About Neutrinos

QuarkNet lecture Summer 2018

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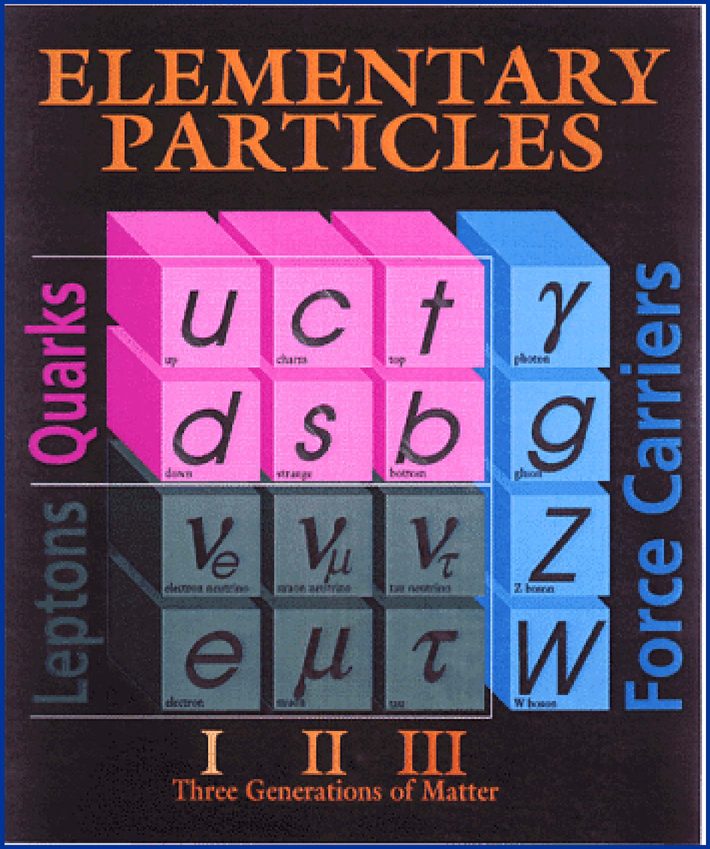
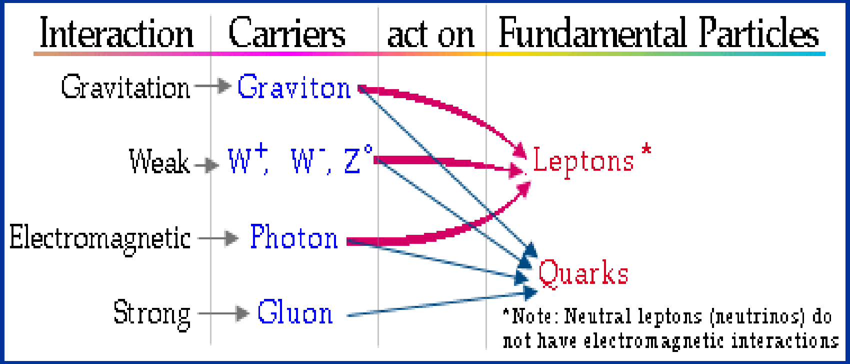
Outline

- Standard model of particle physics
- Neutrinos are everywhere
- What do we know about neutrinos now?
- How did we get to this point?
- Outlook

- Note: many slides stolen / adapted from many different websites, e.g.
  - Dirac Lectures at FSU 2016
  - CERN Summer Student lectures
  - Neutrino 2018 conference in Heidelberg

“Standard Model” of Particle Physics

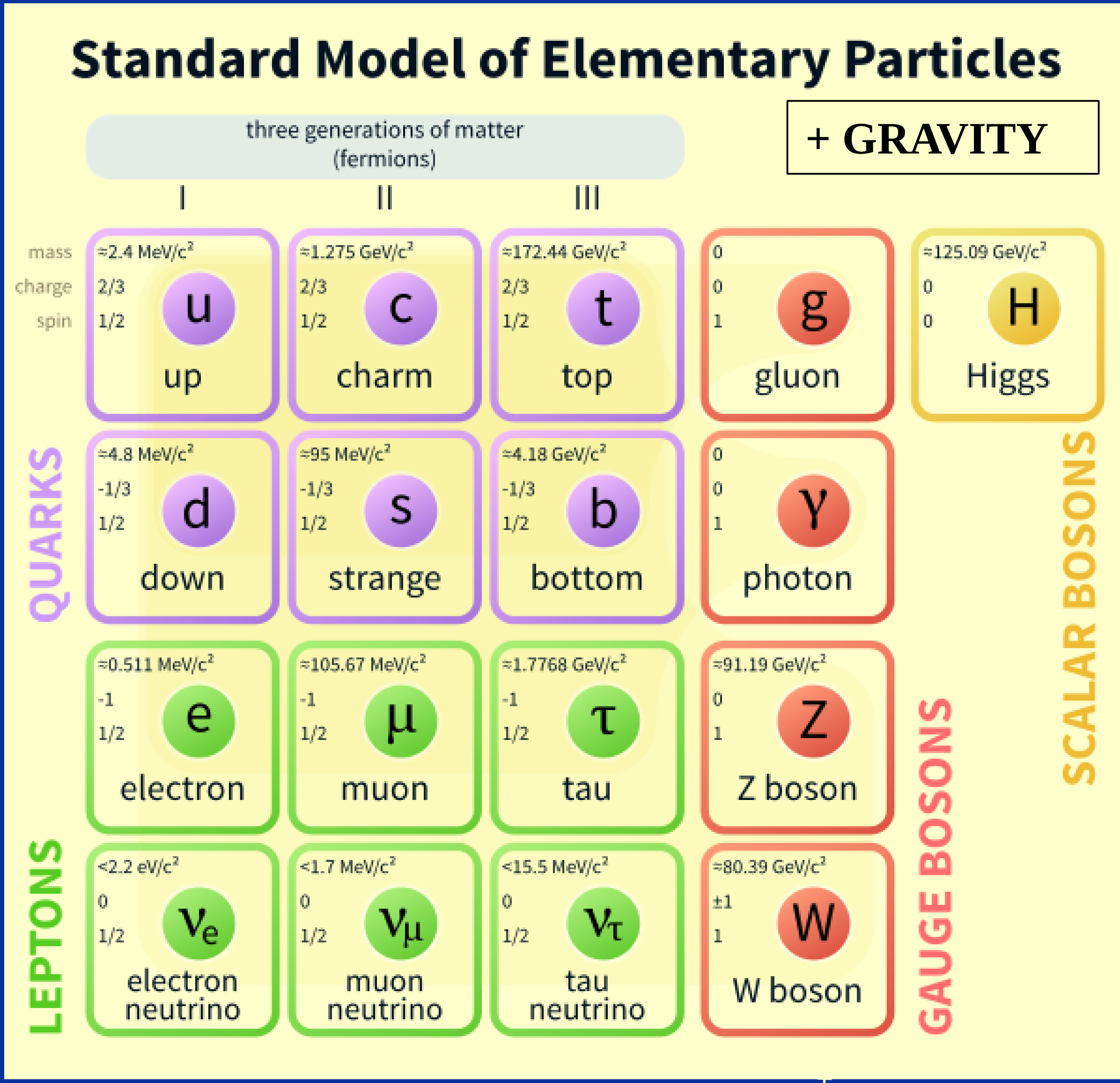




- A theoretical model of interactions of elementary particles, based on quantum field theory
- Symmetry:
  - SU(3) x SU(2) x U(1)
- Matter particles: fermions
  - Quarks: up, down, charm, strange, top, bottom
  - Leptons: electron, muon, tau, + their neutrinos
- Force particles
  - Gauge Bosons
    - o γ (electromagnetic force)
    - o $W^\pm$, Z (weak, electromagnetic)
    - o g gluons (strong force)
- Higgs boson
  - spontaneous symmetry breaking of SU(2)
  - mass

Our current understanding of ordinary matter

ANTI MATTER:
Every particle has an equivalent anti-particle.
Positron Emission Tomography (PET): e^+ e^- annihilation γ



- Neutrinos feel only the weak force (and gravity), are produced in some forms of radioactivity or in nuclear or particle reactions in the stars or at accelerators
- Original std model assumed them massless

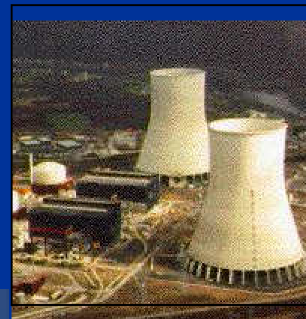
Three “flavors” of each particle.

Force Carriers

Neutrinos – why are they interesting?

- Neutrinos are everywhere:
  - at the Big Bang
  - from the Sun
  - from Cosmic Rays from Supernovas
  - from Nuclear Reactors
  - from Particle Accelerators
  - all around you
- For physicists:
  - Neutrinos provide clues for
    - Understanding weak interaction
    - understanding stars
    - understanding supernovae
    - Understanding the early universe
    - Maybe clue to matter-antimatter asymmetry?

Where do Neutrinos Appear in Nature?

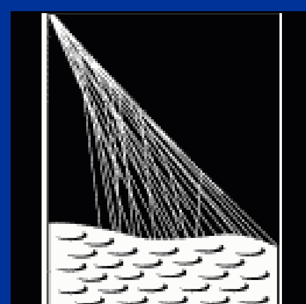


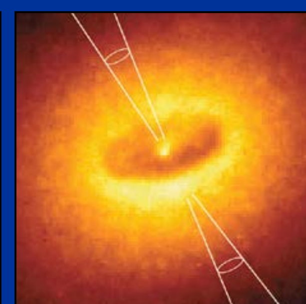
✓ Nuclear Reactors

Sun ✓

✓ Particle Accelerators

Supernovae
(Stellar Collapse)
SN 1987A ✓





✓ Earth Atmosphere
(Cosmic Rays)

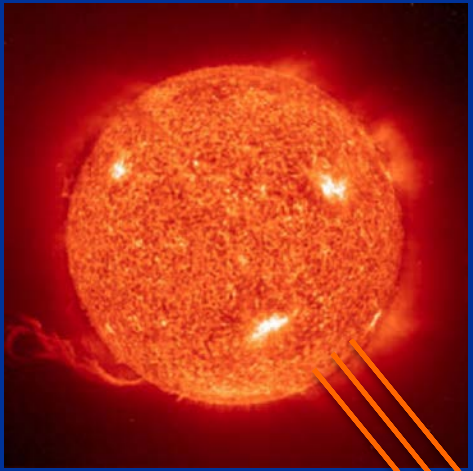
Astrophysical Accelerators
Seen?

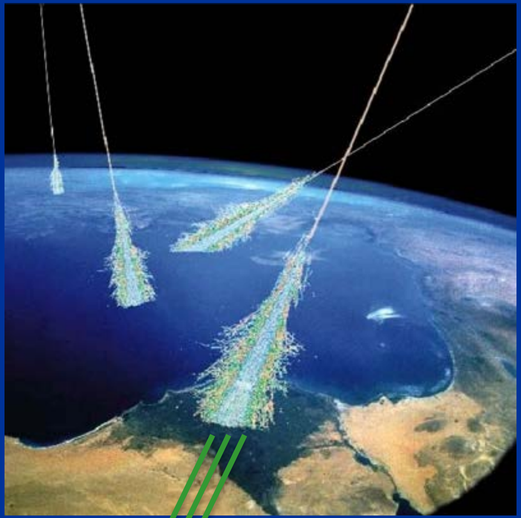
✓ Earth Crust
(Natural
Radioactivity)

Cosmic Big Bang
Indirect Evidence

Ubiquitous Neutrinos

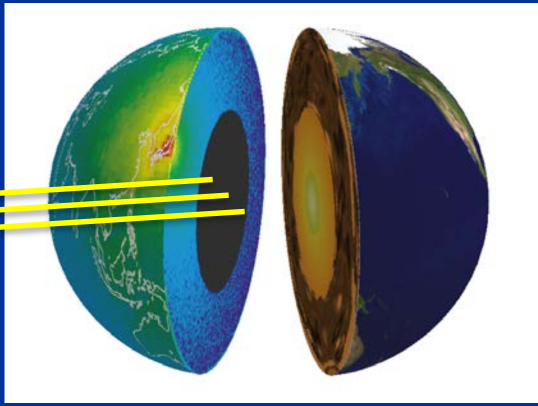
They are everywhere…





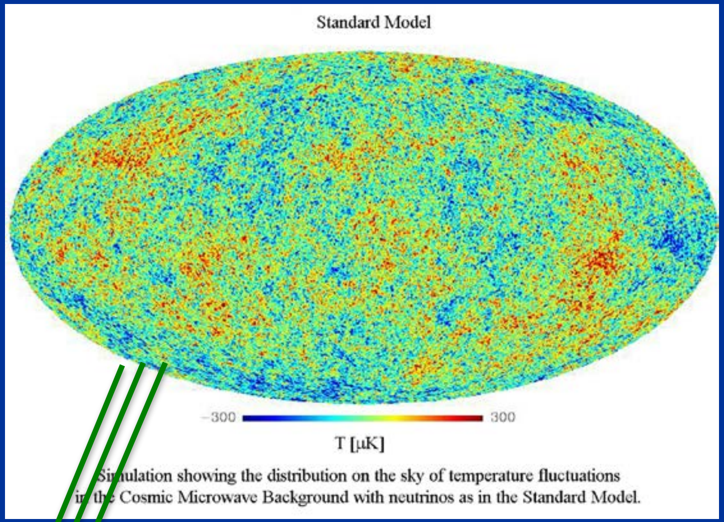
Atmosphere: ~20/second

Sun: 5 x 10^{12}/second



Earth: ~10^9/second

Ubiquitous Neutrinos



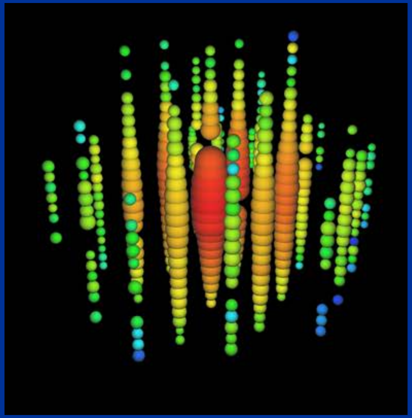
Big Bang: ~2 x 10^{12}/second

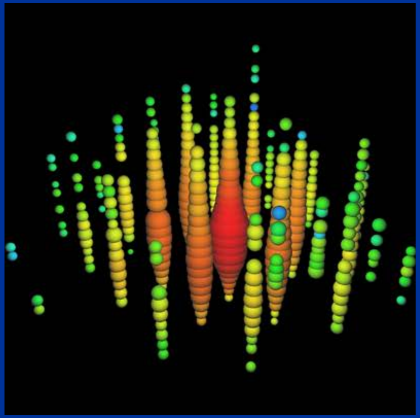
Supernova 1987: ~10^{12}/second

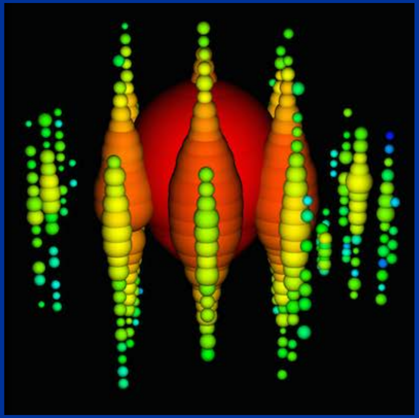
@168000 Light years!
10^8 times farther from Earth than the Sun

Ubiquitous Neutrinos

PeV neutrinos from still unknown sources…





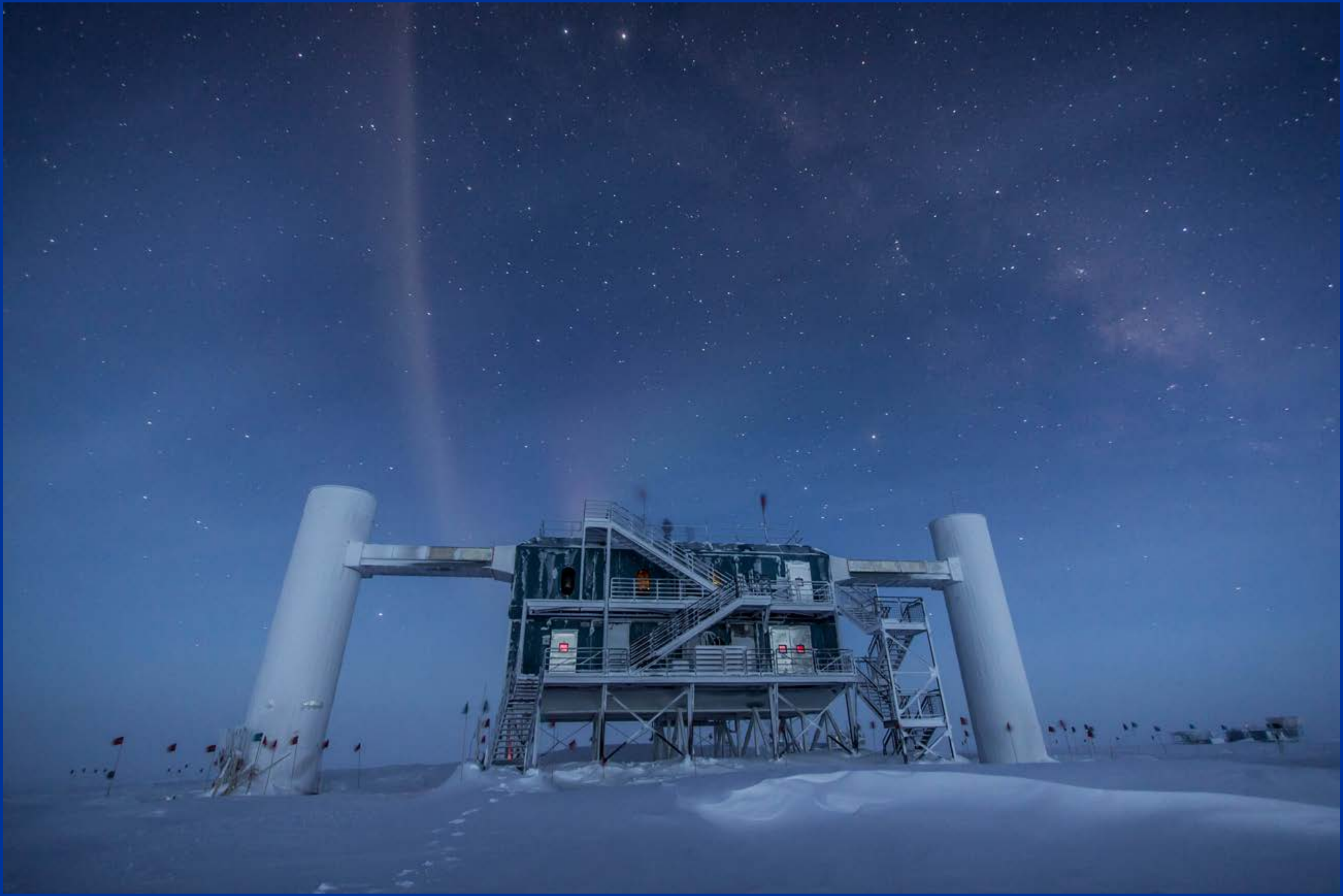


Icecube

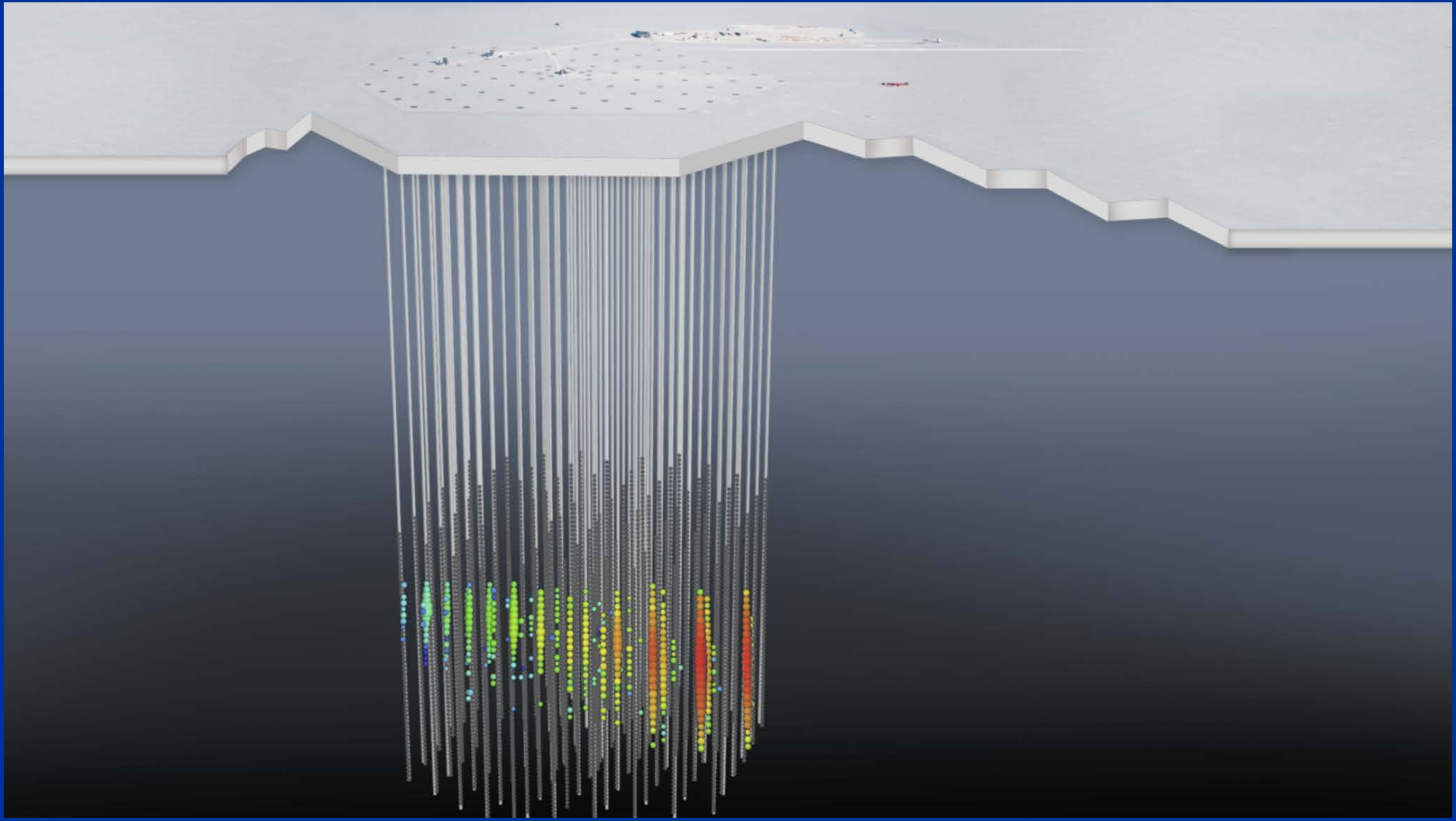
ICE CUBE

IceCube Neutrino Observatory beneath the Aurora australis (Southern Lights)

Ice Cube

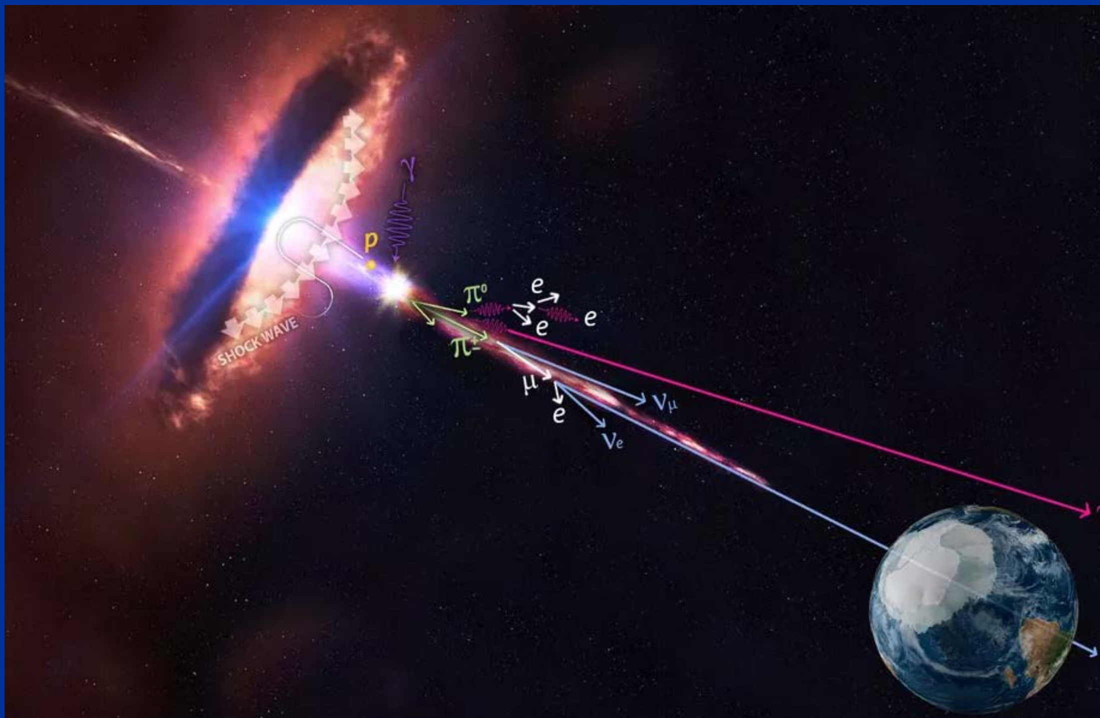


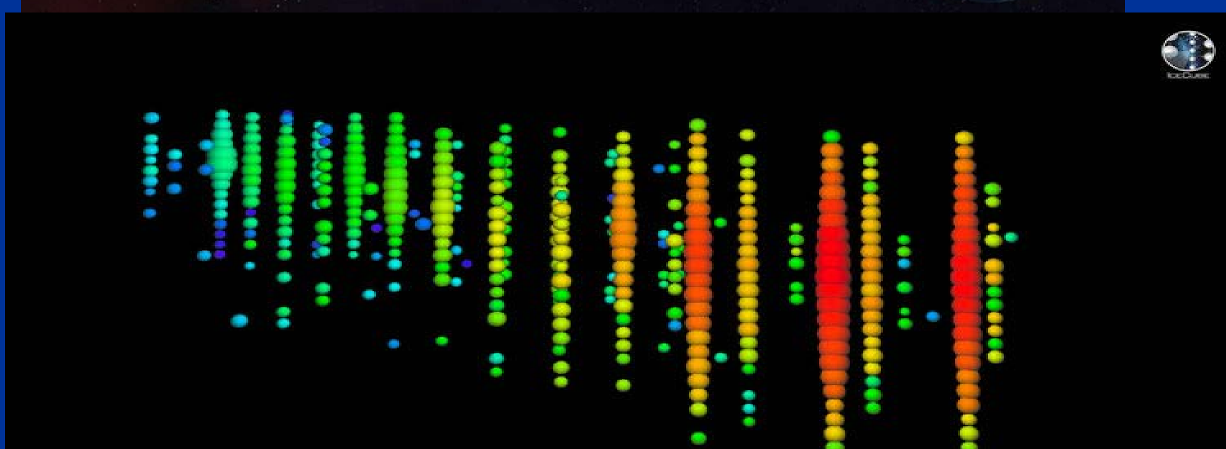
Neutrino event in Ice Cube



Ice Cube: 1km^3 of ice with photomultipliers embedded in the ice
https://icecube.wisc.edu/

High energy neutrino from a Blazar?

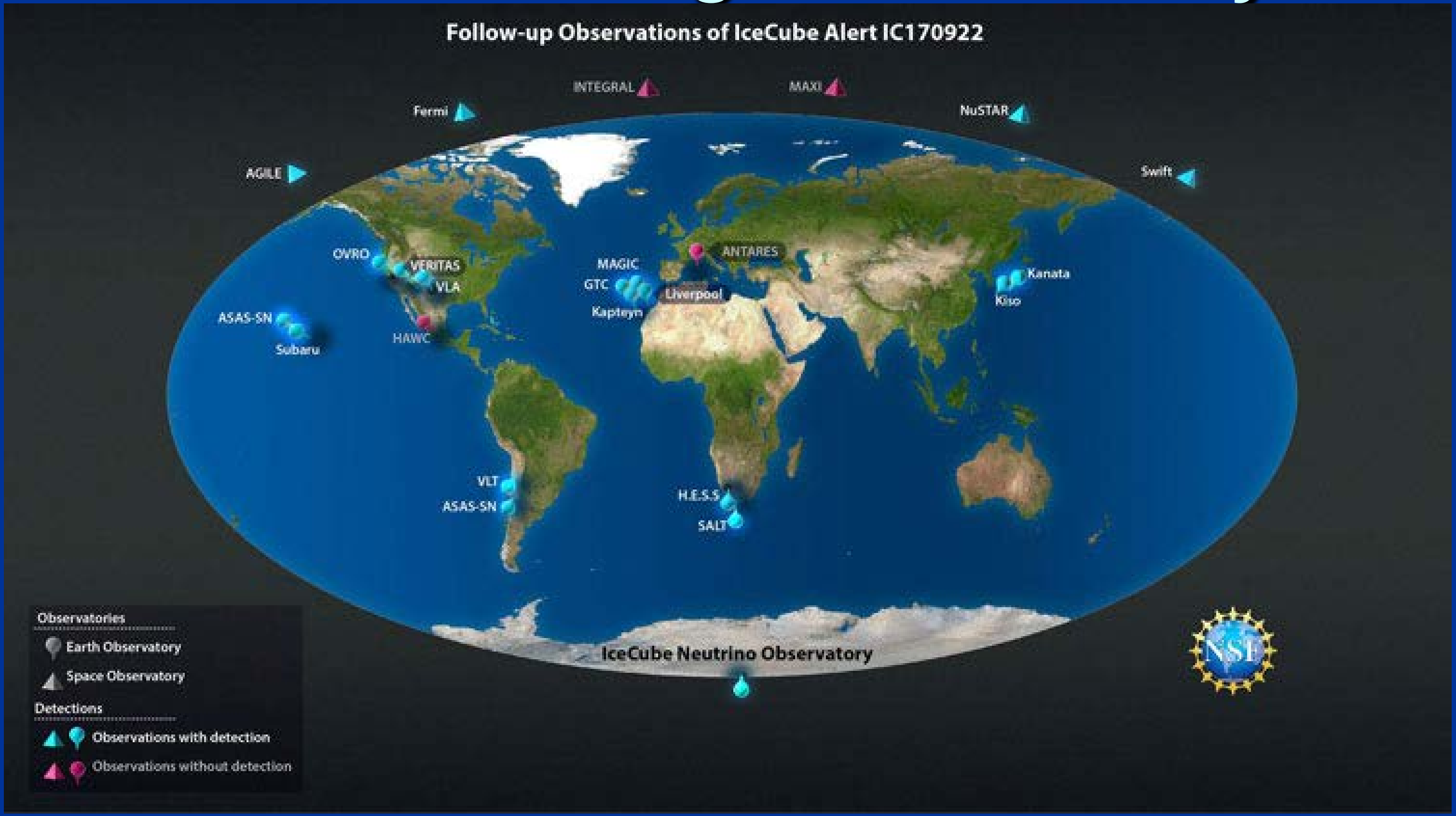




* blazar = giant elliptical galaxy with a massive, rapidly spinning black hole at its core.
* twin jets of light and elementary particles emitted from the poles along the axis of the black hole’s rotation.
* blazar TXS 0506+056 is situated in the night sky just off the left shoulder of the constellation Orion and is about 4 billion light years from Earth.

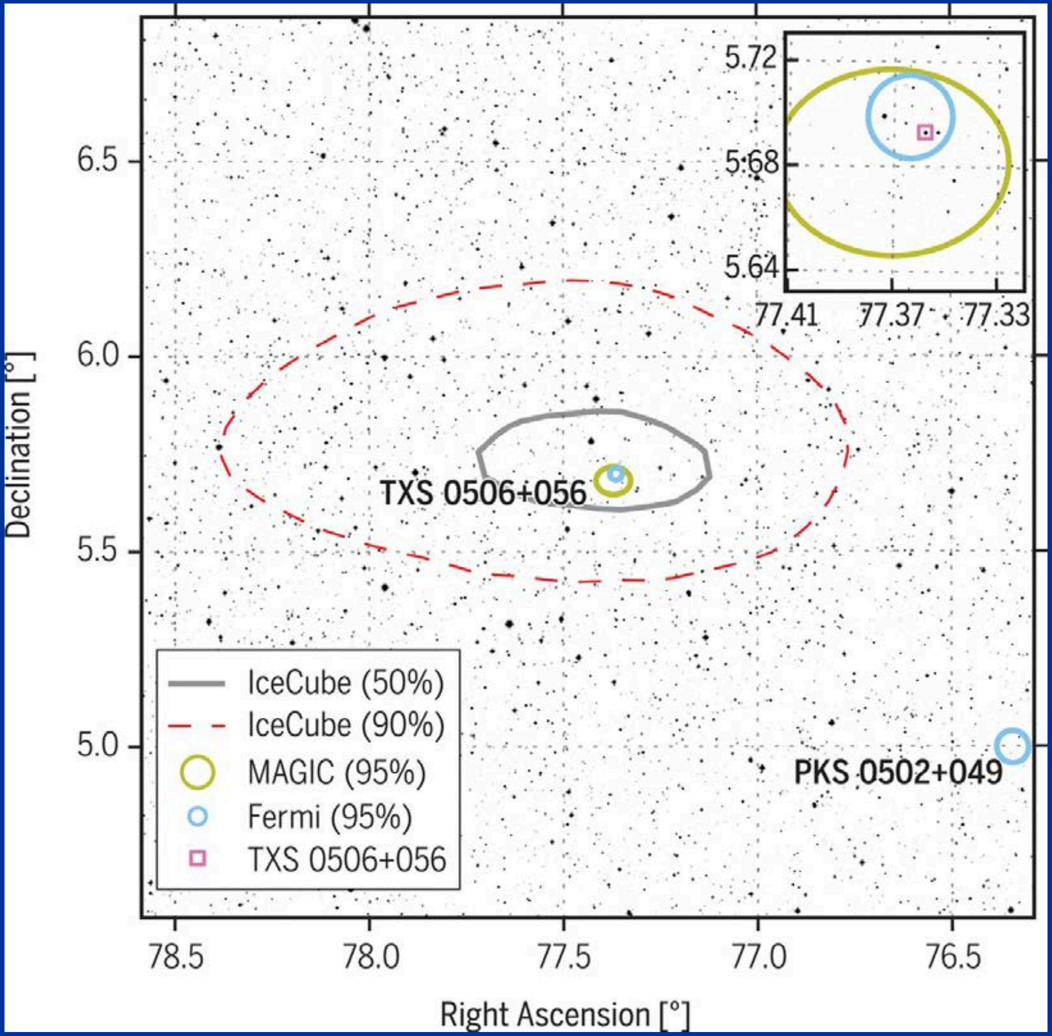
https://icecube.wisc.edu/news/view/586

“Multi-messenger astronomy”



http://science.sciencemag.org/content/361/6398/eaat1378

Multimessenger observations of blazar TXS 0506+056.

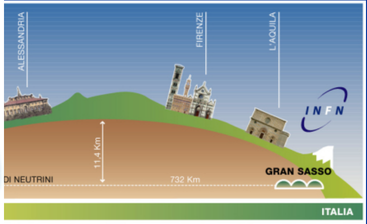


Multimessenger observations of blazar TXS 0506+056.
The 50% and 90% containment regions for the neutrino IceCube-170922A (dashed red and solid gray contours, respectively), overlain on a V-band optical image of the sky. Gamma-ray sources in this region previously detected with the Fermi spacecraft are shown as blue circles, with sizes representing their 95% positional uncertainty and labeled with the source names. The IceCube neutrino is coincident with the blazar TXS 0506+056, whose optical position is shown by the pink square. The yellow circle shows the 95% positional uncertainty of very-high-energy γ-rays detected by the MAGIC telescopes during the follow-up campaign. The inset shows a magnified view of the region around TXS 0506+056 on an R-band optical image of the sky.

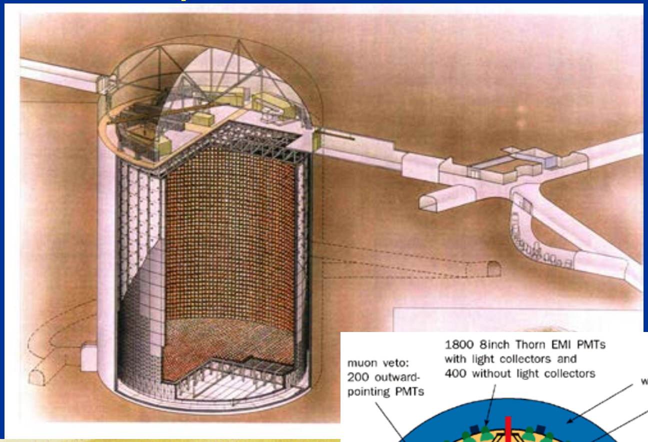
The IceCube Collaboration et al. Science 2018;361:eaat1378

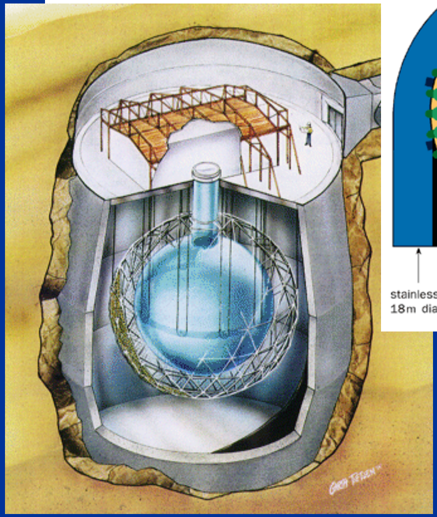
Using many of these natural sources, as well as others man-made, decades of revolutionary neutrino experiments have demonstrated that neutrinos are not quite standard,
because they have a tiny mass & massive neutrinos require new dofs!

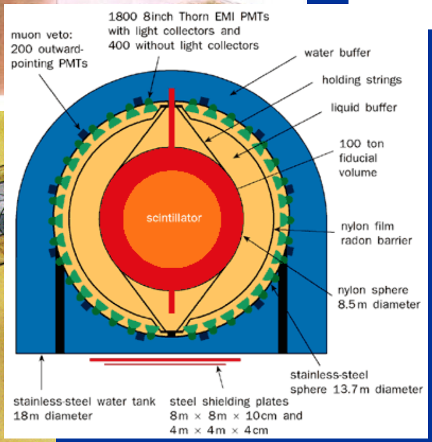
MINOS, Opera



SuperKamiokande



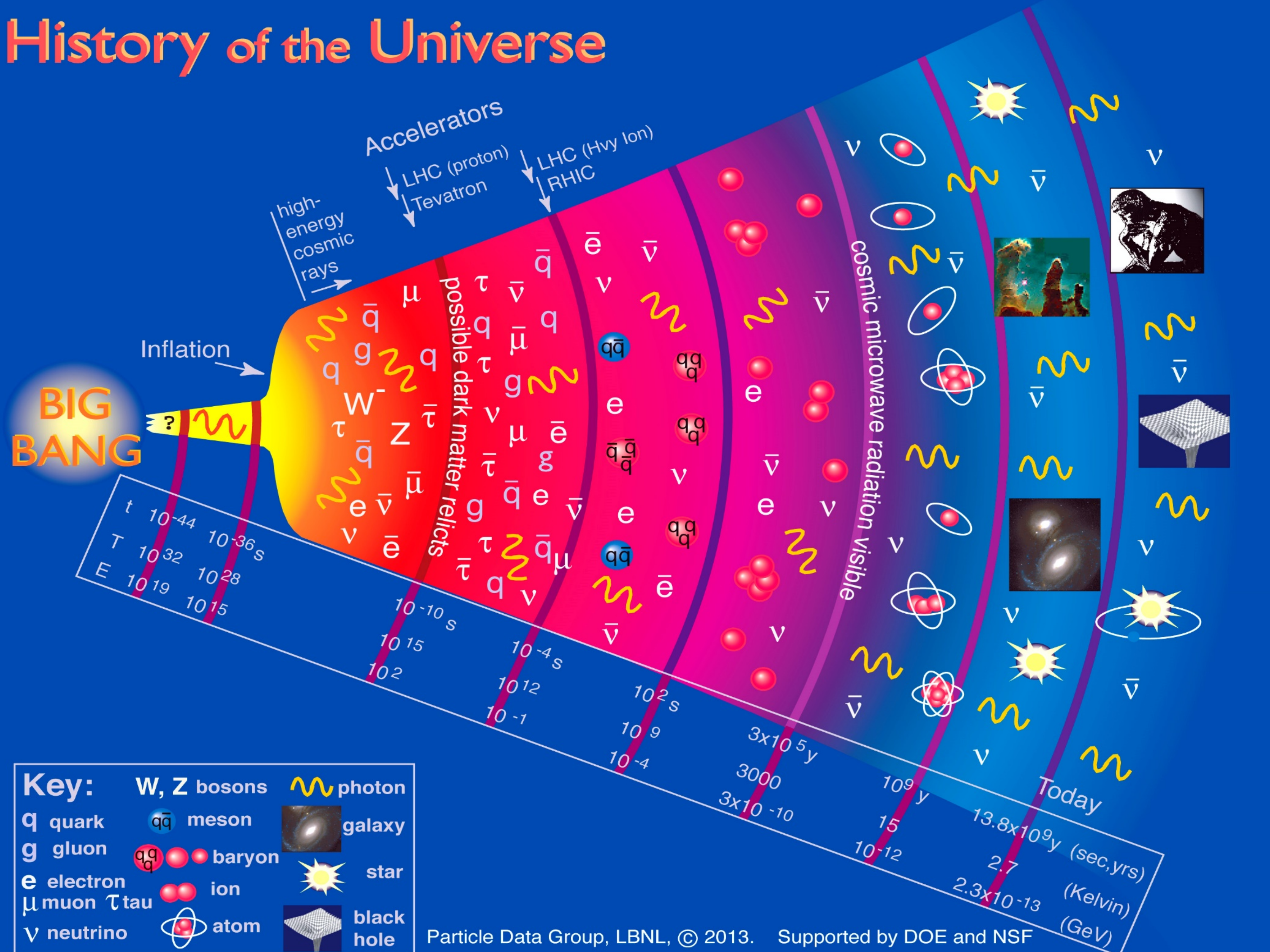




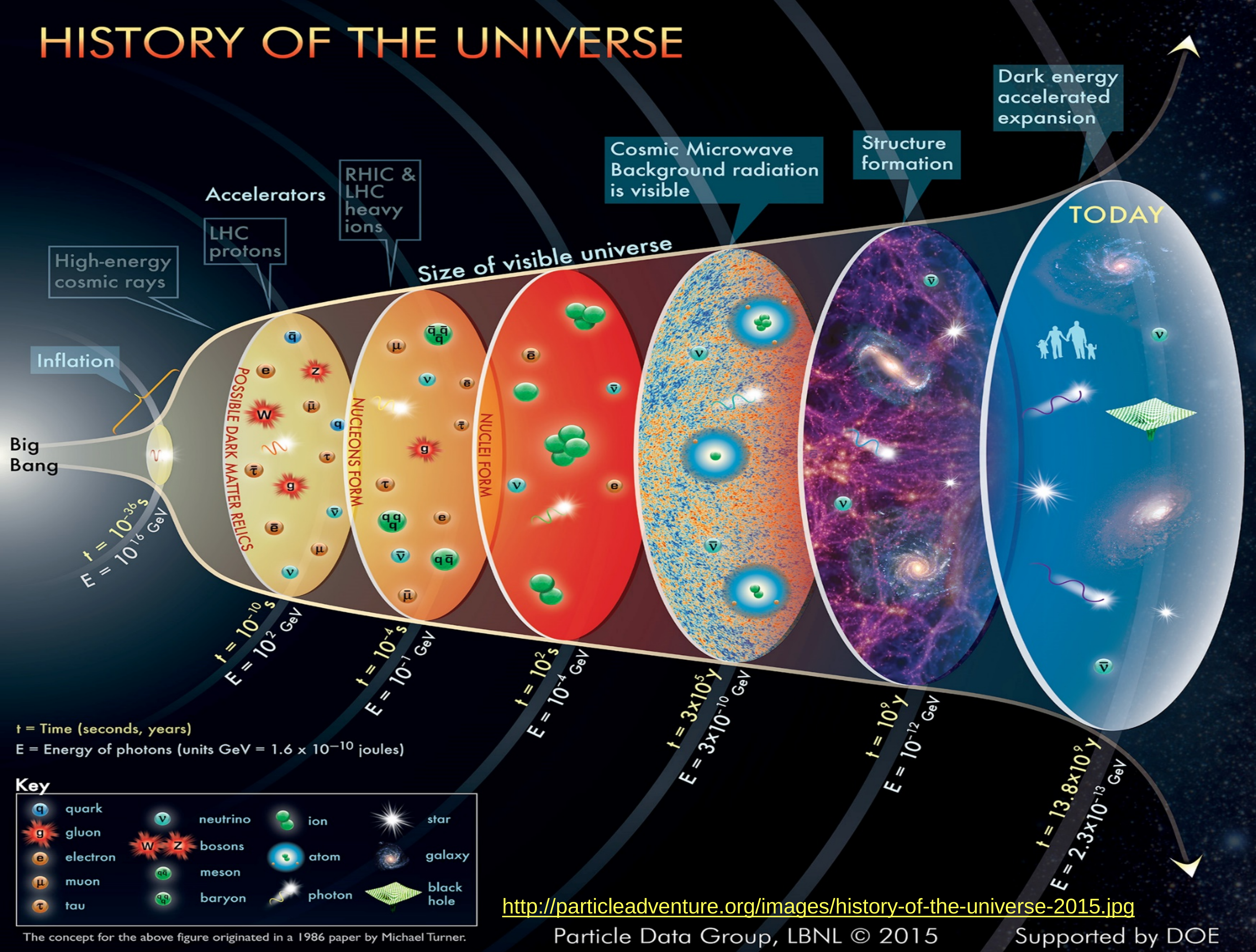
Borexino

SNO

...and more



http://particleadventure.org/images/history-universe-2013.jpg



http://particleadventure.org/images/history-of-the-universe-2015.jpg

What do we know about neutrinos now

- Neutrinos are "fundamental" constituents of matter (i.e. to the best of our knowledge, they have no substructure)
- Come in 3 "flavors" (electron ν_e, mu ν_μ, tau ν_τ)
- Feel only weak interaction $\Rightarrow$ difficult to detect
- Neutrino experiments during the last 50 years (accelerated during last 10 years) showed "neutrino oscillation" $\Rightarrow$
  - Neutrinos have very small but non-zero mass (in original standard model, assumed mass=0)
  - They "oscillate", i.e. different flavors can turn into each other
  - Neutrinos of a given flavor do not have a well-defined mass – "flavor eigenstates" $\neq$ "mass eigenstates"

Neutrino oscillations

- When a neutrino of a given flavor is created in an interaction (at time 0 of its life), it has a well-defined flavor (determined by the production process), but is a superposition of mass eigenstates.
- Mass eigenstates “evolve” in time (oscillate) with a frequency $\propto$ to their mass
- If masses are different $\Rightarrow$ relative sizes of amplitudes of mass eigenstates in the mix change $\Rightarrow$ the neutrino is not a well-defined flavor state anymore, but a superposition of flavor states
- When you measure its flavor, i.e. force it to “fess up” by making it interact at some time later, it has a calculable probability of showing up as a different flavor from its initial one

Neutrino Mixing

States produced in a CC interaction in combination with e, μ, τ

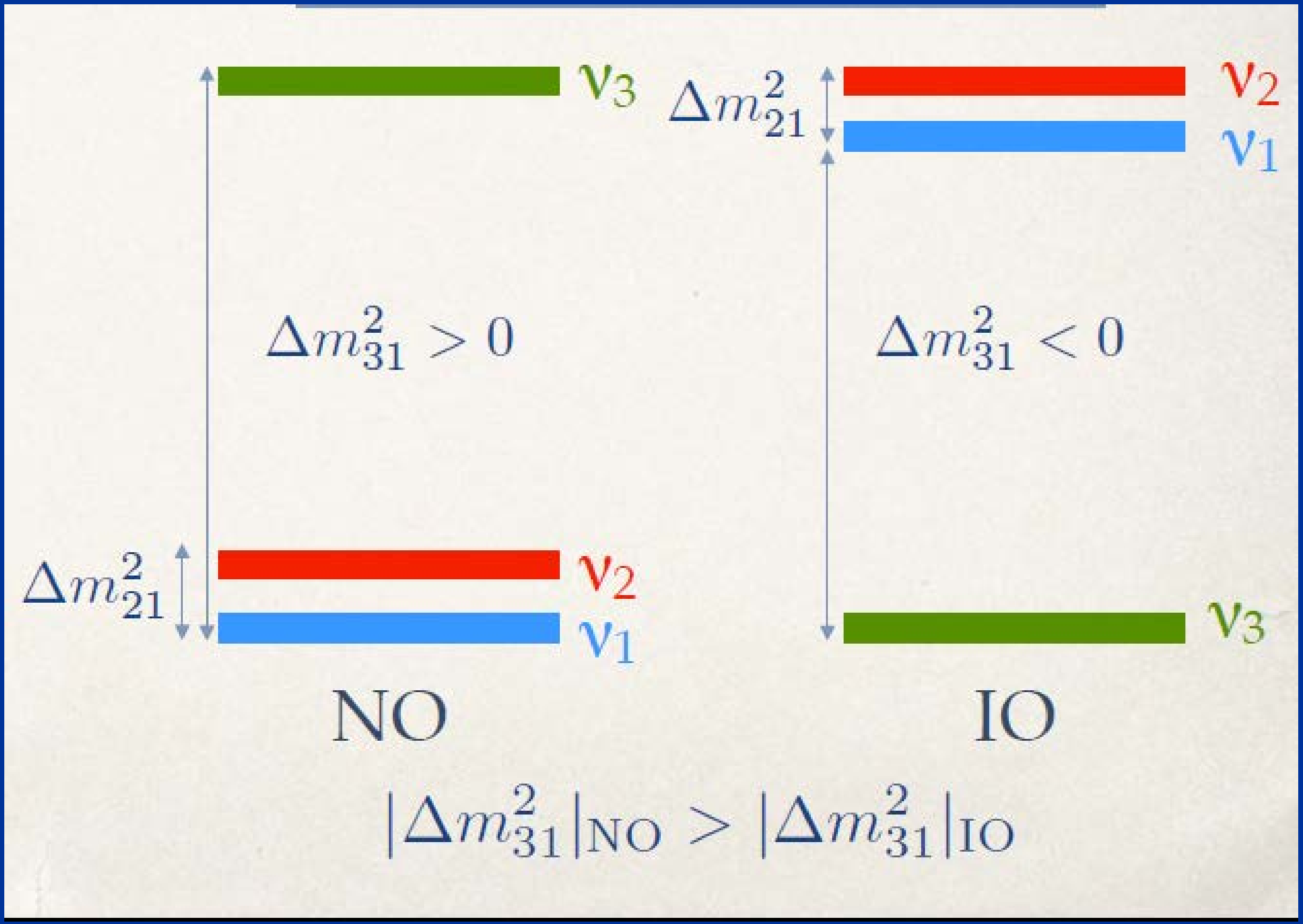
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Eigenstates of the free Hamiltonian

- The “Flavor eigenstates” are not the same as the mass eigenstates;
- Flavor eigenstates are q.m. superposition of mass eigenstates
- U_{PMNS} = “Pontecorvo-Maki-Nakagawa-Sakata” matrix
- U = “unitary” matrix, i.e. kind of rotation in 3-dimensional complex space

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Mass hierarchy



- NO = “normal order”, IO=“inverted order”
- Present data indicate preference for NO

Global fit to neutrino oscillations

https://globalfit.astroparticles.es/

parameter	best fit $\pm$ 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

deSalas et al, 1708.01186 (May 2018)

Neutrino oscillation parameters 2018

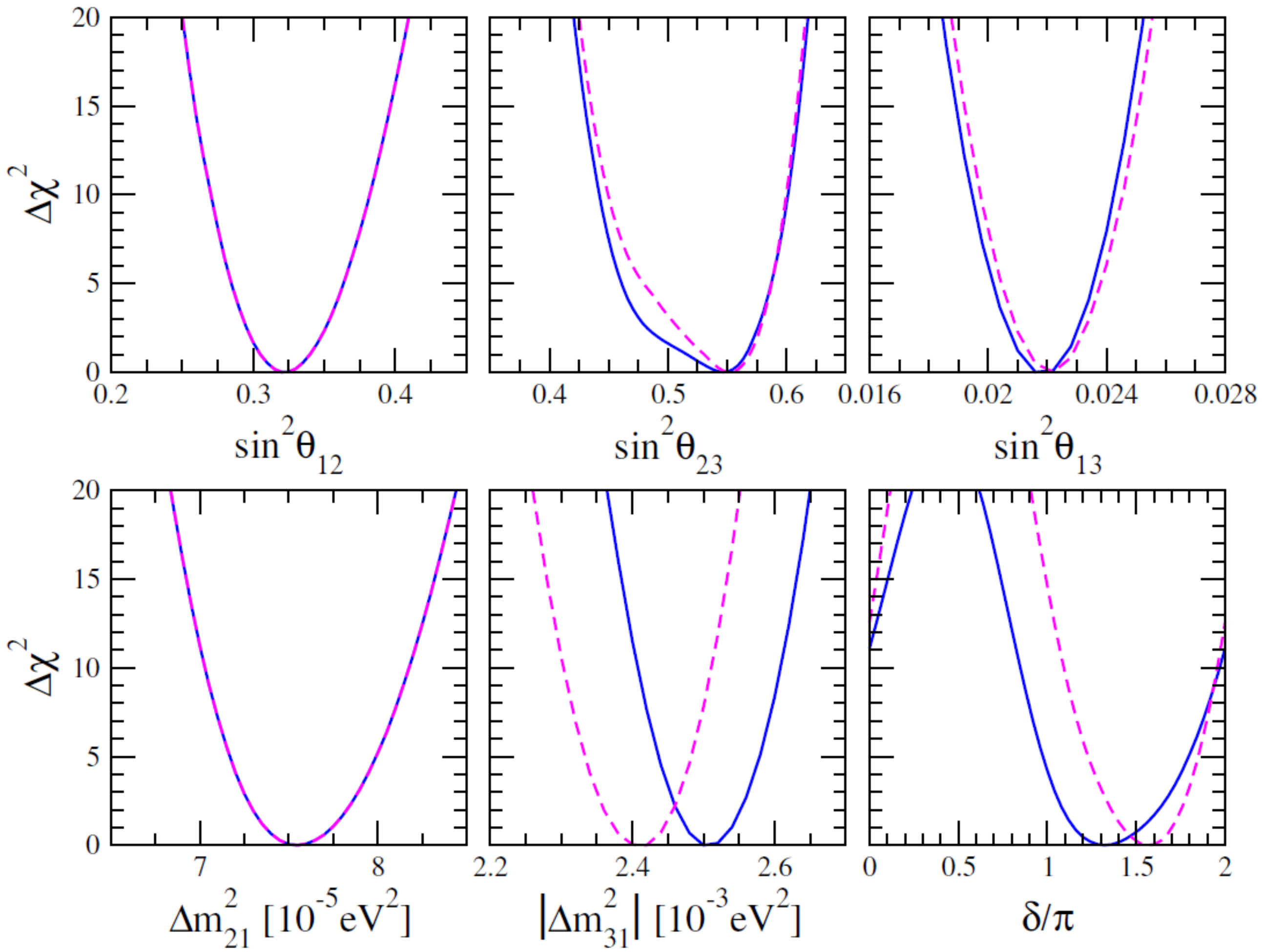


FIG. 7: Summary of neutrino oscillation parameters, 2018. Blue (solid) lines correspond to NO and magenta (dashed) lines to IO. Notice that the $\Delta\chi^2$–profiles for inverted ordering are plotted with respect to the minimum for this neutrino mass ordering.

From P.F. de Salas et al., Arxiv hep 1708.01186

SM+3 massive neutrinos: Global Fits

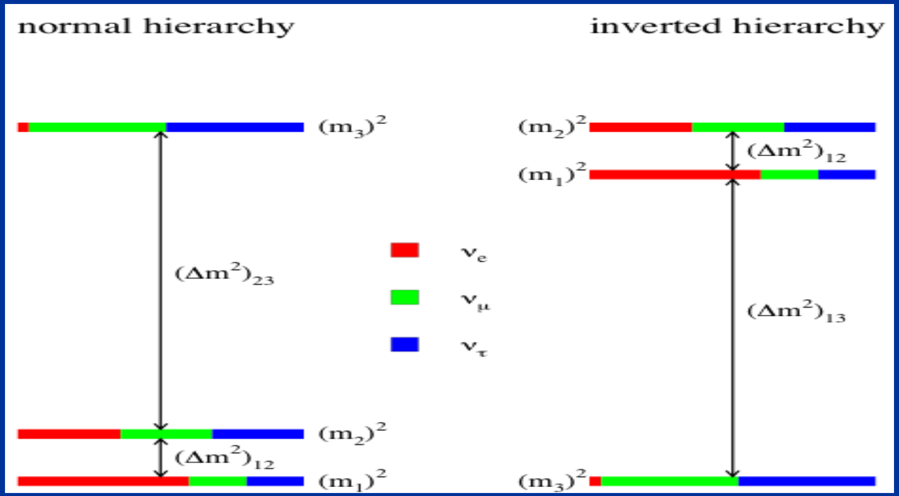
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12},\theta_{23},\theta_{13},\delta,..)\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{12} \sim 34^o,$

$\theta_{23} \sim 42^o \quad \text{or} \quad 48^o$

$\theta_{13} \sim 8.5^0,$

$\delta \sim ?$



$\Delta m^2_{12} \sim 7.5\times10^{-5} eV^2$

$\Delta m^2_{13} \sim 2.5\times10^{-3} eV^2$

Summary

- Current status of three-neutrino oscillation parameters:
  - very precise and robust determinations for most of them (1.3-10%)
  - preference for normal mass ordering
  - preference for $\pi < \delta < 2\pi$ with CP conservation allowed at 2σ

- Expectations of future measurements:
  - oscillation parameters will be measured with precision 0.6-3%
  - 2-3σ sensitivity to CP violation at NOvA and T2K-II
  - 3σ sensitivity to mass ordering from reactor, accelerator and nu-telescopes
- Expect big step forward in improvement from new experiments DUNE, Hyper-Kamiokande,…

How did we get there?

- beta decay puzzle (1915 – 1930)
- new neutral particle proposed (Pauli 1930)
- beta decay theory, “neutrino” (Fermi 1934)
- How to detect them? Hopeless?
- Pontecorvo: maybe not: reactors (1946)
- Reines and Cowan (1950-1951) ν detection
- muon neutrino (1962)
- 3rd lepton (1975)
- limit on number of neutrinos (1987, 1997)
- Neutrino properties
    - weak interaction
    - Helicity and mass

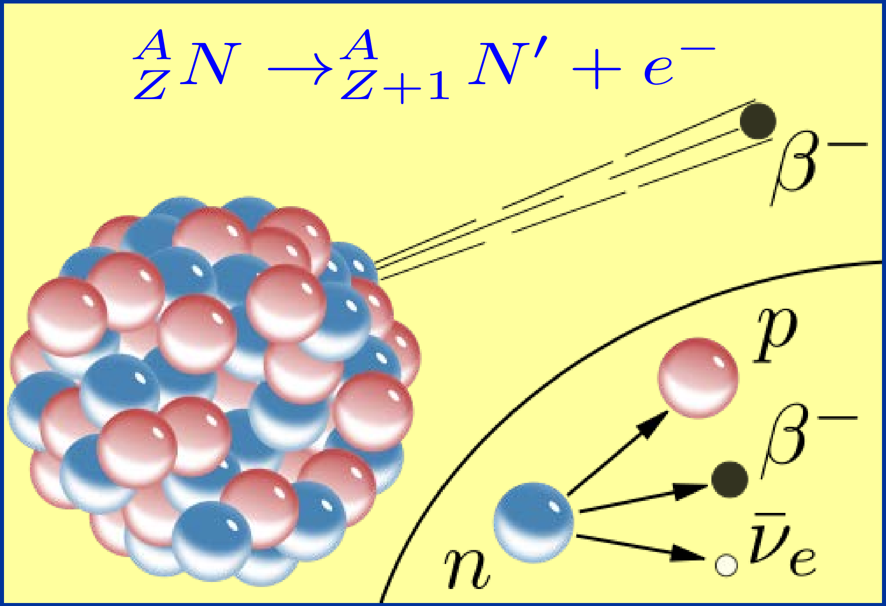
How did we get there? (2)

- Sources of neutrinos
- Neutrinos from the Sun
- Interlude on nuclear physics
- Neutrino puzzles
- Fusion processes in the Sun
- Standard solar model (Bahcall)
- Detection of solar neutrinos – Ray Davis (1968 – 1995)
- Kamiokande
- Neutrino oscillations
- Experimental evidence: Super-K, SNO
- Open questions

Neutrino: the dark particle

1900 Radioactivity: Becquerel, M & P Curie, Rutherford….

β decay



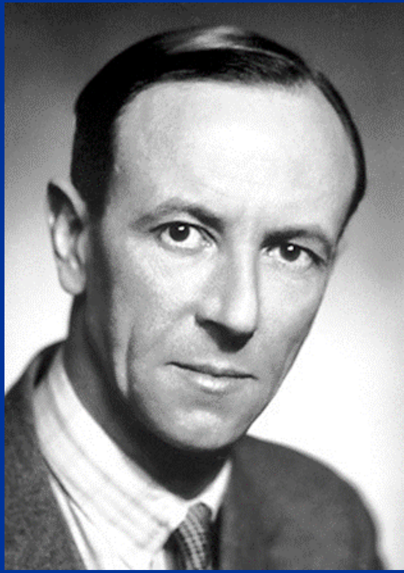
Before Pauli, Fermi

After

Energy-momentum conservation $\Rightarrow$ expect

$$E_{electron} = (M_N - M_{N'})c^2 = Q = const$$

Beta decay puzzle



- Three-types of radioactivity: α, β, γ
- Both α, γ discrete spectrum because

$$E_{\alpha,\gamma} = E_i - E_f$$

- James Chadwick’s (U. Manchester) studies of β decay (1914)

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

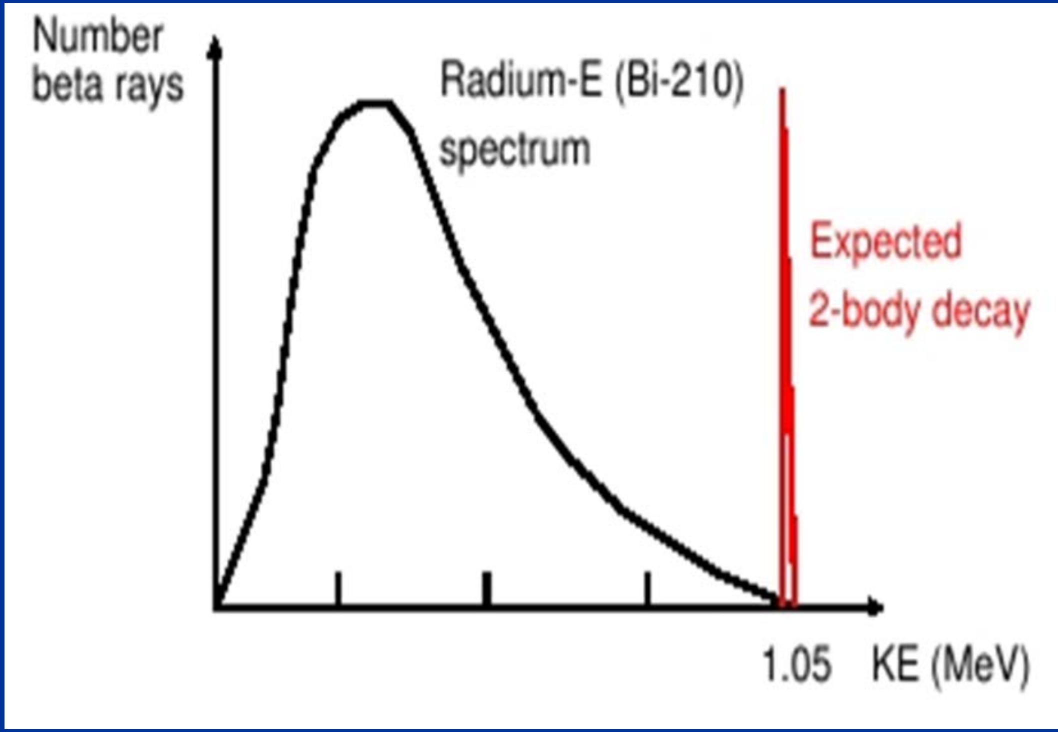
  - Observation: energy spectrum of electrons continuous — violate energy conservation???
  - Speculation: some unobserved radiation emitted in addition

- Ellis and Wooster (1927): study decay $^{210}Bi \rightarrow {}^{210}Po + e^-$
  - measure the total energy deposited in a thick target
  - Find: average deposited energy = 0.337 MeV per decay
  - but nuclear mass difference = 1.05 MeV $\Rightarrow$ missing energy!!!

http://www.nobelprize.org/nobel_prizes/physics/laureates/1935/chadwick-bio.html
http://web.calstatela.edu/faculty/kaniol/f2000_lect_nuclphys/lect1/betadecay_queens_hist.htm

Beta spectrum

- Beta spectrum continuous
- Also problem with angular momentum conservation:
  - Parent and daughter nucleus had integer spin, but electron carried spin ½



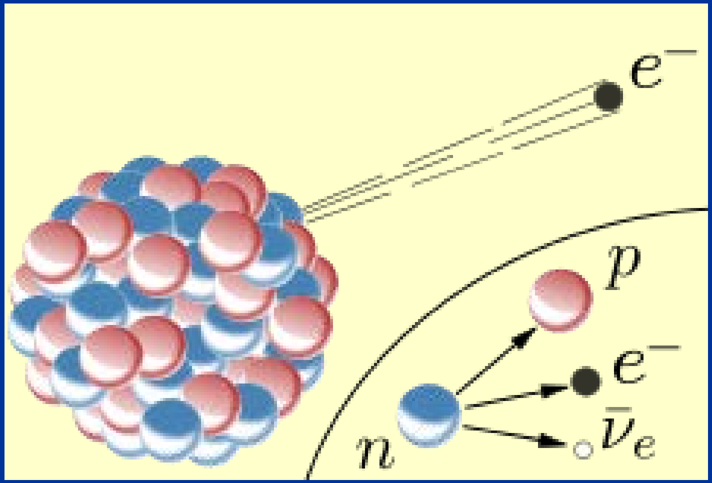
Niels Bohr:
“At the present stage of atomic theory we have no arguments for upholding the concept of energy balance in the case of β-ray disintegrations.”

Wolfgang Pauli:
“Desperate remedy.....”
“I do not dare publish this idea....”
“I admit my way out may look improbable....”
“Weigh it and pass sentence....”

“You tell them. I'm off to a party”

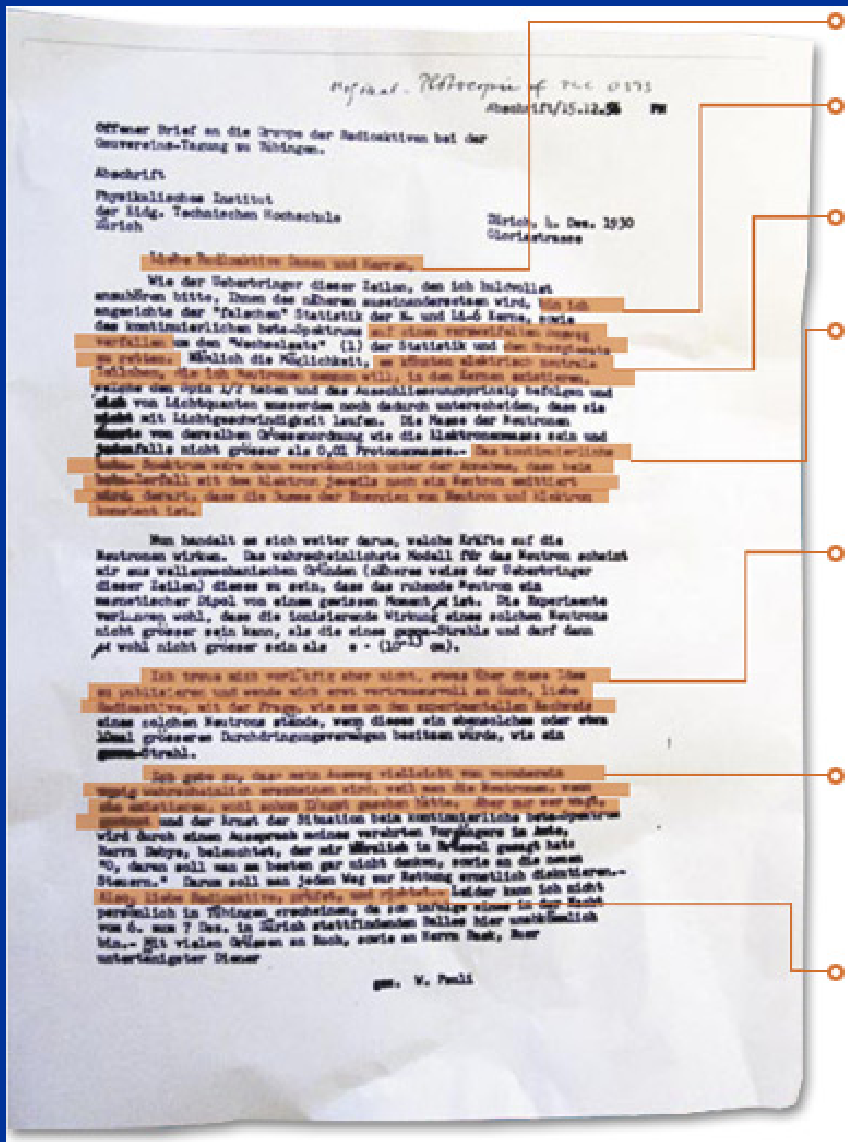
Pauli's solution to part of the puzzle

Suppose that beta decay were a 3 body process, with an additional invisible particle
new particle would have to be:
  * Neutral
  * Very light or massless
  * have only rare interactions



Pauli: letter to a Physical Society meeting in Tübingen:
"Dear Radioactive Ladies and Gentlemen..."
postulated the invisible neutrino

Pauli's neutrino letter



- *Dear Radioactive Ladies and Gentlemen!*
- *I have hit upon a desperate remedy to save…the law of conservation of energy.*
- *…there could exist electrically neutral particles, which I will call neutrons, in the nuclei…*
- *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.*
- *But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive ones, with the question of how likely it is to find experimental evidence for such a neutron…*
- *I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained…*
- *Thus, dear radioactive ones, scrutinize and judge.*

http://www.symmetrymagazine.org/cms/?pid=1000450

Desperate Idea of Pauli

4th December 1930

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, how 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" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which 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 masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

Pauli's "desperate" attempt to save appearances

- Hypothesis of Pauli (1930):
  - Tried to explain puzzle of decay $^{14}Ca \rightarrow {}^{14}N + e^-$
    - Missing energy and wrong spin of ^{14}N
  - an unobserved neutral, spin-1/2 "neutron" accounts for the apparent anomaly -- a new particle with mass < 1% that of the proton (later called neutrino by Fermi)
  - Initial thought:
    - neutrino Is a stable constituent of the nucleus
    - Suggested by the spin puzzle presented by ^{14}N, with Z=7
      - A system of 14 protons and 7 electrons should have half-integer spin,
      - addition of a spin-half neutrino constituent would resolve this problem
  - "I have done a terrible thing: I have postulated a particle that cannot be detected"
- Chadwick's discovery of neutron (1932)
  - Fermi proposes "neutrino" as name for the particle, made in decay, not part of nucleus before

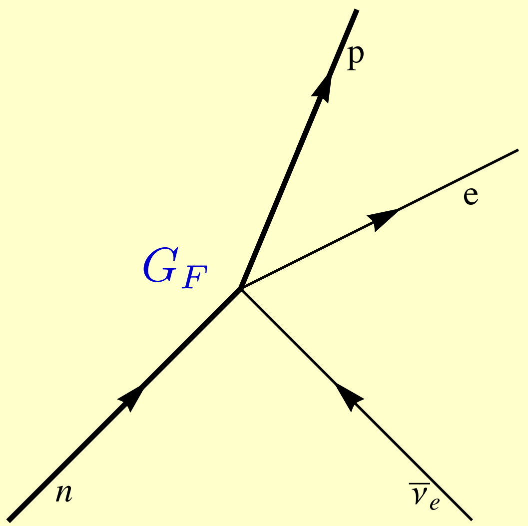
Weak interaction

- 1932:Chadwick's discovery of the "neutron"
- 1933 Solvay conference:
  - Pauli finally presented his theory of the "neutrino."
  - Fermi suggested the name "neutrino" to distinguish it from Chadwick's heavy neutral nucleon
- 1934: Fermi "effective theory" of β decay
  - incorporates both the neutron and the neutrino

$$n_{bound} \rightarrow p_{bound} + e^{-} + \bar{\nu}_e$$

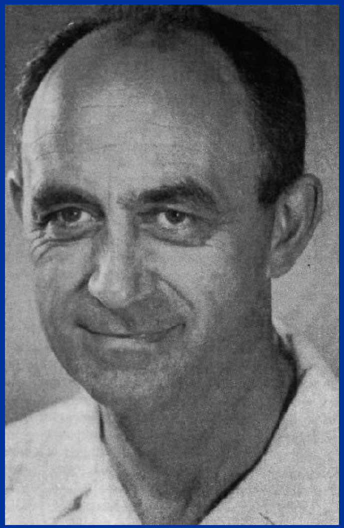
  - Proposed that the neutrino was produced in the decay, accompanying the outgoing electron

1934: Theory of beta decay



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

$$p + \bar{\nu} \to n + e^+$$



E. Fermi
(Nobel 1938)

Nature did not publish his article: “contained speculations too remote from reality to be of interest to the reader…”

Bethe-Peierls (1934): compute the neutrino cross section using this theory

$$\sigma \simeq 10^{-44} cm^2,\ E(\bar{\nu}) = 2 \text{ MeV}$$

“there is not practically possible way of detecting a neutrino”

How to detect them ?

$$\lambda \simeq \frac{1}{n\sigma}$$

$$\lambda_{water} \simeq 1.5 \times 10^{21} cm \simeq 1600\ ly$$

$$\lambda_{\text{interstellar}} \simeq 10^{44} cm \simeq 10^{26}\ ly$$

" I have done a terrible thing. I have postulated a particle that cannot be detected"

W. Pauli

Bruno Pontecorvo (1946):
maybe it's possible with neutrinos from reactors
In a 1000kg detector, a $10^{11}\ \nu$/s/cm^2 $\Rightarrow$ a few events per day

Neutrinos from reactors

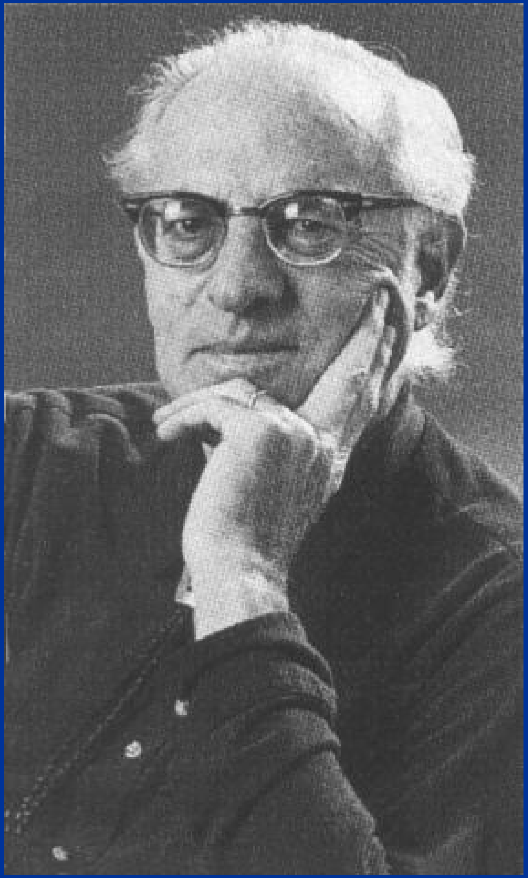
Then the (by-then) recently invented nuclear reactors could be this source…

Reactors: ~ 10^{20}/second!

(10^{13}/s@100 meters)

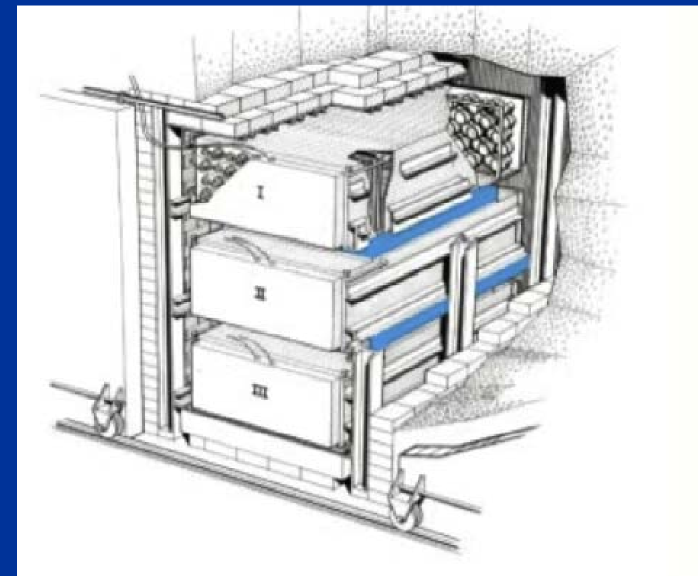
Detection of the Neutrino

1950 – Reines and Cowan set out to detect ν



Discovery, Reines & Cowan 1956

- Conducted a series of experiments
- Stage 1: Hanford site, Washington
  - Too much background from cosmic rays
- Stage 2: Savannah River, South Carolina
  - Better shielding
  - 11 m from reactor
  - 12 m underground
- 200 liters of water with 40 kg $CdCl_2$
- Sandwiched between scintillator layers

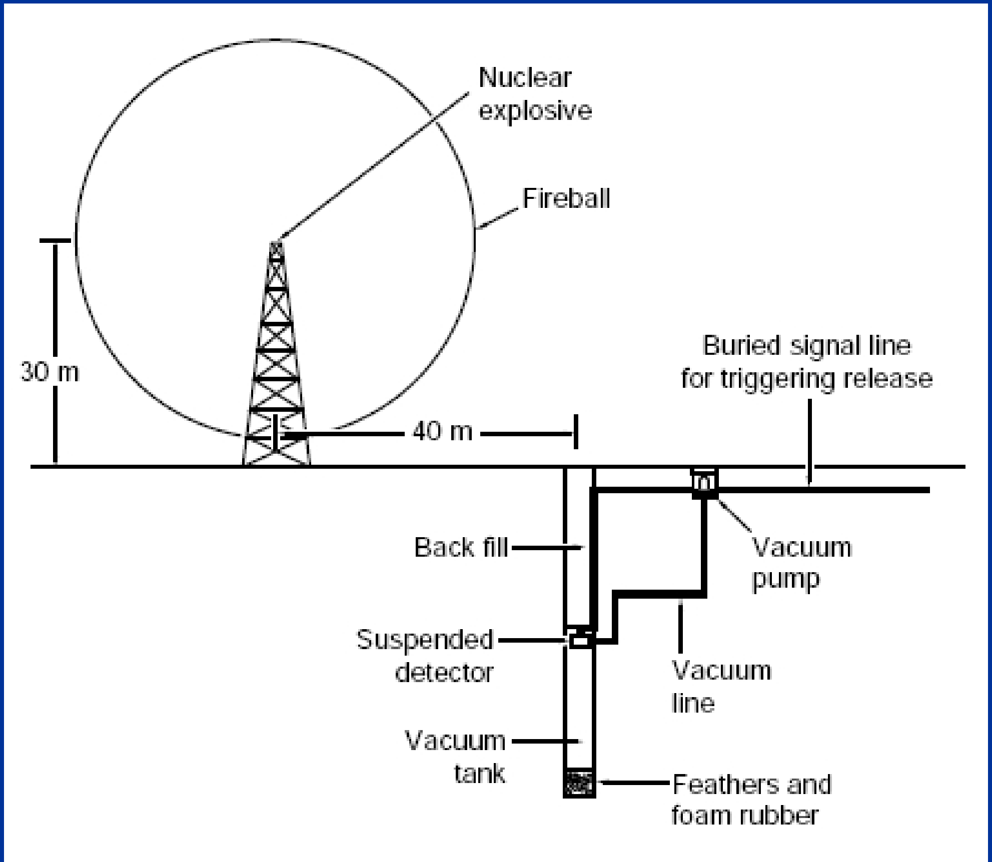


Results:

- ~3 neutrino events per hour detected
- Used on-off switch on reactor
- Neutrinos disappeared when reactor was off

Cowan died in 1974, but Reines awarded Nobel Prize in 1995

1951



I. Explode bomb
II. At same time let detector fall in vacuum tank
III. Detect neutrinos
IV. Collect Nobel prize

OK – but repeatability is a bit of a problem

Project Poltergeist

- Use reactor as neutrino source,
  - First Hanford, later Savannah river
  - Use water tank with liquid scintillator and $CdCl_2$
  - Reaction “inverse beta decay” (proton of hydrogen in water becomes neutron when hit by a neutrino, positron emitted)
  - Positron annihilates with an electron $\Rightarrow 2\gamma$
  - Neutron absorbed by Cadmium-108 $\rightarrow$ excited state of Cadmium-109 $\Rightarrow$ emits photon (γ)
  - γ detected by scintillation counter

Clyde Cowan Fred Reines

Detecting the neutrino

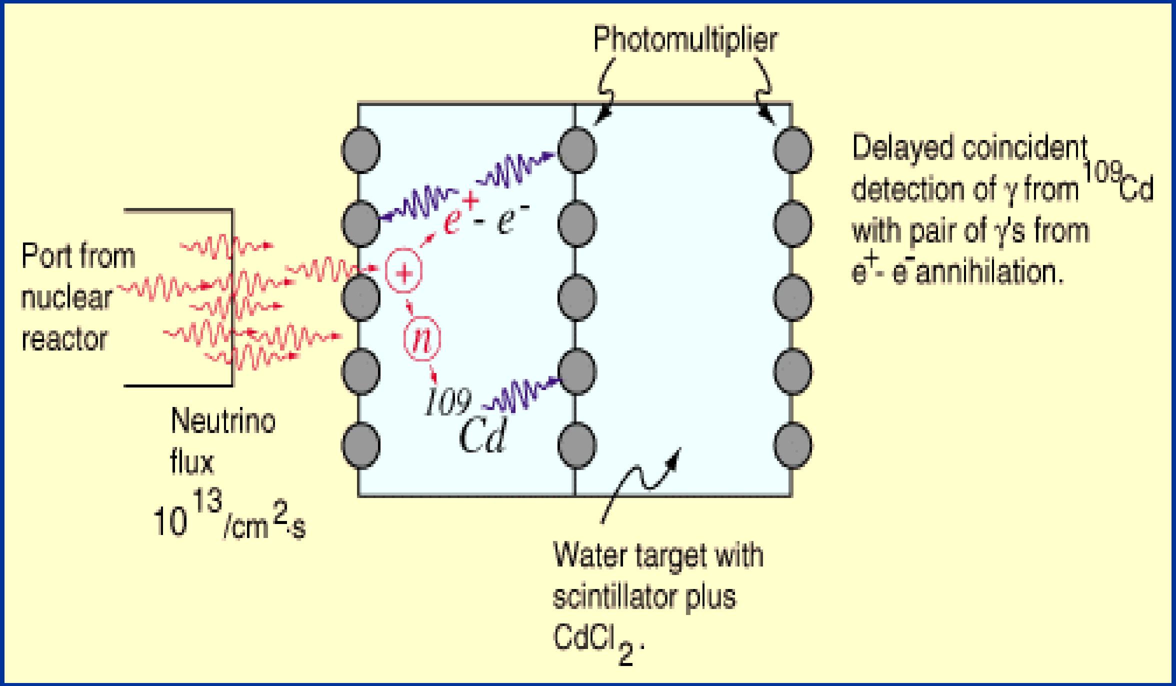
Inverse beta decay, followed by e+ e- annihilation:

$$\nu_e + p \rightarrow e^+ + n$$
$$e^+ + e^- \rightarrow 2\gamma$$

$$n + {}^{108}Cd \rightarrow {}^{109m}Cd$$
$$\rightarrow {}^{109}Cd + \gamma$$

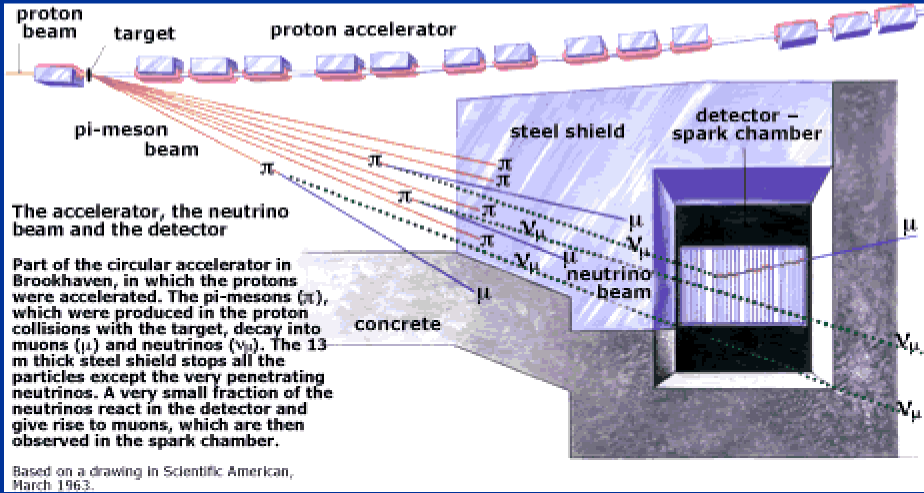
Experimental needs:

- Strong neutrino source → reactor
- Proton target → H in water
- Positron and neutron detector
  - Liquid scintillator to detect gammas
  - $CdCl_2$ target to capture neutrons
  - Delayed (5μs) coincidence of γ from Cd with γ from annihilation



More than one neutrino!

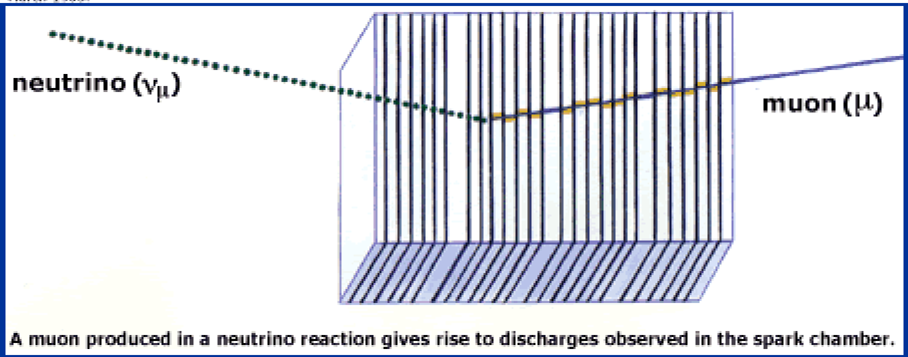
- Lederman, Schwartz, Steinberger (1962)
  - Experiment at BNL (Brookhaven Nat. Lab.)
  - Use neutrinos from pion decay
  - Show that they are different from the neutrinos emitted in beta decay
  - Shielding: 2000 tons of steel from scrapped warships (armor)
  - Nobel Prize 1988



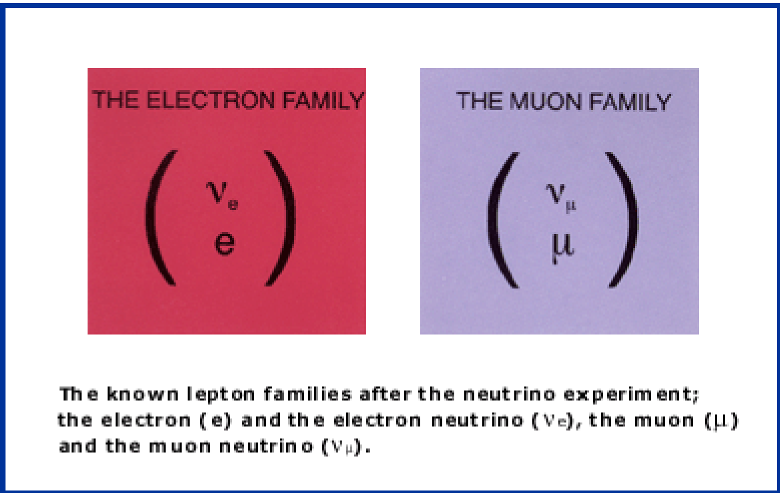
The accelerator, the neutrino beam and the detector

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.



A muon produced in a neutrino reaction gives rise to discharges observed in the spark chamber.

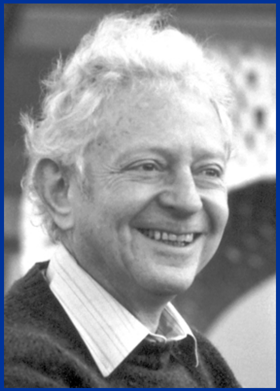


The known lepton families after the neutrino experiment; the electron (e) and the electron neutrino (ν_e), the muon (μ) and the muon neutrino (ν_μ).

https://www.bnl.gov/bnlweb/history/nobel/1988.php

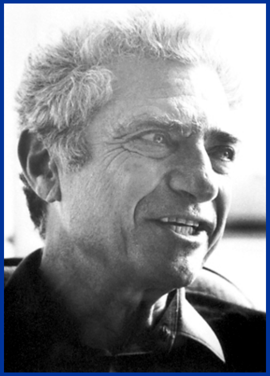
Neutrino Flavor

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$



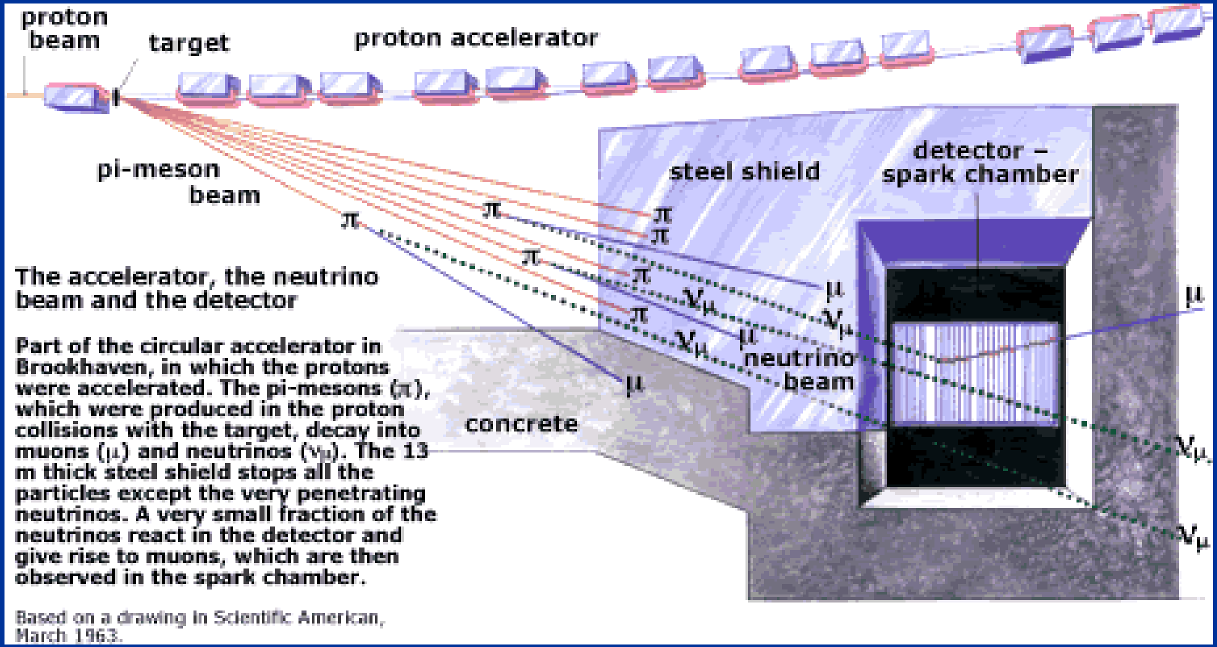
Lederman

Schwartz



Steinberger

Nobel 1988



Modern versions of Lederman, Schwartz, Steinberger experiment are accelerator neutrino experiments: Minos, Opera, T2K, NoVA,…

A 3rd Lepton -- τ

- SPEAR ($e^+ e^-$ storage ring at SLAC), 1975
- Find evidence for reaction

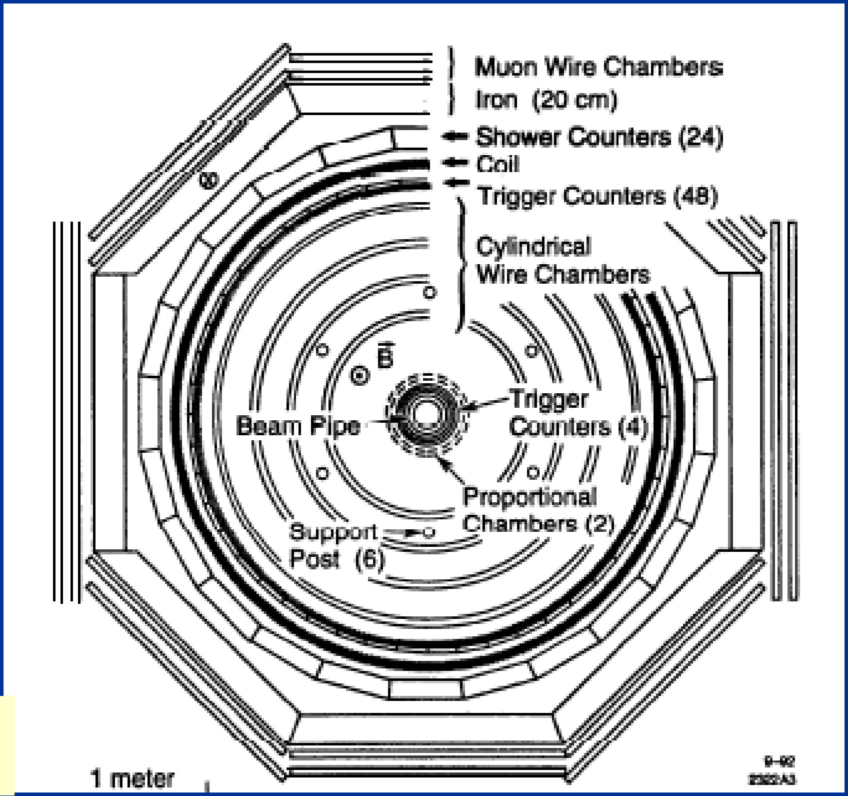
$$e^+ + e^- \to e^\pm + \mu^\mp + X$$

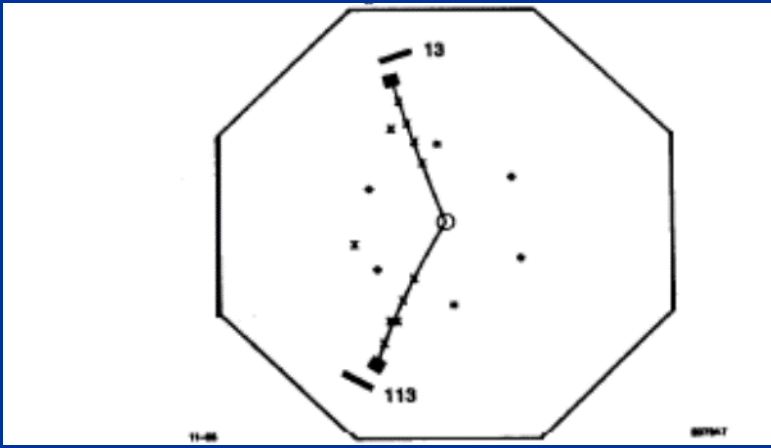
where X = at least 2 undetected particles

- Interpretation (Martin Perl)

$$e^+ + e^- \to \tau^+ + \tau^- \to e^\pm + \mu^\mp + 4\nu$$

- $\Rightarrow$ 3rd lepton τ ($\tau\rho i\tau o\nu$ – *the 3rd*)
- Verified by experiment at DESY (Hamburg)
- Nobel Prize 1995 for M. Perl (shared with Frederick Reines)





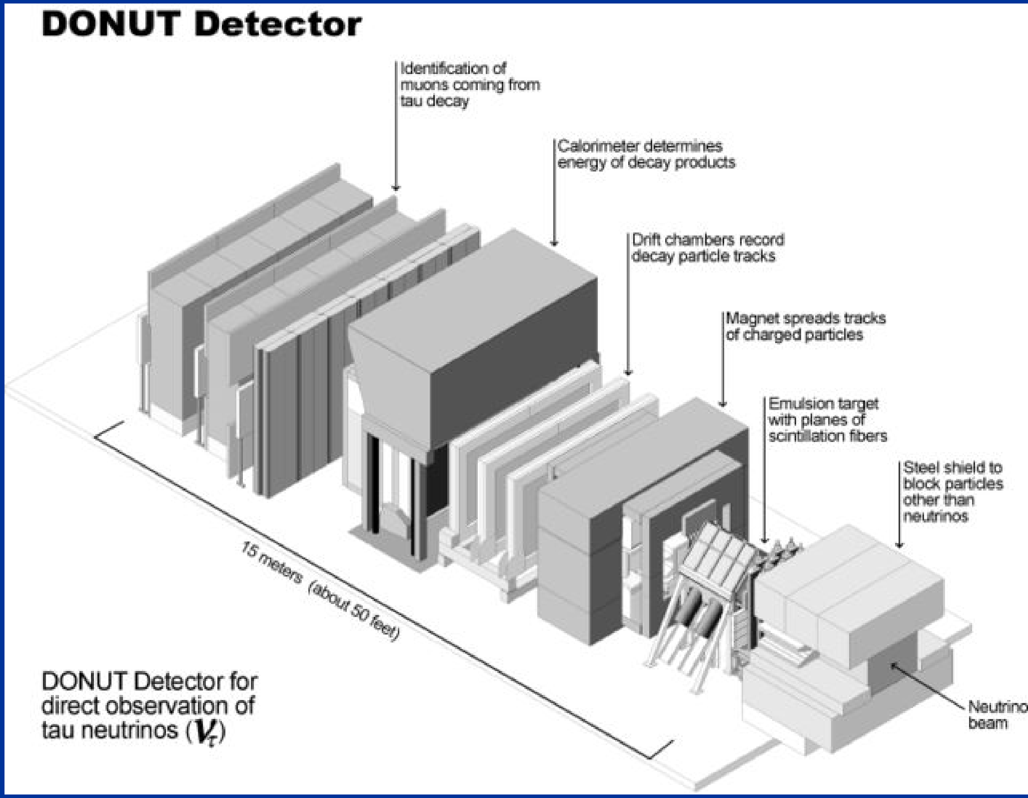
http://www.nobelprize.org/nobel_prizes/physics/laureates/1995/perl-lecture.html

3rd neutrino -- ν_τ

- DONUT (direct observation of ν_τ) at Fermilab (1997)
- Produce tau-neutrinos from decay of charmed particles
- Observation of events of type

$$\nu_\tau + p \rightarrow \tau^+ + X$$

- Observe decay products of τ in detector

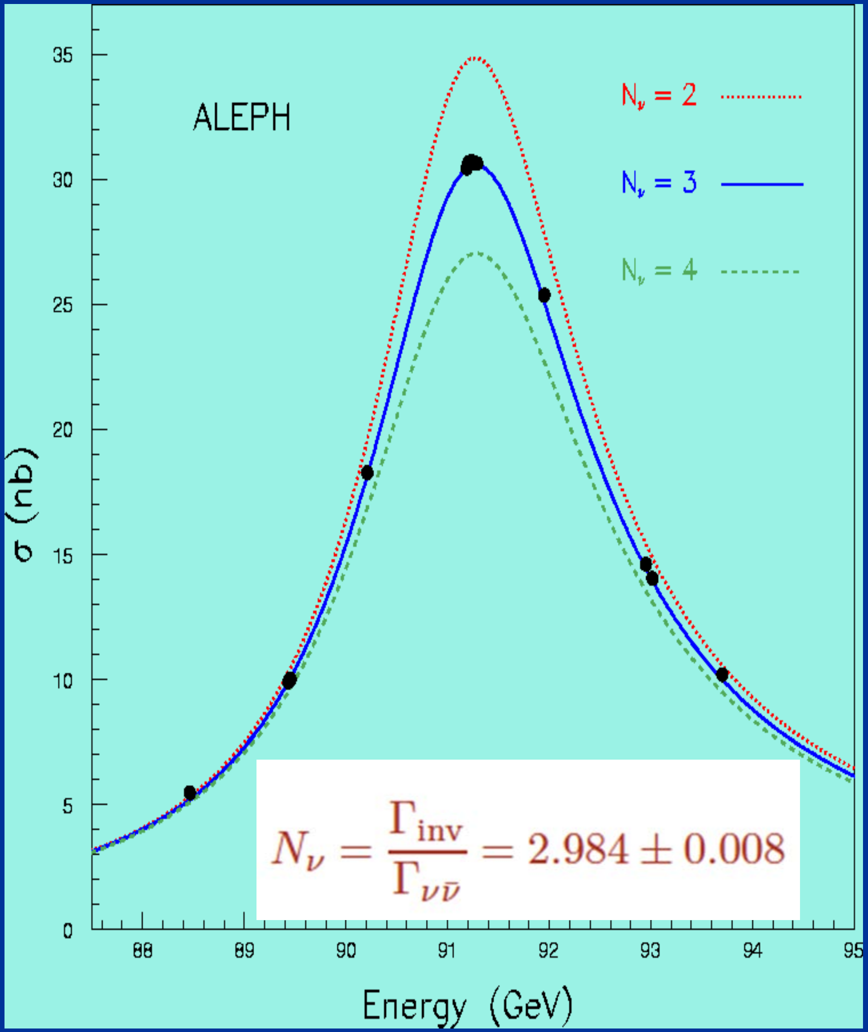


https://arxiv.org/abs/hep-ex/0012035

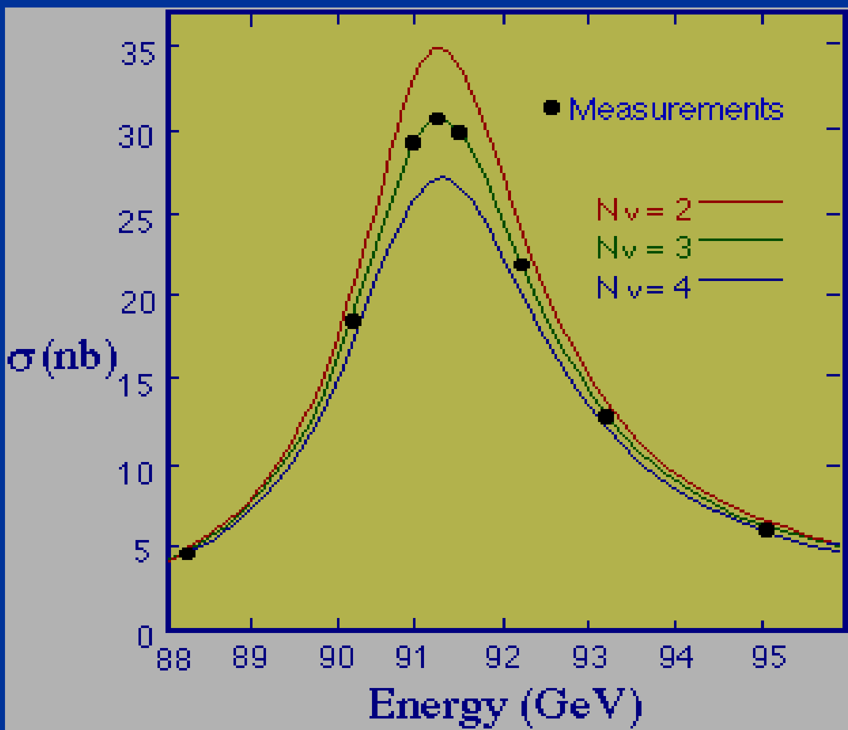
The Number of light neutrinos

- Discovery of Z^o (1983 by UA1, UA2 at CERN)
  - From "width" of Z decay, get upper limit on number of "light neutrinos: N_ν < 3.8 (1987)
  - ("light" means mass of ν < $m_Z/2$ ~ 45 GeV
- Studies of Z at LEP (2003):
  - measurement of cross section vs beam energy allows determination of number of light neutrinos

  (Z^o can decay to a neutrino and antineutrino)



Three neutrinos ...



σ measures rate at which e+e- collisions occur

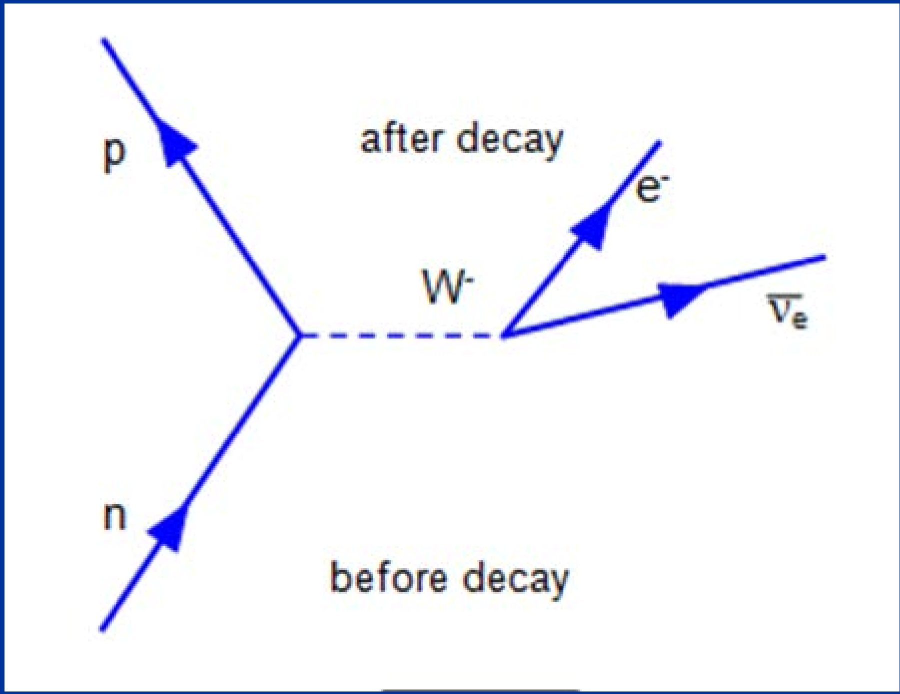
Number of different “light” neutrinos = 2.984 ± 0.008

u	c	t	ν_e	ν_μ	ν_τ
d	s	b	e	μ	τ

Weak Interactions and the Neutrino

- Neutrinos have weak interaction:
  - No electric charge
  - No color charge
- Weakness of weak interactions:
  - Mediated by $W^{\pm}$, Z^{o}
  - W and Z massive
    m_w = 80 GeV
    m_z = 91 GeV
  - for E << m_w , m_z,
    Coupling ~ $1/m_W{}^2$
  - Uncertainty relation $\Delta E \cdot \Delta t \geq \frac{\hbar}{2}$

Beta decay of neutron:



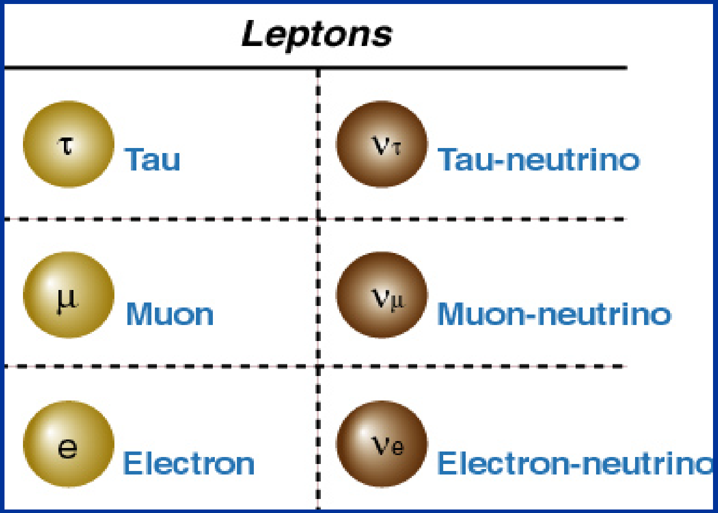
- I can borrow an elephant, provided I give it back on time (soon)!
- Interactions can only occur over very small distances
- Result: small cross section, or "weak" strength of interaction

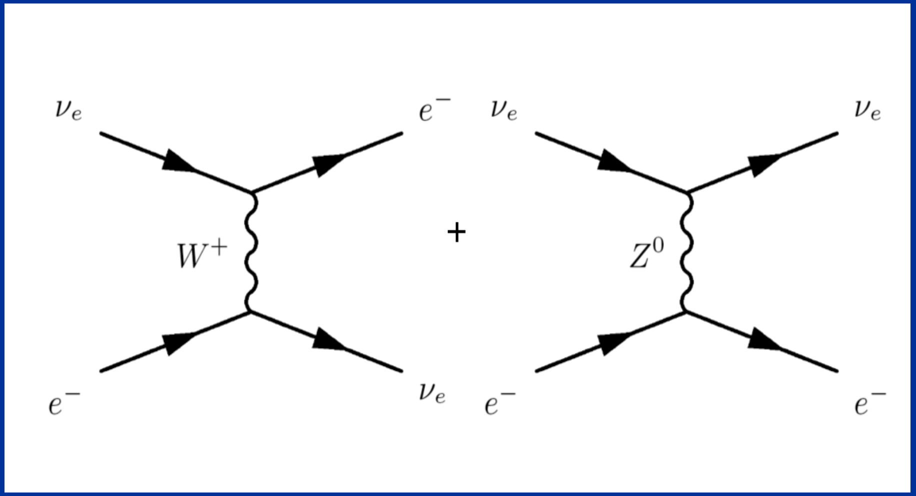
Neutrino Properties

Lepton number:
- Total number of leptons conserved
- Leptons minus antileptons
- Example: Electrons always produced with antineutrinos

Lepton flavor number (e, μ, τ) :
- Total number of leptons in each generation conserved
- Only one flavor allowed at a vertex

Spin:
Neutrinos are fermions: spin ½

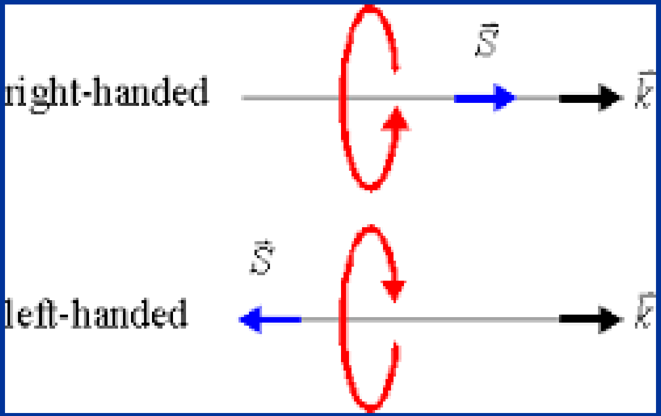




Neutrino-electron scattering

Helicity and Mass

- Helicity: projection of spin along momentum axis
- For spin ½ particles, two states
- +½, -½
- Right or Left handed



Observation:

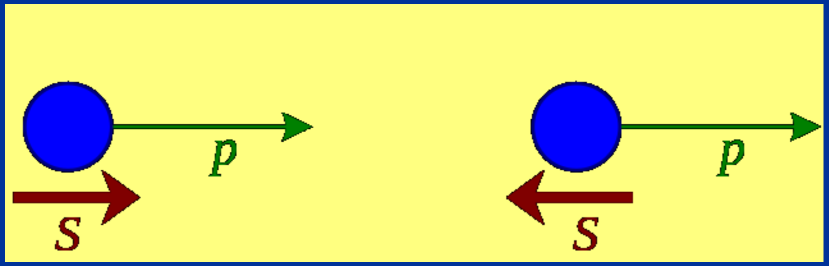
- All leptons in weak interactions are left handed.
- All anti leptons in weak interactions are right handed

But helicity is not a Lorentz invariant:

- I can transform to a frame where the particle is moving in the opposite direction

One solution: Massless neutrinos

- Move at c in all frames
- Helicity becomes a good quantum number
- Chirality (handedness) is intrinsic property
- Same as helicity for massless particles

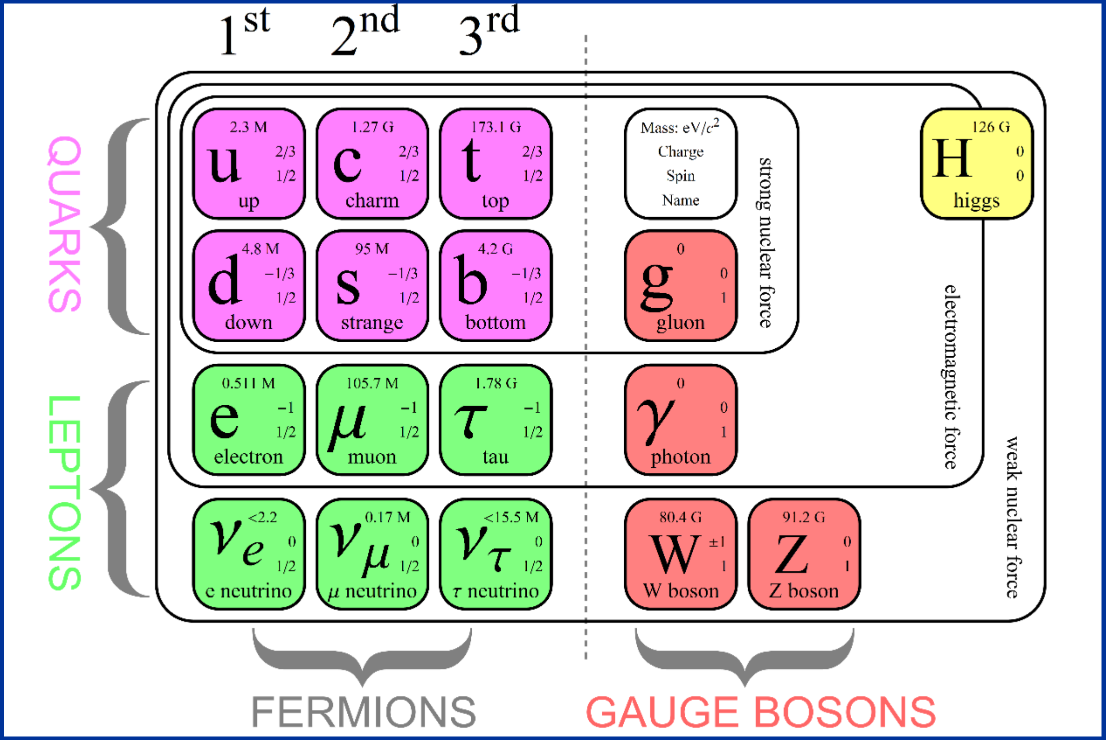


Neutrino in the (original) Standard Model

- weak interaction mediated by W and Z bosons
- Couple to left handed fermions, right handed antifermions

- Neutrinos have exactly zero mass
- One neutrino flavor per lepton
- Higgs, which is responsible for mass, does not interact with neutrinos
- Neutrinos and antineutrinos are distinct (different chirality)

Particles of the Standard Model



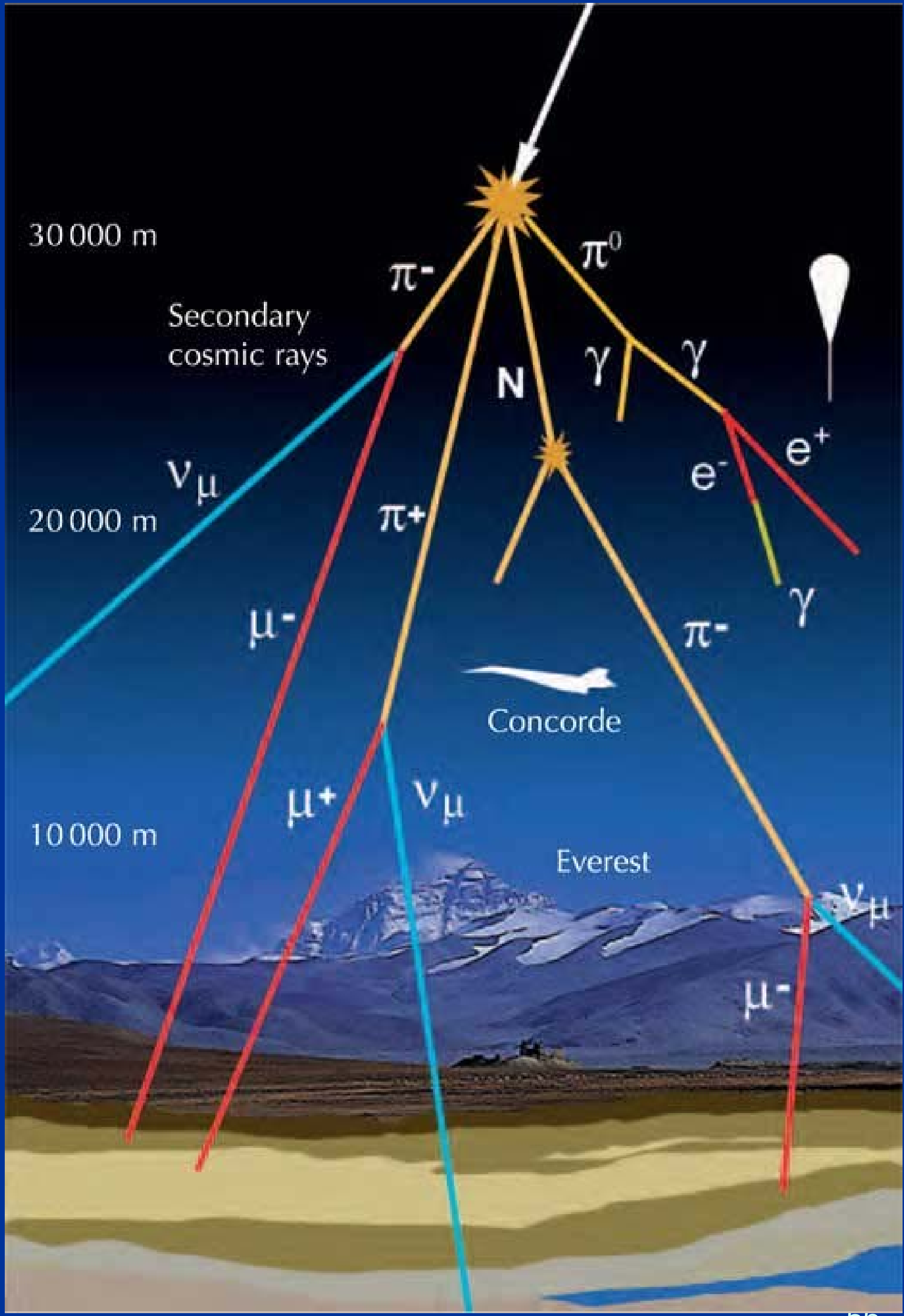
Sources of Neutrinos

Nuclear reactions

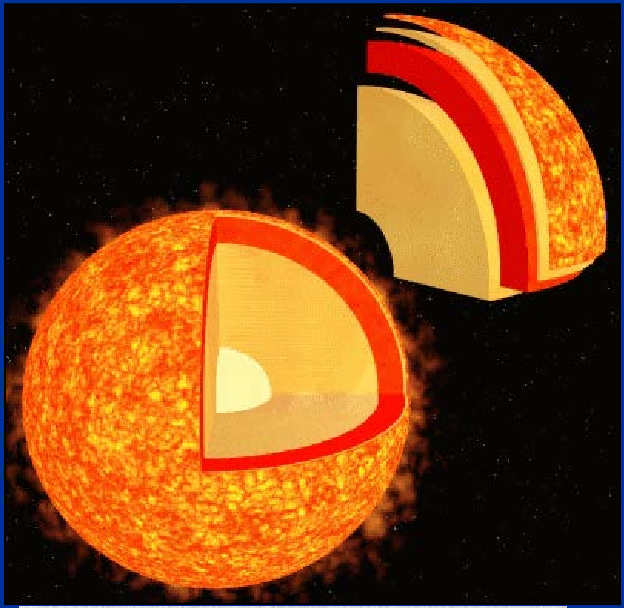
- Fusion in the sun (and other stars)
- SuperNovae
- Big bang nucleosynthesis
- Fission in reactors

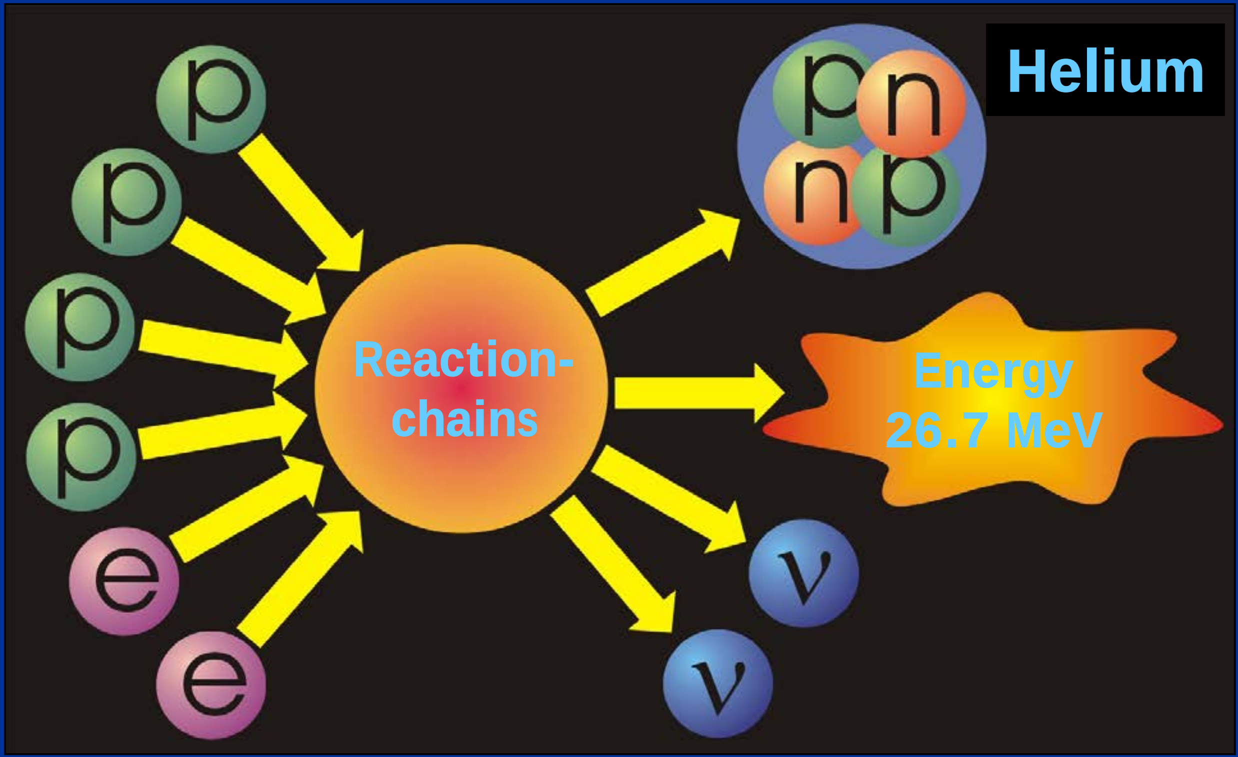
High energy collisions

- Particle colliders
- Cosmic ray showers



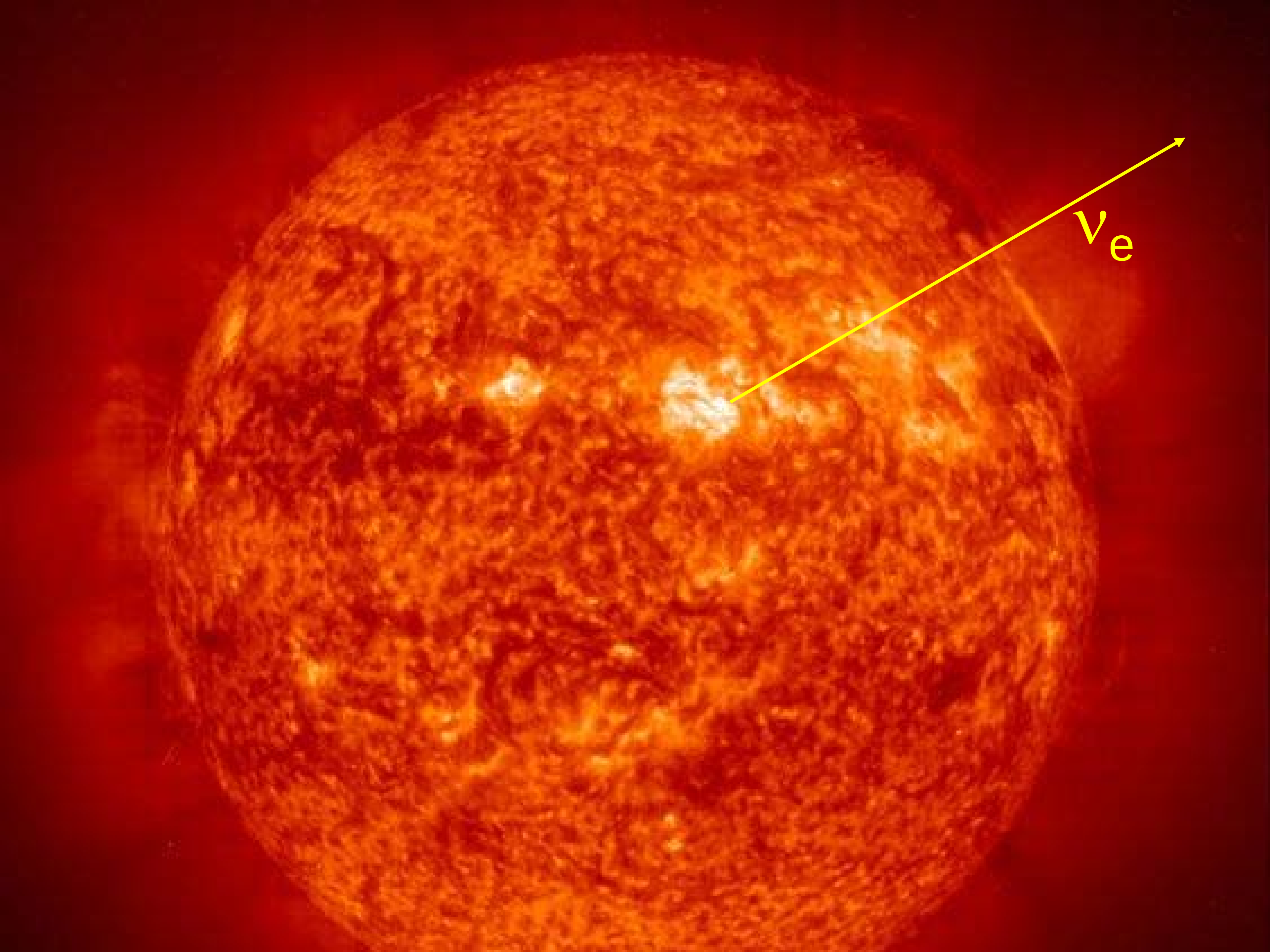
Neutrinos from the Sun





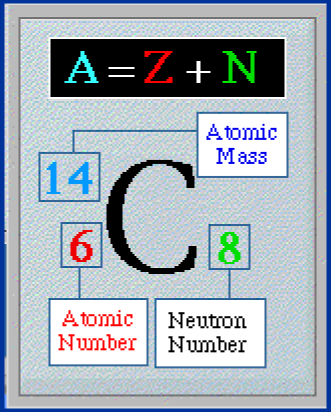
Solar radiation: 98 % light
2 % neutrinos
At Earth 66 billion neutrinos/cm² sec

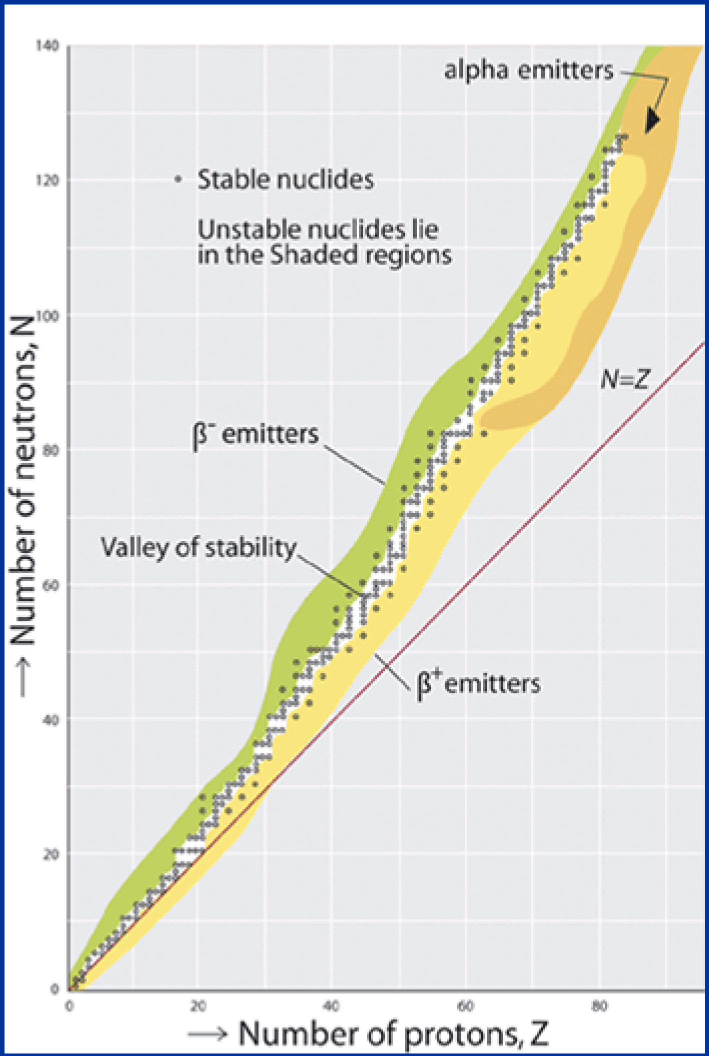
Hans Bethe (1906–2005, Nobel prize 1967)
Thermonuclear reaction chains (1938)


ν_e

A, N, Z

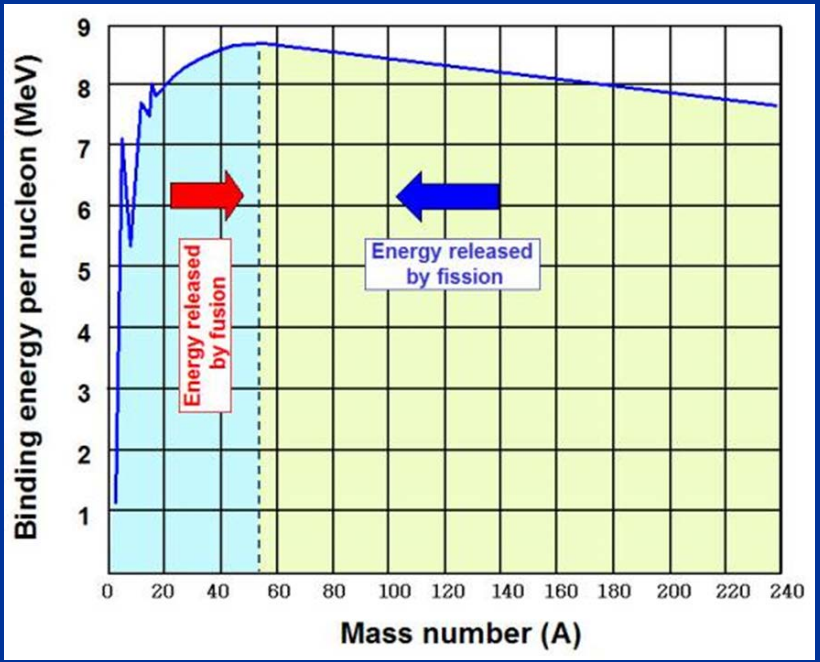
- for natural nuclei:
  - Z range 1 (hydrogen) to 92 (Uranium)
  - A range from 1 ((hydrogen) to 238 (Uranium)
- N = neutron number = A-Z
- N – Z = “neutron excess”; increases with Z
- nomenclature:
  - $_{Z}^{A}X_{N}$ or $^{A}X_{N}$ or ^{A}X or X-A





http://www.nndc.bnl.gov/chart/
http://amods.kaeri.re.kr/
https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html
http://wwwndc.jaea.go.jp/CN10/
http://ie.lbl.gov/toi/perchart.htm

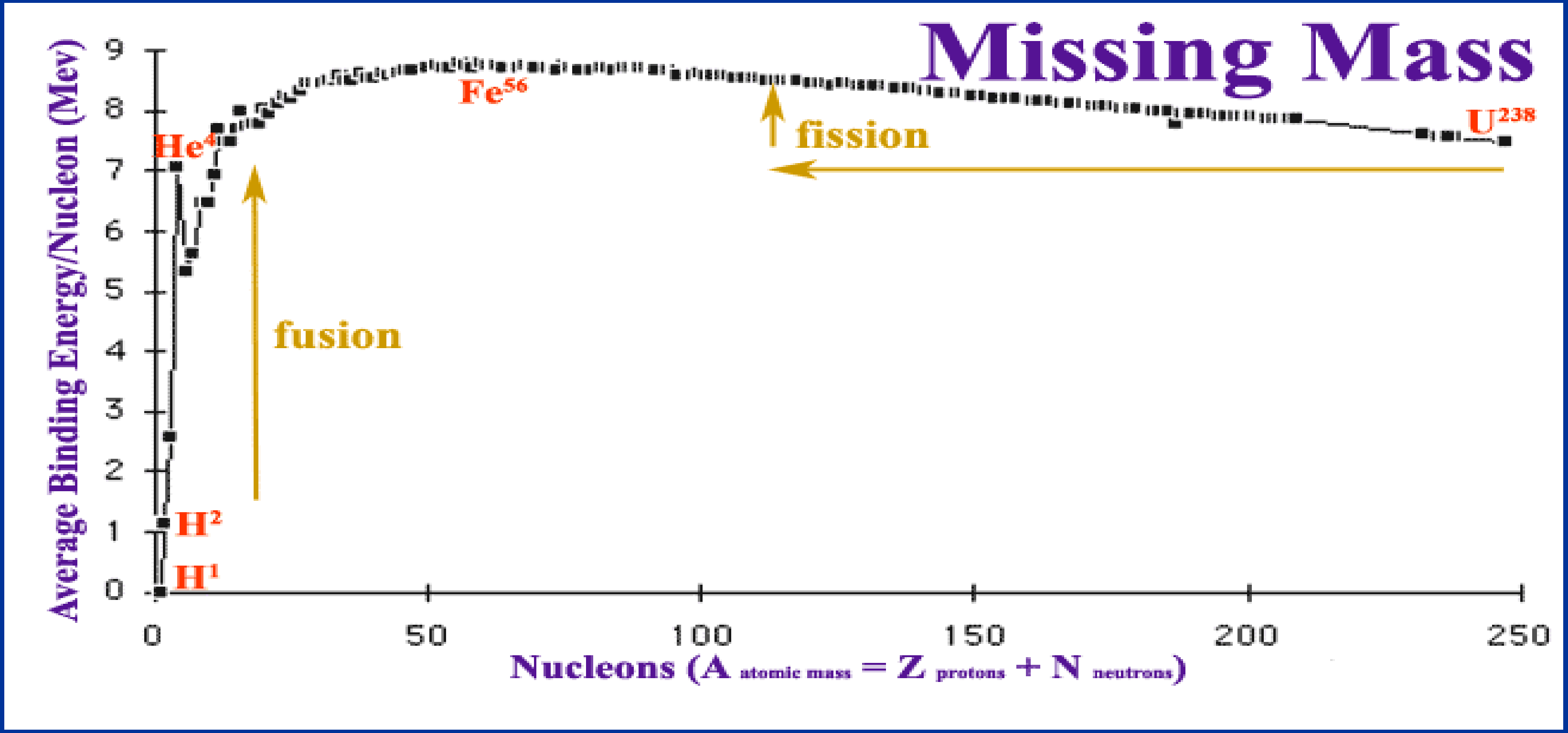
binding energy vs A



- small nuclei (A<10):
  - All nucleons are within range of strong force exerted by all other nucleons;
  - add another nucleon $\Rightarrow$ enhance overall cohesive force $\Rightarrow$ E_B/A rises sharply with increase in A
- medium size nuclei (10 < A < 60)
  - nucleons on one side are at edge of nucl. force range from nucleons on other side $\Rightarrow$ each add'l nucleon gives diminishing return in terms of binding energy $\Rightarrow$ slow rise of E_B/A
- heavy nuclei (A>60)
  - adding more nucleons does not increase overall cohesion due to nuclear attraction
  - Repulsive electrostatic forces (infinite range!) begin to have stronger effect
  - N-Z must be bigger for heavy nuclei (neutrons provide attraction without electrostatic repulsion
  - heaviest stable nucleus: 209Bi – all nuclei heavier than 209Bi are unstable (radioactive)

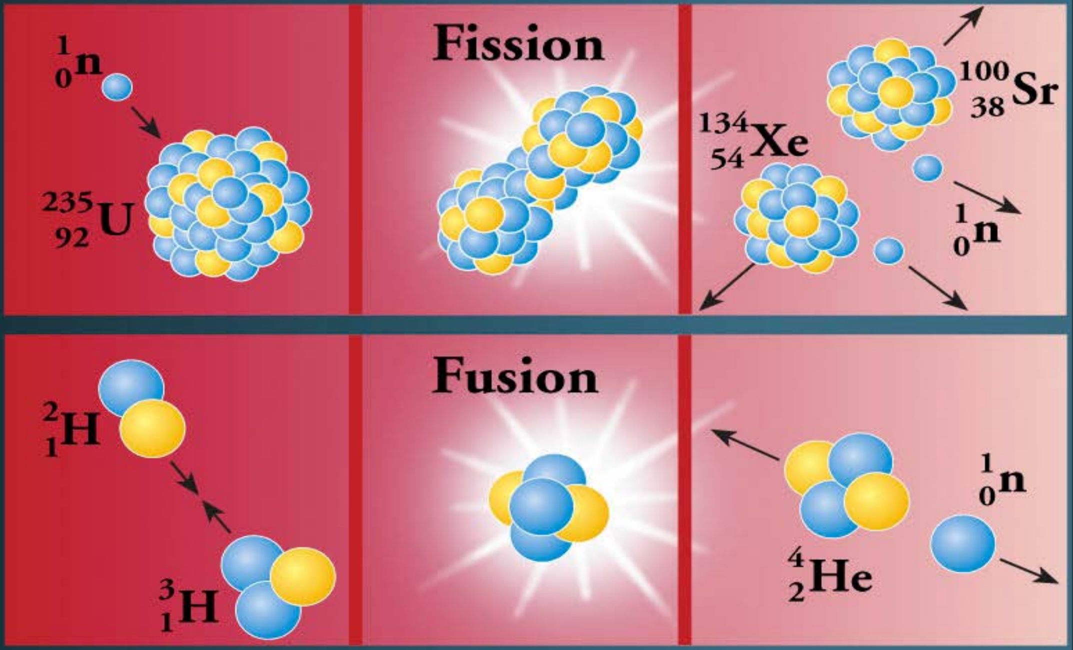
Nuclear energy

- very heavy nuclei:
  - energy released if break up into two medium sized nuclei
  - “fission”
- light nuclei:
  - energy released if two light nuclei combine -- “fuse” into a heavier nucleus – “fusion”

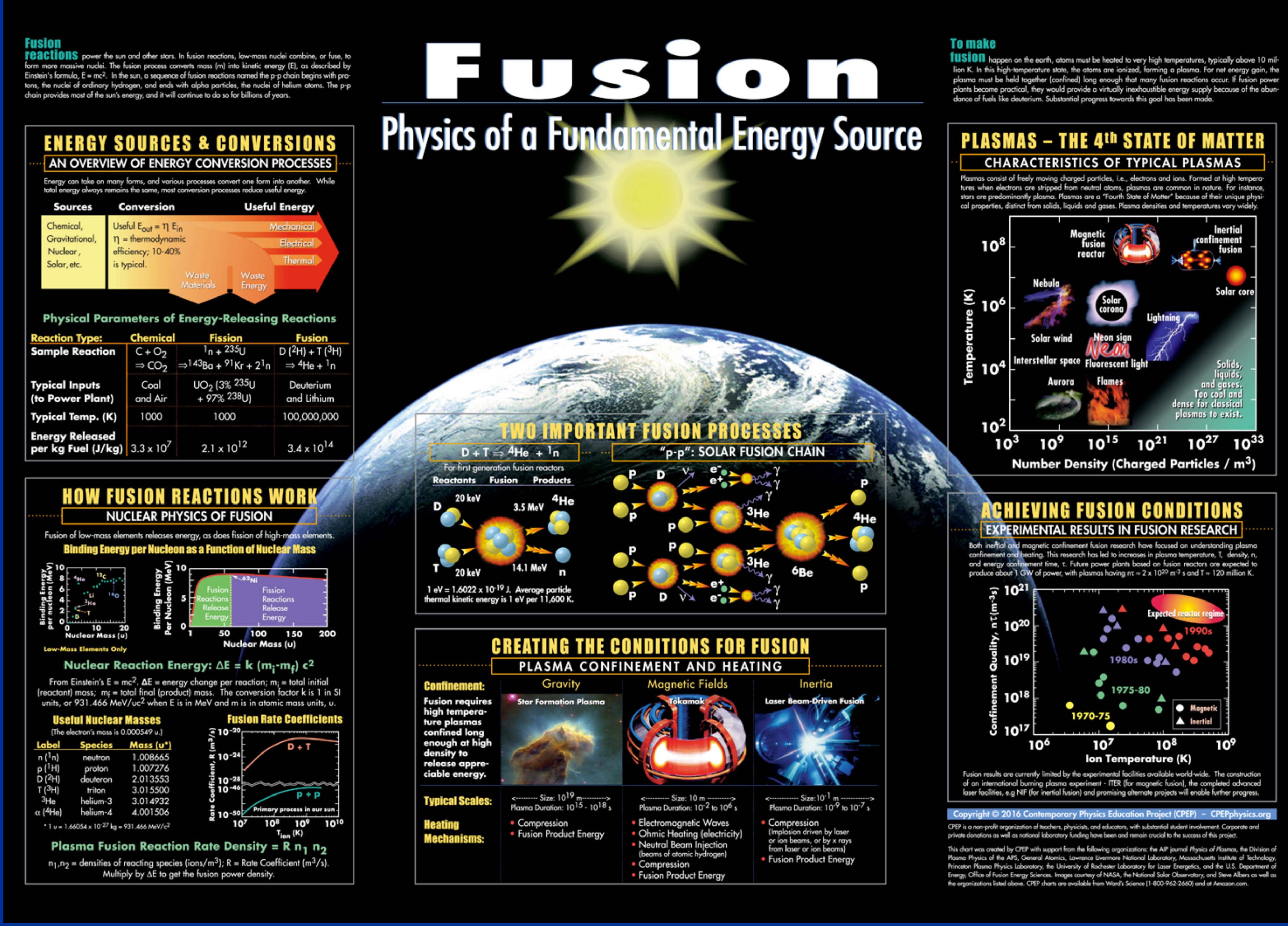


Nuclear Energy

*N*uclear reactions release energy when the total mass of the products is less than the sum of the masses of the initial nuclei. The "lost mass" appears as kinetic energy of the products ($E = mc^2$). In fission, a massive nucleus splits into two major fragments that usually eject one or more neutrons. In fusion, low mass nuclei combine to form a more massive nucleus plus one or more ejected particles—neutrons, protons, photons, or alpha particles.



*I*n the early stages of stellar evolution of our sun and other stars, hydrogen fuses to form helium, releasing energy in the form of photons (light) and neutrinos. During the later stages of stellar evolution, more massive nuclei up to and beyond uranium are synthesized by fusion. By measuring the number of neutrinos that come from the Sun, scientists recently have demonstrated that neutrinos must have a mass greater than zero.

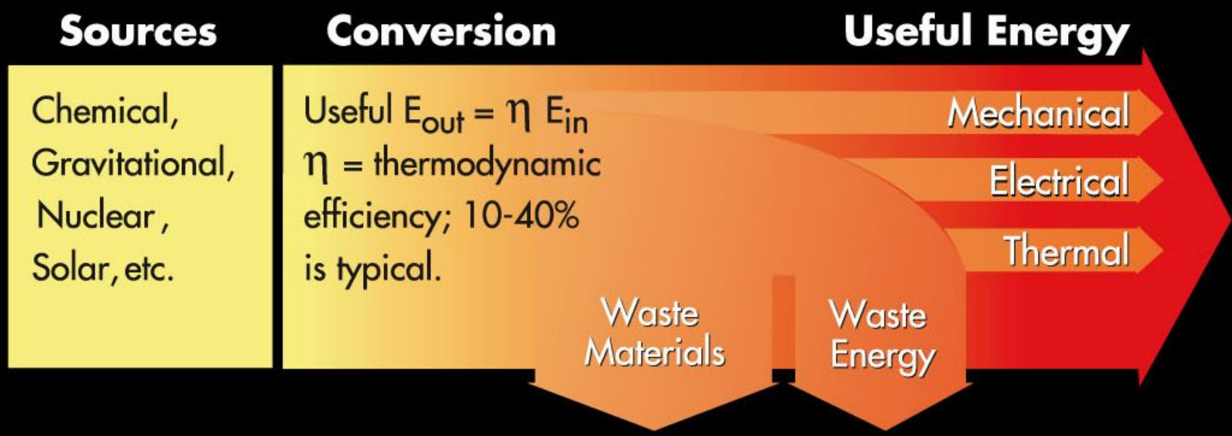


http://www.cpepphysics.org/fusion_chart.html#

ENERGY SOURCES & CONVERSIONS

AN OVERVIEW OF ENERGY CONVERSION PROCESSES

Energy can take on many forms, and various processes convert one form into another. While total energy always remains the same, most conversion processes reduce useful energy.



Physical Parameters of Energy-Releasing Reactions

Reaction Type:	Chemical	Fission	Fusion
Sample Reaction	$C + O_2 \Rightarrow CO_2$	$^{1}n + {}^{235}U \Rightarrow {}^{143}Ba + {}^{91}Kr + 2\,{}^{1}n$	$D\,({}^{2}H) + T\,({}^{3}H) \Rightarrow {}^{4}He + {}^{1}n$
Typical Inputs (to Power Plant)	Coal and Air	UO_2 (3% ^{235}U + 97% ^{238}U)	Deuterium and Lithium
Typical Temp. (K)	1000	1000	100,000,000
Energy Released per kg Fuel (J/kg)	3.3×10^{7}	2.1×10^{12}	3.4×10^{14}

CPEP contemporary education project

http://www.cpepphysics.org/fusion_chart.html#

Neutrino production from Nuclear Reactions in the Sun

- Fusion of H to He is the basic energy source of the Sun: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.7\ MeV$

pp	$\rightarrow$	${}^2H + e^+ + \nu_e$	
${}^2H + p$	$\rightarrow$	${}^3He + \gamma$	
${}^3He + {}^3He$	$\rightarrow$	${}^4He + 2p$	85%
${}^3He + {}^4He$	$\rightarrow$	${}^7Be + \gamma$	15%
$e^- + {}^7Be$	$\rightarrow$	${}^7Li + \nu_e$	
${}^7Li + p$	$\rightarrow$	$2\,{}^4He$	
$p + {}^7Be$	$\rightarrow$	${}^8B + \gamma$	0.02%
${}^8B$	$\rightarrow$	${}^8Be^* + e^+ + \nu_e$	
${}^8Be^*$	$\rightarrow$	$2\,{}^4He$	

G. S

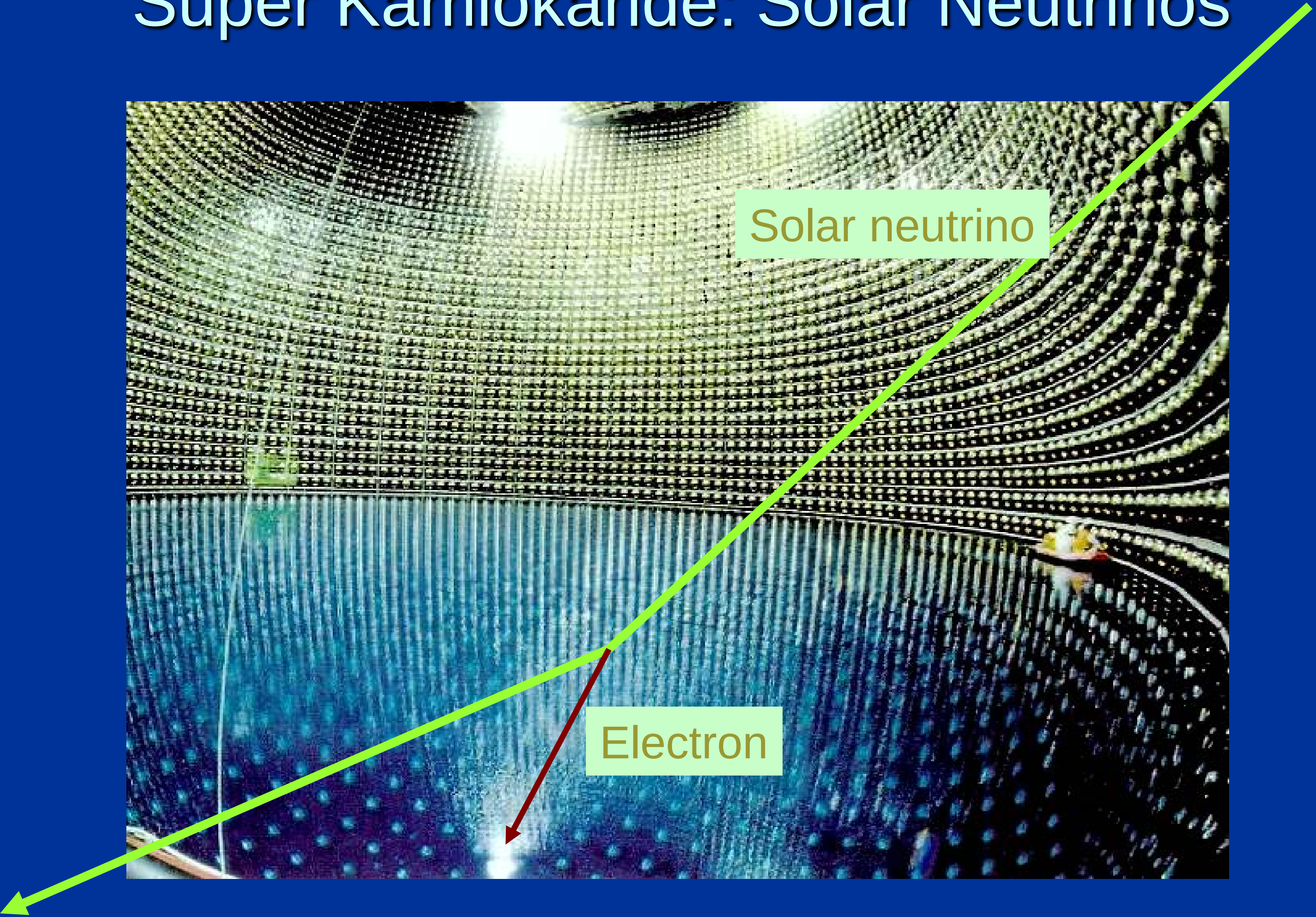
Neutrino puzzles

- Solar Neutrinos "Problem"
  - 3 experiments showed a deficit of solar neutrinos.
    - o Going back ~30 years
  - About 1/3 to ½ of the expected number were observed
  - results could not be reconciled with the standard solar model
- Atmospheric Neutrino "Anomaly"
  - IMB and Kamiokande saw less than expected ratio of ν_μ / ν_e
- One Proposed Explanation was:

  Neutrino Oscillations

  - Solar neutrinos might be $\nu_e \rightarrow \nu_\mu$
  - Atmospheric neutrinos might be $\nu_\mu \rightarrow \nu_\tau$
- Confirmed by Kamiokande and Sudbury experiments

Super Kamiokande: Solar Neutrinos



Solar Neutrino puzzle

- Missing neutrinos from the Sun
  - Now explained as due to "neutrino oscillations"
  - three neutrino types: electron neutrino ν_e , muon neutrino ν_μ, tau neutrino ν_τ
  - can change their identity – "oscillate" if masses are not all the same
  - Oscillation period depends on mass^2 difference
  - only possible if not all neutrinos are massless

http://www.chemistry.bnl.gov/sciandtech/sn/default.htm
http://www.talkorigins.org/faqs/faq-solar.html
http://www.sns.ias.edu/~jnb/
http://www.sns.ias.edu/~jnb/Papers/Popular/snhistory.html
http://www.sns.ias.edu/~jnb/SNviewgraphs/snviewgraphs.html
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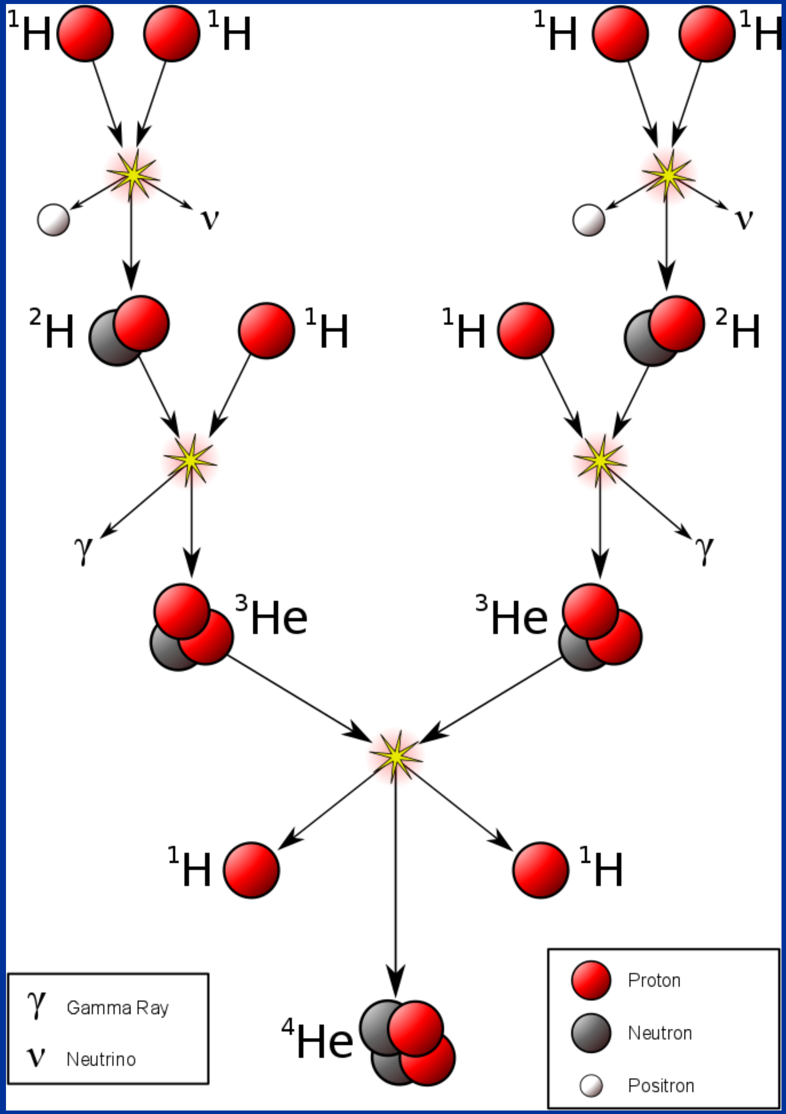
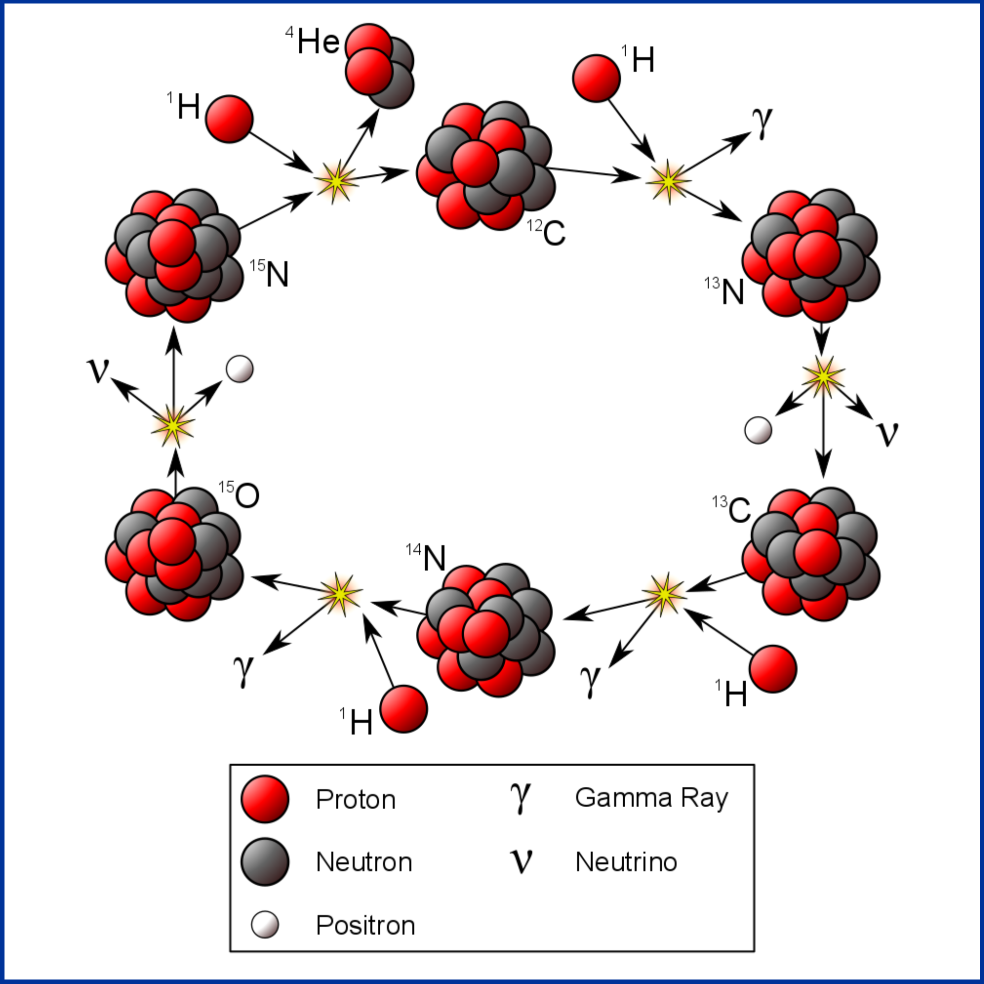
pp chain

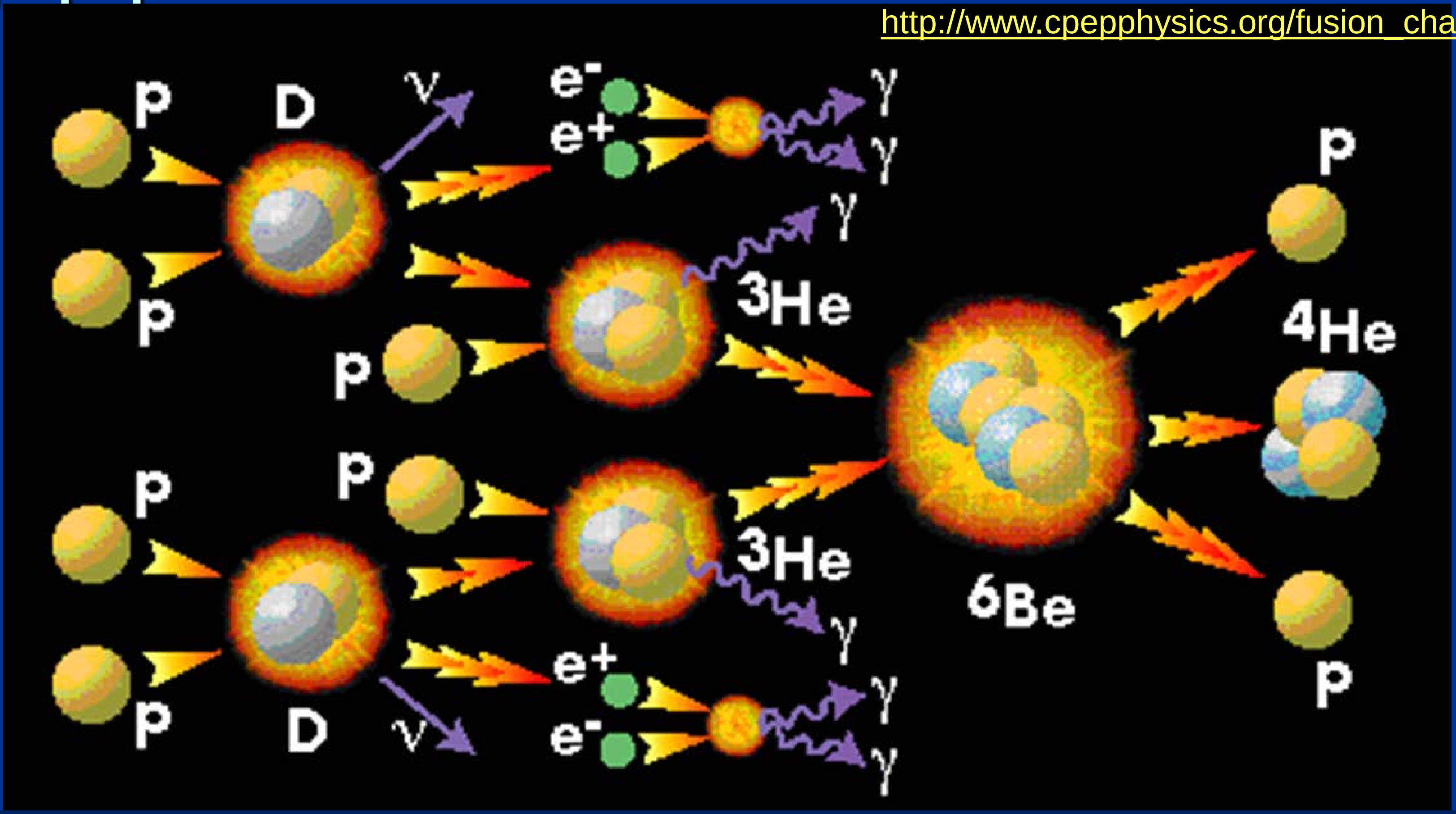


CNO cycle



Net result is: $4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + 26.7\ MeV$

p p process in the Sun



- Photons take $3 \cdot 10^4$ years to get out (diffusion time of single photon)
- Energy takes $\approx 3 \cdot 10^7$ years to get out (energy transport slower due to heat capacity of star)*)
- Neutrinos come out at ~ the speed of light!

*) (M. Stix, Sol Phys (2003) 212:3) (http://link.springer.com/article/10.1023%2FA%3A1022952621810)

Net reaction is 4p $\rightarrow$ 4He + 2e+ + 2ν_e

- Releases 25.7 MeV/c^2, or $4.12 \cdot 10^{-12}$ J, per Helium nucleus produced (or half that per neutrino)
- solar constant = energy received per unit time per unit area: 1370 Watts/m^2 at Earth's orbit
- $\Rightarrow$ neutrino flux should be $1370/(2.06\times10^{-12})/m^2/sec$ = **6.65×10^{10} /cm²/sec**
- Good News: this is accurate to better than 10%
- But: this is flux for all neutrino energies, detectors need minimum neutrino energy ("threshold")
- Neutrinos detected by some reaction/conversion that they cause (e.g. "inverse beta decay")
- Unit 1 SNU = "solar neutrino unit" = 10^{-36} events per target atom (in the detector)

Hydrogen burning: Proton-Proton Chains

$$p + p \rightarrow {}^2H + e^+ + \nu_e$$

< 0.420 MeV

$$p + e^- + p \rightarrow {}^2H + \nu_e$$

1.442 MeV

99.76% | 0.24%

$${}^2H + p \rightarrow {}^3He + \gamma$$

85% | 15%

PPI

$${}^3He + {}^3He \rightarrow {}^4He + 2p$$

$${}^3He + {}^4He \rightarrow {}^7Be + \gamma$$

hep

$${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$$

< 18.8 MeV

90% | 10% | 0.02%

$${}^7Be + e^- \rightarrow {}^7Li + \nu_e$$

0.862 MeV

$${}^7Be + e^- \rightarrow {}^7Li^* + \nu_e$$

0.384 MeV

$${}^7Be + p \rightarrow {}^8B + \gamma$$

$${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$$

< 15 MeV

PPII

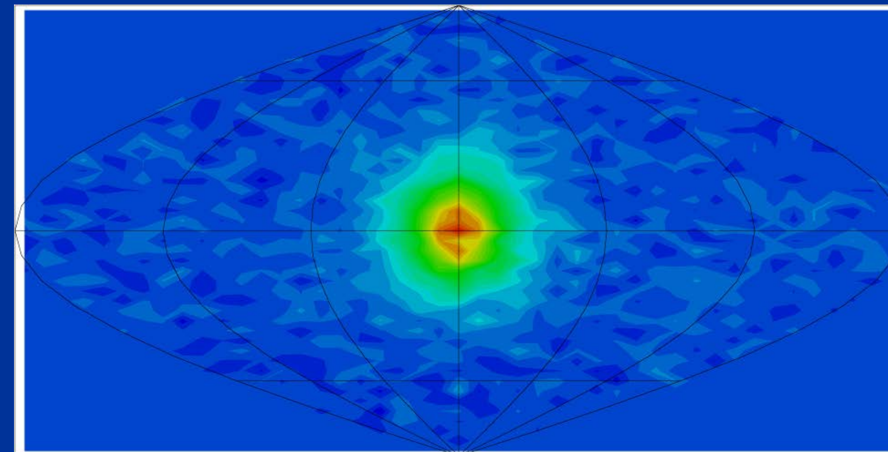
$${}^7Li + p \rightarrow {}^4He + {}^4He$$

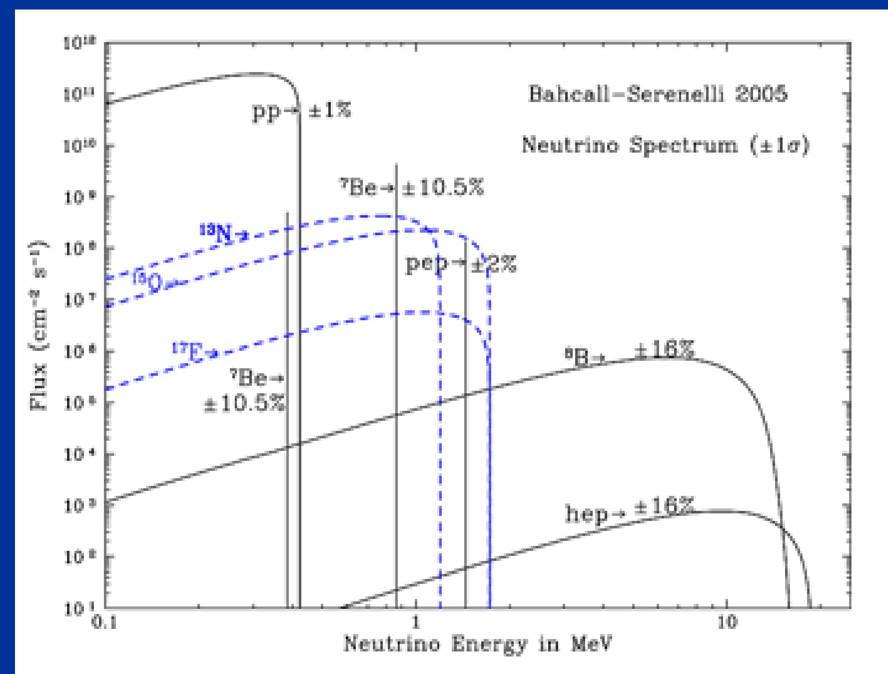
PPIII

$${}^8Be^* \rightarrow {}^4He + {}^4He$$

Solar Neutrinos

- Solar neutrinos:
  - 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 $\Rightarrow$ easier to detect
- John Bahcall:
  - prediction of solar neutrino flux in 1964
  - Over next 50 years:
    - Continued to refine his solar model -- incredibly precise





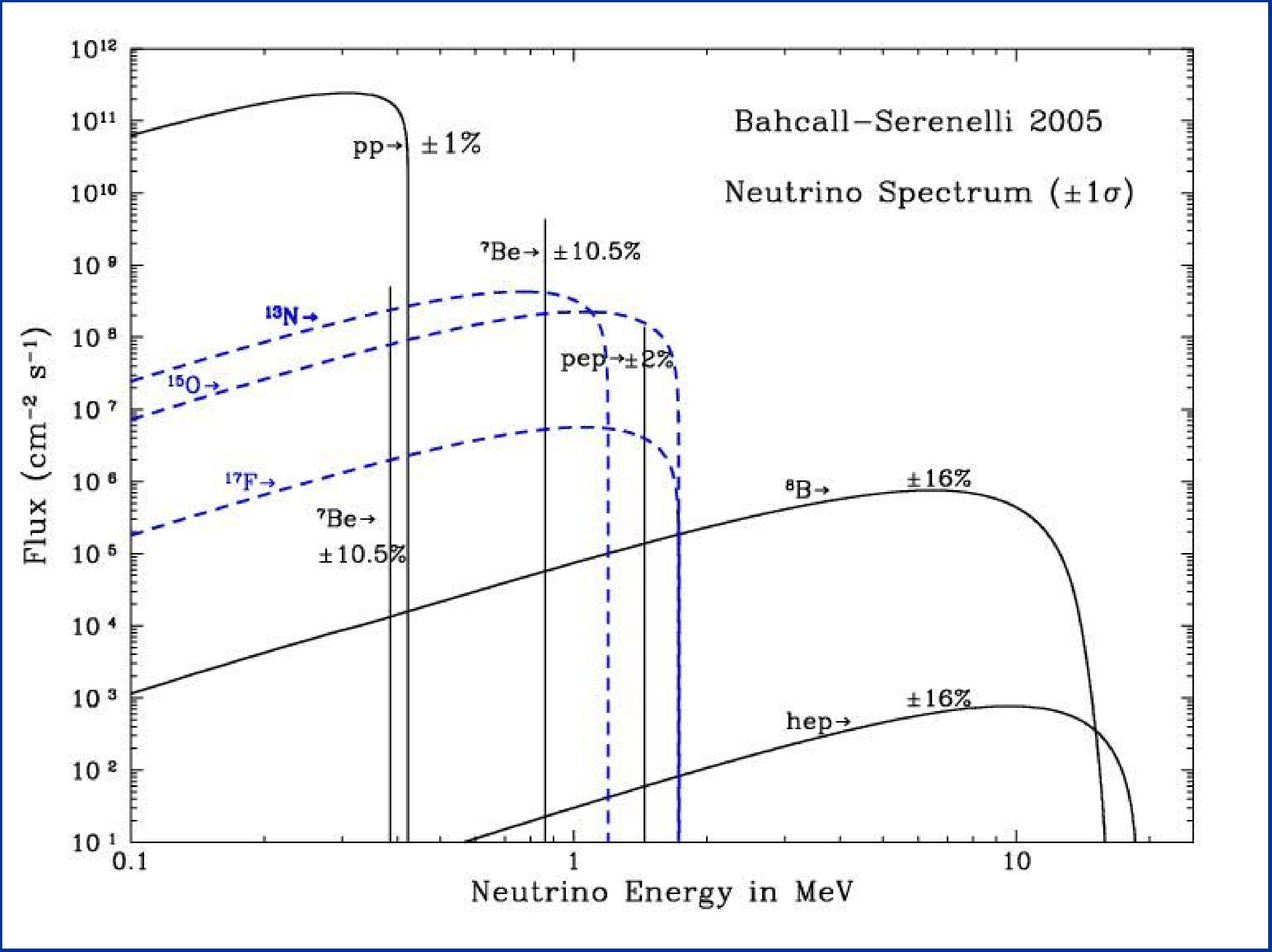
Neutrinos from the Sun: How many?

"Standard Solar Model"

- Main player: John Bahcall (1934-2005)
  - With help from Marc Pinsonneault, Sarbani Basu, Aldo Serenelli
- Combines all the knowledge that we have about atoms, molecules, plasma, nuclear reactions, thermodynamics, magnetohydrodynamics,…
- Predicts
  - Spectrum of e.m. radiation from the Sun, proton energy spectrum, speed of sound in the sun, …..neutrino energy spectrum
  - Compare predictions with observations, refine model
- All predictions agree with observations except neutrinos – way too few neutrinos observed – "Solar neutrino puzzle"

https://www.wikiwand.com/en/John_N._Bahcall
http://www.sns.ias.edu/~jnb/

Predicted neutrino spectrum



How to detect solar neutrinos?

- detection of neutrinos:
  - extreme challenge for the experiments of the mid-twentieth century –
  - Pauli's apology: "I have done a terrible thing. I have postulated a particle that cannot be detected."
- Bruno Pontecorvo (1946):
  - Suggests a radiochemical experiment based on $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ (mentioned solar neutrino detection using this method).
  - before the Reines-Cowan experiment.
- Ray Davis used this method

About Ar-37:
http://www.periodictable.com/Isotopes/018.37/index.p.full.html

1st Particle Astrophysics Experiment

<u>Homestake Experiment</u>
Ray Davis went to a gold mine in South Dakota

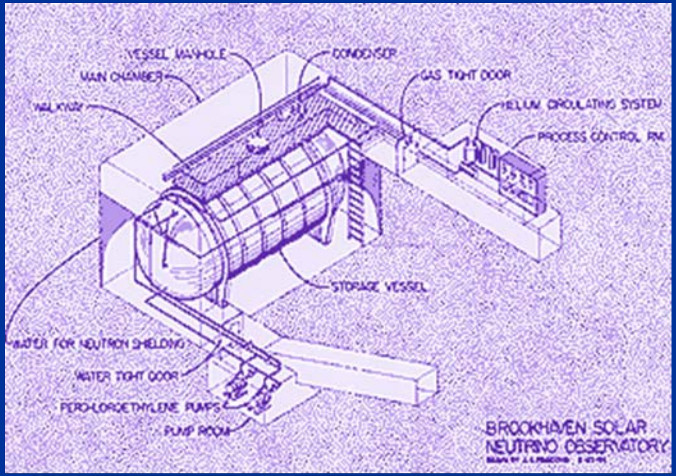
<u>His Idea:</u>

- Build a large detector to see rare interactions
- Bury it deep underground to avoid backgrounds
- Use sophisticated techniques (even by today's standards!) to detect individual electron neutrino captures

A true pioneer for particle astrophysics
We still use techniques he developed
LUX experiment uses the “Davis Cavern”, even his original water tank as a shield

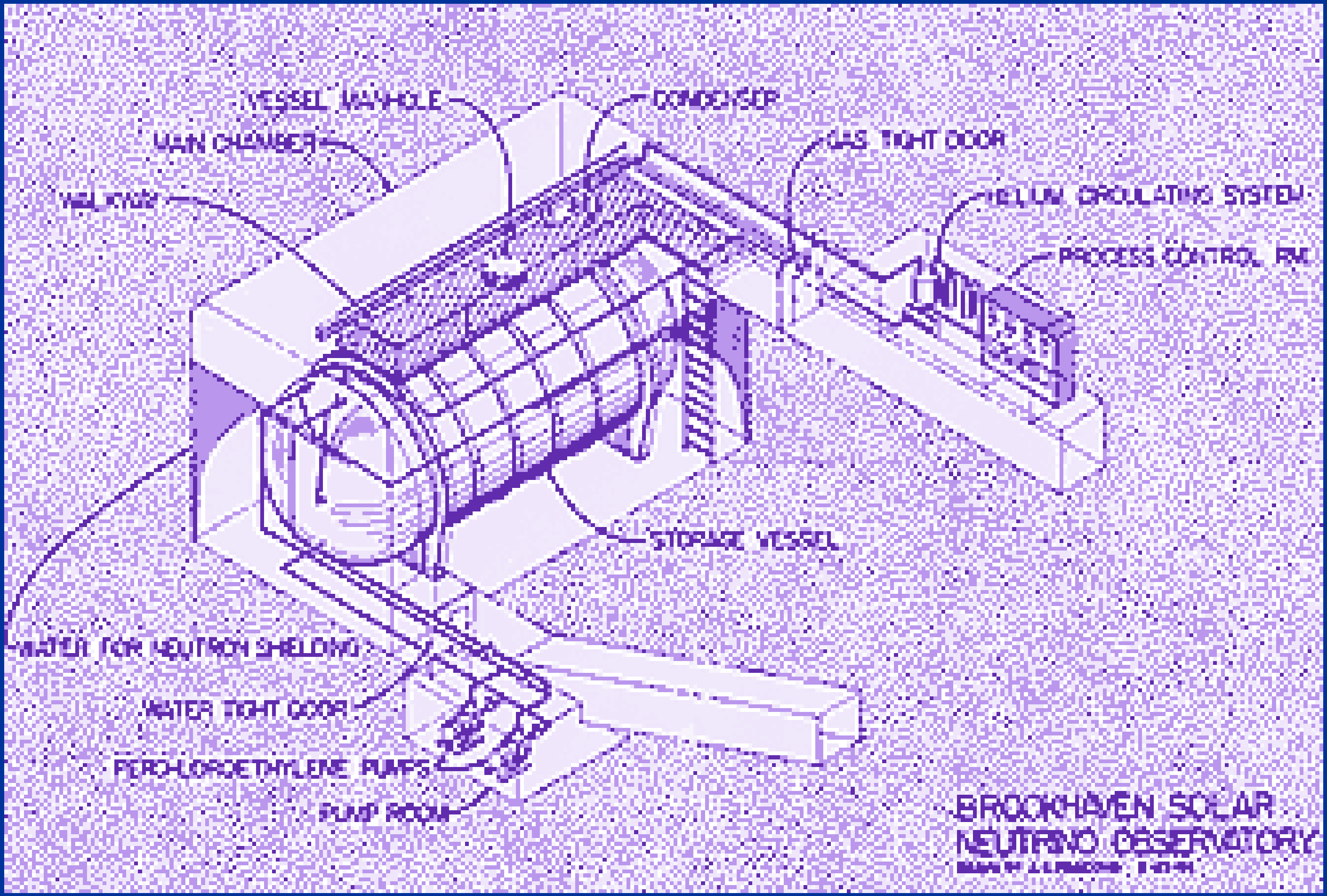
Ray Davis' neutrino detection

- Look for reaction $\nu_e \rightarrow {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
- Detector:
  - 380 m^3 (105 gallon) tank of dry cleaning fluid (Perchloroethylene (rich in Cl))
  - Reaction threshold, 0.814 MeV
  - Integrate neutrino flux above this energy



- Detection of Ar:
  - Bubble He through detector every few weeks
  - Flush Ar out
  - Collect Ar in a container
  - Take container out of mine
  - Detect decays of ^{37}Ar
  - Counting a handful of atoms from tons of material!

Ray Davis' Experiment



Ray Davis' experiment

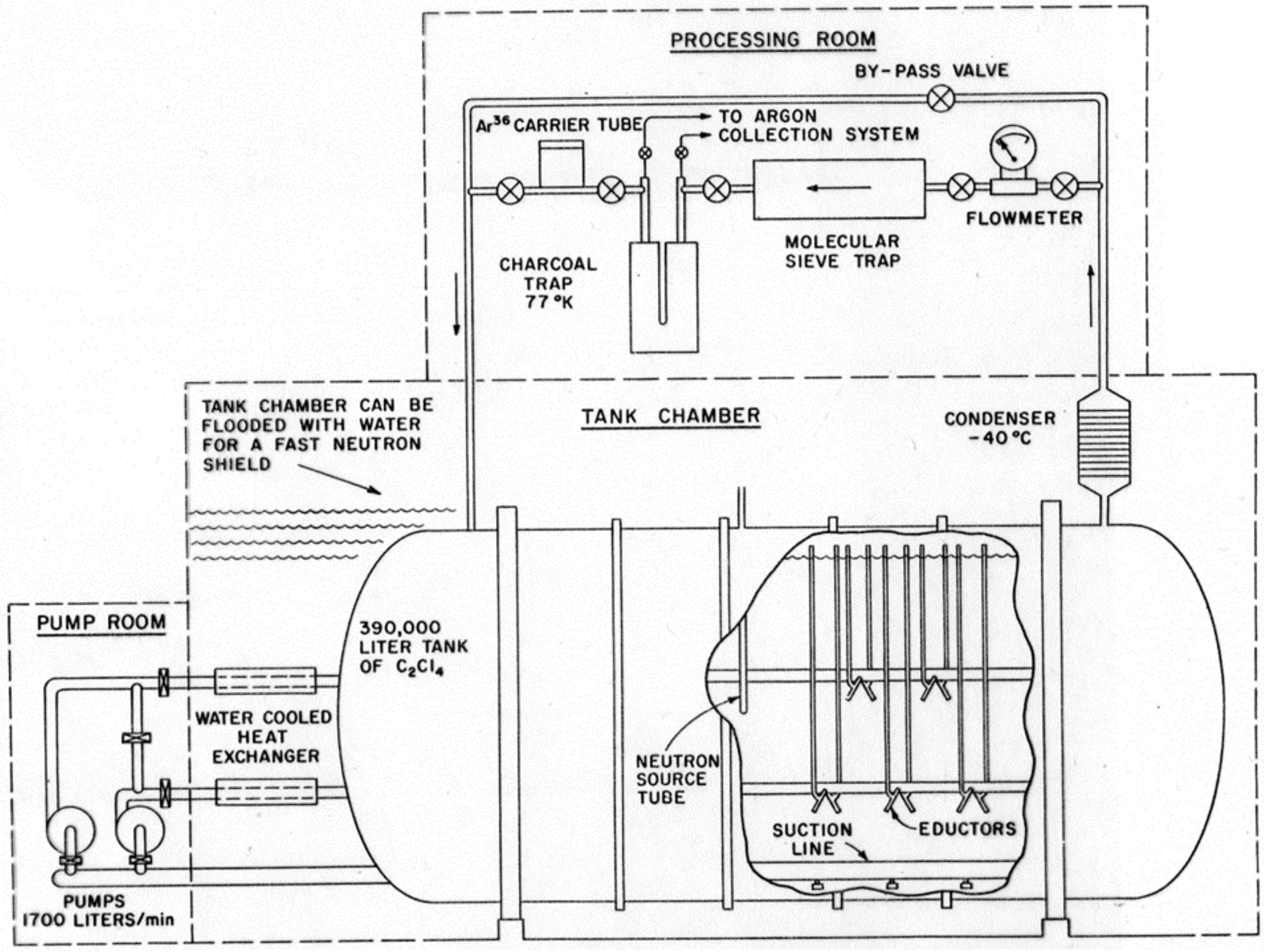
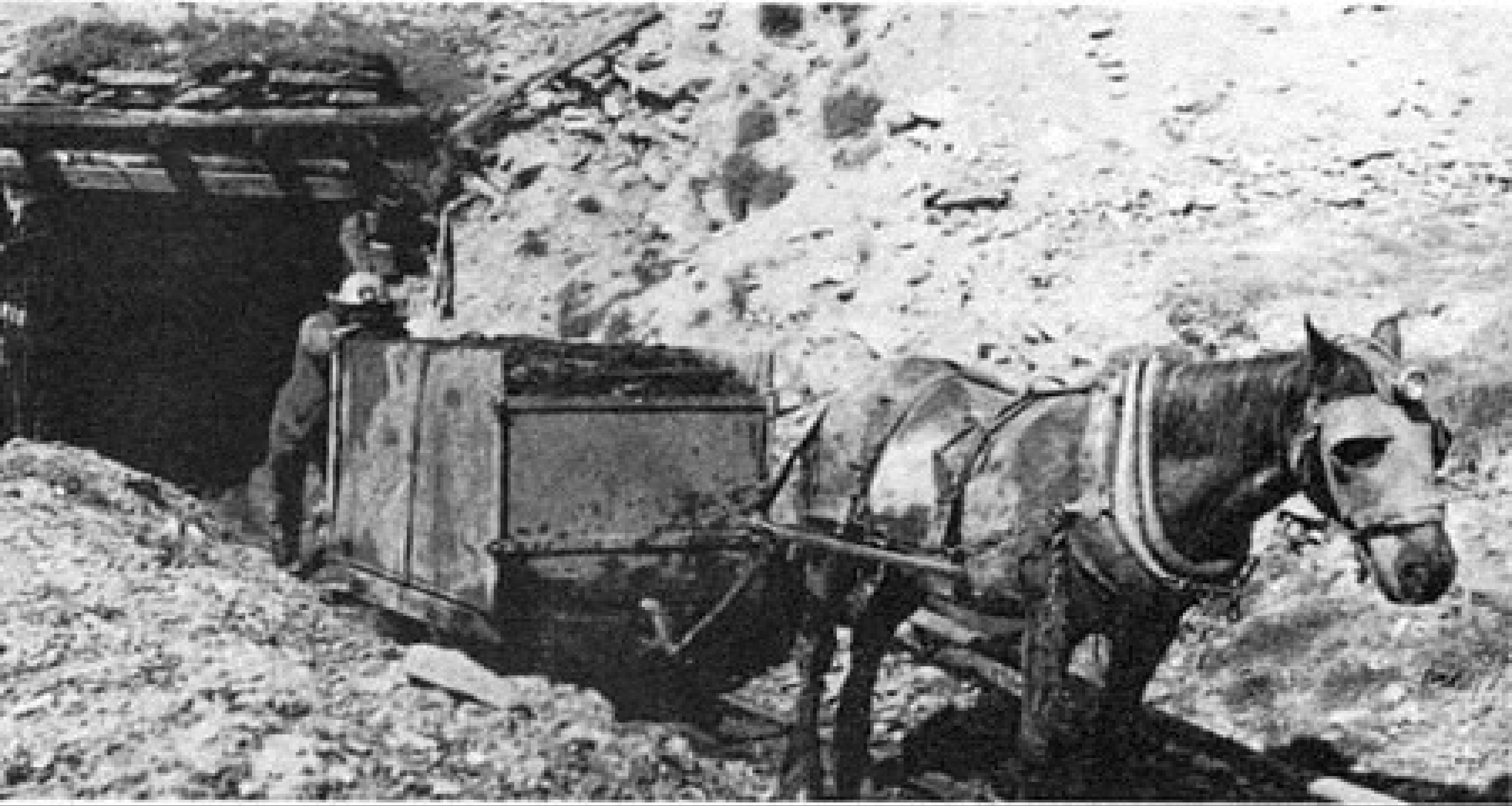


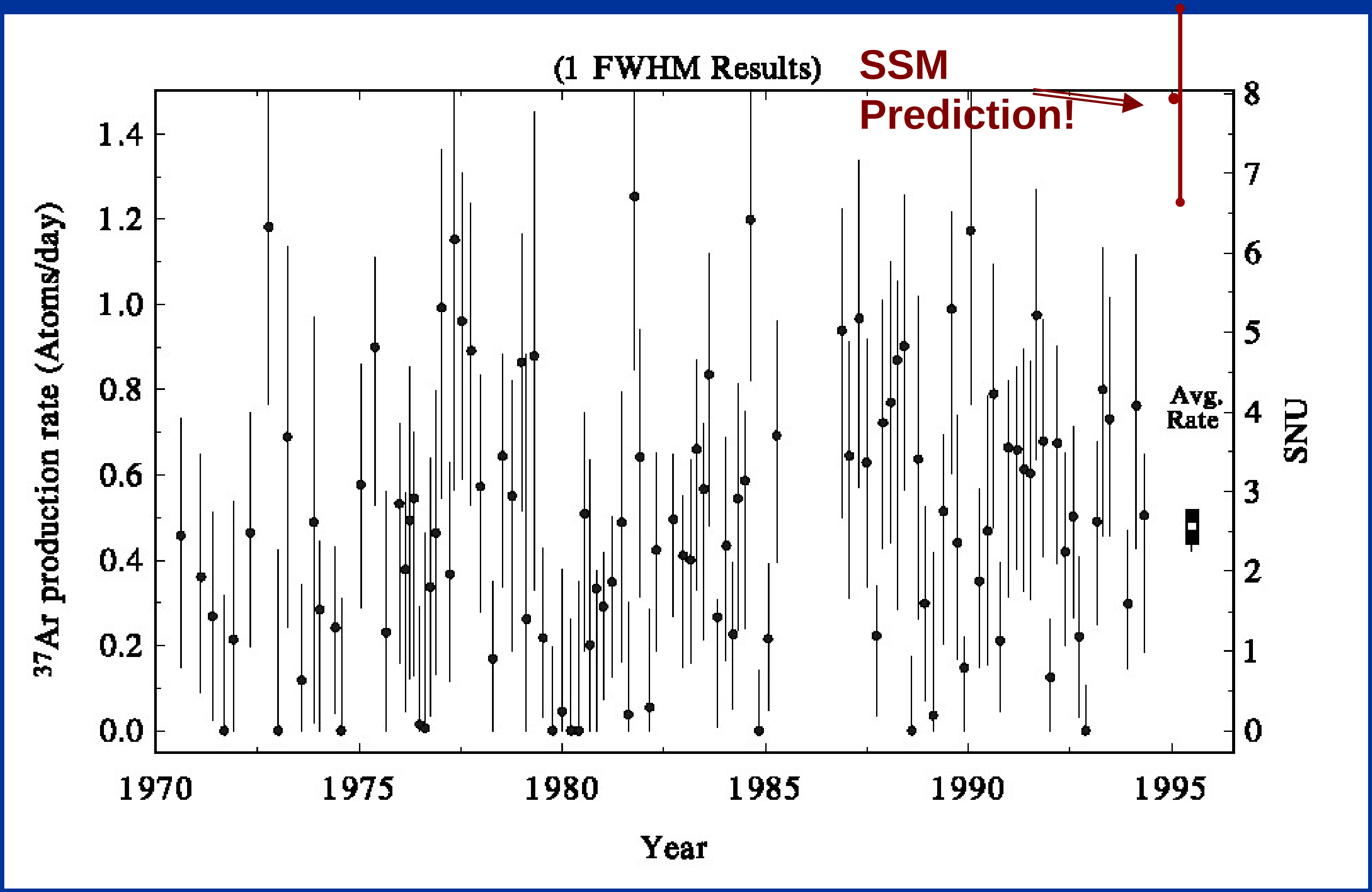
Figure 2.3. Schematic drawing of the argon recovery system. The pump-eductor system forces helium gas through the tetrachloroethylene liquid and provides the helium gas flow through the argon collection system.

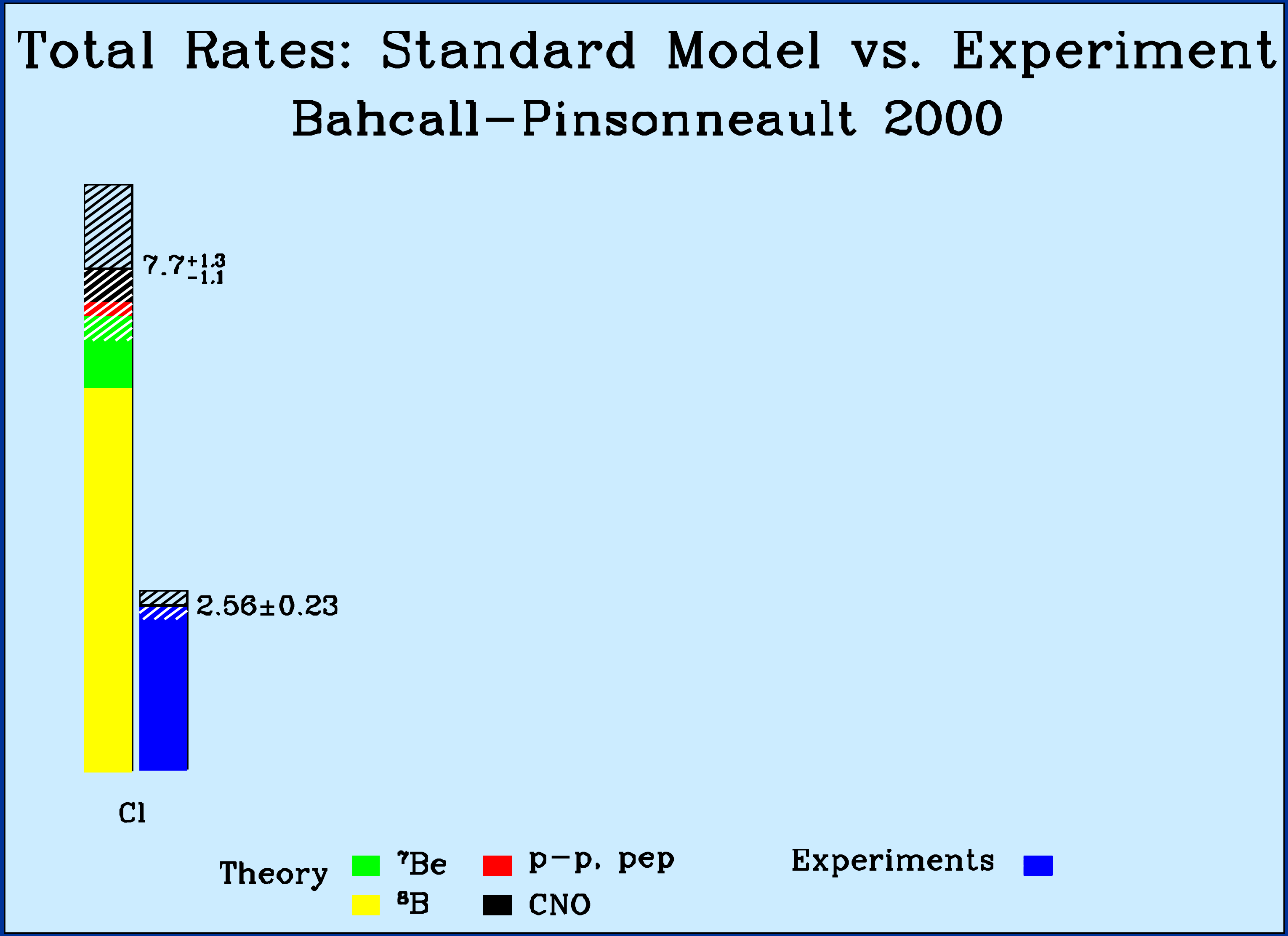
Argon counting in Ray Davis' experiment



- Every two months, Davis' graduate students bring out the Argon atoms and count them

Davis Experiment: Results





Maybe the experiment is wrong…

Result: Problem

- Measurements
  - over a quarter century, starting in 1968
  - using lots of graduates students and mules
  - Find: one third of the expected rate
- Reaction:
  - Experiment is wrong
  - Theory is wrong
- Many other experiments confirm findings

Results: The Solar Neutrino Problem

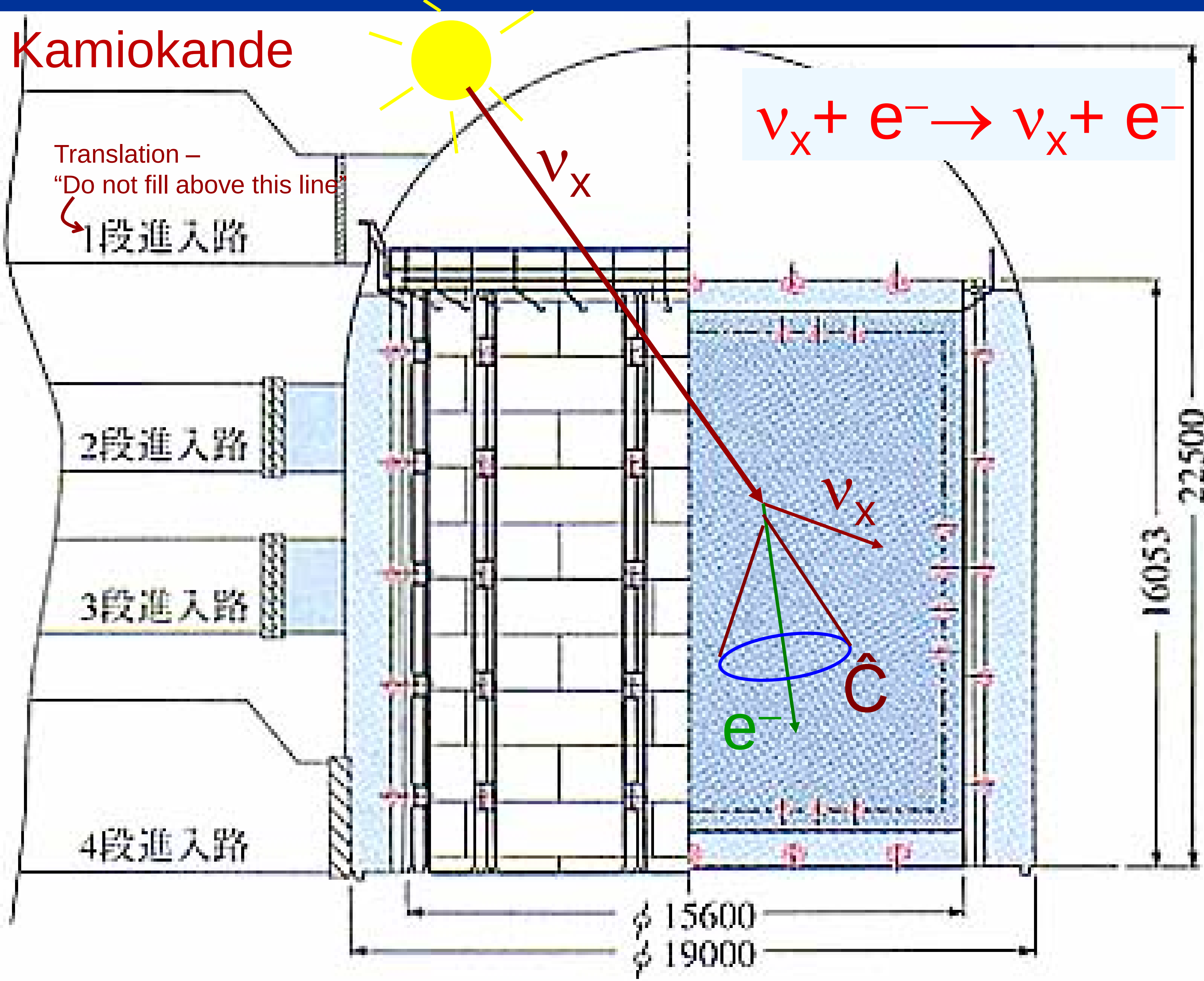
In 1968, Davis reported results
Solar neutrino flux factor 3 too low
This became the Solar Neutrino Problem

Why was the flux measurement too low?
- Did Davis undercount the ^{37}Ar atoms?
- Was Bahcall's solar model wrong?
- Do neutrino's behave differently than expected?

- Davis continued refining his measurement
  - Consistent results
  - Flux always too low
- Other experiments also measured solar neutrino deficit
  - Kamiokande, GALLEX, Sage
  - Between 1/3 and 2/3 expectation

Crazy hypothesis: Neutrinos have mass!

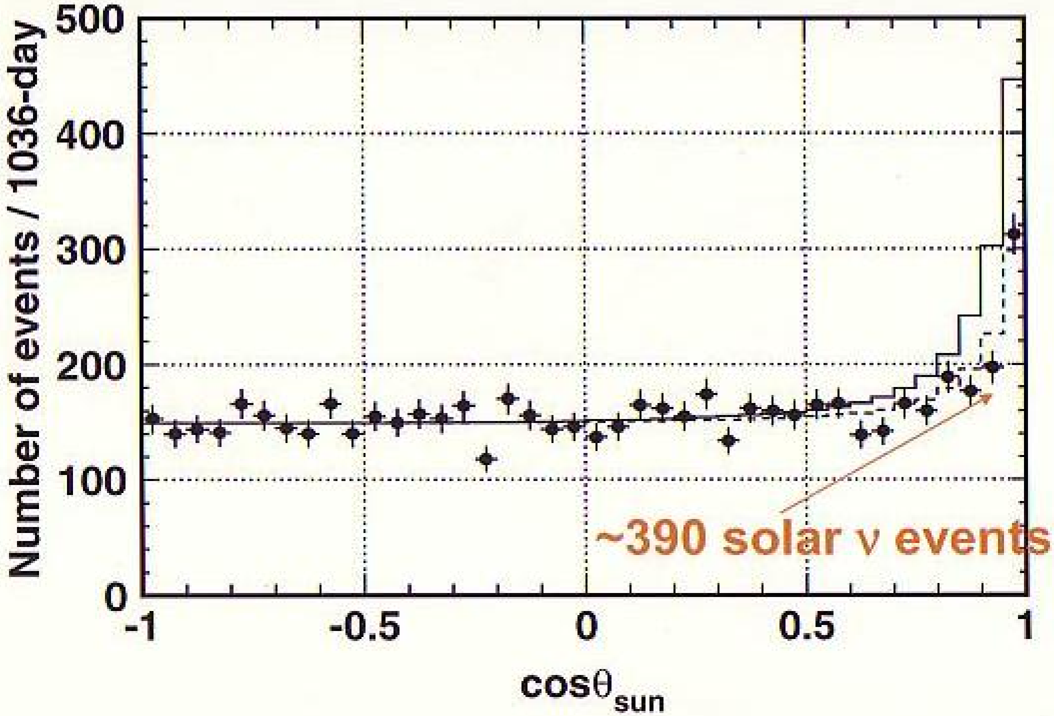
Kamiokande



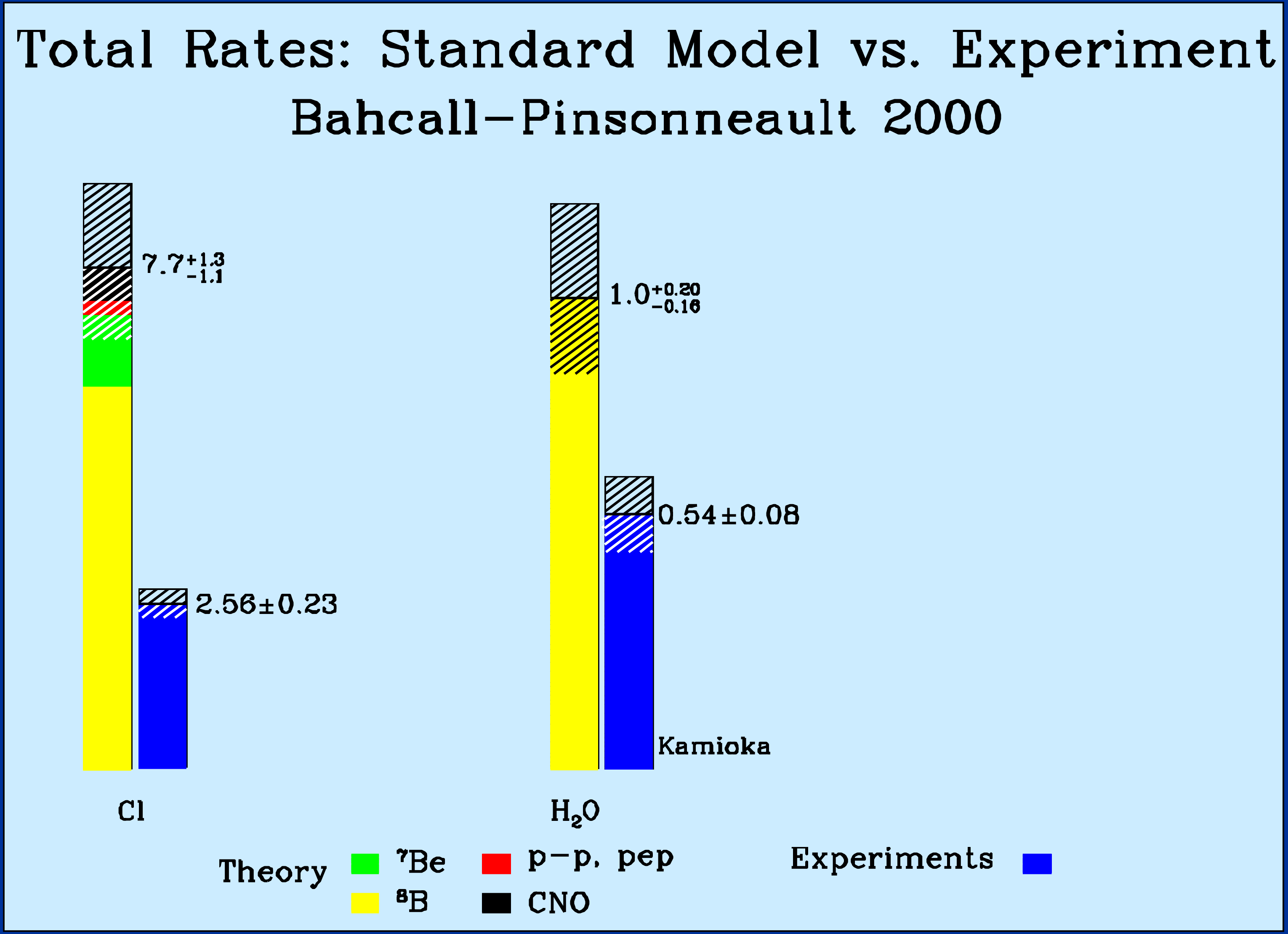
$\nu_x + e^- \rightarrow \nu_x + e^-$
Translation –
“Do not fill above this line”
1段進入路
2段進入路
3段進入路
4段進入路
ν_x
ν_x
e^-
Ĉ
16053
22500
ϕ 15600
ϕ 19000

Solar neutrinos (Kamiokande-III)

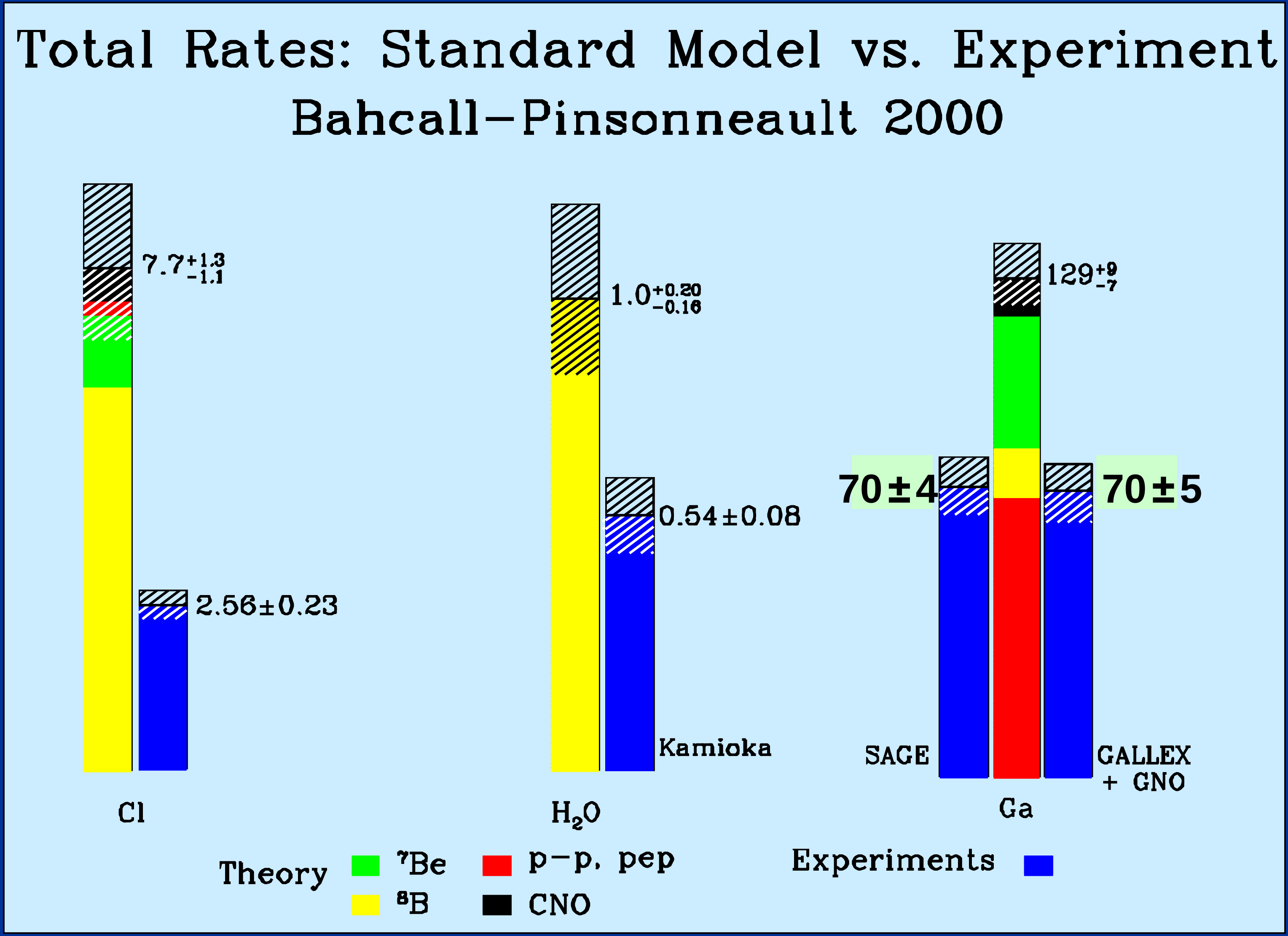
Dec. 28, 1990 – Feb. 6, 1995 (1036 days)



Y.Fukuda et al., Phys. Rev. Lett. 77 (1996) 1683



Total Rates: Standard Model vs. Experiment
Bahcall−Pinsonneault 2000
$7.7^{+1.3}_{-1.1}$
2.56±0.23
$1.0^{+0.20}_{-0.16}$
0.54±0.08
Kamioka
Cl
H_2O
Theory
^{7}Be
^{8}B
p−p, pep
CNO
Experiments


Total Rates: Standard Model vs. Experiment
Bahcall-Pinsonneault 2000
7.7 +1.3 −1.1
2.56±0.23
1.0 +0.20 −0.16
0.54±0.08
Kamioka
129 +9 −7
70±4
70±5
SAGE
GALLEX + GNO
Cl
H2O
Ga
Theory
7Be
8B
p−p, pep
CNO
Experiments

Theoretical ideas

- 1957 – Bruno Pontecorvo:
  - Suggests possibility of neutrino - anti-neutrino oscillations
- 1962 – Maki, Nakagawa, and Sakata:
  - (in the context of what looks today like a very odd model of nucleons) proposed that the weak neutrinos known at the time were superpositions of “true” neutrinos with definite masses, and that this could lead to transitions between the different weak neutrino states.
- 1967 – Pontecorvo:
  - considered the effects of all different types of oscillations in light of what was then known,
  - pointed out (before any results from the Davis experiment were known) that the rate in that experiment could be expected to be reduced by a factor of two!
- 1972 – Pontecorvo is informed by John Bahcall that Davis does indeed see a reduced rate, and responds with a letter….

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Москва, Главный почтамт п/я 79. Head Post Office, P.O. Box 79, Moscow, USSR

№ 994/31 April 6/10 1972

Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. It starts to be really interesting! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately, it will not be easy to demonstrate this, even if nature works that way.

looking forward to see you there.

Yours sincerely,

B Pontecorvo

B.Pontecorvo

BMP/nn

2ν Vacuum Oscillations

- For two neutrino flavors in vacuum: oscillations lead to the appearance of a new neutrino flavor:

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

$$\Delta m^2 = m_2{}^2 - m_1{}^2 \text{ in eV}^2\text{, L in meters, E in MeV}$$

- With the corresponding disappearance of the original neutrino flavor
- These oscillations can be significantly modified by the MSW effect when the neutrinos pass through matter…

MSW =Mikheyev–Smirnov–Wolfenstein, see e.g.
https://www.wikiwand.com/en/Mikheyev%E2%80%93Smirnov%E2%80%93Wolfenstein_effect
http://hepwww.rl.ac.uk/ricciardi/Lectures/MSW-1.pdf

Mass vs Flavor Eigenstates

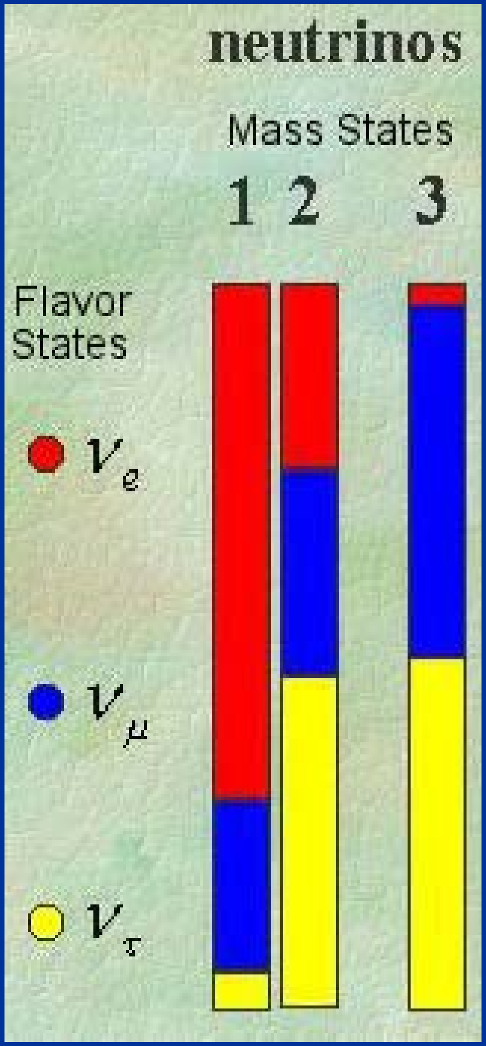
Flavor eigenstates ≠ Mass eigenstates
Flavor states are superposition of mass states

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

Mixing matrix U parametrized by:
- 3 angles (θ_{12}, θ_{13}, θ_{23}) that describe mixing
- complex phases (not discussed here)

Flavor states are not eigenstates of the Hamiltonian
- They are not the states that propagate!
- Those would be the mass eigenstates

- We can create and detect flavor states:
  - Electron, muon, tau neutrinos
- Created as superposition of mass states
- The phases change with time
- Consequence: Neutrinos change flavor!

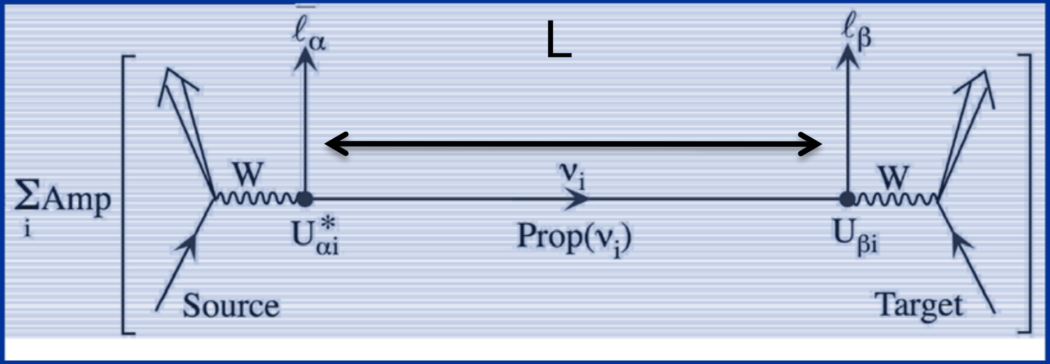


Neutrino oscillations

Neutrinos are produced and detected via weak interactions as flavor states:

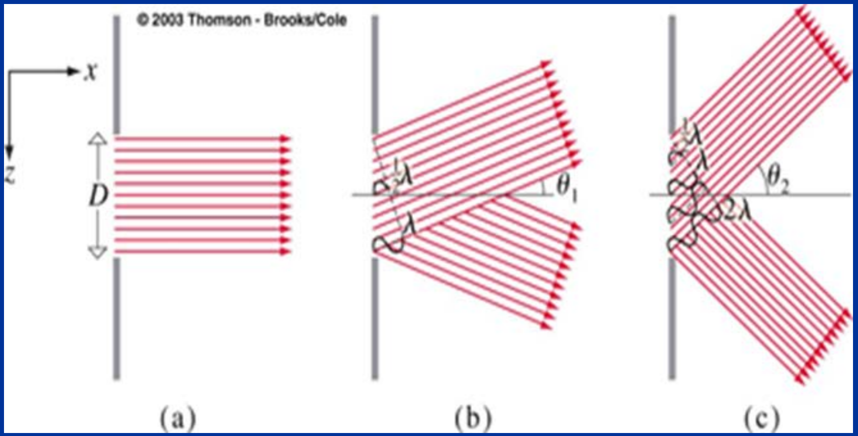
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}^{*} |\nu_i\rangle, \quad \alpha = e, \mu, \tau$$

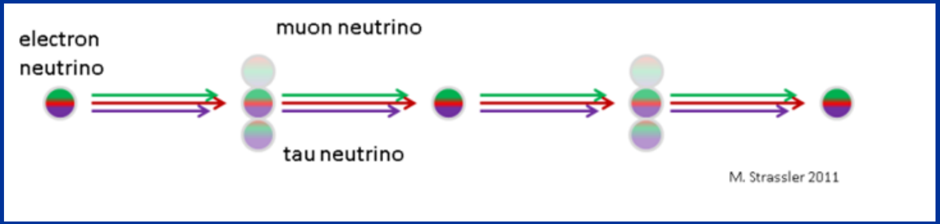
A neutrino experiment is an interferometer in flavor space, because neutrinos are so weakly interacting that they can keep coherence over very long distances !



Neutrino oscillations

- Interference:
  - Recall single slit diffraction
  - Probability to measure light depends on phase
- Neutrino oscillations behave similarly
  - Difference in phase for different mass eigenstates
  - Not due to path difference
  - Due to difference in mass squared
  - Time dependence of mass state depends on mass
  - Probability for an electron neutrino to be detected as an electron neutrino depends on phase





Example: 2 Neutrinos

Mass and flavor states connected by 2×2 matrix
Single parameter, θ ("mixing angle")

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Propagation:
$|\Psi(t)\rangle = e^{-i\,Ht}\,|\Psi(0)\rangle$

Using this, and the eigenvalues of H, the electron neutrino disappearance probability can be derived:

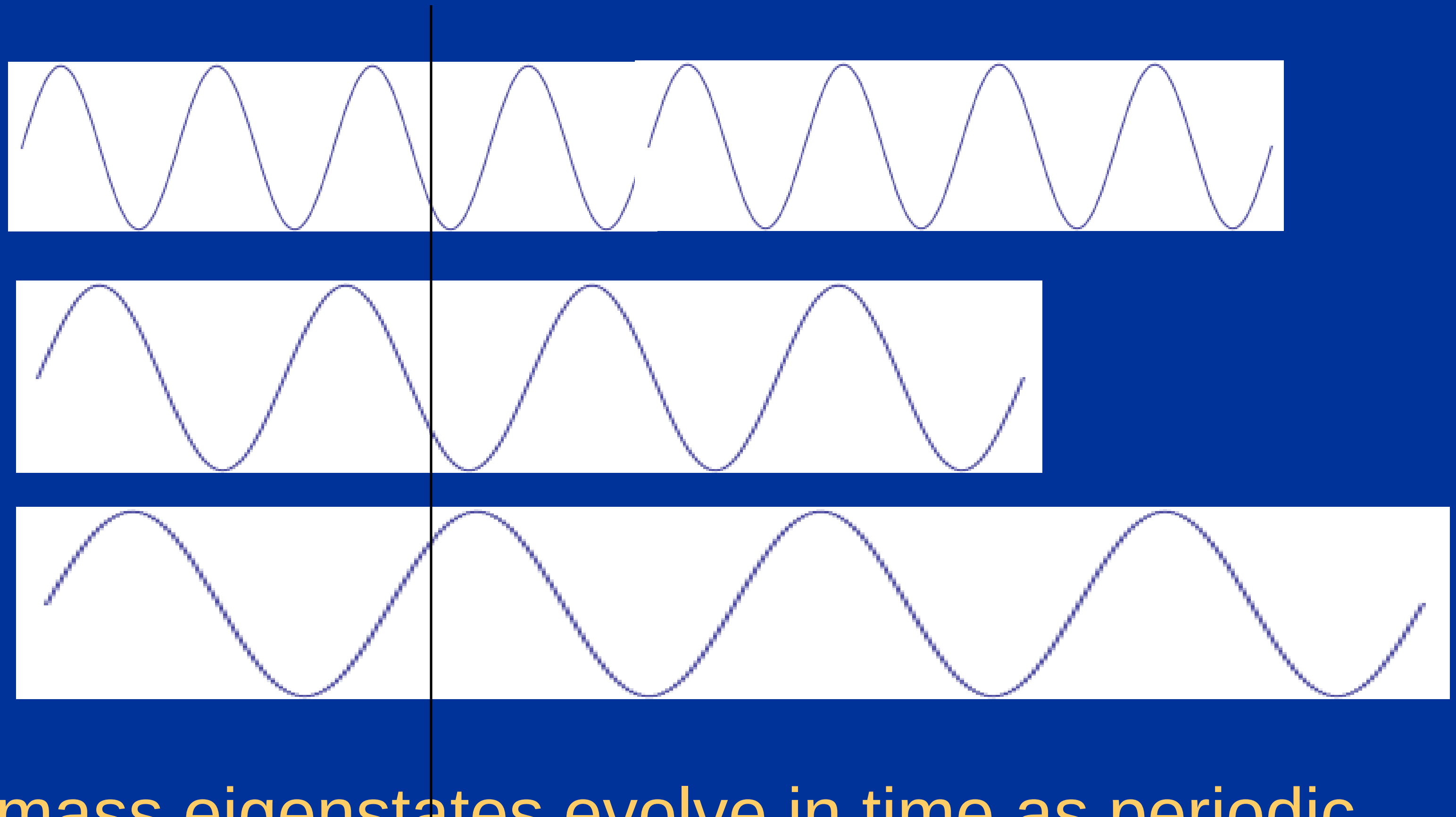
$$P_{\alpha\to\beta} = sin^2(2\theta) sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Two important features:
Mixing angle θ comes from mixing matrix U
Phase depends on Δm^2, difference in mass squared

The (real) 3 neutrino case is similar, just more terms:

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right),$$

Oscillation, superposition



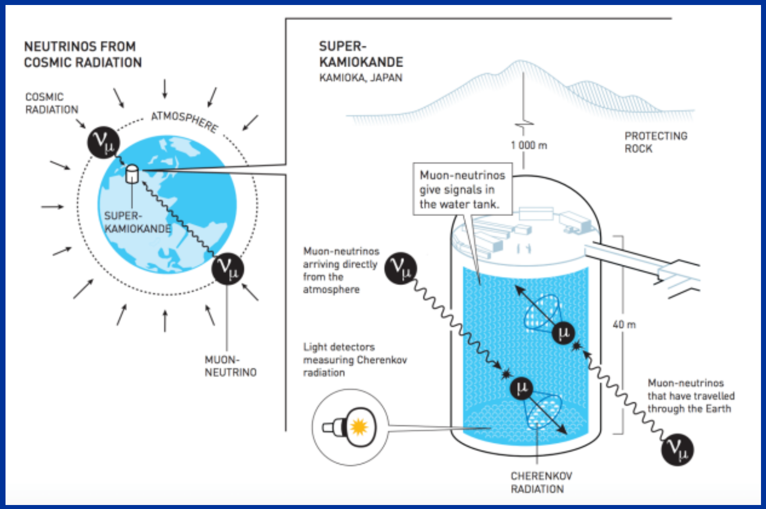
- 3 mass eigenstates evolve in time as periodic function, with mass dependent frequency ($\propto$ mass)

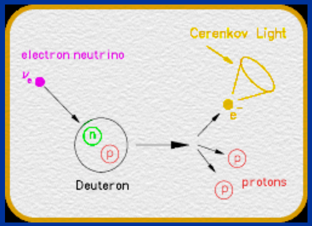
Measuring Neutrino Oscillations

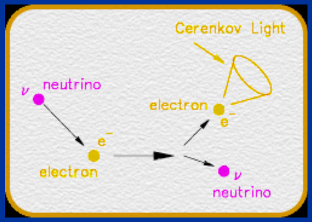
Must demonstrate that neutrinos change flavor (not just a deficit)
Two methods discussed here:

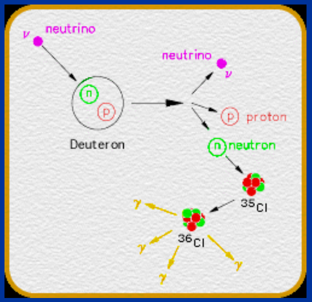
Measure neutrinos generated at different distance
Probe P as function of L
Super Kamiokande (S-K)

Measure electron neutrino flux and total neutrino flux from the sun
Sudbury Neutrino Observatory (SNO)



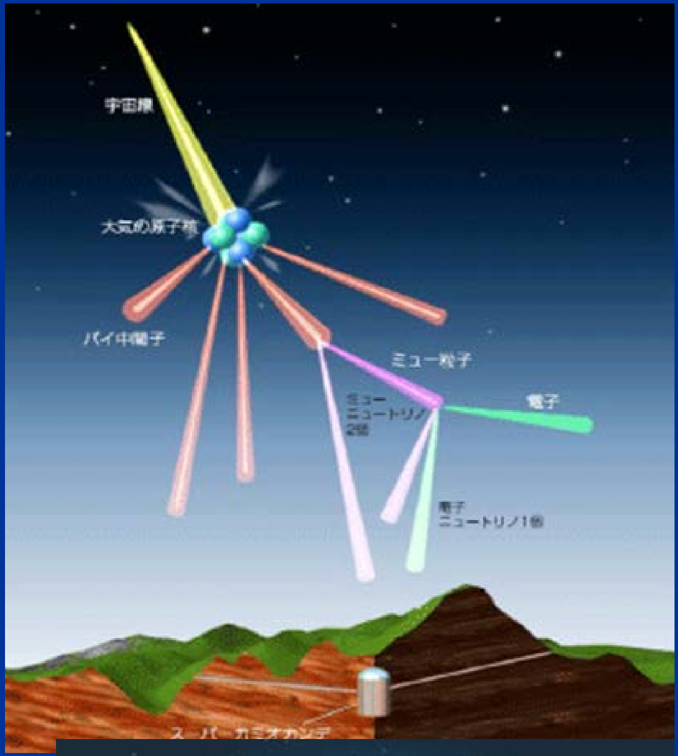


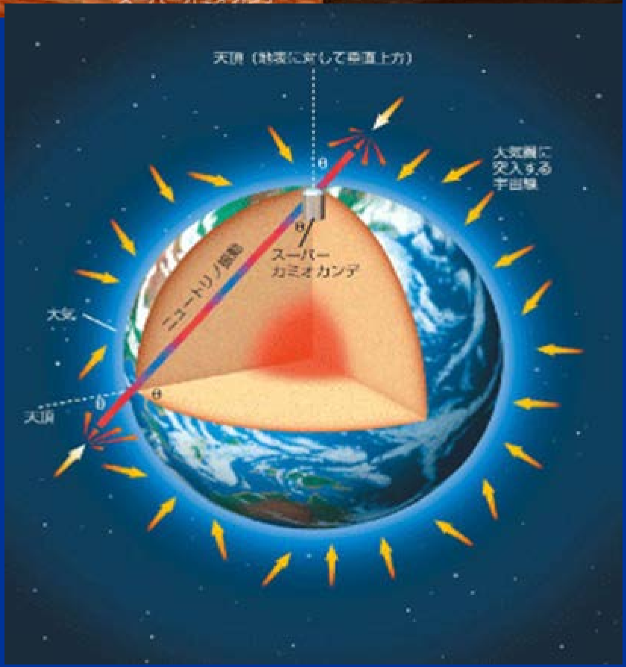




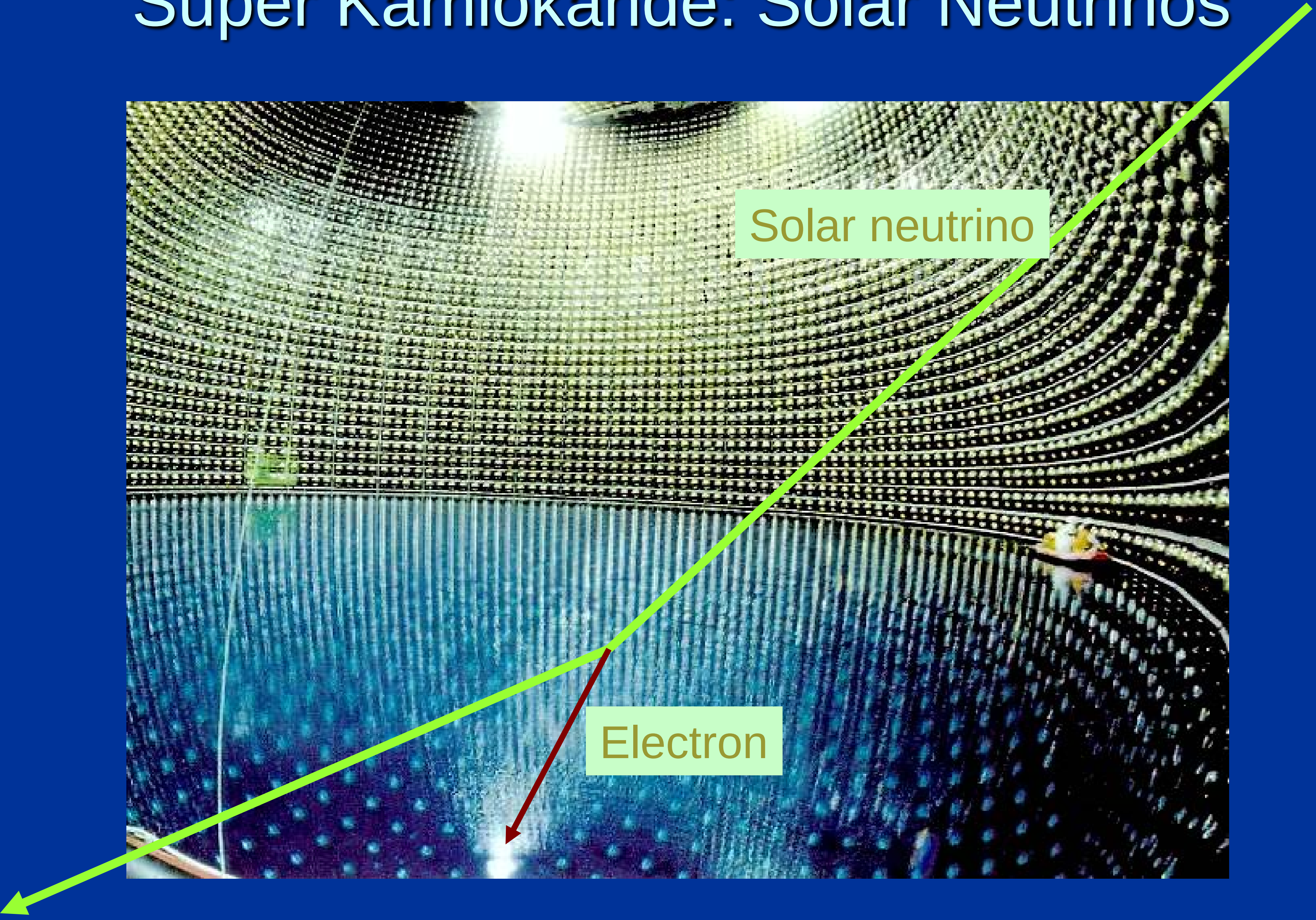
Super Kamiokande (Super K)

- Neutrino observatory in the Kamioka mine in Japan
- upgrade of successful Kamiokande experiment
- Muons produced by cosmic rays in atmosphere:
  - Since neutrinos pass right through the earth, a directional detector can measure muon neutrino flux vs zenith
  - Difference in path length
  - = difference in phase
  - = difference in oscillation probability

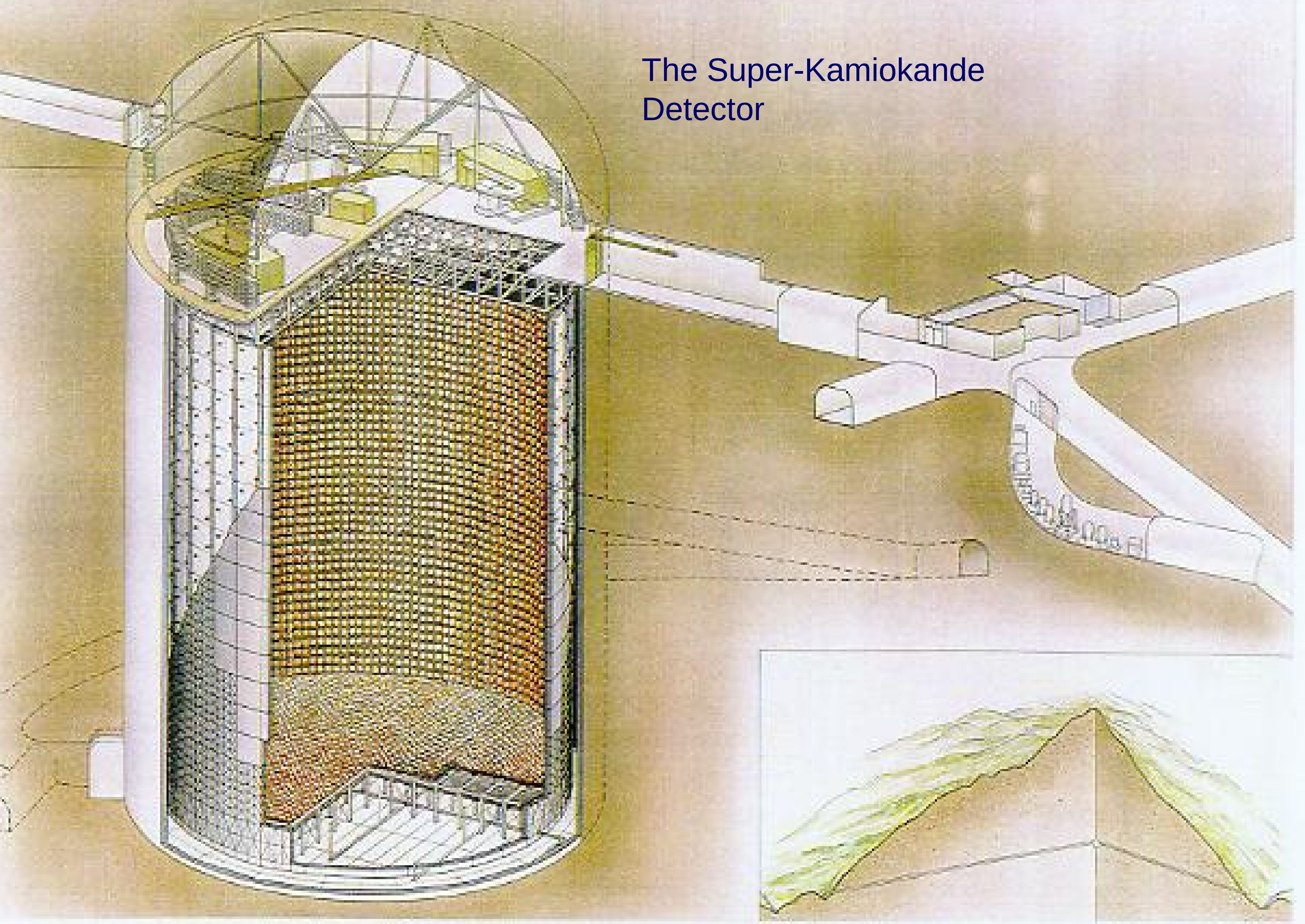




Super Kamiokande: Solar Neutrinos

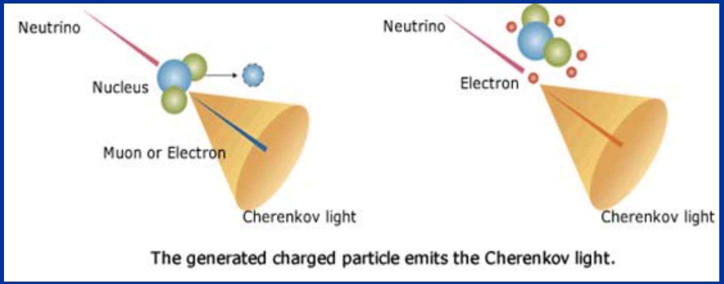


The Super-Kamiokande Detector

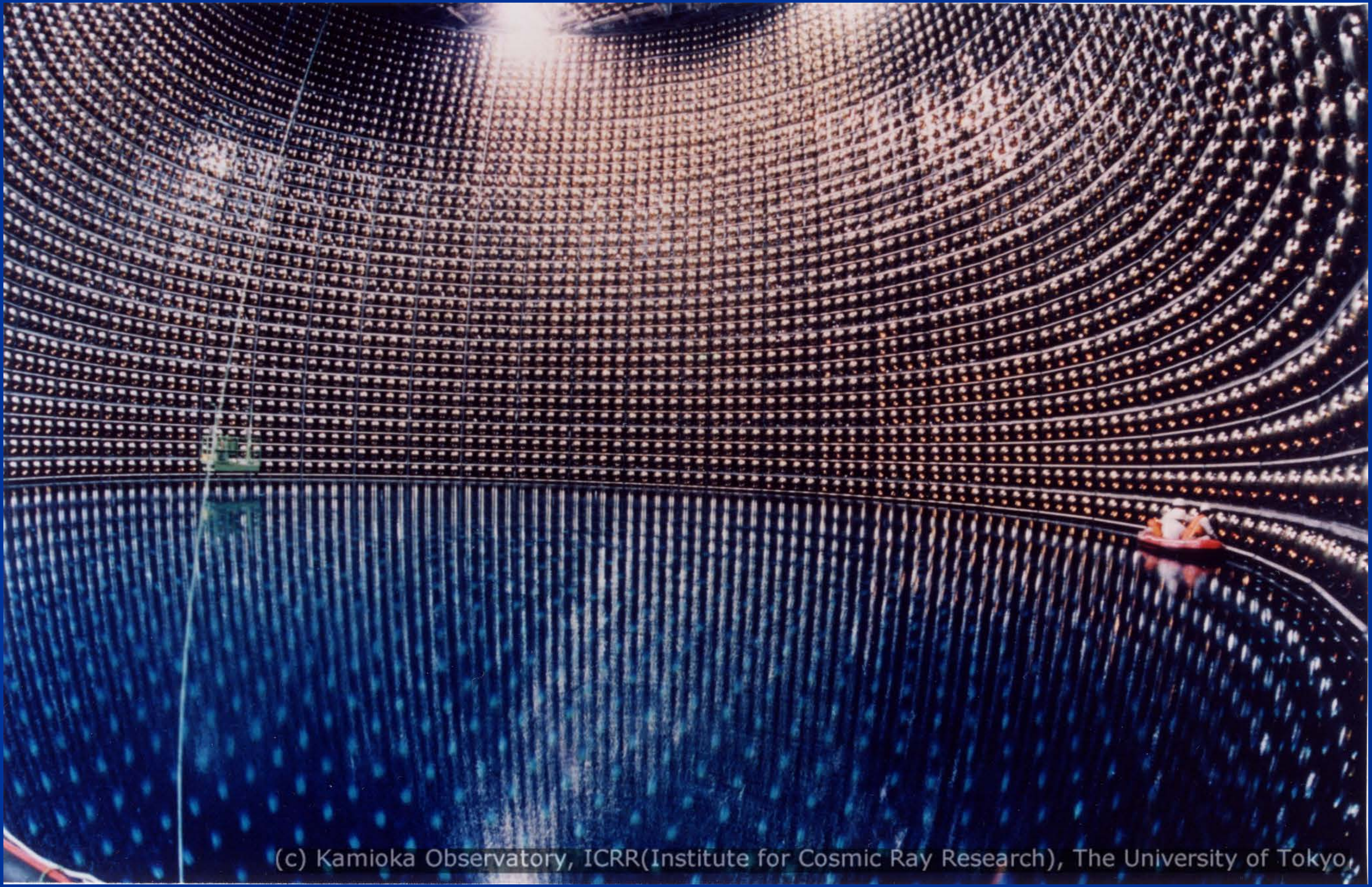


Super-K Detection Concept

- 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)
- $\Rightarrow$ cone of Cherenkov light
- Same principle as a sonic boom
- Light is detected by photo sensors



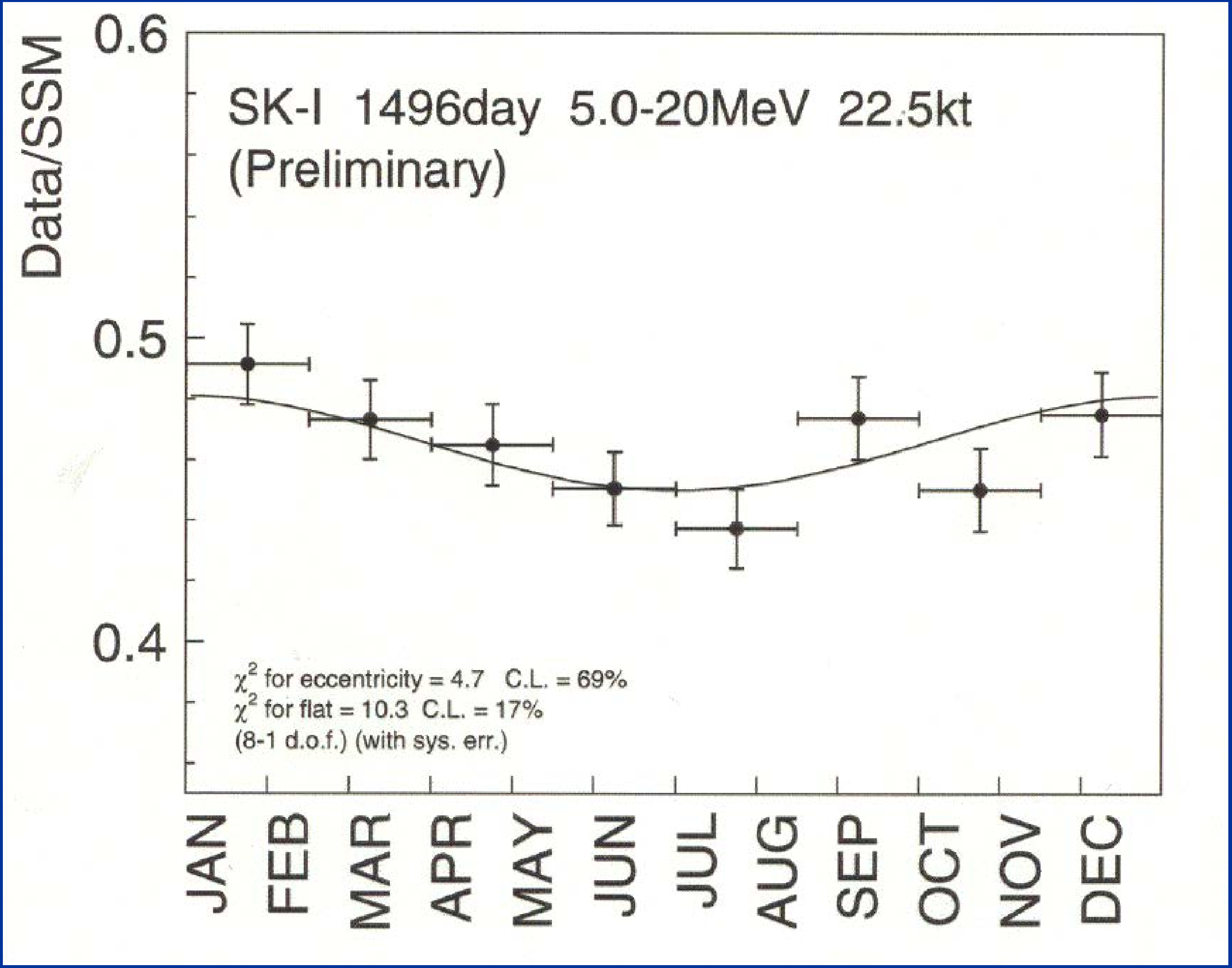
Super K detector



Super Kamiokande 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 seasonal variation

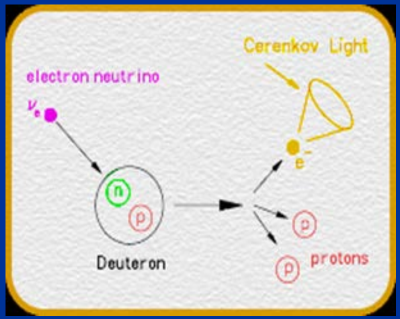


Sudbury Neutrino Observatory (SNO)

- Look directly for solar neutrinos
- Measure electron neutrino flux
- Measure total neutrino flux

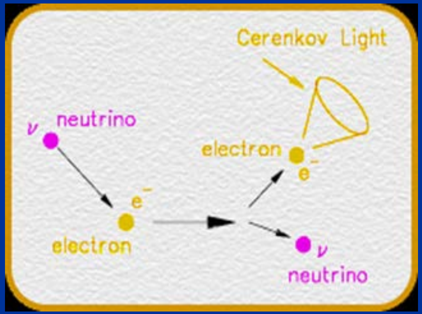
- Three interactions measured

- Ratio proves oscillation!



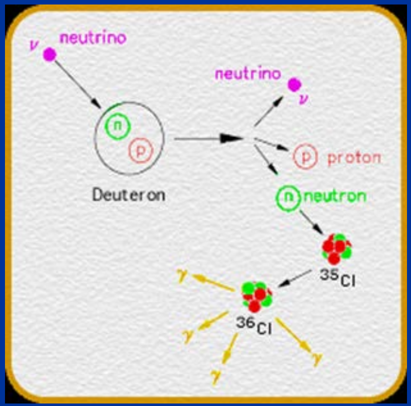
- Only ν_e
~ 30 events/day

$$\nu_e + d \to e^- + p + p \quad \text{(CC)}$$



- All ν flavors equally
~30 events/day

$$\nu_x + e^- \to \nu_x + e^- \quad \text{(ES)}$$

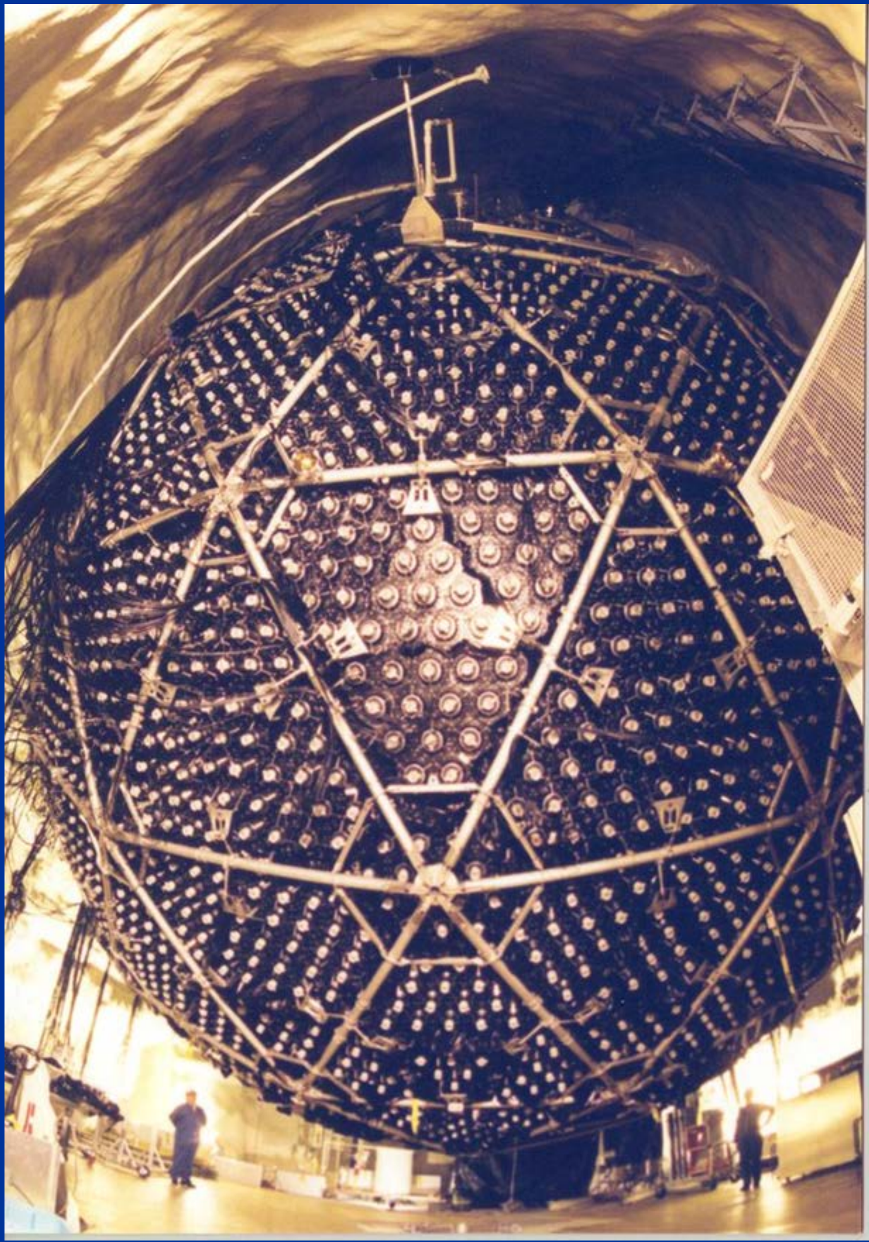


- All ν flavors, but favors ν_e by factor of 6
- ~3 events/day

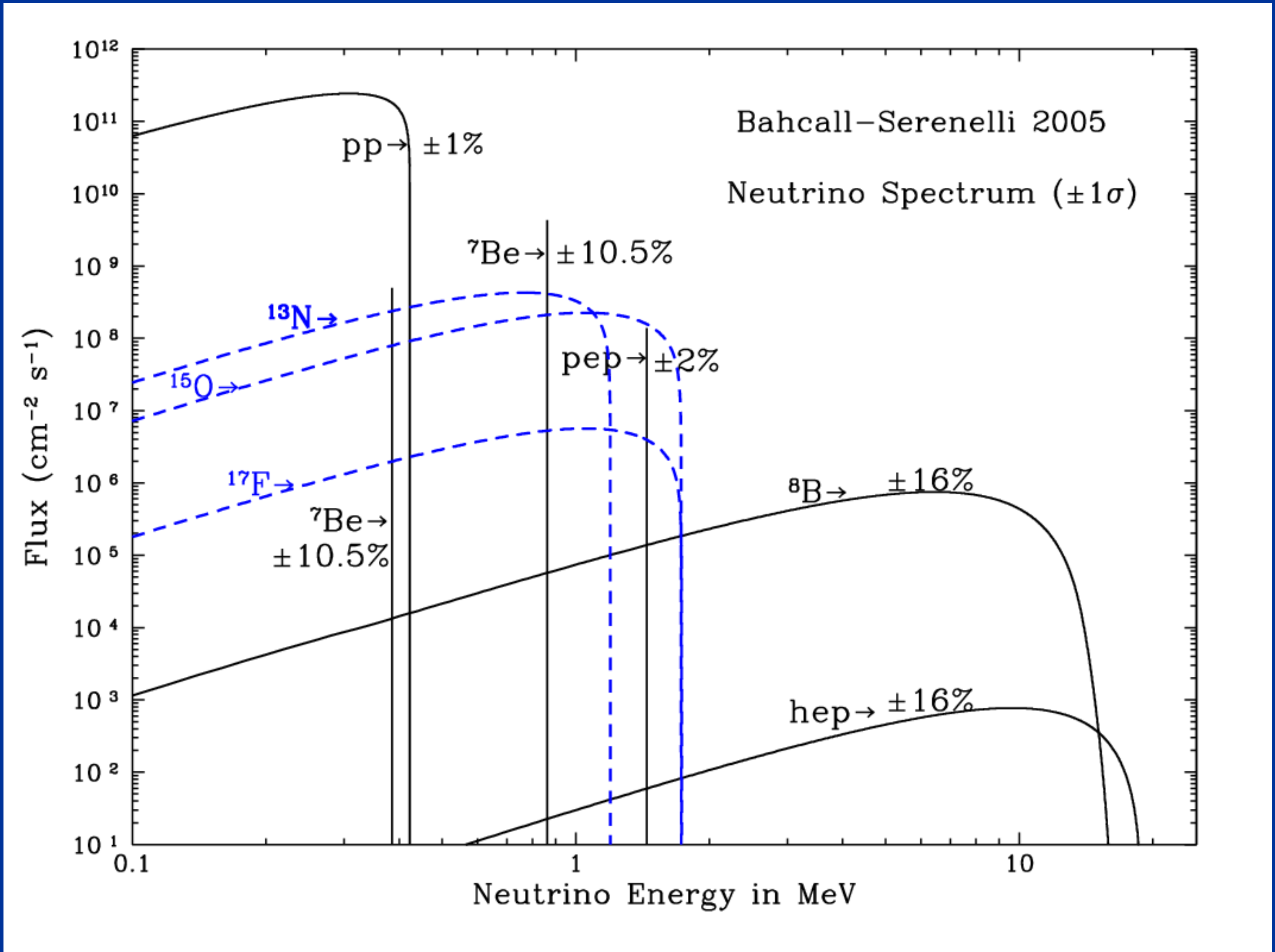
$$\nu_x + d \to \nu_x + p + n \qquad \text{(NC)}$$
$$n + {}^{35}Cl \to {}^{36}Cl^* \to {}^{36}Cl + 4\gamma$$

SNO Detector

- SNOLab:
  - underground laboratory in Sudbury, Ontario (Canada) inside an active nickel mine
- 12 m acrylic sphere
  - Filled with 1,000 tons of heavy water, D_2O
  - Doped with NaCl (in upgrade) for neutron capture on ^{35}Cl
- 10,000 PMTs mounted externally on an 18 m sphere
- Directional capability



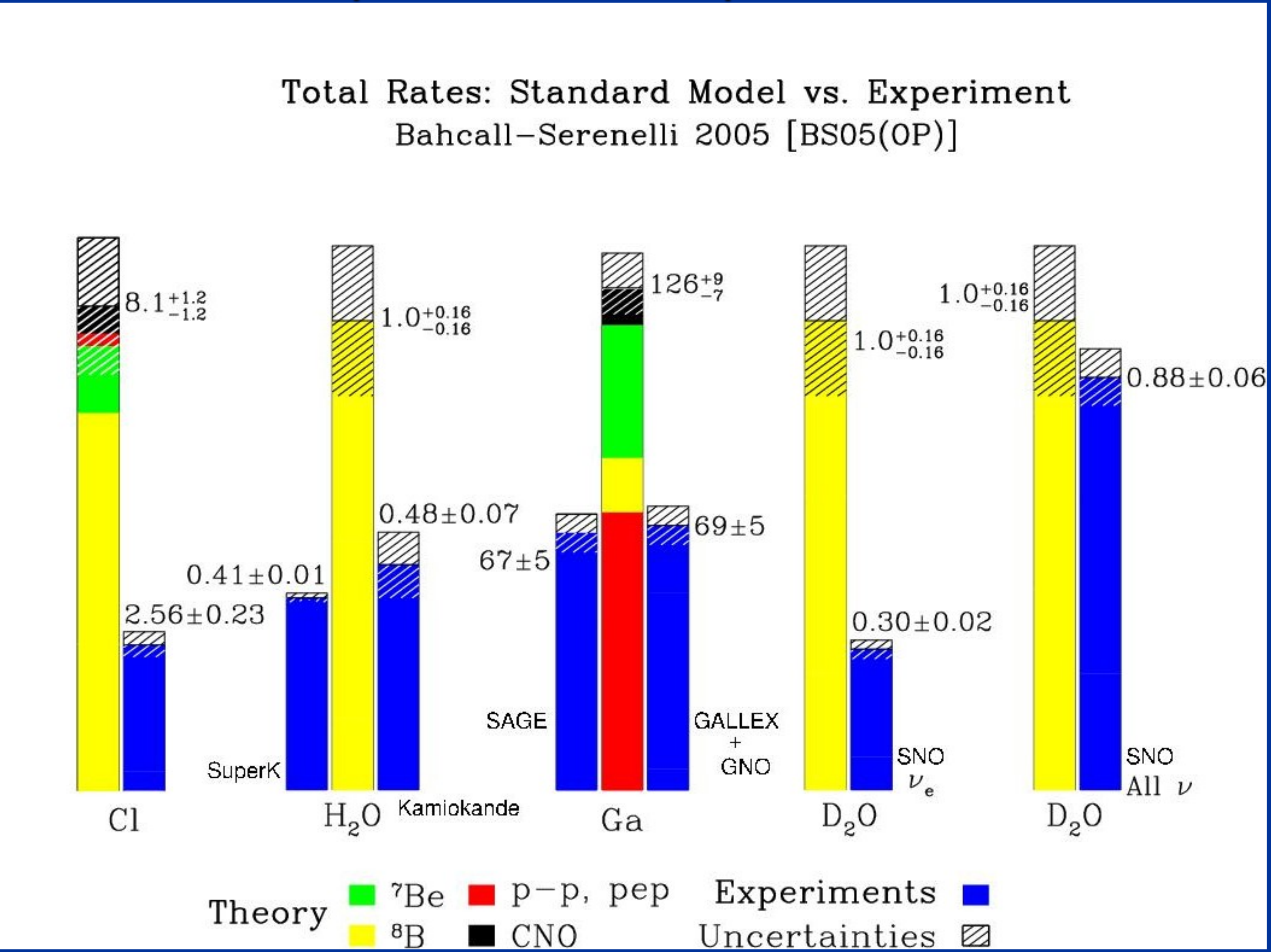
Standard Solar Model (2005)
Solar neutrino spectra



Neutrino oscillations observed

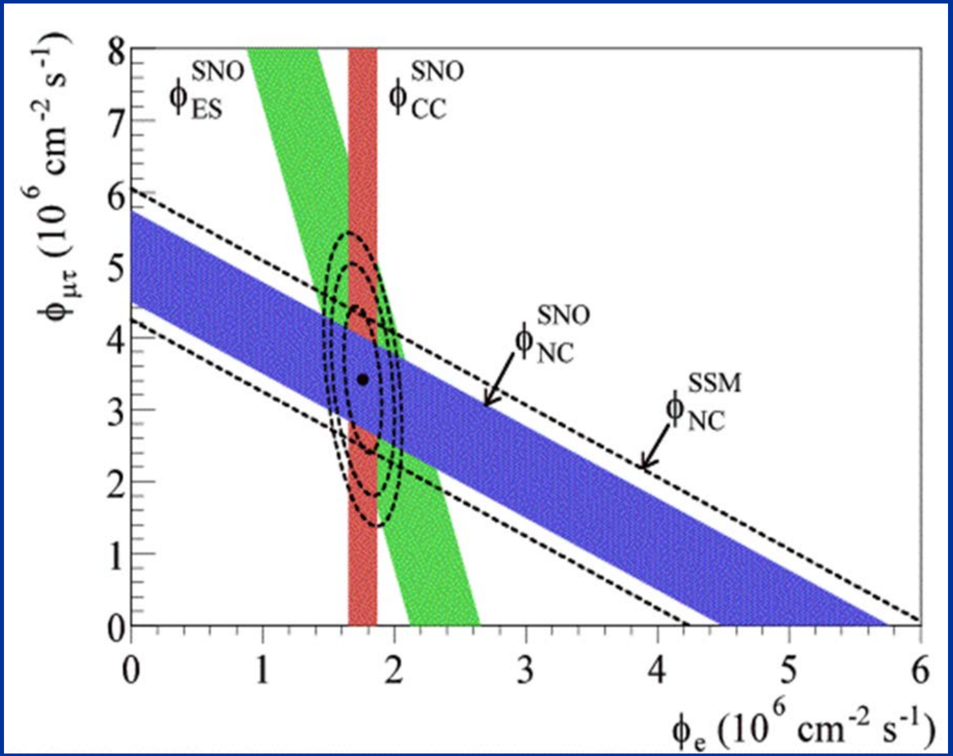
- Results from Super Kamiokande and SNO experiments
  - Not compatible with expectations if there are no neutrino oscillations
  - Confirm solar ν_e deficit
  - Are in agreement with predictions assuming neutrino oscillations
  - Give estimates for phases and mass differences

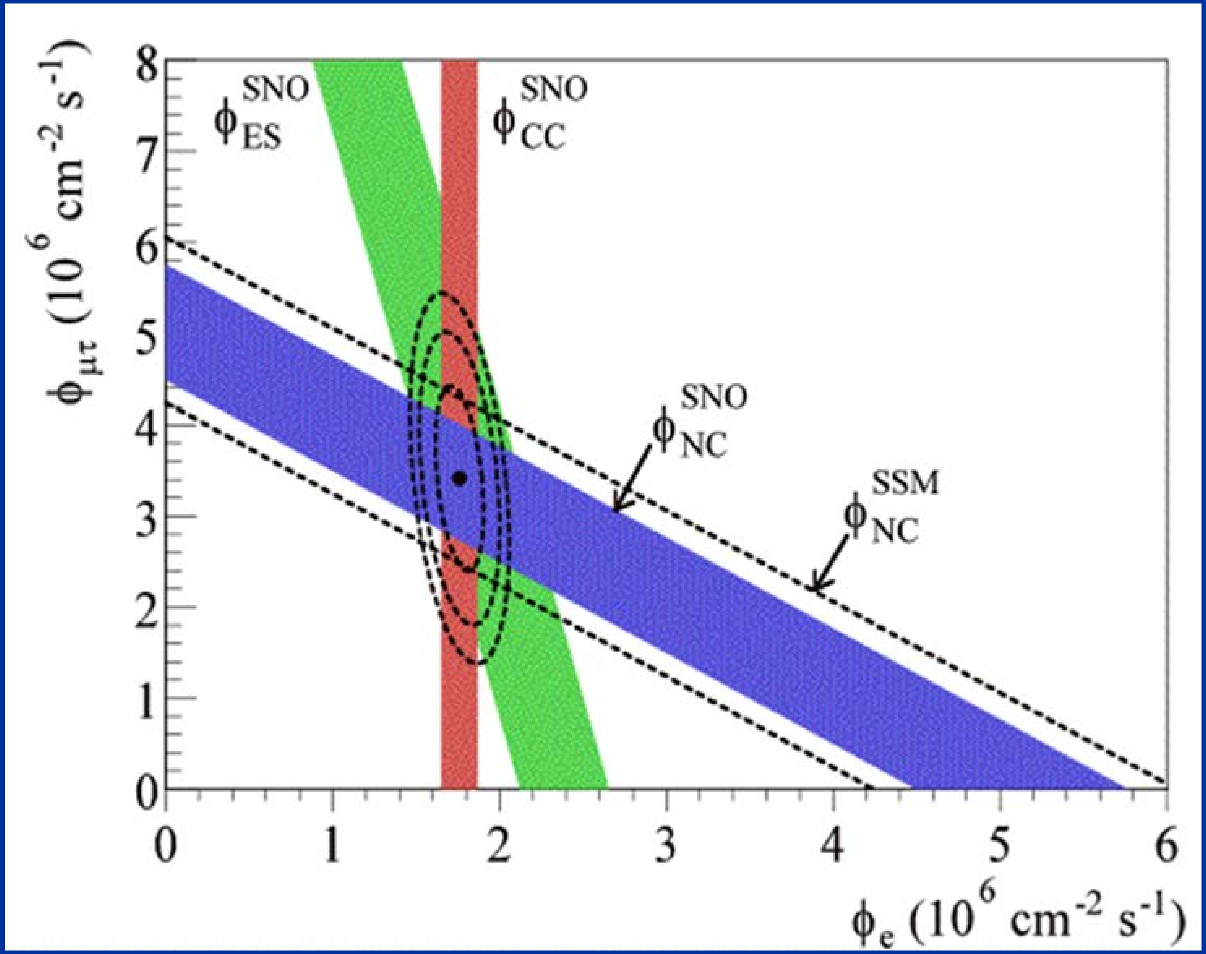
Standard Solar Model (2005)
Comparison with experiments



SNO result

- Results in 2001 and 2002, without/with NaCl
- Definitive proof that solar neutrinos oscillate!
- Solved the solar neutrino problem
- Neutrinos must have mass
- Δm^2 is incredibly small
- 10^{-5}, 10^{-3} eV^2
- Absolute mass must also be small
- We thought it was zero for 65 years!





SNO's CC, NC and ES measurements from the D_2O phase. The x- and y-axes are the inferred fluxes of electron neutrinos and muon plus tau neutrinos.

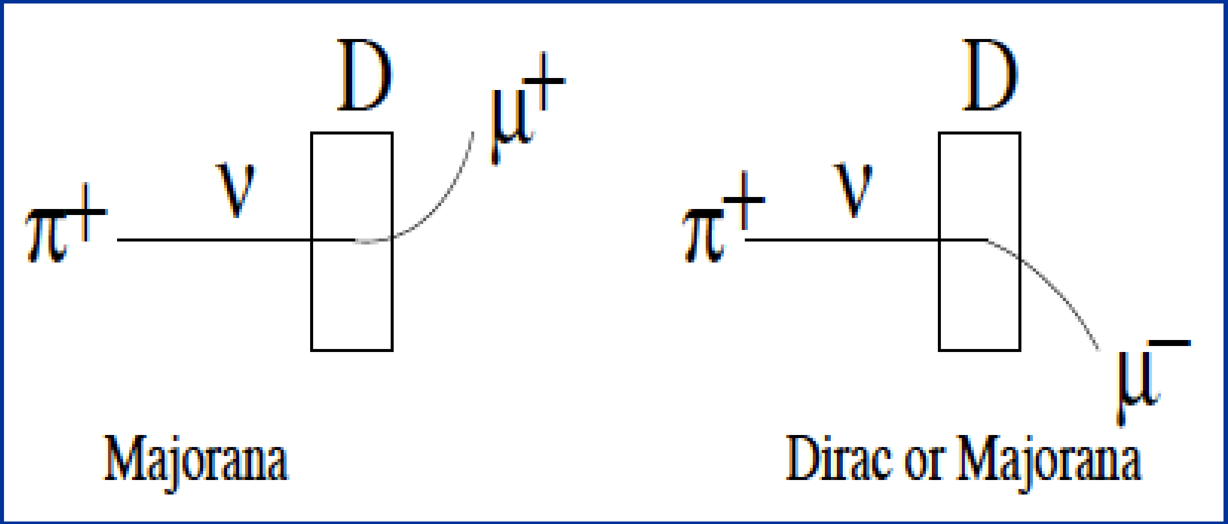
Since the NC and ES measurements are sensitive to both ν_e and ν_μ/ν_τ , the ES and NC bands have definite slopes. The CC measurement is sensitive to ν_e only, so has an infinite slope. The widths of the bands represent the uncertainties of the measurements. The intersection of the three bands gives the best estimate of $\Phi_{\mu\tau}$ and Φ_e. The dashed ellipses around the best fit point give the 68%, 95%, and 99% confidence level contours for $\Phi_{\mu\tau}$ and Φ_e. The flux of neutrinos predicted by the SSM is indicated by Φ_{SSM}.

Open questions

- ❑ Measure mass differences
- ❑ Establish “mass hierarchy”
- ❑ Measure absolute mass scale
- ❑ Majorana or Dirac Neutrinos?
  - Is there neutrinoless double beta decay?
- ❑ many experiments being upgraded/constructed/planned
- ❑ Is there a sterile neutrino in addition to the 3 ordinary ones? (some hints…)

Majorana versus Dirac ?

In principle clear experimental signatures



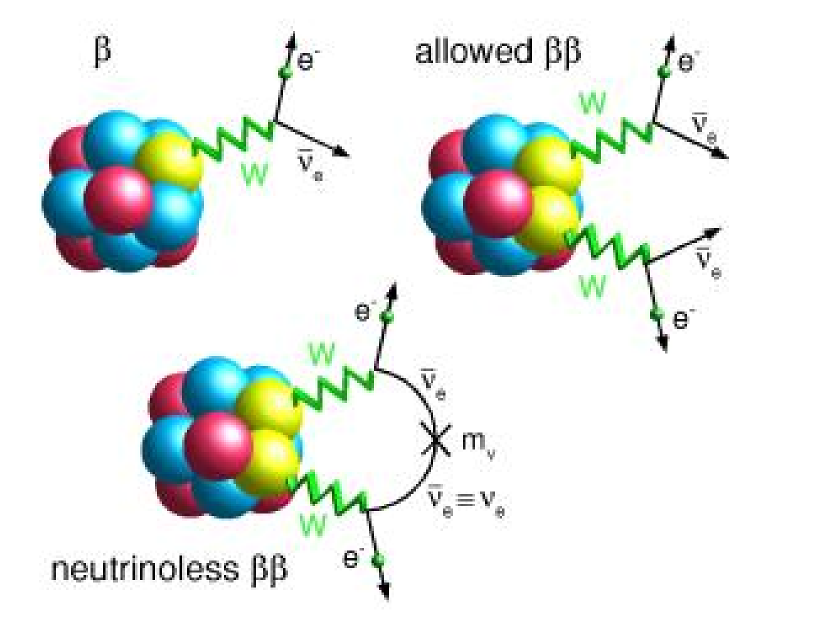
In practice theses processes are extremely rare:

$$\mathrm{Rate}(+) = \mathrm{Rate}(-)\left(\frac{m_\nu}{E}\right)^2$$

Neutrinoless double β decay

Best hope:

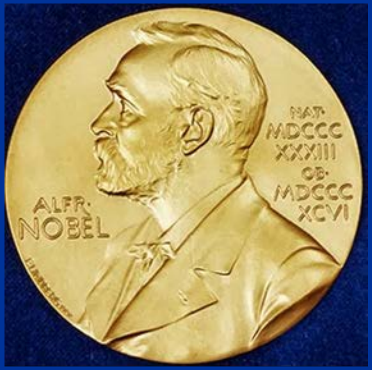
neutrinoless double-β decay



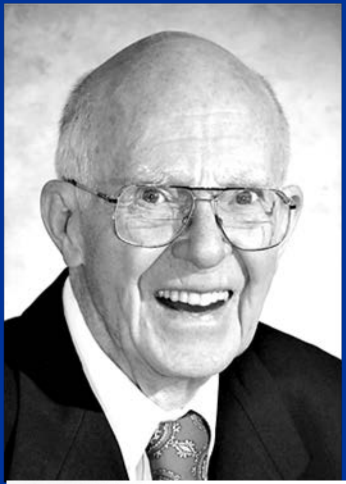
$$T_{2\beta 2\nu} = 10^{18} - 10^{21} \text{ years}$$

If neutrinos are Majorana type ⇒ there must be neutrinoless process at some (small?) level

Rewards..



- 2002 Nobel Prize
  - Ray Davis, ¼ prize "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"
  - ¼ prize also went to Masatoshi Koshiba for detection of supernova neutrinos (Kamiokande experiment, predecessor of Super K)



- there is plenty of evidence indicating that the SM is incomplete
- but this is the ONLY physics discovery so far leading to a modification of the standard model

https://www.nobelprize.org/nobel_prizes/physics/laureates/2002/

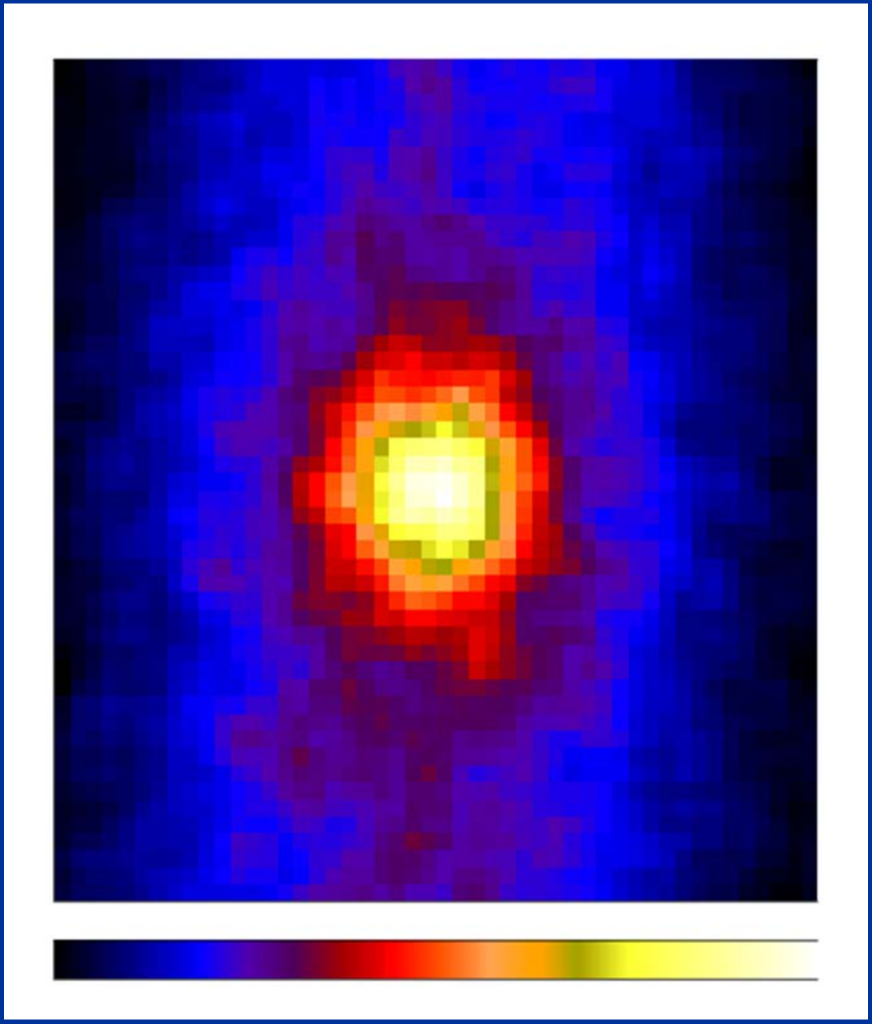
Reward 13 years later..

- The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

https://www.nobelprize.org/nobel_prizes/physics/laureates/2015/

Neutrino image of the Sun

- SuperK : Solar neutrino-gram



- Light from the solar core takes a million years to reach the surface
- Fusion processes generate electron neutrinos which take 2s to leave
- Solar neutrinos are a direct probe of the solar core
- Roughly 4.0 x 10^{10} solar neutrinos (ν_e) per cm^2 per second on Earth

Mass measurement

Next generation of tritium beta decay experiment: Katrin (KArlsruhe TRItium Neutrino experiment)

Goal:
$m_{\nu e} < 0.2$ eV

https://www.katrin.kit.edu/