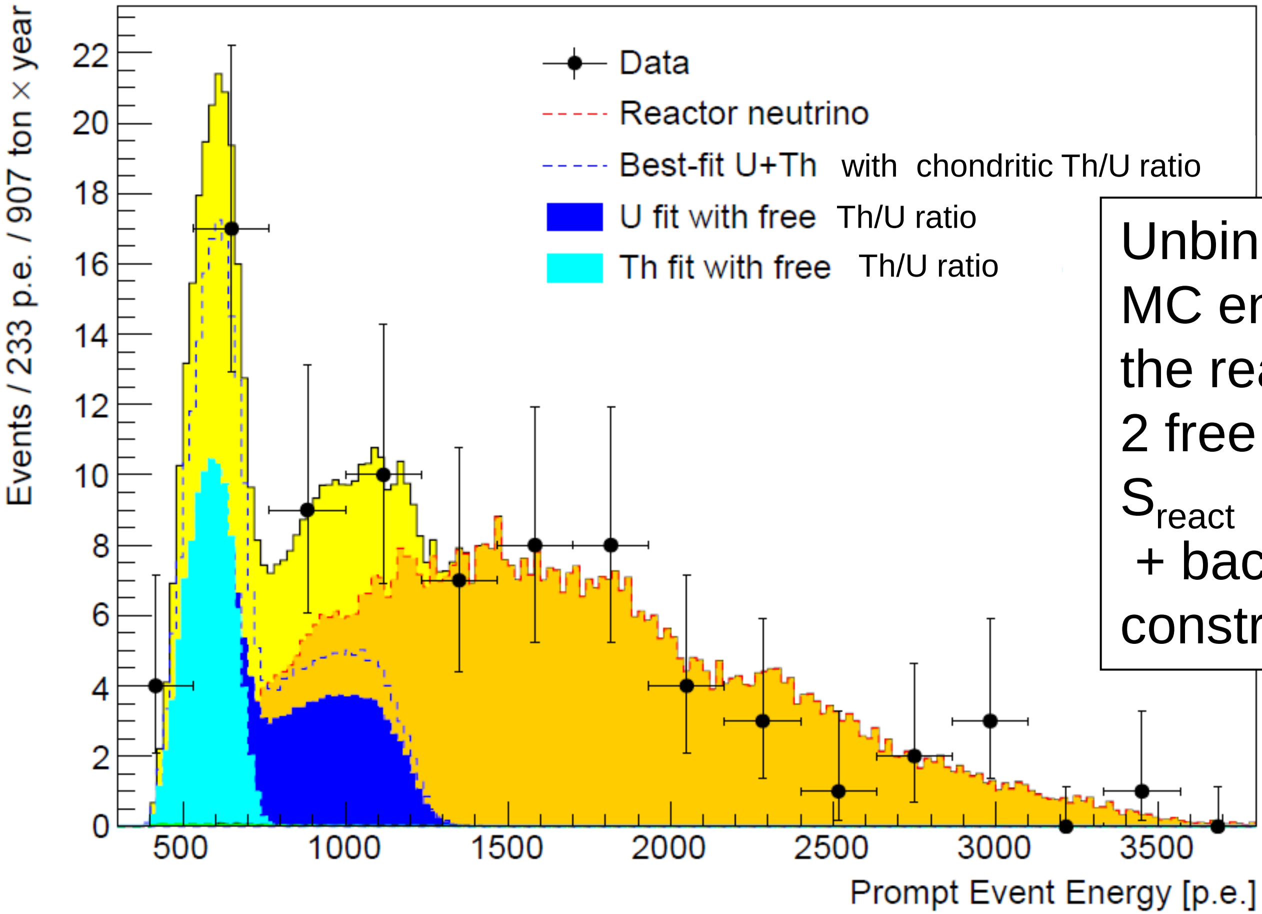


How much U and Th in the crust?

Is the standard geochemical model (BSE) consistent with geo-neutrino data?

How much U and Th in the mantle?

# Borexino 2015: antineutrino spectrum (77 events)




Unbinned likelihood fit using MC energy spectra for geo and the reactor antineutrinos
2 free parameters $S_{geo}$ and $S_{react}$
+ backgrounds components constrained

~500 p.e./MeV (electrons)
gammas are quenched

$$Q_{vis} = 438\,p.e.(2\gamma) + Q(E_{\bar{\nu}} - 1.8 MeV)$$

# Borexino started taking data in 2007

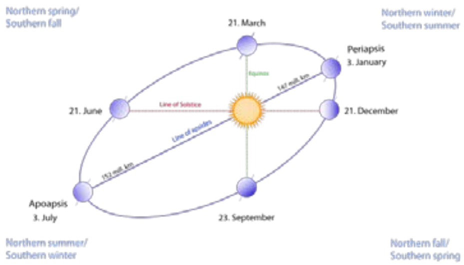
**RECENT DEVELOPMENTS**
**IN NEUTRINO PHYSICS AND ASTROPHYSICS**

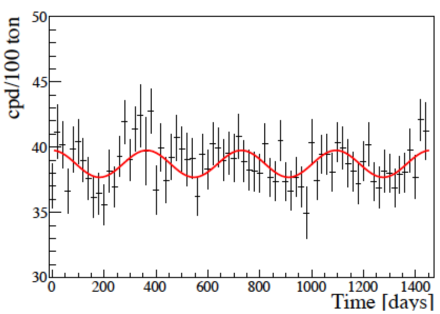
*The Borexino Collaboration celebrates in L'Aquila (Italy)*
*the 10° anniversary of data-taking*

SEPTEMBER 4-7, 2017 @ LNGS and GSSI

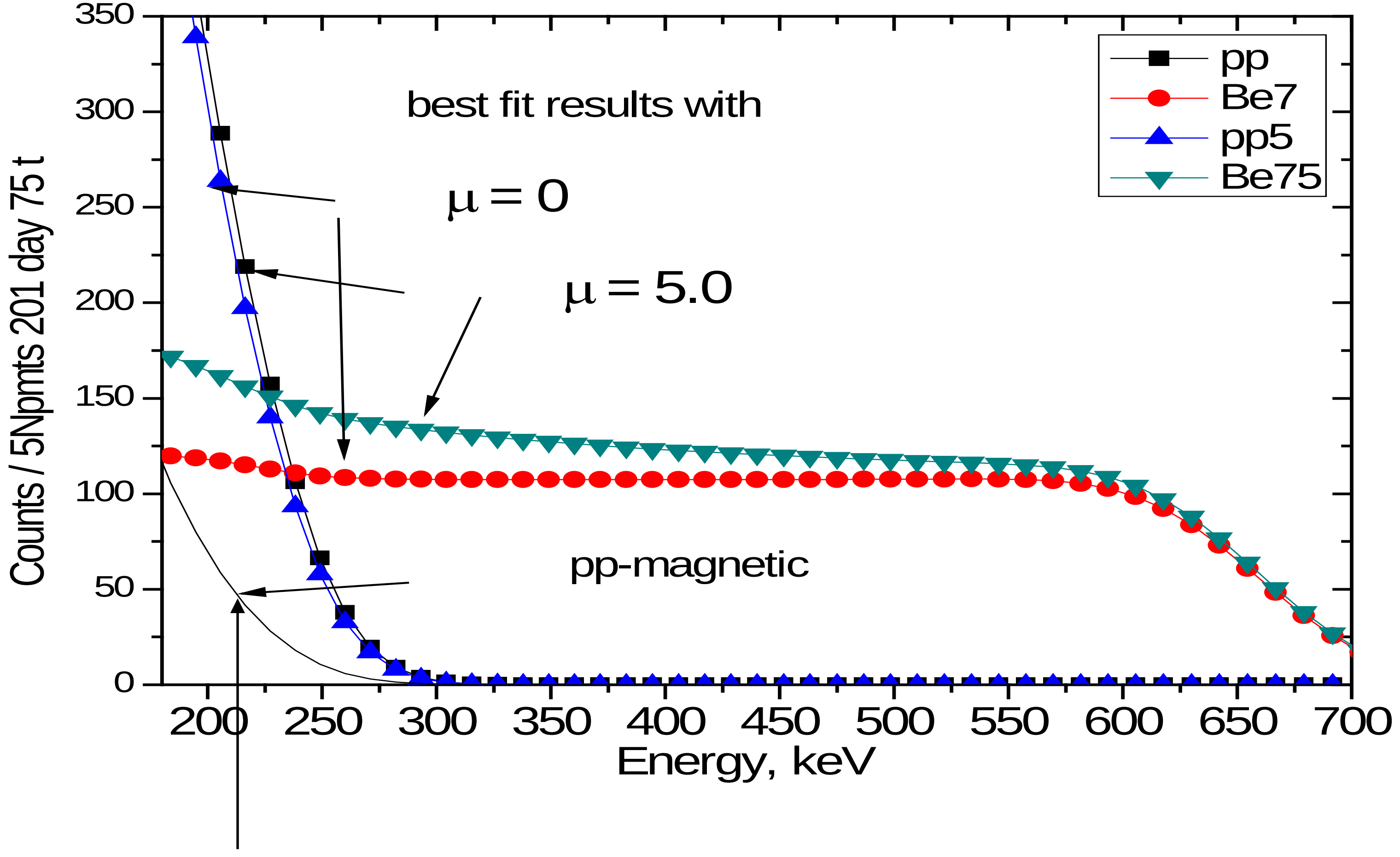
**Observation of seasonal variations of the Be-7 neutrino signal**
**T=367±10 days**

**(measurement of the duration of astronomical year),**
**Confirmation of the solar origin of the signal**

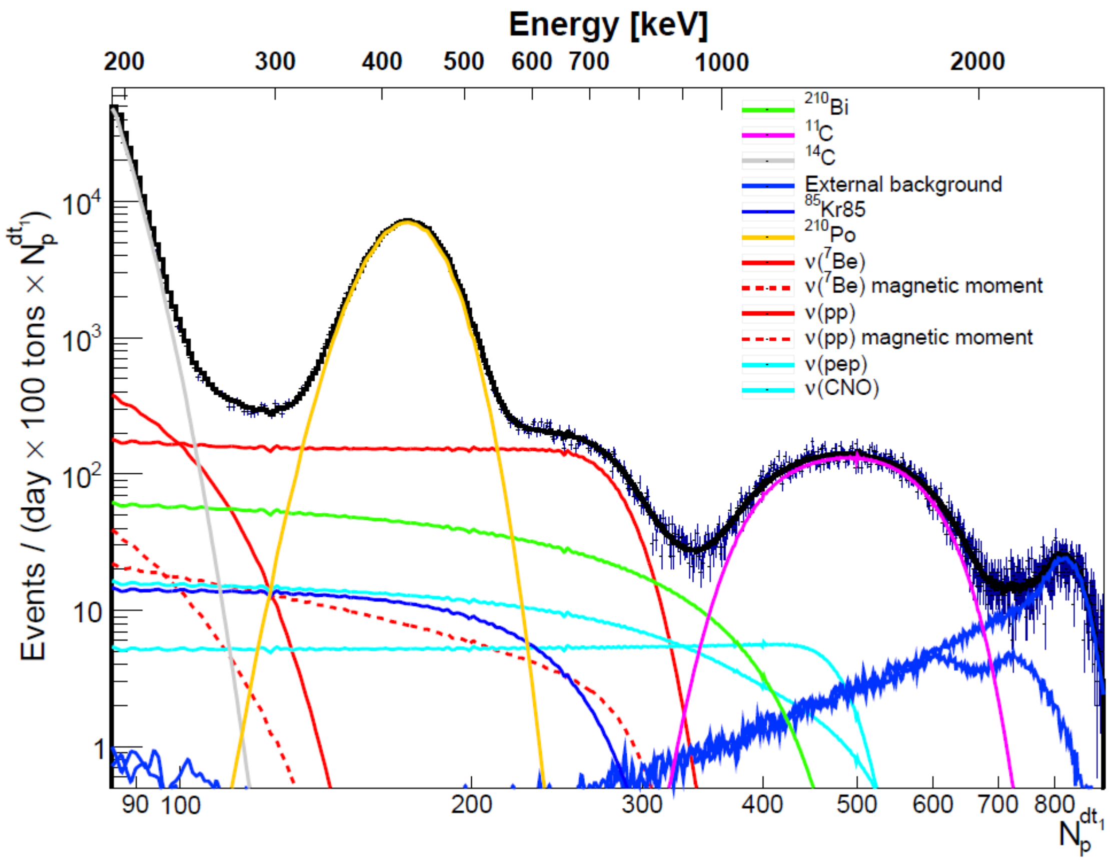


## The Borexino response to pp- and $^{7}$Be-neutrino with $\mu = 0$ and $\mu = 5.0 \times 10^{-11} \mu_B$.



# Neutrino magnetic moment




With Ga constraint:

$\mu_\nu$**<2.8·10$^{-11}$ $\mu_B$**, 90% C.L.

$$\mu_{\nu_e} < 3.9 \cdot 10^{-11} \mu_B$$

$$\mu_{\nu_\mu} < 5.8 \cdot 10^{-11} \mu_B$$

$$\mu_{\nu_\tau} < 5.8 \cdot 10^{-11} \mu_B$$

# GW 170817

## birth of multimessenger astronomy

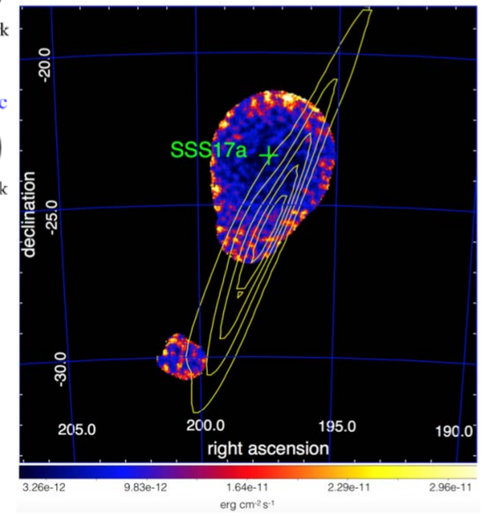
The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9


**Multi-messenger Observations of a Binary Neutron Star Merger***

The Astrophysical Journal Letters, 848:L13 (27pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa920c


**Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A**

LIGO Scientific Collaboration and Virgo Collaboration, *Fermi* Gamma-ray Burst Monitor, and INTEGRAL

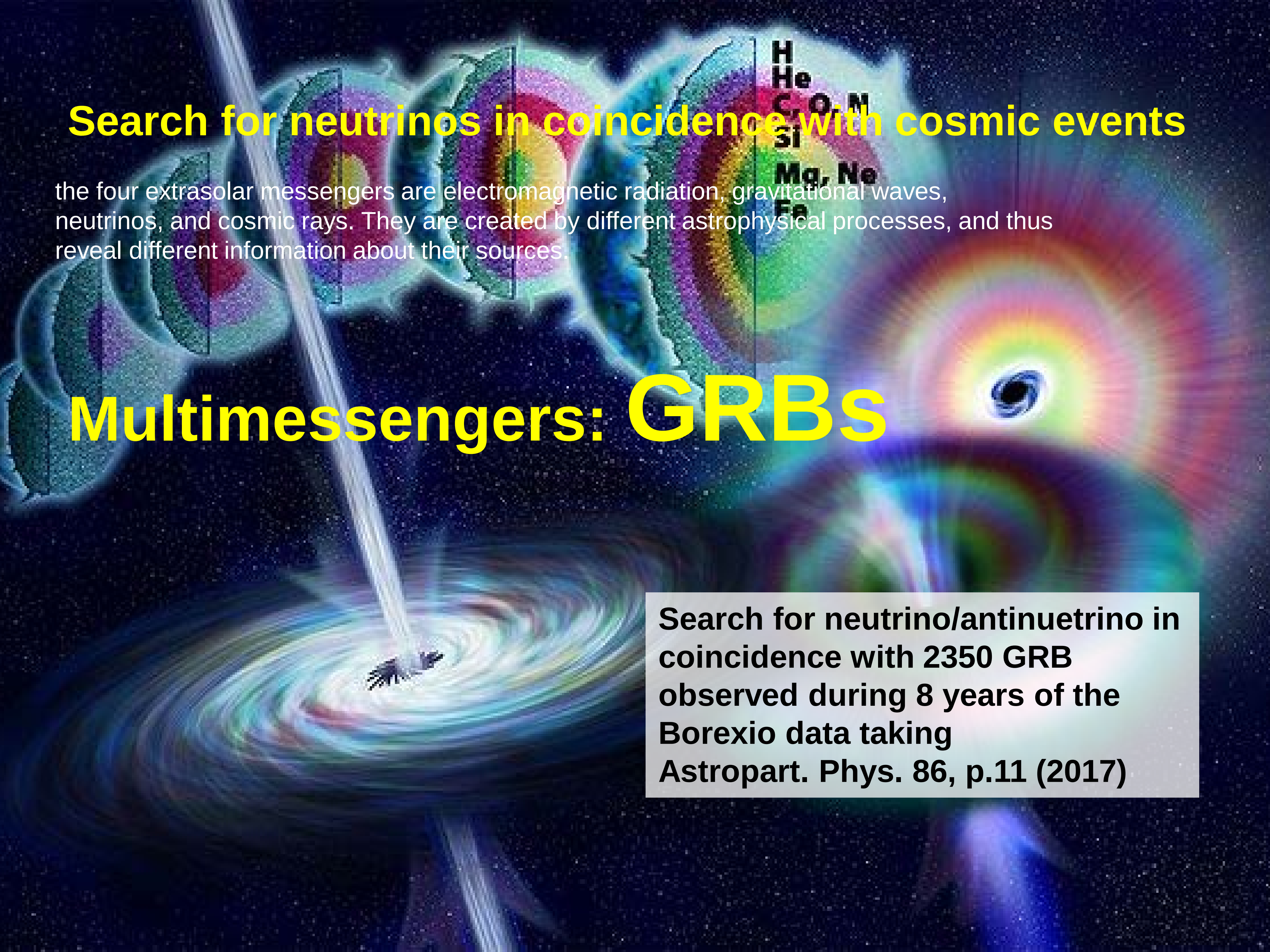



**The Supernova Early Warning System (SNEWS), established in 1999 at BNL,**

**The Astrophysical Multimessenger Observatory Network (AMON), created in 2013, a broader project to facilitate the sharing of preliminary observations and to encourage the search for "sub-threshold" events which are not perceptible to any single instrument. It is based at Pennsylvania State University.**

**August 2017: A neutron star collision that occurred in the galaxy NGC 4993 produced the gravitational wave signal GW170817, which was observed by the LIGO/Virgo collaboration. After 1.7 seconds, it was observed as the gamma ray burst GRB 170817A by the Fermi Gamma-ray Space Telescope and INTEGRAL, and its optical counterpart SSS17a was detected 11 hours later at the Las Campanas Observatory.**

**September 2017: On September 22, the extremely-high-energy neutrino event EHE170922A[12] was recorded by the IceCube Collaboration. Consistent detections of gamma rays above 100 MeV by the Fermi-LAT Collaboration[13] and above 100 GeV by the MAGIC Collaboration[14] were announced. The signal is consistent with ultra-high-energy protons accelerated in blazar jets, producing neutral pions (decaying into gamma rays) and charged pions (decaying into neutrinos).[15]**




# Search for neutrinos in coincidence with cosmic events

the four extrasolar messengers are electromagnetic radiation, gravitational waves, neutrinos, and cosmic rays. They are created by different astrophysical processes, and thus reveal different information about their sources.

# Multimessengers: GRBs

**Search for neutrino/antinuetrino in coincidence with 2350 GRB observed during 8 years of the Borexio data taking**
**Astropart. Phys. 86, p.11 (2017)**

# Multimessengers: GW

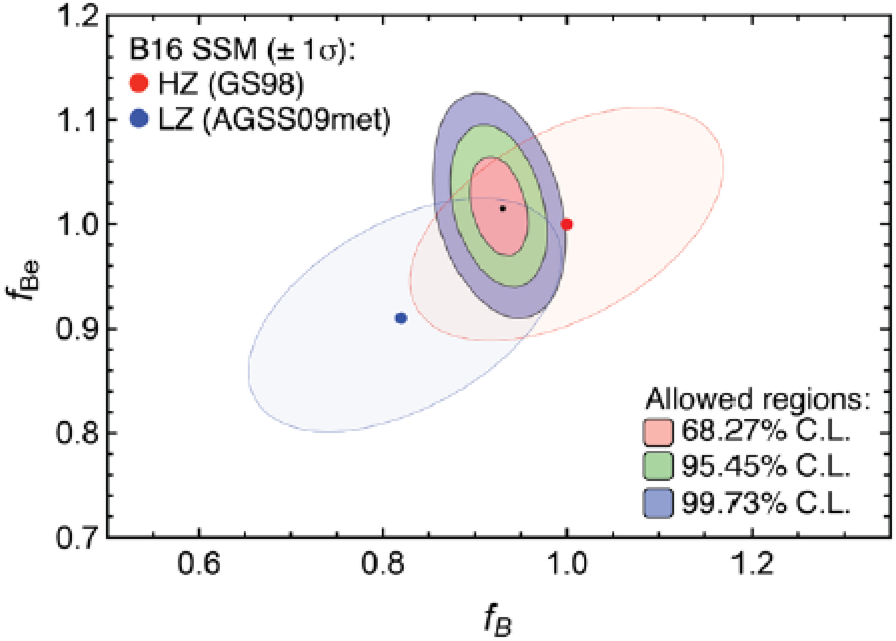

**Search for neutrino/antineutrino in coincidence with GW events (GW150914, GW151226, GW170104)**
**Astrophys. J., 850:21 (2017)**

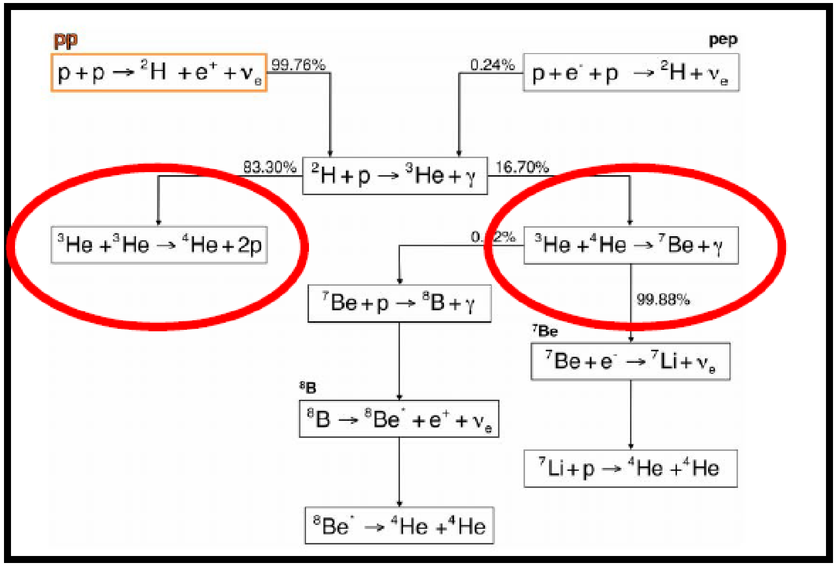
**Statistically significant event count above expected background is not observed**

# Borexino Phase-II physics program

- **Improvement of the $^{7}$Be-neutrino flux (3%) and its seasonal variations (5σ)**
- **Measurement of *pep*-neutrino flux with better than 3σ accuracy→ 5σ**
- **$^{8}$B-neutrino flux measurement with 10% accuracy (x4 higher statistics)→8%**
- **Limits on effective solar neutrino magnetic moment→x2**
- **Improvement of geo-neutrino flux measurement → planned for 2018**
- **Study of non-standard neutrino interactions (NSI)→ planned for 2018**
- **Measurement (or limits on) of the CNO-neutrino flux→2019-2021**
- **Measurements with artificial neutrino sources – search for sterile neutrinos and neutrino magnetic moment: SOX project (Short distance Oscillations with BoreXino) →Program oficially stopped at February 1, 2018**
- **Dark Matter search with the updated Borexino's prototype detector (CTF): DarkSide project. DarkSide-50 (50 kg of liquid Underground Ar (UAr), sensitivity at $2 \cdot 10^{-44}$ cm$^2$ for 100 GeV WIMP over 3 year statistics), first results are obtained. DarkSide-G2 (the second generation, 3.3 t of UAr). Expected sensitivity is $2 \cdot 10^{-47}$ cm$^2$ for WIMP-nuclei scattering over 5 year statistics, that is 400 times better then the current level.**

# Solar metallicity problem




$$R \equiv \frac{<^3\,\mathrm{He} + ^4\mathrm{He}>}{<^3\,\mathrm{He} + ^3\mathrm{He}>} = \frac{2\phi(^7\mathrm{Be})}{\phi(\mathrm{pp}) - \phi(^7\mathrm{Be})}$$

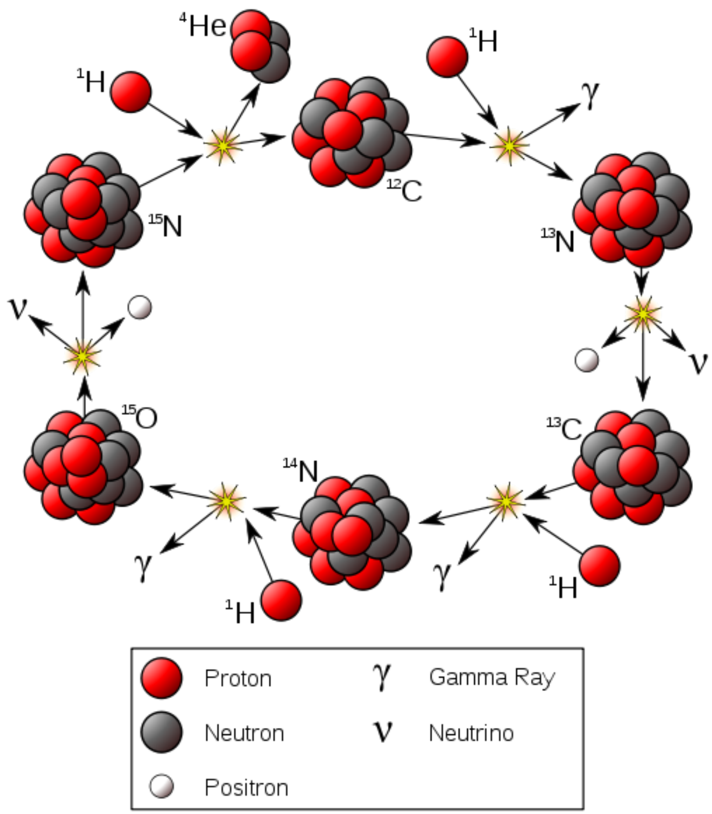
$\mathbb{R}$(HZ)= 0.18 ± 0.01

$\mathbb{R}$(LZ)= 0.16 ± 0.01

From the pp and $^7$Be flux new measurement

$\mathbb{R}$ = 0.18 ± 0.02

# CNO




Prediction for HZ ~5 cpd/100 t

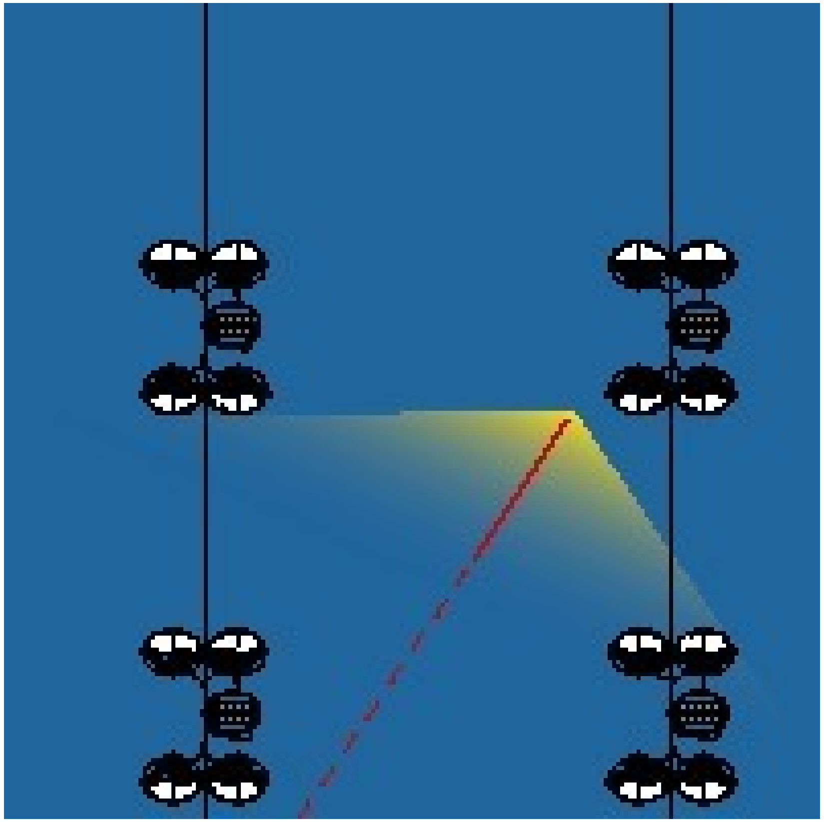
LZ ~3 cpd/100 t

Main background from $^{210}$Bi :

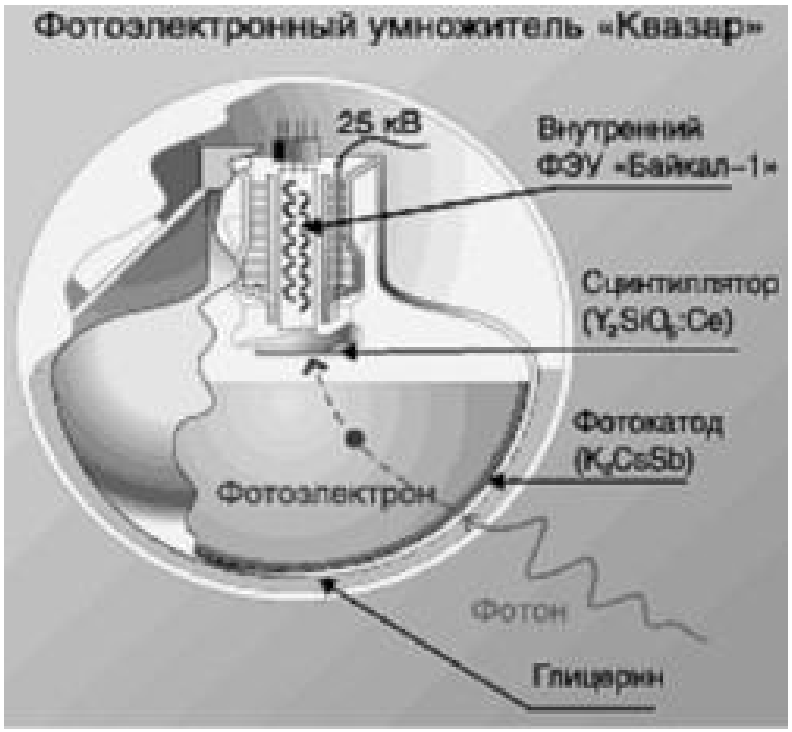
~20 cpd/100 t

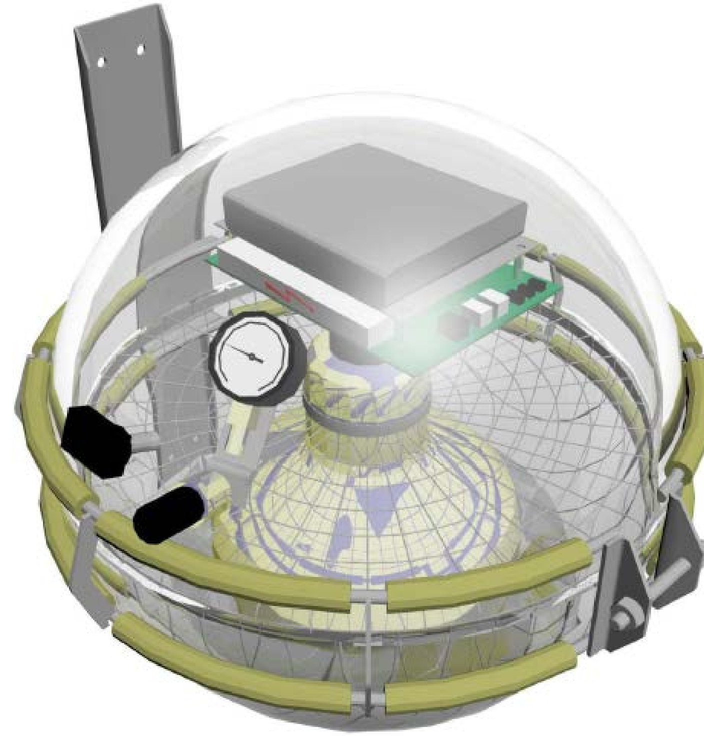
If we will be able to extract $^{210}$Bi with few counts precision, we will be able to constraint it in the spectral fit and extract the CNO flux at 1-2σ level.

# Baikal deep underwater neutrino experiment

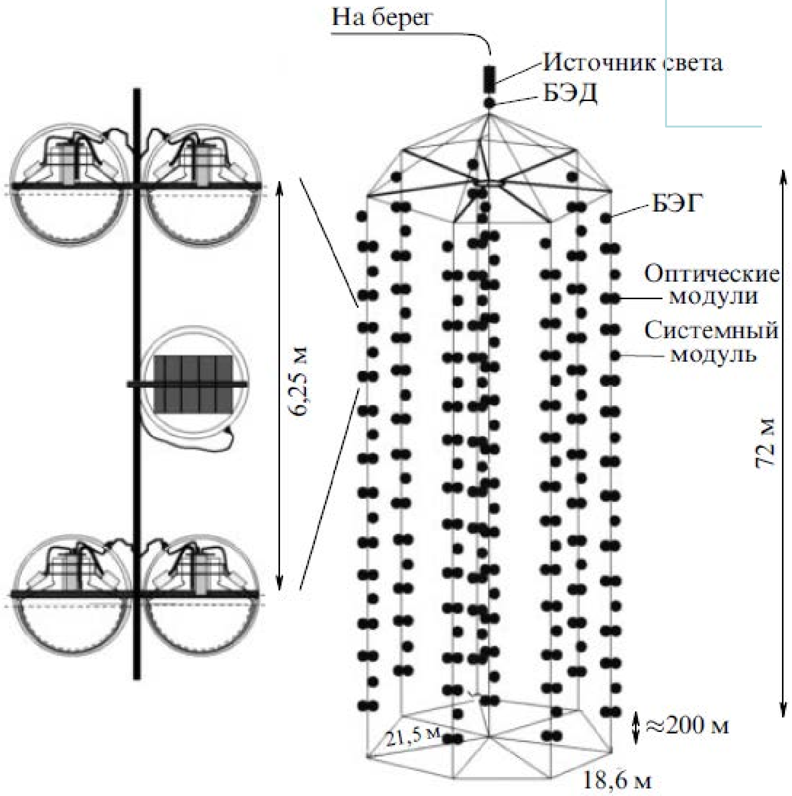



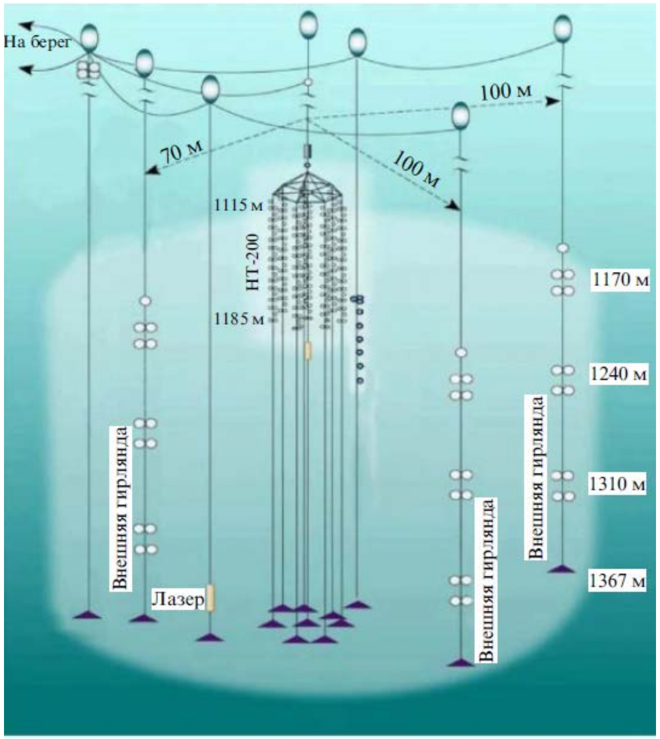
# PMT


Фотоэлектронный умножитель «Квазар»
25 кВ
Внутренний ФЭУ «Байкал-1»
Сцинтиллятор ($Y_2SiO_5$:Ce)
Фотокатод ($K_2CsSb$)
Фотоэлектрон
Фотон
Глицерин



# HT200→HT200+

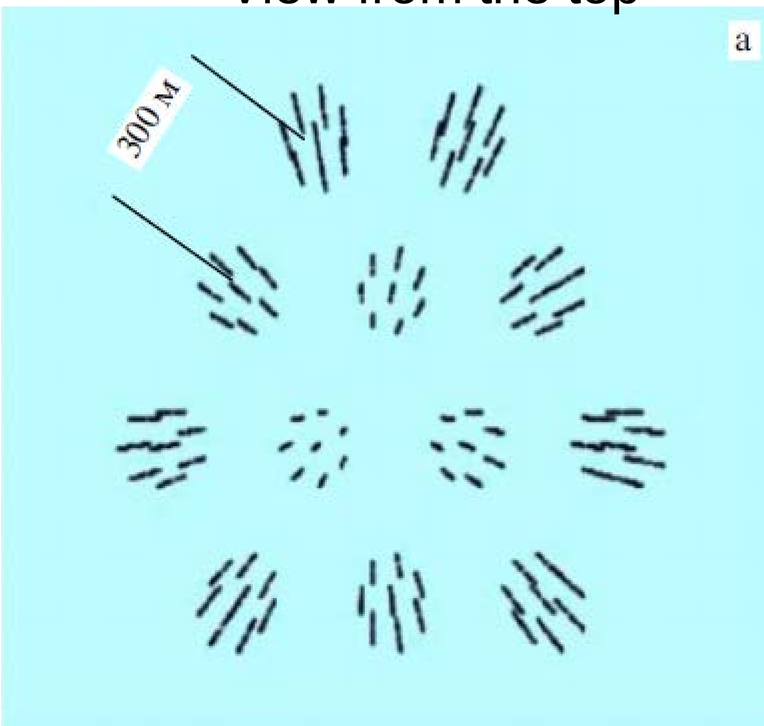


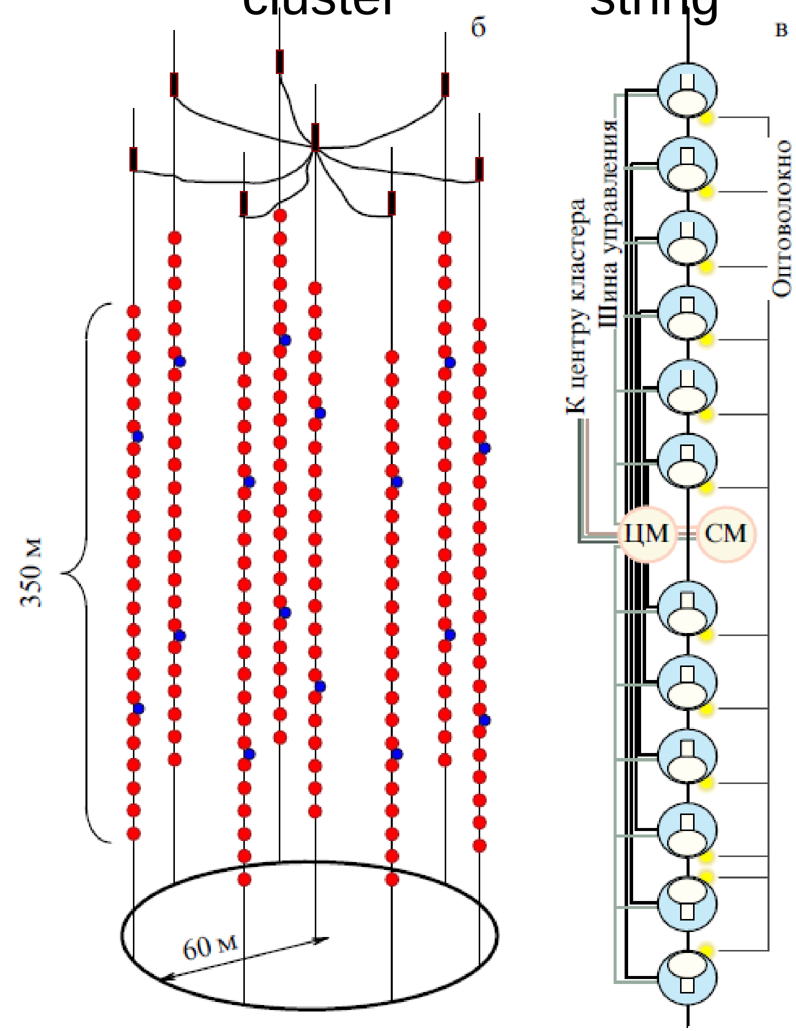

Limits on the natural diffuse neutrino flux of all types in the enrgy range from 10 TeV up to 10 PeV;
Limits of the electron antineutrino flux in the region of resonanse with energy of E=6.3 PeV

# $\rightarrow$HT1000 (1 km$^3$)

View from the top




cluster string

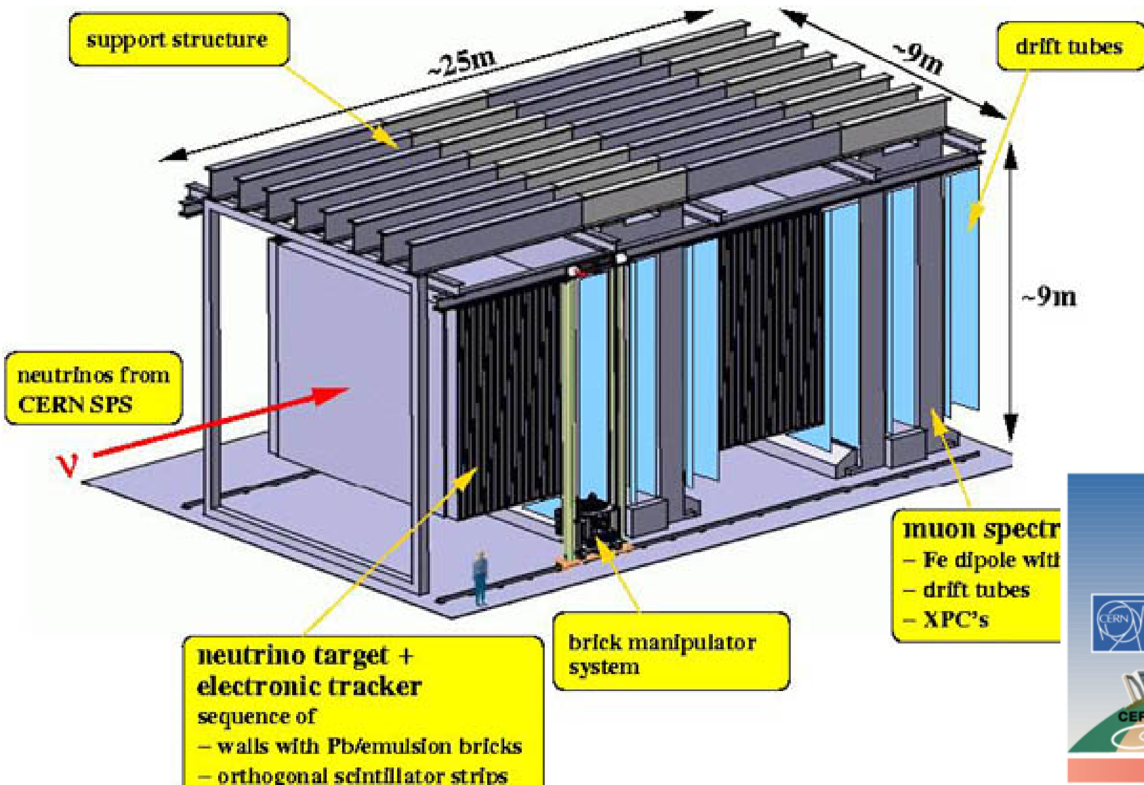



Neutrino from astrophysical objects
Diffuse neutrino fluxes
Atmospheric neutrino
Magnetic monopoles
Dark matter

# Dubna is contributing to the development of experiment

The first cluster of the neutrino telescope is called “Dubna”, it works for two years already. At present Dubna segment consists of two extended clusters, 300 PMTs are placed at the depth of down to 1300 m, the data are being accumulated. The setup will be completed in 2020.

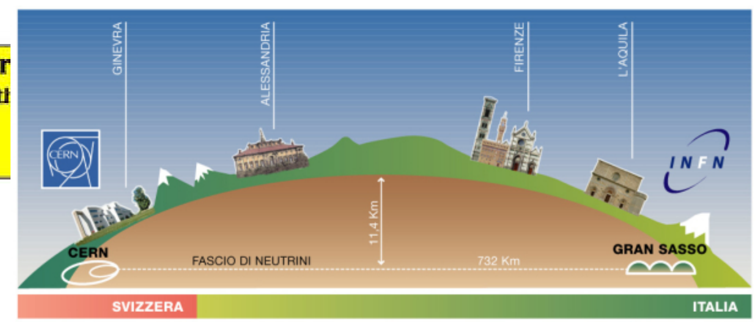
# OPERA experiment




**Oscillation Project with Emulsion-tRacking Apparatus**

Search for tau neutrino In muon neutrino beam

(~17 GeV)




In total, five tau neutrinos were detected. On 31 May 2010, OPERA researchers observed the first tau neutrino candidate event in a muon neutrino beam. On 6 June 2012 - a second tau neutrino event. On 26 March 2013 - the third. The fourth one was found in 2014, and the fifth was seen in 2015.

The neutrino indeed started its flight at CERN as muon neutrino and, after travelling 730 km through the Earth, it arrived at the Gran Sasso laboratory transformed into a tau neutrino.

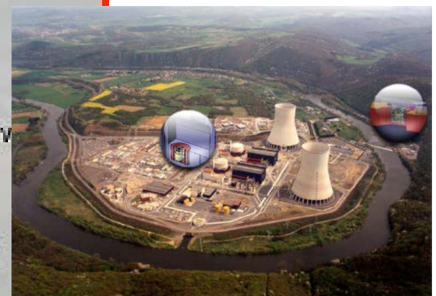
# Sensation of 2011 – superluminal neutrino

Borexino: $\delta t = 2.7 \pm 1.2$ (stat) $\pm$ 3(sys) ns

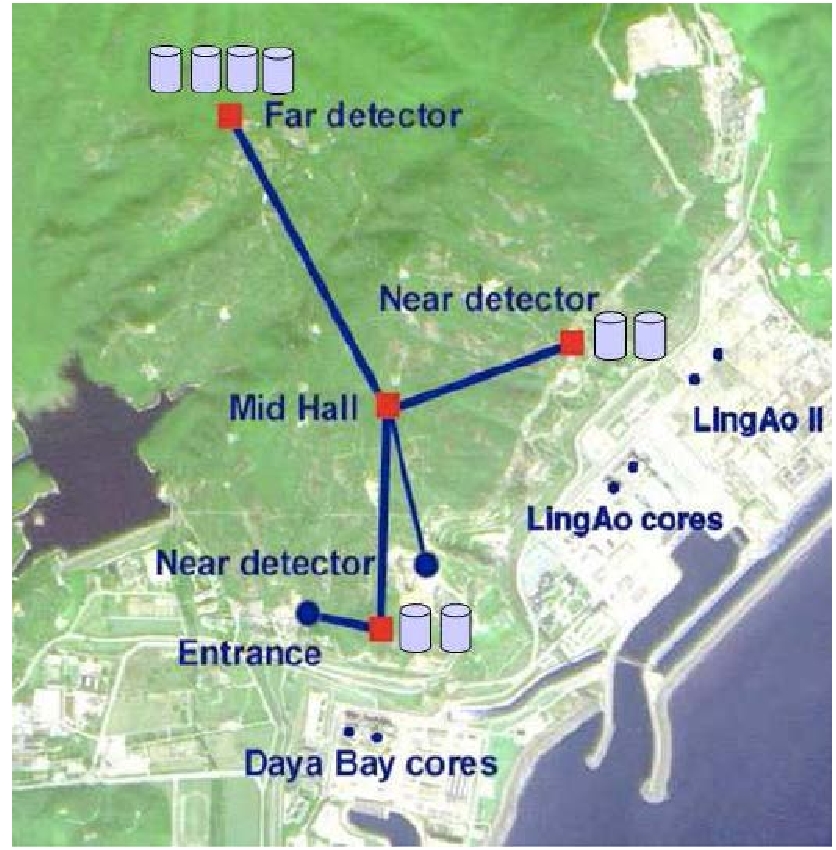
ICARUS: $\delta t = 5.1 \pm 1.1$(stat) $\pm$ 5.5(sys) ns

LVD: $\delta t = 2.9 \pm 0.6$(stat) $\pm$ 3(sys) ns

OPERA: $\delta t = 1.6 \pm 1.1$(stat) [+ 6.1, -3.7](sys) ns

# Double Chooz

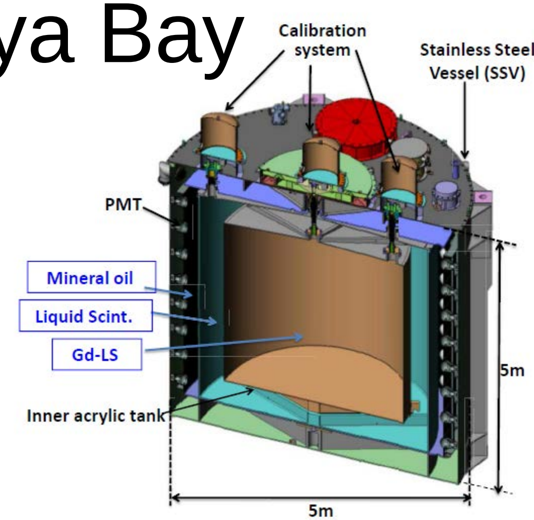



# Daya Bay


**YongGwang**

**(靈光) :**

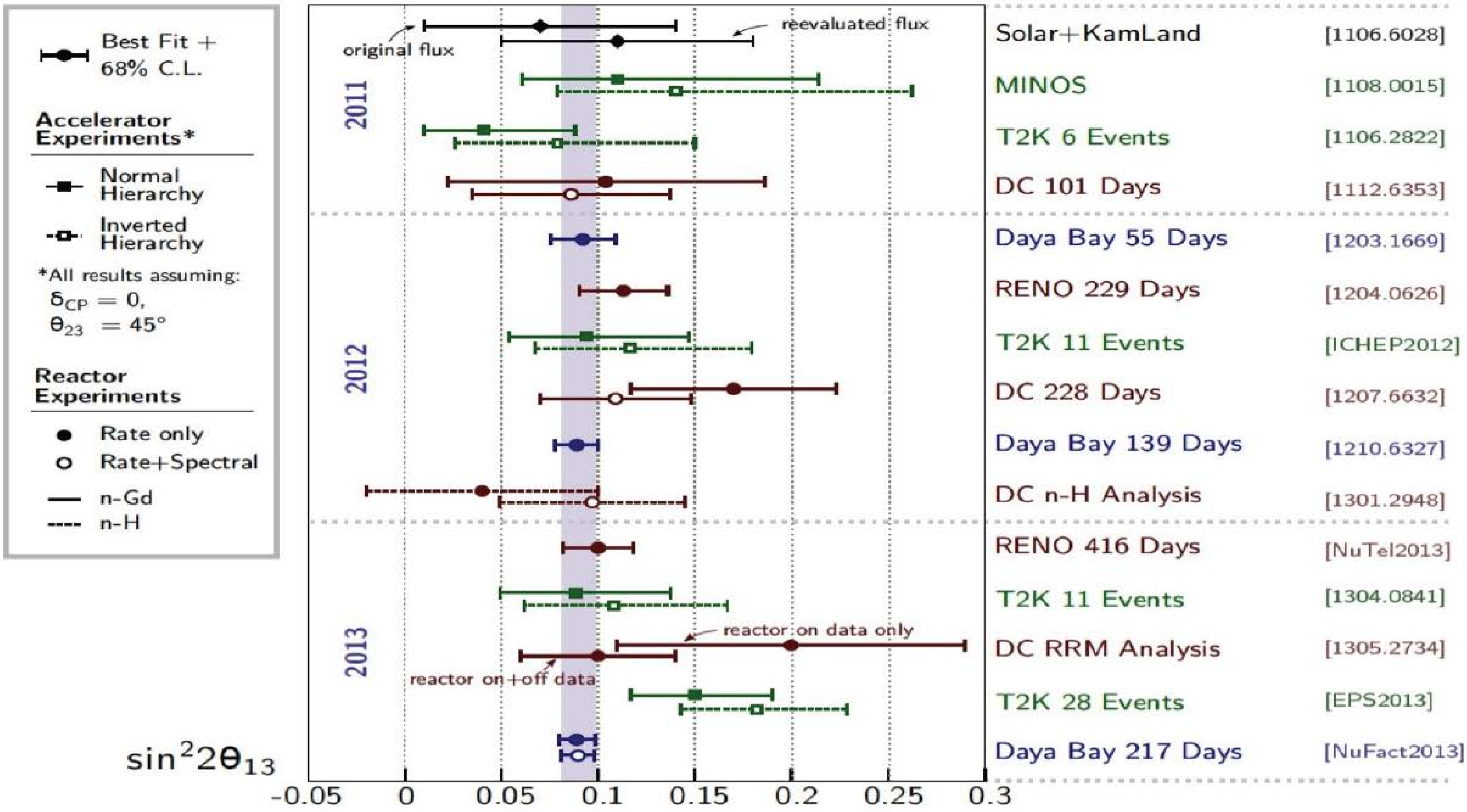
# RENO



# Results ($sin^2 2\Theta_{13}$)

| Date | Daya Bay | Double CHOOZ | RENO |
| --- | --- | --- | --- |
| 11.2011 | | 0.102±0.028±0.033 (<3σ) | |
| 08.03.2012 | 0.092±0.016±0.005 (>3σ) | | |
| 03.04.2012 | | | 0.113±0.013±0.019 (>3σ) |
| Neutrino-2014 | 0.084±0.005 | 0.09±0.03 | 0.101±0.013 |

# Quest for theta13



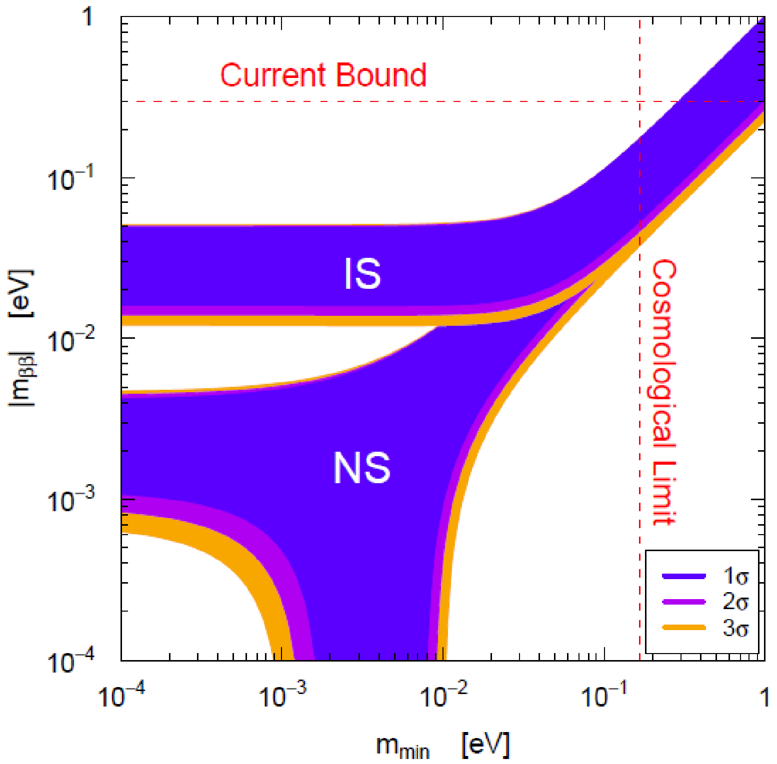
# Neutrino mass hierarchy experiments

| Project | $\nu$ source | Detector | Goal | Challenges |
|---|---|---|---|---|
| NOVA | LBL (810 km) | 14 kt tracking calorimeter | $2\sigma$ (2020) | Parameter degeneracy |
| JUNO | Reactor (53 km) | 20 kt LS | $(3-4)\sigma$ (2026) | Energy resolution |
| PINGU/ORCA | Atmosphere | (1-10) Mt of ice | $(3-5)\sigma$ (unknown) | Energy resolution, systematics |
| INO | Atmosphere | 50 kt magnetized calorimeter | $3\sigma$ (2030) | Low statistics (10 years) |
| T2HK | LBL (295 km) | 1Mt of water | $3\sigma$ (2030) | Parameter degeneracy |
| DUNE | LBL (1300 km) | 1kt of liquid argon | $(3-5)\sigma$ (2030) | Parameter degeneracy |
| Cosmology | Early Universe | CMB-S4 bolometers | $4\sigma$ (>2023) | Dependence on cosmological models |

# Why to measure neutrino mass hierarchy?

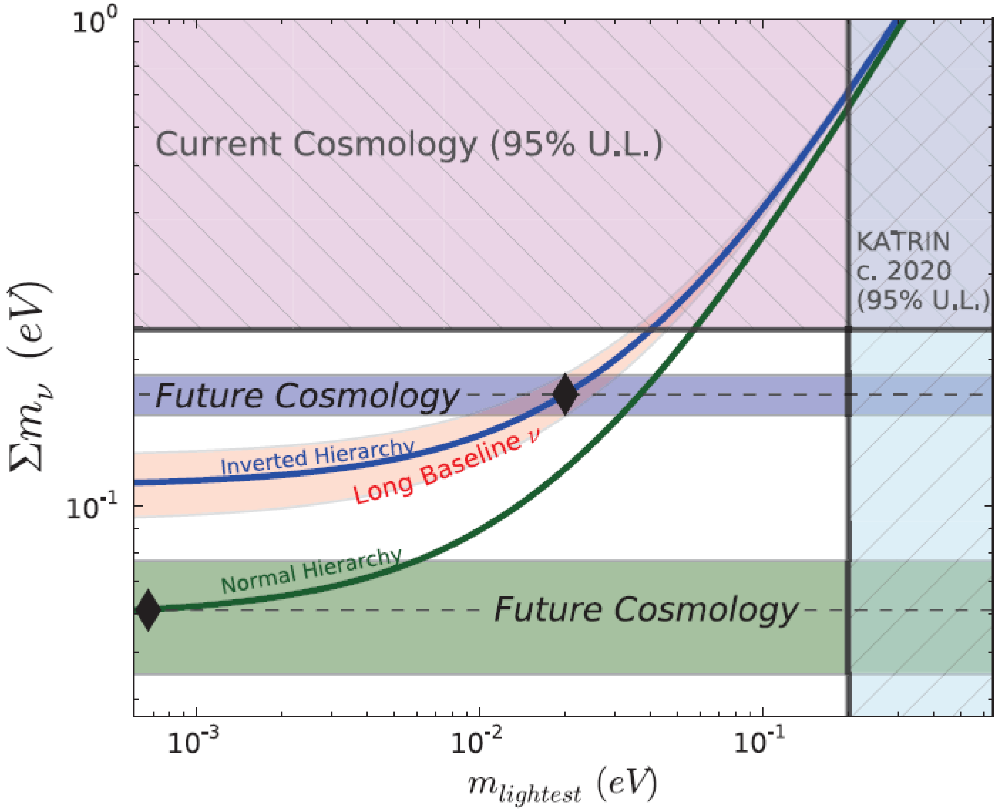
- **Important for setting goals for $0\nu\beta\beta$ experiments**

- **The MH is crucial for measuring the CP-violating phase. The wrong MH give a fake local minimum for $\delta_{CP}$ reducing the significance of the CP measurement. Even more important for a shorter base accelerator experiments (HyperK)**



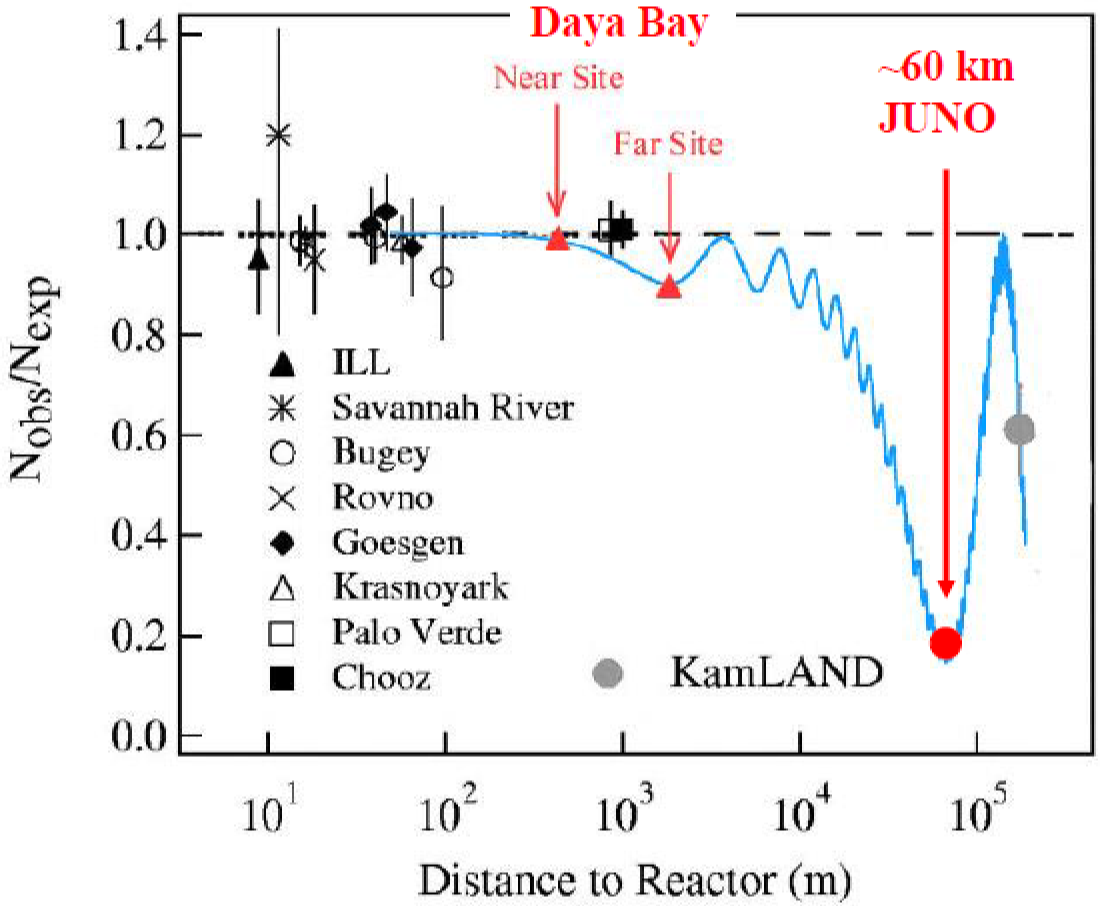
# Neutrino astronomy and neutrino cosmology

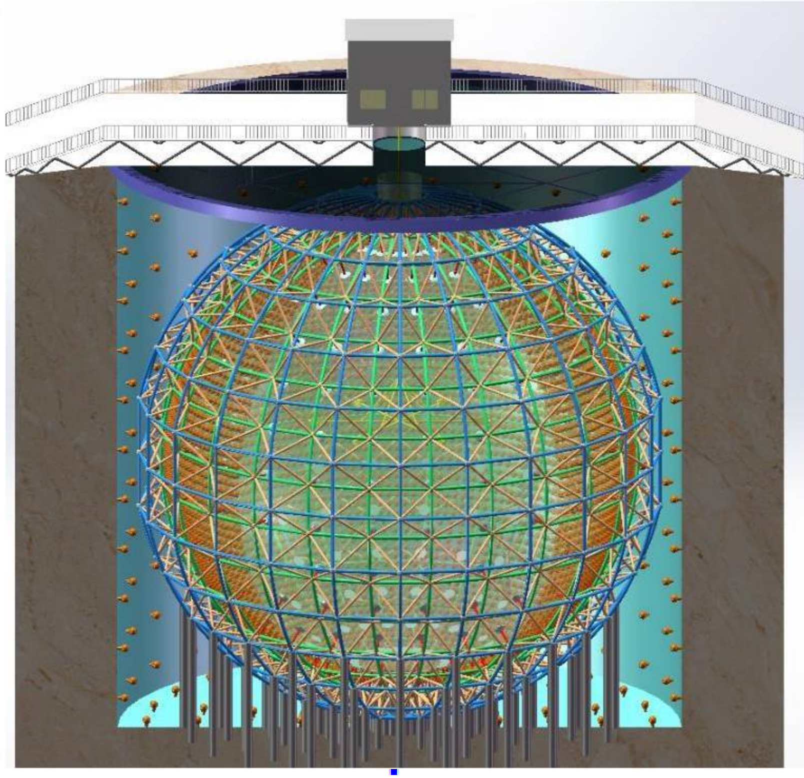
- **MH is a key parameter of the neutrino astronomy and neutrino cosmology. The spectral split patterns in SN neutrino fluxes are significantly different for the normal and inverted MHs. MH is also important for the supernova nucleosynthesis, where the prediction of the 7Li/11B ratio is also distinct for different MHs.**
- **On the other hand, MH may have important implications on the cosmological probe of the neutrino mass scale (i.e. $\sum m_\nu$).**



# JUNO Experiment

- Jiangmen Underground Neutrino Observatory (was Daya Bay II)
- Primary goals: mass hierarchy and precision meas.
  - 20 kton LS detector, 3%/$\sqrt{E}$ energy resolution
- Proposed in 2008, approved in Feb.2013. ~300M US$



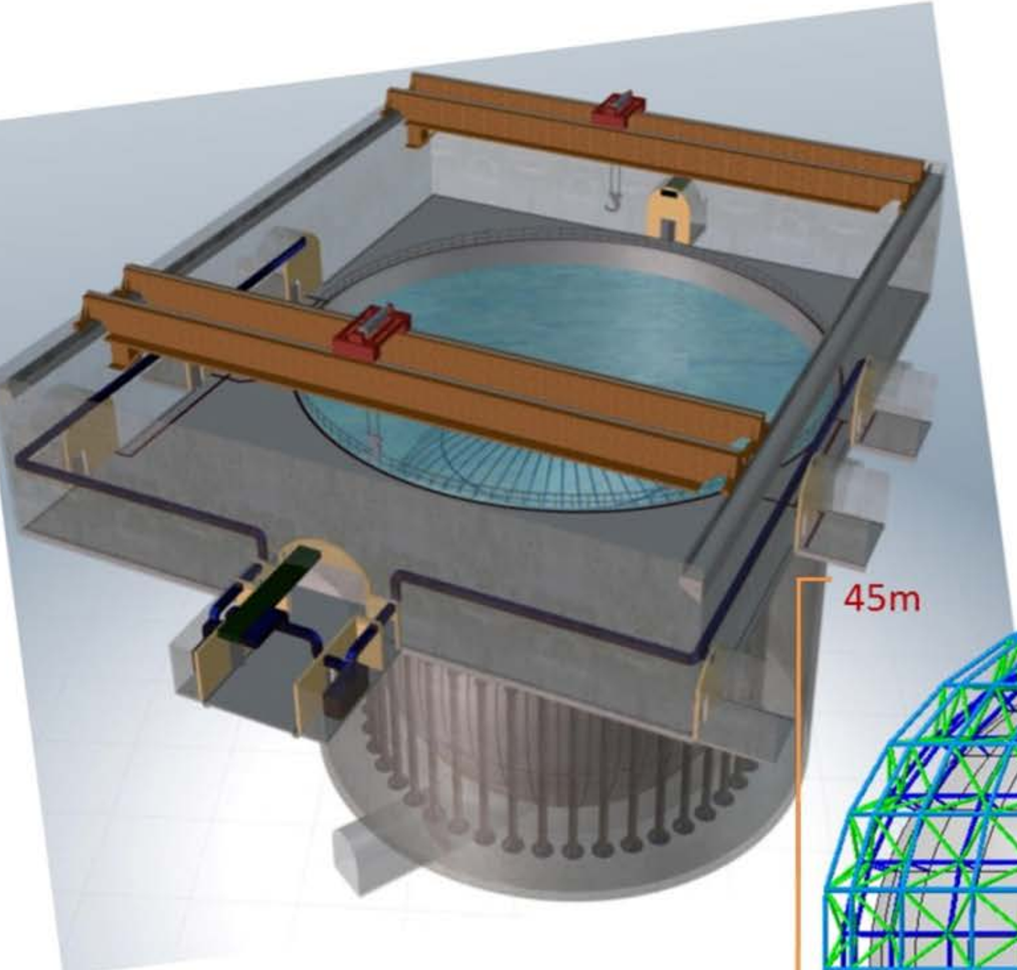



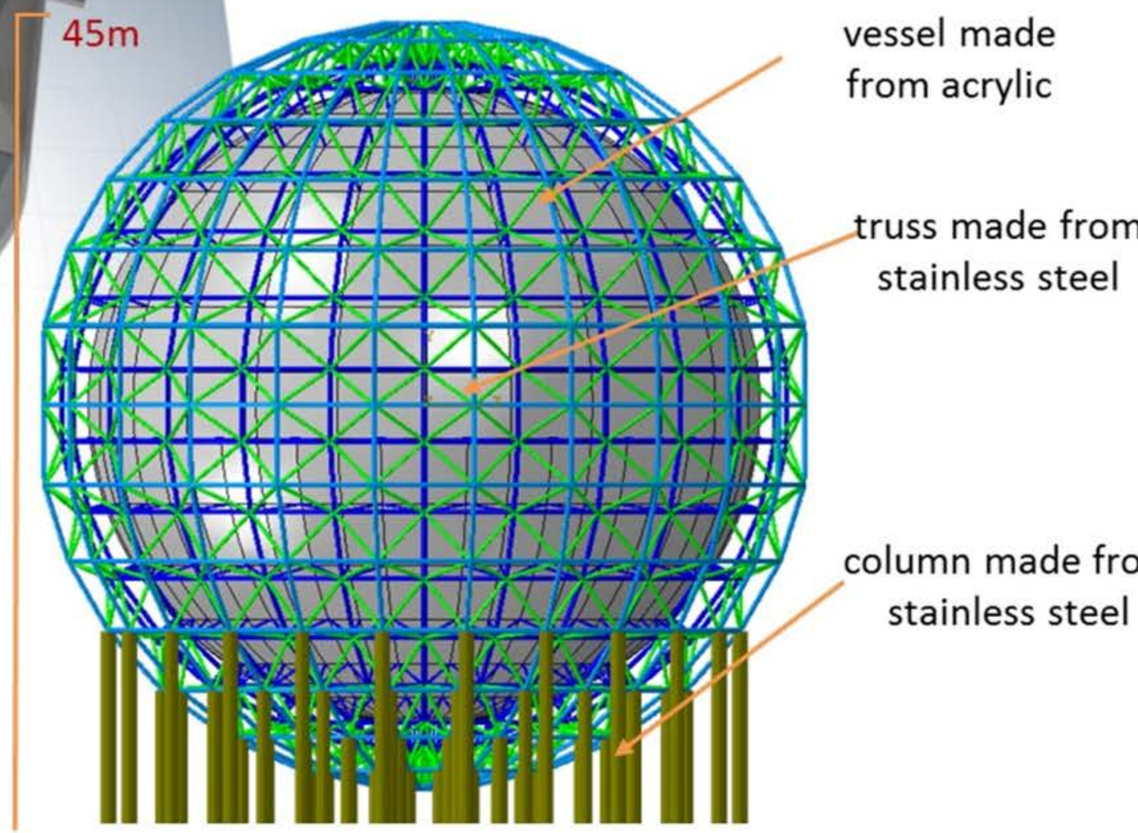
# JUNO detector

*35m diameter*

*20kt of liquid scintillator*

*15,000 PMTs*

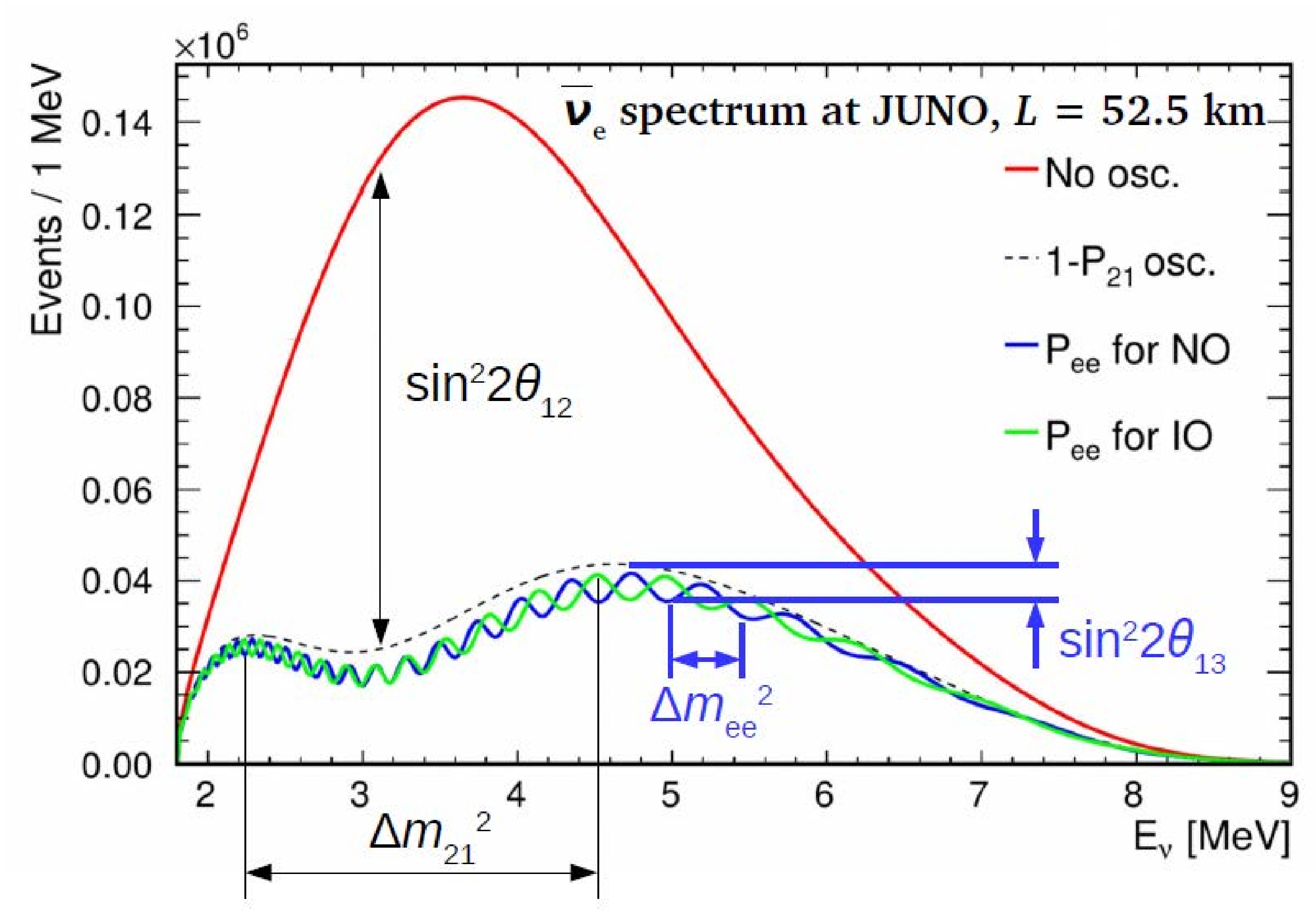




# Location of JUNO

| NPP | Daya Bay | Huizhou | Lufeng | Yangjiang | Taishan |
|---|---|---|---|---|---|
| Status | Operational | Planned | Planned | Under construction | Under construction |
| Power | 17.4 GW | 17.4 GW | 17.4 GW | 17.4 GW | 18.4 GW |

# JUNO antineutrino spectrum

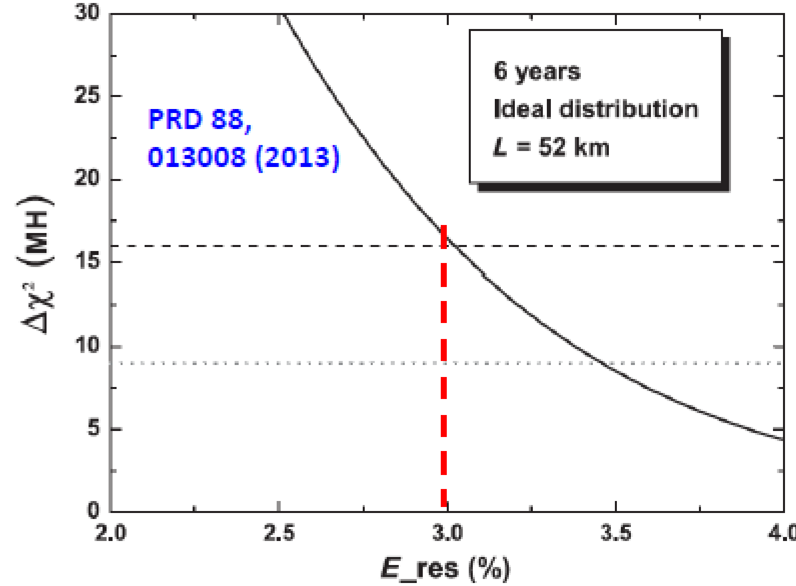


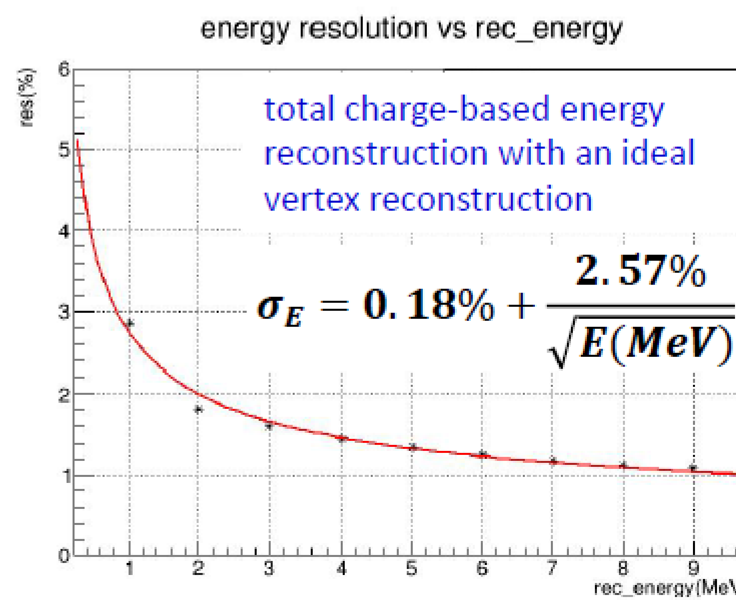
# Requirements on Energy Resolution

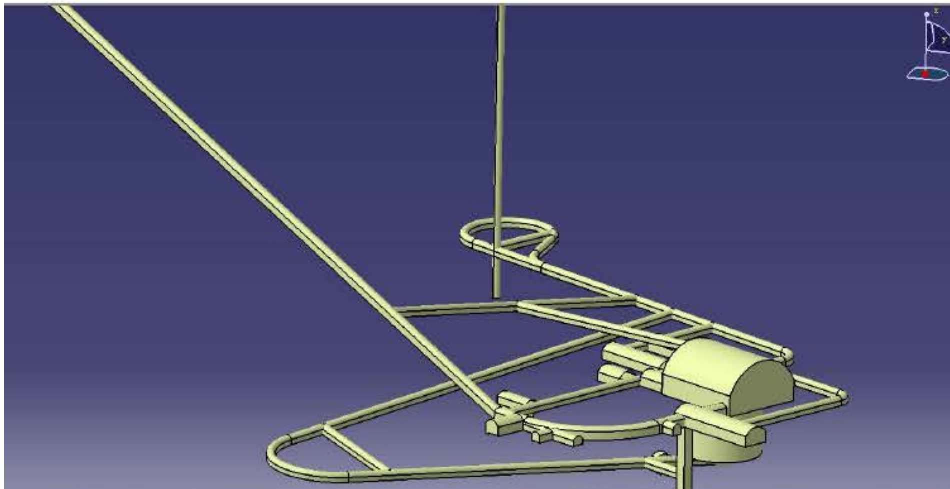
- $3\%/\sqrt{E}$ energy resolution
- Take JUNO MC as example
  - Based on DYB MC
  - JUNO Geometry
  - 77% photocathode coverage (KamLAND: ~34%)
  - High QE PMT, $QE_{max}$: 25% → 35%
  - LS attenuation length (1 m-tube measurement @ 430nm)

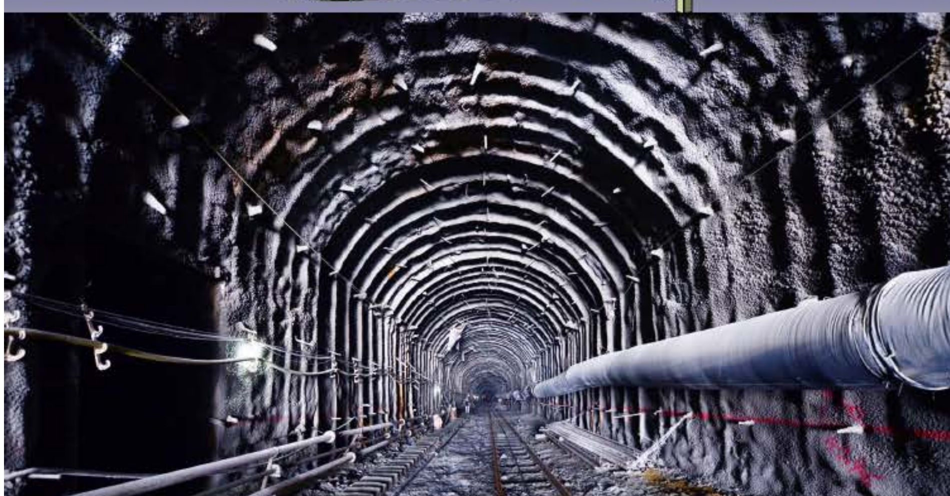
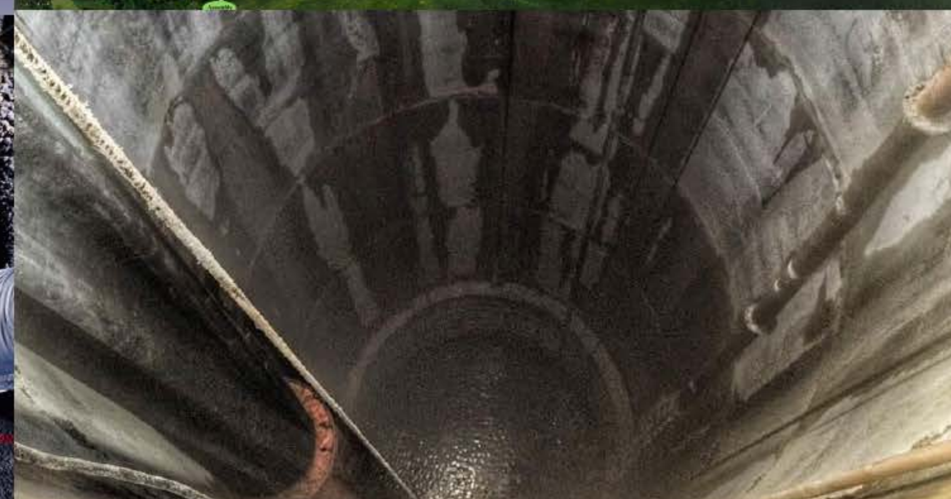
from 15 m
= absorption 30 m + Rayleigh scattering 30 m
to 20 m
= absorption 60 m + Rayleigh scattering 30 m

The Highlighted parameters are input to MC

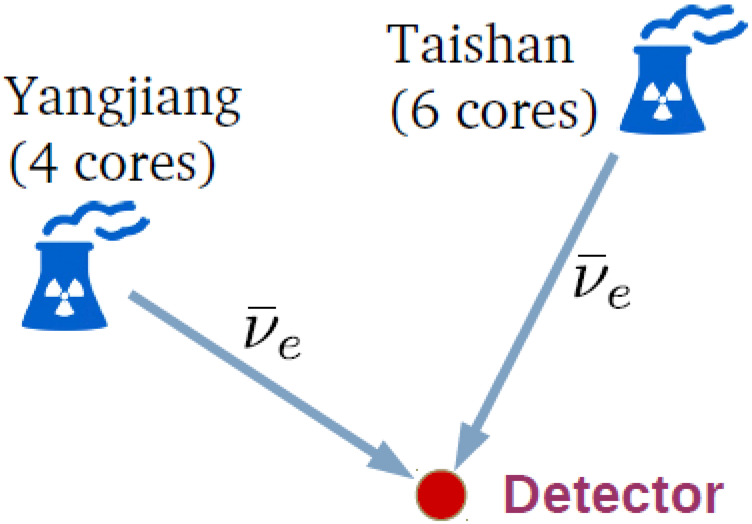




江门中微子实验站配套基建工程整体鸟瞰图



# JUNO




- 20 kt LAB-based LS
- sphere in cylindrical water pool
- $10^5$ IBD events/6 yr
- Res(E)=3% @ 1 MeV
- 18,000 20” PMTs + 25,000 3” PMTs
- LY~1200 p.e./MeV
- 75% geometric coverage
- Needs good position reconstruction
- Cosmic muons tracking : water pool (Cherenkov detector) + top tracker

- Baseline 52.5 km
- Overburden 700 m (1900 m.w.e.)

# JUNO schedule

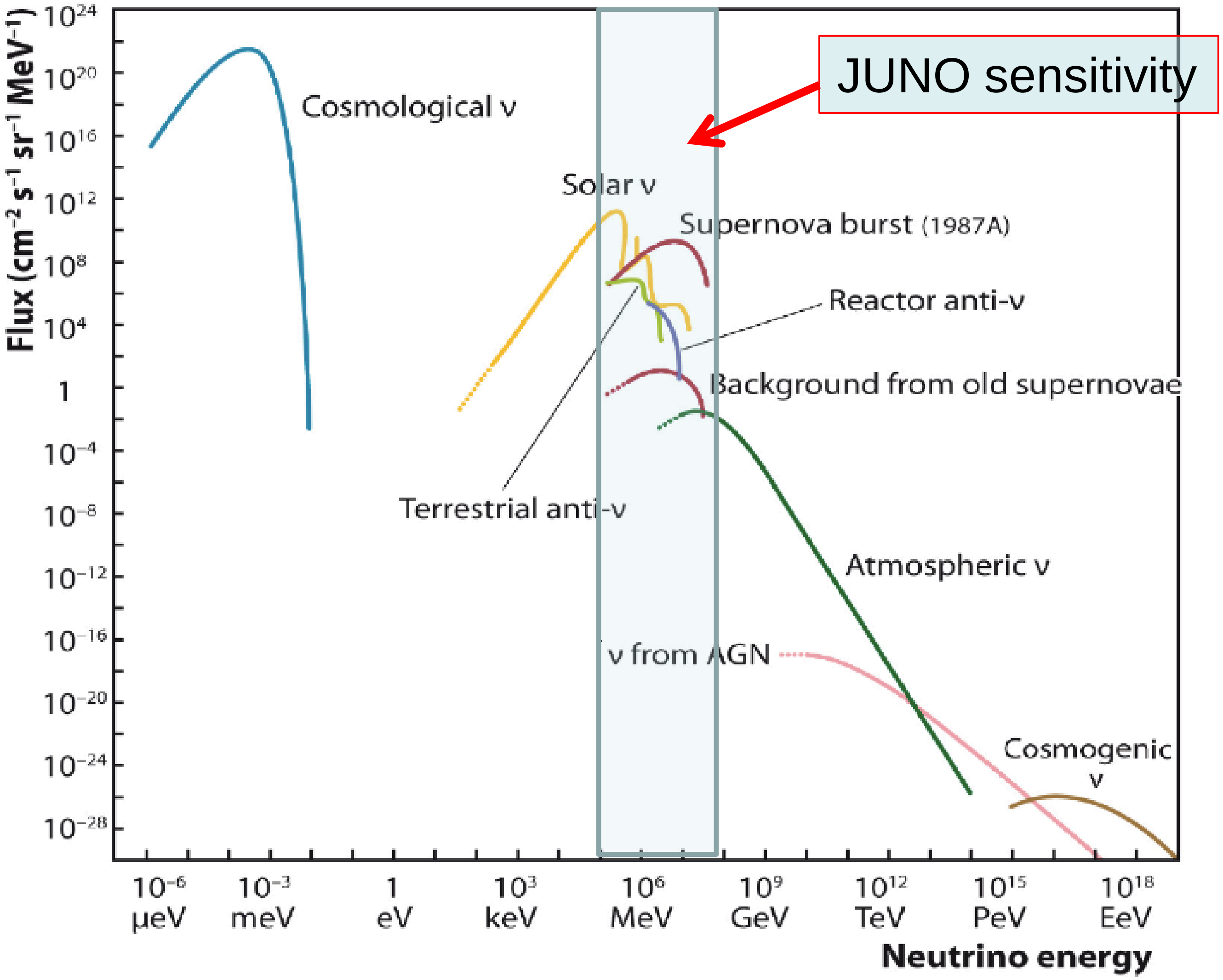
- **2013** Funding approved
- **2014** Collaboration officially formed
- **2014-2018** Civil construction
- **2016-2019** Detector component and PMT production
- **2018-2019** Detector assembly & installation
- **2020** Liquid scintillator filling
- **2020** Start of data taking

# JUNO is mupltipurpose detector

“Neutrino physics with JUNO”, J.Phys.G 43 (2016) 030401

- **Neutrino mass hierarchy study**
- **Precision measurement of neutrino oscillation parameters**
- **Supernova bursts and diffuse supernova neutrinos**
- **Solar neutrinos**
- **Atmospheric neutrino**
- **Geo-neutrino**
- **Sterile neutrino**
- **Nucleon decays**
- **Neutrinos from DM**
- **Exotic searches with neutrinos**

# Neutrino fluxes in nature



# JUNO's impact on oscillation parameters

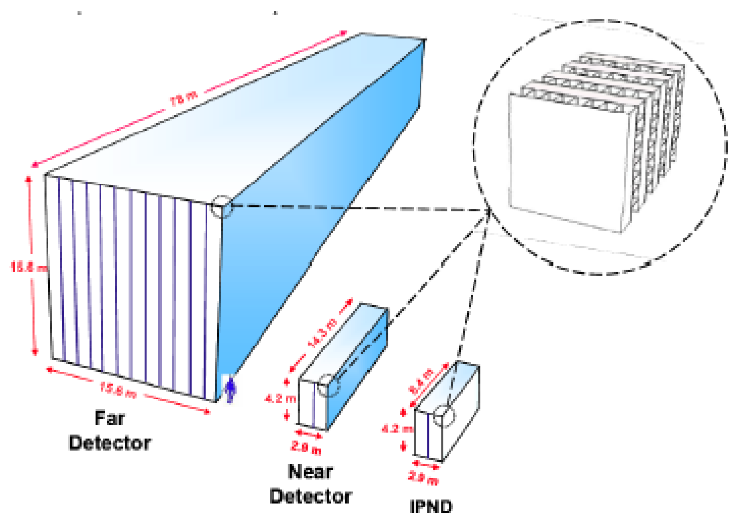
| Parameter | NH | IH | Uncertainty (1σ) | JUNO |
|---|---|---|---|---|
| $\Delta m_{21}{}^2/10^{-5}$ | 7.37 | | 2.2% | <1% |
| $\|\Delta m_{31}{}^2\|/10^{-3}$ | 2.50 | 2.46 | 2.5% | <1%+sign(3-4σ) |
| $\sin^2\Theta_{12}$ | 0.297 | | 5% | <1% |
| $\sin^2\Theta_{13}$ | 0.0214 | 0.0218 | 4% | ~15% |
| $\sin^2\Theta_{23}$ | 0.425 | 0.589 | 9.6%<br>(octant unresolved at 3σ) | ------- |
| $\delta^{CP}/\pi$ | 1.35 | 1.32 | ~50% | -------- |

# **N**uMI **O**ff-axis $\boldsymbol{\nu_e}$ **A**ppearance (NOvA)

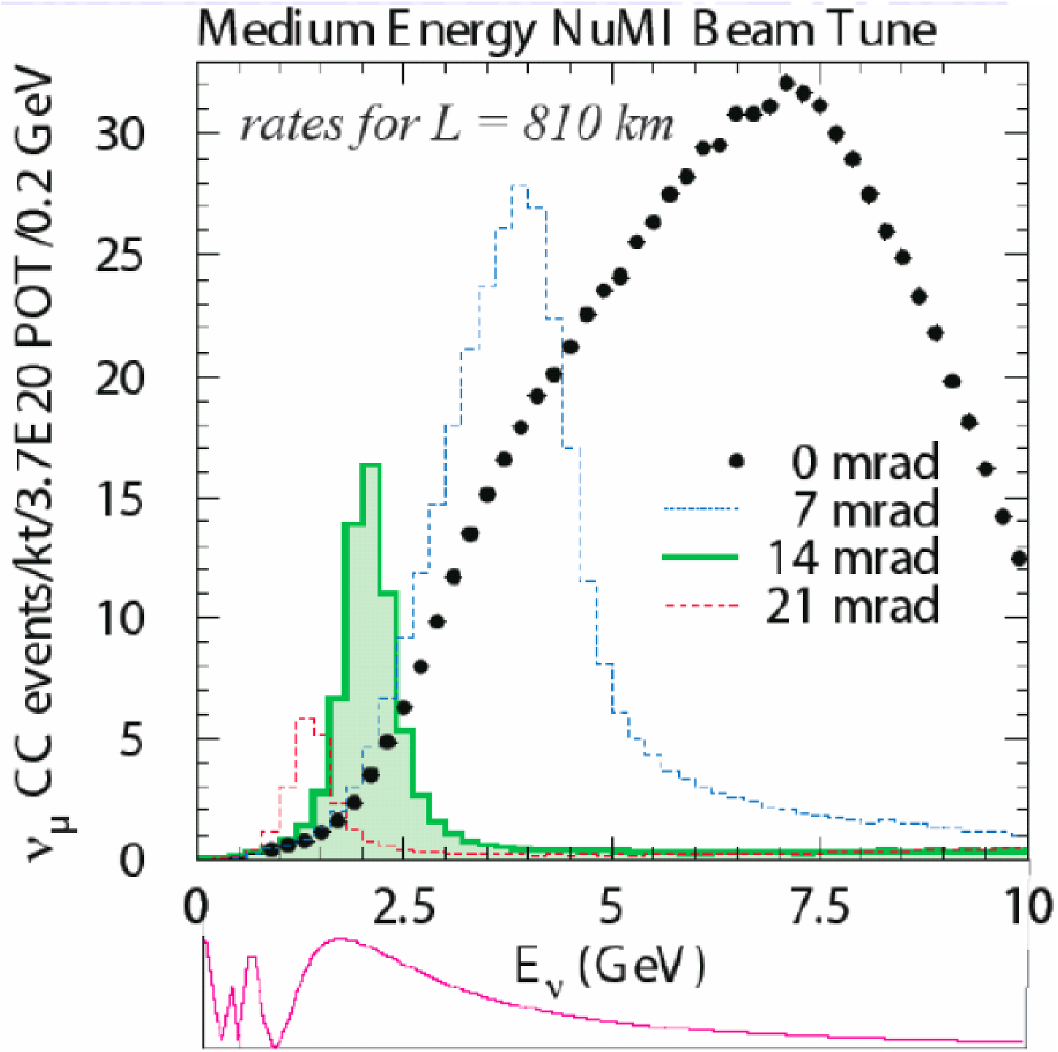
Two detectors (14 kt far and 0.3 kt near), long base (810 km), off-axis (14 мрад, ~2 GeV), precision measurement $\nu_\mu$ : oscillations:

- mass hierarchy
- CP-violating phase
- sign of $\theta_{13}$ angle of PMNS
- $\nu_3$ state mainly consists of $\nu_\mu$ or $\nu_\tau$ ?($\theta_{23}>\pi/4$)

NOvA detectors: active trecking LS calorimeters. The basic cell of the far detector consists of column or row of LS cells 4 cm x 15.6 m x 6 cm



# Off-axis concept

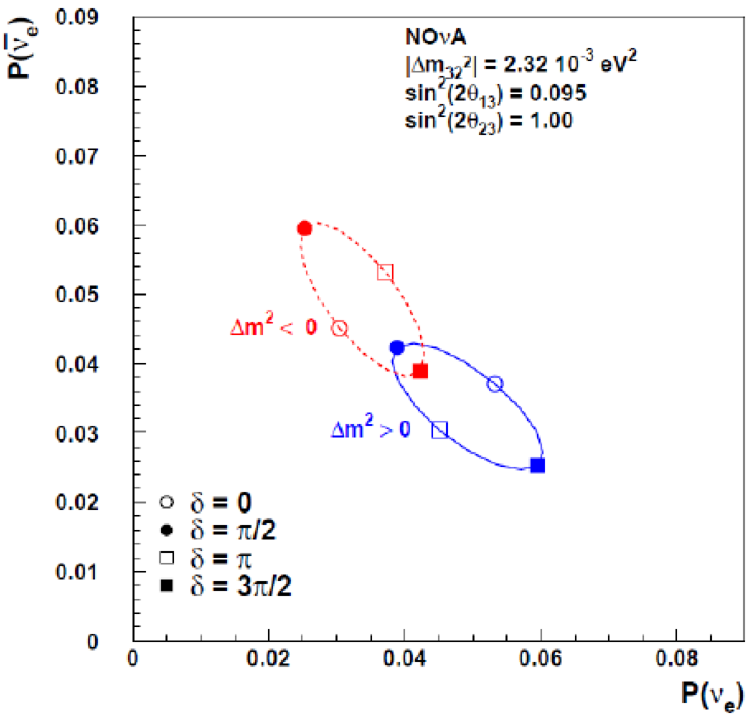



$$P(\nu_\mu \rightarrow \nu_e)$$

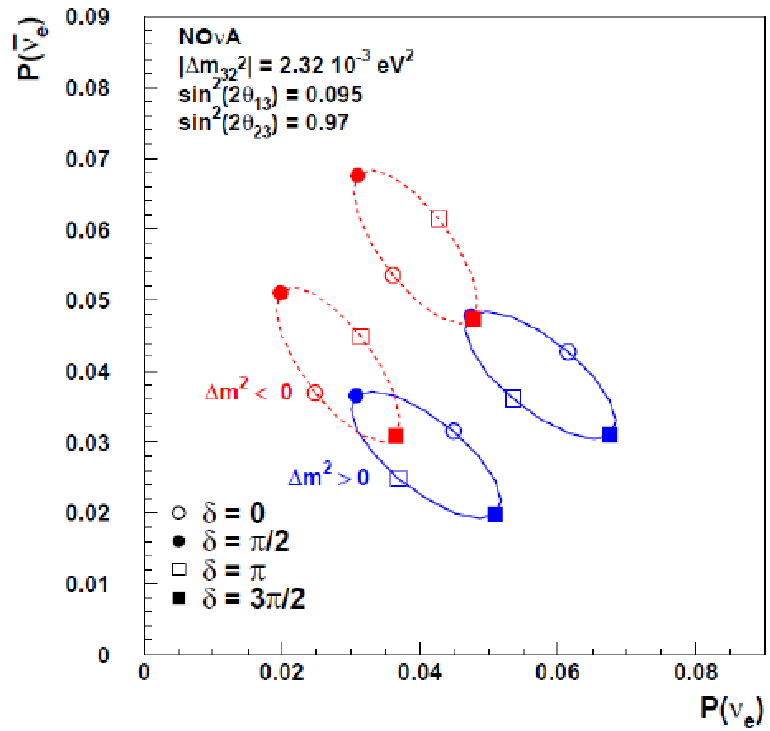
# $\upsilon_e$ appearence

$\sin^2(2\theta_{13})=0.095$.

$P(\bar{\nu}_e)$ vs. $P(\nu_e)$ for $\sin^2(2\theta_{23}) = 1$



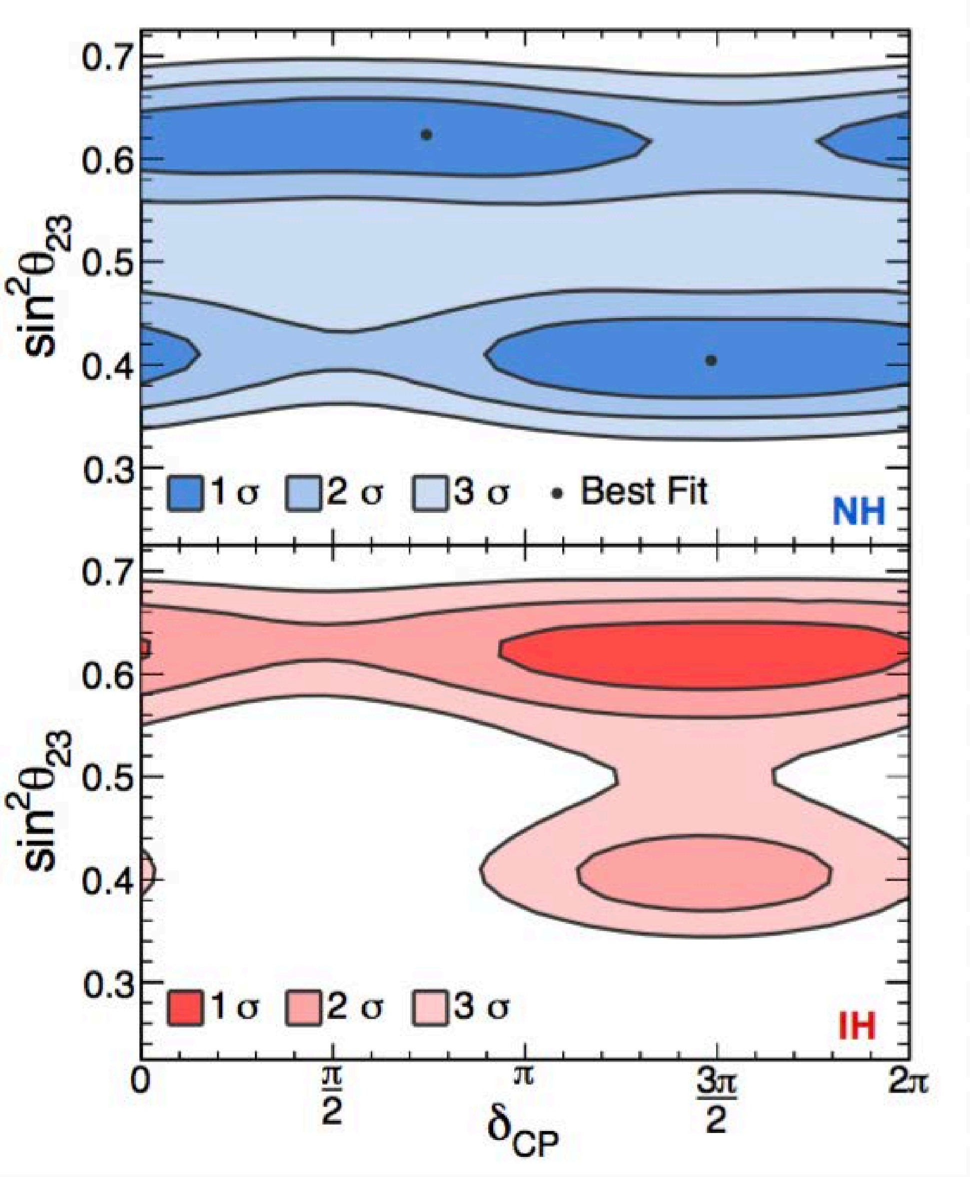

$P(\bar{\nu}_e)$ vs. $P(\nu_e)$ for $\sin^2(2\theta_{23}) = 0.97$



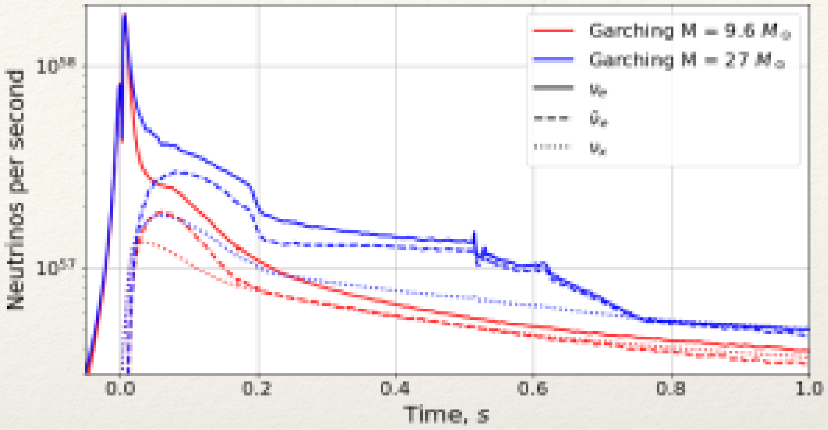

$\upsilon_\mu \rightarrow \upsilon_e$ oscillations are sensitive to both $\sin^2(2\theta_{13})$ and $\sin^2(2\theta_{23})$, with large perturbations caused by the mass ordering (through the matter effect) and by CP violation. CP-violating phase δ traces out the ovals and the multiplicity of ovals represents the two possible mass orderings and, for right figure, the ambiguity of whether $\theta_{23}$ is larger or smaller than π/4.

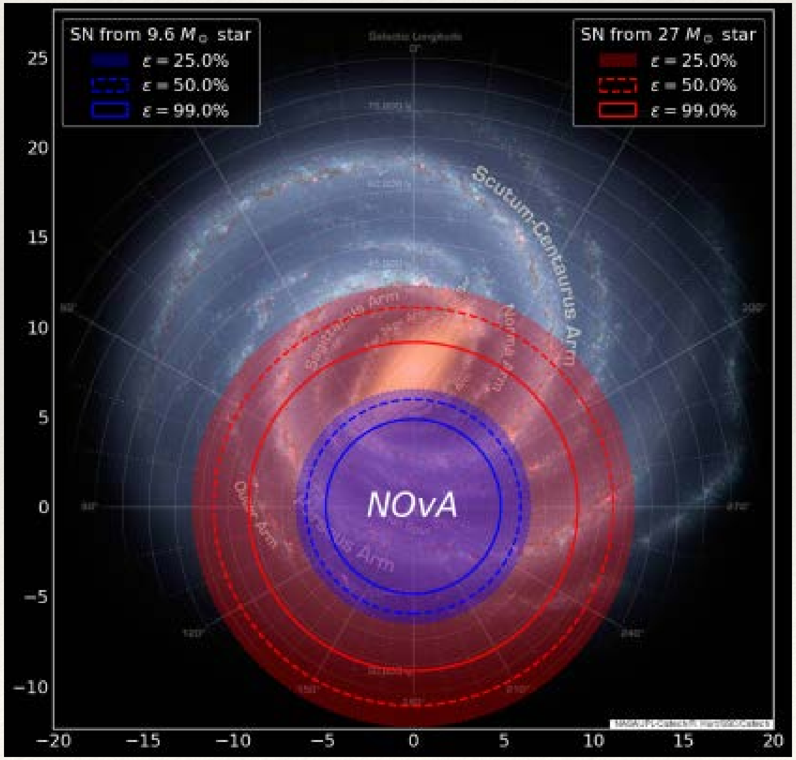
# NOvA

- Accumlatd statistics NuMI $6{,}05 \times 10^{20}$ POT
- Expected count of $\nu_\mu$ events without oscillations 473±30. 78 $\nu_\mu$ and 33 $\nu_e$ events are observed – robjust confirmation of oscillations.
- Joint analysis shows some preferencies for NI and excludes at IH with 3 $\sigma$ $\delta_{CP} = \pi/2$.
- On January 12th (2018) latest oscillation results were presented. (~50% more data and improvements to the analysis). Joint-fit analysis of muon neutrino disappearance and electron neutrino appearance prefers $\theta_{23}$ mixing near-maximal with a competitive measurement of $\Delta m^2_{32}$. The analysis is approaching 2σ Inverted Hierarchy rejection.



# System of SN detection

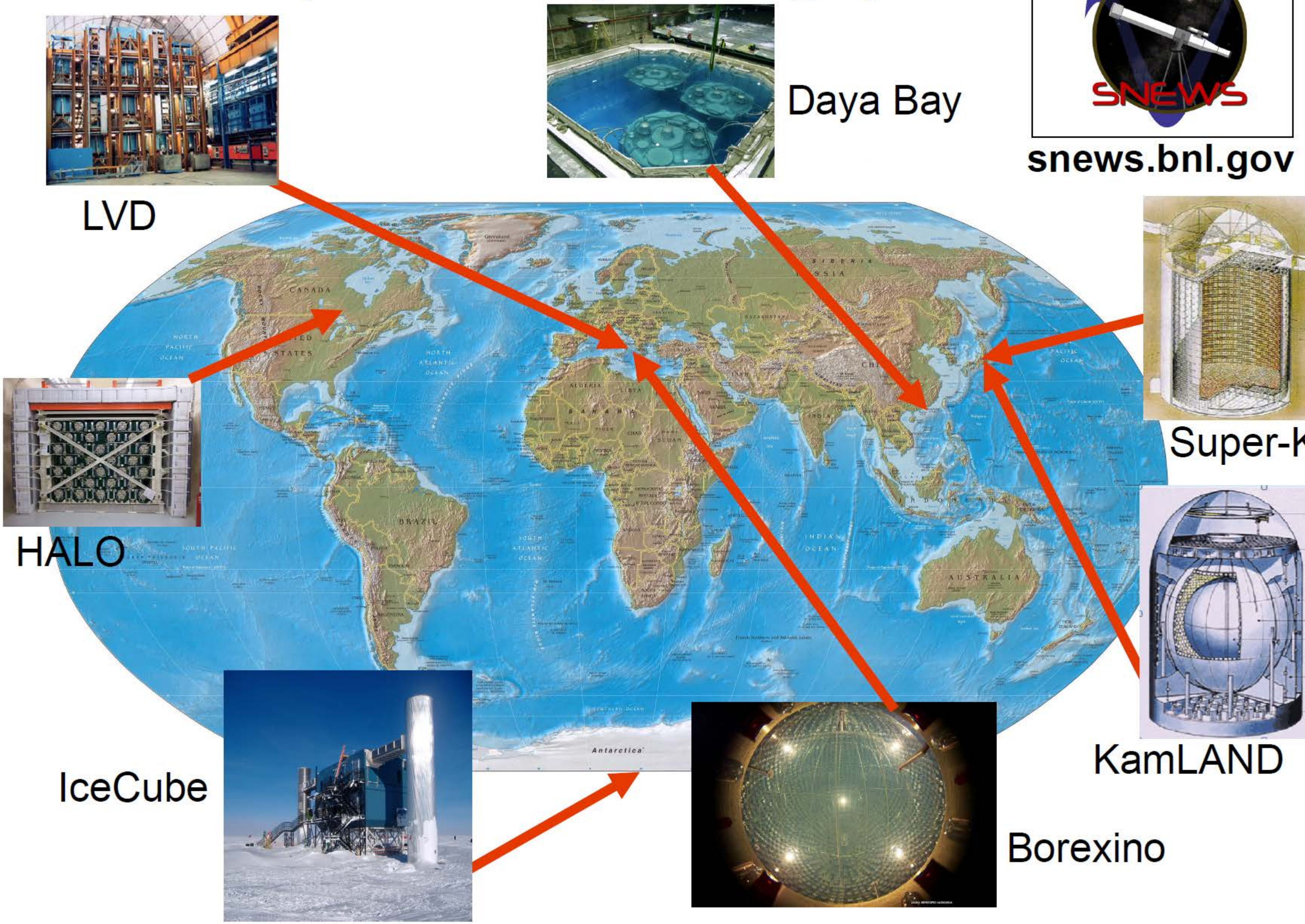



- Tested with near and far detectors, now the system is on and waiting for SN.
- .

# SNEWS: SuperNova Early Warning System

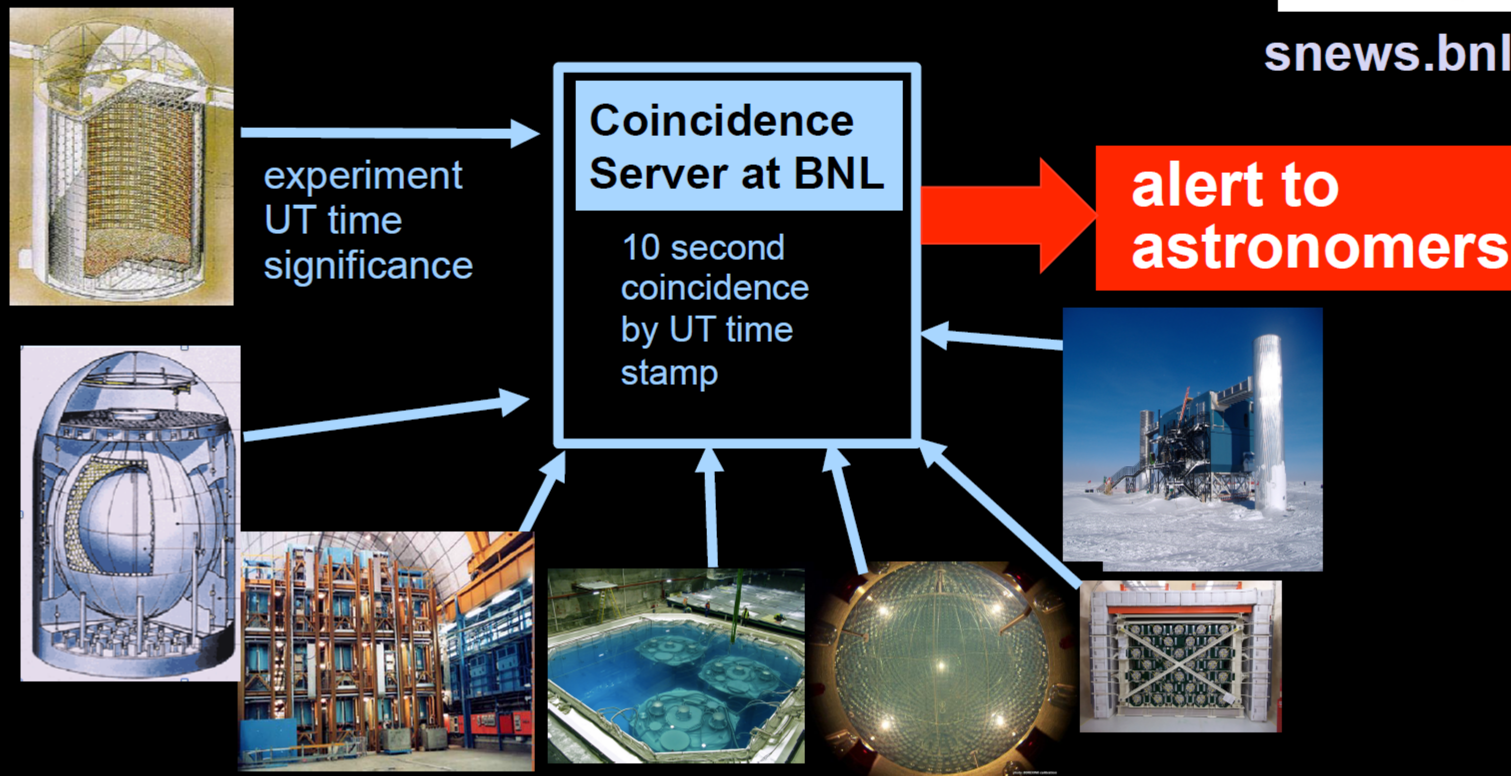
snews.bnl.gov



# SNEWS: SuperNova Early Warning System

- Neutrinos (and GW) precede em radiation by hours or even days
- For promptness, require ***coincidence*** to suppress false alerts

snews.bnl.gov



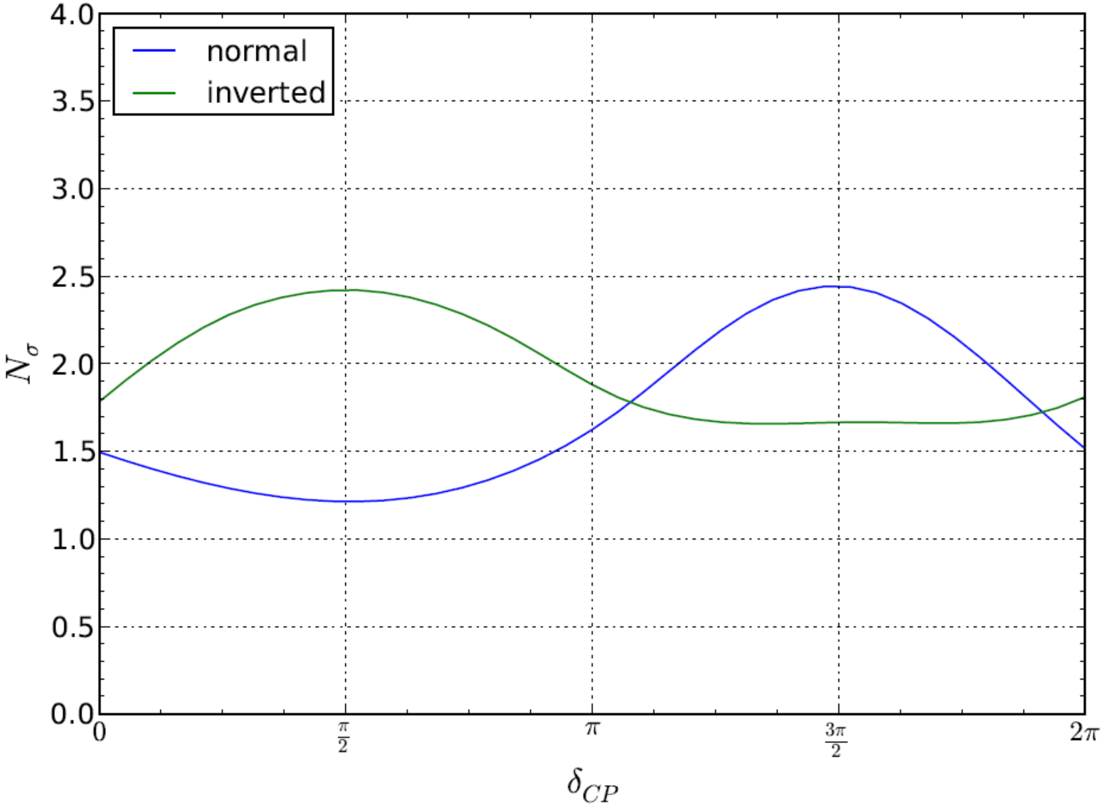

- Running smoothly for more than 10 years, automated since 2005

# Joint analysis of the NOvA and JUNO experiments

- Interpretation $\Delta\chi^2$ : $\Delta\chi^2 = \Delta\chi^2(NH) - \Delta\chi^2(IH) \approx 15$, corresponding to ≈4σ sensitivity
- Sensitivity from likelihood ratio analysis at fixed $\Delta m_{atm}$ : 2.6σ
- Allowing $\Delta m_{atm}$ to vary within $\pm 0.1 \cdot 10^{-3}$ $eV^2$: 2σ

Combined analysis JUNO+NOvA: up to 2.5σ

Figure from D.Taichenachev diploma thesis (May 2014)

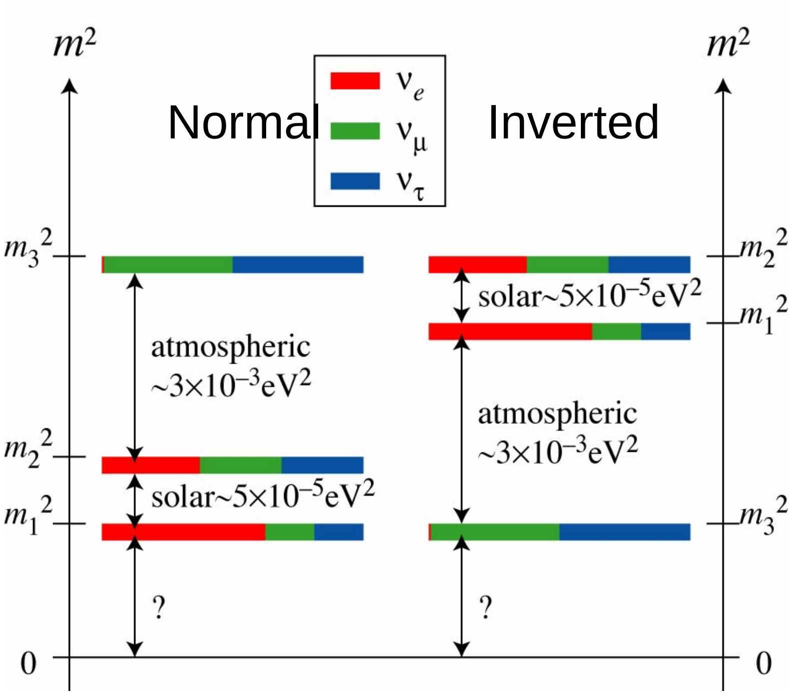


# Neutrino mass

- $m_{\upsilon_e}{}^2$ <2.05 $eV^2$ (95% C.L.)
- $m_{\upsilon_\mu}$ < 170 keV
- $m_{\upsilon_\tau}$ < 15.5 MeV

Lower bound on neutrino masses from $\Delta m_{31}{}^2 \sim 0.0024\ eV^2$:
Normal hierarchy: $m_3$ >0.05 eV
Inverted hierarchy: $m_1+m_2$ > 0.1 eV

- Cosmological bound $\sum_i m_i$<0.58 eV
- In theory: three cases
  - Normal **hierarchy**: $m_1 < \sqrt{\Delta m_{21}}$
  - Inverted **hierarchy**: $m_3 \ll \sqrt{\Delta m_{31}}$
  - (Quasi-)**Degenerate**: $m_1 \sim m_2 \sim m_3 \gg \sqrt{\Delta m_{31}}$ (**ordering**: normal or inverted)



# Double beta-decay

- The idea of double beta decay - Maria Goeppert-Mayer in 1935.

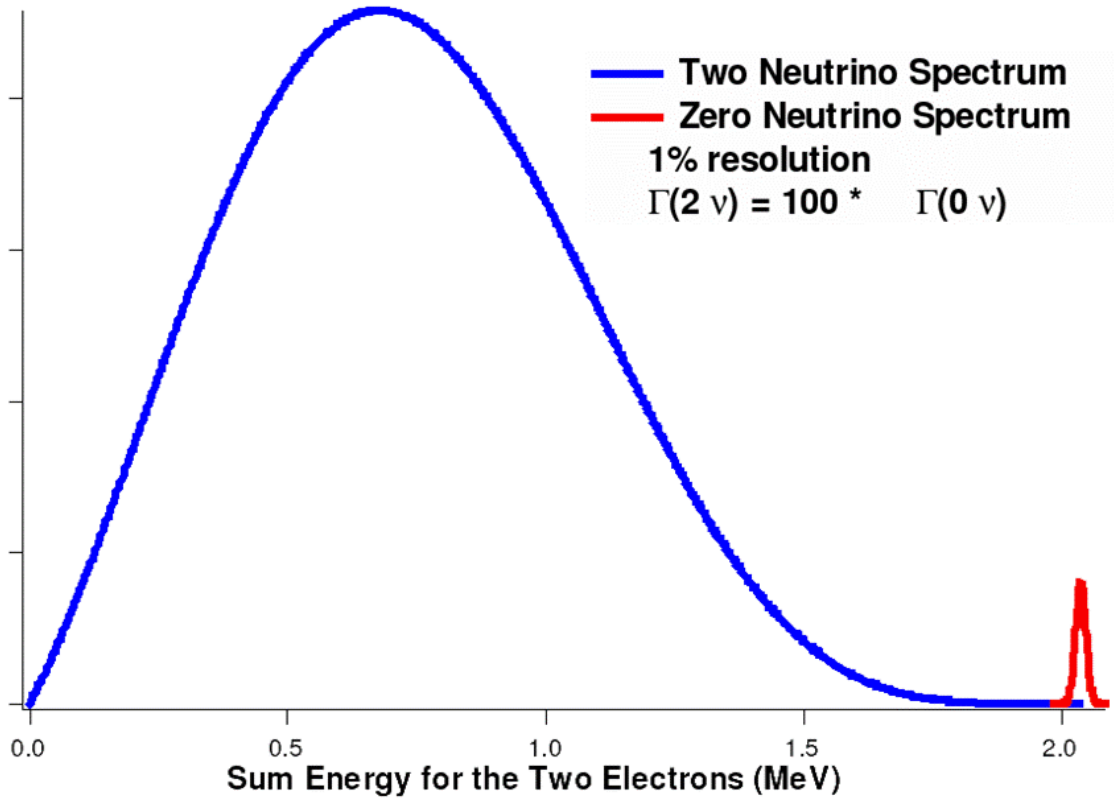
$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e$$

- In 1937 Ettore Majorana theoretically demonstrated that all results of beta decay theory remain unchanged if the neutrino is its own anti-particle, i.e. if it is a Majorana particle.
- In 1939 Wendell H. Furry : if neutrino is a Majorana particle, double beta decay can proceed without emission of any neutrino; the process which is now called the neutrinoless beta decay.

$$(A, Z) \rightarrow (A, Z + 2) + 2e^-$$

- First calculations showed that neutrinoless double beta decay should be much more likely to occur than ordinary double beta decay (if neutrinos are Majorana) with $T_{1/2}$~$10^{15}$–$10^{16}$ years.
- In 1948 Edward L. Fireman made the first attempt to measure the half-life of the $^{124}Sn$ isotope, up to 60s all radiometric experiments were negative (or false positive). In 1950 for the first time the half-life of the $^{130}Te$ isotope was measured by geochemical methods wit h result, $1.4\times10^{21}$ years, close to the modern value.

# How to search for $0\upsilon\beta\beta$?




The fraction of $2\upsilon\beta\beta$ events under the $0\upsilon\beta\beta$ peak can be approximated by

$$F = \frac{7Q\delta^6}{m_e}$$

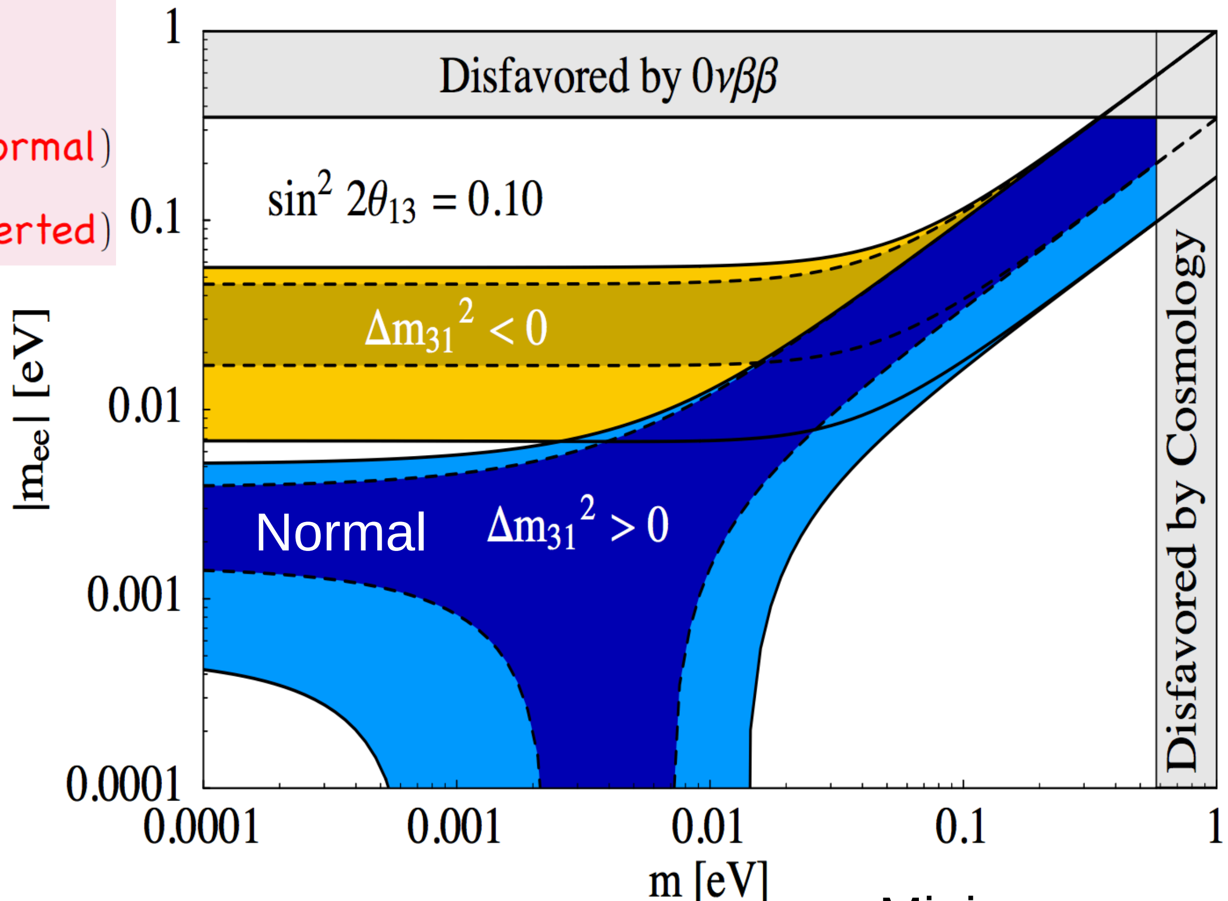
where $\delta = \frac{\Delta E}{Q}$ is relative FWHM resolution

Light-ν-exchange amplitude proportional to "effective mass"

$$m_{eff} \equiv \sum_{i=1}^{3} m_i U_{ei}^2$$

If lightest neutrino is light:

- $m_{eff} \approx \sqrt{\Delta m^2_{sol}} \sin^2\theta_{sol}$ (normal)
- $m_{eff} \approx \sqrt{\Delta m^2_{atm}} \cos 2\theta_{sol}$ (inverted)



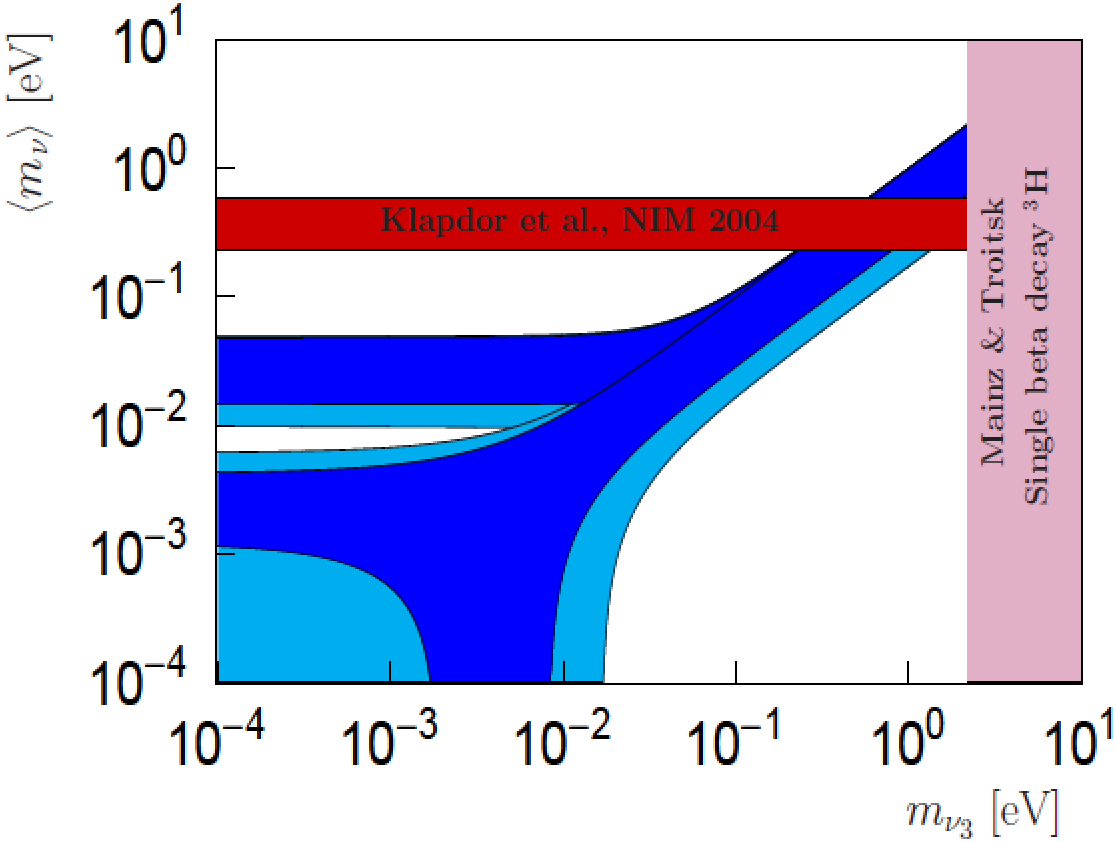

Minimum ν mass

hierarchical

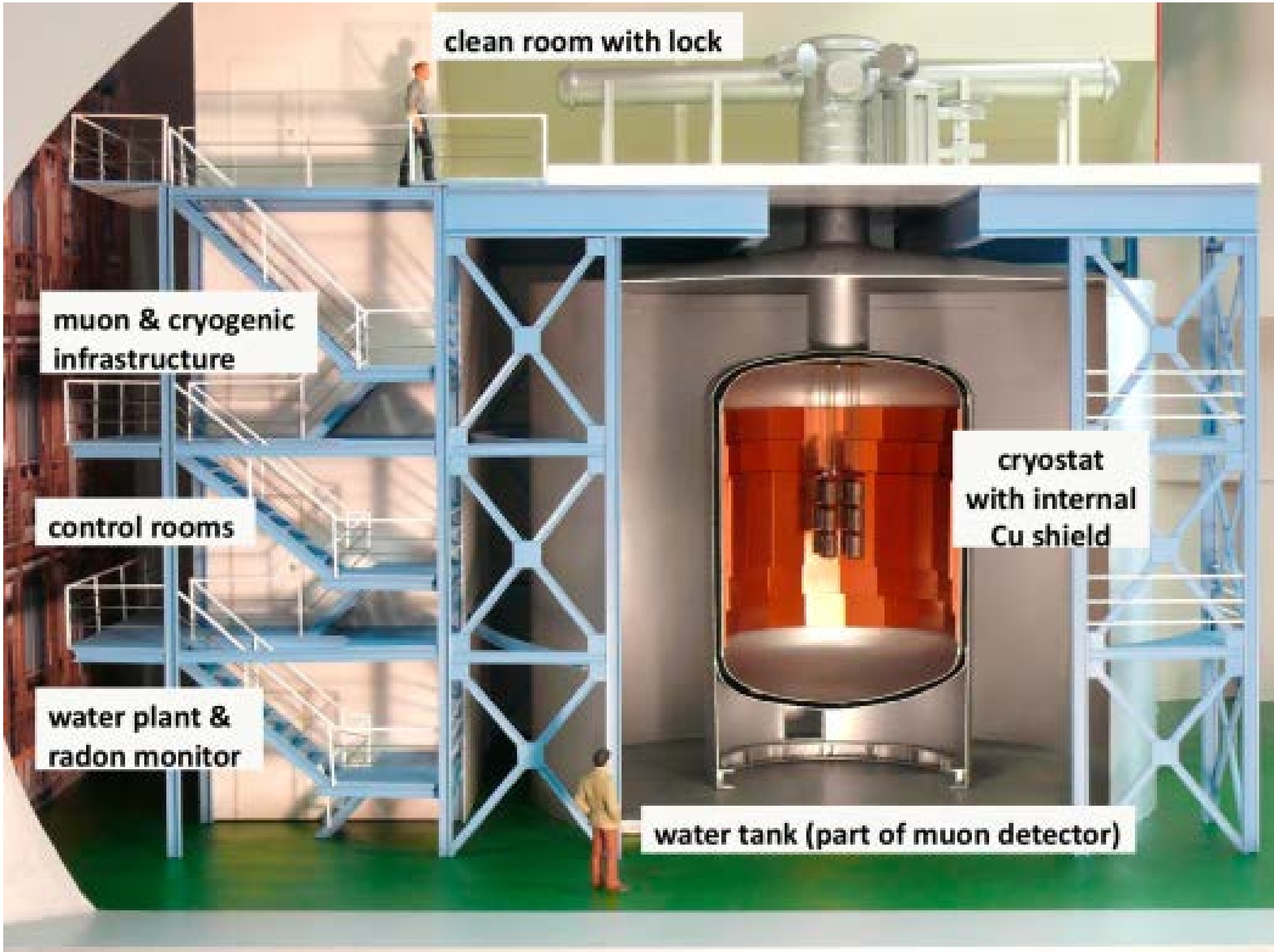
degenerate

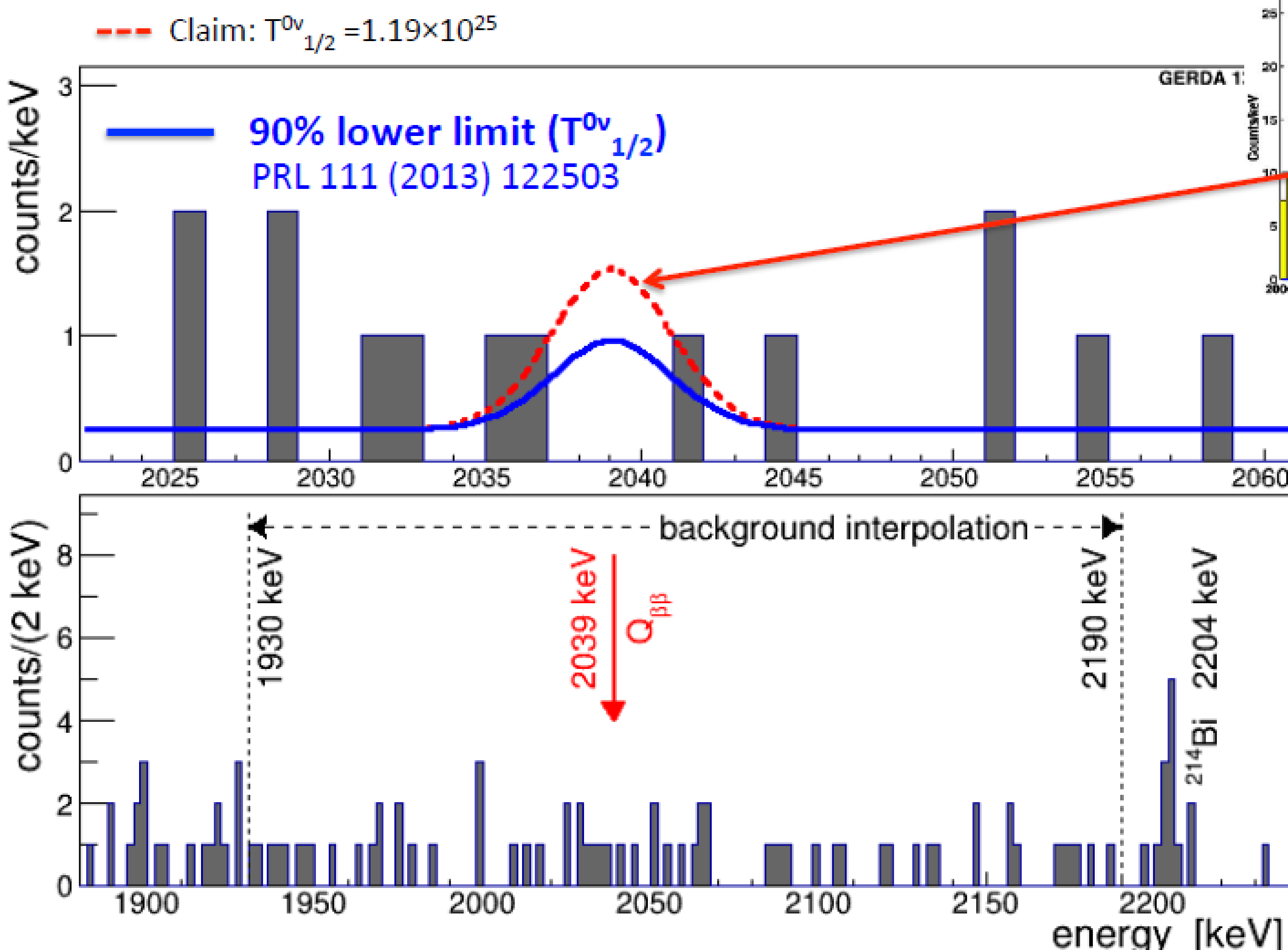
# Heildelberg-Moscow experiment

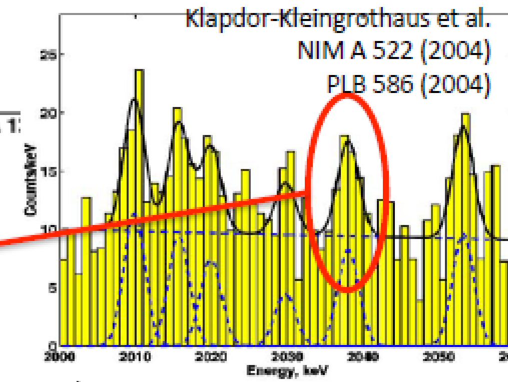
$^{76}Ge$
Result published by a part of the collaboration:
$T_{1/2}=1.2 \cdot 10^{25}$ y or
$T_{1/2}=2.2 \cdot 10^{25}$ y
For the first time the
The Moscow part of the Collaboration does not agree with this conclusion and there are others who are critical of this result.
At present, this "positive" result is not accepted by the 2β-decay community and it has to be checked by new experiments.



# GERDA


clean room with lock
muon & cryogenic infrastructure
control rooms
water plant & radon monitor
cryostat with internal Cu shield
water tank (part of muon detector)




**H0**: background only

**H1**: claimed signal plus background

**p-value** from profile likelihood

P(N=0|H1 ) = 0. 01

(0.006 if 1/T unconstrained)

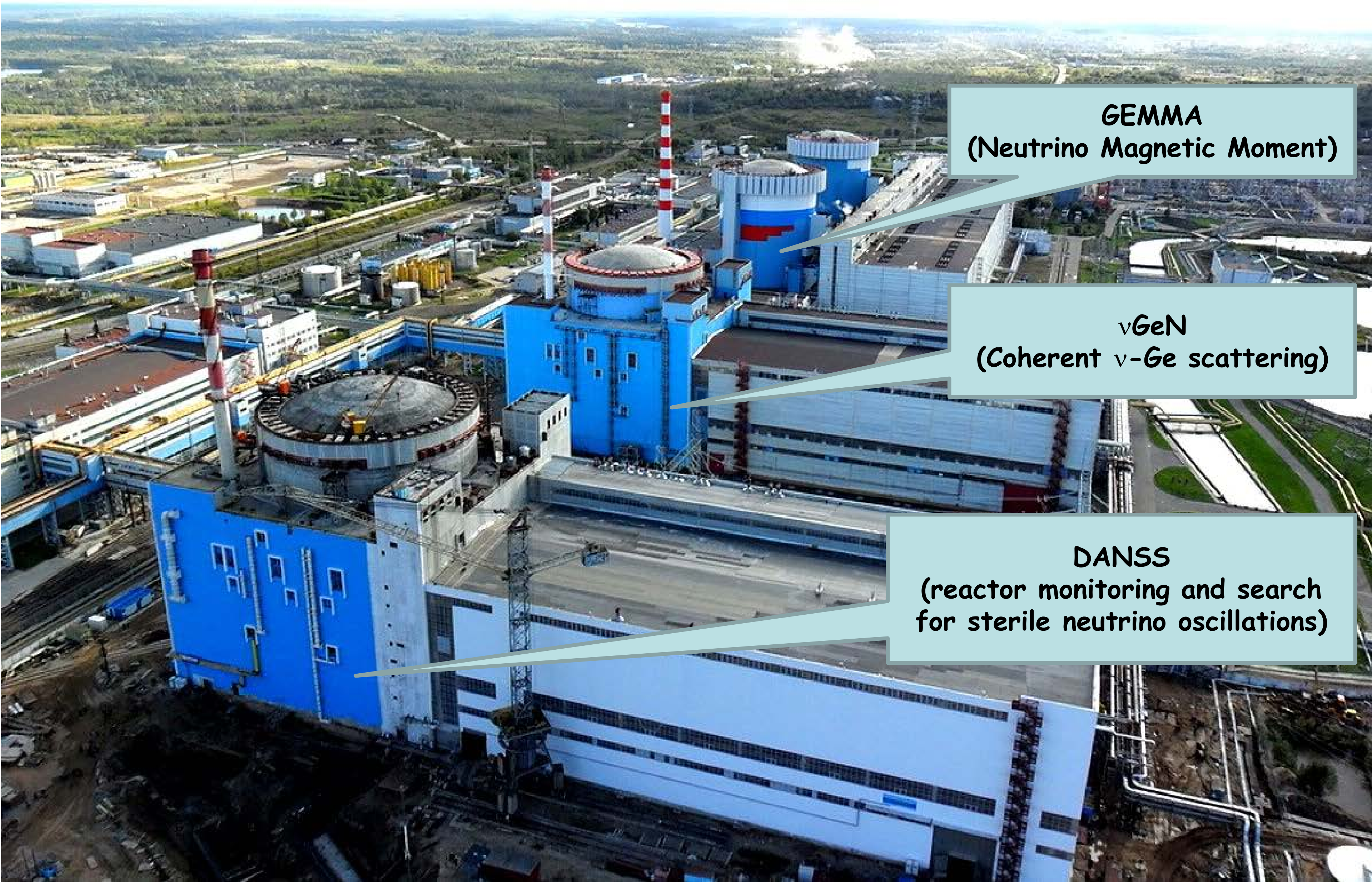
**Bayes factor**:

P(H1)/P(H0 )=0. 024

→Claim refuted with high probability independent of NME and lepton number violating mechanism

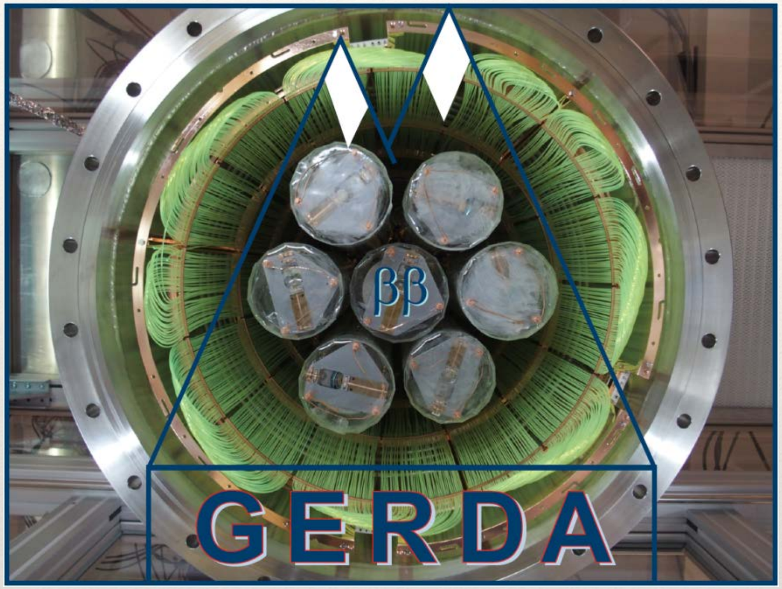
# Neutrino experiments on Kalininskaya power plant

( Tver region, Udomlya
285 km from Dubna)



# GERDA

## first background-free $0\nu\beta\beta$ experiment




ARTICLE

Nature 544 (2017) 47

doi:10.1038/nature21717

**Background-free search for neutrinoless double-$\beta$ decay of $^{76}$Ge with GERDA**

The GERDA Collaboration*


Background for BEGe-detectors: $1.0^{+0.6}_{-0.4} \times 10^{-3} event/(keV \cdot kg \cdot yr)$

Broad energy

$T^{0\nu}_{1/2}$ >5.8· $10^{25}$yr (90%CL) $\quad m_{\beta\beta} < 0.15 - 0.33\ eV$

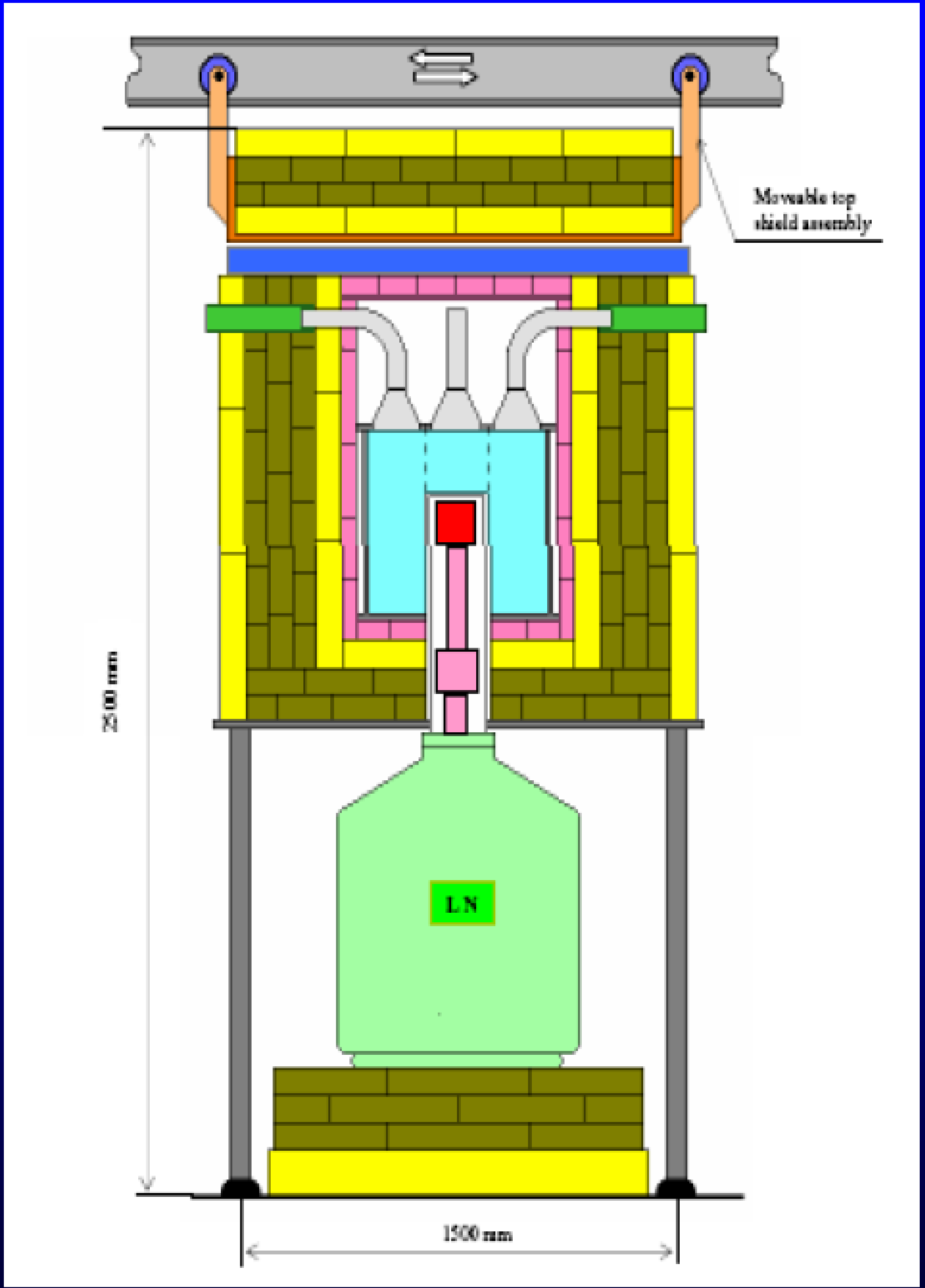
**LEGEND experiment is planned (1 t Ge) with sensitivity** $\quad m_{\beta\beta} < 10 - 20\ meV$

# Experiment **GEMMA**

(**G**ermanium **E**xperiment for measurement of **M**agnetic **M**oment of **A**ntineutrino)

*[Phys. of At. Nucl.,**67**(2004)1948]*

- Spectrometer includes a HPGe detector of 1.5 kg installed within NaI active shielding.
- HPGe + NaI are surrounded with multi-layer passive shielding : electrolytic copper, borated polyethylene and lead

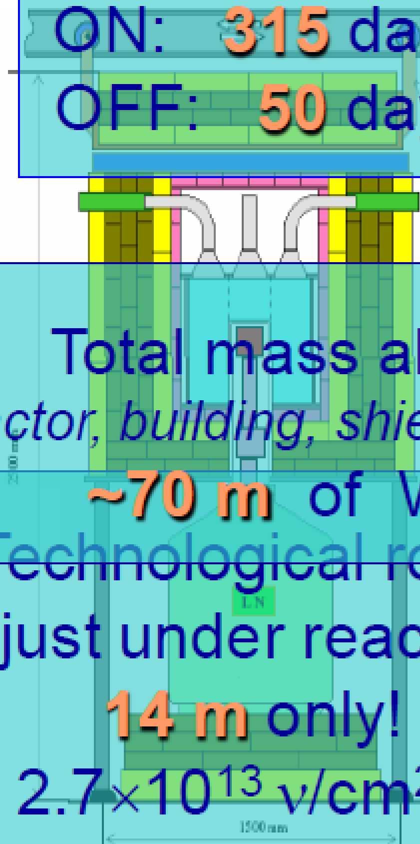


## Reactor unit #2 of the "Kalinin" Nuclear Power Plant (400 km North from Moscow)

Power: 3 GW

ON: **315** days/y

OFF: **50** days/y



Total mass above

*(reactor, building, shielding, etc.):*

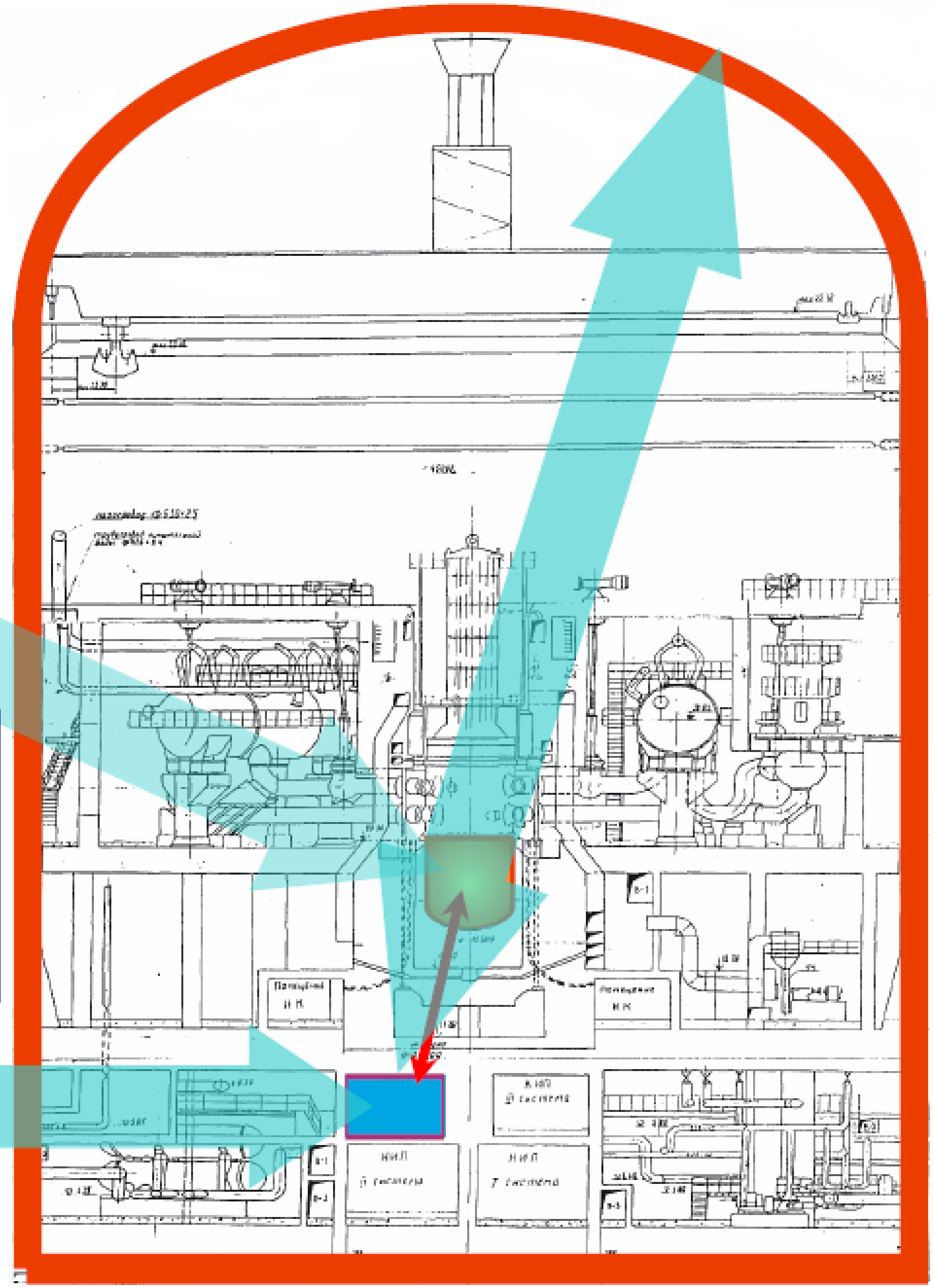
**~70 m** of W.E.

Technological room

just under reactor

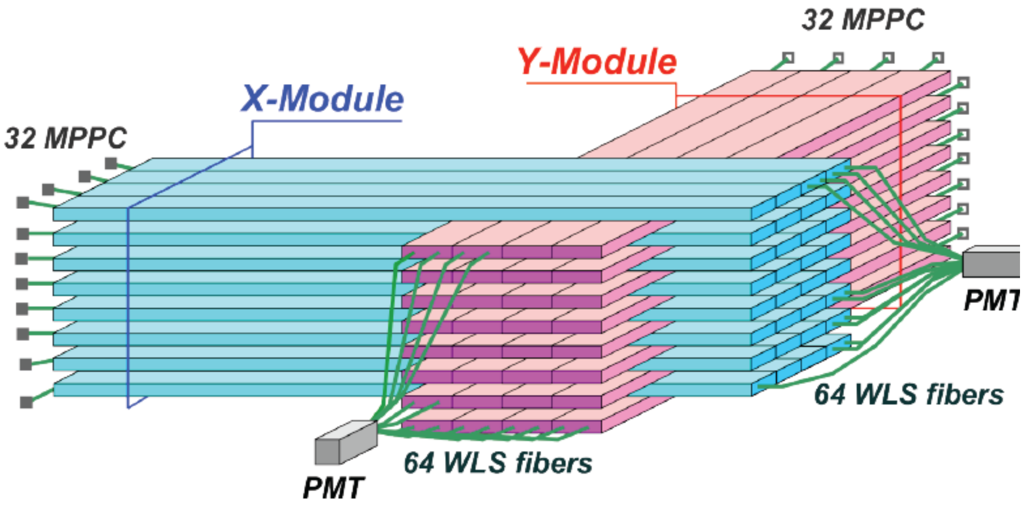
**14 m** only!

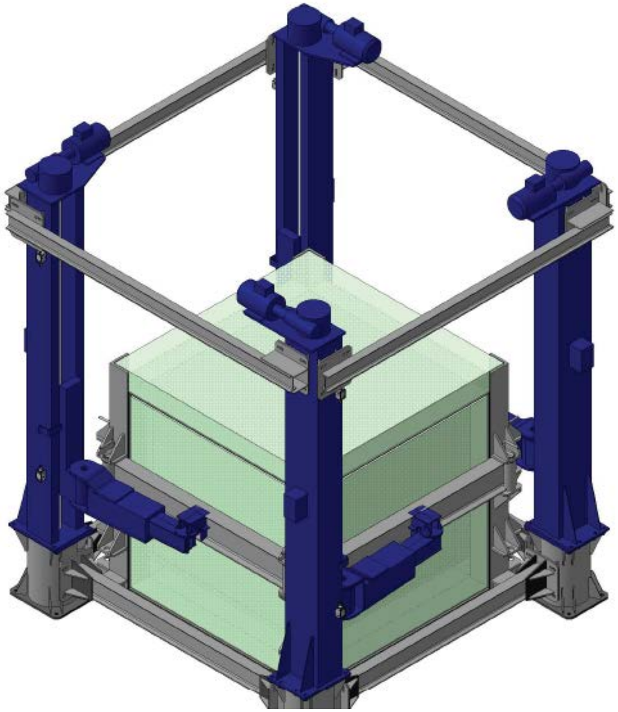
$2.7 \times 10^{13}$ $\nu/cm^2/s$

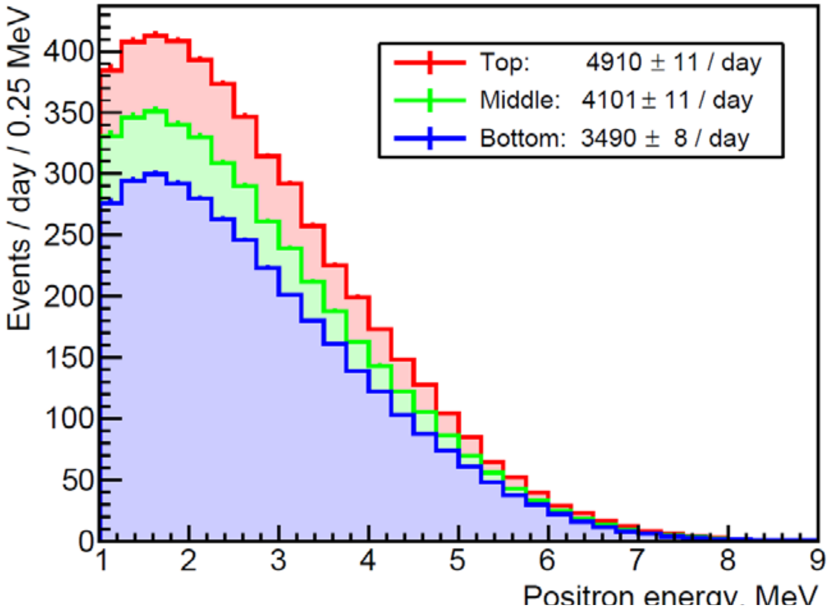


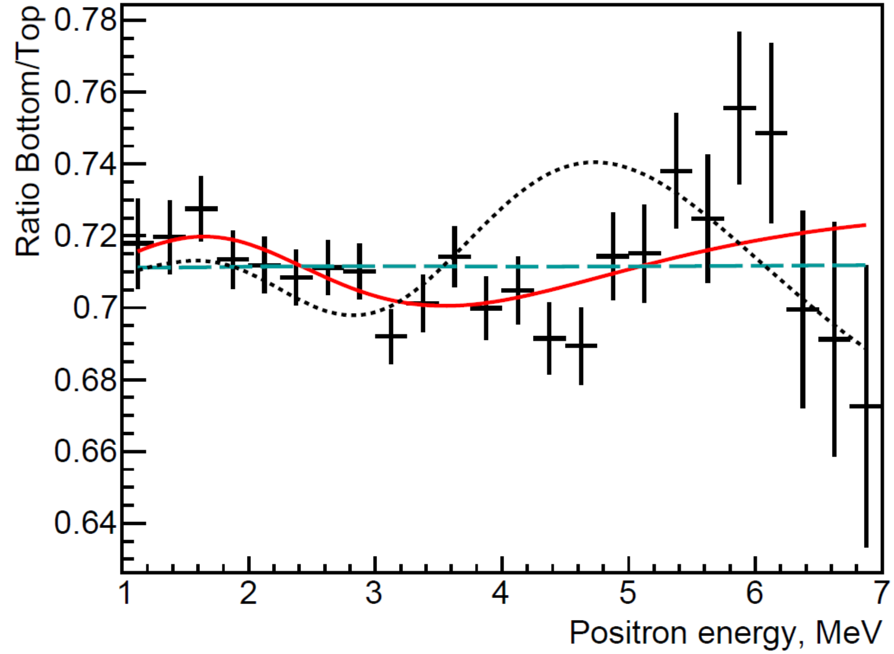
# DANSS (ОИЯИ+ИТЭФ)

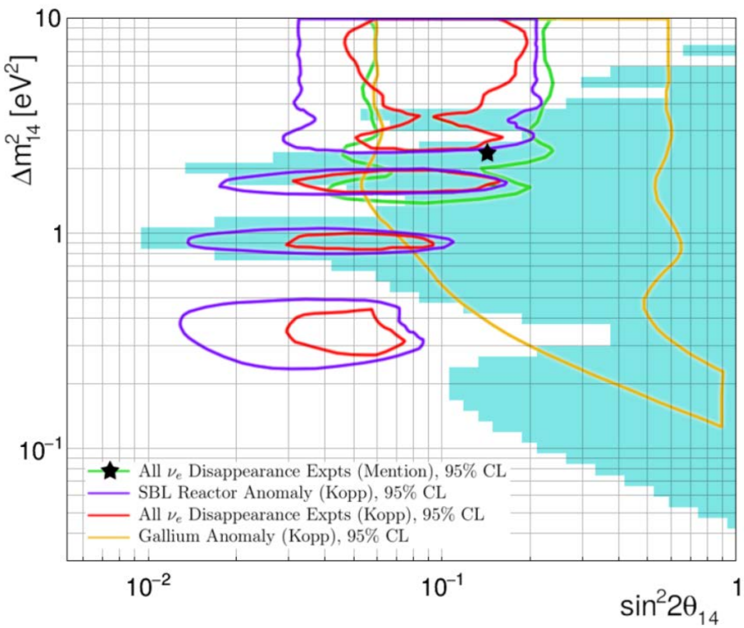
## (*Detector Anti Neutrino from Solid Scintillator*)






efficiency. The excluded area covers a large fraction of regions indicated by the GA and RAA. In particular, the most preferred point $\Delta m^2_{14} = 2.3$ eV$^2$, $\sin^2 2\theta_{14} = 0.14$[5] is excluded at more than 5 $\sigma$ CL. In our analysis the point $\Delta m^2_{14} = 1.4$ eV$^2$, $\sin^2 2\theta_{14} = 0.05$ has the smallest $\chi^2 = 21.9$. The difference in $\chi^2$ with the $3\nu$ case is 13.1 which corresponds to $\sim 3\sigma$. The significance of this indication of the existence of the sterile neutrino will be studied taking into account systematic uncertainties after collection of more data this year.

# Project νGeN

- Detection of neutrino coherent scattering on Ge nucleus

10 ev/kg day at 10 meters from reactor and 300 eV threshold

HPGe detectors (JINR), 450 g each

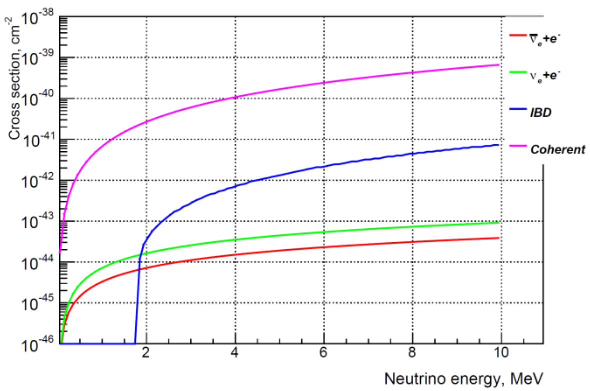
# Coheret scattering

**Full cs :**

$$\sigma \simeq \frac{G_F^2}{4\pi} N^2 E_\nu^2 \simeq 0{,}42 \times 10^{-44} N^2 \frac{E_\nu^2}{1\ \text{МэВ}^2}\ \text{см}^2$$

**Average energy of recoil ncleus**

$$\bar{E}_A = \frac{2}{3A}\left(\frac{E_\nu}{1\ \text{МэВ}}\right)^2 [\text{кэВ}]$$




for $E_\upsilon$=6 MeV on Ge <E>=360 eV


Science REPORTS

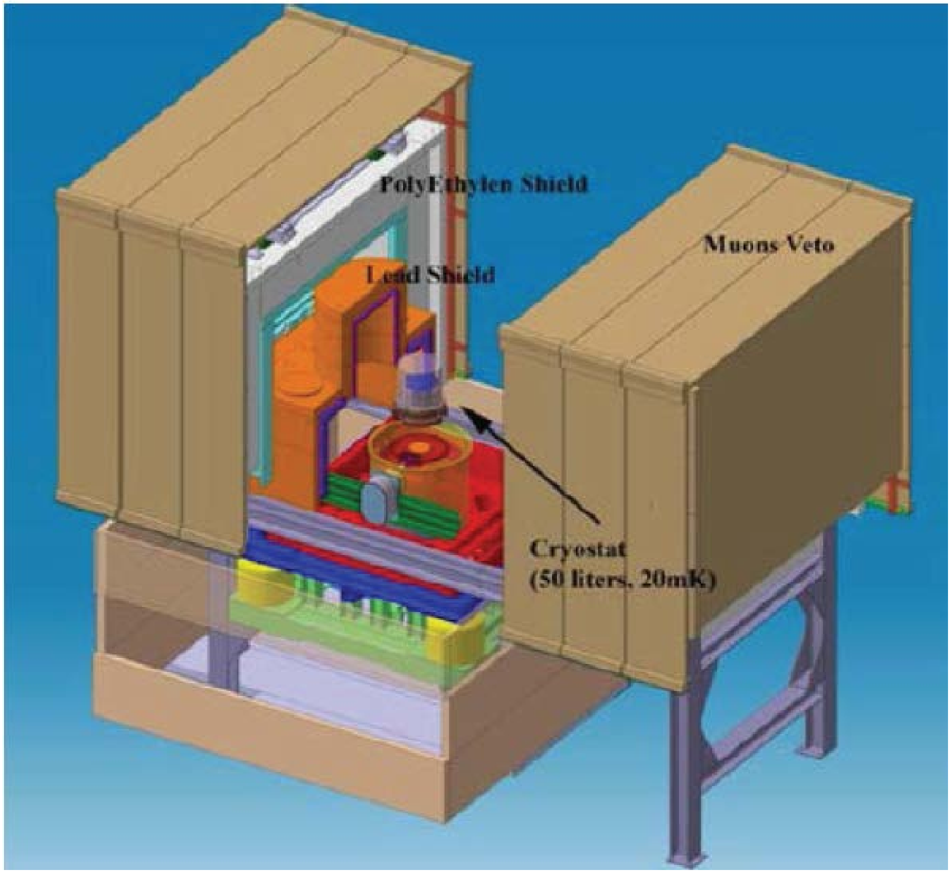
Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

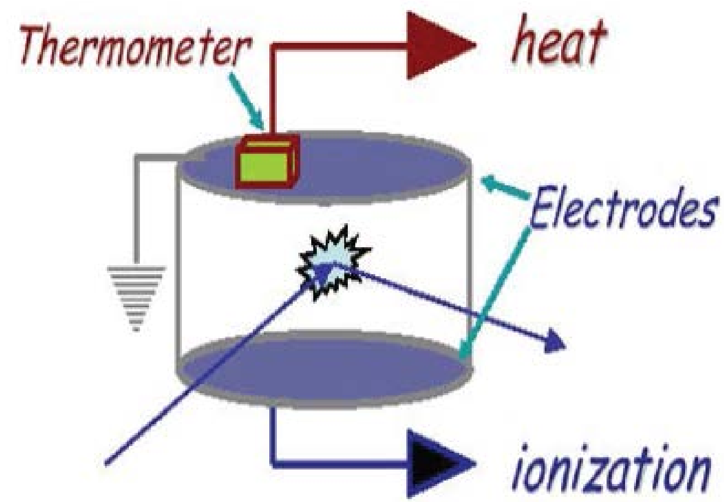

**Observation of coherent elastic neutrino-nucleus scattering**

Signal obcerved at 6.7σ CL.
Low background CsI[Na] detector, **14.6 kg**
Spallation Neutron Source (SNS) at Oak Ridge National Laboratory.

# EDELWEISS

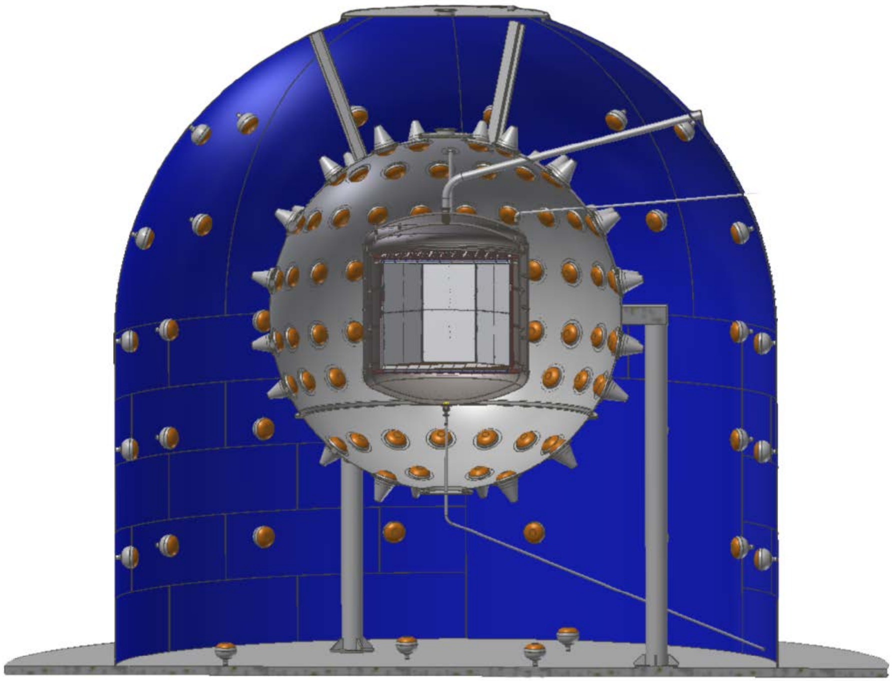
(Expérience pour DEtecter Les Wimps En Site Souterrain)

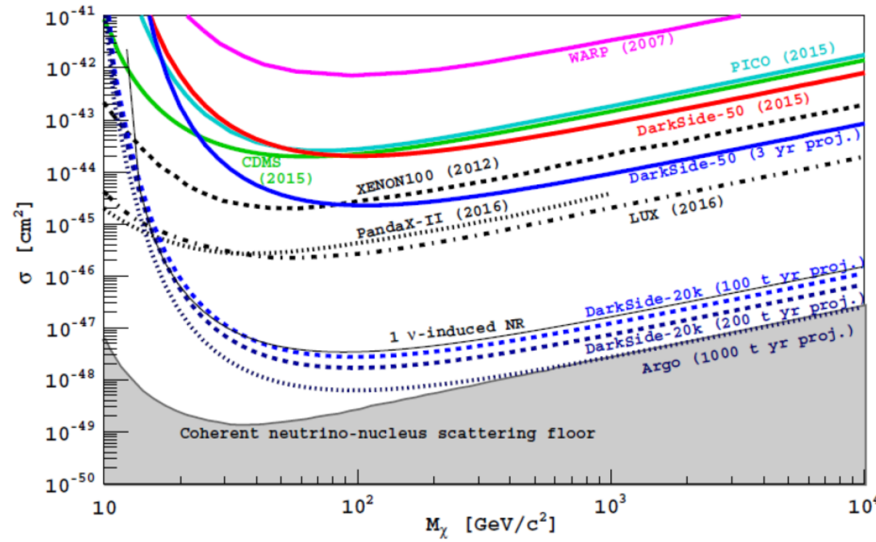



20 mK; HPGe detector-bolometers
Simultaneous detection of
ionzation and heat

# DS20k






**04/2017: Funded by INFN to be hosted at LNGS +Italian government, regione Abruzzo and Regione Autonoma della Sardegna**

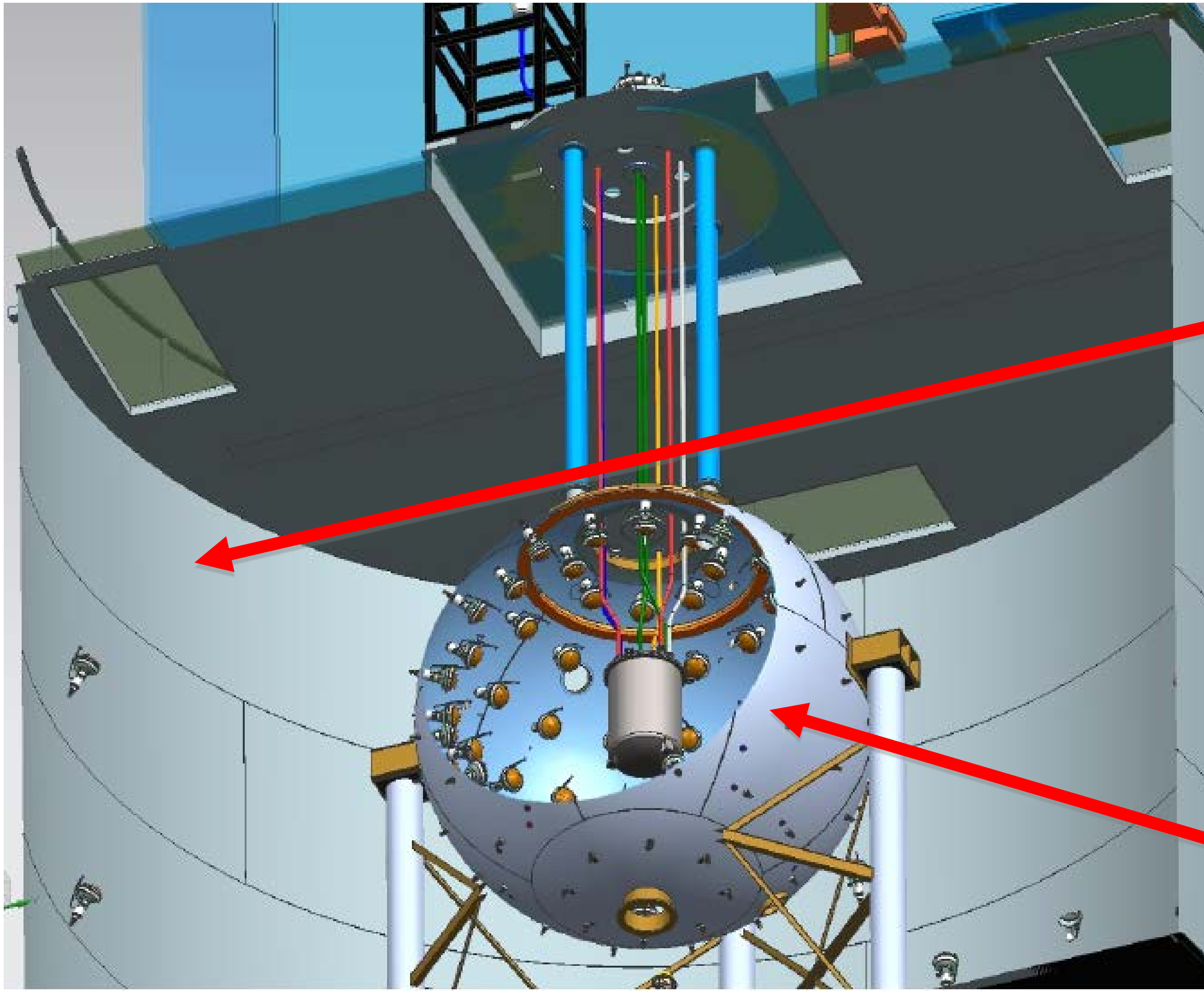
**ArDM(LSC),DS50(LNGS),DEAP3600 and MiniCLEAN (SNOlab) agreed to join forces to carry out DS20k as a single G2 experiment : Global Argon Dark Matter Collaboration (GADMC)**

**08/2017 : officially supported by LNGS+LSC+SNOlab**
**10/2017 : NSF approved DS20k construction proposal + approval obtained for existing Canadian funding from CFI for extraction of undeground Ar.**

**Subprojects:**
**ARIA : undeground radon**
**URANIA : isotope separation**

# Counting Test Facility (1995)

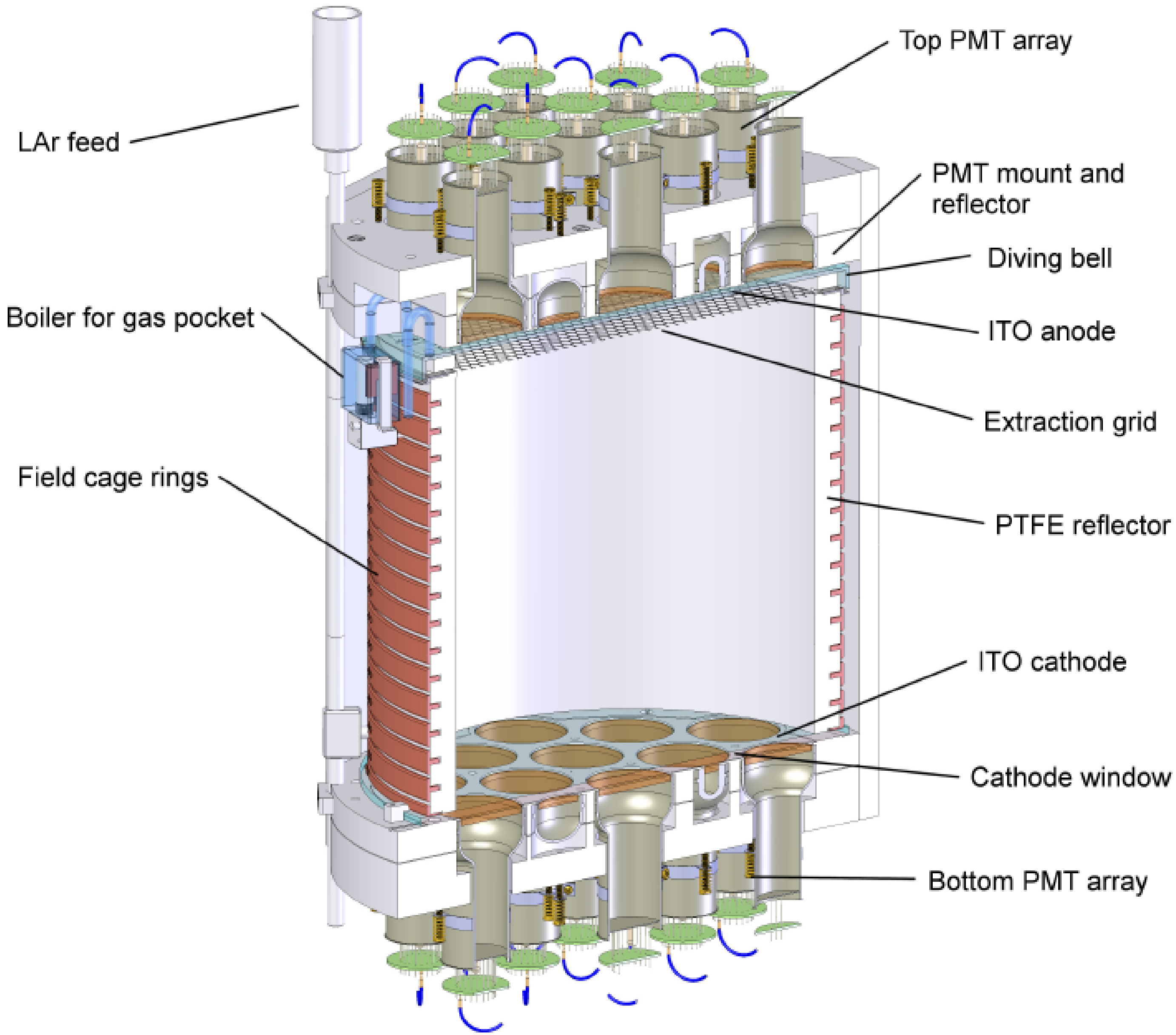
# DS-50



water Čerenkov active muon veto + passive neutron veto

Liquid scintillator active neutron veto

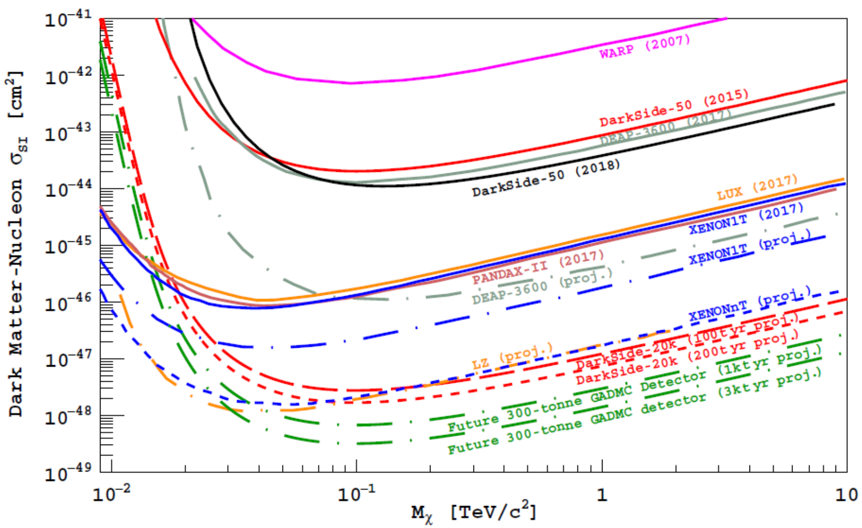
# 2-Phase Argon TPC

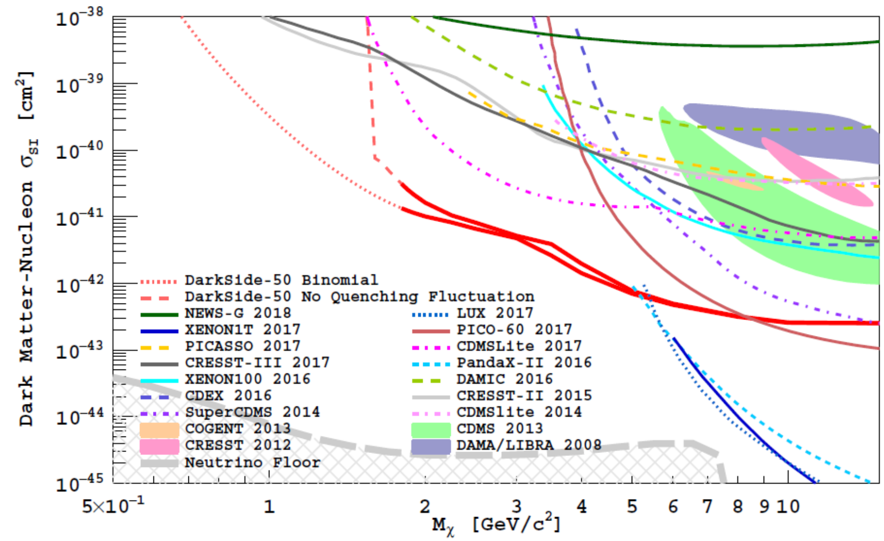


# DarkSide detector features

- Low-energy recoil nuclei (< 100 keV)
- ~1 event/(ton·year) for $10^{-47}$ $cm^2$ cross-section
- Ultra-low background conditions is a must
- Scintillation signal Pulse-Shape discrimination
- Ionization-to-Scintillation signals ratio discrimination
- Geometrical reconstruction with $\sigma \leq 1$cm
- Underground argon (~1500 times less $^{39}Ar$ in comparison with atmospheric argon)
- The experiment is aiming for discovery

- **Low-energy analysis**



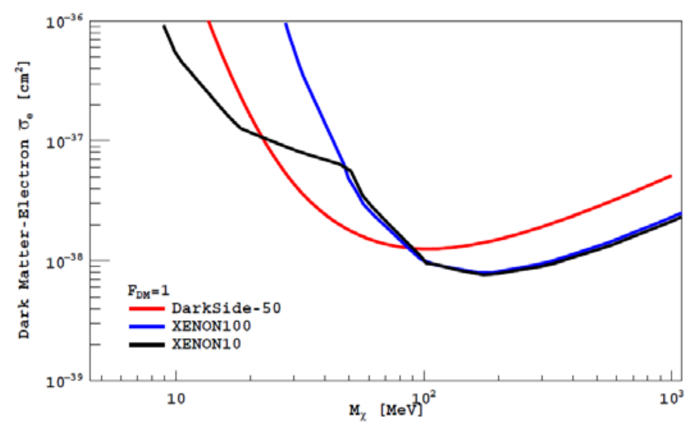




FIG. 4. 90 % C.L. limits on the DM-electron scattering cross section for $F_{DM} = 1$ for DarkSide-50 (red) alongside limits calculated in [30] using data from XENON10 (black) and XENON100 (blue).

# JINR neutrino program

- 1. BAIKAL (Deep water detector of muons and neutrino in Baikal lake)
- 2. BOREXINO (LS Solar neutrino detector at LNGS)
- 3. Проект νGeN  (Experiment at Kalininskaya nuclear power plan on coherent neutrino scattering on Ge nucei)
- 3. DANSS (Detector of the Reactor AntiNeutrino based on Solid Scintillator)
- 4. Daya Bay Experiment (reactor antineutrino experiment)
- 5. GEMMA (Germanium Experiment Searching for Magnetic Moment of Antineutrino)
- 6. GERDA (double beta-decay)
- 7. JUNO  (new generation reactor experiment)
- 8. NOVA (new generation accelerator experiment)
- 9. OPERA (accelerator experiment on neutrino oscillations)
- 10. SuperNEMO (Search for neutrinoless double beta decay with NEMO-3 and the next generation double beta decay experiment SuperNEMO)
- 11. EDELWEISS (Experience pour DEtecter Les Wimps En Site Souterrain.)