Past, Present, and future discoveries with Neutrinos

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KASI Colloquium

Nov 18, 2015

Nobel Prize

- **Takaaki Kajita**, Japanese citizen. Born 1959 in Higashimatsuyama, Japan. Ph.D. 1986 from University of Tokyo, Japan. Director of Institute for Cosmic Ray Research and Professor at University of Tokyo, Kashiwa, Japan.
- **Arthur B. McDonald**, Canadian citizen. Born 1943 in Sydney, Canada. Ph.D. 1969 from California Institute of Technology, Pasadena, CA, USA. Professor Emeritus at Queen's University, Kingston, Canada.

Nobel Prize

http://www.kva.se/en/pressroom/2015/the-nobel-prize-in-physics-2015/

PRESS RELEASE 2016-10-06

The Nobel Prize in Physics 2015

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to
Takaaki Kajita, Super-Kamiokande Collaboration, University of Tokyo, Kashiwa, Japan and
Arthur B. McDonald, Sudbury Neutrino Observatory Collaboration, Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass".

Listen to interview with Arthur B. McDonald from the press conference (mp3)

Metamorphosis in the particle world

The Nobel Prize in Physics 2015 recognises Takaaki Kajita in Japan and Arthur B. McDonald in Canada, for their key contributions to the experiments which demonstrated that neutrinos change identities. This metamorphosis requires that neutrinos have mass. The discovery has changed our understanding of the innermost workings of matter and can prove crucial to our view of the universe.

Around the turn of the millennium, **Takaaki Kajita** presented the discovery that neutrinos from the atmosphere switch between two identities on their way to the Super-Kamiokande detector in Japan.

Meanwhile, the research group in Canada led by **Arthur B. McDonald** could demonstrate that the neutrinos from the Sun were not disappearing on their way to Earth. Instead they were captured with a different identity when arriving to the Sudbury Neutrino Observatory.

A neutrino puzzle that physicists had wrestled with for decades had been resolved. Compared to theoretical calculations of the number of neutrinos, up to two thirds of the neutrinos were missing in measurements performed on Earth. Now, the two experiments discovered that the neutrinos had changed identities.

The discovery led to the far-reaching conclusion that neutrinos, which for a long time were considered massless, must have some mass, however small.

For particle physics this was a historic discovery. Its Standard Model of the innermost workings of matter had been incredibly successful, having resisted all experimental challenges for more than twenty years. However, as it requires neutrinos to be massless, the new observations had clearly showed that the Standard Model cannot be the complete theory of the fundamental constituents of the universe.

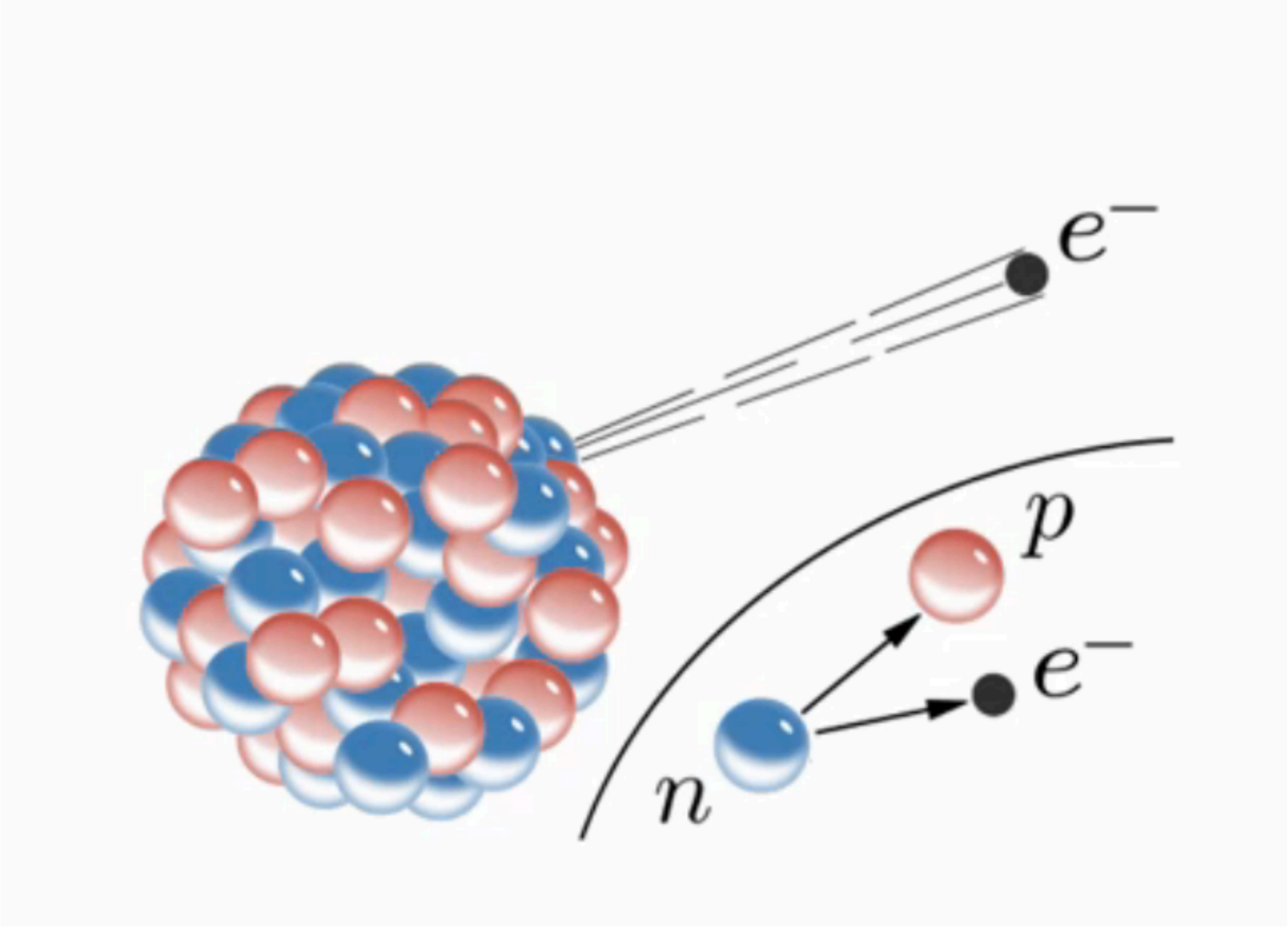
The discovery rewarded with this year's Nobel Prize in Physics have yielded crucial insights into the all but hidden world of neutrinos. After photons, the particles of light, neutrinos are the most numerous in the entire cosmos. The Earth is constantly bombarded by them.

Many neutrinos are created in reactions between cosmic radiation and the Earth's atmosphere. Others are produced in nuclear reactions inside the Sun. Thousands of billions of neutrinos are streaming through our bodies each second. Hardly anything can stop them passing; neutrinos are nature's most elusive elementary particles.

Now the experiments continue and intense activity is underway worldwide in order to capture neutrinos and examine their properties. New discoveries about their deepest secrets are expected to change our current understanding of the history, structure and future fate of the universe.

Discovery of the Neutrino

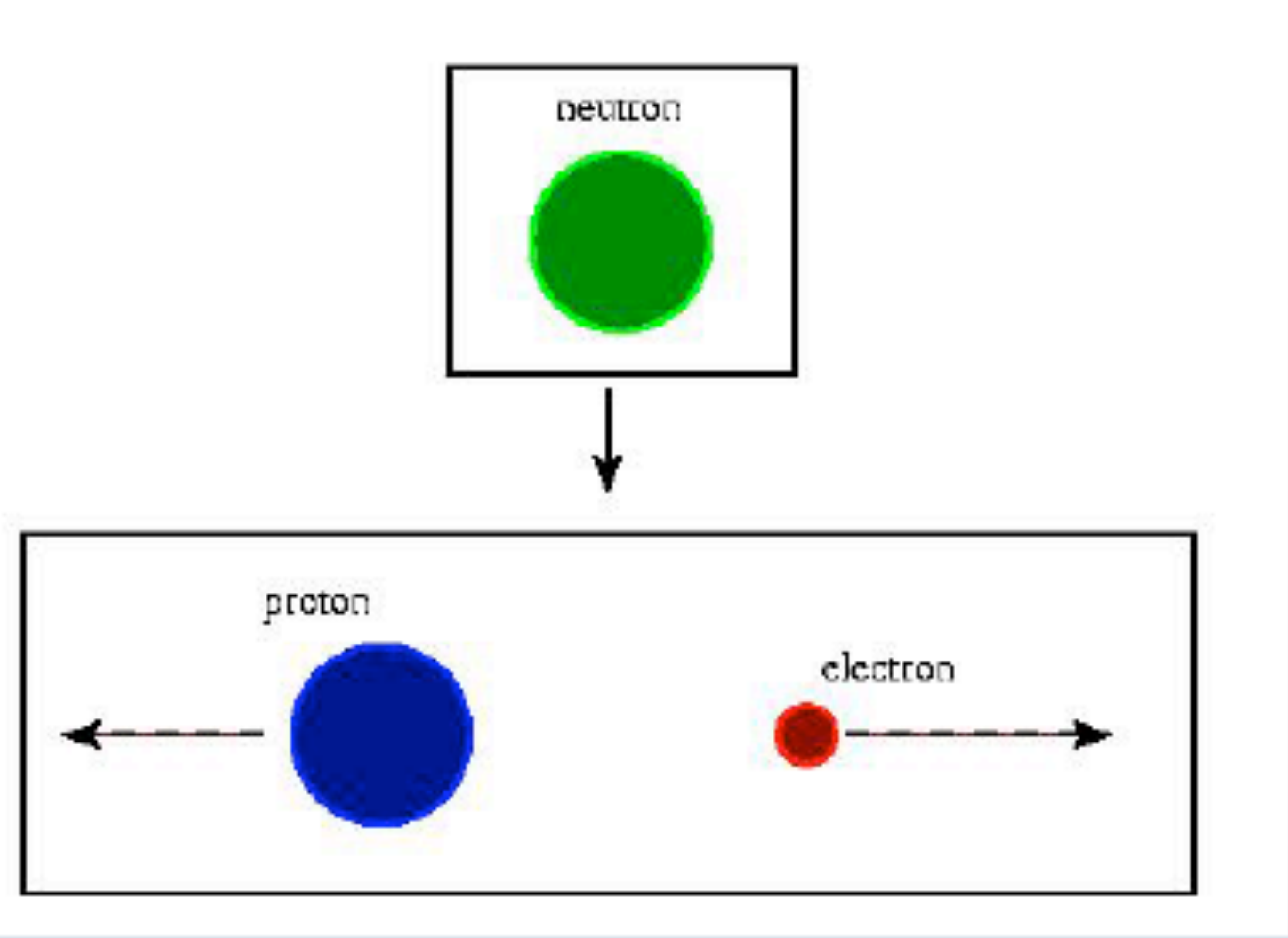
Beta decay (~1900)



Brief history of the neutrino

Beta decay mystery:

2-body decay should give mono-energetic electron



... but observed spectrum is continuous

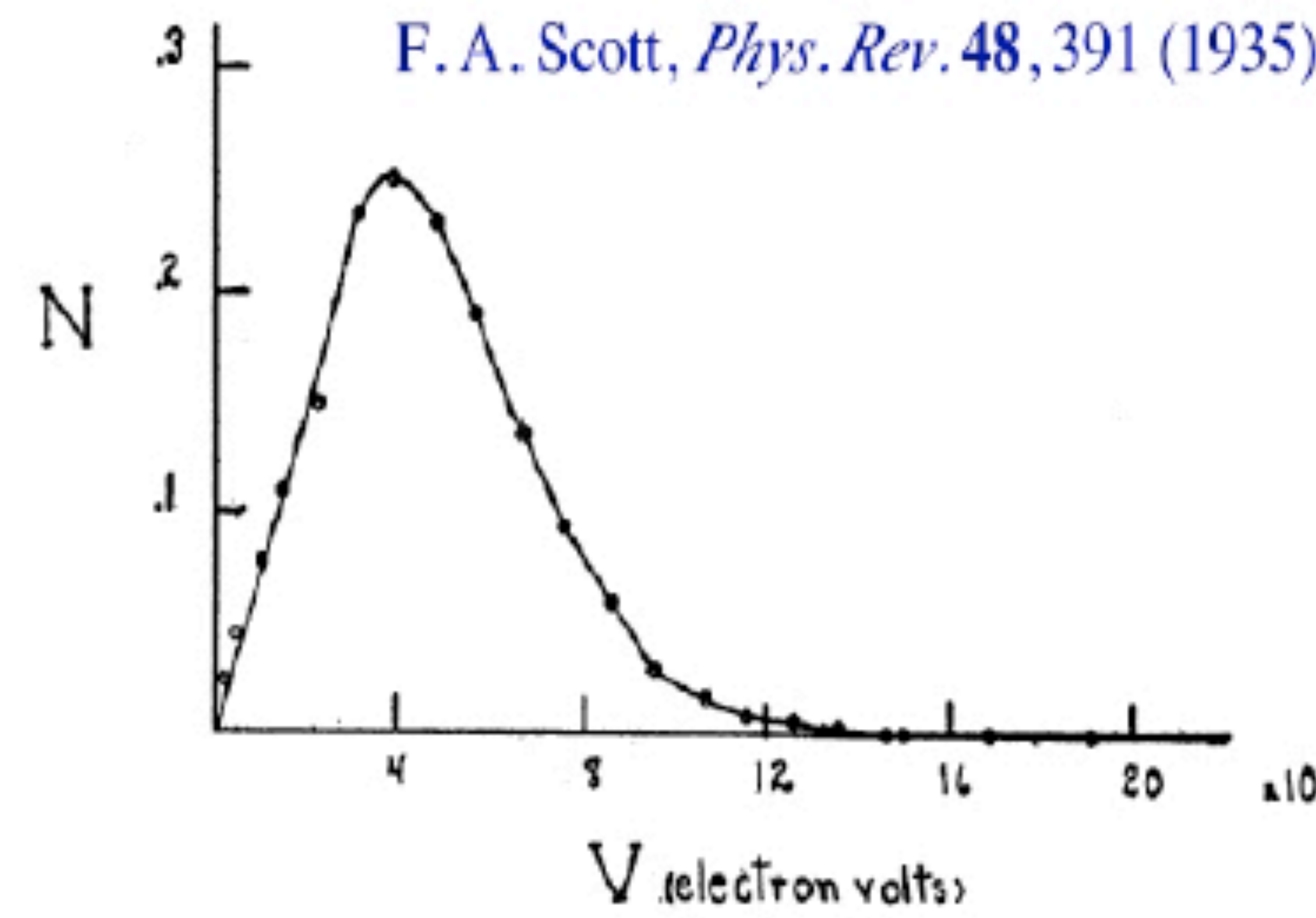
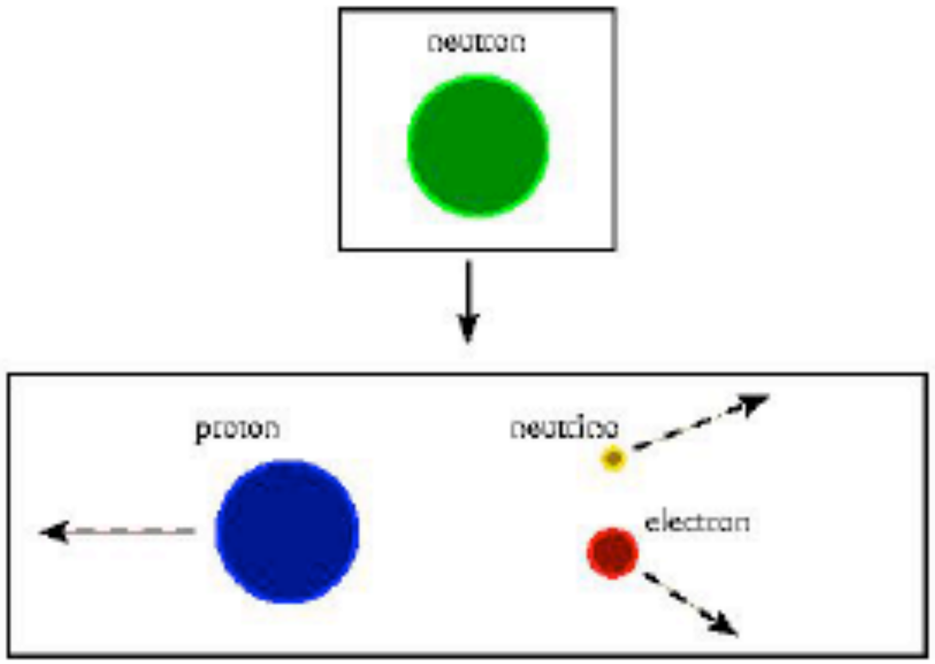


FIG. 5. Energy distribution curve of the beta-rays.

Postulation of the Neutrino

Pauli suggests a third particle (1930)



Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

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

Designed to be impossible to detect ... almost

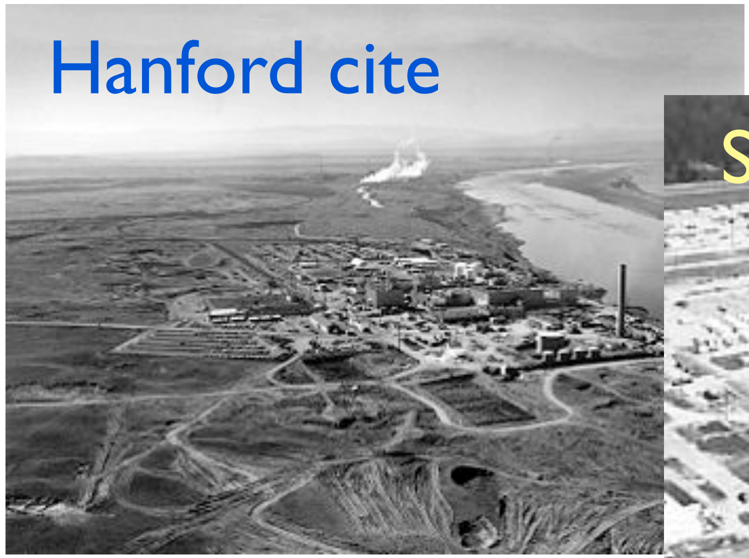
Poltergeist (Cowan–Reines neutrino experiment)

- Idea:
  - Observe inverse beta-decay reaction
  - Utilize extremely high anti-neutrino flux near nuclear reactor

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

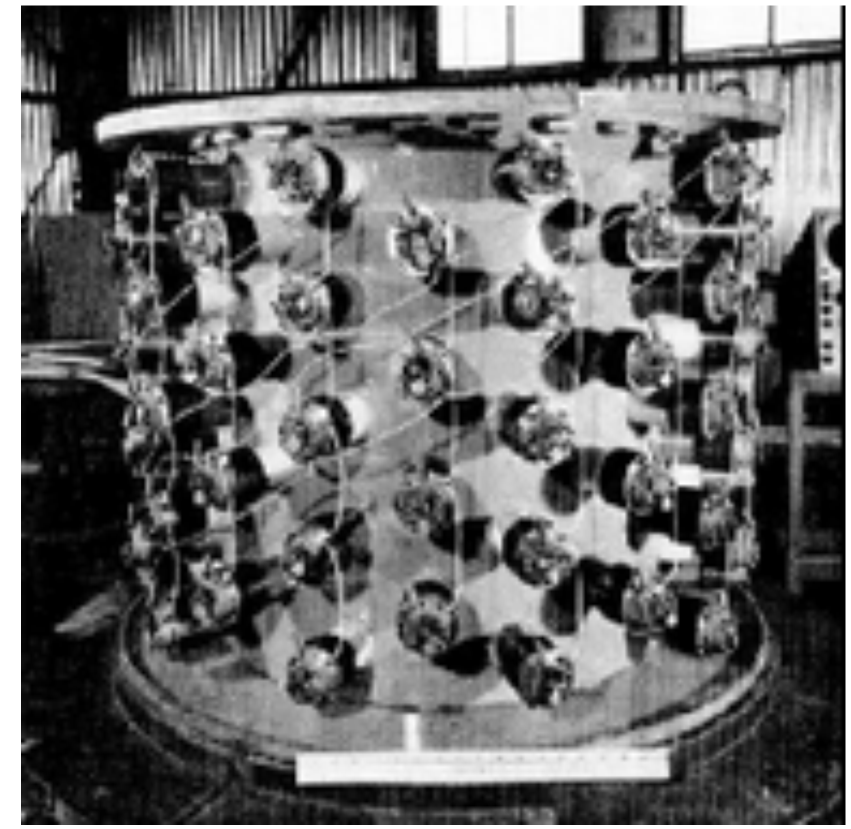
$\sim 5 \times 10^{13} cm^2/s$

- Location:
  - Hanford, WS
  - Savannah River, SC



… 1956 Science

- 11m from reactor and 12m underground
- 200liters of H_2O with 40kg of dissolved $CdCl_2$
- 110 x 5"PMTs + scintillation layers



Signal:

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

annihilates with e^-

capture on Cd

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

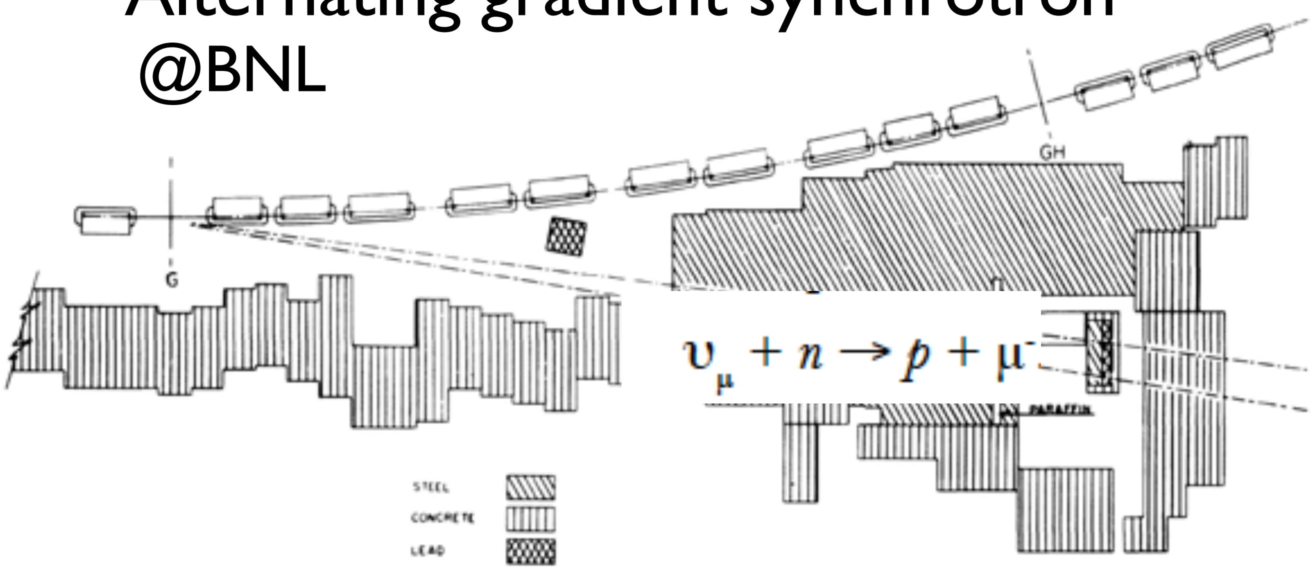
delay ~5ms

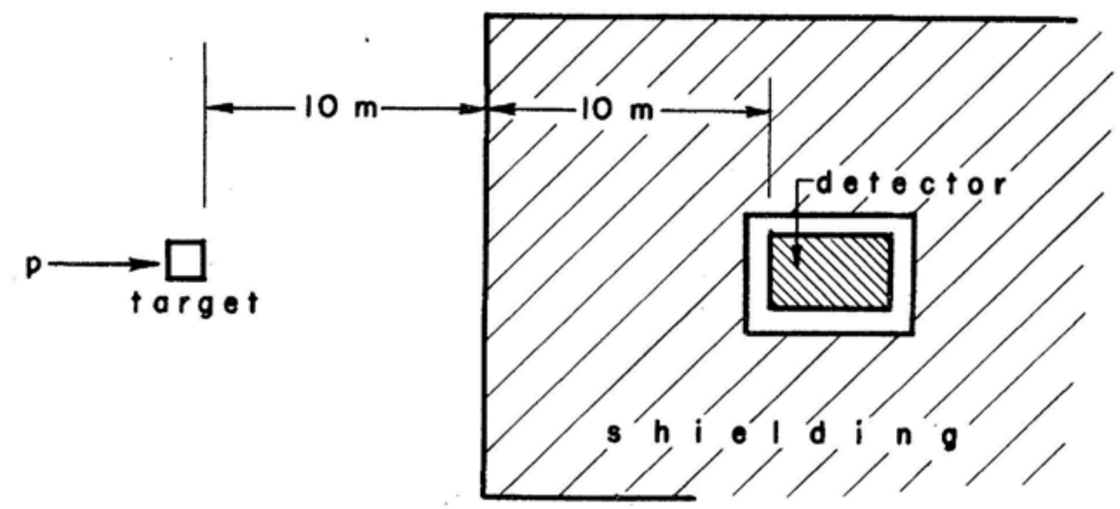
Frederick Reines honored with Nobel Prize in 1995

Clyde Cowan died in 1974

Muon Neutrino

Alternating gradient synchrotron
@BNL



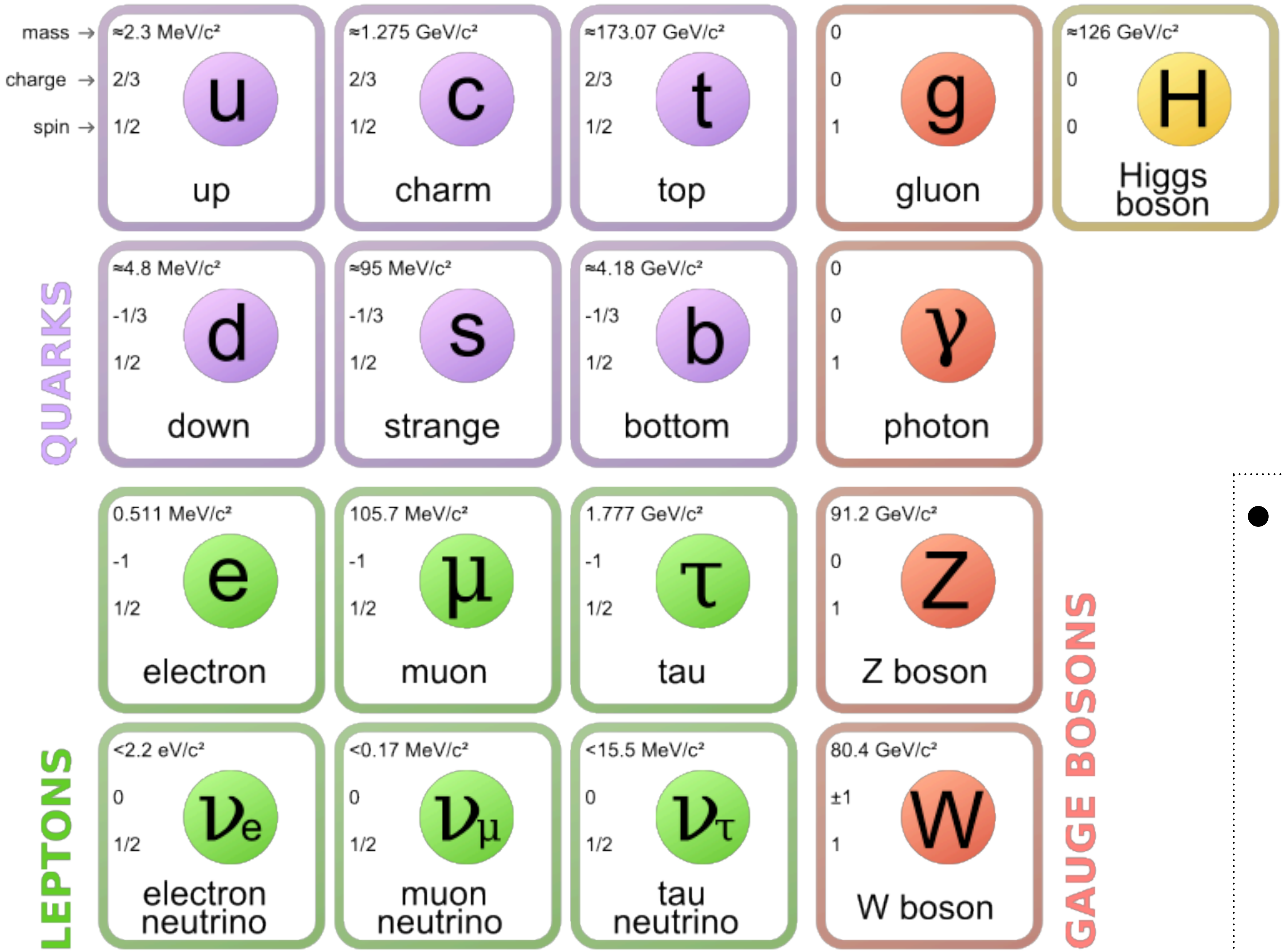


Mel Schwartz, standing by his spark chambers

Left to right: Jack Steinberger, Melvin Schwartz, and Leon Lederman in 1988

Standard Model of Particle Physics

- The Standard Model of Particle Physics



- Success of the Standard Model (SM):
  - Extremely well tested in precision measurements
  - No indication yet of any physics beyond SM from collider searches

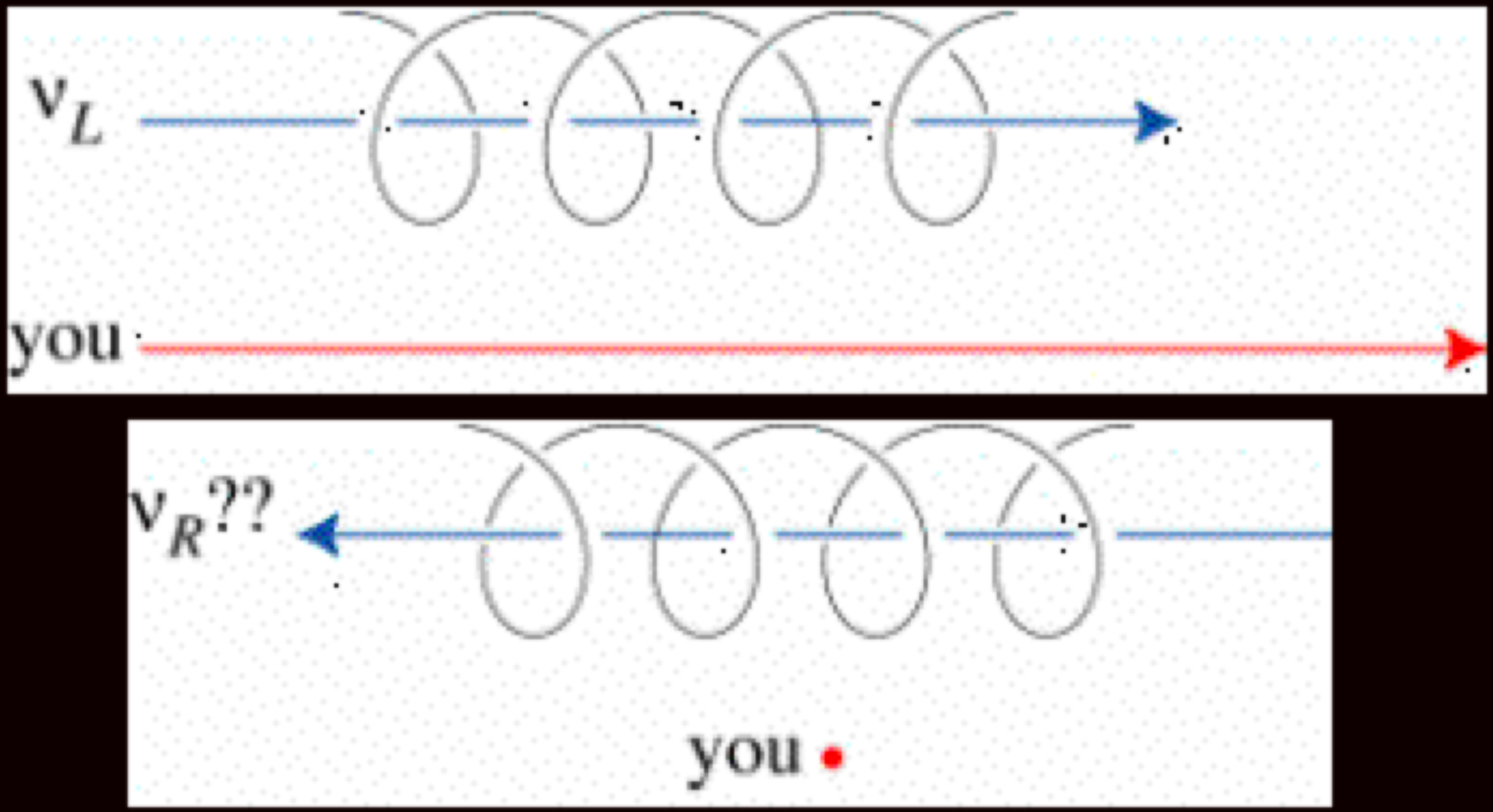
Neutrinos and SM

- For the Standard Model it is assumed:
  - Neutrinos are massless (have exactly zero mass);
  - there are exactly three neutrinos, one for each of the three charged leptons, and lepton number is conserved separately for each of the three lepton families (e, ν_e), (μ, ν_μ), (τ, ν_τ);
  - neutrinos and antineutrinos are distinct;
  - all neutrinos are left-handed, and all antineutrinos are right-handed
- Physics of the neutrino might lead to new physics beyond the standard model

Neutrinos and SM

All neutrinos left-handed $\Rightarrow$ massless

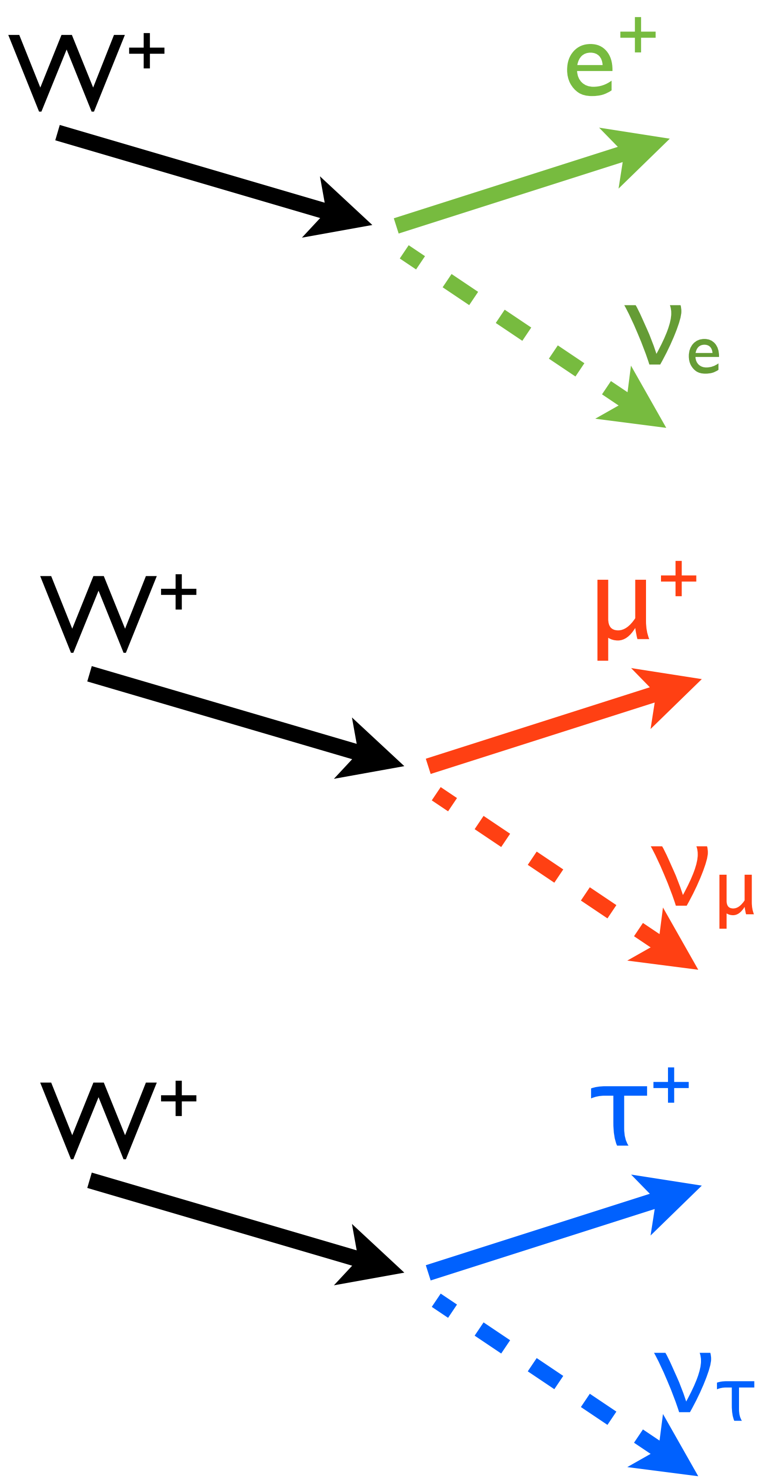
If they have mass, can't go at speed of light.



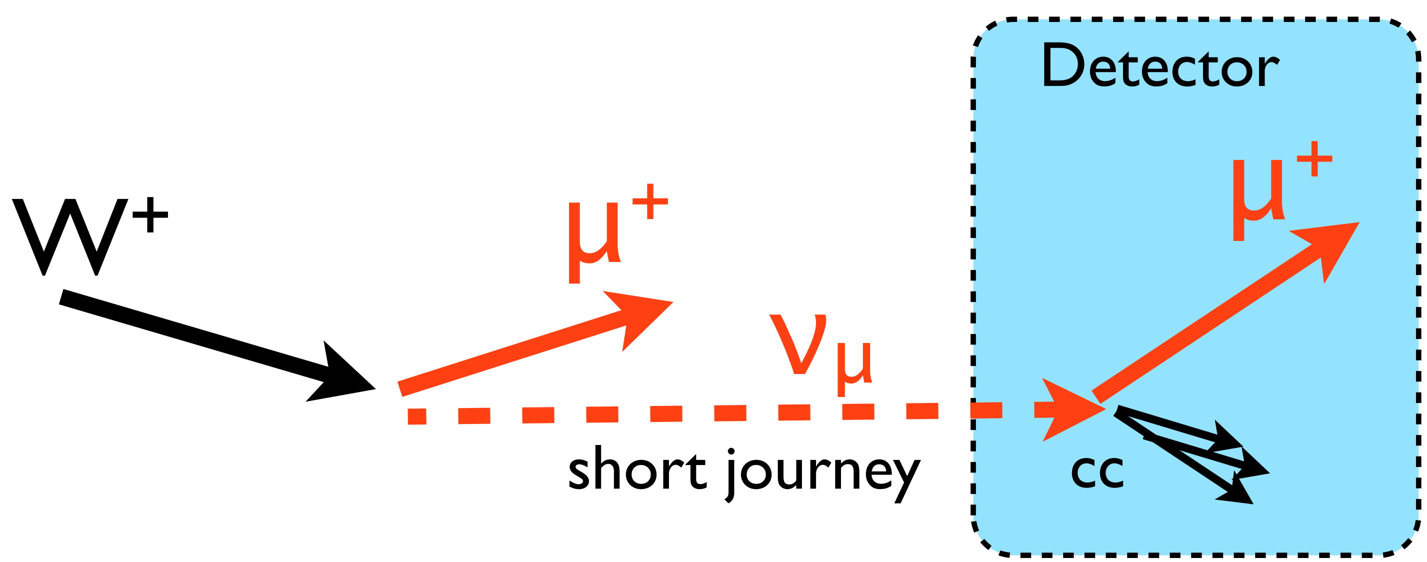
Now neutrino right-handed??

$\Rightarrow$ contradiction $\Rightarrow$ can't be massive

Neutrino Flavor

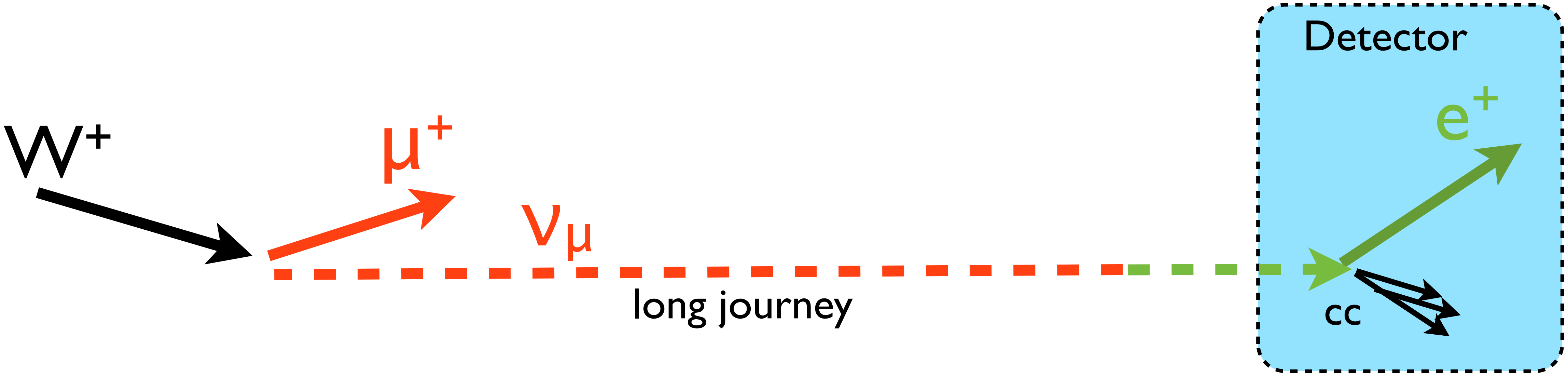


- Define neutrino flavors ν_e, ν_μ, ν_τ by the associated lepton produced in a W decay
- A neutrino of flavor $\alpha = e, \mu, \tau$ will all ways produce the corresponding lepton l_α



Neutrino Flavor Change

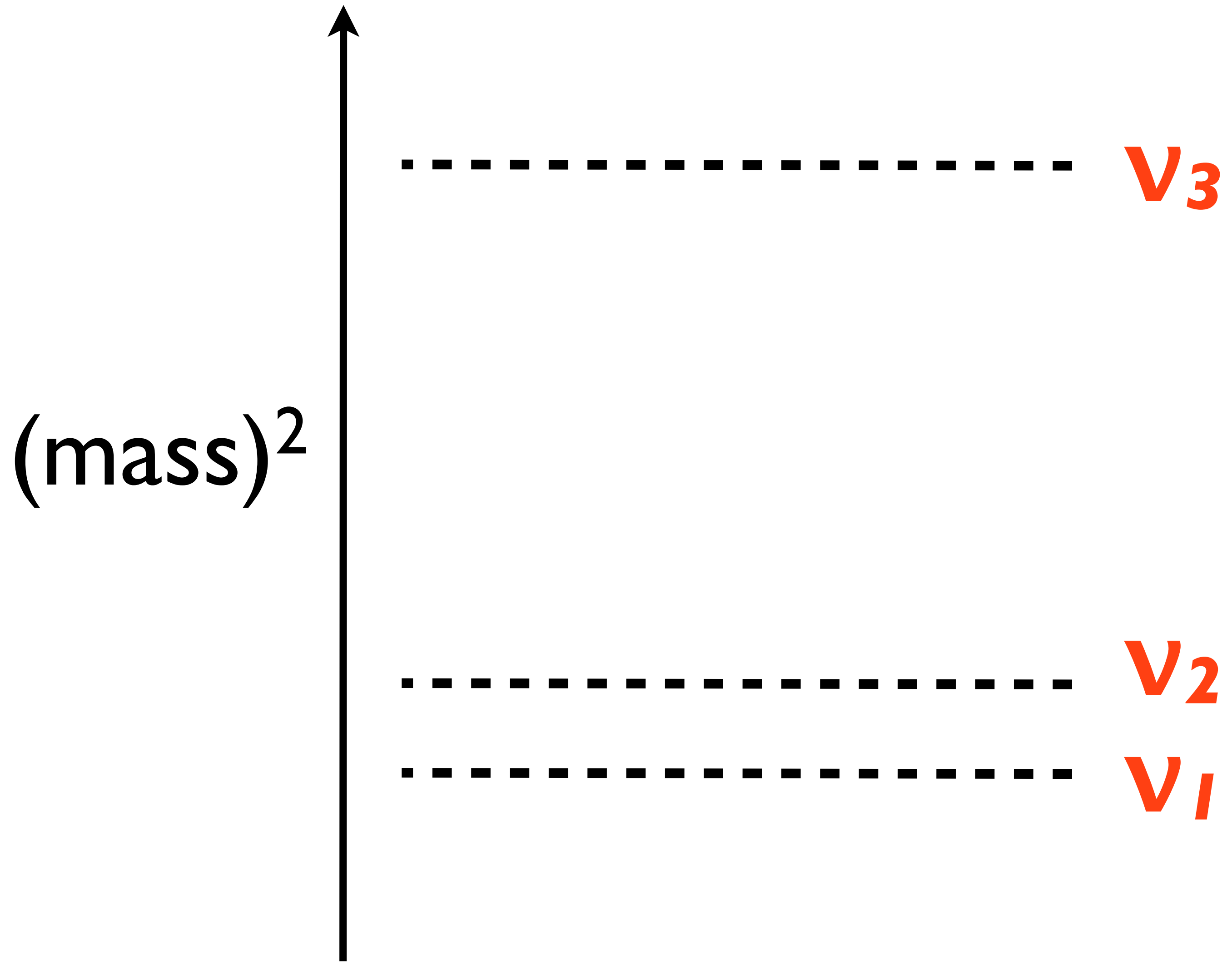
- If neutrinos have mass and leptons mix than we have a non-zero probability to observe any of the active neutrino flavors ν_e, ν_μ, ν_τ



neutrino has time to change flavor ...
this indeed has been observed

Neutrino Masses

- Flavor change requires neutrino masses
  - some spectrum of neutrino mass eigenstates ν_i must exist
  - the mass eigenstates ν_i have a mass of m_i



Leptonic Mixing

- Flavor change requires leptonic mixing

Neutrinos of flavor $\nu_{e,\mu,\tau}$ must be superpositions of the mass eigenstates:

PMNS Leptonic Mixing Matrix (Pontecorvo–Maki–Nakagawa–Sakata)

Neutrino of flavor α = e, μ, or τ

Neutrino of definite mass m_i

$$|\nu_\alpha> = \sum_i U^*_{\alpha i} |\nu_i>$$

As we have 3 orthogonal neutrinos of defined flavor ν_α

-> there must be at least 3 mass eigenstates ν_i

Mass eigenstates

The expression for a neutrino of definite flavor in a superposition of mass eigenstates, may be inverted to express each mass eigenstate ν_i as a superposition of flavors

$$|\nu_i >= \sum_\alpha U_{\alpha i}|\nu_\alpha >$$

$$U = \begin{array}{c} \\ e \\ \mu \\ \tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \end{array}$$

Flavor-α fraction of ν_i is $|U_{\alpha i}|^2$

Neutrino Oscillations

$$P(\nu_\alpha \to \nu_\beta, t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right) \qquad \Delta m^2_{ij} \frac{L}{4E} = 1.27\, \Delta m^2_{ij}(\mathrm{eV}^2) \frac{L\,(\mathrm{km})}{E\,(\mathrm{GeV})}$$

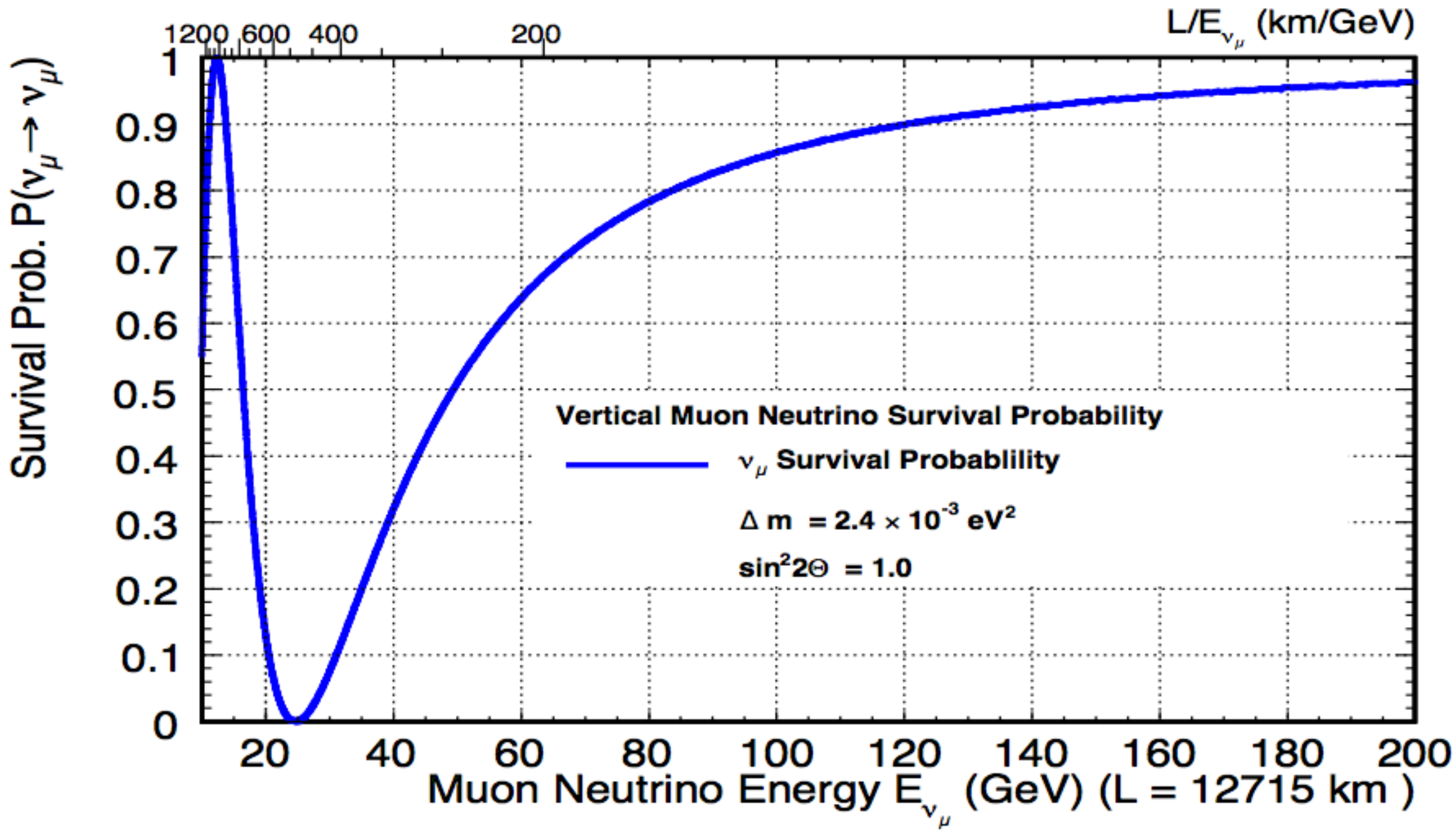
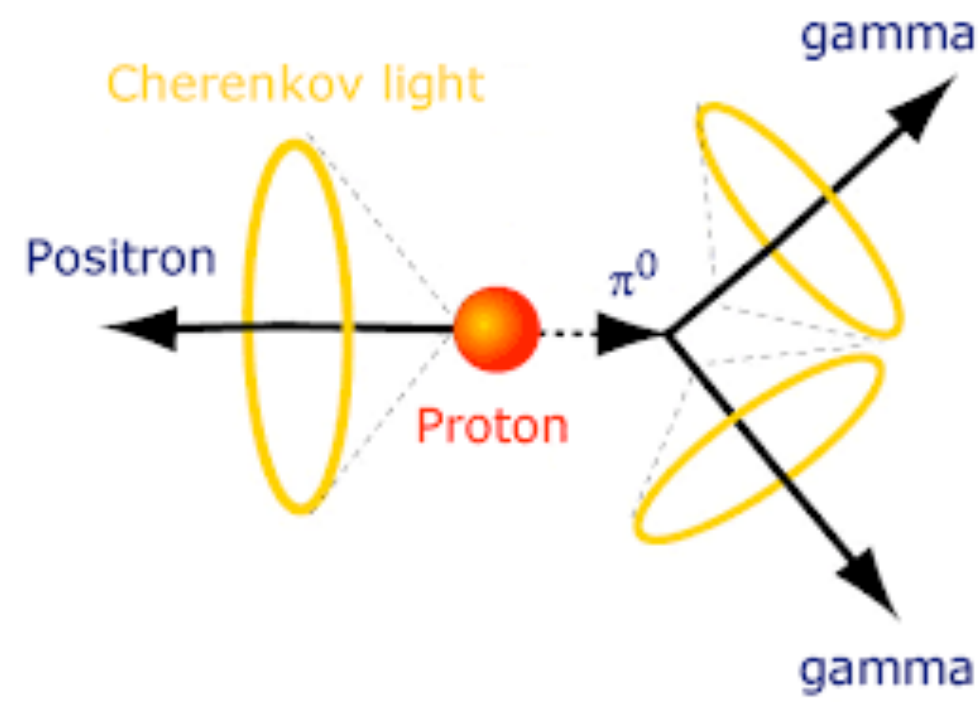


Fig. 1. Muon neutrino survival probability under the assumption of effective 2-flavor neutrino oscillations $\nu_\mu \leftrightarrow \nu_\tau$ as function of energy for vertically traversing neutrinos.

Large Underground detectors

Origins of Super-K

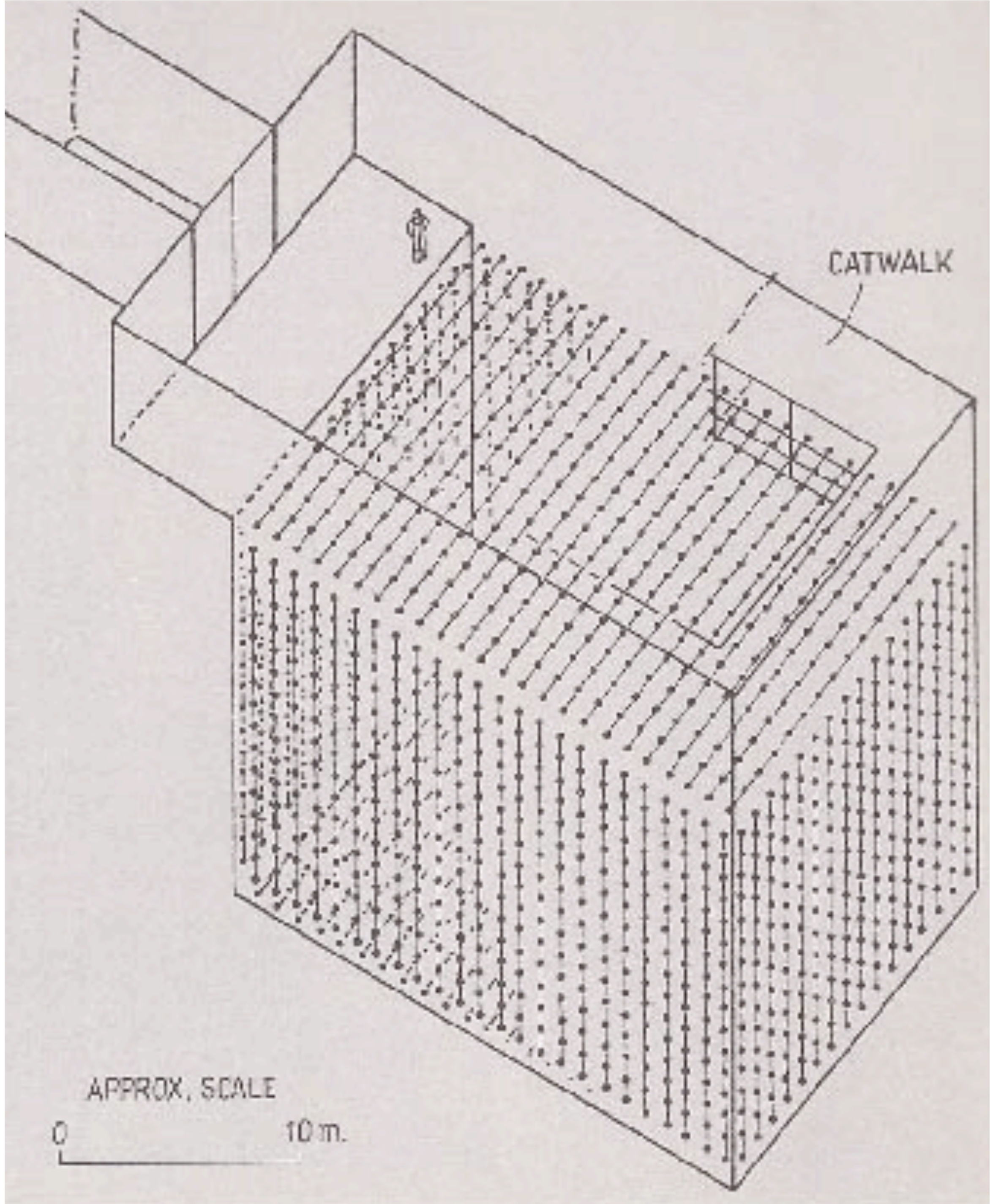
- In 1980s Grand Unified Theories (GUTs) predicted proton lifetimes ~10^{30}yrs
- 1983: KamiokaNDE (Kamioka Nucleon Decay Experiment)
  - Water tank 10m*10m*10m = 1000tons
  - ~1000 PMTs
  - Energy detection threshold >20MeV
    - good to test proton decays hypothesis
    - too high to see solar neutrinos
- 1986: KamiokaNDE-II (Kamioka Neutrino Detector Experiment)
  - better electronics
  - water purification to reduce backgrounds



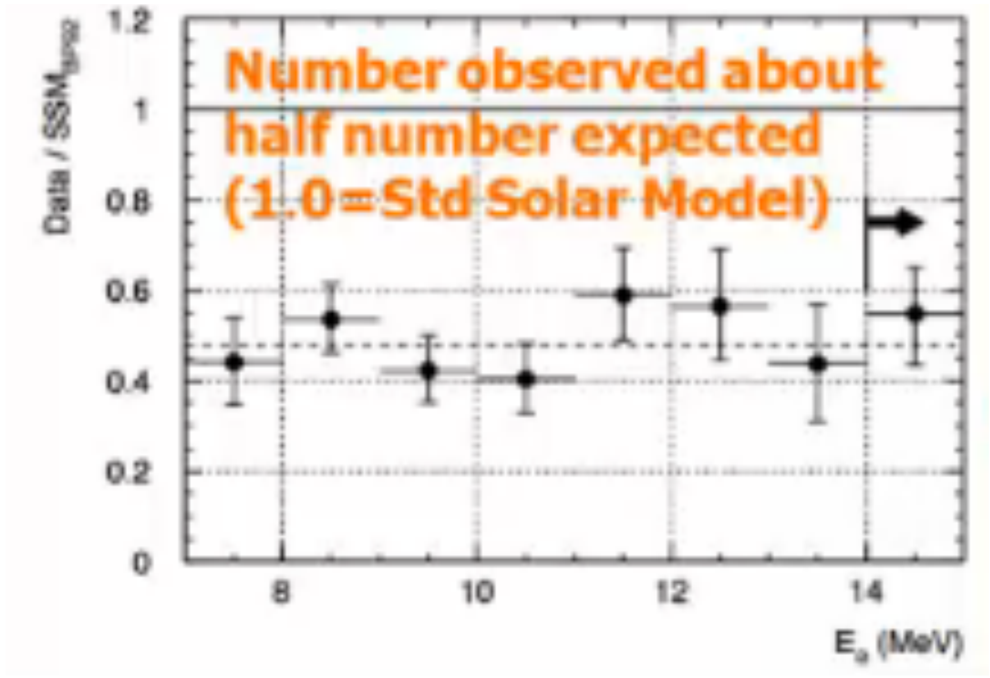
Irvine–Michigan–Brookhaven (IMB)

http://www-personal.umich.edu/~jcv/imb/imb.html

- Nucleon decay experiment and neutrino observatory located in a Morton Salt company's Fairport mine in the US state of Ohio on the shore of Lake Erie.
- 17m × 17.5m × 23m, filled with ultrapure water which was surrounded by 2,048 photomultiplier tubes
- operated from 1981 - 1991
  - ended in catastrophic event after waterleak developed



- No proton decay observed
  - limits up to 10^{32}yrs
- Identified neutrinos are coming from the Sun
- Atmospheric neutrino puzzle ... adding to the solar neutrino puzzle

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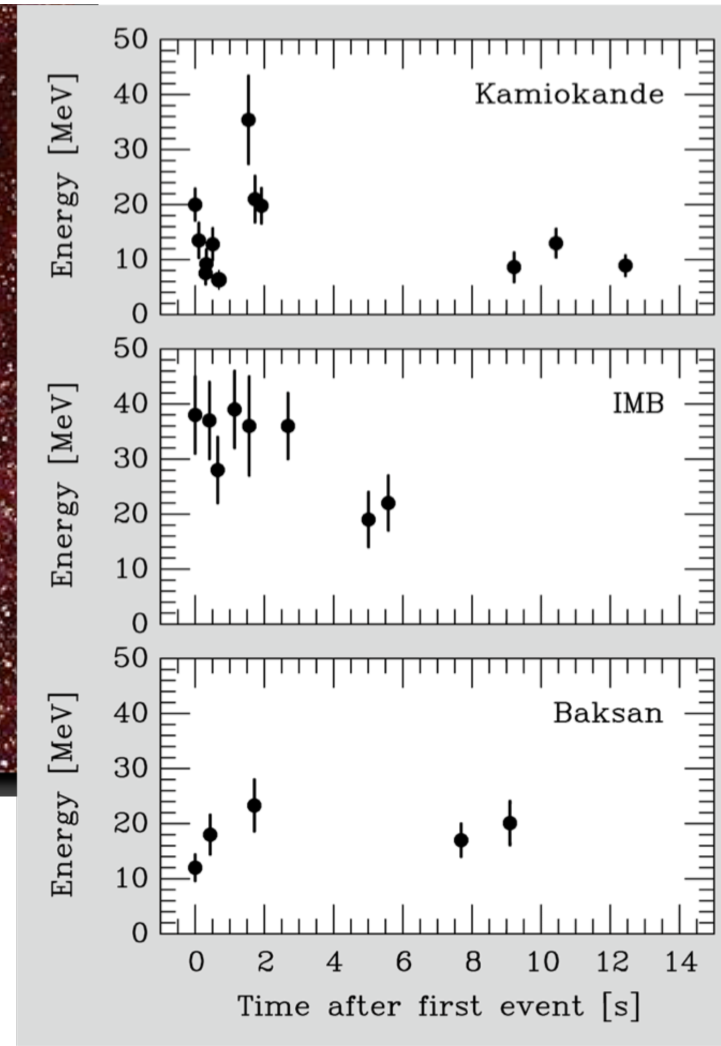
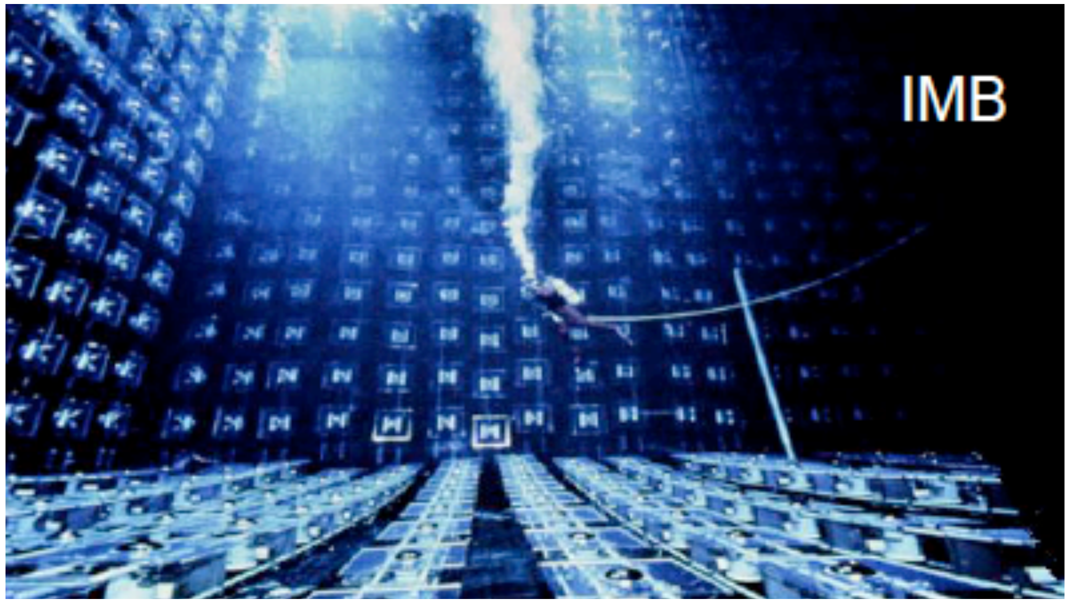
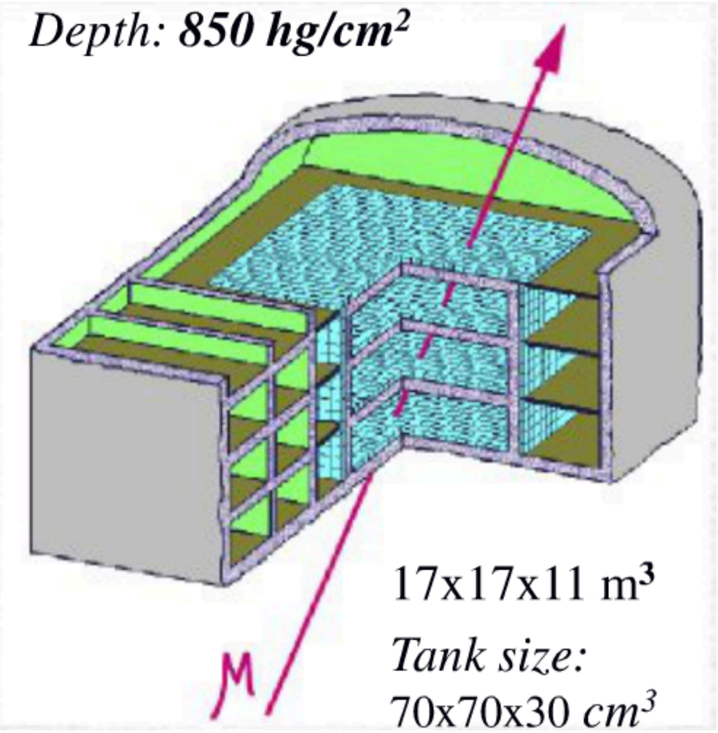




- SN1987A in LMC
  - ~10^{57} neutrinos
- Detection of Supernova burst neutrinos gave tremendous momentum to the field

Baksan Neutrino

- Baksan Underground Scintillator Telescope with muon energy threshold about 1 GeV for the longest exposure time toward the Sun.
- Operating since Dec 1978 ; More than 34 years of continuous operation
- location of the Baksan telescope (43,16°N and 42,41°E)
- Trajectories of penetrating particles are reconstructed using the positions of hit tanks, which represent together a system of 3,150 liquid scintillation counters of standard type (70 cm x 70 cm x 30 cm) in configuration of parallelepiped (17 m x 17 m x 11 m). The counters entirely cover all its sides and two horizontal planes inside at the distances 3.6 m and 7.2 m from the bottom.
- Angular resolution on muons ~ 1.5°

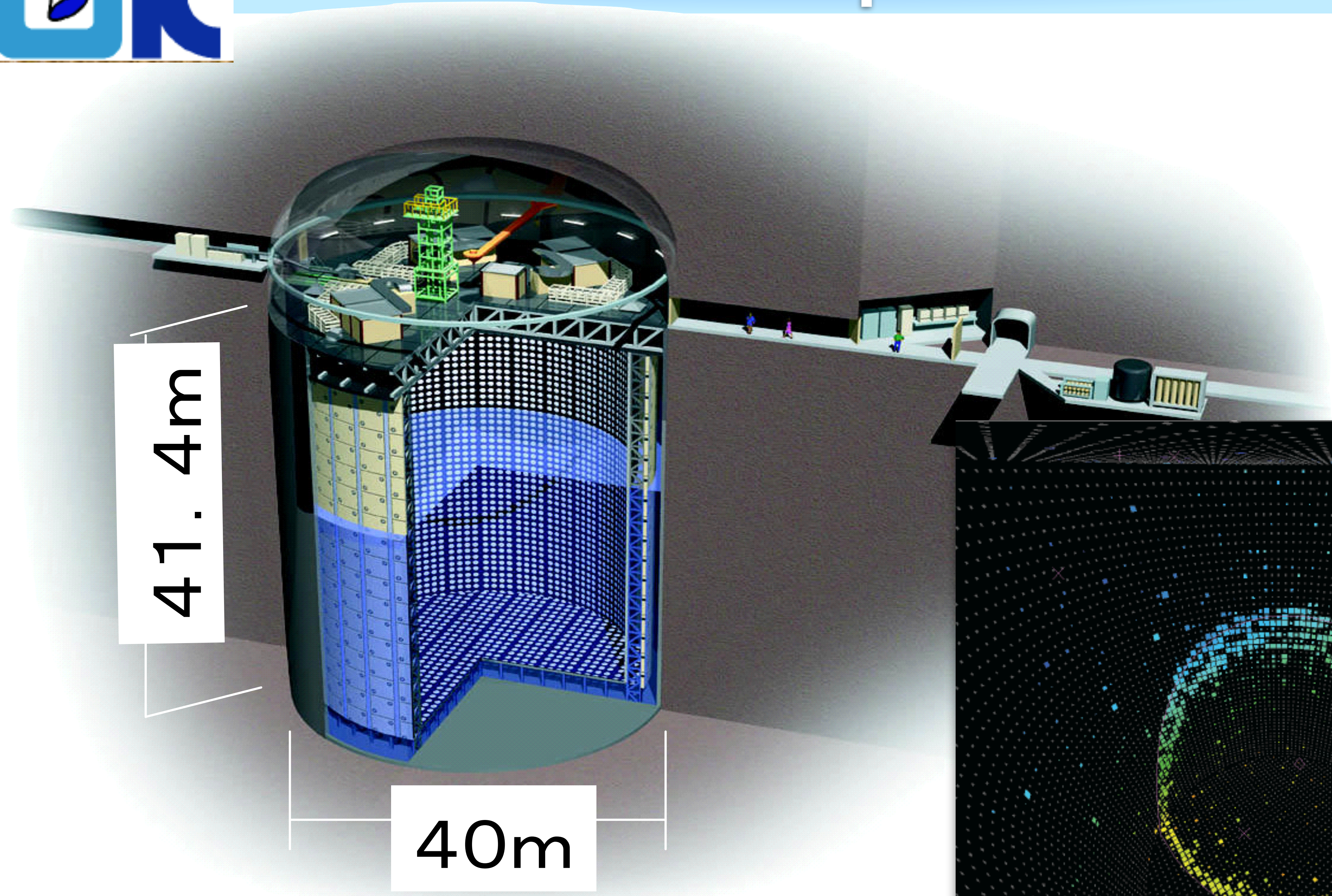


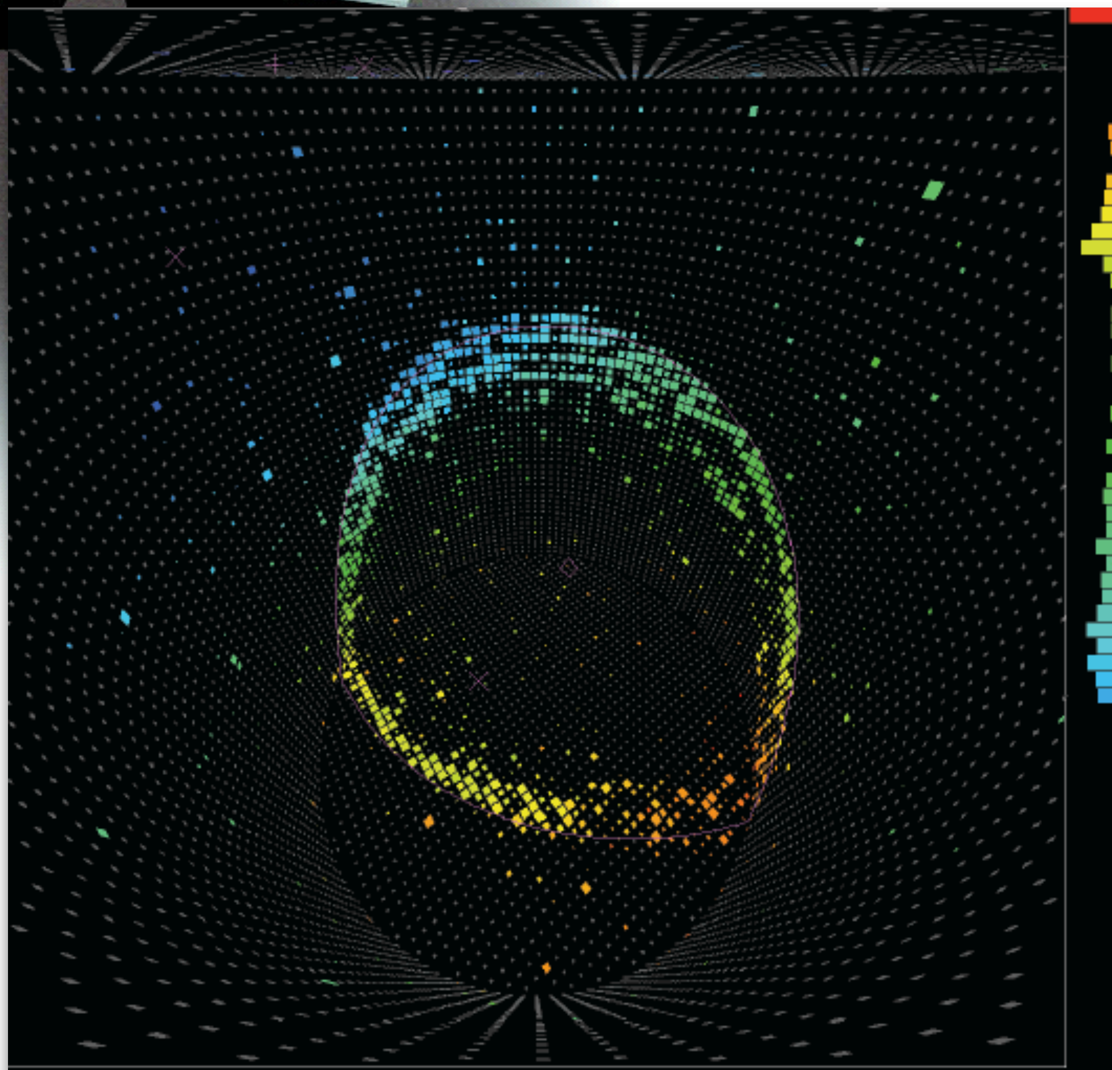
Grandfather of Super-K

- Masato Koshiba, University of Tokyo, ICRR
  - Leader of Kamiokande
  - Led effort to design and build Super-Kamiokande
  - 2002 Nobel Prize

with Ray Davis for "... for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

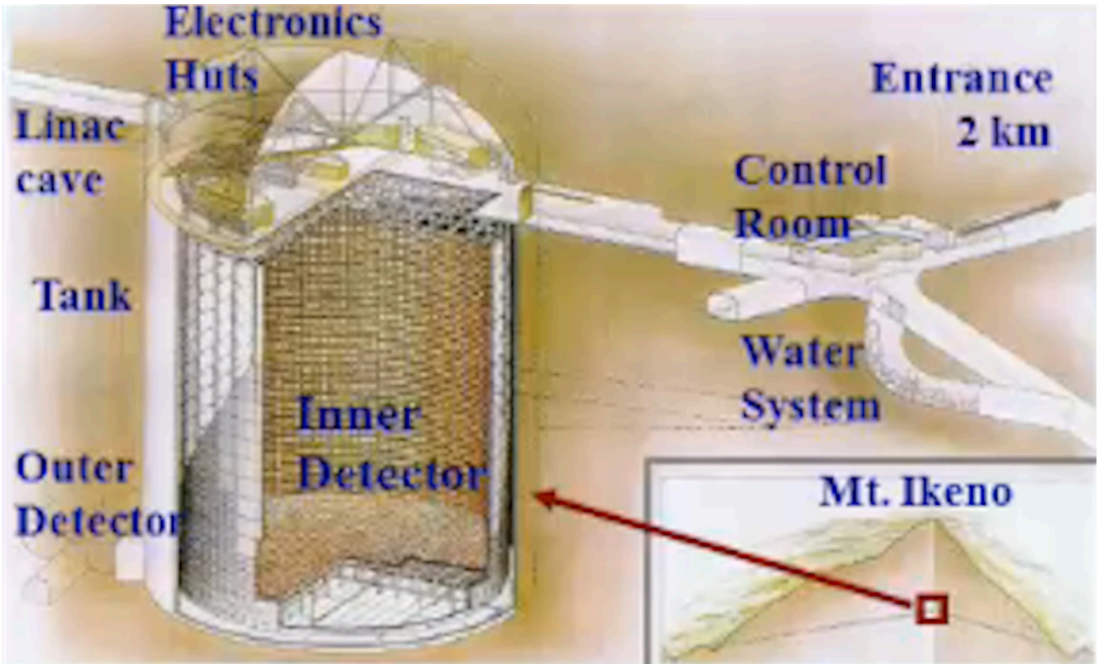
Super-Kamiokande

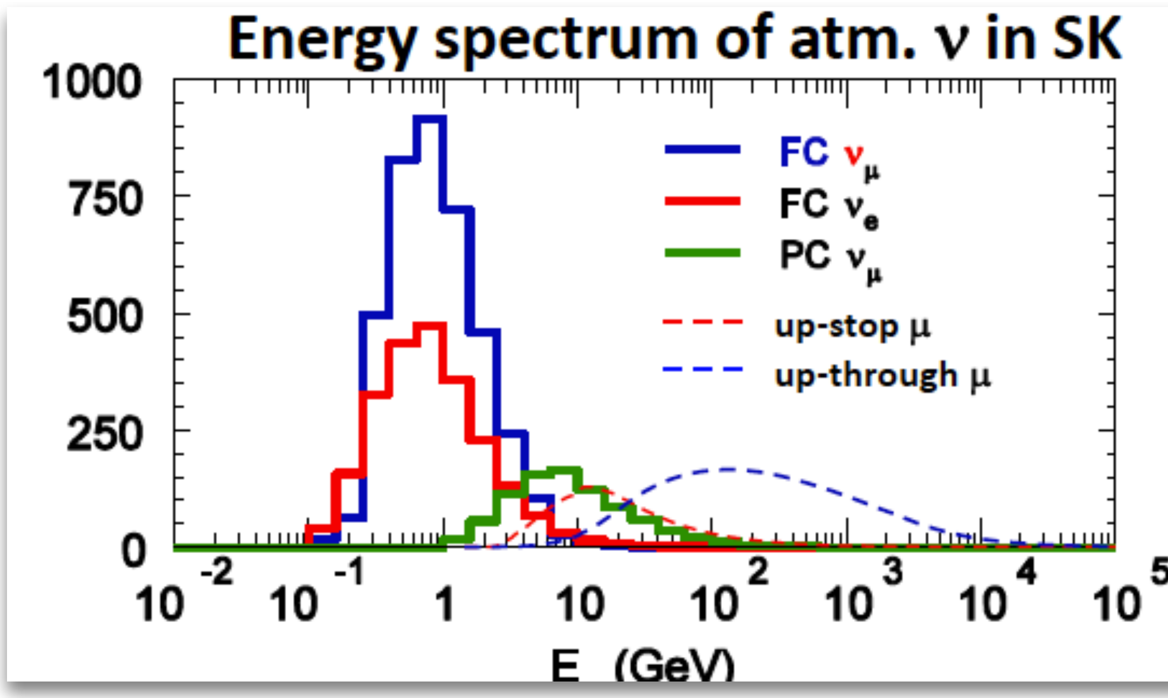




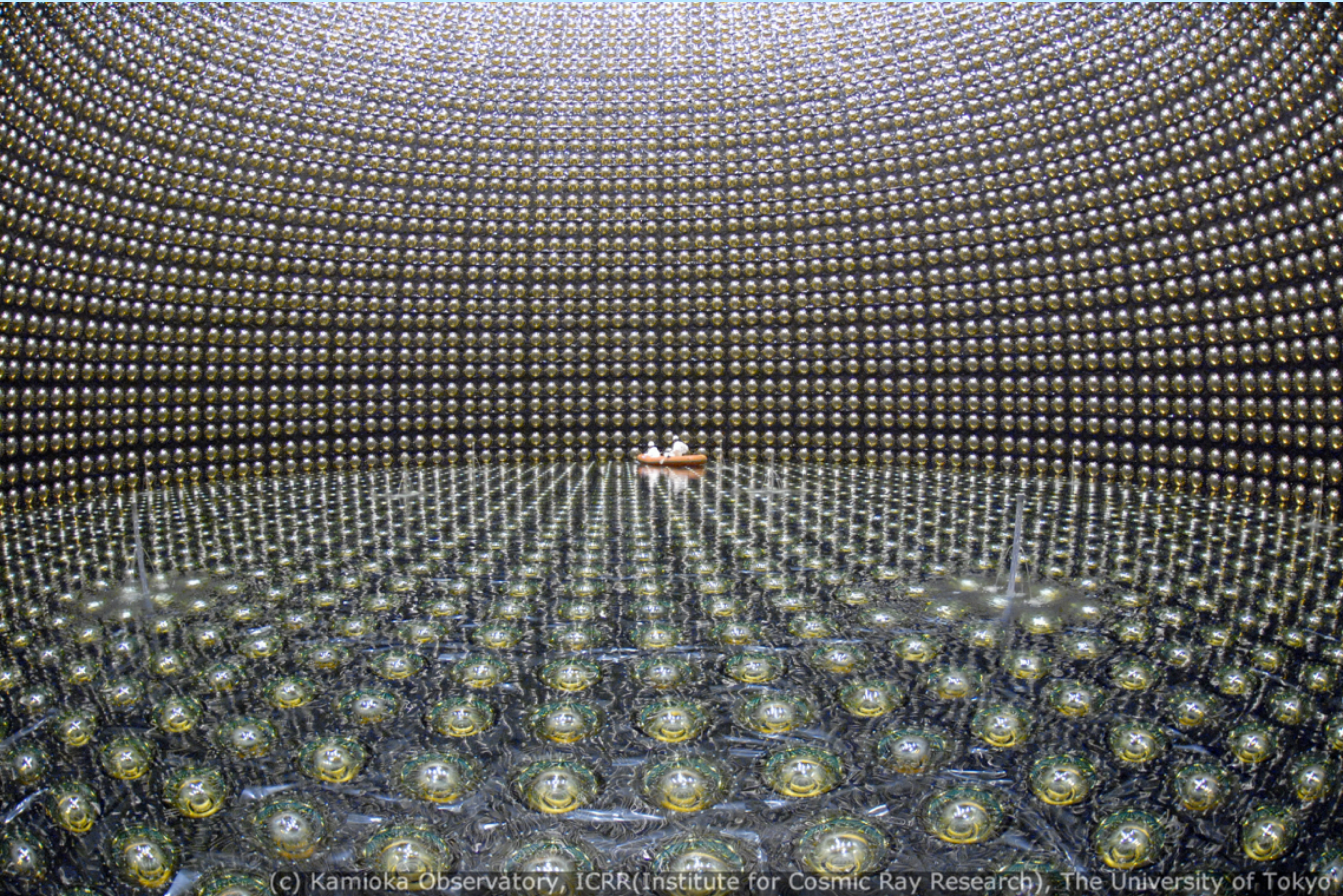
Super-Kamiokande

- US-Japan collaboration
- Operating since 1996
- 50,000 ton ring-imaging water Cherenkov detector
- Inner detector 11,000 x 20"PMTs
    - 40% photo coverage
- Outer detector 1,885 x 8"PMTs
- In Mozumi mine of Kamioka Mining Co, near Toyama Japan
    - ~1000m of rock overburden to block cosmic rays



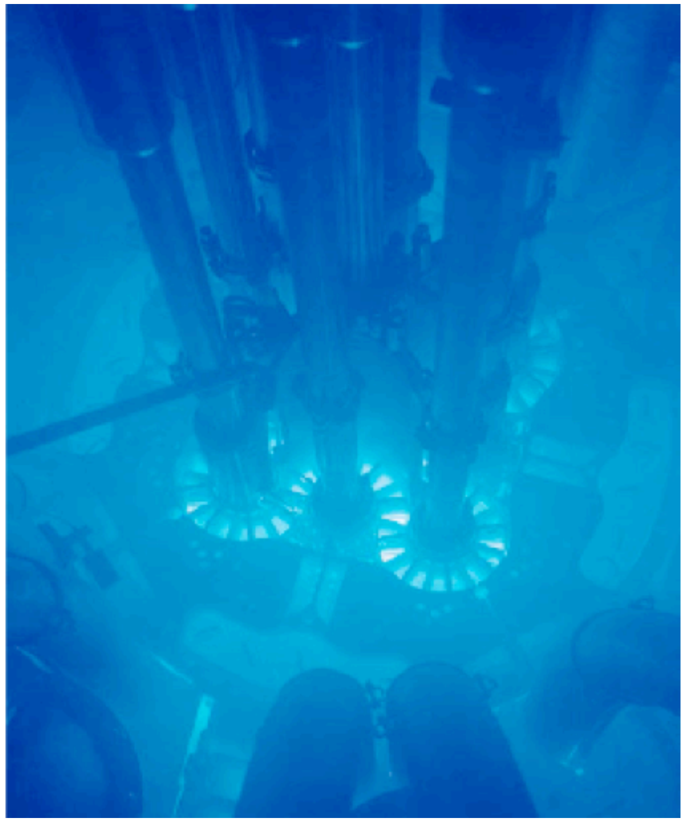


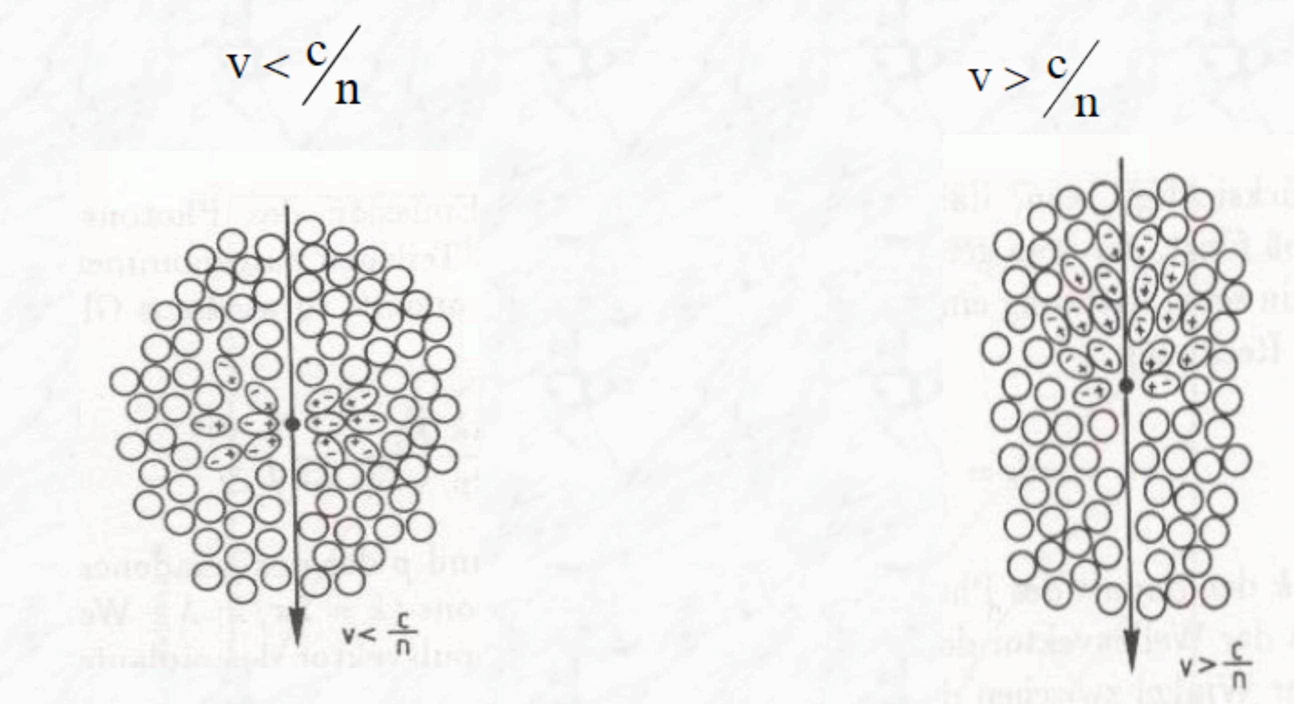
Polishing PMTs while filling the water



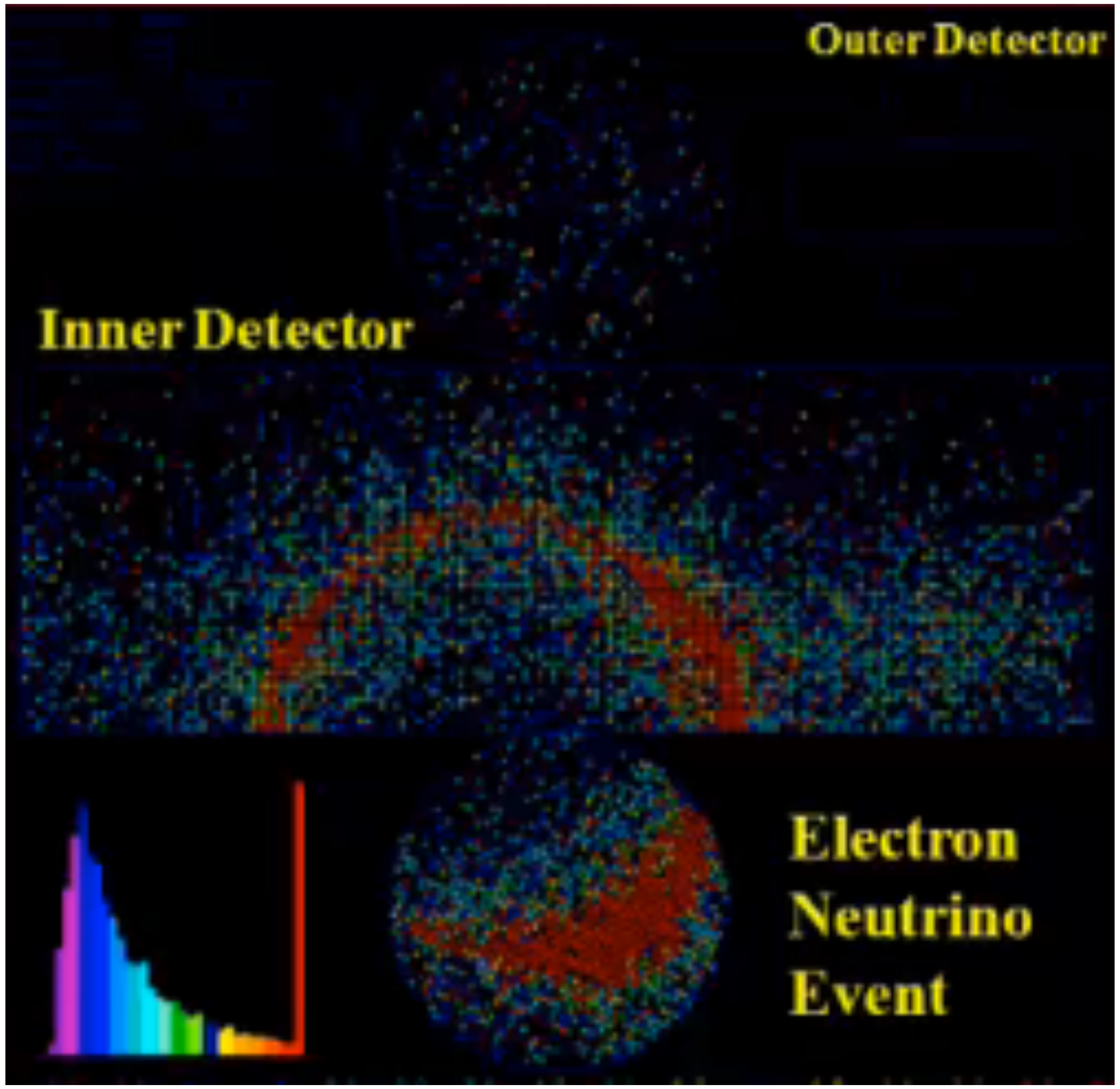
Cherenkov light in water

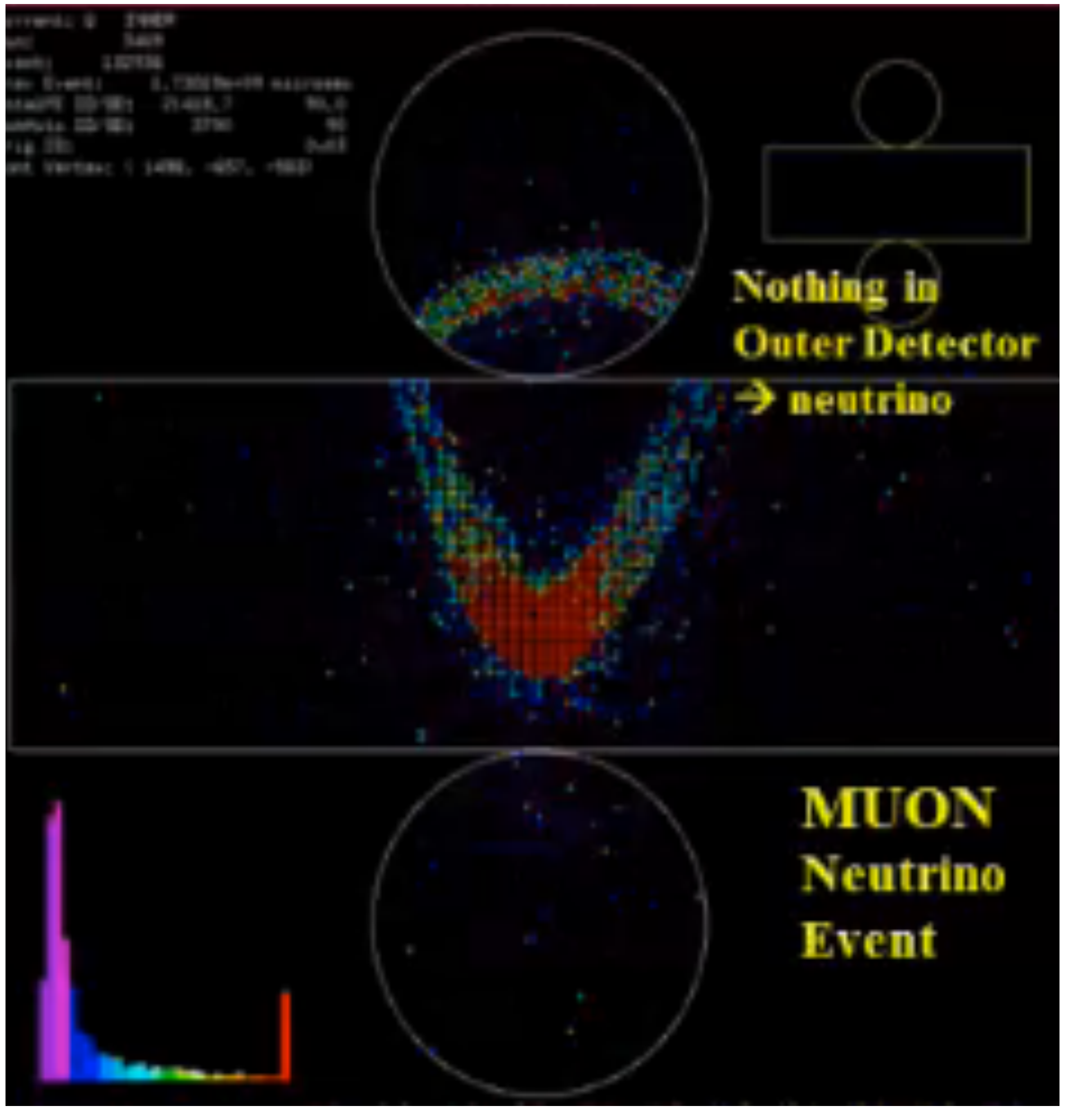
- Neutrinos interact in water
  - Produces charged particle (muon for example)
  - Energetic muon is relativistic travels with the speed of light, speed of light in water v=c/n
    - Index of refraction of water n = 1.33
  - Cherenkov light is emitted
    - Characteristic emission angle ~42°





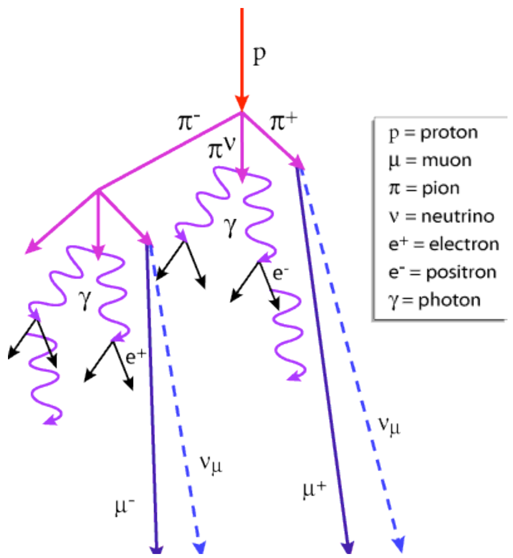
Particle Identification





- Electron scatters in water and produces fuzzy Cherenkov ring
- Muon travels straight and produces sharp ring

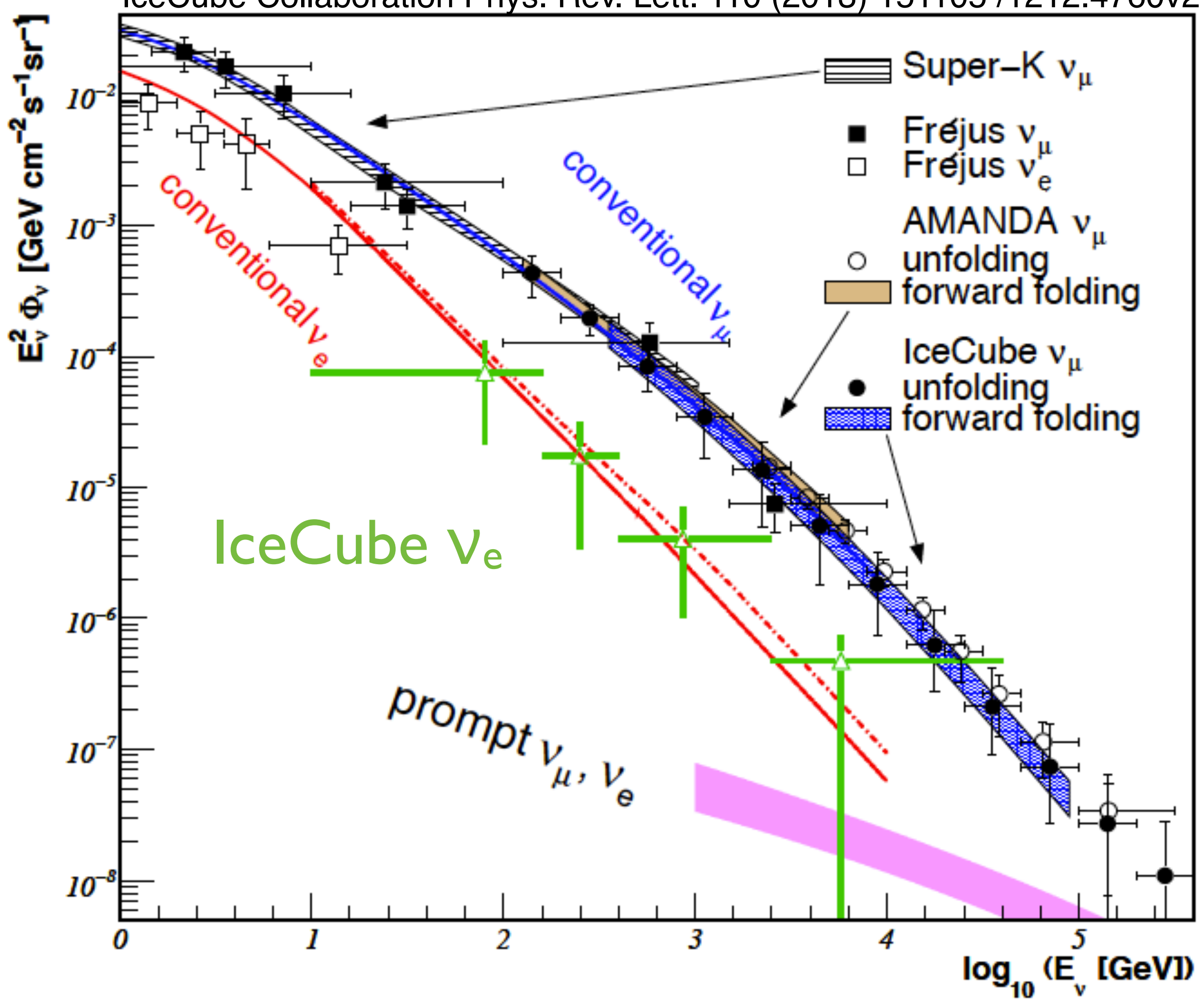
Atmospheric Neutrinos



Cosmic rays interact in the upper atmosphere:

$p + A \rightarrow \pi^{\pm} (K^{\pm})$ + other hadrons ... $\pi^{+} \rightarrow \mu^{+}\nu_{\mu} \rightarrow e^{+}\nu_{e}\nu_{\mu}\nu_{\mu}$

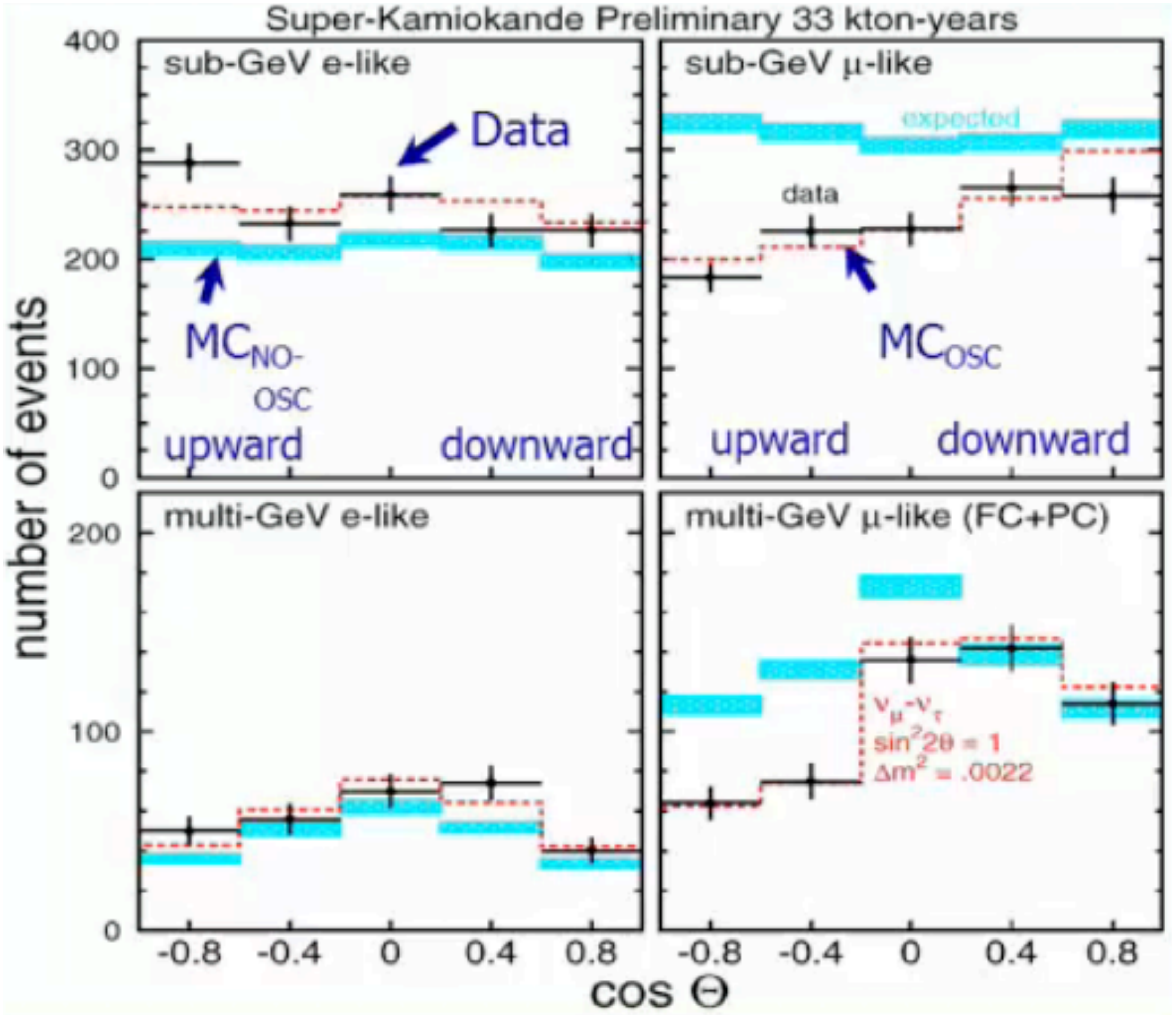
IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 /1212.4760v2



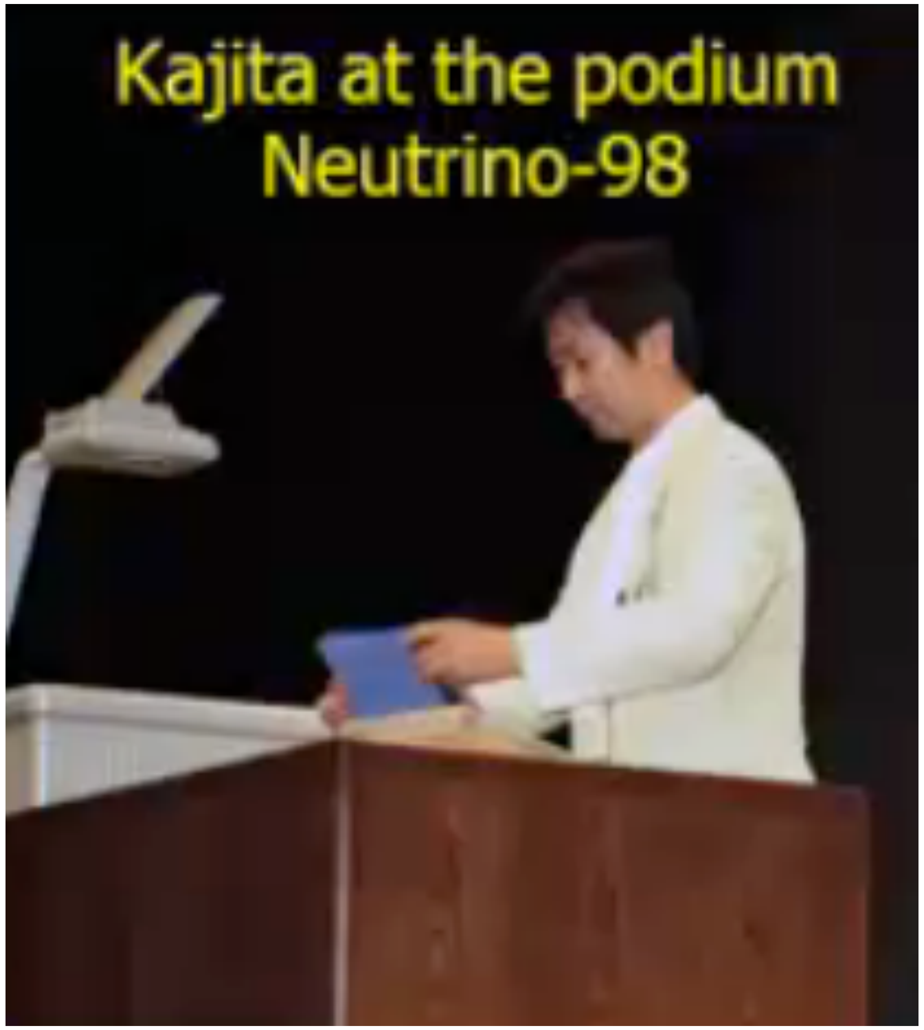
- Collisions of cosmic-rays with nuclei in the Earth's atmosphere produce neutrinos
  - pions, kaons → ν's
  - Neutrino energies extend up to ~100 TeV
- Higher energy contribution from "prompt" ν's from charm decays not yet observed
  - $(D_0, D_{\pm}, D_{s\pm}, \Lambda_{c\pm}) \rightarrow \nu$'s

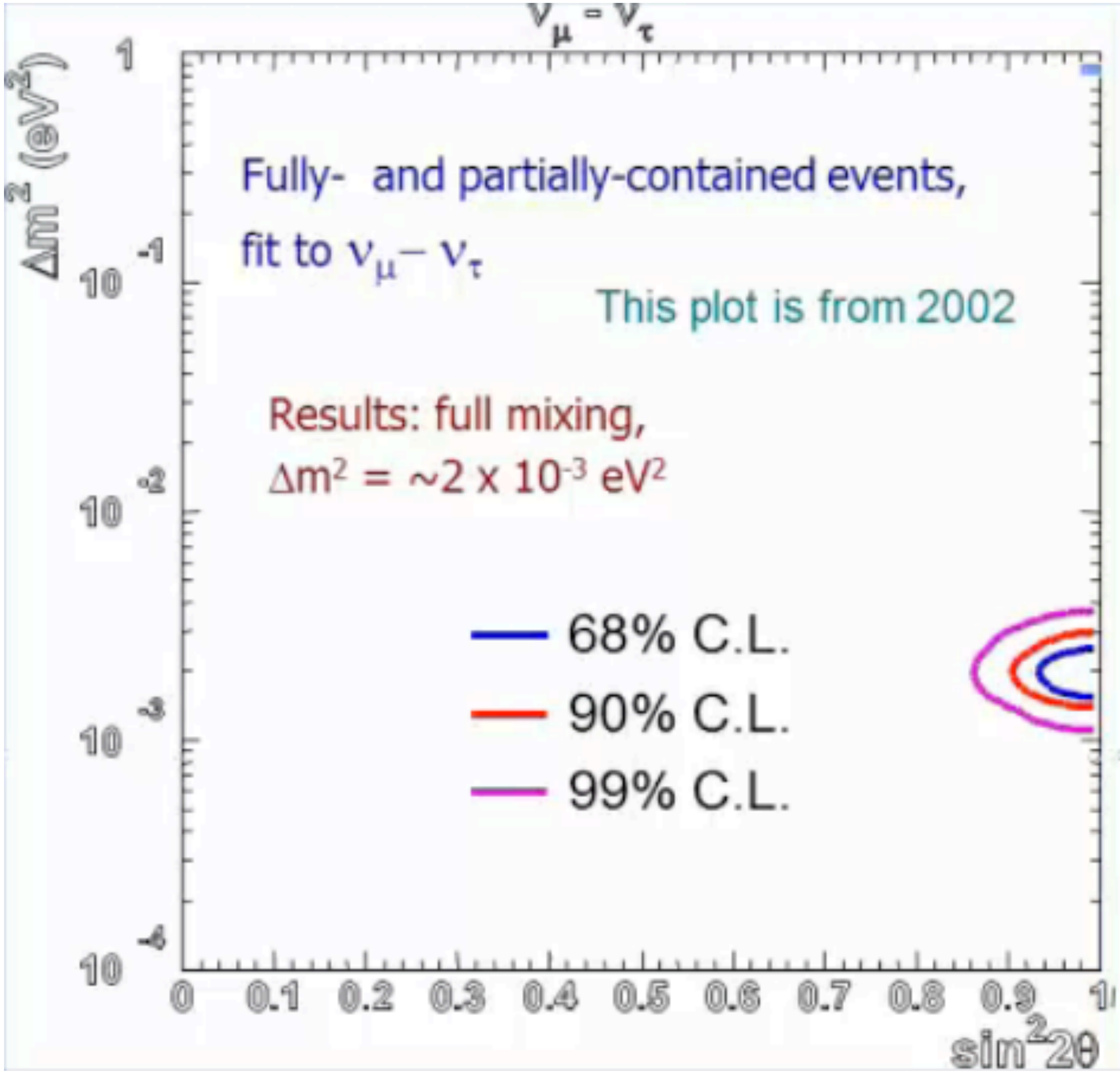
Atmospheric Neutrino Analysis 1998

- Used MC to compare to data
- Electron neutrinos as expected
- Muon neutrino data shows large up/down asymmetry
- Only viable explanation is that muon neutrinos oscillate to tau, which is not observed

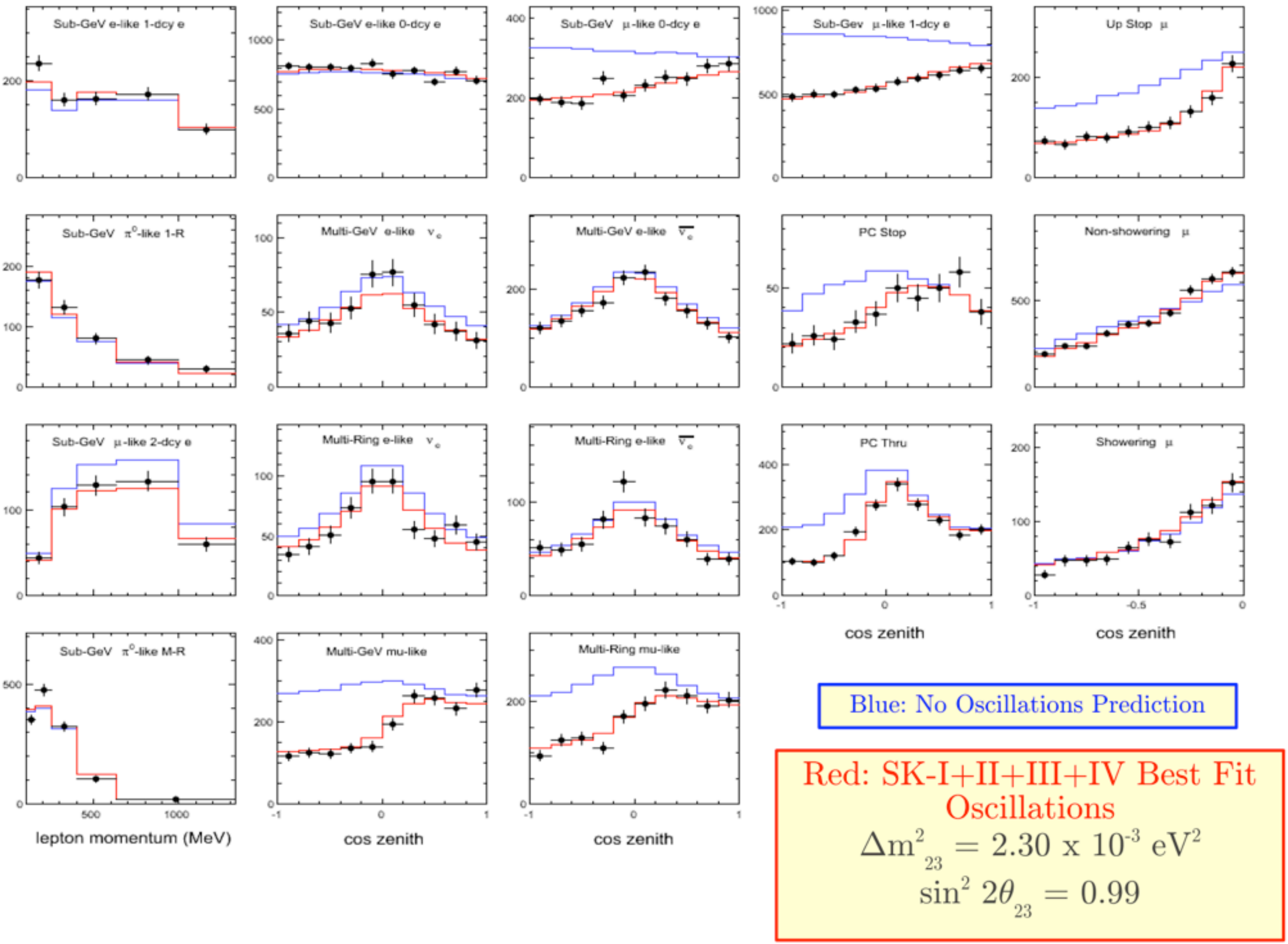


Atmospheric Neutrino Analysis 1998





- First conclusive accepted evidence that neutrinos oscillates and have mass


Sub-GeV e-like 1-dcy e
Sub-GeV e-like 0-dcy e
Sub-GeV μ-like 0-dcy e
Sub-Gev μ-like 1-dcy e
Up Stop μ
Sub-GeV π⁰-like 1-R
Multi-GeV e-like ν_e
Multi-GeV e-like $\bar{\nu}_e$
PC Stop
Non-showering μ
Sub-GeV μ-like 2-dcy e
Multi-Ring e-like ν_e
Multi-Ring e-like $\bar{\nu}_e$
PC Thru
Showering μ
Sub-GeV π⁰-like M-R
Multi-GeV mu-like
Multi-Ring mu-like
lepton momentum (MeV)
cos zenith
cos zenith
cos zenith
cos zenith
Blue: No Oscillations Prediction
Red: SK-I+II+III+IV Best Fit Oscillations
$\Delta m^2_{23} = 2.30 \times 10^{-3}\ eV^2$
$\sin^2 2\theta_{23} = 0.99$

SNO Experiment and Solar Neutrino Problem

Solar neutrinos

$$p + p \longrightarrow {}^2H + e^+ + \nu_e \qquad (\nu_{pp})$$

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

86 % (pp-I) | 14 %

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

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

14 % (pp-II) | 0.02 % (pp-III)

$$(\nu_{Be}) \quad {}^7Be + e^- \longrightarrow {}^7Li + \nu_e$$

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

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

$${}^8B \longrightarrow {}^8Be^* + e^+ + \nu_e \quad (\nu_B)$$

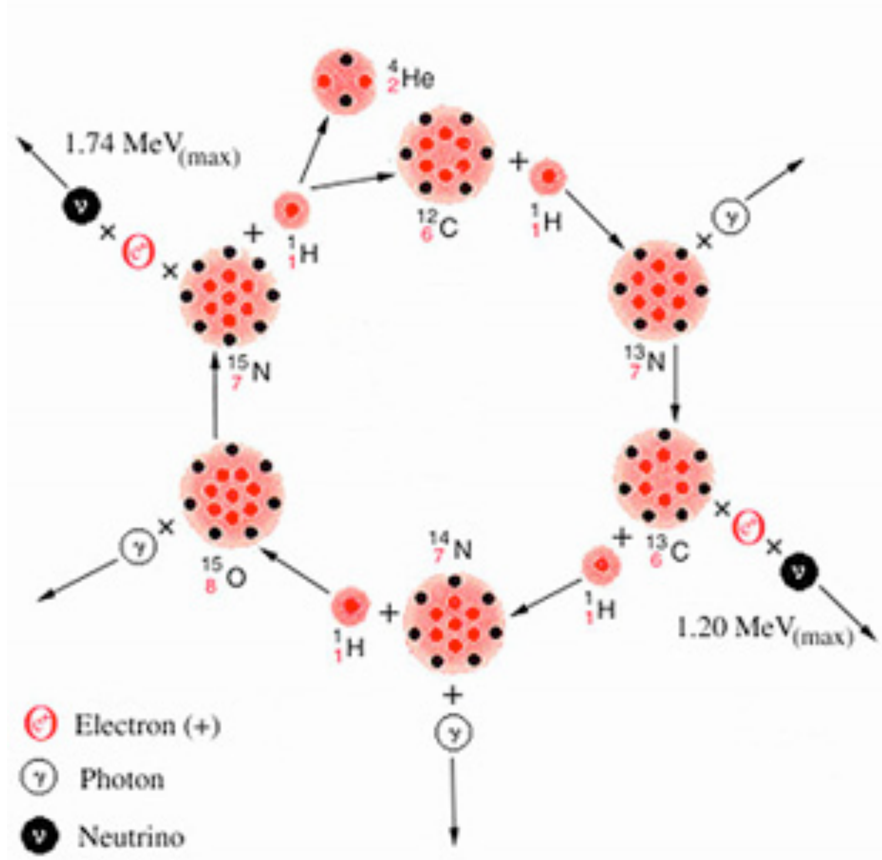
$$\hookrightarrow {}^4He + {}^4He$$

$$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e \qquad \text{(pep)}$$

$${}^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e \qquad \text{(hep)}$$

Two distinct processes are expected to produce solar neutrinos with different energy spectra and flux,

- pp fusion chain (main process)
- CNO cycles (sub-dominant)



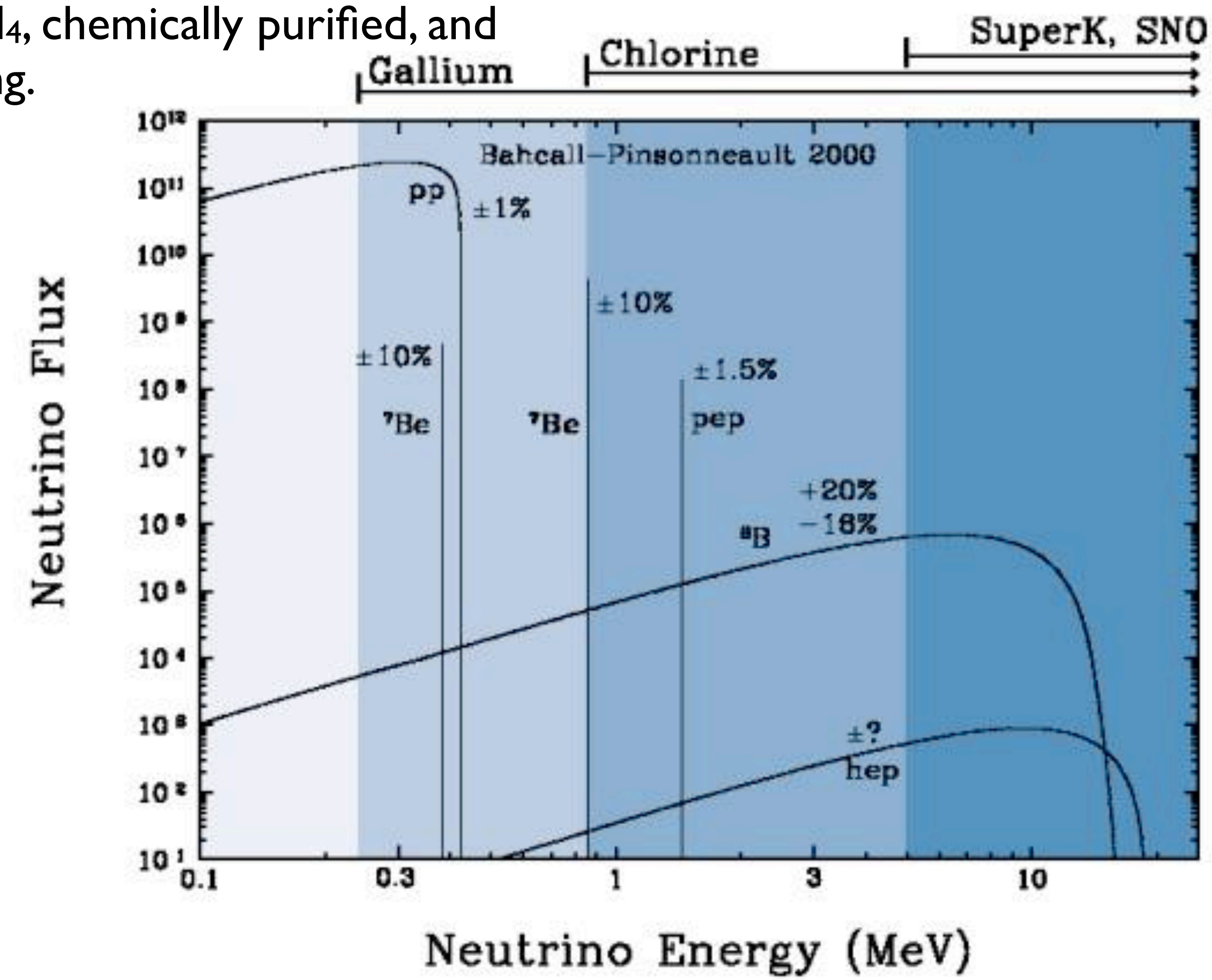
Solar Neutrino Detection

radiochemical neutrino detector

- Chlorine: Neutrino capture on the ^{37}Cl, with an energy threshold of 0.814 MeV, produces radioactive ^{37}Ar, a gas, which can be removed from the target, purified, and counted. The results of this experiment revealed a "solar neutrino problem"
- Gallium: Neutrino capture on ^{71}Ga as the target. Neutrino capture on the ^{71}Ga produces radioactive ^{71}Ge with an energy threshold of 0.233 MeV. This ^{71}Ge can be removed from a liquid target in the form of gaseous $GeCl_4$, chemically purified, and converted to GeH_4 gas for counting.

real time neutrino detection

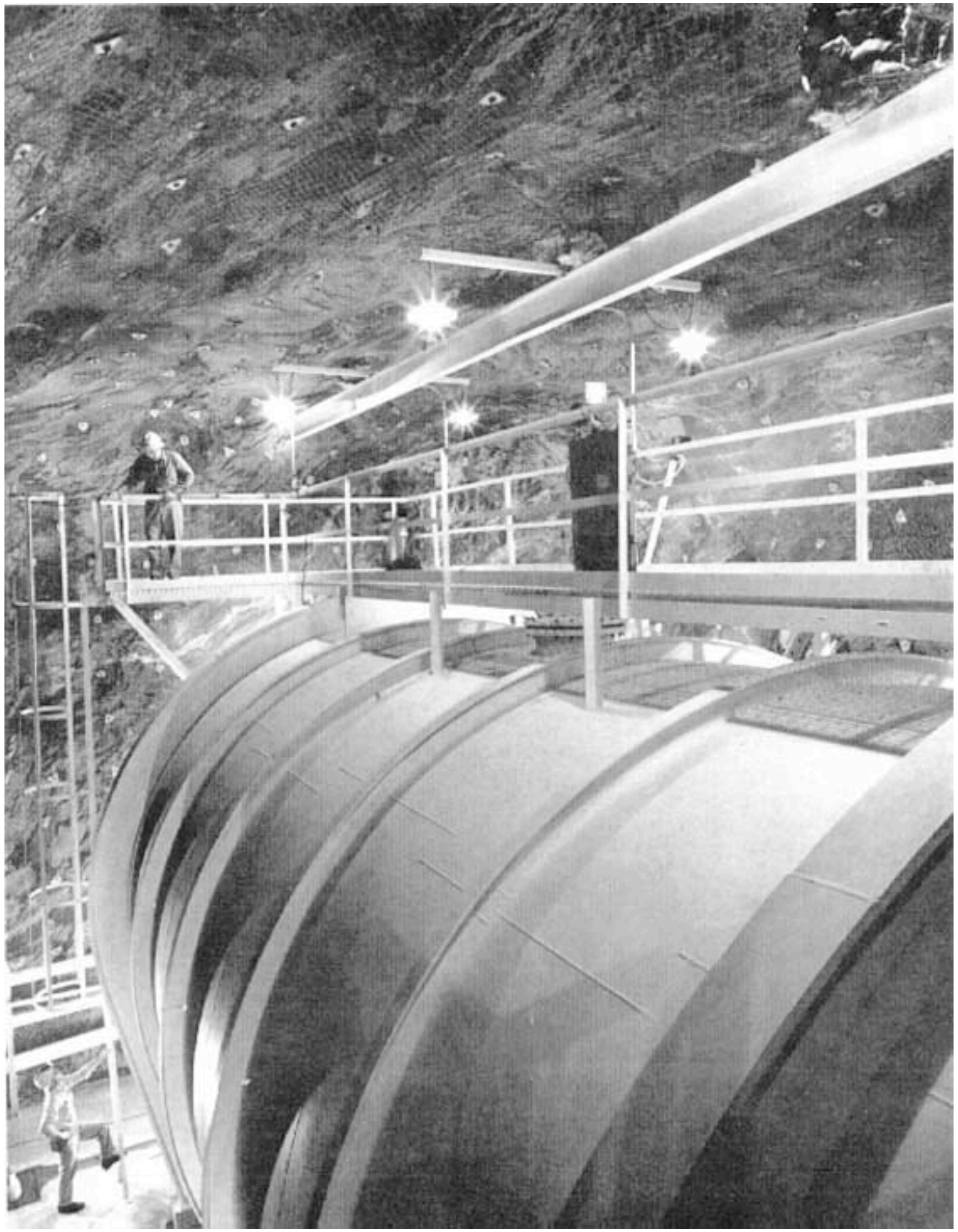
- Water cherenkov: Cherenkov light emission from charged particle passing through optical transparent medium
- Scintillation detector: the process by which ionization produced by charged particles excites a material and light is emitted by the de-excitation. Light is collected by photo sensor



Cl-Ar Experiment

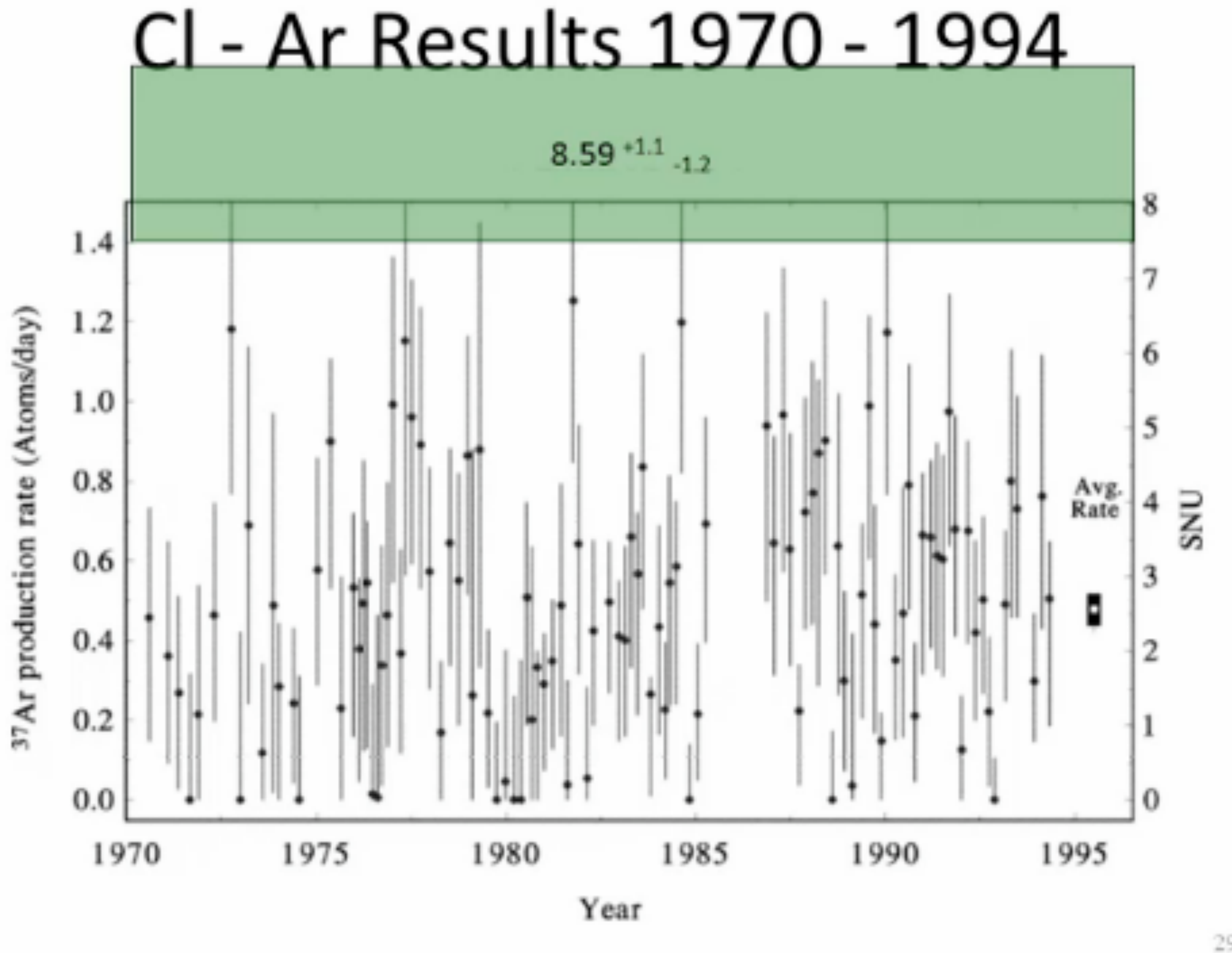
- The Cl-Ar Experiment at Homestake 1968-1998

Ray Davis John Bahcall

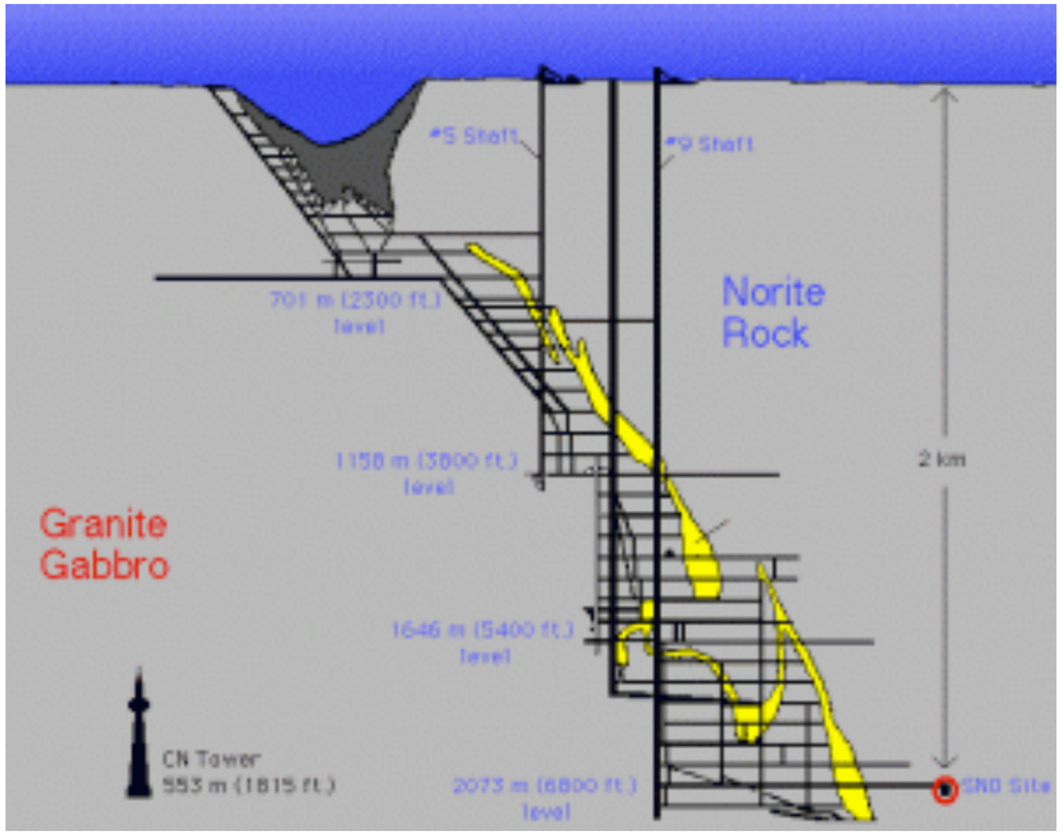


100,000gallons of perchloroethylen

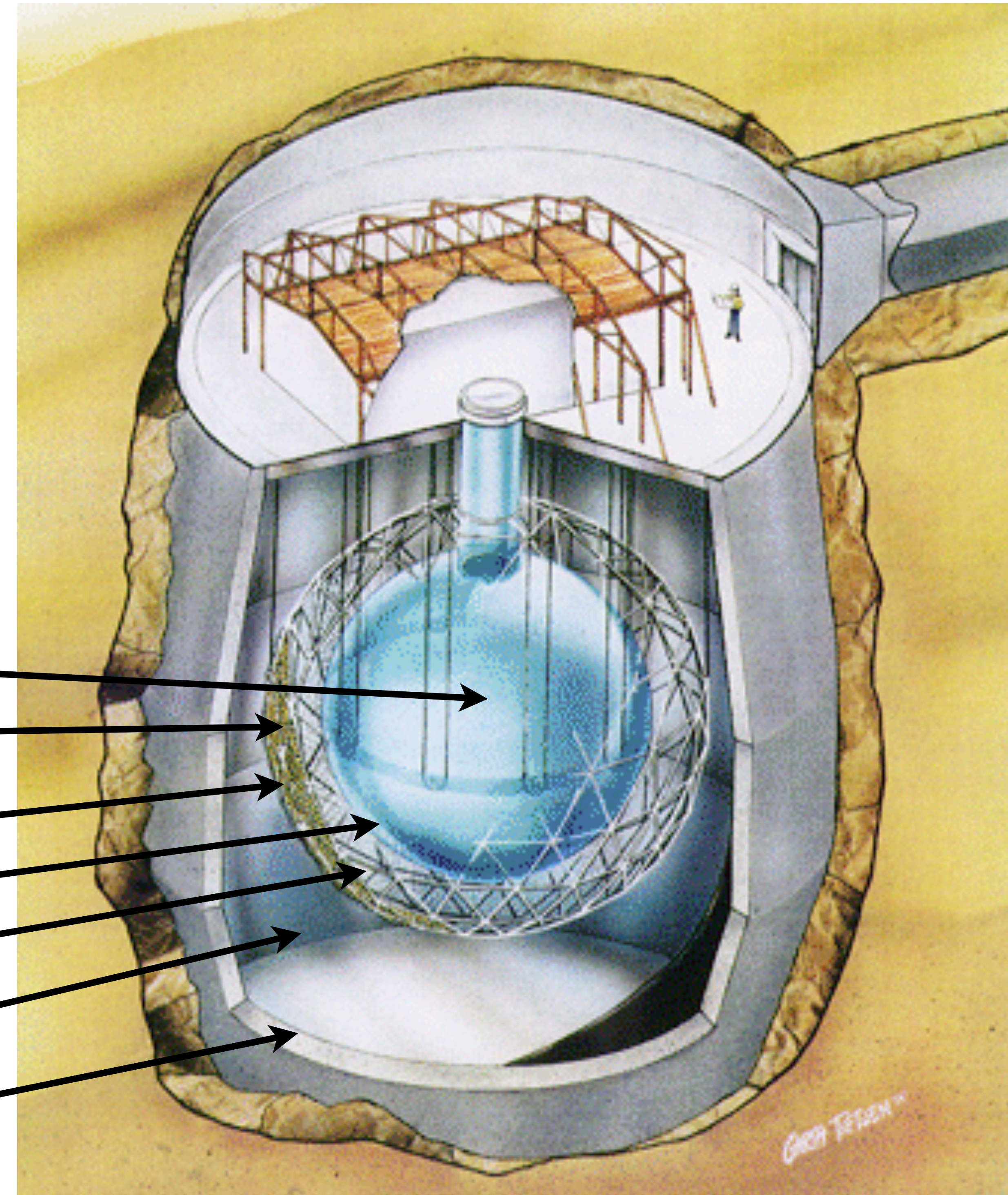
Cl-Ar Results



Sudbury Neutrino Observatory

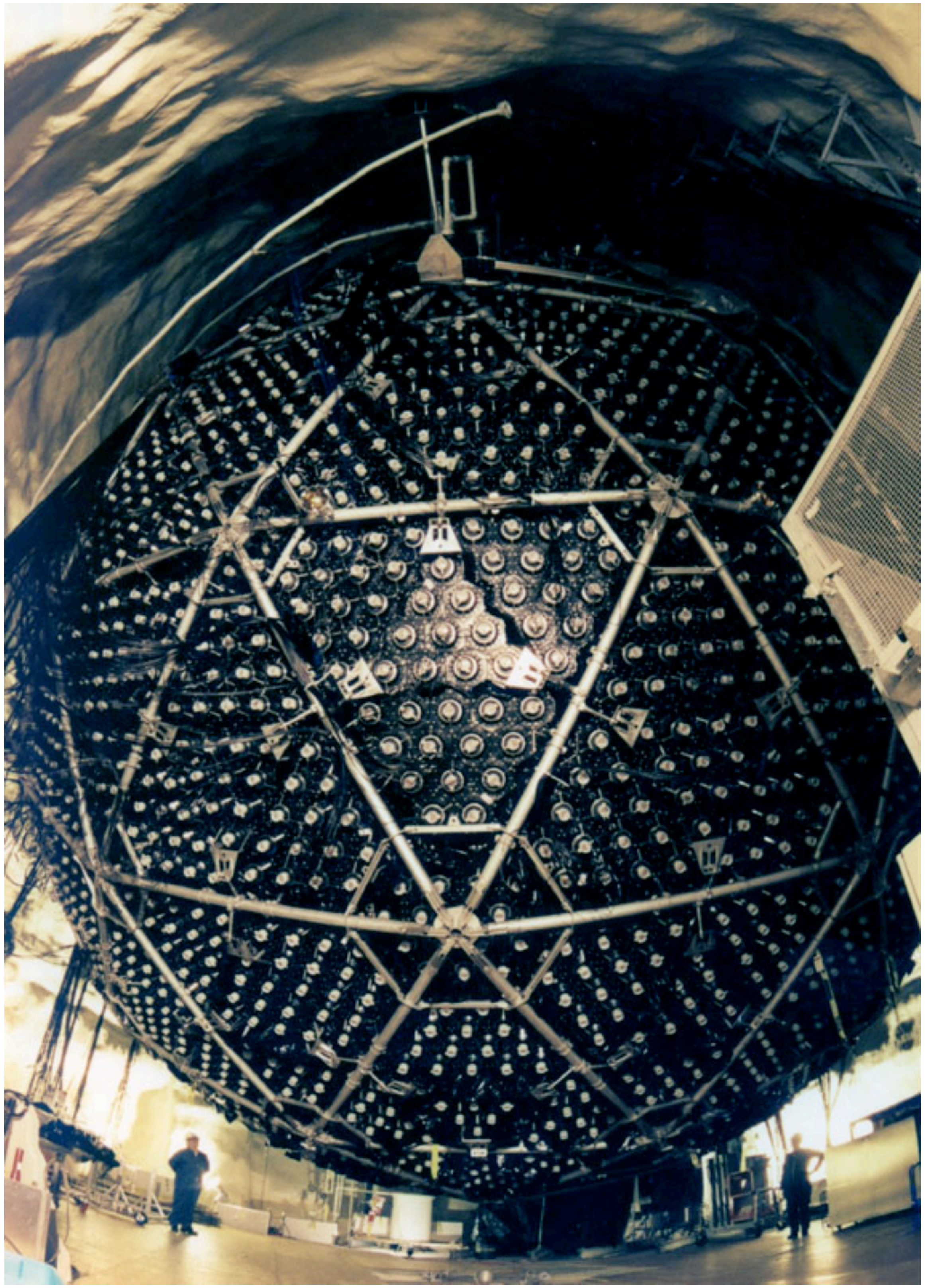


- Need an experiment which is directly sensitive to all neutrinos -- PRL55, 1534 (1985)



- 1000 tons D_2O
- Support structure
- 9500 PMTs to achieve 60% photo coverage
- 12m diameter arcrylic vessel
- 1700tons Inner Shielding H_20
- 5300tons Outer Shielding
- Urylon Liner and Radon Seal

SNO



- 62 trucks of heavy water

ν Reactions in SNO

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

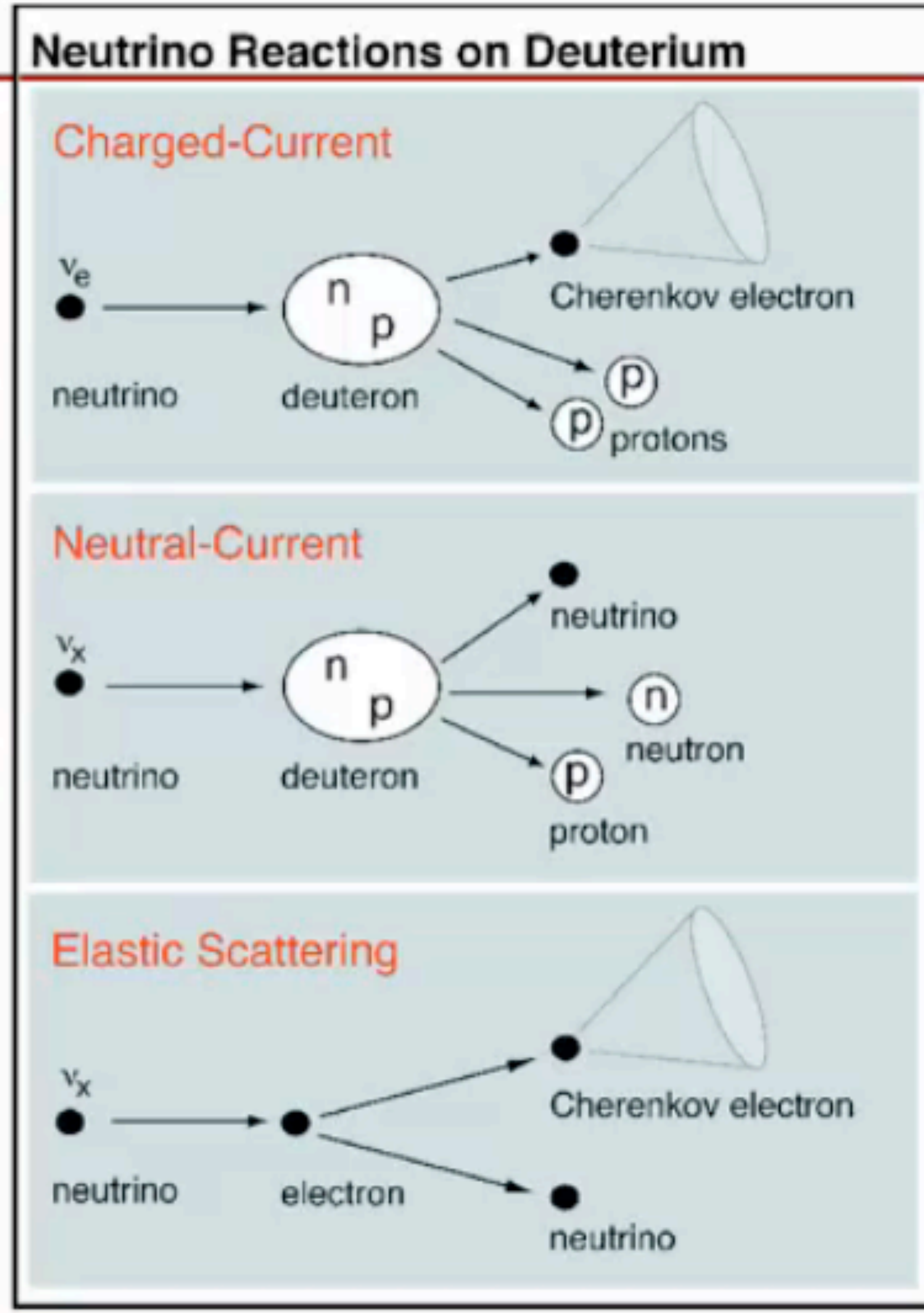
-Gives ν_e energy spectrum well
-Weak direction sensitivity $\propto$ 1-1/3cos(θ)
- ν_e only.

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

-Measure total ^8B ν flux from the sun.
- Equal cross section for all ν types

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

-Low Statistics
-Mainly sensitive to ν_e, some
-sensitivity to ν_μ and ν_τ
-Strong direction sensitivity



2001 SNO Result

Neutrino Flavor Composition of ^8B Flux

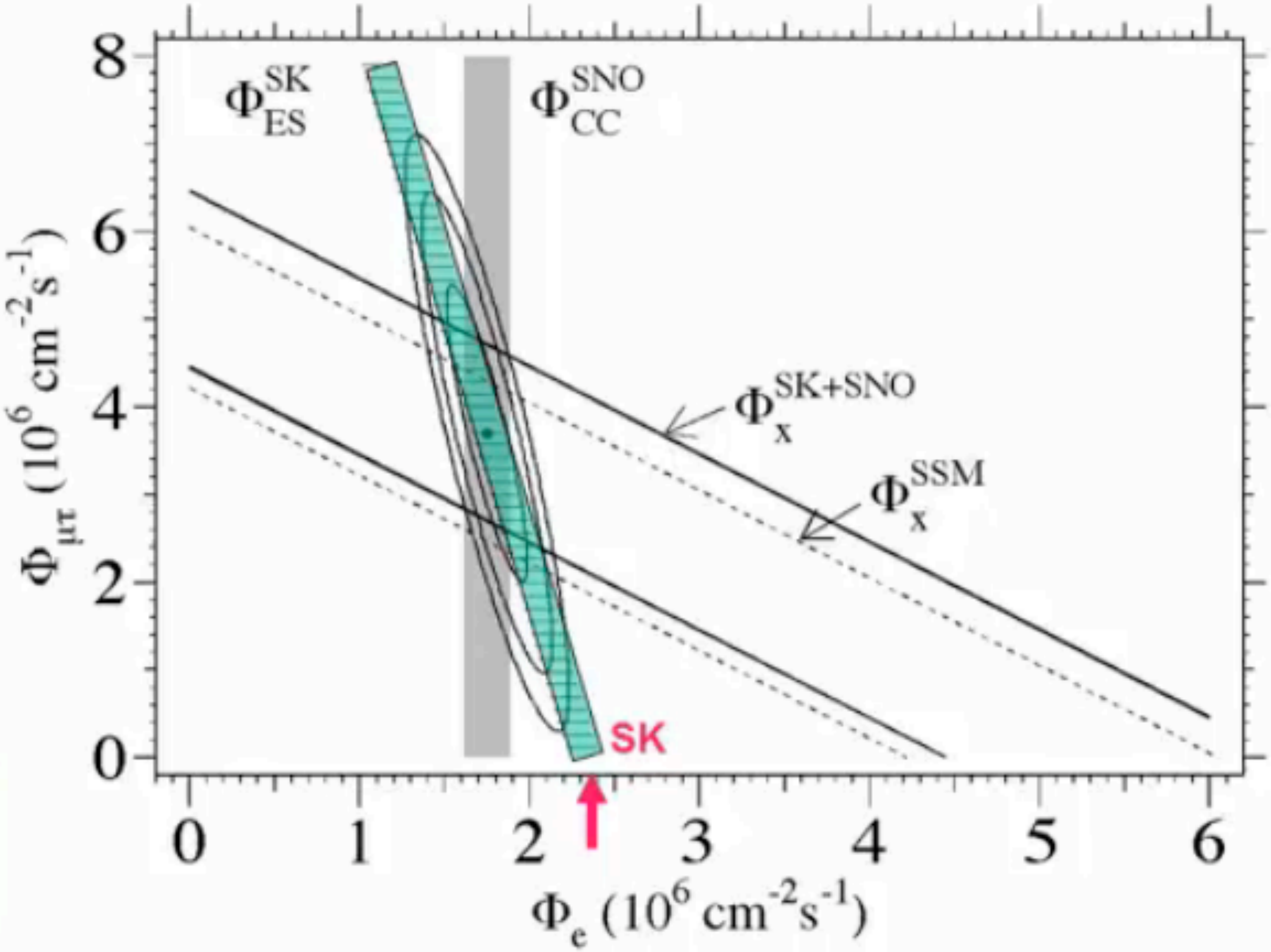
Fluxes

(10^6 cm^{-2} s^{-1})

ν_e:	1.75(15)
$\nu_{\mu\tau}$:	3.69(113)
ν_{total}:	5.44(99)
ν_{SSM}:	5.05

$\phi_{CC} = \phi_e$

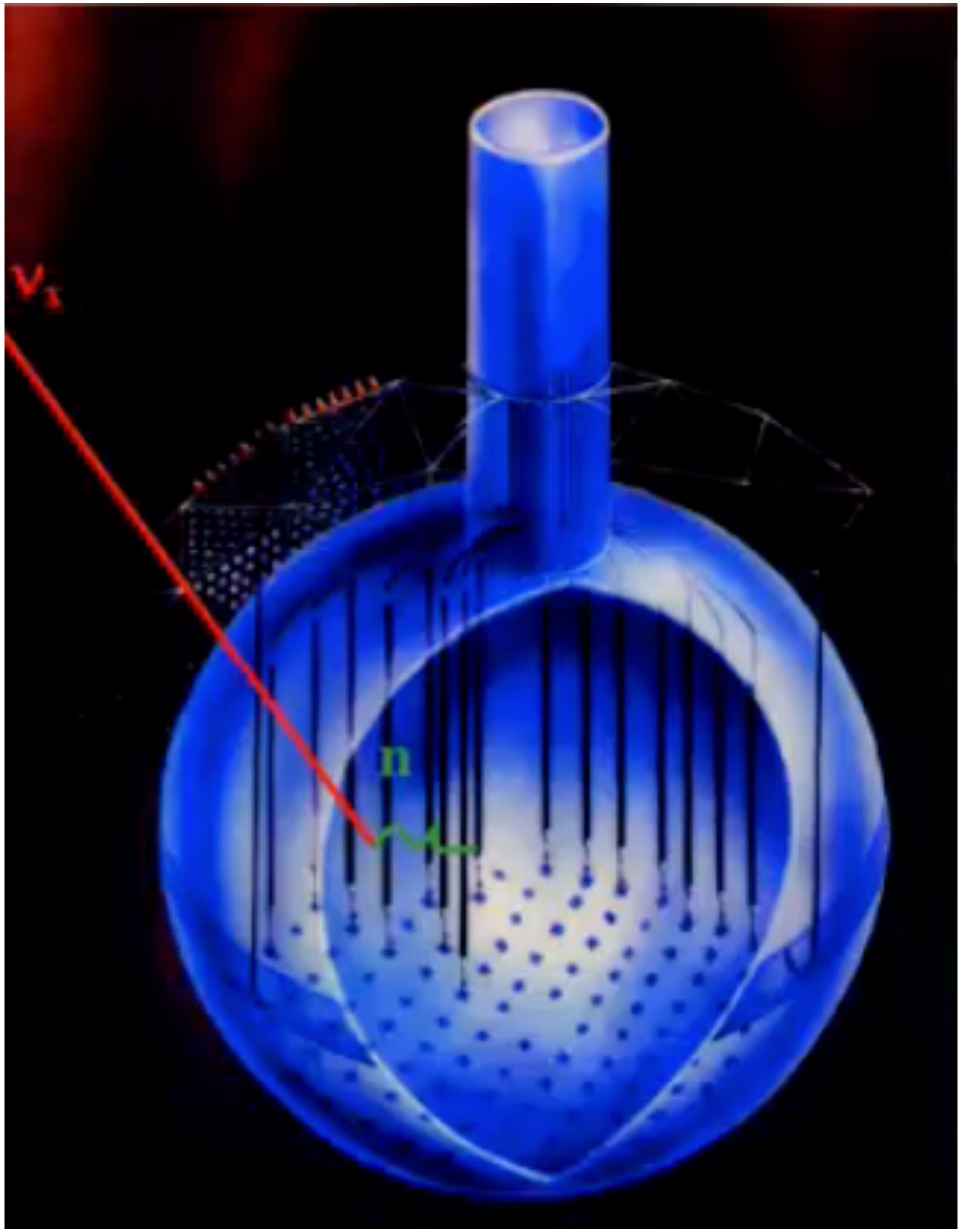
$\phi_{ES} = \phi_e + 0.154\, \phi_{\mu,\tau}$



Phys. Rev Lett. 87, 071301 (2001)

SNO Phase III

- Neutral Current Detection Array
  - ^{3}He proportional counters detect neutrons liberated from deuterium in NC interactions
  - Total length ~400m
  - 40 Vertical strings
  - 21% neutron capture efficiency

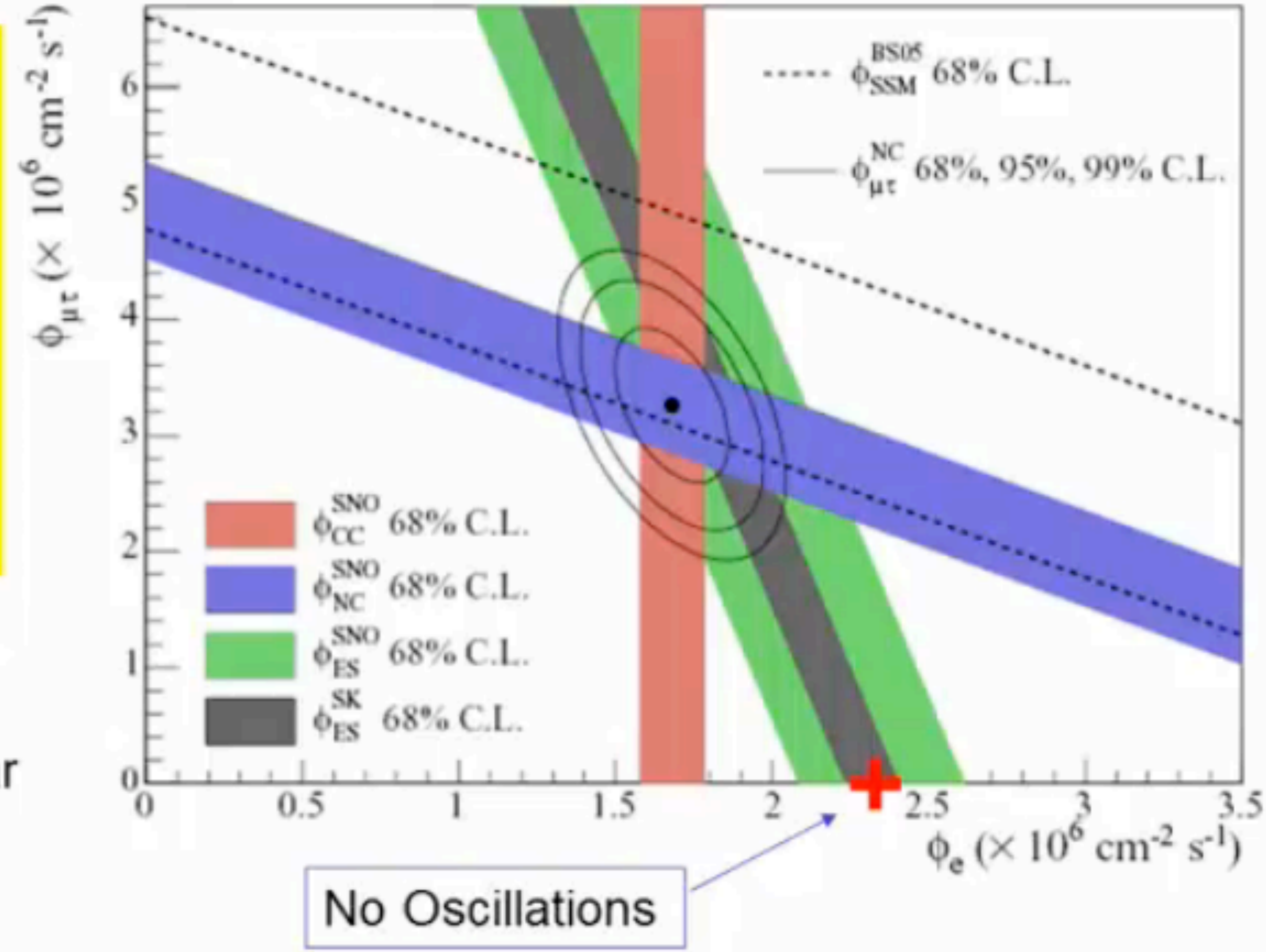


Fluxes

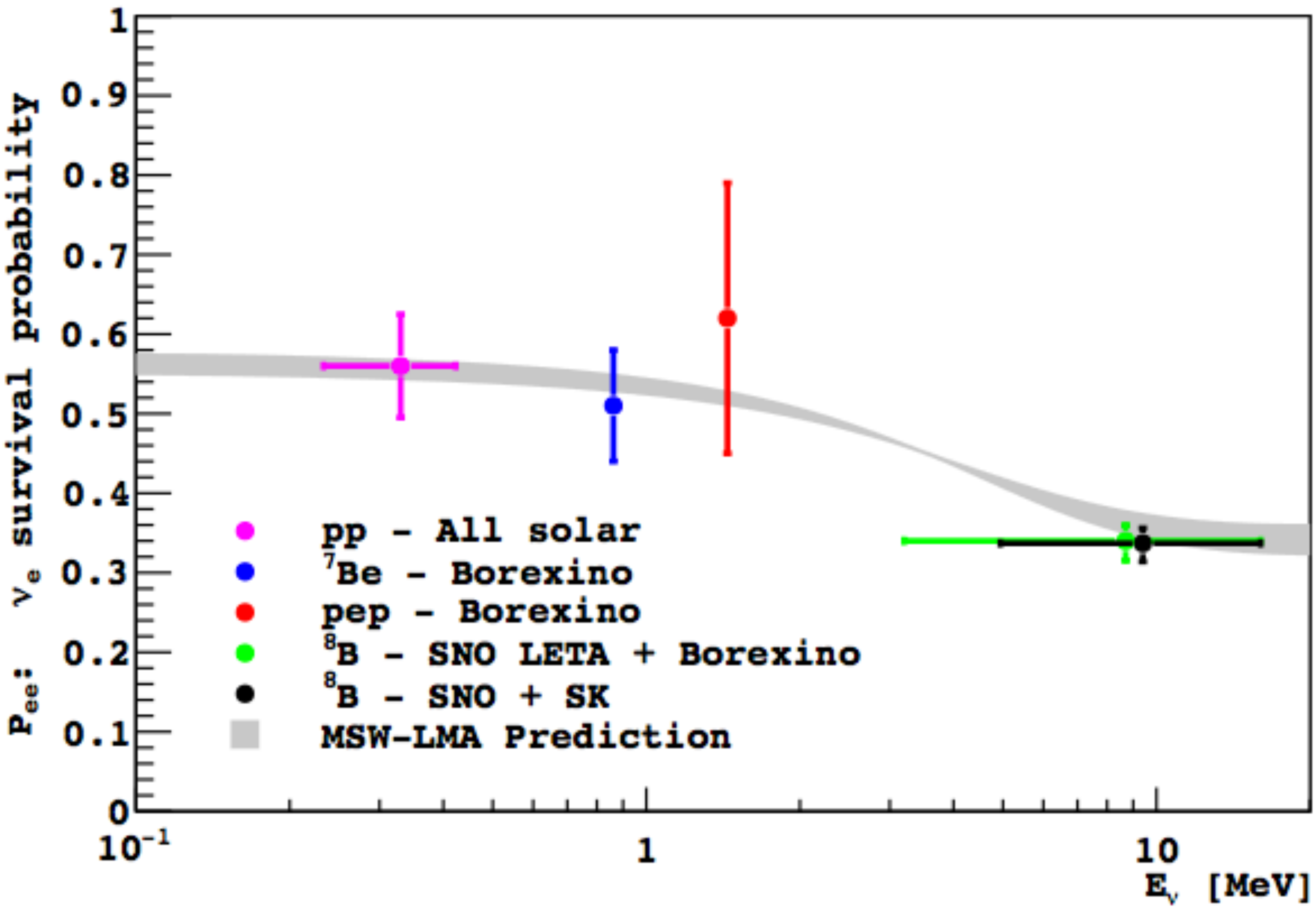
(10^6 cm^{-2} s^{-1})

ν_e:	1.68(11)
$\nu_{\mu\tau}$:	3.26(47)
ν_{total}:	4.94(43)
ν_{SSM}:	5.69

Clear evidence for flavors besides *electron* in the solar neutrino flux.



Borexino

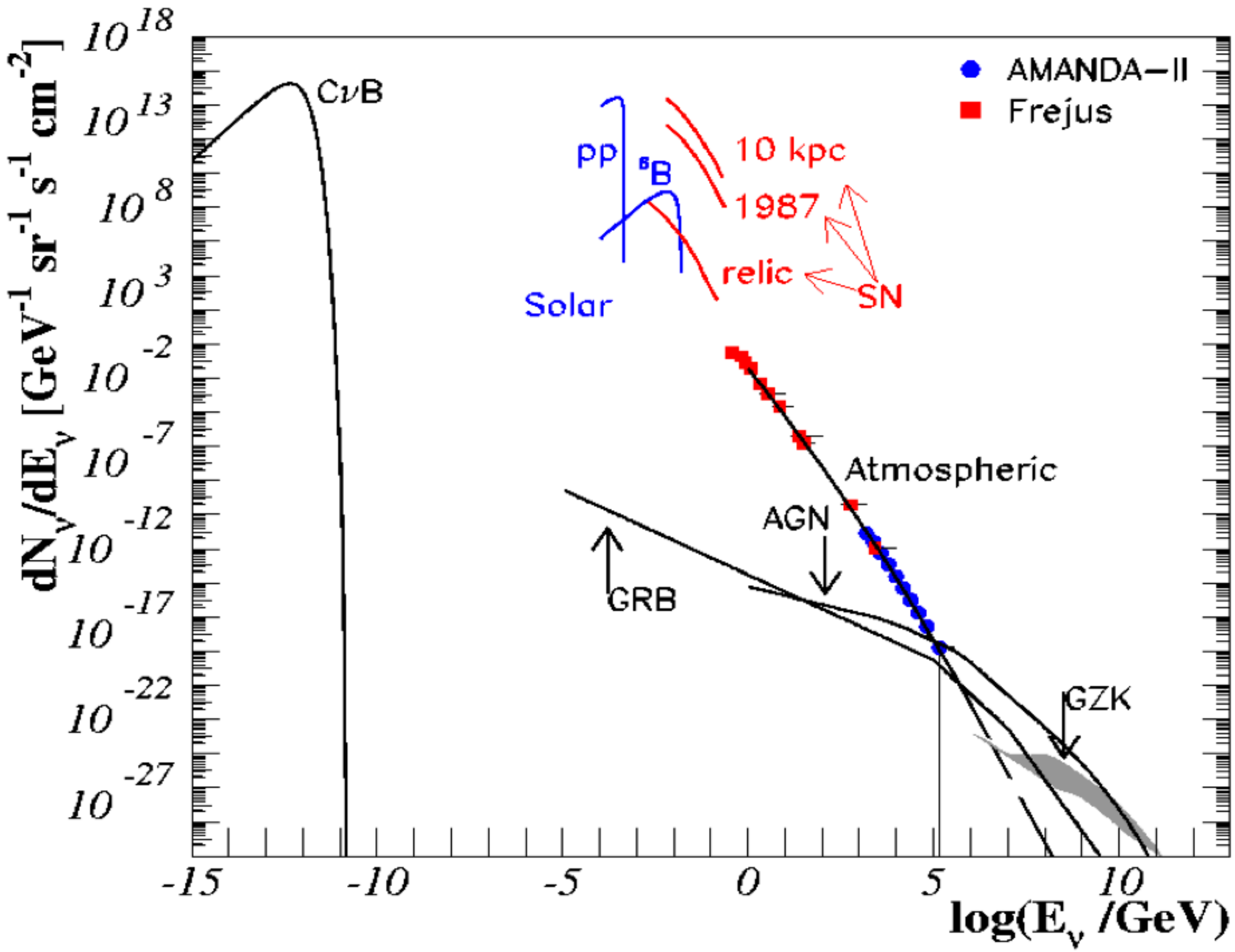


P_{ee}: ν_e survival probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^{-1}
1
10
E_ν [MeV]
pp - All solar
^{7}Be - Borexino
pep - Borexino
^{8}B - SNO LETA + Borexino
^{8}B - SNO + SK
MSW-LMA Prediction

Astrophysical Neutrinos

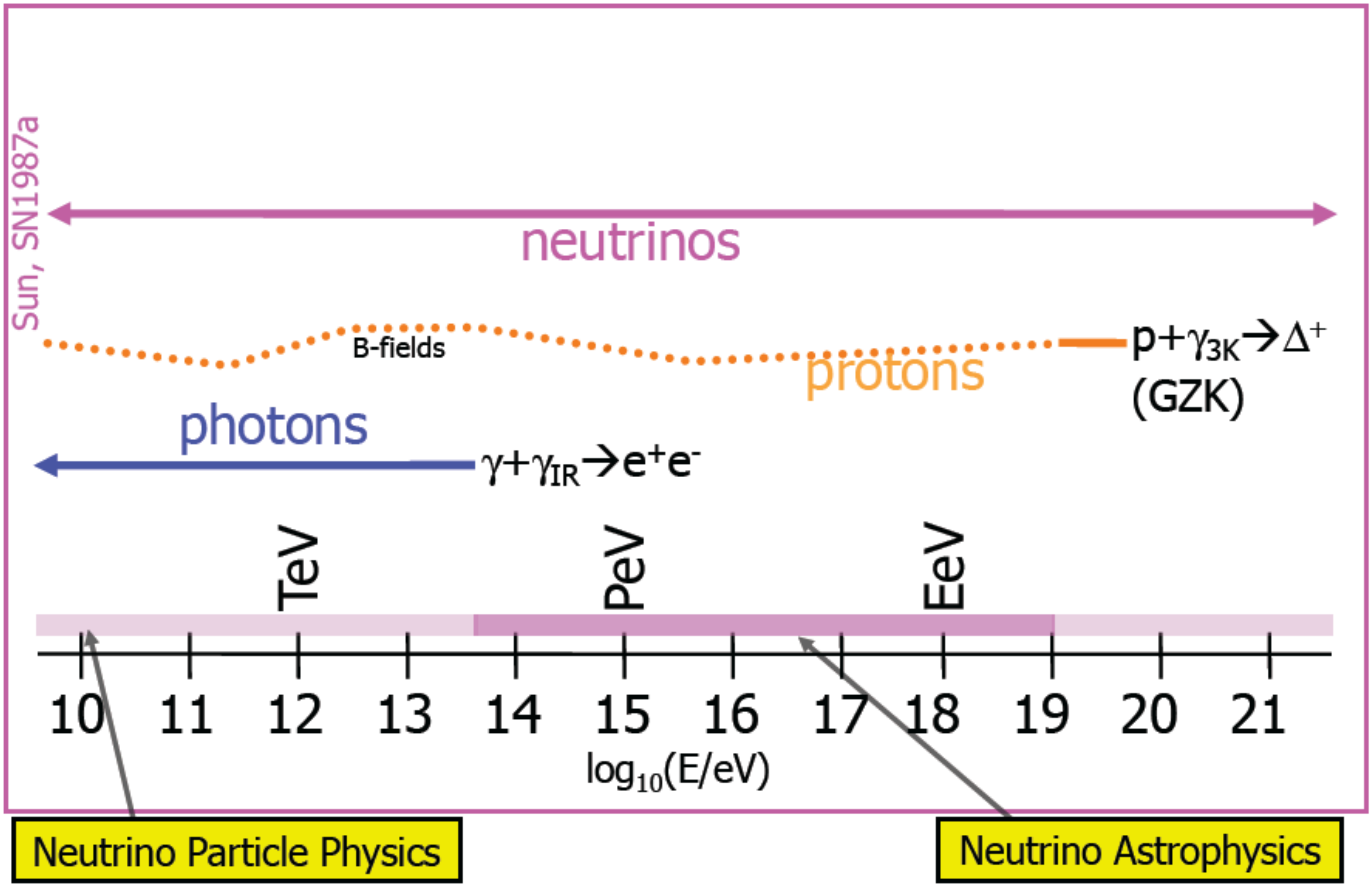
Neutrino Sources

- Sources of neutrinos:
  - relic neutrinos
  - reactor,
  - particle accelerator,
  - sun,
  - atmosphere,
  - supernova,
  - galactic,
  - extra-galactic,
  - GZK,
  - ...

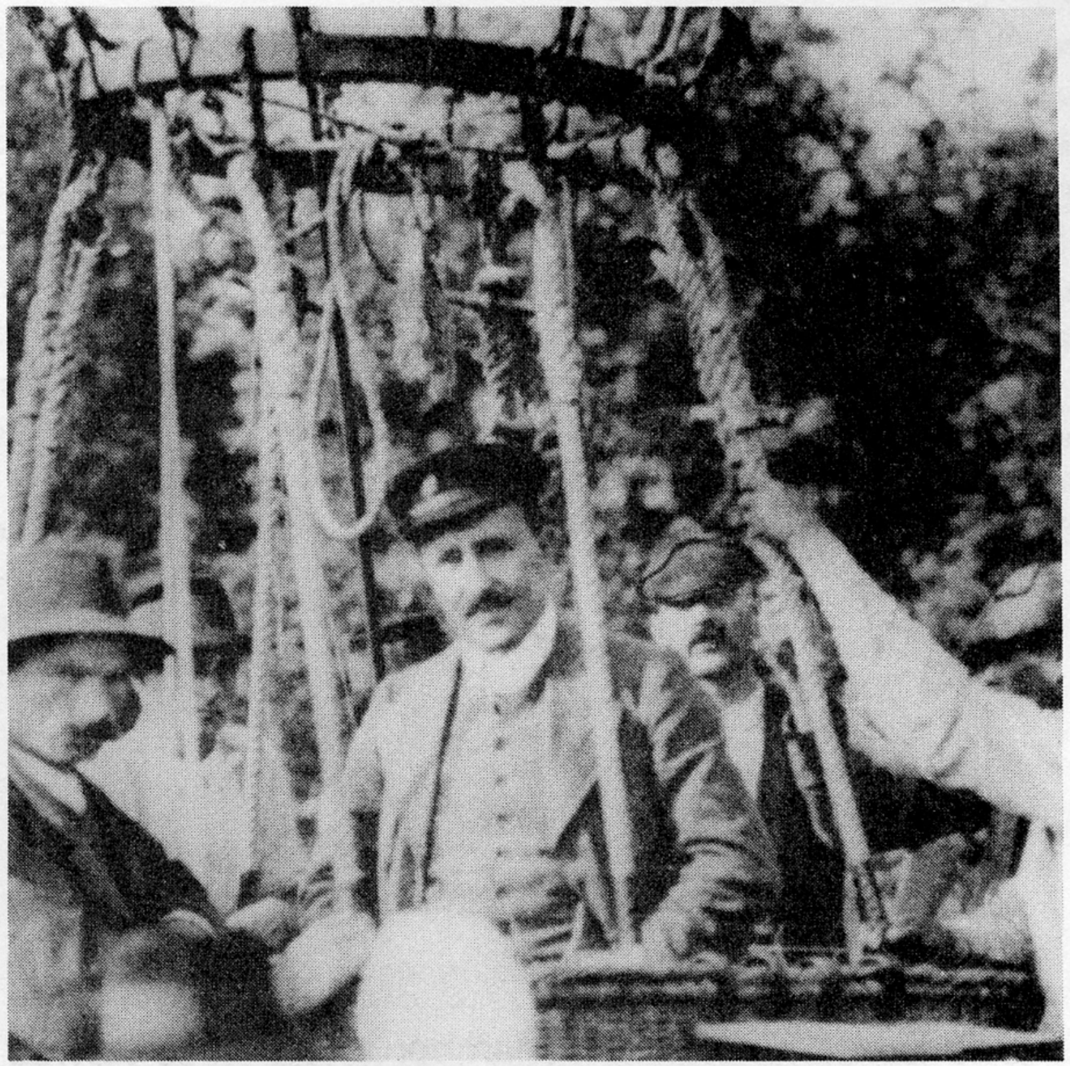


Understanding neutrino sources is key to measure any neutrino physics

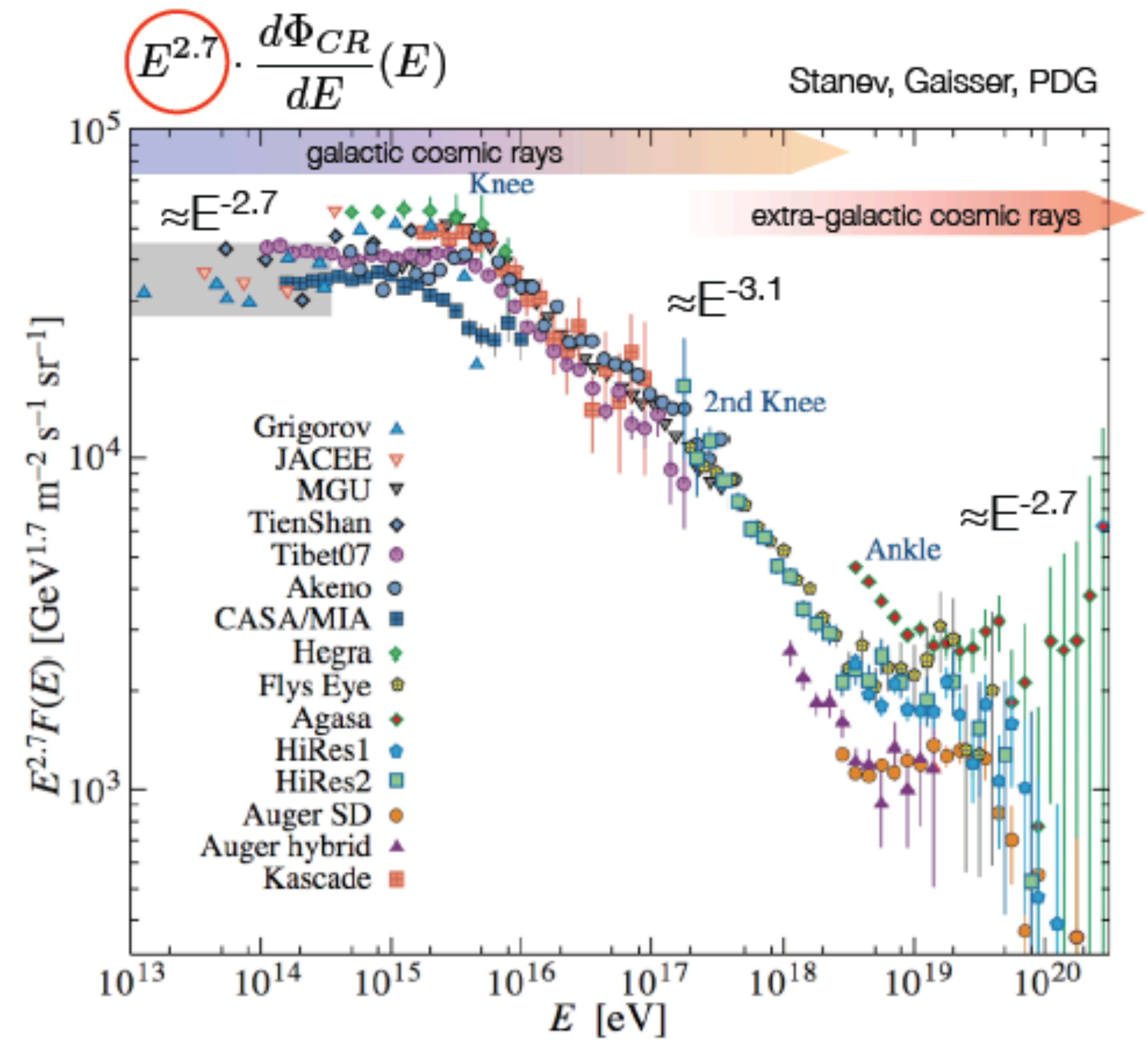
Astronomical Messengers



High Energy Cosmic Ray Mystery

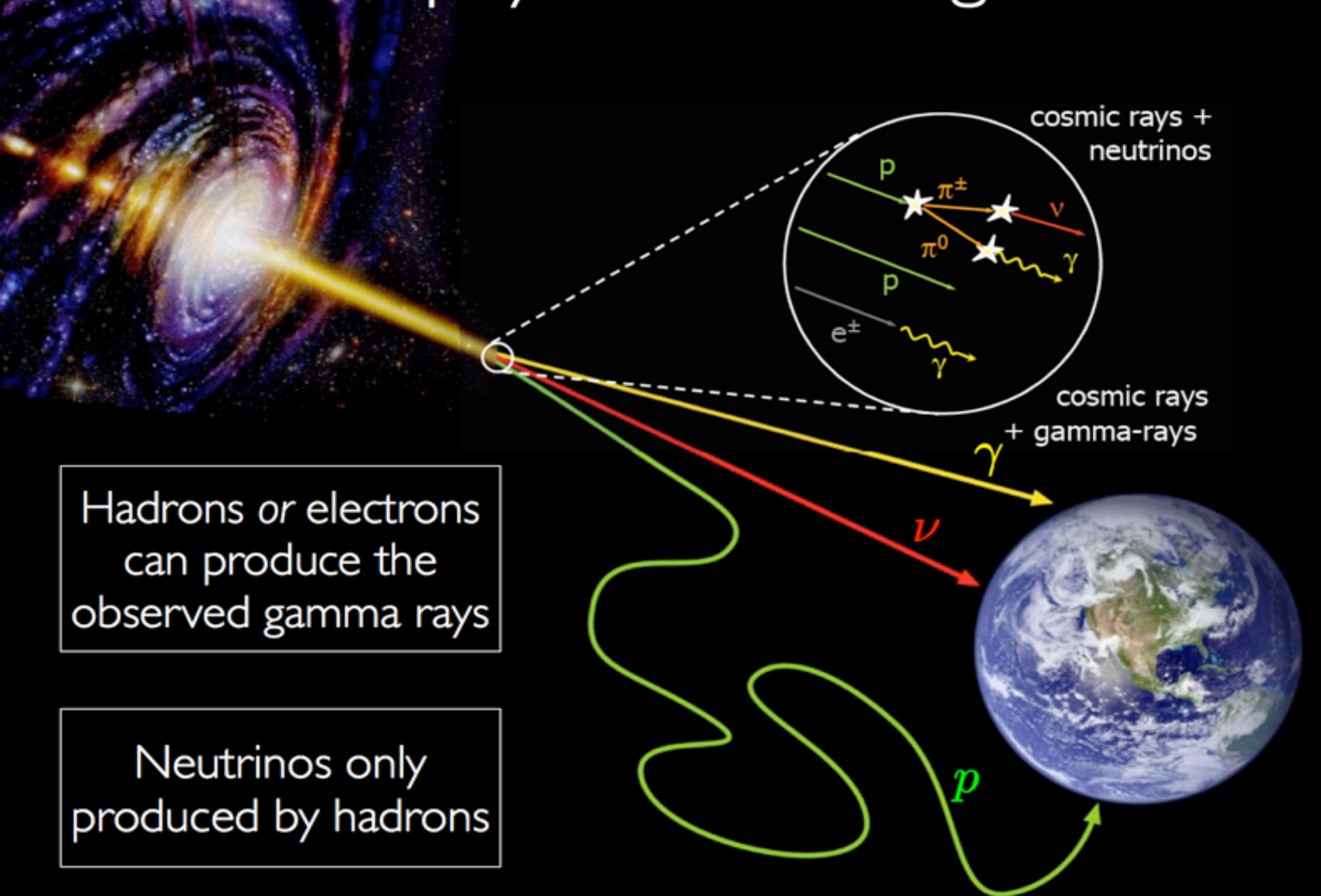


Victor Hess surrounded by Austrian peasants after landing from one of his ascensions a few weeks before his record breaking ascent in the Böhmen.



- Where are they coming from ?
- What cosmic sources accelerate these particles to energies in the EeV range ?

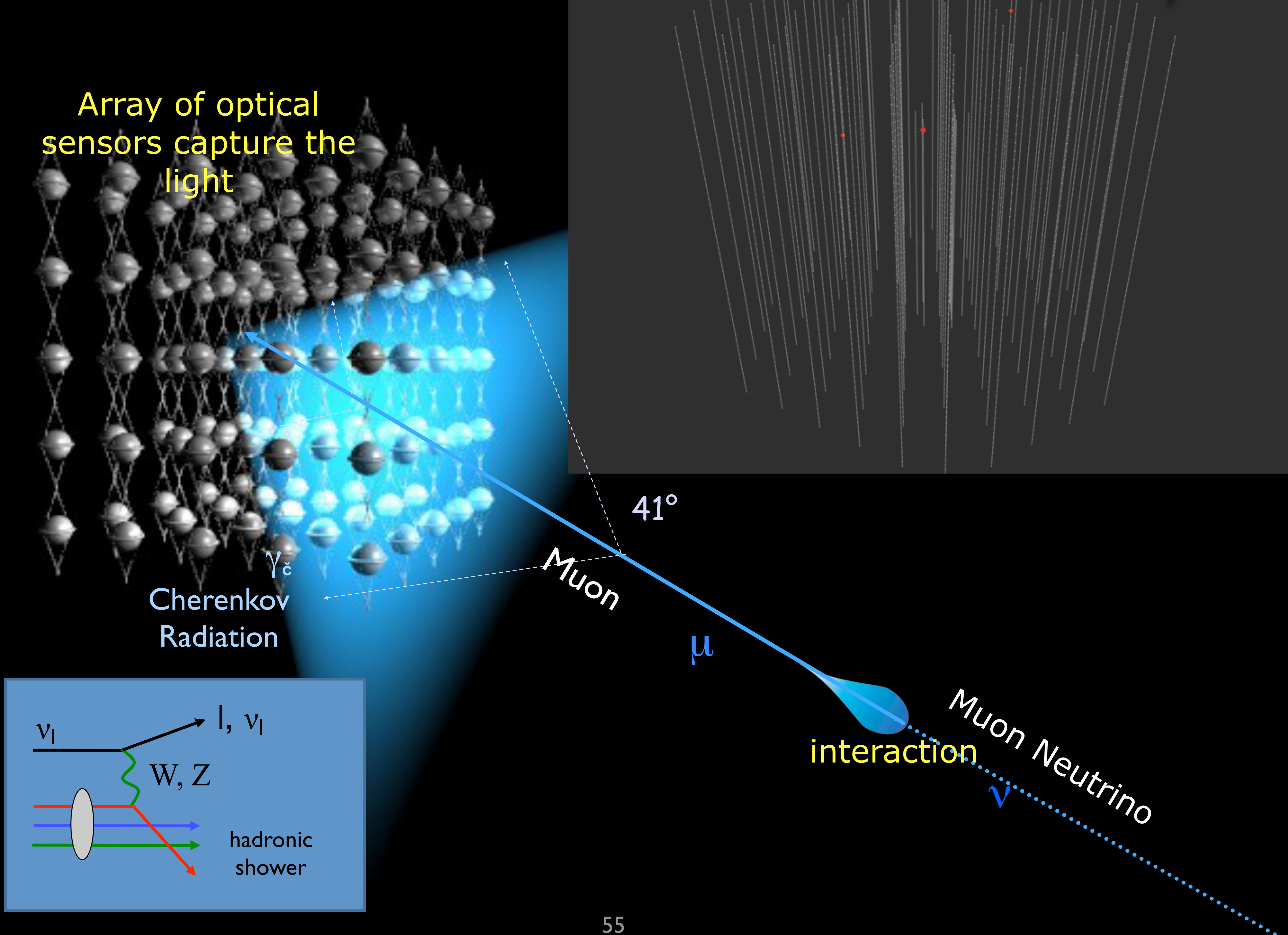
Astrophysical Messengers



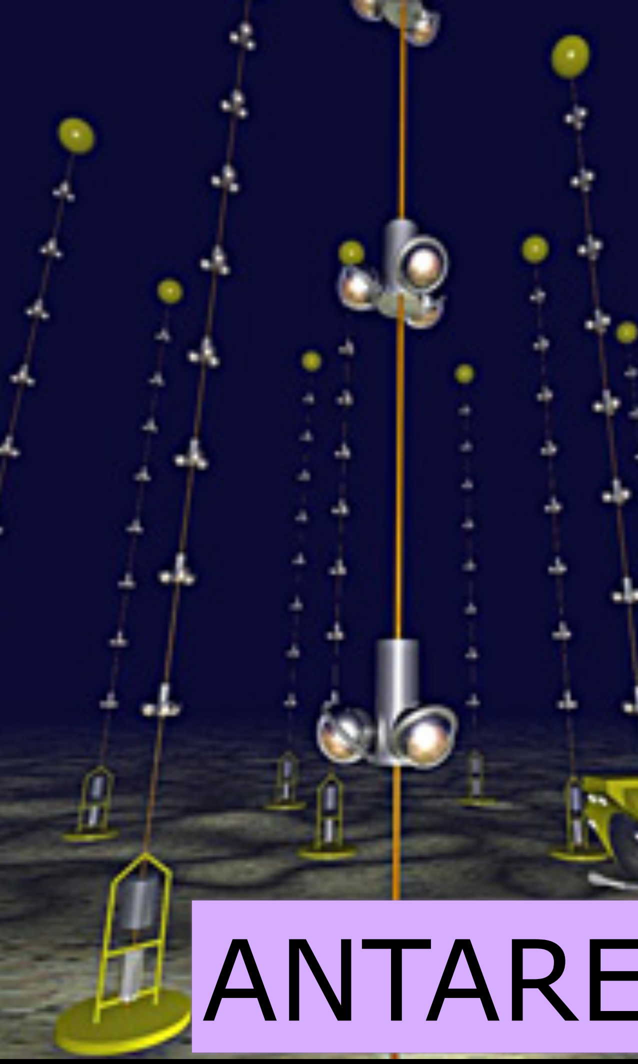
Hadrons *or* electrons can produce the observed gamma rays

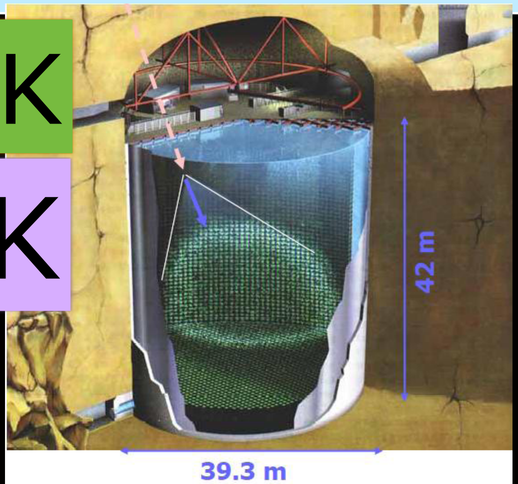
Neutrinos only produced by hadrons

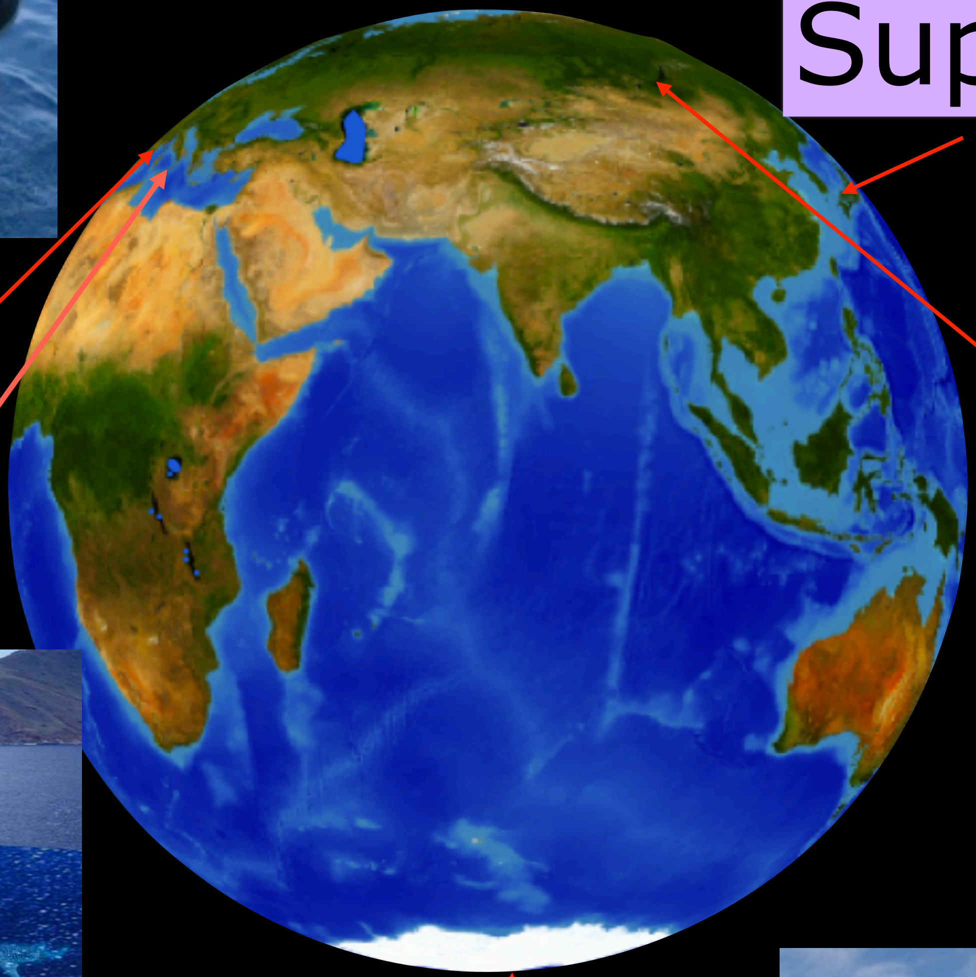
Principle of an optical Neutrino Telescope

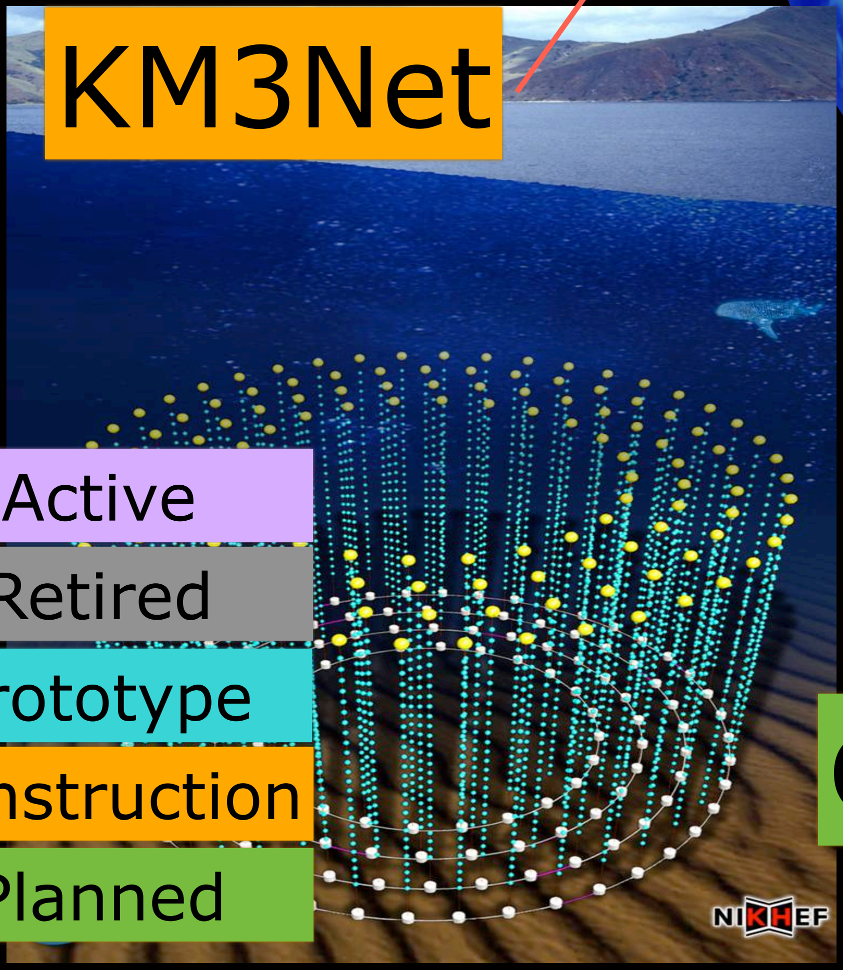


Neutrino Telescopes & Detectors









Hyper-K

Super-K

ANTARES

KM3Net

Lake Baikal

GVD

IceCube

Gen2/PINGU

Active

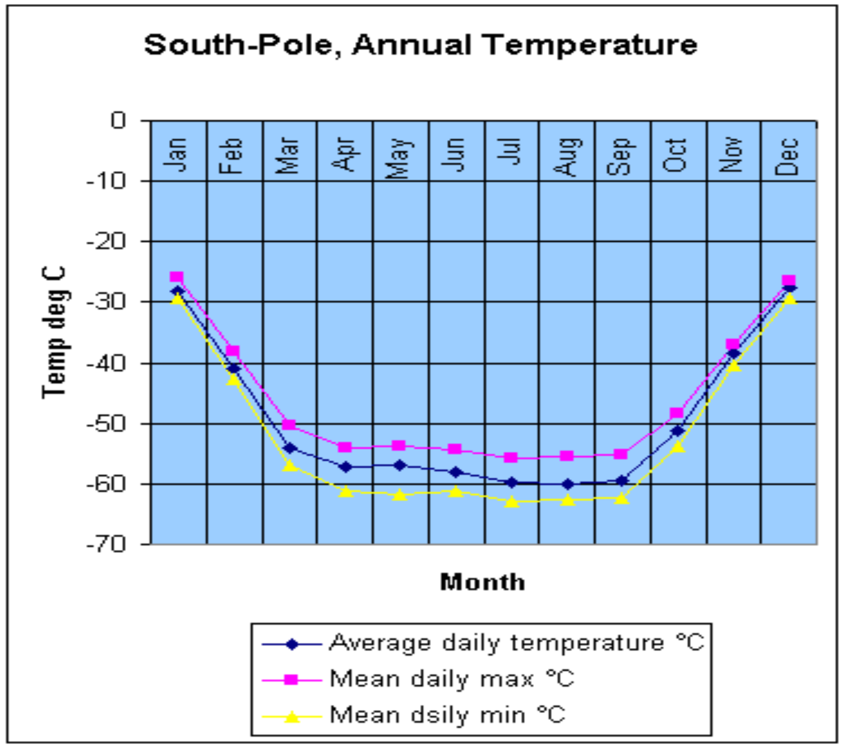
Retired

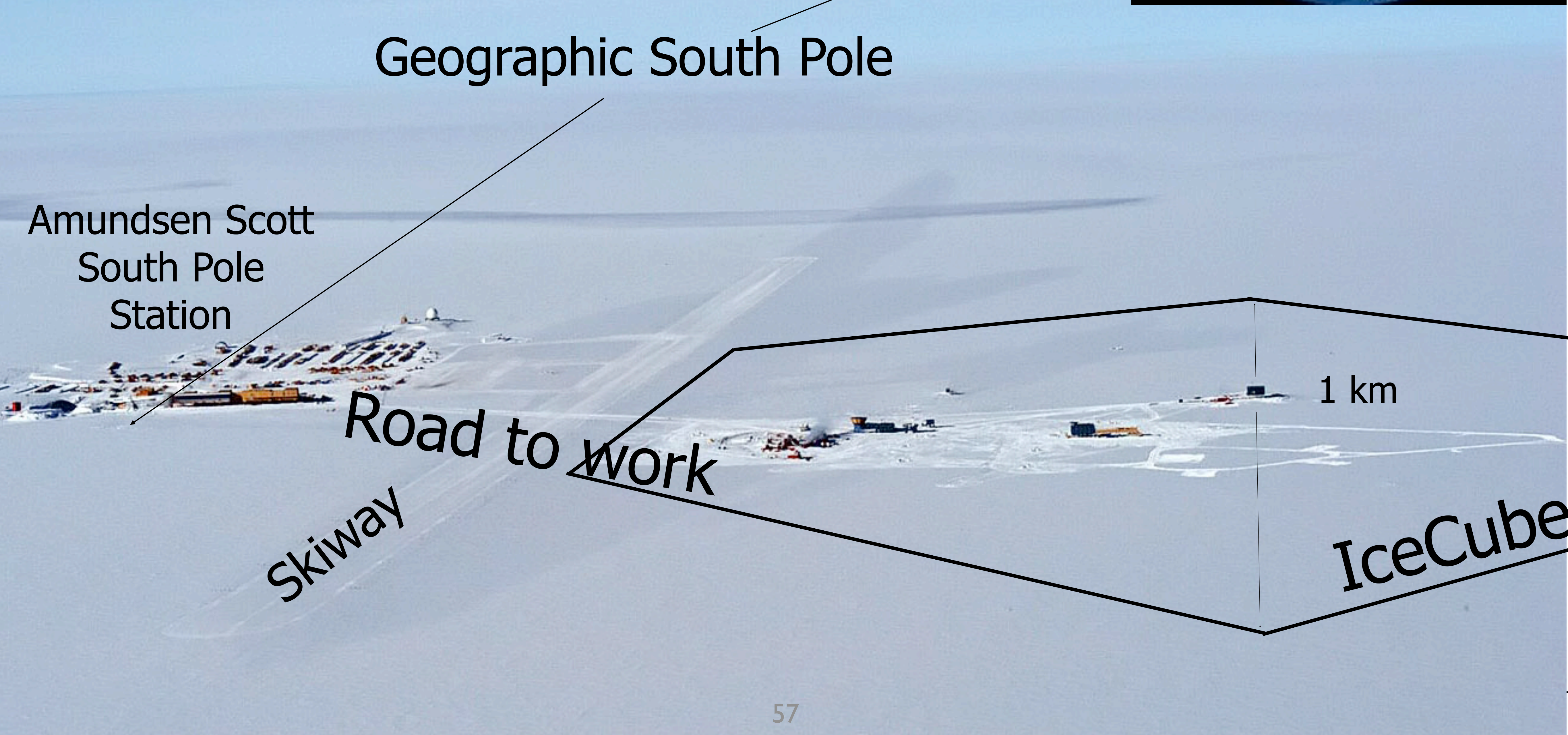
Prototype

Construction

Planned

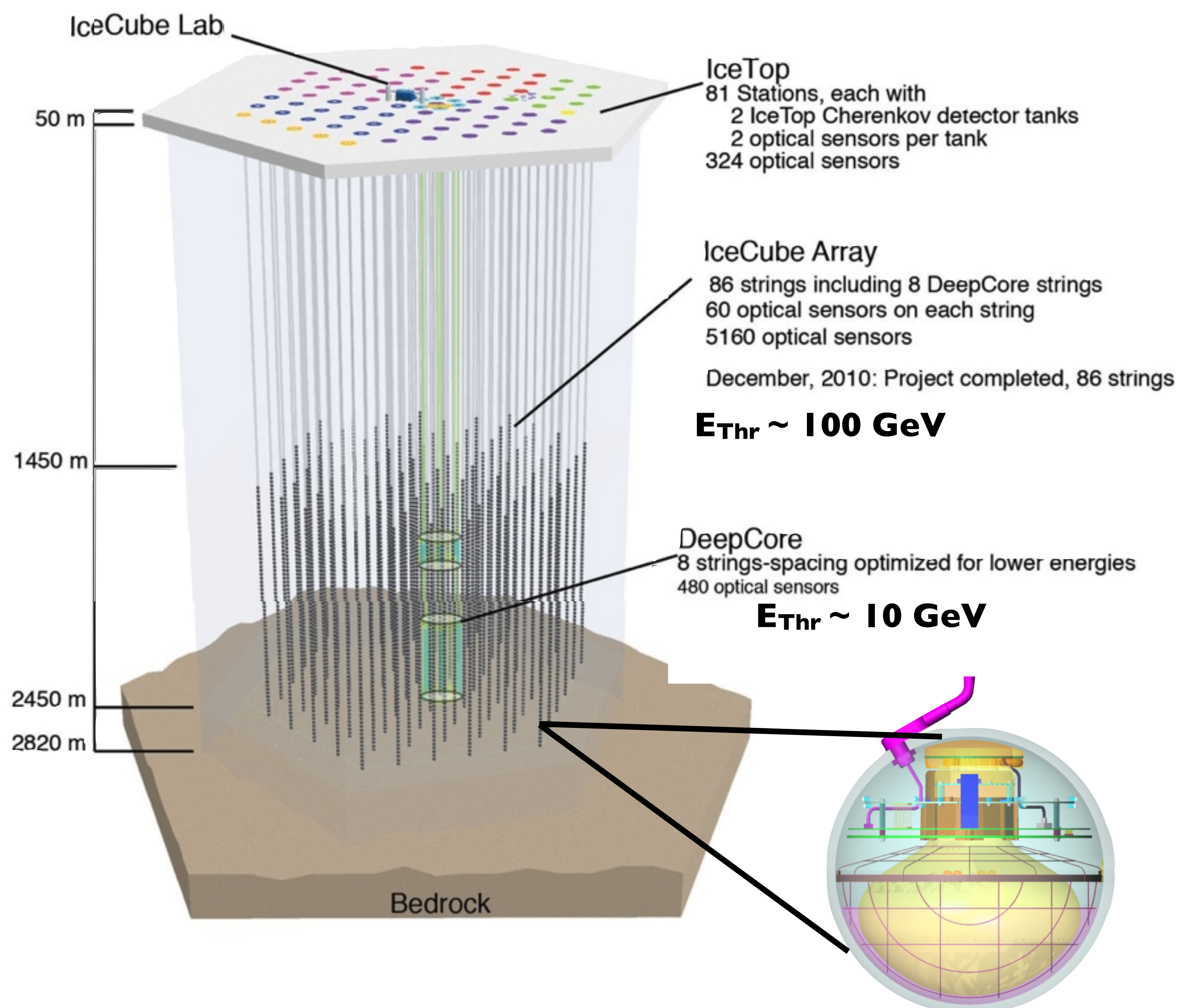
Laboratory at the South Pole

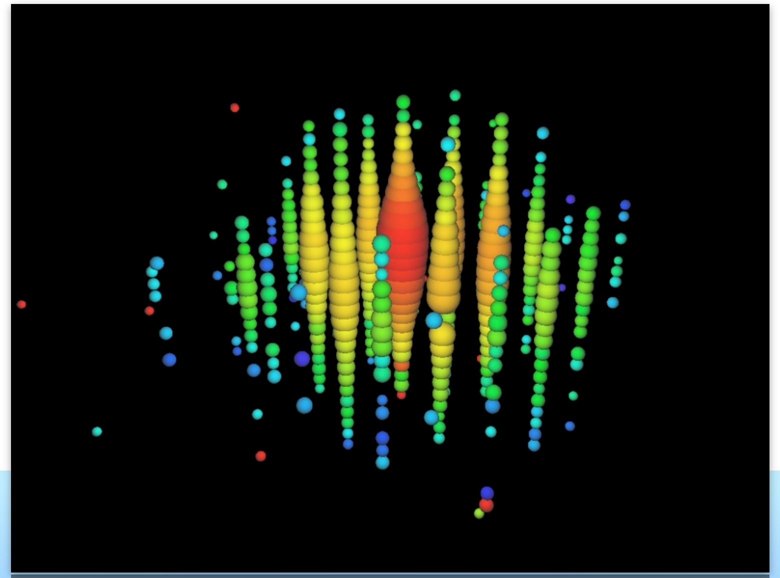




The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010, start of data taking with full detector May 2011
- Data acquired during the construction phase has been analyzed
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice





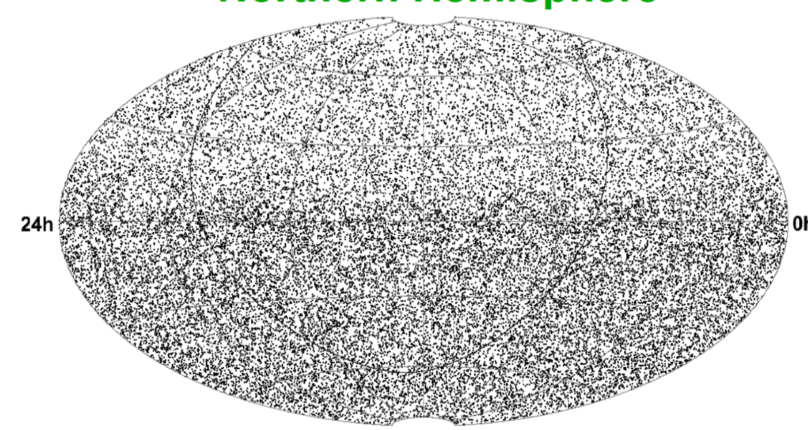
Astro-physical Neutrino Search

Finding Astrophysical Neutrinos

- How to overcome the large atmospheric neutrino background
- We need to rely on statistical methods to pick out neutrinos from this mess
  - Do neutrinos cluster anywhere in space, time, or arriving in coincidence with astronomical events or objects ?
  - Do we see any spectral features ?

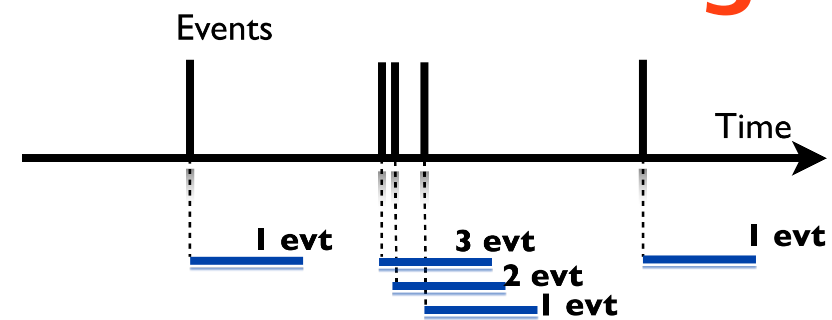
1. Point Source

single dominant source



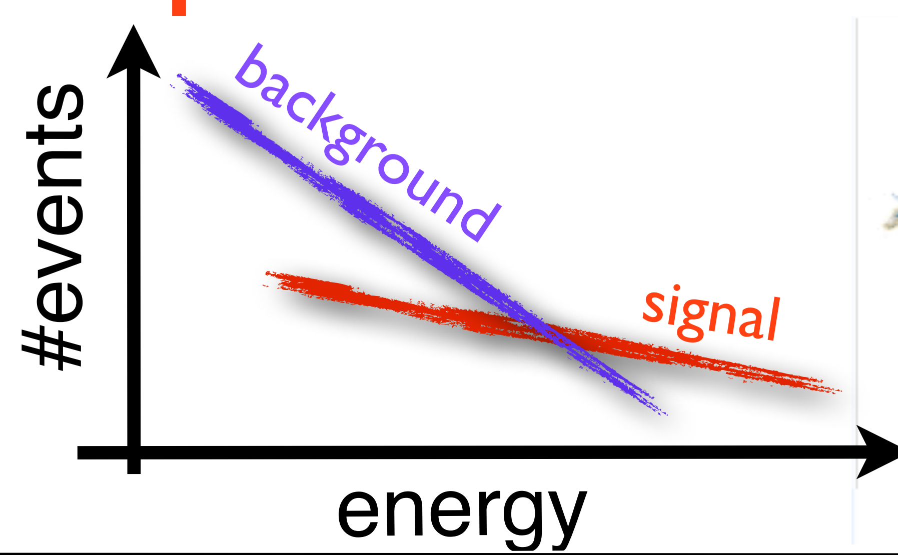
2. Time clustering

transient source

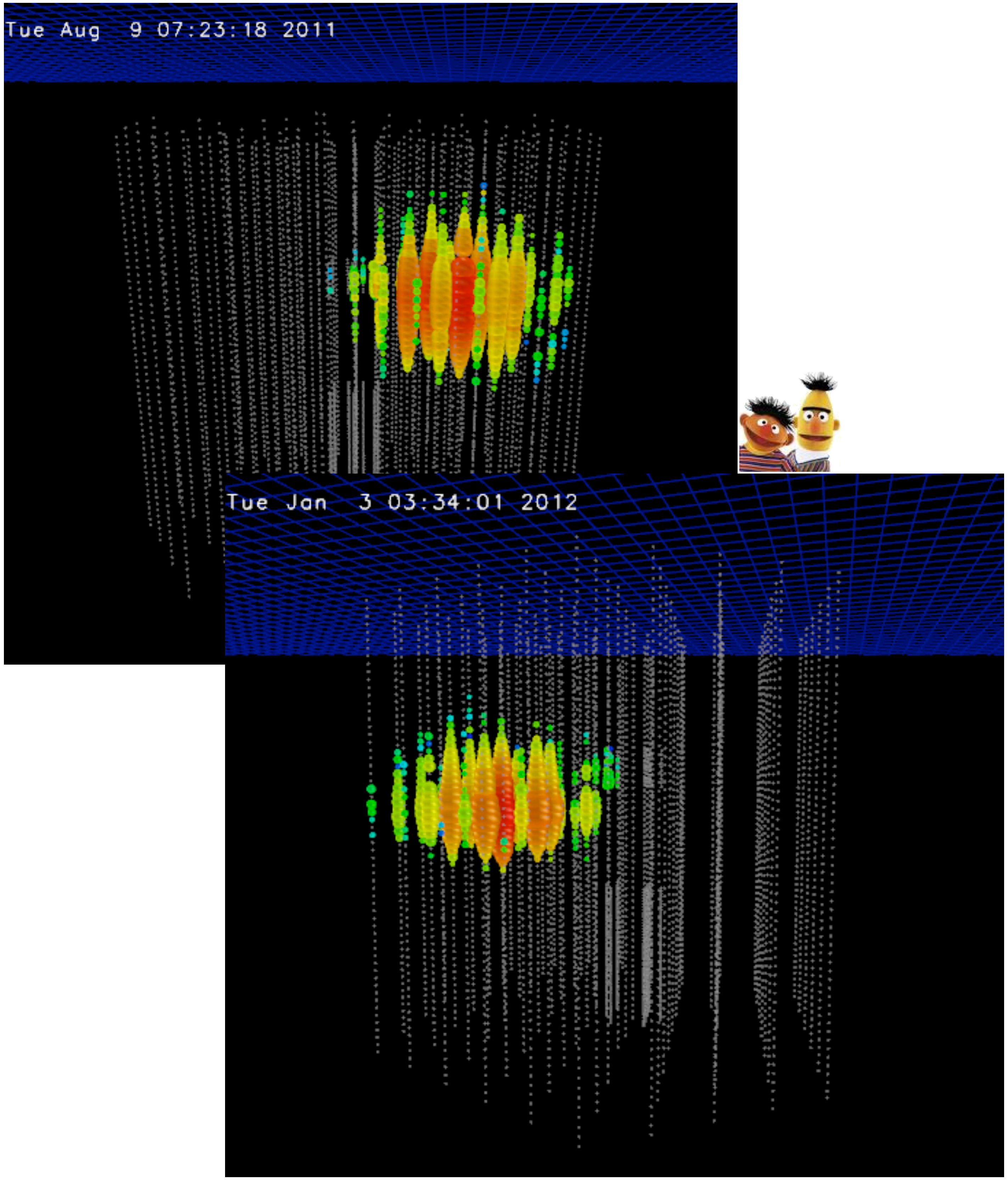


3. Spectral feature

cumulative flux



IceCube Coll. Phys.Rev.Lett. 111 (2013) 021103 / arXiv 1304.5356



Dataset / Results
(670days of IC79/IC86 data)
expected 0.08 events
observed 2 events (→ 2.7σ)

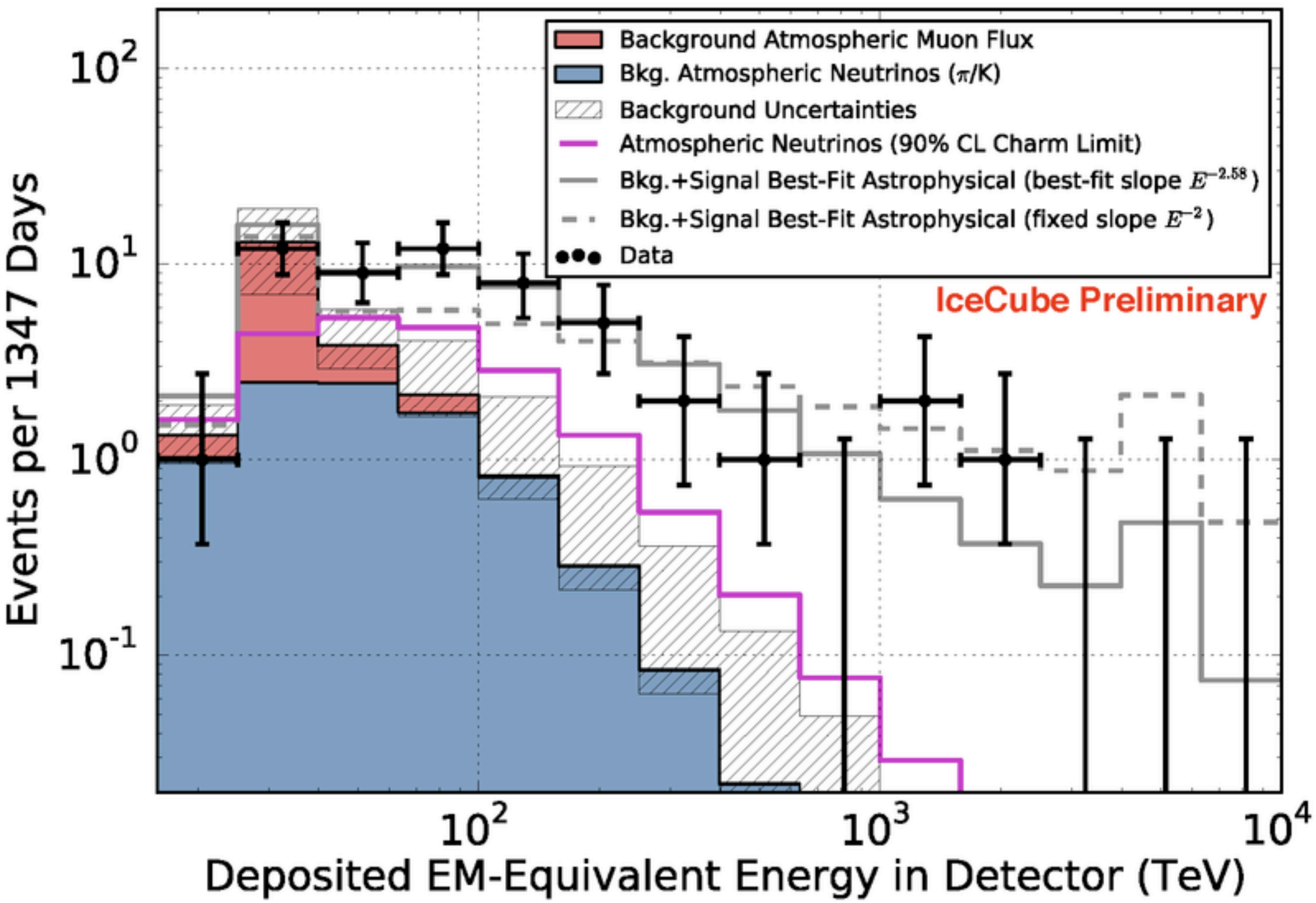
- Ernie ~1.15 PeV (~1.9 $\cdot 10^{-4}$J)
- Bert ~ 1.05 PeV (~1.7 $\cdot 10^{-4}$J)
- Energy is the visible energy of the cascade, could originate from NC event, ν_τ CC, or ν_e CC
- Angular resolution on cascade events at this energy ~10°
- Energy resolution is about 15% on the deposited energy

Ernie & Bert are not GZK, but ...

High-energy neutrino search 4yrs

54 events (15 track-like, 39 showers) observed

Expectation from conventional atm. muons and neutrinos ~21.6

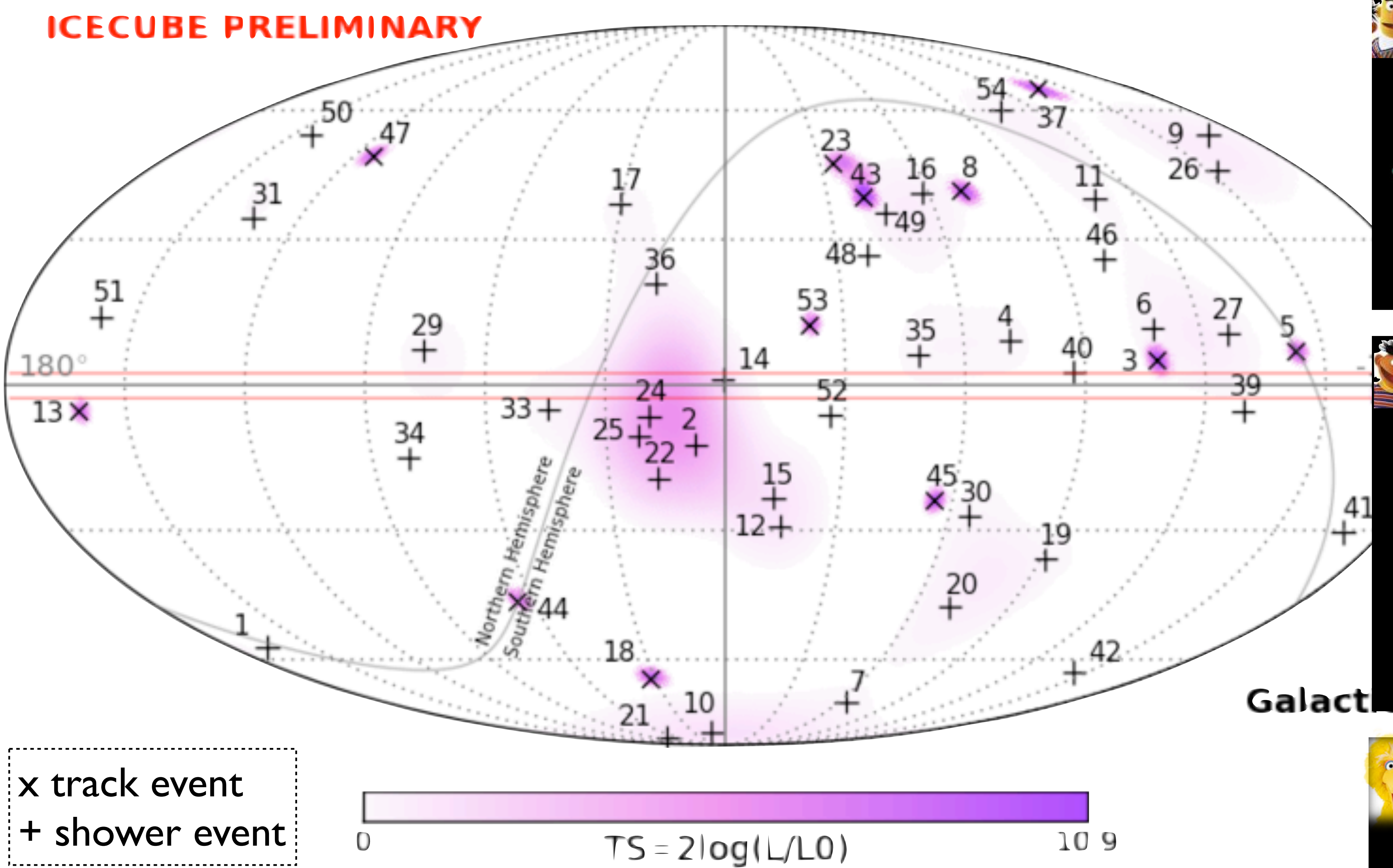


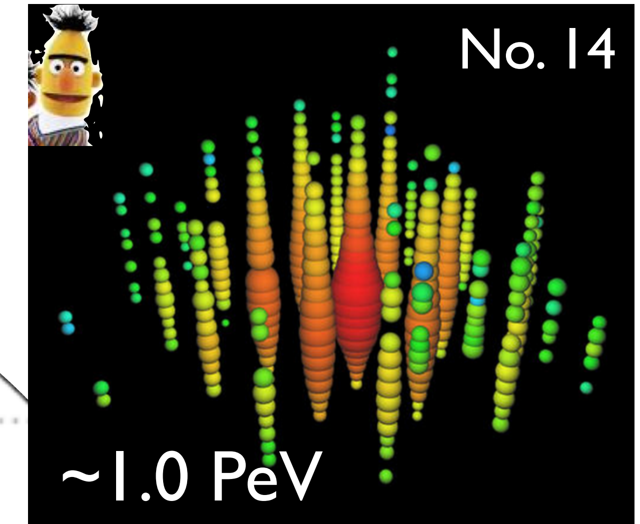
- Mesons including charm quarks in the atmosphere decay immediately to produce neutrinos, known as prompt neutrinos which are not observed yet.
- ERS, or Enberg et al. Phys. Rev. D 78, 043005 (2008) is used as a baseline prompt model
- Significance are based on the exact neutrino flux model, not including the uncertainty of the model.
- Atmospheric Bkg : CR Muon (12.6±5.1), Conv. Neutrino ($9.0^{+8.0}_{-2.2}$),
- Over 60 TeV < E < 2000 TeV, the spectrum best fit with $E^{-2.58}$
- E^{-2} spectrum predicts too may neutrinos above ~2 PeV. So, a cutoff or steeper spectrum needed.

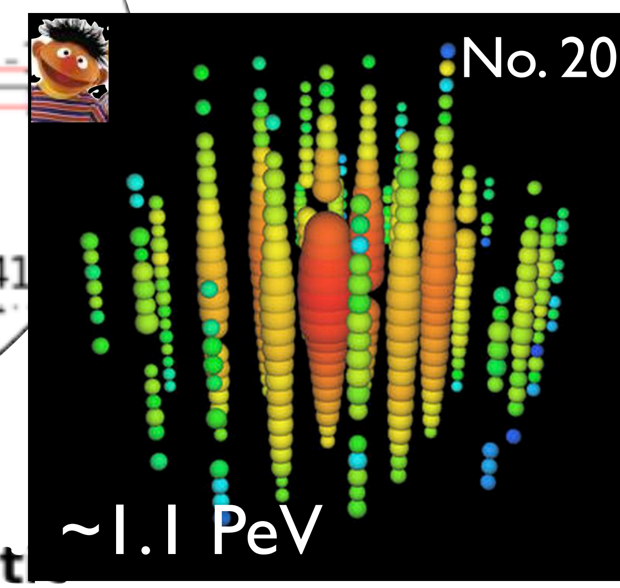
~7 sigma rejection of atmospheric-only hypothesis

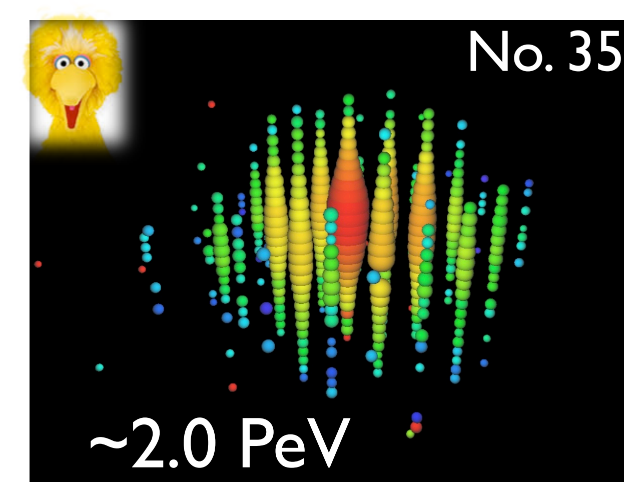
ICRC 2015 proceedings
IceCube Collaboration, *Science 342, 1242856 (2013),*
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

Skymap HESE-4yrs







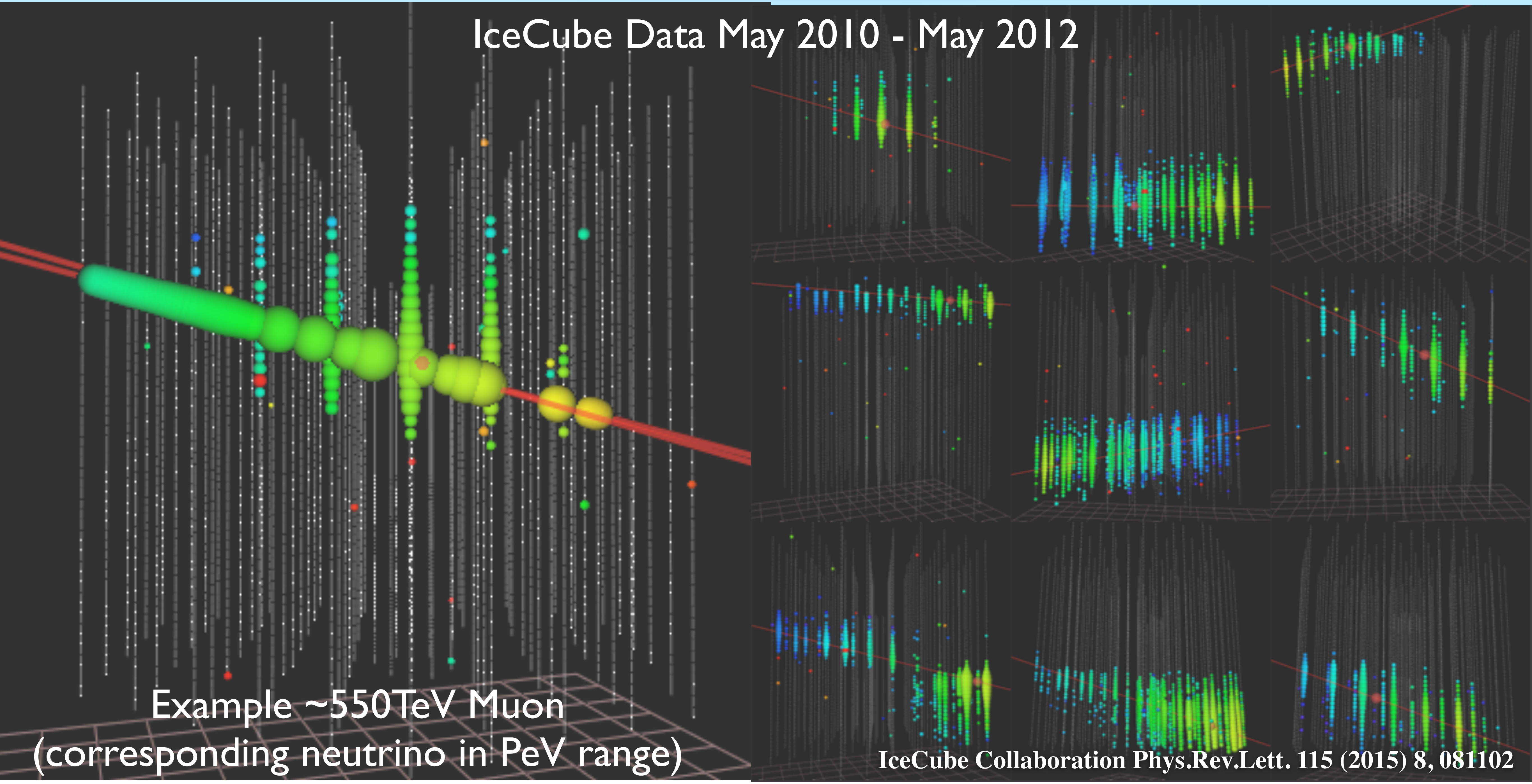


no significant correlations -- spacial or temporal

p-value for cascade events "clustering" 18%

Can we make an independent confirmation of the "Observation of Astrophysical Neutrinos"

IceCube -- Through-going muons

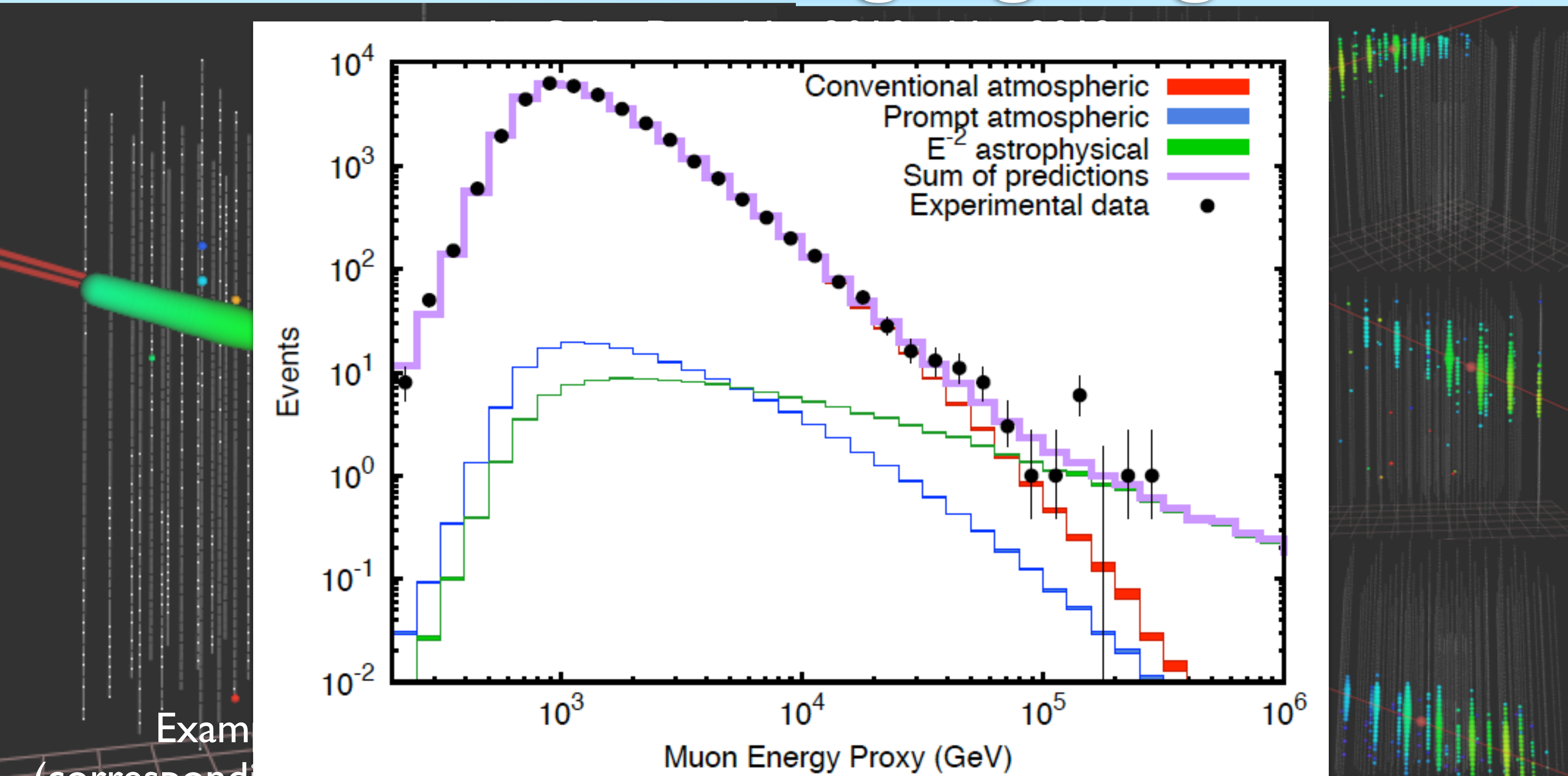


Highest energy events are inconsistent with a hypothesis of solely terrestrial origin at **3.7σ**

Best fit astrophysical flux consistent with High-Energy Starting Events

Normalization for E^{-2}: $0.99^{+0.4}_{-0.3}\ 10^{-8}\ E^{-2}$ GeV $cm^{-2}\ s^{-1}\ sr^{-1}$

Through-going muons



IceCube Collaboration Phys.Rev.Lett. 115 (2015) 8, 081102

Highest energy events are inconsistent with a hypothesis of solely terrestrial origin at **3.7σ**

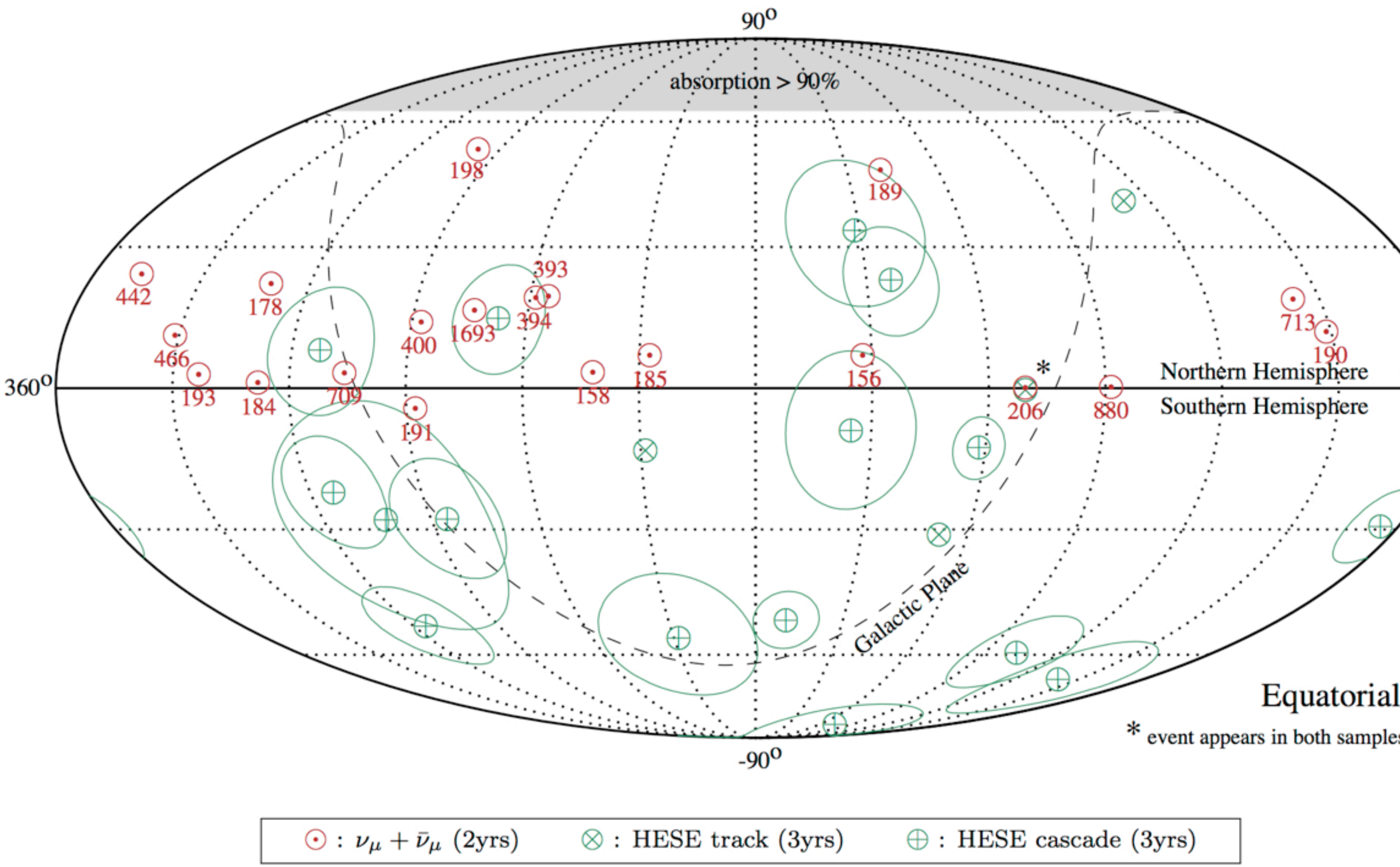
Best fit astrophysical flux consistent with High-Energy Starting Events

Normalization for E^{-2}: $0.99^{+0.4}_{-0.3}$ 10^{-8} E^{-2} GeV cm^{-2} s^{-1} sr^{-1}

IceCube Collaboration Phys.Rev.Lett. 115 (2015) 8, 081102

http://icecube.wisc.edu/news/view/348

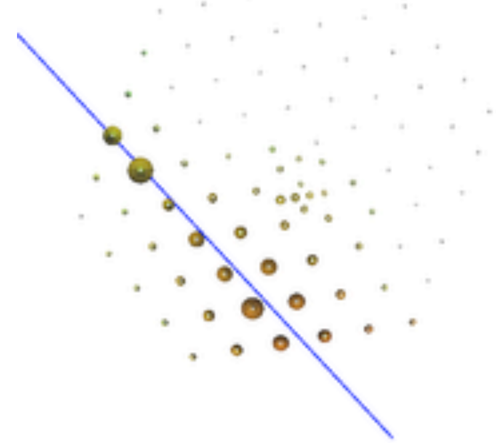
Up-going muons + HESE



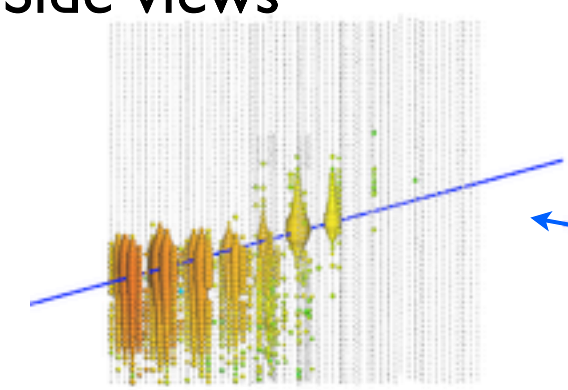
Sky map in equatorial coordinates of the arrival direction of the 21 highest-energy events of this analysis (red dotted circles). The most probable neutrino energy (in TeV) indicated for each event assumes the best-fit astrophysical flux of the analysis. For comparison, the events of the 3-year high-energy starting event (HESE) analysis with deposited energy larger than 60 TeV (tracks and cascades) are also shown. Cascade events are indicated together with their median angular uncertainty (thin circles). Image: IceCube Collaboration

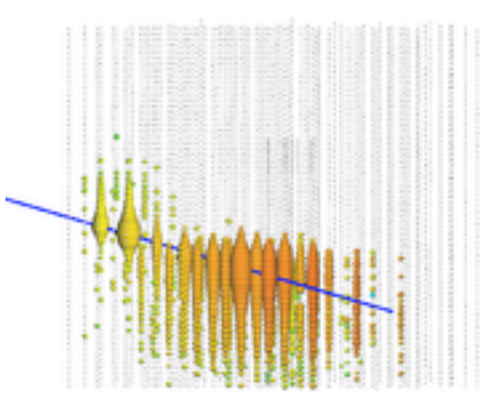
Multi-PeV Track Event

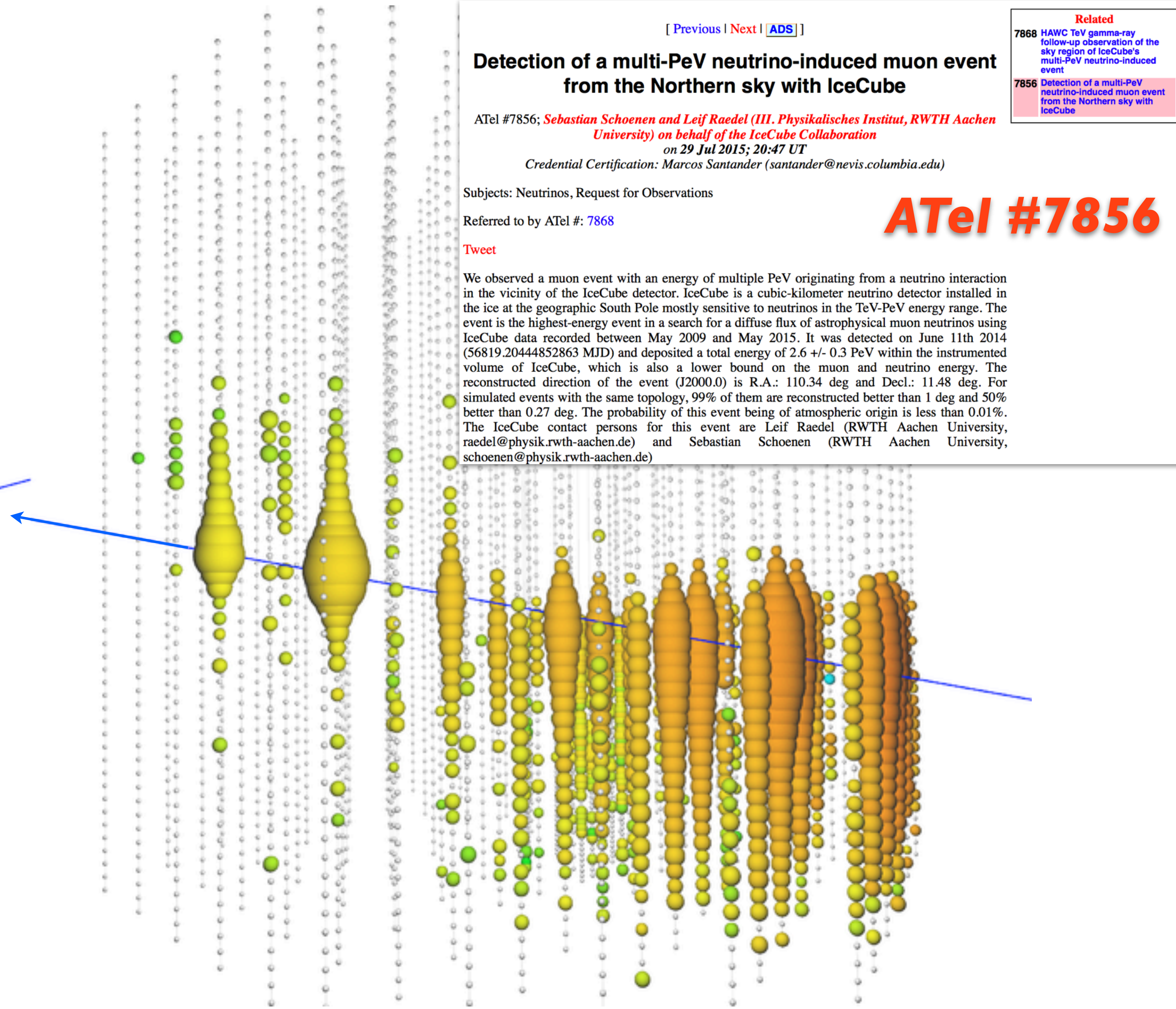
Top view



Side views







[Previous | Next | ADS]

Detection of a multi-PeV neutrino-induced muon event from the Northern sky with IceCube

ATel #7856; *Sebastian Schoenen and Leif Raedel (III. Physikalisches Institut, RWTH Aachen University) on behalf of the IceCube Collaboration*
on 29 Jul 2015; 20:47 UT
Credential Certification: Marcos Santander (santander@nevis.columbia.edu)

Subjects: Neutrinos, Request for Observations

Referred to by ATel #: 7868

Tweet

We observed a muon event with an energy of multiple PeV originating from a neutrino interaction in the vicinity of the IceCube detector. IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole mostly sensitive to neutrinos in the TeV-PeV energy range. The event is the highest-energy event in a search for a diffuse flux of astrophysical muon neutrinos using IceCube data recorded between May 2009 and May 2015. It was detected on June 11th 2014 (56819.20444852863 MJD) and deposited a total energy of 2.6 +/- 0.3 PeV within the instrumented volume of IceCube, which is also a lower bound on the muon and neutrino energy. The reconstructed direction of the event (J2000.0) is R.A.: 110.34 deg and Decl.: 11.48 deg. For simulated events with the same topology, 99% of them are reconstructed better than 1 deg and 50% better than 0.27 deg. The probability of this event being of atmospheric origin is less than 0.01%. The IceCube contact persons for this event are Leif Raedel (RWTH Aachen University, raedel@physik.rwth-aachen.de) and Sebastian Schoenen (RWTH Aachen University, schoenen@physik.rwth-aachen.de)

Related

7868 HAWC TeV gamma-ray follow-up observation of the sky region of IceCube's multi-PeV neutrino-induced event

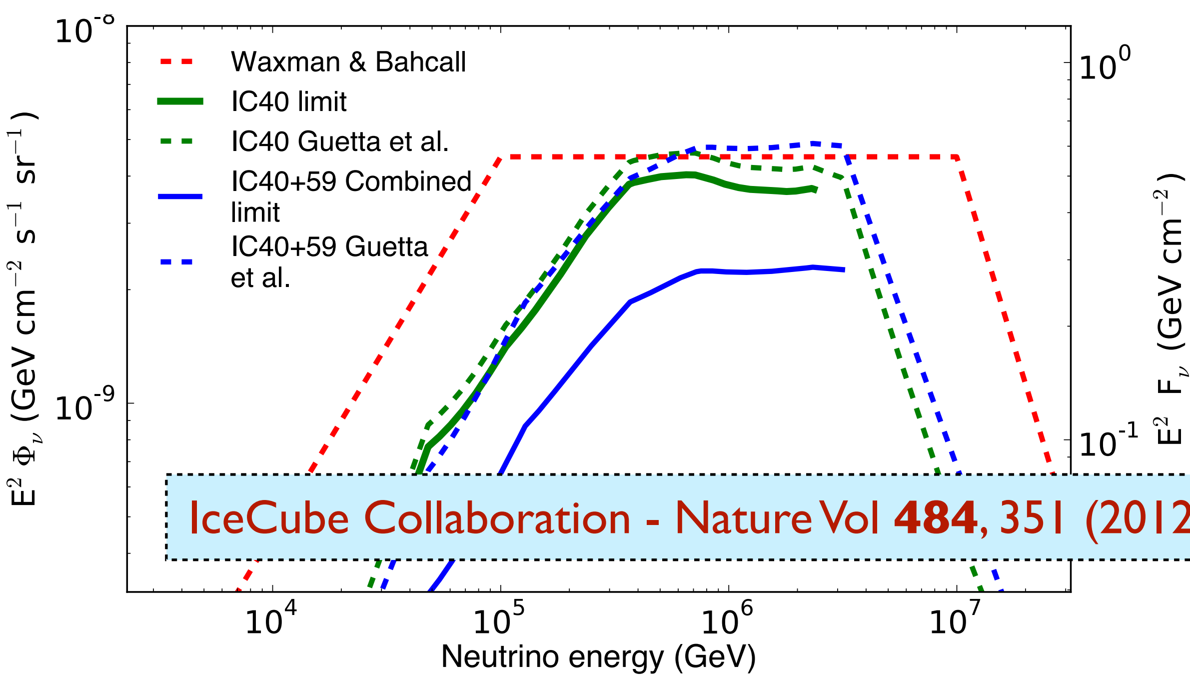
7856 Detection of a multi-PeV neutrino-induced muon event from the Northern sky with IceCube

ATel #7856

Origin of the high-energy neutrinos ?

Extra Galactic

Gamma Ray Burst



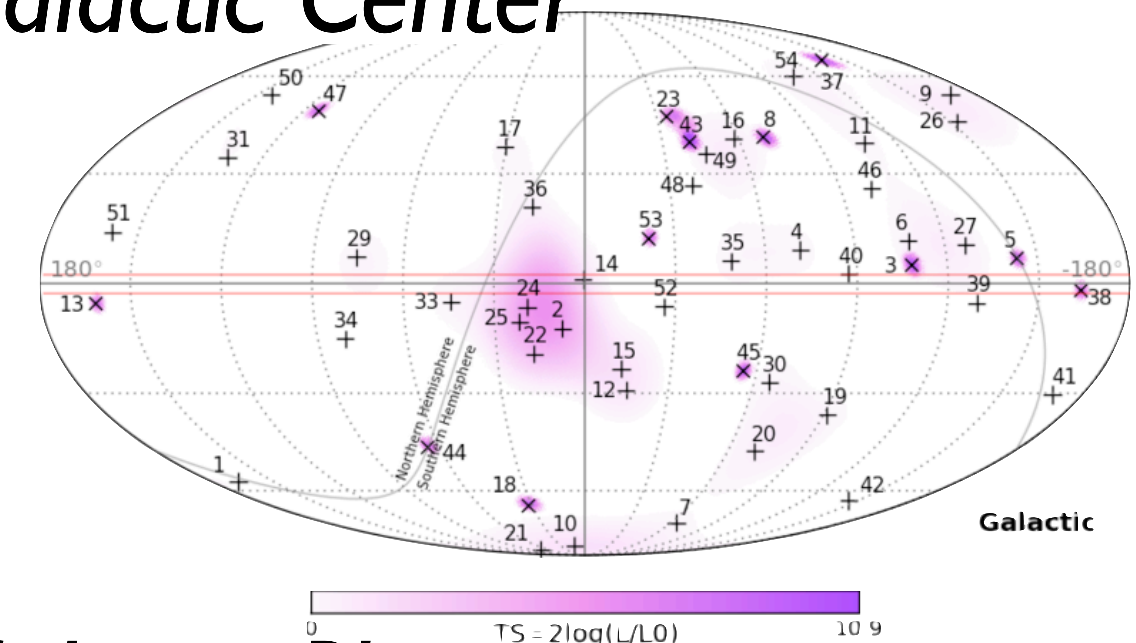
IceCube Collaboration - Nature Vol **484**, 351 (2012)

Active Galactic Nuclei / Starburst Galaxies

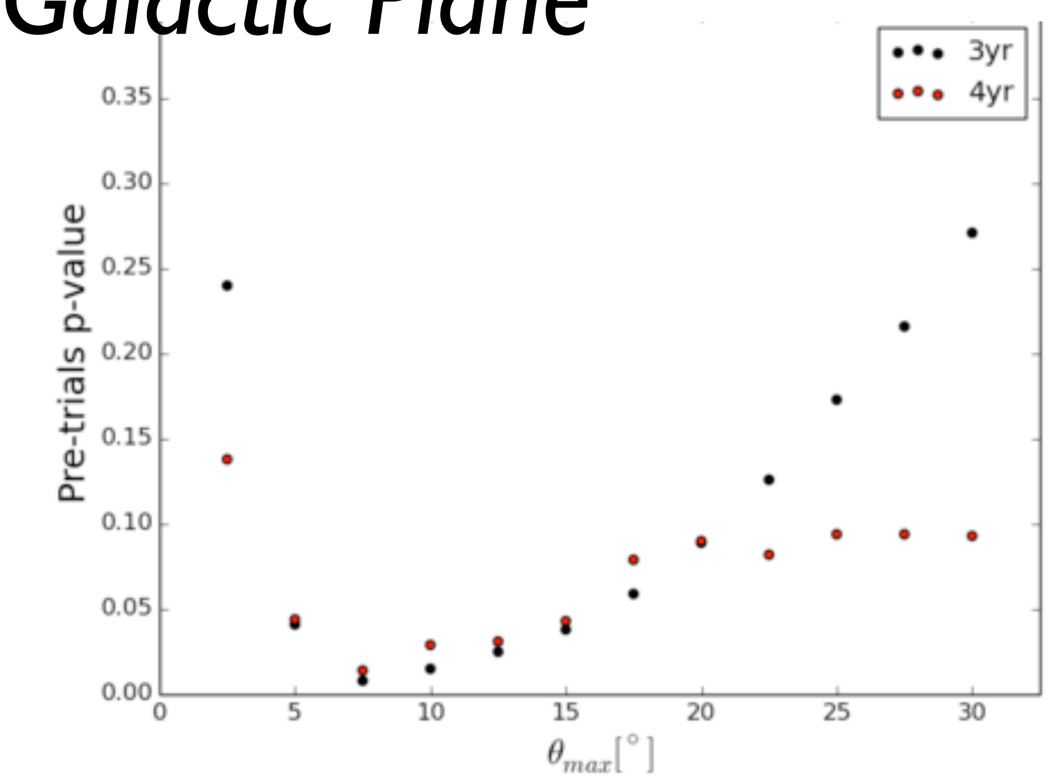
Starburst	M82	148.97	69.68	0.07	0.15
Radio Galaxies	NGC 1275	49.95	41.51	0.0	–
	Cyg A	299.87	40.73	0.9	0.03
	3C 123.0	69.27	29.67	0.0	–
	M87	187.71	12.39	0.0	–
	Cen A	201.37	-43.02	0.03	0.49

Galactic

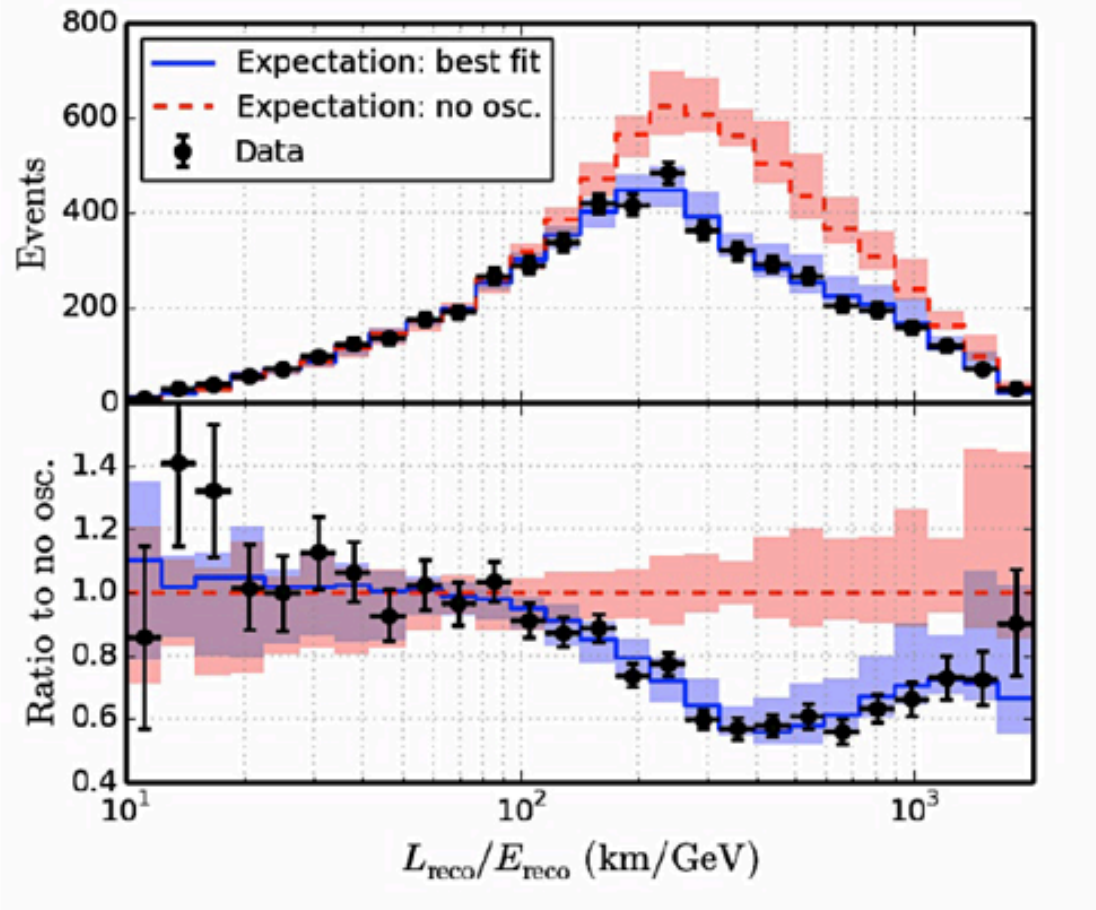
Galactic Center



Galactic Plane



IceCube Neutrino Oscillations

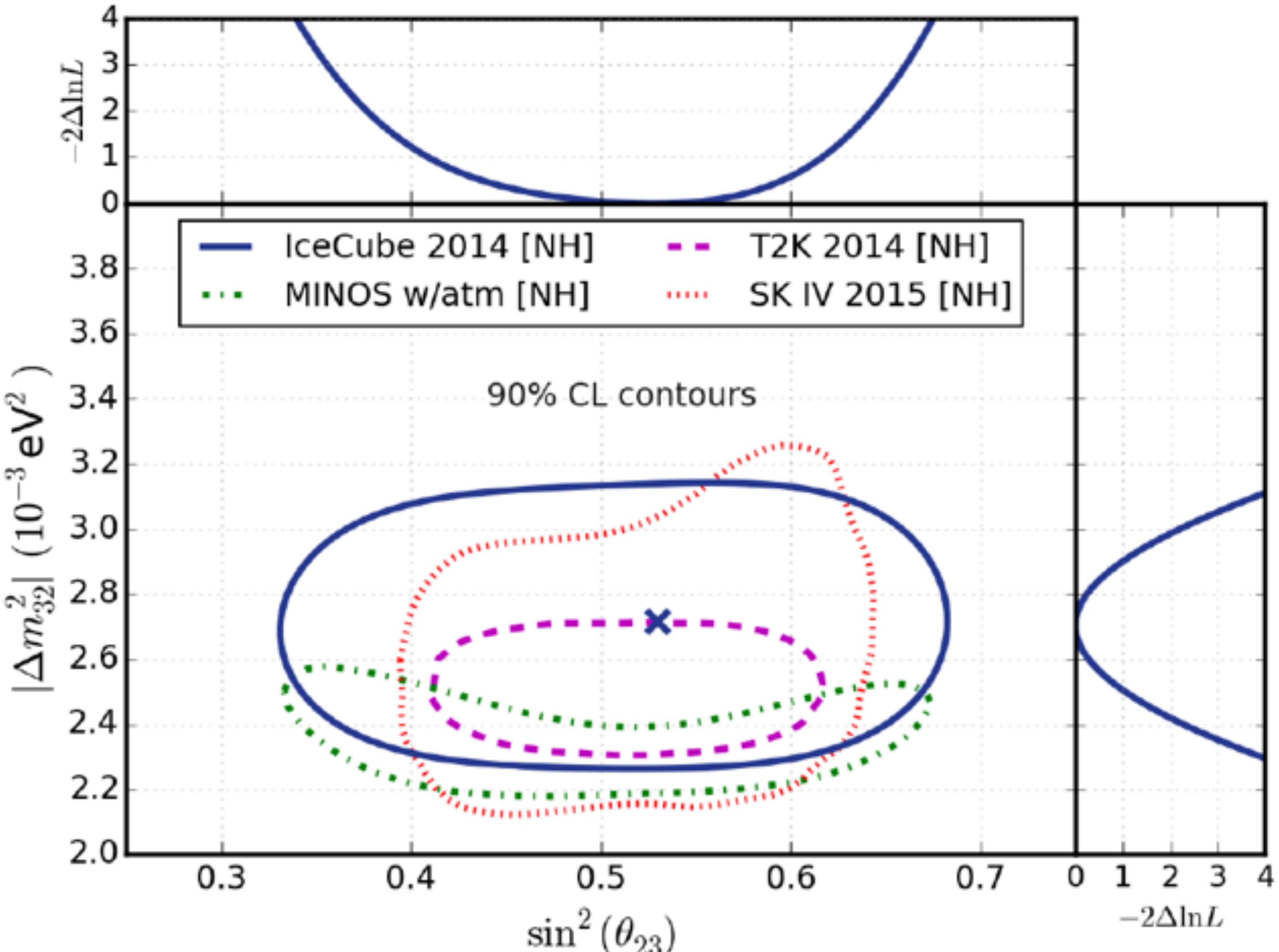


- select
  - starting events
  - clear μ tracks
  - rely on direct photons
- 5174 events observed cf. 6830 expected if no oscillation
- perform 2D fit in *E* and *cos(θ)*

[IceCube, Phys.Rev.D91:072004 (2015)]

- competitive result (3 years)
- will improve further

$$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\ \text{eV}^2$$
$$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$

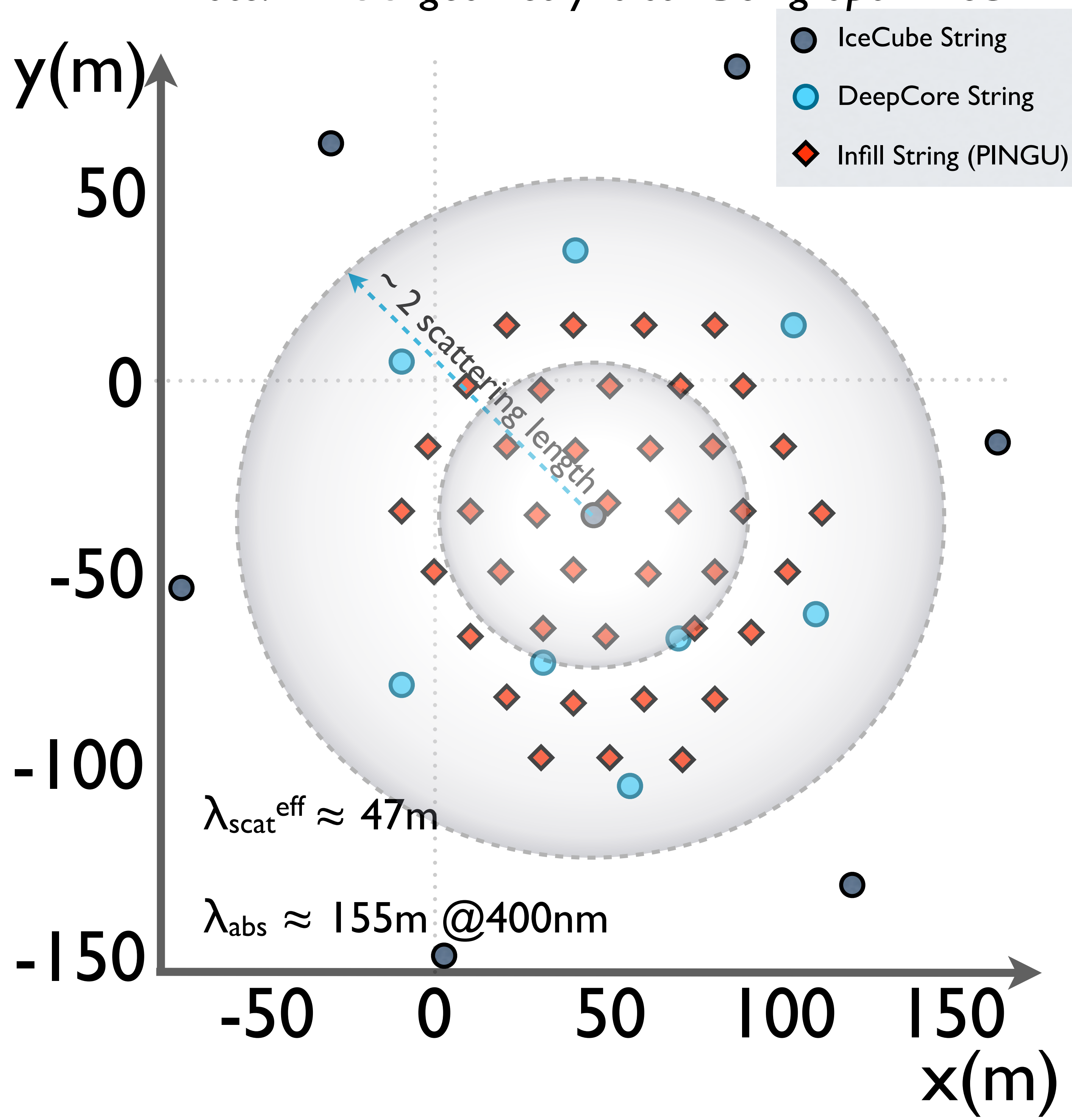


PINGU - Precision IceCube Next Generation Upgrade

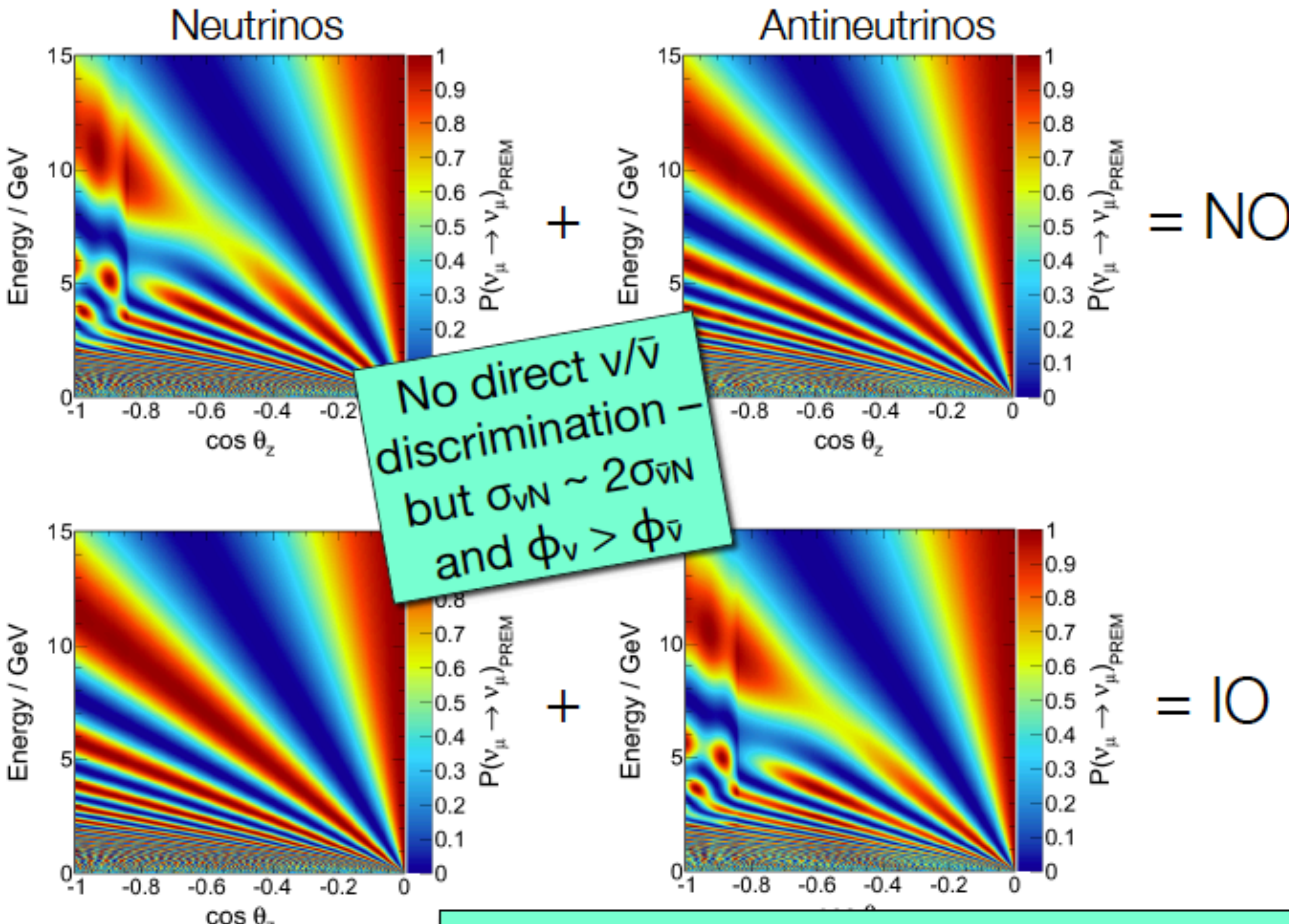
- PINGU upgrade plan
  - Instrument a volume of about 5MT with ~40 strings each containing 96 optical modules
  - Rely on well established drilling technology and photo sensors
  - Create platform for calibration program and test technologies for future detectors
- Physics Goals:
  - Precision measurements of neutrino oscillations (mass hierarchy, ...)
  - Test low mass dark matter models

An example PINGU geometry (40 strings)

Note: PINGU geometry is still being optimized



Neutrino Mass Hierarchy

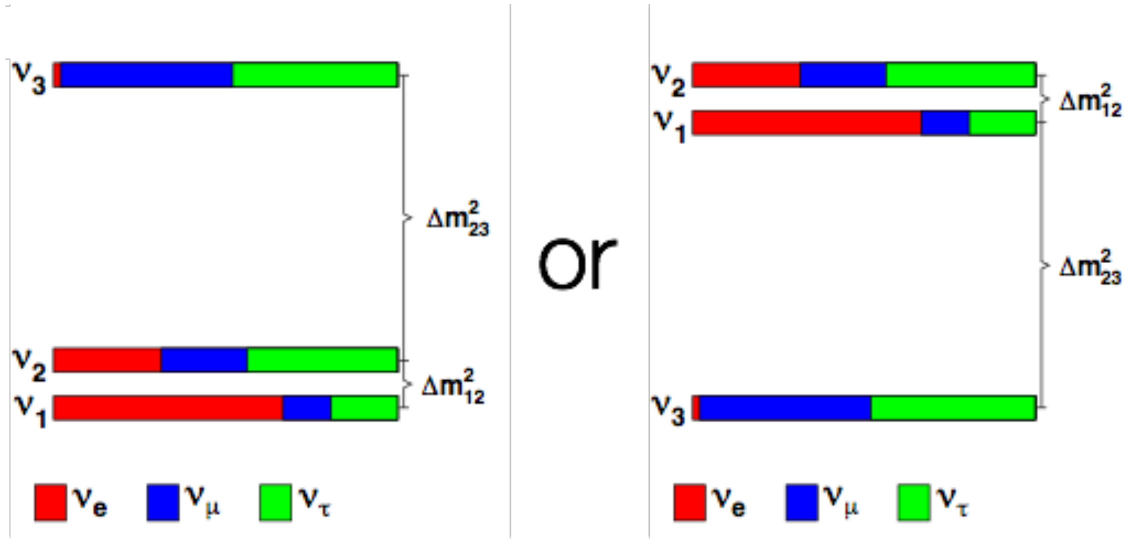


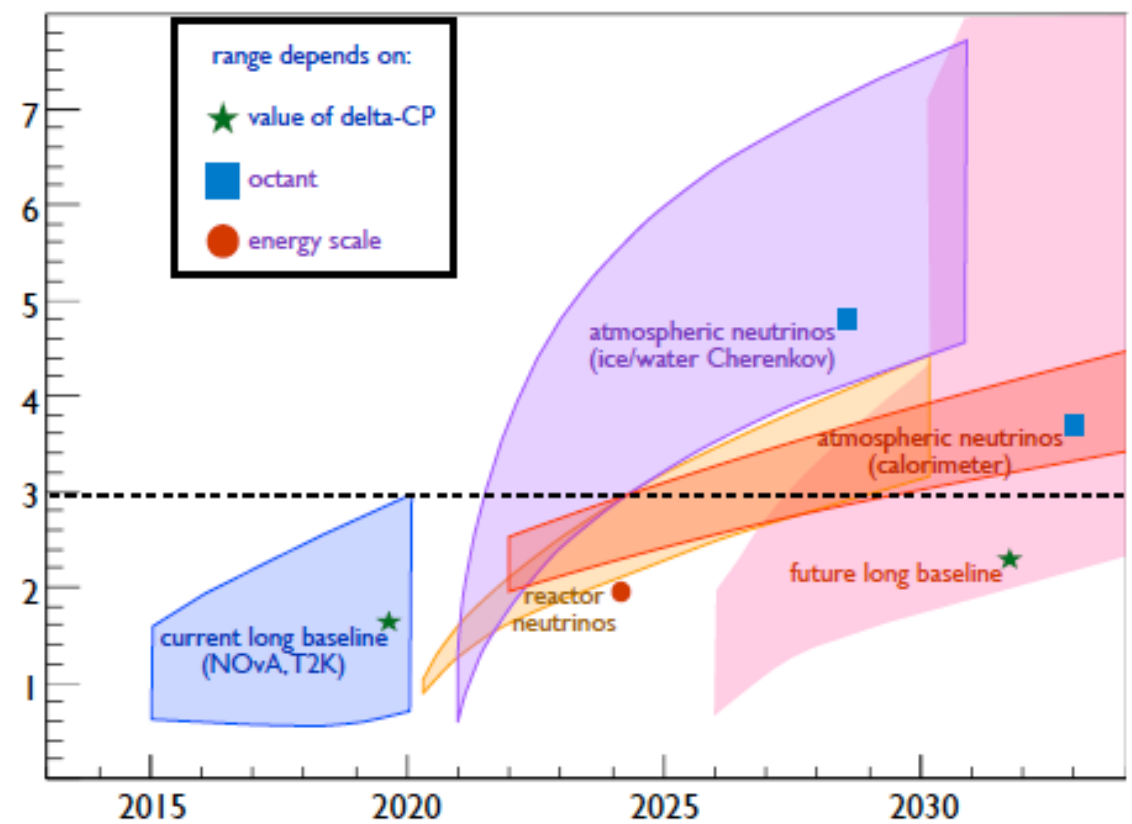
No direct $\nu/\bar{\nu}$ discrimination – but $\sigma_{\nu N} \sim 2\sigma_{\bar{\nu} N}$ and $\phi_{\nu} > \phi_{\bar{\nu}}$

Matter effects on cascades (ν_e and ν_τ) also important

Science Potential of PINGU and ORCA

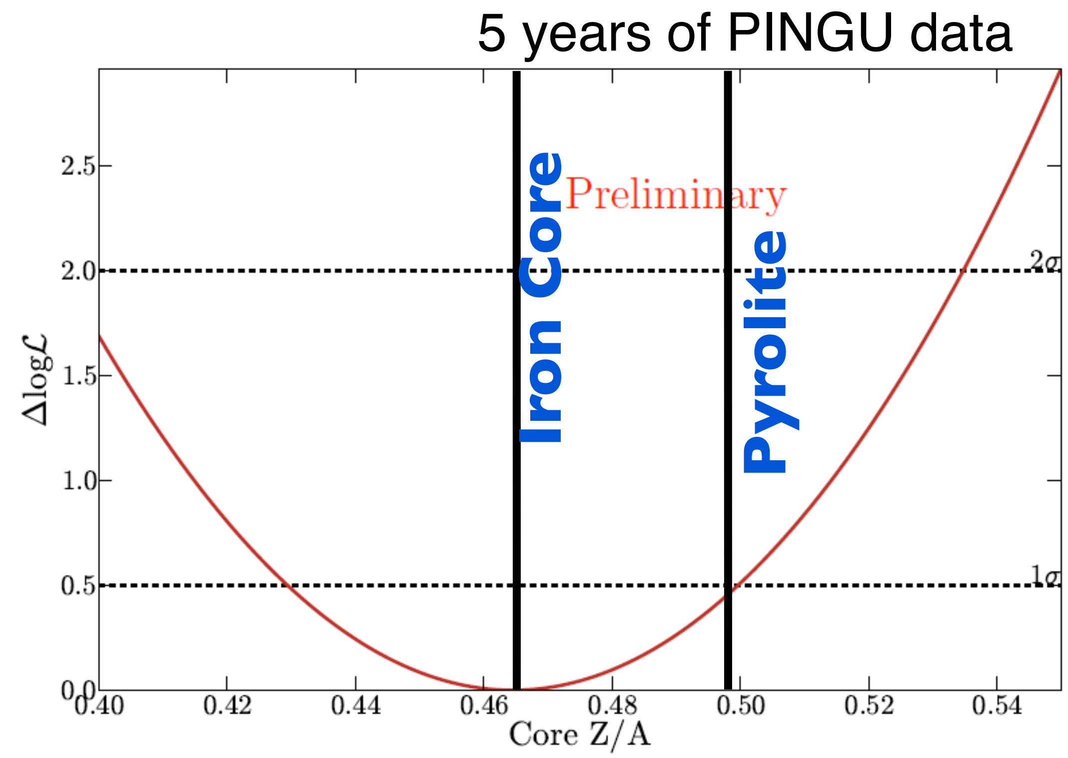
- Well-established detector and construction technology (low risk)
- Rapid schedule
  - PINGU: 3 seasons (first deployments in 2018/2019 ?)
  - ORCA: 5% till 2017 (100% by 2020 ?)
- Quick accumulation of statistics once complete
- Provides a platform for more detailed calibration systems to reduce detector systematics
- Multipurpose detector: Neutrino Properties, Dark Matter, Galactic Neutrino Sources, Neutrino Tomography, ...
- Opportunity for R&D toward other future ice/water Cherenkov detectors
- PINGU LOI released *arXiv:1401.2046* update later this year
- ORCA see www.km3net.org/

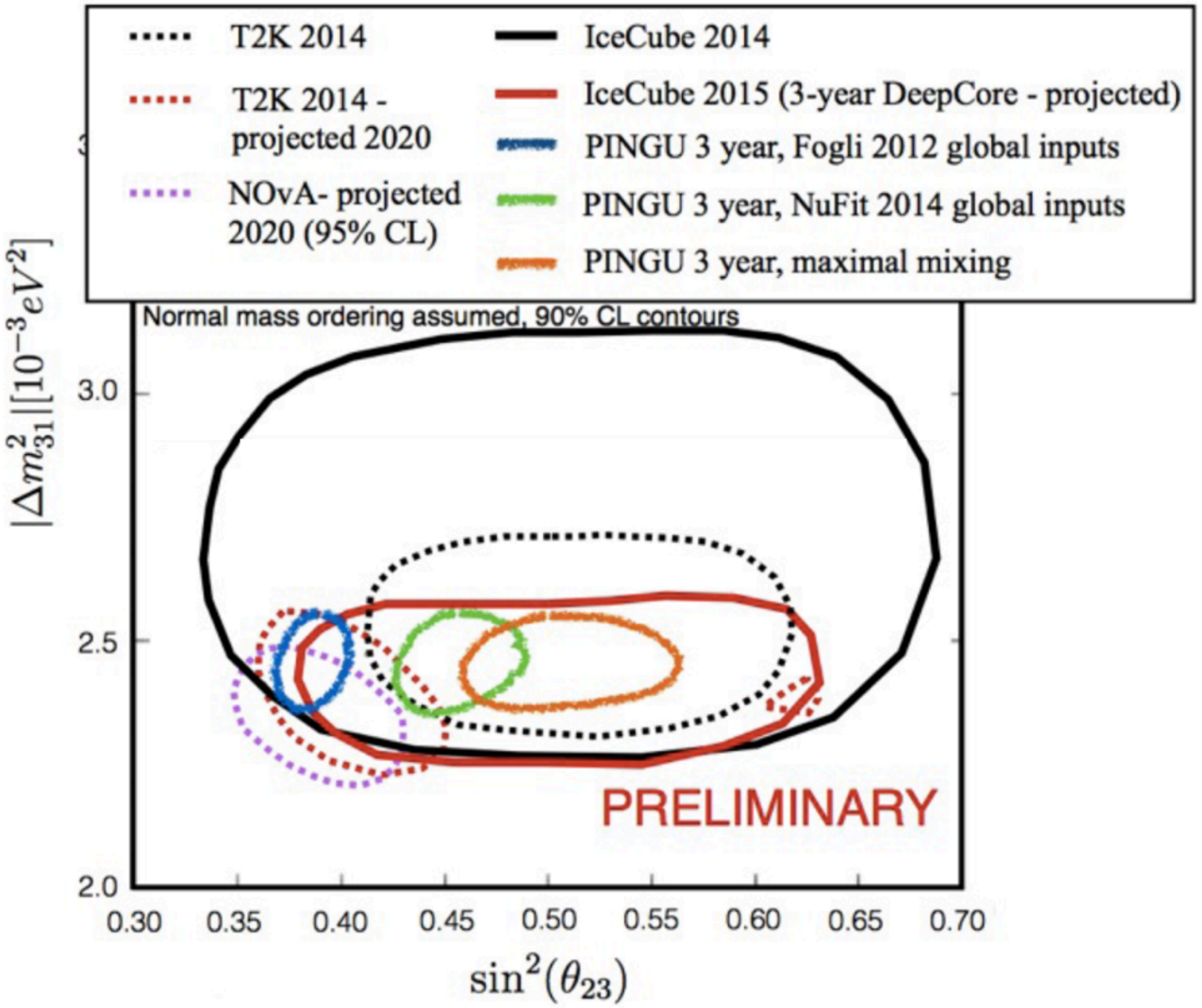


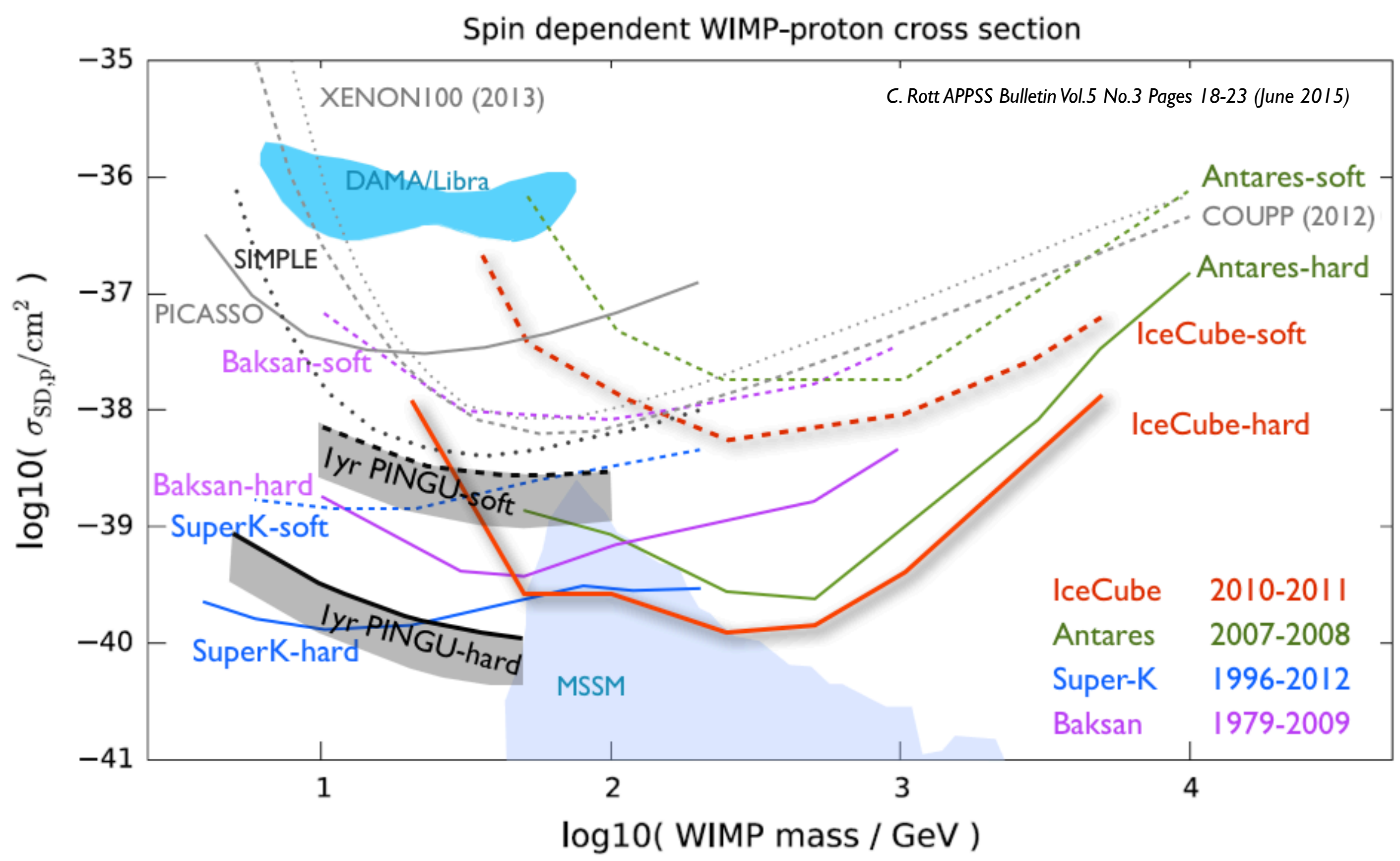


PINGU Multi-purpose experiment

- <u>Multipurpose detector</u>: Neutrino Properties, Dark Matter, Supernovae, Galactic Neutrino Sources, Neutrino Tomography, ...

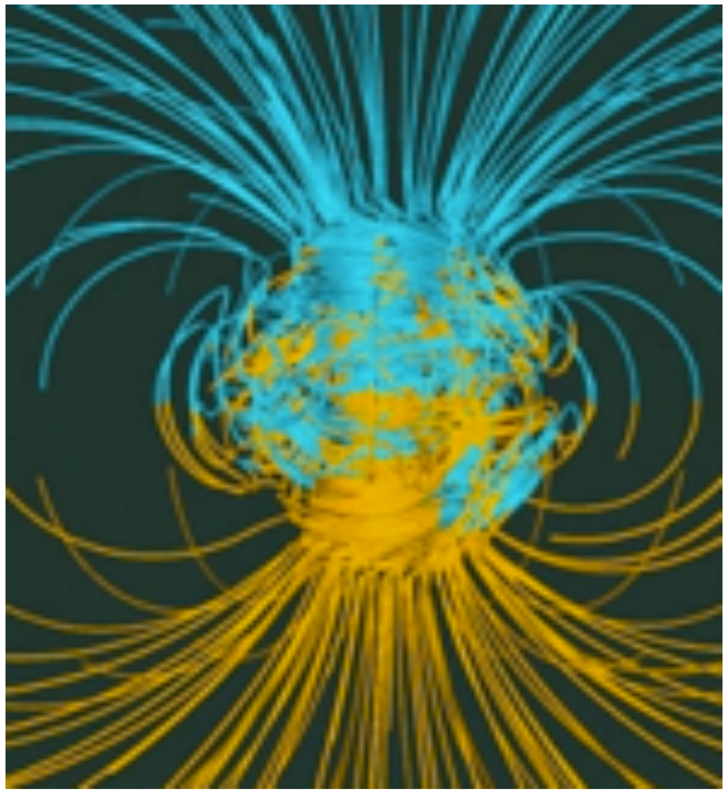


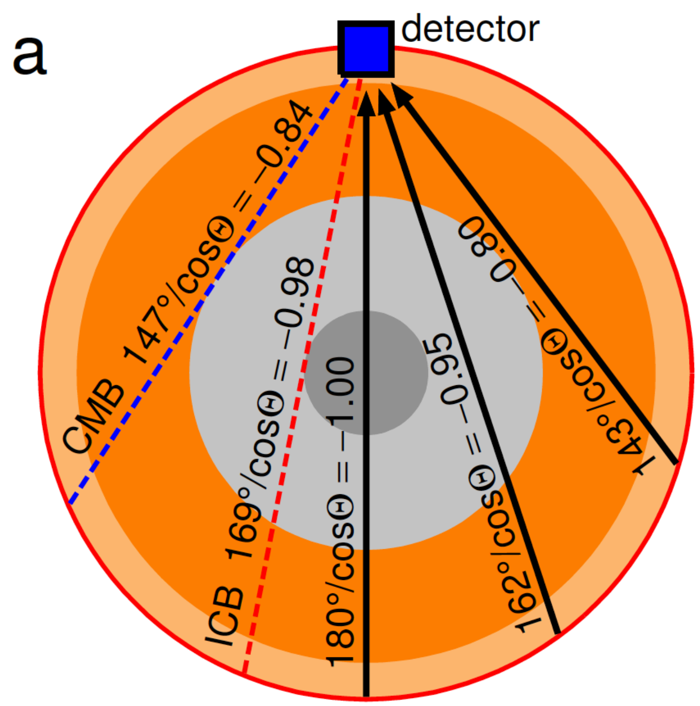


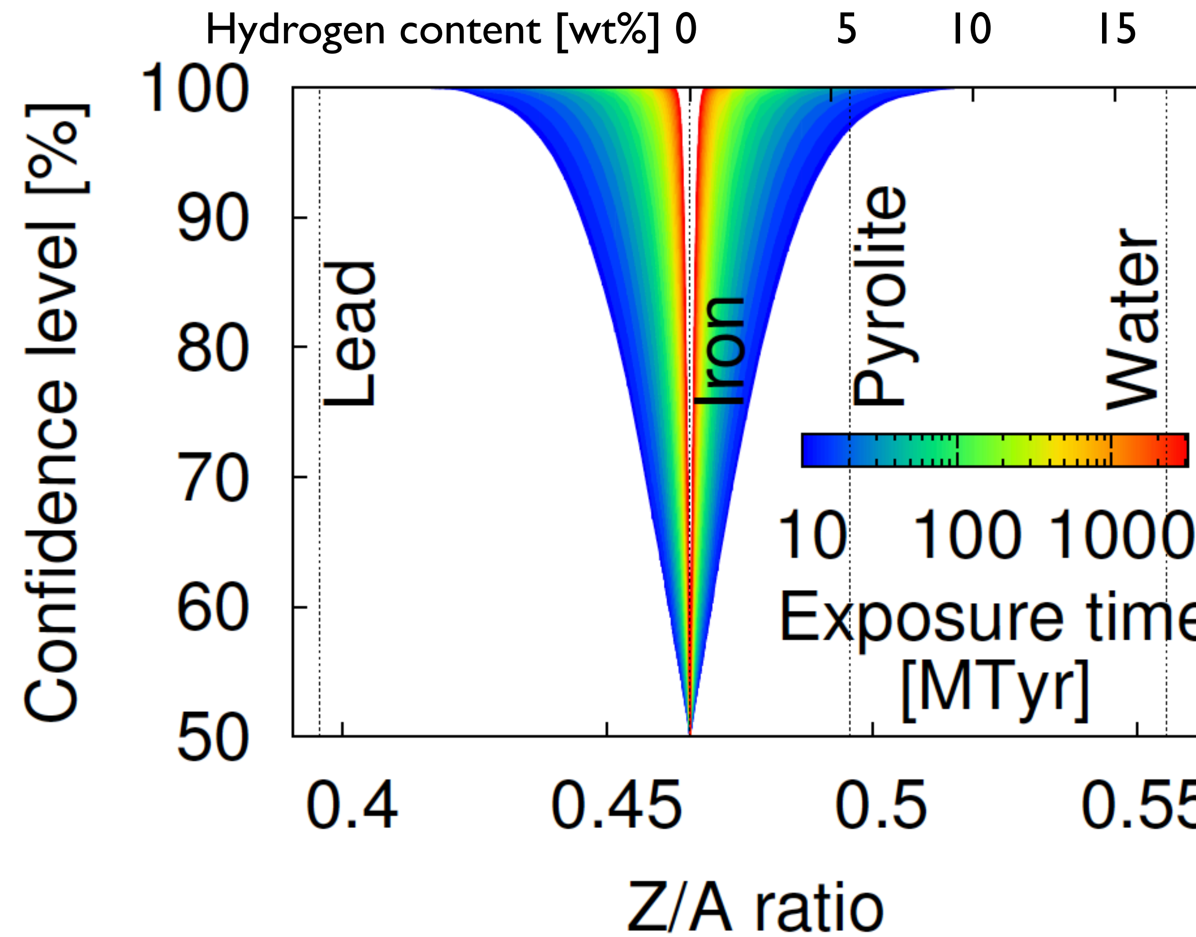


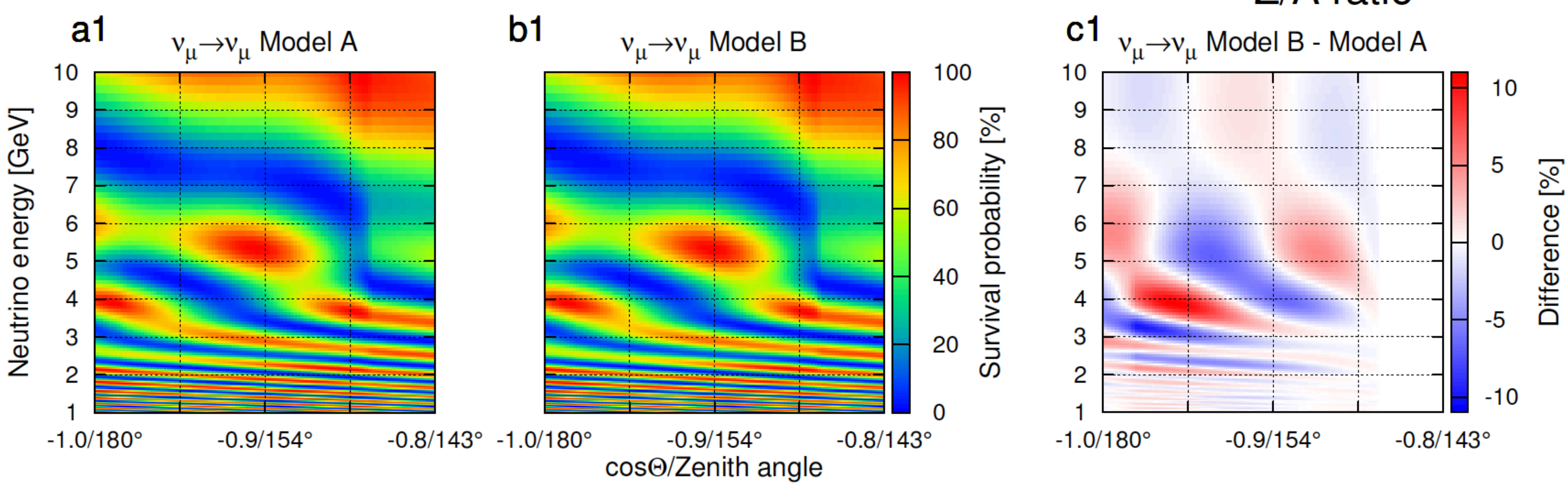
Rott & Taketa et al. Scientific Reports 5, Article number: 15225 (2015) arxiv:1502.04930)

Neutrino Tomography







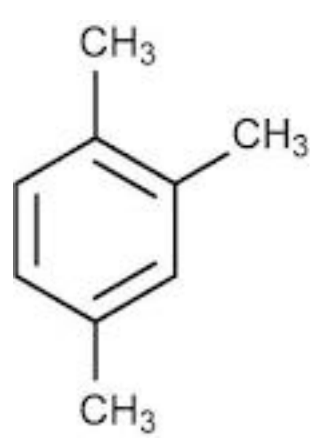


- Neutrinos are certainly the most mysterious particles in the standard model
- Do they lead the way beyond ?
- Neutrinos have masses and oscillate !
- High-energy astrophysical neutrinos have been detected ... on the verge of neutrino astronomy

Image:Stephan Richter, IceCube/NSF

Borexino

- Borexino is a large volume detector for low energy neutrino spectroscopy
  - currently running underground at the Laboratori Nazionali del Gran Sasso, Italy.
    - 3800 meters of water equivalent, m.w.e.
  - The main goal of the experiment is the real-time measurement of sub-MeV solar neutrinos, and particularly of the mono energetic (862 keV) ^{7}Be electron capture neutrinos, via neutrino-electron scattering in an ultra-pure liquid scintillator.
  - Further aims at the spectral study of other solar neutrino components, such as the CNO, pep (3) and, possibly, pp, and ^{8}B neutrinos
  - very competitive in the detection of anti-neutrinos, particularly those of geophysical origin.
  -



PC (pseudocumene, 1,2,4-trimethylbenzene)

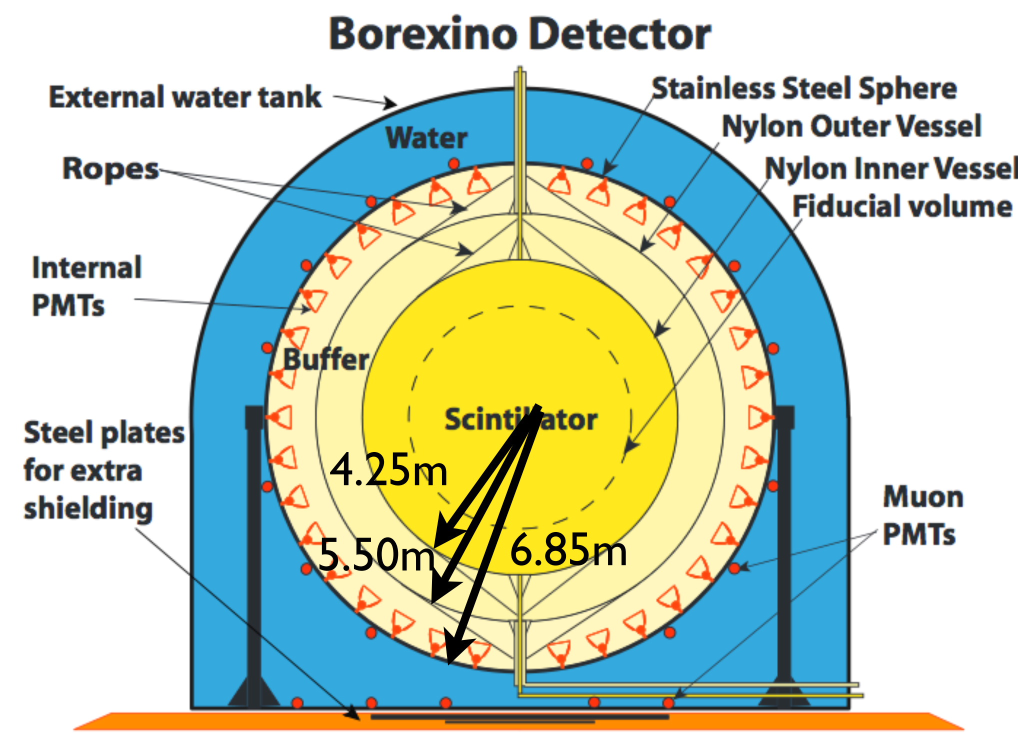


Fig. 1. Schematic drawing of the Borexino detector.

Low energy neutrinos of all flavors are detected by means of their elastic scattering of electrons

Electron anti-neutrinos detection via inverse beta decay on protons or carbon nuclei.

The electron (positron) recoil energy is converted into scintillation light which is then collected by a set of photomultipliers.

Borexino

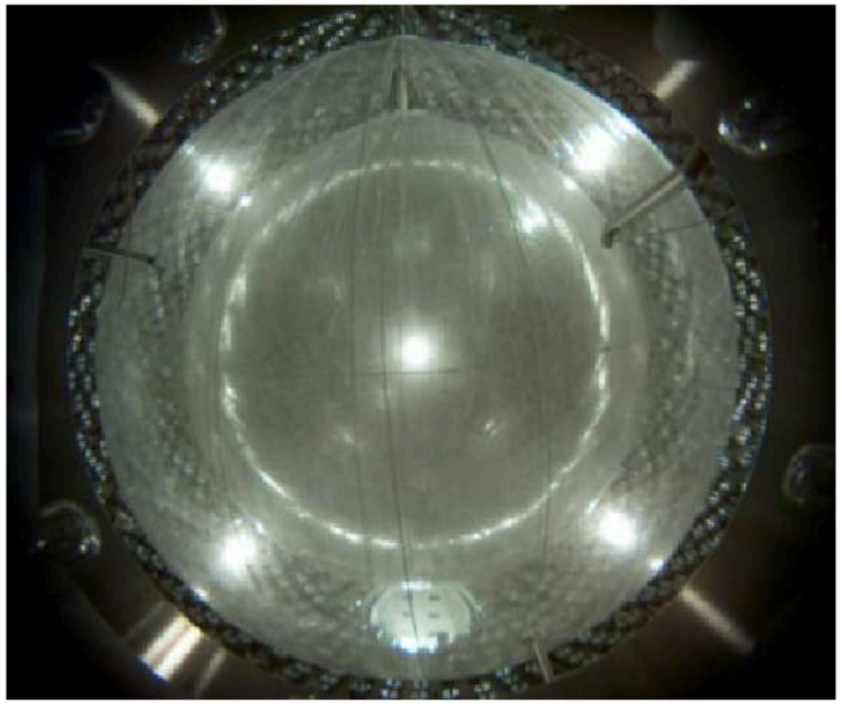


Fig. 2. The Inner and Outer Nylon Vessels installed and inflated with nitrogen in the Stainless Steel Sphere.

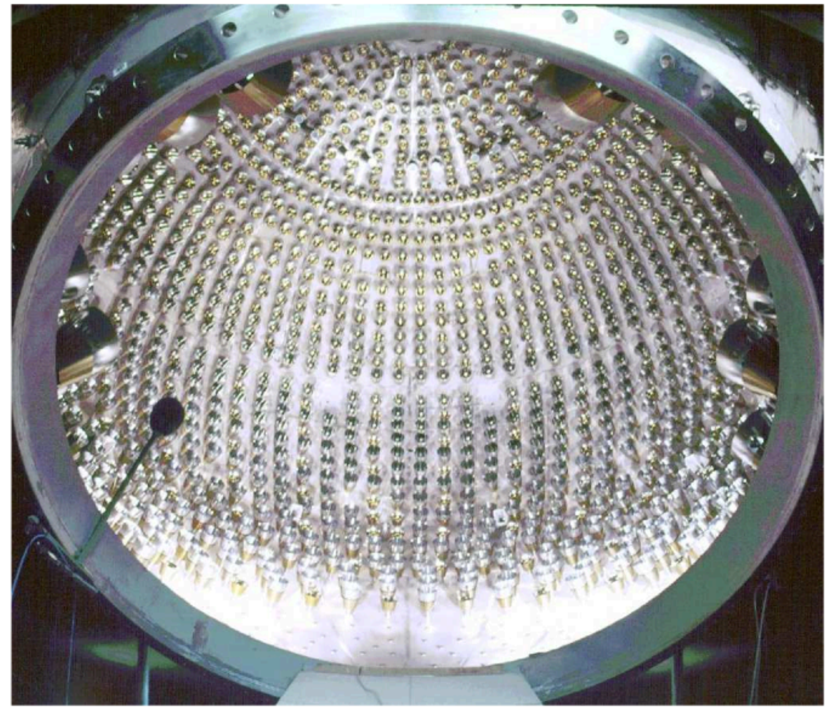


Fig. 3. Inner surface of the Stainless Steel Sphere. The picture is taken from the main SSS door, and shows the internal surface of the sphere with PMTs evenly mounted inside. The

- 2212 PMTs inner detector
- 208 PMTs outer detector

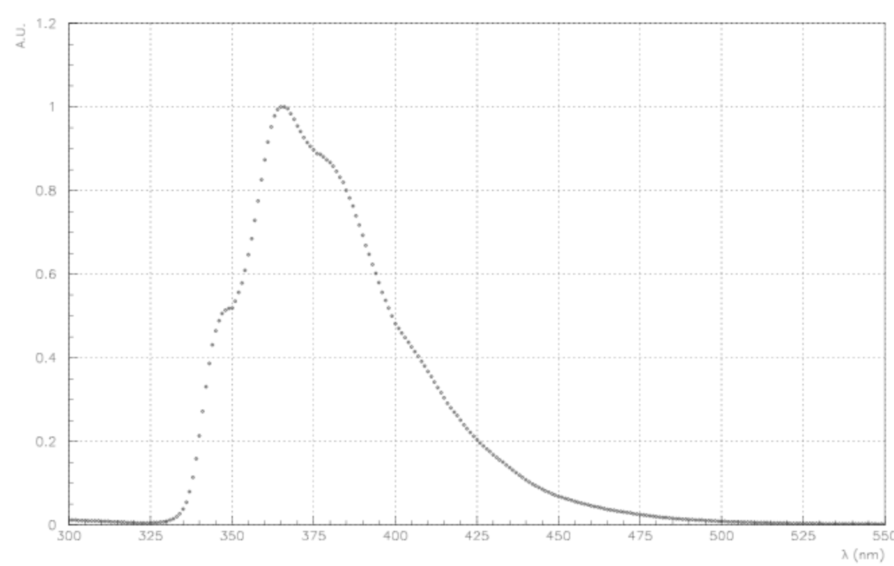
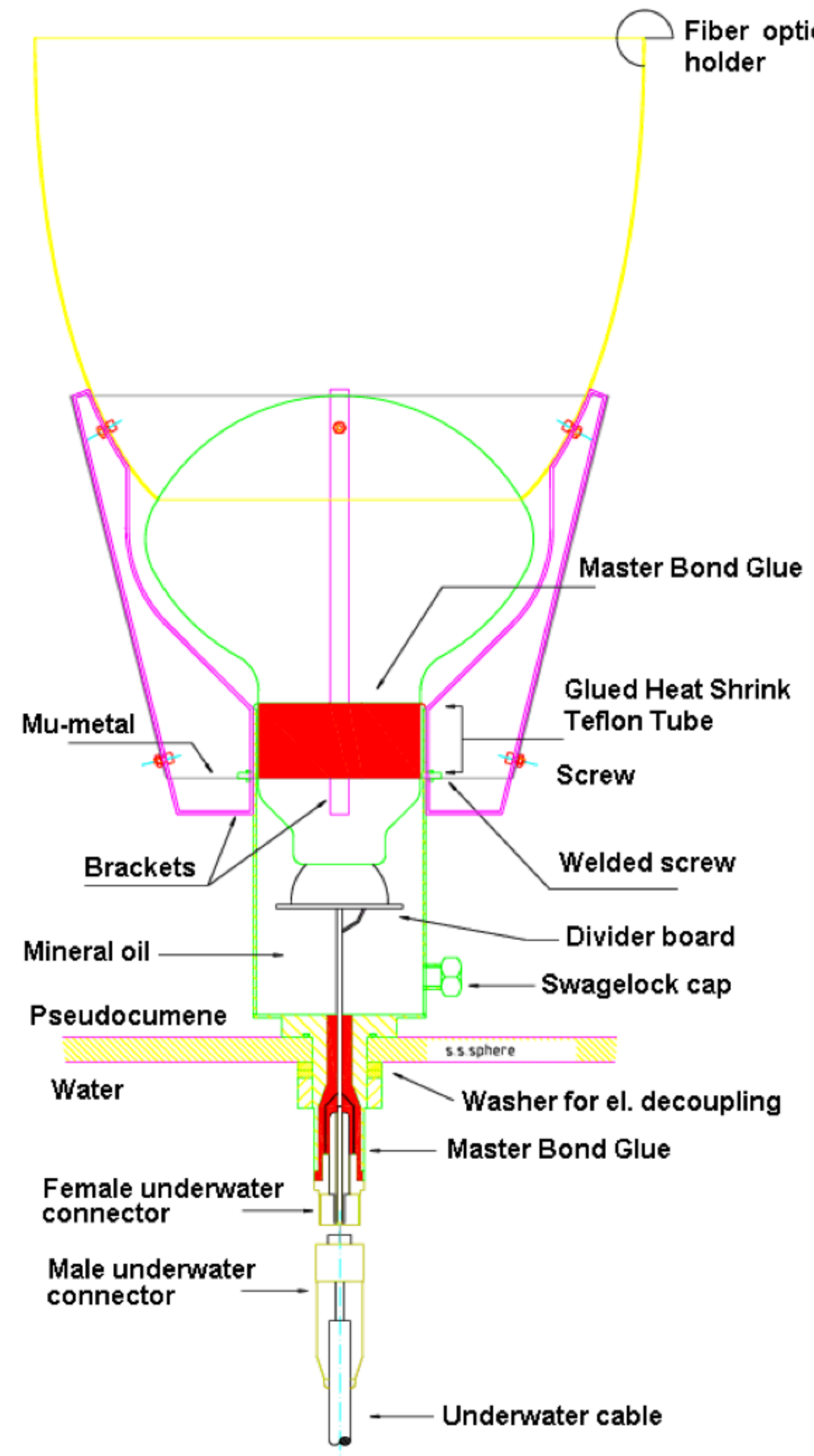


Fig. 6. Emission spectrum of the PC+PPO mixture used in Borexino



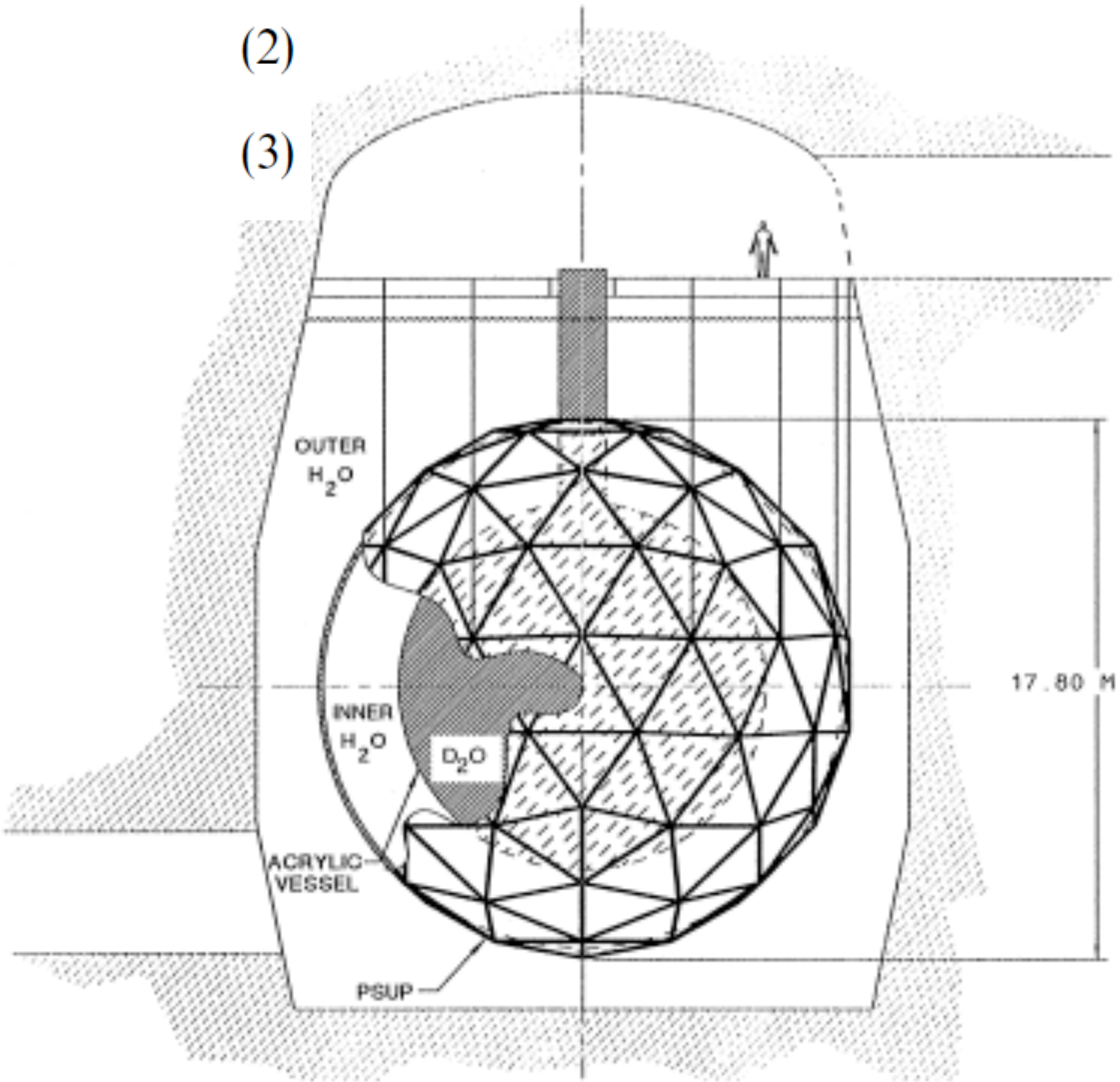
- The SNO detector is located in a huge rock cavern – 22 meters in diameter and 30 meters high, 2 kilometers underground at the Inco Creighton Mine, 20 minutes west of Sudbury Ontario.
- SNO experiment utilized heavy water
  - D2O permits the detection of neutrinos through the following channels:

$$\nu_x + e^- \rightarrow \nu_x + e^-, \quad (1)$$

$$\nu_e + d \rightarrow e^- + p + p, \quad (2)$$

$$\nu_x + d \rightarrow \nu_x + n + p, \quad (3)$$

The elastic scattering (ES) of electrons by neutrinos (Eq. (1)) is highly directional, and establishes the sun as the source of the detected neutrinos. The charged-current (CC) absorption of ν_e on deuterons (Eq. (2)) produces an electron with an energy highly correlated with that of the neutrino. This reaction is sensitive to the energy spectrum of ν_e and hence to deviations from the parent spectrum. The neutral-current (NC) disintegration of the deuteron by neutrinos (Eq. (3)) is independent of neutrino flavor and has a threshold of 2.2 MeV.



Radio chemical measurements

- The GALLEX and SAGE Gallium solar neutrino experiments
- GALLEX or Gallium Experiment was a radiochemical neutrino detection experiment that ran between 1991 and 1997 at the Laboratori Nazionali del Gran Sasso (LNGS)
    - The 54m^3 detector tank was filled with 101 tons of gallium trichloride-hydrochloric acid solution, which contained 30.3 tons of gallium. The gallium in this solution acted as the target for a neutrino-induced nuclear reaction, which transmuted it into germanium through the following reaction:

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

Gallium Anomaly

- GALLEX and SAGE collaborations used a gallium-targets
  - radiochemical experiments focused on studying solar neutrinos.
  - For calibration purposes, measured flux of electron neutrinos produced by artificial radioactive sources placed inside the detectors.
  - The observed-to-expected flux ratio to be 0.86 ± 0.06
  - Neutrinos are vanishing by oscillating into sterile ones ?