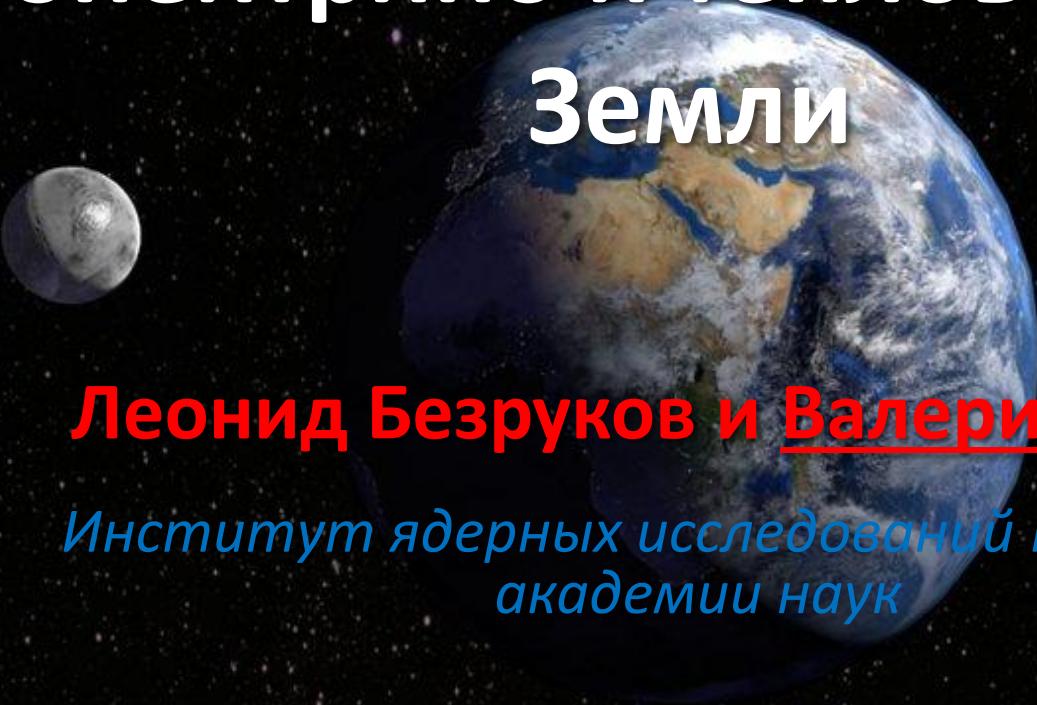


Геонейтрino и тепловой поток Земли



Леонид Безруков и Валерий Синев

*Институт ядерных исследований Российской
академии наук*

Юбилейный семинар Л.Б. Безрукова в ИЯИ РАН, 15 апреля 2015

Geoneutrinos and Earth thermal flux



Leonid Bezrukov and Valery Sinev

*Institute for nuclear researches of Russian
Academy of Sciences*

Bezrukov Jubilee seminar at INR RAS, April, 15 2015

План доклада

- Свойства нейтрино.
- История геонейтрино, энергетический спектр геонейтрино и нахождение в Земле
- Реакторные нейтрино: происхождение, энергетический спектр
- Предлагаемые места расположения детекторов для регистрации геонейтрино, соотношение эффектов геонейтрино и реакторных нейтрино
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- Заключение

Neutrino properties

- Charge is zero
- Negligible mass value
- Mixing and oscillations
- Tiny interaction cross sections (10^{-43} cm 2 at energy 2 MeV in IBD reaction and $\sim 10^{-45}$ cm 2 in scattering reaction)
- Possibility of penetrating through any defenses

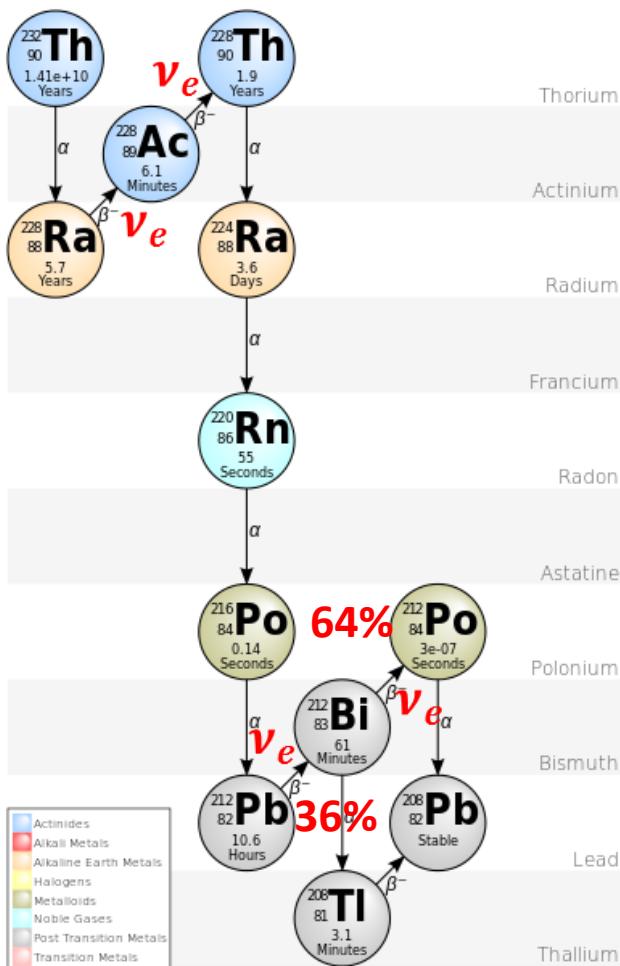
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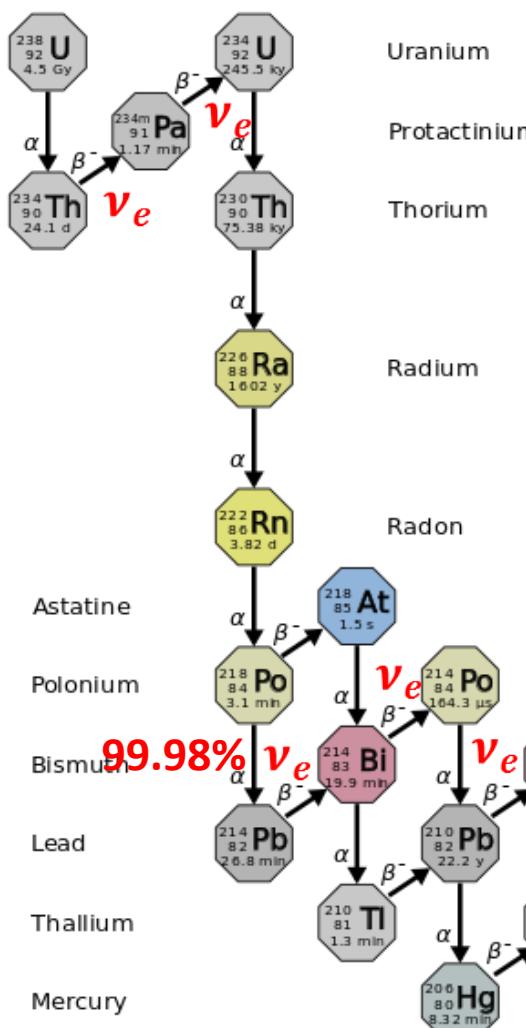
Radioactive isotopes in the Earth

Isotope	T _{1/2} , years	Abundance, %	Activity	E _{max} , MeV	H, TW
⁴⁰ K	1.2775×10 ⁹	0.024 – 1.5	Beta	1.31	4-300
²³² Th	1.405×10 ¹⁰	8.0×10 ⁻⁶	Beta. alpha	2.23	12
²³⁸ U	4.468×10 ⁹	2.0×10 ⁻⁶	Beta. Alpha	3.5	11-12
⁸⁷ Rb	4.75×10 ¹⁰	6.0×10 ⁻³	Beta	0.28	1-5
¹⁷⁶ Lu	3.78×10 ¹⁰	5.6×10 ⁻⁵	Beta	0.6	0.02
¹⁴⁷ Sm	1.06×10 ¹¹	6.0×10 ⁻⁴	Alpha	2.223	1.5
¹³⁸ La	1.05×10 ¹¹	5.6×10 ⁻⁵	Beta	0.13	0.01
¹⁹⁰ Pt	6.5×10 ¹¹	3.7×10 ⁻⁶	Alpha	3.249	0.002

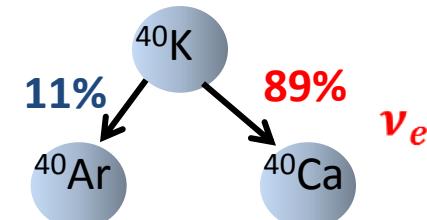
^{232}Th family



^{238}U family

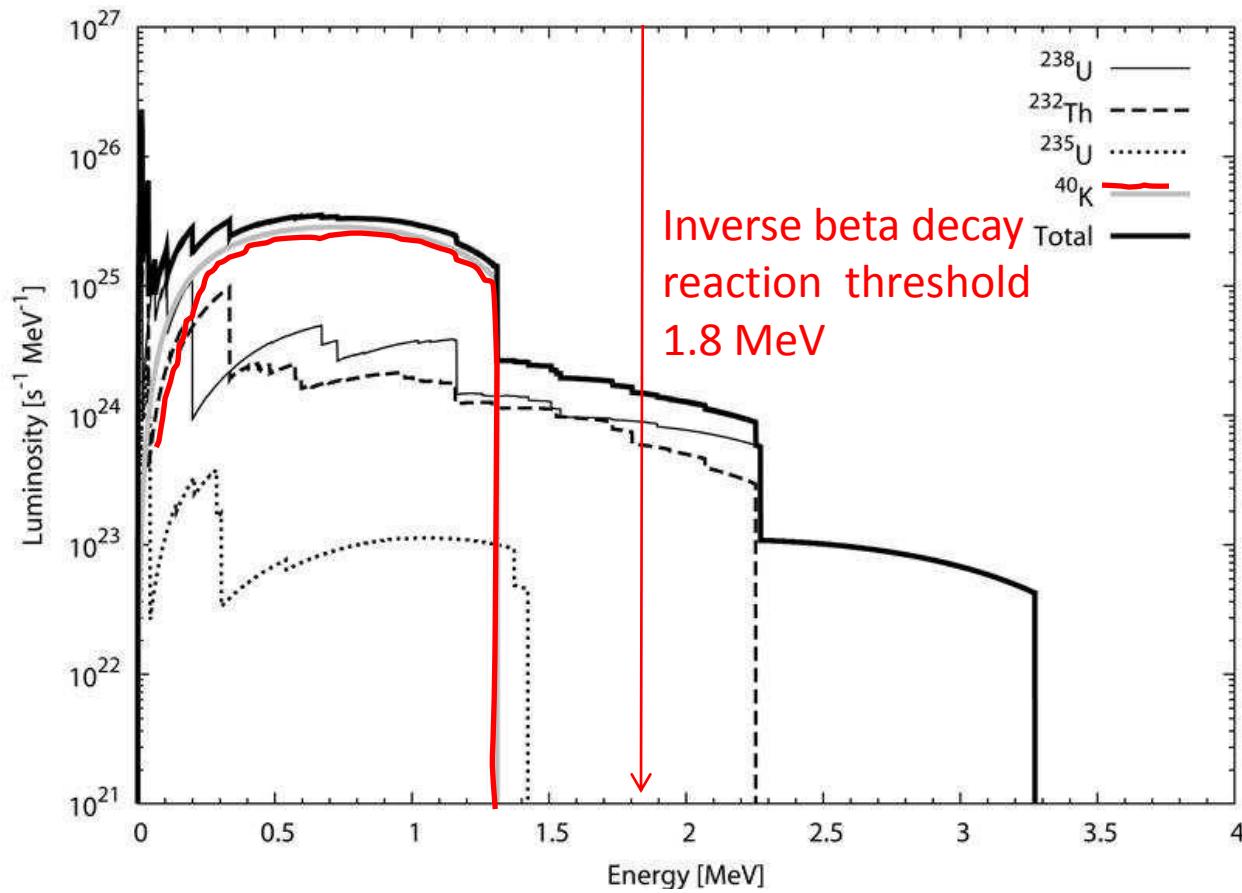


^{40}K



Geoneutrino energy spectra

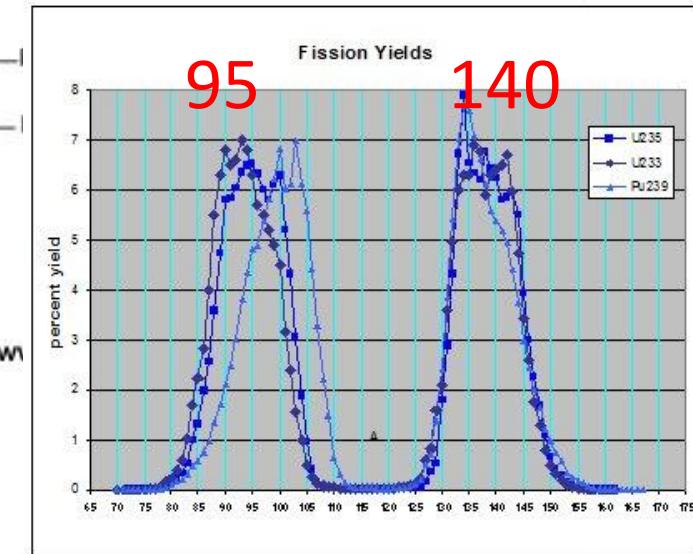
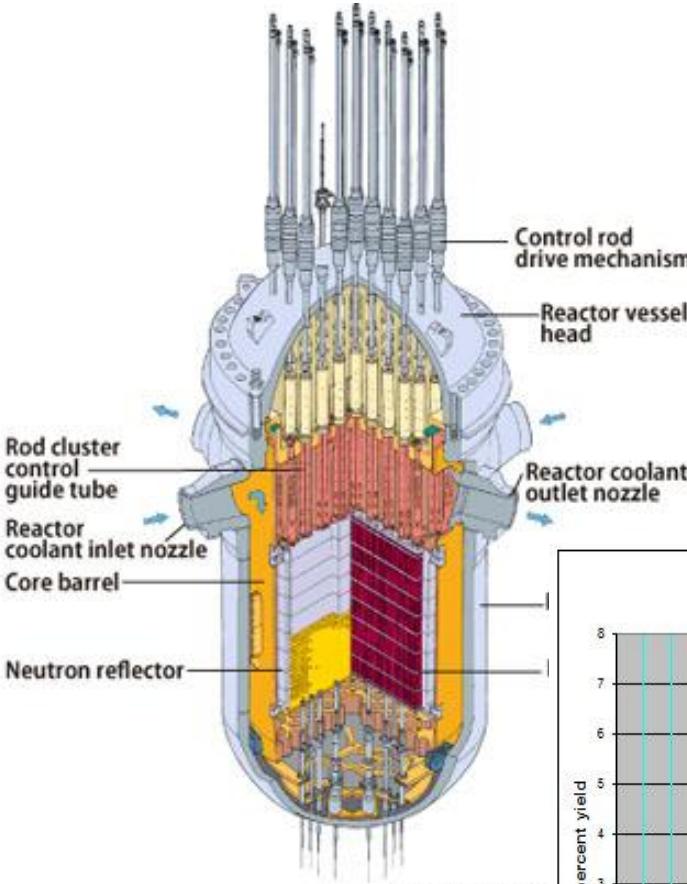
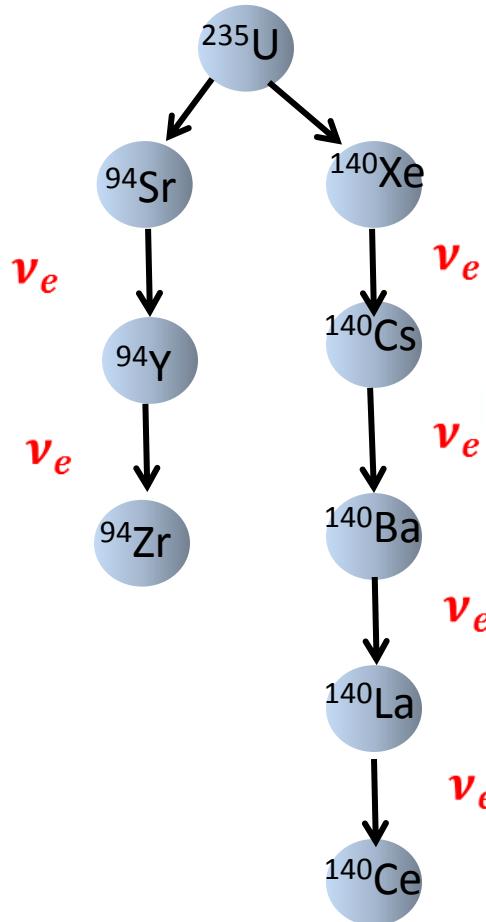
From Gianni Fiorentini, Marcello Lissia and Fabio Mantovani, “Geo-neutrinos and Earth’s interior”, ArXiv: 0707.3203 [physics.geo-ph]



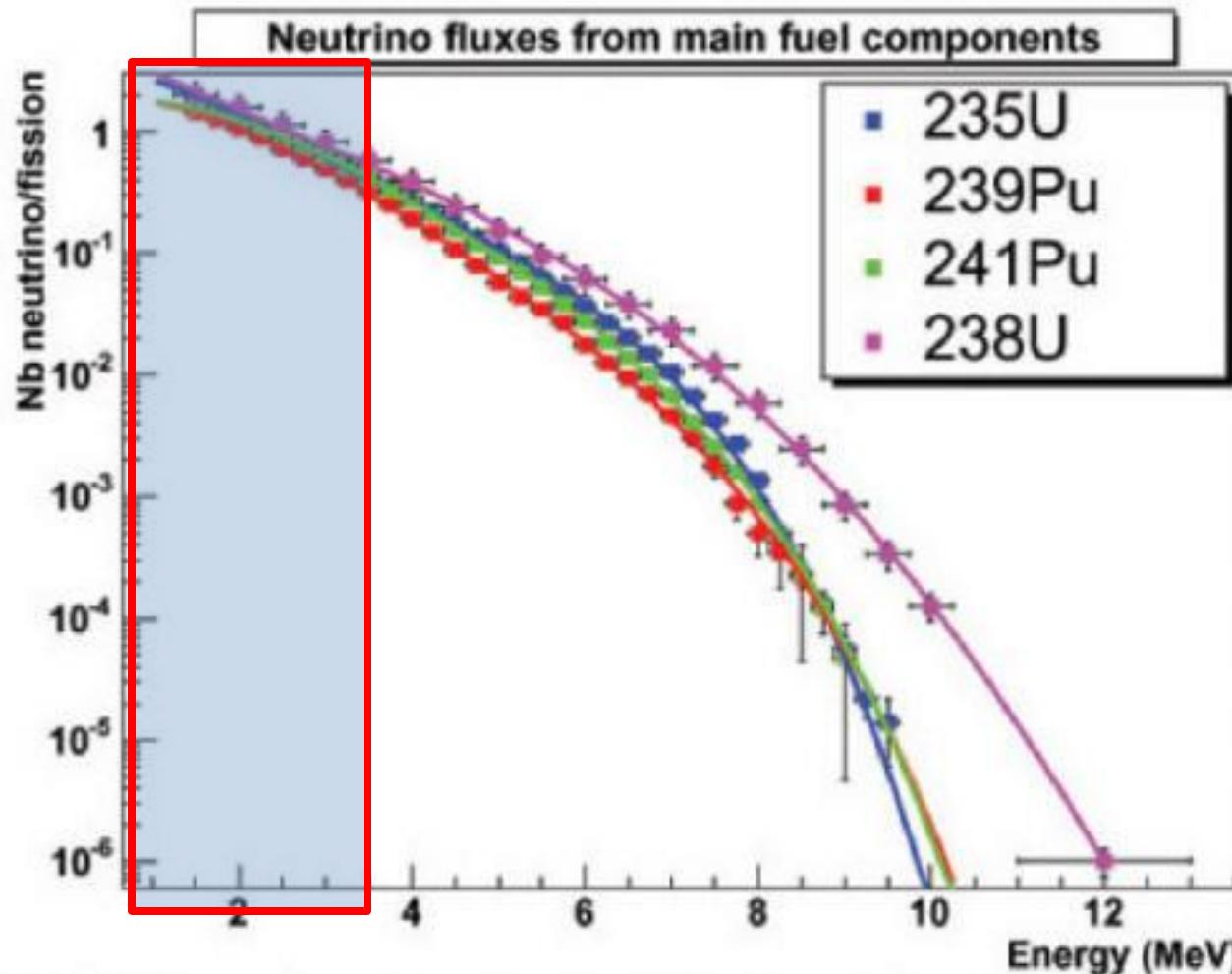
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Reactor neutrinos



Reactor neutrinos energy spectra

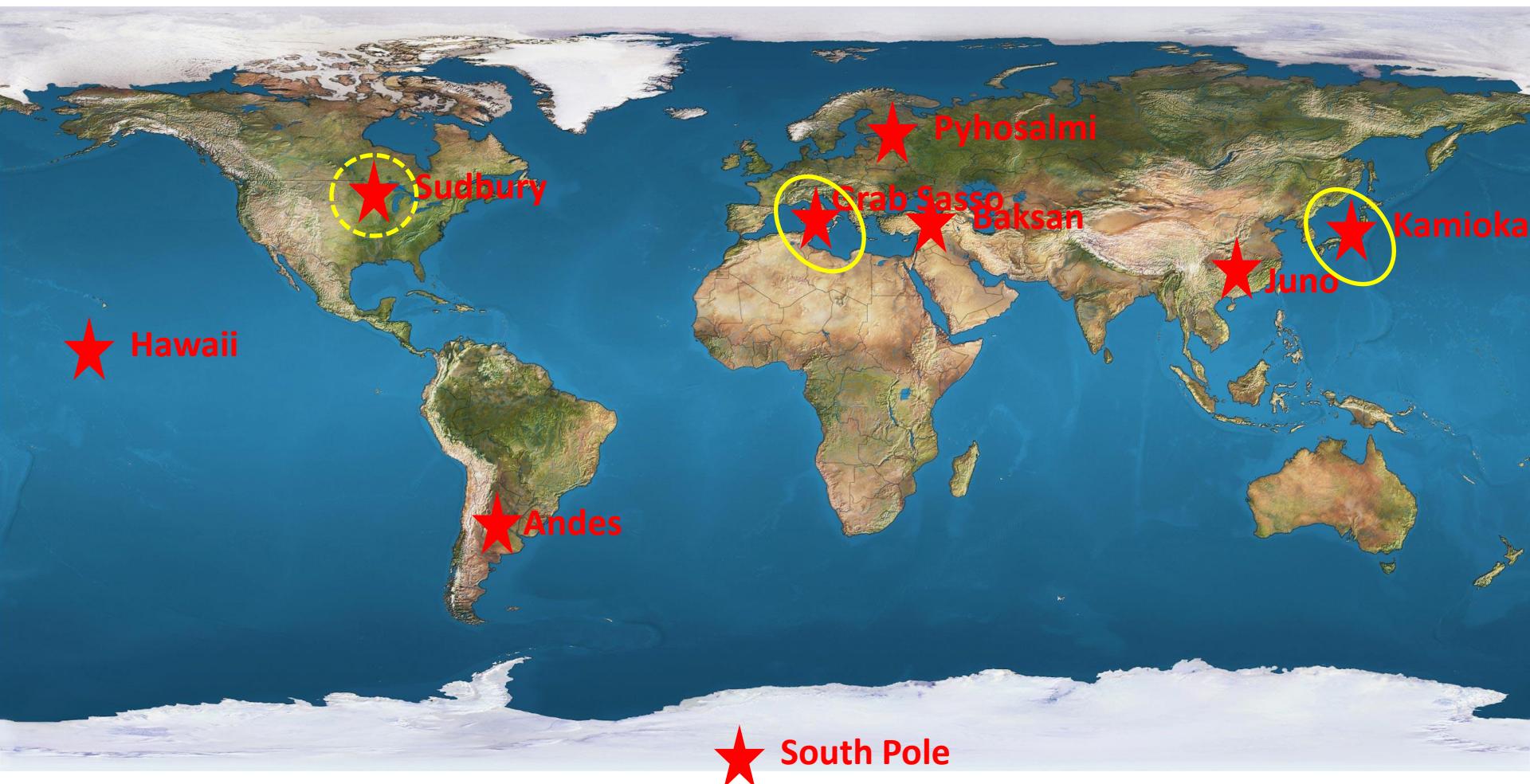


Спектр
реакторных
нейтрино
формируется
преимуществе
нно четырьмя
делящимися
изотопами.
 ^{235}U (60%),
 ^{239}Pu (30%)
 ^{238}U (7%),
 ^{241}Pu (3%).

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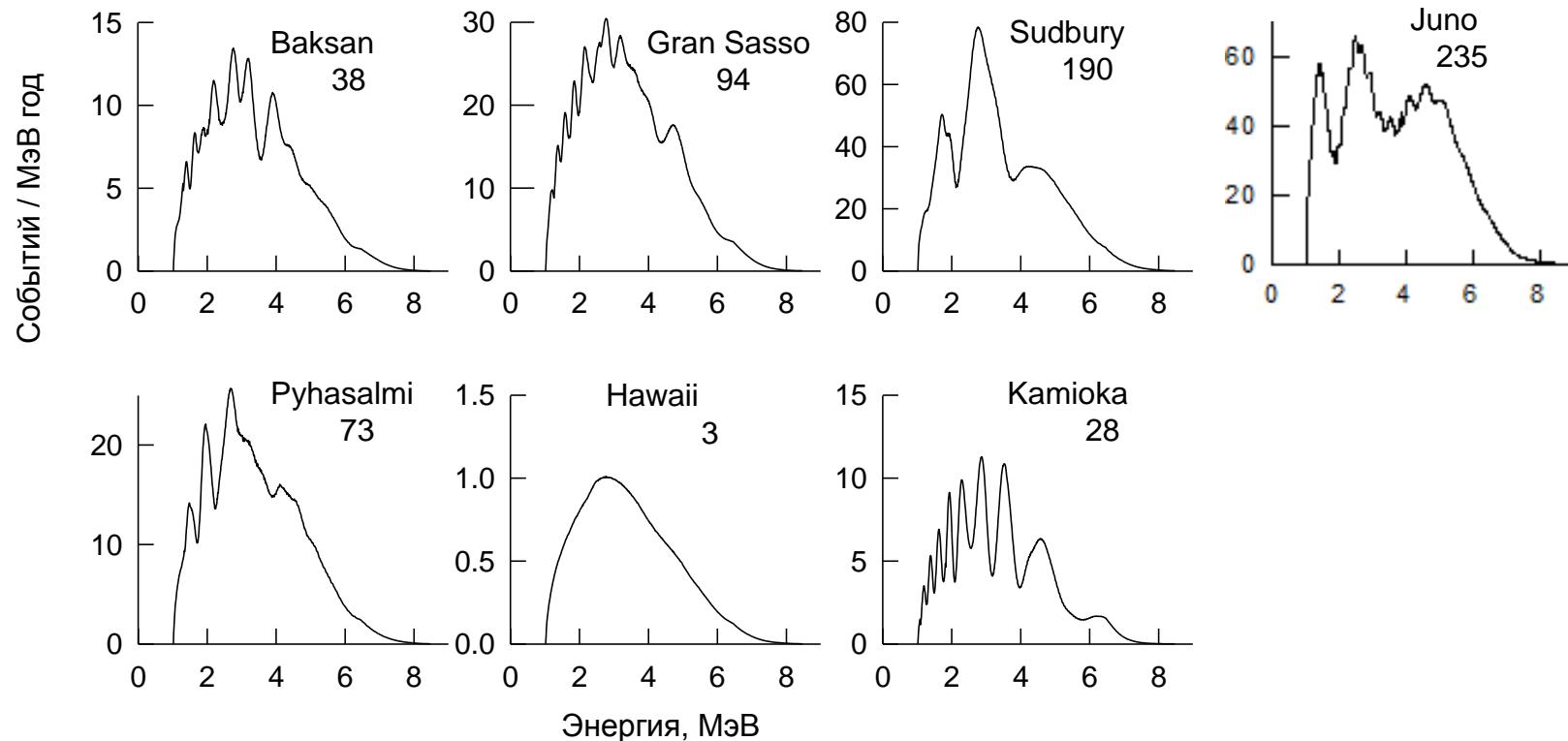
Возможные места постройки детектора генонейтрино и для исследования Земли



Rates of geoneutrinos and reactor antineutrinos at proposed sites

Detector site	$\langle D \rangle$, km	R , TNU Total reactor spectrum	R_G , TNU The same but in energy window of geoneutrinos	G , TNU Geoneutrinos spectrum	R_G/G
Baksan	1738.1	38.24	14.37	52.6	0.3
Gran Sasso	1135.8	94.15	35.35	39.8	0.9
Sudbury	605.6	190.74	72.85	49.9	1.4
Pyhasalmi	1184.7	72.97	27.61	52.9	0.5
Hawaii	7720.5	3.44	1.29	15.3	0.1
Kamioka	1675.0	27.79	10.30	31.7	0.3
Juno	289.8	235.26	83.28	50	1.7

Reactor neutrinos energy spectra at proposed sites

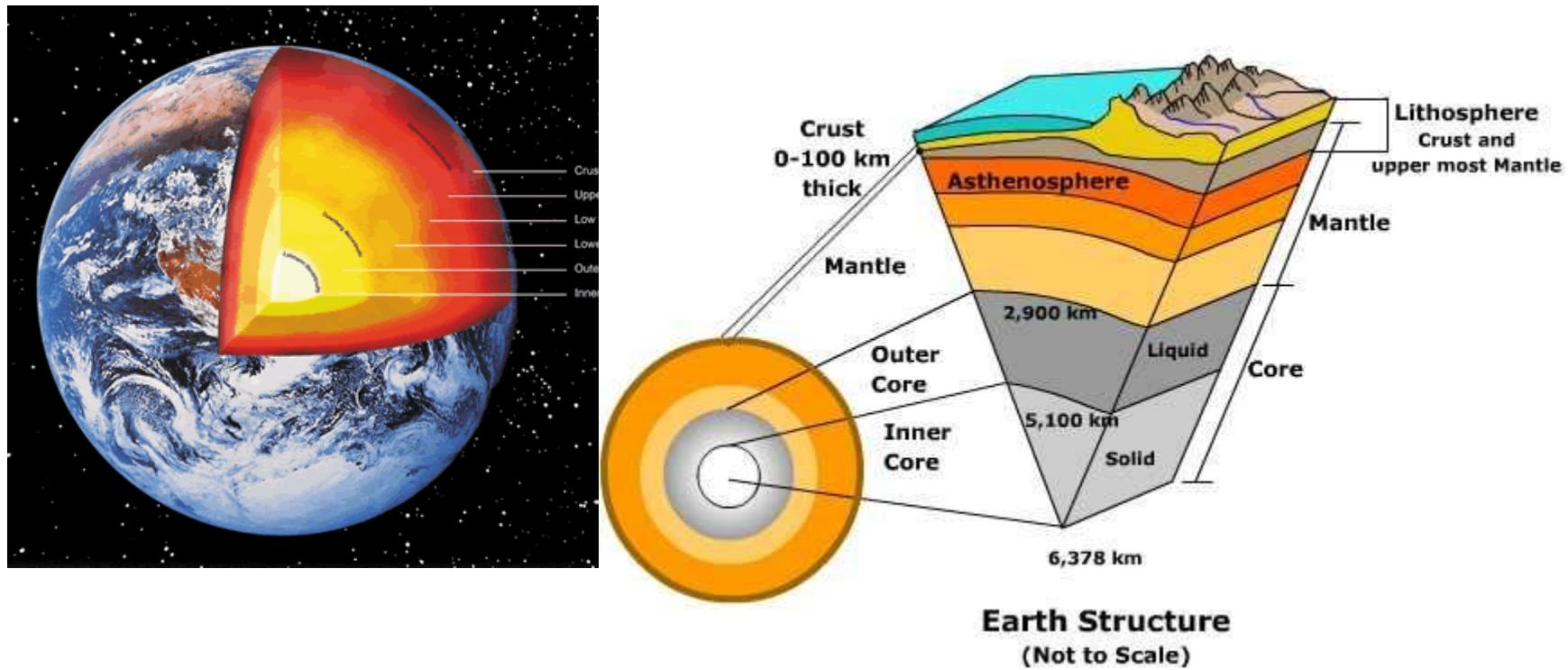


Spectra were calculated for the target containing 10^{32} protons (about 1 kt)

План доклада

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Earth interior

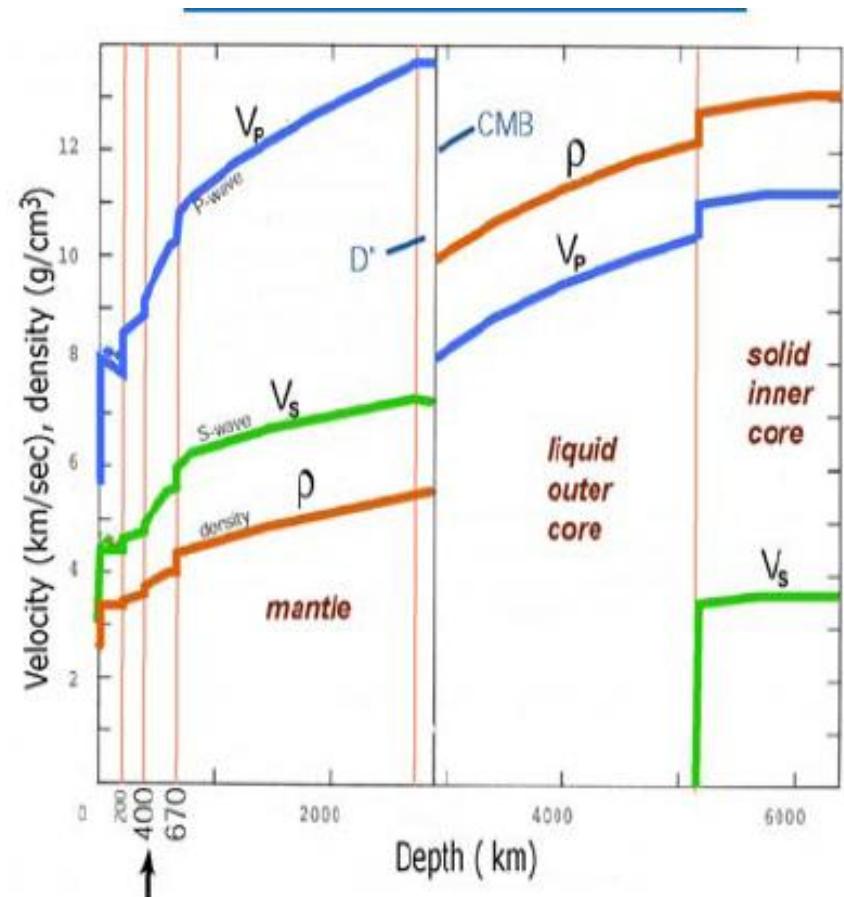
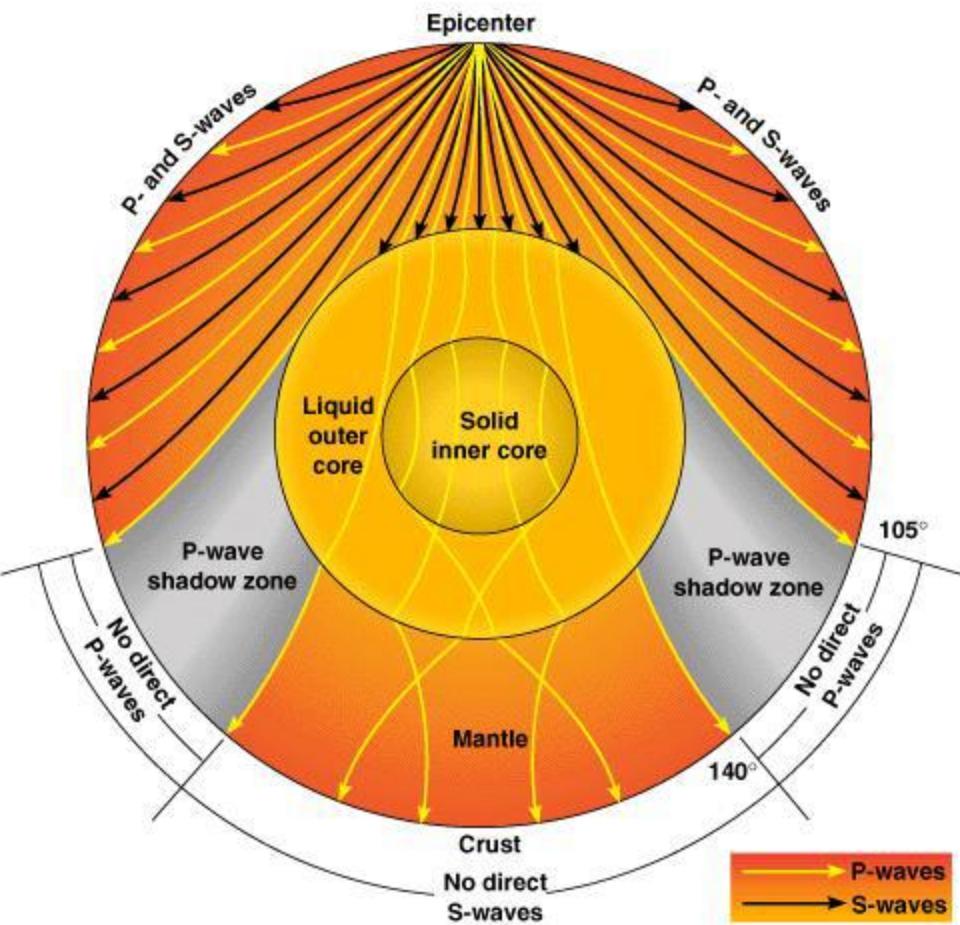


Not solved problems inside the Earth:

Element abundances, existence of liquid core, magnetic field production and energy, thermal flux etc.

The deepest hole is on Kola peninsula 12262 m, crust thickness ~30-50 km

Seismology



P – primary, longitudinal waves

S – secondary, transverse/shear waves

Open questions in our knowledge of the Earth

- Inner element composition
- Exact density, phase conditions of the layers
- The origin of Earth magnetic field and the source of energy supplying it
- Origin of Earth thermal flux (partially is known – radioactive elements) and places of its production (also the value)
- Others: seismicity, volcanism. Is it really hot inside (core, mantle)?

- The conception of similarity of the Earth content and asteroids (BSE) gives some approximate answers.
- The conception accounting magnetic element separation (HE) may give more accurate answers and does some predictions.
- Let's try to fix the differences of these two concepts for testing them using neutrino detection method.

BSE – Bulk Silicate Earth

- Earth composition = meteorites composition = asteroids composition.
- Thorium to uranium ratio in the Earth = **3.9**
- In upper mantle the U, Th, K contents are low, and they are **absent in the core**.
- The core made of **iron**.
- Radiogenic heat is only a part of total Earth thermal flux. Total flux = **47** TW, but radiogenic is ~ 20 TW.

HE – Hydridic Earth

- Earth composition **differs** from the meteorites composition because of magnetic elements separation.
- Thorium to uranium ratio = **1.7 (about 2.0)** (Leonid Bezrukov. Geoneutrino and Hydridic Earth model. Preprint INR 1378/2014. arXiv:1308.4163)
- U, Th, K **present in mantle** as well as in the **core**.
- Core contents some light elements (**not pure of iron**).
- Solid core consists of **metal hydrides**, but not pure metals.
- Thermal flux is not a constant in time, but can change. It can achieve values **more than 300 TW**.

**Predicted overall initial composition of the Earth. Major elements are typed in bold
(mass fraction larger than 0.1%).**

[Chemical differentiation of planets: a core issue.](#) [Herve Toulhoat](#), [Valerie Beaumont](#), [Viacheslav Zgennik](#),
[Nikolay Larin](#), [Vladimir N. Larin](#). Aug 2012. 15 pp. e-Print: [arXiv:1208.2909](#) [astro-ph.EP]

Element	wt %	mol %	Element	wt %	mol %	Element	wt %	mol %
H	1.830E+01	87.43	Mg	1.389E+01	2.75	Sc	3.601E-03	<0.01
He	1.856E-05	<0.01	Al	8.769E+00	1.57	Ti	2.100E-01	0.02
B	4.220E-05	<0.01	Si	9.028E+00	1.55	V	2.329E-02	<0.01
C	7.550E-01	0.30	P	5.715E-03	<0.01	Cr	1.046E+00	0.10
N	5.562E-03	<0.01	S	3.793E-01	0.06	Mn	4.518E-01	0.04
O	1.391E-01	0.04	Cl	4.210E-04	<0.01	Fe	1.942E+01	1.67
F	1.260E-07	<0.01	Ar	1.883E-04	<0.01	Co	6.153E-02	0.01
Ne	2.675E-06	<0.01	K	3.760E+00	0.46	Ni	1.627E+00	0.13
Na	1.341E+01	2.81	Ca	8.792E+00	1.06			
					Balance		1,00E+02	100

Сравнение содержания элементов в весовых % в крайних предсказаниях и коре

Isotope	BSE	Data from Wiki (crust only)	HE
K	0.024	2.09	3.76
Fe	6.26	5	19.4
U	2×10^{-6}	1.8×10^{-6}	5.3×10^{-6}
Th	8×10^{-6}	6×10^{-6}	9.07×10^{-6}
Si	21	27	9.03

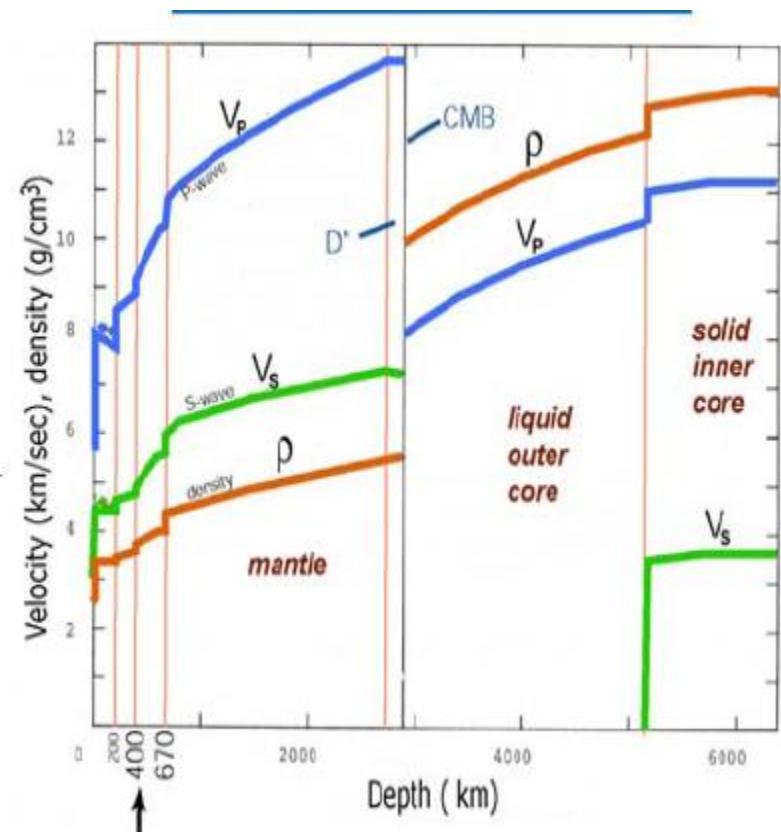
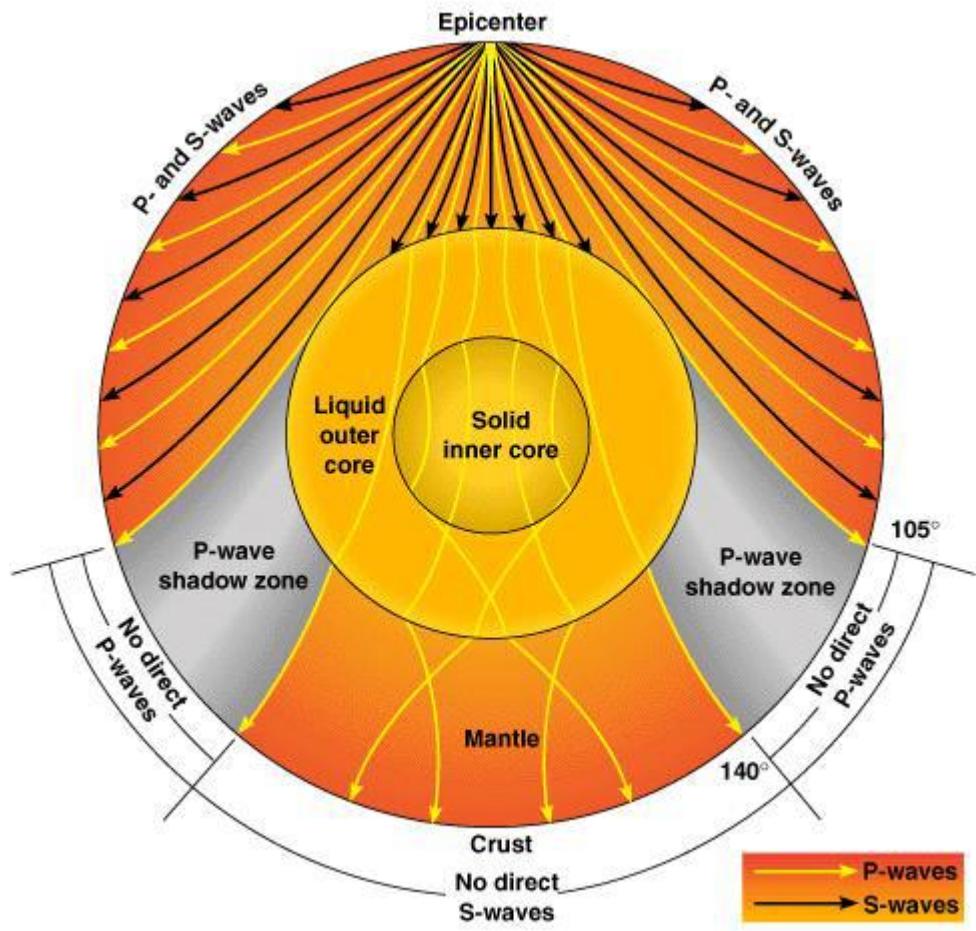
ArXive: 0707.3203

ArXive: 1308.4163

1208.2909

Если ядро состоит из железа, то содержание Fe в Земле должно быть 24%

Some remarks on accuracy of layers density knowledge.



P – primary, longitudinal waves

S – secondary, transverse/shear waves

Sound speed in solids

- There may be two types of acoustic waves in solids: longitudinal waves (p) and transverse or shear waves (s)

$$V_p = \sqrt{\frac{K + \frac{4G}{3}}{\rho}}$$
$$V_s = \sqrt{\frac{G}{\rho}}$$

where ρ – density, K – bulk modulus or coefficient of stiffness, G – shear modulus.

We do not know how the change, in compare with normal conditions, at temperature and pressures inside the Earth.

Temperature and chemical compositions are also unknown.

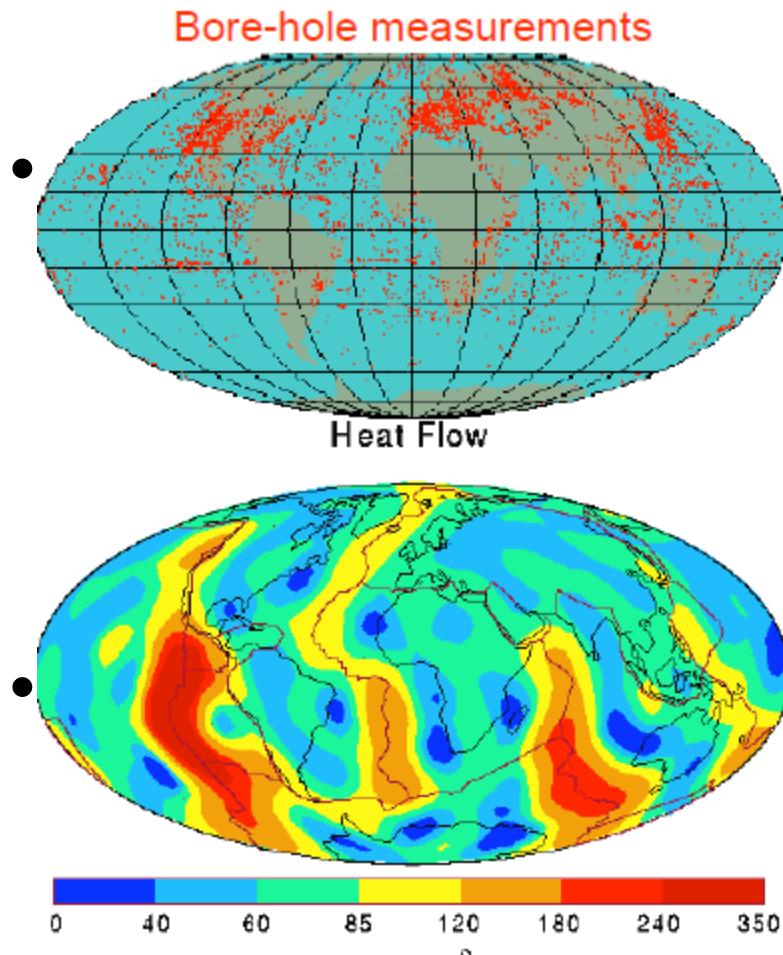
Earth thermal flux

Two methods of measurements:

- Direct, at continents and on the shelf 47 TW
- Indirect, in world ocean. Up to 300 TW

Sufficient difference in value

Surface heat flux



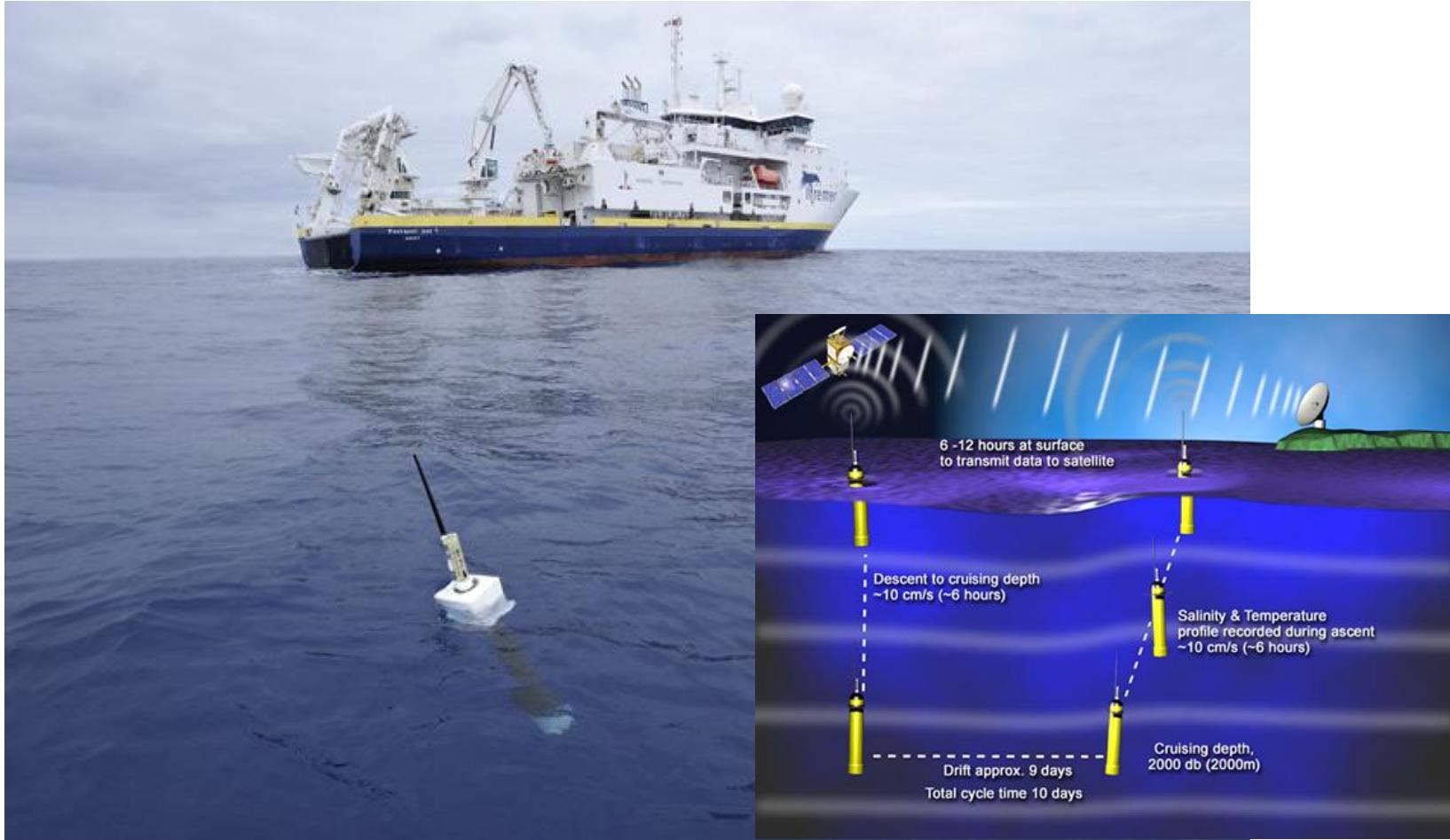
Global Heat Flow Data (Pollack et al.)

- Conductive heat flow from bore-hole temperature gradient;
- **Total surface heat flux:**
 $31 \pm 1 \text{ TW}$ (Hofmeister&Criss 2005)
 $46 \pm 3 \text{ TW}$ (Jaupart et all 2007)
 $47 \pm 2 \text{ TW}$ (Davis&Davies 2010)
(same data, different analysis)

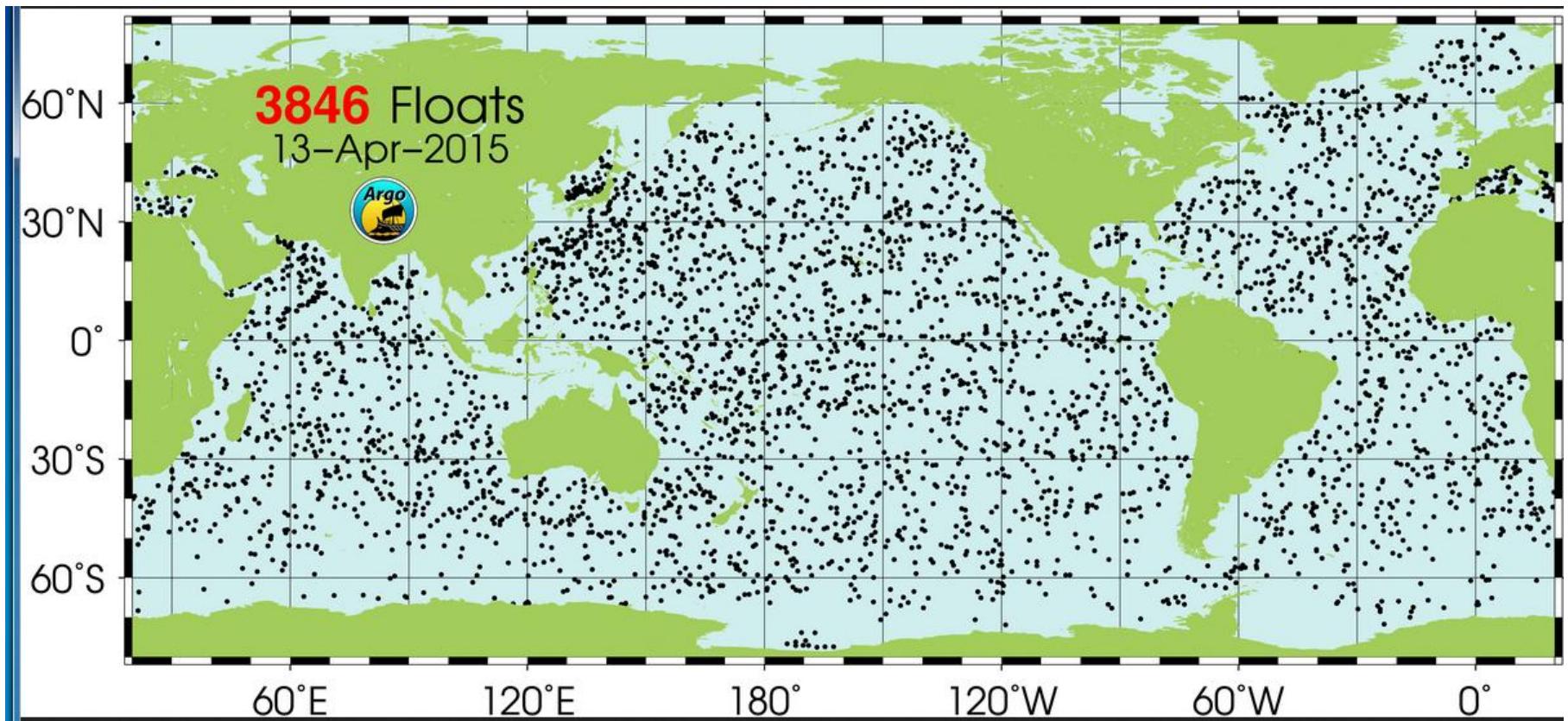
SYSTEMATIC ERRORS

Different assumptions concerning the role of fluids in the zones of mid ocean ridges.

About 90% of the heat Earth accumulates in the world ocean.
Oceanic researches are very important for future Climate
changing models (the picture from Argo Project).

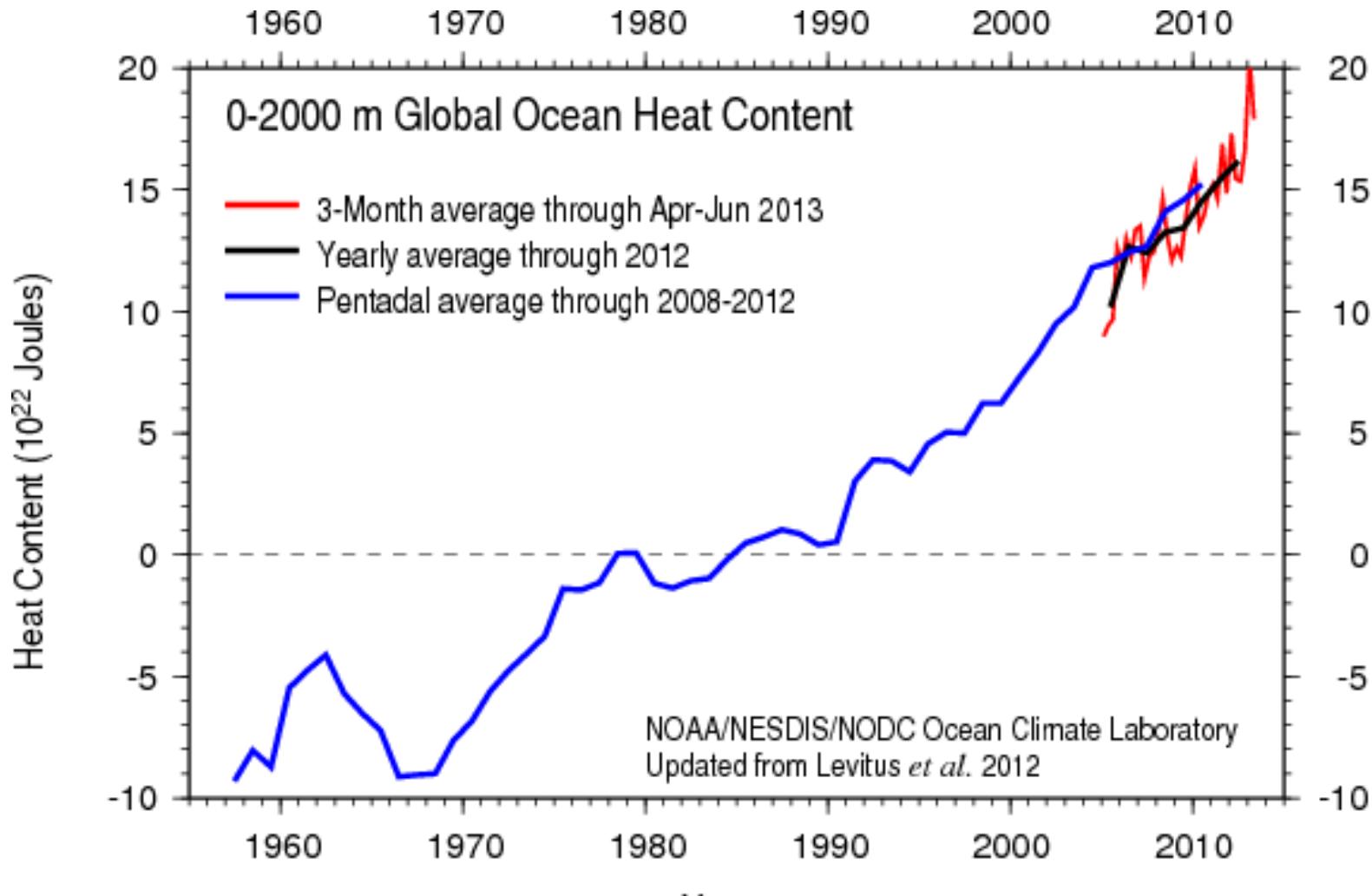


Thermal flux in the ocean (Argo project). Map of floats for today.

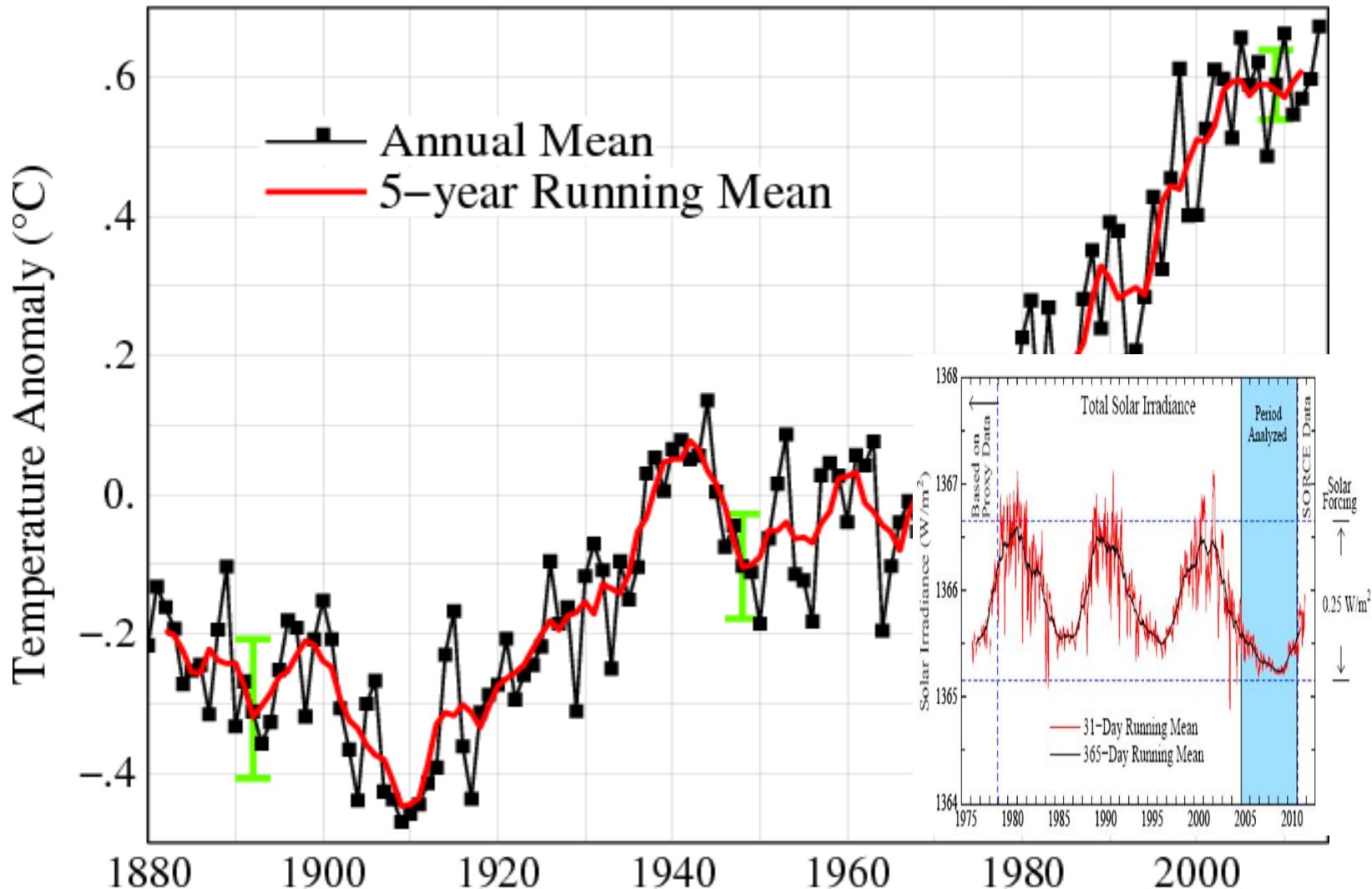


$$H = \rho c_p \int_{h2}^{h1} T(z) dz$$

ρ - water density, C_p - sea water specific heat capacity,
 h_2 - bottom depth, h_1 - top depth, $T(z)$ - temperature profile.



Global Land–Ocean Temperature Index



Earth's energy imbalance

Atmos. Chem. Phys., 11, 13421-13449, 2011

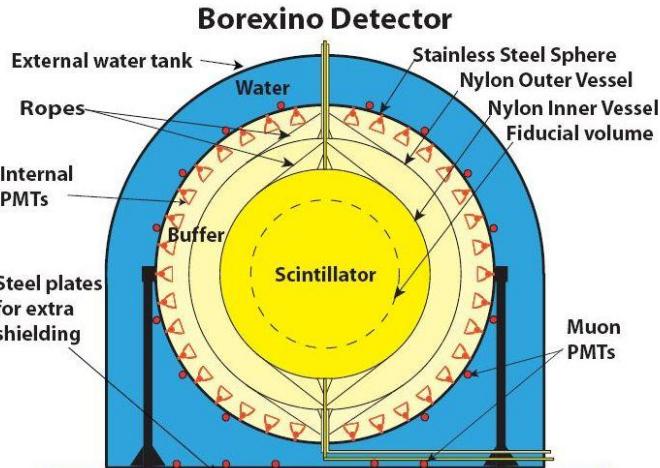
www.atmos-chem-phys.net/11/13421/2011/

- **J. Hansen^{1,2}, M. Sato^{1,2}, P. Kharecha^{1,2}, and K. von Schuckmann³**
¹NASA Goddard Institute for Space Studies, New York, NY 10025, USA
²Columbia University Earth Institute, New York, NY 10027, USA
³Centre National de la Recherche Scientifique, LOCEAN Paris, hosted by Ifremer, Brest, France
- Improving observations of ocean heat content show that Earth is absorbing more energy from the Sun than it is radiating to space as heat, even during the recent solar minimum. The inferred planetary energy imbalance is $0.58 \pm 0.15 \text{ W m}^{-2}$ during the 6-yr period 2005–2010
- $0.58 \text{ W m}^{-2} \cdot 5.1 \cdot 10^{14} \text{ m}^2 = 3 \cdot 10^{14} \text{ W} = 300 \pm 76 \text{ TW}$

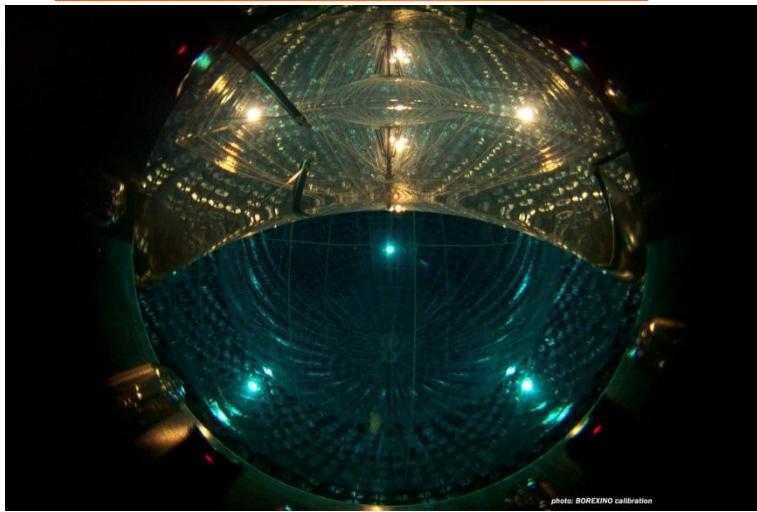
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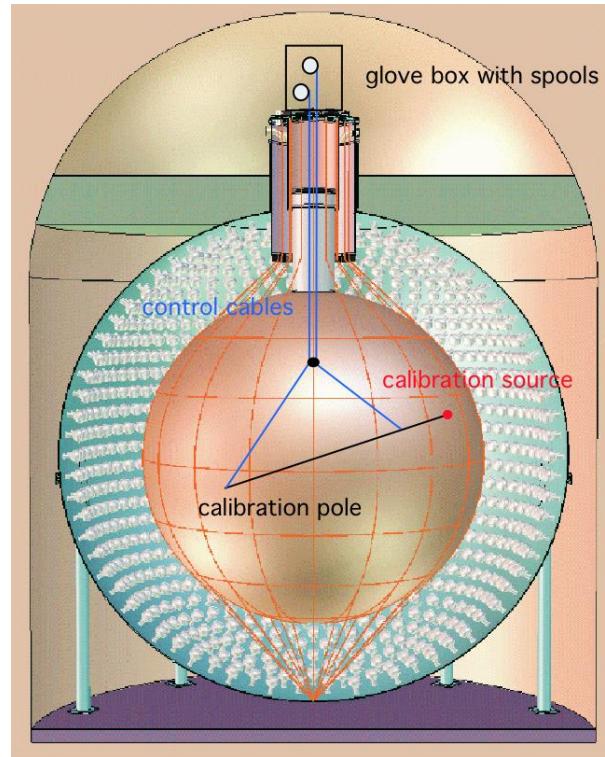
Детекторы, зарегистрировавшие поток геонейтрино



100 t fiducial
volume. Total
300 t.
 $R \sim 4 \text{ ev./year}$



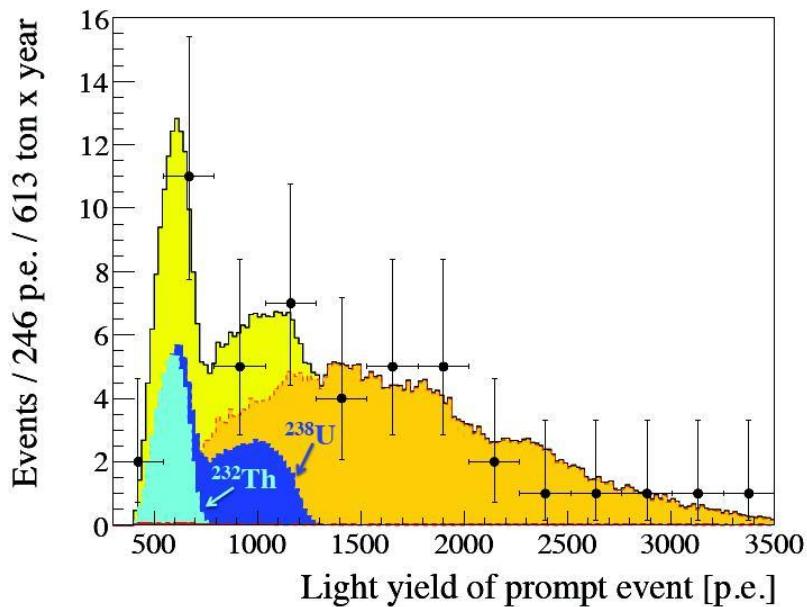
KamLAND Detector



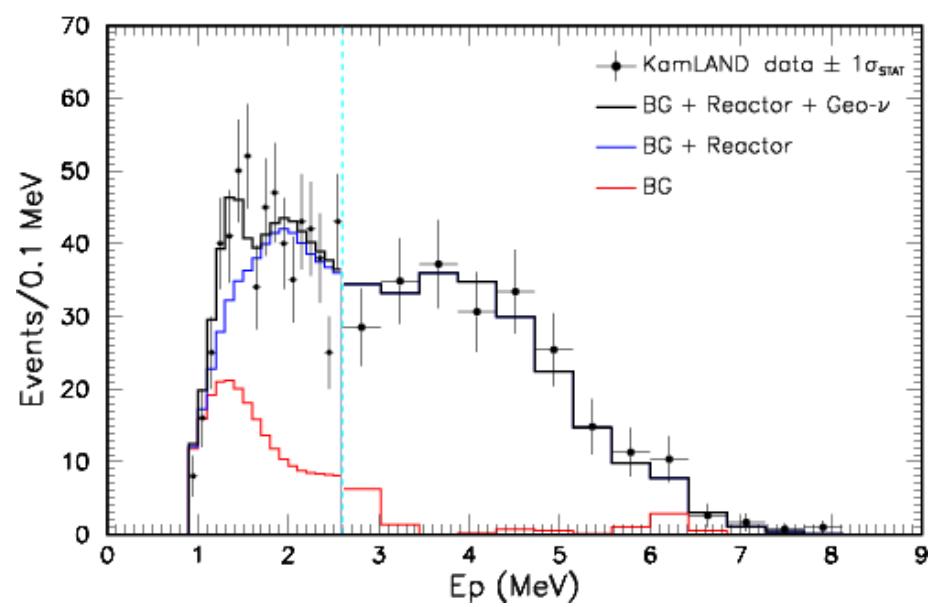
600 t fiducial volume. Total
1000 t. $R \sim 25 \text{ ev./year}$

Measured geoneutrino spectra

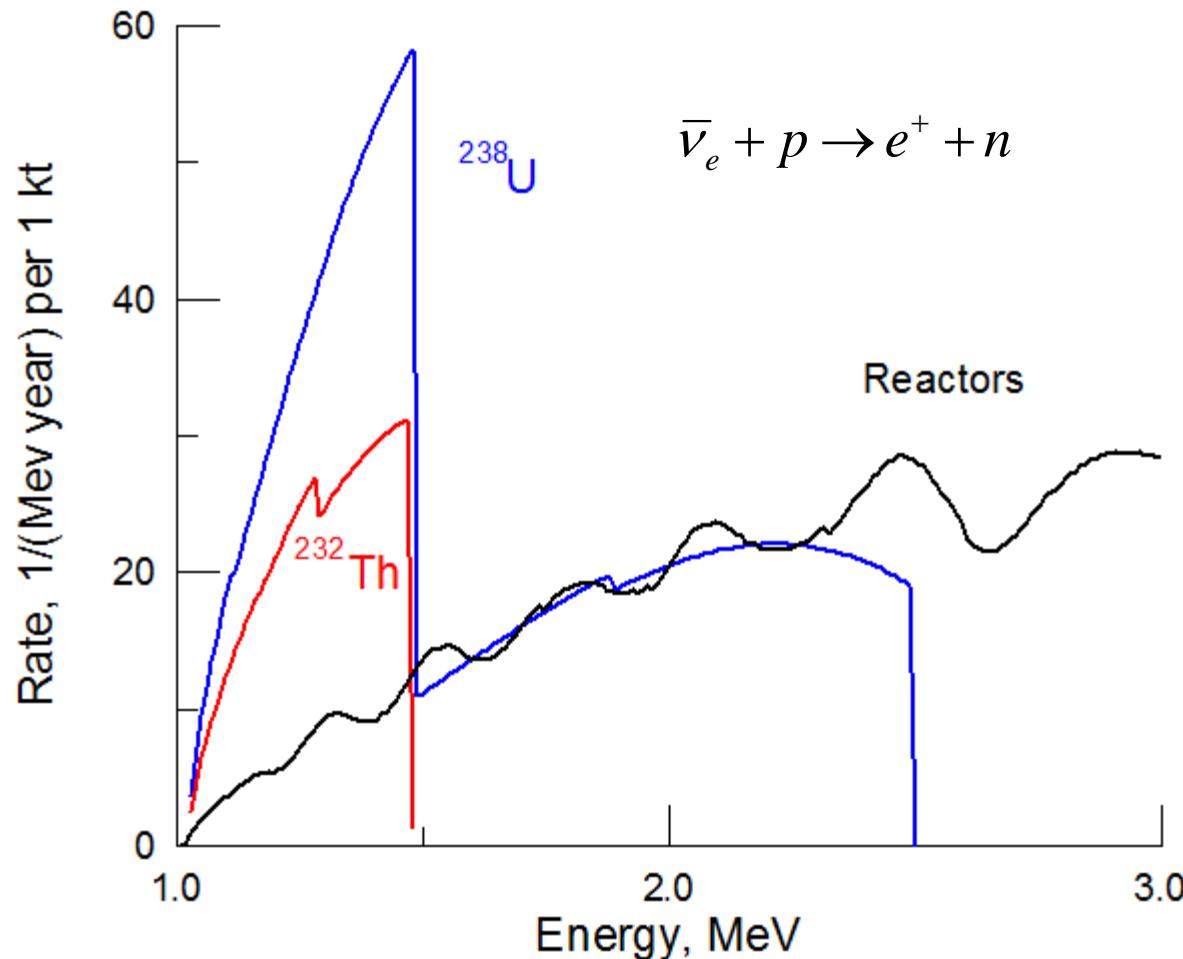
Borexino



KamLAND



Calculated dependence of counting rate of geoneutrino inverse beta decay reactions in 1 kt scintillation detector per year versus energy release in the first flash after neutrino reaction in detector. Blue curve - geoneutrino from U decay, red curve - geoneutrino from Th decay, black curve - calculated background from reactors for Gran-Sasso location



- To distinguish the difference in predicted by BSE (3.9) and HE (1.7) hypotheses one should measure no less than $25 \text{ kt} \cdot \text{years}$

L. Bezrukov, V. Sinev arXiv: 1405.3161 [astro-ph.EP]

^{40}K problem in the Earth

- ^{40}K content in the Earth is very important for the Earth thermal flux prediction.
- In our days ^{40}K abundance is accounted negligible, but this contradicts to its abundance in the crust (2%).
- If ^{40}K neutrino flux will not be found this may mean that we should find another heat sources to explain the observed ocean heating during last 24 years. In opposite, its observing explains this perfectly.

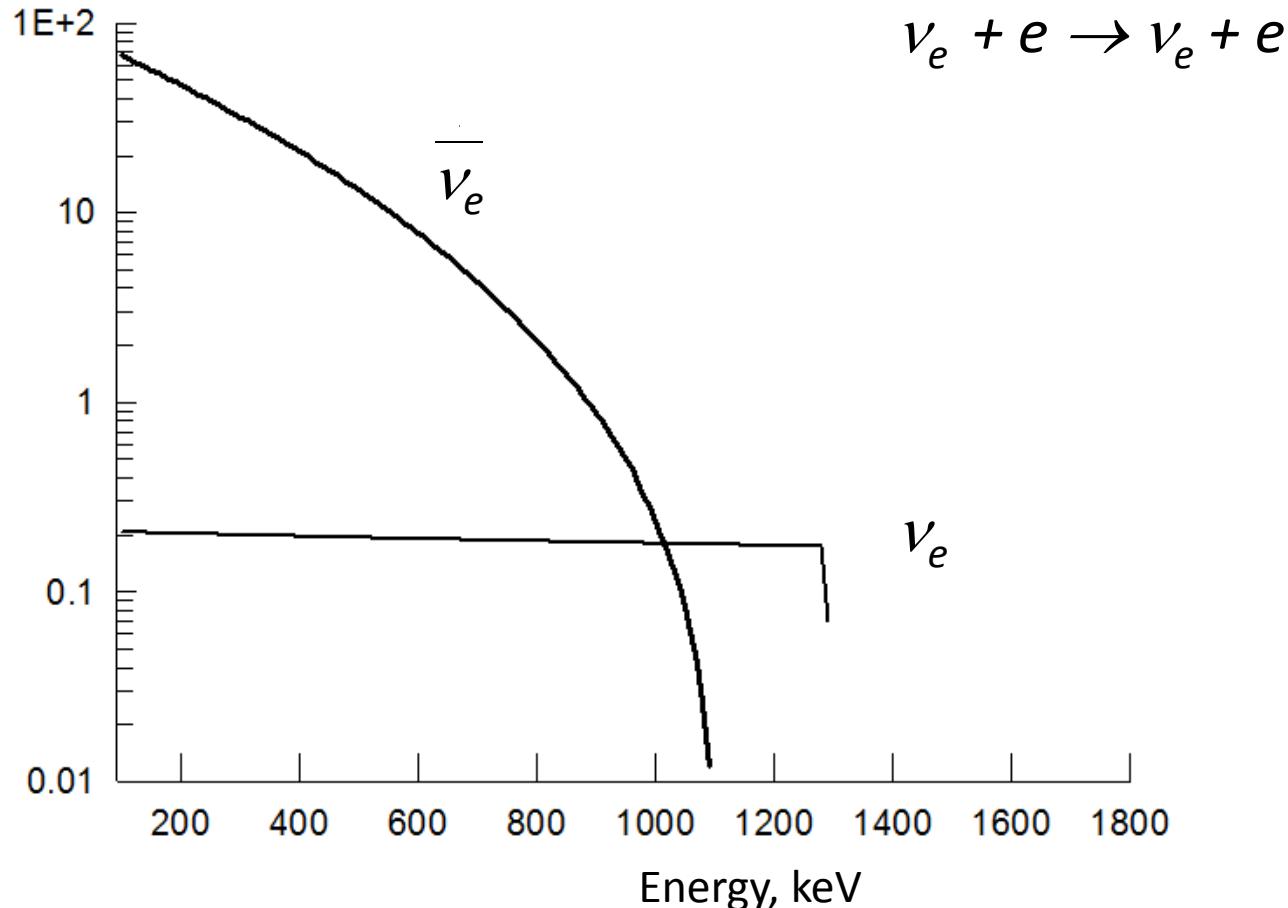
Abundances of K for calculations

Earth layers	0.37%	3.74%
Crust	2.1%	2.1%
Upper mantle	2.6%	2.6%
Lower mantle	0	3.6%
Liquid core	0	4.6%
Solid core	0	5.6%

Sediments – 0.2%.

Океаны – 0.042%

Recoil electrons spectra



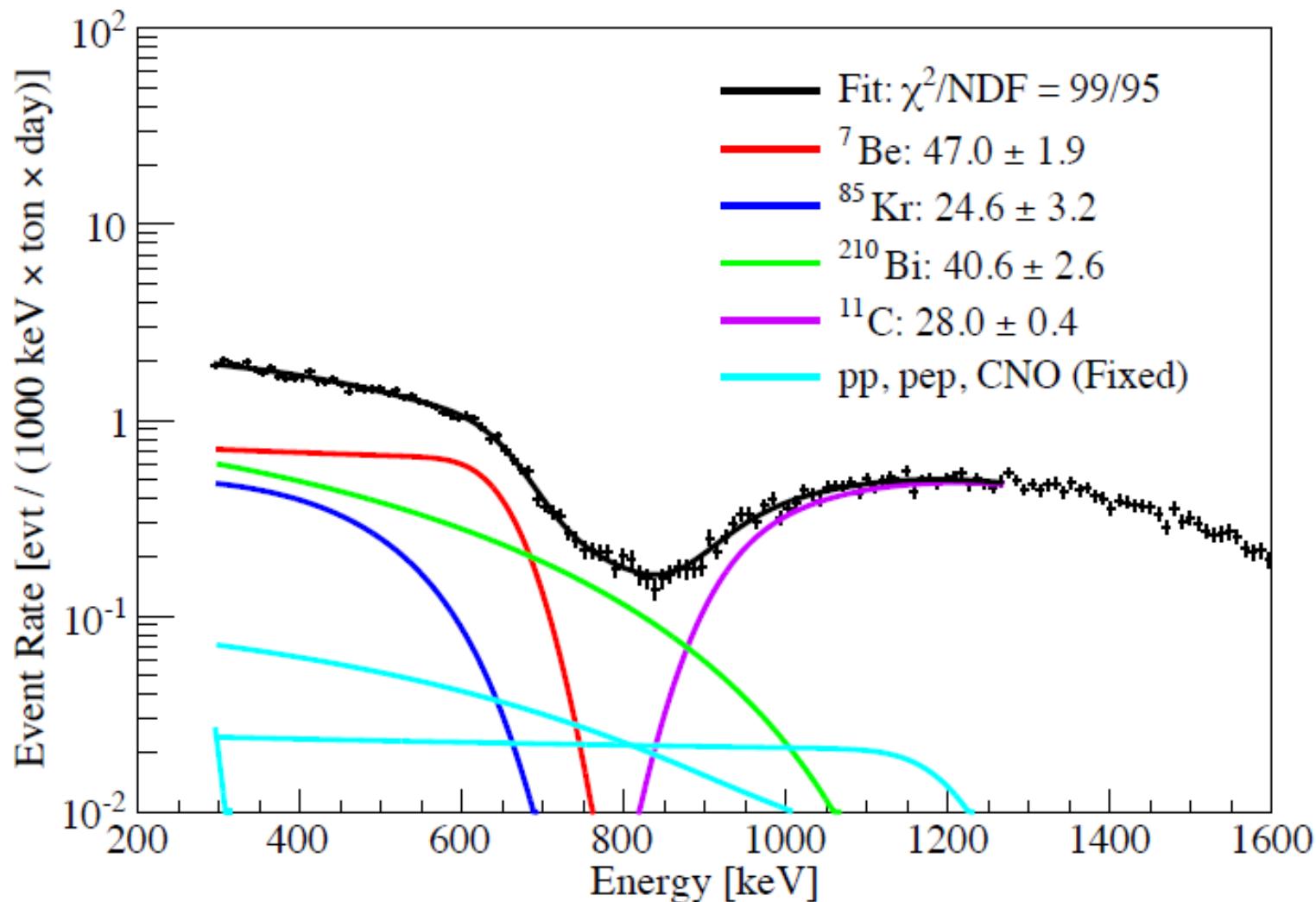
Neutrino rates from ^{40}K in 100 t PC

	neutrino	antineutrino	neutrino	antineutrino
Flux, $\text{cm}^{-2}, \text{s}^{-1}$	1.83×10^6	8.15×10^8	3.05×10^5	1.36×10^8
Rate, 1/day	0.7	4.5	0.02	1.5

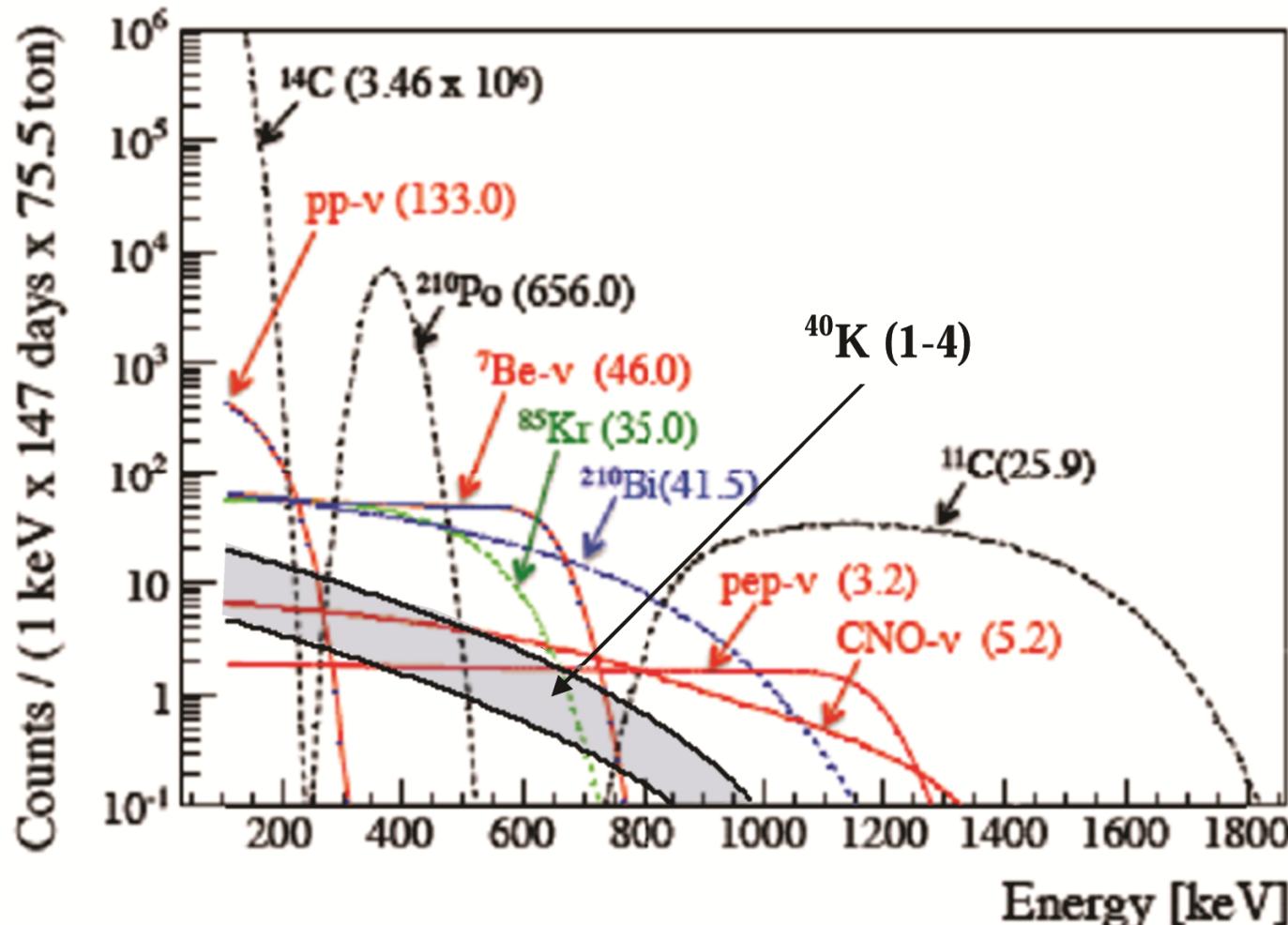
$$M(K) = 2.18 \times 10^{23} \text{ kg}$$

$$M(K) = 2.16 \times 10^{22} \text{ kg}$$

Borexino



Recoil electrons spectrum from ^{40}K in BOREXINO



Conclusions and outlook

- Mankind is stepped in the epoch of using neutrino fluxes for researches of the Earth.
- Modern data on the value of the Earth thermal flux are in contradiction between them. To solve this problem the neutrino detection method is suitable.
- Accurate measuring of Th/U ratio can help to make choice in existing hypotheses (BSE or HE). But to measure it accurately one needs no less than 25 kt·years of measuring with low background detector.

Conclusions and outlook (continue)

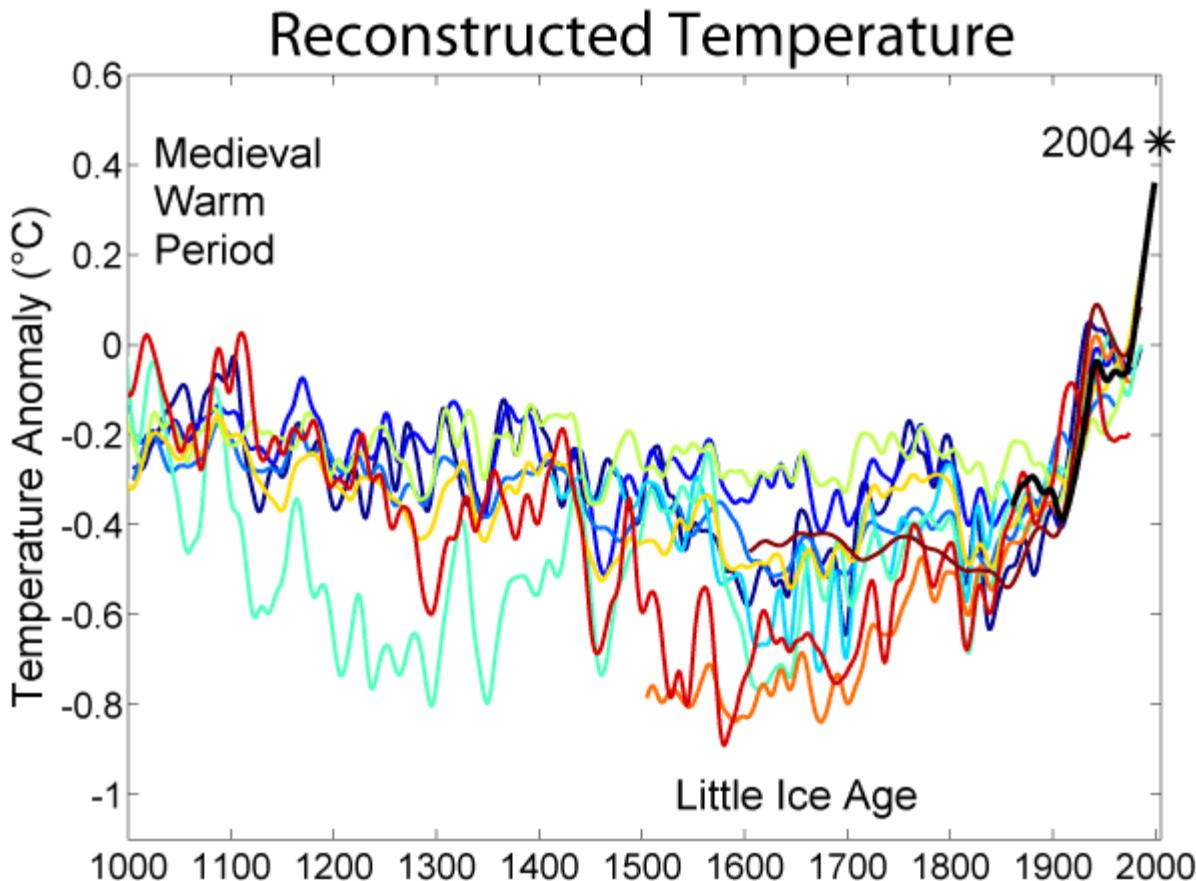
- To understand better the value of Earth thermal flux one needs to measure the potassium content in the Earth. This can be done by measuring ^{40}K neutrino flux using neutrino-electron elastic scattering reaction. Detecting of ^{40}K flux can be done with only low background detector and decreased content of ^{14}C .
- Earth thermal flux may be unstable in time and for understanding processes inside the Earth it might be important to monitor it with several methods including the neutrino one.
- Basing on the value of 25 kt years seems it might be preferable to construct a net of identical detectors placed at several sites of the world.

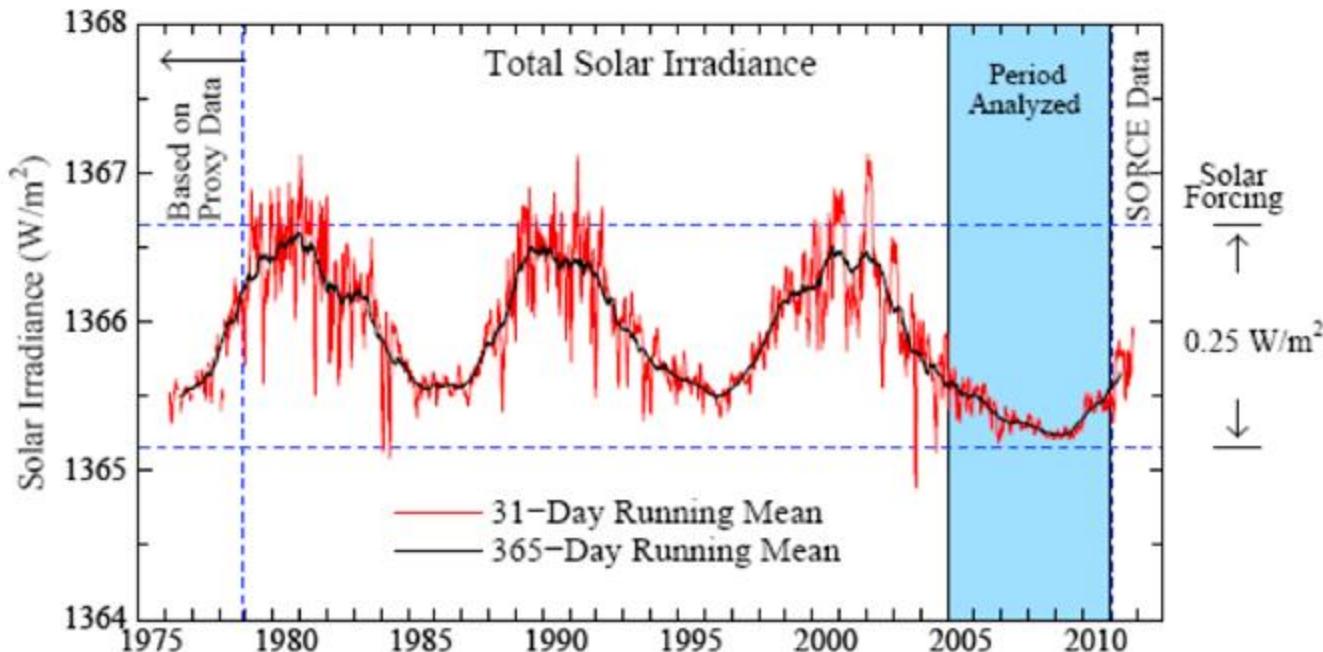
Thank you for attention!

Спасибо за внимание!

Slides besides

http://upload.wikimedia.org/wikipedia/commons/b/bb/1000_Year_Temperature_Comparison.png





- A graph of the sun's total solar irradiance shows that in recent years irradiance dipped to the lowest levels recorded during the satellite era. The resulting reduction in the amount of solar energy available to affect Earth's climate was about .25 watts per square meter, less than half of Earth's total energy imbalance.*

Geoneutrinos

Next step of geoneutrino research

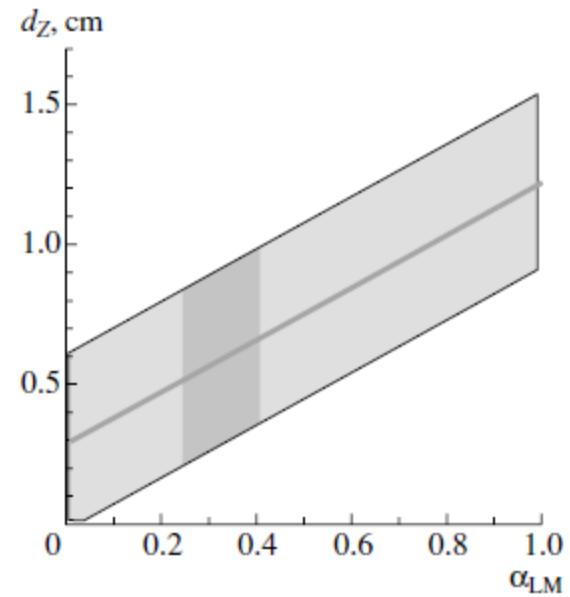
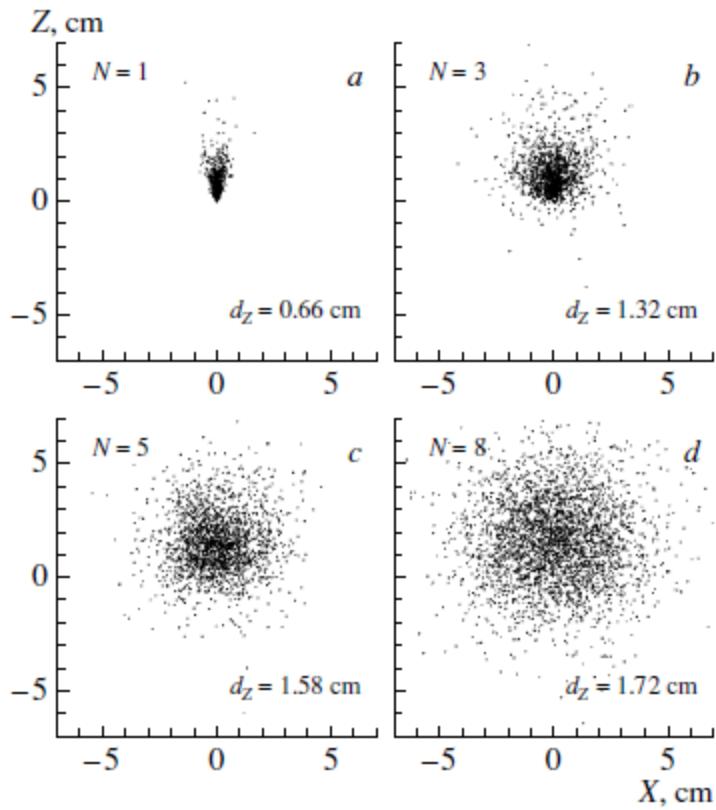
- ^{238}U , ^{235}U , ^{232}Th , ^{40}K decays in the Earth body are the source of geoneutrinos.
- $^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8\alpha + 6e + 6\tilde{\nu}_e + 51,7 \text{ MeV}$
- $^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6\alpha + 4e + 4\tilde{\nu}_e + 42,8 \text{ MeV}$
- $^{40}\text{K} \rightarrow ^{40}\text{Ca} + e + \tilde{\nu}_e + 1.31 \text{ MeV}$

Some characteristics of LAB and PC

	LAB	PC
1000 t	$C_6H_5-C_nH_{2n+1}$ or $C_{18}H_{30}$	$C_6H_3-(CH_3)_3$ or C_9H_{12}
H	7.465×10^{31}	6.012×10^{31}
C	4.479×10^{31}	4.510×10^{31}
electrons	3.434×10^{32}	3.307×10^{32}

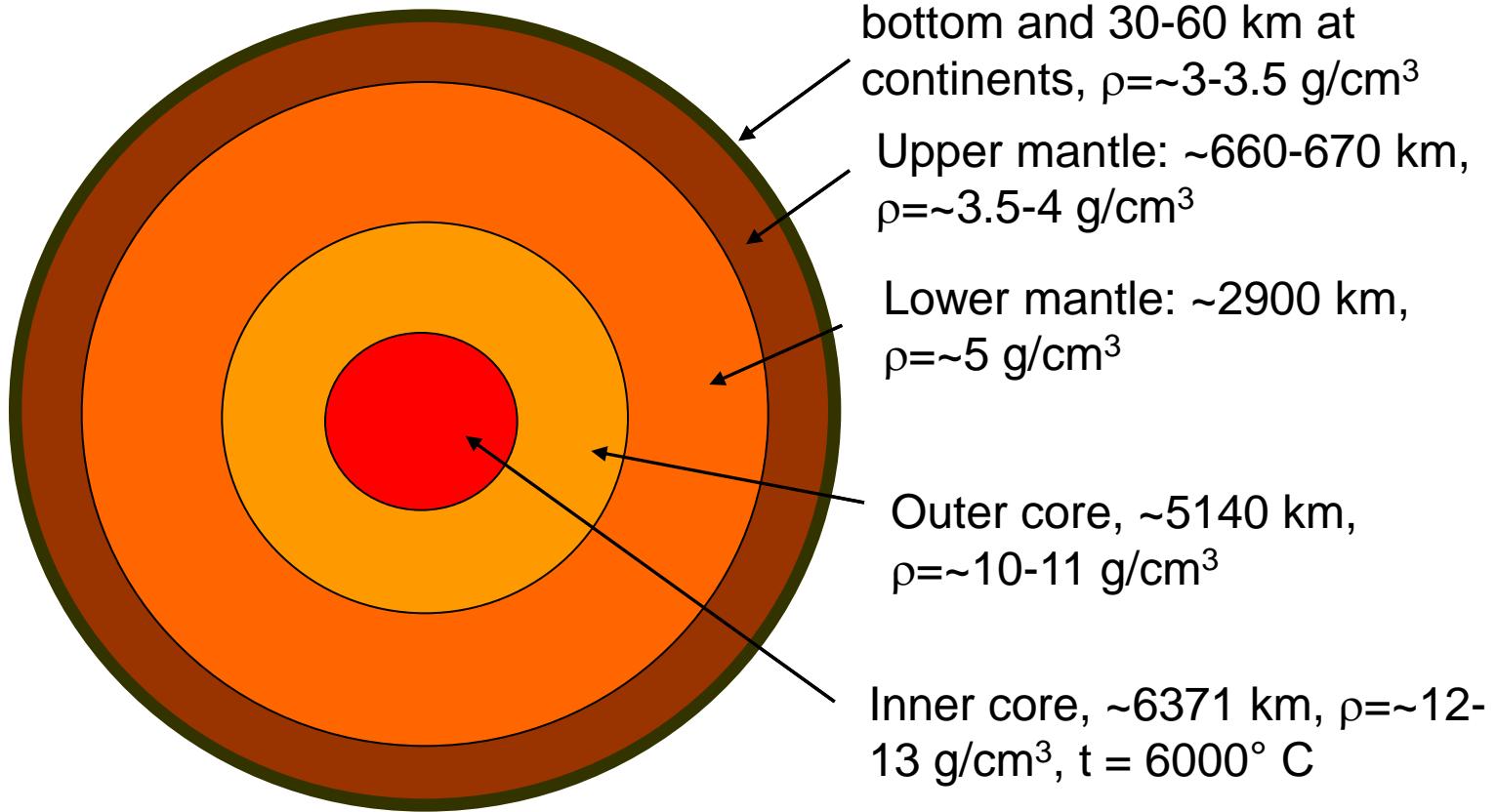
$$n = 10-14, n = 12$$

Направление на источник нейтрино в реакции обратного бета распада



$$\langle \mathbf{R}_{enX} \rangle = \langle \mathbf{R}_{enY} \rangle = 0 \pm \sigma_X / \sqrt{N},$$
$$d_{LM} = \langle \mathbf{R}_{enZ} \rangle = 1.2 \text{ cm} \pm \sigma_Z / \sqrt{N}.$$

Earth model



At site <http://igppweb.ucsd.edu/~gabi/> data for $2^\circ \times 2^\circ$ were available. (Now $1^\circ \times 1^\circ$)

Radioactive isotopes producing geoneutrino flux

	$T_{1/2}$, years	$M, 10^{17}$ kg	$W_{th},$ $W \text{ kg}$	$H, TW/10^{17}$ kg	Ht, TW
^{238}U	4.468×10^9	0.8	0.95×10^{-4}	9.52	7.62
^{232}Th	1.405×10^{10}	3.2	0.26×10^{-4}	2.67	8.54
^{40}K	1.277×10^9	1.1	0.24×10^{-4}	2.85	3.14
^{235}U	7.038×10^8	0.0056	5.63×10^{-4}	55.53	0.31
^{87}Rb	4.75×10^{10}	-	-	-	
Total					19.6

From Gianni Fiorentini, Marcello Lissia and Fabio Mantovani, “Geo-neutrinos and Earth’s interior”, ArXiv: 0707.3203 [physics.geo-ph]

From Gianni Fiorentini, Marcello Lissia and Fabio Mantovani, “Geo-neutrinos and Earth’s interior”, ArXiv: 0707.3203 [physics.geo-ph]

TABLE VII The composition of the silicate Earth. Abundances are given in $\mu\text{g} \cdot \text{g}^{-1}$ (ppm), unless stated as “%” which are given in weight percentage. Data from (McDonough, 2003).

H	100	Zn	55	Pr	0.25
Li	1.6	Ga	4	Nd	1.25
Be	0.07	Ge	1.1	Sm	0.41
B	0.3	As	0.05	Eu	0.15
C	120	Se	0.075	Gd	0.54
N	2	Br	0.05	Th	0.1
O (%)	44	Rb	0.6	Dy	0.67
F	15	Sr	20	Ho	0.15
Na (%)	0.27	Y	4.3	Er	0.44
Mg (%)	22.8	Zr	10.5	Tm	0.068
Al (%)	2.35	Nb	0.66	Yb	0.44
Si (%)	21	Mo	0.05	Lu	0.068
P	90	Ru	0.005	Hf	0.28
S	250	Rh	0.001	Ta	0.037
Cl	17	Pd	0.004	W	0.029
K	240	Ag	0.008	Re	0.0003
Ca (%)	2.53	Cd	0.04	Os	0.003
Sc	16	In	0.01	Ir	0.003
Ti	1200	Sn	0.13	Pt	0.007
V	82	Sb	0.006	Au	0.001
Cr	2625	Te	0.012	Hg	0.01
Mn	1045	I	0.01	Tl	0.004
Fe (%)	6.26	Cs	0.021	Pb	0.15
Co	105	Ba	6.6	Bi	0.003
Ni	1960	La	0.65	Th	0.08
Cu	30	Ce	1.68	U	0.02

Hydridic Earth

Гидридная Земля

Hydrid Earth model can explain the hydrogen degasation of the Earth.

The Earth hydrogen degasation – the hydrogen starts from surface of the Earth core and goes to the cosmos space through the long chain of processes.

1. Ларин В.Н. Гипотеза изначально гидридной Земли (новая глобальная концепция). М., «Недра», 1975, 101 с., (АН СССР. Министерство геологии СССР. ИМГРЭ).
2. Ларин В.Н. Гипотеза изначально гидридной Земли. 2-е изд., перераб. и доп.. - М., Недра. 1980, 216 с
3. Ларин В.Н. Наша Земля (происхождение, состав, строение и развитие изначально гидридной Земли). М. «Агар» 2005, 248 с.
4. Larin,V. N., ed. C. Warren Hunt. Hydridic Earth: the New Geology of Our Primordially Hydrogen-Rich Planet. Polar Publishing, Calgary, Alberta, Canada, 1993.

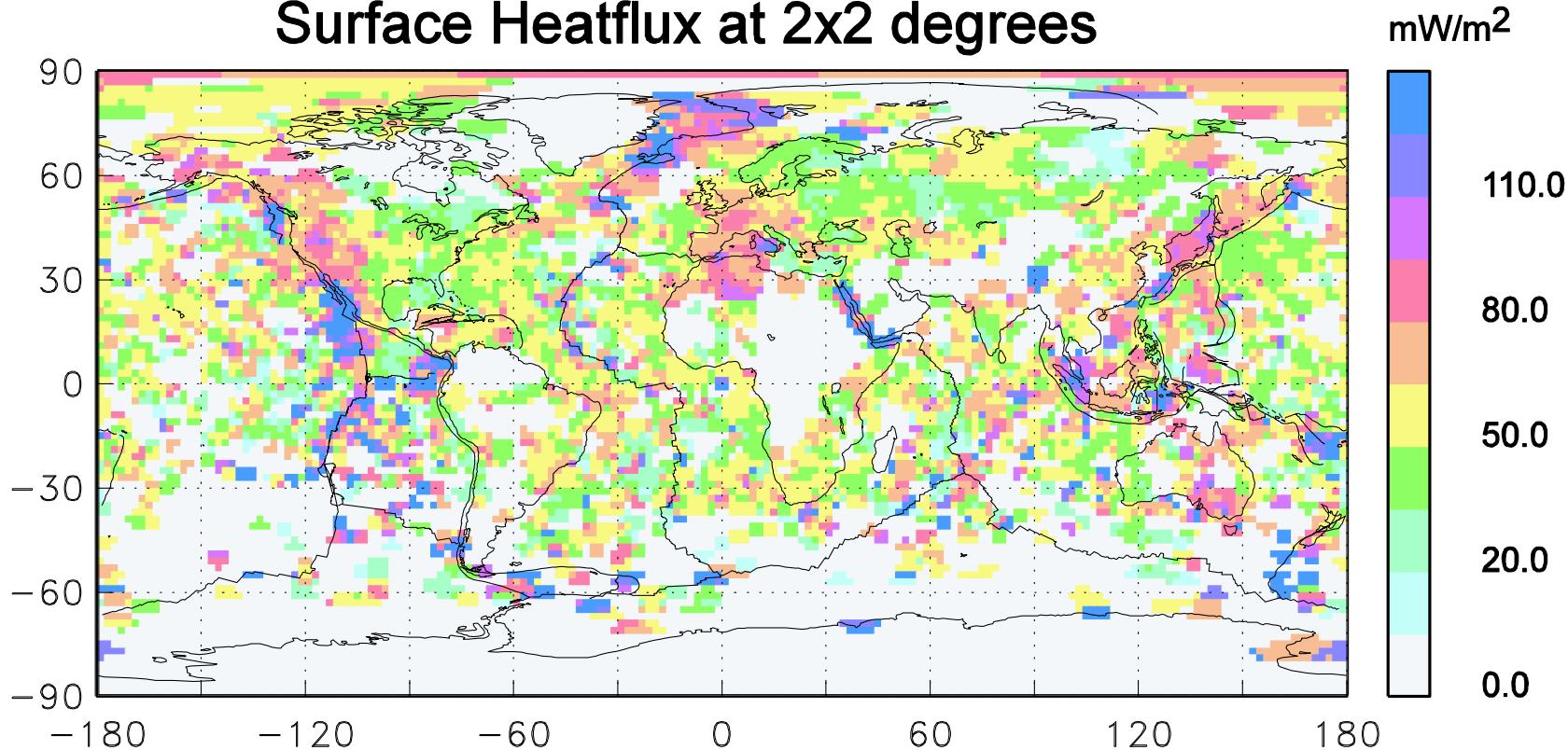
Arxiv: 0707.3203 [physics.geo-ph]

TABLE X Sources of thermal energy in the Earth's interior, adapted from (Anderson, 2005).

Energy supply (potential contributions)	TW
Non radiogenic:	
Conducted from core	8.6
Mantle differentiation	0.6
Thermal contraction	2.1
Earthquake induced gravitational energy	2
Radiated seismic energy	0.3
Tidal friction	1 \div 2
Total (non radiogenic)	15 \div 16
Radiogenic:	
Present radiogenic	19 \div 31
Delayed radiogenic (1 to 2 Ga delay between production and arrival at surface)	5
Total (radiogenic)	24 \div 36
Secular cooling (0 \div 100 K/Ga)	0 \div 14
Total input	39 \div 66

Earth thermal flux

Surface Heatflux at 2x2 degrees



Total flux is ~47 TW

What are heat sources in inner parts of the Earth producing such a flux

Первые публикации по использованию нейтрино для исследования внутренних слоев Земли появились еще в 60х годах XX столетия в работах Marx and Eder.

В 80х годах появилась работа Krauss, Glashow and Shramm, в которой обсуждались возможности регистрации геонейтрино и нейтрино от сверхновых.

С начала 2000х уже активно велись расчеты по регистрации геонейтрино и проектировались детекторы.

Наконец, в 2005 появилось первое сообщение коллаборации KamLAND о регистрации первых геонейтрино. Затем и коллаборация Borexino объявила о наблюдении событий от геонейтрино.

Тогда же стало понятно, что основным конкурирующим потоком является поток антинейтрино от ядерных реакторов.

Недавно появились предложения исследовать внутренние области Земли при помощи атмосферных нейтрино.

Moon in infrared rays

