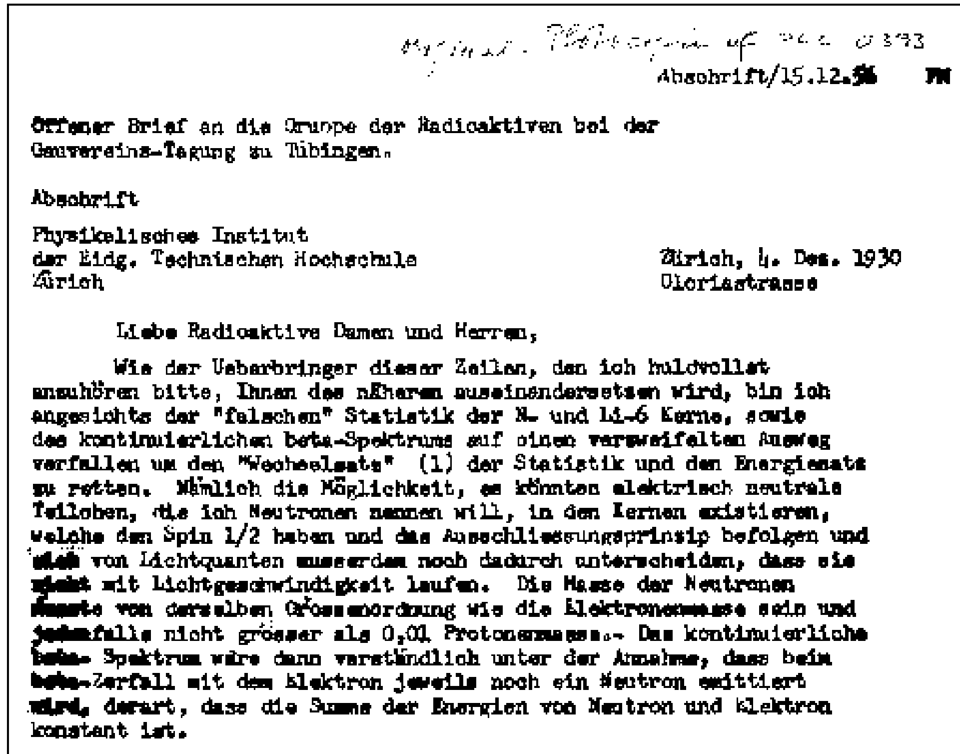
The strange tale of tiny neutrinos

Neutrinos were "invented" in 1930 by W.Pauli to explain some features of nuclear beta decay



Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

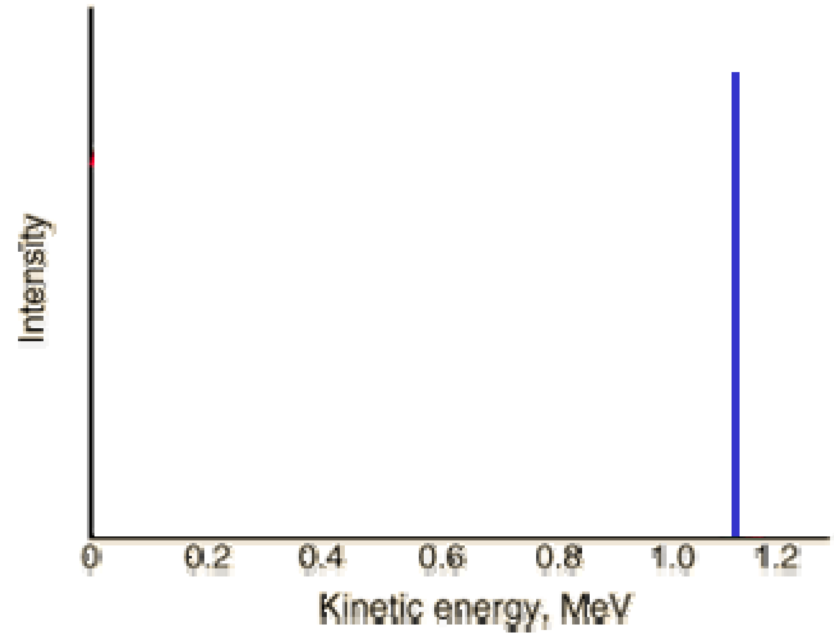
Dear Radioactive Ladies and Gentlemen,

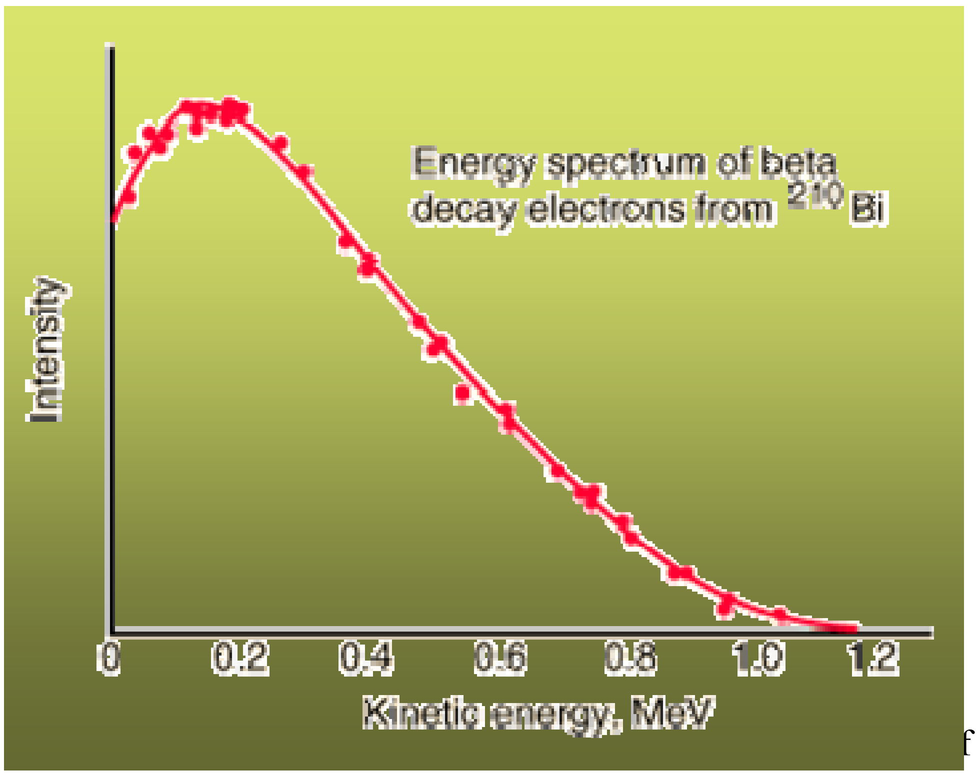
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call *neutrons*, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the *neutrons* should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant.........

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant
W. Pauli

Energy and momentum conservation fix the energy in 2-body decays
Example: N → N'+α





The continuum of energies observed in β decay implies that either energy and momentum are not conserved …or that there is another particle difficult to detect
N → N'+β+ν

Today neutrinos occupy an important role in particle physics…

ν_e	ν_μ	ν_τ	Leptons
e	μ	τ	

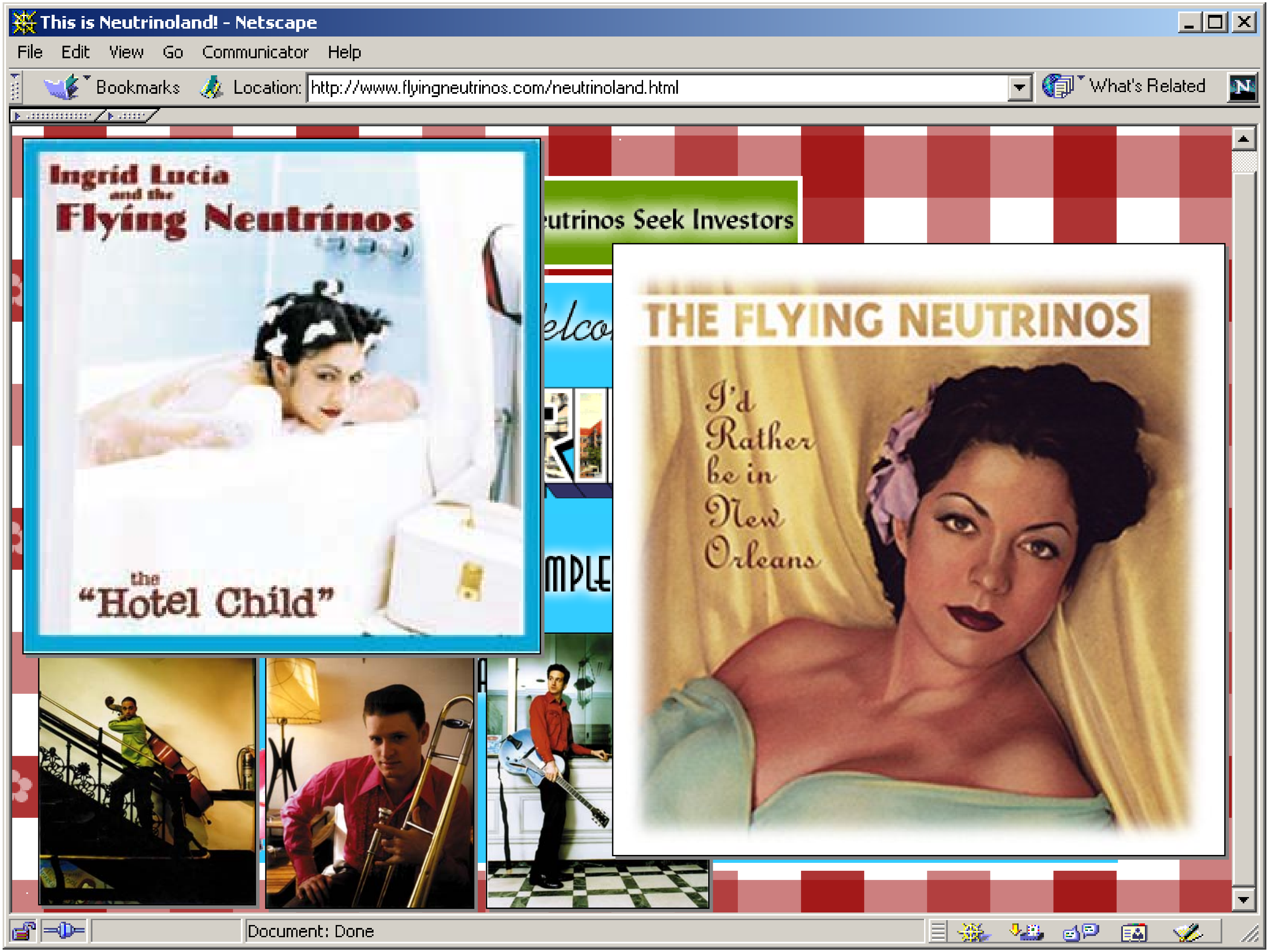
u	c	t	Quarks
d	s	b	

25% of elementary particles are neutrinos

So… where can we find neutrinos ?

A Google™ search for "neutrino" gives about 7,390,000 hits !

…a clear sign that neutrinos are everywhere !


This is Neutrinoland! - Netscape
File Edit View Go Communicator Help
Bookmarks Location: http://www.flyingneutrinos.com/neutrinoland.html
What's Related
eutrinos Seek Investors
Ingrid Lucia and the Flying Neutrinos
the "Hotel Child"
THE FLYING NEUTRINOS
I'd Rather be in New Orleans
Document: Done

Named for a subatomic particle with almost zero mass …

Sources of neutrinos: artificial and natural

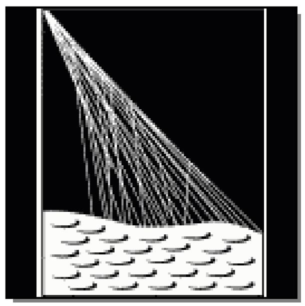
✓ Nuclear Reactors
(power stations, ships)

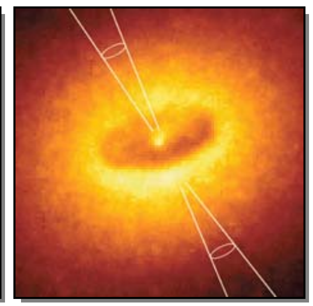
Sun ✓

✓ Particle Accelerator

Supernovae
(star collapse)
SN 1987A ✓

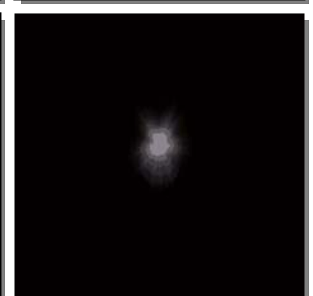
✓ Earth's Atmosphere
(Cosmic Rays)





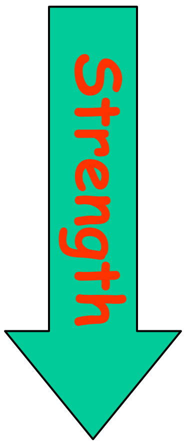
Astrophysical
Accelerators
Soon ?

✓ Earth's Crust
(Natural
Radioactivity)



Big Bang
(here 330 ν/cm^3)
Indirect Evidence

We know of 4 types of
fundamental interactions in nature:



- Gravity: every object is affected
  (it is actually a property of space-time)
- Weak force: affects most particles
  including neutrinos
- Electromagnetism: affects all particles with charge
- Strong force: affect only quarks

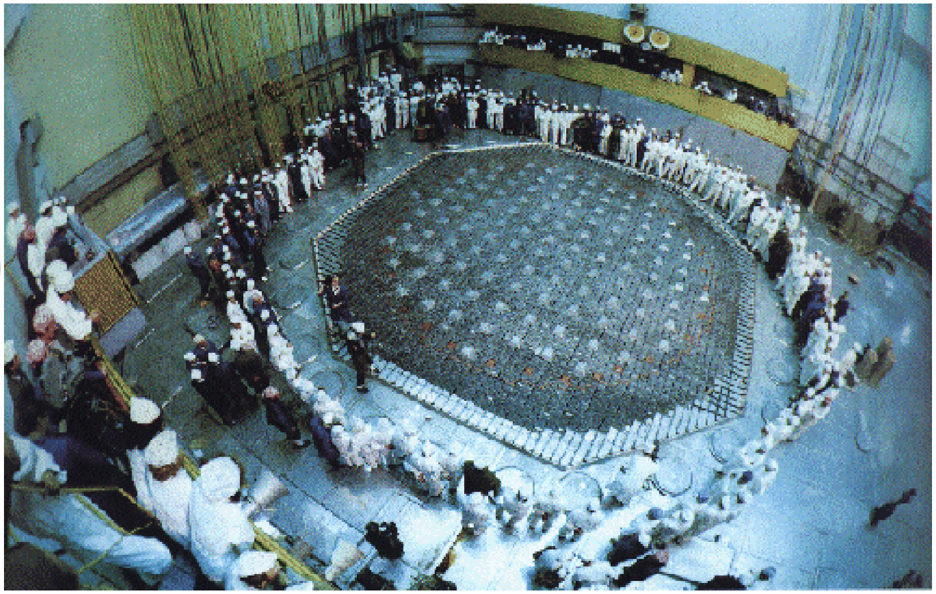
Neutrinos having no electric charge interact only by the weak force (and gravity)

→ interact very little

Radioprotection for neutrinos ?

- Mean free path of neutrinos from a reactor in lead is ~ 0.3 light years !

- A big nuclear reactor makes $6 \cdot 10^{20}$ neutrinos/s: at 20 meter distance (just outside the building) only one neutrino every 3 sec interacts with our body !



<u>Bethe & Peierls 1934:</u>

"… this implies that one evidently never will be able to detect Neutrinos."

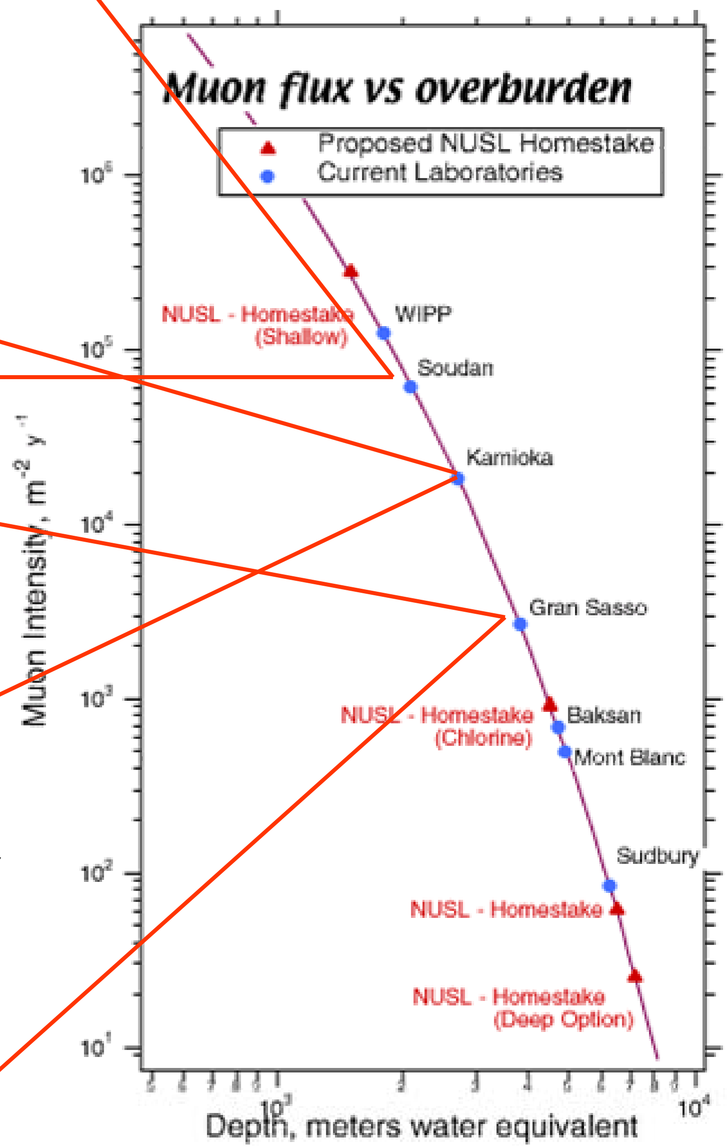
So
r
to sc

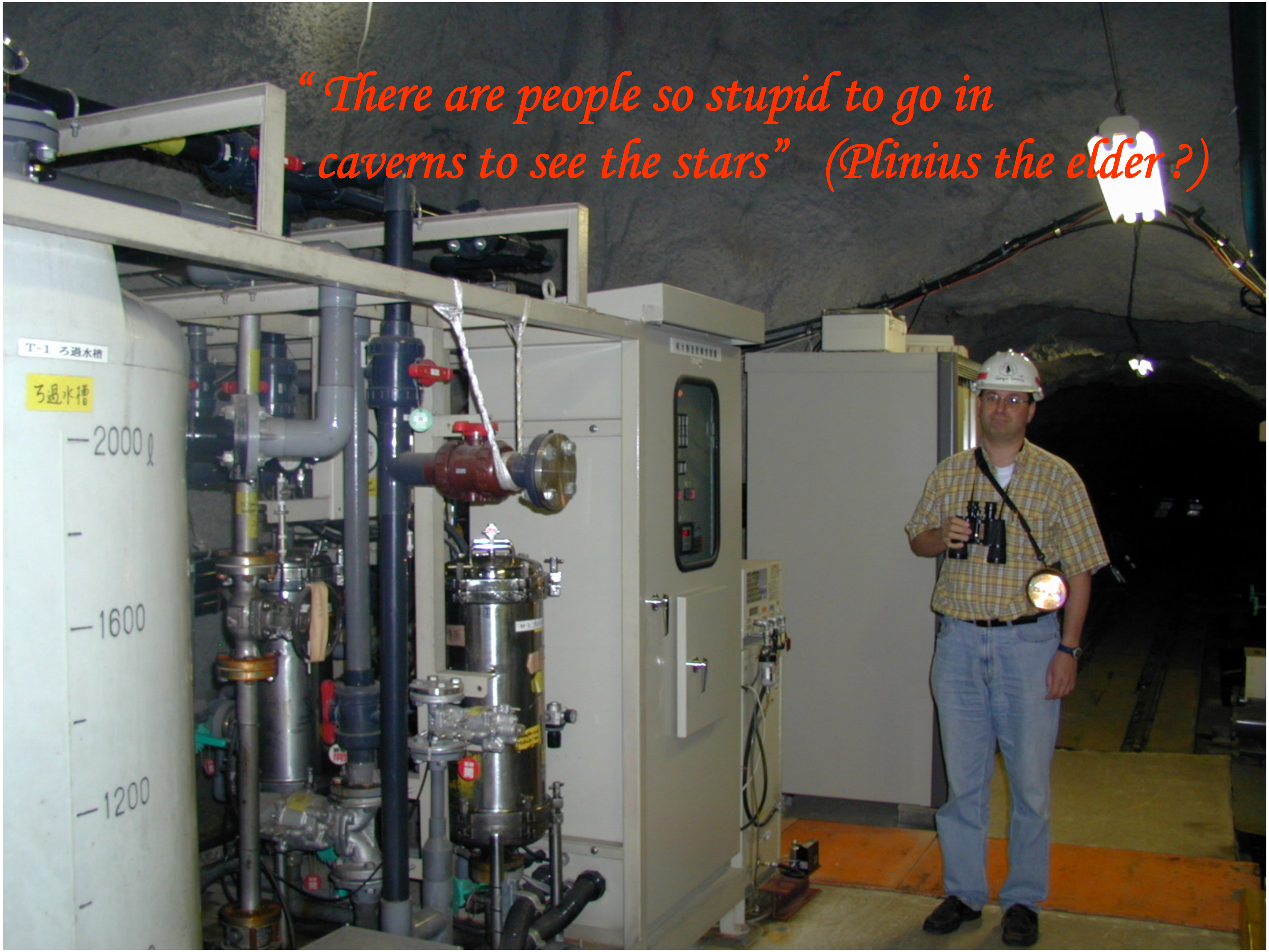
Onl
plac

rinos

sea level: 10^8

6 orders of magnitude reduction in cosmic ray flux



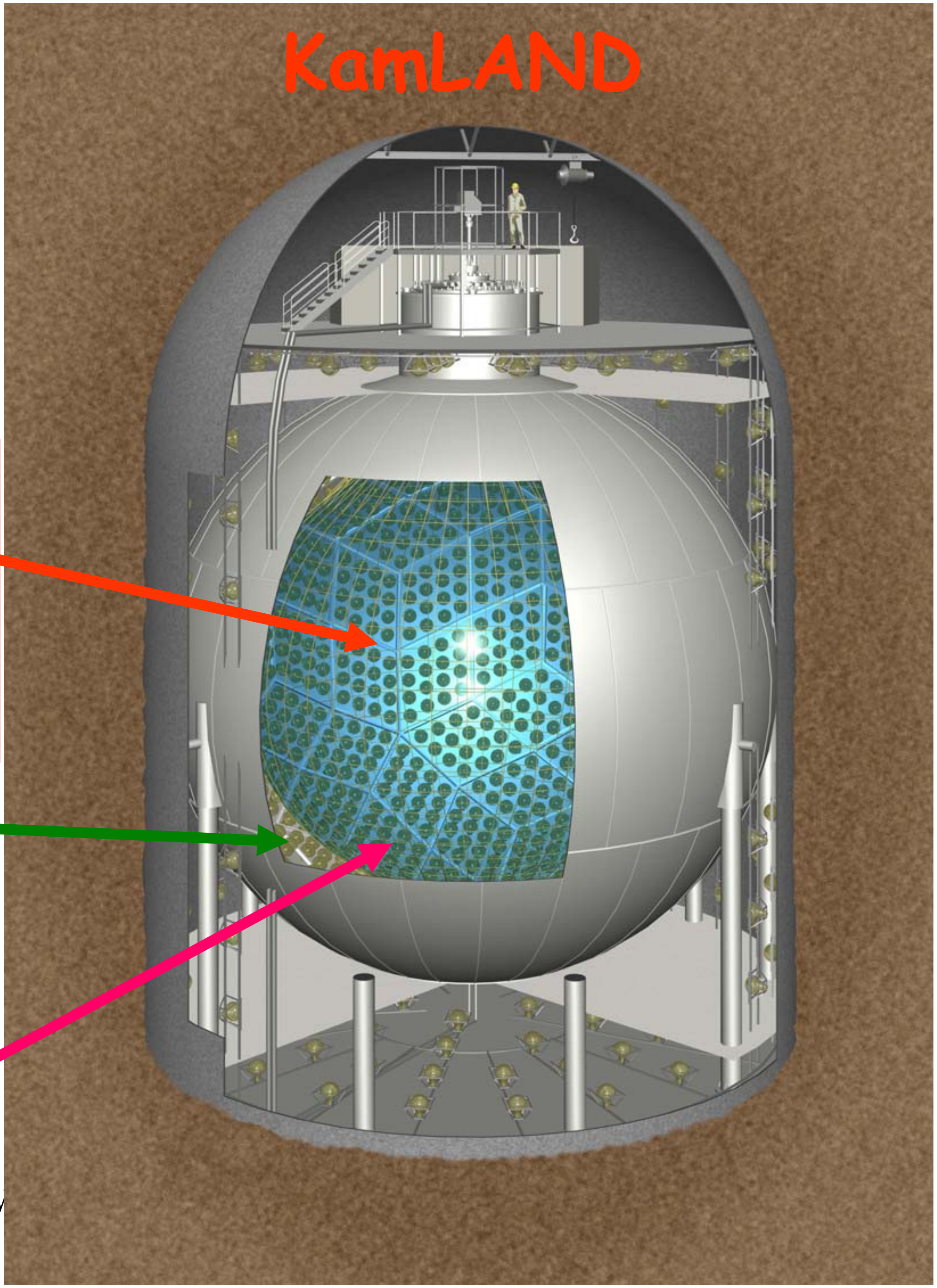

" There are people so stupid to go in
caverns to see the stars" (Plinius the elder ?)
T-1 ろ過水槽
ろ過水槽
2000ℓ
1600
1200

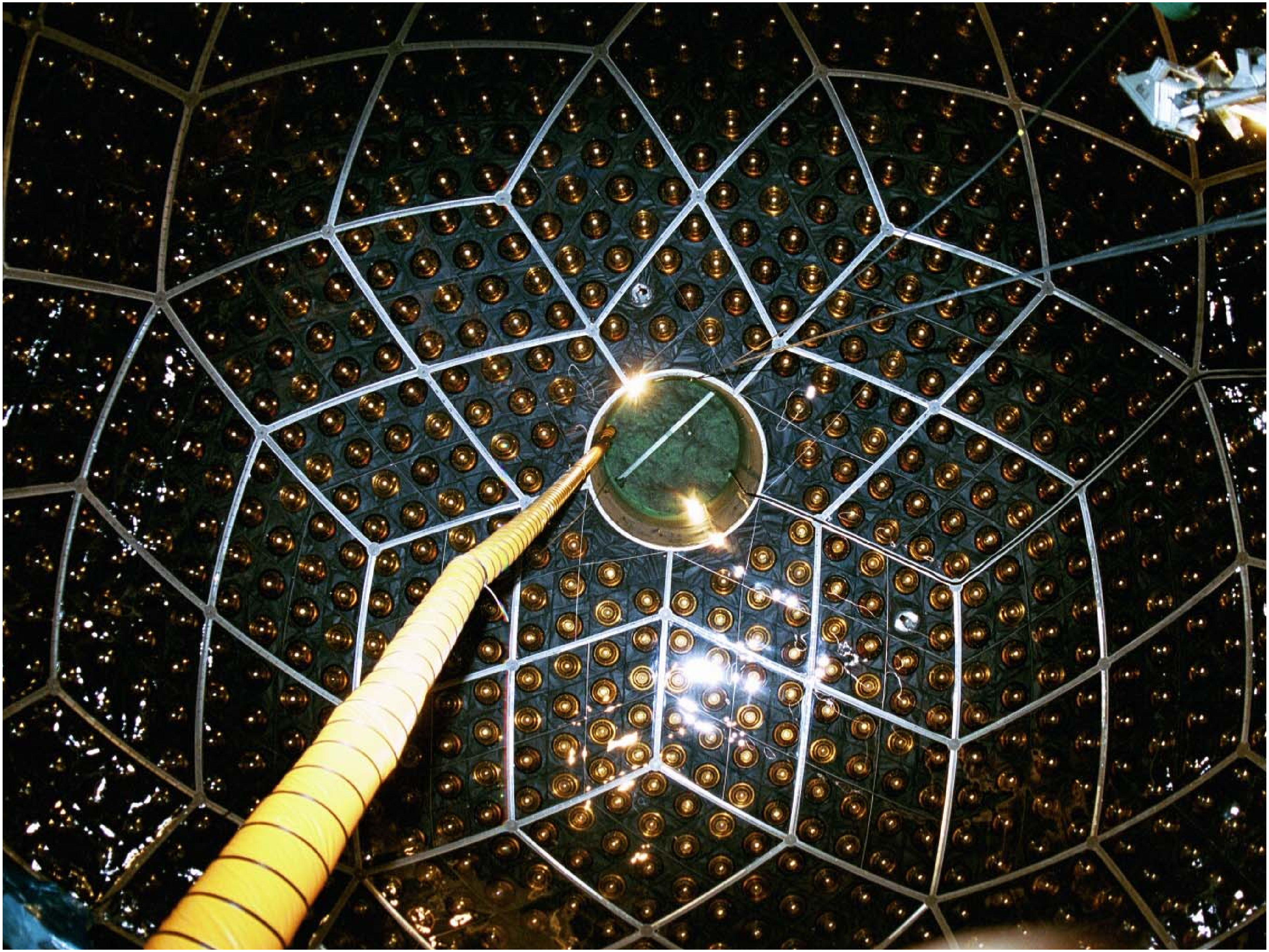
Detectors tend to be large and require extensive shielding against natural radioactivity

Material where neutrinos interact and are detected (1000 tons liquid scintillator… ever bought liquid scintillator in… bulk ?)

Shielding oil (2.5 m thick, or about 2 kton)

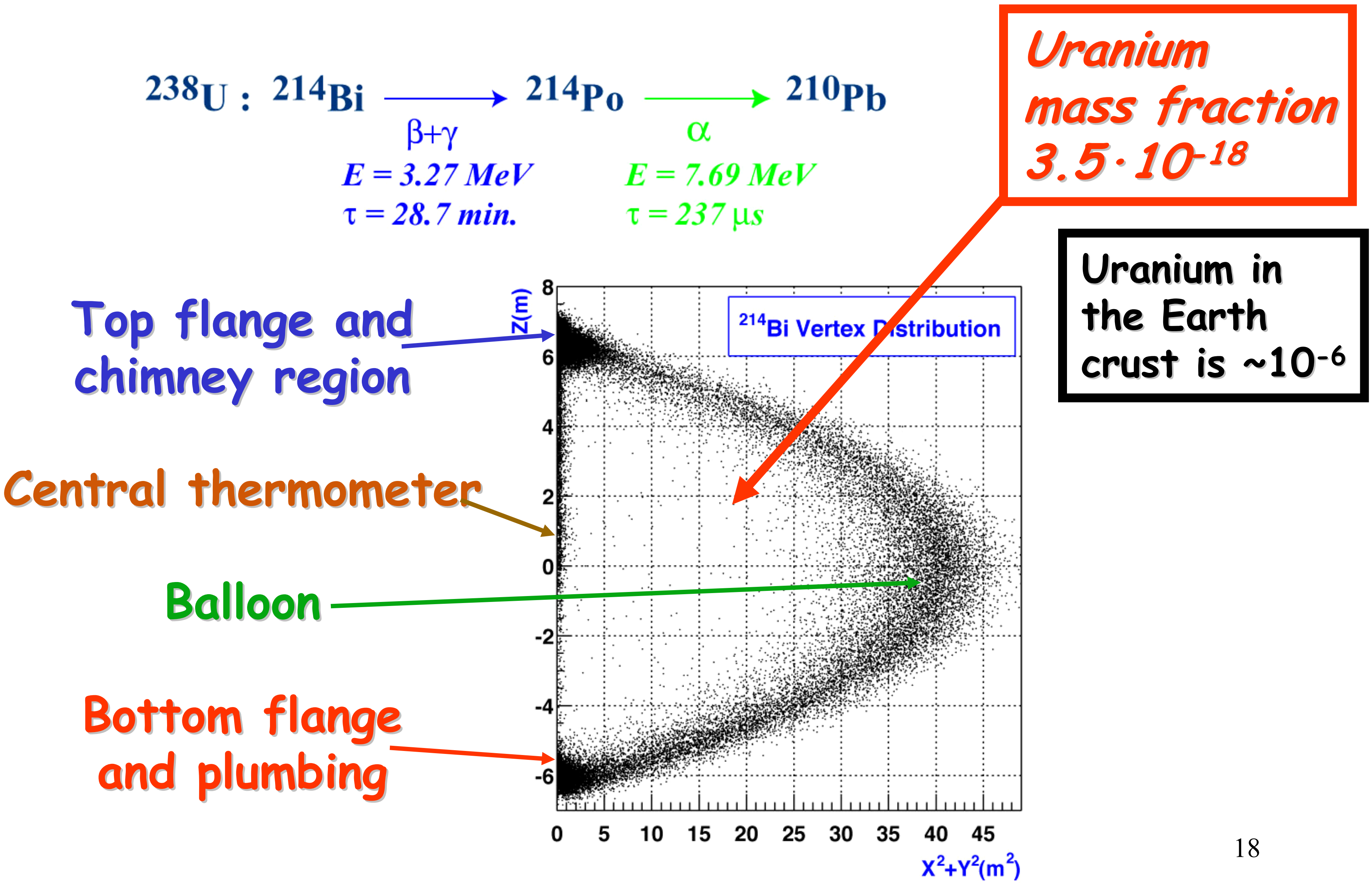
2000 photomultipliers (20 inch diameter)

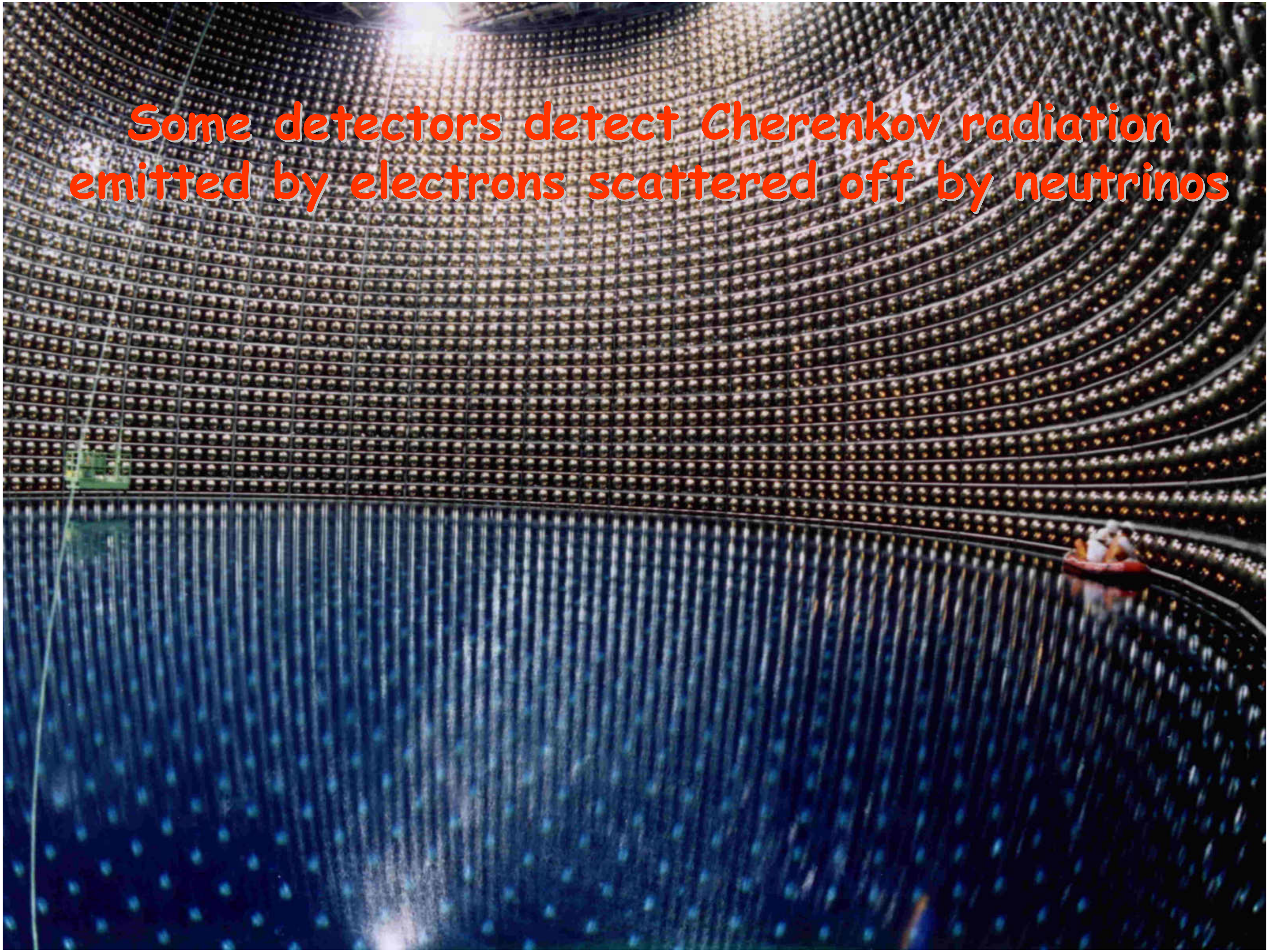




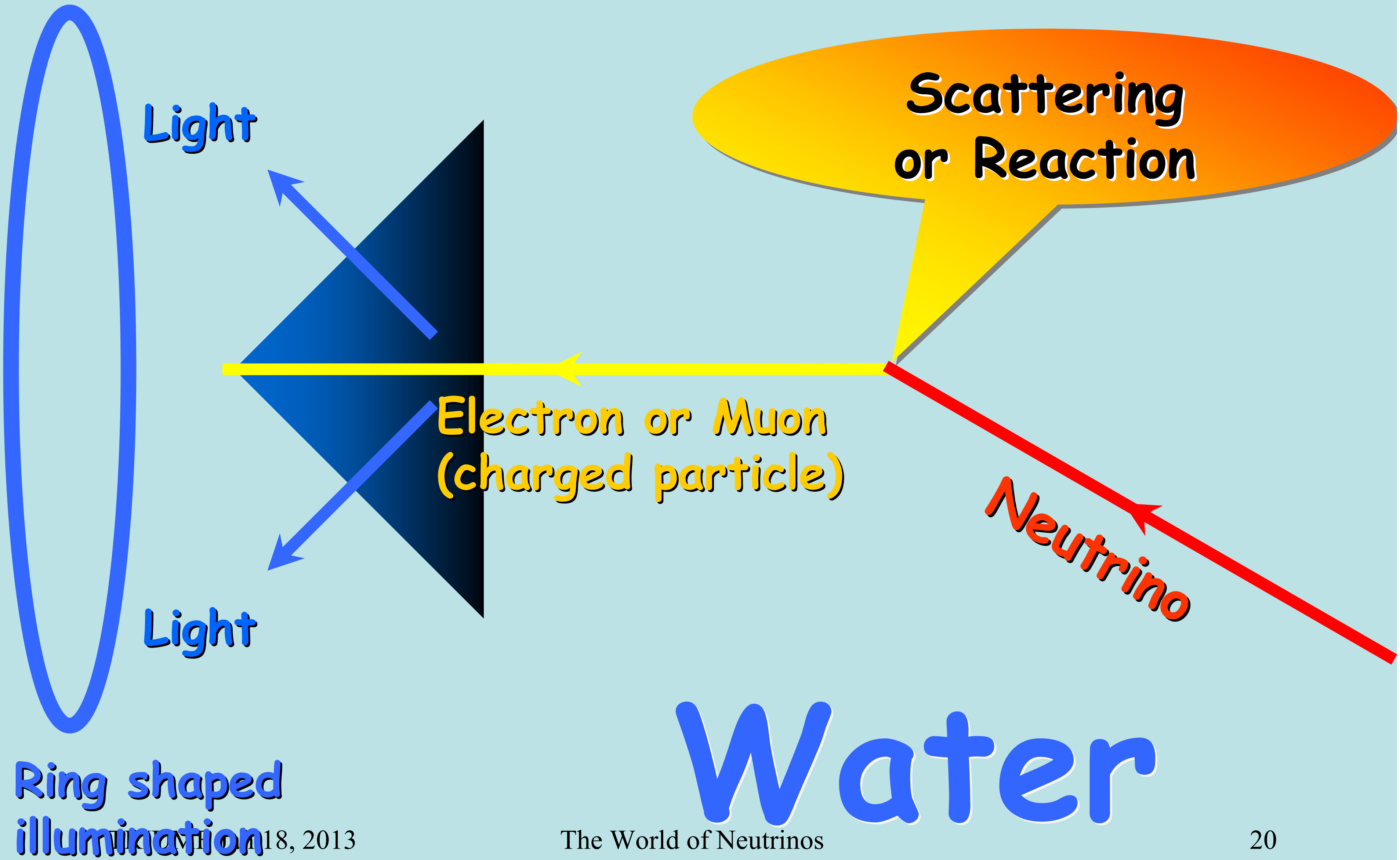
Make your own scintillator, underground

And it even works !

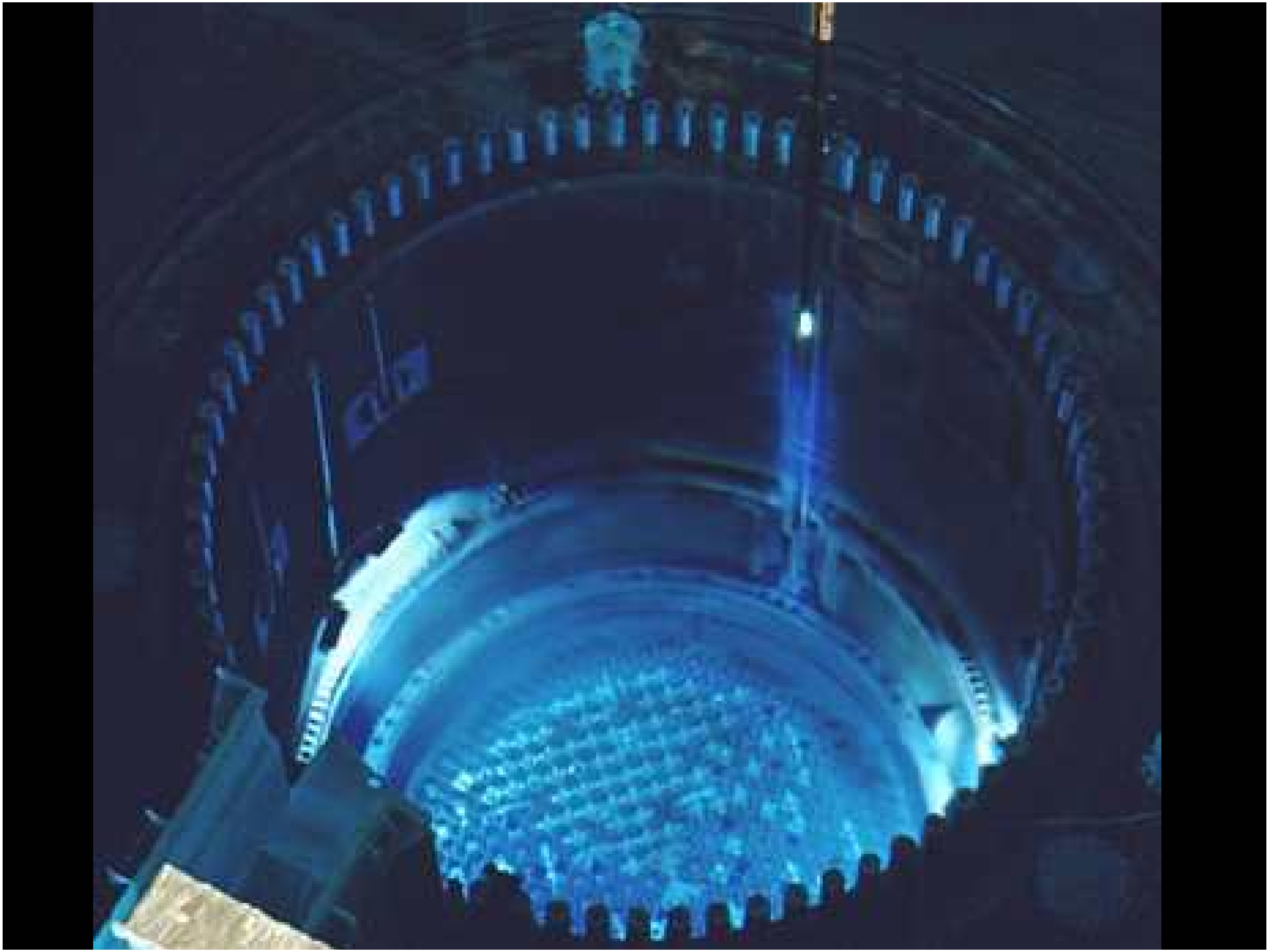


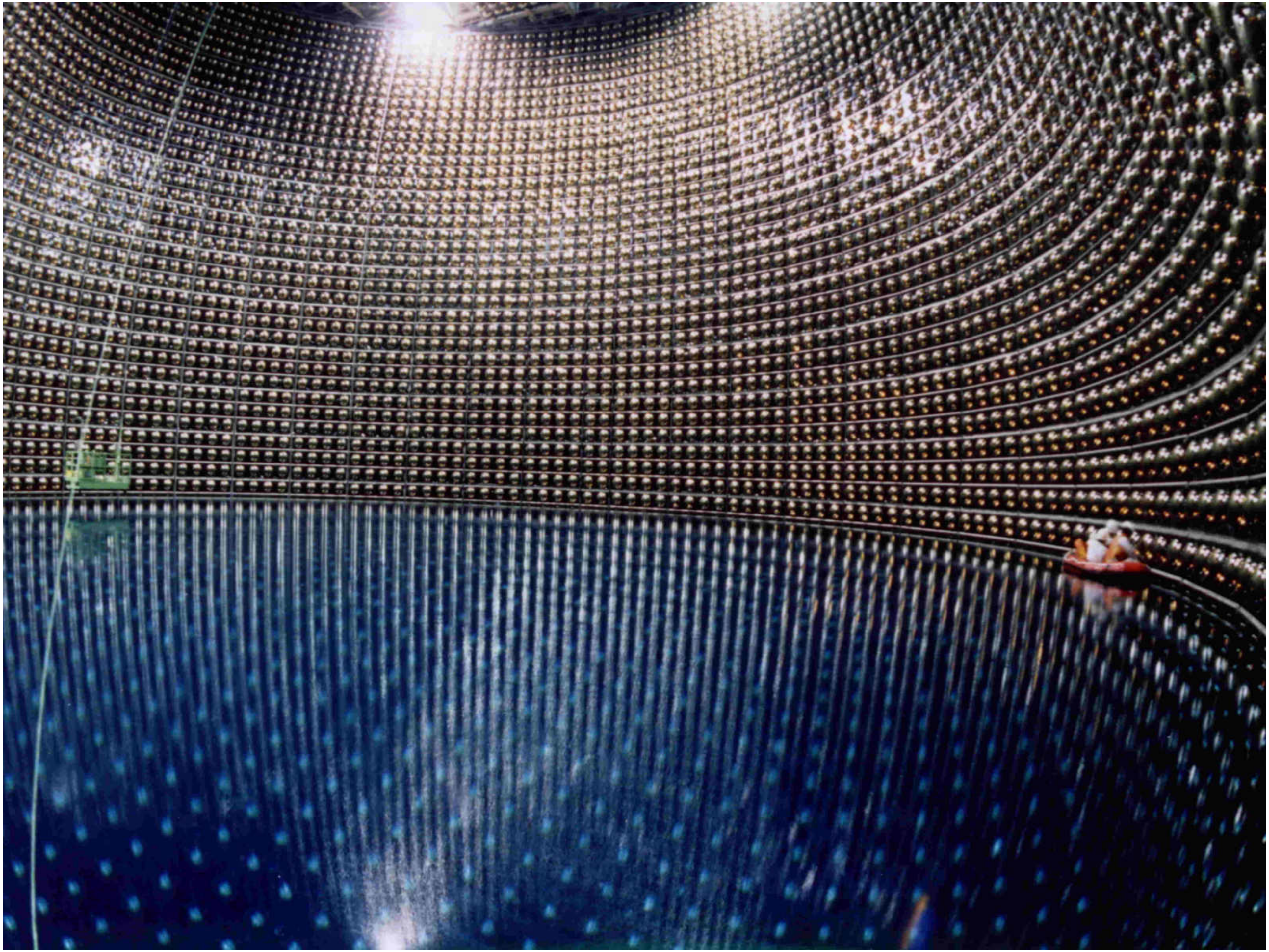

Some detectors detect Cherenkov radiation
emitted by electrons scattered off by neutrinos

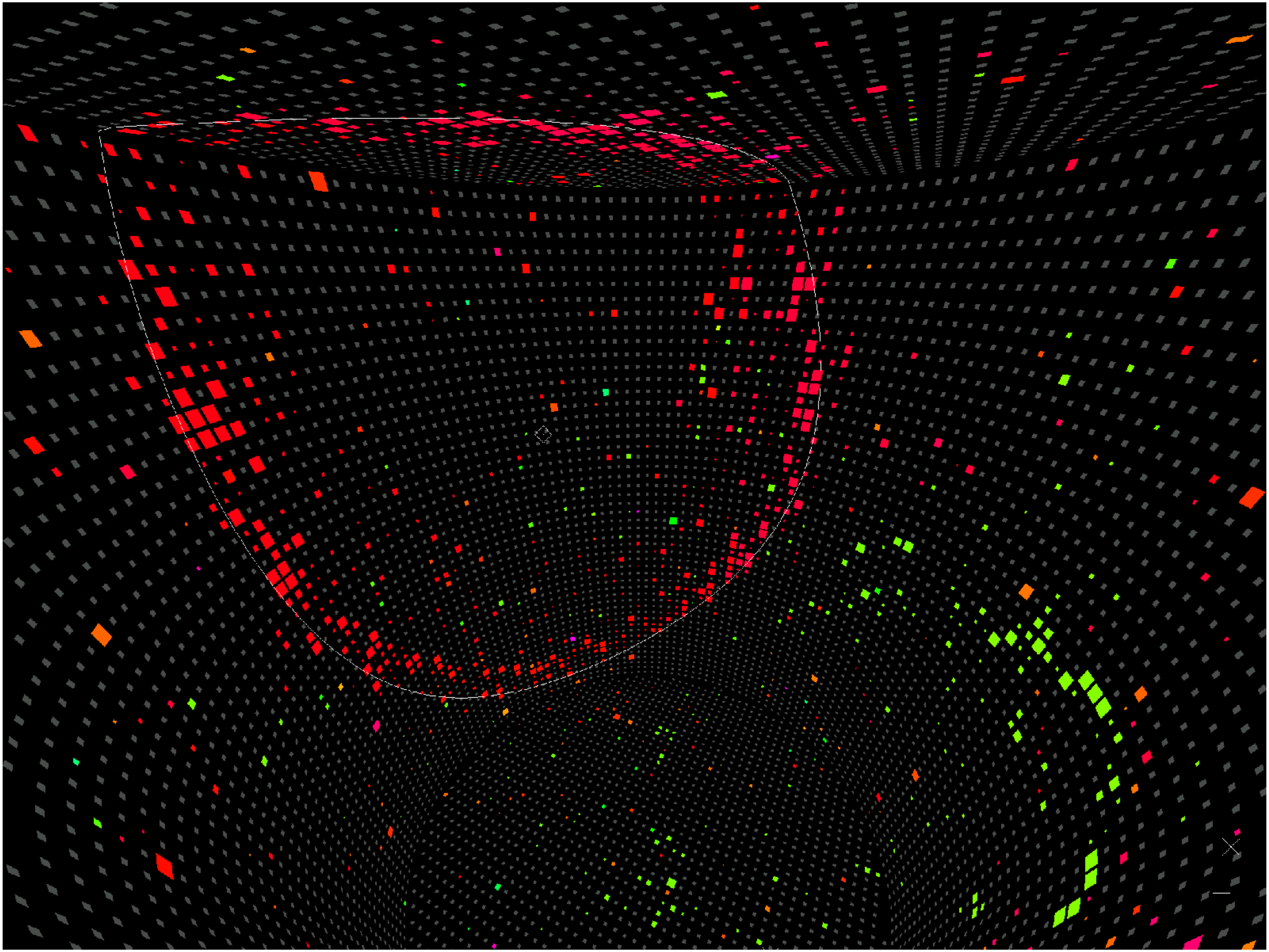
Cherenkov Effect



This is the optical analogous of the
sonic boom produced by an aircraft

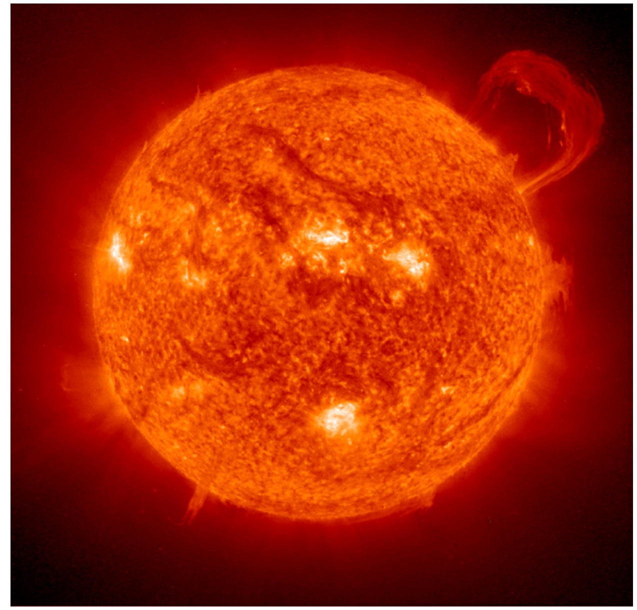






Let's use these tools…

ν_e are abundant by-products of nuclear fusion in the sun



$p+p \rightarrow {}^2H + e^+ + \nu_e + 0.42 MeV$

"pp" 99.75%

$p+e^- + p \rightarrow {}^2H + \nu_e + 1.44 MeV$

"pep" 0.25%

$^2H + p \rightarrow {}^3He + \gamma + 5.49\ MeV$

86%

$^3He + {}^3He \rightarrow \alpha + 2p + 12.86 MeV$

14%

$^3He + \alpha \rightarrow {}^7Be + \gamma + 1.59 MeV$

"hep" $2.4*10^{-5}$

$^3He + p \rightarrow \alpha + e^+ + \nu_e$

"7Be" 99.89%

$^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e + 0.8617 MeV$

$^7Li + p \rightarrow \alpha + \alpha + 17.35 MeV$

0.11%

$^7Be + p \rightarrow {}^8B + \gamma + 0.14 MeV$

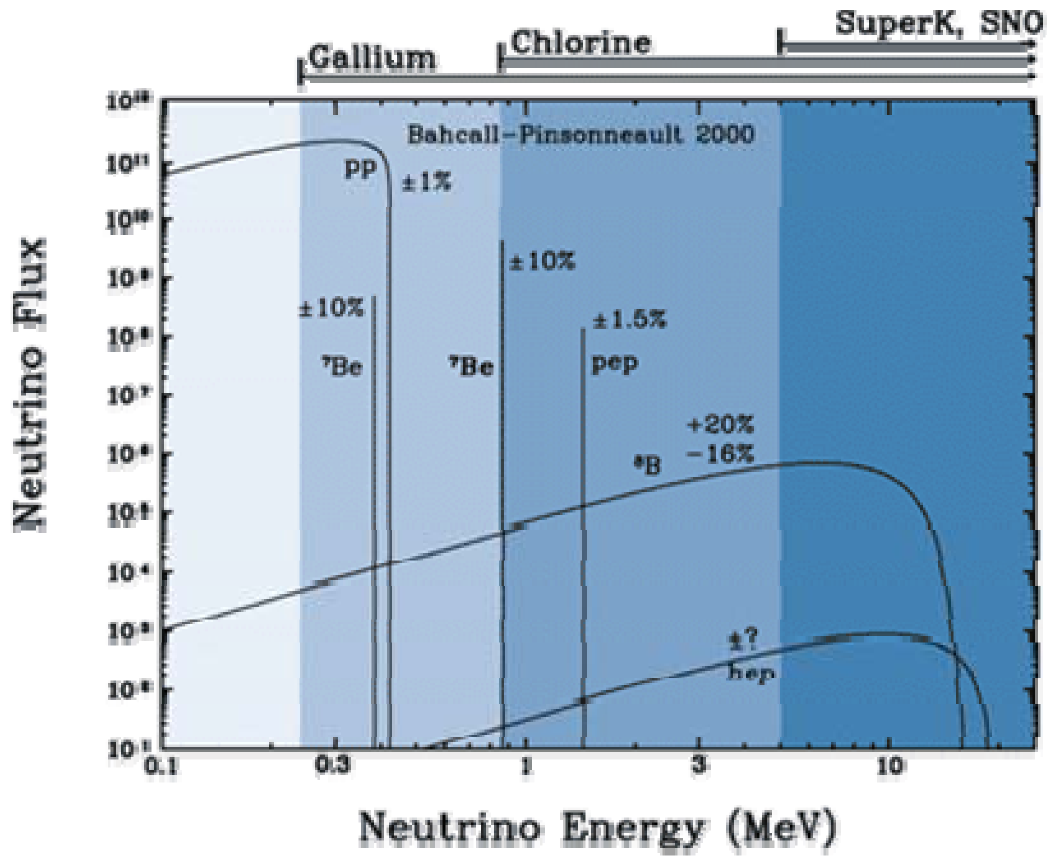
"8B" 0.11%

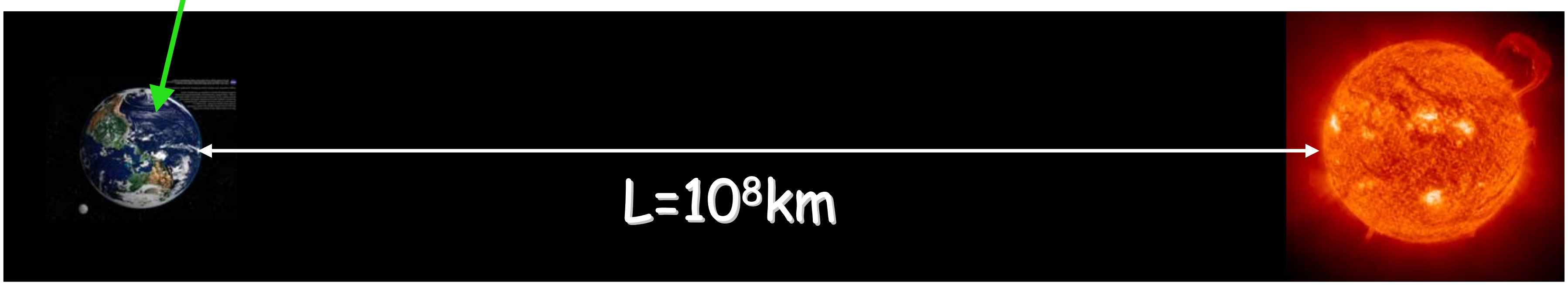
$^8B \rightarrow {}^8Be + e^+ + \nu_e + 14.6 MeV$

$^8Be \rightarrow \alpha + \alpha + 3 MeV$

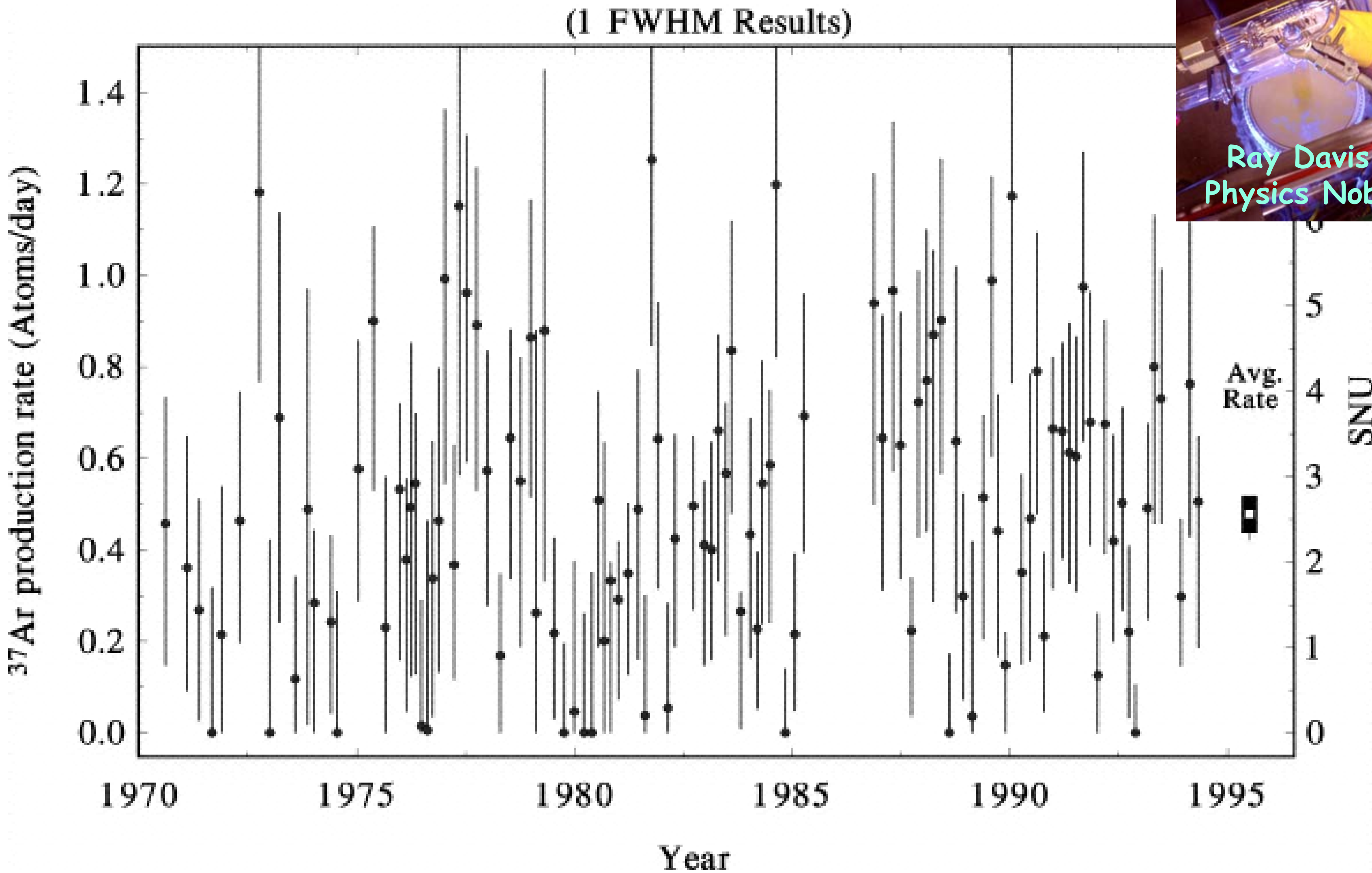
3 types of experiments detecting solar neutrinos

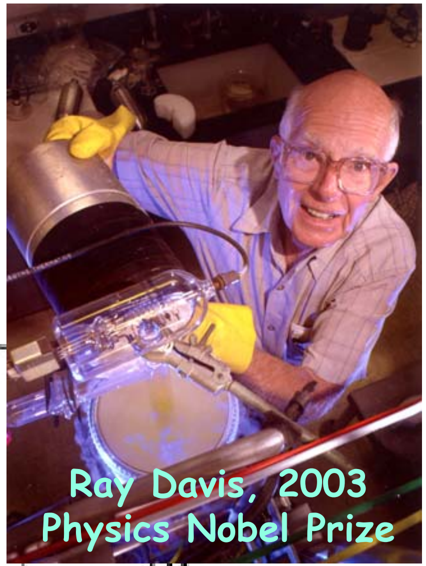
- Chlorine: $^{37}Cl+\nu_e={}^{37}Ar+e^-$
  1 exp running >30 yrs (US)
- Gallium: $^{71}Ga+\nu_e={}^{71}Ge+e^-$
  3 exp (Russia, Italy)
- Cerenkov: $e^-+\nu_x=e^-+\nu_x$
  $\nu_e+{}^2H=p+p+e^-$
  3 exp (Japan, Canada)



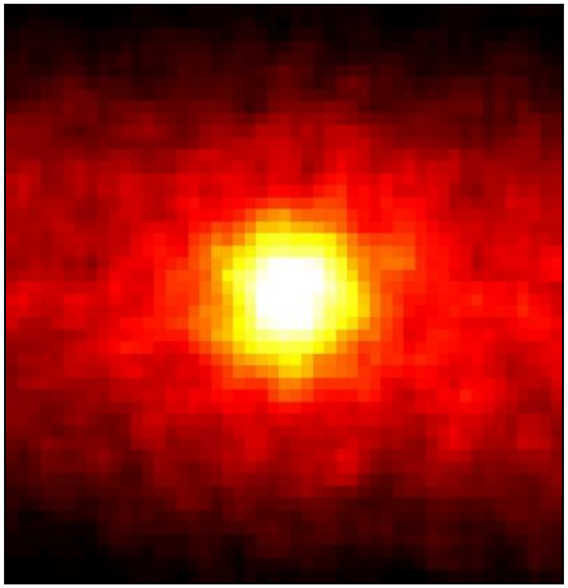


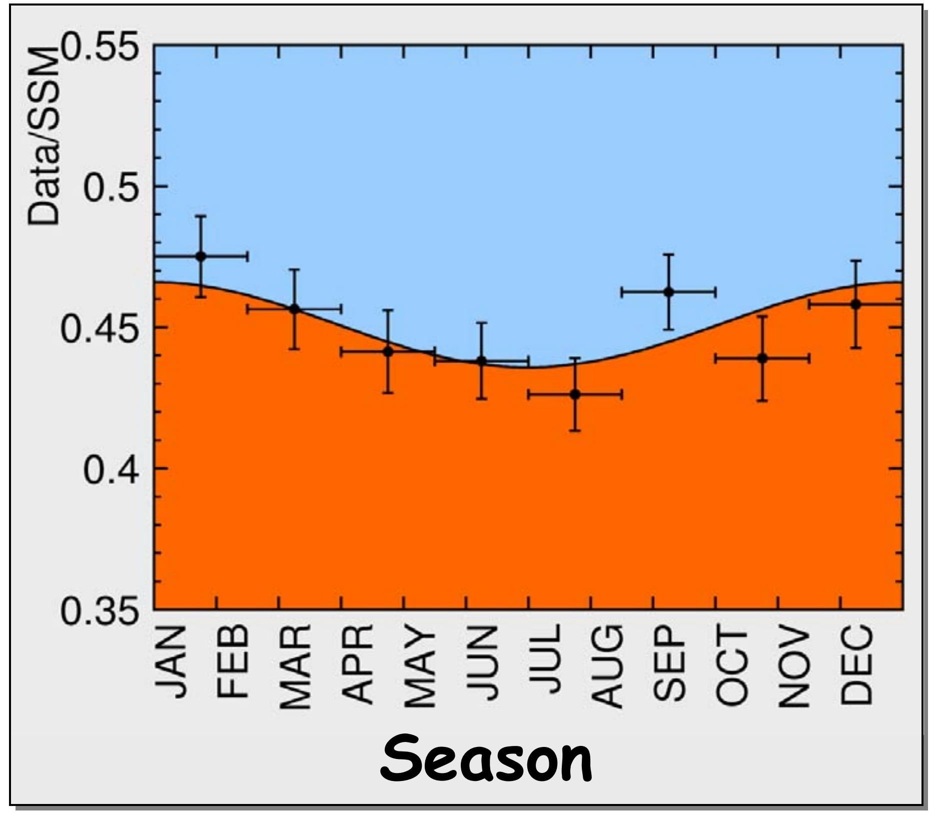
30 years of solar neutrinos with the Chlorine detector

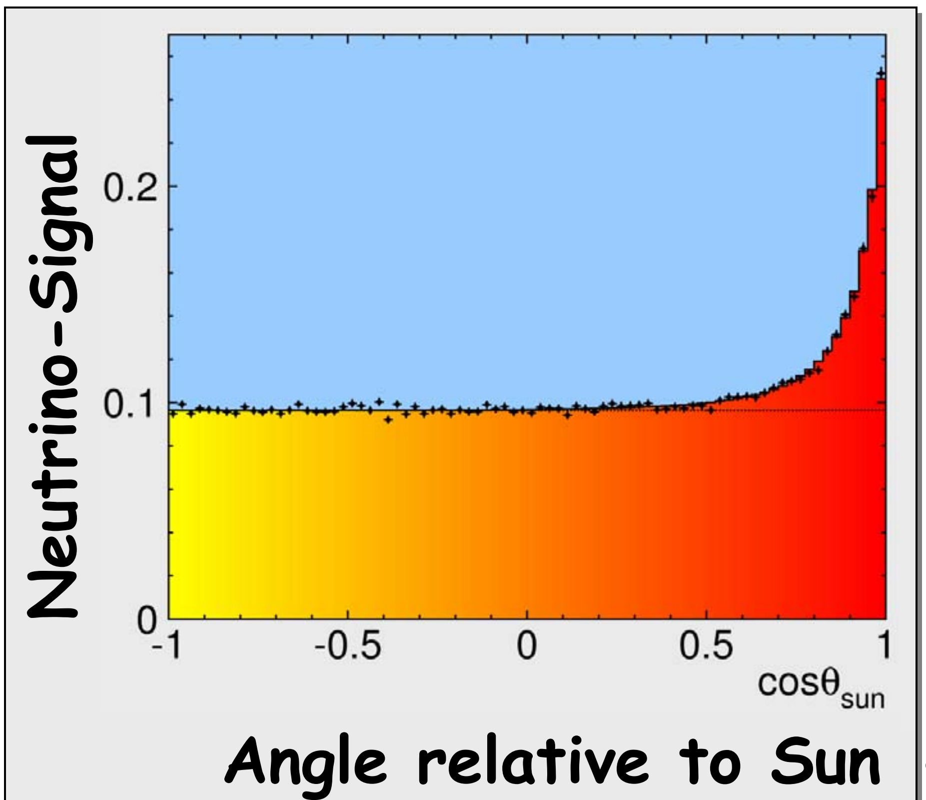




The Sun imaged with neutrinos







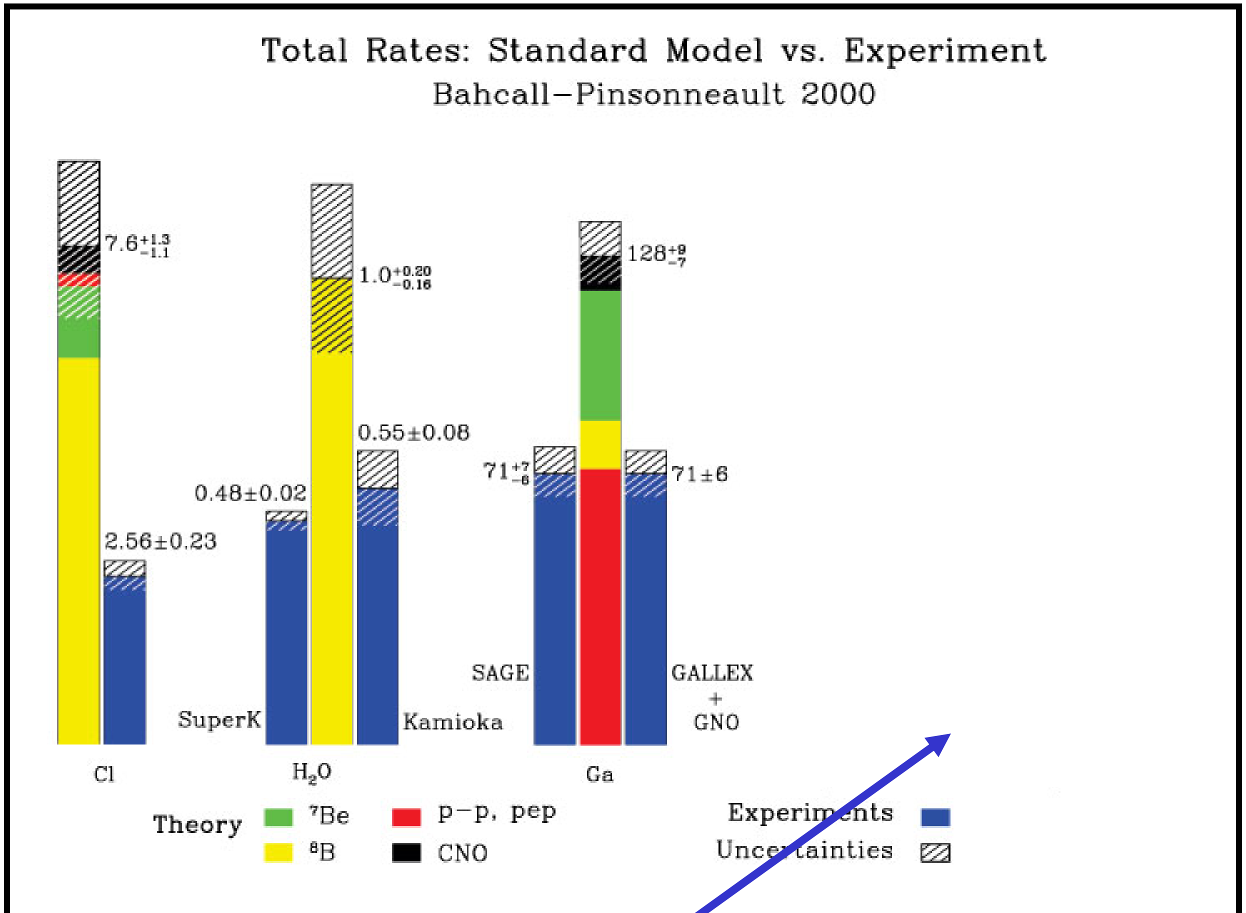
Conclusion 1:

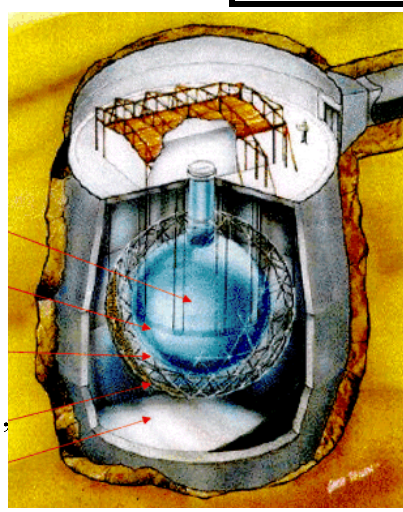
- We detect vs ! nuclear fusion powers the sun
- The sun is still shining (this is not trivial: it takes ~ 1Myr for a photon to emerge from the sun)

Conclusion 2:

We do not see enough vs !

→ *something happens to the neutrinos in their journey from the core of the sun to the earth*





Data collected with the SNO detector:
- 1 kton of heavy water
- ~2000 m underground in Ontario

So… what happens ?

In Quantum Mechanics there are 2 representations for our neutrinos if $m_\nu \neq 0$:

- "Weak interaction eigenstate"

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

this is the state of definite flavor: interactions couple to this state

- "Mass eigenstate"

$$\begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

this is the state of definite energy: propagation happens in this state

The 2 eigenstates are connected by a 3·3 matrix ("mixing matrix")

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

A source produces –say- ν_e
always via weak interactions

$$\nu_e$$

To see what propagates to the detector I have to project this flavor state onto the mass state using the matrix inverse of U

$$\nu_m = U^{-1}\nu_e$$

Now each of the ν_m will evolve in time as prescribed by the wave functions

$$\nu_{m1}(t) = e^{-i(E_1 t - p_1 L)}\nu_{m1}$$
$$\nu_{m2}(t) = e^{-i(E_2 t - p_2 L)}\nu_{m2}$$
$$\nu_{m3}(t) = e^{-i(E_3 t - p_3 L)}\nu_{m3}$$

but note that the periodic term contains the neutrino mass via $E_i=m_ic^2$

So at the end of their flight -at the detector- the mix of ν_{m1}, ν_{m2}, ν_{m3} will not necessarily be the one that makes "exactly" ν_e!

The neutrinos are then detected via weak interactions and so we need to find again the composition in terms of ν_e, ν_μ, ν_τ

Formally

$$\left|\nu_j\right\rangle = \sum_{j'}\sum_{l} U_{lj} e^{-i(E_j t - p_j L)} U^{*}_{j'l}\left|\nu_{j'}\right\rangle$$

So after some propagation one can "find" a neutrino of a flavor that was not originally present

This is a pure quantum-mechanical effect, there is no classical interpretation of it (this is why it looks so weird)

<u>It can ONLY happen if the mass is non-0</u>

The situation is analogous to the case of beats in sound

The wavefunctions of the two neutrino mass eigenstates need to be combined in a linear combination to obtain the flux of a particular flavor eigenstate

The beat represents the oscillating intensity of a detected neutrino flavor

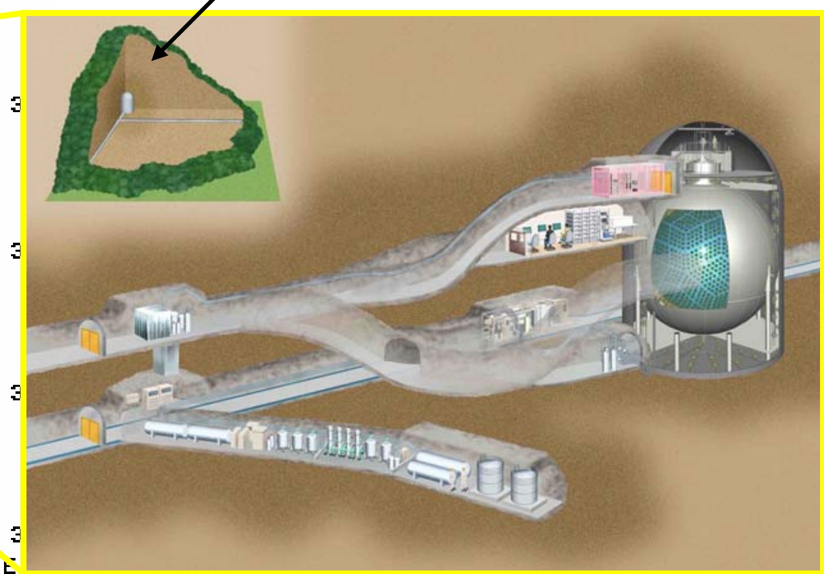
beats\beats.html

The mass (together with the kinetic energy) of the neutrino give the frequency of the wavefunction

So this quantum mechanical "beat" phenomenon allows us to detect extremely small neutrino masses

Can we detect oscillations in phenomena other than solar neutrinos ?

~1 km high
Mt Ikenoyama



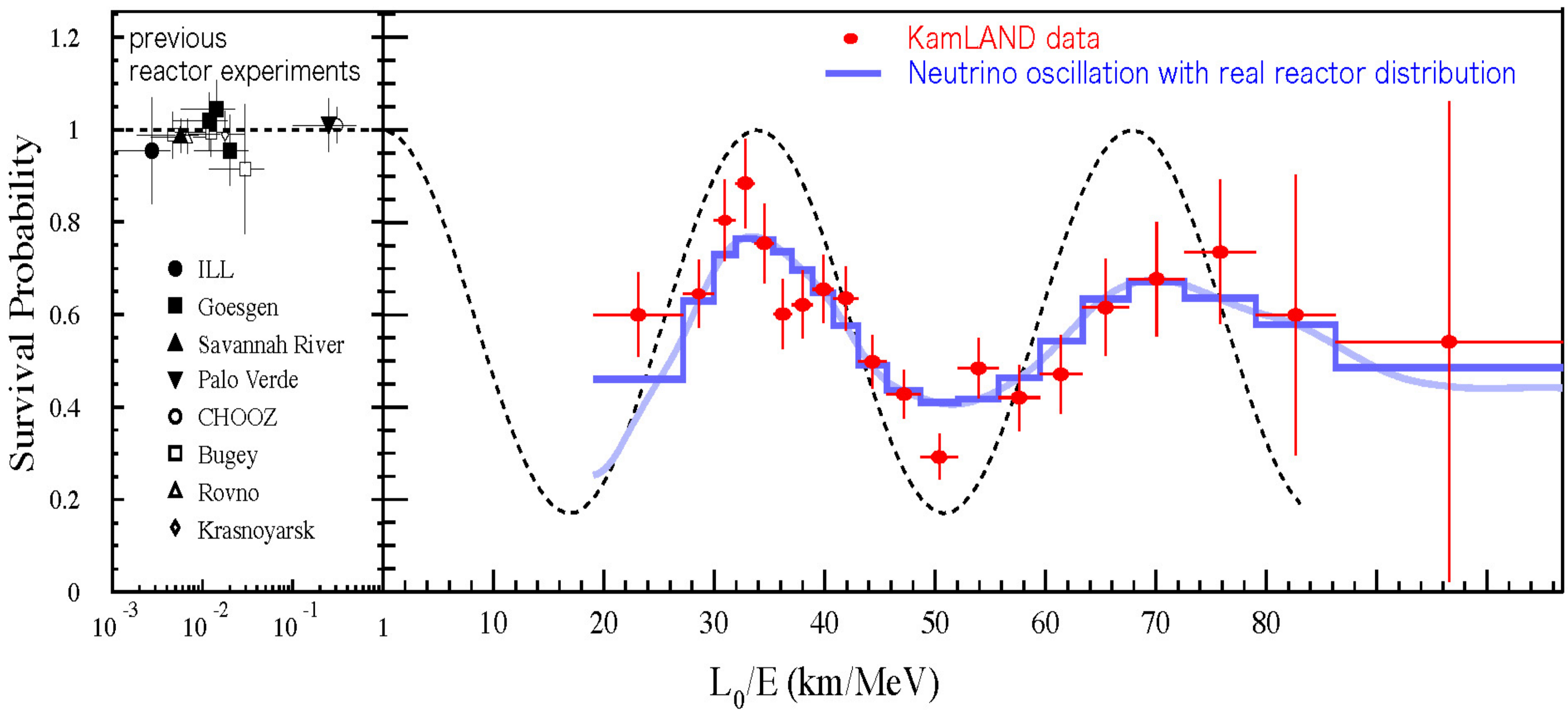
69 reactor cores from Japan and (South) Korea

Baseline is limited:
85.3% of signal has
140 km < L < 344 km

The total electric power produced "as a by-product" of the νs is:

- ~60 GW or...
- ~4% of the world's manmade power or...
- ~20% of the world's nuclear power

The result from reactors agrees very well with what expected from the phenomenon of solar neutrinos

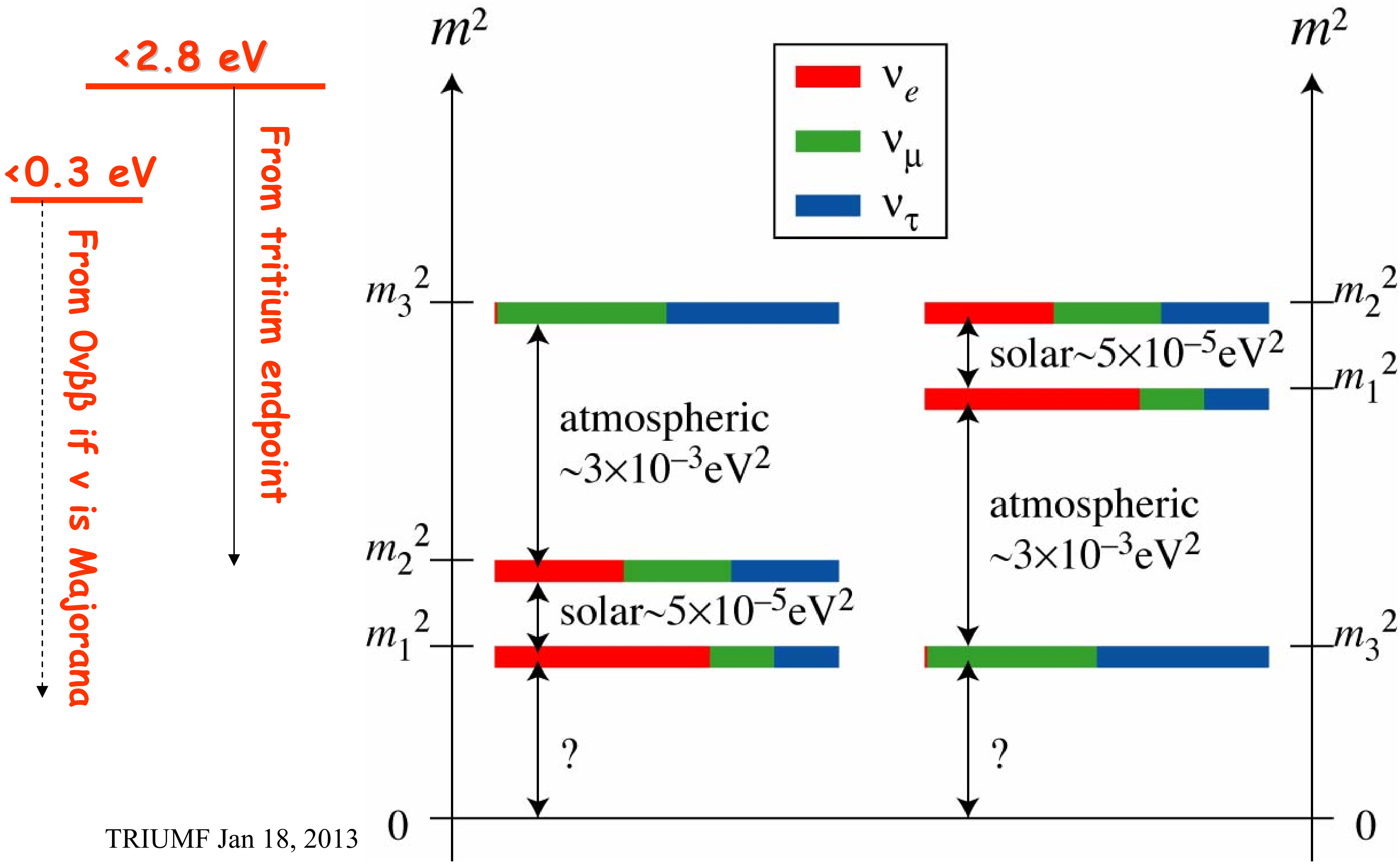


So, we have now observed neutrino oscillations and hence we know that neutrinos have a finite mass

However measuring beats only provide information about the *difference* between two frequencies…

→ We still do not know the neutrino mass scale !

Summary of knowledge on neutrino masses



Allright, this is lots of fun but…
can we use these neutrinos for something useful ?!

The answer is usually "no", among other things because neutrinos are so difficult to detect…

...but, remember the story of M.Faraday and the King…

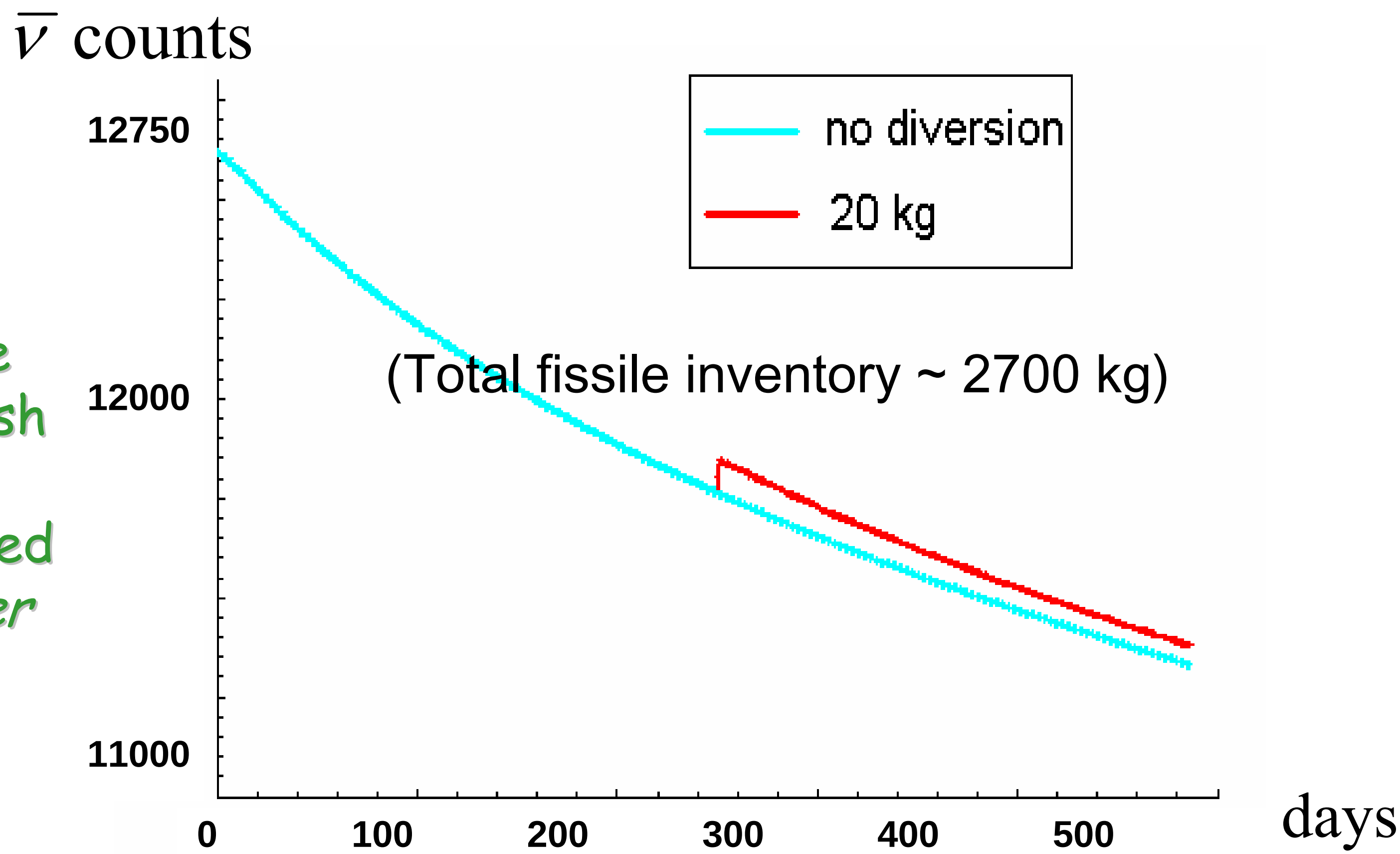
Let's go back to a device that makes LOTS of antineutrinos: a nuclear reactor

We can turn things around and use antineutrinos to "peek inside" the reactor's core
(neutrinos don't care that there are heavy walls !)

The antineutrino count rate varies in a known way as Pu is produced even at constant power

Example:

20 kg of fuel containing Pu are replaced with fresh U and then the reactor is restarted at the *same power level*



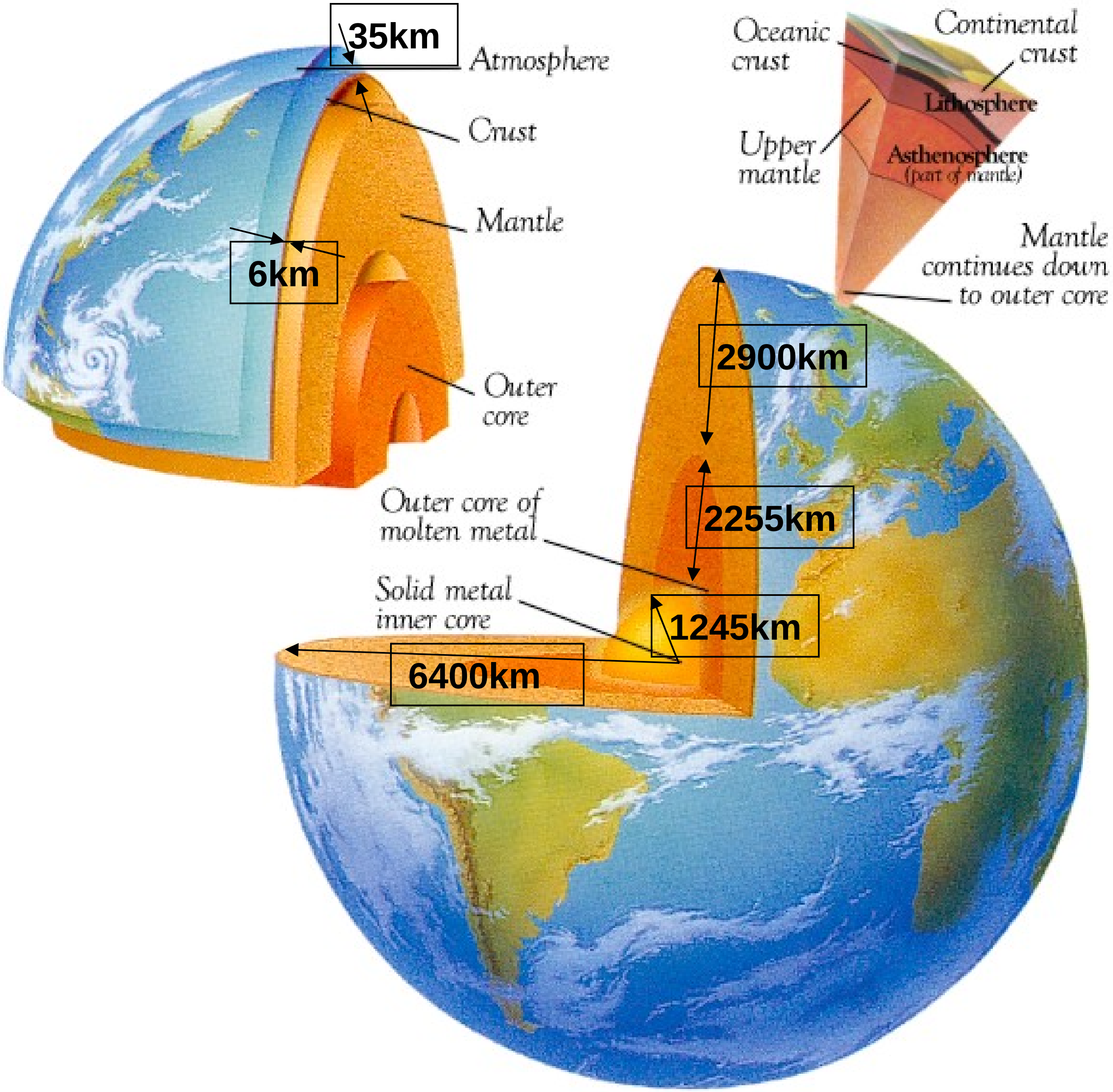
Technology demonstration detector being prepared at the San Onofre Nuclear Generating Station (CA) [Sandia Natl Lab]

Set the 1m^3 detector in the “tendon gallery” 24.5 m from the core

Heavy reactor building provides shielding from cosmic rays

Expect 2600 ν/day with 40% detector efficiency

Earth sciences and the neutrinos

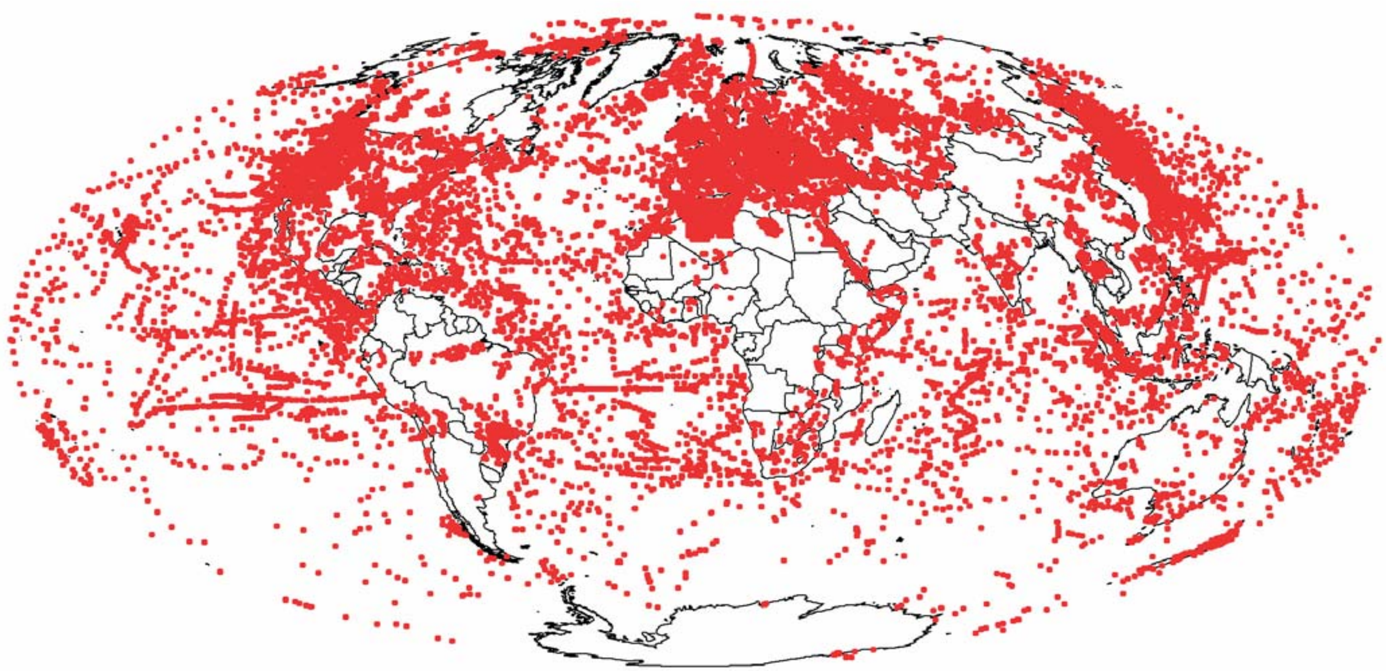


Structure of the Earth

- From seismic data
  5 basic regions:
  - inner core,
  - outer core,
  - mantle,
  - oceanic crust,
  - continental
    crust and
    sediments

- All these regions behave like solids except the outer core.

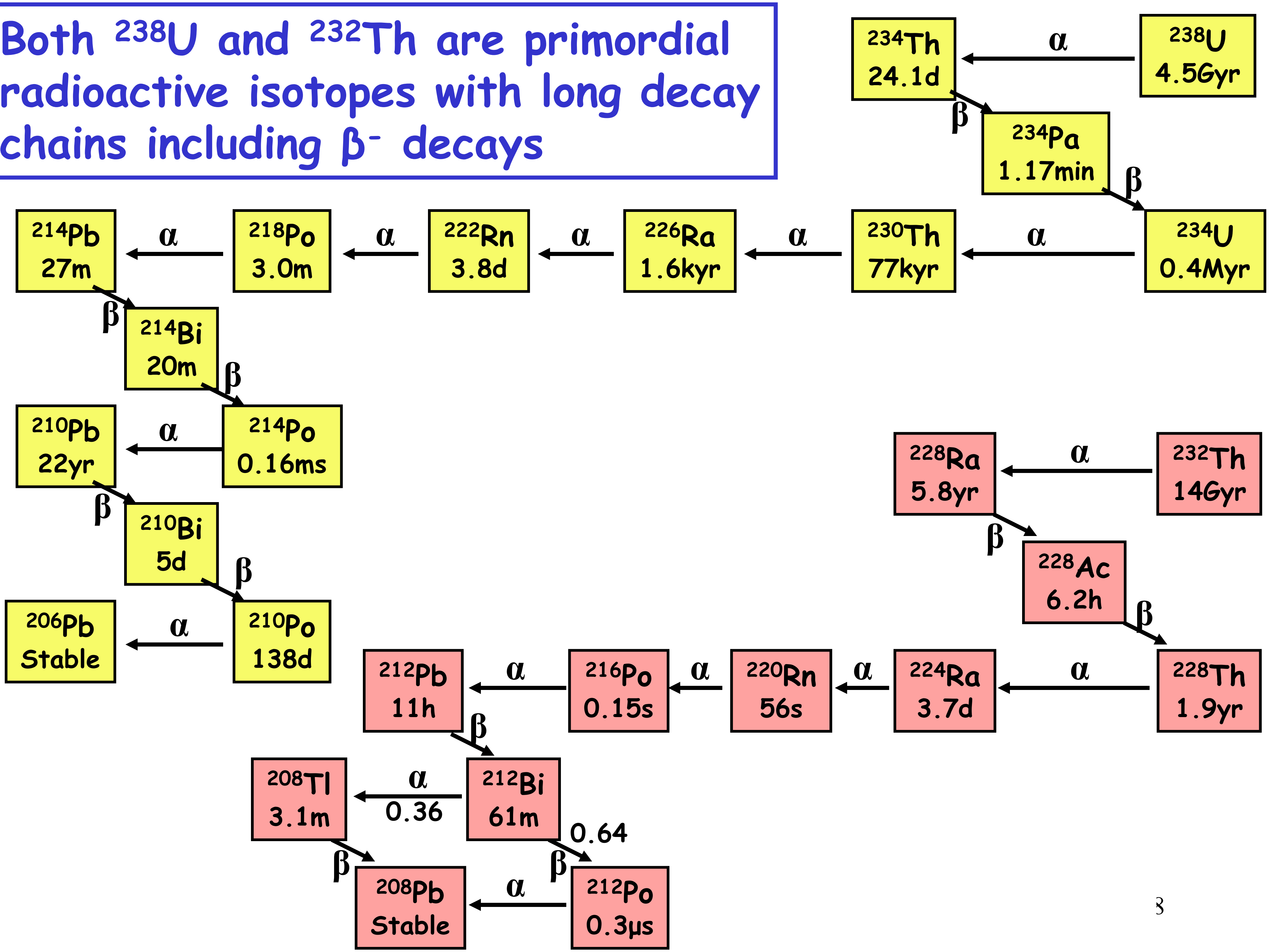
Only a shallow layer has been sampled for chemical composition by drilling/sampling



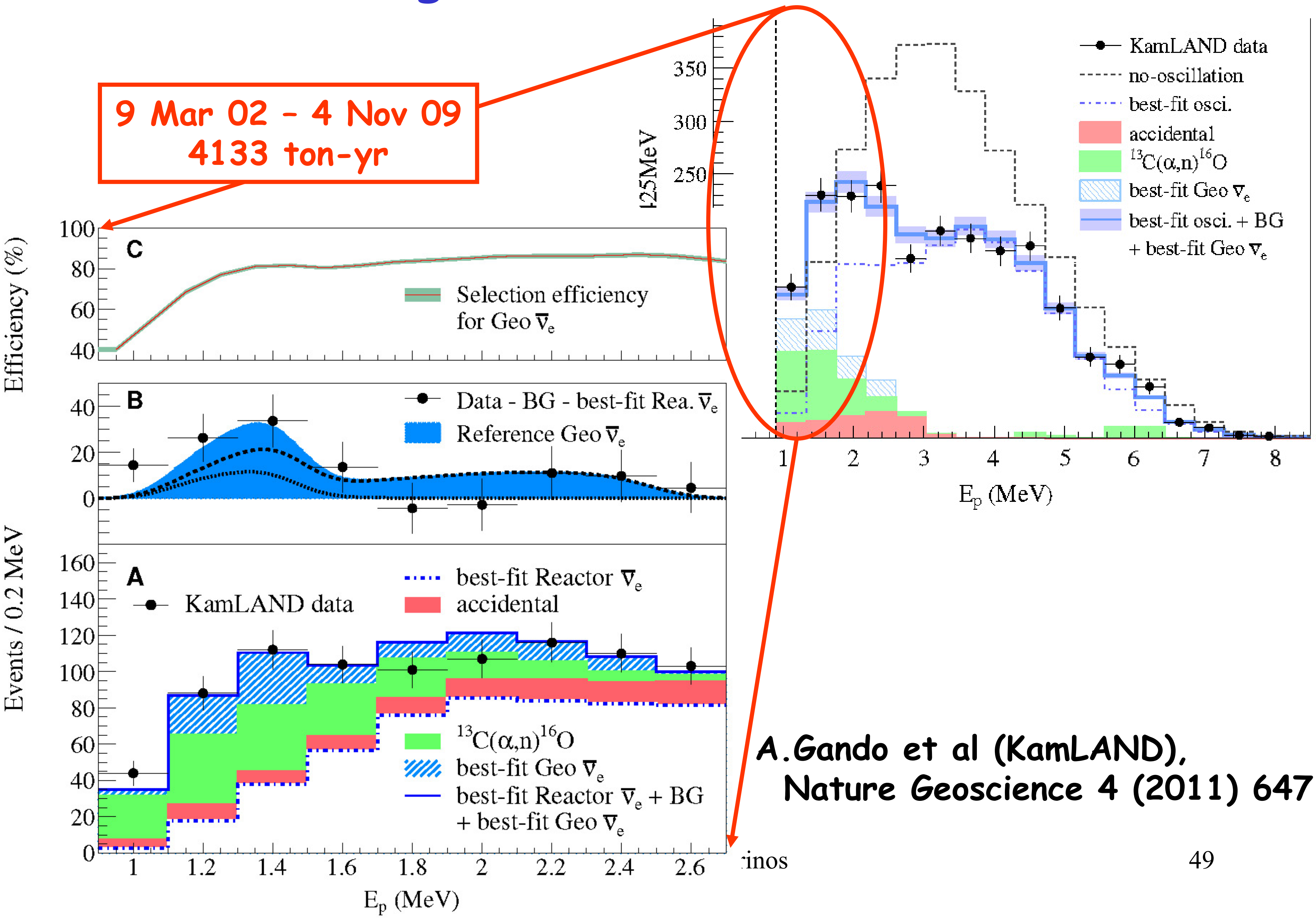
Global distribution of heat flow data.
38,347 data points from Davies and Davies, 2010.

- Deepest bore-hole (12km) is only ~1/500 of the Earth's radius
- Oceans and southern hemisphere substantially less studied

Both ^{238}U and ^{232}Th are primordial radioactive isotopes with long decay chains including β^- decays

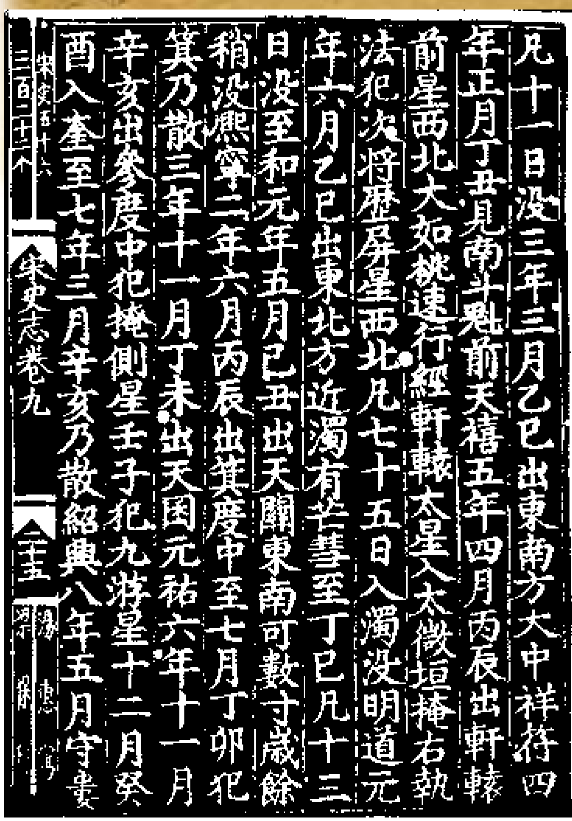


Detecting Geoneutrinos!



A.Gando et al (KamLAND), Nature Geoscience 4 (2011) 647

Supernovae and the neutrinos


凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九斿星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁
宋史志卷九

"type II" SN in the Crab;
Jul 4, 1054 AD
(as recorded by the
Anasazi in Chaco Canyon, NM
and the ancient Chinese)

The Crab Nebula formed by the
expelled outer shell of the same star
(as recorded by the VLT,
Cerro Paranal, Chile)

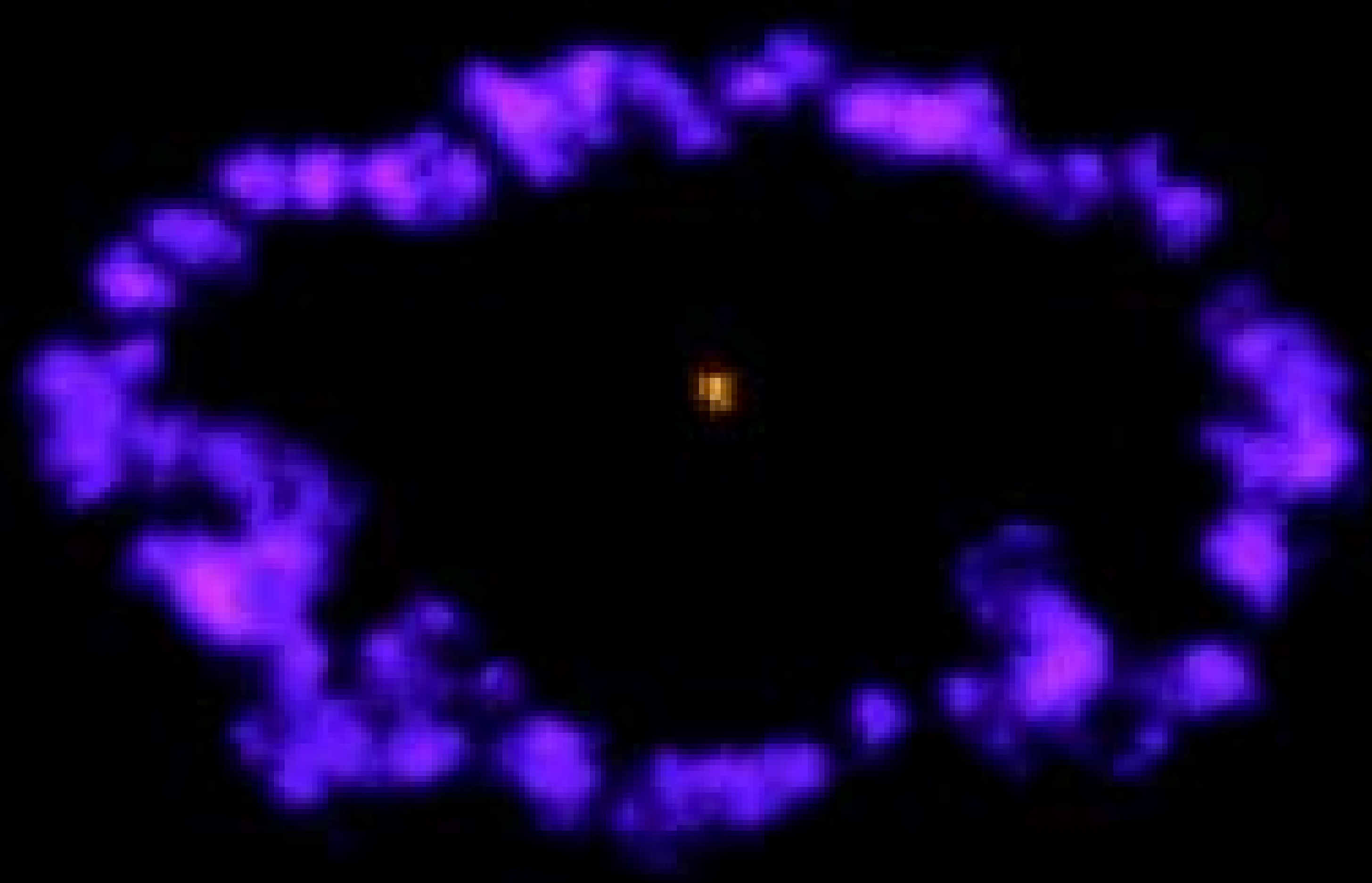
Type II supernovae: explosive phase of a star with $M>6$ to $8\ M_{sun}$

- Nuclear fuel burnt through Fe: no mechanism to hold further gravitational collapse
- $T=0.8*10^{10}$ K = 0.7 MeV
  $\rho=3*10^9$ g/cm^3 (this is a billion times the density of the earth, or the entire KamLAND in a teaspoon)
- The pressure causes the reaction $p+e^- \rightarrow n+\nu_e$ to occur

Very intense ν_e flash (~1 s duration)

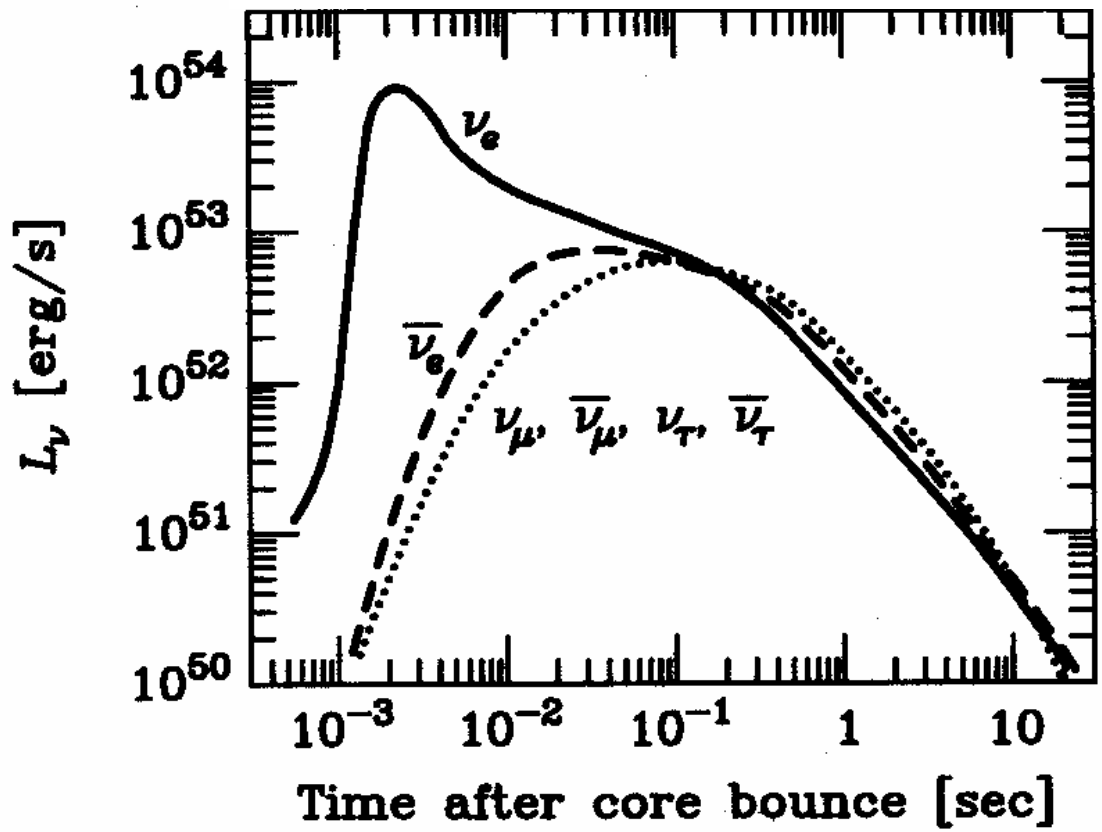
- Neutrinos cool the star that collapses further
- The collapsing soup become so dense to be opaque to ν (!)
- Following mechanisms that we do not completely understand the fireball re-bounces blowing up the outer envelope (eventually like the Crab photo)
- ν of all flavors escape when density low enough (after ~10 s)

SN1987A reconstruction from real astronomical images



99% of the supernova explosive energy is carried away by neutrinos

*...~3.8*10^33 erg, in 10 s it would take the sun 2000 billion years to produce that much energy !*

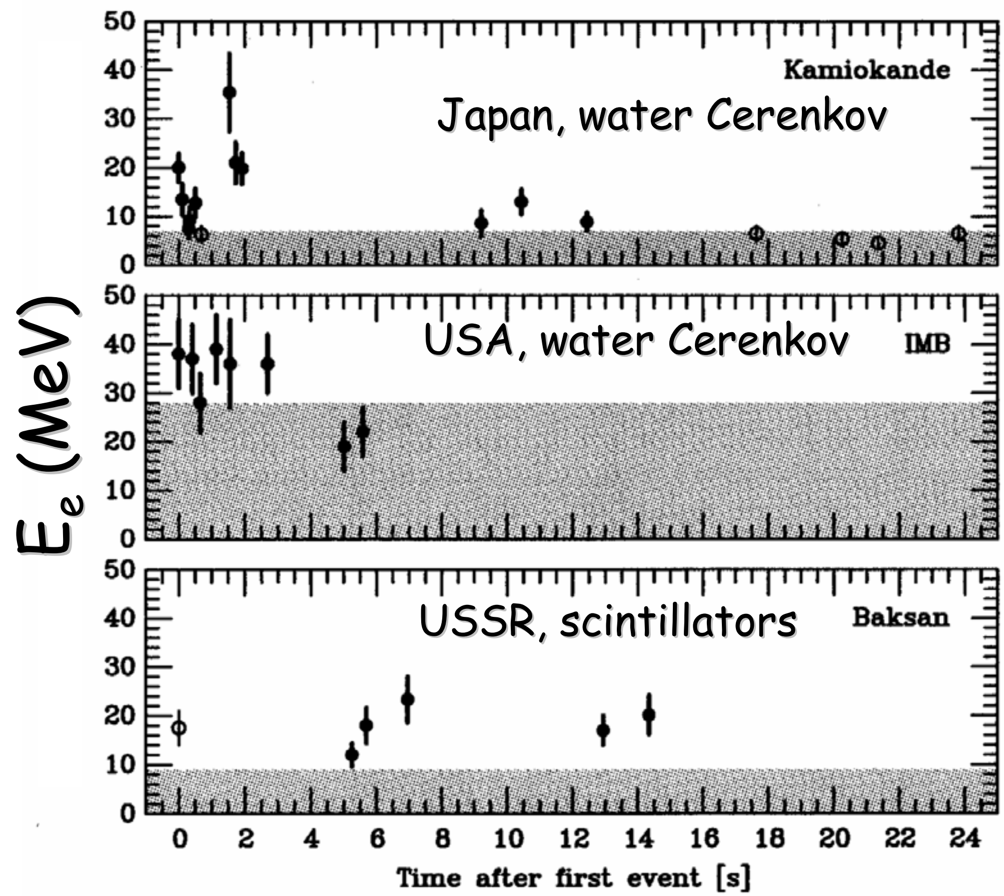


Only hours later the density is low enough for light to escape the star and the supernova flash appears

We have seen the neutrinos from a supernova only once

Feb 23, 1987 about 20 ν events were detected from an explosion in the Large Magellanic Cloud: SN1987A

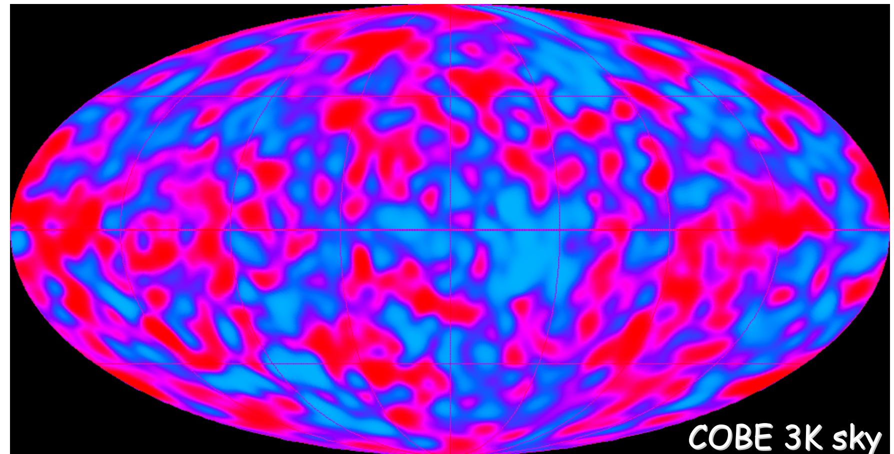
The dawn of neutrino astronomy

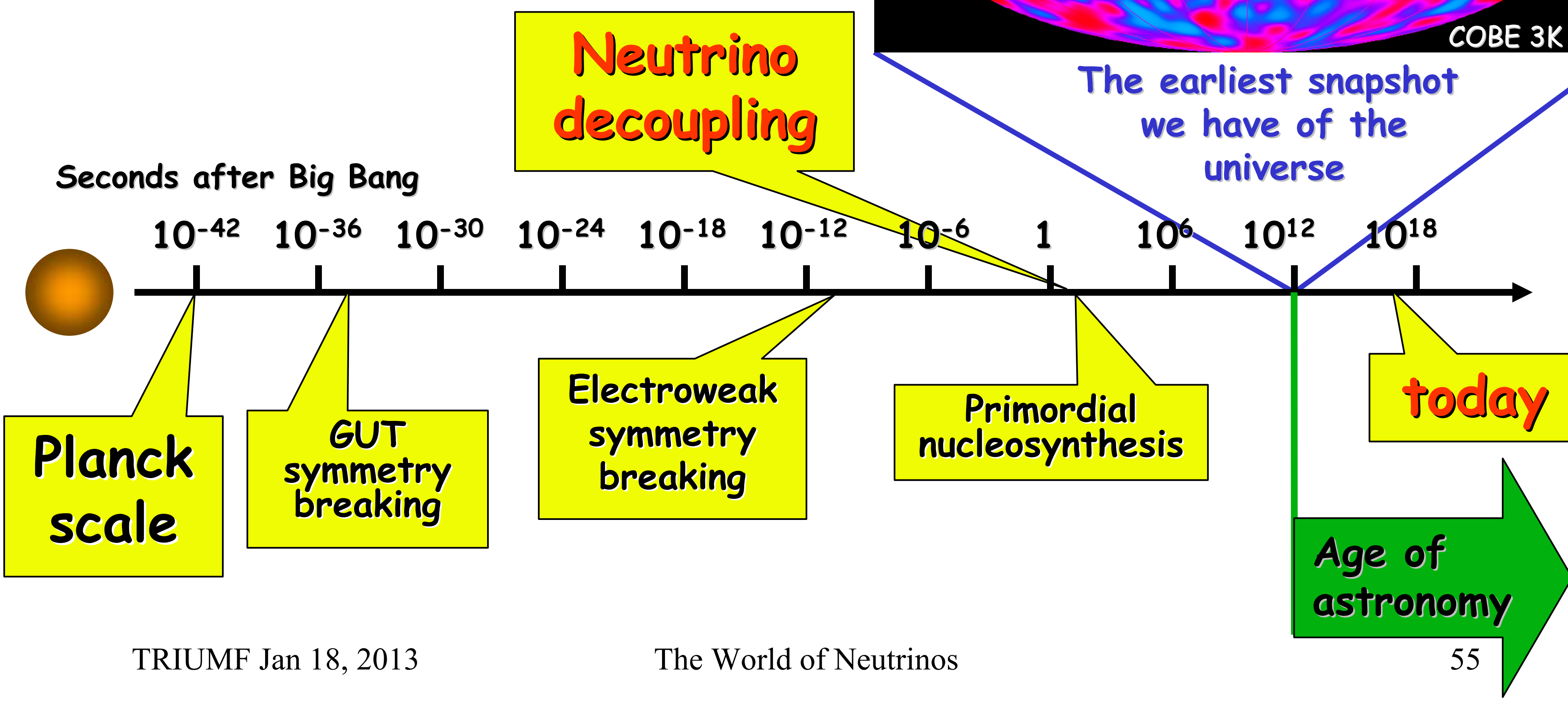


Cosmology

Primordial neutrinos where produced when nuclei formed, at the time the Universe was 1 second old

We believe that they are still among us





Relic neutrinos have been "red-shifted" by the by the expansion of the Universe

Their temperature now is supposed to be ~2K, lower than the temperature (3K) of the microwave background radiation that was produced when the Universe was 30,000 years old

We do not have the technology to directly detect these neutrinos

But… we can see how their presence shaped the density fluctuations of matter in the early Universe as imaged by the microwave background radiation

Neutrinos,

mysterious ambassadors
from the microworld
to the remote cosmos,
what lessons do you
have for us next?