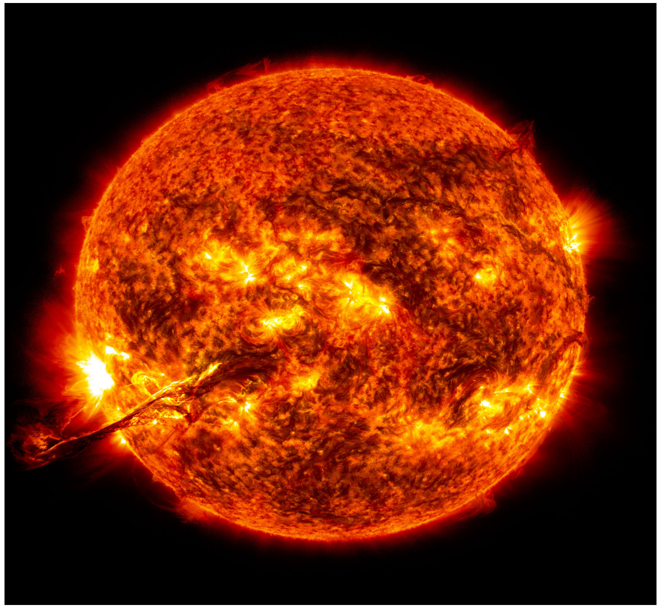
7h Georgian-German
School and Workshop in Basic Science
GGSWBS'16

Neutrino Physics with Scintillator - Based Detectors

Livia Ludhova

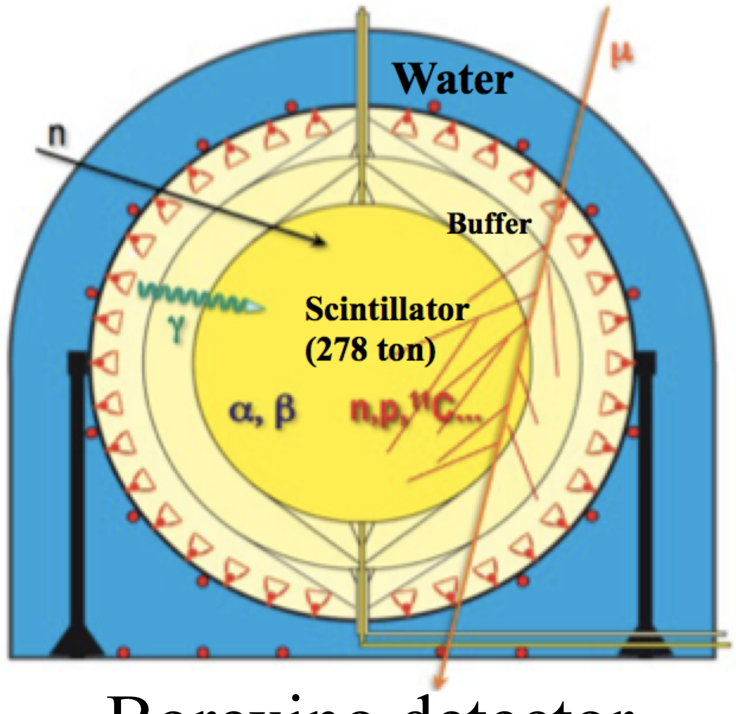
IKP-2 Forschungzentrum Jülich, JARA – FAME, RWTH Aachen

Imagine….



On Earth, the flux of solar neutrinos ~70 000 milions / cm^2 / s

and about 200 interactions / day / 100 tons of liquid scintillator

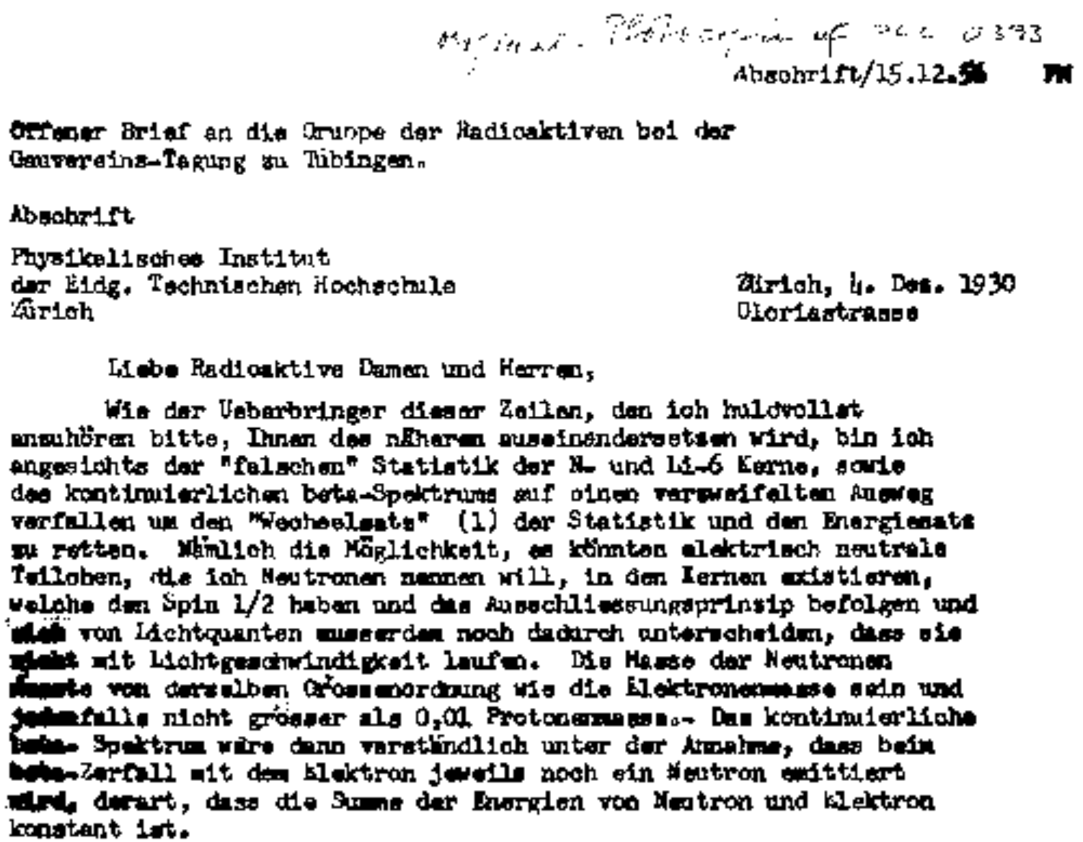


Borexino detector

Neutrinos cannot be detected…

Pauli around 1950

'I have done a terrible thing. I have postulated a particle that cannot be detected."



Abschrift/15.12.56 PM

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

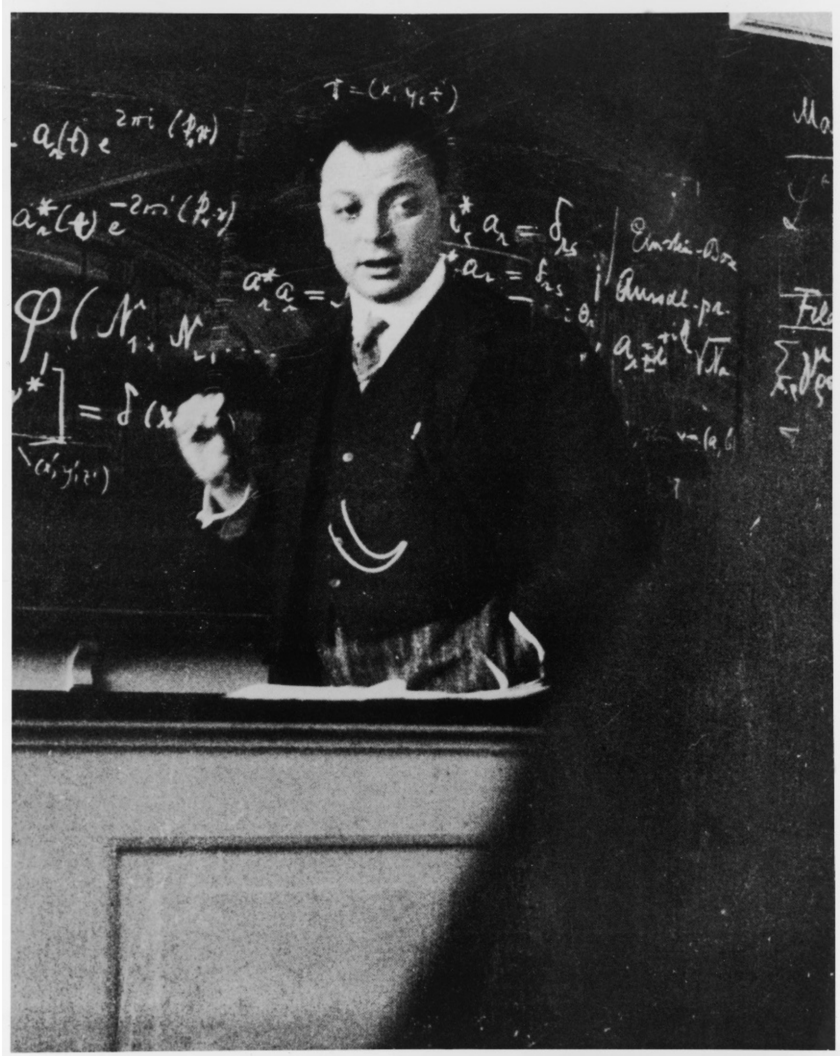
Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

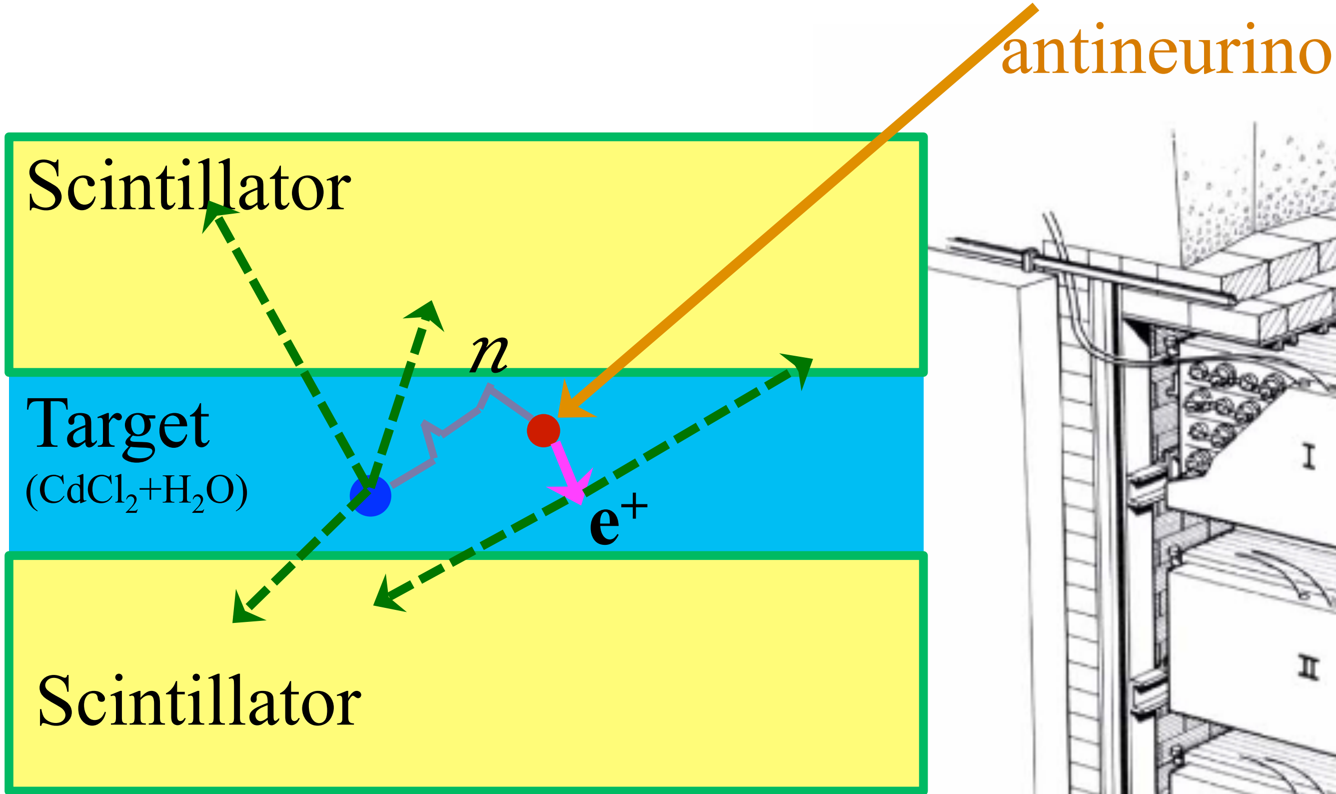
Zürich, 4. Dez. 1930
Gloriastrasse

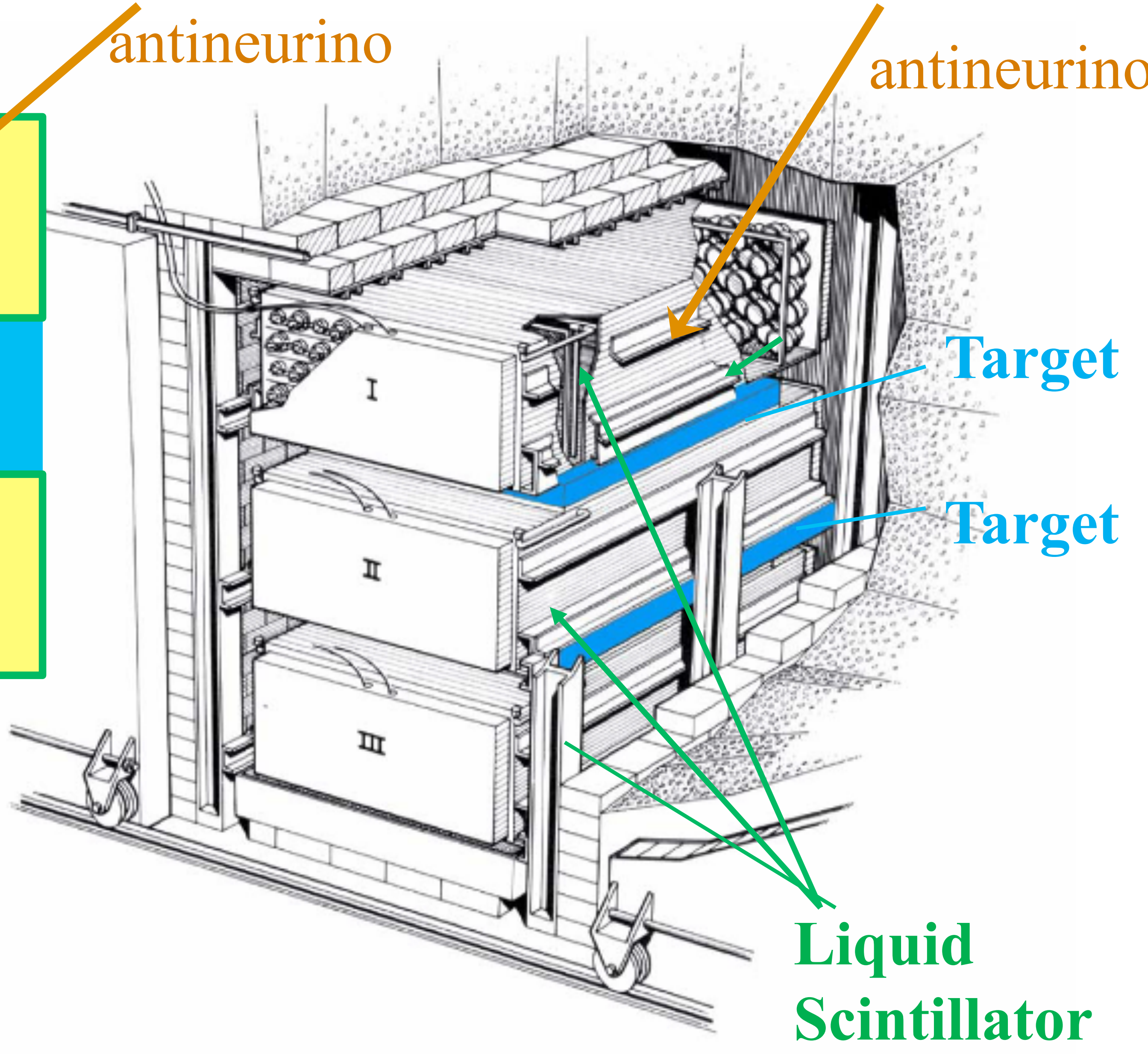
Liebe Radioaktive Damen und Herren,

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.



…and neutrino discovery in 1956





Nobel Prize in 1995

Reines-Cowan experiment

Savannah River Reactor

Neutrinos are special

Unique physics properties

Bring direct information about their source (Sun, SN, Earth)

Neutrino basics

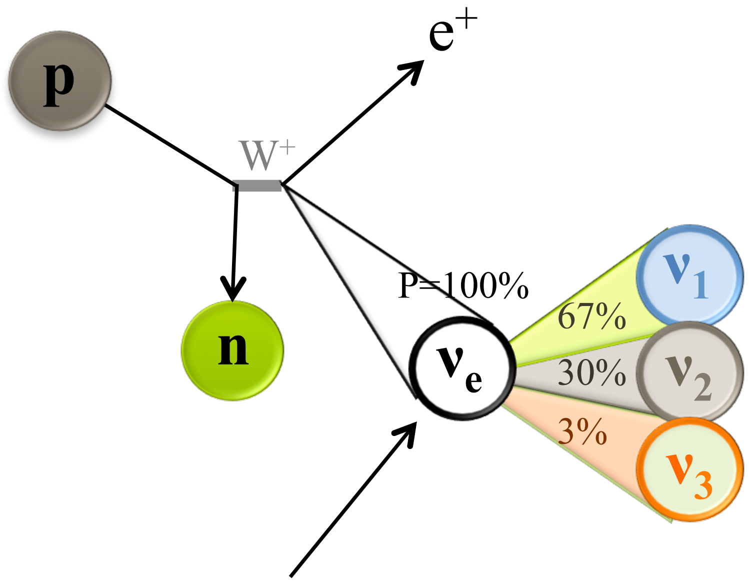
- No electric charge
  = no elmag interactions;
- No color
  = no strong interactions;
- only weak interactions
  = very small cross sections;

- Measured neutrinos are all left-handed and all antineutrinos are right handed;
- Thus, in the original Standard Model, neutrinos have exactly zero mass;
- Discovery of **neutrino oscillations (Nobel Prize 2015)**: **non-zero mass** required!
- Non-zero mass requires at least a minimal extension of the Standard Model;
- Origin of their masses: Dirac or Majorana particles?

Neutrino oscillations

ν production

e.g. β⁺-decay
as **flavor-eigenstate**:



Weak interaction creates neutrino in **flavor-eigenstate**.

Michael Wurm (JGU Mainz)

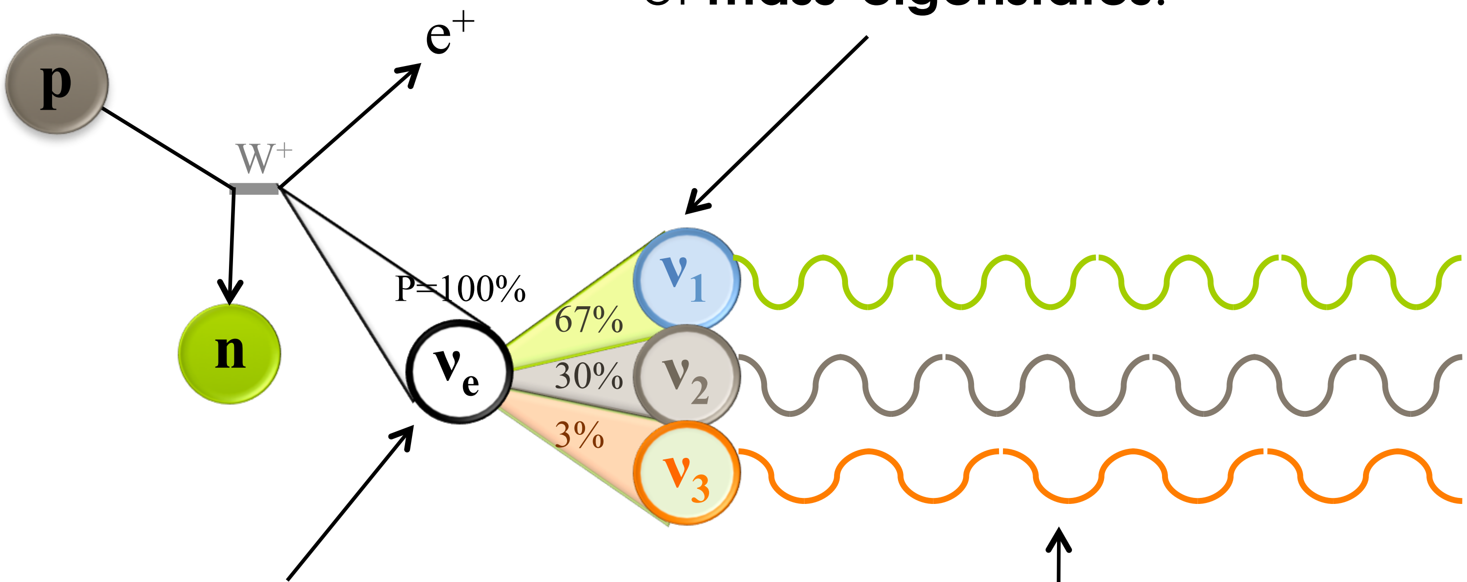
Neutrino oscillations

ν production

e.g. β^+-decay
as **flavor-eigenstate**:

ν propagation

as coherent superposition
of **mass-eigenstates**.



Weak interaction creates neutrino in **flavor-eigenstate**.

Different masses create a **phase difference** over time.

Michael Wurm (JGU Mainz)

Neutrino oscillations

ν production

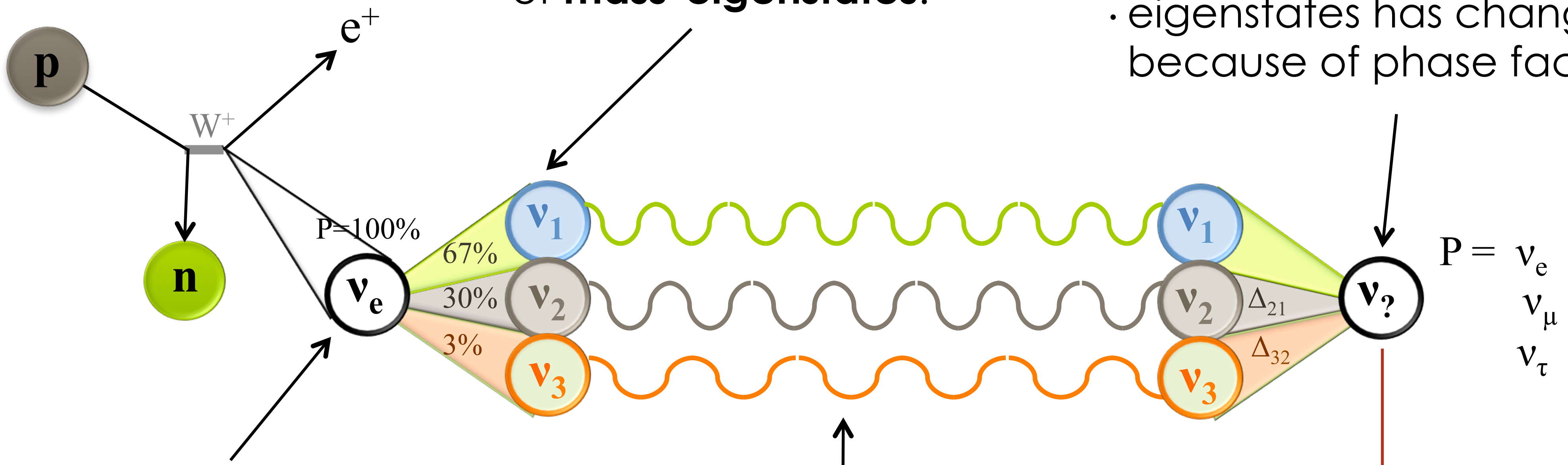
e.g. β^+-decay
as **flavor-eigenstate:**

ν propagation

as coherent superposition of **mass-eigenstates.**

ν detection

as **flavor-eigenstate**:
Superposition of mass eigenstates has changed because of phase factors.



Weak interaction creates neutrino in **flavor-eigenstate.**

Different masses create a **phase difference** over time.

*Finite probability to detect a different **neutrino-flavor**!*

Michael Wurm (JGU Mainz)

Neutrino mixing matrix

α = e, μ, τ
Flavour eigenstates
INTERACTIONS

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle$$

i = 1, 2, 3
Mass eigenstates
PROPAGATION

U: Pontecorvo – Maki – Nagawa – Sakata matrix

Atmospheric | Reactor | Solar | ? Majorana phases ?

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha 1/2} & 0 \\ 0 & 0 & e^{i\alpha 2/2} \end{pmatrix}$$

$\theta_{23} \approx 45°$ | $\theta_{13} \approx 9°$ | $\theta_{12} \approx 35°$

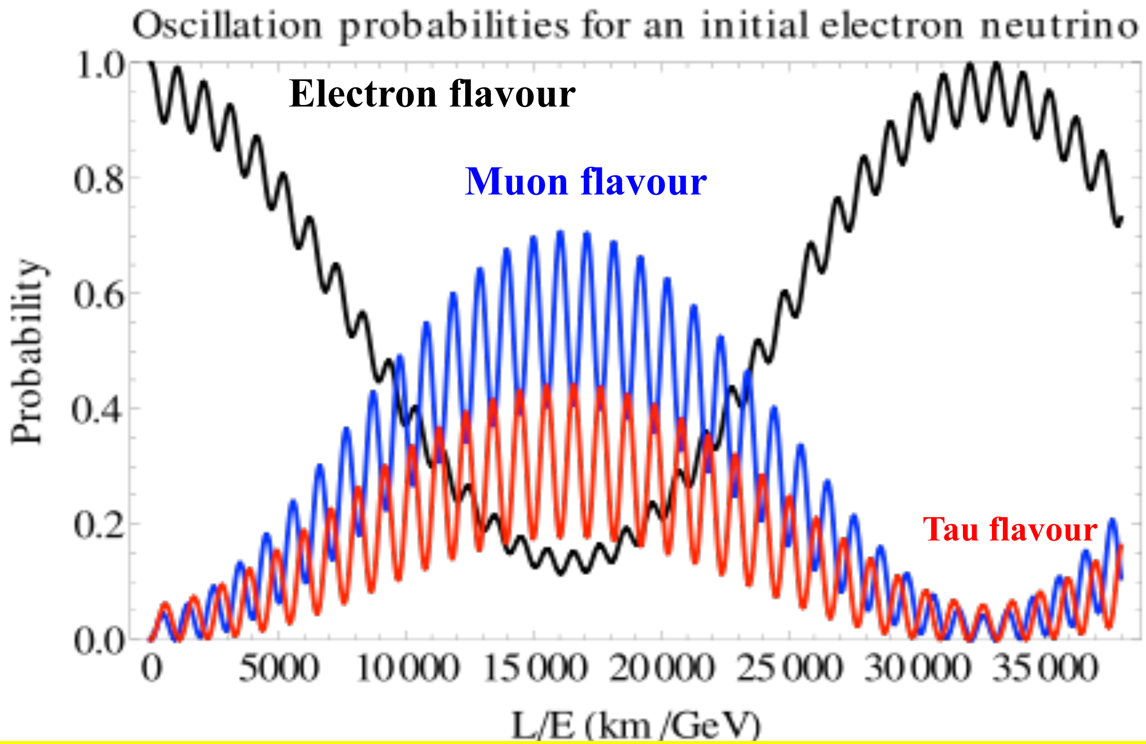
- **3 mixing angles θ_{ij}:** measured (bad precision for θ_{23});
- Non-zero θ_{13} confirmed only in 2012 by Daya Bay in China!
- **Majorana phases $\alpha 1$, $\alpha 2$** and **CP-violating phase δ** unknown;

Oscillation probability

is a function of neutrino energy E and travelled distance L

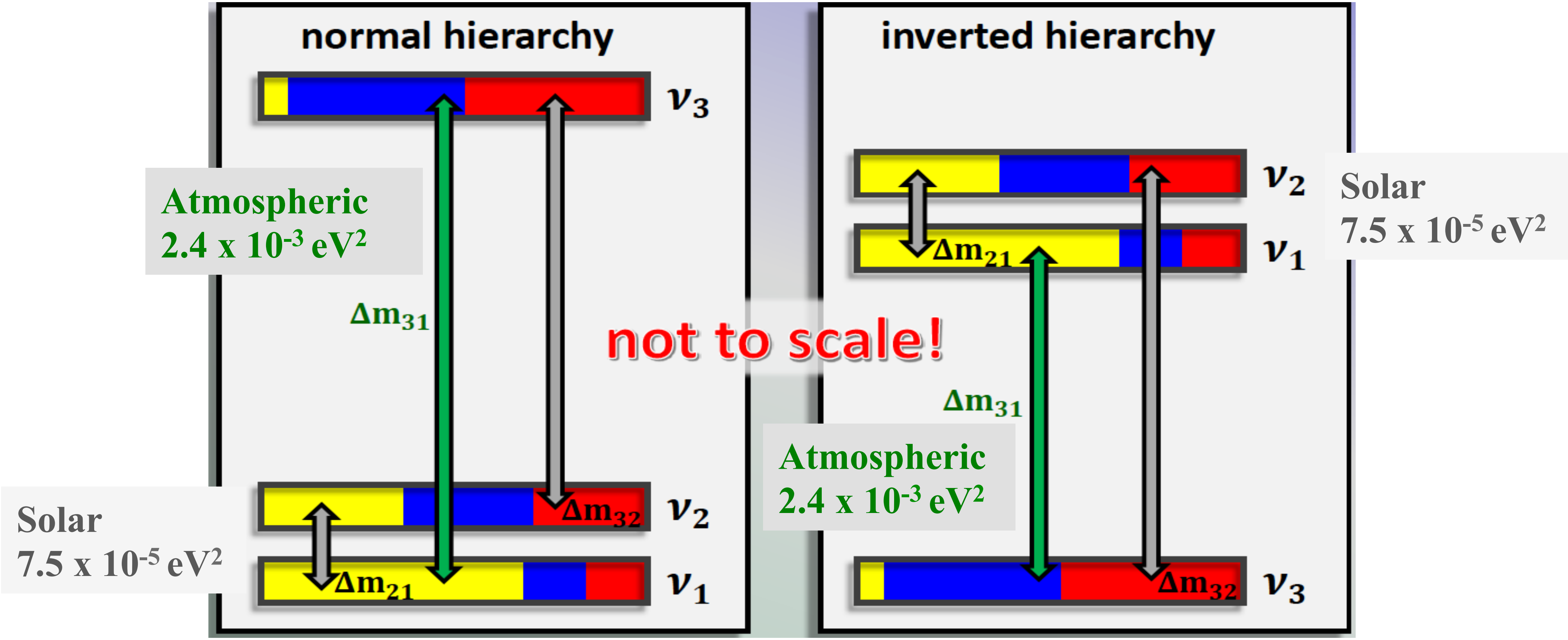
$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E})$$

$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E})$$



Combinations of E and L optimized to study different parameters!

Neutrino mass hierarchy

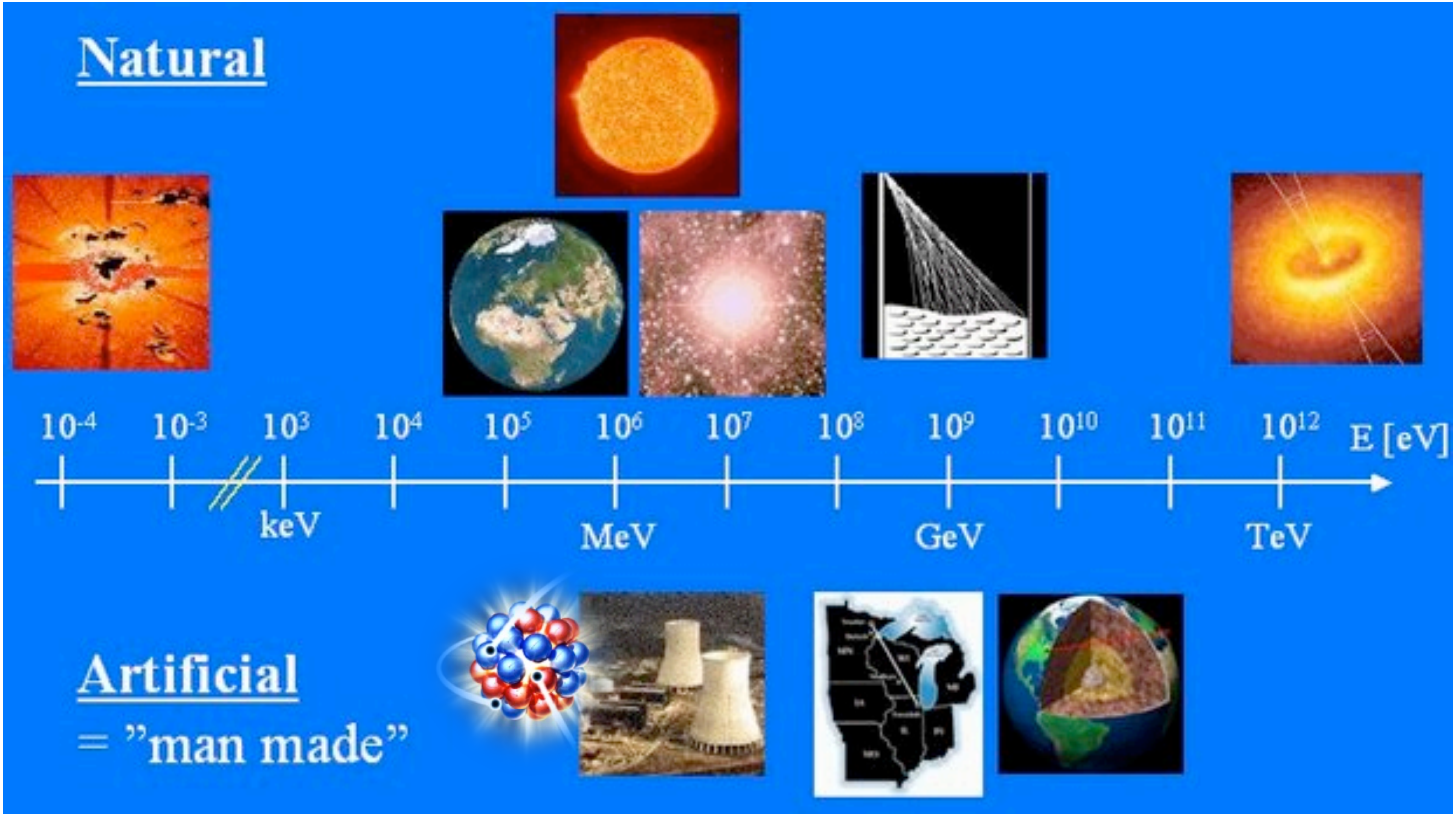


$\Delta m_{31,\text{normal}} > \Delta m_{31,\text{inverted}}$

+ -

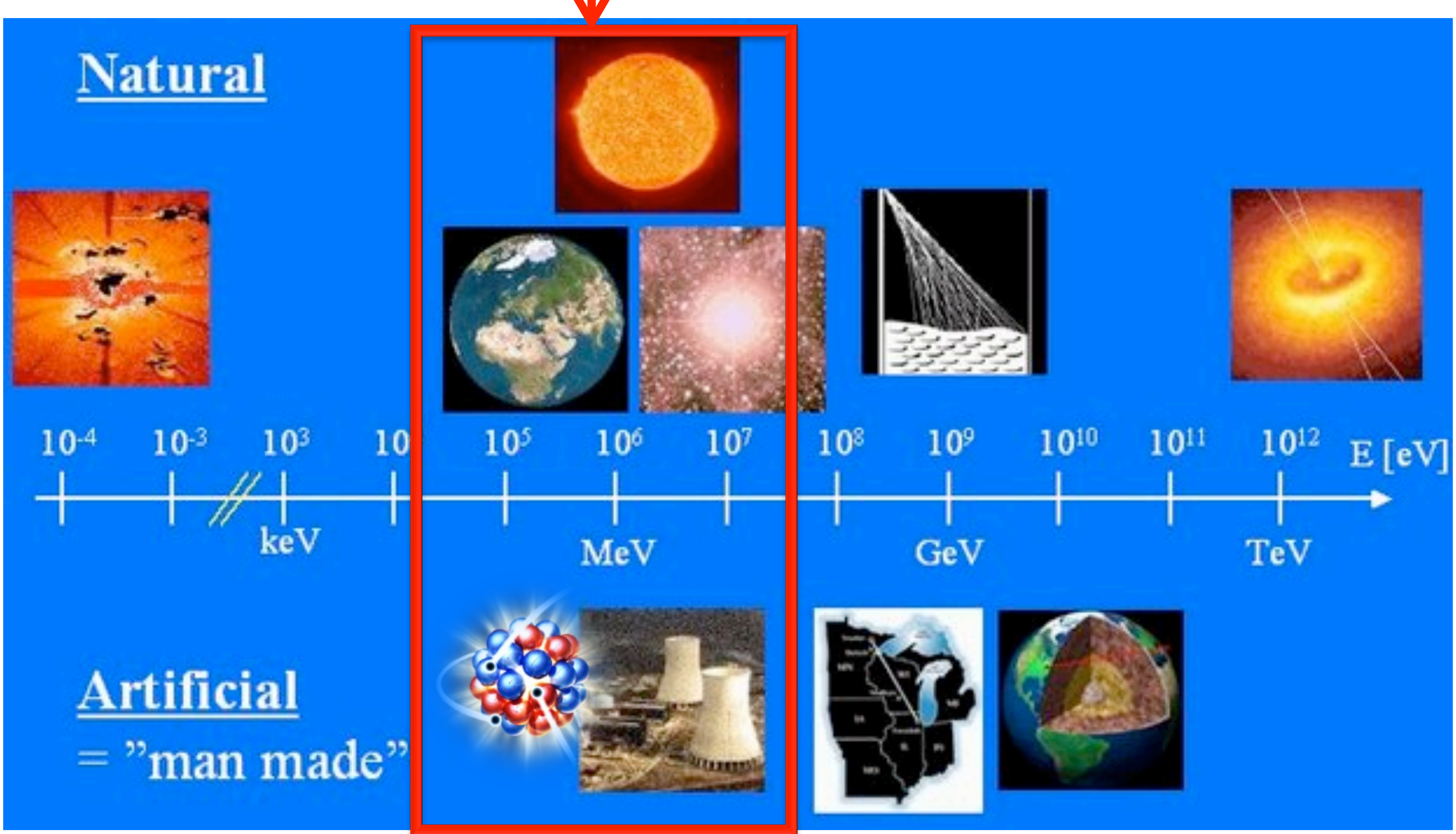
$|\Delta m^2_{31}| = m^2{}_3 - m^2{}_1$ *has opposite signs in the two hierarchies!*

Neutrino sources



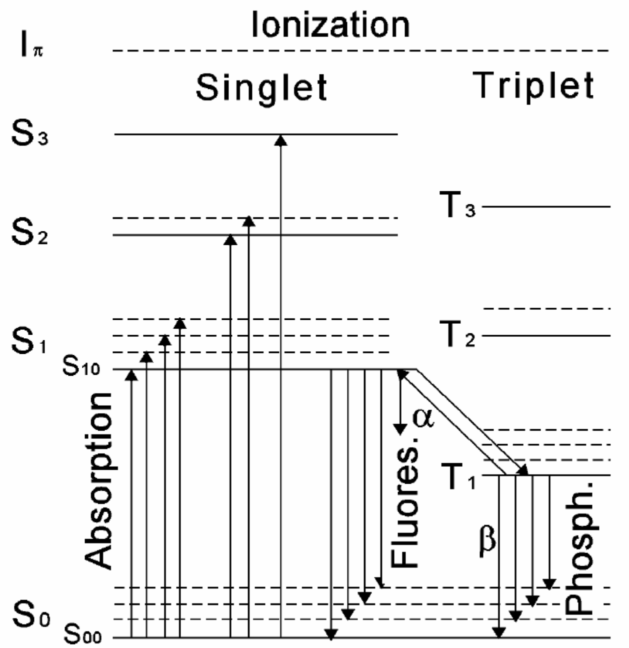
Neutrino sources

MeV neutrinos with liquid scintillator detectors



Detection principle in liquid scintillators

Moving
charged particle



Emission
of scintillation light.
Its amount is
f(deposited energy,
particle type)

Liquid aromatic carbohydrates
solvent (pseudocumene, LAB, PXE)
+
fluor (PPO, bis-MSB)

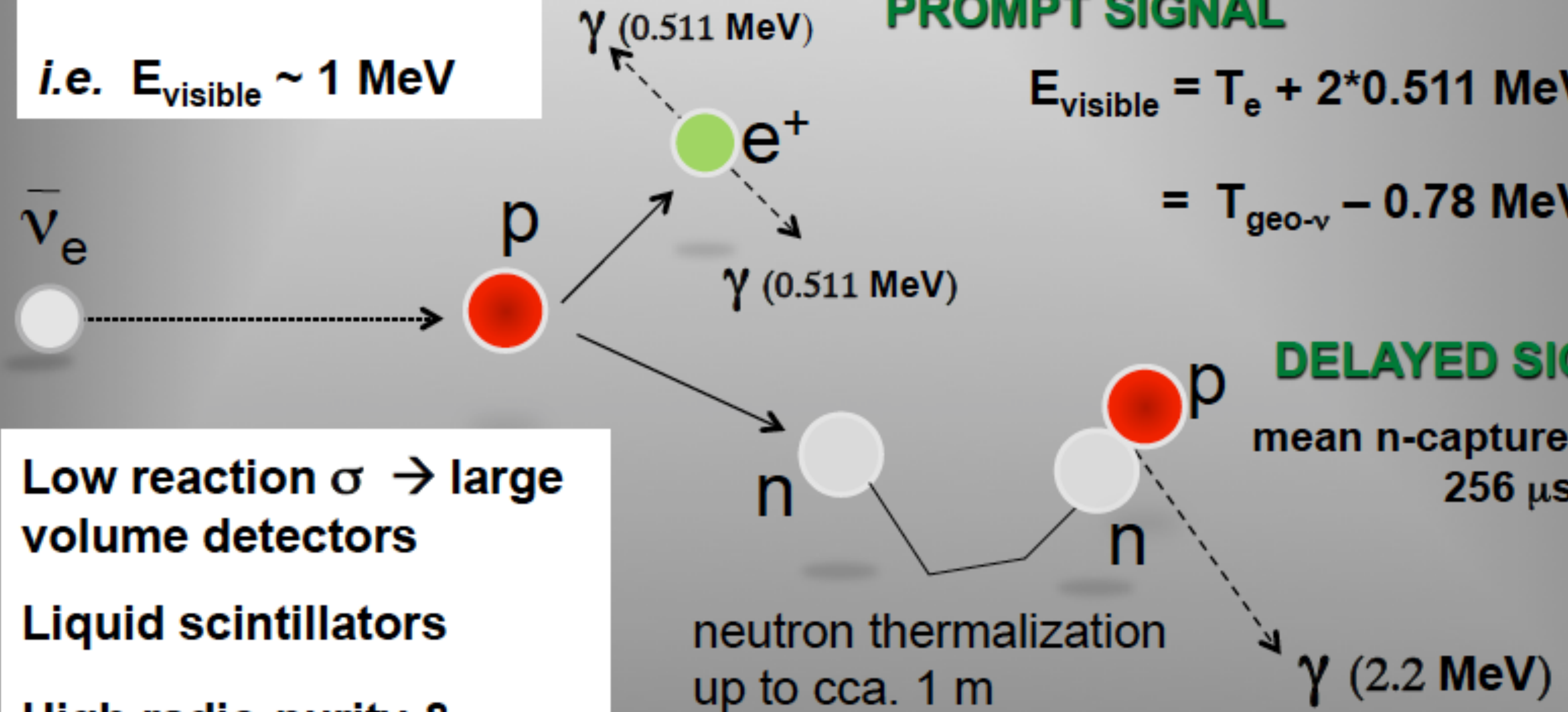
Detection of anti-ν_e : inverse β-decay

Energy **threshold** of

$T_{geo\text{-}\nu}$ = **1.8 MeV**

i.e. $E_{visible}$ ~ 1 MeV

Charge current, only $\overline{\nu}_e$, σ ~10^{-42} cm^2



PROMPT SIGNAL

$E_{visible} = T_e + 2 \cdot 0.511$ MeV =

= $T_{geo\text{-}\nu}$ – 0.78 MeV

DELAYED SIGNAL

mean n-capture time on p
256 μs

Low reaction σ → large volume detectors

Liquid scintillators

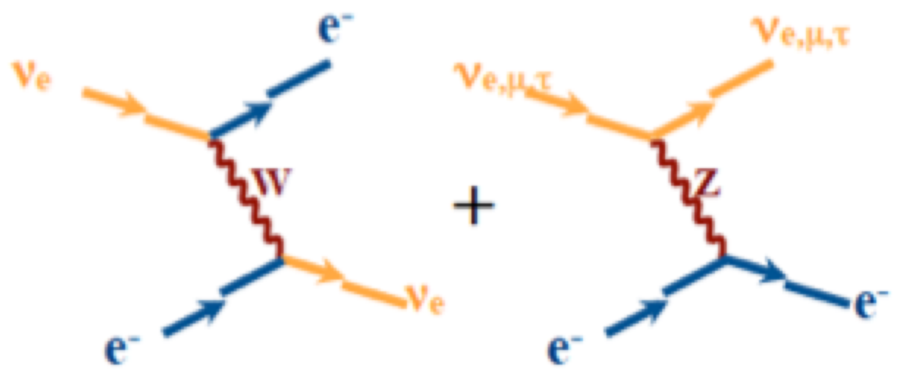
High radio-purity & underground labs to shield from cosmic rays

Only in liquid scintillators

ν-detection with liquid scintillators

Elastic scattering (ES) off an electron

- ✓ All flavours through NC
- ✓ **ν_e only** also through CC
- ✓ ν_e has thus higher cross-section NC + CC
- ✓ @ 1-2 MeV for electron flavour: ~10^{-44} cm^2
- ✓ for μ,τ flavours about 6 x smaller cross sectio



Liquid scintillator

- ✓ elastic scattering: T ~200 keV for neutrino
- ✓ IBD: T = 1.8 keV for antineutrino
- ✓ real- time technique: E_ν spectrum!
- ✓ High light yield (Borexino: 500 pe/MeV)
- ✓ No directionality
- ✓ Extreme radio-purity
- ✓ Underground laboratories to shield from cosmic radiation
- ✓ particle identification (α/β, e^+/e^- separation)

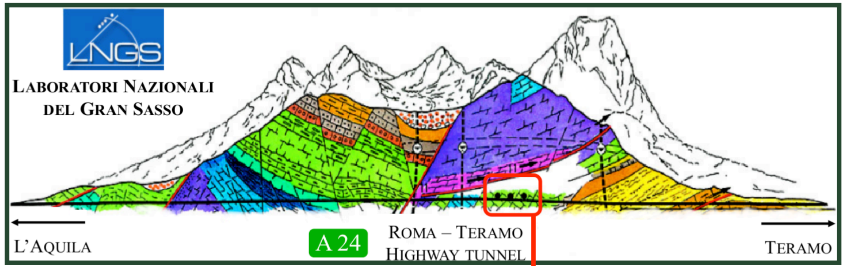
World liquid scintillator detectors

Detector	Location/ depth [m]	Status	Mass [ton]	Neutrino sources and the main physics goals
Borexino/ SOX	LNGS, Italy /1400	Running	280	**Solar, geo,** supernovae, rare processes/ $^{144}Ce/^{144}Pr$ antinu source: **sterile neutrinos**
KamLAND/ ZEN	Kamioka, Japan/1000	Running	1200	Reactor neutrinos (L = 260 km, Δm^2_{12}), **geo/** ^{136}Xe loaded: **0-ββ decay**
Double Chooz	France /300	Running	Far: 8 Near: 8	Reactor neutrinos L_{far} = 1050 m, L_{near} = 400 m
Daya Bay	Guangdong China/ 860	Running	Far: 80 2xNear: 40	Reactor neutrinos $L_{far/eff}$ = 1579 m, $L_{near/eff}$ = 512 and 561 m
RENO	South Korea/450	Running	Far: 16 Near: 16	Reactor neutrinos L_{far} = 1380 m, L_{near} =290 m
SNO+	Sudbury, Canda/2070	About to start	1000	Nd loaded: **0-ββ decay** Geo, solar
JUNO	Jiangmen, China/ 750	Start in 2020	20 000	Reactor neutrinos (L = 53 km, **mass hierarchy,** Δm^2_{12}, θ_{13},), Solar, geo, supernovae, rare processes

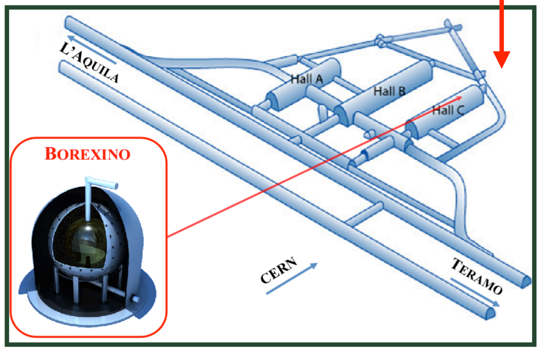
θ_{13}

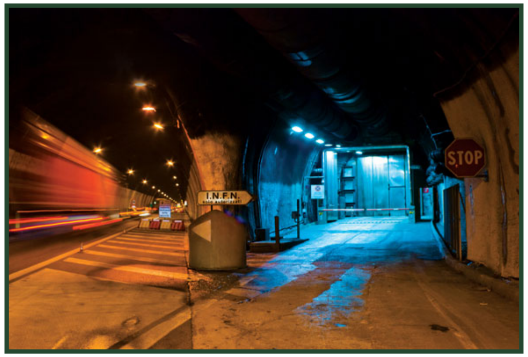
Borexino

Laboratori Nazionali del Gran Sasso, Italy

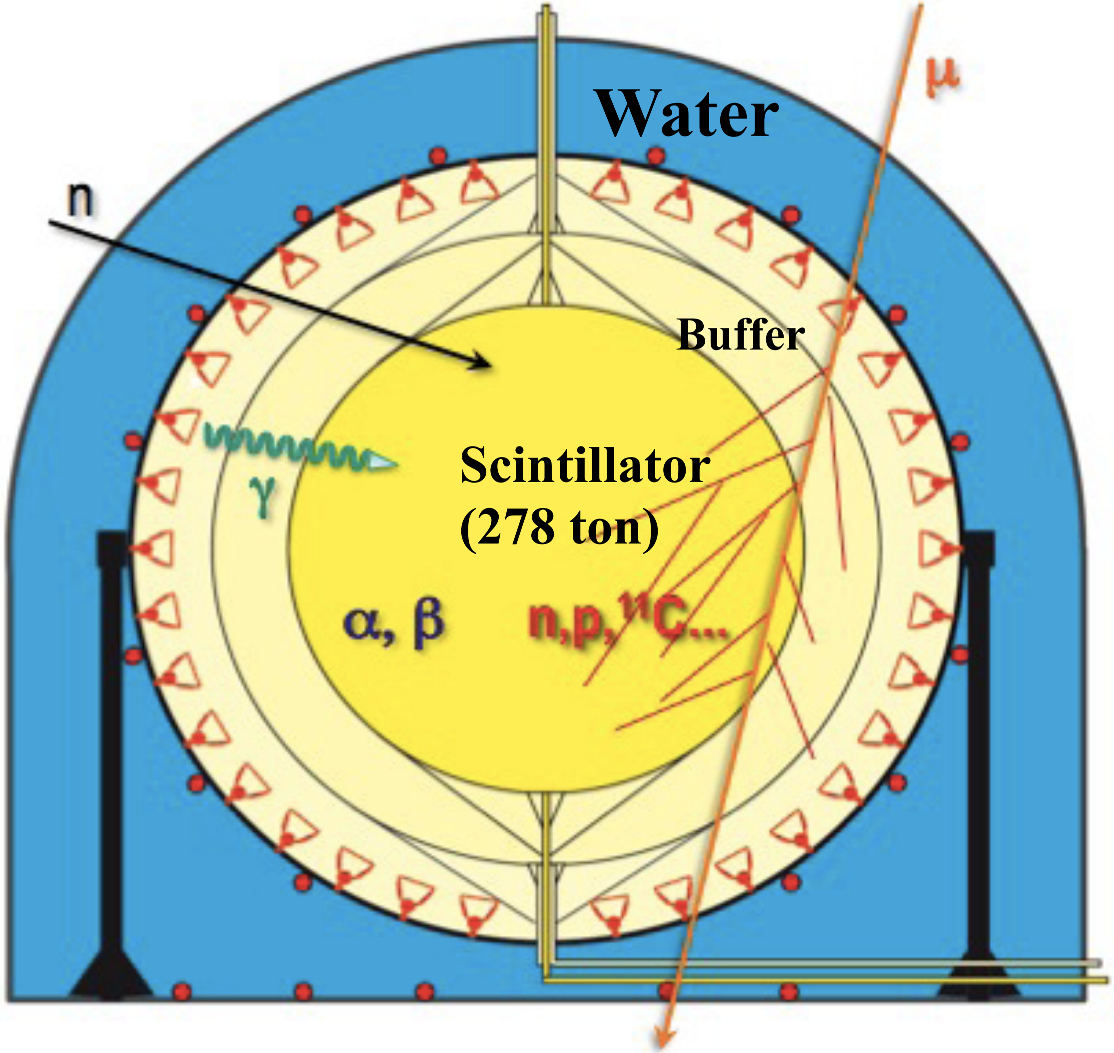


Principal goal: ^{7}Be solar-ν





Borexino detector



- ✓ Principle of **graded shielding:** materials get more pure towards the detector core
- ✓ **15 years of work to reach the required radio-purity**
- ✓ To reduce the background from natural radioactivity to the level of expected solar neutrino signal: reduction of 9-10 orders of magnitude required!

Backgrounds now : $^{238}U < 8\ 10^{-20}$ g/g at 95% C.L., $^{232}Th < 9\ 10^{-19}$ g/g at 95% C.L.

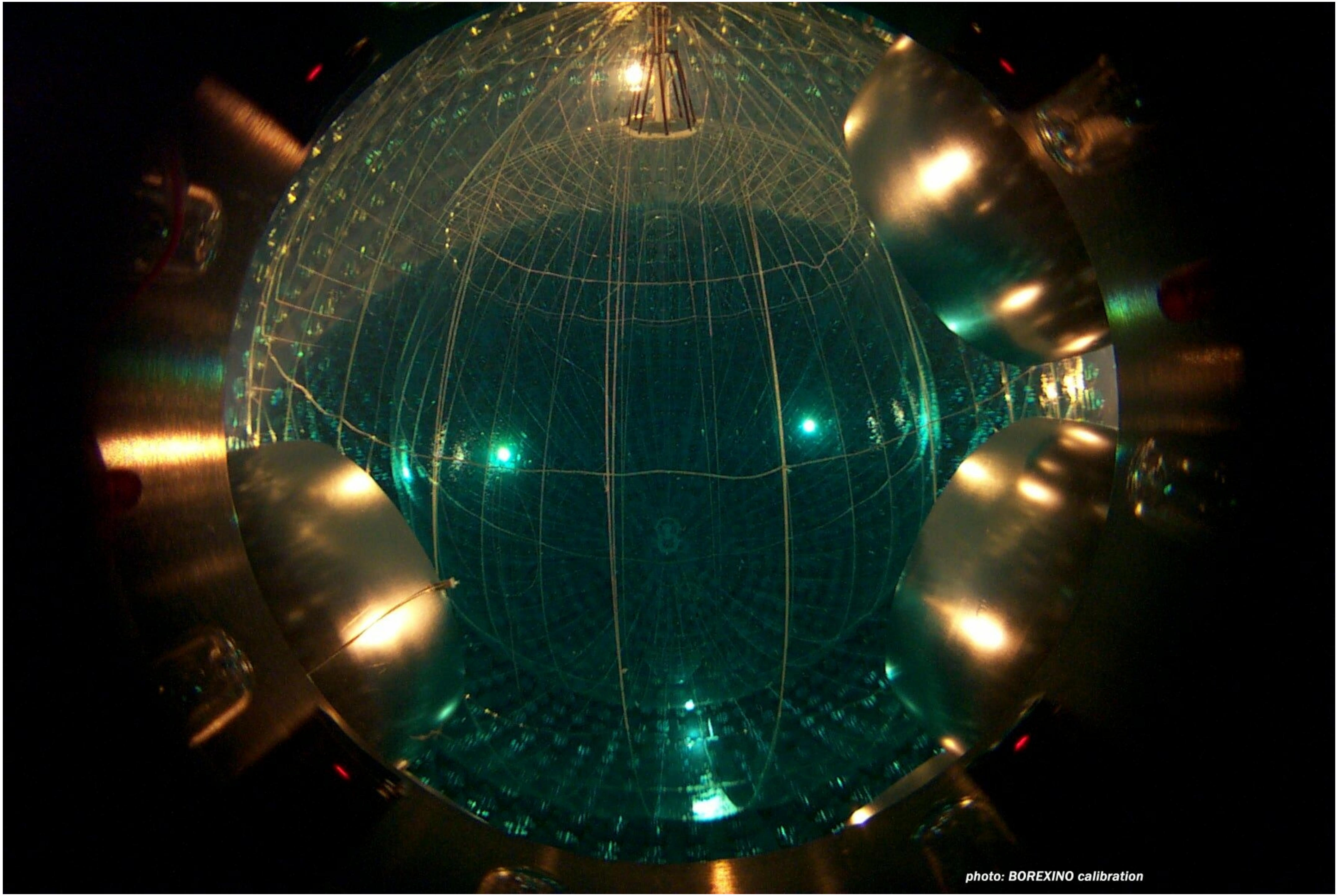
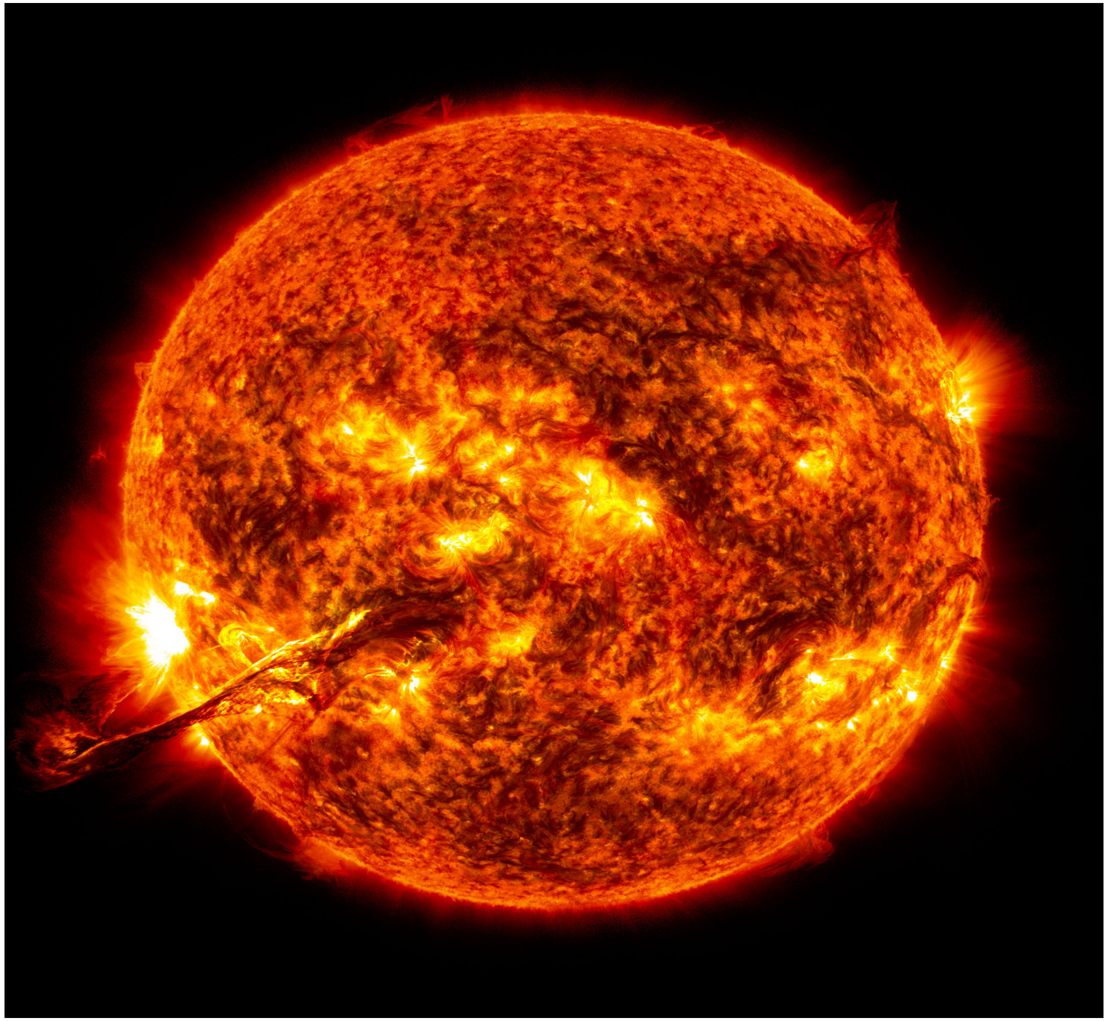
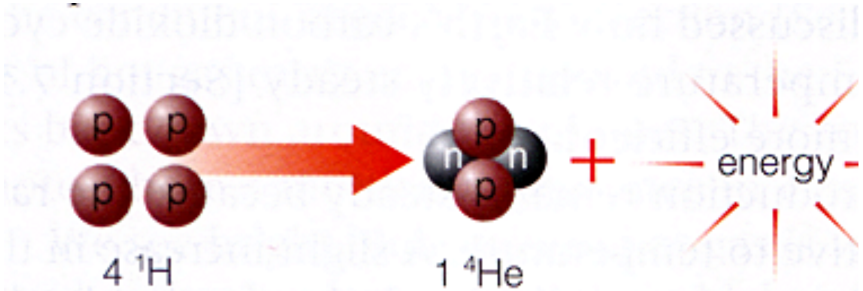


photo: BOREXINO calibration

Solar neutrinos

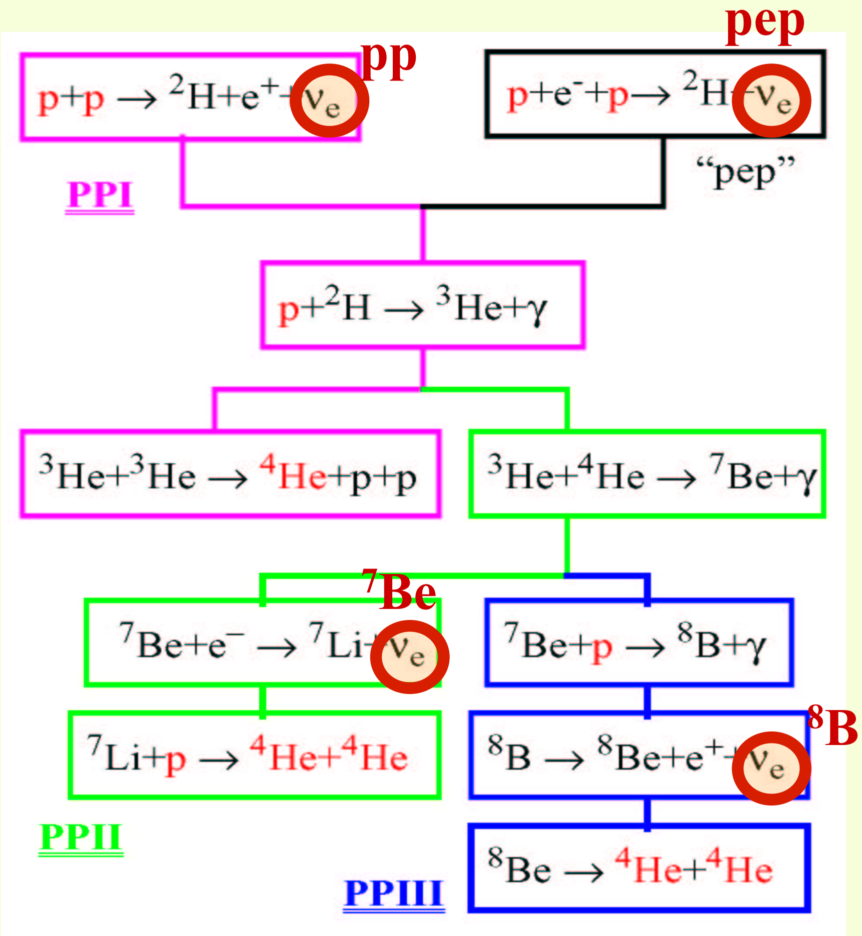


Nuclear reactions in the Sun

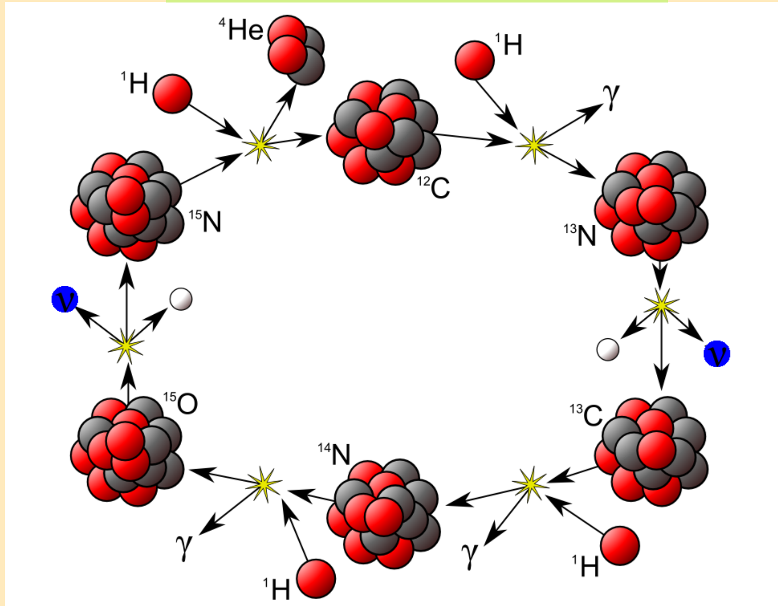


(26.7 MeV) (+ 2ν)

99% **pp-cycle**

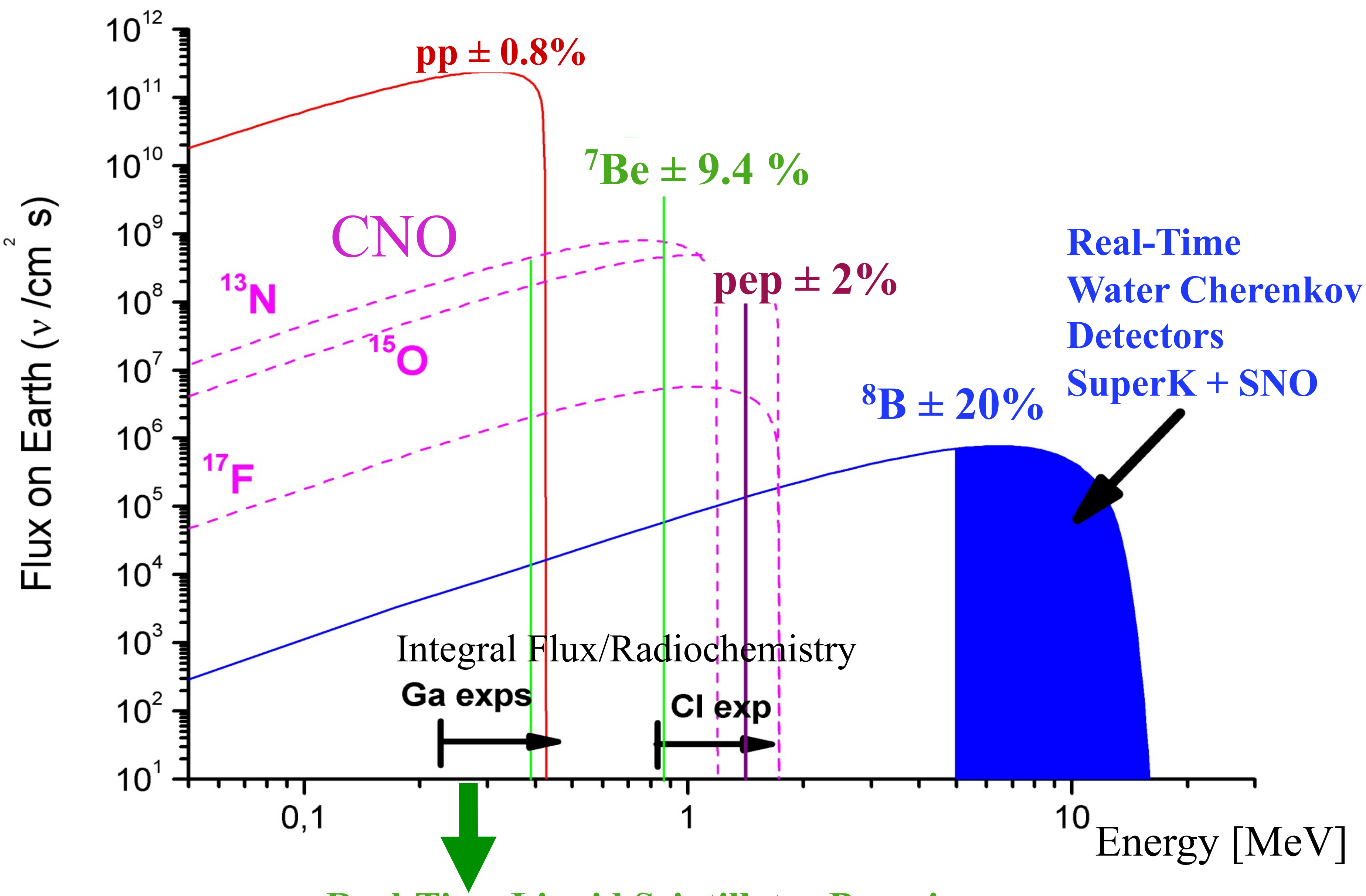


<1% ? **CNO-cycle**

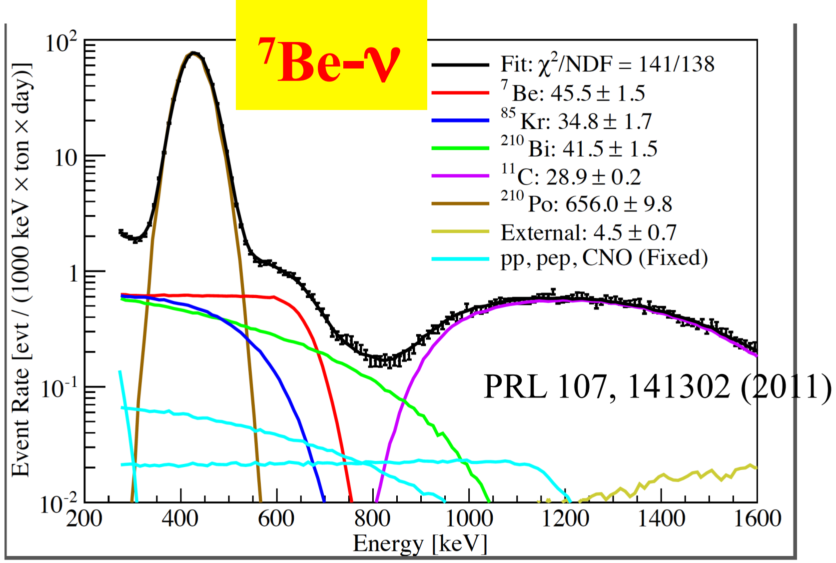


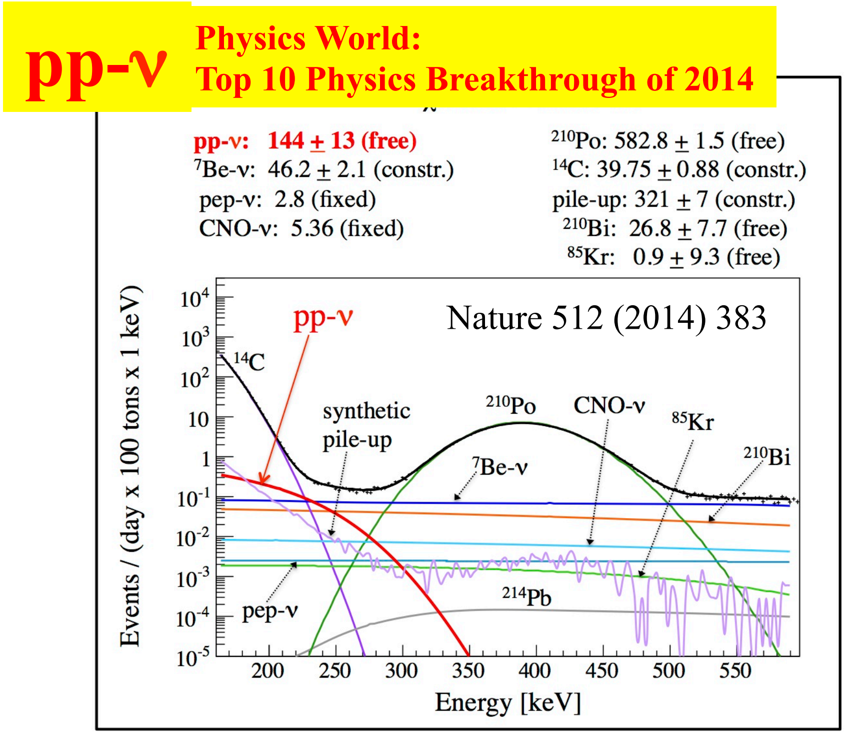
- Sun: should contribute <1%
- Heavy stars: should be dominant!
- Never observed until now

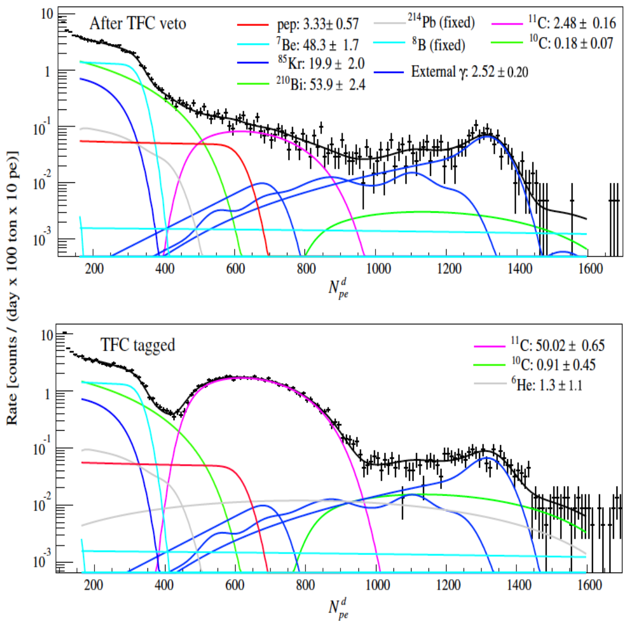
Energy spectrum of solar neutrinos



Borexino solar neutrino results

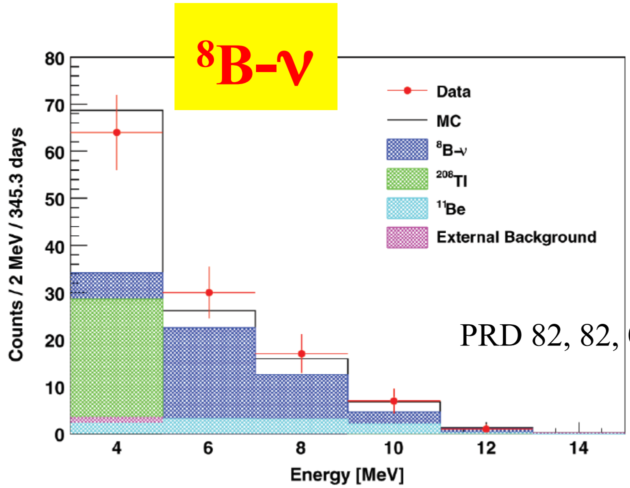






pep-ν
limit on CNO-ν

PRL 108, 051302 (2012)



PRD 82, 82, 033006 (2010)

Why to measure solar neutrinos today?

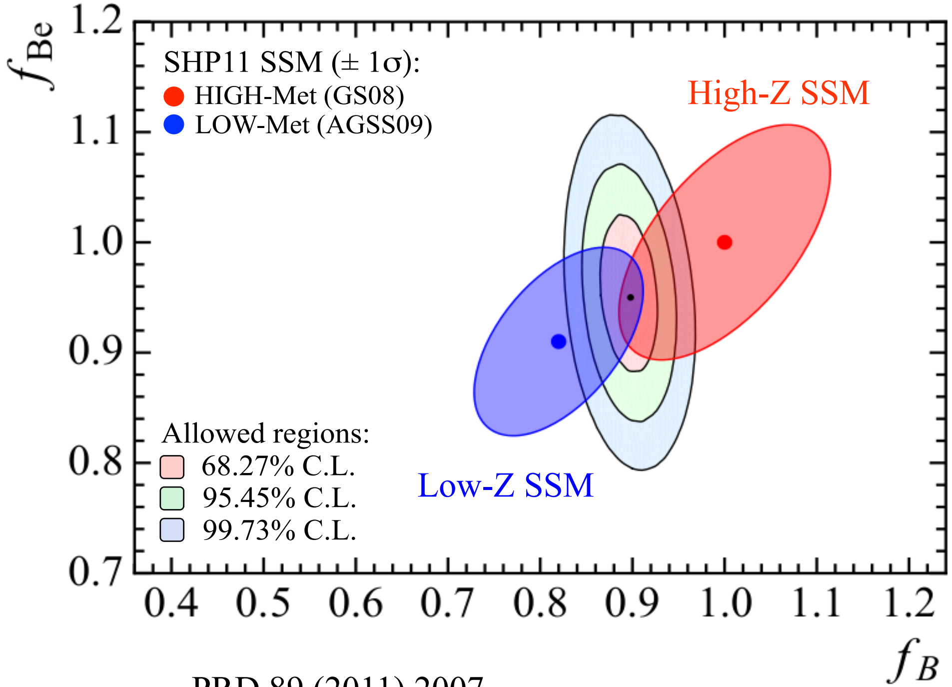
SOLAR AND STELLAR PHYSICS

- neutrinos: the only direct prove about the nuclear fusion reactions
- agreement between optical and neutrino luminosity: solar stability at 10^5 years scale
- Standard Solar Models and helio-seismology data vs predictions
- high vs low solar metallicity (abundance of heavy elements)

Solar ν fluxes: $cm^{-2}s^{-1}$

	Diff.		GS98	AGS09
	1%	pp	5.98×10^{10}	6.03×10^{10}
	2%	pep	1.44×10^{8}	1.47×10^{8}
	3%	hep	8.04×10^{3}	8.31×10^{3}
	9%	^{7}Be	5.00×10^{9}	4.56×10^{9}
	18%	^{8}B	5.58×10^{6}	4.59×10^{6}
C	27%	^{13}N	2.96×10^{8}	2.17×10^{8}
N	30%	^{15}O	2.23×10^{8}	1.56×10^{8}
O	38%	^{17}F	5.52×10^{6}	3.40×10^{6}

A. Serenelli ApJ 743 (2011) 24

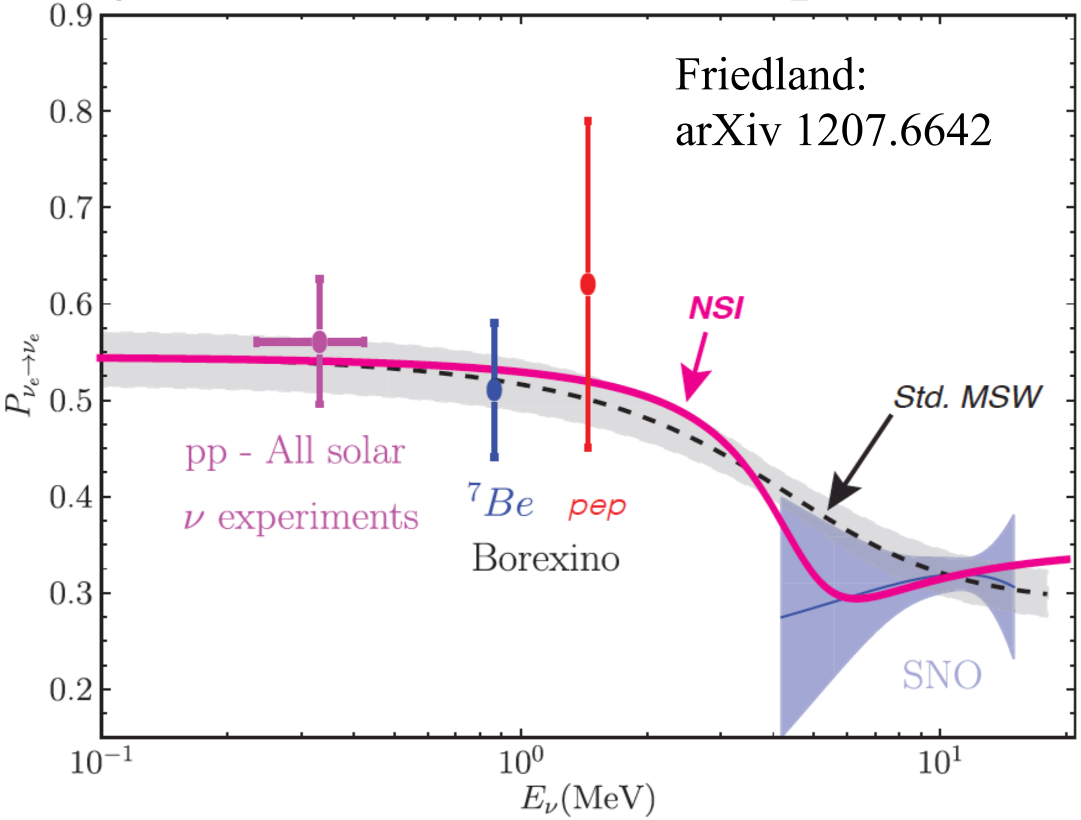


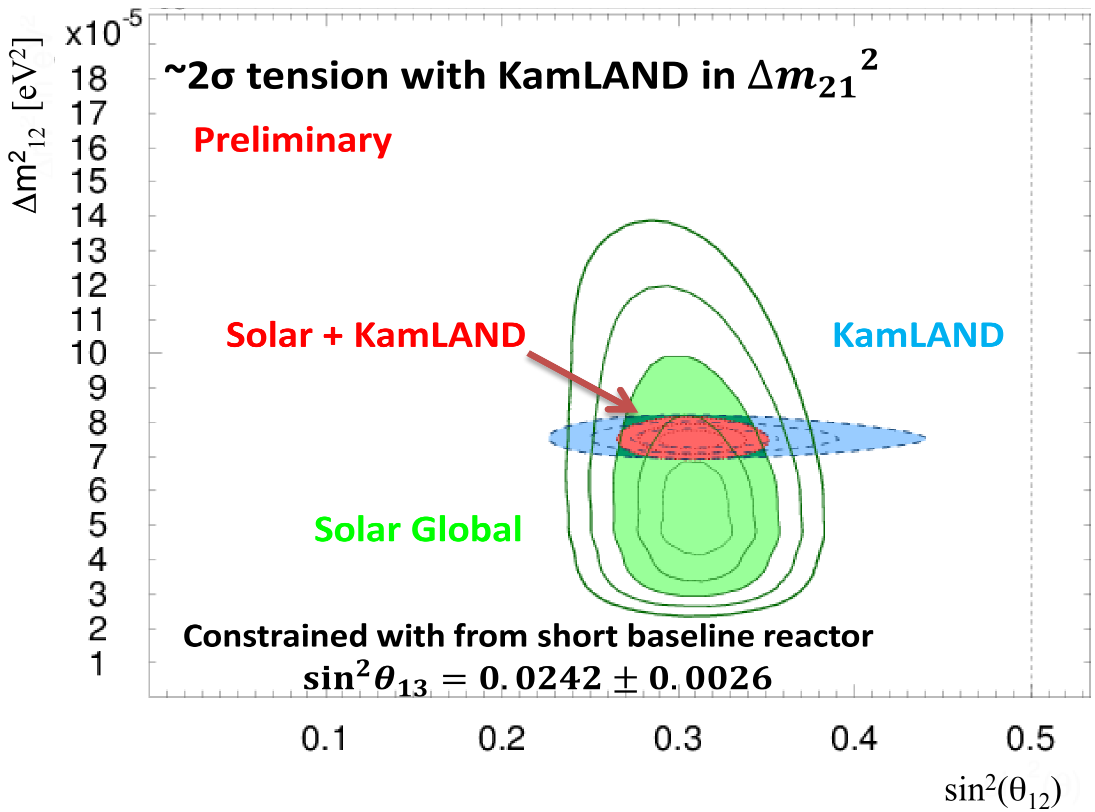
PRD 89 (2011) 2007

Why to measure solar neutrinos today?

NEUTRINO PHYSICS

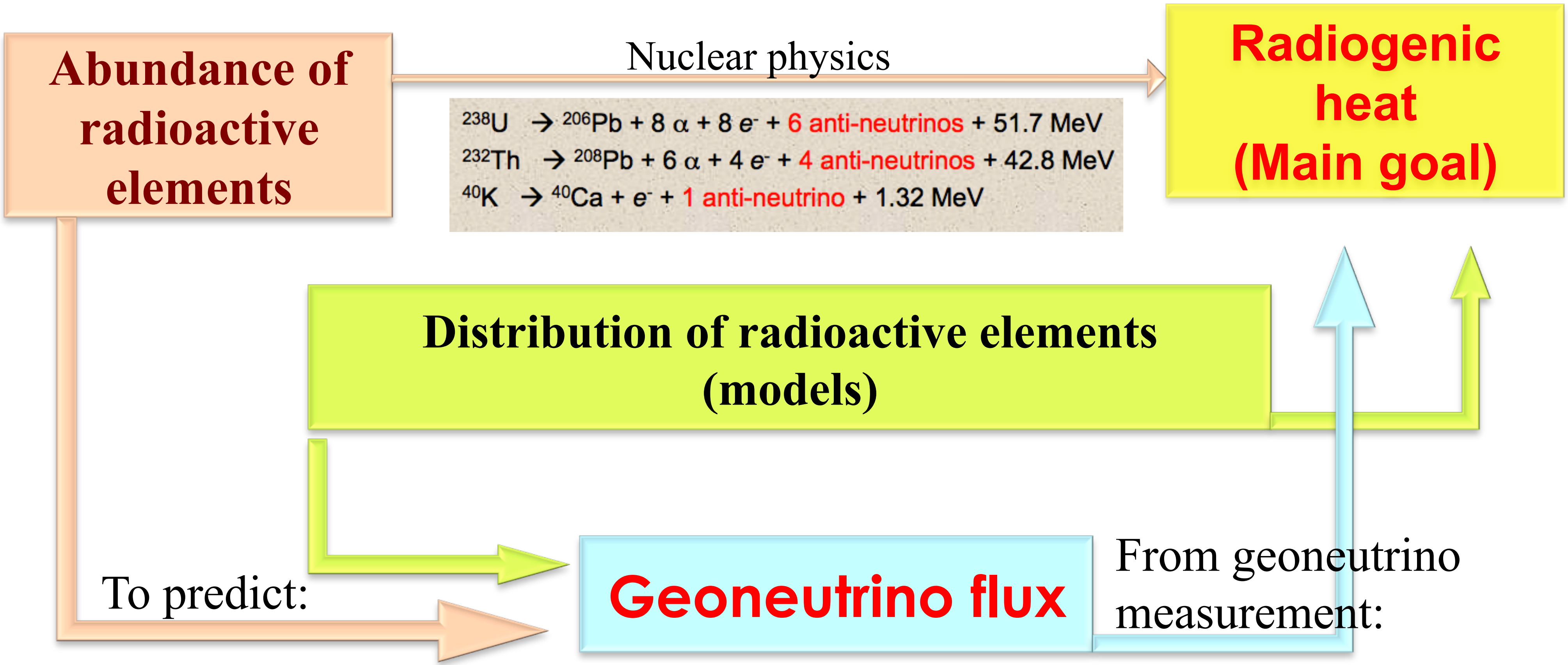
- P_{ee} (electron neutrino survival probability) and searches for new physics
- testing the LMA (Large Mixing Angle) – MSW (matter effects) solution to neutrino oscillations (energy dependent day/night effects)
- global fits of oscillation parameters





Geoneutrinos

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

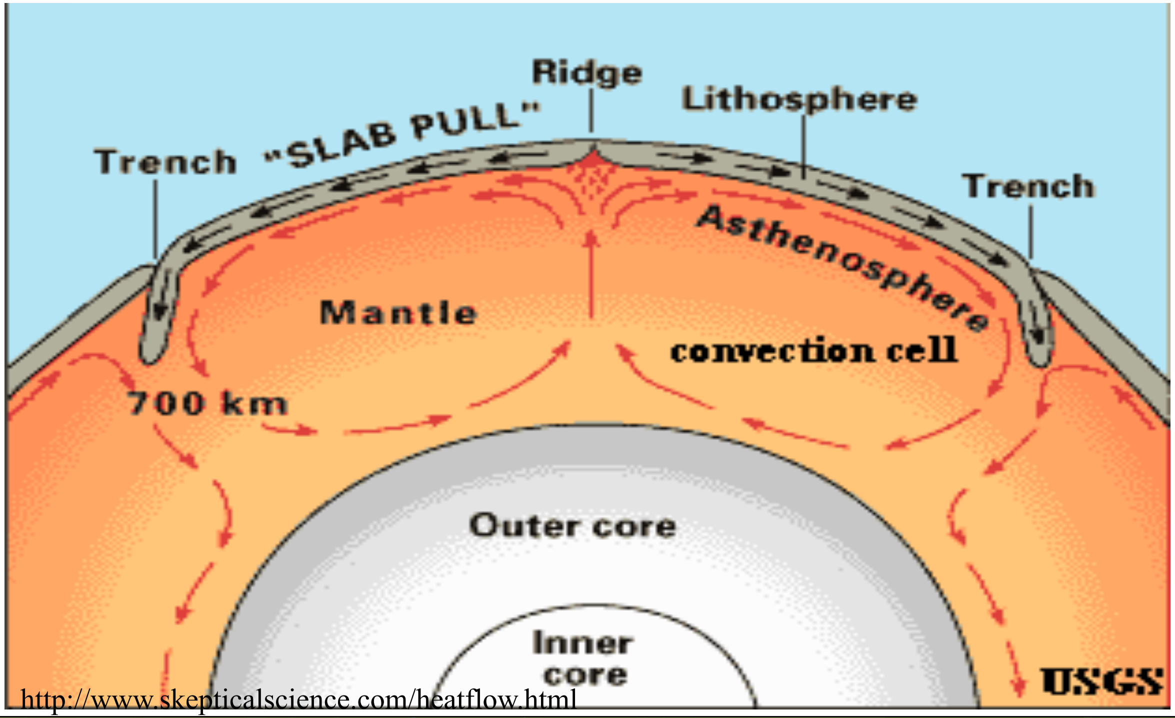


- **Collaboration between neutrino physicists and geoscientists is a must**
- **NEUTRINO GEOSCIENCE IS TRULY INTERDISCIPLINRY**

The Earth's interior

- ✓ **Seismology:** S and P-waves velocity and density profiles
- ✓ **Geochemistry:** limited depth of direct rock samples
- ✓ **Bulk Silicate Earth models**: composition of "remixed" mantle + crust
- ✓ Surface heat flux measurements: **47 ± 2 TW**
- ✓ **Geoneutrinos:** new tool to determine the radiogenic heat

THE MAIN UNKNOWN: THE MANTLE CONTRIBUTION



http://www.skepticalscience.com/heatflow.html

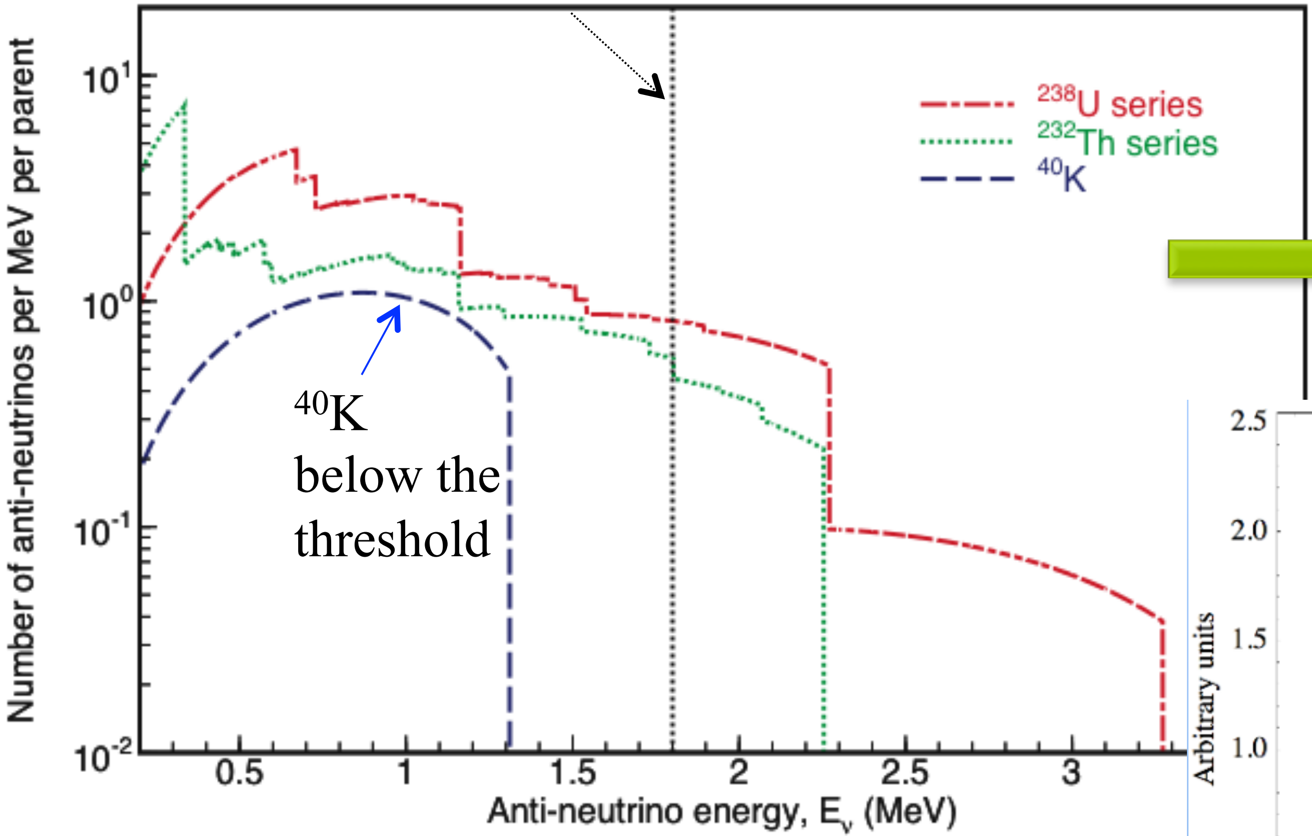
U, Th, K: refractory lithophile elements

concentration for ^{238}U
(Mantovani *et al.* 2004)

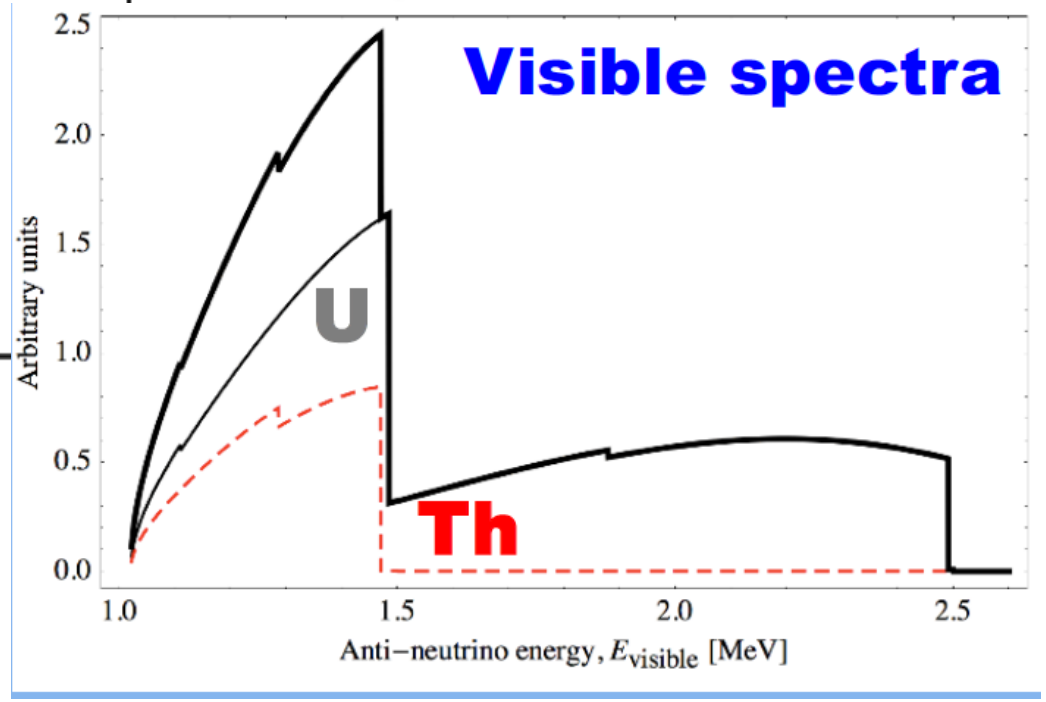
upper continental crust:	2.5	ppm
middle continental crust:	1.6	ppm
lower continental crust:	0.63	ppm
oceanic crust:	0.1	ppm
upper mantle:	6.5	ppb
core	NOTHING	

Geoneutrino energy spectrum

1.8 MeV kinematic threshold



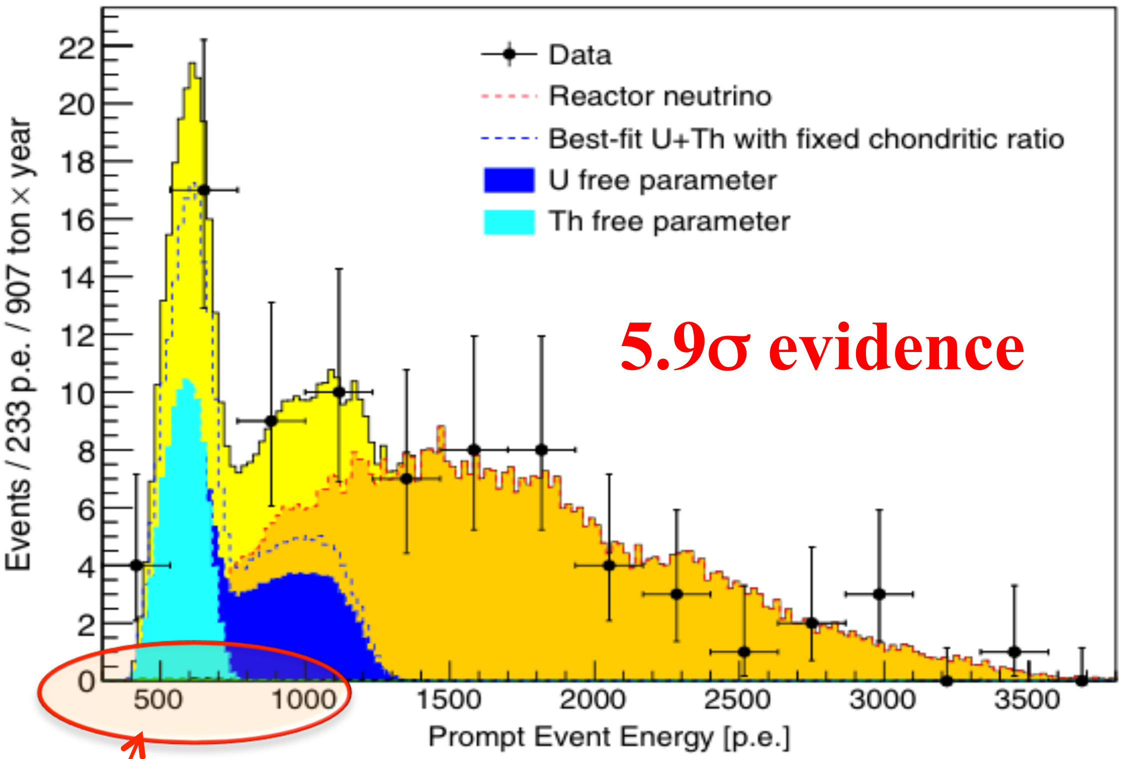
IBD cross section



Latest Borexino geoneutrino results

PRD 92 (2015) 031101 (R)

Borexino 2015: **23.7 $^{+6.5}$ (stat) $^{+0.9}$ (sys)** geonu's

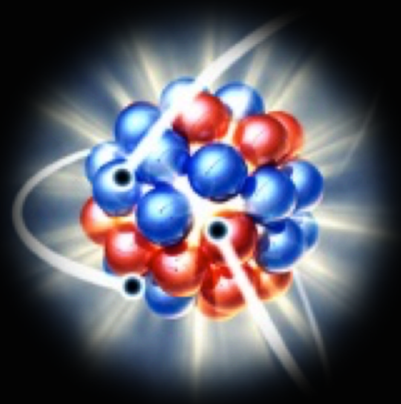


- ✓ Non antineutrino background almost invisible!
- ✓ 5.5 x 10^{31} target-proton year
- ✓ 0-hypothesis @ 3.6 x 10^{-9}

- ✓ Using the chondritic mass ratio Th/U = 3.9 and m(K)/m(U) = 10^{4}: **the total Earth radiogenic power is 33^{+28}_{-20} TW** to be compared with the total Earth surface heat flux 47 $\pm$ 2 TW.

- ✓ Borexino **rejects a null S(mantle) at 98% CL**

Sterile - ν



Borexino - SOX

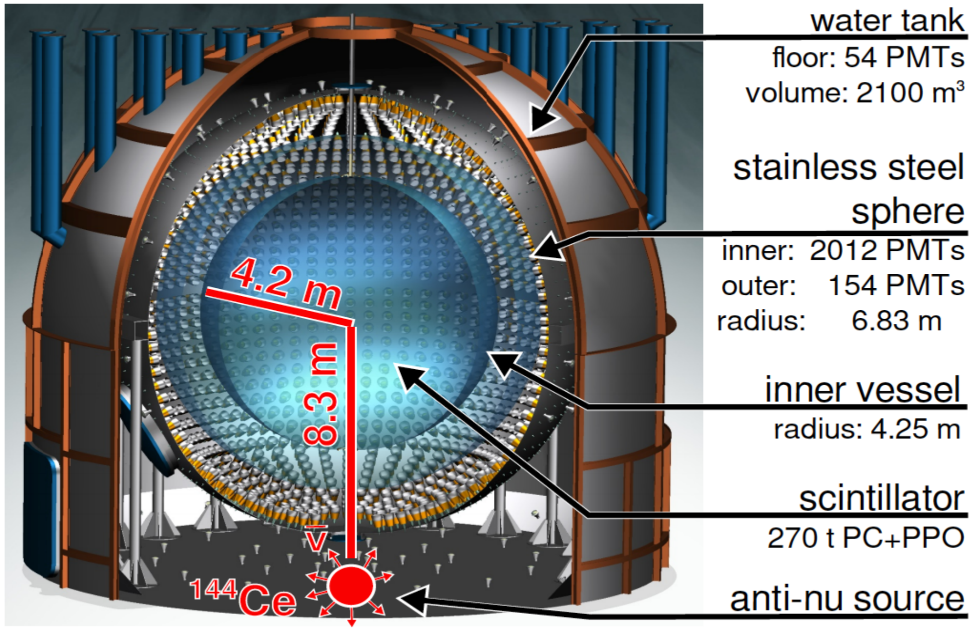
Sterile neutrino neutrino ?

We know that there are only 3-active flavour neutrinos (mass < m(Z0)/2)
Decay of Z0 boson

Some experimental results in a tension with a 3-flavour neutrino model
disappearance: reactor and GALLEX/SAGE anomaly,
appearance: accelerator anomaly – LSND, Mini/MicroBoNe)

Possible existence of a 4th flavour STERILE neutrino
(no weak interactions, but active flavour neutrinos could oscillate into it)

SOX: Short-distance neutrino oscillation with Borexino



^{144}Ce/ Pr antineutrino source arrival to LNGS: end of 2017

In (3 + 1) scenario:
$\Delta m^2_{41} \sim 1\text{-}2\ eV^2$

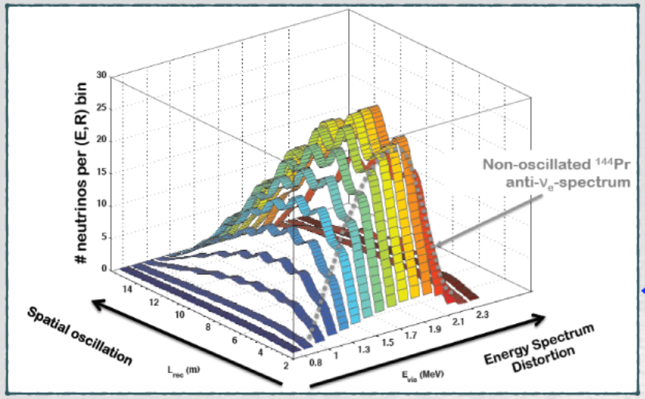
for MeV (anti)neutrinos: oscillation length of few meters

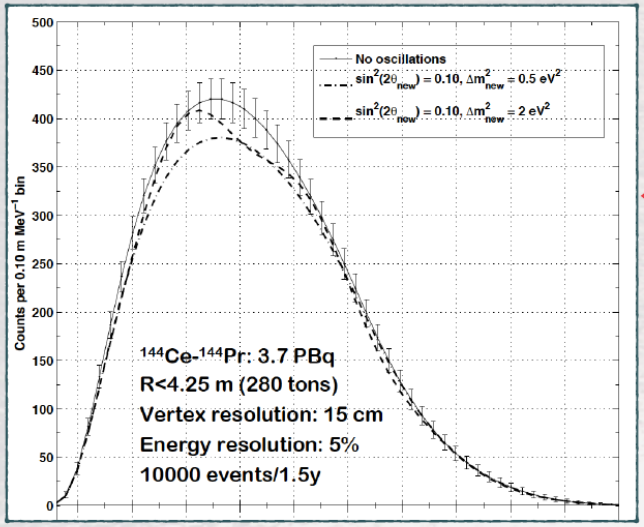
SOX sensitivity

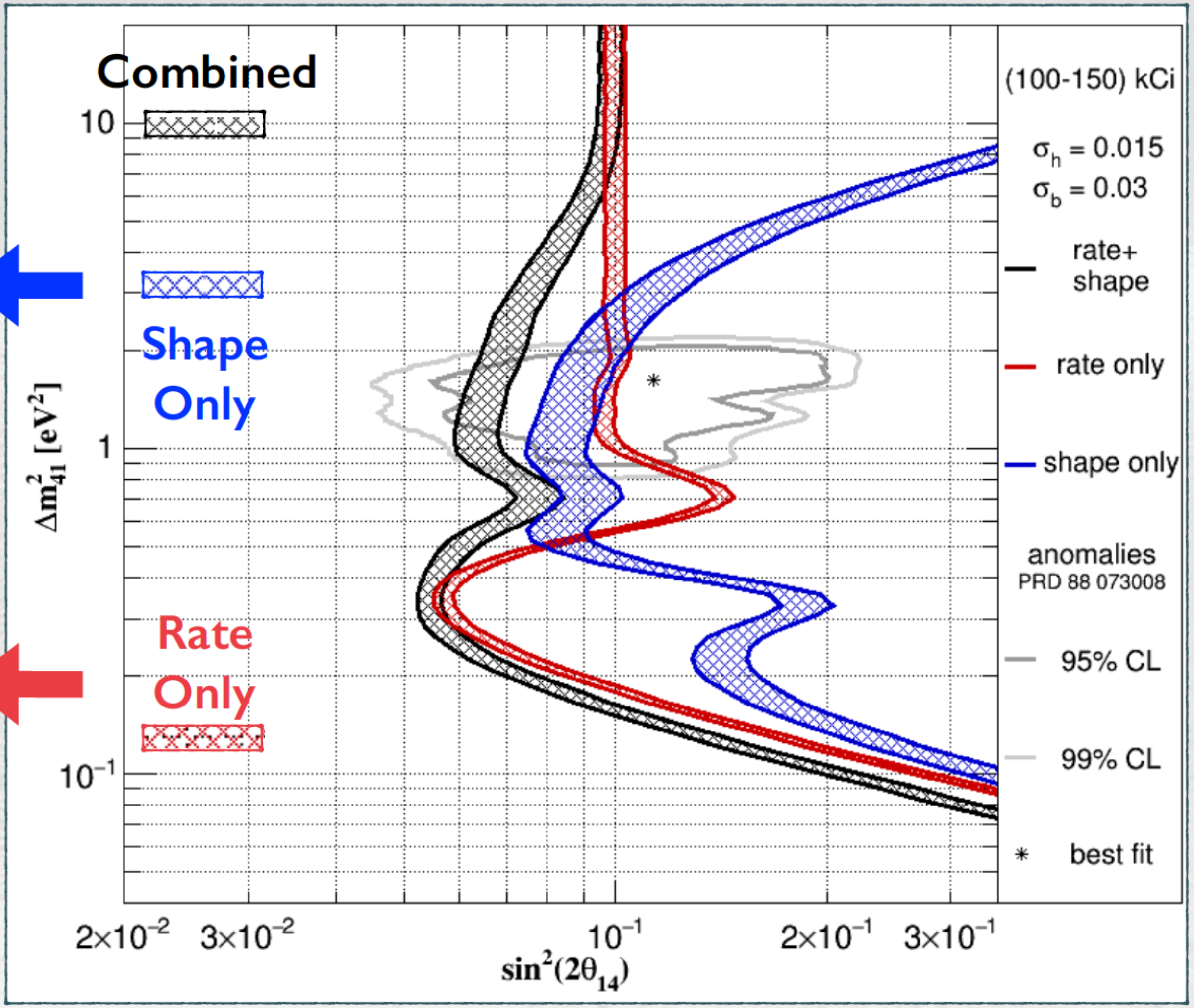
<u>technical and bureaucratic challenge</u>:
3.7 PBq (in ^{144}Ce(β), 100 kCi and > 10^{15} antineutrinos/s

^{144}Ce source @ 8.2 m from the center. **1.5% calibration.** **100-150 kCi bands.**

- *<u>Under the assumption that a single sterile dominates</u>*





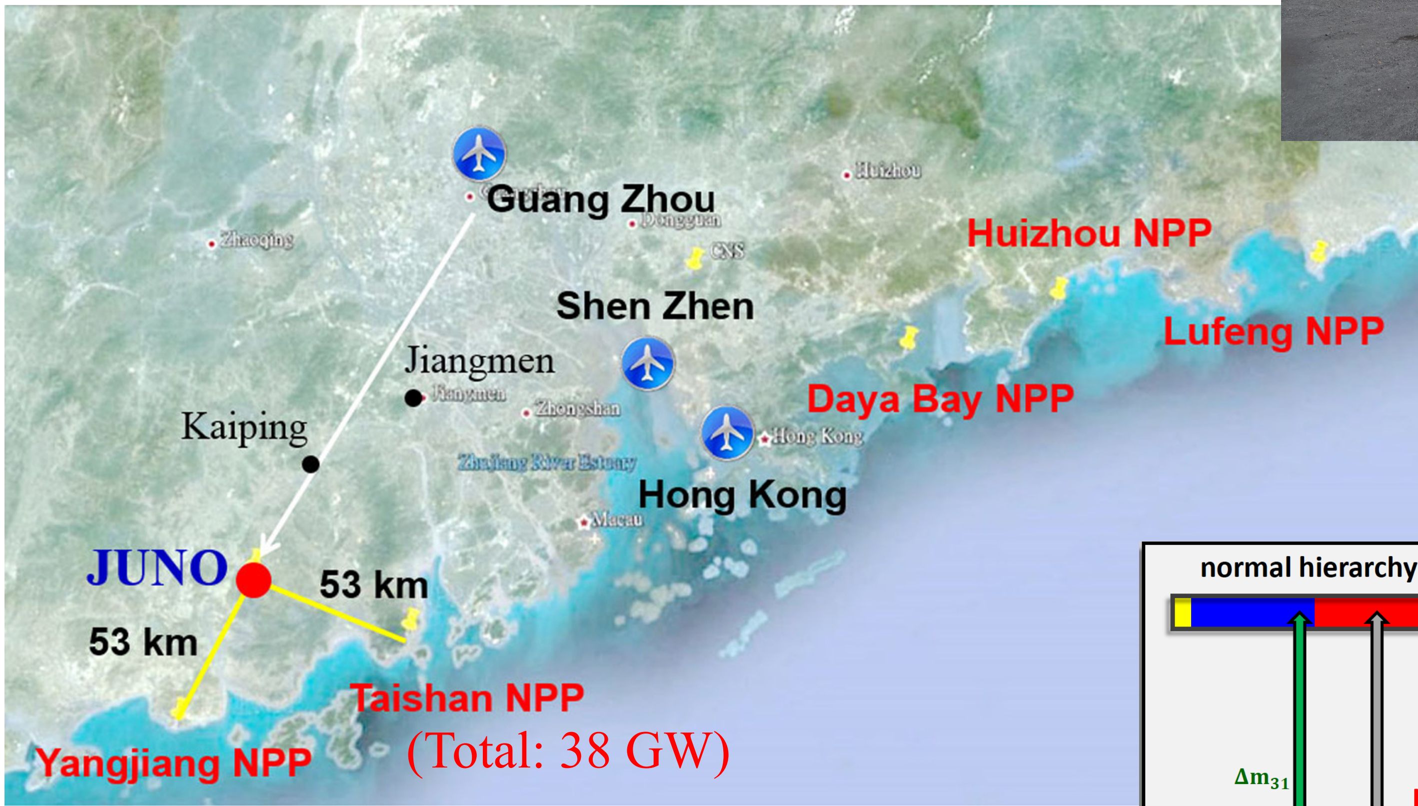


Jiangmen Underground Neutrino Observatory

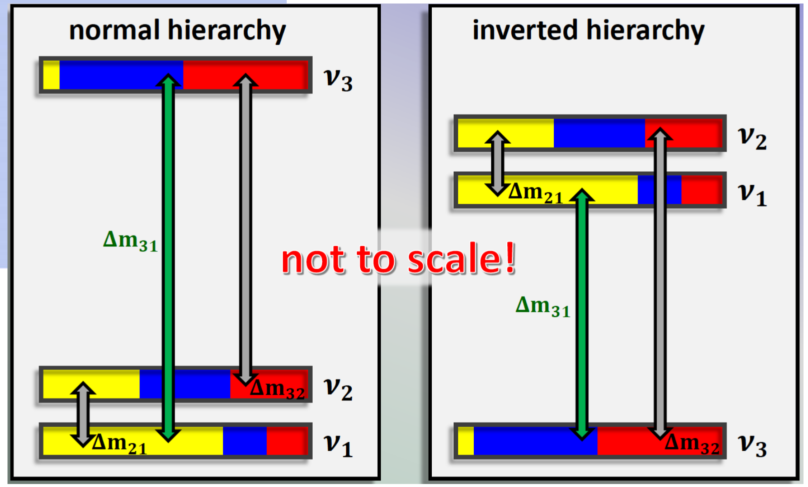
the first multi-kton liquid scintillator detector ever

JUNO in Jiangmen, China

the first multi-kton liquid scintillator detector ever



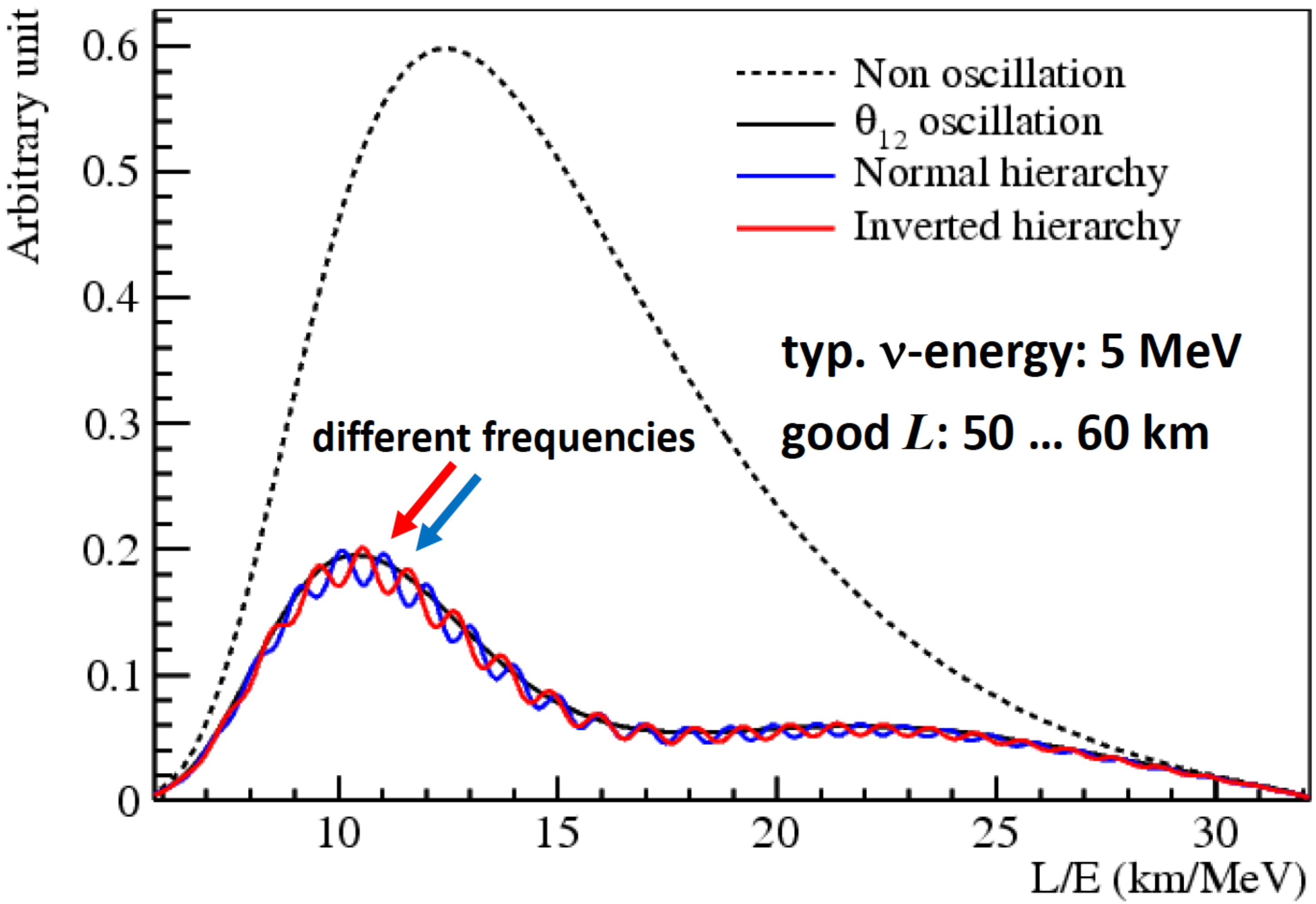
After 4 years of running > 3σ CL



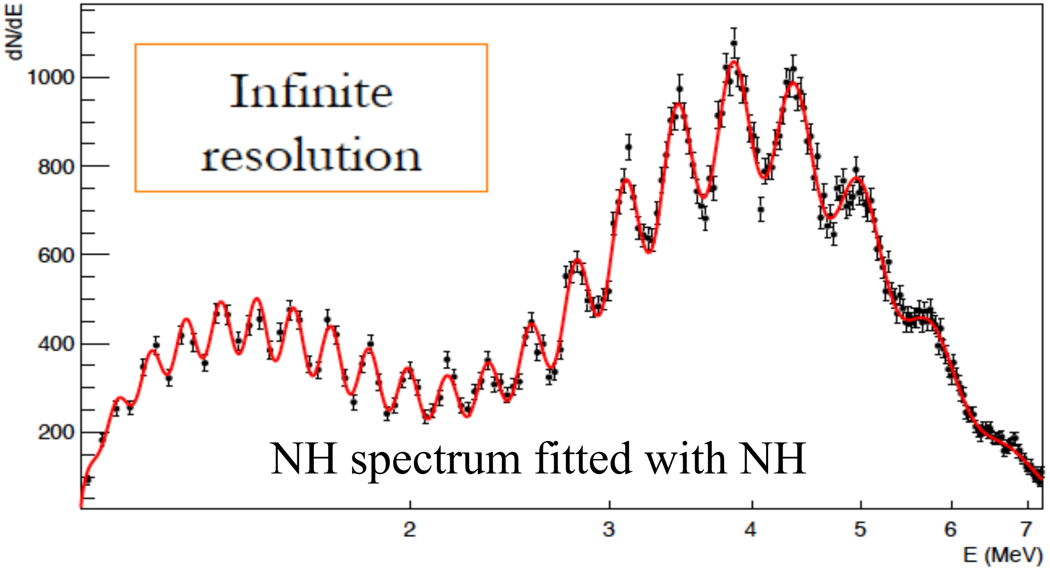
Main goal: neutrino mass hierarchy

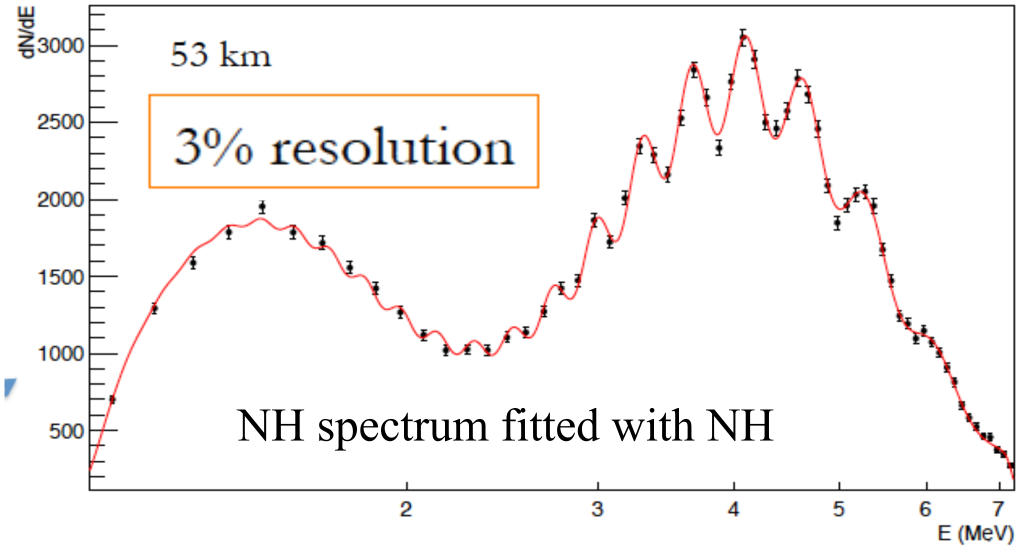
Principle of the mass-hierarchy measurement

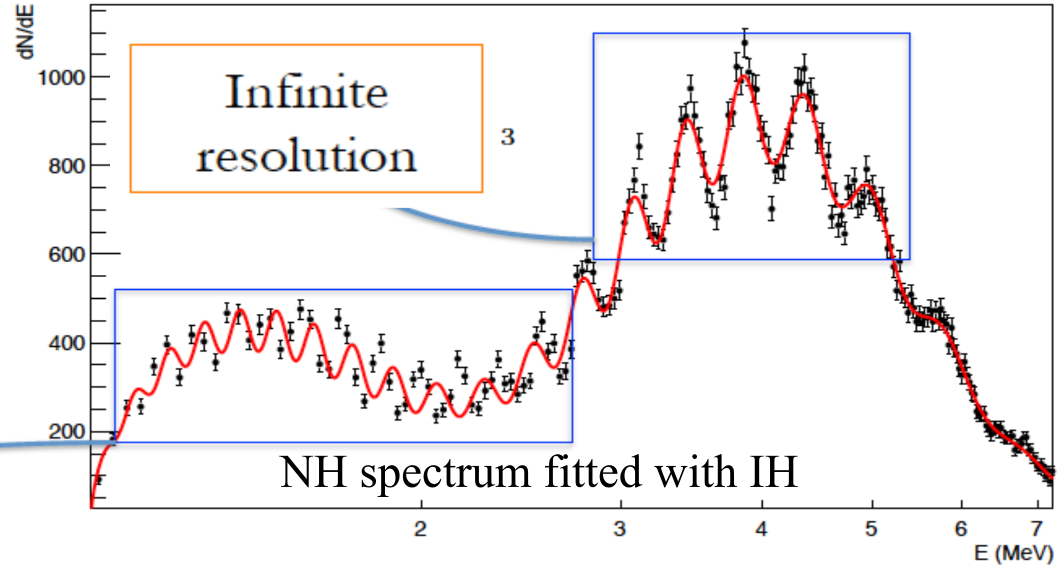
- 700 m rock overburden
- **3% @ 1 MeV resolution**
- LY = 1200 pe / MeV
- Non-linearities well known

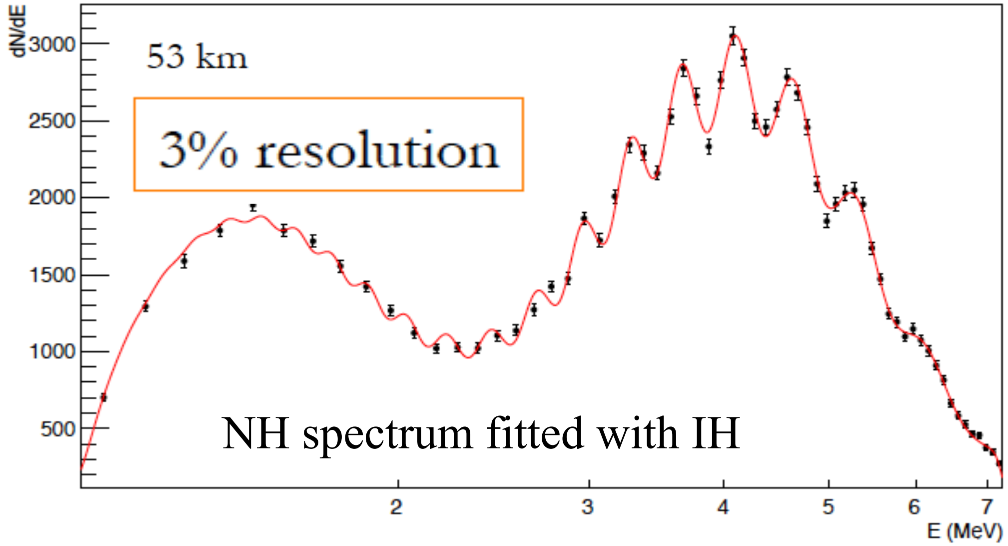


Spectral fit with both hypothesis: NH and IH







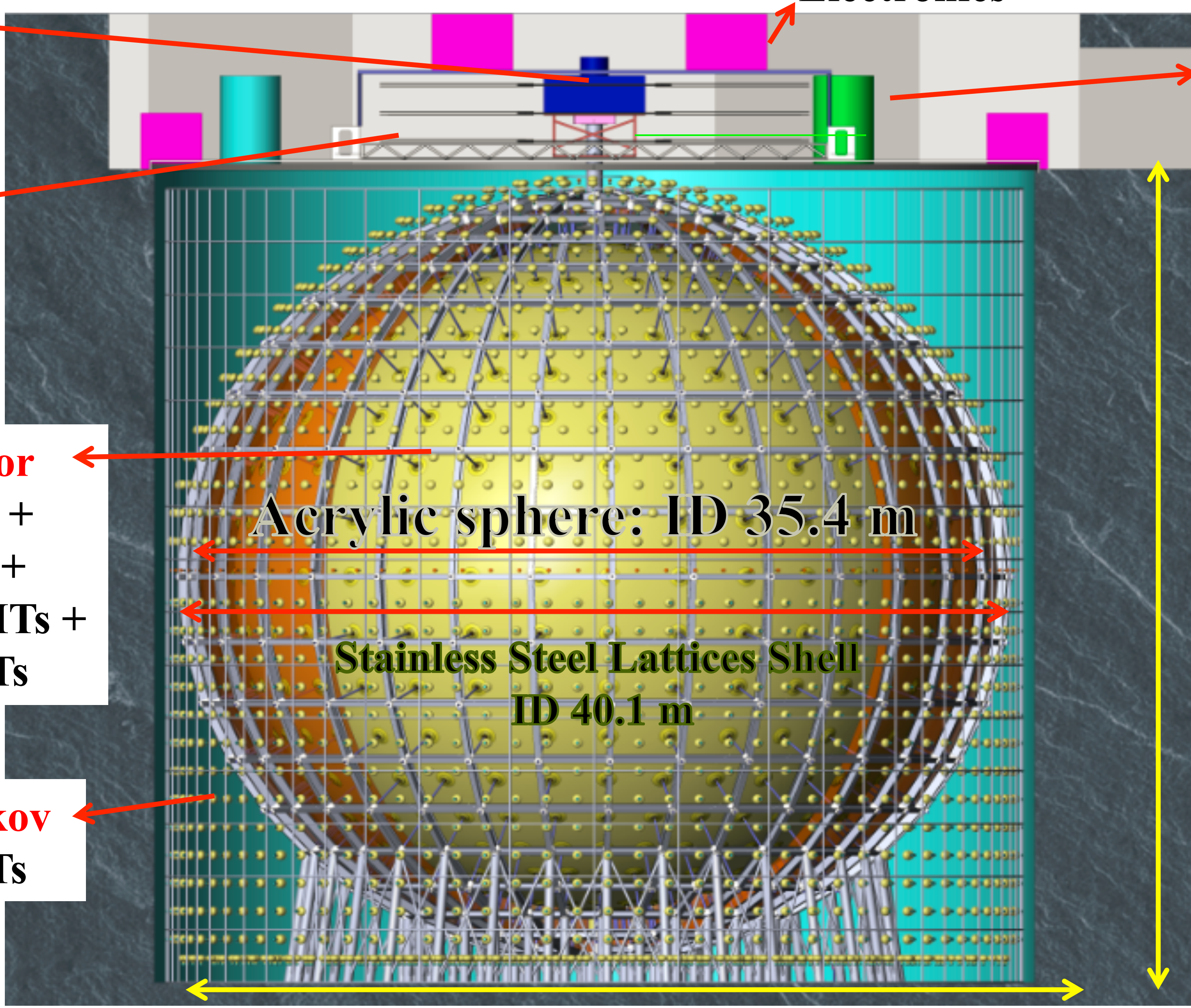


Calibration

Electronics

Filling + Overflow

Top muon tracker



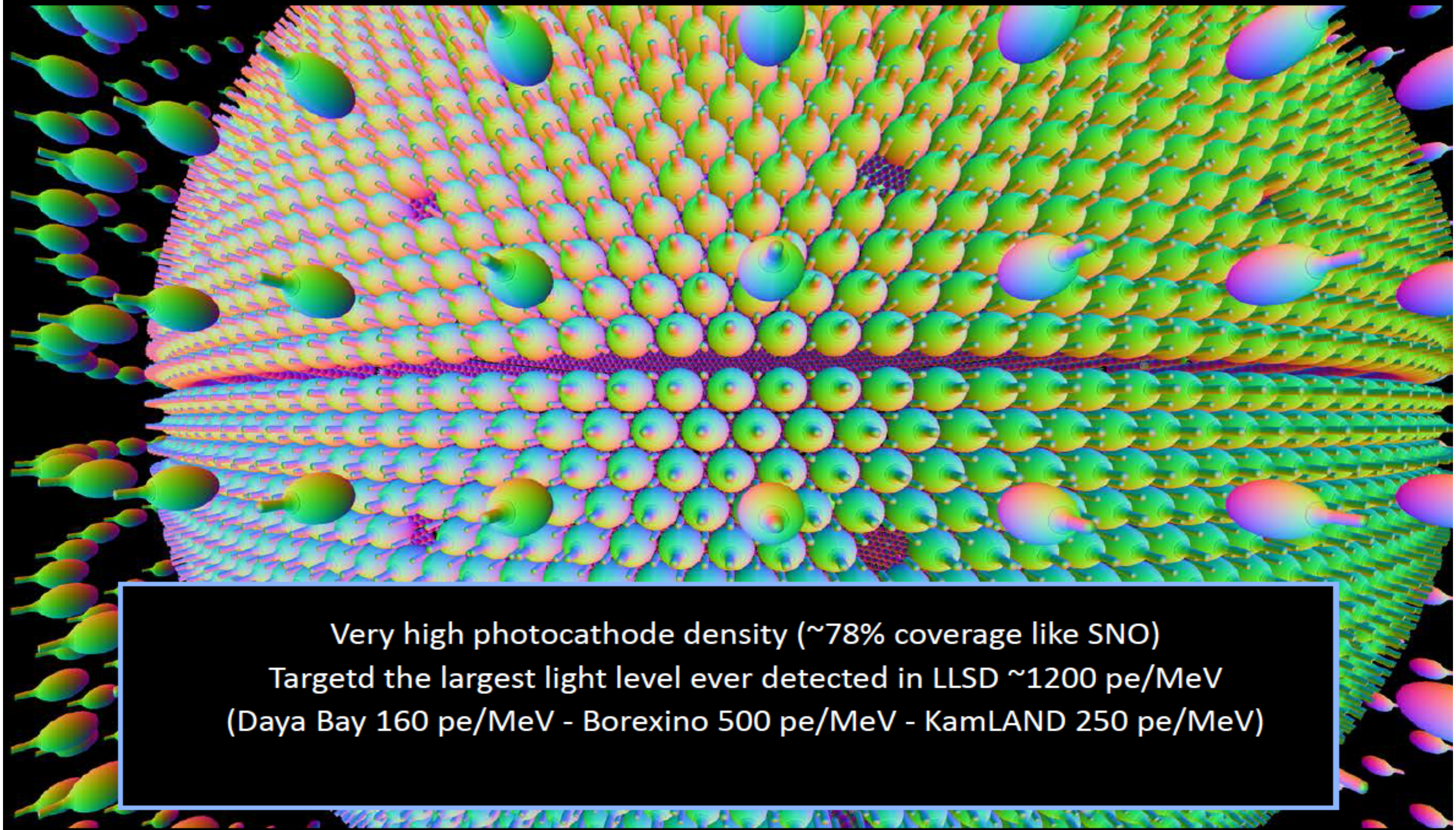
Central Detector
Acrylic Sphere +
20 kton Scintil +
~17000 20" PMTs +
~34000 3" PMTs

Water Cherenkov
~2000 20" PMTs

43.5 m

43.5 m

Central detector distinctive feature: resolution



Very high photocathode density (~78% coverage like SNO)
Targetd the largest light level ever detected in LLSD ~1200 pe/MeV
(Daya Bay 160 pe/MeV - Borexino 500 pe/MeV - KamLAND 250 pe/MeV)

More on JUNO physics program

- **Reactor neutrinos:**

Precision measurement of oscillation parameters

	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant Exps.	KamLAND	MINOS	SNO	Daya Bay	SK/T2K
Individual 1σ	2.7% [20]	4.1% [25]	6.7% [6]	10% [21]	14% [23, 24]
Global 1σ	2.6%	2.7%	4.1%	8.6%	11%

Probing the unitarity of U_{PMNS} to ~1%
more precise than CKM matrix elements !

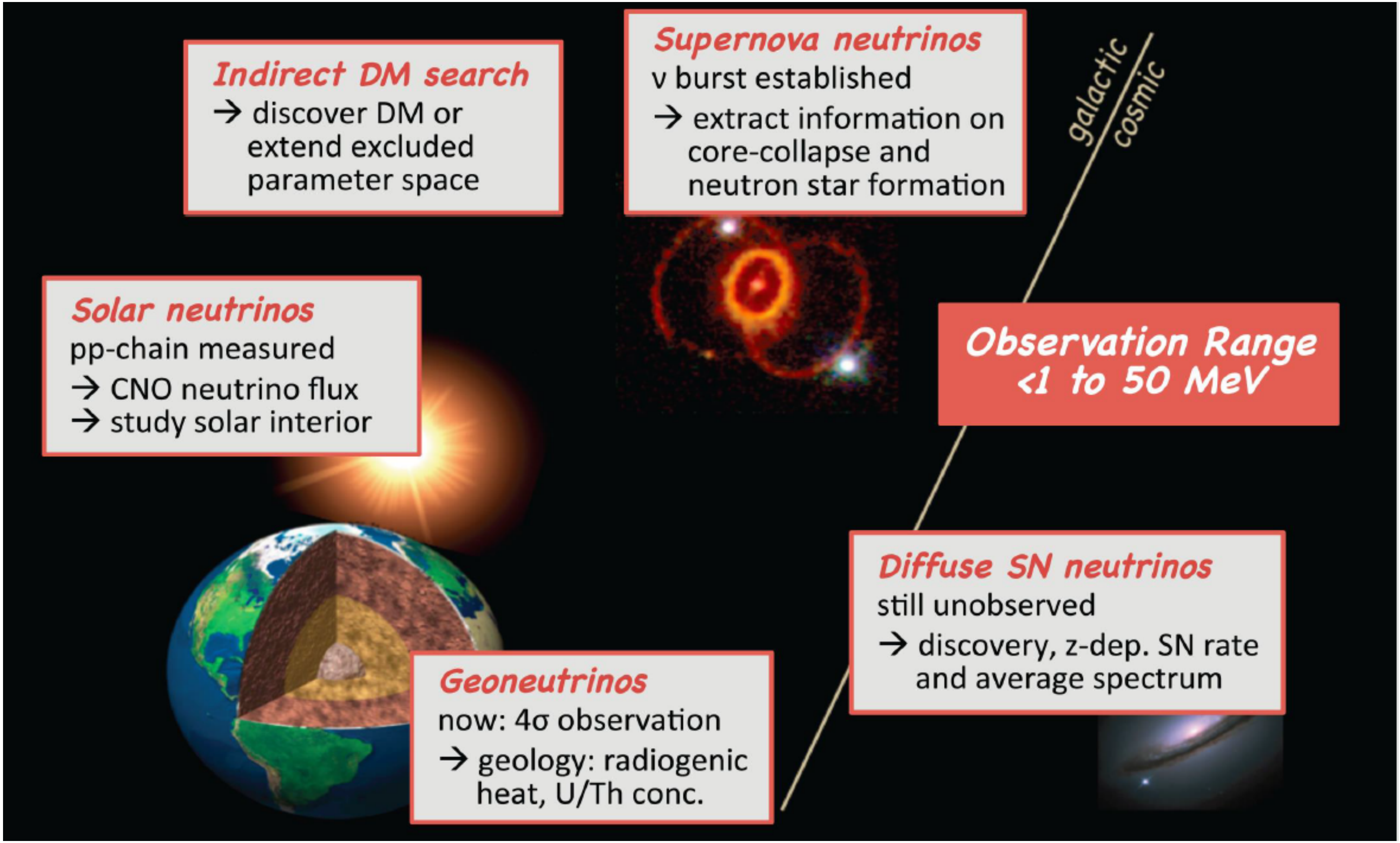
	Statistics	+BG +1% b2b +1% EScale +1% EnonL
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%

New physics tests in low-energy oscillation phenomena

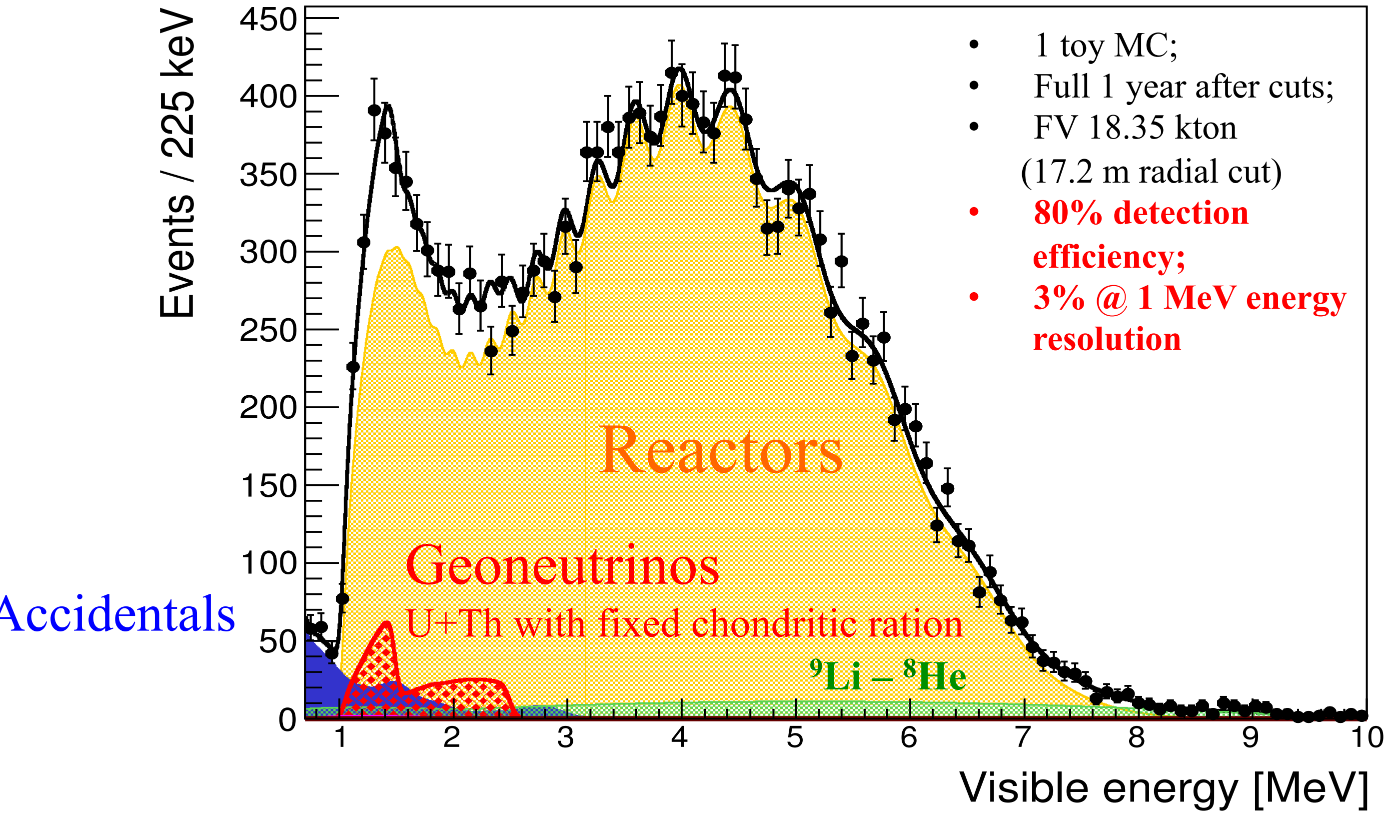
- **Rare processes**

Proton decay into K + antineutrino

More on JUNO physics program



JUNO potential to measure geoneutrinos



Big advantage:

- ✓ Big volume and thus high statistics (400 geonu / year)!

Main limitations:

- ✓ Huge reactor neutrino background;
- ✓ Relatively shallow depth – cosmogenic background;

Critical:

- ✓ Keep other backgrounds (^{210}Po contamination!) at low level and under control;

JUNO can provide another geoneutrino measurement with a comparable or even a better precision than existing results at another location in a completely different geological environment;

Conclusions

- Liquid scintillator detectors have provided a very rich budget of different experimental results

- **Stay tuned for new results concerning:**
  - ✓ Solar neutrinos
  - ✓ Geoneutrinos
  - ✓ Sterile neutrino
  - ✓ Mass hierarchy
  - ✓ Neutrino oscillation parameters
  - ✓ Reactor spectra
  - ✓ Supernovae neutrinos
  - ✓ Limits on rare processes
  - ✓ 0-$\beta\beta$ beta decay

Thank you!

Kazbegi (*Mkinvartsveri)* vulcano (5047 m) and Gergeti Trinity Church

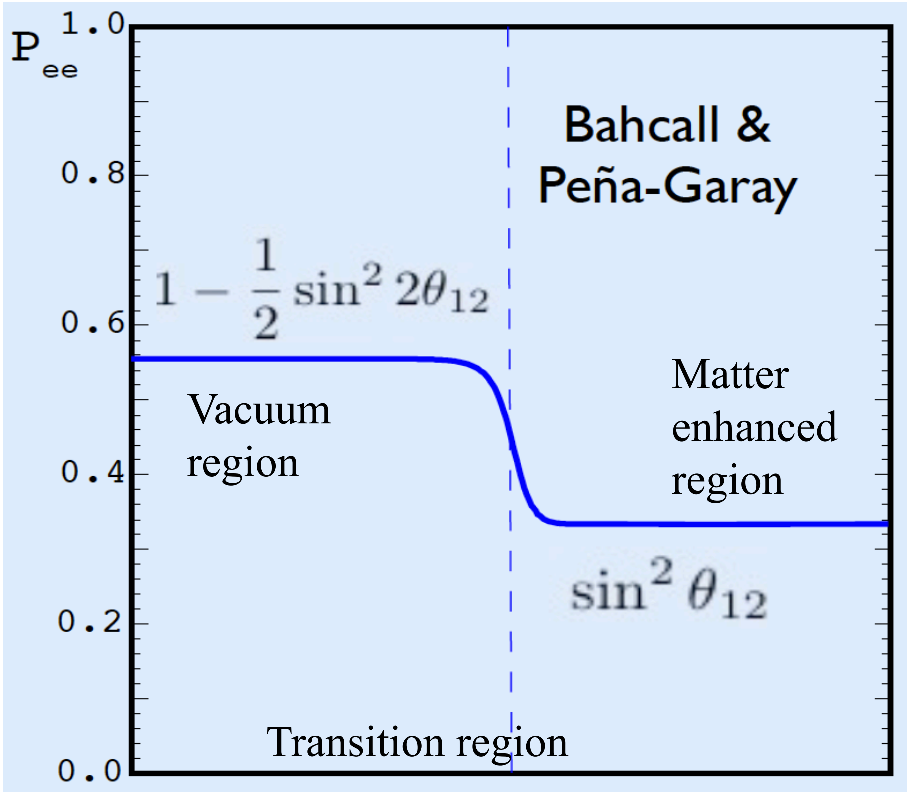
ν-oscillations in matter: MSW effect

- Being matter made of e^- (and not μ/τ), it affects oscillations (Wolfenstein, '78)
- Neutral current (Z-exchange) interactions: ν_e, ν_μ, ν_τ
- Charge current (**W-exchange**) interactions: **ν_e only**

"Refractive index" for ν_e

is different from the other flavors

- The effect can be enhanced by a **resonance**
  Mikheyev–Smirnov–Wolfenstein effect
- **This yields the energy dependence of the "survival probability":**
  $P_{ee}(E)$



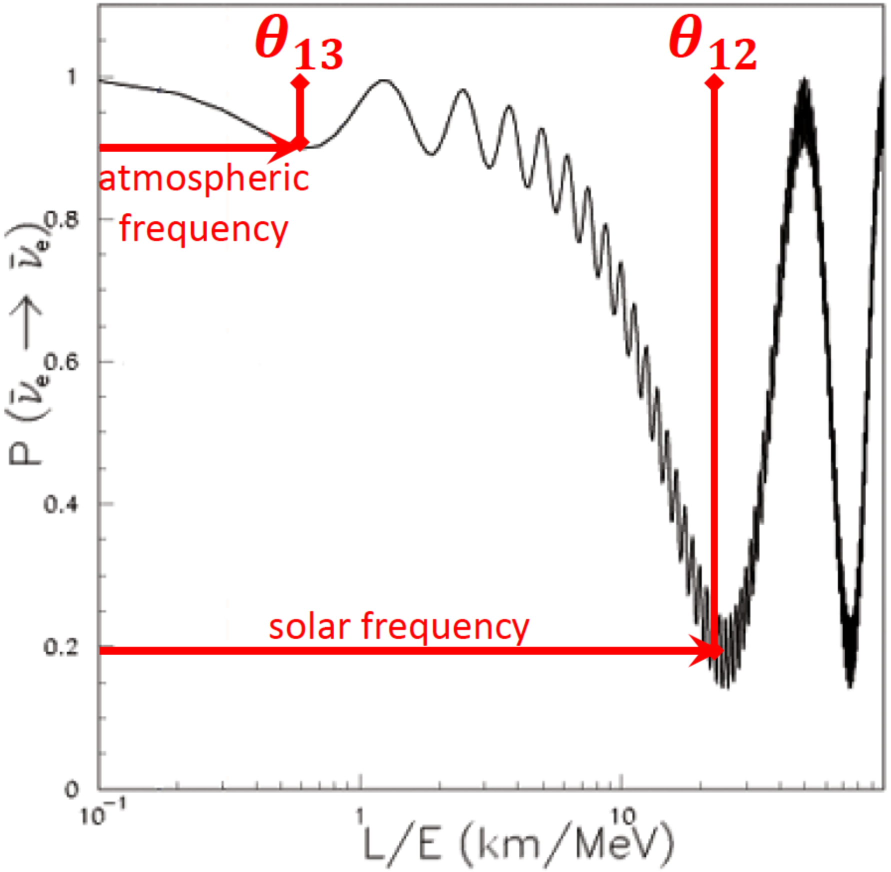
Energy

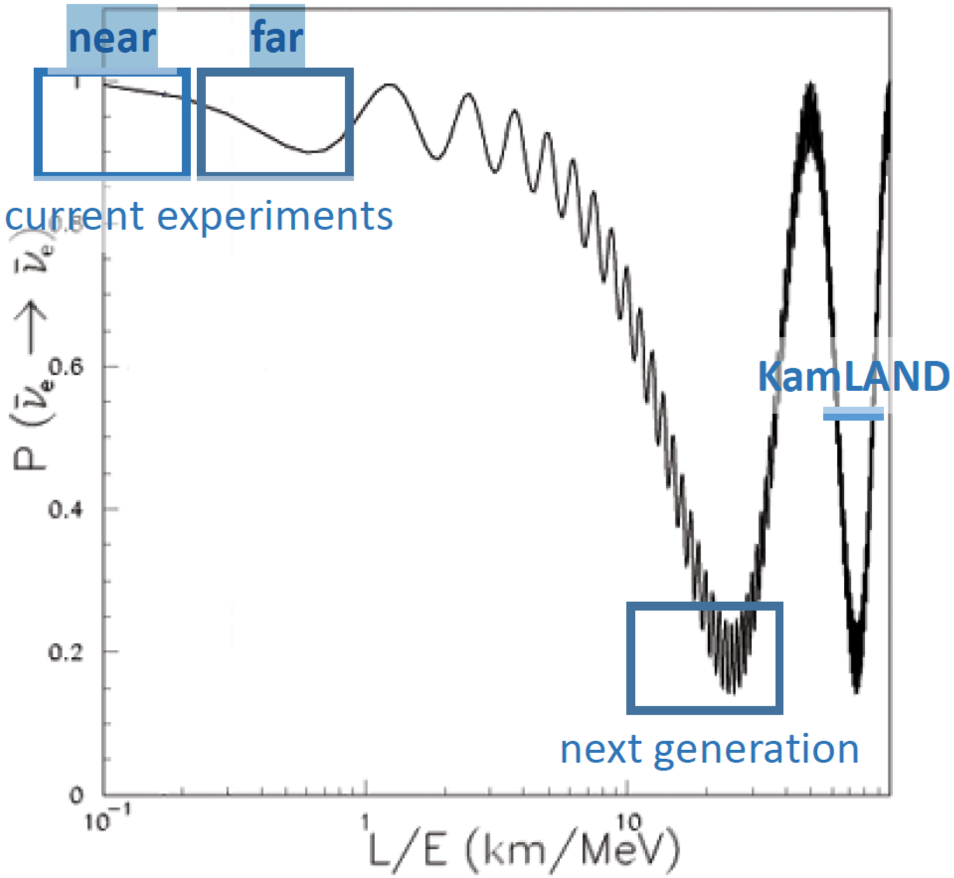
Oscillation pattern

short baseline — long baseline

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{ee} \frac{L}{4E}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta m^2_{21} \frac{L}{4E})$$

$$\sin^2(\Delta m^2_{ee} \frac{L}{4E}) \equiv \cos^2 \theta_{12} \sin^2(\Delta m^2_{31} \frac{L}{4E}) + \sin^2 \theta_{12} \sin^2(\Delta m^2_{32} \frac{L}{4E})$$





Summary of unknown parameters

- ❑ Absolute mass scale
- ❑ Origin of neutrino mass (Majorana versus Dirac)
- ❑ Mass hierarchy (inverted vs normal)
- ❑ CP-violating phase
- ❑ Octant of the θ_{23} mixing angle
- ❑ Existence of a sterile neutrino

?

Discovery of neutrino oscillations

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

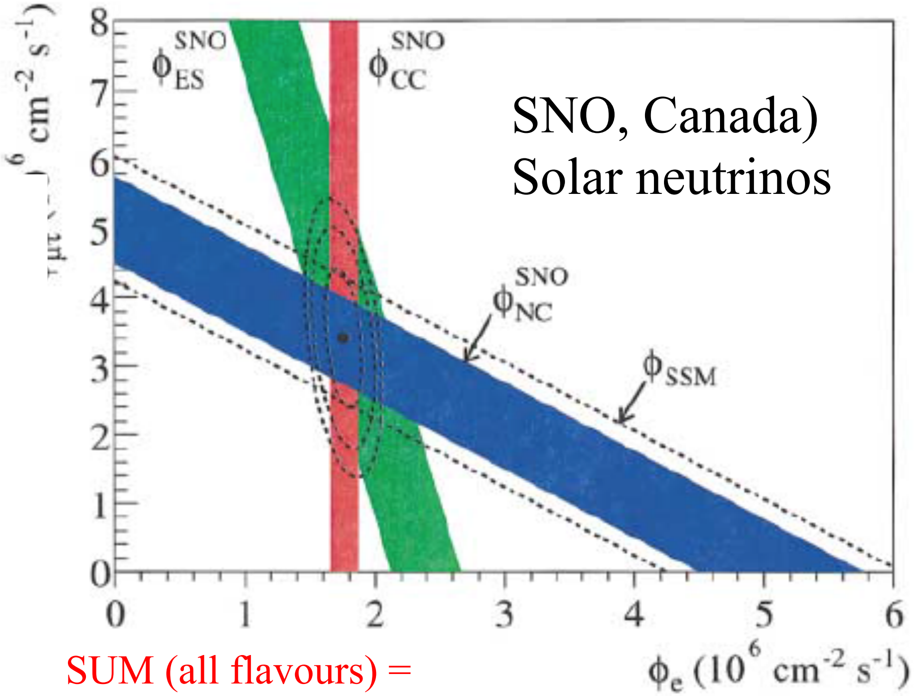
Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB

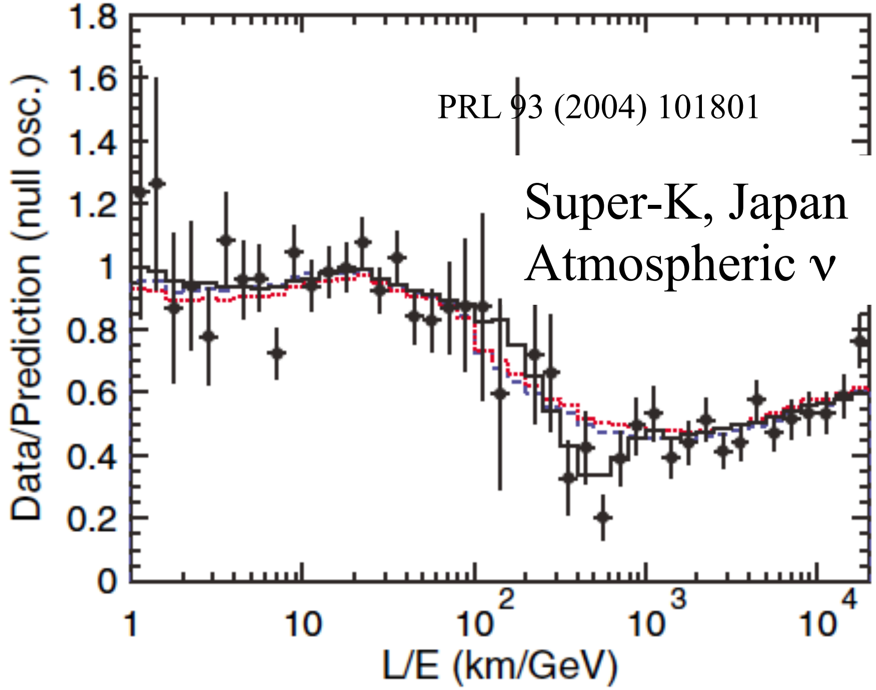
Arthur B. McDonald

Prize share: 1/2

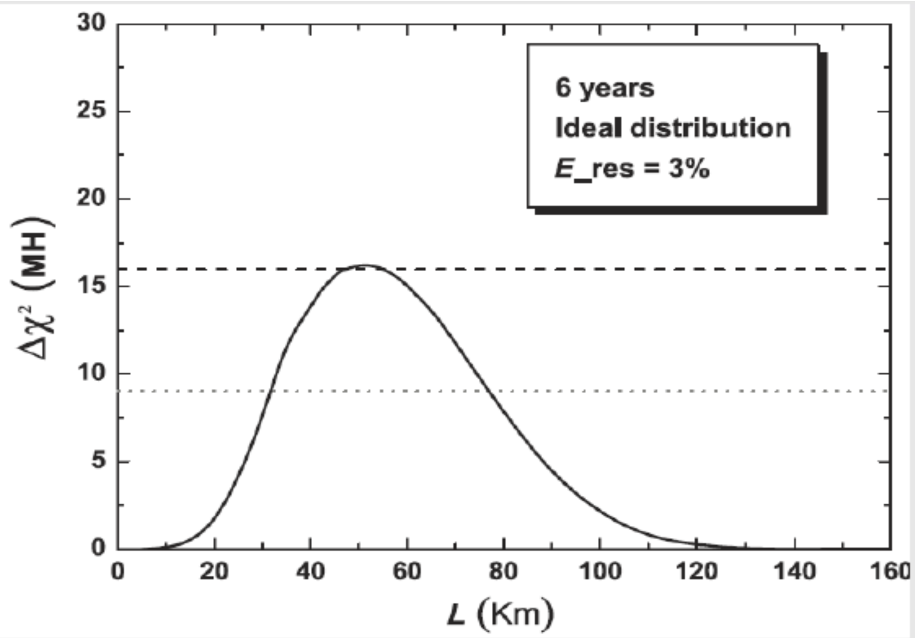
The Nobel Prize in Physics 2015 was awarded jointly to Takaa Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

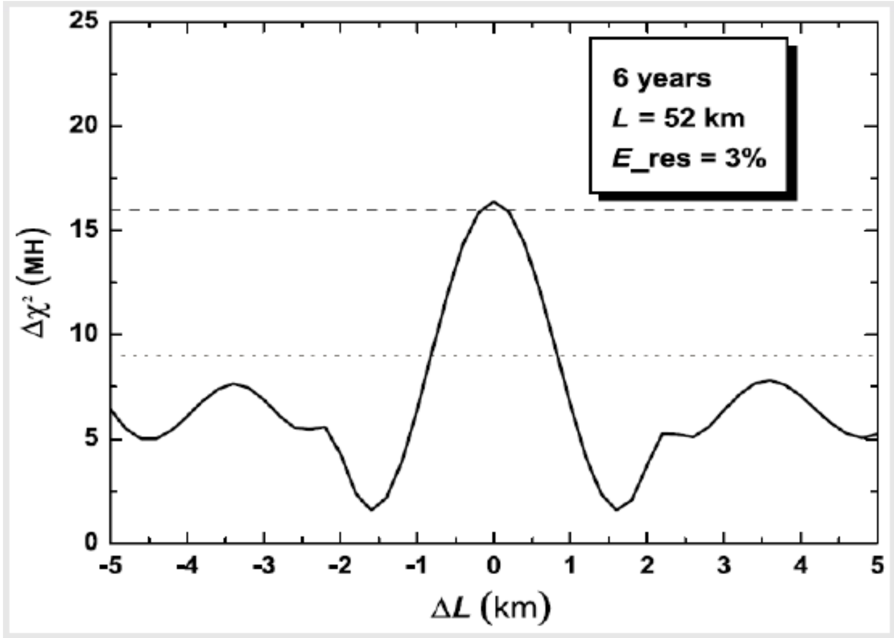


SUM (all flavours) =
Standard Solar Model predictions



Baseline optimization





Optimal baseline is at L = 50-60 km, at the oscillation maximum of Δm^2_{12}

In case of multiple reactors, minimize the spread of L

Choice of the experimental site

Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265