

# Lost and Found: Solar Neutrinos & Oscillations

The Physics of Neutrinos: Progress and Puzzles

The 87th Compton Lecture Series

Enrico Fermi Institute, University of Chicago



Andrew T. Mastbaum

# The Physics of Neutrinos: Progress and Puzzles

## The 87th Compton Lecture Series

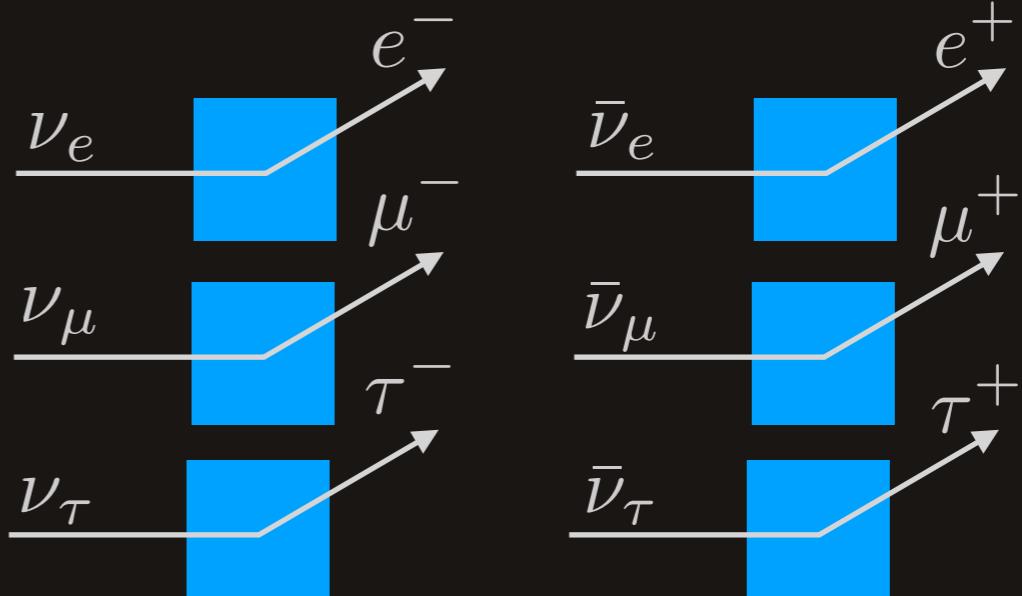
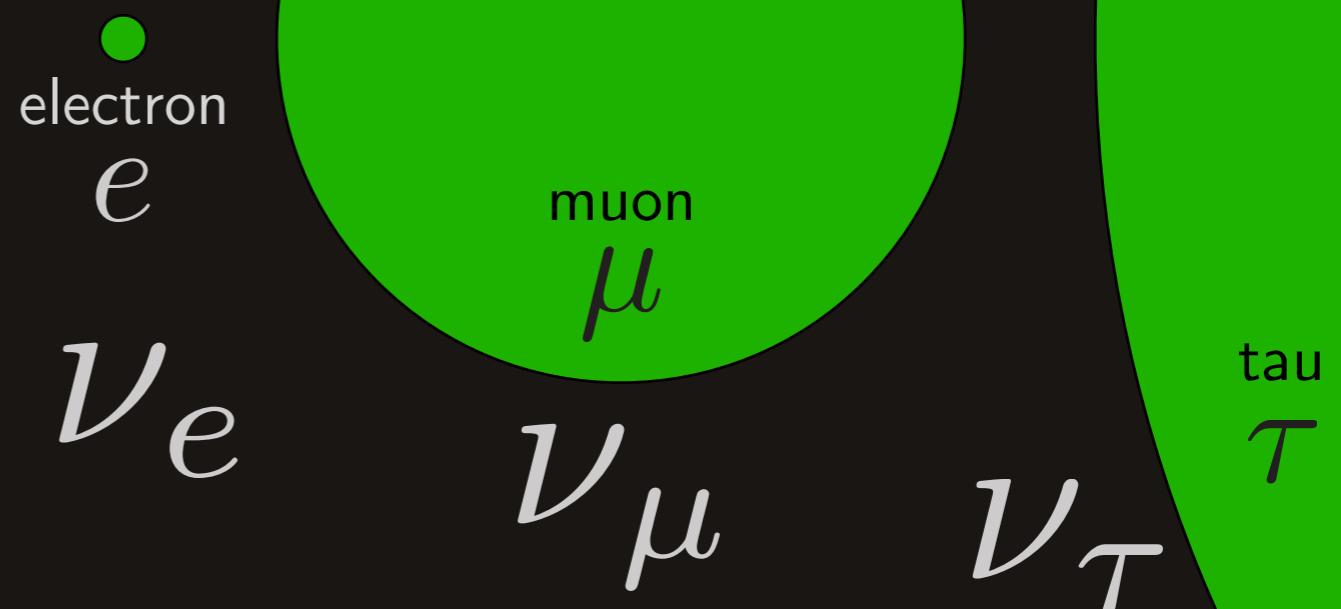
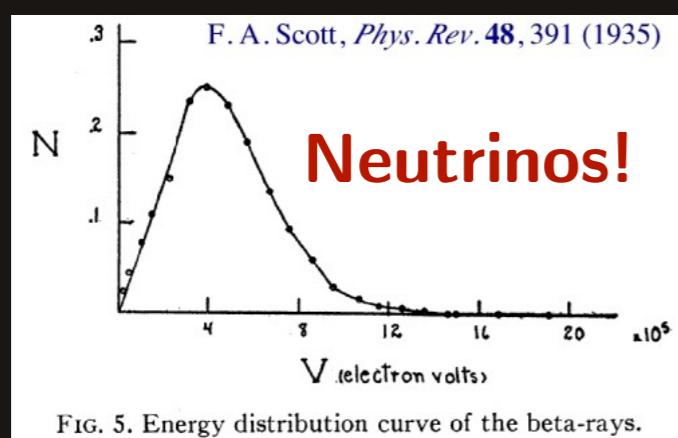
### Agenda (with some adjustments)

<b>March 31</b>	Little, Neutral, Mysterious: An Introduction to Neutrino Physics
<b>April 7</b>	Lost and Found: Solar Neutrinos and Oscillations
<b>April 14</b>	Neutrinos From the Beyond the Solar System
<b>April 21</b>	Neutrinos in Cosmology (Dr. Marco Raveri, KICP)
<b>April 28</b>	Neutrino Physics at Nuclear Reactors
<b>May 5</b>	How Small is Small? Neutrino Mass and Neutrinoless Double-Beta
<b>May 12</b>	How Many Neutrinos Are There? Sterile Neutrinos
<b>May 19</b>	Long-Baseline Neutrino Oscillations and CP Violation
<b>May 26</b>	<i>No lecture</i>
<b>June 2</b>	Where We Are/Where We're Going: Open Questions and Future

# Introduction to Neutrinos

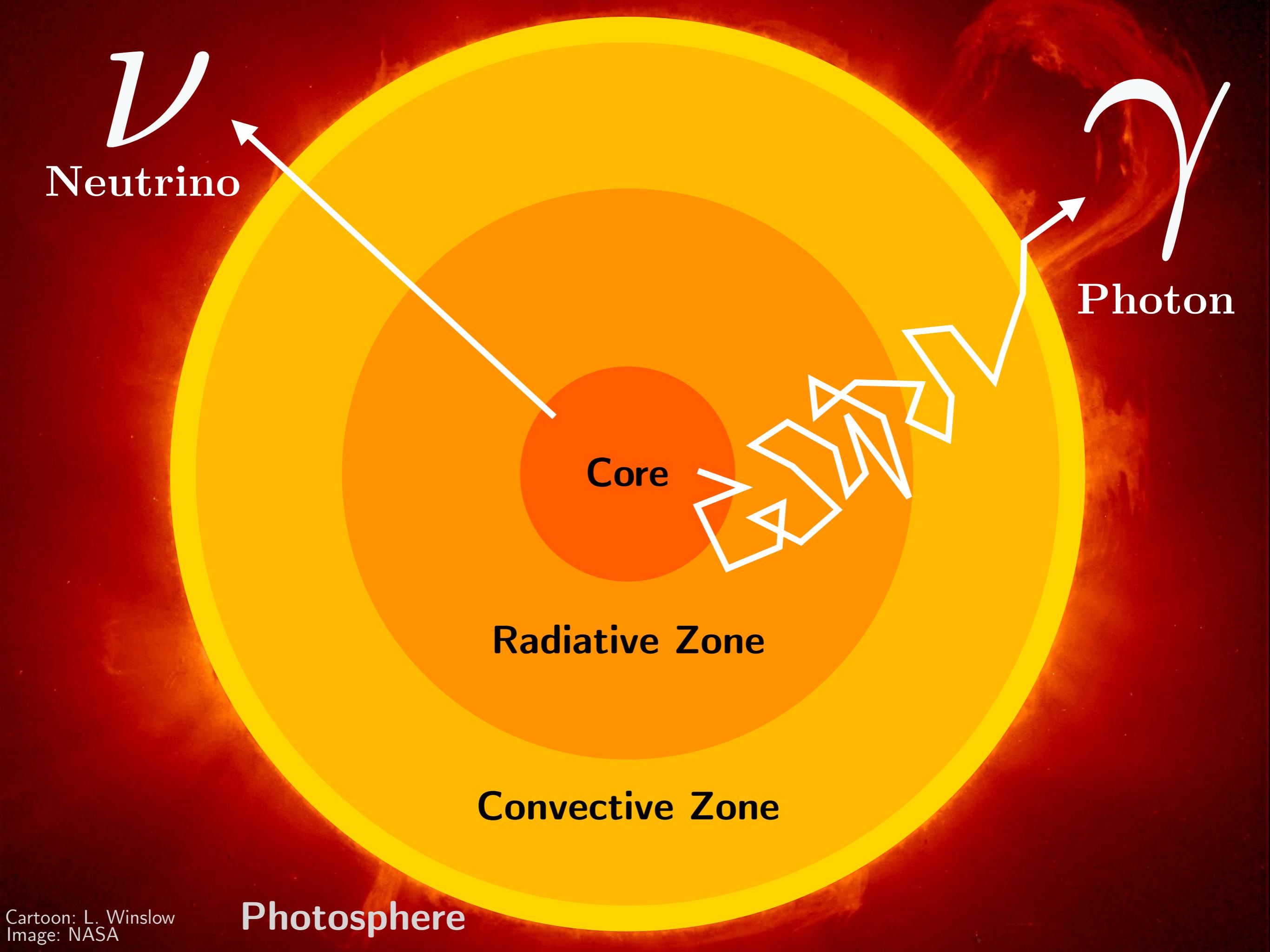
- Fundamental particles
- Very light (massless?)
- No electric charge
- Weak interactions

$$(A, Z) \rightarrow (A, Z + 1) + \beta$$



Interact with matter via the **weak nuclear force**... and don't interact very much at all.

$\nu$   
Solar Neutrinos



$\nu$

Neutrino

$\gamma$

Photon

Core

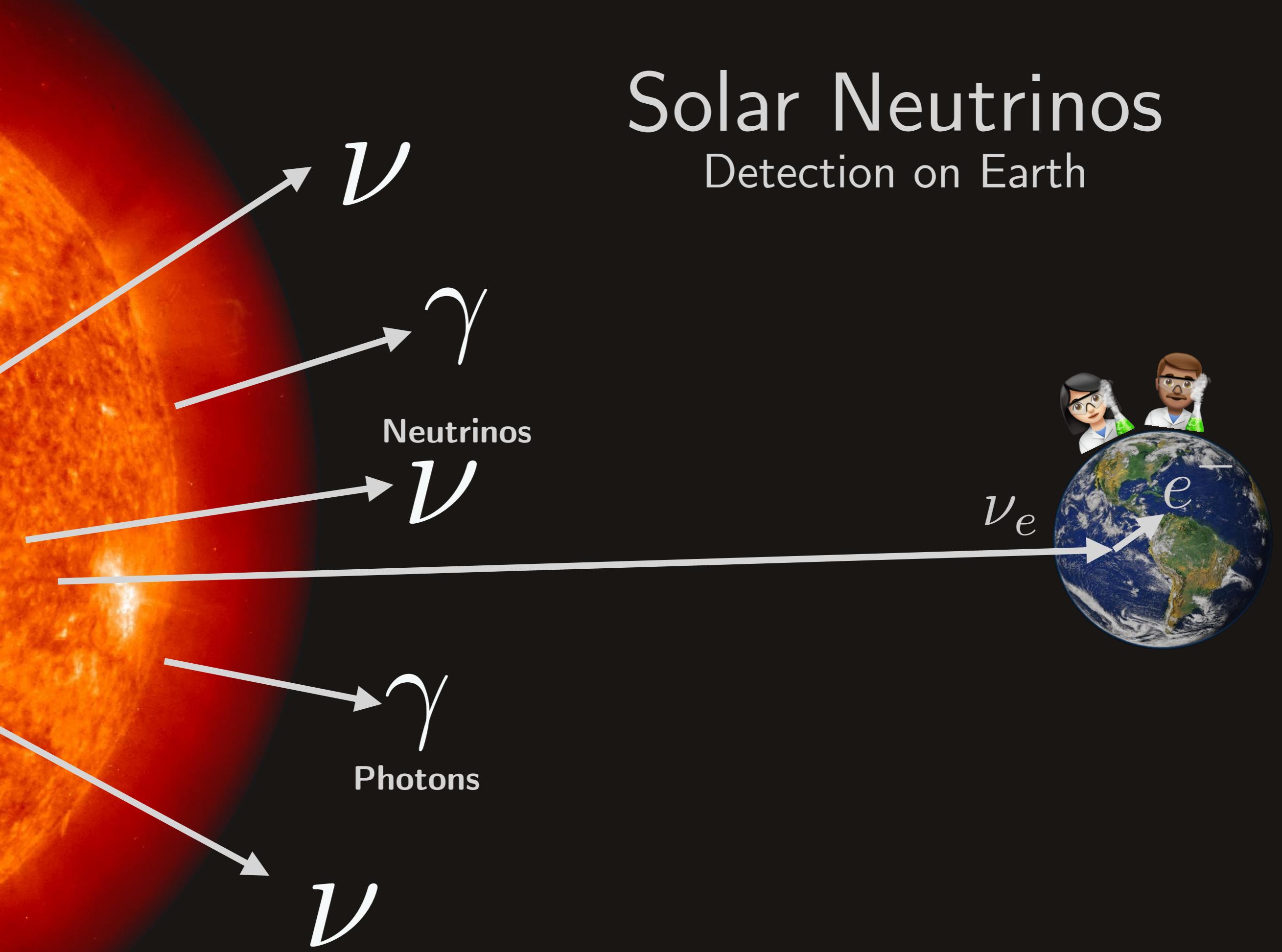
Radiative Zone

Convective Zone

Photosphere

# Solar Neutrinos

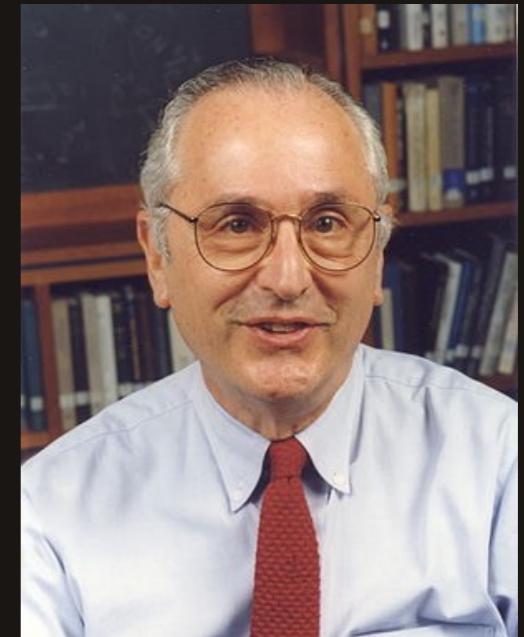
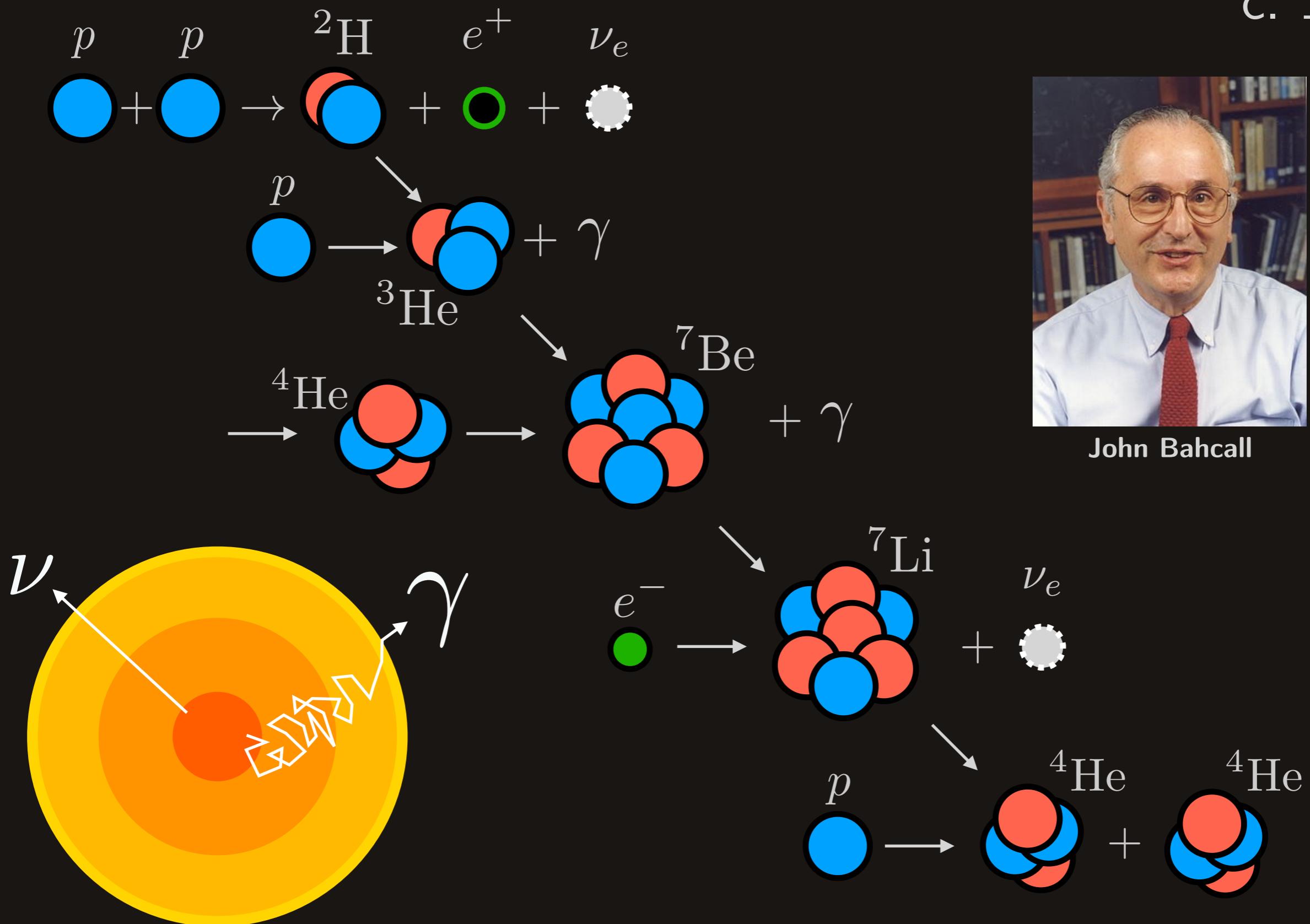
## Detection on Earth



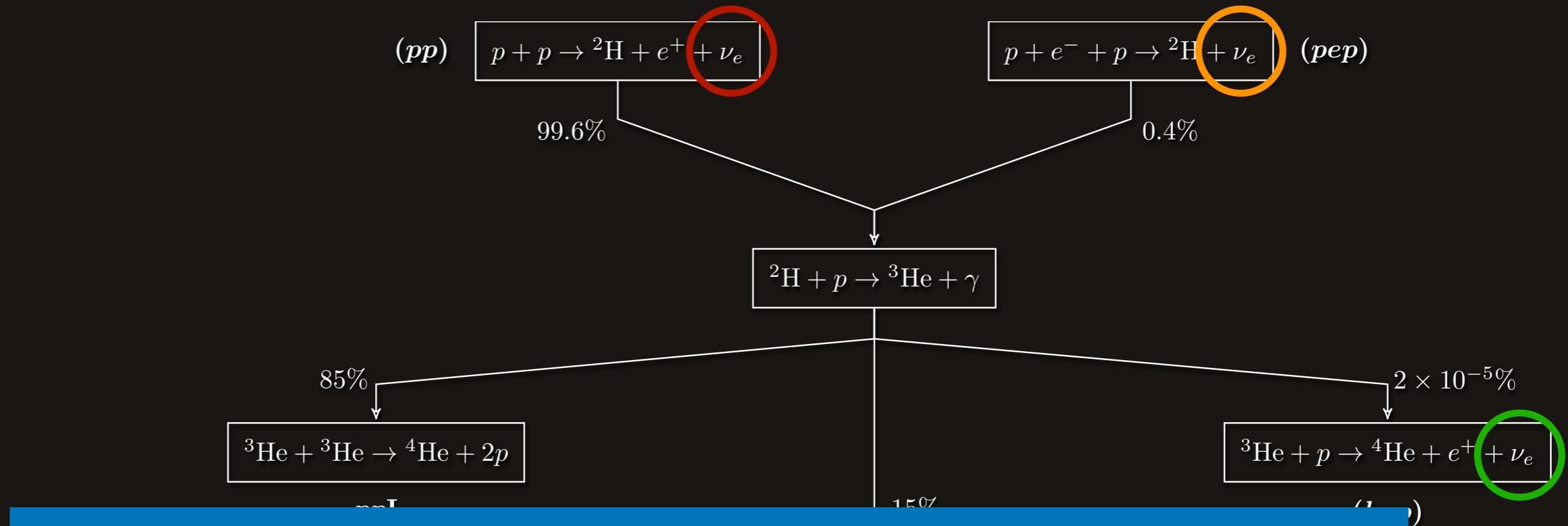
# A Model of the Sun

c. 1960s

## The *ppII* Chain



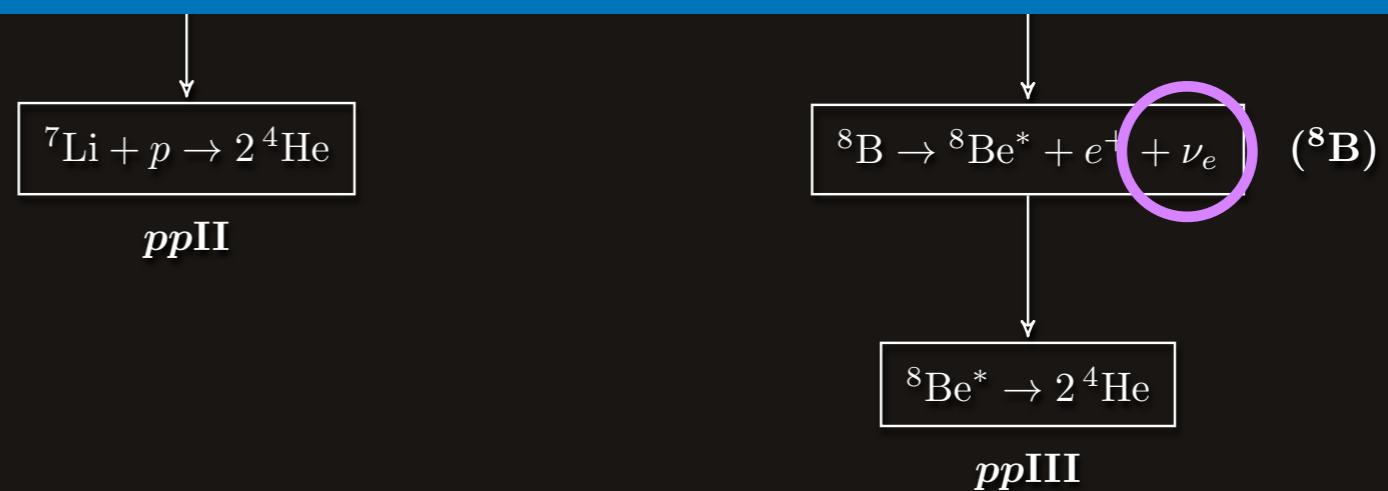
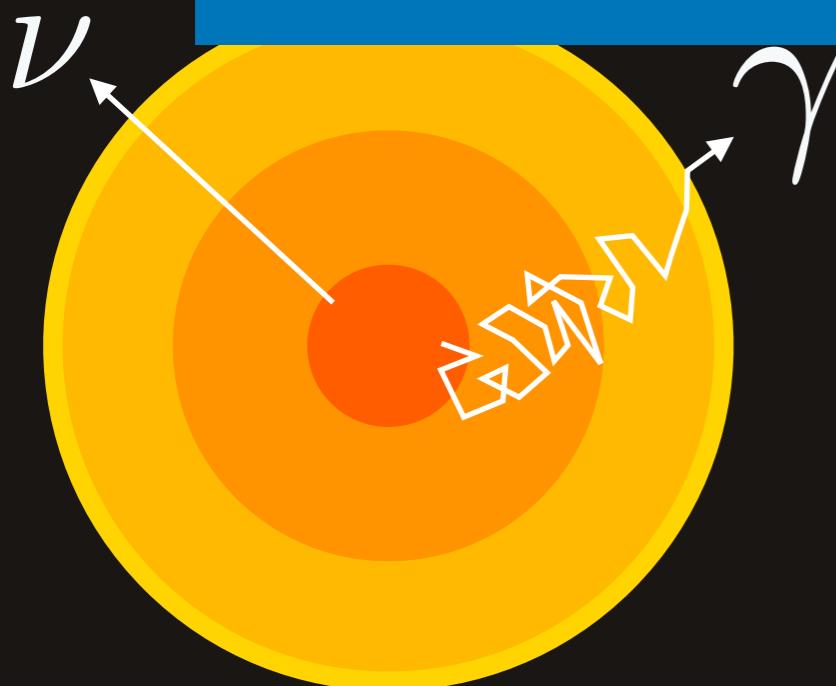
John Bahcall



Several paths, all doing this:



Two electron-type neutrinos for each chain reaction



# A Standard Solar Model

(approximately)

## What We Know

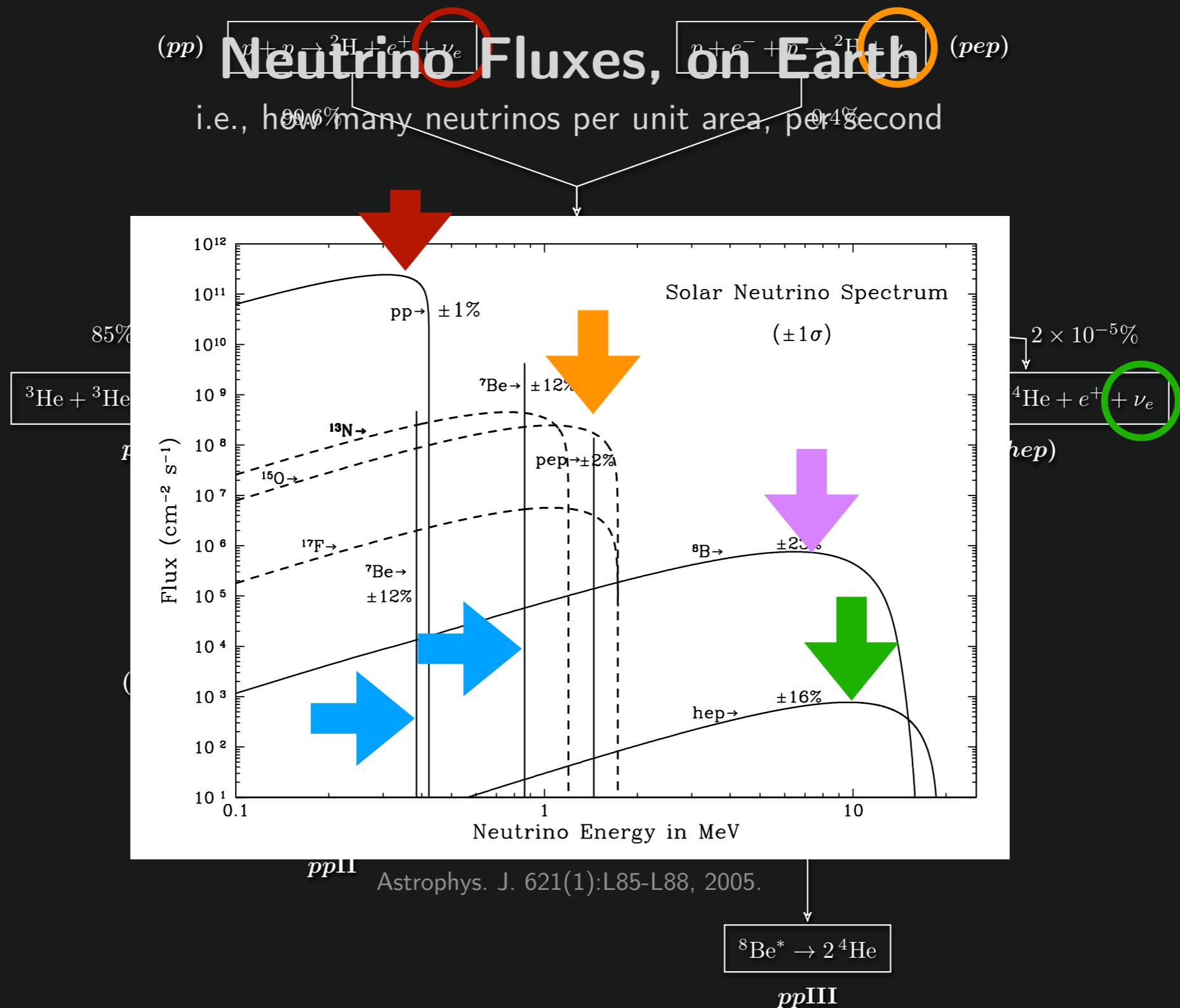
- Mass ( $2 \times 10^{30}$  kg)
- Radius (700,000 km)
- Age (4.6 Gyrs)
- Photon Luminosity ( $3.8 \times 10^{33}$  erg/s)
- Nuclear physics
  - Fusion cross sections
  - Beta decay rates
- Chemical abundances at the photosphere

## What We Don't Know

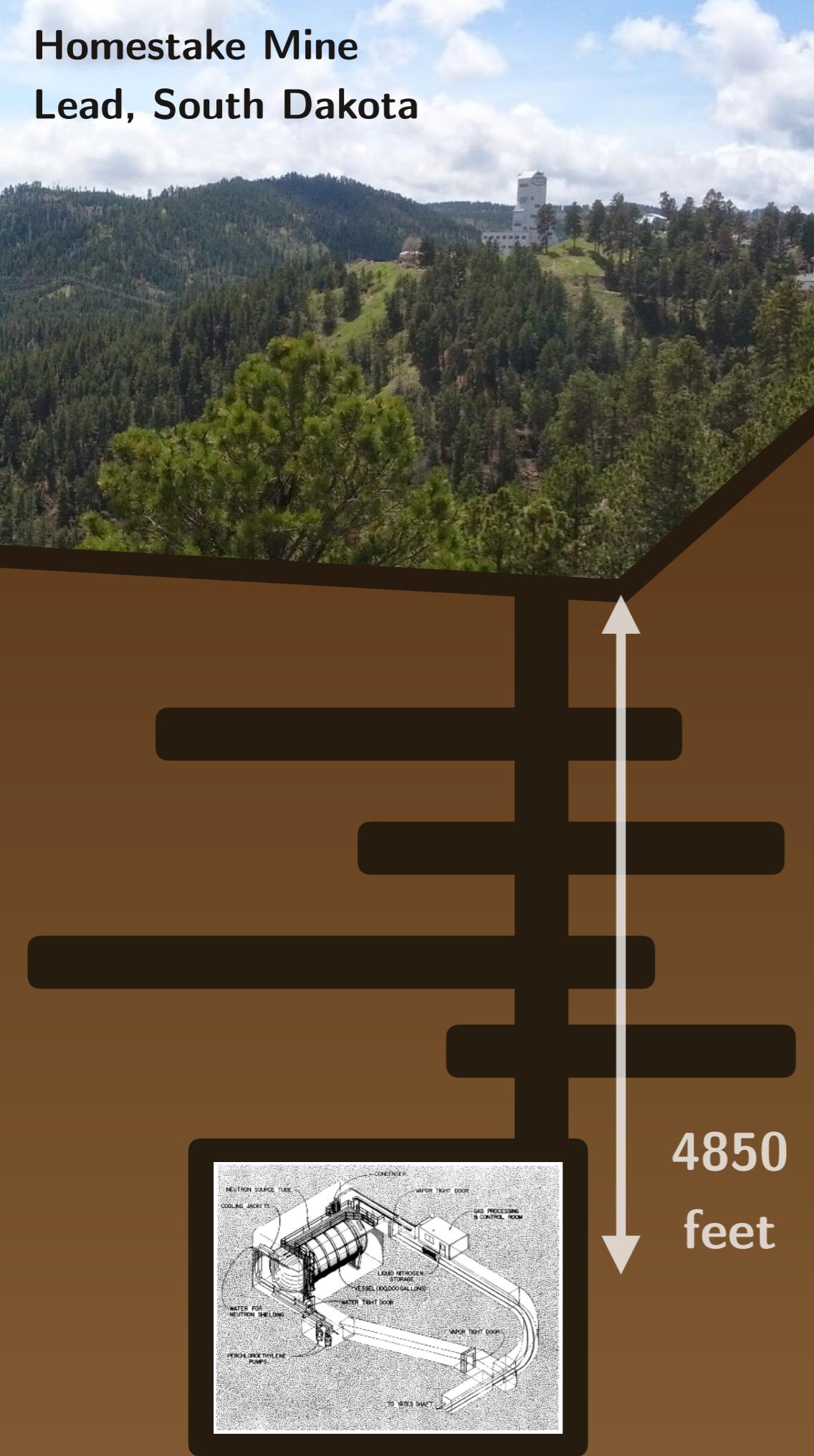


Photo: Princeton University Archives

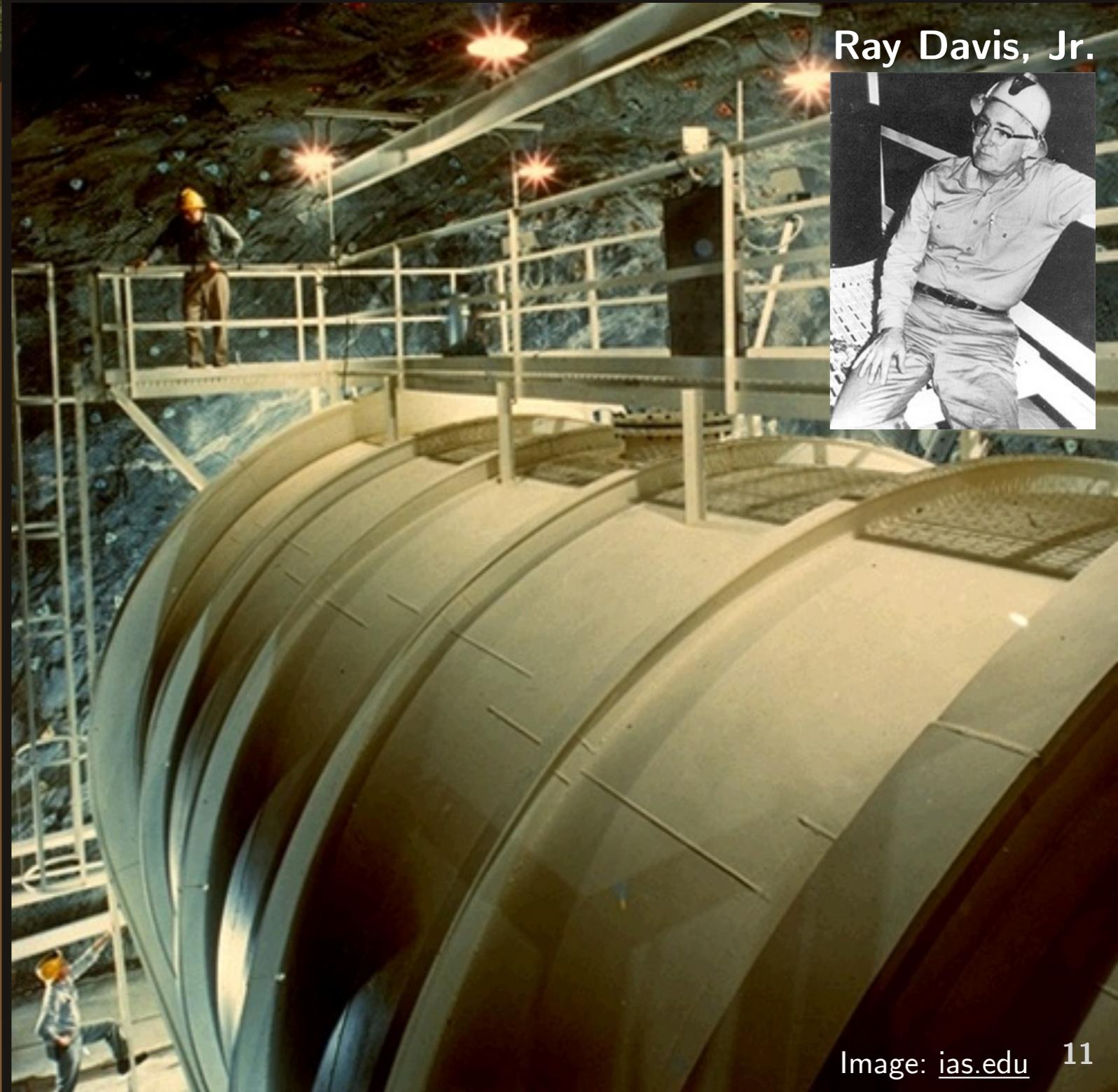
# A Standard Solar Model

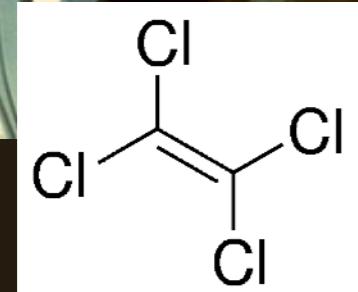


# Homestake Mine Lead, South Dakota



# The Homestake Experiment 1969

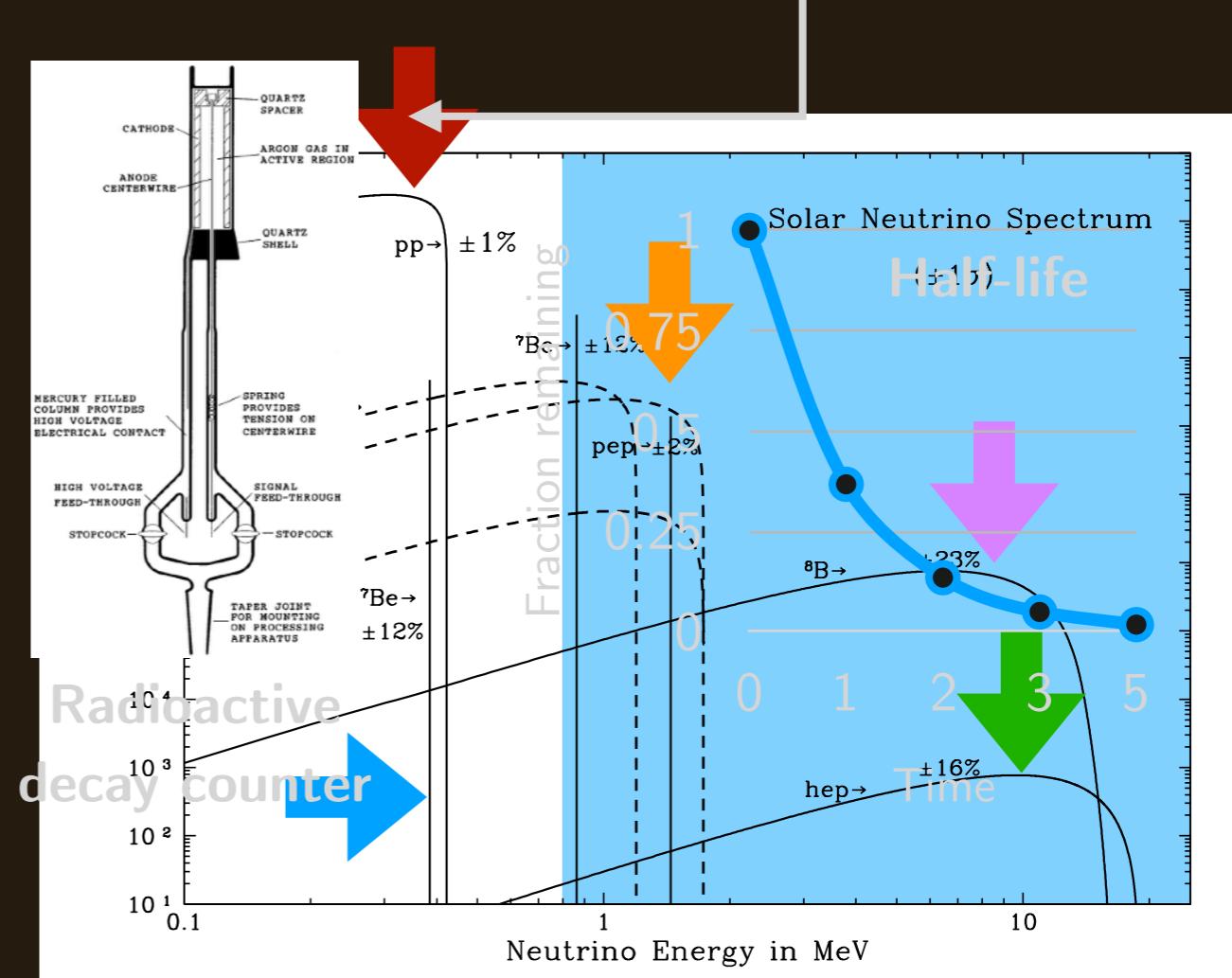




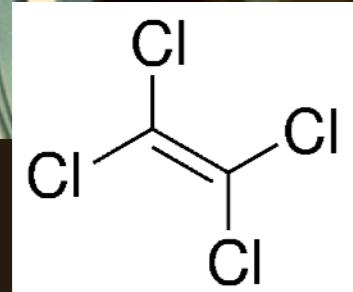
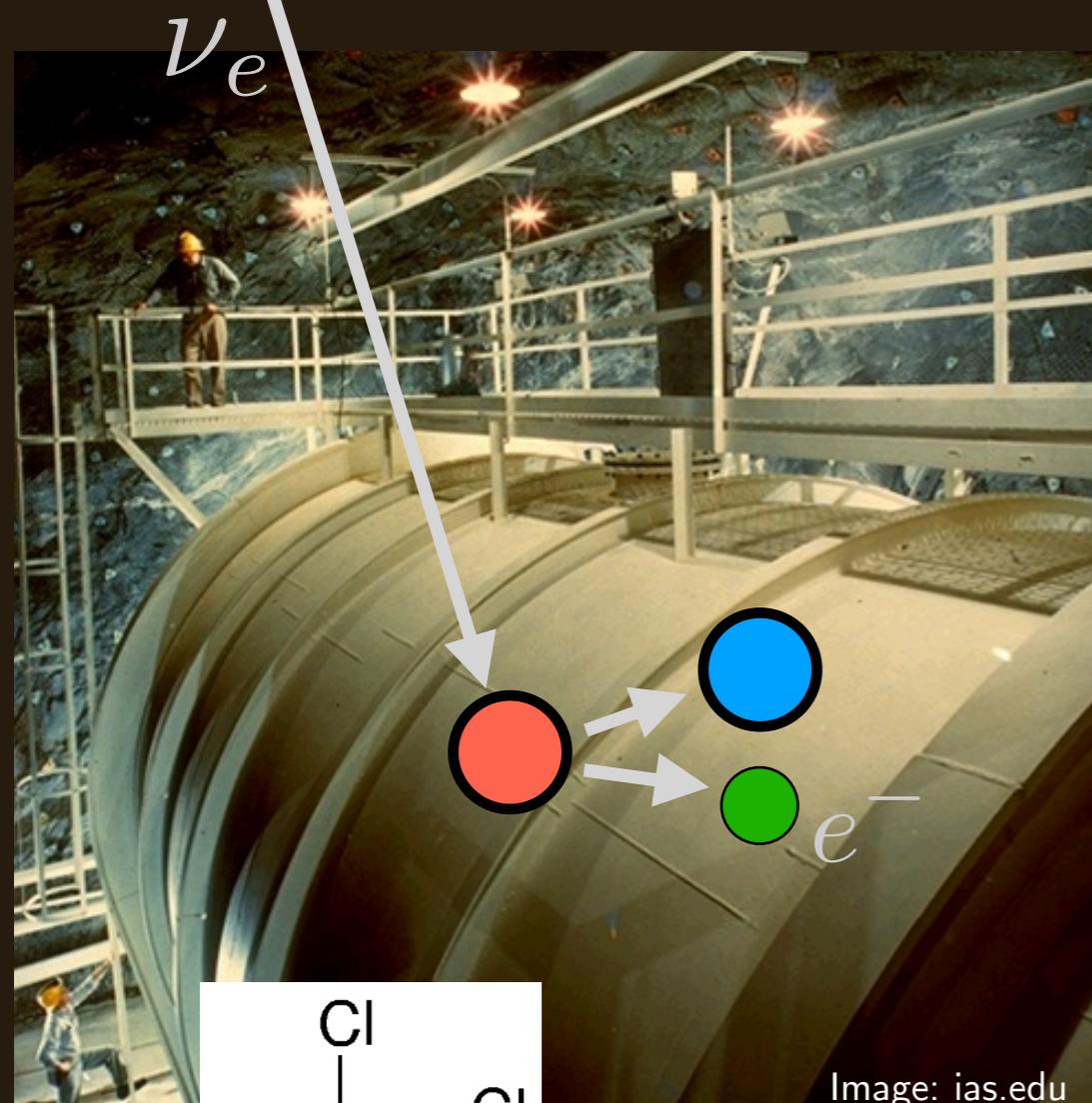
100,000 gallons

Image: [ias.edu](http://ias.edu)

# The Homestake Experiment



Astrophys. J. 621(1):L85-L88, 2005.

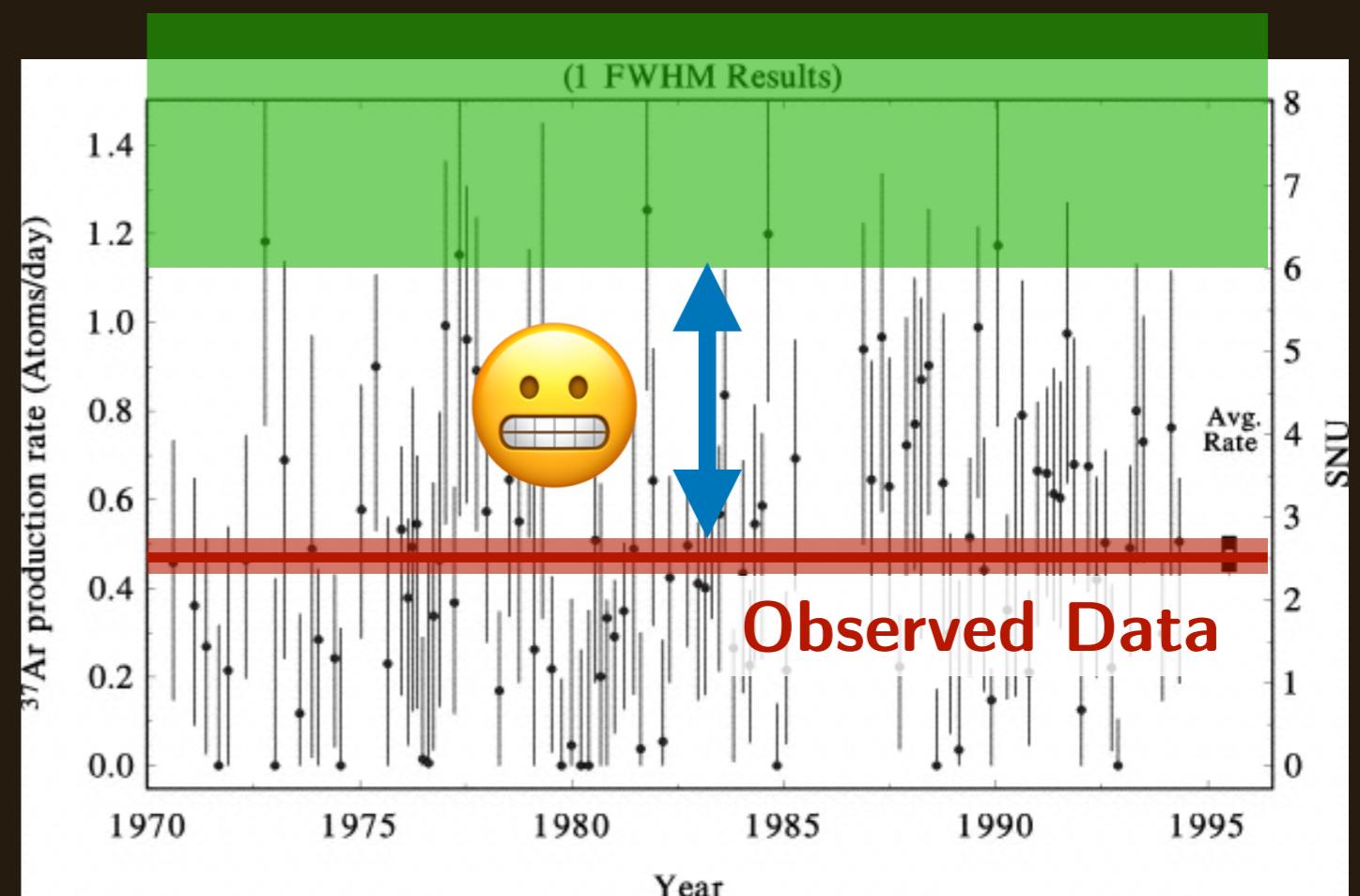


100,000 gallons

# The Homestake Experiment

Data, 1970 - 1995

Theoretical Prediction



# The Solar Neutrino Problem

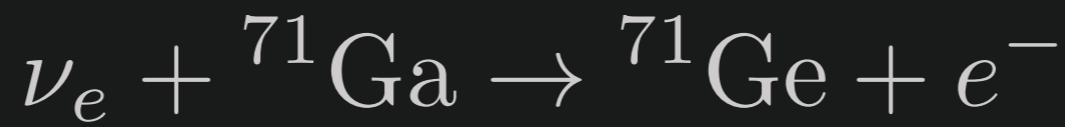
## More Solar Neutrino Experiments

**GALLEX/GNO**

Gran Sasso, Italy



<https://lappweb.in2p3.fr/neutrinos/anexp.html>

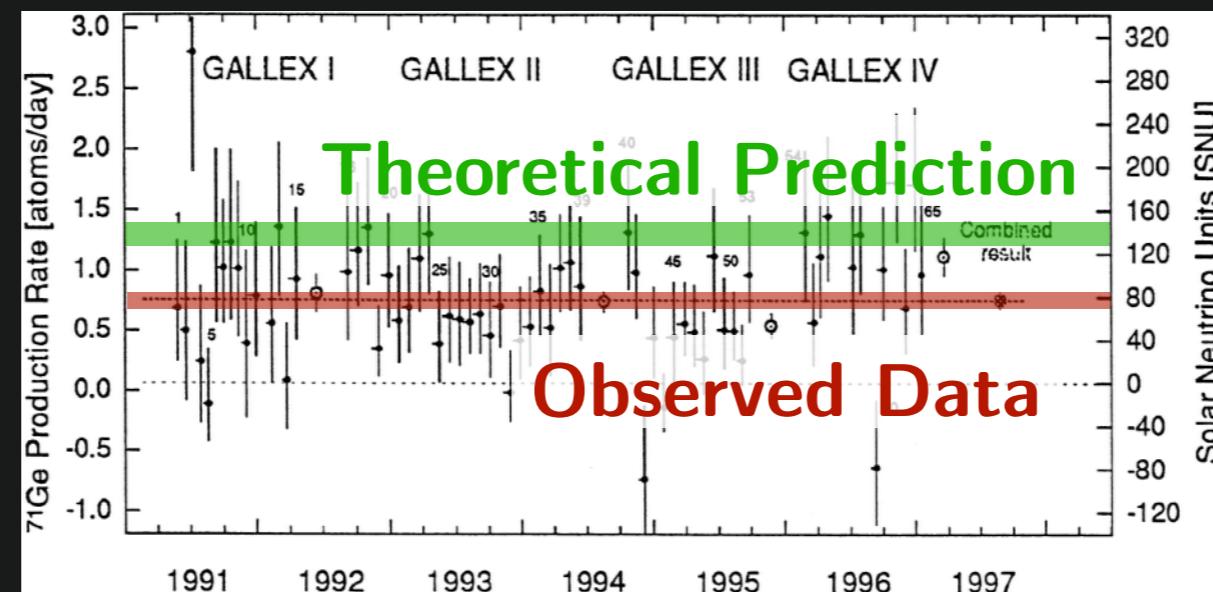


**SAGE**

Baksan, Russia

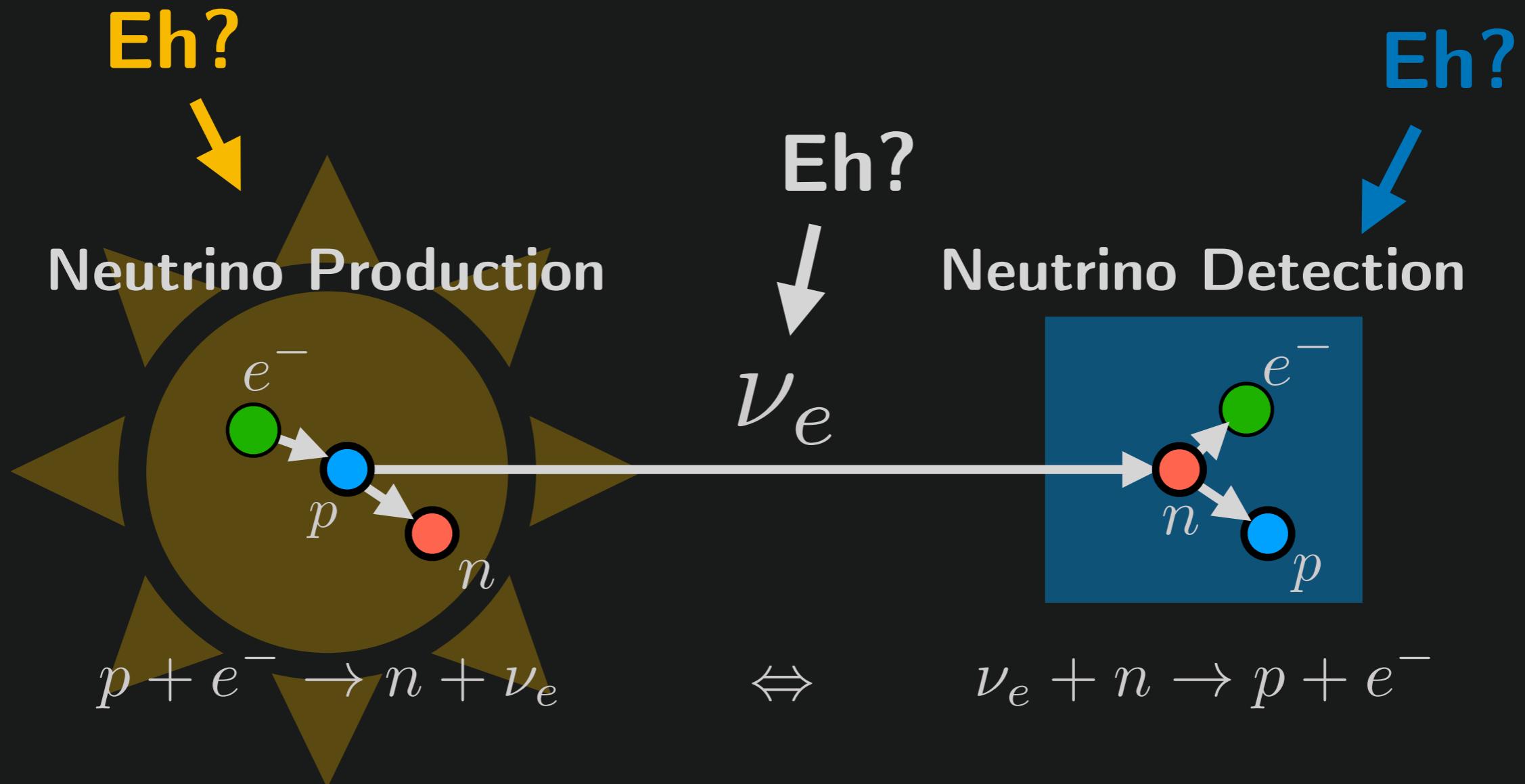


<http://cerncourier.com/cws/article/cern/68795>



Also a significant discrepancy  
with the theory!

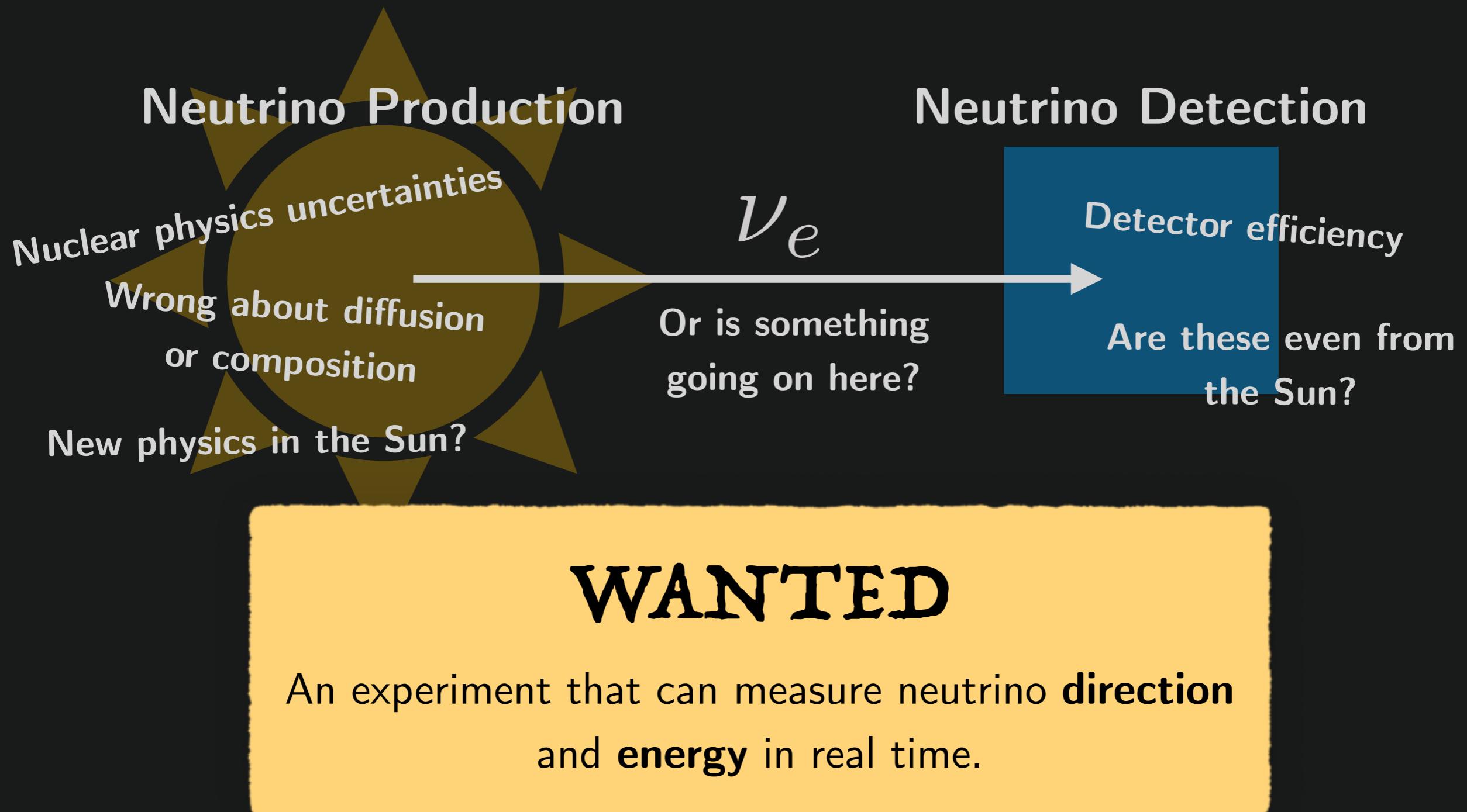
# The Solar Neutrino Problem



But only about 1/3 of them show up!

# The Solar Neutrino Problem

## Some Healthy Skepticism



# KamiokaNDE-II

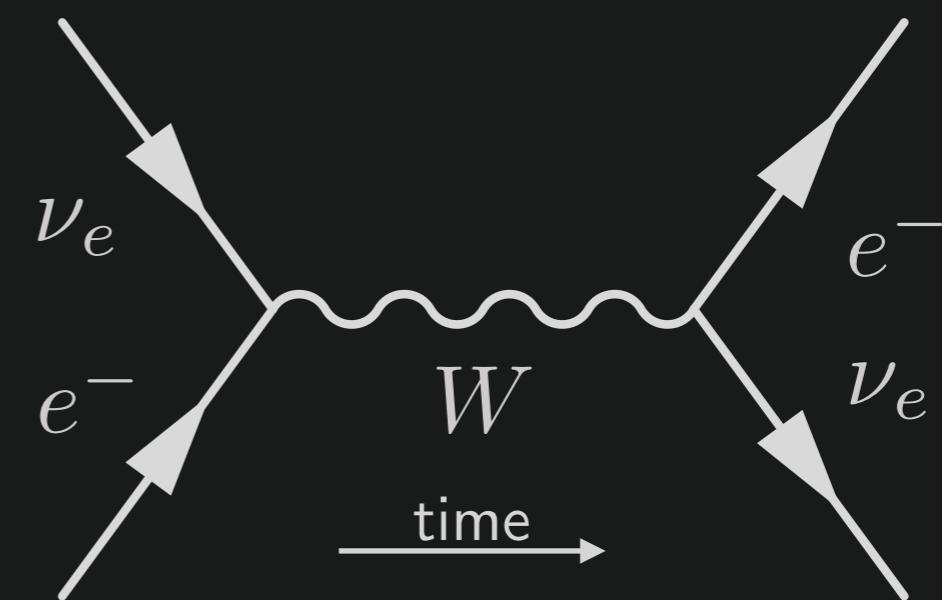
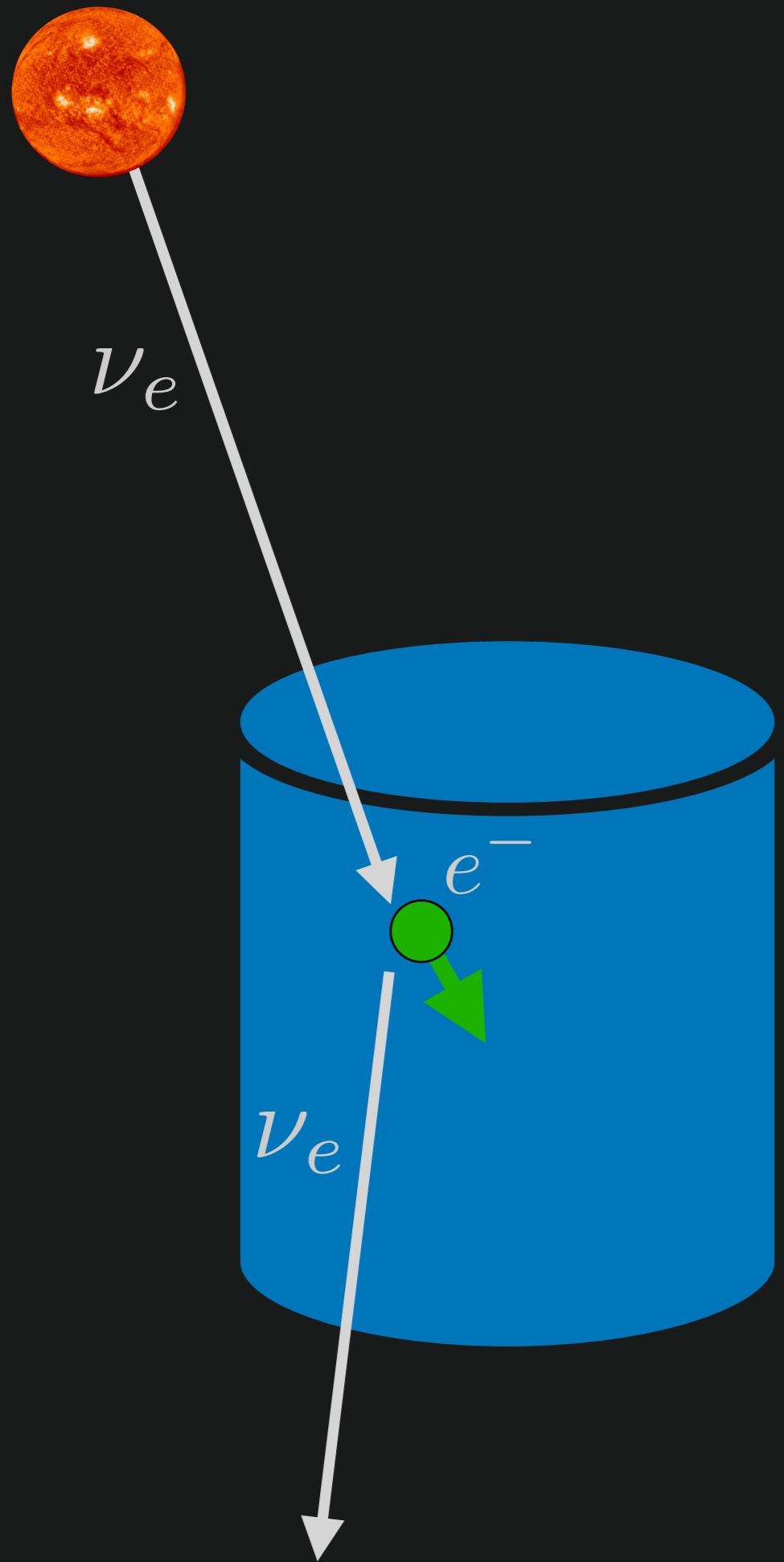
Kamioka, Hida, Japan

Water  
(3000 tons)

16 m



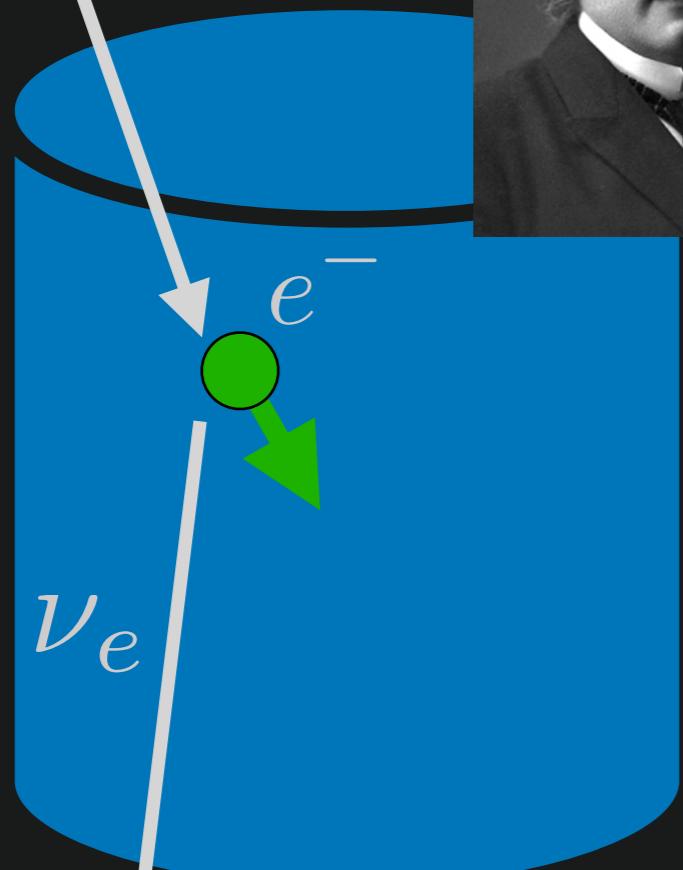
Photomultiplier  
Tube  
( $\times 1000$ )



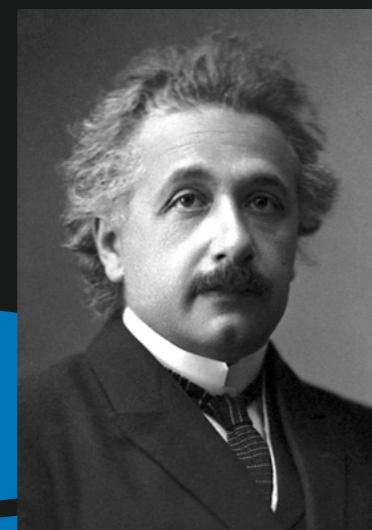


# Special Relativity Detour

$\nu_e$



A. Einstein



**SPEED  
LIMIT**

$c$

**186,282**  
mi / second

in empty  
space!

**SLOW  
WATER  
ZONE**

**SPEED  
LIMIT**  
 $c/1.33$

**140,061**  
mi / second

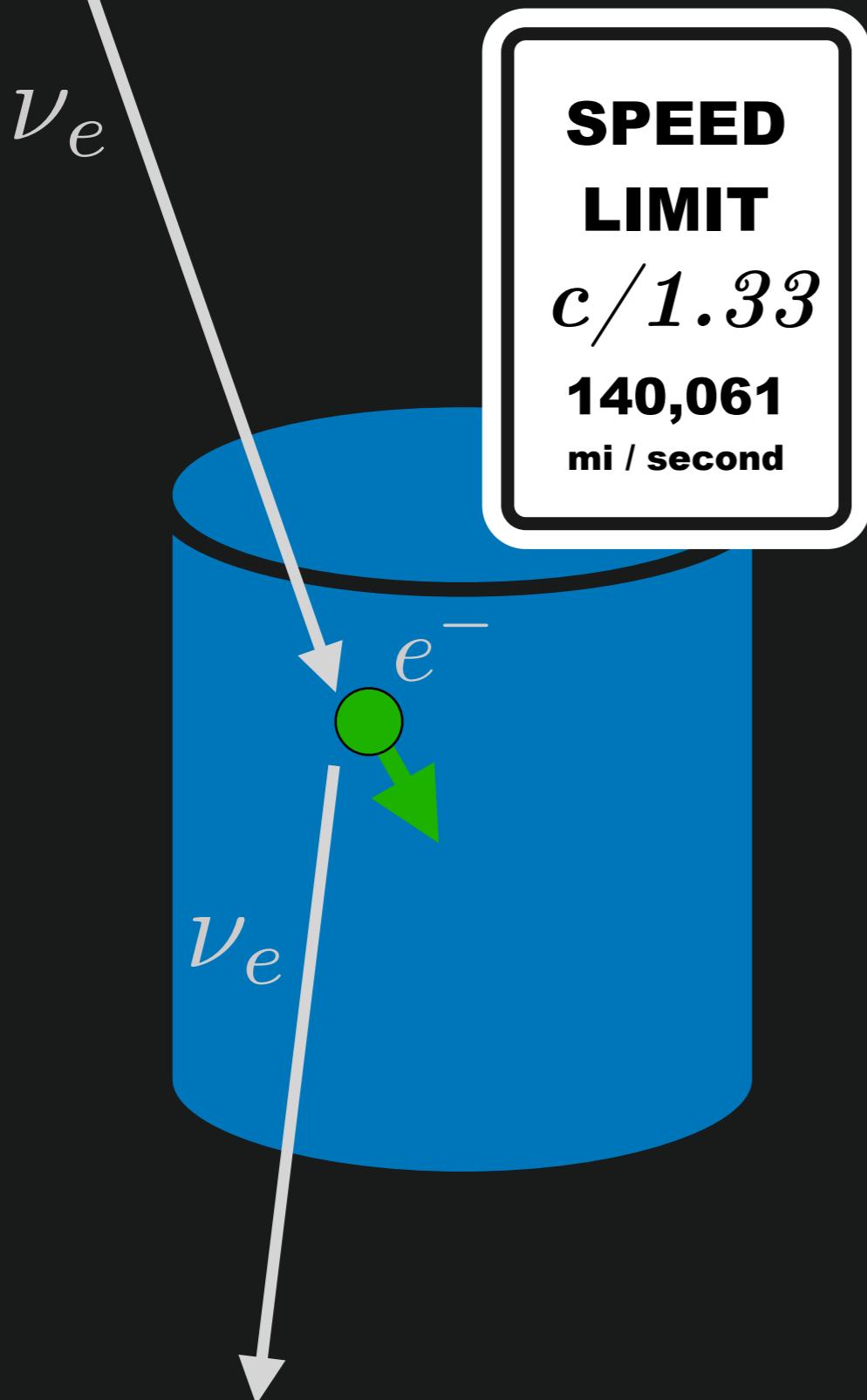
In general,  $v = c / n$

velocity  
of light

index of  
refraction



# Special Relativity Detour



**Solar Neutrino Energy**

$$T_e = E_\nu = 15 \text{ MeV}$$

**Special Relativity**

$$v_e = \frac{c\sqrt{T(T + 2m_e c^2)}}{K + m_e c^2}$$

**Electron Velocity**

$$\begin{aligned} v_e &= 186,181 \text{ mi/second} \\ &= 0.99946c \end{aligned}$$

**Now What!?**



# Special Relativity Detour

$\nu_e$

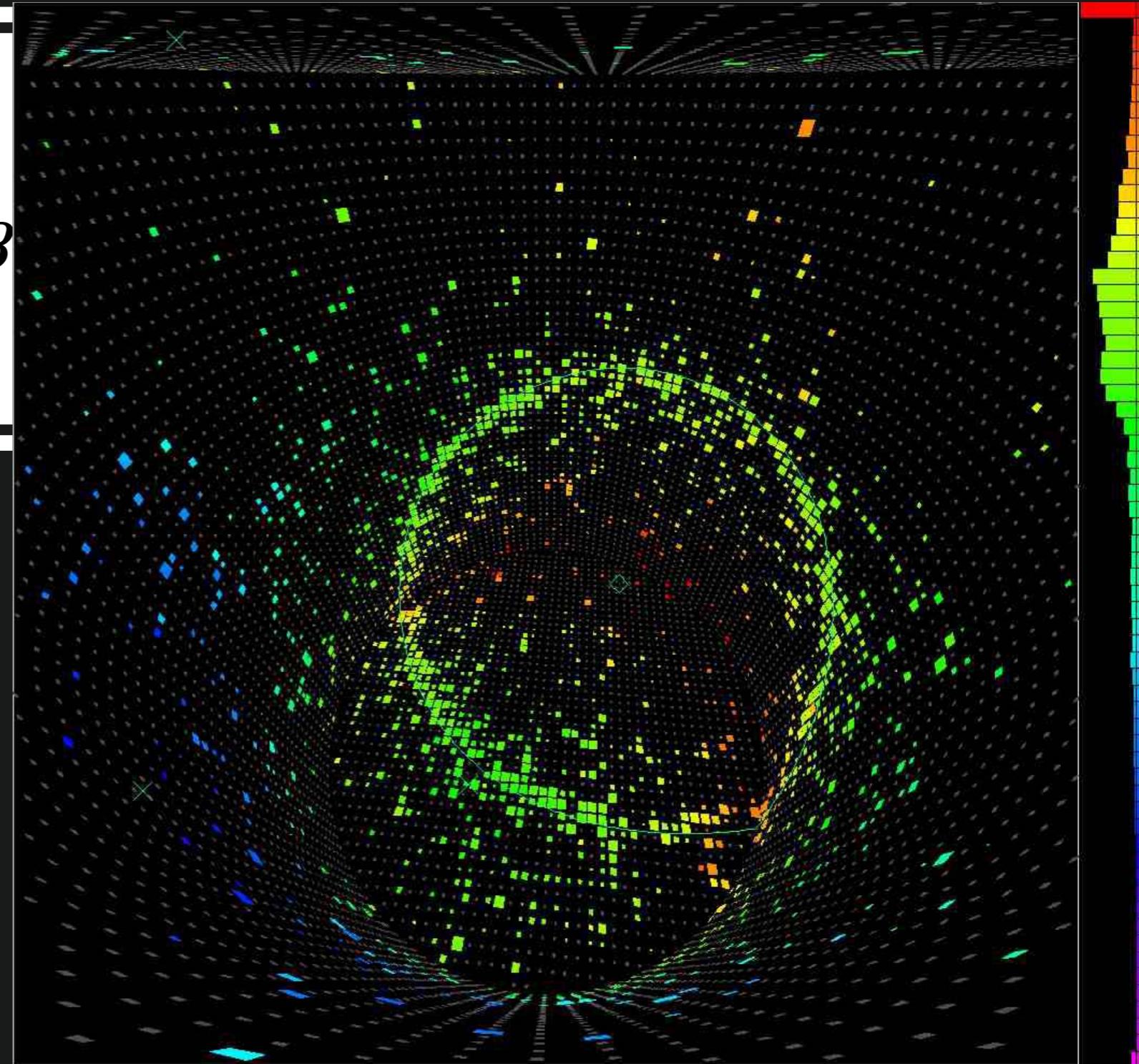
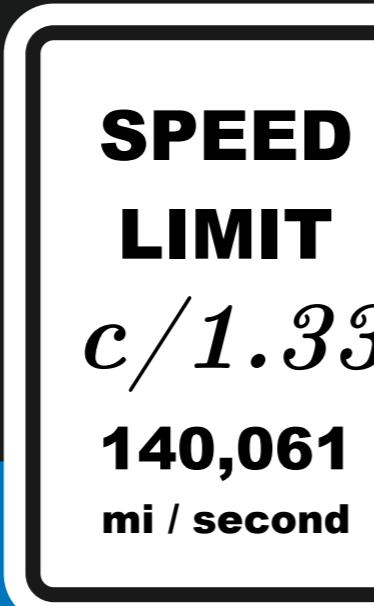
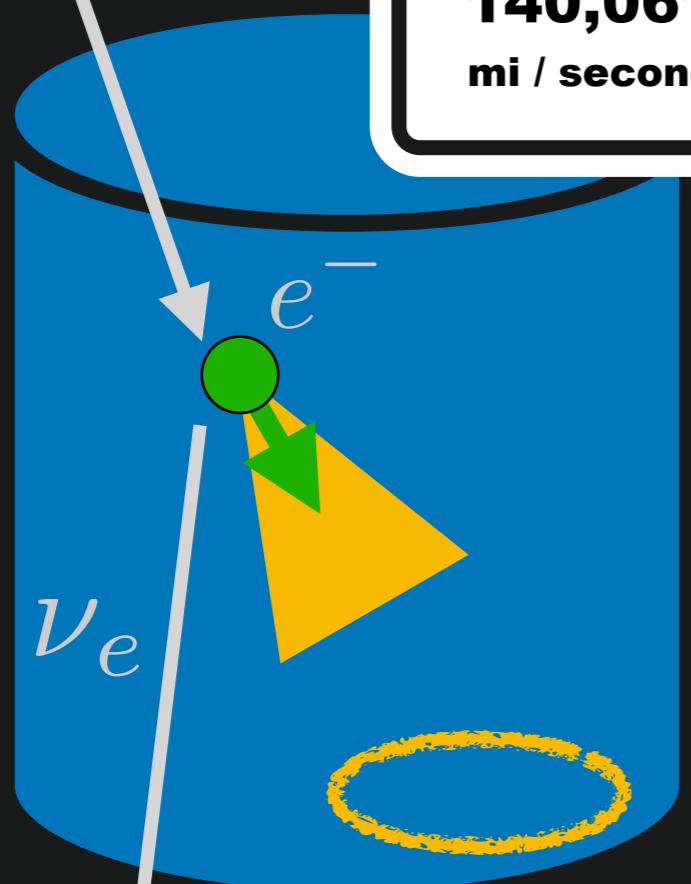
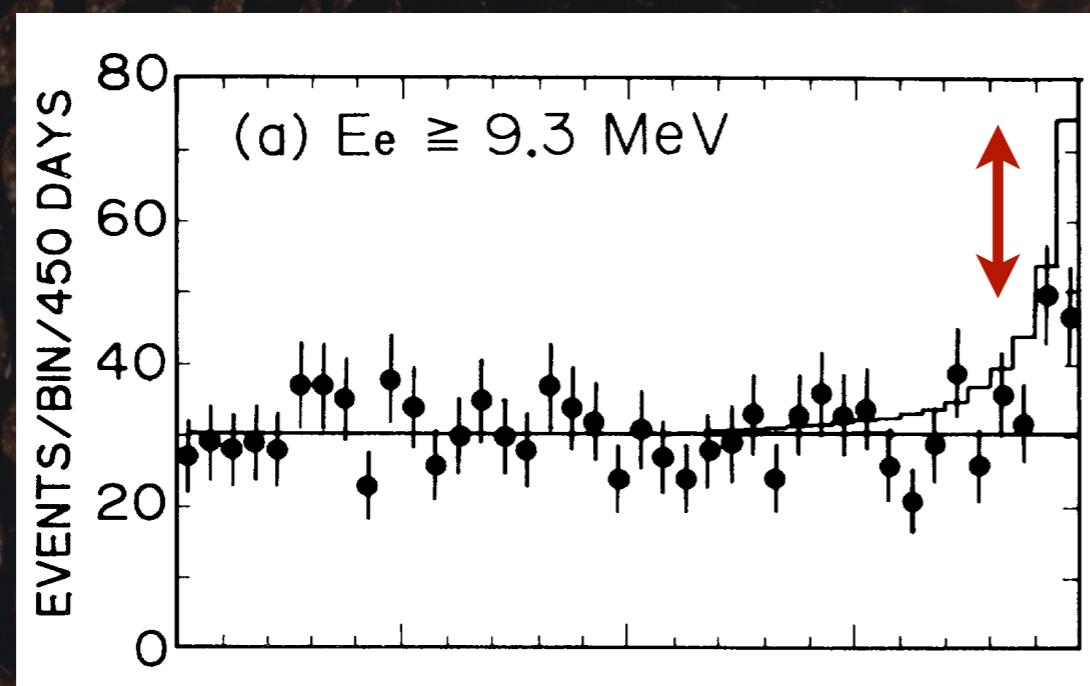


Image: Super-Kamiokande Collaboration

**Observation of  ${}^8\text{B}$  Solar Neutrinos in the Kamiokande-II Detector**

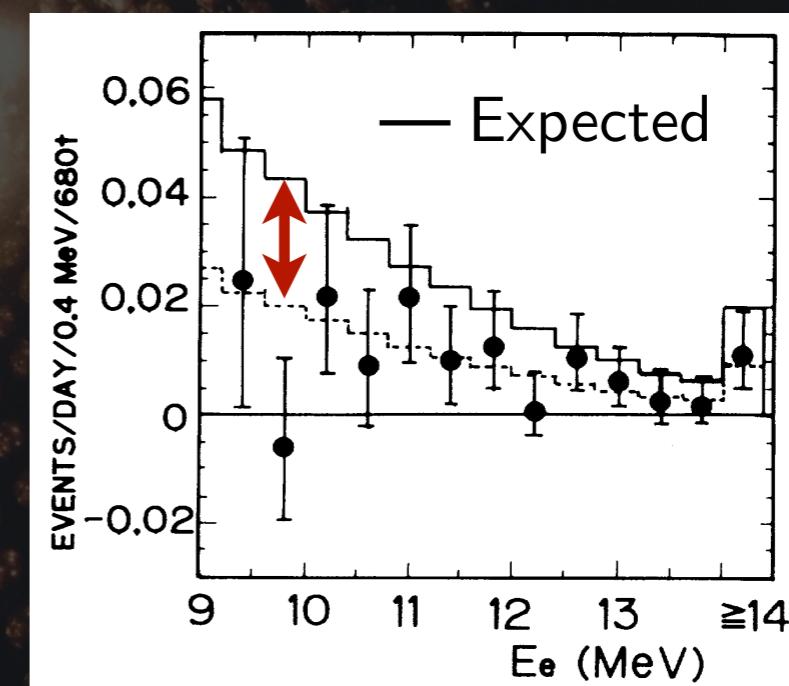


Toward the Sun

From the Sun

### Angle to the Sun

These neutrinos are coming from the Sun



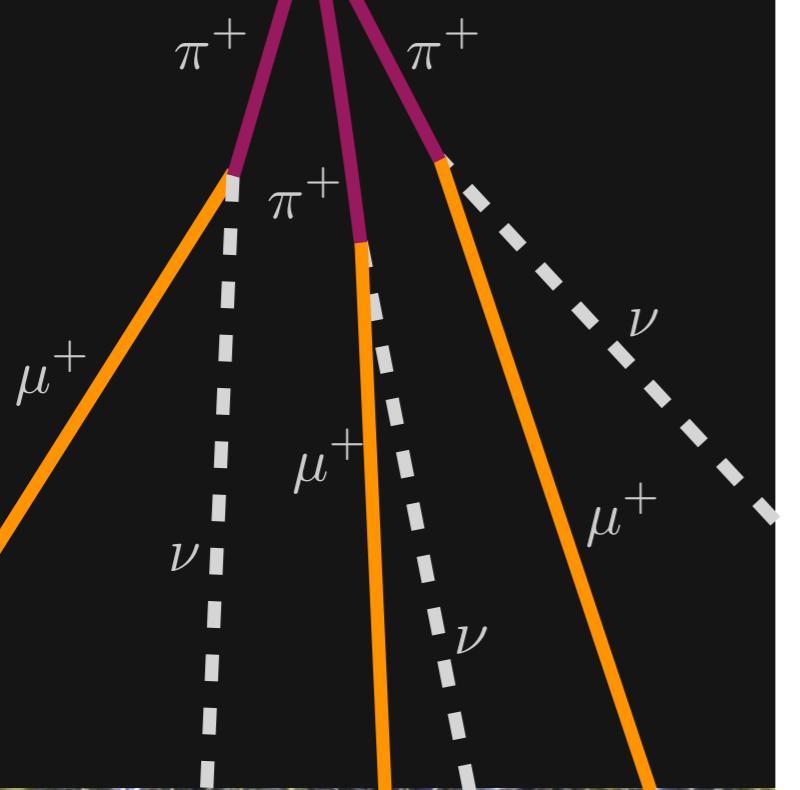
9    10    11    12    13     $\geq 14$   
 $E_e (\text{MeV})$

### Neutrino Energy

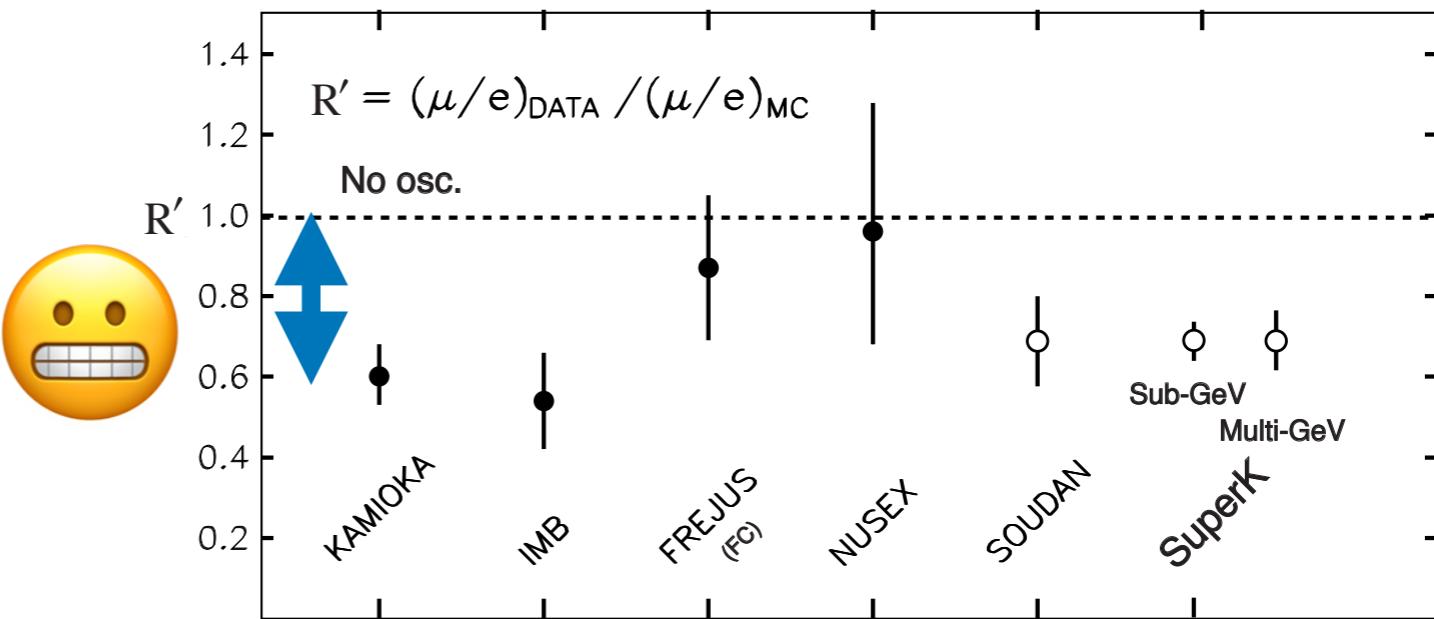
Agrees with the solar model... just too few neutrinos

Primary  
Cosmic Ray

Atmosphere  
Stuff



## The Atmospheric Neutrino Anomaly



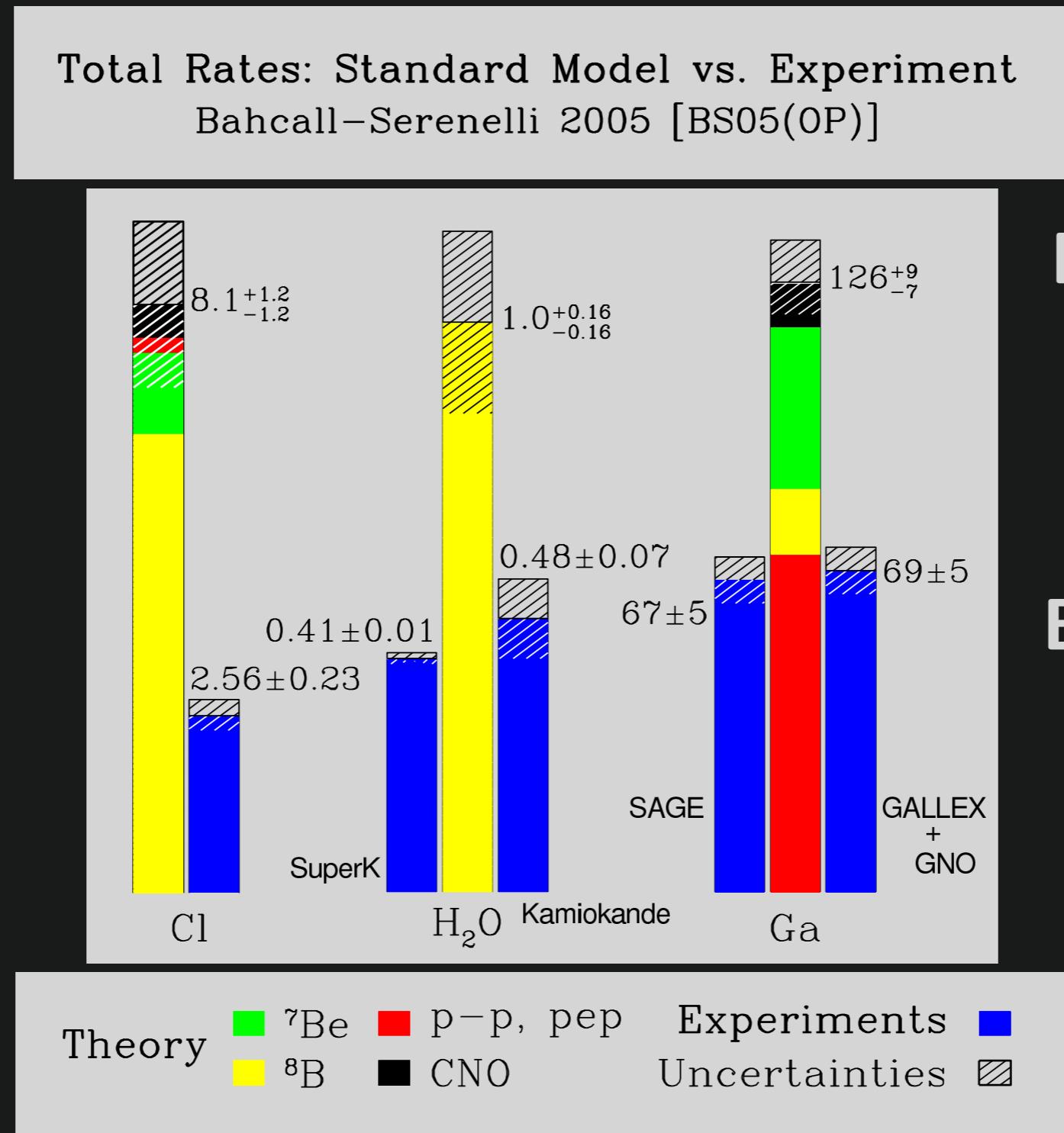
Missing neutrinos from cosmic rays, too!

This turns out to be the same issue as the solar neutrinos,  
and what we learn is thanks to **both** measurements.

Super-Kamiokande  
Kamioka, Hida, Japan

50,000 tons of water

# The Solar Neutrino Problem



$\nu\nu\nu$

# Solving the Solar Neutrino Problem

## Neutrino Oscillations

Perhaps solar neutrinos start out  
as  $\nu_e$ , but en route to Earth some  
of them change to other types ...



... evading detection in our  
solar neutrino detectors, which  
can only see  $\nu_e$

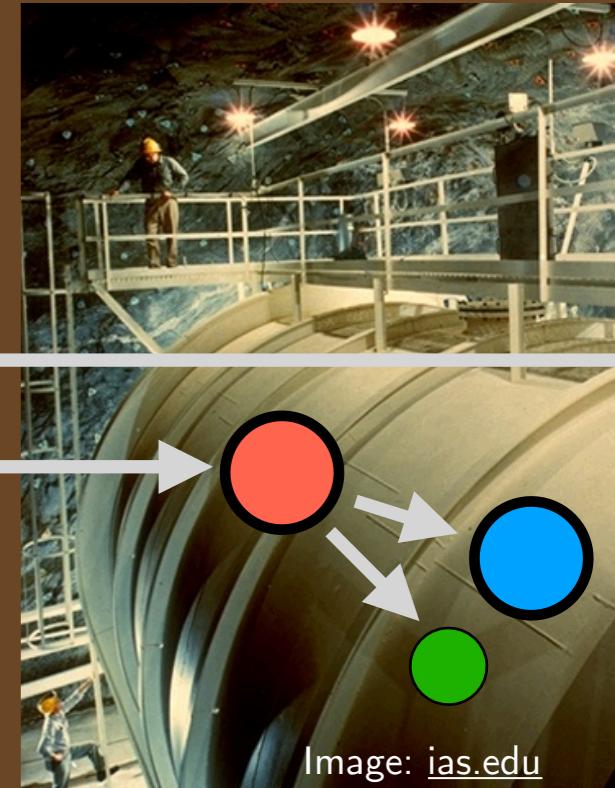
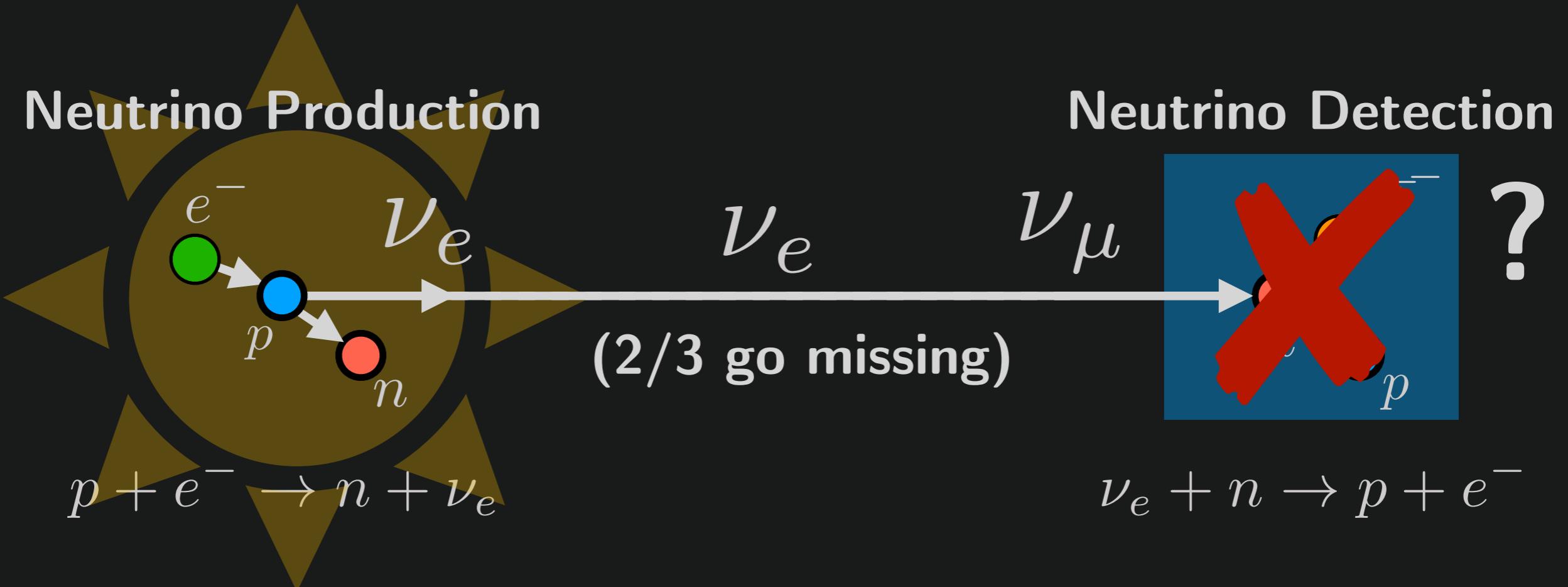


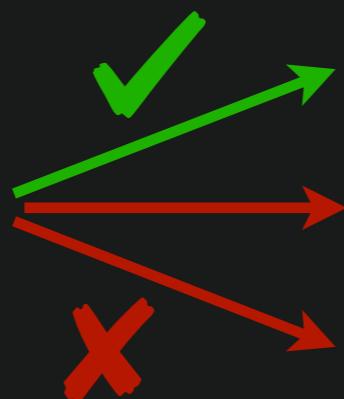
Image: [ias.edu](http://ias.edu)

# The Solar Neutrino Problem



$$E = mc^2$$

$$E_\nu \sim 20 \text{ MeV}$$



$m_e = 0.511 \text{ MeV}/c^2$  **electron**

$m_\mu = 105 \text{ MeV}/c^2$  **muon**

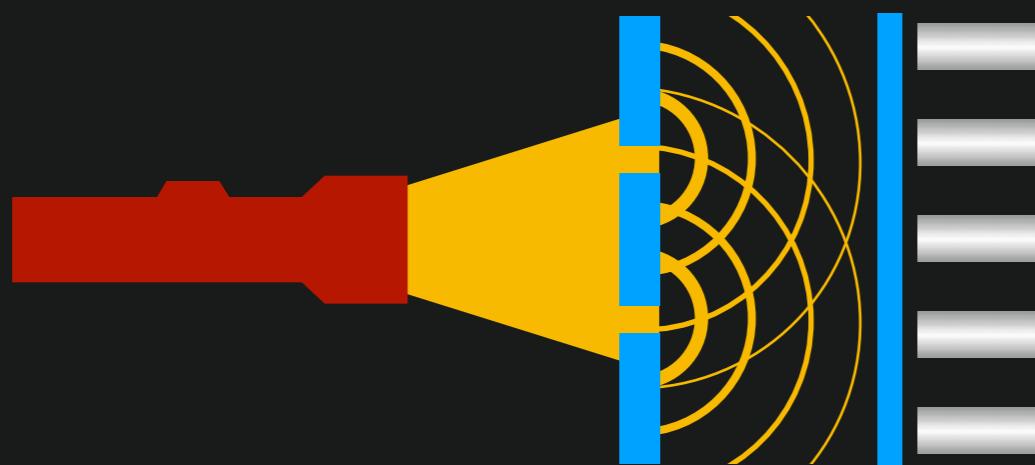
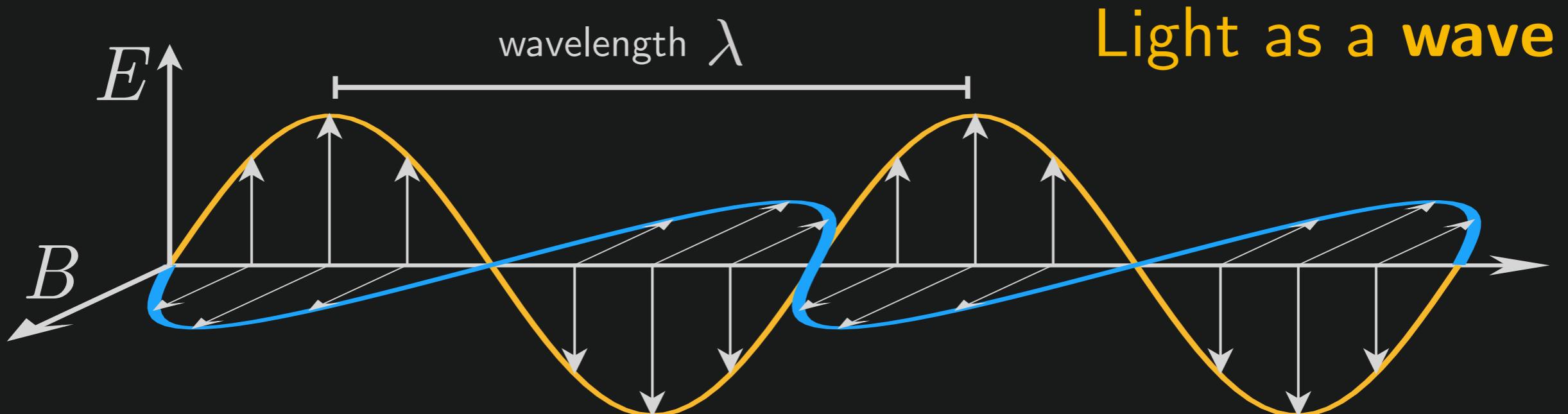
$m_\tau = 1776 \text{ MeV}/c^2$  **tau**

v  
A Little  
Quantum Physics

# A Little Bit of Quantum Physics

## 1. Wave-Particle Duality

Sometimes things behave like **particles**, sometimes like **waves**



Interference  
patterns,  
like water



# A Little Bit of Quantum Physics

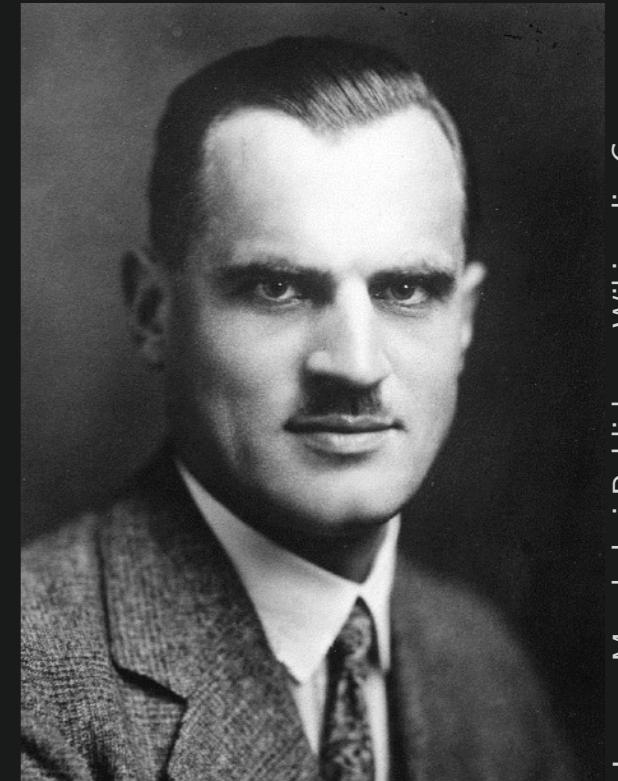
## 1. Wave-Particle Duality

Sometimes things behave like **particles**, sometimes like **waves**

Light as a **particle**  
(Compton scattering)



Scattering changes the wavelength, hence energy



Arthur Holly Compton, 1927

(Like the lecture series!)

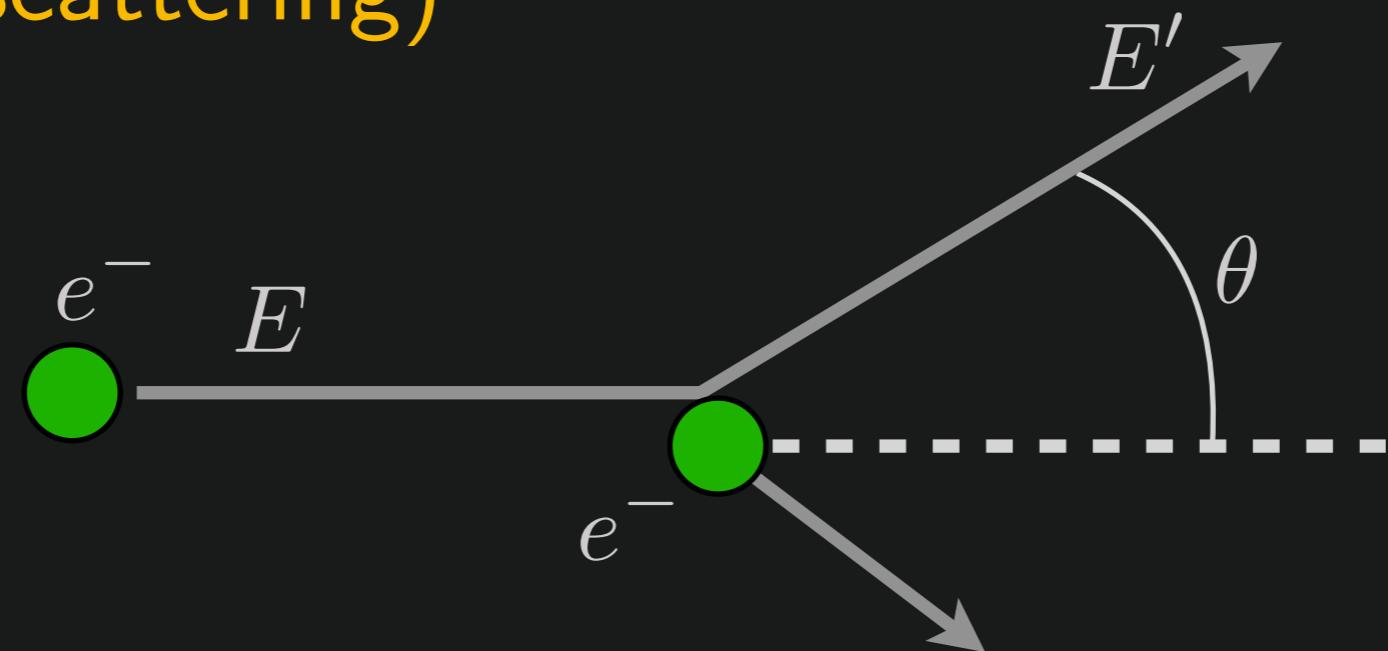
$$E = \frac{hc}{\lambda} \quad \lambda' - \lambda = \frac{h}{m_e c} (1 - \cos \theta)$$

# A Little Bit of Quantum Physics

## 1. Wave-Particle Duality

Sometimes things behave like **particles**, sometimes like **waves**

Electron as a **particle**  
(Møller scattering)



Scattering changes the energy

# A Little Bit of Quantum Physics

## 1. Wave-Particle Duality

Sometimes things behave like **particles**, sometimes like **waves**

Electron as a **wave**



Interference  
patterns,  
like water



CC BY 2.0 Scott Robinson, Wikimedia Commons

Matter acts like  
a wave!

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

de Broglie wavelength



Louis de Broglie

# A Little Bit of Quantum Physics

## 2. Superposition of States

A quantum mechanical system can be in multiple states simultaneously

Two Kinds of Pets



cat



dog

A Quantum Mechanical Pet

$$\frac{|\text{cat}\rangle + |\text{dog}\rangle}{\sqrt{2}}$$

cat 50% of the time,  
dog 50% of the time

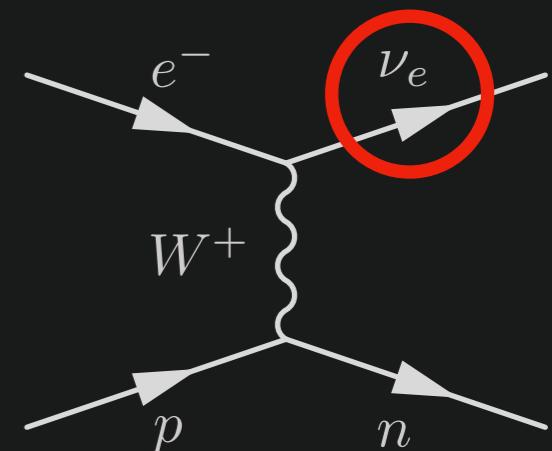
$\nu$

Back to Neutrinos

# Neutrino Oscillations

First, let's assume the neutrino has a **tiny but nonzero mass**

Now, let's say the neutrinos produced in weak interactions do not have a well-defined mass  
("flavor eigenstates")

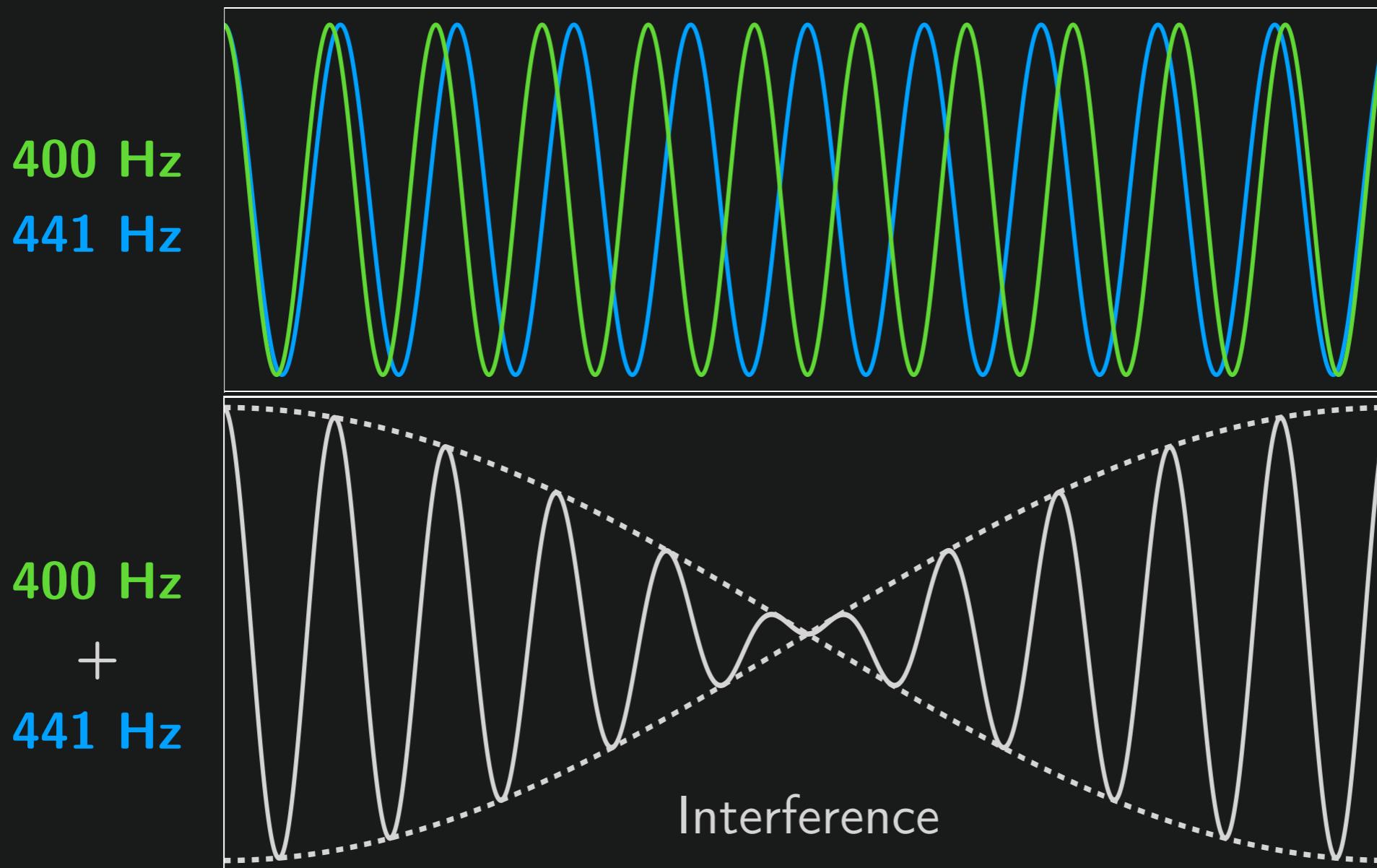


But rather are different mixtures of neutrinos that do have well-defined masses (and hence wavelengths)  
("mass eigenstates")



# Neutrino Oscillations

Sound Waves

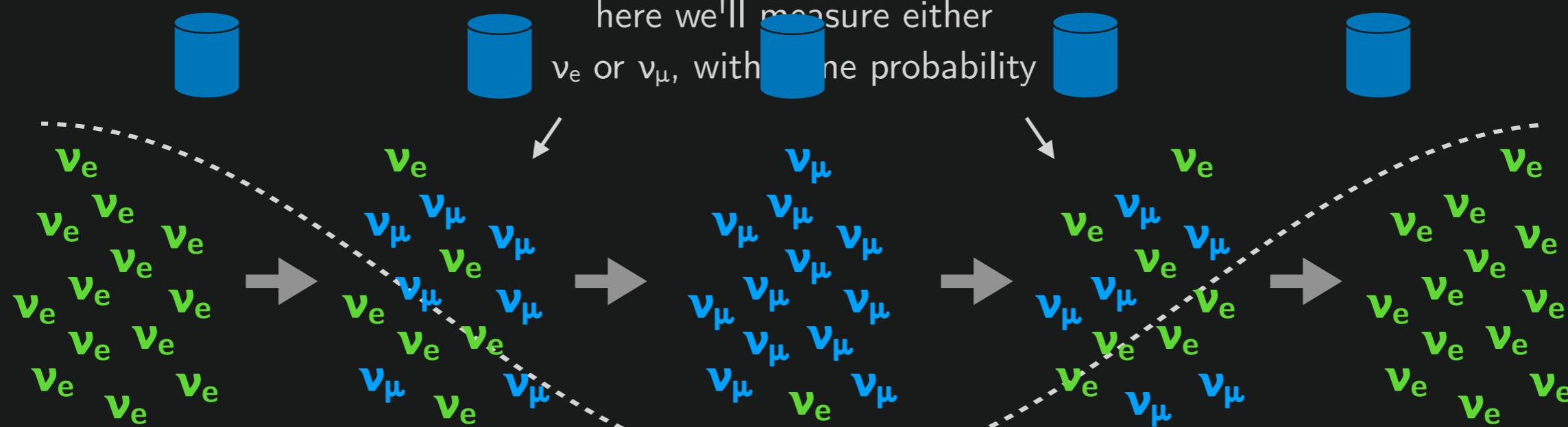


# Neutrino Oscillations

Neutrino Waves (in a two-neutrino world)

neutrino detectors everywhere!

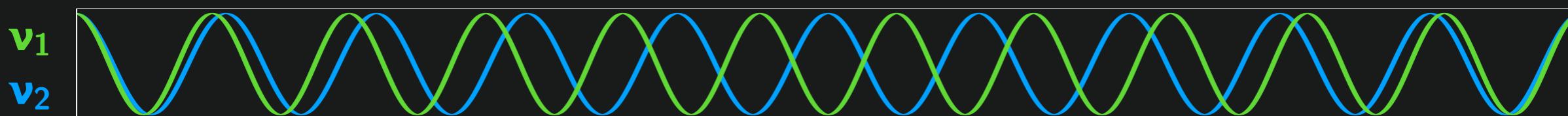
measure the **amplitude** and **wavelength!**



start out with the mixture  
of  $\nu_1$  and  $\nu_2$  we call " $\nu_e$ "

this is the mixture  
of  $\nu_1$  and  $\nu_2$  we call " $\nu_\mu$ "

back where we started,  
with "pure  $\nu_e$ "



# Neutrino Oscillations

## Two-Neutrino Oscillations, for Enthusiasts



$$\begin{aligned} |\nu_e\rangle &= A |\nu_1\rangle + B |\nu_2\rangle \\ |\nu_\mu\rangle &= C |\nu_1\rangle + D |\nu_2\rangle \end{aligned}$$

↑  
numbers between 0 and 1

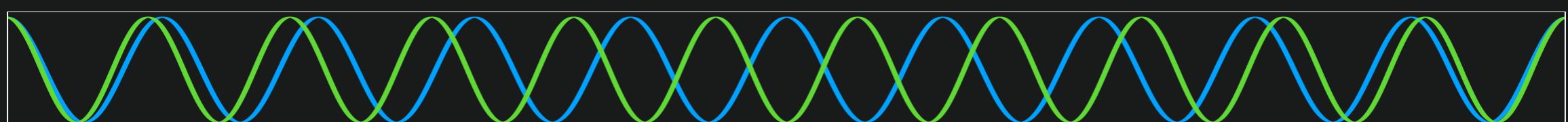
probability that your  $\nu_e$  is still a  $\nu_e$

$$P(\nu_e \rightarrow \nu_e) = 1 - \frac{\sin^2 2\theta}{\sin^2 2\theta} \sin^2 \left( 1.27 \frac{(m_1^2 - m_2^2) [\text{eV}^2] \cdot L [\text{km}]}{E [\text{GeV}]} \right)$$

difference in masses of  $\nu_1$  and  $\nu_2$   
(have to go measure this)

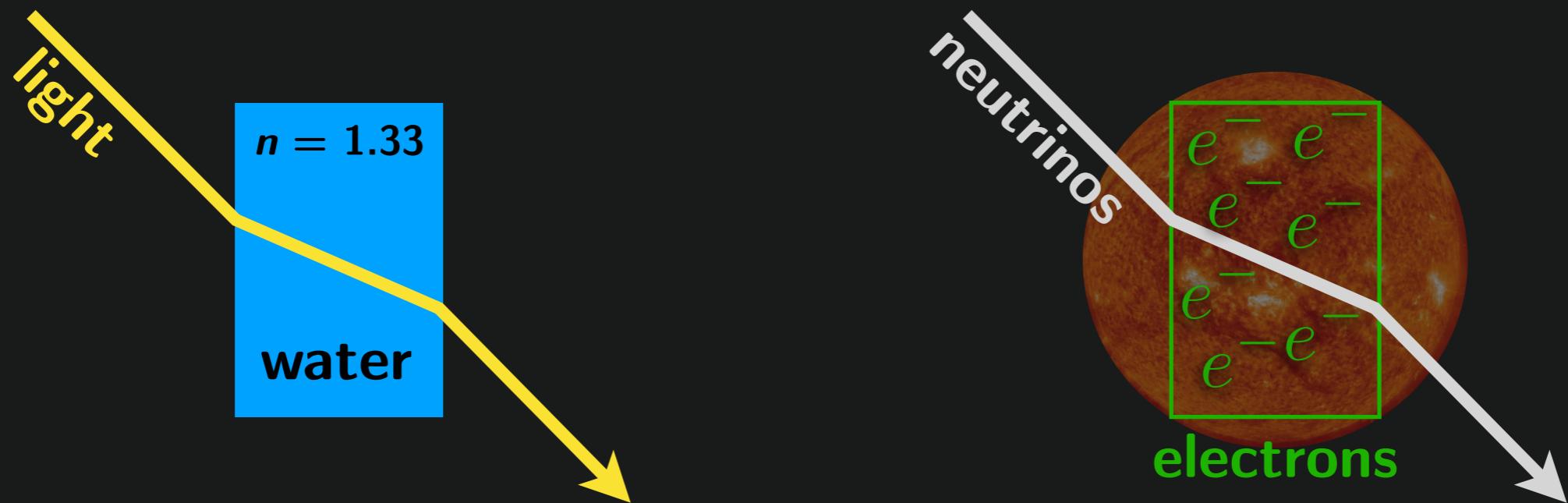
sets how much  $\nu_e$  and  $\nu_\mu$  mix together  
(have to go measure this)

↓  
distance traveled  
↓  
↑  
neutrino energy



# Neutrino Oscillations

One More Complication: Matter Matters!



The propagation of light waves is affected by matter

Same for neutrinos!

The presence of electrons in the Sun alters the oscillation patterns

The MSW (Mikheyev-Smirnov-Wolfenstein) or "matter" effect

Perhaps solar neutrinos start out as  $\nu_e$ , but en route to Earth some of them change to other types ...



... evading detection in our solar neutrino detectors, which can only see  $\nu_e$

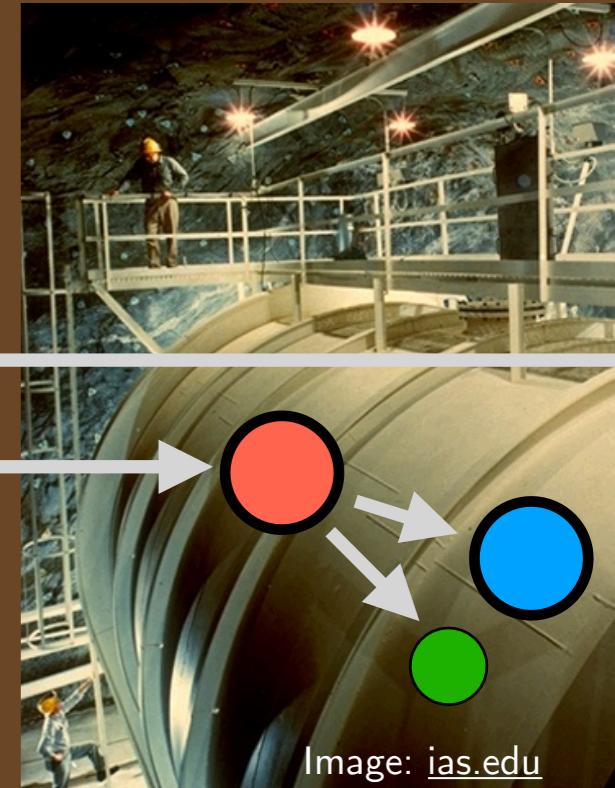
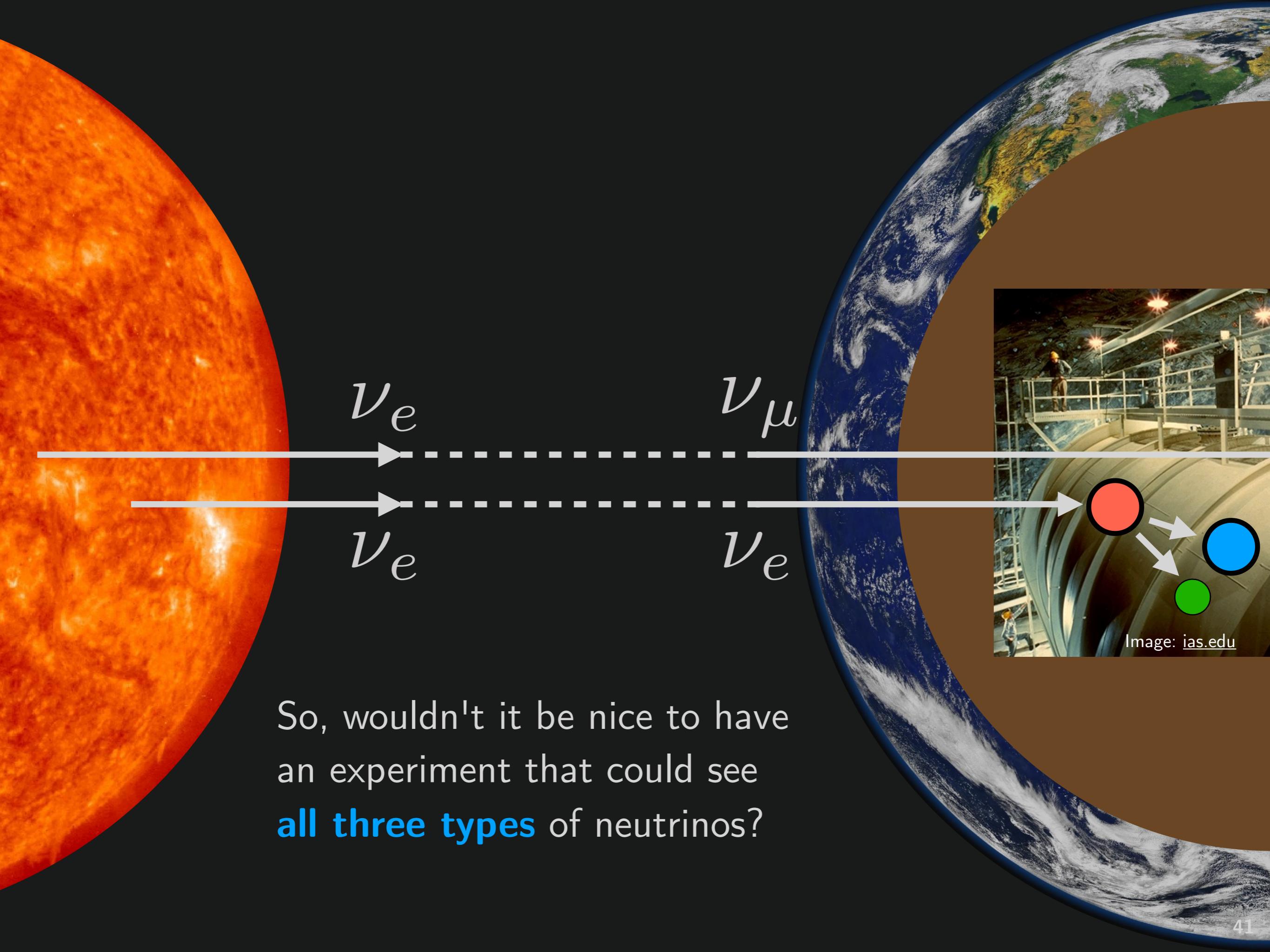
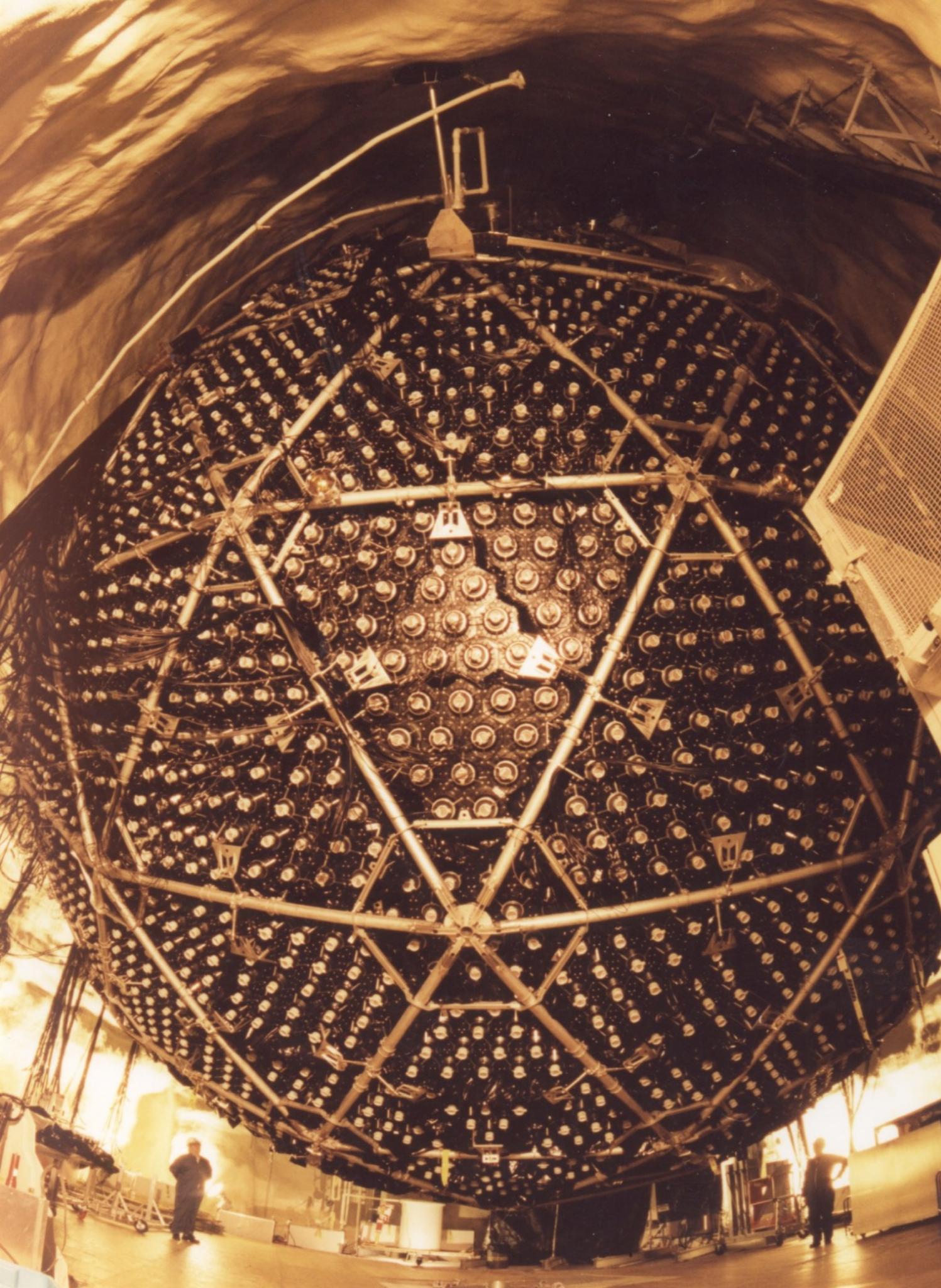


Image: [ias.edu](http://ias.edu)



So, wouldn't it be nice to have  
an experiment that could see  
**all three types** of neutrinos?

Image: [ias.edu](http://ias.edu)

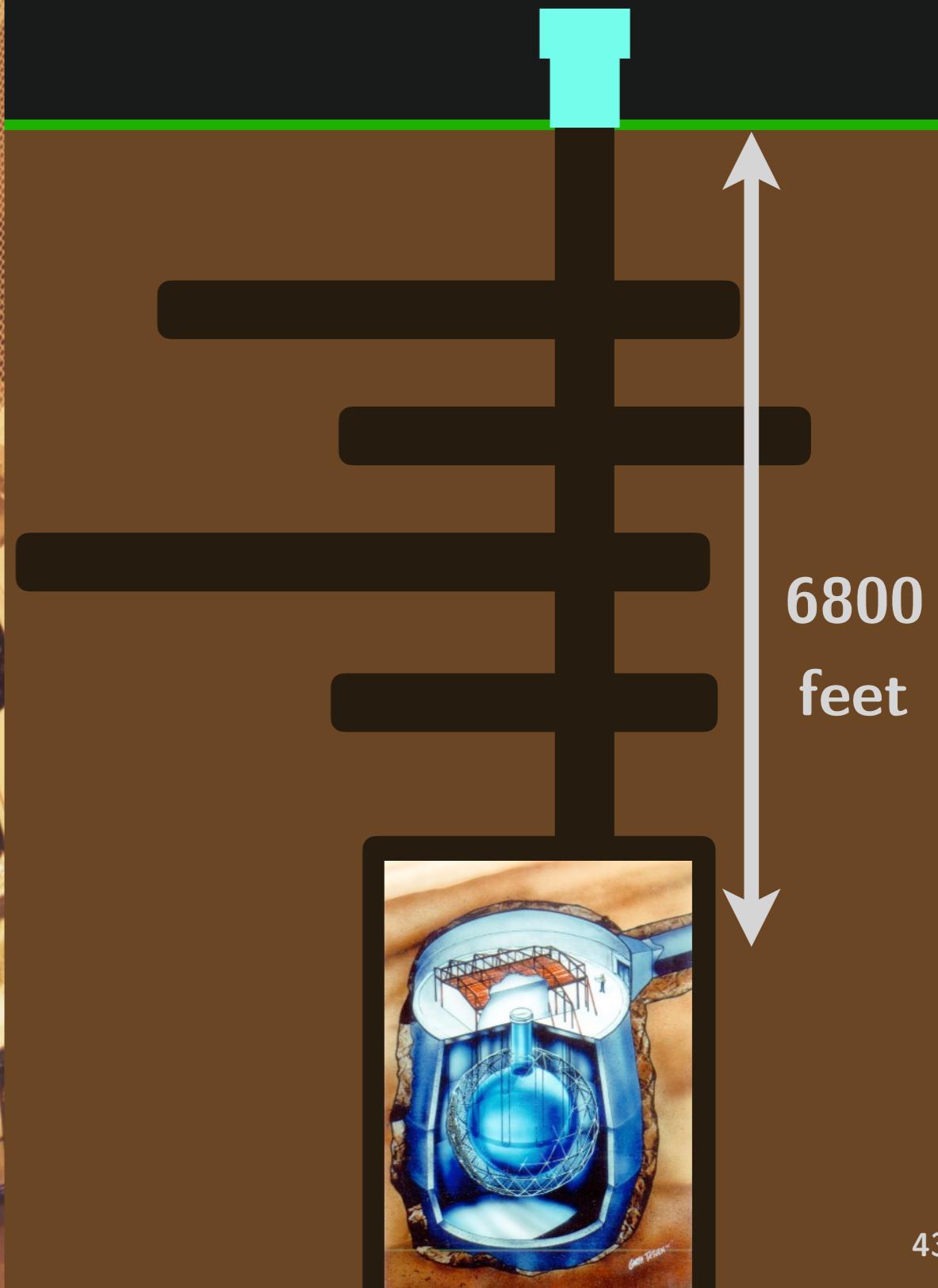
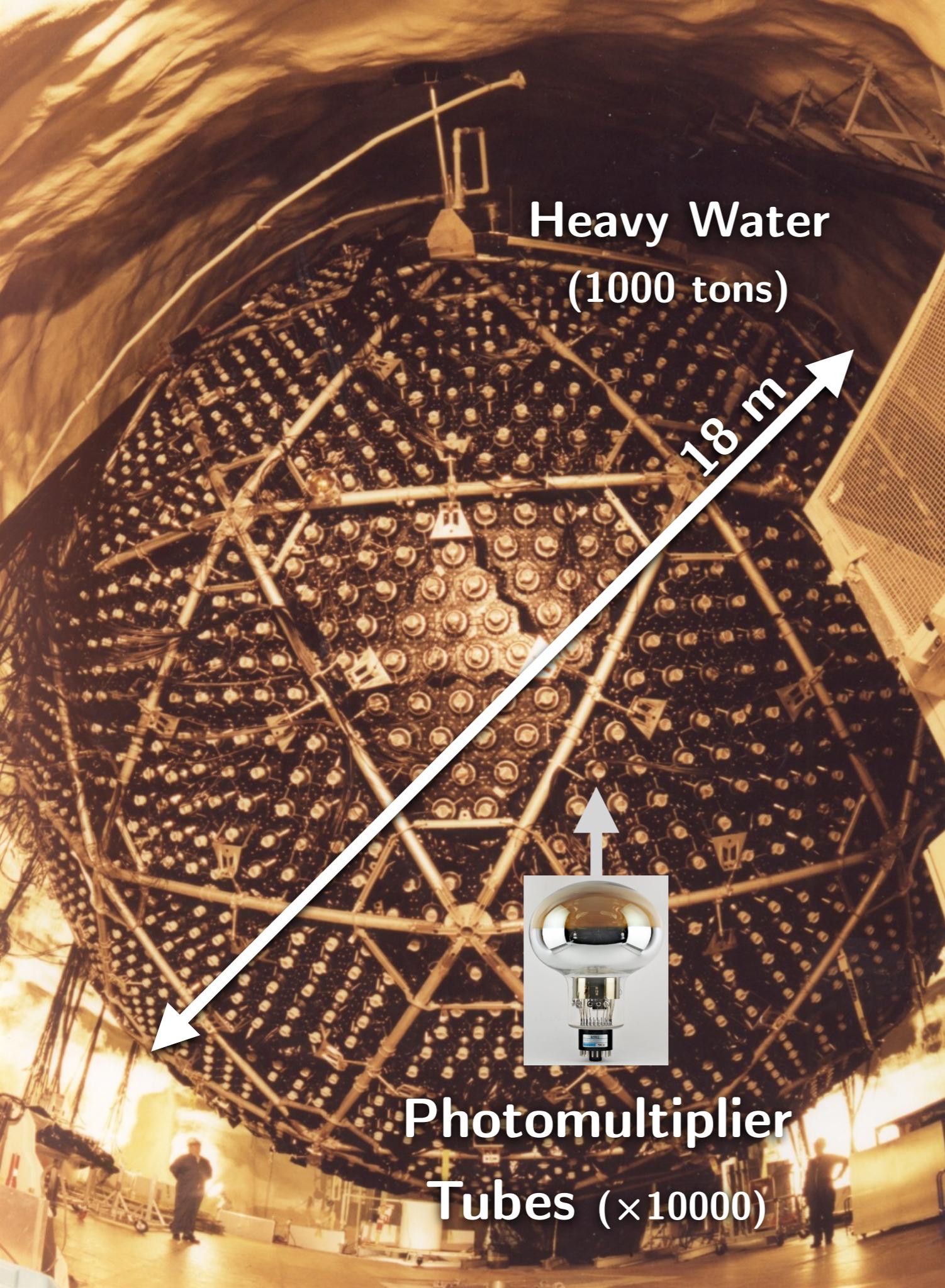


# The Sudbury Neutrino Observatory

Sudbury, Ontario, Canada

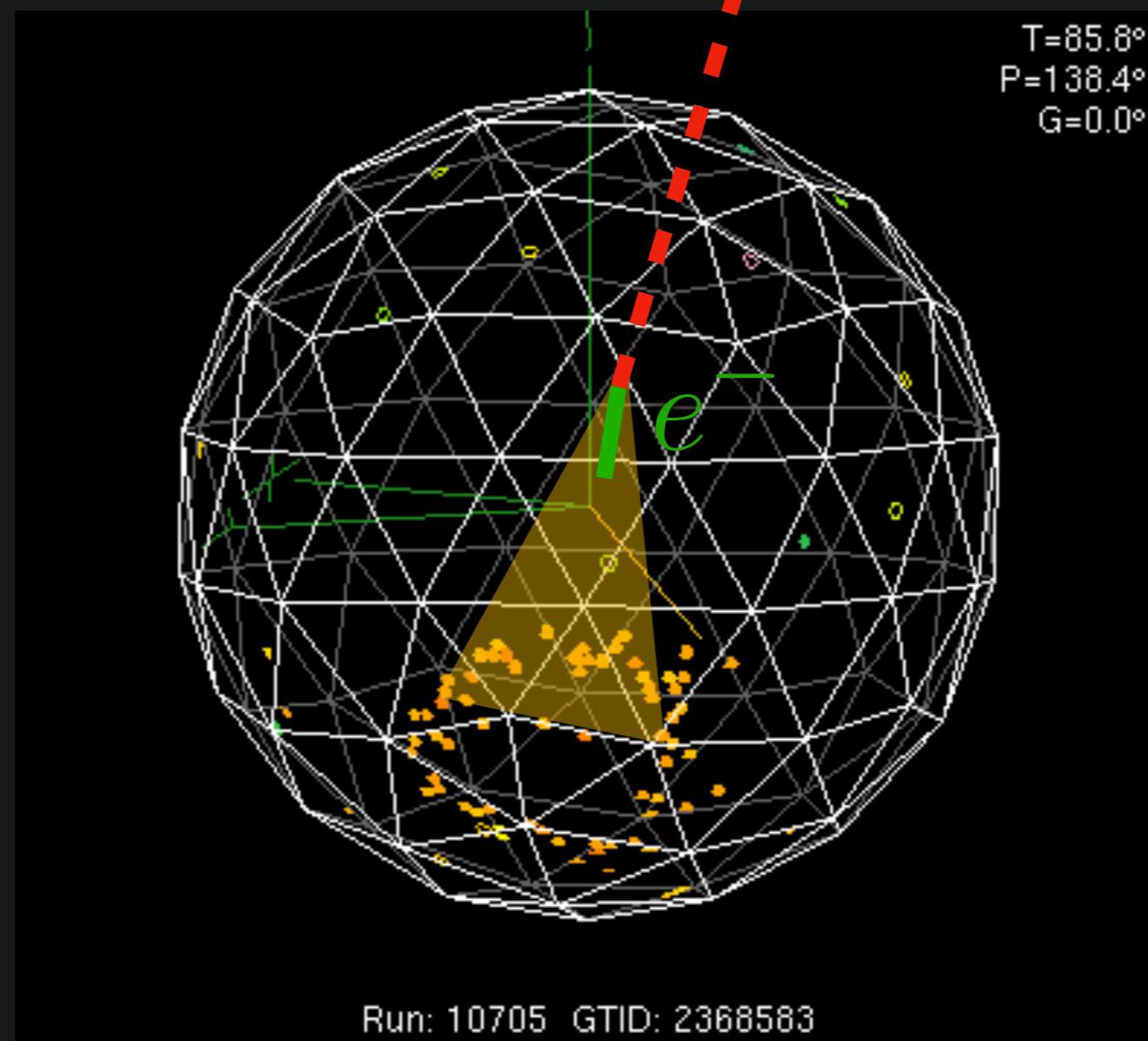
2001 — 2006

# The Sudbury Neutrino Observatory



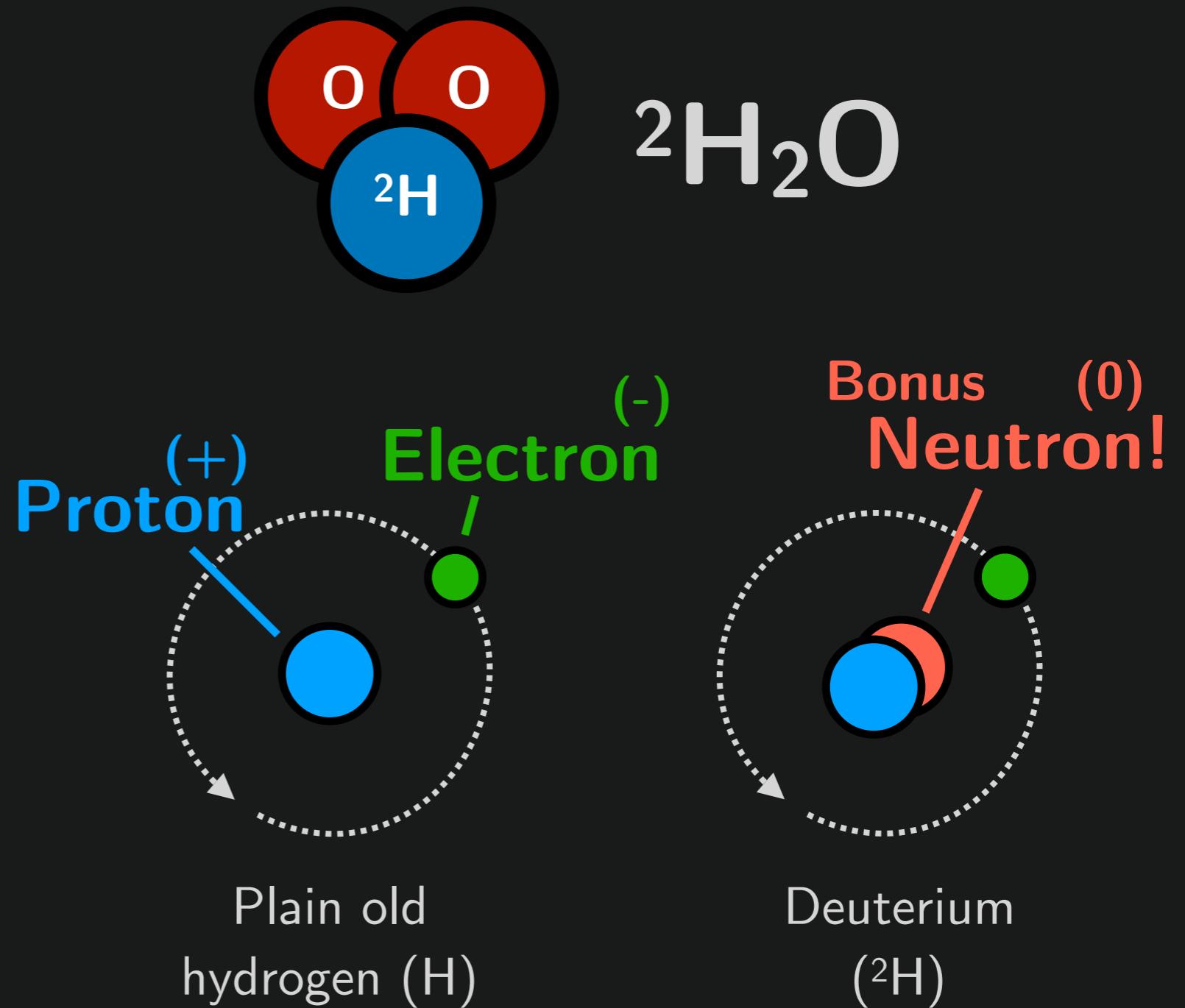


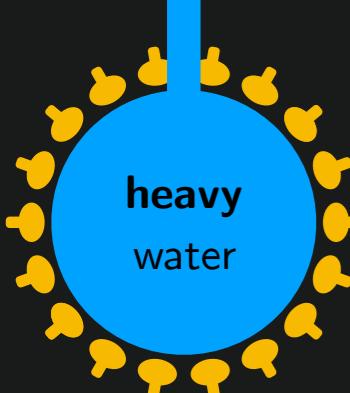
# Sudbury Neutrino Observatory





# Sudbury Neutrino Observatory

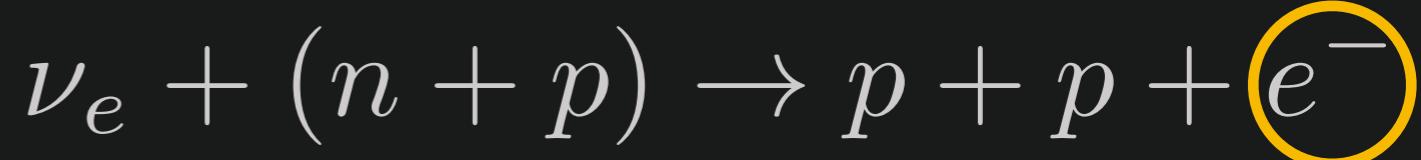




# Sudbury Neutrino Observatory

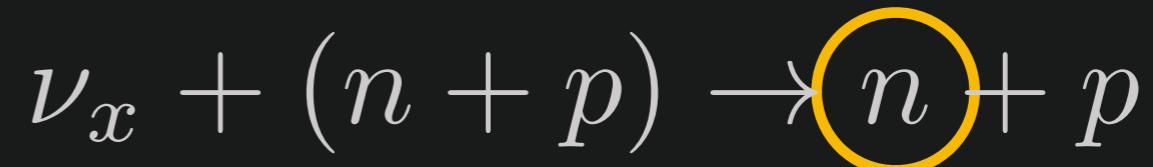
**CC**  
charged current

## **Electron type** solar neutrino makes $^2\text{H}$ into two protons



**NC**  
neutral current

**Any type** solar neutrino  
breaks up a  $^2\text{H}$

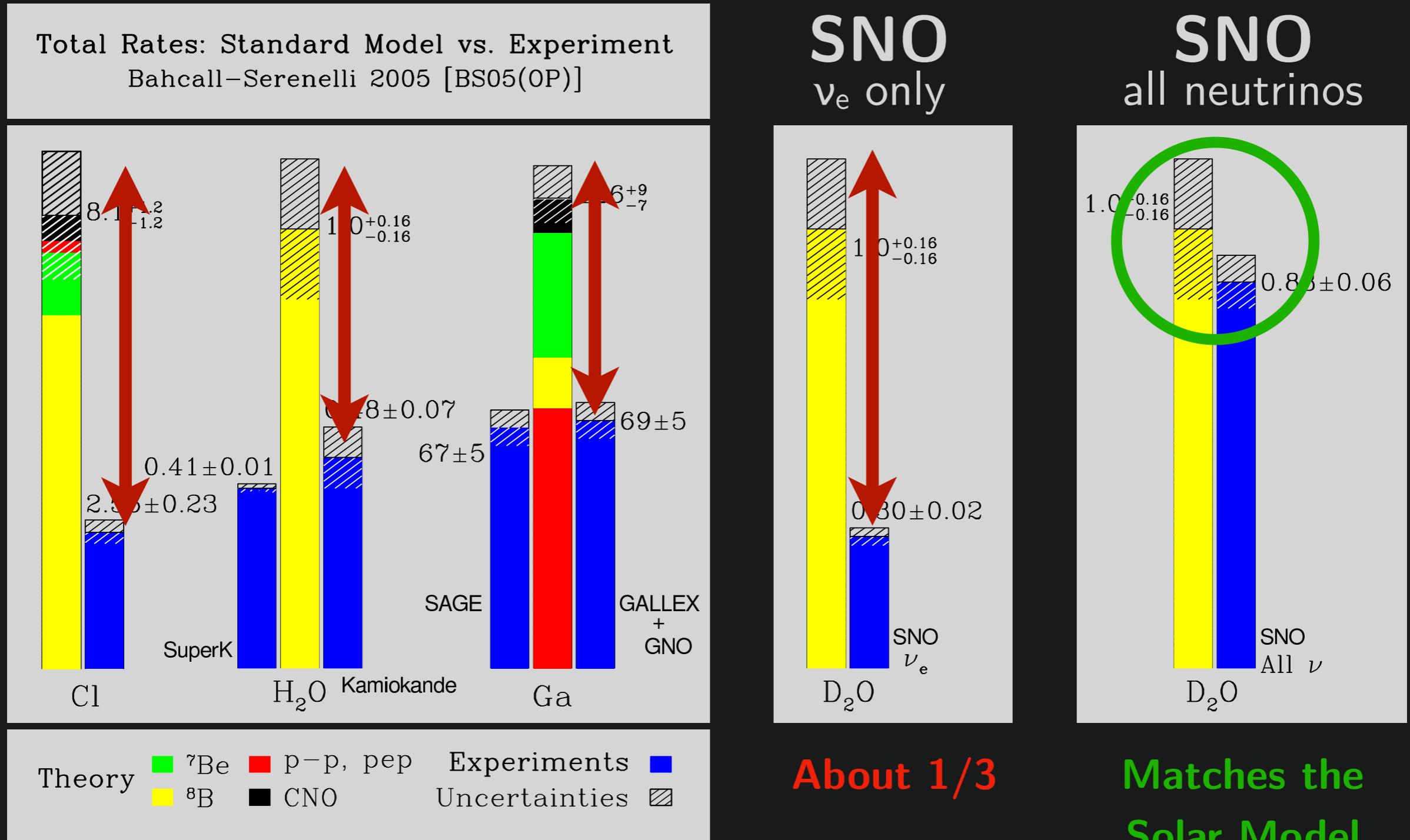


SNO measures **electron type** and **all types** at the same time

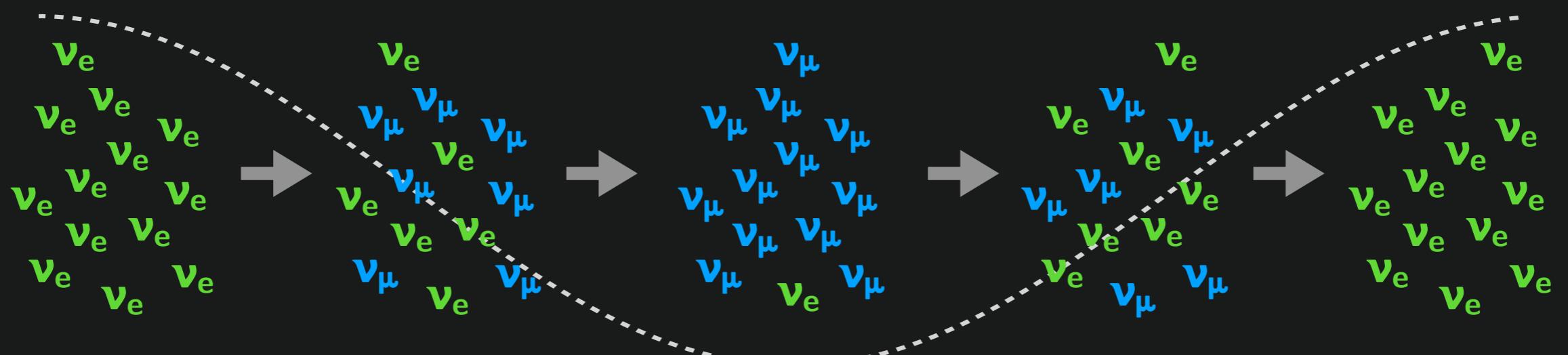
(expect to see 1/3)

(expect to see all  
of them!)

# The Solar Neutrino Problem

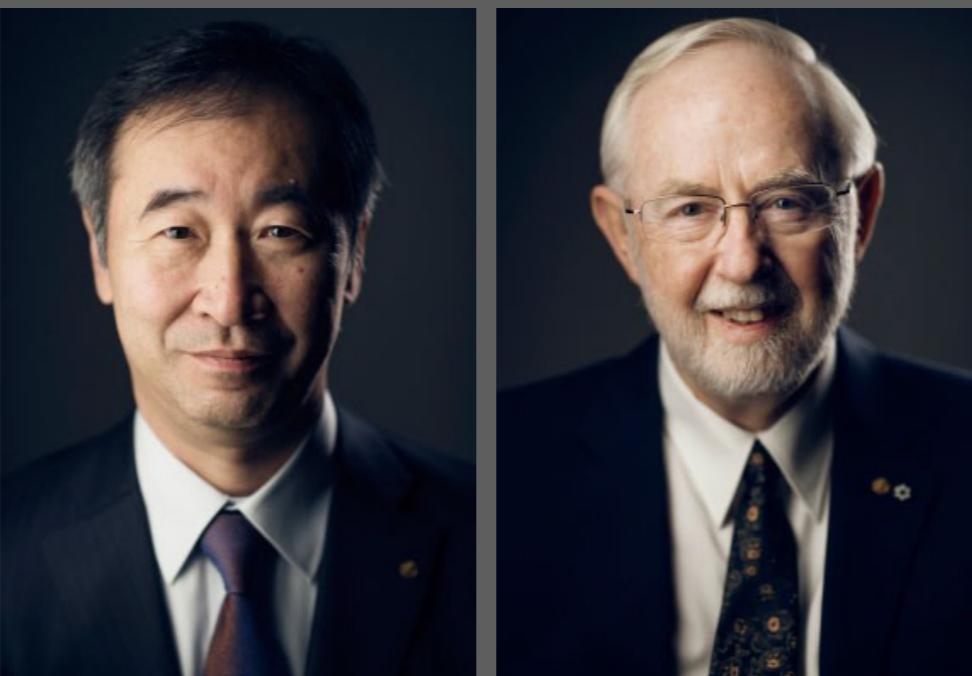


1. Neutrinos can change flavor (type)
2. They have a tiny but nonzero mass
3. Non-electron type neutrinos were invisible to early searches





# 2015 Nobel Prize in Physics



# Takaaki Kajita Art McDonald (Super-K) (SNO)

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

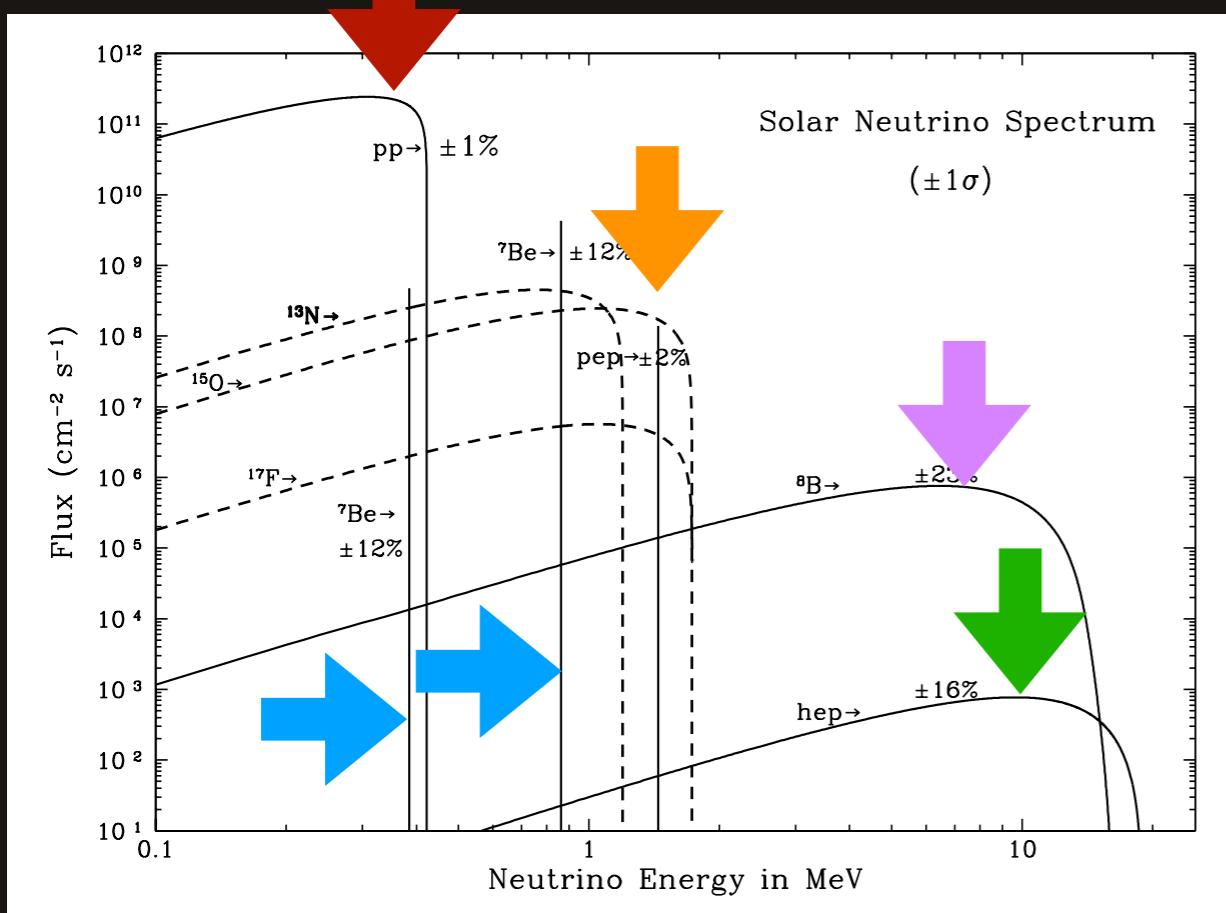
This is the  
textbook-  
rewriting  
sort of  
big news!

$\nu$

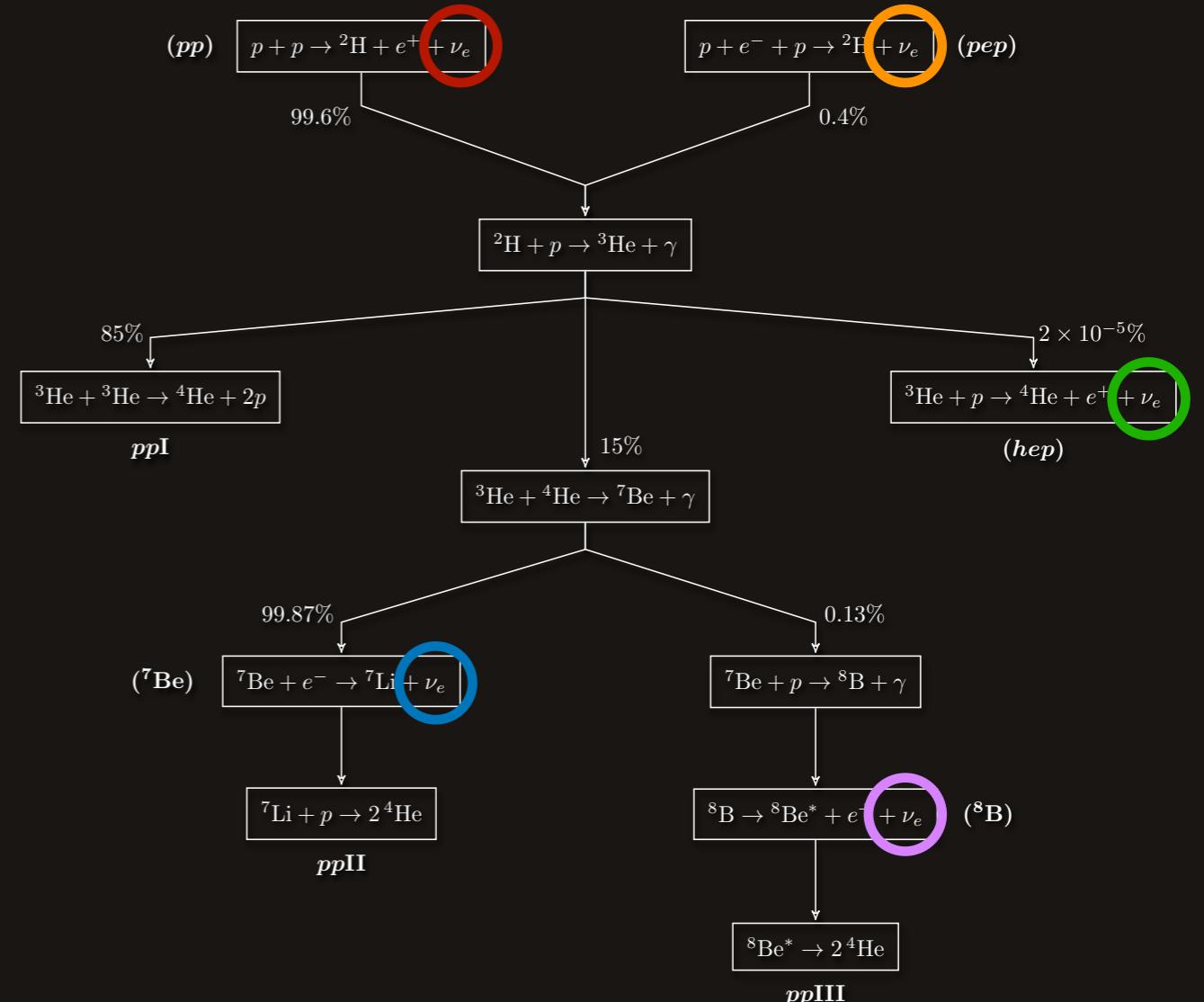
# Today's Solar Neutrino Problems

# Several different neutrino-producing reactions in the core of the Sun

**Measure them all!**



Astrophys. J. 621(1):L85-L88, 2005.



**8B** 1998-2001, SNO & Super-K

**7Be** 2008-2011, Borexino

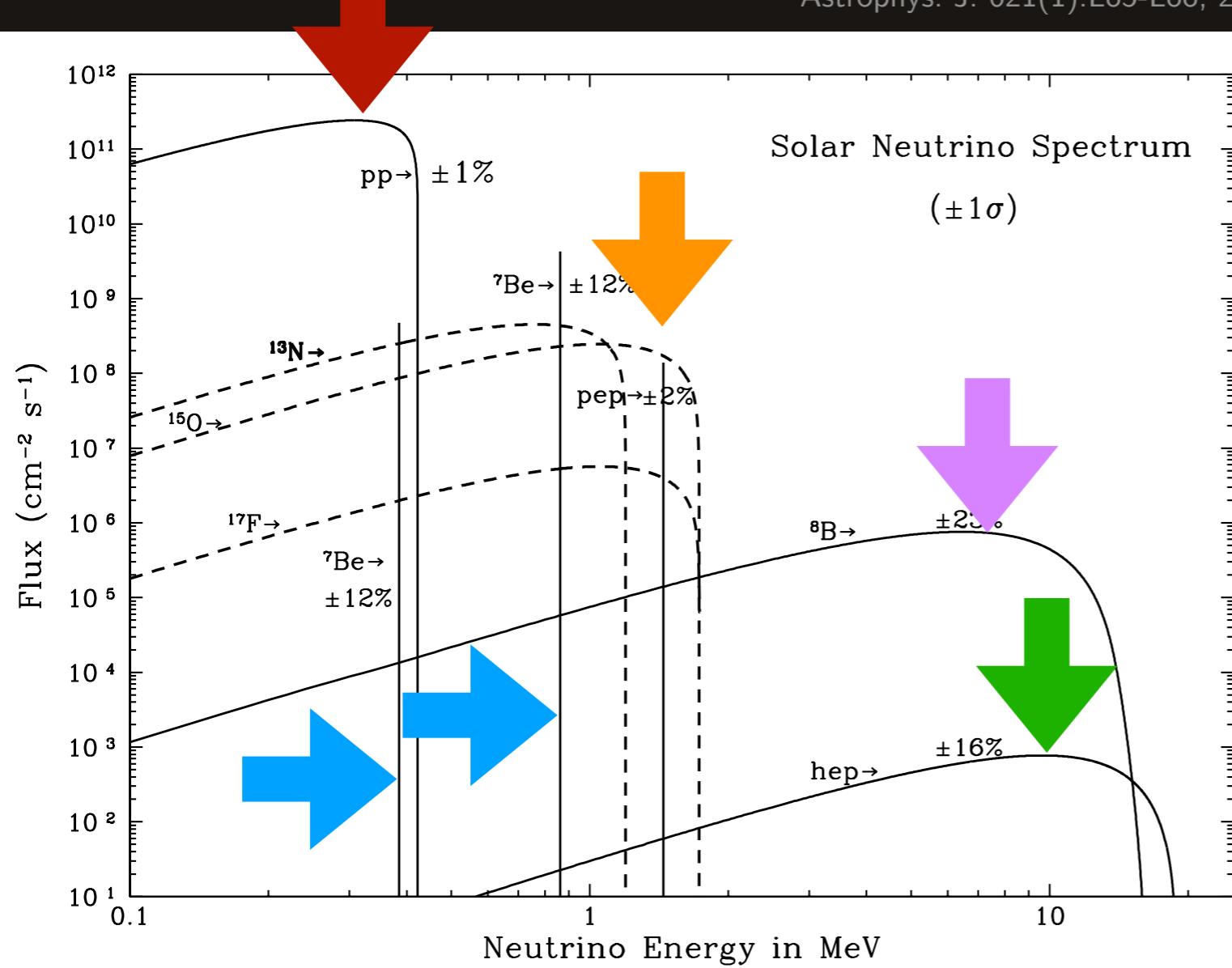
**pep** 2011, Borexino

**pp** 2014, Borexino

**hep** Not yet observed!

*we're working on it!*

Astrophys. J. 621(1):L85-L88, 2005.



CONSTRAINING THE HEP SOLAR NEUTRINO AND  
DIFFUSE SUPERNOVA NEUTRINO BACKGROUND  
FLUXES WITH THE SUDBURY NEUTRINO  
OBSERVATORY

Andrew T. Mastbaum

A DISSERTATION

in

Physics and Astronomy

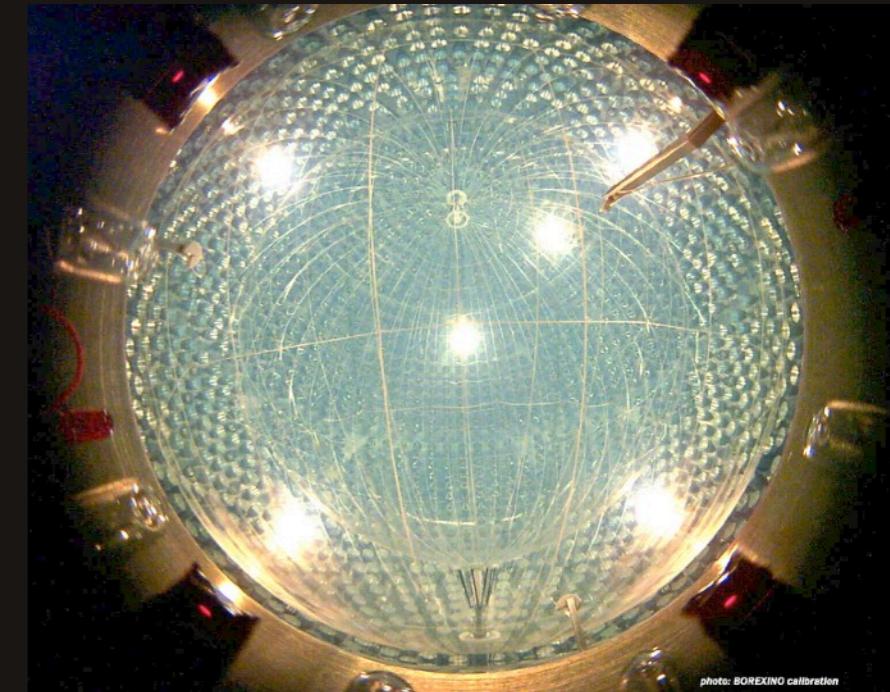
Presented to the Faculties of the University of Pennsylvania

in

Partial Fulfillment of the Requirements for the Degree of  
Doctor of Philosophy

2016

My Ph.D. thesis, 2016



**Borexino, Gran Sasso, Italy**

300 tons of scintillator

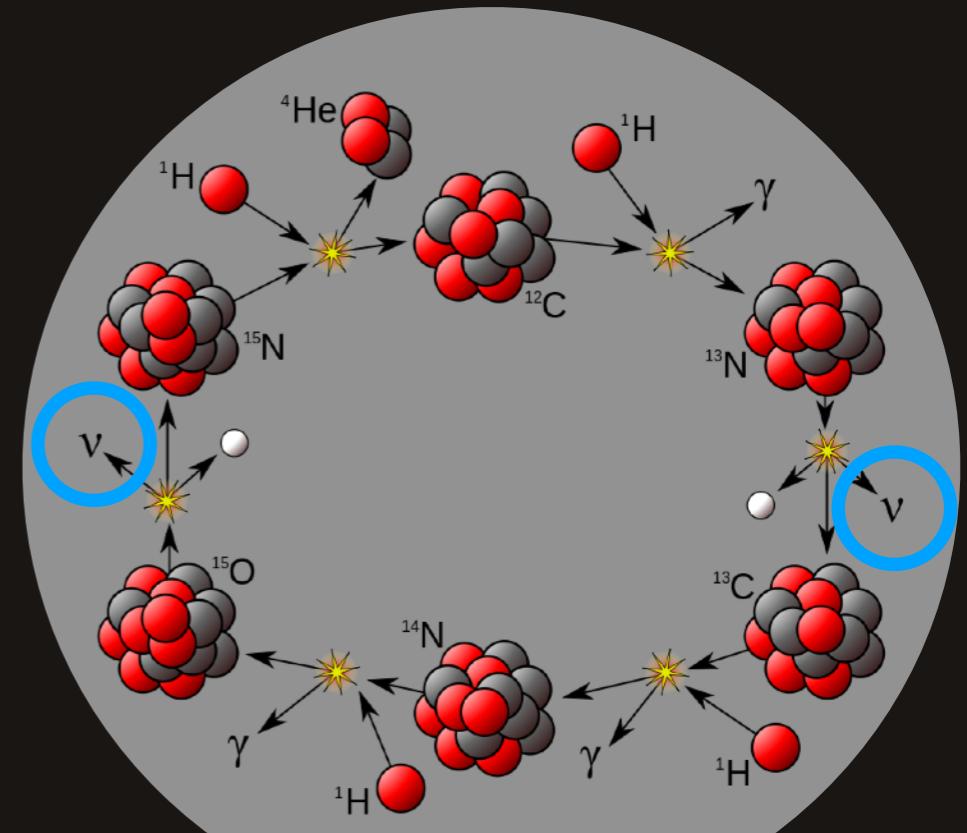
# The CNO Cycle

(Carbon-Nitrogen-Oxygen)

A second fusion chain,  
along with *pp*

(About 1-2% of our Sun's energy,  
but very important for larger stars)

Important to measuring the composition of  
the solar interior, to resolve the  
**"solar metallicity problem"**



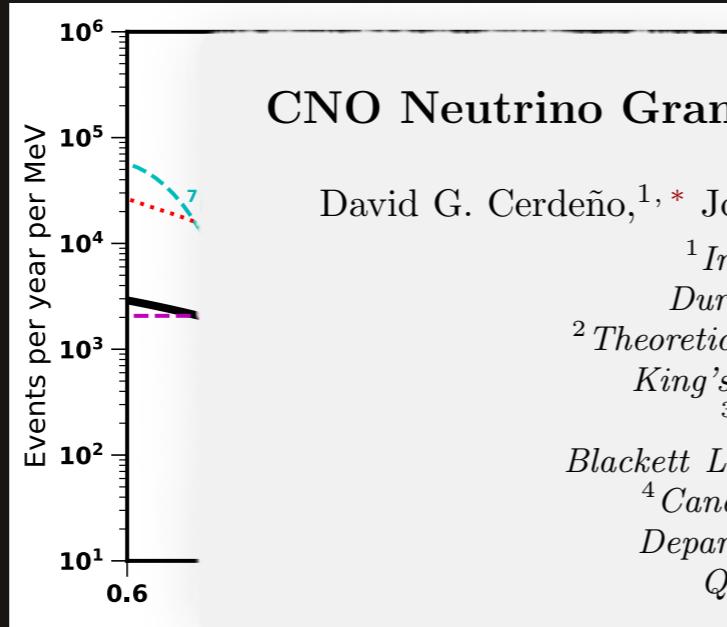
● Proton	γ Gamma Ray
● Neutron	ν Neutrino
● Positron	

CC BY-SA 3.0 Borb, Wikimedia Commons



arxiv:1712.06522, 2017

Expected in  
Borexino:  
(tiny signal)



## CNO Neutrino Grand Prix: The race to solve the solar metallicity problem

David G. Cerdeño,<sup>1,\*</sup> Jonathan H. Davis,<sup>2,†</sup> Malcolm Fairbairn,<sup>2,‡</sup> and Aaron C. Vincent<sup>3,4,§</sup>

<sup>1</sup>*Institute for Particle Physics Phenomenology (IPPP),  
Durham University, Durham DH1 3LE, United Kingdom*

<sup>2</sup>*Theoretical Particle Physics and Cosmology, Department of Physics,  
King's College London, London WC2R 2LS, United Kingdom*

<sup>3</sup>*Department of Physics, Imperial College London,  
Blackett Laboratory, Prince Consort Road SW7 2AZ, United Kingdom*

<sup>4</sup>*Canadian Particle Astrophysics Research Centre (CPARC),  
Department of Physics, Engineering Physics and Astronomy,  
Queen's University, Kingston ON K7L 3N6, Canada*

# Non-Standard Interactions

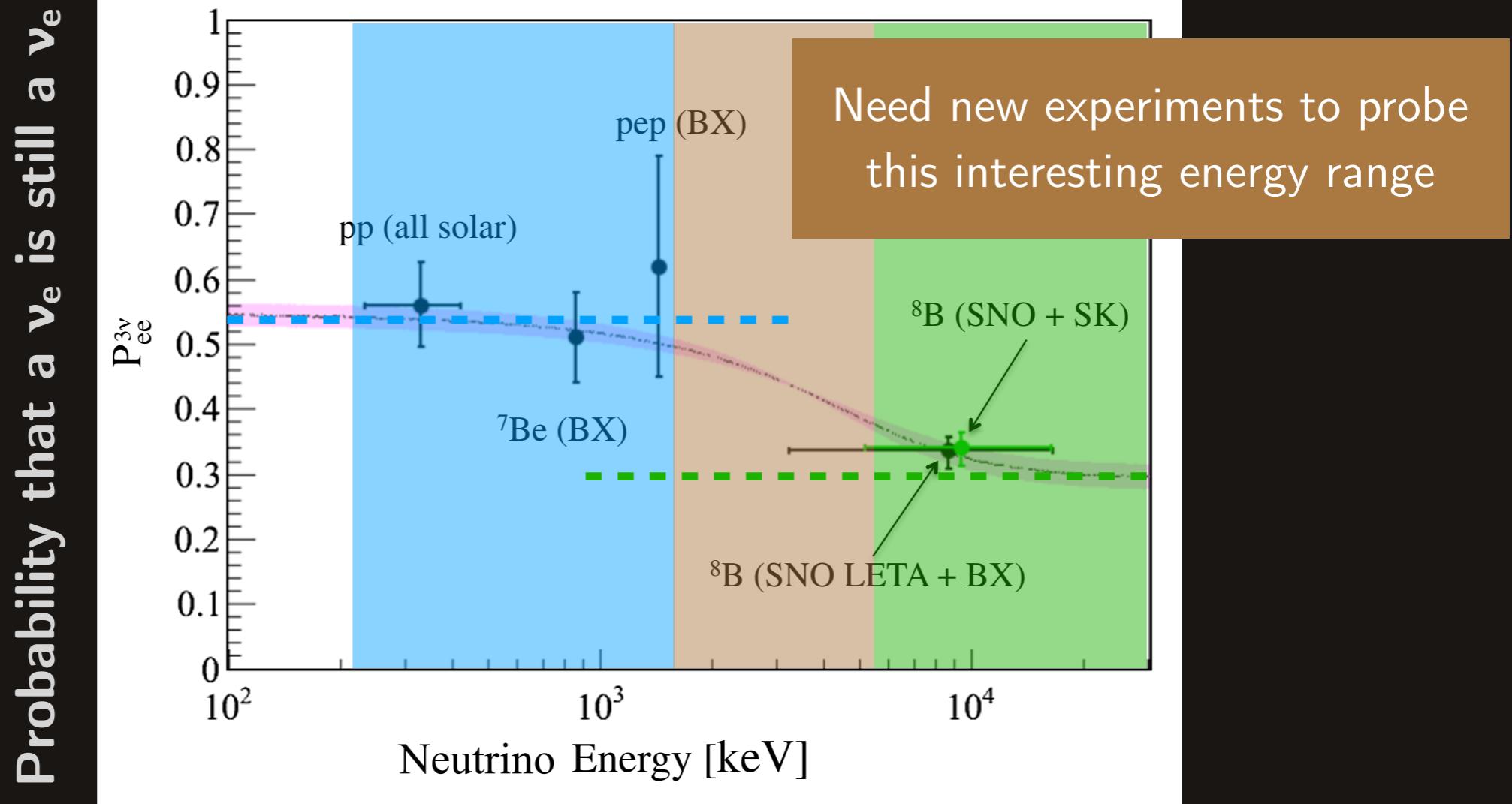
Any other funny business in the Sun?

A Desert!

Borexino,  
Homestake, SAGE, GALLEX

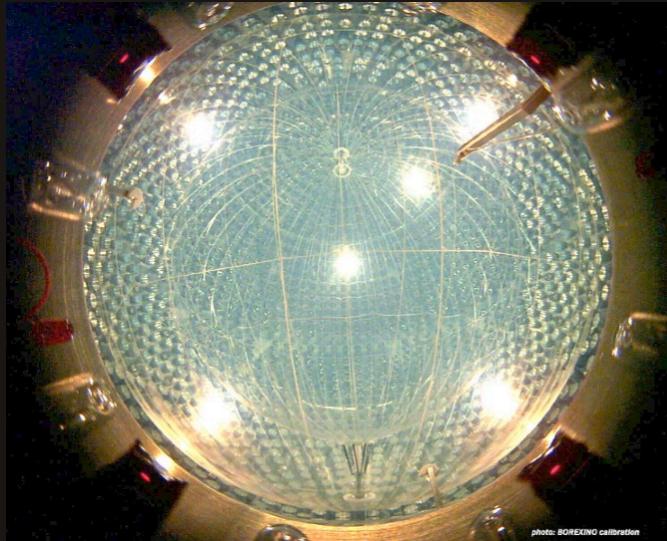


SNO, Super-Kamiokande,  
Borexino

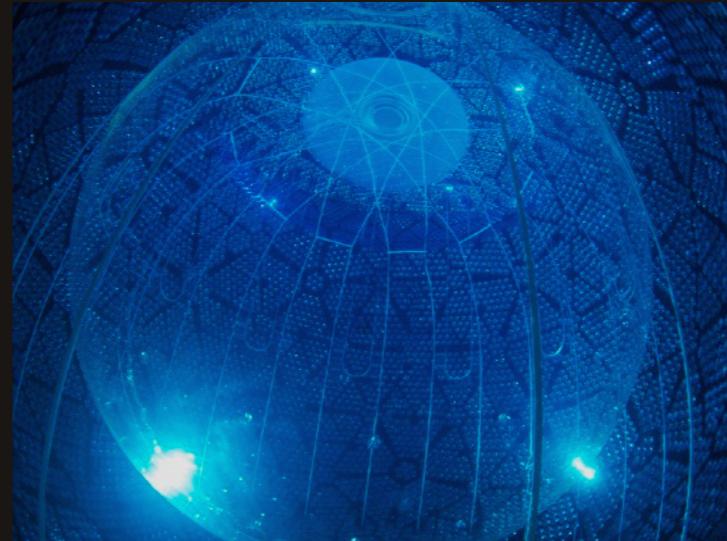


# The Future Is Bright

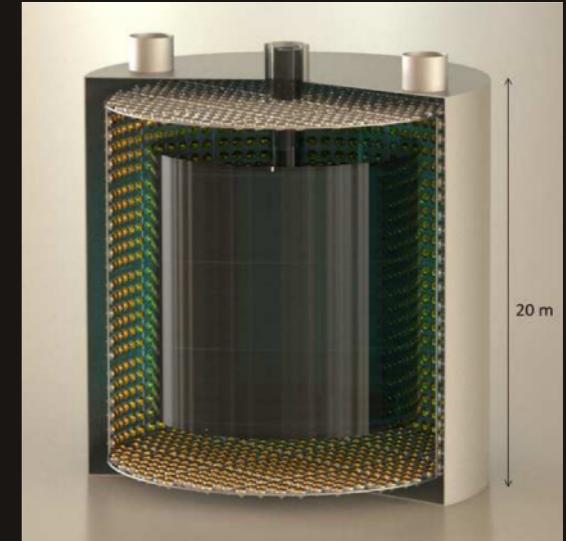
A few current & proposed experiments



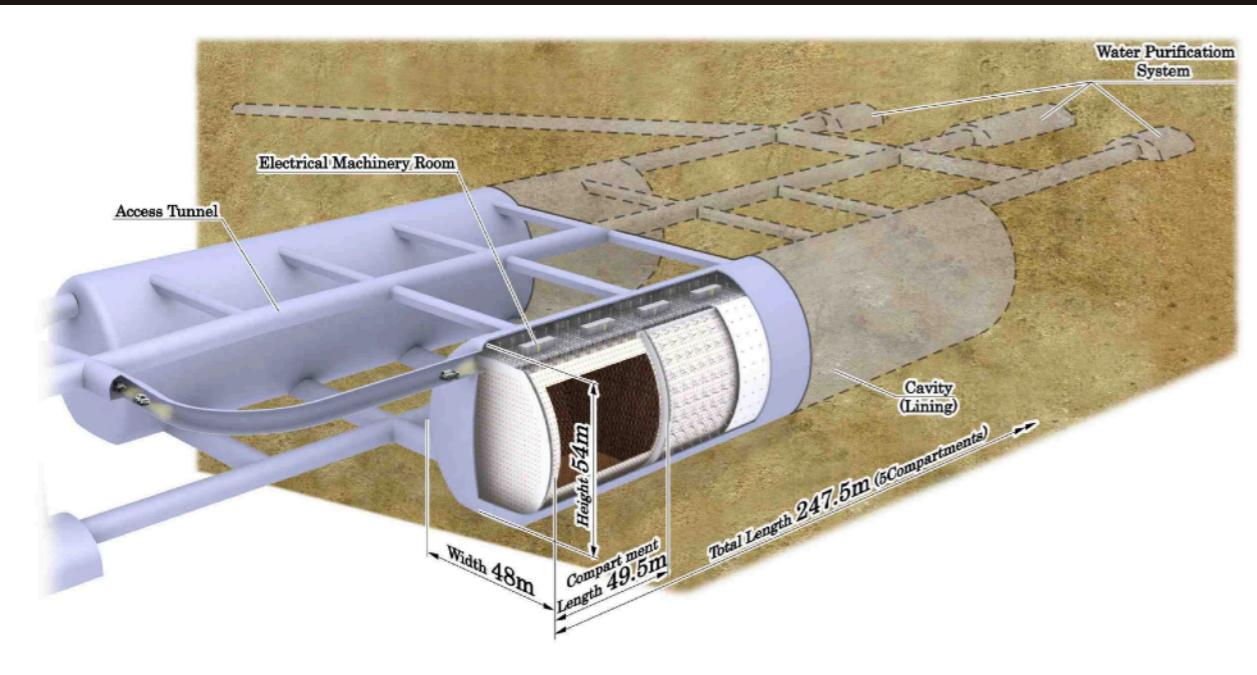
Borexino, Italy



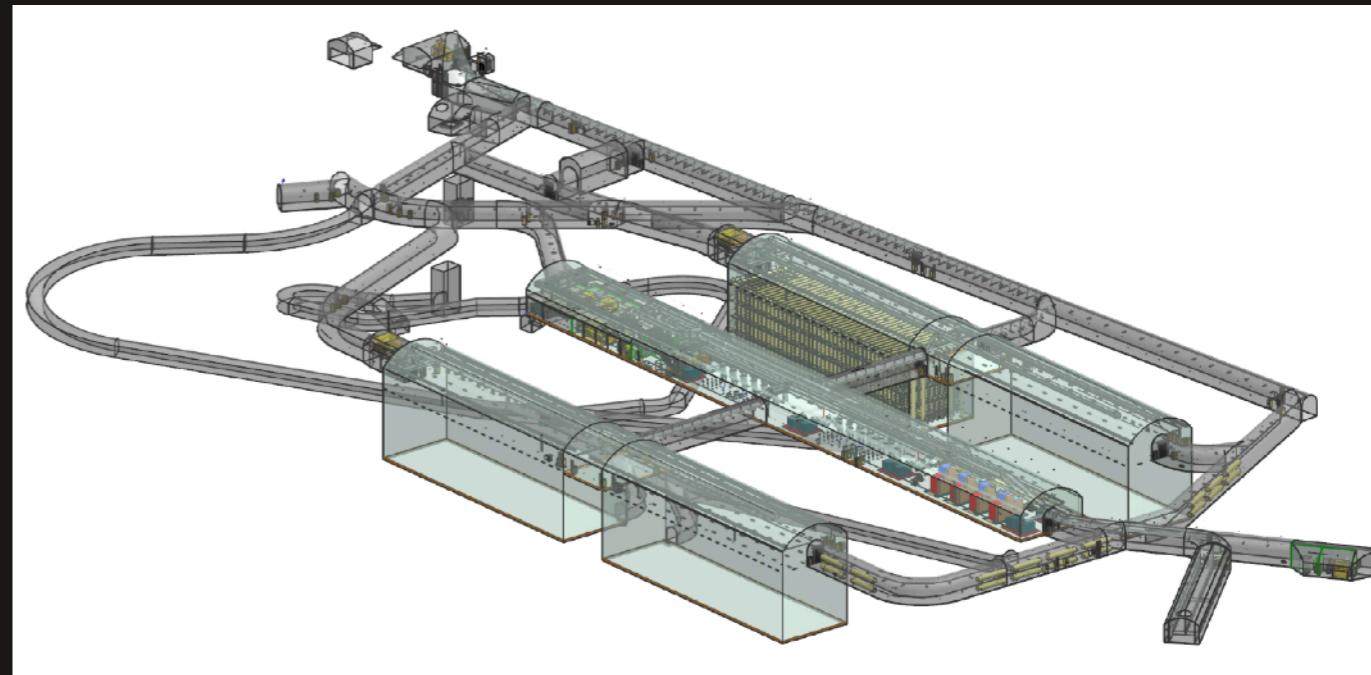
SNO+, Canada



Jinping, China

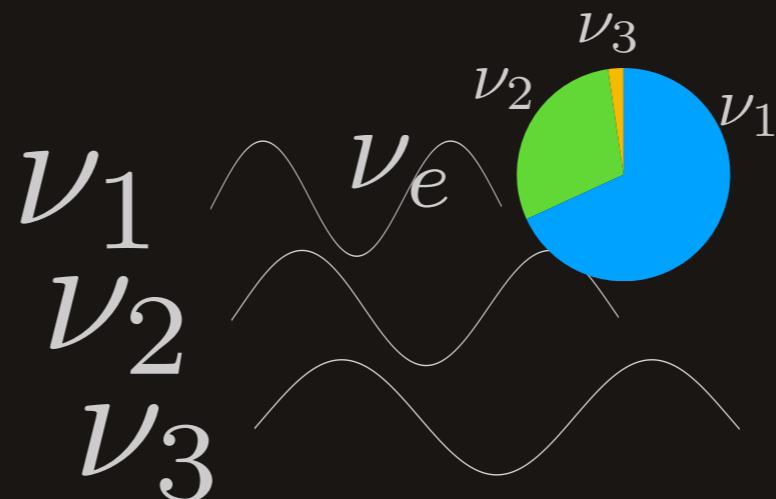
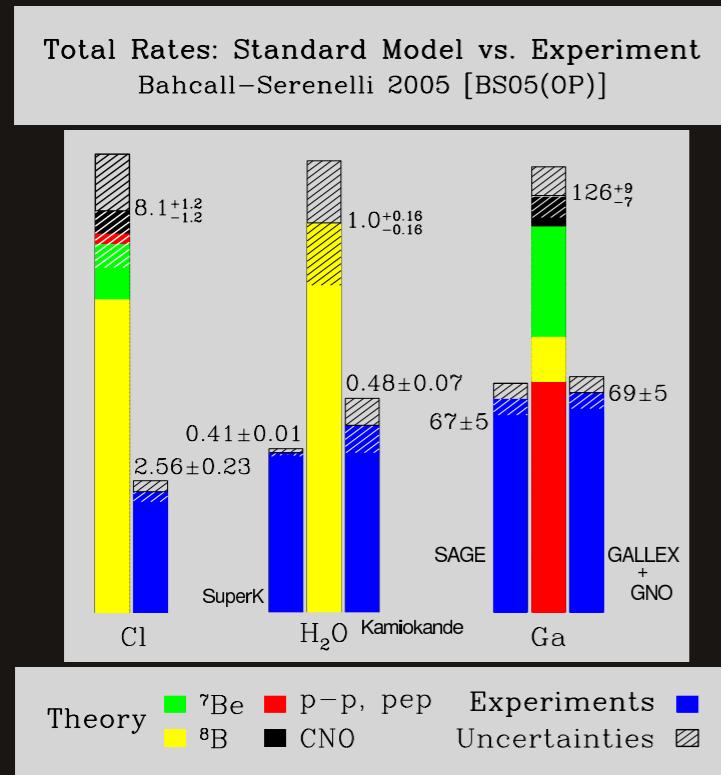


Super-K & Hyper-K, Japan



DUNE, US

# The Solar Neutrino Problem



Homestake Experiment sees  
**too few solar neutrinos**,  
and others confirm

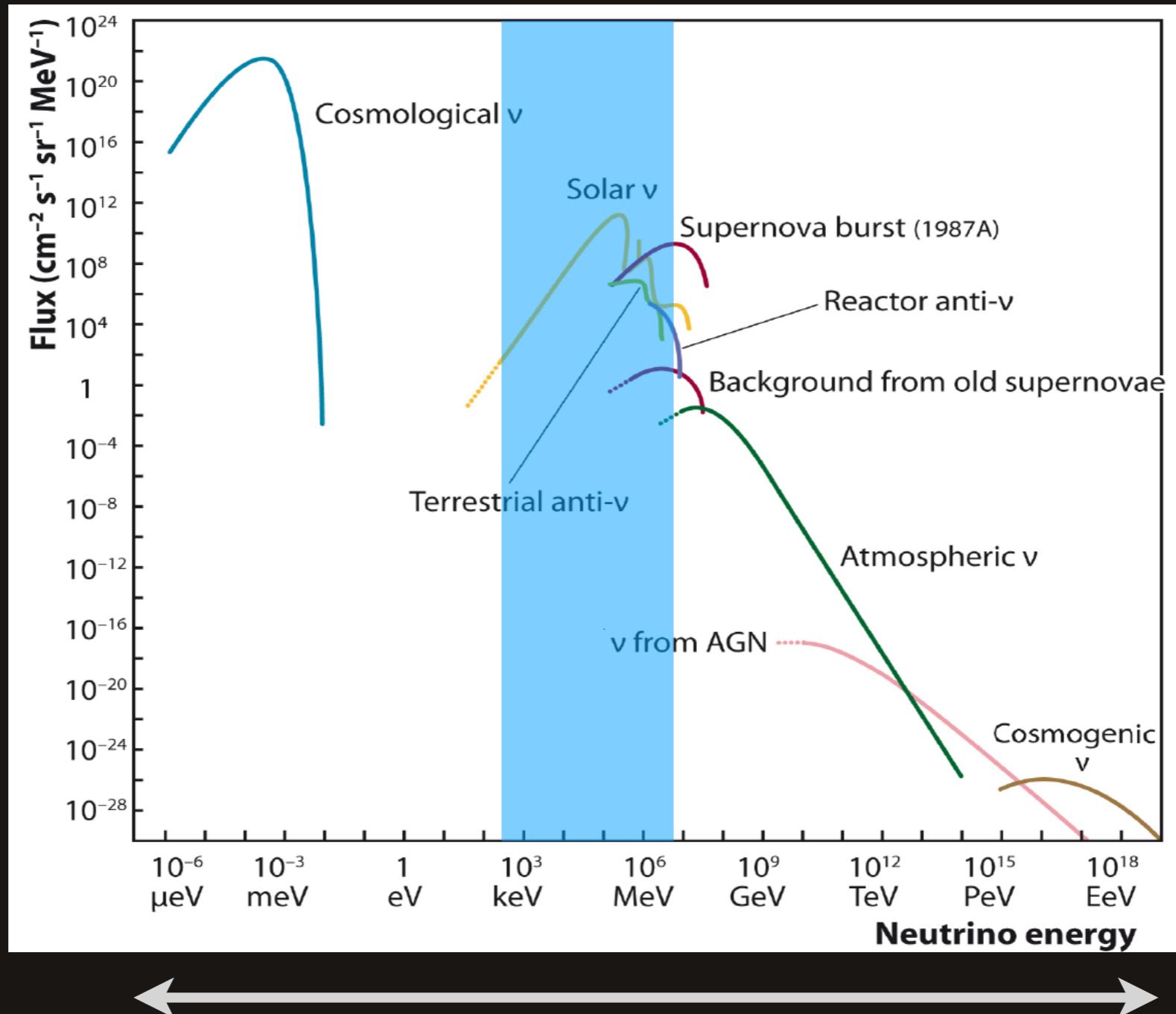
Give neutrinos **tiny masses**,  
which allows them  
to **change type**

**SNO confirms**, the  
solar neutrinos are  
changing type

Neutrinos have **mass**, and can **change type**

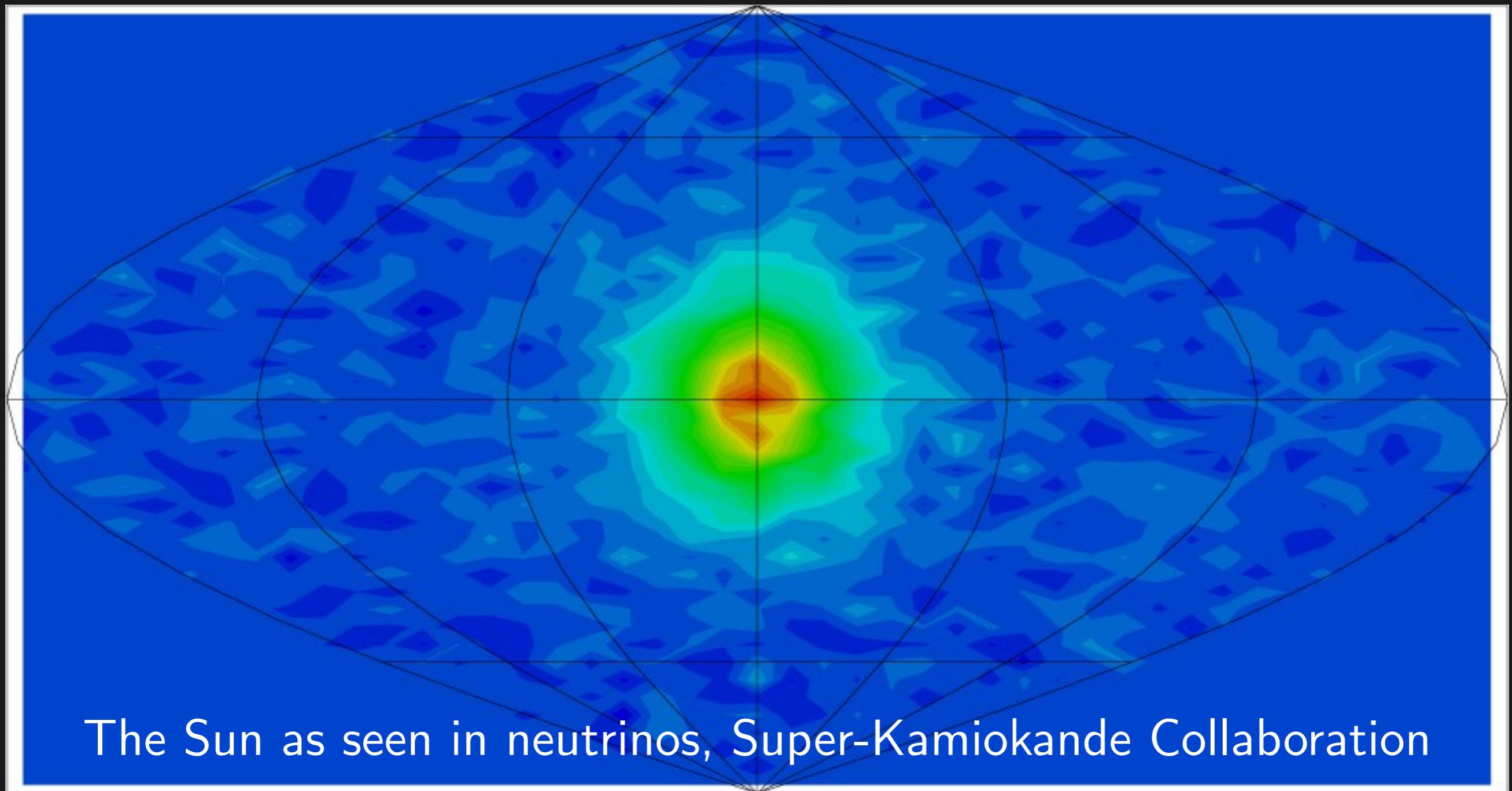
# Beyond Solar Neutrinos

Katz & Spiering, arxiv:1111.0507 (2011)



Neutrinos with energies spanning 24 orders of magnitude!

# Thank You!



The Sun as seen in neutrinos, Super-Kamiokande Collaboration

**Next week:** Neutrinos from Beyond the Solar System!