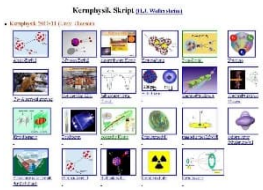
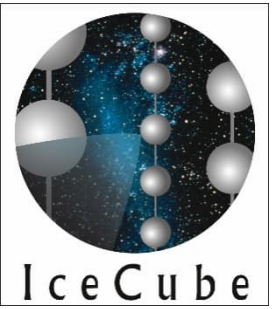
# Outline: Ice Cube and the Discovery of Cosmic Neutrinos

Lecturer: Hans-Jürgen Wollersheim

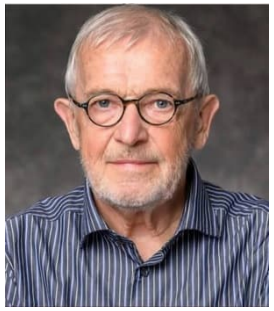
e-mail: h.j.wollersheim@gsi.de

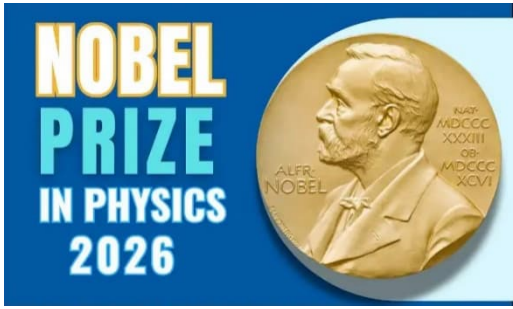
web-page: https://web-docs.gsi.de/~wolle/ and click on






http://icecube.wisc.edu



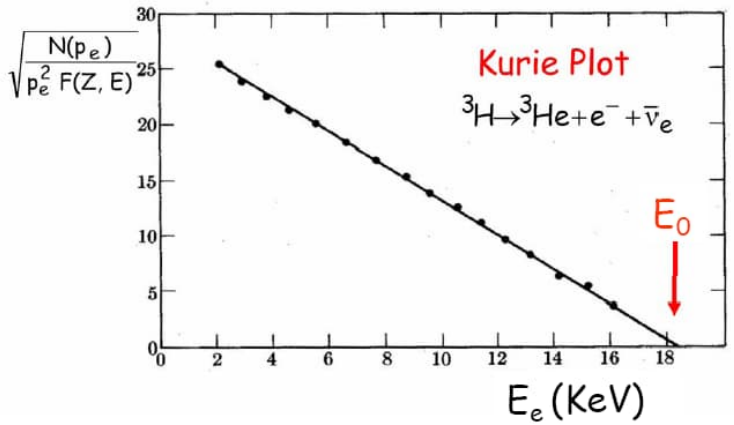



1. history
2. flavors of neutrino
3. cosmic rays & neutrinos
4. Super-Kamiokande
5. IceCube observatory
6. first results

# Beta decay & Neutrinos (~1930)

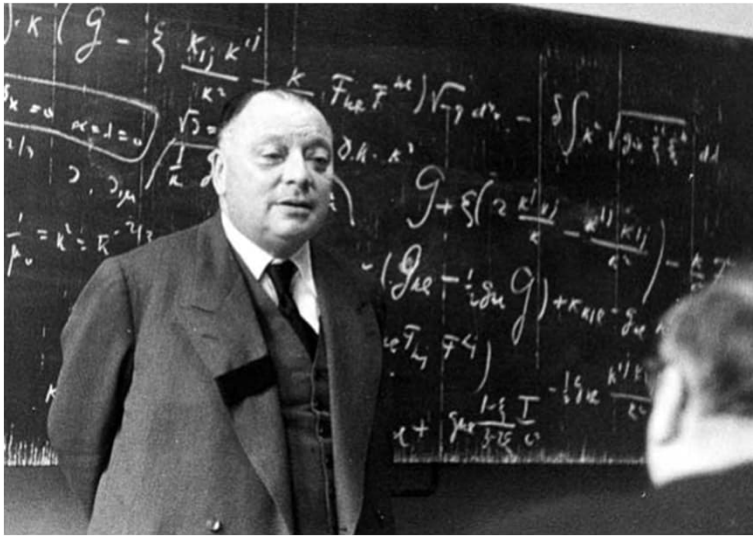
Problem observed in β-decays of radioactive nuclei, $A \rightarrow B + e^-$. If A is at rest, the two decay particles B and electron are back-to-back and the electron should be monochromatic.

$$E = \left( \frac{m_A^2 - M_B^2 + m_e^2}{2m_A} \right) \cdot c^2$$




However, a continuous spectrum was observed and Pauli postulated the existence of a neutral weakly interacting particle (called later **neutrino** by Fermi)

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



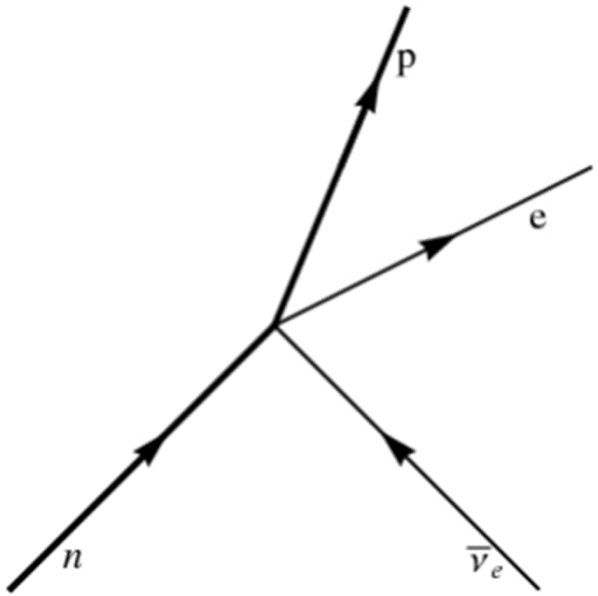
*Wolfgang Pauli (1953)*



Pauli Nobel prize in 1945

# Fermi: 4-fermion interaction

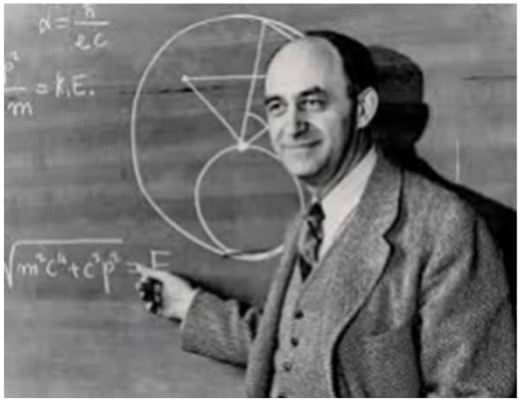
Enrico Fermi was the first one who calculated the β-decay, making the hypothesis of a 4-fermion interaction




The matrix element would be simply something like:

$$= \frac{4G_F}{\sqrt{2}} J^{\mu} J_{\mu}^{\dagger}$$

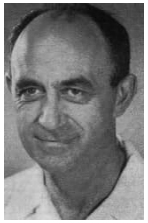
where $G_F$ is called the Fermi constant



*Enrico Fermi*

Note that this approximation is still valid at low energies and in fact $G_F$ can be measured for instance in muon decay.

# Fermi´s golden rule



Fermi´s golden rule:

$$W_{if} = \frac{2\pi}{\hbar} \cdot \left|\langle \Psi_f | H_{int} | \Psi_i \rangle\right|^2 \cdot \rho(E_f)$$

it depends on the transition matrix element and on the level density of final states (phase space).

The decay rate with the emission of an electron in the energy range between $E_e$ and $E_e + dE_e$ and an anti-neutrino in the energy range between $E_{\bar{\nu}}$ and $E_{\bar{\nu}} + dE_{\bar{\nu}}$ is given by

$$W_{if}(E_e, E_{\bar{\nu}})dE_e dE_{\bar{\nu}} = \frac{2\pi}{\hbar}\left|\langle \Psi_f | H_{int} | \Psi_i \rangle\right|^2 \rho_f \cdot \delta(E_0 - E_R - E_e - E_{\bar{\nu}})dE_e dE_{\bar{\nu}}$$

$E_0$ decay energy
$E_R$ recoil energy of the nucleus, which is neglected since it is small due to its large mass.
$\rho_f$ level density of the final states
$\langle \Psi_f | H_{int} | \Psi_i \rangle$ matrix element of the weak interaction

The state of a particle is determined by its position and its momentum

$$\Delta x \cdot \Delta y \cdot \Delta z \cdot \Delta p_x \cdot \Delta p_y \cdot \Delta p_z \approx h^3$$

Each particle has a volume of $h^3$ in phase space. The number of states in momentum shell $\Delta p = 4\pi \cdot p^2 dp$ is given by

$$dn = \frac{V \cdot 4\pi \cdot p^2}{h^3} dp$$

level density of free particles

$$\Delta x \cdot \Delta y \cdot \Delta z = V$$

matrix element must be small compared to the energy intervals in the system (otherwise no perturbation theory)

# Fermi´s golden rule

number of final states: $$\rho_f dN_e dN_{\bar{\nu}} = \frac{V^2 \cdot (4\pi)^2 \cdot p_e^2 dp_e \cdot p_{\bar{\nu}}^2 dp_{\bar{\nu}}}{(2\pi \cdot \hbar)^6}$$

For the absolute values of the momenta one uses relativistic energy and momentum relations:

$$E_e = \sqrt{p_e^2 \cdot c^2 + m_e^2 \cdot c^4} \qquad E_{\bar{\nu}} = p_{\bar{\nu}} \cdot c$$

$$p_e dp_e = E_e dE_e / c^2 \qquad dp_{\bar{\nu}} = dE_{\bar{\nu}} / c$$

number of states in the energy interval $dE_e$ and $dE_{\bar{\nu}}$

$$\rho_f dN_e dN_{\bar{\nu}} = \frac{V^2 \cdot (4\pi)^2}{(2\pi \cdot \hbar)^6 \cdot c^6} E_e \sqrt{E_e^2 - m_e^2 \cdot c^4}\, E_{\bar{\nu}}^2\, dE_e dE_{\bar{\nu}}$$

Since the anti-neutrino is not measured, one obtains with $E_{\bar{\nu}} = E_0 - E_e$ after the integration over the anti-neutrino energy $E_{\bar{\nu}}$ the decay rate for the emission of an electron with an energy between $E_e$ and $E_e + dE_e$.

$$W_{if}(E_e) dE_e = \frac{2\pi}{\hbar} \left|\langle \Psi_f | H_{int} | \Psi_i \rangle\right|^2 \cdot \frac{V^2 \cdot (4\pi)^2}{(2\pi \cdot \hbar)^6 \cdot c^6} \; E_e \sqrt{E_e^2 - m_e^2 \cdot c^4 (E_0 - E_e)^2} \; dE_e$$

The phase space factor, which yields from the level density, determines the essentially shape of the energy spectrum!

# β-decay spectrum: matrix element

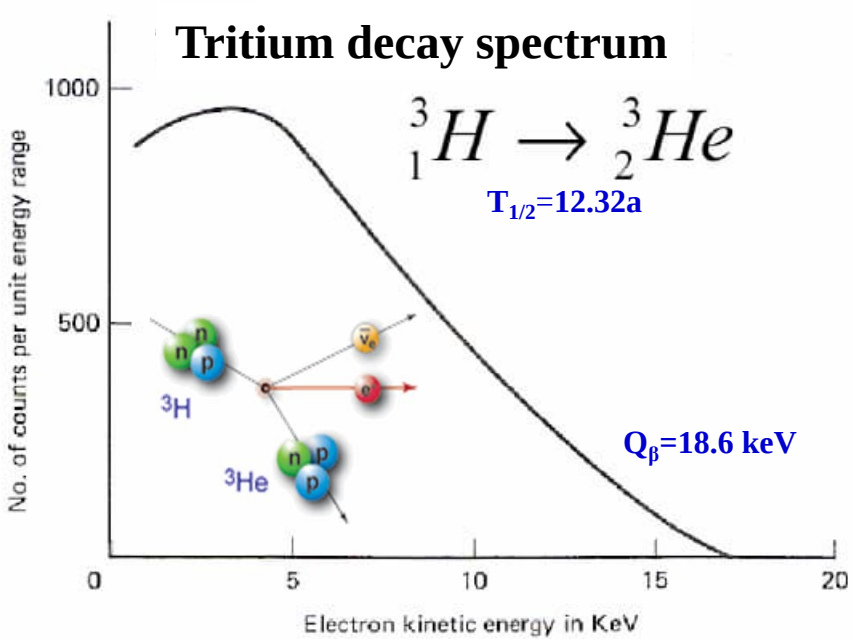
The phase space factor $E_e\sqrt{E_e^2 - m_e^2 \cdot c^4}(E_0 - E_e)^2$, which results from the level density, determines essentially the shape of the energy spectrum.

The matrix element is obtained by integrating over the position and spin variables for the electron, anti-neutrino and the nucleon in the nucleus.

Electron and anti-neutrino are described by plane waves (de Broglie wave length of electron $2 \cdot 10^{-13}$ m > $R_{nucleus}$). For the small nucleus one performs an expansion around r = 0.

$$\left|\langle \Psi_f | H_{int} | \Psi_i \rangle\right|^2 = |\Psi_e(0)|^2 \cdot |\Psi_{\bar{\nu}}(0)|^2 \cdot |M_{fi}|^2$$

$M_{fi}$ is the nuclear matrix element that does not depend on the electron energy.



# Neutrinos in 1930

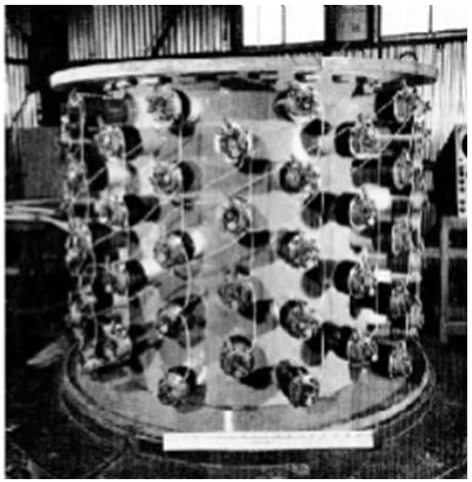
Pauli invented the neutrino in 1930, becoming a tool to investigate weak interactions
*"I have today done something terrible which no theoretician ever should do and proposed something which never will be possible to be verified experimentally".*

Soon after:

- Fermi formulated his theory of β-decay.
- Bethe-Peierls calculated the neutrino cross section, it was small!
- Pontecorvo realized that nuclear plants had high fluxes of anti-neutrinos
- Cowan and Reines (1956) detected the first neutrino reactions at the Savannah River nuclear reactor (*3 events/hr*)

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







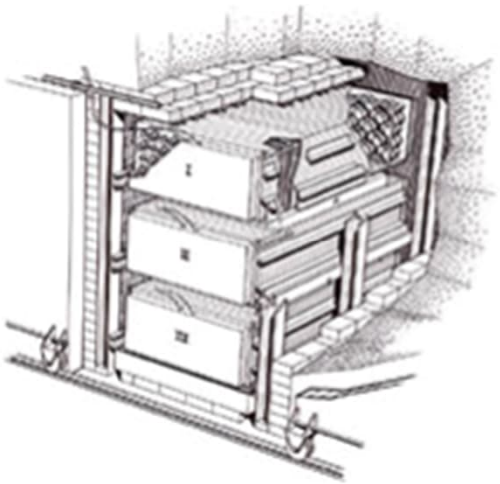
Reines Nobel prize in 1995

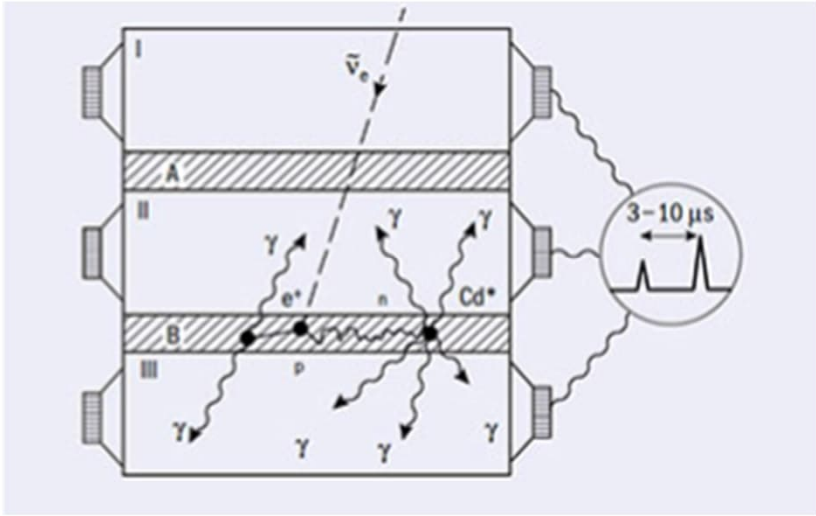
# Cowan-Reines experiment

*200 liter of water with cadmium chloride (26 years later!)*

The positron annihilates in water with the positron giving two photons of 0.511 MeV; followed by

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






Telegram to Pauli: *"We are delighted to tell you that we have definitely found neutrinos through observing inverse of beta-decay"*

Pauli answered: *"Everything comes to him who knows how to wait"*

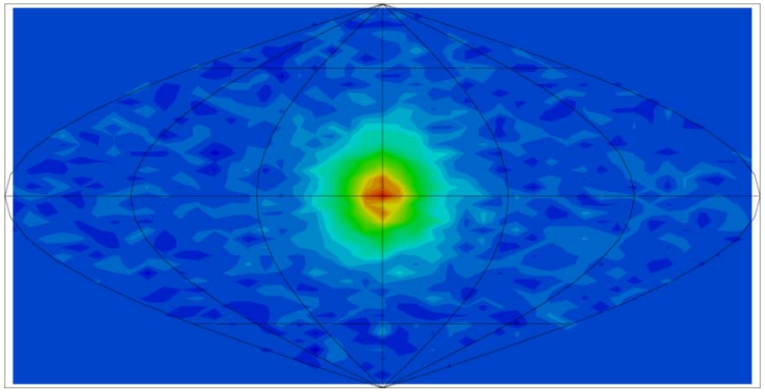


Reines Nobel prize in 1995

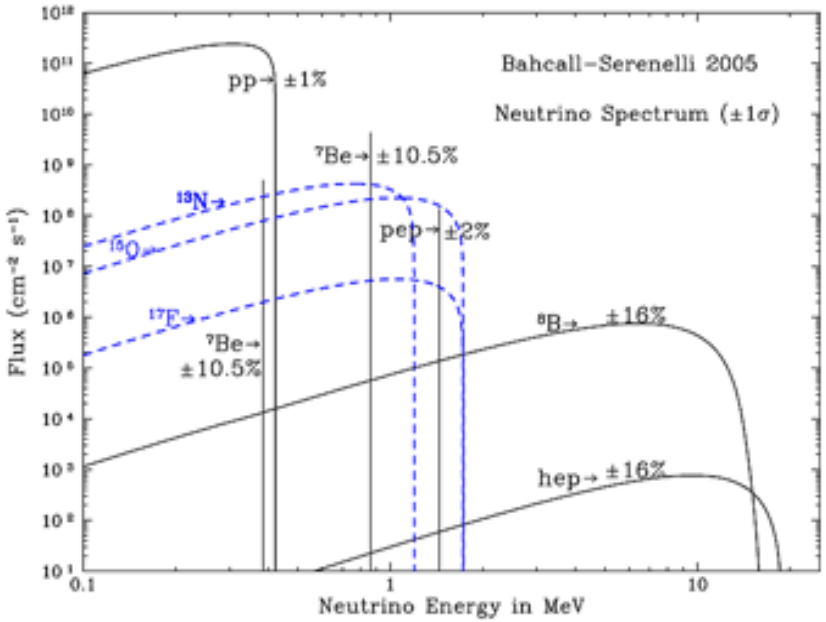
# The Sun, seen in neutrino light

Electron neutrinos produced in fusion chain
99% of solar neutrinos from pp-fusion.

First observed in 2014 by Borexino.
Small fraction from $^{7}$Be and $^{8}$B extend to high E
easier to detect

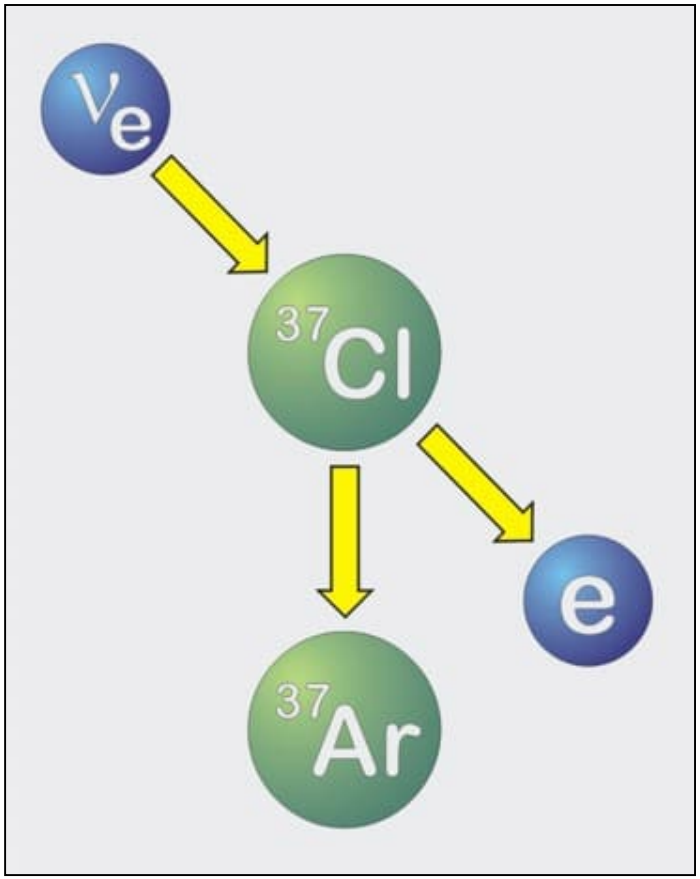


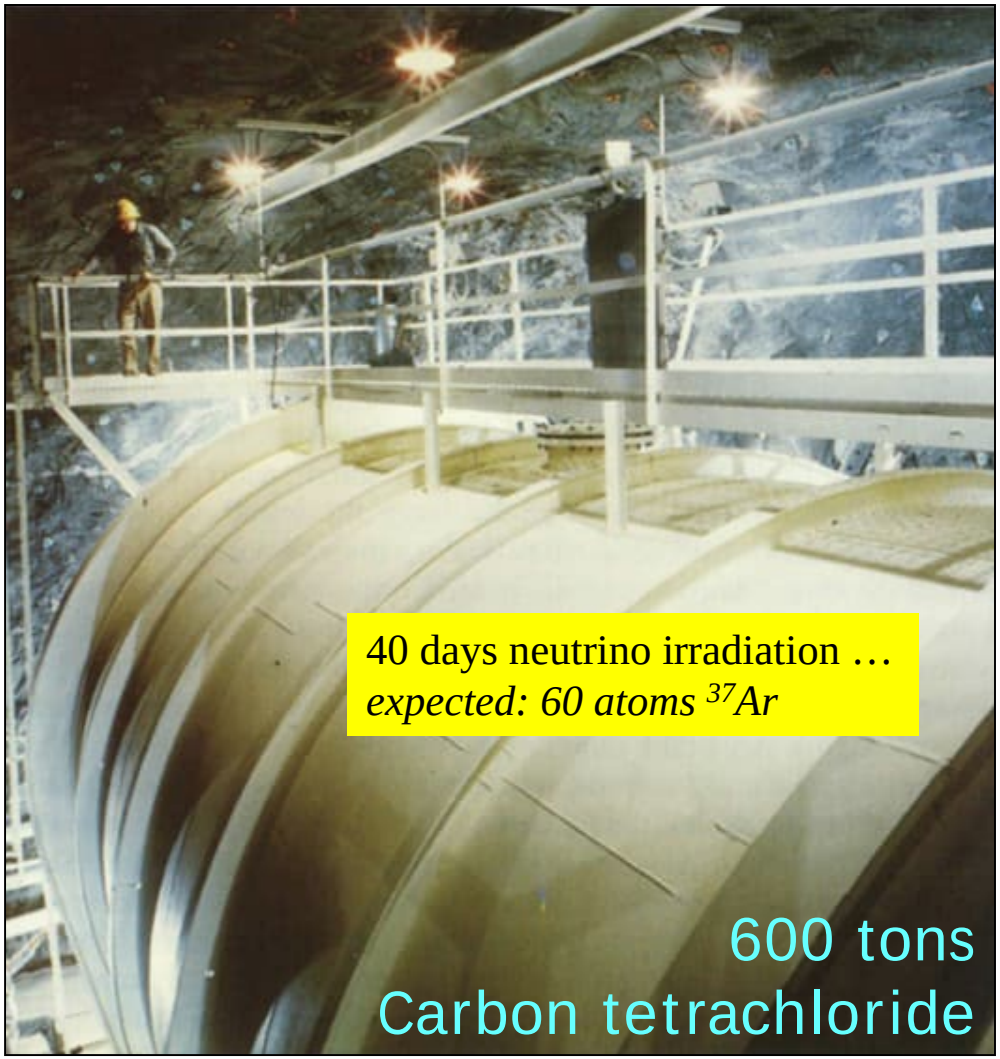
Bahcall predicted the solar neutrino flux in 1964.
He would refine this with an incredible precise solar model over the next 50 years



# First measurement of the solar neutrinos

Inverse beta-decay („neutrino-capture")



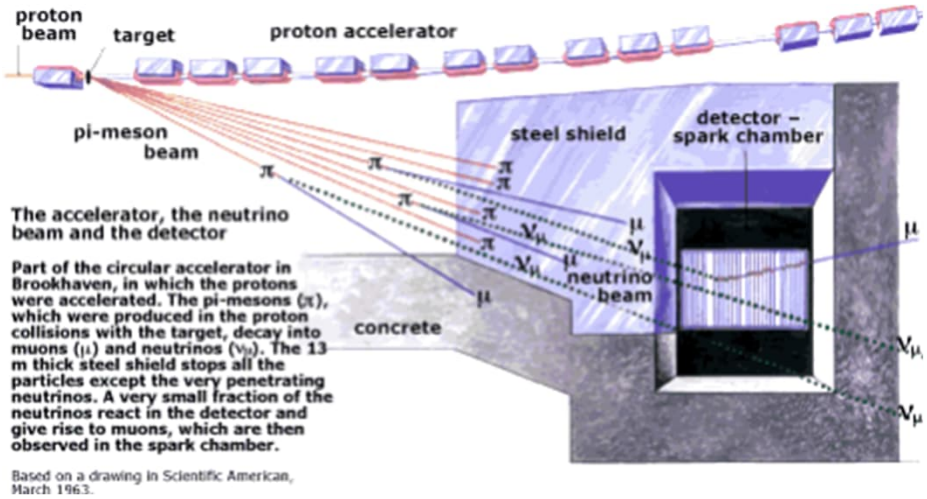




Homestake Sun neutrino-Observatory (1967–2002)

# Muon neutrino

- Pontecorvo at al,: Idea of high energy neutrino beams from pion decays in muons.
- In 1962 Lederman, Schwarz and Steinberger established that more than one type of neutrino exists by first detecting interactions of the muon neutrino.





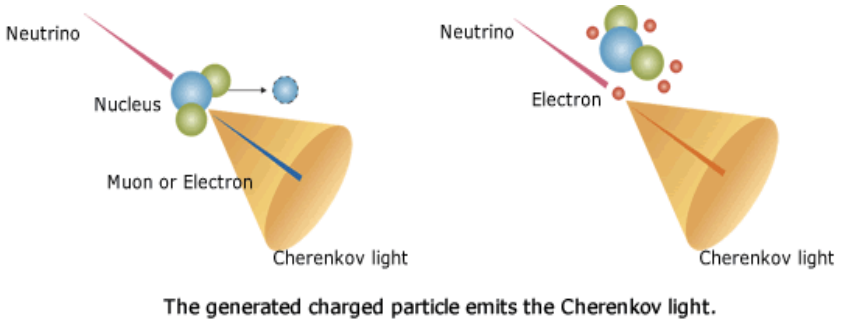





Nobel prize in 1988

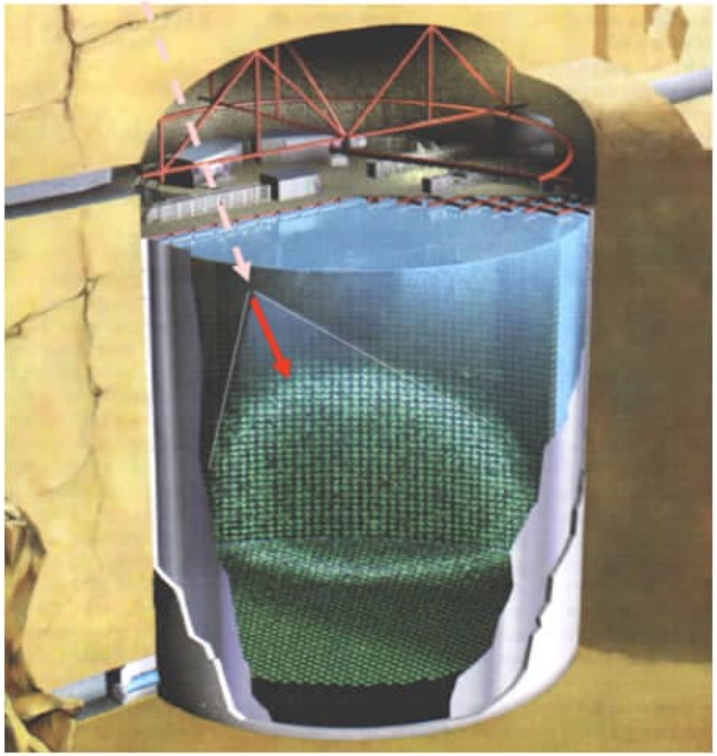
# Super Kamiokande detection concept

- Muon neutrinos interact with nucleons via charged current to produce ultra relativistic muons
- The muons travel faster than the speed of light in the detector (*still slower than c*)
- This produces a cone of Cherenkov light
  same principle as a sonic boom
- Light is detected by photo sensors



The generated charged particle emits the Cherenkov light.





# Super Kamiokande – the Detector

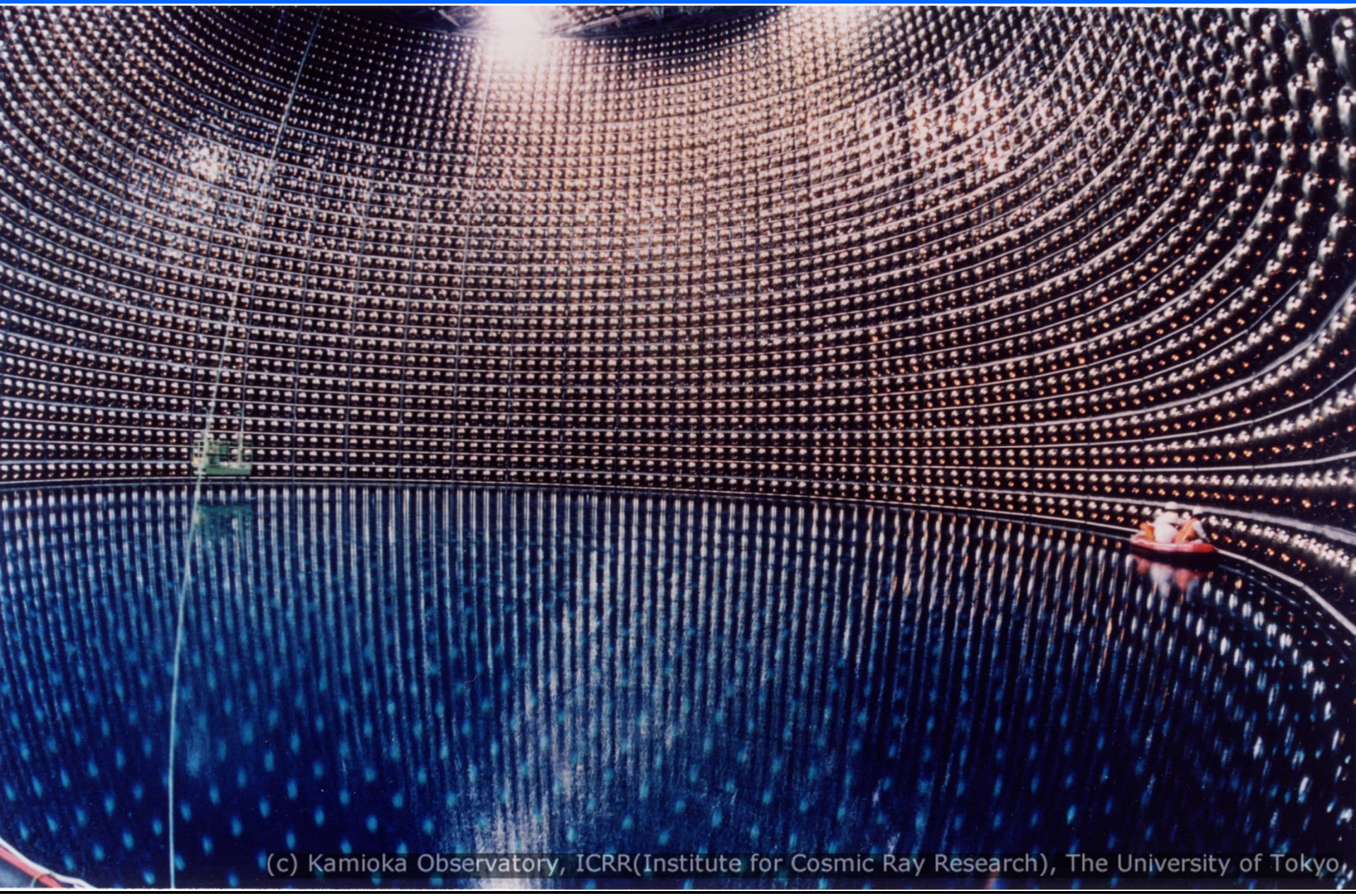
- 40 m water tank
- Filled with 50 ktons pure water
- Largest water Cherenkov detector in the world
- > 11.000 photomultipliers (PMTs to detect light
- PMTs + electrical connections waterproof



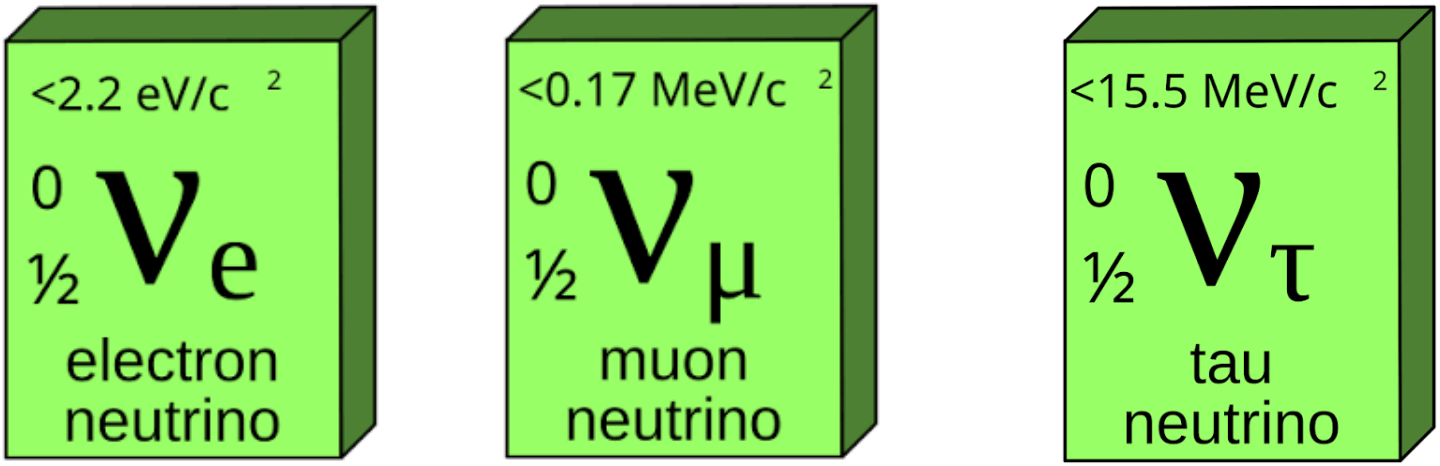




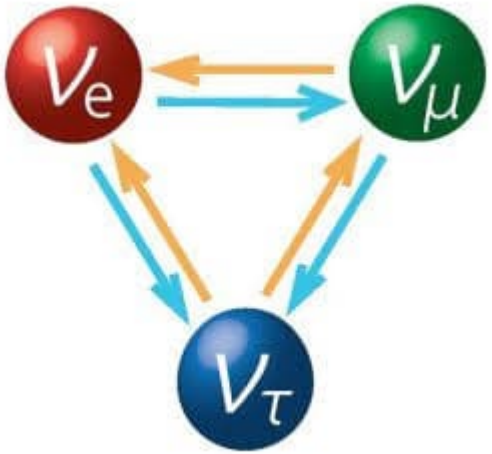
# Super Kamiokande – the Detector



# Flavors of Neutrino




- An electron neutrino ($<0.45$ eV/$c^2$) only decays into an electron + X
- A muon neutrino only decays into a muon + X
- A tau neutrino only decays into a tau + X
- However, they can change into each other






Kajita & McDonald Nobel prize in 2015

# Neutrino Fluxes sources of neutrinos



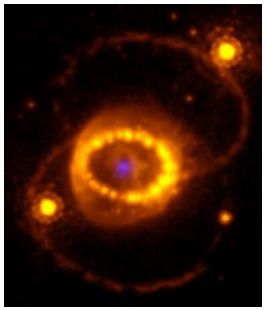

$\Phi_\nu^{Earth} = 6 \cdot 10^{10}\ \nu/cm^2 s$

$E_\nu \sim 0.1 - 20\ MeV$




$\rho_\nu = 330/cm^3$

$E_\nu = 0.0004\ eV$



SN1987

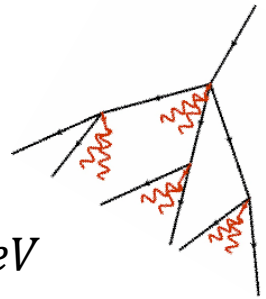
$E_\nu \sim MeV$

Atmospheric ν's

$\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$

$\Phi_\nu \sim 1\ \nu/cm^2 s$

$E_\nu \sim 0.1 - 100\ GeV$



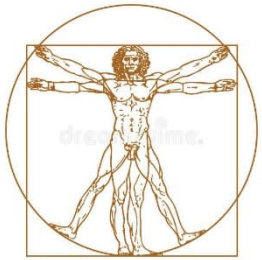
nuclear reactor

$E_\nu \sim few\ MeV$



Human Body

$\Phi_\nu = 340 \cdot 10^6\ \nu/day$



Accelerators

$E_\nu \cong 0.3 - 30\ GeV$

Fermilab

KEK

High Energy Accelerator Research Organization

CERN

$1\ MeV = 1.6 \cdot 10^{-13}\ Joules$

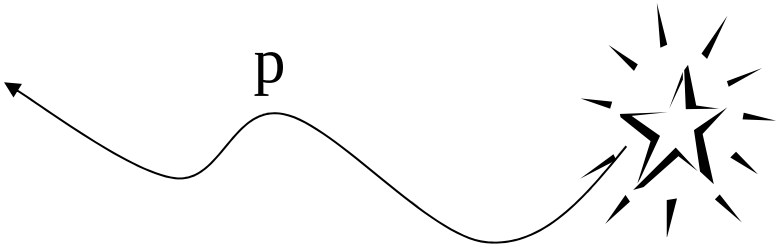
Earth's radioactivity $\Phi_\nu \sim 6 \cdot 10^6\ \nu/cm^2 s$

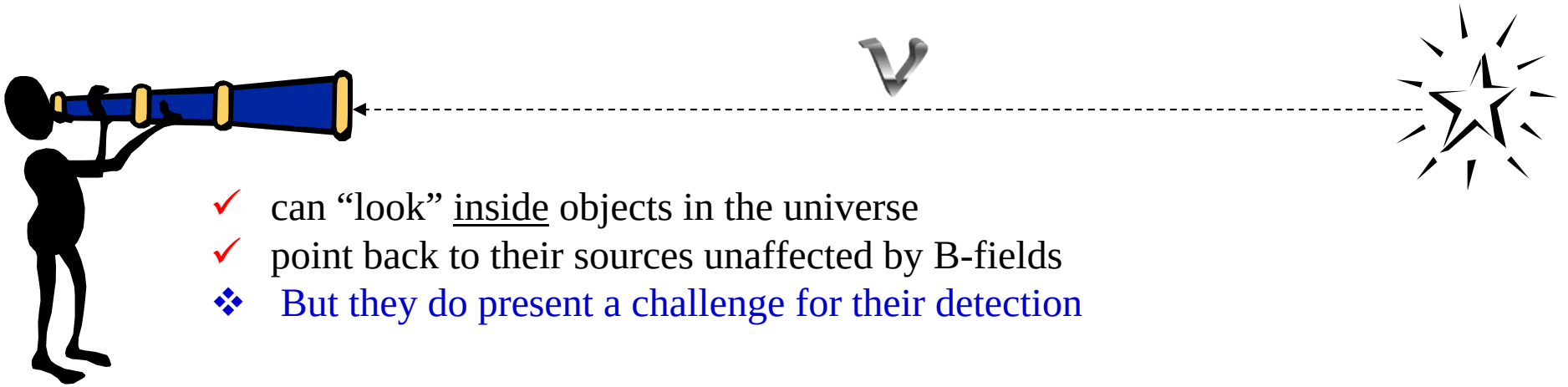
# The Advantage of high energetic Neutrino Astronomy

- ✓ At the highest energies, γ-astronomy is limited by attenuation $(\gamma\gamma \rightarrow e^+e^-)$



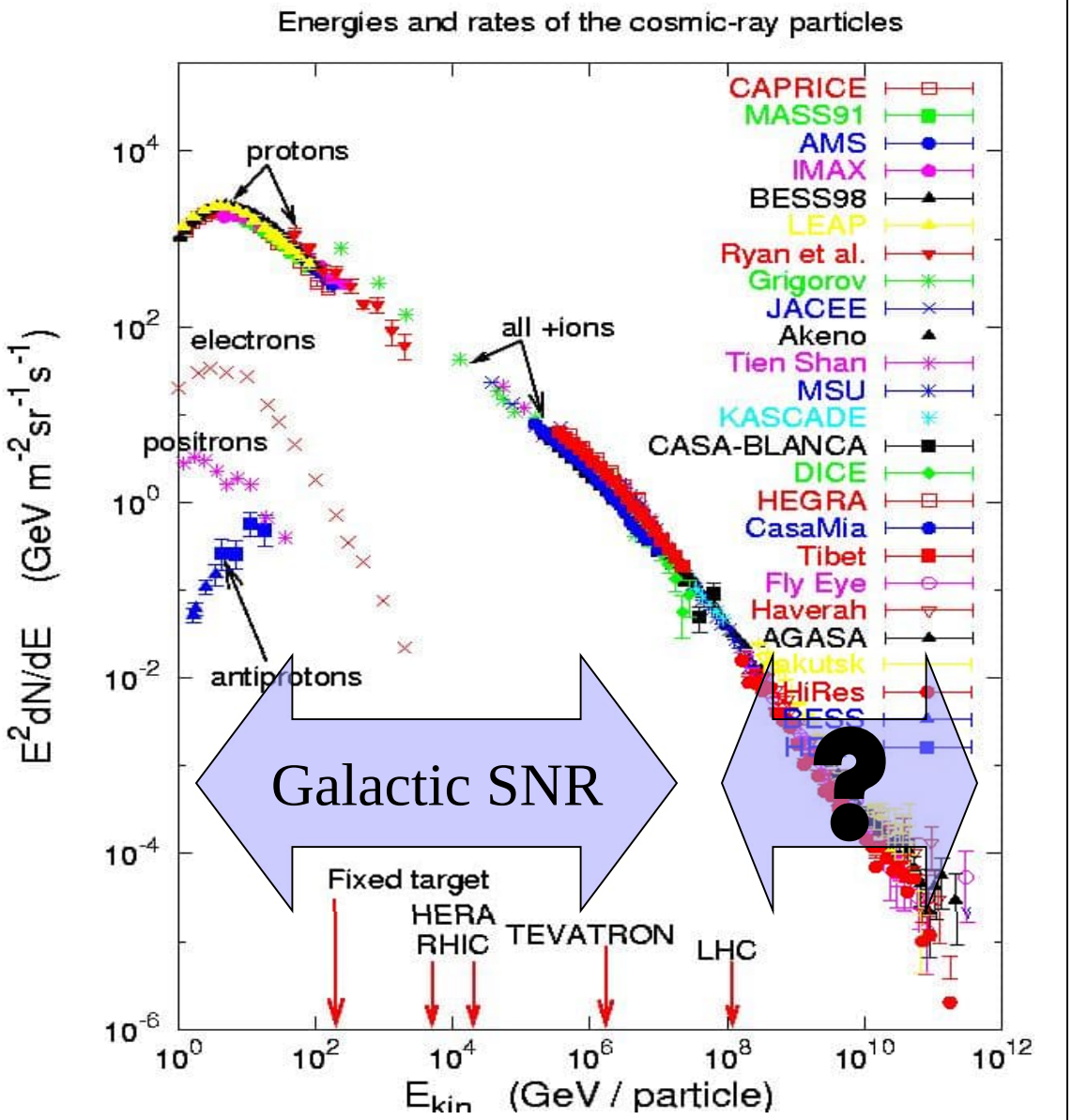

- ✓ Cosmic rays (protons, ions) do not point back to the source (due to B-fields)



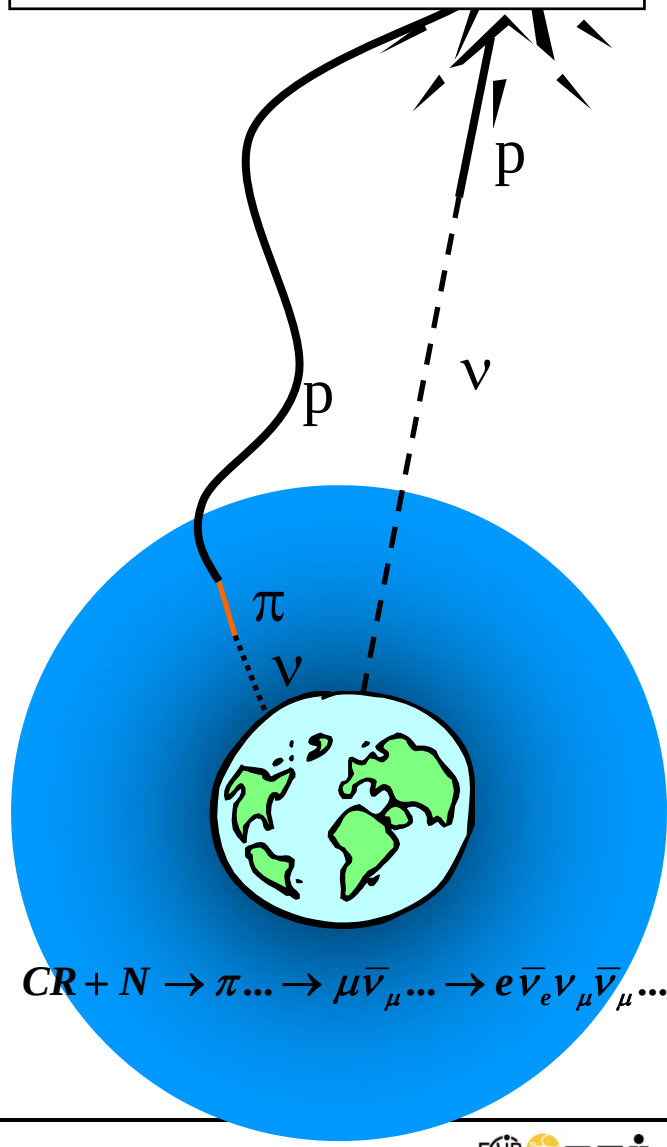

- ✓ can "look" inside objects in the universe
- ✓ point back to their sources unaffected by B-fields
- ❖ But they do present a challenge for their detection

# Cosmic Rays & Neutrinos



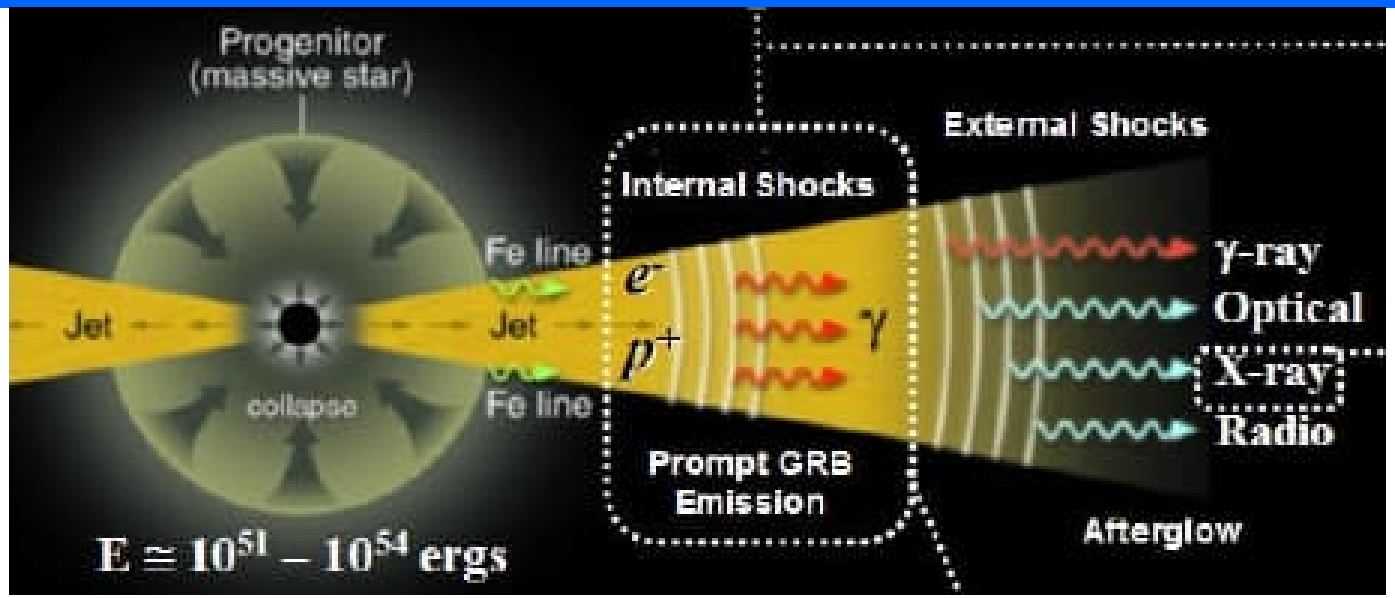

$$p + p \rightarrow \pi + ... \rightarrow \nu + ... \quad \text{or}$$

$$p + \gamma \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + ...$$




$$CR + N \rightarrow \pi ... \rightarrow \mu \bar{\nu}_\mu ... \rightarrow e \bar{\nu}_e \nu_\mu \bar{\nu}_\mu ...$$

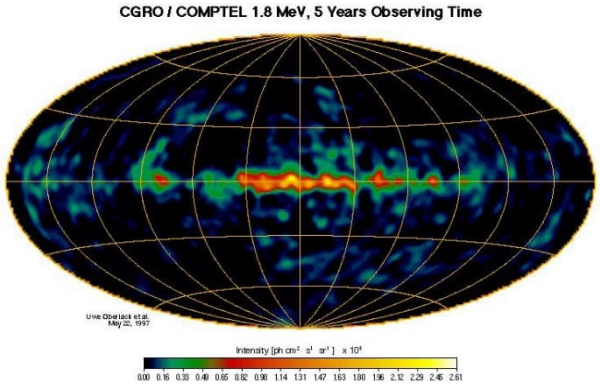
# What to learn from high energetic Neutrino point source

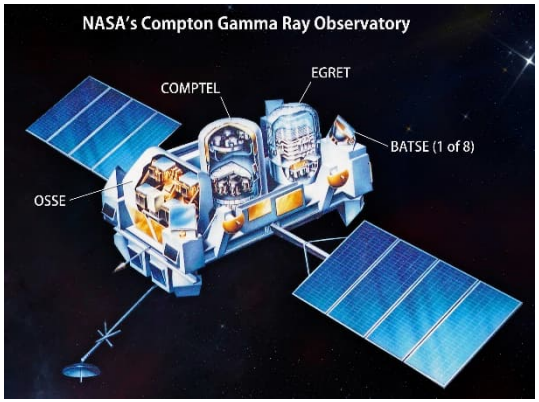



- Origin of Cosmic Rays: “smoking gun” of the Supernova Remnant (SNR) hypothesis
- Origin of the Ultra High Energy Cosmic Rays (UHECR, $E_{CR} > 10^{18}\ eV$) which present an “acceleration challenge”. $\gamma + \gamma_{cmb} \rightarrow e^+ + e^-$
- Inner workings of the most powerful objects in the Universe such as AGN/Blazars, GRB, SNR, Microquasars…

# Driving Force: Data from related fields

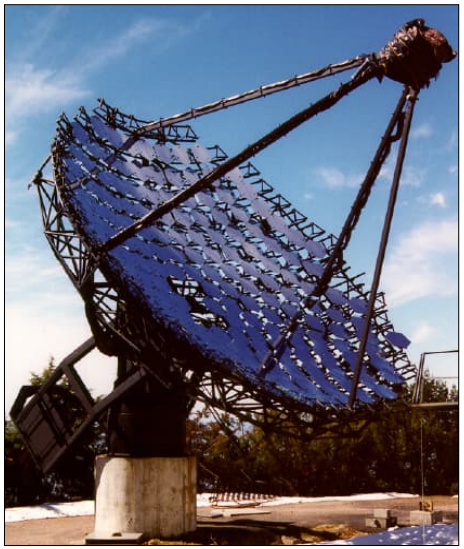
Cosmic Rays physics: ions with $10^9 - 10^{20}\ eV$
tells us there is SOMETHING to look for!



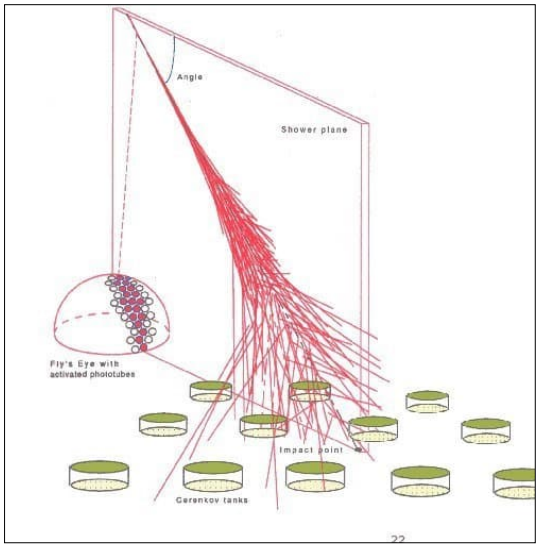




Compton Gamma Ray Observatory

High Energy Photon astronomy: $10^3 - 10^{13}\ eV$
tells us WHERE to look

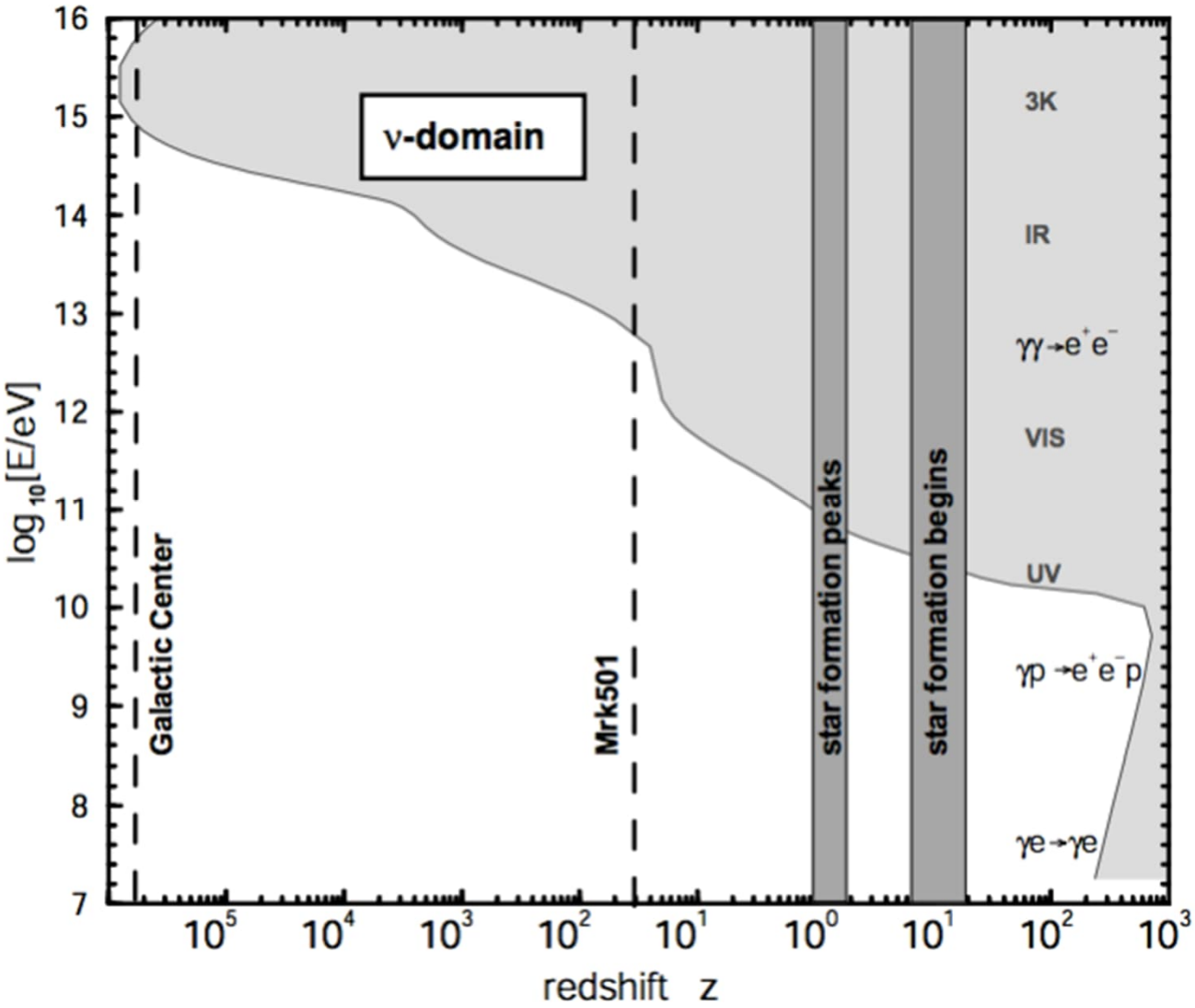


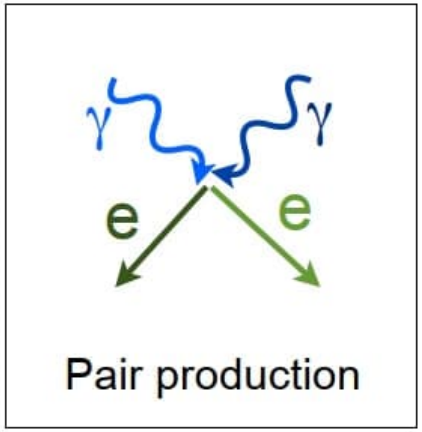
Whipple Observatory




CR detection

# Absorption of γ-rays in extragalactic background light




- TeV gamma rays can reach us only from the local universe
- Re-emission of absorbed TeV photons by inverse Compton processes in the GeV band: ”cascade emission”

# Supernova Remnants (SNR) proving the CR Hypothesis



Supernova Remnant

The “smoking guns” of CR-ions acceleration:

1. A 67.5 MeV peak in the γ-ray spectrum from $\pi^0$ decay:

$$p + p \rightarrow \pi^0 + \cdots \rightarrow \gamma\gamma + \cdots$$

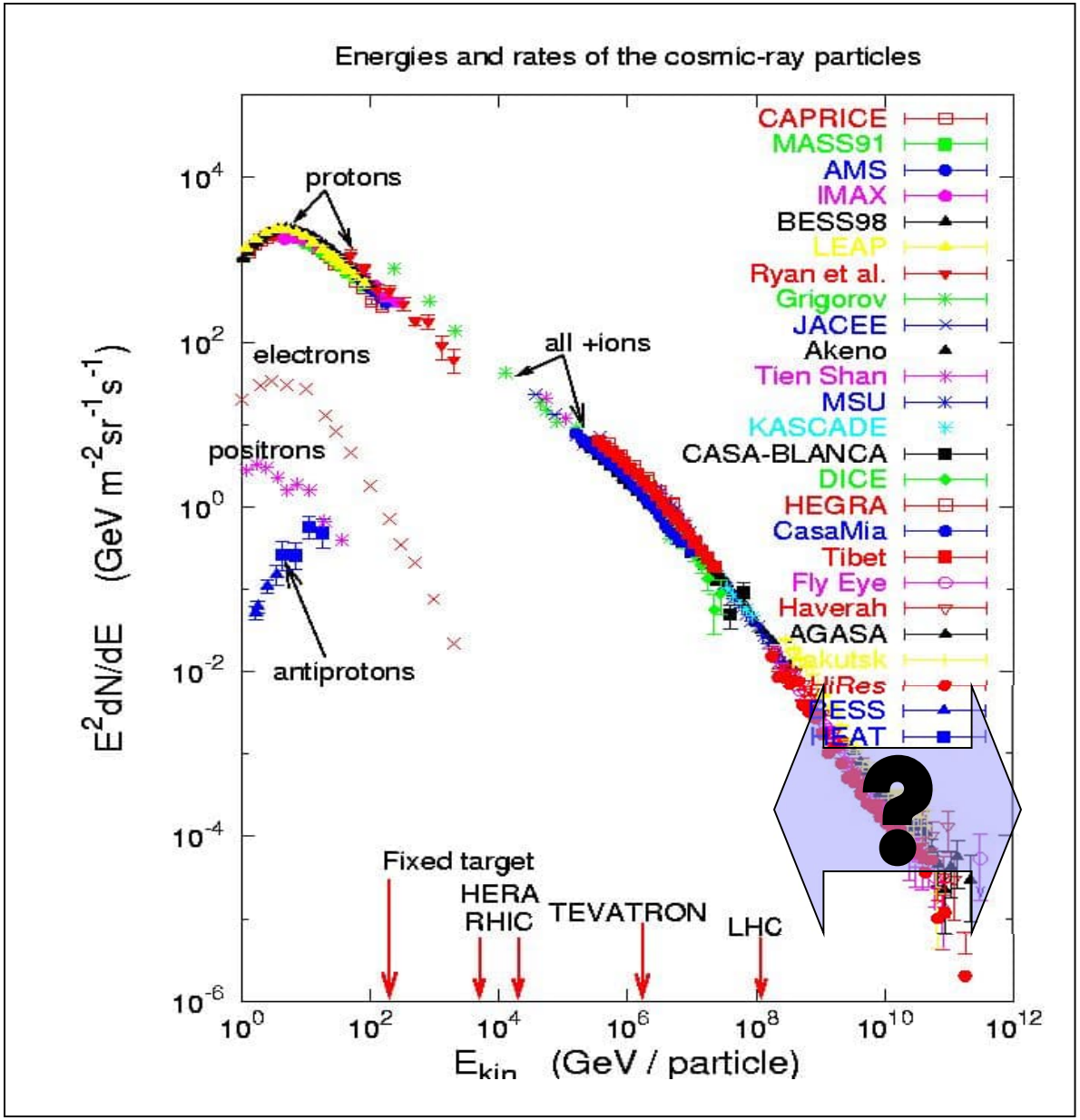
– Searches for the peak are inconclusive so far

**2. Neutrinos:**

$$p + p \rightarrow \pi^{\pm} + \cdots \rightarrow \nu + \cdots$$

**Discovery of high energetic neutrinos from SNR would unequivocally establish the origin of galactic cosmic Rays!**

# Cosmic Rays & Neutrinos



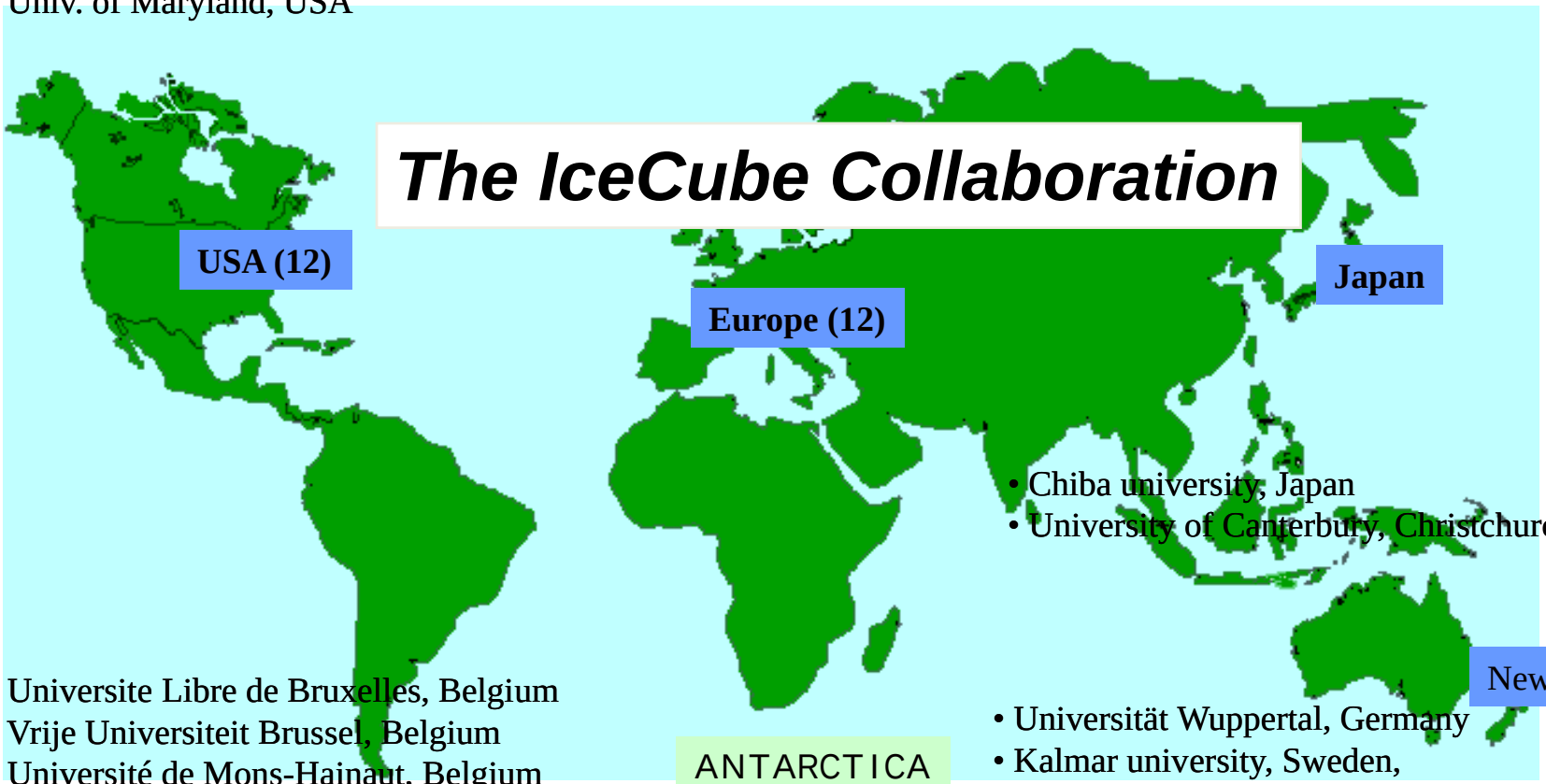


South Pole

road to work

# Amundsen-Scott South Pole station

# The IceCube Collaboration




- Alabama University, USA
- Bartol Research Institute, Delaware, USA
- Pennsylvania State University, USA
- UC Berkeley, USA
- UC Irvine, USA
- Clark-Atlanta University, USA
- Univ. of Maryland, USA
- IAS, Princeton, USA
- University of Wisconsin-Madison, USA
- University of Wisconsin-River Falls, USA
- LBNL, Berkeley, USA
- University of Kansas, USA
- Southern University and A&M College, Baton Rouge, USA

- Chiba university, Japan
- University of Canterbury, Christchurch, NZ

- Universite Libre de Bruxelles, Belgium
- Vrije Universiteit Brussel, Belgium
- Université de Mons-Hainaut, Belgium
- Universiteit Gent, Belgium
- Humboldt Universität, Germany
- Universität Mainz, Germany
- DESY Zeuthen, Germany
- Universität Dortmund, Germany

- Universität Wuppertal, Germany
- Kalmar university, Sweden,
- Uppsala university, Sweden
- Stockholm university, Sweden
- Imperial College, London, UK
- Oxford university, UK
- Utrecht university, Netherlands

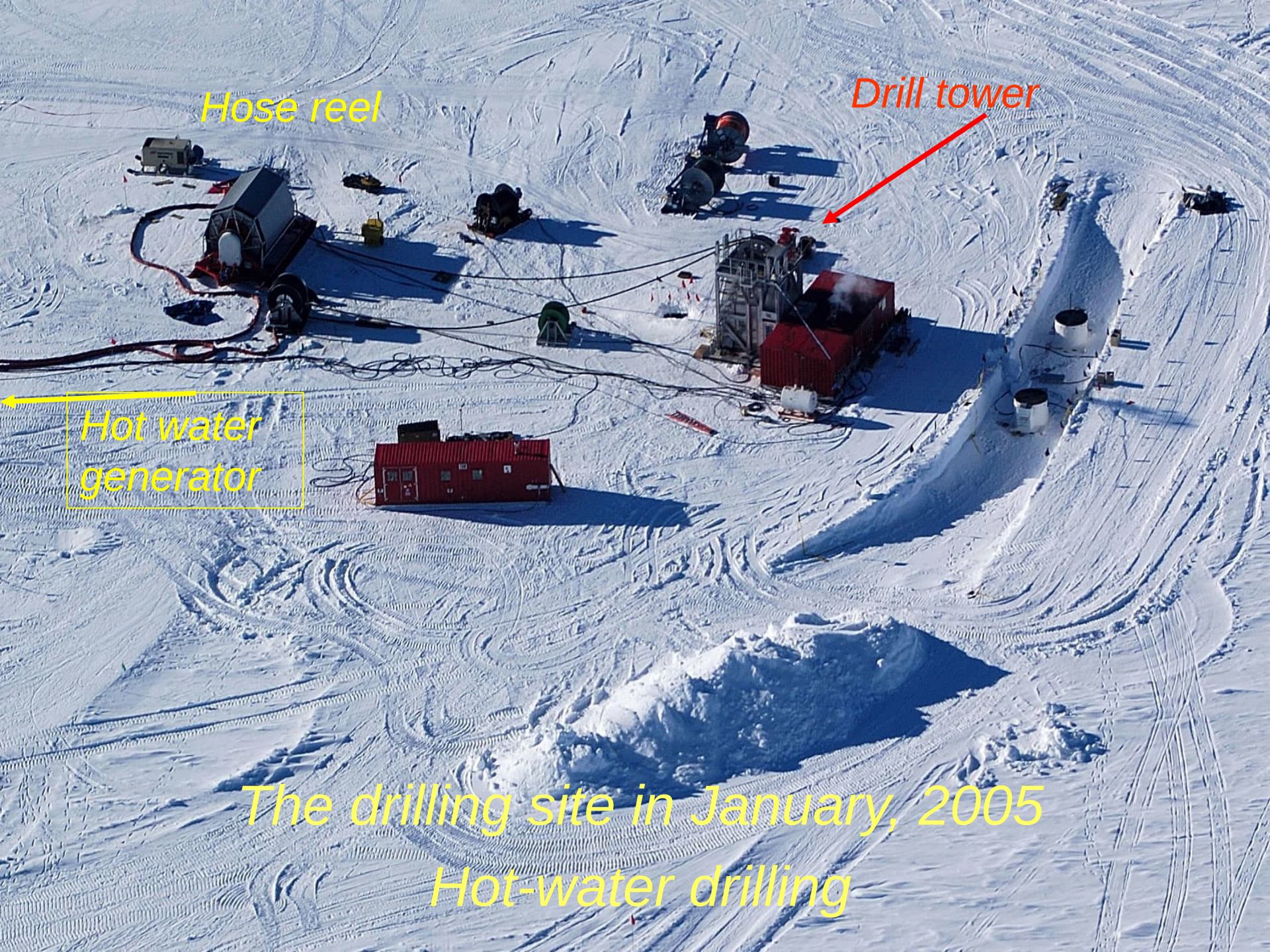
# Schedule & Logistics

- Can work  December → mid-February
- Logistics are a huge concern
  - Freight, power, … are expensive!
  - Weather is always a factor





The new South-Pole station




The drilling site in January, 2005

Hot-water drilling



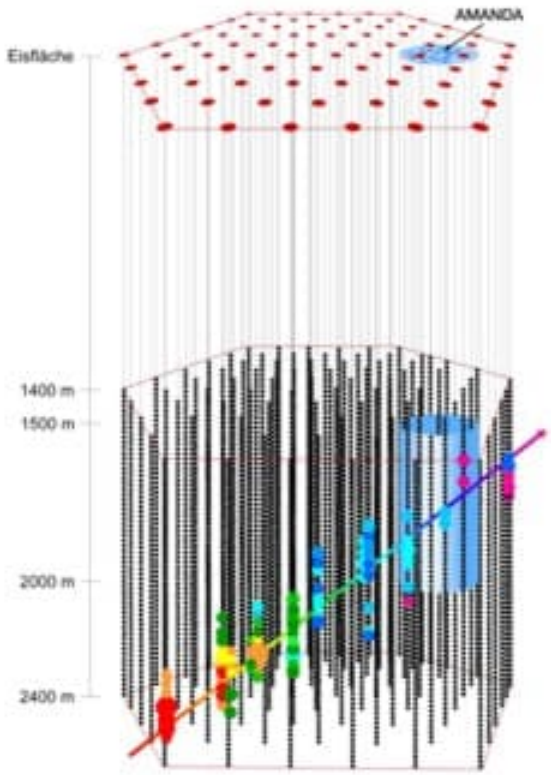

The 5 MW water heater for the hot water drill ($80^0$ C) (car-wash technology)

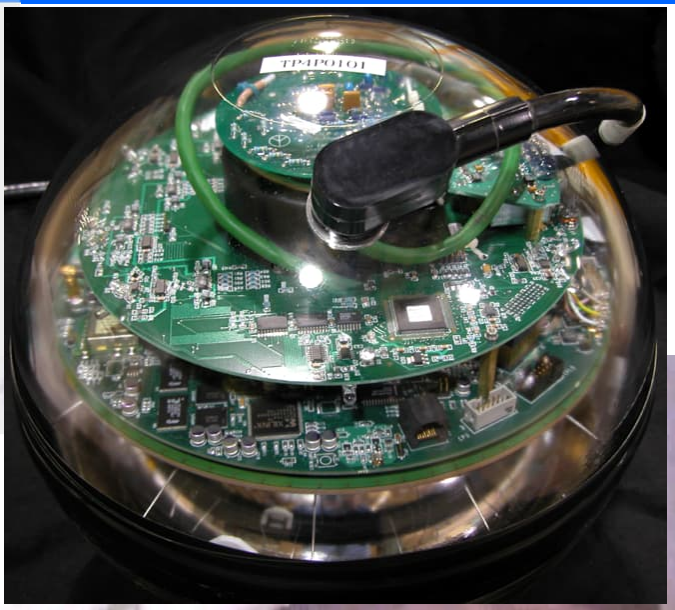
# IceCube

## Deep ice array **IceCube**

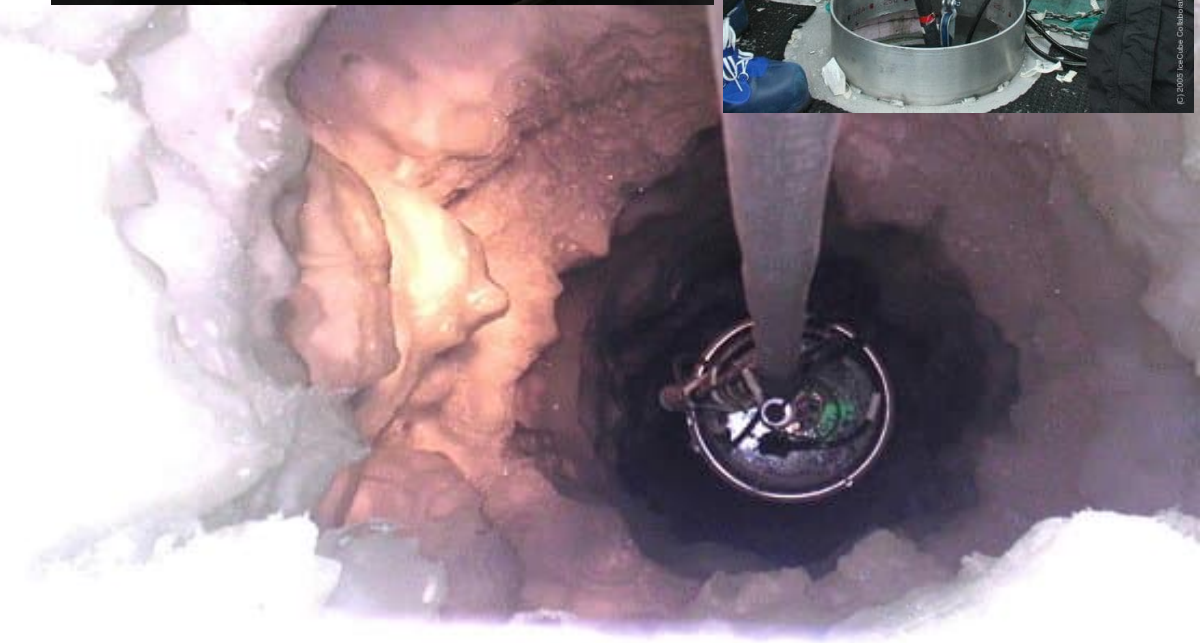
- Digital readout technology
- 80 strings / 60 DOMs each
- 17 m DOM spacing
- 125 m between strings
- hexagonal pattern over 1 km$^2$ x 1 km

Antarctic Muon and Neutrino Detector Array



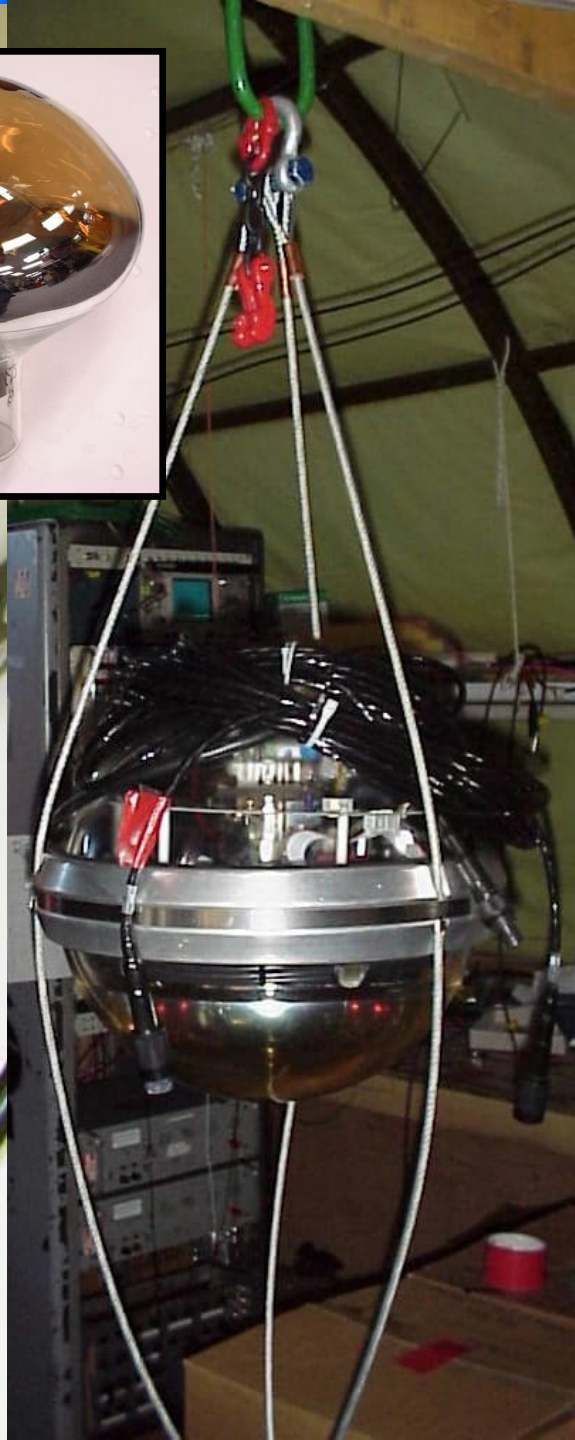













# $\nu_e, \nu_\mu$ *and* $\nu_\tau$ neutrino detection with IceCube

- $\nu_e \rightarrow e$ produce EM showers
  Good energy resolution, poor angular resolution

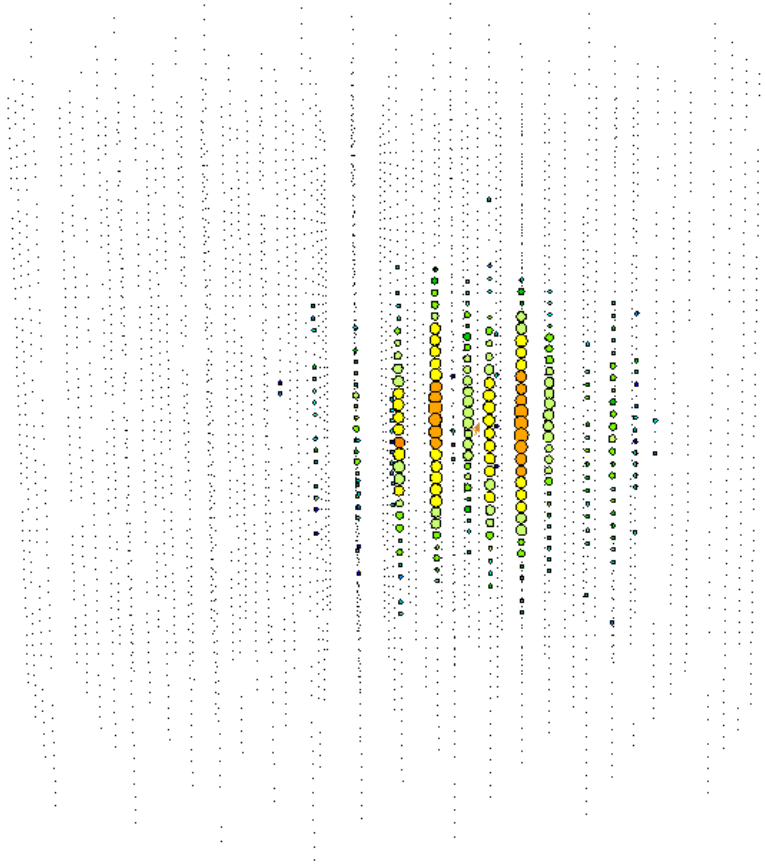
- $\nu_\mu \rightarrow \mu$ produce long muon tracks
  Good angular resolution, limited energy resolution
  Atmospheric $\nu_\mu$ are a significant background to searchers for extra-terrestrial ν
  - soft energy spectra → may improve signal to noise ratio by optimizing for higher energy ν

- above ~$10^{16}$ eV $\nu_\tau$ produce 'double-bang' events
  One shower when the τ is created, another when it decays

# Simulated $\nu_e$-event

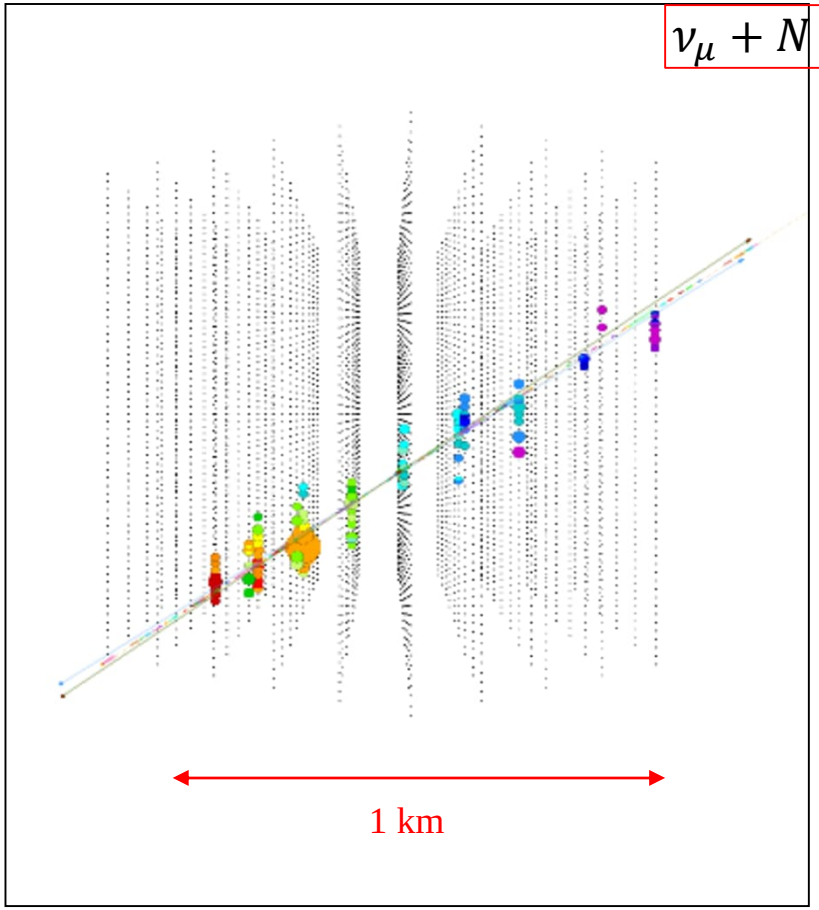
$$\nu_e + N \rightarrow e^- + X$$

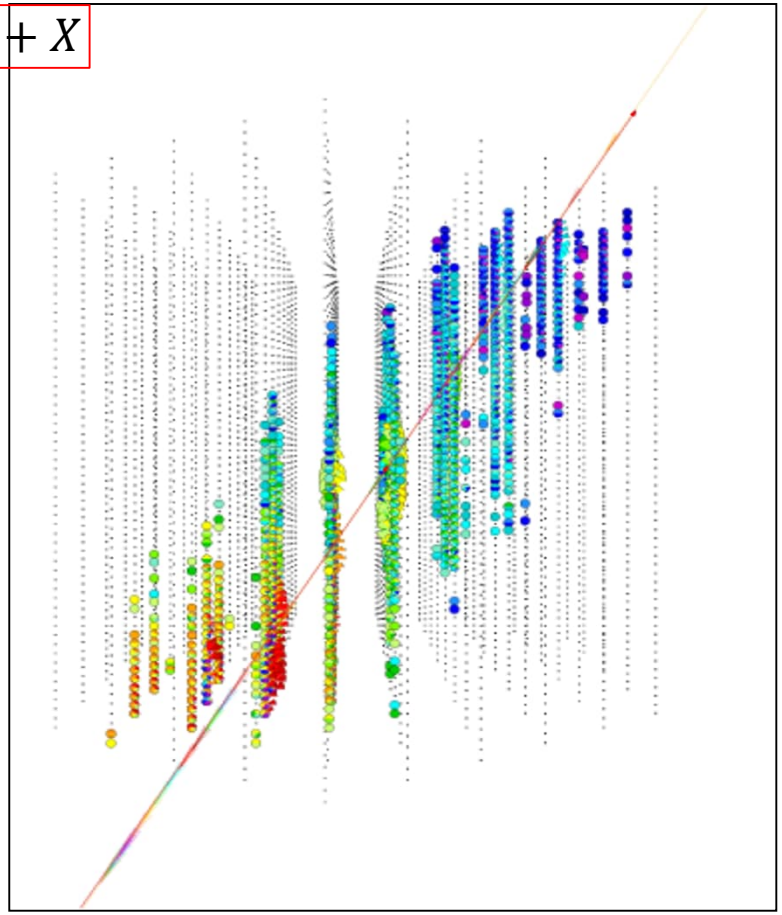
Electron Cascade
1 PeV ≈ 500 m diameter



# Simulated μ-event

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



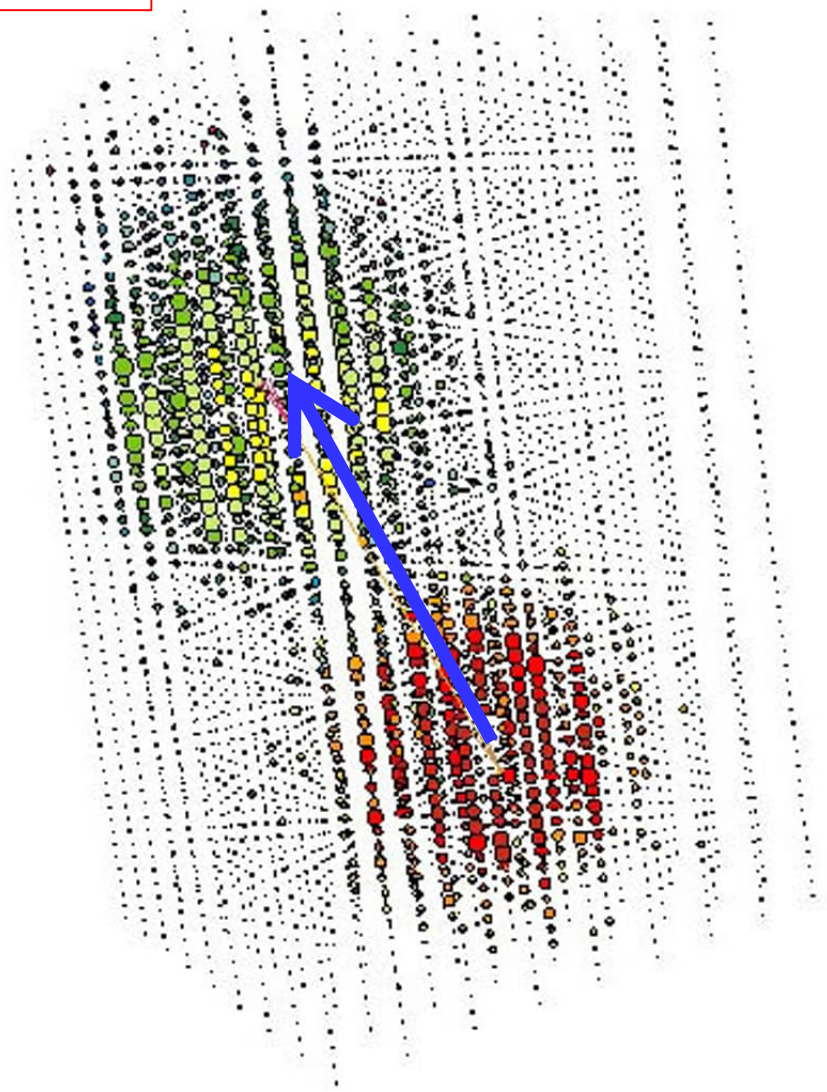



$E_\mu$=10 TeV, 90 hits

$E_\mu$=6 PeV, 1000 hits

# Simulated multi-PeV $\nu_\tau$ event

$$\nu_\tau + N \rightarrow \tau^- + X$$



A $\nu_e$ would appear as a single shower

n.b. $\gamma\beta c\tau$ =300 m for $E_\tau$ = 6 TeV

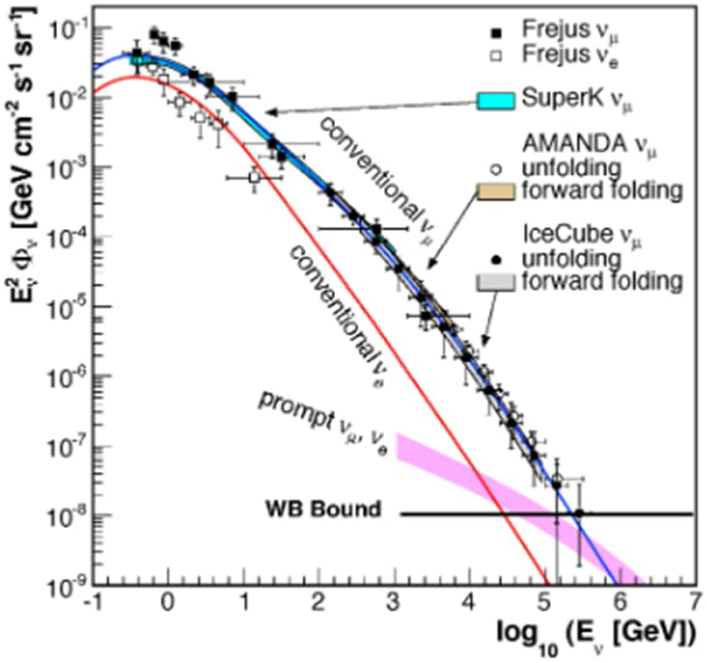
# Nobel Prize 2026 Francis Halzen

The Belgian-American pioneer of neutrino astronomy opened a new window to the universe.

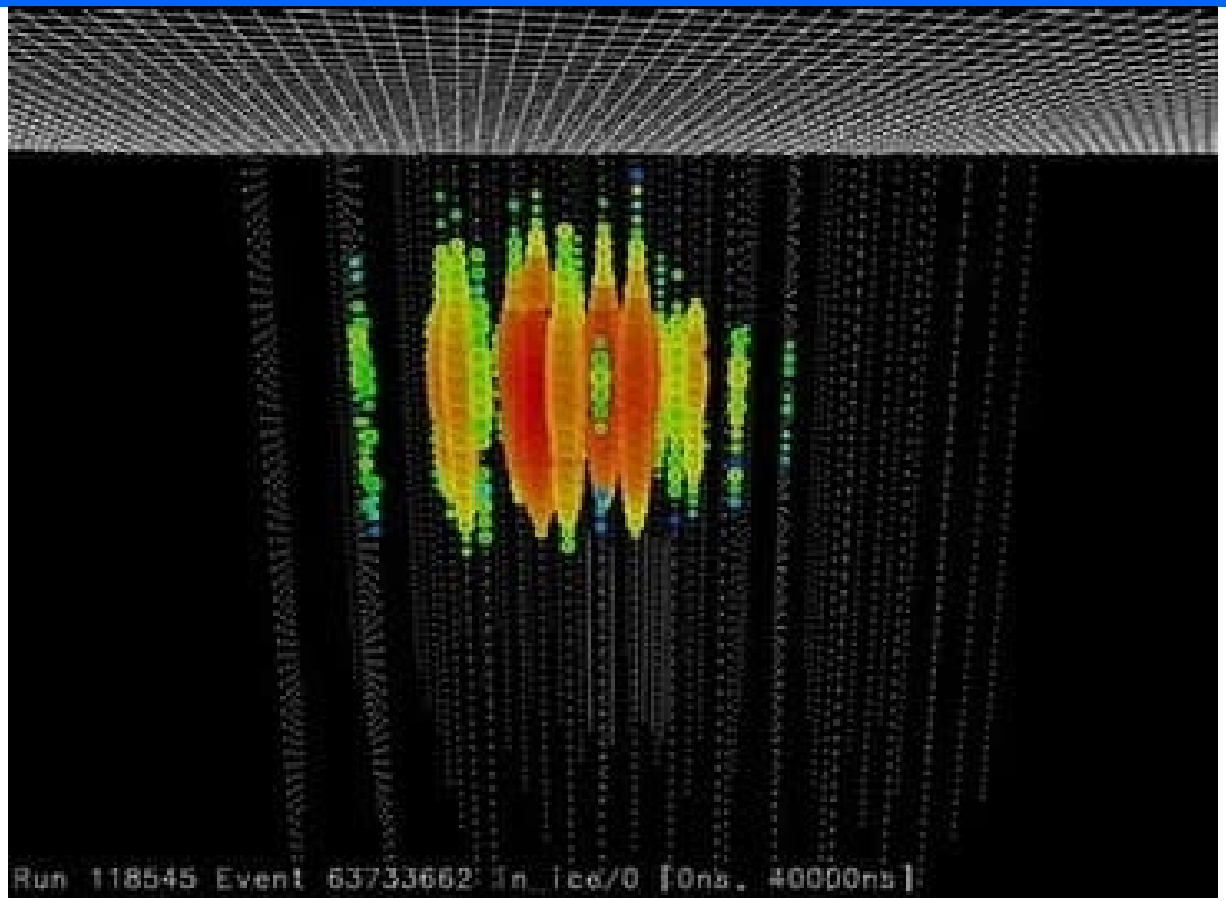
As a particle theorist in the 1980s, he started with the crazy idea of convincing people that it was worth lowering detectors on long cables into the Antarctic ice. It is only because of his great foresight and his unwavering persistence in bringing this idea to fruition that we can now see the cosmos in the light of neutrinos.



Francis Halzen Univ. Wisconsin-Madison



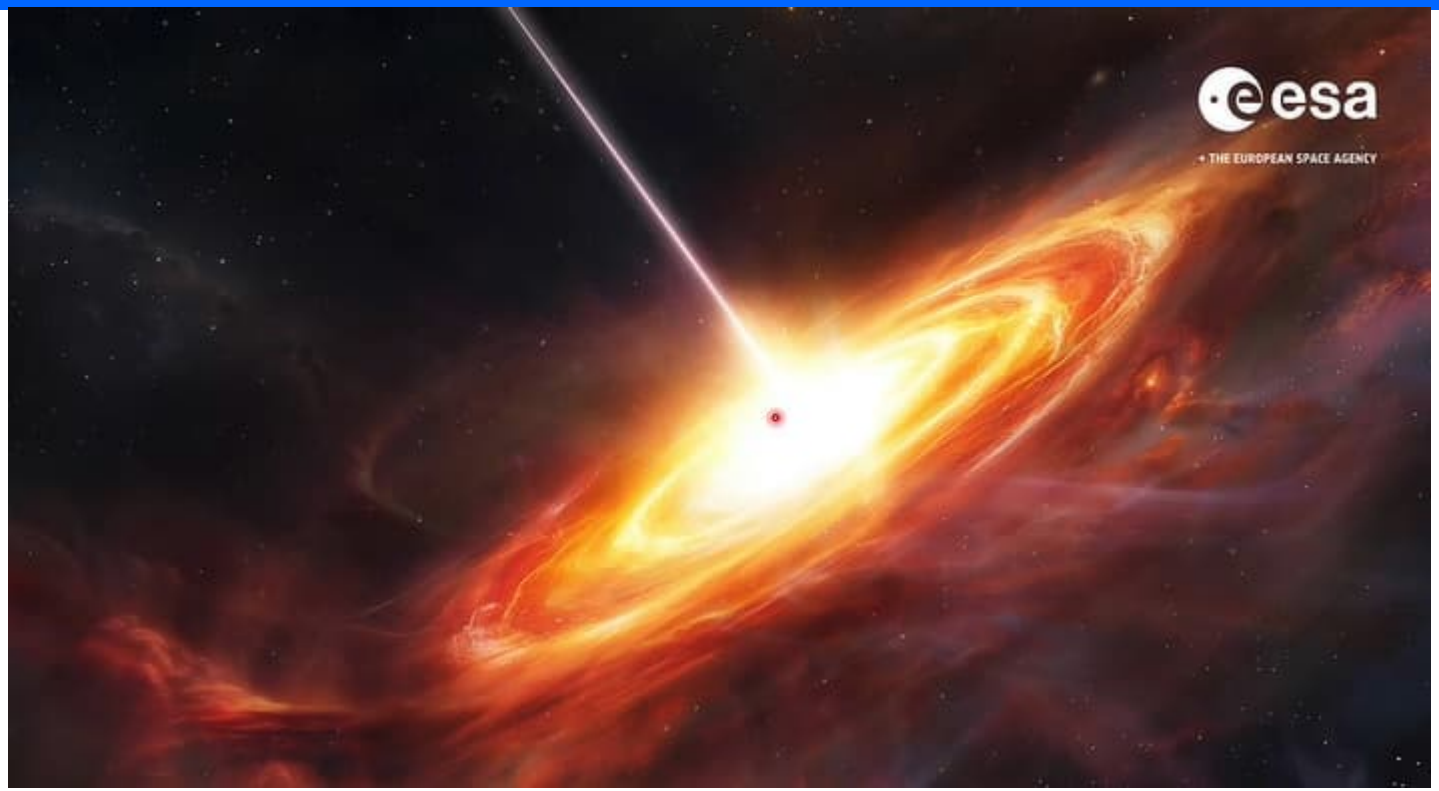
# High-energetic Neutrinos 2010-2013




- 28 events with energies between 30 and 1200 TeV

1 PeV = 1000 TeV = $10^{15}$ eV

# Cosmic Accelerators Blazar




$$p + p \rightarrow \pi^+ + X$$
$$\rightarrow \pi^- + X$$
$$\rightarrow \pi^0 + X$$

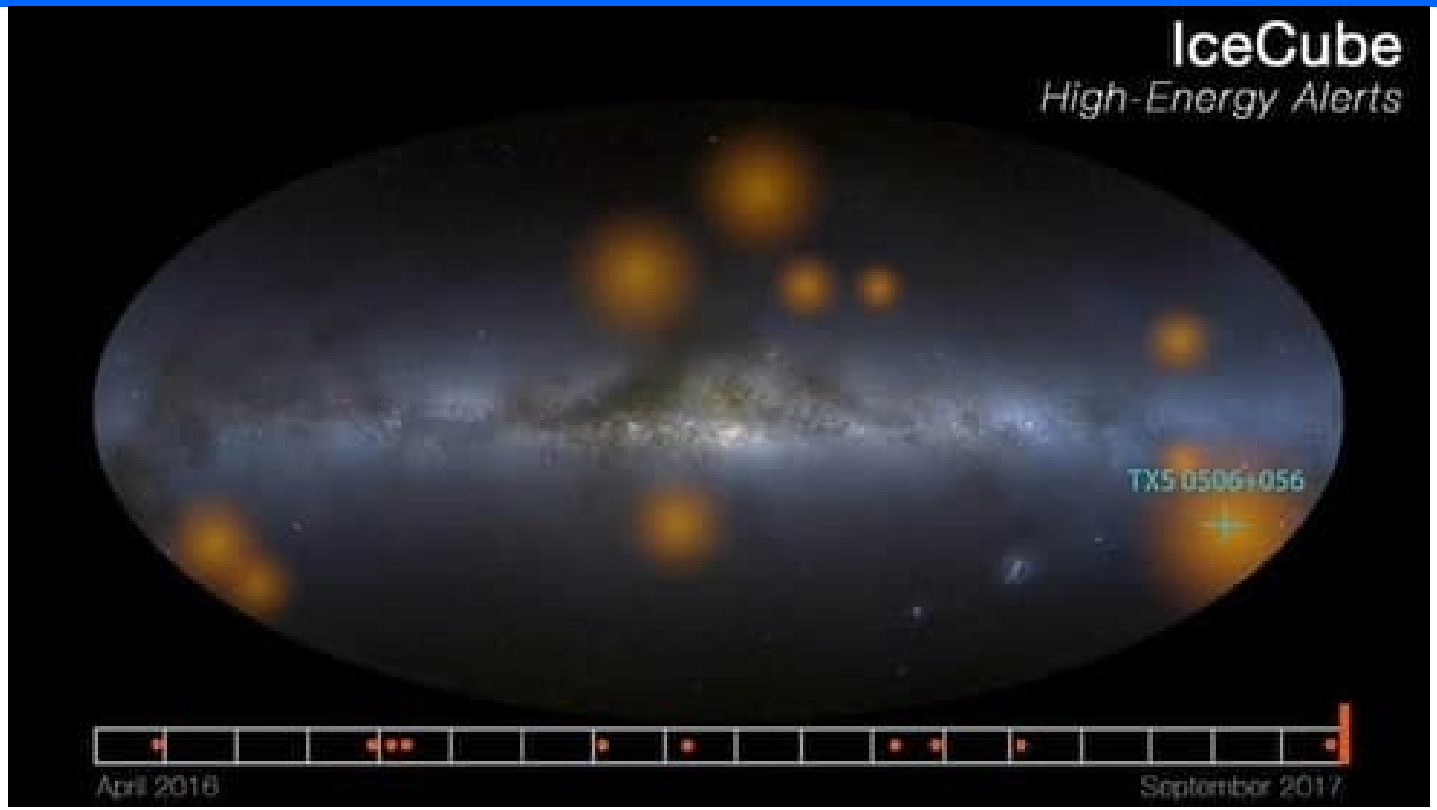
$$p + \gamma \rightarrow \pi^0 + p$$
$$\rightarrow \pi^+ + n$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^0 \rightarrow \gamma + \gamma$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

creation of neutrinos

# Milky Way Blazar TX5 0506+056



# Ghost particles – from space first muon

