Introduction to Neutrino Physics

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ISAPP School 2019
Cosmic Ray Vision from the Southern Sky

Malargue, Argentina march 3rd 2019

Discovery of the Neutrino

Prediction of its existence (1930)
(Wolfgang Pauli)

Neutrino Theory (1933)
(Enrico Fermi)

First Detection (1953)
(F. Reines, C. Cowan)

1930:
PREDICTION of the EXISTENCE of the NEUTRINO.

Wolfgang PAULI

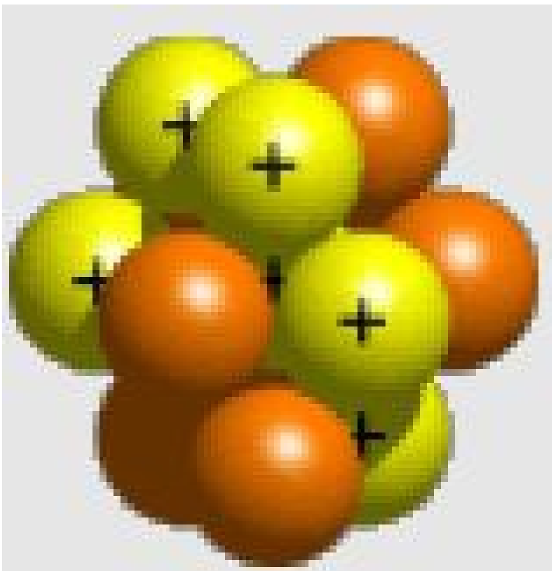
Study of Nuclear Beta Decay

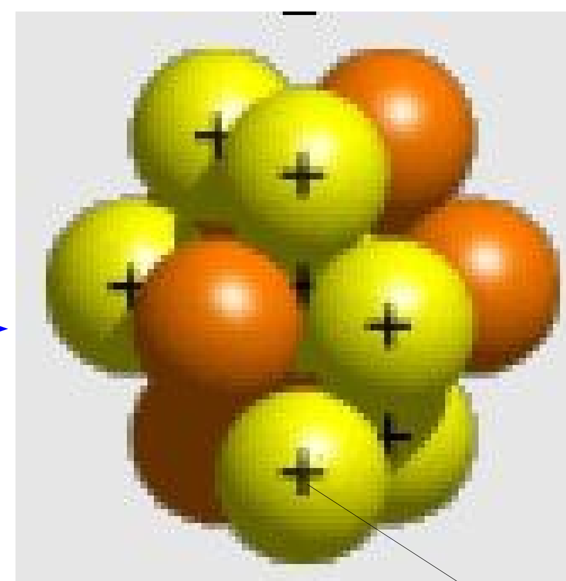
Nuclear BETA Decay

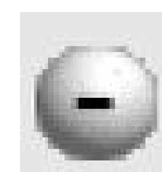
Missing

Energy
Momentum

Angular
momentum





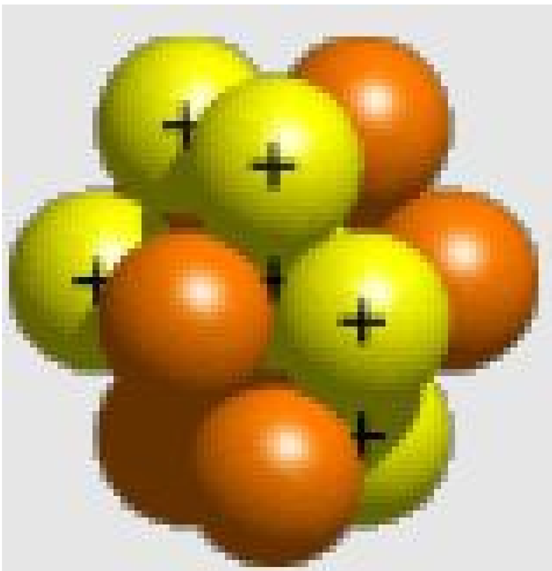


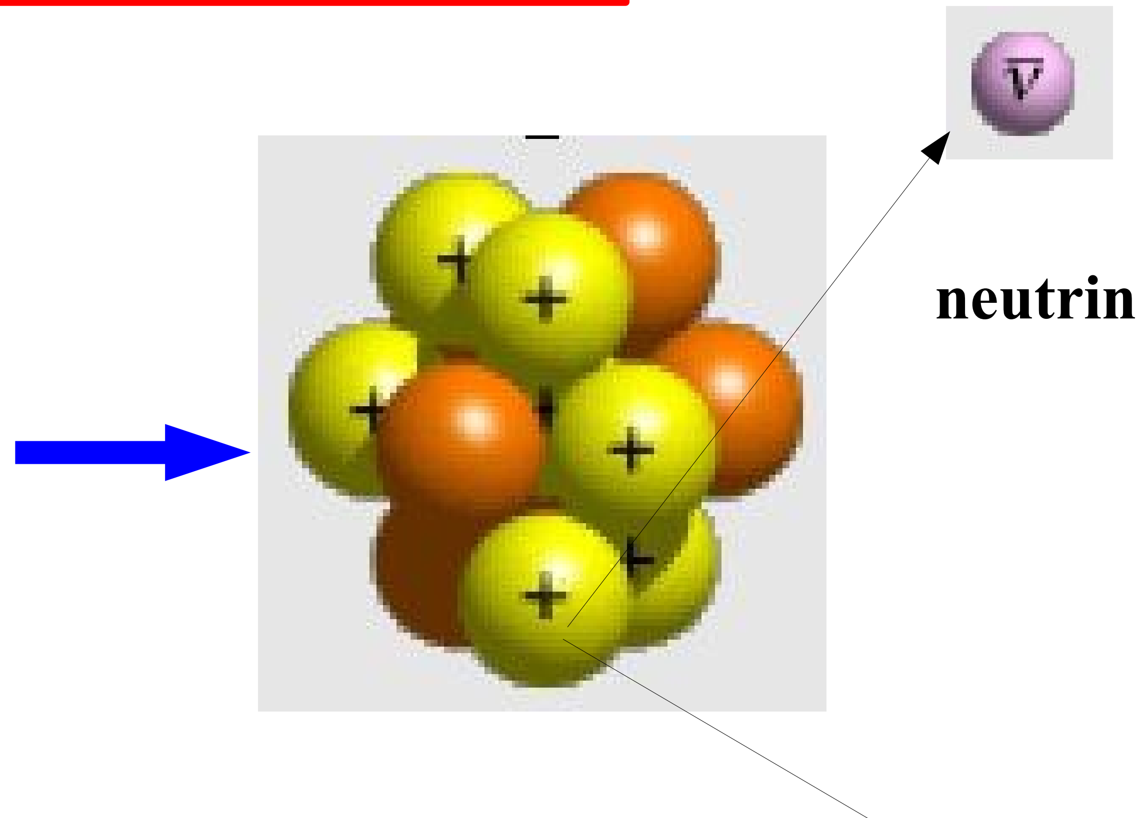
Carbon-14
6 protons,
8 neutrons

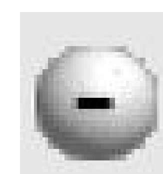
Nitrogen-14
7 protons,
7 neutrons

+ electron

Nuclear BETA Decay





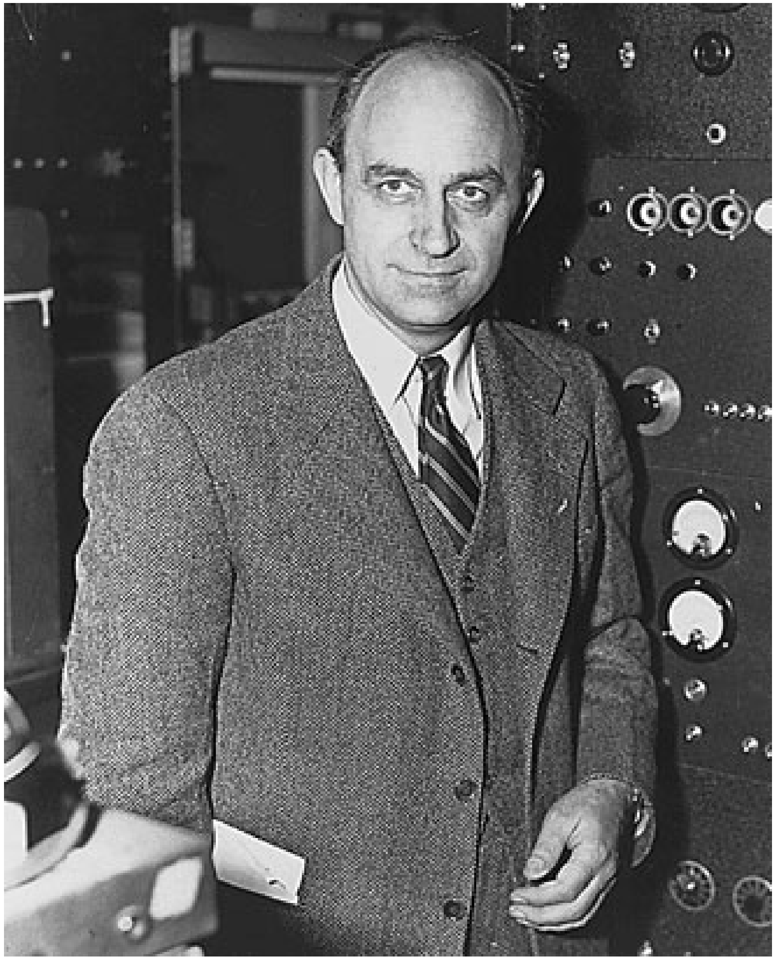


+ electron

Carbon-14
6 protons,
8 neutrons

Nitrogen-14
7 protons,
7 neutrons

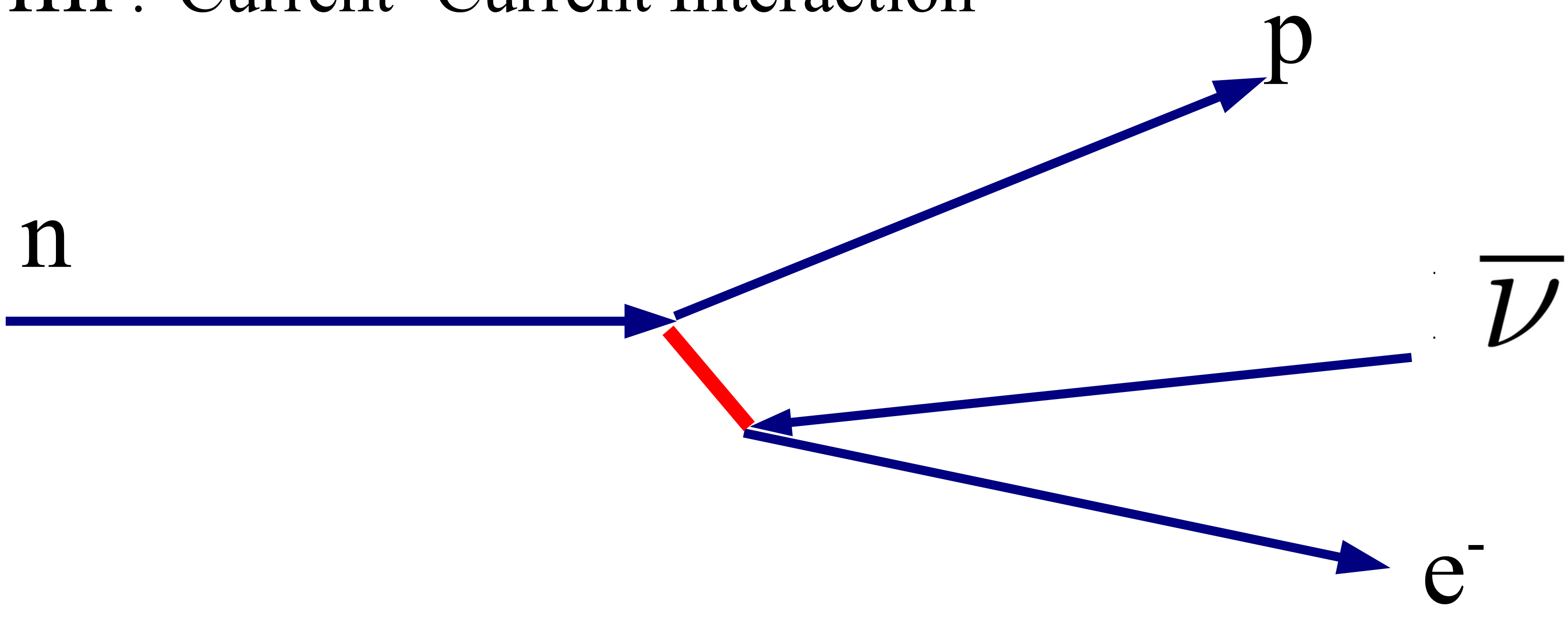
1933
Enrico Fermi
[Nobel Prize in 1938]



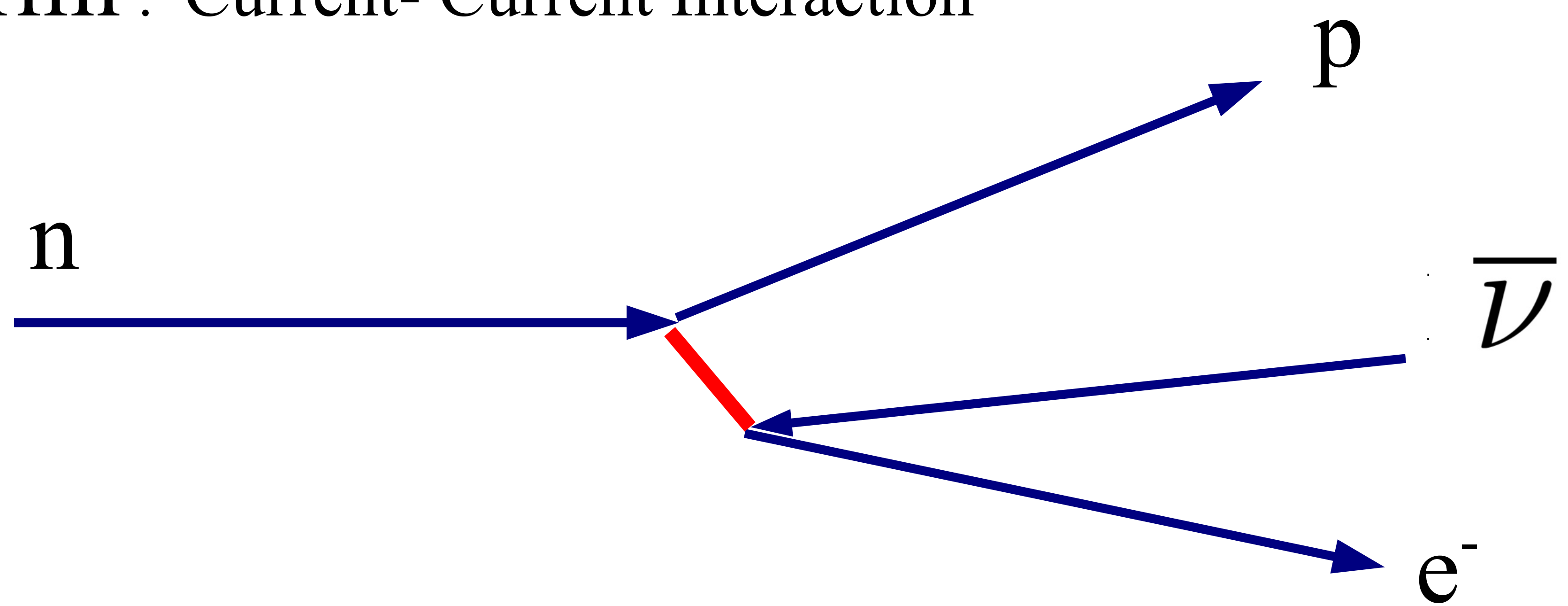
develops
the theory
of Beta Decay

Current-Current
Interaction

Fermi : Current- Current Interaction

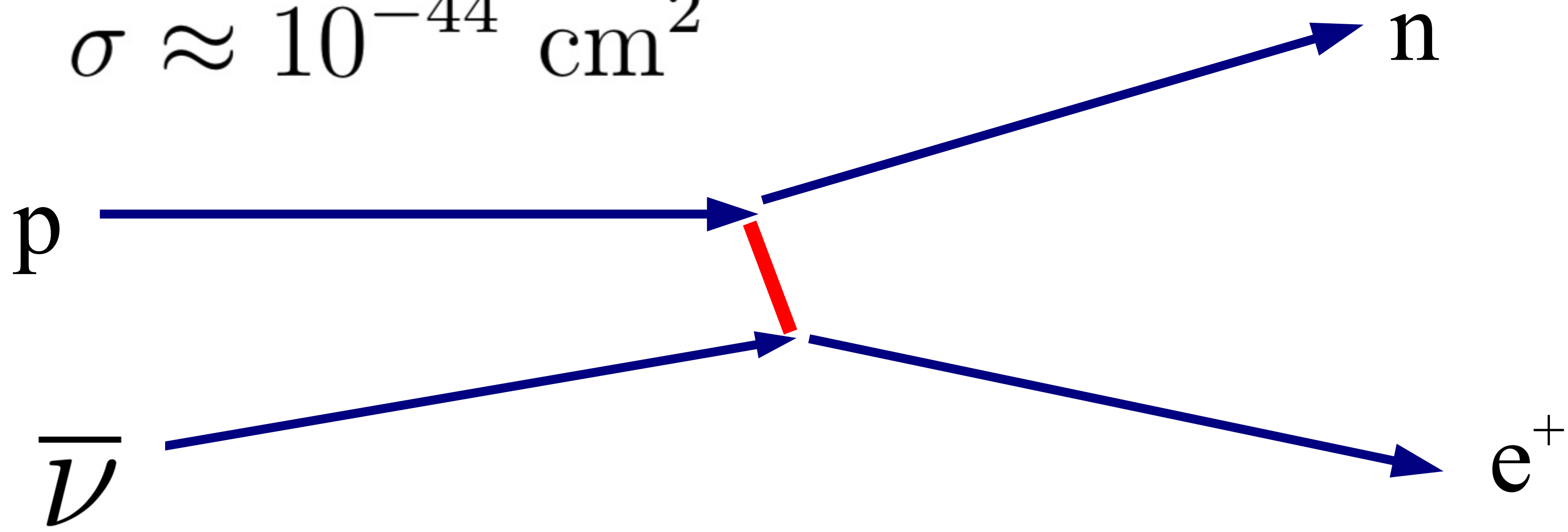


Fermi : Current- Current Interaction

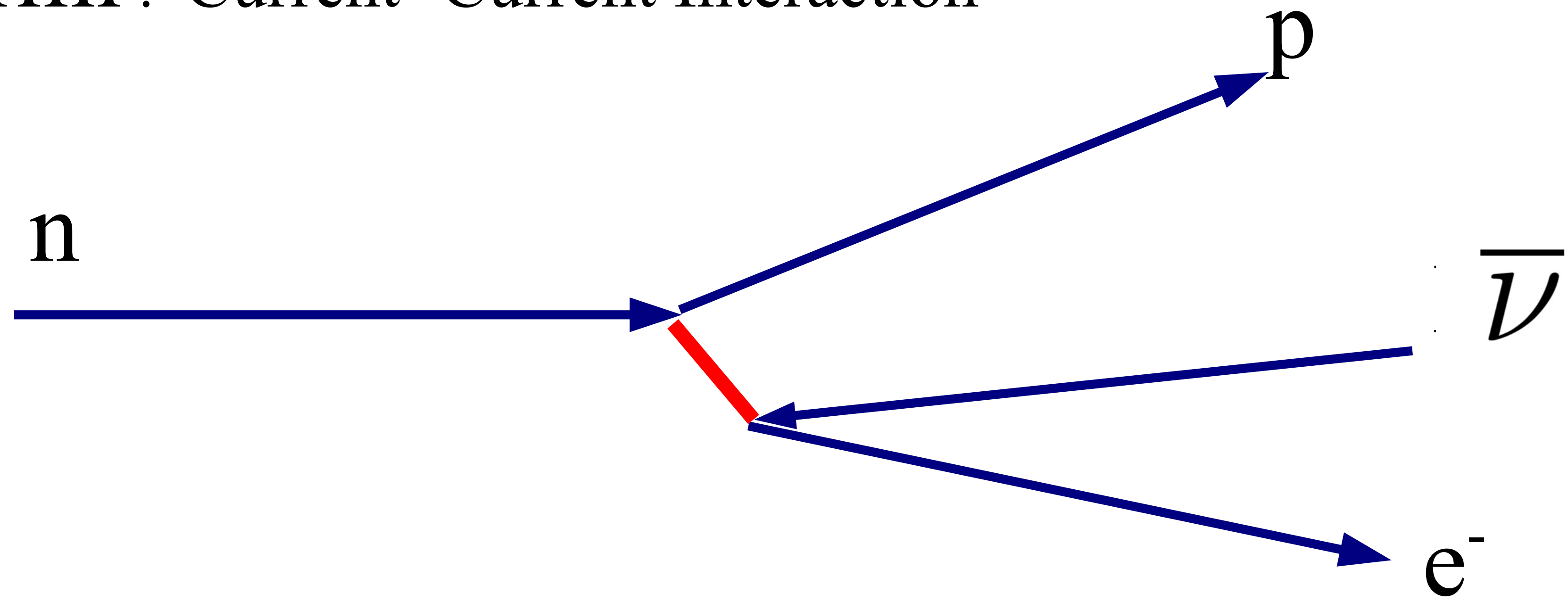


Neutrino Cross section

$$\sigma \approx 10^{-44}\ \mathrm{cm}^2$$



Fermi : Current- Current Interaction



Neutrino Cross section

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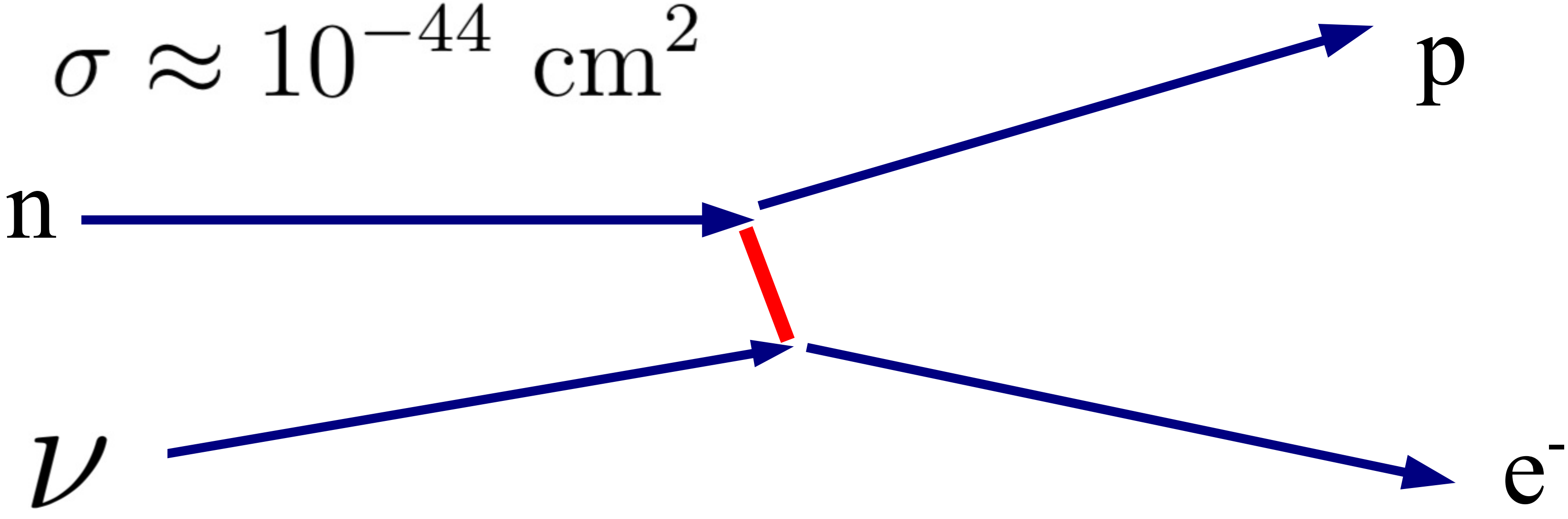
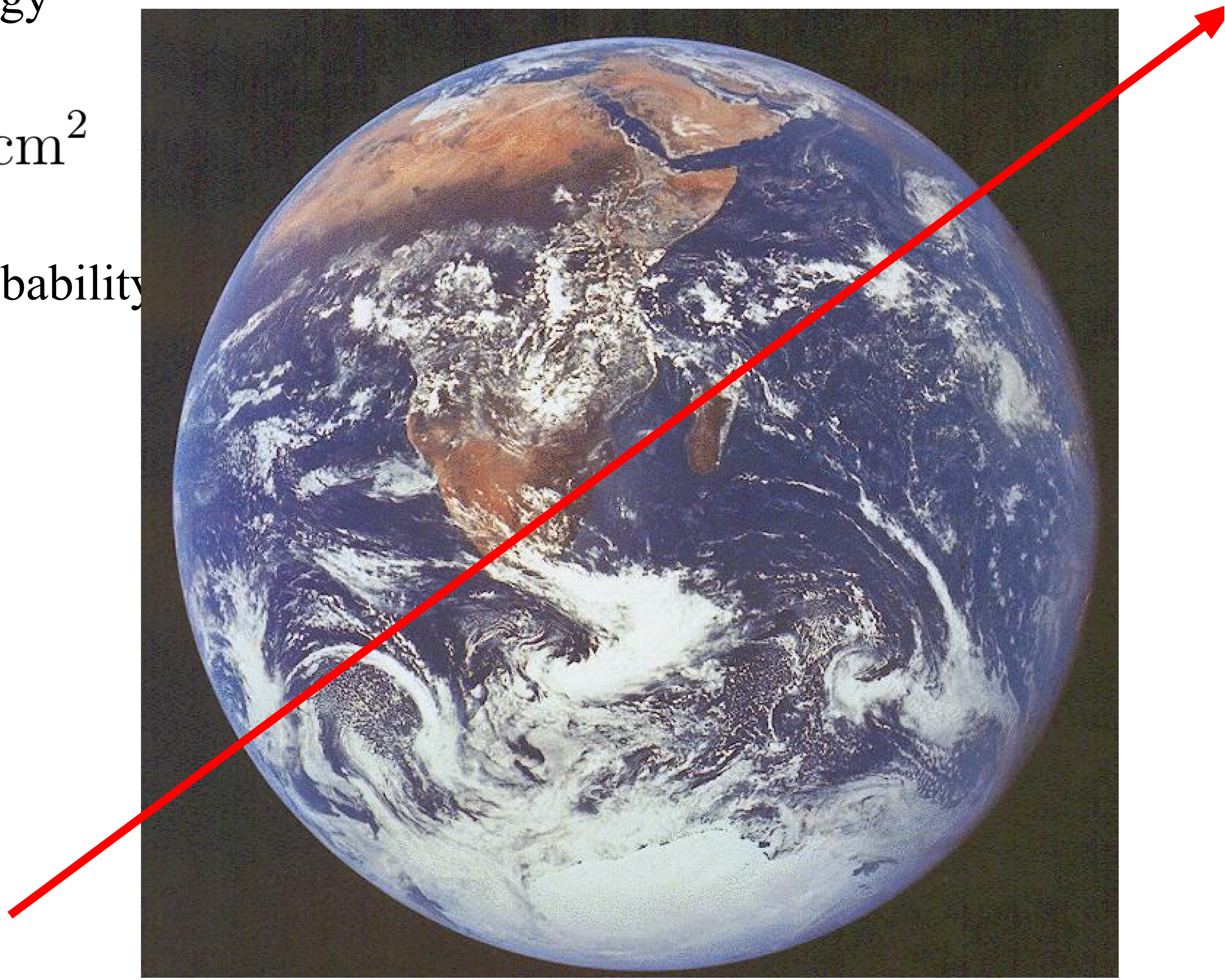


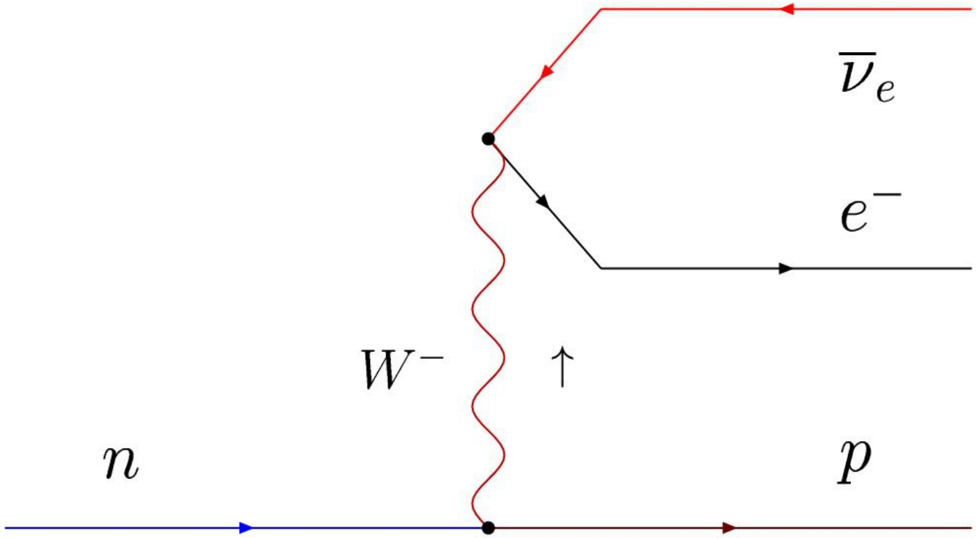
Neutrino Energy
few MeV

$$\sigma \approx 10^{-44}\ \mathrm{cm}^2$$

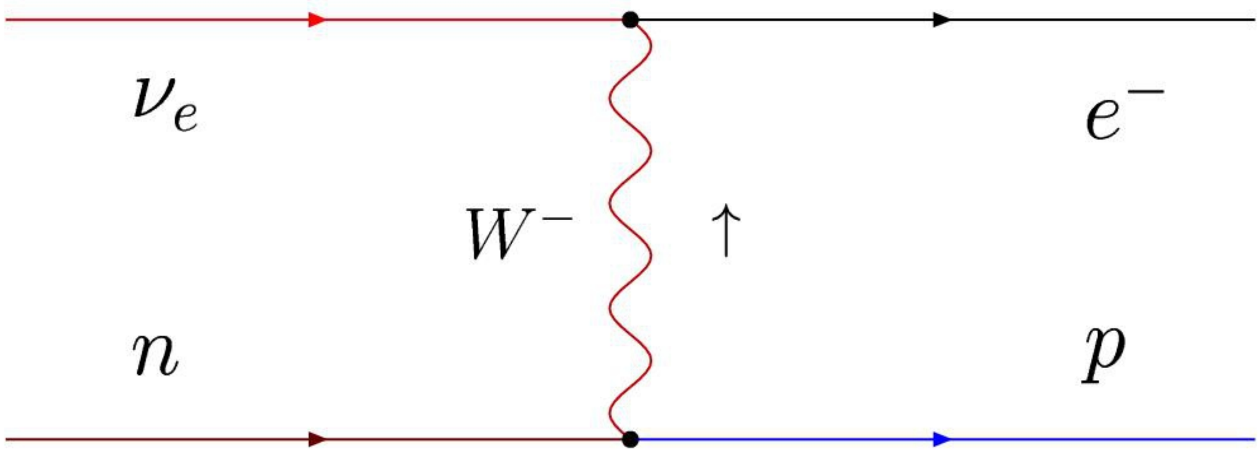
Interaction Probability
$= 10^{-11}$



$$n \to p + e^- + \overline{\nu_e}$$

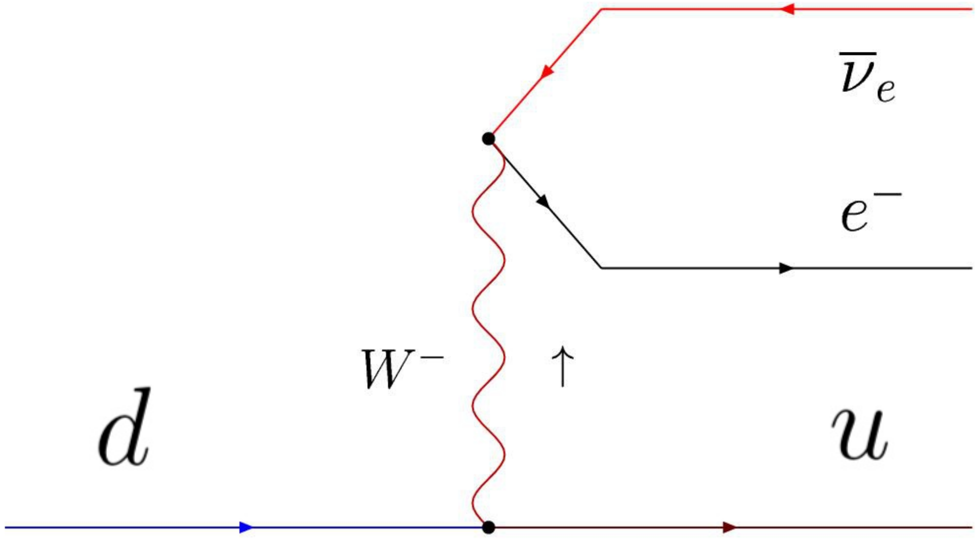


$$\nu_e + n \to p + e^-$$

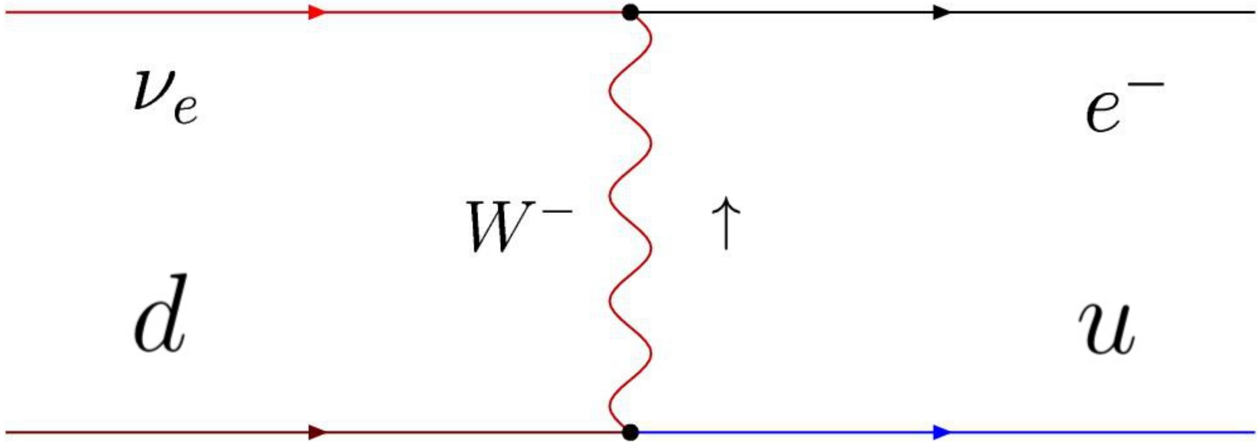


$$n \rightarrow p + e^- + \overline{\nu_e}$$

Quark description



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



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

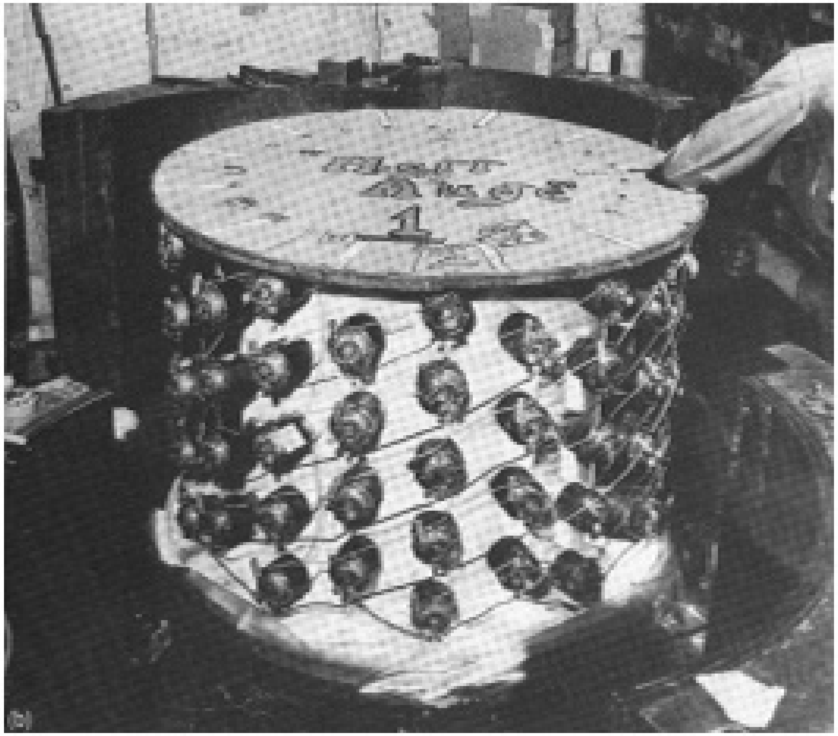
$$\nu_e + n \rightarrow p + e^-$$

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

Detection Method

Neutrino Discovery
(antineutrinos
from Nuclear Reactors

Reines e Cowan
1953-1956



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

$$E_{\text{visible}}^{\text{prompt}} = (E_{e^+} - m_e) + 2\,m_e$$
$$= E_{\overline{\nu}_e} - (m_e + m_n - m_p)$$
$$\simeq E_{\overline{\nu}_e} - 1.8\ \text{MeV}$$

$$m_p + E_{\overline{\nu}_e} \simeq m_n + E_{e^+}$$

$$E_{e^+} \simeq E_{\overline{\nu}_e} - (m_n - m_p)$$

Delayed coincidence
e+ n

Delayed neutron capture
(after thermalization of the neutron)

$$n + p \rightarrow d + \gamma(2.2\ \mathrm{MeV})$$

Neutrino Detection:

Delayed Coincidence
of prompt energy release (the positron)
and delayed neutron capture photon

Standard Model

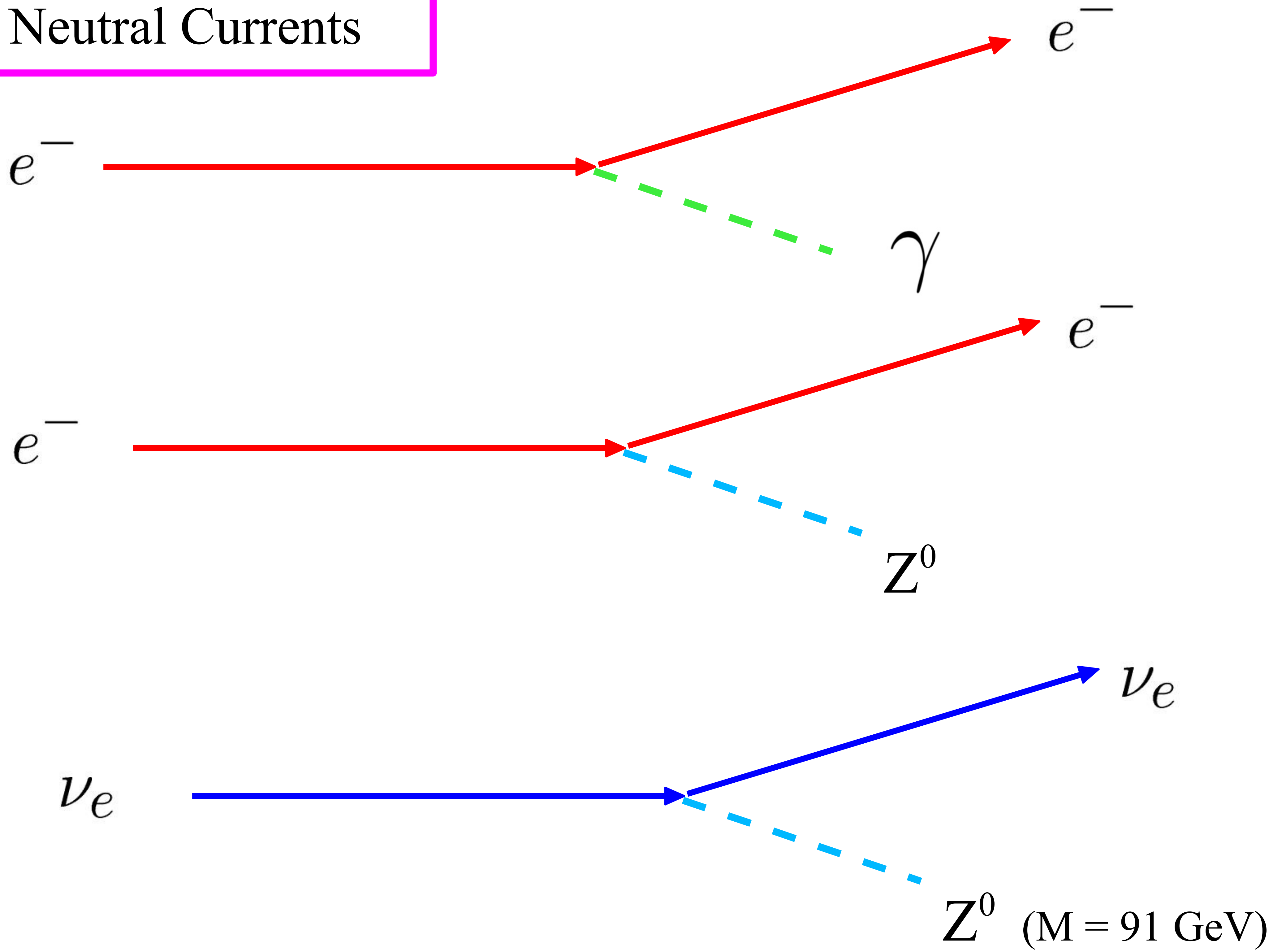
$$SU(3) \otimes SU(2) \otimes U(1)$$

8 Gluons

W^+ W^- Z^0 B

Interactions are due to the EXCHANGE of SPIN 1 Particles

Neutral Currents



Interactions are due to the EXCHANGE of SPIN 1 Particles

ELECTROMAGNETISM
Exchange of Photons

$$M(\gamma) = 0$$

STRONG Interaction
Exchange of Gluons

$$M(\text{gluon}) = 0$$

WEAK Interaction
Exchange of 3 Massive Particles

$$M(W^{\pm}) \simeq 85\, M_{\text{proton}}$$

$$M(Z^{0}) \simeq 97\, M_{\text{proton}}$$

$$V_{\mathrm{elettrico}} = \frac{e}{r}$$

Potential of a point electric charge

$$V_{\mathrm{debole}} = \frac{g}{r}\, e^{-\frac{c}{\hbar} M\, r}$$

Potential Weak Force

$$V_{\mathrm{debole}} = \frac{g}{r}\, e^{-r/R_0}$$

$$R_0 = \frac{\hbar}{c}\frac{1}{M}$$

Short Range

$$R_0 \simeq 2 \times 10^{-16}\ \mathrm{cm}$$

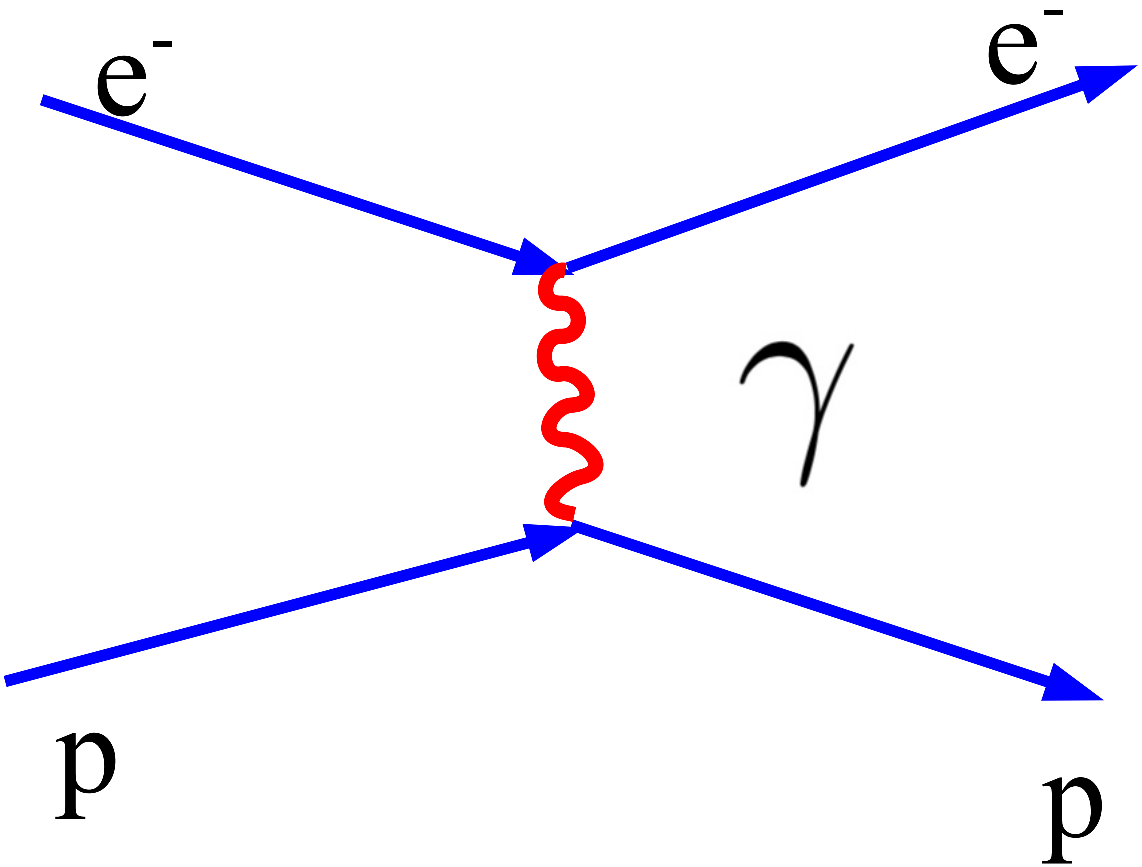
Comparing the Cross section of two Processes:

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

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

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

Rutherford Formula:

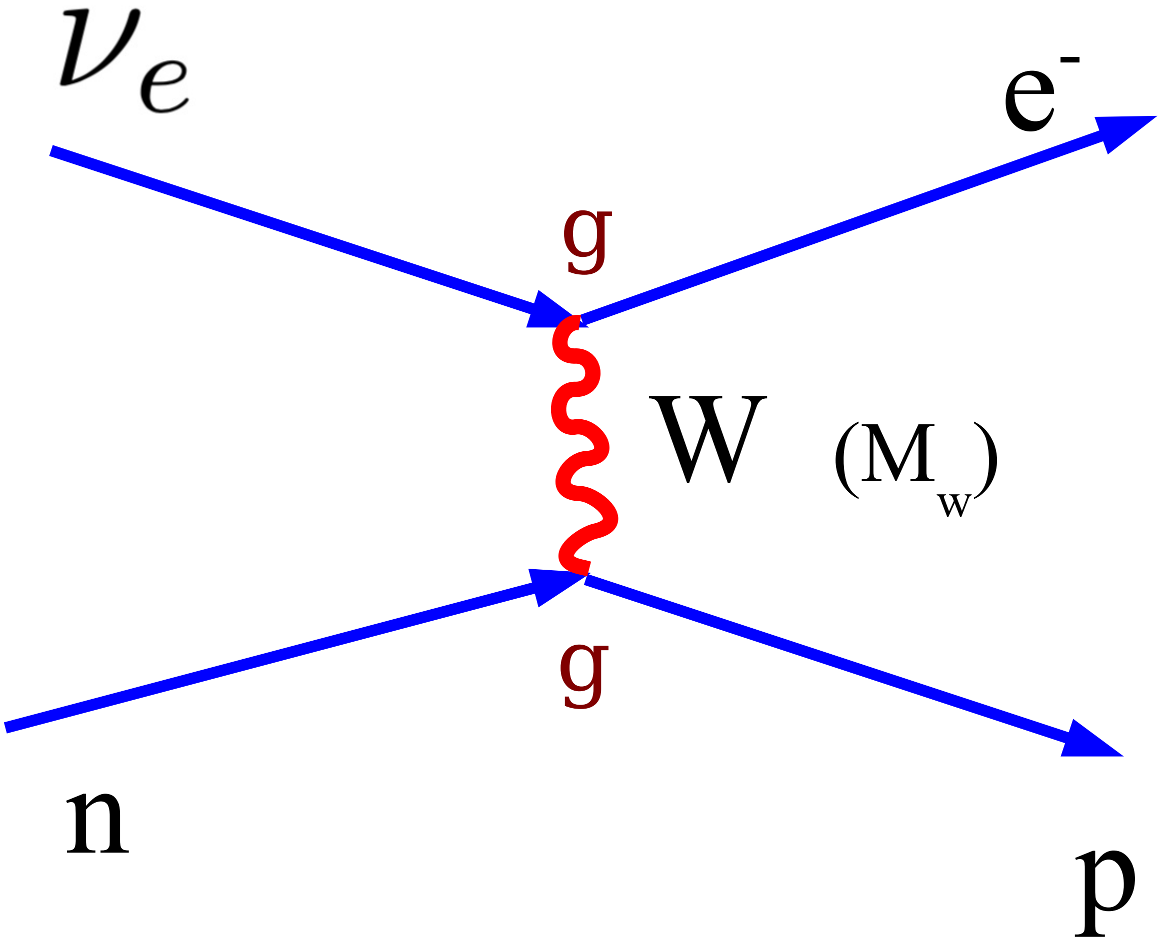


$$Q^2 = (p_e - p_e')^2$$

$$\frac{d\sigma_{ep}}{dQ^2} \simeq \frac{\alpha^2}{Q^4} (\hbar c)^2$$

$$\nu_e + n \to e^- + p$$

$$e \to g = \frac{e}{\sin\theta_{\mathrm{Weinberg}}}$$



$$Q^2 \to (Q^2 + M_W^2)$$

$M_W = 80$ GeV

$$\frac{d\sigma_{\nu n}}{dQ^2} \simeq \frac{(4\pi\, g^2)^2}{(M_W^2 + Q^2)^2}$$

$$\simeq \frac{(4\pi\, g^2)^2}{M_W^4} \frac{1}{(1 + Q^2/M_W^2)^2}$$

$$\sigma_{\nu n} = \int dQ^2 \, \frac{d\sigma_{\nu n}}{dQ^2}$$

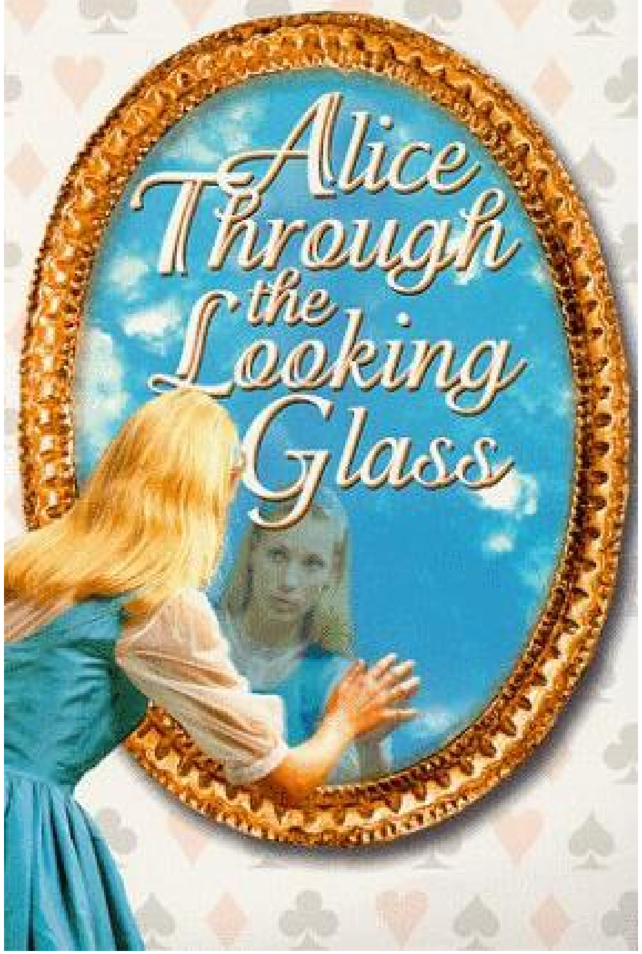
$$\simeq \frac{(4\pi \, g^2)^2}{M_W^4} \left(Q^2_{\text{max}} - Q^2_{\text{min}}\right)$$

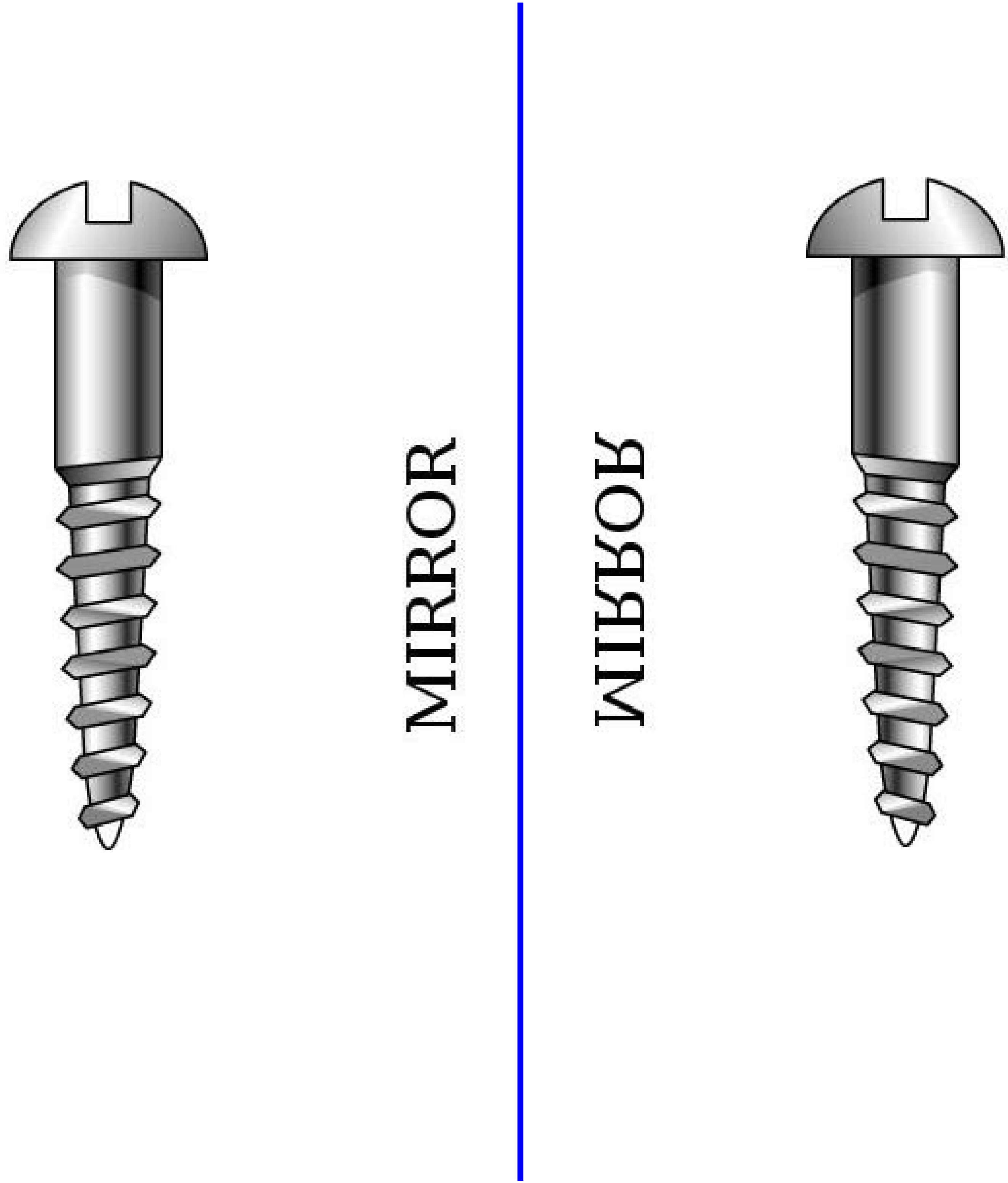
$$Q^2_{\text{max}} = (p_\nu + p_n)^2 = M^2 + 2M \, E_\nu$$

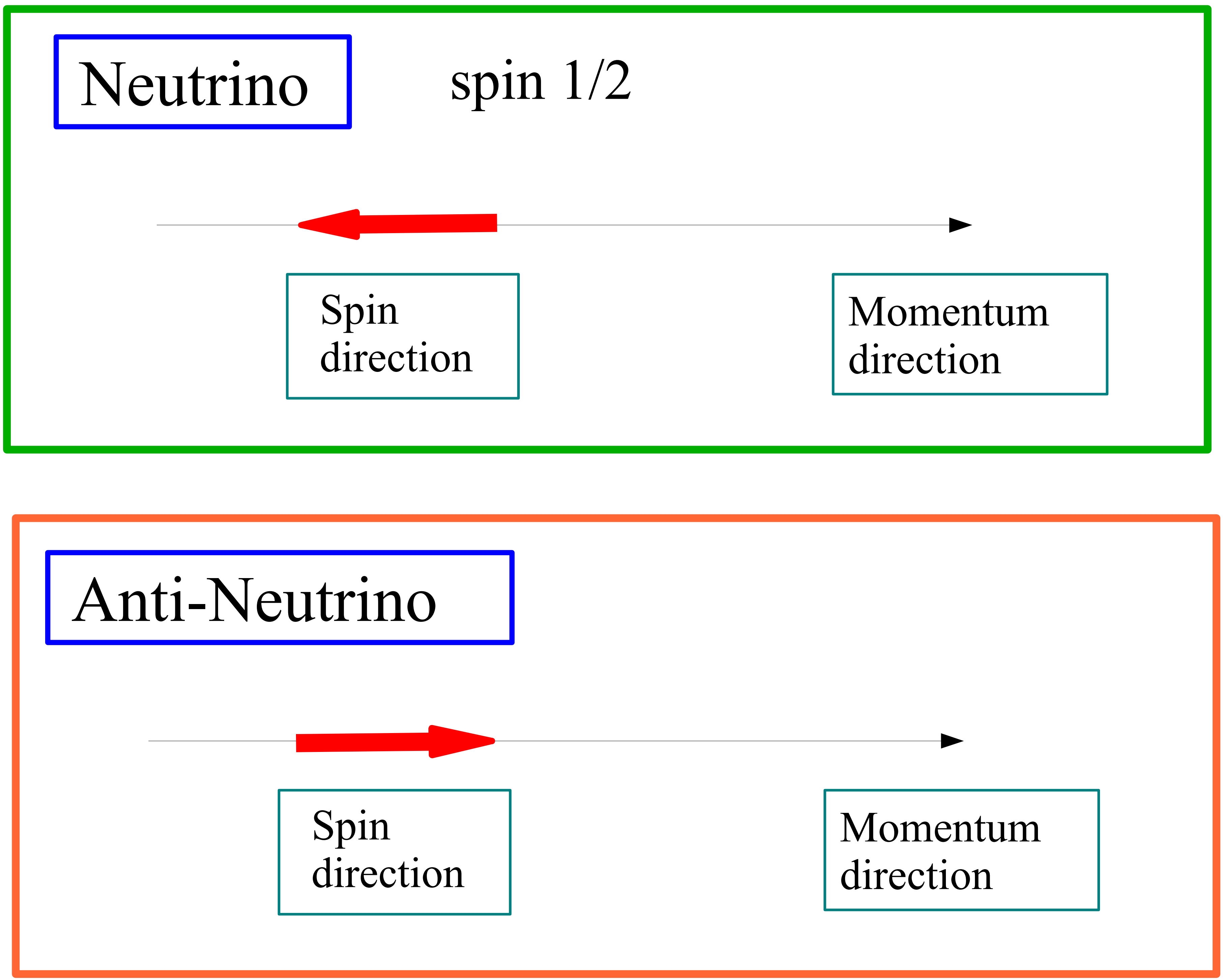
$$\sigma_\nu(E_\nu) \sim \frac{\alpha^2}{M_W^4} M_p \, E_\nu \, (\hbar \, c)^2 \sim 10^{-38} \, E(\text{GeV}) \, \text{cm}^2$$

PARITY SYMMETRY

Can we understand if we see the real world or a "Mirror Image" of the world ?




MIRROR



Neutrino
spin 1/2
Spin direction
Momentum direction
Anti-Neutrino
Spin direction
Momentum direction

Spin ½ Particles are described by
4 components "Dirac Spinors"

Left and Right
Chirality Projectors

$$\psi_L = \left(\frac{1-\gamma_5}{2}\right)\psi$$

$$\psi_R = \left(\frac{1+\gamma_5}{2}\right)\psi$$

Only the
Left-Chirality
component of a fermion
interacts with the W bosons.

For a massless particle
CHIRALITY = HELICITY

$$e^-, \quad \mu^-, \quad \tau^-$$

$$\nu_e, \quad \nu_\mu, \quad \nu_\tau$$

$$u, \quad d, \quad s, \quad c, \quad b, \quad t$$

Particles: Left-chirality

$$P_{\text{Left}} \simeq 1 - \frac{m^2}{E^2}$$

$$P_{\text{Right}} \simeq \frac{m^2}{E^2}$$

$$e^+, \quad \mu^+, \quad \tau^+$$

$$\overline{\nu}_e, \quad \overline{\nu}_\mu, \quad \overline{\nu}_\tau$$

$$\overline{u}, \quad \overline{d}, \quad \overline{s}, \quad \overline{c}, \quad \overline{b}, \quad \overline{t}$$

Anti-Particles: Right-chirality

$$P_{\text{Left}} \simeq \frac{m^2}{E^2}$$

$$P_{\text{Right}} \simeq 1 - \frac{m^2}{E^2}$$

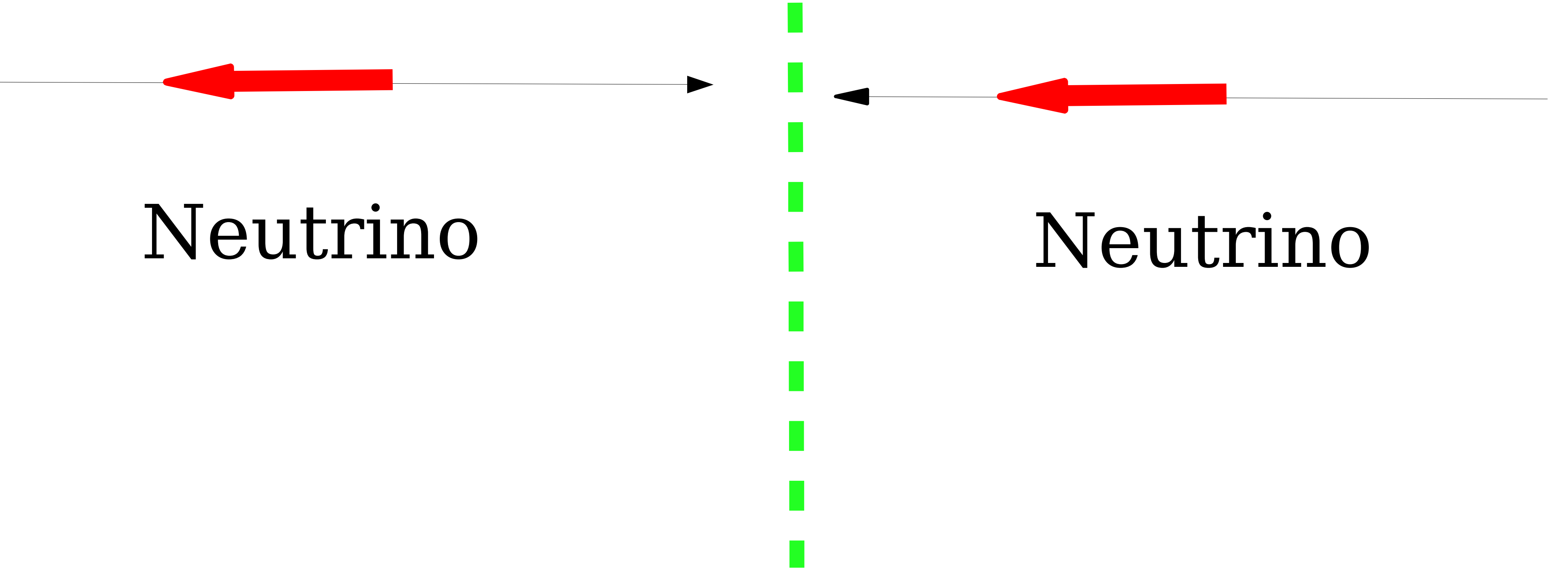
Fermion Particles in the Standard Model

$\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} t \\ b' \end{pmatrix}_L$	$Y = -\frac{1}{2}$
d_R	s_R	b_R	$Y = -\frac{1}{3}$
u_R	c_R	t_R	$Y = +\frac{2}{3}$

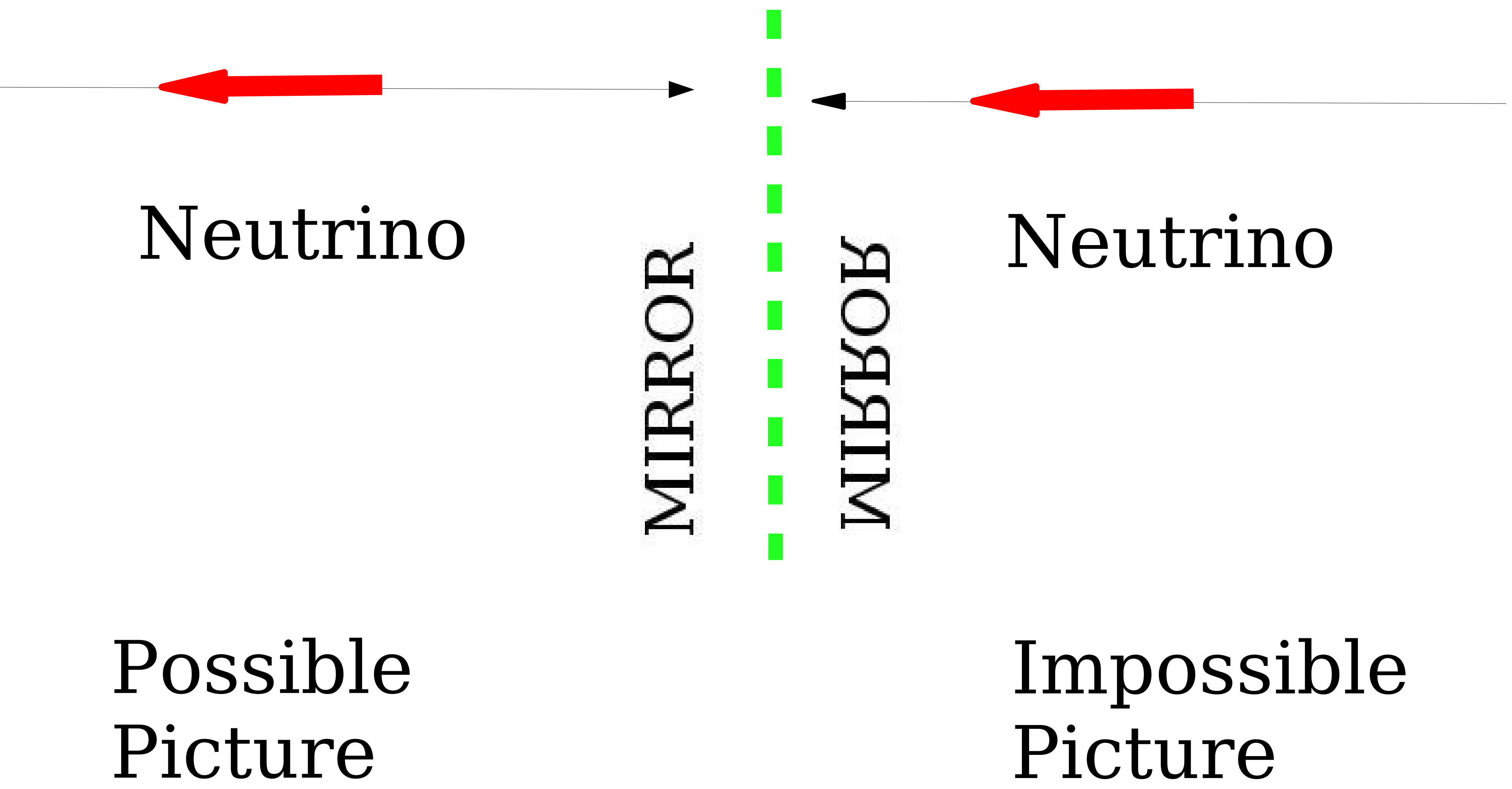
$$\begin{pmatrix} H^+ \\ H^\circ \end{pmatrix}$$

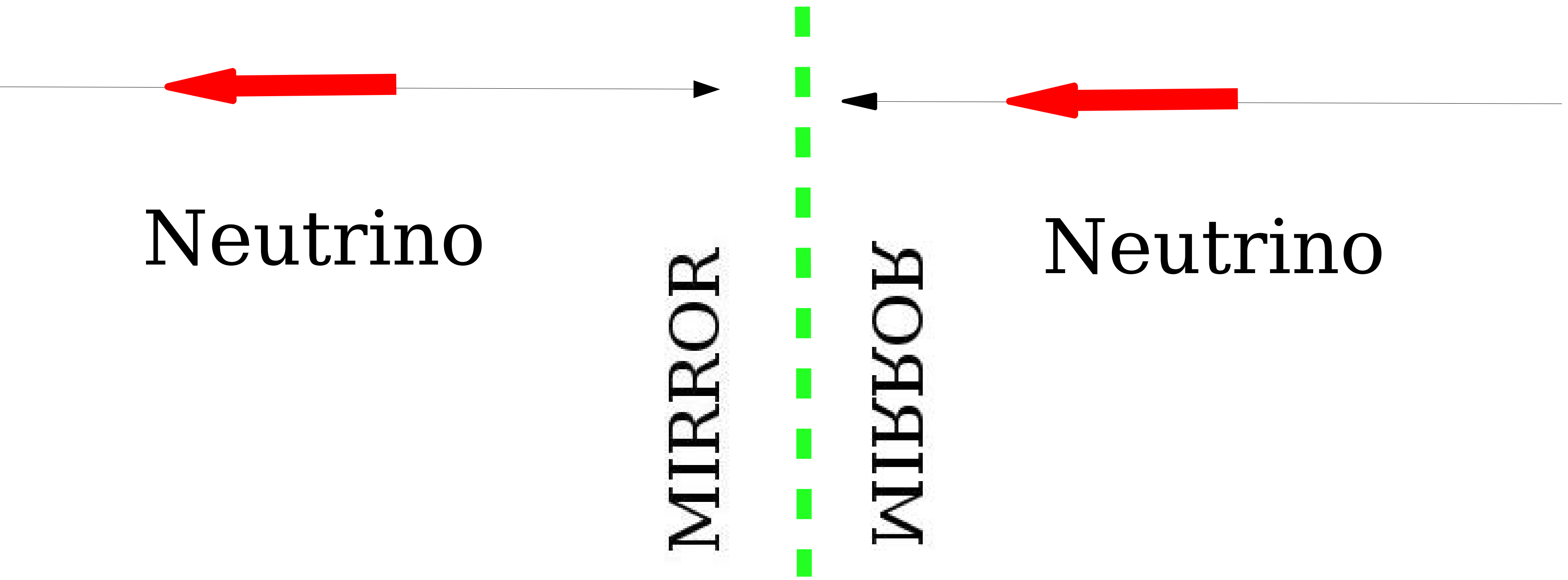
$$Y = +\frac{1}{2}$$

$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$Y = -\frac{1}{2}$
e_R	μ_R	τ_R	$Y = -1$
$(\nu_e)_R$	$(\nu_\mu)_R$	$(\nu_\tau)_R$	$Y = 0$



Neutrino
Neutrino


Neutrino
MIRROR
MIRROR
Neutrino
Possible
Picture
Impossible
Picture

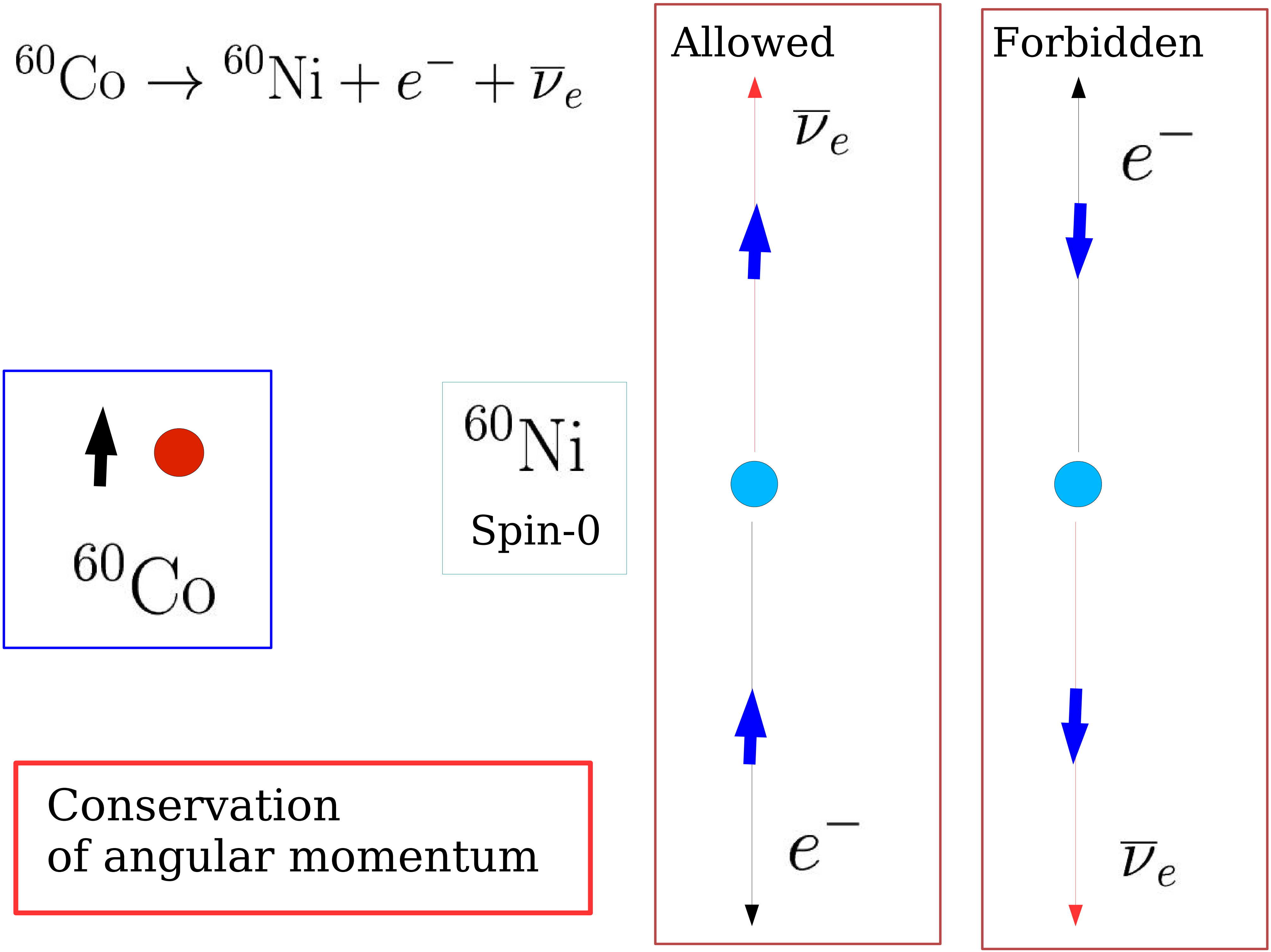


Possible
Picture

Impossible
Picture

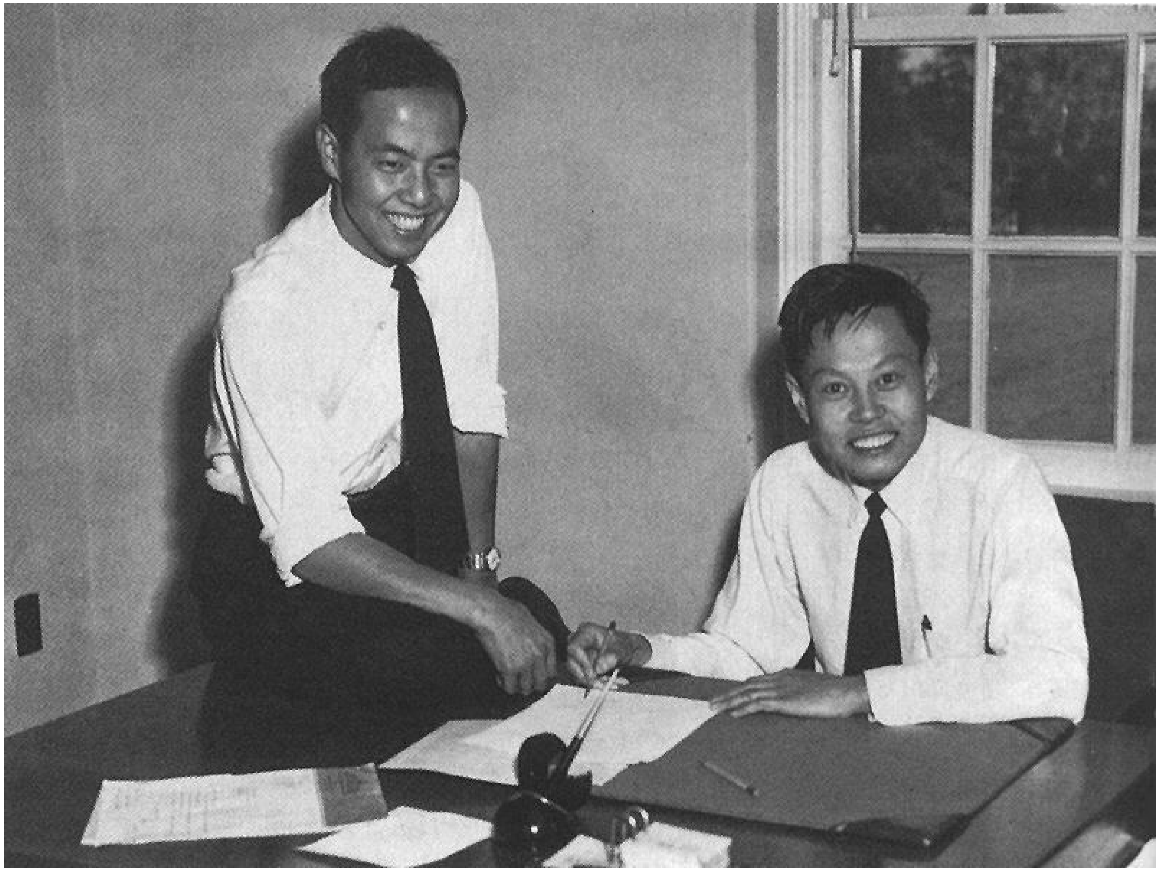
PARITY VIOLATION

$$^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni} + e^- + \overline{\nu}_e$$

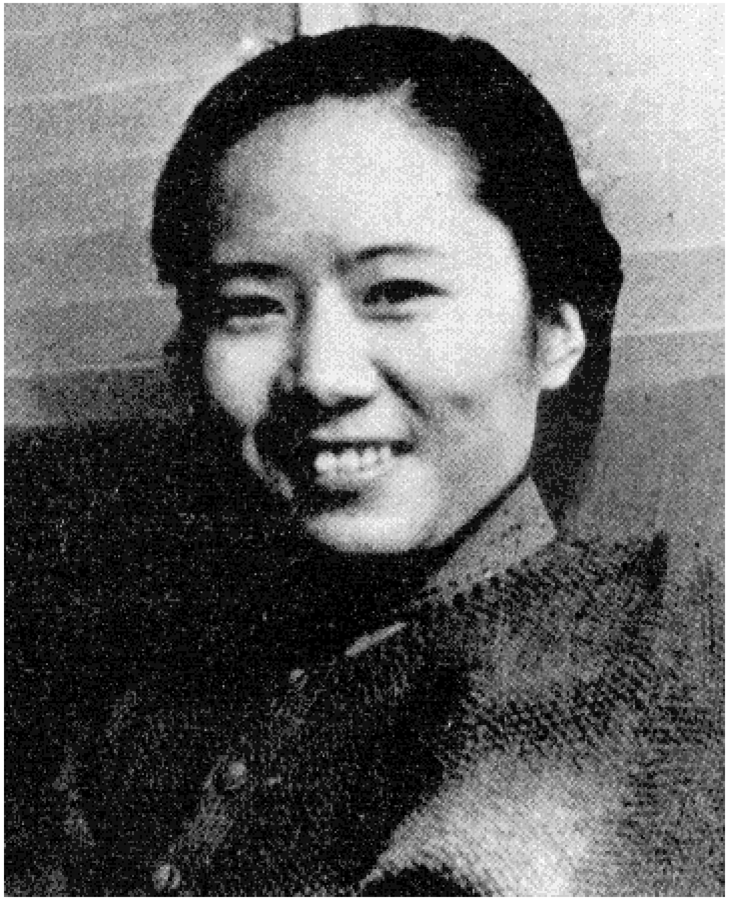


DISCOVERY of PARITY VIOLATION

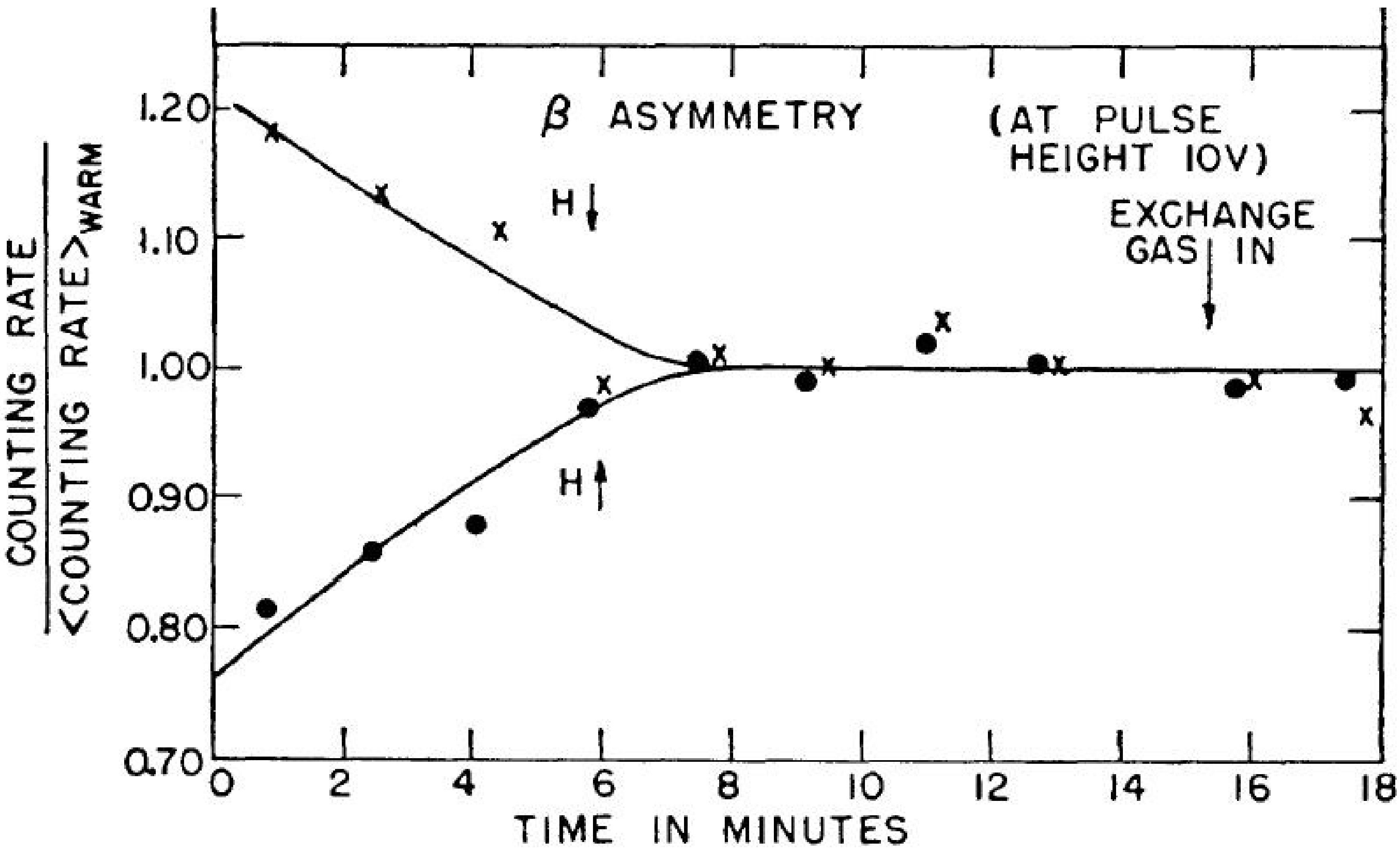
Lee and Yang



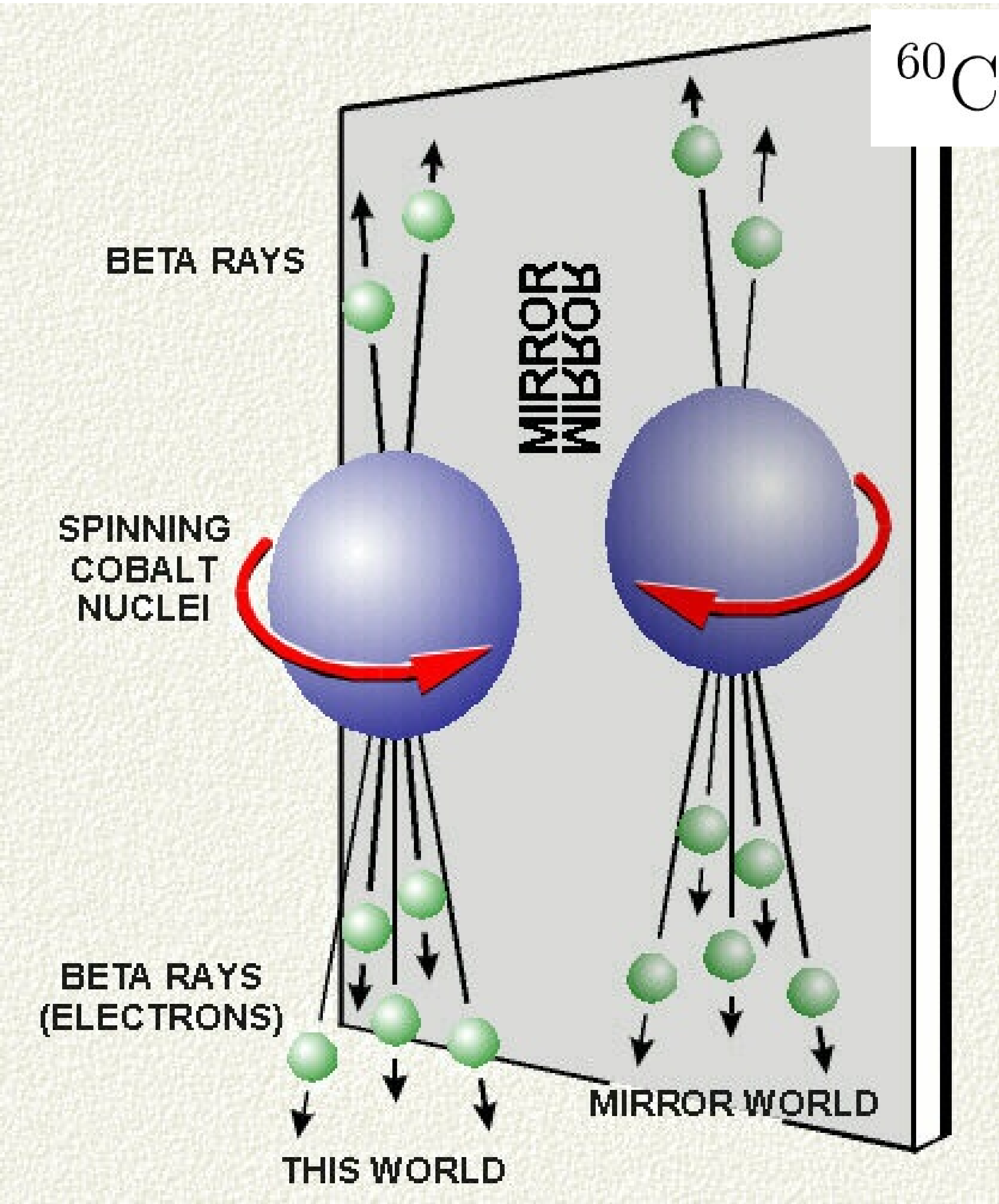
“Madame” Wu



Cobalt-60 in a Cryostat

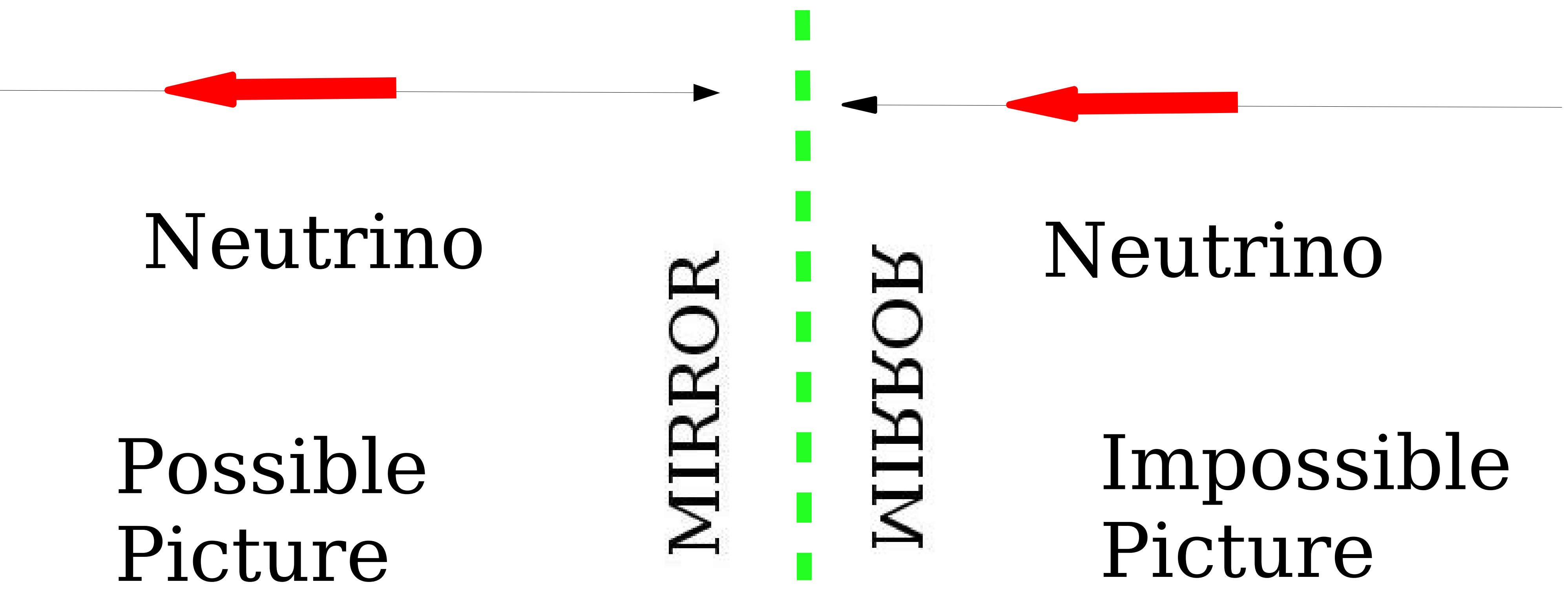


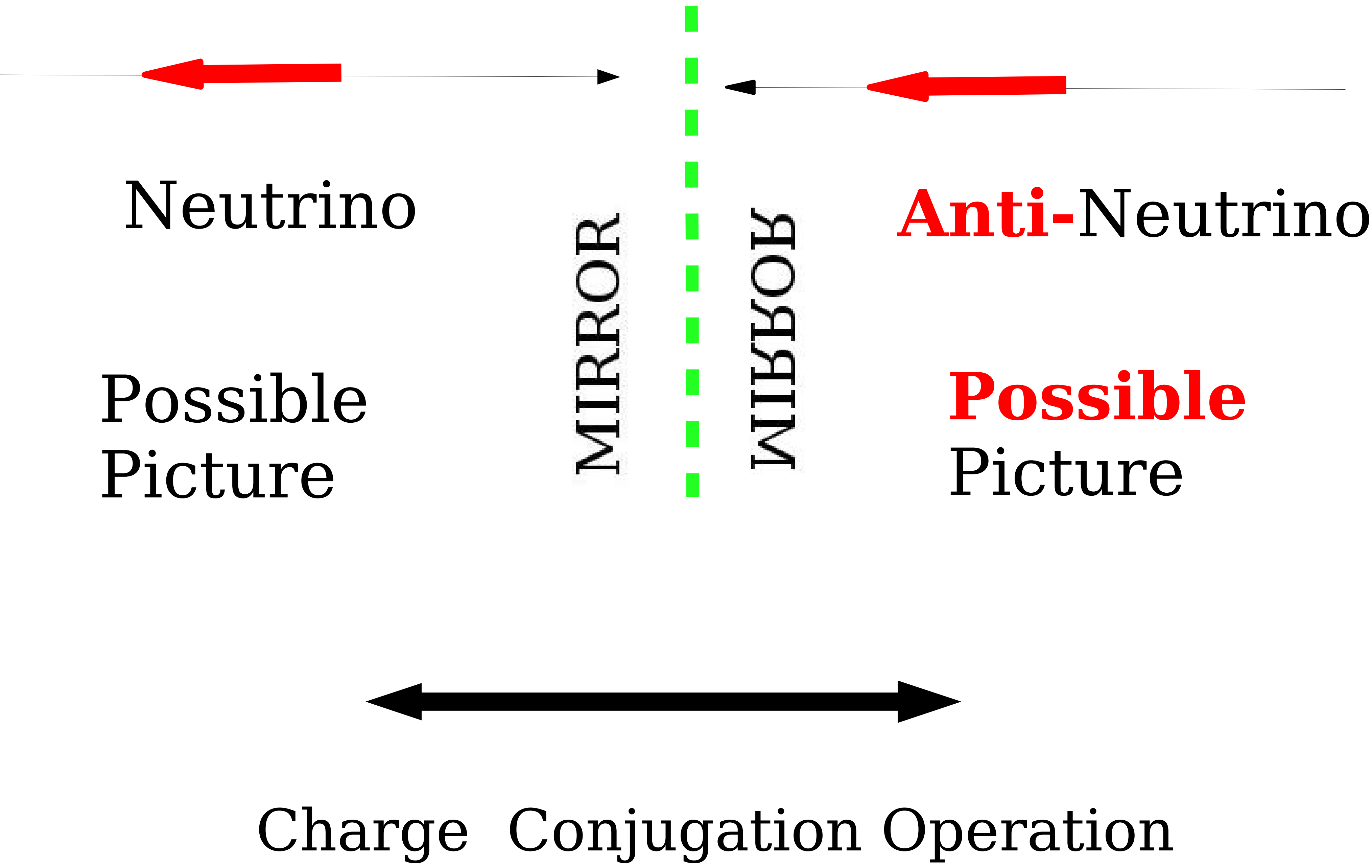
$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^{-} + \overline{\nu}_e$$



The Experiment
(dec. 1956)
lead by:
“Madame”
Chien-Shiung WU

that determined
that
“PARITY”
is VIOLATED


Neutrino
Possible Picture
MIRROR
MIRROR
Neutrino
Impossible Picture



Neutrino
MIRROR
Anti-Neutrino
Possible Picture
Possible Picture
Charge Conjugation Operation

APPROXIMATE SYMMETRY of NATURE

CP Transformation

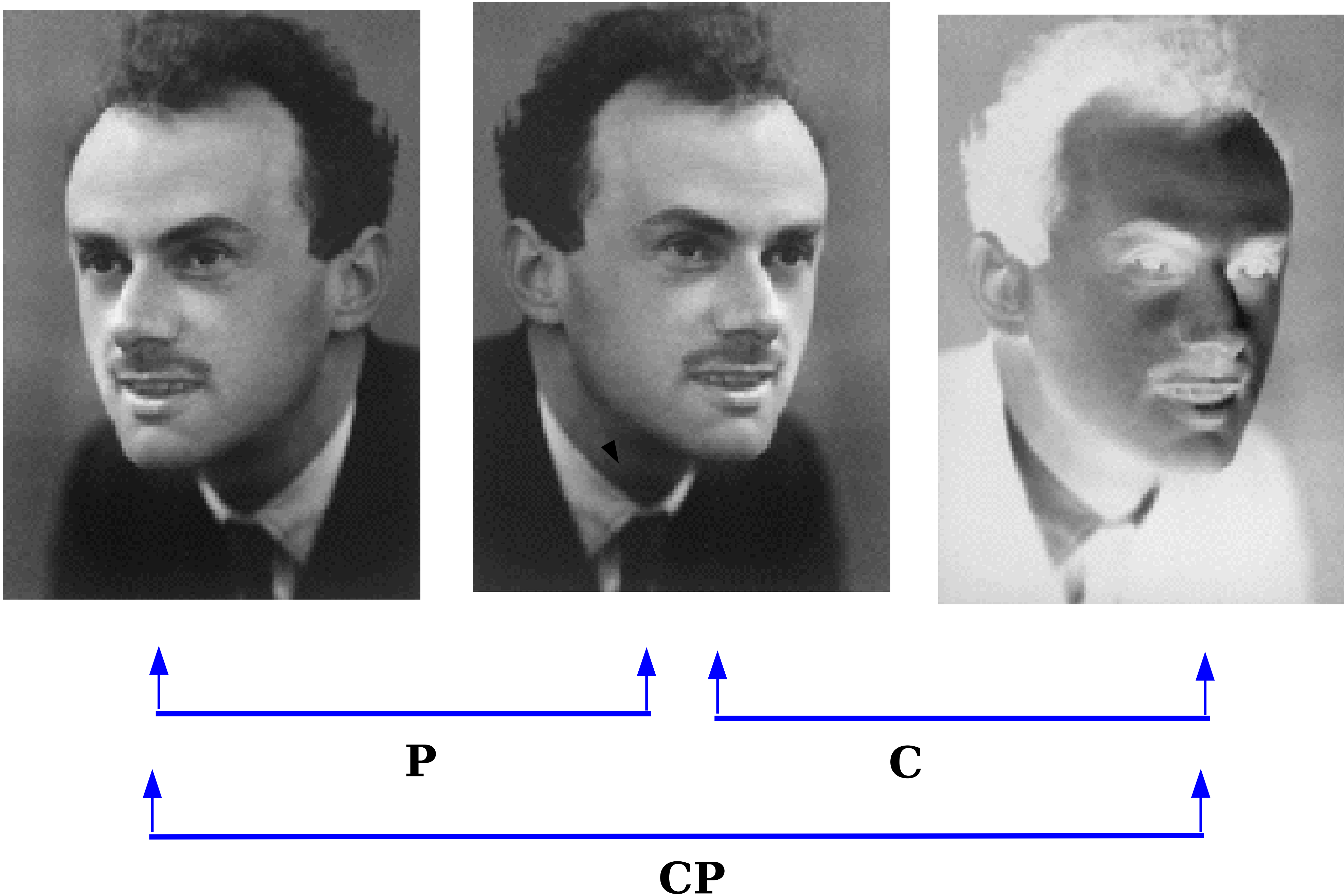
C = Charge Conjugation

[Particle $\longleftrightarrow$ Anti-Particle]

P = Parity

[Reflection in a Mirror]

Paul M. Dirac



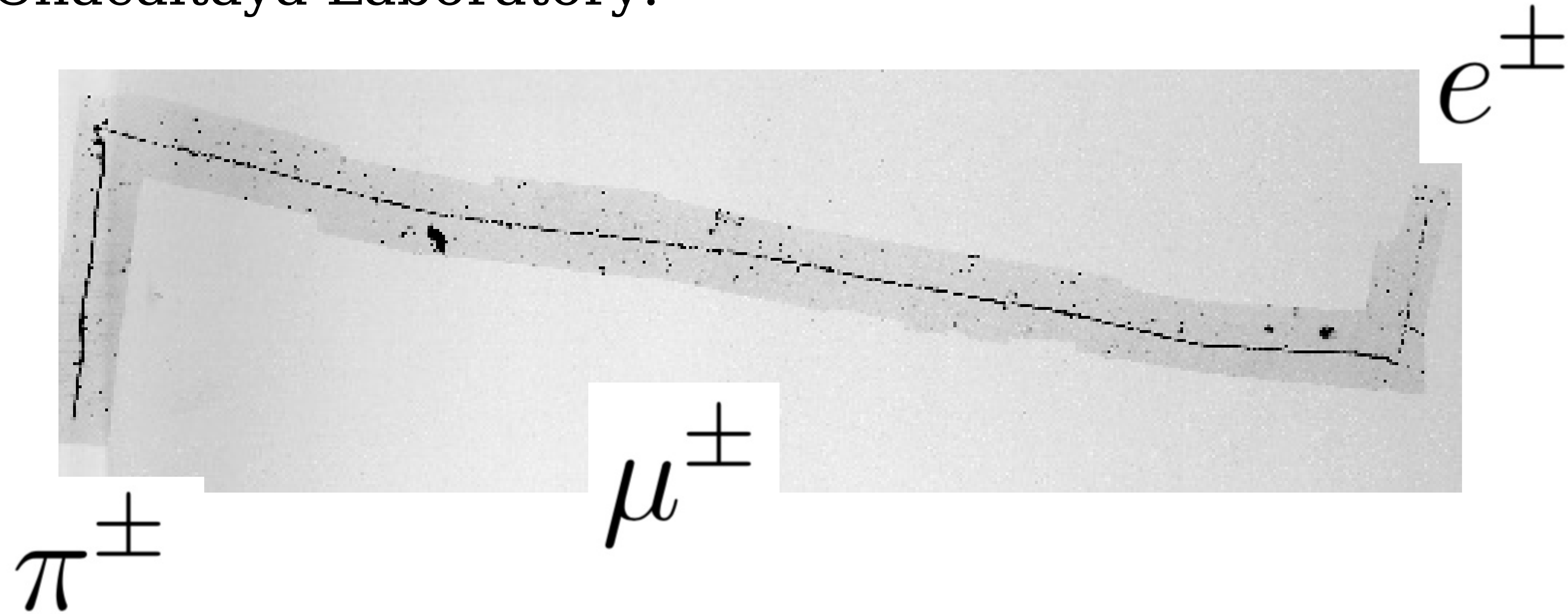
The NEUTRINO FLAVOR

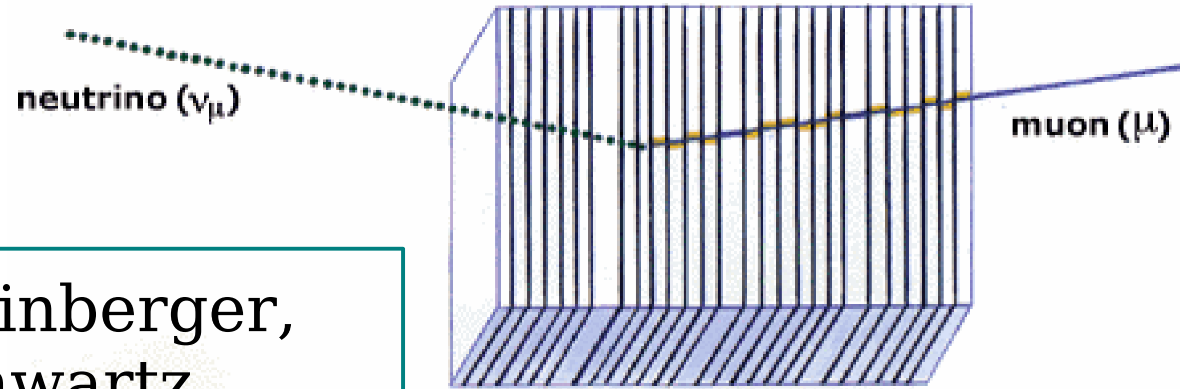
3 type (FLAVORs) of Neutrinos

$$\nu_e \qquad \nu_\mu \qquad \nu_\tau$$

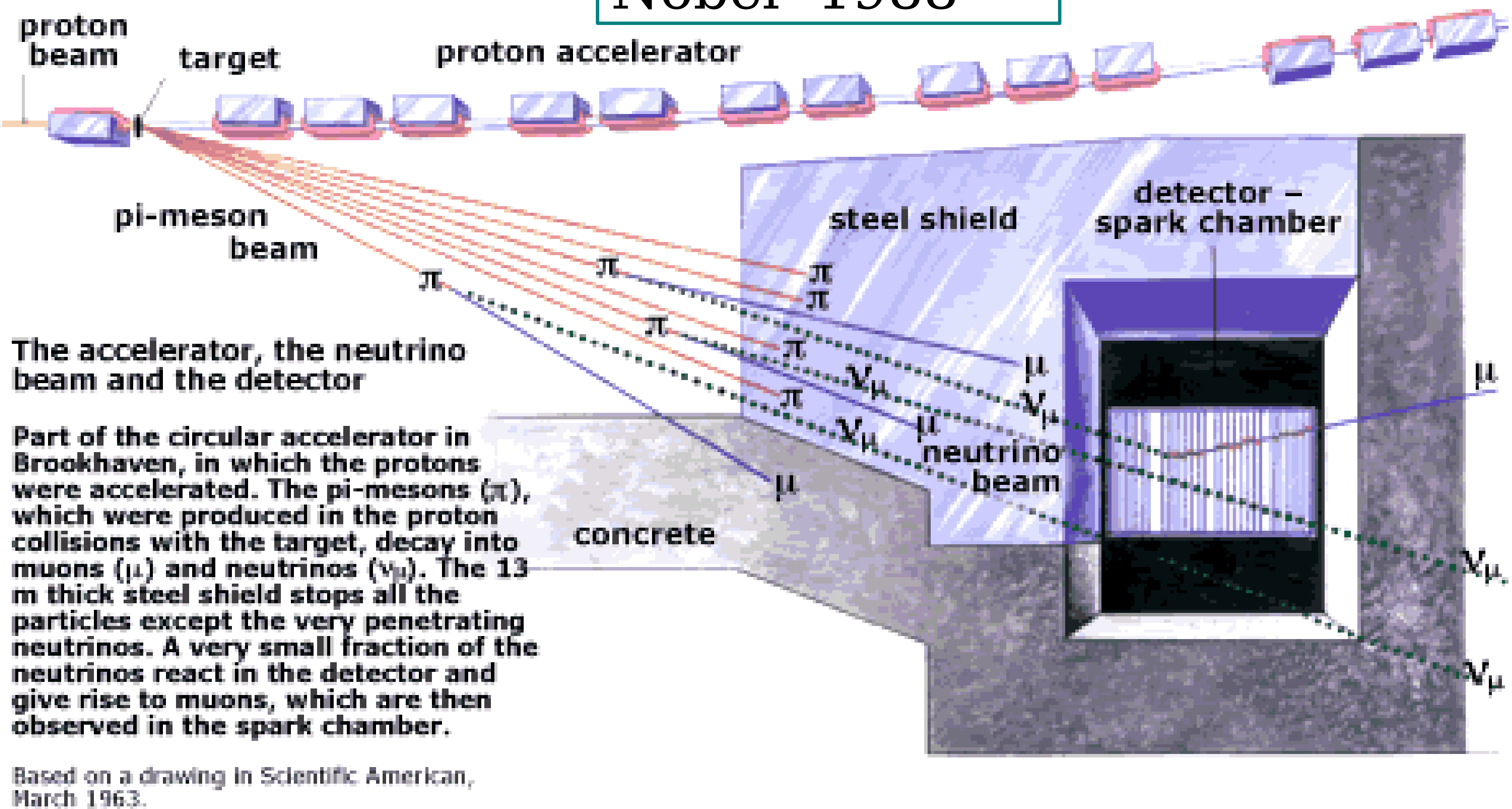
$$\overline{\nu}_e \qquad \overline{\nu}_\mu \qquad \overline{\nu}_\tau$$

In 1947 Powell, Occhialini and Lattes discover the existence of the pion thanks to observation of Cosmic Rays with Emulsions in the Chacaltaya Laboratory.

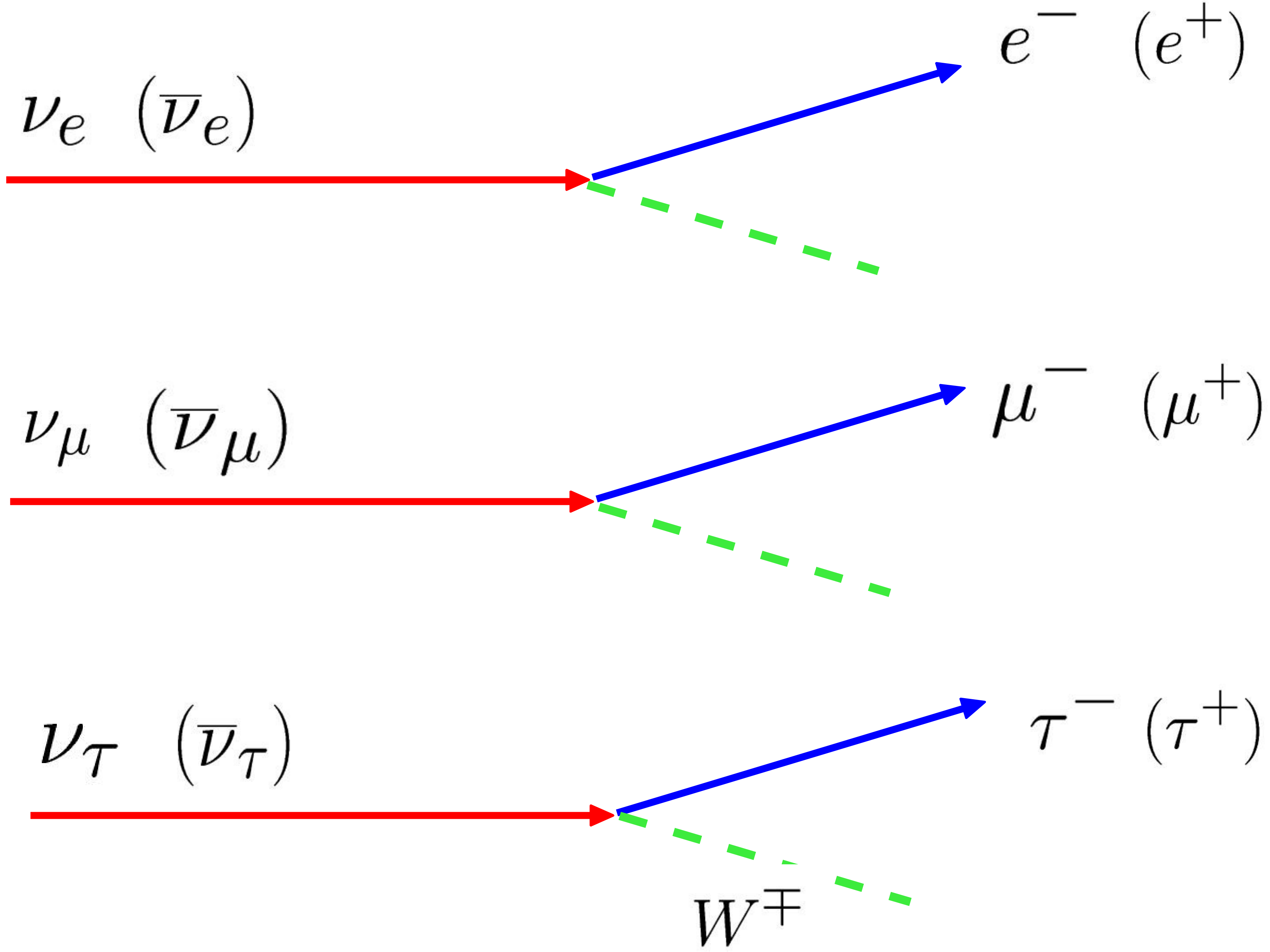




Steinberger,
Schwartz,
Lederman
Measure (1962)
Nobel -1988

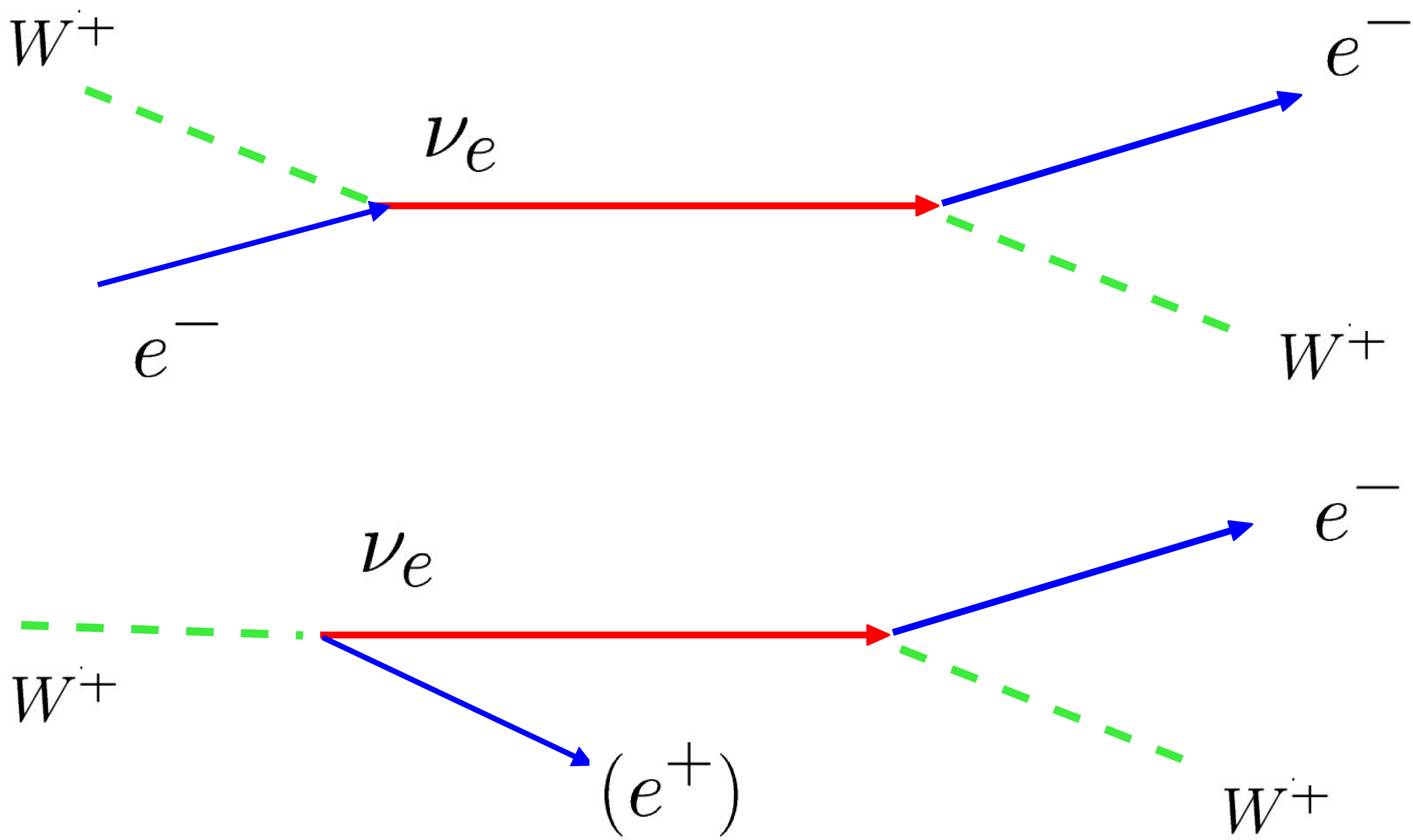


FLAVOR


$\nu_e \quad (\overline{\nu}_e)$
$e^- \quad (e^+)$
$\nu_\mu \quad (\overline{\nu}_\mu)$
$\mu^- \quad (\mu^+)$
$\nu_\tau \quad (\overline{\nu}_\tau)$
$\tau^- \quad (\tau^+)$
$W^\mp$

FLAVOR

Electron-flavor



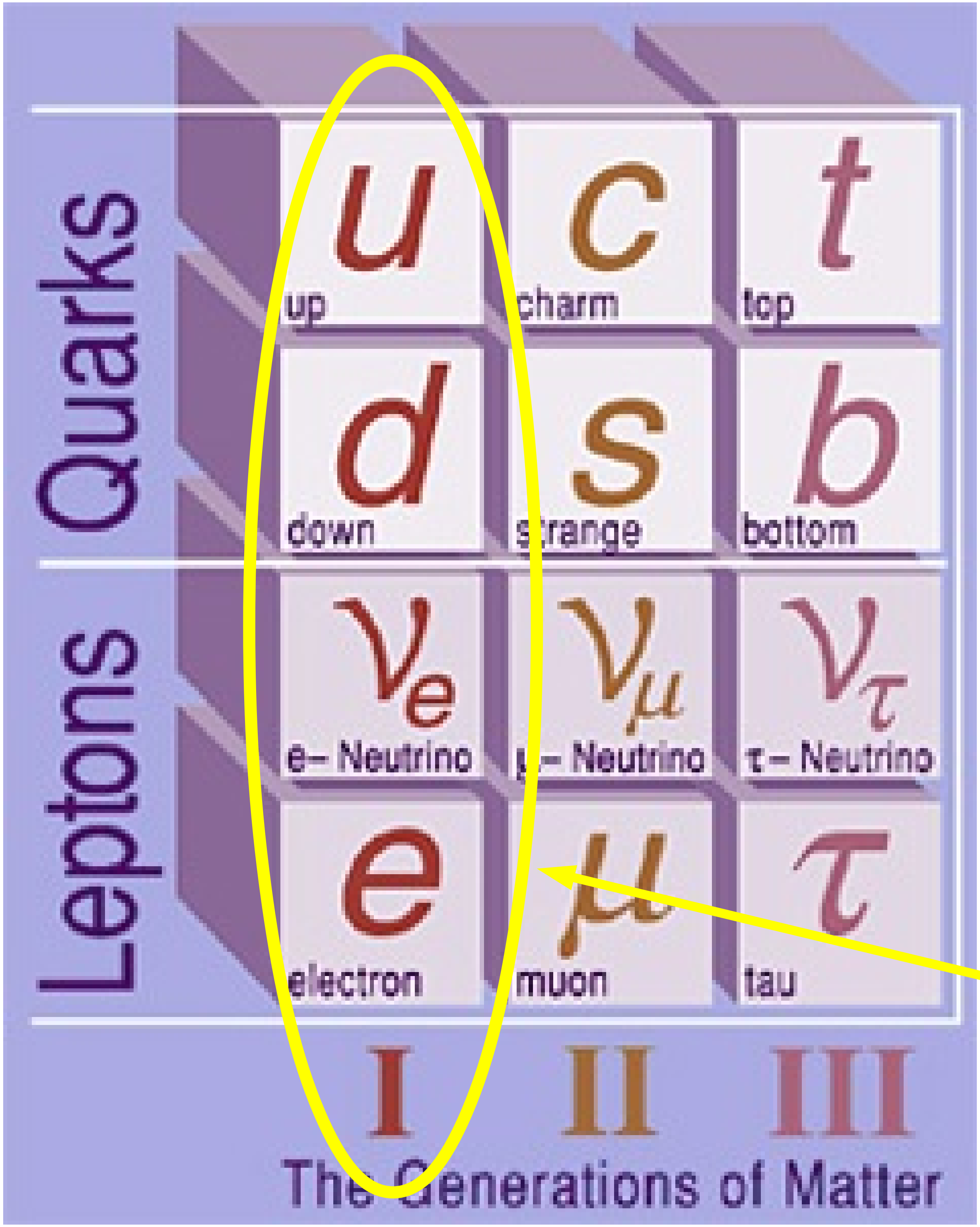
$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s' \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

$$u_R \quad d_R \qquad c_R \quad s_R \qquad t_R \quad b_R$$

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

$$(e^-)_R \qquad (\mu^-)_R \qquad (\tau^-)_R$$

$$(\nu_e)_R \qquad (\nu_\mu)_R \qquad (\nu_\tau)_R$$



3 GENERATIONS of elementary fermions

First Generation:

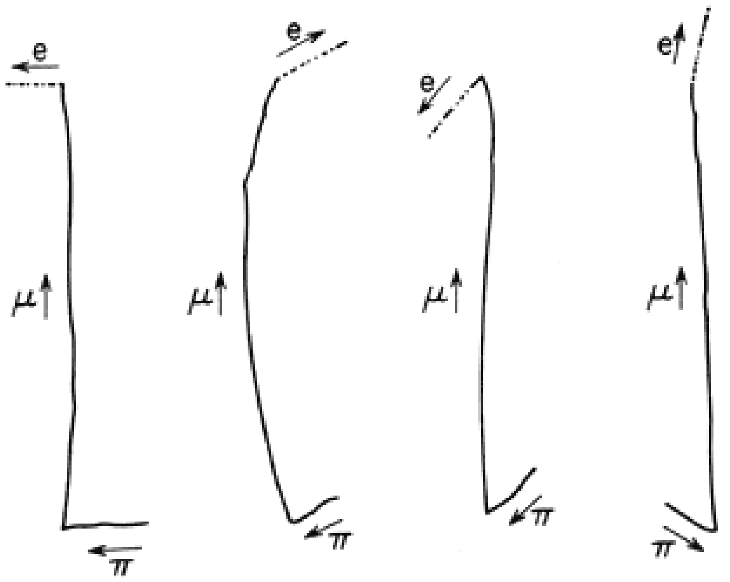
Ordinary Matter

PION DECAY

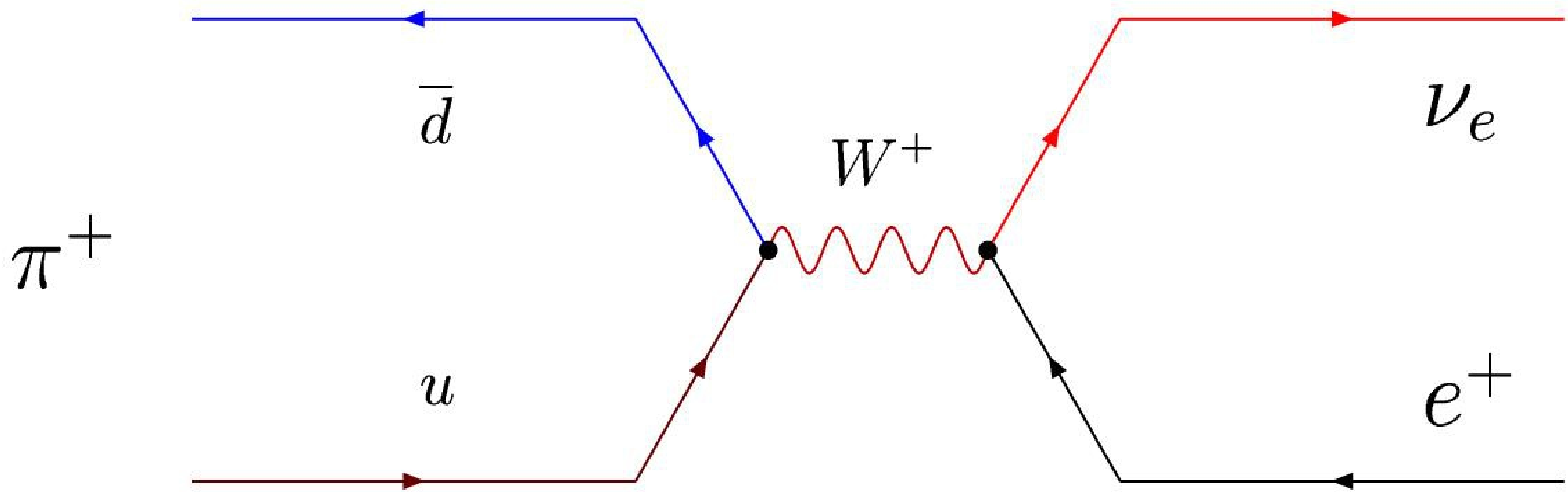
$$\pi^+ = [\overline{u}d]$$

$$\pi^- = [\overline{d}u]$$

$$\pi^0 = \frac{1}{\sqrt{2}}[\overline{u}u + [\overline{d}d]$$



$$\pi^+ \rightarrow \quad \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \overline{\nu}_\mu$$

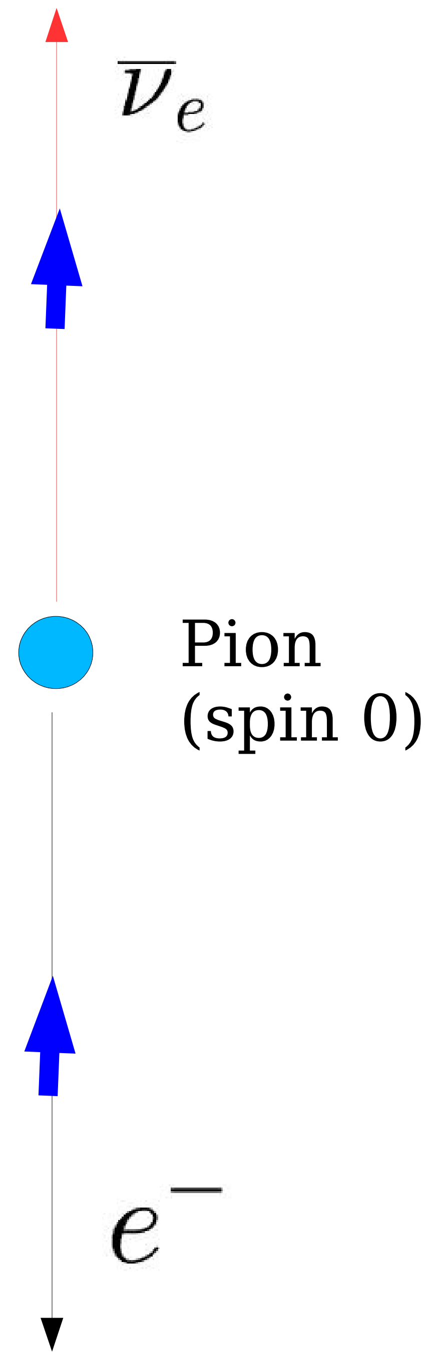


$$\pi^+ \to e^+ \nu_e$$ Dynamically suppressed

$$\pi^+ \to \mu^+ \nu_\mu$$

$$\pi^+ \to \tau^+ \nu_\tau$$ Kinematically Forbidden

Decay is nearly forbidden by Angular Momentum Conservation



CHIRALITY

versus

HELICITY

$$e^-, \quad \mu^-, \quad \tau^-$$

$$\nu_e, \quad \nu_\mu, \quad \nu_\tau$$

$$u, \quad d, \quad s, \quad c, \quad b, \quad t$$

Particles: Left-chirality

$$P_{\text{Left}} = 1 - \frac{m^2}{E^2}$$

$$P_{\text{Right}} = \frac{m^2}{E^2}$$

$$e^+, \quad \mu^+, \quad \tau^+$$

$$\overline{\nu}_e, \quad \overline{\nu}_\mu, \quad \overline{\nu}_\tau$$

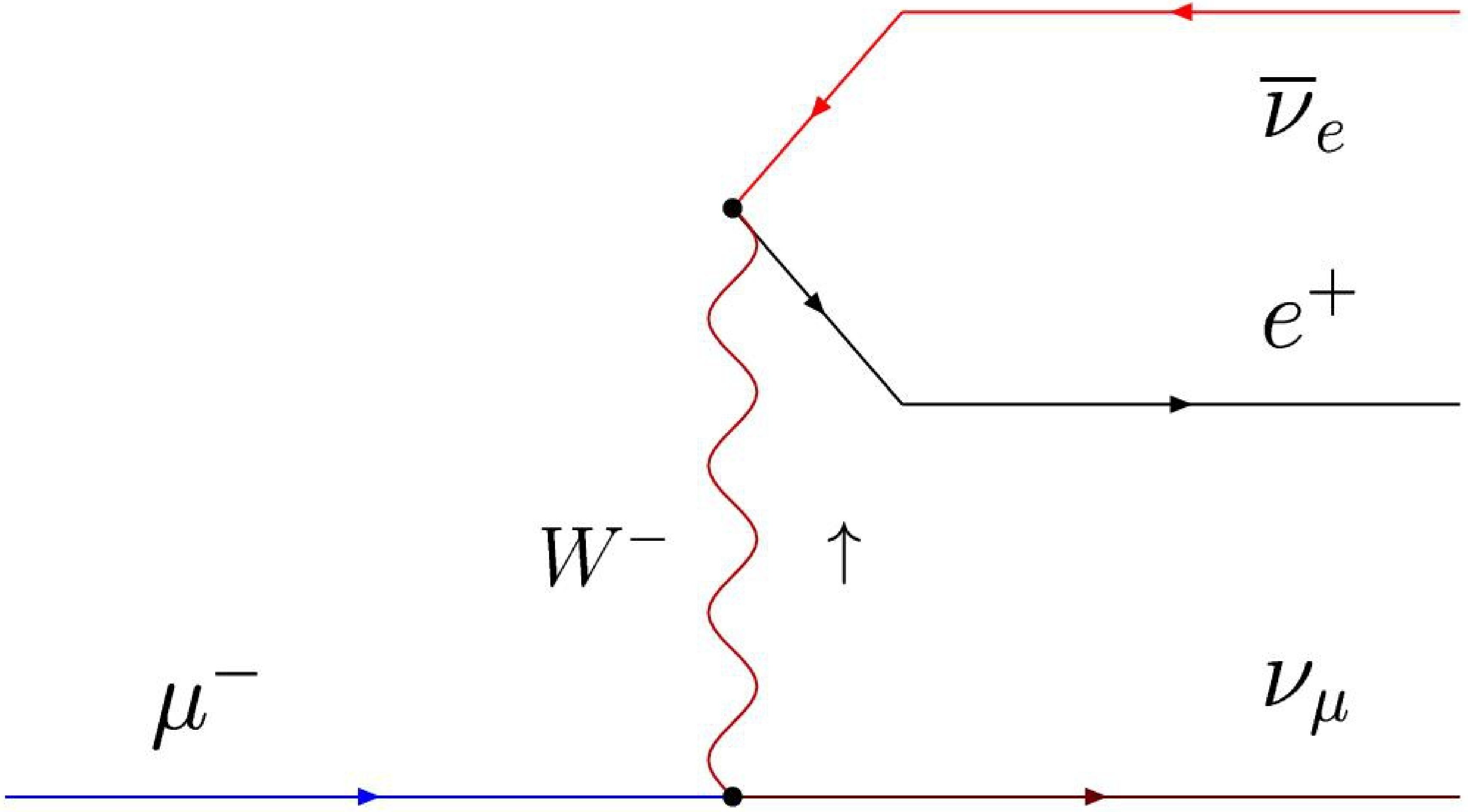
$$\overline{u}, \quad \overline{d}, \quad \overline{s}, \quad \overline{c}, \quad \overline{b}, \quad \overline{t}$$

Anti-Particles: Right-chirality

$$P_{\text{Left}} = \frac{m^2}{E^2}$$

$$P_{\text{Right}} = 1 - \frac{m^2}{E^2}$$

MUON DECAY: $\mu^- \to \nu_\mu + e^- \overline{\nu}_e$



How Many Light Neutrinos Exist ?

Answer : 3

$$Z^0 \rightarrow \nu_\alpha + \overline{\nu}_\alpha$$

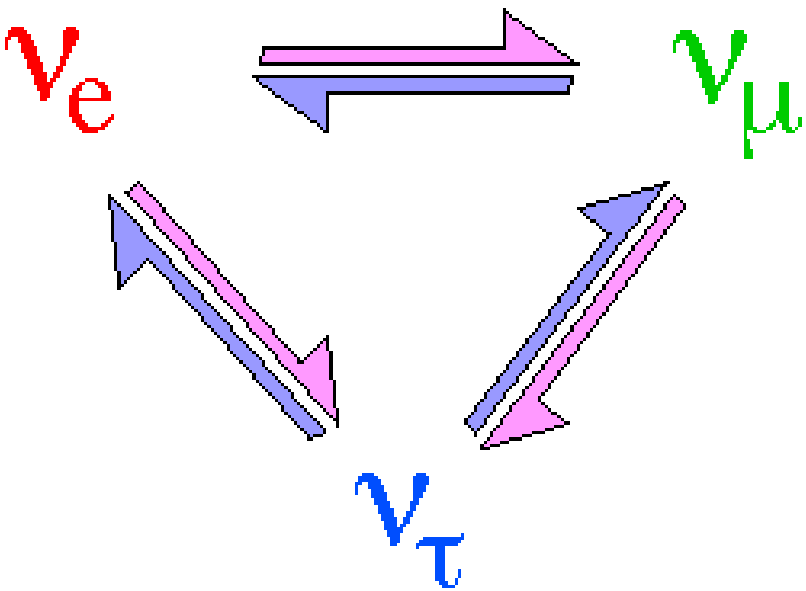
$$\Gamma_{\nu\bar{\nu}} = 166.9 \text{ MeV}$$

$$\Gamma_{\text{invisible}} = N_\nu \, \Gamma_{\nu\overline{\nu}}$$

$$\Gamma_{\text{invisible}} = \Gamma_{\text{tot}} - \Gamma_{\text{vis}} = 498 \pm 4.2 \text{ MeV}$$

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_{\nu\bar{\nu}}} = 2.994 \pm 0.012$$

NEUTRINO FLAVOR OSCILLATIONS



3 Neutrinos states: 3 masses m_1, m_2, m_3

States with definite masses
in general do **not** coincide with the "flavor" states

$$\{ |\nu_e\rangle \quad , \quad |\nu_\mu\rangle \quad , \quad |\nu_\tau\rangle \}$$

Flavor basis

$$\{ |\nu_1\rangle \quad , \quad |\nu_2\rangle \quad , \quad |\nu_3\rangle \}$$

Mass basis

$$\begin{aligned} W^- &\rightarrow \overline{u} + d' \\ &\rightarrow \overline{c} + s' \\ &\rightarrow \overline{t} + b' \end{aligned}$$

-(+2/3) + (-1/3) = -1

$$\begin{aligned} W^+ &\rightarrow e^+ \nu_e \\ &\rightarrow \mu^+ \nu_\mu \\ &\rightarrow \tau^+ \nu_\tau \end{aligned}$$

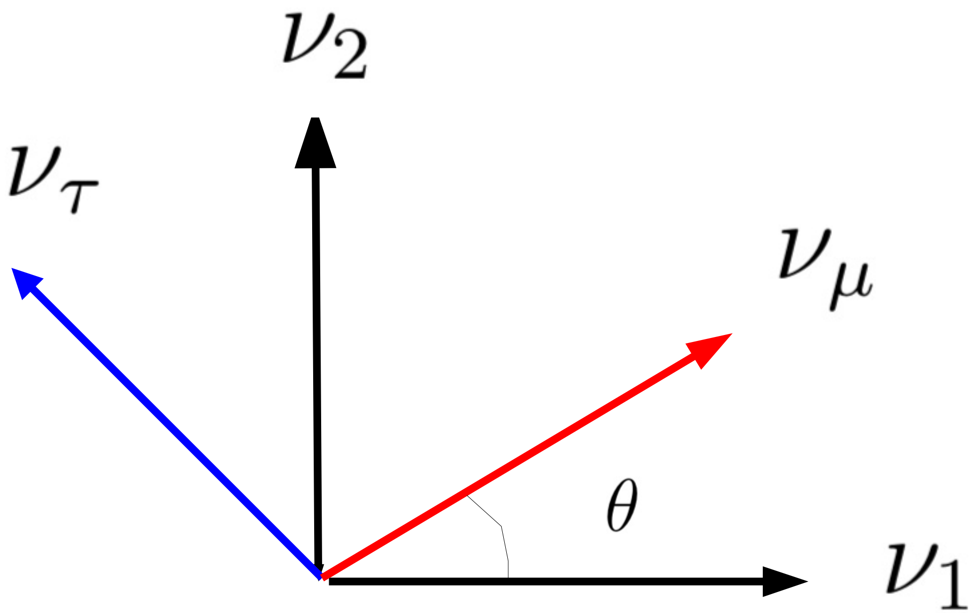
Cabibbo, Kobayashi, Maskawa matrix

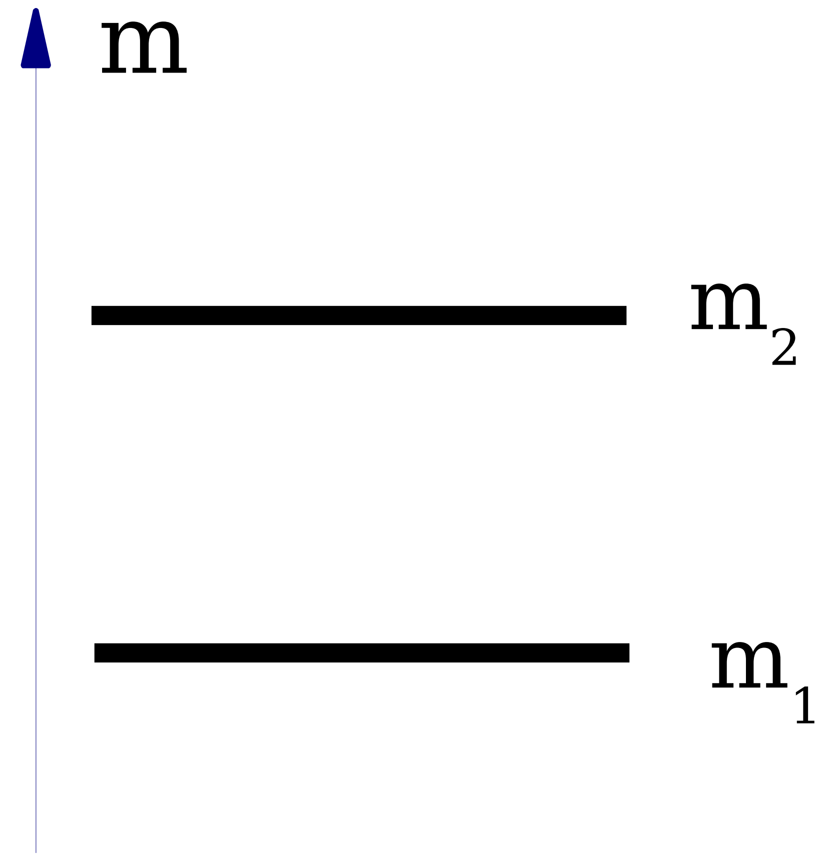
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V^{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo, Maki, Nakagawa, Sakata Matrix

2 Flavor case





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

$$|\nu_\tau\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

$$\Delta m^2 = m_2^2 - m_1^2$$

Neutrino Propagation

ν_μ created at t =0

with momentum p

$$|\nu(0)\rangle = |\nu_\mu\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

Different mass components have different energy

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

ν state at time t

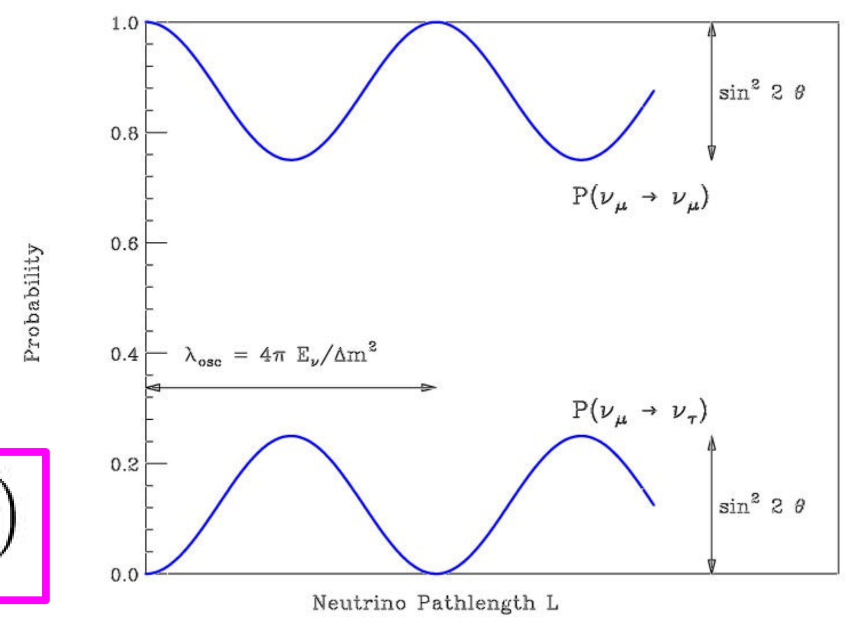
$$|\nu(t)\rangle = \cos\theta\, e^{-iE_1 t}|\nu_1\rangle + \sin\theta\, e^{-iE_2 t}|\nu_2\rangle$$

Oscillation Probability

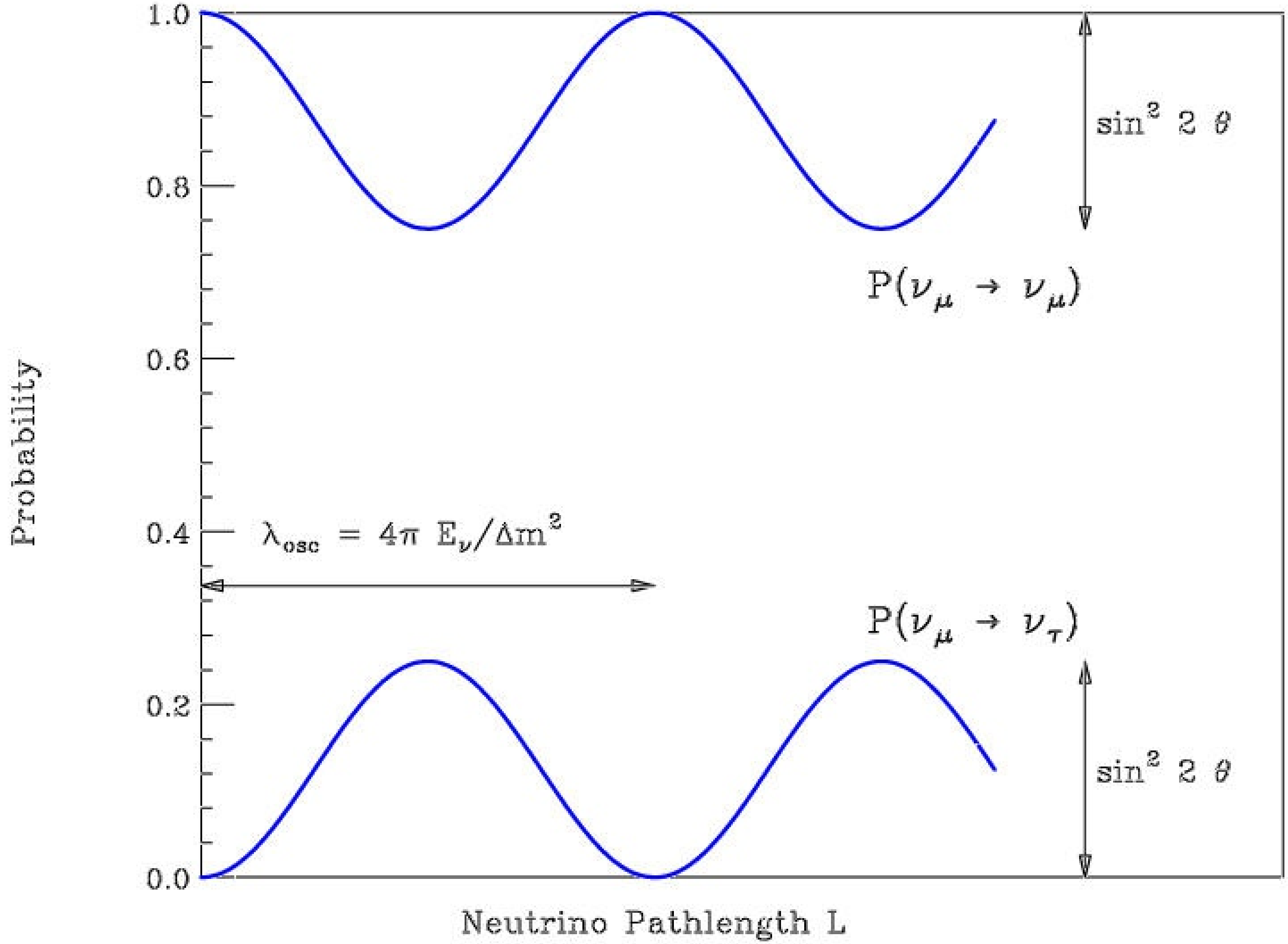
$$P(\nu_\mu \to \nu_\tau;\, t) \;=$$

$$
\begin{aligned}
&= |\langle \nu_\tau | \nu(t) \rangle|^2 \\
&= |\{-\sin\theta\,\langle\nu_1| + \cos\theta\,\langle\nu_2|\}|\{\cos\theta\, e^{-iE_1 t}|\nu_1\rangle + \sin\theta\, e^{-iE_2 t}|\nu_2\rangle\}|^2 \\
&= \cos^2\theta\,\sin^2\theta\,\left|e^{-iE_2 t} - e^{-iE_1 t}\right|^2 \\
&= 2\cos^2\theta\,\sin^2\theta\,\{1 - \cos[(E_2 - E_1)t\} \\
&= \sin^2 2\theta\,\sin^2\left[\frac{\Delta m^2}{4E} t\right]
\end{aligned}
$$

$$P(\nu_\mu \to \nu_\tau;\, t)$$



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



3 Flavor Oscillations

$$|\nu_e\rangle = U^*_{e1}\,|\nu_1\rangle + U^*_{e2}\,|\nu_2\rangle + U^*_{e3}\,|\nu_3\rangle$$

$$|\nu_\mu\rangle = U^*_{\mu 1}\,|\nu_1\rangle + U^*_{\mu 2}\,|\nu_2\rangle + U^*_{\mu 3}\,|\nu_3\rangle$$

$$|\nu_\tau\rangle = U^*_{\tau 1}\,|\nu_1\rangle + U^*_{\tau 2}\,|\nu_2\rangle + U^*_{\tau 3}\,|\nu_3\rangle$$

$$N^{\text{Dirac}}_{\text{(physical phases)}} = \frac{n(n+1)}{2} - (2n-1)$$

3 X 3
Unitary Matrix
3 angles
6 phases

Mixing Matrix: 3 angles, 1 phase

(relevant for neutrino oscillations)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

U* : Mixing Matrix for Antineutrinos

More complex expressions
for the Oscillation Probabilities

3 - Flavor Transitions

$$|\nu(0)\rangle = |\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$$

$$|\nu(t)\rangle = \sum_j U^*_{\alpha j}\, e^{-iE_j t} |\nu_j\rangle$$

$$\begin{aligned} A(\nu_\alpha \to \nu_\beta;\, t) &= \langle \nu_\beta | \nu(t) \rangle \\ &= \{U_{\beta k}\, \langle \nu_k|\}\ \left\{ e^{-iE_j t}\, U^*_{\alpha j} |\nu_j\rangle \right\} \\ &= U_{\beta k}\, U^*_{\alpha j}\, e^{-iE_j t} \langle \nu_k | \nu_j \rangle \\ &= U_{\beta j}\, U^*_{\alpha j}\, e^{-iE_j t} \end{aligned}$$

Oscillation Probability

L, E

$$
\begin{aligned}
P(\nu_\alpha \to \nu_\beta) &= \left| \sum_j U_{\beta j} U^*_{\alpha j} \; e^{-i\, m_j^2 \, \frac{L}{2E_\nu}} \right|^2 \\
&= \sum_{j=1,3} \; |U_{\beta j}|^4 \; |U_{\alpha j}|^4 \\
&+ \sum_{j<k} 2\,\mathrm{Re}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \; \cos\left(\frac{\Delta m^2_{jk}\, L}{2E} \right) \\
&+ \sum_{j<k} 2\,\mathrm{Im}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \; \sin\left(\frac{\Delta m^2_{jk}\, L}{2E} \right)
\end{aligned}
$$

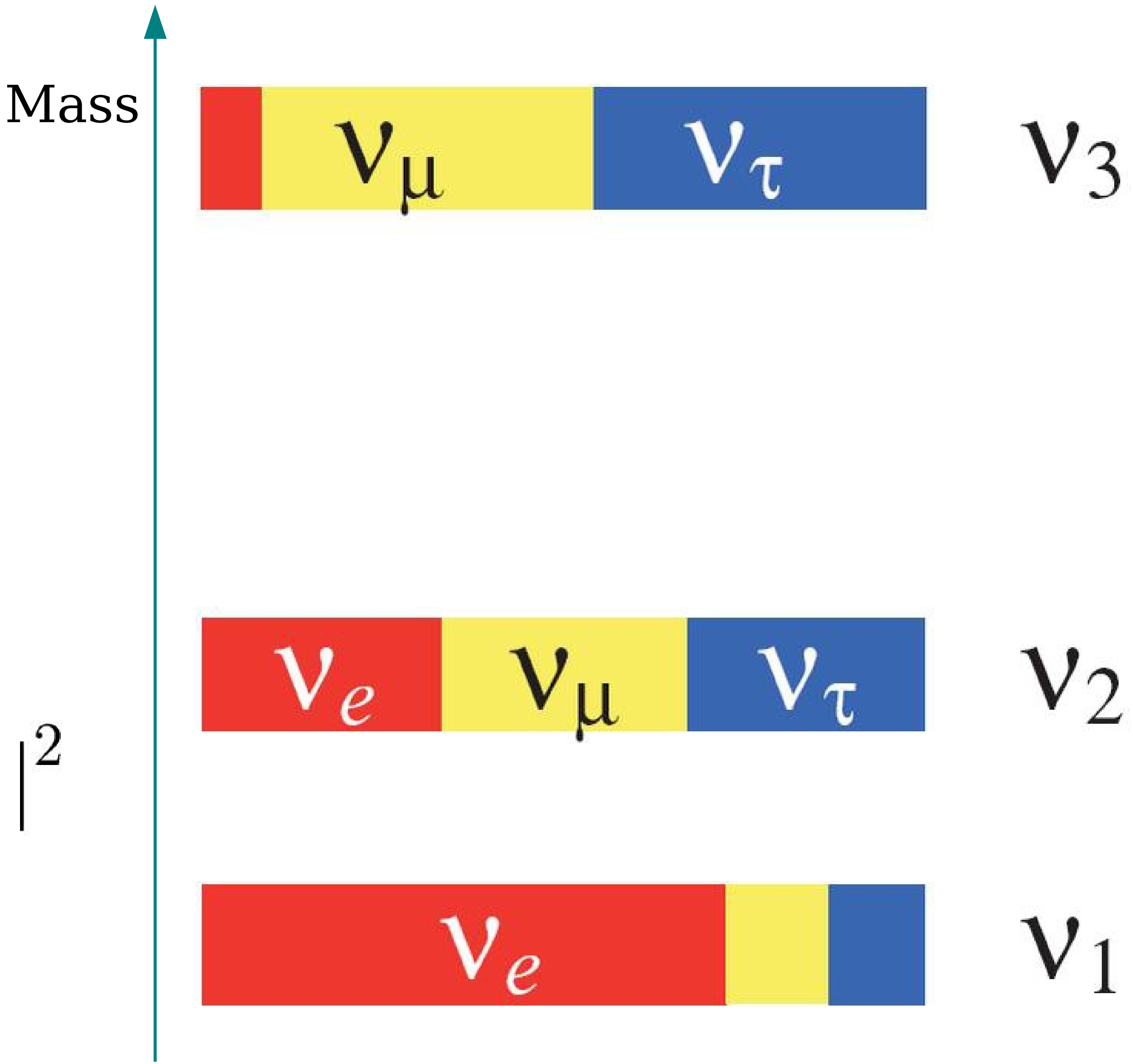
$$P(\nu_\alpha \to \nu_\beta) \;=\; \left|\sum_j U_{\beta j} U^*_{\alpha j}\, e^{-i\, m_j^2 \frac{L}{2E\nu}}\right|^2$$

$$P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$$ **CP** violated

$$P(\nu_\alpha \to \nu_\beta) \neq P(\nu_\beta \to \nu_\alpha)$$ **T** violated

$$P(\nu_\alpha \to \nu_\beta) = P(\overline{\nu}_\beta \to \overline{\nu}_\alpha)$$ **CPT** conserved

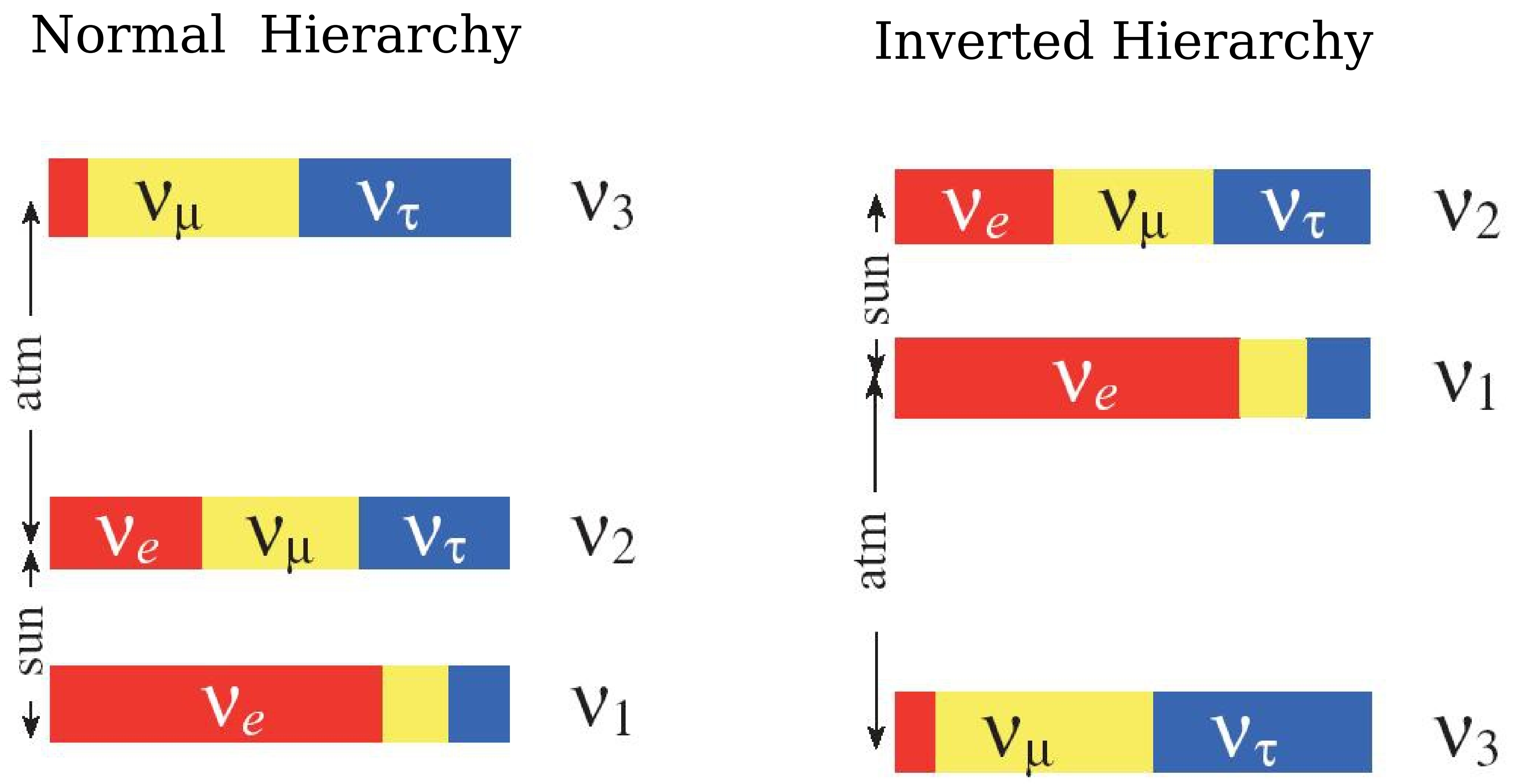
The “BOX description” of the Neutrinos



$$P_{\alpha j} = \left|\langle \nu_\alpha | \nu_j \rangle\right|^2$$

$$= \left|U_{\alpha j}\right|^2$$

Neutrino Description



Mass of the lightest Neutrino m_0

DIRAC or MAJORANA ?

ν_{L} ν_{R}

$\overline{\nu}_{\mathrm{L}}$ $\overline{\nu}_{\mathrm{R}}$

ν_{L}

$\overline{\nu}_{\mathrm{R}}$

Dirac Particle

Majorana Particle

e^-_L	e^-_R
e^+_L	e^+_R

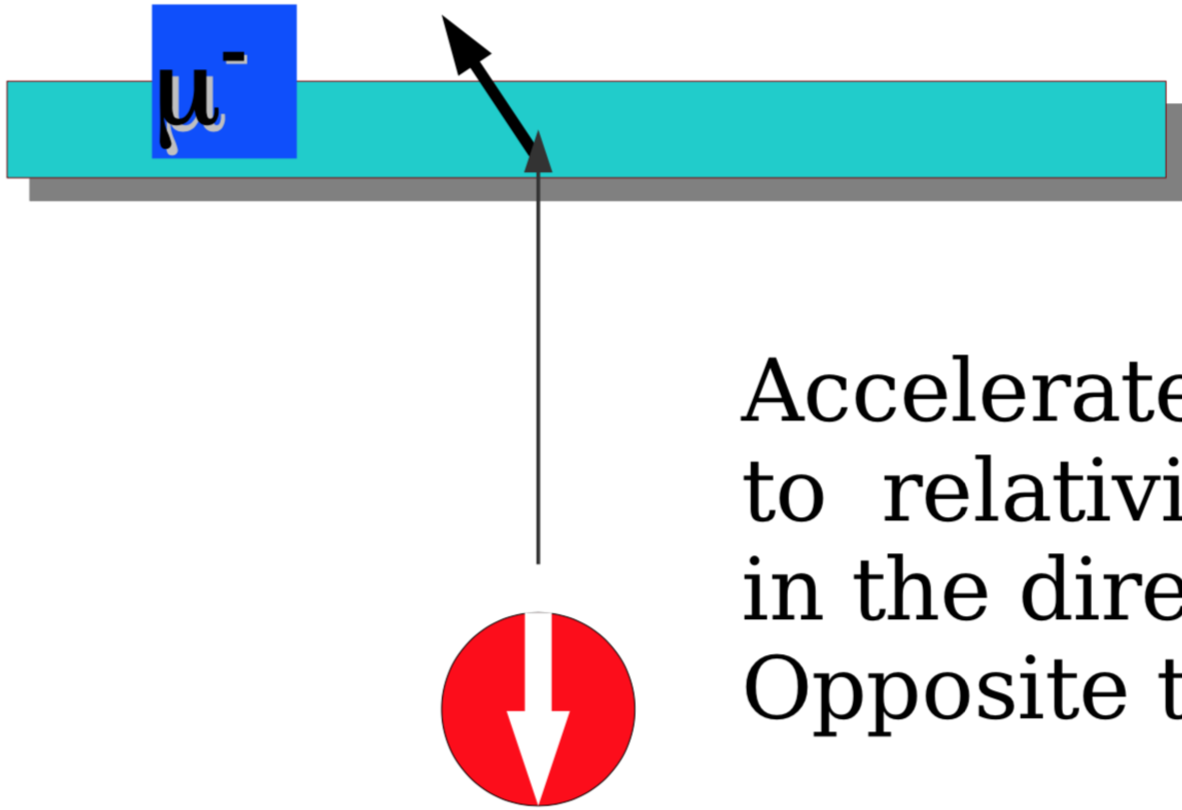
ν_L	ν_R
$\overline{\nu}_L$	$\overline{\nu}_R$

ν_L	
	$\overline{\nu}_R$

Gedanken Experiment

Massive Neutrino at rest in the center of this room.

Spin pointing Down



Layer of Matter

Accelerate the neutrino to relativistic energy in the direction Opposite to the spin.

A few of the Left-Handed particles interact and generate **Negative Muons**

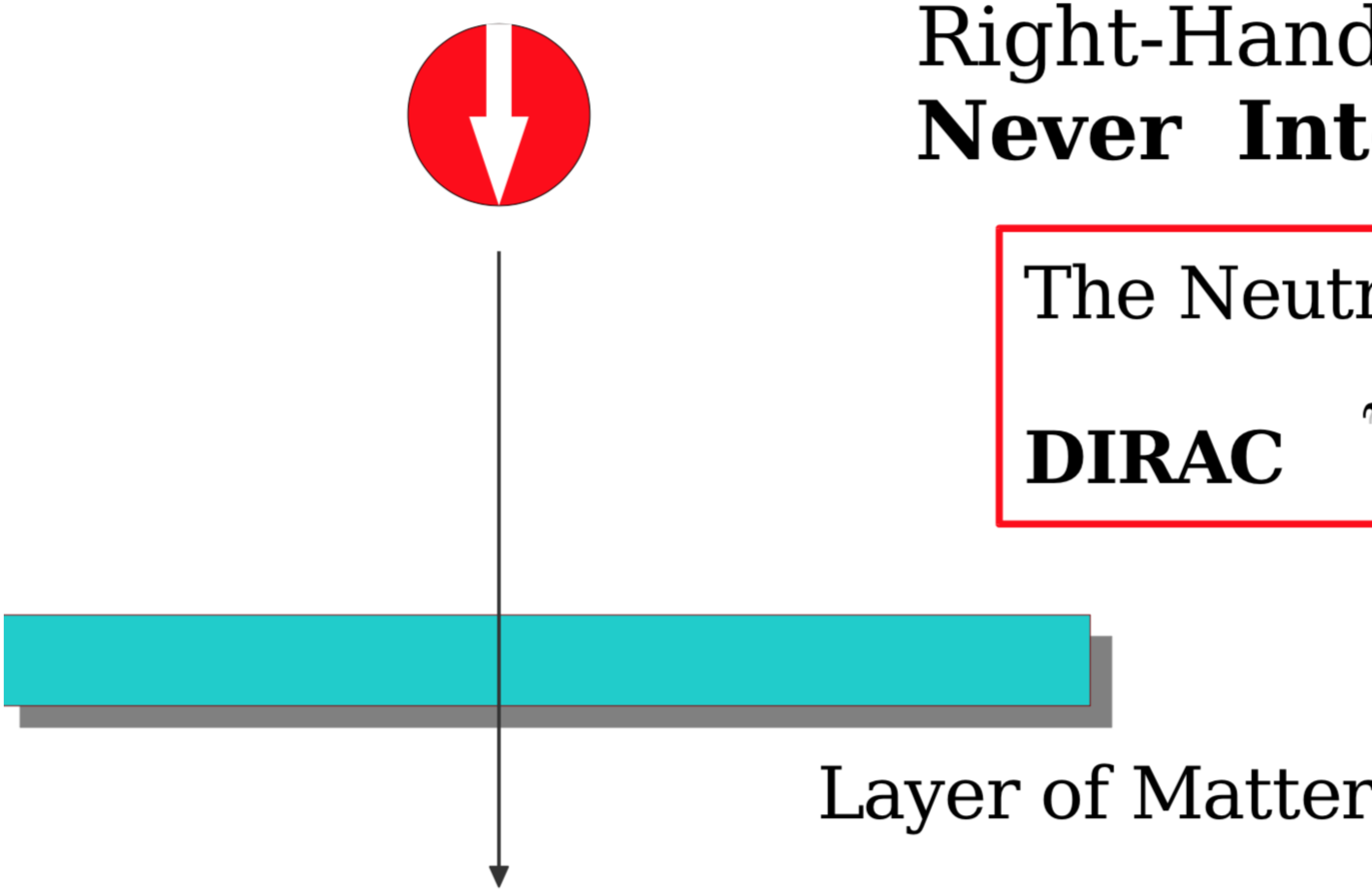
Crucial
Gedanken
Experiment

Accelerate the neutrino
to relativistic energy
In the direction parallel
to the spin

Right-Handed particles
Never Interact

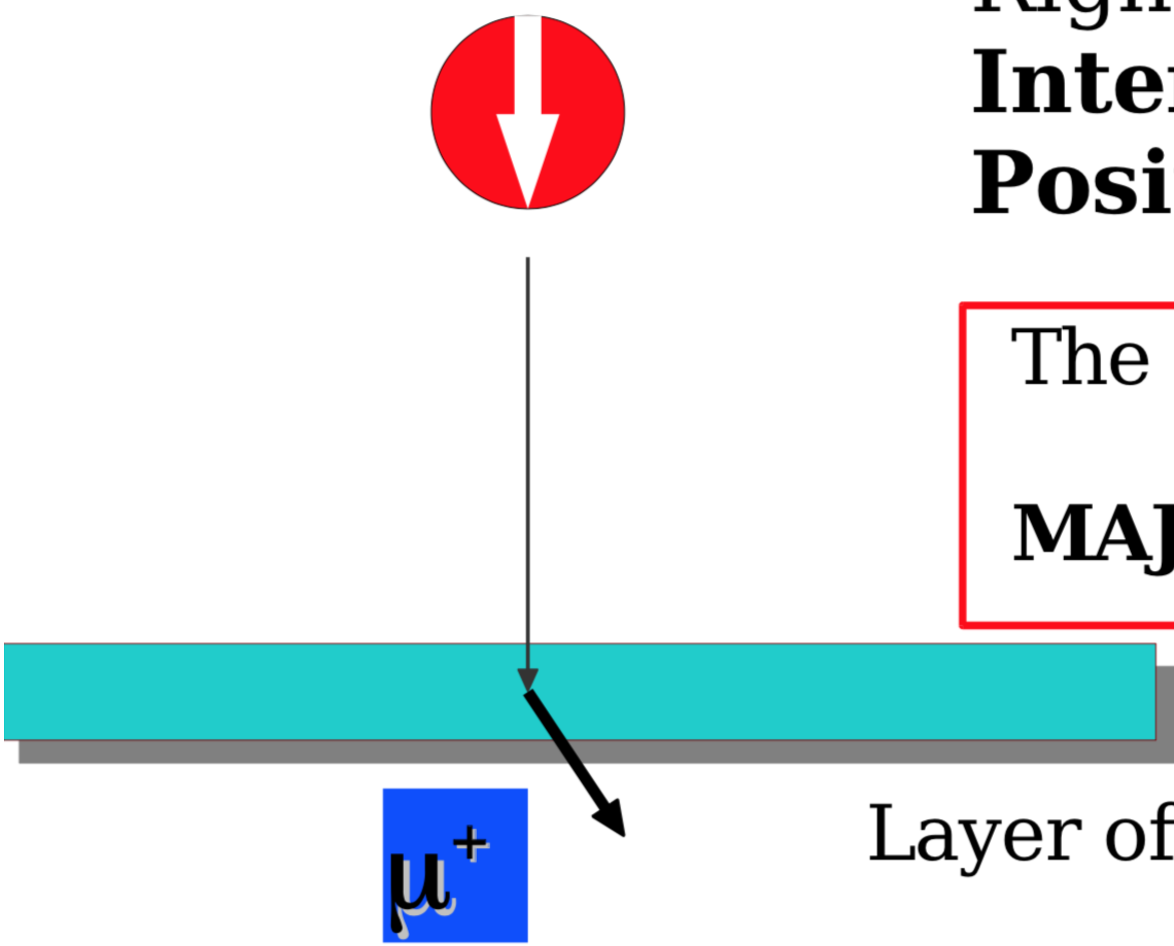
The Neutrino is a

DIRAC ν_μ **Particle**



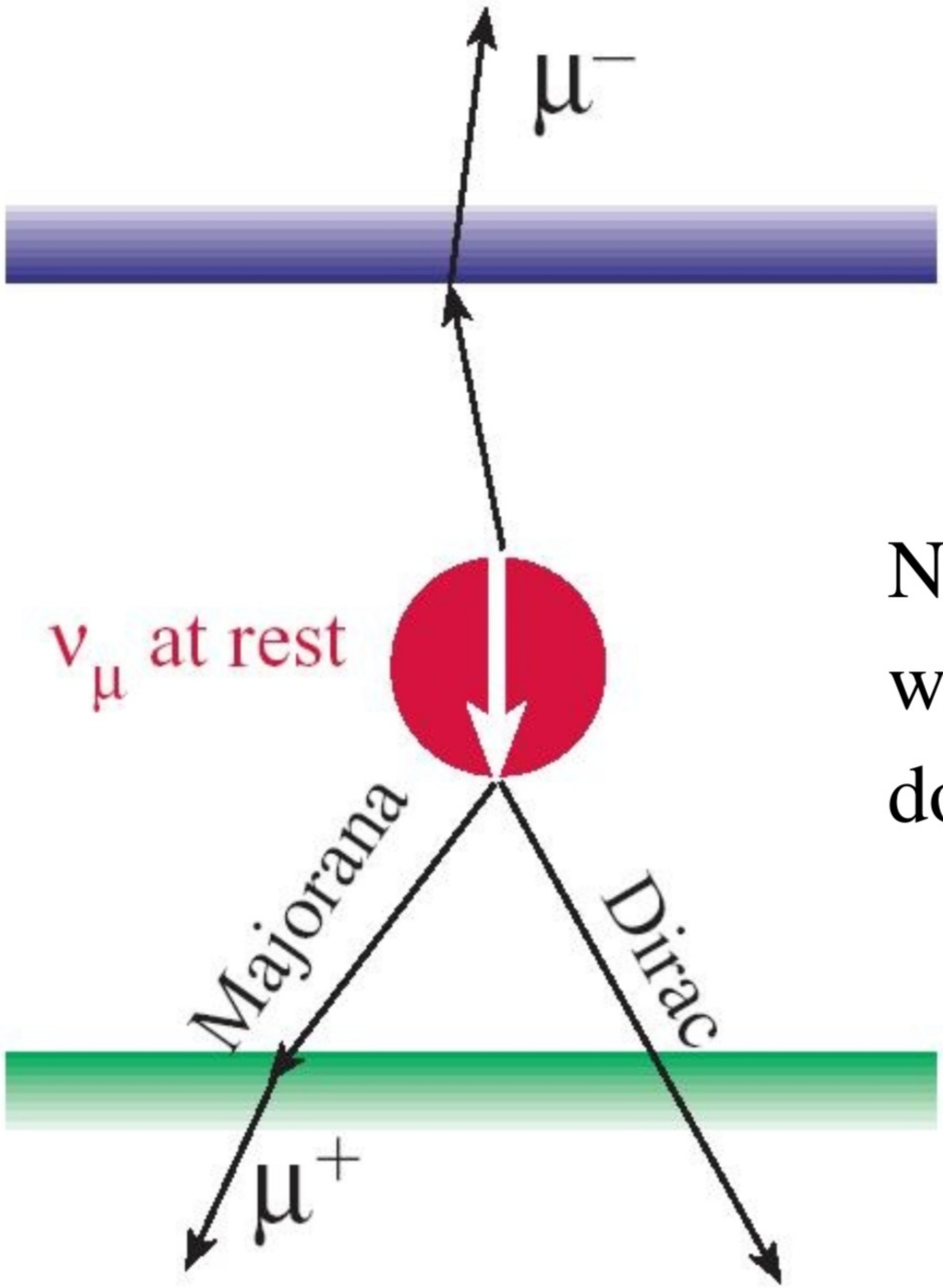
Accelerate the neutrino
to relativistic energy
In the direction parallel
to the spin

Right-Handed particles
Interacting generate
Positive Muons



The Neutrino is a

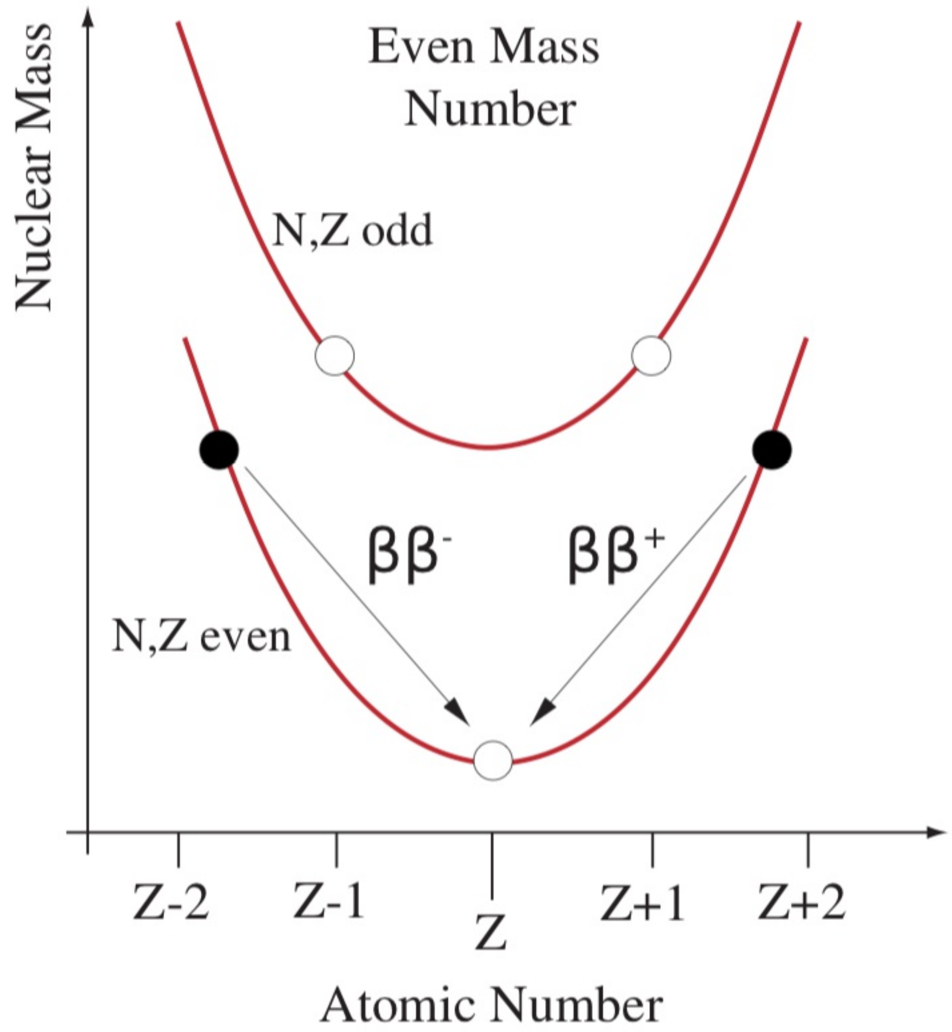
MAJORANA ν_μ **Particle**



Gedanken Experiment

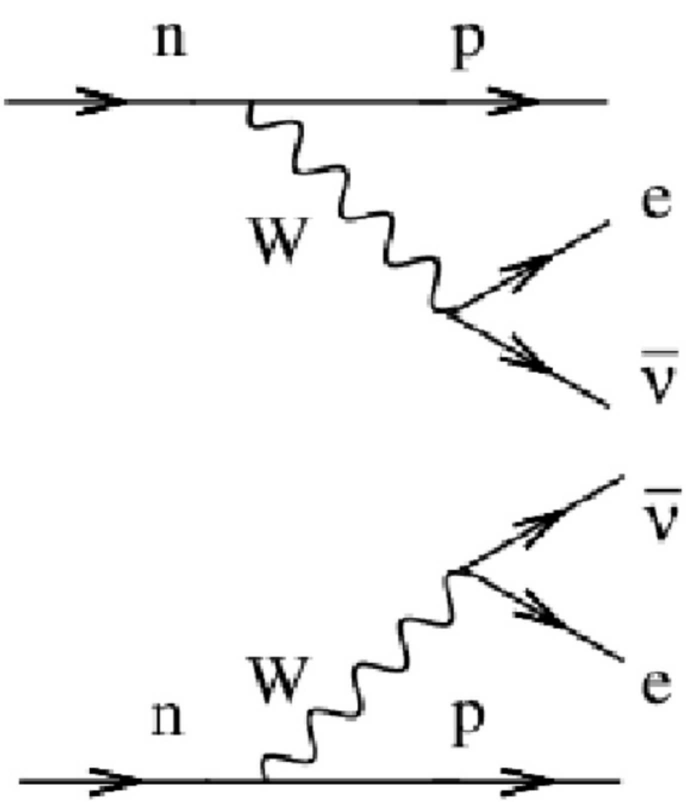
Neutrino at Rest with spin pointing downward.

Double beta decay



Double Beta Decay

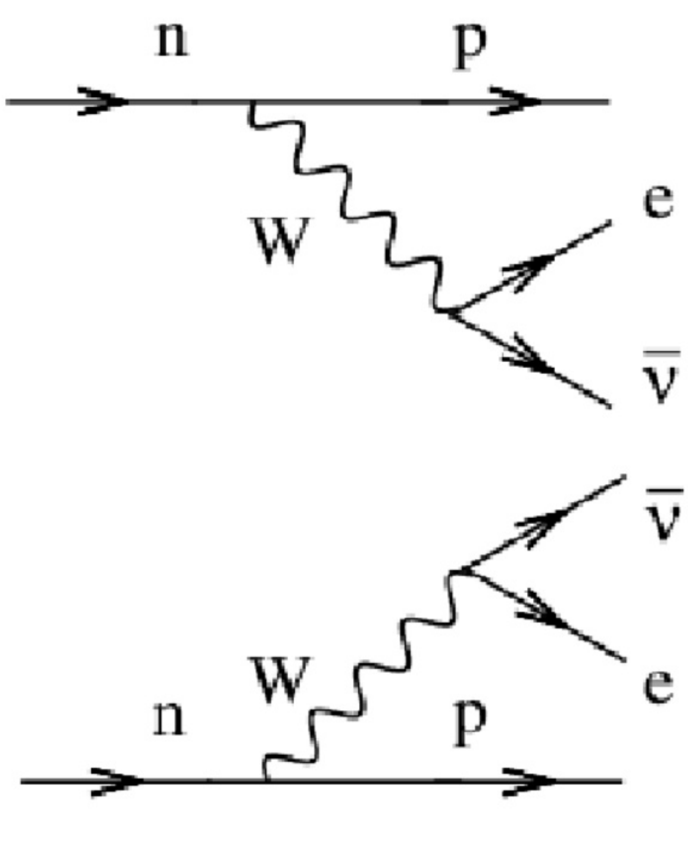
$$^{76}_{32}\mathrm{Ge} \rightarrow {}^{76}_{34}\mathrm{Se} + e^- \; e^- \; \overline{\nu}_e \; \overline{\nu}_e$$

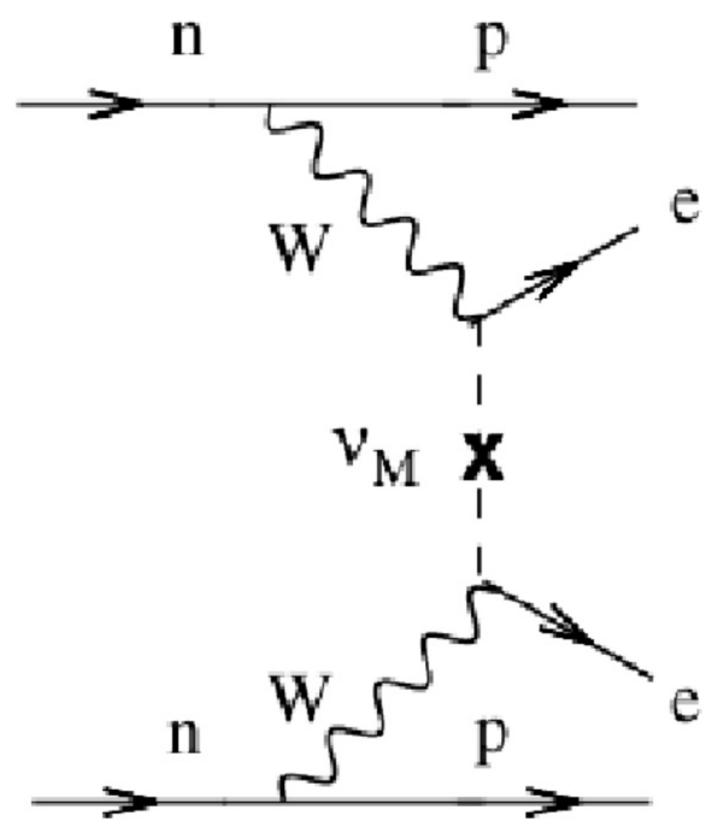


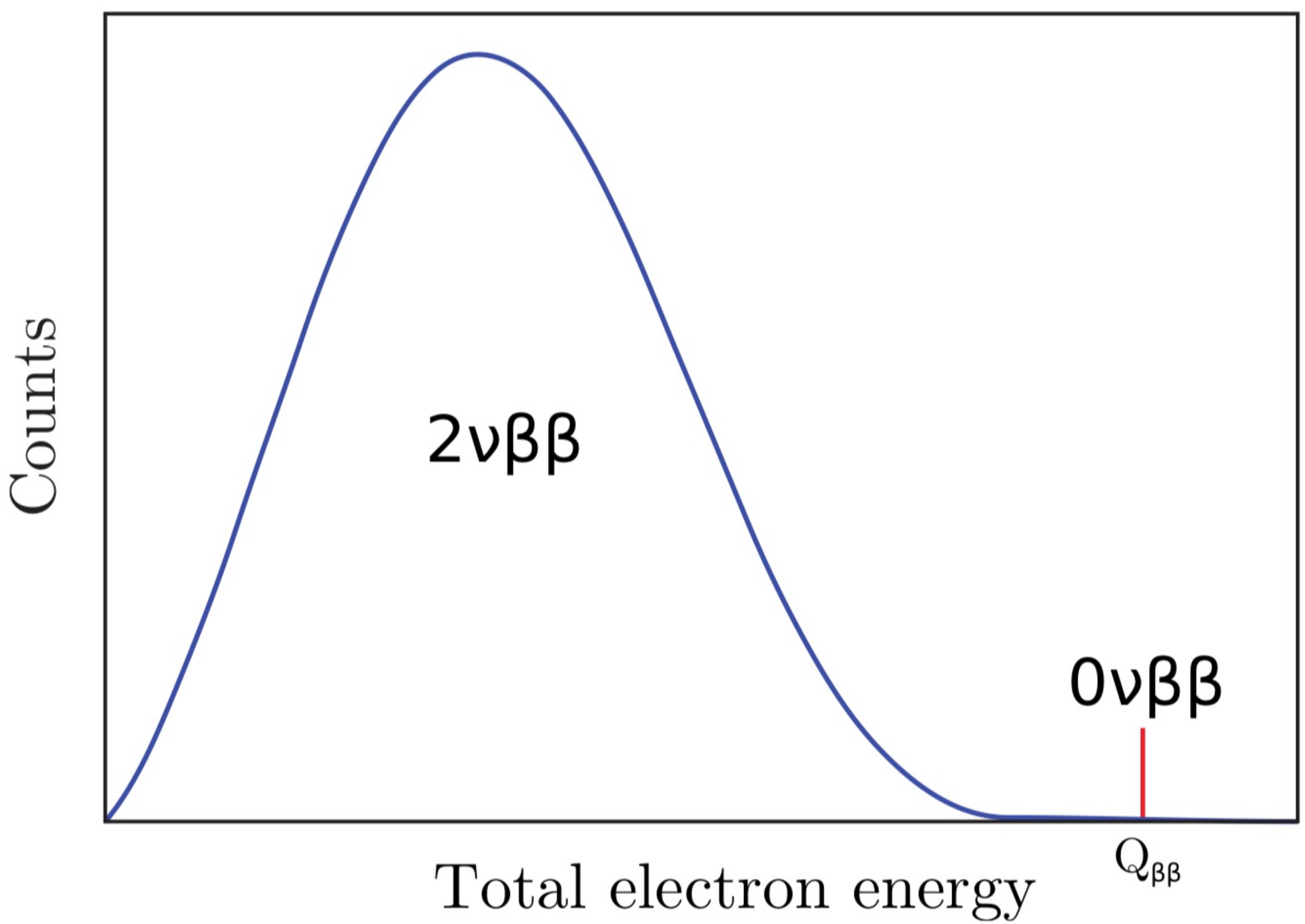
Double Beta Decay

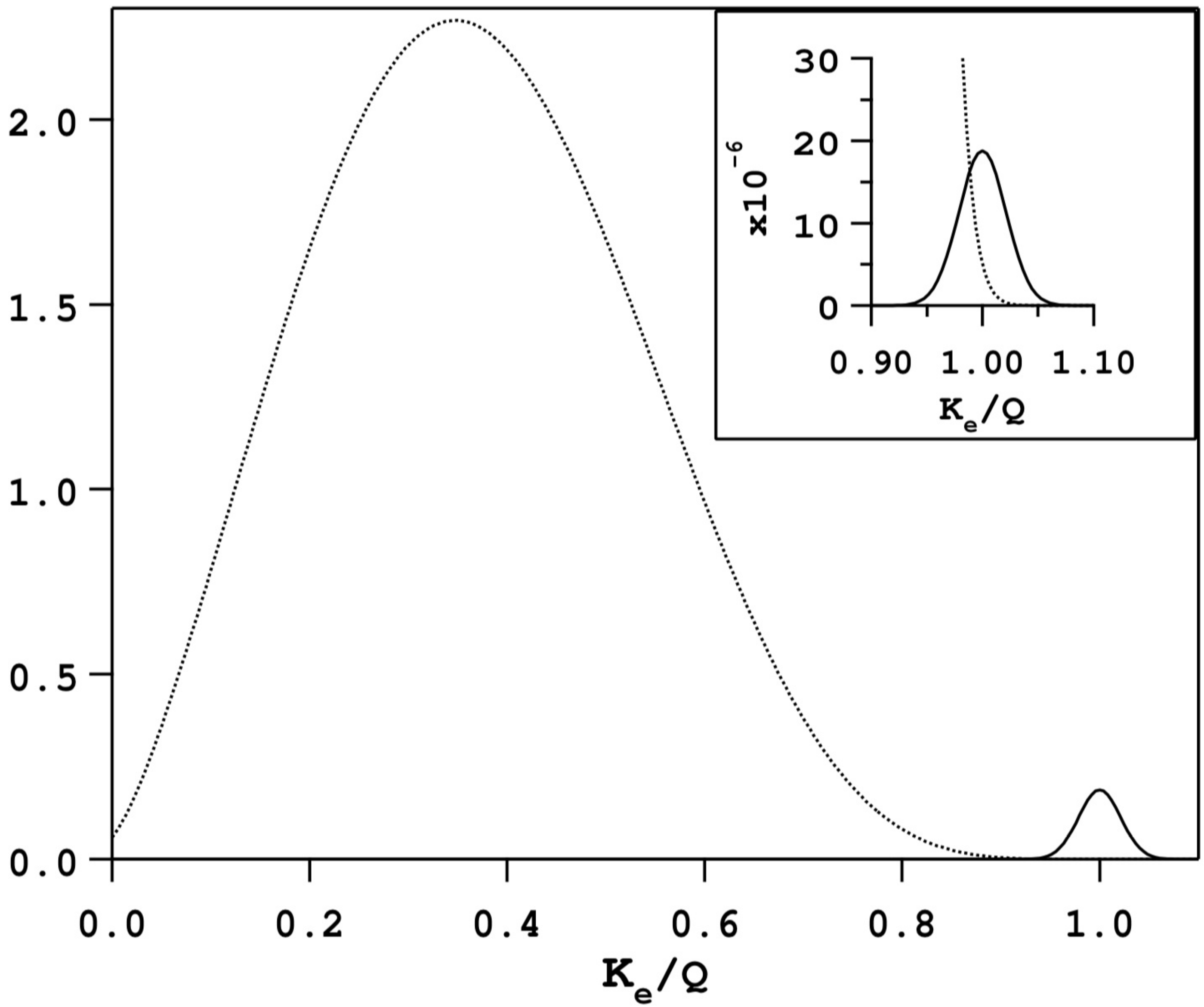
$$\nu_e = \overline{\nu}_e$$

Neutrino-less
Double beta decay






Counts
2νββ
0νββ
Total electron energy
Qββ



Resolution

TABLE V. Isotopic abundance and Q-value for the known $2\nu\beta\beta$ emitters [175].

Isotope	isotopic abundance (%)	$Q_{\beta\beta}$ [MeV]
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	9.2	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.6	3.035
^{116}Cd	7.6	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

$$T_{1/2}^{2\nu}[^{76}\mathrm{Ge}] \simeq 1.78 \times 10^{21}\ \mathrm{yr}$$

$$T_{1/2}^{0\nu}[^{76}\mathrm{Ge}] \gtrsim 2 \times 10^{25}\ \mathrm{yr}$$

TABLE VII. In this table, the main features and performances of some past, present and future $0\nu\beta\beta$ experiments are listed.

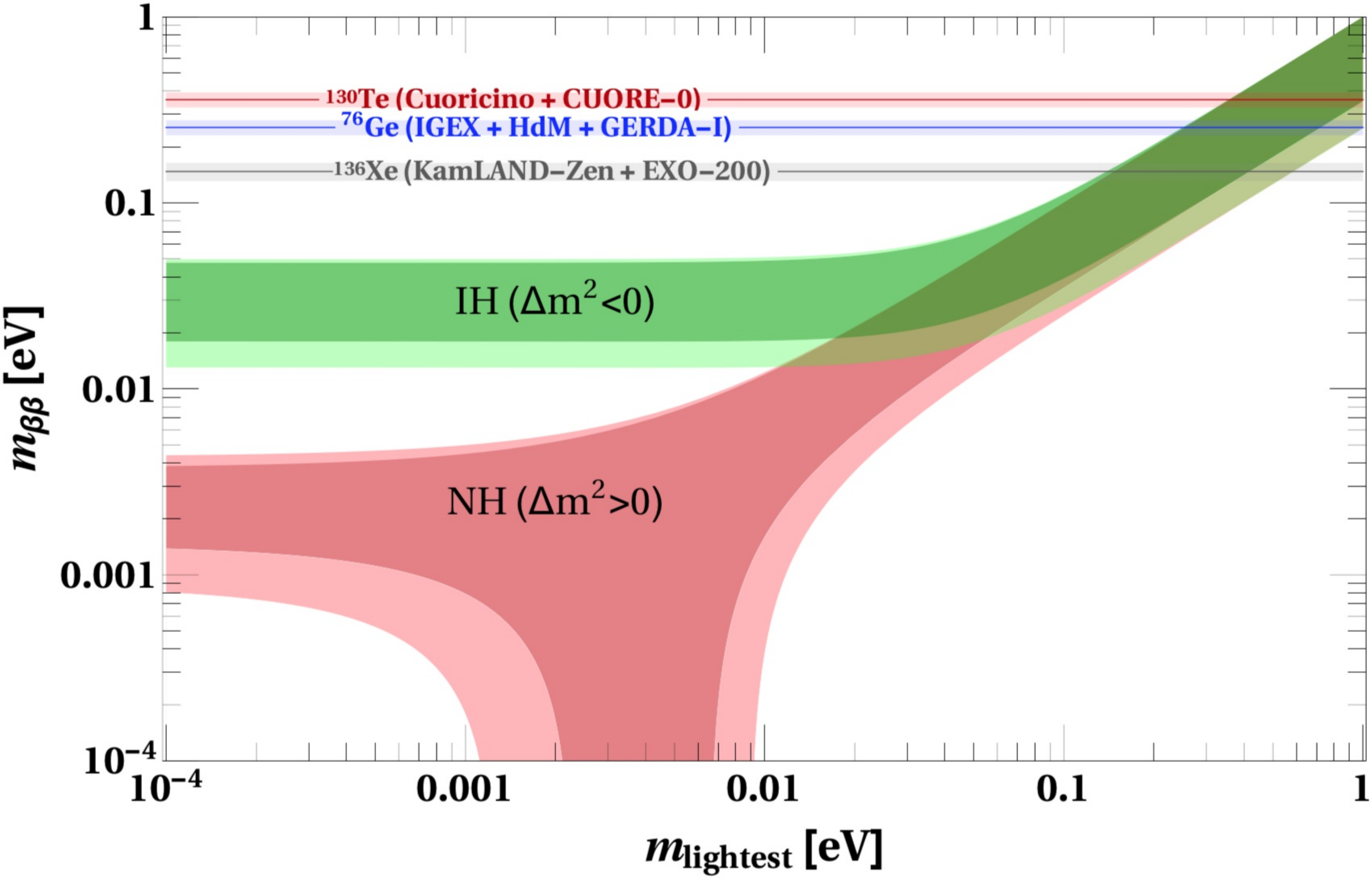
Experiment	Isotope	Techinique	Total mass [kg]	Exposure [kg yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Background [counts/keV/kg/yr]	$S^{0\nu}$ (90% C. L.) [10^{25} yr]
Past							
Cuoricino, [179]	^{130}Te	bolometers	40.7 (TeO_2)	19.75	5.8 ± 2.1	0.153 ± 0.006	0.24
CUORE-0, [180]	^{130}Te	bolometers	39 (TeO_2)	9.8	5.1 ± 0.3	0.058 ± 0.006	0.29
Heidelberg-Moscow, [181]	^{76}Ge	Ge diodes	11 (^{enr}Ge)	35.5	4.23 ± 0.14	0.06 ± 0.01	1.9
IGEX, [182, 183]	^{76}Ge	Ge diodes	8.1 (^{enr}Ge)	8.9	~ 4	$\lesssim 0.06$	1.57
GERDA-I, [167, 184]	^{76}Ge	Ge diodes	17.7 (^{enr}Ge)	21.64	3.2 ± 0.2	~ 0.01	2.1
NEMO-3, [185]	^{100}Mo	tracker + calorimeter	6.9 (^{100}Mo)	34.7	350	0.013	0.11
Present							
EXO-200, [186]	^{136}Xe	LXe TPC	175 (^{enr}Xe)	100	89 ± 3	$(1.7 \pm 0.2) \cdot 10^{-3}$	1.1
KamLAND-Zen, [187, 188]	^{136}Xe	loaded liquid scintillator	348 (^{enr}Xe)	89.5	244 ± 11	~ 0.01	1.9
Future							
CUORE, [189]	^{130}Te	bolometers	741 (TeO_2)	1030	5	0.01	9.5
GERDA-II, [174]	^{76}Ge	Ge diodes	37.8 (^{enr}Ge)	100	3	0.001	15
LUCIFER, [190]	^{82}Se	bolometers	17 ($Zn^{82}Se$)	18	10	0.001	1.8
MAJORANA D., [191]	^{76}Ge	Ge diodes	44.8 ($^{enr/nat}$Ge)	100 [a]	4	0.003	12
NEXT, [192, 193]	^{136}Xe	Xe TPC	100 (^{enr}Xe)	300	12.3 – 17.2	$5 \cdot 10^{-4}$	5
AMoRE, [194]	^{100}Mo	bolometers	200 ($Ca^{enr}MoO_4$)	295	9	$1 \cdot 10^{-4}$	5
nEXO, [195]	^{136}Xe	LXe TPC	4780 (^{enr}Xe)	12150 [b]	58	$1.7 \cdot 10^{-5}$ [b]	66
PandaX-III, [196]	^{136}Xe	Xe TPC	1000 (^{enr}Xe)	3000 [c]	12 – 76	0.001	11 [c]
SNO+, [197]	^{130}Te	loaded liquid scintillator	2340 (^{nat}Te)	3980	270	$2 \cdot 10^{-4}$	9
SuperNEMO, [198, 199]	^{82}Se	tracker + calorimeter	100 (^{82}Se)	500	120	0.01	10

[a] our assumption (corresponding sensitivity from Fig. 14 of Ref. [191]).
[b] we assume 3 tons fiducial volume.
[c] our assumption by rescaling NEXT.

$$[t^{1/2}]^{-1} = G_{0\nu} \, |\mathcal{M}|^2 \, |f(m_i, U_{\mathrm{e}i})|^2$$

$$f(m_i, U_{\mathrm{e}i}) \equiv \frac{m_{\beta\beta}}{m_{\mathrm{e}}} = \frac{1}{m_{\mathrm{e}}} \left| \sum_{k=1,2,3} U_{\mathrm{e}k}^2 m_k \right|$$

$$m_{\beta\beta} = \left| \sum_{i=1,2,3} \mathrm{e}^{i\xi_i} \, |U_{\mathrm{e}i}^2| \, m_i \right|$$



130Te (Cuoricino + CUORE-0)
76Ge (IGEX + HdM + GERDA-I)
136Xe (KamLAND-Zen + EXO-200)
IH (Δm²<0)
NH (Δm²>0)
m_ββ [eV]
m_lightest [eV]
1
0.1
0.01
0.001
10⁻⁴

WHY is the NEUTRINO MASS so much smaller than the other Fermion Masses ?

Possible Answer:

Because the Neutrino is a Majorana Fermion.

Neutrino as Astrophysical Messenger

Essentially *all our knowledge*
about the Universe outside the solar system
Stars, Galaxies, ...
is because we have *"seen"* it

[that is we have observed *photons*
emitted from this far regions of space.

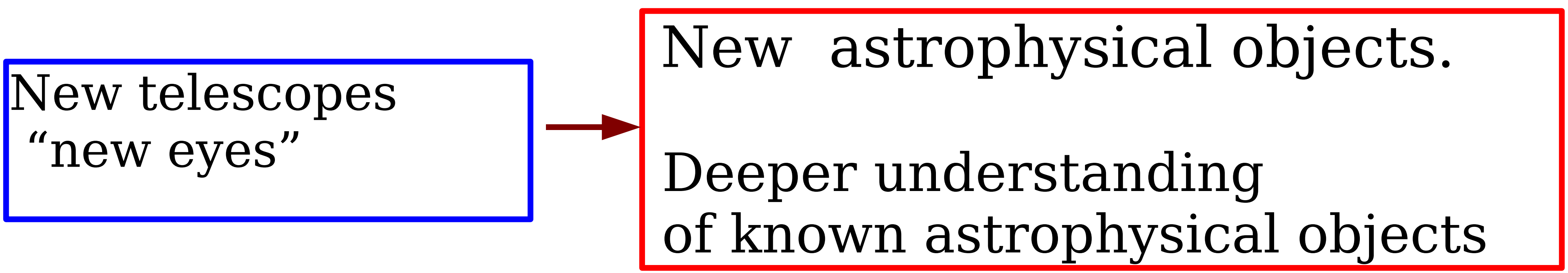
Light (Photons)

“Nuncius Sidereus”

Messenger from the stars

History of Astronomy :

Improvement of the “telescope”.
expansion of the range of wavelengths
available for observations.



New, more dramatic expansion of
our method to *"SEE"* the Universe

Use of NEW PARTICLES as
"MESSENGERS of the STARS"

Photons

Neutrinos

Cosmic Rays

Gravitational Waves

New, more dramatic expansion of
our method to "SEE" the Universe

Use of NEW PARTICLES as
"MESSENGERS of the STARS"

Photons

Neutrinos

Cosmic Rays

Gravitational Waves

A "Messenger"
with very different properties
that will allow us to
"SEE" the universe
in a profoundly different way

Very small cross section.
neutrinos arrive from
the "deep interior"
of astrophysical sources

Neutrino Astronomy
has just been born at the end of
the last Century

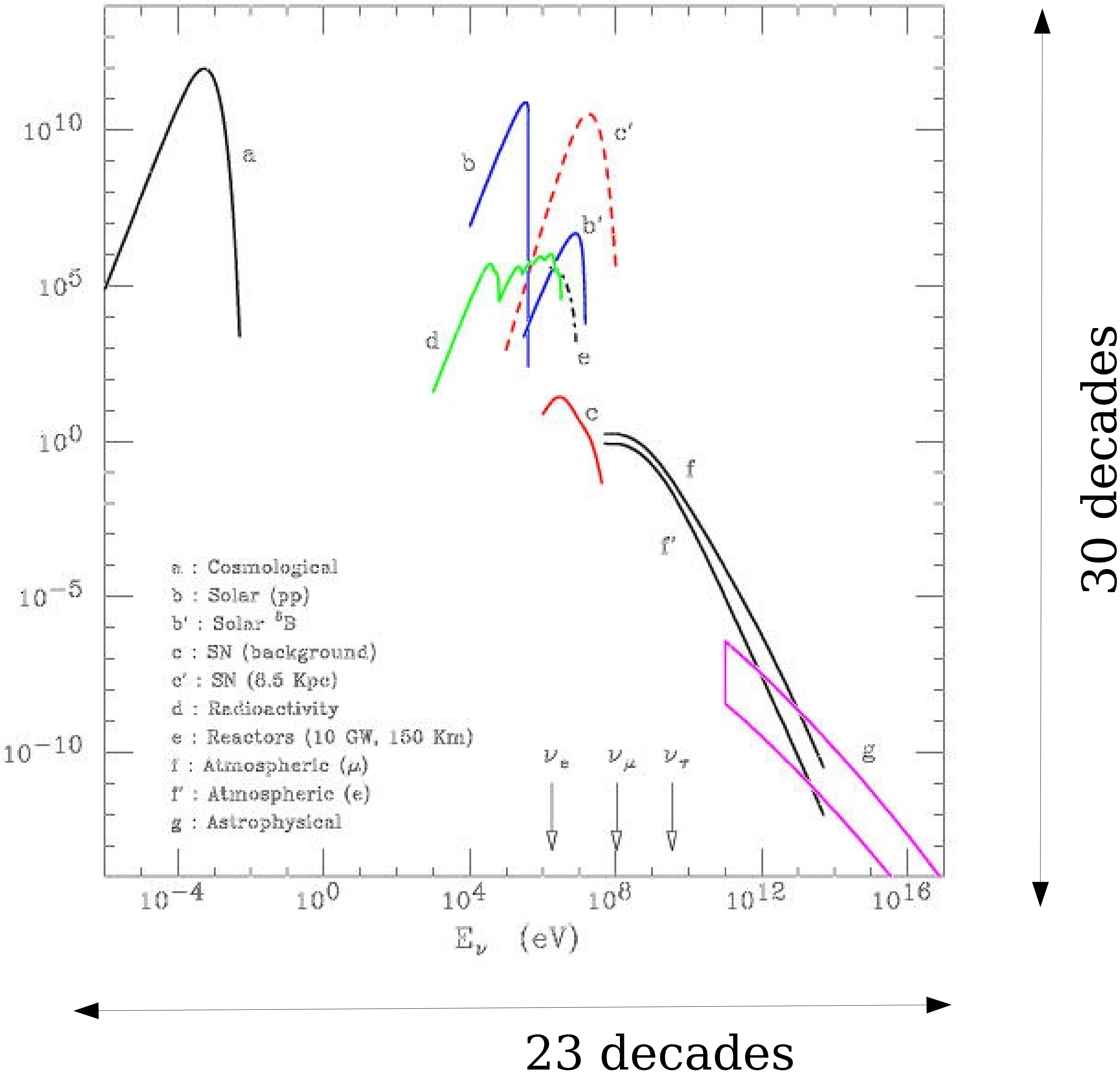
TWO (+1) ASTROPHYSICAL OBJECTS
have been "seen" in neutrinos"

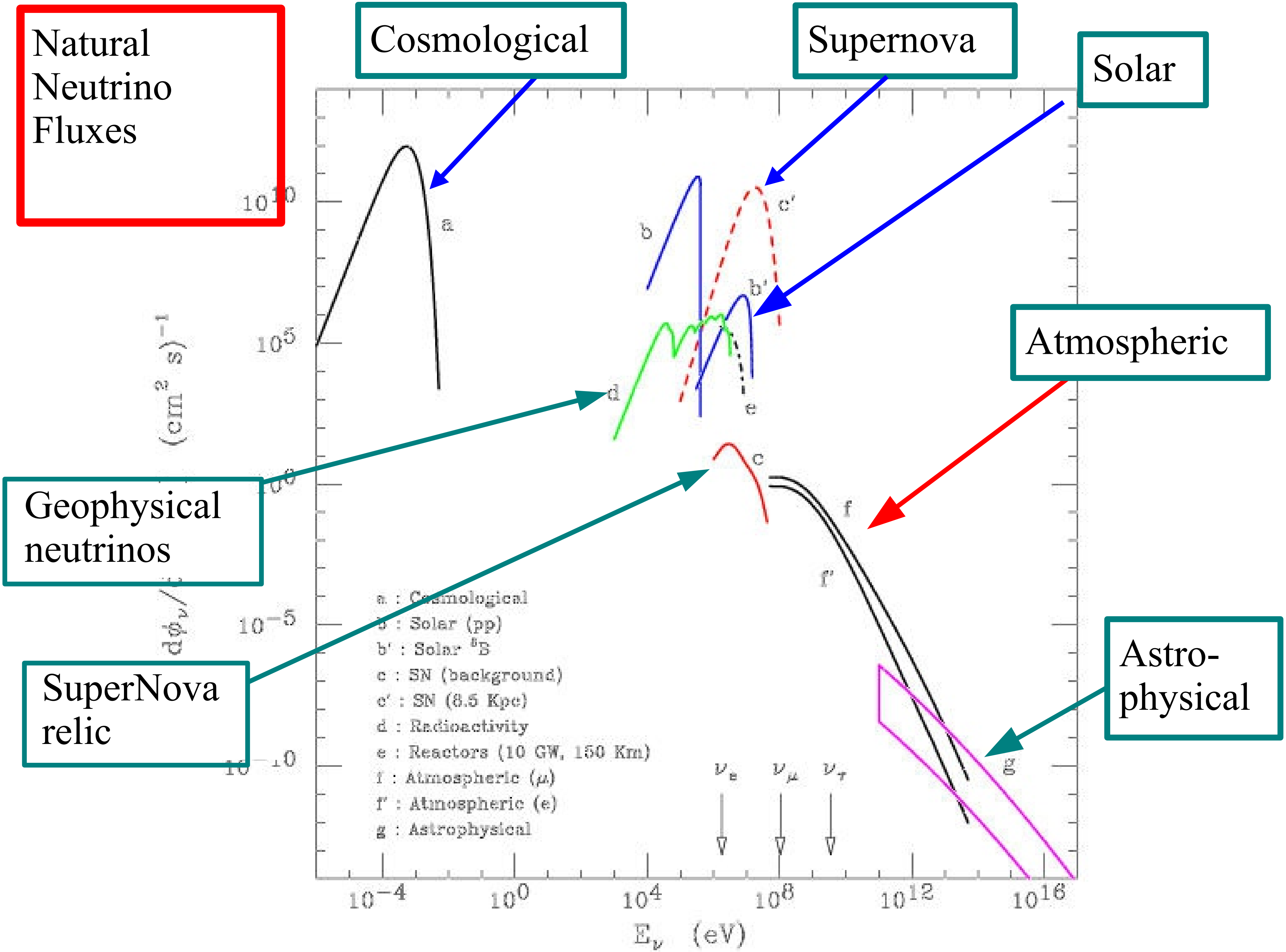
The SUN

SuperNova SN1987A

The Earth: (Geophysical Neutrinos detection)

Natural Neutrino Fluxes




Natural Neutrino Fluxes
Cosmological
Supernova
Solar
Atmospheric
Geophysical neutrinos
SuperNova relic
Astro-physical
a
b
b'
c
c'
d
e
f
f'
g
a : Cosmological
b : Solar (pp)
b' : Solar ^{8}B
c : SN (background)
c' : SN (8.5 Kpc)
d : Radioactivity
e : Reactors (10 GW, 150 Km)
f : Atmospheric (μ)
f' : Atmospheric (e)
g : Astrophysical
ν_e ν_μ ν_τ
10^{10}
10^5
10^{-5}
10^{-4} 10^0 10^4 10^8 10^{12} 10^{16}
E_ν (eV)
$(cm^2\ s)^{-1}$

SOLAR NEUTRINOS

Source of Energy of the SUN : Nuclear Fusion

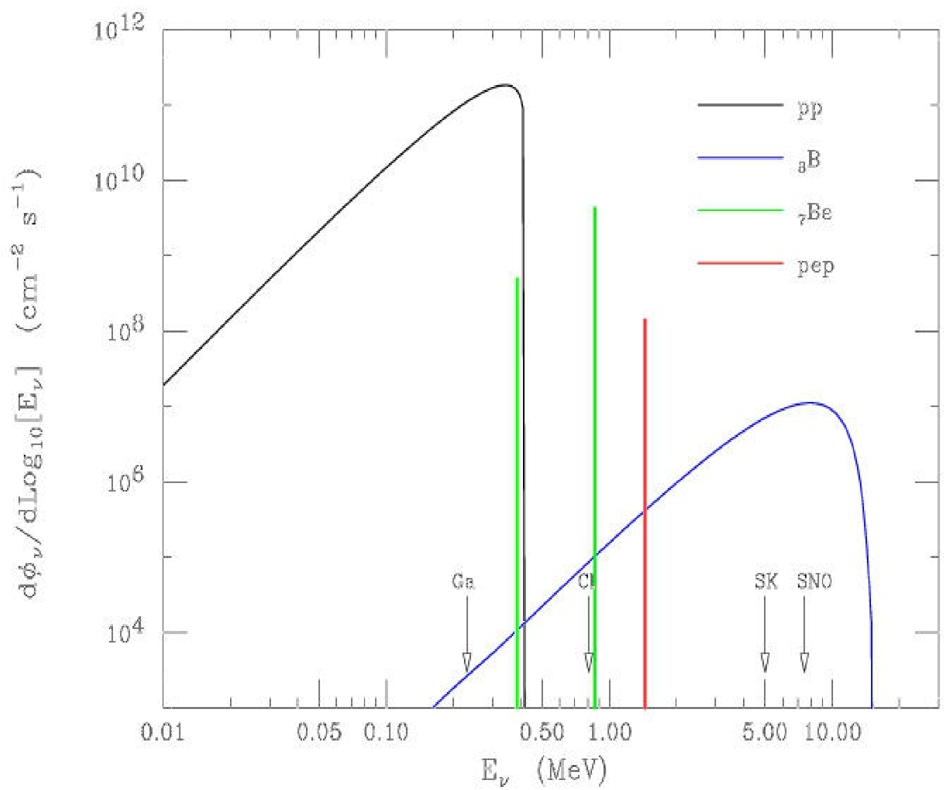
$$4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu_e$$

Energy Released per each Cycle

$$Q = 4m_p + 2m_e - m_{He} = 26.73 \ \mathrm{MeV}$$

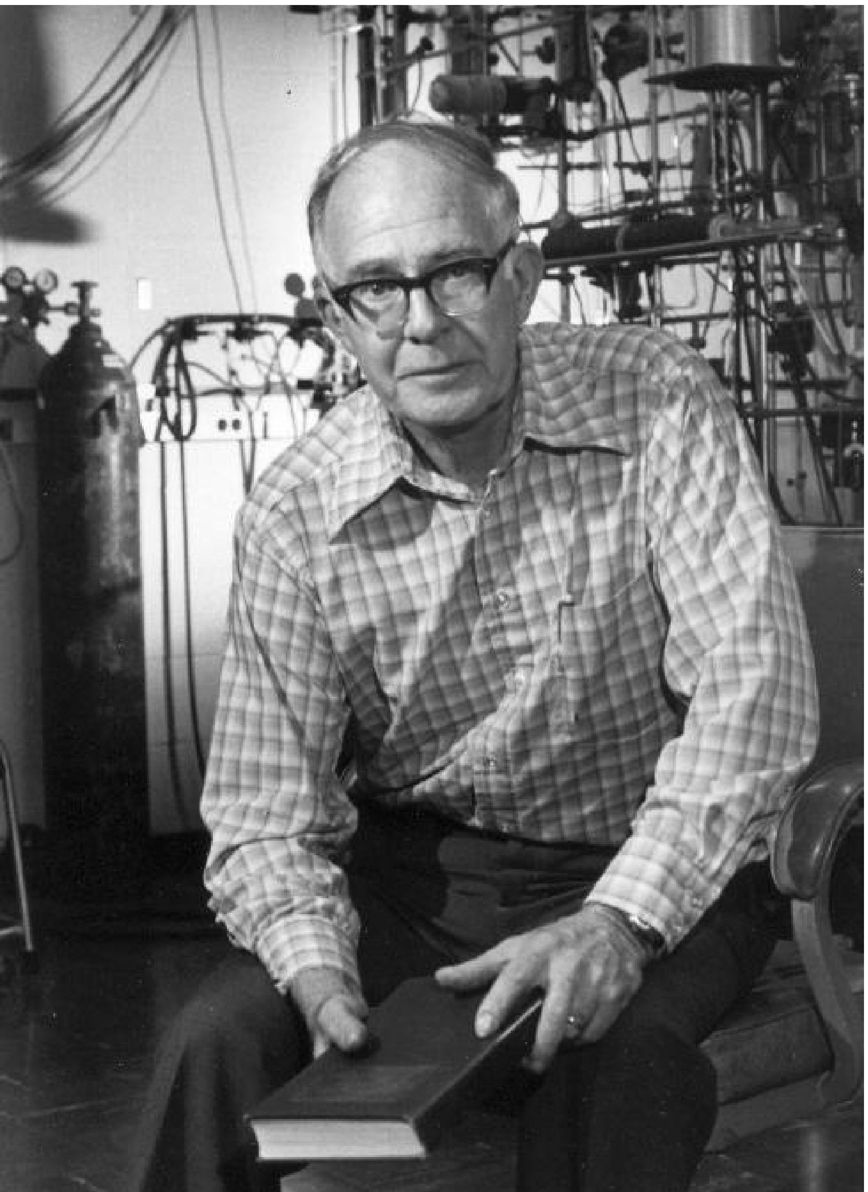
$$\Phi_{\nu_e} \simeq \frac{1}{4\pi\, d_\odot^2} \, \frac{2\, L_\odot}{(Q - \langle E_\nu \rangle)}$$

$$\phi_{\nu_\odot} \sim 6 \times 10^{10} \ (\mathrm{cm}^2 \ \mathrm{s})^{-1}$$



SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

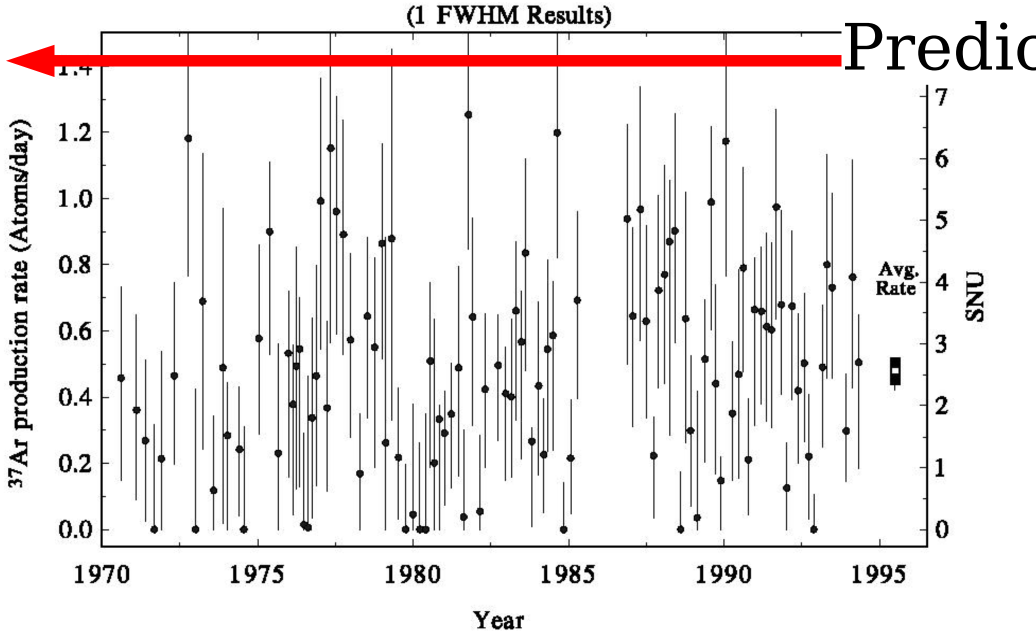


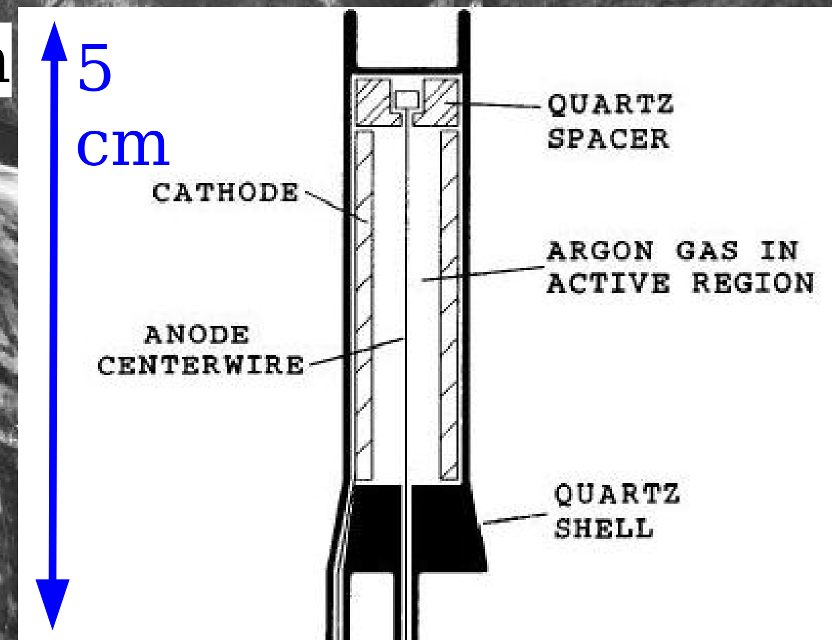
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

On the other hand, if one wants to measure the solar neutrino flux by this method one must use a much larger amount of C_2Cl_4, so that the expected ^{37}Ar production rate is well above the background of the counter, 0.2 count per day. Using Bahcall's expression,

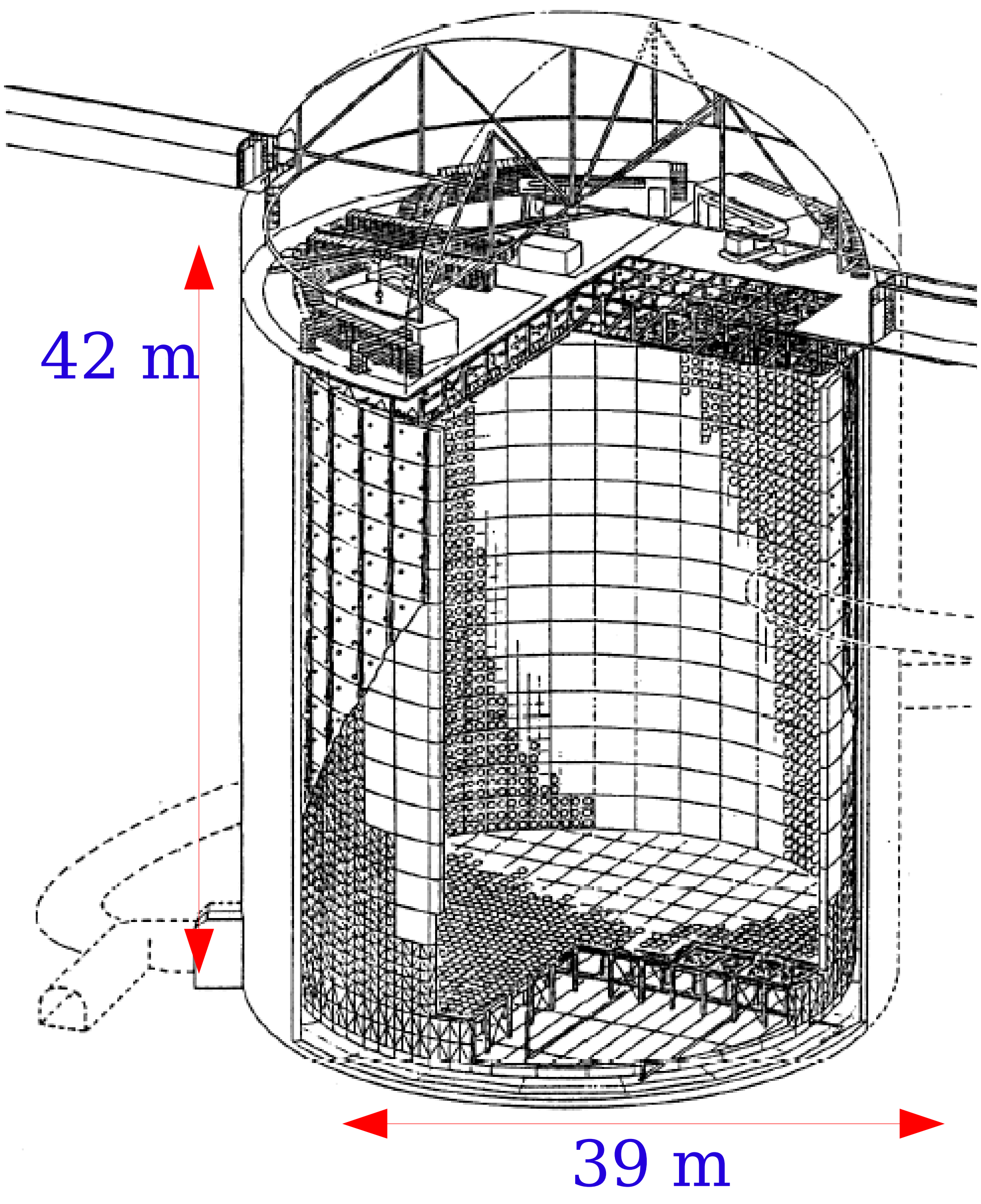
$$\sum\varphi_\nu(\text{solar})\,\sigma_{\text{abs}}$$
$$= (4\pm2)\times10^{-35}\ \text{sec}^{-1}\ ({}^{37}\text{Cl atom})^{-1},$$

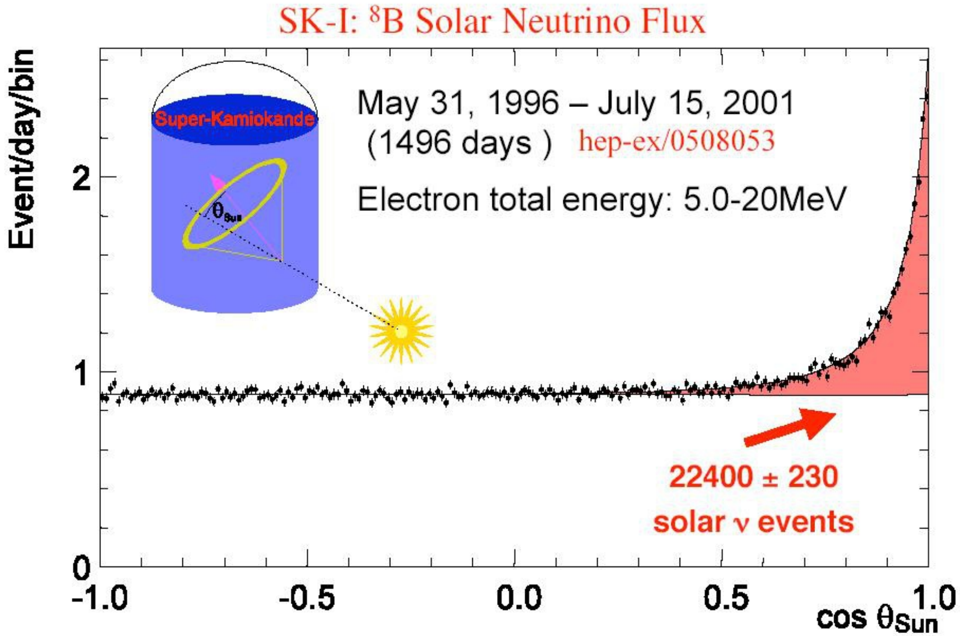
then the expected solar neutrino captures in 100 000 gallons of C_2Cl_4 will be 4 to 11 per day, which is an order of magnitude larger than the counter background.


(1 FWHM Results)
Prediction
37Ar production rate (Atoms/day)
Avg. Rate
SNU
Year
1970
1975
1980
1985
1990
1995

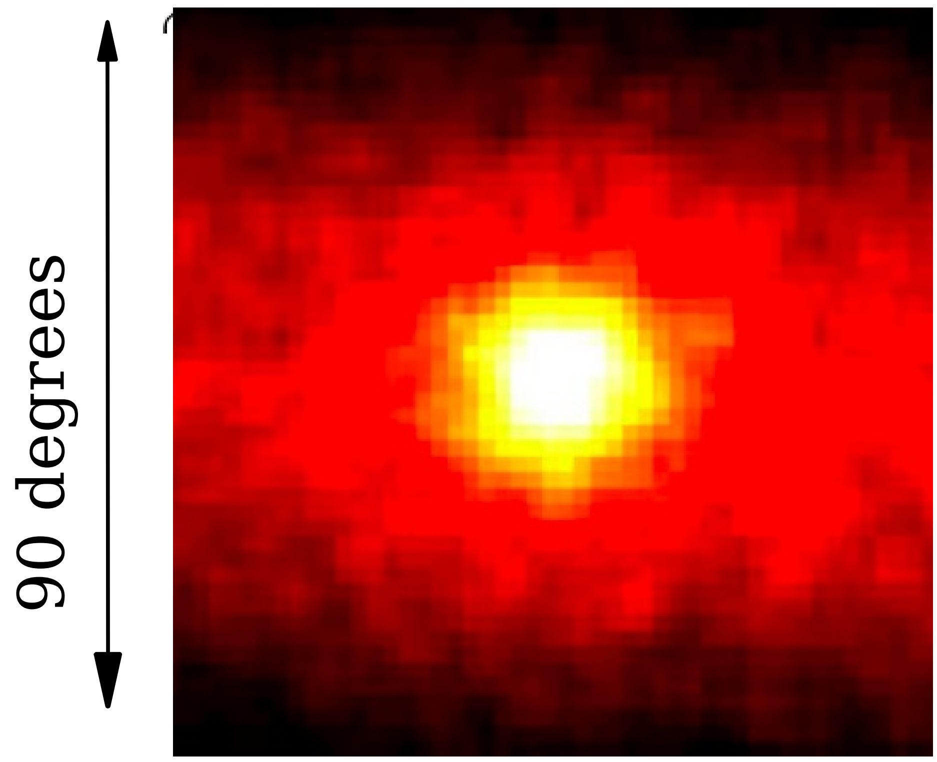

5 cm
QUARTZ SPACER
CATHODE
ARGON GAS IN ACTIVE REGION
ANODE CENTERWIRE
QUARTZ SHELL

Super Kamiokande





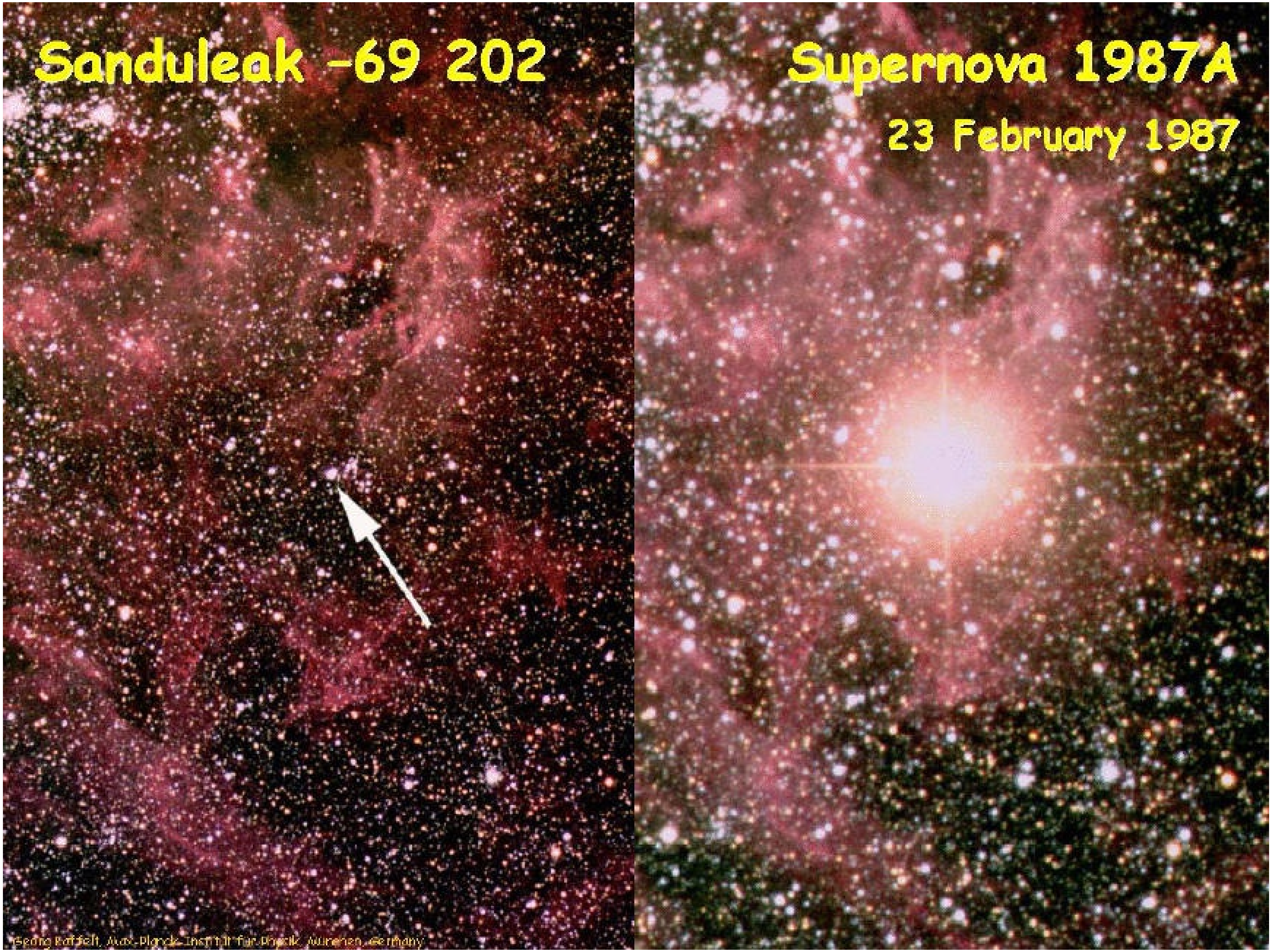
DATA/SM = 0.465± 0.015

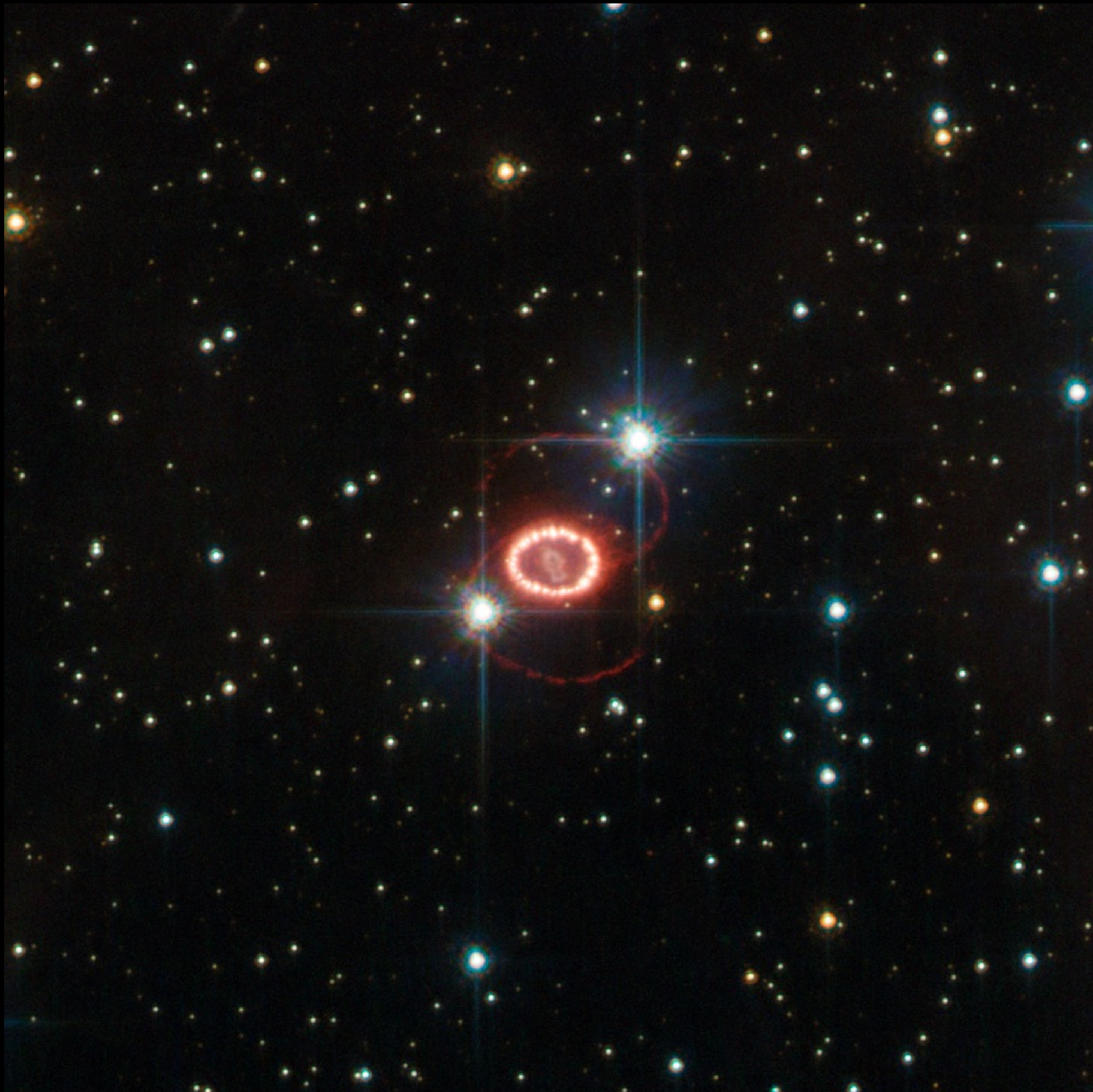


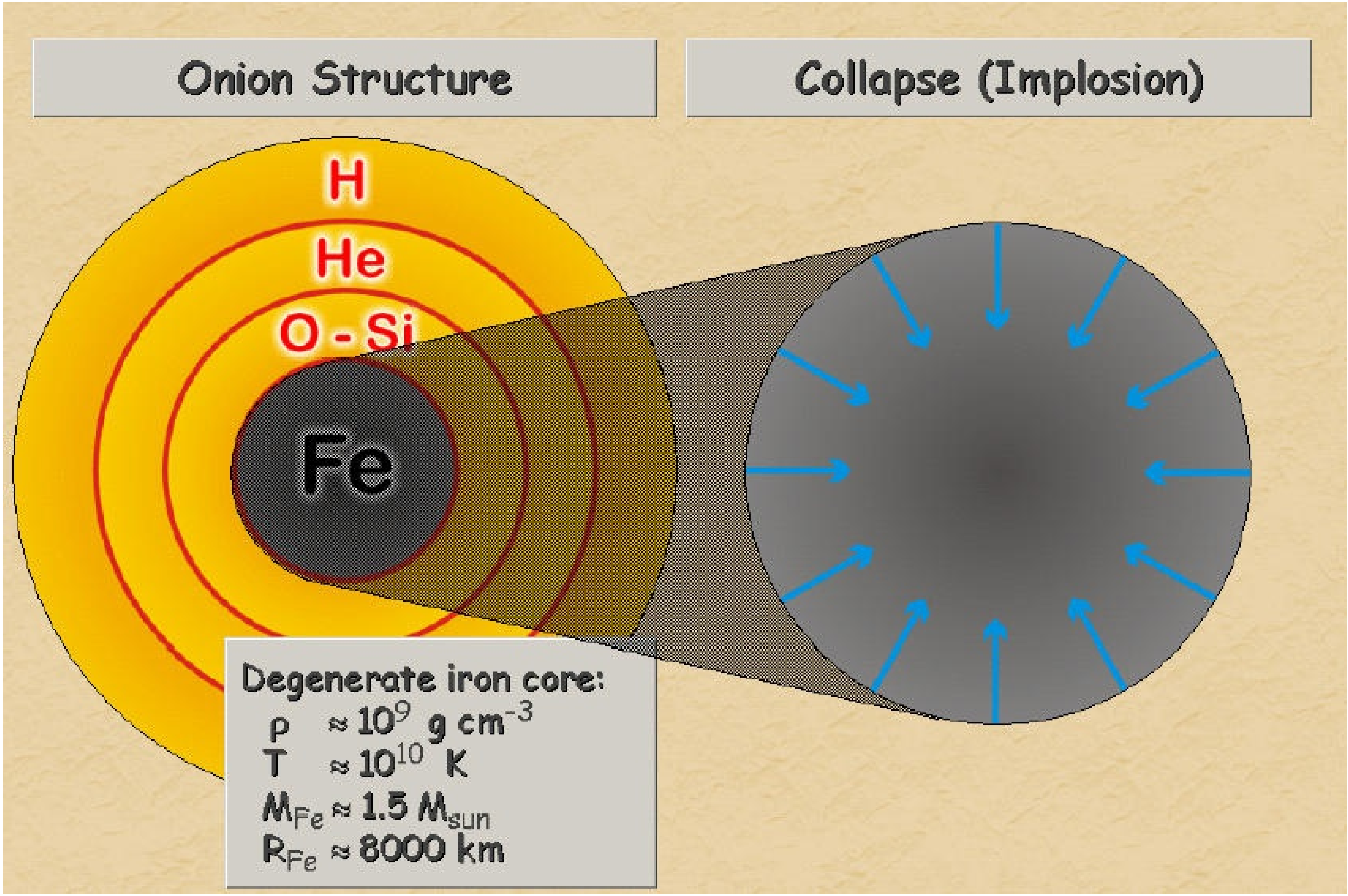
NEUTRINOS
from
SUPERNOVAE
EXPLOSIONS
(Gravitational Collapse)

Energy ~ 30 MeV

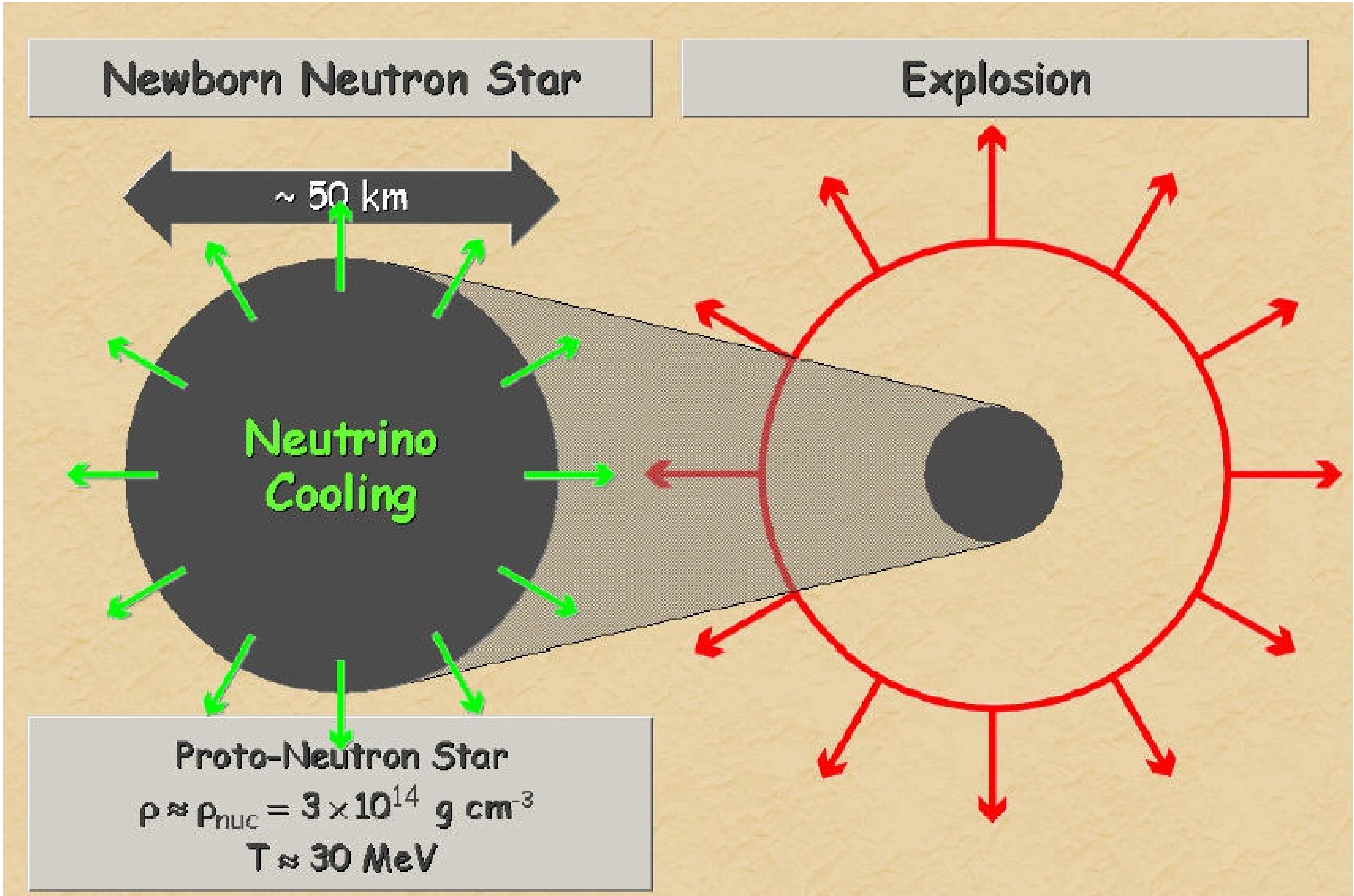
Neutrinos from Supernovae





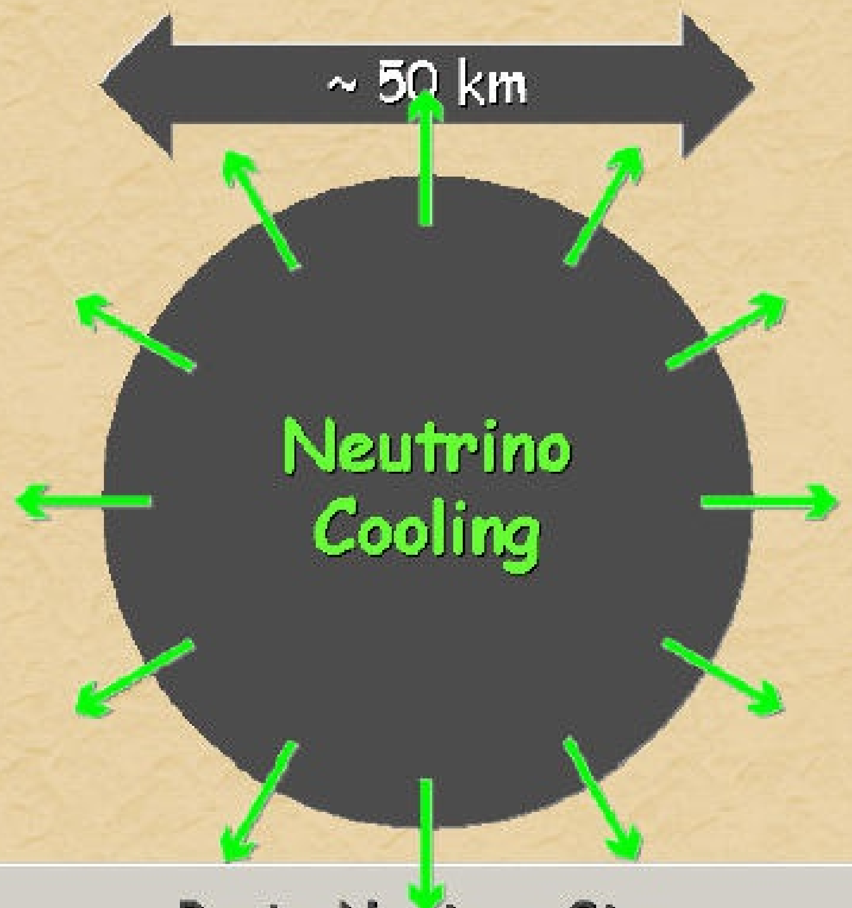


From Georg Raffelt



From Georg Raffelt

Newborn Neutron Star



Proto-Neutron Star

$\rho \approx \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \approx 30\ \mathrm{MeV}$

Gravitational binding energy

$E_b \approx 3 \times 10^{53}\ \mathrm{erg} \approx 17\%\ M_{SUN}\, c^2$

This shows up as

99% Neutrinos

1% Kinetic energy of explosion
(1% of this into cosmic rays)

0.01% Photons, outshine host galaxy

Neutrino luminosity

$L_\nu \approx 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$

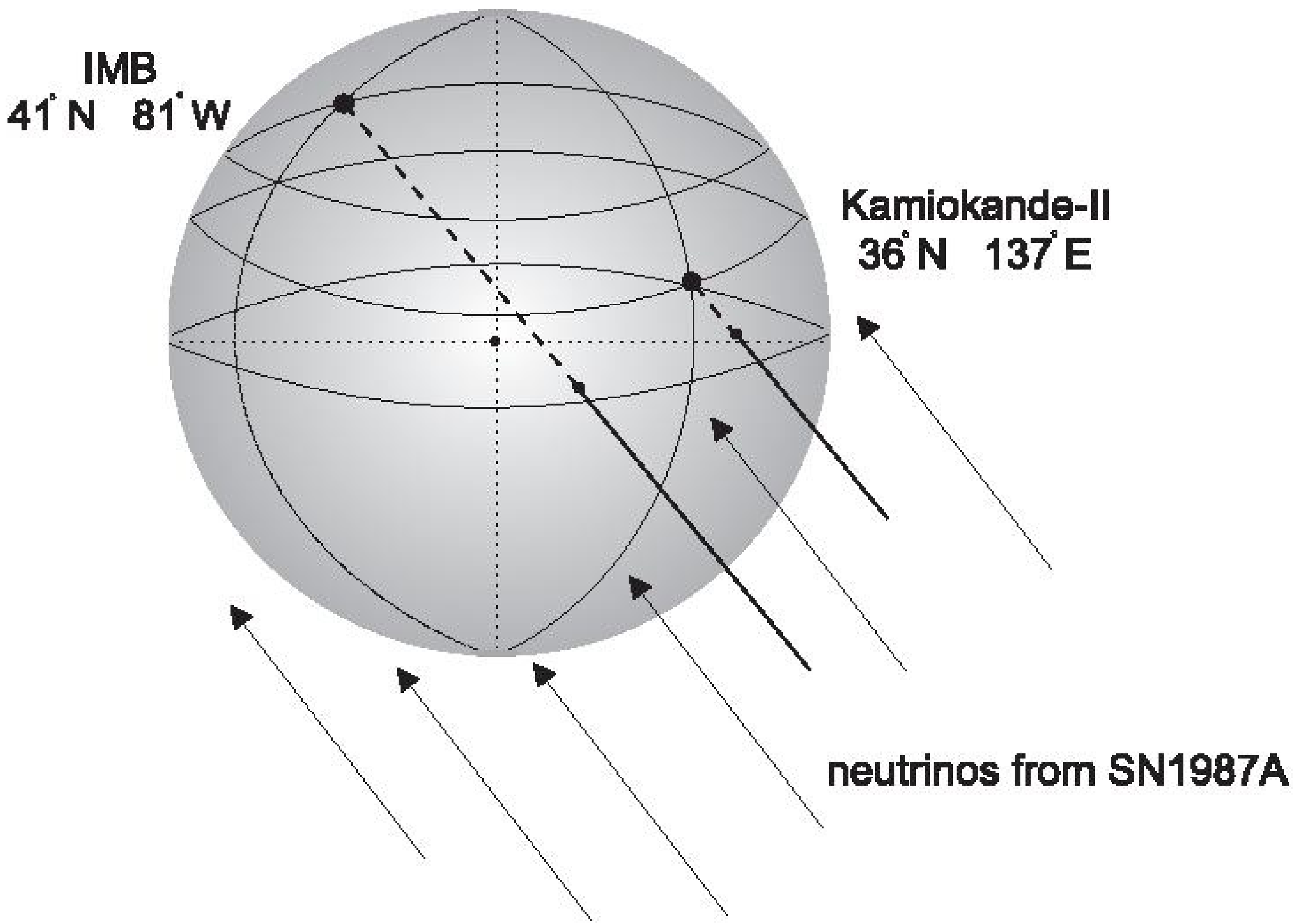
$\approx 3 \times 10^{19}\ L_{SUN}$

While it lasts, outshines the entire visible universe

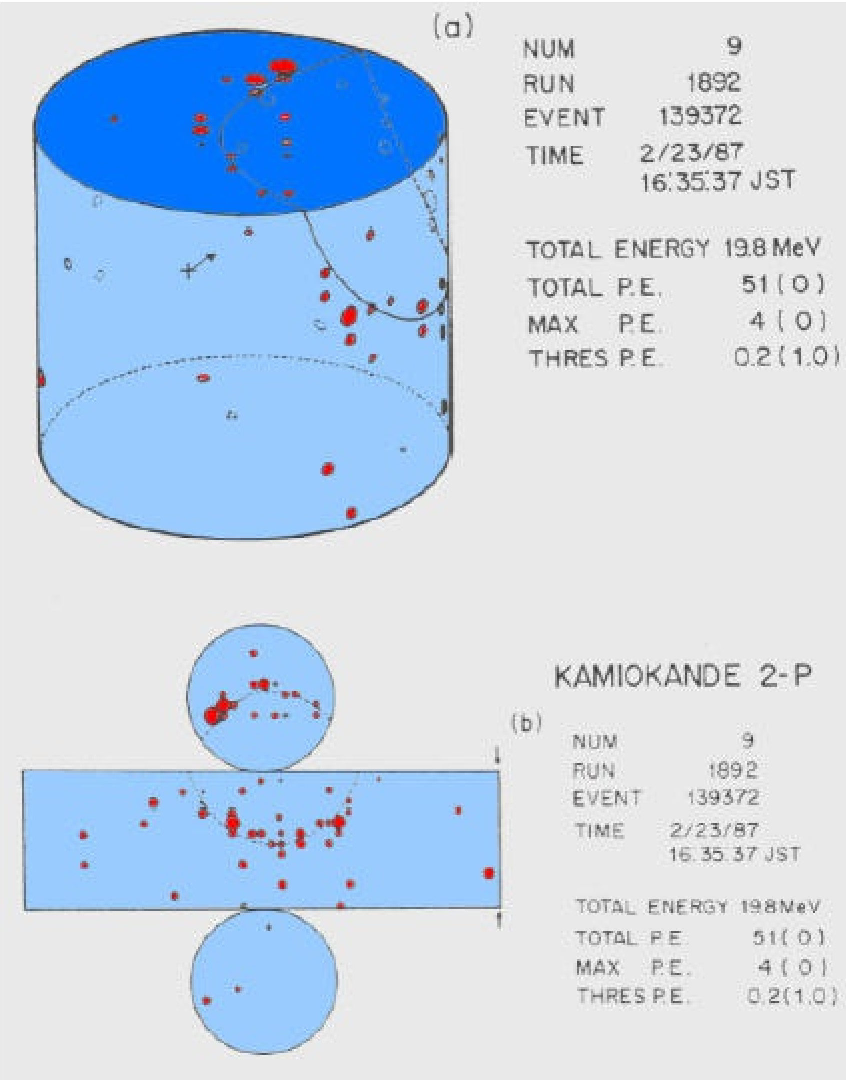
From Georg Raffelt

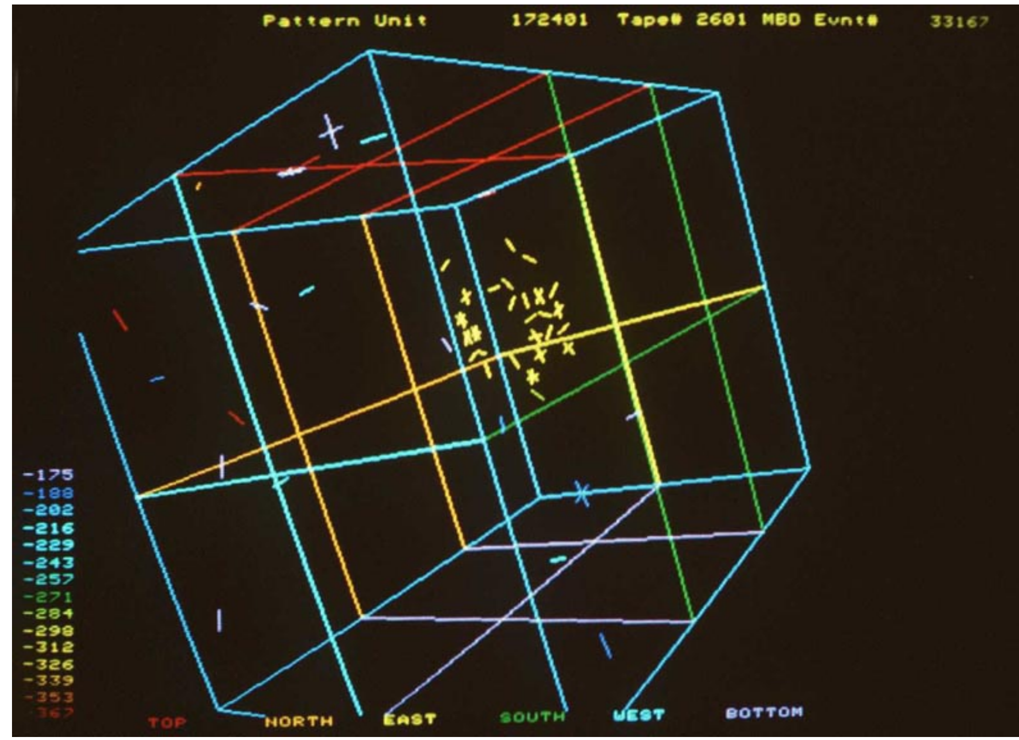
The neutrinos from SN1987A

still the subject of many works every year !



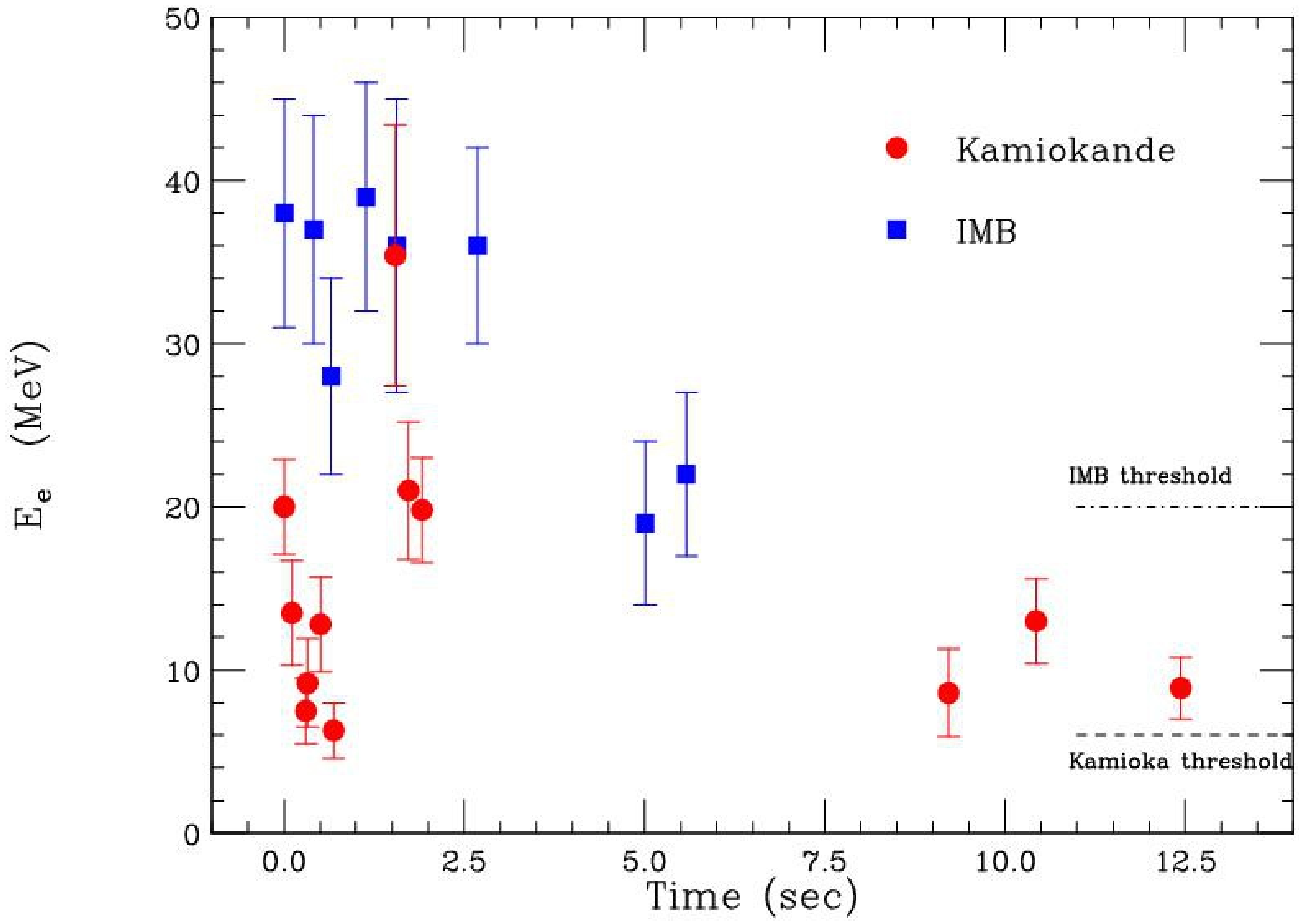
SN1987A





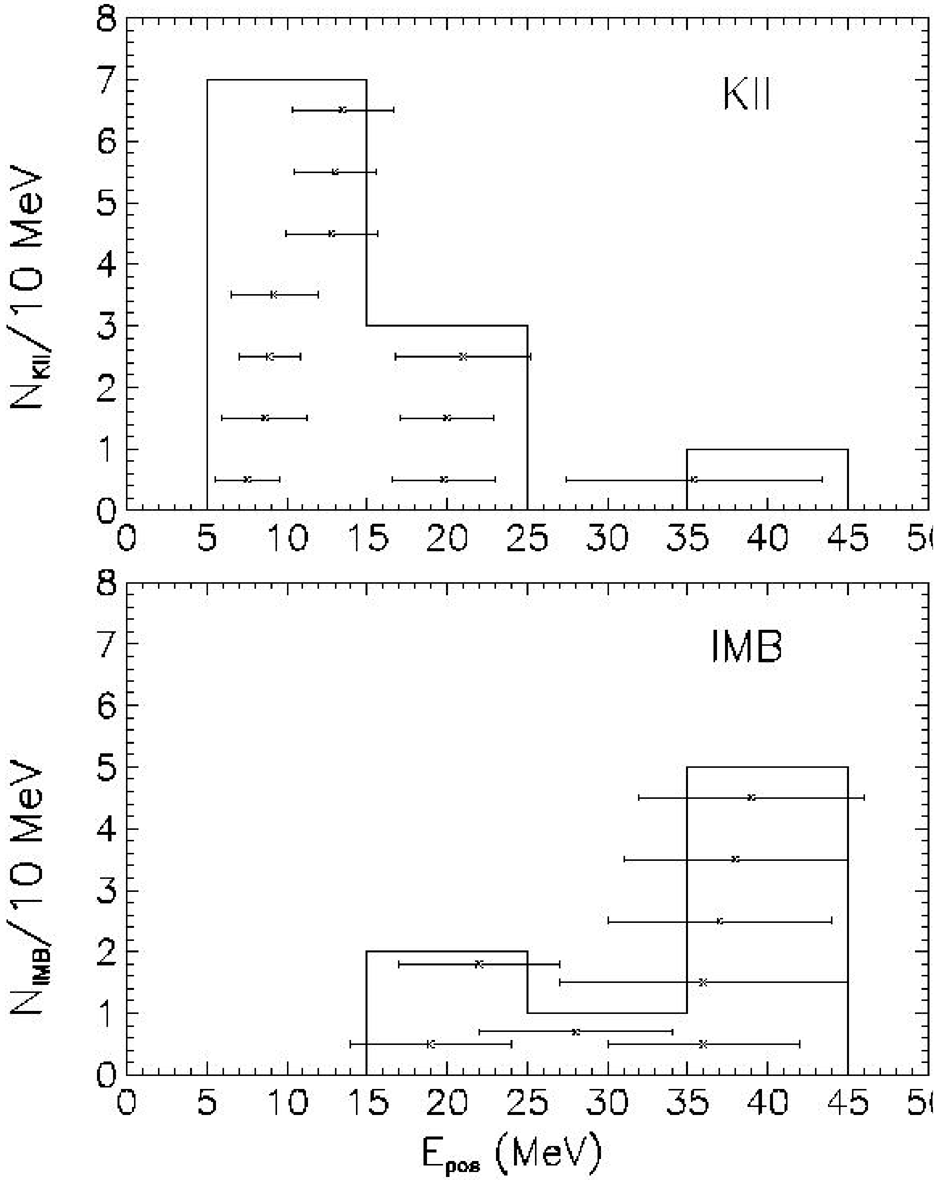
Detector	N_{events}	$\langle E_{e^+} \rangle$ [MeV]
KII	11	15.4 ± 1.1
IMB	8	31.9 ± 2.3

Kamiokande + IMB   detection of SN1987A

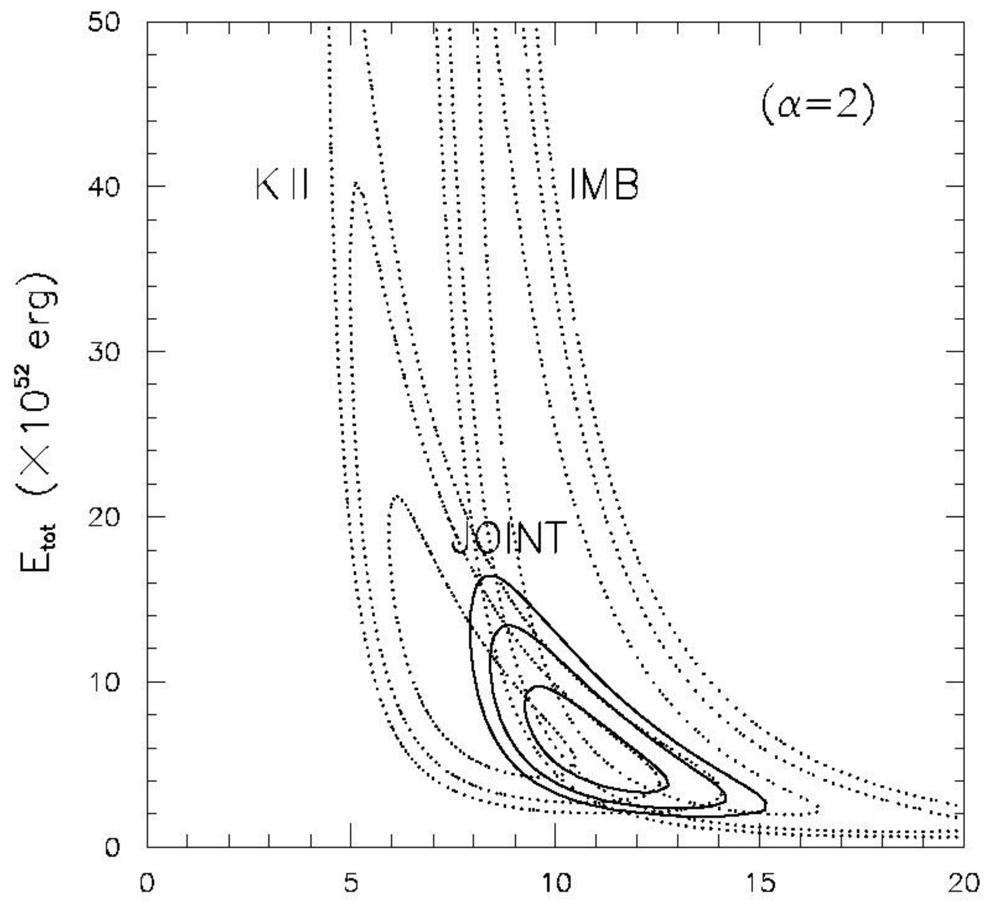


Controversial Results from other detectors [LSD – Mont Blanc]

A. Mirizzi and G. G. Raffelt,
"New analysis of the SN 1987A neutrinos with a flexible spectral shape,"
Phys. Rev. D **72**, 063001 (2005) [astro-ph/0508612].

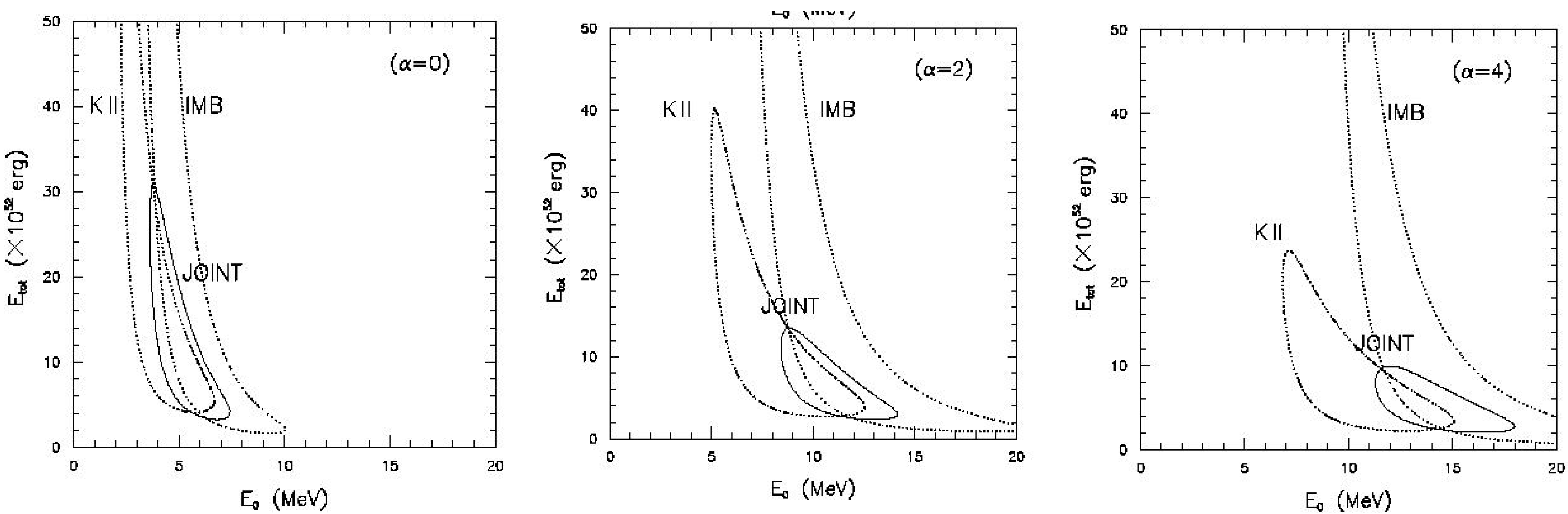


Maxwell-Boltzmann
Energy Distribution



[Average Energy (MeV)]

$$\varphi(E) = \frac{1}{E_0}\frac{(\alpha+1)^{(\alpha+1)}}{\Gamma(\alpha+1)}\left(\frac{E}{E_0}\right)^{\alpha}\exp\left[-(\alpha+1)\frac{E}{E_0}\right]$$



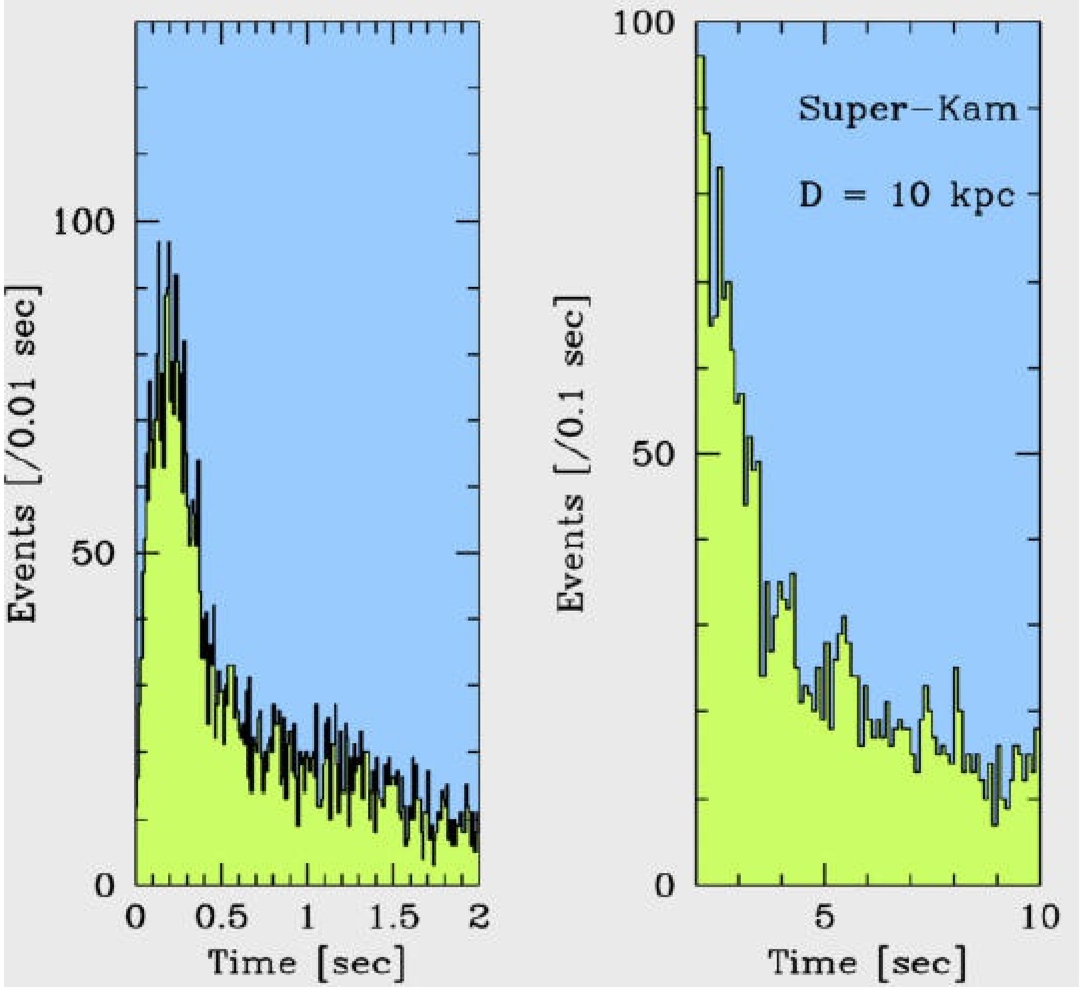
A. Mirizzi and G. G. Raffelt,
"New analysis of the SN 1987A neutrinos with a flexible spectral shape,"
Phys. Rev. D **72**, 063001 (2005) [astro-ph/0508612].

23 february 1987

…. 32 years ago …….

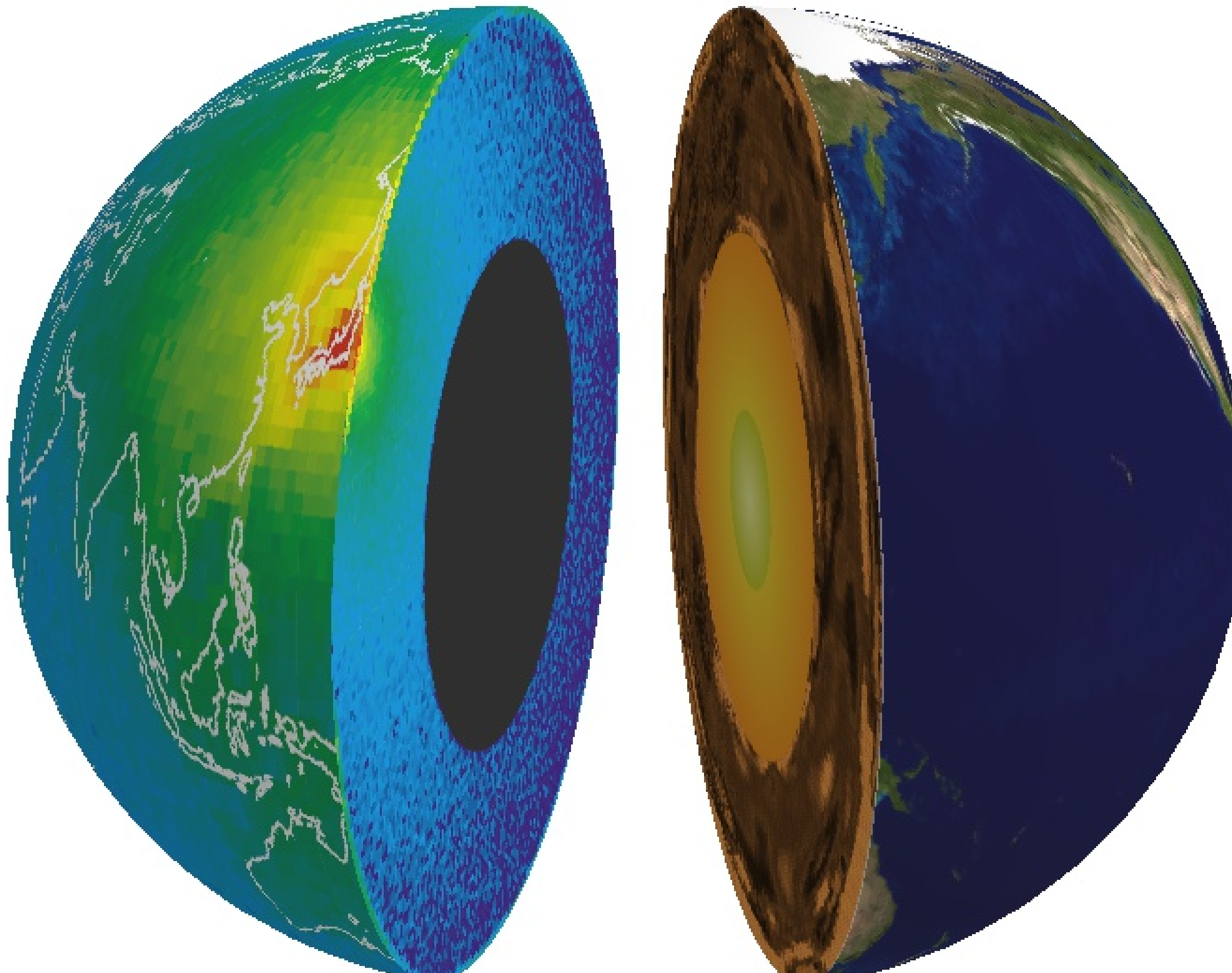
We want a new close-by
(… but not too much…..)
Gravitational Collapse
Supernova

Scientific Potential
(with the new detectors)
is very important



GEOPHYSICAL

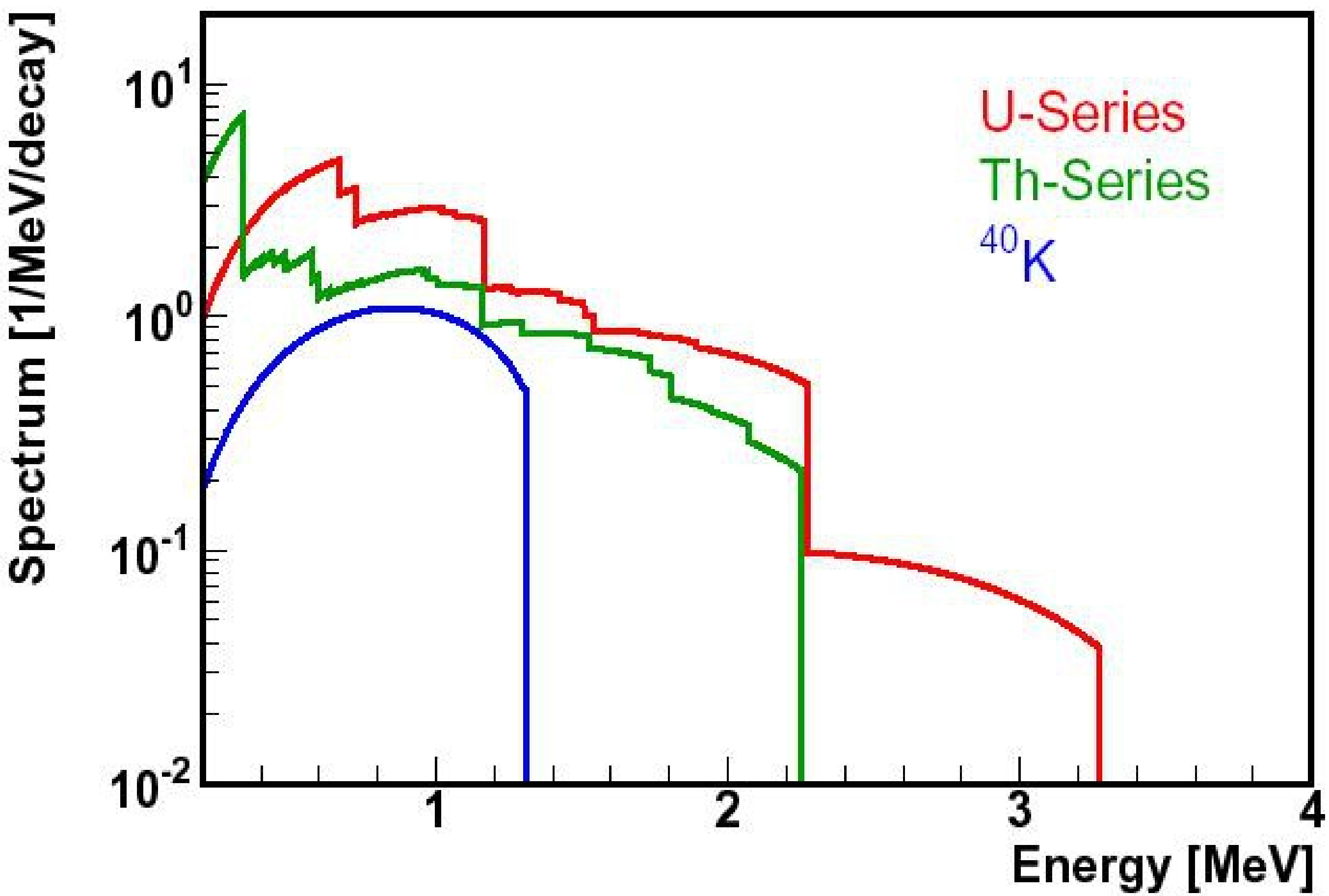
NEUTRINOS



$$^{238}\mathrm{U} \xrightarrow[100\%]{} {}^{206}\mathrm{Pb} + 8\,{}^{4}\mathrm{He} + 6e^{-} + 6\bar{\nu}_e + 51.7\ [\mathrm{MeV}]$$

$$^{232}\mathrm{Th} \xrightarrow[100\%]{} {}^{208}\mathrm{Pb} + 6\,{}^{4}\mathrm{He} + 4e^{-} + 4\bar{\nu}_e + 42.7\ [\mathrm{MeV}]$$

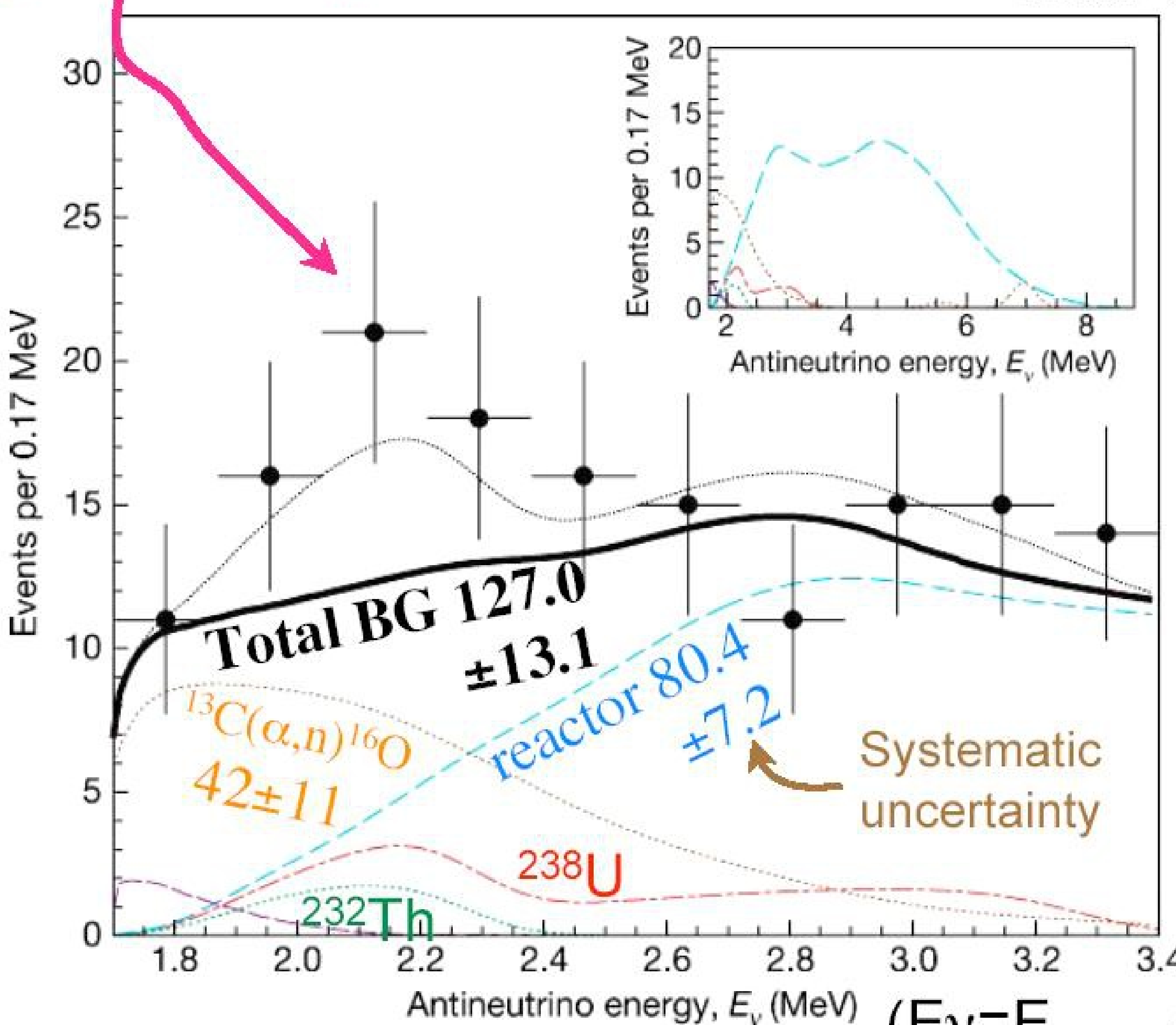
$$^{40}\mathrm{K} \xrightarrow[89.28\%]{} {}^{40}\mathrm{Ca} + e^{-} + \bar{\nu}_e + 1.311\ [\mathrm{MeV}]$$



152 events observed
"signal" 25 $^{+19}_{-18}$

Geoneutrino results

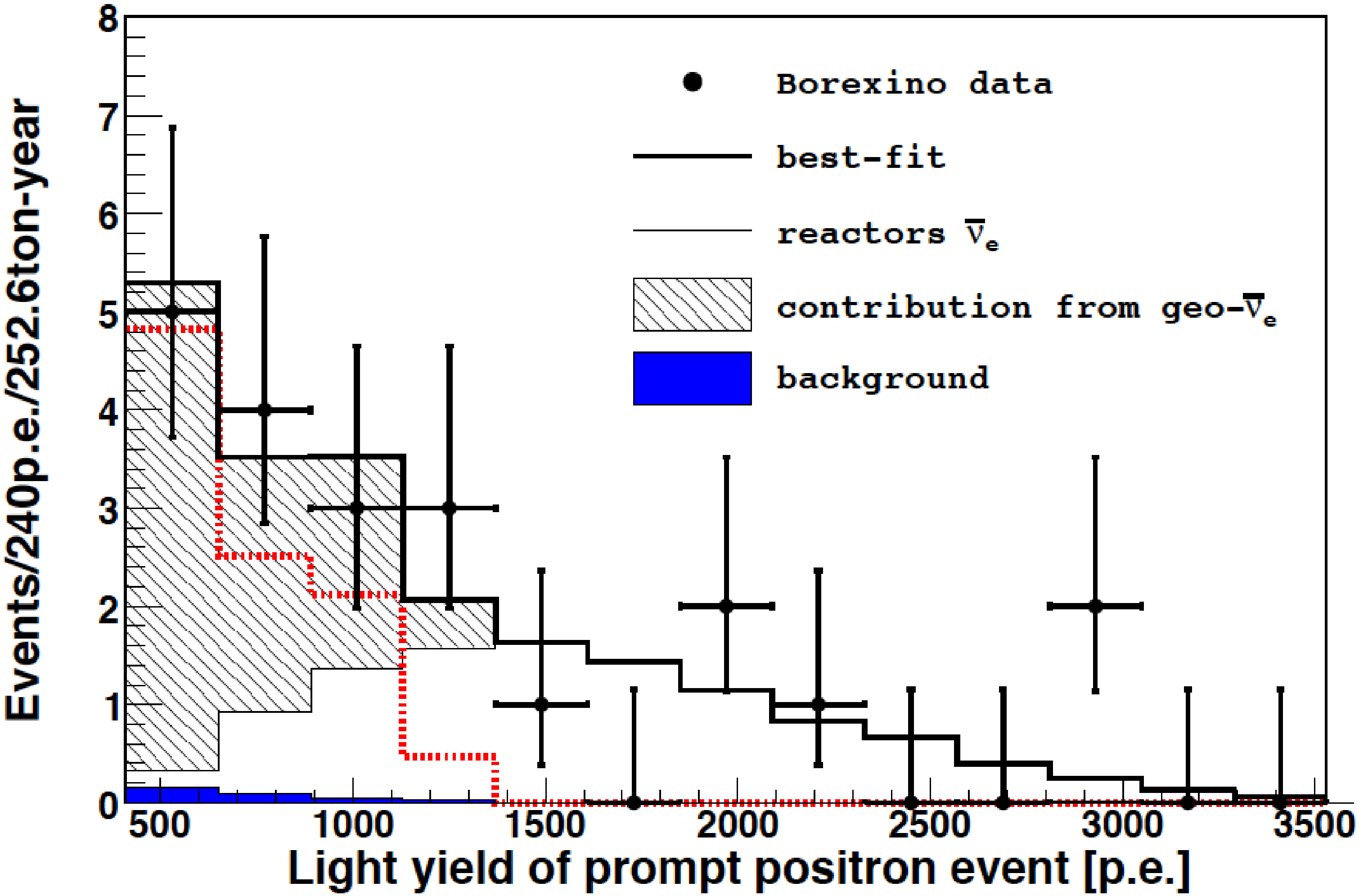
Nature 436, 28 July 2005



Data-set:
749.1 days
(Mar. 9, 2002 -Oct. 30, 2004)

Fiducial:
5 m radius

($E\nu = E_{prompt} + 0.8MeV$)



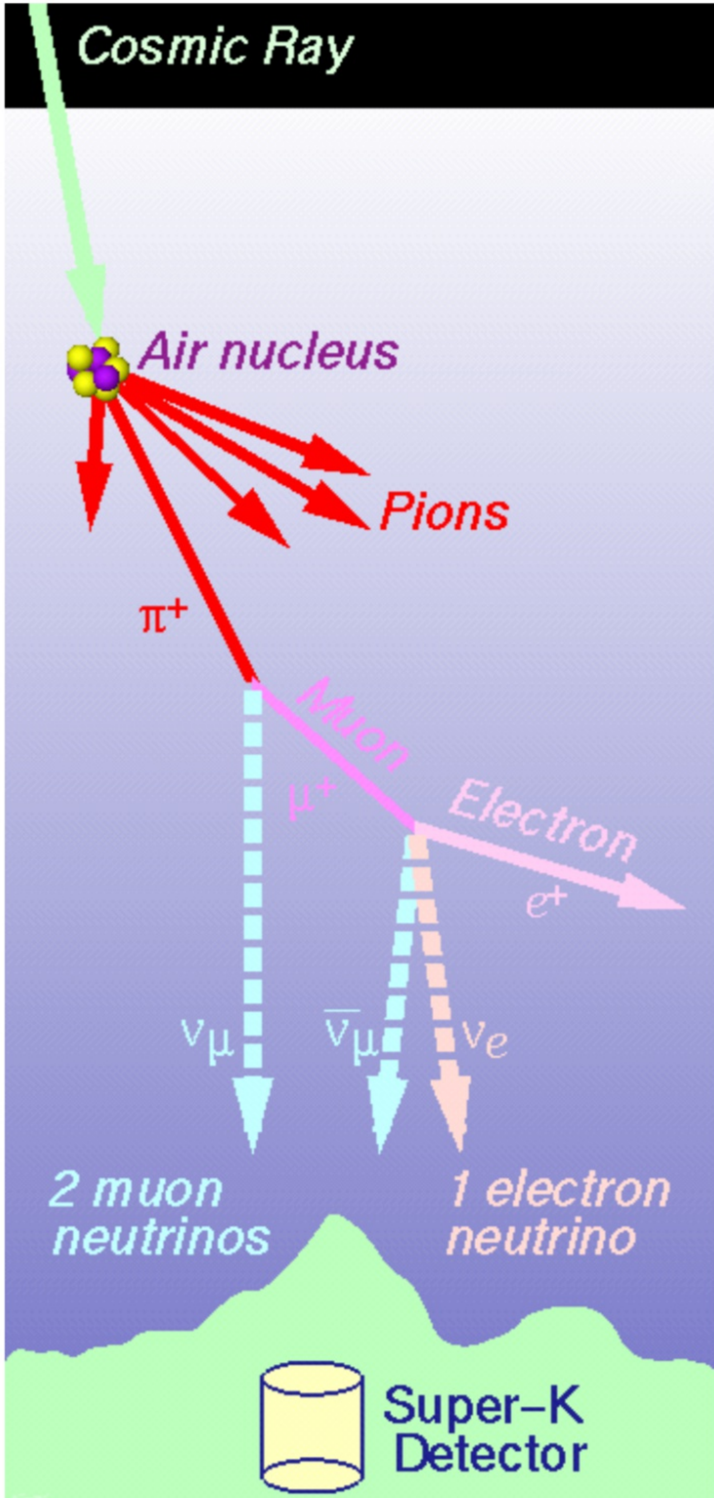
BOREXINO

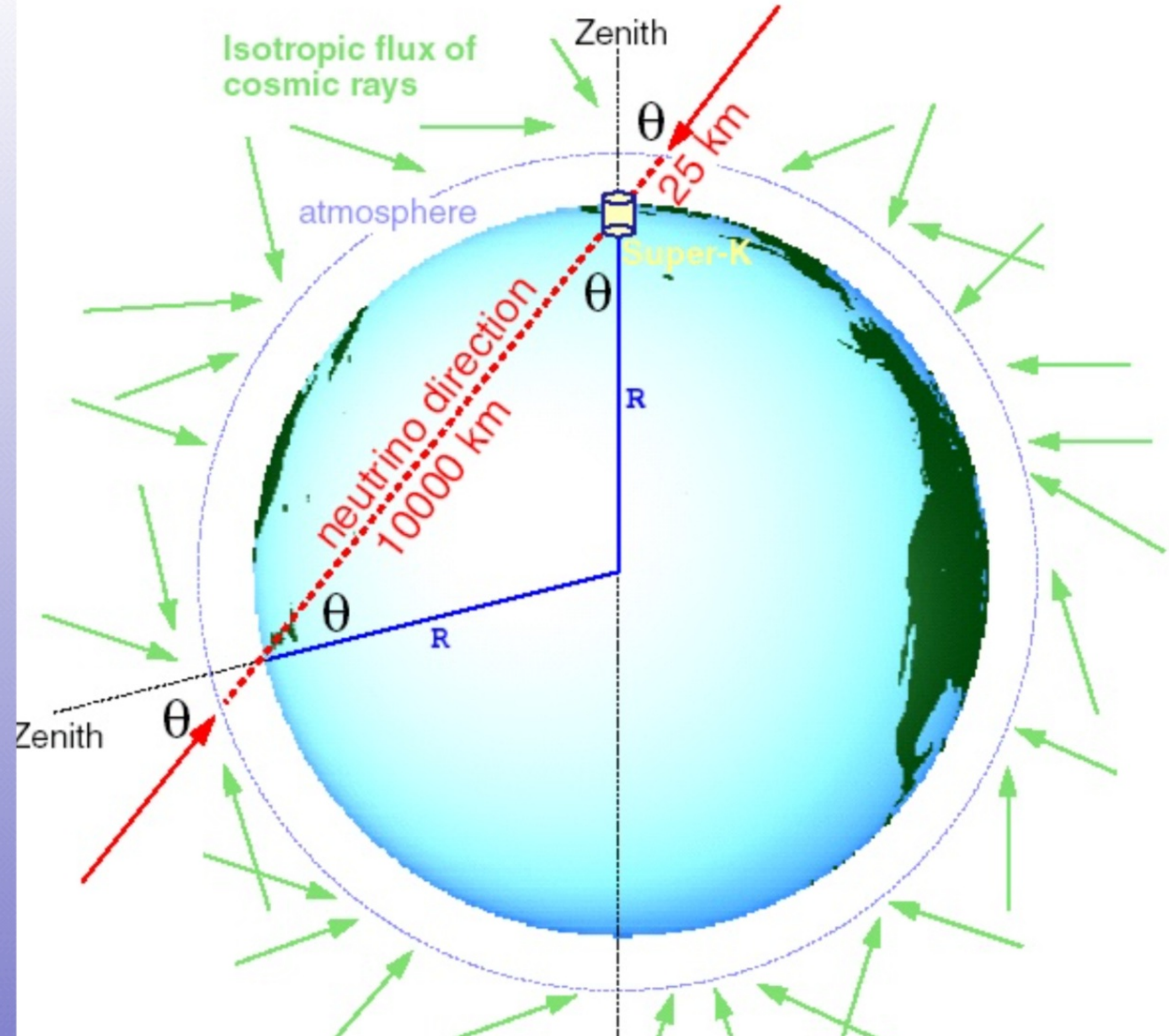
(march 2010)

$$9.9^{+4.1}_{-3.4}$$ Events (1 sigma)

$$3.9^{+1.6}_{-1.3}(^{+5.8}_{-3.2})\ \text{events}/(100\ \text{ton}\cdot\text{yr})$$

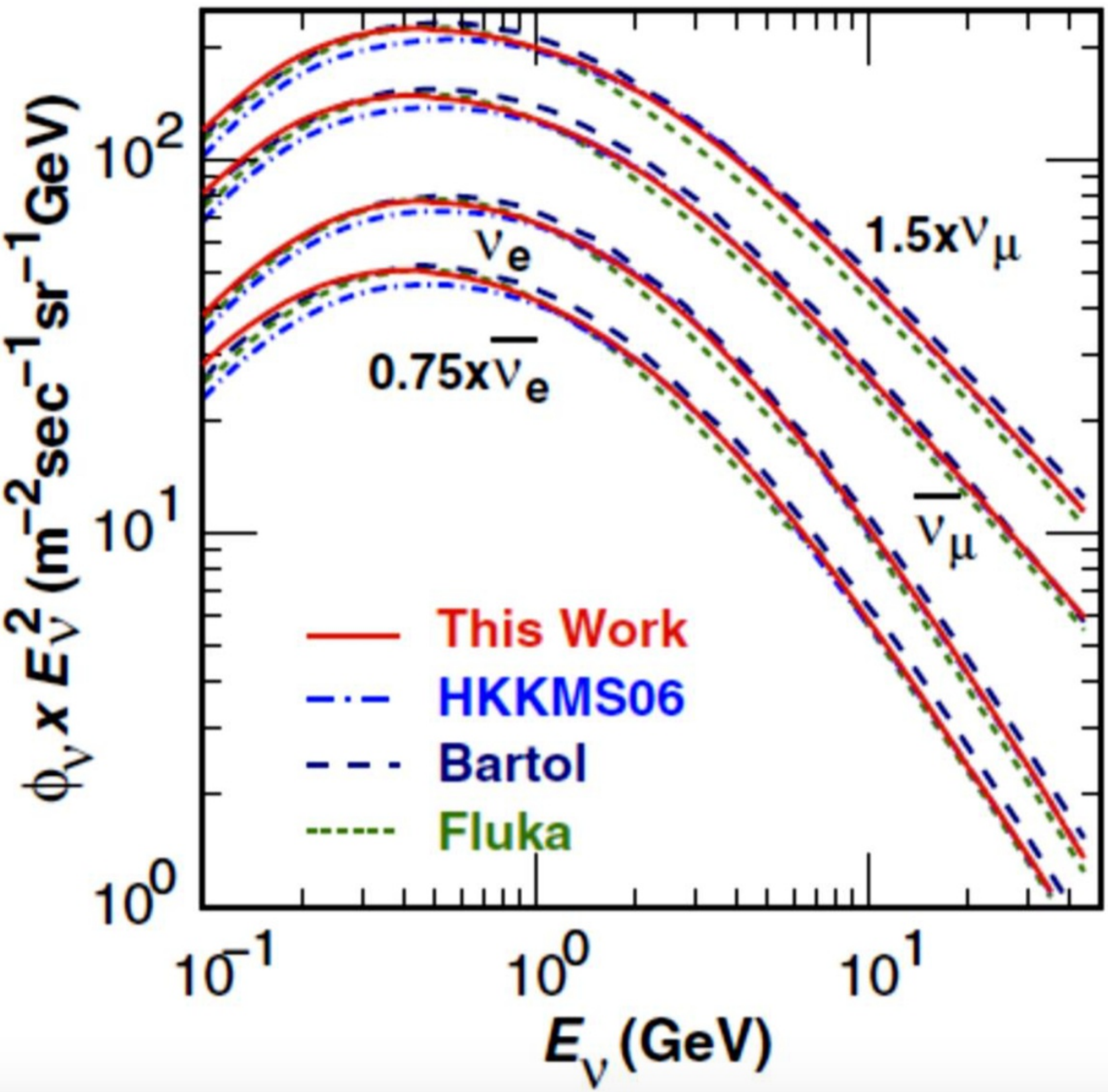
ATMOSPHERIC NEUTRINOS





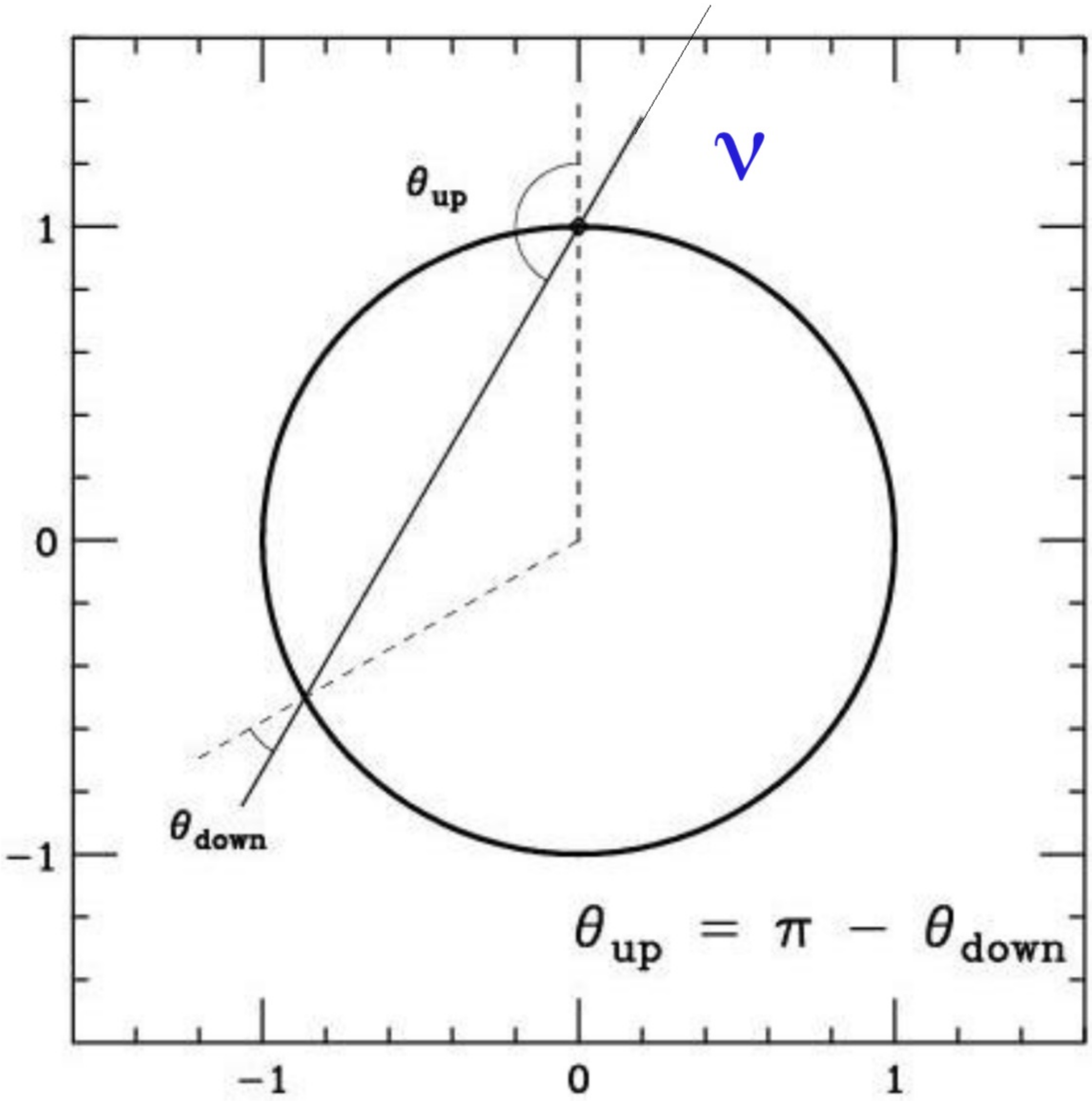
Up-Down Symmetric Flux
(for Eν > few GeV)

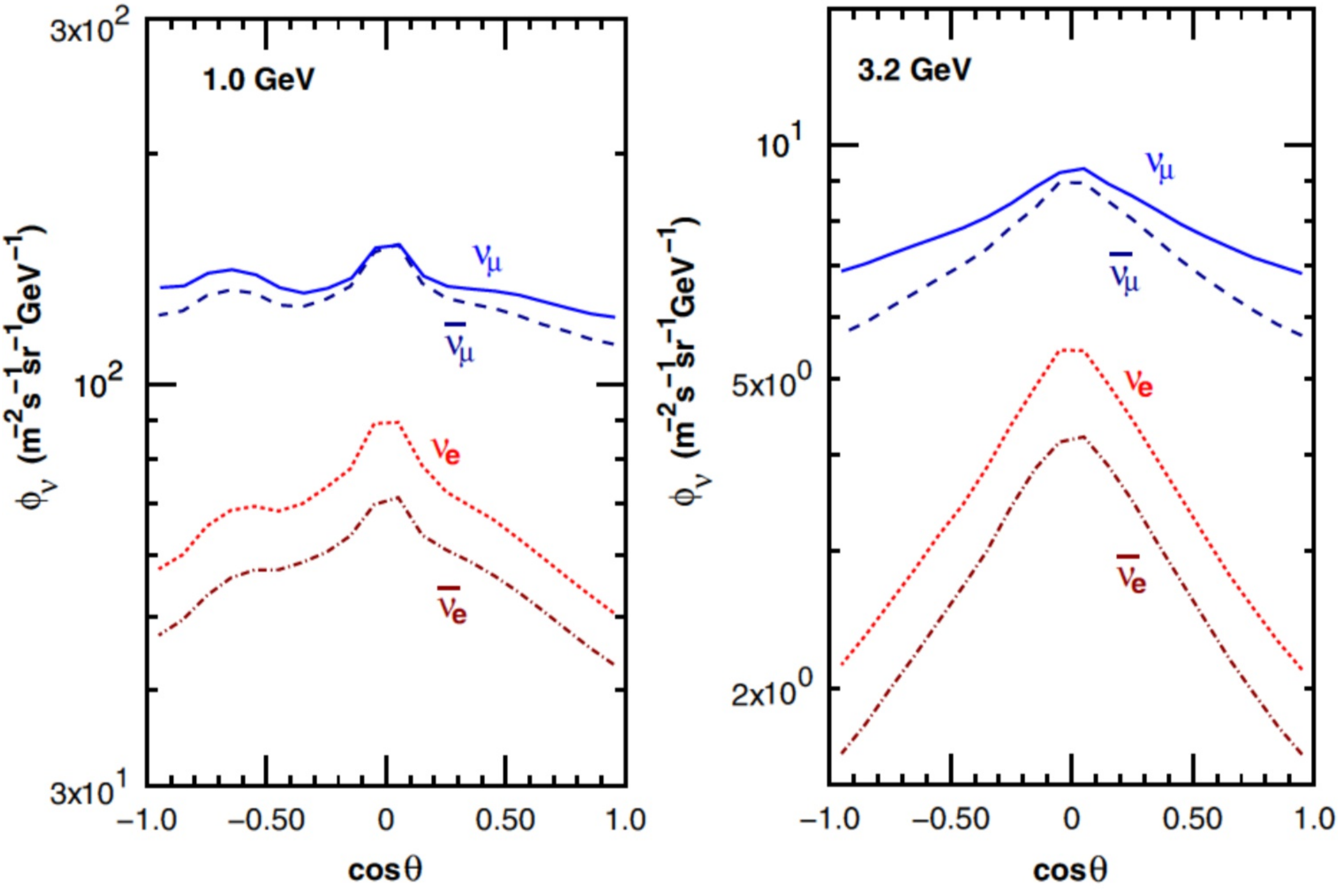
Atmospheric ν energy spectrum



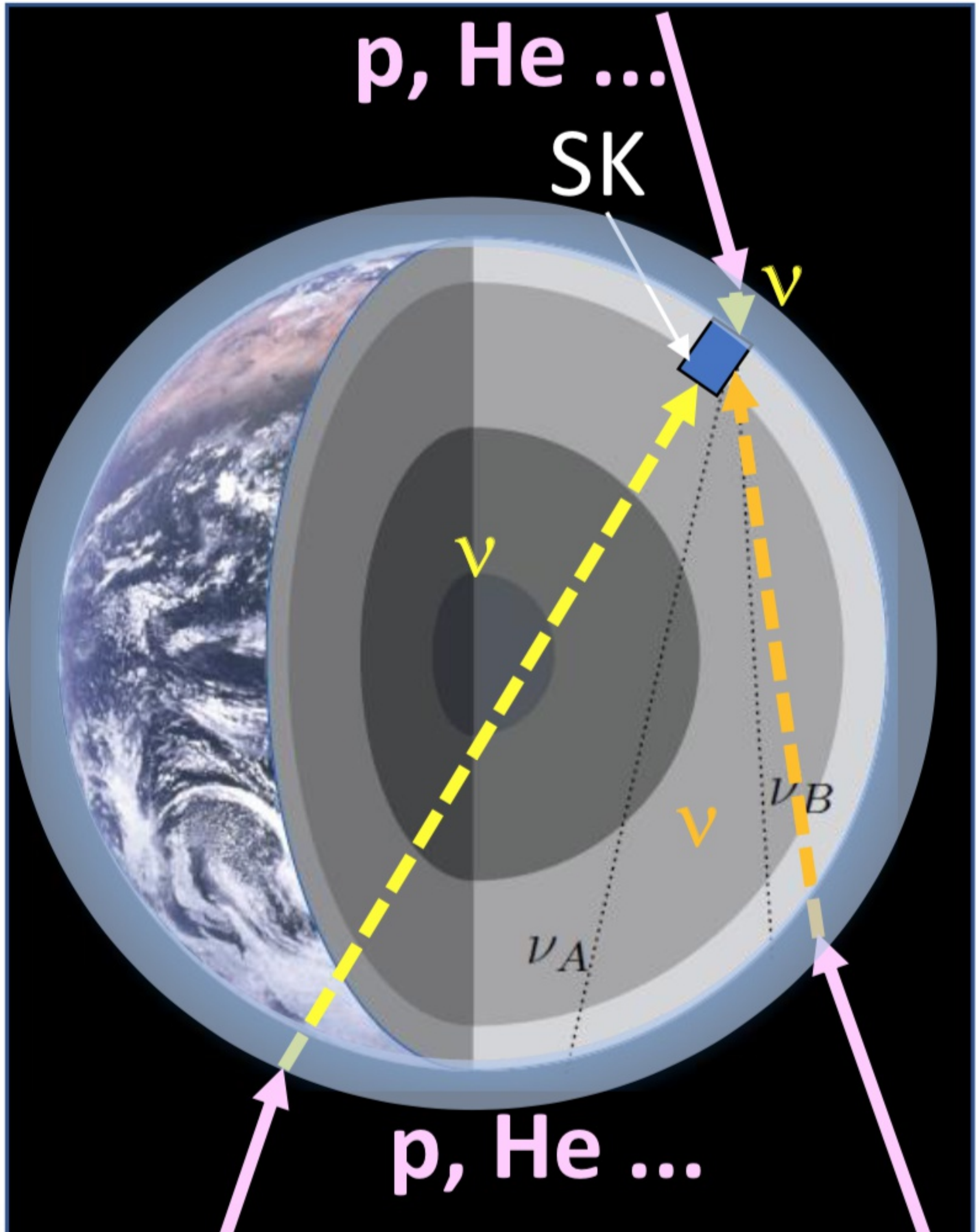
$$\phi_{\nu_\alpha}(E,\theta) = \phi_{\nu_\alpha}(E,\pi-\theta)$$

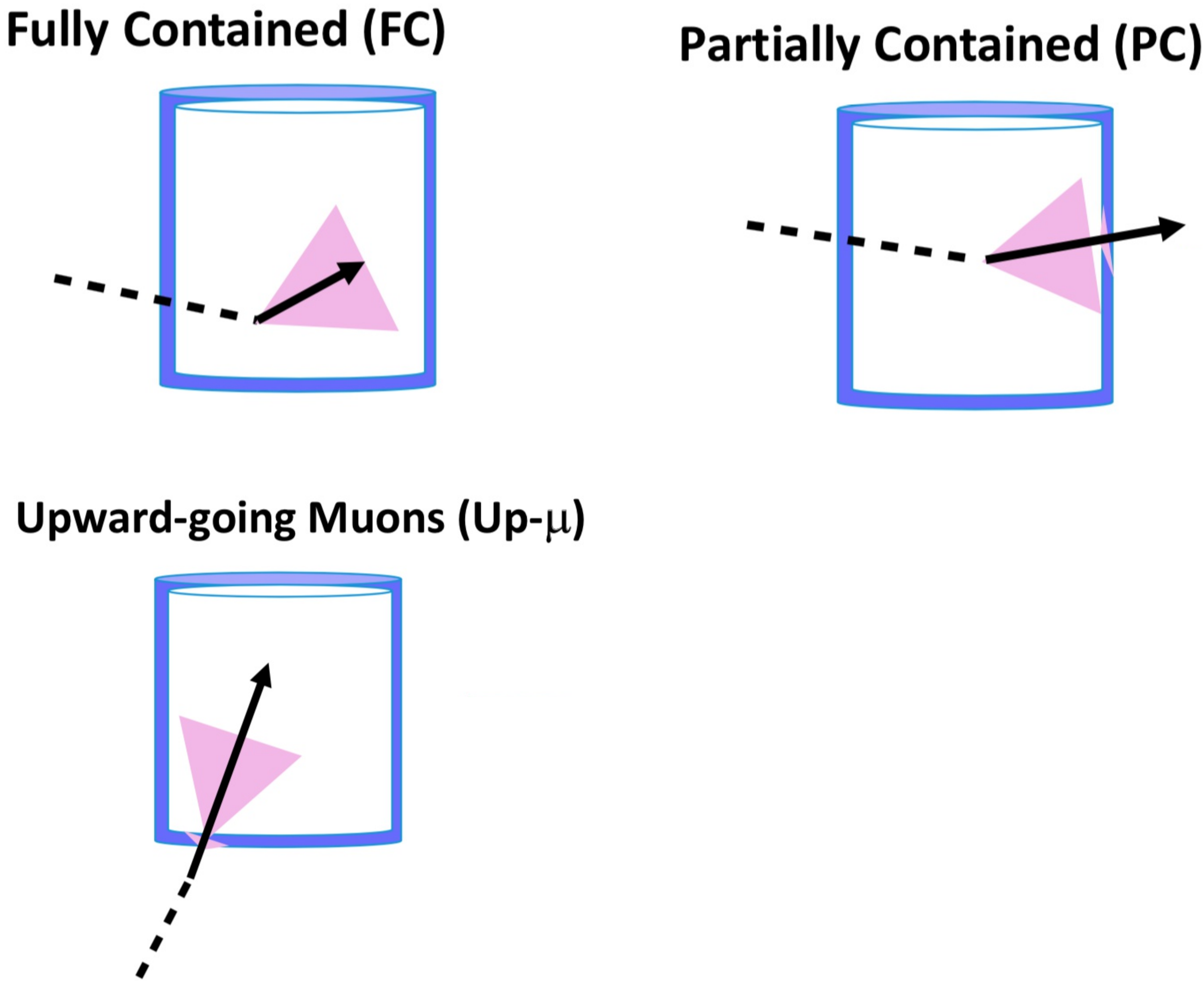
Up-Down Symmetry





1.0 GeV
3.2 GeV
ϕ_ν (m^{-2}s^{-1}sr^{-1}GeV^{-1})
3x10^2
10^2
3x10^1
10^1
5x10^0
2x10^0
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
−1.0
−0.50
0
0.50
1.0
cosθ


p, He ...
SK
ν
ν
ν_B
ν
ν_A
p, He ...

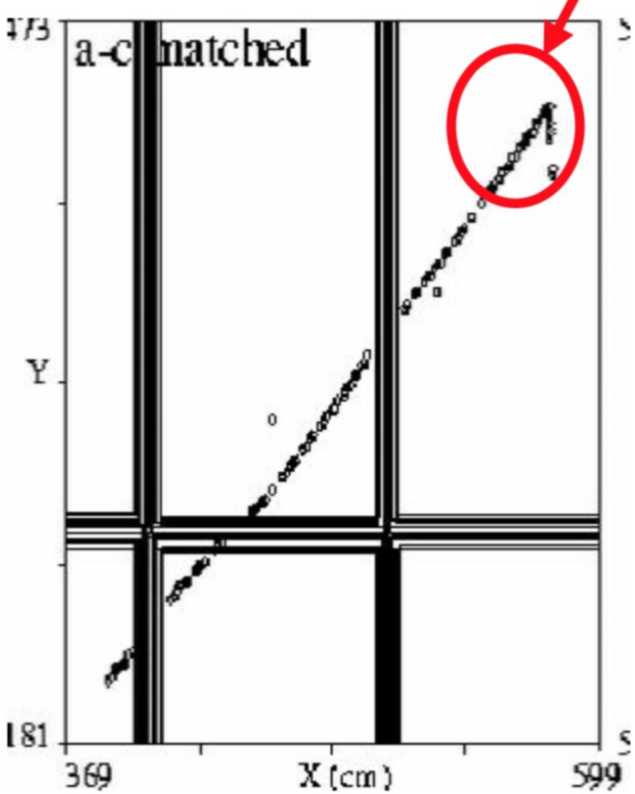

Fully Contained (FC)
Partially Contained (PC)
Upward-going Muons (Up-μ)

Atmospheric Neutrino events

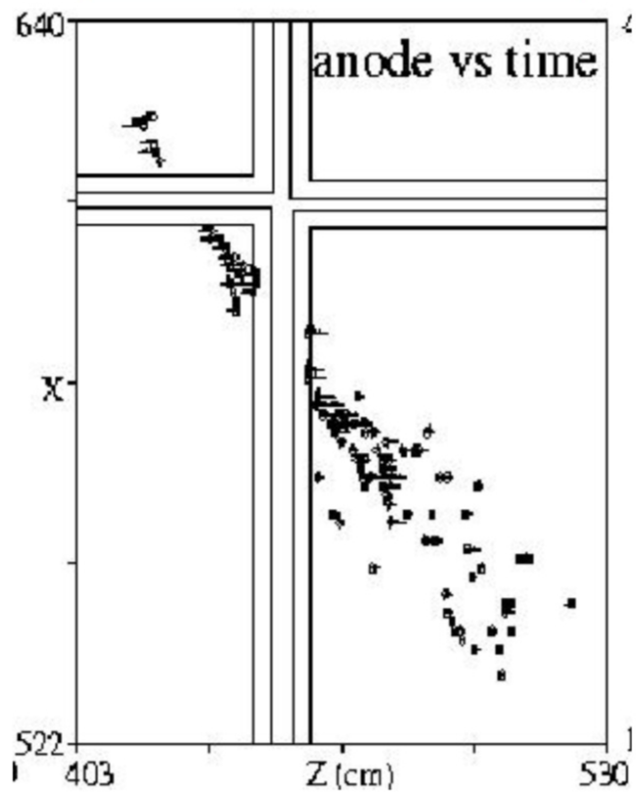
Soudan-2 detector

ν interaction vertex

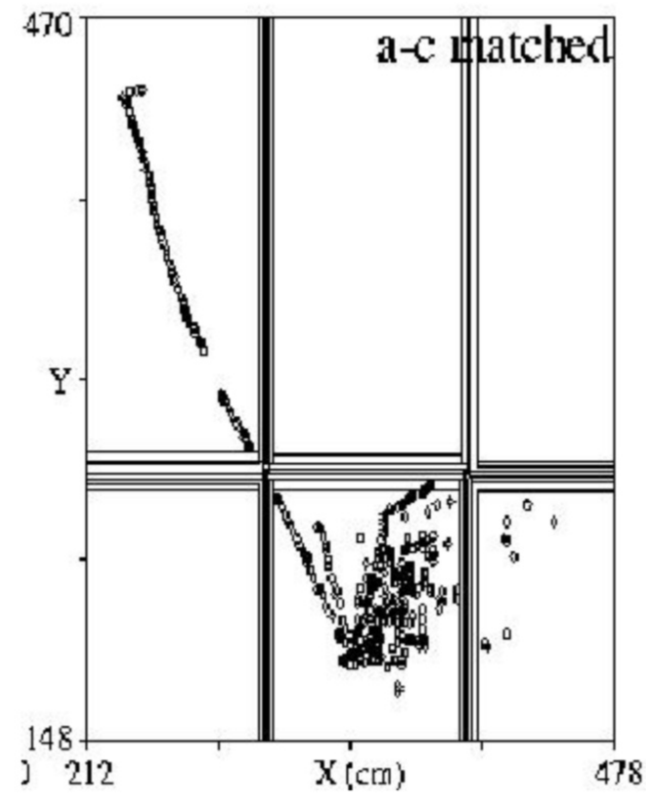
$\nu_\mu + n \rightarrow \mu^- + p$



$\nu_e + N \rightarrow e^\pm + N'$



$\nu_\mu + N \rightarrow \mu^\pm + X$

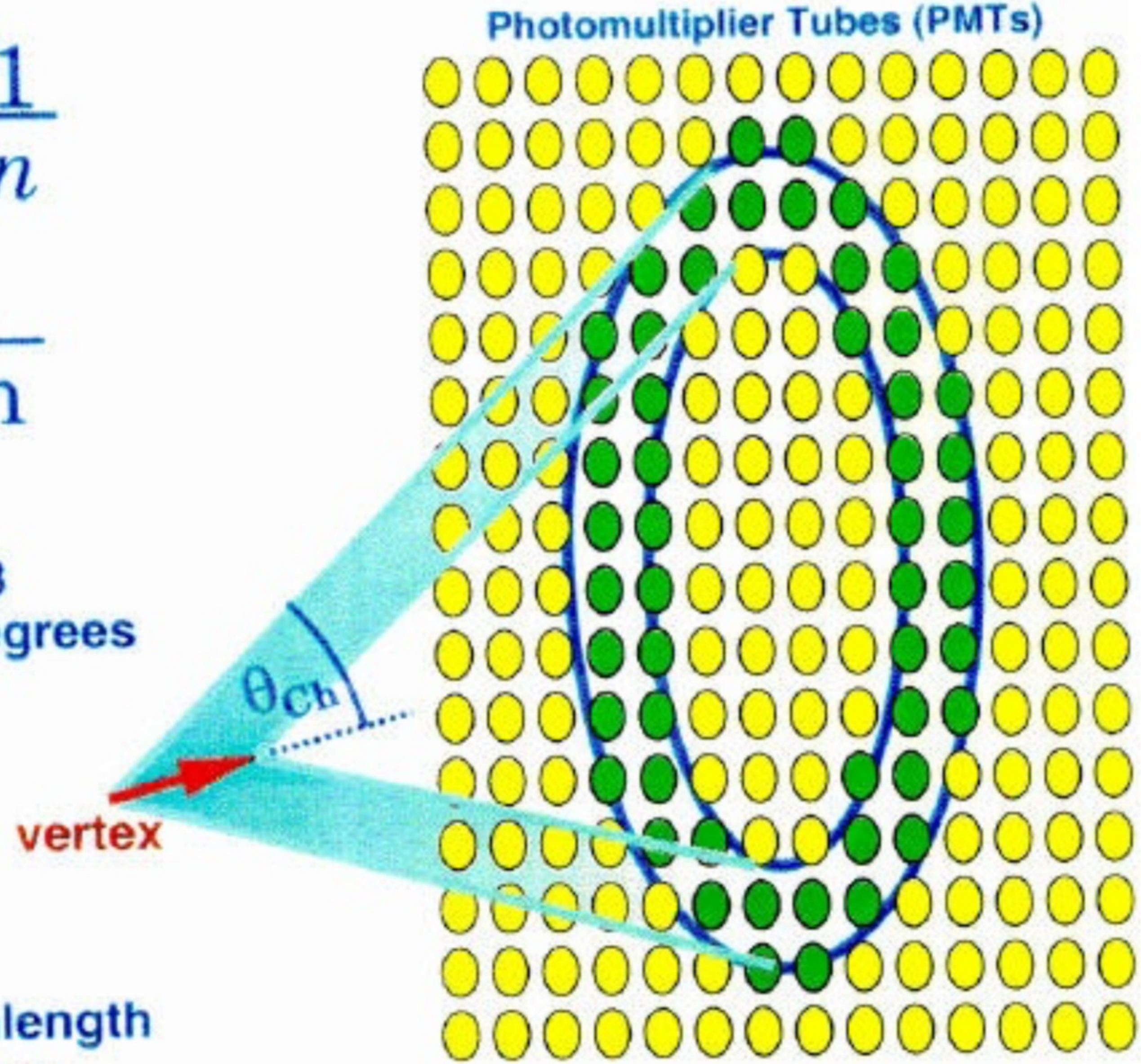


Cherenkov Radiation

$$\beta \left(= \frac{v}{c}\right) > \frac{1}{n}$$

$$\cos \theta_{Ch} = \frac{1}{\beta n}$$

in water, $n = 1.33$
as $\beta \rightarrow 1$, $\theta_{Ch} \rightarrow 41$ degrees



~340 photons/cm pathlength
300 nm < λ < 600 nm


IMB detector

SuperKamiokande **detector**

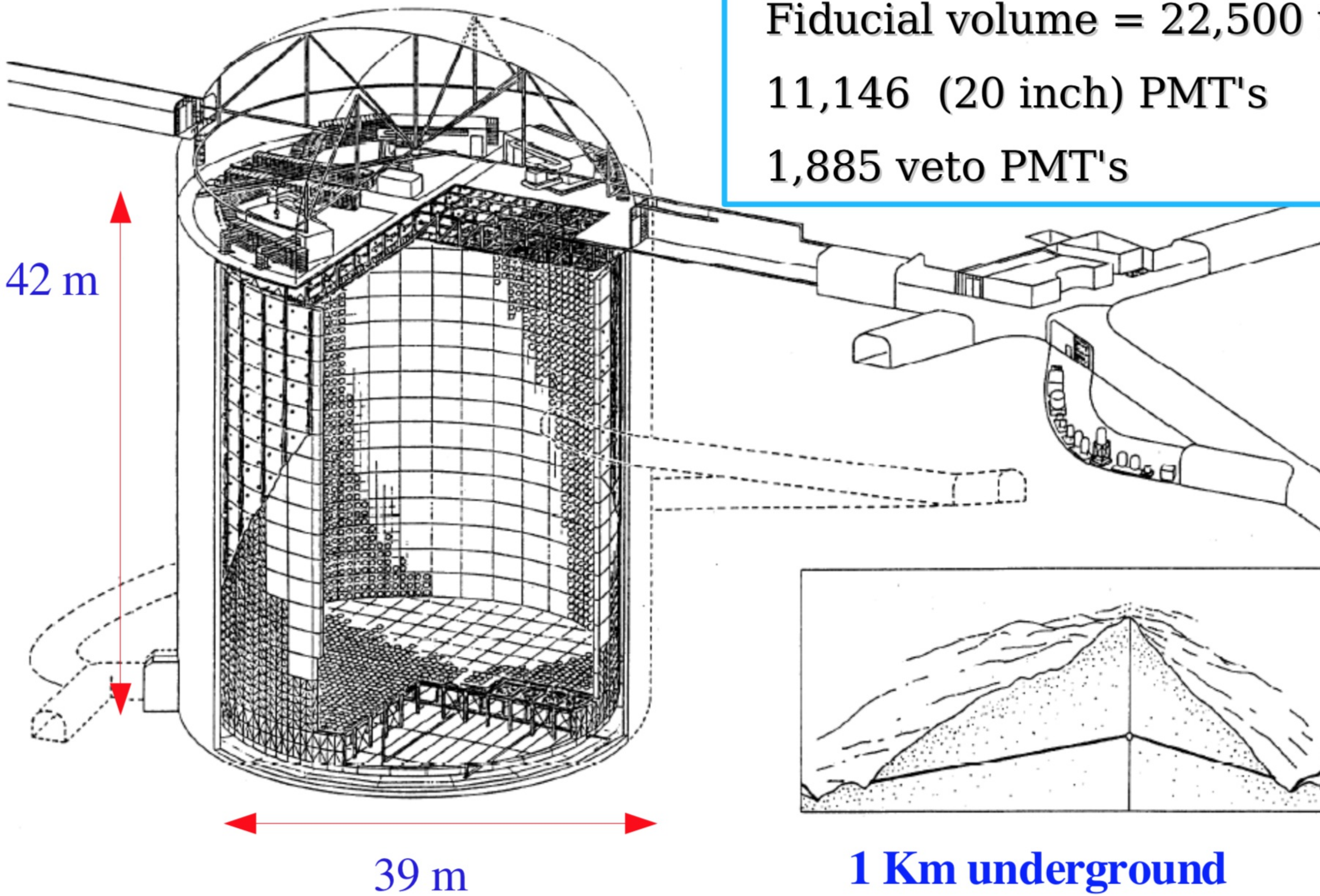
50,000 tons of ultrapure water

2 m of water = veto counter

Fiducial volume = 22,500 tons

11,146 (20 inch) PMT's

1,885 veto PMT's

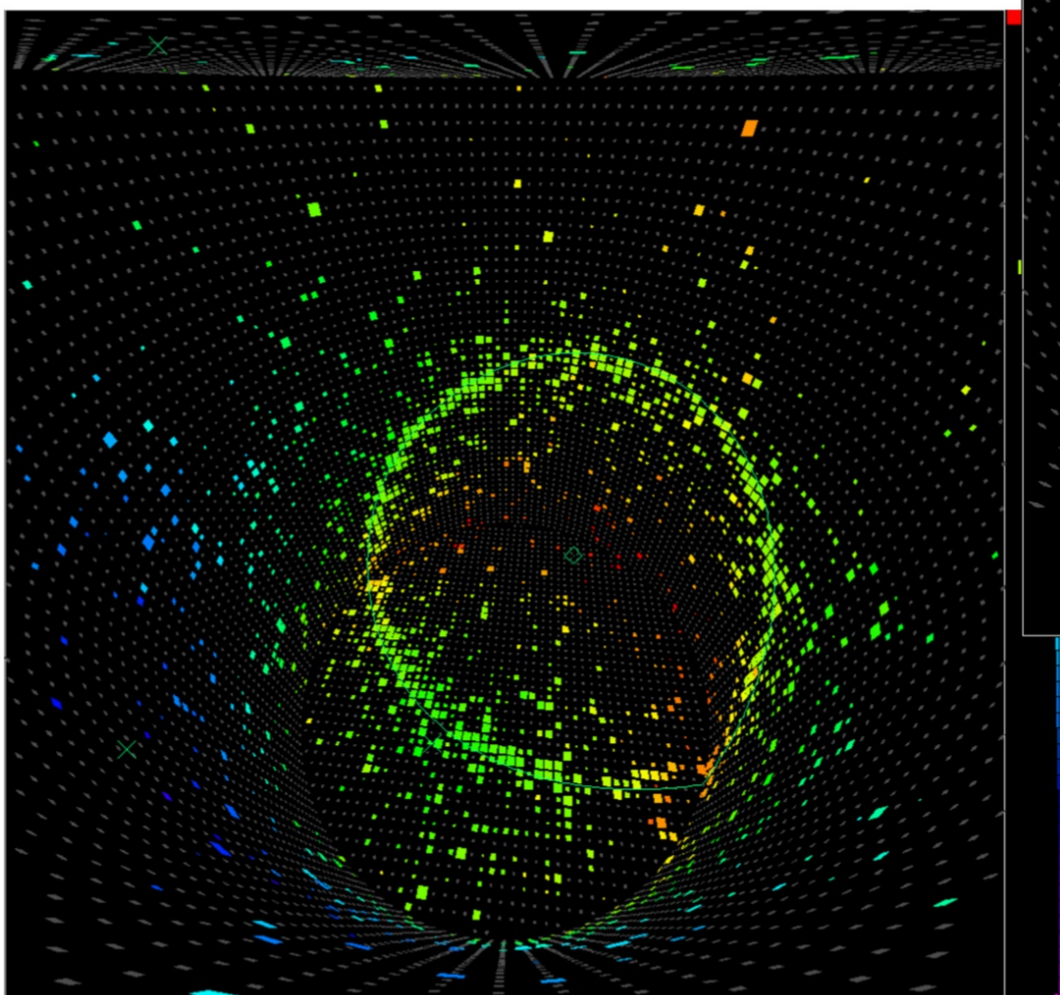


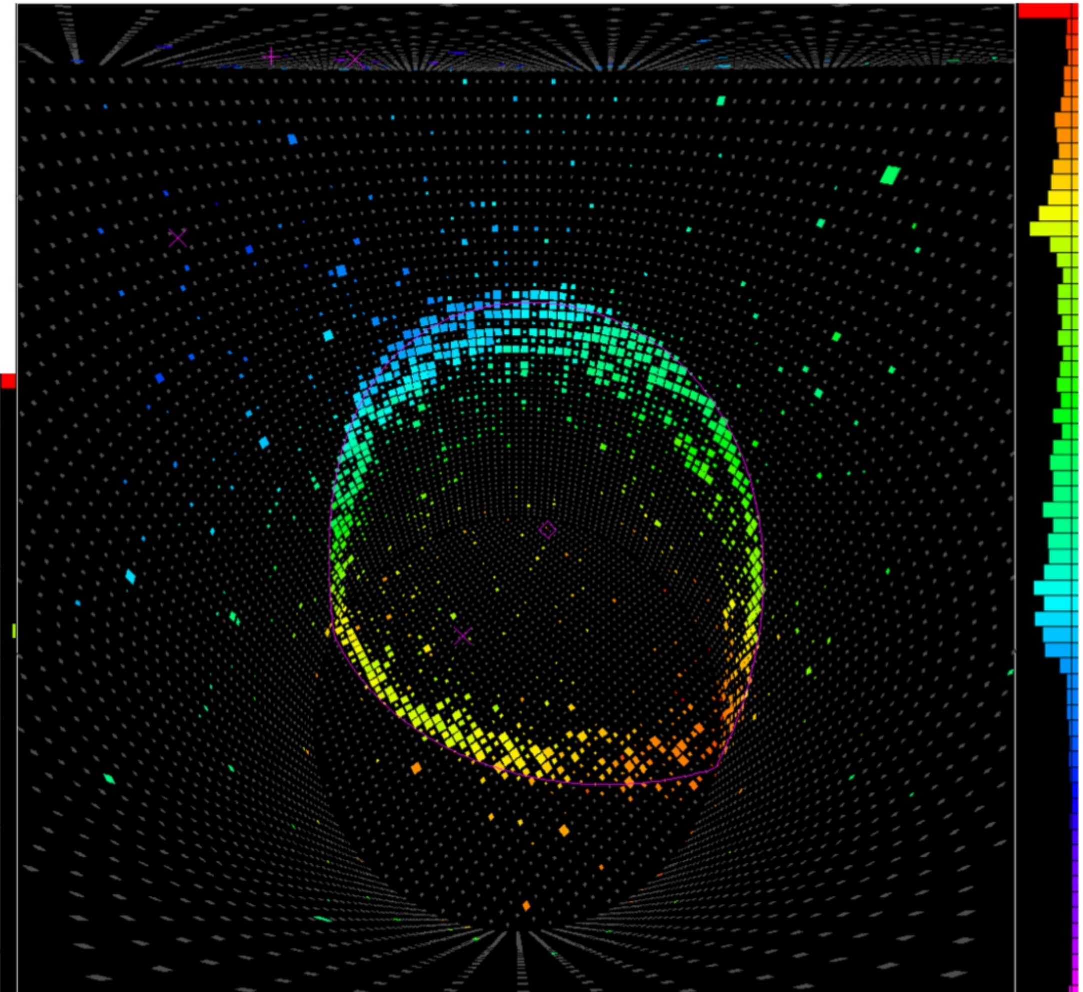
1 Km underground

11,146 20 inch Photomultipliers (PMT's)

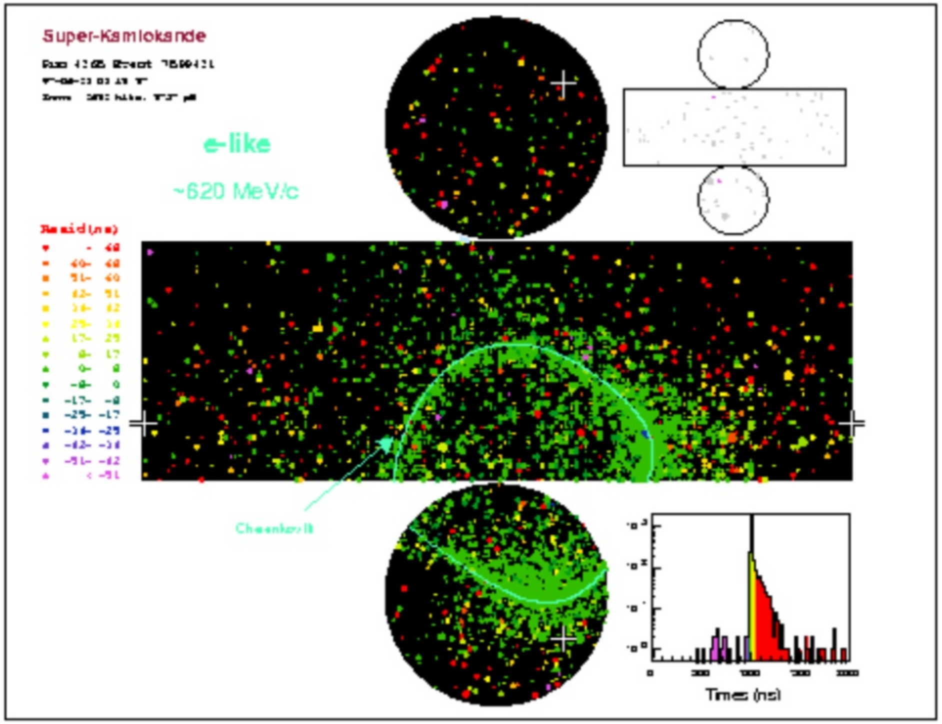
(<u>40 %</u> of surface is sensitive)

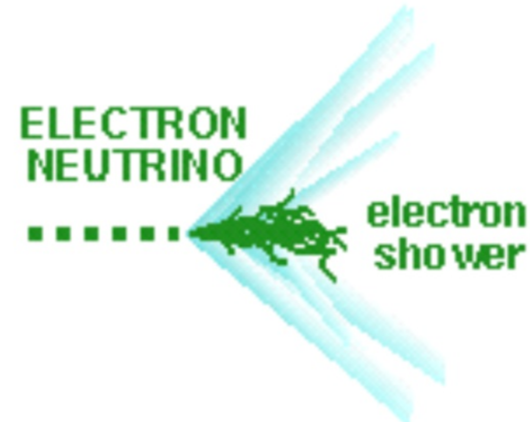
e-like

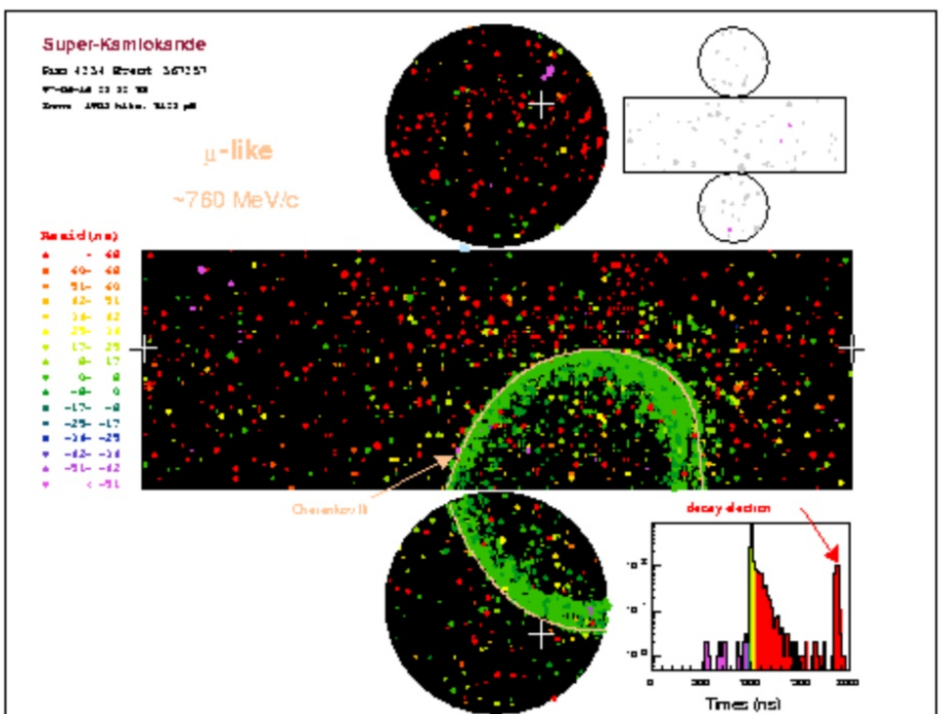


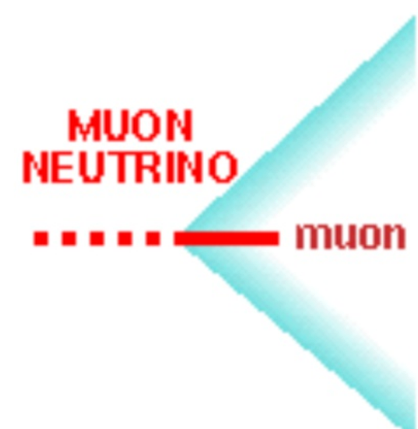


μ-like

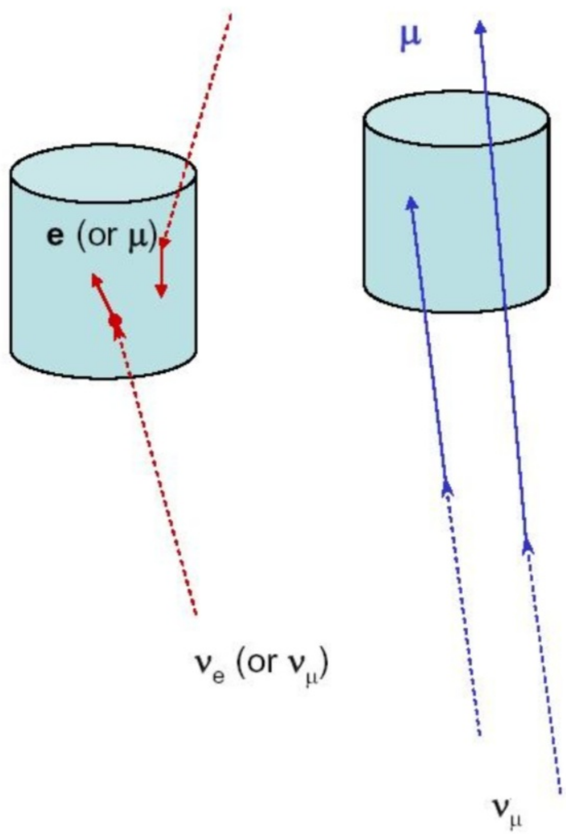

Super-Kamiokande
e-like
~620 MeV/c
Times (ns)

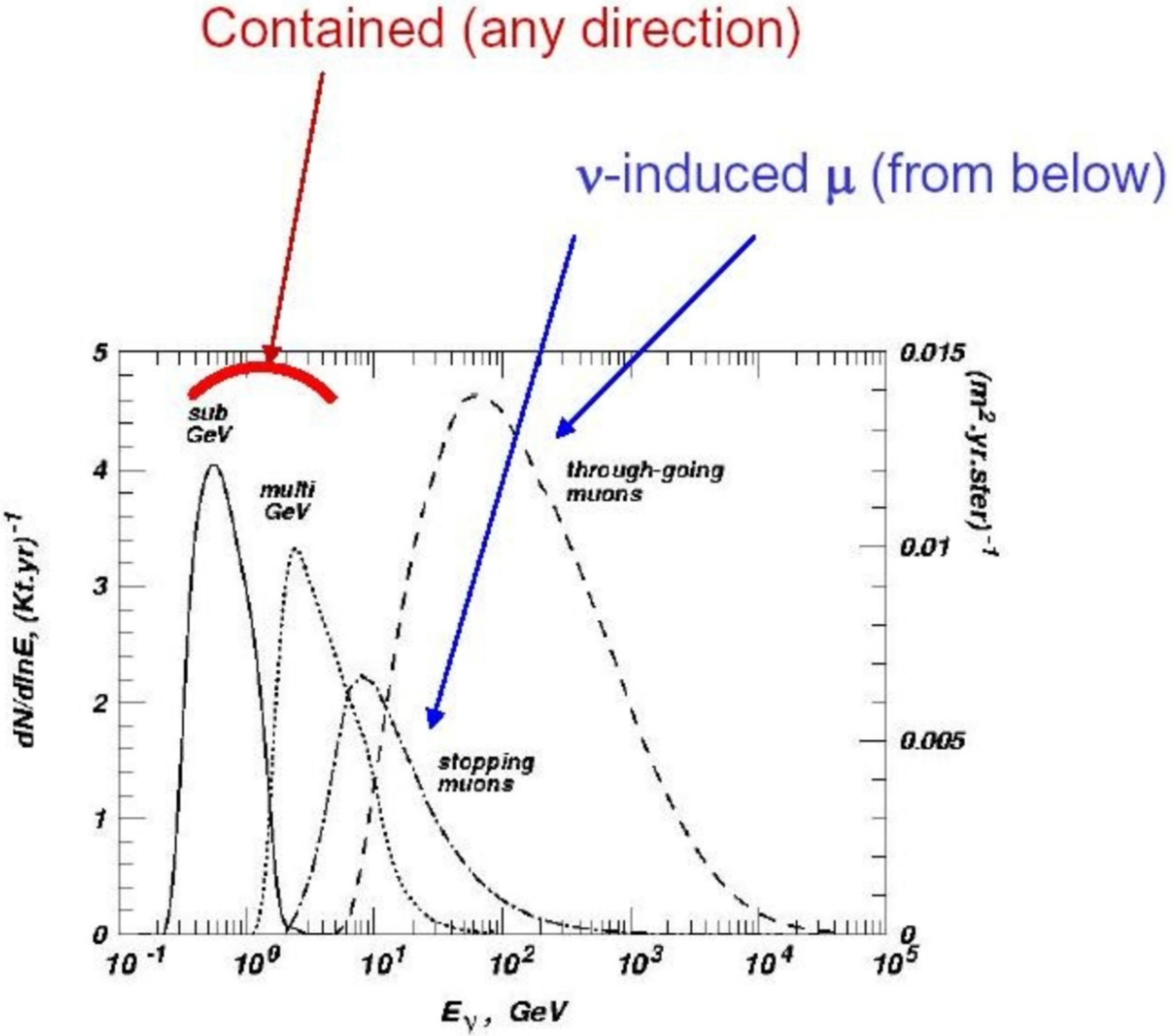

ELECTRON NEUTRINO
electron shower


Super-Kamiokande
μ-like
~760 MeV/c
decay electron
Times (ns)


MUON NEUTRINO
muon

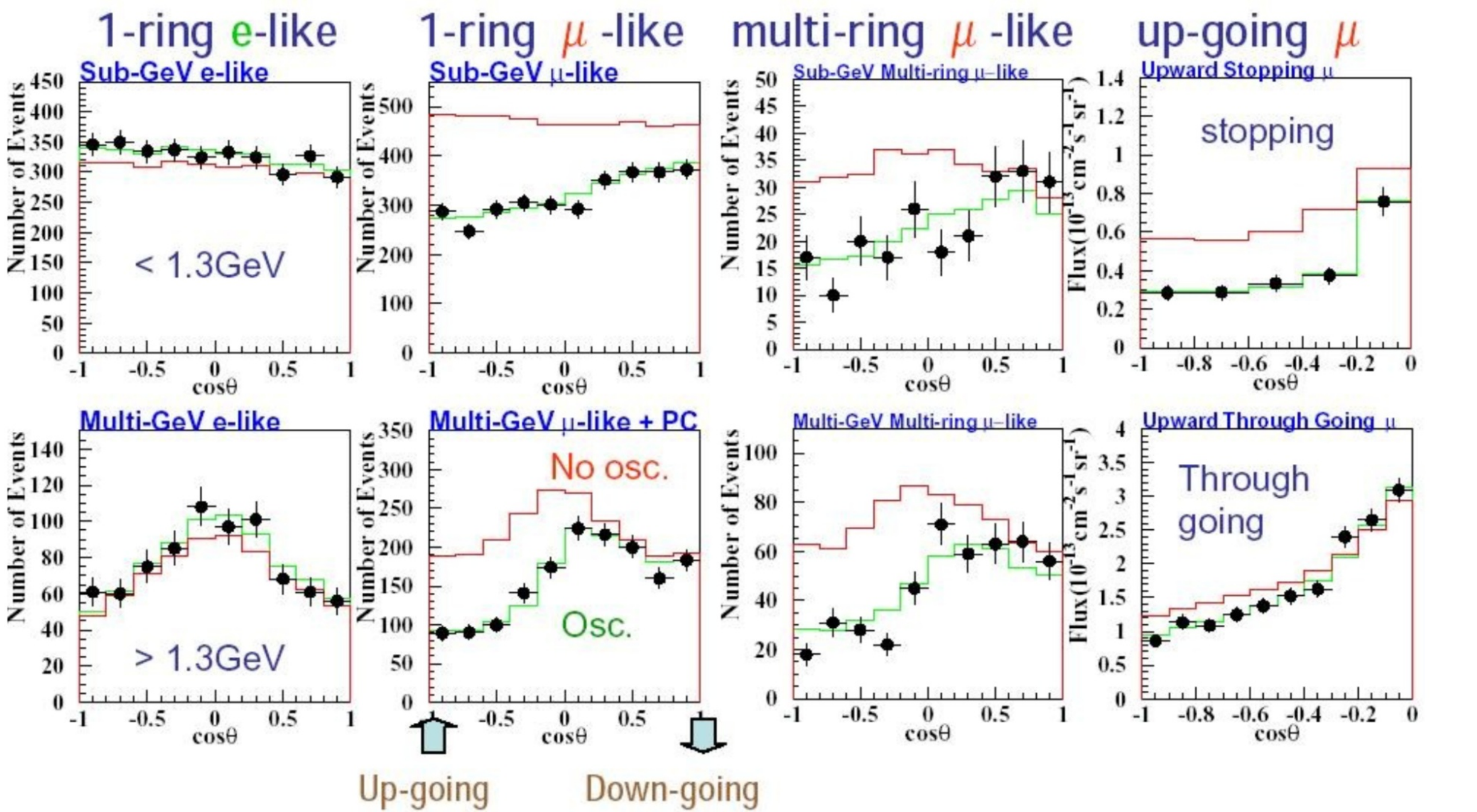
Neutrino Event Classes



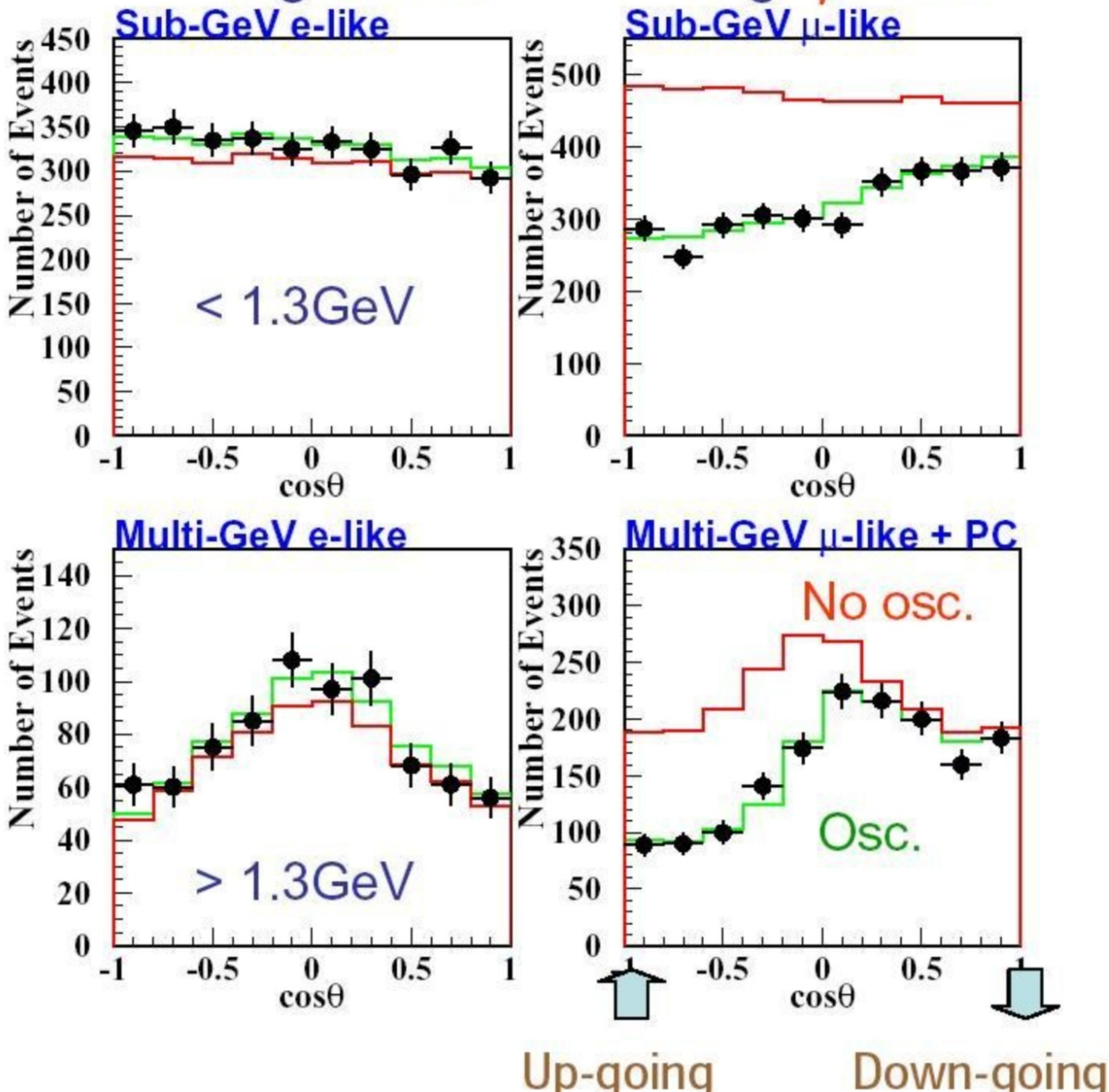


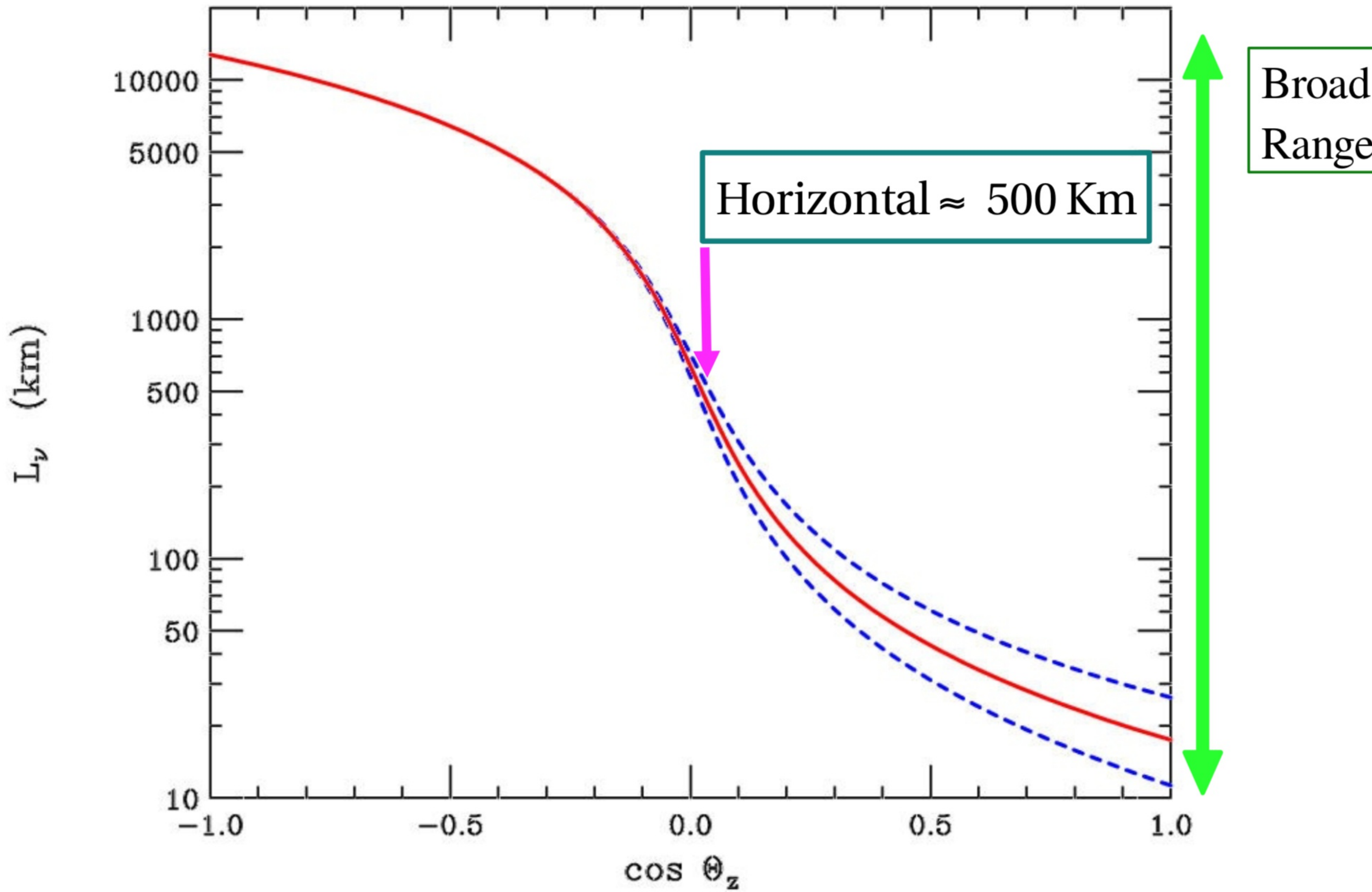
Super-Kamiokande data

1489day FC+PC data + 1678day upward going muon data



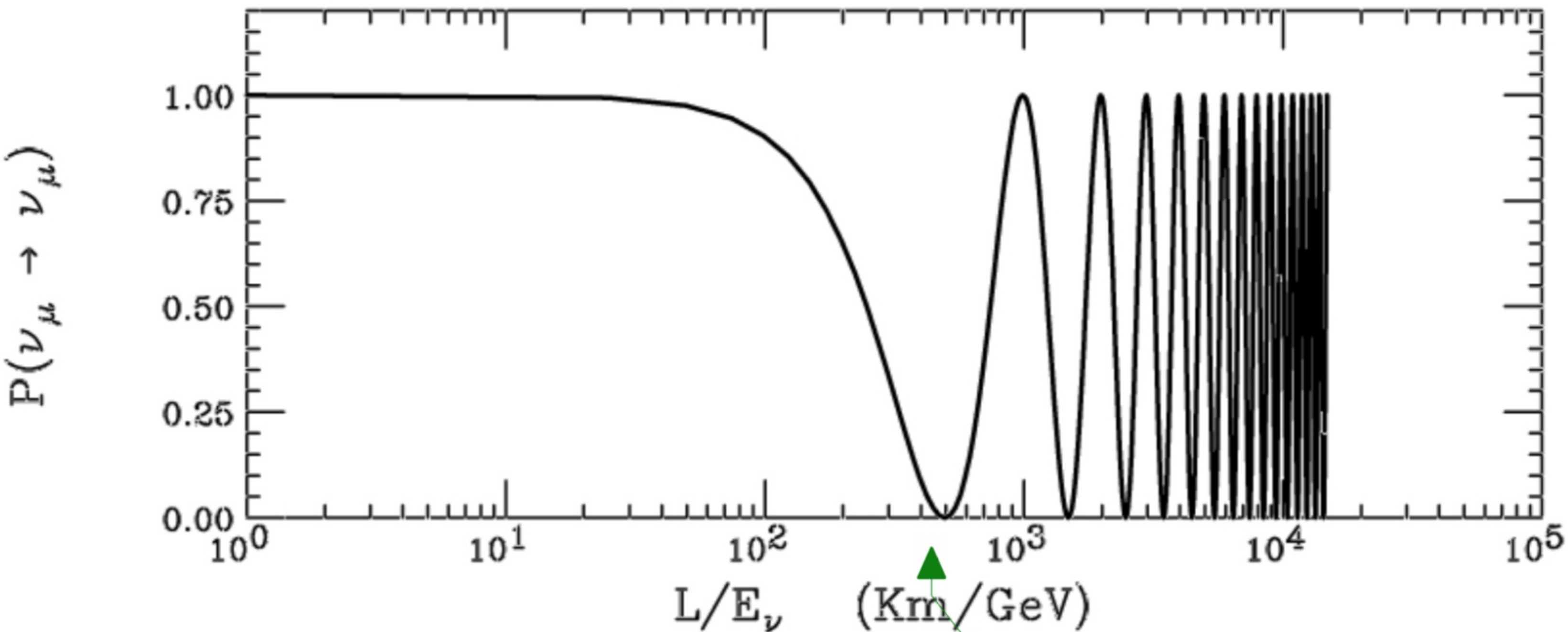
1-ring e-like   1-ring μ-like





10000
5000
1000
500
100
50
10
−1.0
−0.5
0.0
0.5
1.0
cos Θz
Lν (km)
Horizontal ≈ 500 Km
Broad Range

$$P_{\nu_\mu \to \nu_\mu}(L, E_\nu) = 1 - \sin^2 2\theta \ \sin^2 \left[\frac{\Delta m^2 \, L}{4 E_\nu} \right]$$

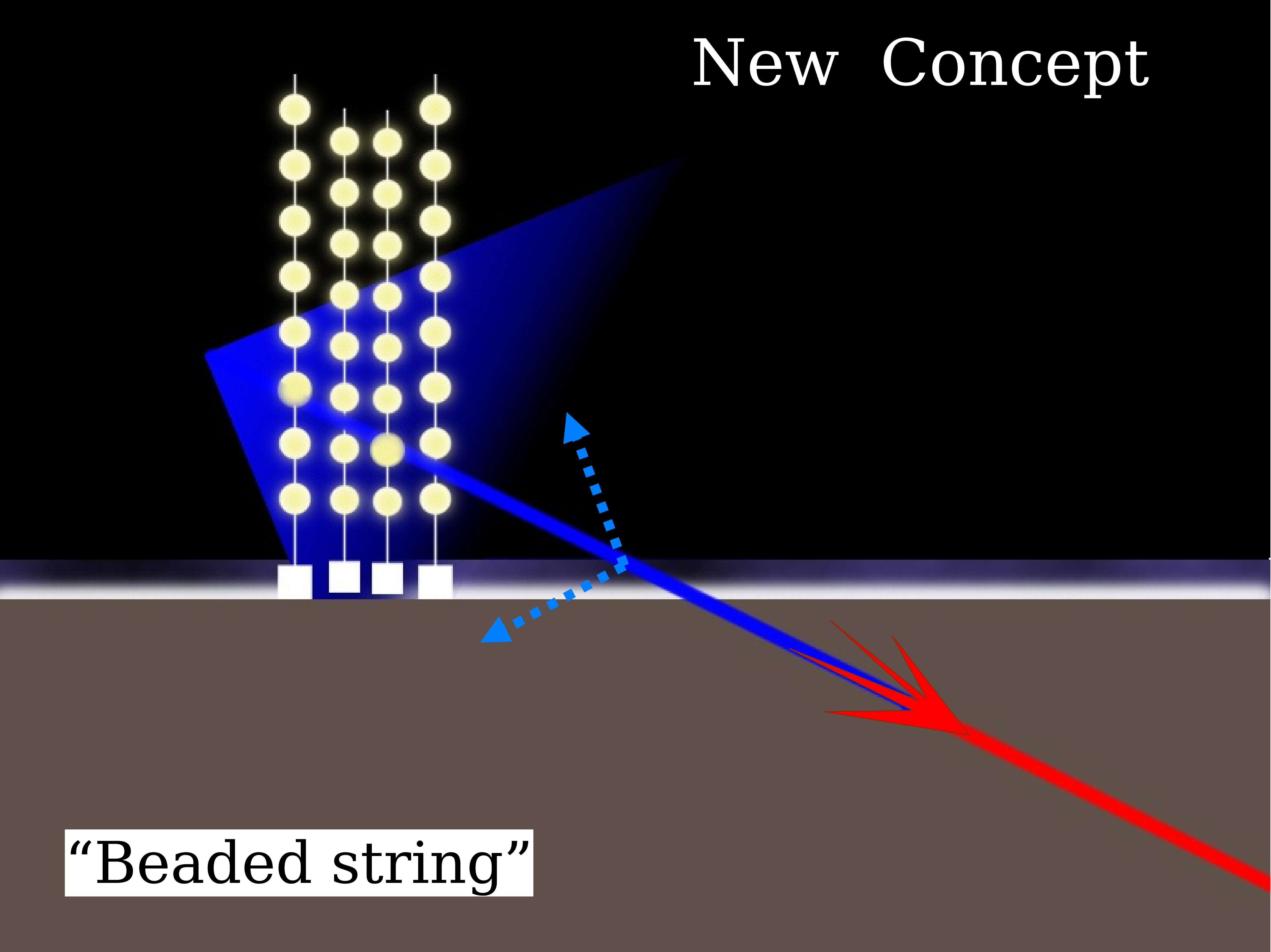


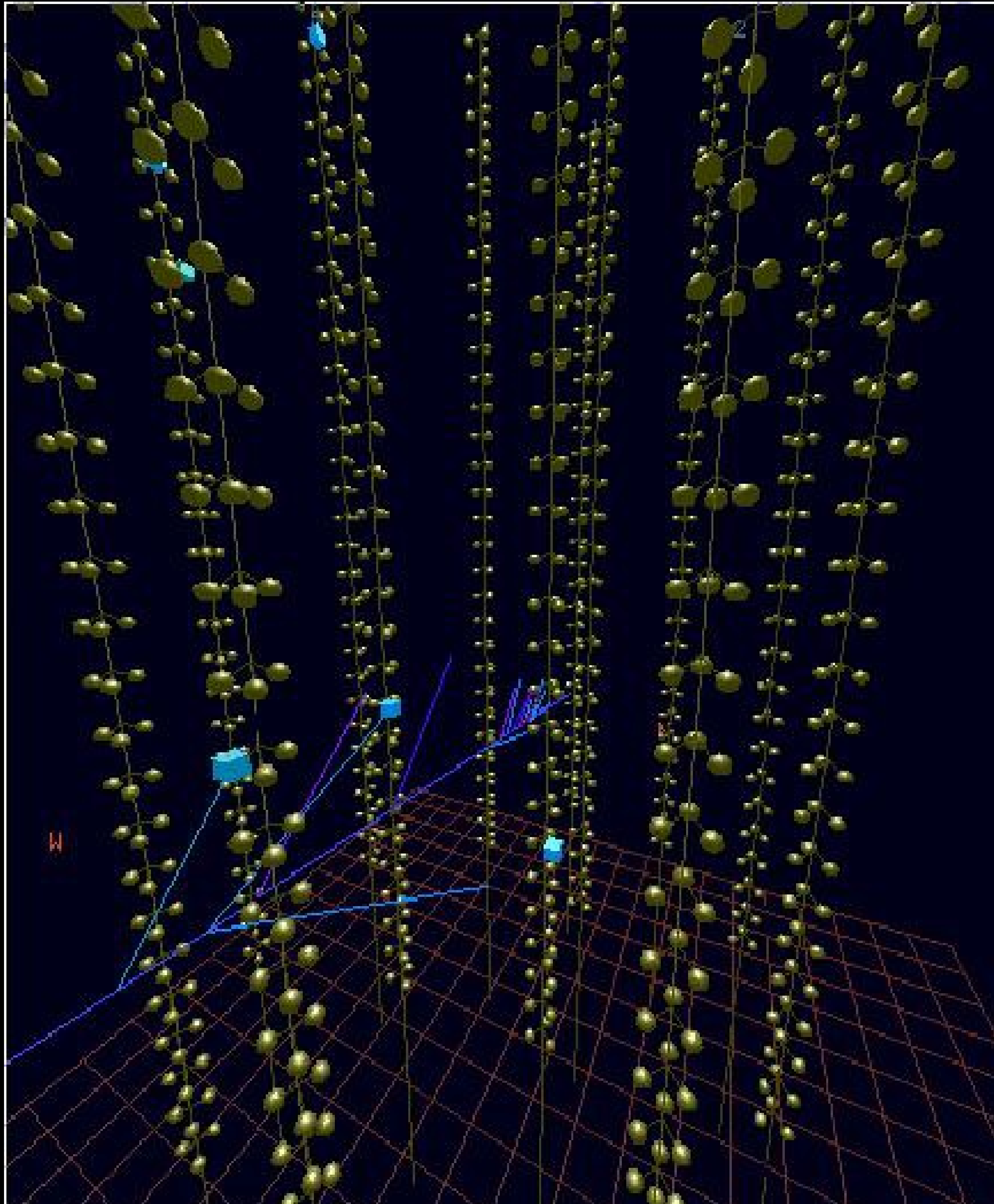
$$P_{\nu_\mu \to \nu_\mu} = \begin{cases} 1 & \text{for } L \text{ small,} \\ 1 - \frac{\sin^2 2\theta}{2} & \text{for } L \text{ large.} \end{cases}$$

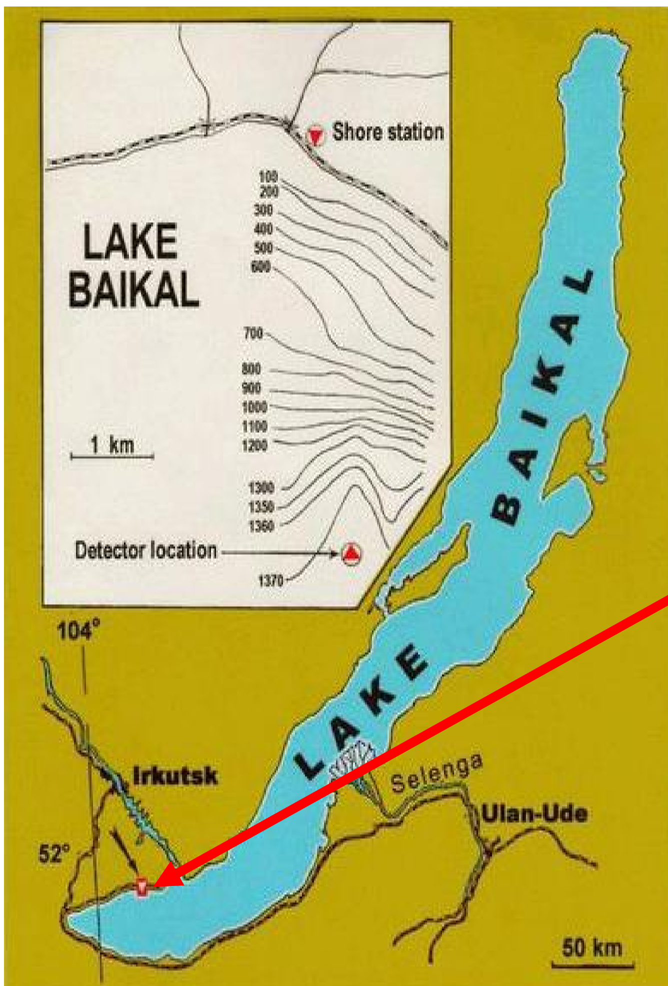
$$\simeq \frac{\lambda^*_{\text{osc}}}{2} \simeq \frac{2\pi \, \langle E_\nu \rangle}{|\Delta m^2|}$$

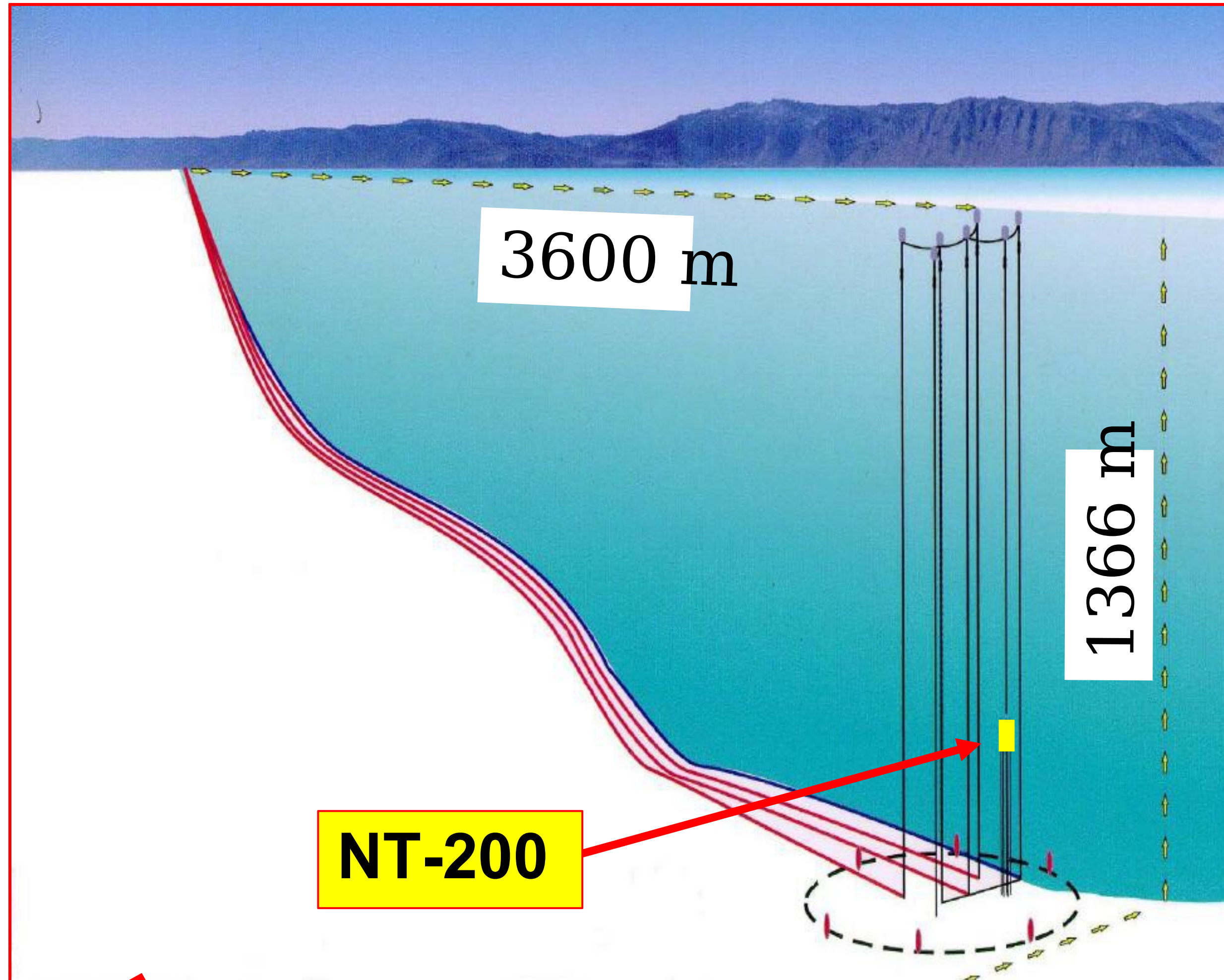
HIGH ENERGY NEUTRINO DETECTION

The Km3 concept


New Concept
“Beaded string”

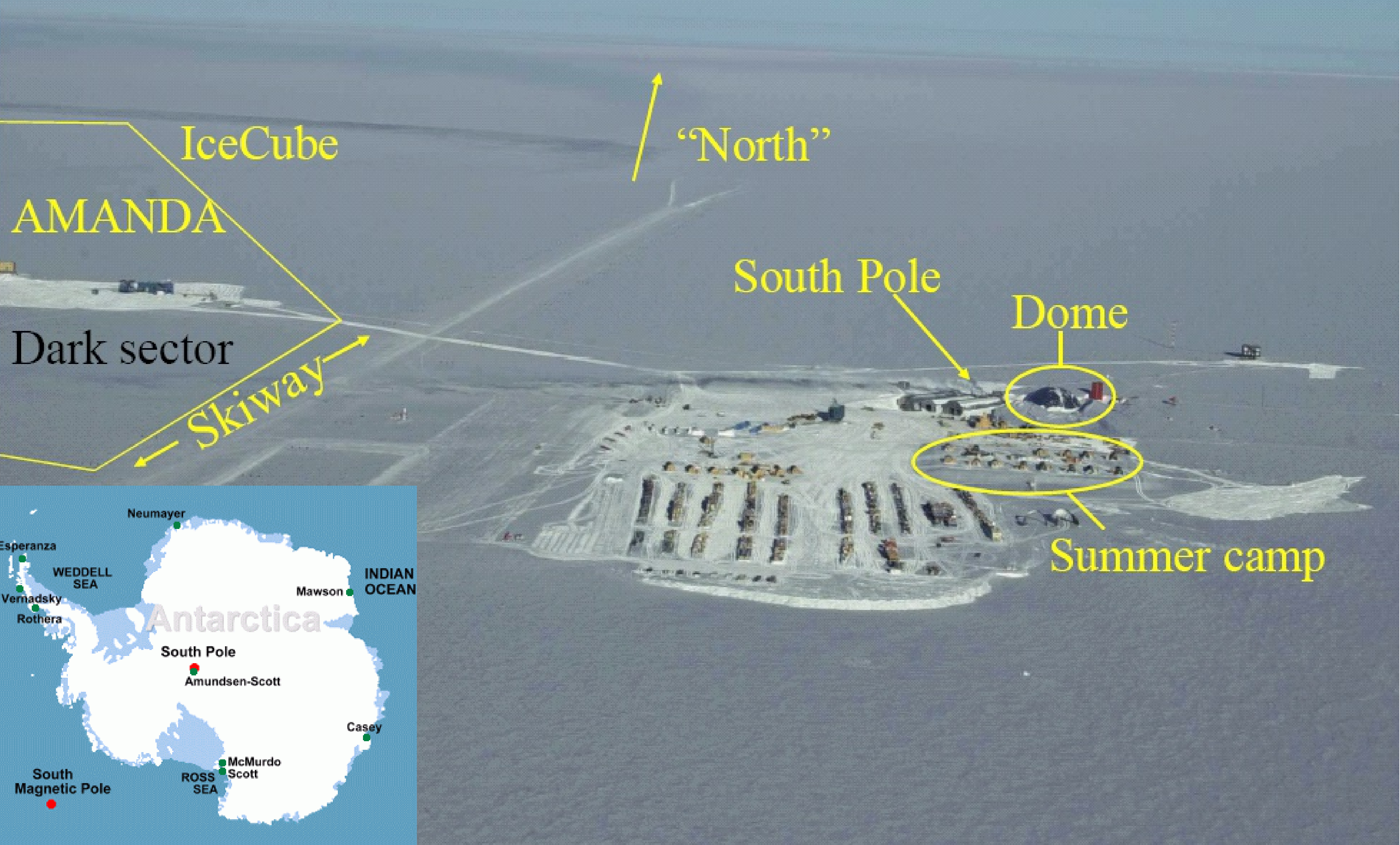

W

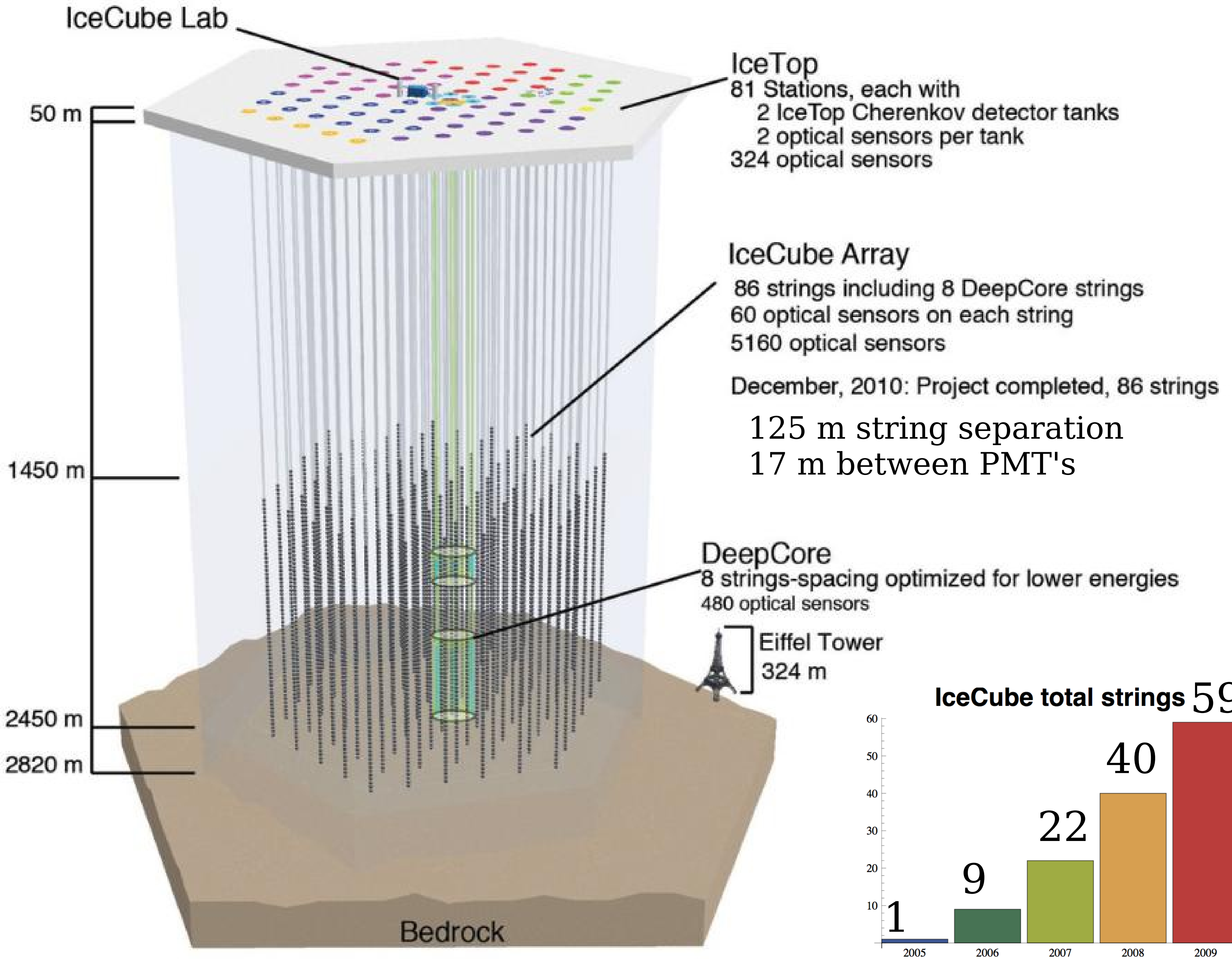




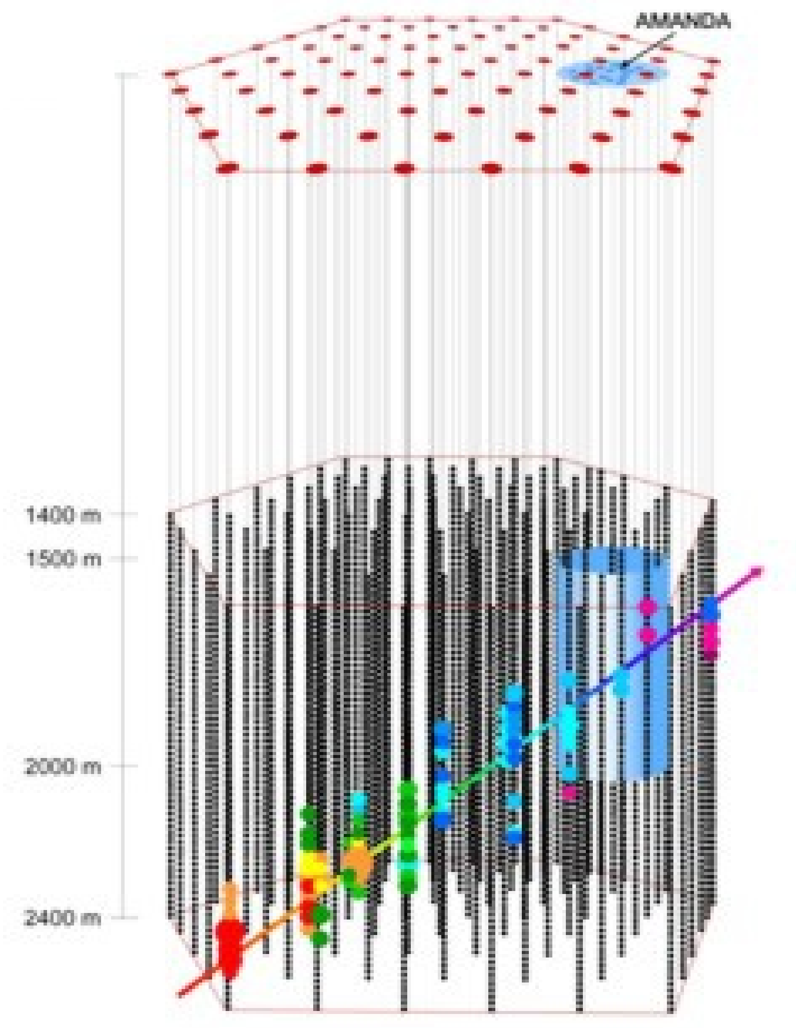
- 4 cables x 4km to shore.
- 1070m depth

Amundsen-Scott South Pole station




IceCube Lab
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
125 m string separation
17 m between PMT's
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock
IceCube total strings
1
9
22
40
59
2005
2006
2007
2008
2009
10
20
30
40
50
60

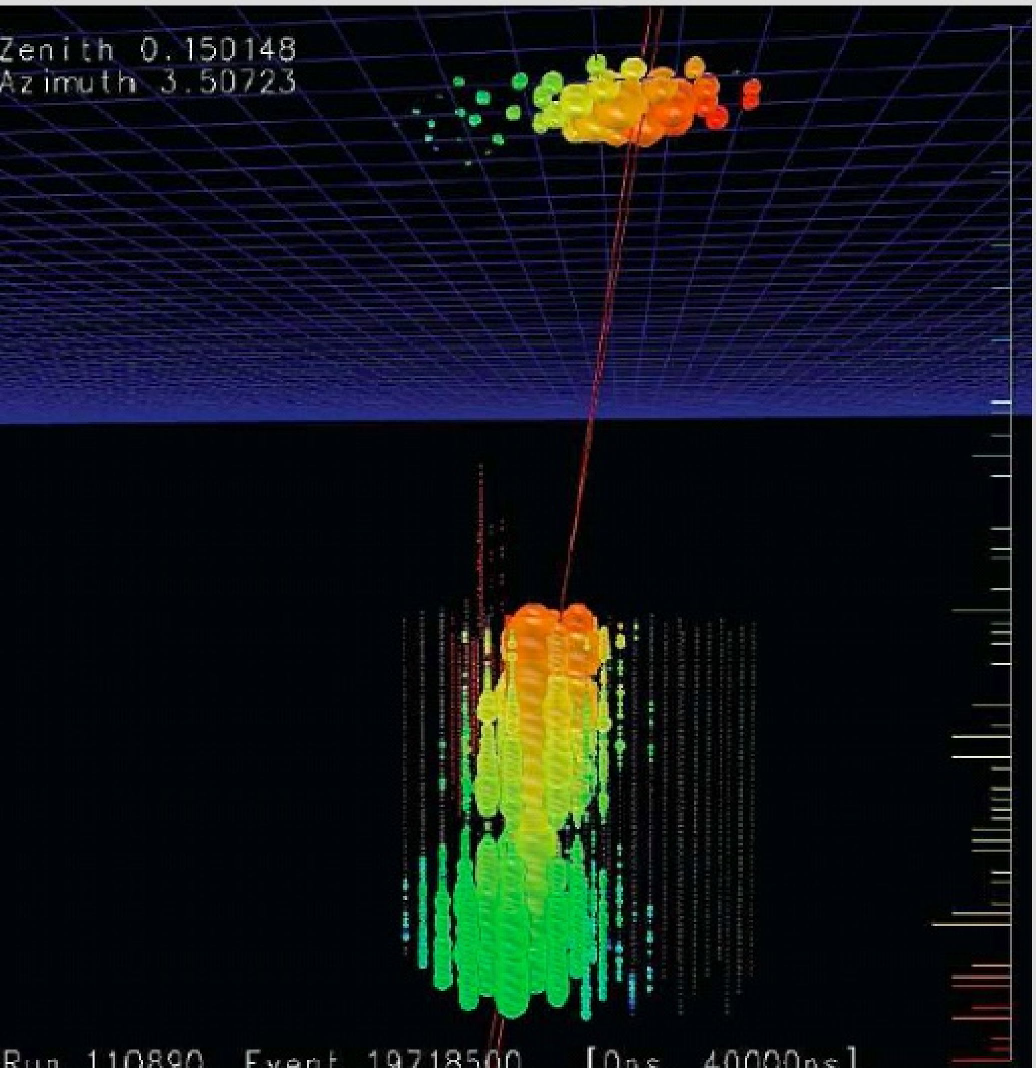
Deployment of the strings

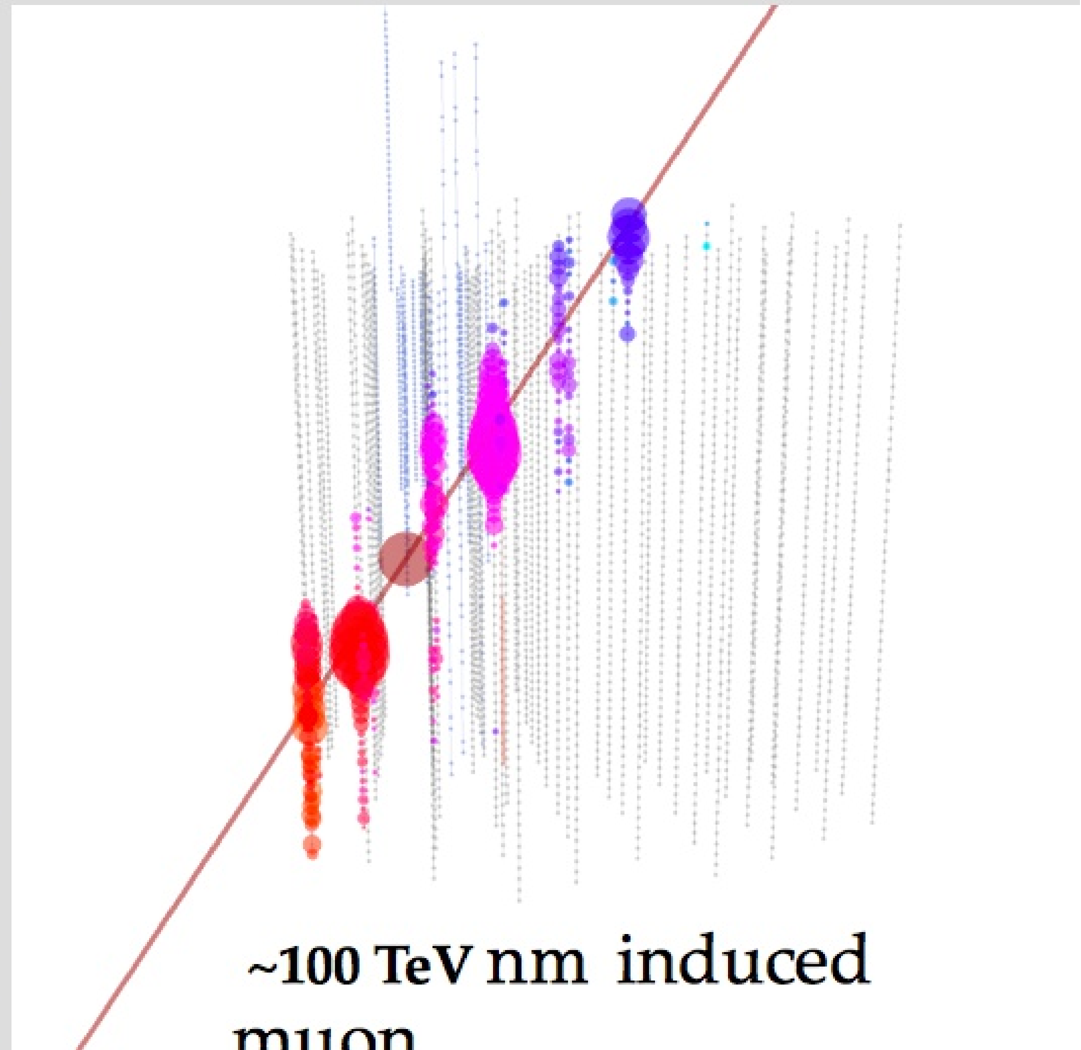



ANTARES
Running since 2007
885 10” PMTs
12 lines
25 storeys/line
3 PMTs / storey
2500 m deep
~0.01 km^3
450 m
40 km to shore
Junction Box
70 m
Interlink cables
© François Montanet
Nantes
France
Switzerland
Zurich
Liechtenstein
Geneva
Lyon
Milan
Venice
Turin
Genoa
Bologna
Toulouse
Montpellier
Marseille
Monaco
San Marino
Italy
Bilbao
Andorra
Barcelona
Madrid
Spain
Valencia
Palma
Murcia
Malaga
Algiers
Tunis
Fes
Google
ANTARES

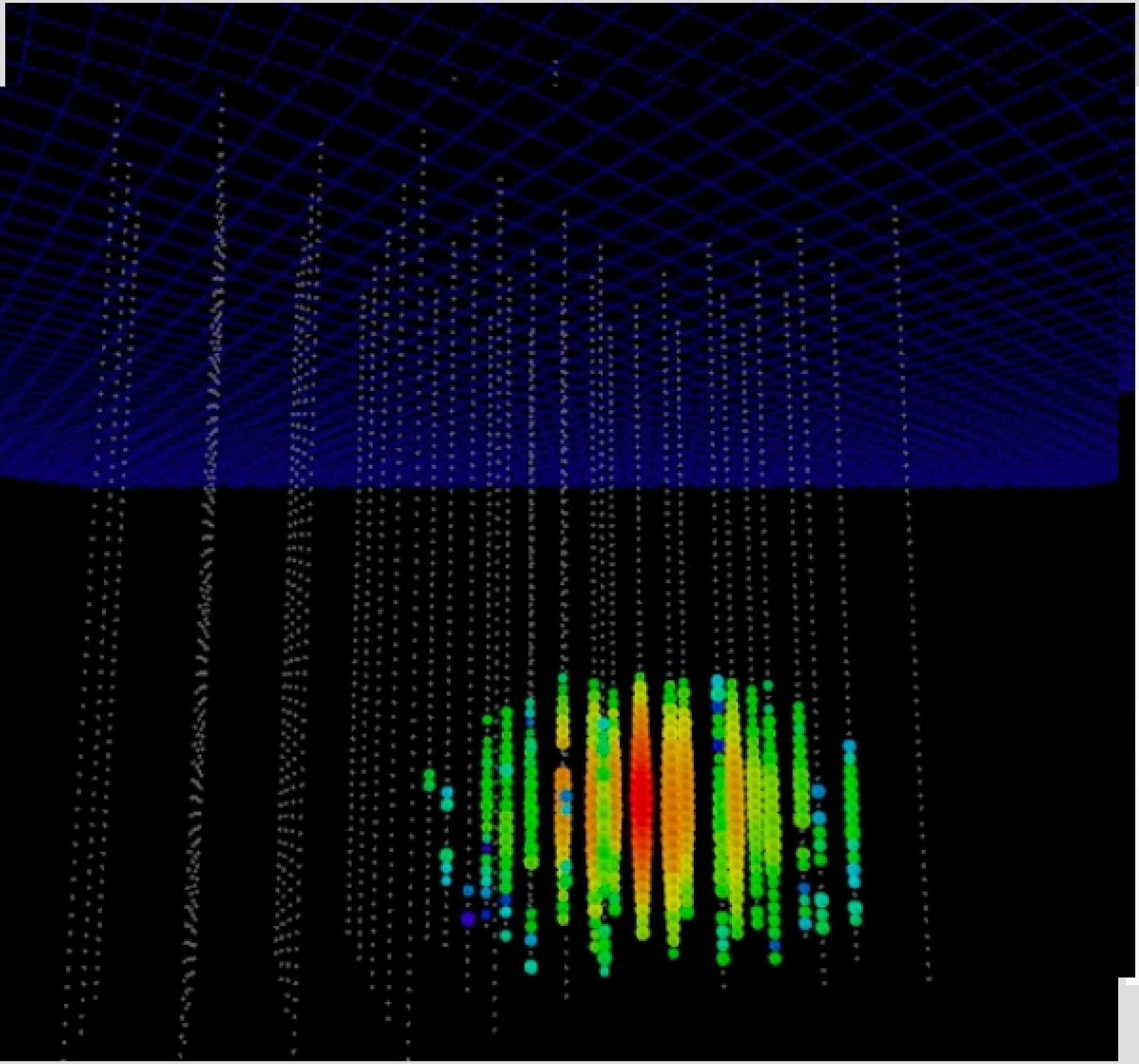
High-energy events in IceCube-40

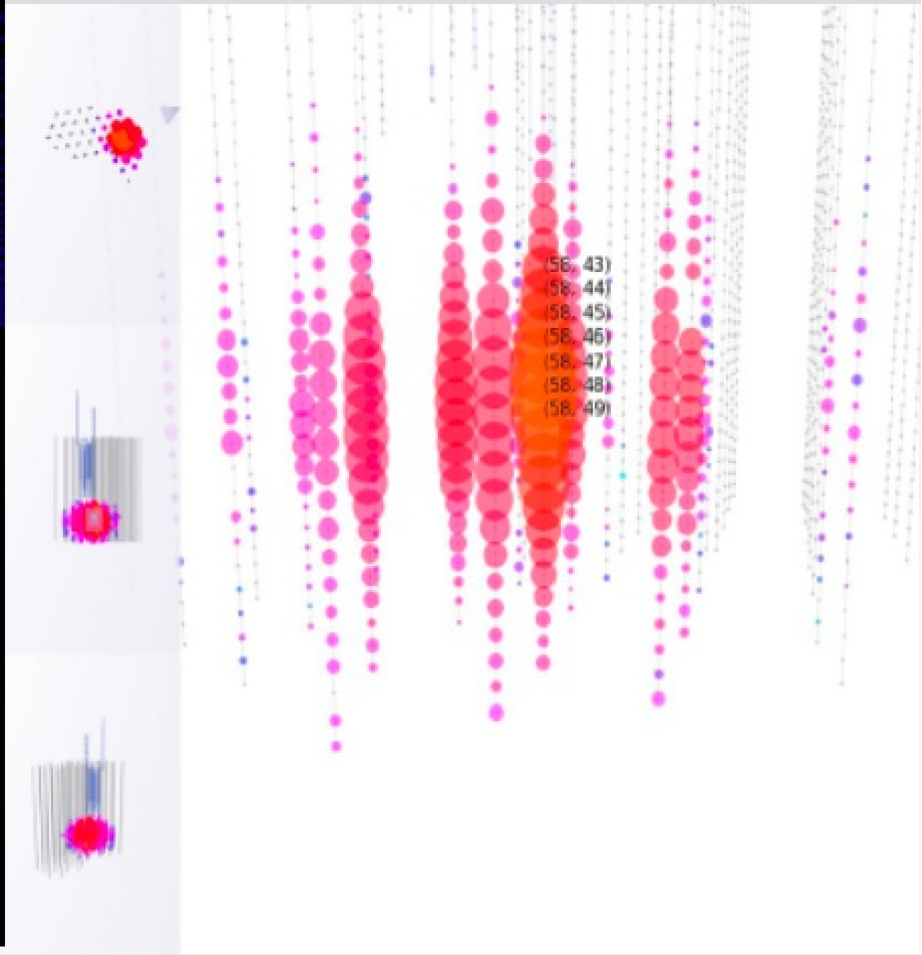
~ EeV air shower



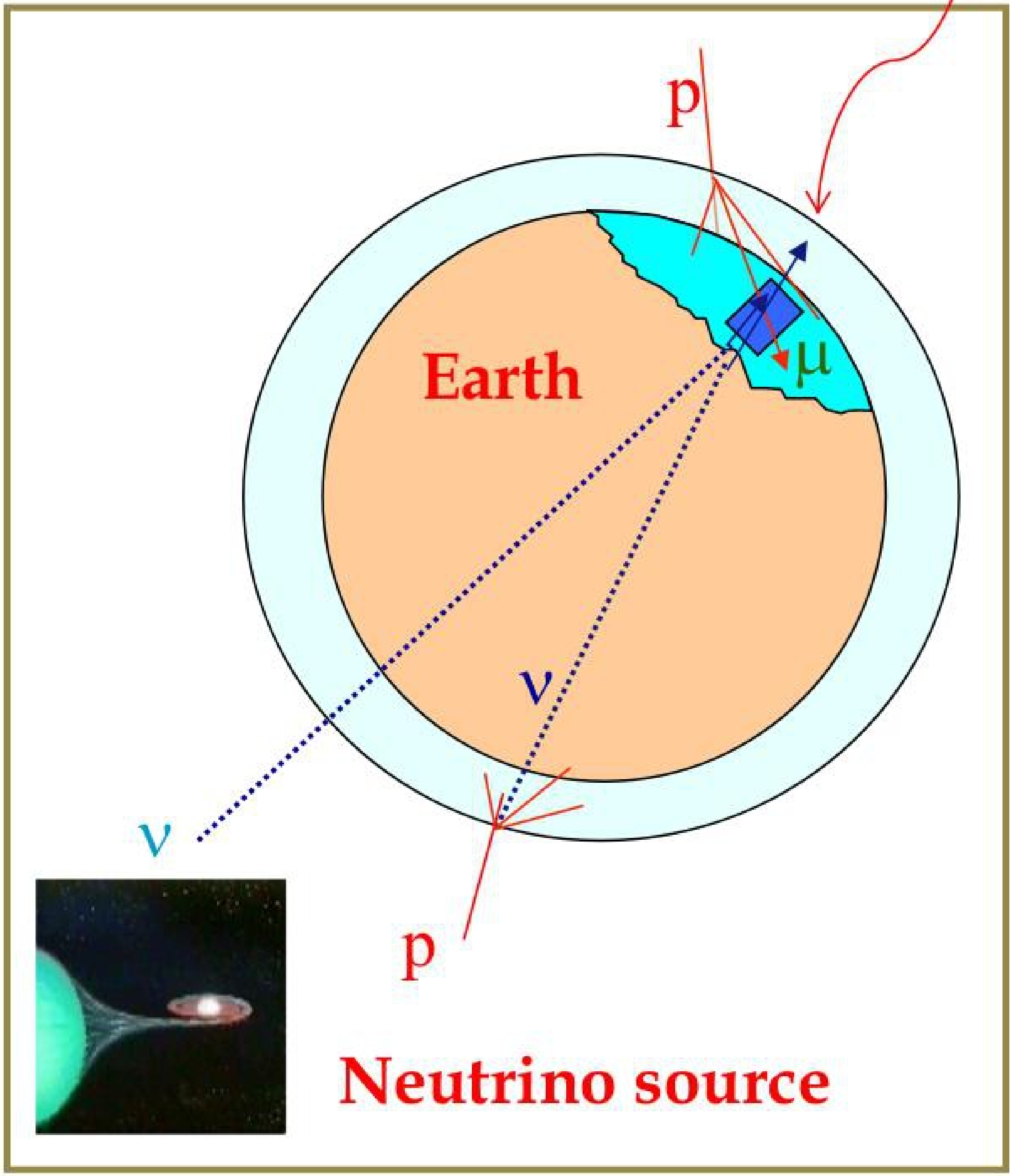


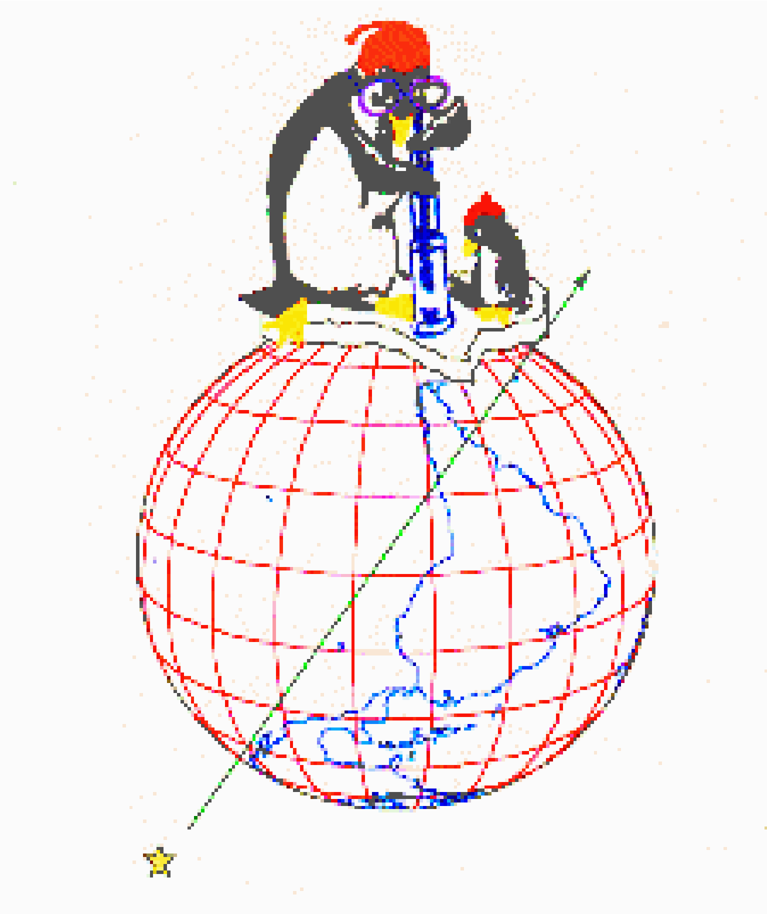
More events





A cascade event, candidate for a high energy **ne** ~50 TeV

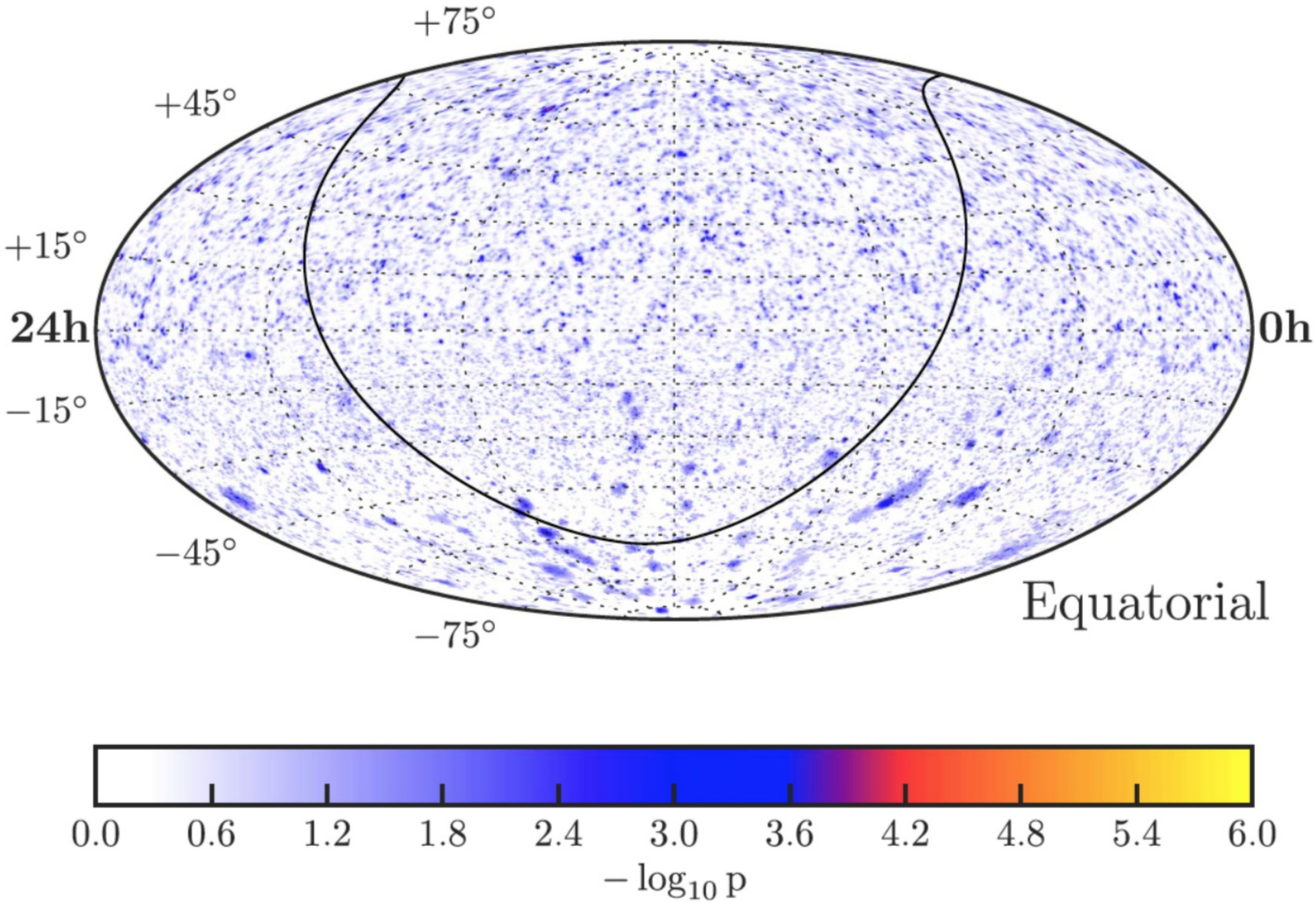




Observation of
neutrino-induced muons

(see ½ of the sky)

IceCube - Point Sources – 7 years



No significant PS reported

No correlation with list of 74 sources in both hemispheres. Galactic & Extragalactic

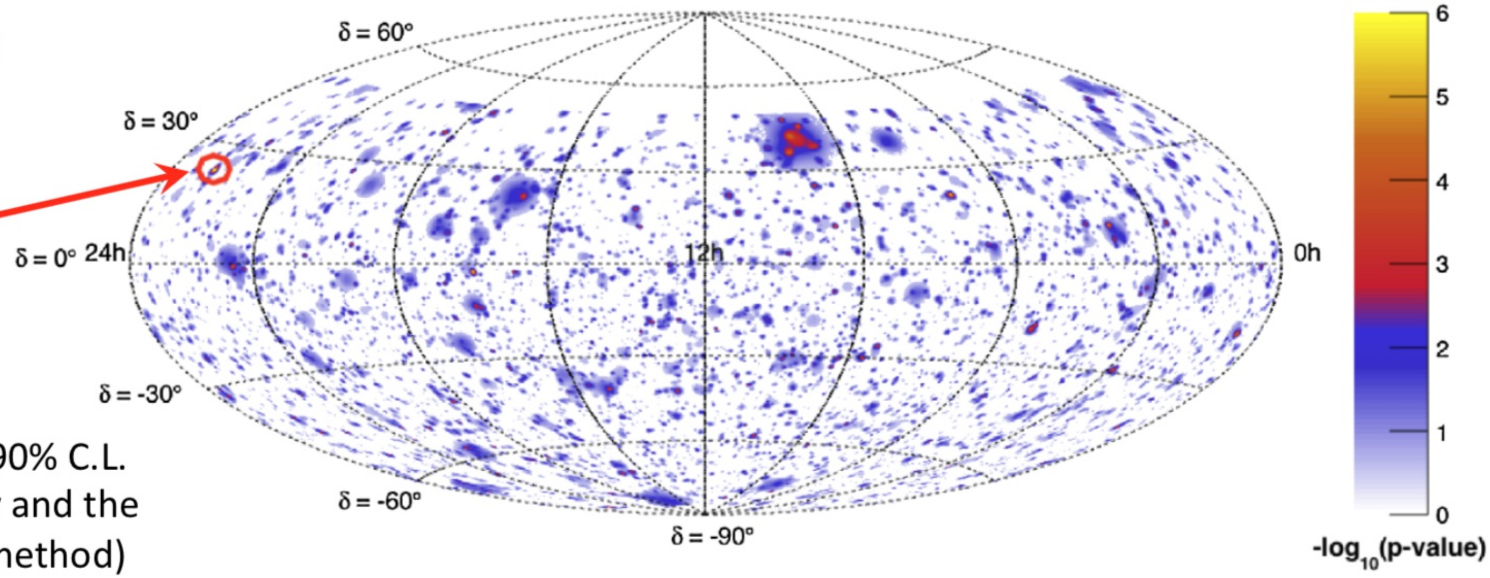
Most recent data periods:
~80k nothern hemisephere evt/yr (atm ν)
~35k southern hemisepher evt/yr (atm μ)
~200 starting tracks. Southern sky

ApJ 835 (2017) 151

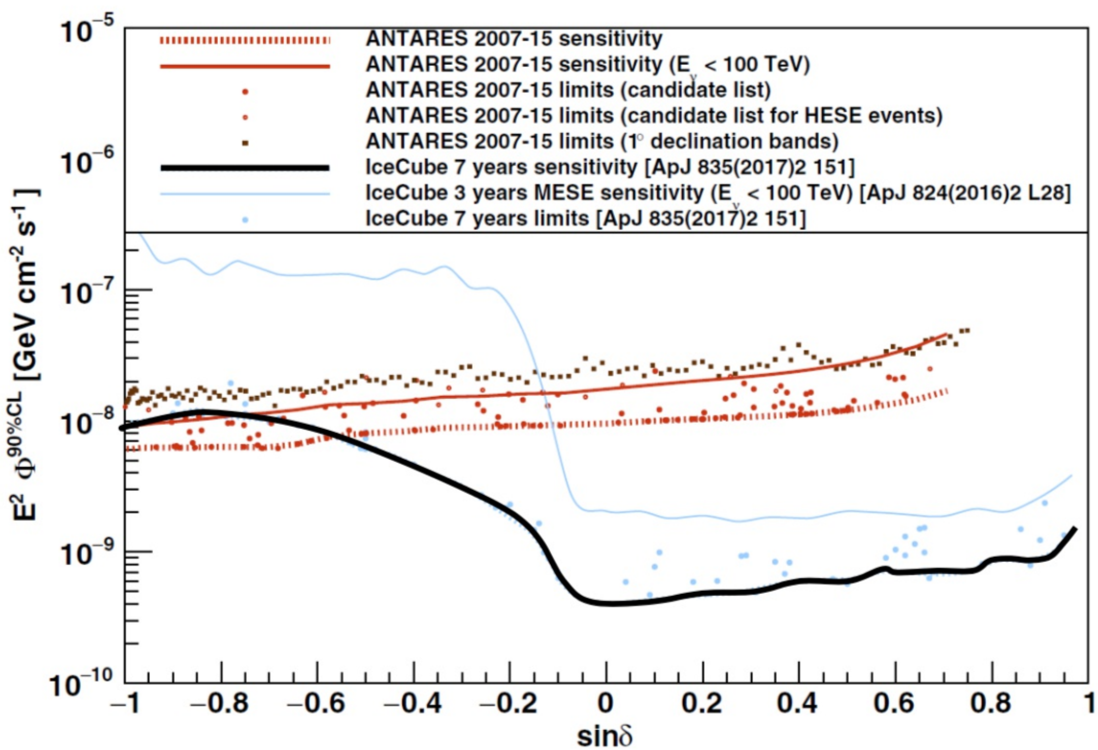
ANTARES – Point Sources

Most significant cluster c
the full-sky search (1.9σ
post-trial significance)
$\alpha = 343.8°$ $\delta = 23.5°$

Sky map in equatorial coordinates of pre-trial p-values



Sensitivities and upper limits at a 90% C.L. on the signal flux from the Full-sky and the Candidate list searches (Neyman method)



Phys. Rev. D96 (2017), 082001

ANTARES is the most sensitive instrument for a large fraction of the southern sky below 100 TeV

IceCube is the most sensitive instrument in the northern sky and a fraction of the southern sky

New class of events where the
Neutrino interacts inside
the detector Fiducial Volume

“High Energy Starting Events"

HESE

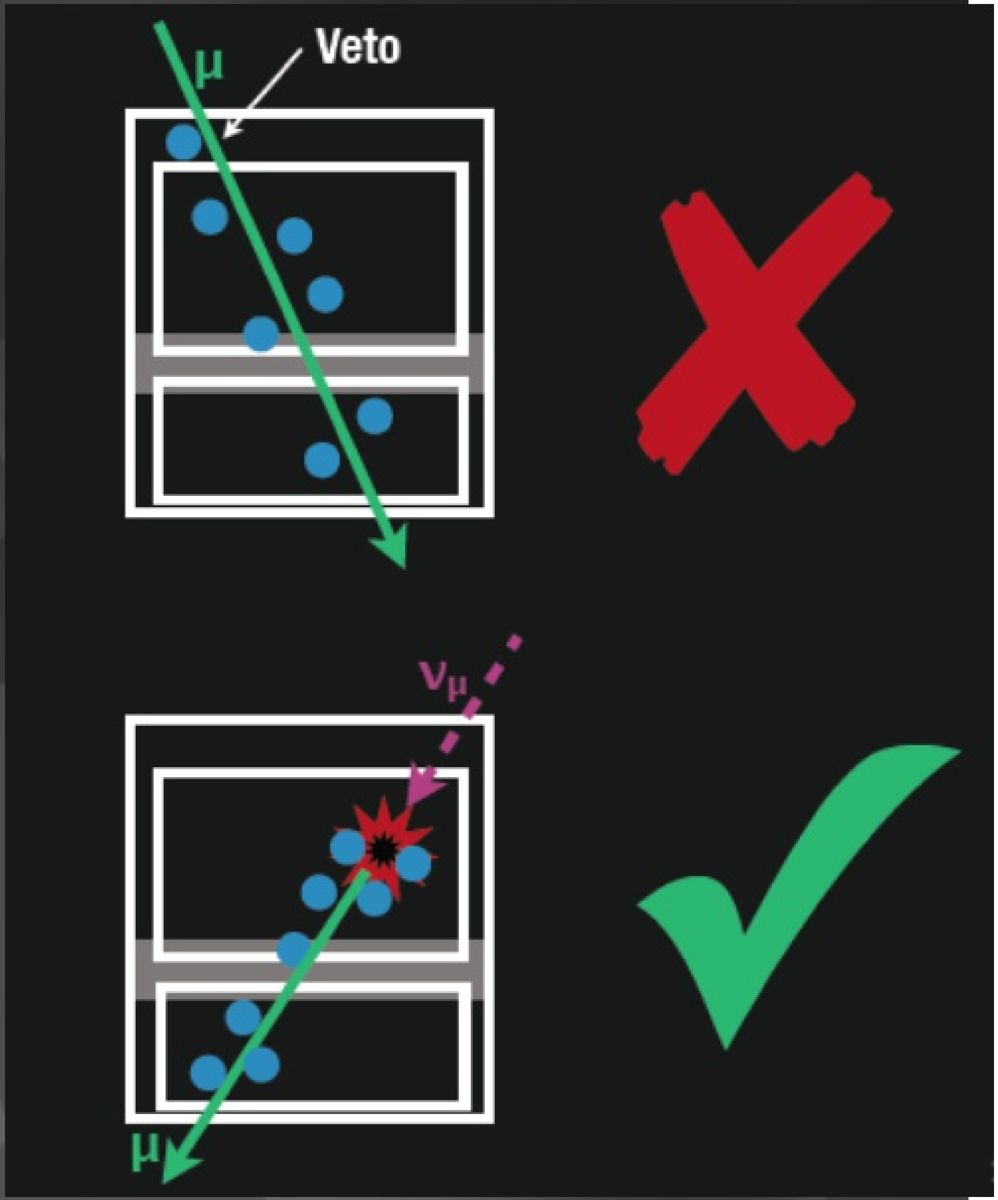
Outer Layer of the detector is used as a veto

No PMT us have a hit in the veto
With an “early time”

[charged particles can exit the detector, but not enter]

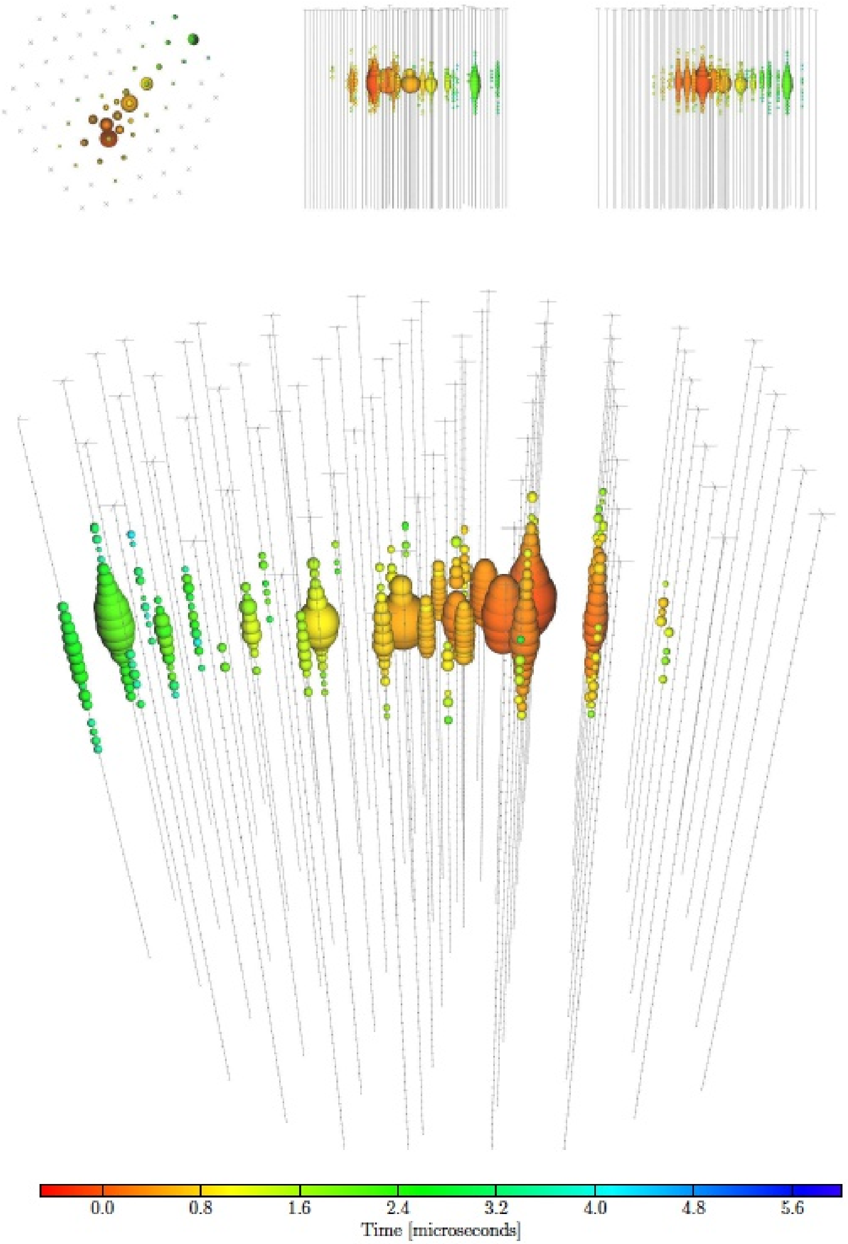
Starting events

- total calorimetry
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution



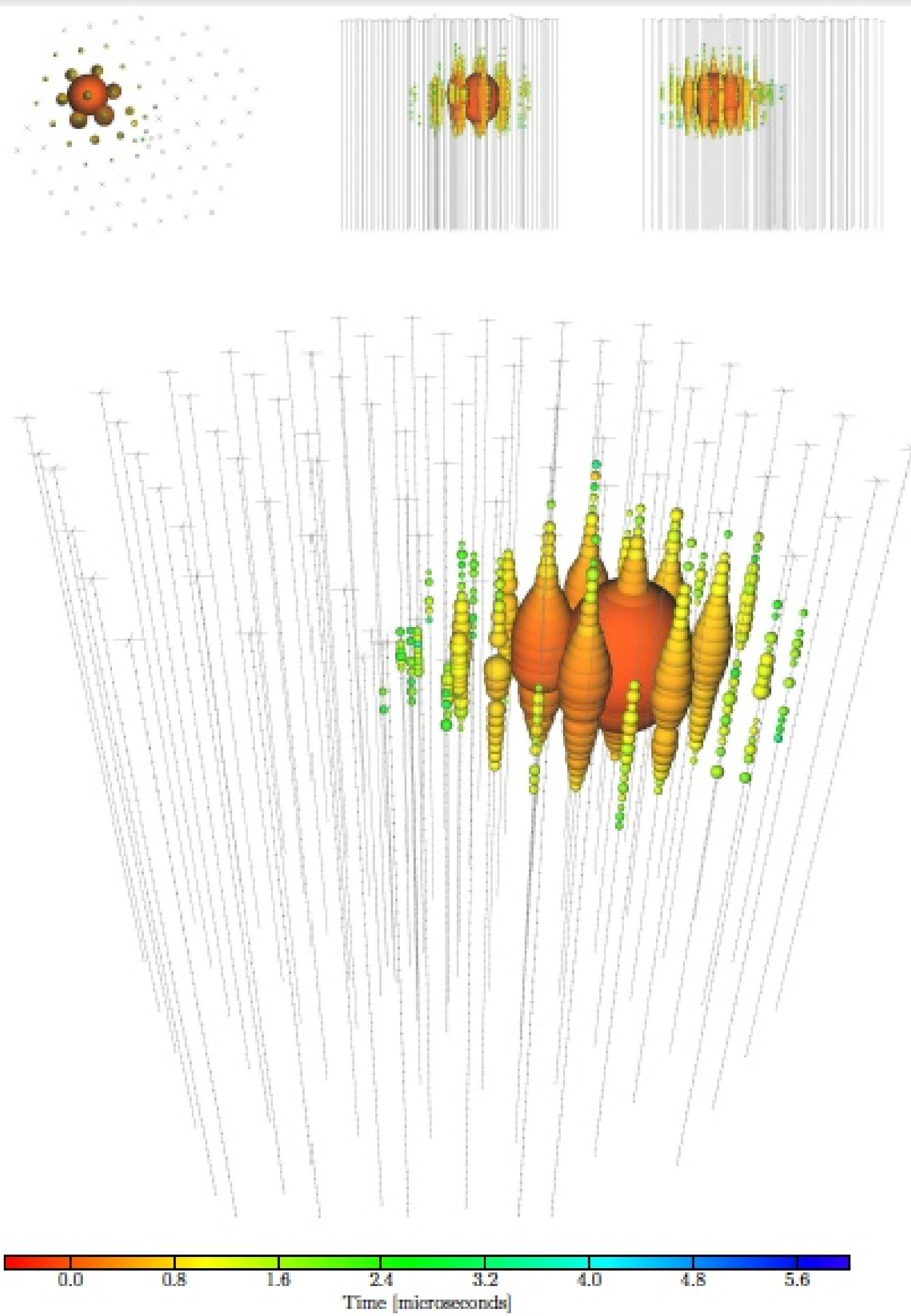
loss in statistics is compensated by event definition

“TRACK”



Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$71.4^{+9.0}_{-9.0}$	55512.5516214	-0.4	110.6	$\lesssim 1.2$	Track

“Shower”



Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$1040.7^{+131.6}_{-144.4}$	55782.5161816	-27.9	265.6	13.2	Shower

Two Classes of events

“Tracks"

$$\nu_\mu(\overline{\nu}_\mu) + N \to \mu^\mp + \text{hadrons}$$

"Showers"

$$\nu_e(\overline{\nu}_e) + N \to e^\mp + \text{hadrons}$$

$$\nu_\tau(\overline{\nu}_\tau) + N \to \tau^\mp + \text{hadrons}$$

$$\nu_\alpha(\overline{\nu}_\alpha) + N \to \nu_\alpha(\overline{\nu}_\alpha) + \text{hadrons}$$

Tau Neutrinos

$$\tau^- \to \nu_\tau + (\mu^- + \overline{\nu}_\mu)$$

$$\tau^- \to \nu_\tau + (e^- + \overline{\nu}_\mu)$$

$$\tau^- \to \nu_\tau + (q_d + \overline{q}_u)$$

Path-length of tau's before decay

$$\tau_\tau = 2.9 \times 10^{-13}$$

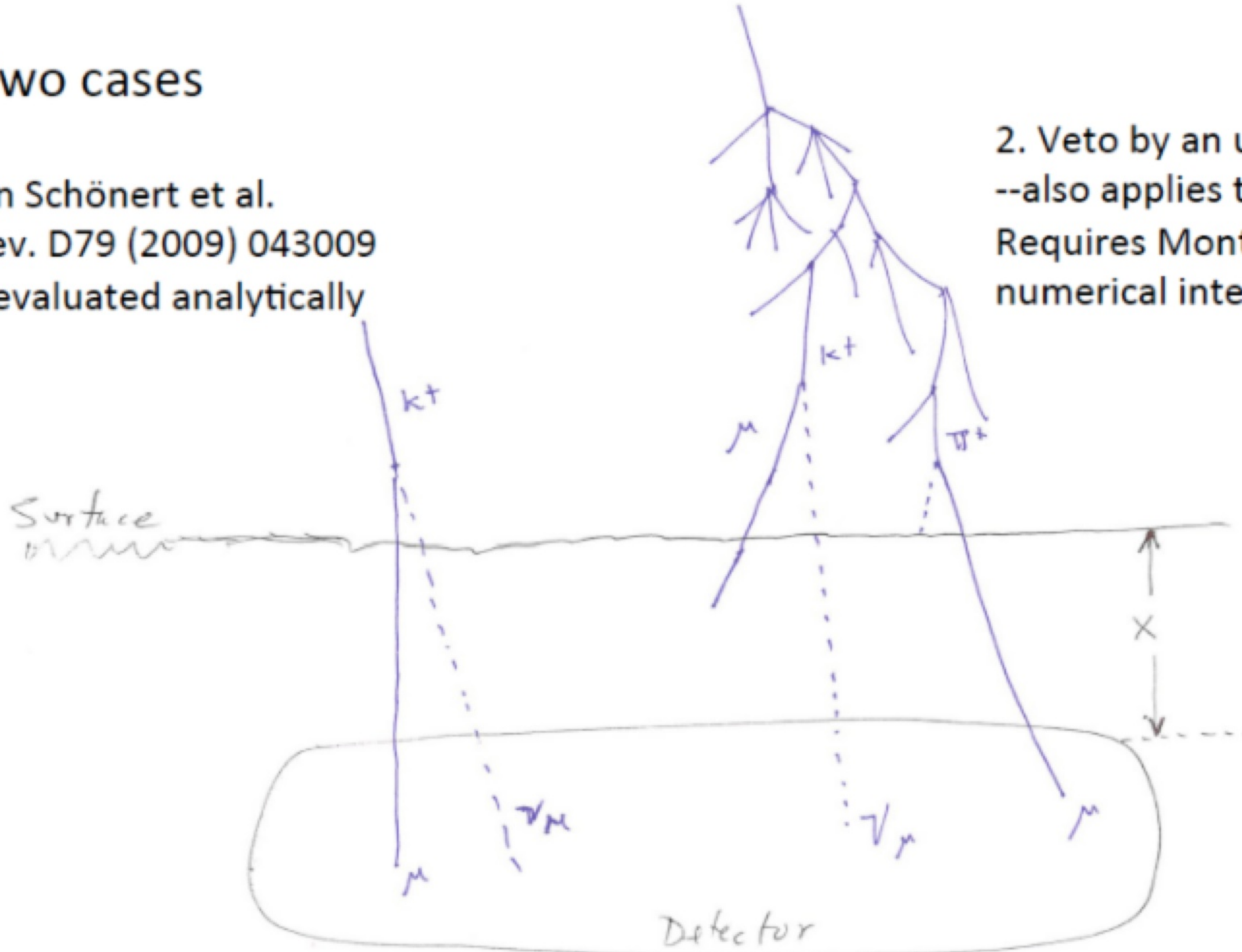
$$\ell_\tau = c\,\tau\,\frac{E}{m} \simeq 49 \text{ m } E_{PeV}$$

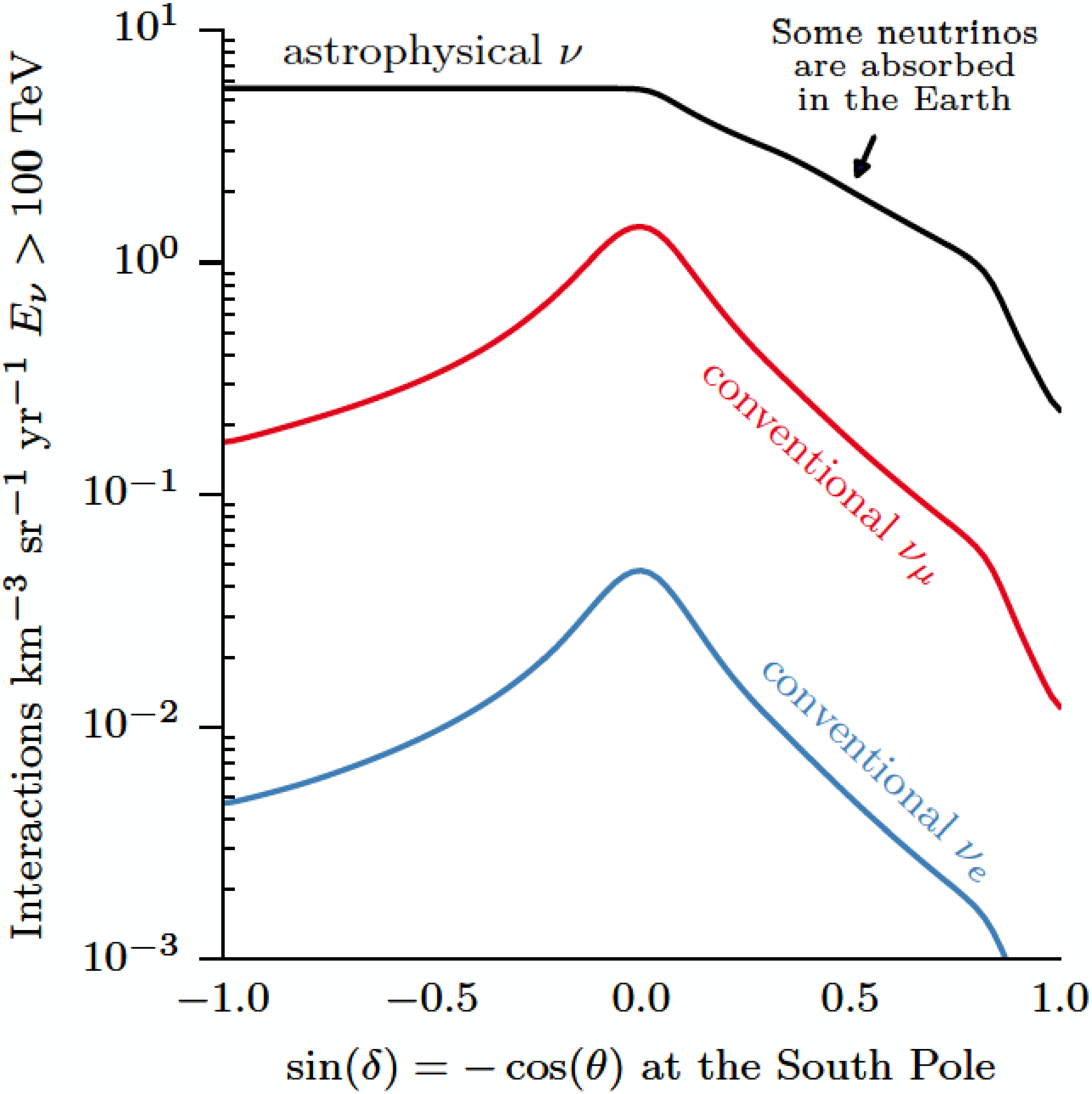
Atmospheric neutrino self veto

Two cases

1. Stefan Schönert et al.
Phys. Rev. D79 (2009) 043009
Can be evaluated analytically

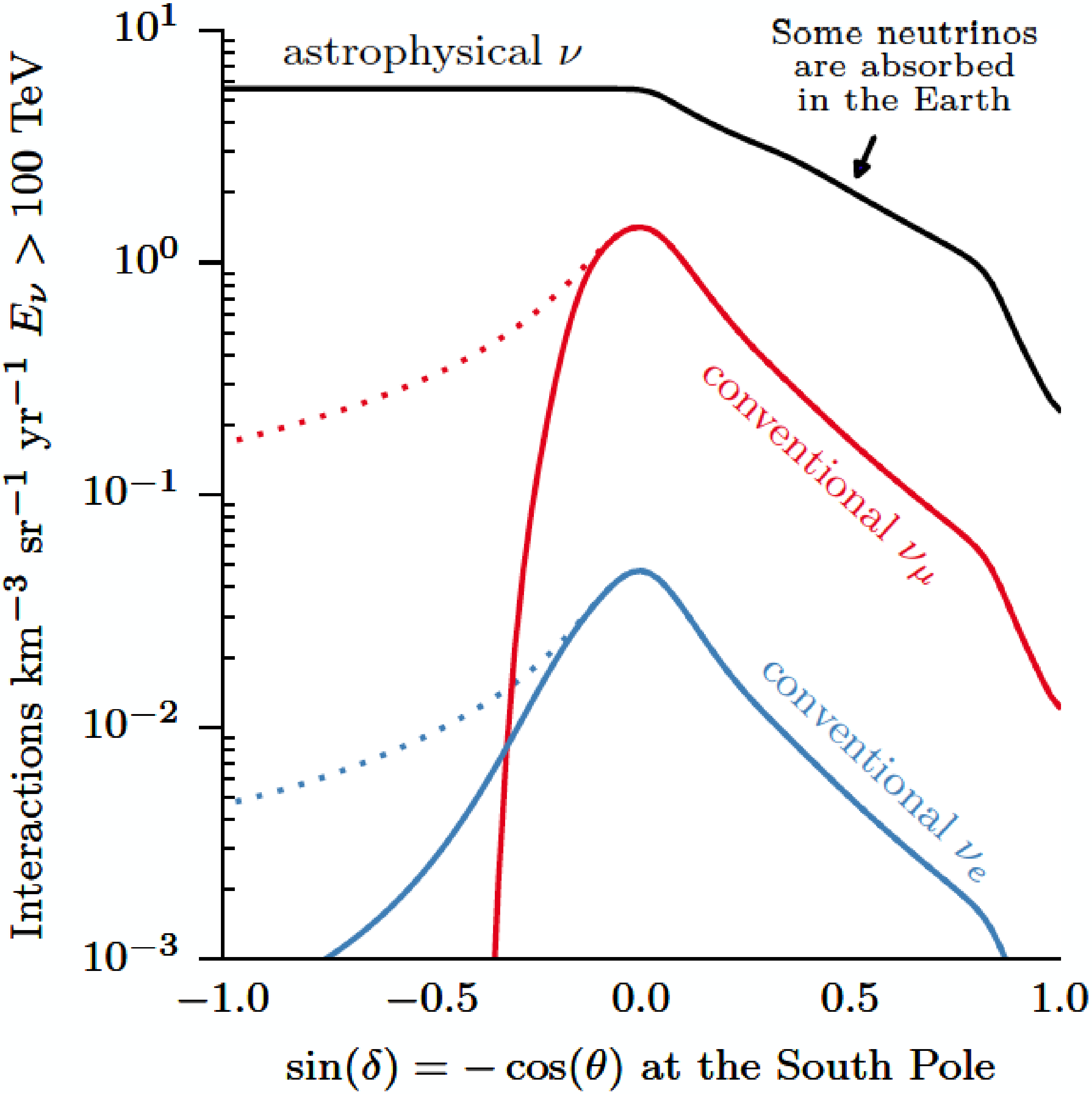
2. Veto by an unrelated μ
--also applies to ν_e
Requires Monte Carlo or numerical integration

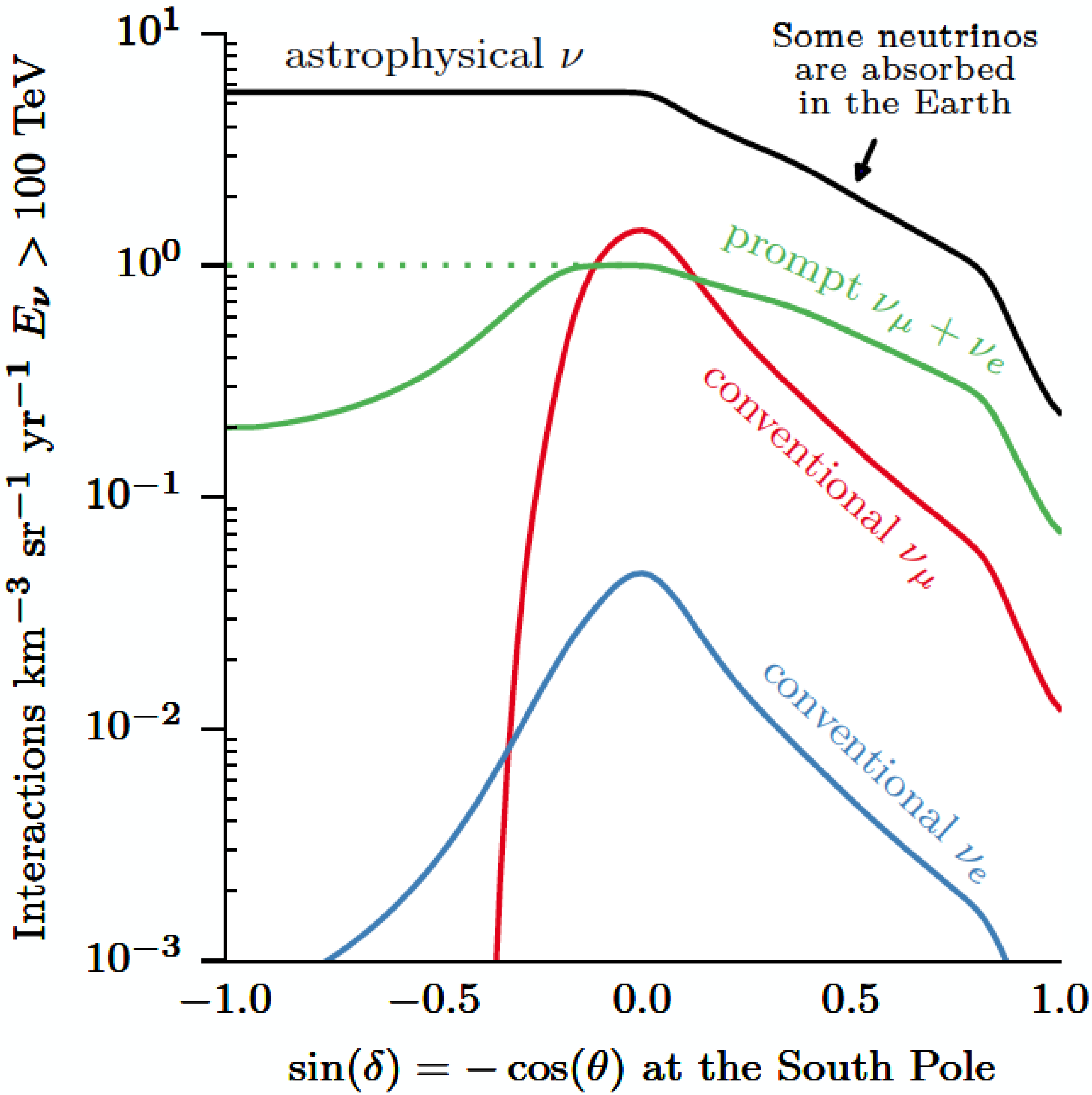




astrophysical ν
Some neutrinos are absorbed in the Earth
conventional ν_μ
conventional ν_e
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Interactions km^{-3} sr^{-1} yr^{-1} $E_\nu > 100$ TeV
−1.0
−0.5
0.0
0.5
1.0
$\sin(\delta) = -\cos(\theta)$ at the South Pole

Effect of VETO: *rejection of atmospheric neutrinos*



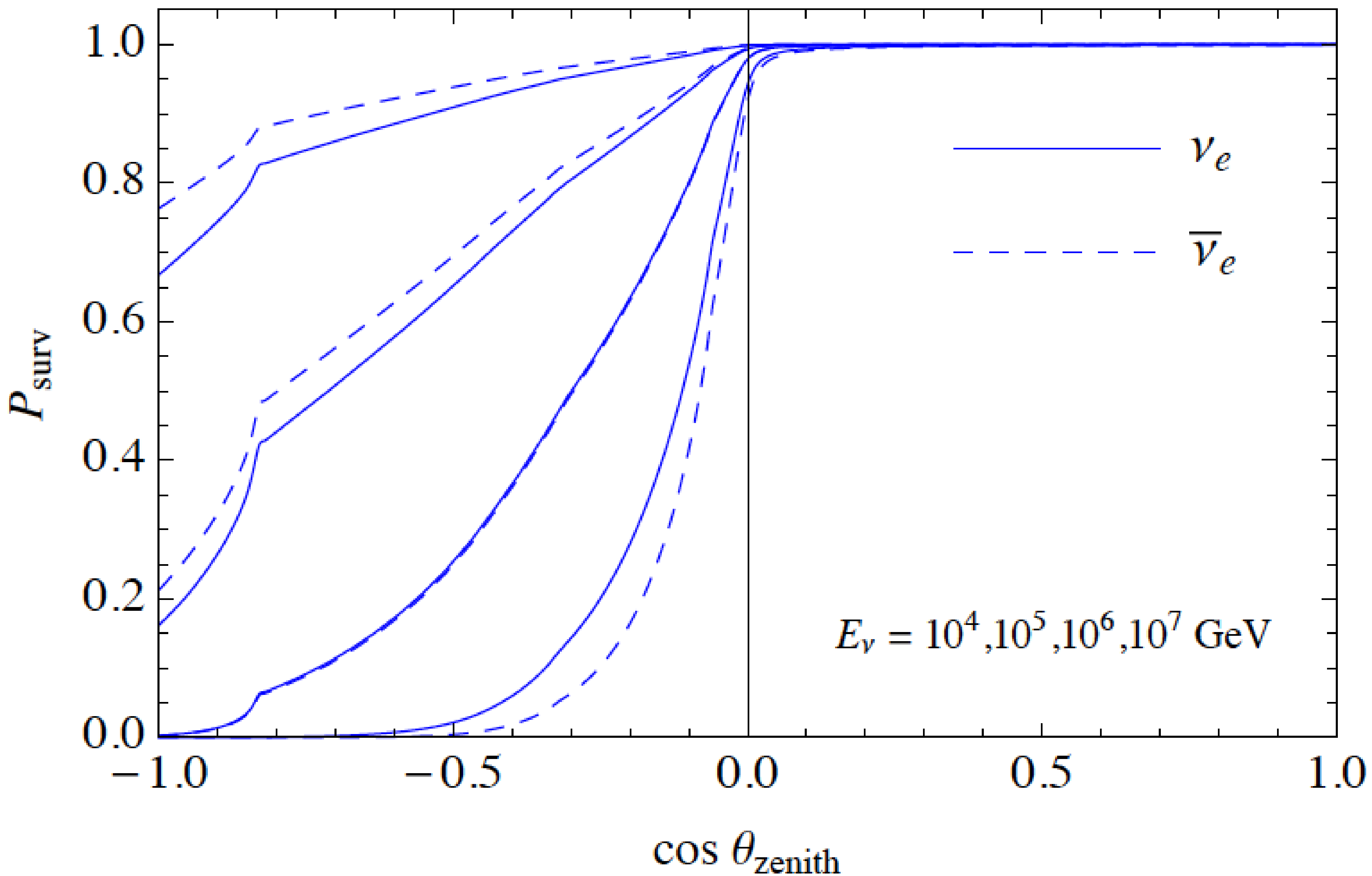


Effect allows to separate

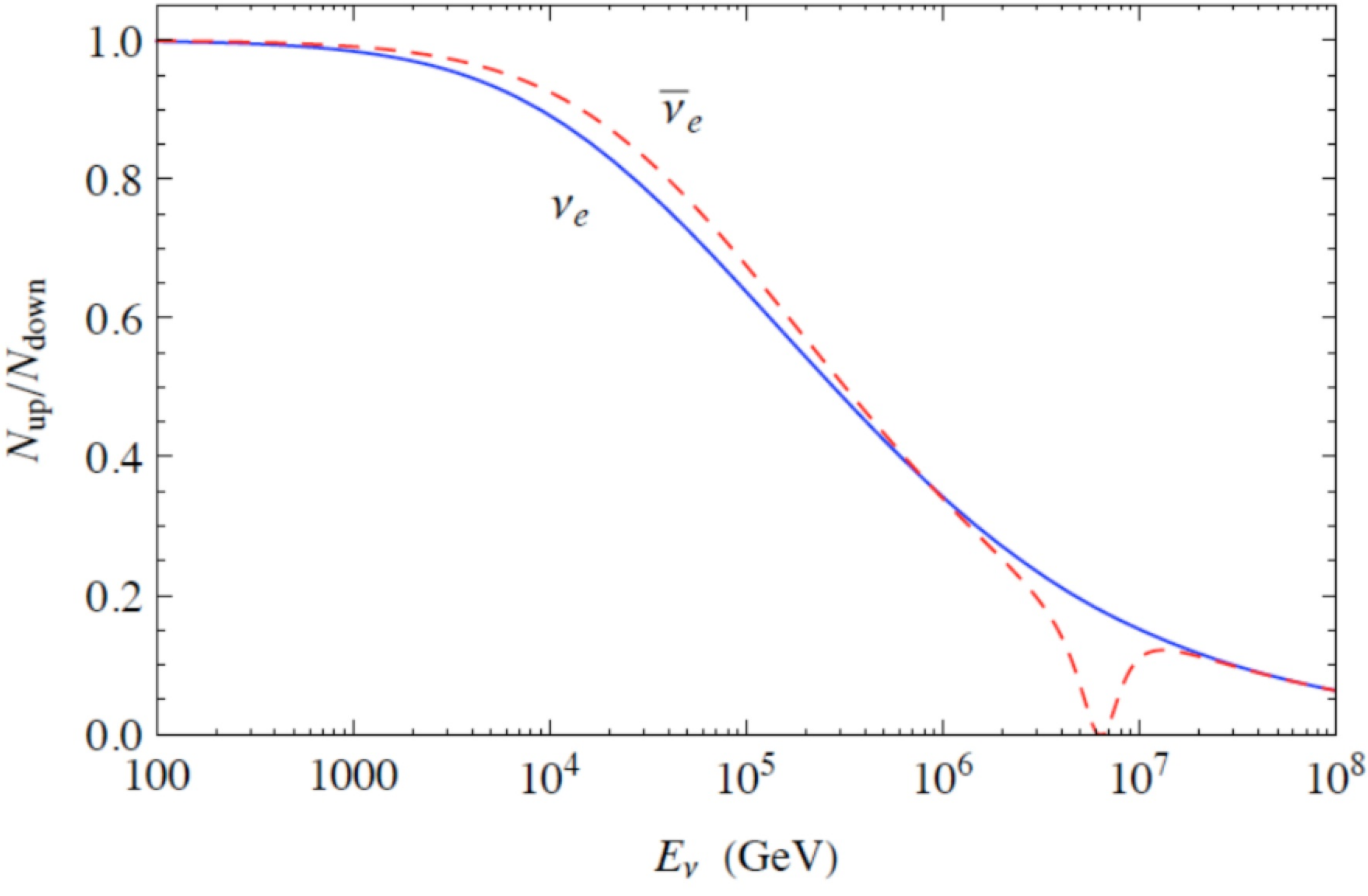
Atmospheric-charm

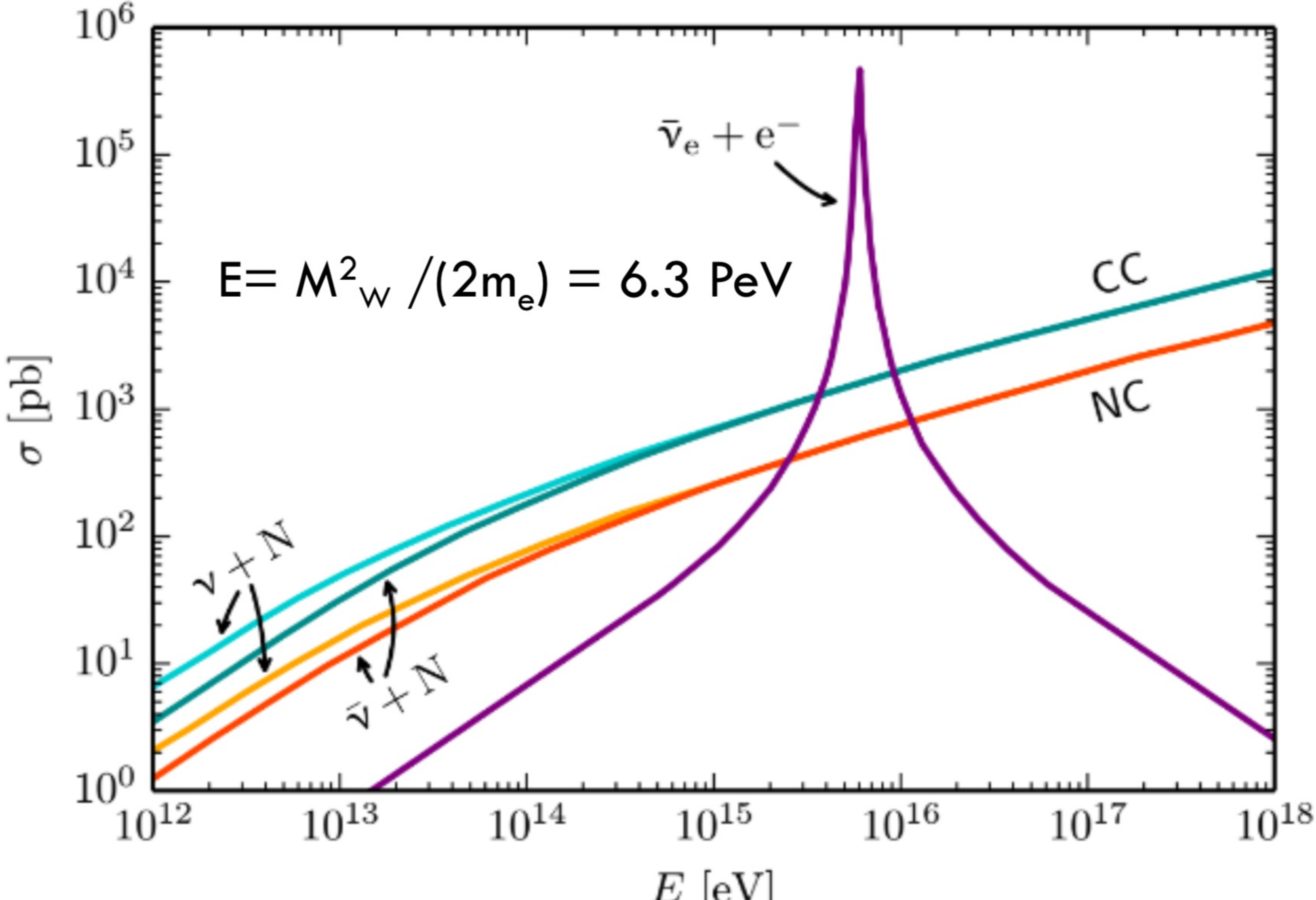
from isotropic astrophysical

Absorption of neutrinos in the Earth



Fraction of up-going neutrinos (isotropic flux) that survives crossing the Earth





$\bar{\nu}_e + e^-$
E= M²_W /(2m_e) = 6.3 PeV
CC
NC
$\nu + N$
$\bar{\nu} + N$
σ [pb]
E [eV]
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}

“Glashow Resonance”

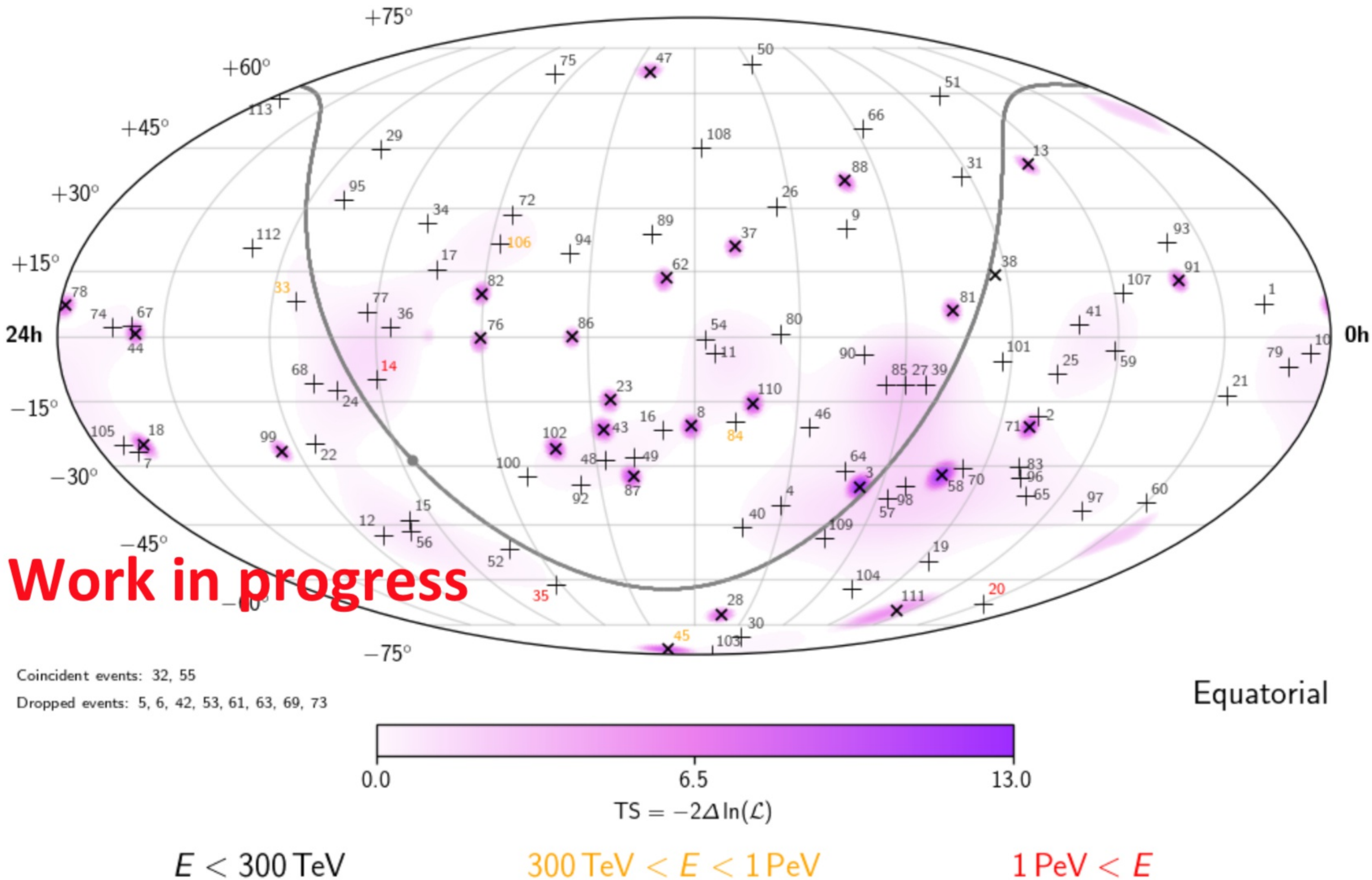
$$E^* = \frac{M_W^2 - m_e^2}{2\,m_e} \simeq 6.4\ \mathrm{PeV}$$

$$\overline{\nu}_e + e^- \to W^- \to \ldots$$

$$(p_{\overline{\nu}_e} + p_e)^2 = M_W^2$$

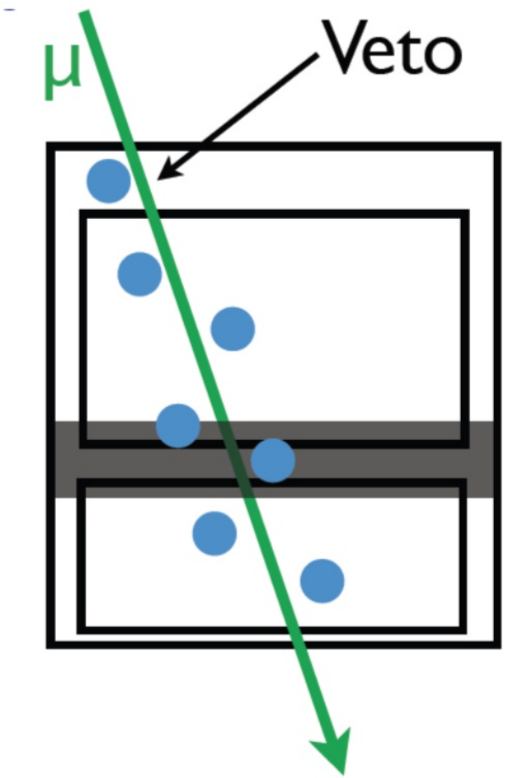
$$m_e^2 + 2\,m_e\,E_{\overline{\nu}} = M_W^2$$

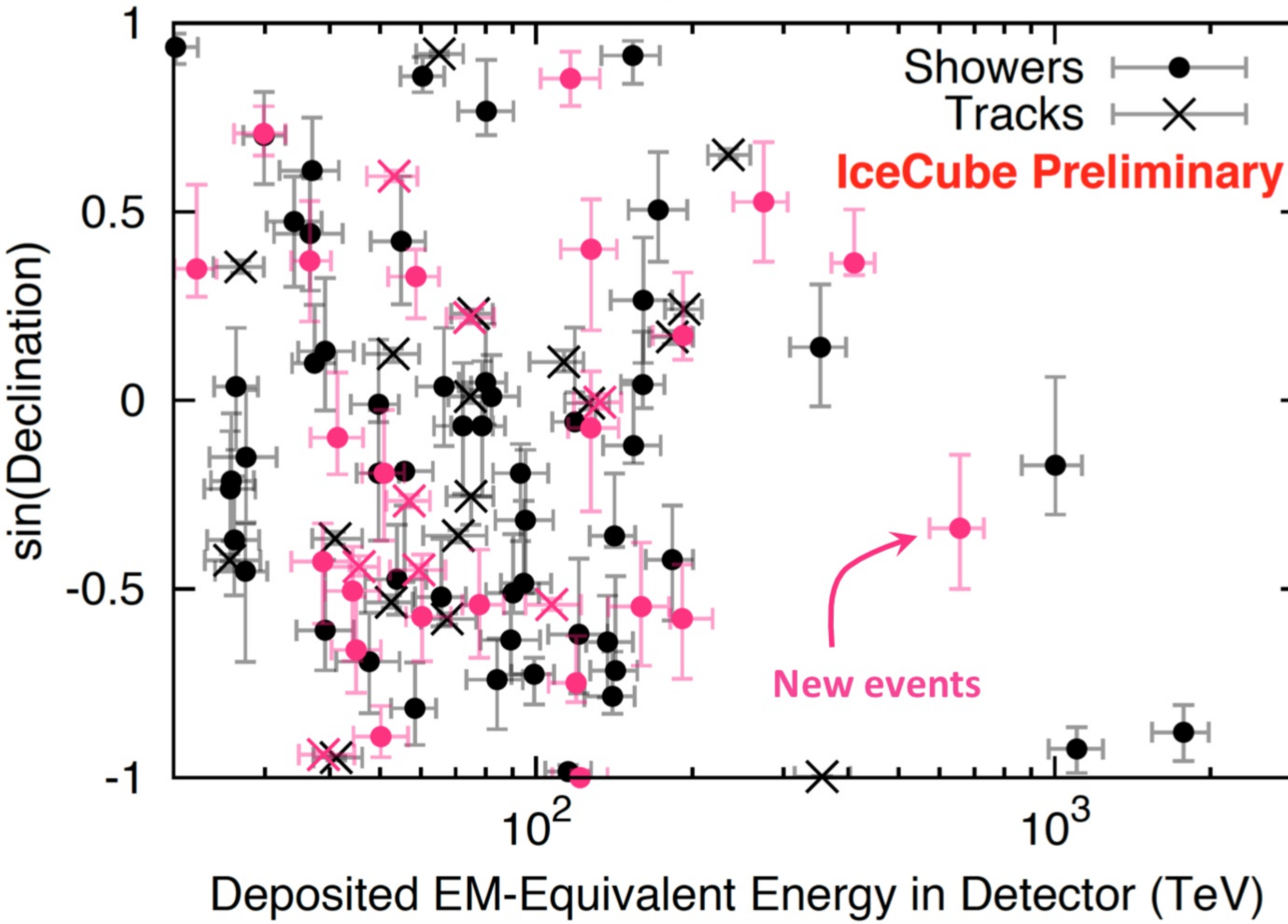
High-Energy Starting Events (HESE) – 7.5 yr



No evidence for point sources, nor a correlation with the galactic plane

High-Energy Starting Events (HESE) – 7.5 yr





Prior result 6 years ICRC 2017 arXiv:1710.01191

Updates to calibration and ice optical properties

103 events, with 60 events >60 TeV

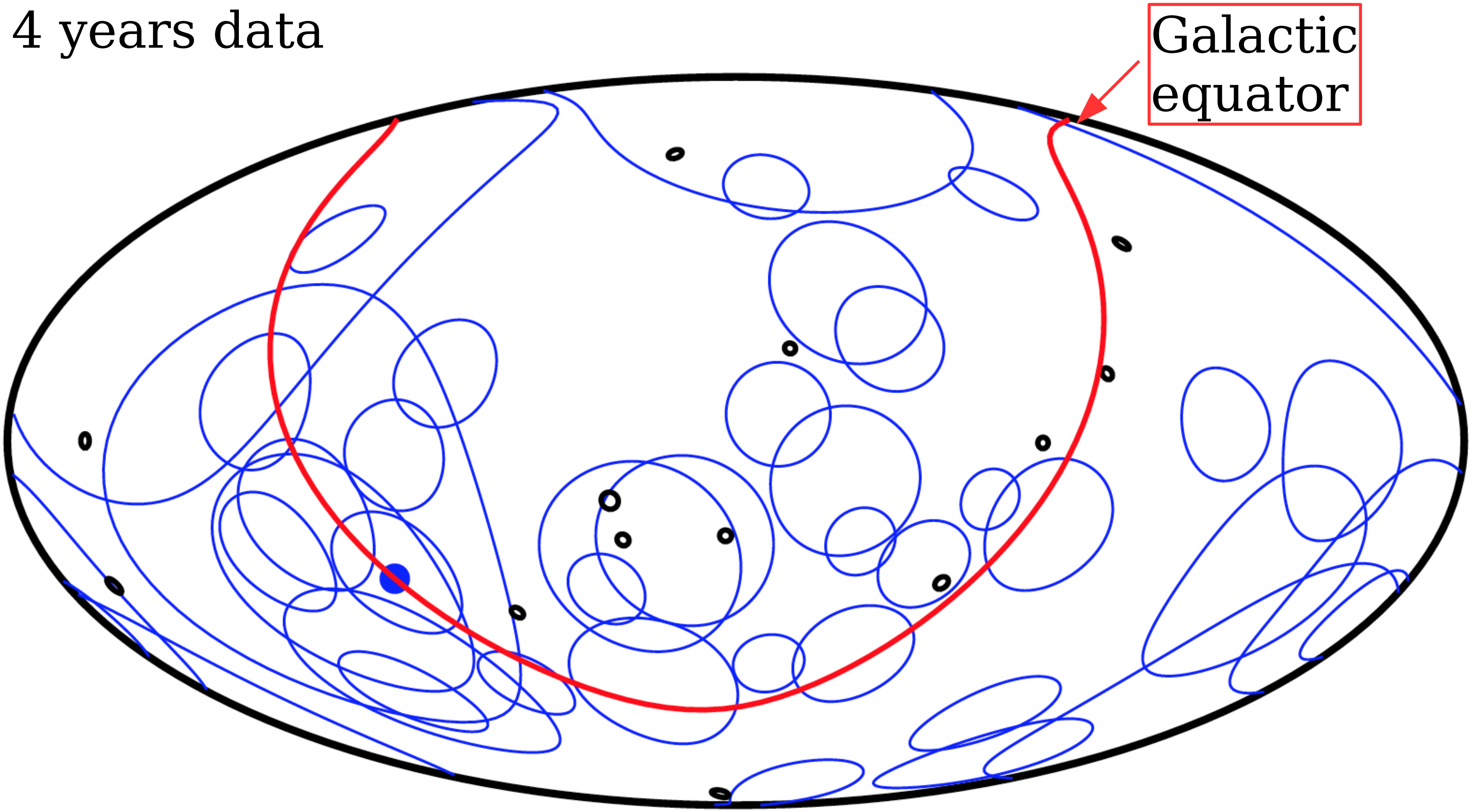
→ Changes to RA, Dec, energy

IceCube. Nature volume 551 (2017) 596

Poster #175. Wandkowsky et al. (IceCube)

High Energy Starting Events

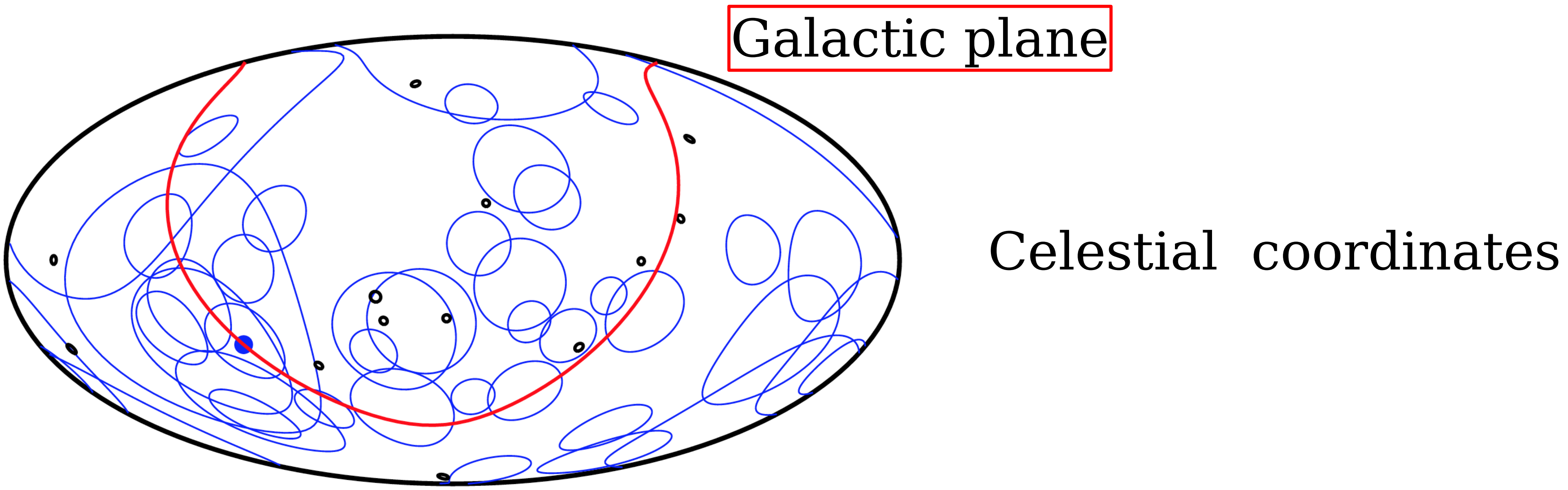
4 years data

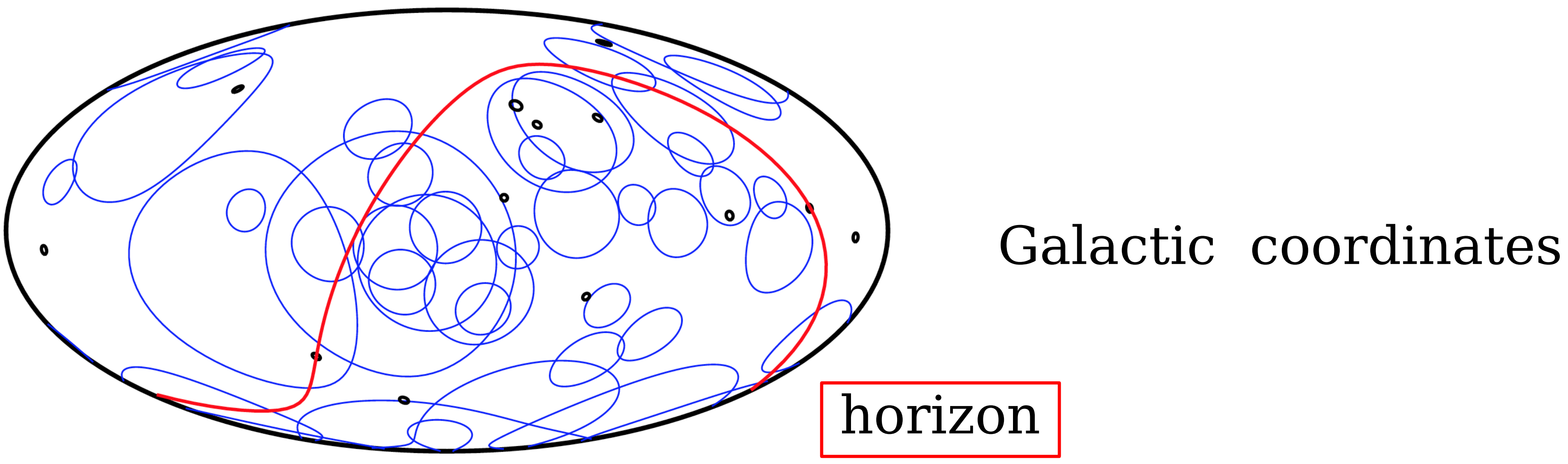


Track [(small) black circles]
Showers [(large) blue circles]

$E_{\rm vis} \gtrsim 30$ TeV

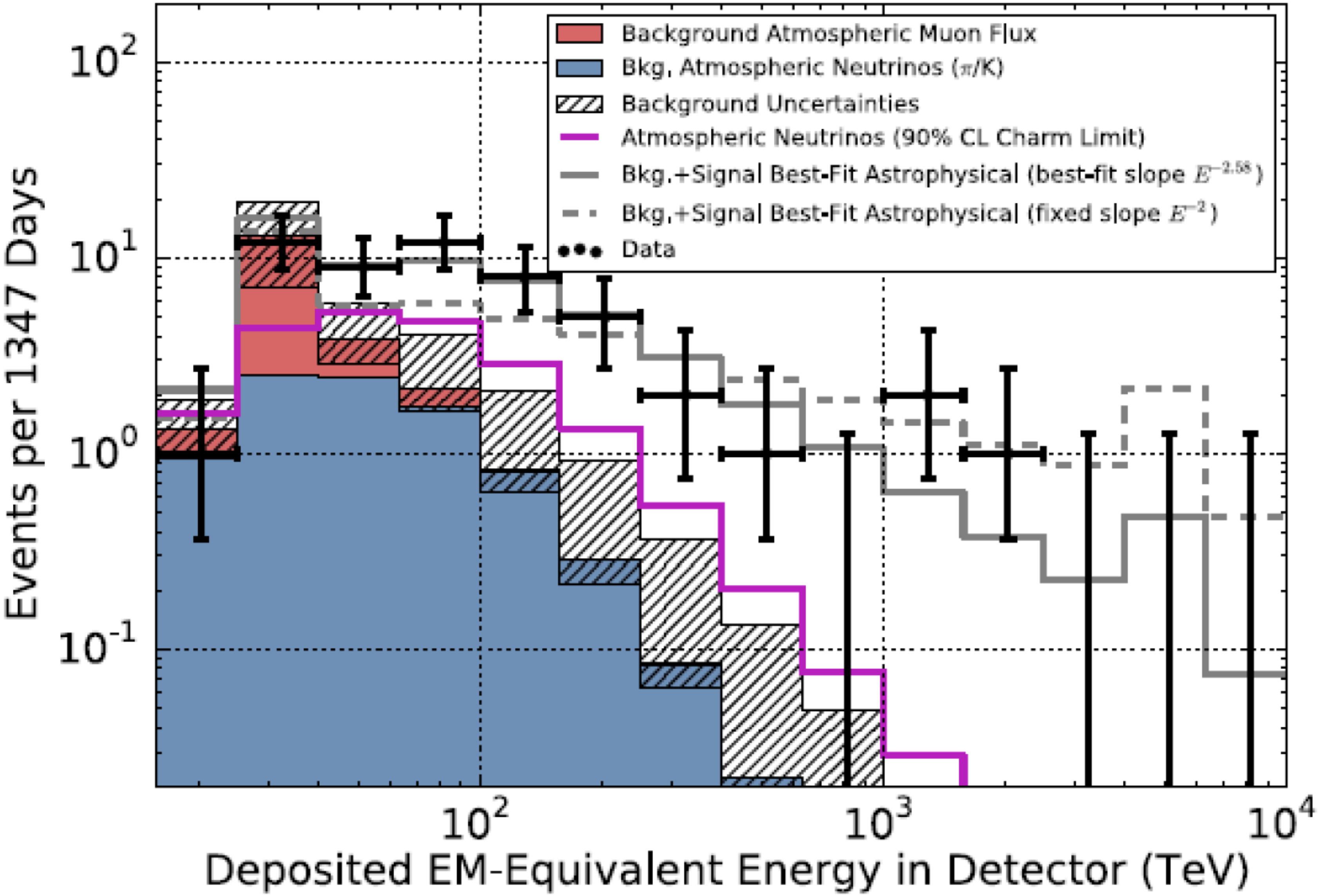
IceCube 4-years HESE events





High Energy Starting Events [HESE]

First evidence for an extra-terrestrial h.e. neutrino flux



High Energy Starting Events [HESE]

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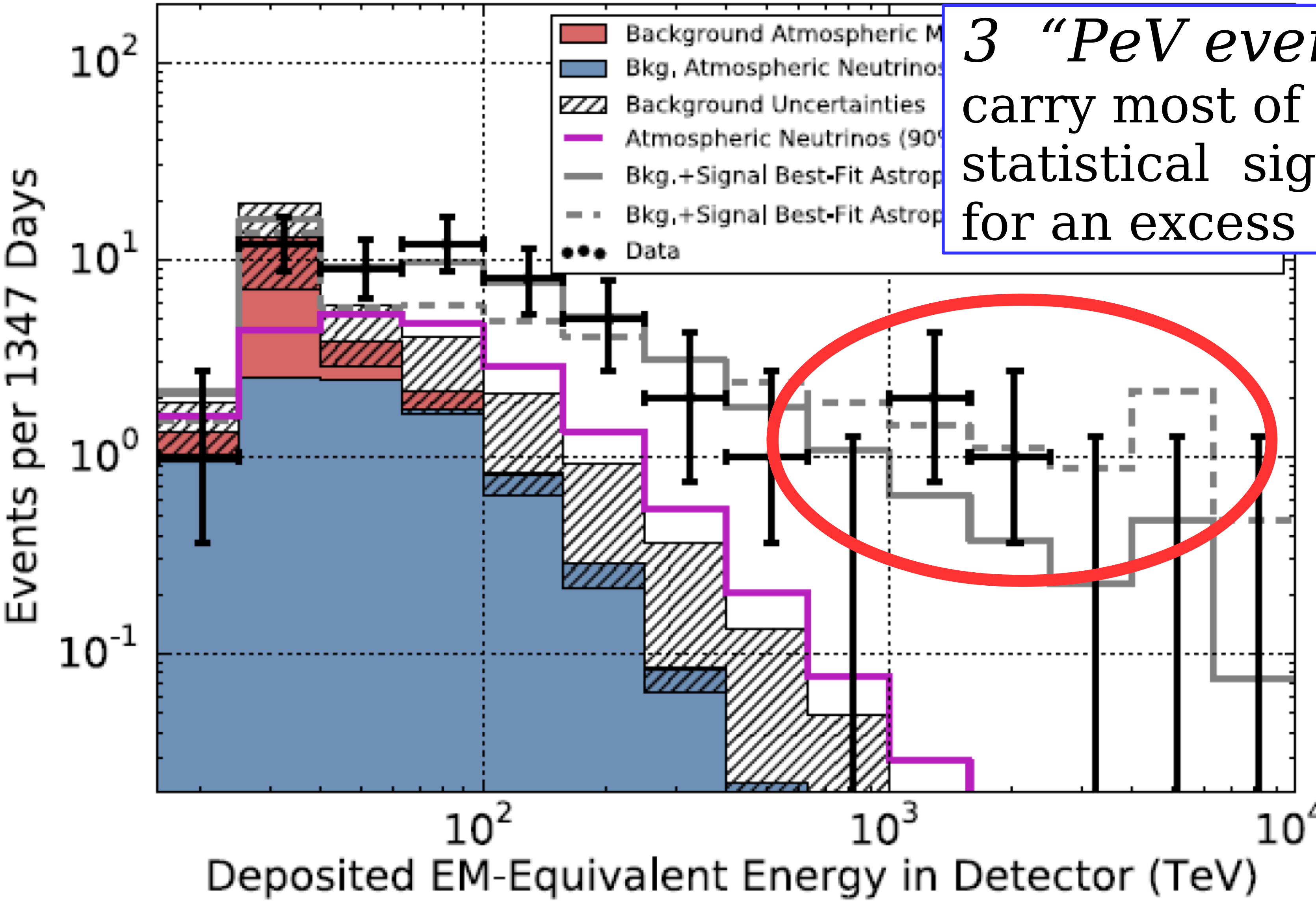
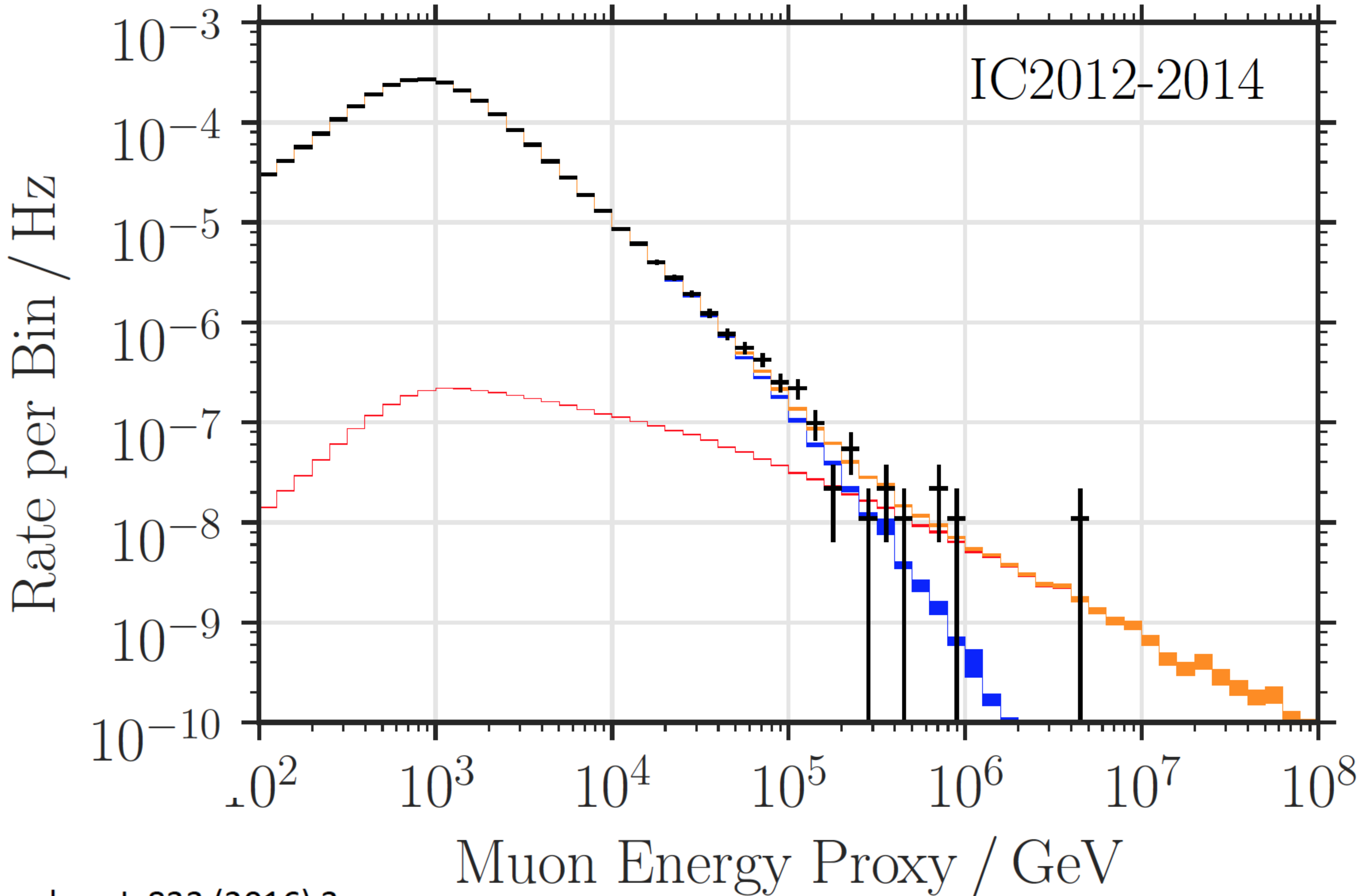


3 "PeV events" carry most of the statistical significance for an excess

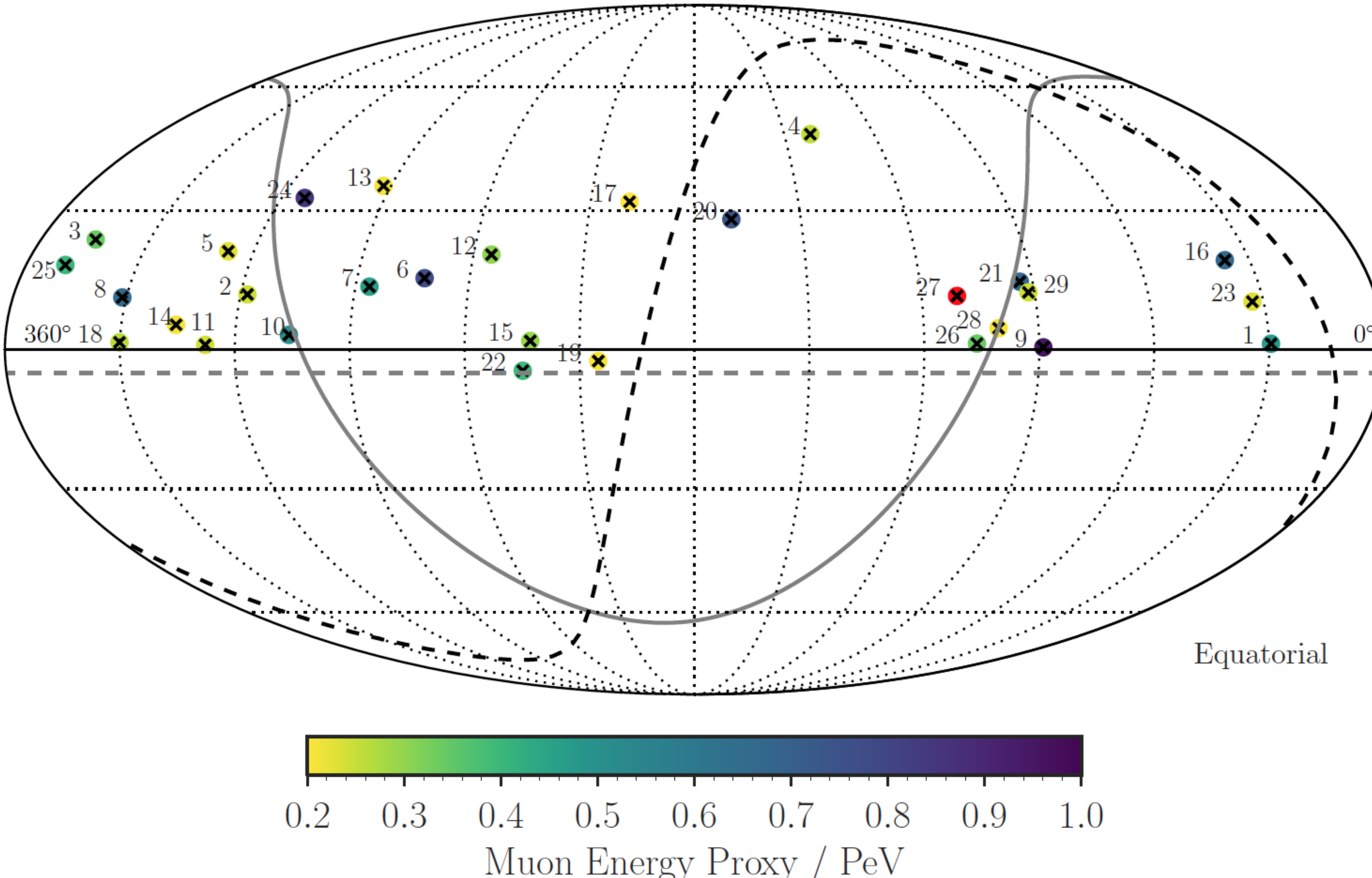
Upgoing (neutrino induced) Muons



Astrophys. J. 833 (2016) 3

Upgoing muon events

$E_\mu \gtrsim 200$ TeV



Astrophys. J. 833 (2016) 3

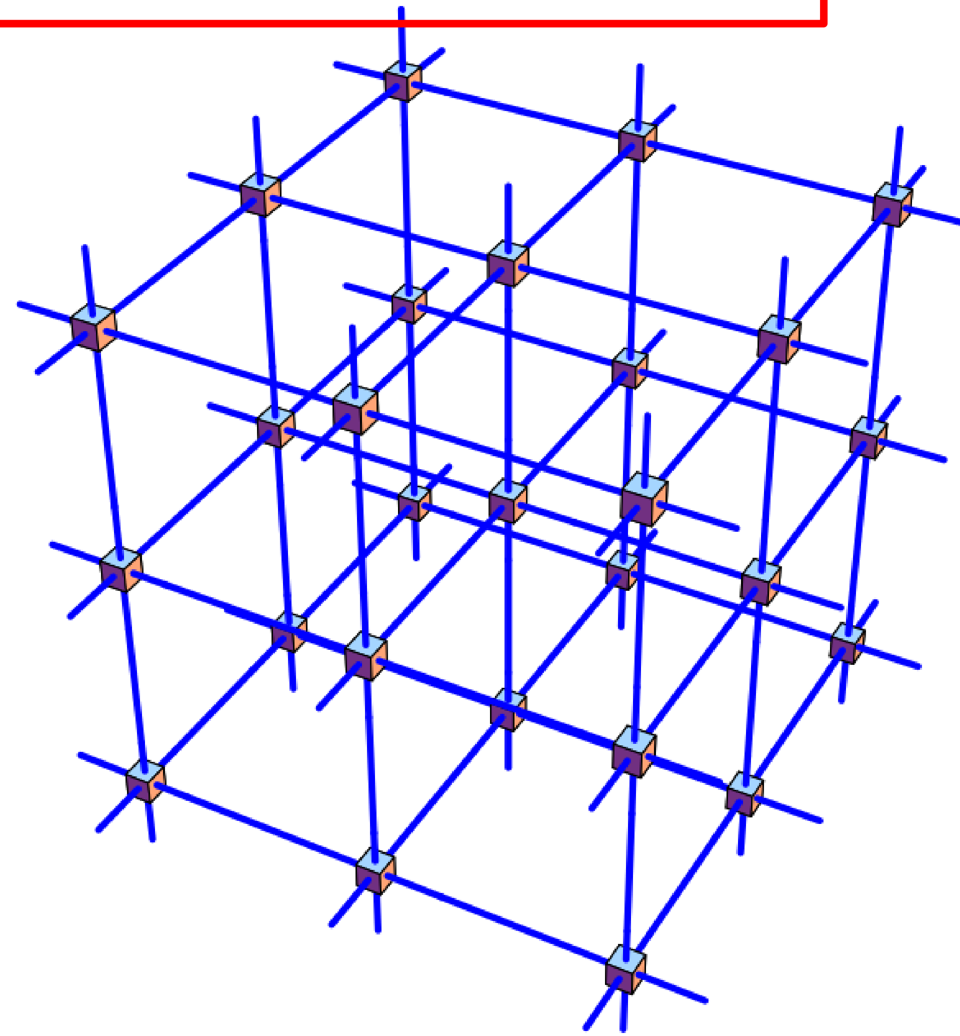
EXTRA-GALACTIC NEUTRINOS

AGN
GRB
......

Main candidate sources

Intimate relation with
UHECR [extragalactic cosmic rays]

The 3-dimensional lampposts ensemble "paradox" [Kepler – Olbers paradox].



Linear sequence of lampposts:

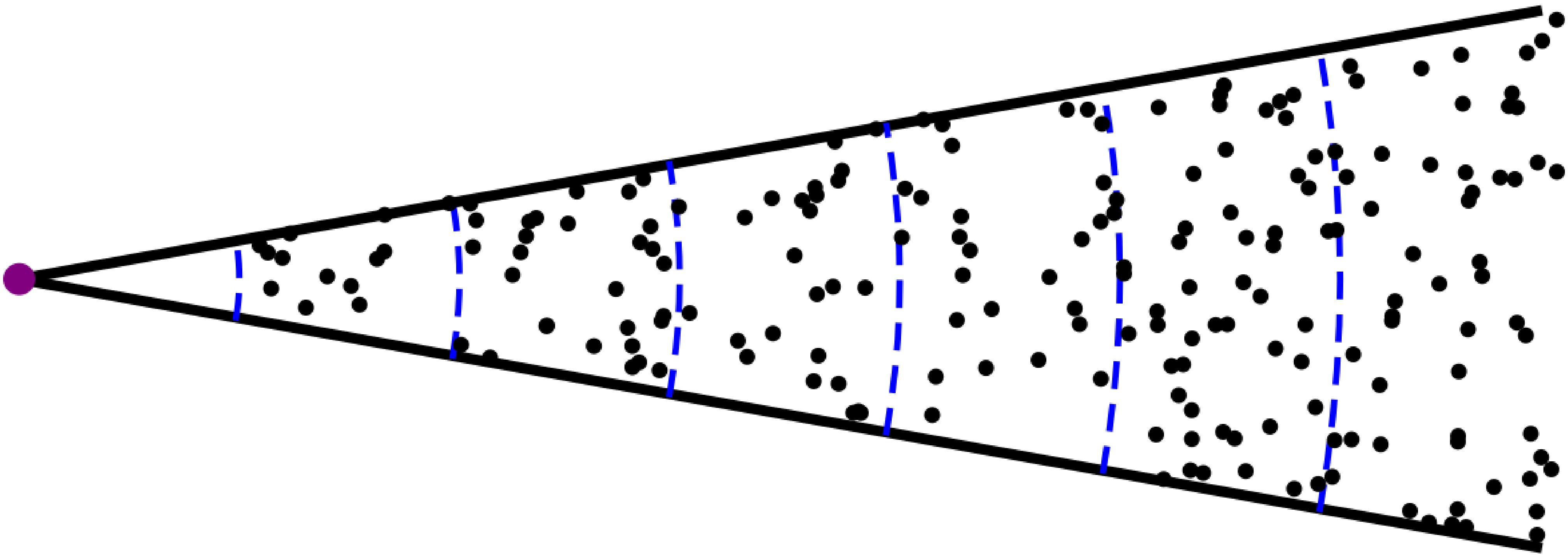
Most of the light you receive from the nearest lamppost

3D ensemble of lampposts: [Euclidean static space]

Light diverges !

Homogeneous (in average) density of sources:
spherical shells between radii: 1, 2, 3, 4, ...

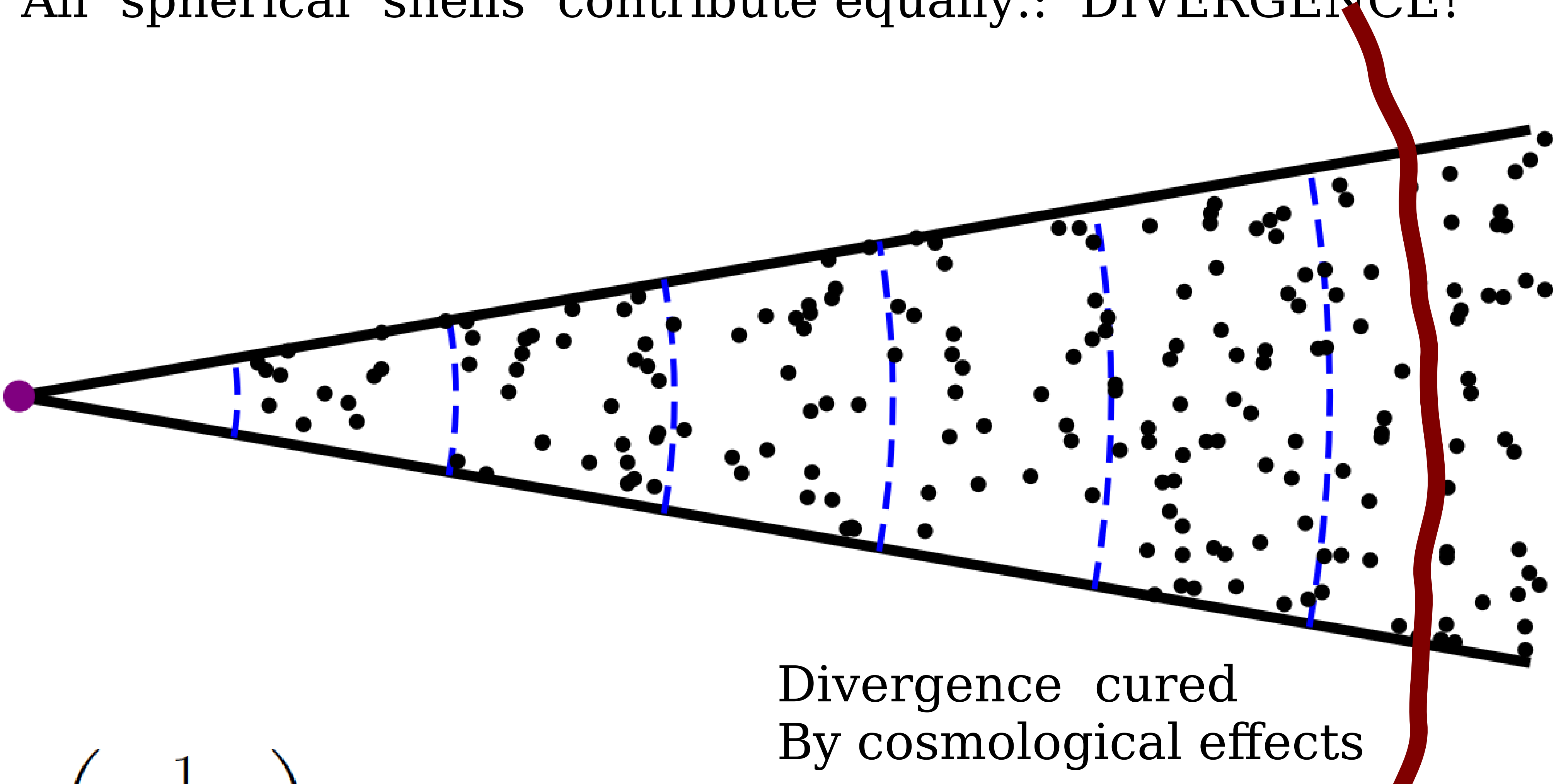
All spherical shells contribute equally.: DIVERGENCE!



$$\left(\frac{1}{4\pi R^2}\right) \left(4\pi R^2 \Delta R\right)$$

Homogeneous (in average) density of sources:
spherical shells between radii: 1, 2, 3, 4, ...

All spherical shells contribute equally.: DIVERGENCE!



Divergence cured
By cosmological effects

$$\left(\frac{1}{4\pi R^2}\right) \quad (4\pi R^2 \Delta R)$$

$$R_{\rm Hubble} = \frac{c}{H_0} \simeq 3 \text{ Gpc}$$

Expected flavor composition of High energy astrophysical neutrinos

[Standard mechanism of production]

$$\nu_e \simeq \nu_\mu \simeq \nu_\tau$$

$$P_{\nu_\alpha \to \nu_\beta}(E_\nu, L) = \left| \sum_j U_{\beta j} U^*_{\alpha j} \; e^{-i\, m_j^2 \frac{L}{2E_\nu}} \right|^2$$

$$= \sum_{j=1,3} |U_{\beta j}|^2 \; |U_{\alpha j}|^2$$

$$+ \sum_{j<k} 2\,\mathrm{Re}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \;\cos\left(\frac{\Delta m^2_{jk}\, L}{2E} \right)$$

$$+ \sum_{j<k} 2\,\mathrm{Im}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \;\sin\left(\frac{\Delta m^2_{jk}\, L}{2E} \right)$$

Space averaged
flavor transition probability

Neutrinos created in volume
of sufficiently large linear size

$X_{\text{source}} \gg E/|\Delta m^2_{jk}|$

Oscillating terms average to zero

$$\langle P(\nu_\alpha \to \nu_\beta)\rangle = \sum_j |U_{\alpha j}|^2 \, |U_{\beta j}|^2$$

$$\simeq \begin{pmatrix} 1-2v & v & v \\ v & (1-v)/2 & (1-v)/2 \\ v & (1-v)/2 & (1-v)/2 \end{pmatrix} \simeq \begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix}$$

$$\theta_{13} \simeq 0$$

$$\theta_{23} \simeq 45^\circ$$

$$v = \cos^2\theta_{12}\sin^2\theta_{12} \simeq 0.2$$

$$\begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$\pi^+ \to \mu^+ \quad \nu_\mu$

$\quad\hookrightarrow \quad e^+ \quad \nu_e \quad \overline{\nu}_\mu$

"Standard mechanism"

$$\begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

much more "astrophysically plausible"

"Muon absorption"

Very high magnetic field

$$\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} v \\ (1-v)/2 \\ (1-v)/2 \end{pmatrix} \approx \begin{pmatrix} 0.2 \\ 0.4 \\ 0.4 \end{pmatrix}$$

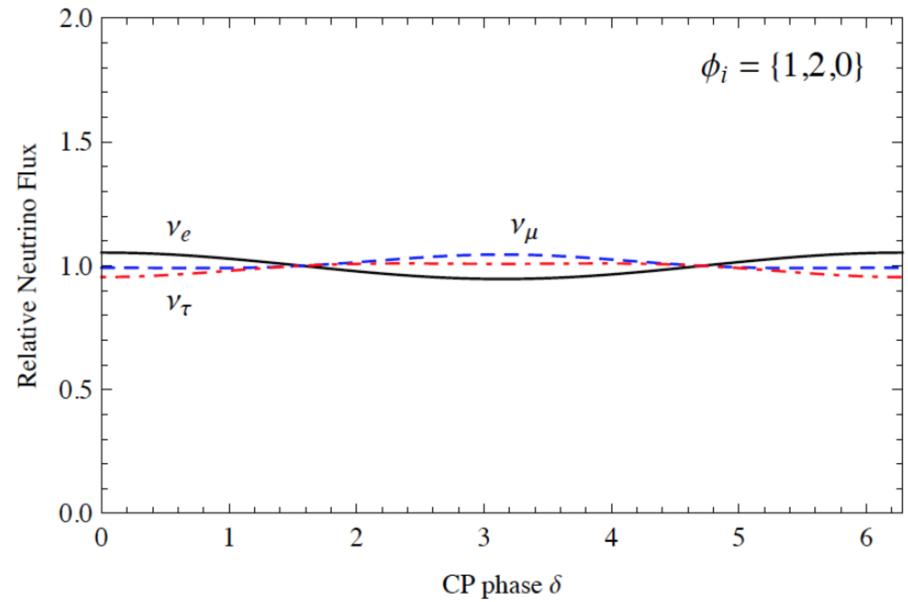
"Neutron decay"

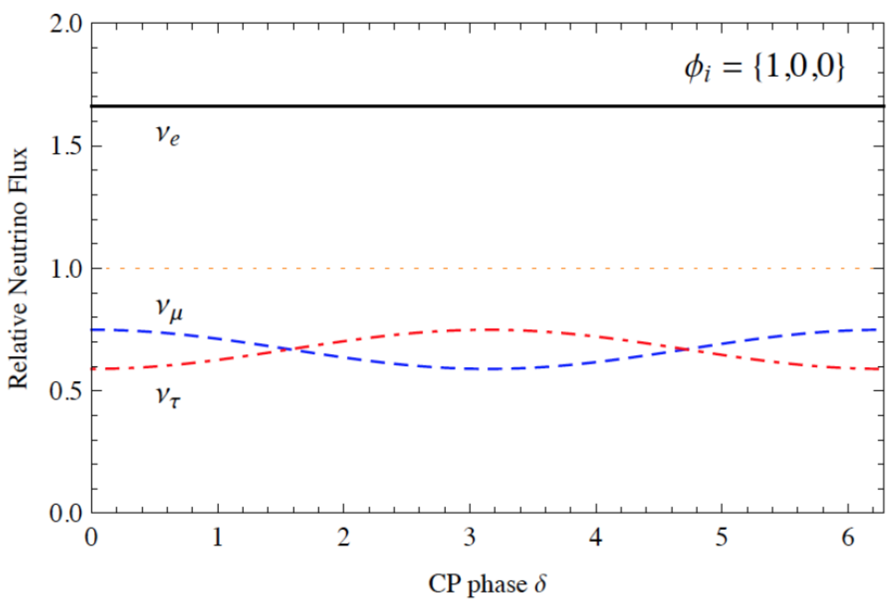
Nuclear fragmentation

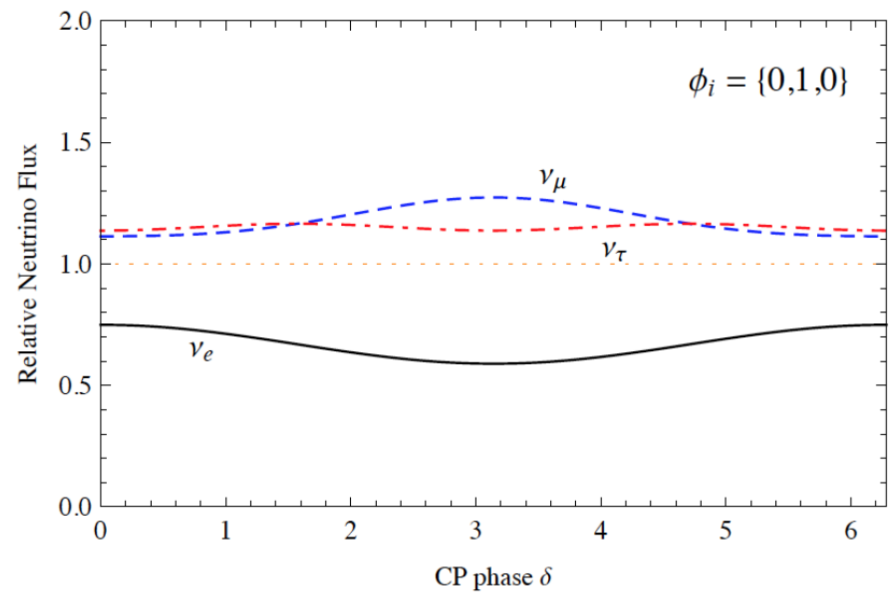
$$\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} 1-2\,v \\ v \\ v \end{pmatrix} \approx \begin{pmatrix} 0.6 \\ 0.2 \\ 0.2 \end{pmatrix}$$

Include
best fit of oscillation
parameters
(delta dependence)

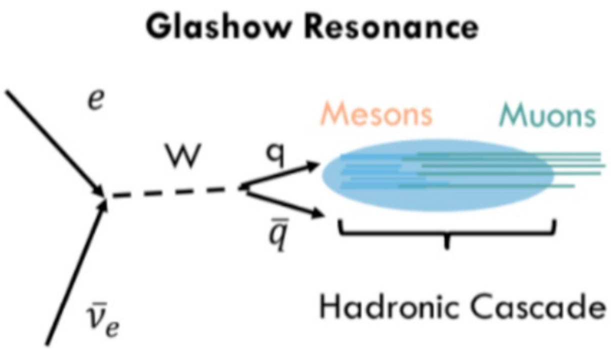
Significant presence of
tau-neutrinos





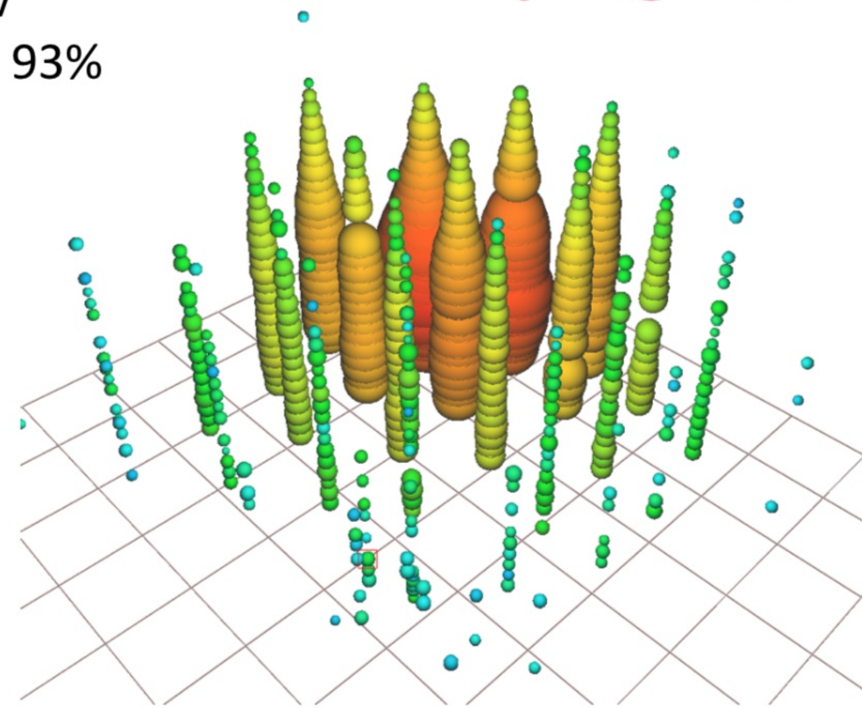


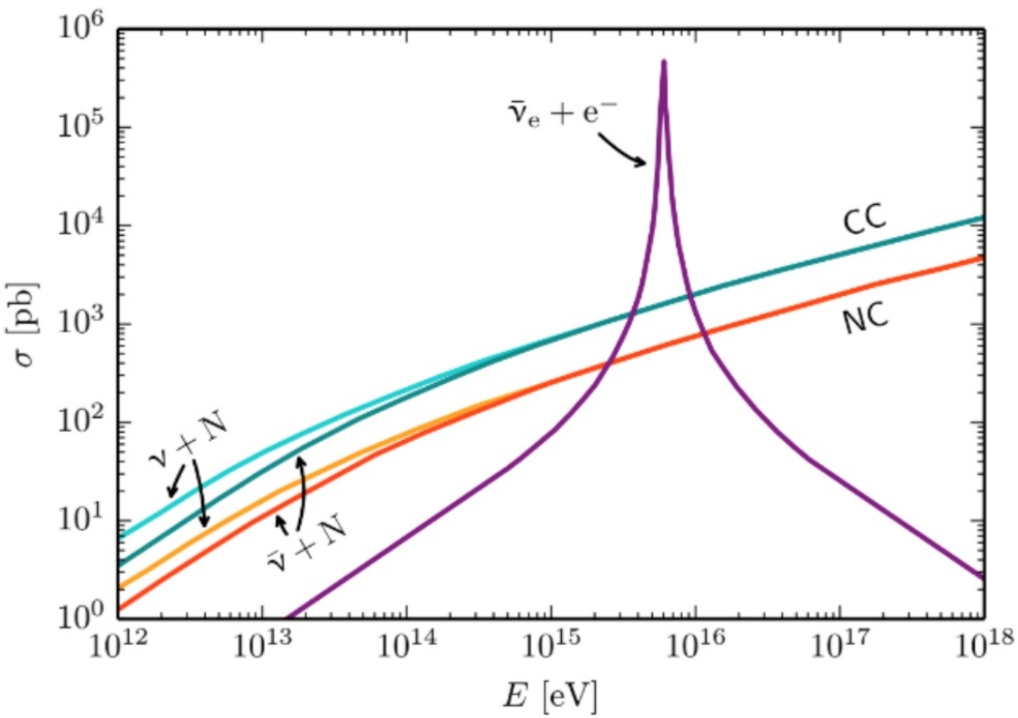
A 5.9 PeV event in IceCube



Resonance: E_ν = 6.3 PeV
Typical visible energy is 93%

Work in progress



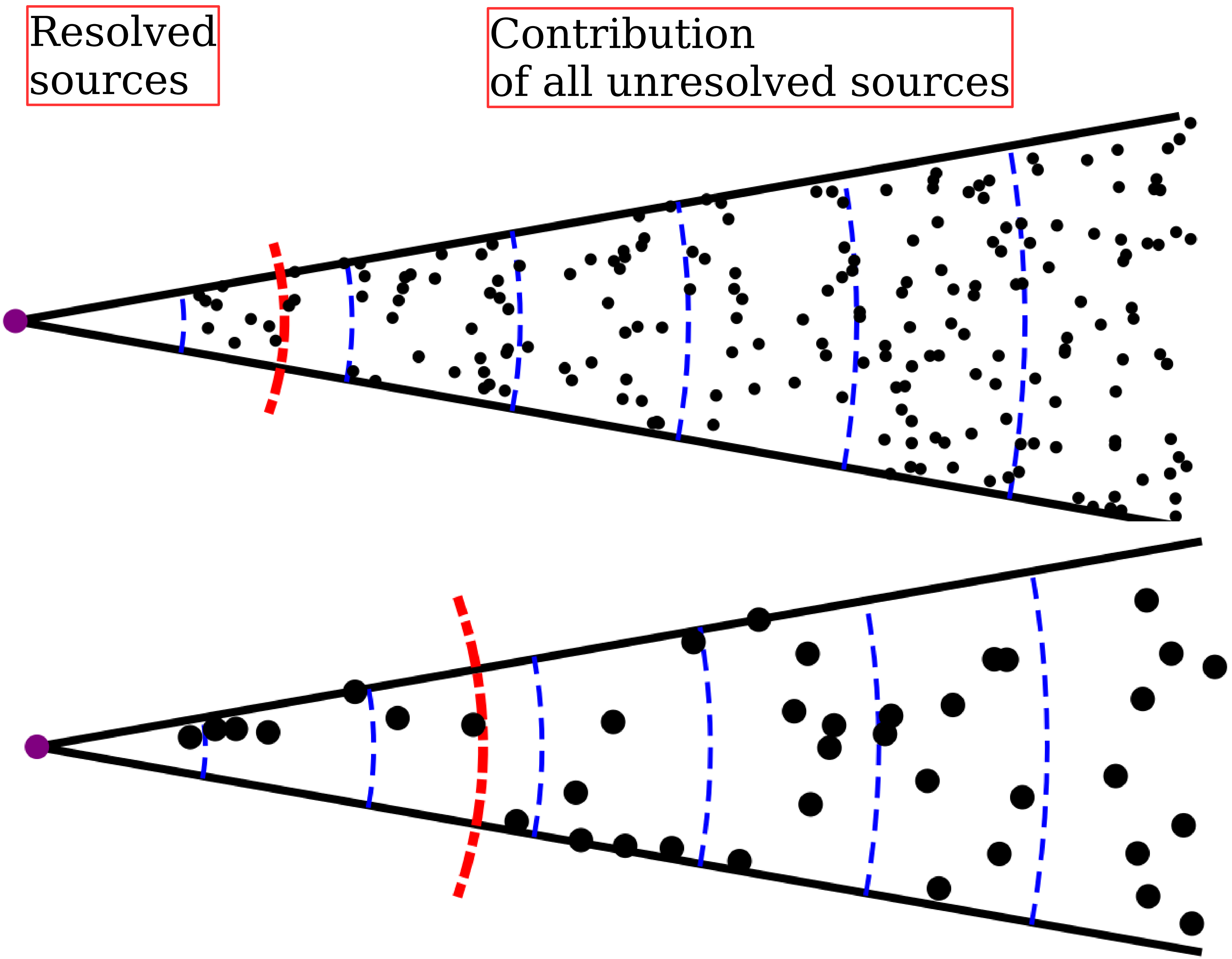


Event identified in a partially-contained PeV search (PEPE)

Deposited energy: 5.9±0.18 PeV (stat only)

ICRC 2017 arXiv:1710.01191

Potential hadronic nature of this event under study


Resolved sources
Contribution of all unresolved sources

IceCube GCN 21916 17/09/23

```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube  <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of  Maryland) report on behalf of the IceCube
Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical
origin. The event was identified by the  Extremely High Energy (EHE) track event selection. The IceCube detector was in a
normal operating state. EHE events typically have a neutrino interaction vertex that is outside the detector, produce a muon
that traverses the detector volume, and have a high light level (a proxy for energy).

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon), more
sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg  90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the
candidate neutrino.

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica.
The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu
```

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
*on **28 Sep 2017; 10:10 UT***
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430

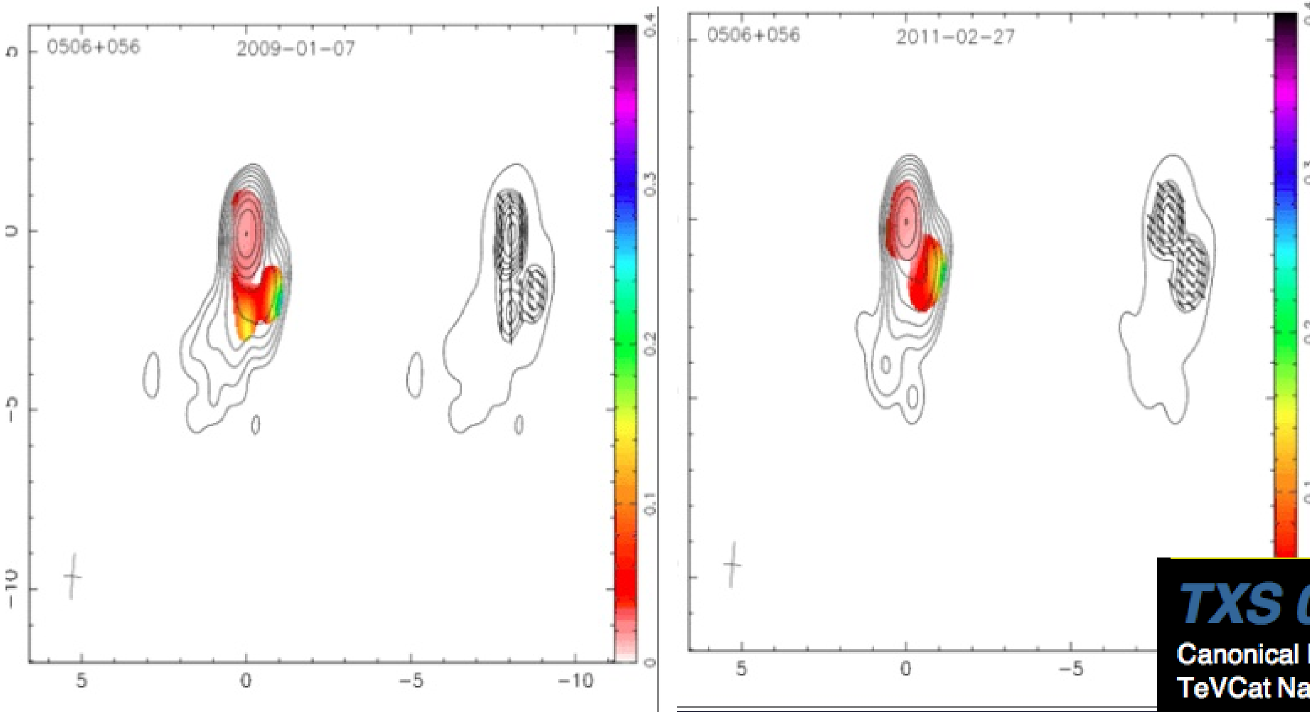
…. Great source of excitement ……

Texas Survey of Radio Sources [365 Mhz, (1974-1983)]
66841 sources [TXS …..]

Very Long Baseline Array (VLBA)
[ensemble of 10 radio telescopes]

8000 km
baseline

TXS 0506+056



$$z = 0.3365 \pm 0.0010$$

$$\dot{\Omega} = 332 \pm 82\ \mu\text{as/year}$$

$$d = 706\ \text{Mpc}$$

$$\beta_{\text{app}} = \frac{\dot{\Omega}\, d}{c} = 3.7 \pm 0.9$$

TXS 0506+056 SIMBAD

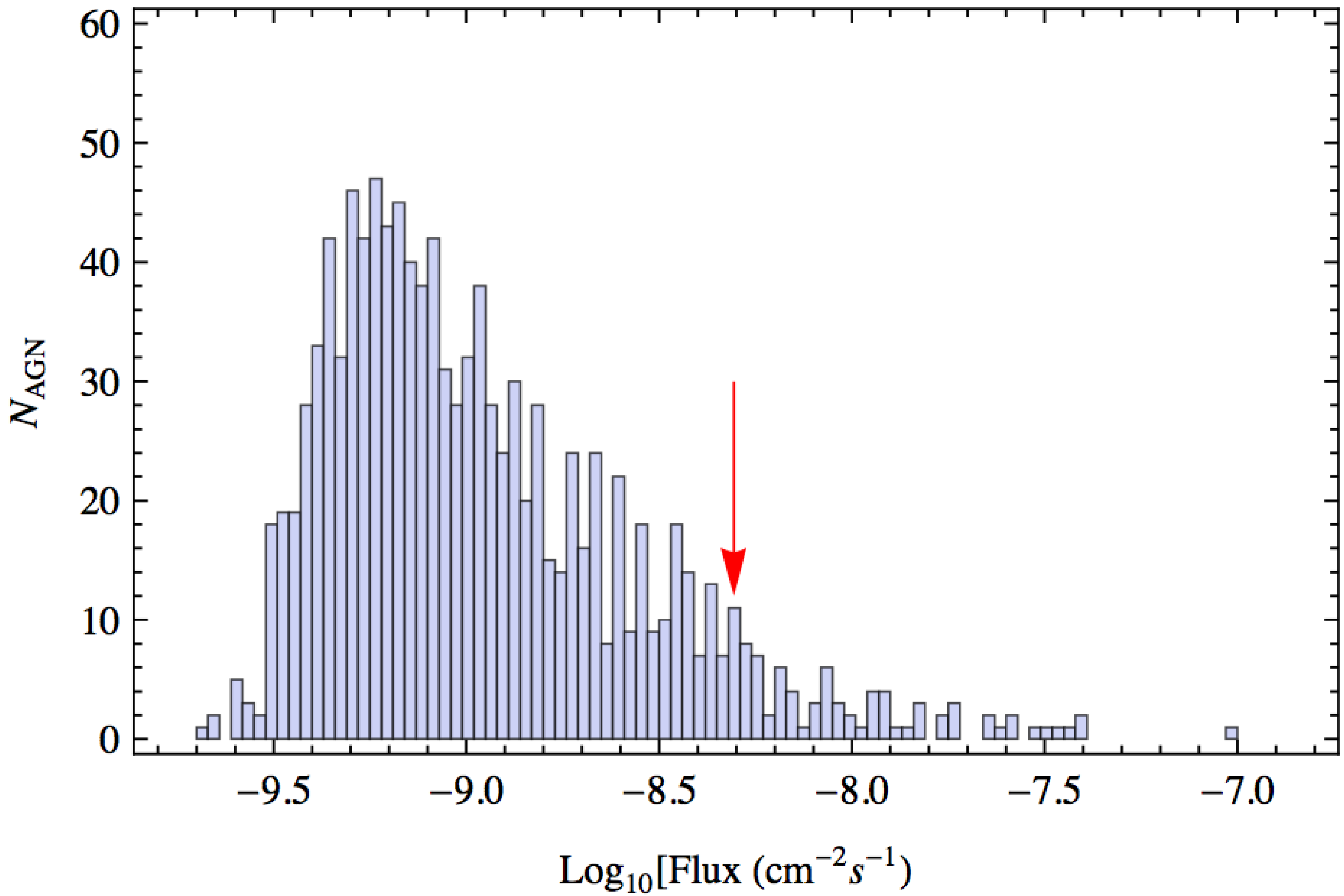
Canonical Name:	TXS 0506+056
TeVCat Name:	TeV J0509+056
Other Names:	EHE 170922A 3FGL J0509.4+0541 3FHL J0509.4+0542
Source Type:	Blazar
R.A.:	05 09 25.96370 (hh mm ss)
Dec.:	+05 41 35.3279 (dd mm ss)
Gal Long:	195.41 (deg)
Gal Lat:	-19.64 (deg)
Distance:	z=0.3365
Flux:	(Crab Units)
Energy Threshold:	100 GeV
Spectral Index:	
Extended:	No
Discovery Date:	2017-10
Discovered By:	MAGIC
TeVCat SubCat:	Newly Announced
Source Notes:	

The blazar TXS 0506+056 lies within the error circle of IceCube-170922A, the IceCube high-energy neutrion candidate event whose detection was reported in GCN circular #21916. Follow-up observations were performed by a number of GeV-TeV instruments with both Fermi-LAT and MAGIC reporting evidence for gamma-ray emission from positions consistent with the IceCube neutrino error circle which they thus associate with the blazar TXS 0506+056. Upper limits on the gamma-ray emission from the region were reported by H.E.S.S, HAWC and VERITAS.

1	3C	454.3	9.65
2	PKS	1510-08	4.06
3	PKS	1502+106	4.01
4	PKS	0537-441	3.71
5	4C	21.35	3.54
6	PKS	0426-380	3.11
7	Mkn	421	2.97
8	3C	66A	2.56
9	3C	279	2.56
10	PKS	2155-304	2.35
11	PKS	0454-234	2.27
12	PKS	0727-11	2.2
13	NGC	1275	1.88
14	AO	0235+164	1.87
15	S5	0716+71	1.83
16	B2	1520+31	1.76
17	PMN	J1802-3940	1.69
18	3C	273	1.51
19	PKS	0805-07	1.5
20	PKS	B1424-418	1.47
21	PG	1553+113	1.4
22	PMN	J1603-4904	1.29
23	MG2	J201534+3710	1.2
24	PKS	1830-211	1.19
25	PKS	1454-354	1.19

70	MG2	J071354+1934	0.519
71	PKS	0735+17	0.516
72	AP	Librae	0.516
73	4C	1.28	0.512
74	B2	2234+28A	0.508
75	PKS	0250-225	0.503
76	PMN	J1626-2426	0.503
77	PKS	1329-049	0.501
78	PMN	J1344-1723	0.501
79	PKS	0829+046	0.5
80	TXS	0506+056	0.494
81	PKS	0521-36	0.488
82	PKS	1551+130	0.487
83	TXS	1055+567	0.479
84	BZQ	J0850-1213	0.464
85	4C	31.03	0.456

Flux [$10^{-9}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$]



$$\alpha = 2.059 \pm 0.042$$

$$\Phi_\gamma[1 \div 100\ \text{GeV}] = 4.94 \times 10^{-9}\ \text{cm}^{-2}\ \text{s}^{-1}$$

$$L(E) = \phi_\gamma(E) \times E^2 \simeq 4.5 \times 10^{45}\ \frac{\text{erg}}{\text{s}}$$

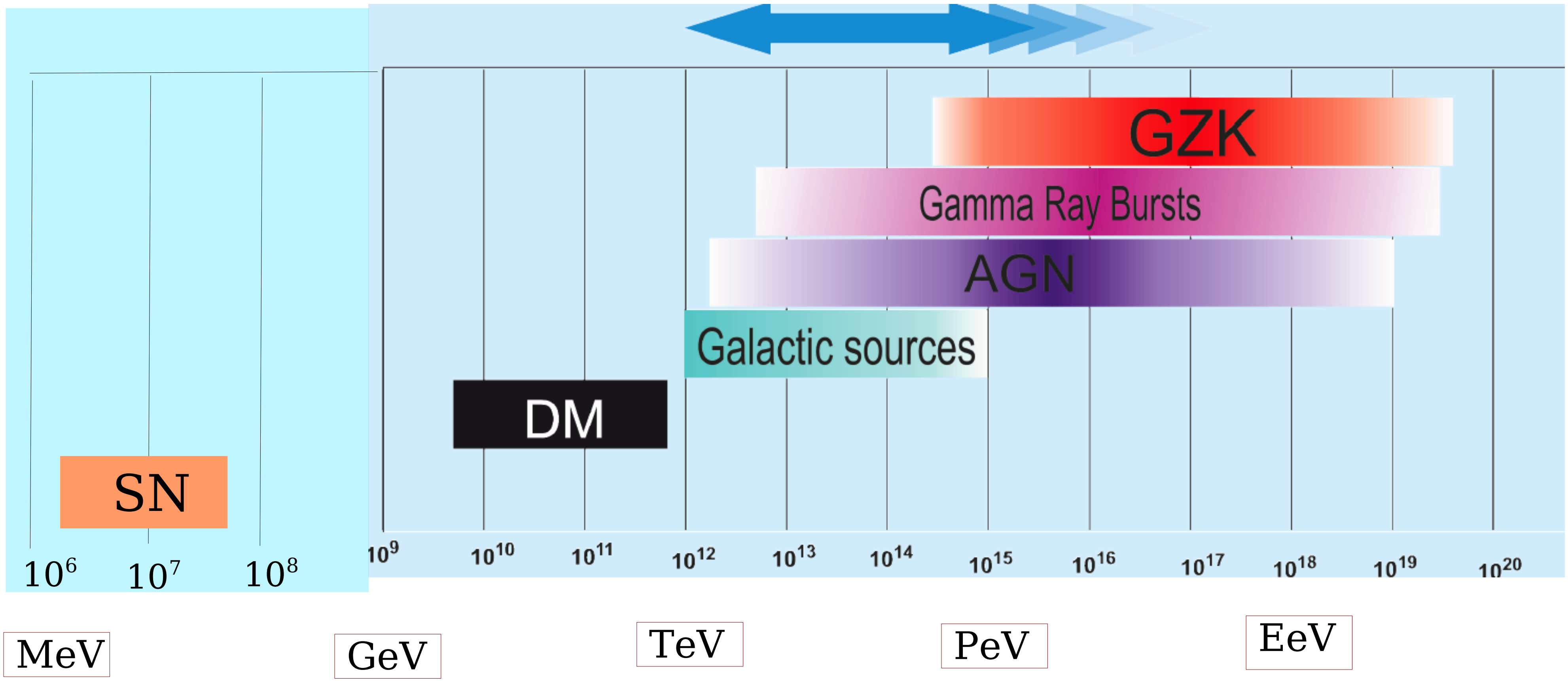
Three More Topics:

[1.] “Cosmogenic Neutrinos”

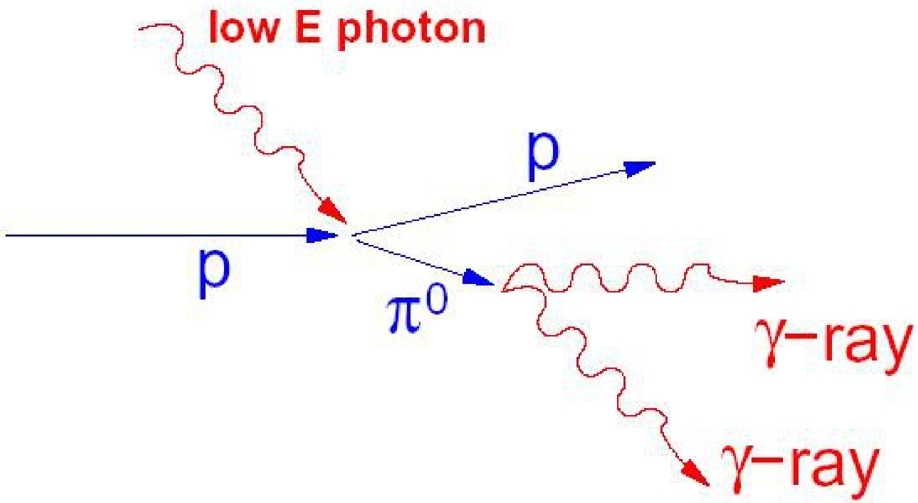
[2.] Neutrinos from Dark Matter Self-annihilation

[3.] New Concepts for Neutrino detection

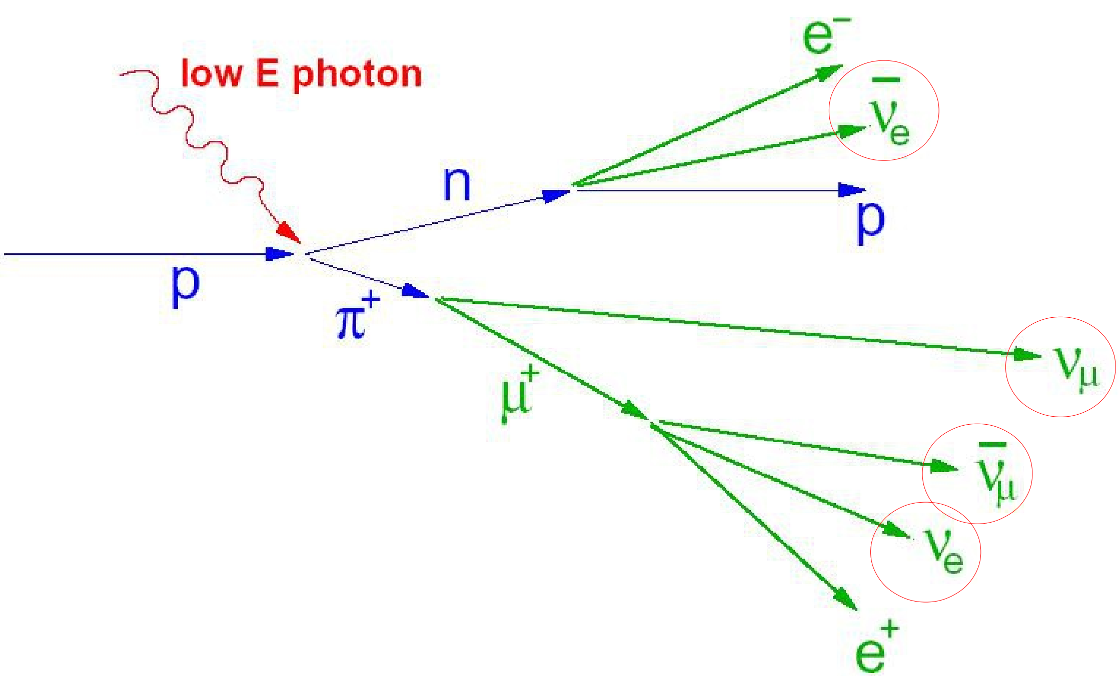
Neutrino Astronomies



Energy Loss Mechanisms for Protons:

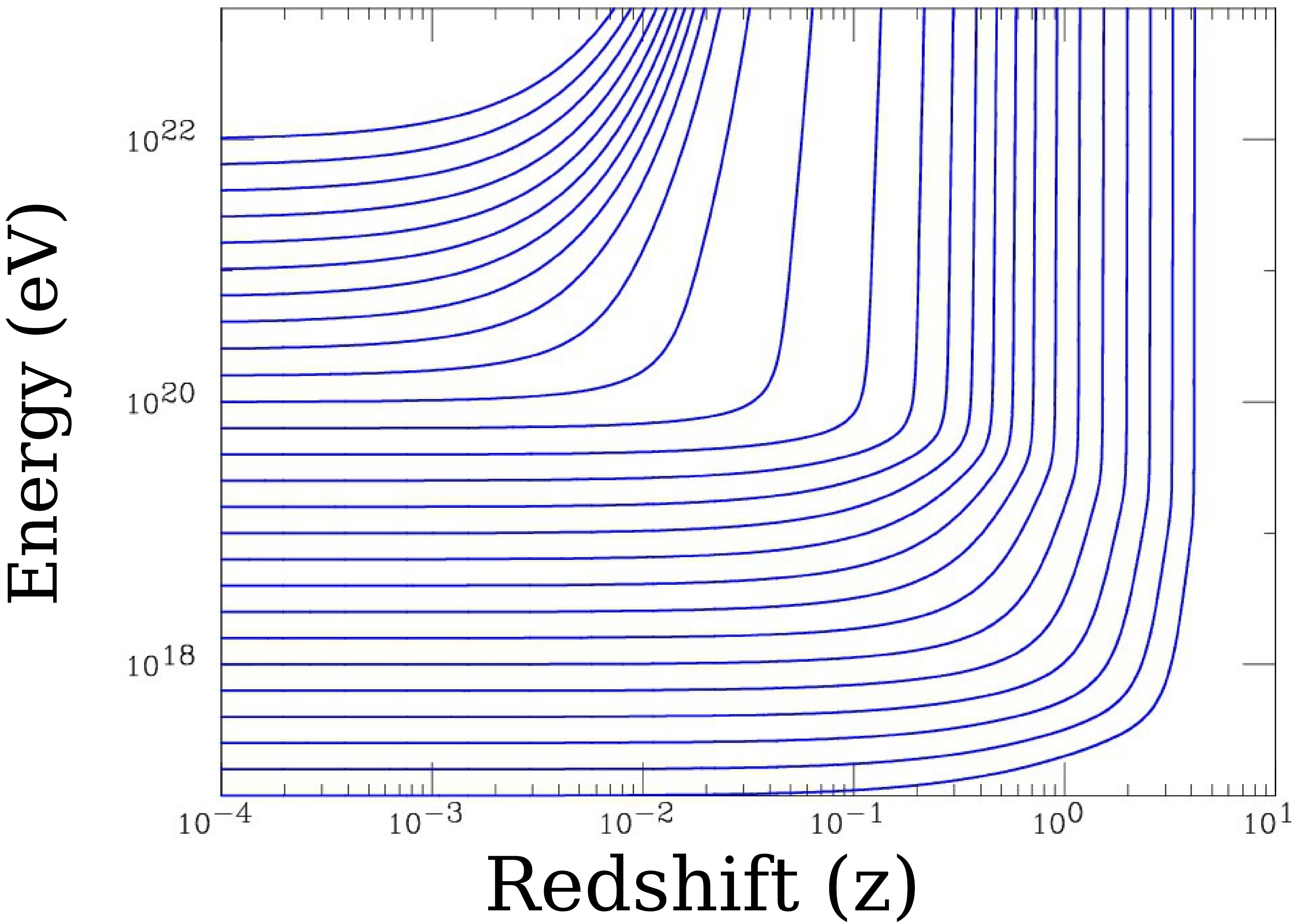


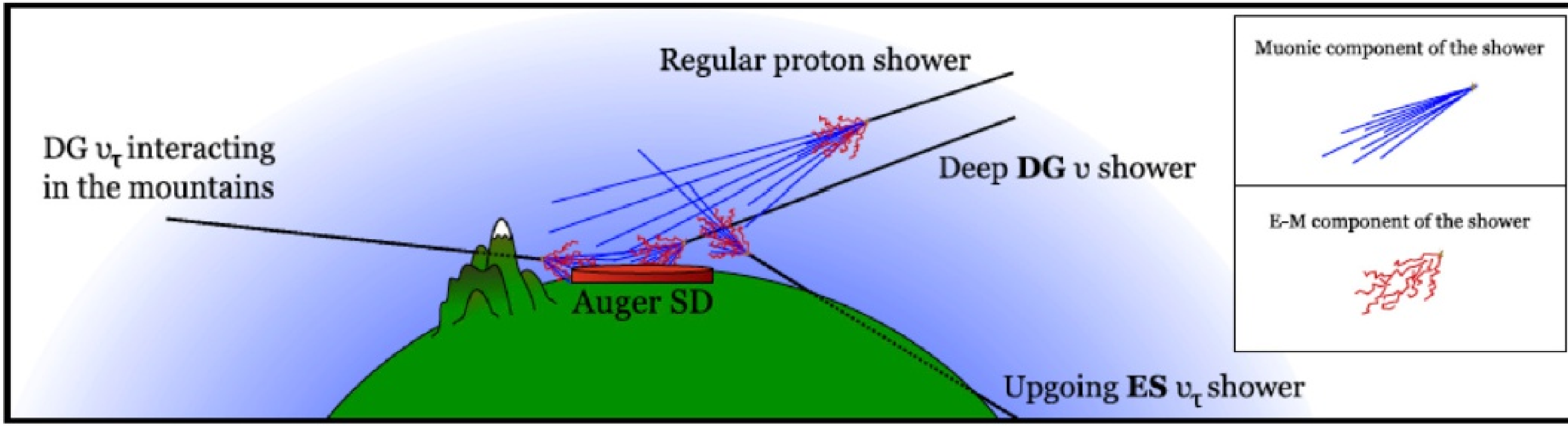
Greisen-Zatsepin- Kuzmin (GZK) suppression



NEUTRINO PRODUCTION

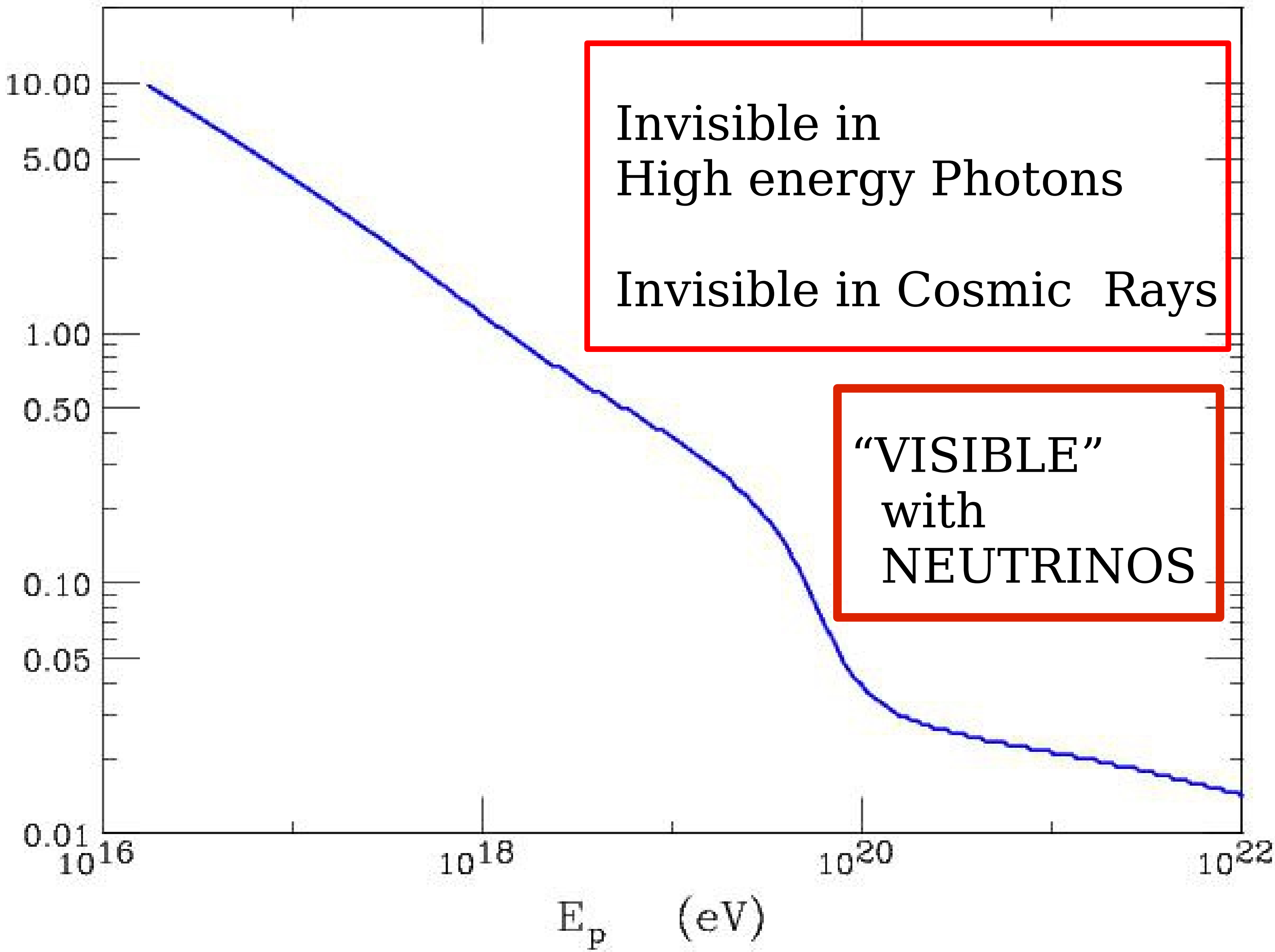
Proton Energy Evolution with Redshift



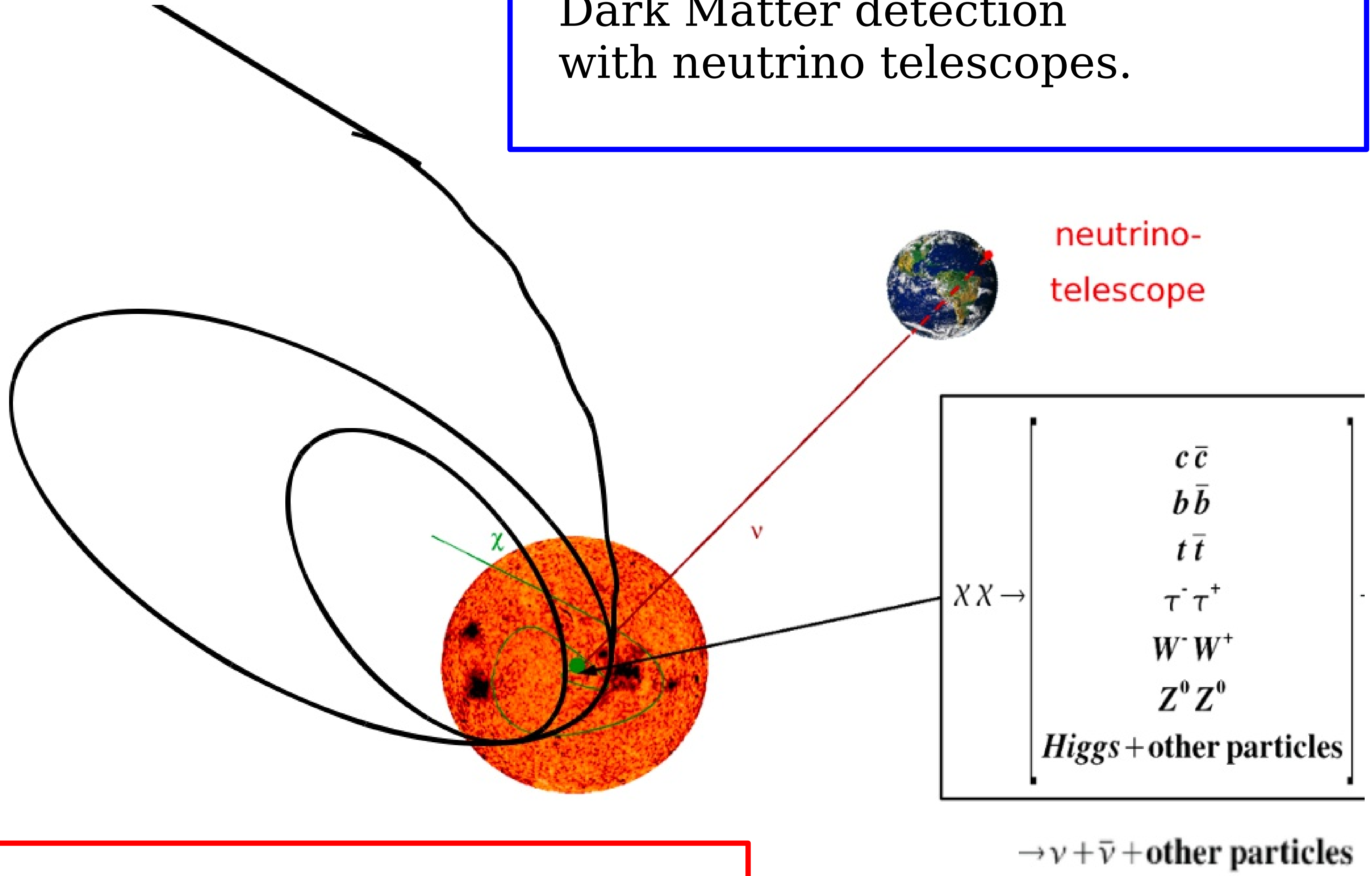


Regular proton shower
DG υ_τ interacting
in the mountains
Deep **DG** υ shower
Auger SD
Upgoing **ES** υ_τ shower
Muonic component of the shower
E-M component of the shower

High Energy Proton Horizon



Dark Matter detection
with neutrino telescopes.



Accretion of DM
Particles in the Sun (and Earth)

Number of neutrinos in the sun

$$\frac{dN}{dt} = C_c - C_a N^2 - C_e N$$

Capture Rate

Annihilation Rate

Evaporation Rate

$$\Gamma_a(t) = \eta \int_{\text{Sun}} d^3\mathbf{x} \, \langle \sigma_{\text{ann}} v \rangle \, n^2(t, \mathbf{x}) = \frac{C_a}{2} N^2$$

$$\frac{dN}{dt} = C_c - C_a N^2$$

$$N(t) = \sqrt{\frac{C_c}{C_a}} \tanh\left\{\frac{t}{\tau_c}\right\}$$

$$\tau_c \equiv (C_c C_a)^{-1/2}$$

$$\xrightarrow{t \gg \tau_c} \sqrt{\frac{C_c}{C_a}}$$

$$t = t_\odot = 4.6 \text{ Gyr}$$

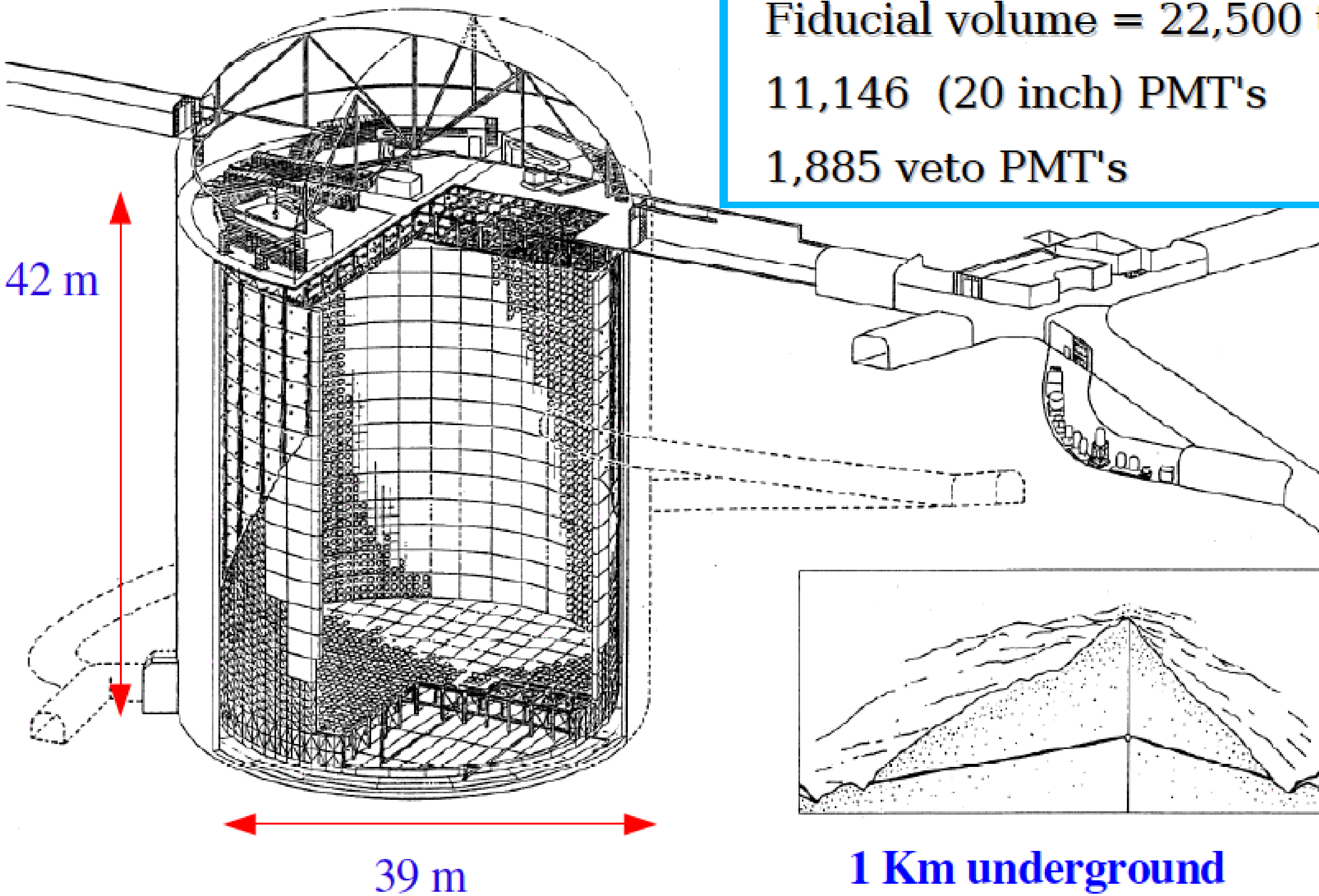
$$\tau_{c,\odot} \approx 10^8 \text{ yr}$$

$$\Gamma_a(t) = \frac{C_c}{2} \tanh^2\left\{\frac{t}{\tau_c}\right\} \xrightarrow{t \gg \tau_c} \frac{C_c}{2}$$

Annihilation Rate

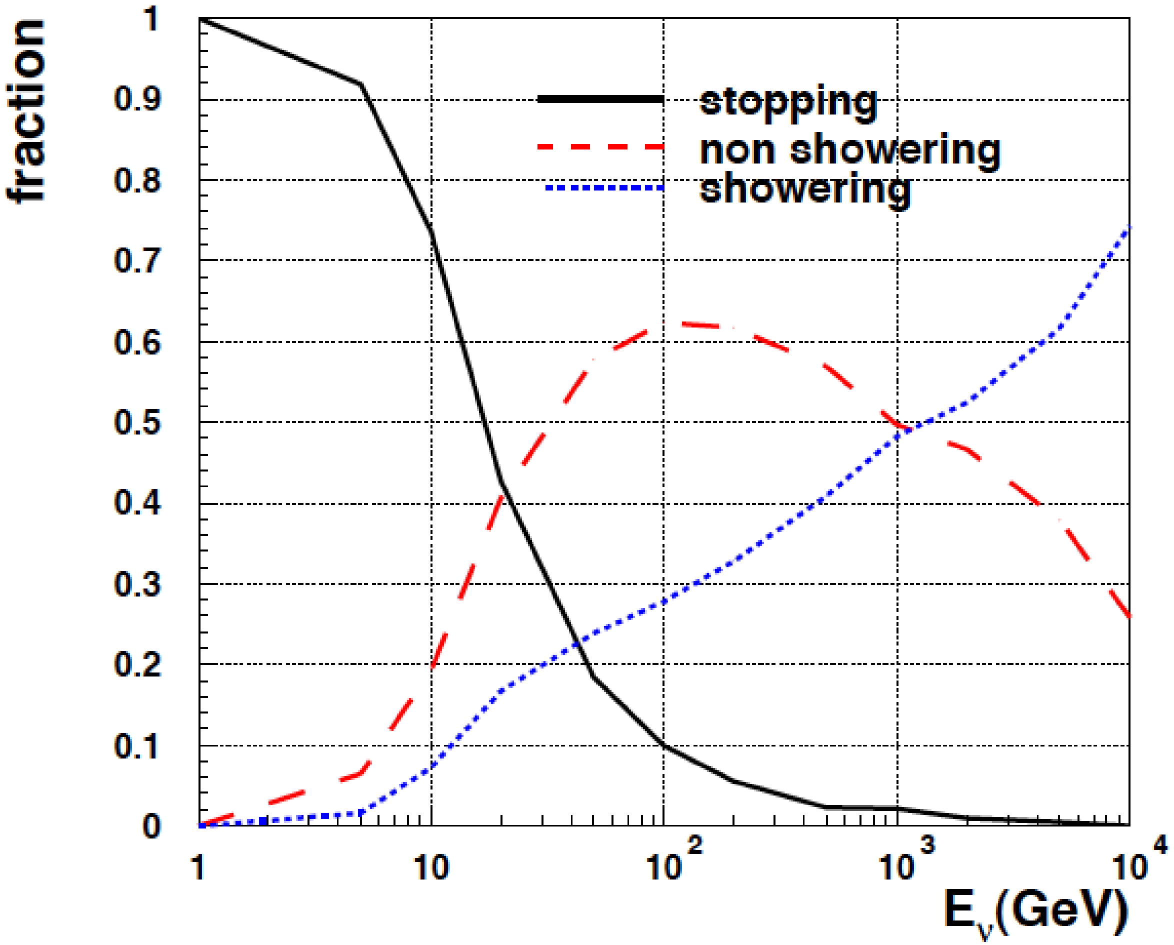
SuperKamiokande **detector**

- 50,000 tons of ultrapure water
- 2 m of water = veto counter
- Fiducial volume = 22,500 tons
- 11,146 (20 inch) PMT's
- 1,885 veto PMT's

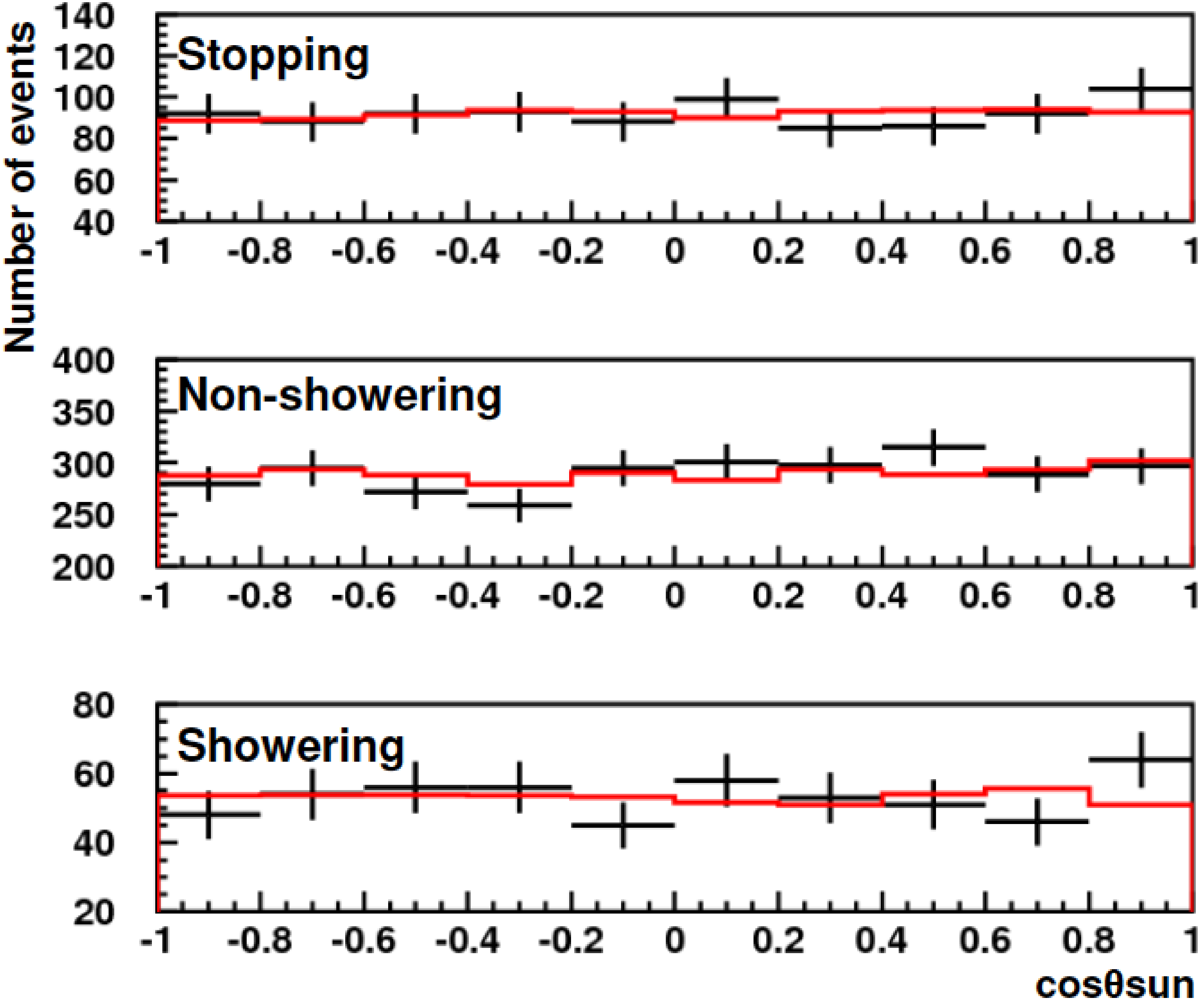


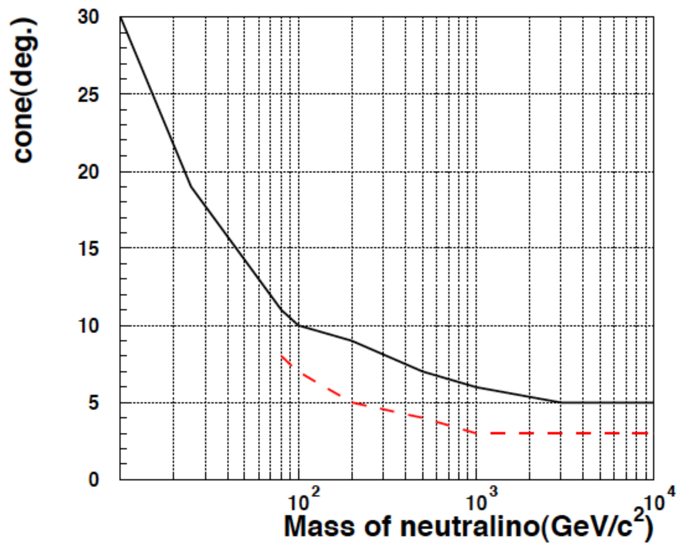
1 Km underground

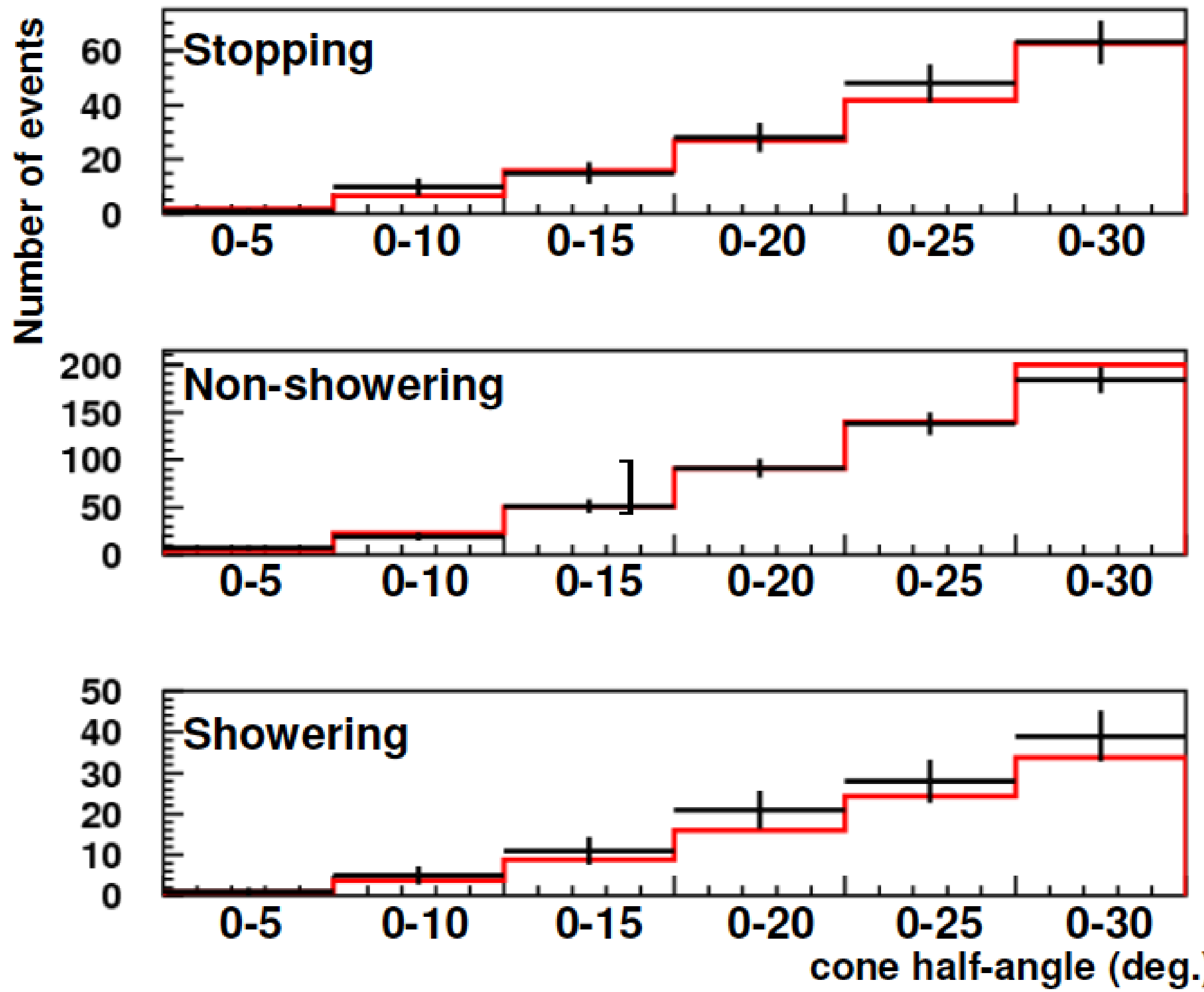
Muon (up-going) fron the direction of the SUN.



No excess from the sun direction (cos theta = 1)







Red line=
estimated Background from atmospheric neutrinos

Neutrino Astronomy: beyond the "Km3 concept"

Radio, Acoustic,.....

Radio Detection of neutrinos

ANITA-II over Antarctica

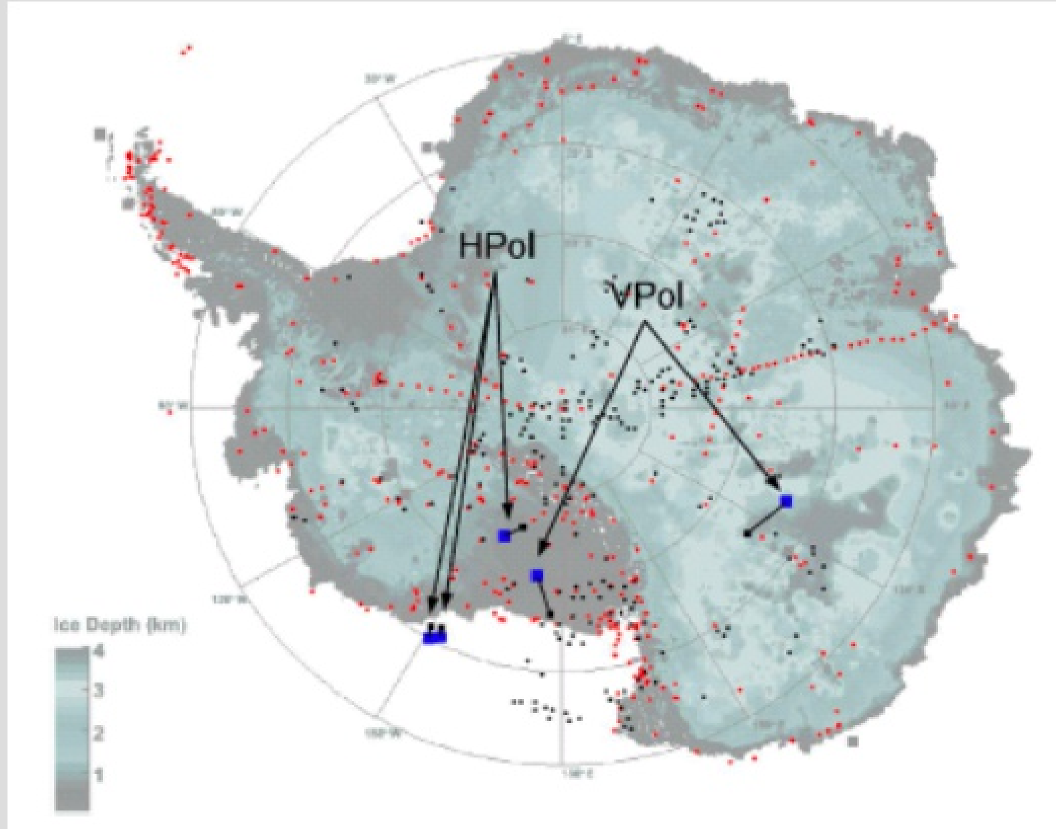


FIG. 3: Events remaining after unblinding. The Vpol neutrino channel contains two surviving events. Three candidate UHECR events remain in the Hpol channel. Ice depths are from BEDMAP [12].

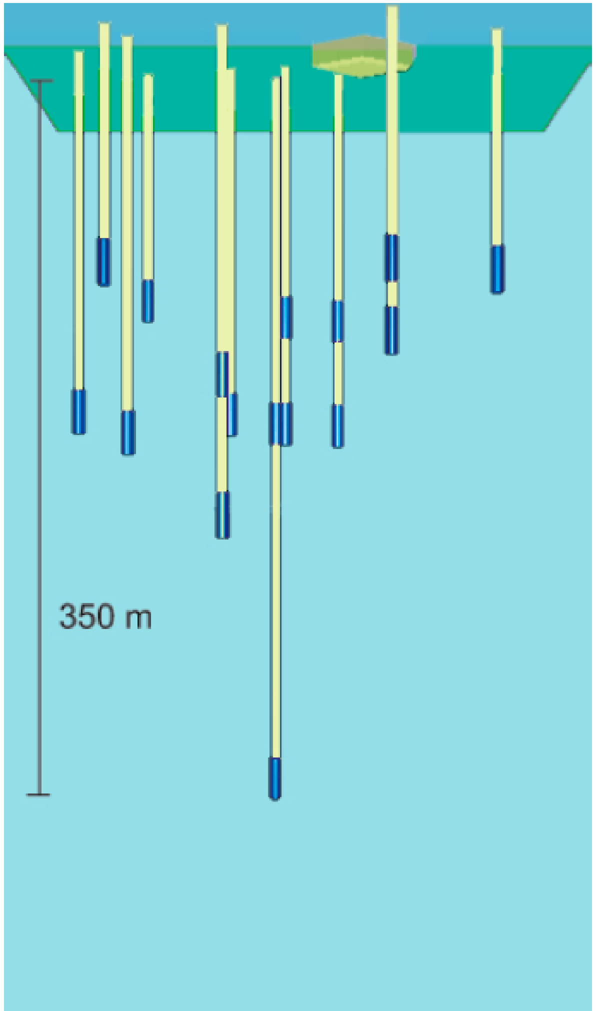
Vpol:1 neutrino candidate;

HPol:3525 1019 eV

http://arxiv.org/abs/1003.2961

RICE experiment architecture

- Antarctic ice is neutrino target
- In-ice array of radio antennas
- 20 channels, 200-500 MHz
- Depths 100-300 meters
- Signal digitized at the surface
- Deployed near South Pole Station



10^7 to 10^{11} GeV: Radio ice Cherenkov detection

Askaryan Radio Array (ARA)

- a very large radio neutrino detector at the South Pole

Ref: Allison et al., Astropart.Phys. 35 (2012) 457-477, arXiv:1105.2854 (Design and performance paper)

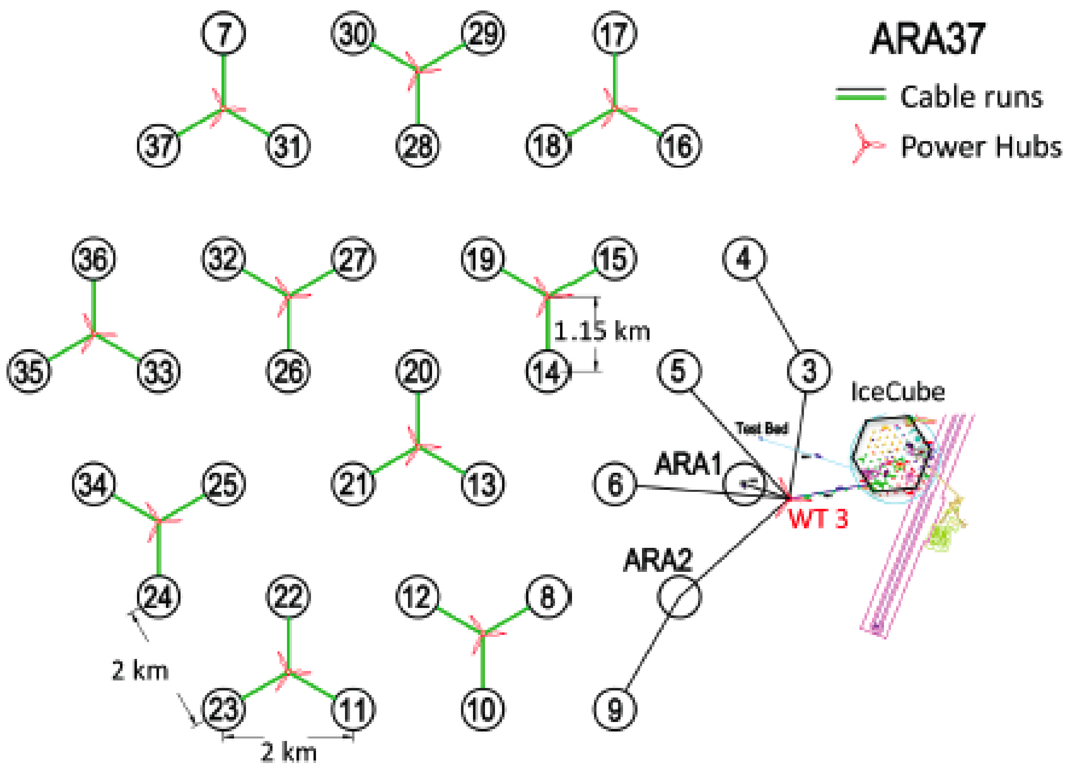
Poster session at this conference:
→ H. Landsman, ARA Design and Status
→ J. Davies, ARA prototype and first station

Scientific Goal:

- Discover and determine the flux of highest energy cosmic neutrinos.
- Understanding of highest energy cosmic rays, other phenomena at highest energies.

Method:

Monitor the ice for radio pulses generated by interactions of cosmic neutrinos with nuclei of the 2.8km thick ice sheet at the South Pole



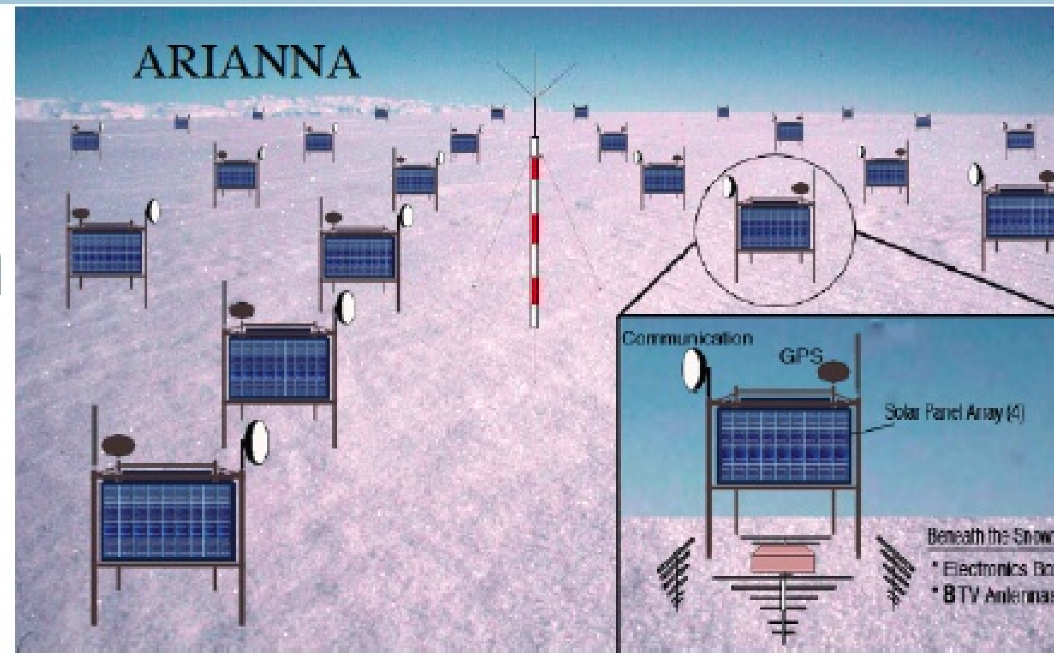
Areal coverage: ~150km^2

10^7 to 10^{11} GeV: Radio ice Cherenkov detection

ARIANNA

- L. Gerhardt et al., Nucl.Instrum.Meth. A624 (2010) 85-91
- Poster 18-3: J. Tatar. S. Barwick

31 x 31 array
[30 km x 30 km]



ARIANNA

US, S. Korea, England, New Zealand

Barwick, astro-ph/0610631