Detection and phenomenology of cosmic neutrinos I

An overview biased towards the Mediterranean Sea

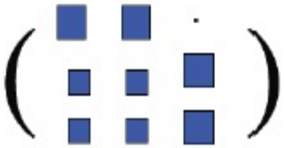
Antoine Kouchner
Université Paris Cité
Laboratoire APC

Credits: Ch. Spiering, F. Halzen, A. Karle, P. Coyle, Th. Patzak, D. Vignaud, E. Resconi, A. Coleiro J. Vandenbroucke …many others

COST CA18108 2022 Second Training Scool

Belgrade (Serbia), September 2022

Outline



Introduction to neutrinos

Today's picture

Historical aspects

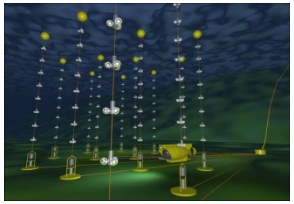
Neutrino astronomy

Scientific motivations

Historical aspects

Oscillation detour

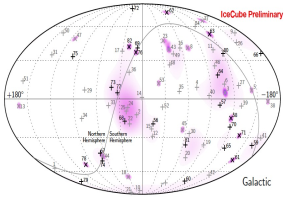
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



Selected results

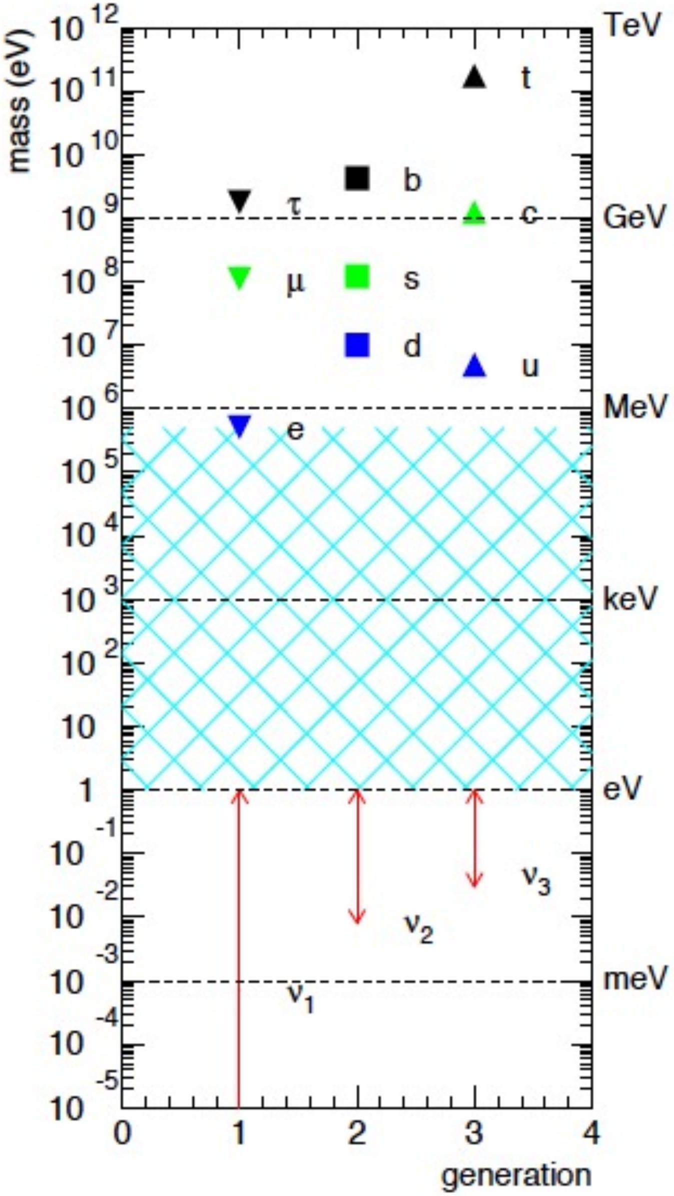
Diffuse Flux, point sources

Multi-messenger search

KM3NeT

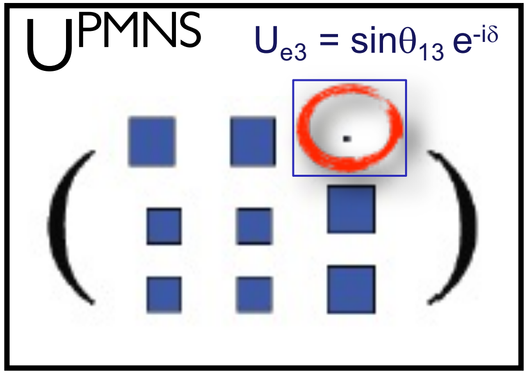
Future prospects

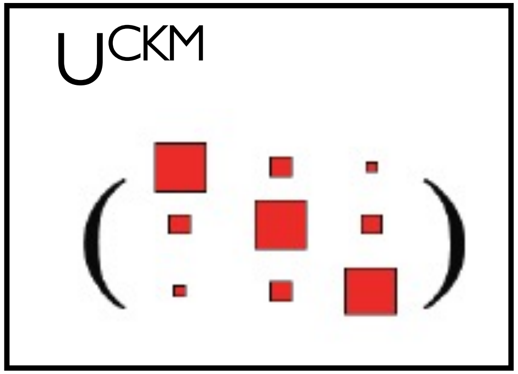
Today’s picture



- Neutrino is the only fermion with charge = 0
- Neutrinos have distinct masses => why so light?
- Neutrinos mix like quarks ⟹ why so similar/different?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{e\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$





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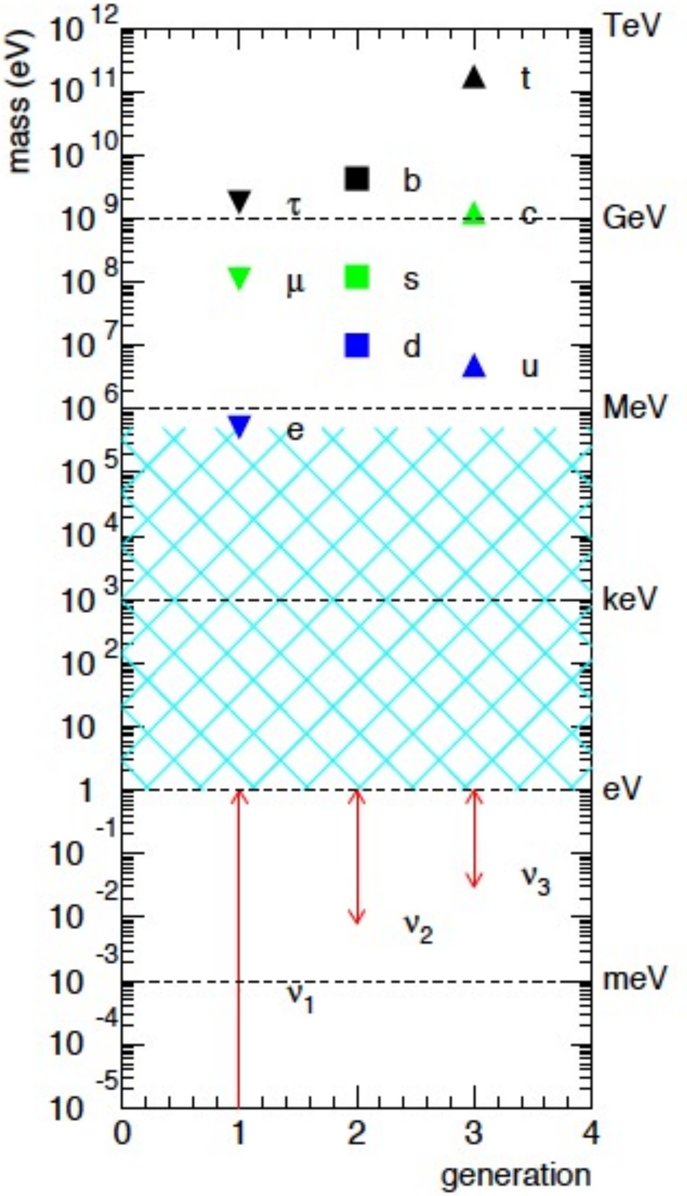


- Neutrino is the only fermion with charge = 0
- Neutrinos have distinct masses => why so light?
- Neutrinos mix like quarks ⟹ why so similar/different?
- Often considered as first evidence of physics beyond the Standard Model.
- Are neutrinos fundamentally different ?
- Dirac or Majorana fermion ?

  - Leptogenesis in the Early Universe
  - See-saw mechanism to explain the small mass
  - Heavy right handed Majorana neutrinos
  - Neutrino nature being tested in ββ decay experiment

Neutrino oscillations today

PMNS (Pontecorvo–Maki–Nakagawa–Sakata) unitariy matrix.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric
θ_A~45°

Reactor
θ_{13}~9°
↓
CP violating phase δ_{CP}

Solar
$\theta_\odot$~30°

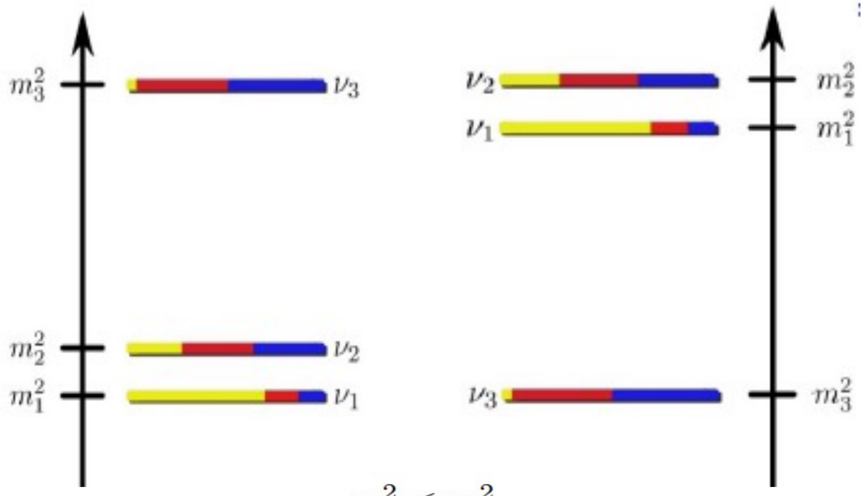
Majorana

5 Knowns:

δm^2 ~ 7 x 10^{-5} eV^2
Δm^2 ~ 2 x 10^{-3} eV^2
$\sin^2\theta_{12}$ ~ 0.3
$\sin^2\theta_{23}$ ~ 0.5
$\sin^2\theta_{13}$ ~ 0.02

All parameters measured to fair precision except:

- mass hierarchy
- octant of θ_{23} (i.e. <45° or >45°)
- CP phase



$$m_1^2 < m_2^2$$

$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

Nobel Prize in Physics 2015

Takaaki Kajita
SuperKamiokande
University of Tokyo, Japan

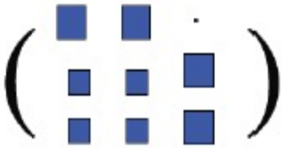
Atmospheric Neutrinos 1998

Arthur B. McDonald
Sudbury Neutrino Observatory
Queen’s University, Canada

Solar Neutrinos 2001

For the discovery of neutrino oscillations, which shows that neutrinos have mass

Outline



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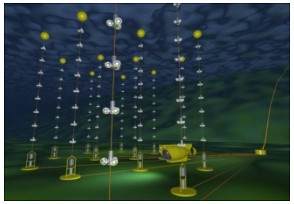

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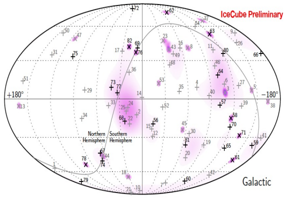

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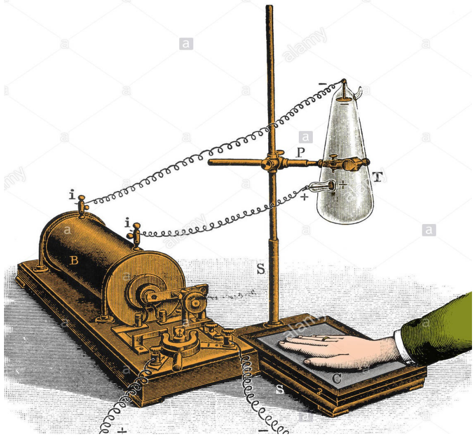
Historical context

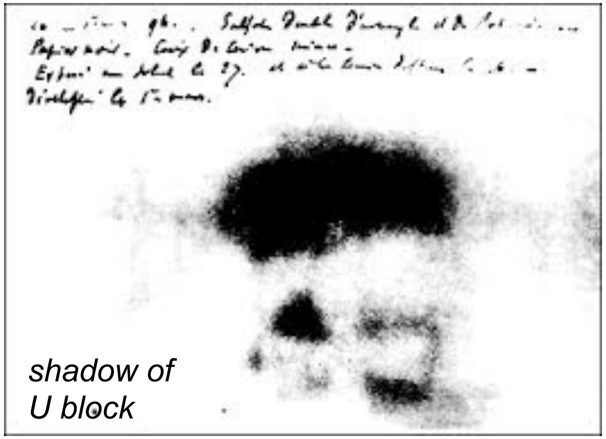
At the turn of century: Discovery of radioactivity

1895, Roentgen
Discovery of X-rays

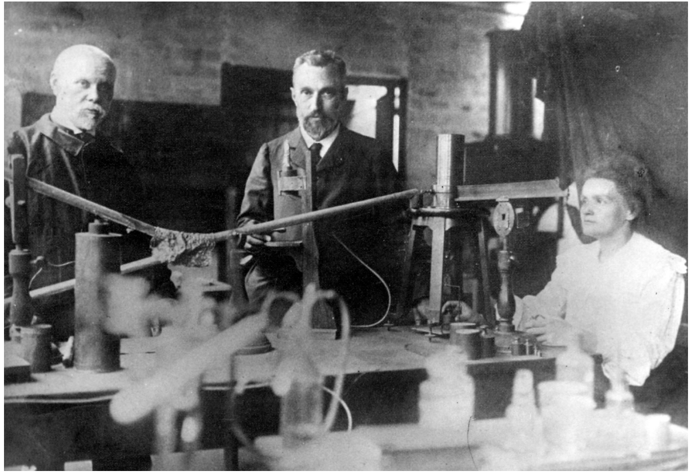


First Nobel Prize 1901 !

1896, Becquerel
Accidental discovery of radioactivity

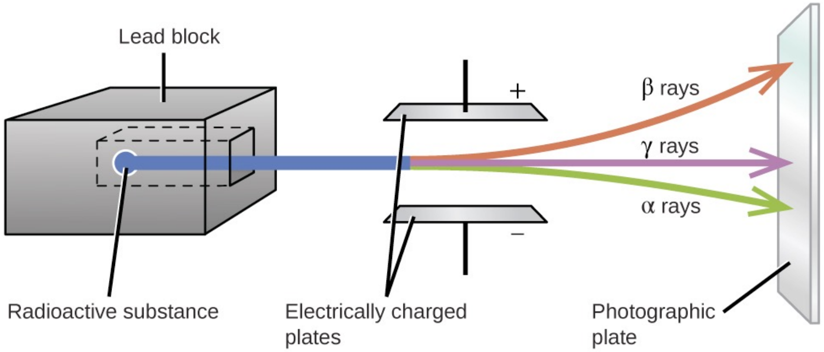


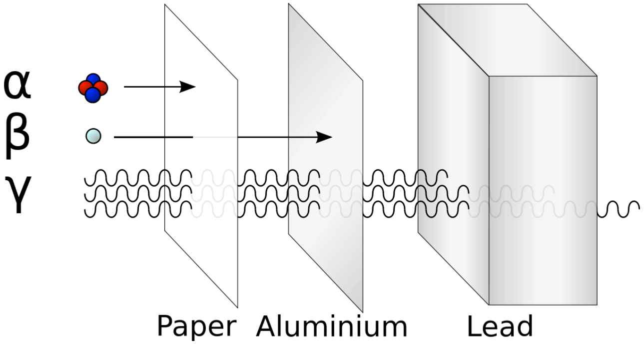
1898, Marie & Pierre Curie
Discovery of Po and Ra



Shared Nobel Prize 1903

1899-1900: Rutherford & Villard identify 3 types of nuclear radiation: α, β and γ « rays »with different properties





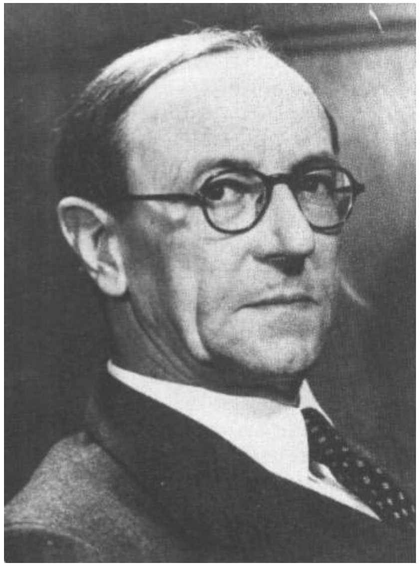
β Radioactivity : beginning of the story

1911-1912 : Van Bayer, O. Hahn, L. Meitner
measure the energy of β electrons → discrete spectrum !
📖 Z Physik 12 (1911) 273

1878 - 1968

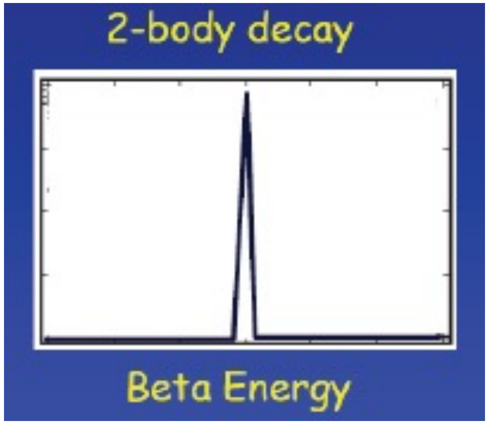
Compatible with interpretations of that time:
nucleus = A protons + (A-Z) electrons [+Z orbital electrons]
β Disintegration : (A, Z) —> (A, Z-1) + e^-

1914: James Chadwick: the electron energy spectrum is continuous (ionization chamber)

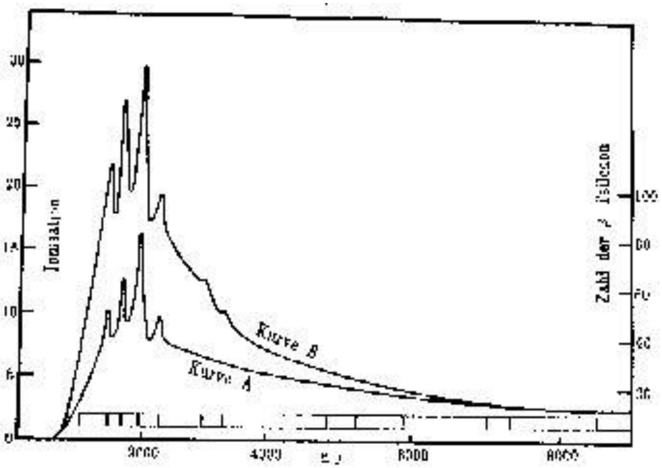


1891 - 1974

Expected



Measured

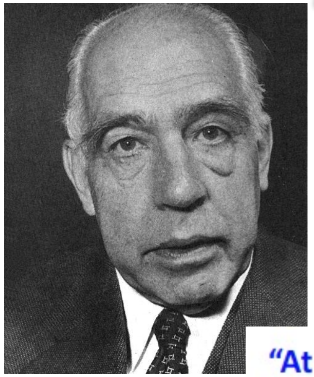


"there is probably some silly mistake somewhere" → *persisting*

Possible theoritical solutions

“We have verified your results completely. It seems to me now that there can be absolutely no doubt that you were completely correct in assuming that beta radiations are primarily inhomogeneous. But I do not understand this result at all.”

Lise Meitner, letter to Ellis (1930)

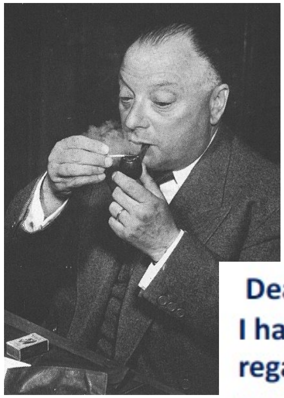


Niels Bohr (+ Kramer, Slater):

Energy is conserved only statistically (on average)

“At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-decay disintegrations, and are even led to complications and difficulties in trying to do so. Of course, a radical departure from this principle would imply strange consequences if such a process could be reversed.”

Bohr 1932



Wolfgang Pauli

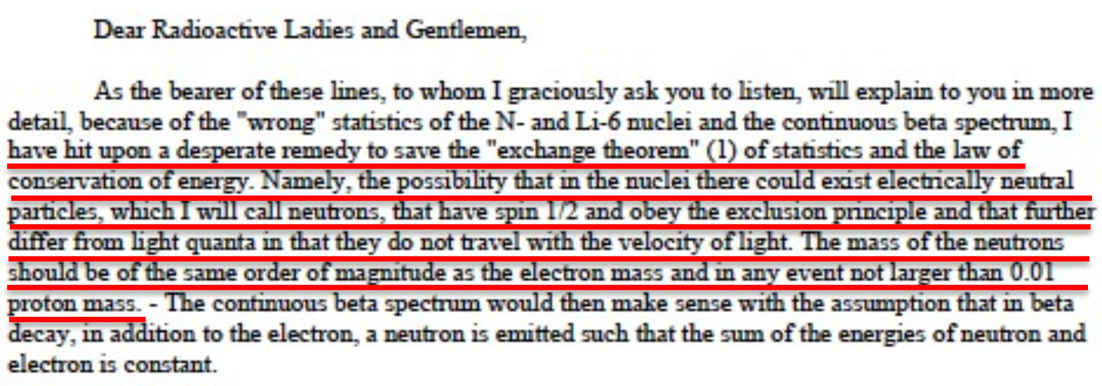
Another, undetected particle is emitted along with the electron

Dear Radioactive ladies and gentleman,

I have come upon a desperate way out regarding the wrong statistics of the – and Li-6 nuclei, as well as to the continuous β-spectrum, in order to save the “alternation law” of statistics and the energy law. To wit, the possibility that there could exist in the nucleus electrically neutral particles, which I shall call neutrons, which have spin ½ and satisfy the exclusion principle and which are further distinct from light-quanta in that they do not move with light velocity.

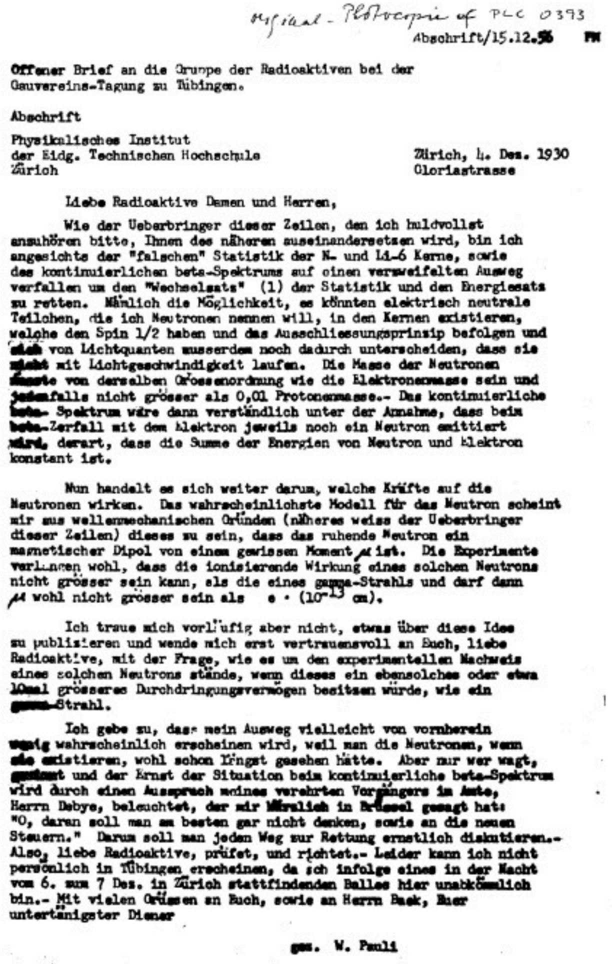
Pauli, 1931

Dec 4th 1930: Pauli's letter



Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.



Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

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

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm$)$.

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

- ❖ **solves the « wrong» statistics of ^{14}N and ^{6}Li**

At the time: Nucleus = A protons + (A-Z) nuclear electrons
& Parity of atomic number Z thought to determine
the spin of the nucleus (WRONG!)

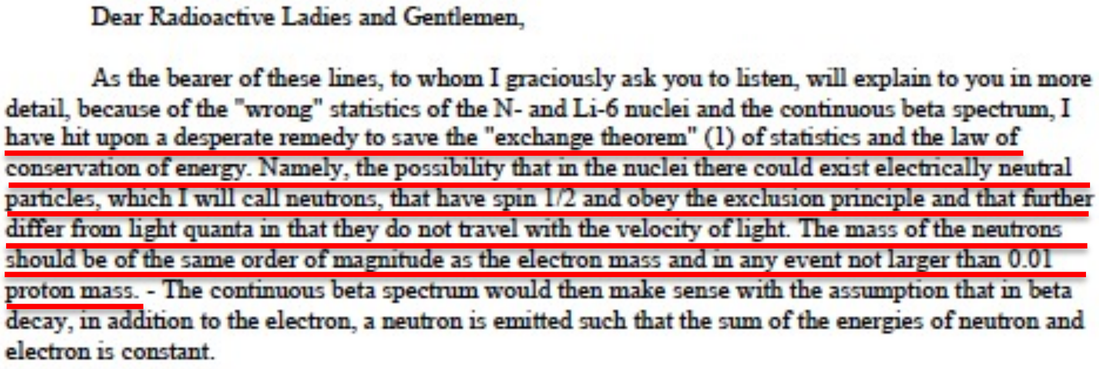
For Nitrogen: 14p +7 e- → total spin half-integer
In contradiction with experimental measurement
(Kronig, Heitler & Hezberg): spin is integer (probably 1)

→ Solution:

The nucleus is made of protons and other neutral particles
The mass number determines the spin

…a motivation for W. Pauli to introduce another **spin ½ , neutral particle** inside the nucleus

Dec 4th 1930: Pauli's letter



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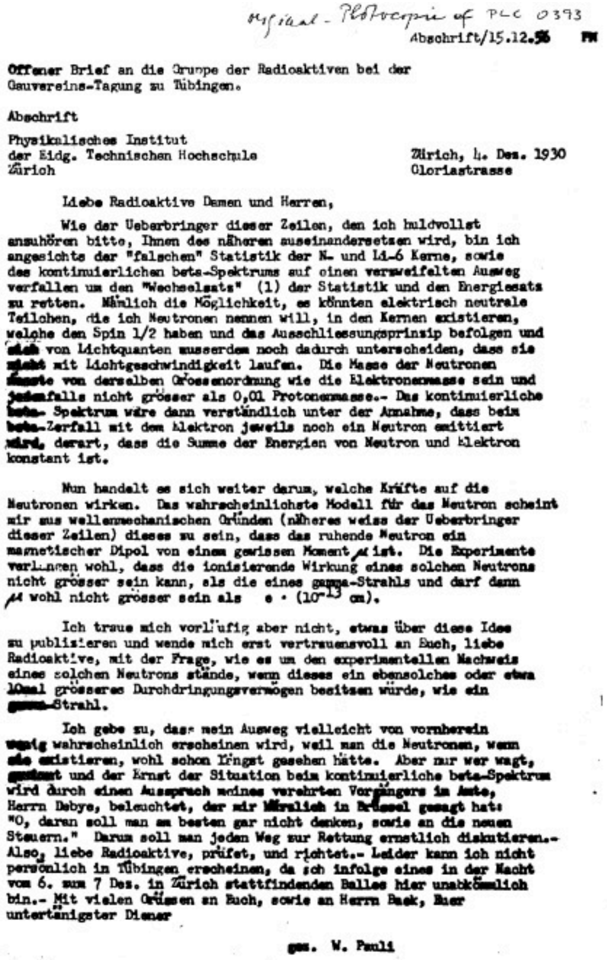

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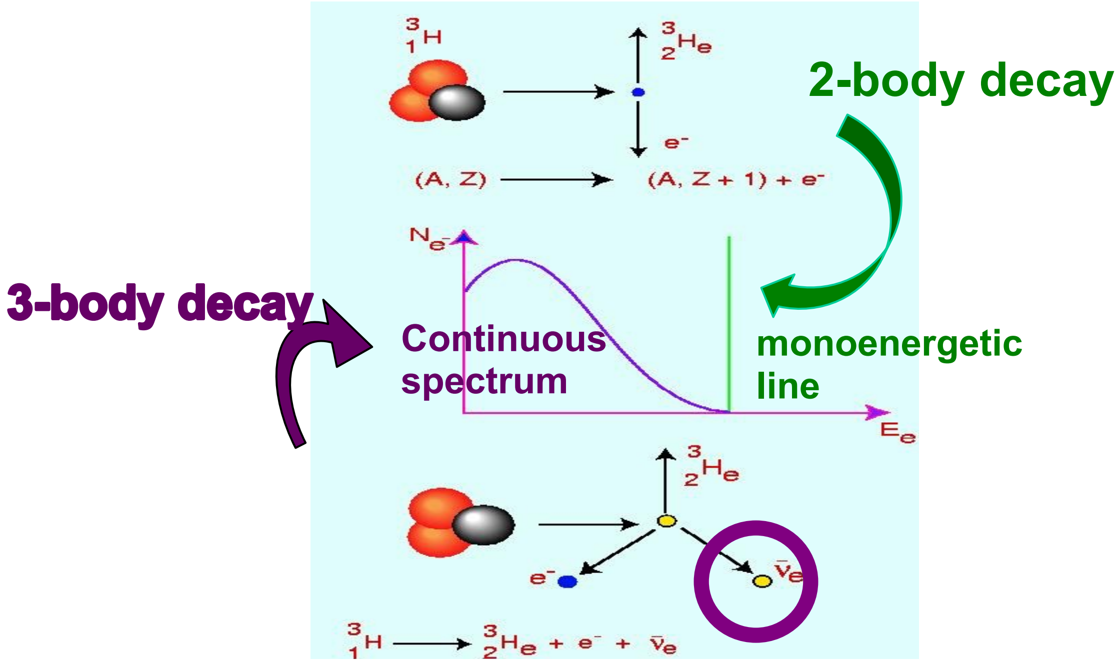
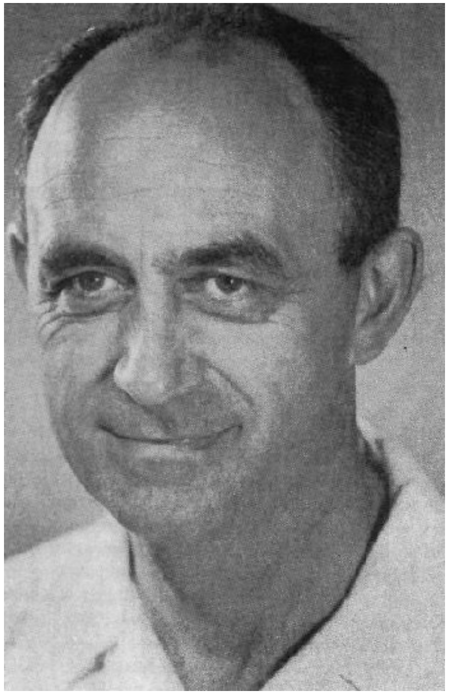
gez. W. Pauli

- ❖ **solves the problem of continuous beta spectrum**:



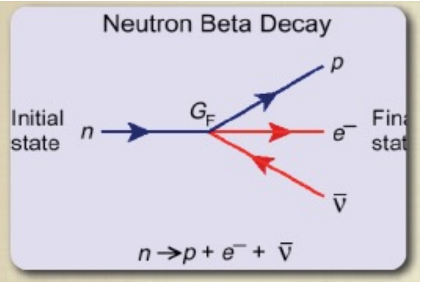
Pauli called the new particle « neutron »…

1933: Fermi theory (β)



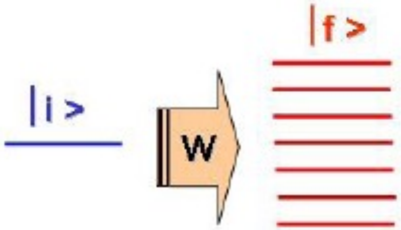
1901 - 1954

📖 Nuovo Cimento 11 (1934) 1; Z Physik 88 (1934) 161.



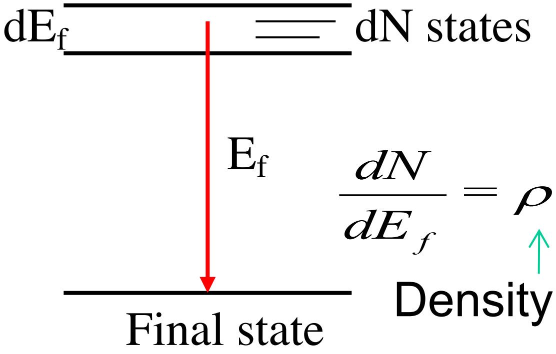
- A nuclear transition takes place when a neutron is destroyed and a proton is created. An electron and a neutrino are emitted. Local interaction.
- Neither the electron nor (anti)neutrino pre-exist in the nucleus. Both are created in the decay process.

- The neutrino is formally treated as a ½ spin particle
- Fermi inspires from the **theory of perturbations at first order**
- **Fermi's Golden Rule**



$$\delta P_{i \to f} = \frac{2\pi}{\hbar} |<f|\, W \,|i>|^2 \, \rho(E_f) \quad \mathrm{sec}^{-1}$$

$$\boxed{\lambda = \frac{2\pi}{\hbar} |<f|\, W \,|i>|^2 \, \rho(E_f) \quad \mathrm{sec}^{-1}}$$



$$\frac{dN}{dE_f} = \rho(\mathrm{E})$$

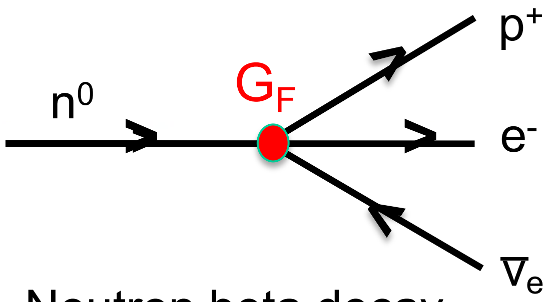
$\uparrow$

Density of final states

$$\lambda = \frac{1}{\tau} \ll \frac{\Delta E}{\hbar}$$

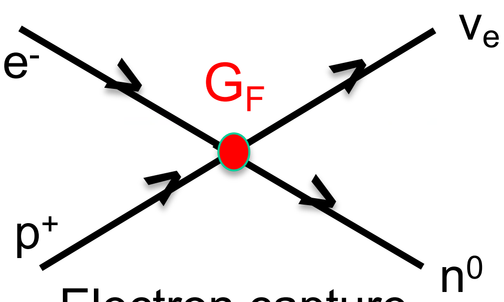
Slowness of weak interactions justifies treatment at 1st order

From Fermi theory to V-A theory



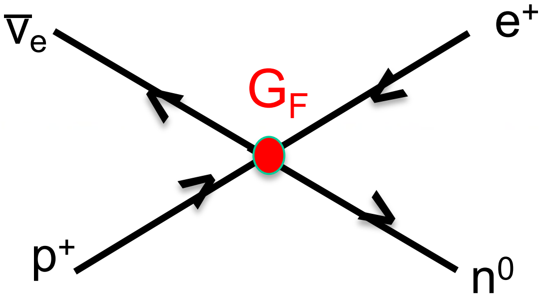
Neutron beta decay

$n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$



Electron capture

$p^+ + e^- \rightarrow n^0 + \nu_e$



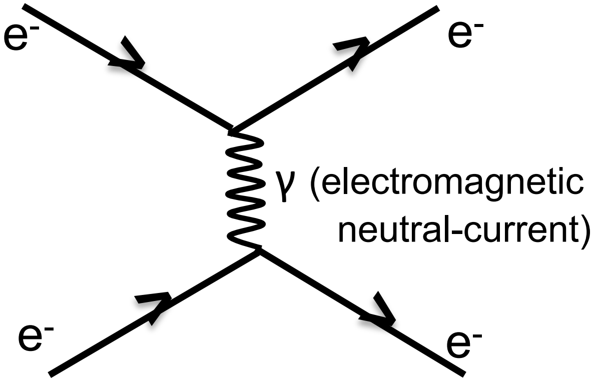
Inverse beta decay

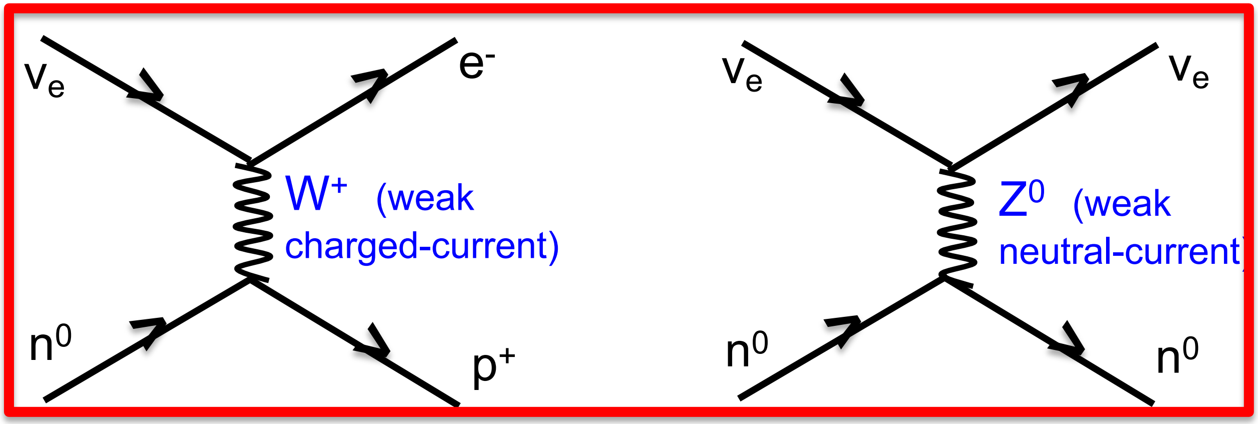
$\bar{\nu}_e + p^+ \rightarrow n^0 + e^+$

1934: Gian-Carlo Wick: Modification of Fermi's theory to account for β^+ decays

1937: Luis Walter Alvarez: Experimental proof of electronic capture

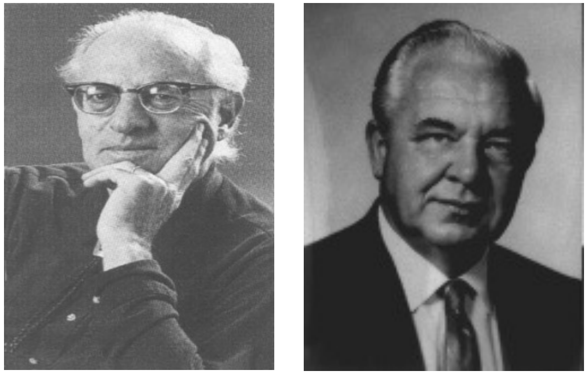
…which leads later on to the modern quantum field theory of electroweak interactions:





Reines and Cowan

Cf tutorial



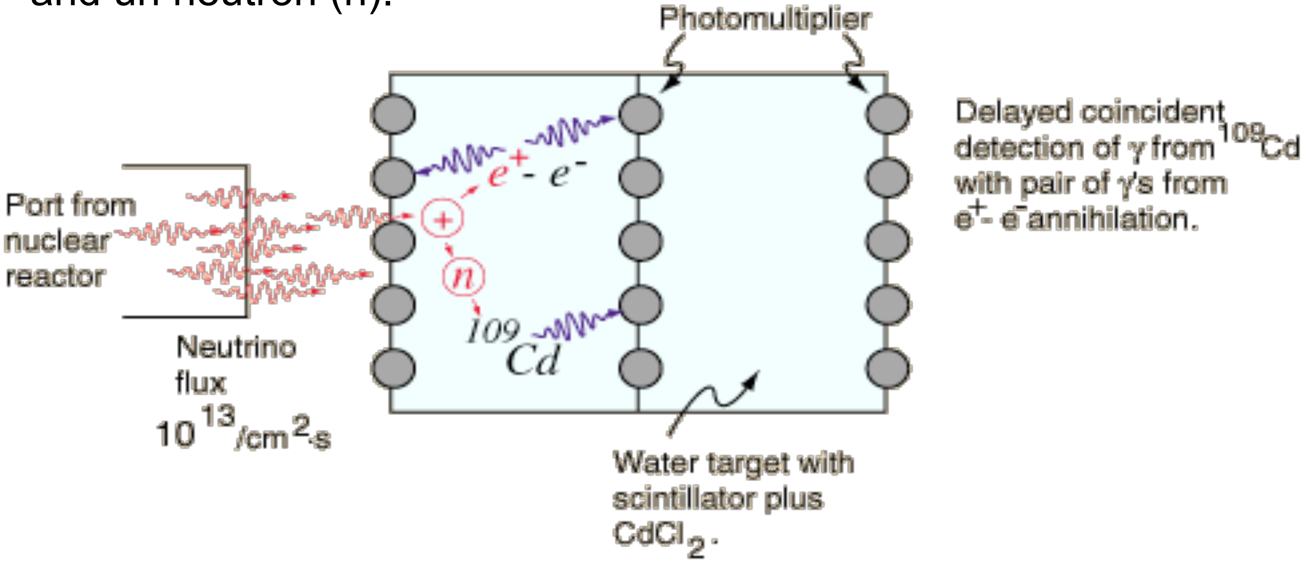
$$p+\overline{\nu} \rightarrow n+e^{+}$$

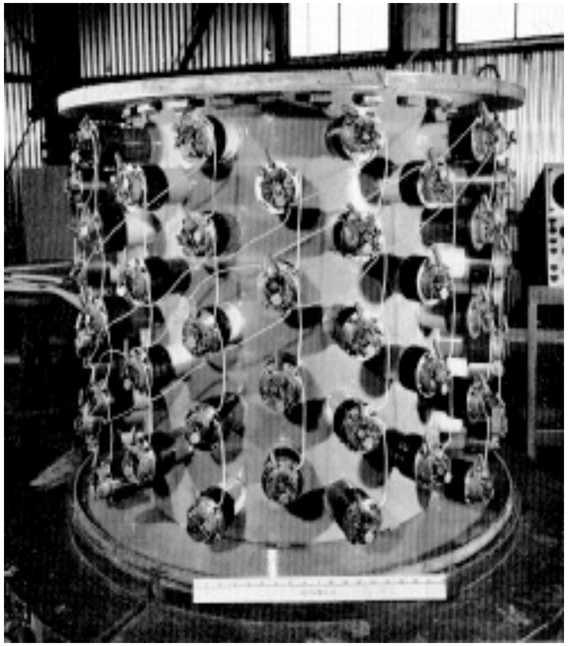
Reaction threshold = 1,8 MeV

1953 : Hanford
300 liters of scintillators only.
Encouraging results, but too high background

'Poltergeist' project

1956 : Savanah River
Target made of 400 liters of water and Cadmium Chlorure.
The neutrino interacts with a proton and undergo a positon (e+) and un neutron (n).

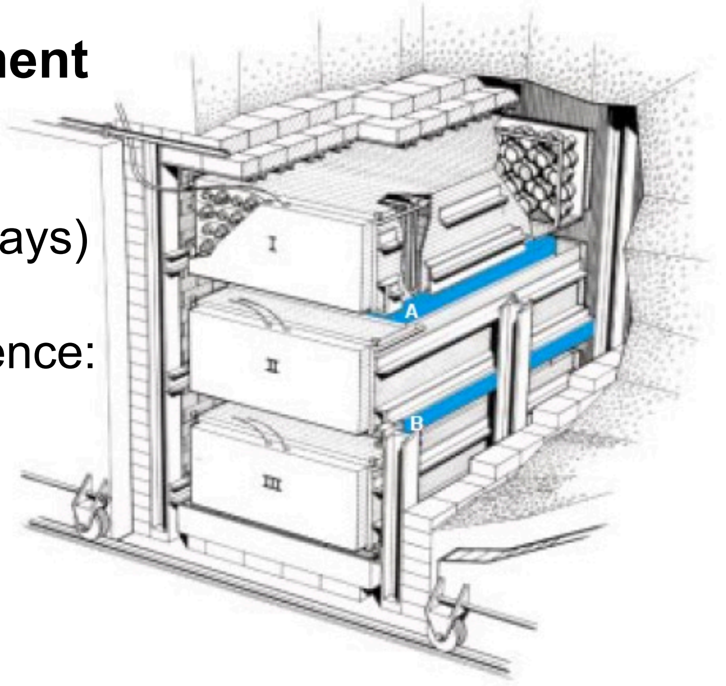




Reines and Cowan : $\bar{\nu}$ discovery

1956: Cowan & Reines, the Savannah experiment

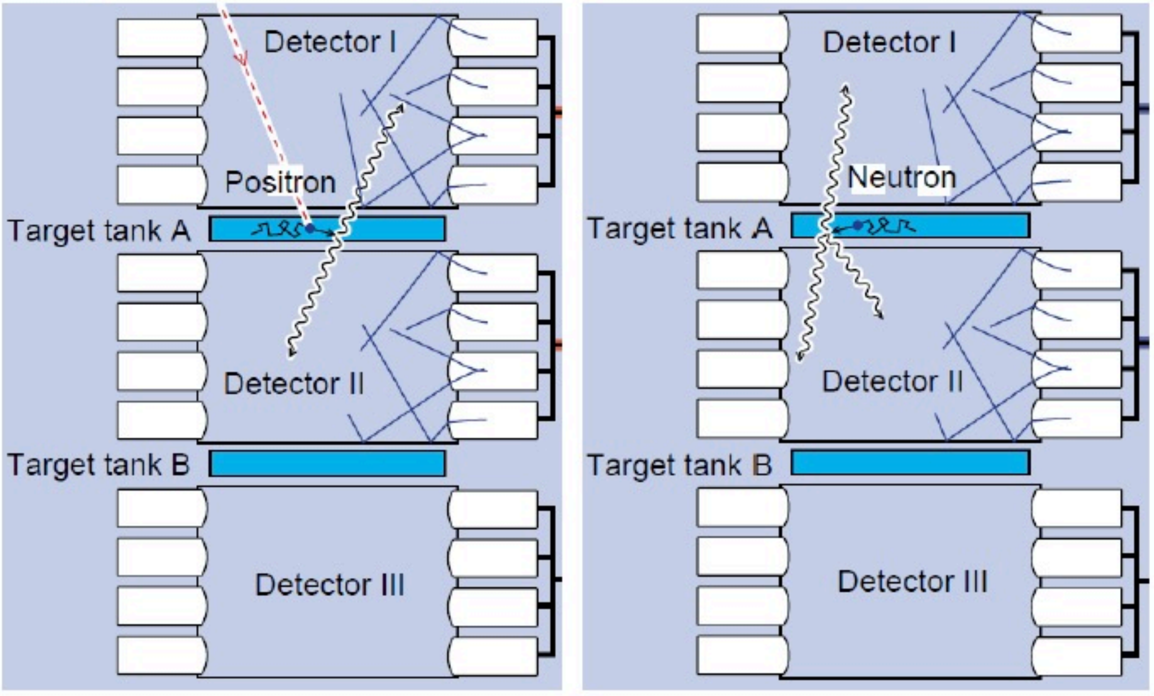
- Larger detector
- Better background rejection (mainly due to cosmic rays)
  - → 12 m overburden
  - → « Sandwich » detector to perform (anti)coincidence:



$e^+ + e^- \rightarrow \gamma + \gamma$

delayed

$n + Cd \rightarrow Cd^* \rightarrow Cd + \gamma' s$



A, B: 200 liters H_2O+$CdCl_2$ (neutron capture)

I,II,III: 1400 l liquid scintillator (photon detection)

Reines and Cowan : $\bar{\nu}$ discovery

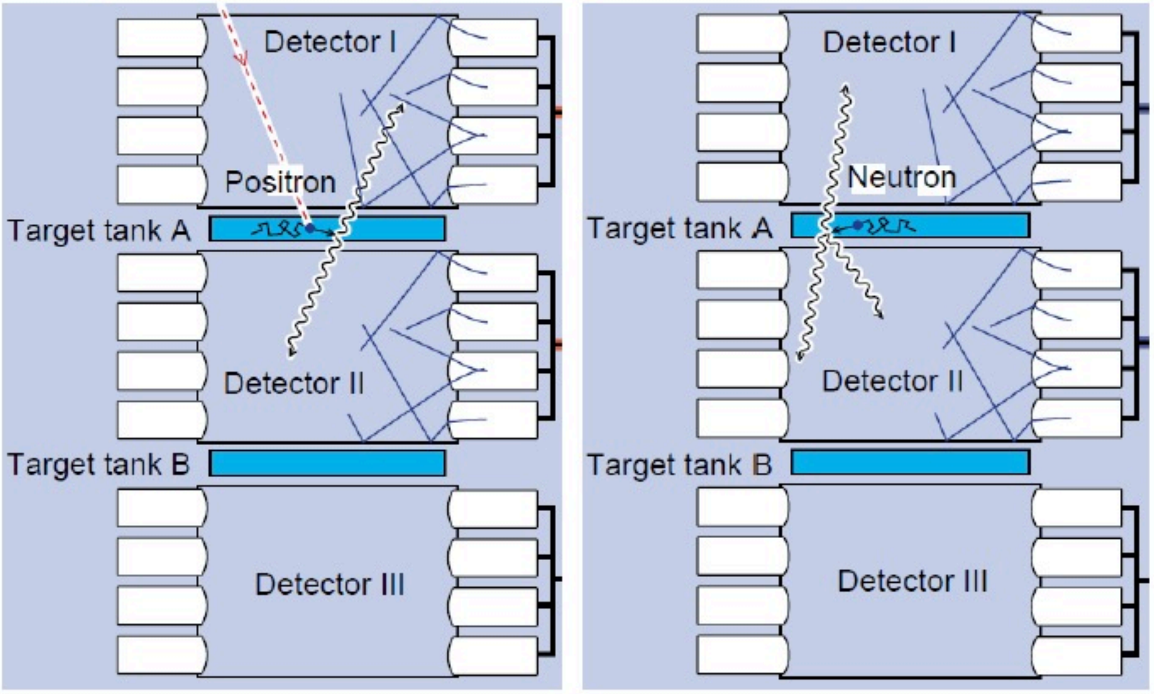
1956: Cowan & Reines, the Savannah experiment

- ❖ Larger detector
- ❖ Better background rejection (mainly due to cosmic rays)
  - → 12 m overburden
  - → « Sandwich » detector to perform (anti)coincidence

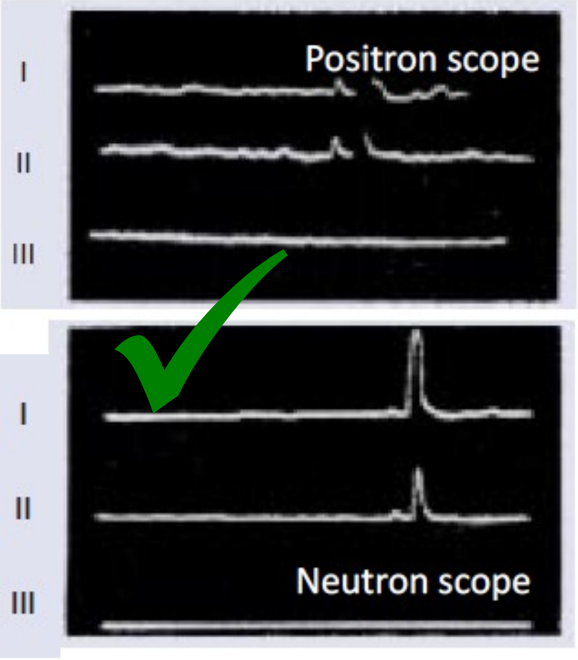
delayed

$e^+ + e^- \to \gamma + \gamma$

$n + Cd \to Cd^* \to Cd + \gamma' s$



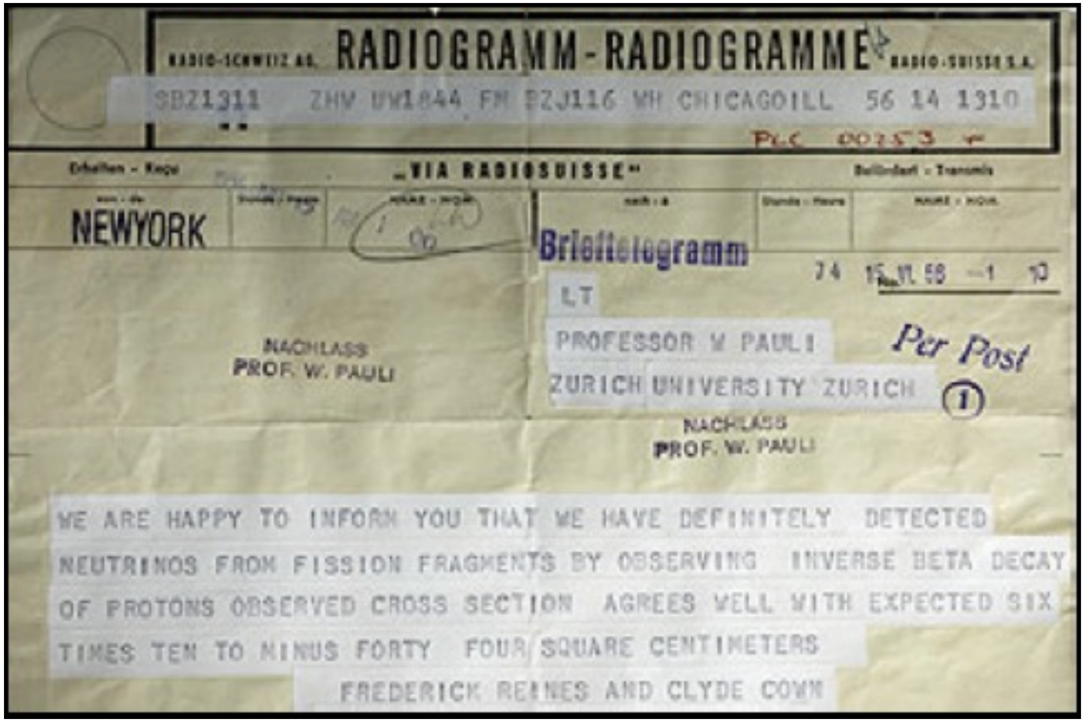
Oscilloscope signals



Probably due to cosmic ray crossing the whole detector

The discovery of the (anti)neutrino

…The neutrino was discovered ! (actually: the **electron antineutrino**)



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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

①

NACHLASS
PROF. W. PAULI

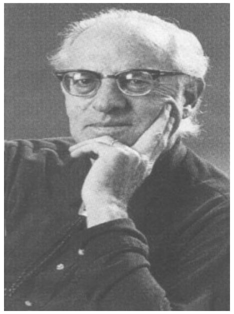
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

Nobel Prize 1995

> *"The first observation of neutrinos was a pioneering contribution that opened the doors to the region of "impossible" neutrino experiments."*
> *The Royal Swedish Academy of Sciences*

F. Reines



1918-1998

C. Cowan

1919-1974

A different path: radiochemical methods

1946: Pontecorvo proposes a radiochemical method for neutrino detection

$$\nu + {}^{Z}_{A}X \rightarrow {}^{Z+1}_{A}Y + e^{-}$$

(neutrino capture on neutron)

Based on the observation of the decay of daughter nucleus

1913 - 1993

A promising candidate reaction:

$$\nu + {}^{37}_{17}\mathrm{Cl} \longrightarrow e^{-} + {}^{37}_{18}\mathrm{Ar}$$

- CCl_4, C_2Cl_4 are cheap, non-flammable liquids
- ^{37}Ar are unstable with a convenient half-life (34.8 days)
- Relatively easy extraction of ^{37}Ar (rare gas)
- **Low neutrino capture threshold**:

$$E_\nu \gtrsim 0.814\ \mathrm{MeV}$$

Sources of neutrinos suggested by Pontecorvo:
- Nuclear fission (reactor neutrinos)
- Solar neutrinos

Neutrino vs. antineutrino

1955-1958: R. Davis, first radiochemical experiment

$$\nu + {}^{37}_{17}\mathrm{Cl} \longrightarrow e^- + {}^{37}_{18}\mathrm{Ar}$$

(later applied to solar neutrino detection)

1914-2006

❖ 3800 liters of carbon tetrachloride (CCl_4)
First at Brookhaven (Research reactor),
Then at Savannah River (most intense reactor at the time)
Repeated at Savannah with 11,400 liters

❖ Exposure of CCl_4 during 100 days;
then extraction of ^{37}Ar atoms and measurement of radioactivity with Geiger counters (^{37}Ar: inert gas, half-life 35 days)

❖ **Negative results and constraint on the (anti)neutrino capture cross-section:**

$$\sigma_\nu < 0.9 \times 10^{-45}\ \mathrm{cm}^2 \ < \mathrm{predictions}$$

the « neutrinos » emitted along the electron by nuclear fission reactions…

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

…can interact with free protons (Reines & Cowan)

$$\overline{\nu}_e + p^+ \longrightarrow n + e^+ \quad \checkmark$$

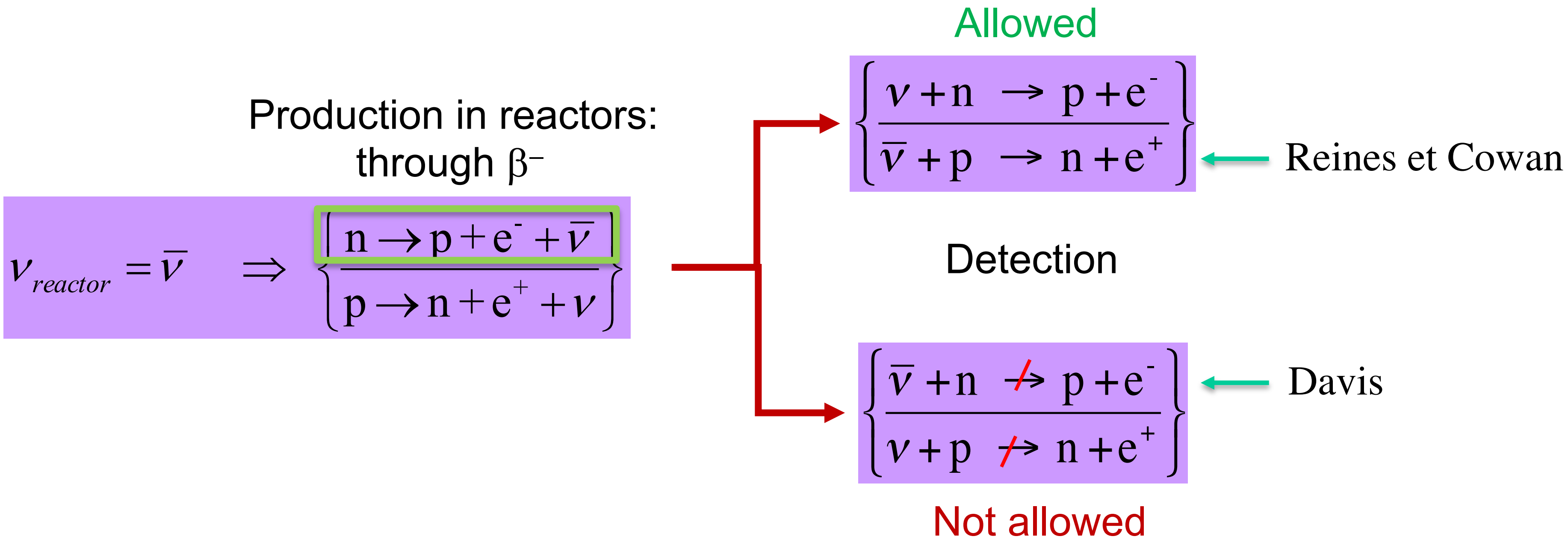
…but not be captured by Cl atoms

$$\overline{\nu}_e + n \not\longrightarrow p^+ + e^-$$

The neutrino is different from the antineutrino !

Summary: what is then known about the neutrino

- Spin : 1/2
- Mass : < 1/500 electron mass, if massive…
- Cross-section of IBD process ν_e + p → n + e^+ at 3 MeV ≈ 10^{-43} cm^2
- Neutrino emitted in β^+ decay is different from anti-neutrino emitted in β^- decay.
- Introduction of leptonic number $L_{e^-} = L_{\nu} = 1 \quad \text{and} \quad L_{e^+} = L_{\bar{\nu}} = -1$



Production in reactors: through β⁻

$$\nu_{reactor} = \bar{\nu} \quad \Rightarrow \quad \left\{ \begin{array}{c} \boxed{n \rightarrow p + e^- + \bar{\nu}} \\ \hline p \rightarrow n + e^+ + \nu \end{array} \right\}$$

Allowed

$$\left\{ \begin{array}{c} \nu + n \rightarrow p + e^- \\ \hline \bar{\nu} + p \rightarrow n + e^+ \end{array} \right\}$$

Reines et Cowan

Detection

$$\left\{ \begin{array}{c} \bar{\nu} + n \not\rightarrow p + e^- \\ \hline \nu + p \not\rightarrow n + e^+ \end{array} \right\}$$

Davis

Not allowed

The neutrino and its weak interactions

1954: The « τ–θ » puzzle:

Two particles with same mass, spin and lifetime BUT different (weak) decay modes:

$$\tau \rightarrow 2\pi \quad \ell = 0 \quad \mathrm{P} = \mathrm{P}_{\pi}^{2} = +1$$

$$\theta \rightarrow 3\pi \quad \ell = 0 \quad \mathrm{P} = \mathrm{P}_{\pi}^{3} = -1$$

→ Two different particles ? … or the same ???

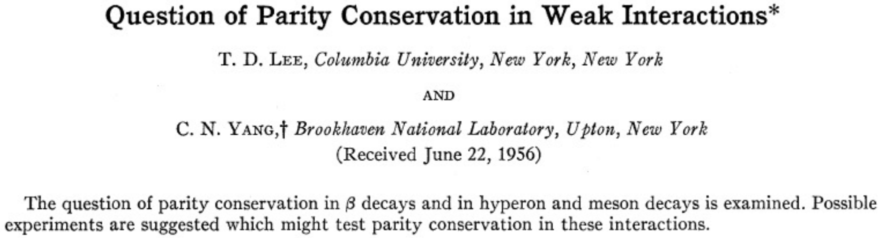
1956: Yang & Lee - weak interations violate parity ?

Chen Ning Yang
1922-

Tsung Dao Lee
1926-

Nobel Prize 1957

📖 Phys. Rev. 104 (1956) 254



Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

AND

C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*
(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

> « Select a nucleus which has an intrinsic spin and which decays radioactively by emitting high-speed electrons. Orient a bunch of such nuclei so that their spins are in the same direction - say counterclockwise when viewed from above. Count the numbers of electrons emitted upward and downward. »

Proposal for an experiment

The neutrino and its weak interactions

❖ Under parity transformation

Vectors
change sign

$$\left\{\begin{array}{ll} \vec{r} \xrightarrow{\hat{P}} -\vec{r} & \\ \vec{p} \xrightarrow{\hat{P}} -\vec{p} & \qquad (p_x = \frac{\partial}{\partial x}, \; etc.) \end{array}\right.$$

Axial vectors
stay same

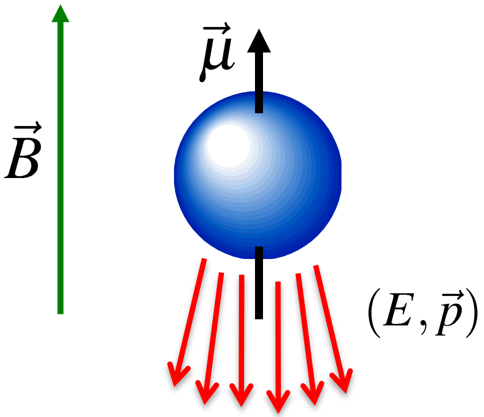
$$\left\{\begin{array}{ll} \vec{L} \xrightarrow{\hat{P}} \vec{L} & \qquad (\vec{L} = \vec{r} \wedge \vec{p}) \\ \vec{\mu} \xrightarrow{\hat{P}} \vec{\mu} & \qquad (\vec{\mu} \propto \vec{L}) \end{array}\right.$$

To demonstrate that a processus violates a symmetry, it is enough to show that a distribution which characterizes it depends on a parameter changing sign under this symmetry → choose as observable **$S_N. p_e$**

1957: Observation of parity violation in β decay of polarized ^{60}Co (C.S. Wu et al.)

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

electrons are emitted preferentially
In the direction opposed to
spin of the nucleus



C. S. Wu 1912 – 1997

The neutrino and its weak interactions

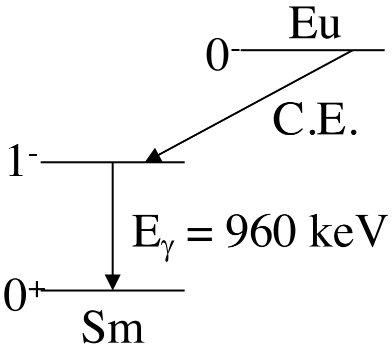
1958: Measurement of the helicity of the neutrino (Goldhaber et al.)

(electronic capture)

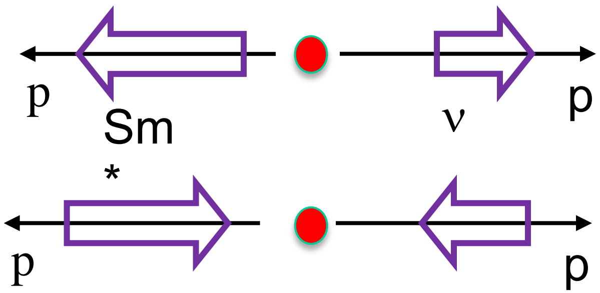
$$\boxed{e^- + {}^{152}Eu \longrightarrow {}^{152}Sm^* + \nu_e}$$

angular momentum conservation

$$\vec{J} \quad \underbrace{\tfrac{1}{2} \qquad 0}_{\vec{J}_{tot} = \frac{1}{2}} \qquad\qquad \underbrace{1 \qquad \tfrac{1}{2}}_{\vec{J}_{tot} = \frac{1}{2}}$$



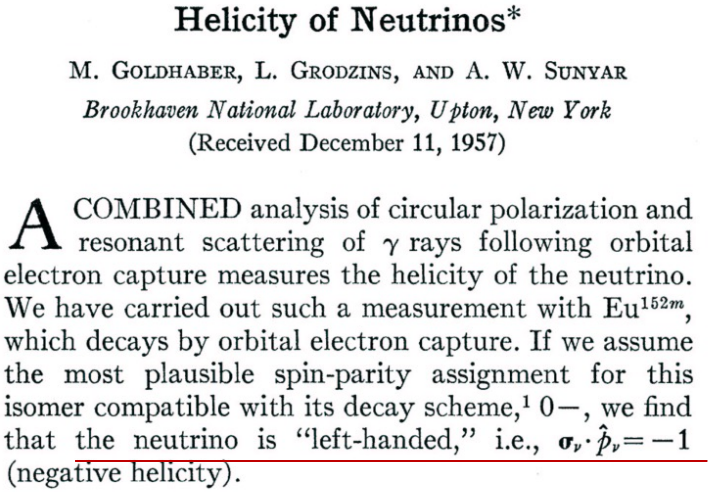
Only 2 helicity configurations are allowed in final state:



ν positive helicity
Sm* positive helicity

ν negative helicity
Sm* negative helicity

→ helicity of Sm* must be same as neutrino's !



Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] $0-$, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

📖 Phys. Rev. 109, 1015-1017 (1958)

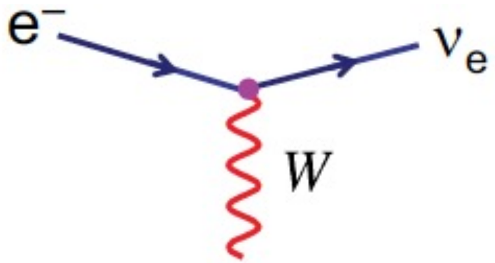
The neutrino and its weak interactions

Violation of parity in weak interactions
Negative helicity of the neutrino

« V-A » structure for the weak interaction vertex

★The charged current (W±) weak vertex is:

$$\boxed{\frac{-ig_W}{\sqrt{2}}\frac{1}{2}\gamma^\mu(1-\gamma^5)}$$



★Since $\frac{1}{2}(1-\gamma^5)$ projects out left-handed **chiral** particle states:

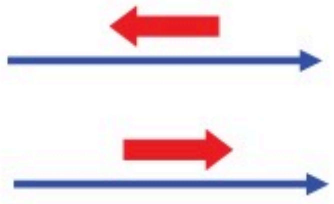
$$\bar{u}\frac{1}{2}\gamma^\mu\left(1-\gamma^5\right)u=\bar{u}_L\gamma^\mu u_L$$

Only the left-handed chiral components of particle spinors and right-handed chiral components of anti-particle spinors participate in charged current weak interactions

★At very high energy $(E \gg m)$, the left-handed chiral components are helicity eigenstates :

$\frac{1}{2}(1-\gamma^5)u \Rightarrow$

$\frac{1}{2}(1-\gamma^5)v \Rightarrow$



LEFT-HANDED PARTICLES
Helicity = -1

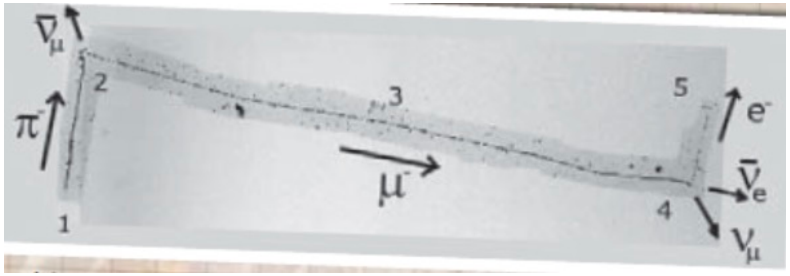
ν_L

RIGHT-HANDED ANTI-PARTICLES
Helicity = +1

$\overline{\nu}_R$

Holds for massless neutrinos !

Neutrino flavours



(Powell 1947: discovery of pion in cosmic rays)

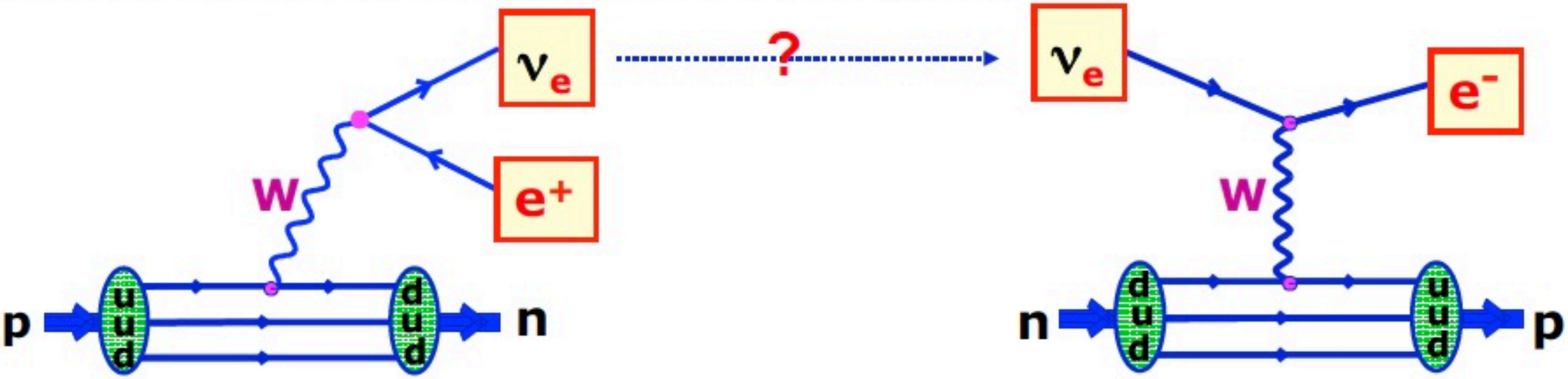
QUESTION: are the neutrinos produced
- in beta decay: $n \rightarrow p^+ + e^- + \nu$

&
- in pion decay: $\pi^+ \rightarrow \mu^+ + \nu$

the same particle ?

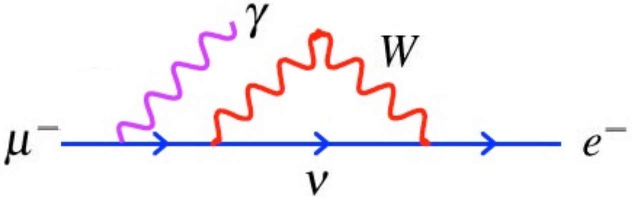
★ **Never directly observe neutrinos – can only detect them by their weak interactions.**

- **Experimental evidence:** neutrinos produced along with an electron always produced an electron in CC Weak interactions, etc.



- **Experimental evidence:** absence $\mu^- \rightarrow e^- \gamma$ $\quad \mathrm{BR}(\mu^- \rightarrow e^- \gamma) < 10^{-11}$

Suggests that ν_e and ν_μ are distinct particles otherwise decay could go via:

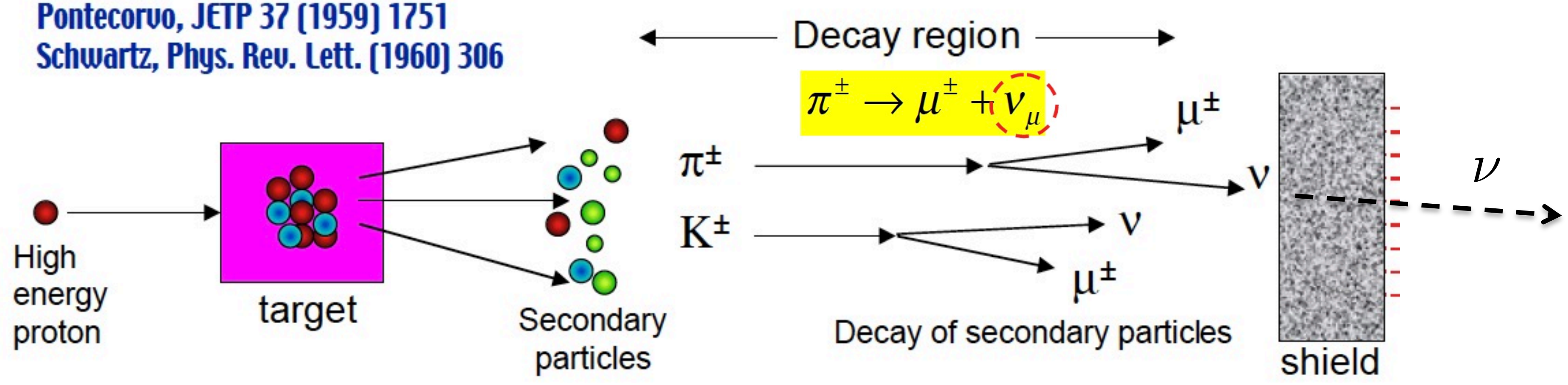


Discovery of muon neutrino

Need intense sources of putative « ν_μ »

❖ In the early 1960’s it was realized that **particle colliders could be used to produce intense high-energy neutrino beams:**

Pontecorvo, JETP 37 (1959) 1751
Schwartz, Phys. Rev. Lett. (1960) 306



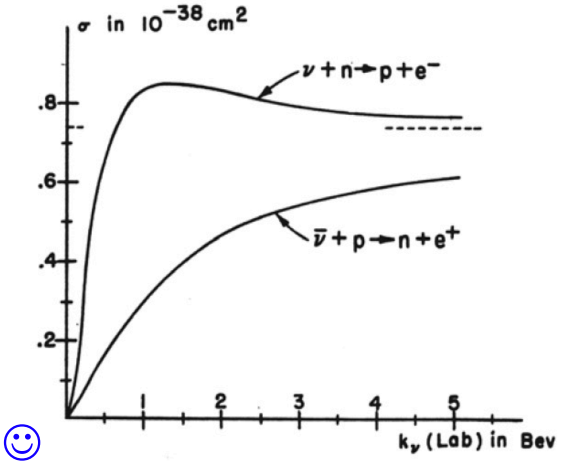
❖ 1960: Lee and Yang estimate the neutrino-nucleon cross-section at high energies:
from Fermi theory:

$$\sigma \propto G_F^2 s$$

$$s = (p_\nu + p_N)^2 \approx 2M_N E_\nu^{lab}$$

$$\sigma \propto G_F^2 \, M_N \, E_\nu^{lab} \simeq 10^{-38} \text{ cm}^2 \text{ at } 1 \text{ GeV}$$

10^5 x bigger than for MeV neutrinos ☺



Discovery of muon neutrino

Cf tutorial

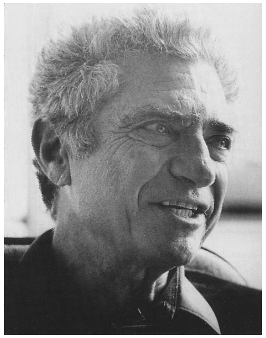
1962: Brookhaven experiment

PRL 9, 36-44, 1962

Nobel Prize 1988

M. Schwartz
1932- 2006

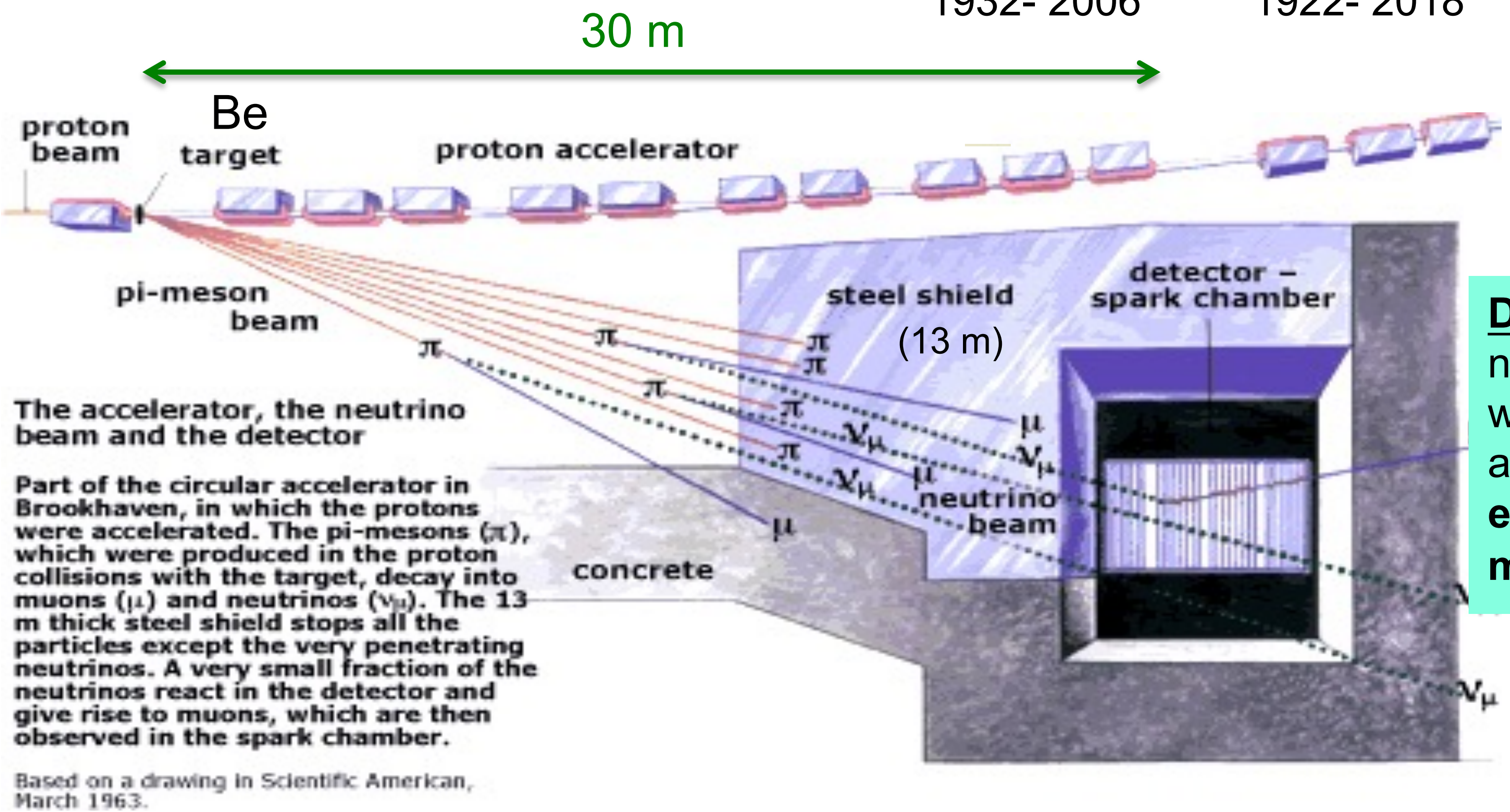
L. Lederman
1922- 2018



J. Steinberger
1921- 2020

AGS 15 GeV Proton Beam

4×10^{11} protons per pulse
3000 pulses per day



The accelerator, the neutrino beam and the detector

Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

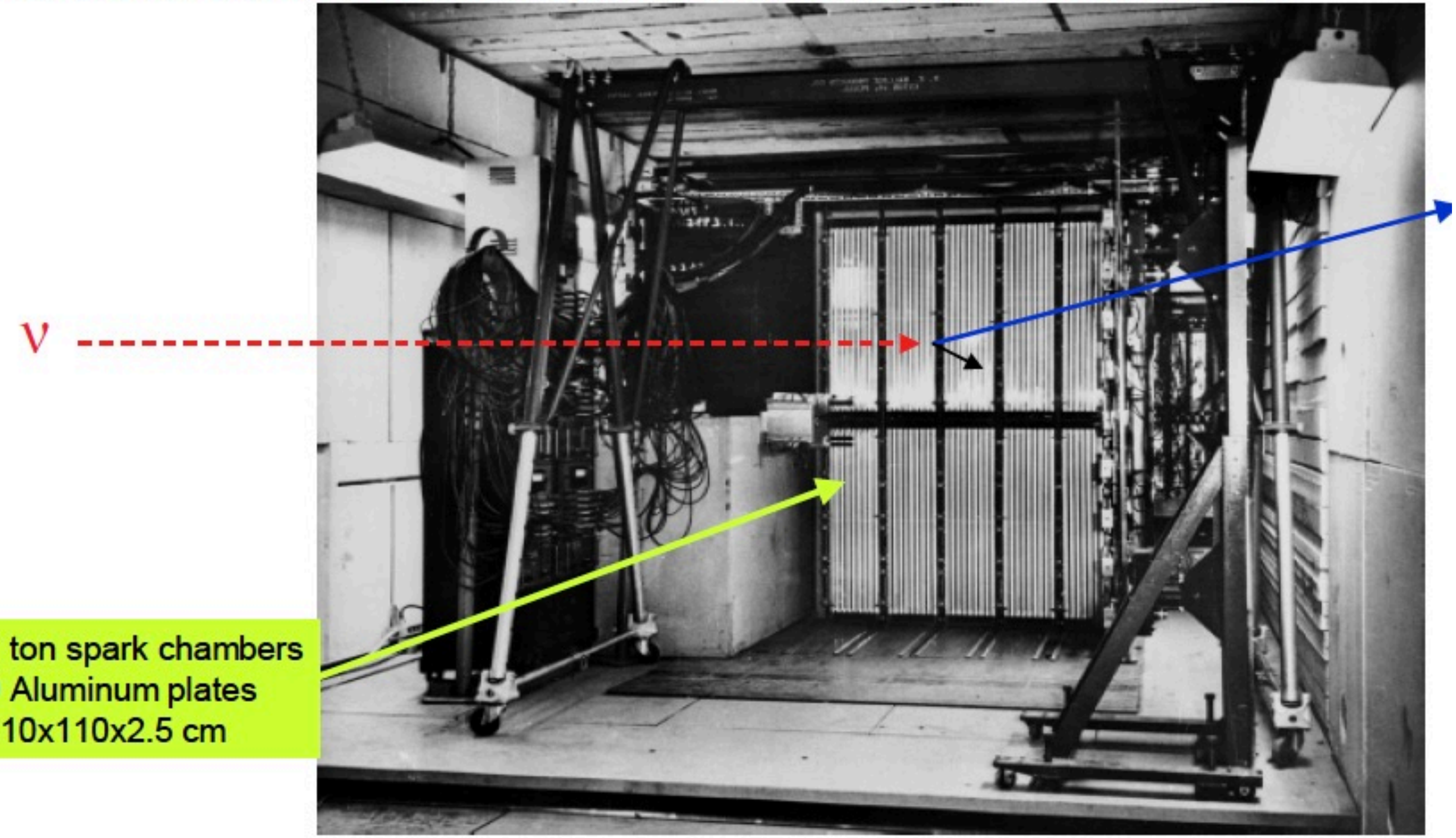
Based on a drawing in Scientific American, March 1963.

Double challenge: need a detector with **large mass** & able to **distinguish electrons from muons**

Discovery of muon neutrino

… A 10-ton spark chamber detector

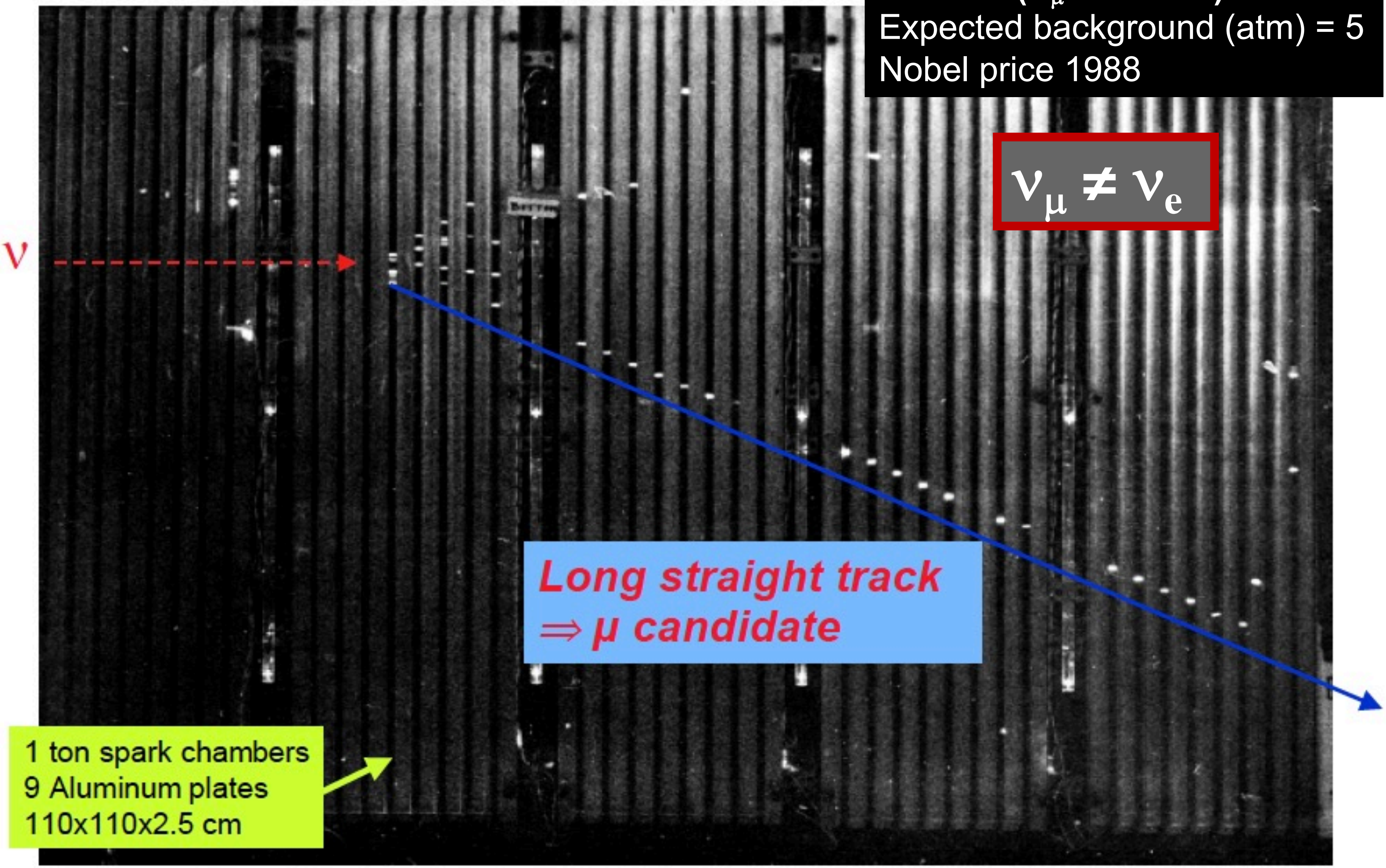
Danby, Gaillard, Goulianos, Lederman, Mistry, Steinberger, Schwartz, Phys. Rev. Lett. 9 (1962) 36



1 ton spark chambers
9 Aluminum plates
110x110x2.5 cm

Discovery of muon neutrino

34 evts (P$_\mu$>300MeV)
Expected background (atm) = 5
Nobel price 1988



$\nu_\mu \neq \nu_e$

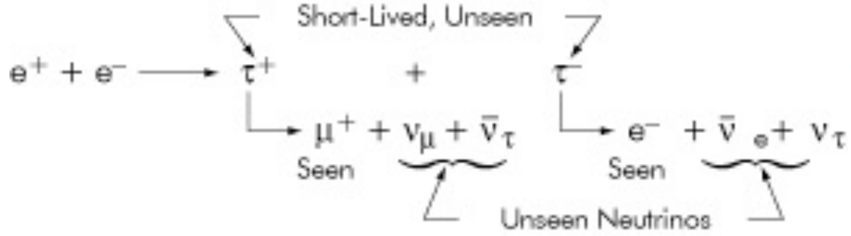
Long straight track
⇒ μ candidate

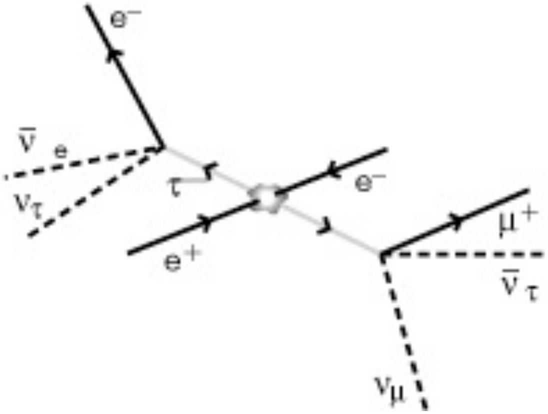
1 ton spark chambers
9 Aluminum plates
110x110x2.5 cm

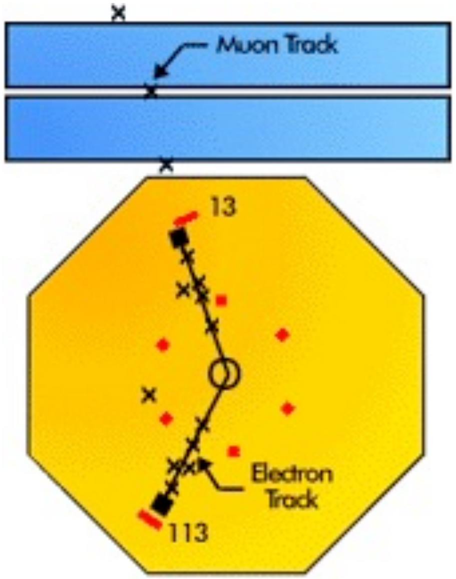
1975: The 3rd charged lepton is observed

Martin Perl
1927 -
Nobel price 1995

MARK I experiment at SLAC (Stanford)







Pair creation $\tau^+ \tau^-$ with one τ decaying into e^- and the other into μ^+

Final state: a single track of electron and a single track of muon in the detector

24 events found (expected background = 5 events)

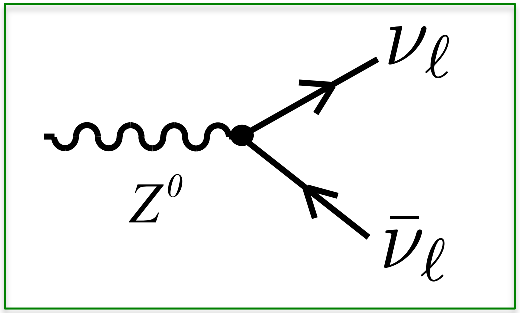
3rd family of leptons ! What about the tau neutrino ?

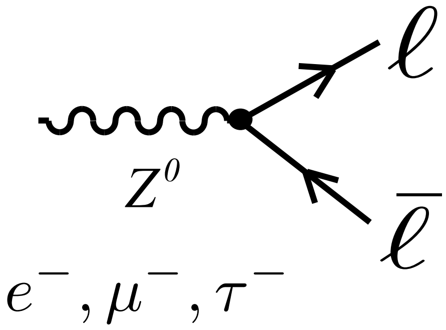
(M. L. Perl et al., « Evidence for Anomalous Lepton Production in $e^+ e^-$ annihilation », 📖 Phys. Rev. Lett., 1975)

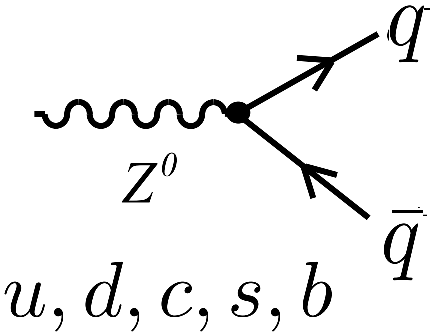
A third generation

1989: Measurement of the invisible decay width of Z boson

Z decay modes:







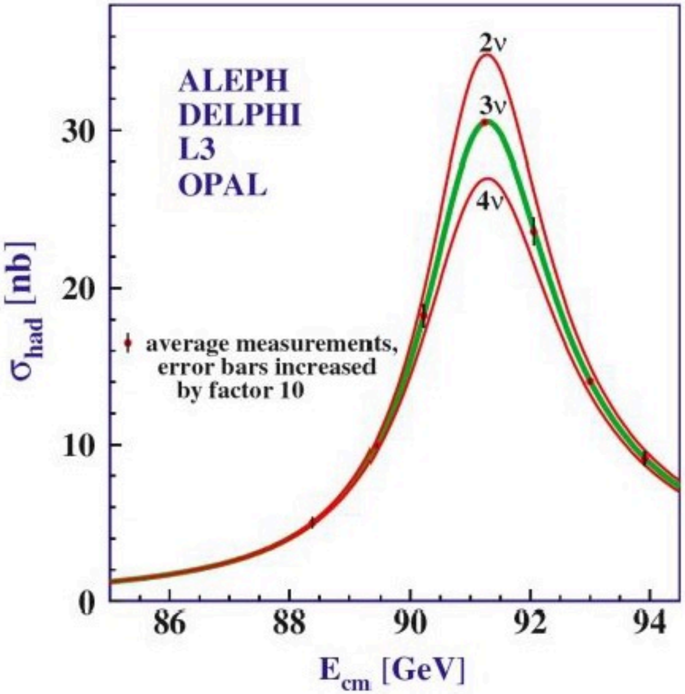
No visible signal in detector

…First indirect evidence of the existence of 3 active neutrinos through precision studies of Z line shape :

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\text{SM}}$$

From LEP, one finds:

$N_\nu = 2.984 \pm 0.008$



A third generation

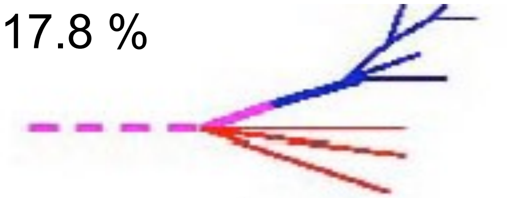
2000: Direct observation of the ν_τ in the DONUT experiment

❖ Experimental challenges:
  - small interaction cross-section of ν_τ
  - short lifetime of τ

Branching ratios:

Leptonic

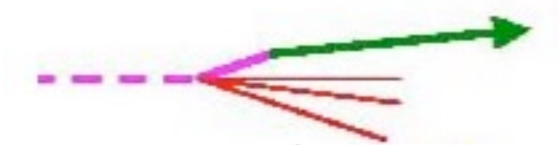
17.8 %



$$\tau^- \to \boxed{e^-} \nu_\tau \bar{\nu}_e$$

short track
+ EM shower

17.4 %

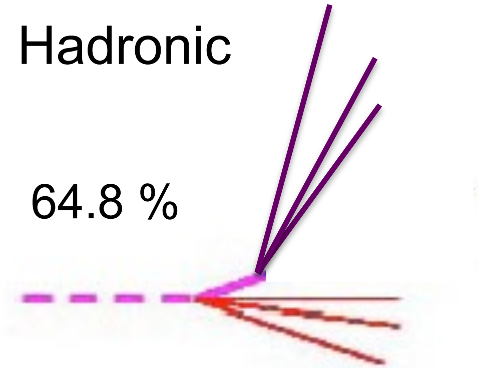


$$\tau^- \to \boxed{\mu^-} \nu_\tau \bar{\nu}_\mu$$

long, penetrating track

Hadronic

64.8 %



$$\tau^- \to \nu_\tau + \text{hadrons}$$

$$(\pi^-\pi^0, \pi^-, \pi^-\pi^0\pi^0, \pi^-\pi^+\pi^-, \ldots)$$

86% of all tau decays (leptonics+hadronics) involve only 1 charged particle

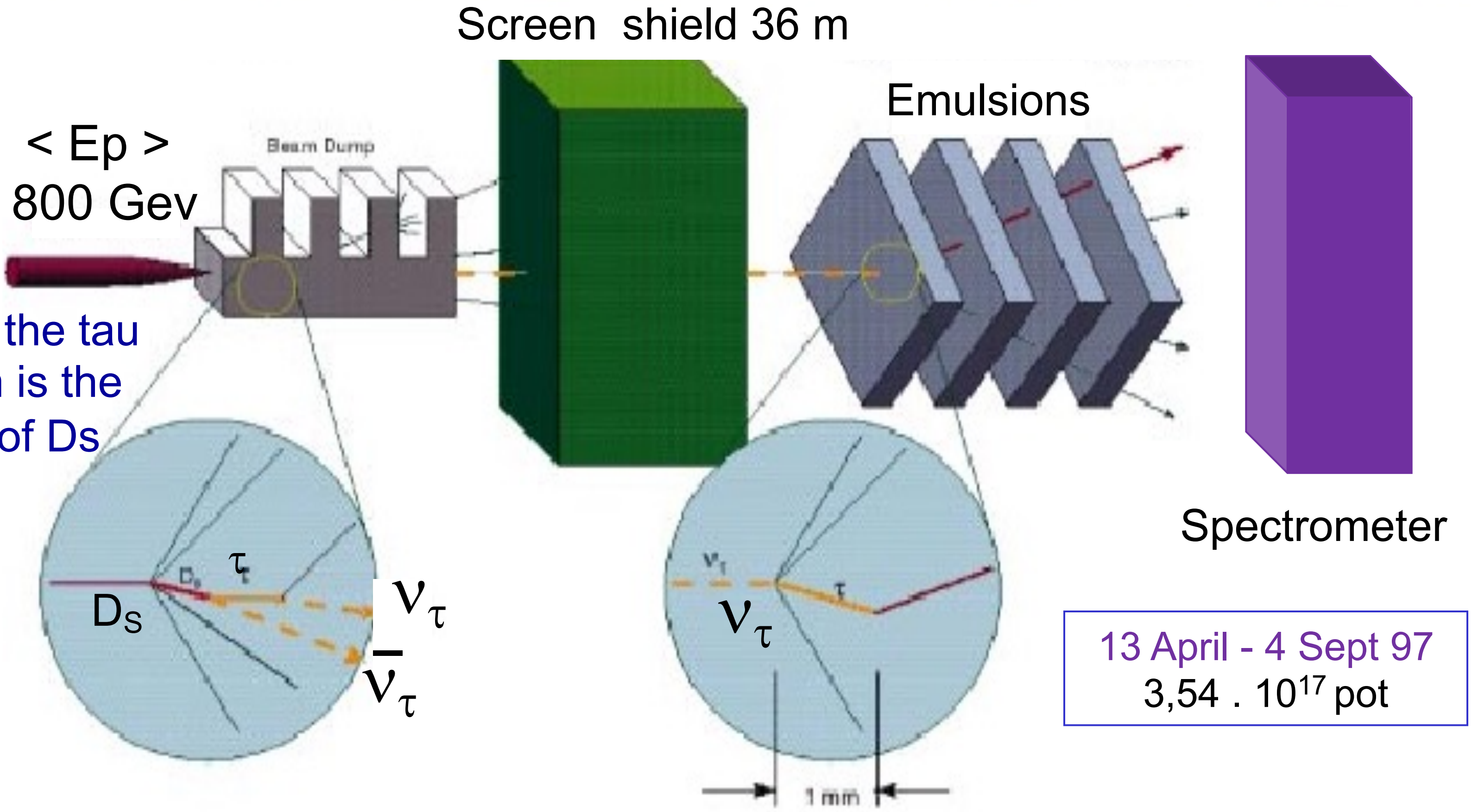
→ Need large AND fine-grained detector

Chosen technique: nuclear emulsions

Direct observation of tau neutrino

2000: Results of the **DONUT (E872)** experiment at Fermilab
Observation of the charged current interaction of tau neutrino —> detection of τ lepton

The source of the tau neutrino beam is the disintegration of Ds
$<E_\nu>$=111GeV

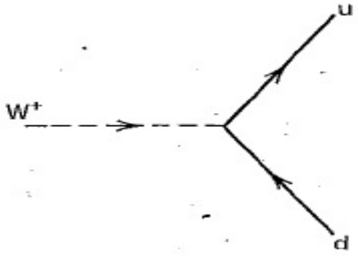


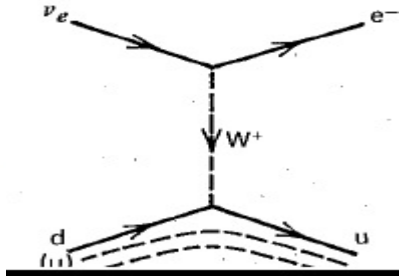
13 April - 4 Sept 97
3,54 . 10^{17} pot

Typical event:
One track (tau lepton) + disintegration kink with high transverse momentum Pt + missing energy
$\tau \rightarrow e\ \nu_\tau\ \nu_e$ (18%) $\tau \rightarrow \mu\ \nu_\tau\ \nu_\mu$ (18%) $\tau \rightarrow h$ + neutral (50%)

Neutrino quark scattering

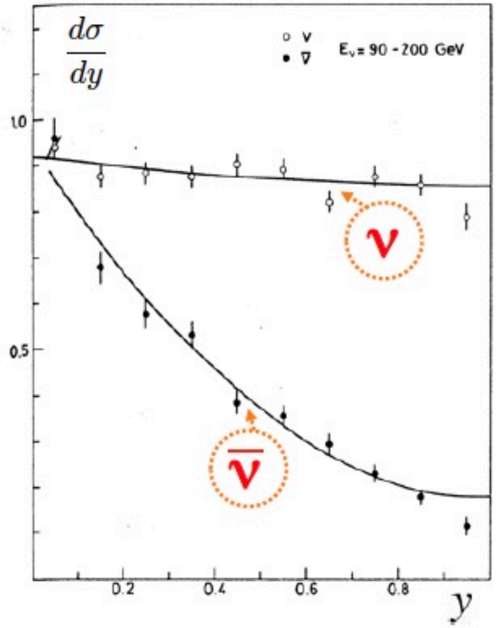
$$J_q^\mu = \bar{u}_u \gamma^\mu \tfrac{1}{2}(1-\gamma^5)\, u_d \quad \Rightarrow$$





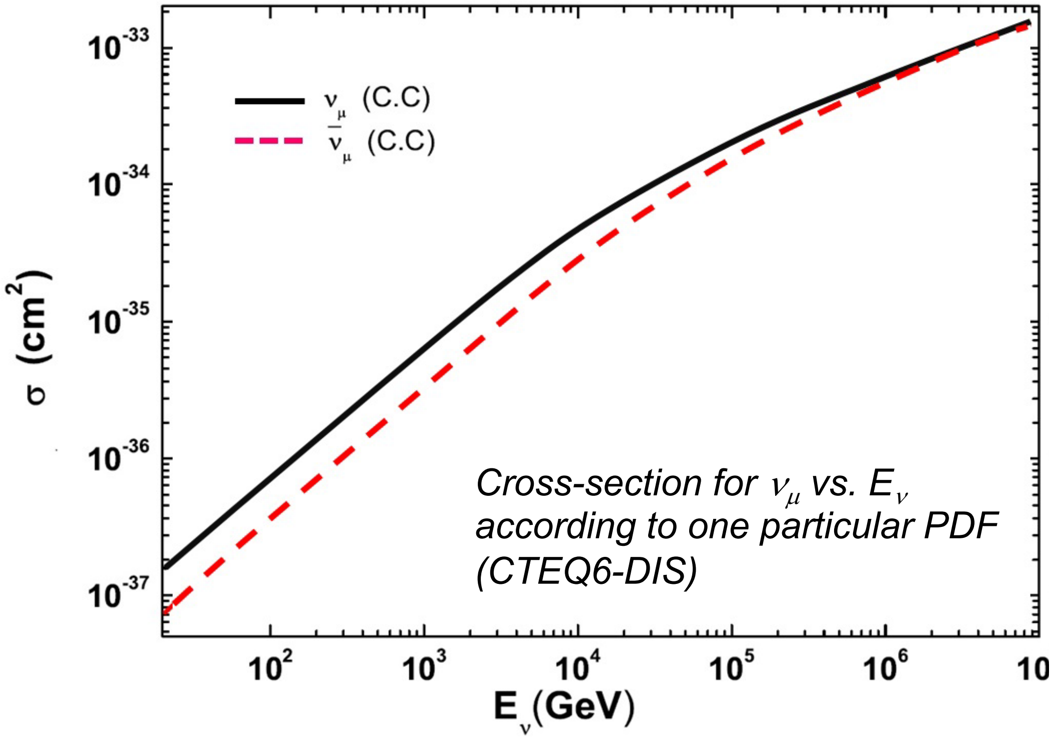
- The V-A structure means that the weak current couples only left handed u and d (right handed ū and đ)

- **CDHS measured y distribution**



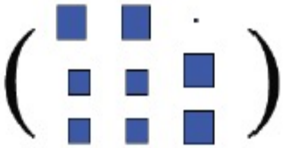
J. de Groot et al., Z.Phys. C1 (1979) 143

- **Shapes can be understood in terms of (anti)neutrino – (anti)quark scattering**



Cross-section for ν_μ vs. E_ν according to one particular PDF (CTEQ6-DIS)

Outline



Introduction to neutrinos

Today's picture

Historical aspects

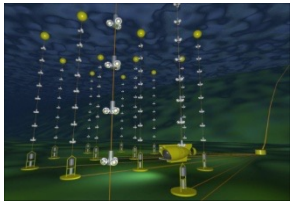
Neutrino astronomy

Scientific motivations

Historical aspects

Oscillation detour

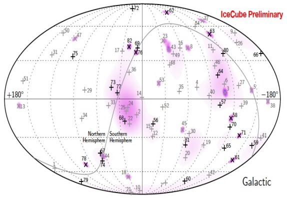
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



Selected results

Diffuse Flux, point sources

Multi-messenger search

Future prospects

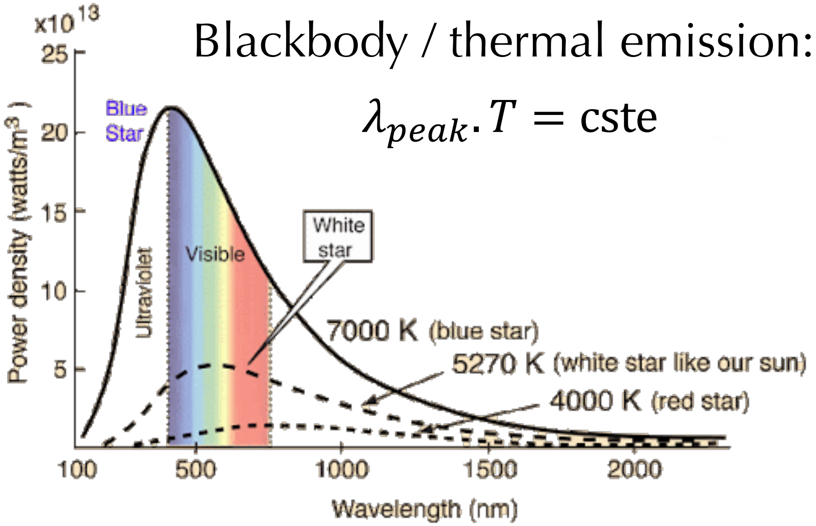
Multi-wavelength Astronomy

Why do we observe the sky at different wavelengths & using different messengers ?

… because we don’t observe the same processes at different energies !

→ Andromeda as an exemple

Multi-wavelength Astronomy



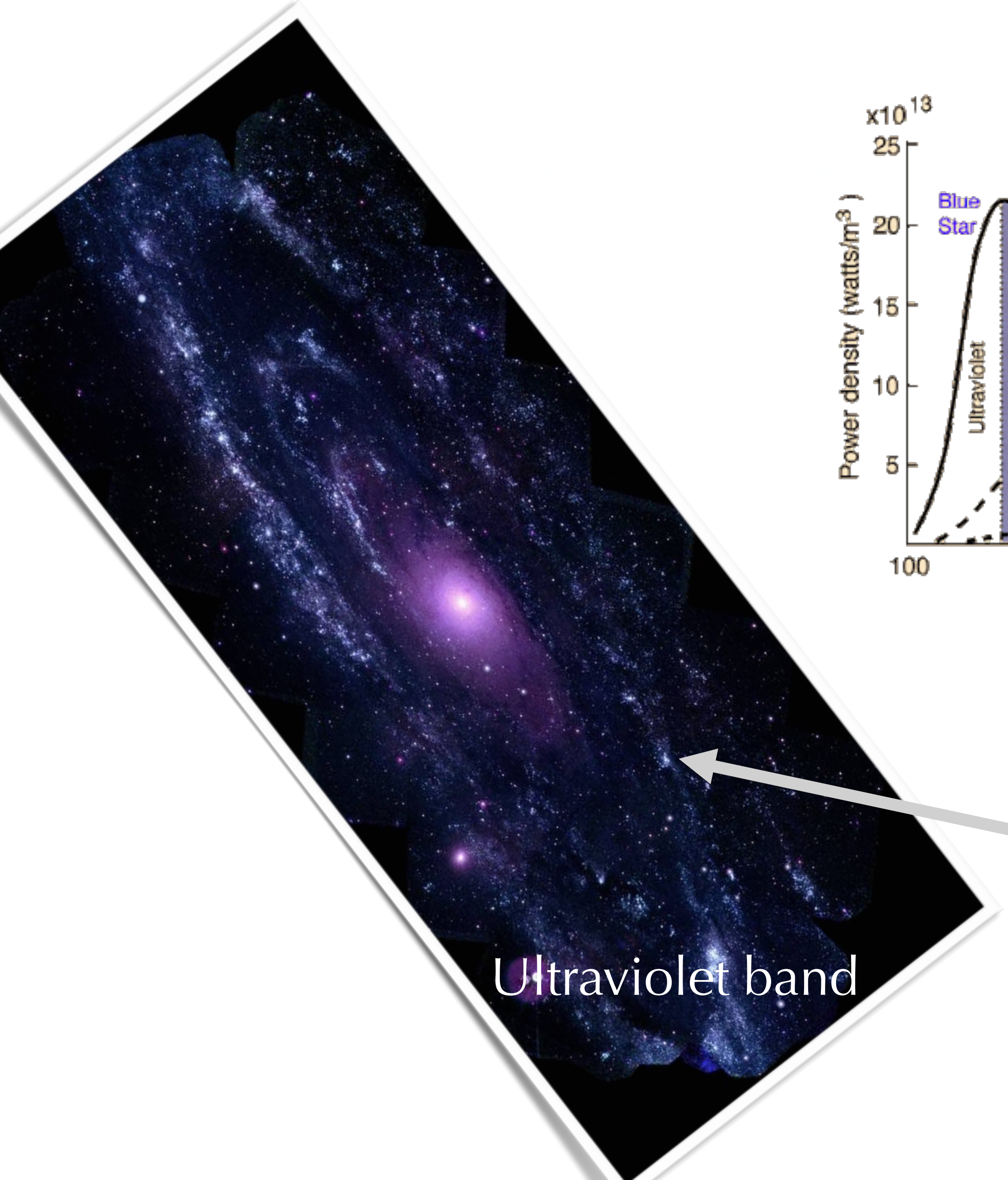
Blackbody / thermal emission:

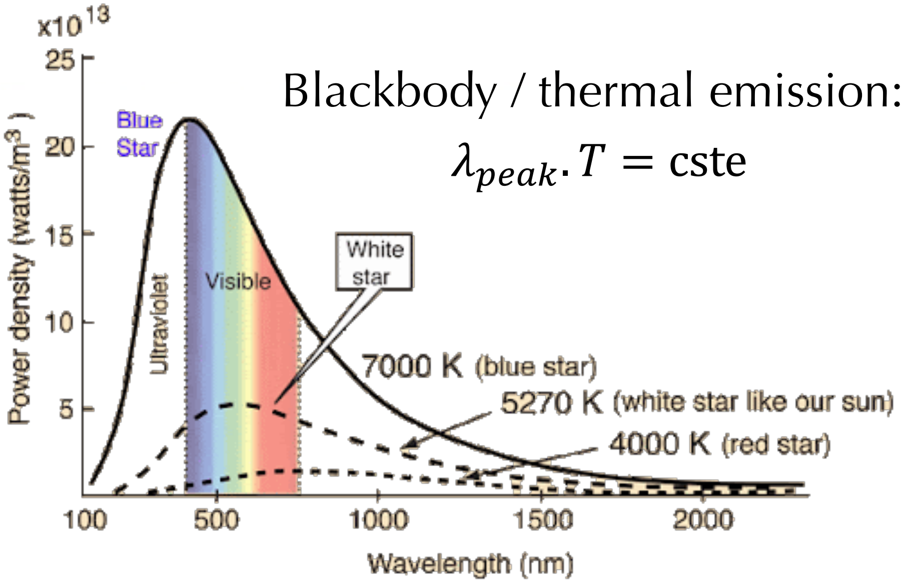
$$\lambda_{peak}.T = \text{cste}$$

Thermal emission of stars in other galaxies or galaxy clusters

Thermal emission of stars in the Milky Way or in M31

Multi-wavelength Astronomy



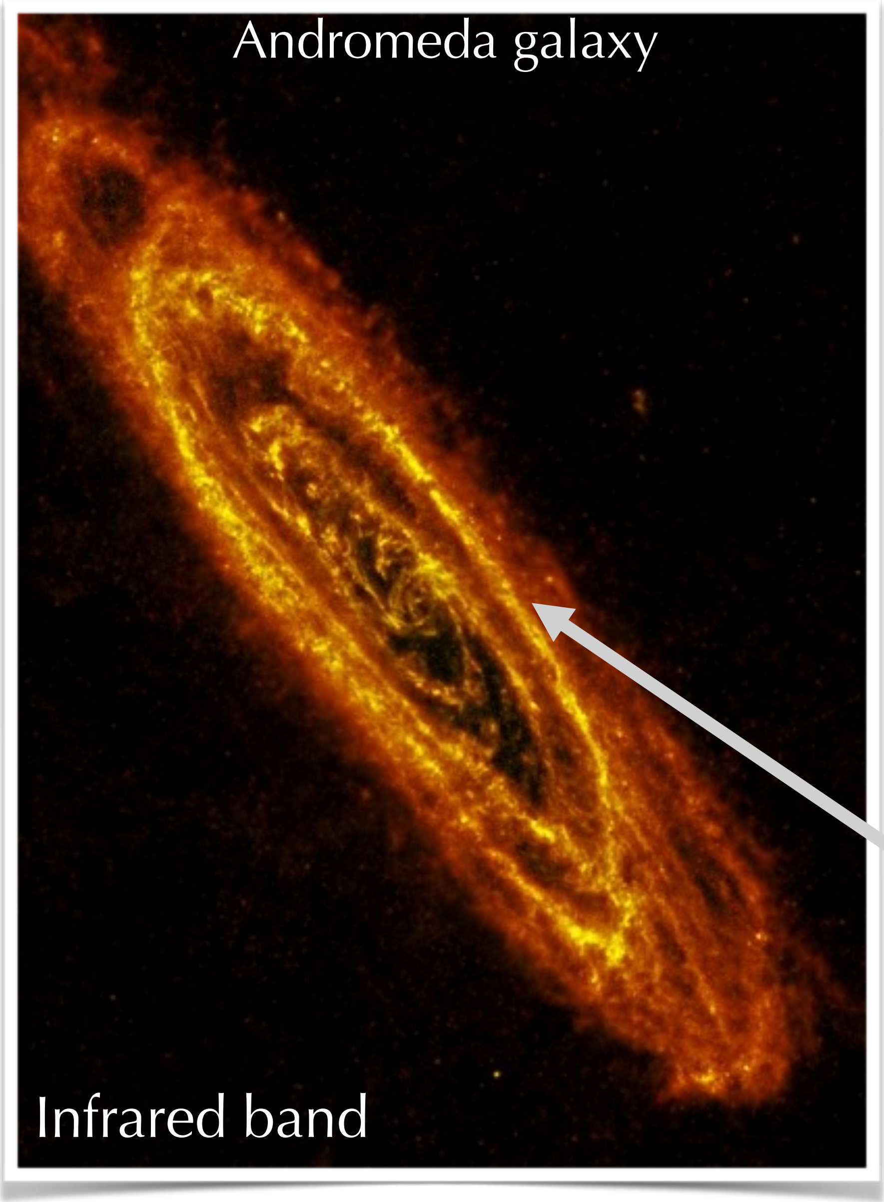


Blackbody / thermal emission:

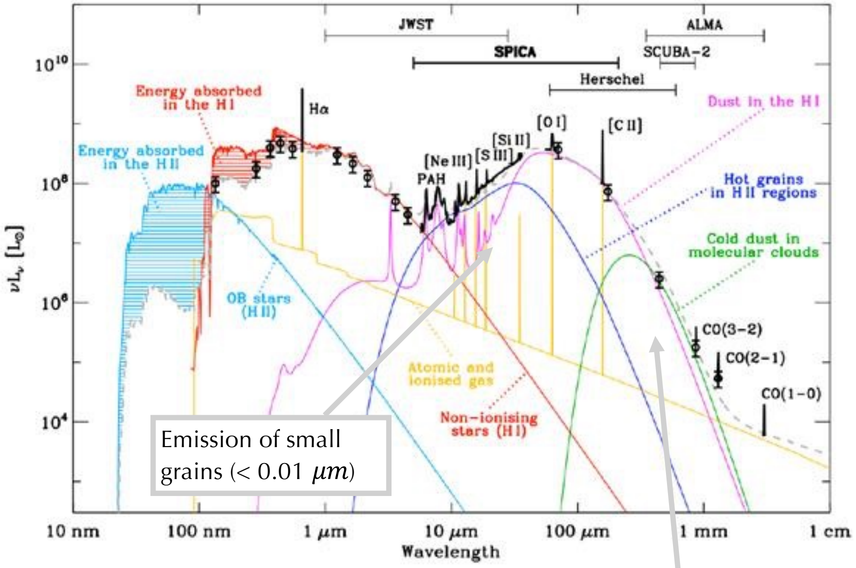
$$\lambda_{peak}.T = \text{cste}$$

Thermal emission of massive stars in the galaxy

Multi-wavelength Astronomy



Different dust composition radiate at different energies:

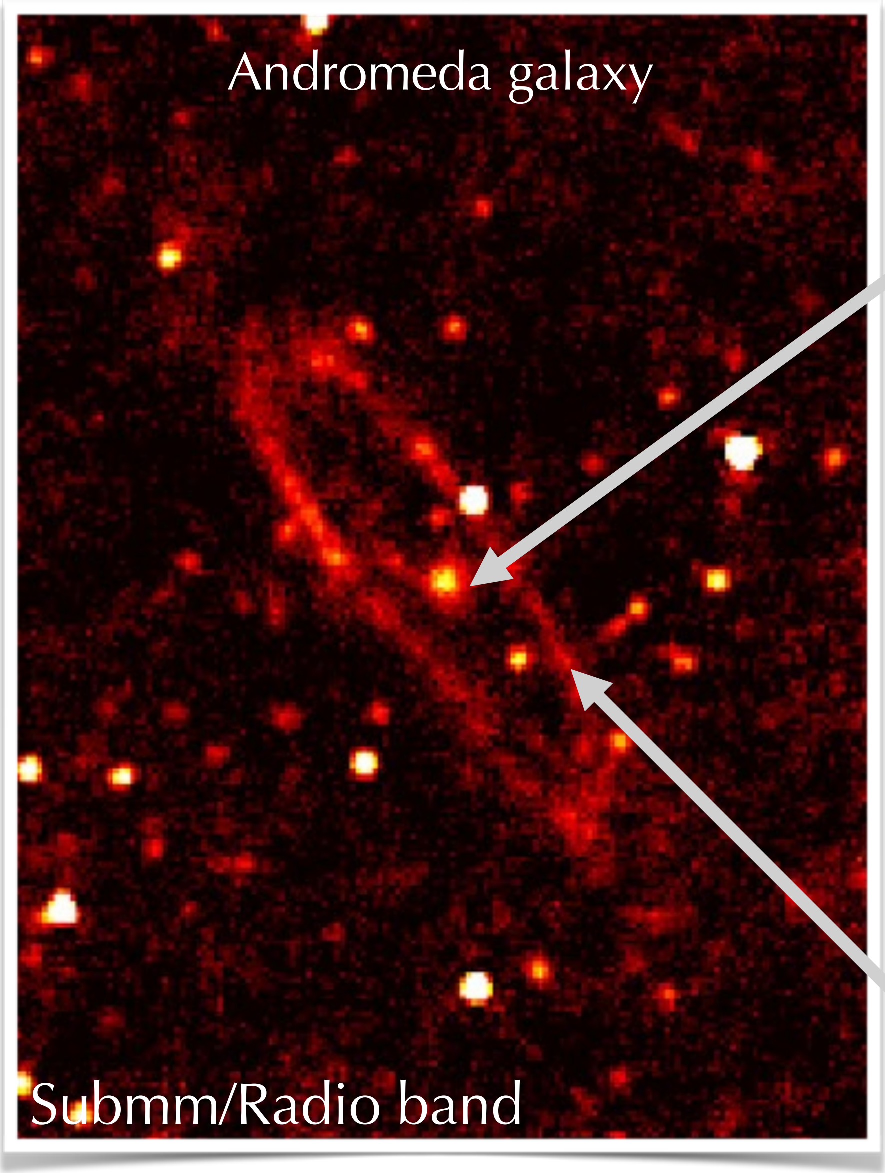


Emission of small grains (< 0.01 μm)

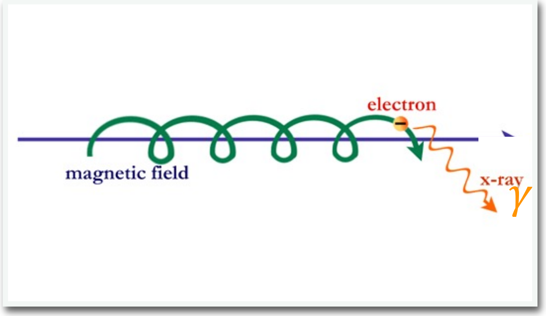
Emission of large grains (> 0.01 μm)

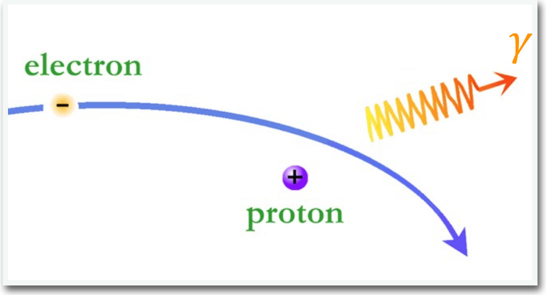
Dust in Molecular clouds: dense gas concentrations hosting star formation sites

Multi-wavelength Astronomy



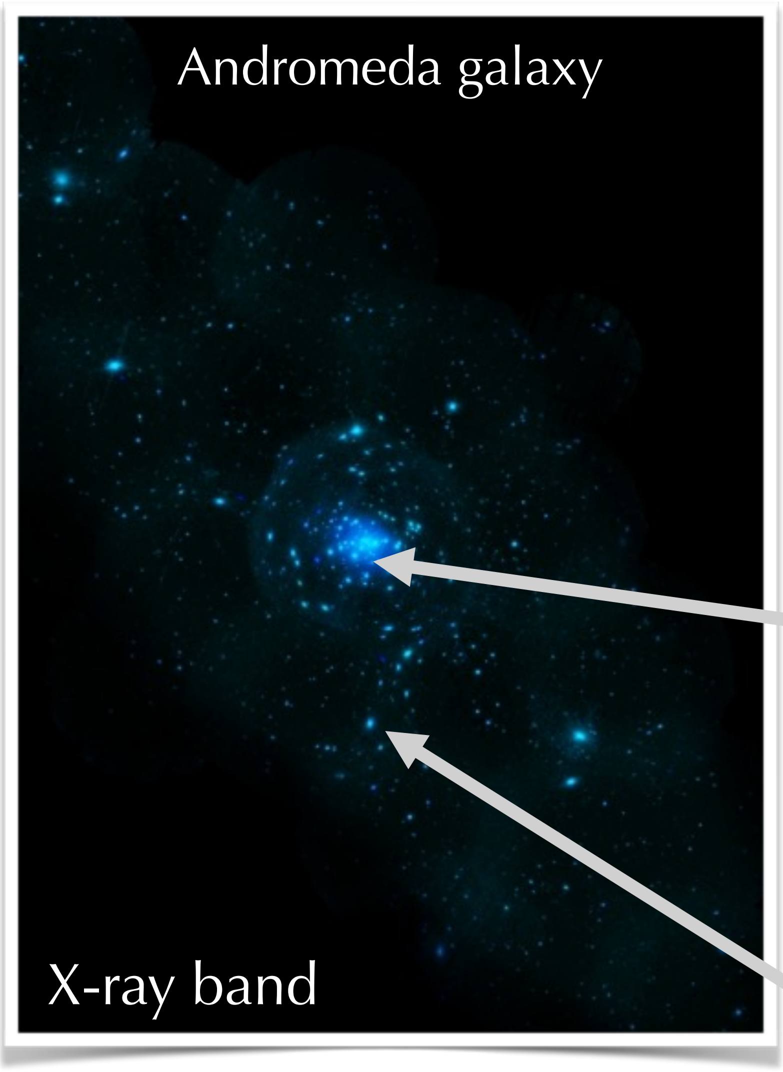
Synchrotron (non-thermal) + bremsstrahlung emission (star forming regions)

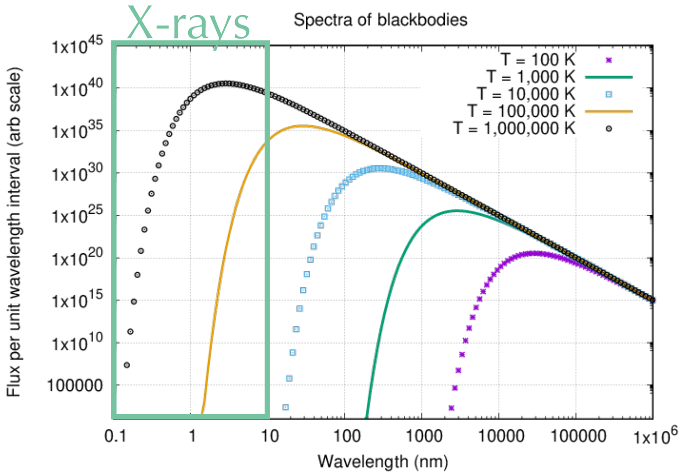




Gas in Molecular clouds: dense gas concentrations hosting star formation sites

Multi-wavelength Astronomy



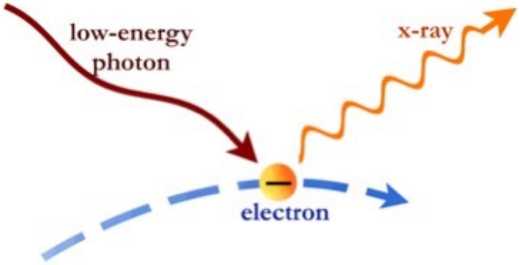


Thermal emission (blackbody + bremsstrahlung):

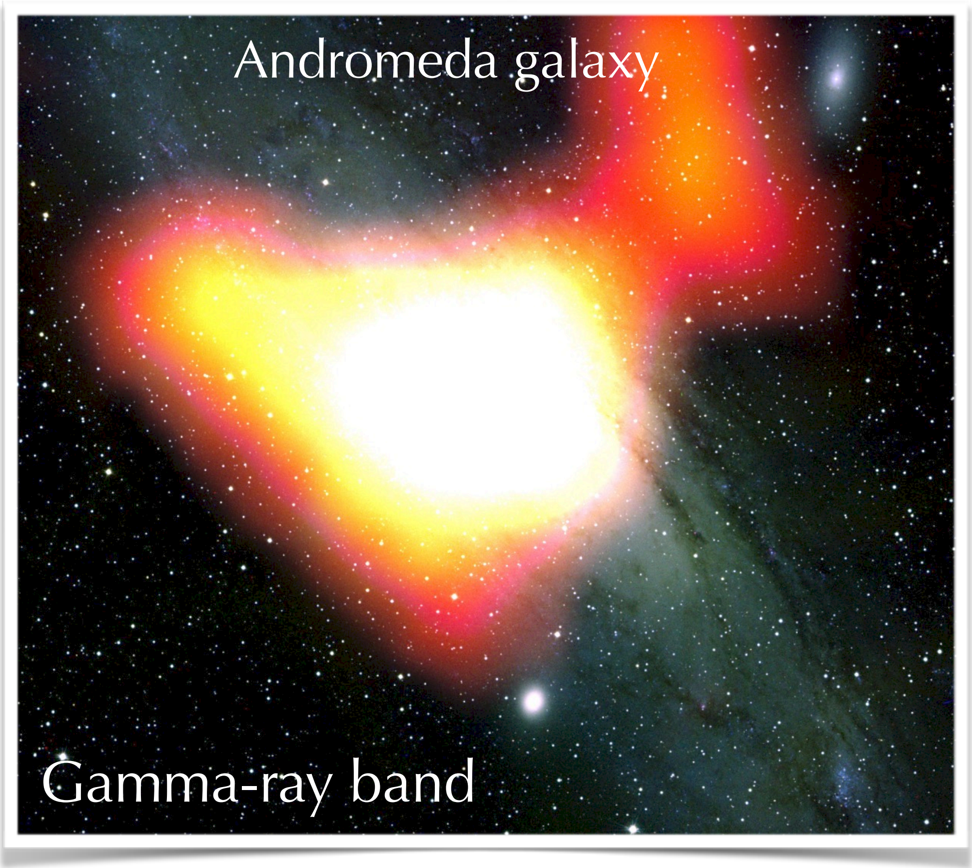
- *gas in galaxy clusters (T~10^7 K)*
- *accretion onto compact object (potential energy converted to kinetic energy + radiation)*

Non-thermal emission:

- *synchrotron*
- *inverse Compton*



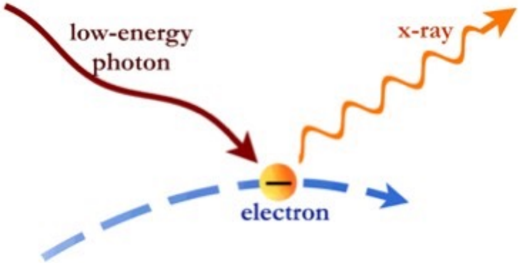
Multi-wavelength Astronomy

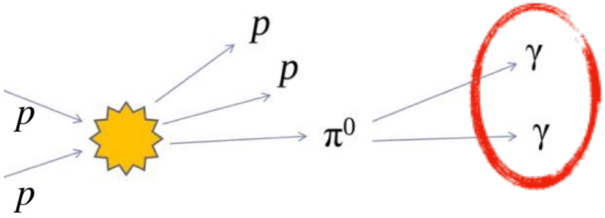


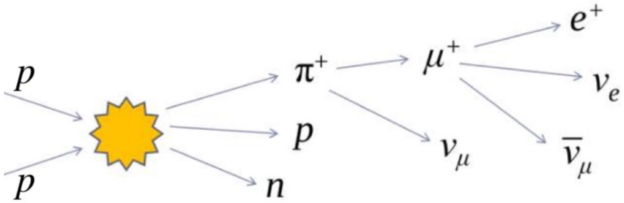
Angular resolution: ~1° (70 000 lower than in optical)

Non-thermal processes:

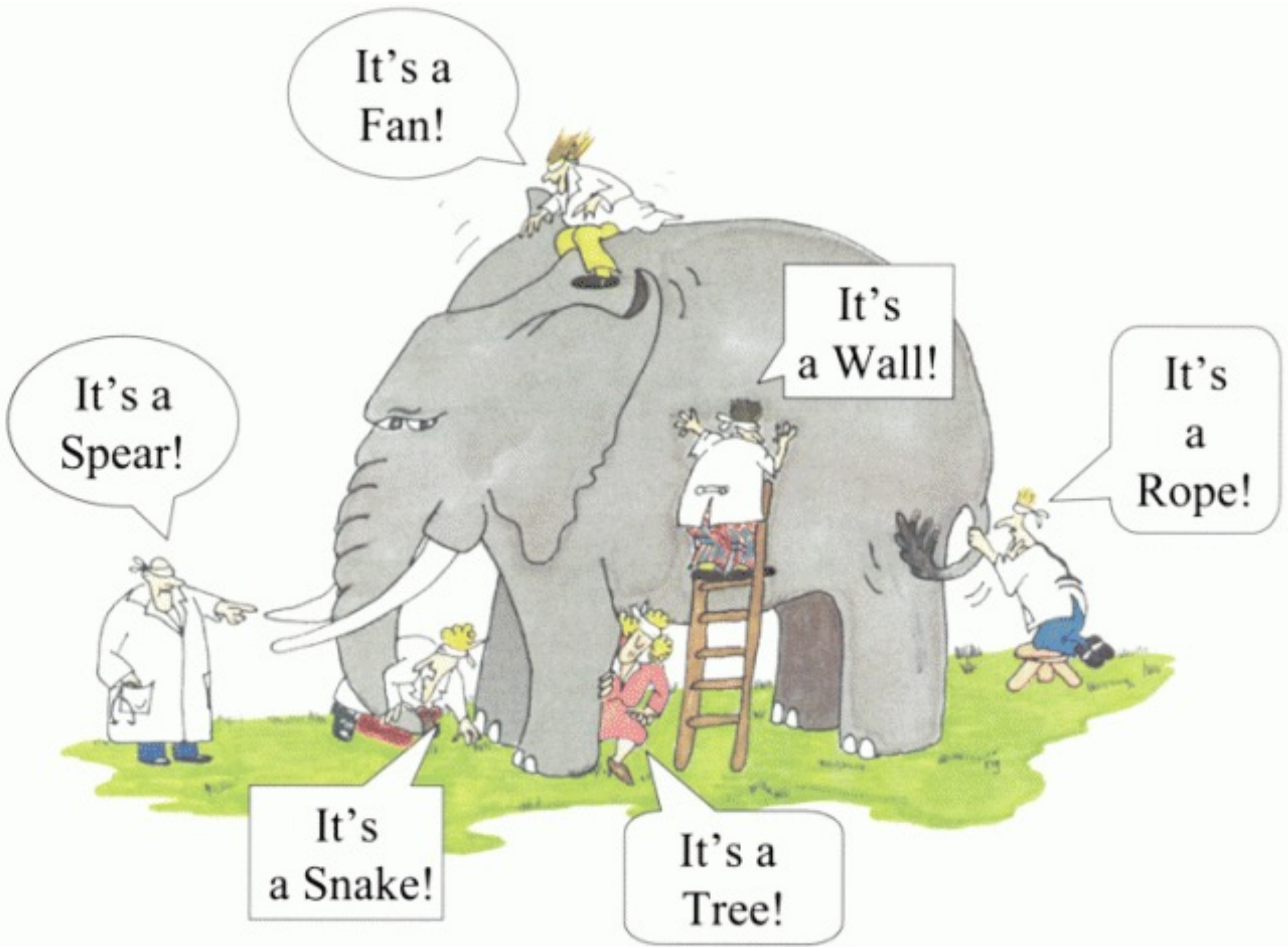
- *inverse Compton (leptonic origin)*
- *Interaction of high-energy protons with interstellar gas (hadronic origin)*
- *Unknown sources (dark matter) ?*





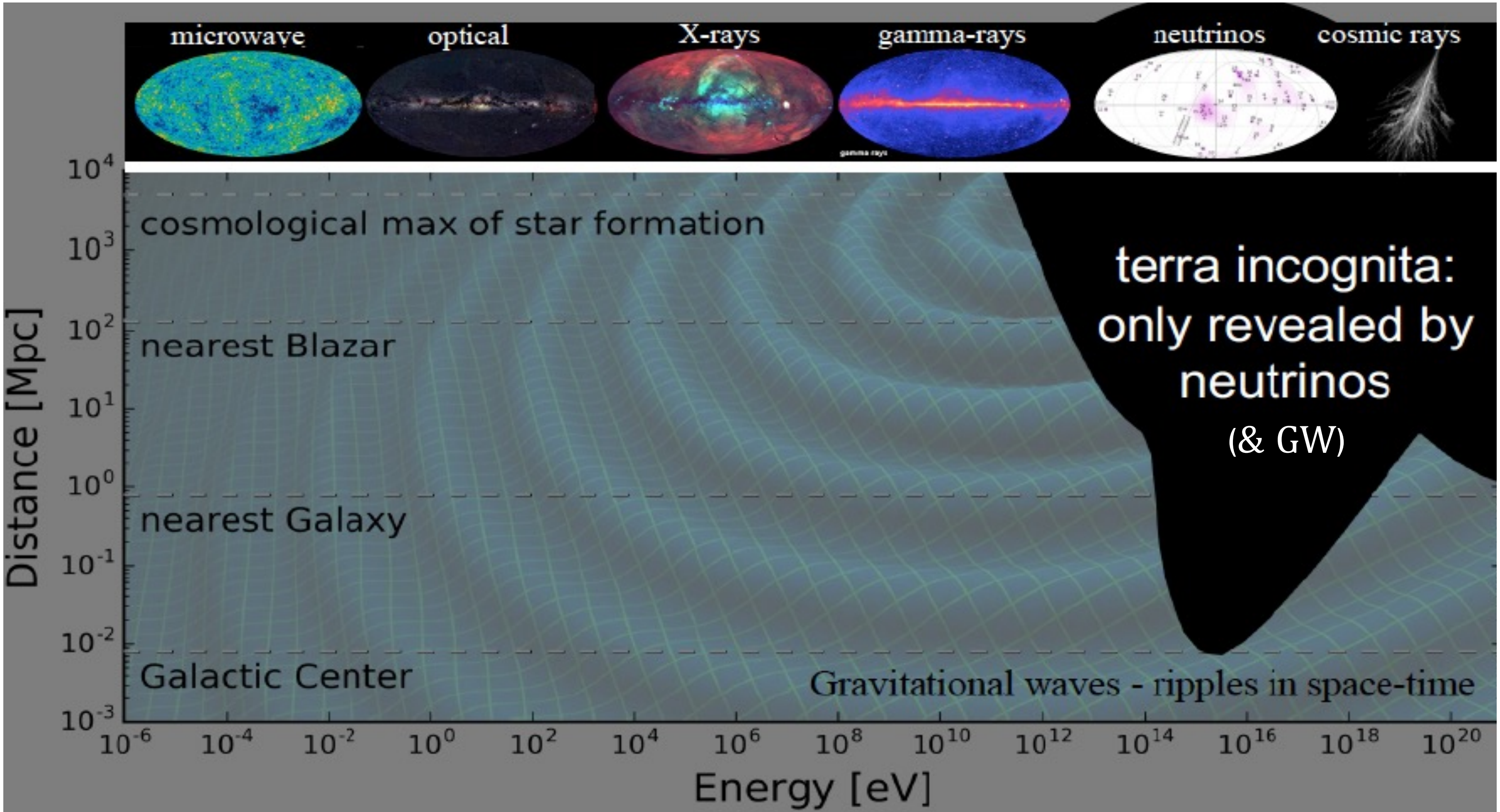


Another way of convincing you ?



Multi-messenger astronomy

Cf tutorial



From F. Halzen

Neutrinos

✓Transient sources

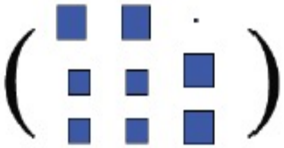
✓Core of astrophysical bodies

✓ Point source

✓Cosmological distance

⇒ Signature of hadronic acceleration

Outline



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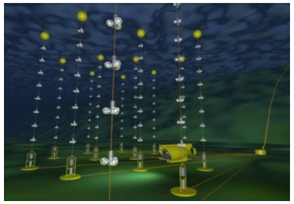

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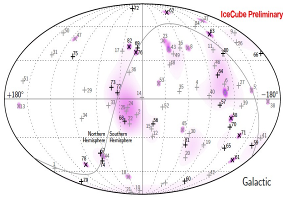

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Multi-messenger search

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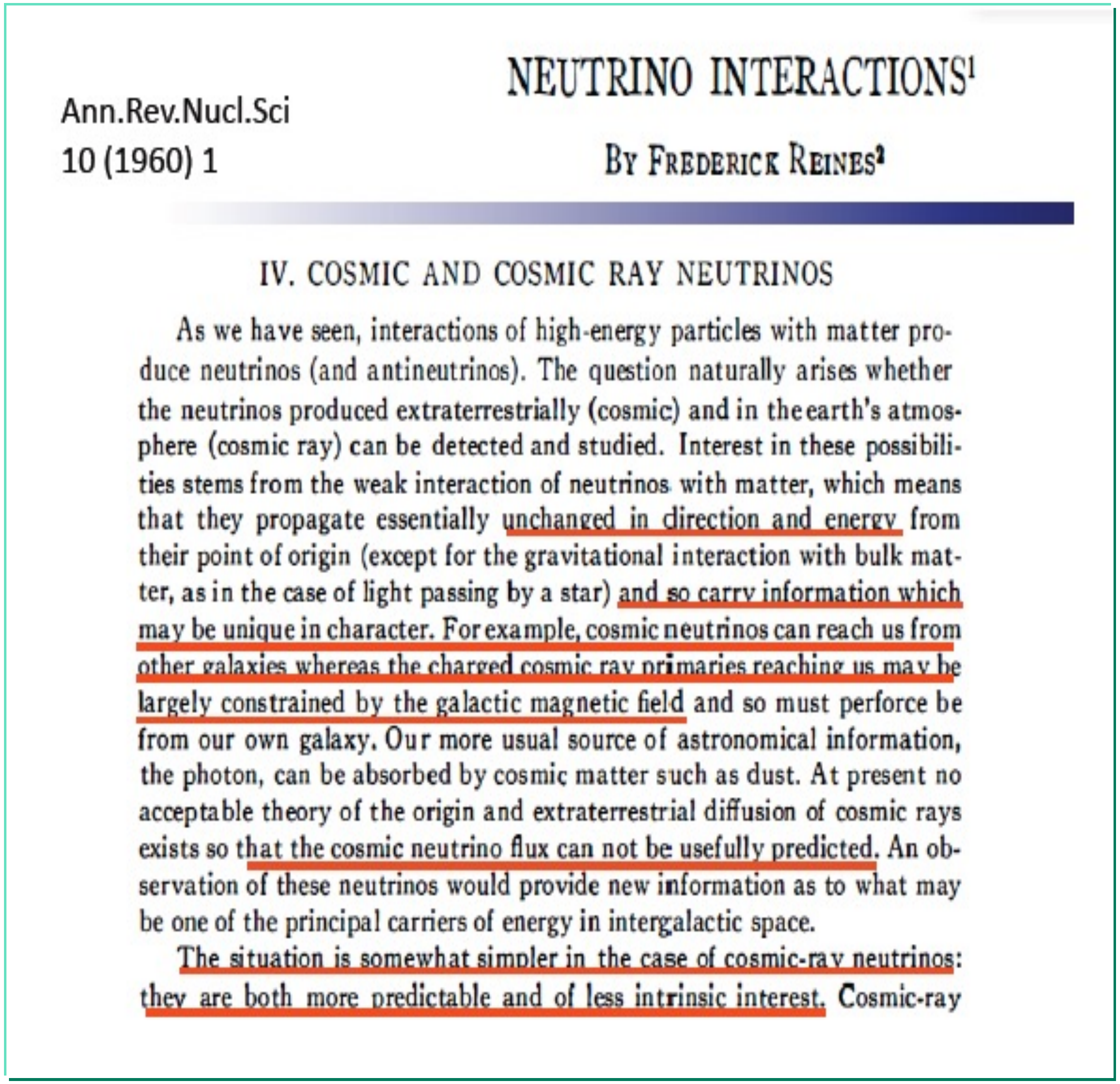
First ideas early 60's…science



Ann.Rev.Nucl.Sci
10 (1960) 1

NEUTRINO INTERACTIONS[1]

BY FREDERICK REINES[2]

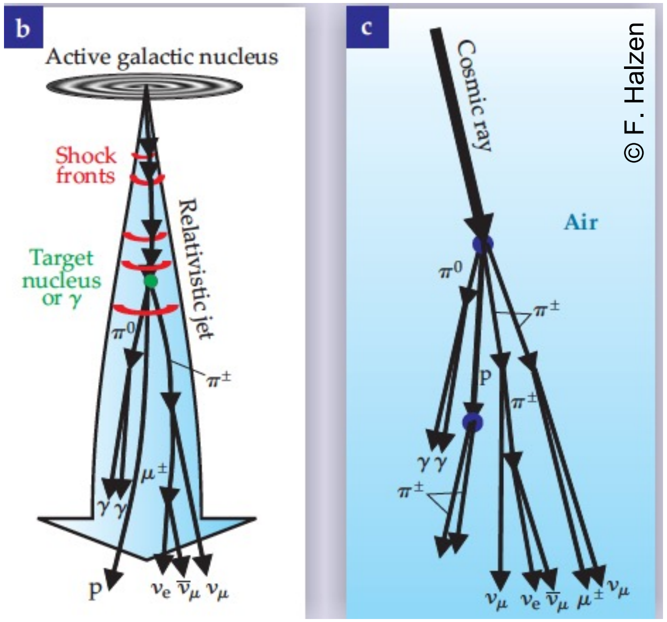
IV. COSMIC AND COSMIC RAY NEUTRINOS

As we have seen, interactions of high-energy particles with matter produce neutrinos (and antineutrinos). The question naturally arises whether the neutrinos produced extraterrestrially (cosmic) and in the earth's atmosphere (cosmic ray) can be detected and studied. Interest in these possibilities stems from the weak interaction of neutrinos with matter, which means that they propagate essentially unchanged in direction and energy from their point of origin (except for the gravitational interaction with bulk matter, as in the case of light passing by a star) and so carry information which may be unique in character. For example, cosmic neutrinos can reach us from other galaxies whereas the charged cosmic ray primaries reaching us may be largely constrained by the galactic magnetic field and so must perforce be from our own galaxy. Our more usual source of astronomical information, the photon, can be absorbed by cosmic matter such as dust. At present no acceptable theory of the origin and extraterrestrial diffusion of cosmic rays exists so that the cosmic neutrino flux can not be usefully predicted. An observation of these neutrinos would provide new information as to what may be one of the principal carriers of energy in intergalactic space.

The situation is somewhat simpler in the case of cosmic-ray neutrinos: they are both more predictable and of less intrinsic interest. Cosmic-ray

Greisen, 1960, Proc. Int. Conf on Instrum for HE physics

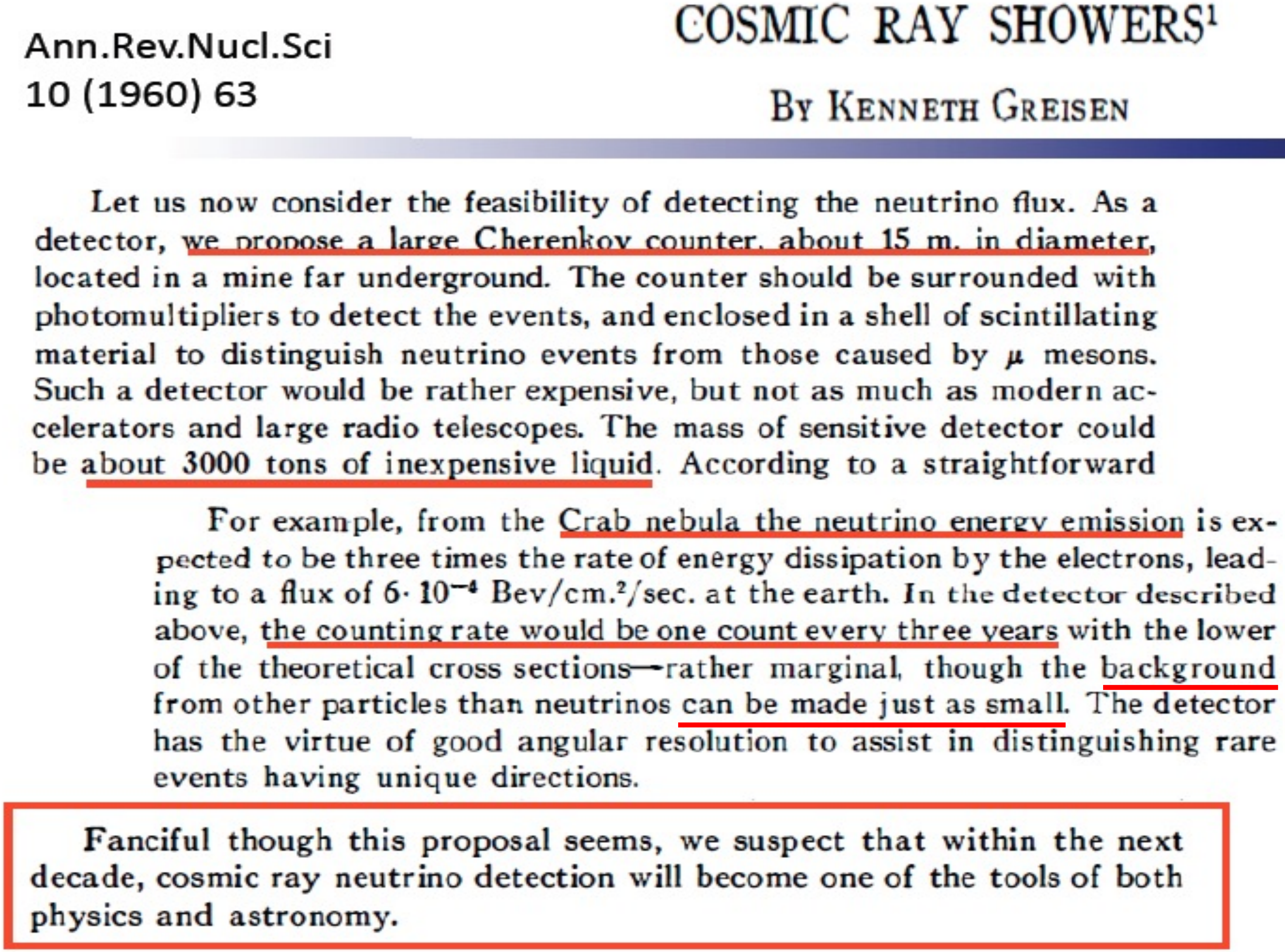
One may even anticipate eventual high-energy neutrino astronomy, since neutrino travel in straight lines, unlike the usual primary cosmic rays, and the neutrinos will convey a new type of astronomical information quite different from that carried by visible light and radio waves



Courtesy: Ch. Spiering

First ideas early 60's…method

Ann.Rev.Nucl.Sci
10 (1960) 63



COSMIC RAY SHOWERS[1]

By Kenneth Greisen

Let us now consider the feasibility of detecting the neutrino flux. As a detector, we propose a large Cherenkov counter, about 15 m. in diameter, located in a mine far underground. The counter should be surrounded with photomultipliers to detect the events, and enclosed in a shell of scintillating material to distinguish neutrino events from those caused by μ mesons. Such a detector would be rather expensive, but not as much as modern accelerators and large radio telescopes. The mass of sensitive detector could be about 3000 tons of inexpensive liquid. According to a straightforward

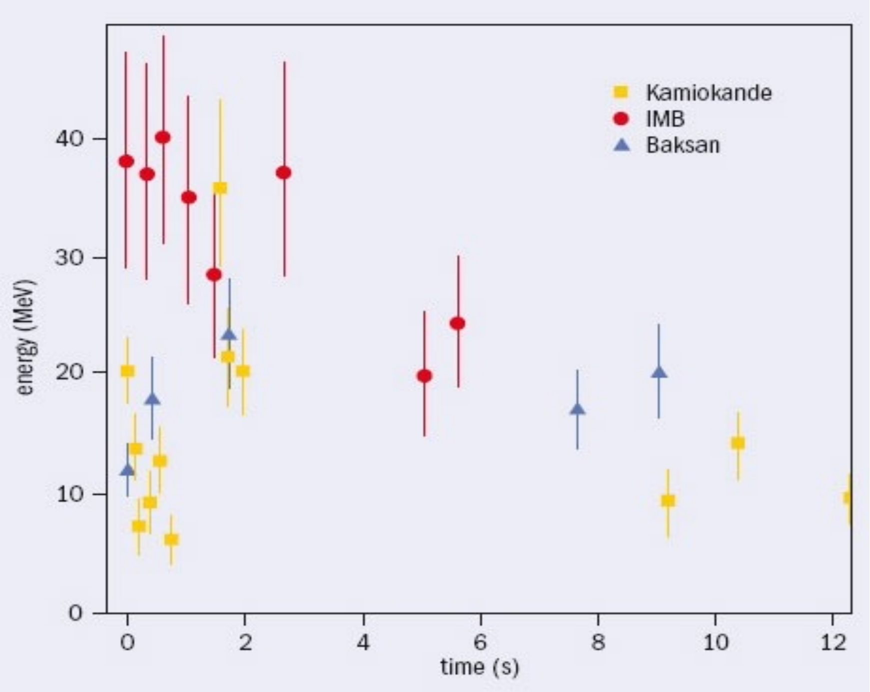
For example, from the Crab nebula the neutrino energy emission is expected to be three times the rate of energy dissipation by the electrons, leading to a flux of $6 \cdot 10^{-4}$ Bev/cm.^{2}/sec. at the earth. In the detector described above, the counting rate would be one count every three years with the lower of the theoretical cross sections—rather marginal, though the background from other particles than neutrinos can be made just as small. The detector has the virtue of good angular resolution to assist in distinguishing rare events having unique directions.

Fanciful though this proposal seems, we suspect that within the next decade, cosmic ray neutrino detection will become one of the tools of both physics and astronomy.

First extraterrestrial neutrinos : SN

- **1987:** Observation of a neutrino burst from the supernova SN1987A in the Large Magellanic Cloud

Tarantula nebula: D ~ 51,4 kpc



24 neutrinos detected in ~10 seconds
about 3 hours before the electromagnetic emission
Typical energy ~10 MeV

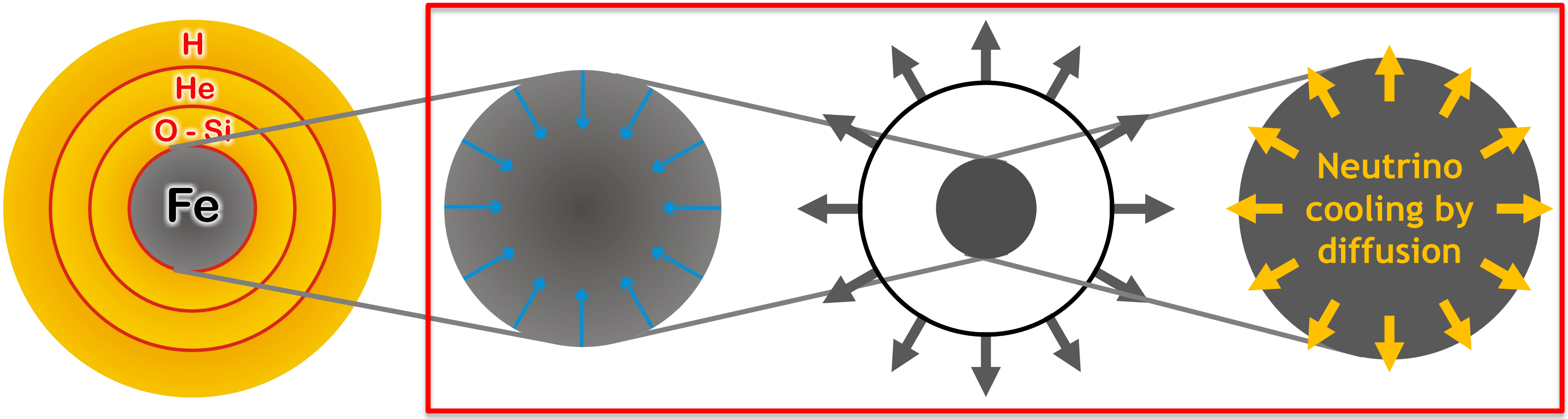
Supernovae neutrinos

End state of a massive star
$M \gtrsim 6\text{–}8\ M_{\odot}$

Collapse of degenerate core

Bounce at $\rho_{\rm nuc}$
Shock wave forms explodes the star

Grav. binding E $\sim 3 \times 10^{53}$ erg emitted as nus of all flavors



Nuclear burning
H→ He → C – O
→ Si → Fe

Neutronisation burst
$e^- + p^+ \rightarrow n + \nu_e$
during collapse

Neutrino emission powered by infalling matter

Phases with Neutrino emission

Neutrinos carry 99% of the gravitational energy released during the collapse

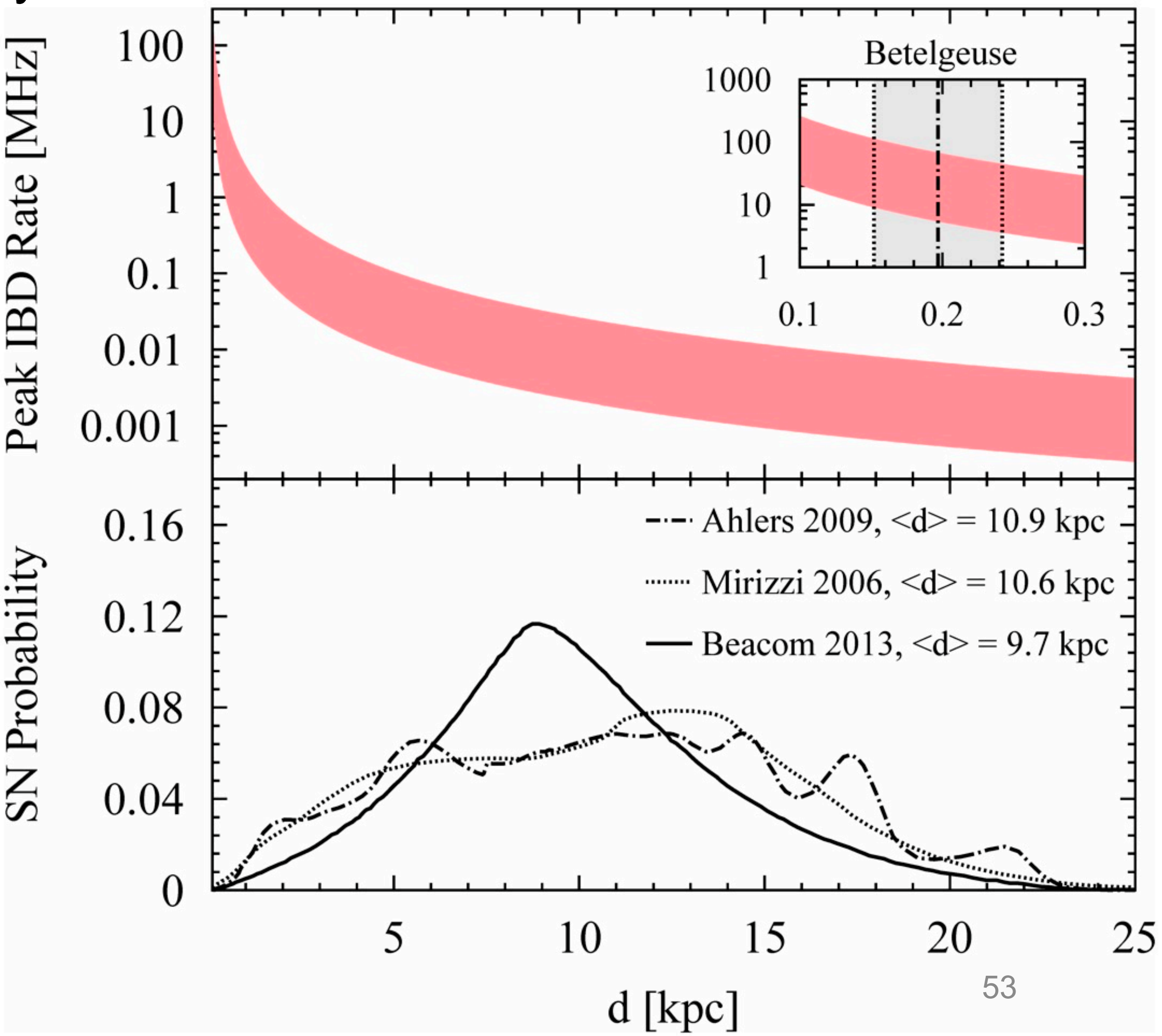
Supernovae neutrinos

- ❖ Huge rate of low-energy (MeV) neutrinos emitted over a few seconds
- ❖ A few core-collapse supernovae expected in our galaxy per century…

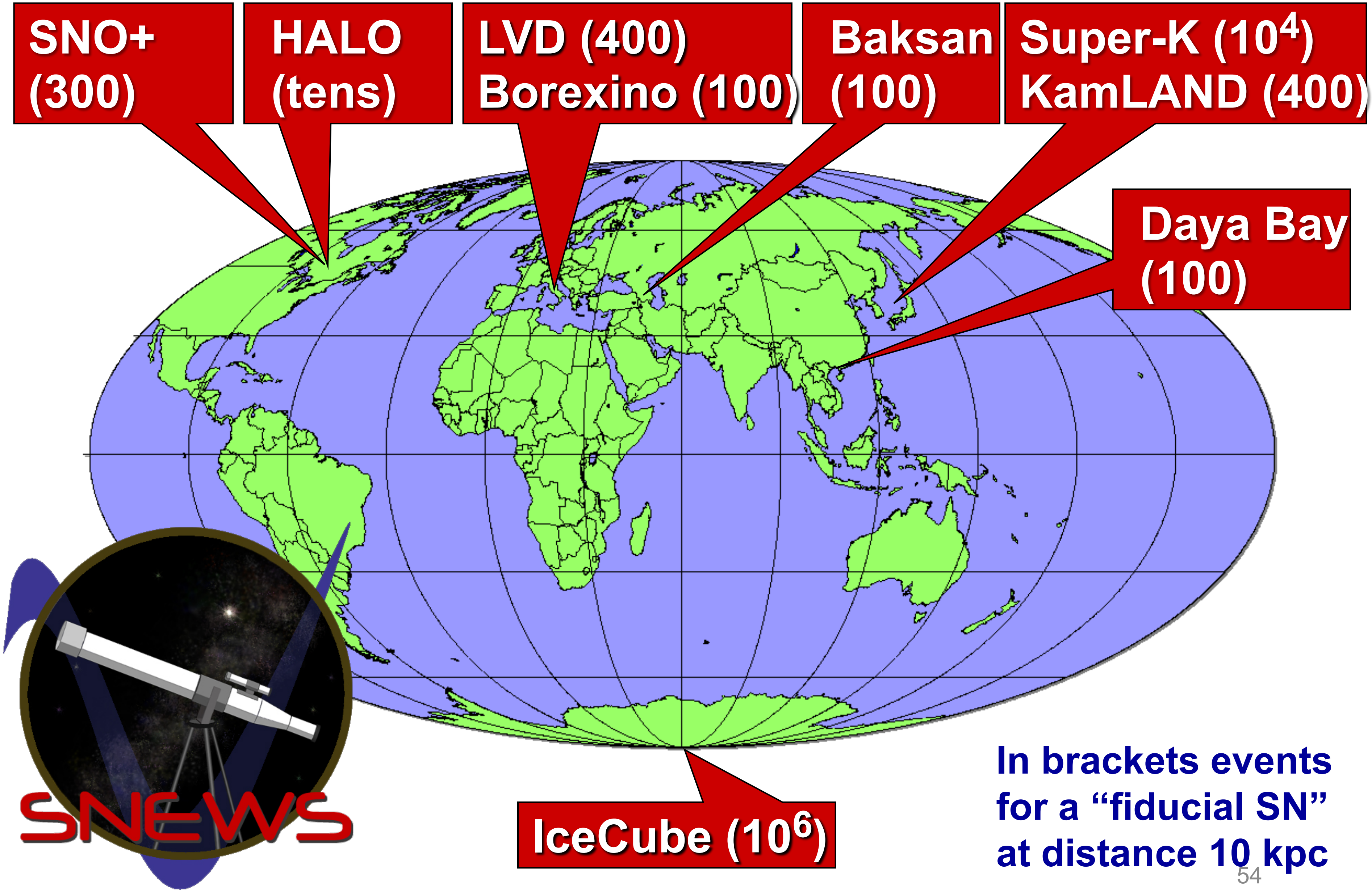
→ Unique detection opportunity!

Peak count rate
in a 20 kt
Inverse beta decay
Detector (here: JUNO)
depending on
SN distance

SN distance
probability
in Milky Way



Supernovae neutrinos



SNO+ (300)

HALO (tens)

LVD (400)
Borexino (100)

Baksan (100)

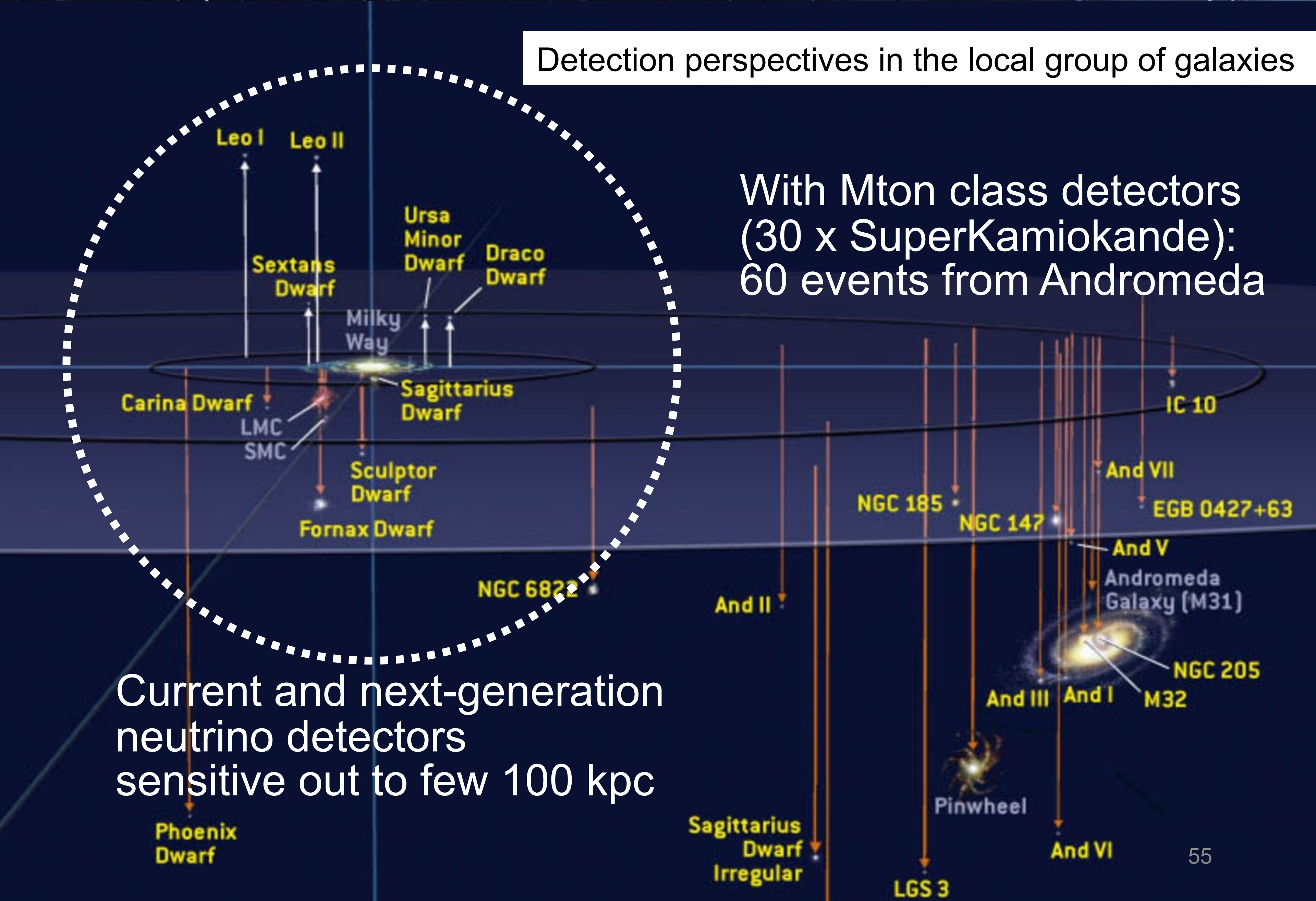
Super-K (10^4)
KamLAND (400)

Daya Bay (100)

IceCube (10^6)

In brackets events for a “fiducial SN” at distance 10 kpc

Supernovae neutrinos



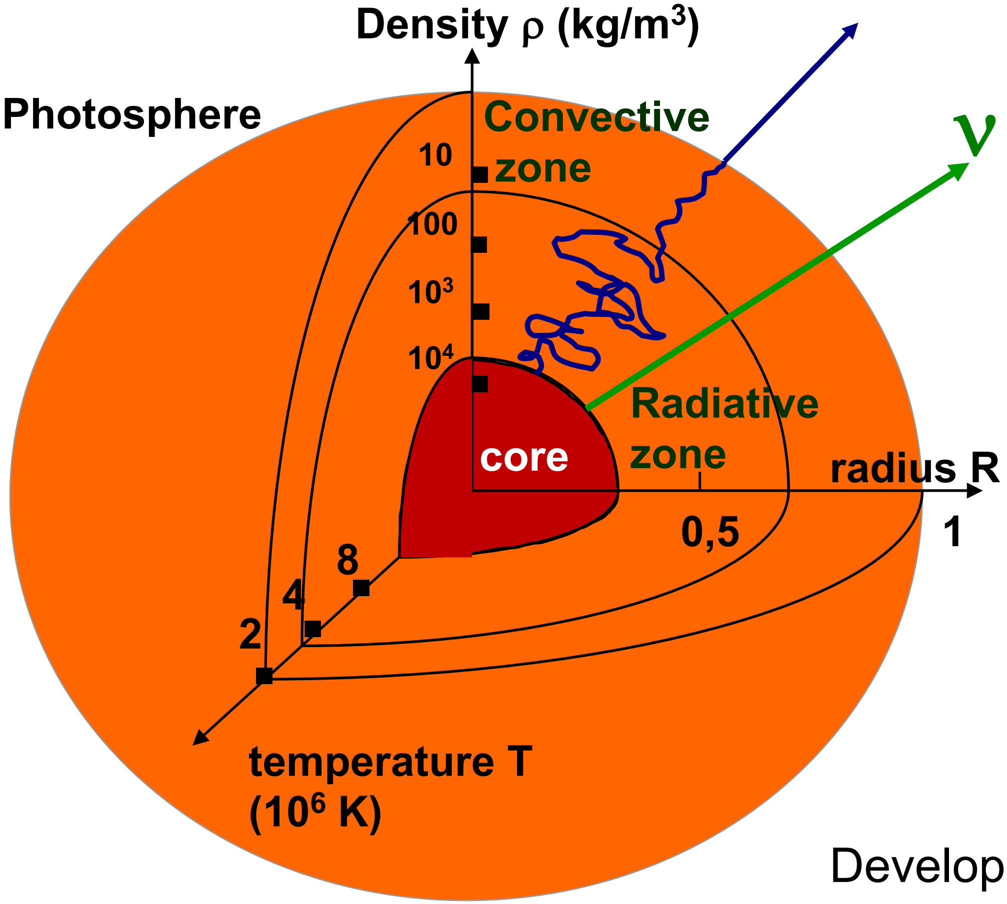
Detection perspectives in the local group of galaxies

With Mton class detectors (30 x SuperKamiokande): 60 events from Andromeda

Current and next-generation neutrino detectors sensitive out to few 100 kpc

First extraterrestrial neutrinos : The Sun

❖ **4 concentric layers characterized by :**
Temperature T(r), pressure P(r), luminosity L(r), opacity κ(r) & relative abundances $\frac{\rho(^4He)}{\rho(H)}, \frac{\rho(^3He)}{\rho(H)}, \frac{\rho(d)}{\rho(H)}$



Numerical resolution of 4 fundamental equations

$$
\begin{aligned}
P(r) &= n(r)kT(r) \\
\frac{dP}{dr} &= -\rho(r)\frac{GM(r)}{r^2} \\
L(r) &= -4\pi r^2 \frac{4}{3\kappa(r)\rho(r)} \frac{d(\sigma)T^4}{dr} \\
\frac{dL}{dr} &= 4\pi\rho r^2\epsilon
\end{aligned}
$$

Developed e.g. by J. Bahcall & S. Turck-Chièze

The Standard Solar Model

❖ Thermonuclear fusion:

= reaction between repulsive nuclei: thermal motion help to cross the Coulomb barrier
The fusion of heavier nuclei requires higher temperatures.
Dominant process in the sun:

$\boxed{p + p \rightarrow d + e^+ + \nu_e}$	(x2) Weak interaction + Coulomb barrier
$d + p \rightarrow {}^3\mathrm{He} + \gamma$	(x2) Weak and strong interaction + Coulomb barrier
${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$	Strong interaction + Coulomb barrier

$$4p \longrightarrow {}^4\mathrm{He} + 2\,e^+ + 2\,\nu_e$$

The first reaction, slower, is dominant.
This cycle is referred to as ppI cycle.

$$\langle Q\rangle = 4m_p - 2m_e - m_{^4\mathrm{He}} - 2\underset{\overset{\uparrow}{0.25\ \mathrm{MeV}}}{\langle E_\nu\rangle} = 27\ \mathrm{MeV}$$

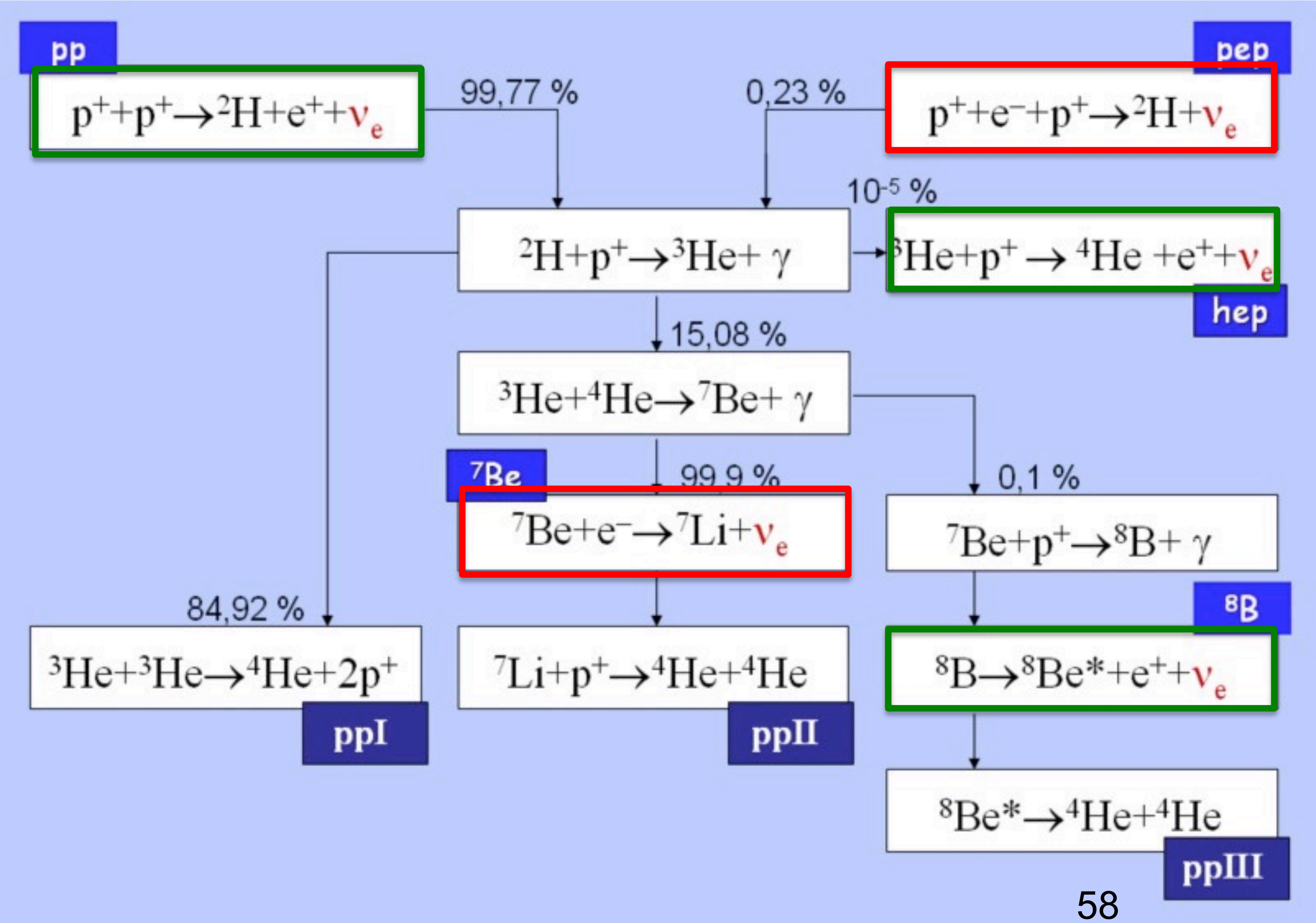
Estimation of the solar neutrino flux at Earth:

$$\Phi_\nu = 2\,\frac{L_{sun}}{Q}\,\frac{1}{4\pi R^2} = 2\,\frac{3.8\,10^{26}\ \mathrm{W}}{27\mathrm{MeV}}\,\frac{1}{4\pi(5.10^{11}\,\mathrm{m})^2} \approx 6.3\,10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Solar Neutrinos

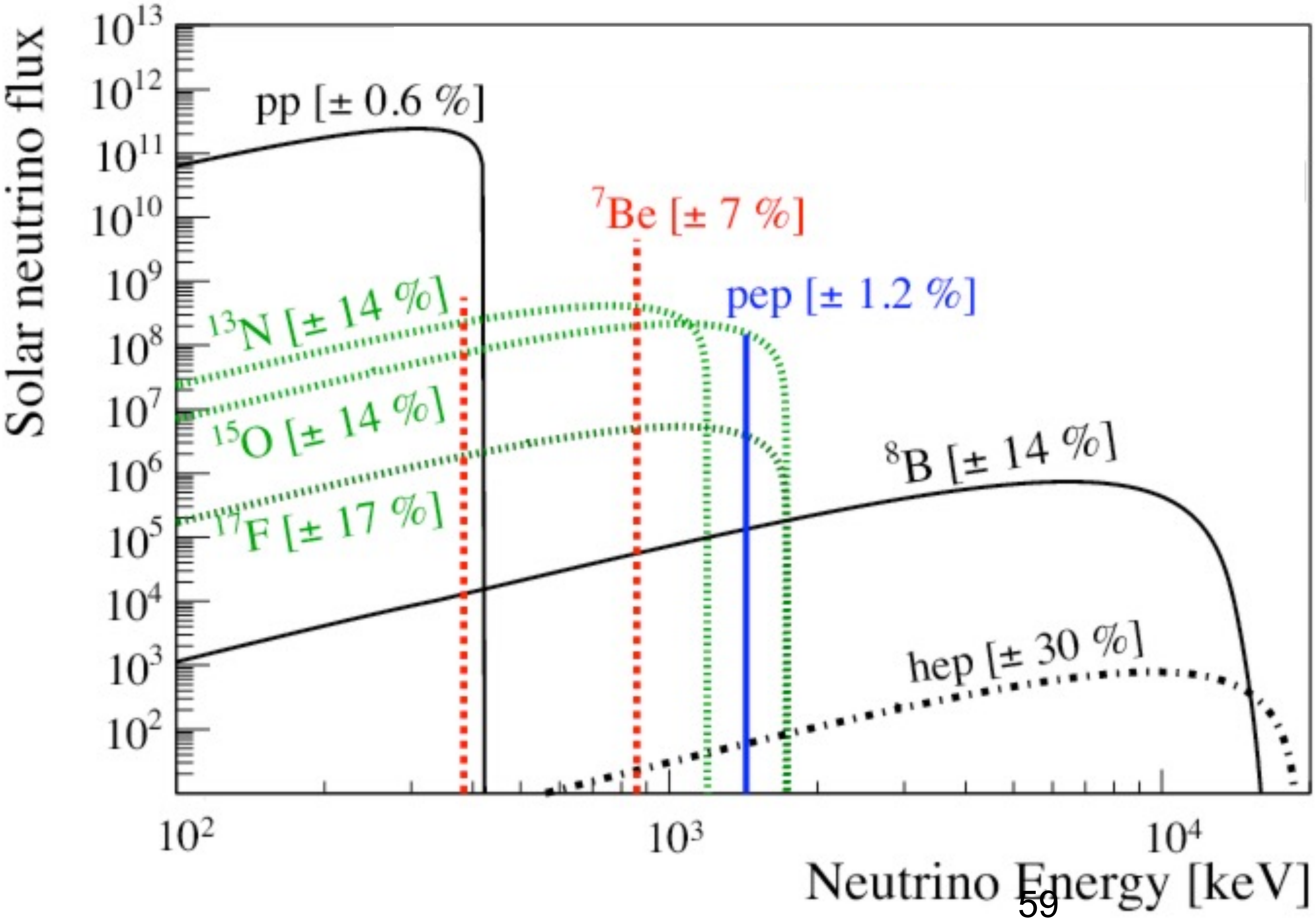
- ❖ **The full pp cycle: 98.4% of solar energy**

Continuous spectrum
Discrete spectrum



Solar Neutrinos

Continuous spectra in /cm^2/s/MeV
Discrete spectra in n /cm^2/s



Solar neutrinos: detection strategies

2 experimental approaches

Radiochemical experiments

$\nu_e + (A,Z) \longrightarrow e^- + (A,Z+1)^*$

→ Based on counting of daughter nuclei
→ No time information
→ No energy/direction information

Event rate: $R \equiv N_T \times \phi_\nu \times \sigma$

Target:
1 ton matter

pp flux:
$\sim 10^{11}$ cm^{-2}s^{-1}

$\sim 10^{-44}$ cm^2

10^{30} atoms needed to reach detection rate of 1 per day

Detection rate expressed in Solar Neutrino Units:

1 SNU = 10^{-36} capture atom^{-1} sec^{-1}

Real-time detection

$\nu_x + e^- \longrightarrow \nu_x + e^-$ (ES)
$\nu_e + N \longrightarrow X + e^-$ (CC)
$\nu_x + N \longrightarrow Y + \nu_x$ (NC)

→ For ES, CC: e- detected in (heavy) water or scintillator liquid provides information on the neutrino energy

→ For ES in water: e- also provides direction information
BUT high threshold in energy: ~ 5 MeV
…only sensitive to neutrinos from ^{8}B ($\sim 10^7$ cm^{-2}s^{-1})

→ Need ~kiloton-size water detectors

Radiochemical experiments

Cf tutorial

1968: First detection of solar ν_e – The Homestake experiment

…v2 of Davis' experiment!

Homestake gold mine, South Dakota, USA
1480m underground

615 tons C_2Cl_4 (Perchloroethylene)
~ 380 000 litres(cheap, commercially available)

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

$\hookrightarrow {}^{37}Cl \quad (T_{1/2}=35\ d)$

$E_{threshold}=0.8\ MeV > E_{pp}$

→ Mainly sensitive to ^{7}Be neutrinos

Principle of a cycle :

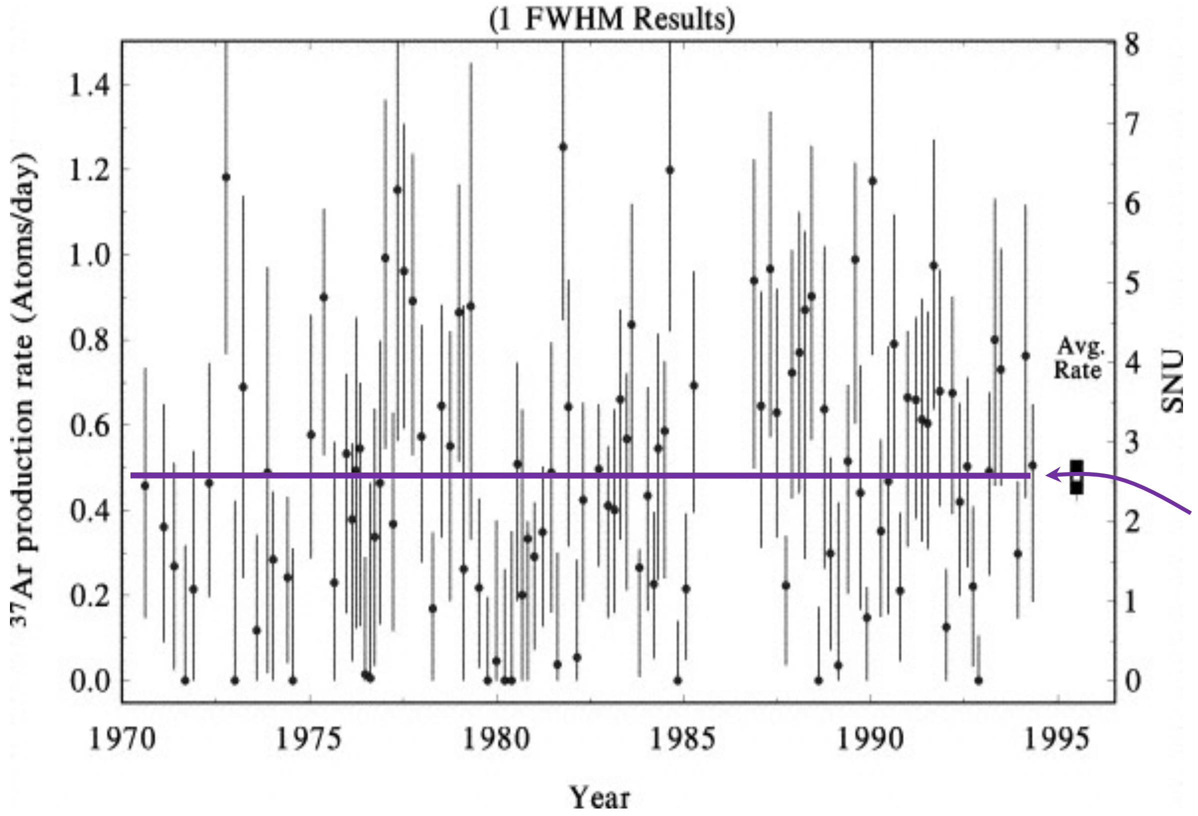
-Exposition (~2 months)
-Extraction of the produced Ar

-Counting
Observation of Ar disintegration (e_{AUGER}):
Energy deposit and signal rise time

Radiochemical experiments

- **25 years of data (108 runs)**

📖 **B.T.Cleveland et al., Ap. J. 496 (1998) 505**



R. Davis, Nobel Prize in 2002

Averaged result
2.56 ± 0.20 SNU
= 1/3 of flux
prediction
based on Standard
Solar Model
(7.6 ± 1.2 SNU)

About 750 decays observed: ~0.5 par jour

Already in the 1970's (~10 extractions): the birth of the "solar neutrino problem"

…deficit confirmed by other radiochemical experiments with Gallium

Radiochemical experiments

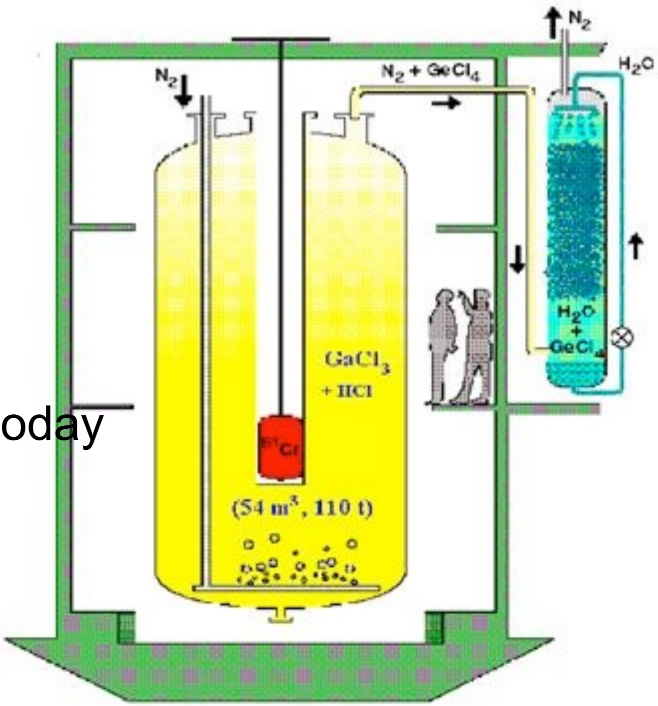
- **Gallium experiments:**

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

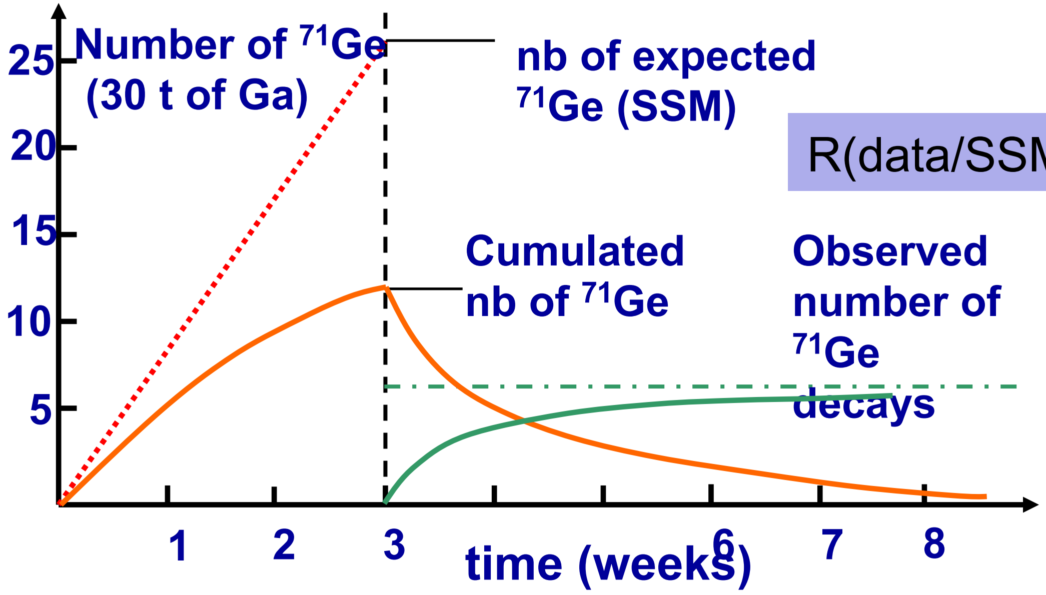
τ = 16.5 days

→ ^{71}Ga + ν_e + X-rays

Threshold = 233 keV
→ sensitive to pp neutrinos!



- SAGE (Soviet-American Gallium Experiment) 1990-today
  60 t of metallic Ga
- GALLEX/GNO (at Gran Sasso) 1991-2004
  60 t of $GaCl_3$ + HCl



R(data/SSM) ≈ 0.5

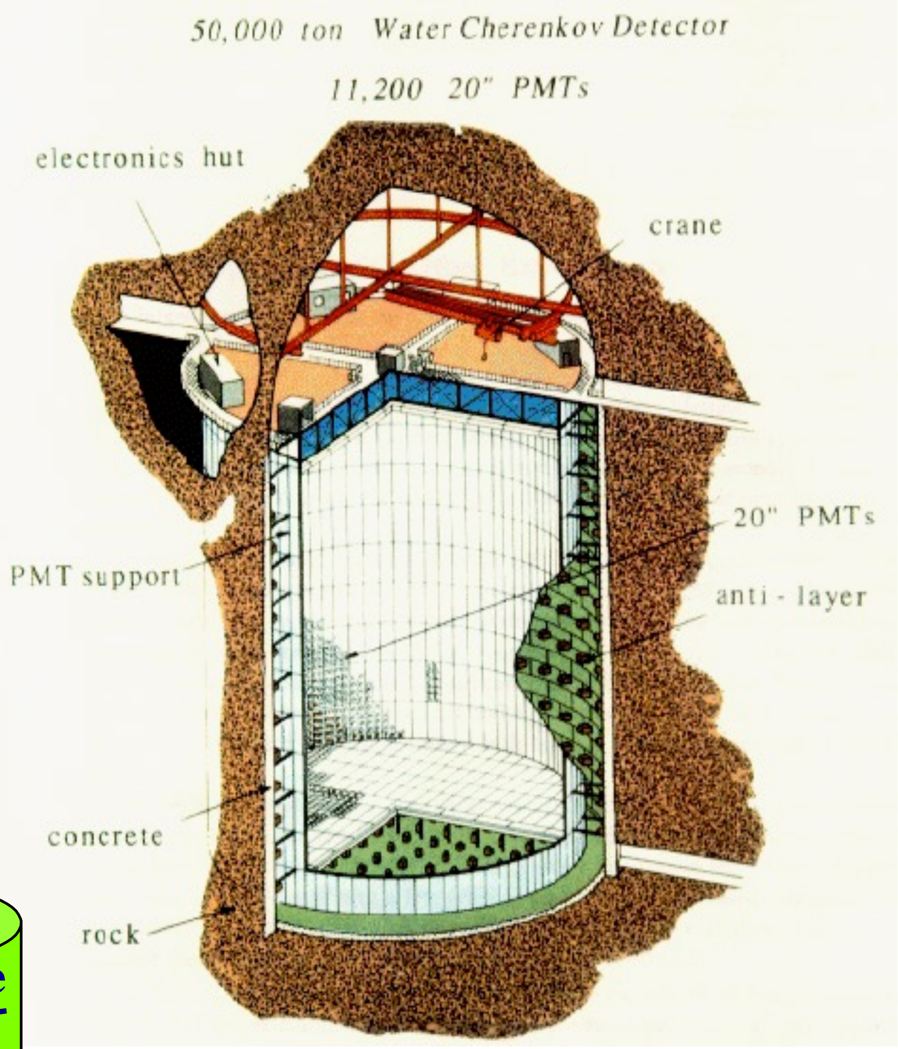
Real-time detection: water Cherenkov

- **Kamiokande 1987-1996**

5000 tons of water
Kamioka mine, 100m depth (2700m we)

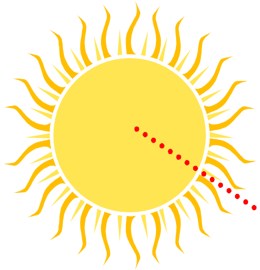
- **SuperKamiokande 1996 - 2018**

50 000 tons of water
11 146 PMTs 20 ”



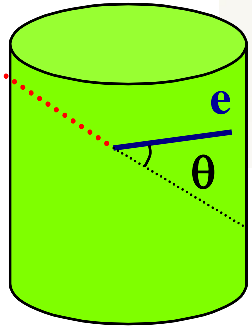
Detection threshold:
E_ν ~ 5 MeV (instrumental)

→ mainly sensitive to ^8B neutrinos !

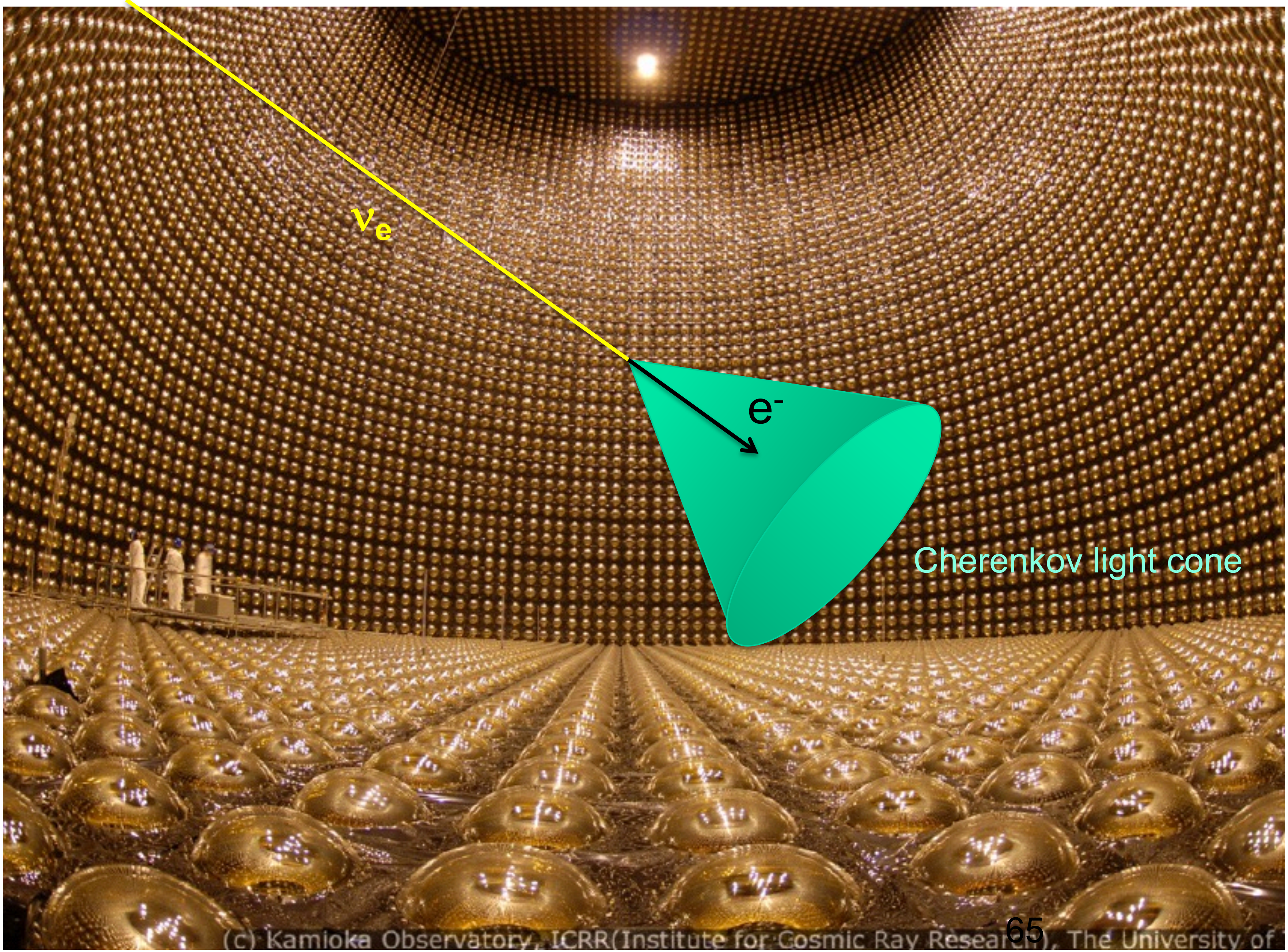


Elastic scattering on
Electrons (CC or NC)

$$\nu_e + e^- \longrightarrow \nu_e + e^-$$



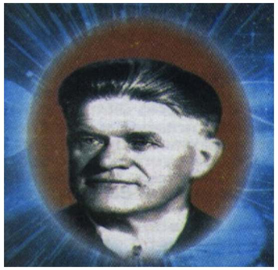
Real-time detection: water Cherenkov



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Resea[illegible]), The University of

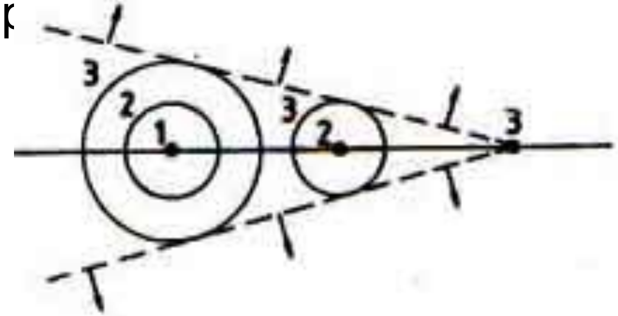
Real-time detection: water Cherenkov

Cf tutorial

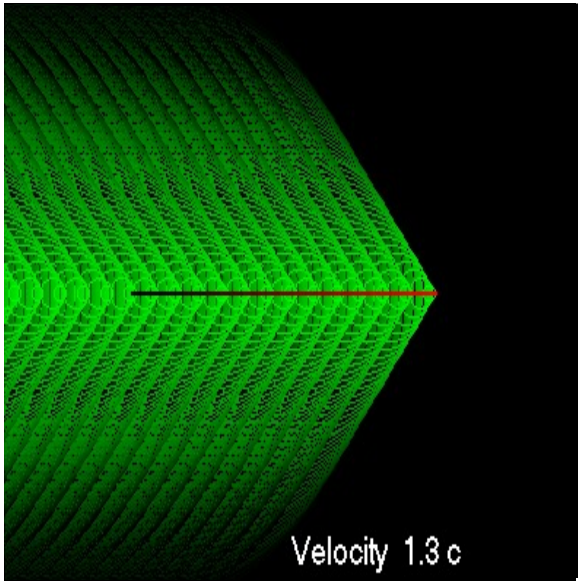


Coherent emission of light produced by relativistic charged particles, observable in a transparent medium

The charged particles polarize the molecules of the medium, which then turn back rapidly to their ground state, emitting radiation in the



$$\cos\theta_c = \frac{1}{\beta n}$$

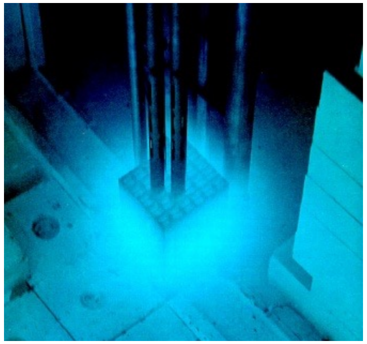


Cherenkov emission angle depends on the refraction index of the medium

Water → ϑ ≅ 41°

Number of Cherenkov photons emitted in the range 400 – 700 nm:

$$N_C \approx 5\cdot10^4\left(1-\frac{1}{\beta^2 n^2}\right) \approx 5\cdot10^4 \sin^2\theta_c \left(\text{photons m}^{-1}\right)$$



Real-time detection: water Cherenkov

- **Cherenkov threshold:**

$$\beta > 1/n \simeq 0.75 \quad ⇨ \quad \gamma = \frac{1}{\sqrt{1-\beta^2}} \simeq 1.5$$

⇨ $E_{threshold} = \gamma mc^2$

$\sim 1.5\ mc^2$

(special relativity)

n: refractive index of the medium
m: mass of the charged particle
β, γ: Lorenz factor

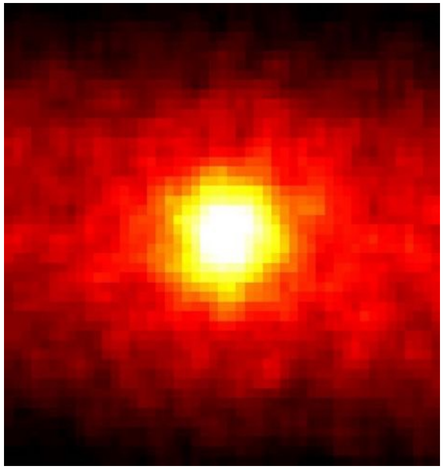
Particle	Energy threshold (MeV)
Electron	0.775
Muon	160.3
Charged pion	211.7
Proton	1407

$n \simeq 1.34$

Cannot observe particles below the thresholds…

Real-time detection: water Cherenkov

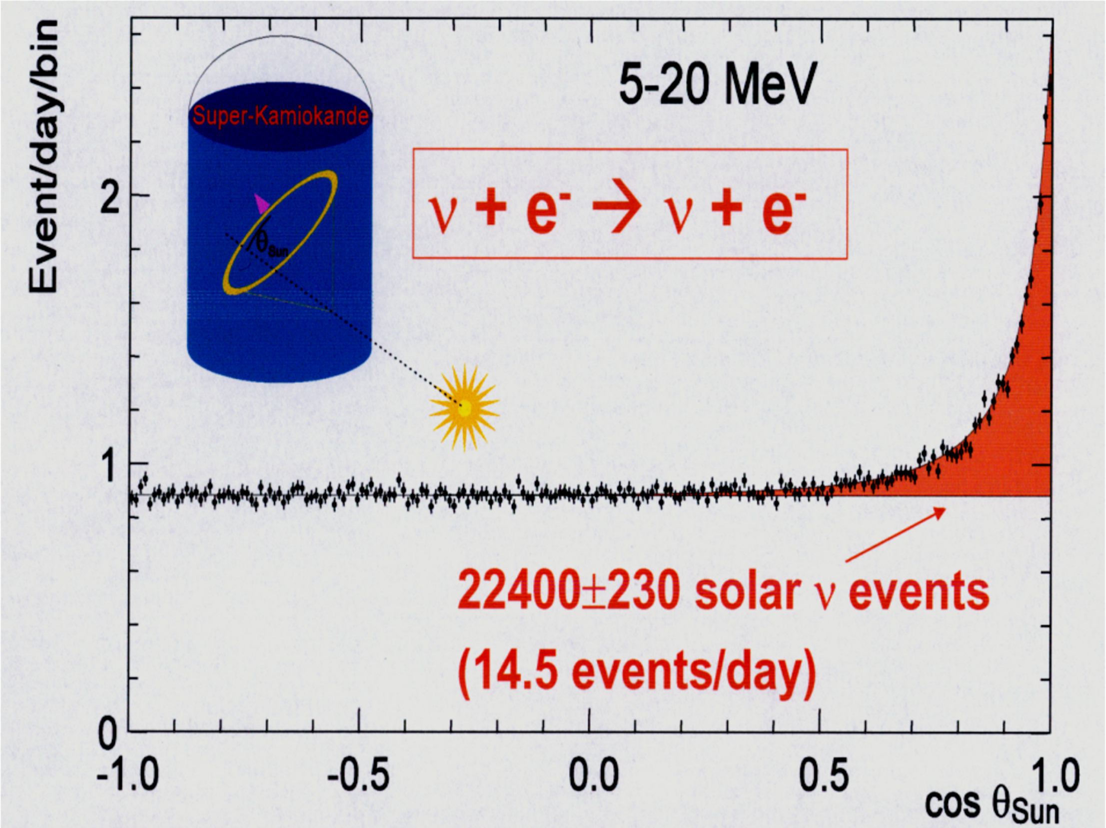
❖ **1998: Superkamiokande provides first picture of the Sun in neutrinos !**



- directionality performances allow to unambiguously identify neutrinos from the Sun

- 1500 days of data taking:
  22000 events detected
  48000 predicted by the SSM

→ Confirmation of deficit of ν_e already observed in radiochemical experiments

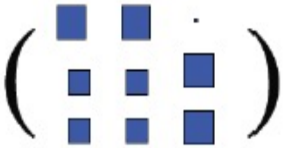


^{8}B flux : $2.35 \pm 0.02 \pm 0.08$ [x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM(BP2004)}} = 0.406 \pm 0.004 \, ^{+0.014}_{-0.013}$$

(Data/SSM(BP2000) = $0.465 \pm 0.005 \, +0.016/-0.015$)

Outline



Introduction to neutrinos

Today’s picture

Historical aspects

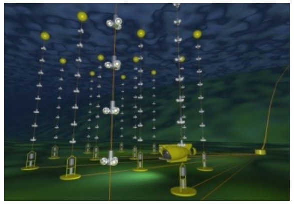
Neutrino astronomy

Scientific motivations

Historical aspects

Oscillation detour

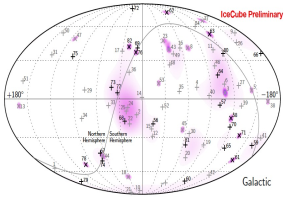
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



Selected results

Diffuse Flux, point sources

Multi-messenger search

KM3NeT

Future prospects

Neutrino oscillations

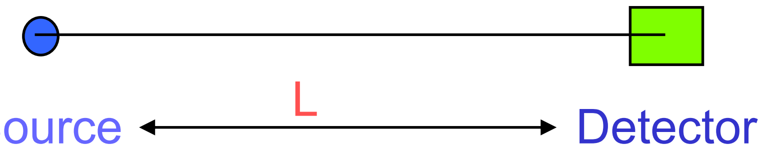
…To solve the solar neutrino puzzle and interpret it as neutrino oscillations:

→ **need to detect different neutrino flavours from a common, well-known source**

→ **need large statistics of events (even more to detect flavour appearance)**

→ **the experimental configuration (L: distance to the source, E: energy range) will determine the range of sensitivity in oscillation parameters (ϑ, Δm²)**

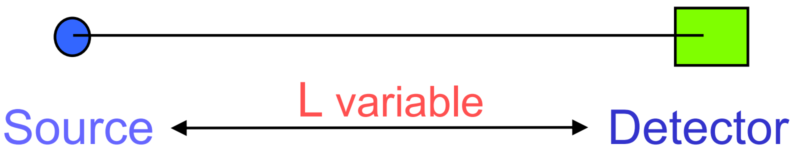
☺ Ideal experiment



- point-like
- pure flavor
- known intensity
- mono-energetic

- known efficiency
- flavour identification
- good energy resolution
- low background

😐 Reality



- Extended
- Mix of flavors
- Time-variable
- energy band

- efficiency uncertain
- uncertain flavour ID
- Energy calibration
- background estimate

… the more different experiments the better !

Neutrino oscillations

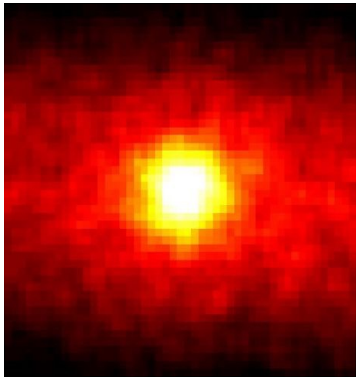
…To solve the solar neutrino puzzle and interpret it as neutrino oscillations:

→ **need to detect different neutrino flavours from a common, well-known source**

→ **need large statistics of events (even more to detect flavour appearance)**

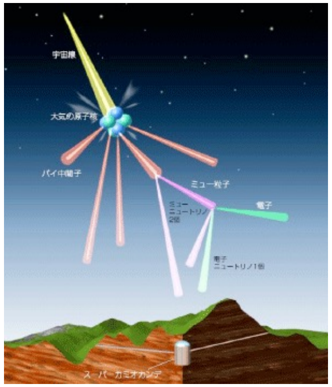
→ **the experimental configuration (L: distance to the source, E: energy range) will determine the range of sensitivity in oscillation parameters (ϑ, Δm²)**

Solar neutrinos



Superkamiokande,
SNO, Borexino,…

Atmospheric neutrinos



SuperKamiokande,
ANTARES, IceCube,..

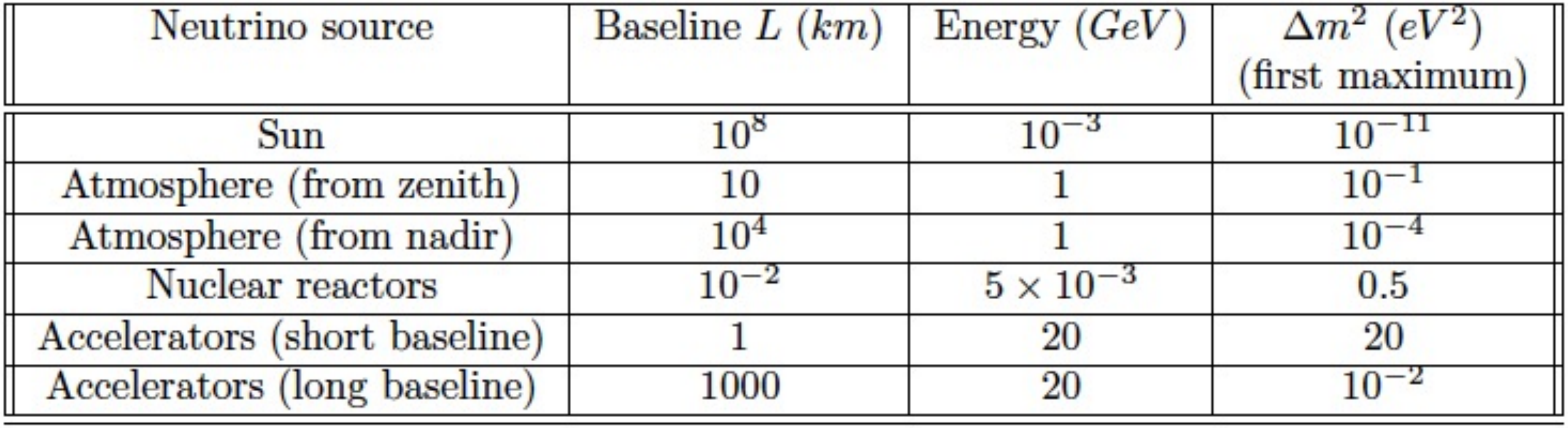
Reactor neutrinos

KamLAND, (Double) Chooz,
RENO, Daya Bay,…

Neutrino Beams

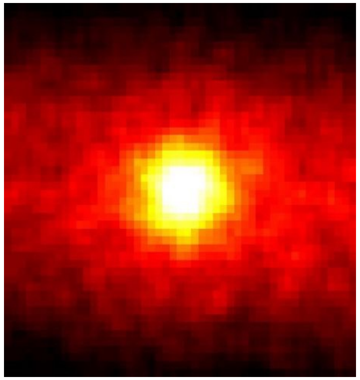
CHORUS, NOMAD,
LSND, MiniBOOnE,
T2K, CNGS, MINOS,.

Neutrino oscillations



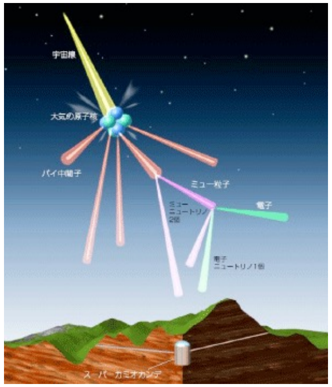
Neutrino source	Baseline L (km)	Energy (GeV)	Δm^2 (eV^2) (first maximum)
Sun	10^8	10^{-3}	10^{-11}
Atmosphere (from zenith)	10	1	10^{-1}
Atmosphere (from nadir)	10^4	1	10^{-4}
Nuclear reactors	10^{-2}	5×10^{-3}	0.5
Accelerators (short baseline)	1	20	20
Accelerators (long baseline)	1000	20	10^{-2}

Solar neutrinos



Superkamiokande, SNO, Borexino,…

Atmospheric neutrinos



SuperKamiokande, ANTARES, IceCube,..

Reactor neutrinos

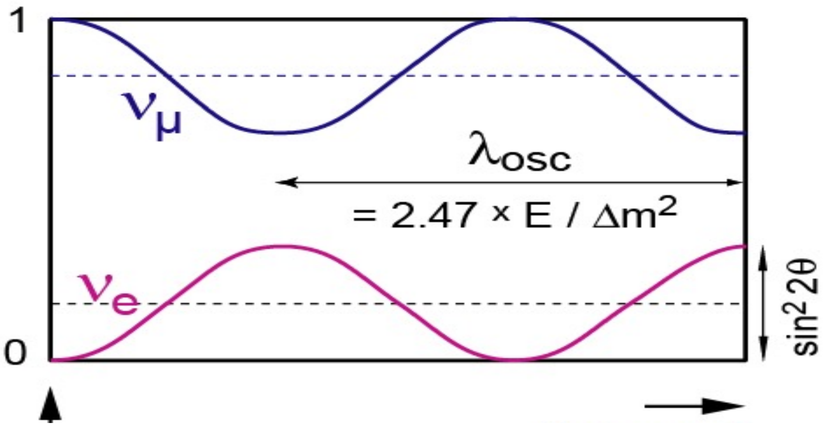
© CORBIS

KamLAND, (Double) Chooz, RENO, Daya Bay,…

Neutrino Beams

CHORUS, NOMAD, LSND, MiniBOOnE, T2K, CNGS, MINOS,.

Neutrino oscillations



2 possible strategies:

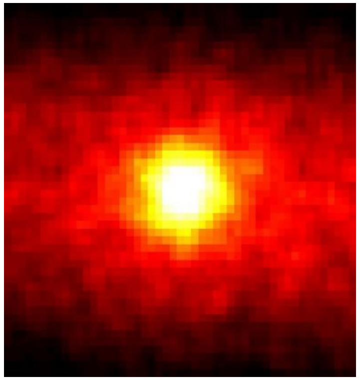
- Disappearance experiments

Using a neutrino source of given flavour, look for a deficit of neutrinos of same flavour

- Appearance experiment

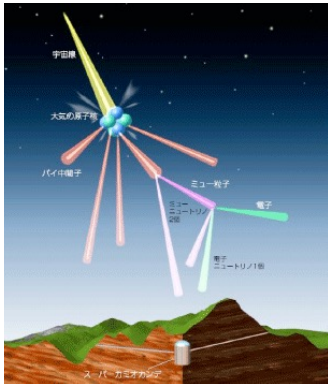
Using a neutrino source of given flavour, look for the appearance of neutrinos of different flavour

Solar neutrinos



Superkamiokande, SNO, Borexino,…

Atmospheric neutrinos



SuperKamiokande ANTARES, IceCube…

Reactor neutrinos

KamLAND, (Double) Chooz, RENO, Daya Bay, JUNO

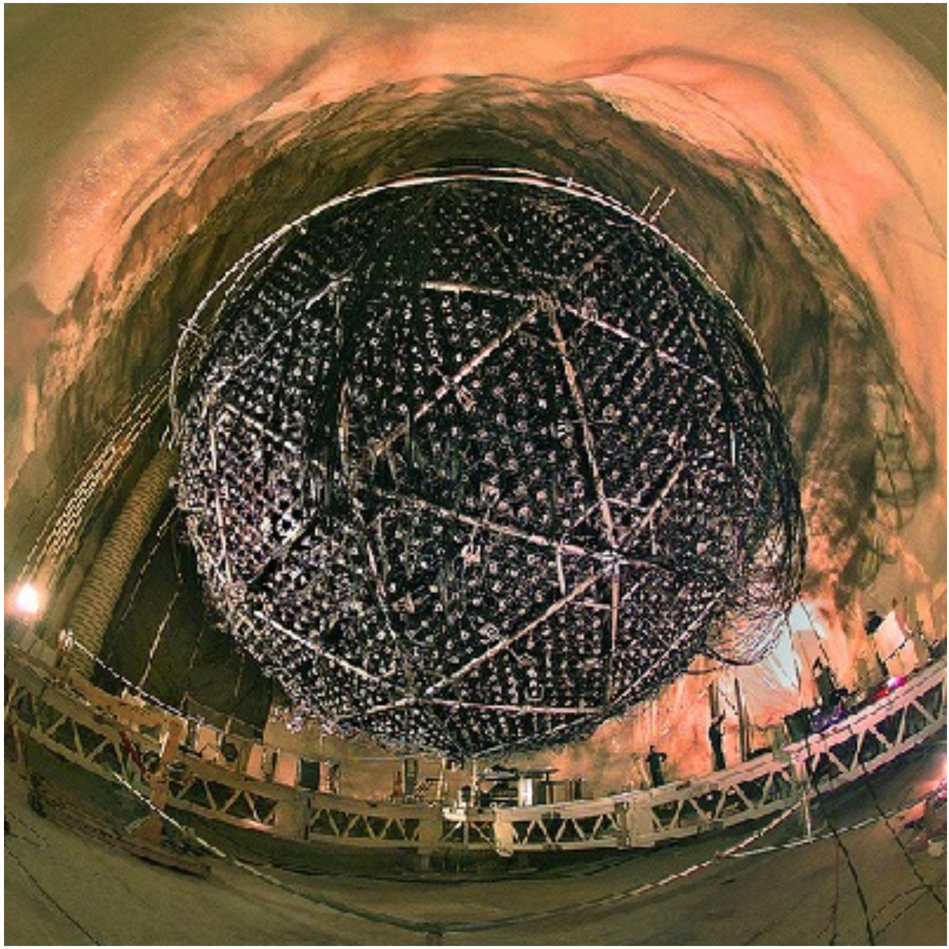
Neutrino Beams

CHORUS, NOMAD, LSND, MiniBOOnE, T2K, CNGS, MINOS,….

The decisive results: SNO (1999 –2006)

- 18 m sphere underground (~2.5km), in Ontario - Canada
- Heavy water (D_2O) inside a transparent acrylic sphere (12m diameter)
- 10,000 photomultiplier tubes (PMTs)
- PMTs collect Cherenkov light photons
- Pure salt is added to increase sensitivity of NC reactions (≥2002)
- SNO measure the flux of all flavors '$\Phi(\nu_x)$' from NC and electron neutrinos '$\Phi(\nu_e)$' with CC
- The flux of non-electron neutrinos is

$$\Phi(\nu_\mu, \nu_\tau) = \Phi(\nu_x) - \Phi(\nu_e)$$



Reactions in SNO

CC $\nu_e + d \Rightarrow p + p + e^-$

-Gives ν_e energy spectrum well

-Weak direction sensitivity $\propto$ 1-1/3cos(θ)

- ν_e only.

-SSM: 30 CC events day^{-1}

NC $\nu_x + d \Rightarrow p + n + \nu_x$

- Measure total ^{8}B ν flux from the sun.
- Equal cross section for all ν types
- SSM: 30/day

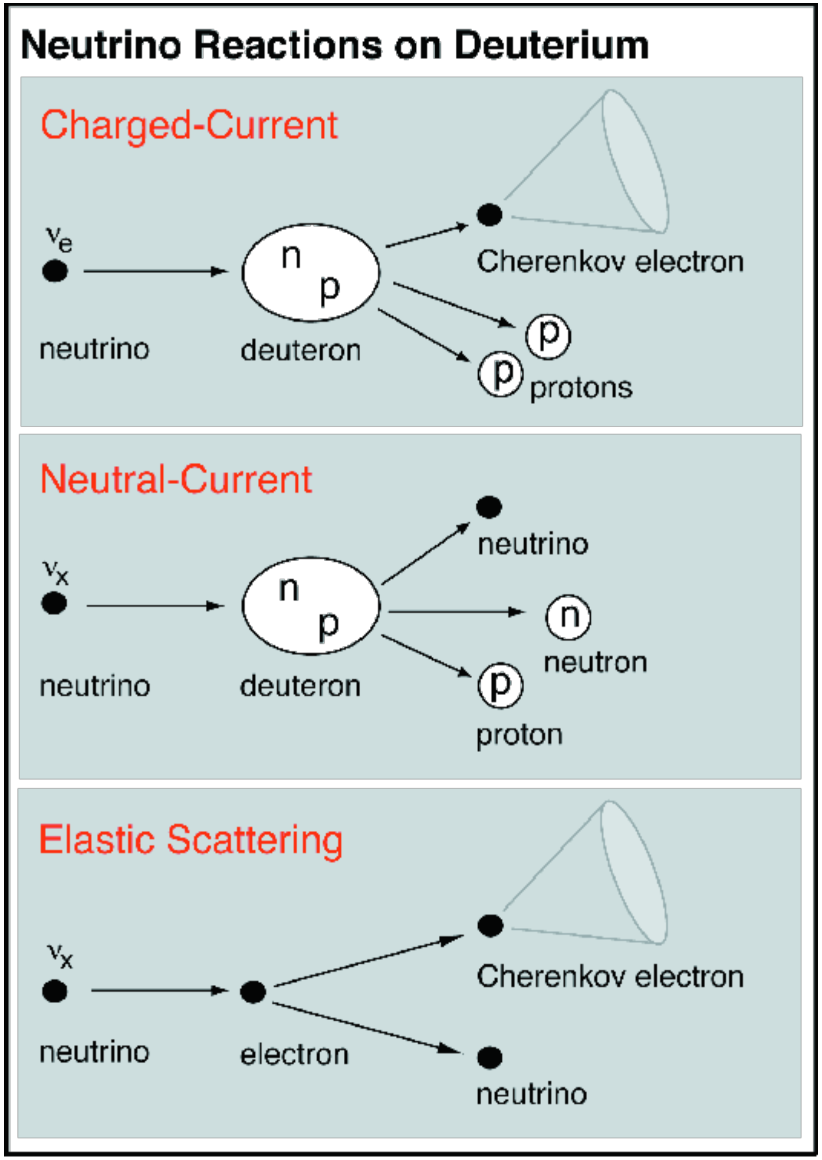
ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

-Low Statistics (3/day)

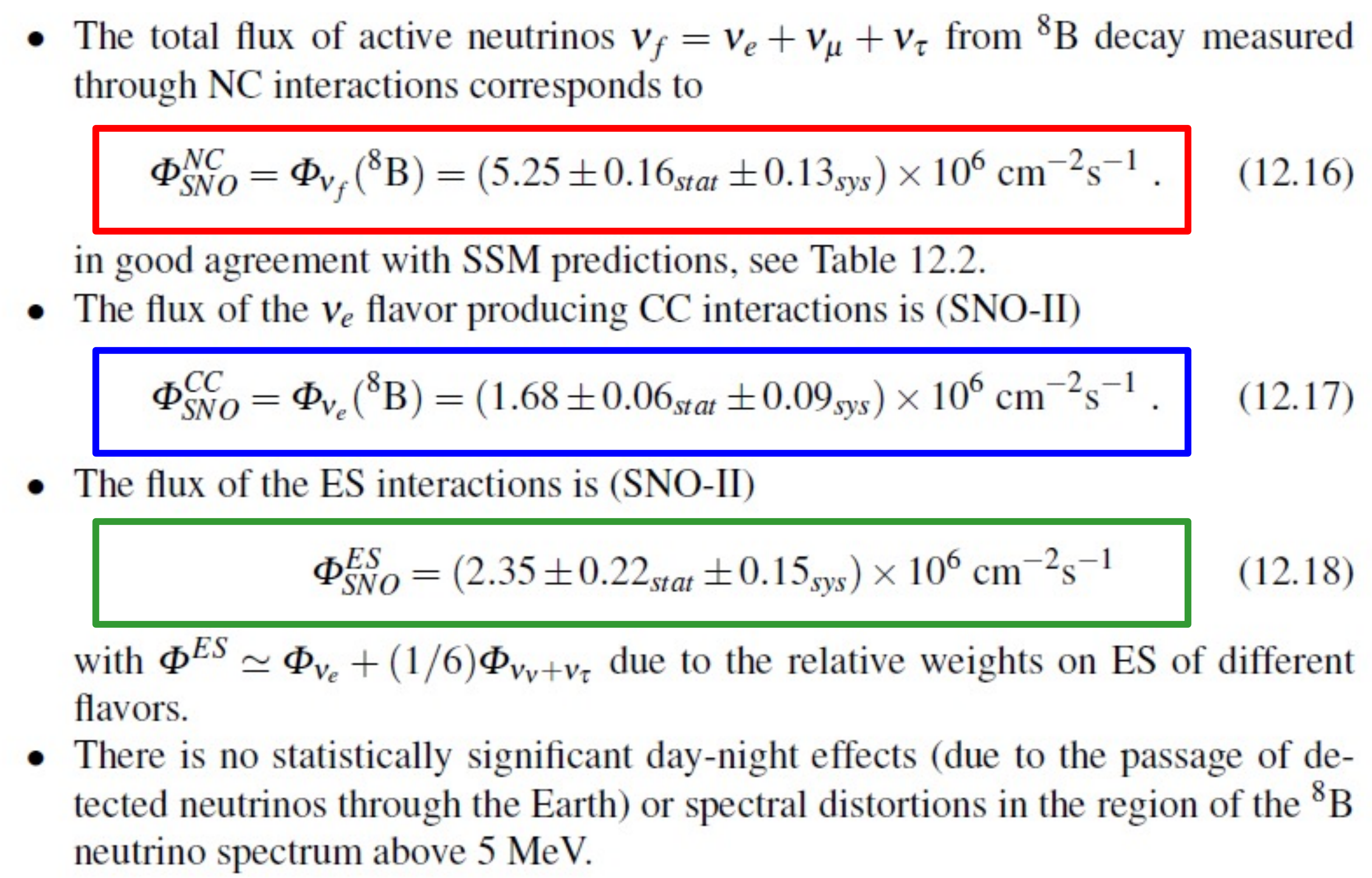
-Mainly sensitive to $\nu_{e,}$, some

-sensitivity to ν_μ and ν_τ

-Strong direction sensitivity



Final SNO Solar ν Results



- The total flux of active neutrinos $\nu_f = \nu_e + \nu_\mu + \nu_\tau$ from ^{8}B decay measured through NC interactions corresponds to

$$\boxed{\Phi^{NC}_{SNO} = \Phi_{\nu_f}(^8\mathrm{B}) = (5.25 \pm 0.16_{stat} \pm 0.13_{sys}) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\ .} \qquad (12.16)$$

in good agreement with SSM predictions, see Table 12.2.

- The flux of the ν_e flavor producing CC interactions is (SNO-II)

$$\boxed{\Phi^{CC}_{SNO} = \Phi_{\nu_e}(^8\mathrm{B}) = (1.68 \pm 0.06_{stat} \pm 0.09_{sys}) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\ .} \qquad (12.17)$$

- The flux of the ES interactions is (SNO-II)

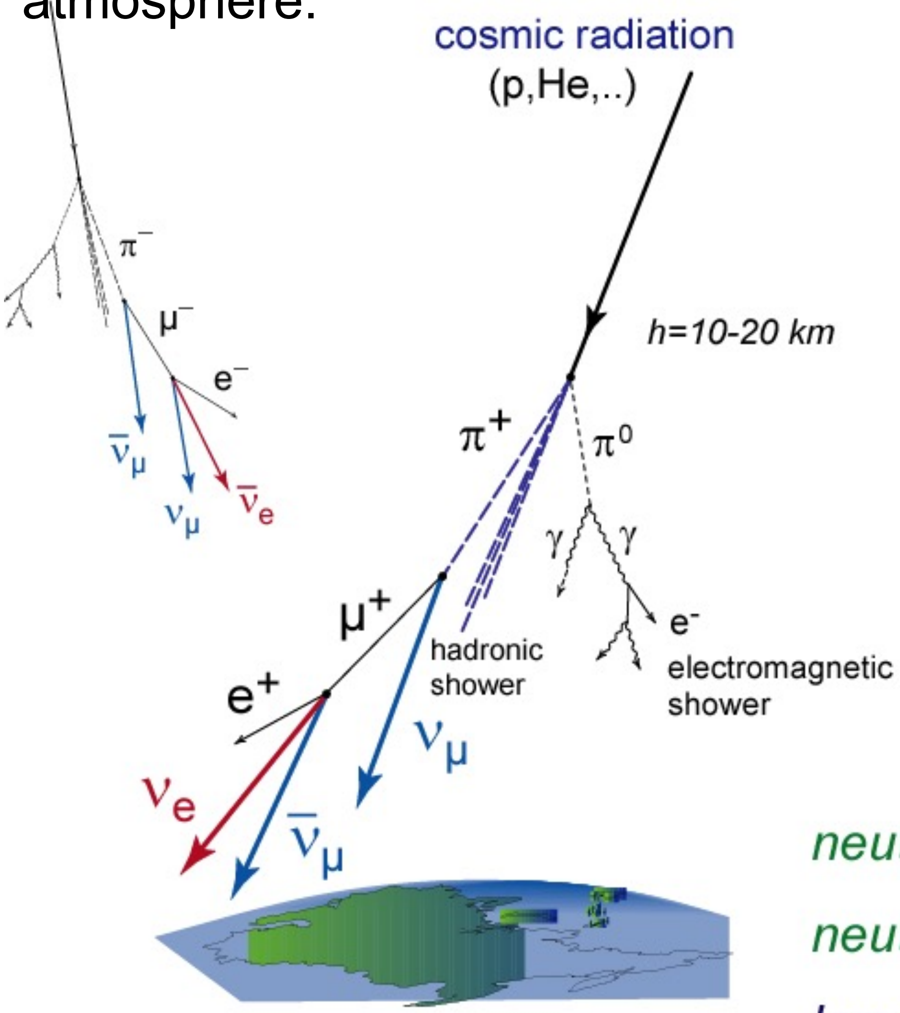
$$\boxed{\Phi^{ES}_{SNO} = (2.35 \pm 0.22_{stat} \pm 0.15_{sys}) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}} \qquad (12.18)$$

with $\Phi^{ES} \simeq \Phi_{\nu_e} + (1/6)\Phi_{\nu_\nu + \nu_\tau}$ due to the relative weights on ES of different flavors.

- There is no statistically significant day-night effects (due to the passage of detected neutrinos through the Earth) or spectral distortions in the region of the ^{8}B neutrino spectrum above 5 MeV.

Oscillations with atmospheric neutrinos

Neutrinos are produced in the interactions of cosmic rays with the atmosphere:



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

also: π^- μ^- e^- decay chain
decays of kaons K^+, K^-

flavour ratio $\nu_\mu : \nu_e = 2 : 1$

for wide range of energies: E_ν = 1-20 GeV!

geomagnetic effects for $E_\nu < 2$ GeV !

neutrino energies: E_ν = 0.5 - 500 GeV

neutrino pathlength: L_ν = 12 - 12.000 km

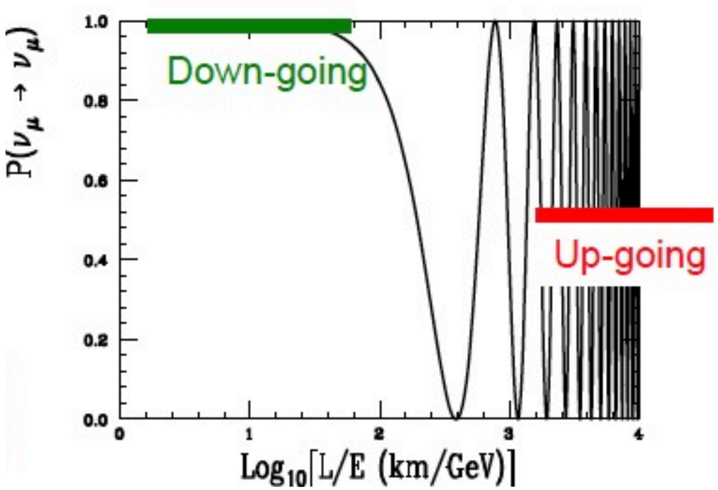
large L/E variation, explore small Δm^2 - values

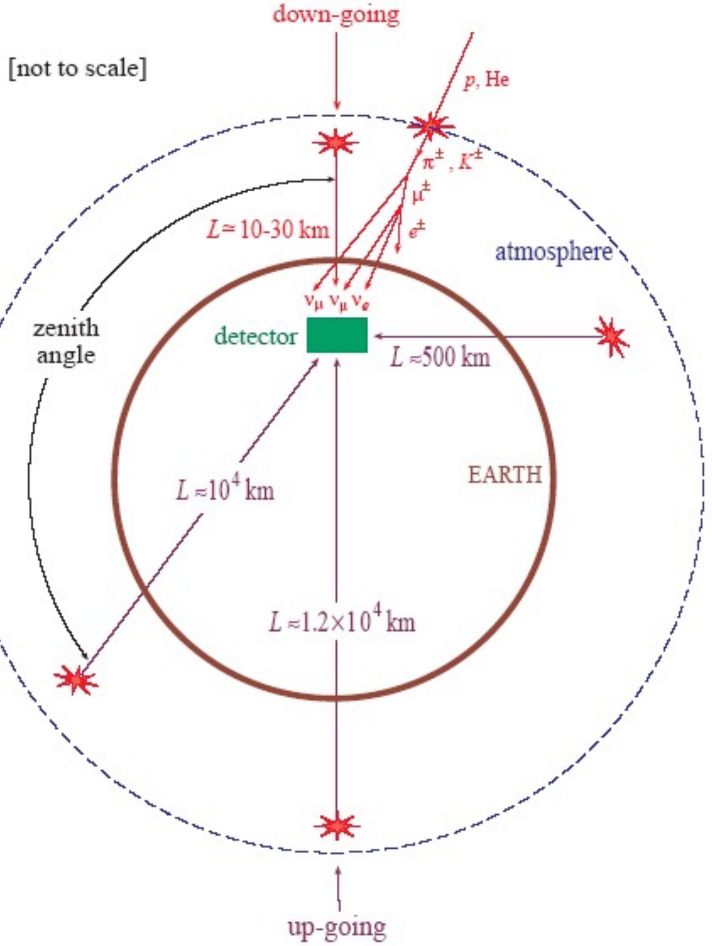
search for ν_μ - ν_e and ν_μ - ν_τ oscillations

Oscillations with atmospheric neutrinos

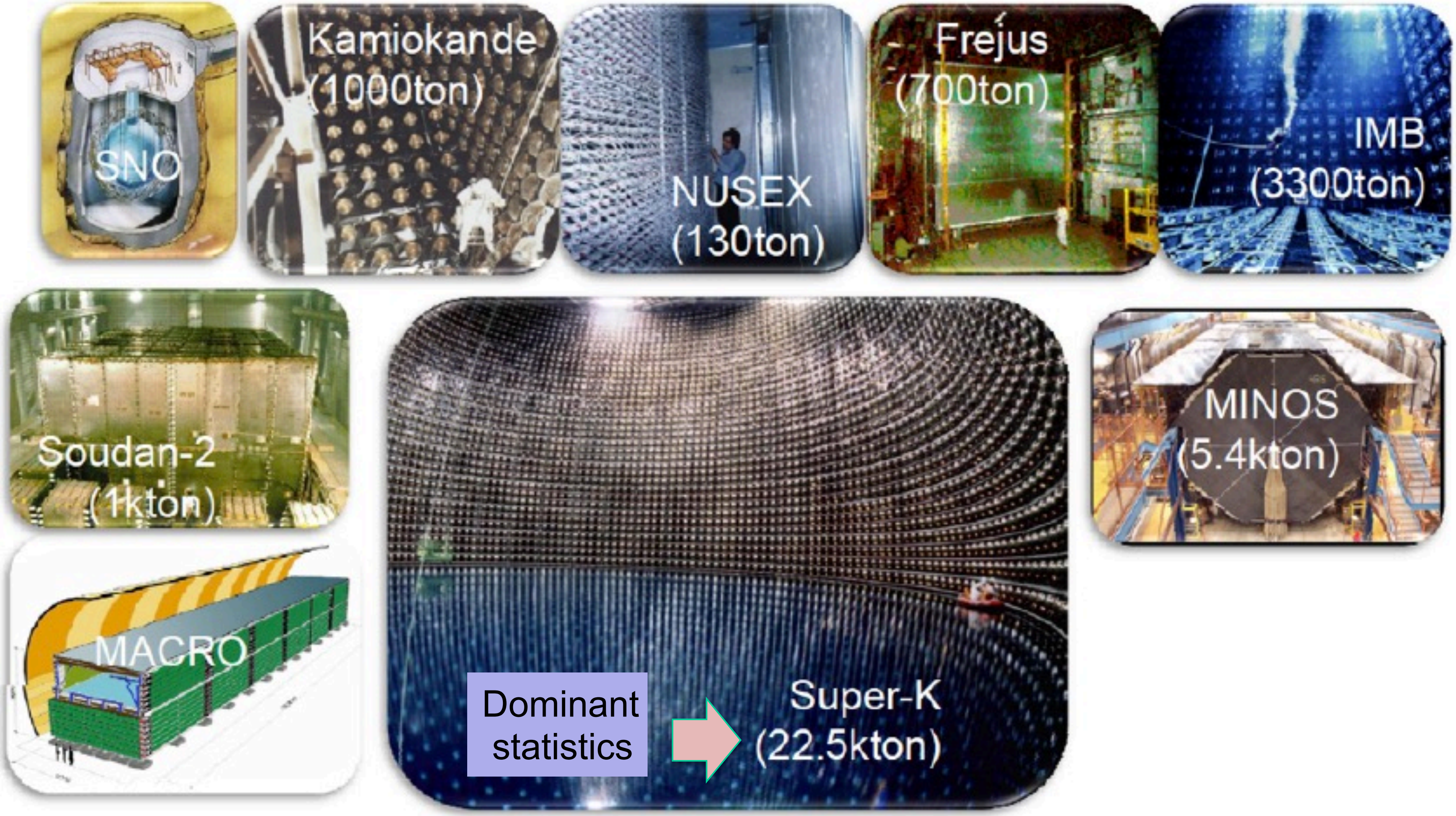
$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\vartheta_{23} \sin^2\left[1.27 \frac{\Delta m^2_{23}\, L}{E_\nu}\right]$$

- $\boldsymbol{\Delta m^2_{23}}$, $\boldsymbol{\vartheta_{23}}$ → from Nature;
- $\boldsymbol{E_\nu}$ = experimental parameter (energy distribution of neutrino giving a particular configuration of events)
- $\boldsymbol{L}$ = experimental parameter (neutrino path length from production to interaction)





Oscillations with atmospheric neutrinos



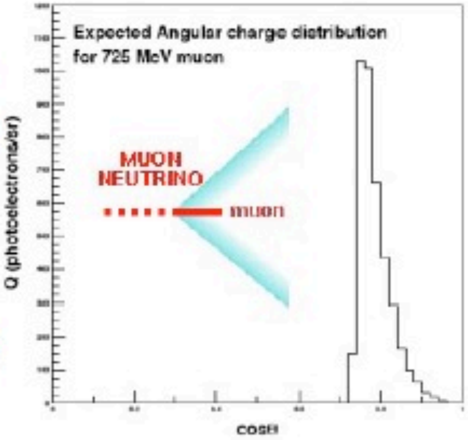
Dominant statistics

…most of these detectors originally built to **study proton decay** (atmospheric neutrinos were background!)

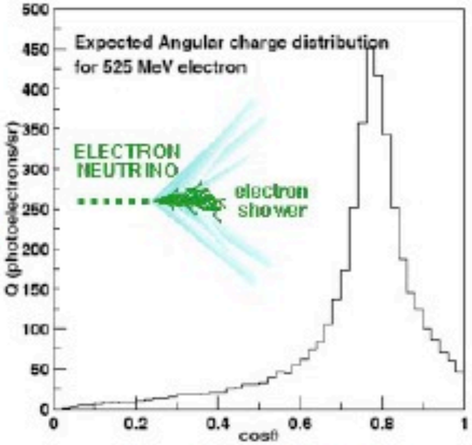
Oscillations with atmospheric neutrinos: SuperKamiokande

Water Cherenkov: e/μ identification

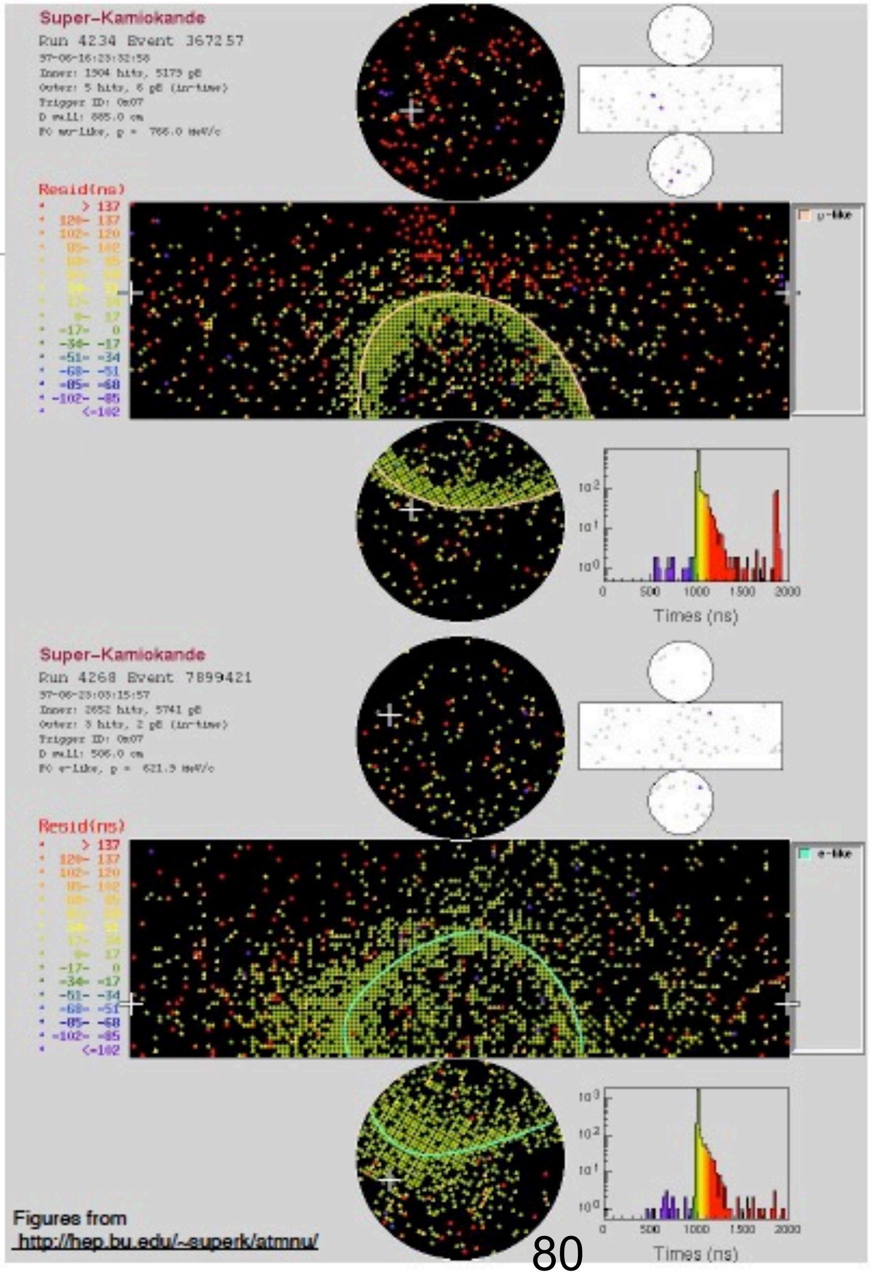
- At low momenta one can correlate the particle visible energy with the Cherenkov angle. Muons will have “collapsed” rings while electrons are ~always at 42º.



- At higher momenta, look at the distribution of light around Cherenkov angle. Muons are “crisp”, electron showers are “fuzzy”. See plots and figures at the right.



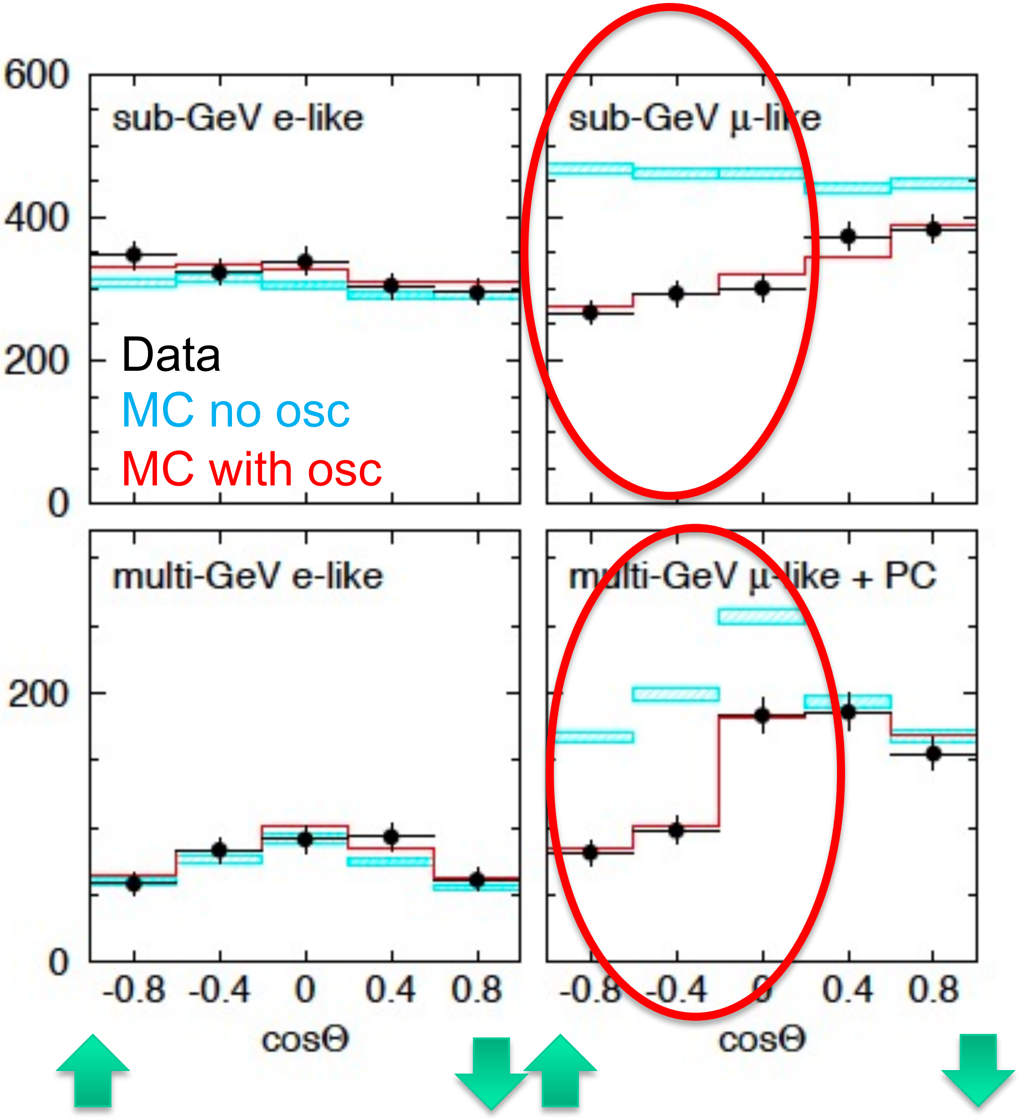
Figures from M. Earl's PhD Thesis



Figures from
http://hep.bu.edu/~superk/atmnu/

Oscillations with atmospheric neutrinos: SuperKamiokande

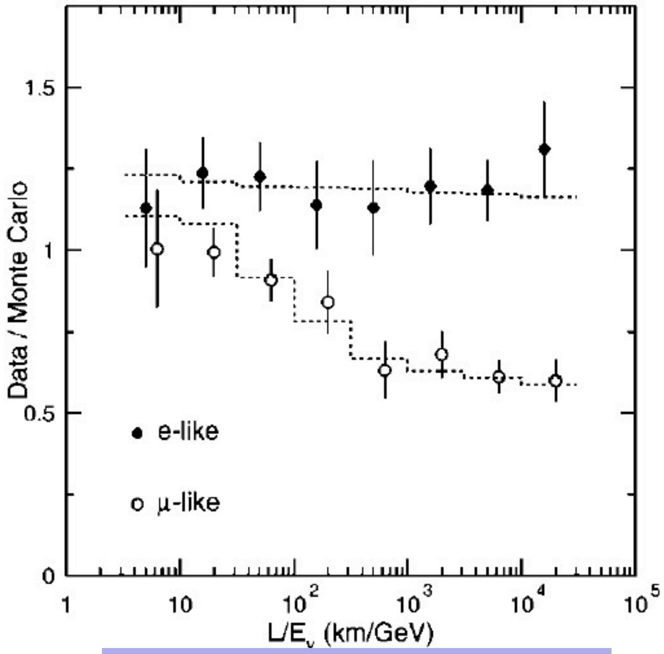
1998: discovery of atmospheric neutrino oscillations



(here shown 45 kton yr exposure)

Angular distribution of ν_e consistent with no-oscillation expectations

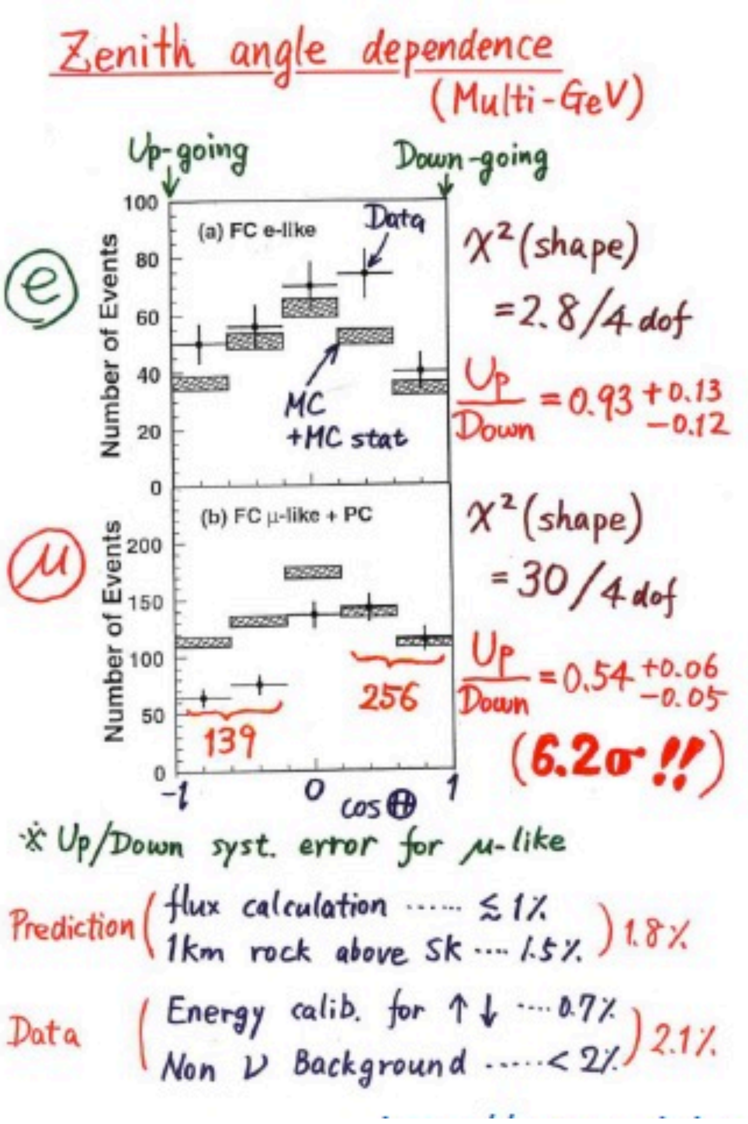
…BUT deficit of up-going ν_μ events (ie. large L/E)



Interpreted as ν_μ ←→ ν_τ oscillation (ν_μ disappearance)

Oscillations with atmospheric neutrinos: SuperKamiokande

…announced at Neutrino 1998 Conference (Kajita):



Zenith angle dependence
(Multi-GeV)

χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93 {}^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

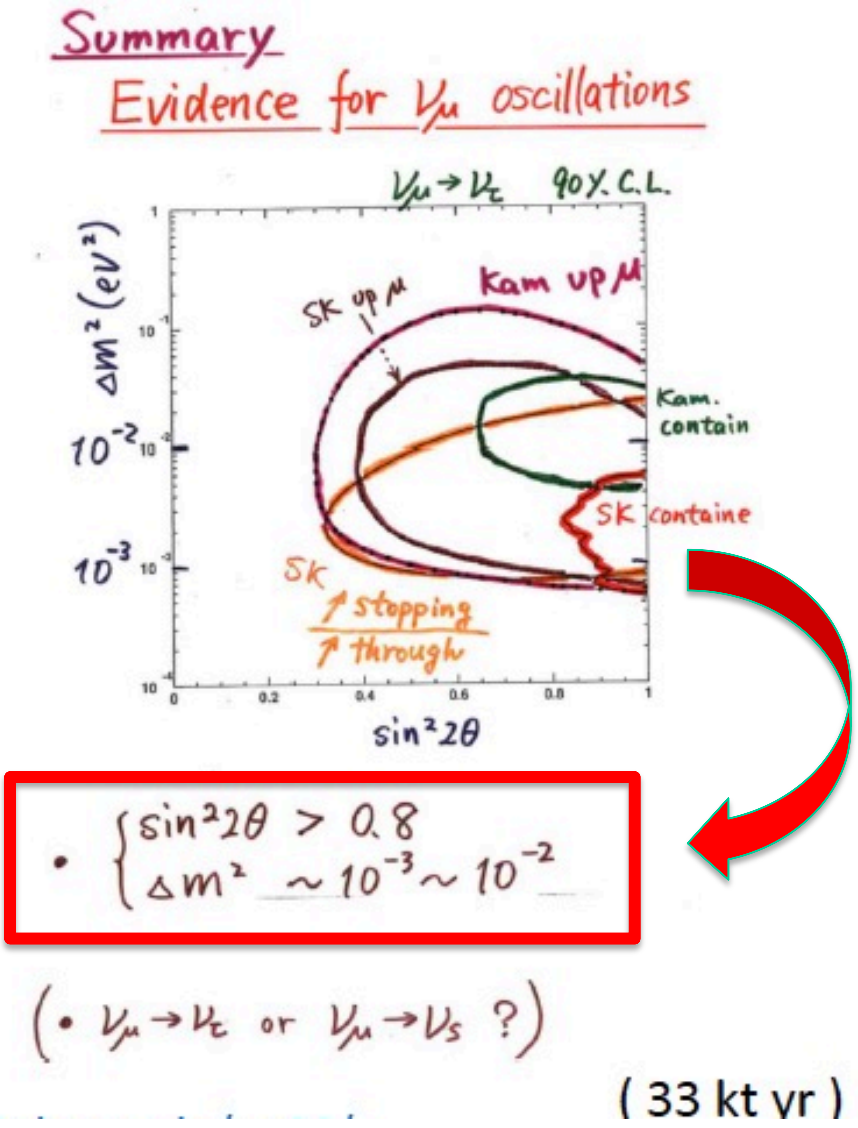
$\frac{\text{Up}}{\text{Down}} = 0.54 {}^{+0.06}_{-0.05}$

(6.2σ !!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1% ; 1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7% ; Non ν Background ….. < 2%) 2.1%



Summary
Evidence for ν_μ oscillations

$\nu_\mu \to \nu_\tau$ 90% C.L.

- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

(33 kt yr)

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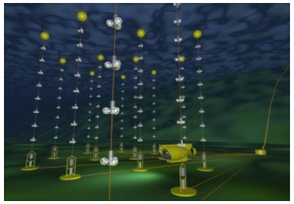
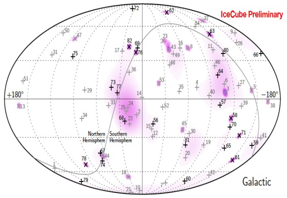


Neutrino telescope

Detection principles

Current telescopes



Selected results

Diffuse Flux, point sources

Multi-messenger search

Future prospects

Neutrinos from space: the long quest

The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

Raymond Davis Jr.	**Masatoshi Koshiba**	**Riccardo Giacconi**
◔ 1/4 of the prize	◔ 1/4 of the prize	◑ 1/2 of the prize
USA	Japan	USA
University of Pennsylvania Philadelphia, PA, USA	University of Tokyo Tokyo, Japan	Associated Universities Inc Washington, DC, USA
b. 1914	b. 1926	b. 1931 (in Genoa, Italy)

Solar neutrinos

(MeV energies)

Davis et al. 1955 – 1978

Koshiba et al., 1987 – 1988

Presence of cosmic neutrinos E > GeV?

Galactic
Extragalactic

« These neutrino observations are so exciting and significant that I think we're about to see the birth of an entirely new branch of astronomy: neutrino astronomy.»

J.Bahcall
New York Times (3 Apr 1987)

Why HE neutrino astronomy?

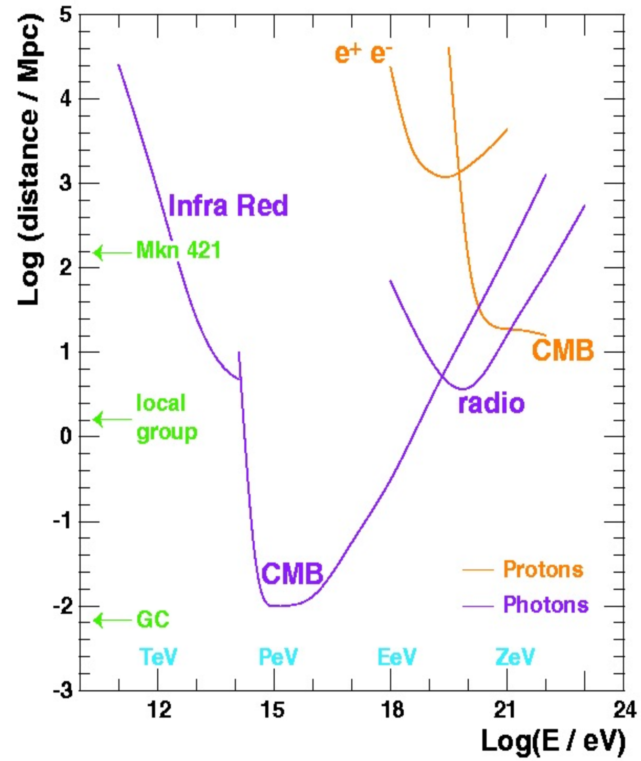
- Neutrino Astronomy is a quite recent and very promising experimental field.

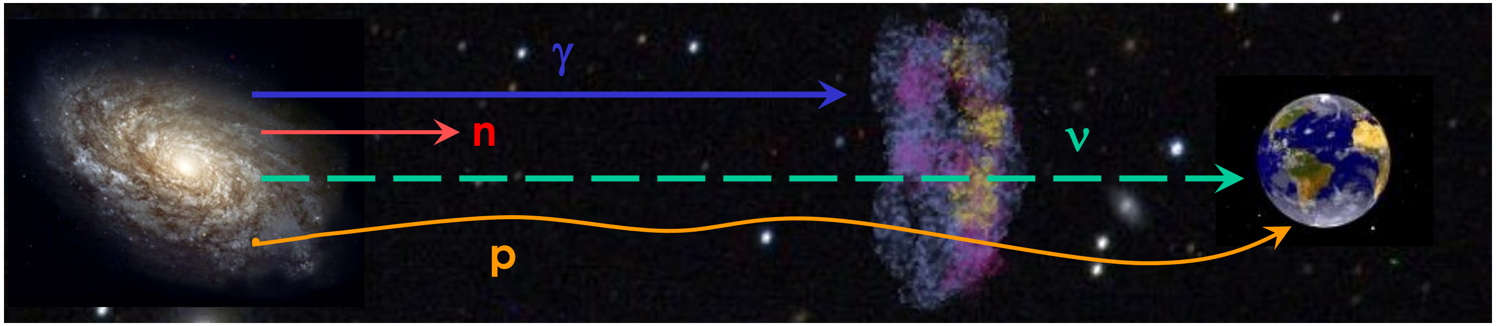
- Advantages:
  - **γ-rays**: interact with CMB and matter

    (r~10 kpc @100 TeV)
  - **Protons**: interact with CMB (r~10 Mpc@10^{11} GeV) and are deflected by magnetic fields

    (Δθ>3°, E<5·10^{10} GeV)
  - **Neutrons**: are not stable (r~10 kpc @10^9 GeV)
- Drawback: large detectors (~GTon) are needed.

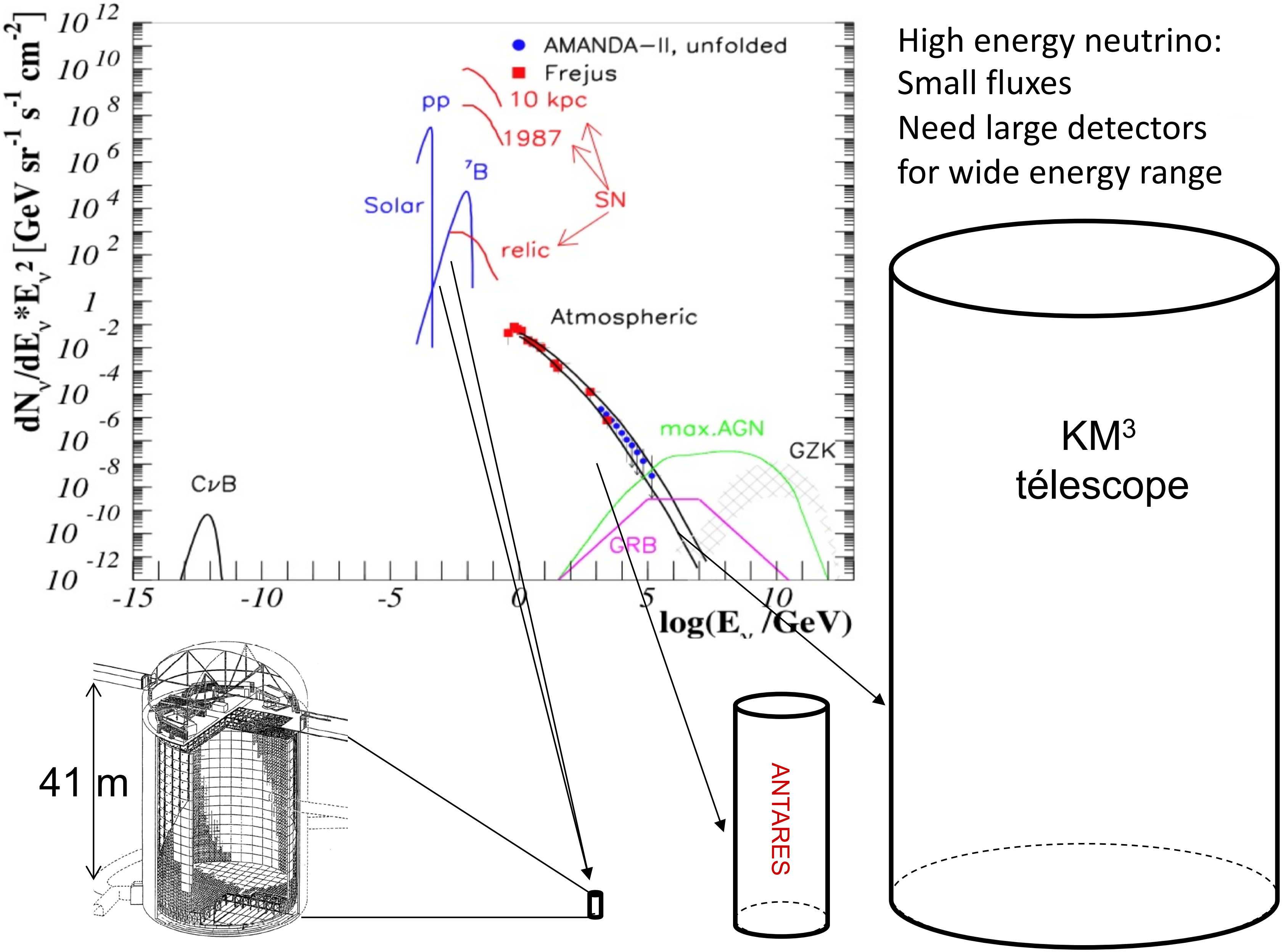
Photon and proton mean free range path



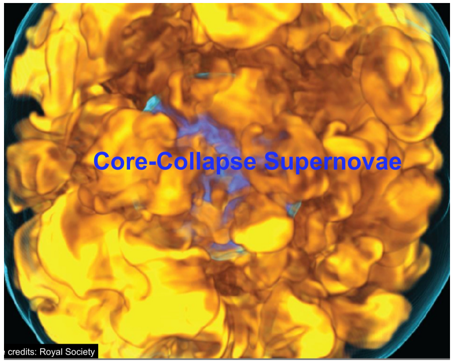


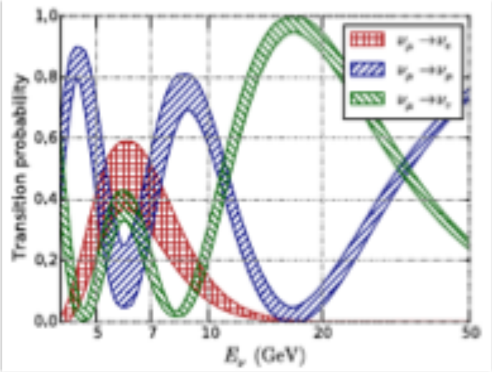
From MeV ν to PeV ν

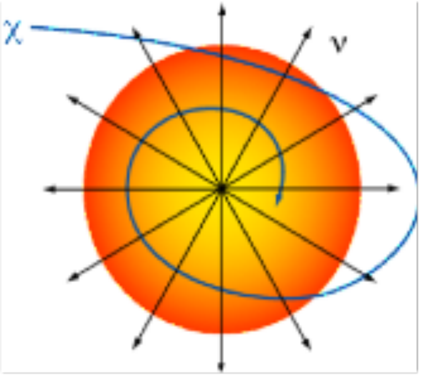
High energy neutrino:
Small fluxes
Need large detectors
for wide energy range

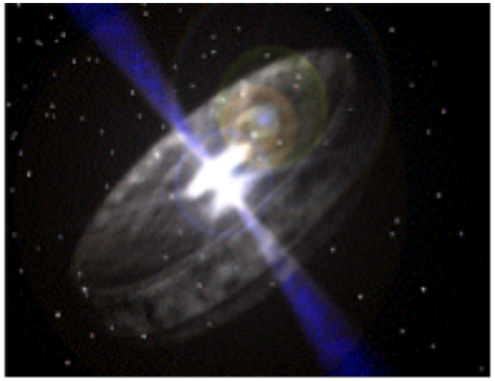


Neutrino telescopes: science scope









MeV Energy
No reco. in HE NT

CCSNe

Full Galactic coverage
All mass progenitors
Triangulations
⬇
Localisation
Coleiro et al., Eur. Phys. J. C 80, 856 (2020)

Low Energy
GeV < E < 50 GeV

Oscillation

Focus at the end of these lectures

Medium Energy
10GeV < E < 1 TeV

Dark Matter

Not covered here

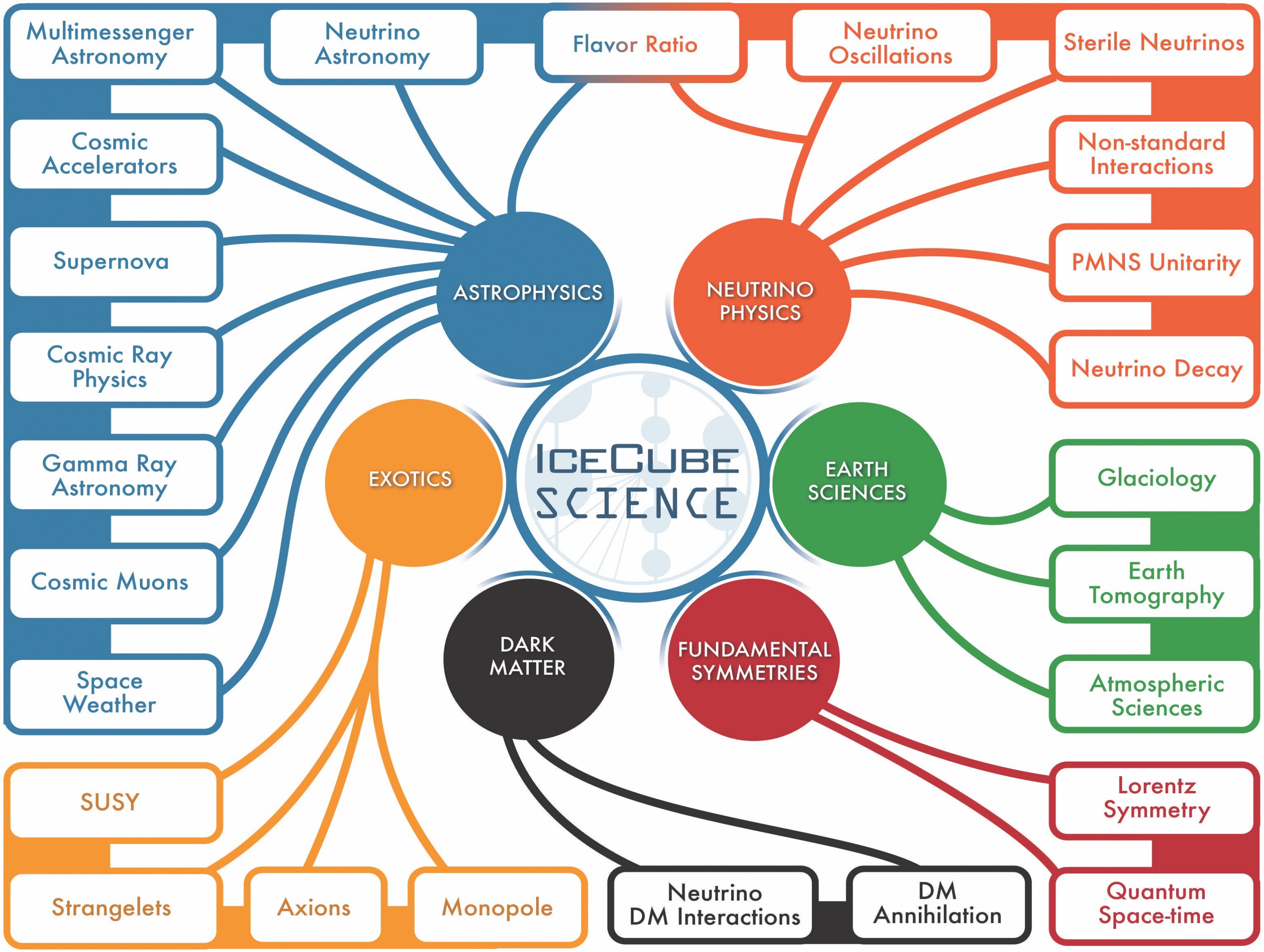
High Energy
E > 1 TeV

HE Astrophysics

Focus here

+ Exotics (Monopoles, Nuclearites, etc.)
+ Environmental Sciences

Science scope: another view



ICECUBE SCIENCE

ASTROPHYSICS

- Multimessenger Astronomy
- Neutrino Astronomy
- Flavor Ratio
- Cosmic Accelerators
- Supernova
- Cosmic Ray Physics
- Gamma Ray Astronomy
- Cosmic Muons
- Space Weather

NEUTRINO PHYSICS

- Flavor Ratio
- Neutrino Oscillations
- Sterile Neutrinos
- Non-standard Interactions
- PMNS Unitarity
- Neutrino Decay

EARTH SCIENCES

- Glaciology
- Earth Tomography
- Atmospheric Sciences

FUNDAMENTAL SYMMETRIES

- Lorentz Symmetry
- Quantum Space-time

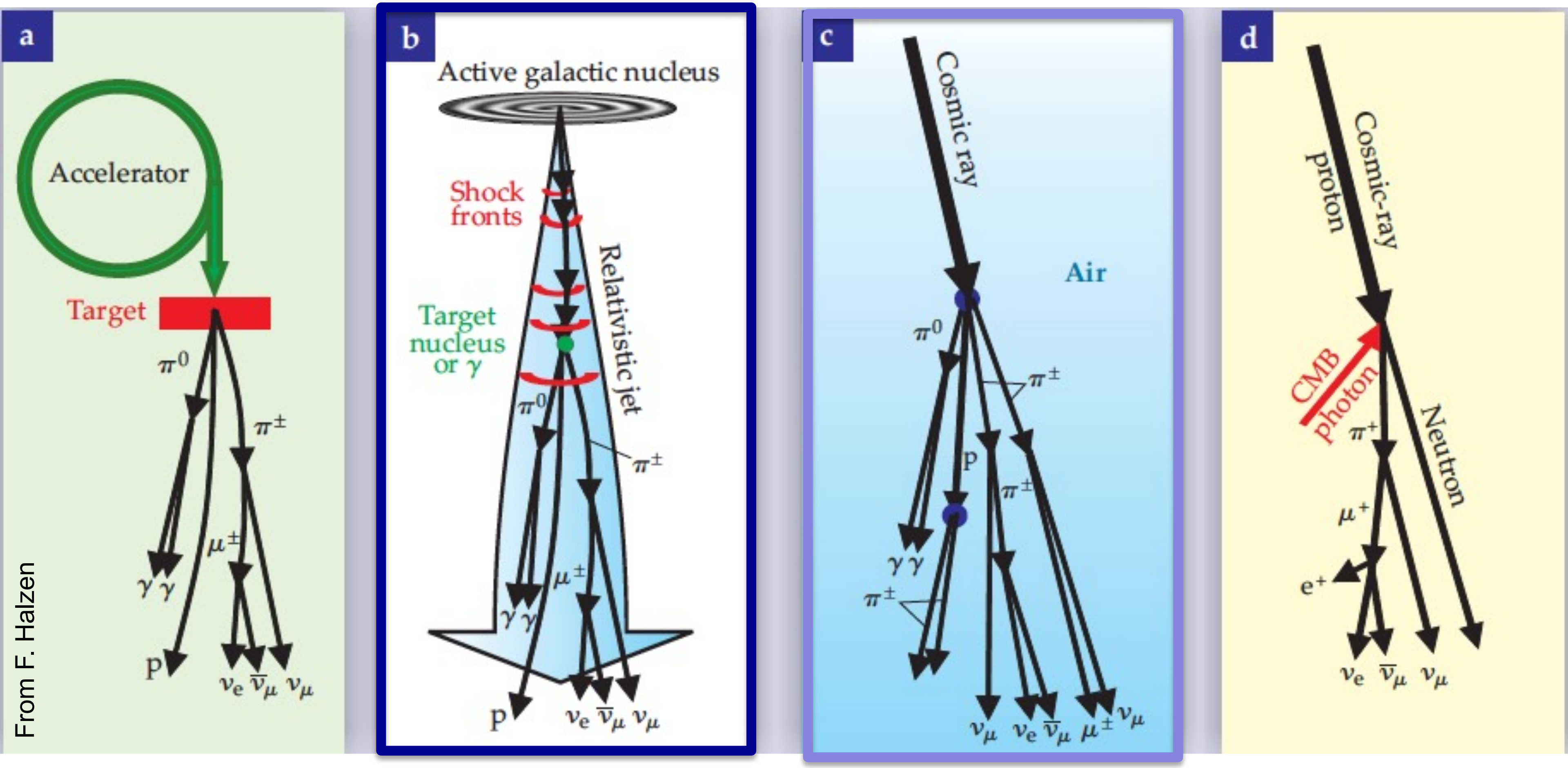
DARK MATTER

- Neutrino DM Interactions
- DM Annihilation

EXOTICS

- SUSY
- Strangelets
- Axions
- Monopole

Common production mechanism



From F. Halzen

Neutrino beam | cosmic neutrinos | atmospheric neutrinos | cosmogenic ν (GZK)

→ Guaranteed source of >100 PeV neutrinos
→ Provide information on the composition of primaries
→ Alternative techniques (e.g Radio)

Not covered here

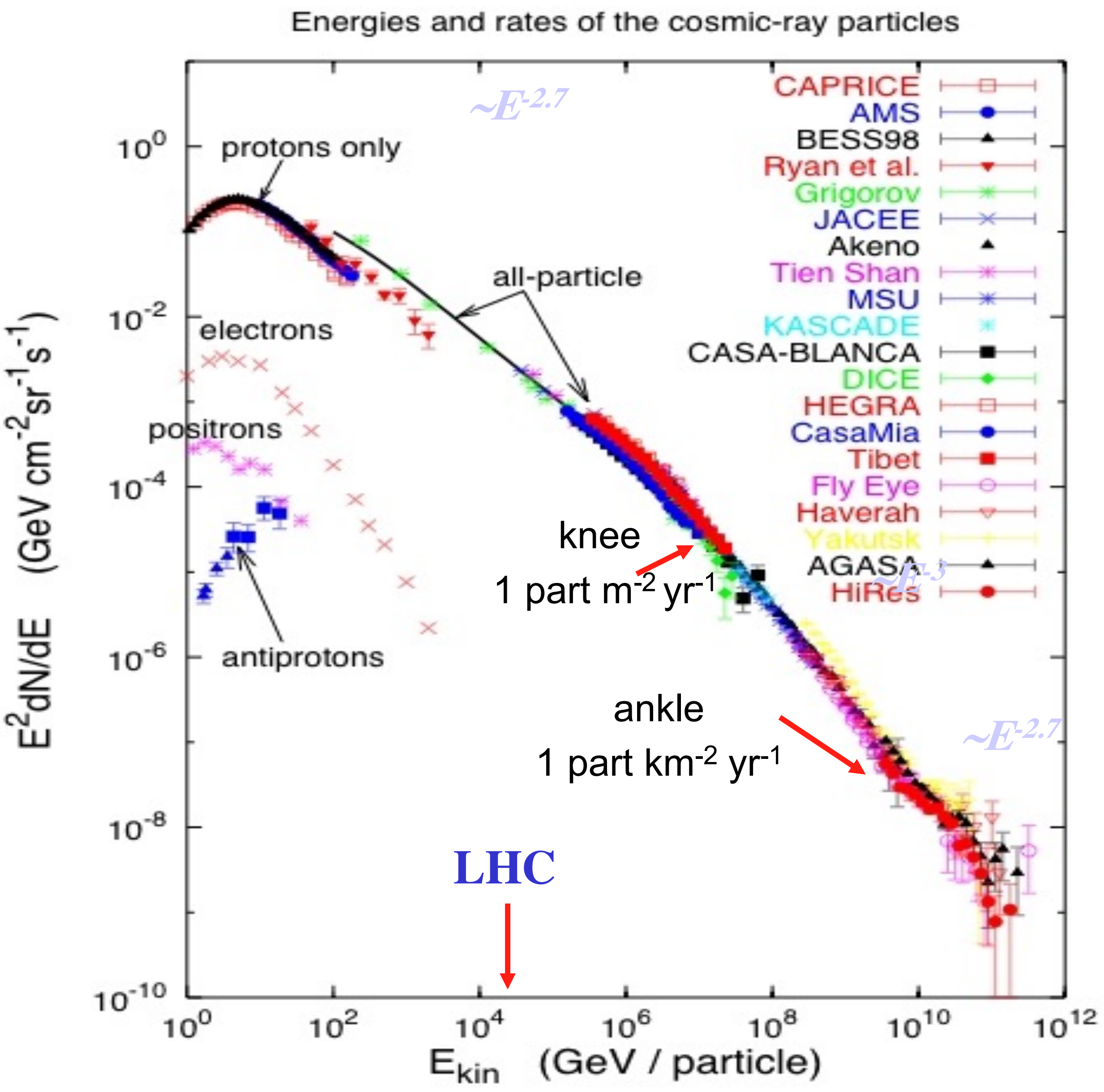
Neutrinos tracing UHE cosmic rays

Nature accelerates particles 10 ^{7} times the energy of LHC!

Cutoff now confirmed
But…

where?

how?

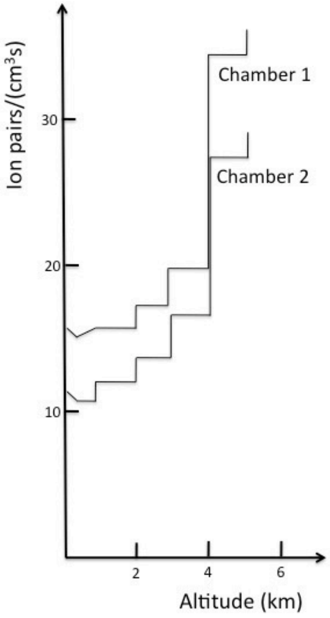


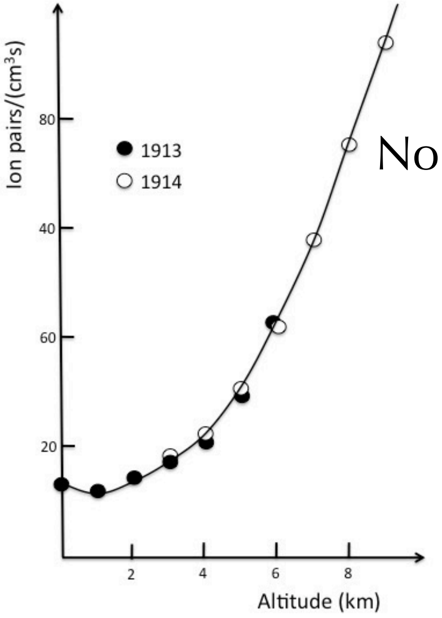
Cosmic rays

Cosmic rays are charged nuclei coming from outside the atmosphere

Discovered by V. Hess in 1912, through the detection of increase of the ionization rate with the altitude.

« The results of the observations seem most likely to be explained by the assumption that radiation of very high penetrating power enters from above into our atmosphere. »

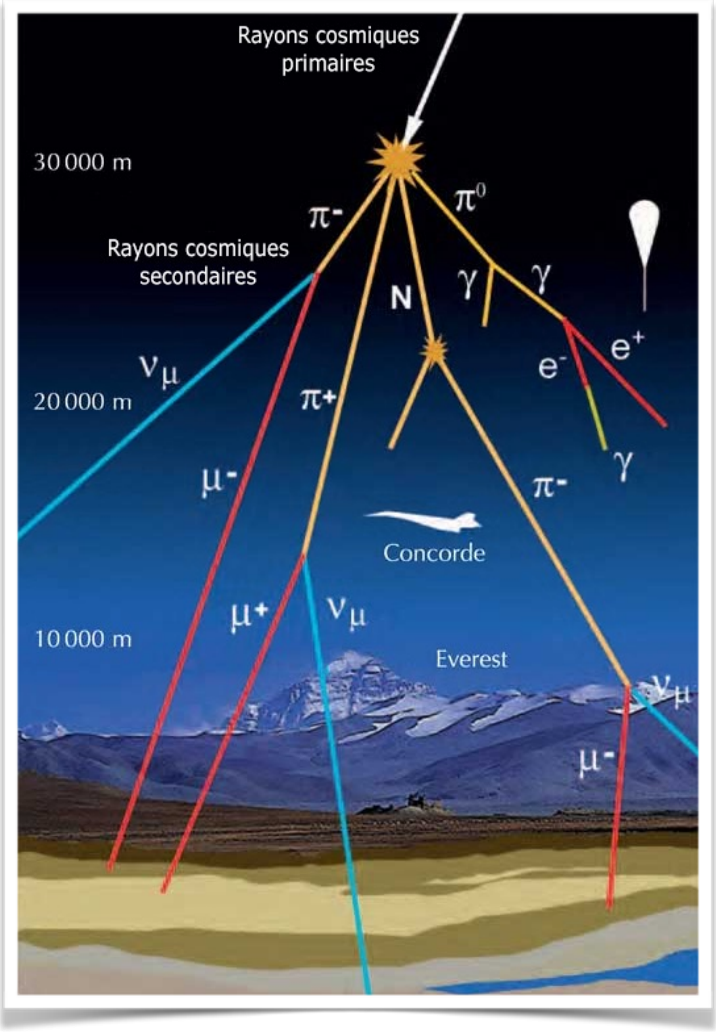




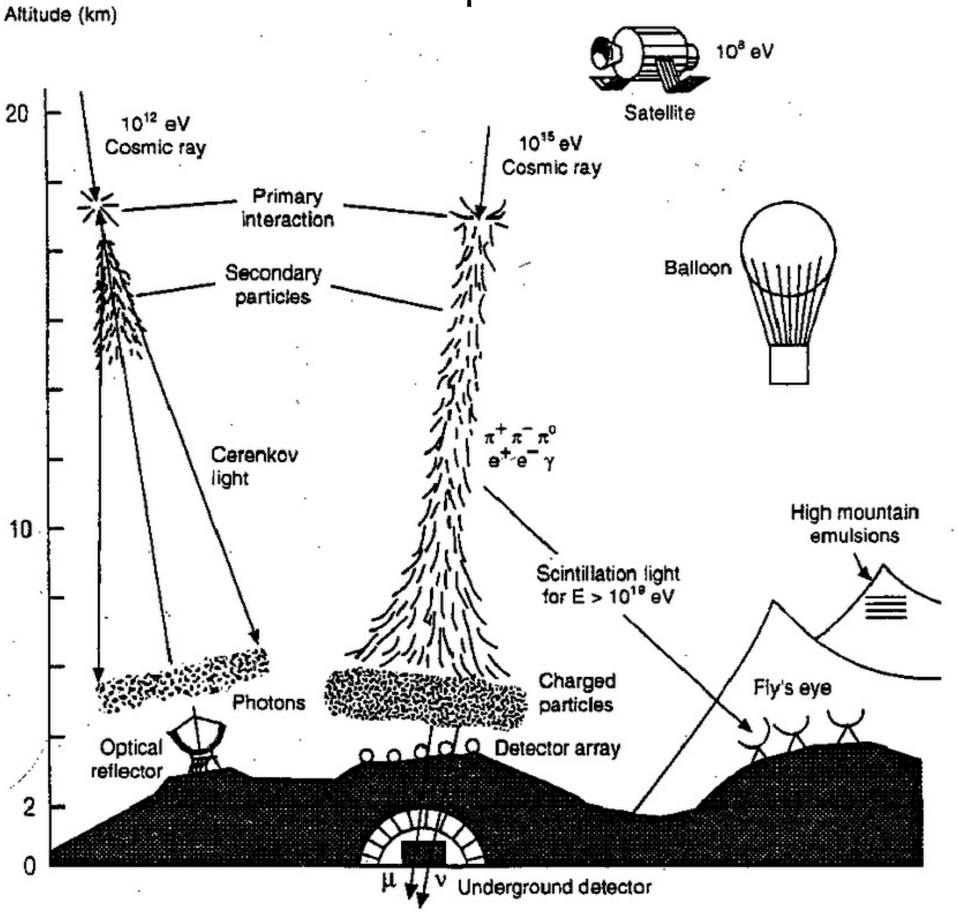
Nobel Prize in Physics - 1936

Cosmic rays

V. Hess' observations: secondary particles produced by the interaction of high-energy particles with the atmosphere.



From 1950: first direct observations using satellites and stratospheric ballons.



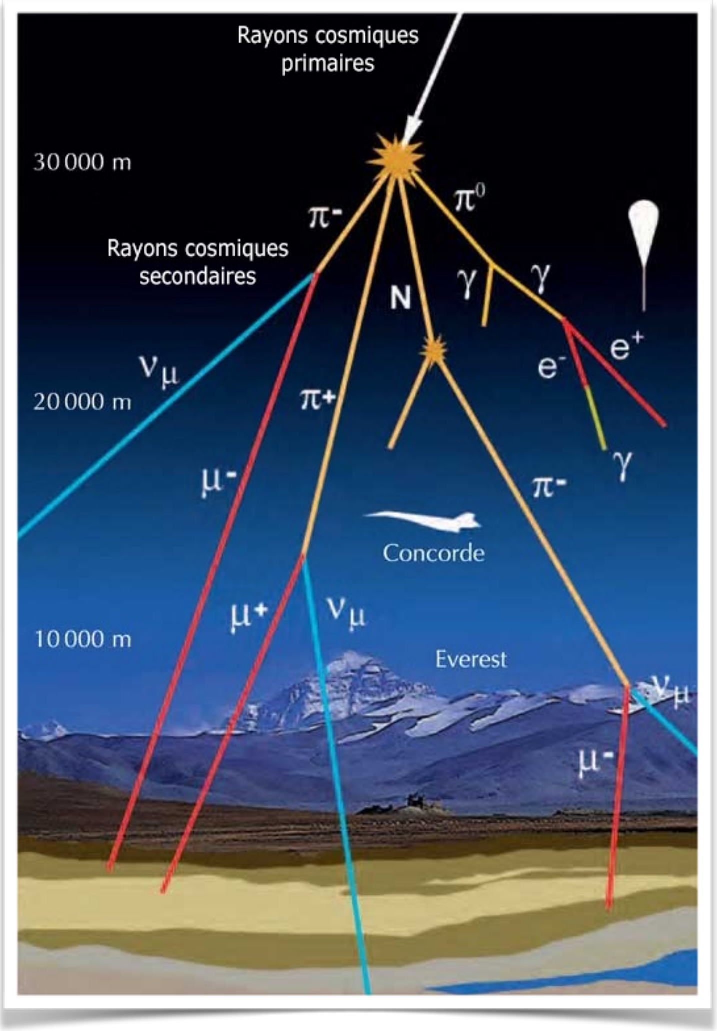
Hadron flux:	1 particle/m²/s	@	TeV	10¹² eV
	1 particle/m²/day	@	PeV	10¹⁵ eV
	1 particle/km²/day	@	EeV	10¹⁸ eV
	1 particle/km²/century	@		10²⁰ eV

Satellites + ballons

Ground detectors (indirect detection)

Cosmic rays

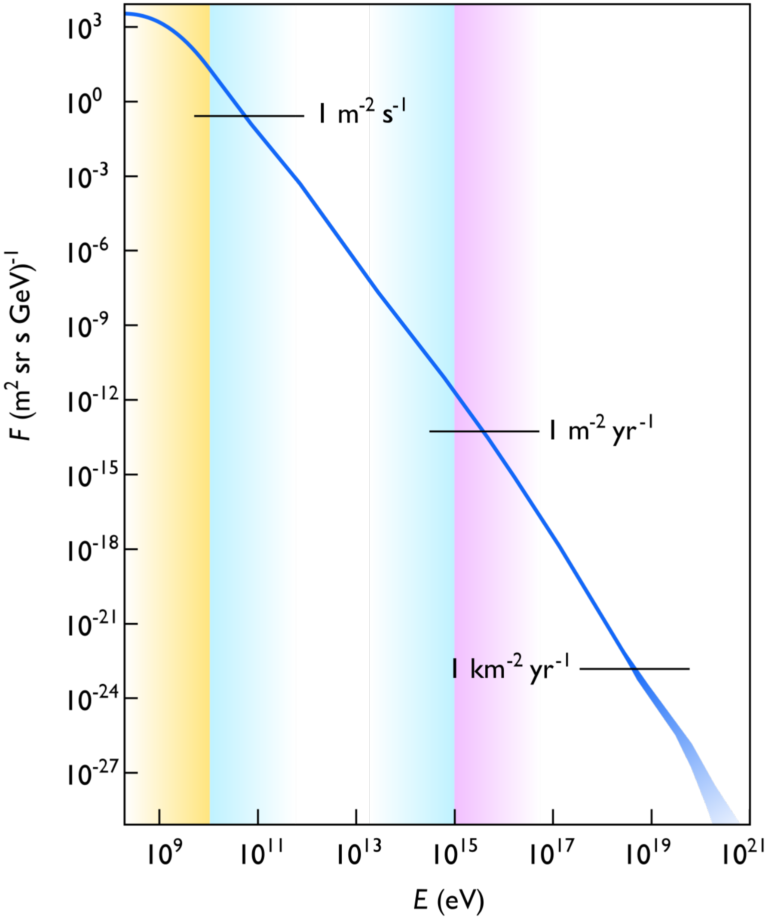
V. Hess' observations: secondary particles produced by the interaction of high-energy particles with the atmosphere.



From 1950: first direct observations using satellites and stratospheric ballons.

⇒ cosmic ray **composition**: 88% of protons, 9% of He nuclei, + électrons, heavier nucleons, … + **spectrum**

Nb of particles with energy $\in [E; E + dE]$, crossing a surface dS, with an observing direction $d\Omega$, in a time interval dt



Cosmic rays

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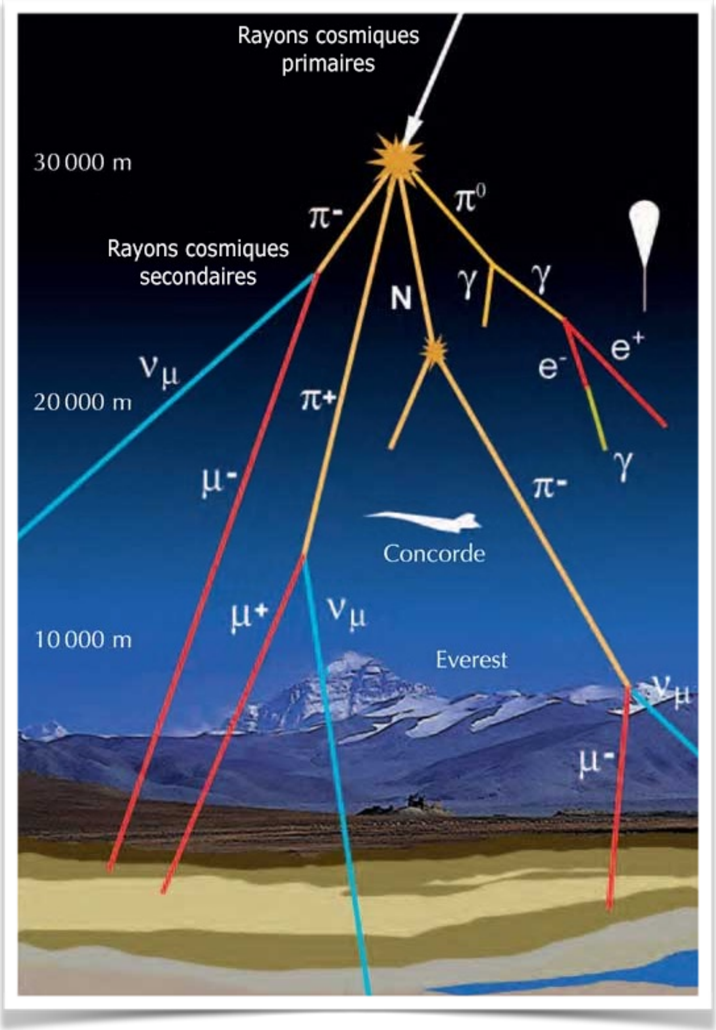

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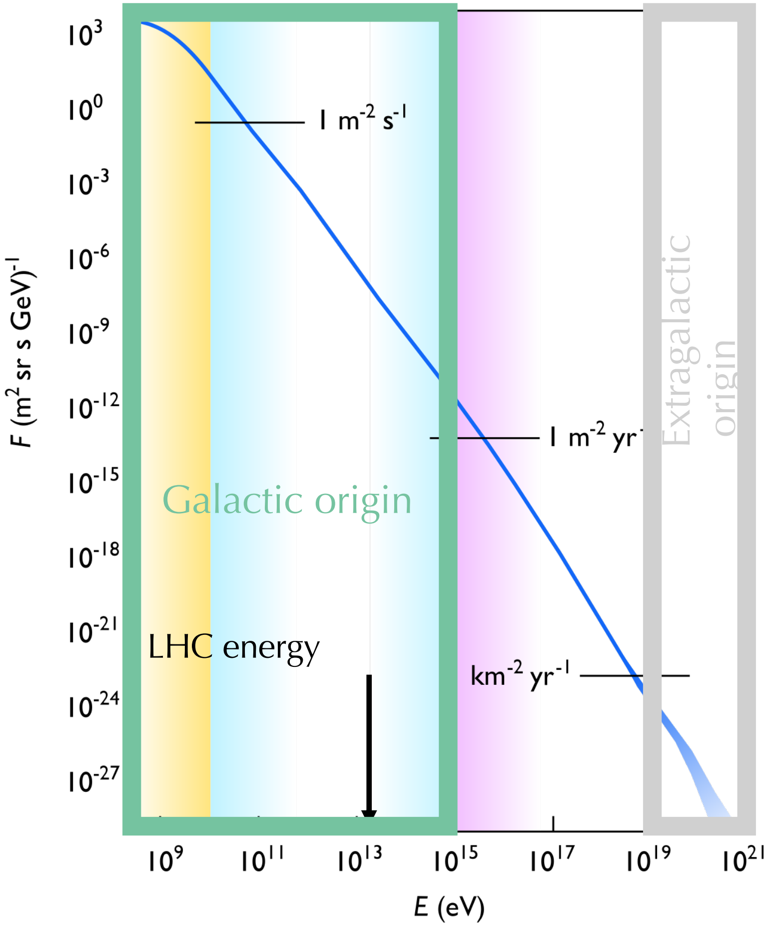
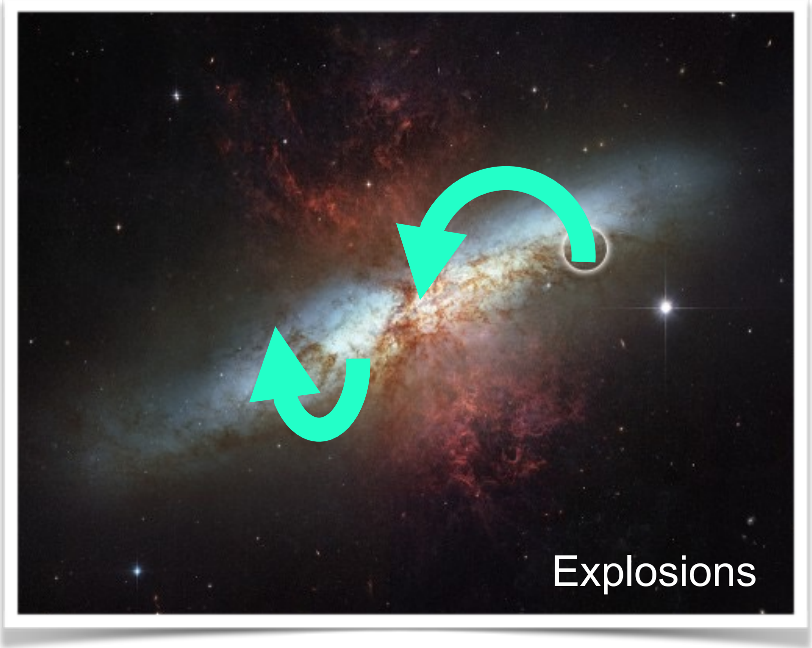
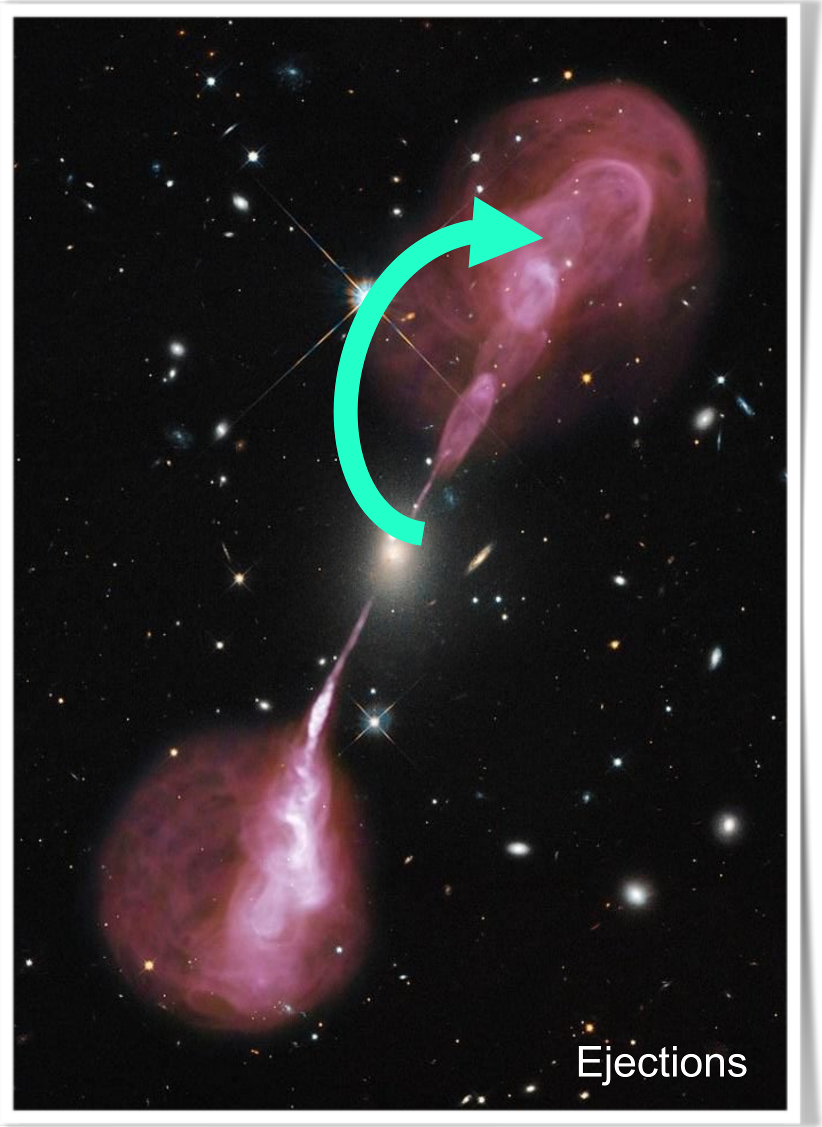


High-energy processes

Physical processes taking the energy at small scale and redistribute it at larger scale





What astrophysical objects?

The Quest for Extragalactic Sources of UHECRs

- The extragalactic acceleration mechanisms must satisfy the following criteria:
  - must provide enough energy to reach the largest observed energies;
  - the accelerated population should have an injection energy spectrum that fit the observed UHECR spectrum after propagation.
- Generic models of acceleration from “Faraday law”: $\boldsymbol{E_{max} = ZeLB(\frac{v}{c})}$

Ingredients:

1. **Charged particles, Ze**
2. **Magnetic fields, B**
3. **Acceleration regions, L**

- Electric fields through the Faraday law that can supply a consequent amount of energy: the E^{max} of a CR of charge Ze, accelerated in a region where the magnetic **field B** changes in a **spatial region of size L** is, using the conversion from erg to eV:

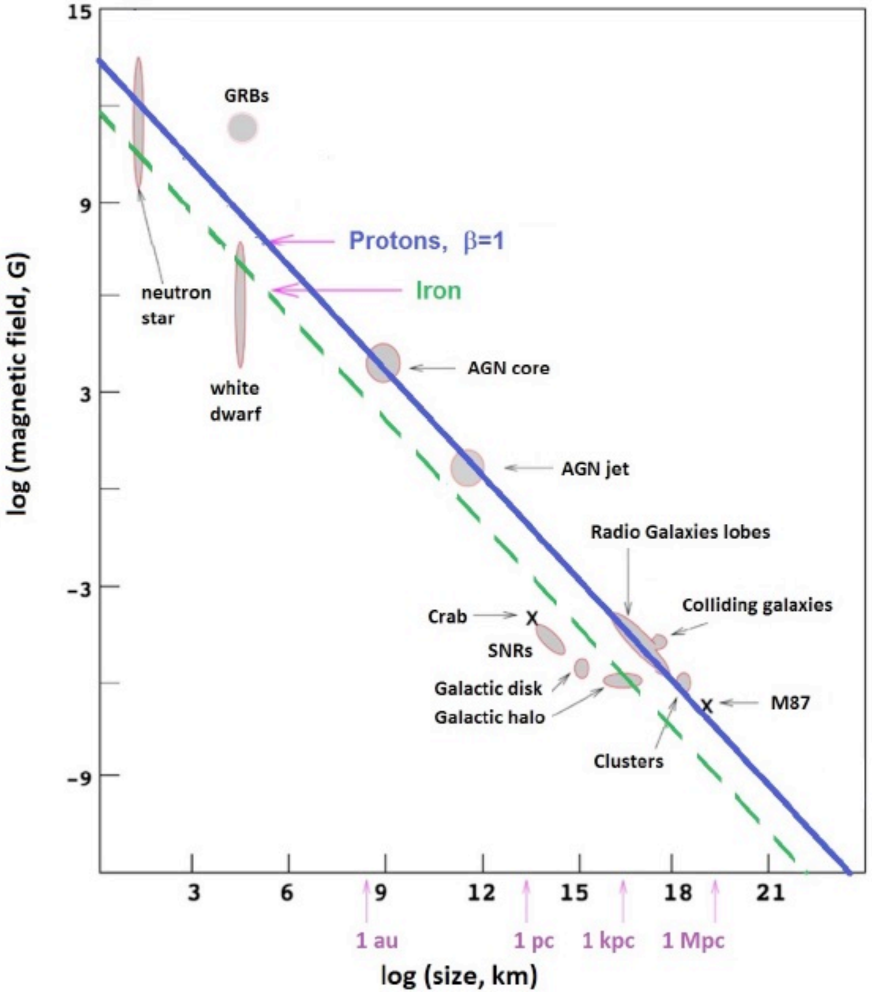
$$\frac{E^{\max}}{Ze\beta} = LB. \qquad (7.8)$$

$$E^{\max} = Z\beta(4.8\times10^{-10})\cdot(10^{-6})\left(\frac{B}{1\,\mu\mathrm{G}}\right)\cdot(3.1\times10^{21})\left(\frac{L}{1\mathrm{kpc}}\right)\,[\mathrm{erg}]. \qquad (7.9)$$

The Hillas Plot

$$E^{\max} \simeq Z\beta \cdot \left(\frac{B}{\mu\mathrm{G}}\right) \cdot \left(\frac{L}{\mathrm{kpc}}\right) \quad [\mathrm{EeV}]. \qquad (7.10)$$

- Eq. (7.10) defines the Hillas criterion for CR sources
- In the figure, several possible galactic and extragalactic acceleration sources are considered. Among them:
  - AGN
  - Gamma Ray Bursts (GRBs)
  - Magnetars



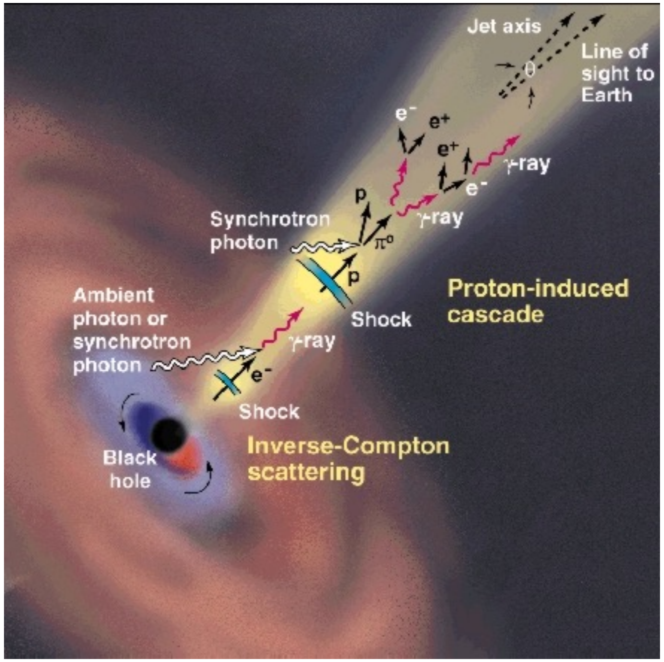
*Example of the **Hillas plot**. Acceleration of CRs up to a given energy requires magnetic fields and sizes above the respective line. The full (dashed) line corresponds to the condition for B,L to accelerate protons (iron) at 10^{20} eV. Some source candidates are still controversial*

Potential extragalactic sources

Active Galactic Nuclei (AGN)

Steady (though flaring) sources

Observed luminosities $10^9 - 10^{15}\ L_\odot$

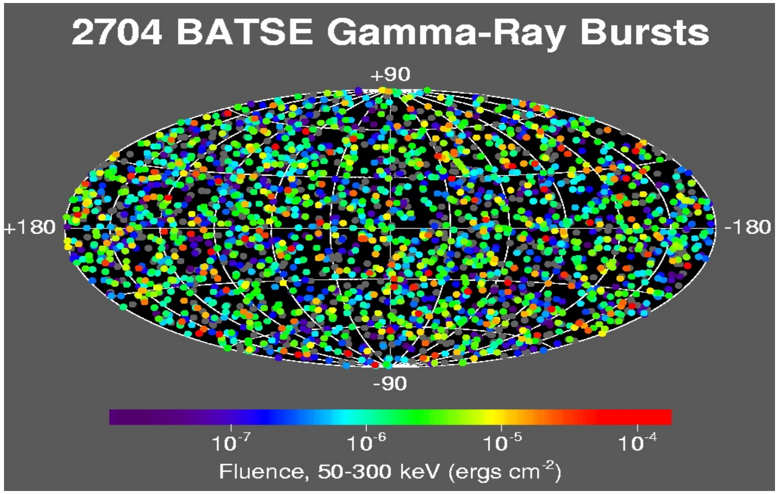


Gamma Ray Bursters (GRB)

Short emissions (~1s)
Very bright ~ $10^{18} \times L_\odot$

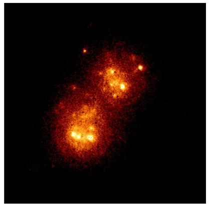
Counterparts : z up to 8.3

BATSE : 1 burst/day



Starburst Galaxies

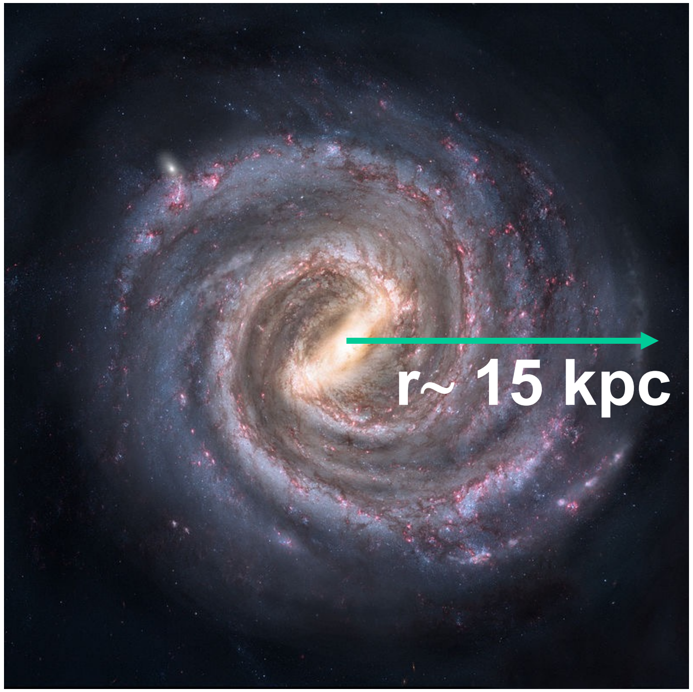
supernovae -> cosmic rays + dense gas -> pions



The Physical Properties of the Galaxy

- **CR propagate in the Galaxy.** It is necessary to have some information on the properties of our Galaxy (the Milky way)
- The Milky Way which is very similar to the spiral galaxies that we observe in the Universe.
- Thin disk (200-300 pc) with radius of 15 kpc
- The Sun is about 8.5 kpc from the center.

$$\boxed{1\ \mathrm{pc} = 3.086 \times 10^{18}\ \mathrm{cm}\ .}$$

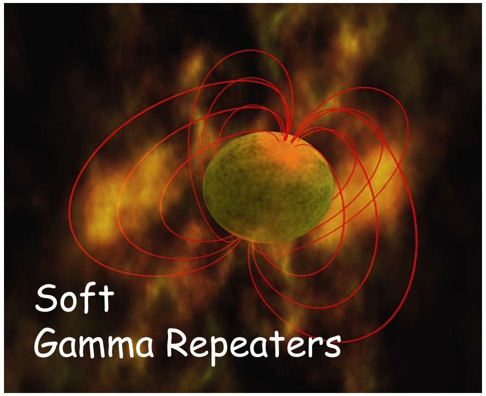


- The galactic volume, assuming a flat disk

$$\mathcal{V}_G = [\pi(15 \times 10^3)^2 \times 300] \times (3 \times 10^{18})^3 = 5 \times 10^{66}\ \mathrm{cm}^3\ .$$

- The Milky way hosts about 100 billion of stars and a supermassive black hole in its center

Potential Galactic sources



Microquasars X-ray binaries with compact object (neutron star or black hole) accreting matter and re-emitting it in relativistic jets (intense radio & IR) flares.

→ HEN from jets

SGRs X-ray pulsars with a soft γ-ray bursting activity.
Magnetar model: highly magnetized neutron stars whose outbursts are caused by global star-quakes

→ HEN from GRB-like flares

Galactic Center
seen with TeV photons

- *Supernovae remmants*

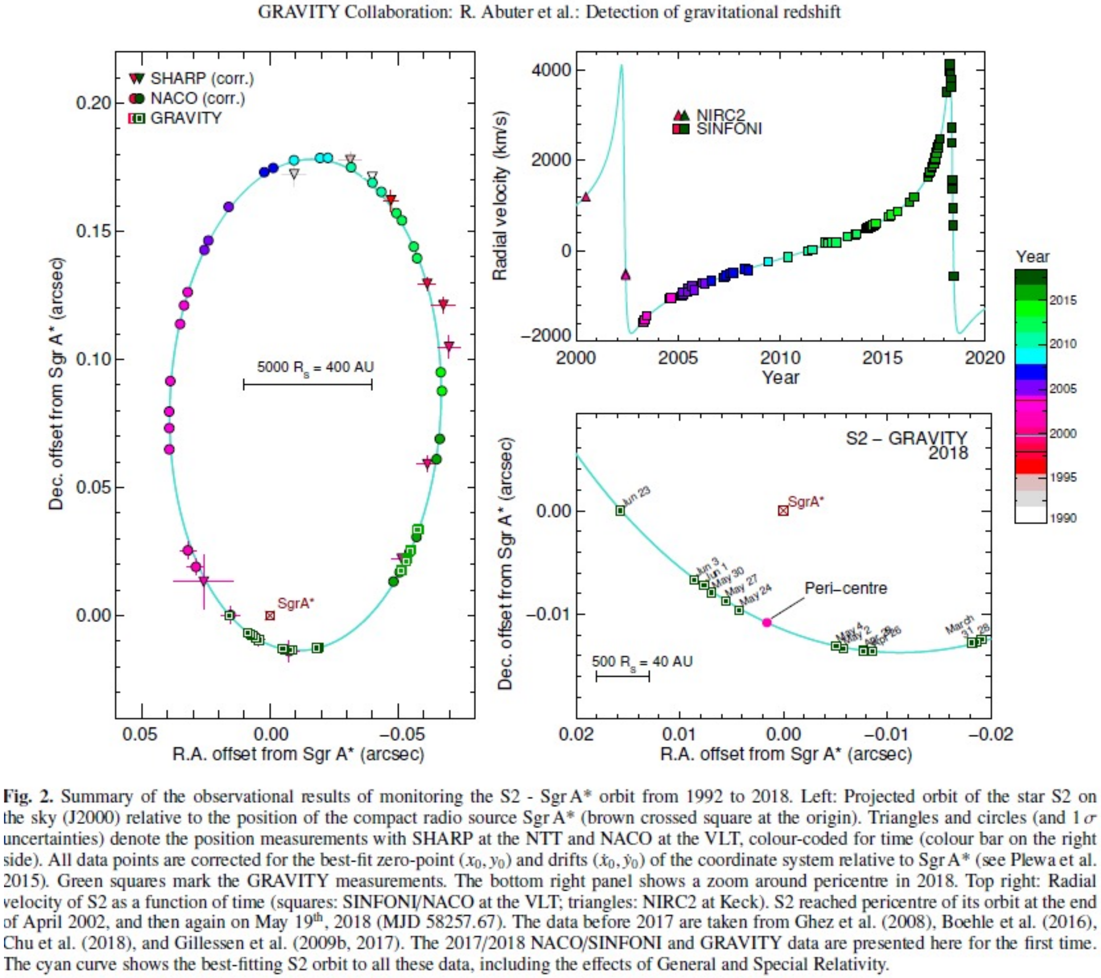
  pulsars, neutron stars

- *Dense regions*

  Sun , Galactic Centre,
  Interstellar medium

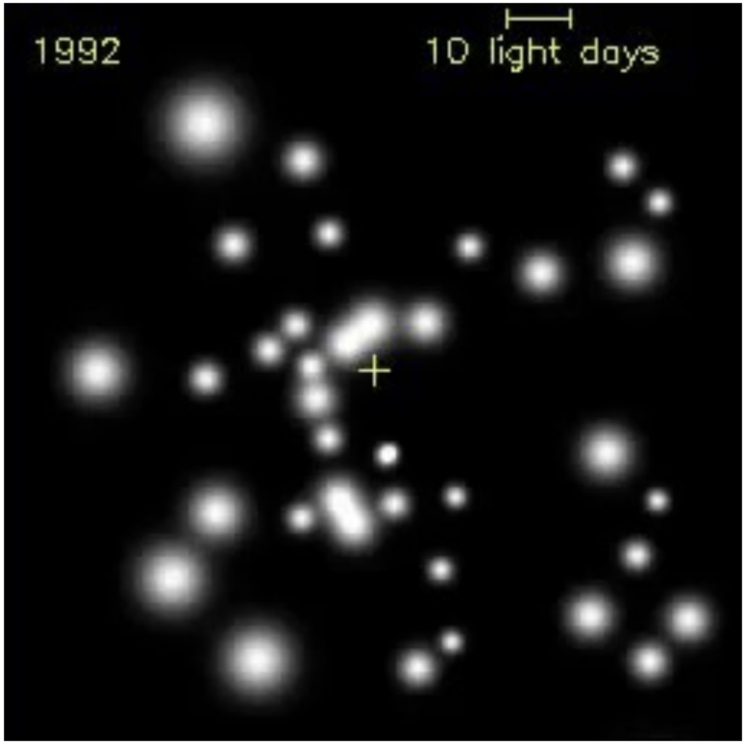
→ Mosty seen by Northern Hemisphere neutrino telescopes

The black hole in our Galaxy (Nobel 2020)



GRAVITY Collaboration: R. Abuter et al.: Detection of gravitational redshift

Fig. 2. Summary of the observational results of monitoring the S2 - Sgr A* orbit from 1992 to 2018. Left: Projected orbit of the star S2 on the sky (J2000) relative to the position of the compact radio source Sgr A* (brown crossed square at the origin). Triangles and circles (and 1σ uncertainties) denote the position measurements with SHARP at the NTT and NACO at the VLT, colour-coded for time (colour bar on the right side). All data points are corrected for the best-fit zero-point (x_0, y_0) and drifts $(\dot{x}_0, \dot{y}_0)$ of the coordinate system relative to Sgr A* (see Plewa et al. 2015). Green squares mark the GRAVITY measurements. The bottom right panel shows a zoom around pericentre in 2018. Top right: Radial velocity of S2 as a function of time (squares: SINFONI/NACO at the VLT; triangles: NIRC2 at Keck). S2 reached pericentre of its orbit at the end of April 2002, and then again on May 19th, 2018 (MJD 58257.67). The data before 2017 are taken from Ghez et al. (2008), Boehle et al. (2016), Chu et al. (2018), and Gillessen et al. (2009b, 2017). The 2017/2018 NACO/SINFONI and GRAVITY data are presented here for the first time. The cyan curve shows the best-fitting S2 orbit to all these data, including the effects of General and Special Relativity.

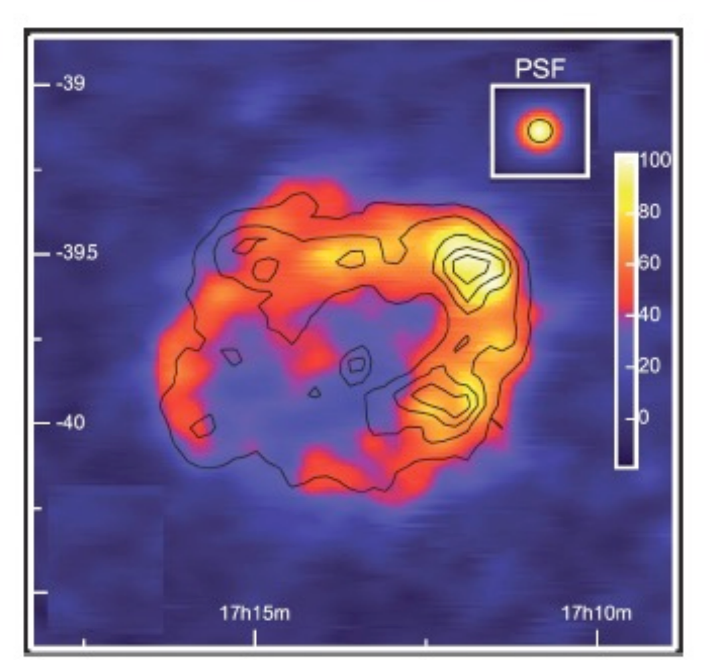


+ photo du trou noir

About the Identification of Galactic CR Sources

- The diffusive shock acceleration (DSA) model predicts the production CRs in SNRs;
- The amount of relativistic particles present in the acceleration region increases with time as the SNR passes through its free expansion phase, and reaches a maximum in the early stages of the so-called *Sedov phase*.
- Correspondingly, the peak in γ-ray luminosity typically appears some 10^3–10^4 years after the supernova explosion.
- Thanks to the HESS survey of the galactic plane, we know that acceleration sites up to $\sim$ 100 TeV are spatially superimposed with regions of non-thermal X-ray emission.

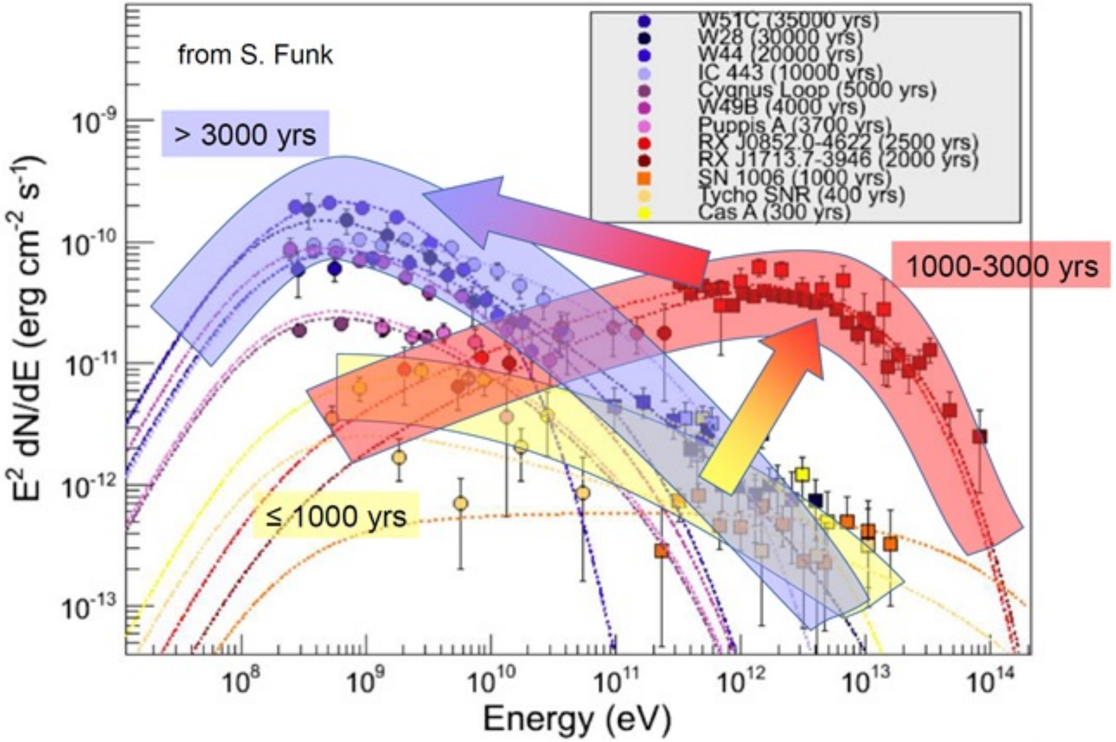
- This has strengthened the hypothesis that galactic CRs up to the knee are accelerated in SNRs.
- Figure shows the morphological structure of the RX J1713.7-3946 SNR. This shows a correlation of TeV emission with non-thermal X-rays.
- Even if radio and X-ray data suggest that SNRs are indeed the sources of CR electrons, **no compelling evidence for the acceleration of protons in SNRs up to the PeV energies has been found.**



About the Identification of Galactic CR Sources

- A straightforward test of the acceleration of CRs in SNRs up to PeV energies would be the detection of γ-rays produced through the hadronic mechanism directly from young remnants and/or from dense clouds overtaken by the expanding shells.
- Multiwavelength observations are fundamental (and still not sufficient in most cases) to **disentangle leptonic or hadronic** mechanisms.
- Only the presence of HE neutrinos will be the proof of hadronic acceleration

- *The figure presents the SED of γ-rays from different SNRs at different ages. The largest energies are for SNe about 1-3 ky old.*
- *The Green catalog on radio observations contains 295 SNRs. Only 11 SNR have been firmly detected at TeV energies*



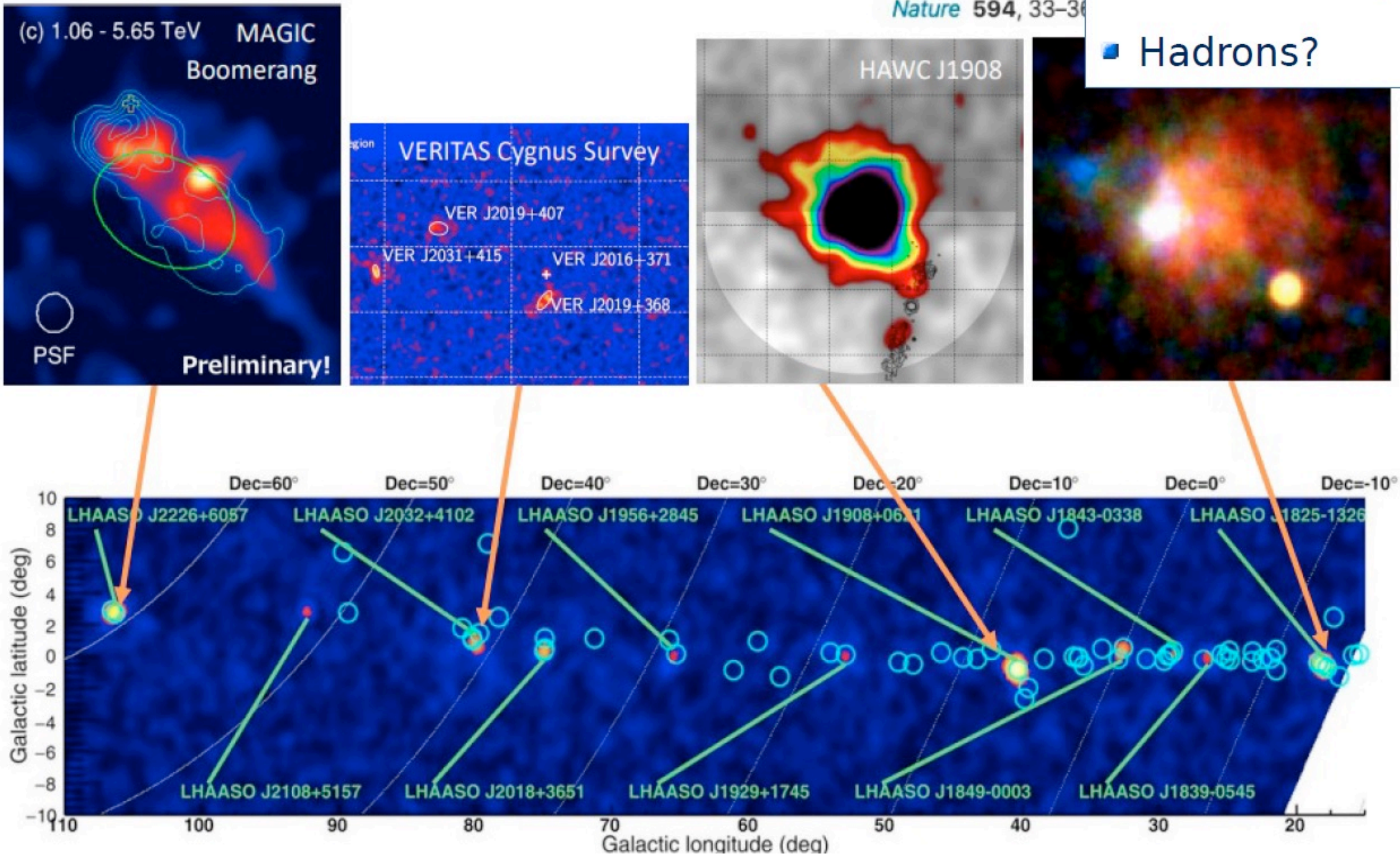
(2021) LHAASO first PeVatrons

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Zhen Cao, F. A.

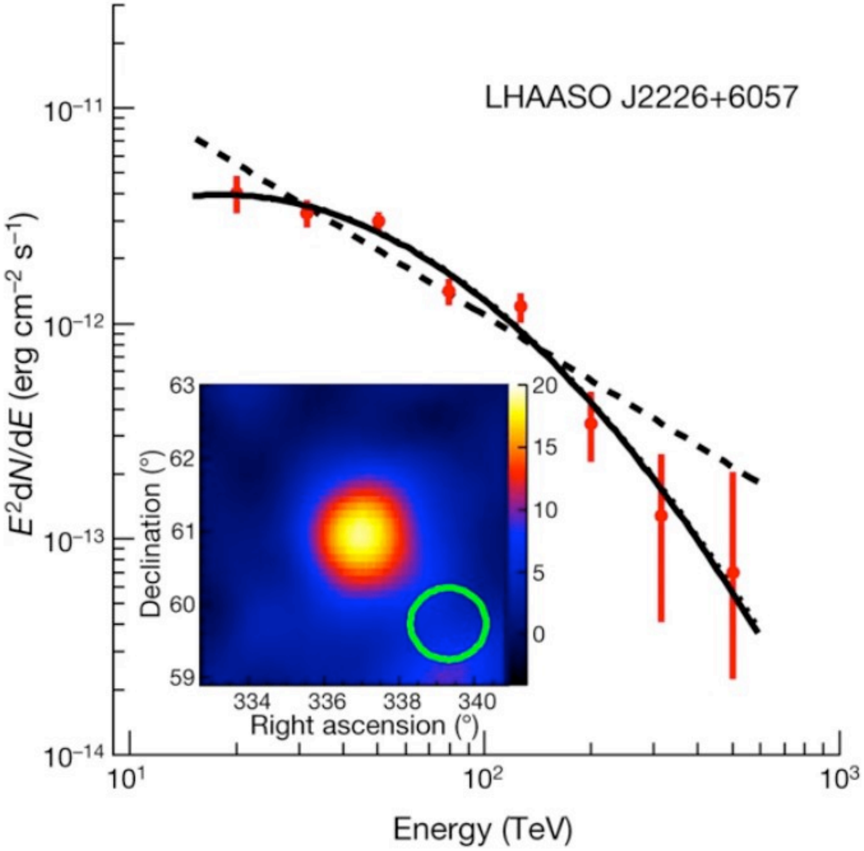
Nature **594**, 33–3

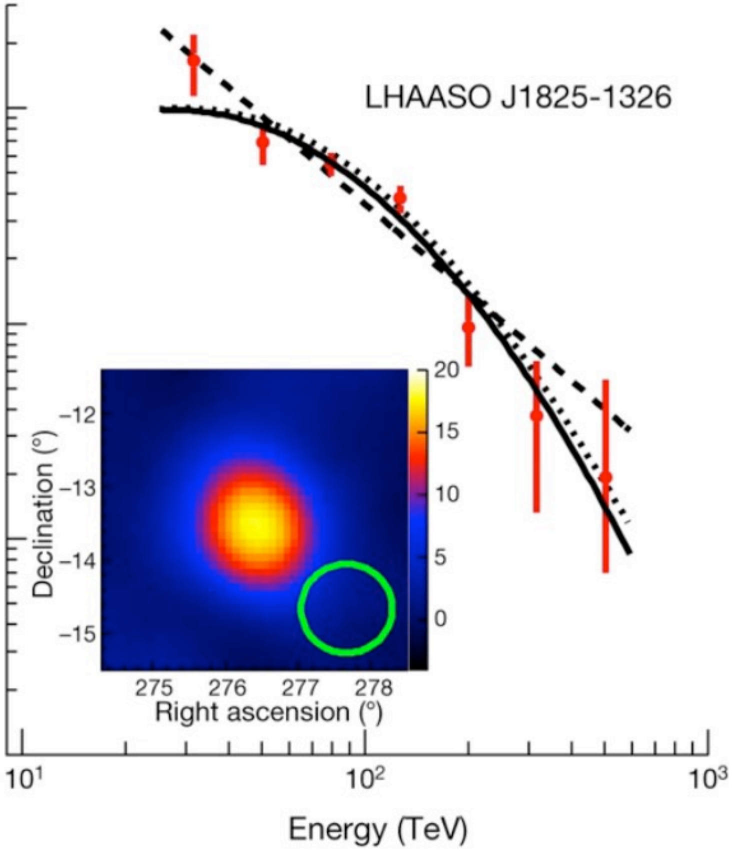
- 1y, KM2A
- E > 100 TeV, >7σ
- Hadrons?



Hadronic PeVatrons ?

- Not yet demonstrated…but challenging for electrons
- To prove hadronic process in spectral signature:
  - neutral Pion bump vs IC/SSC
  - association with dense Molecular Clouds
  - smoking gun: neutrinos association





And more…

- Star-forming galaxies
- Galaxy clusters
- Galactic diffuse emission
- Discrete Galactic sources
- Binary black hole or neutron star mergers
- Novae
- Tidal disruption events
- Fast radio bursts
- Dark Matter
- Exotic heavy particles
- ???