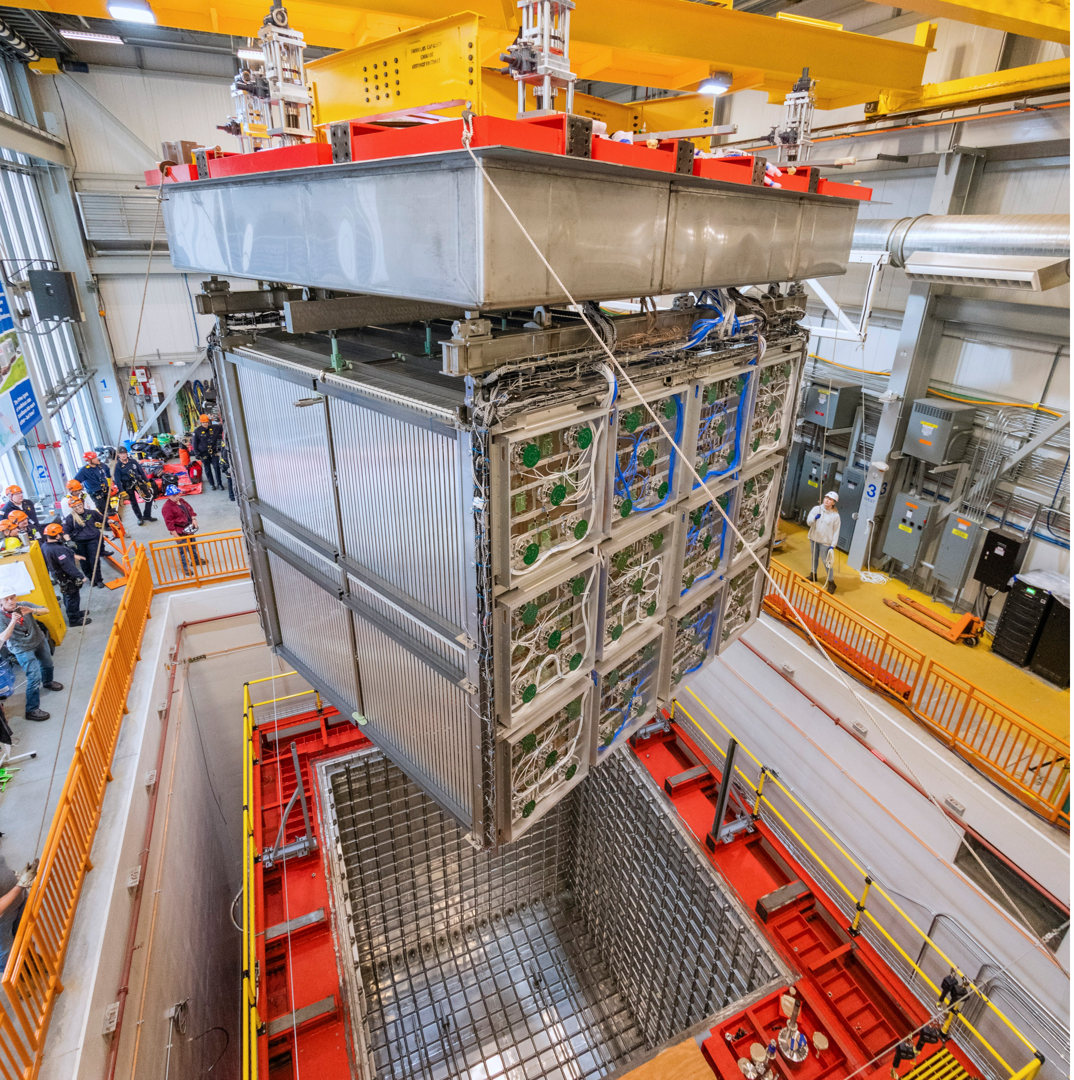


Neutrinos: Detectors & Discoveries

Thomas Wester

Enrico Fermi Institute, University of Chicago

Arthur H. Compton Lecture #2

Spring 2025

ENRICO FERMI INSTITUTE

Welcome Back

ν

Lecture I: How the neutrino was discovered, and what its properties are

Electrically neutral & weakly interacting

Welcome Back

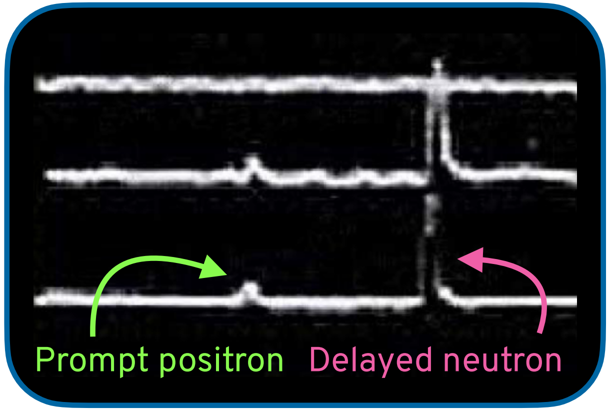
Lecture I: How the neutrino was discovered, and what its properties are

ν

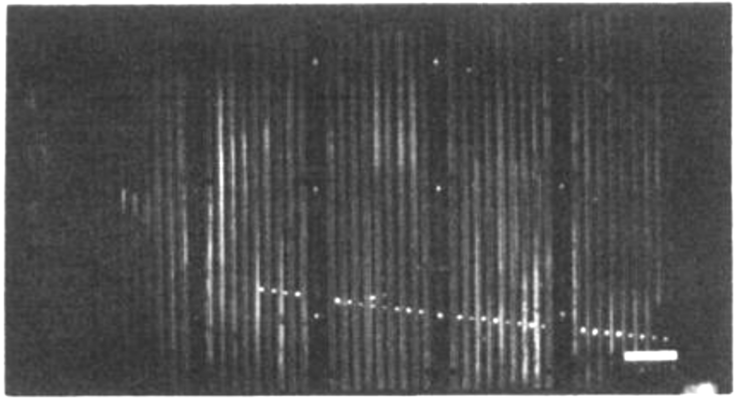
Electrically neutral & weakly interacting

Two important experiments:

Reines & Cowan – Double Coincidence
Discovery of the neutrino



Lederman et al. – Spark Chamber
Multiple flavors: $\nu_e \neq \nu_\mu$



Lecture 2:

Neutrinos from the Sun & Sky

Chemical Reactions

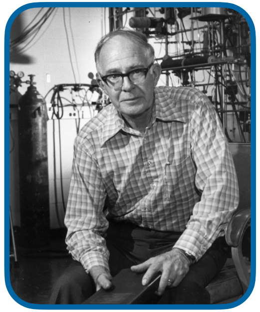
If the neutrino can change a proton into a neutron,
it should induce certain chemical reactions, e.g.,

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

A good candidate, possible to extract & count argon-37 from chlorine via chemical methods

Bruno Pontecorvo

Luis Alvarez



Ray Davis Jr.

Proposed the method, but never did the experiment

Made it a reality

Davis' Experiment at Brookhaven

Like Reines & Cowan: Put the experiment near a nuclear reactor

Lots of neutrinos!

Davis’ Experiment at Brookhaven

Like Reines & Cowan: Put the experiment near a nuclear reactor

Lots of neutrinos!

PHYSICAL REVIEW VOLUME 97, NUMBER 3 FEBRUARY 1, 1955

Attempt to Detect the Antineutrinos from a Nuclear Reactor by the $Cl^{37}(\bar{\nu},e^{-})A^{37}$ Reaction*

RAYMOND DAVIS, JR.
Department of Chemistry, Brookhaven National Laboratory, Upton, Long Island, New York
(Received September 21, 1954)

Nothing!

Particles & Anti-Particles

Anti-particles have the opposite electric charge of a particle, but have the same mass & experience the same forces

e^-

Electron

Charge: -1

Mass: m_e

e^+

Anti-electron (AKA "Positron")

Charge: +1

Mass: m_e

Anti-Neutrinos

Neutrinos have no charge, so what's an anti-neutrino?

(We will revisit this in future lectures)

ν_e

Electron neutrino

Bar indicates "anti"

$\bar{\nu}_e$

Electron anti-neutrino

(or anti-electron neutrino)

Anti-Neutrinos

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Electron neutrino

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Bar indicates "anti"

Electron anti-neutrino

(or anti-electron neutrino)

Lepton number: another type of charge. +1 for leptons, -1 for anti-leptons

+1: $e^-, \mu^-, \tau^-, \nu_e, \nu_\mu, \nu_\tau$

-1: $e^+, \mu^+, \tau^+, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

Playing by the Rules

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

Is this allowed?

Playing by the Rules

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

(struck through)

Left side:	Right side:
+1 “muon” number	+1 “muon” number
+1 charge (proton)	-1 charge (muon)

Playing by the Rules

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

Left side:	Right side:
+1 "muon" number	+1 "muon" number
+1 charge (proton)	-1 charge (muon)

→

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

Left side:	Right side:
+1 "muon" number	+1 "muon" number
0 charge	0 charge

Playing by the Rules

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

Left side:	Right side:
+1 "muon" number	+1 "muon" number
+1 charge (proton)	-1 charge (muon)

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

Left side:	Right side:
+1 "muon" number	+1 "muon" number
0 charge	0 charge

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

Is this allowed?

Playing by the Rules

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

Left side:	Right side:
+1 "muon" number	+1 "muon" number
+1 charge (proton)	-1 charge (muon)

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

Left side:	Right side:
+1 "muon" number	+1 "muon" number
0 charge	0 charge

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

Left side:	Right side:
-1 "electron" number	-1 "electron" number
+1 charge (proton)	+1 charge (muon)

Playing by the Rules

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

Left side:	Right side:
+1 "muon" number	+1 "muon" number
+1 charge (proton)	-1 charge (muon)

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

Left side:	Right side:
+1 "muon" number	+1 "muon" number
0 charge	0 charge

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

Left side:	Right side:
-1 "electron" number	-1 "electron" number
+1 charge (proton)	+1 charge (muon)

$$\mu^- \rightarrow \nu_\mu + e^- + \nu_e$$

(Muon decay?)

Playing by the Rules

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

Left side:
+1 "muon" number
+1 charge (proton)

Right side:
+1 "muon" number
-1 charge (muon)

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

Left side:
+1 "muon" number
0 charge

Right side:
+1 "muon" number
0 charge

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

Left side:
-1 "electron" number
+1 charge (proton)

Right side:
-1 "electron" number
+1 charge (muon)

$$\mu^- \rightarrow \nu_\mu + e^- + \nu_e$$

Left side:
+1 "muon" number
0 "electron" number
-1 charge (muon)

Right side:
+1 "muon" number
+2 "electron" number
-1 charge (electron)

Playing by the Rules

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

Left side:	Right side:
+1 “muon” number	+1 “muon” number
+1 charge (proton)	-1 charge (muon)

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

Left side:	Right side:
+1 “muon” number	+1 “muon” number
0 charge	0 charge

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

Left side:	Right side:
-1 “electron” number	-1 “electron” number
+1 charge (proton)	+1 charge (muon)

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

Left side:	Right side:
+1 “muon” number	+1 “muon” number
0 “electron” number	0 “electron” number
-1 charge (muon)	-1 charge (electron)

Don't Forget About Energy!

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

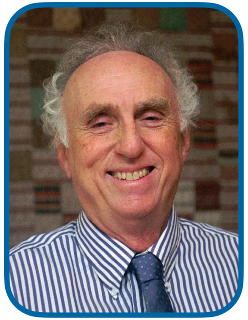
Left side:	Right side:
+1 "muon" number	+1 "muon" number
0 charge	0 charge
Energy?	Energy?

Assuming the lepton after the interaction has no momentum (at rest), one can calculate the minimum energy required:

$$E_{\nu_\mu(\text{Min.})} \approx m_\mu \left(\frac{m_\mu + 2m_n}{2m_p} \right) \approx 110\,\text{MeV}$$

Another Example

- Tau (τ) particle discovered at Stanford Linear accelerator (SLAC) in electron-electron collisions
- A lepton like the electron & muon, but even heavier

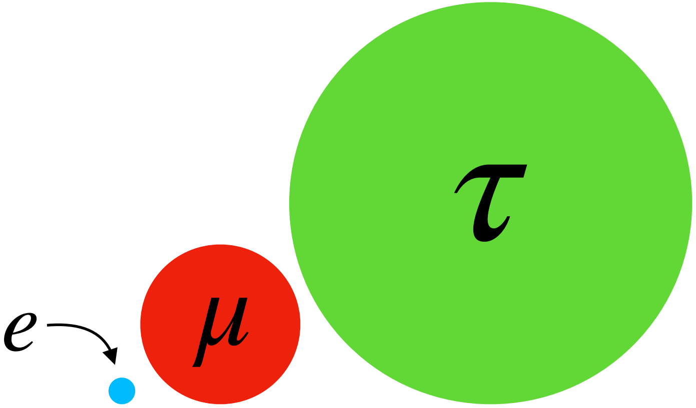


Martin Perl
1995 Nobel Prize

How much energy required to produce a τ in a neutrino interaction?

$$m_\tau \approx 1776\,\text{MeV}$$

$$E_{\text{Min.}} \approx m_\tau \left(\frac{m_\tau + 2m_n}{2m_p} \right) \approx 3400\,\text{MeV}$$



Back to Davis' Experiment

Reactor neutrinos

From beta decays

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

Reines & Cowan

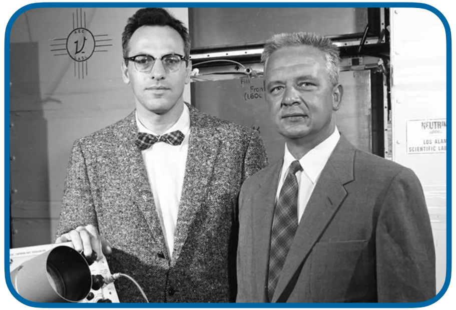
Inverse Beta Decay, detection 1956

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

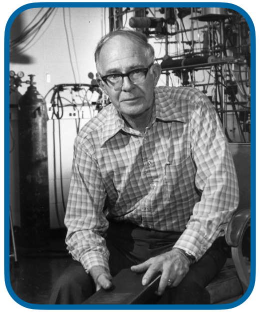
Davis

Chlorine→Argon reaction, no detection

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



Fred Reines & Clyde Cowan



Ray Davis Jr.

Back to Davis' Experiment

Reactor neutrinos

From beta decays

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

Left side:
0 lepton number
0 charge

Right side:
0 lepton number
0 charge

Reines & Cowan

Inverse Beta Decay, detection 1956

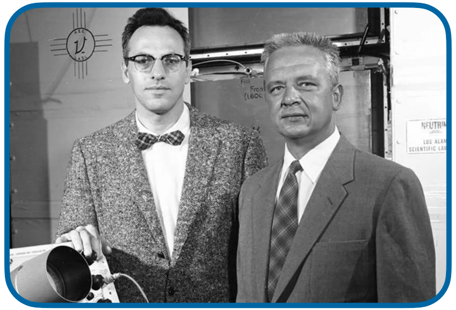
$$\bar{\nu}_e + p \rightarrow n + e^+$$

Davis

Chlorine→Argon reaction, no detection

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

Requires neutrinos (not anti-neutrinos)



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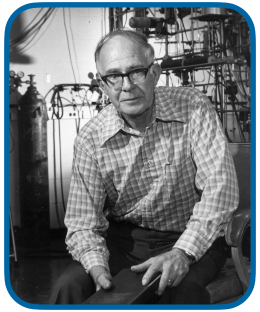
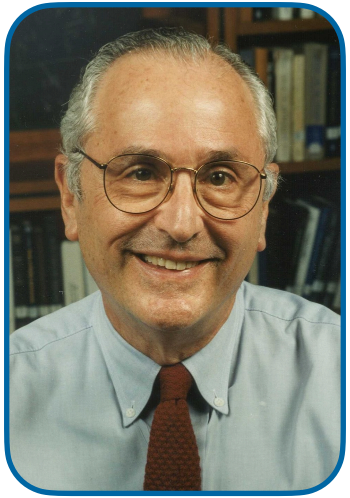


Ray Davis Jr.

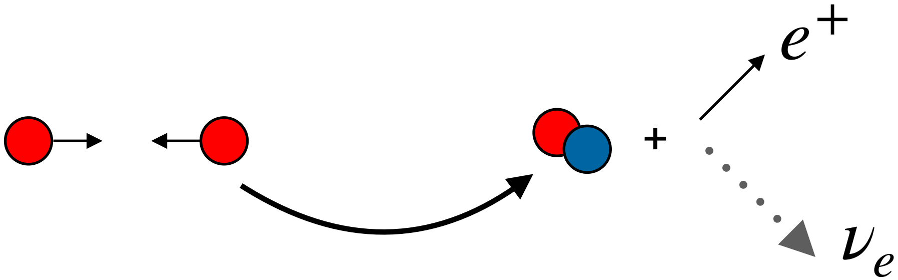
What about the Sun?



John Bachall

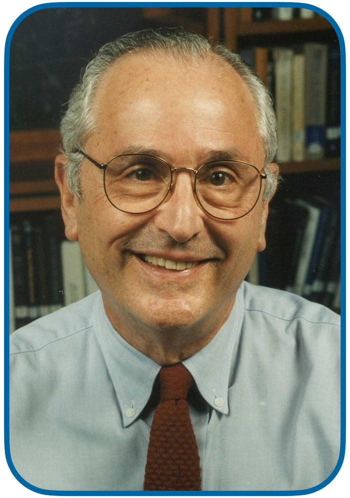
“Do we understand how the sun shines?”

An application for neutrinos!



Fusion in the Sun… …should produce a *lot* of neutrinos

What about the Sun?



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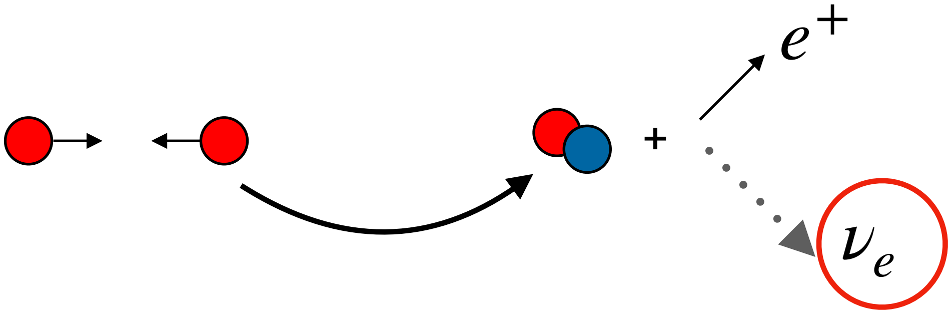


Fusion in the Sun...

...should produce a *lot* of neutrinos

...and specifically *not* anti-neutrinos

The Sun

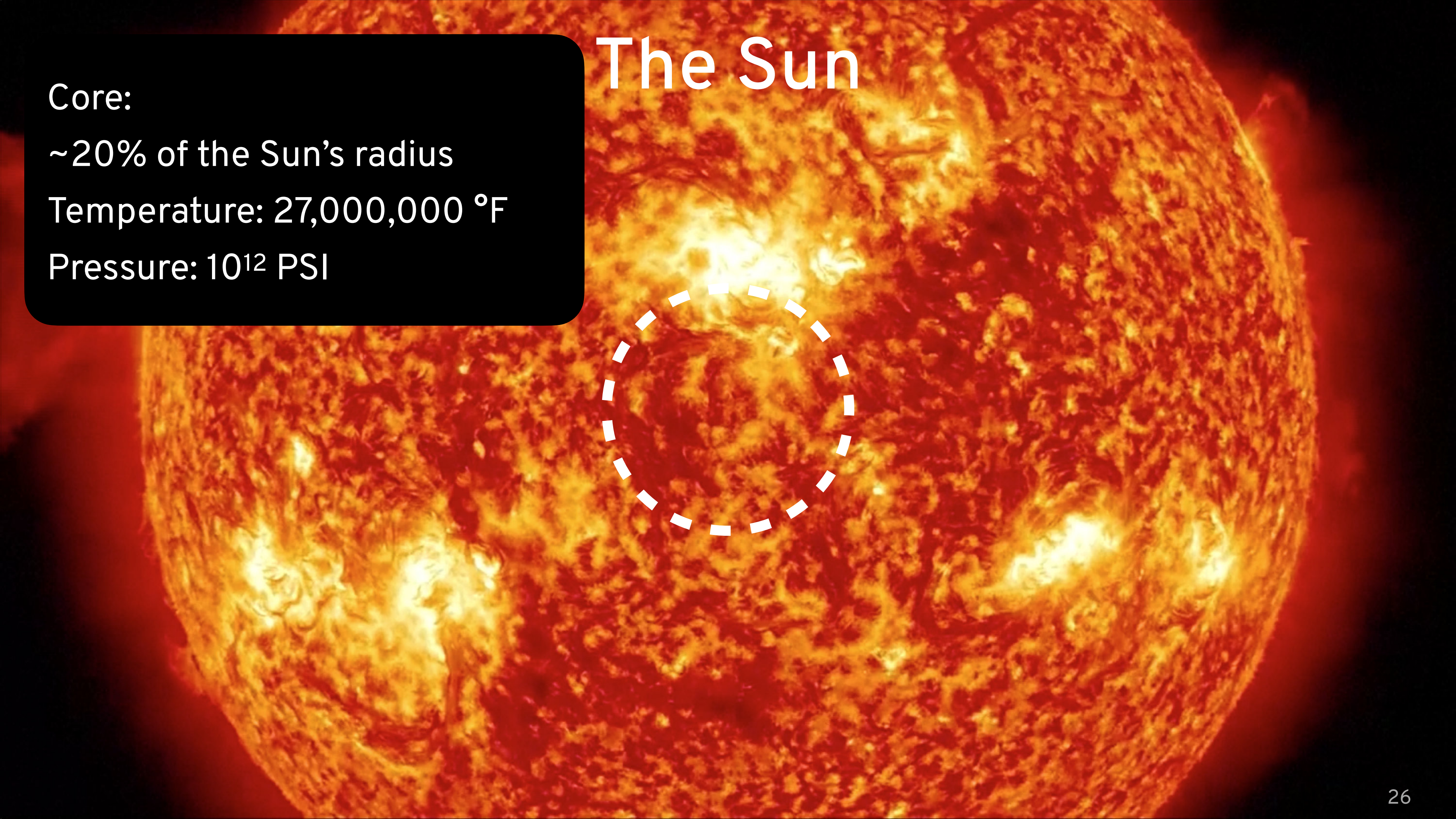
The Sun

Core:

~20% of the Sun’s radius

Temperature: 27,000,000 °F

Pressure: 10^{12} PSI



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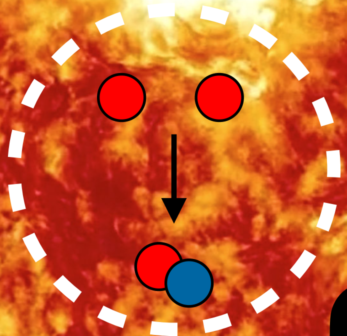


In the core: Fusion

Hydrogen atoms fuse together, producing deuterium and energy

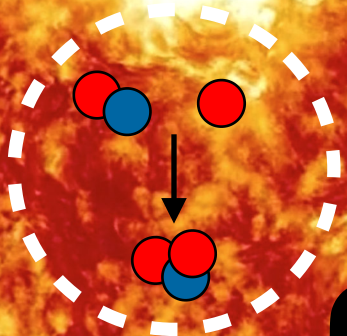
The Sun

Core:

~20% of the Sun’s radius

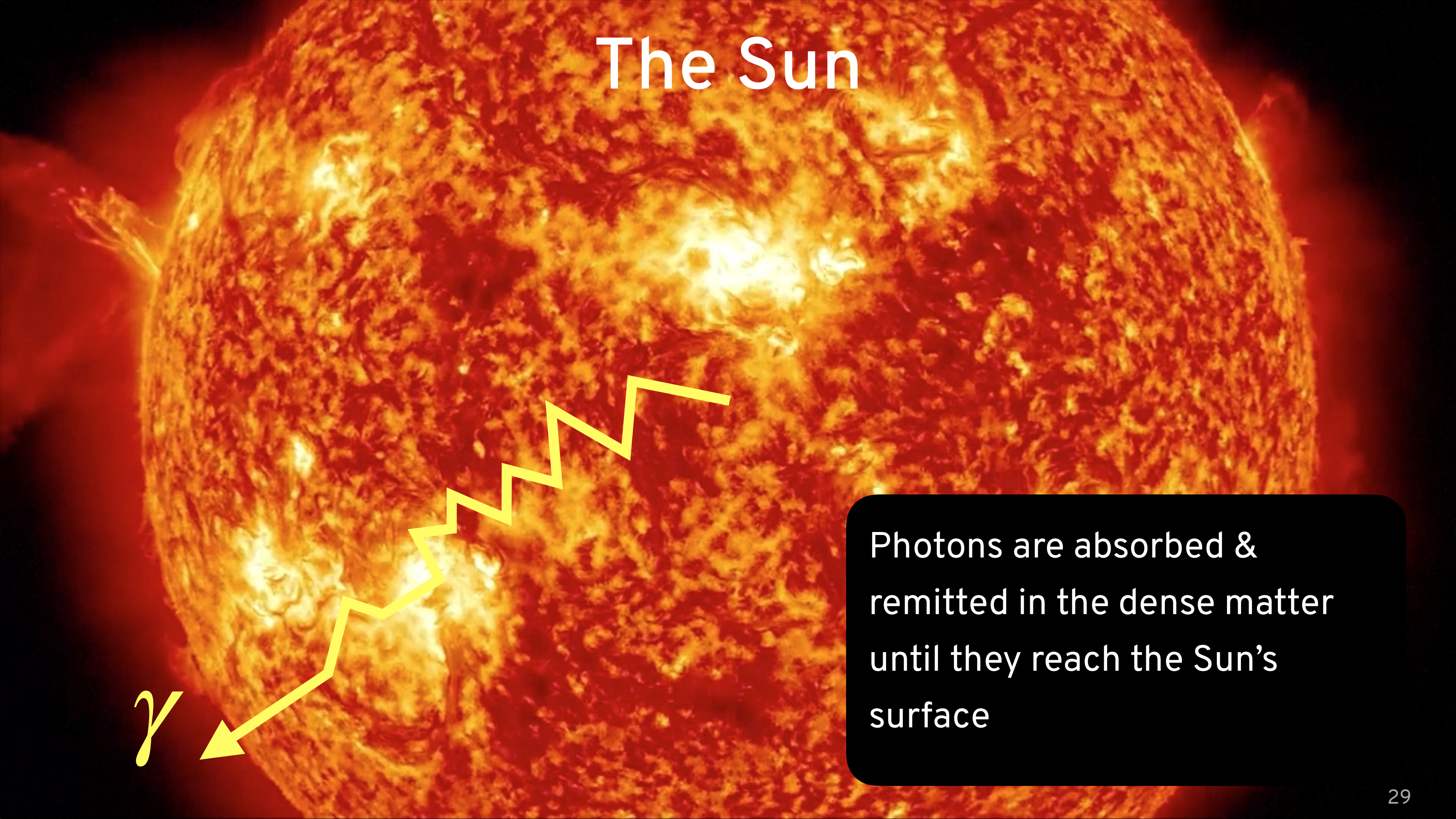
Temperature: 27,000,000 °F

Pressure: 10^{12} PSI



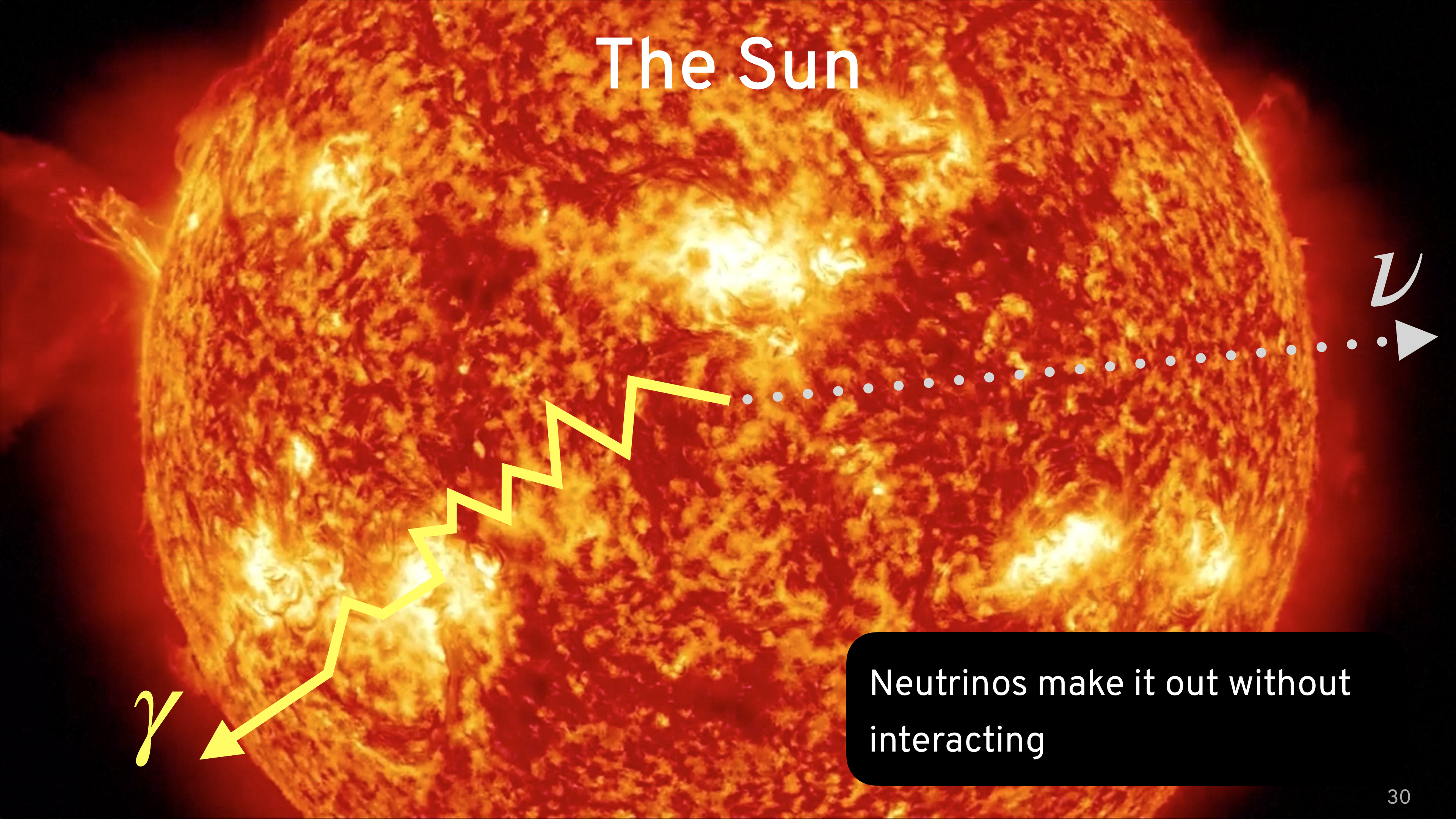
Fusion takes deuterium and builds heavier elements, releasing energy each time

The Sun



Photons are absorbed & remitted in the dense matter until they reach the Sun’s surface

The Sun



Neutrinos make it out without interacting

Solar Neutrinos from Fusion
Standard Solar Model

$$\mathrm{H} + \mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \boxed{\nu_e}$$ Proton-proton (*pp*) neutrinos

Solar Neutrinos from Fusion

Standard Solar Model

$$\mathrm{H} + \mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \boxed{\nu_e}$$

$$\downarrow$$

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

Solar Neutrinos from Fusion

Standard Solar Model

$$\mathrm{H} + \mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \boxed{\nu_e}$$

$$\downarrow$$

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

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

Helium-proton (*hep*) neutrinos

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

Solar Neutrinos from Fusion

Standard Solar Model

$$\mathrm{H} + \mathrm{H} \rightarrow {}^2\mathrm{H} + e^+ + \boxed{\nu_e}$$

↓

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

↓ (branches)

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

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

↓ (from $^7\mathrm{Be}$, branches)

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

↓

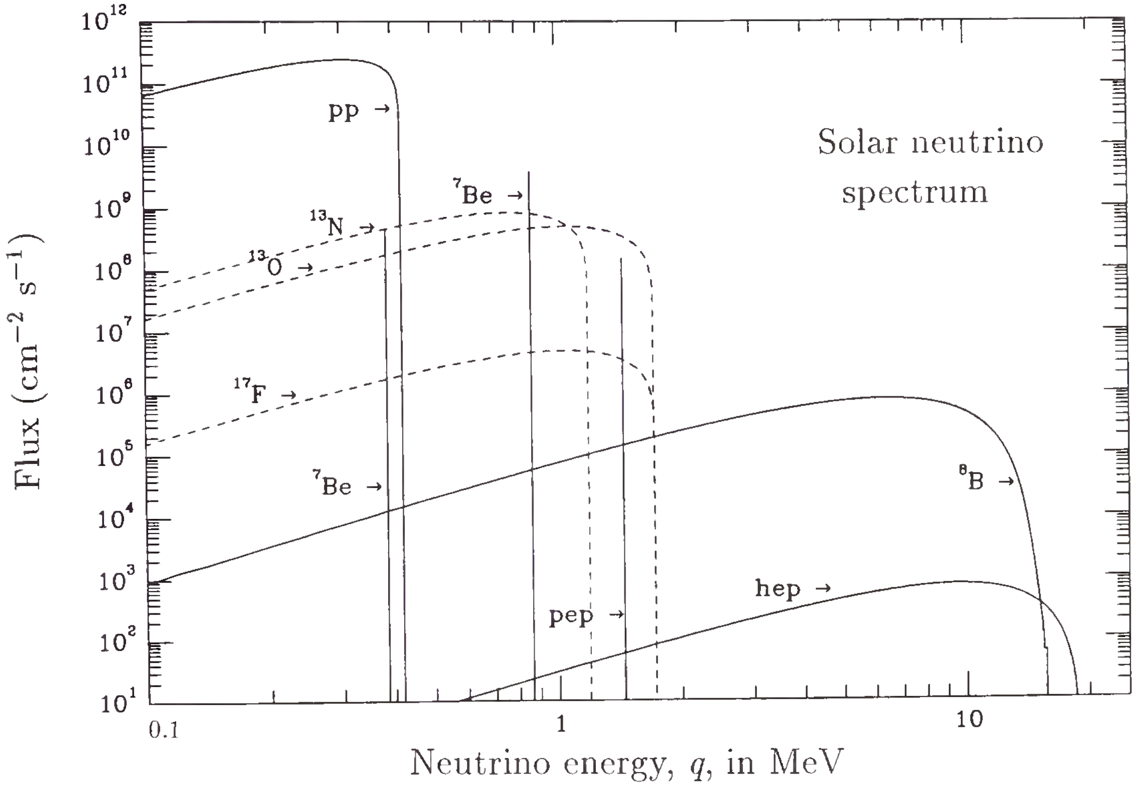
$$^8\mathrm{B}* \rightarrow {}^8\mathrm{B} + e^+ + \boxed{\nu_e}$$

Boron-8 neutrinos

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

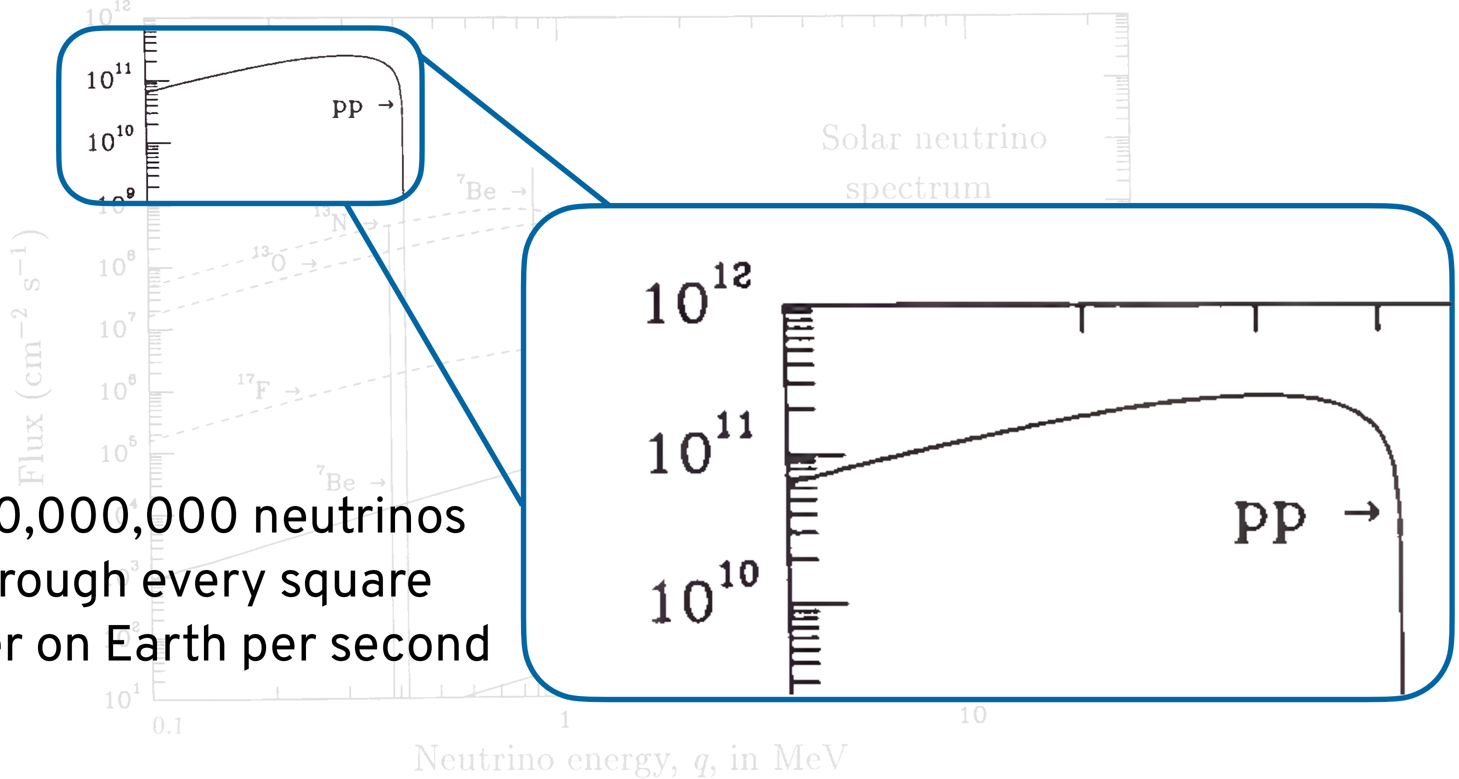
Beryllium-7 neutrinos

Solar Neutrino Spectrum on Earth



J. N. Bahcall, *Neutrino Astrophysics*, Cambridge University Press, Cambridge (1989)

Solar Neutrino Spectrum on Earth



~100,000,000,000 neutrinos pass through every square centimeter on Earth per second

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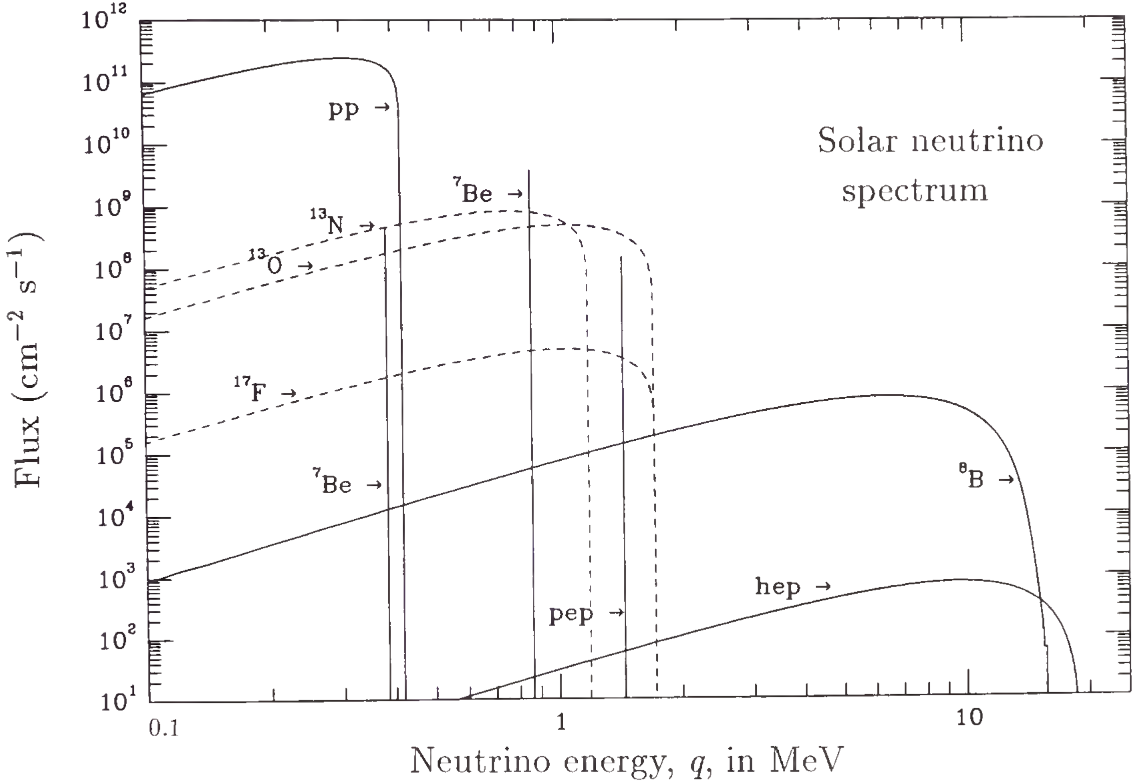
Solar Neutrino Spectrum on Earth



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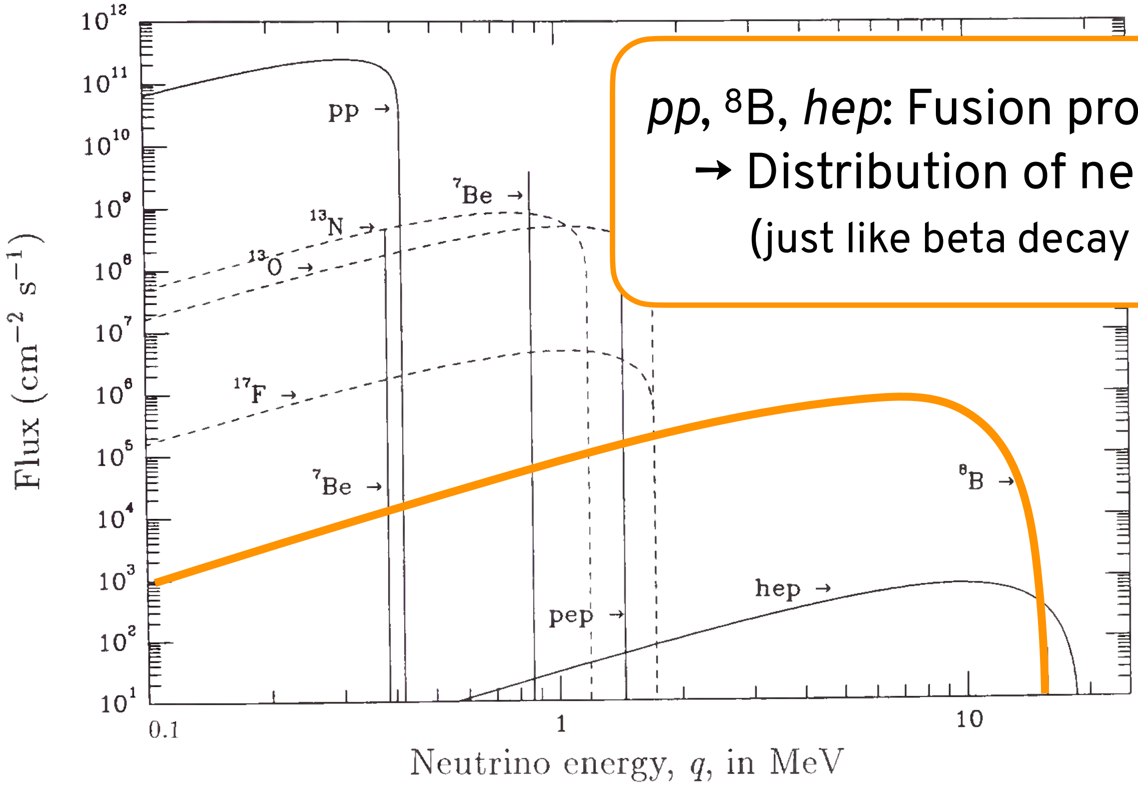
Solar Neutrino Spectrum on Earth



pp, ^{8}B, *hep*: Fusion produces 3 particles
→ Distribution of neutrino energies
(just like beta decay from Lecture I)

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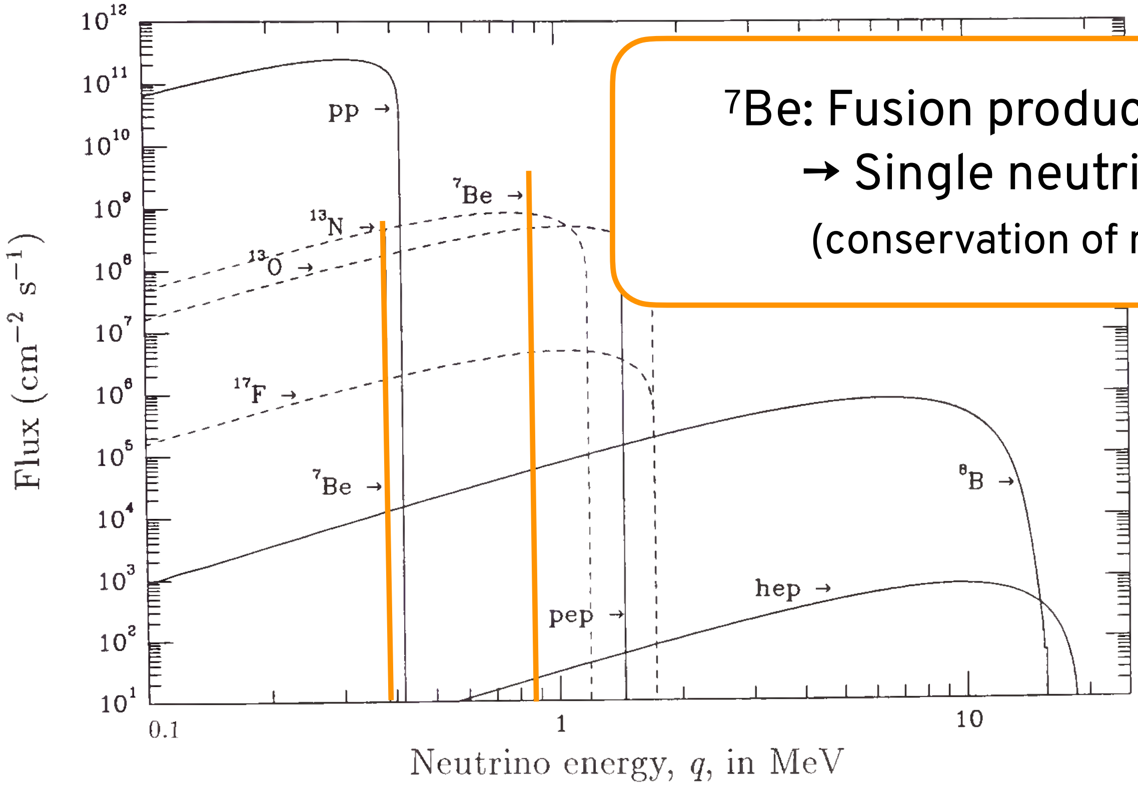
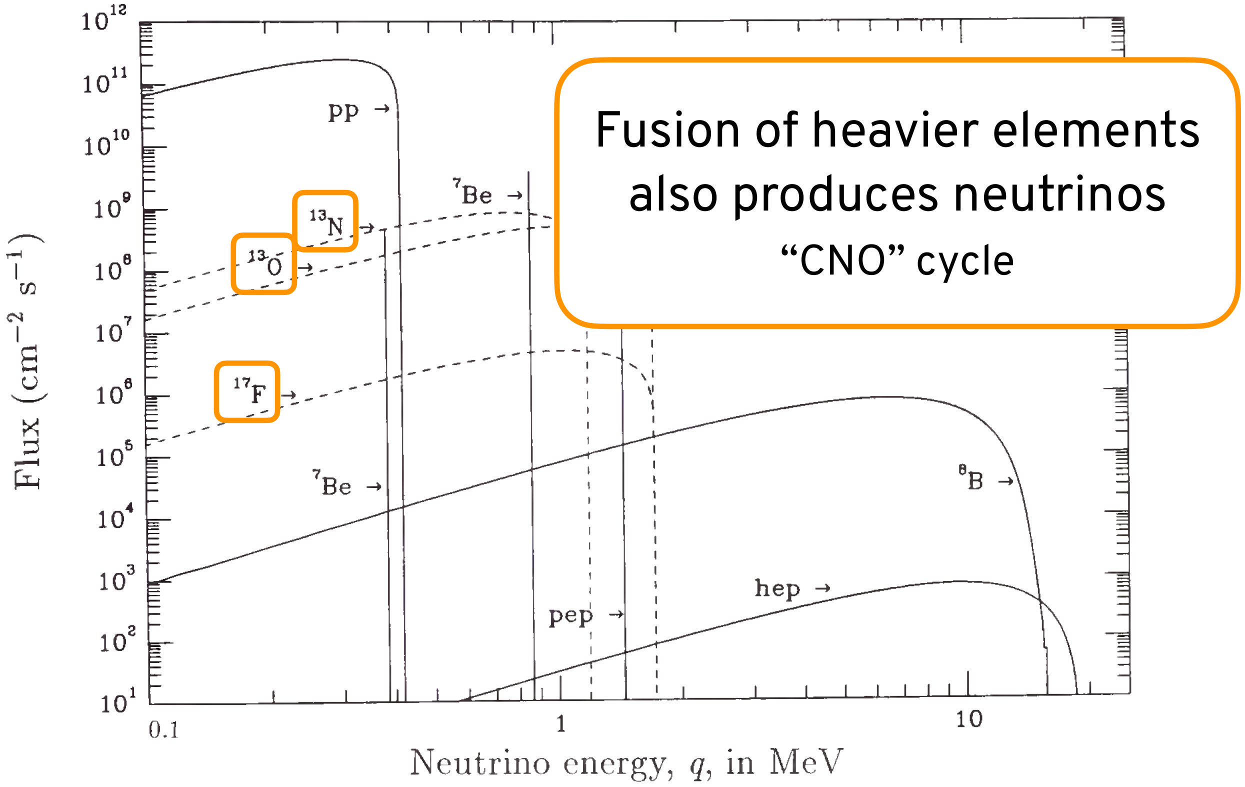
Solar Neutrino Spectrum on Earth



^{7}Be: Fusion produces 2 particles
→ Single neutrino energy
(conservation of momentum)

J. N. Bahcall, *Neutrino Astrophysics*, Cambridge University Press, Cambridge (1989)

Solar Neutrino Spectrum on Earth



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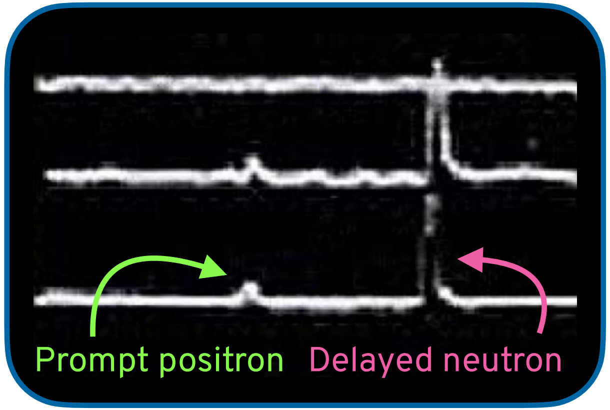
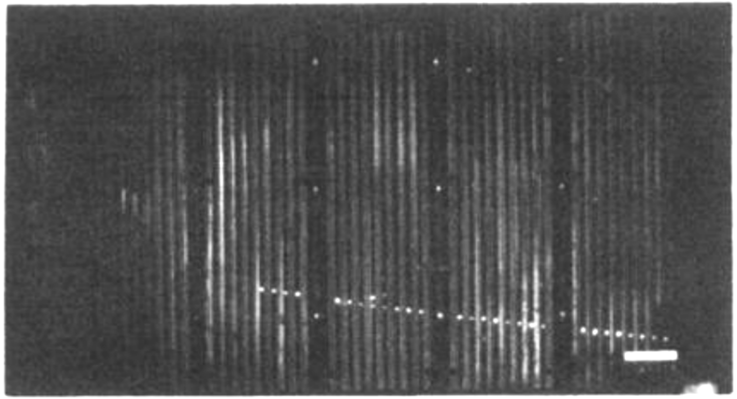
Detecting Solar Neutrinos

Last time, we discussed two types of detectors:



Reines & Cowan – Double Coincidence



Lederman et al. – Spark Chamber

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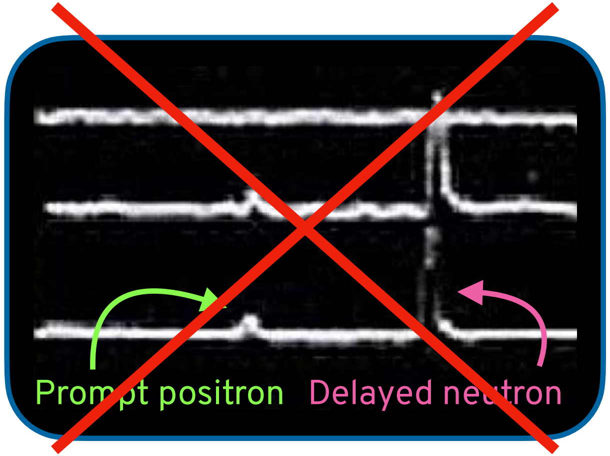
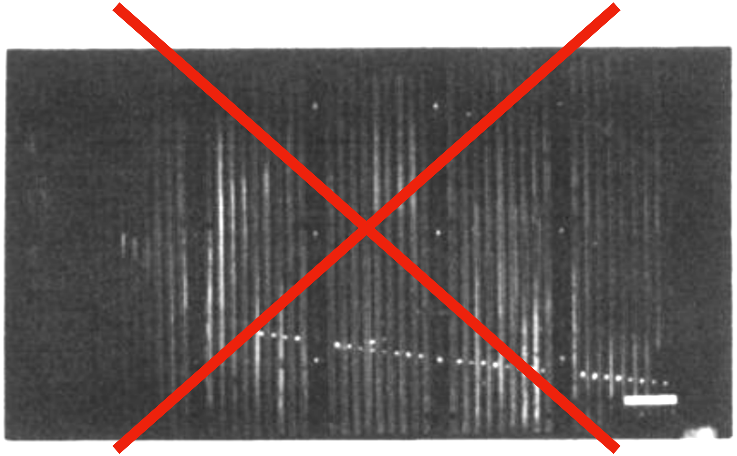


Reines & Cowan – Double Coincidence

Inverse beta decay requires anti-neutrinos



Lederman et al. – Spark Chamber

Electrons from solar neutrinos are too low-energy

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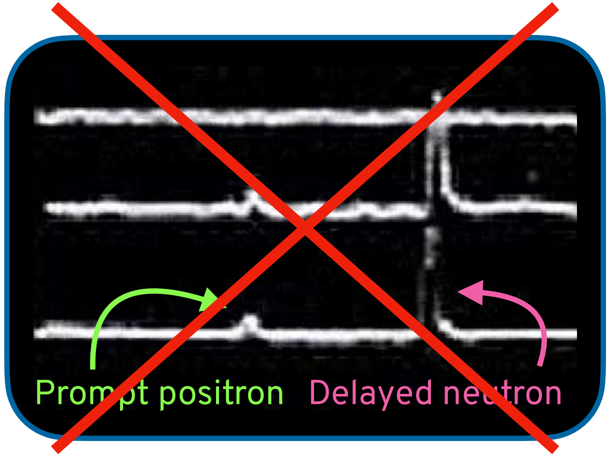

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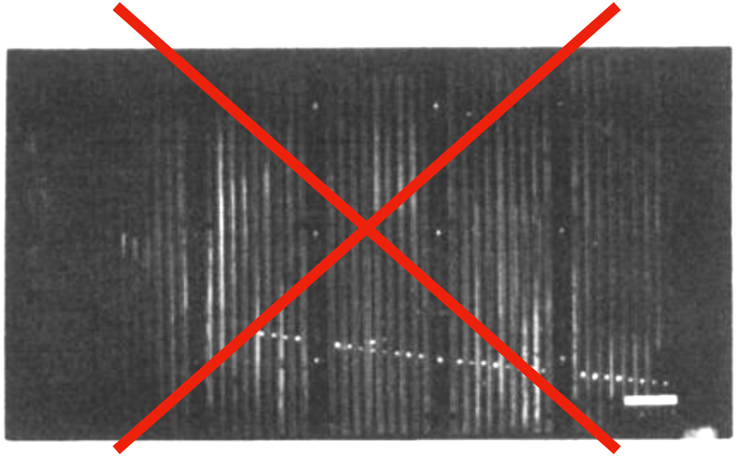
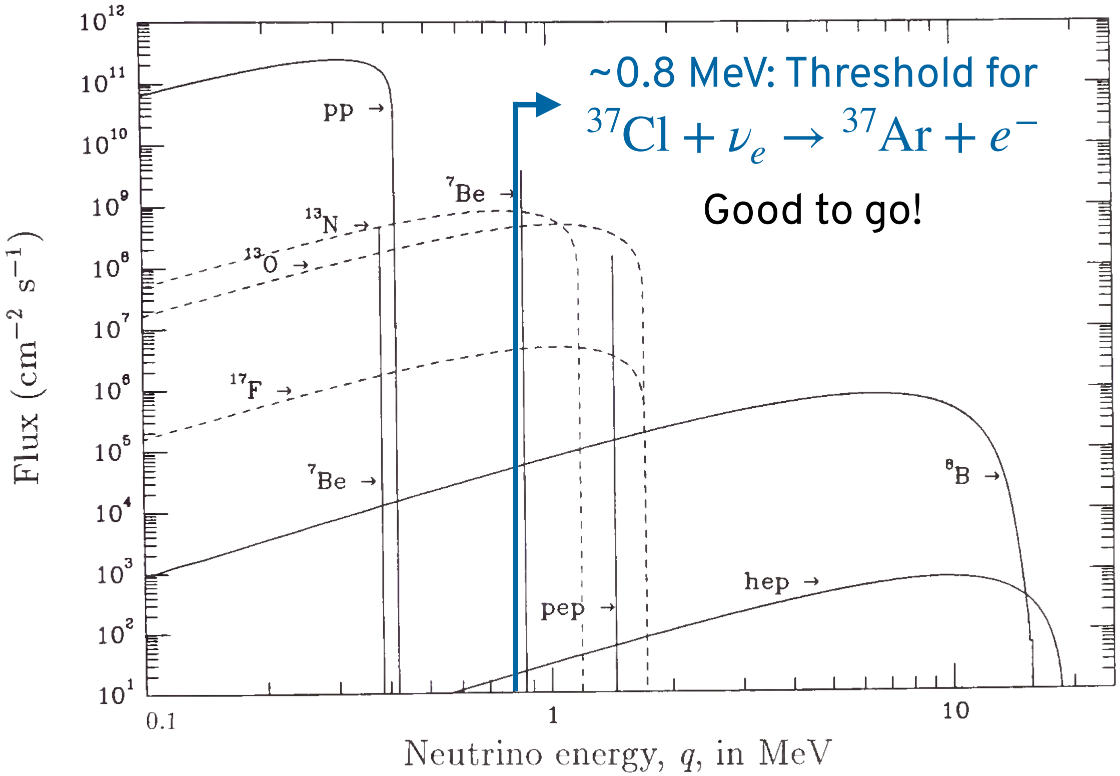


Lederman et al. – Spark Chamber

Electrons from solar neutrinos are too low-energy

Davis to the rescue!

What are their Energies?



J. N. Bahcall, *Neutrino Astrophysics*, Cambridge University Press, Cambridge (1989)

Davis' First Measurement Again

PHYSICAL REVIEW VOLUME 97, NUMBER 3 FEBRUARY 1, 1955

Attempt to Detect the Antineutrinos from a Nuclear Reactor by the $Cl^{37}(\bar{\nu},e^-)A^{37}$ Reaction*

RAYMOND DAVIS, JR.
Department of Chemistry, Brookhaven National Laboratory, Upton, Long Island, New York

(Received September 21, 1954)

No reactor neutrinos detected, but why didn't Davis see neutrinos from the Sun?

neutrinos is about 3×10^{-46} cm² for the reaction. The experiment with the buried 3900-liter tank sets an upper limit on the neutrino flux from the sun of 1×10^{14} neutrinos/cm² sec if the energy production of the sun is entirely through the carbon-nitrogen cycle.

Peer Review

"Any experiment such as this, which does not have the requisite sensitivity, really has no bearing on the question of the existence of neutrinos."

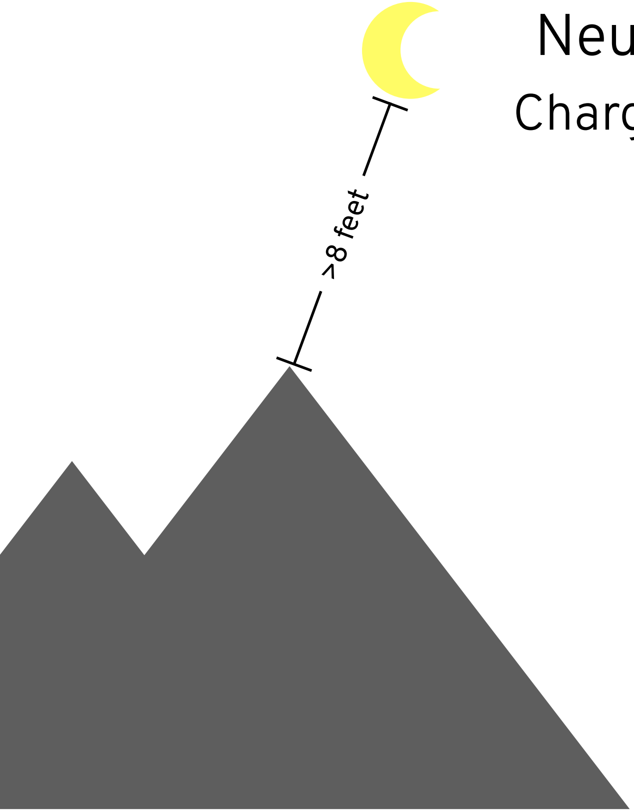
Peer Review

"Any experiment such as this, which does not have the requisite sensitivity, really has no bearing on the question of the existence of neutrinos."

"…To illustrate my point, one would not write a scientific paper describing an experiment in which an experimenter stood on a mountain and reached for the moon, and concluded that the moon was more than eight feet from the top of the mountain."

—Reviewer on Davis' first paper

The Problem



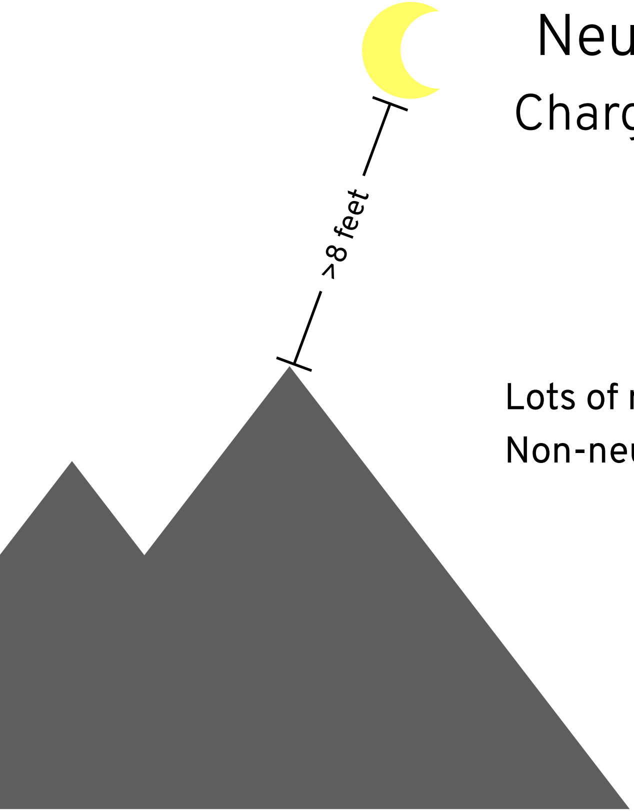
Neutrinos aren't the only way to produce argon-37

Charged particles produced in the atmosphere can also do it

The Problem

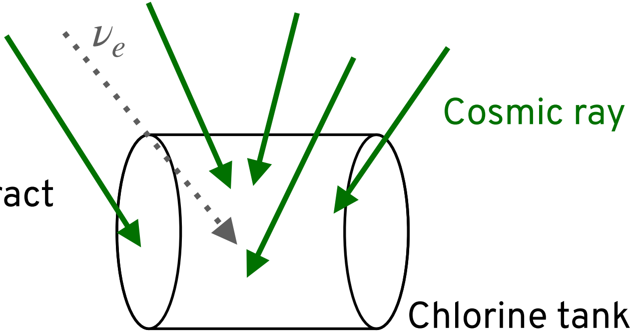
Neutrinos aren't the only way to produce argon-37

Charged particles produced in the atmosphere can also do it

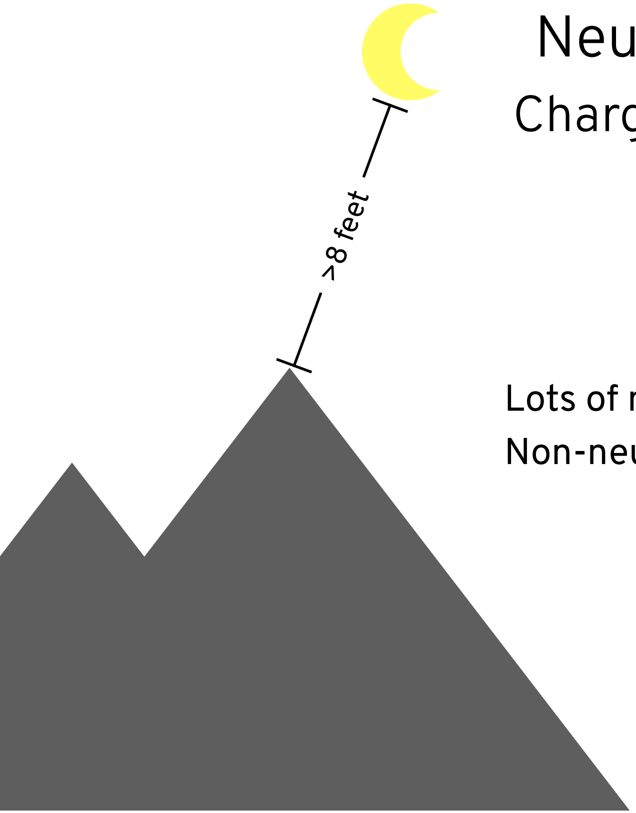


Lots of neutrinos, but most don't interact

Non-neutrino "backgrounds" present



The Problem



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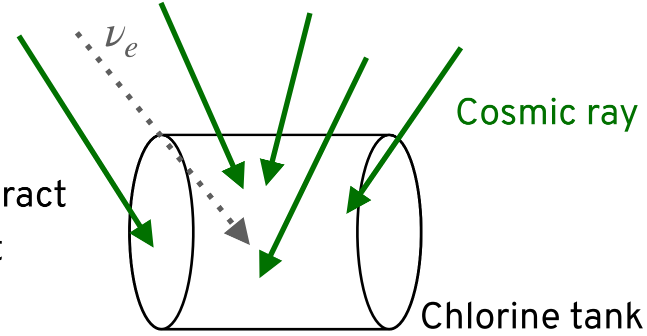
Lots of neutrinos, but most don't interact

Non-neutrino "backgrounds" present



Davis' experiment was looking for a couple extra argon-37 atoms on top of hundreds!

Going Deep

R. Davis. *Physical Review Letters* **12**, 303 (1964)

VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

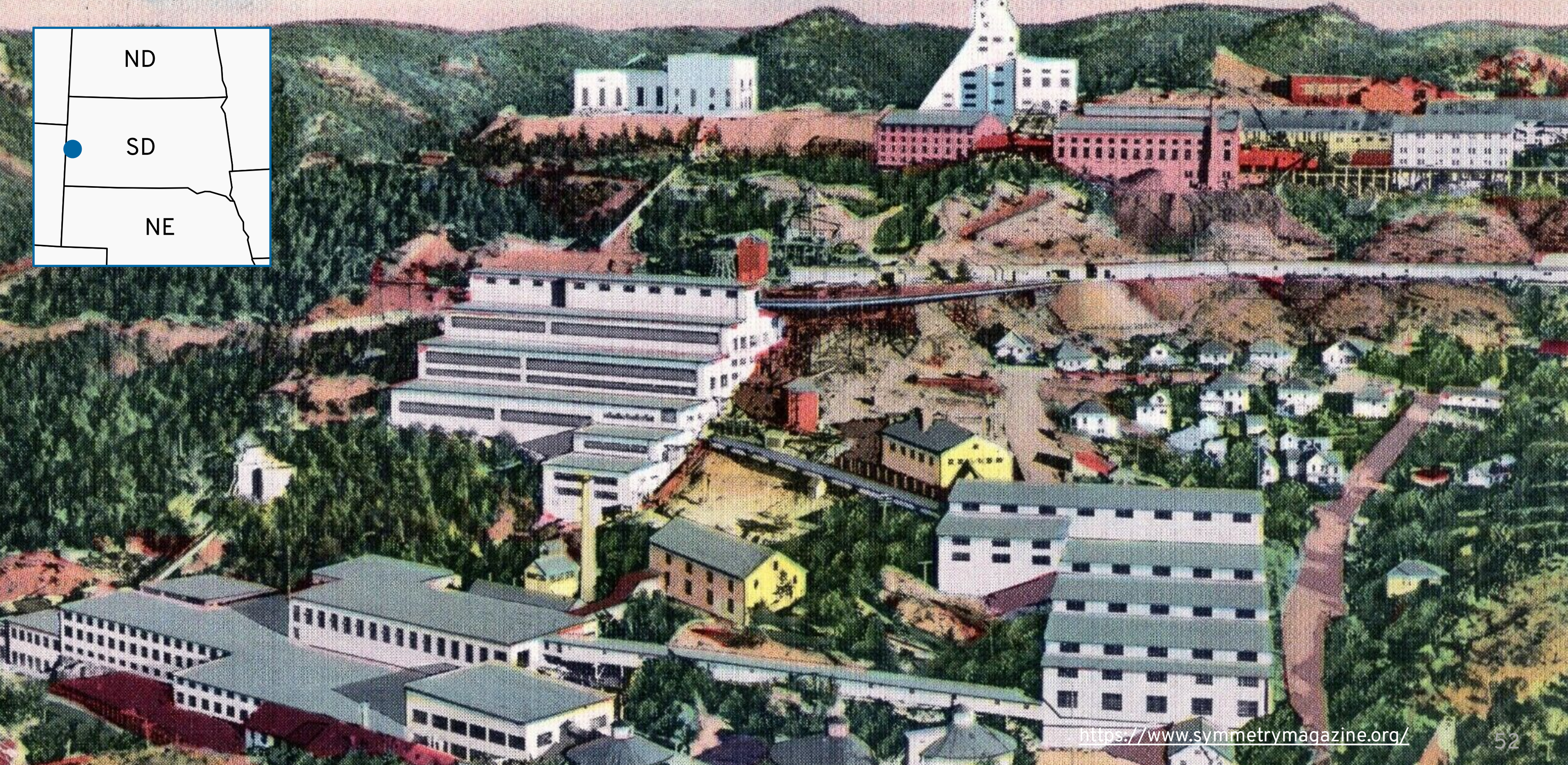
Table I. ^{37}Ar production rates in C_2Cl_4 by cosmic-ray muons underground.

Depth below surface (m.w.e.)	Muon intensity (cm^{-2} sec^{-1} sr^{-1})	Muon star production cross section (cm^2/nucleon)	^{37}Ar production rate per day for 10^5 gallons C_2Cl_4
25	2×10^{-3}	3×10^{-30}	6500 (measured)
1800	2×10^{-7}	17×10^{-30}	3.5
4000	6×10^{-9}	22×10^{-30}	0.14

~40,000 times fewer background counts

The Homestake Experiment

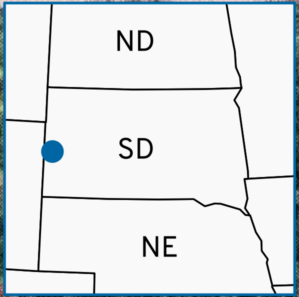
Lead, South Dakota

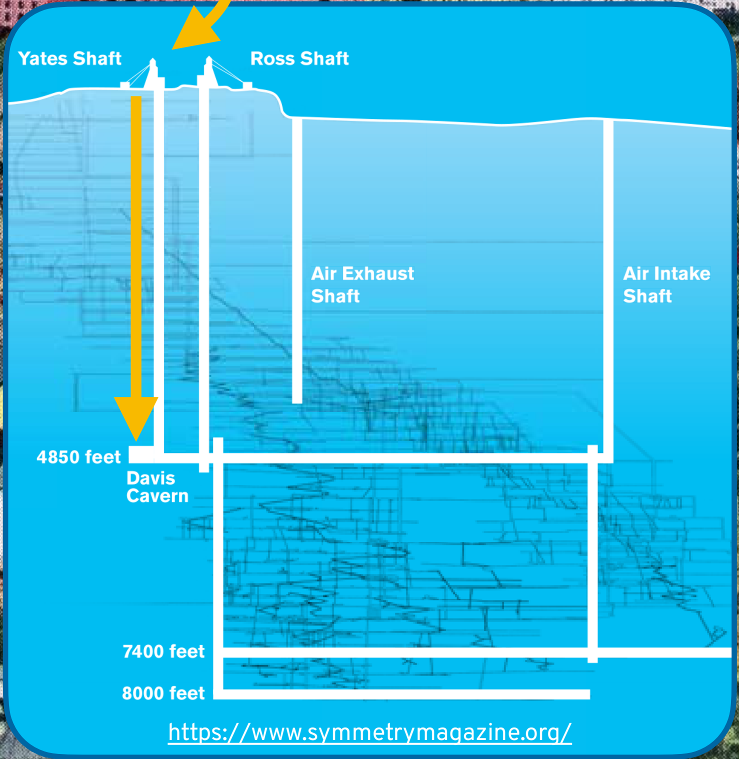


https://www.symmetrymagazine.org/

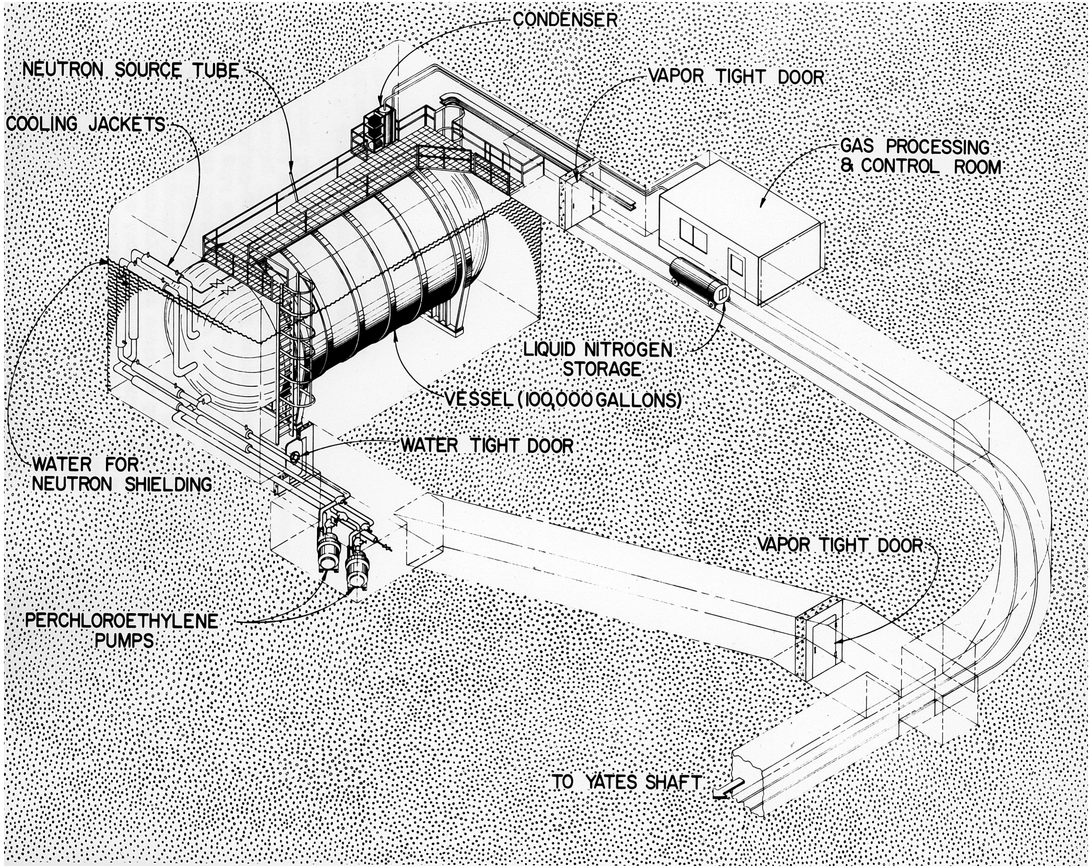
The Homestake Experiment

Lead, South Dakota





The Detector



What Davis Saw Underground

R. J. Davis, *Proceedings of the 11th International Conference on Cosmic Rays*, **29** (1970).

Conclusions

The cosmic ray muon background must be subtracted from the ^{37}Ar production rate limit of 0.18 ± 0.10 given above. The resulting rate that could be attributed to solar neutrinos is then 0.06 ± 0.11 ^{37}Ar atoms per day. We then conclude that the solar neutrino production rate is less than 0.2 ^{37}Ar atoms/day. The corresponding flux-cross section product limit is

Nothing!

Net ^{37}Ar rate: Consistent with 0

What Davis Saw Underground

R. J. Davis, *Proceedings of the 11th International Conference on Cosmic Rays*, **29** (1970).

Conclusions

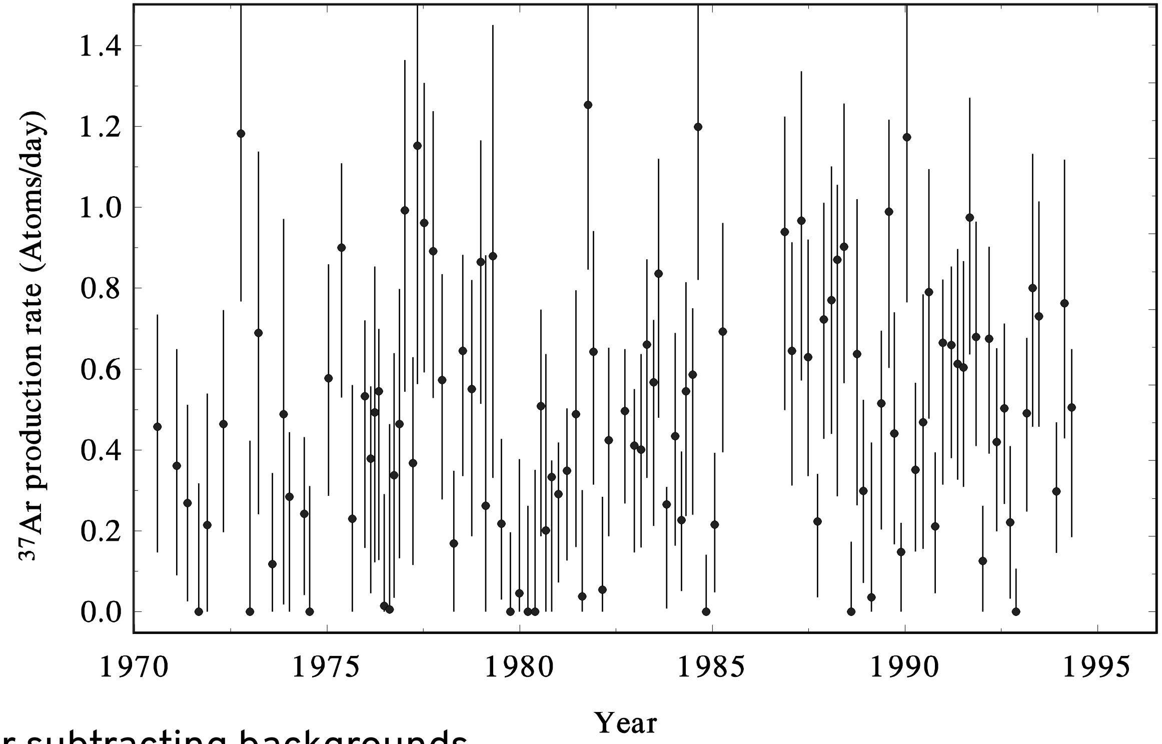
The cosmic ray muon background must be subtracted from the ^{37}Ar production rate limit of 0.18 $\pm$ 0.10 given above. The resulting rate that could be attributed to solar neutrinos is then 0.06 $\pm$ 0.11 ^{37}Ar atoms per day. We then conclude that the solar neutrino production rate is less than 0.2 ^{37}Ar atoms/day. The corresponding flux-cross section product limit is

Nothing!

(at first)

Decades of Data from Homestake

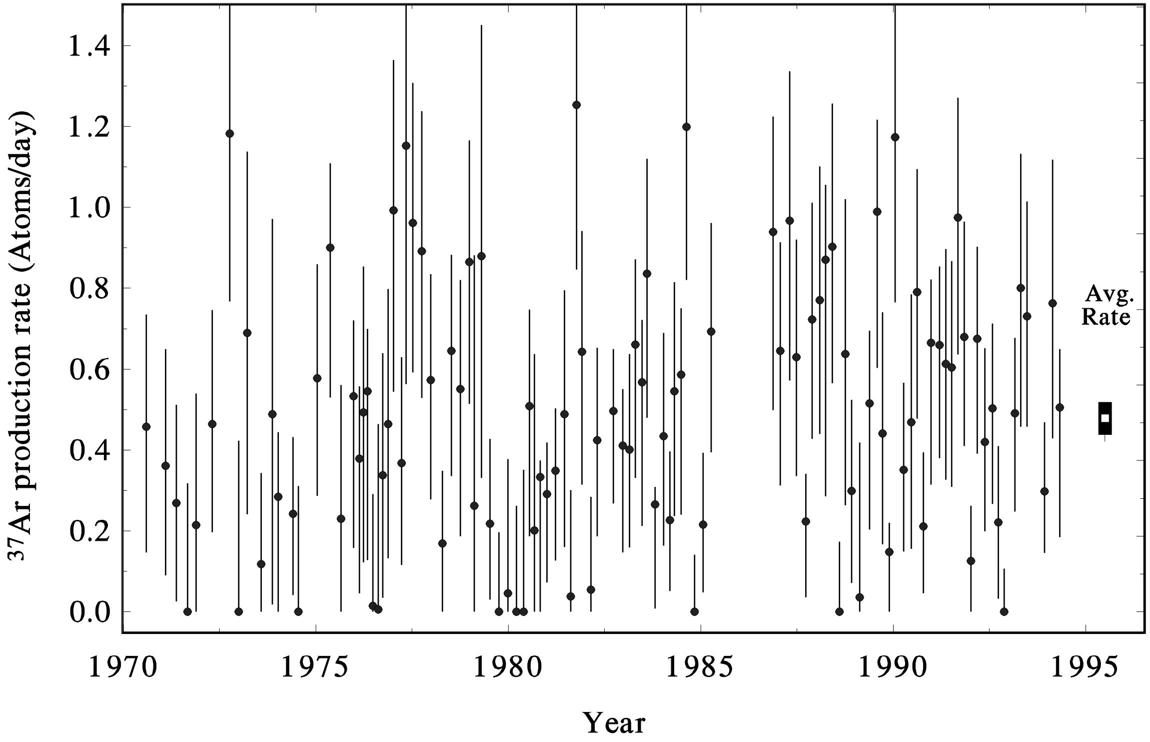
Bruce T. Cleveland *et al. Astrophysical Journal* **496** 505 (1998)



After subtracting backgrounds

Decades of Data from Homestake

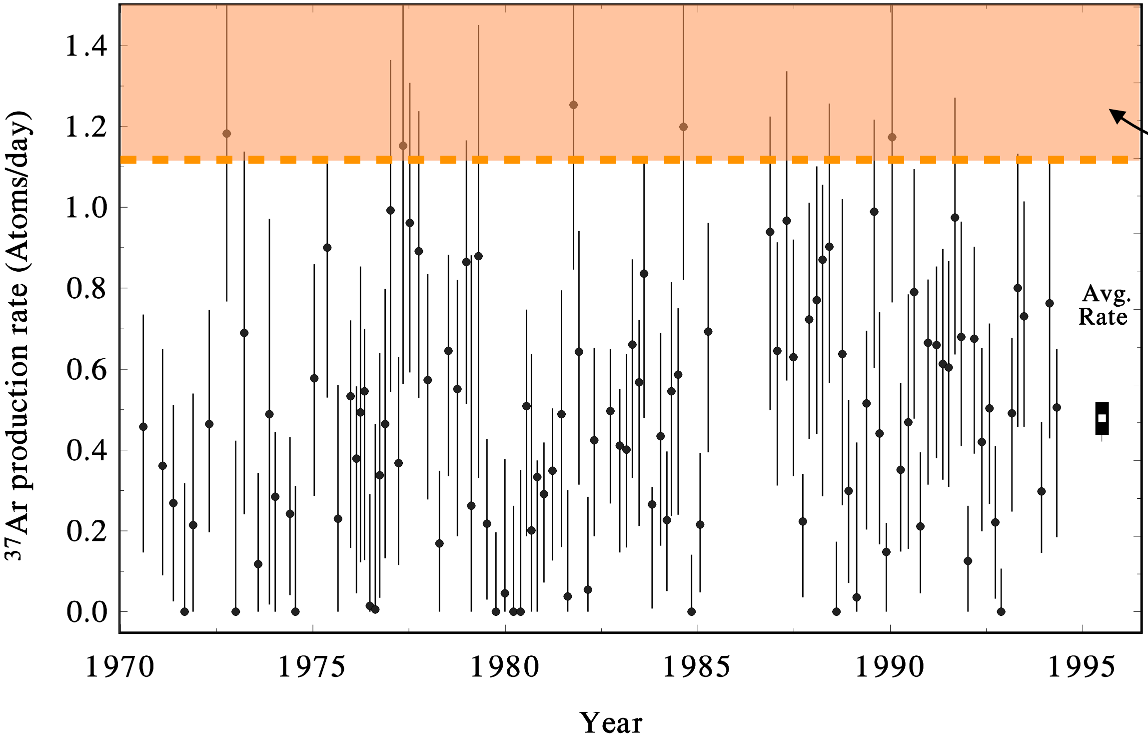
Bruce T. Cleveland *et al.* *Astrophysical Journal* **496** 505 (1998)



A very precise,
nonzero measurement

Decades of Data from Homestake

Bruce T. Cleveland *et al. Astrophysical Journal* **496** 505 (1998)



Range of predictions from Bachall & others ~3× higher!

The "Solar Neutrino Problem"

Bachall's theory & Davis' experiment called into question!

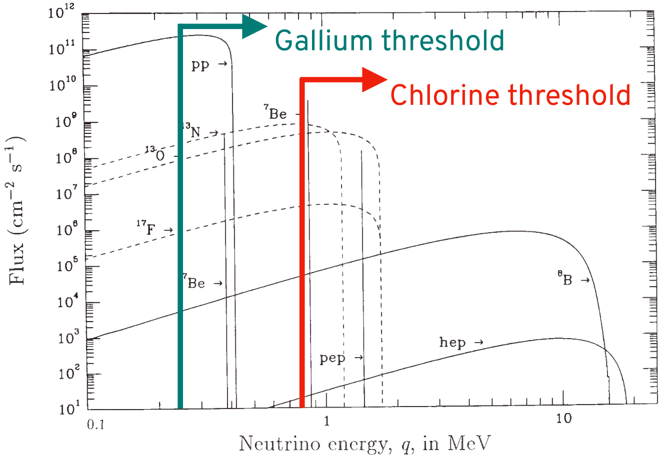
What's the deal with the missing neutrinos?

The “Solar Neutrino Problem”

Bachall’s theory & Davis’ experiment called into question!

What’s the deal with the missing neutrinos?

Missing *pp* neutrinos confirmed by other chemical experiments (c. 1990s):



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

Meanwhile: Searching for the Theory of Everything

$$p \rightarrow e^{+} + \pi^{0}$$

Does this ever happen?

If observed, evidence for a new type of interaction that unifies quarks & leptons

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$$p \to e^+ + \pi^0$$

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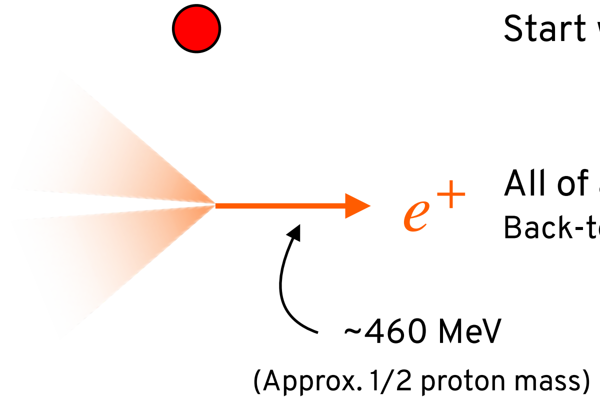

Start with a proton at rest

All of a sudden: Positron + photons appear

Back-to-back due to conservation of momentum

Proton Decay Detector

Need a *lot* of protons

Reines & Cowan: 100 liters of water ~ 10^{27} protons.

Can we do better?

The IMB Experiment

(Irvine–Michigan–Brookhaven)

Ohio, USA

2.5 million gallons of water

~10^{31} protons

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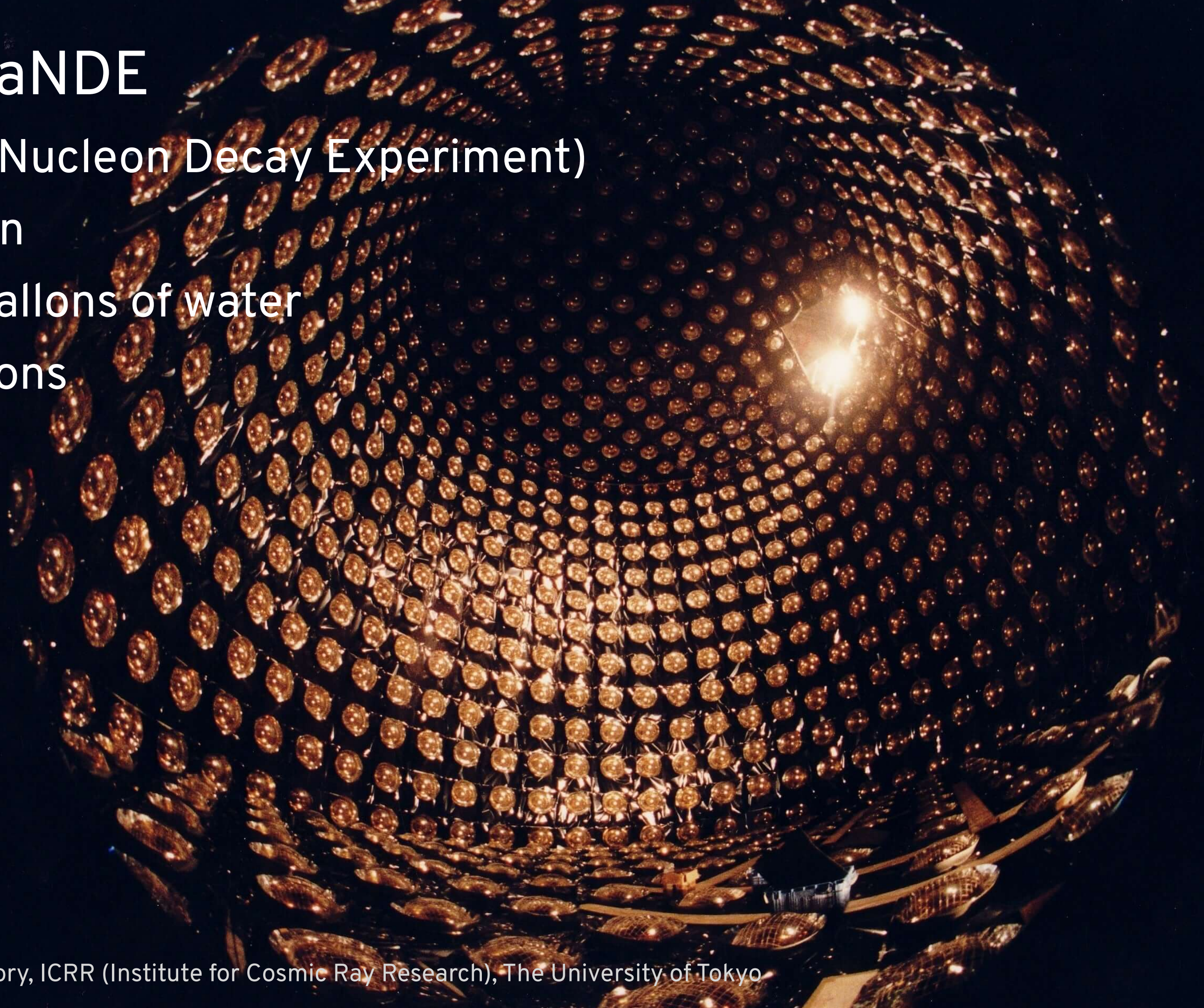
KamiokaNDE

(Kamioka Nucleon Decay Experiment)

Gifu, Japan

1 million gallons of water

~10^{31} protons



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(Kamioka Nucleon Decay Experiment)

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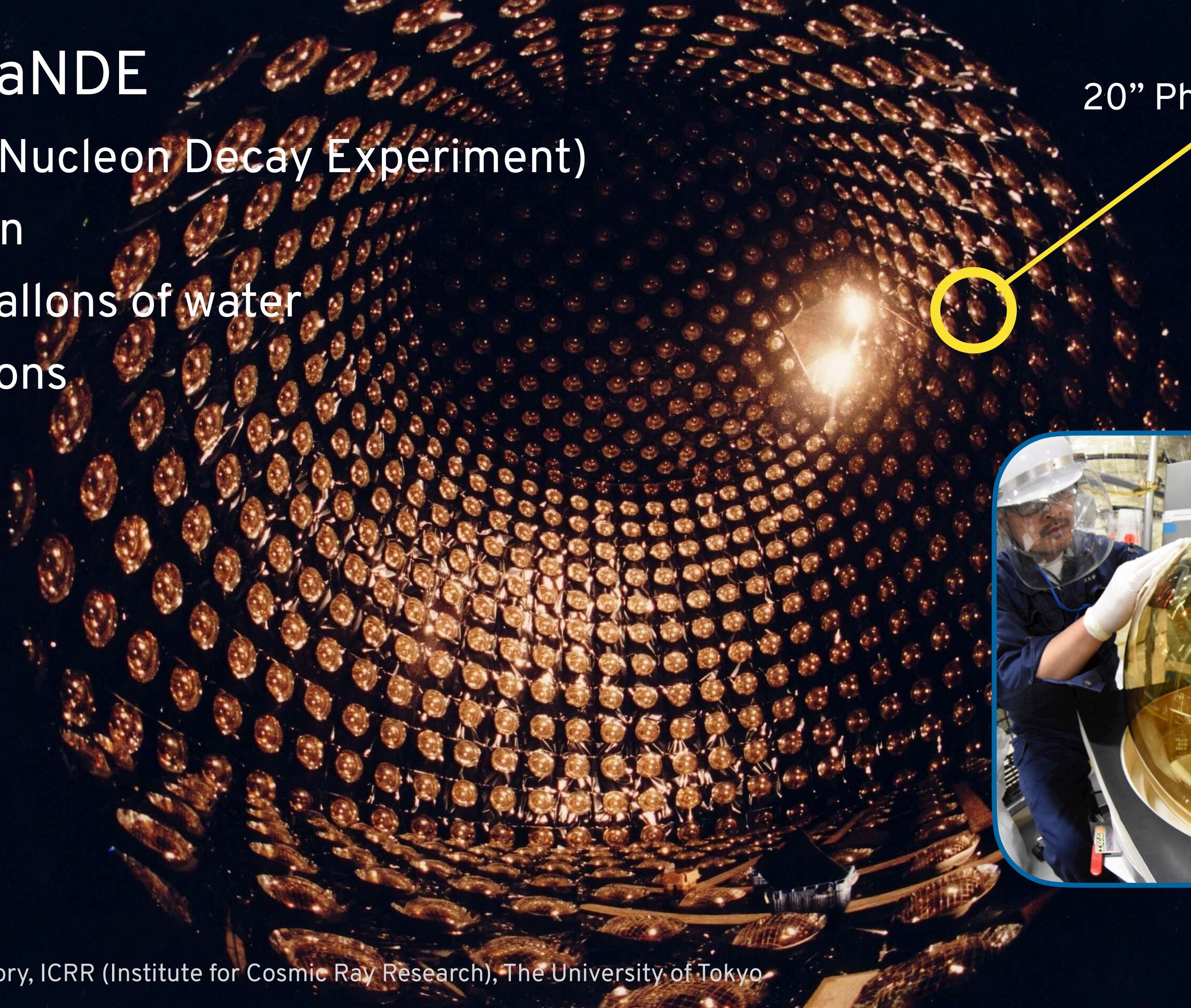
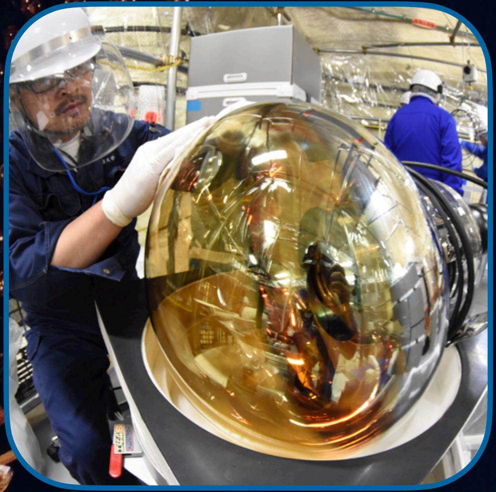


20” Photomultiplier tube (×1000)



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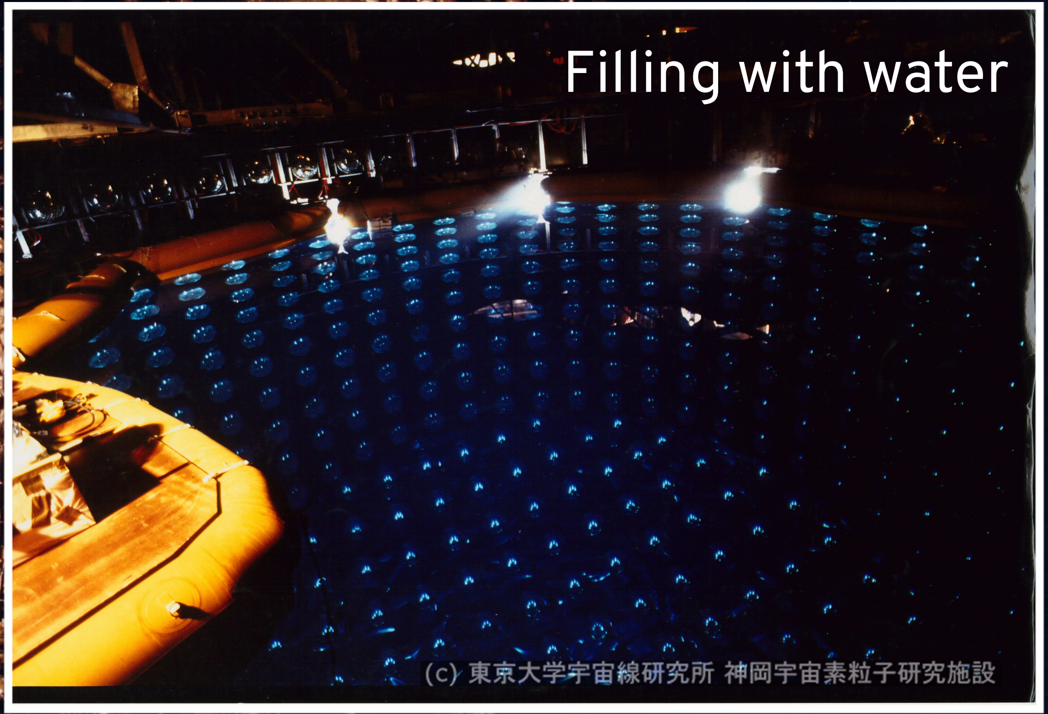
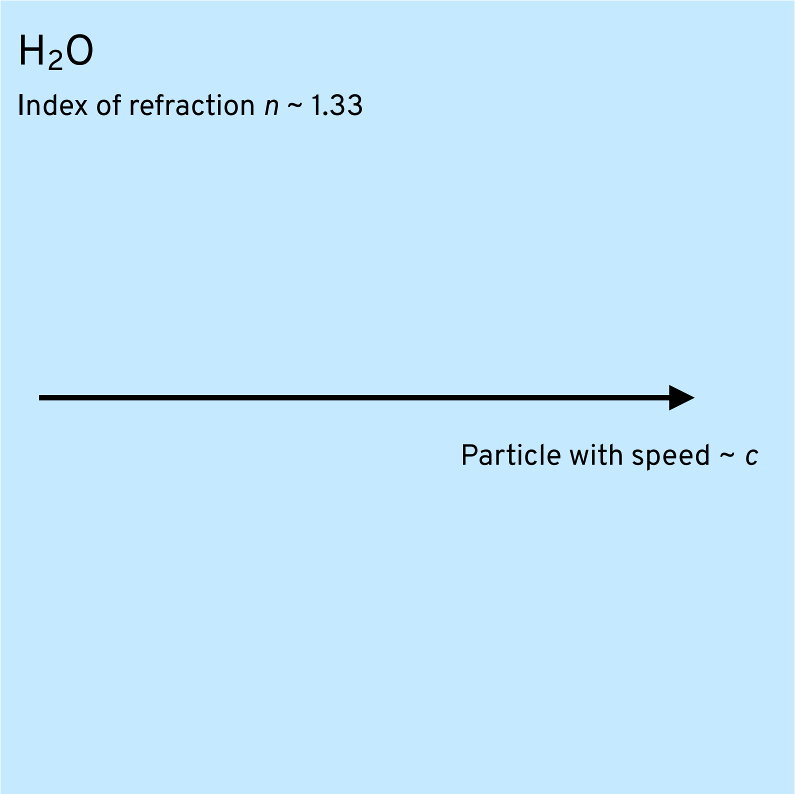


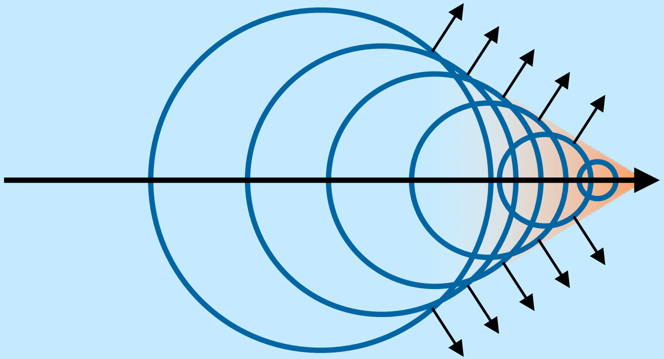
How it Works: Cherenkov Radiation



How it Works: Cherenkov Radiation

Radiation emitted along overlapping wave fronts

Lags behind the particle: $v = c/n$



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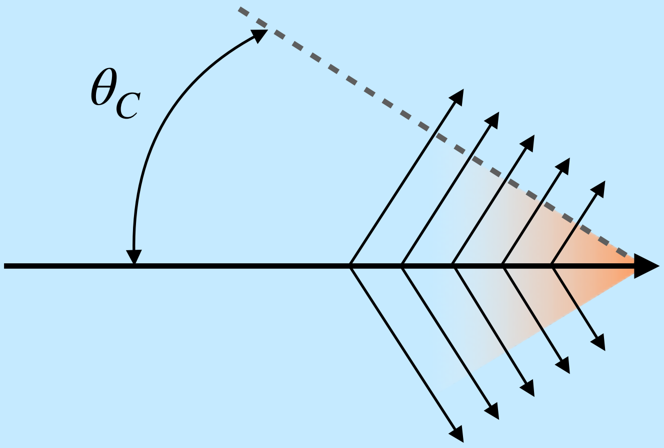
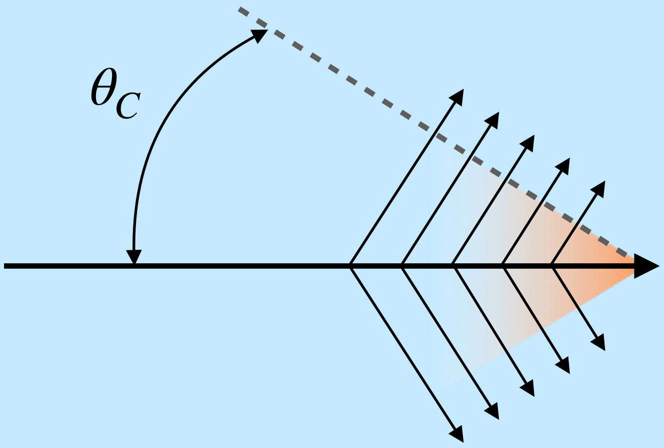


$$\theta_C = \cos^{-1}(1/n)$$

n ~1.33 in water → θ ~ 42°

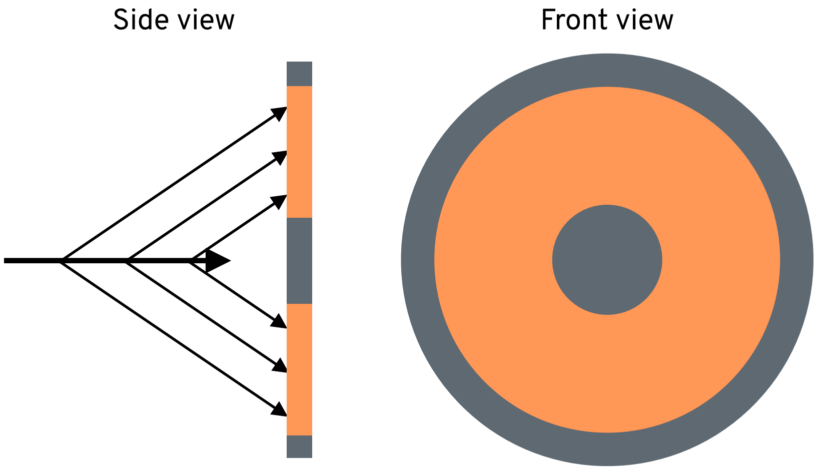
How it Works: Cherenkov Radiation



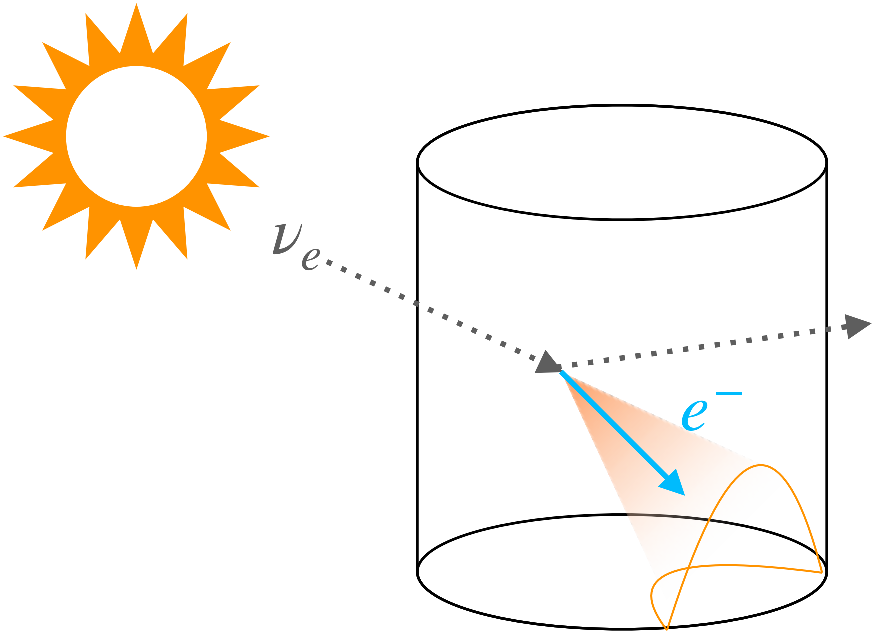
$$\theta_C = \cos^{-1}(1/n)$$

n ~1.33 in water → θ ~ 42°

Cherenkov radiation projected onto a wall makes rings



Proton Decay Detector → Solar Neutrino Detector

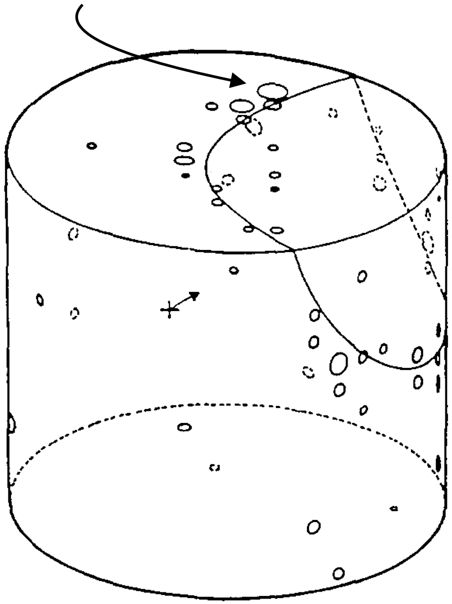


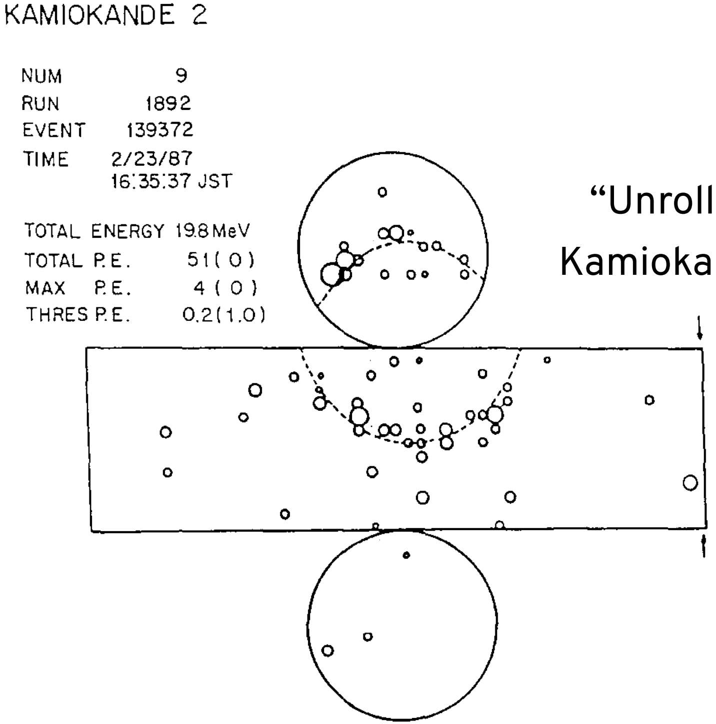
It was realized boron-8 neutrinos had enough energy could produce electrons above the Cherenkov threshold.

Kamiokande upgraded: Water purification system & cosmic ray detection system to help reject backgrounds

A few-MeV Electron in Kamiokande

Size of the circles:
Amount of light seen by each PMT



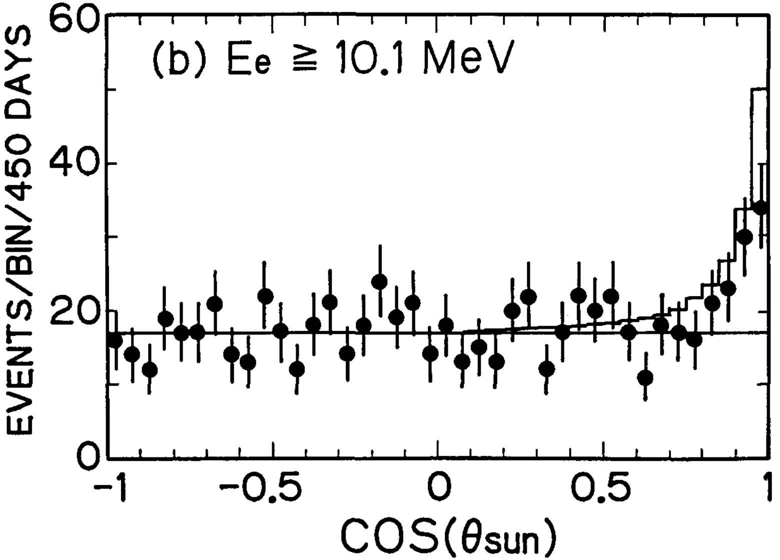


“Unrolled” view of
Kamiokande detector

M. Koshiba, *Observational neutrino astrophysics*, Physics Reports. **220** 229–381 (1992)

A "Real-Time" Measurement

Number of counts vs. relative direction
to the Sun at the time of observation



K. S. Hirata *et al.*, *International Astronomical Union Colloquium*, **121** 179–186 (1990)

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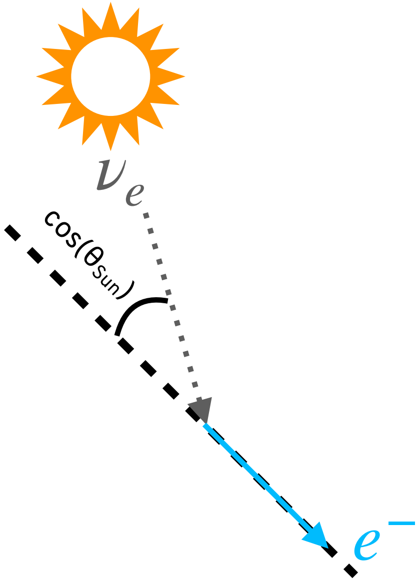

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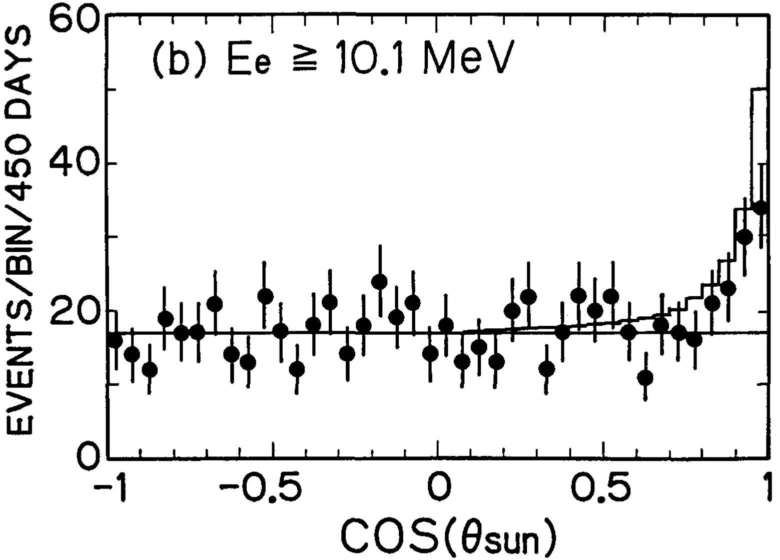
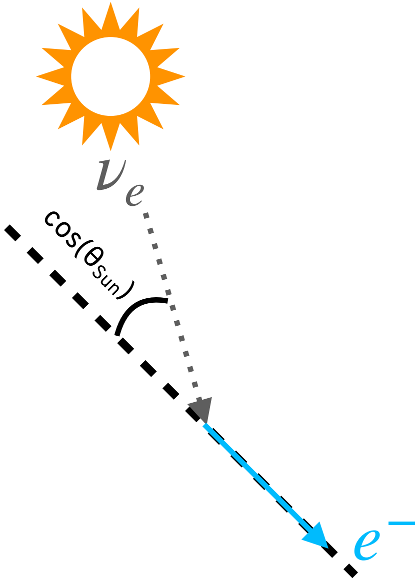


Record the angle of each electron to the Sun’s current position

K. S. Hirata *et al.*, *International Astronomical Union Colloquium*, **121** 179–186 (1990)

A "Real-Time" Measurement



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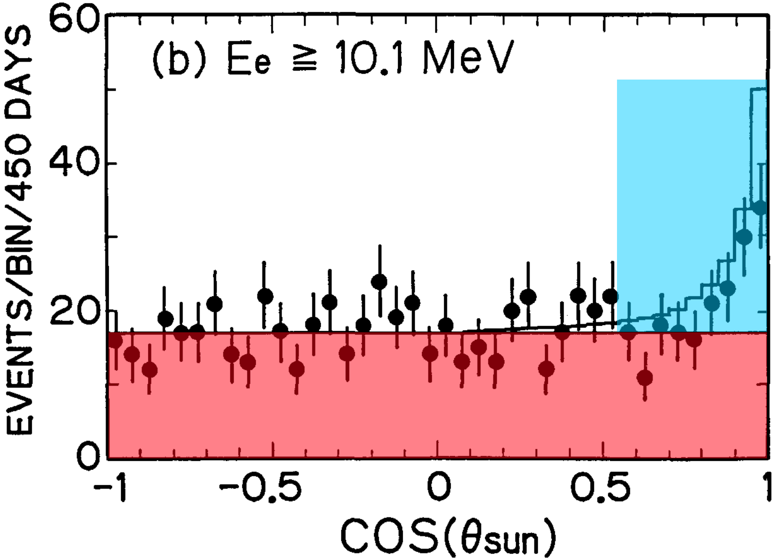


Excess counts near $\cos(\theta_{Sun})=1$

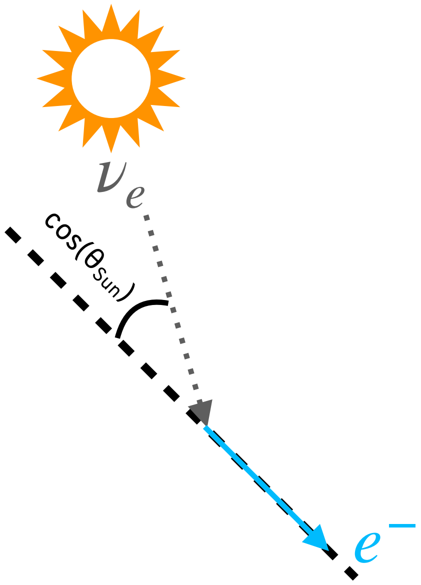
From solar neutrinos, which mostly point back to the Sun

Counts from non-solar neutrino backgrounds

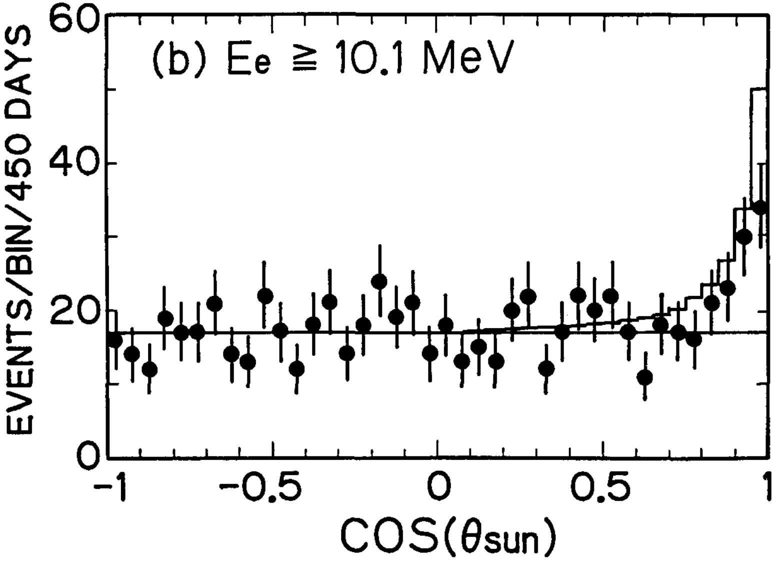
Uncorrelated with the Sun's direction (e.g., radioactivity)

K. S. Hirata *et al.*, *International Astronomical Union Colloquium*, **121** 179–186 (1990)

A “Real-Time” Measurement



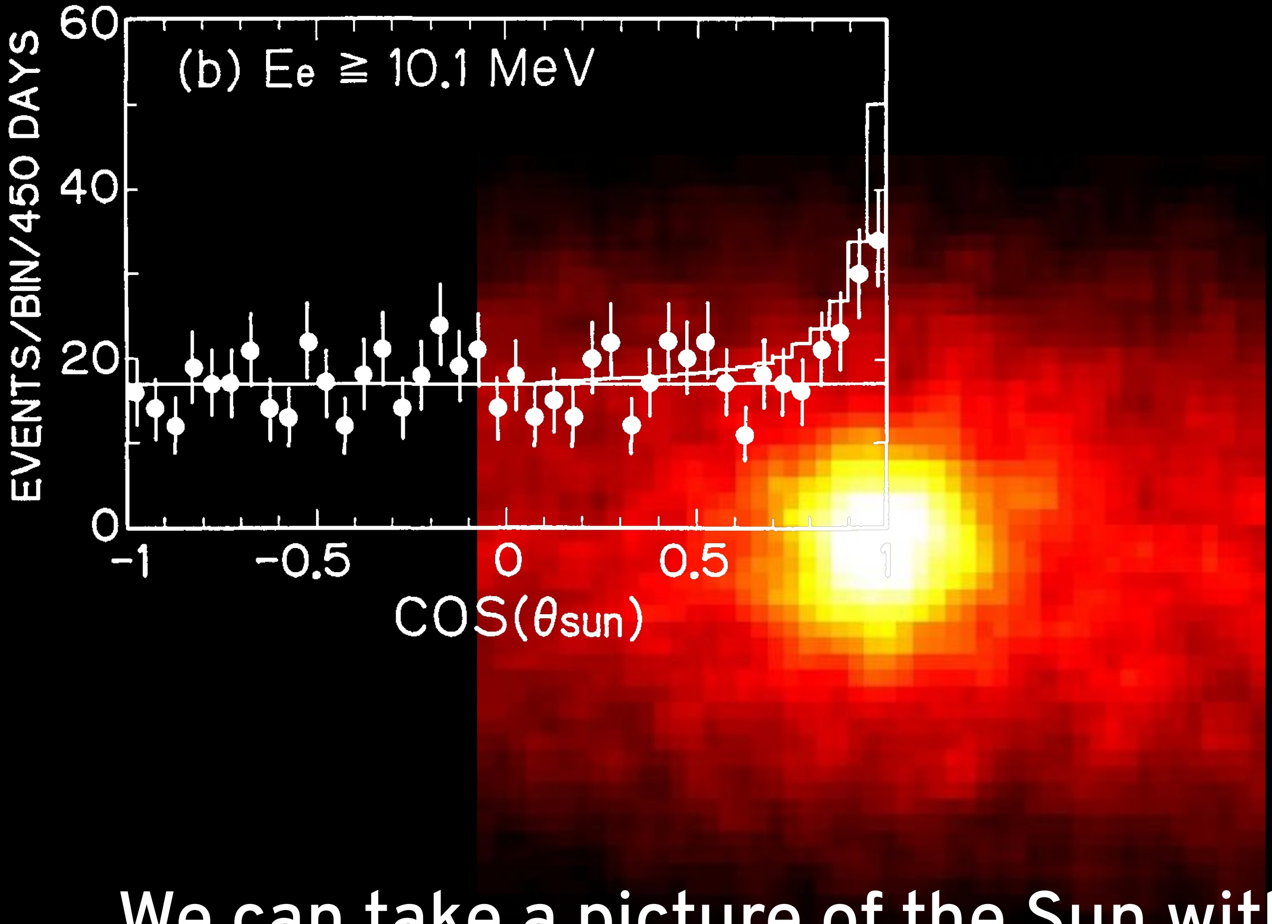
Number of counts vs. relative direction to the Sun at the time of observation



Still missing neutrinos compared to prediction!

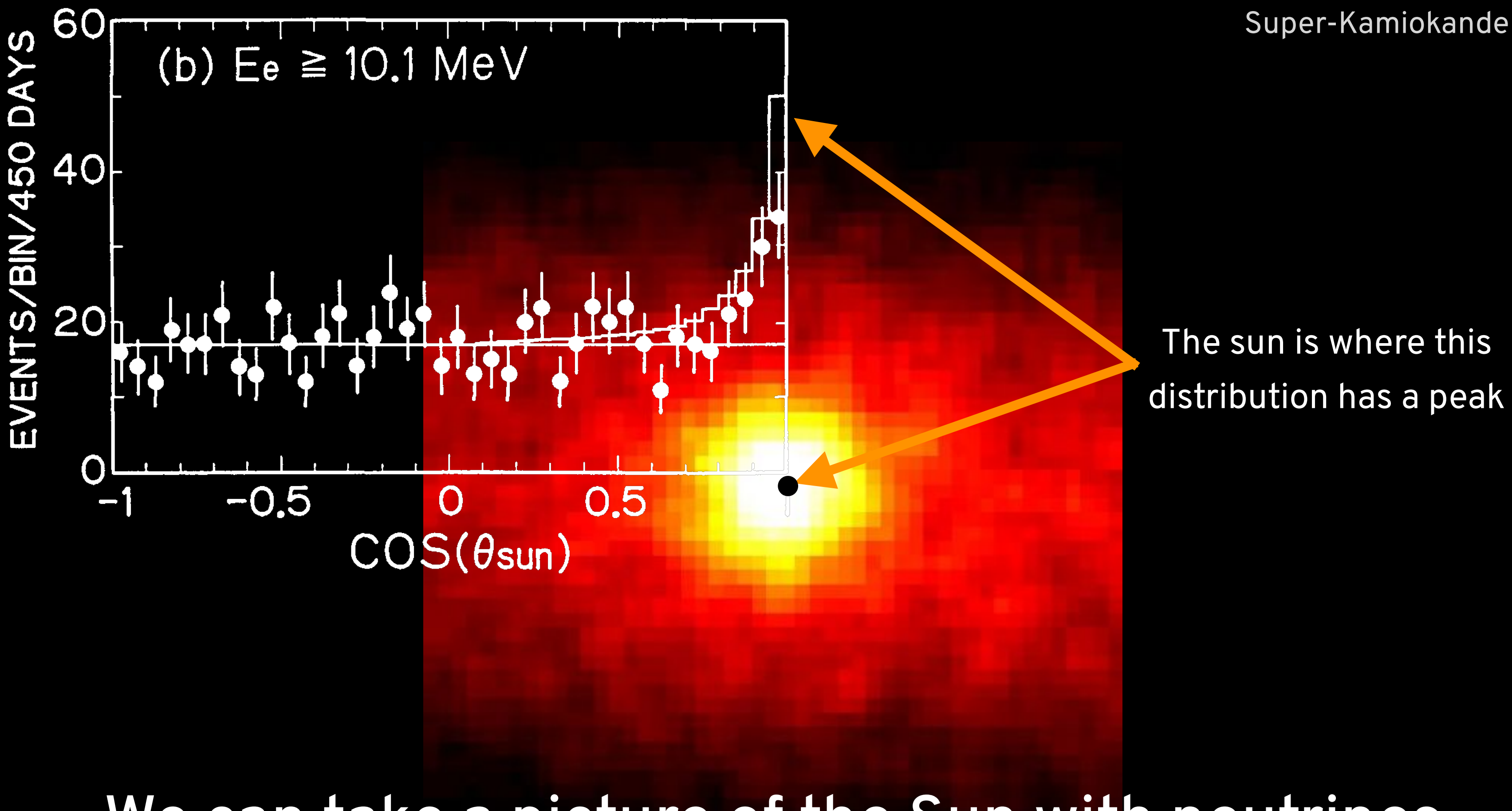
K. S. Hirata *et al.*, *International Astronomical Union Colloquium*, **121** 179–186 (1990)

Super-Kamiokande (1998)



We can take a picture of the Sun with neutrinos

Each pixel is the intensity of electrons vs. angle to the Sun



Super-Kamiokande (1998)

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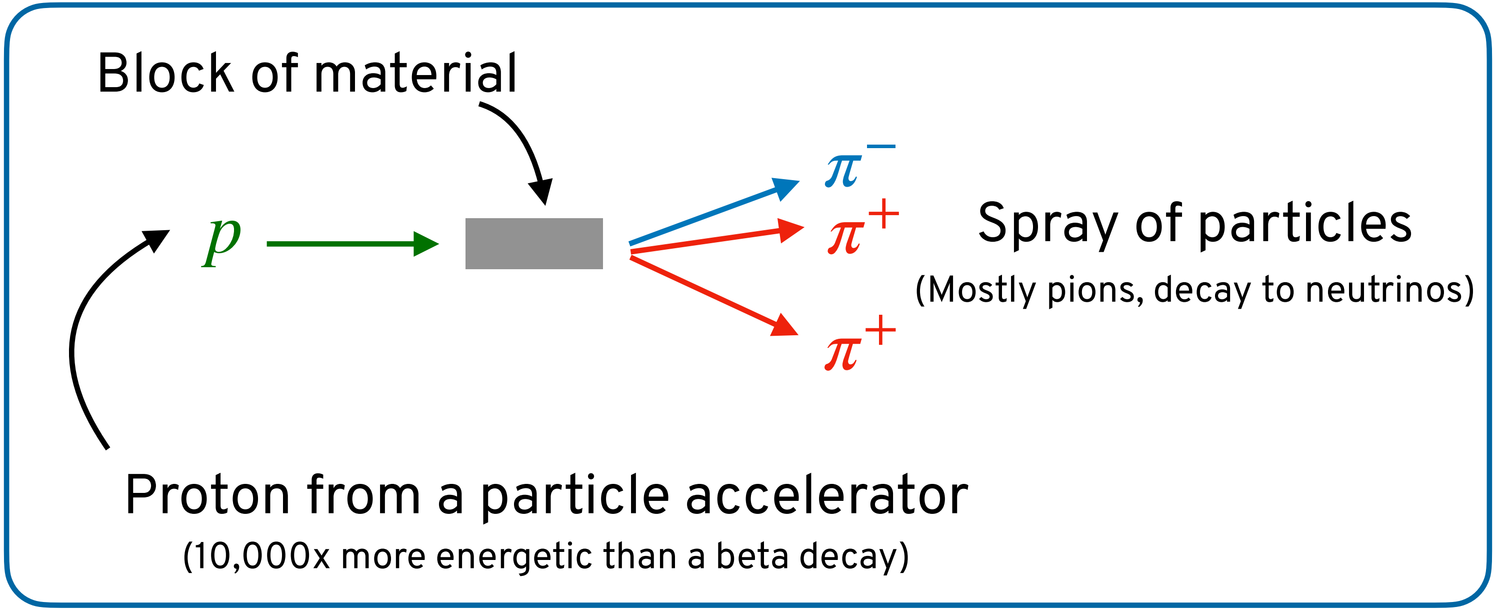
We can't explain the Sun, what about the Sky?

Cosmic rays produce neutrinos, just like the neutrino beam used by Lederman et al.



From Lecture I

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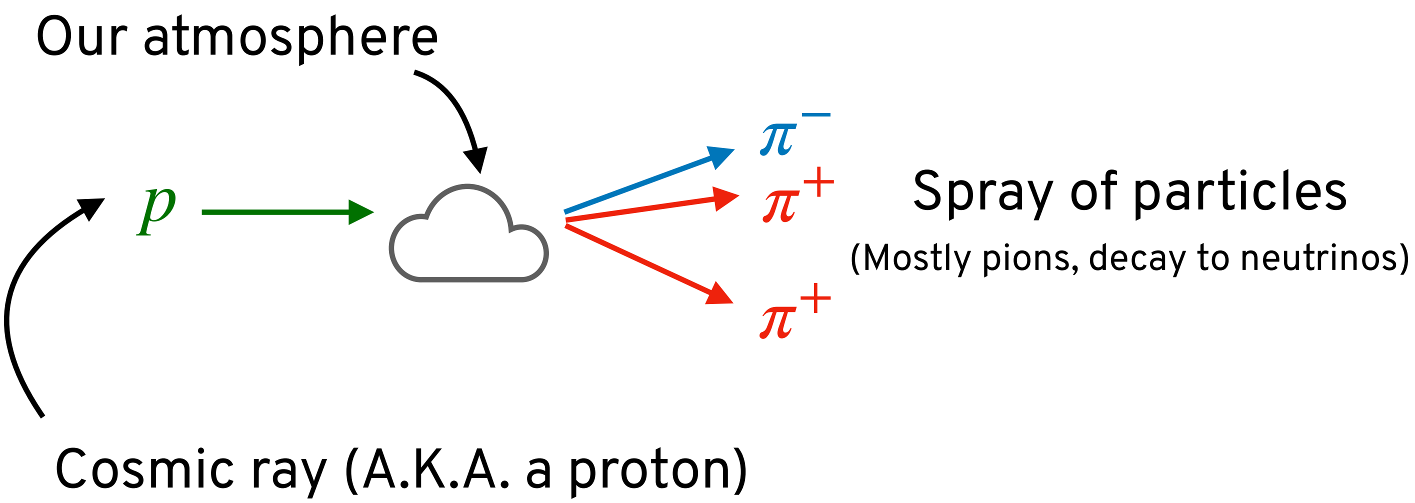
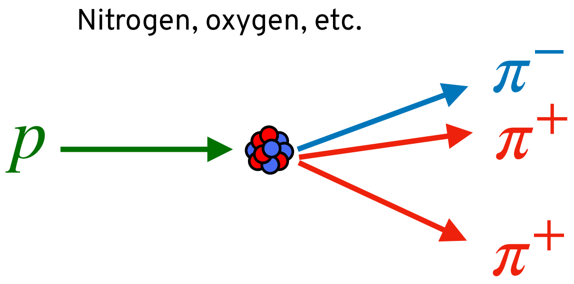


Atmospheric Neutrinos



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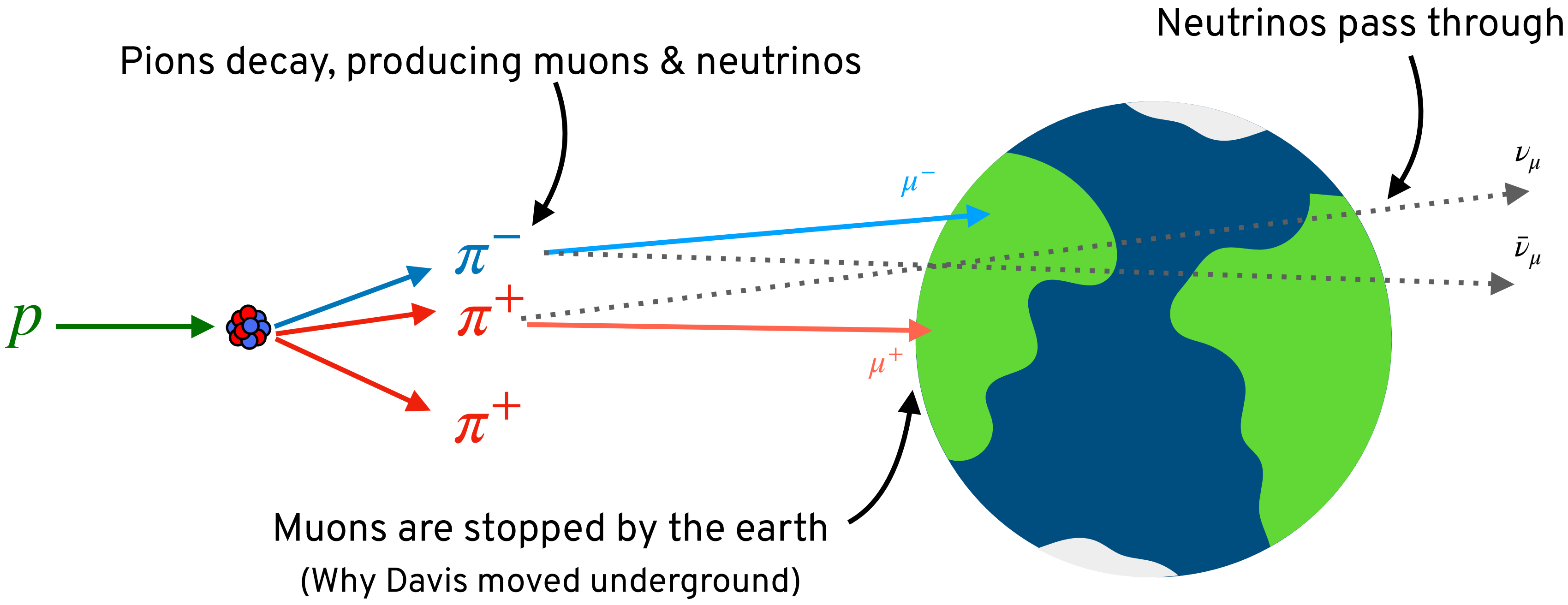

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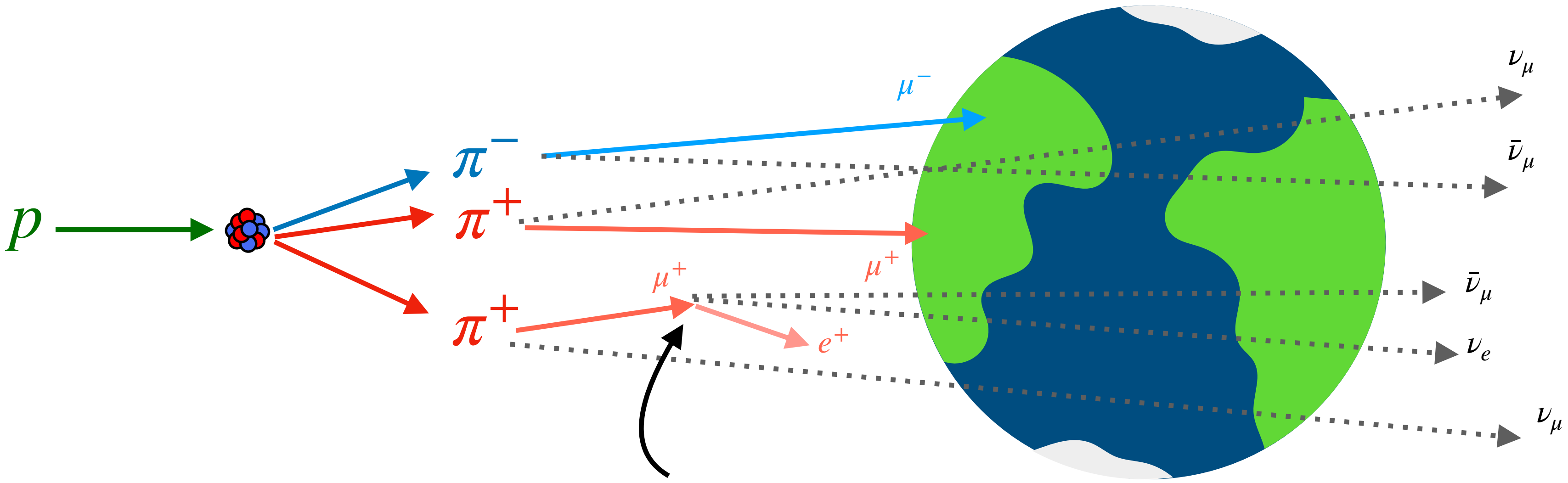
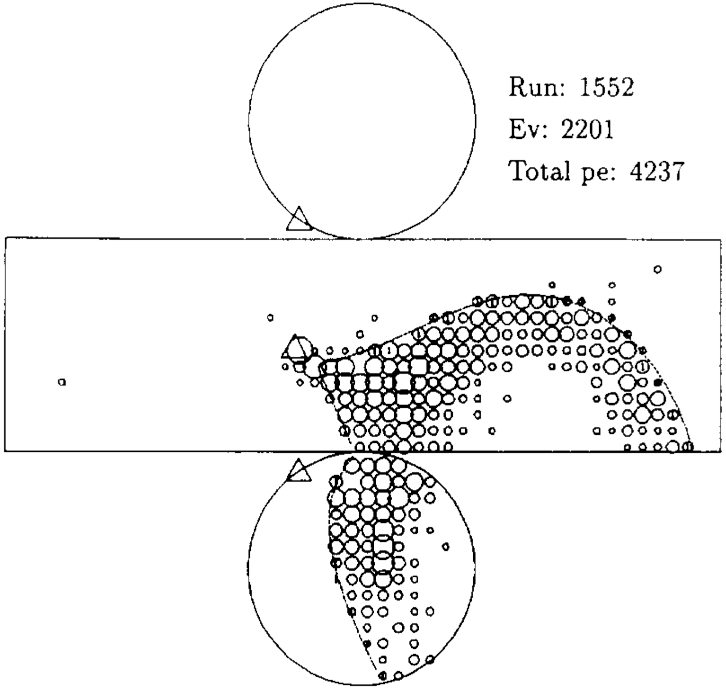
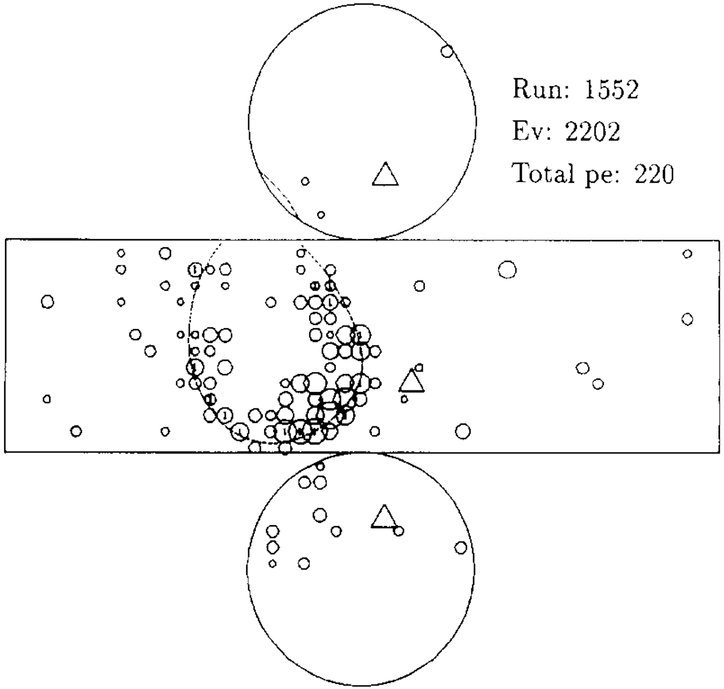


Muons can also decay: Produce ν_e and ν_μ flavors

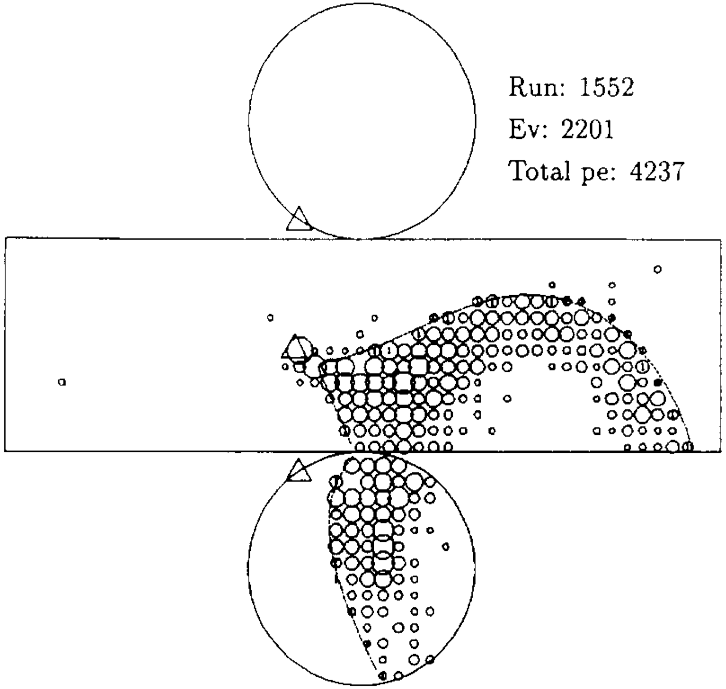
Atmospheric Neutrinos in Cherenkov Detectors





M. Koshiba, *Observational neutrino astrophysics*, Physics Reports. **220** 229–381 (1992)

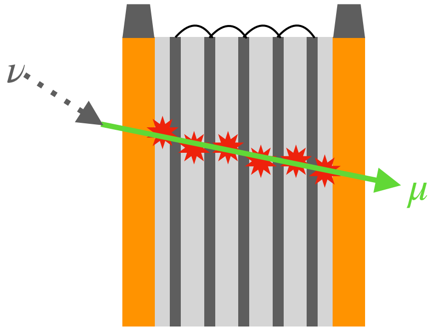
Atmospheric Neutrinos in Cherenkov Detectors



A “sharp” ring indicates a muon

Heavy & does not scatter

Same principle as Lederman et al.



Spark chamber from Lecture I

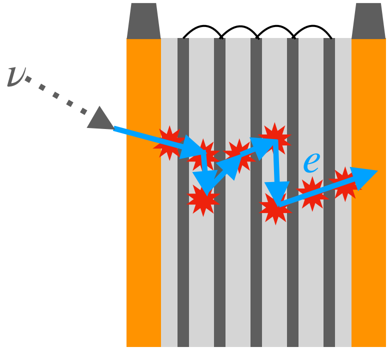
M. Koshiba, *Observational neutrino astrophysics*, Physics Reports. **220** 229–381 (1992)

Atmospheric Neutrinos in Cherenkov Detectors

A "fuzzy" ring indicates an electron

Light & scatters easily

Same principle as Lederman et al.



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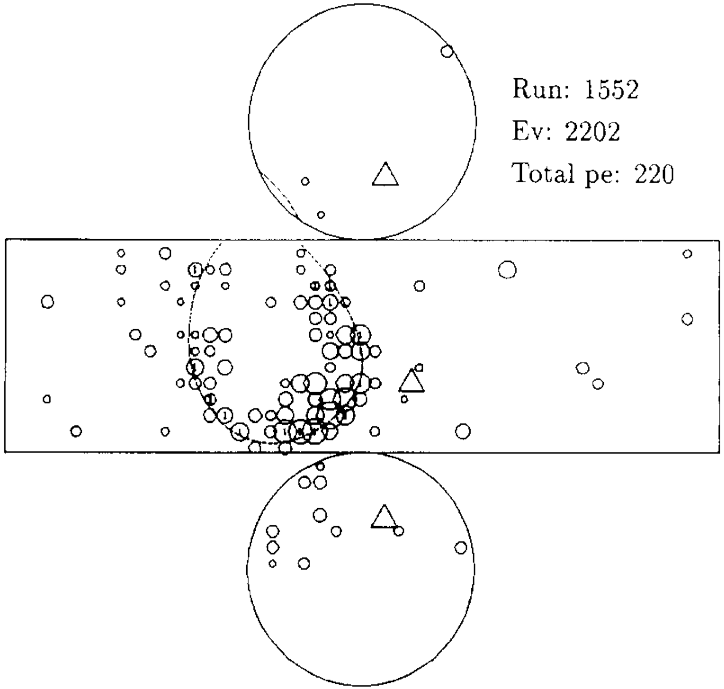

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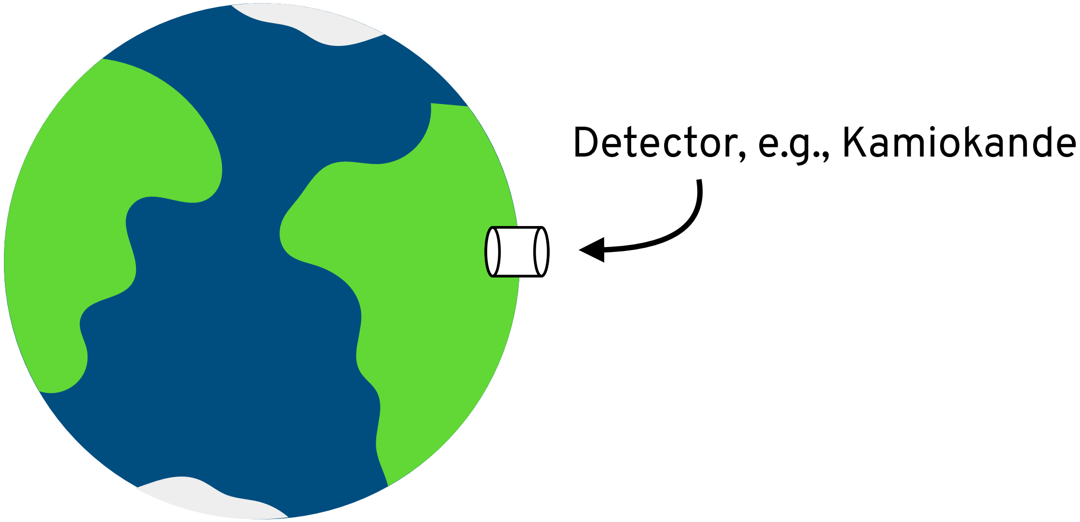
Atmospheric Neutrinos

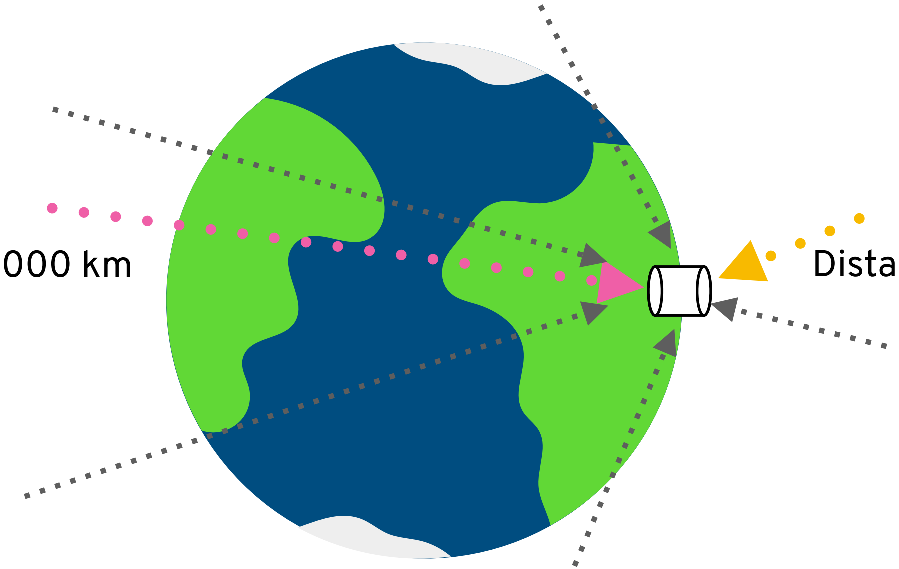
Atmospheric neutrinos come from all directions, including directly overhead



Atmospheric Neutrinos

Atmospheric neutrinos come from all directions, including directly overhead

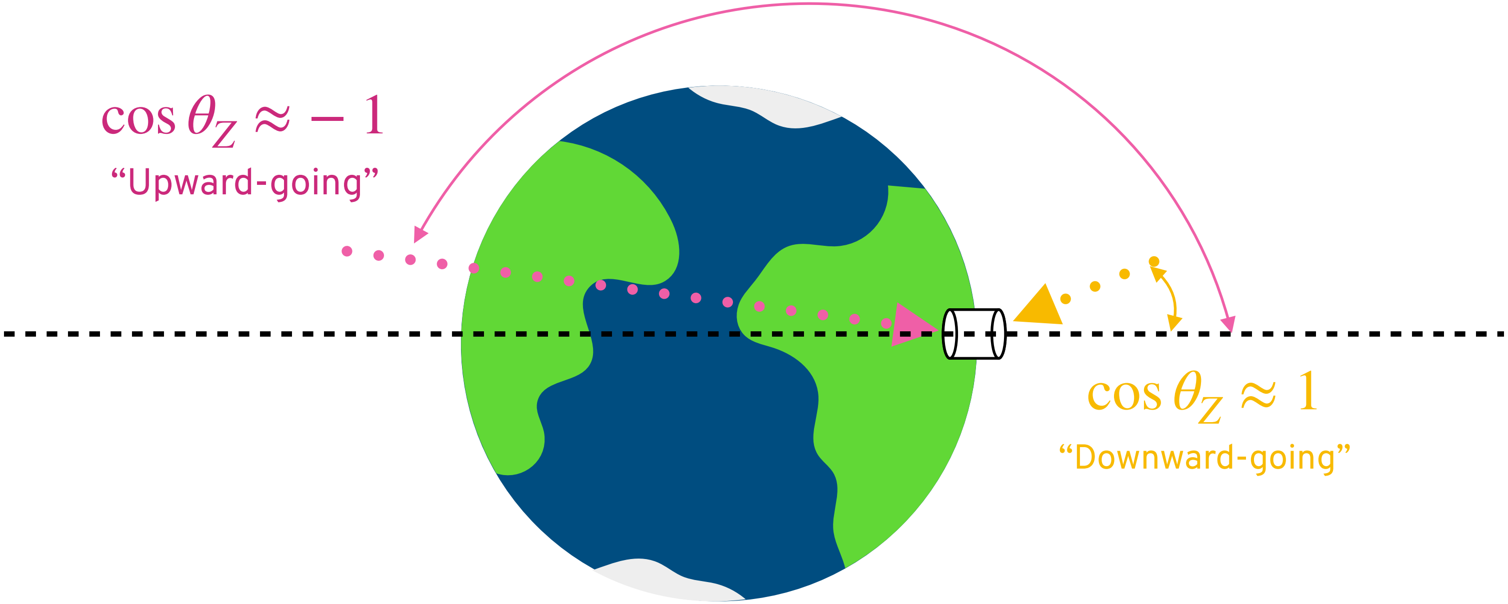
From below:
Distance to detector ~ 13,000 km



From above:
Distance to detector ~15 km

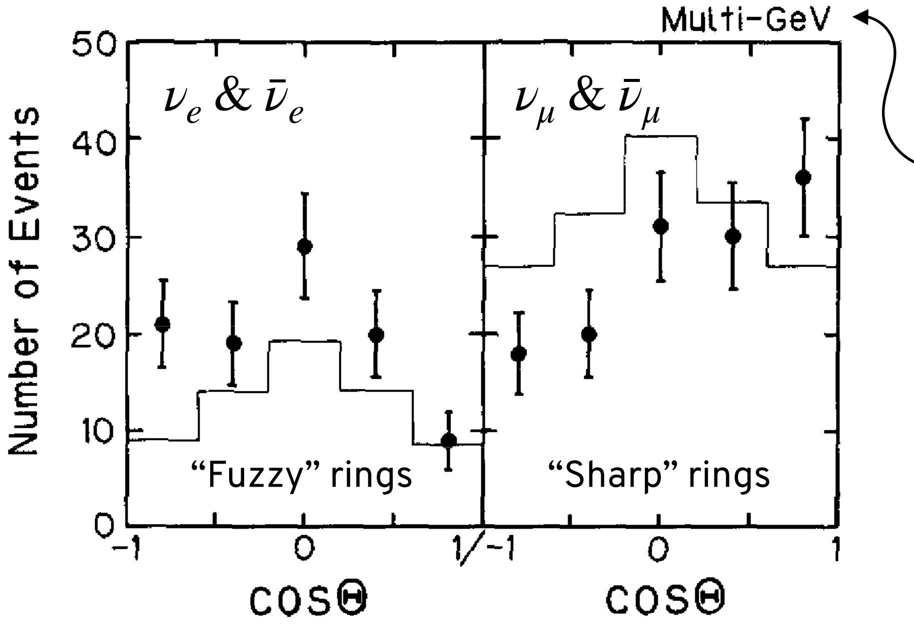
Atmospheric Neutrinos

Atmospheric neutrinos come from all directions, including directly overhead



Atmospheric Neutrinos in Kamiokande

Kamiokande Atmospheric Neutrino Data

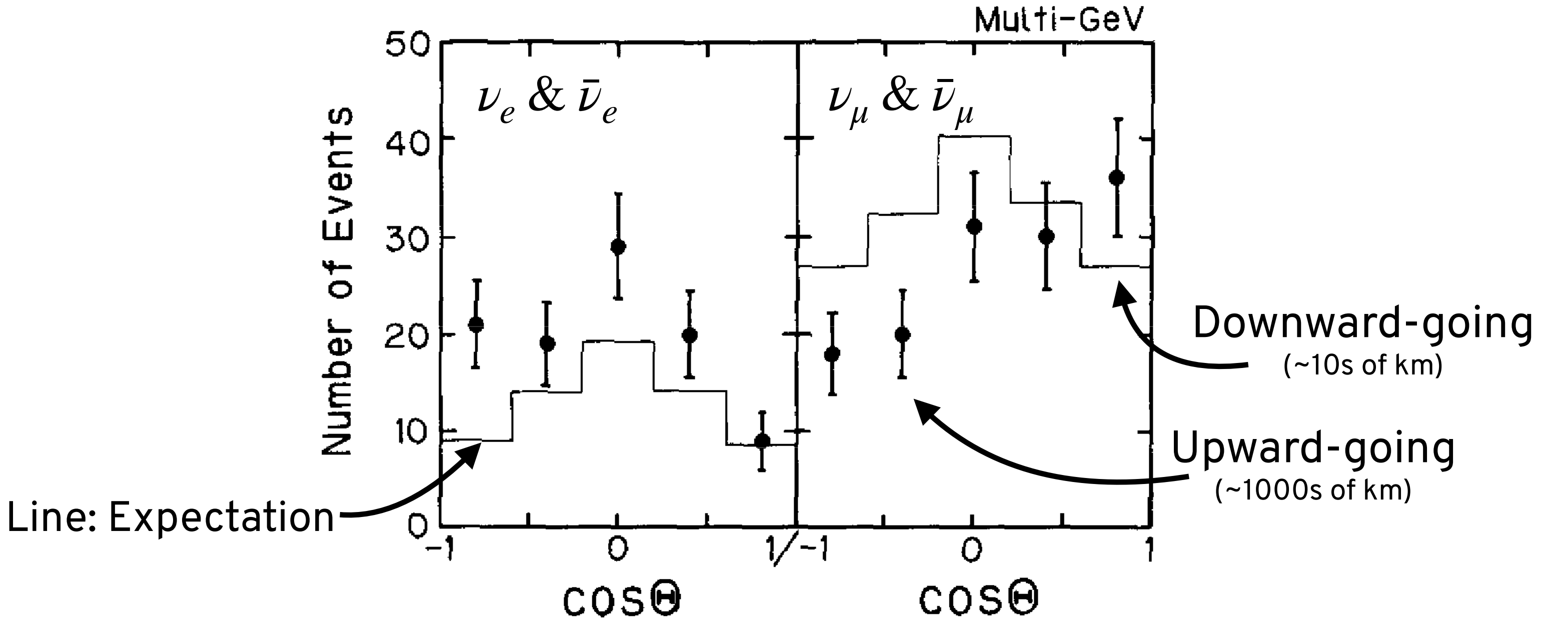


~100 times more energetic than solar neutrinos

Y. Fukuda et al. *Physics Letters B* **335** 237-245 (1994)

Atmospheric Neutrinos in Kamiokande

Kamiokande Atmospheric Neutrino Data

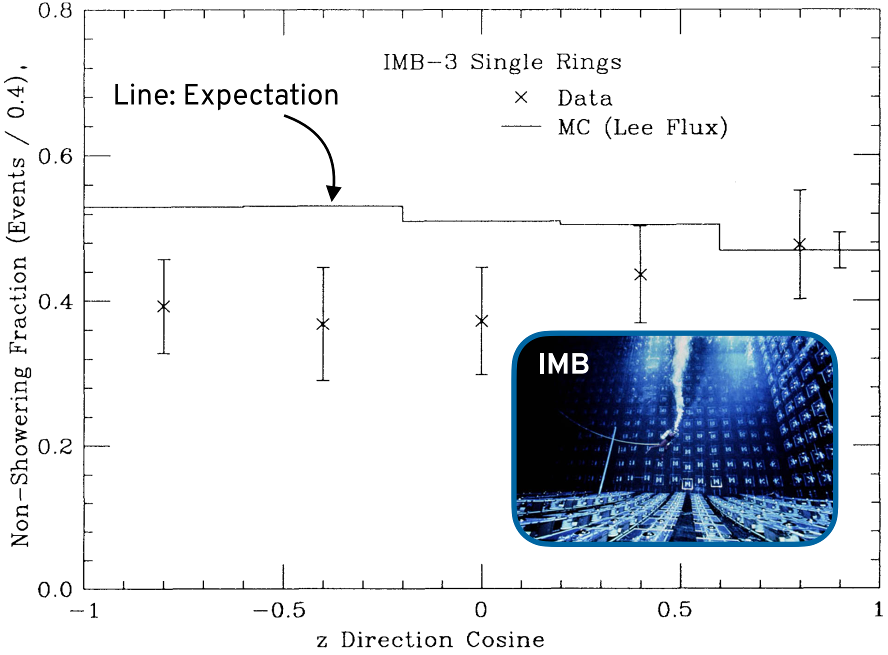


Missing muon neutrinos coming from below?

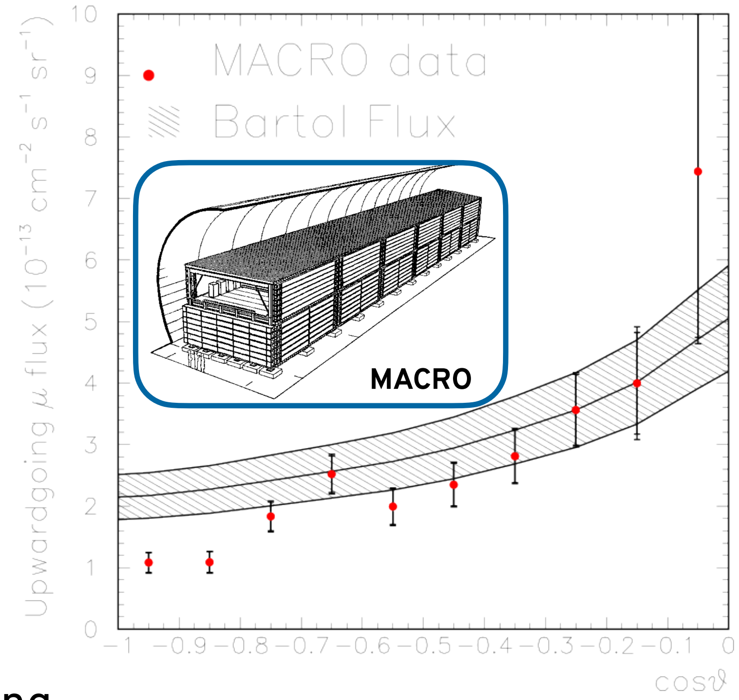
Y. Fukuda et al. *Physics Letters B* **335** 237-245 (1994)

Kamiokande was one of several hints

IMB Collaboration. Physical Review Letters **66**, 2561 (1991)



MACRO Collaboration. Physics Letters B 434, 451-457 (1995)



Upward-going (~1000s of km) ⟷ Downward-going (~10s of km)

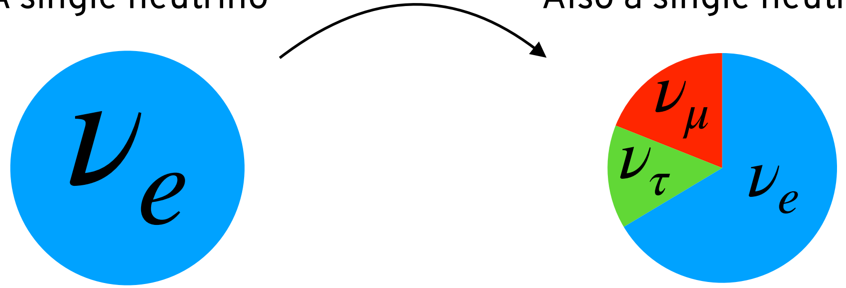
One not-so-simple Idea

What if neutrino flavor changes over time?

(We'll discuss how this happens in the next lecture)

A single neutrino

Also a single neutrino



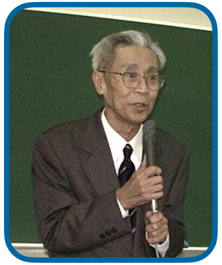
100% electron-flavor

Mixture of flavors

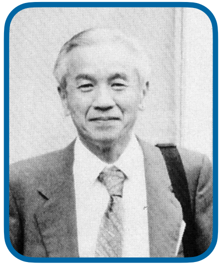
One not-so-simple Idea

Many years of theoretical development happened in parallel with experimental results

Bruno Pontecorvo (Again)



Ziro Maki



Masami Nakagawa

Shoichi Sakata

Lincoln Wolfenstein

Stanislav Mikheyev

Alexei Smirnov

Idea

~1950s

Theoretical framework

~1960s

Application to solar neutrinos

~1970–1980s

Solar Neutrino Problem Revisited

Flavor at Earth

Fixed Flavor Case

ν_e

~ 10 MeV
(Average Boron-8 energy)

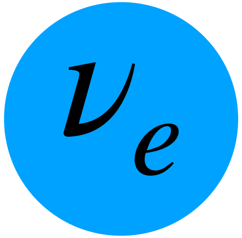
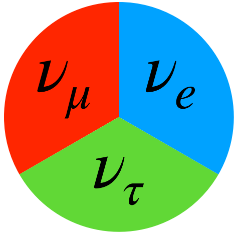
What happens in our Detector

$\nu_X + n \rightarrow \nu_X + n$ ✓

X can be e, μ, τ, any OK

$\nu_e + n \rightarrow p + e^-$ ✓

Solar Neutrino Problem Revisited

Flavor at Earth	What happens in our Detector	
Fixed Flavor Case 	$\nu_X + n \rightarrow \nu_X + n$ ✓ X can be e, μ, τ, any OK	$\nu_e + n \rightarrow p + e^-$ ✓
Multiple Flavor Case 	$\nu_X + n \rightarrow \nu_X + n$ ✓	$\nu_e + n \rightarrow p + e^-$ Reduced!

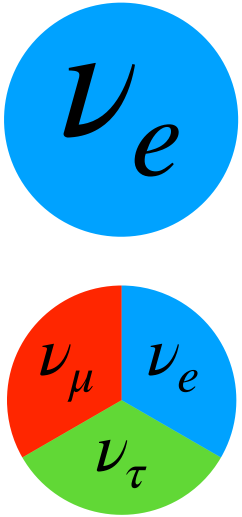
~ 10 MeV
(Average Boron-8 energy)

Solar Neutrino Problem Revisited

Flavor at Earth

Fixed Flavor Case

Multiple Flavor Case



~ 10 MeV
(Average Boron-8 energy)

What happens in our Detector

Fixed Flavor Case:

$$\nu_X + n \rightarrow \nu_X + n$$ ✓

X can be e, μ, τ, any OK

$$\nu_e + n \rightarrow p + e^-$$ ✓

Multiple Flavor Case:

$$\nu_X + n \rightarrow \nu_X + n$$ ✓

$$\nu_e + n \rightarrow p + e^-$$ ⊖ Reduced!

Should also happen…

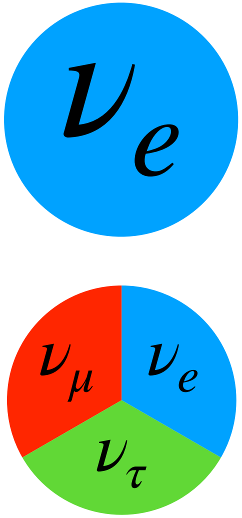
$$\nu_{\mu,\tau} + n \rightarrow p + (\mu^- \text{ or } \tau^-)$$

Solar Neutrino Problem Revisited

Flavor at Earth

Fixed Flavor Case

Multiple Flavor Case



~ 10 MeV
(Average Boron-8 energy)

What happens in our Detector

Fixed Flavor Case:

$$\nu_X + n \rightarrow \nu_X + n$$ ✓

X can be e, μ, τ, any OK

$$\nu_e + n \rightarrow p + e^-$$ ✓

Multiple Flavor Case:

$$\nu_X + n \rightarrow \nu_X + n$$ ✓

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

Reduced!

$$\nu_{\mu,\tau} + n \rightarrow p + (\mu^- \text{ or } \tau^-)$$ (crossed out)

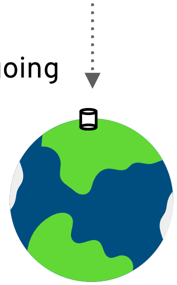
Not enough energy! μ & τ too heavy

Atmospheric Neutrino Problem Revisited

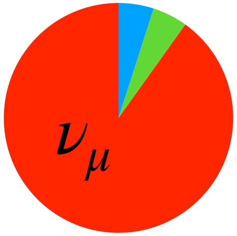
Flavor in the atmosphere

Downward-going

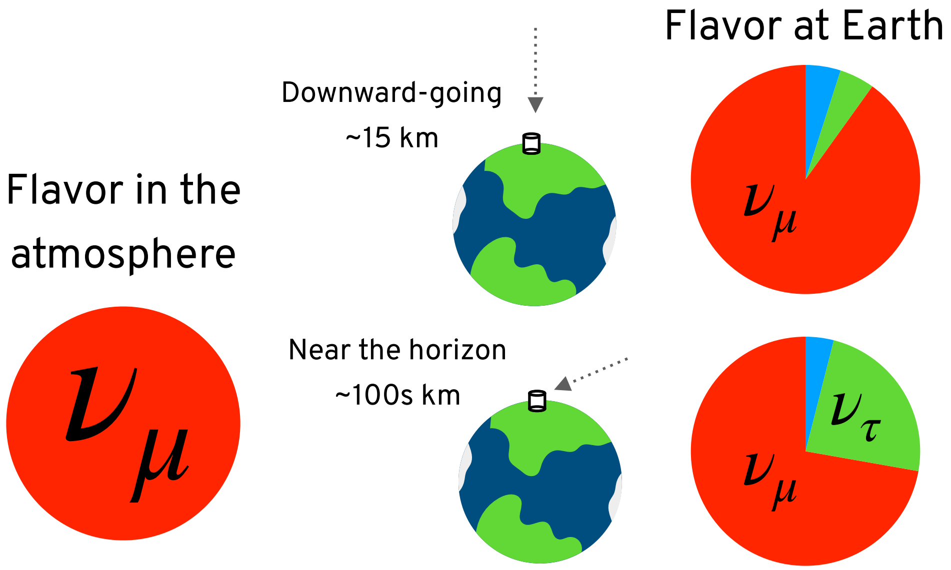
~15 km



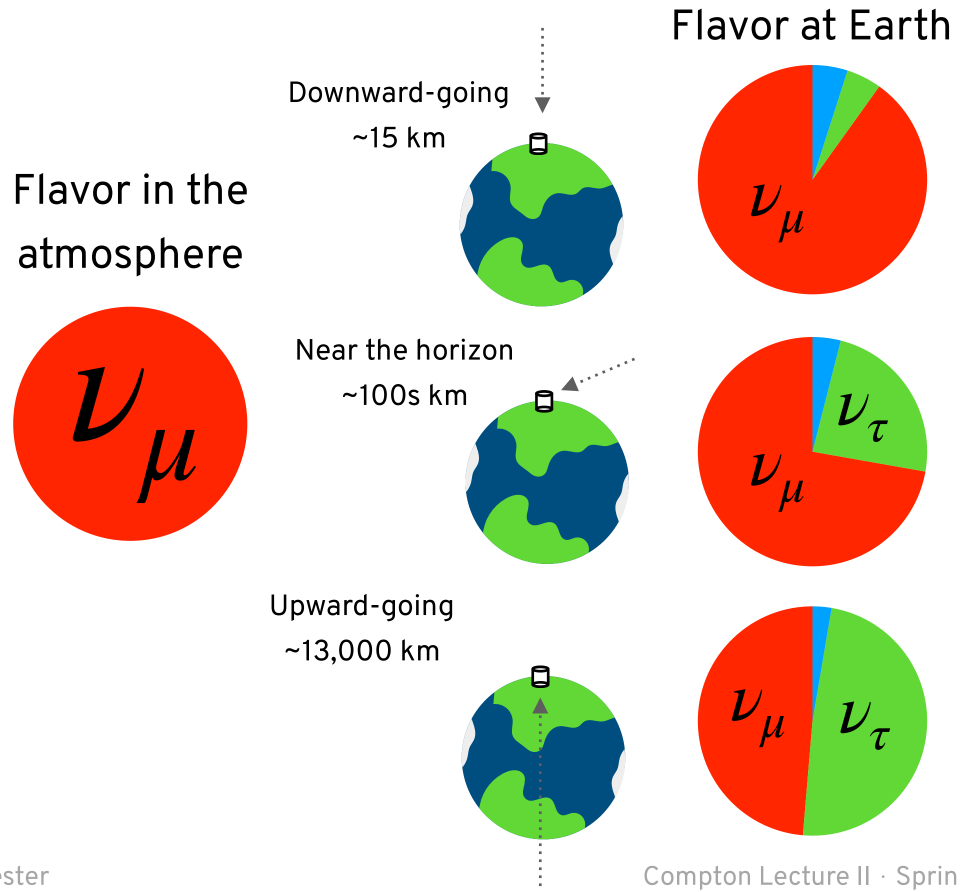
Flavor at Earth



Atmospheric Neutrino Problem Revisited



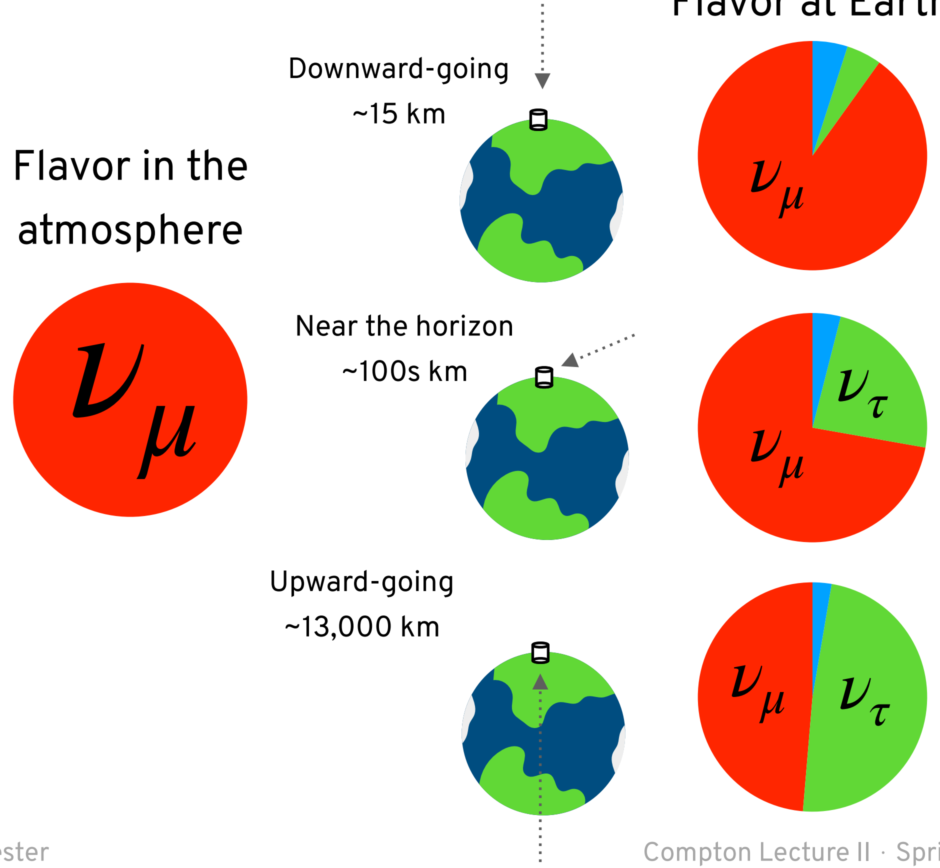
Atmospheric Neutrino Problem Revisited



Atmospheric Neutrino Problem Revisited

Flavor in the atmosphere

Flavor at Earth



Rate of

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

decreases with neutrino distance travelled

The Test: Super-Kamiokande & SNO

Experiments built in the 90s to definitively answer solar & atmospheric neutrino anomalies

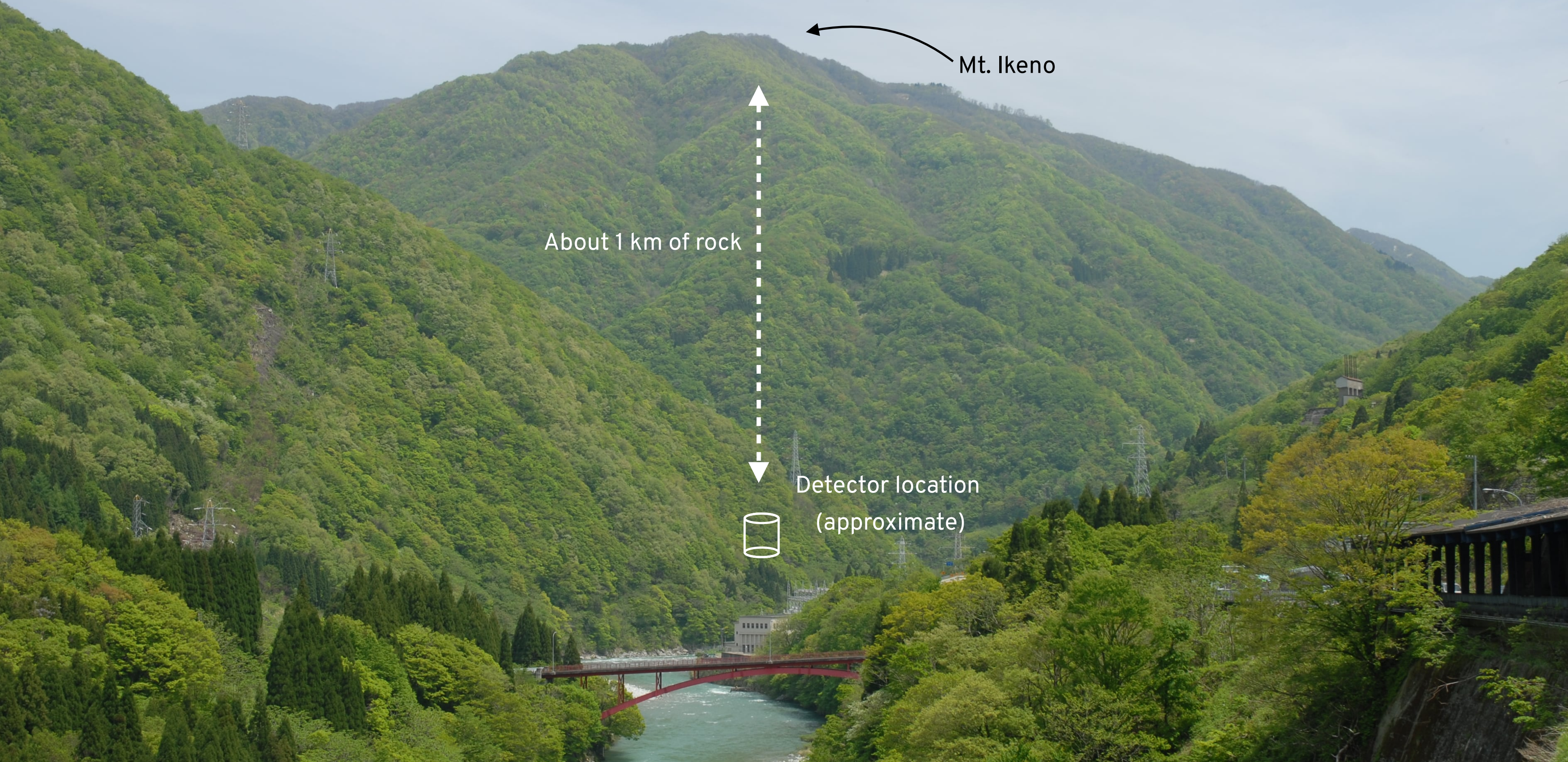
Expand Kamiokande physics program –
Precision solar & atmospheric measurements

Joint effort between Kamiokande & IMB collaborations

Low-background experiment deep underground with a new detection technique


Super-Kamiokande
(View from the outside)
Mt. Ikeno

Super-Kamiokande
(View from the outside)



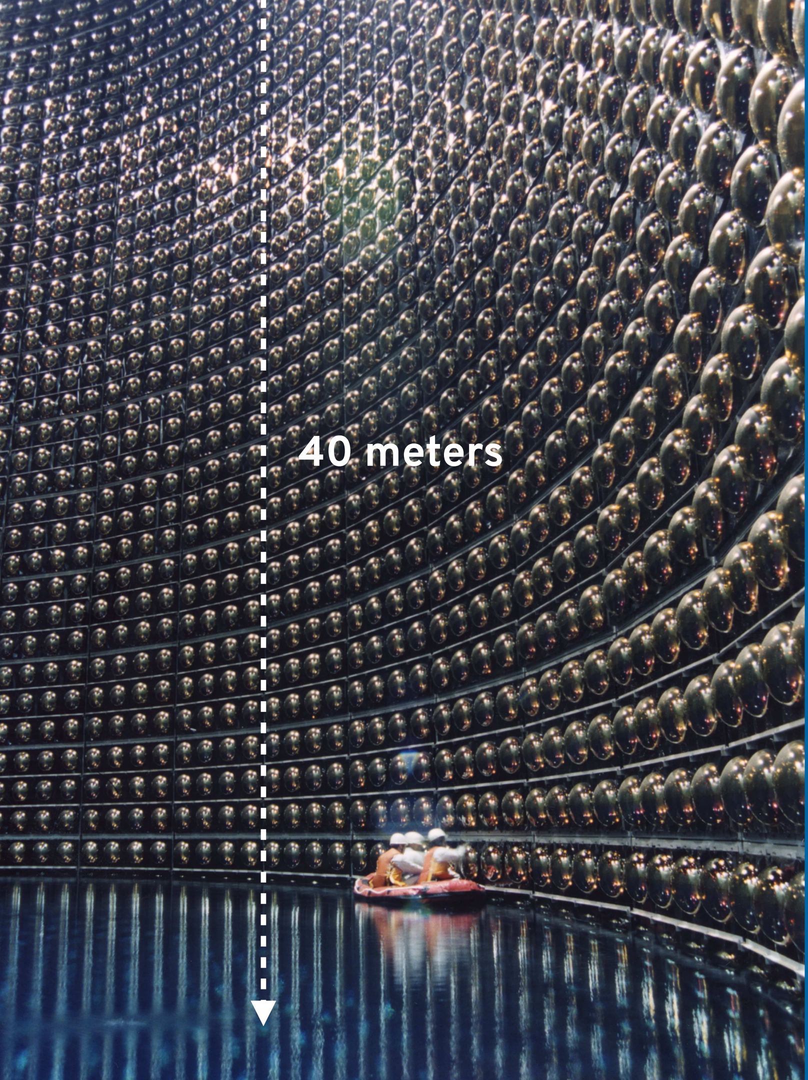
Super-Kamiokande (SK)

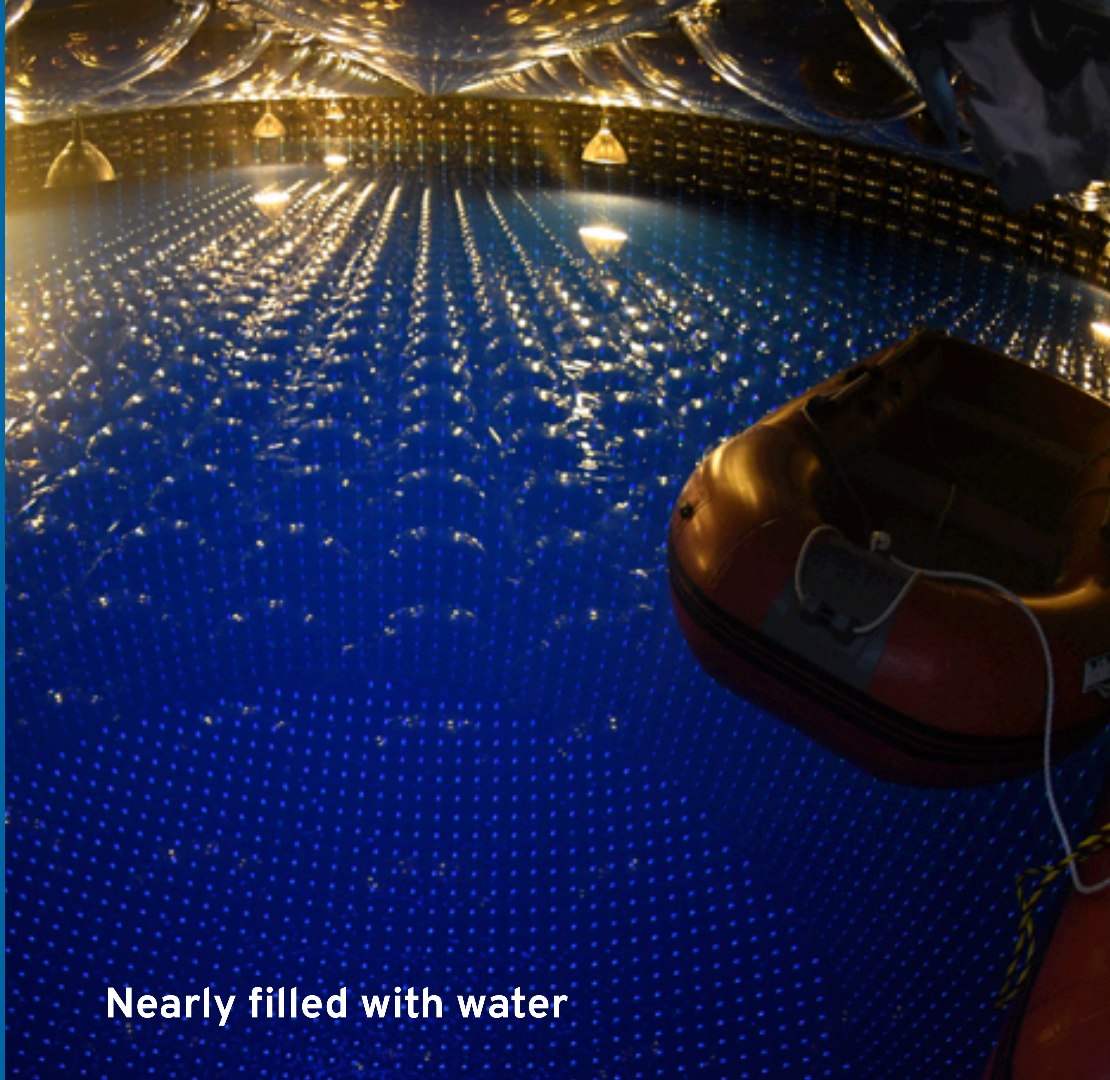
Construction 1993–1996

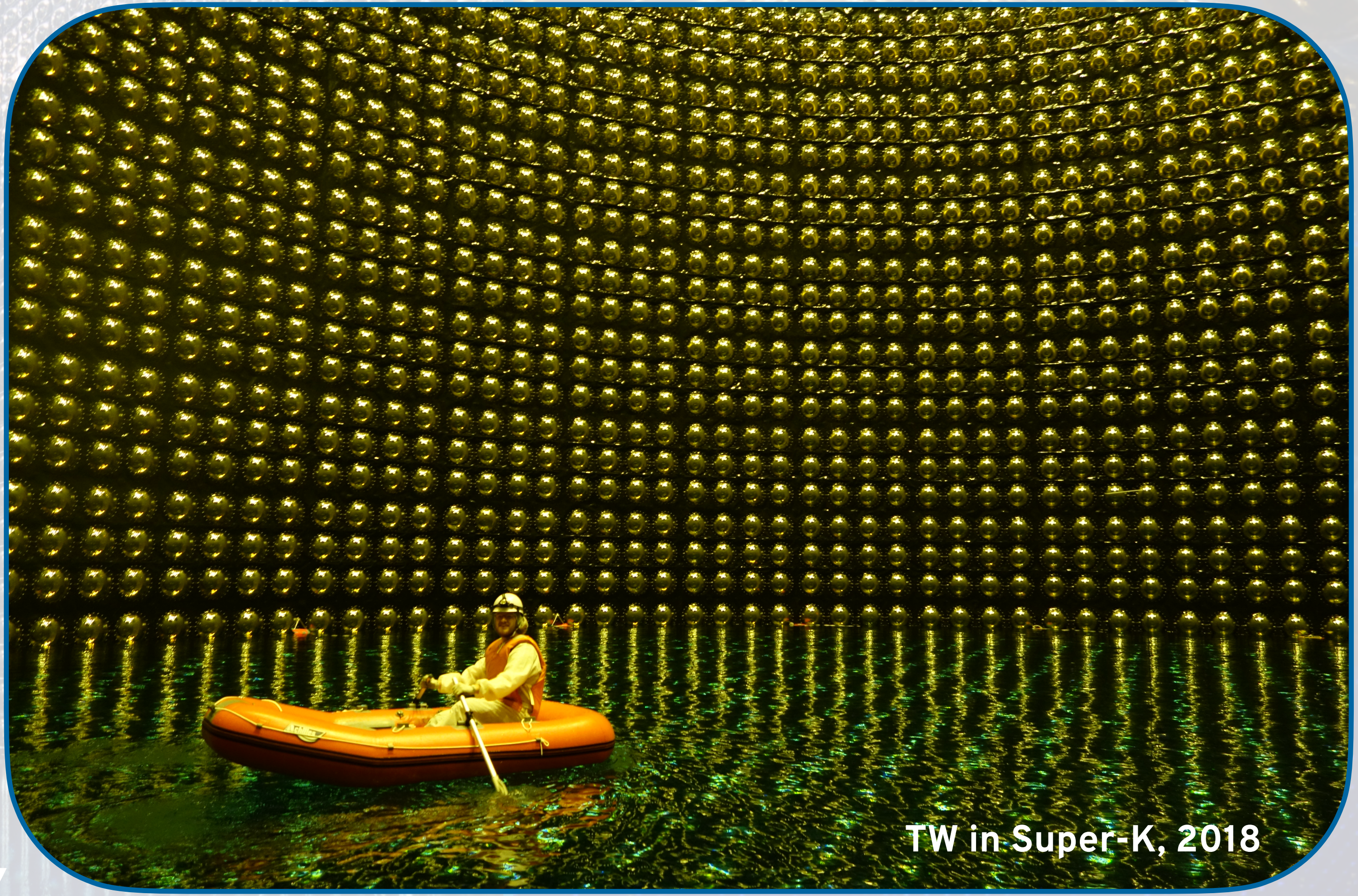
Data-taking 1996–Present

50,000 tons of water
(20 Olympic swimming pools)

11,000 photomultiplier tubes

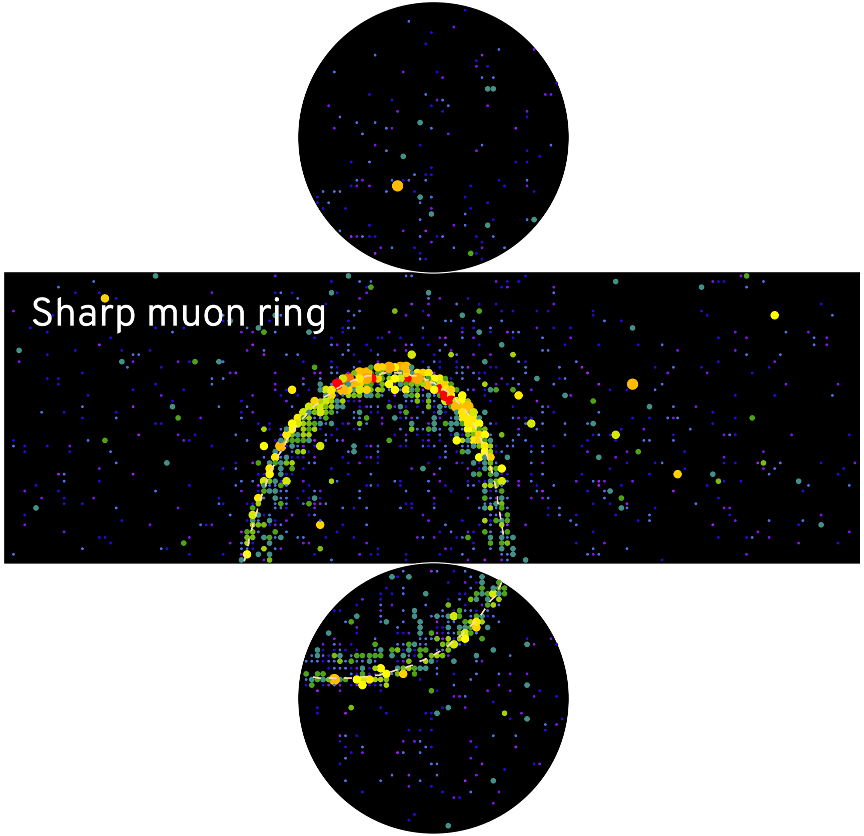

40 meters

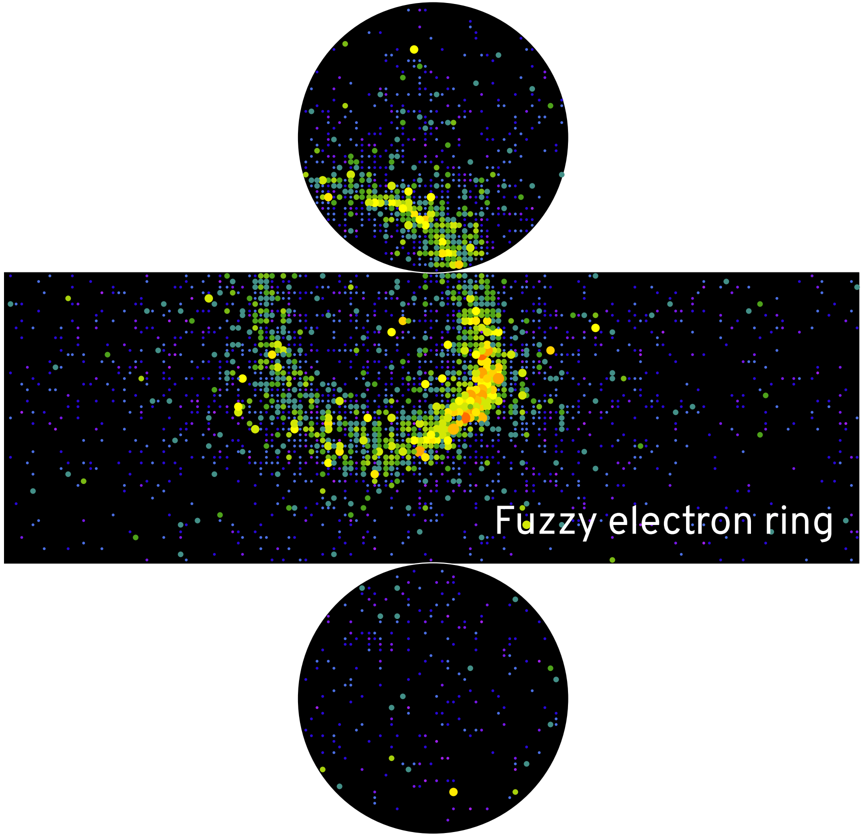

Nearly filled with water



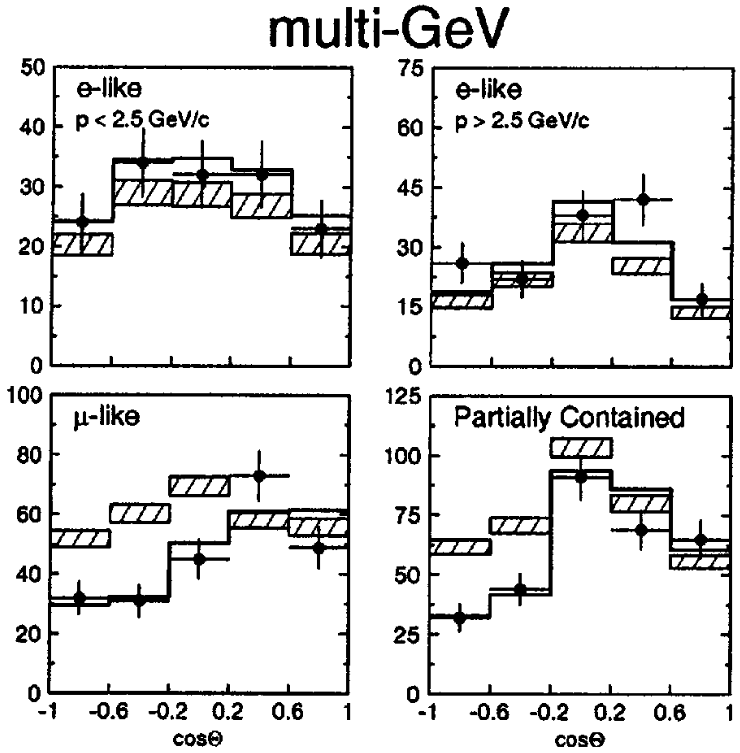
TW in Super-K, 2018

Super-Kamiokande Atmospheric Neutrinos



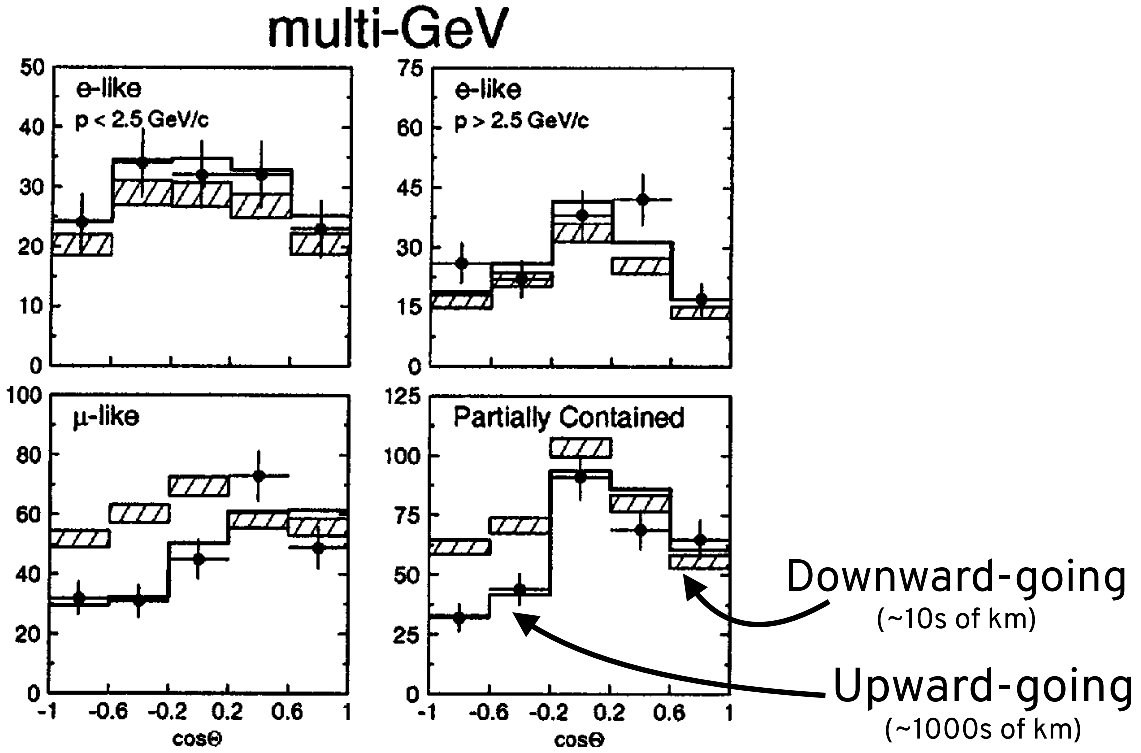


Super-Kamiokande Data



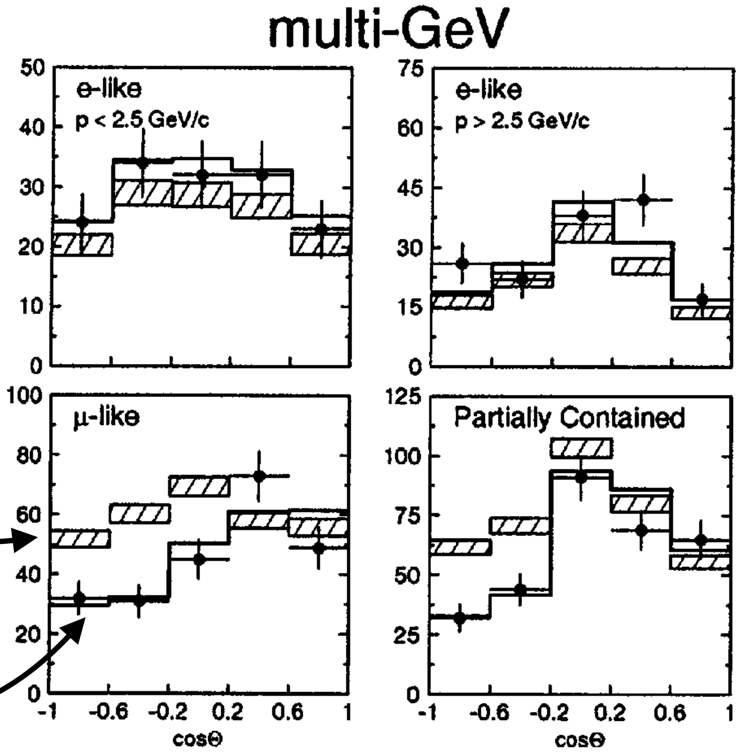
Physical Review Letters **81**, 1562 (1998)

Super-Kamiokande Data



Physical Review Letters **81**, 1562 (1998)

Super-Kamiokande Data



Hatched region:
Expectation with no
flavor change

Solid line: Include $\nu_\mu \to \nu_\tau$
flavor change vs. distance
Excellent agreement!

Physical Review Letters **81**, 1562 (1998)

Sudbury Neutrino Observatory (SNO)

1,000 tons of heavy water in an acrylic shell

10,000 photomultiplier tubes

2000 meters underground

https://sno.phy.queensu.ca/

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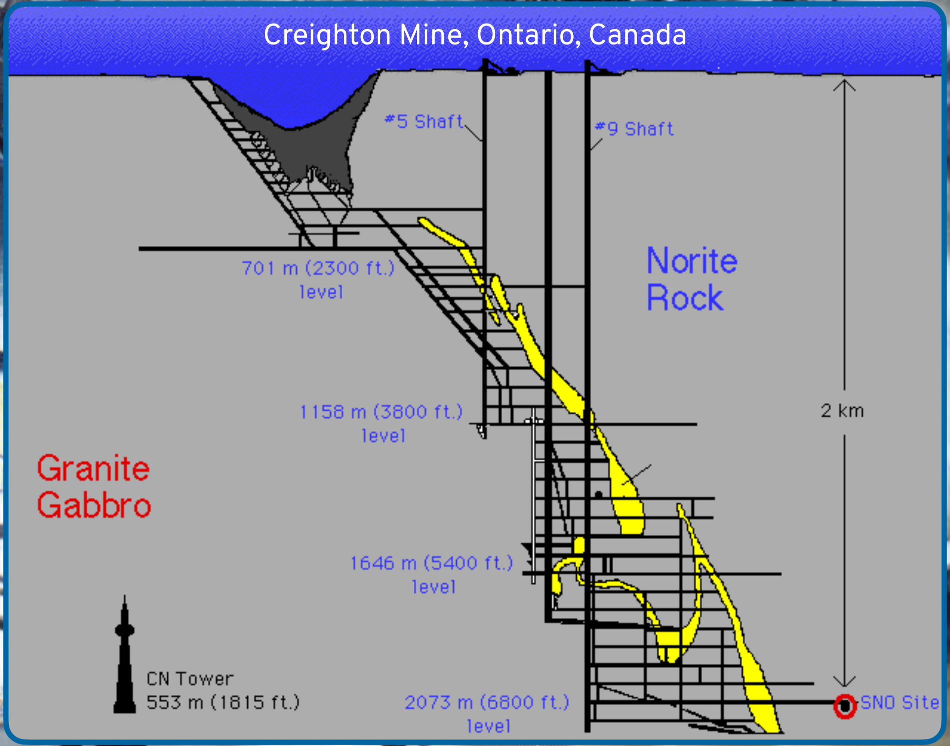


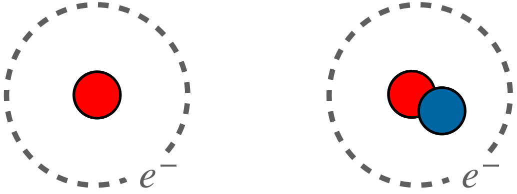
https://sno.phy.queensu.ca/

SNO

Sudbury Neutrino Observatory

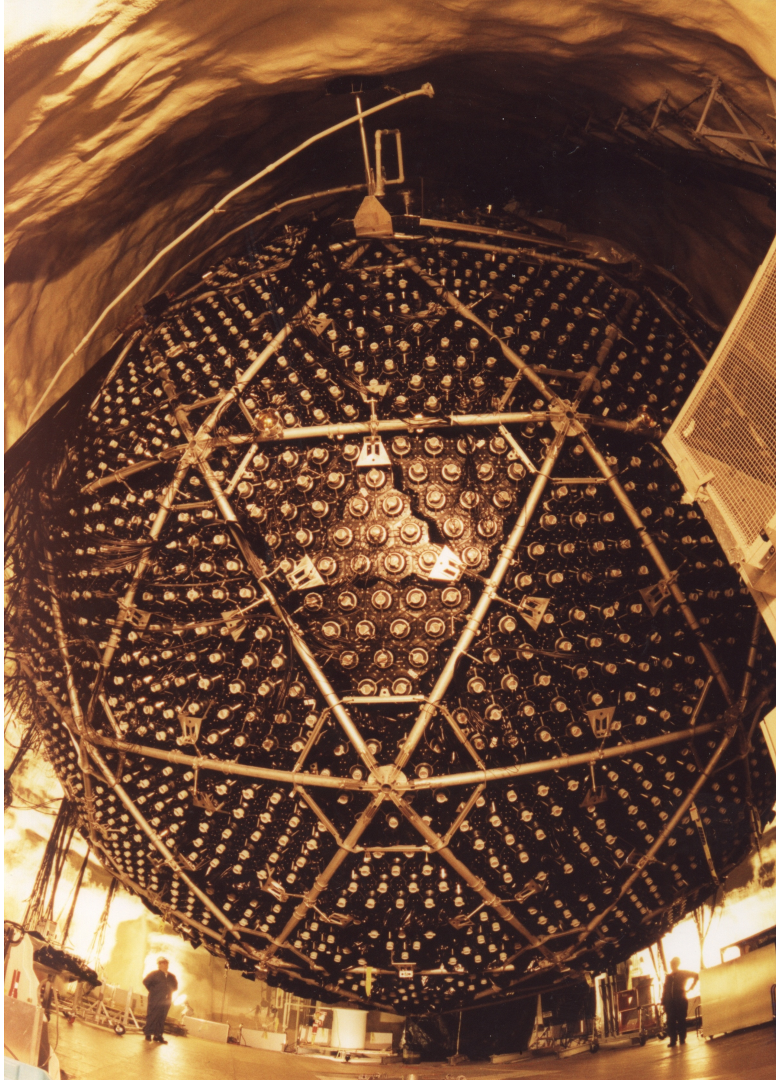
Cherenkov detector like Kamiokande, but with heavy water, ^2H_2O

The extra neutron makes all the difference!



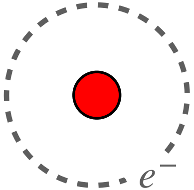
Hydrogen (H)

Deuterium (^{2}H or *d*)

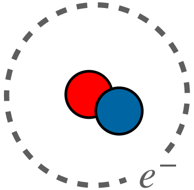


SNO

Sudbury Neutrino Observatory



Hydrogen (H)



Deuterium

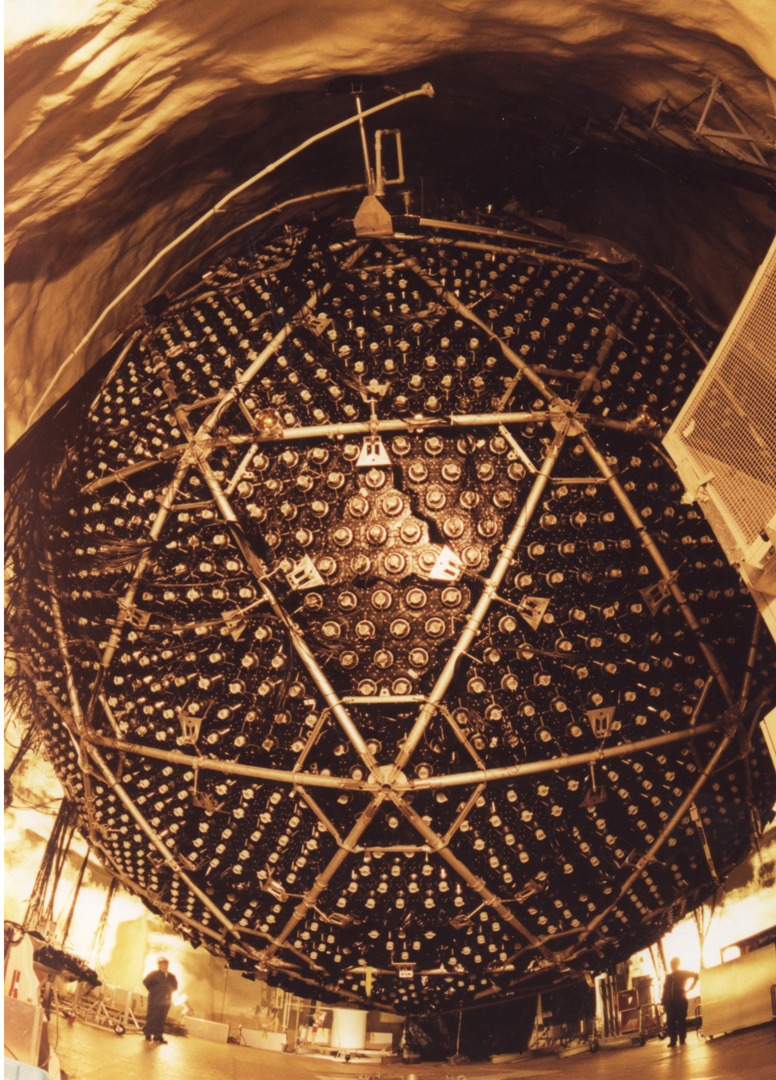
(^{2}H or d)

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

Can only happen for ν_e

$$\nu_X + d \to p + n + \nu_x$$

X can be e, μ, τ, any OK



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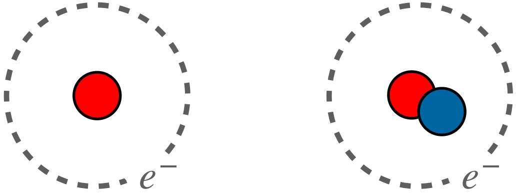
Sudbury Neutrino Observatory



Hydrogen (H)

Deuterium (^{2}H or *d*)

Detect the electron

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

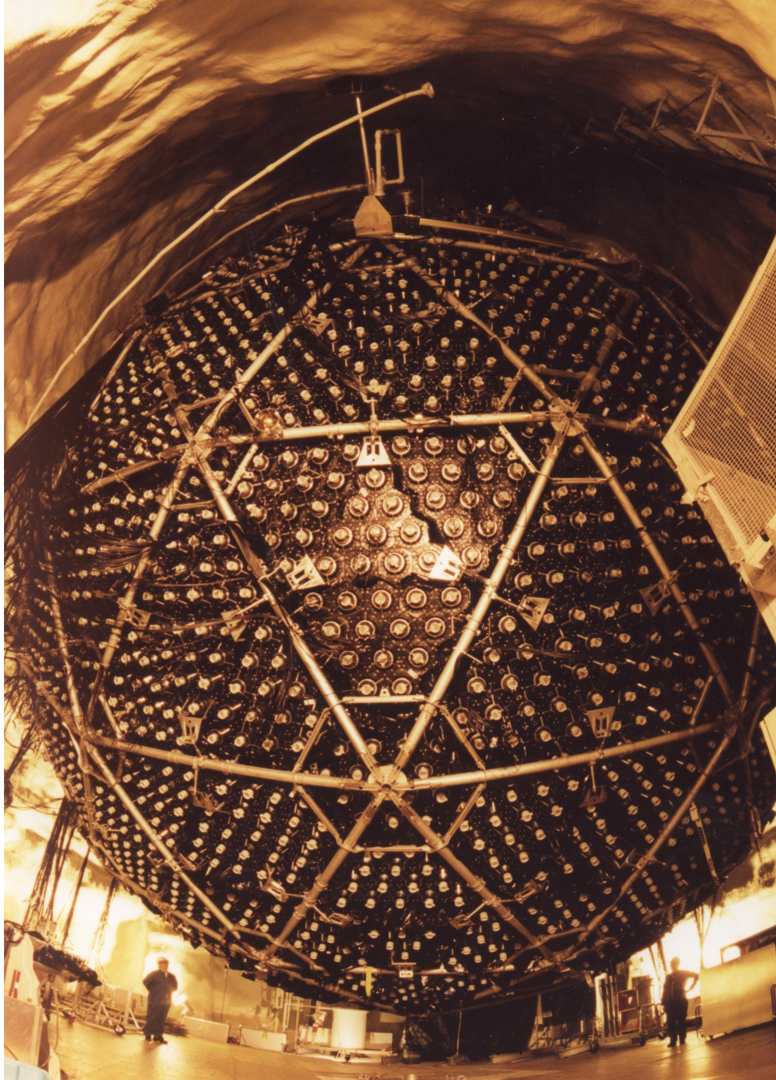
Can only happen for ν_e

Detect the neutron

$$\nu_X + d \rightarrow p + n + \nu_x$$

X can be e, μ, τ, any OK

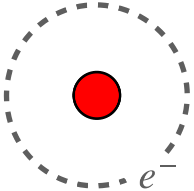
Multiple solar neutrino processes in one detector



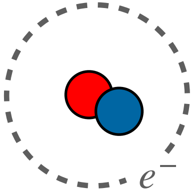
T. Wester

SNO

Sudbury Neutrino Observatory



Hydrogen (H)



Deuterium

(^{2}H or d)

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

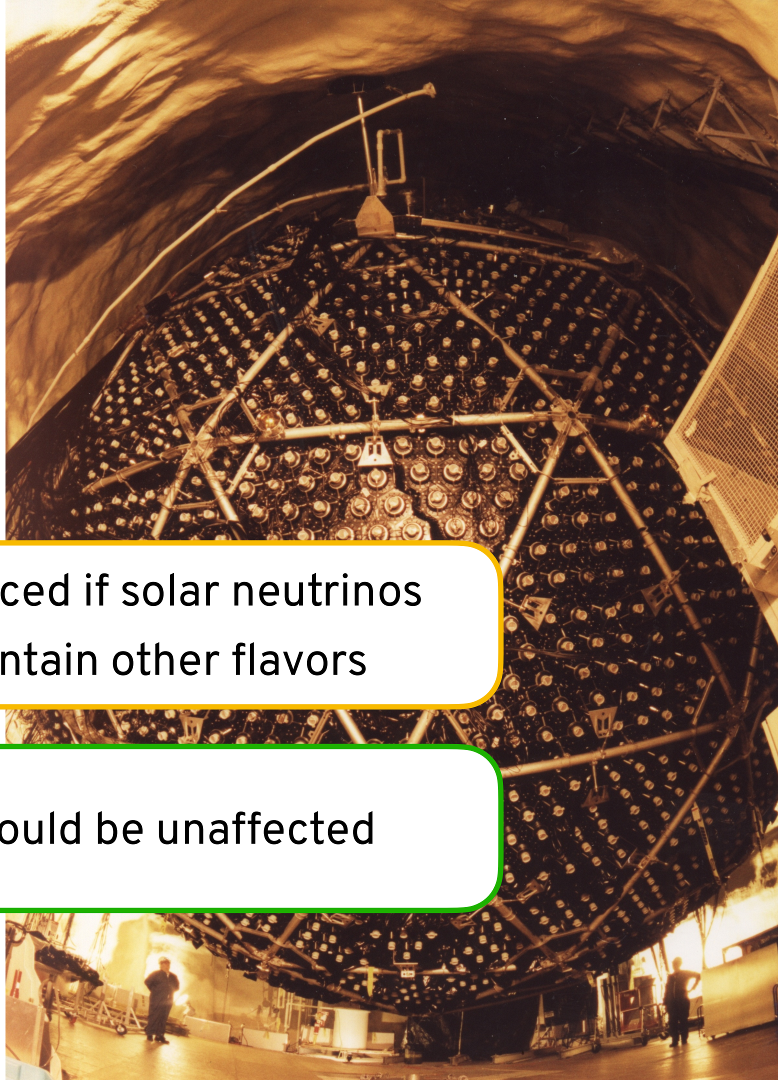
Can only happen for ν_e

Reduced if solar neutrinos contain other flavors

$$\nu_X + d \rightarrow p + n + \nu_x$$

X can be e, μ, τ, any OK

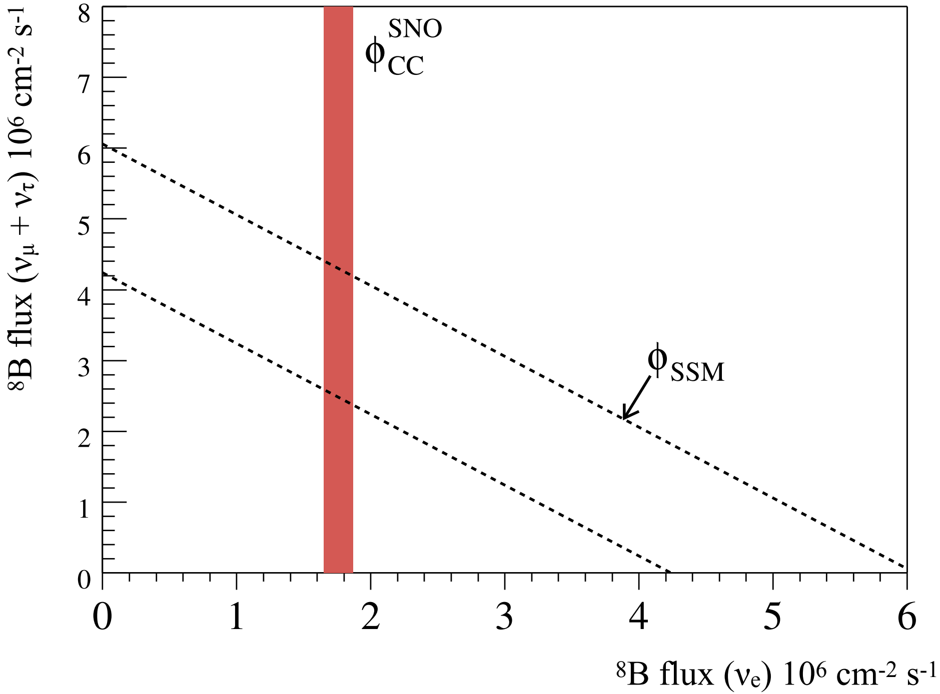
Should be unaffected



T. Wester

SNO Results

SNO collaboration. *Physical Review Letters* **89**, 011301 (2002)



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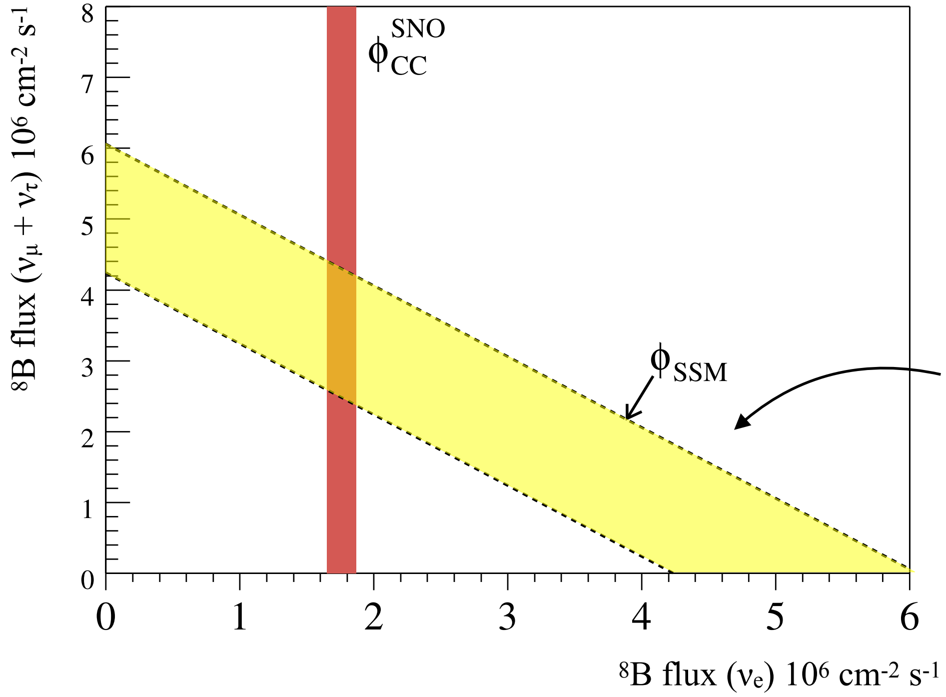


Dashed diagonal lines

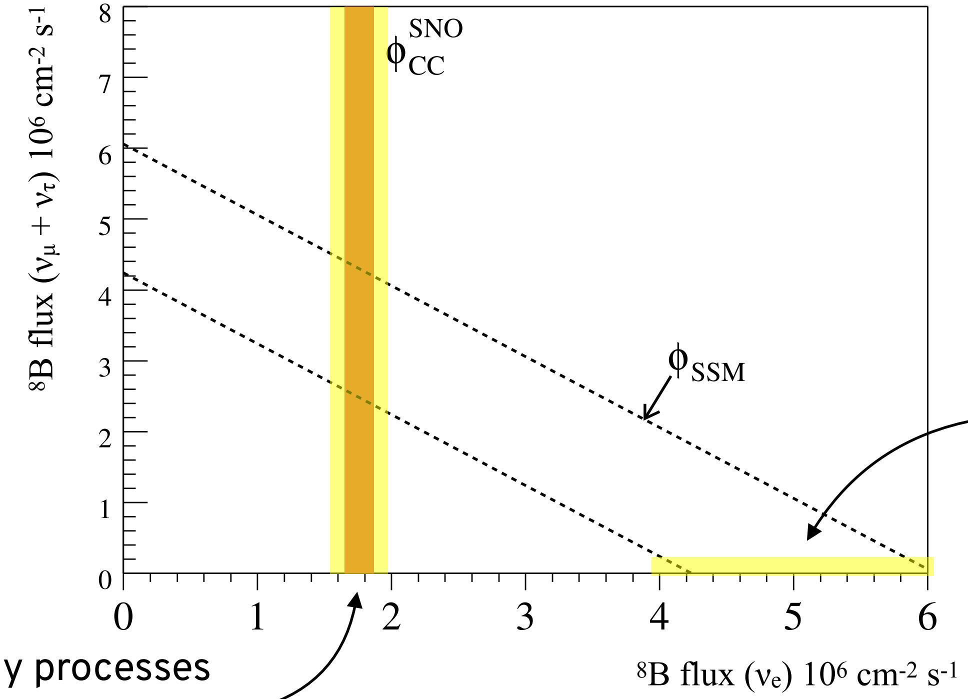
SSM, Standard Solar Model

Range of total ^{8}B flux

$\nu_e + \nu_\mu + \nu_\tau = \text{Constant}$

SNO Results

SNO collaboration. *Physical Review Letters* **89**, 011301 (2002)



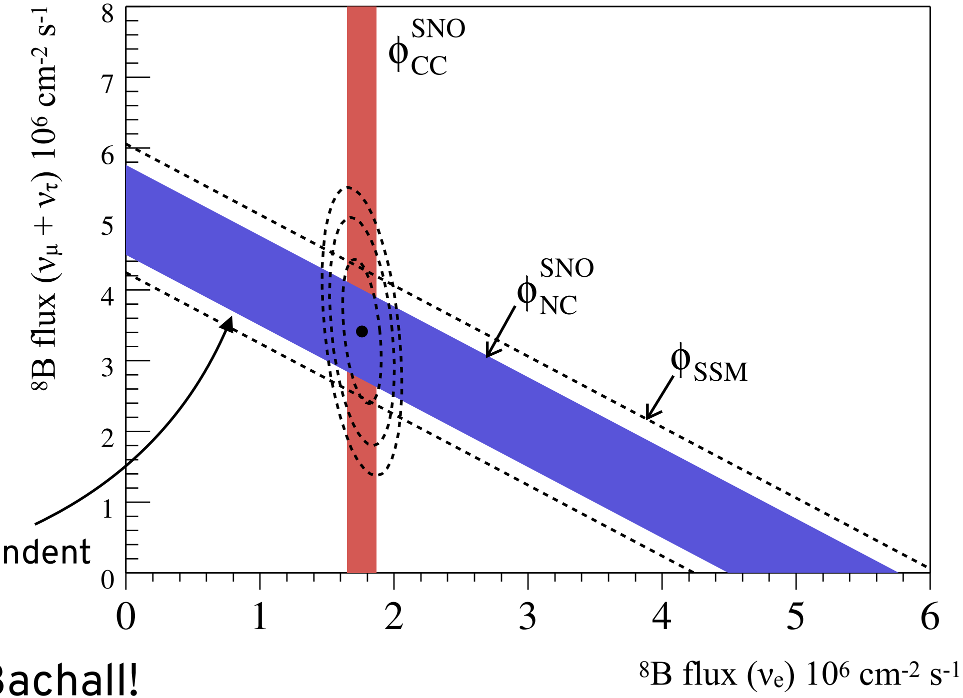
Expected rate if solar neutrinos are entirely ν_e

Rate of electron-only processes

Like Davis, SNO saw ~ 1/3 too few of these

SNO Results

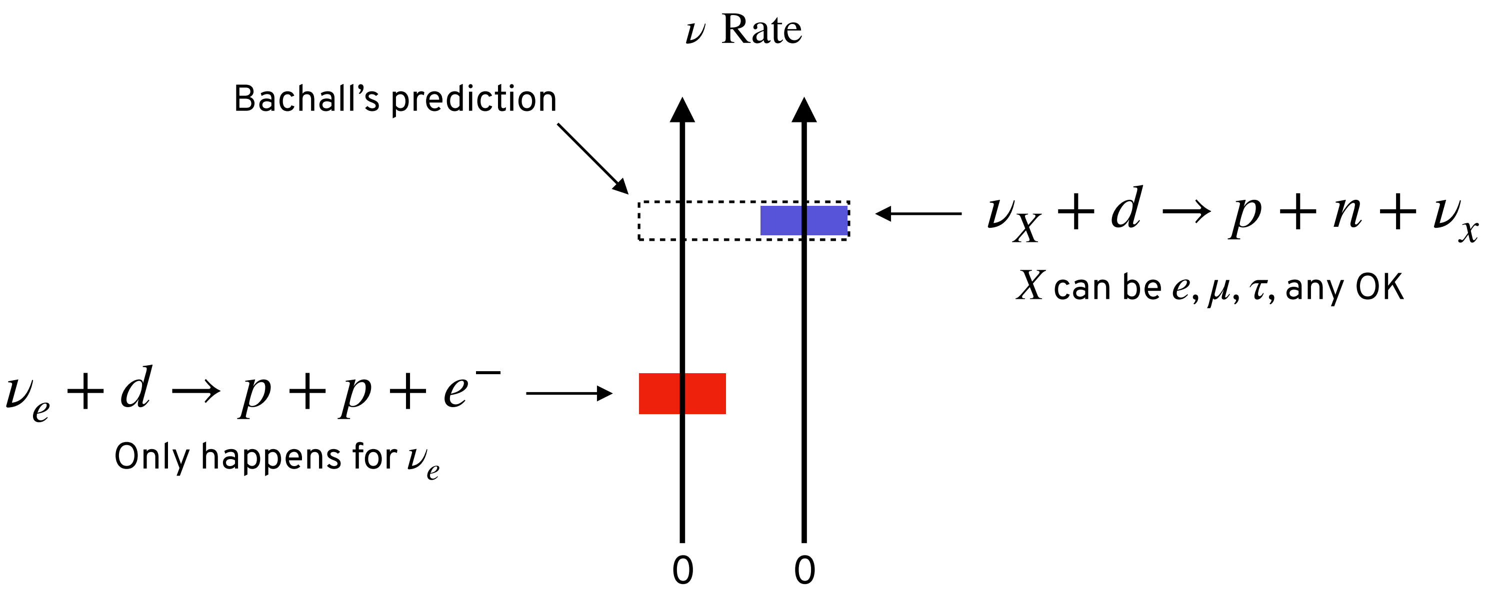
SNO collaboration. *Physical Review Letters* **89**, 011301 (2002)



Rate of flavor-independent processes

SNO Agrees with Bachall!

Missing Neutrinos Found



To see all the neutrinos, SNO measured a flavor-independent process

2002 Nobel Prize

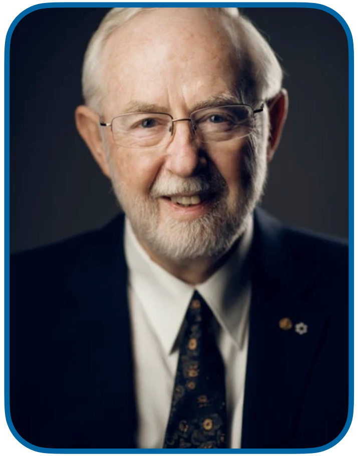
Ray Davis Jr.

Masatoshi Koshiba

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

2015 Nobel Prize

Takaaki Kajita

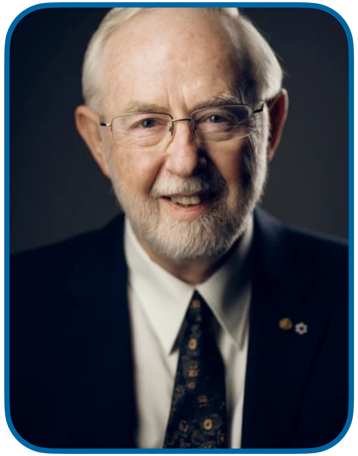


Arthur McDonald

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

2015 Nobel Prize

Takaaki Kajita



Arthur McDonald

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

Next time!

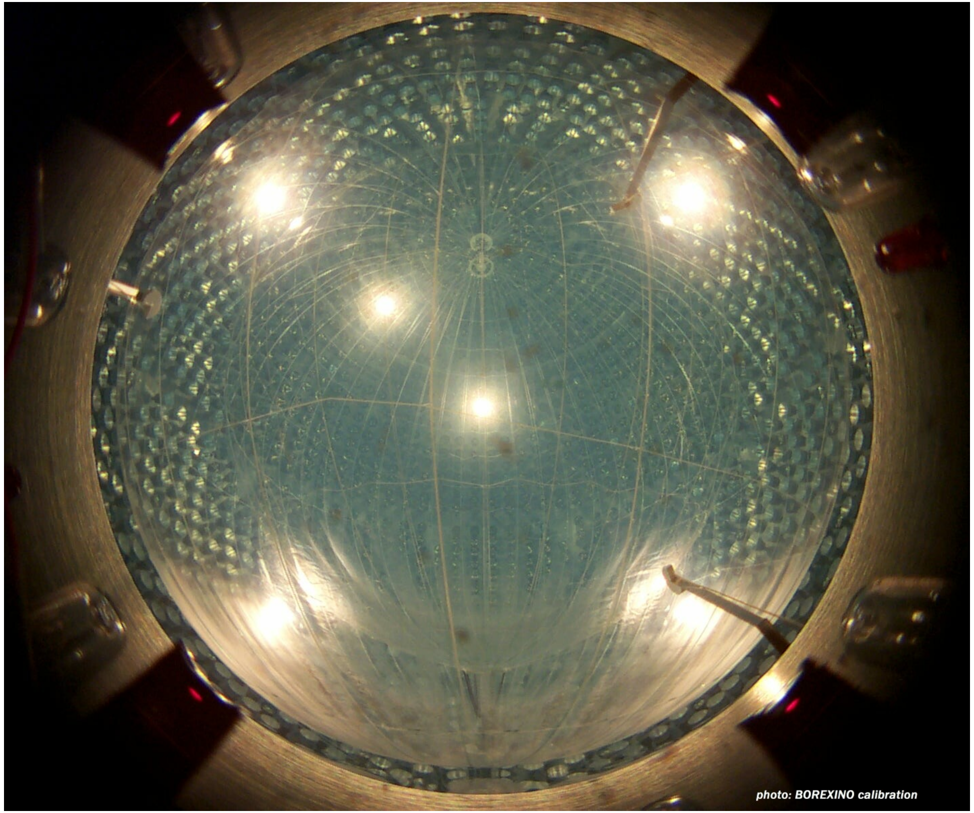
Solar Neutrinos Today

BOREXINO experiment:

An “onion” detector

Liquid scintillator contained within a nylon vessel, surrounded by buffer liquid, surrounded by water…

Result: Ultra-clean, low background experiment for measuring low-energy solar neutrinos



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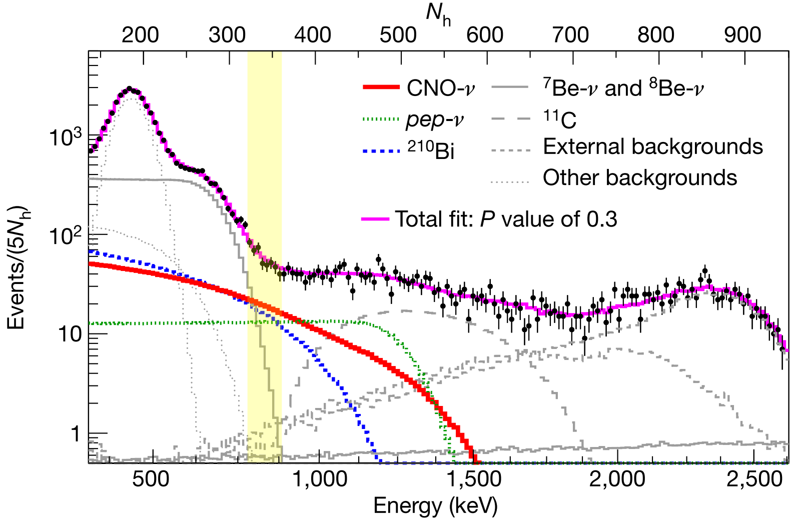


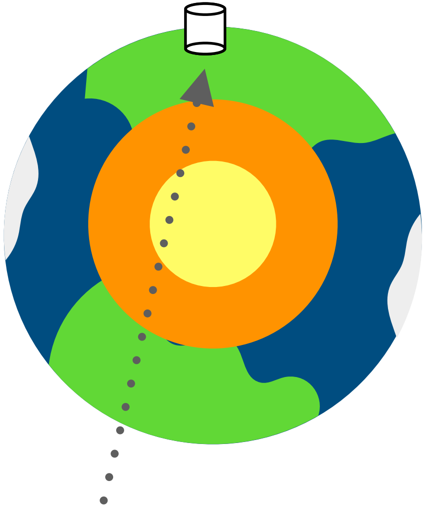
Nature **587** 577–582 (2020)

CNO solar neutrinos measured for the first time by BOREXINO in 2020

CNO neutrinos probe the amount of heavy elements in our Sun

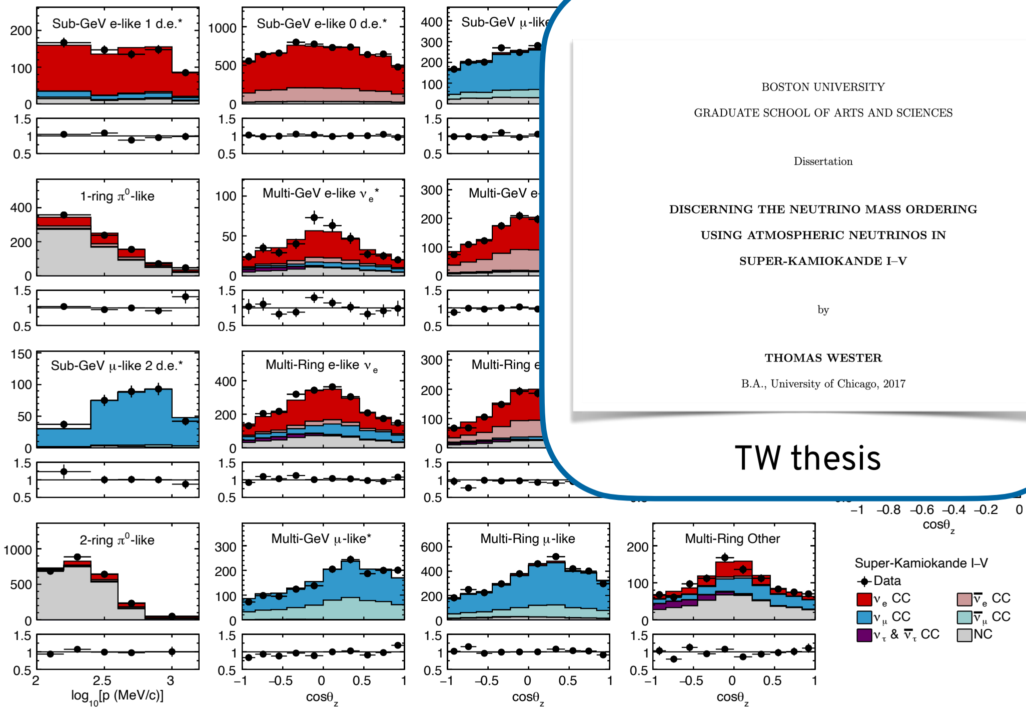
photo: BOREXINO calibration

Atmospheric Neutrinos Today



Dense core of the earth acts like a refractor for electron-flavor neutrinos, changing the flavor slightly

We see hints of this effect!



BOSTON UNIVERSITY

GRADUATE SCHOOL OF ARTS AND SCIENCES

Dissertation

DISCERNING THE NEUTRINO MASS ORDERING USING ATMOSPHERIC NEUTRINOS IN SUPER-KAMIOKANDE I–V

by

THOMAS WESTER

B.A., University of Chicago, 2017

TW thesis

Super-K has a lot more data today than in 1998
~25 years of near-continuous operation!

In Summary

By studying natural neutrino sources with new detectors, we discovered a new feature of neutrinos:
They change flavor

To better measure the effect, we'll need controlled, precision experiments…

Ray Davis Jr. & John Bachall at the Homestake experiment in 1967
https://www.nobelprize.org/

Lecture 3:

Reactors & Neutrino Beams