The Physics of Neutrinos

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" Some scientific revolutions arise from the invention of new tools or techniques for observing nature; others arise from the from the discovery of new concepts for understanding nature."

" The progress of science requires both new concepts and new tools"

Freeman Dyson

Lectures :

1. Panorama of Experiments
2. Neutrino Oscillations
3. Models for Neutrino Masses
4. Neutrinos in Cosmology

Neutrinos are everywhere ...

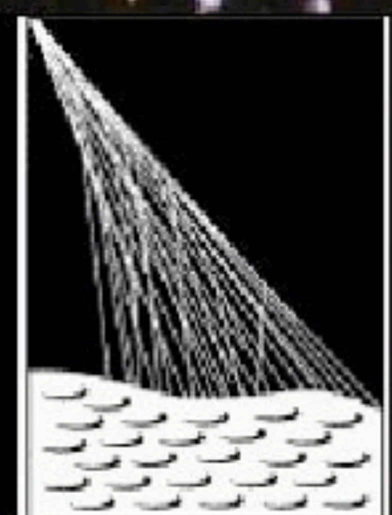
Nuclear Reactors

SUN

Accelerators

Supernova (Stellar Collapse)

Atmospheric (Cosmic Rays)



Astrophysical Accelerators

Earth's Crust/Mantle

Big Bang ($330\ \nu/cm^3$)

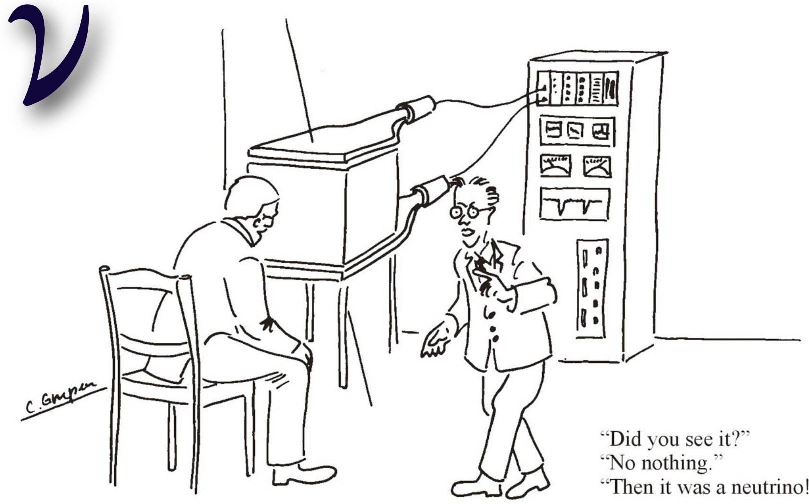
Some Numbers ...

our body emits ~350 million neutrinos a day

we receive:

- ~400 trillion neutrinos/s from the Sun
- ~50 billion neutrinos/s from the Earth
- ~ 10-100 billion neutrinos/s from nuclear reactors

The Imponderable Lightness of ν



"Did you see it?"
"No nothing."
"Then it was a neutrino!"

Cosmic Gall
by John Updike (1963)

Neutrinos, they are very small.
They have no charge and have no mass,
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass
Like dirt maids down a drafty hall,
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter from Nepal
And pierce the lover and his lass
From underneath the bed. You call
It wonderful; I call it crass.

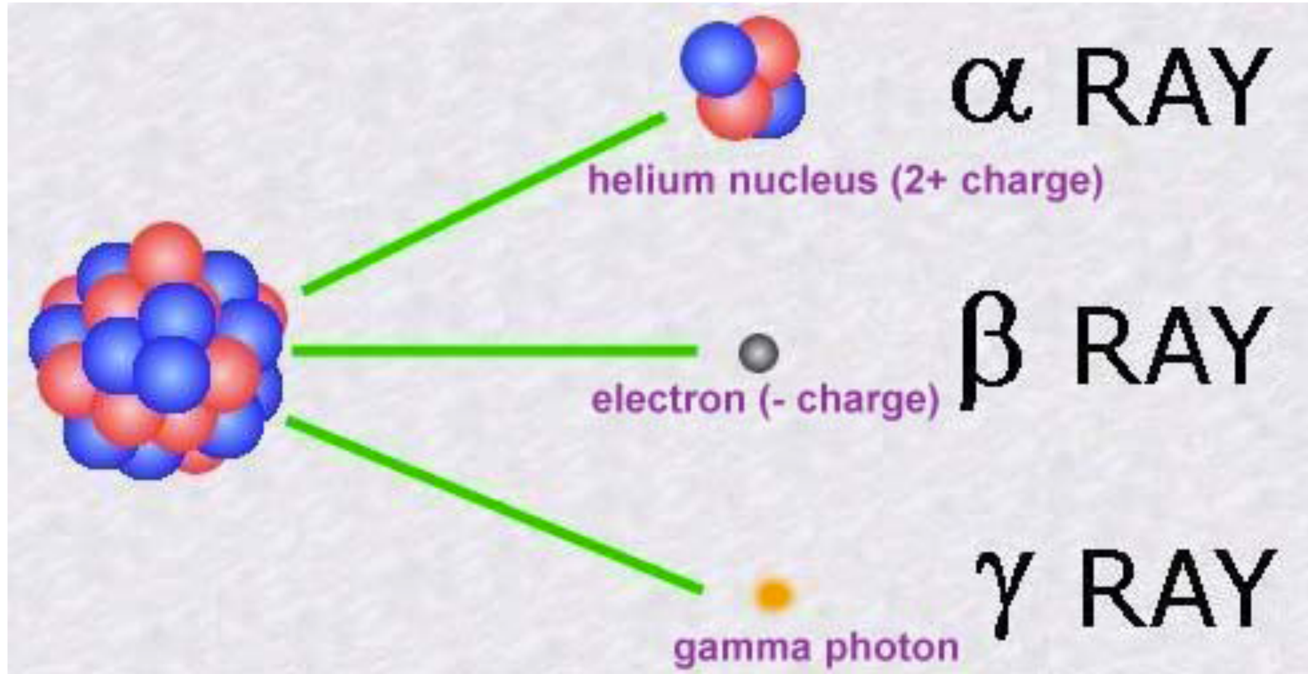
Lecture I

Panorama of Experiments

The Early Discoveries

Problems with β decay

Ernest Rutherford

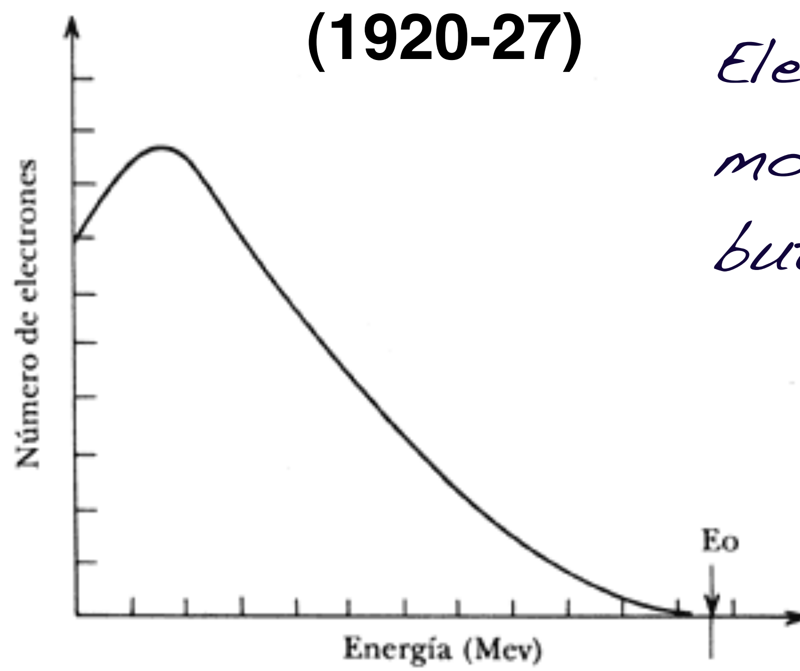


discovered in 1899

$$A(N,Z) \rightarrow A(N-1,Z+1) + e^-$$

James Chadwick

(1920-27)



Electron should be monochromatic ... but was not !

Pauli's Invention

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,

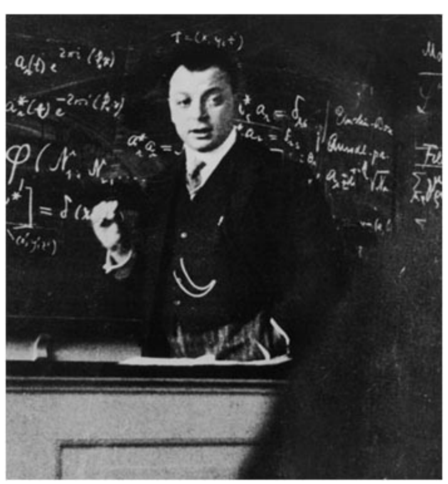
As the bearer of these lines [...] will explain more exactly, considering the 'false' statistics of N-14 and Li-6 nuclei, as well as the continuous β-spectrum, **I have hit upon a desperate remedy** to save the "exchange theorem" of statistics and the energy theorem. Namely [there is] **the possibility 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 additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass. **The continuous β-spectrum would then become understandable by the assumption that in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant.** [...]

But I don't feel secure enough to publish anything about this idea, so I first turn confidently to you, dear radioactives, with a question as to the situation concerning experimental proof of such a neutron, if it has something like about 10 times the penetrating capacity of a γ ray.

I admit that my remedy may appear to have a small *a priori* probability because neutrons, if they exist, would probably have long ago been seen. However, only those who wager can win, and the seriousness of the situation of the continuous β-spectrum can be made clear by the saying of my honored predecessor in office, Mr. Debye, [...] "One does best not to think about that at all, like the new taxes." [...] So, dear radioactives, put it to test and set it right. [...]

Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With many greetings to you, also to Mr. Back, your devoted servant,

W. Pauli

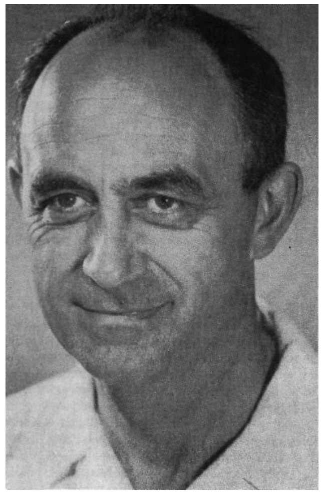


Wolfgang Pauli

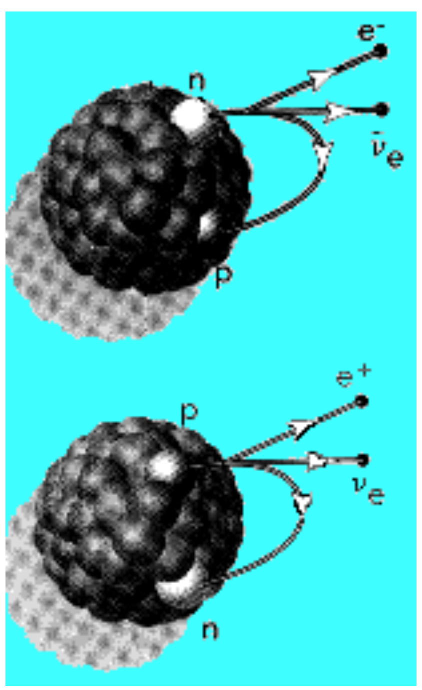
"It is difficult to find a case where the word 'intuition' characterizes a human achievement better than in the case of the neutrino invention by Pauli "

(Bruno Pontecorvo, 1980)

Fermi's Theory



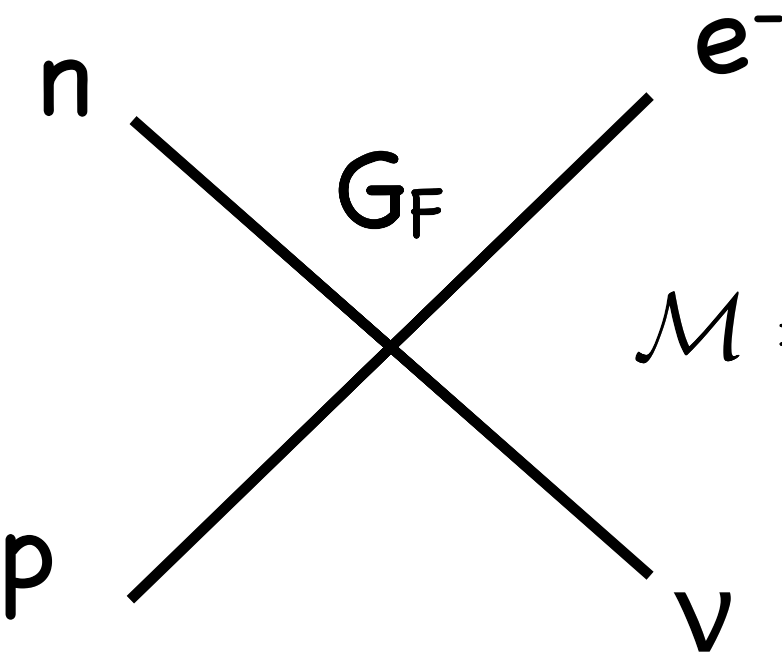
Enrico Fermi



1932 - discovery of the neutron by Chadwick

1934 - discovery of β^+ decay by Joliot-Curie

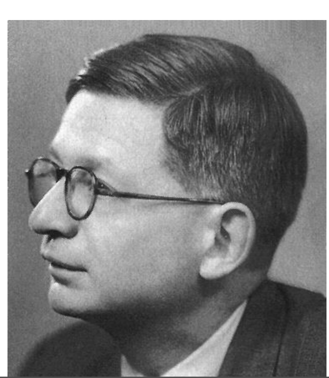
- Fermi starts to call Pauli's particle neutrino ("little neutron") and proposes his theory for the "weak interaction" (refused by Nature)



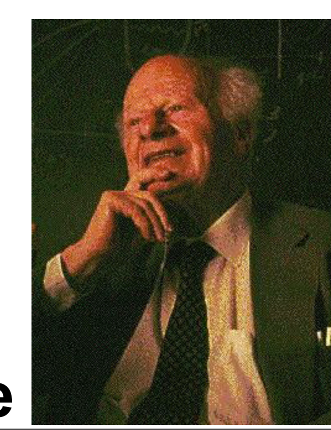
$$\mathcal{M} = \frac{G_F}{\sqrt{2}}[\bar{\Psi}_p \gamma^\alpha \Psi_n][\bar{\Psi}_e \gamma^\beta \Psi_\nu]$$

$$\sigma(n + \nu_e \rightarrow e^- + p) \sim E_\nu(\mathrm{MeV}) \times 10^{-43}\,\mathrm{cm}^2$$

50 light-years of water needed to stop a 1 MeV neutrino ...



Rudolf Peierls

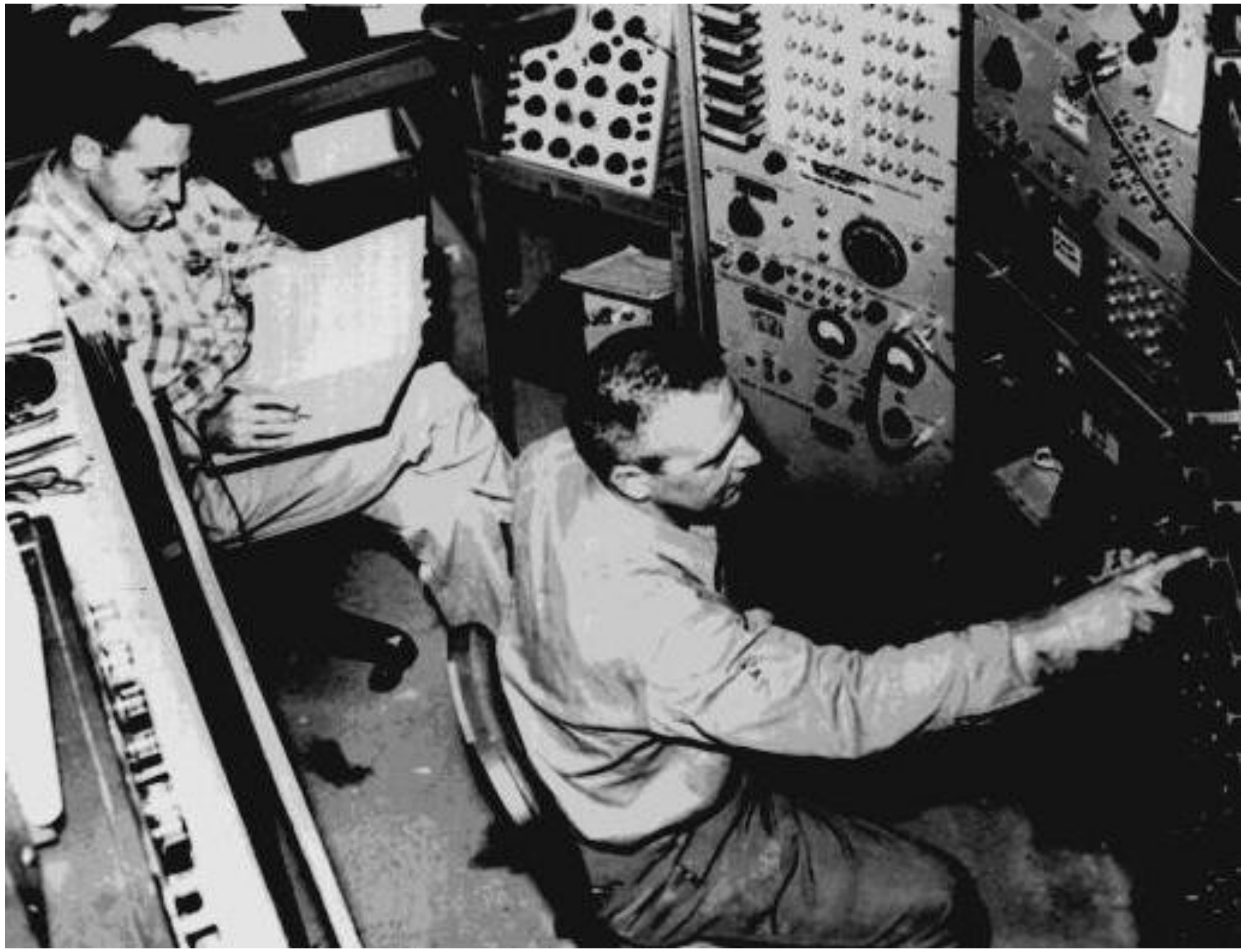


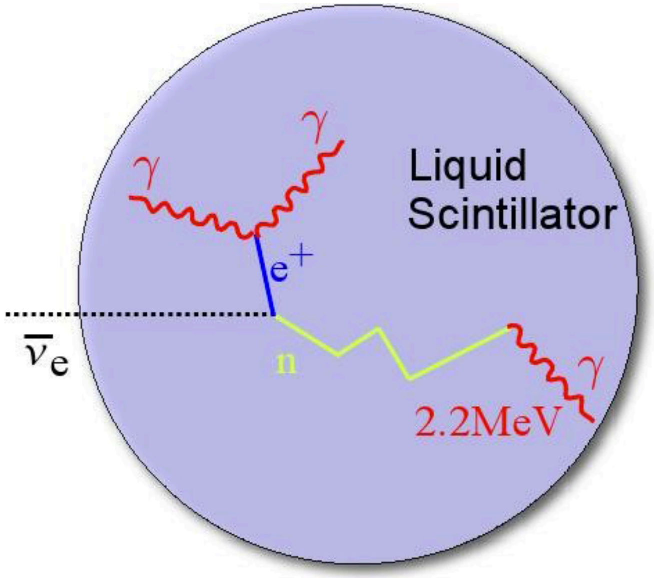
Hans Bethe

Discovery of the First Neutrino

the electron neutrino

Savannah River, South Carolina, EUA





$$\overline{\nu}_e + p \rightarrow e^+ + n$$

207 μs

$$n + p \rightarrow d + \gamma$$

1956 : Fred Reines & Clyde Cowan

C.L. Cowan Jr, *et al.* Science 124, 103 (1956)
F. Reines and C.L. Cowan Jr, Nature 178, 446 (1956)

"We are happy to inform you that we have definitely detected neutrinos ..."

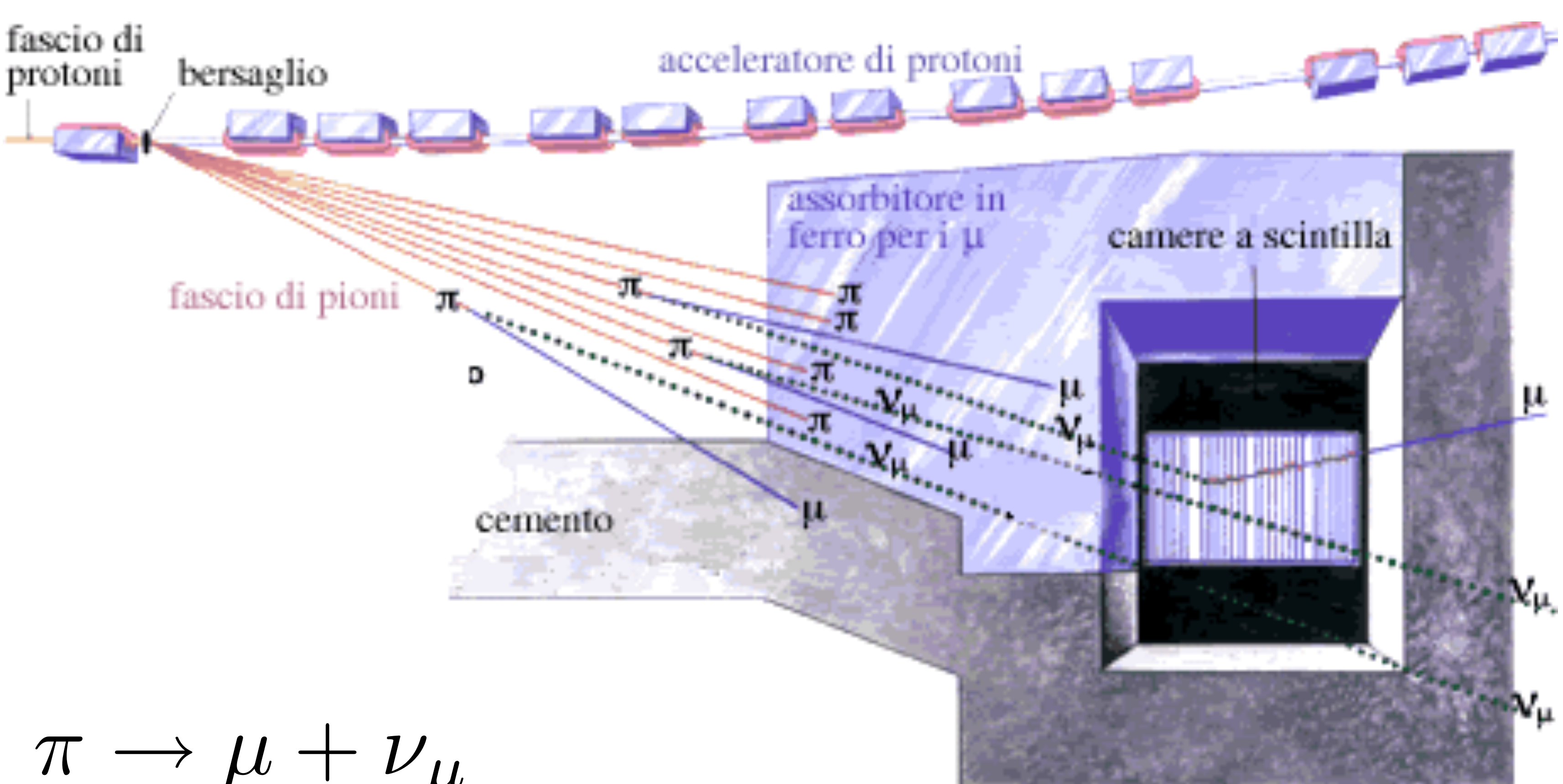
Towards the Standard Model

Discovery of the Second Neutrino

1962 : Steinberger, Lederman & Schwartz

the muon neutrino

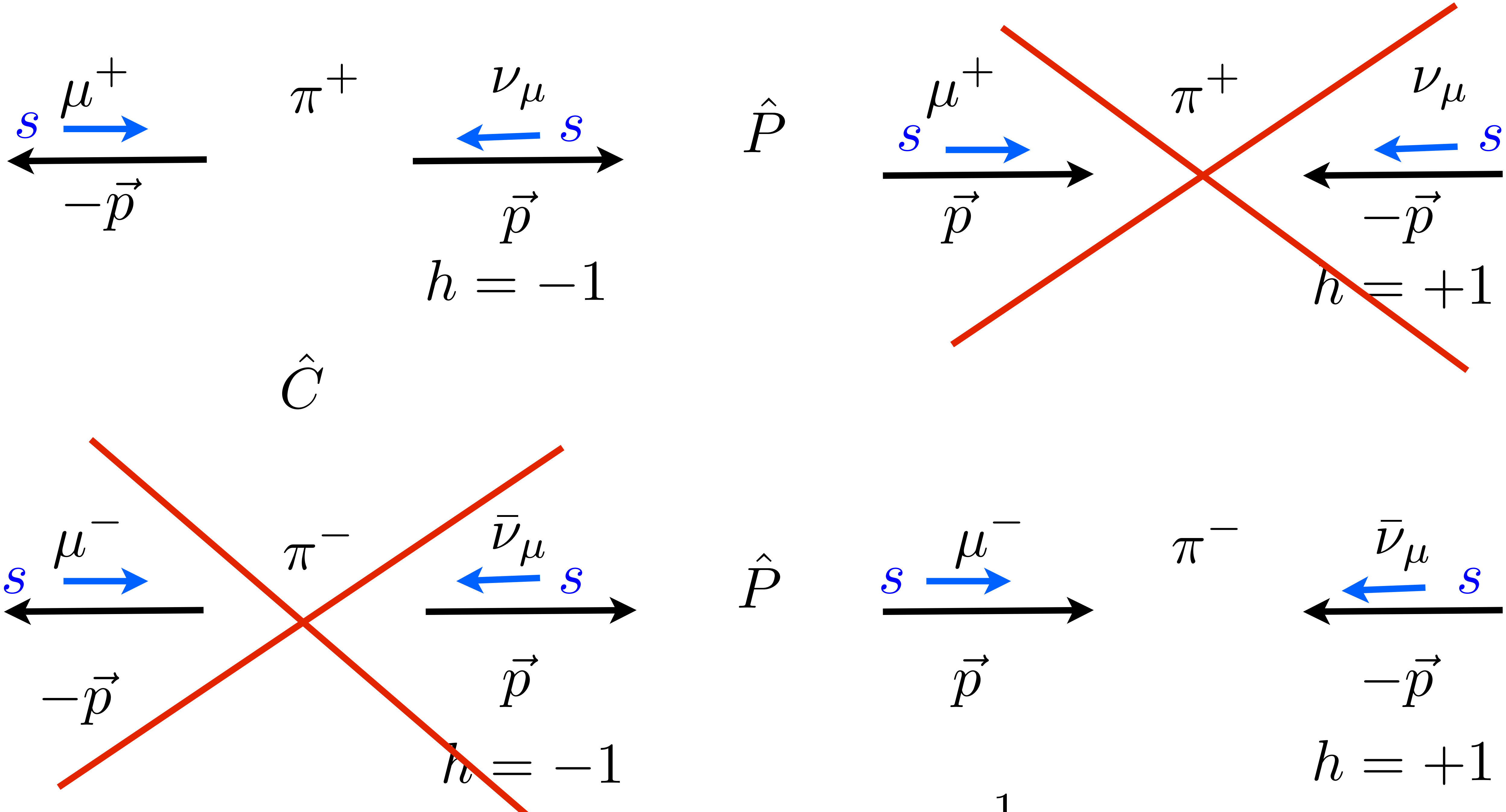
$$p + p \rightarrow \pi + X$$



$$\nu_\mu + N \rightarrow \mu + Y$$

$$\pi \rightarrow \mu + \nu_\mu$$

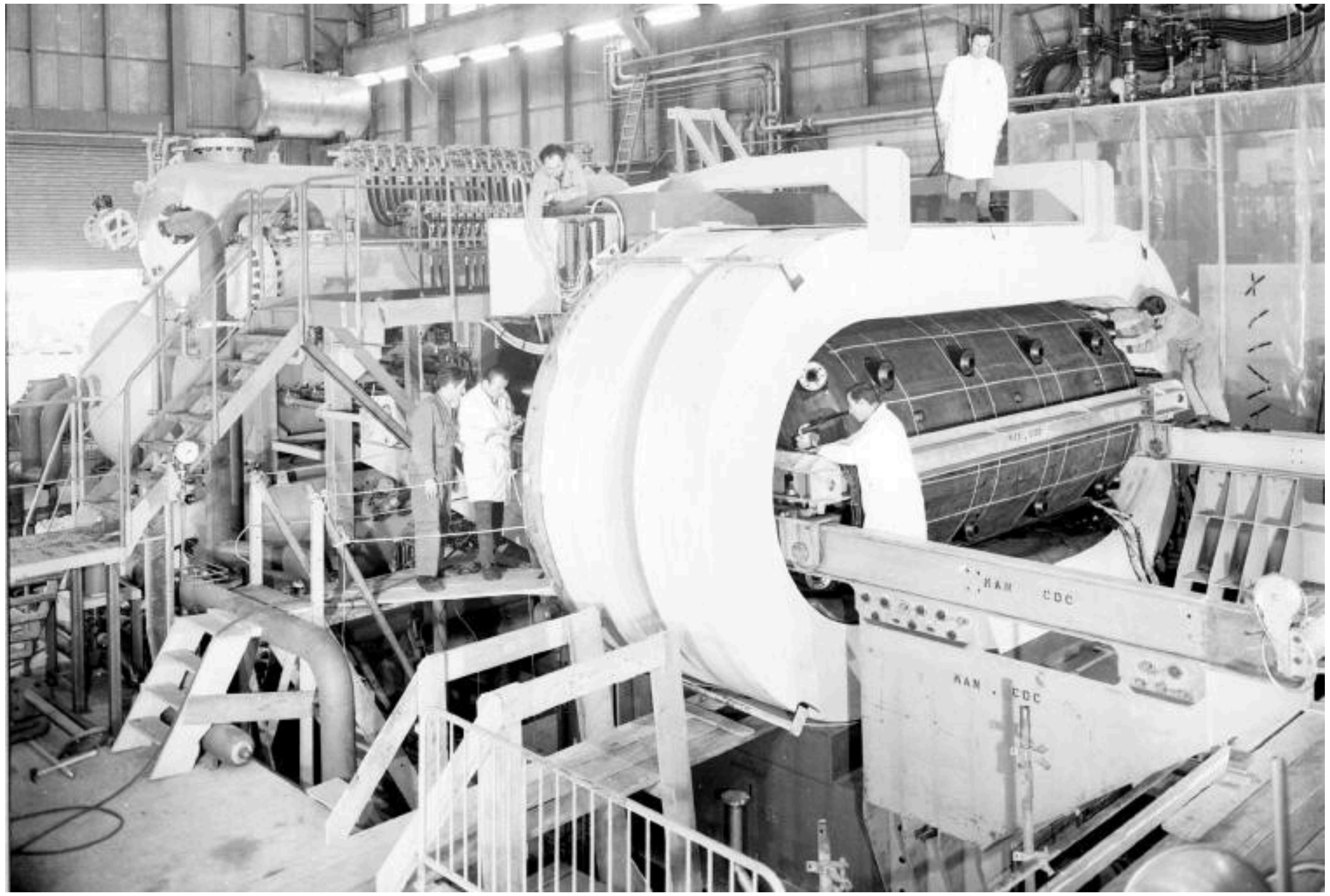
Parity & Charge Conjugation Violation

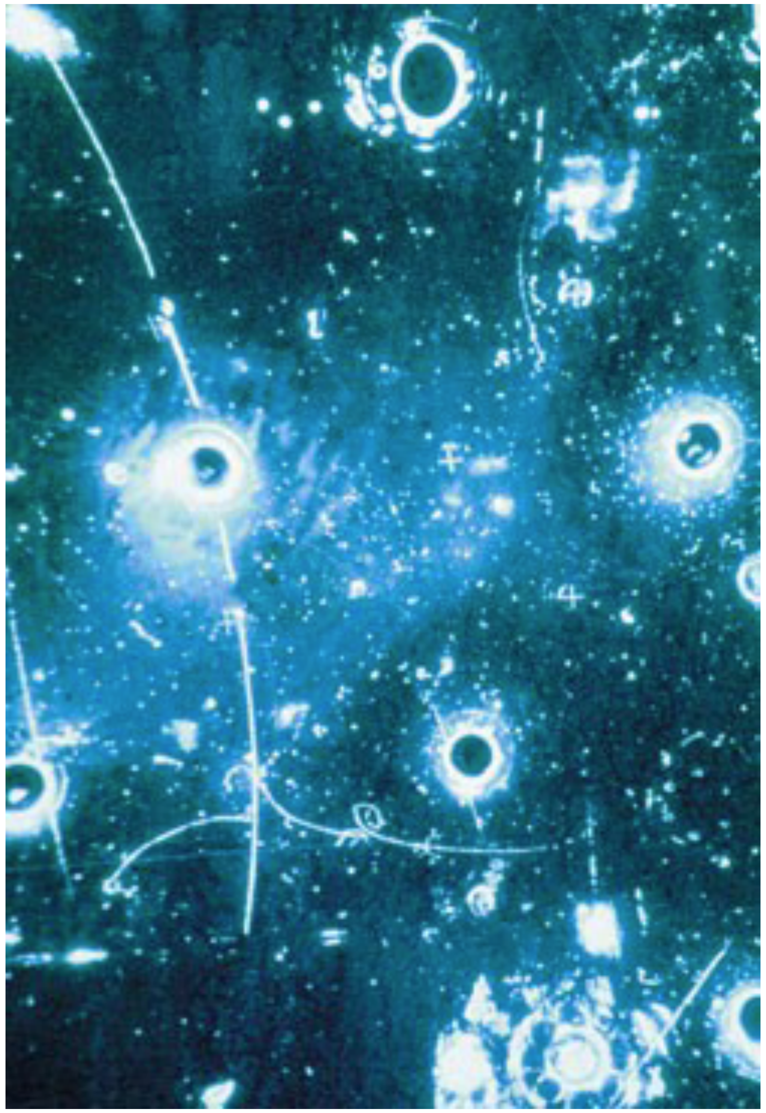


$$\bar{\Psi}\gamma^\mu\Psi \rightarrow \bar{\Psi}\gamma^\mu \frac{1}{2}(1-\gamma^5)\Psi$$

V-A interaction

Discovery of Neutral Currents



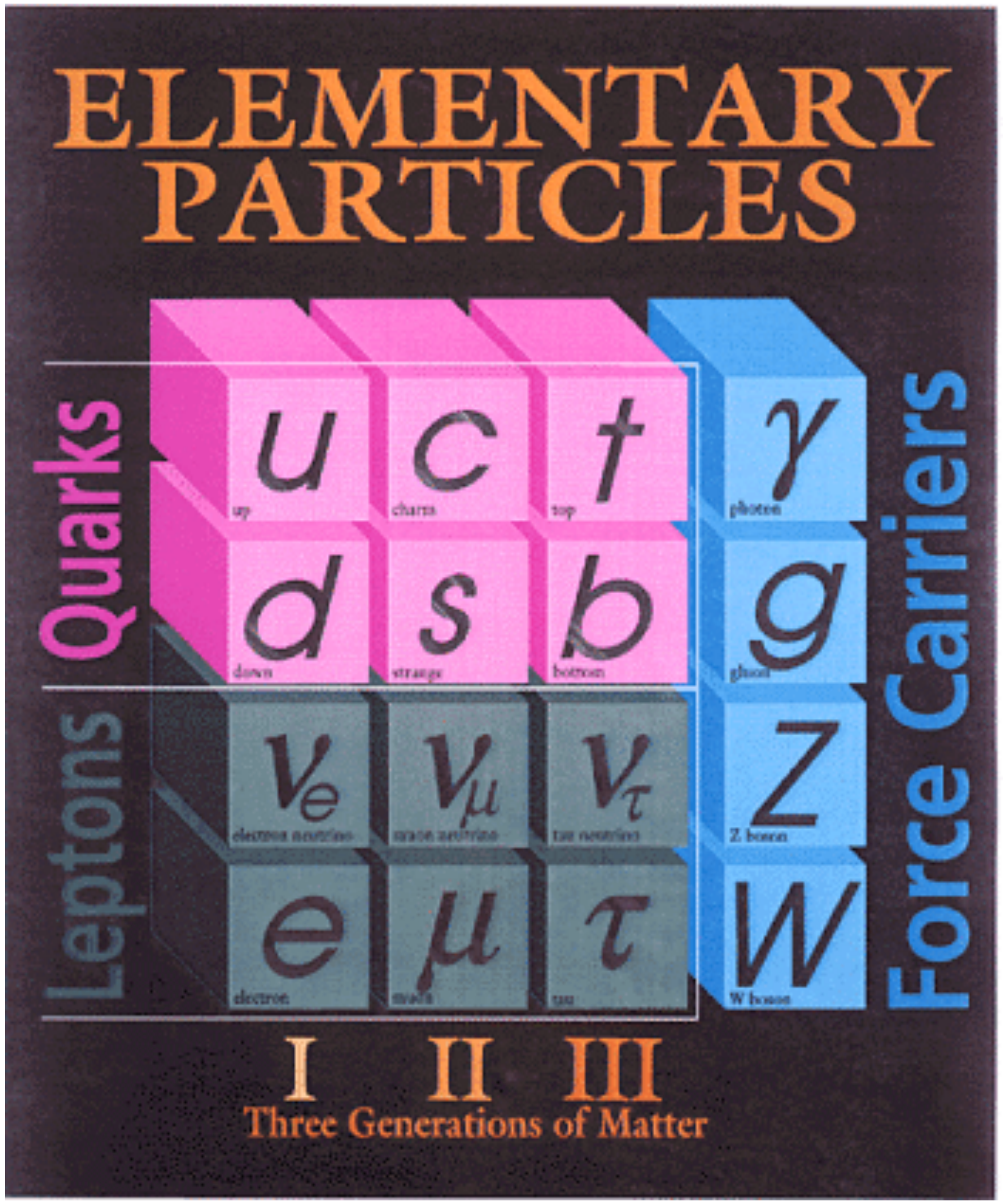


1973 : Gargamelle Bubble Chamber (CERN)

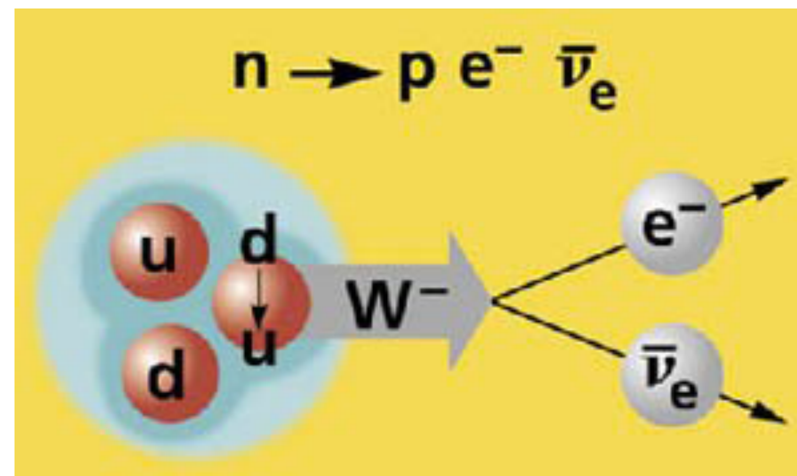
$$\nu_\mu + N \rightarrow \nu_\mu + \text{hadrons}$$

$$\bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu + \text{hadrons}$$

Standard Model



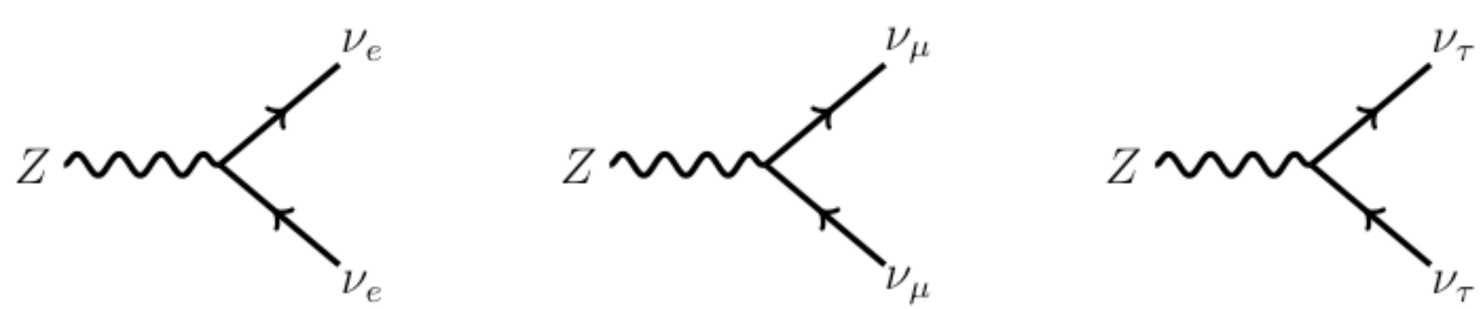
$$\mathcal{L}_{\rm cc} = -\frac{g}{\sqrt{2}} j^\mu_{\rm cc} W_\mu + \text{h.c.}$$



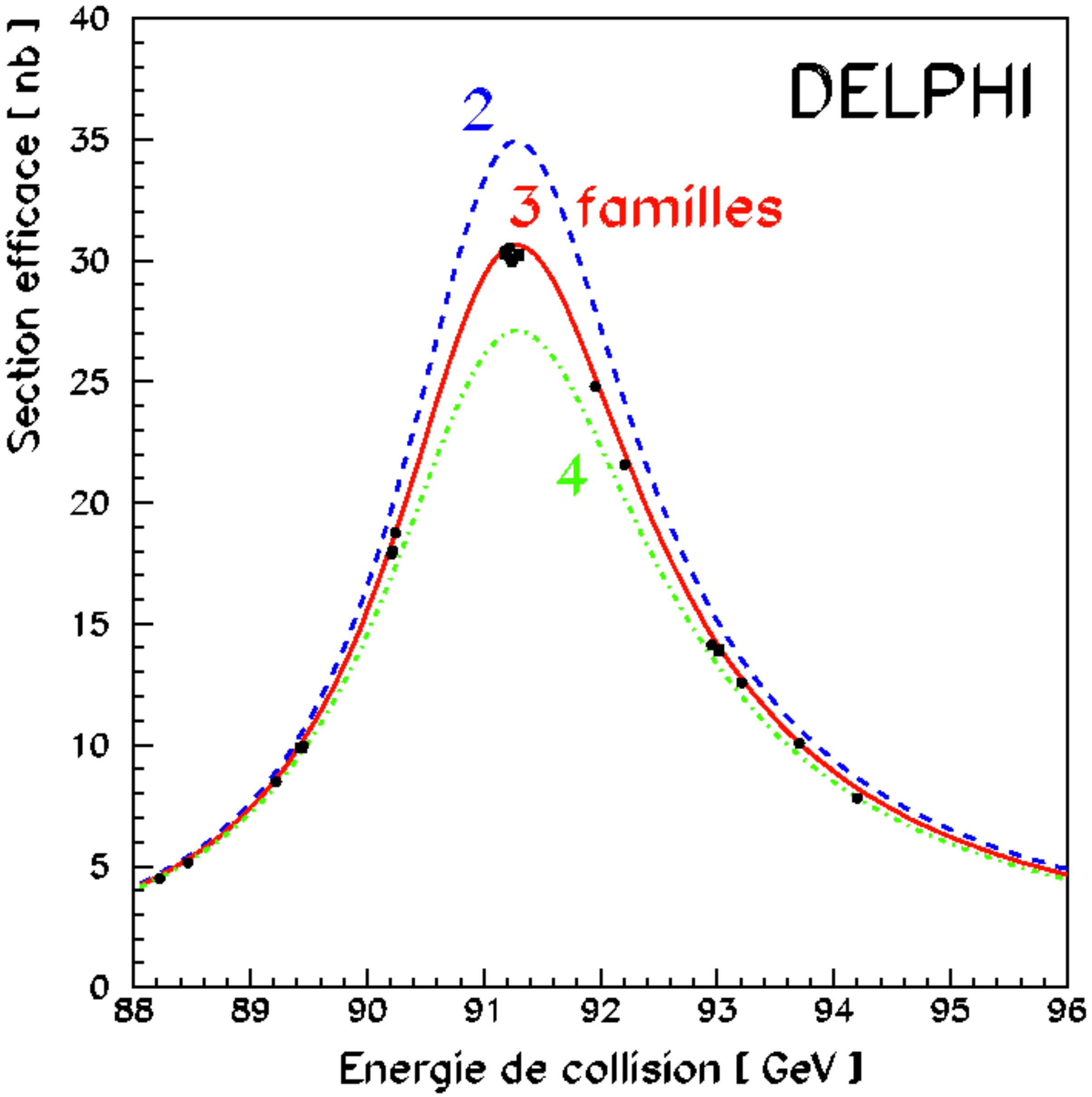
$$\mathcal{L}_{\rm nc} = -\frac{g}{\cos\theta_W} j^\mu_{\rm nc} Z_\mu + \text{h.c.}$$

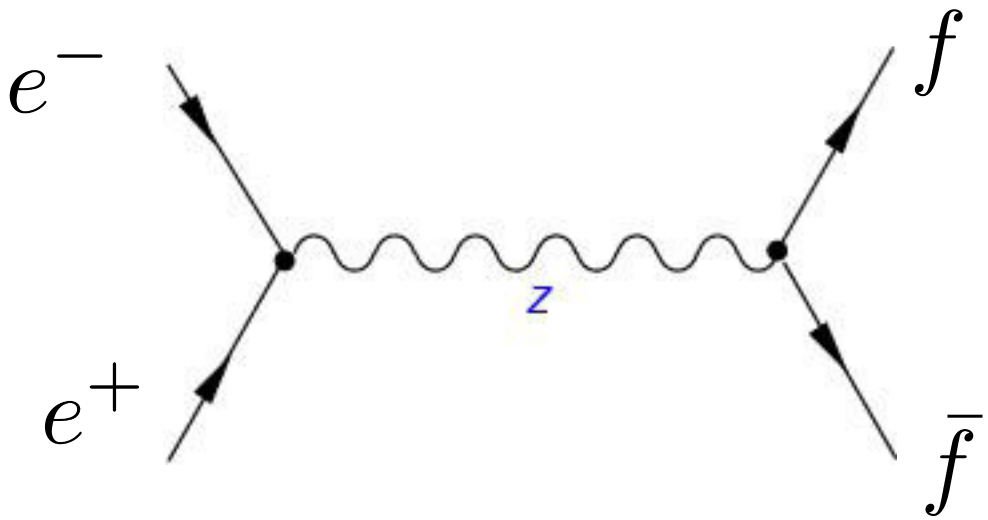
$$j^\mu_{\rm cc} = \bar{f}_\alpha \gamma^\mu P_L f'_\alpha$$

$$j^\mu_{\rm nc} = \bar{f}_\alpha \gamma^\mu P_L f_\alpha$$



There are 3 of them !





Z^0 invisible decay width

N_ν= 2.984 ± 0.008

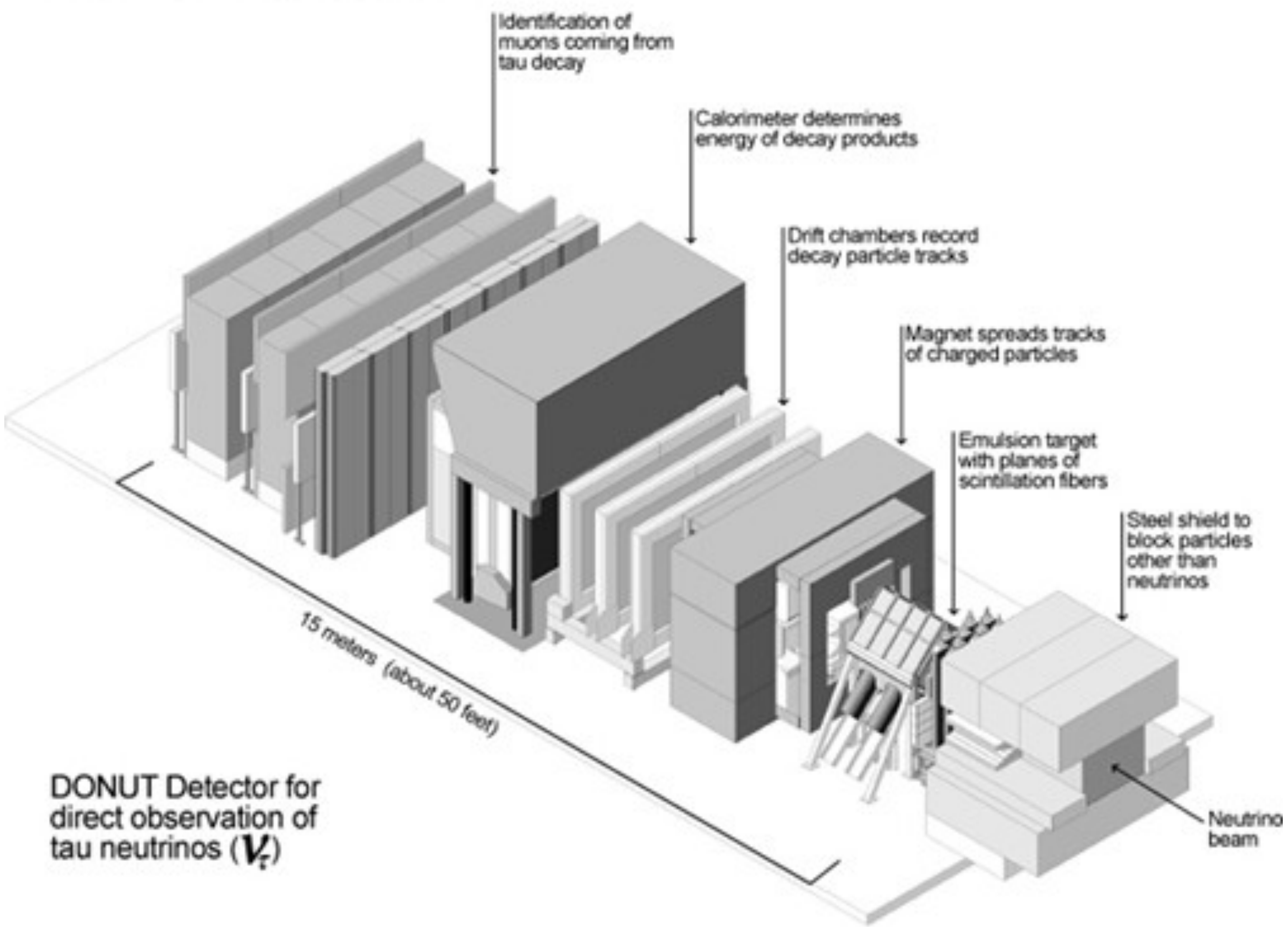
3 light neutrinos that couple with the Z^0 in the usual way

Discovery of the Third Neutrino

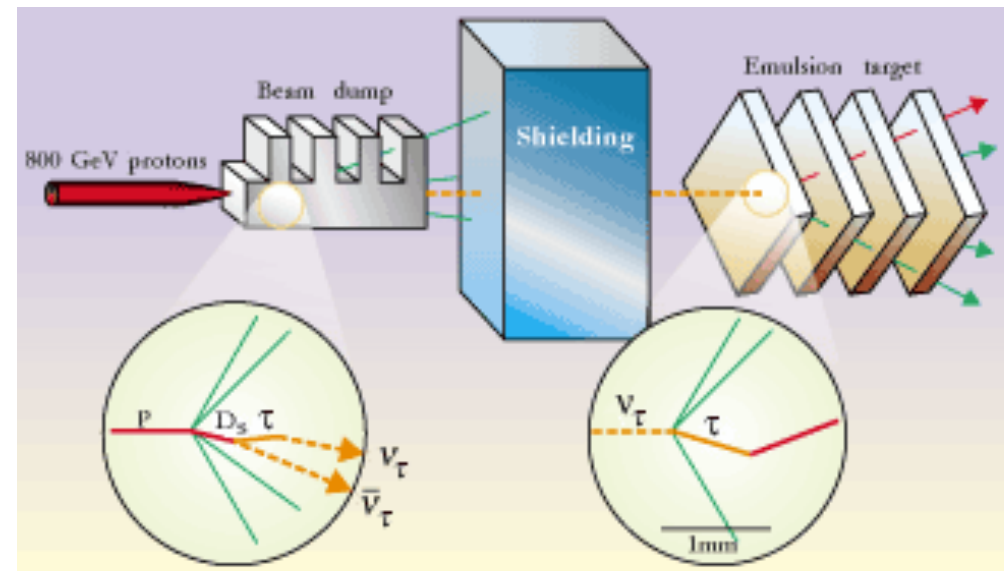
the tau neutrino

2000 : DONUT Collaboration

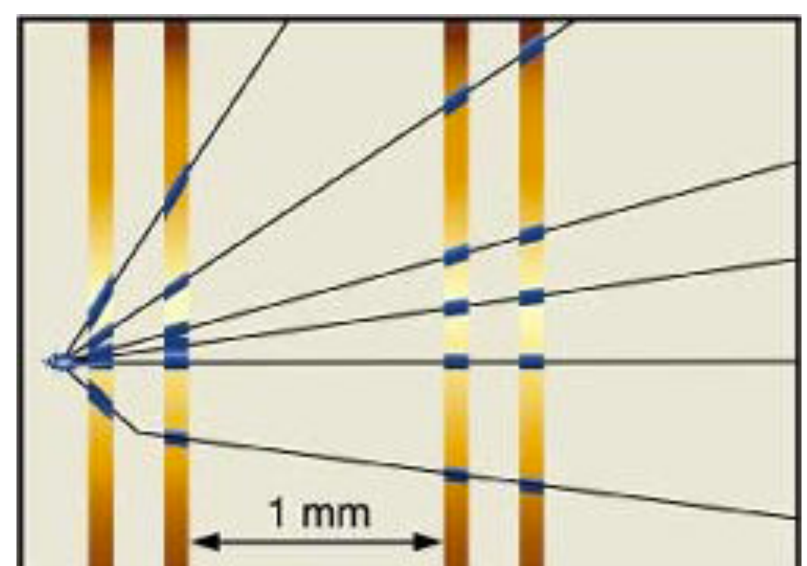
DONUT Detector



DONUT Detector for direct observation of tau neutrinos (ν_τ)



$$\tau \to \nu_\tau + \pi$$



$$\nu_\tau + N \to \tau + X$$

kink

The Quest for Neutrino Oscillations

Two Types of Oscillation Experiments

$$\nu_\alpha \longrightarrow \nu_\alpha$$
$$\bar{\nu}_\alpha \longrightarrow \bar{\nu}_\alpha$$

disappearance experiments

$$\bar{\nu}_\beta \longrightarrow \bar{\nu}_\alpha$$
$$\nu_\beta \longrightarrow \nu_\alpha$$

appearance experiments

$$\beta \neq \alpha$$

From Theory to Experiment

[Experiment]

# of neutrinos

ν Flux

[Theory]

survival probability

$$\mathbf{N}_\alpha(\mathbf{L}) = \mathbf{A} \int \mathbf{\Phi}(\mathbf{E})\, \sigma(\mathbf{E})\, \mathbf{P}(\nu_\alpha \to \nu_\alpha; \mathbf{E}, \mathbf{L})\, \epsilon(\mathbf{E})$$

number of targets x time

[Experiment]

x-section

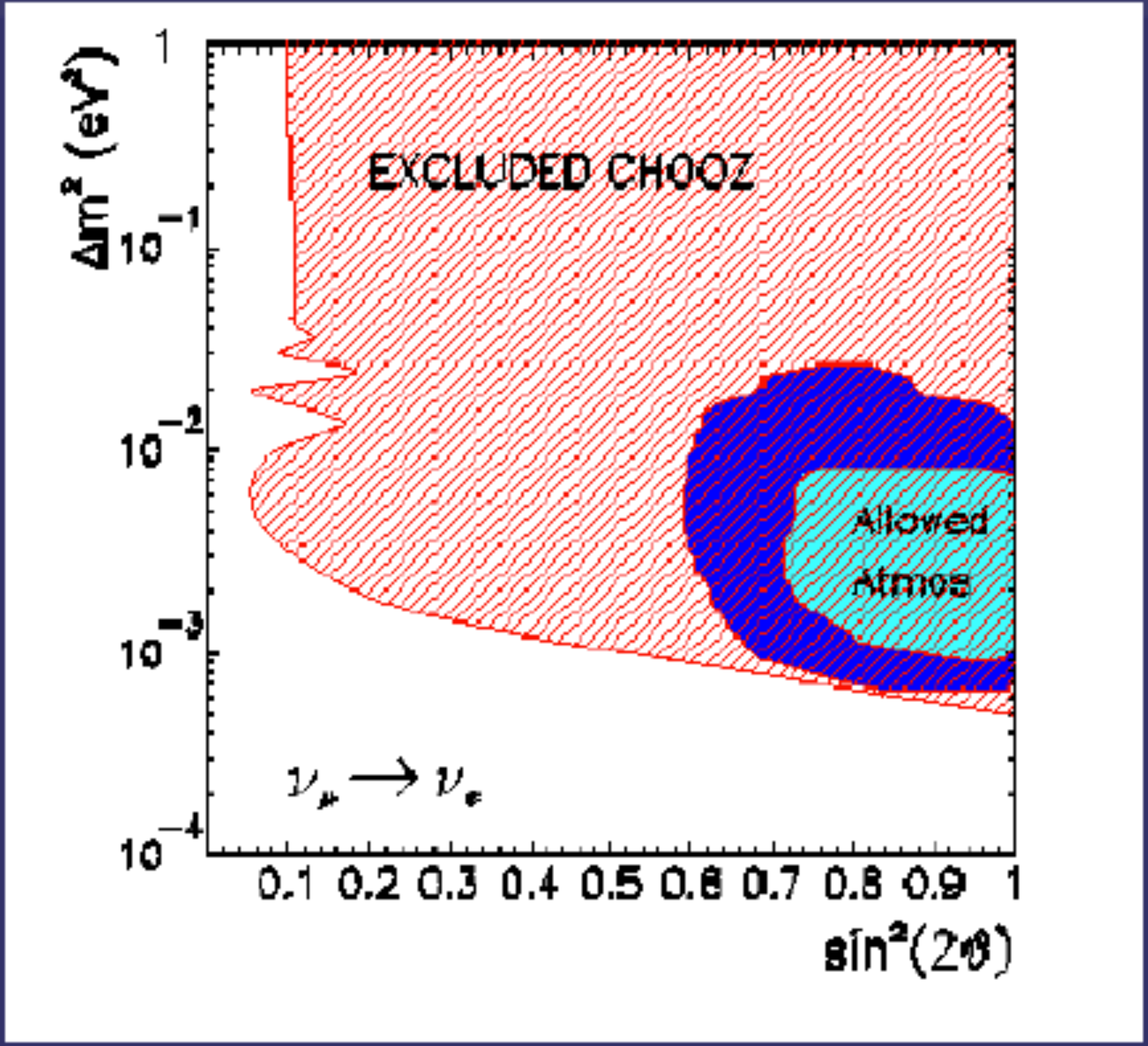
[Theory]

detector efficiency

[Experiment]

$\bar{\nu}_e \longrightarrow \bar{\nu}_e$

CHOOZ (1999)



$P^{osc} < 0{,}05$

$\sin^2 2\theta_{13} < 0{,}15$

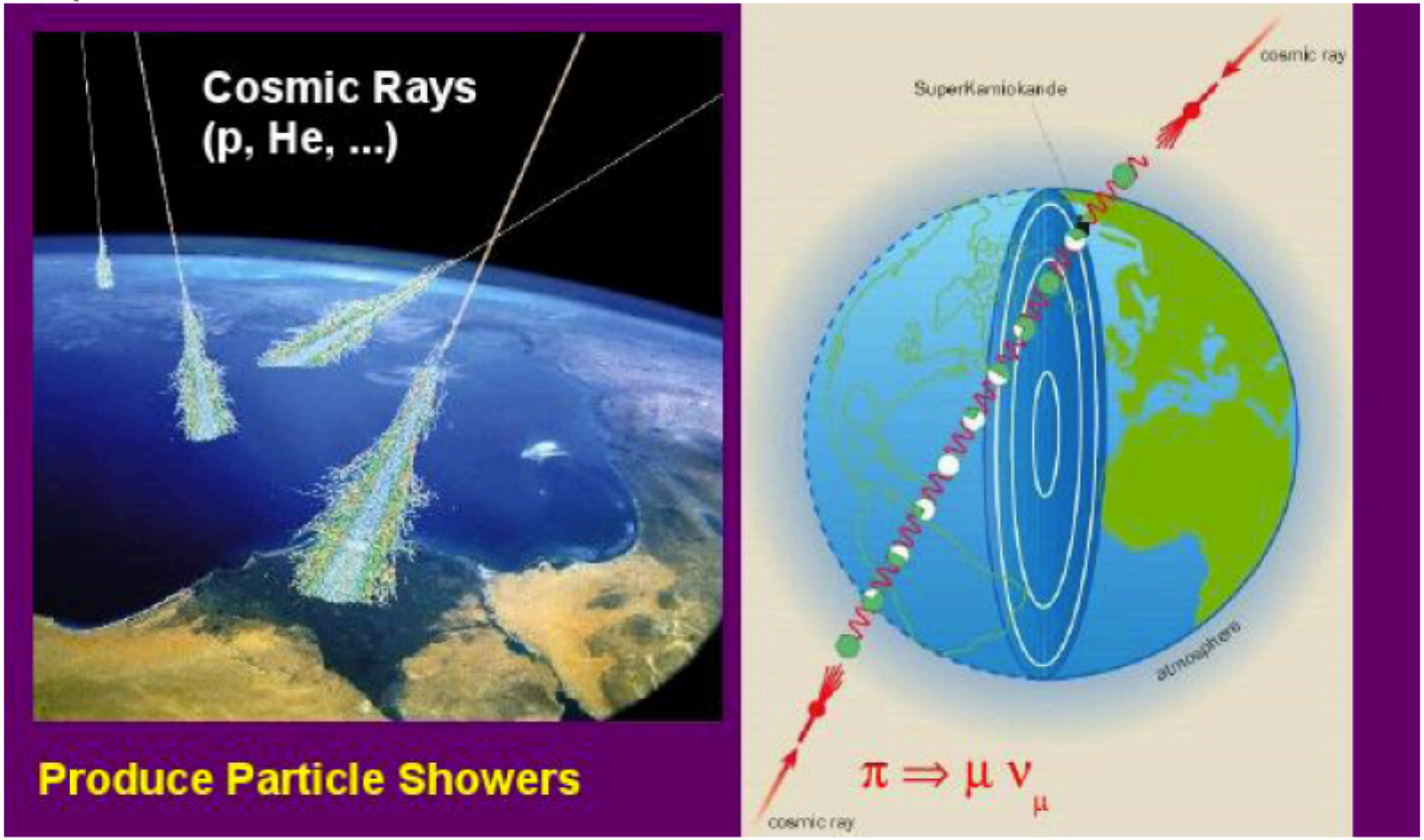
$\sin^2\theta_{13} < 0{,}04$

$$L_{ij}^{\mathrm{osc}} = \frac{4\pi E}{\Delta m_{ij}^2}$$

$$P_{ee}^{\mathrm{CHOOZ}} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\pi L}{L_{32}^{\mathrm{osc}}}\right)$$

Atmospheric Neutrinos

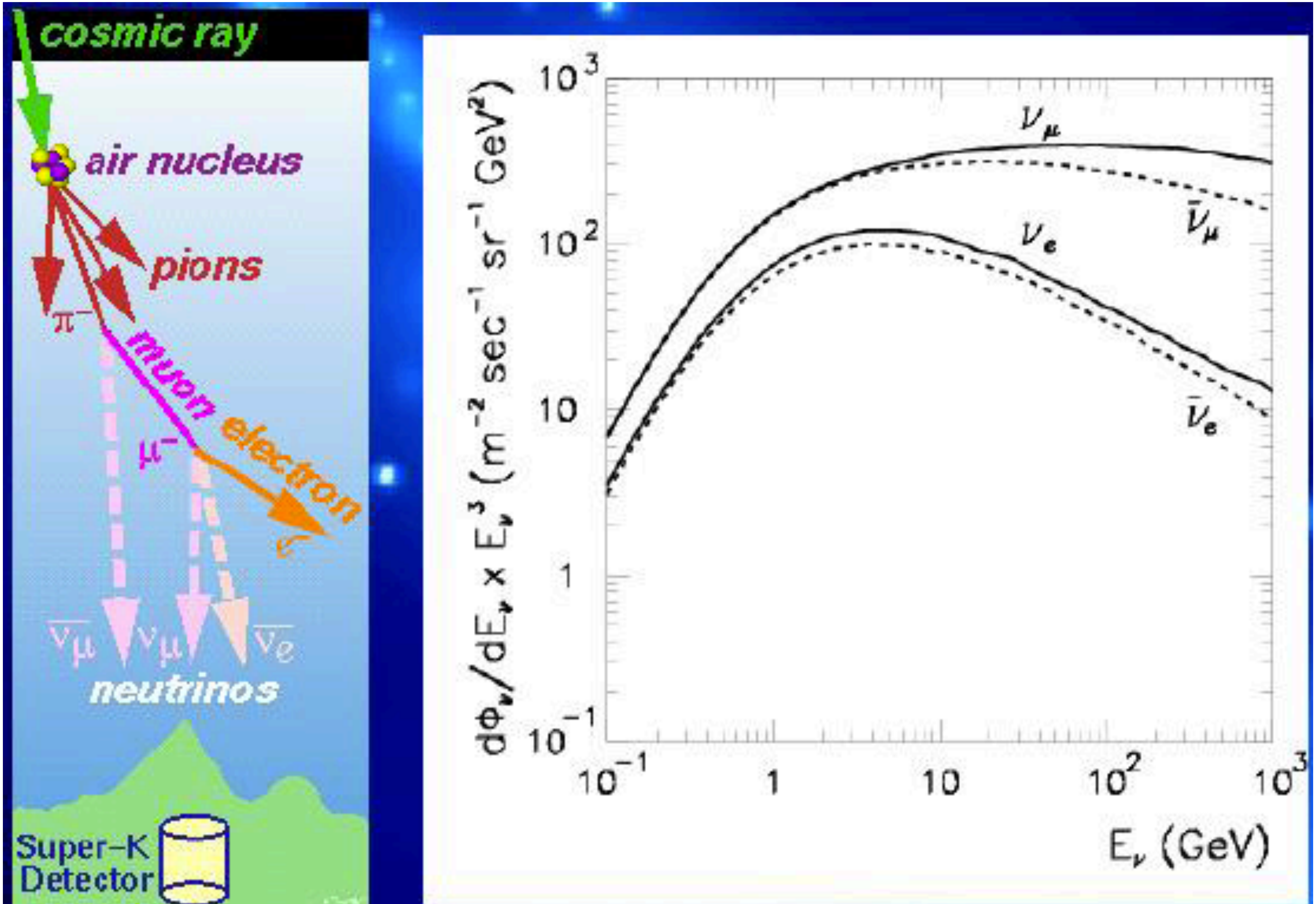
Super-Kamiokande, Soudan2, IMB,...



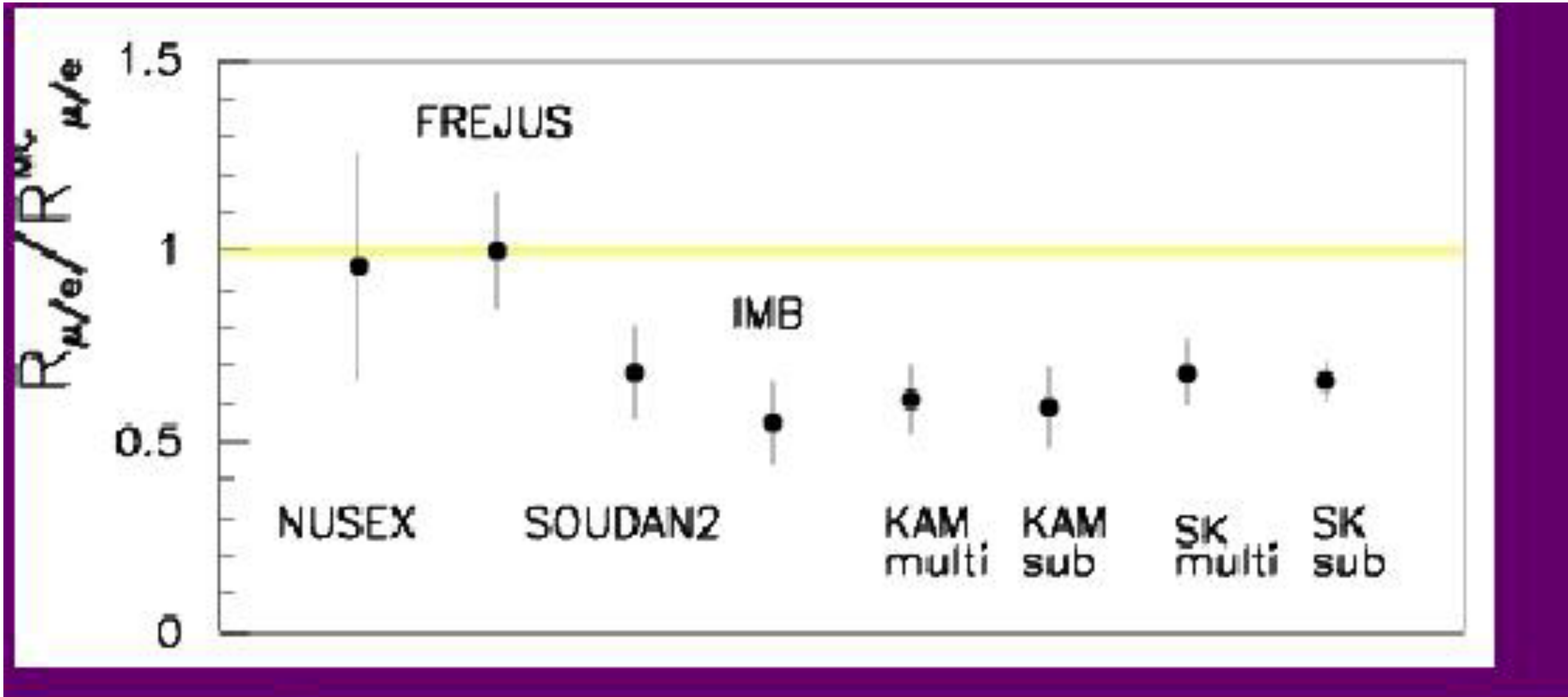
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

Atmospheric Neutrino -Fluxes



Total Rates



$$R_{\mu/e}/R^{theo}_{\mu/e} = (\nu_\mu / \nu_e)^{exp}/(\nu_\mu / \nu_e)^{theo}$$

uncertainty in fluxes 30 % uncertainty in ratios 5 %

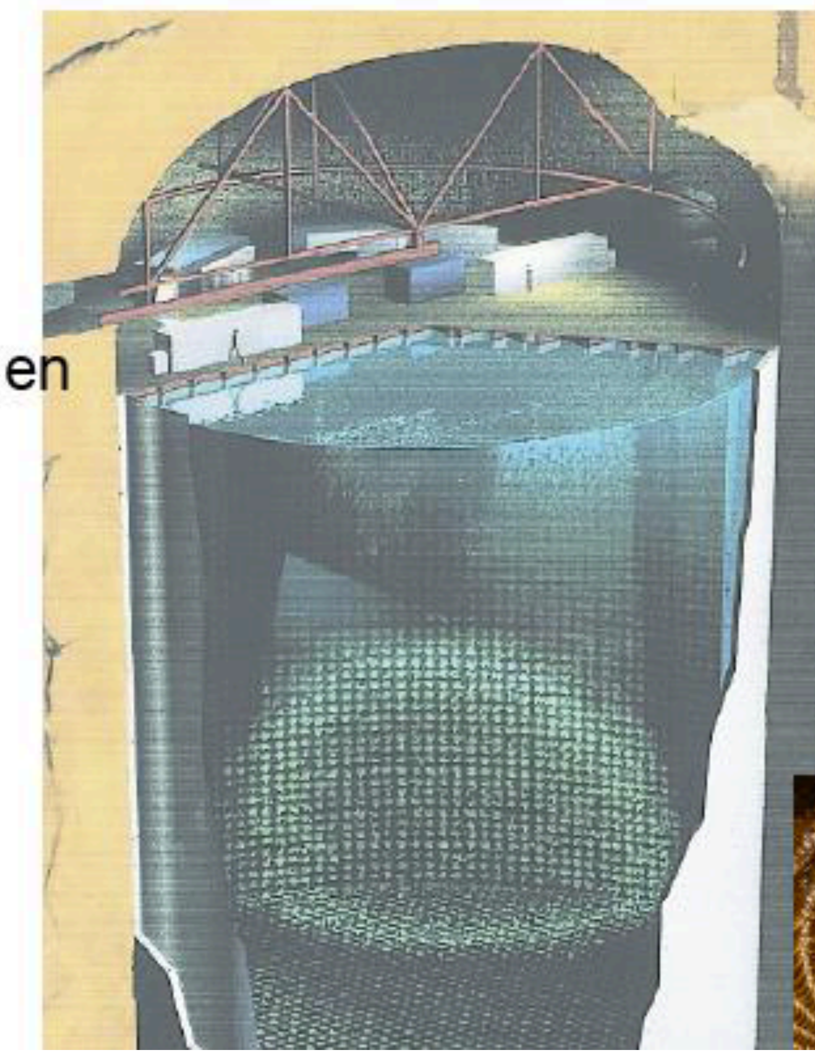
Super-Kamiokande Detector

Super-Kamiokande

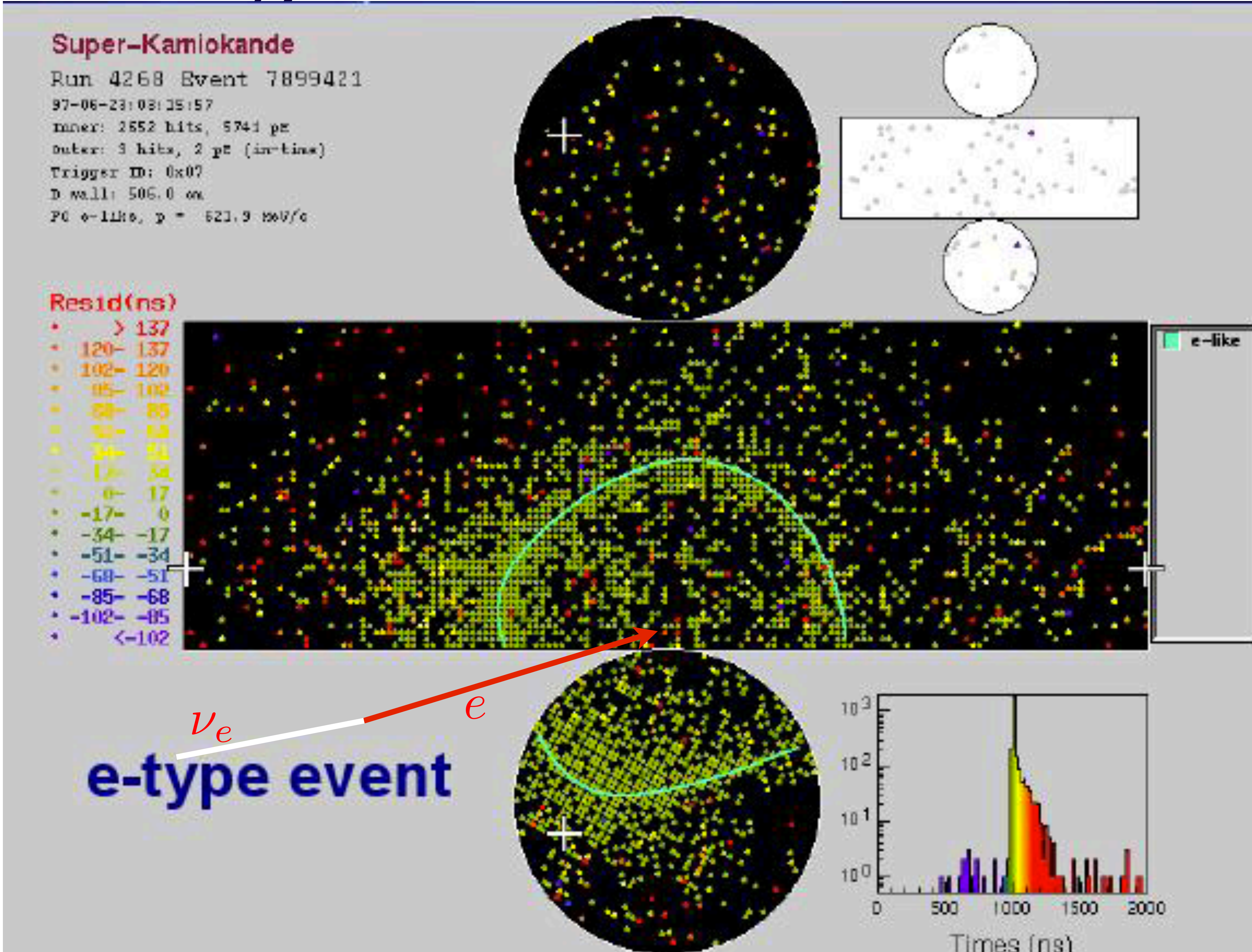
Kamioka-Mozumi zinc mine
1 km (2700 meters-water-equiv.) rock overburden

Water Čerenkov detector
 50 ktons (22.5 ktons fiducial)

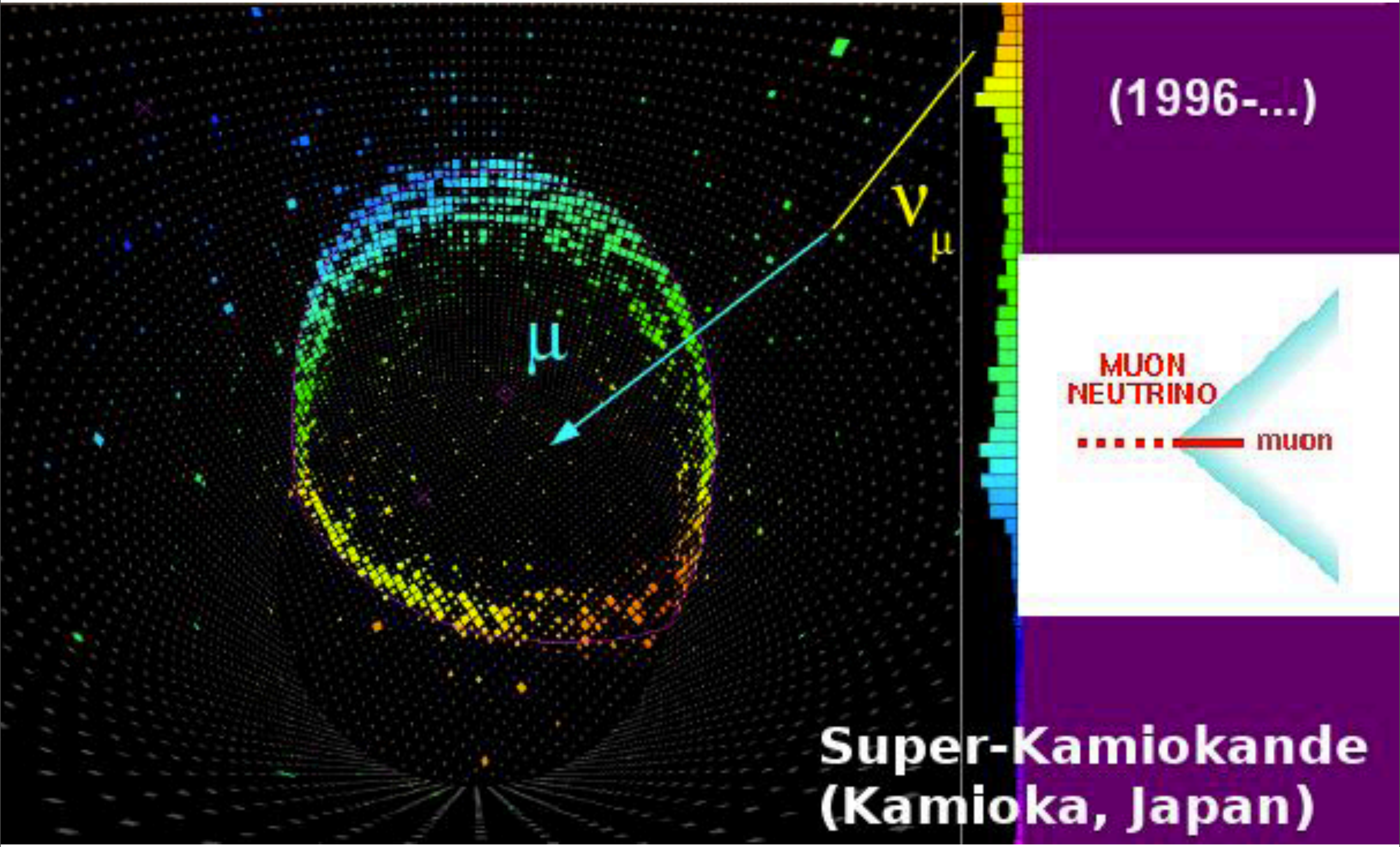
Instrumented with
 50-cm PMTs in Inner Detector (ID)
 20-cm PMTs in Outer Detector (OD)



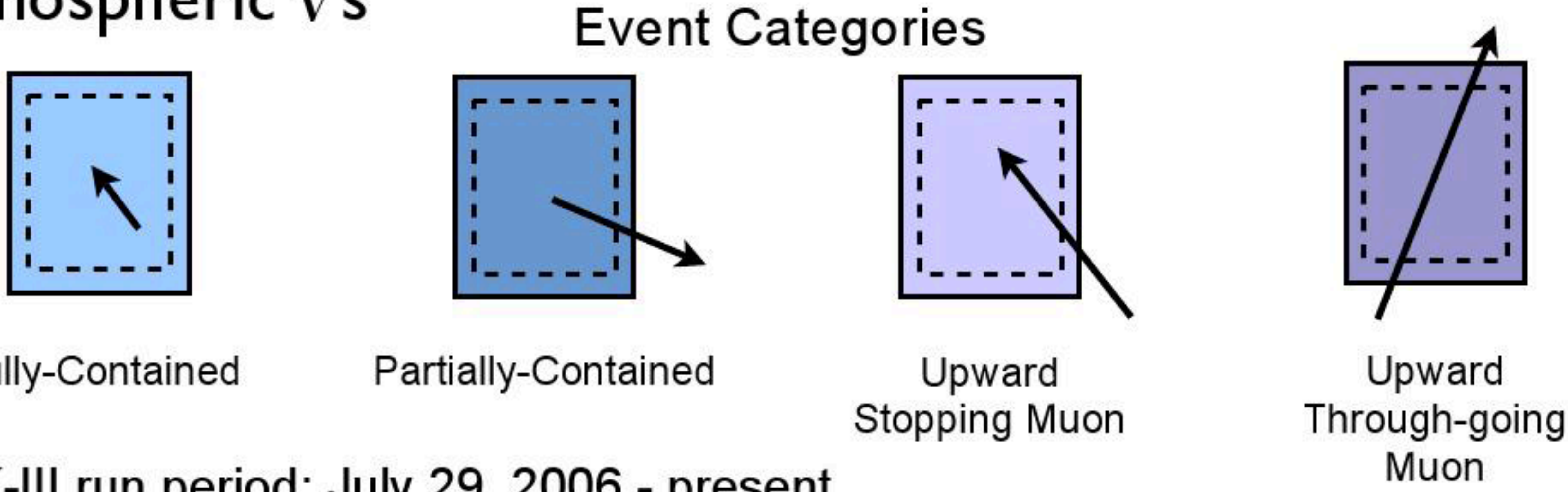
Types of Events



Types of Events



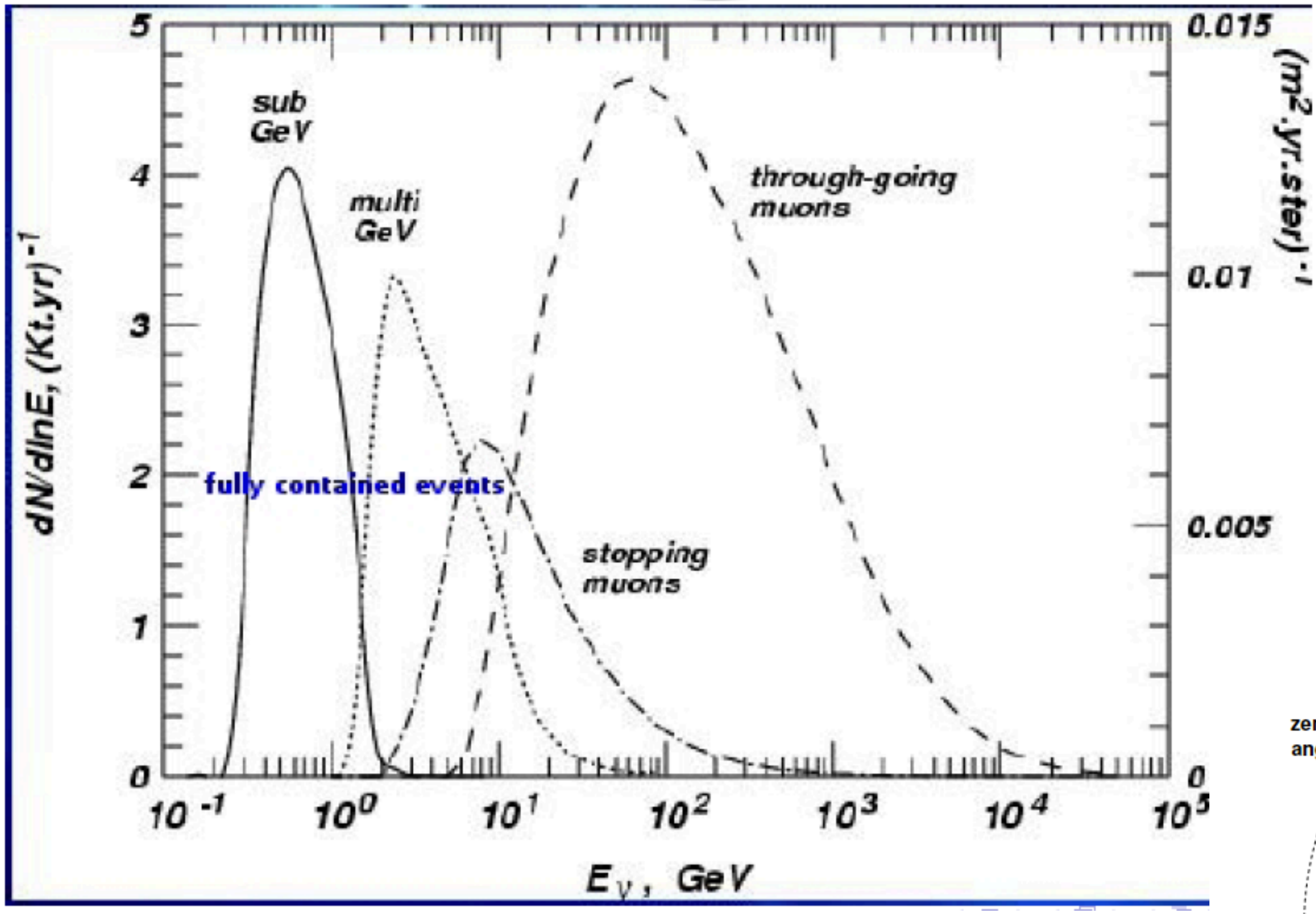
Atmospheric ν's



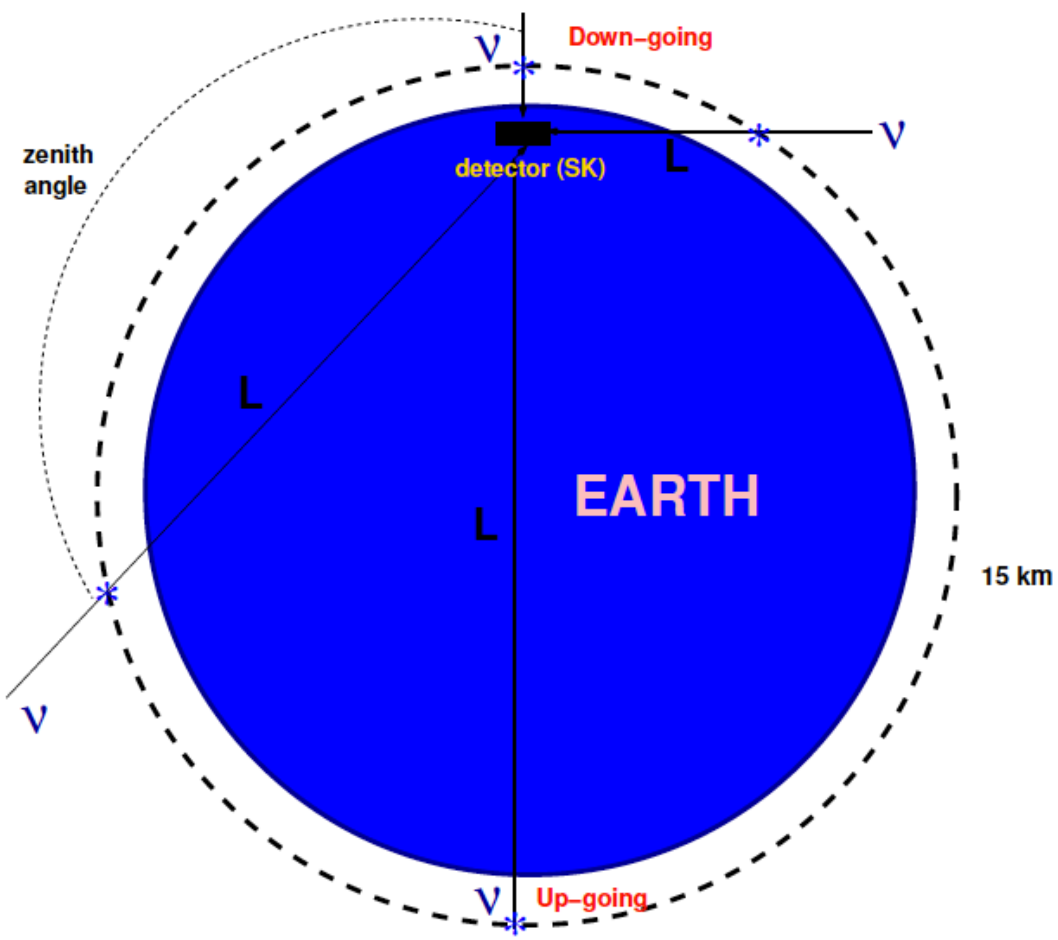
SK-III run period: July 29, 2006 - present

Event Category	Event Rate (events/day)		
	SK-I	SK-II	SK-III (Preliminary)
Fully Contained (FC)	8.18 ± 0.07	8.22 ± 0.10	8.31 ± 0.22
Partially Contained (PC)	0.61 ± 0.02	0.54 ± 0.03	0.57 ± 0.06
Upward-stopping μ (Upstop)	0.25 ± 0.01	0.28 ± 0.02	0.24 ± 0.03
Upward-thrugoing μ (Upthru)	1.12 ± 0.03	1.07 ± 0.04	1.11 ± 0.06

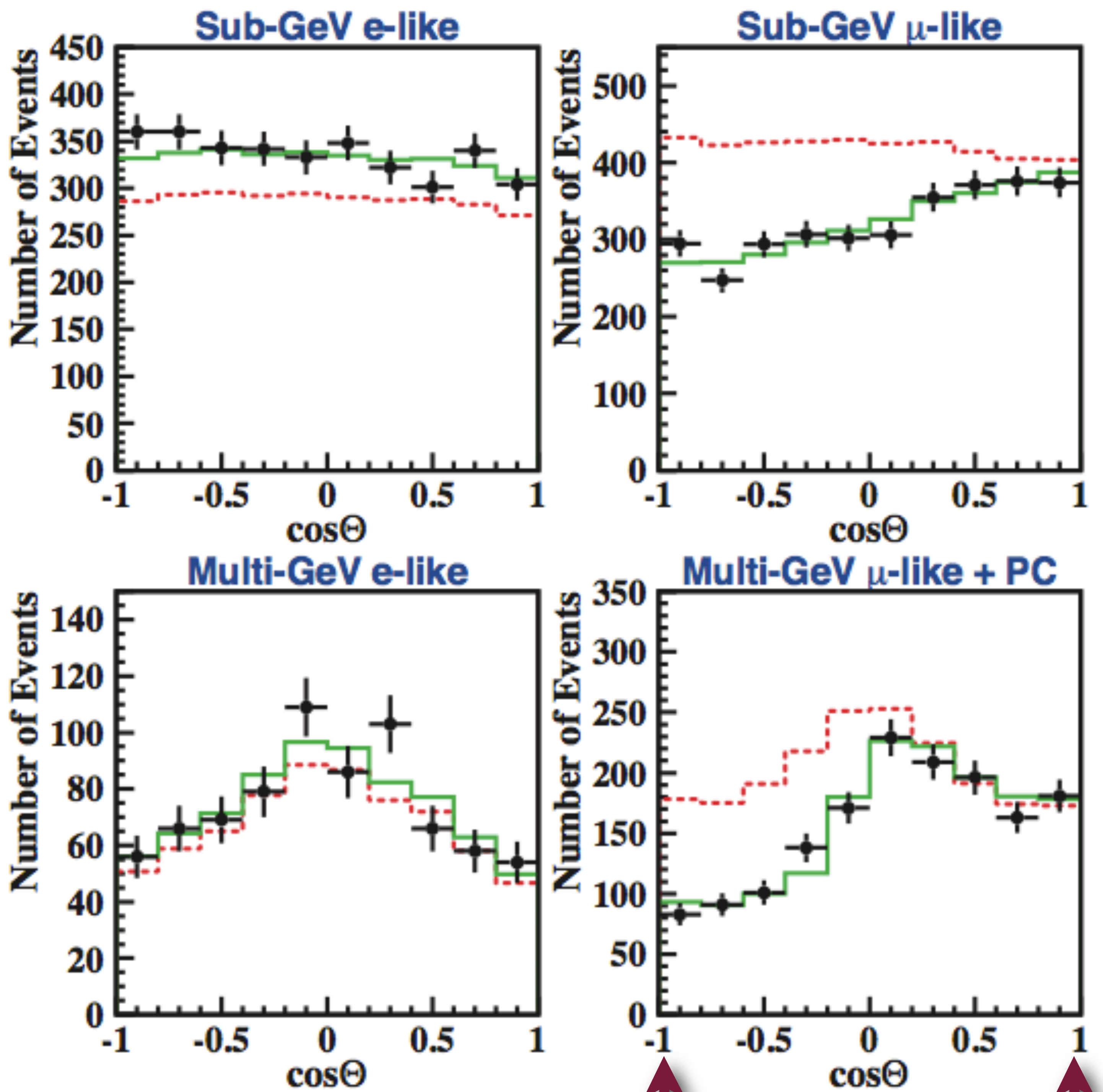
Atmospheric Neutrinos



Super-Kamiokande



Atmospheric Neutrinos

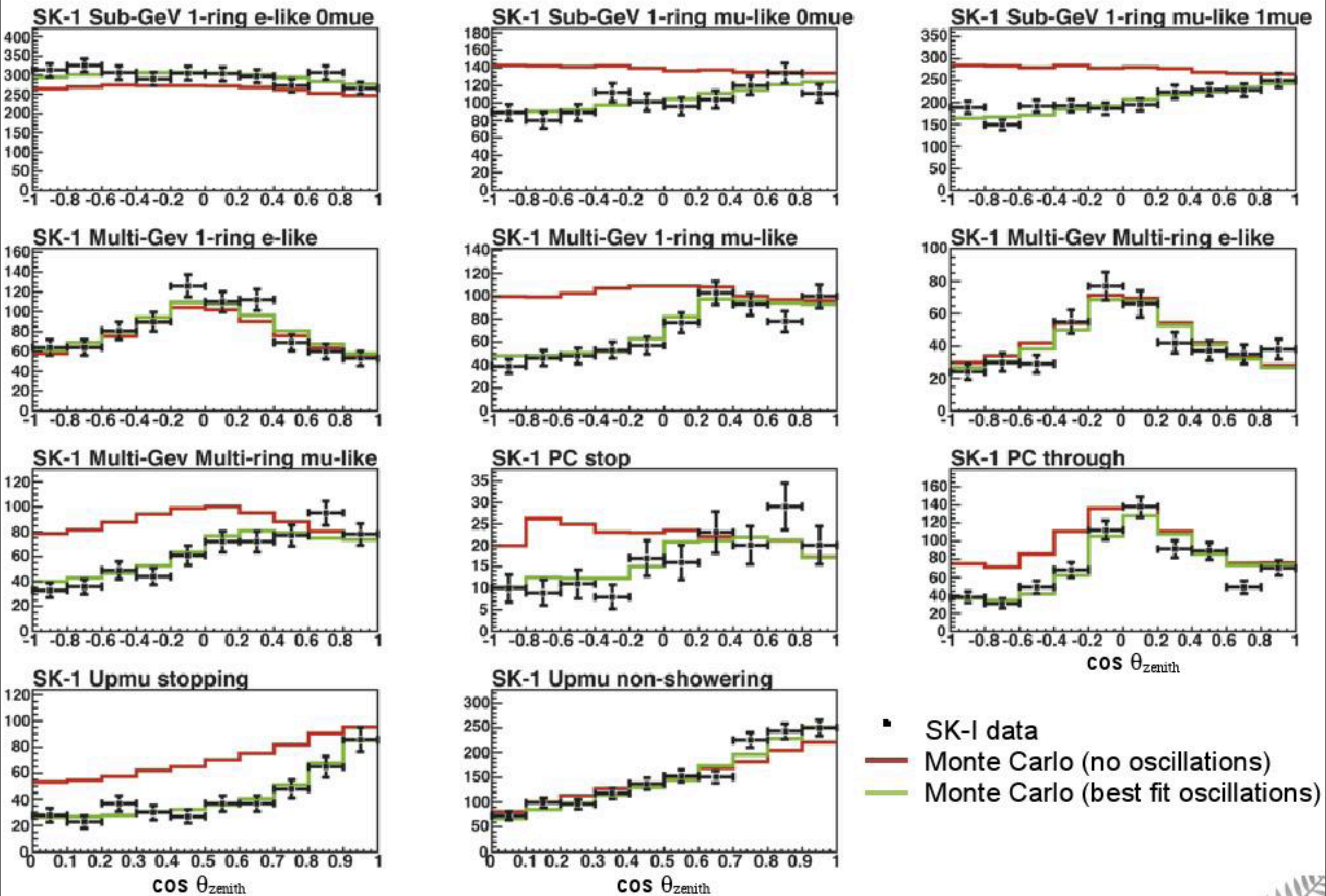


Super-Kamiokande

up going

down going

Zenith Angle Analysis: SK-I + SK-II



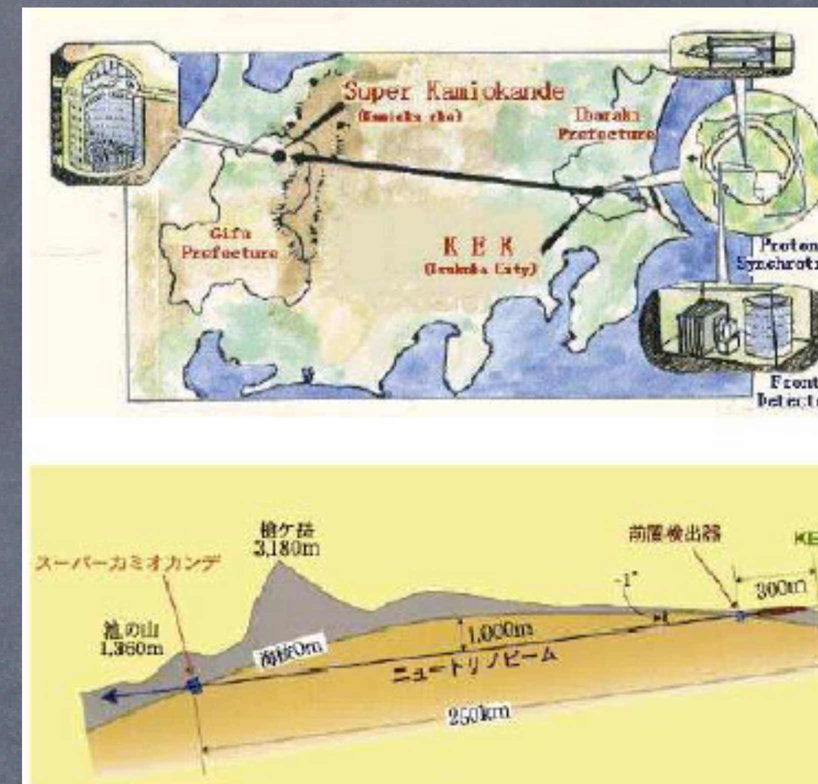
Accelerator Neutrinos

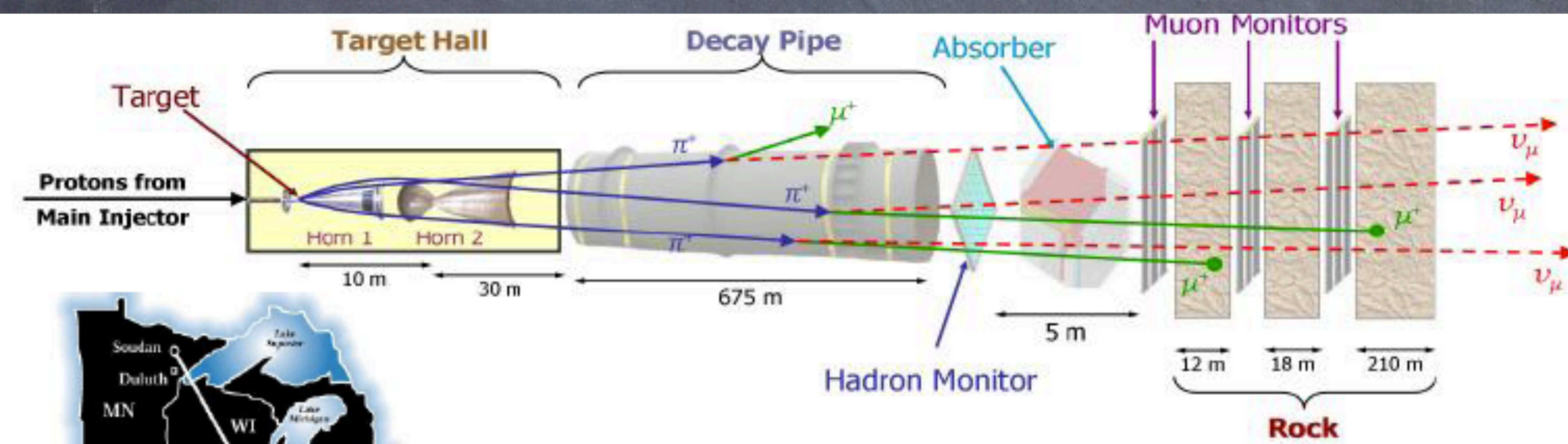
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

disappearance experiments

K2K : Japan
L = 250 km

$\nu_\mu \rightarrow \nu_\mu$





MINOS : USA
L = 735 km

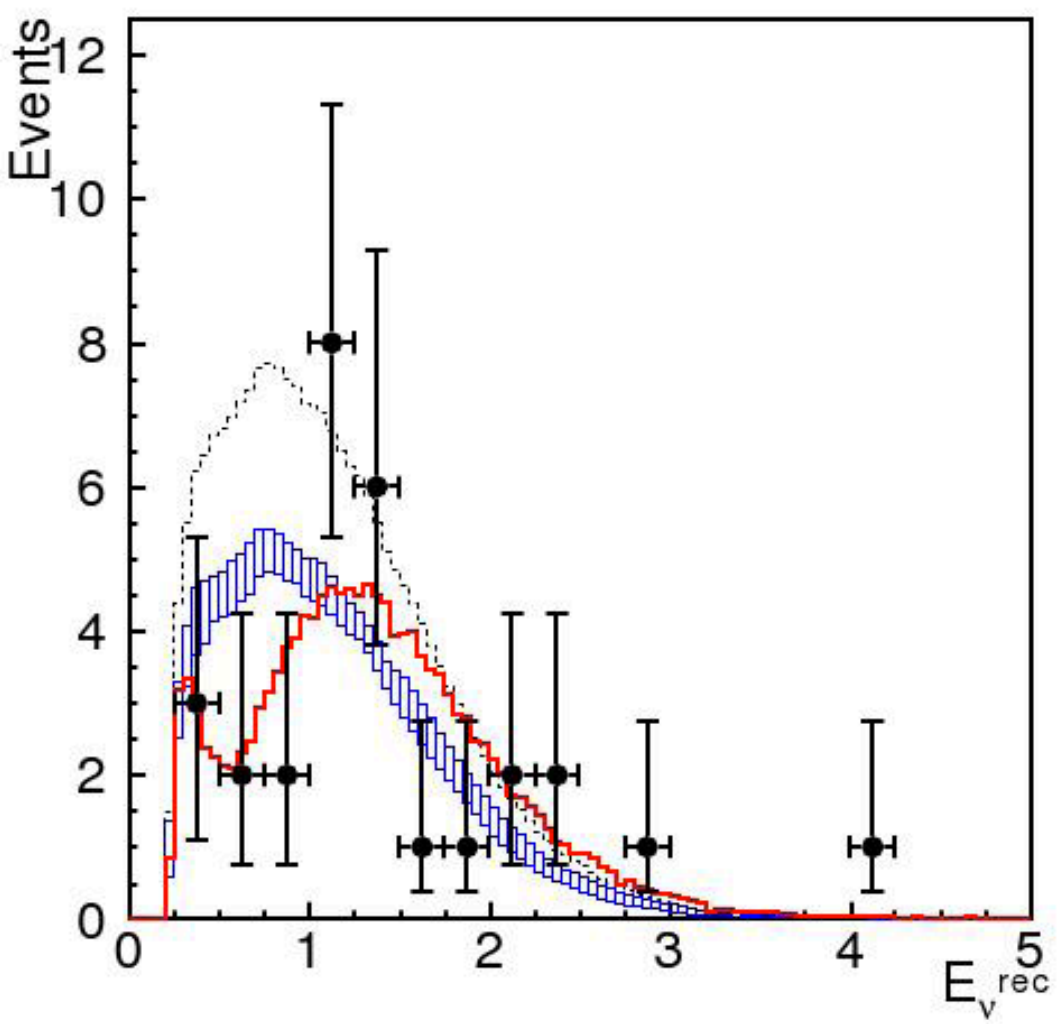
Accelerator Neutrinos

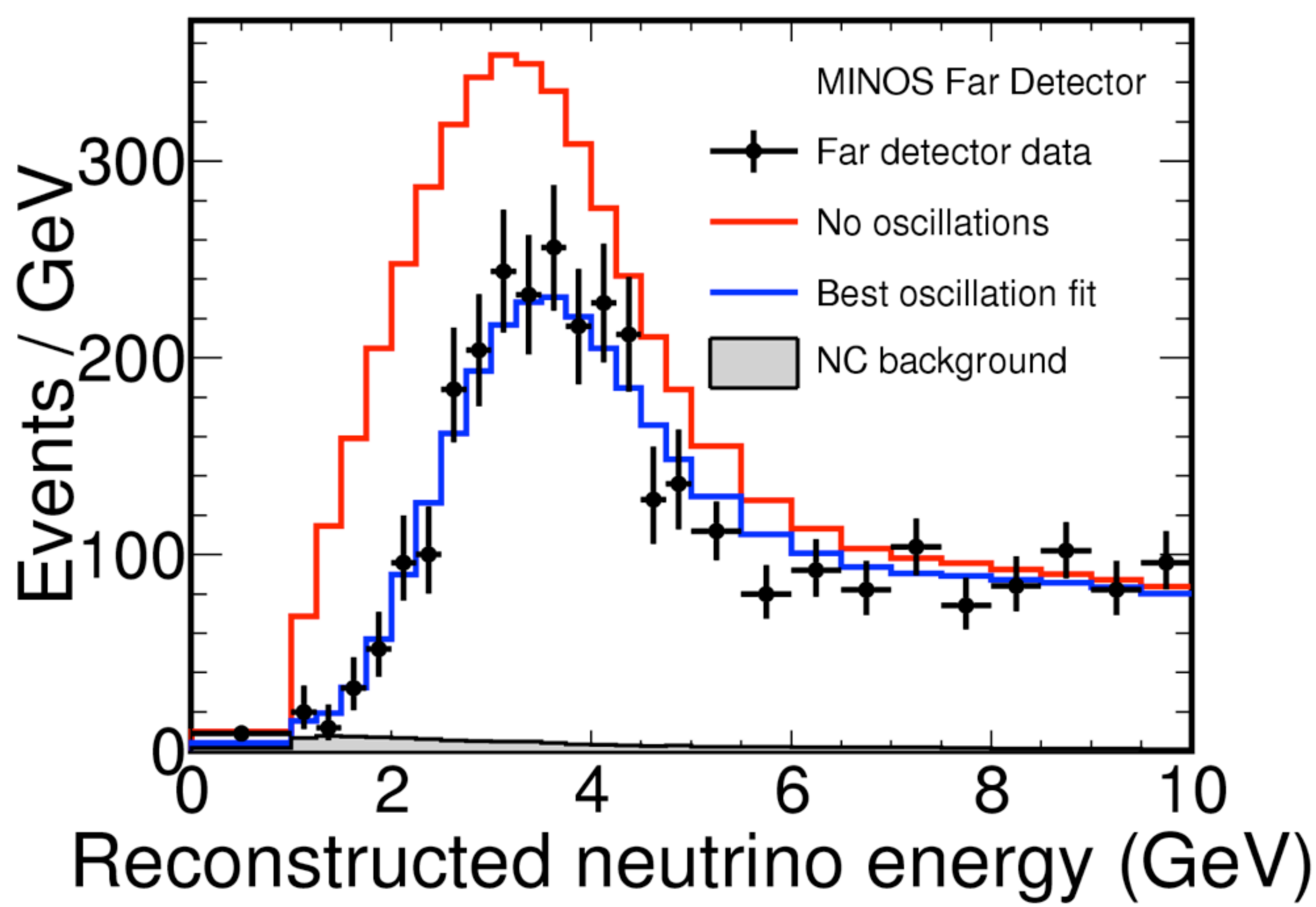
$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\nu_\mu \rightarrow \nu_\mu$

K2K:

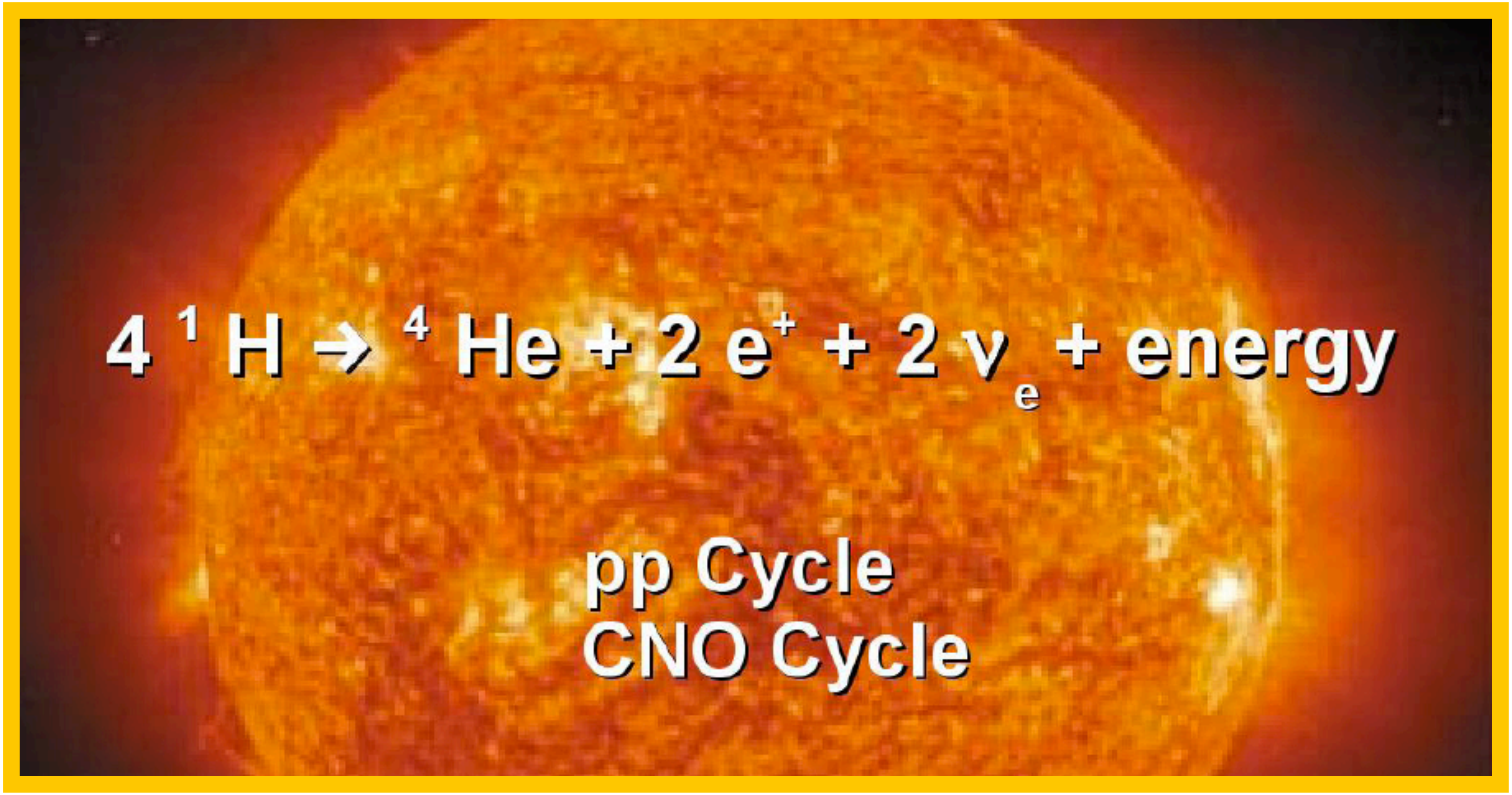
MINOS :

Expected: $80.1^{+6.2}_{-5.4}$ events Observed: 56 events Probability $< 1\%$



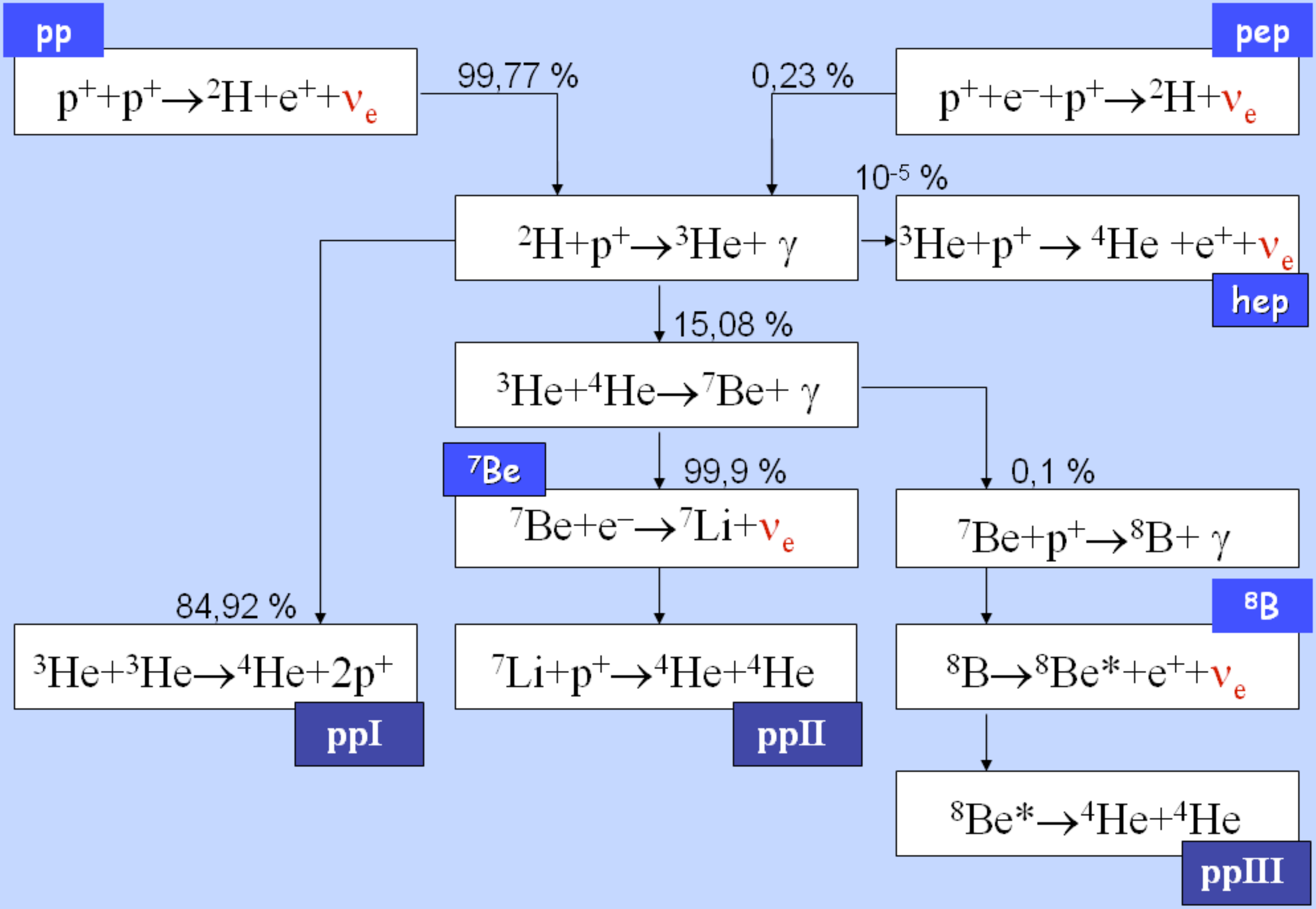


Solar Neutrinos

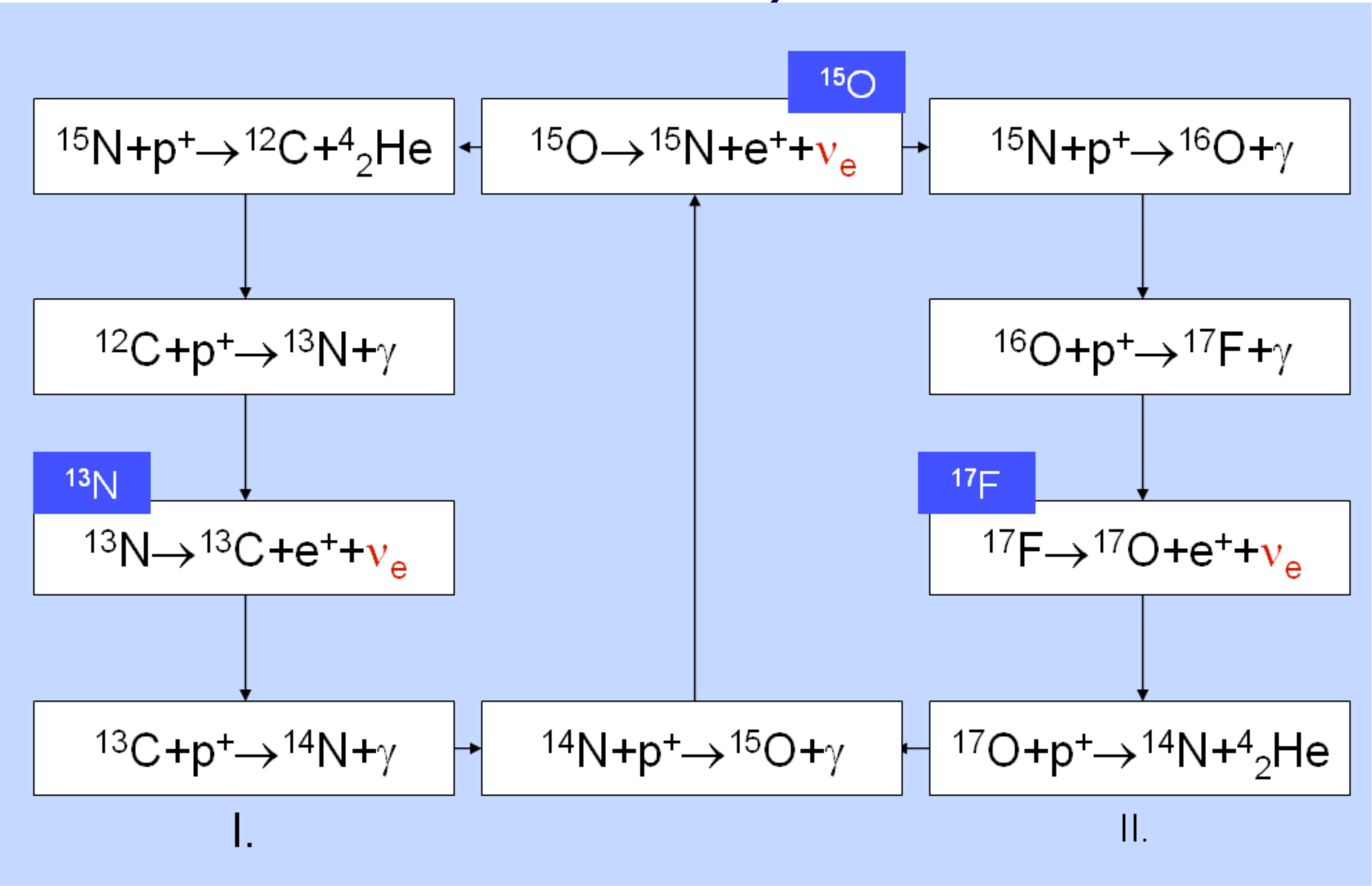


Only electron neutrinos are produced in the Sun

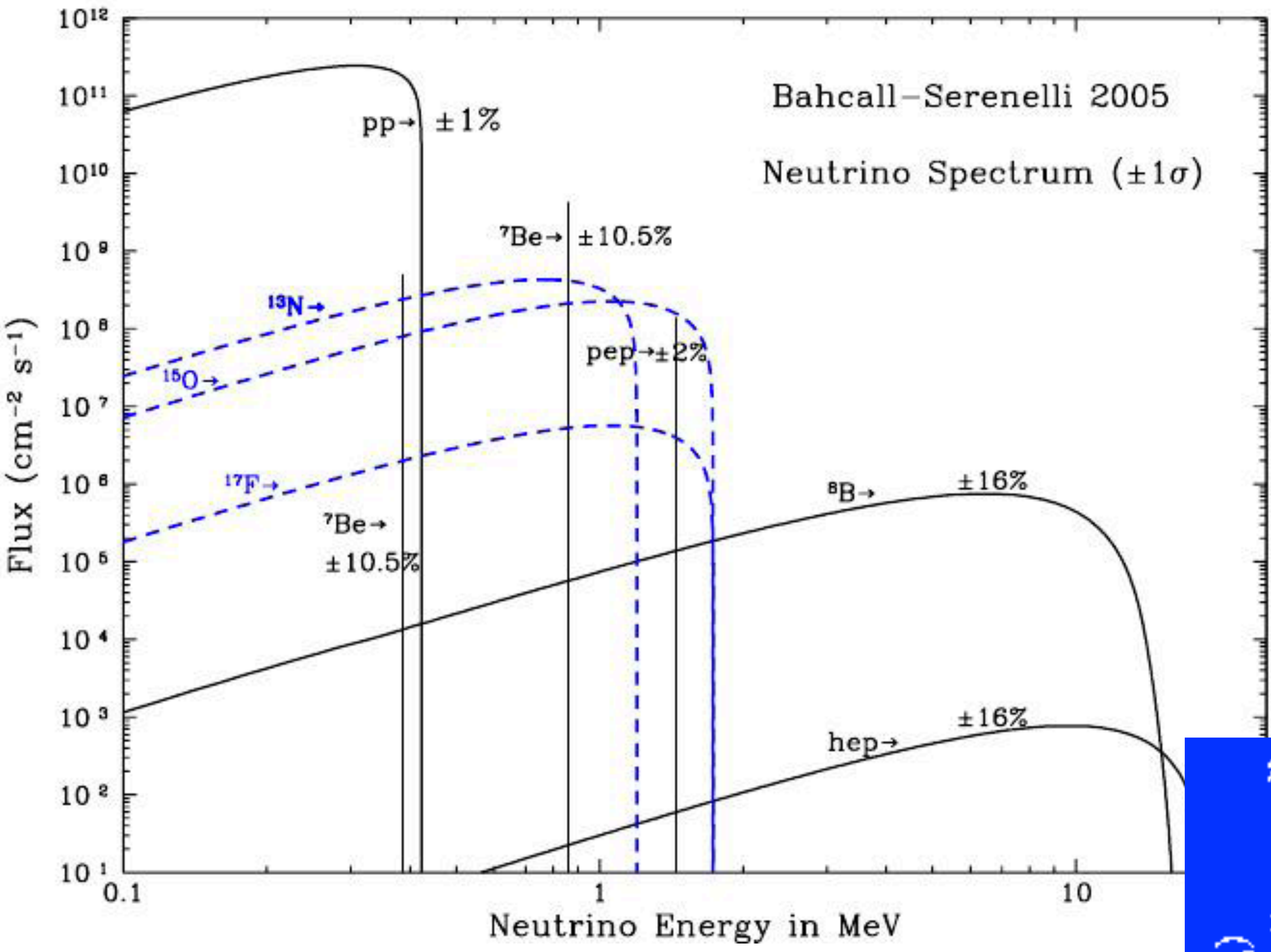
pp- cycle

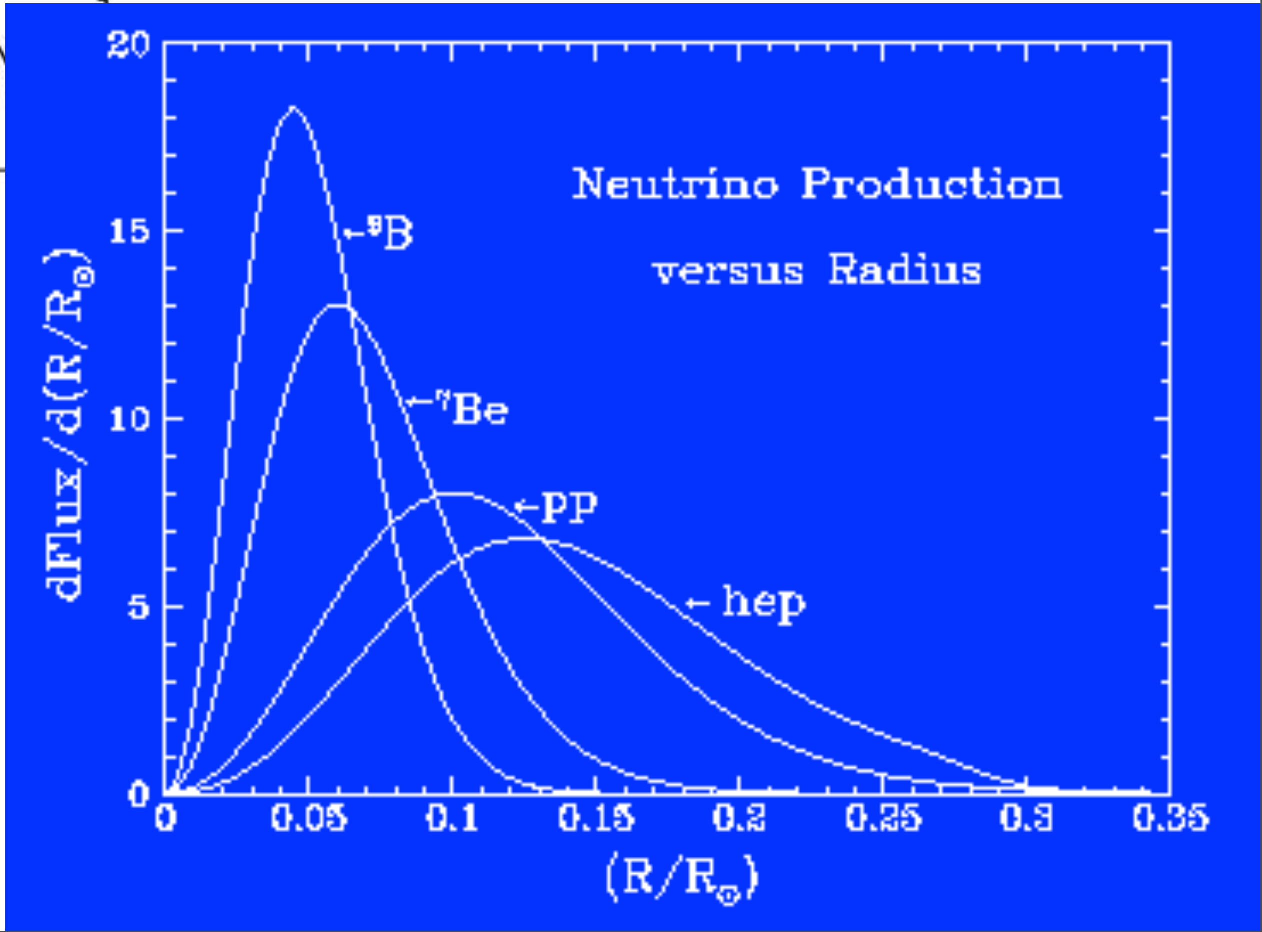

pp
$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$
99,77 %
pep
$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$
0,23 %
$^2H + p^+ \rightarrow {}^3He + \gamma$
10-5 %
$^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$
hep
15,08 %
$^3He + {}^4He \rightarrow {}^7Be + \gamma$
99,9 %
7Be
$^7Be + e^- \rightarrow {}^7Li + \nu_e$
0,1 %
$^7Be + p^+ \rightarrow {}^8B + \gamma$
84,92 %
$^3He + {}^3He \rightarrow {}^4He + 2p^+$
ppI
$^7Li + p^+ \rightarrow {}^4He + {}^4He$
ppII
8B
$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$
$^8Be^* \rightarrow {}^4He + {}^4He$
ppIII

CNO- cycle


^{15}O
$^{15}N + p^+ \rightarrow {}^{12}C + {}^4_2He$
$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$
$^{15}N + p^+ \rightarrow {}^{16}O + \gamma$
$^{12}C + p^+ \rightarrow {}^{13}N + \gamma$
$^{16}O + p^+ \rightarrow {}^{17}F + \gamma$
^{13}N
^{17}F
$^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$
$^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$
$^{13}C + p^+ \rightarrow {}^{14}N + \gamma$
$^{14}N + p^+ \rightarrow {}^{15}O + \gamma$
$^{17}O + p^+ \rightarrow {}^{14}N + {}^4_2He$
I.
II.

Standard Solar Model





Homestake (1968-94)

construction years

1965-67

Homestake Gold mine
Lead, South Dakota, USA
1500 m underground

tank w/ 380,000 l of C_2Cl_4

Homestake (1968-94)

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

$E_{th} = 814$ keV

Charged Current

615 ton

± 1 neutrinos every 2 days

Gallium Experiments

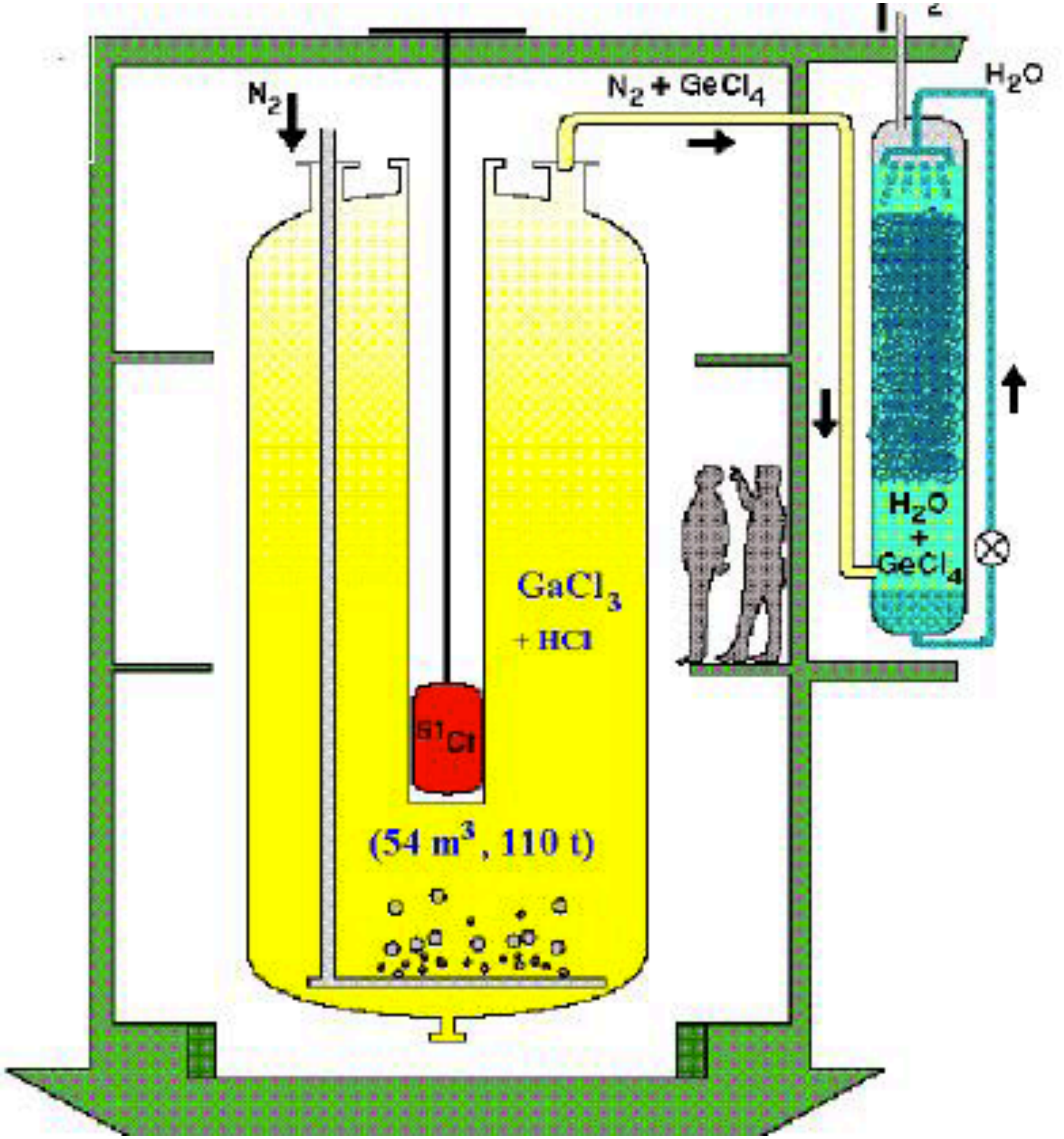
$$\nu_e + {}^{71}\text{Ga} \rightarrow e^- + {}^{71}\text{Ge}$$

E_{th} = 233 keV

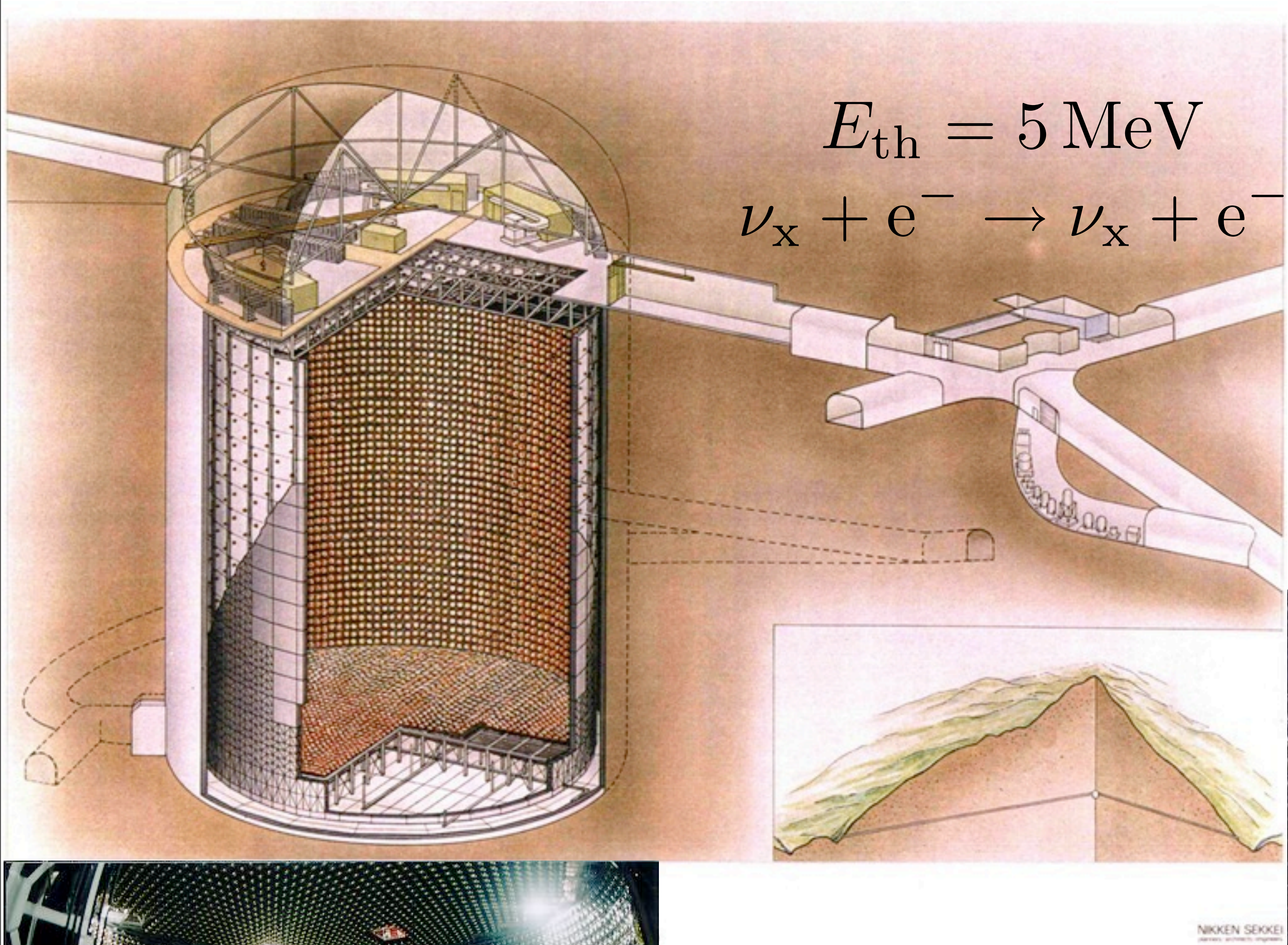
Charged Current

30 ton Ga
100 ton $GaCl_3$
10^{29} Ga nuclei

Gran Sasso, Italy



Super-K Experiment



$$E_{\mathrm{th}} = 5\,\mathrm{MeV}$$

$$\nu_{\mathrm{x}} + \mathrm{e}^- \rightarrow \nu_{\mathrm{x}} + \mathrm{e}^-$$

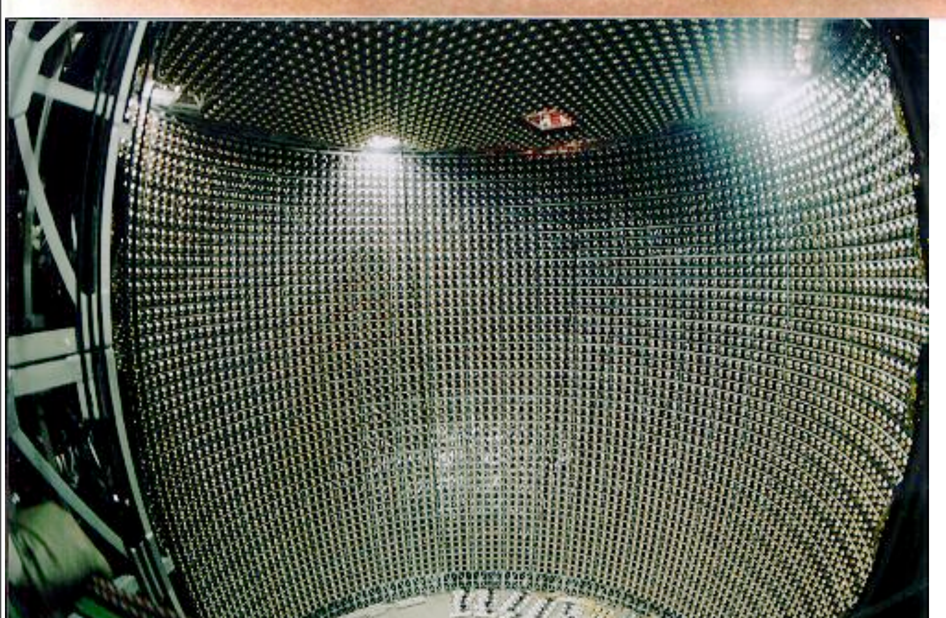
Detector:

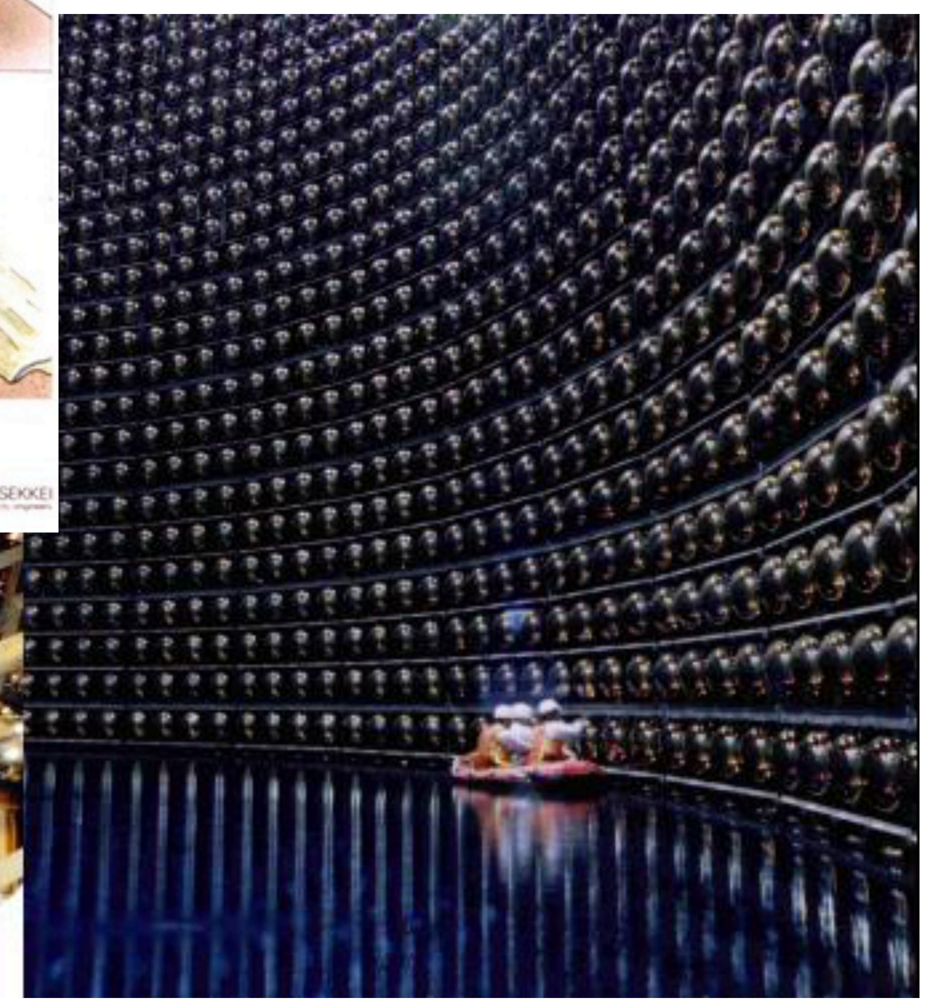
50,000 t of H_2O

11,200 PMTs

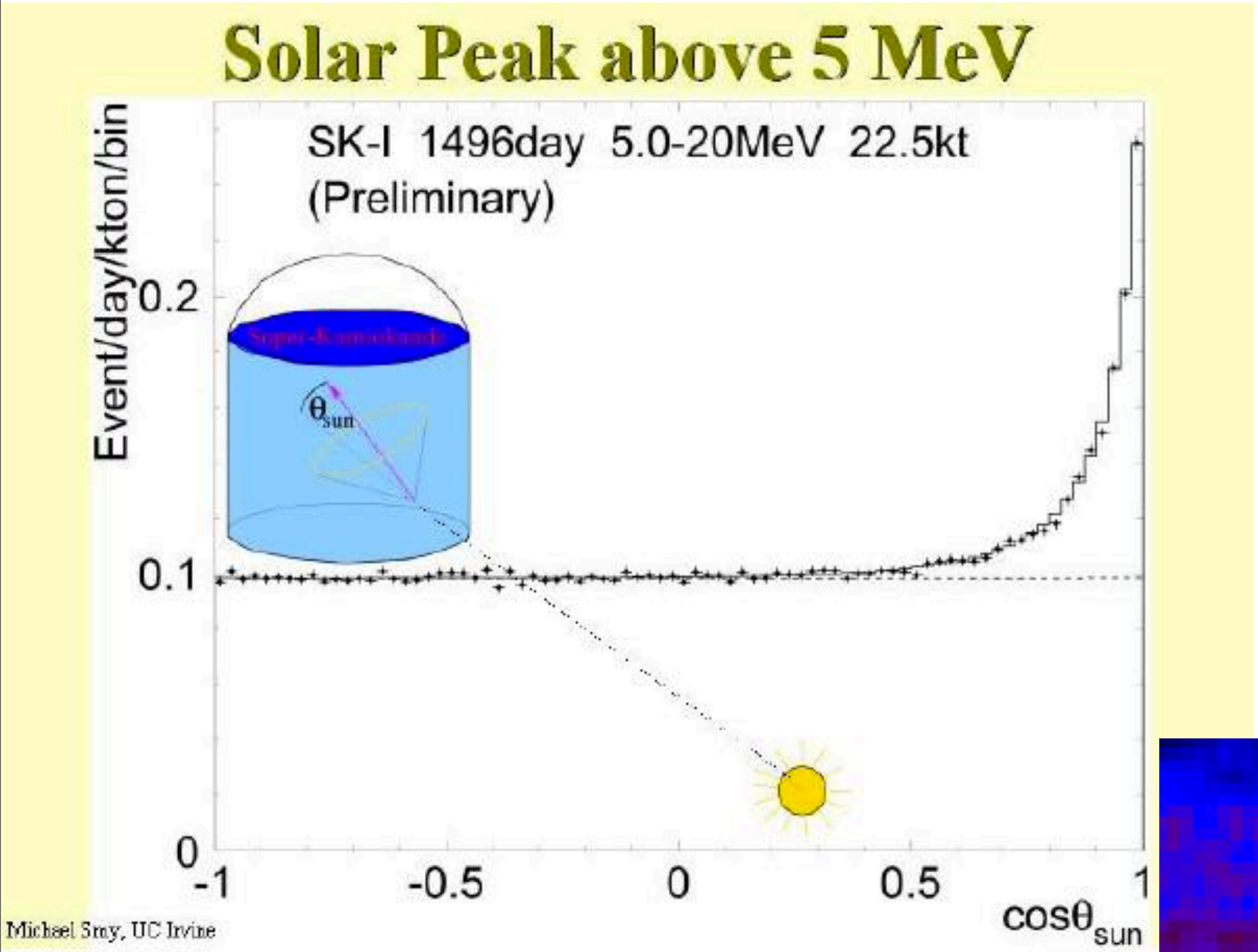
41.4 m height

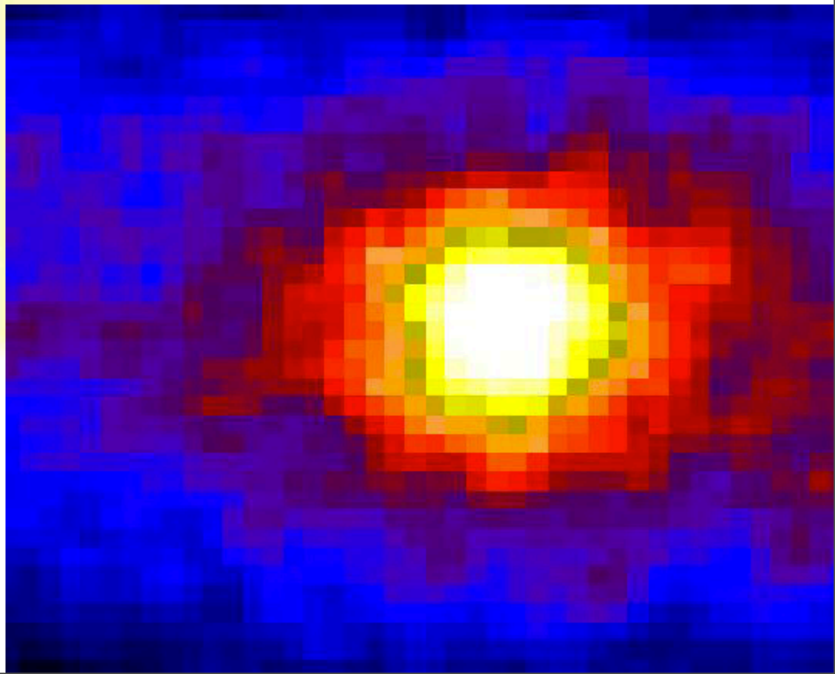
39,3 m diameter



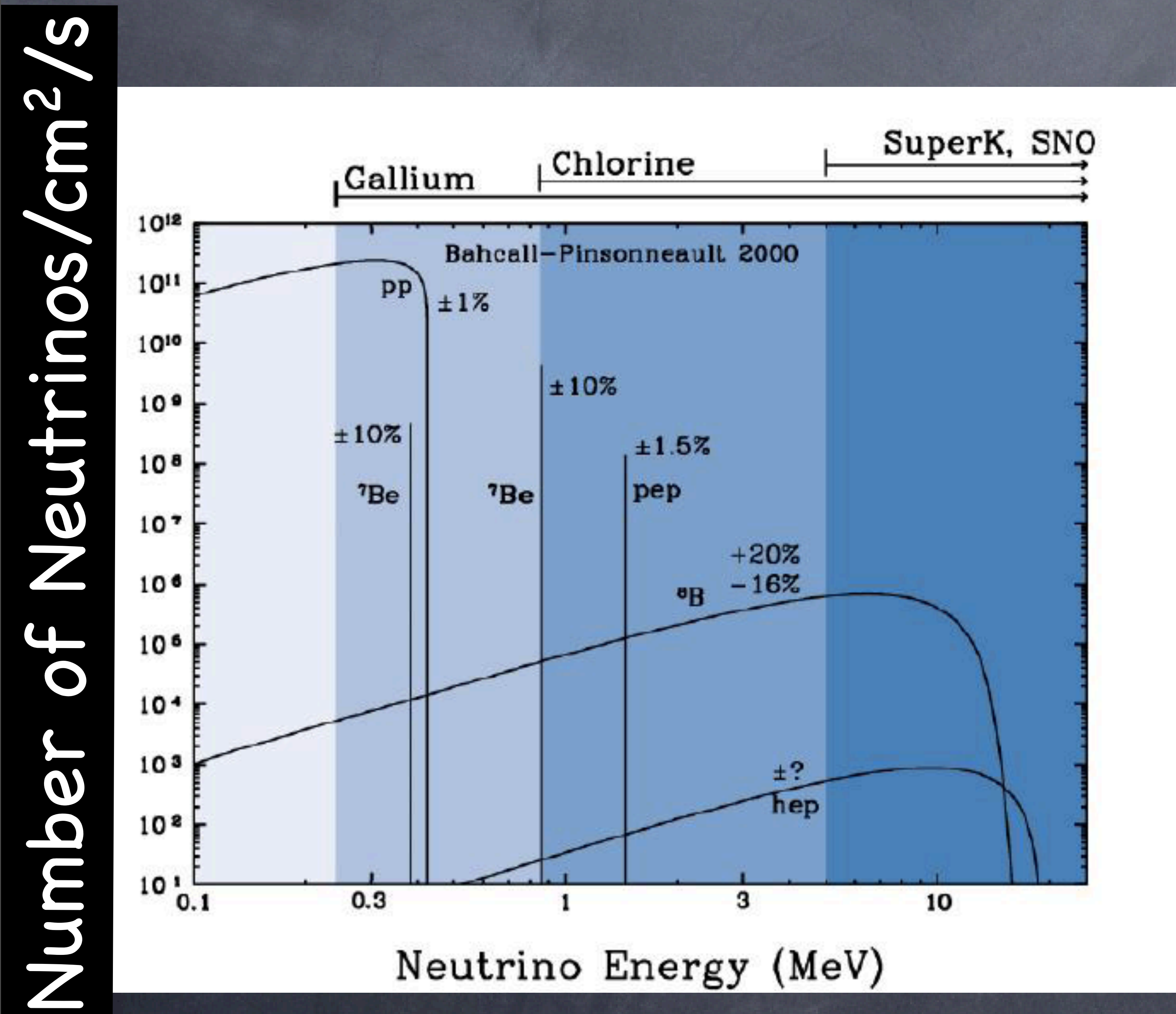


Super-K Experiment





Solar Neutrinos



Reaction	Abbr.	Flux ($cm^{-2}\ s^{-1}$)
$pp \to d\, e^+ \nu$	pp	$5.97(1 \pm 0.006) \times 10^{10}$
$pe^- p \to d\, \nu$	pep	$1.41(1 \pm 0.011) \times 10^{8}$
$^3He\, p \to {}^4He\, e^+ \nu$	hep	$7.90(1 \pm 0.15) \times 10^{3}$
$^7Be\, e^- \to {}^7Li\, \nu + (\gamma)$	^7Be	$5.07(1 \pm 0.06) \times 10^{9}$
$^8B \to {}^8Be^*\, e^+ \nu$	^8B	$5.94(1 \pm 0.11) \times 10^{6}$
$^{13}N \to {}^{13}C\, e^+ \nu$	^{13}N	$2.88(1 \pm 0.15) \times 10^{8}$
$^{15}O \to {}^{15}N\, e^+ \nu$	^{15}O	$2.15(1^{+0.17}_{-0.16}) \times 10^{8}$
$^{17}F \to {}^{17}O\, e^+ \nu$	^{17}F	$5.82(1^{+0.19}_{-0.17}) \times 10^{6}$

Standard Solar Model
BPS 08 (GS)

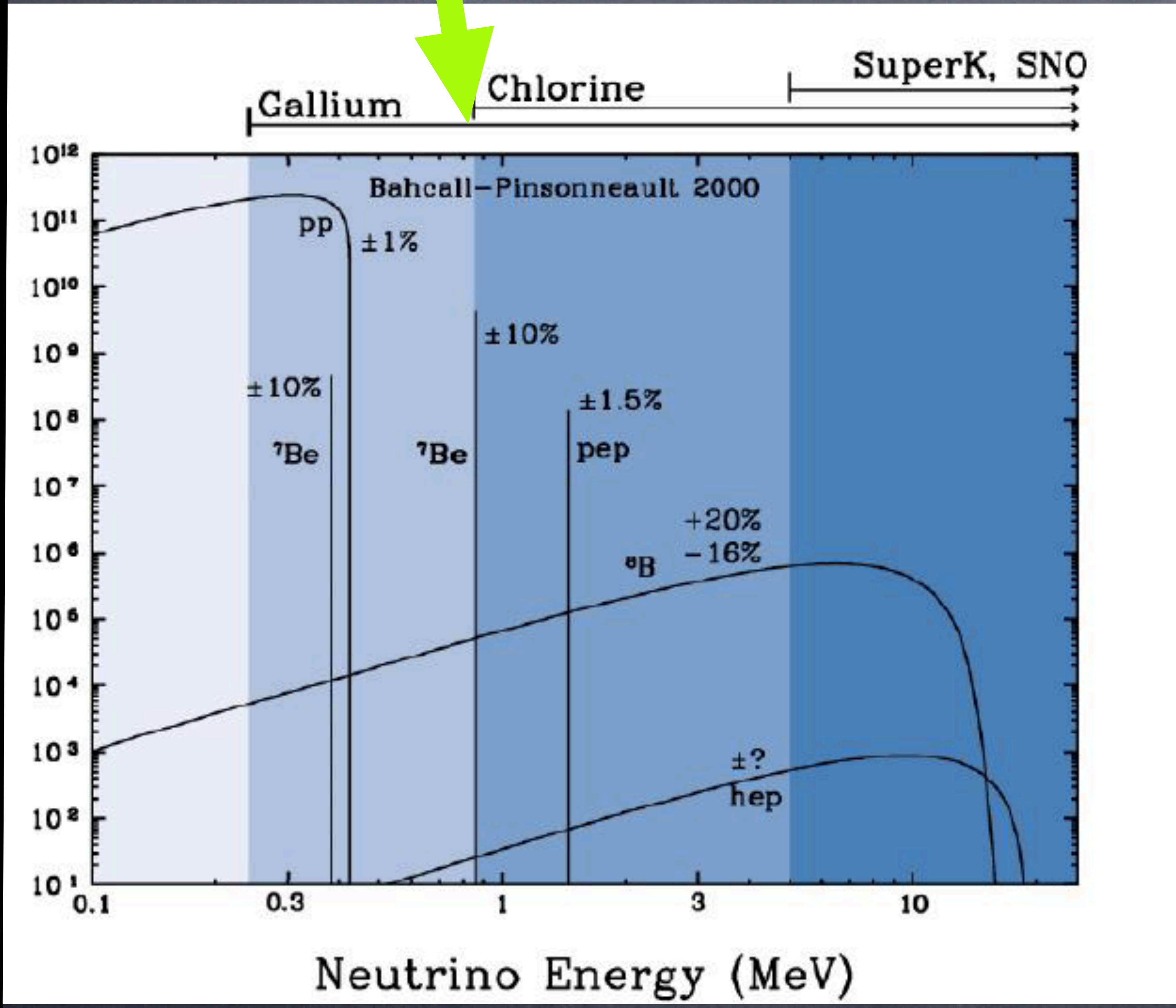
Solar Neutrinos

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

$814\,\mathrm{keV}$

Homestake (1968-1994)

Number of Neutrinos/cm²/s



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Standard Solar Model
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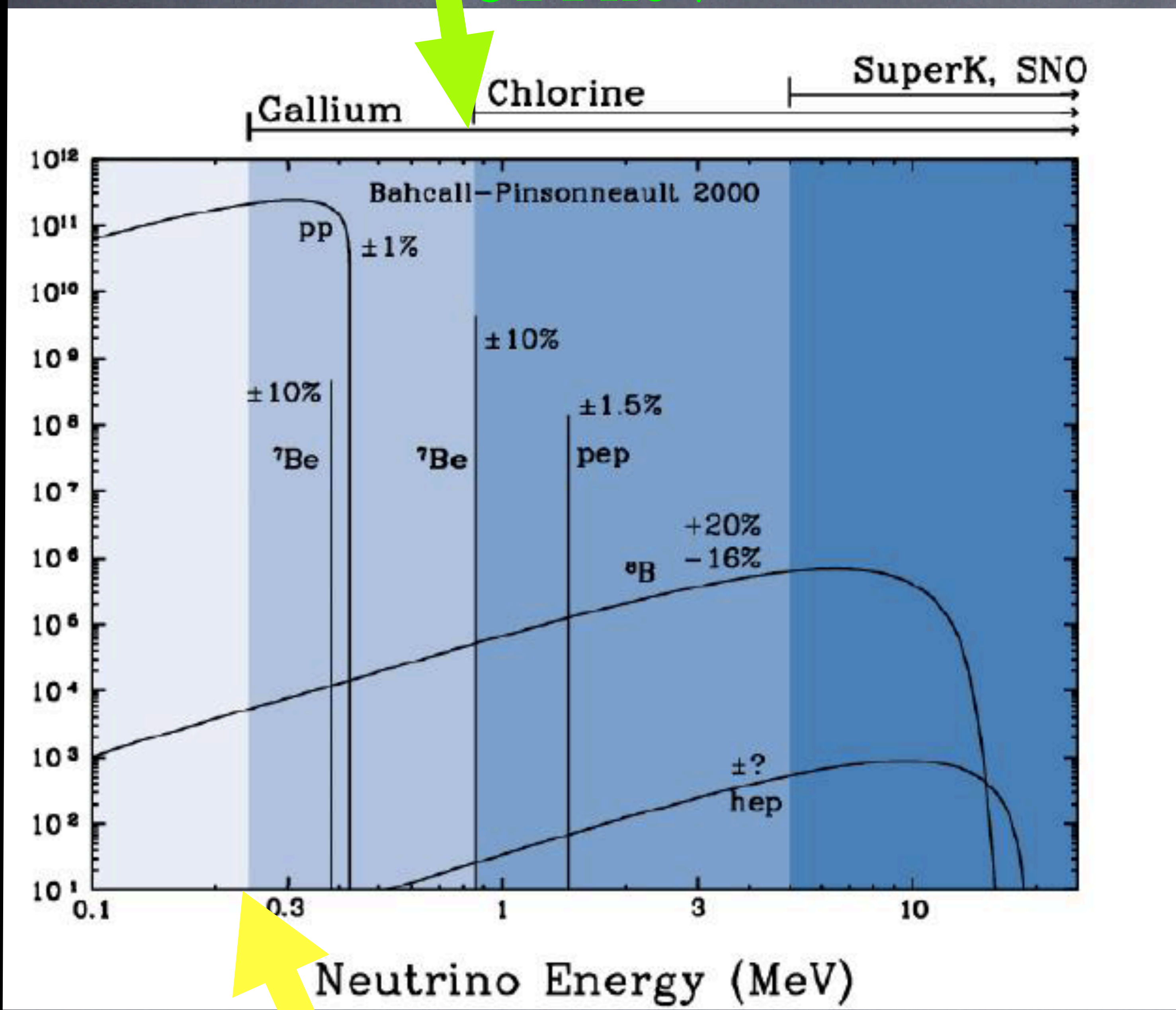

Reaction	Abbr.	Flux ($cm^{-2}\ s^{-1}$)
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Standard Solar Model
BPS 08 (GS)

233 keV

$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$

SAGE/GALLEX/GNO

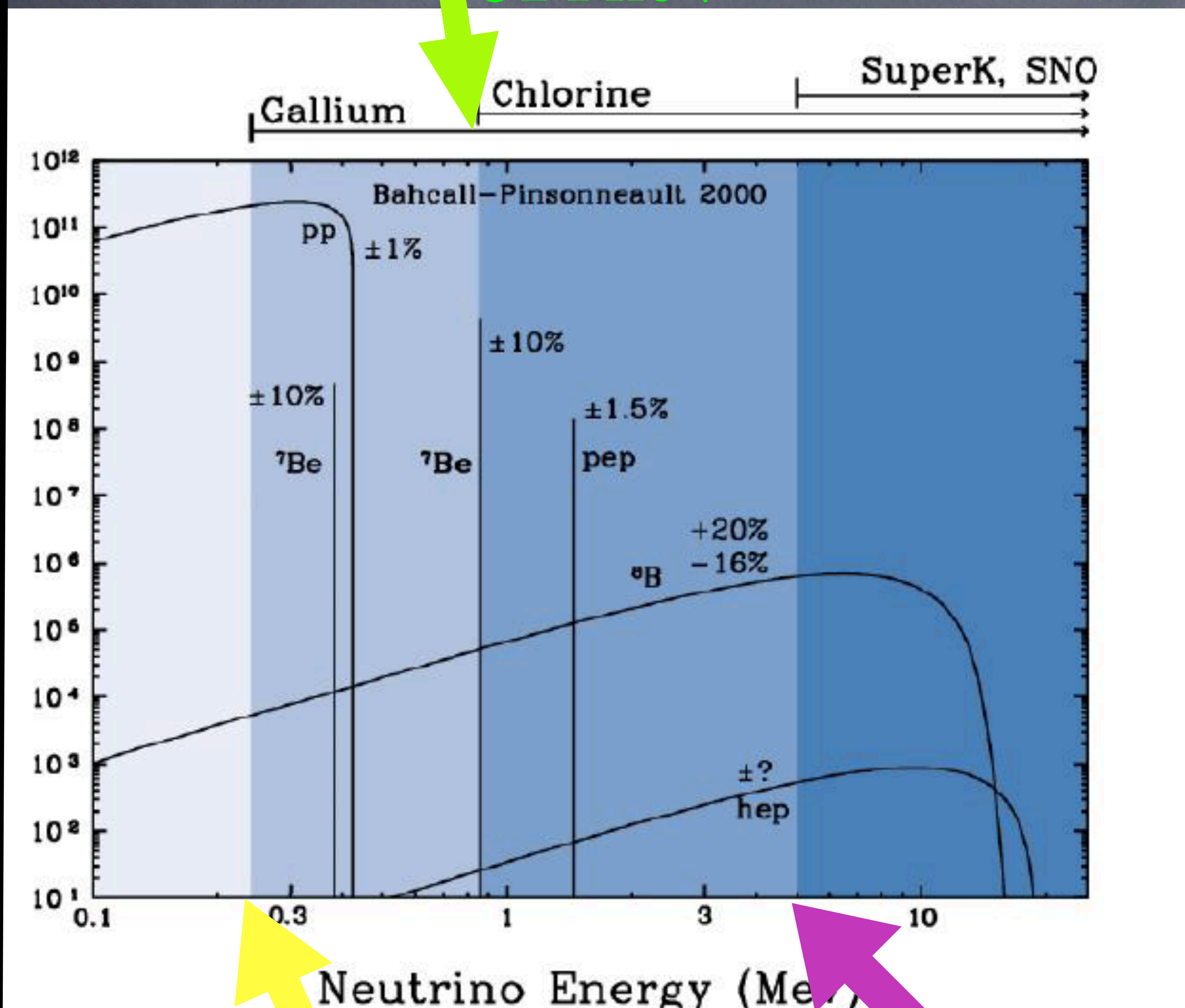
Solar Neutrinos

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

814 keV

Homestake (1968-1994)

Number of Neutrinos/cm²/s



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Standard Solar Model
BPS 08 (GS)

233 keV

$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$

SAGE/GALLEX/GNO

$\nu_x + e \rightarrow \nu_x + e^-$

SK, SNO

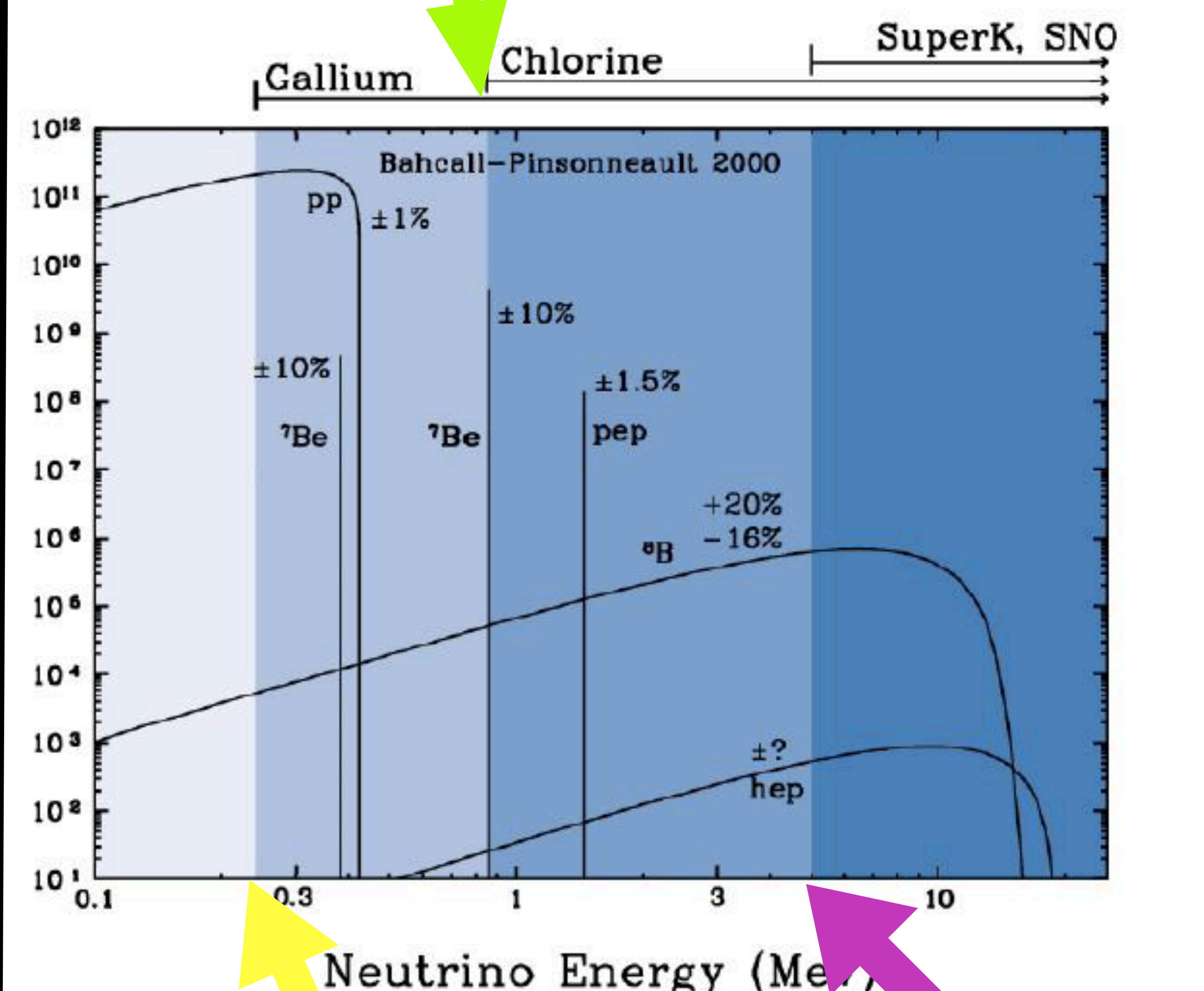
Solar Neutrinos

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

814 keV

Homestake (1968-1994)

Number of Neutrinos/cm²/s



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Standard Solar Model
BPS 08 (GS)

233 keV

$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$

SAGE/GALLEX/GNO

$\nu_x + e \rightarrow \nu_x + e$

SK, SNO

$\nu_e + d \rightarrow e^- + p + p$

$\nu_x + d \rightarrow \nu_x + p + n$

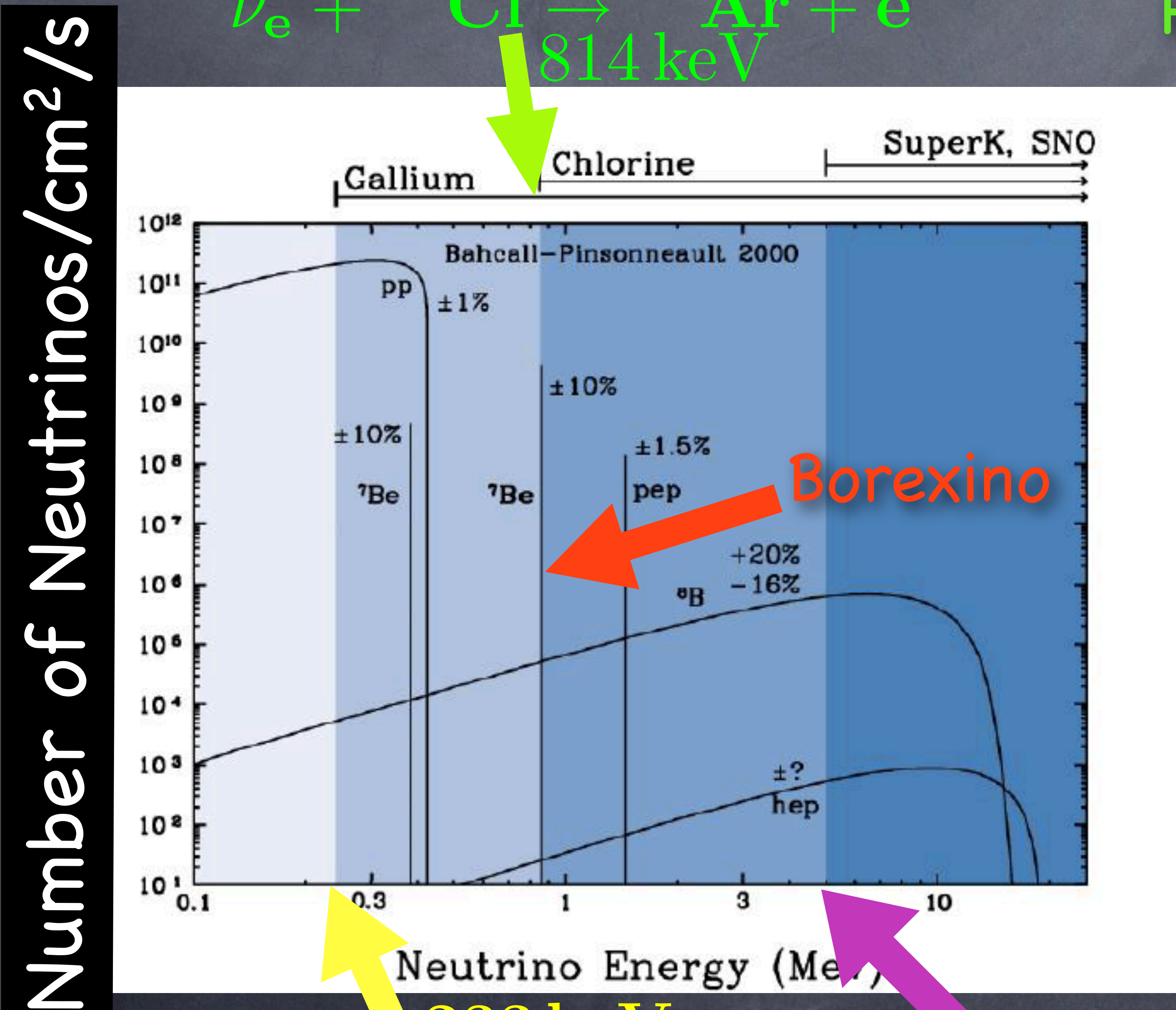
SNO

Solar Neutrinos

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

Homestake (1968-1994)

814 keV



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Standard Solar Model
BPS 08 (GS)

$\nu_e + d \rightarrow e^- + p + p$

$\nu_x + d \rightarrow \nu_x + p + n$

SNO

233 keV

$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$

SAGE/GALLEX/GNO

$\nu_x + e \rightarrow \nu_x + e$

SK, SNO

Solar Neutrinos

	$^{37}Cl \to ^{37}Ar$ (SNU)	$^{71}Ga \to ^{71}Ge$ (SNU)
Homestake [4]	$2.56 \pm 0.16 \pm 0.16$	–
GALLEX [8]	–	$77.5 \pm 6.2^{+4.3}_{-4.7}$
GALLEX-Reanalysis [104]	–	$73.4^{+6.1+3.7}_{-6.0-4.1}$
GNO [9]	–	$62.9^{+5.5}_{-5.3} \pm 2.5$
GNO+GALLEX [9]	–	$69.3 \pm 4.1 \pm 3.6$
GNO+GALLEX-Reanalysis [104]	–	$67.6^{+4.0+3.2}_{-4.0-3.2}$
SAGE [6]	–	$65.4^{+3.1+2.6}_{-3.0-2.8}$
SSM [BPS08(GS)] [100]	$8.46^{+0.87}_{-0.88}$	$127.9^{+8.1}_{-8.2}$

1 SNU (Standard Solar Unit)

=

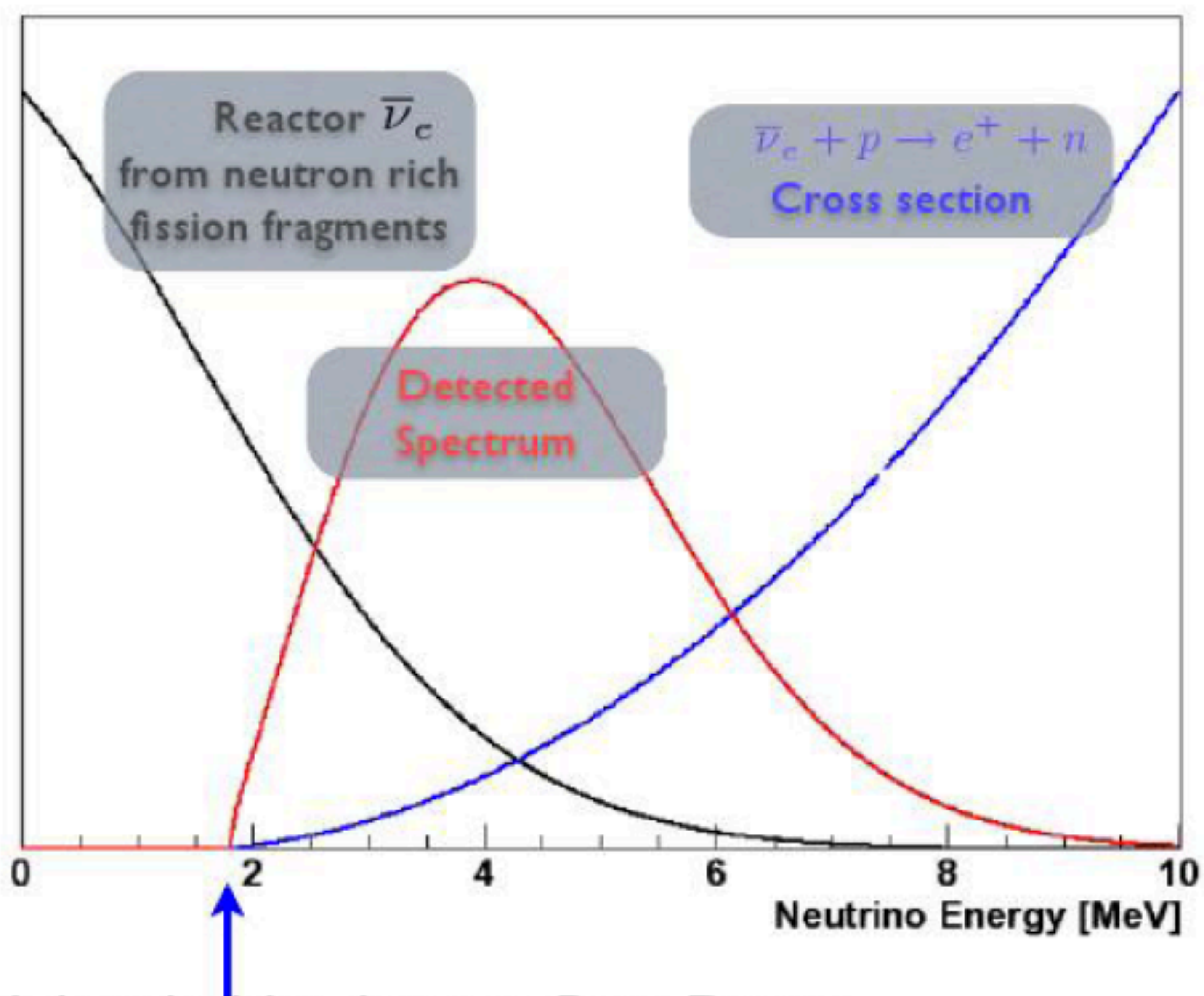
interactions/10^{36} atoms/s

	Reaction	^{8}B ν flux ($10^{6}cm^{-2}s^{-1}$)
Kamiokande [5]	ν_e	$2.80 \pm 0.19 \pm 0.33$
Super-K I [109,111]	ν_e	$2.38 \pm 0.02 \pm 0.08$
Super-K II [110,111]	ν_e	$2.41 \pm 0.05^{+0.16}_{-0.15}$
Super-K III [111]	ν_e	$2.32 \pm 0.04 \pm 0.05$
SNO Phase I [12]	CC	$1.76^{+0.06}_{-0.05} \pm 0.09$
(pure D_20)	ν_e	$2.39^{+0.24}_{-0.23} \pm 0.12$
	NC	$5.09^{+0.44+0.46}_{-0.43-0.43}$
SNO Phase II [112]	CC	$1.68 \pm 0.06^{+0.08}_{-0.09}$
(NaCl in D_2O)	ν_e	$2.35 \pm 0.22 \pm 0.15$
	NC	$4.94 \pm 0.21^{+0.38}_{-0.34}$
SNO Phase III [113]	CC	$1.67^{+0.05+0.07}_{-0.04-0.08}$
(^{3}He counters)	ν_e	$1.77^{+0.24+0.09}_{-0.21-0.10}$
	NC	$5.54^{+0.33+0.36}_{-0.31-0.34}$
SNO Phase I+II [114]	NC	$5.140^{+0.160+0.132}_{-0.158-0.117}$
	Φ_B from fit to all reactions	$5.046^{+0.159+0.107}_{-0.152-0.123}$
SNO Phase I+II+III [115]	Φ_B from fit to all reactions	$5.25 \pm 0.16^{+0.11}_{-0.13}$
Borexino [118]	ν_e	$2.4 \pm 0.4 \pm 0.1$
SSM [BPS08(GS)] [100]	–	$5.94(1 \pm 0.11)$

	Reaction	^{7}Be ($10^{9}cm^{-2}s^{-1}$)
Borexino [117]	ν_e	3.10 ± 0.15
SSM [BPS08(GS)] [100]	–	$5.07(1 \pm 0.06)$

KamLAND

reactor neutrinos @ 180 km from detector



1.8MeV threshold in Inverse Beta Decay

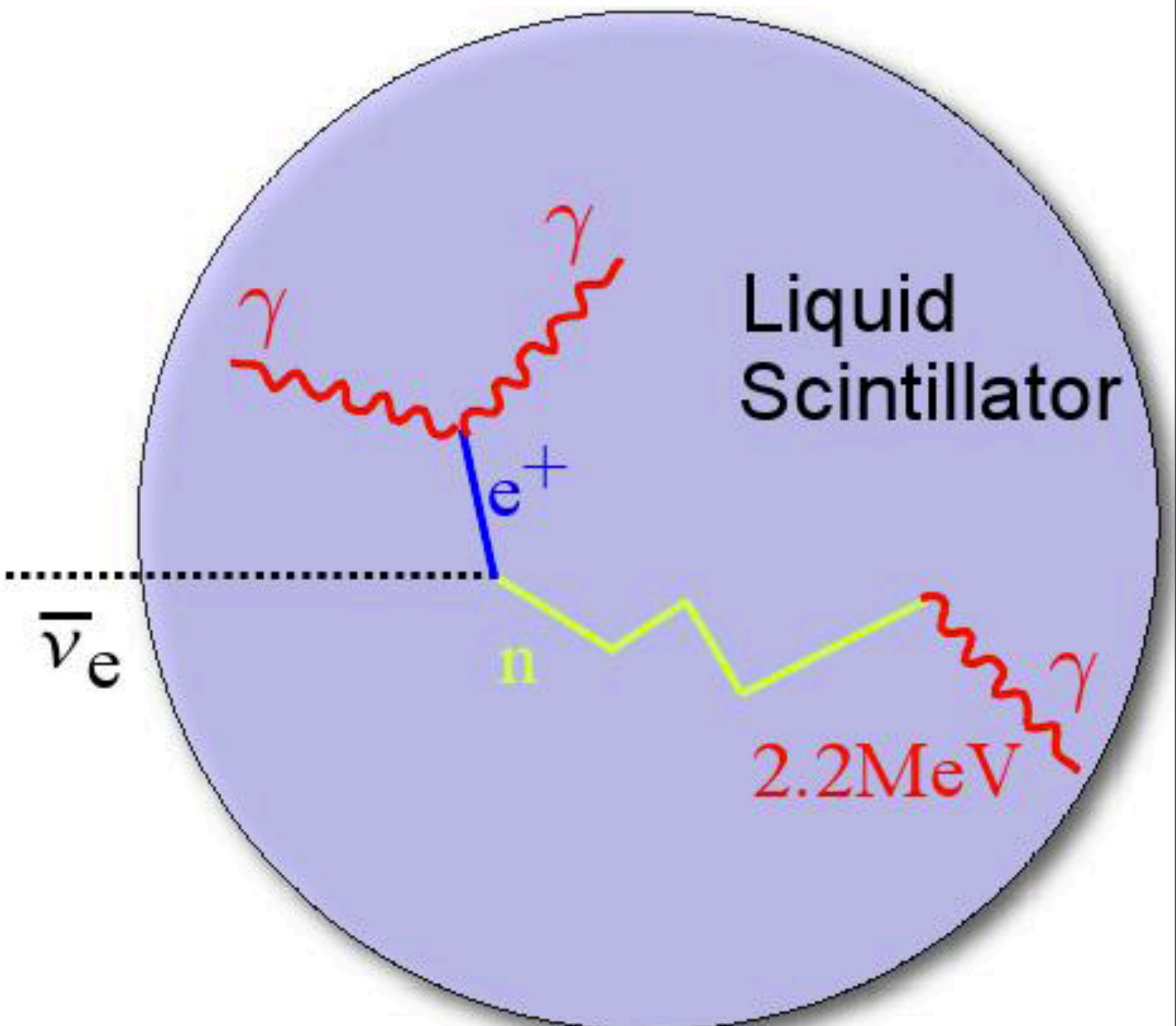
Inverse beta decay

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

↓ 207 μs

$$n + p \rightarrow d + \gamma$$

Scintillator is both target and detector

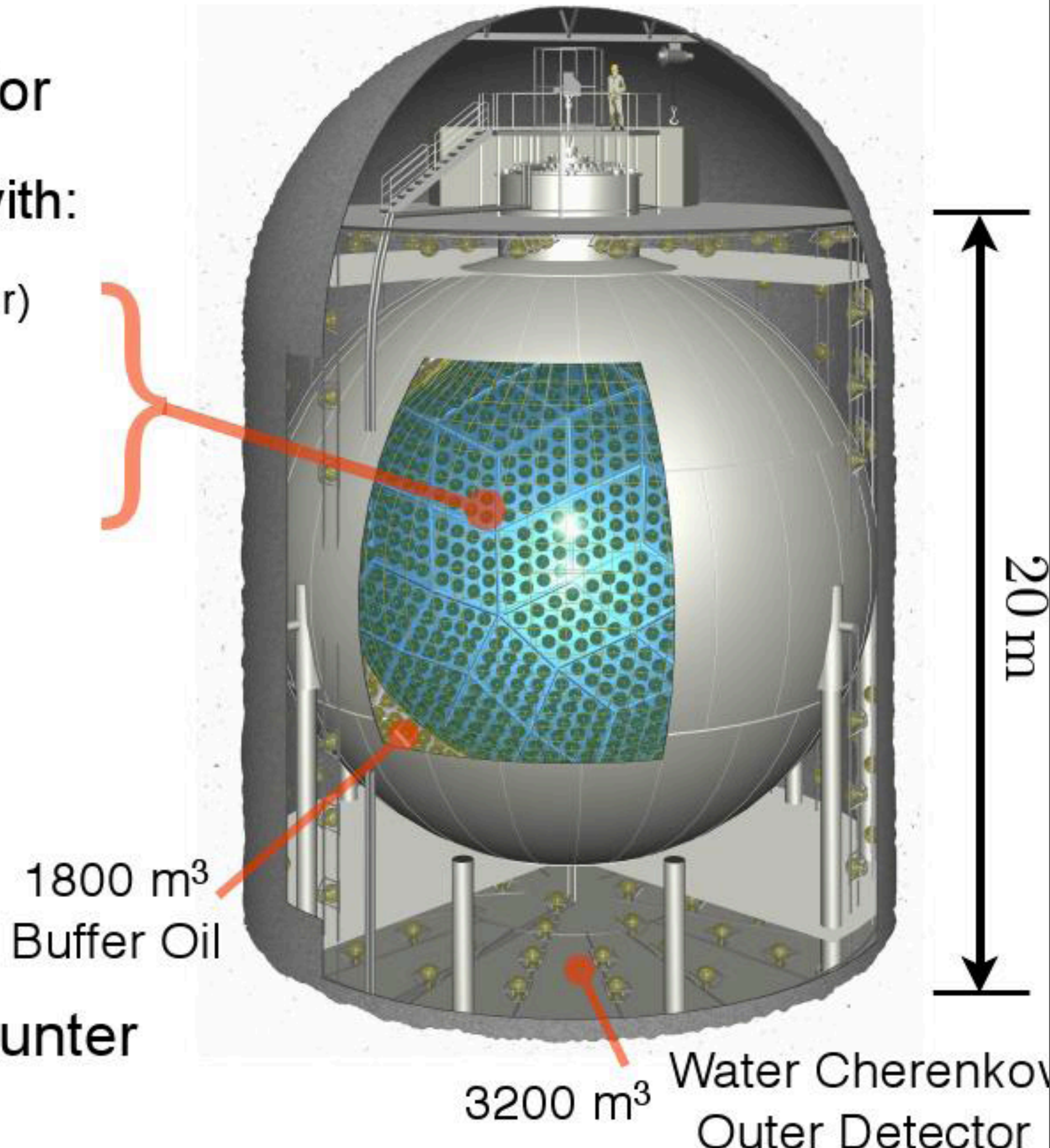


- Distinct two step process:
  - prompt event: positron

    $$E_{\overline{\nu}_e} \simeq E_{prompt} + 0.8 MeV$$

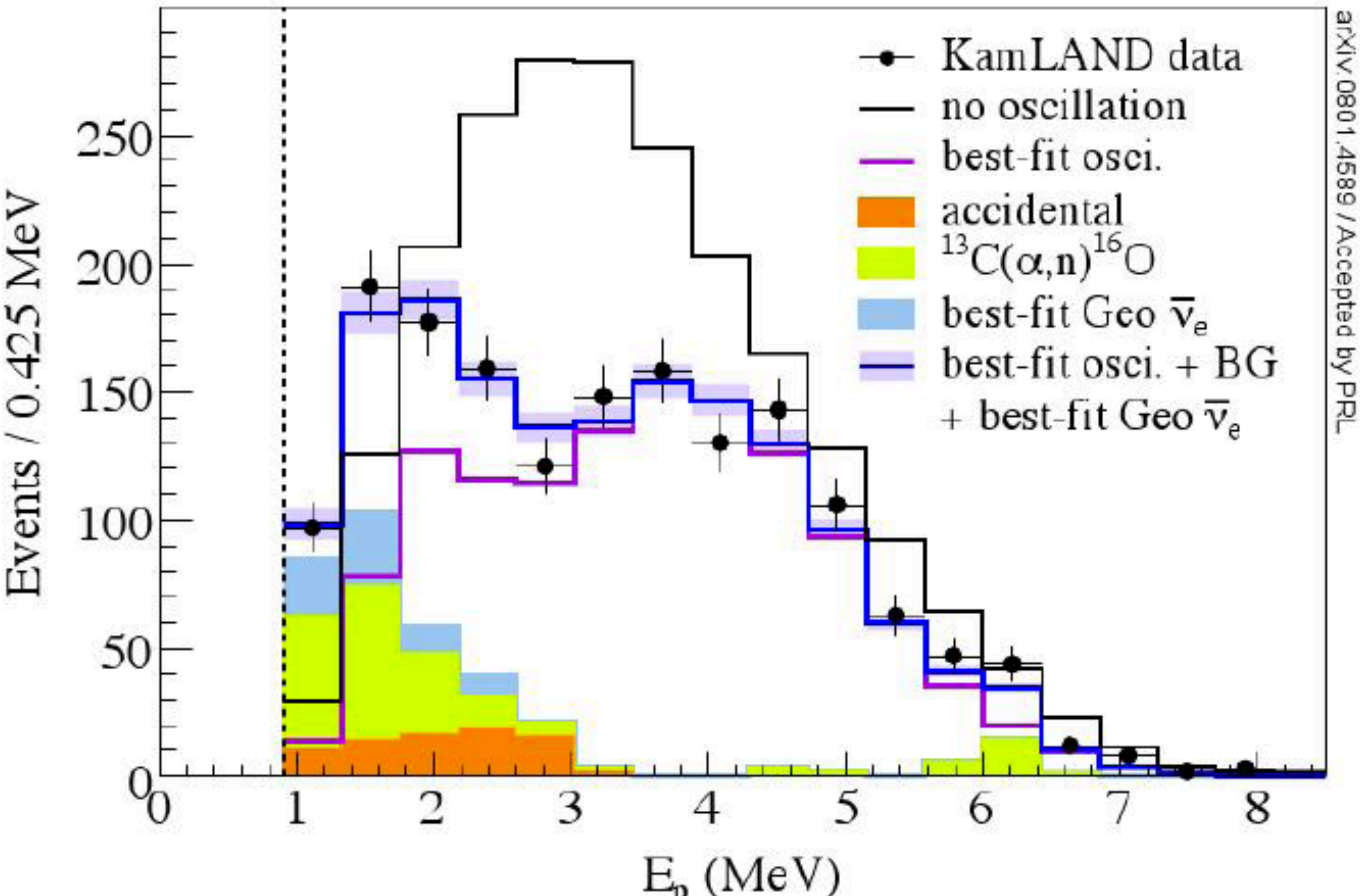
  - delayed event: neutron capture after ~207μs

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% Pseudocumene (scintillator)
    - 80% Dodecane (oil)
    - PPO
- 34% PMT coverage
  - ~1300 17” fast PMTs
  - ~550 20” large PMTs
- Multi-hit electronics
- Water Cherenkov veto counter



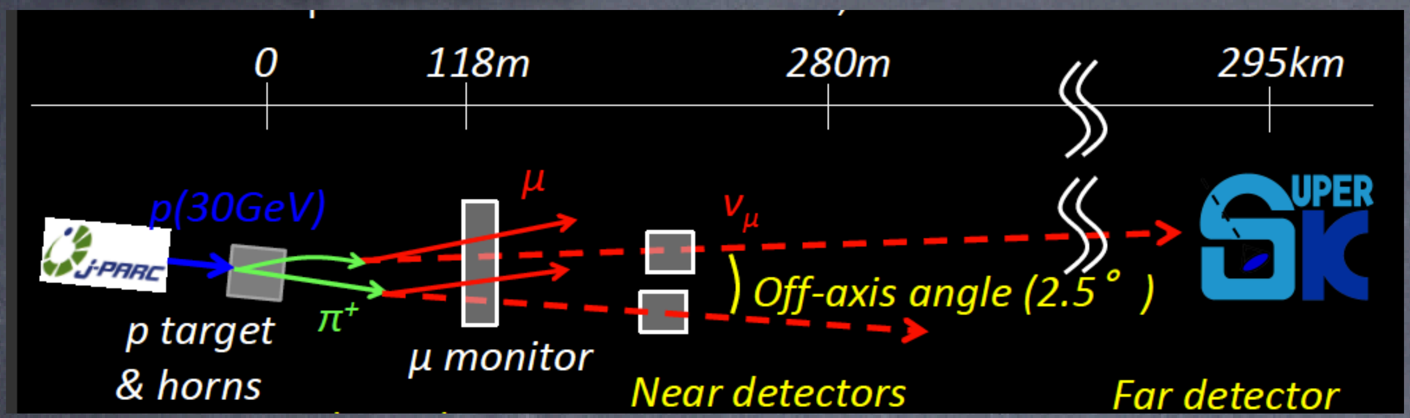
KamLAND

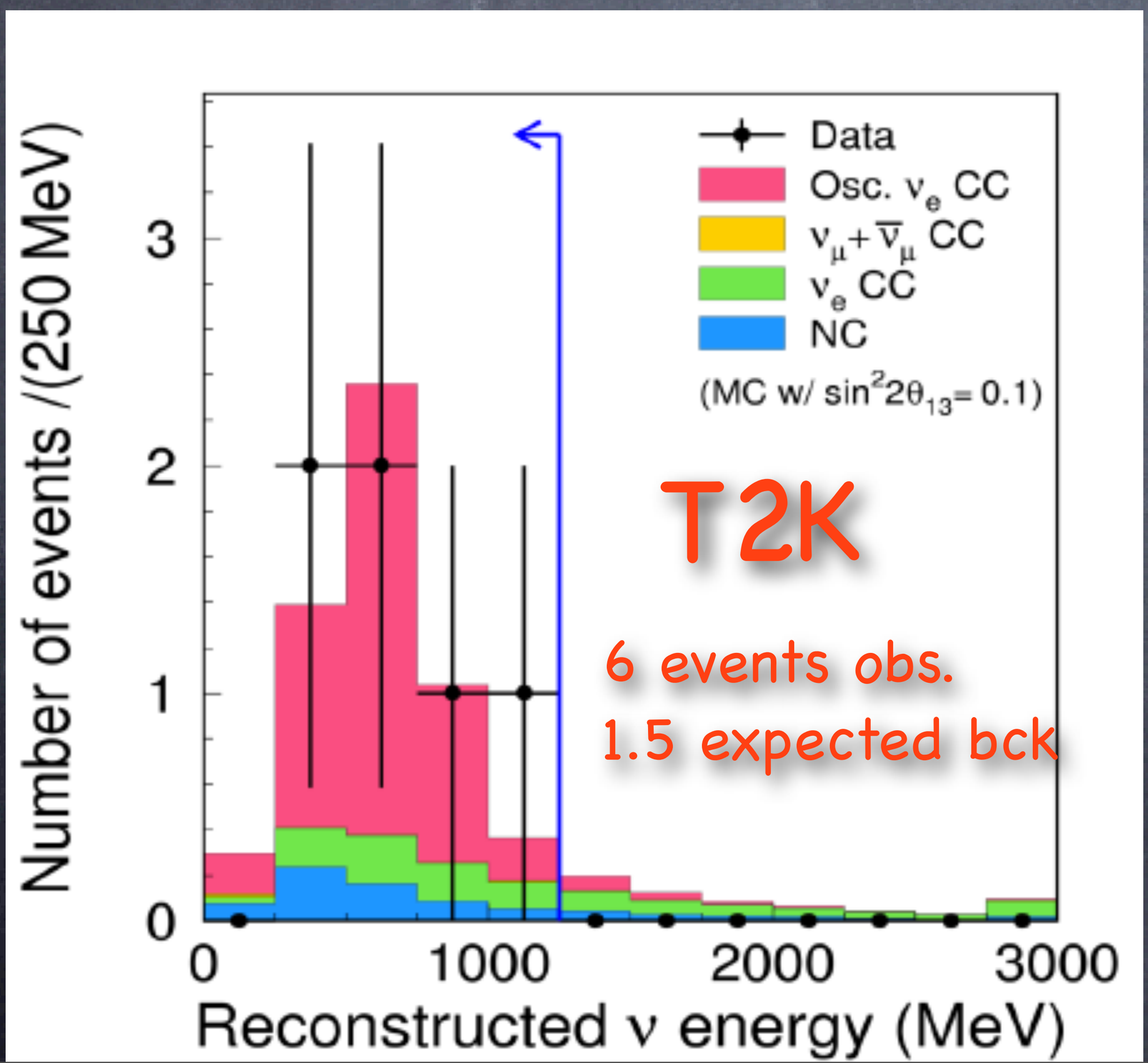
From Mar 9, 2002 to May 12, 2007
1491 live days, 2881 ton-year exposure (3.8x KL2004)



$\nu_\mu \rightarrow \nu_e$

June 2011

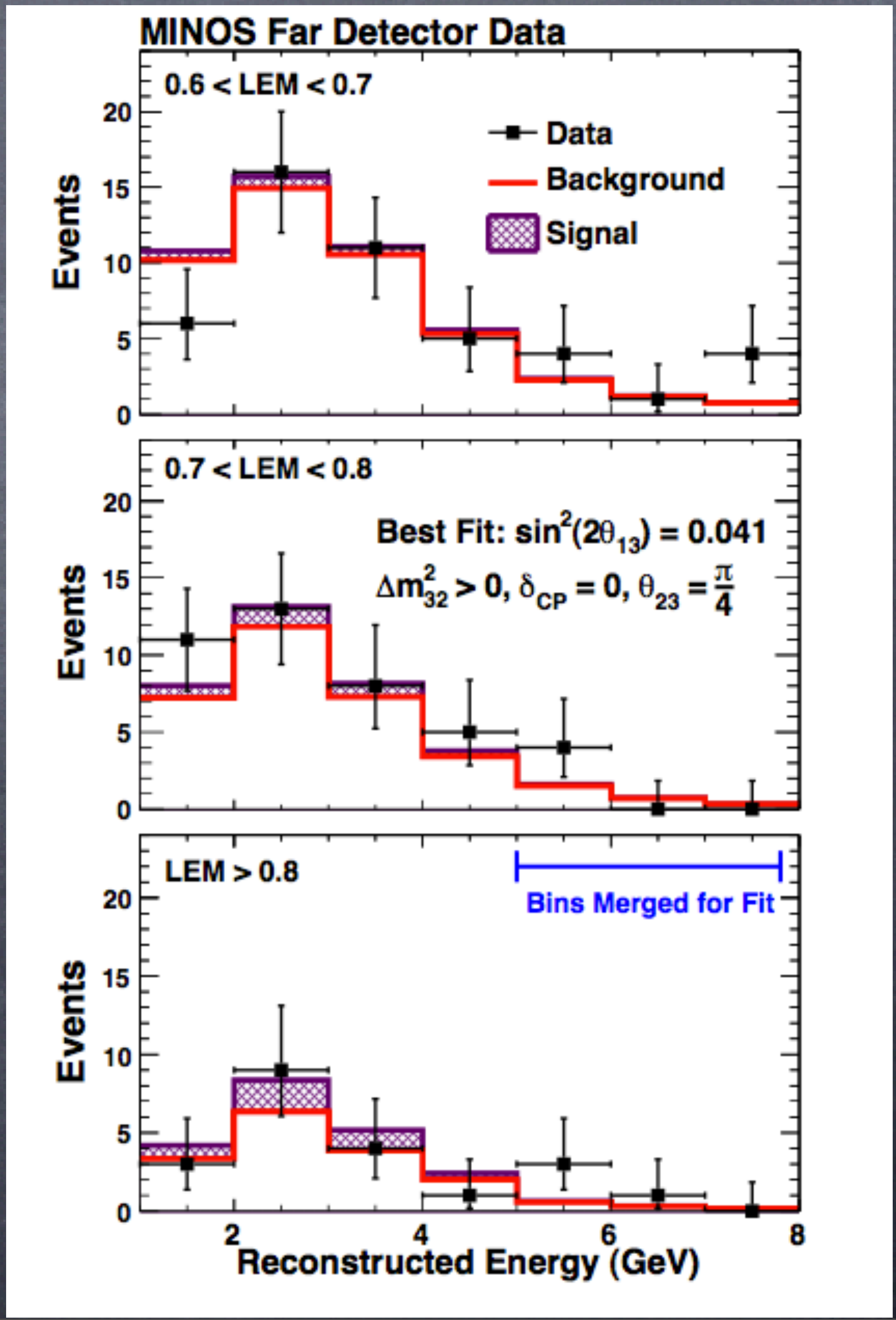




K. Abe et al., Phys. Rev. Lett. 107, 041801 (2011)]

[P. Adamson et al., Phys. Rev. Lett. 107, 181802 (2011)]

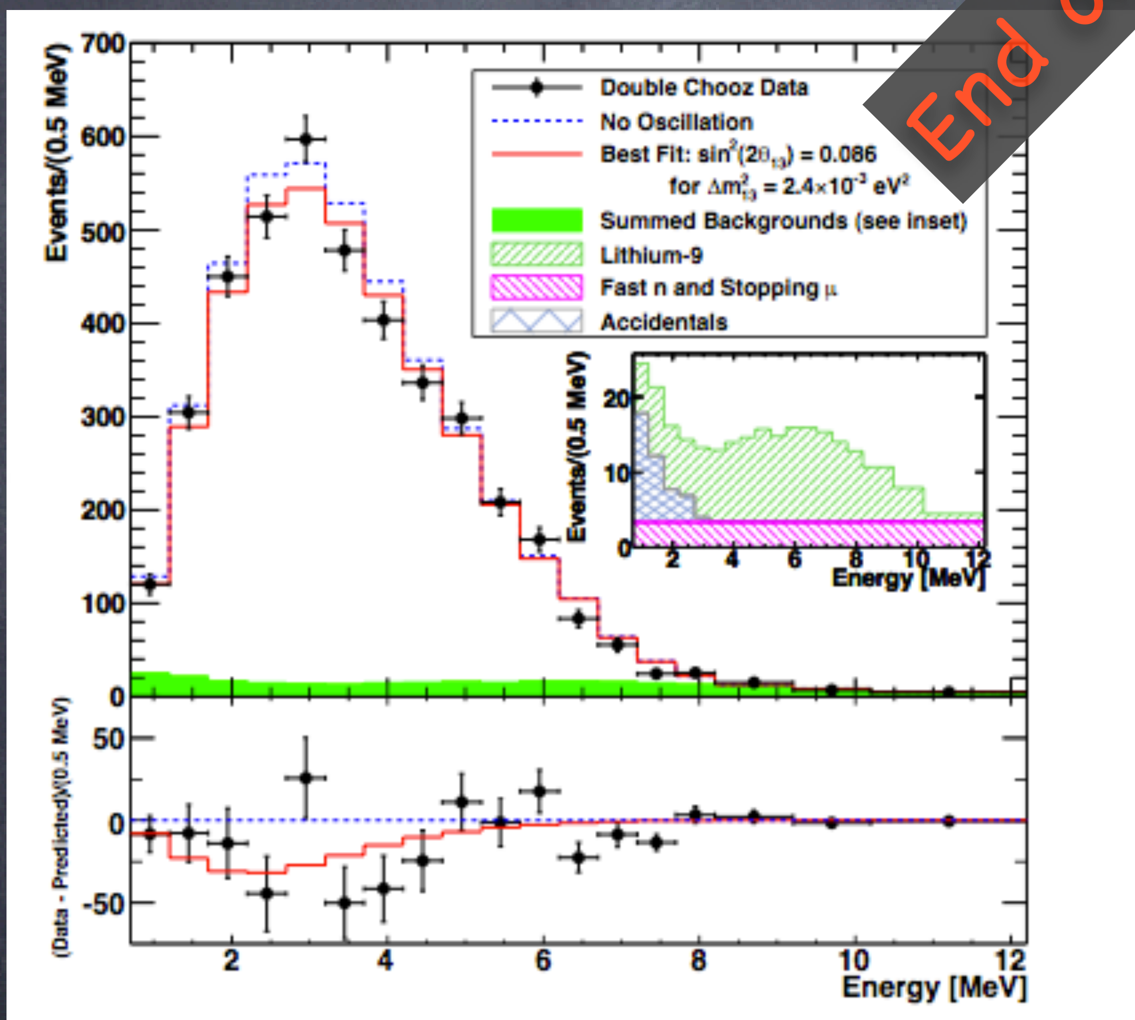
MINOS



$\bar{\nu}_e \rightarrow \bar{\nu}_e$

Double Chooz

End of 2011



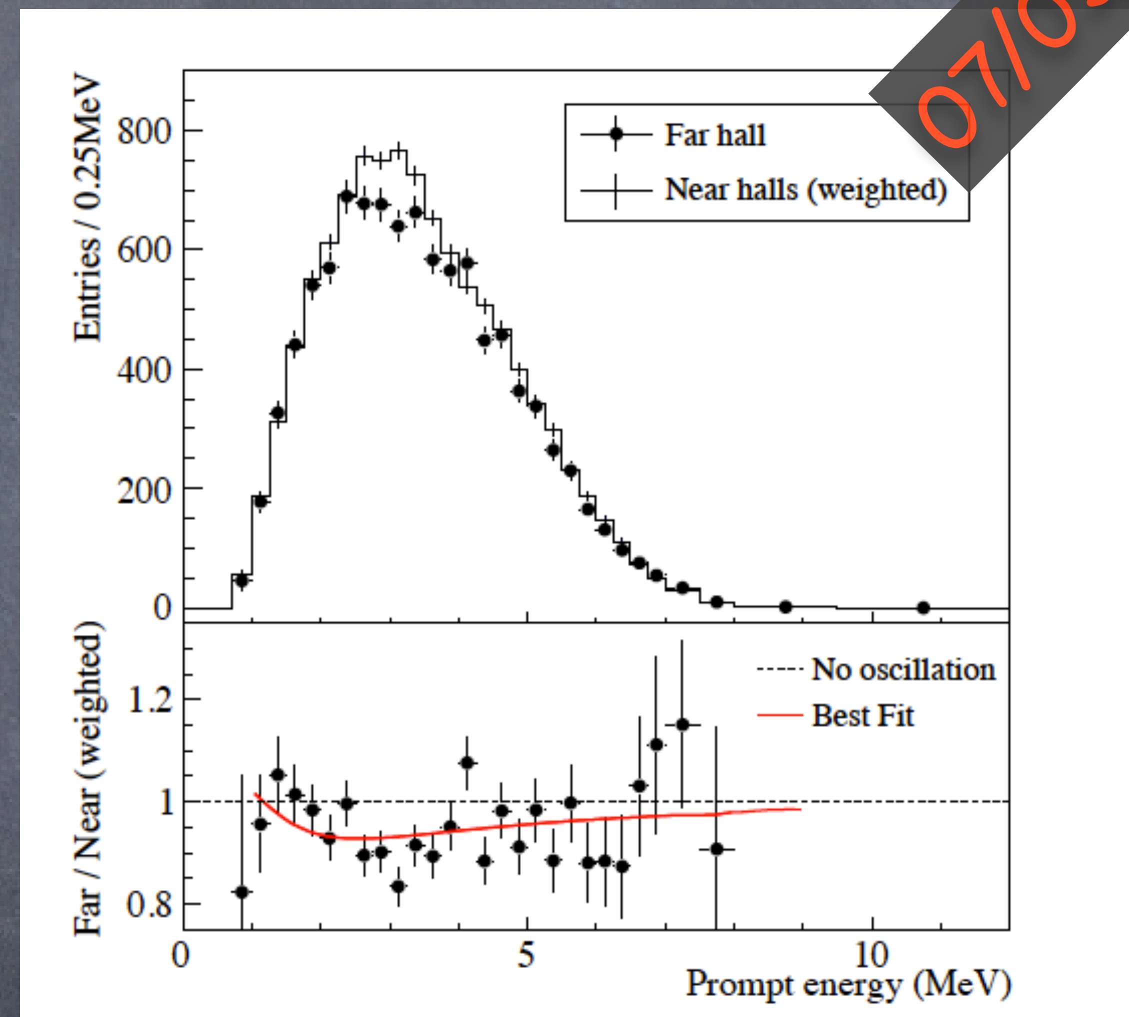
Y. Abe et al., arXiv:1112.6353

$$\frac{\mathrm{N_{obs}}}{\mathrm{N_{exp}}} = \mathbf{0.944 \pm 0.016 \pm 0.040}$$

$$\sin^2 2\theta_{13} = \mathbf{0.086 \pm 0.041 \pm 0.030}$$

Daya Bay

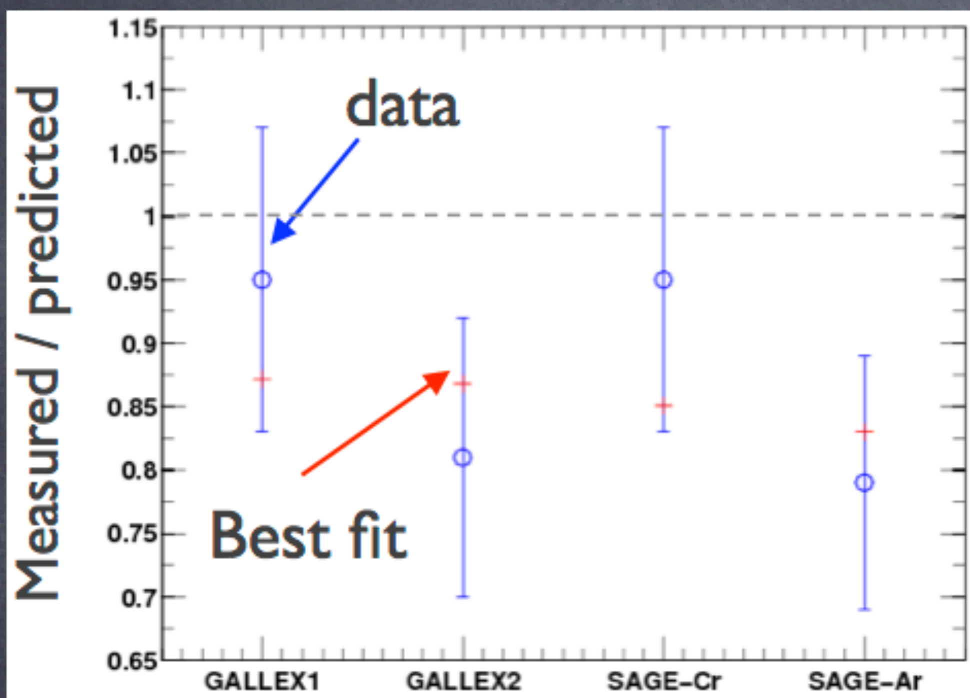
07/03/2012



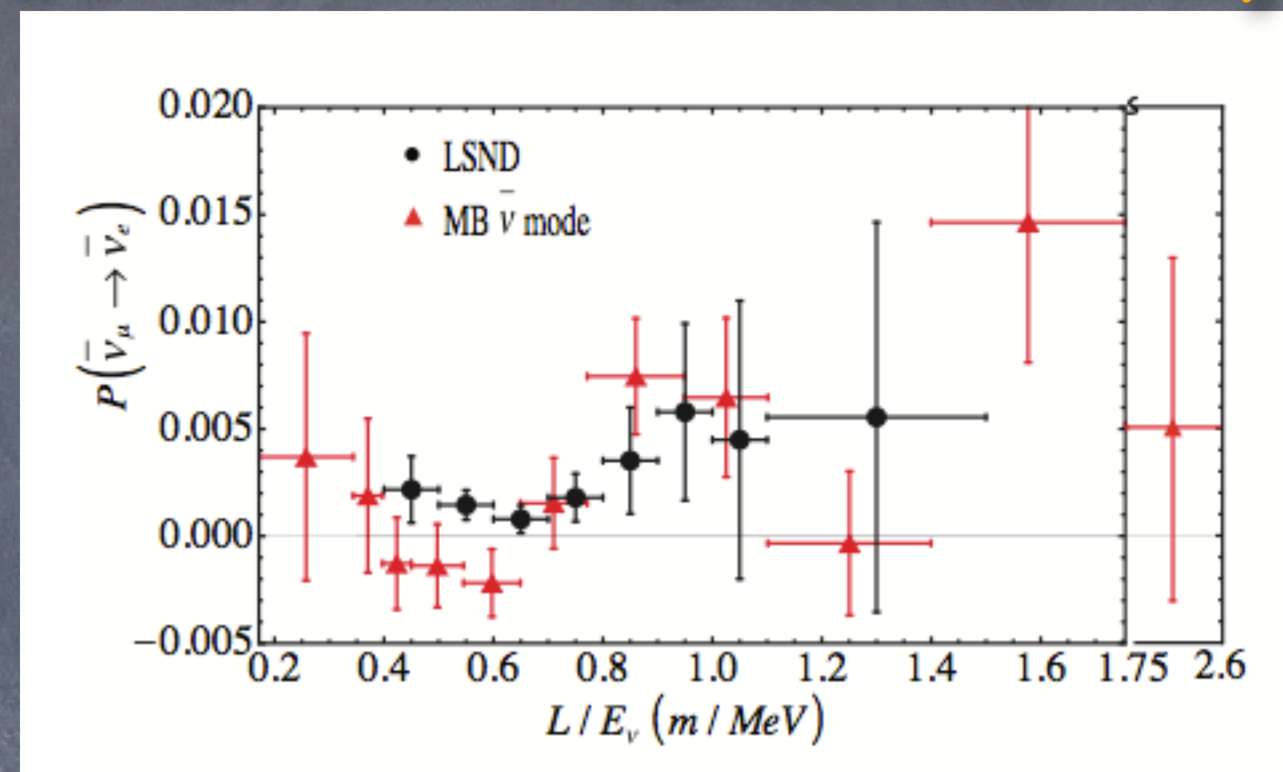
$$\frac{\mathrm{N_{obs}}}{\mathrm{N_{exp}}} = \mathbf{0.940 \pm 0.011 \pm 0.004}$$

$$\sin^2 2\theta_{13} = \mathbf{0.092 \pm 0.016 \pm 0.005}$$

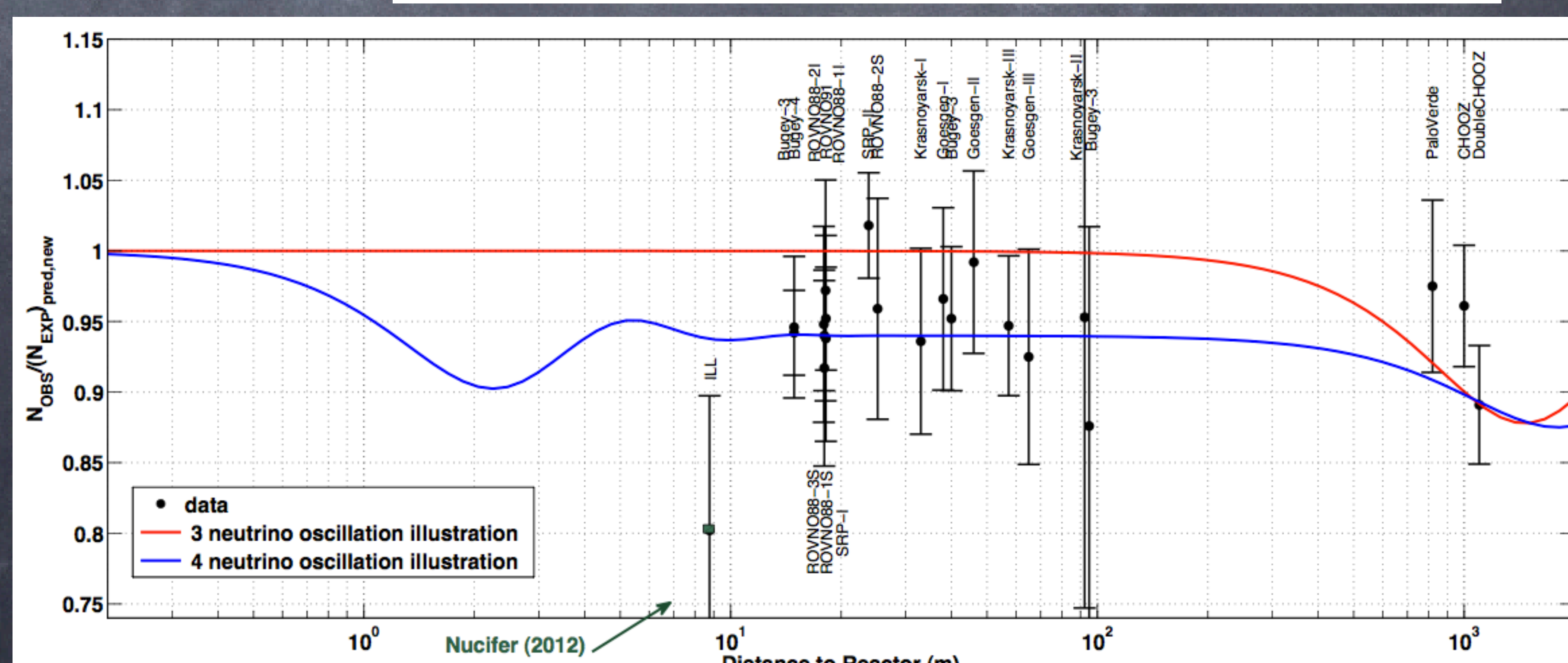
Gallium Anomaly



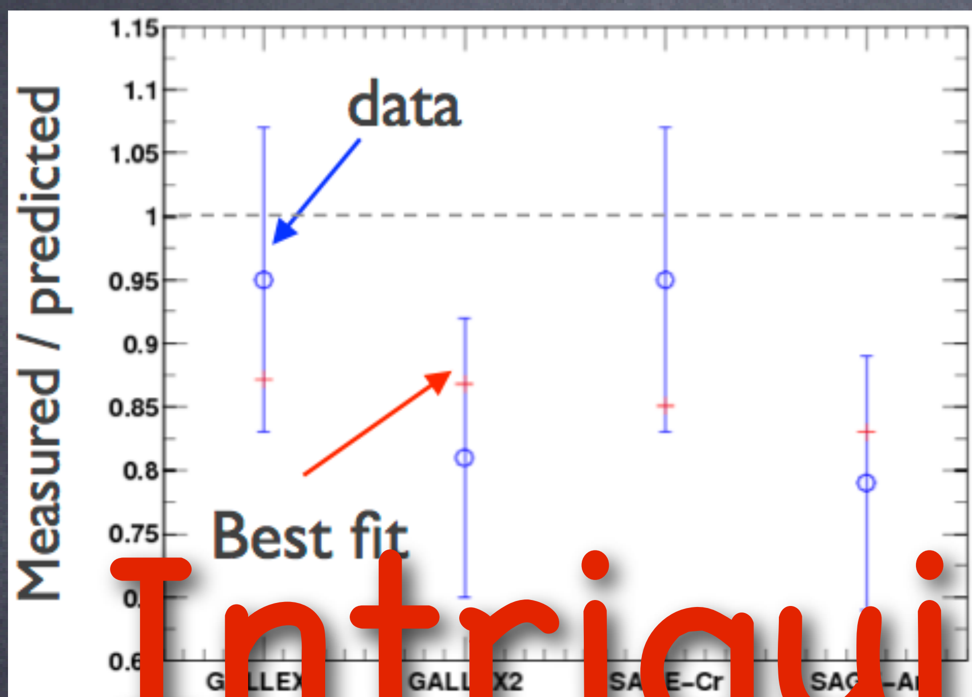
LSND/MiniBooNE Anomaly



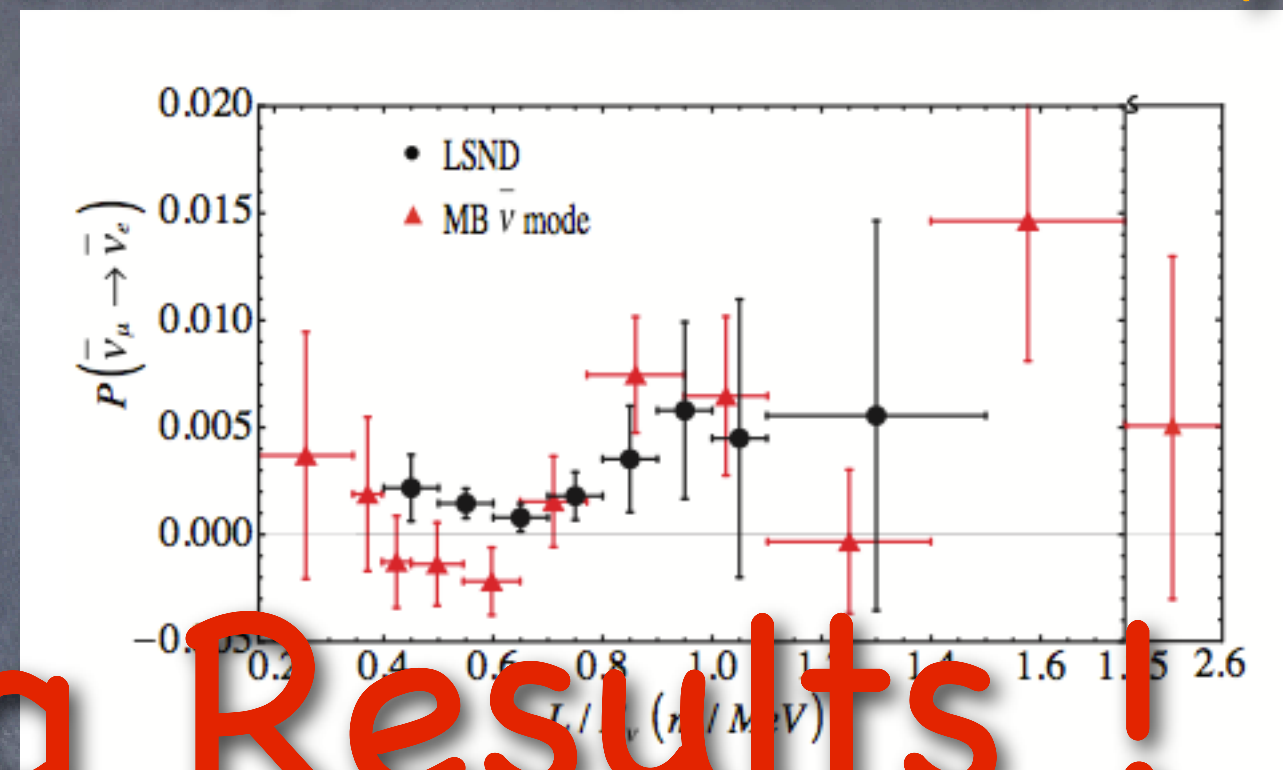
Reactor Anomaly



Gallium Anomaly

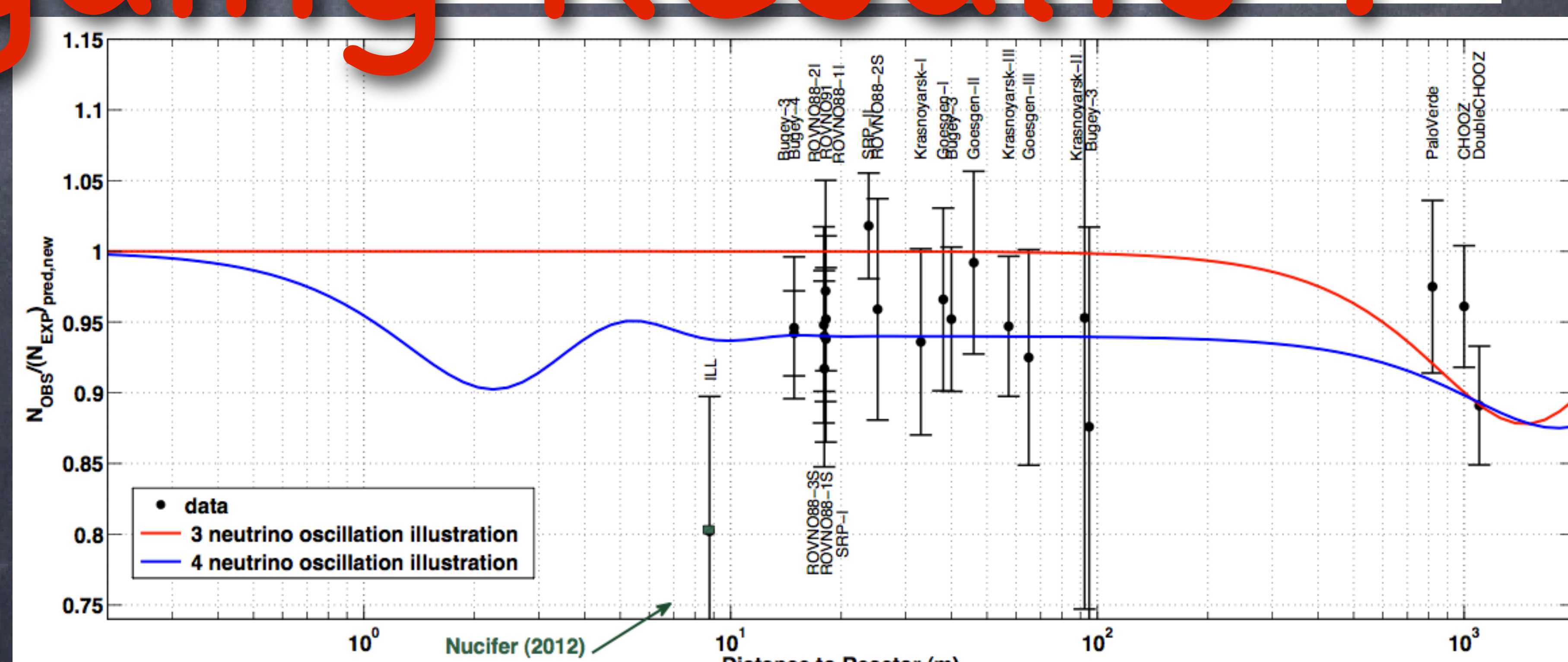


LSND/MiniBooNE Anomaly



Intriguing Results !

Reactor Anomaly



Limits on Neutrino Masses

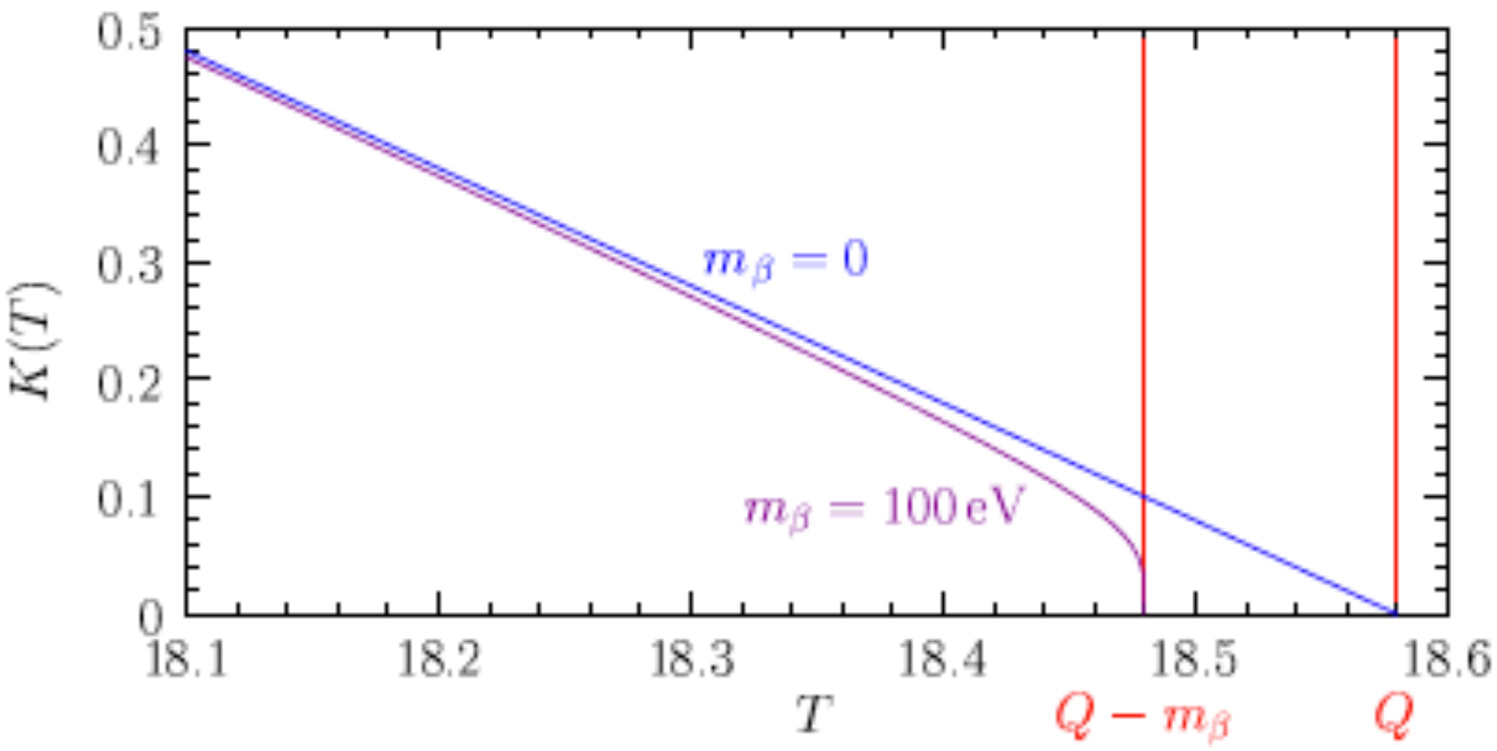
Tritium Beta-Decay

$$^3\mathrm{H} \rightarrow {}^3\,\mathrm{He} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} \qquad Q = M_\mathrm{H} - M_\mathrm{He} - m_e = 18.58\,\mathrm{keV}$$

$$\frac{d\Gamma}{dT} \propto |\mathcal{M}|^2\, F(E)\, p\, E(Q-T)\sqrt{(Q-T)^2 - m_{\bar{\nu}_e}^2}$$

Kurie plot:

$$K(T) = \sqrt{(Q-T)\sqrt{(Q-T)^2 - m_{\bar{\nu}_e}^2}}$$

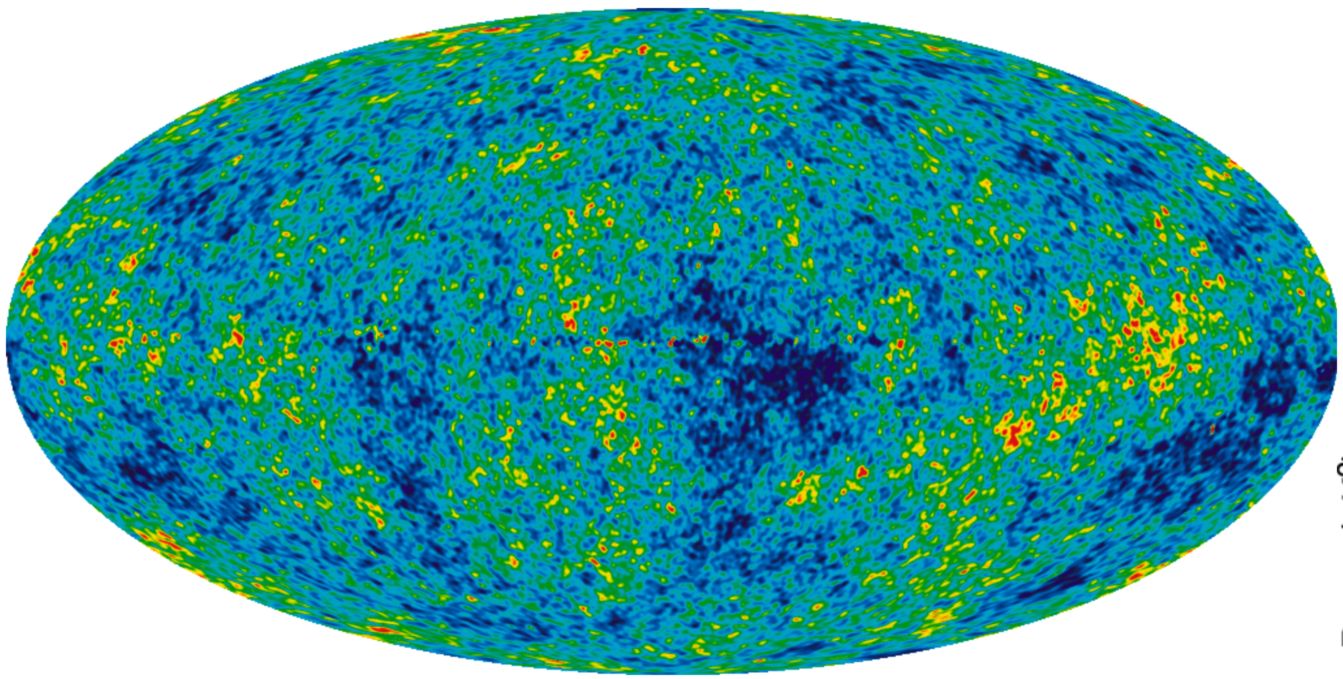


$m_{\nu_e} < 2.2\,\mathrm{eV}$

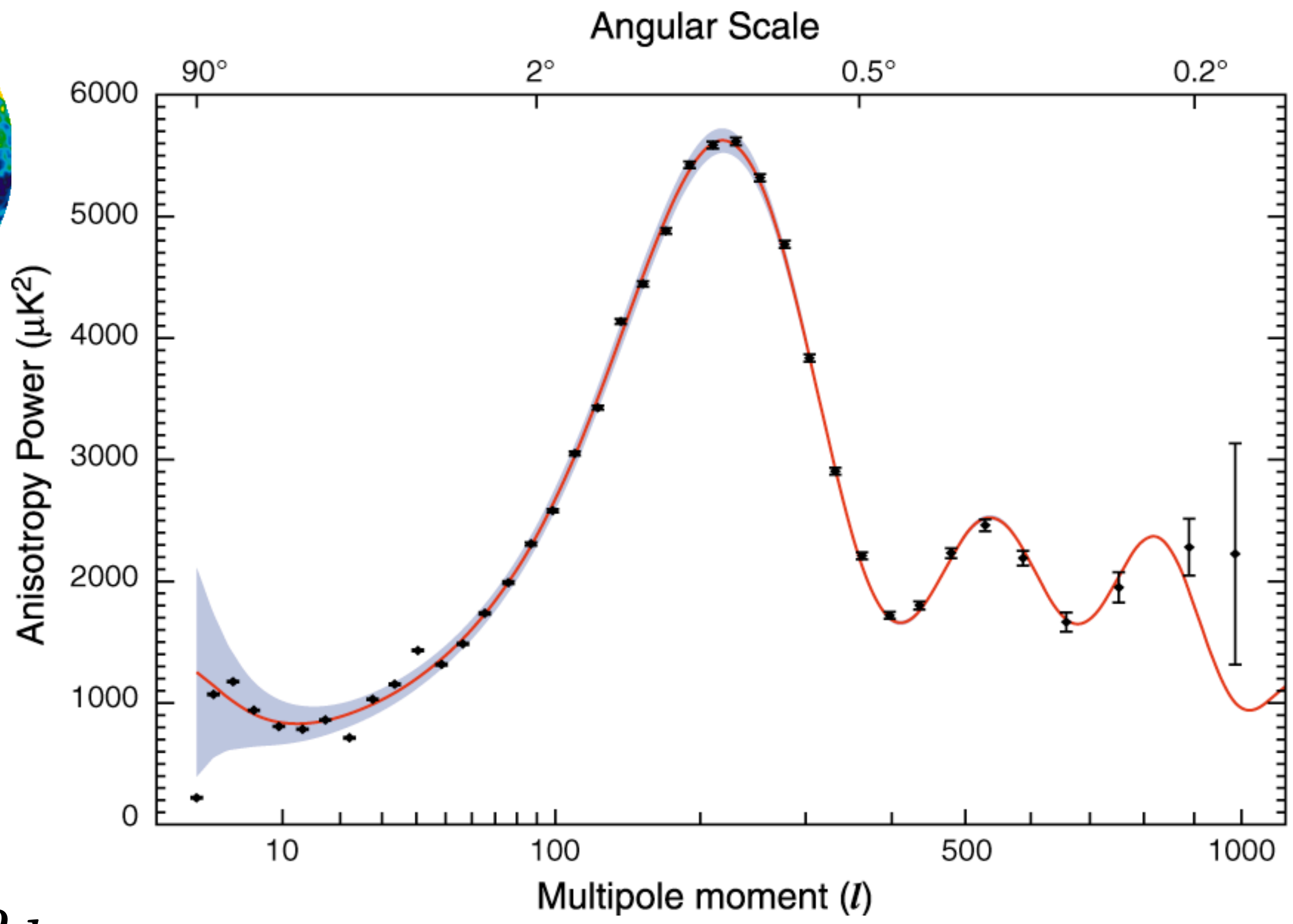
Troitsk & Mainz (2002)

Future KATRIN sensitivity 0.2 eV

Relic Neutrinos



WMAP-9 yrs



$$\Omega_\nu h^2 = \sum_k \frac{n_{\nu_k} m_k}{\rho_c} = \frac{\sum_k m_k}{94.14\ \mathrm{eV}}$$

$$\sum_k m_k < 0.44\ \mathrm{eV}\ @\ 95\%\ \mathrm{CL}$$

Are neutrinos ≠ antineutrinos ?

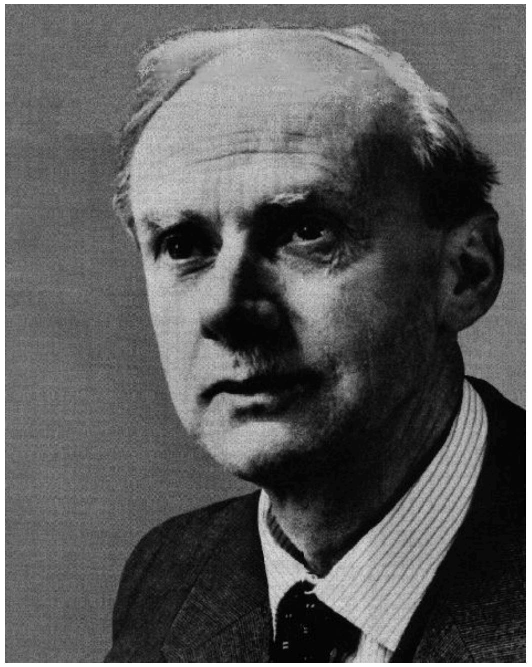
Ettore Majorana

$$\nu = \bar{\nu}$$

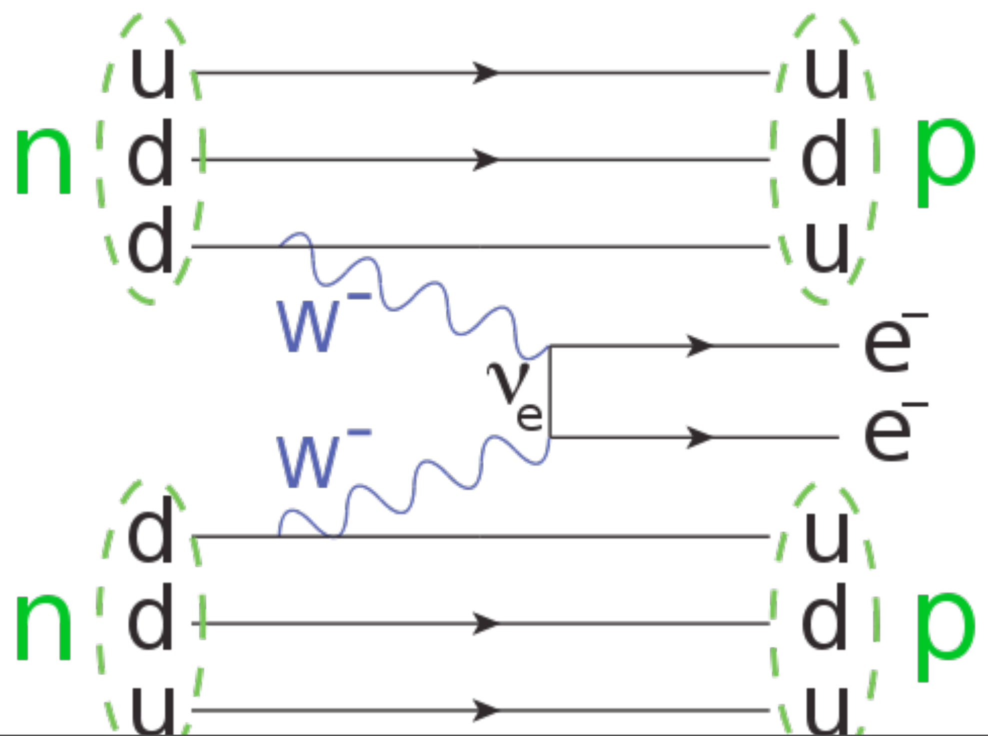
Majorana Neutrino

$$\nu \neq \bar{\nu}$$

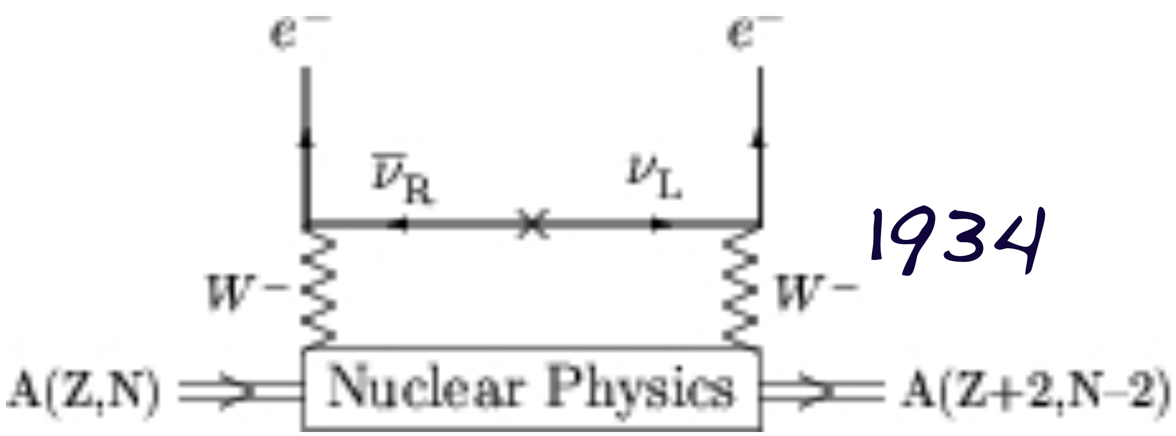
Dirac Neutrino



Paul Dirac



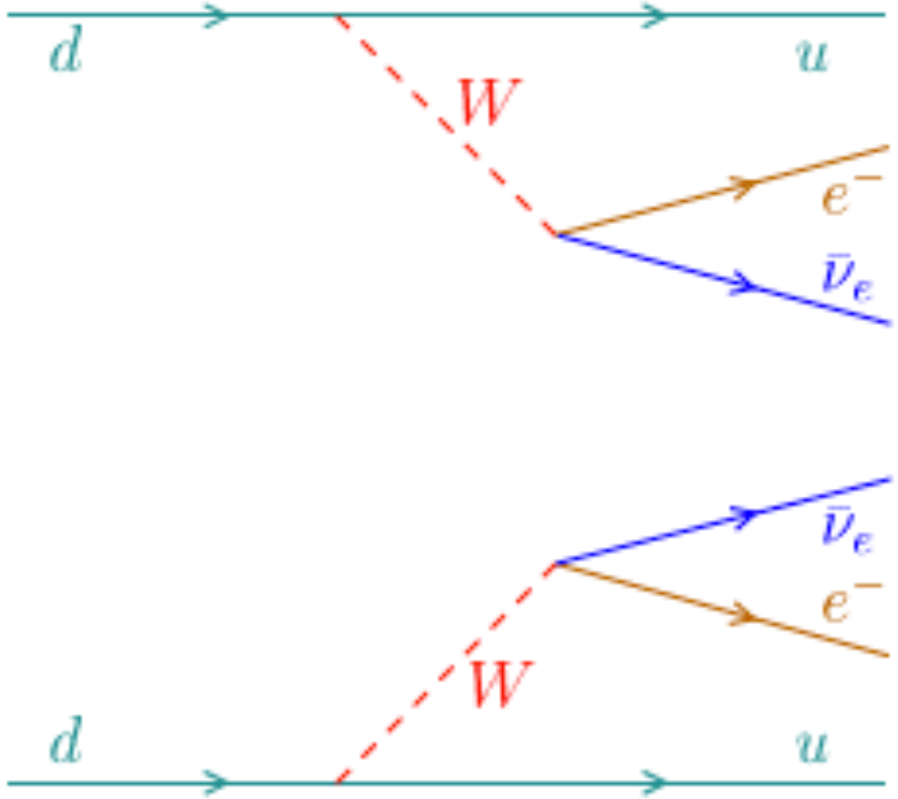
Neutrinoless Double Beta Decay



1934

Two Neutrino Double-β Decay

ΔL = 0

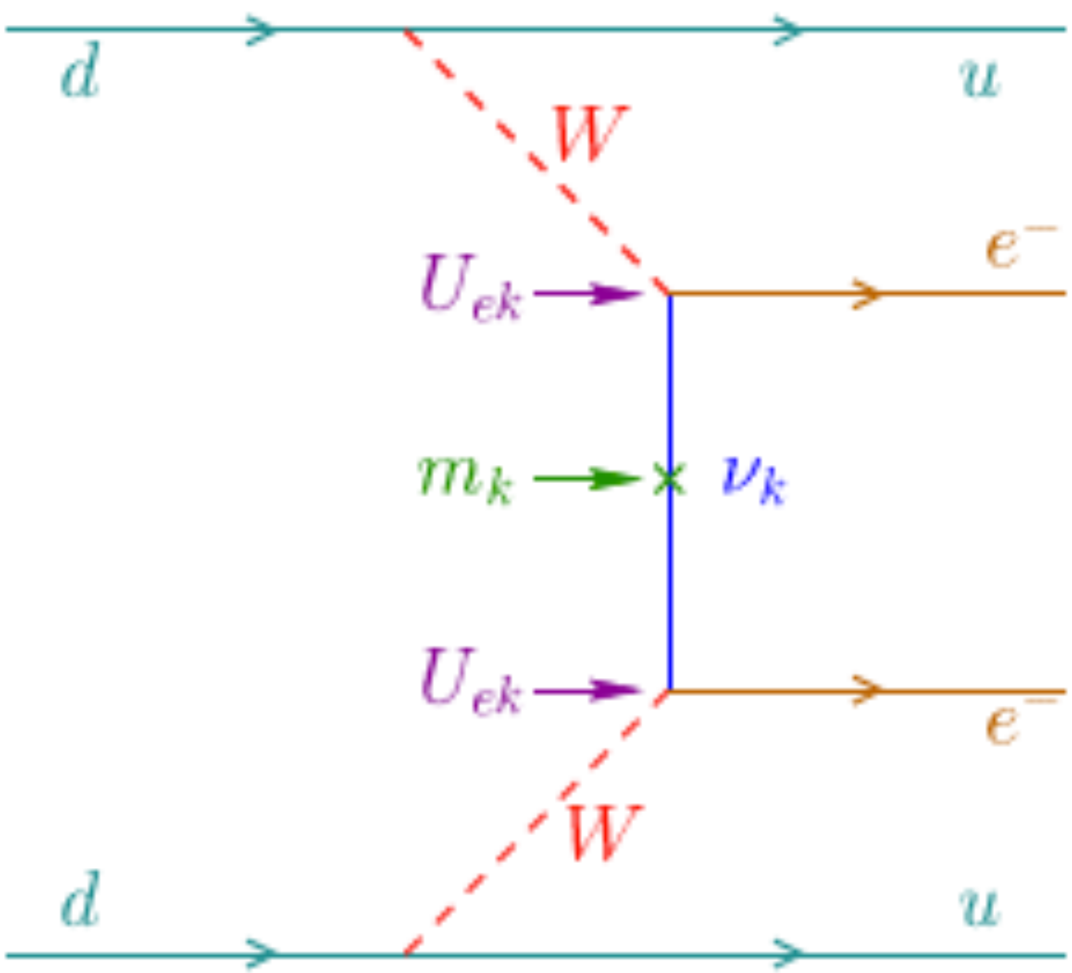


$$(T^{2\nu}_{1/2})^{-1} = G_{2\nu}|M_{2\nu}|^2$$

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

second order weak interaction process

Neutrinoless Double-β Decay



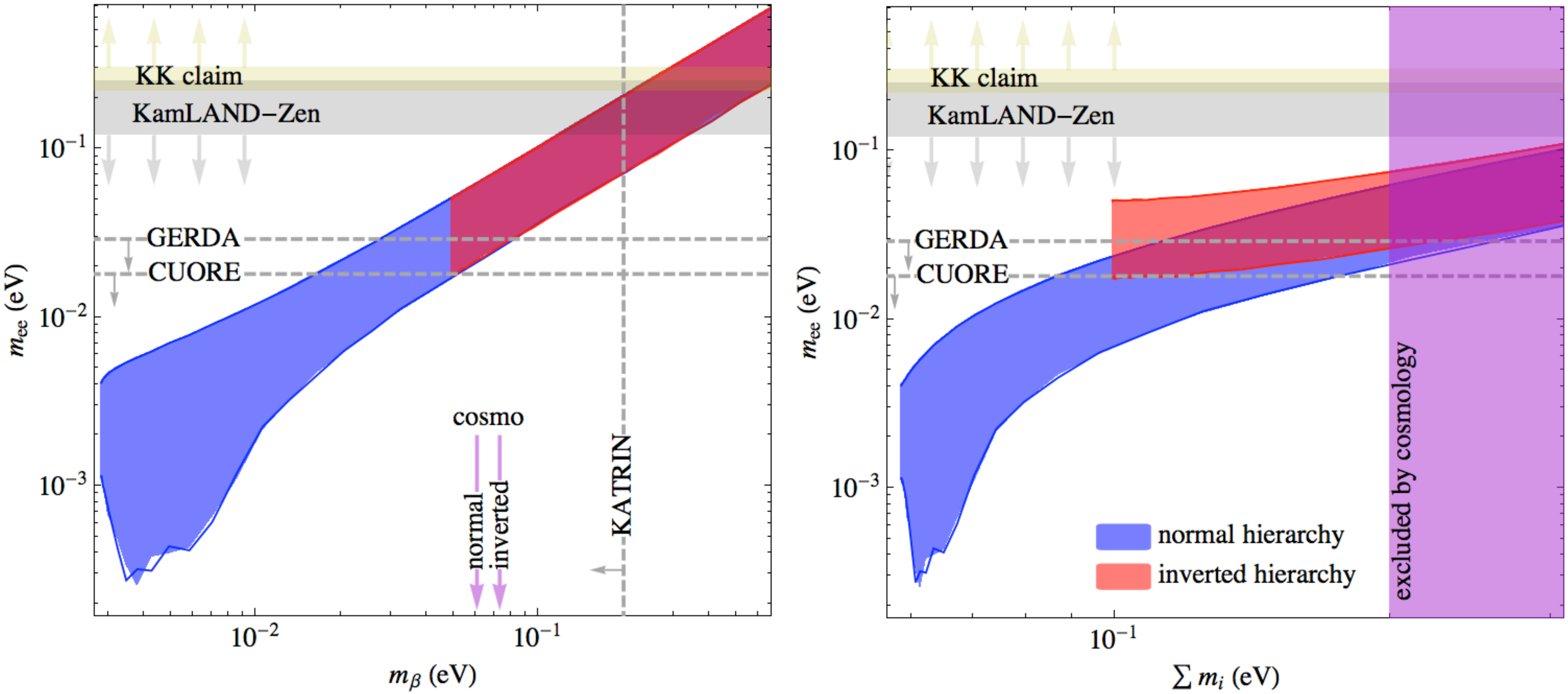
ΔL = 2

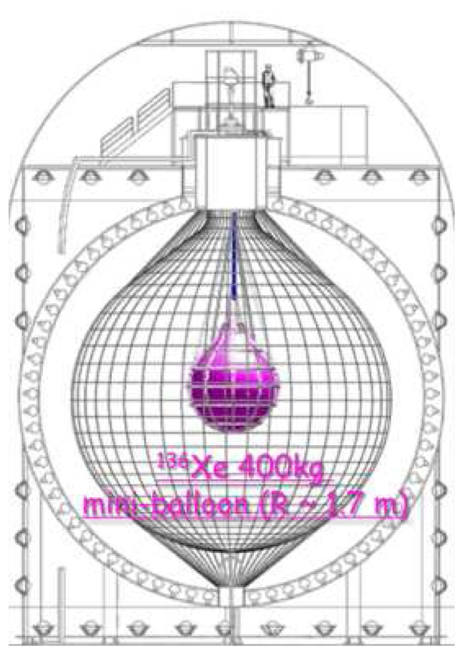
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}|M_{0\nu}|^2|m_{\beta\beta}|^2$$

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

effective Majorana mass $m_{\beta\beta} = \sum_k U_{ek}^2 m_k$

Neutrinoless Double-β Decay





^{136}Xe

$$T_{1/2}^{2\nu} = (2.38 \pm 0.02 \pm 0.14) \times 10^{21} \text{ yr @ } 90\% \text{ CL}$$

$$T_{1/2}^{0\nu} > 3.4 \times 10^{25} \text{ yr @ } 90\% \text{ CL}$$

$$|m_{\beta\beta}| < (120 - 250) \text{ meV}$$