Neutrinos from the Sun: the BOREXINO experiment at LNGS

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Outline…

1. Sun, our closest star: how does it shine?

2. What are neutrinos?

3. Solar neutrinos;

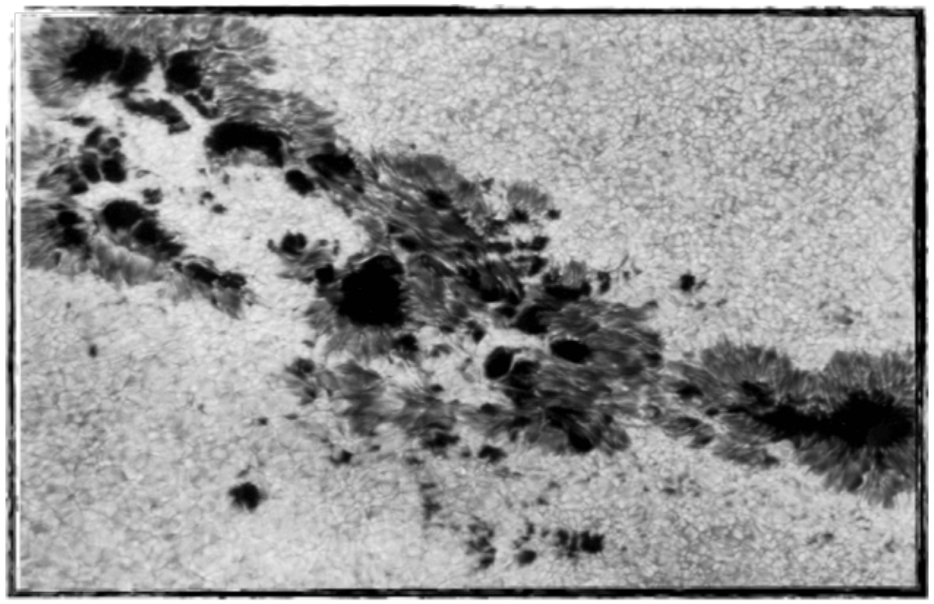
4. Solar neutrino experiments;

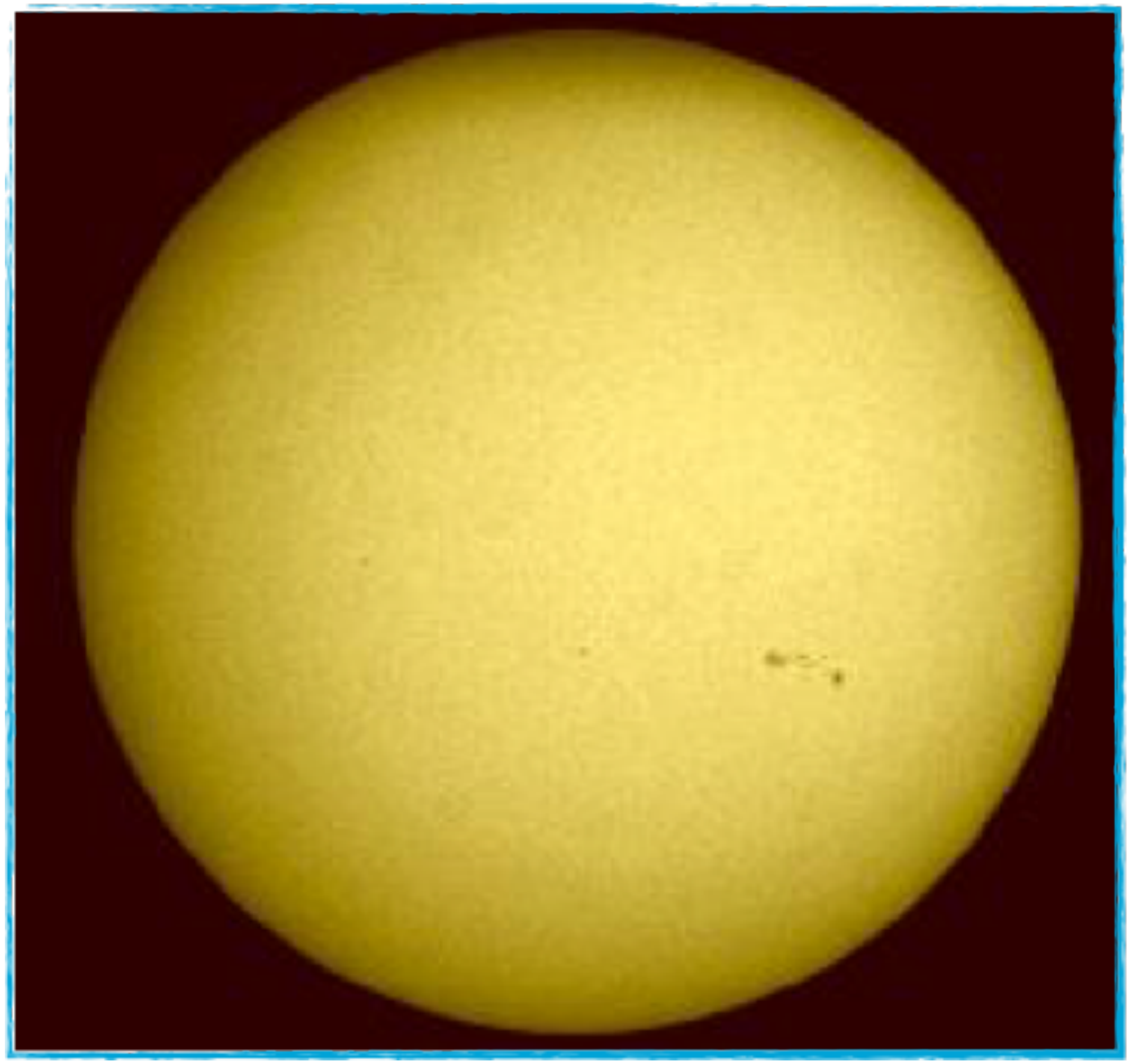
5. Borexino solar neutrino results;

THE SUN
Our closest star!

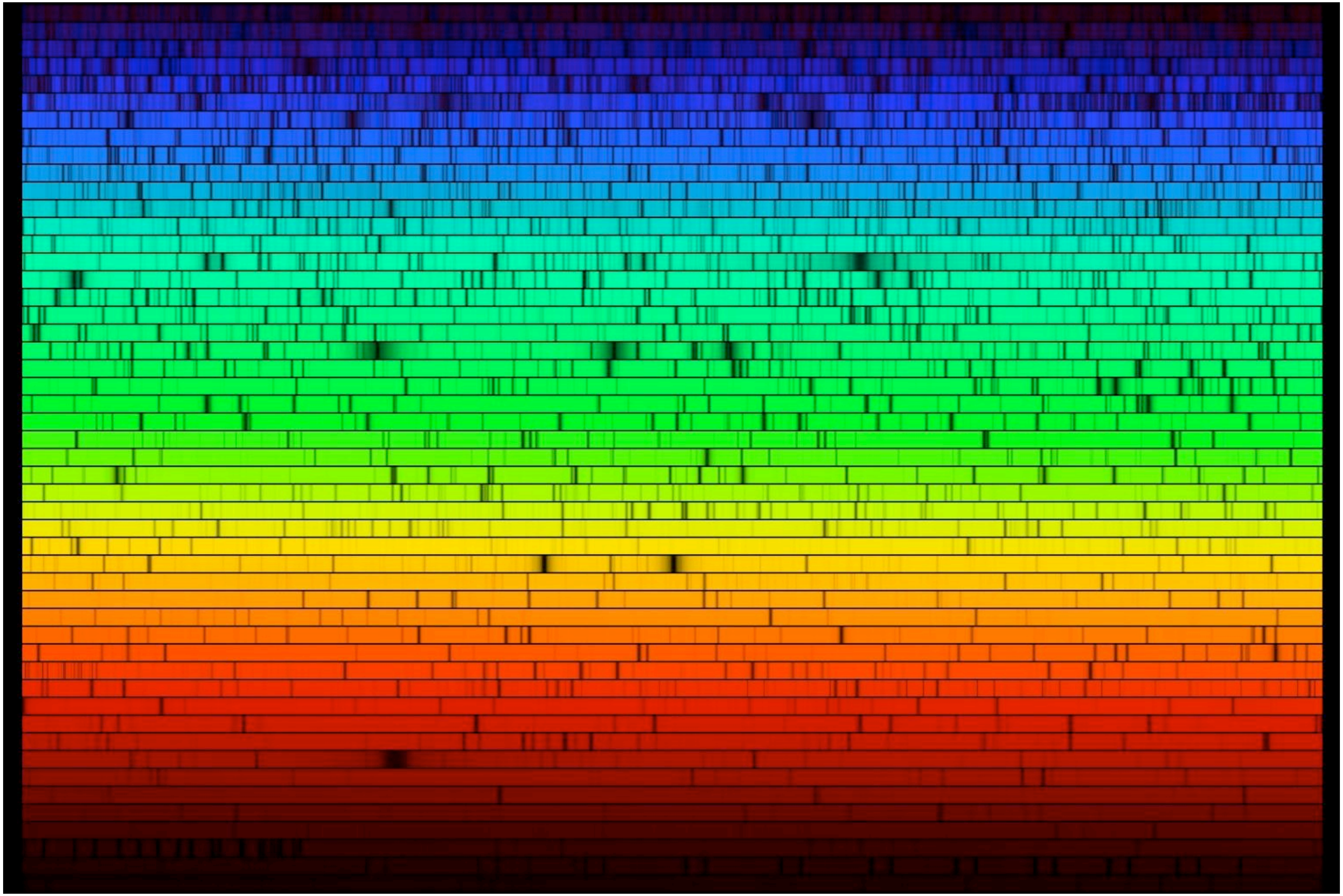
Visible light

- Sun seen with telescope
- Appears to be simple
- Sunspots (Galileo, 1613)

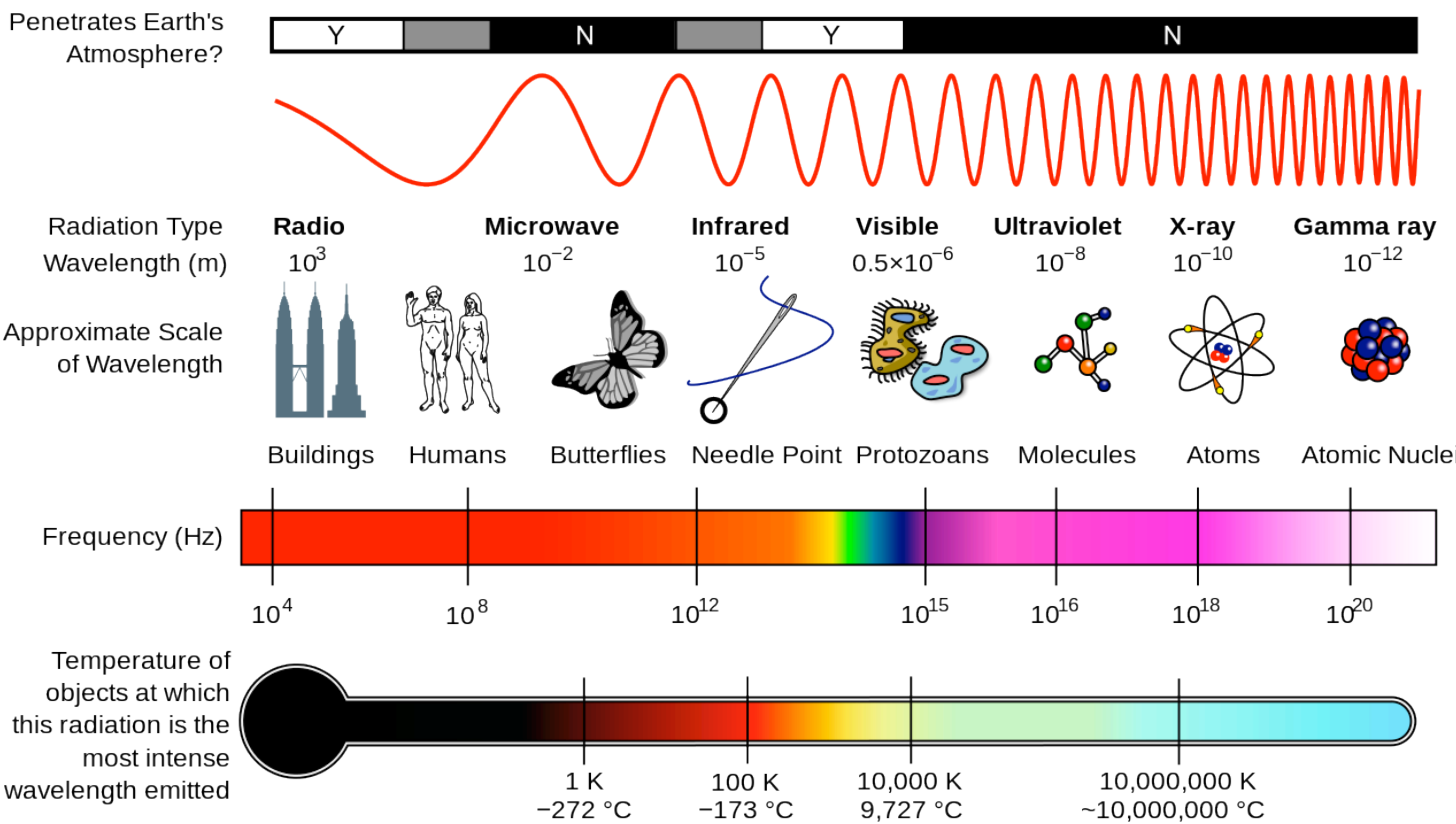




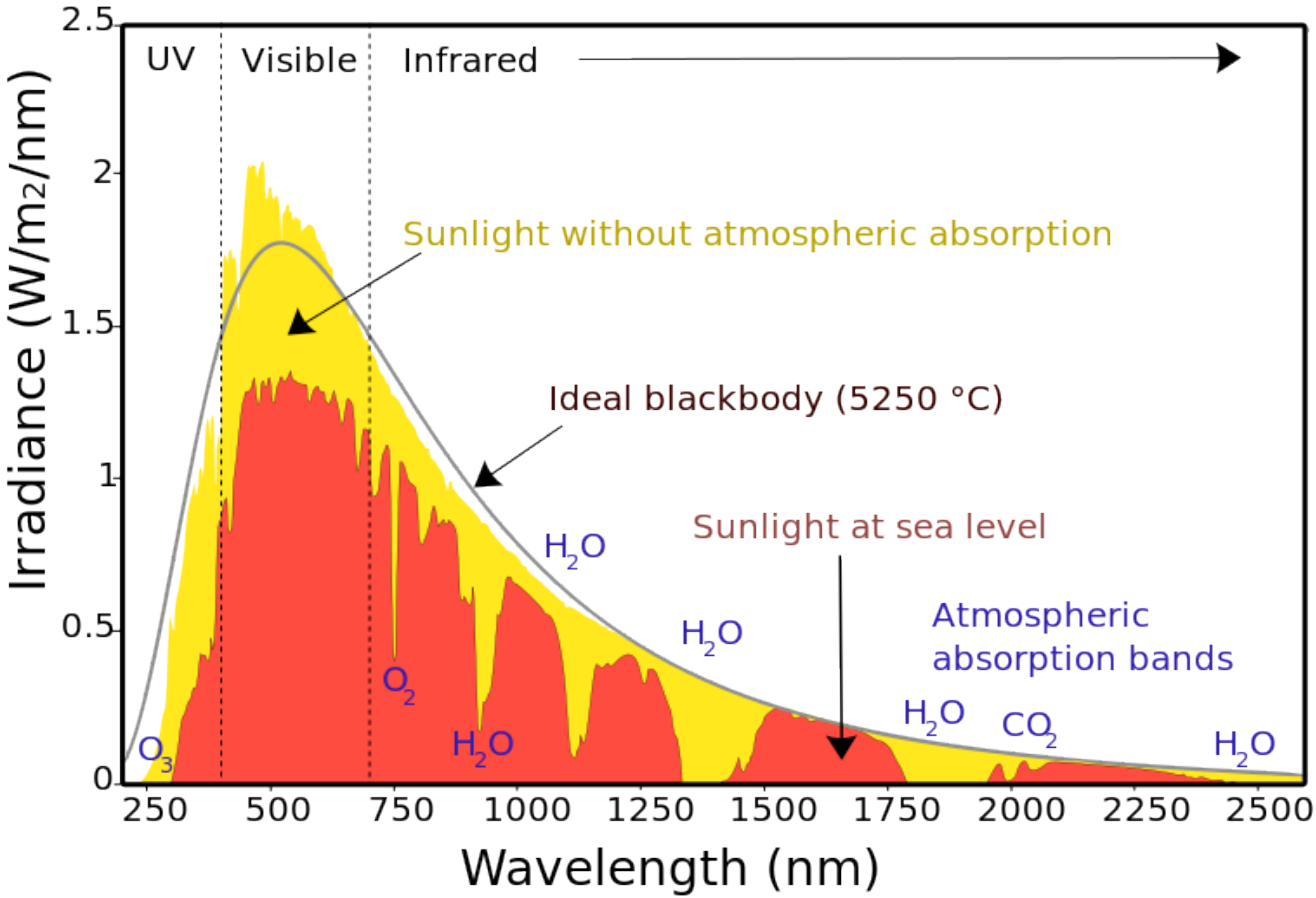
Fraunhofer solar spectrum



Electromagnetic spectrum

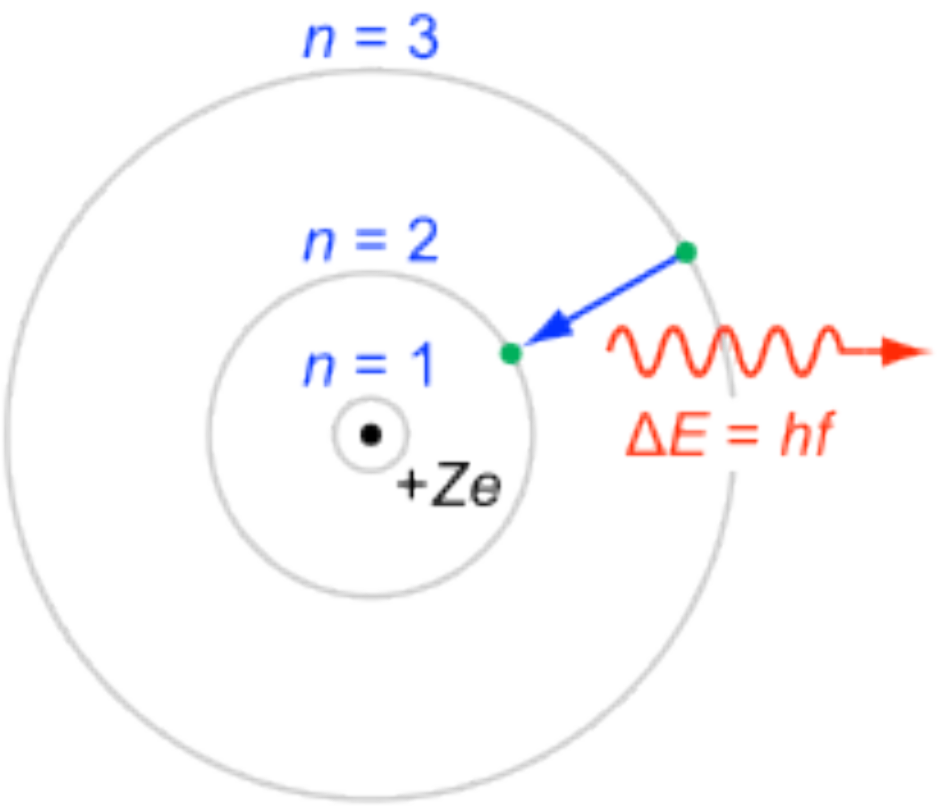


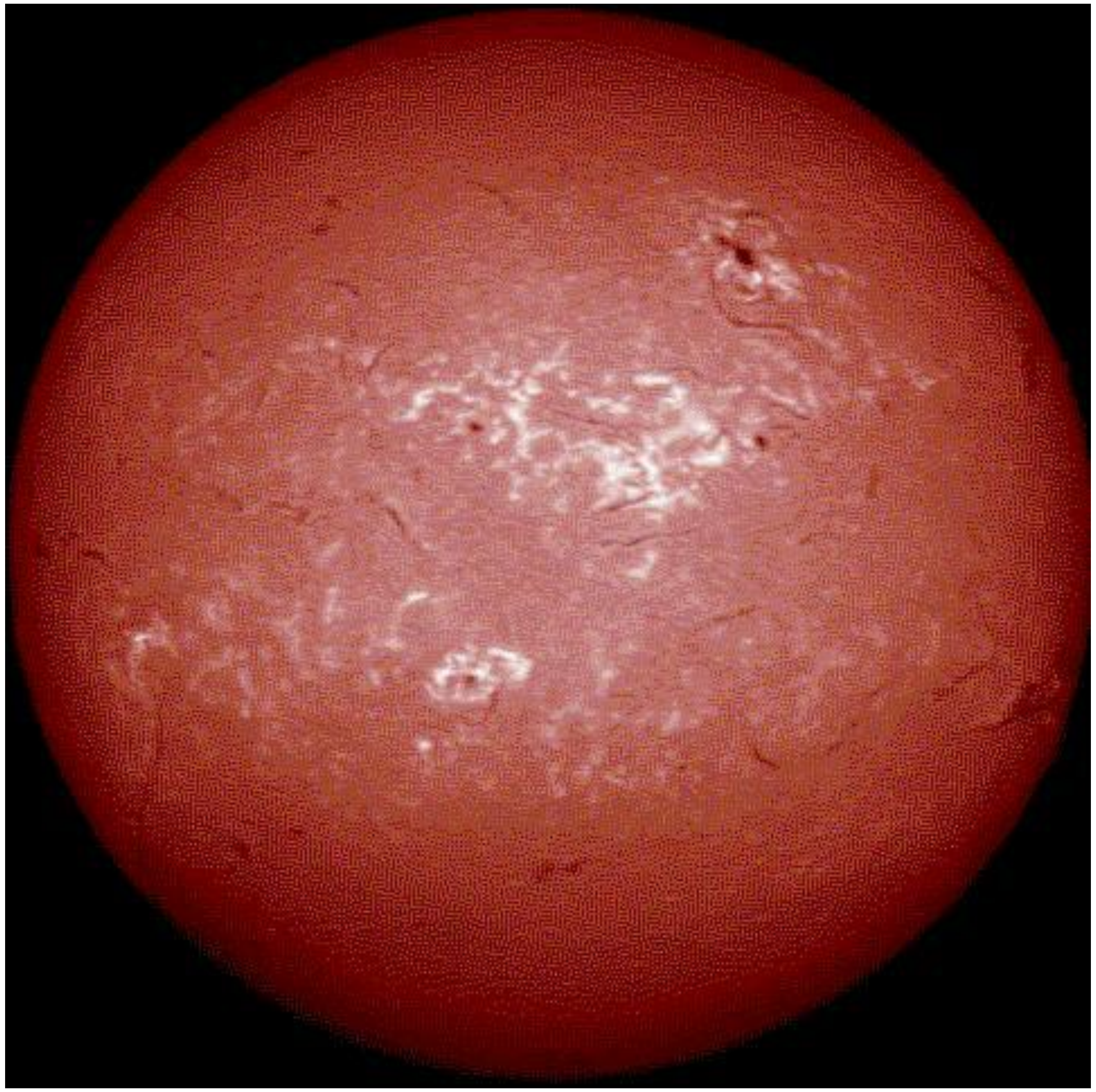
Spectrum of Solar Radiation (Earth)



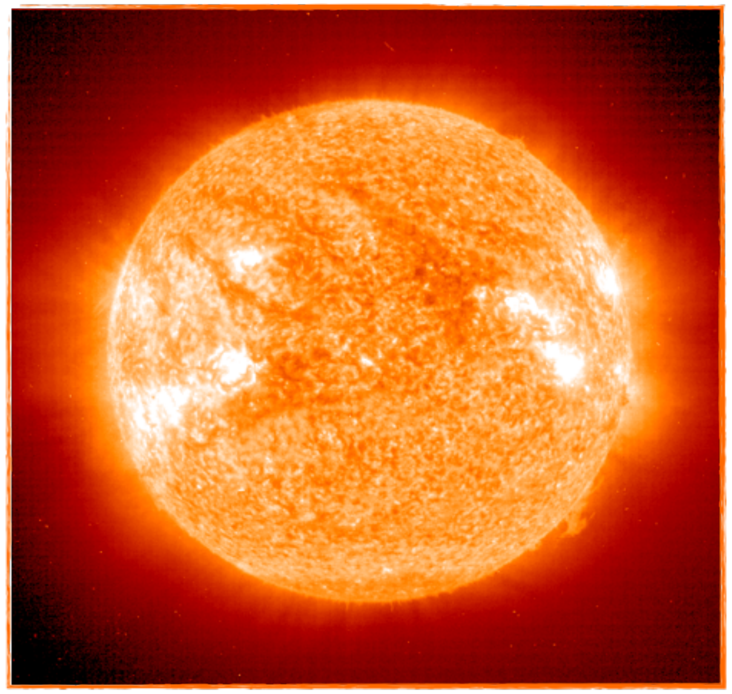
The Sun seen in different wavelengths

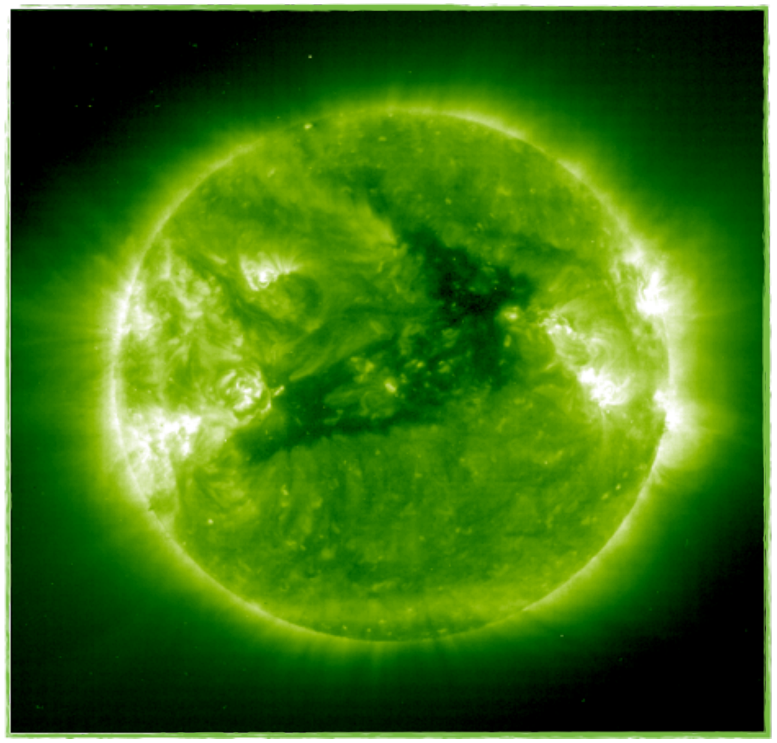
Photosphere seen in Hα line
Balmer series (656.28 nm)

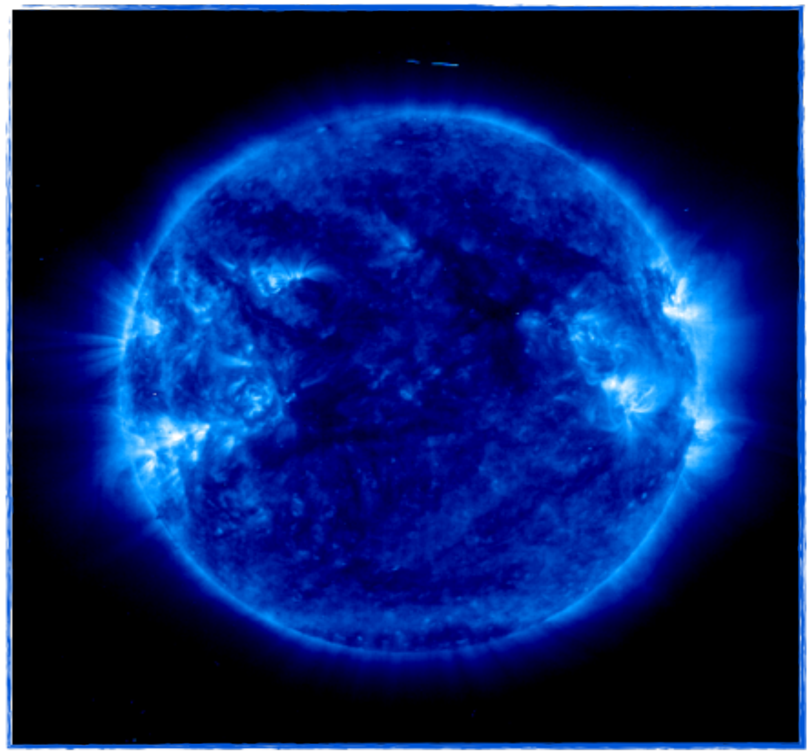


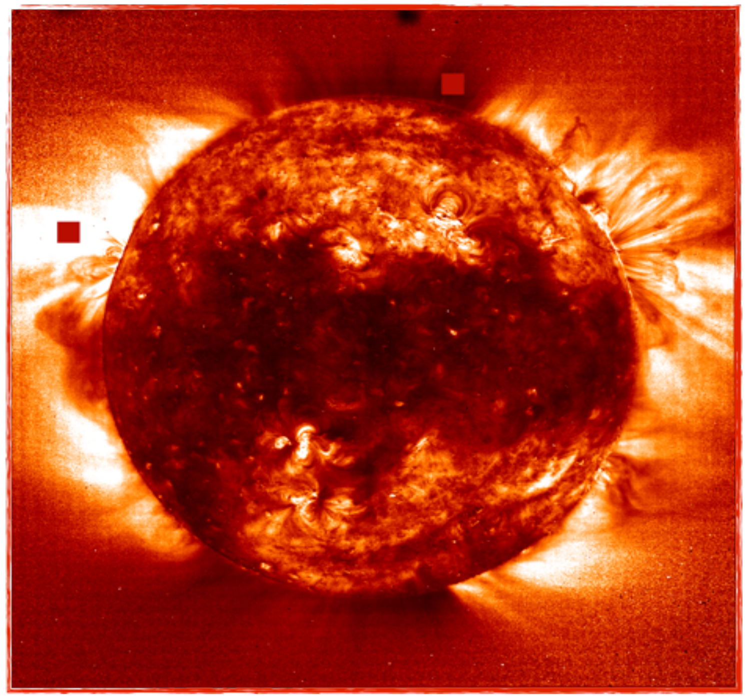


The Sun seen in different wavelengths









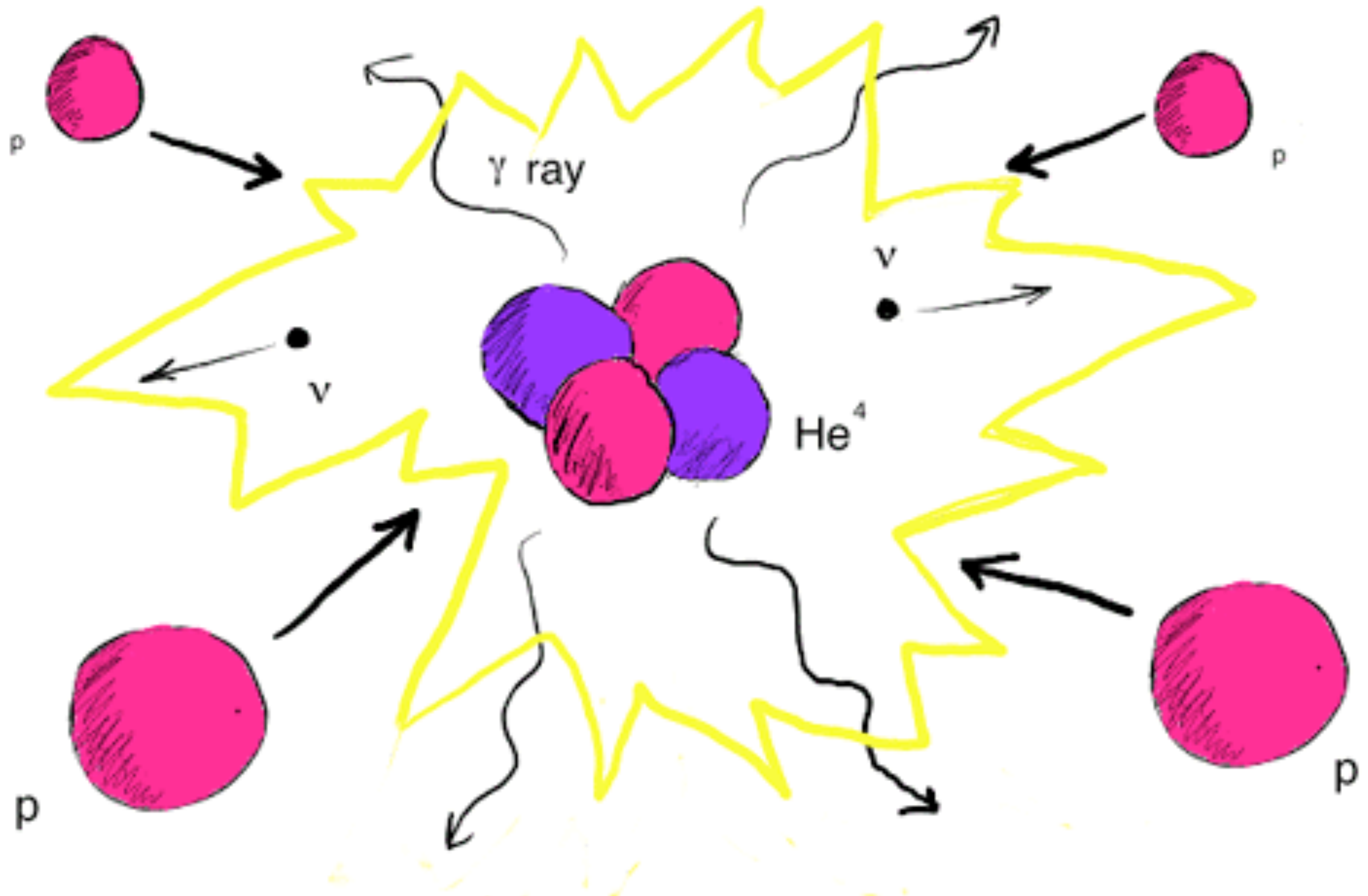
Solar energy in numbers..

- **Sun emits : ~ 3 10^{26} W**
  - 300.000.000.000.000.000.000.000.000 W
- **At the Earth surface (150 milion km from the Sun):**
  - ~1000W / m^2 = power of a microwave
  - 1 milion W (1 GigaW) / km^2 = power of a nuclear power plant
  - Integrated 140 milions GW
  - **From where is coming this enormous energy?**

Neither chemical
nor gravitational
interactions can do that

ONLY NUCLEAR REACTIONS CAN !

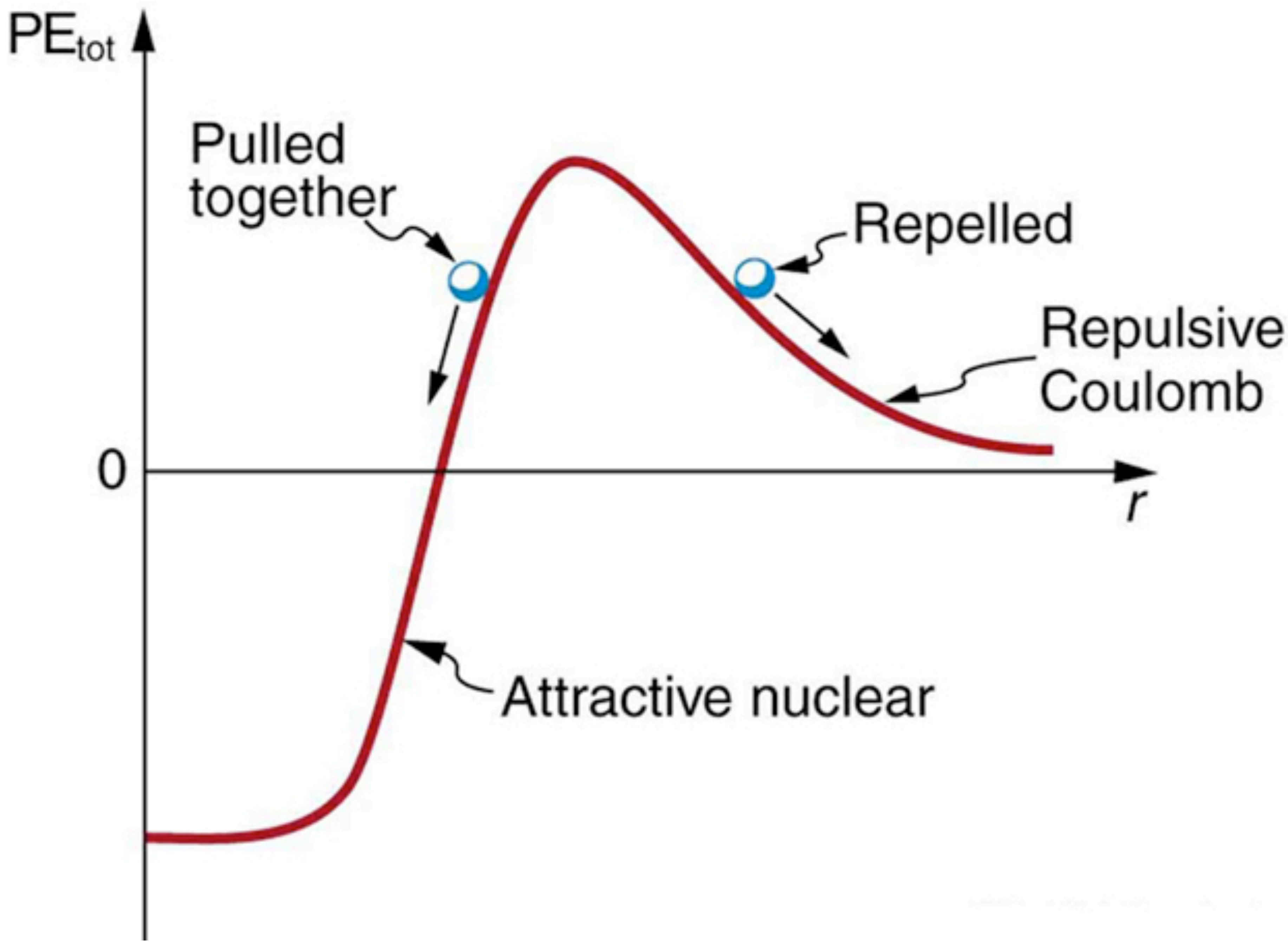
From where does come this energy?



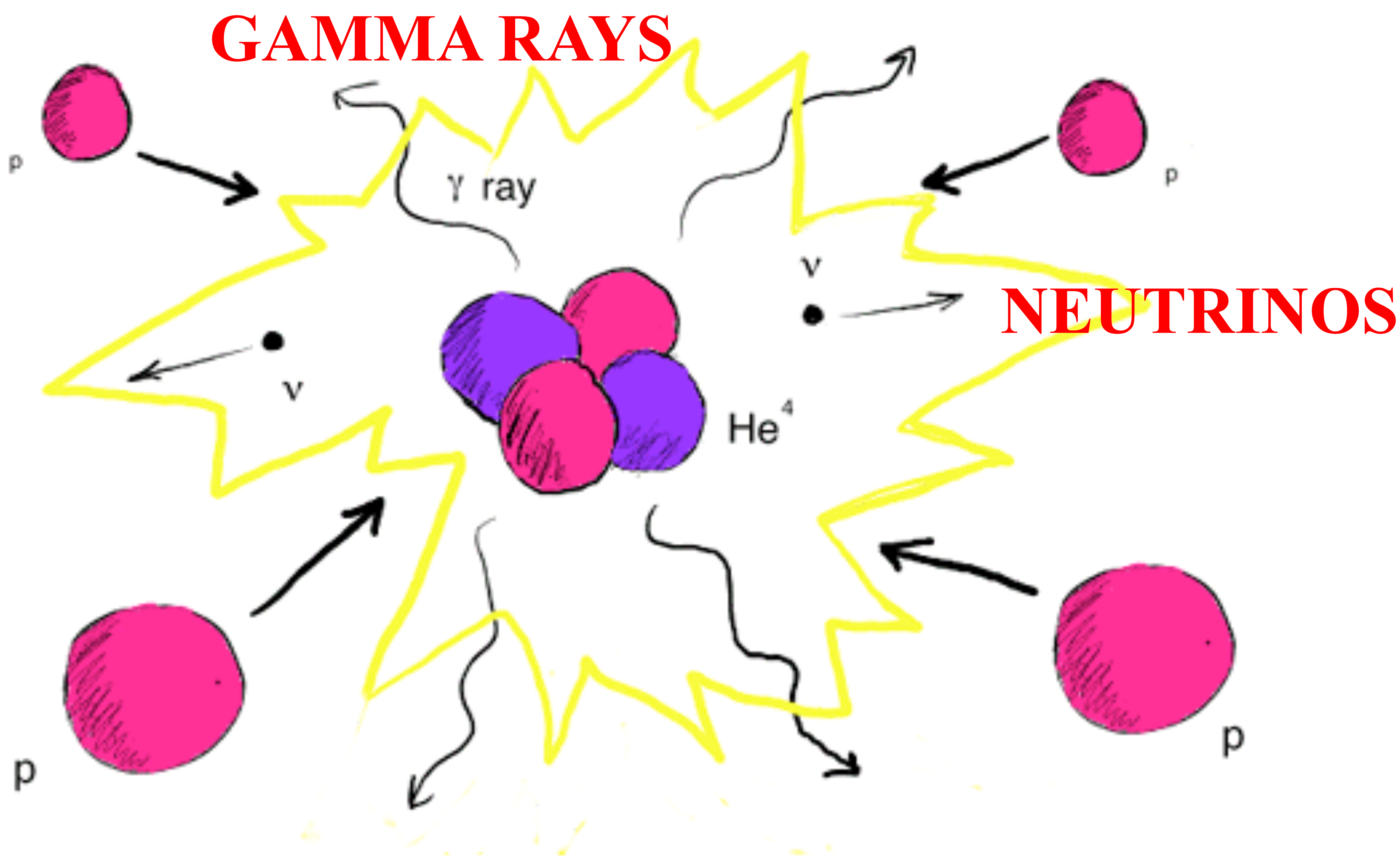
Nuclear fusion reaction!

Binding energy is released!

Quantum mechanical tunneling and need of high temperatures



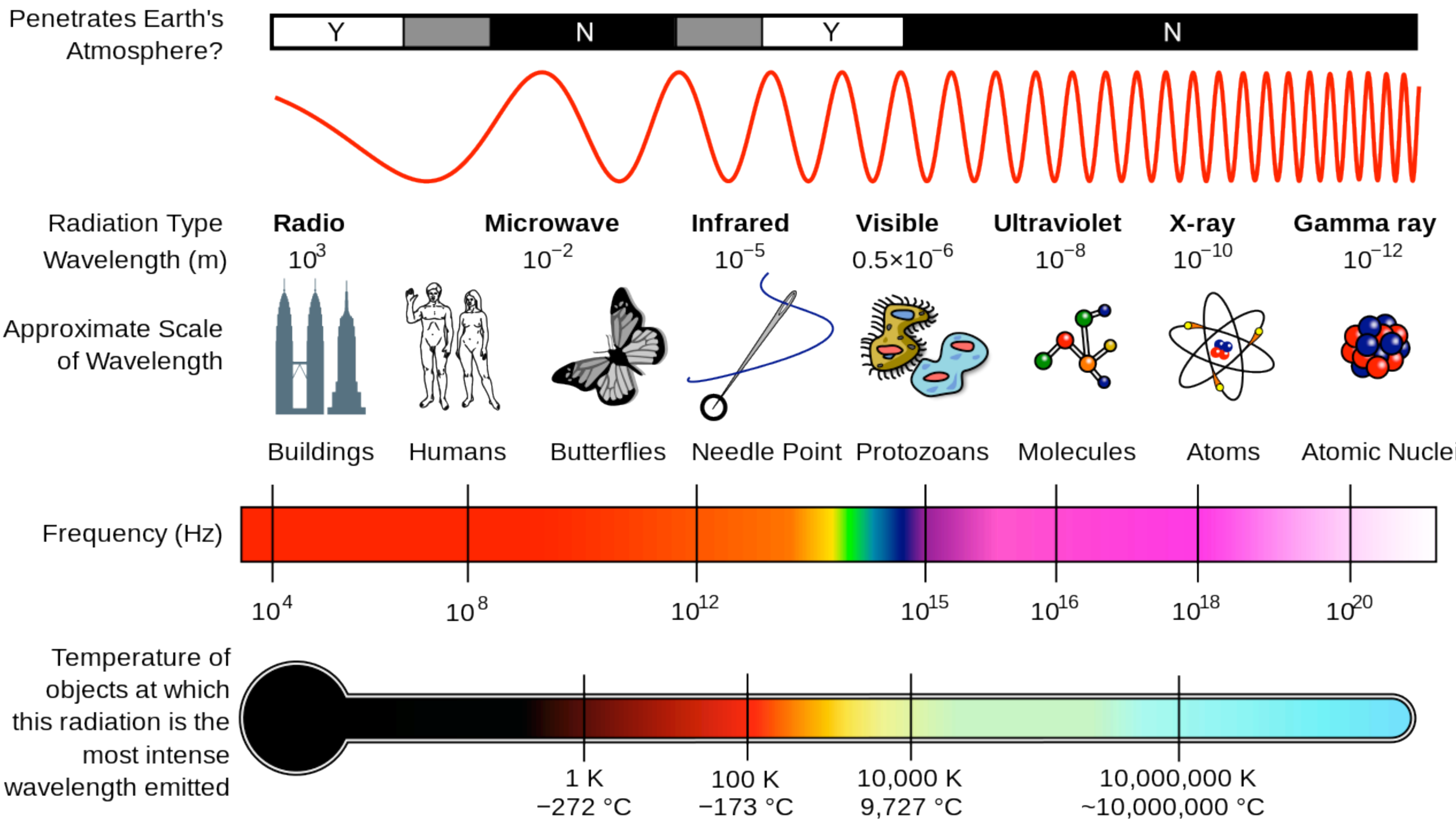
From where does come this energy?



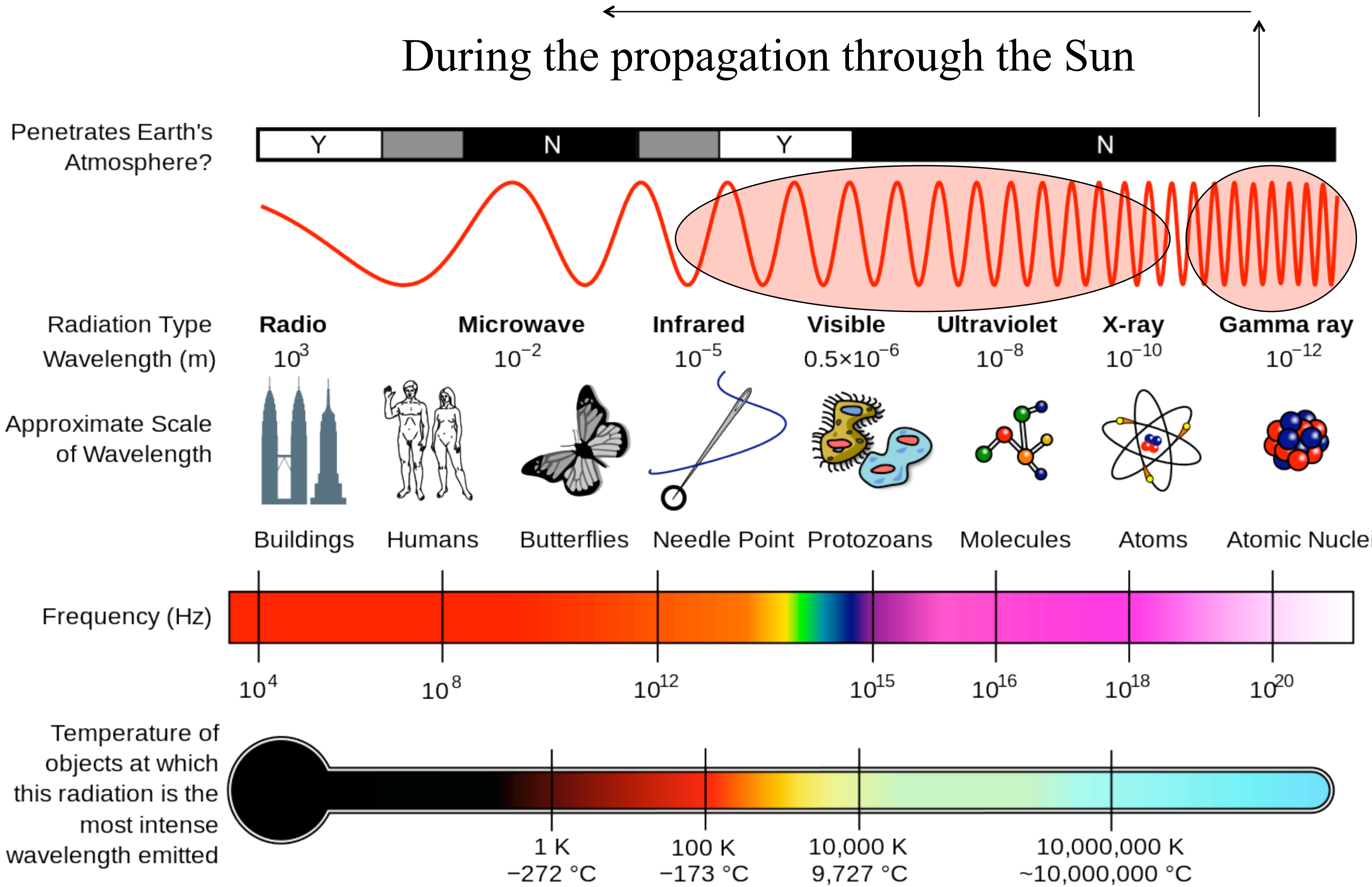
Nuclear fusion reaction!

Binding energy is released!

Gamma rays -> Visible light!

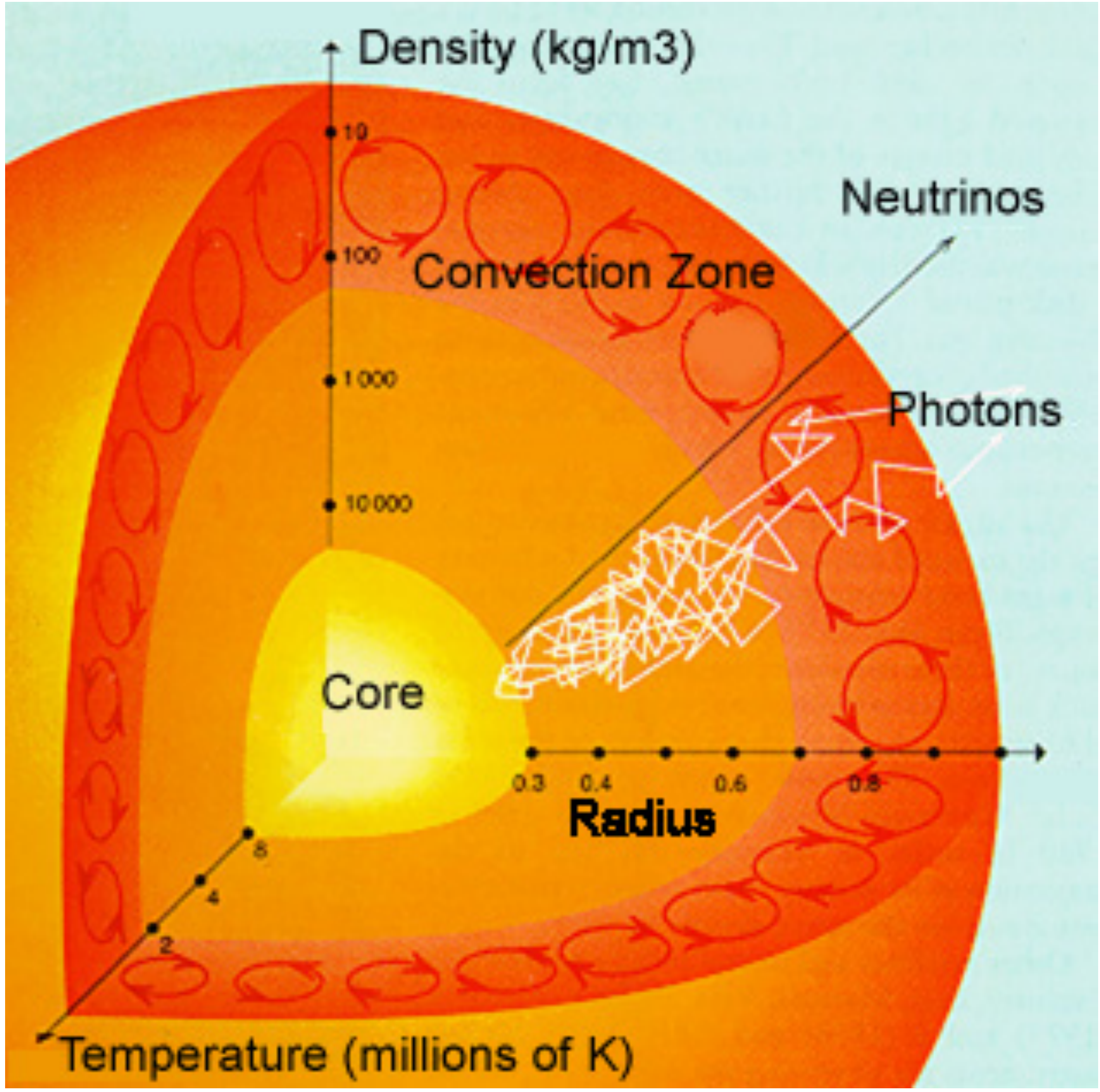


During the propagation through the Sun



Solar structure

- **Core:**
  - ✓ small, hot, dense;
  - ✓ energy is produced here;
- **Radiative zone:**
  - ✓ photons transport energy;
- **Convective zone:**
  - ✓ boiling pot: granulation;
  - ✓ mass transports energy;
- **Photosphere:**
  - ✓ thin film seen by light!
- **Chromosphere:**
  - ✓ less luminose
- **Corona:**
  - ✓ Seen during the solar eclipse!
  - ✓ source of solar wind



Fundamental question:
how can we prove that all this is true?

ANSWER

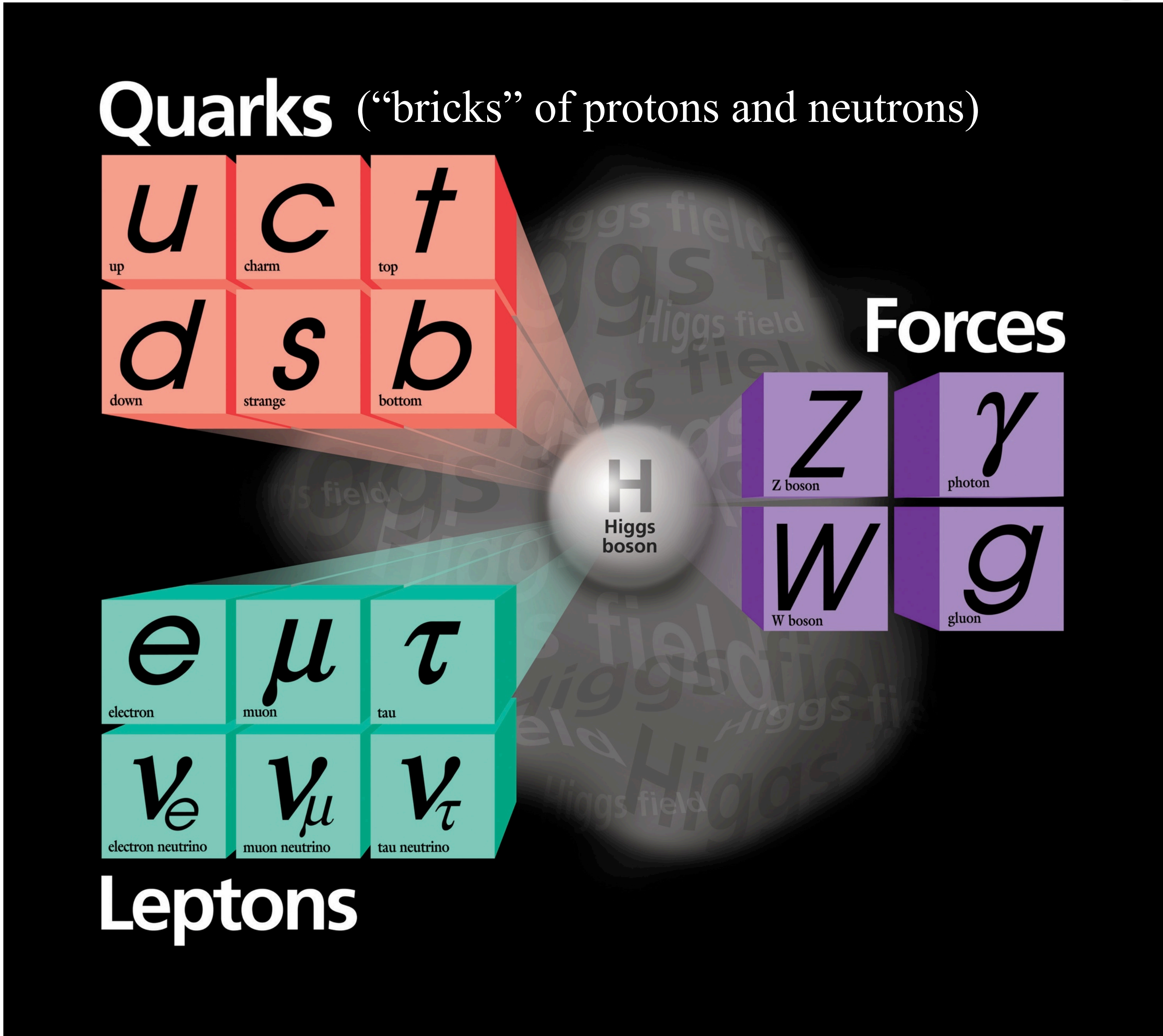
=

NEUTRINOS

How to detect nuclear fusion?

- Nuclear fusion reactions do occur in the Sun's core, at enormous pressures and temperatures !
- Only **neutrinos can escape** undisturbed from there and reach the Earth in **few minutes**!
- **Photons** take something like 100 000 years to escape from the Sun and they undergo many interactions inside the Sun;
- **Only with neutrinos we can "SEE" the nuclear reactions powering the Sun**, in a smilar way as we can see our bones using X-rays (this is because X-rays are not absorbed by the soft tissues, but visible photons are absorbed)

Standard Model (SM) of elementary particles



Describes:

Electromagnetic
Weak
Strong
Interactions!

Neutrino basics….

Elementary particles of the SM

- No electric charge
  = no elmag interactions;
- No color
  = no strong interactions;
- Only weak interactions
  = very small cross sections;

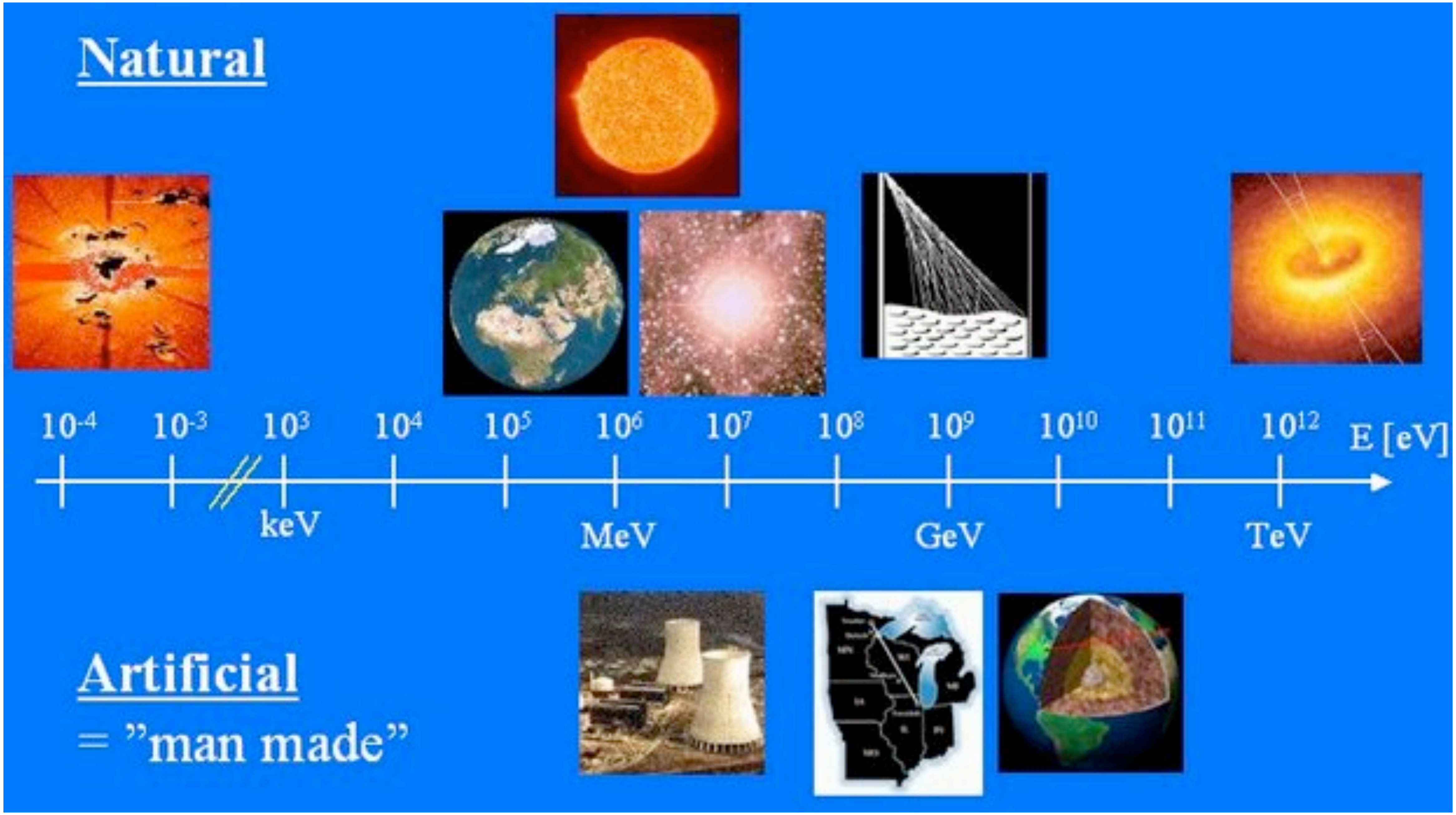
particles - **antiparticles**

lepton number +1 | lepton number -1

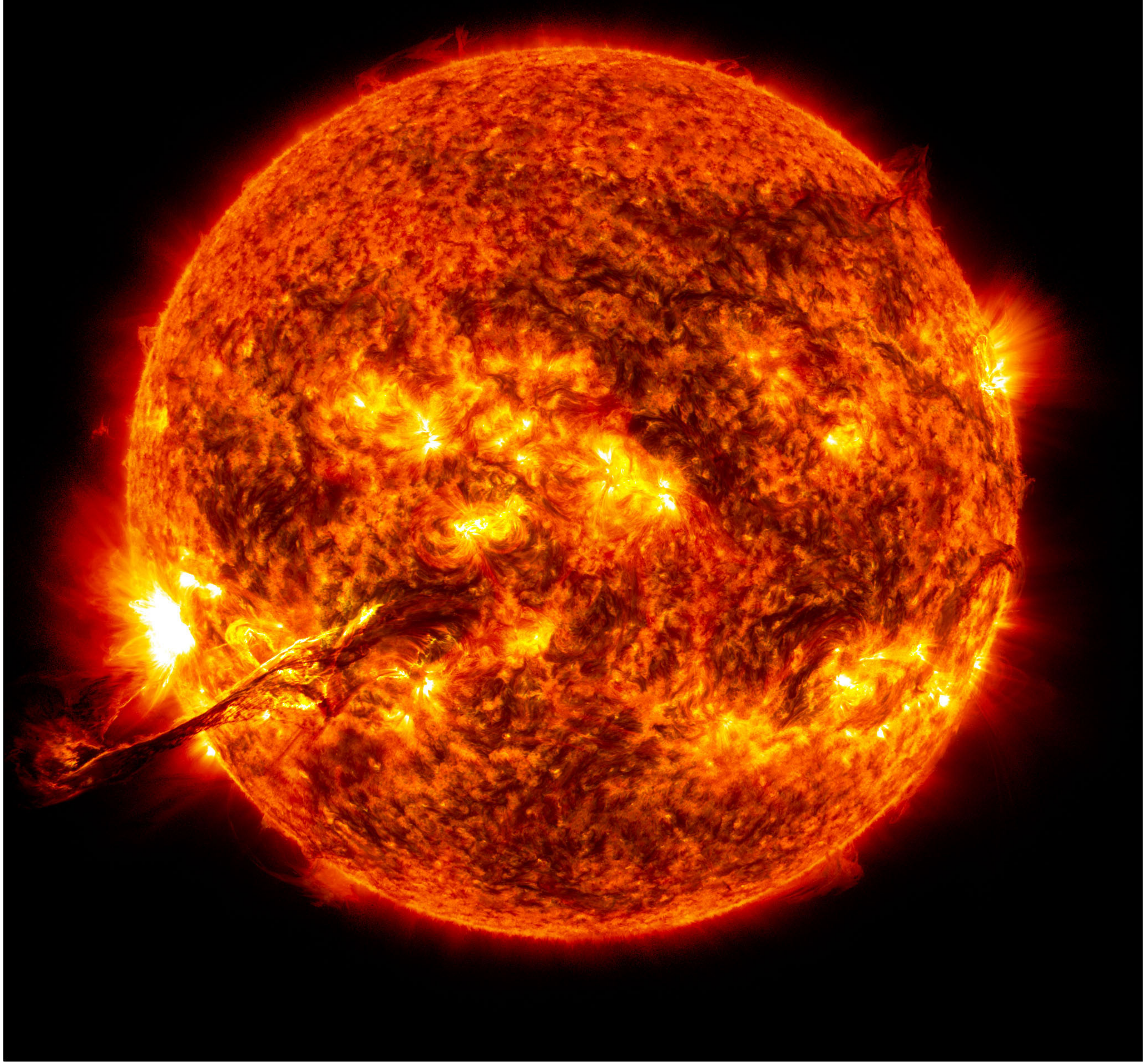
e^-	ν_e	3 flavors	e^+	$\bar{\nu}_e$
μ^-	ν_μ		μ^+	$\bar{\nu}_\mu$
τ^-	ν_τ		τ^+	$\bar{\nu}_\tau$

- The strangest particles among the known ones!
- They have a very **low probability to interact** in the matter, even the Sun is transparent to them, so they can leave the Sun's core undisturbed!
- Originally, in the SM neutrinos have exactly zero mass. Now we know they have **very very small**, but **non-zero mass** – important consequences!!
- **Neutrino oscillations:** the three flavours, types, of neutrinos can transform from one to another!
- **In the universe there are so many neutrinos, that they might be the most abundant particle in the universe!**

Neutrino sources



SOLAR NEUTRINOS

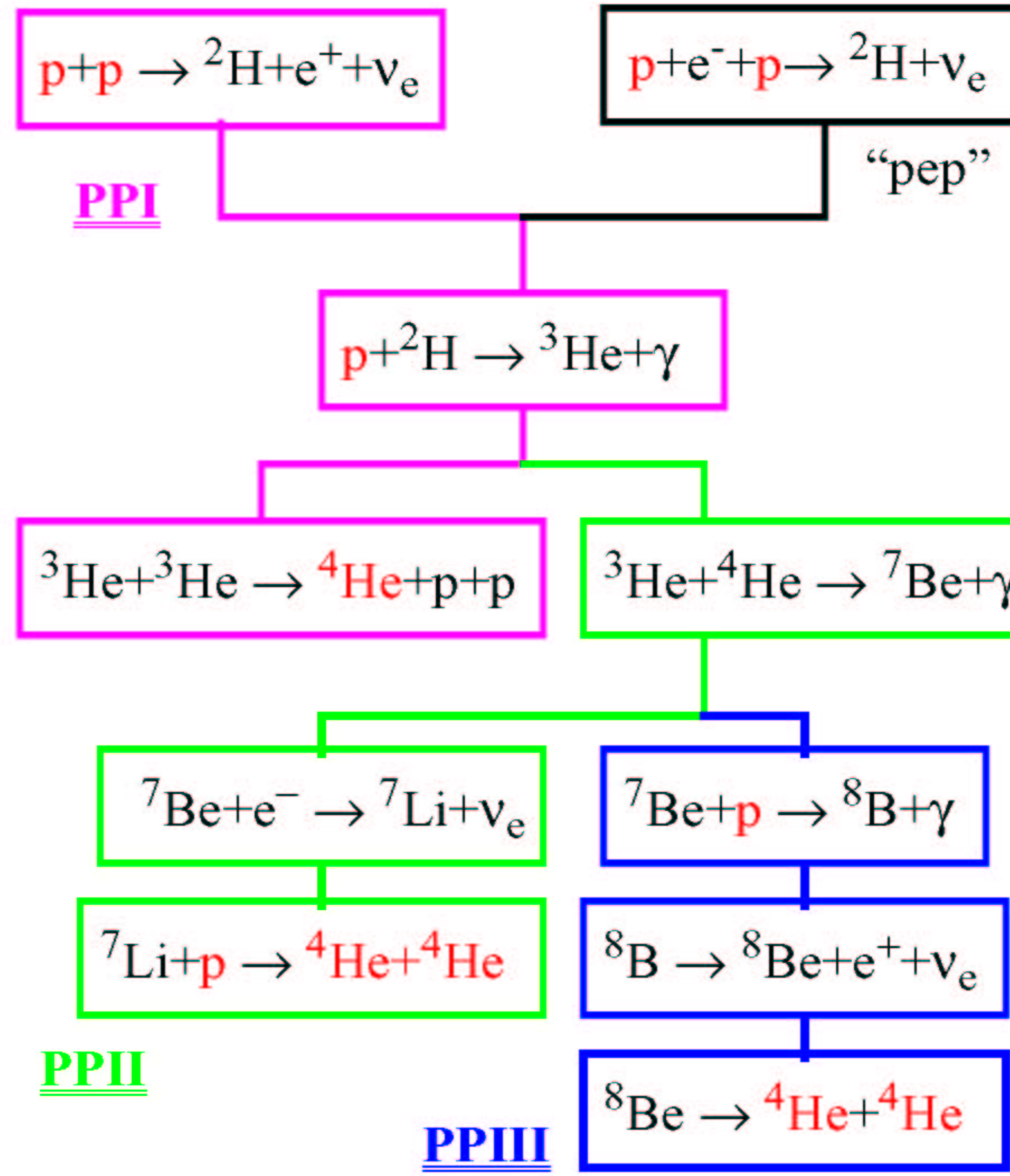


Nuclear reactions in the Sun

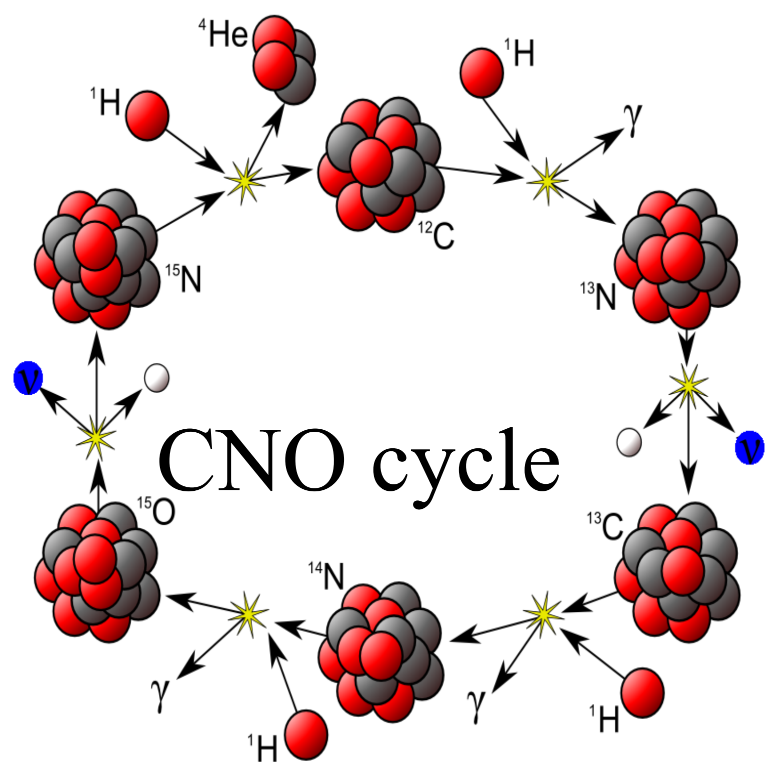
- The Sun burns via fusion reactions
  - **pp** cycle (Fowler):
    - 99% of the energy
  - **CNO** cycle (Bethe, 1938): small (<1%) in stars like the Sun, dominant in heavy stars
    poorly known and never measured

W. Fowler

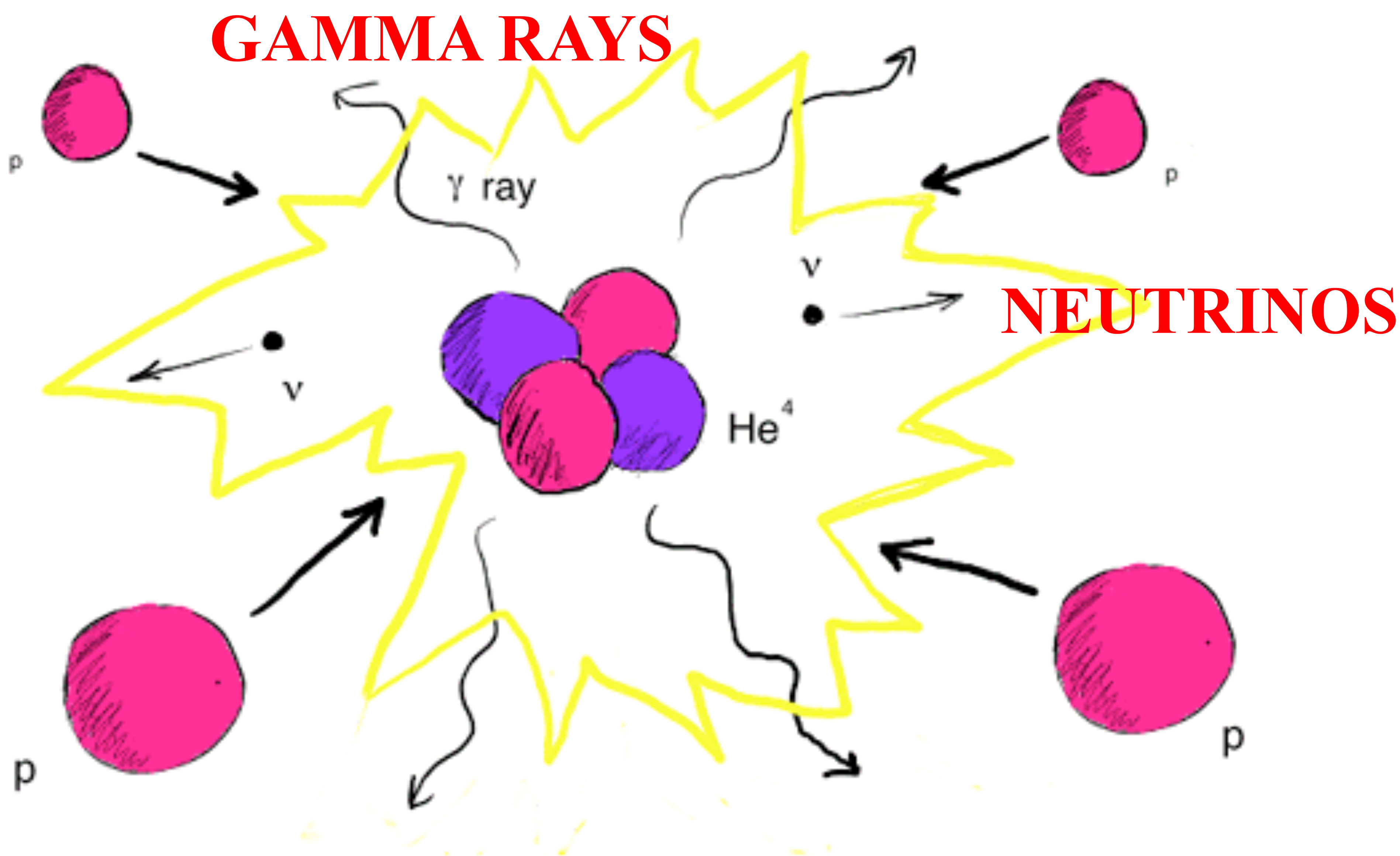
pp cycle



H. Bethe



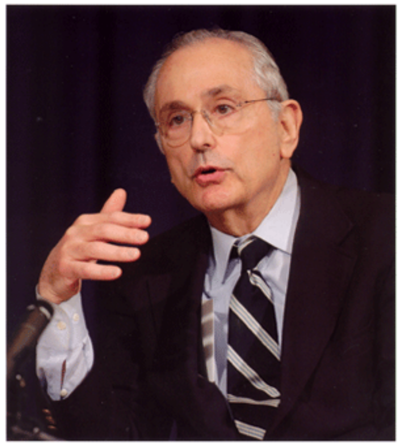
From where does come this energy?



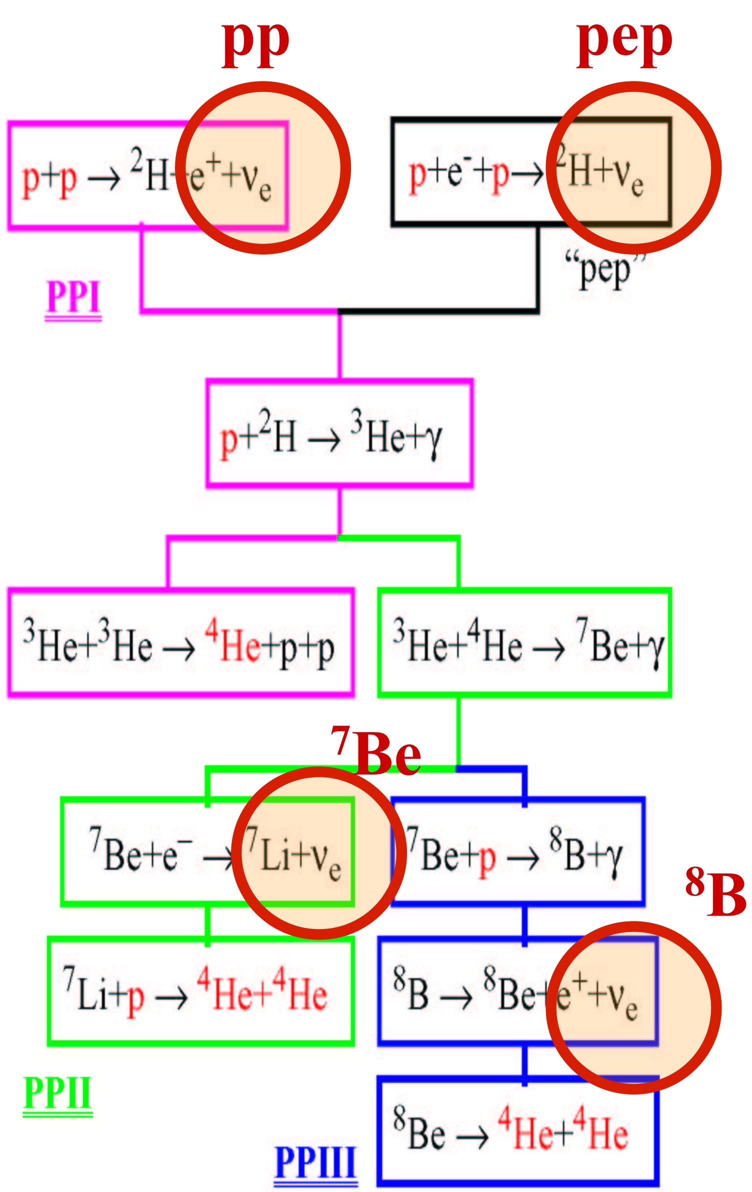
Nuclear fusion reaction!

Binding energy is released!

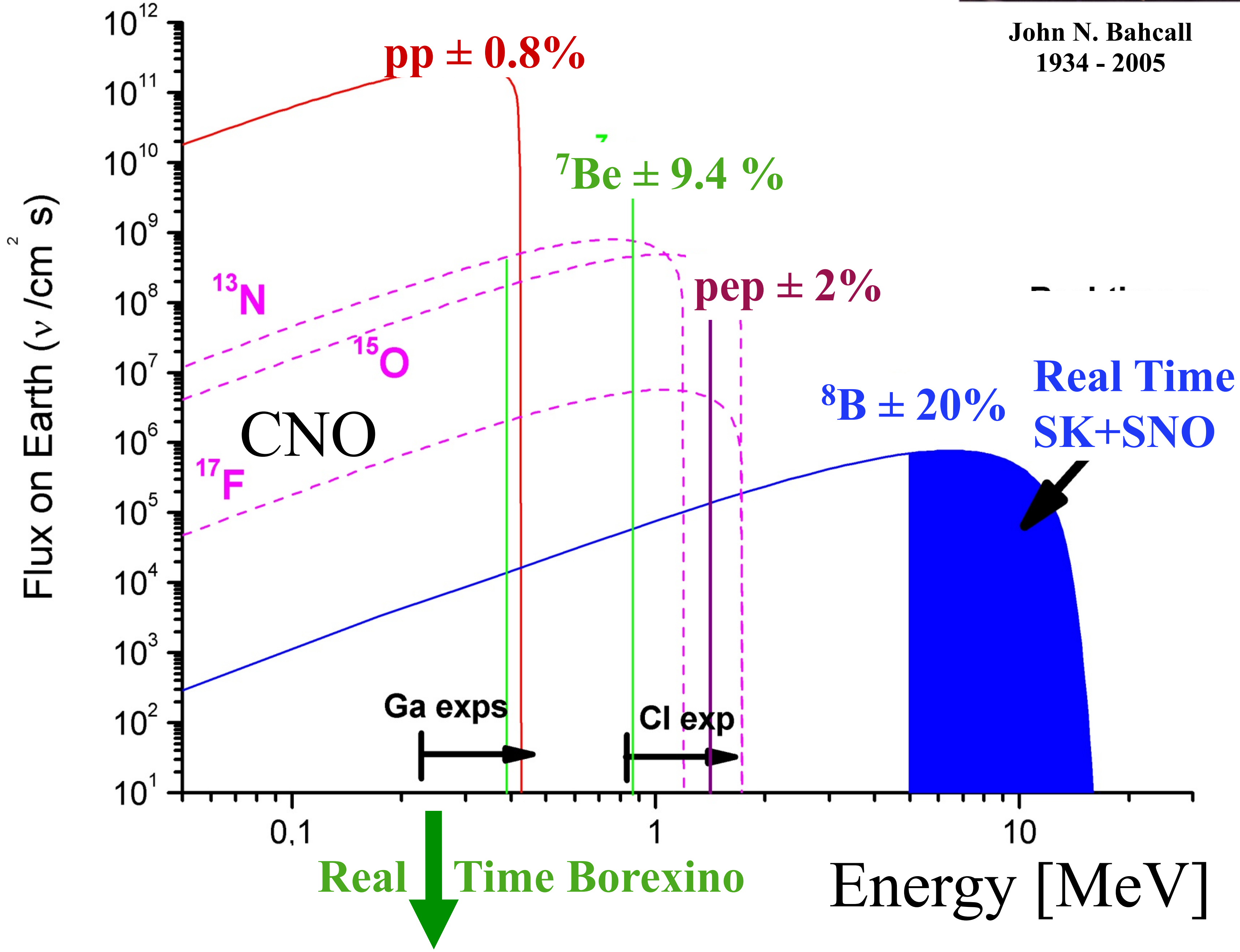
Energy spectrum of solar neutrinos



John N. Bahcall
1934 - 2005



note: hep neutrinos not included
In spectrum (very small)



Hunt for solar neutrinos

- In middle '60, Ray Davies (Nobel 2002) and John Bahcall initiated the hunt for "solar neutrinos"
    - If the Sun is really powered by nuclear reactions, solar neutrinos have to be emitted in huuuuuuge quantities:

  cc $3.\ 10^{37}$/ second or **10 miliards / cm^2 / second here at Earth**

- Physicists developed sophisticated techniques to detect neutrinos and to test whether they have exactly the same properties as we expect!

- From these studies we have learned so much, and we had so many surprises both about neutrinos and the Sun itself!

Going underground

- Even if there is a huge flux of solar neutrinos, they have a very low probability to be detected.
- **Interaction rate of neutrinos is very small:**

about 1 count / day / 1 ton of detector material!

- Detector at the Earth's surface would be completely overwhelmed by

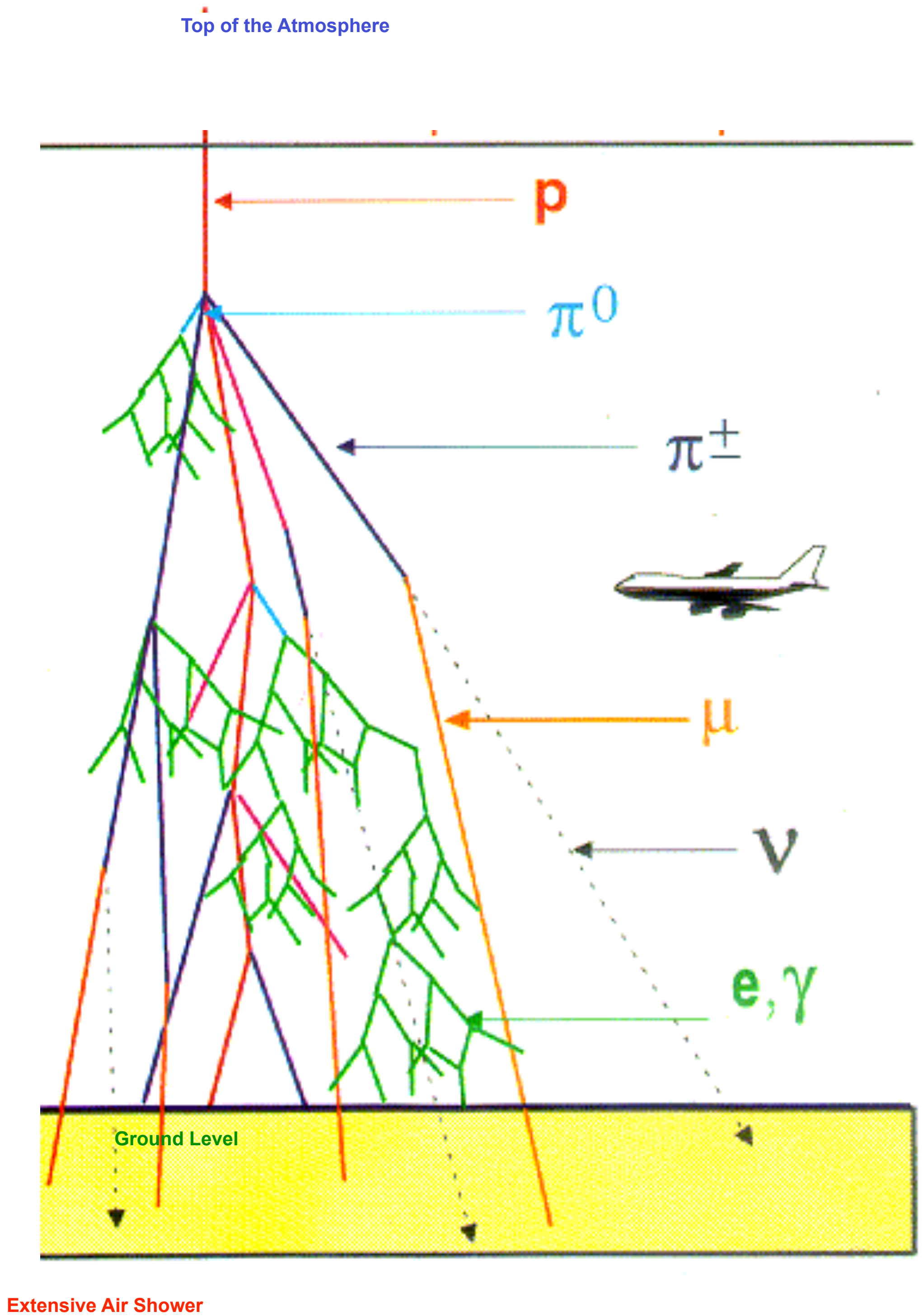
1) Natural radioactivity: from 10 to 1000 radiocative decays / second / kg

2) Cosmic rays: about 200 charged particles / second / m² at the sea leevel

- To **study neutrinos** (and in general rare processes), it is necessary to go **underground**:

The world's largest underground lab is here in Italy, about 160 km Frascati:

Laboratori Nazionali del Gran Sasso




Gran Sasso
underground halls

First detection: Homestake - Nobel 2002

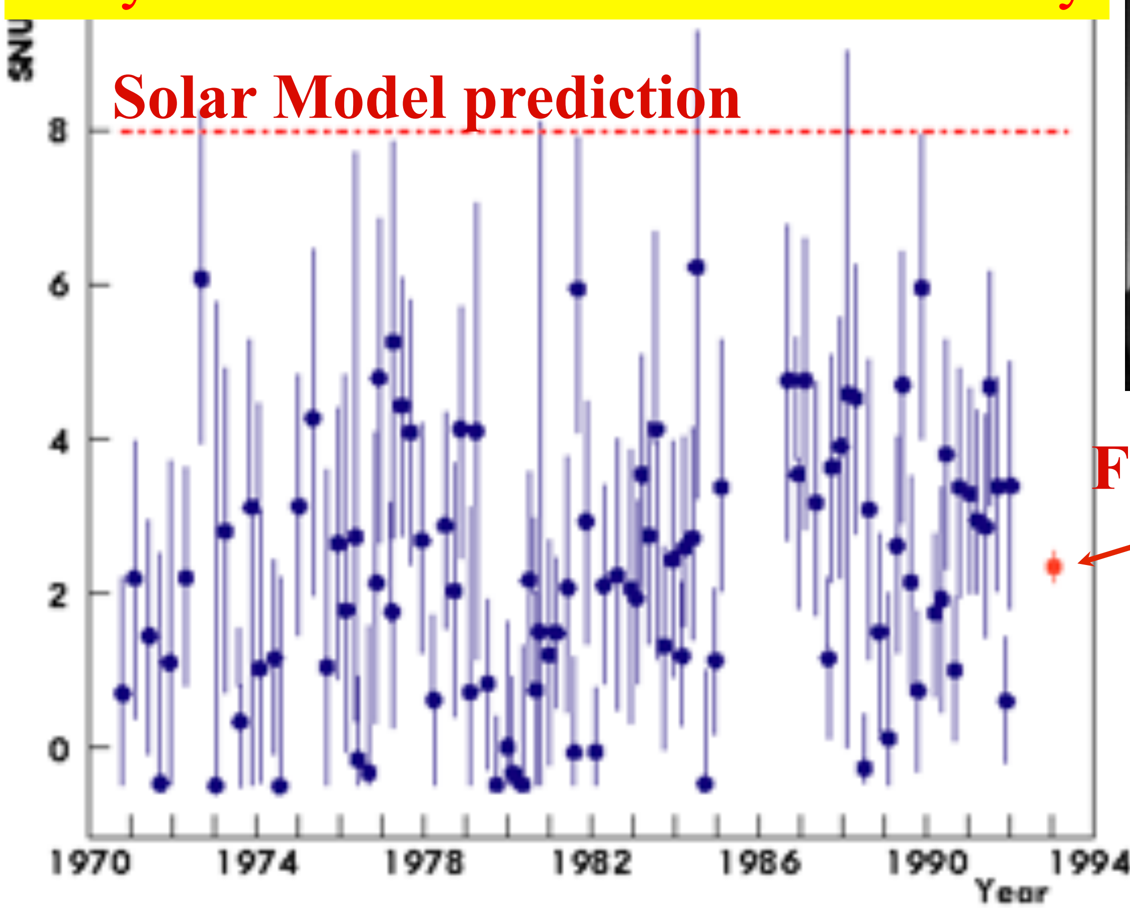
- Raymond Davis experiment: collect ~1 atom/day out of 10^{31}
  - Charged interaction, but no detection of the electron

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

- Target: a tank with 614 t of liquid soap (C_2Cl_4) placed 1.5 km deep underground; taking data 1970 – 1994.
- Extraction with filters and counting of ^{37}Ar decays (32 d)

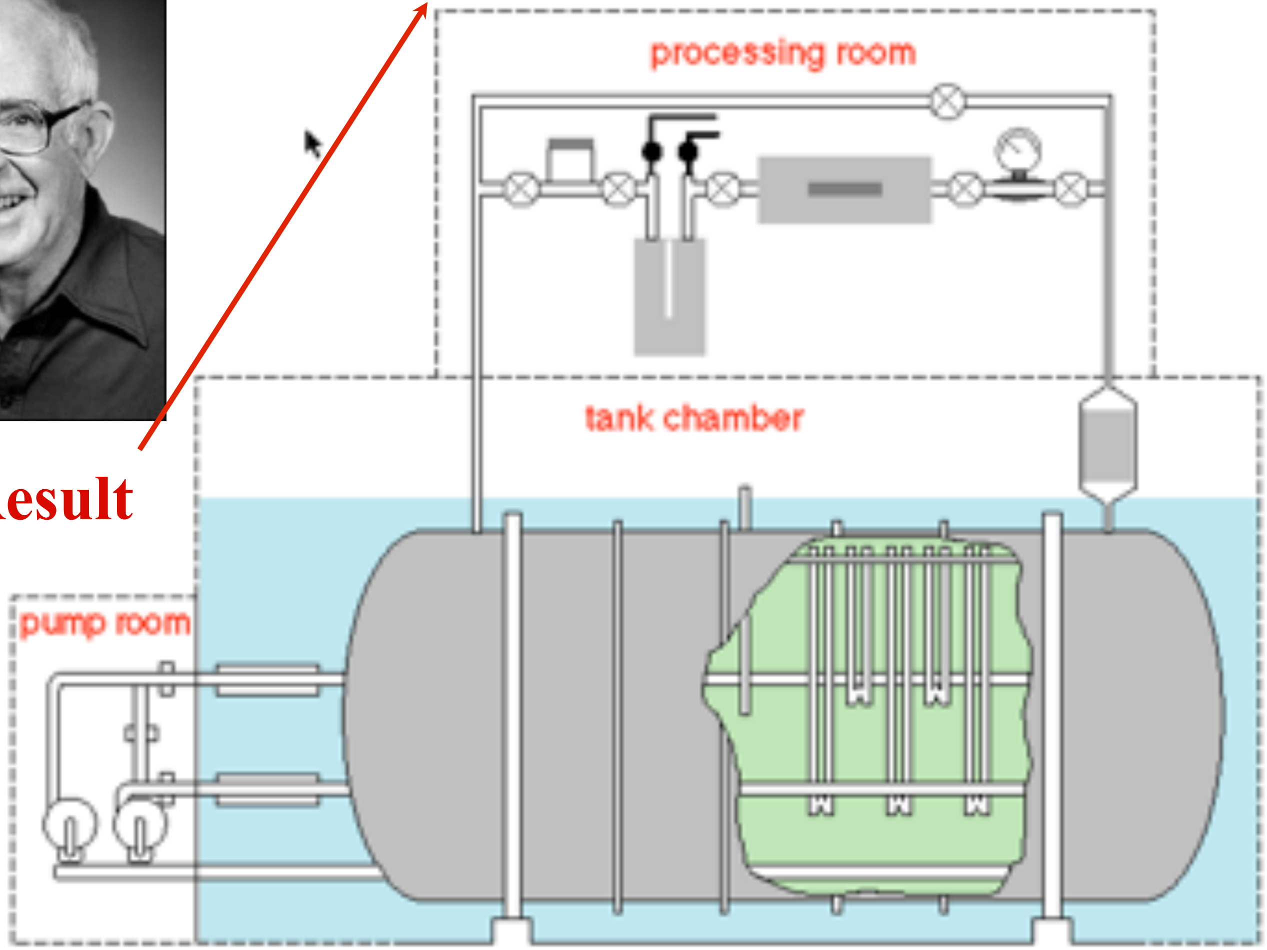
$$e^- + {}^{37}Ar \rightarrow \nu_e + {}^{37}Cl$$

Only 2200 atoms of ^{37}Ar counted in 25 y



Final Result

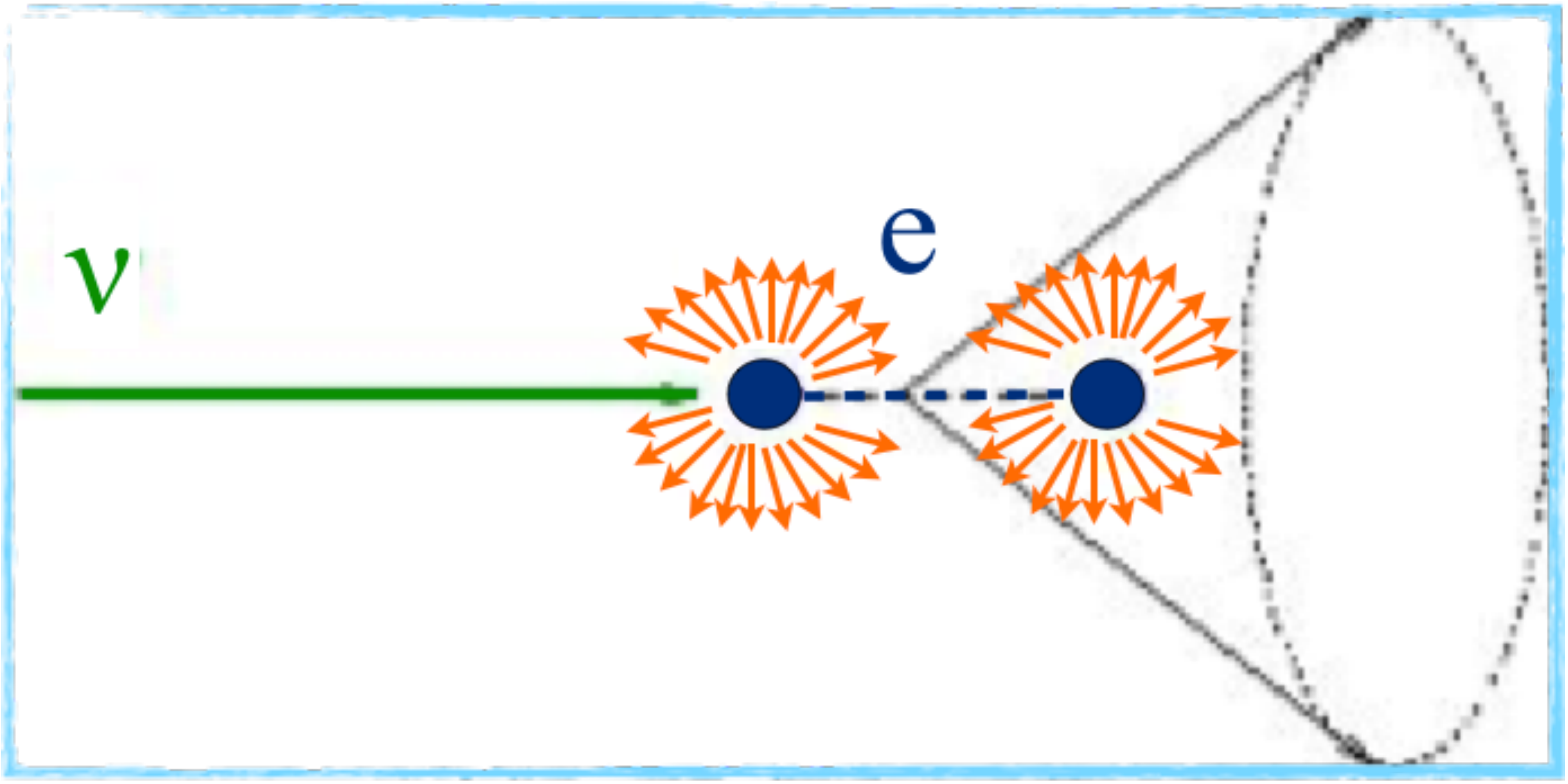
$2.56 \pm 0.16 \pm 0.16$ SNU



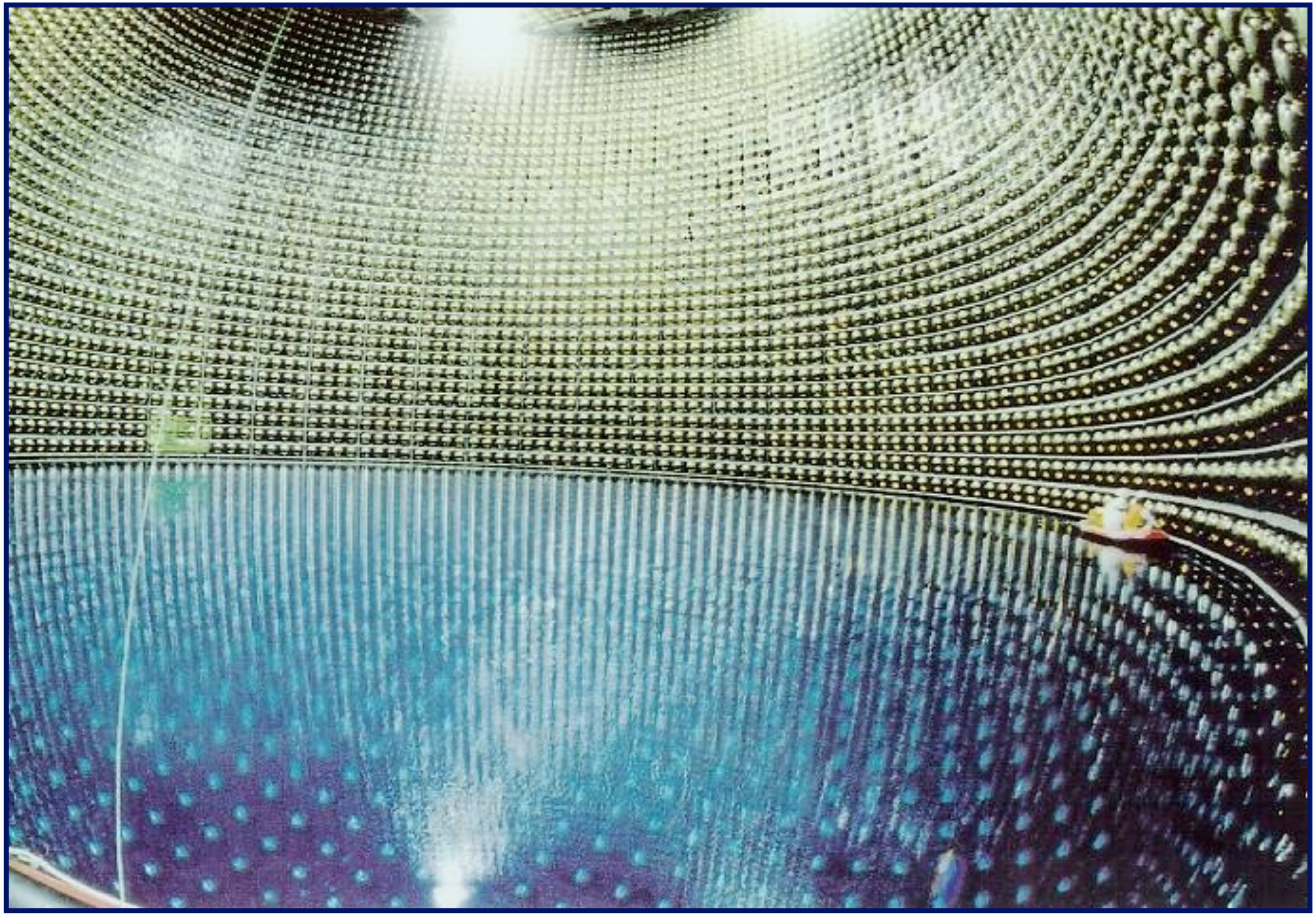
1 SNU (Solar Neutrino Unit) = 10^{-36} interactions on target nuclei per second

How do we detect neutrinos today?

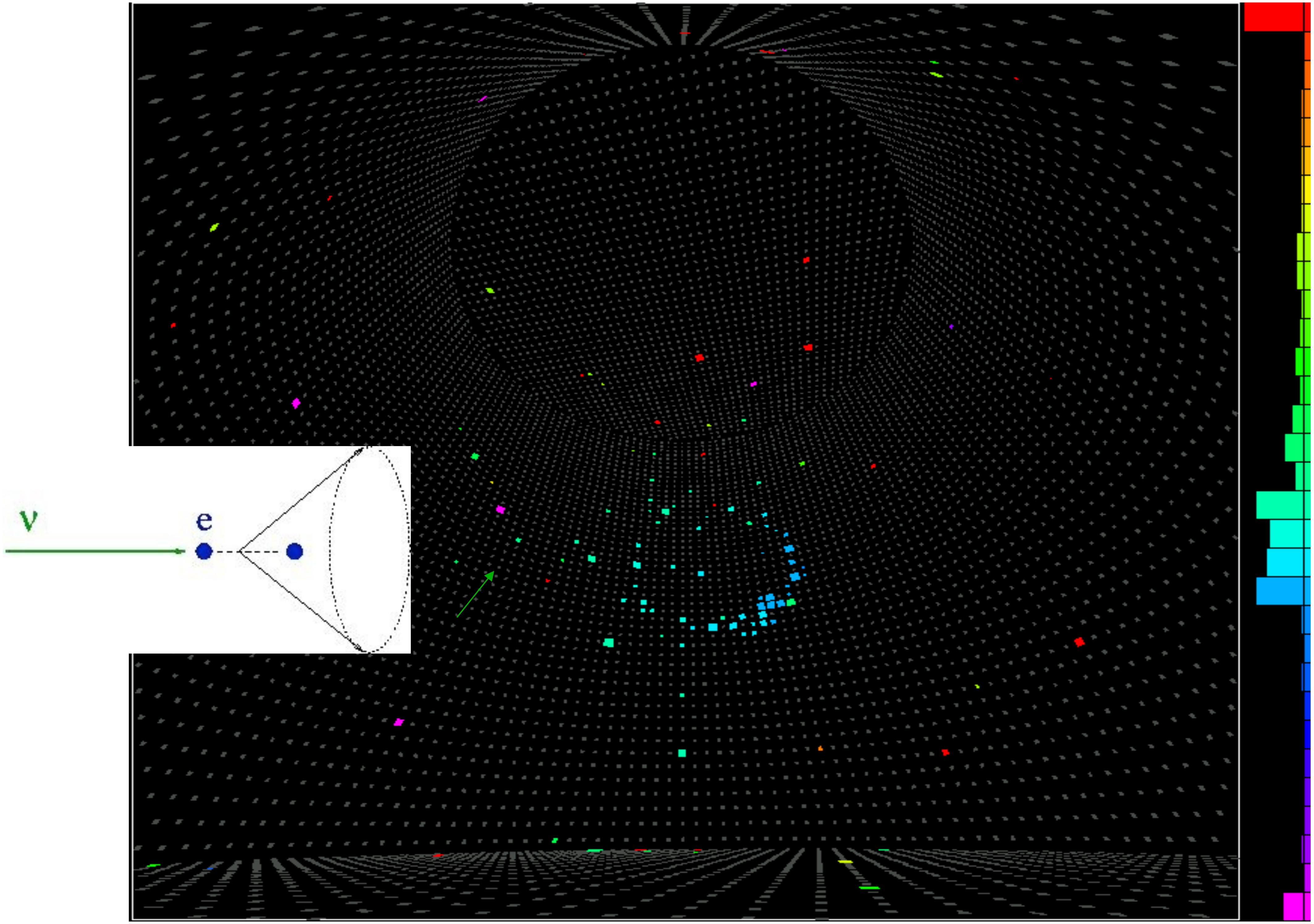
- Interactions between neutrinos and matter are rare, but non zero
- **neutrino can scatter off electrons;**
- **electron** gains energy (as in a billiard game!) and **can be detected**;
- different detection techniques how to detected such an electron;
- Expected rate: less than 1 event / day / 1 ton of target .



Example: water as a target
(SuperKamiokande in Japan)

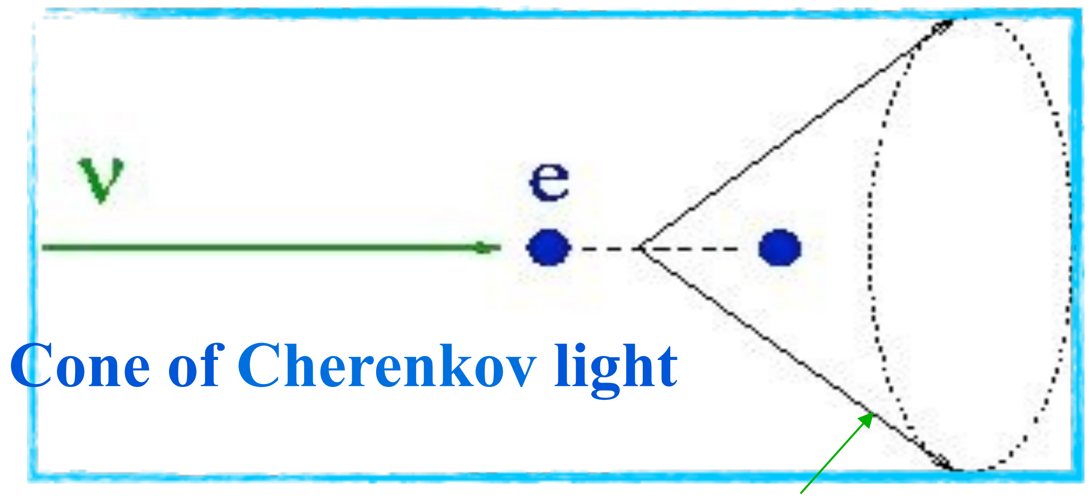


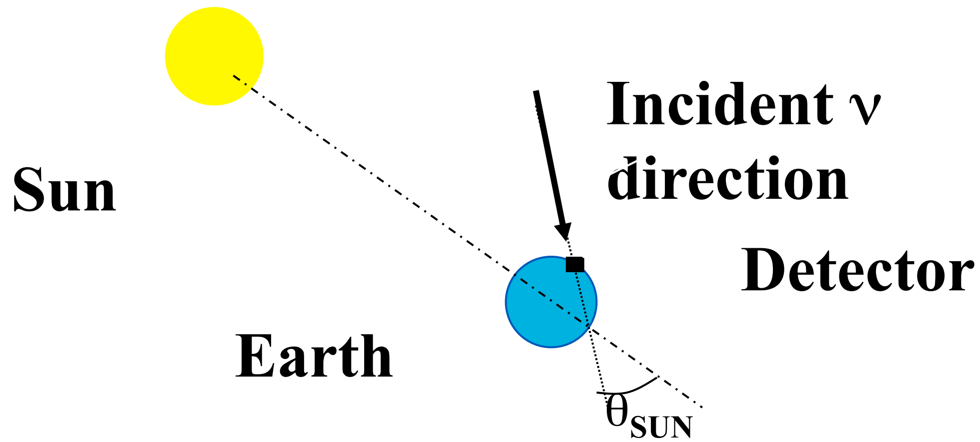
Single neutrino detected in water: cone of Cherenkov light



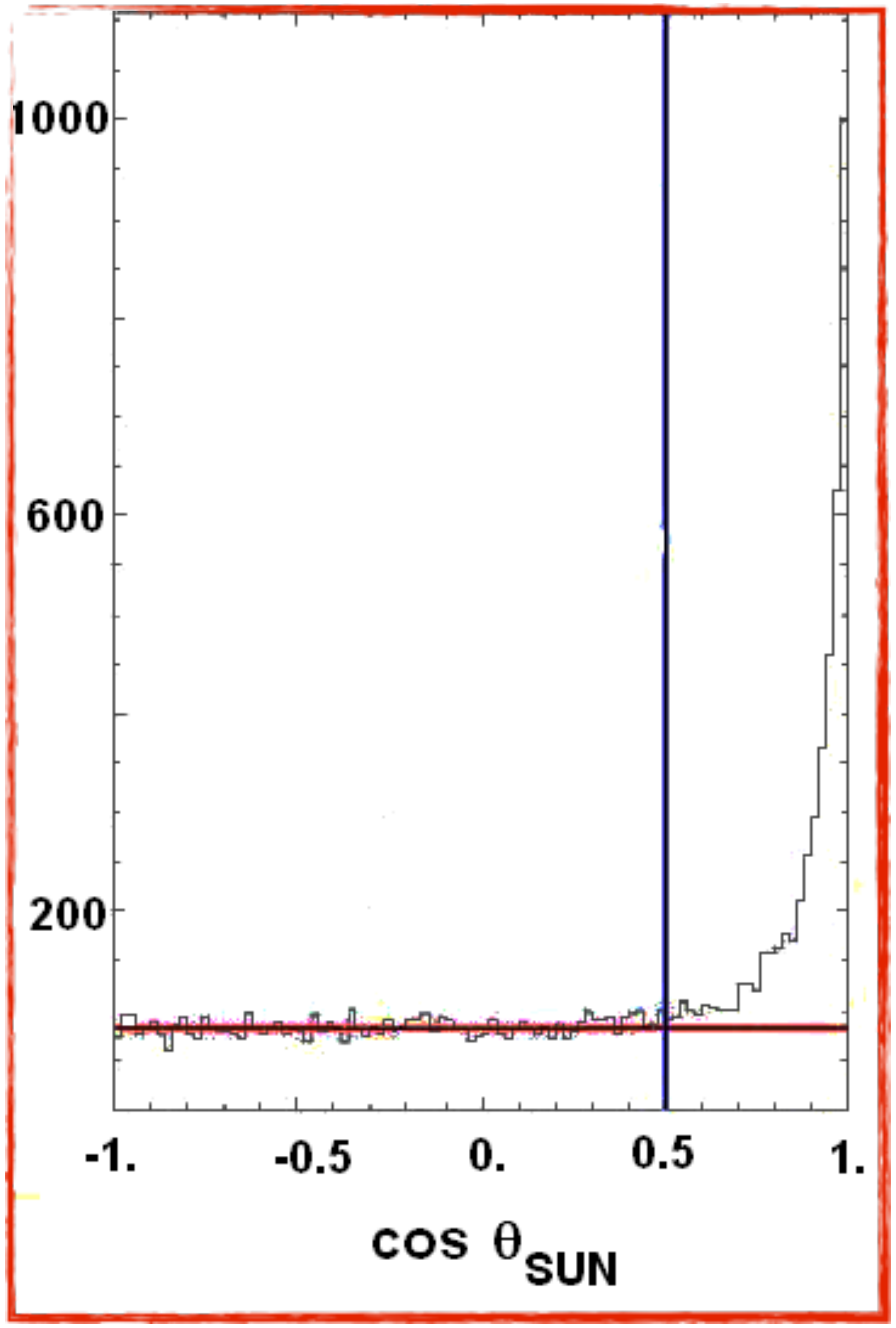
Solar origin proved in 1996

- In water we can measure the direction of incident neutrino!

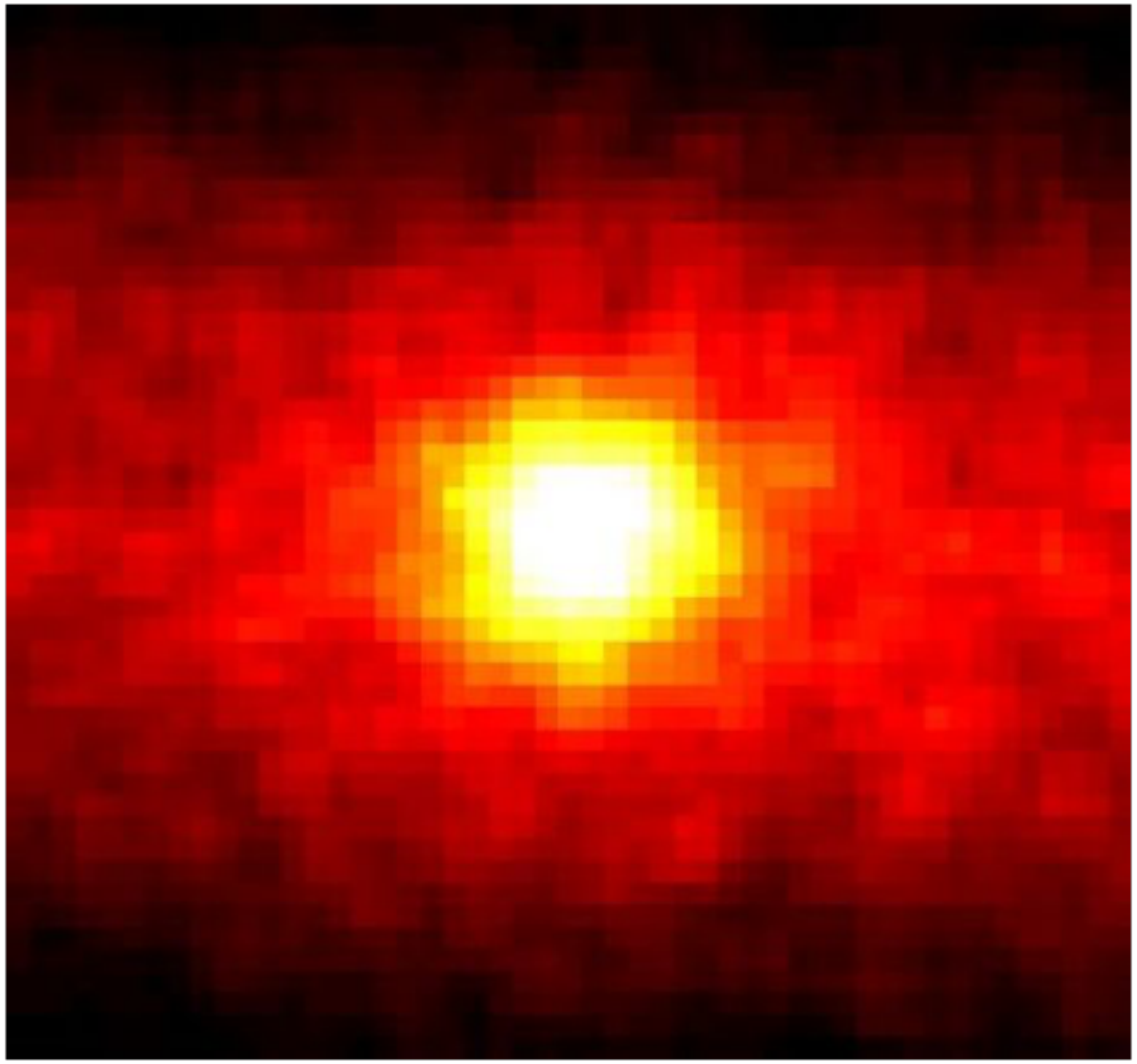




$\cos(0) = 1$

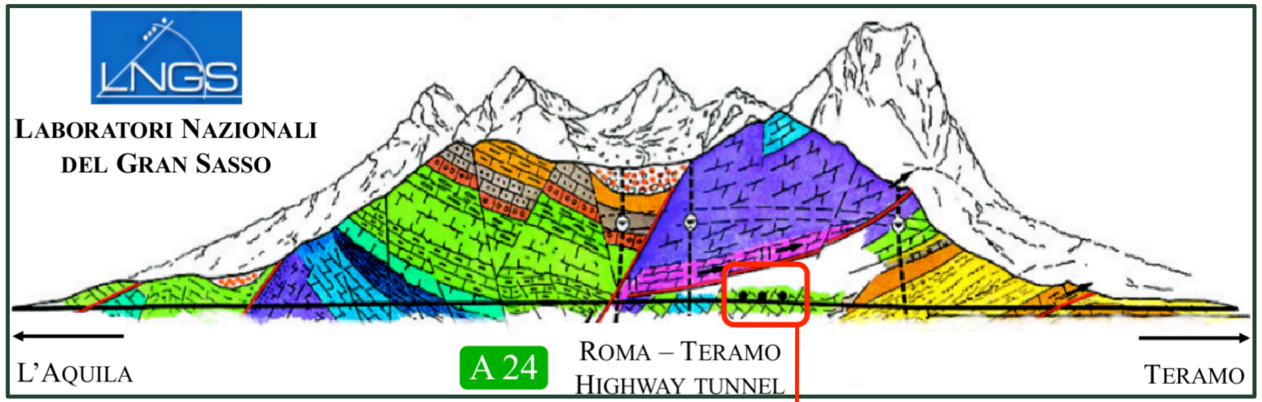


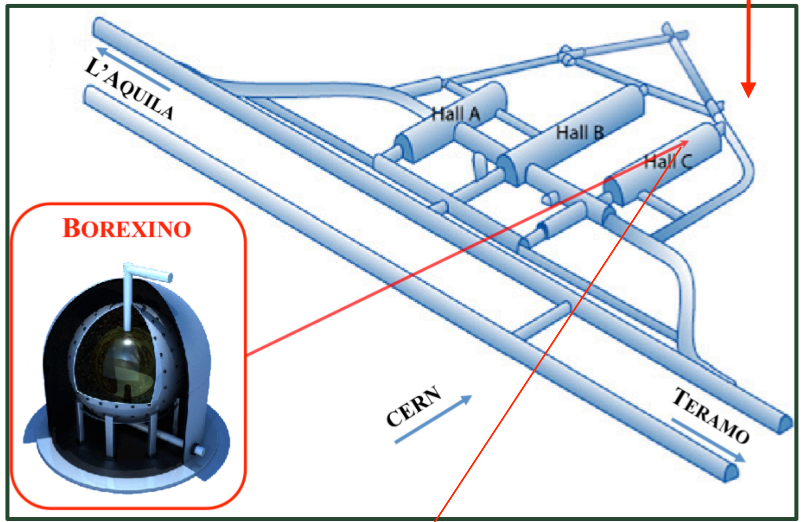
Sun's core seen with neutrinos



SuperKamiokande, Japan

Laboratori Nazionali Gran Sasso / LNGS (Italy)





The **LNGS** altitude is 963 m and the average rock cover is about 1,400 m.

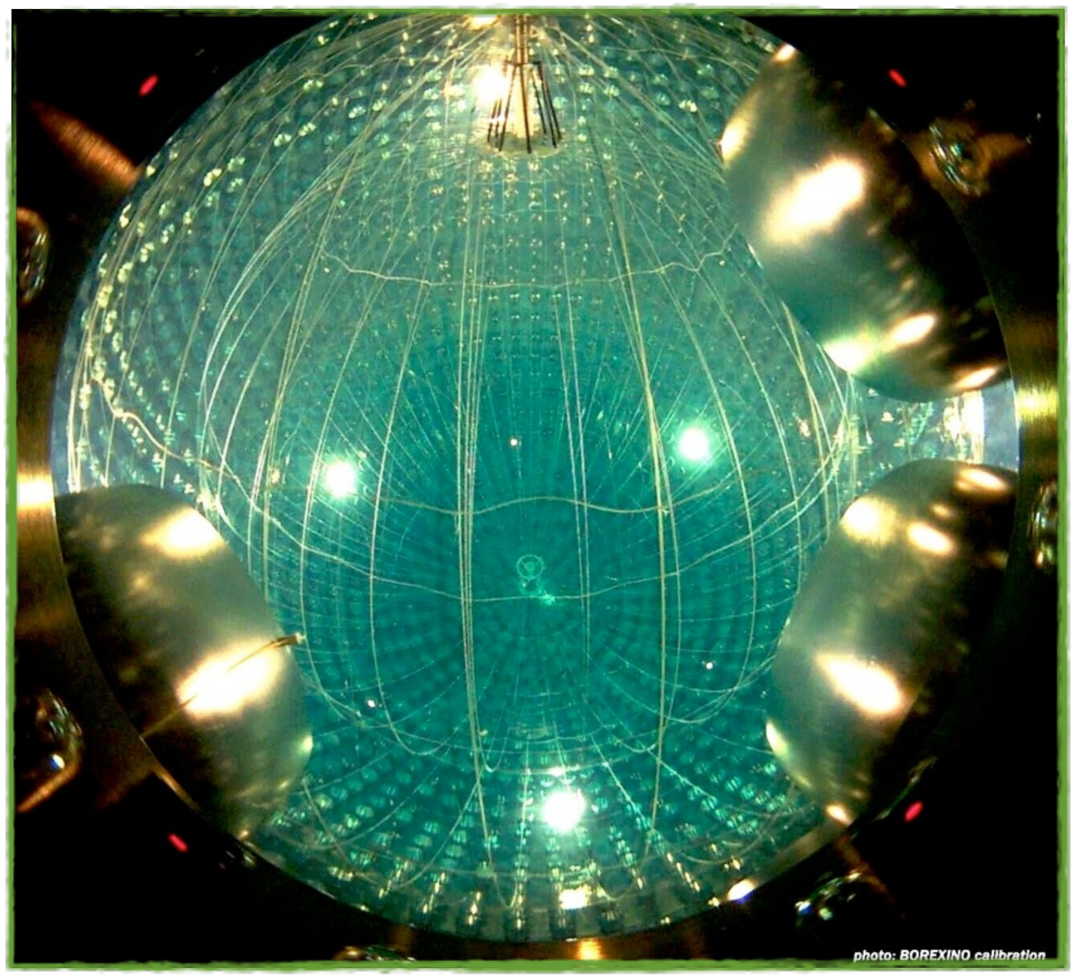
The shielding capacity against cosmic rays is about 3,800 meter water equivalent (m.w.e.): the muon flux is reduced of a factor 10^6 respect to the surface.

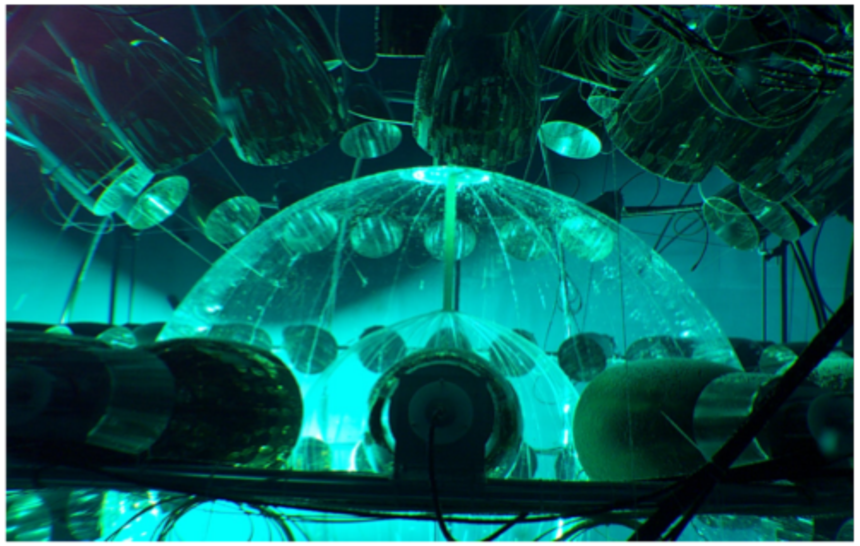
$$\Phi(\mu) \sim 1\,\mu/\mathrm{m}^2/\mathrm{h}$$

Borexino

Today, it is the most important detector of solar neutrinos:

- ✓ Result of 20 years of scientific and technical development;
- ✓ Its core is the least radioactive liquid ever produced;
- ✓ Has detected solar neutrinos and for the first time successfully distinguished neutrinos from different nuclear reactions from the Sun's core;
- ✓ succeffully detected also anti-neutrinsos from the natural radioactivity of the Earth: "geo-neutrinos"





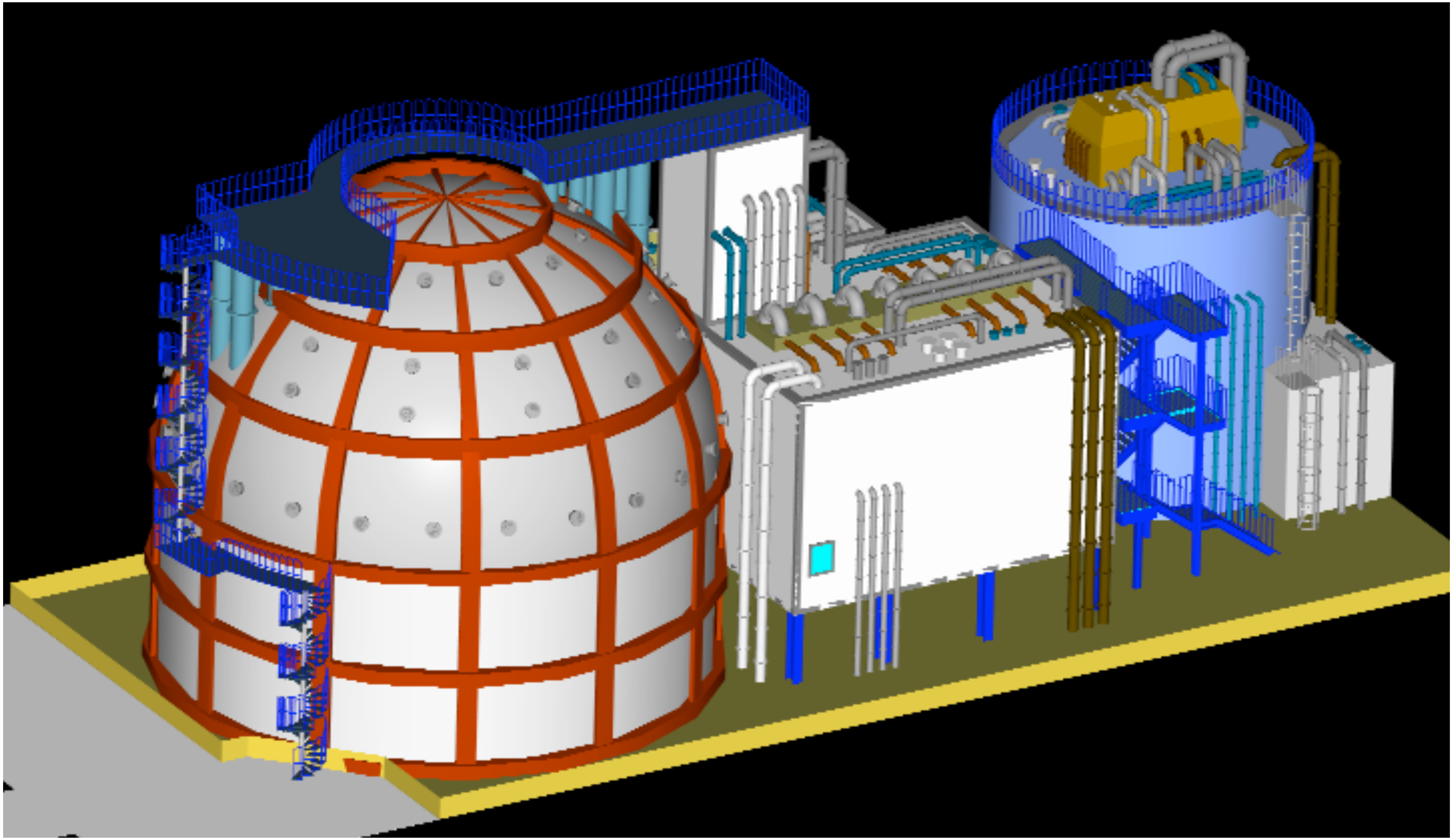
Why 20 years of work?

- Neutrino scatters of an electron from molecules of a special liquid: **scintillator:**
  - Electron gains energy and starts to move;
  - Electron slows down and its kinetic is transformed to light (sparkle = scintilla)
  - Light is propagated through the liquid and is detected by "electronic eyes", so called photo-multiplicators (PMTs), transforming light to electronic signals;

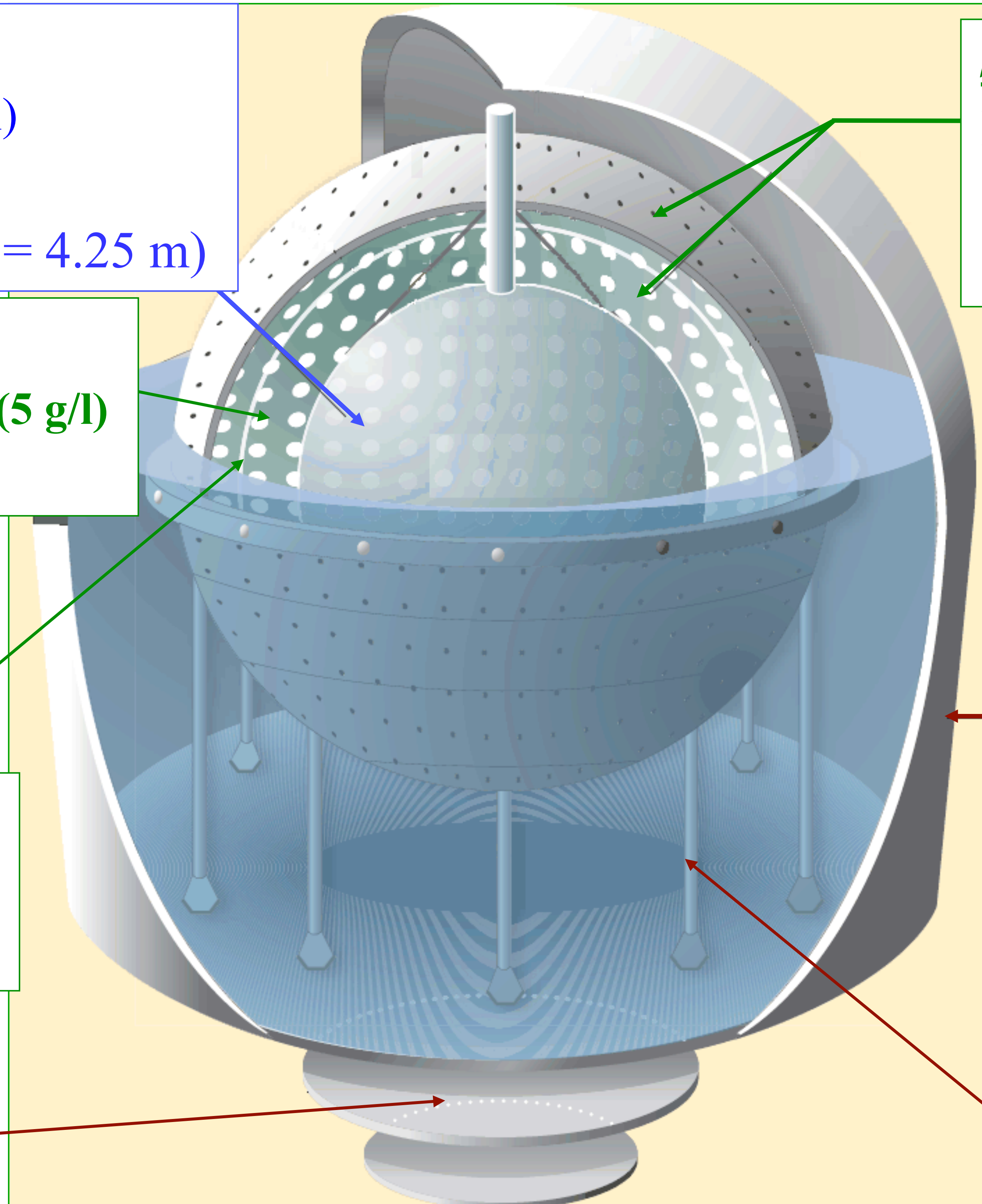
- In principle very simple, but……
  - In Borexino, we detect less than **100 neutrinos / day / 100 ton**
  - **Normal materials** around us are up to **10^9 times more radioactive!**

- **Borexino's scintillator is the only liquid reaching this level of radiopurity 10 orders of magnitudes less than any other thing on the Earth!**

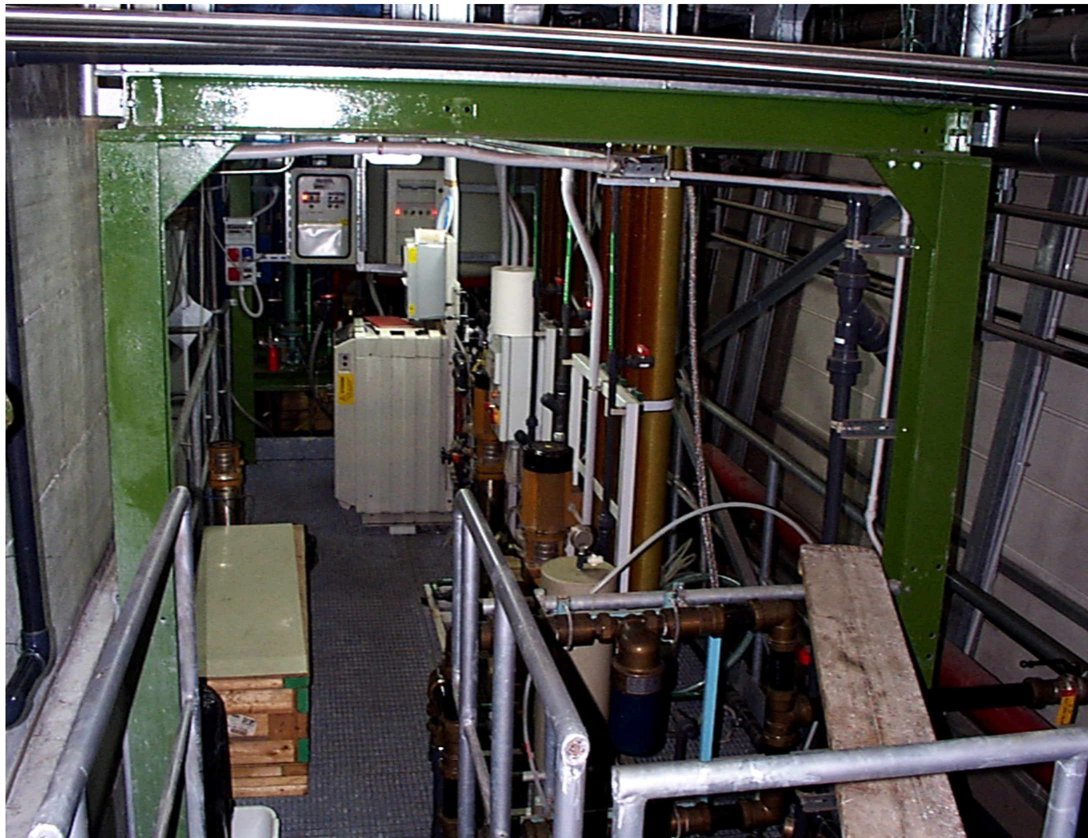
Borexino

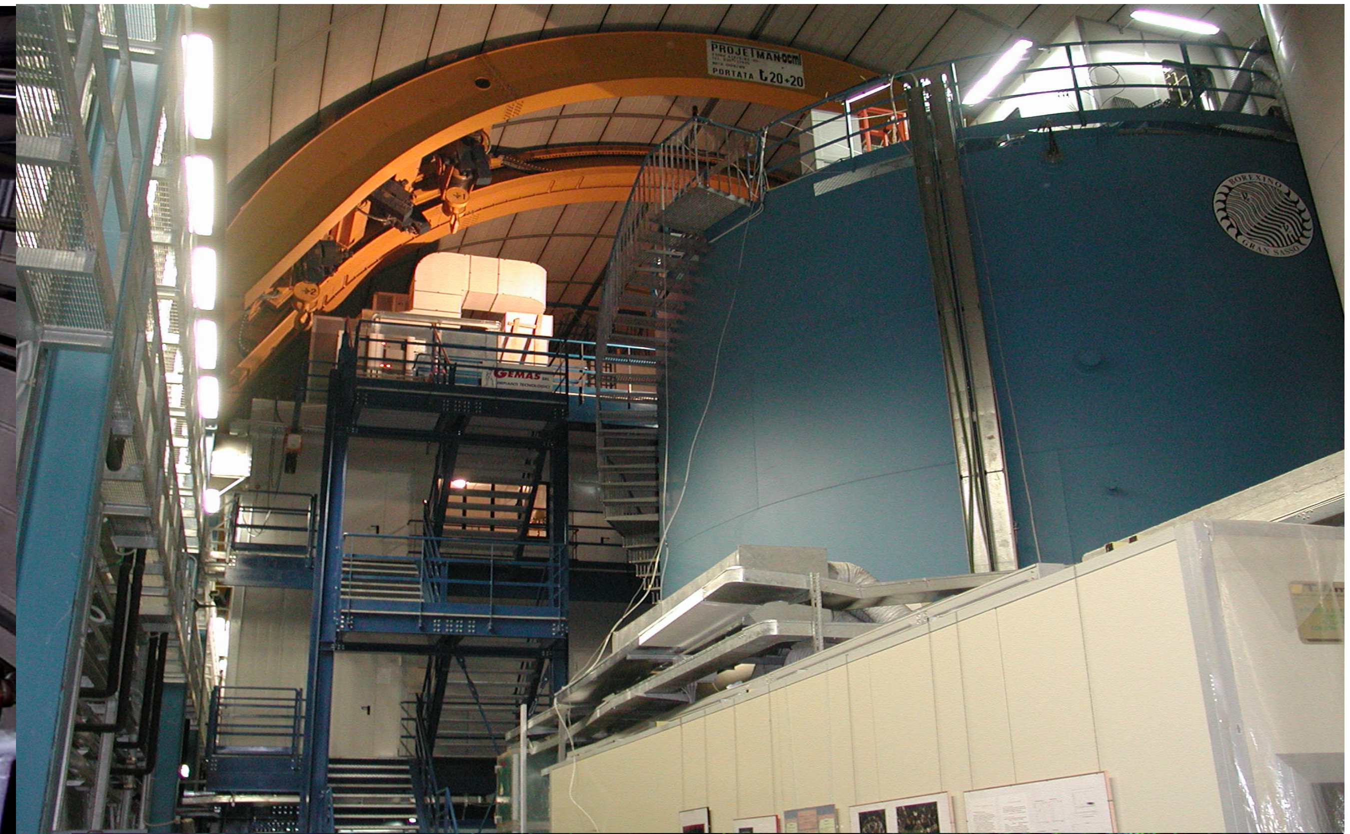


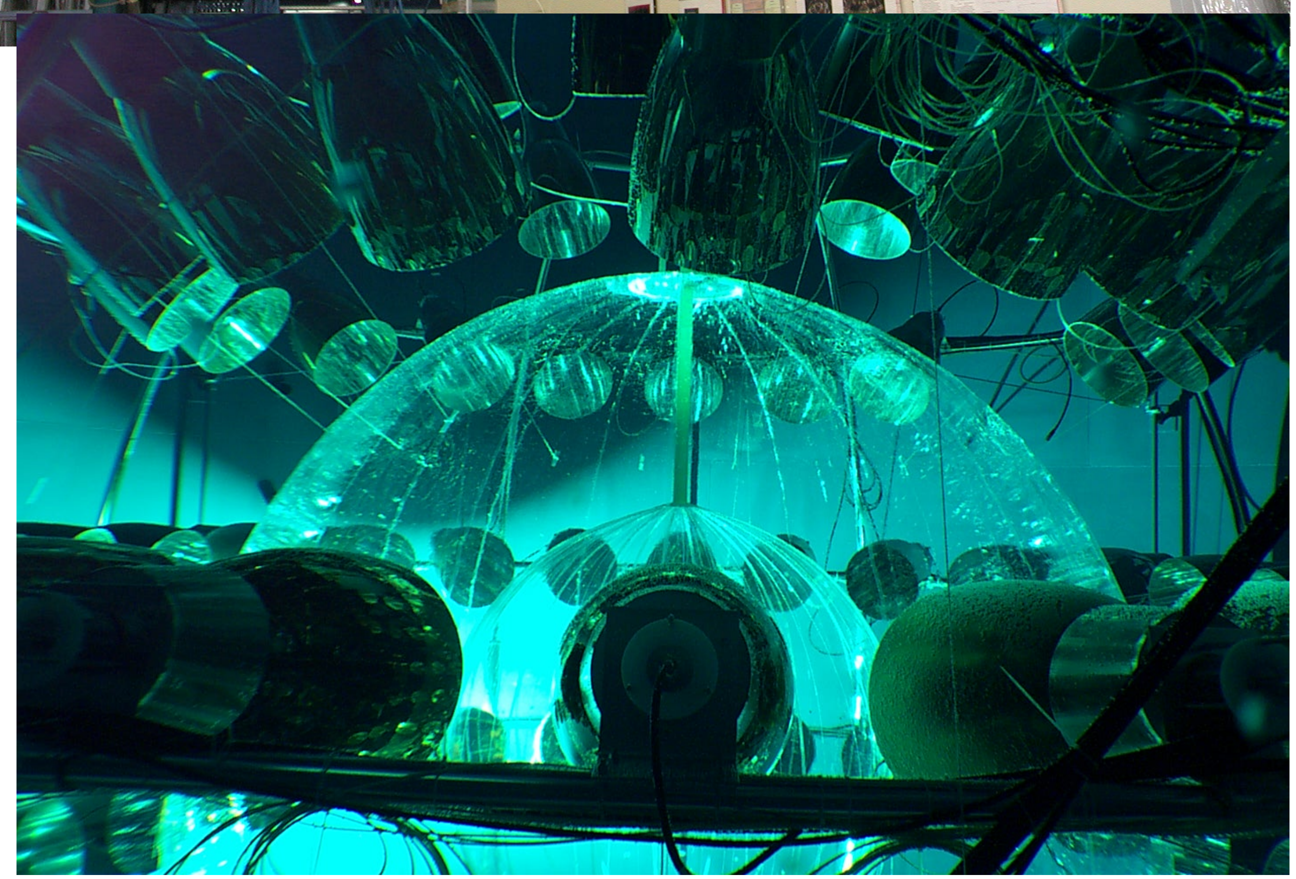
Borexino Detector



Some pictures from the constructions







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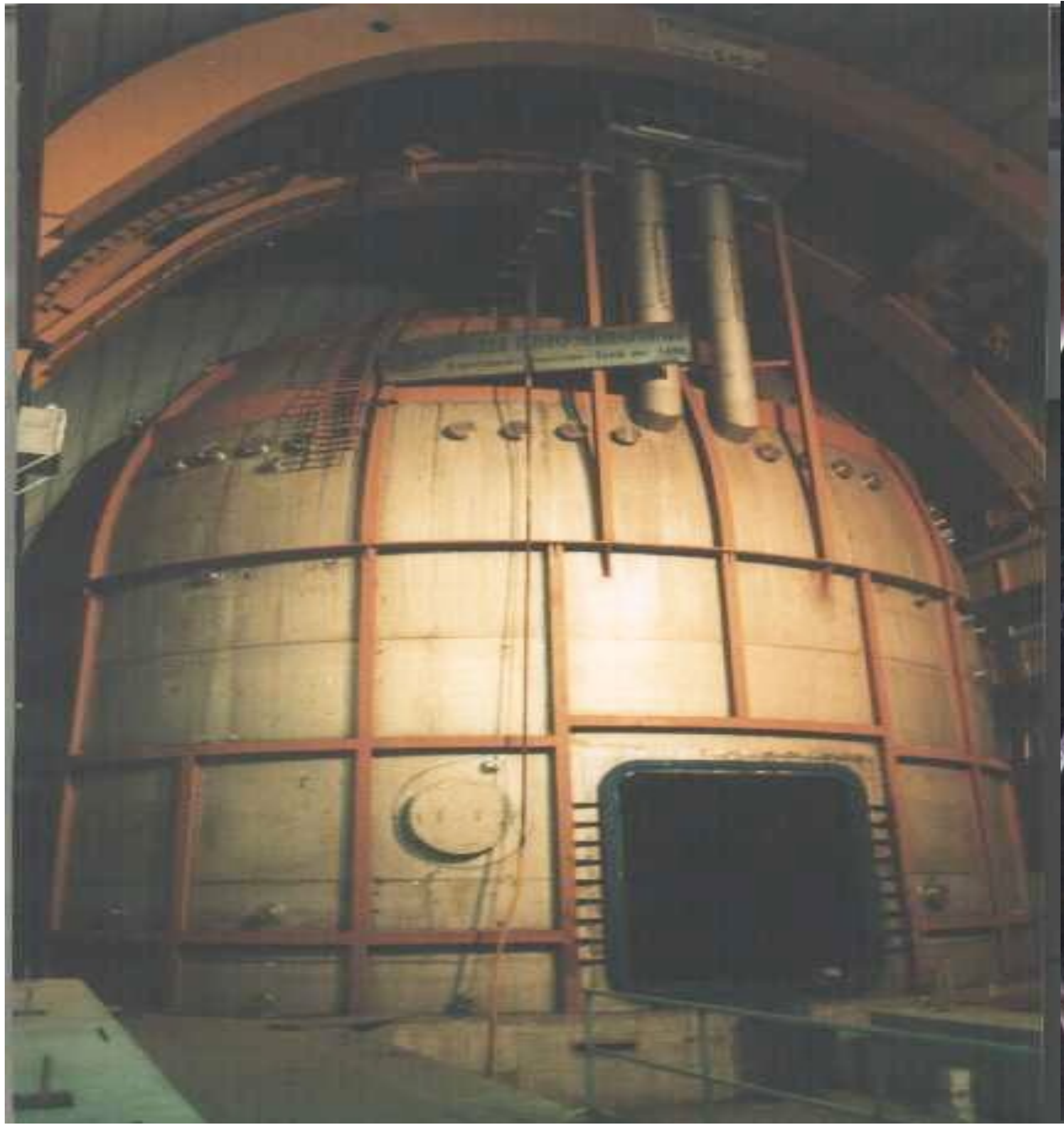
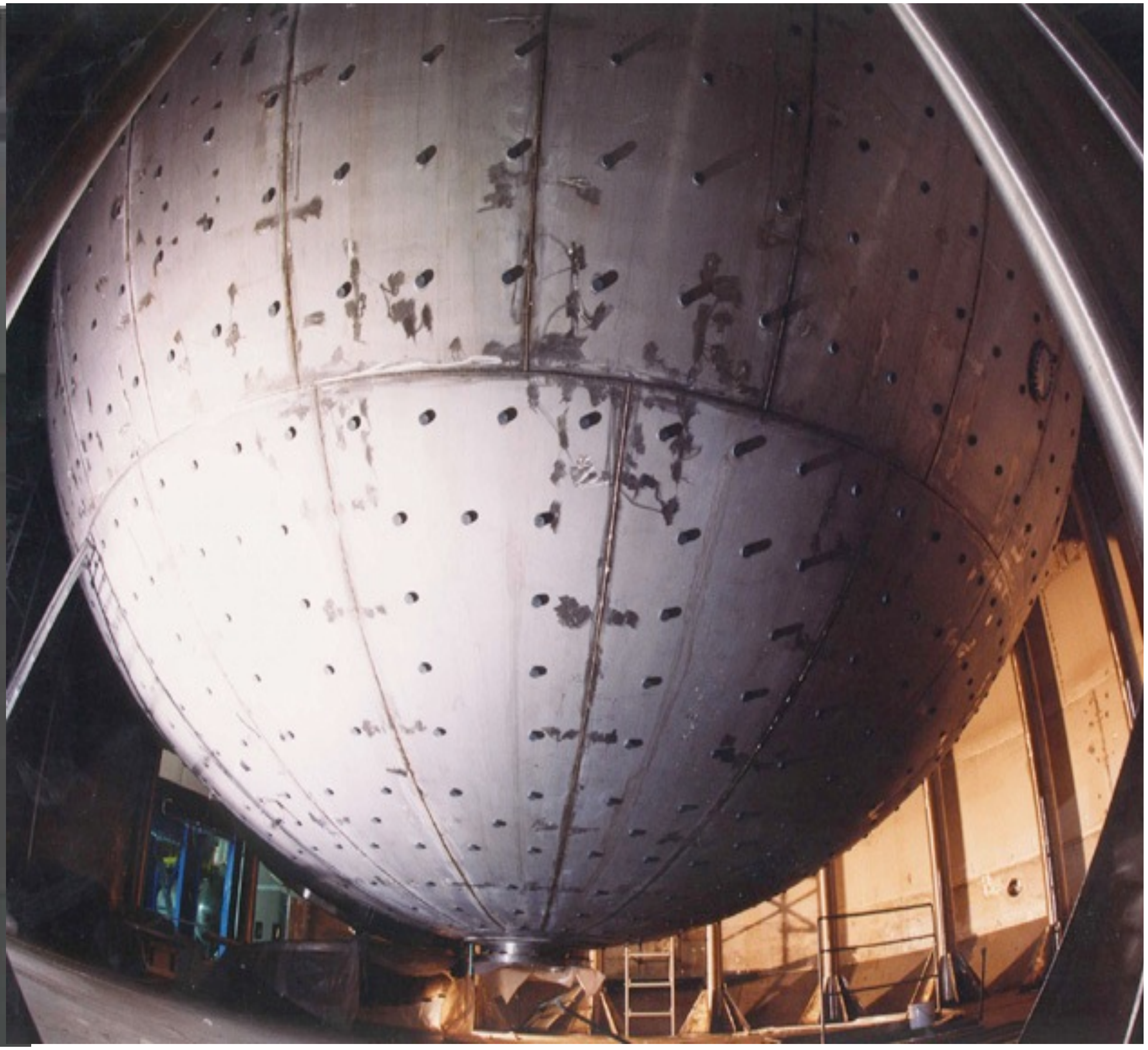
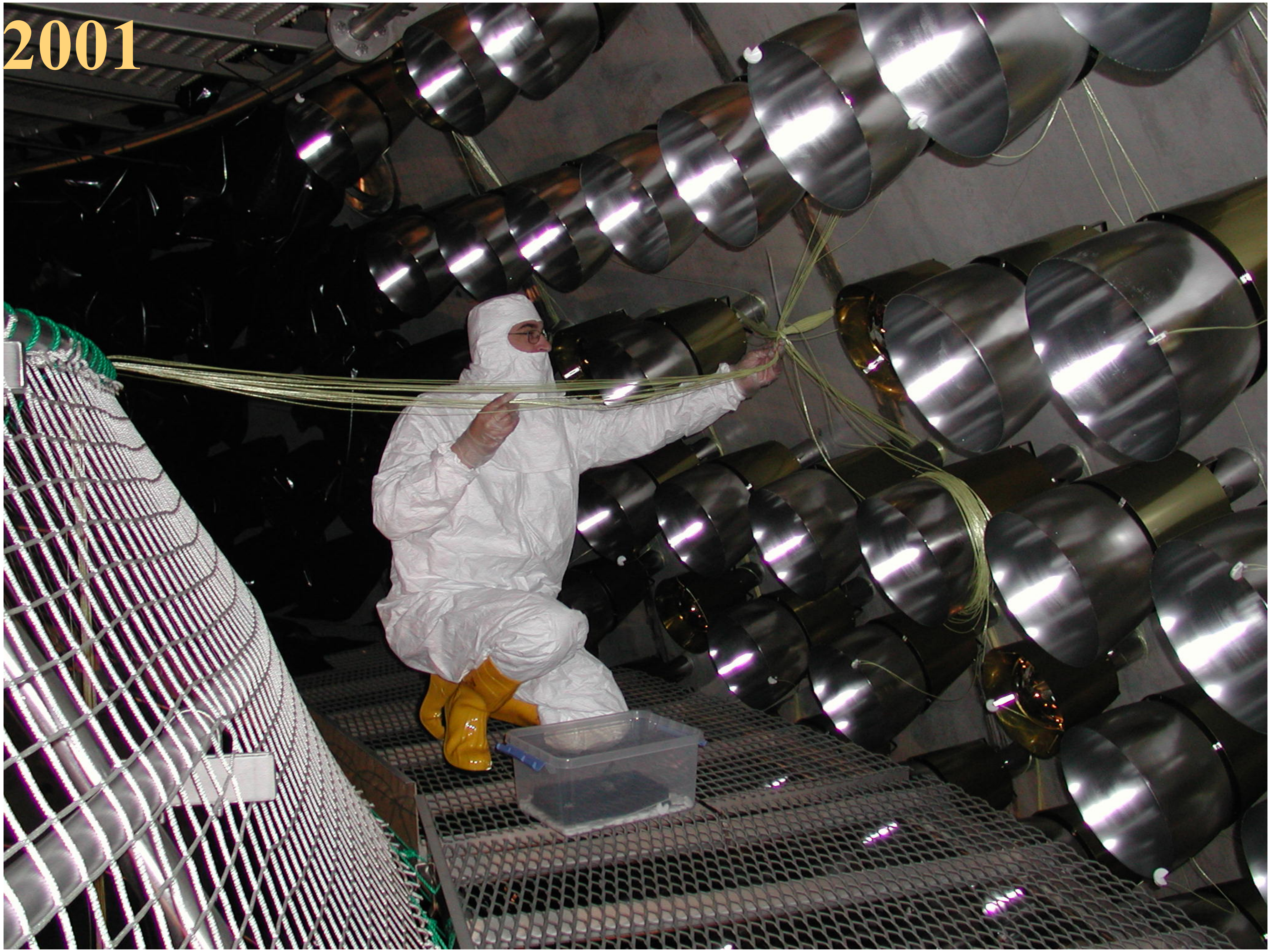
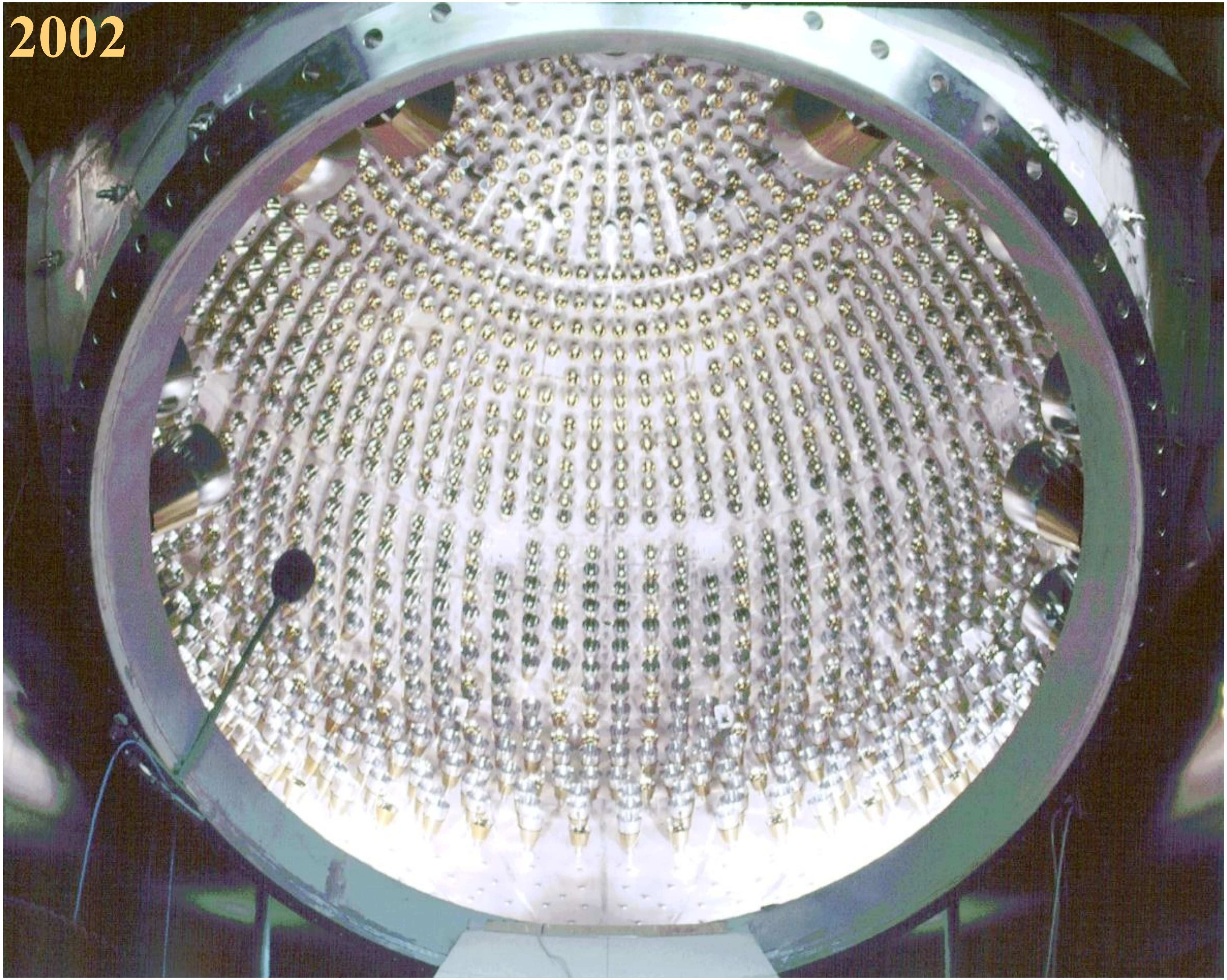




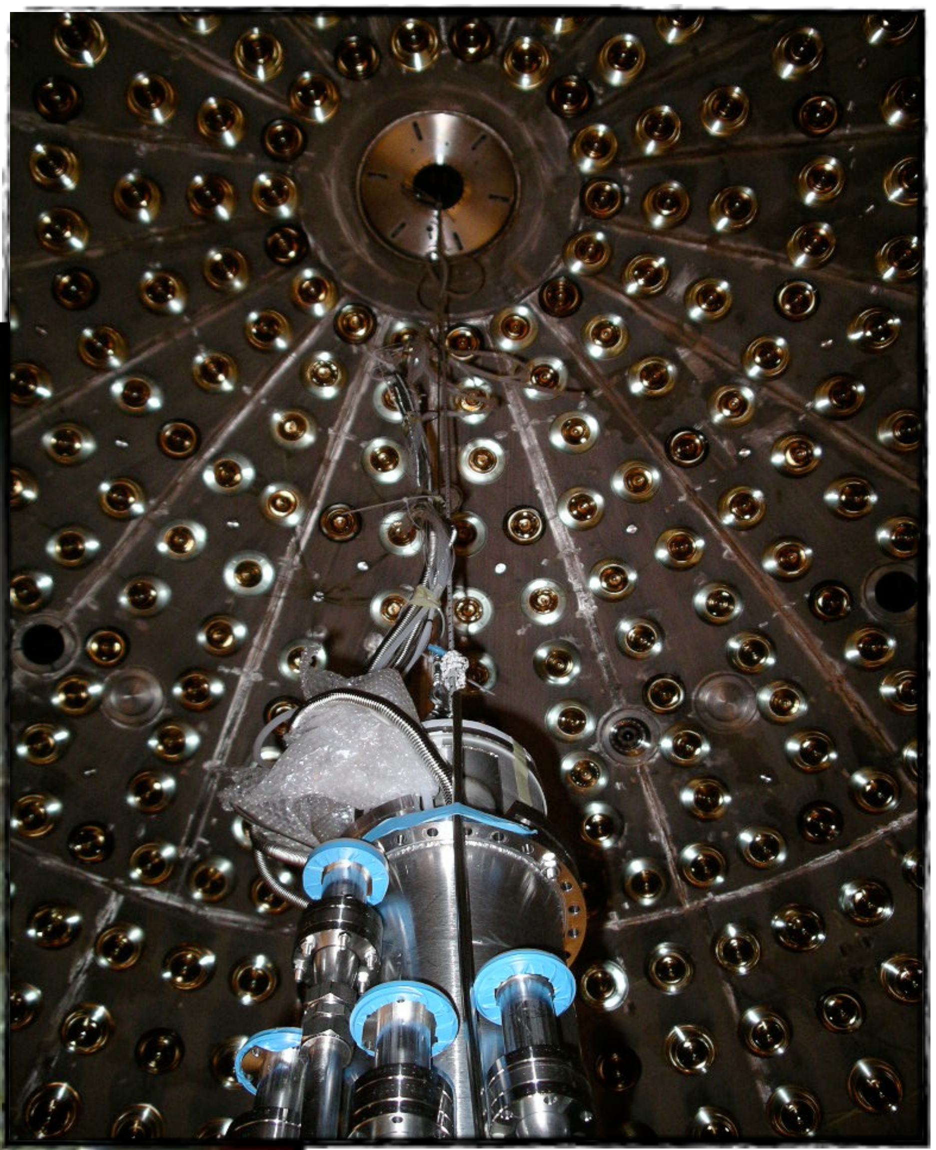
Installation of PMTs and optical fibers



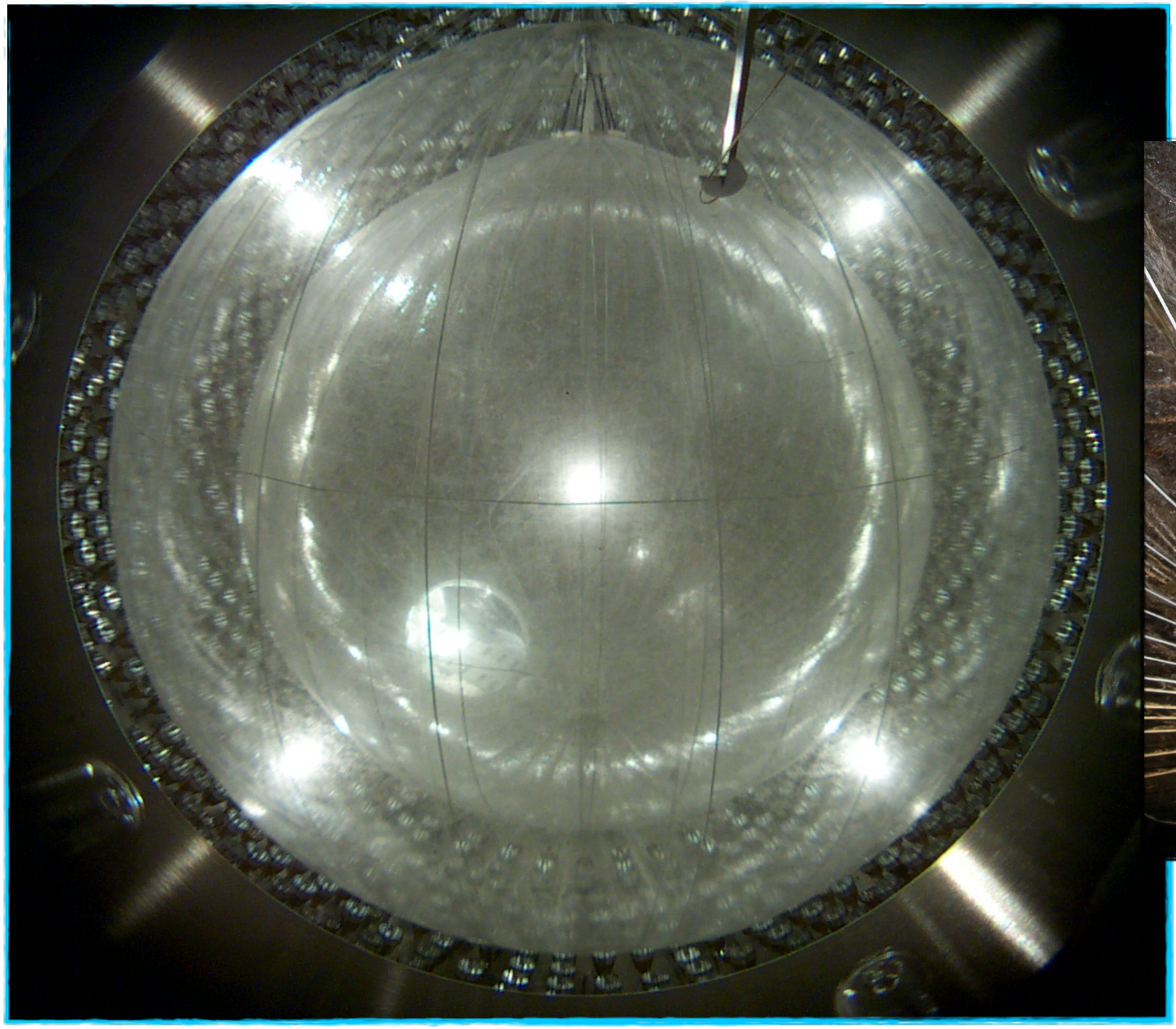
Stainless sphere with PMTs



Installing nylon vessel

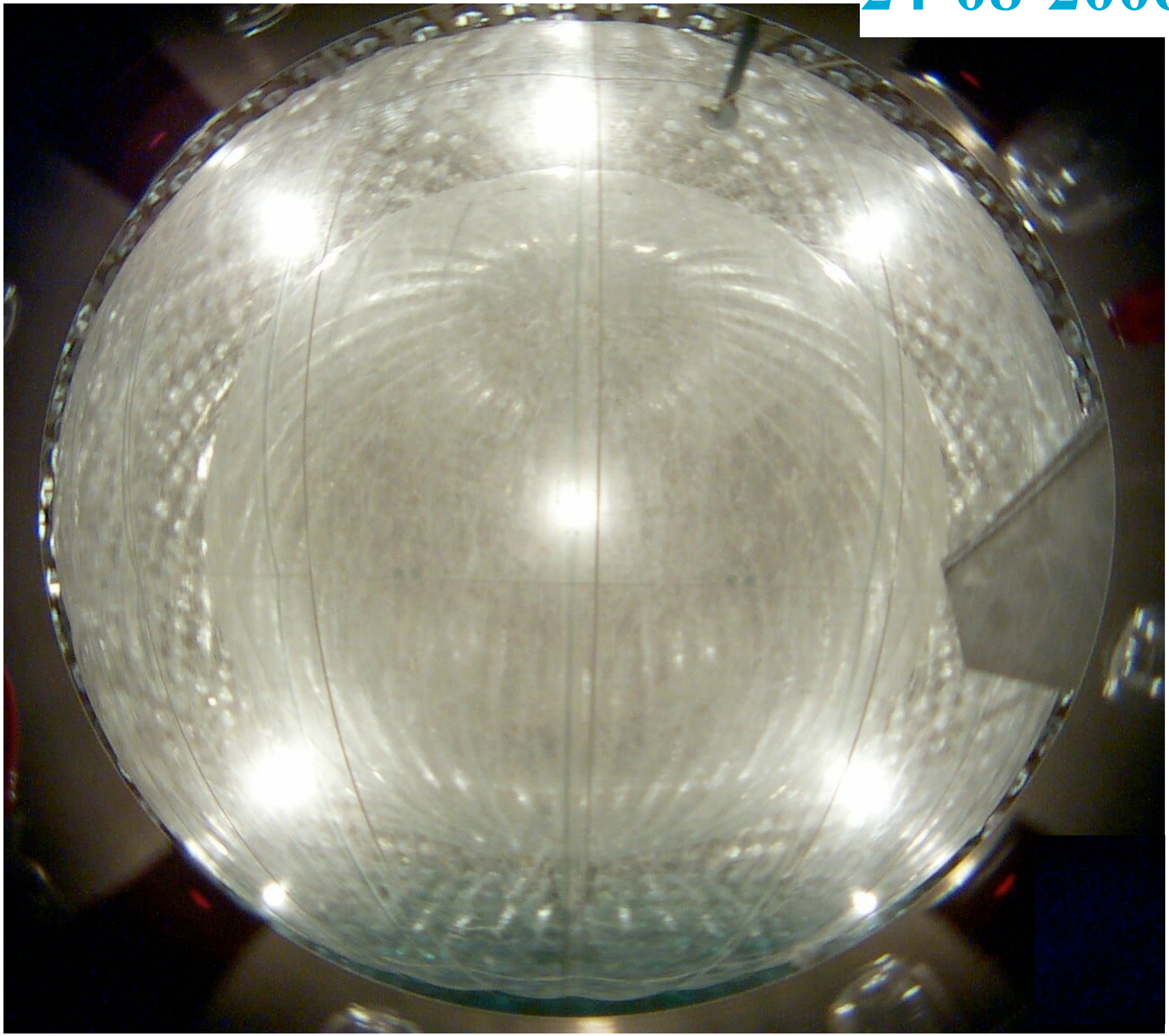


Vessel filled with ultrapure N_2



Water filling (I)

24-08-2006

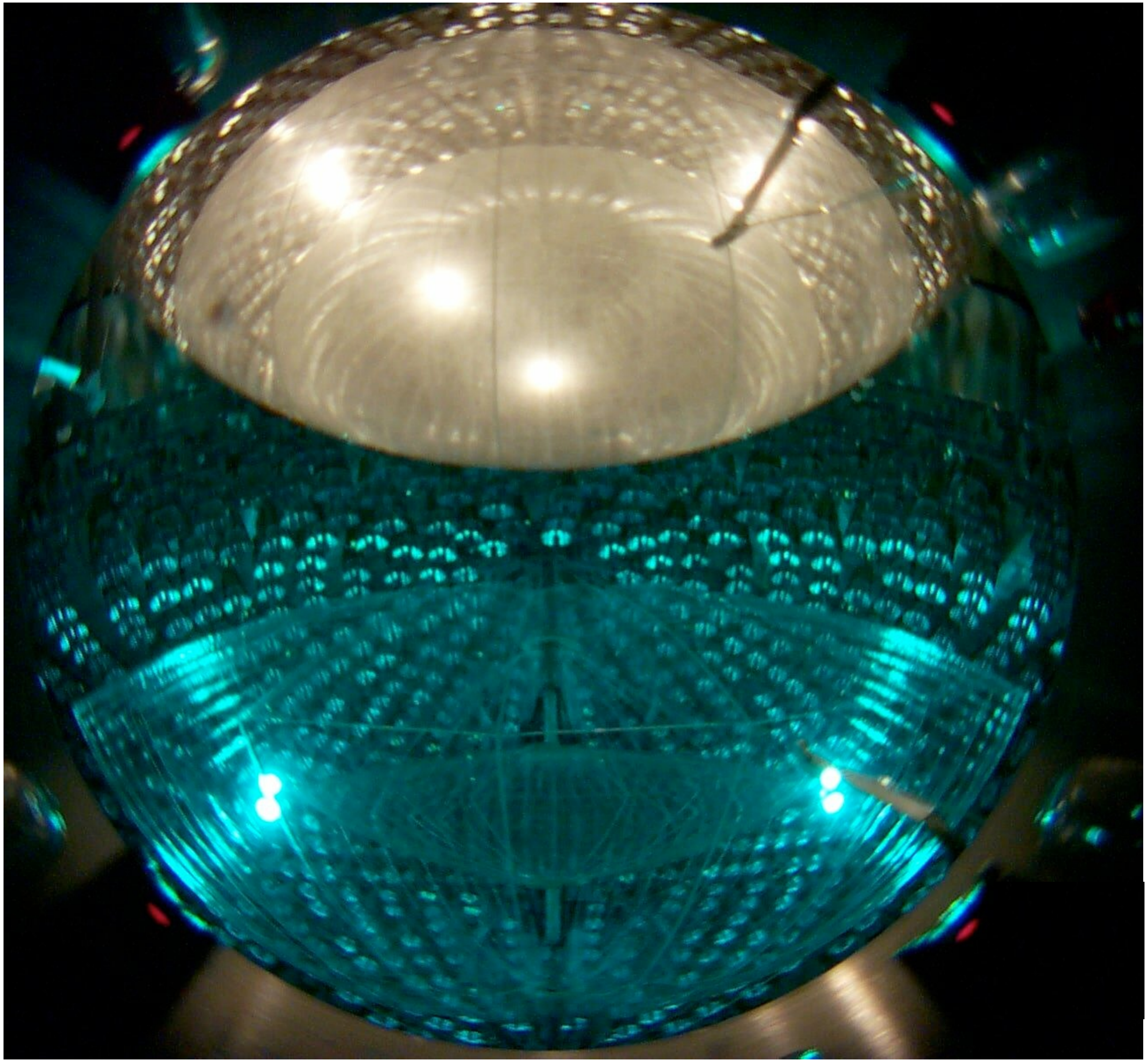


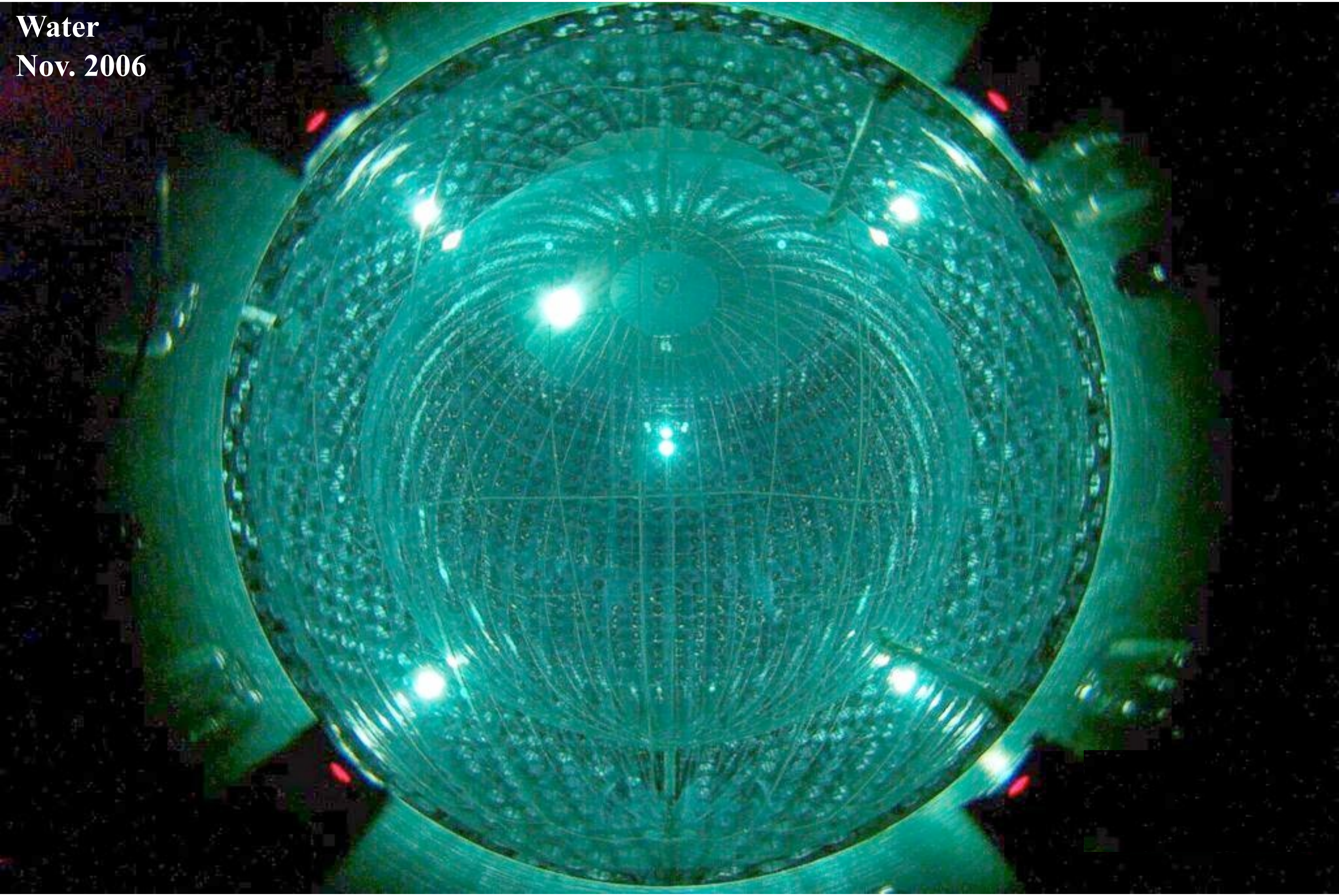
Water filling (II)

20-09-2006

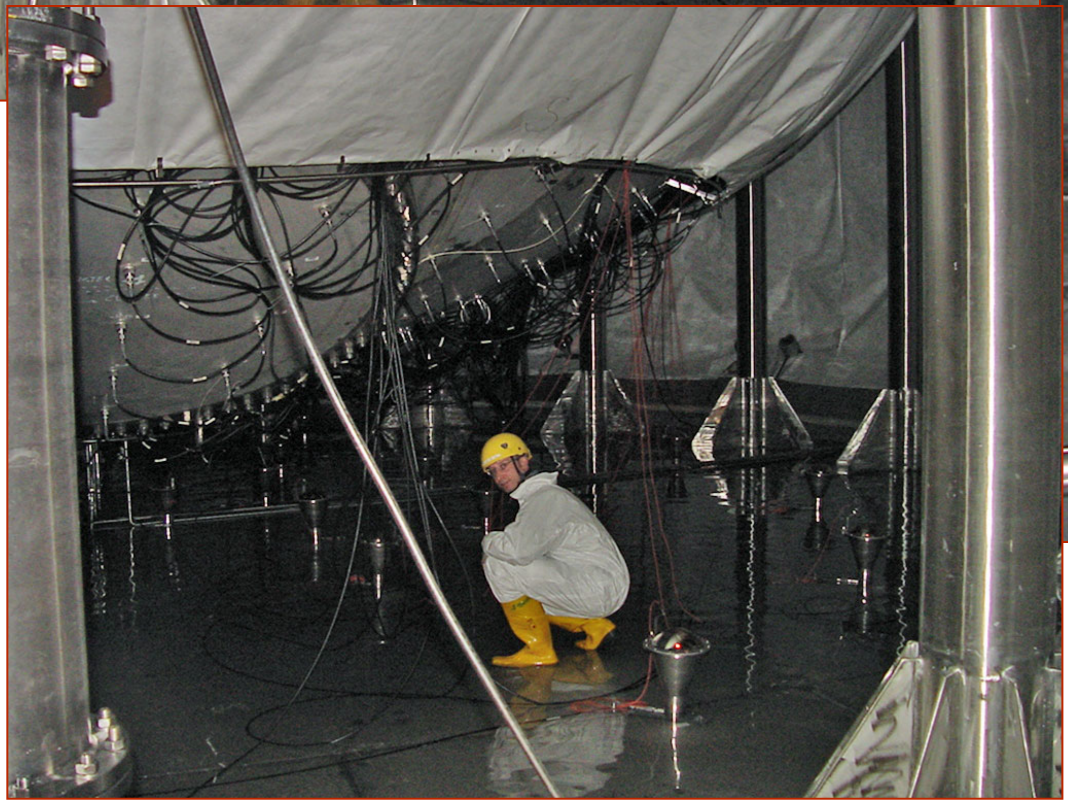
Water filling (III)

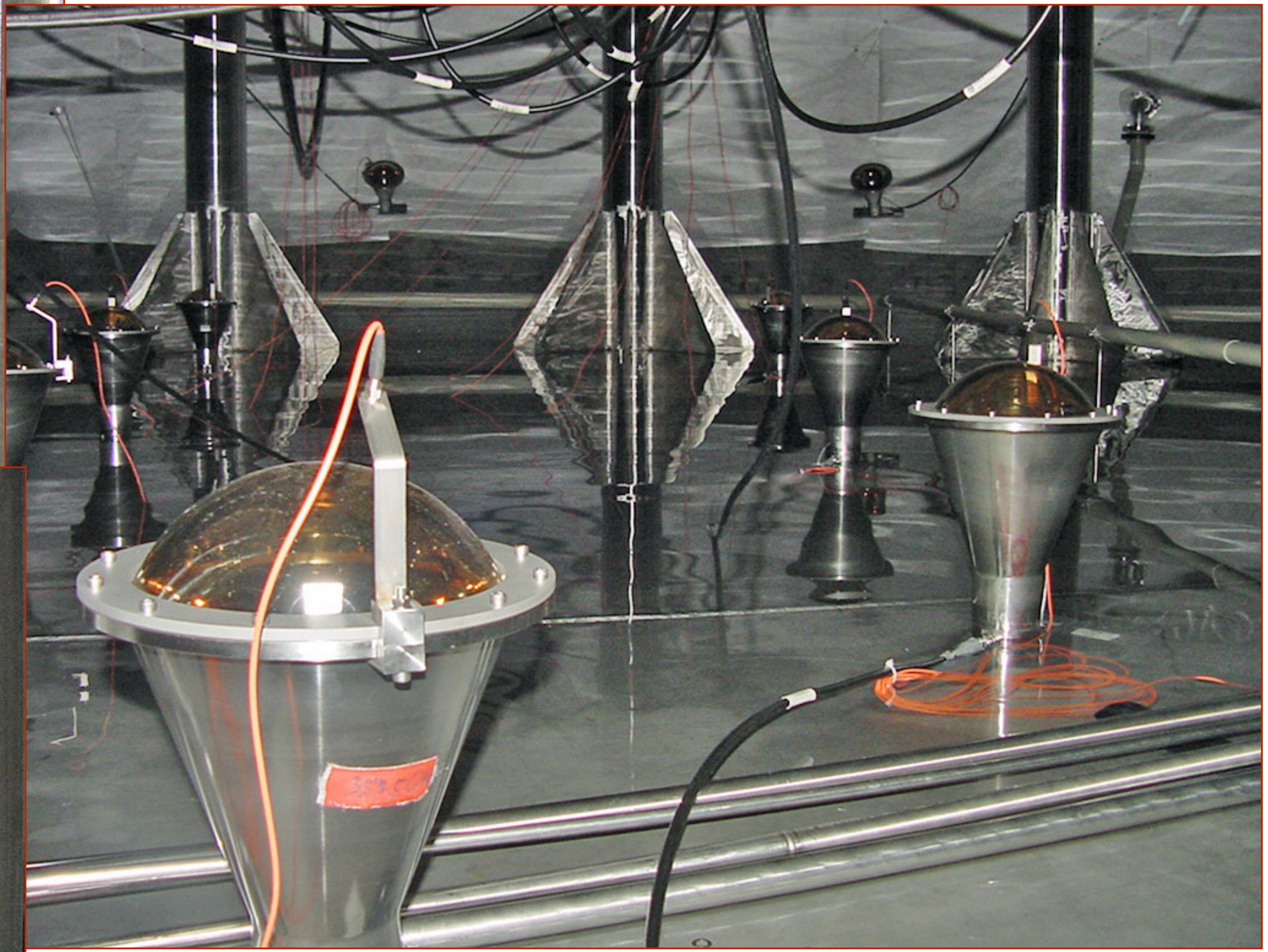
20-10-2006



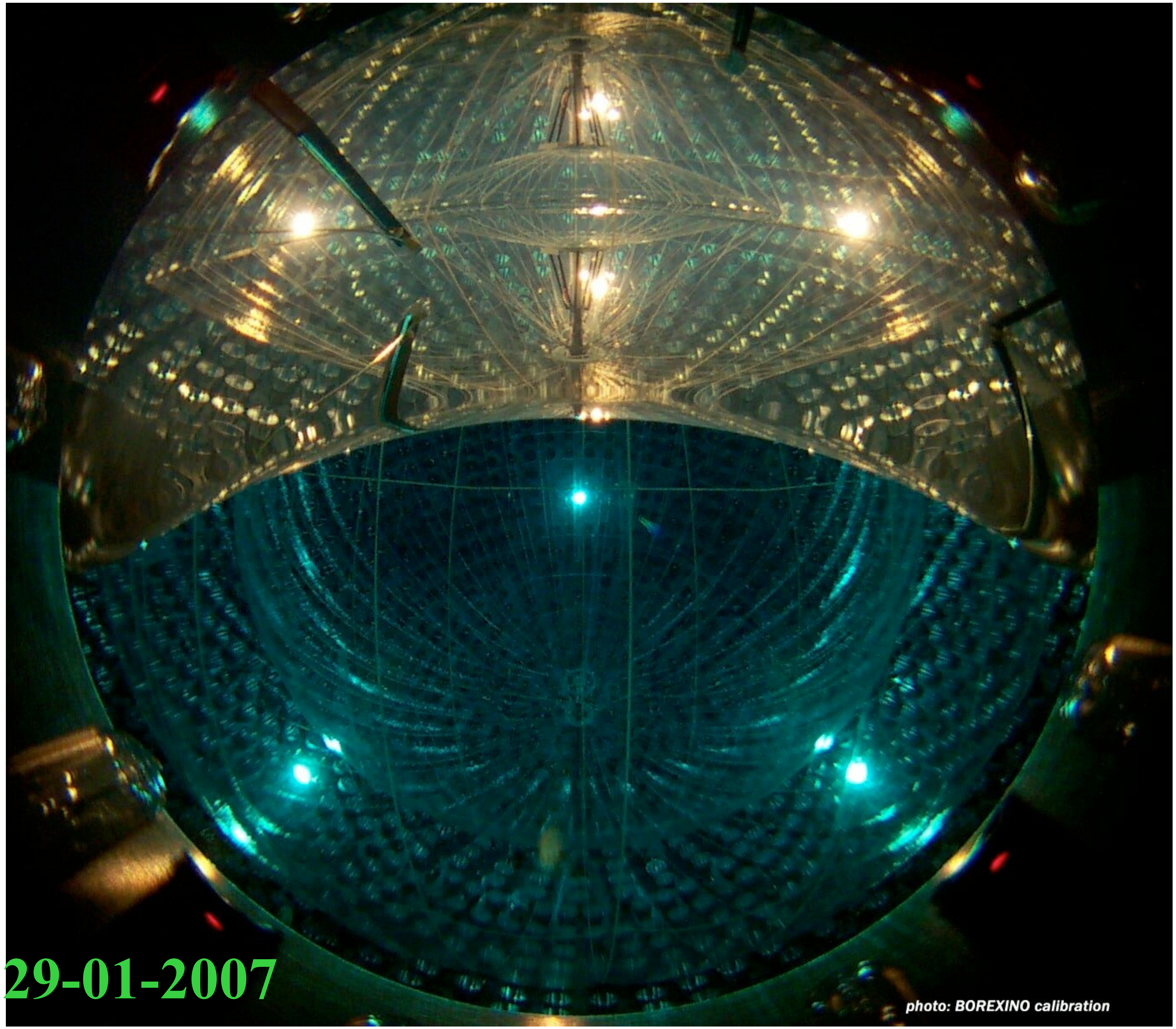

Water
Nov. 2006

Last works inside water tank

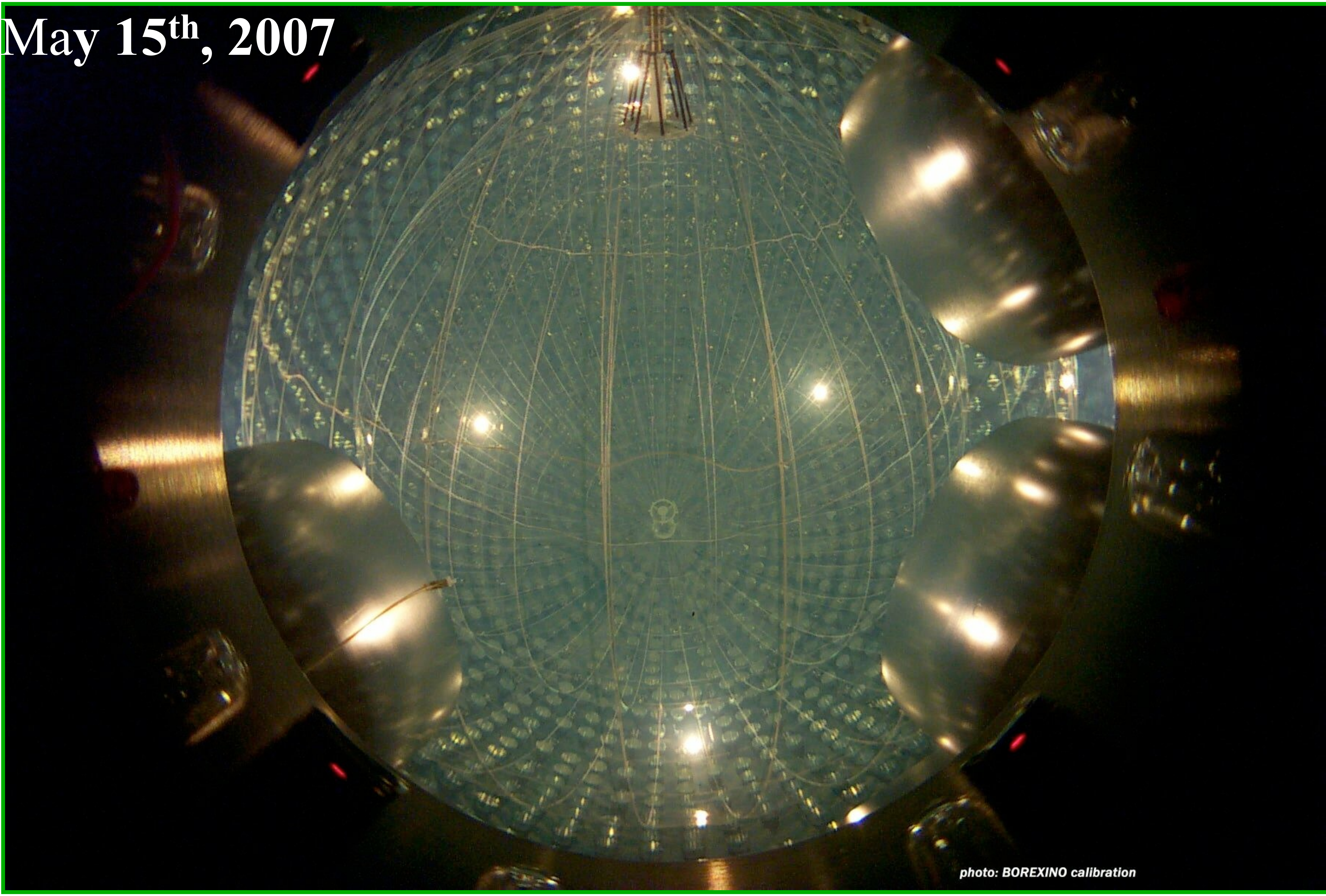




Water and scintillator



May 15th, 2007

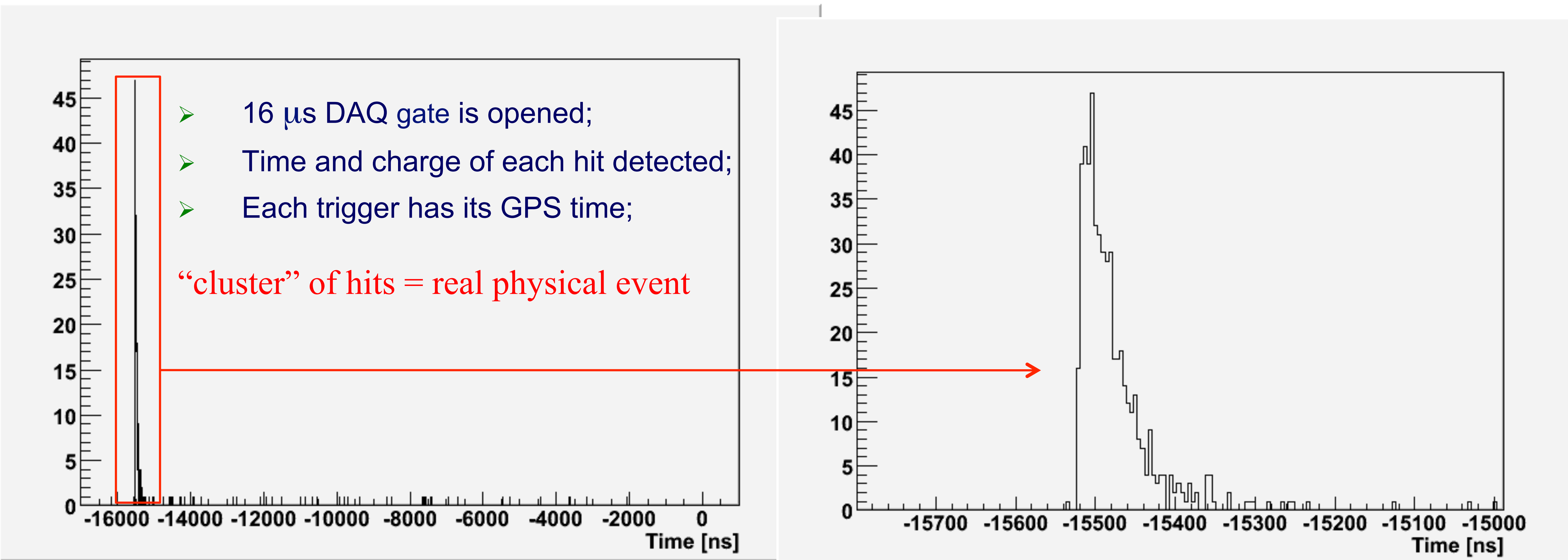


Experimental principle basics

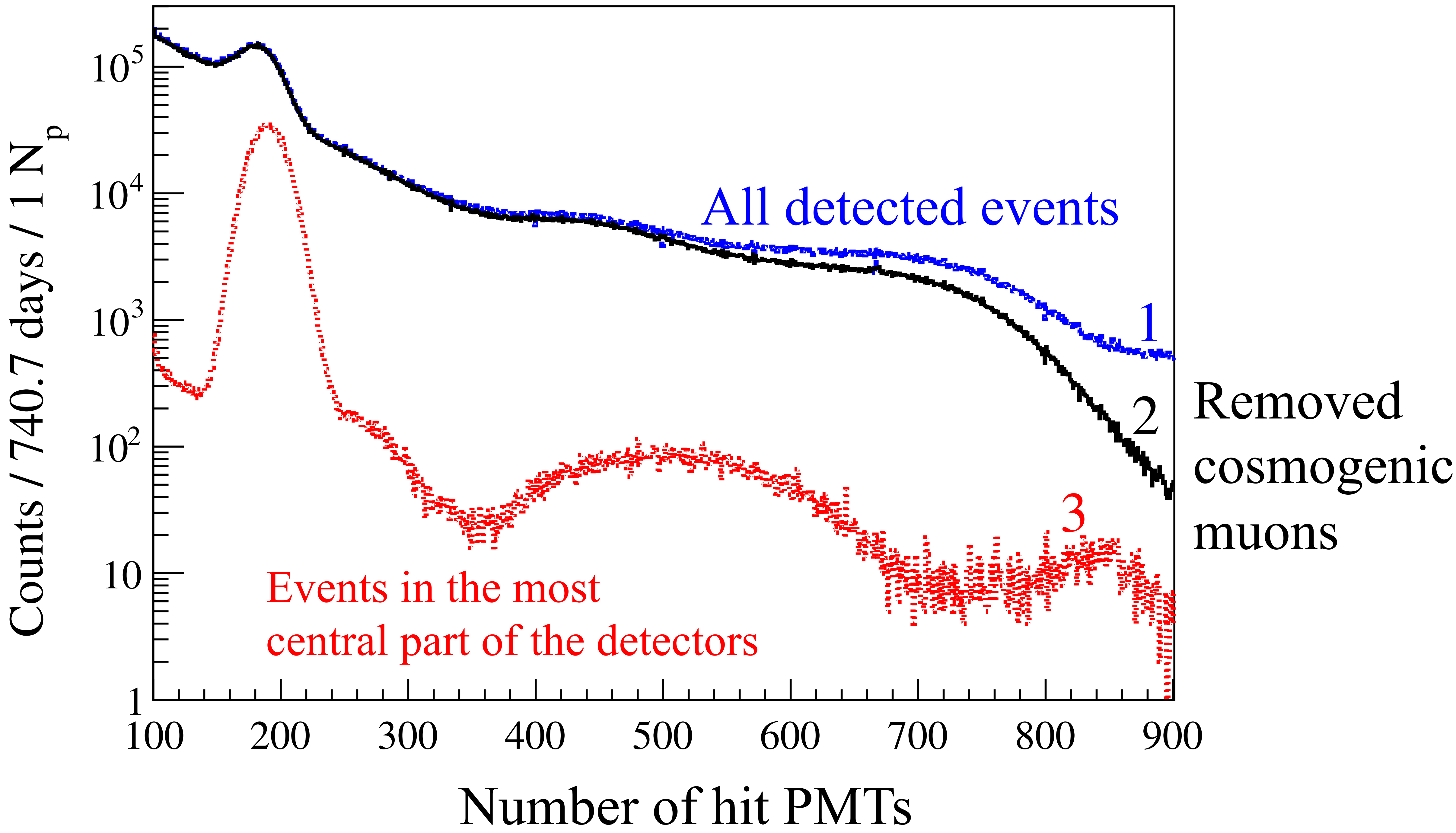
- Charged particles produce **scintillation light;**
- Non charged particles (neutrinos, gamma photons, neutrons) interacts in the scintillator and also produce charged particles, so we can also detect them! (remember, scattered electron!)
- Scintillation light is detected by **an array of phototubes (PMTs)** converting optical signal to electrical signal;
- Number of hit PMTs = function of energy of the particle;
- Hit PMTs time pattern = position reconstruction of the event;
- Each trigger has its GPS time -> Δ time of events

Example of a measured interaction

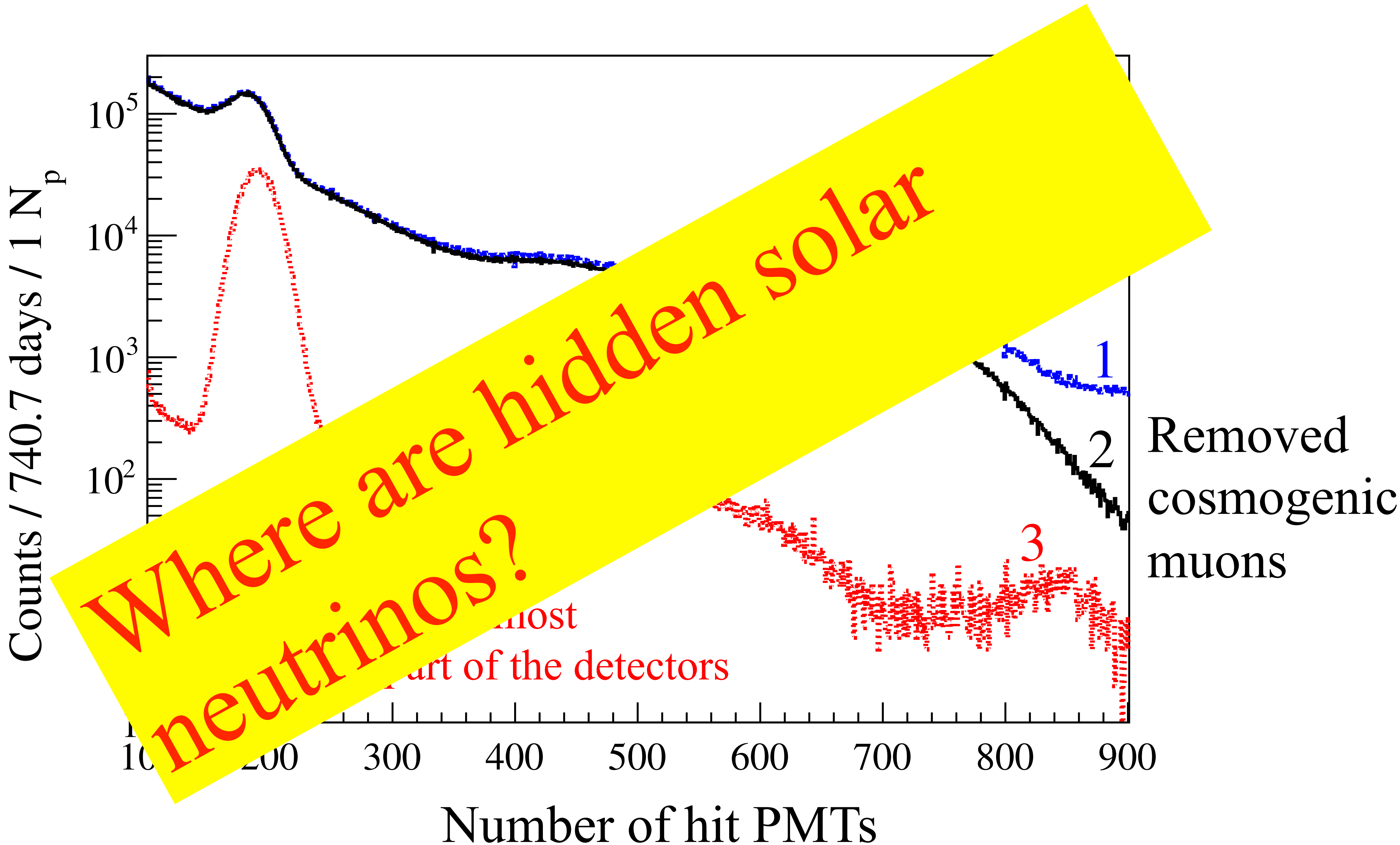
- Charged particles produce scintillation light: photons hit inner PMTs;
- DAQ trigger: > 25 inner PMTs are hit within 60-95 ns:



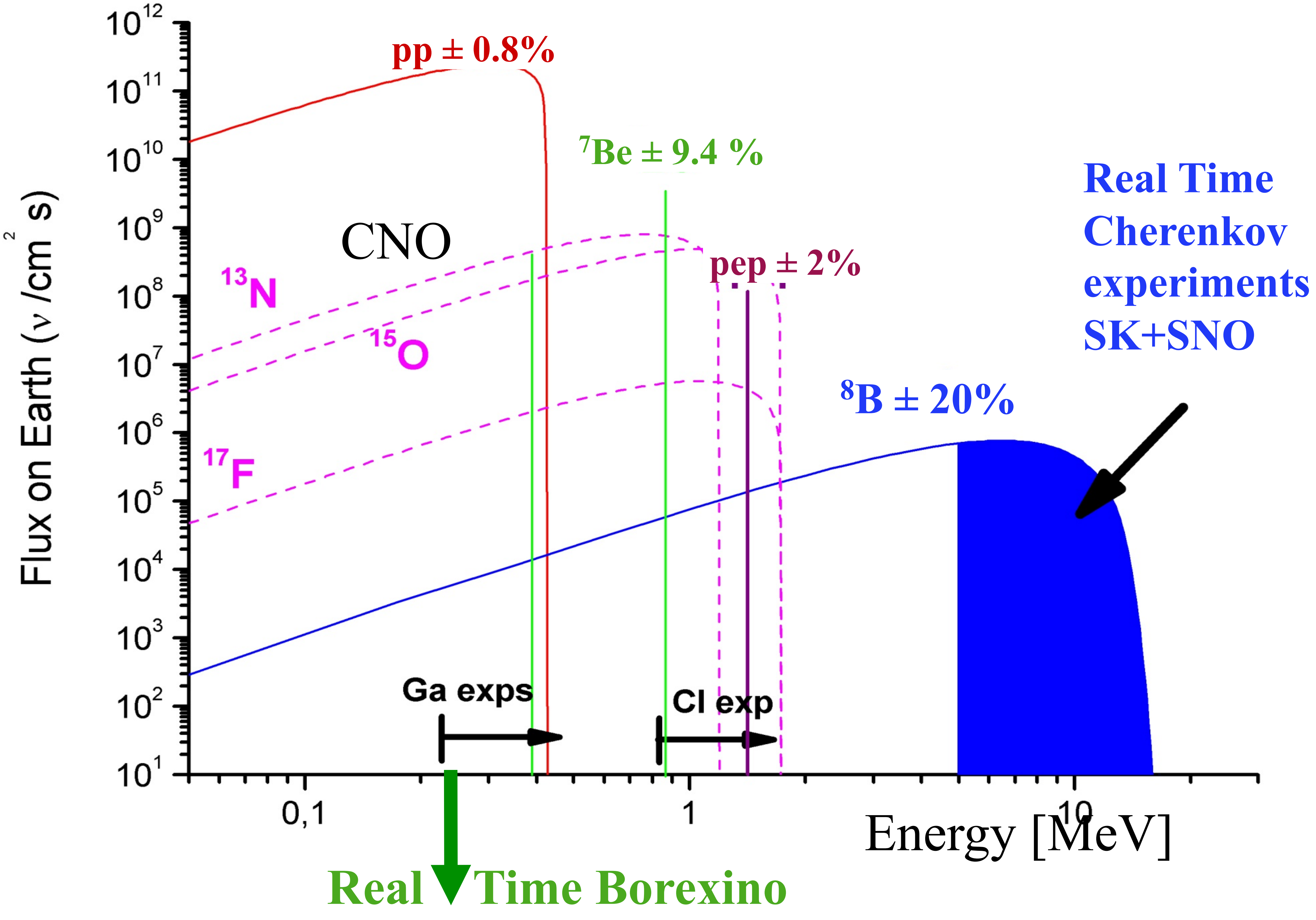
Borexino energy spectrum of ~2 years



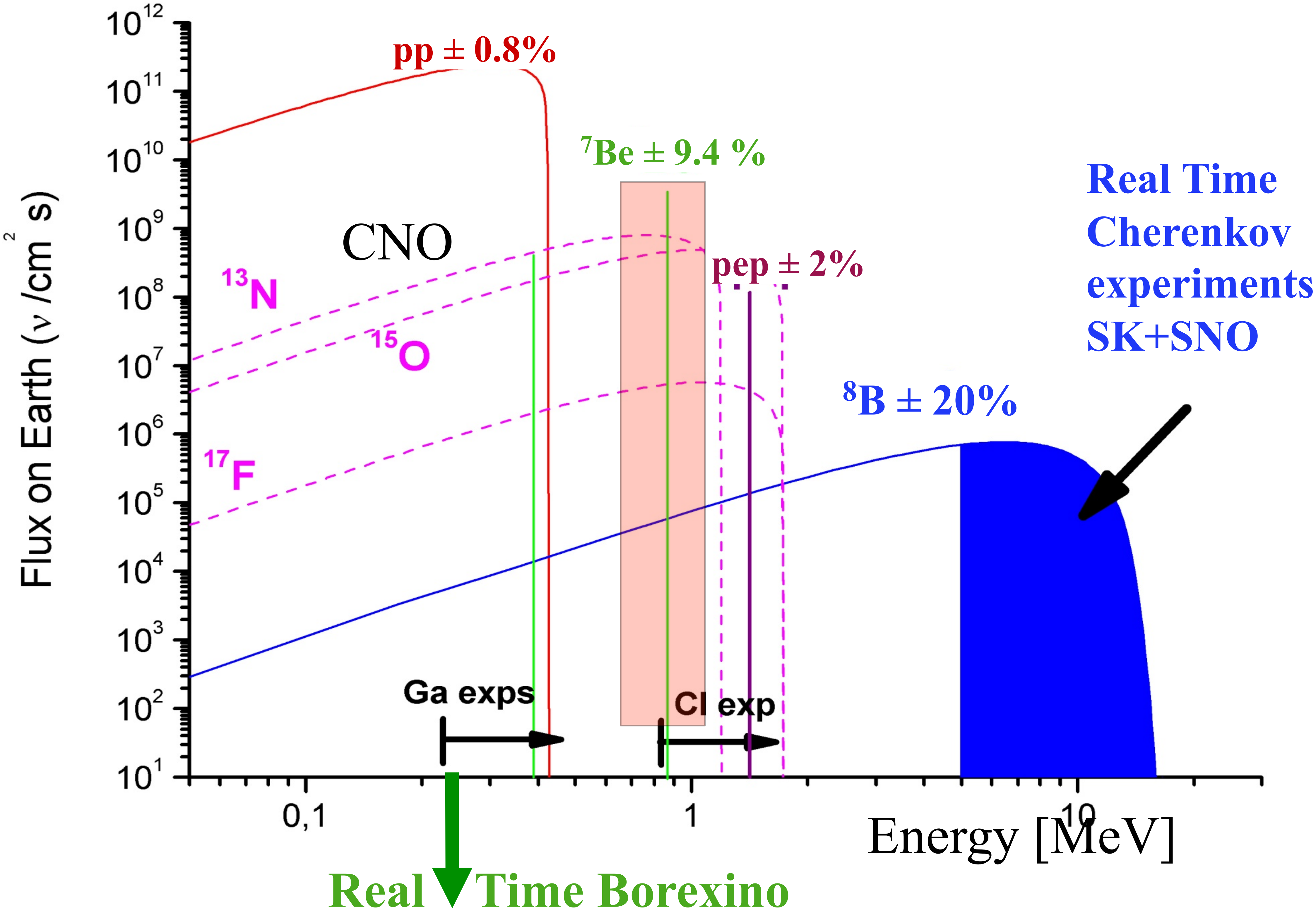
Borexino energy spectrum of ~2 years



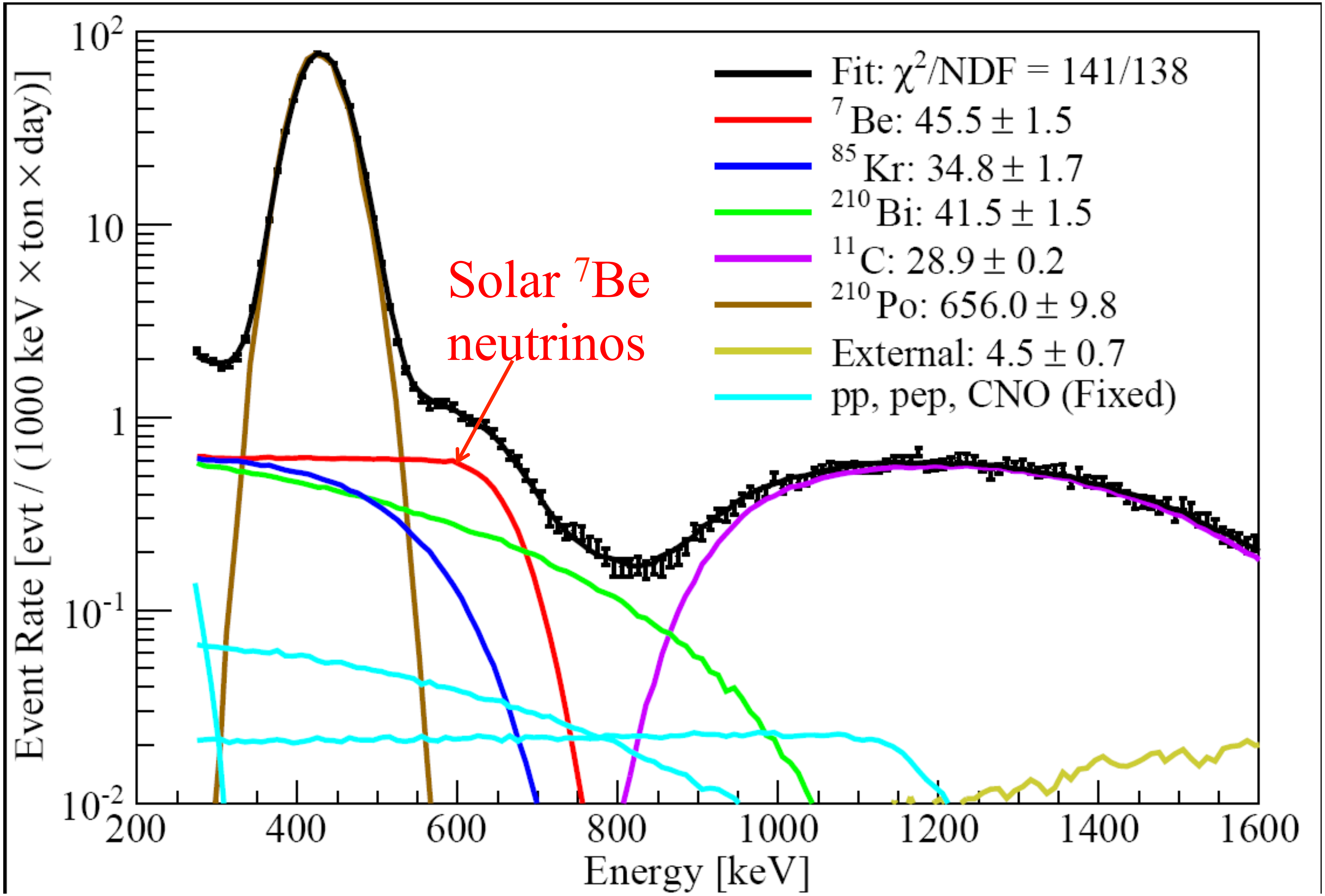
Recalling spectrum of solar neutrinos



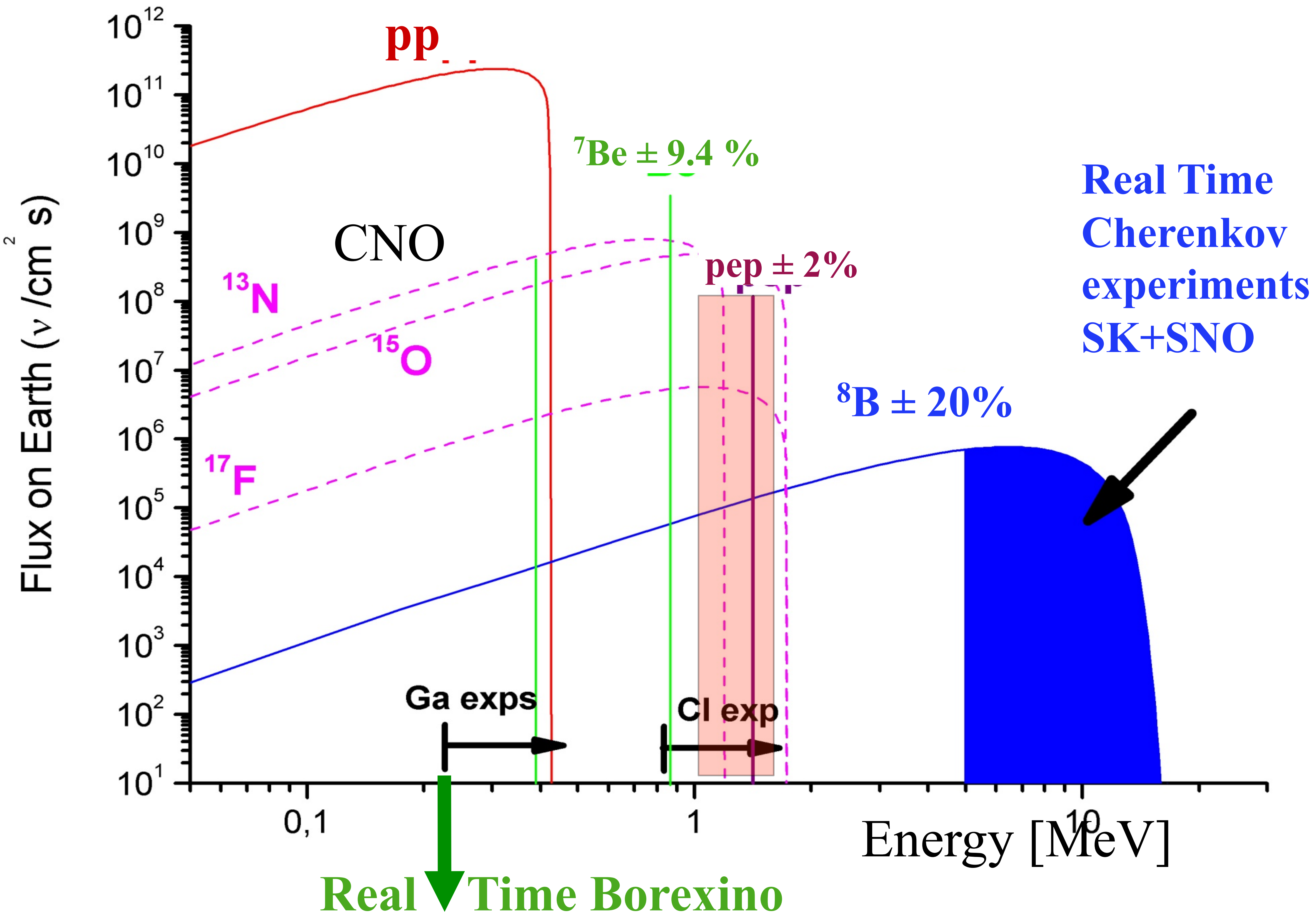
Recalling spectrum of solar neutrinos



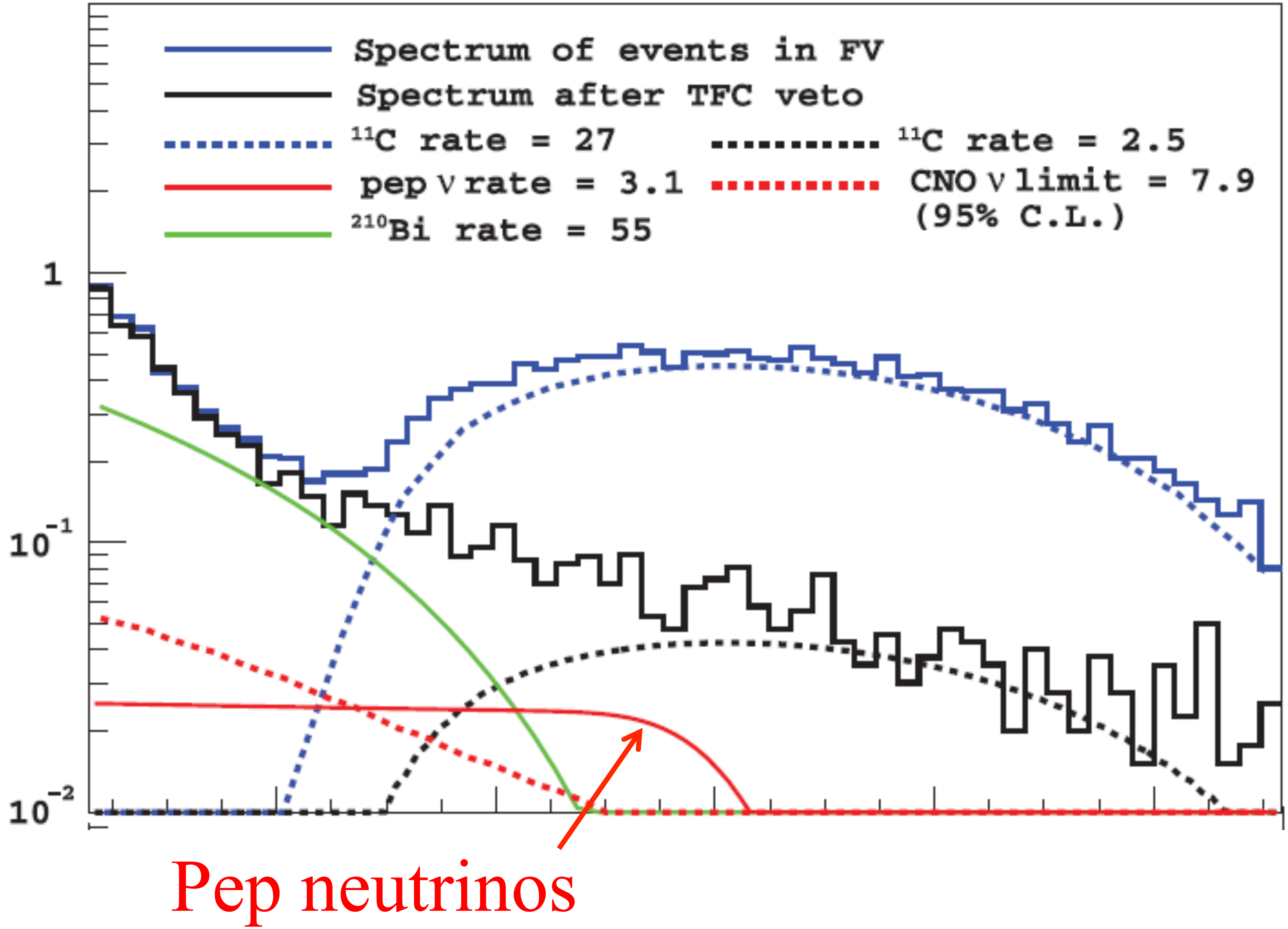
Borexino fit spectrum: ^{7}Be neutrinos



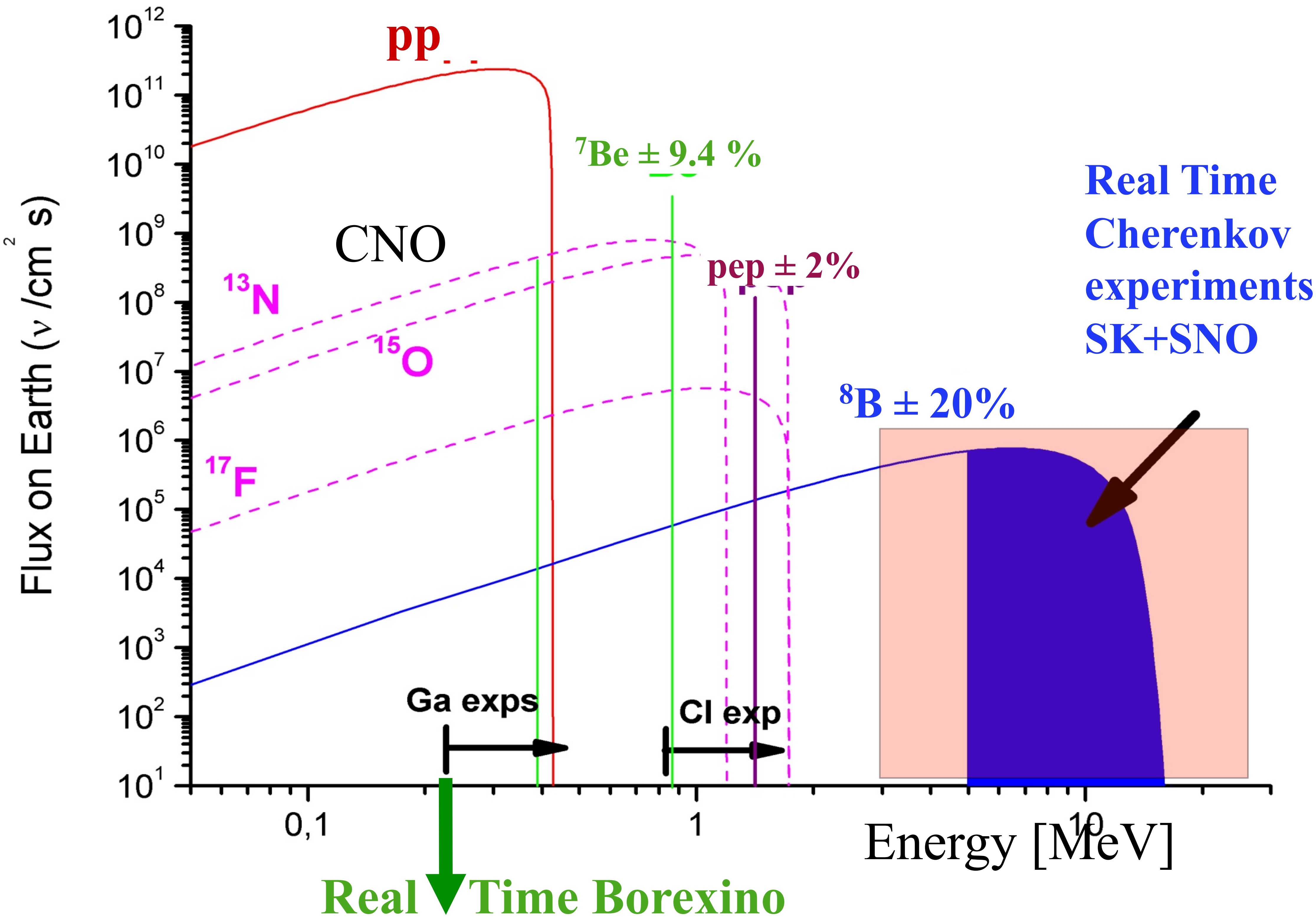
Recalling spectrum of solar neutrinos



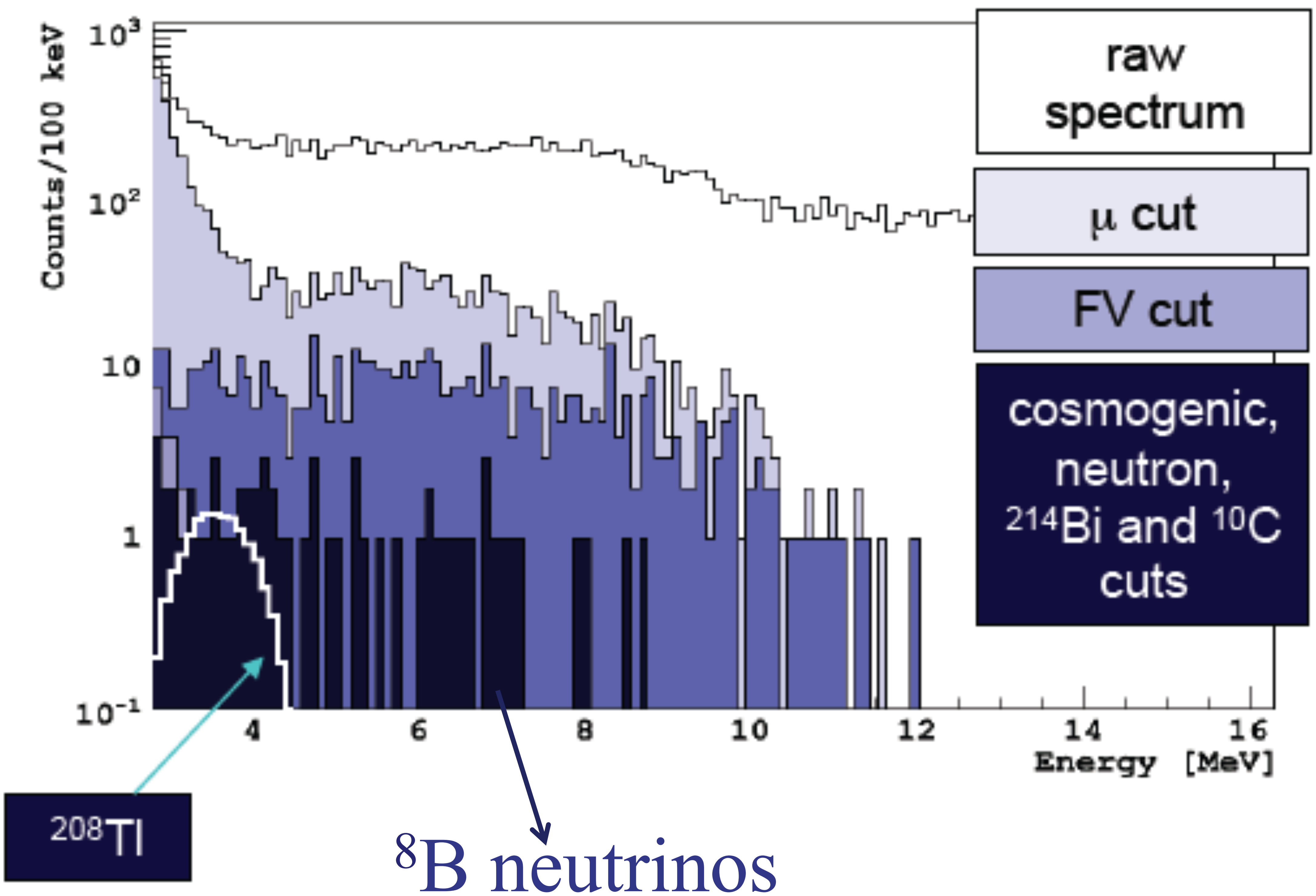
Borexino fit spectrum: pep neutrinos



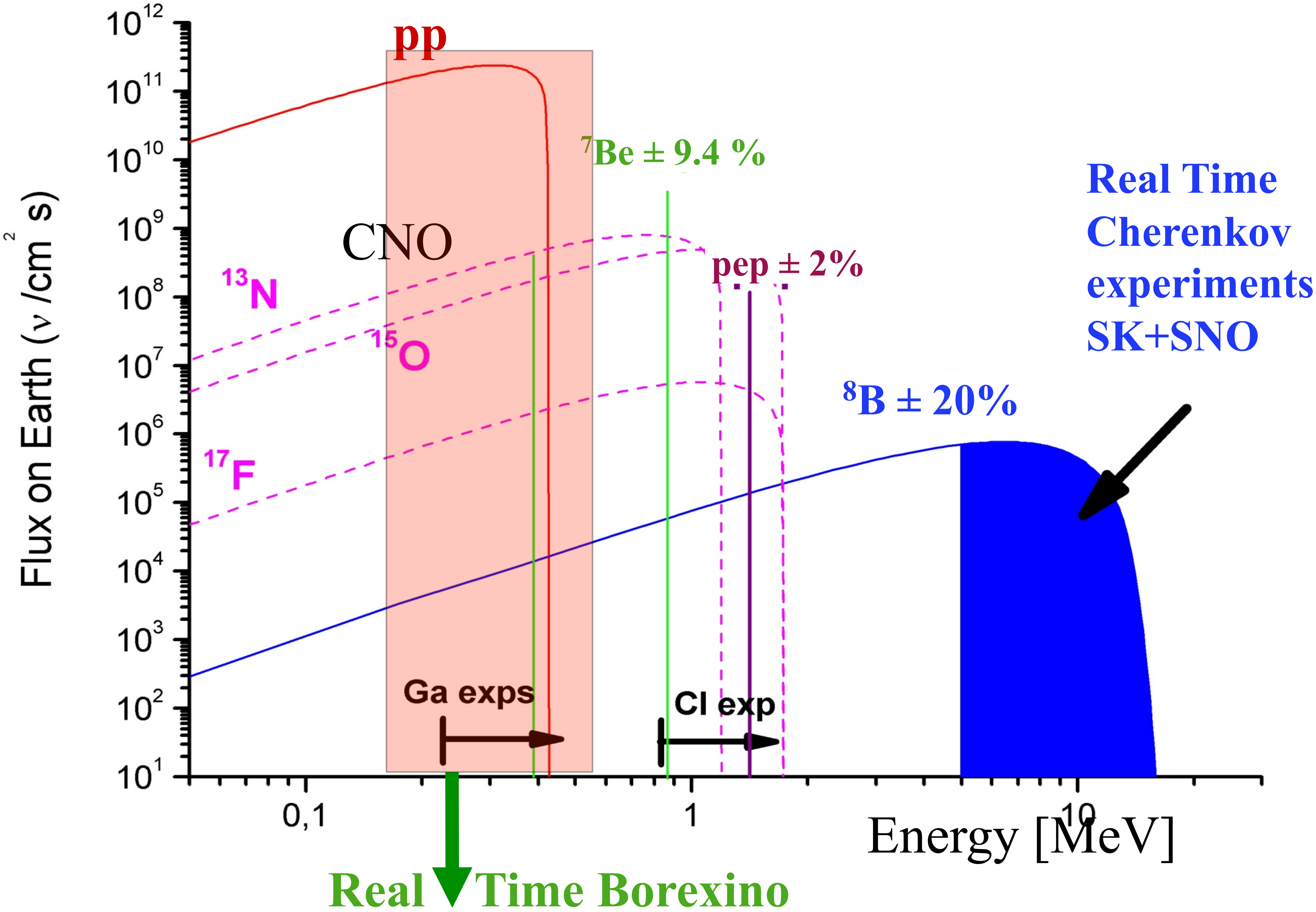
Recalling spectrum of solar neutrinos



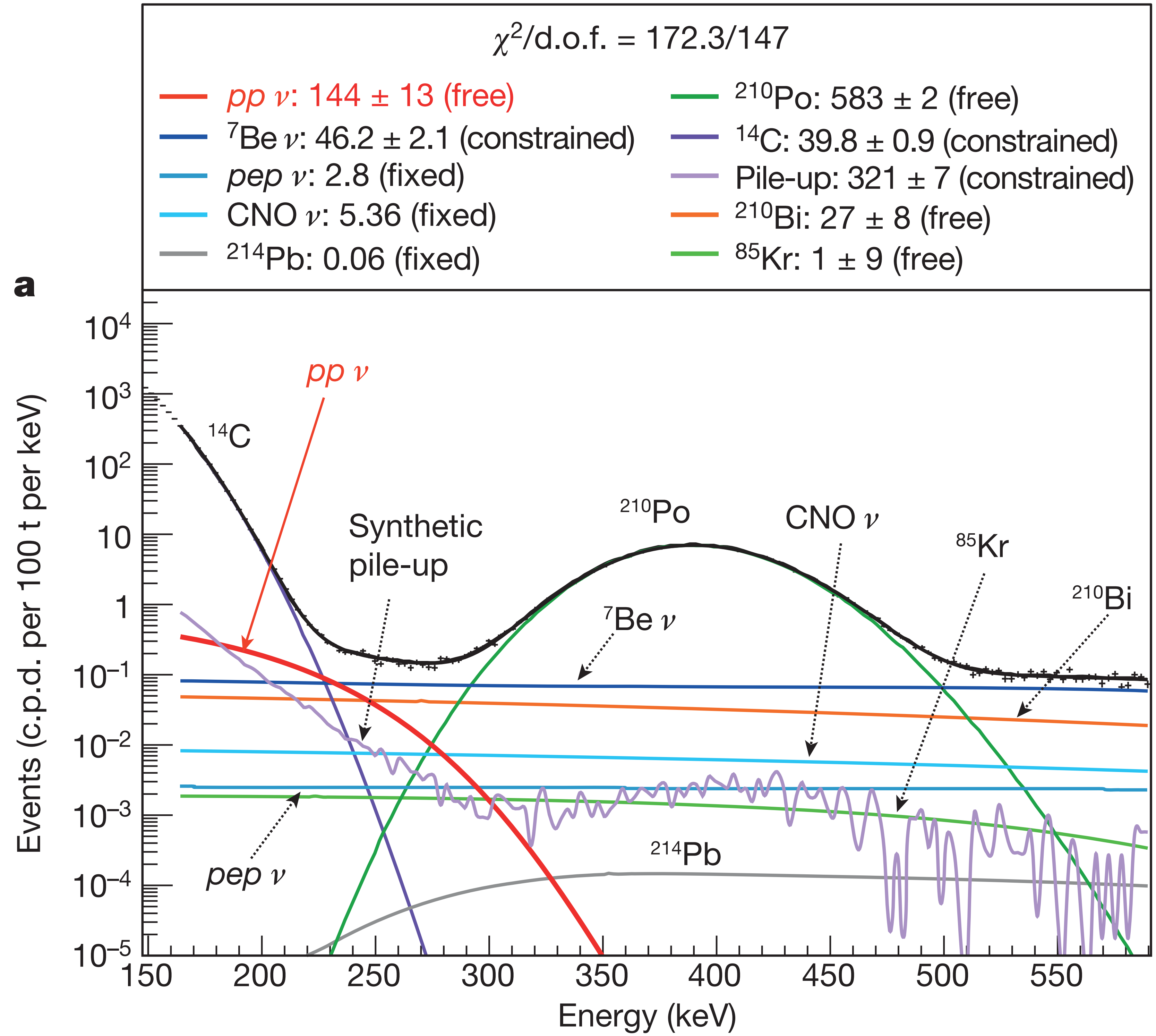
Borexino fit spectrum: pep neutrinos



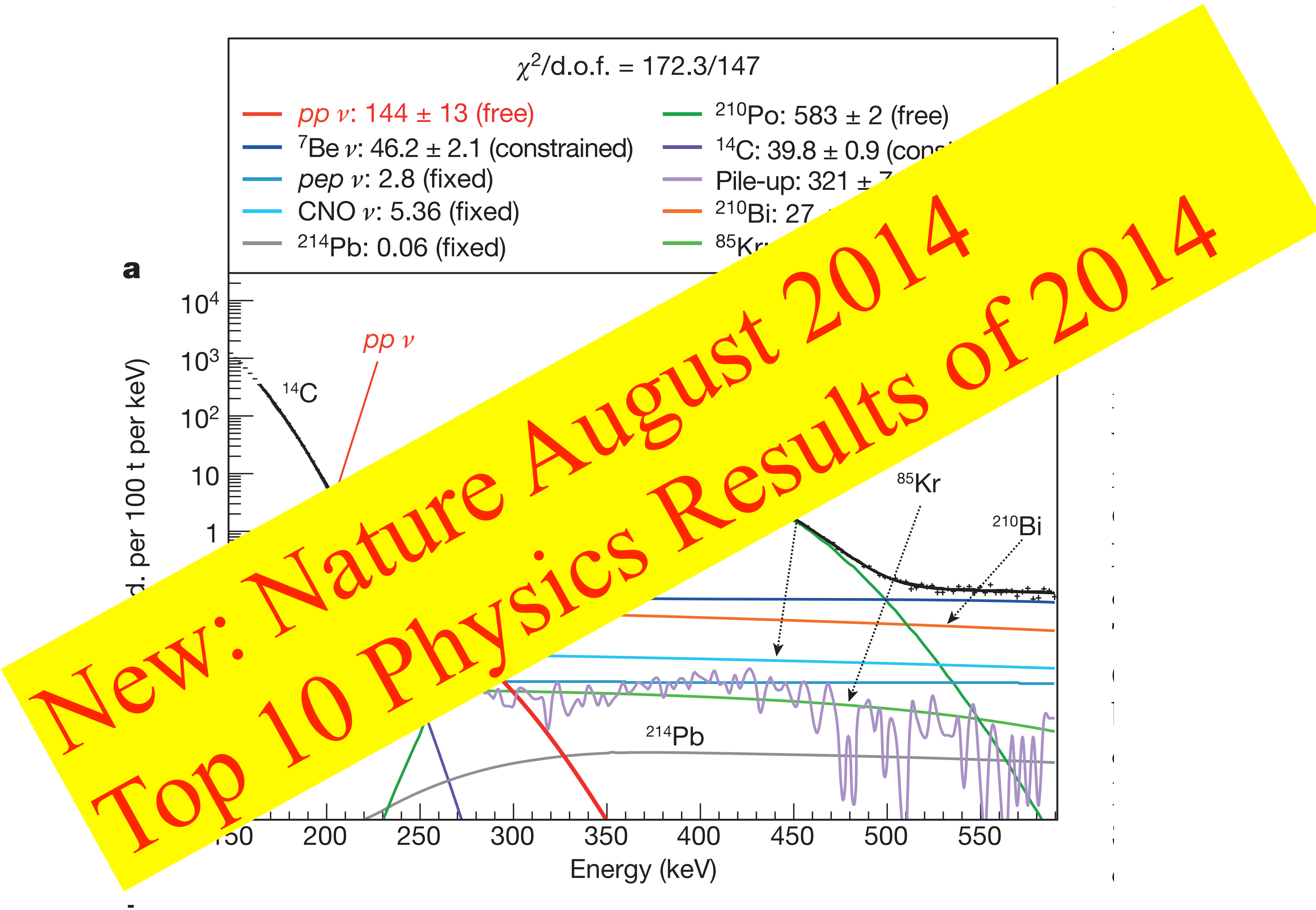
Recalling spectrum of solar neutrinos



Borexino fit spectrum: pp neutrinos



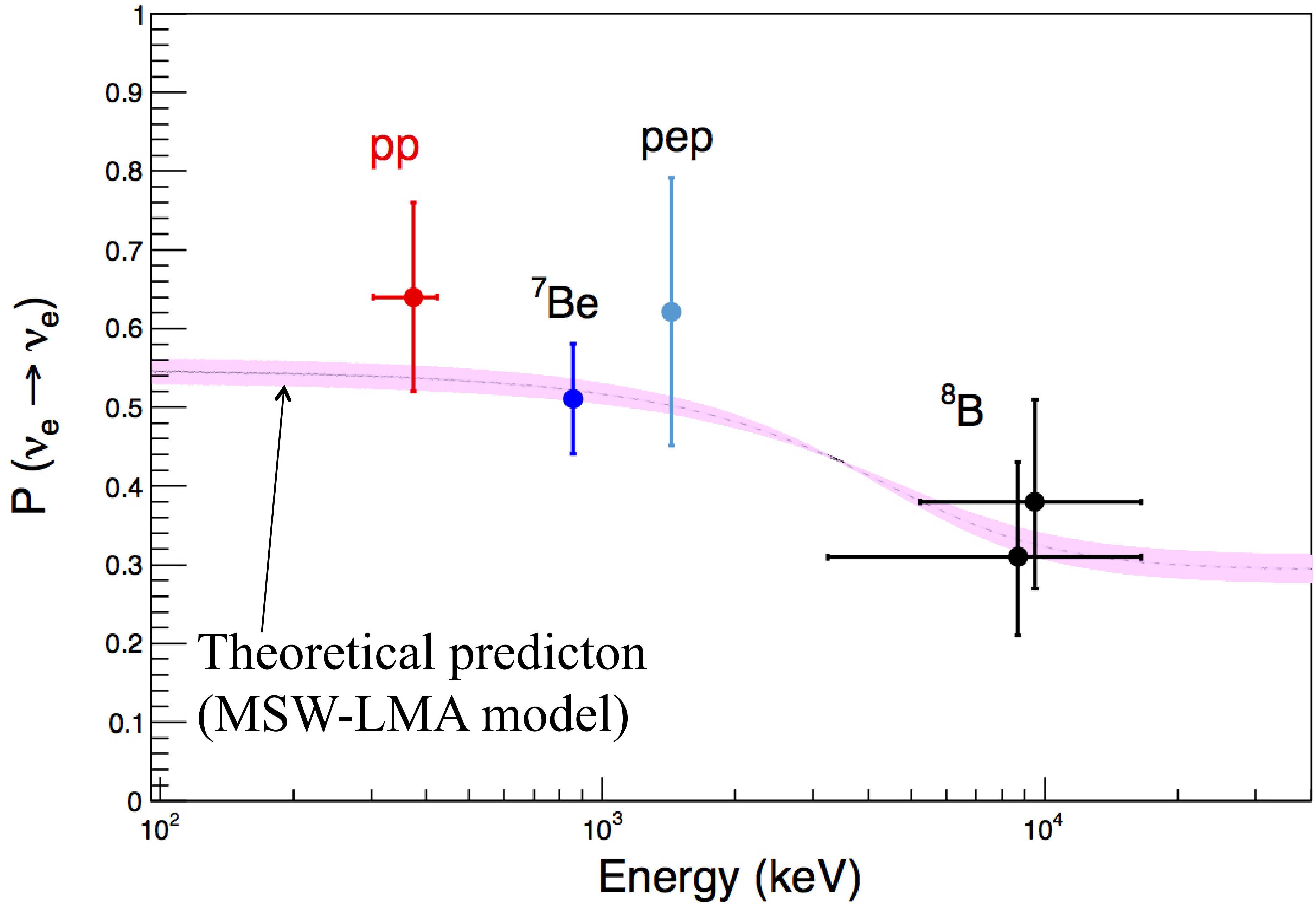
Borexino fit spectrum: pp neutrinos



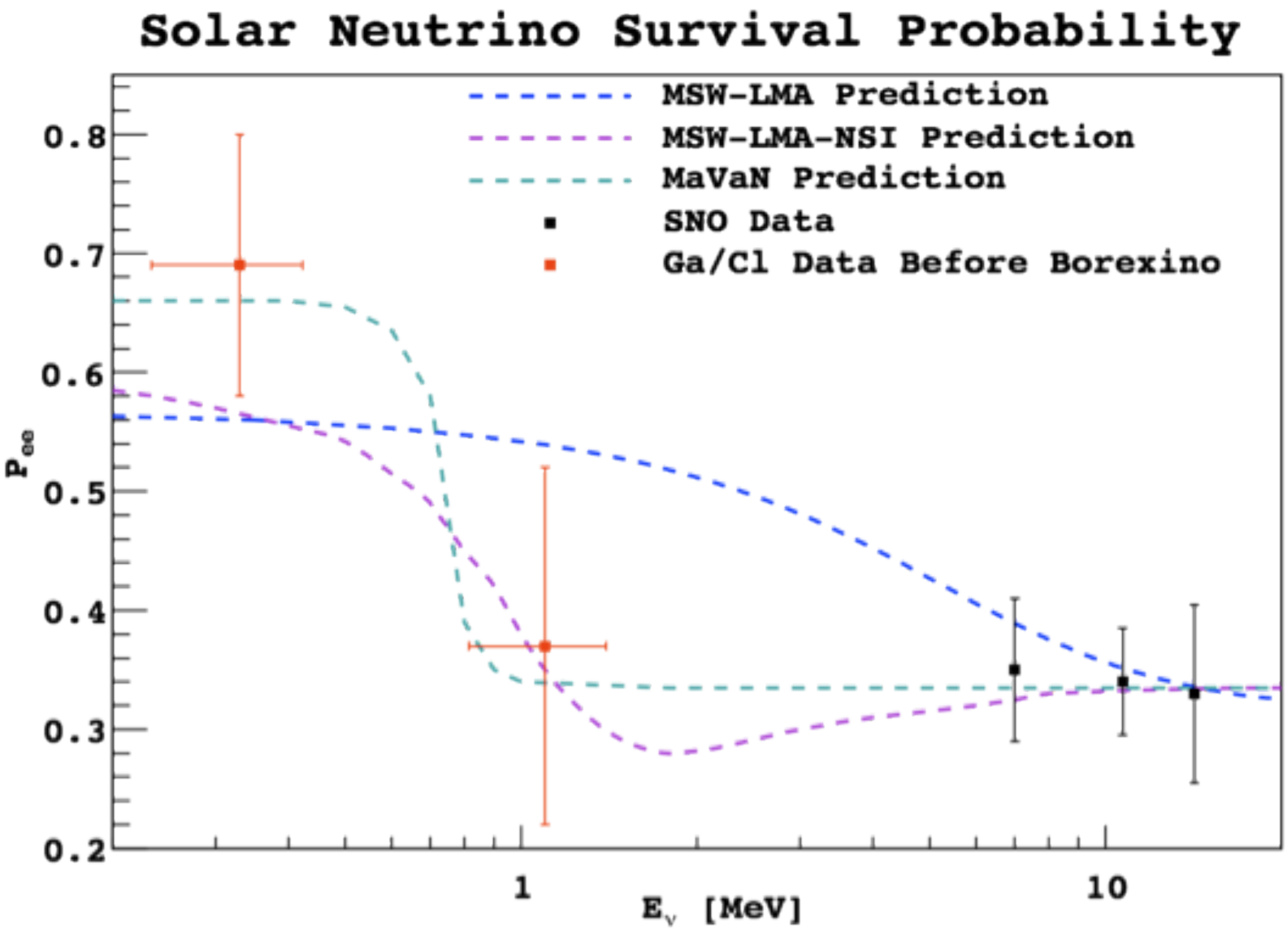
Implications of Borexino solar neutrino measurements: I.

NEUTRINO PHYSICS

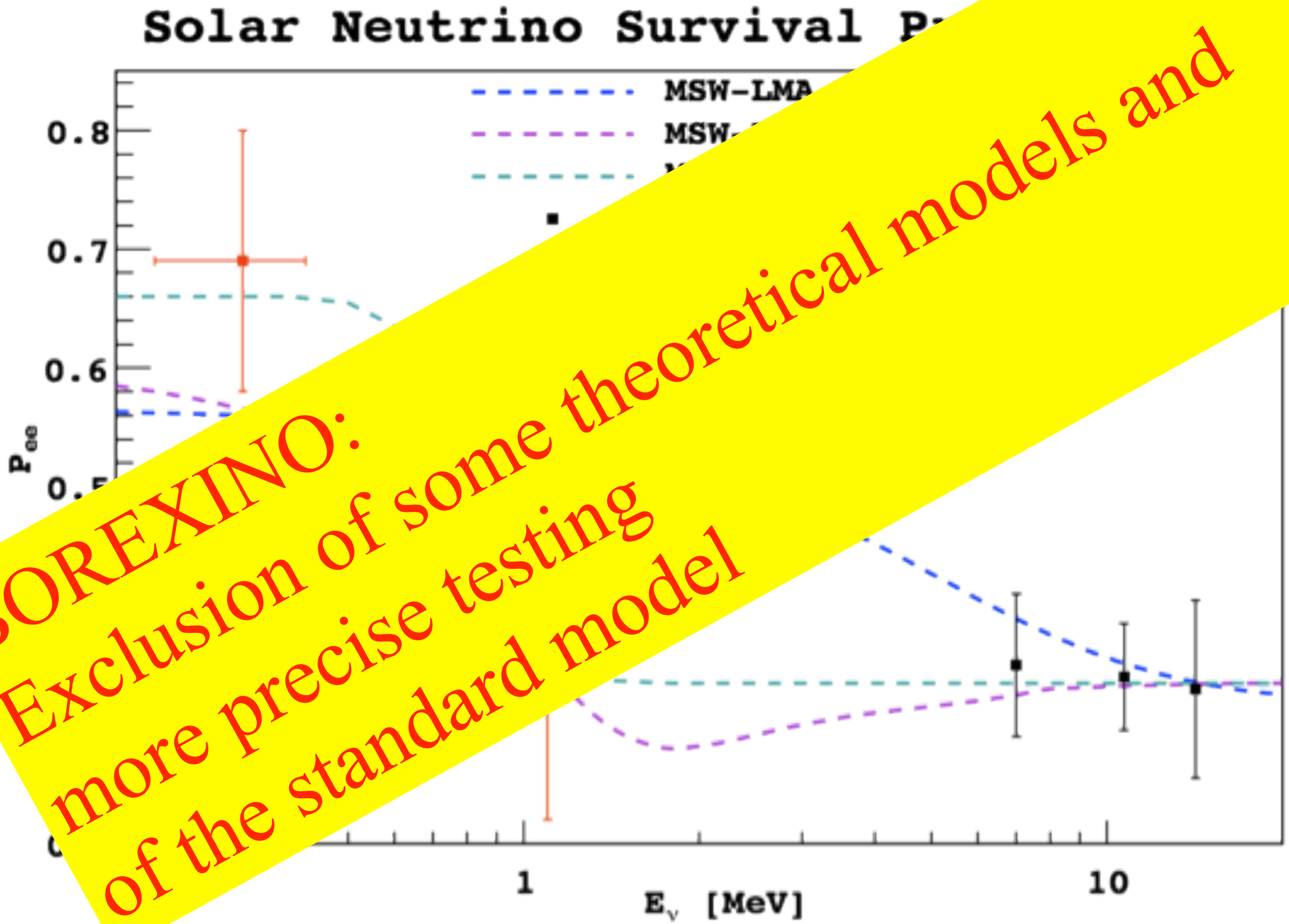
Electron neutrino survival probability as a function of energy



Situation before Borexino



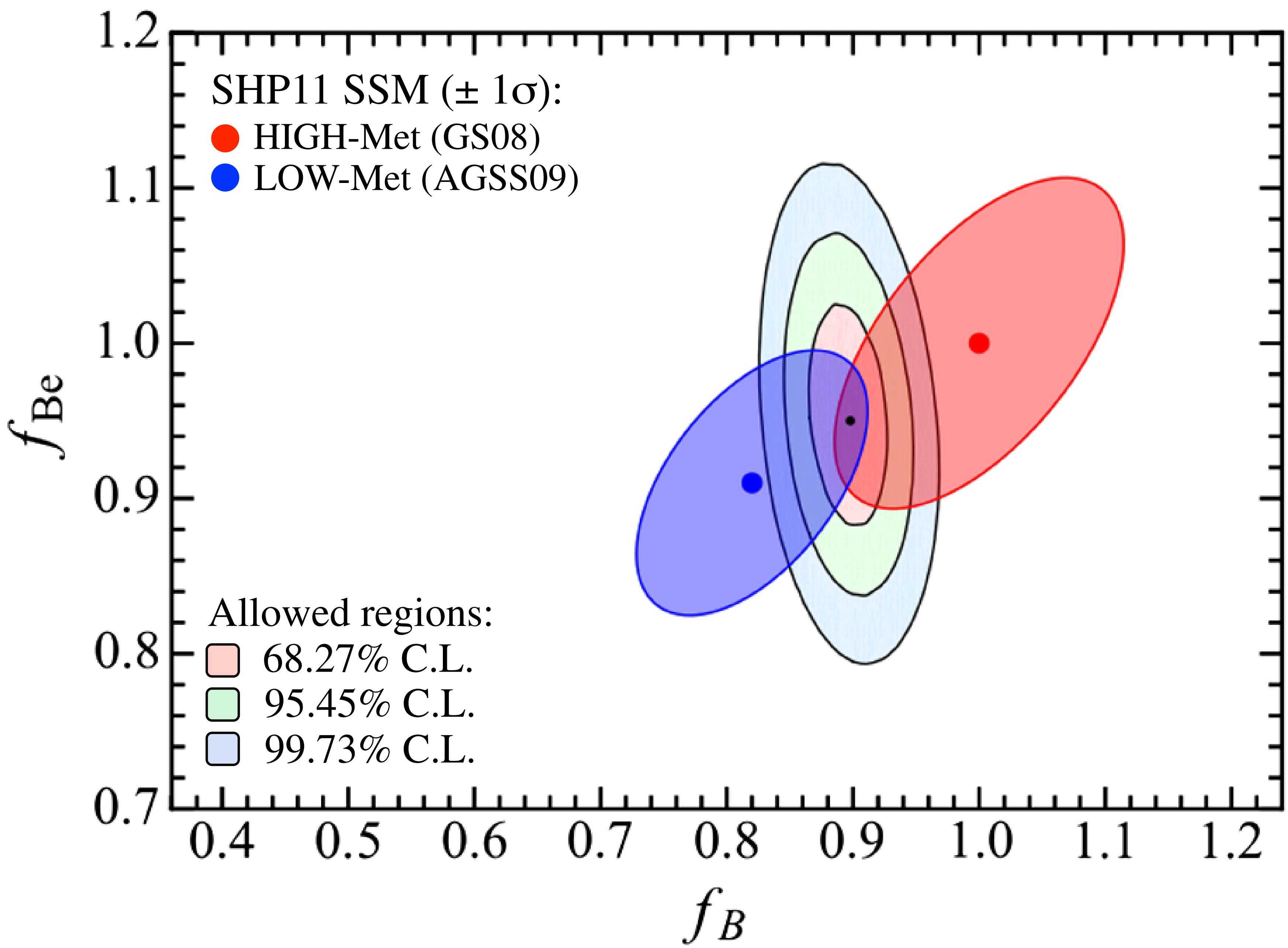
Situation before Borexino



BOREXINO:
Exclusion of some theoretical models and more precise testing of the standard model

Implications of Borexino solar neutrino measurements: II.

SOLAR PHYSICS



Conclusions

- **Sun** is our closest star;
- It produces its energy in **thermonuclear fusion reactions**;
- **Solar neutrinos**

  = witnesses of the processes in the Sun's core;
- Neutrinos

  = particles full of surprises and unknowns;
- **BOREXINO**

  = current experiment with the richest solar neutrino program;

Conclusions

- **Sun** is our closest star;
- It produces its energy in **thermonuc**... **ions**;
- **Solar neutrinos**

  = witnesses of the pr... s core;
- Neutrinos

  = particl... and unknowns;
- **BO**...

  ...riment with the richest solar neutrino program;

NEUTRINO PHYSICS:
NEW DISCOVERIES WAITING FOR YOU!

Thank you!

Backup slides

Short history of solar ν experiments in 1 slide

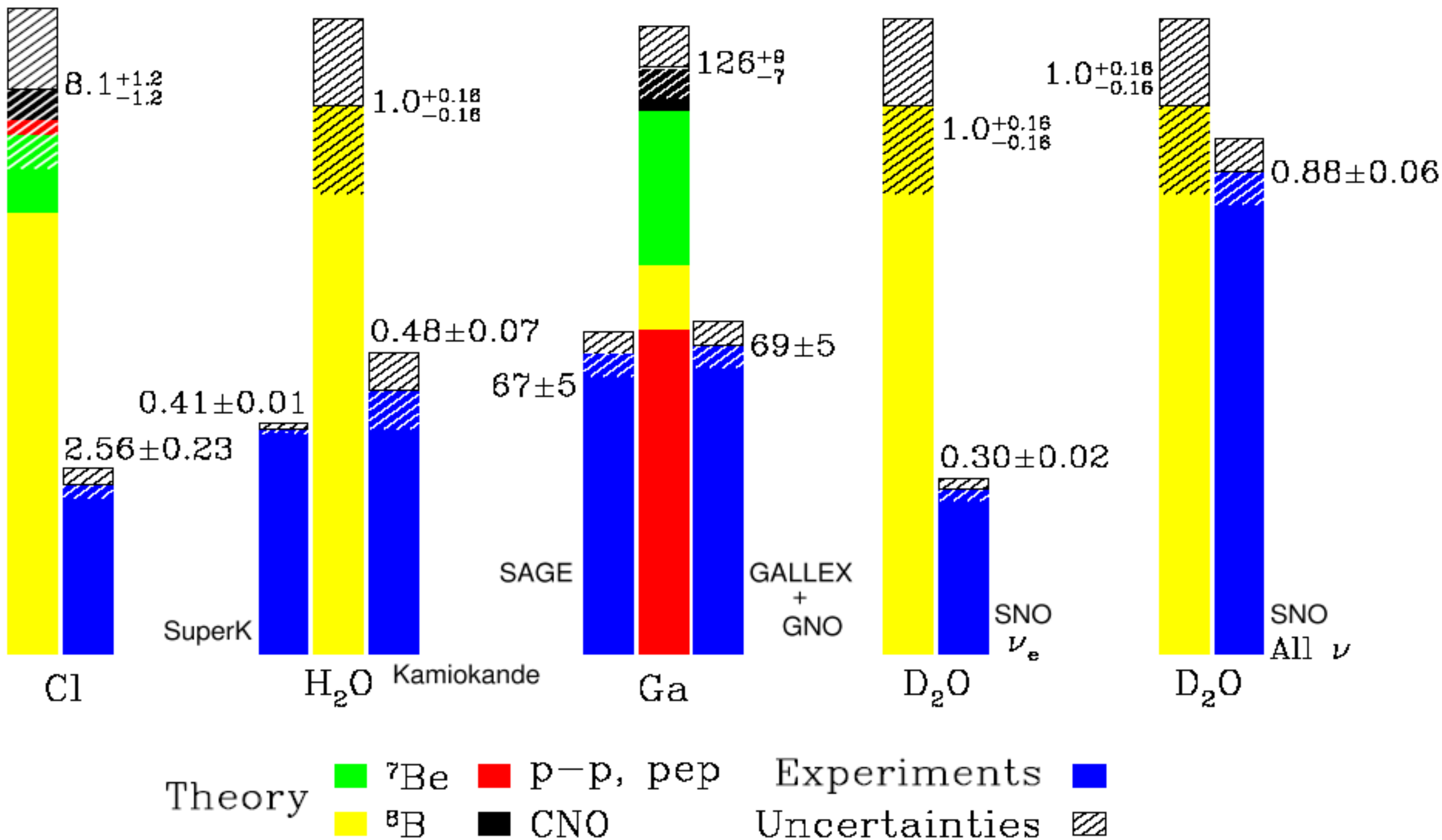
- **70's-80's: Homestake (R. Davies)**
  - $^{37}Cl + \nu \rightarrow {}^{37}Ar + e^-$, radiochemistry; **$E_\nu$ >814 keV**
  - deficit in neutrino flux observed, skepticism
  - final triumph, Nobel prize 2002
  - J. Bahcall continues the development and refinement of the Standard Solar Model

- **80's-90's: (super)Kamiokande (Water Cherenkov)**
  - confirm deficit on ^8B ν and with real time techniques **E_ν > ~ 5 MeV**
  - first neutrino picture of the Sun (directionality)
  - neutrinos from star sother than the Sun observed (supernova SN1987-A)
- **90's: Gallex (GNO) and Sage:** radiochemistry $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
  - deficit observed even at low energy **E_ν >233 keV**
- **2001: SNO (Water Cherenkov)**
  - oscillation of solar neutrinos proved

    by measuring CC (electron flavor) interactions and NC (all flavors) interactions separately in **D_2O**
  - total flux agrees with Standard Solar Model !

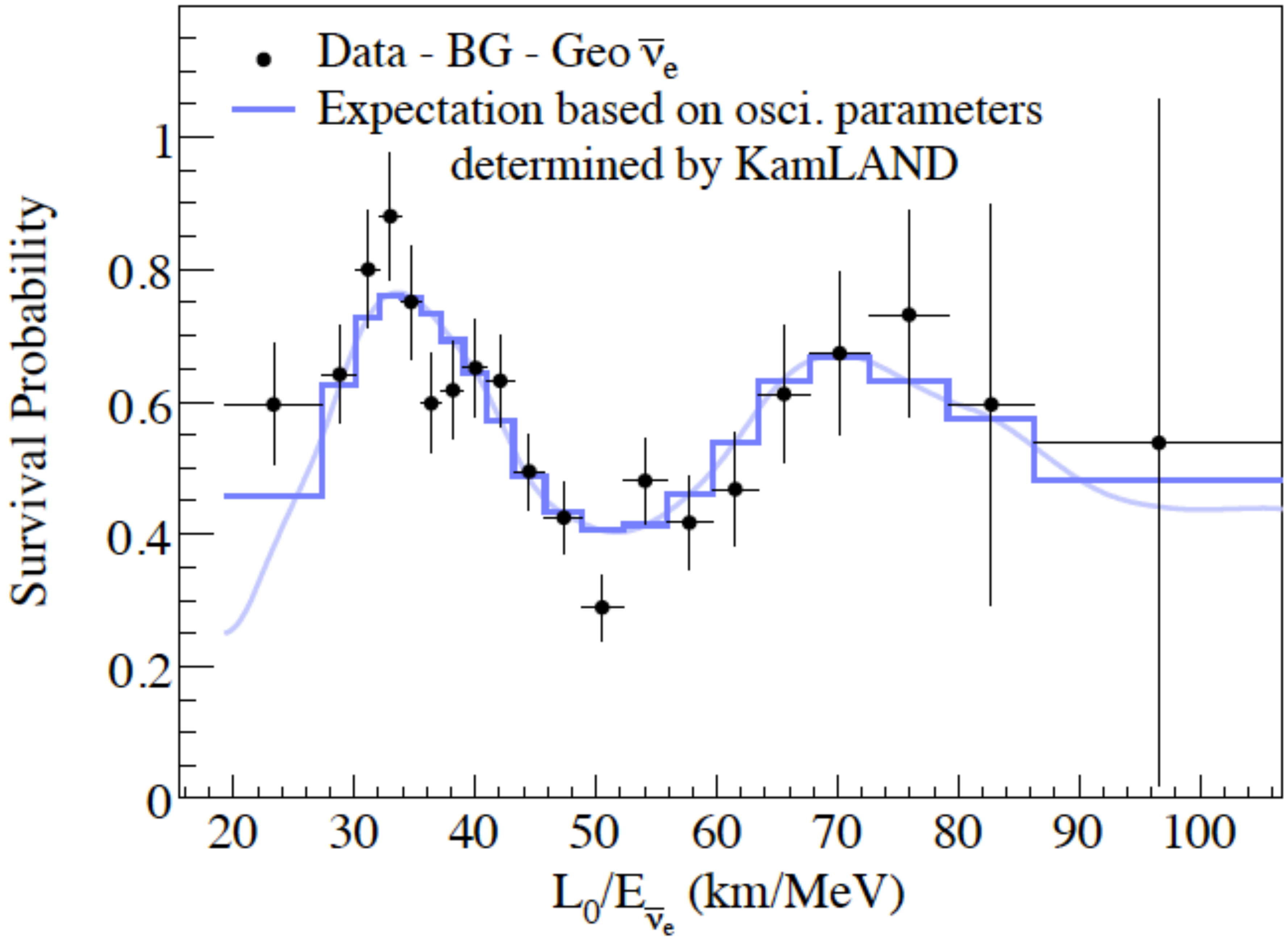
- **2002: KamLAND (reactors neutrinos, liquid scintillator detector)**
  - observe and measure oscillations of electron anti-neutrinos from reactors;
- **2007: Borexino (liquid scintillator)**
  - First real time observation of ^7Be neutrinos, low energy ^8B neutrinos, pep neutrinos, best limit on CNO neutrinos and very recently also pp neutrinos;

Solar Neutrino Problem: energy dependent deficit of observed solar neutrinos with respect to the SSM;



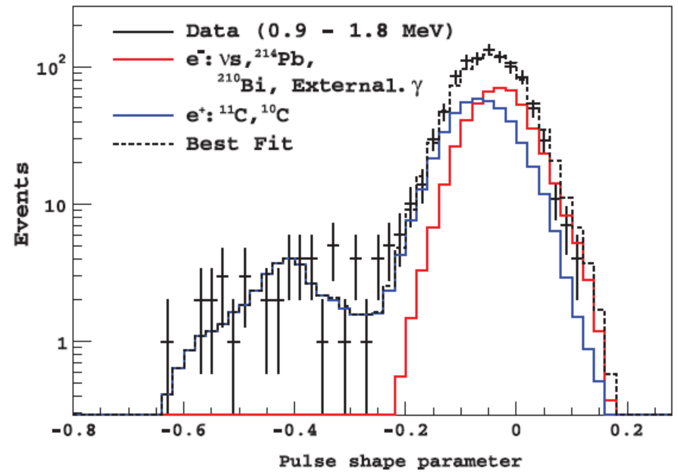
Precise measurement of Δm^2 and final proof of oscillations (on anti-neutrinos from reactor!)

KamLAND, 2002

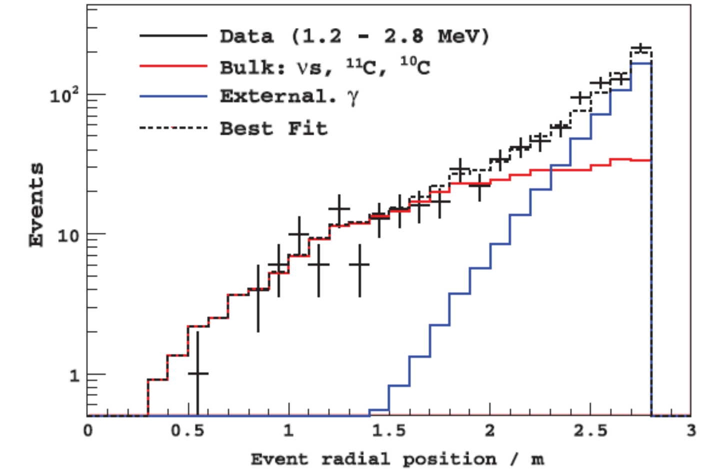


THE FIRST OSCILLATION PATTERN WAS SEEN!

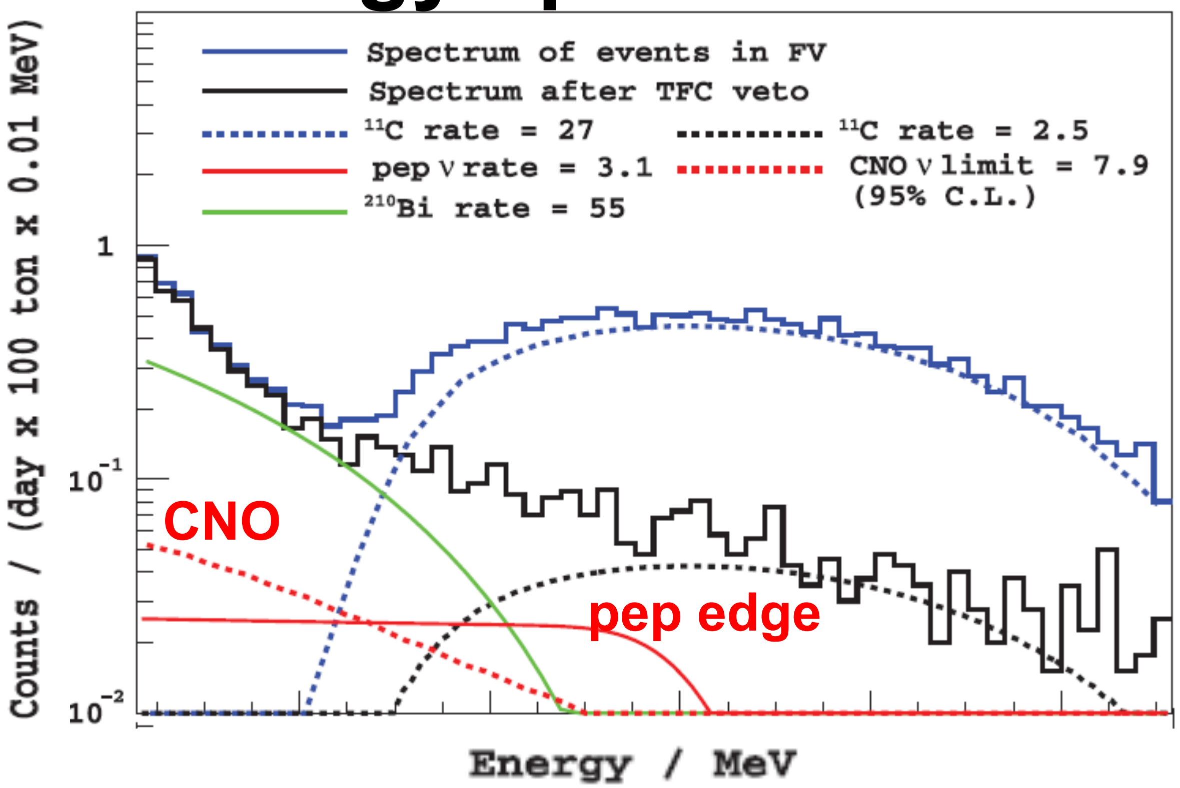
Pulse shape

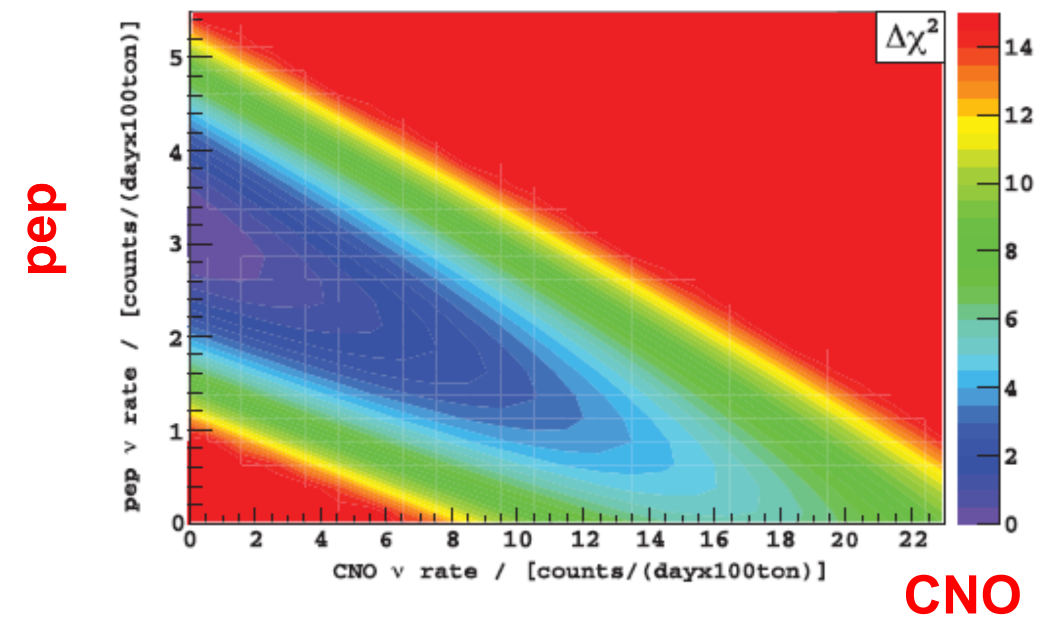


Radial fit



Energy spectral fit





Likelihood ratios for fits with fixed pep/CNO rates and the best fit

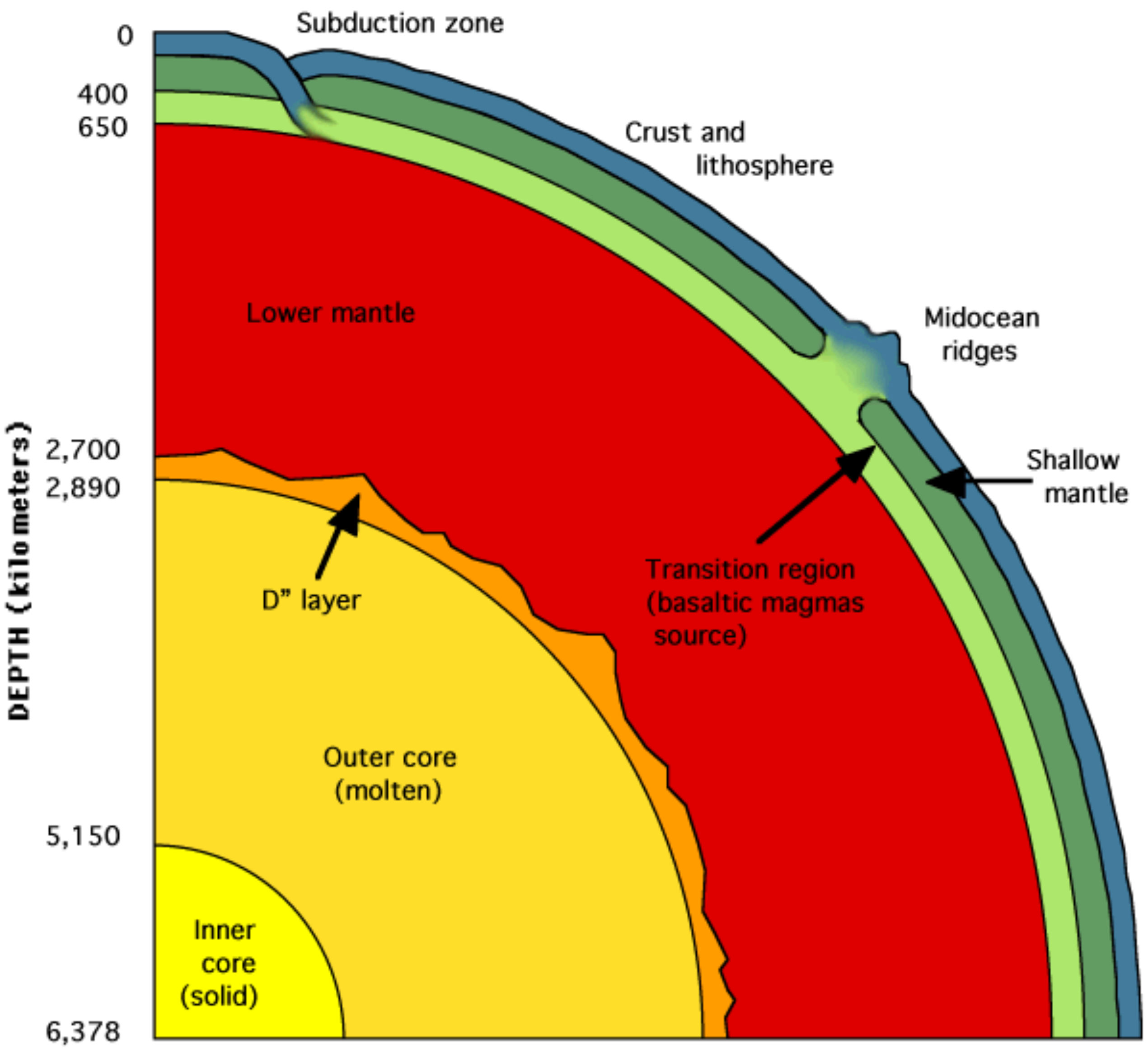
CNO neutrinos

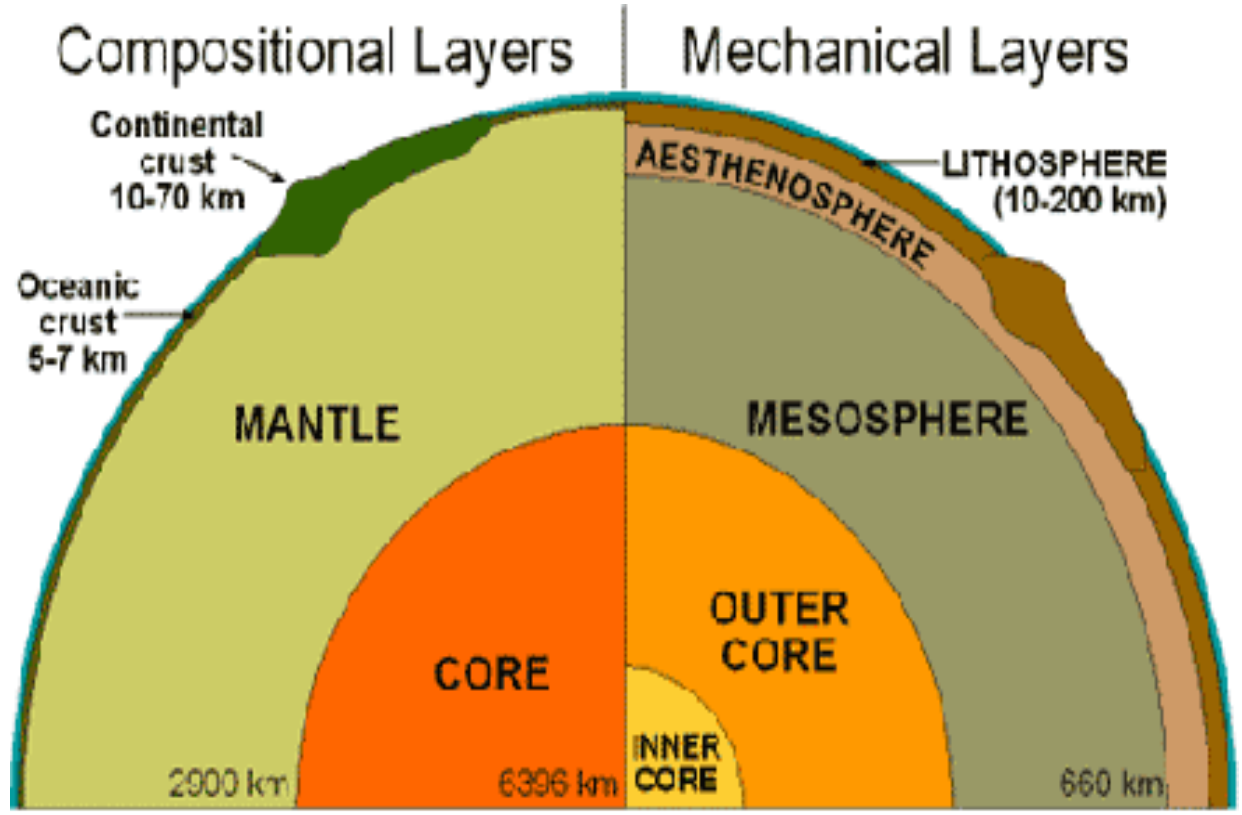
- same analysis as for pep
- only limits, correlation with ^{210}Bi
- **the strongest limit to date**
- **not sufficient to resolve metallicity problem**

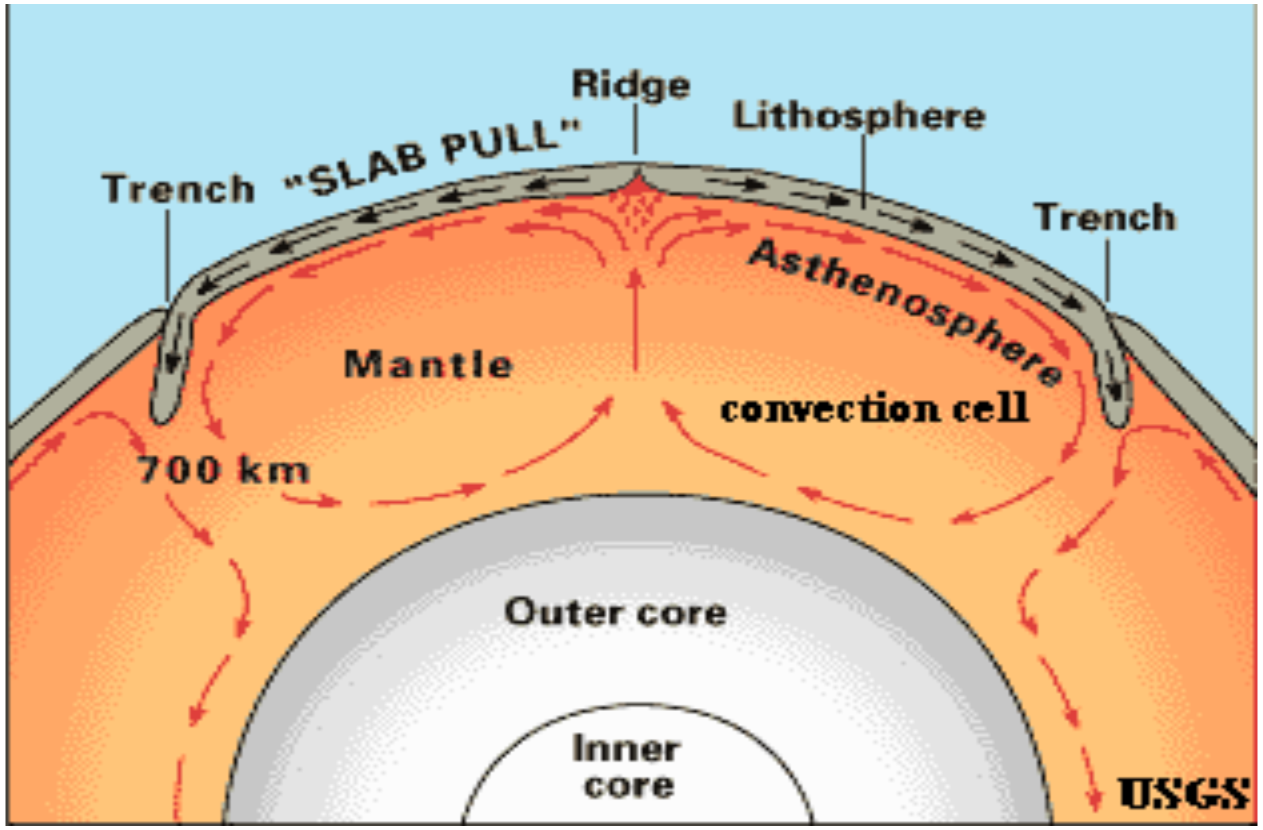
$\boxed{<7.9 \text{ counts/(day} \cdot 100 \text{ ton) (95\% C.L.)}}$

$\boxed{<7.7 \times 10^8 \text{ cm}^{-2}\text{ s}^{-1} \text{ (95\% C.L.)}}$ (assuming MSW-LMA)

Earth structure





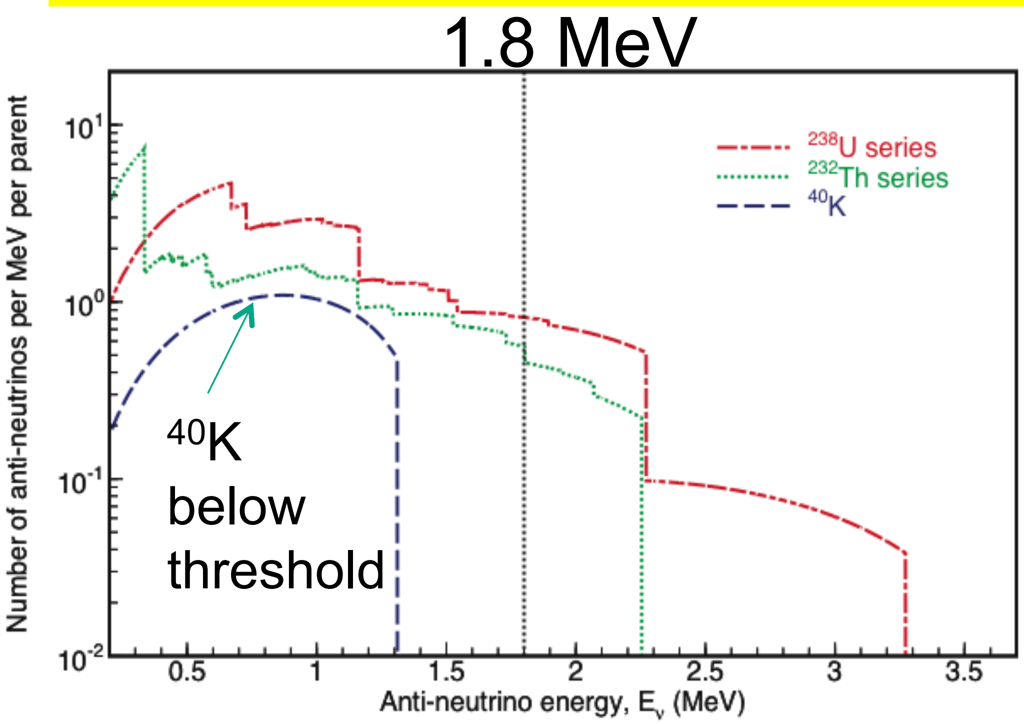


Geoneutrinos
antineutrinos from the decay of ^{238}U, ^{232}Th, ^{40}K in the Earth

Abundance of radioactive elements fixes the amount of radiogenic heat (nuclear physics);
Mass and distribution of radiogenic elements → geoneutrino flux (cca 10^6 cm^{-2} s^{-1});
From measured geoneutrino flux to radiogenic heat….

Main goal: determine the contribution of the **radiogenic heat to the total surface heat flux**, which is an important margin, test, and input at the same time for many geophysical and geochemical models of the Earth;

Further goals: tests and discrimination among geological models, study of the mantle homogeneity, insights to the processes of Earth'formation…..



$$\bar{\nu} + p \rightarrow n + e^+$$

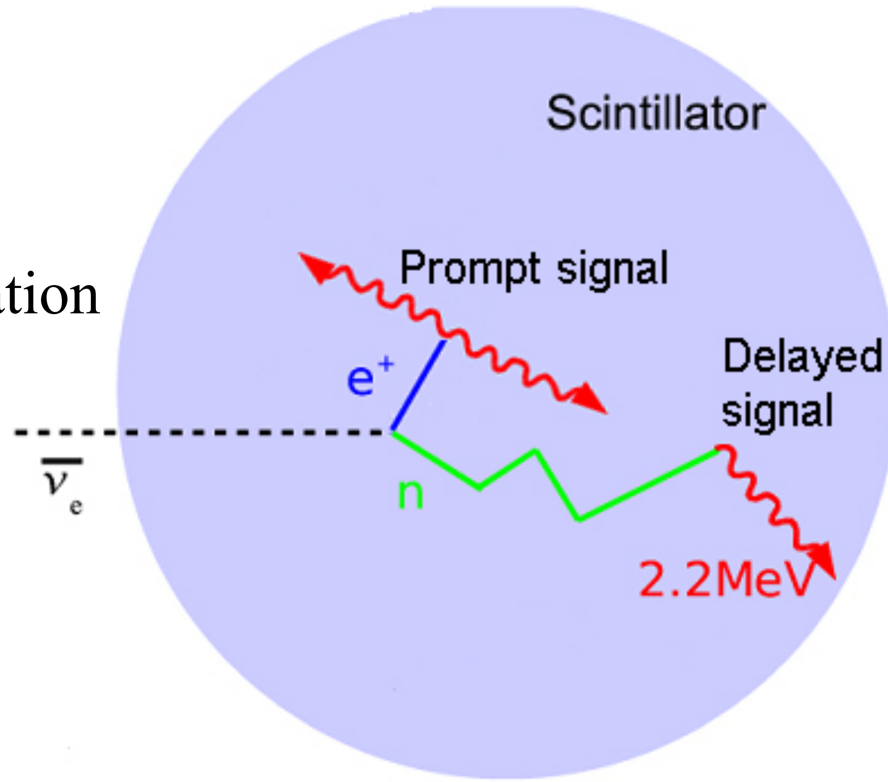
- "prompt signal"

e+: energy loss + annihilation

- "delayed signal"

neutron capture on protons after thermalization 2.2 γ

$E_\nu > 1.8$ MeV



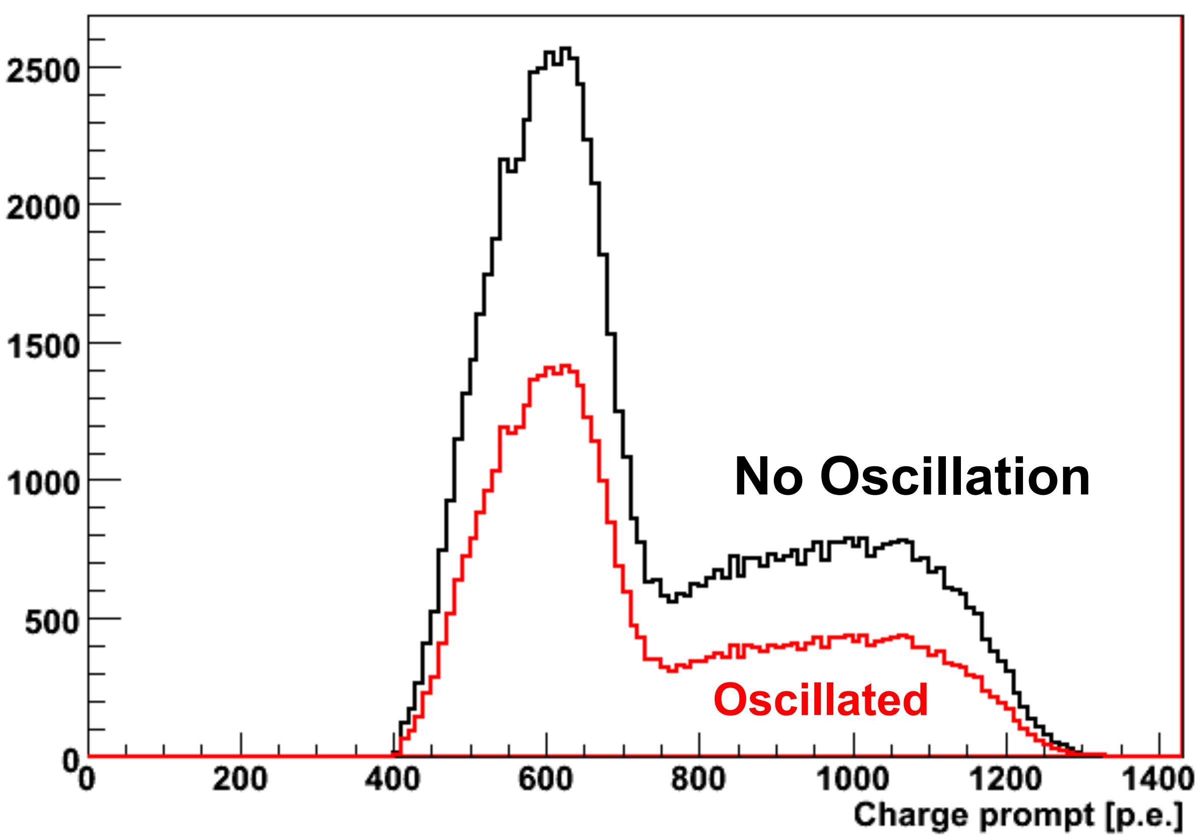
Effect of neutrino oscillations

$$P_{ee} = P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12}\sin^2\left(\frac{\delta m^2 L}{4E}\right)\right) + \sin^4\theta_{13}$$

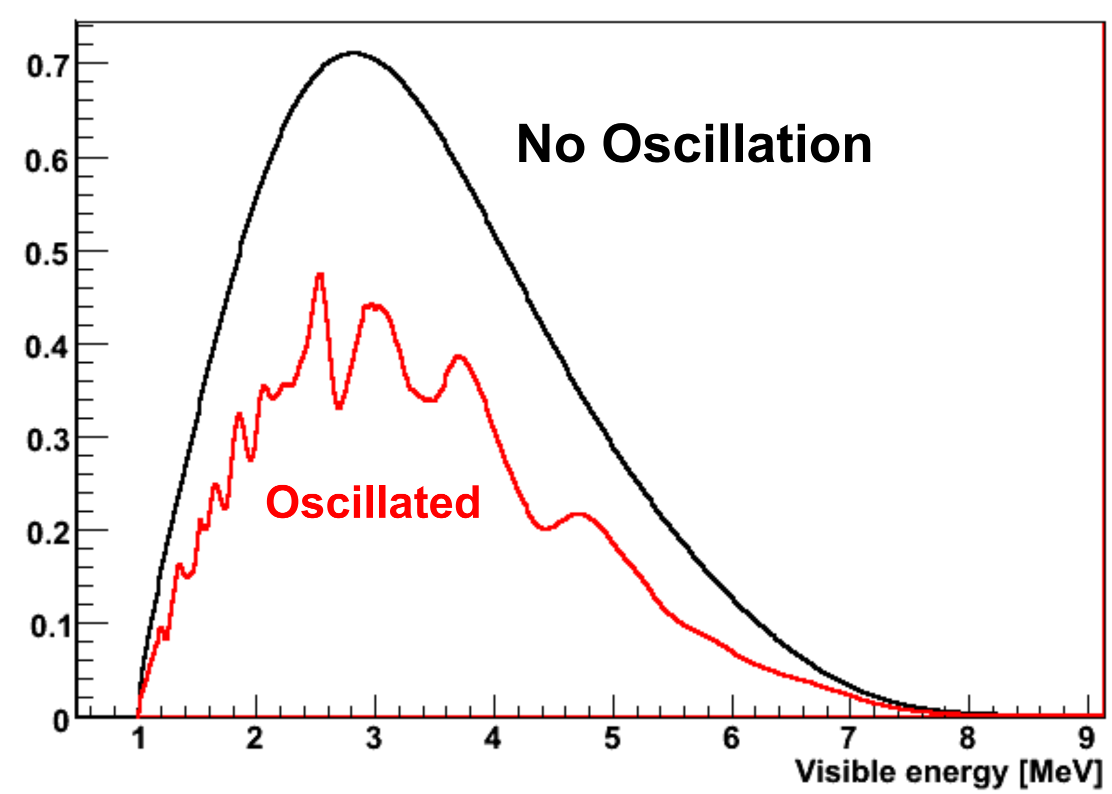
3 MeV antineutrino ..
Oscillation length of ~100 km

for geoneutrinos we can use average survival probability of 0.551 + 0.015 (Fiorentini et al 2012), but for reactor antineutrinos not!

Geoneutrinos



Reactor antineutrinos at LNGS



Geoneutrinos in Borexino