Discovery of Neutrino Oscillations (the massive character of the neutrino) the experimental program

L. Labarga, Dept. Física Teórica U.A.M.

Outline:

- Brief theoretical context
- Neutrino sources
- The discovery of the neutrino / Search for solar neutrinos:
  First hint of massive of neutrinos: “the solar neutrino problem”
- Water-Cherenkov technique; very large amount of mass instrumented
- Super-Kamiokande
  - Discovery of oscillation in atmospheric neutrinos (mainly muon)
  - Precise measurement of solar neutrino deficit
- SNO (Sudbury Neutrino Observatory)
  - Measurement of the whole solar neutrino flux.
  - Discovery of oscillation in solar neutrinos (mainly electron)
- Final remarks

Universidad de Salamanca 20160226

Our current understanding of the Fundamental Laws of Physics is built into the Standard Model: a renormalizable Quantum Field Theory based on matter content (particles) and Interactions

Matter Content

Three families of elementary particles with (almost) identical structure

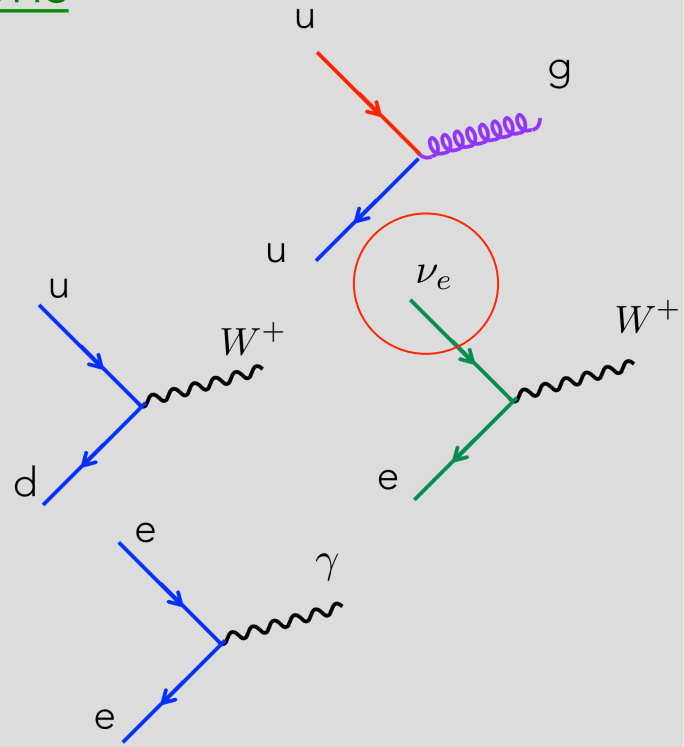
1st family $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix}$

2nd family $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$

3rd family $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$

Alberto Casas, Instituto de Física Teórica, IFT-CSIC/UAM, Madrid

Interactions



Strong

Weak

E.M.

Some peculiarities of the ν s :

the lightest fundamental particles $m_\nu < 10^{-6} m_e$

the particles that interact less: only weak and gravitational

the ≈most abundant particles in the Universe

ν – weak interaction – β decay

basic reaction of the weak interaction

fundamental particle level:

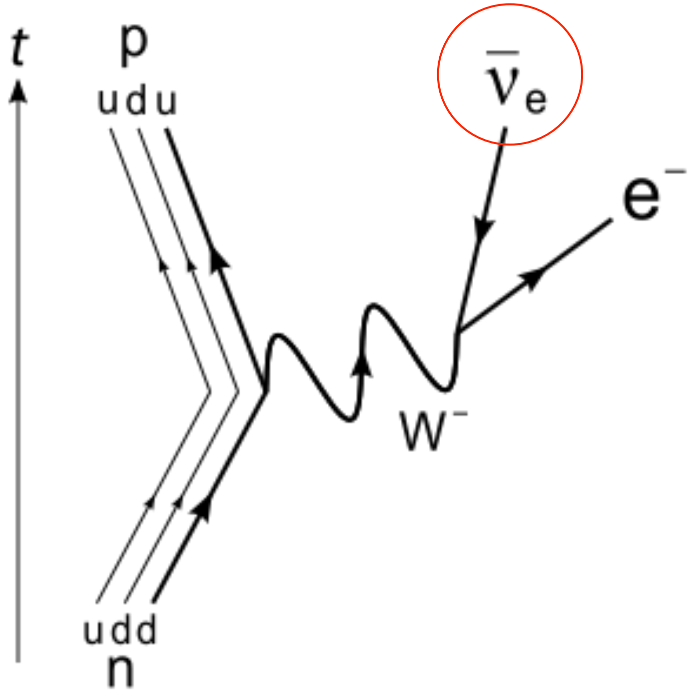
$$d \rightarrow u + e^- + \bar{\nu}_e$$

nucleon level:

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

nucleous level:

$${}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N' + e^- + \bar{\nu}_e;$$



The weak interaction provides the fundamental process for the stability of matter: it allows the nucleus to reach its optimum ration of protons and neutrons

The ν s are thus pivotal already to our daily macroscopic life

….. **but how do we care about their mass** ?

- the SM is based on the gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$
- that is spontaneously broken to $SU(3)_C \times U(1)_{EM}$ by the vacuum expectation value of a Higgs doublet field Φ

- right-handed fields are included for charged fermions as they are needed to build the electromagnetic and strong currents
- no right-handed ν is included in the model since νs are neutral

- the fermion masses arise from the Yukawa interactions which couple the right-handed fermion singlets to the left-handed fermion doublets and the Higgs doublet
- after spontaneous EW symmetry breaking, these interactions lead to charged fermion masses, but leave the νs massless

- no Yukawa interaction can be written that would give a tree-level mass to the ν because no right-handed ν field exists in the model

➔ extend the SM to include right-handed ν fields:
the *new minimal Standard Model (nmSM)*

M. C. Gonzalez-Garcia, Physica Scripta. Vol. T121, 72–77, 2005

neutrino oscillations ←→ massive neutrinos

- A ν produced in a weak decay is always from a specific family that is directly associated with the charged lepton accompanying the decay: e, μ, τ
- When the ν is detected in a CC reaction, it manifests its identity by transforming into the anti-particle of the charged lepton that accompanied its creation: e, μ, τ
- But if, for instance, a ν_μ changes to a ν_e, then a μ^+ is made at the ν creation and an e^- at its demise; this violates lepton family number
- Those ν oscillations are only possible for massive ν_s as the flavor eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$, need not to be mass eigenstates (ν_1, ν_2, ν_3)

➔ If the neutrino flavor eigenstates are a linear combination of the mass eigenstates, the neutrino flavor must change with time because the phases of the mass eigenstates evolve at different rates.

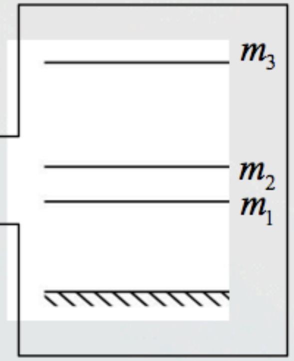
The Leptonic Mixing Matrix

Pontecorvo, B., J. Exp. Theor. Phys. 33, 549 (1957) [Sov. Phys. JETP 6, 429 (1958)]
Pontecorvo, B., J. Exp. Theor. Phys. 34, 247 (1958) [Sov. Phys. JETP 7, 172 (1958)]
Maki, Z., Nakagava, M. and Sakata, S., Prog. Theor. Phys. 28, 870 (1962)

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Standard Model states

Neutrino mass states



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 0 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} e^{i\beta_1} & 0 & 0 \\ 0 & e^{i\beta_2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Atmospheric experiments

Reactors, T2K, NOVA…CP phase,

Solar experiments

Majorana phases

$s_{12} \equiv \sin\theta_{12}$; $c_{12} \equiv \cos\theta_{12}$ etc.; δ_{CP}: CP violation phase

β_1, β_2: Majorana phases

Working out oscillation probabilities

Example with two neutrinos (ν_μ, ν_τ)

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \qquad \nu_\alpha = U_{\alpha i}\ \nu_i$$

$$|\nu_\mu\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu_\mu(t)\rangle = \cos\theta\ e^{-iE_1 t}|\nu_1\rangle + \sin\theta\ e^{-iE_2 t}|\nu_2\rangle$$

$$= A(t)|\nu_\mu\rangle + B(t)|\nu_\tau\rangle$$

$$\mathcal{P}(\nu_\mu \to \nu_\tau) = |B(t)|^2$$

$$|\nu_\mu(t)\rangle = \cos\theta\ e^{-iE_1 t}|\nu_1\rangle + \sin\theta\ e^{-iE_2 t}|\nu_2\rangle$$

$$= A(t)|\nu_\mu\rangle + B(t)|\nu_\tau\rangle$$

$$|B(t)|^2 = \sin^2 2\theta\ \ \sin^2(\frac{\Delta E\ t}{2})$$

Use: $E_i = \sqrt{p^2 + m_i^2} \simeq p + \frac{m_i^2}{2p}$

$t \simeq L/c$

$$\boxed{\mathcal{P}(\nu_\mu \to \nu_\tau) = |B(t)|^2 = \sin^2 2\theta\ \ \sin^2(\frac{\Delta m^2\ L}{4E})}$$

$$\boxed{\mathcal{P}(\nu_\mu \to \nu_\tau) = \sin^2 2\theta\ \ \sin^2\left[1.27\ \frac{\Delta m^2(\mathrm{eV}^2)\ L(\mathrm{Km})}{E(\mathrm{GeV})}\right]}$$

E.g. for

$E \sim 1\mathrm{GeV},\quad \Delta m^2 \simeq 2.5\times 10^{-3}\ \mathrm{eV}^2$ (atmospheric)

we expect large appearance prob. at $L \sim 500\ \mathrm{km}$

Three neutrinos

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) \ &= \ |\mathrm{Amp}[\nu_\alpha \to \nu_\beta]|^2 = \delta_{\alpha\beta} \\ &\quad - 4\sum_{i>j} \Re\,(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*)\sin^2[\Delta m_{ij}^2(L/4E)] \\ &\quad + 2\sum_{i>j} \Im\,(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*)\sin[\Delta m_{ij}^2(L/2E)] \end{aligned}$$

Note: $U_{\alpha i}$ can contain phases (CP violation)

Consequences of massive neutrinos I:

- in the *nmSM* flavor is mixed in the Charged Current interactions of the leptons, and a leptonic mixing matrix appears (analogous to the CKM matrix for the quarks)

- this leptonic mixing is further complicated by two factors:
    - the number of massive ν s is unknown, since there are no constraints on the number of right-handed, SM-singlet, ν s
    - since ν_s carry neither color nor electromagnetic charge they could be Majorana fermions (they coincide with their anti-particle)

- as a consequence the number of new parameters in the model (i.e. the new existing but yet unknown particle/phenomena in Nature) depends on the number of massive ν states and on whether they are Dirac or Majorana particles

M. C. Gonzalez-Garcia, Physica Scripta. Vol. T121, 72–77, 2005

Consequences of massive neutrinos II:

T. Yanagida, *Physica Scripta*. Vol. T121, 137–141, 2005

Heavy Majorana right-handed νs might be key for GUTs:

- an integration of the heavy Majorana νs might induce very small masses for νs (*via the seesaw mechanism*)
  → the small νs masses would be a consequence of a unification at very high energy scale.

And for baryon-number asymmetry in the present Universe:

- the heavy Majorana νs might be produced thermally in the early universe. Then, the heavy νs begin to decay into H and leptons, or H and anti-leptons when the temperature of the Universe cools down to the masses of heavy νs
- the decays of the heavy νs may produce a lepton-number asymmetry if CP invariance is violated in the Yukawa couplings.
- that is converted into the baryon-number asymmetry (leptogenesis) through non-perturbative EW effects

➔ prime reasons for ν mass experimental research

Neutrinos Sources for Experiments:

Sun *many*
Atmosphere *many*

most of this talk
about them

Nuclear Power Plants *many*
Particle Acelerators *many*

Center of the Earth *a few*

Supernova *a few* , DSBN
Cosmos *a few*

Relic Neutrino Cosmic Background

Experimental discovery of the ν

Not easy, most relevant ideas by:

Pontecorvo (1948) use reaction
Alvarez (1949) $\nu + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$

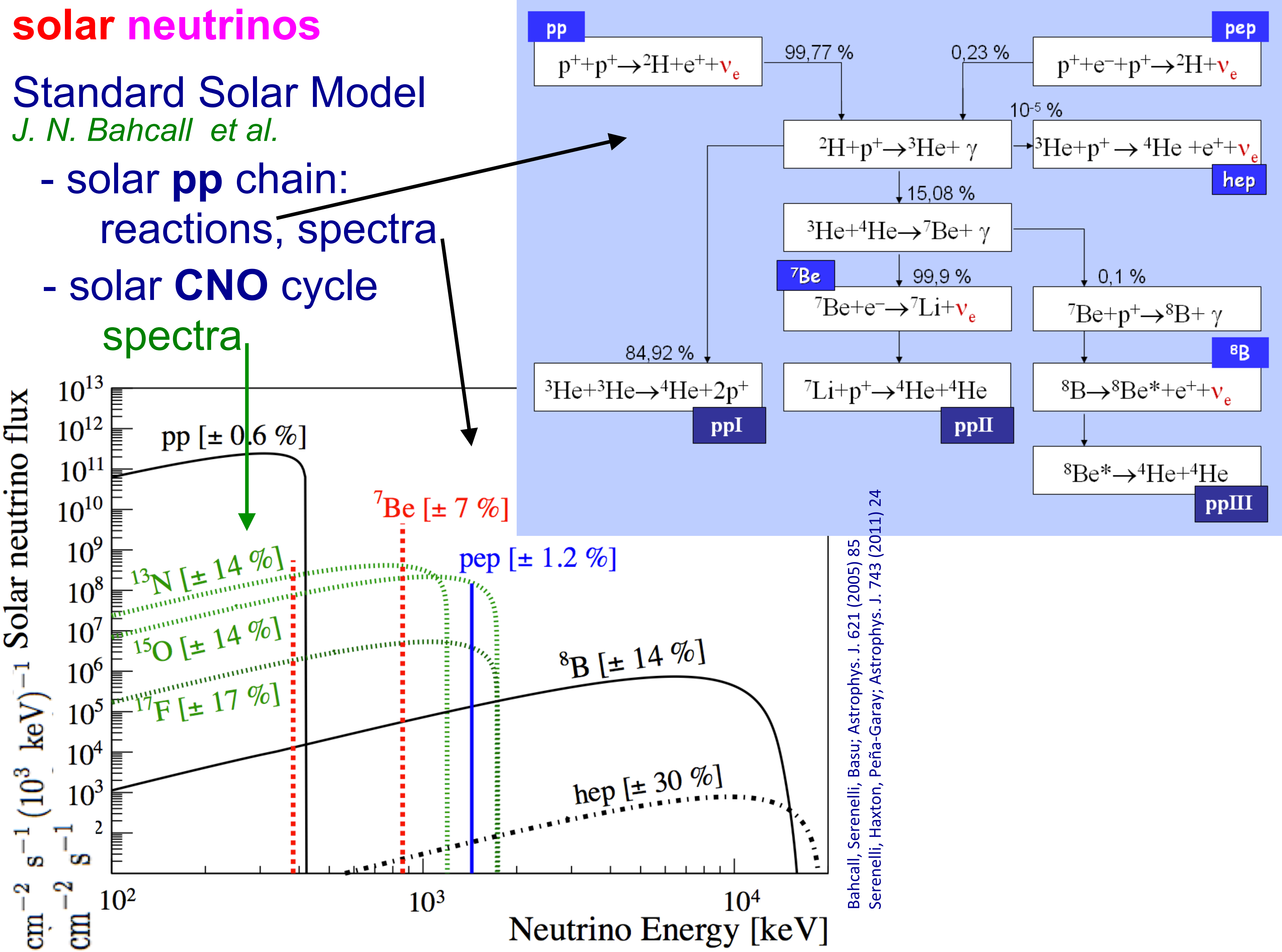
Discovery by Cowan, Raines 1955:
go close to nuclear power reactor
Savannah River in South Carolina
study reaction $\nu + p \rightarrow n + e^-$
delayed coincidence

solar neutrinos

Standard Solar Model

J. N. Bahcall et al.

- solar **pp** chain:
  reactions, spectra
- solar **CNO** cycle
  spectra



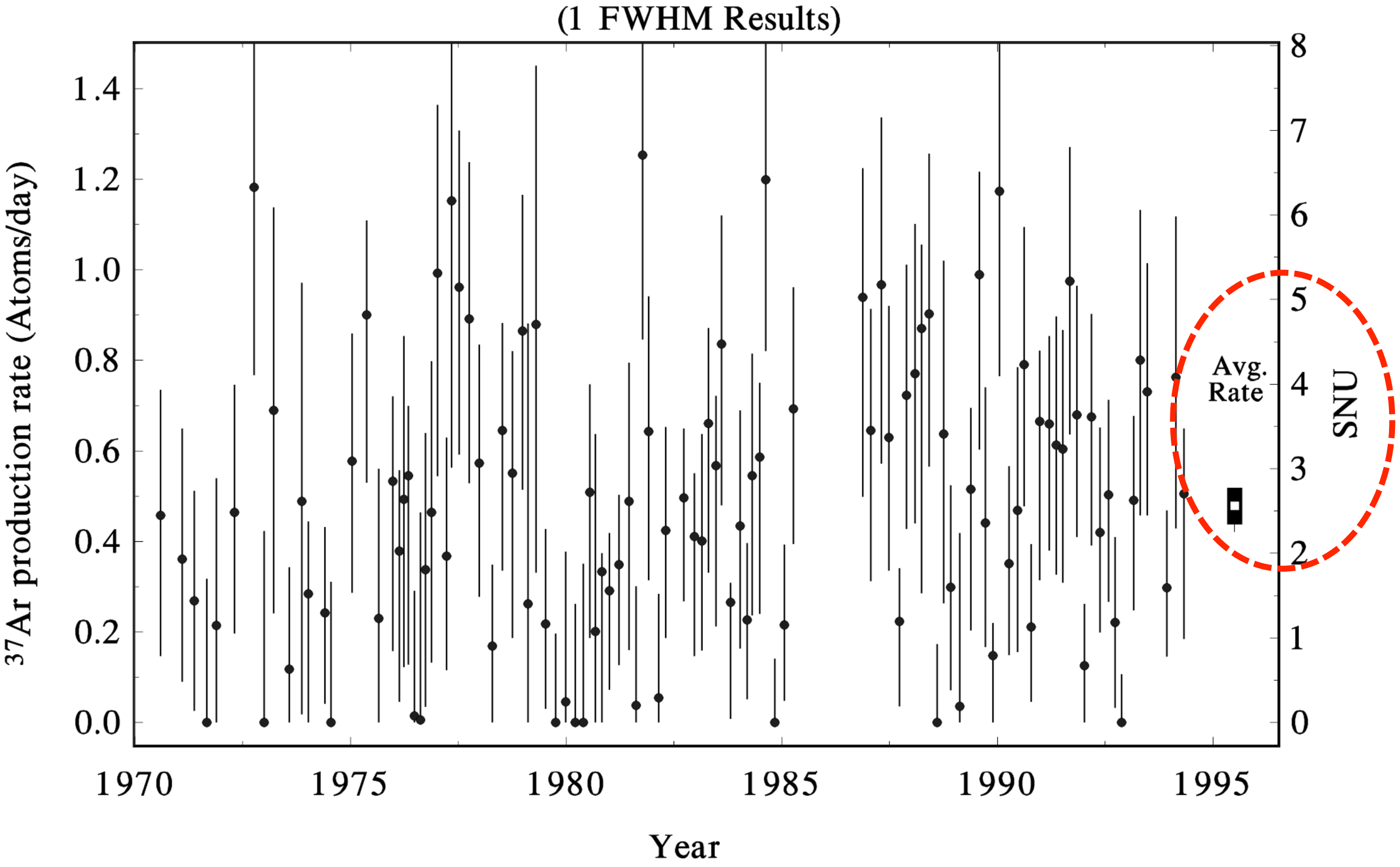
Bahcall, Serenelli, Basu; Astrophys. J. 621 (2005) 85

Serenelli, Haxton, Peña-Garay; Astrophys. J. 743 (2011) 24

Discovery of solar neutrinos; First hints of oscillating neutrinos [of missing e^- neutrinos]

R. Davis, Jr. Homestake Chlorine Detector

J. N. Bahcall $\nu + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$ 1968 → …



Cleveland, Daily, Davis et al.; Astrophys. J. 496-1998-505

Final R. Davis J. et al.: 2.6 ± 0.2 (stat.) ± 0.2 (syst.) *SNU*

1 Solar Neutrino Unit = 1 interaction per 10^{36} target atoms s-1

Nobel 2002

Standard Solar Model: 9.3 ± 1.3 *SNU*

Bahcall, Pinsonneault, M. H. 1995, Rev. Mod. Phys., 67, 781

Nueva generación experimentos: (2)**H_2O-Cherenkov**
origen: búsqueda de la **desintegración del protón**

- en el Modelo Estándar, el protón es absolutamente estable
- sin embargo, dados
  - la estructura físico-matemática del MS,
  - las aproximaciones teóricas realistas para su evolución,
  - el conocimiento actual sobre la creación y desarrollo del Universo…

⇨ existe el “convencimiento” (intuición) de la no estabilidad del protón
es uno de los conceptos científicos más importante de la Humanidad

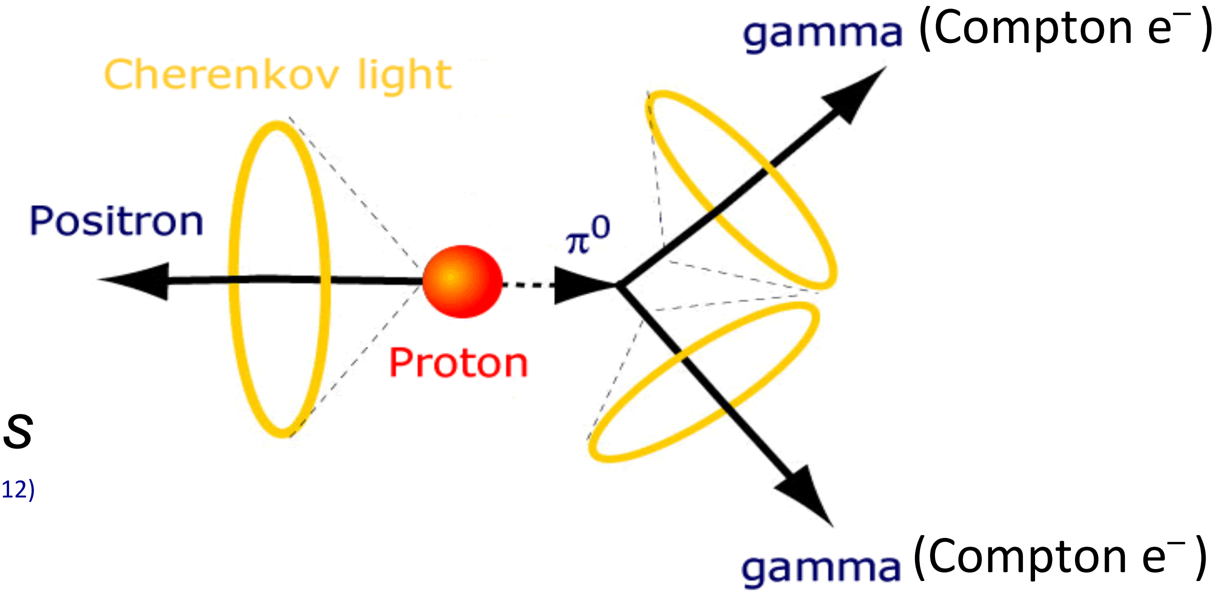
técnica Agua-Cherenkov permite instrumentar
enormes cantidades de materia a observar

p.e.: $p \rightarrow e^+\pi^0$

no candidato
hasta ahora

⇨ $\tau_p > 8.2 \times 10^{33}$ *años*

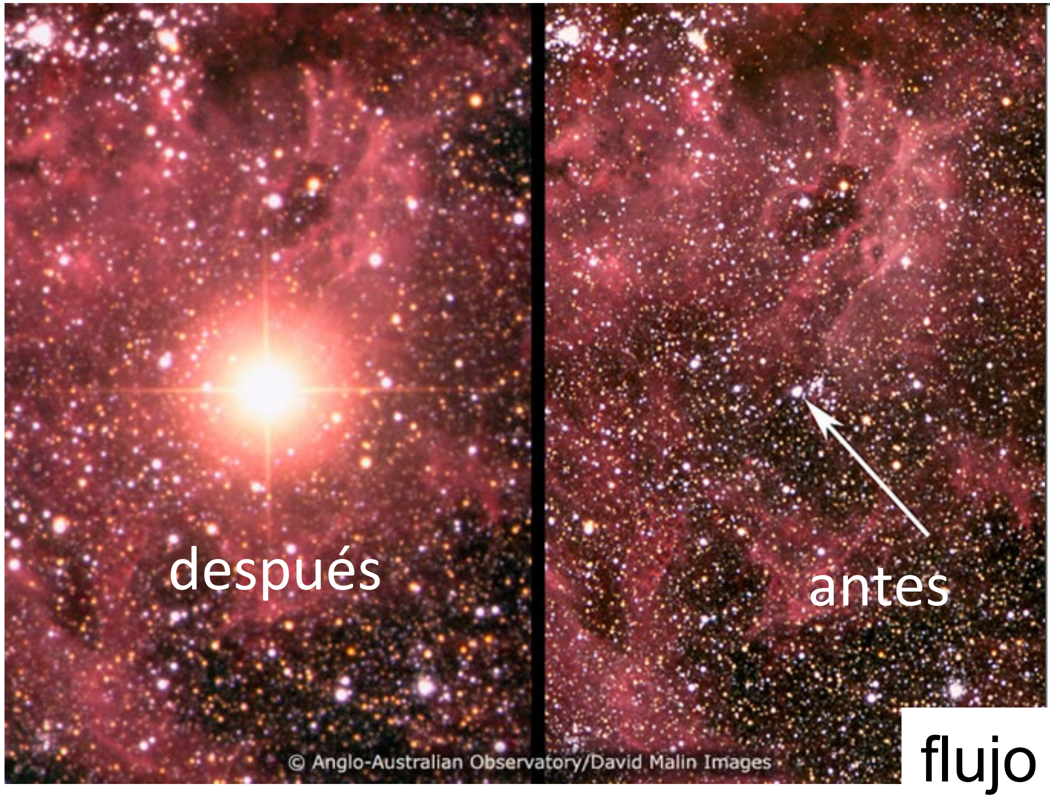
Super-Kamiokande, Phys. Rev. D 85, 112001 (2012)



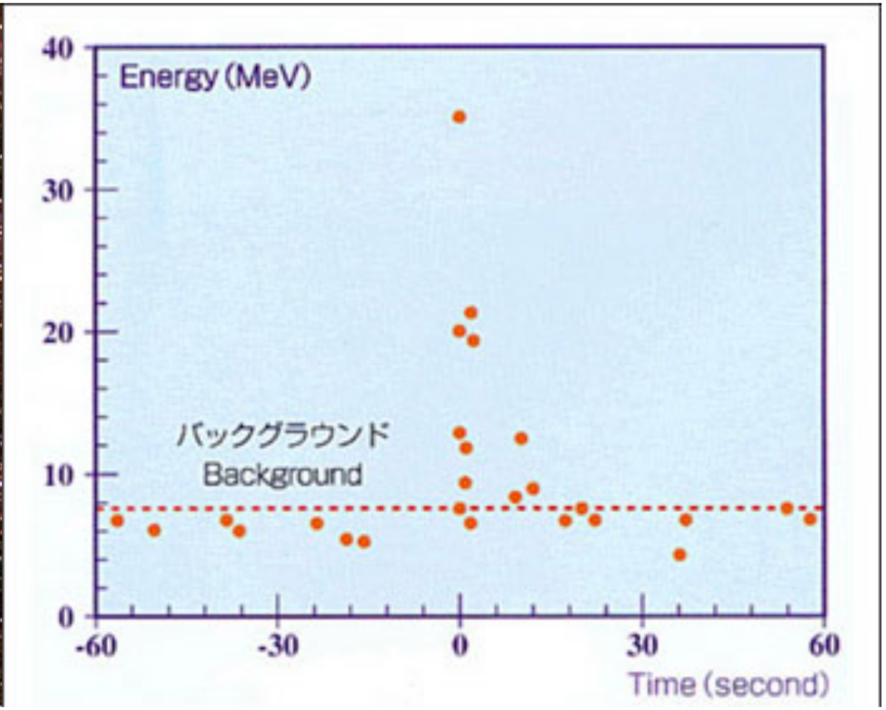
pero la propia Naturaleza nos hizo descubrir que este tipo de detectores son extraordinarios *telescopios de neutrinos*

Kamiokande; Phys. Rev. Lett. 58 (1987) 1490
IMB; Phys. Rev. Lett. 58 (1987) 1494

SuperNova SN1987A (Gran Nube de Magallanes)



© Anglo-Australian Observatory/David Malin Images

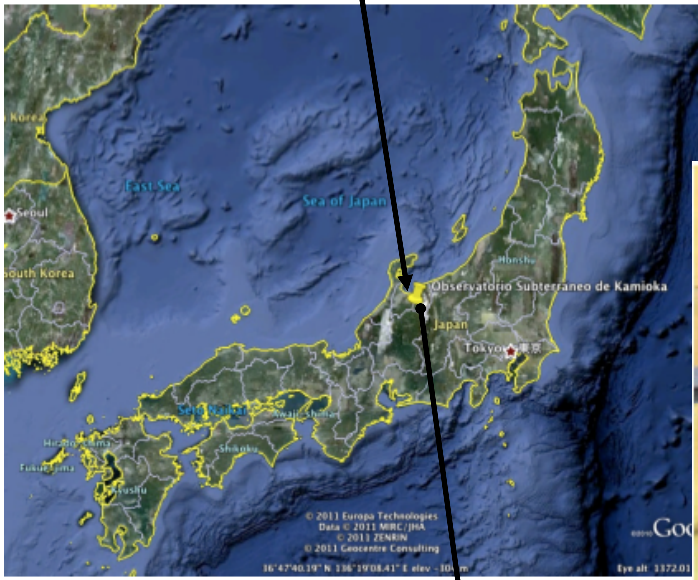


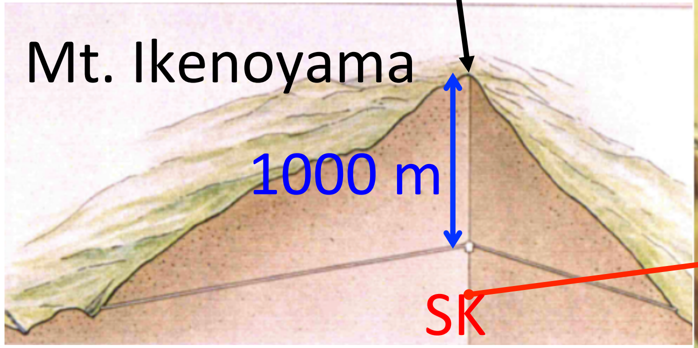
flujo y espectro de ν's medido por Kamiokande (precursor de SK)

telescopios con los que, además de éste (Nobel 2002), se han hecho otros descubrimientos fundamentales (Nobel 2015, …)

Super-Kamiokande (SK) paradigma de detector agua-Cherenkov

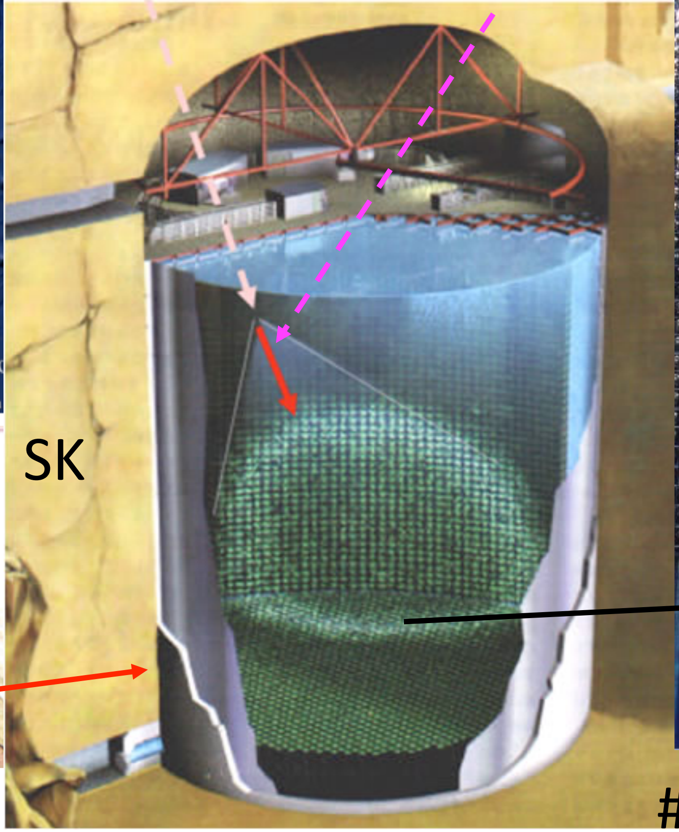
Observatorio de Kamioka
(Prefectura Gifu, Japón)



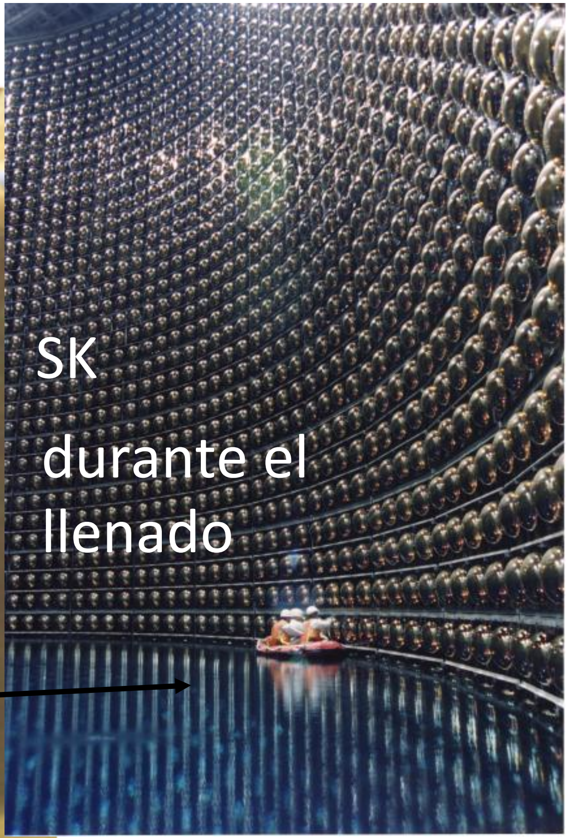


1000 m de tierra para
apantallar muones de
rayos cósmicos

SK mide la radiación Cherenkov generada por las partículas con carga y alta energía

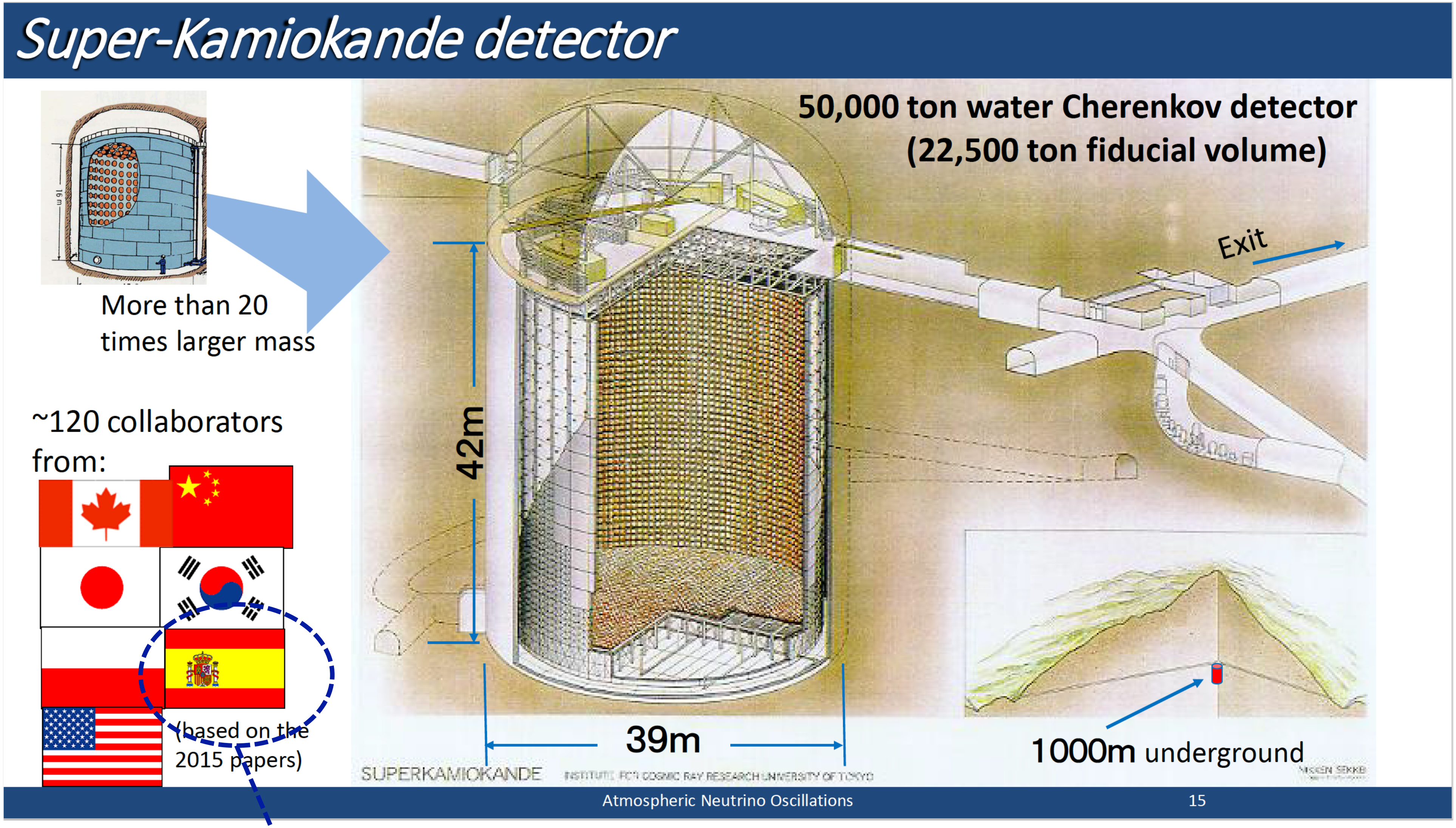


50.000 m^3 de agua
tanque: 40m ∅ x 40m H



fotomultiplicadores
11148 de 50 cm ∅
1885 de 20 cm ∅

T. Kajita; Nobel Lecture; Stockholm , Dec. 8, 2015



Super-Kamiokande detector

50,000 ton water Cherenkov detector
(22,500 ton fiducial volume)

More than 20
times larger mass

~120 collaborators
from:

(based on the
2015 papers)

I am very proud of it !

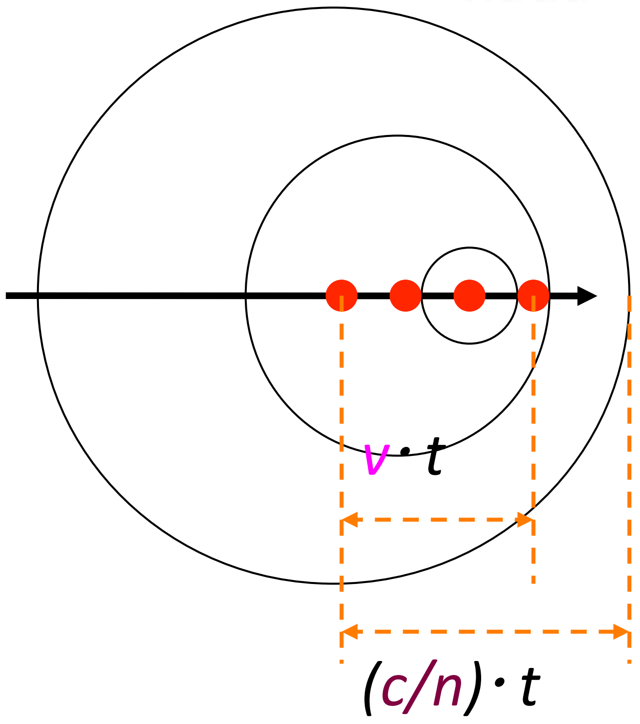
but no funding from the Spanish Ministry for already 5 P.I. Calls (~already 6 years)

Básico de la radiación Cherenkov

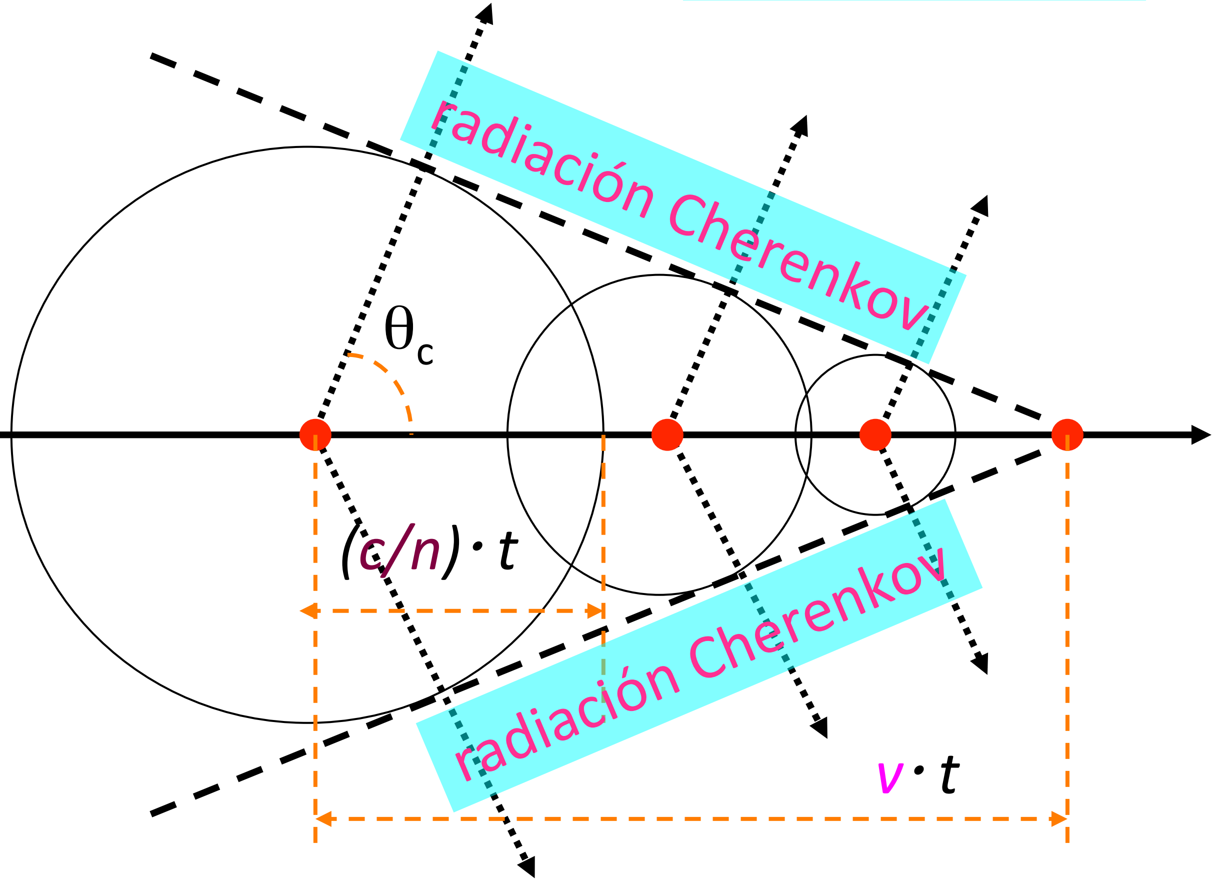
una partícula cargada moviéndose en un medio con velocidad v
genera un campo EM que se propaga con velocidad c/n

dos casos

$v < c/n$ ⇨ “nada”



$v > c/n$ ⇨ onda de choque

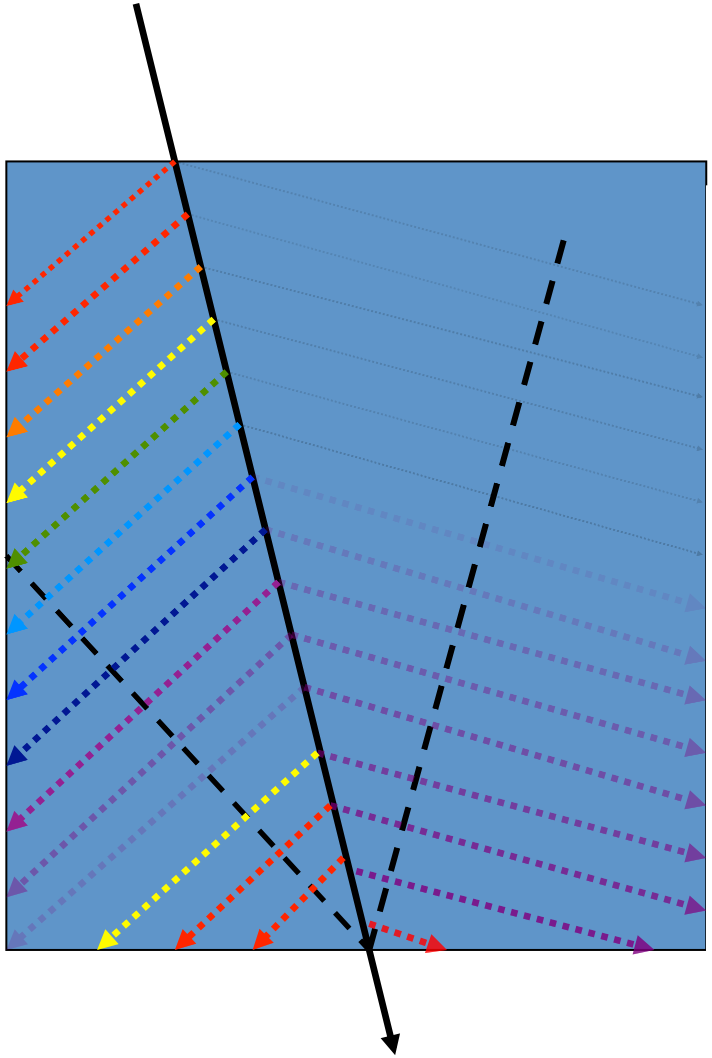


si $v/c \approx 1$, en agua, $\theta_c \approx 42^o$

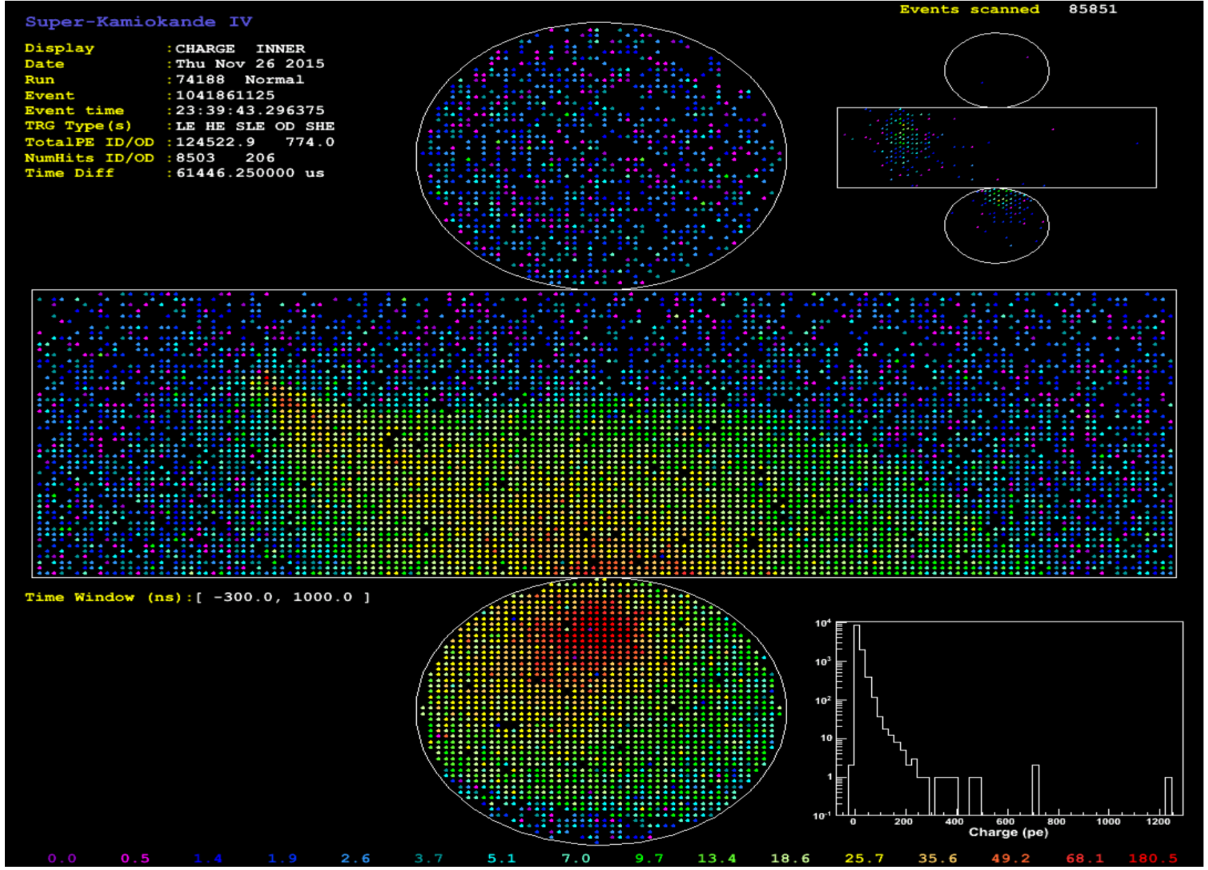
p.e.: la medida del tiempo que tarda la luz Cherenkov en llegar a los PMT’s

rojo: corto
púrpura: largo
púrpura suave: muy largo

nos permite reconstruir la trayectoria de las partículas …



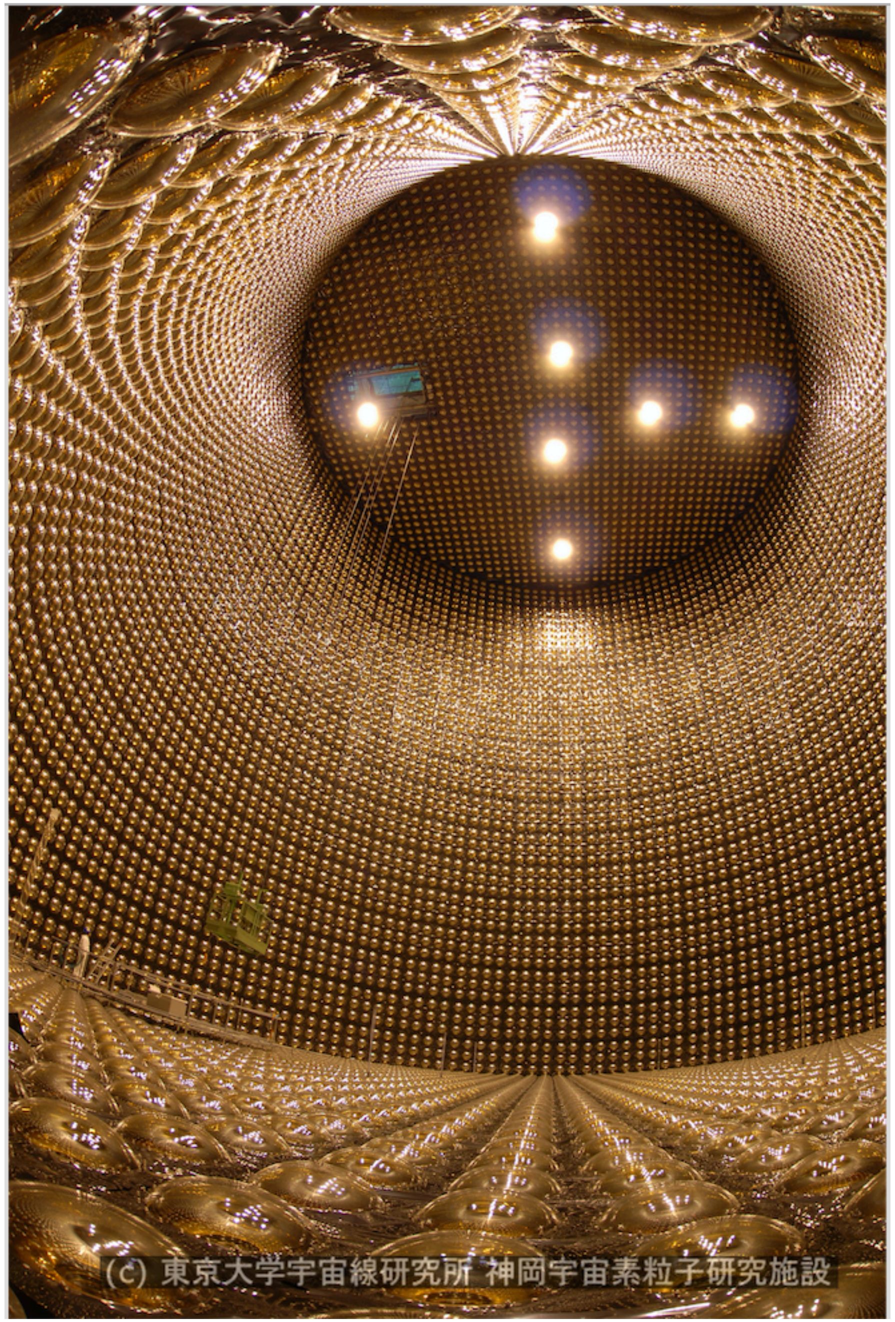
1 muón incidiendo por arriba izquierda
medida de carga



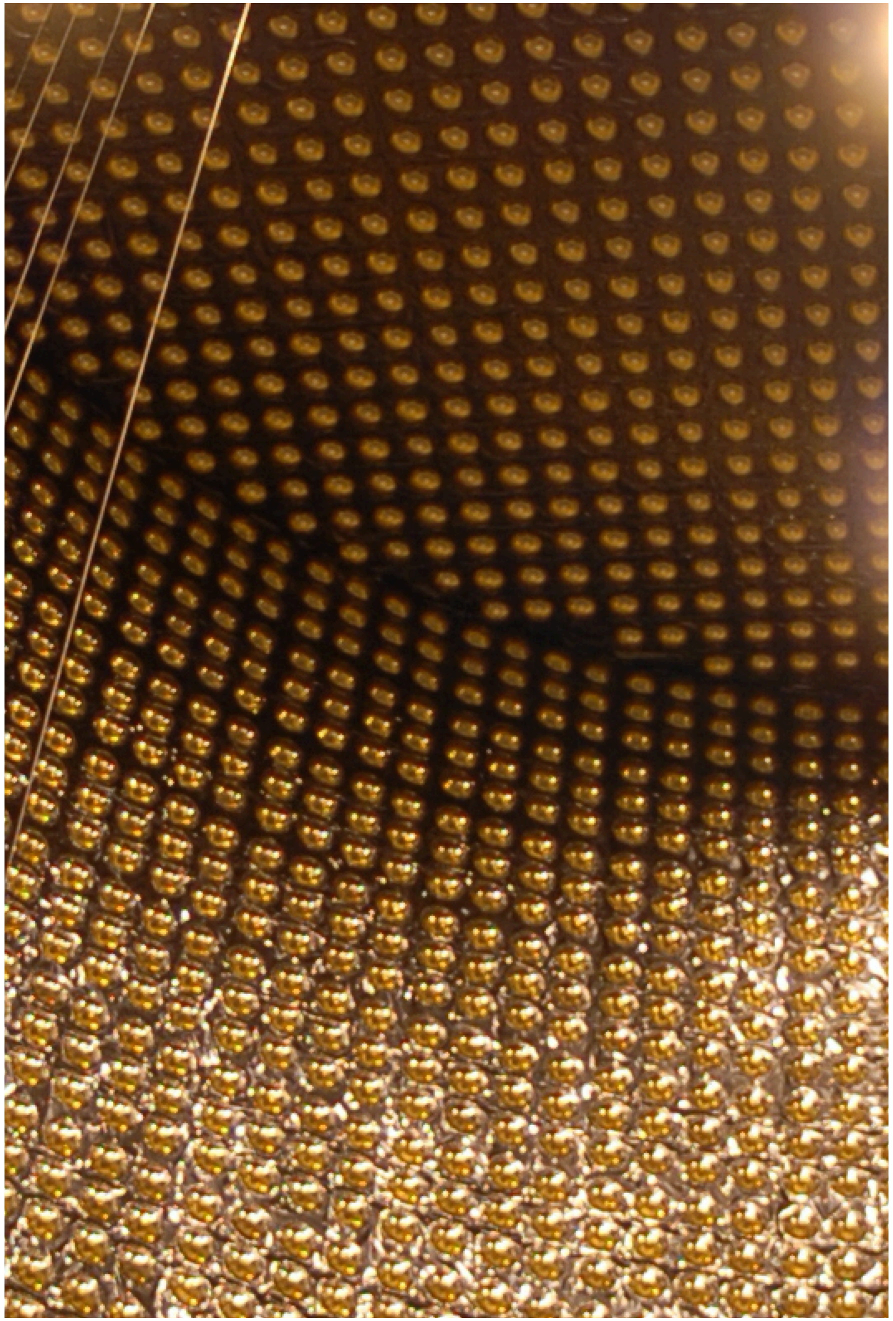
```
Super-Kamiokande IV                                                   Events scanned    85851

Display        :CHARGE   INNER
Date           :Thu Nov 26 2015
Run            :74188   Normal
Event          :1041861125
Event time     :23:39:43.296375
TRG Type(s)    :LE HE SLE OD SHE
TotalPE ID/OD  :124522.9   774.0
NumHits ID/OD  :8503   206
Time Diff      :61446.250000 us

Time Window (ns):[ -300.0, 1000.0 ]
```

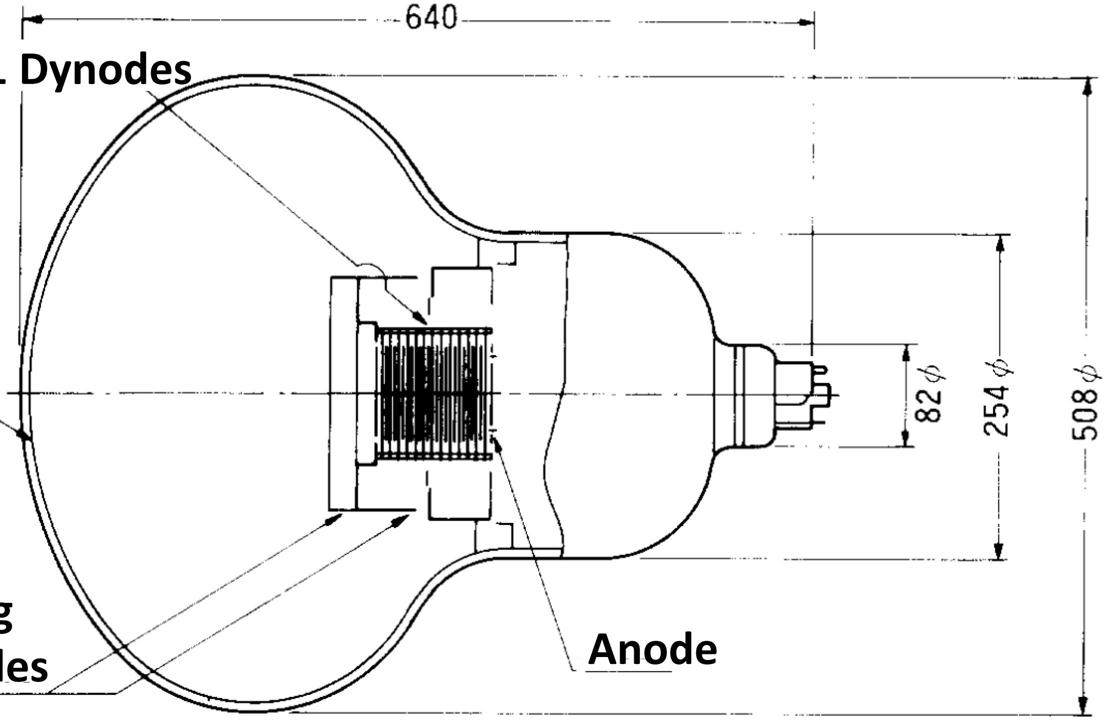


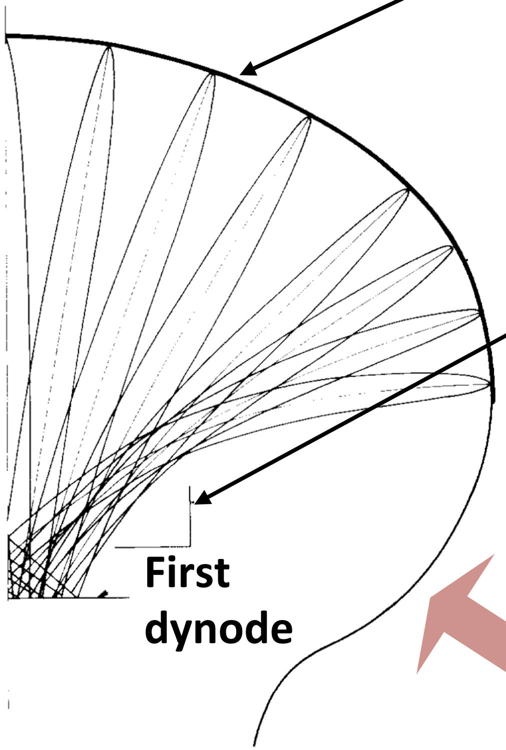
(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設



Hamamatsu R3600

Basic sketch:





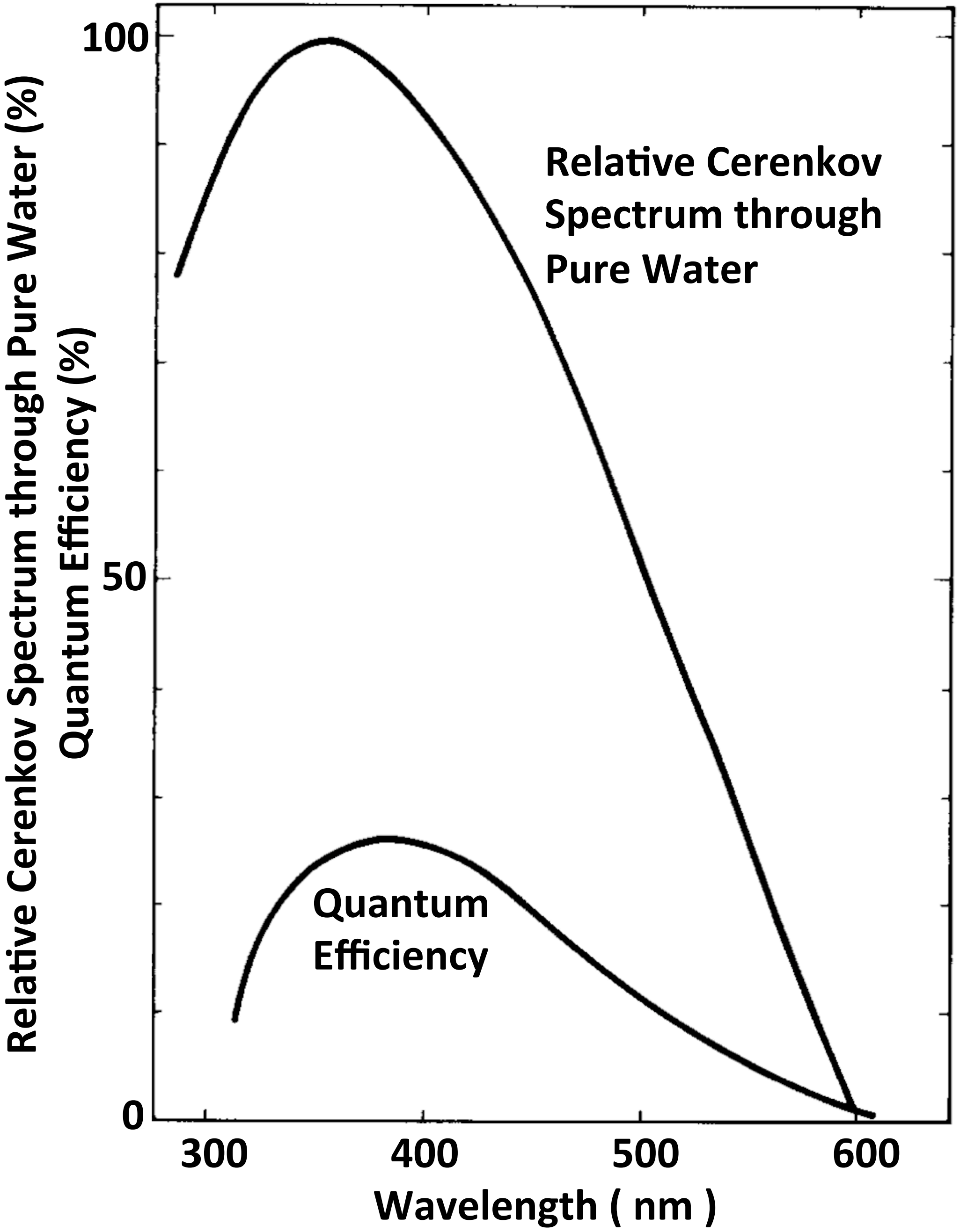
computer simulation of electron trajectories

operating gain / voltage:
10^7 / 1700 – 2000 V

timing resolution ≈2 ns

1 p.e. charge resolution: 53 %

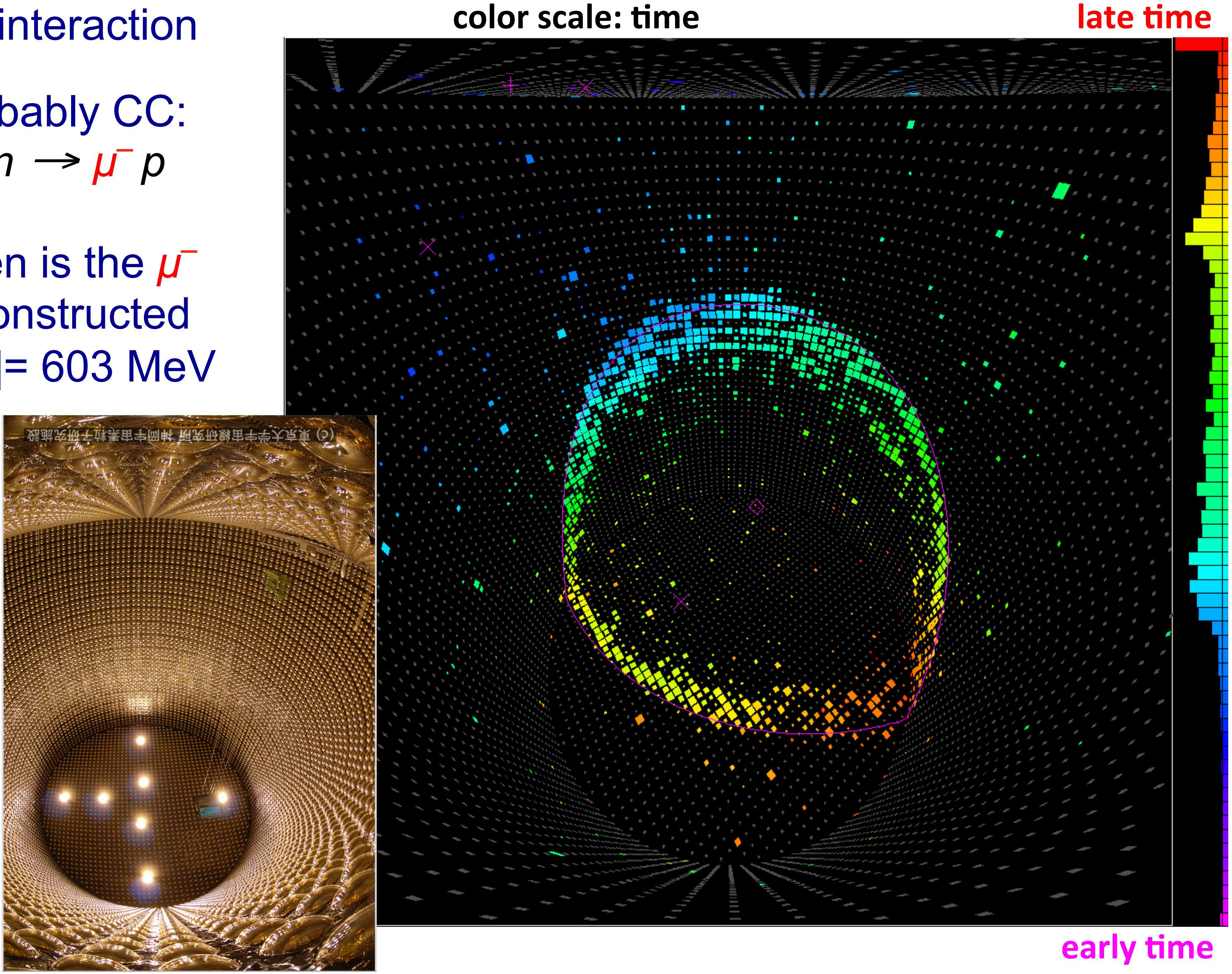
dark noise (< 0.25 p.e.) ≈3 kHz



ν_μ interaction

probably CC:
$\nu_\mu\, n \rightarrow \mu^- p$

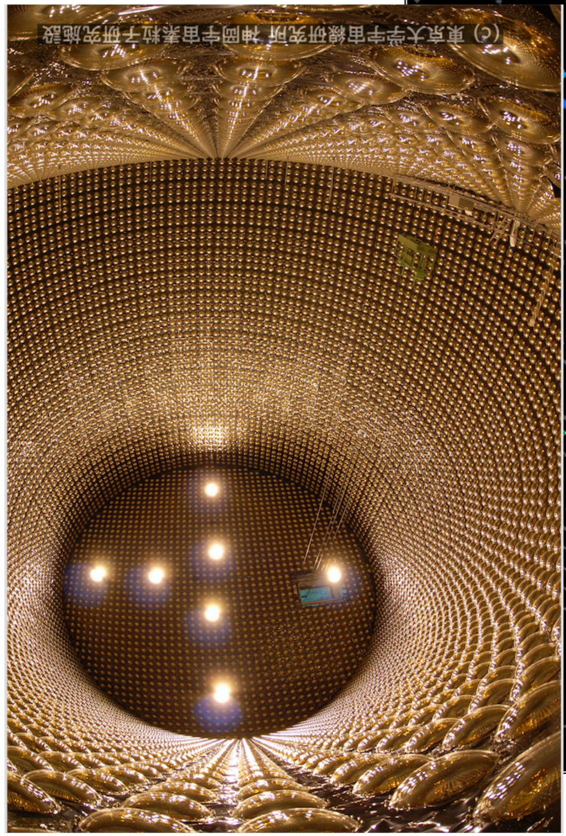
Seen is the μ^-
reconstructed
E[μ]= 603 MeV

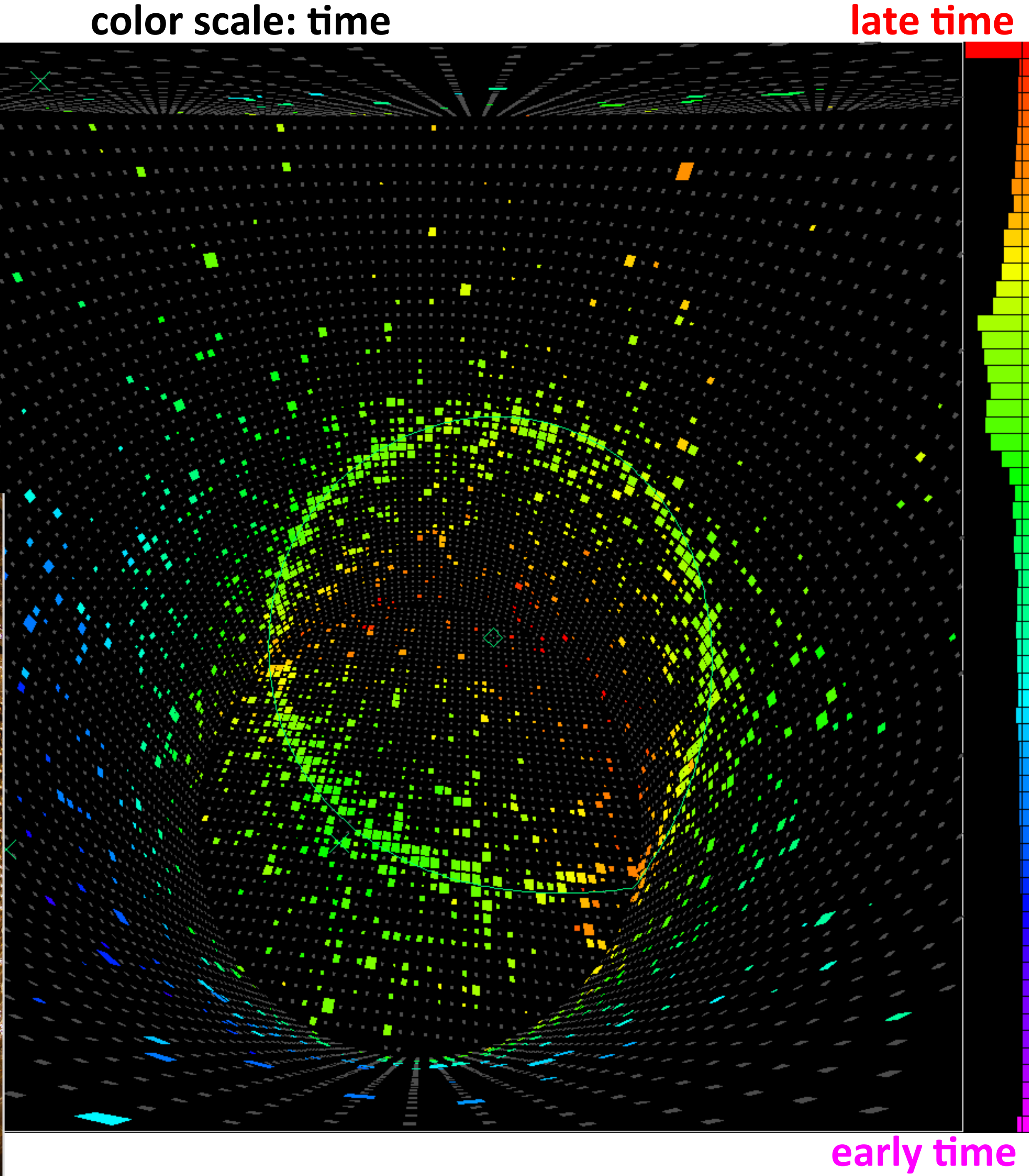


ν_e interaction

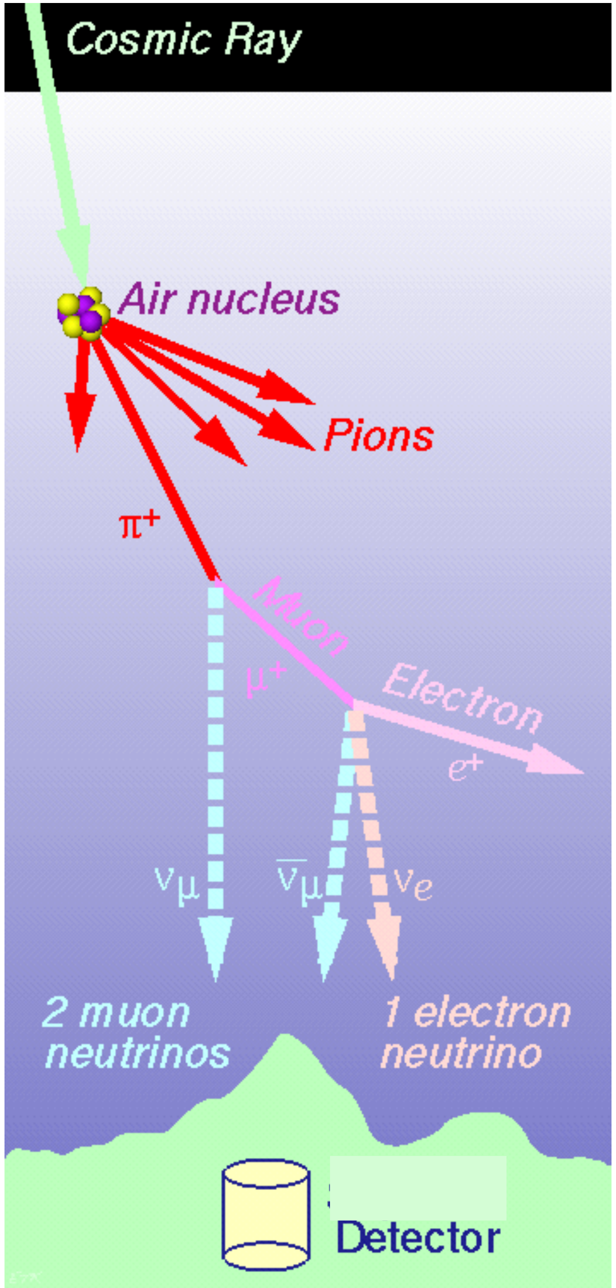
probably CC:
$\nu_e\, n \rightarrow e^- p$

Seen is the e^-
reconstructed
E[e^-]= 492 MeV

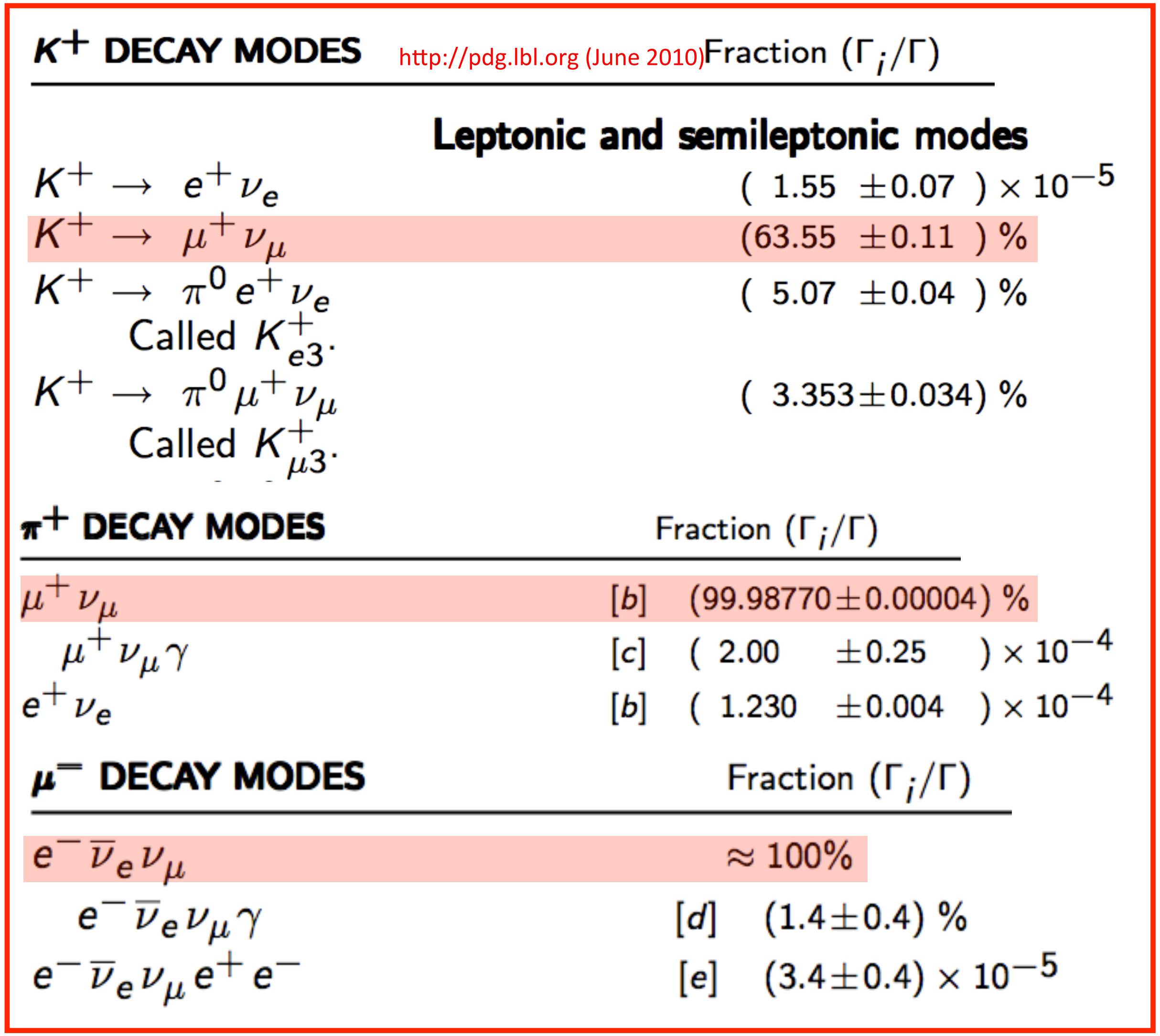




Atmospheric ν's



result from the decay of particles produced in the interactions of Cosmic Rays with the atmosphere (mainly $K^\pm$, $\pi^\pm$, $\mu^\pm$)



http://pdg.lbl.org (June 2010)

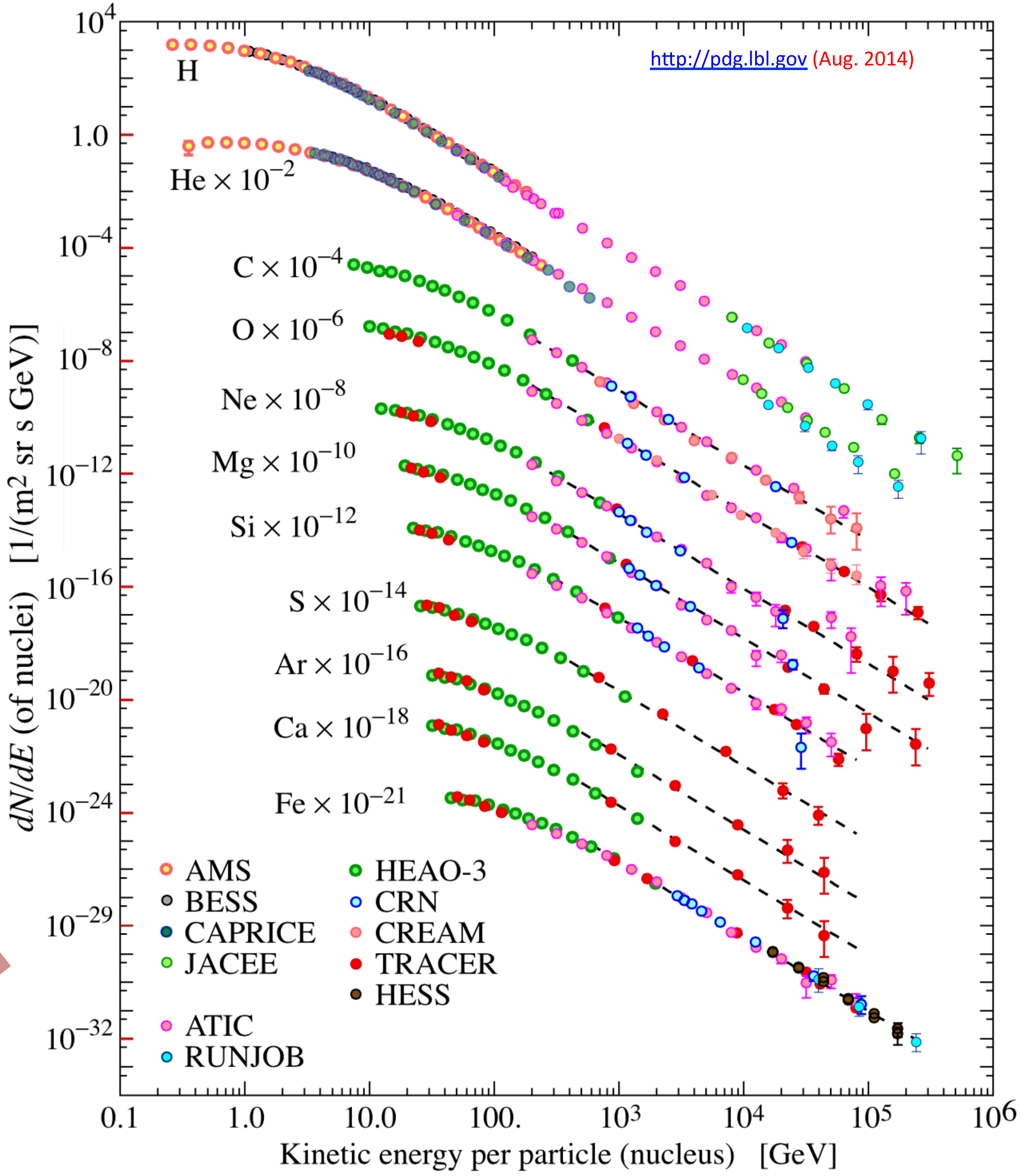
K^+ DECAY MODES	Fraction (Γ_i/Γ)
Leptonic and semileptonic modes	
$K^+ \rightarrow e^+\nu_e$	$(1.55 \pm 0.07) \times 10^{-5}$
$K^+ \rightarrow \mu^+\nu_\mu$	(63.55 ± 0.11) %
$K^+ \rightarrow \pi^0 e^+\nu_e$ Called K^+_{e3}.	(5.07 ± 0.04) %
$K^+ \rightarrow \pi^0 \mu^+\nu_\mu$ Called $K^+_{\mu 3}$.	(3.353 ± 0.034) %

π^+ DECAY MODES		Fraction (Γ_i/Γ)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$
$e^+\nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$

μ^- DECAY MODES		Fraction (Γ_i/Γ)
$e^-\bar{\nu}_e\nu_\mu$		$\approx 100\%$
$e^-\bar{\nu}_e\nu_\mu\gamma$	[d]	(1.4 ± 0.4) %
$e^-\bar{\nu}_e\nu_\mu e^+ e^-$	[e]	$(3.4 \pm 0.4) \times 10^{-5}$

they span a very large range of energy

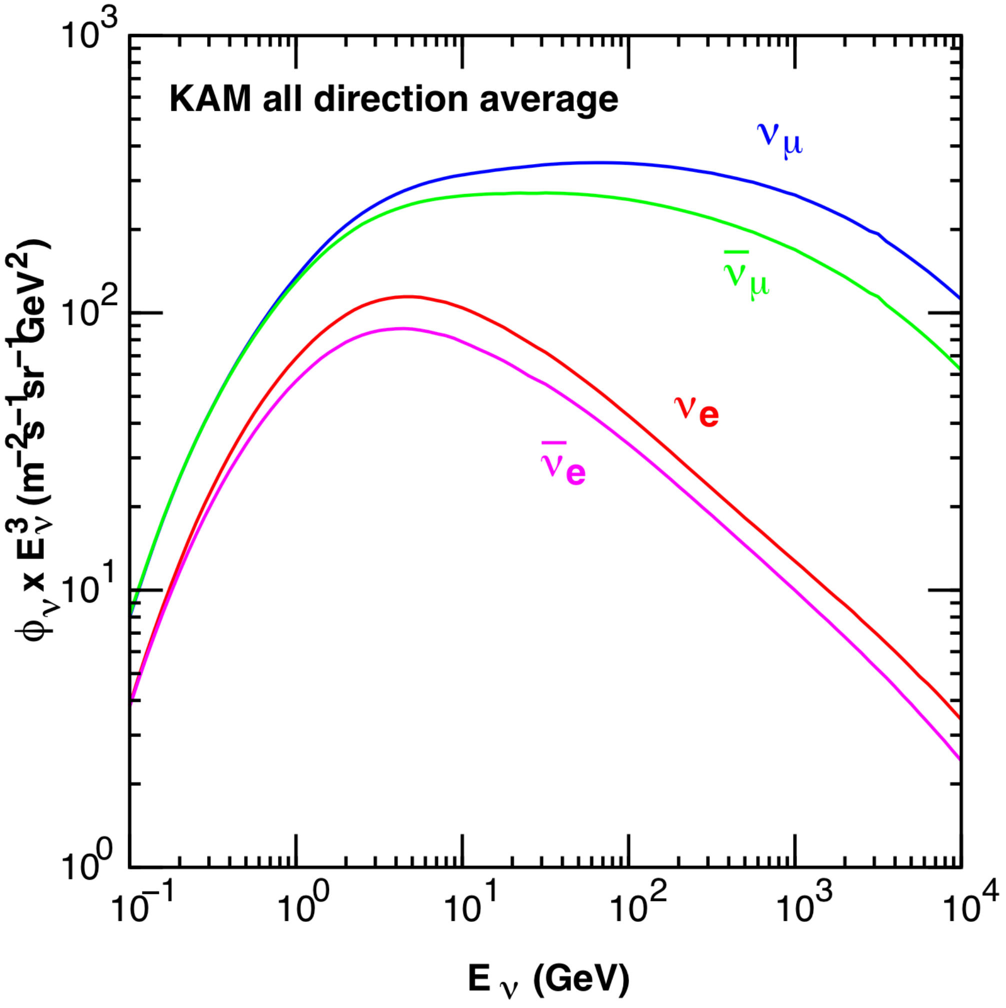
Major components of primary CR radiation:

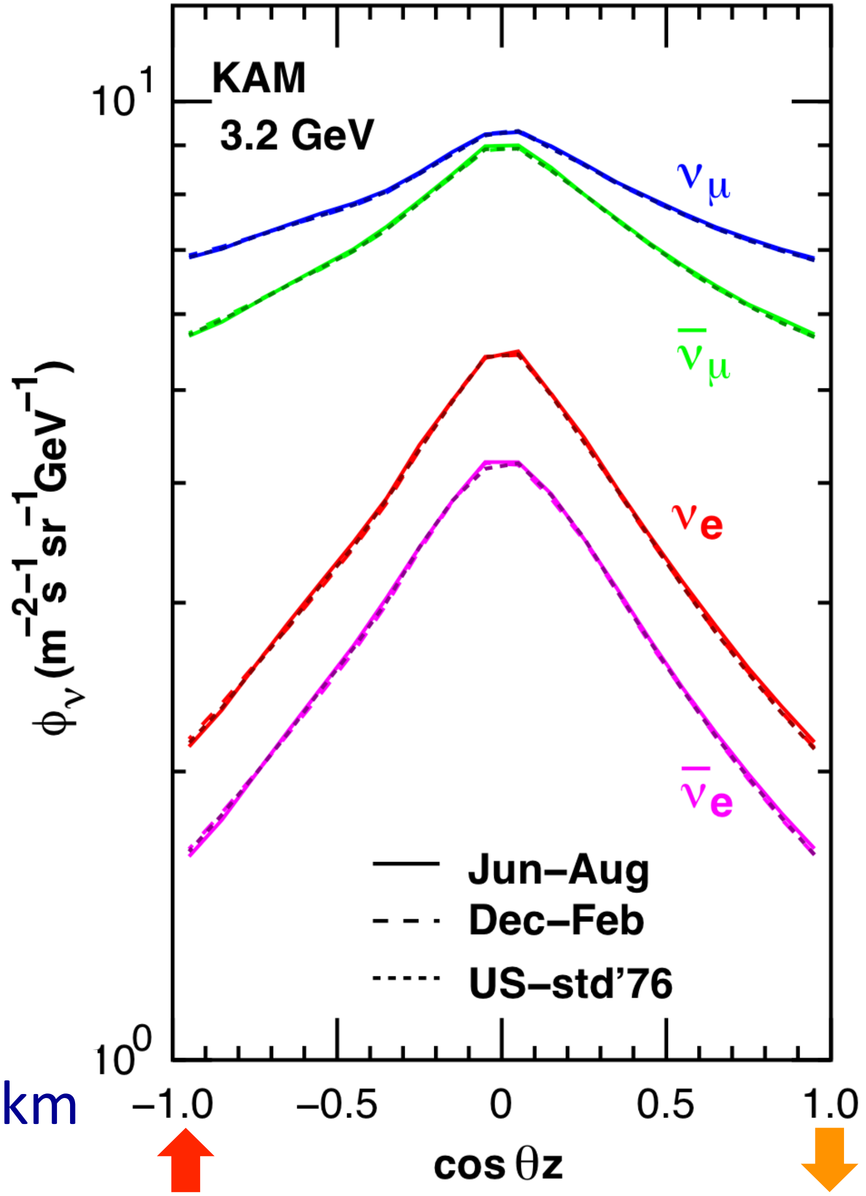


Estimate ν flux:

Atmospheric Neutrinos: Predicted Fluxes at Super-Kamiokande

M. Honda, M.S. Athar, **T. Kajita**, K. Kasahara, S. Mirdorikawa; arXiv:1502.03916v2





⬆ upwards, travel ≈13000 km

⬇ downwards, travel ≈ 15 km

Main interactions

Elastic $\nu + e \longrightarrow \nu + e$

quasi-elastic

CC:

$\nu_l n \longrightarrow l^- p$

$\bar{\nu}_l p \longrightarrow l^+ n$ (IBD) ← **< 1 GeV**

---- CCQE

.... CC single π

-·-·- DIS

—— total

1 meson *CC:*

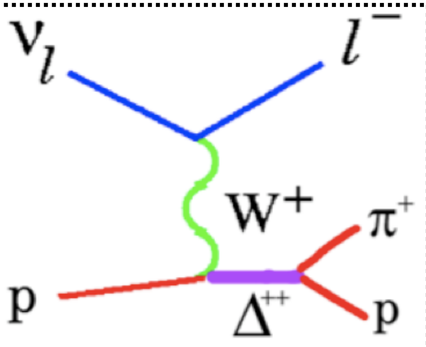
a) $\nu N \longrightarrow l\, N^*,\ N^* \longrightarrow m N'$

N, N': nucleons

N: baryon resonance*

m: meson (π's, also K, η)

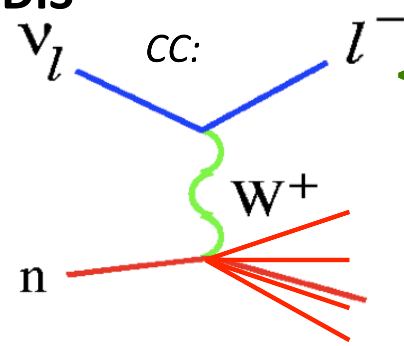
b) coherent π production: $\nu\, ^{16}O \longrightarrow l\, \pi\, ^{16}O$



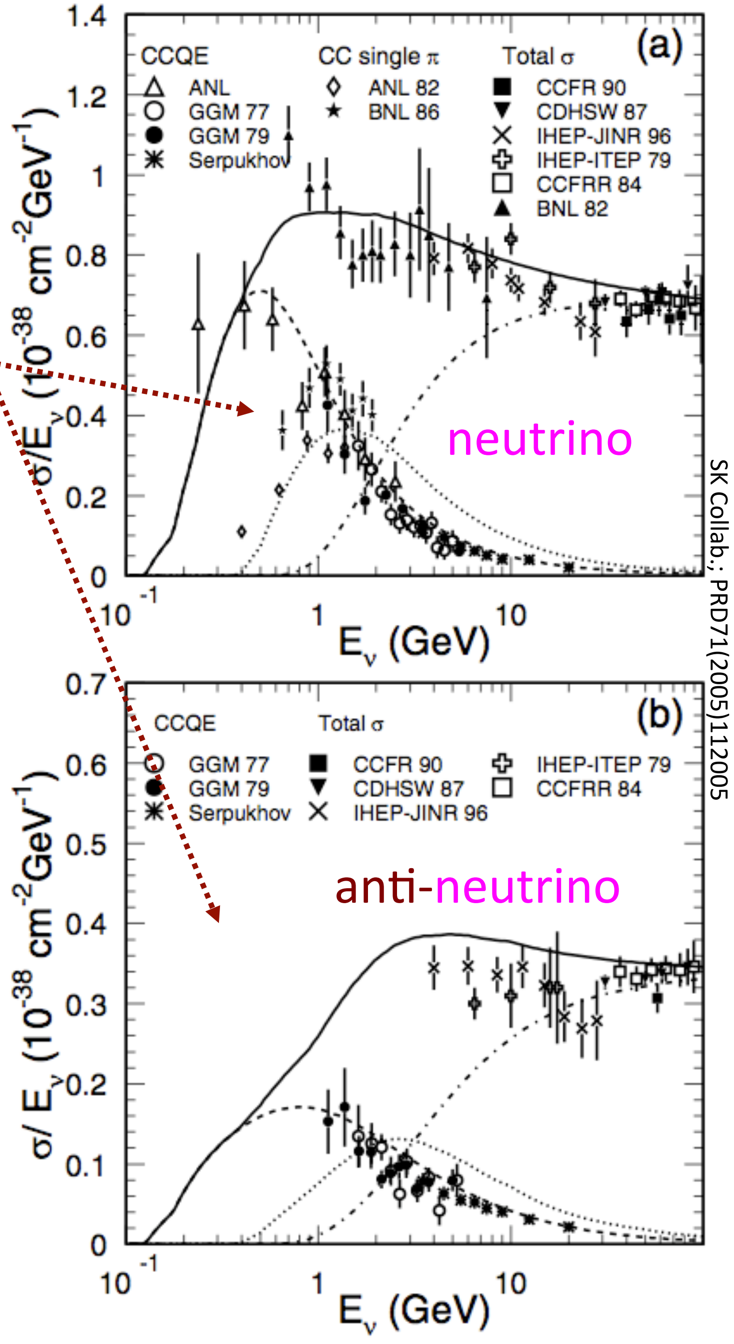
↑ **~ 1 GeV**

DIS

CC:



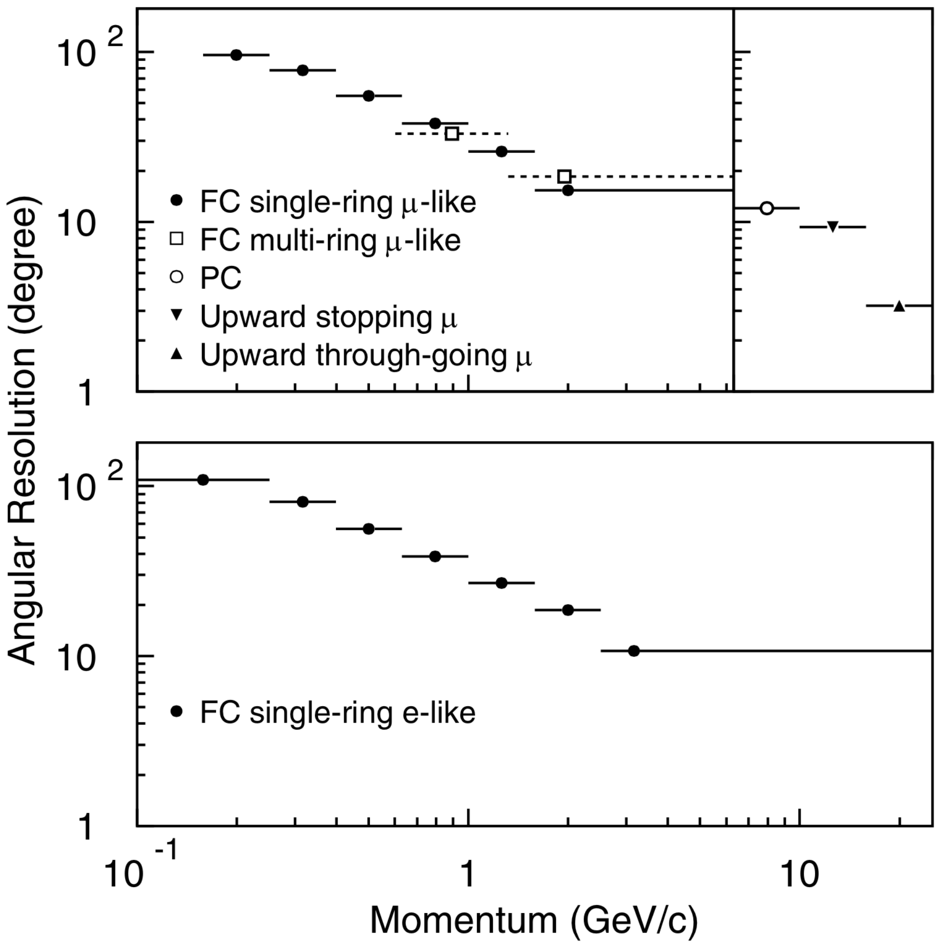
← **High Energy**



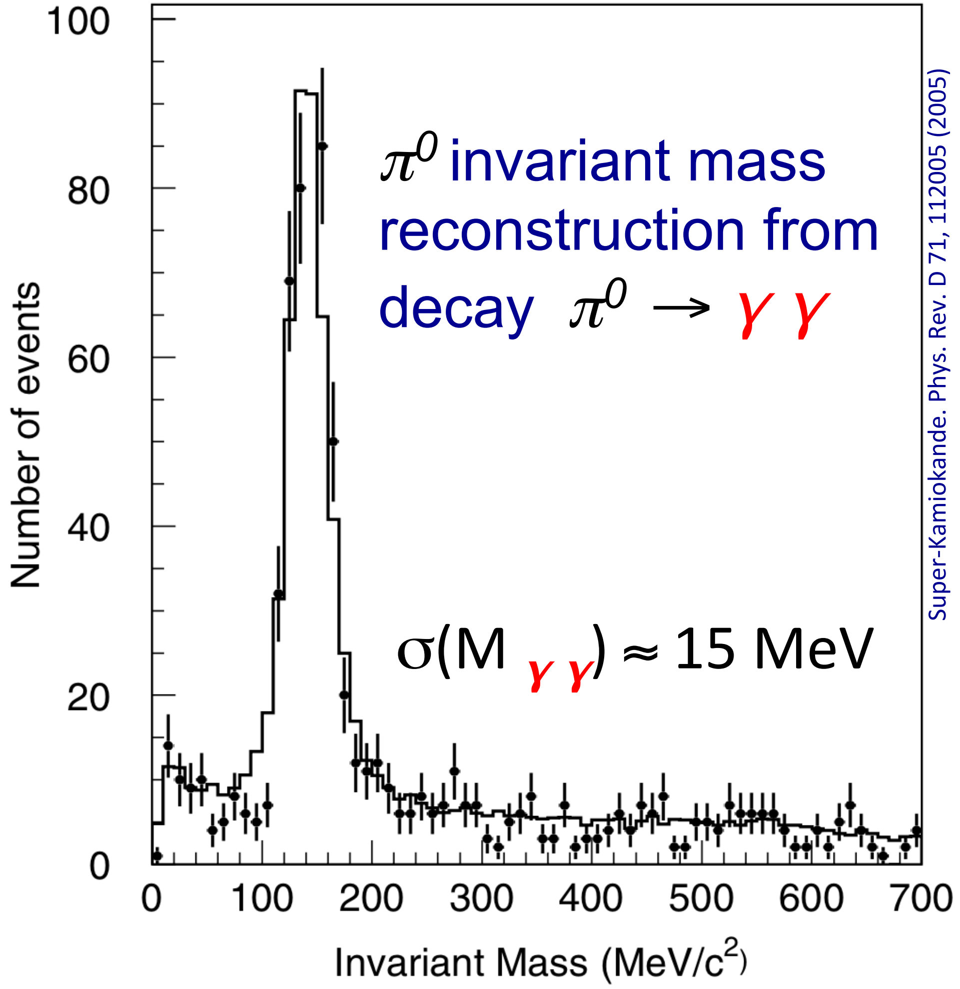
SK Collab.; PRD71(2005)112005

Atmospheric νs reconstruction by Super-Kamiokande

Angular resolution for different type of events vs. momentum



Momentum reconstruction

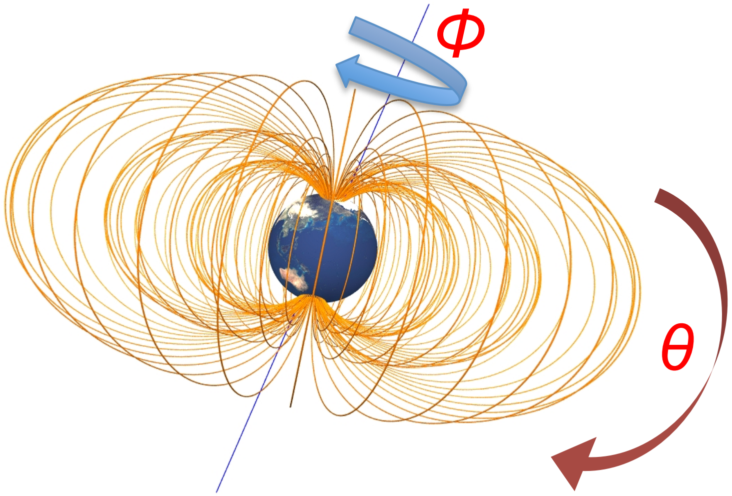


π^0 invariant mass reconstruction from decay $\pi^0 \rightarrow \gamma\,\gamma$

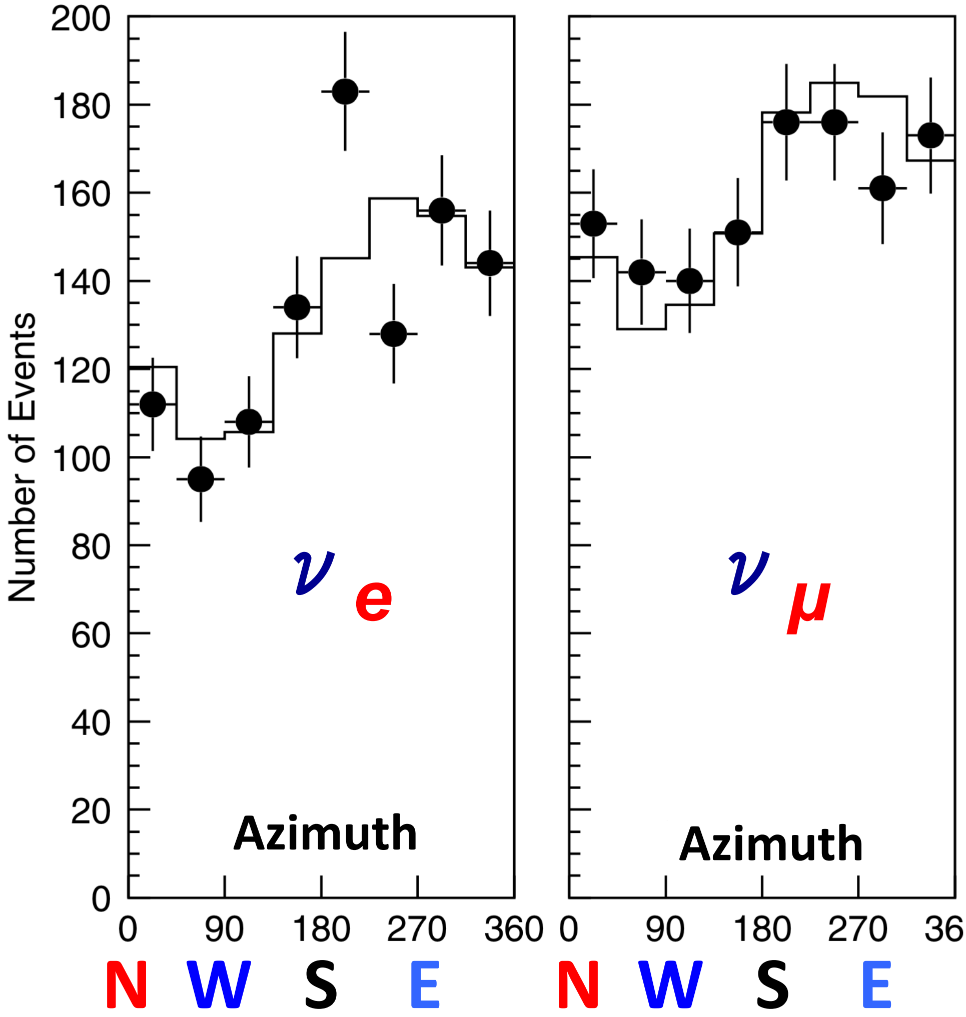
$\sigma(M_{\gamma\gamma}) \approx 15$ MeV

Super-Kamiokande. Phys. Rev. D 71, 112005 (2005)

ν_e, ν_μ fluxes vs. incidence angle: Φ symmetry must hold [not really because of earth magnetic field: **E** – **W** effect]



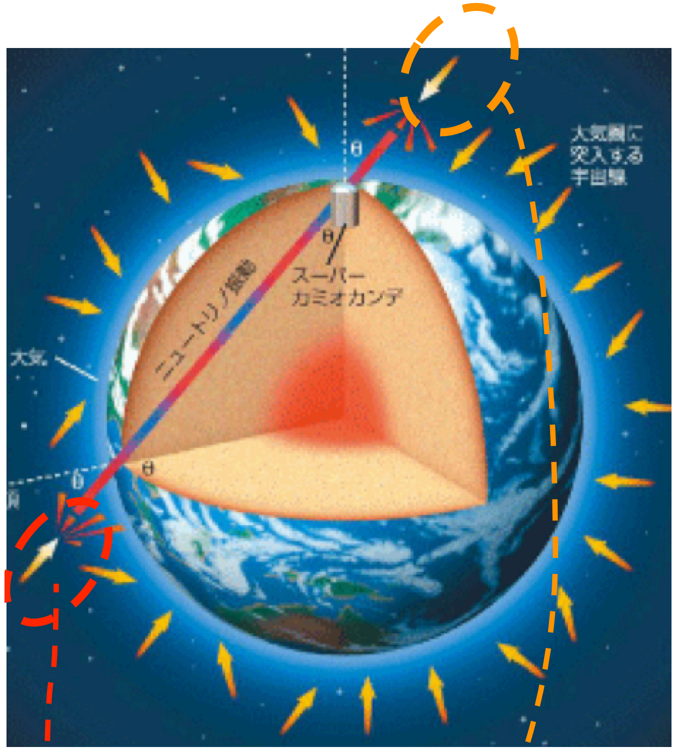
0.4 GeV < E(ν) < 3 GeV
| cos θ | < 0.5

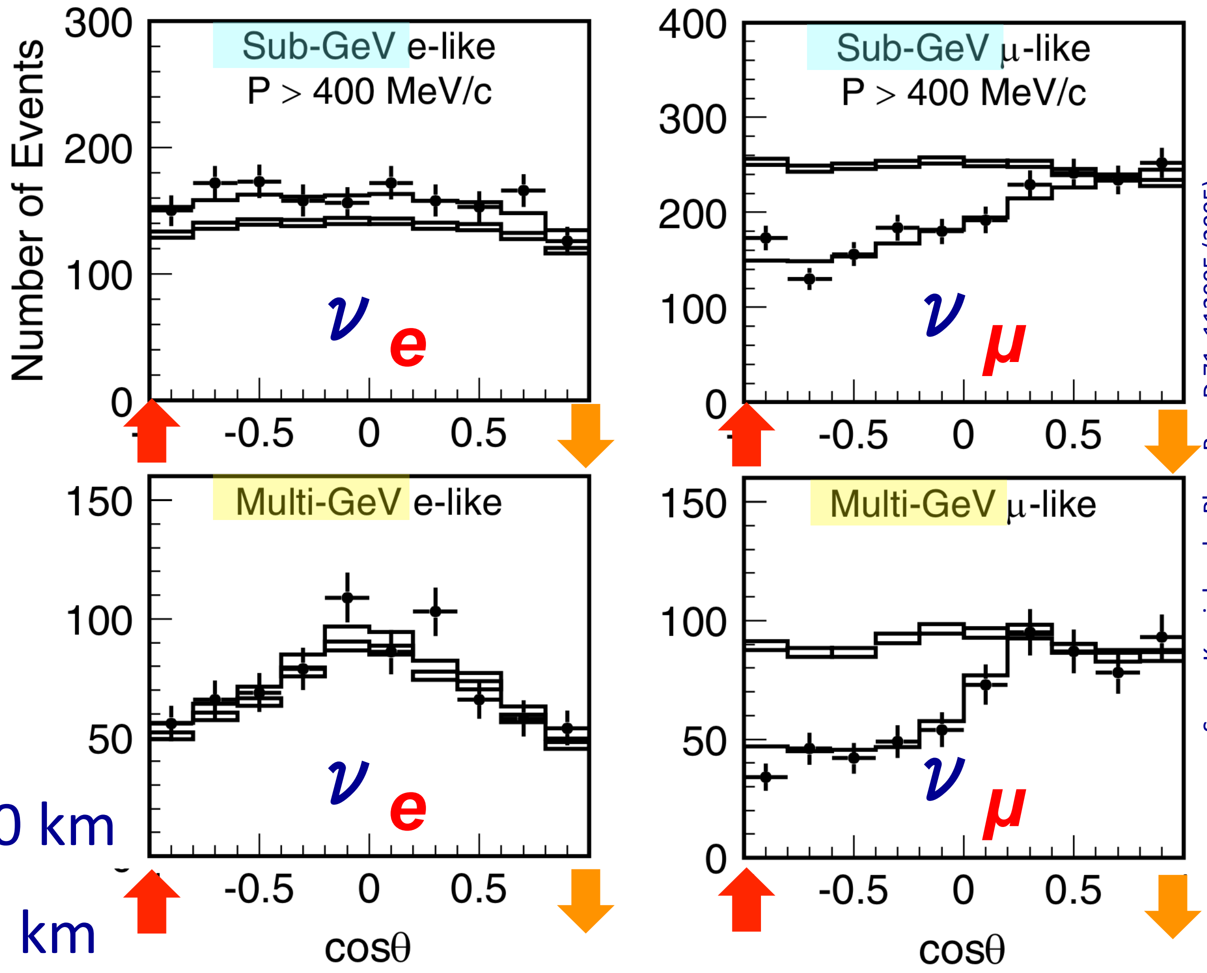


Super-Kamiokande. Phys. Rev. D 71, 112005 (2005)

→ Φ (azimuth) symmetry holds

ν_e , ν_μ fluxes vs. energy and θ incidence angle (zenith)





Super-Kamiokande. Phys. Rev. D 71, 112005 (2005)

upwards, travel ≈13000 km

downwards, travel ≈ 15 km

measured ν_μ flux strongly dependent on travel distance

→ ν_μ oscillates → **massive ν_x** ✓

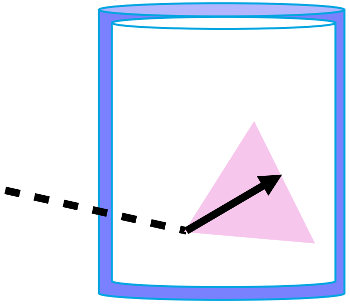
(mainly to ν_τ)

Nobel 2015

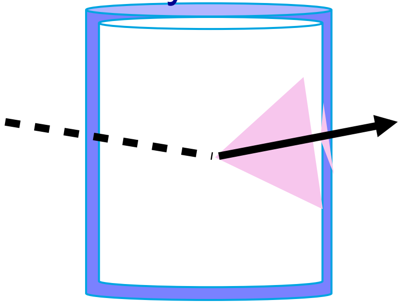
small effects on ν_e
(note high energy)

A full oscillation analysis:

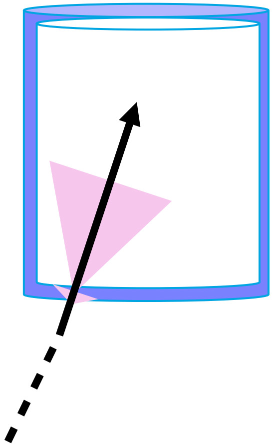
Fully **C**ontained

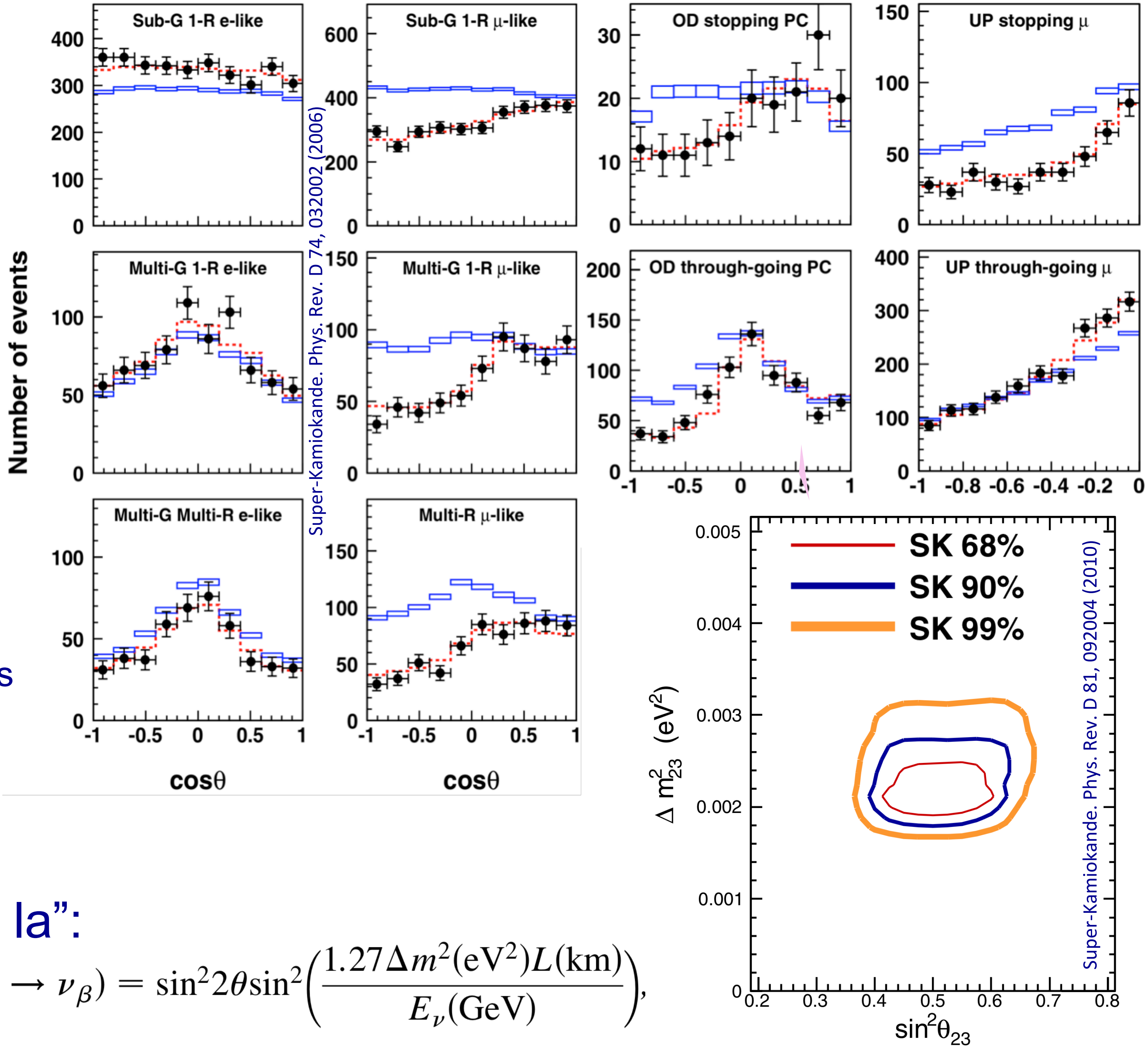


Partially **C**ontained



UPward-going **M**uons





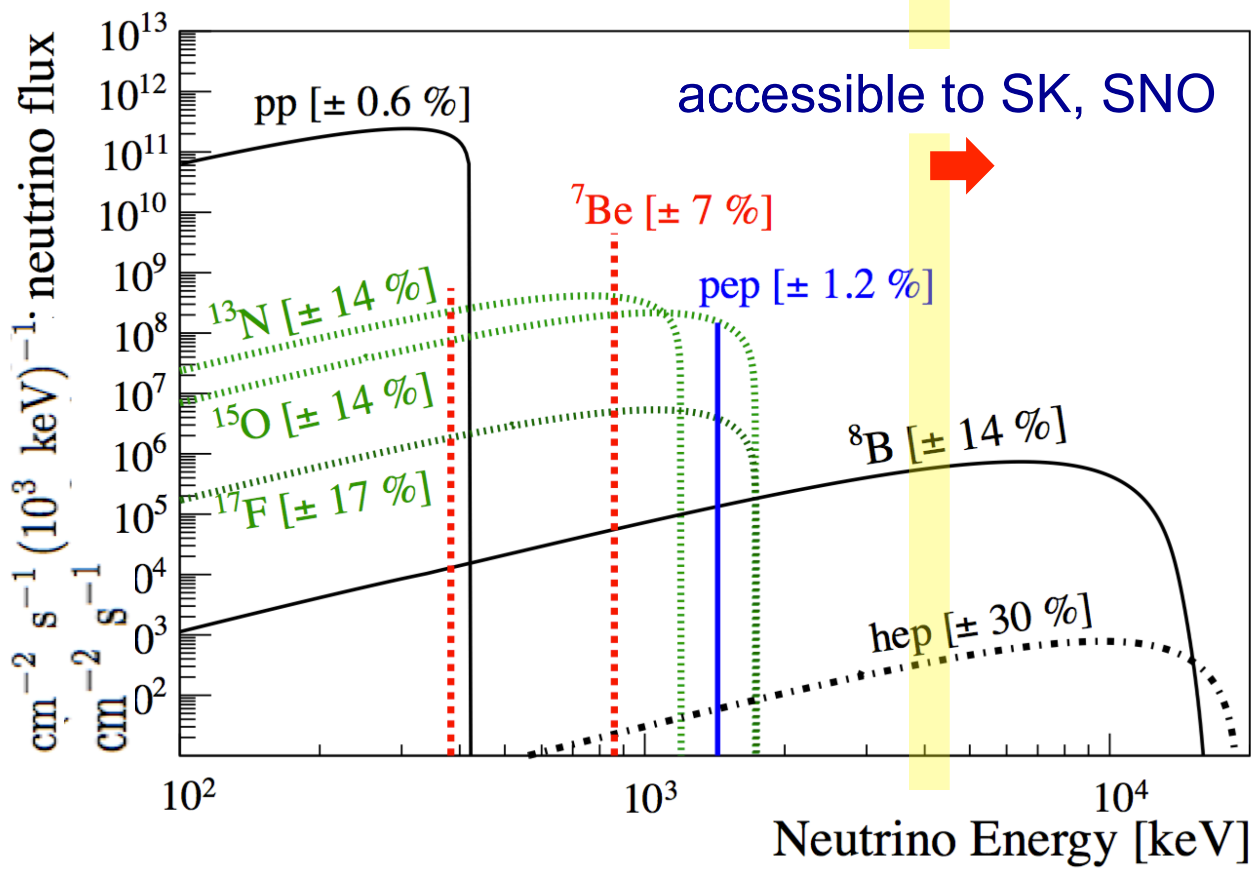
Super-Kamiokande. Phys. Rev. D 74, 032002 (2006)

Super-Kamiokande. Phys. Rev. D 81, 092004 (2010)

“a la”:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\text{eV}^2)L(\text{km})}{E_\nu(\text{GeV})}\right),$$

Solar ν's



accessible to SK, SNO

Bahcall, Serenelli, Basu; Astrophys. J. 621 (2005) 85
Serenelli, Haxton, Peña-Garay; Astrophys. J. 743 (2011) 24

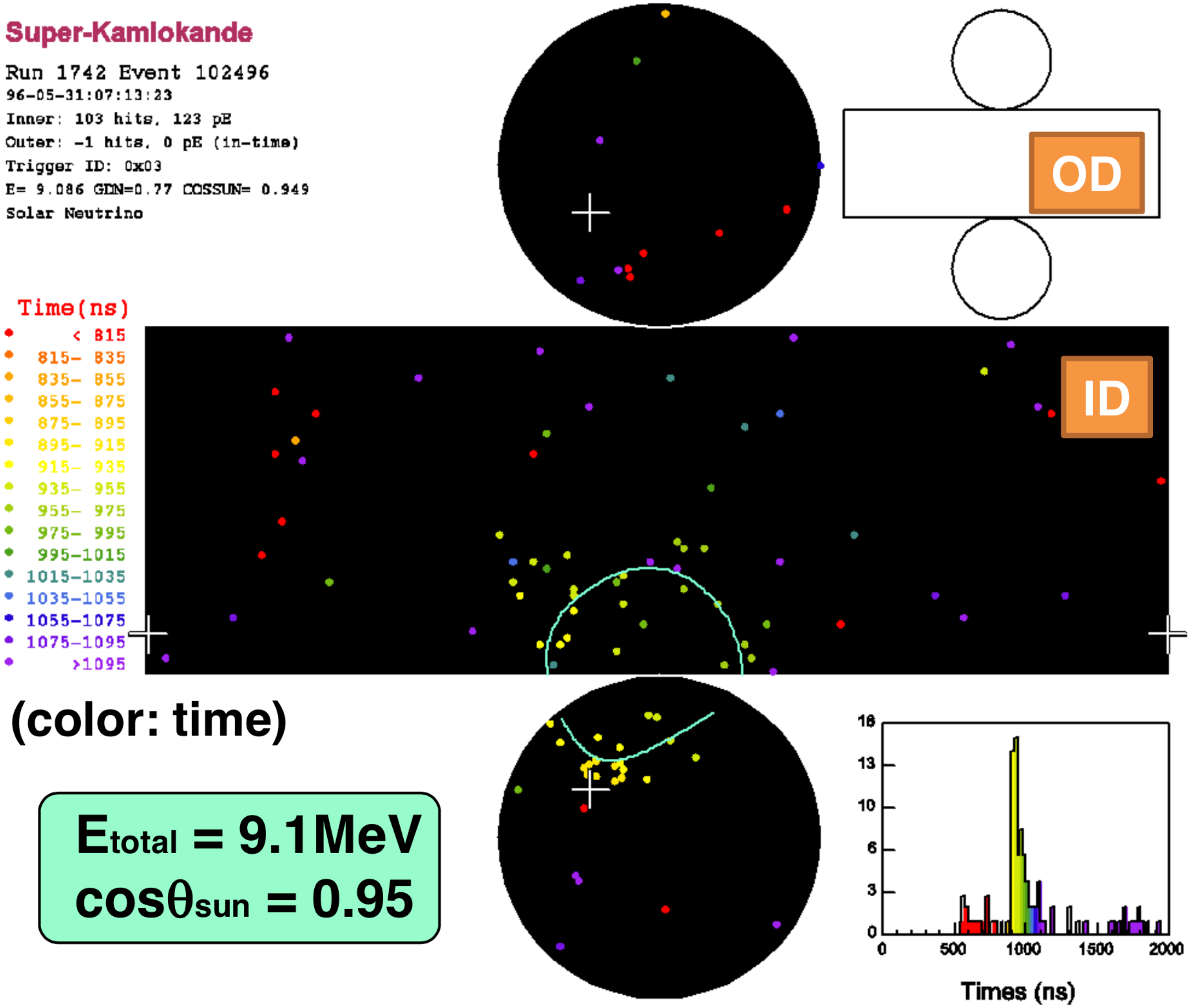
Very low energies:
Cl, Ga experiments. Very difficult, counting experiments

SK: precise measurement of [only] ν_e from elastic scattering

$$\nu + e \longrightarrow \nu + e$$

SNO: also NC → access to ν_e, ν_μ, ν_τ → **direct access to flavor oscillation**

Solar ν's



Super-Kamiokande

Run 1742 Event 102496
96-05-31:07:13:23
Inner: 103 hits, 123 pE
Outer: -1 hits, 0 pE (in-time)
Trigger ID: 0x03
E= 9.086 GDN=0.77 COSSUN= 0.949
Solar Neutrino

(color: time)

E_{total} = 9.1MeV
$\cos\theta_{sun}$ = 0.95

$\nu + e^- \rightarrow \nu + e^-$

Elastic scattering (ES) reaction is used for solar neutrinos

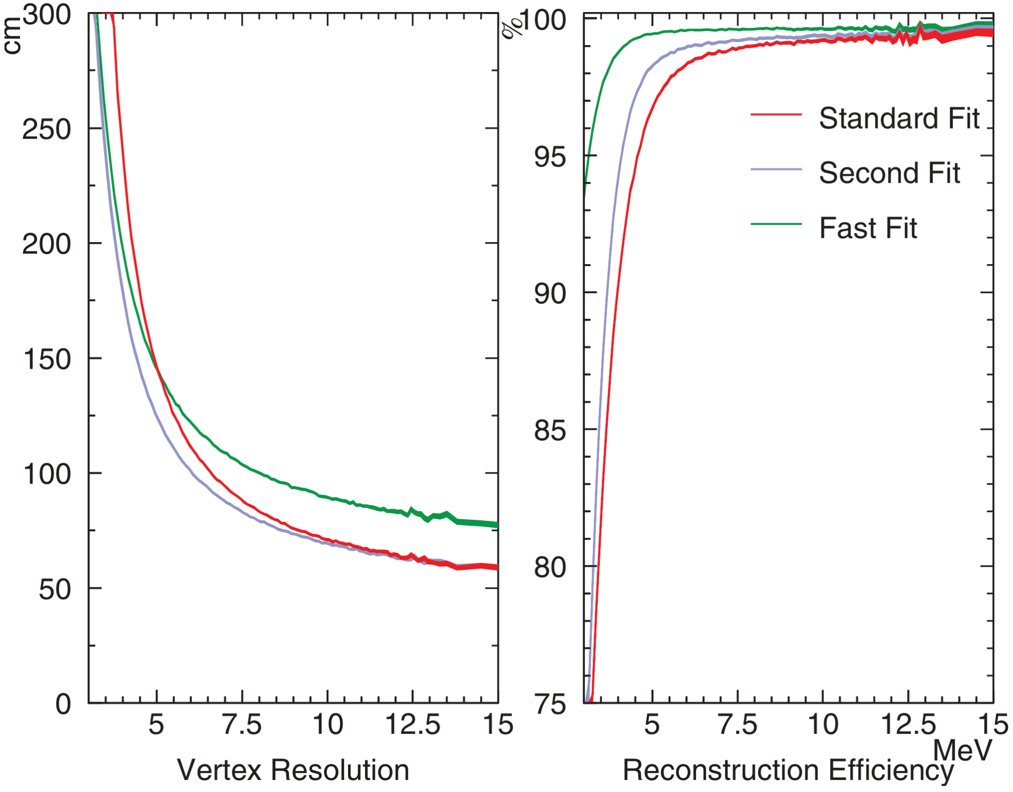
- **Timing information**
  ⇨ **vertex position**
- **Ring pattern**
  ⇨ **direction**
- **Number of hit PMTs**
  ⇨ **energy**

~6hit / MeV
(SK-I, III, IV)

Nakahata: UAM 2012

Solar ν's reconstruction by Super-Kamiokande

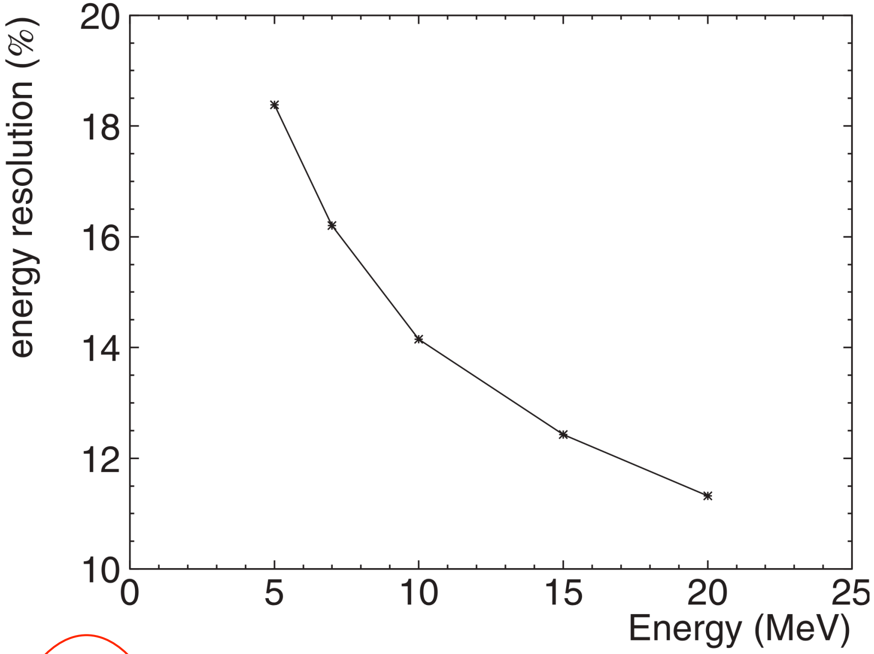
$$\nu + e \longrightarrow \nu + e$$

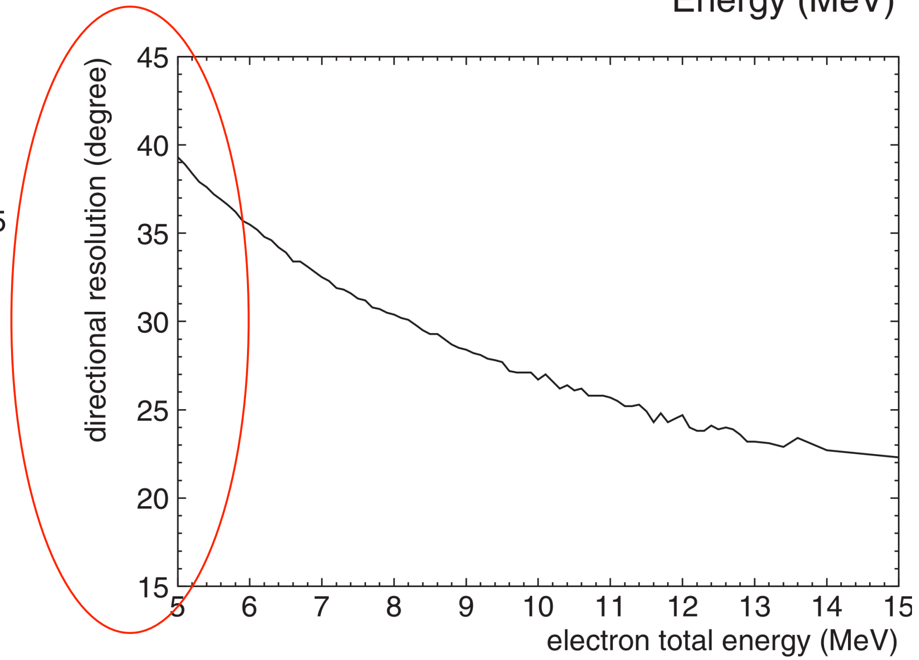


Vertex Resolution

Reconstruction Efficiency

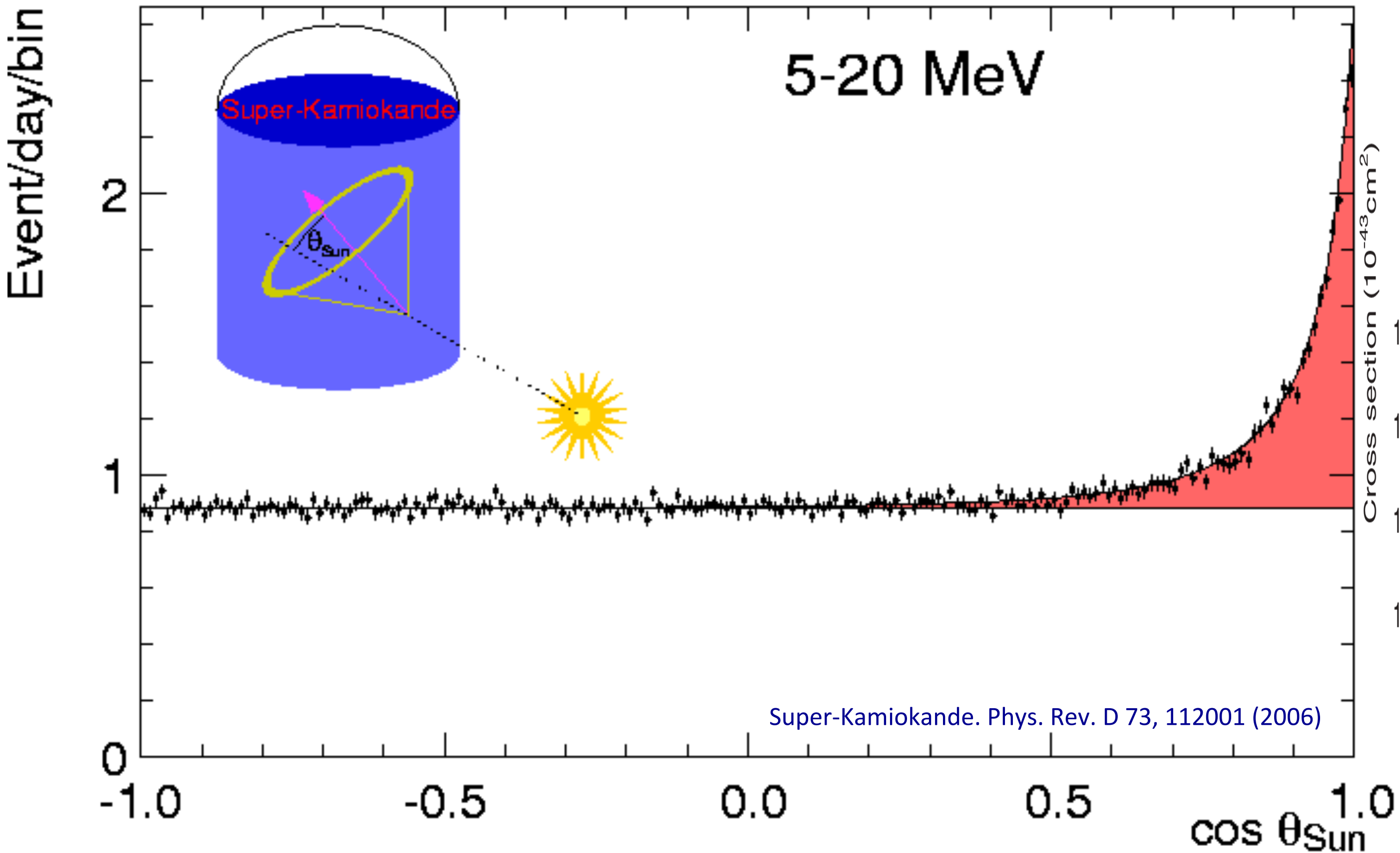
Super-Kamiokande. Phys. Rev. D 73, 112001 (2006)





^{8}B solar ν flux by Super-Kamiokande

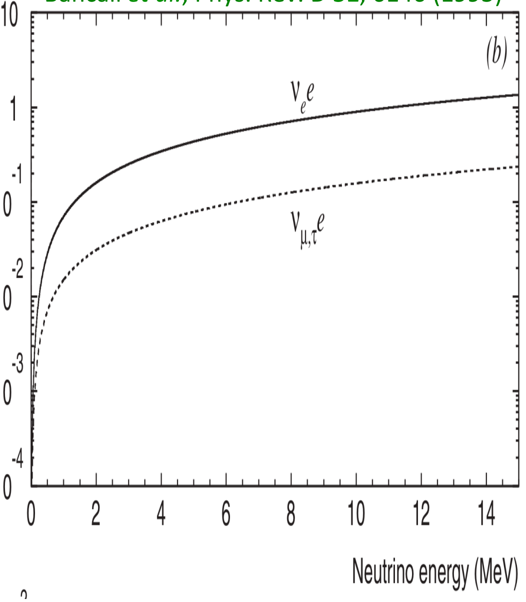
signal extracted from directional correlation of recoiling e^- with incident ν at ν - e^- scattering



Super-Kamiokande. Phys. Rev. D 73, 112001 (2006)

Input: cross-section for ν - e^- elastic

Bahcall *et al.*, Phys. Rev. D **51**, 6146 (1995)



SK-I: 2.36 ± 0.02 (stat) ± 0.08 (sys) • 10^6 cm^{-2} s^{-1}

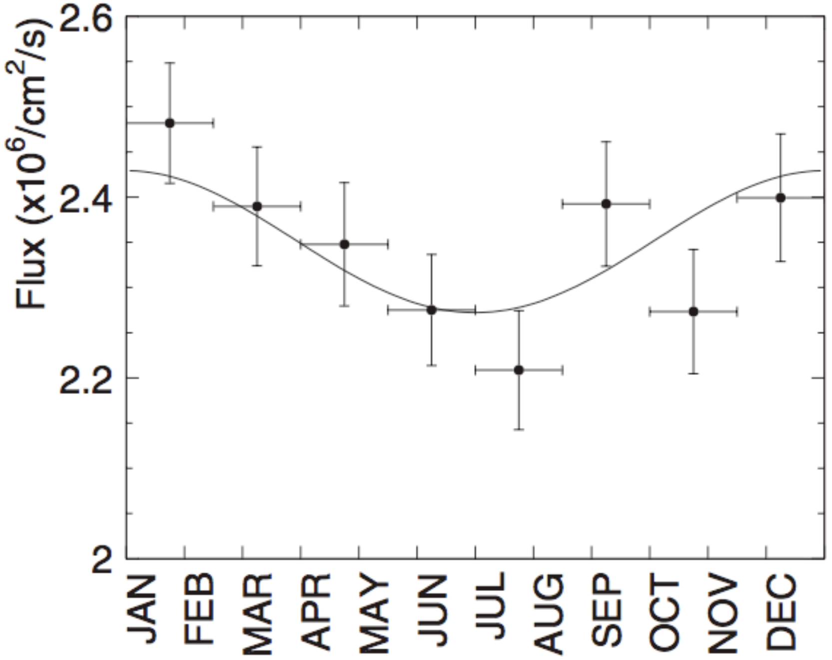
expected SSM: 5.79 • 10^6 cm^{-2} s^{-1}

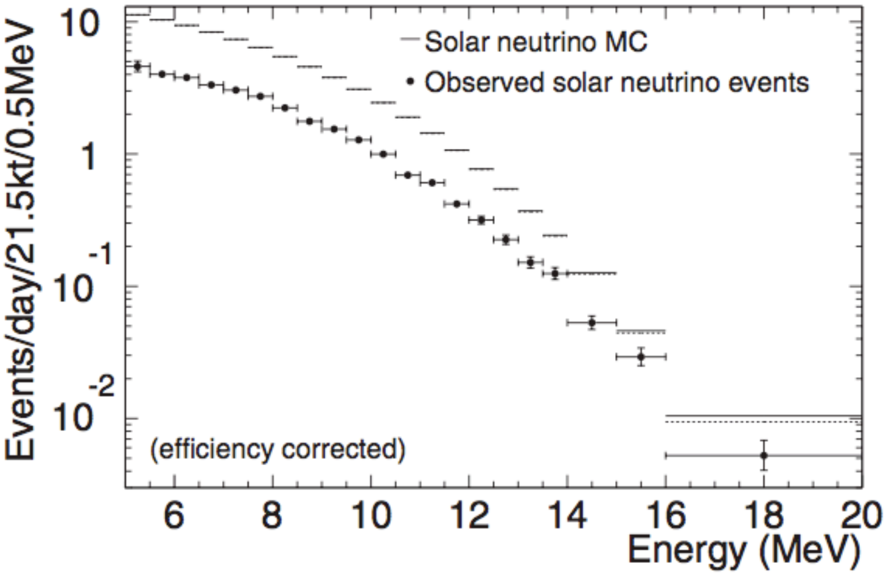
Bahcall, Pinsonneault; Phys. Rev. Lett. 92, 121302 (2004)

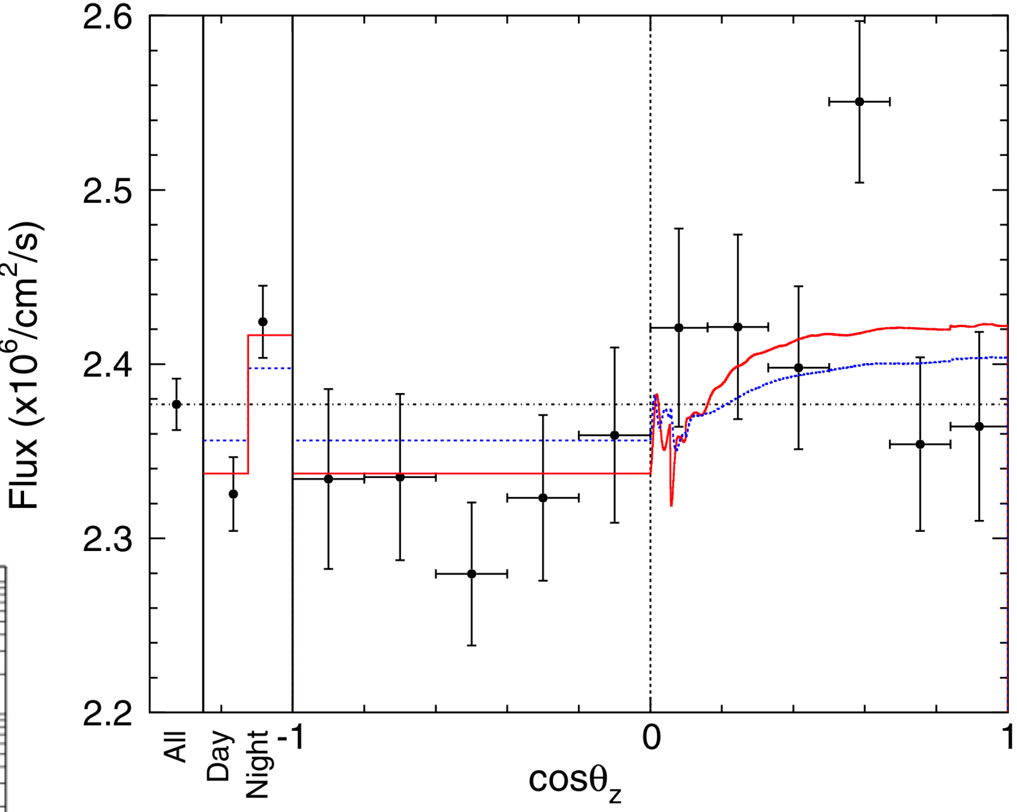
➔ Where are the missing of ν_e from the Sun ? Is SSM wrong ?

^{8}B solar ν flux by Super-Kamiokande; some other relevant results

PHYSICAL REVIEW D **73,** 112001 (2006)

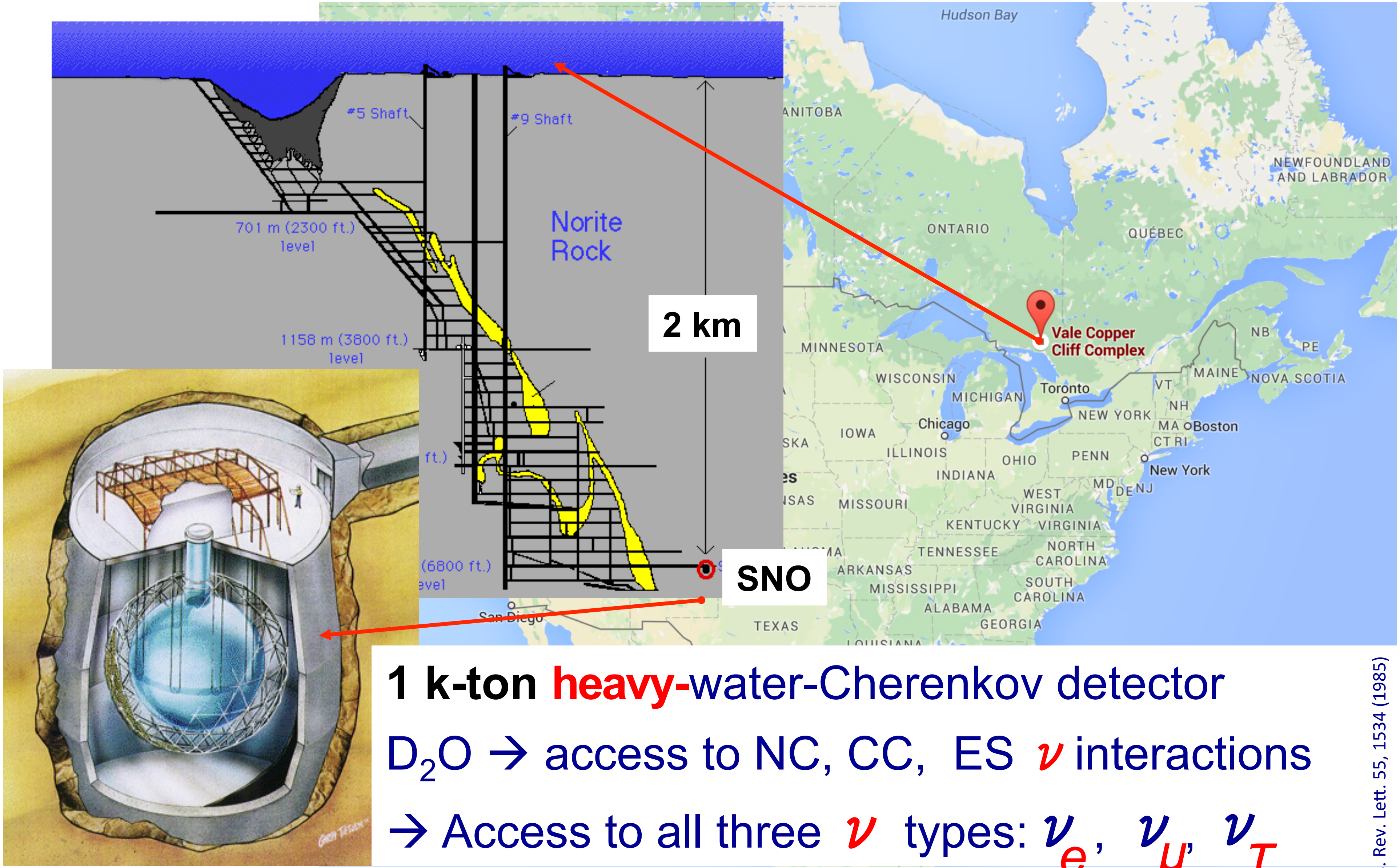






Super-Kamiokande. Phys. Rev. Lett. 112, 091805 (2014)

Sudbury Neutrino Observatory



1 k-ton heavy-water-Cherenkov detector

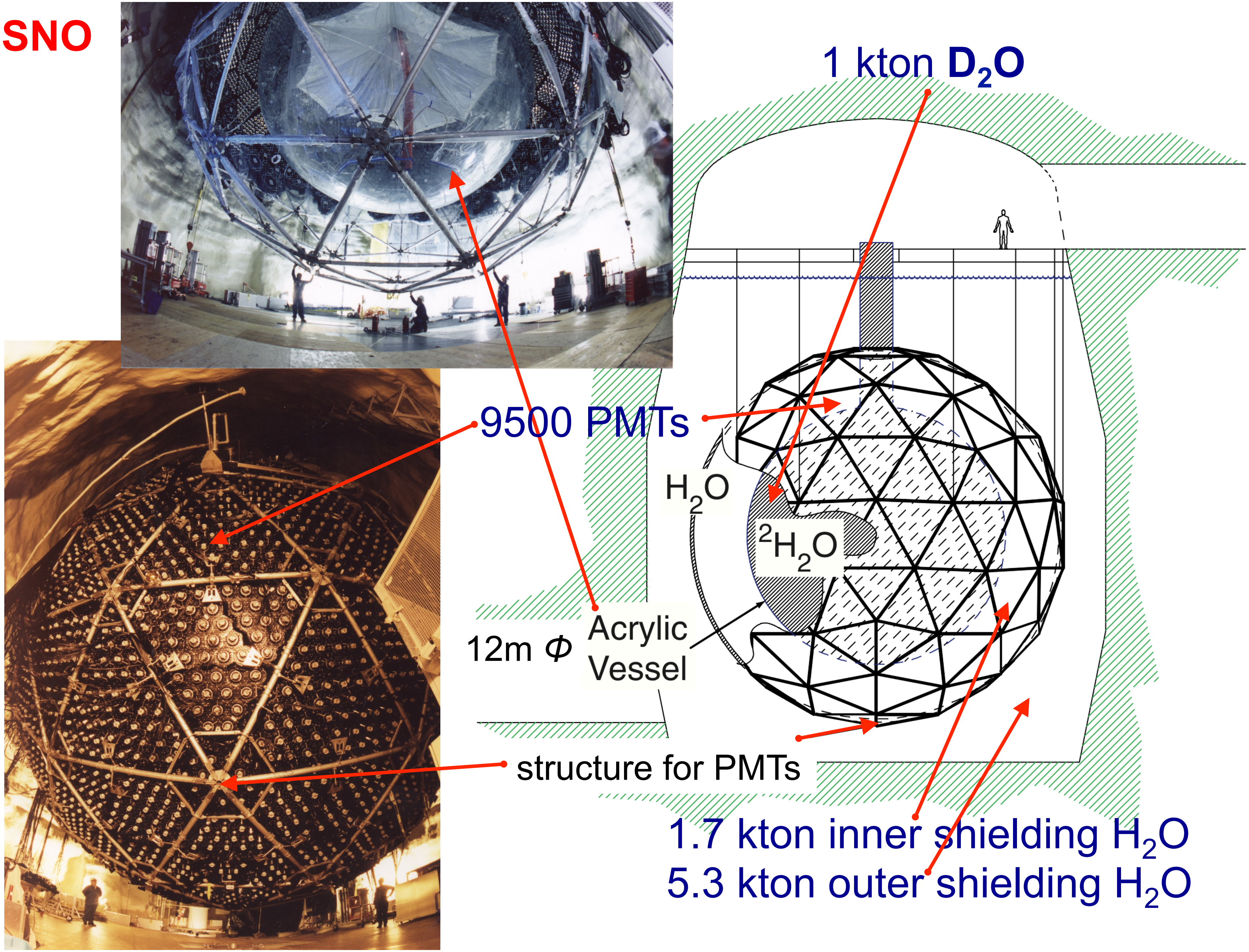
D_2O → access to NC, CC, ES ν interactions

→ Access to all three ν types: ν_e, ν_μ, ν_τ

➔ Access to the whole ν flux from the sun

Chen; Phys. Rev. Lett. 55, 1534 (1985)

SNO



1 kton D_2O

9500 PMTs

12m Φ

Acrylic Vessel

structure for PMTs

1.7 kton inner shielding H_2O

5.3 kton outer shielding H_2O

Main reactions at SNO

Elastic **S**cattering

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

Cerenkov ring; directionality

sensitive to ν_e , ν_μ , ν_τ

but ν_μ , ν_τ suppressed by ~ 1/6,

similar as in Super-Kamiokande

Charged **C**urrent scattering

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

Cerenkov ring; energy information

sensitive **only** to ν_e

(for solar ν energies)

Neutral **C**urrent scattering

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

neutron capture:

$^2H + n \rightarrow {}^3H + \gamma$ [6.2 MeV]

Cerenkov ring; just event counting

sensitive to **all three** ν_e , ν_μ , ν_τ

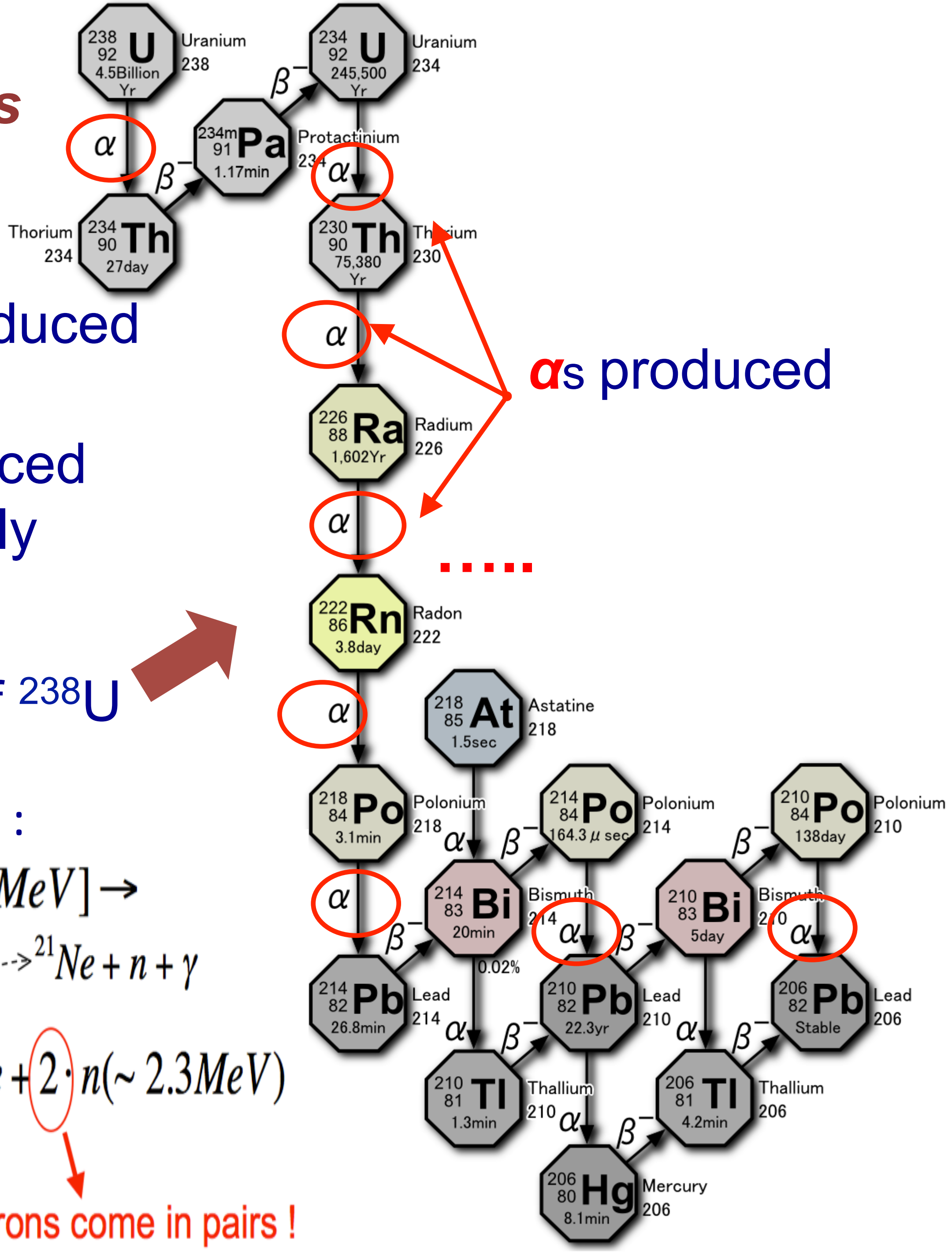
with E[ν_x] > 2.2 MeV (binding E.)

A very severe problem for NC is *background neutrons*

irreducible background
there are many naturally produced

for instance neutrons produced from **α** decays in the naturally present radioactive chains

for instance that of ^{238}U



αs produced

the **α**s interact with the water :

$$^{18}O + {}^{4}\alpha(\sim 6MeV) \rightarrow {}^{22}Ne^*[\sim 15MeV] \rightarrow$$

$$\times \dashrightarrow {}^{22}Ne + \gamma \qquad \times \dashrightarrow {}^{21}Ne + n + \gamma$$

$$\rightarrow {}^{21}Ne^*[\sim 12.5MeV] + n(\sim 2.5MeV) \rightarrow {}^{20}Ne + \boxed{2} \cdot n(\sim 2.3MeV)$$

neutrons come in pairs !

P. Fernández

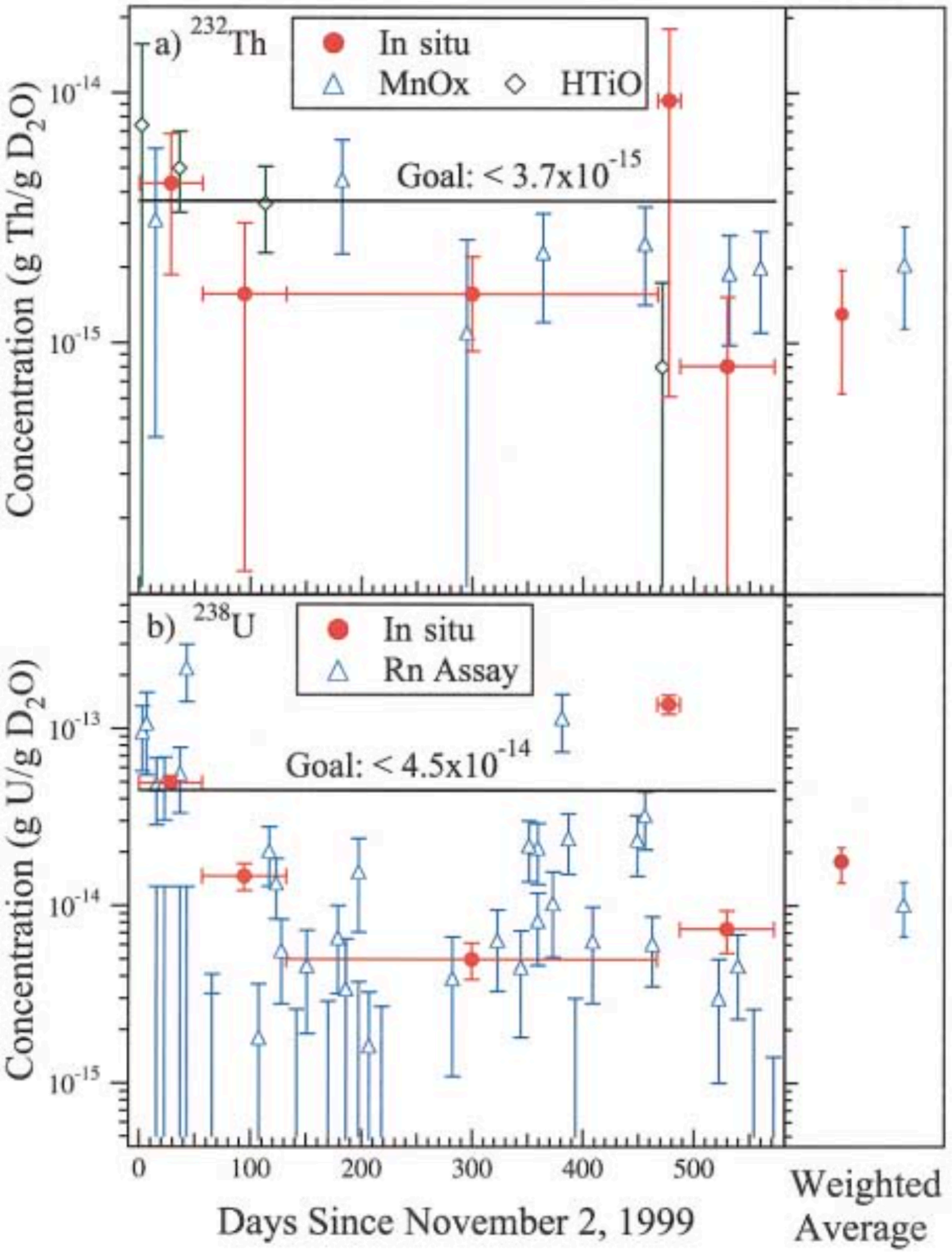
A very severe problem for NC is ***background neutrons***

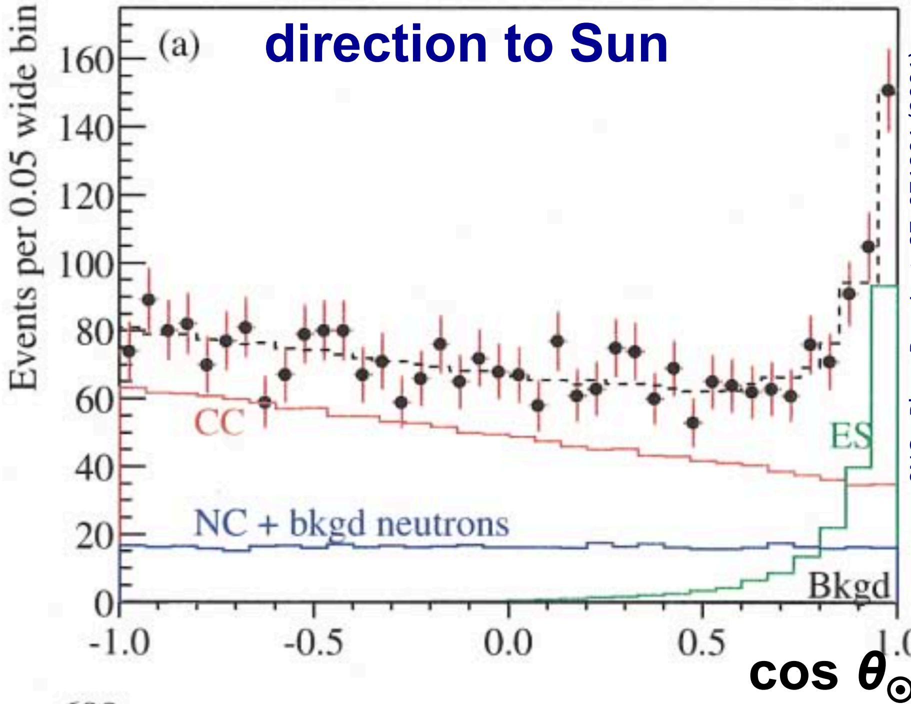
irreducible background →

a) minimize to the maximum
  - purest D_2O
  - acrylic vessel to isolate D_2O from external contamination

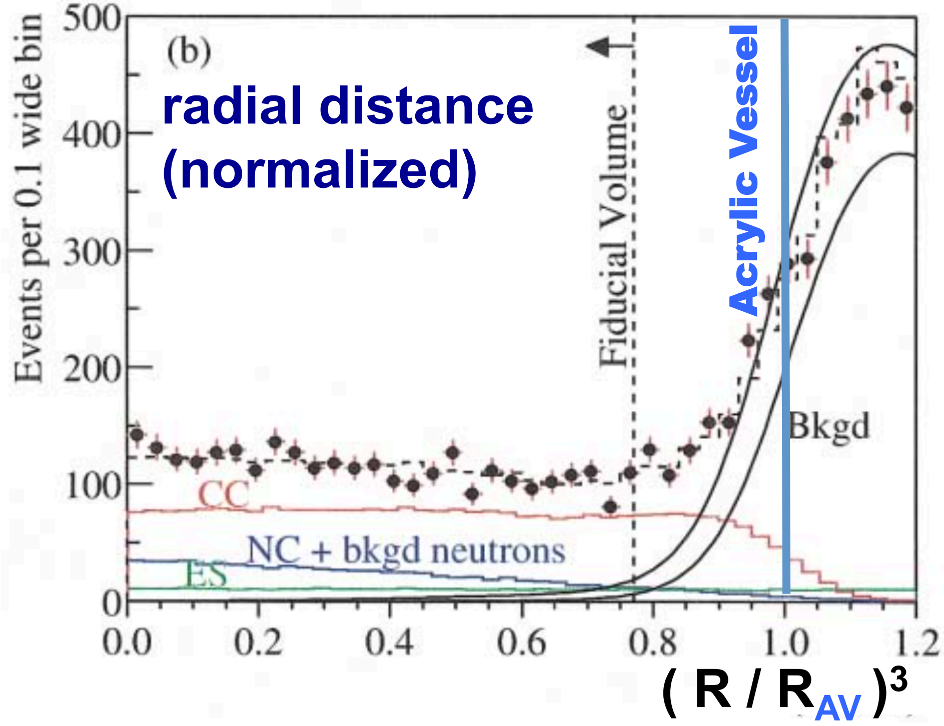
b) quantify to the highest precision:
  - permanent monitoring by
  - 2 ex-Situ radioactivity cont. meas. systems
  - 1 in-situ technique

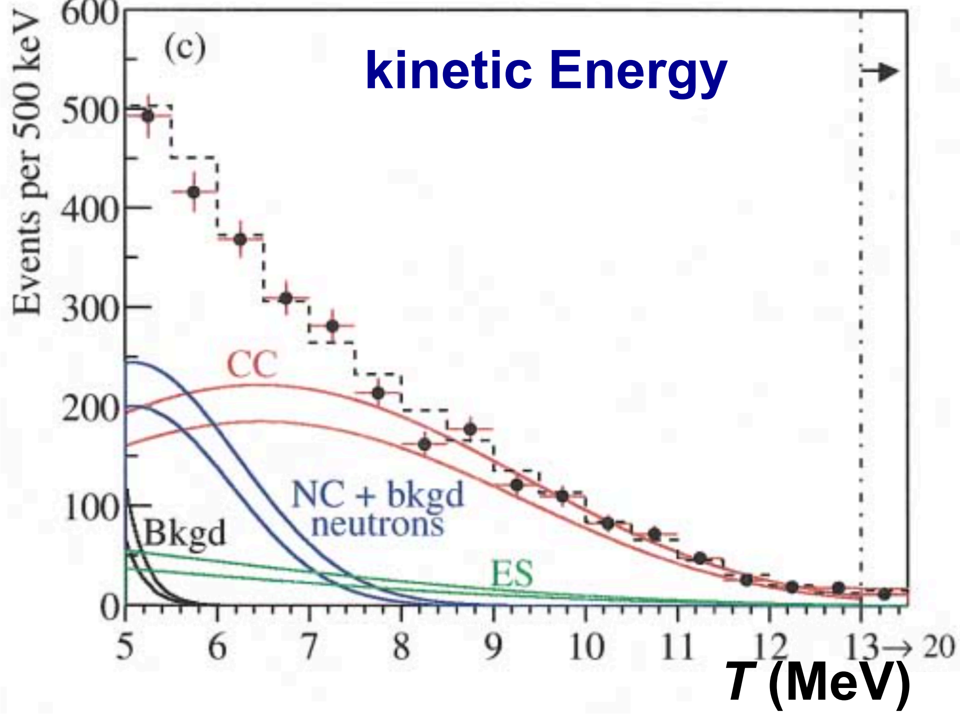
SNO; Phys. Rev. Lett. 89, 011301 (2002)





SNO; Phys. Rev. Lett. 87, 071301 (2001)
SNO; Phys. Rev. Lett. 89, 011301 (2002)

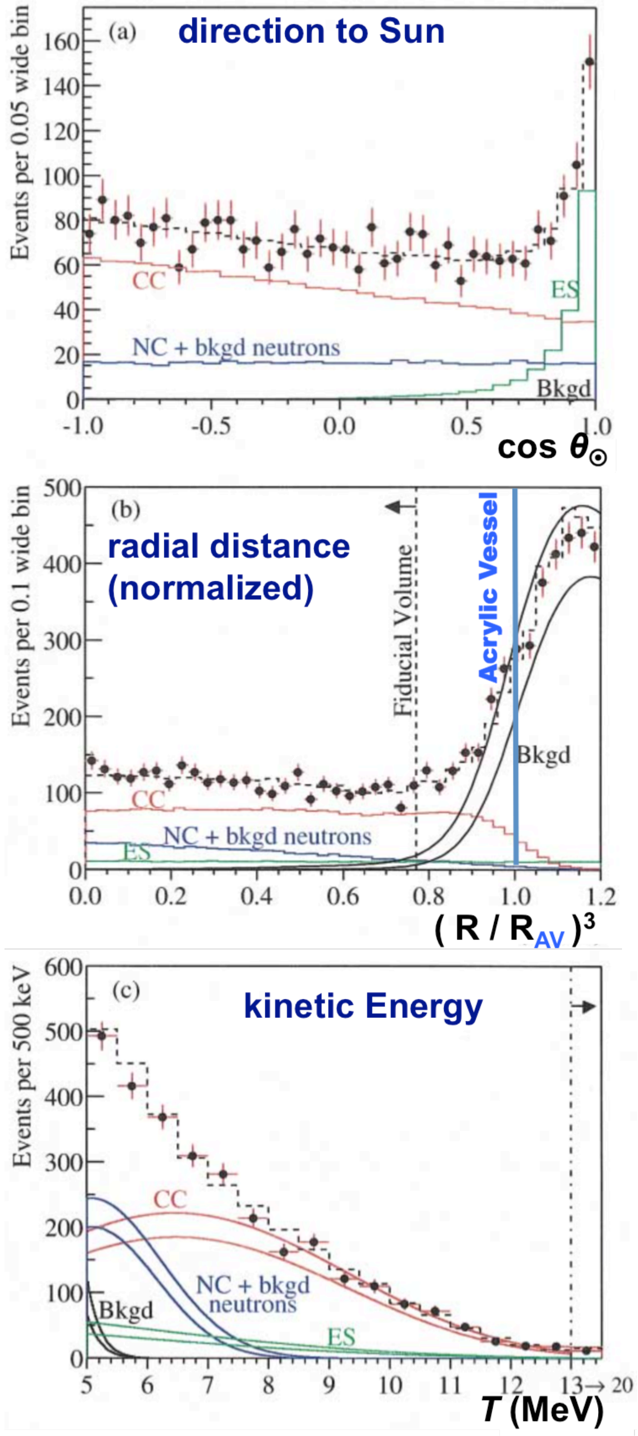




Fit measured flux to

$$\phi_{CC}\,[\,\cos\theta_\odot,\ (R / R_{AV})^3,\ T\,] +$$
$$\phi_{ES}\,[\,\cos\theta_\odot,\ (R / R_{AV})^3,\ T\,] +$$
$$\phi_{NC}\,[\,\cos\theta_\odot,\ (R / R_{AV})^3,\ T\,] +$$
$$\mathrm{Bkgd}\,[\,\cos\theta_\odot,\ (R / R_{AV})^3,\ T\,]$$

using MC generated *pdf*s
assuming no flavor transformation
and ^{8}B spectral shape



Results: $[\,\bullet\, 10^{6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\,]$

$$\phi^{\mathrm{SNO}}_{\mathrm{CC}} = 1.76^{+0.06}_{-0.05}(\mathrm{stat})^{+0.09}_{-0.09}(\mathrm{syst})\,,$$

$$\phi^{\mathrm{SNO}}_{\mathrm{ES}} = 2.39^{+0.24}_{-0.23}(\mathrm{stat})^{+0.12}_{-0.12}(\mathrm{syst})\,,$$

$$\phi^{\mathrm{SNO}}_{\mathrm{NC}} = 5.09^{+0.44}_{-0.43}(\mathrm{stat})^{+0.46}_{-0.43}(\mathrm{syst})\,.$$

SK-I [ES]: 2.36 ± 0.02 (stat) ± 0.08 (sys) ✓

expected SSM: 5.75 $\bullet\ 10^{6}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Bahcall, Pinsonneault; Phys. Rev. Lett. 92, 121302 (2004)

SNO; Phys. Rev. Lett. 87, 071301 (2001)
SNO; Phys. Rev. Lett. 89, 011301 (2002)

➔ There is no deficit of ν_e from the Sun w.r.t. the SSM, but they have **oscillated to** ν_μ , ν_τ in their way to the Earth ! ✓

Nobel 2015

ν_x fluxes are from a change of variables:

$$\phi^{\mathrm{SNO}}{}_{\mathrm{CC}}\,,\ \phi^{\mathrm{SN}}{}_{\mathrm{ES}}\,,\ \phi^{\mathrm{SNO}}{}_{\mathrm{NC}} \longrightarrow \phi_e\,,\ \phi_\mu\,,\ \phi_\tau$$

$$\phi_e = 1.76^{+0.05}_{-0.05}(\mathrm{stat})^{+0.09}_{-0.09}(\mathrm{syst})$$

$$\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\mathrm{stat})^{+0.48}_{-0.45}(\mathrm{syst})$$

Some final remarks

This is an enormous step forward in Science
… but certainly not the end

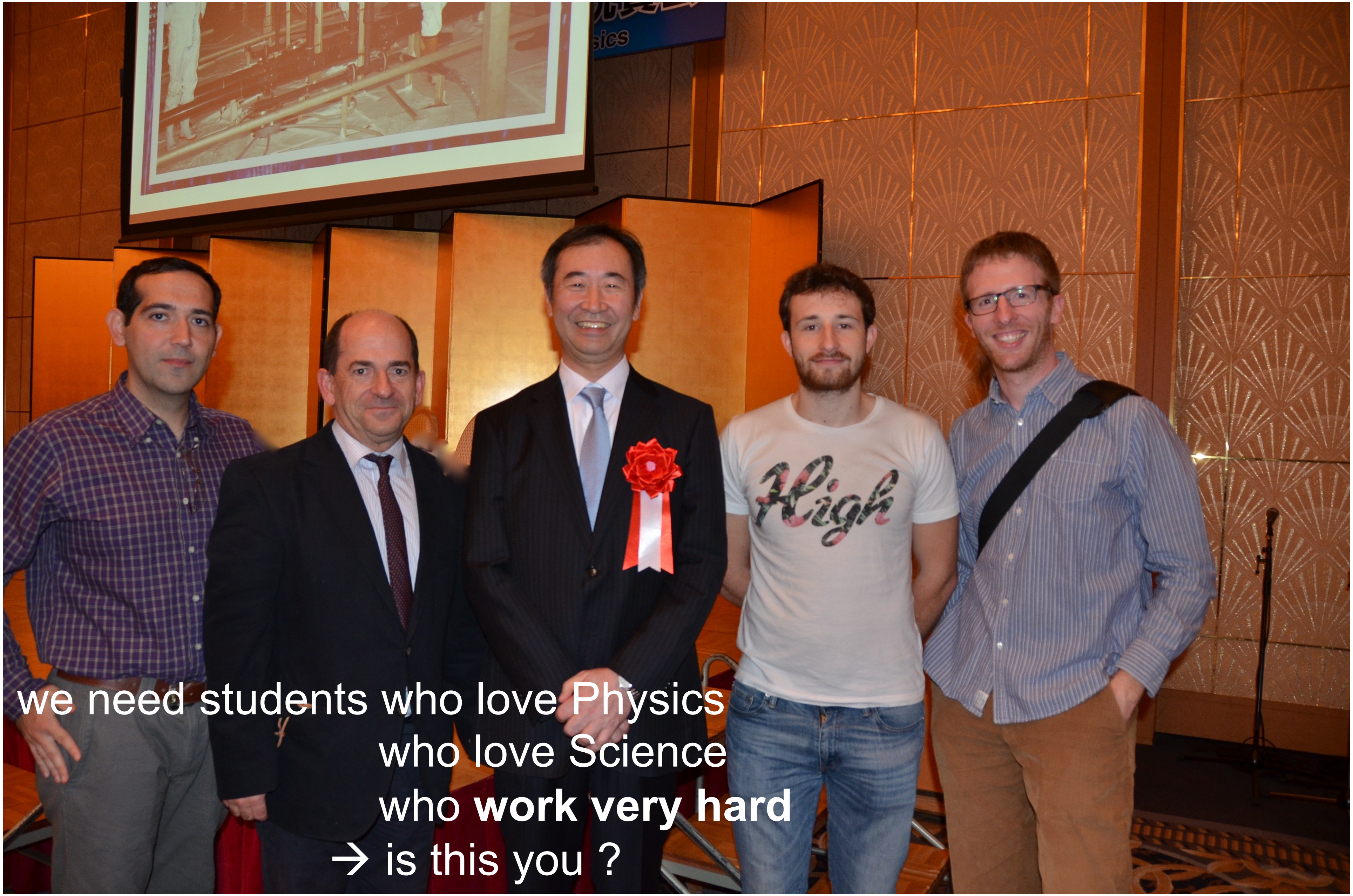
There is yet to discover / learn … basically everything in our process of understanding Nature

Some very important next related steps:

- CP violation in the leptonic sector
- Majorana / Dirac nature of neutrinos, sterile neutrinos
- Proton decay
- *High statistics/precision Neutrino astrophysics*

We (UAM) are very much involved in this research program:

- NEXT experiment at Canfranc Underground Lab.
- Super-Kamiokande at Kamioka Observatory
- Super-Kamiokande-Gadolinium
- Hyper-Kamiokande (~20 x SK) at Kamioka Observatory



we need students who love Physics
who love Science
who **work very hard**

→ is this you ?