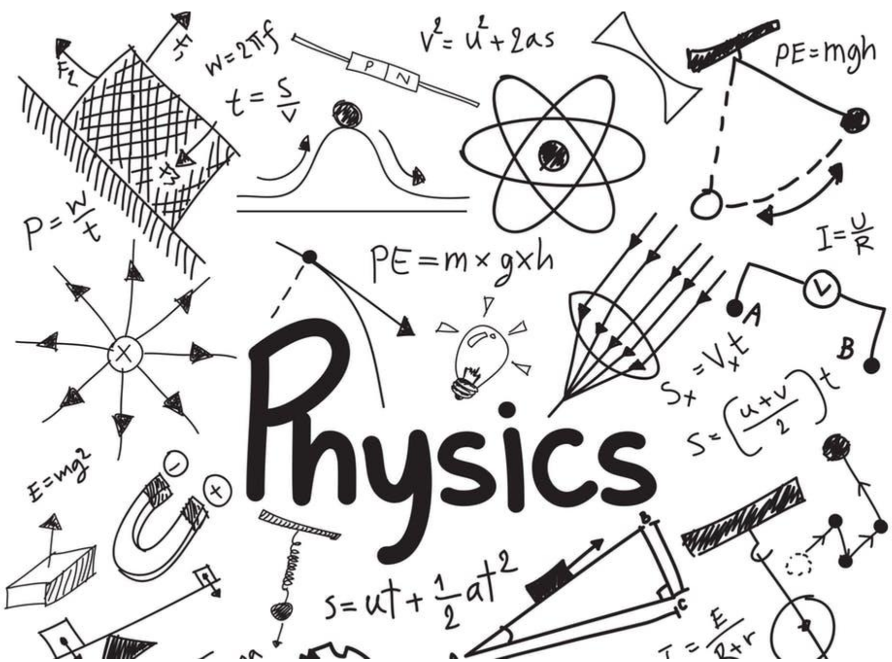
Frontiers in Physics and Astrophysics

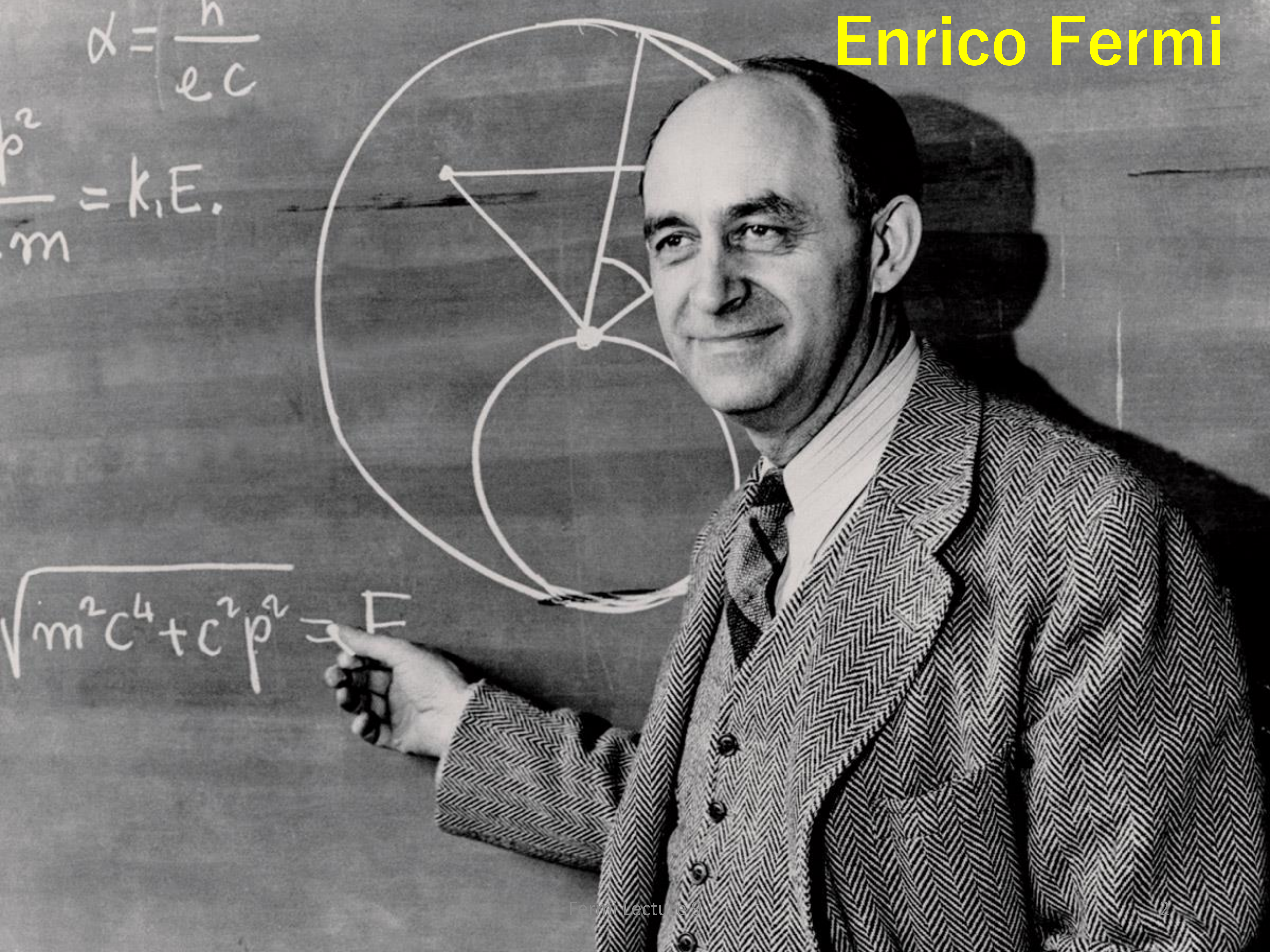
Fermi Lecture 9 –Neutrinos (2)



Barry C Barish

9-January-2020

Enrico Fermi



Enrico Fermi Lectures 2019-2020
Frontiers of Physics and Astrophysics

- Explore frontiers of Physics and Astrophysics from an Experimental Viewpoint
- Some History and Background for Each Frontier
- Emphasis on Large Facilities and Major Recent Discoveries
- Discuss Future Directions and Initiatives

- Thursdays 4-6 pm
- Oct 10,17,24,one week break, Nov 7
- Nov 28, Dec 5,12,19 Jan 9,16,23
- Feb 27, March 5,12,19

Frontiers

Fermi Lectures 2019-2020 - Barry C Barish

- Course Title: **Large Scale Facilities and the Frontiers of Physics**
- The Course will consist of 15 Lectures, which will be held **from 16:00 to 18:00** in **aula Amaldi**, Marconi building, according to the following schedule:
- 10 October 2019 - Introduction to Physics of the Universe
  17 October 2019 - Elementary Particles
  24 October 2019 - Quarks
  7 November 2019 – Particle Accelerators
  28 November 2019 – Big Discoveries and the Standard Model
  5 December 2019 – Force Carriers – Z, W
  12 December 2019 – Higgs Discovery, Supersymmetry?, Future??
  19 December 2019 – Introduction/History of Neutrinos
  9 January 2020 – Neutrino(2)
  16 January 2020 – Neutrinos(3)
  23 January 2020 – Neutrinos (4)
  27 February 2020 – Gravitational Waves (1)
  5 March 2020 – Gravitational Waves (2)
  12 March 2020 – Particle Astrophysics / Experimental Cosmology
  19 March 2020 – Future Perspectives
- All Lectures and the supporting teaching materials will be published by the Physics Department.

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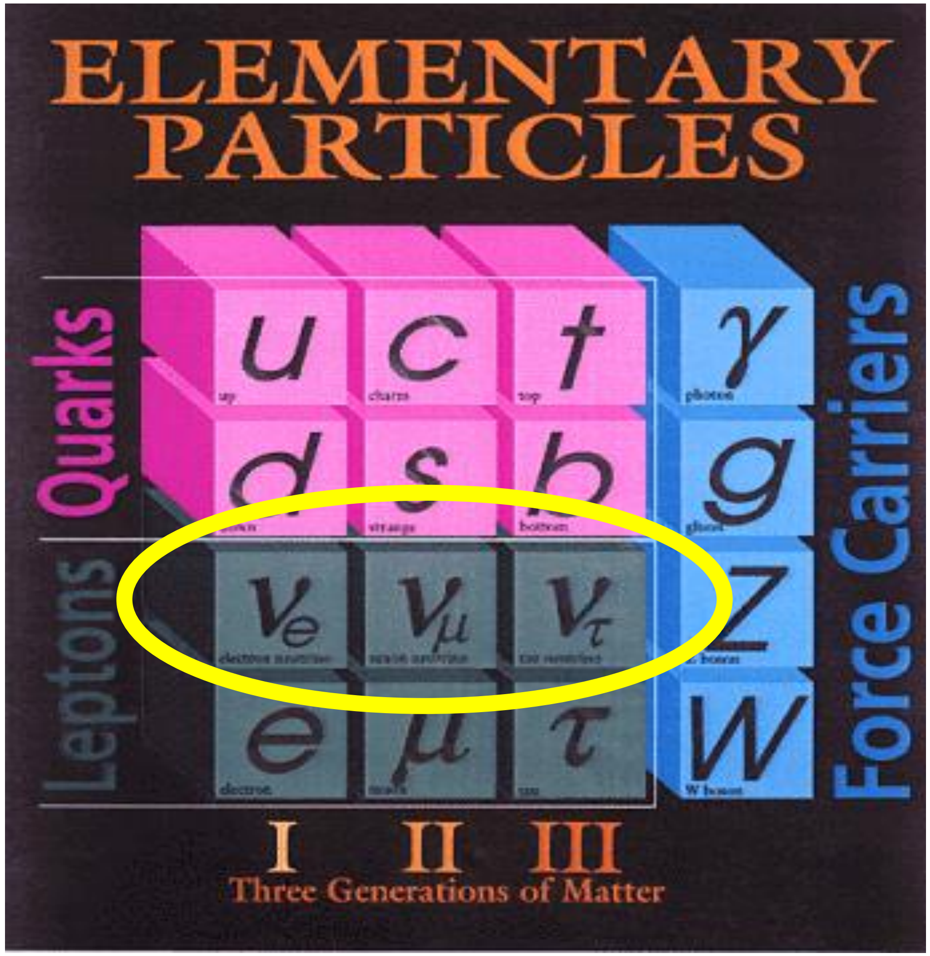
A Third Neutrino: ν_τ



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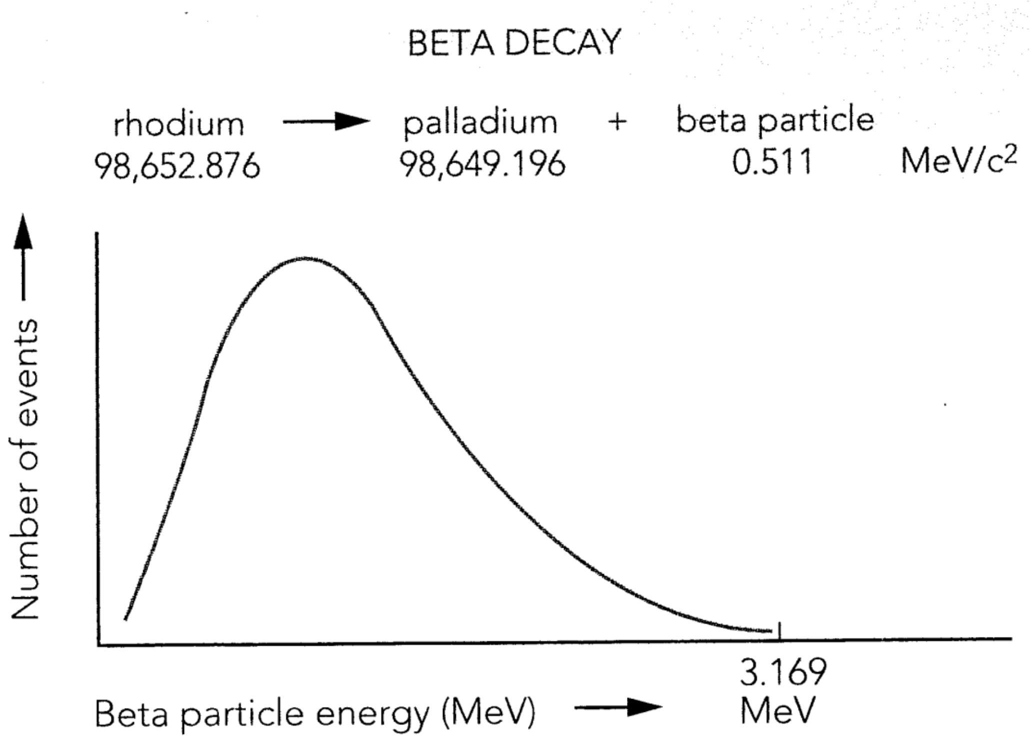
1. Some History

- During the period 1913 – 1930
- β beta decay spectrum was a big problem (puzzle).



- Continuous spectrum was observed for final state β spectrum

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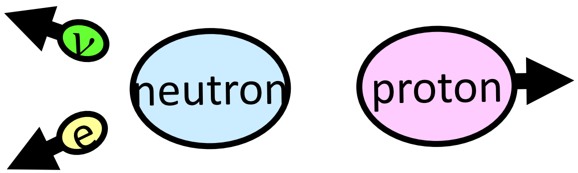
Wolfgang Pauli proposes a solution



Wolfgang Pauli

December 4, 1930

"Dear radioactive ladies and gentlemen,

...I have hit upon a 'desperate remedy' to save...the law of conservation of energy. Namely the possibility that there exists in the nuclei electrically neutral particles, that I call neutrons...I agree that my remedy could seem incredible...but only the one who dare can win...

Unfortunately I cannot appear in person, since I am indispensable at a ball here in Zurich.

Your humble servant
W. Pauli"

Note: this was before the discovery of the real neutron

1. Some History

- **1933 Fermi's β-decay Model**
  - He accepted Pauli's "invisible" particle, renamed it ***"neutrino***" to distinguish from Chadwick's neutron
  - Proposed all β-decays were due to the same underlying process

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

  - The neutrino was treated as a ½ spin particle (conservation of angular momentum -→ neutrino is a fermion) and obeys Dirac equation.
  - Fermi developed formalism parallel to Dirac's equation for e/m interaction except intermediate propagator is G_F

Enrico Fermi

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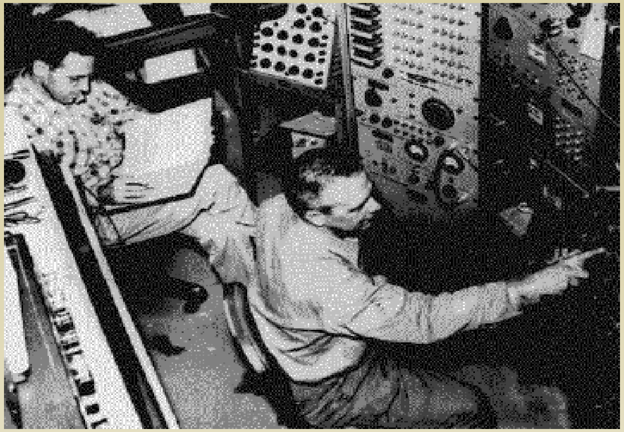
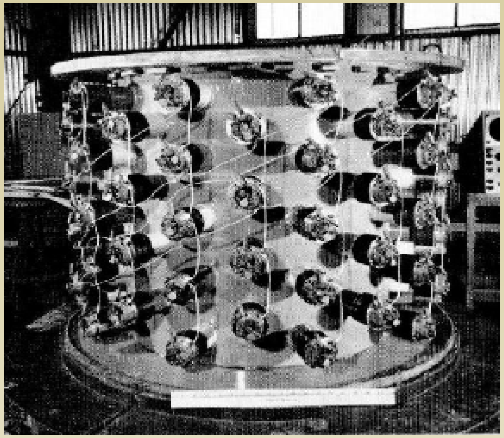
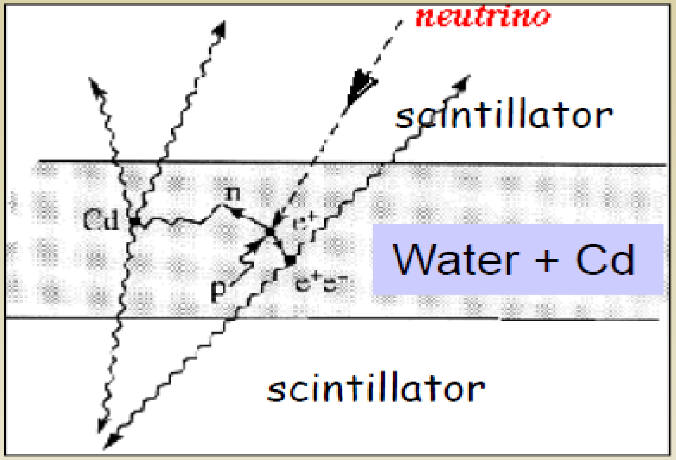
At the Savannah River nuclear power plant

1. Some History

Neutrino flux ~ 10^{13} /cm^2 s







$\bar{\nu}$ + p → e$^+$ + n

Typical signal :

- prompt 2-γ coincidence from e^+ annhilation on e^-
- delayed γ's from n capture by neutrophage nuclei (Cadmium)

Results:

Run time	Reactor	Counting rate
900 hr	ON	~ 1 /hr
250 hr	OFF	0.25 /hr

9

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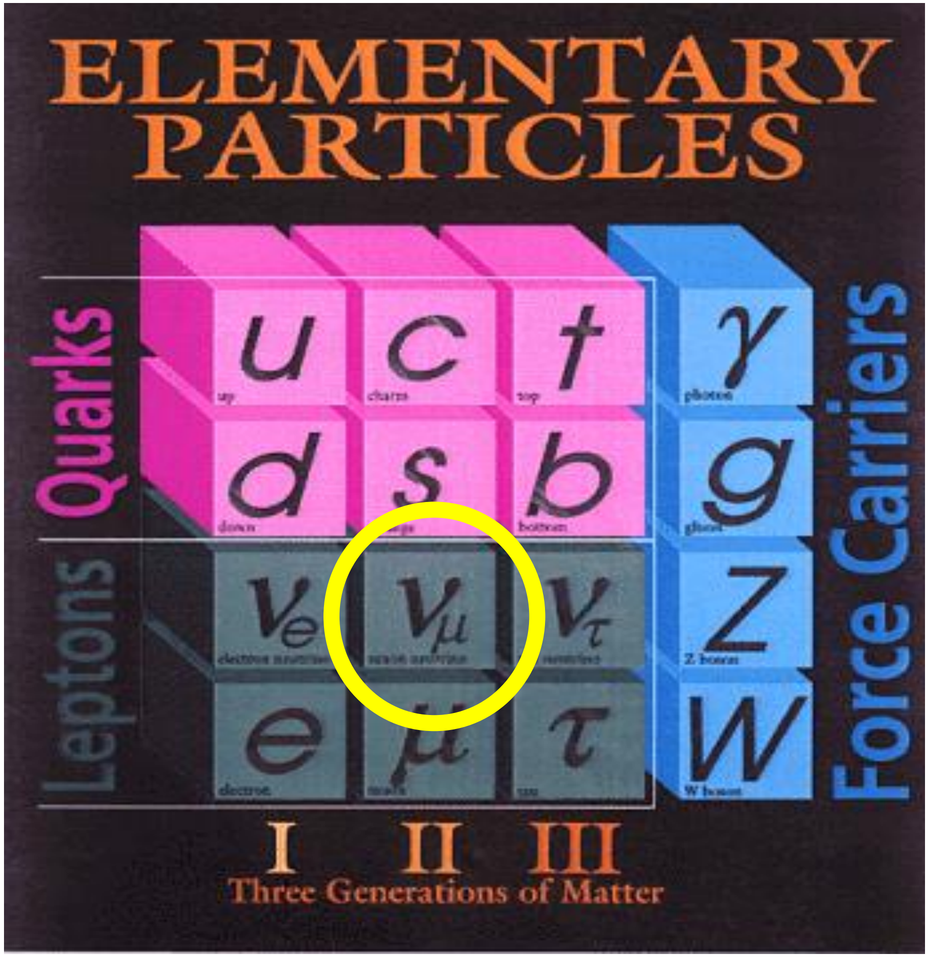
The Second Neutrino: ν_μ



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Two Neutrinos

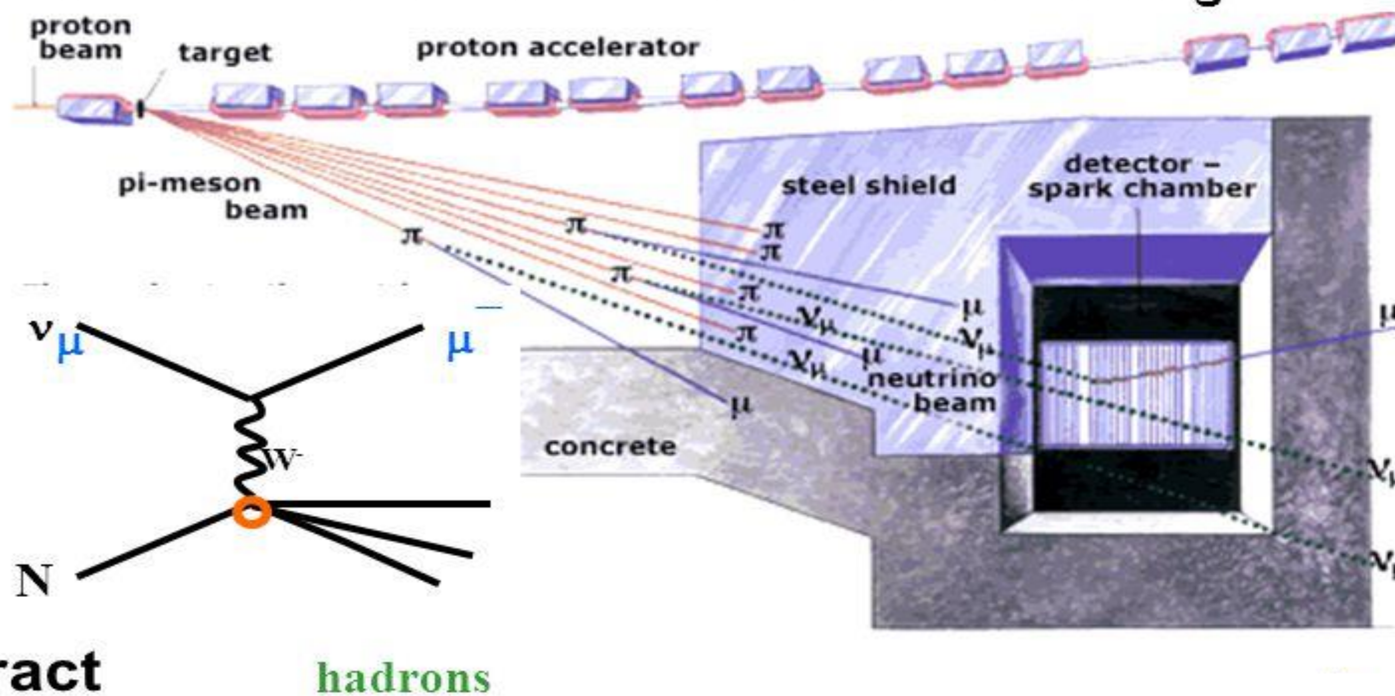
1962

Schwartz

Lederman

Steinberger

AGS Proton Beam



Neutrinos from π-decay only produce muons (not electrons)

when they interact in matter

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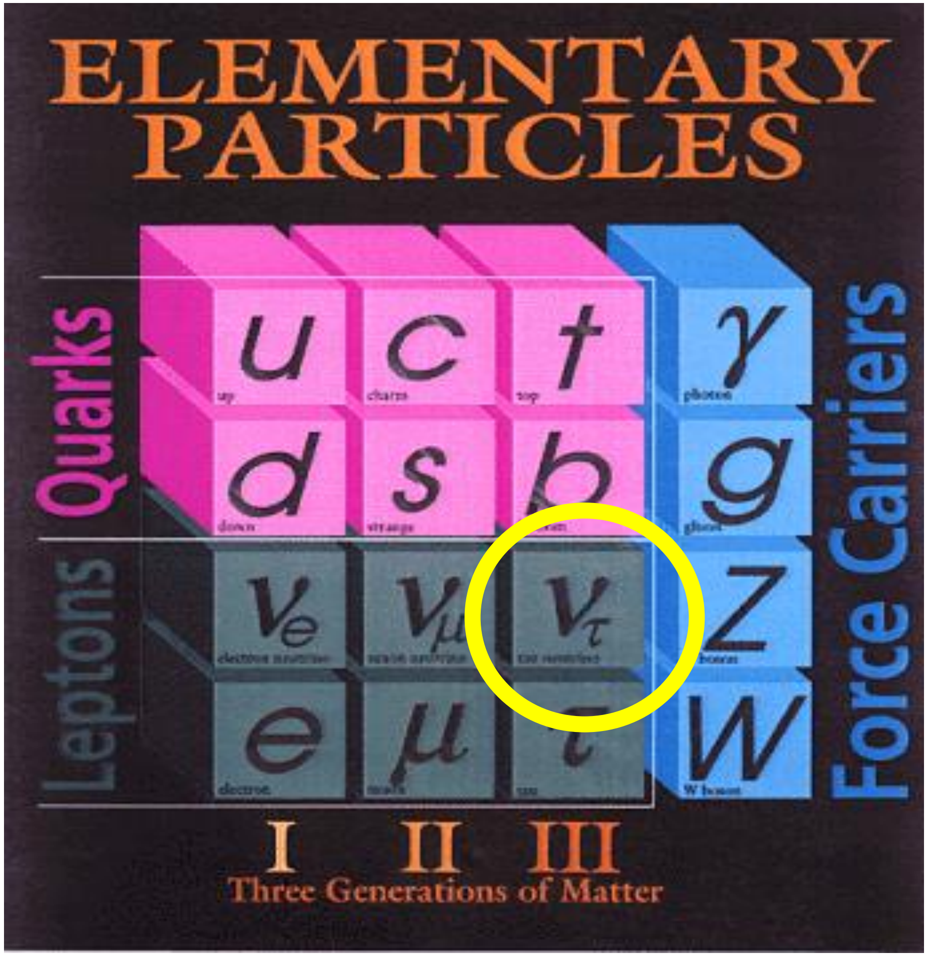
The Third Neutrino: ν_τ



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The detection of the ν_τ was a challenge -- 2000

- ν_τ has to produce a τ lepton
- one has to track a τ
- τ lifetime is $3\text{x}10^{-13}$ sec $(ct=90\ \mu m)$

use emulsion

Experiment: DONUT (Direct Observation of the NU Tau) at FermiLab accelerator.

Out of 10^{13} neutrinos , only 1000 ν interactions recorded, out of which 4 were identified as ν_τ

DONUT searched for decays into 1 charged particle (86% of taon decays)

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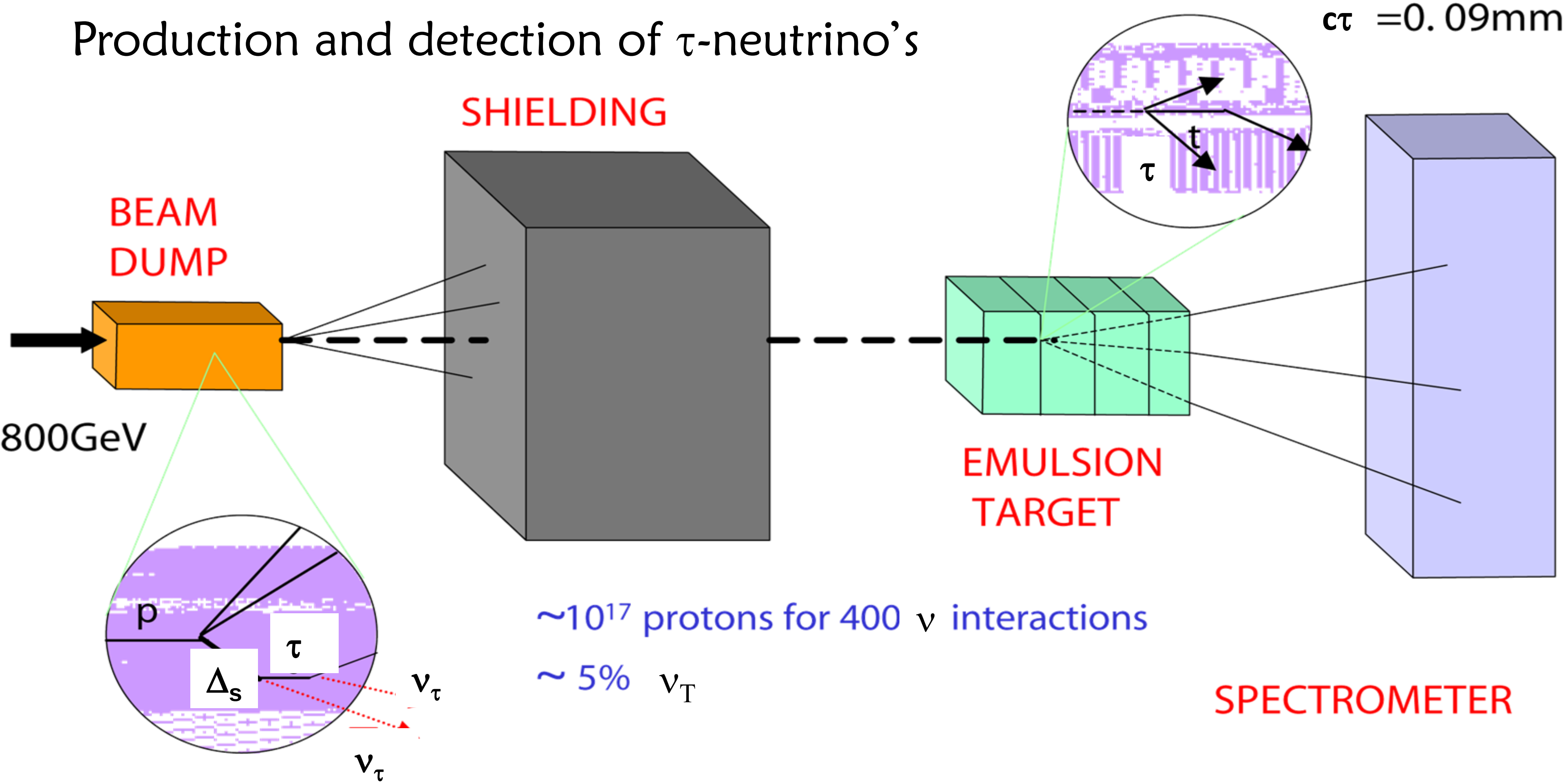
Discovery of τ-neutrino (2000)

DONUT collaboration
Production and detection of τ-neutrino's



~10^{17} protons for 400 ν interactions

~ 5% ν_T

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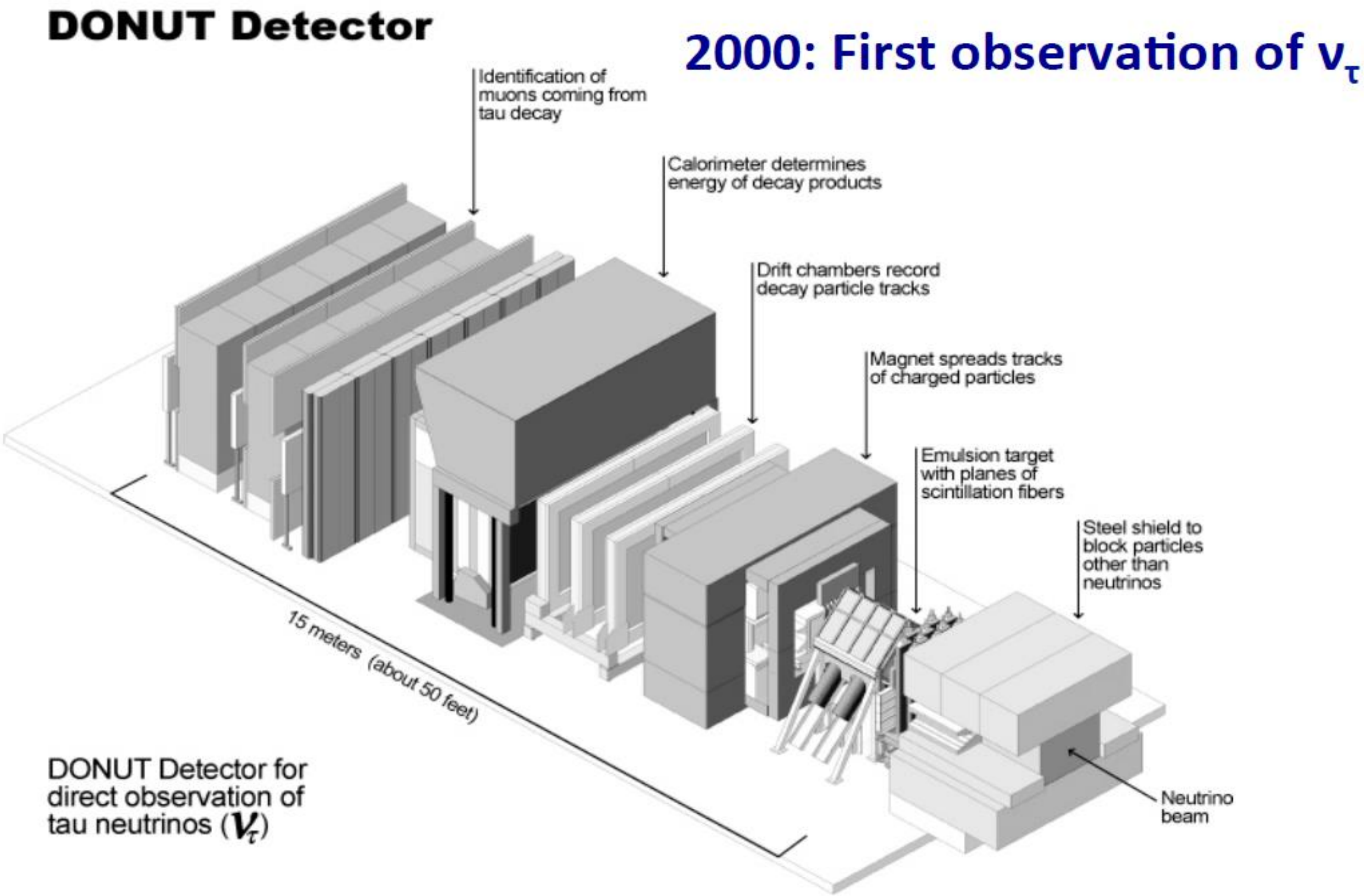
The detection of the ν_τ was a challenge -- 2000



Phys. Lett. B 504, 218 (2001)

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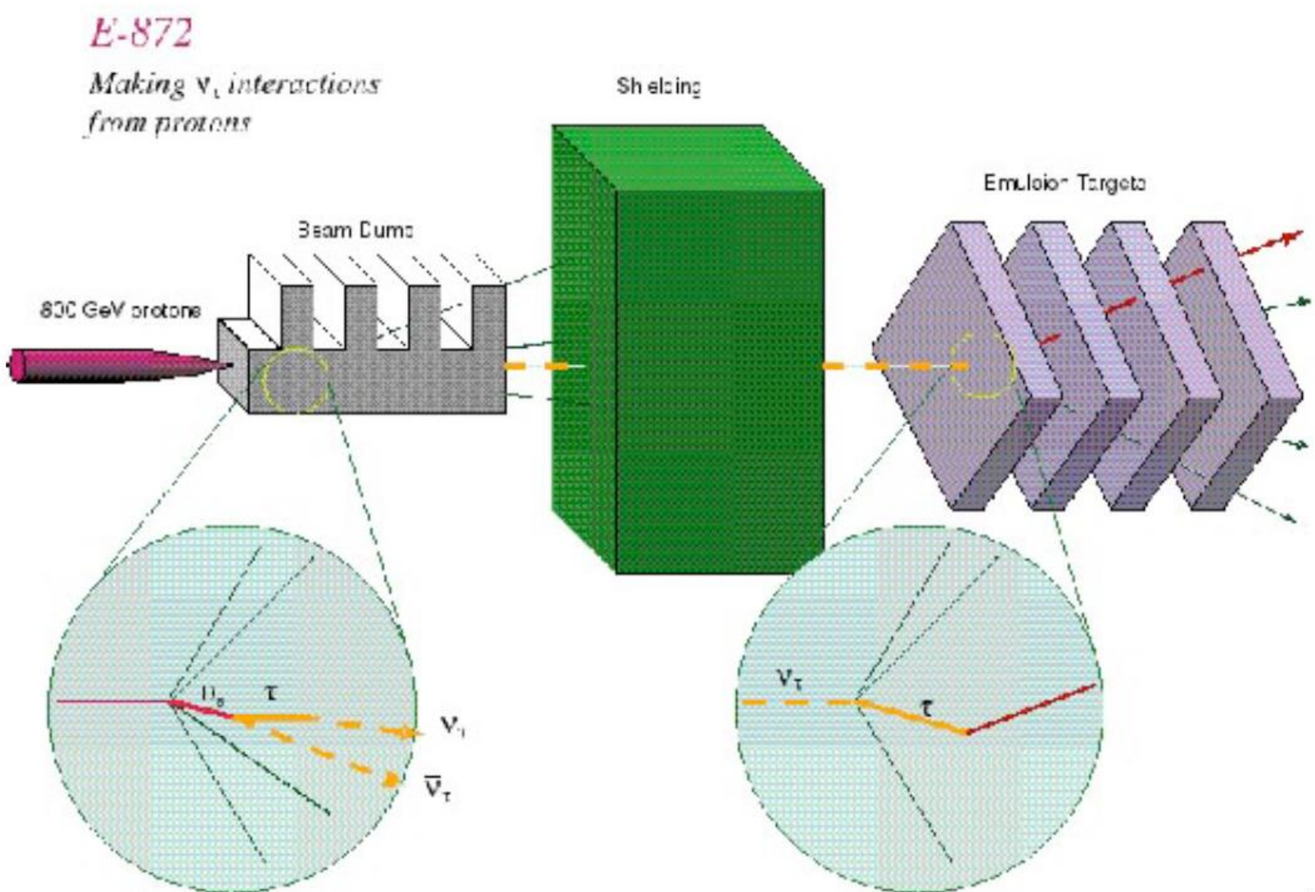
DONUT: The detection of the ν_τ

800 GeV protons produced mesons containing c and s quarks, which decay into τ and ν_τ



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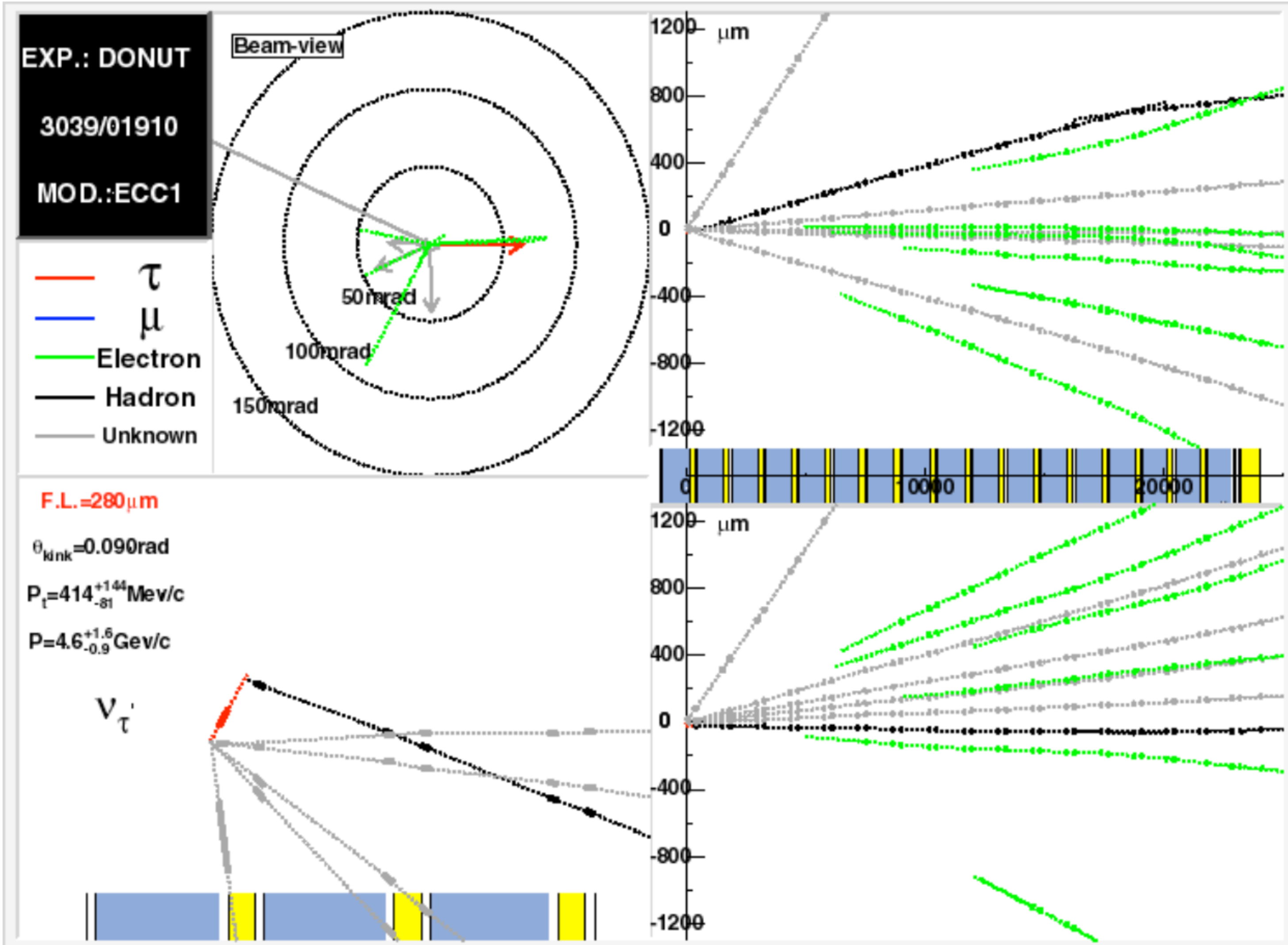
DONUT: The detection of the ν_τ



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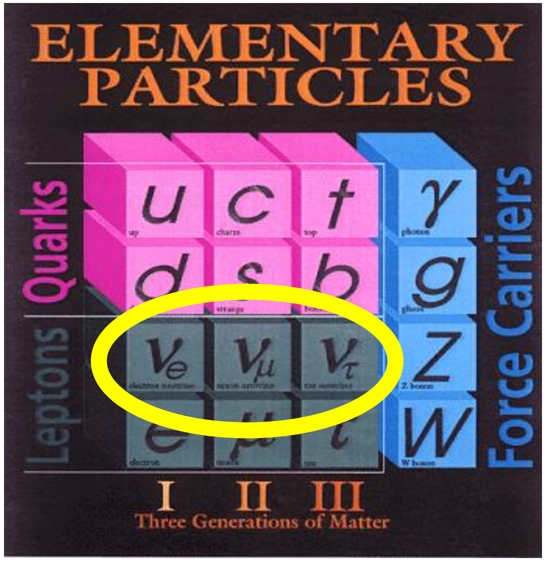
Three families – three neutrinos

WHY ????

One of the big unanswered questions !!

No good answer !!!



BUT, are there really only three ????

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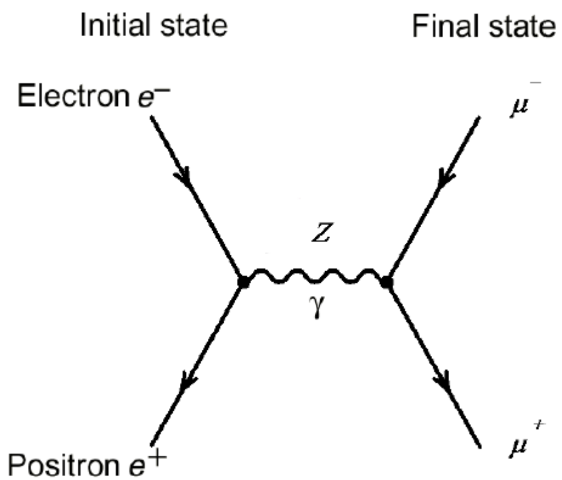
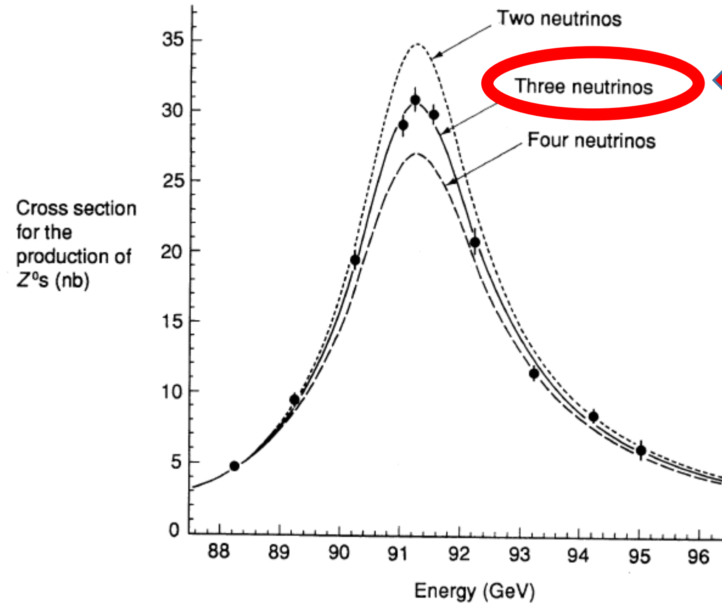
How many neutrinos are there?



$\nu\bar{\nu}$



$$Z^0 \to q\bar{q}(u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, b\bar{b})$$
$$Z^0 \to l\bar{l}(e^-e^+, \mu^-\mu^+, \tau^-\tau^+)$$
$$Z^0 \to \nu\bar{\nu}(\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau)$$

$\Gamma_Z, \Gamma_l, \Gamma_h$ - measured
Γ_ν - calculated

Total width: $\Gamma \sim$ decay probability ($\sim 1/$lifetime)
Partial widths: $\Gamma_i \sim$ branching rate (channel i)

$$\Gamma_Z = \Gamma_{had} + 3\Gamma_l + N_\nu \Gamma_\nu$$
$$N_\nu = 2.99 \pm 0.02$$

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To Address the question of how many neutrinos there are, let me first present some evidence

- *Neutrinos Have Mass*
- *Neutrinos can oscillate from one type to another*

We will return to neutrino mass and oscillations in the following lectures, including the current state of the subject

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Neutrinos as a Tool: Sources of Neutrinos

Natural:

(i) Atmospheric (10^{-4} s),
(ii) Solar (8 min),
(iii) Supernova (>10^4 yr),
(iv) Other astrophysical sources (GRB, AGN) (10^6 yr),
(v) Early Universe (10^{12} yr),
(vi) Earth's Interior (0.01 s).

Understanding the Sun +

- Artificial (Man-made):
  - (i)Reactors (10^{-4} s)
  - (ii)Accelerators (0.001 s)

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The Sun

•It is our sole source of light and heat in the solar system

•Our sun is a very common, rather small star

•It is a glowing ball of gas: held together by its own gravity and powered by nuclear fusion at its center.

Visible Image of the Sun

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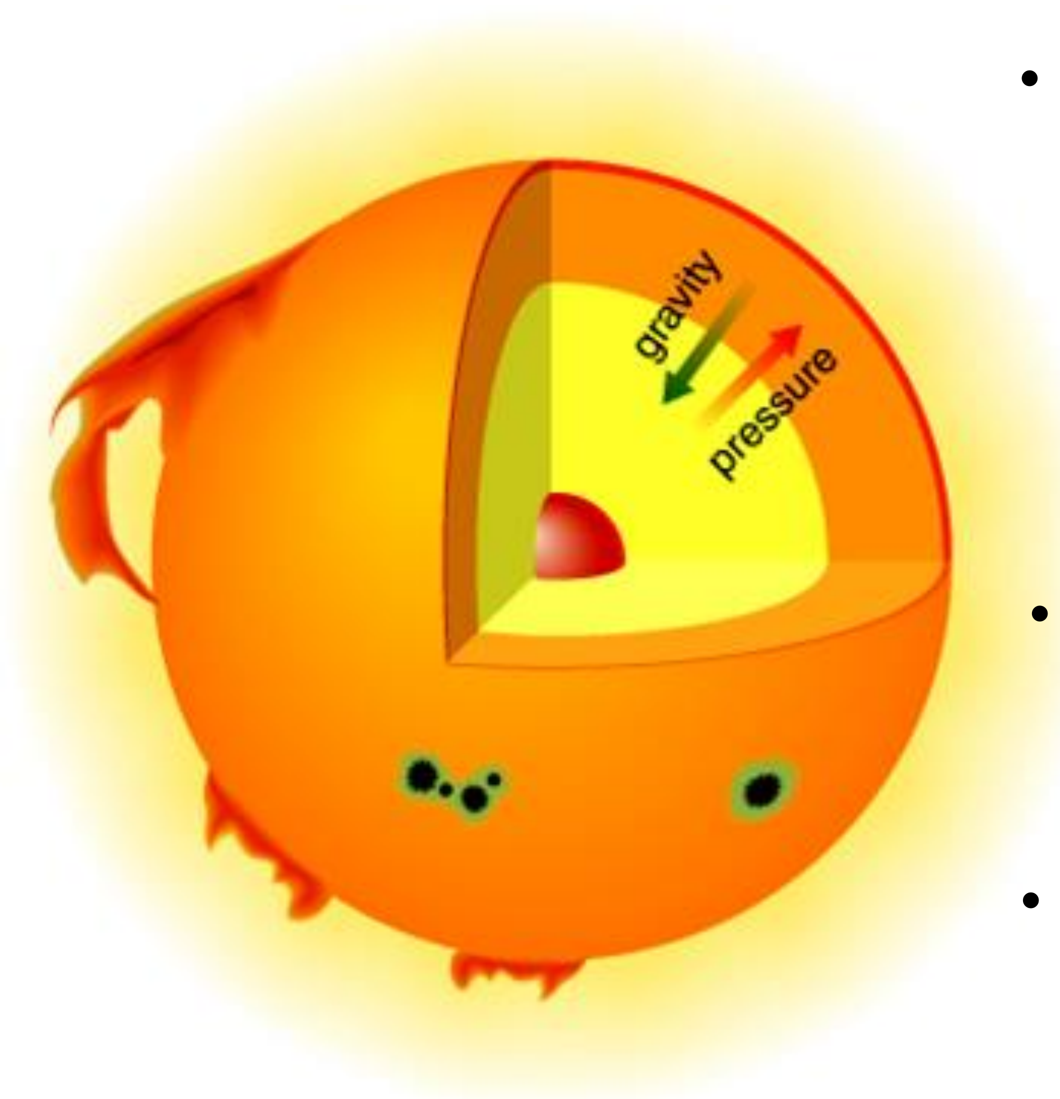
The Sun (and stars) during their lifetime burning cycle



- Pressure (from heat resulting from nuclear reactions) is balanced by the gravitational pull toward the Sun's center. This is called ***"Hydrostatic Equilibrium.***
- This balanced state is a large spherical ball of gas, we call the ***"Sun."***
- This continues until the sun (star) burns up its fuel, then gravity wins and it collapses into ???

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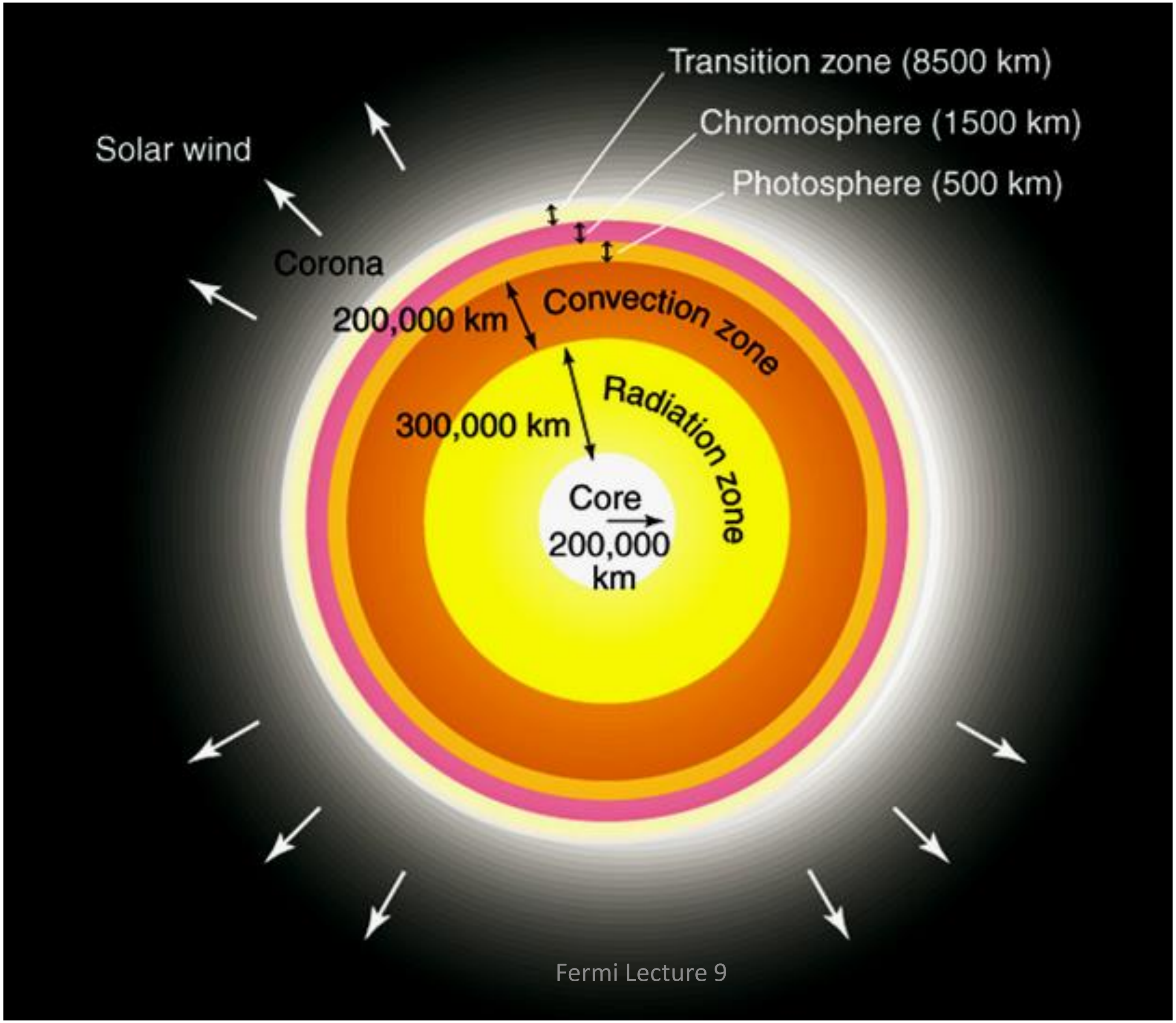
Different regions of the sun (star)



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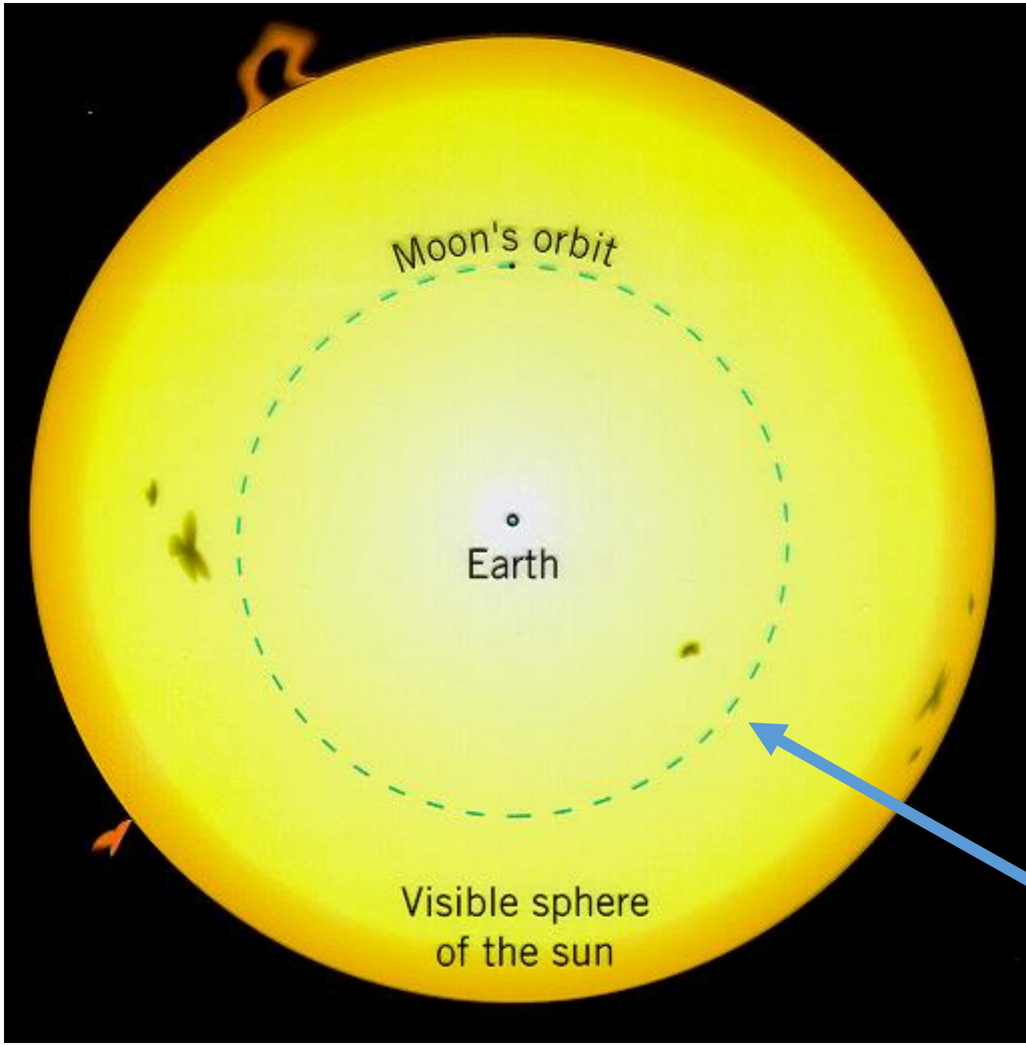
Solar Properties



Radius = 696,000 km
(100 times Earth)

Mass = 2 x 10^{30} kg
(300,000 times Earth)

Av. Density = 1410 kg/m^3

Rotation Period =
24.9 days (equator)
29.8 days (poles)

Surface temp = 5780 K

The Moon's orbit around the Earth would easily fit within the Sun!

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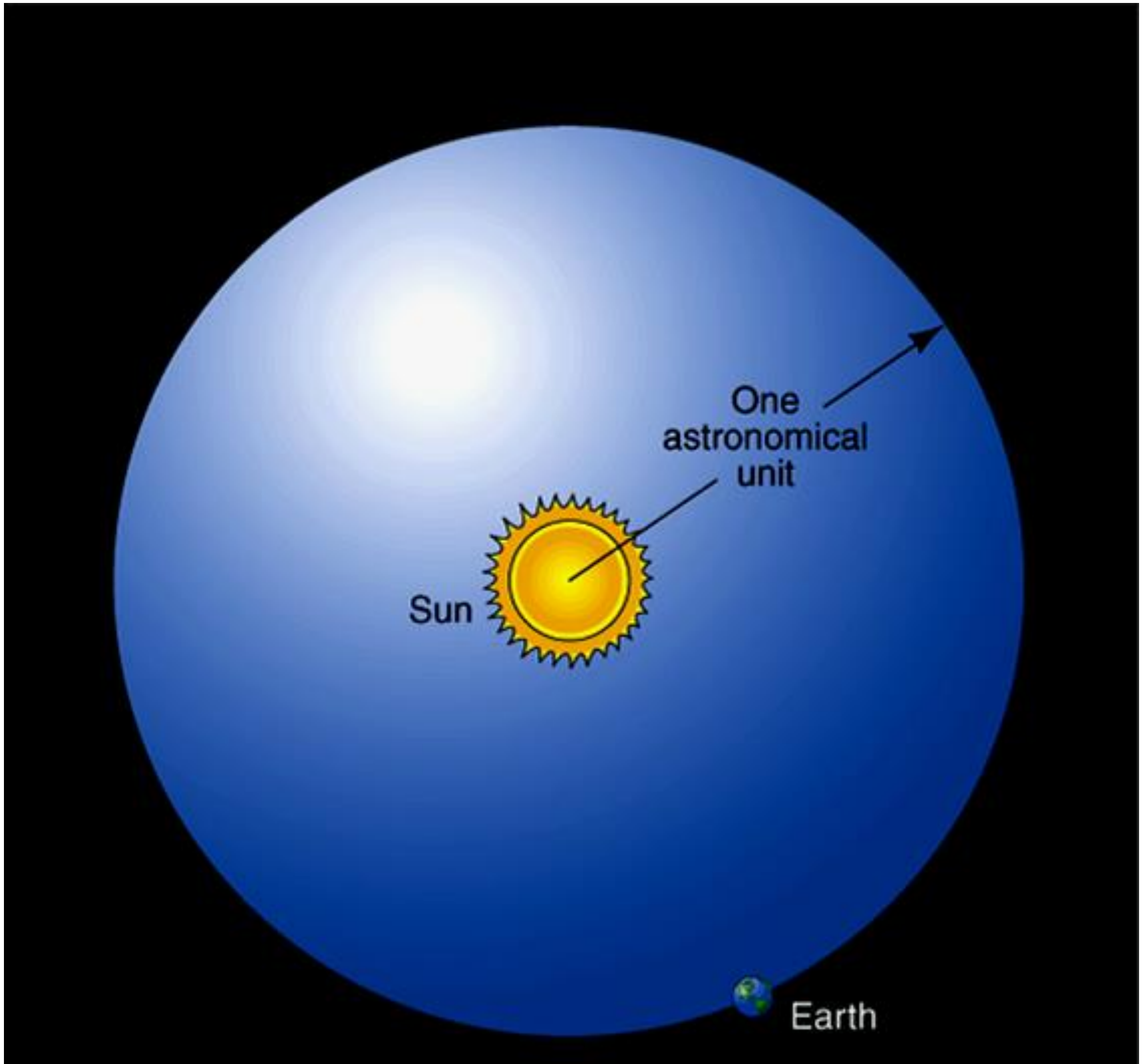
Luminosity of the Sun

L = Total photon energy emitted per second

L = ~ 4 x 10^{26} W
(equivalent to 100 billion one-megaton nuclear bombs every second!)



Solar constant:

$L_{SUN} / 4\pi R^2$

(energy/second/area at the radius of Earth's orbit)

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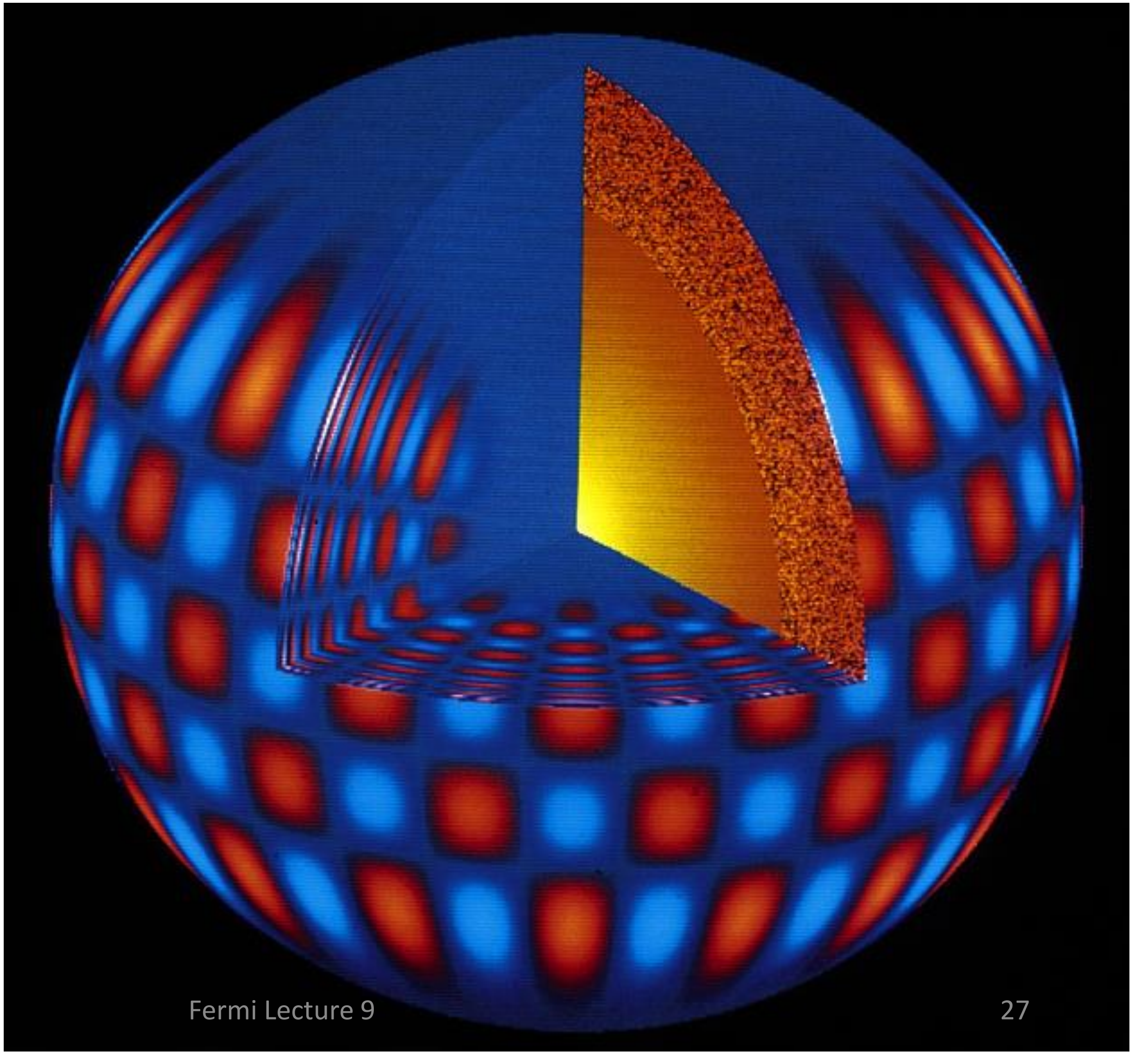
Solar Interior "Helioseismology

Learning about the Interior of the Sun

- •In the 1960s, it was discovered that the surface of the Sun vibrates like a bell
- •Internal pressure waves reflect off the photosphere
- •Analysis of the surface patterns of these waves tell us about the inside of the Sun



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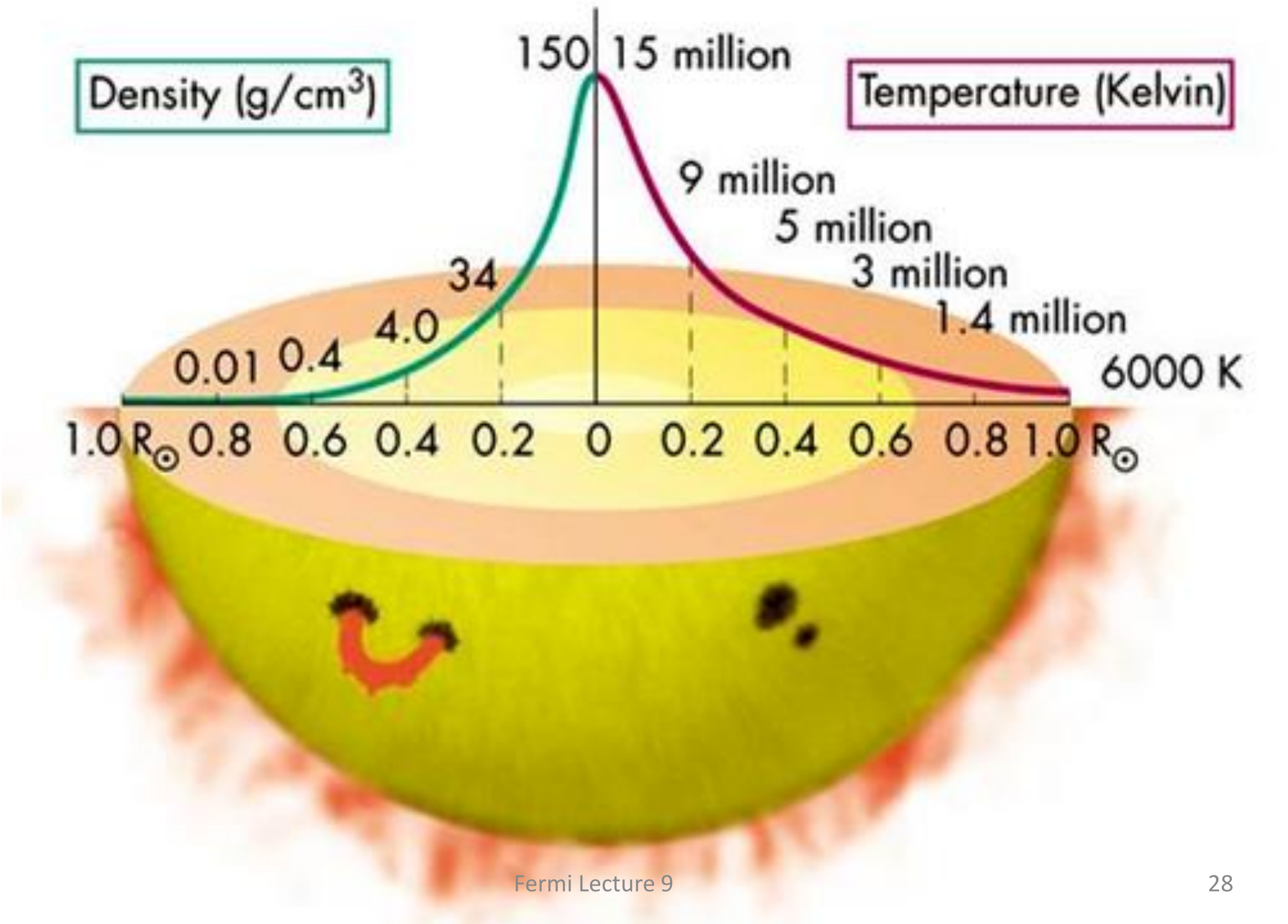
The Standard Solar Model



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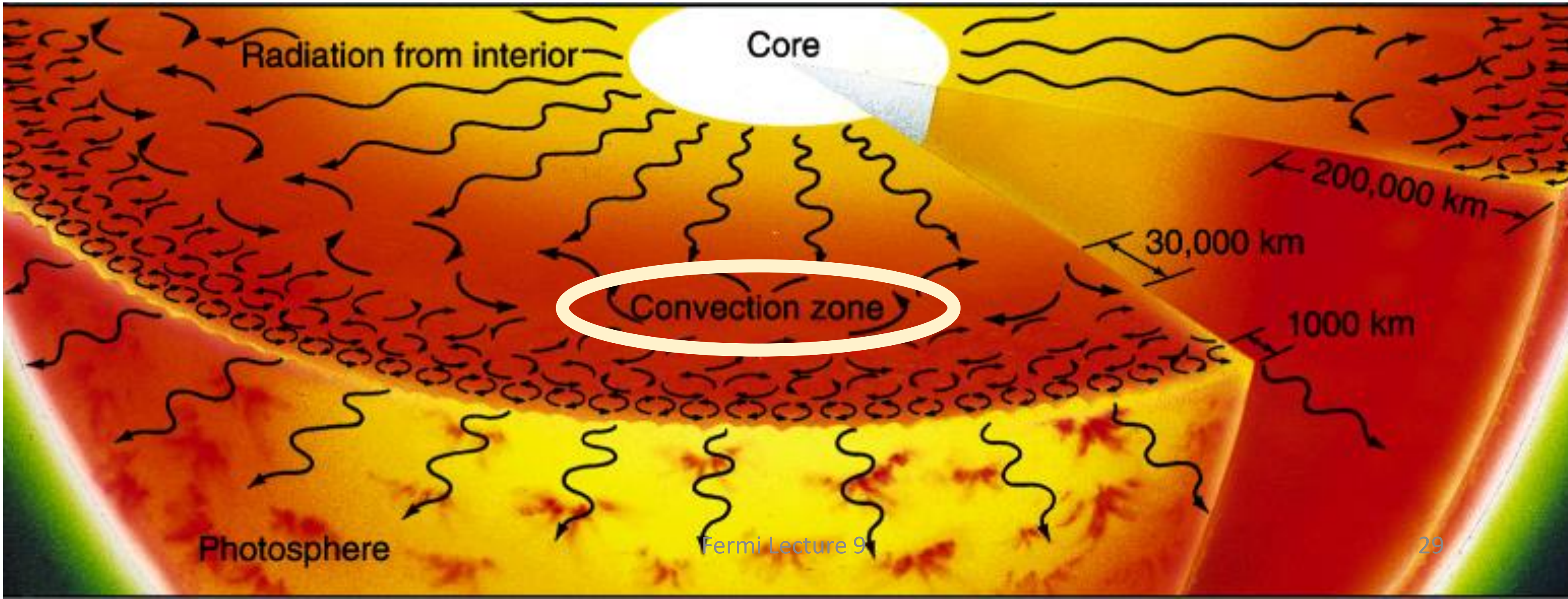
Energy Transport within the Sun

- Extremely hot core - ionized gas
- No electrons left on atoms to capture photons - core/interior is transparent to light (**radiation zone**)
- Temperature falls further from core - more and more non-ionized atoms capture the photons - gas becomes opaque to light in the **convection zone**
- The low density in the photosphere makes it transparent to light - radiation takes over again



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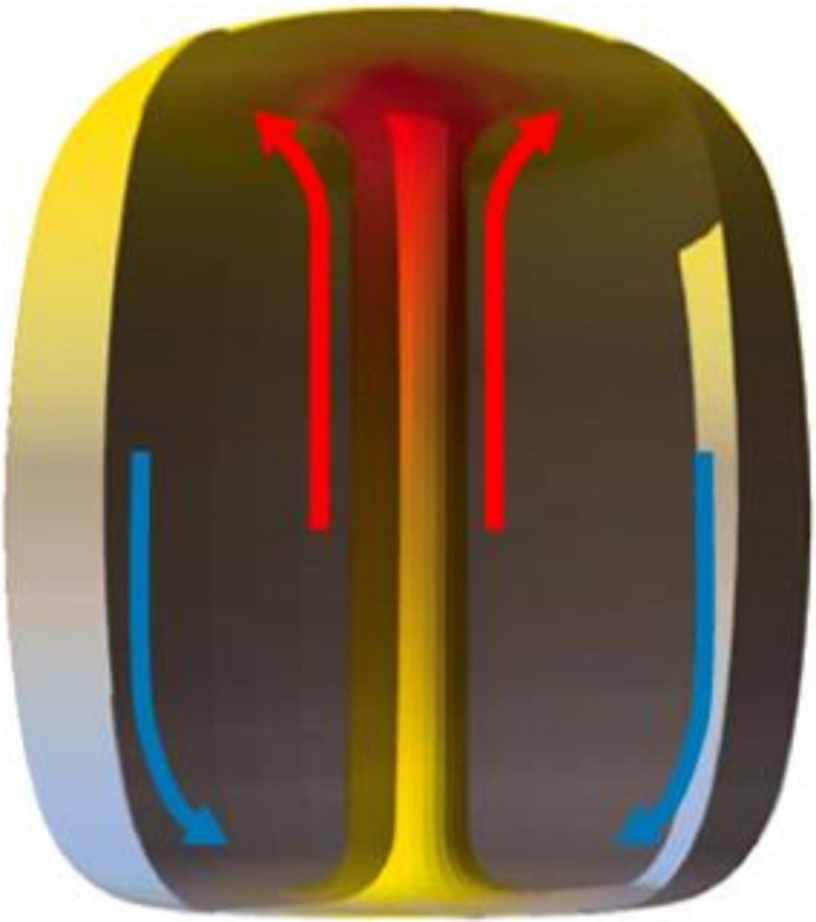
Convection Zone



- Convection takes over when the gas is too opaque for radiative energy transport.
- Hot gas is less dense and rises
- Cool gas is more dense and sinks

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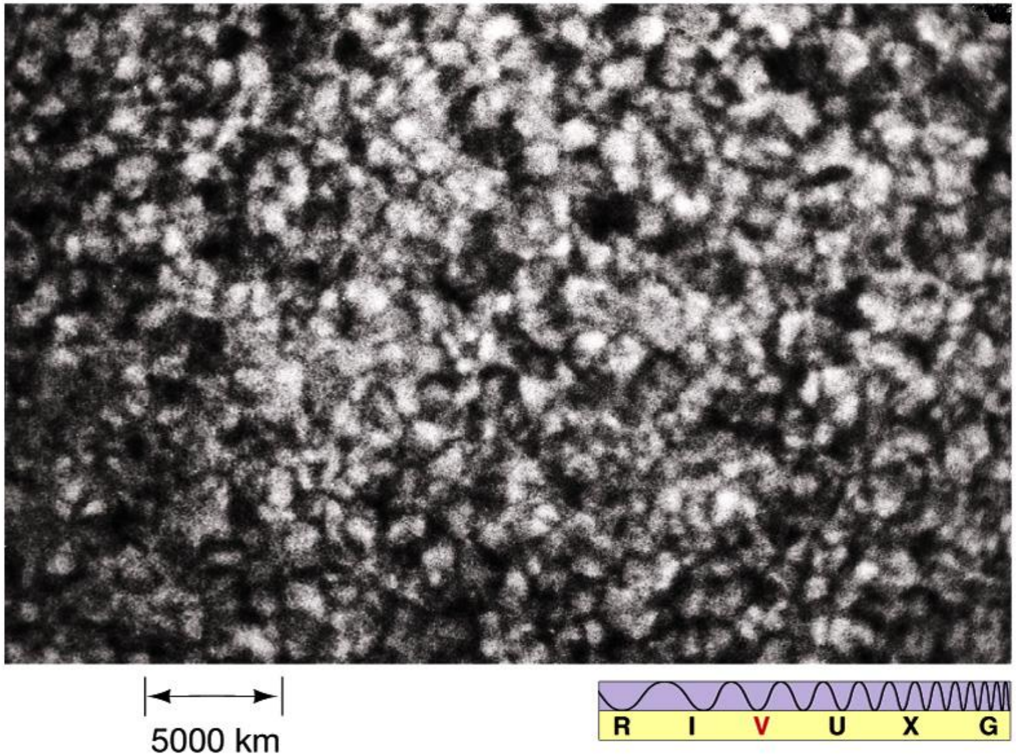
Convection Zone

- Solar Granules are the tops of convection cells.
- Bright regions are where hot material is upwelling (1000 km across).
- Dark regions are where cooler material is sinking.
- Material rises/sinks @ ~1 km/sec (2200 mph; Doppler).



Solar Granulation Evidence for Convection

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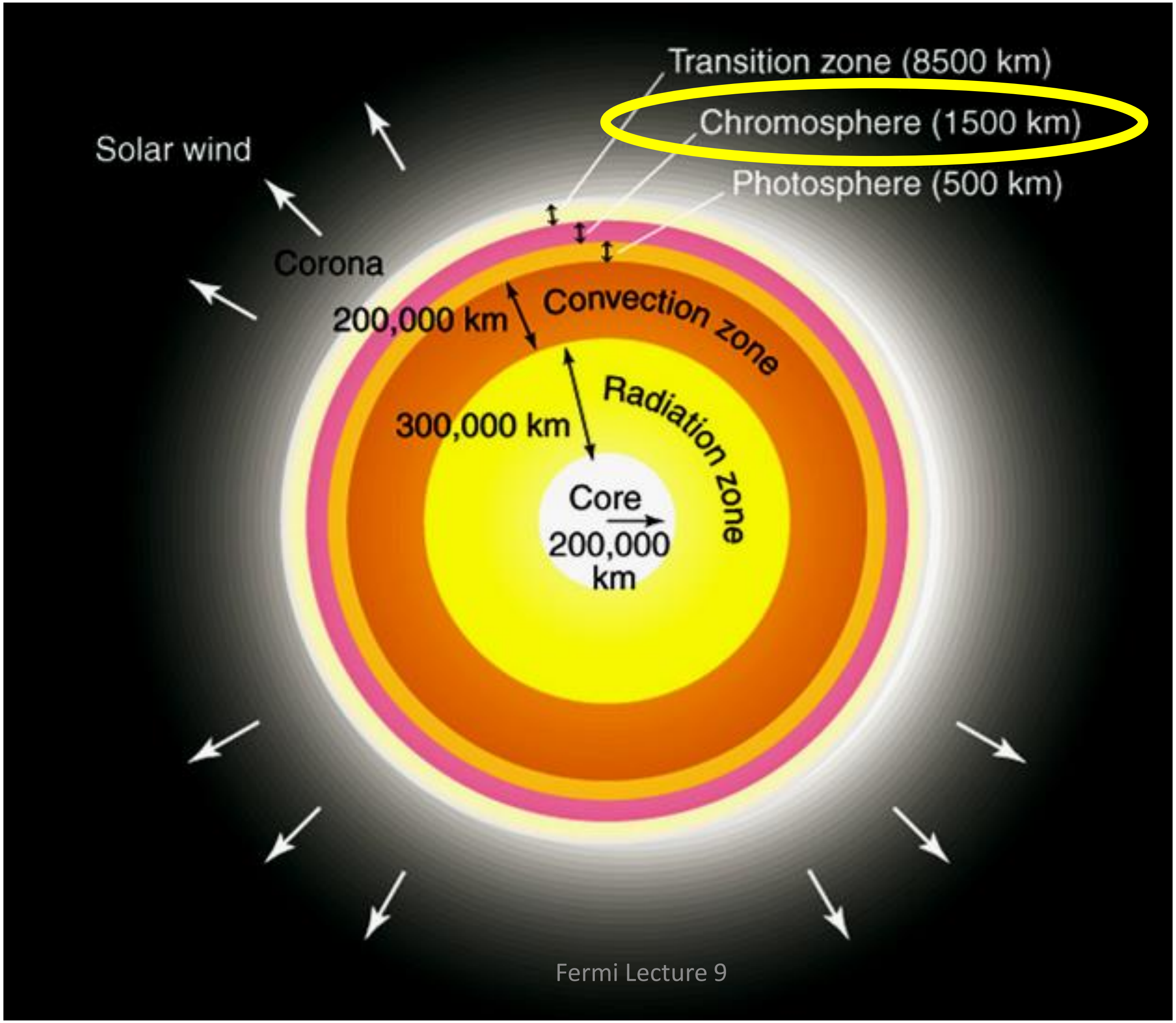
Different regions of the sun (star)



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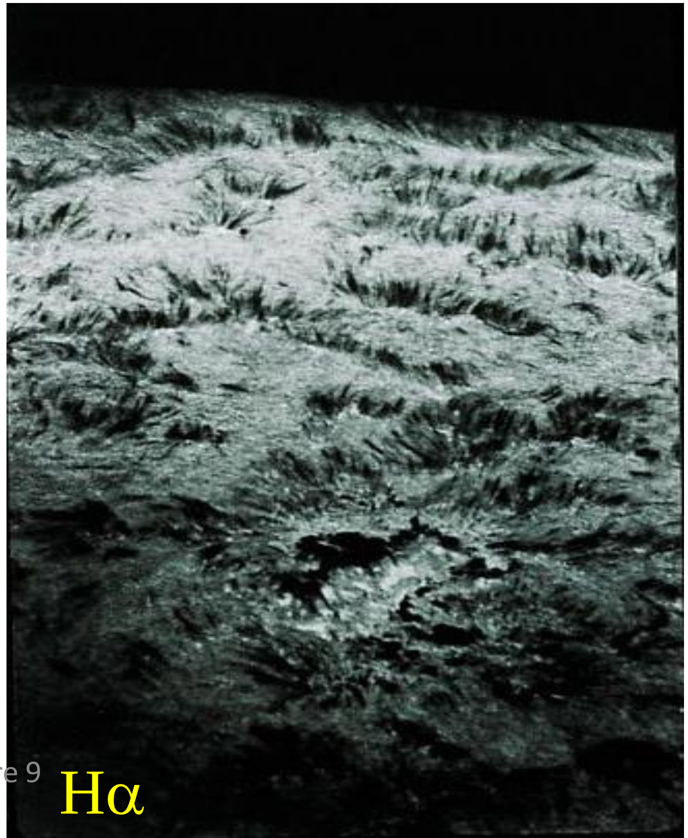
Chromosphere (seen during full Solar eclipse)

Chromospheric Spicules: warm jets of matter shooting out at ~100 km/s last only minutes, from magnetic disturbances



- Chromosphere emits very little light because it is of low density
- Reddish hue due to 3→2 (656.3 nm) line emission from Hydrogen

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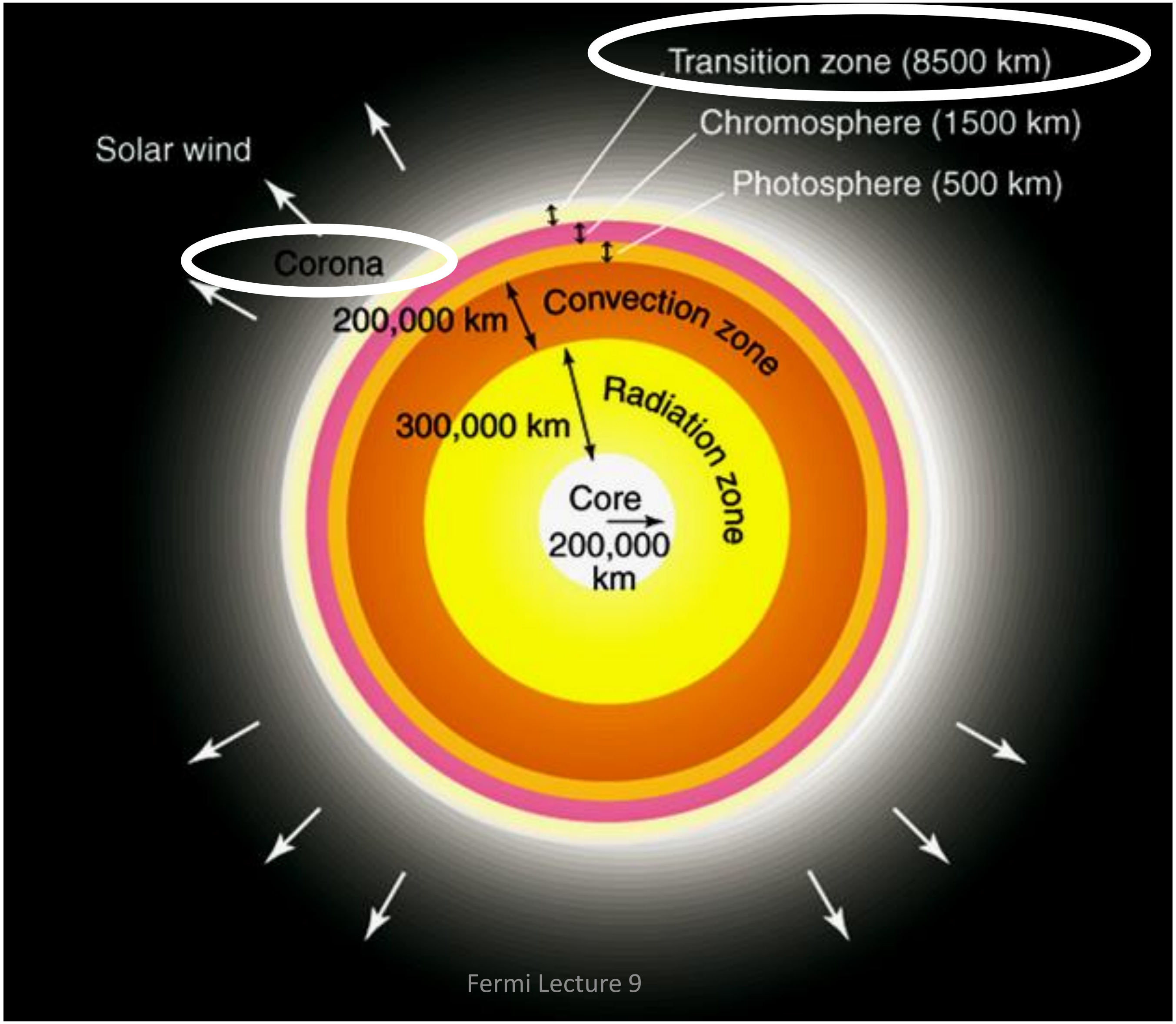
Transition zone and Corona



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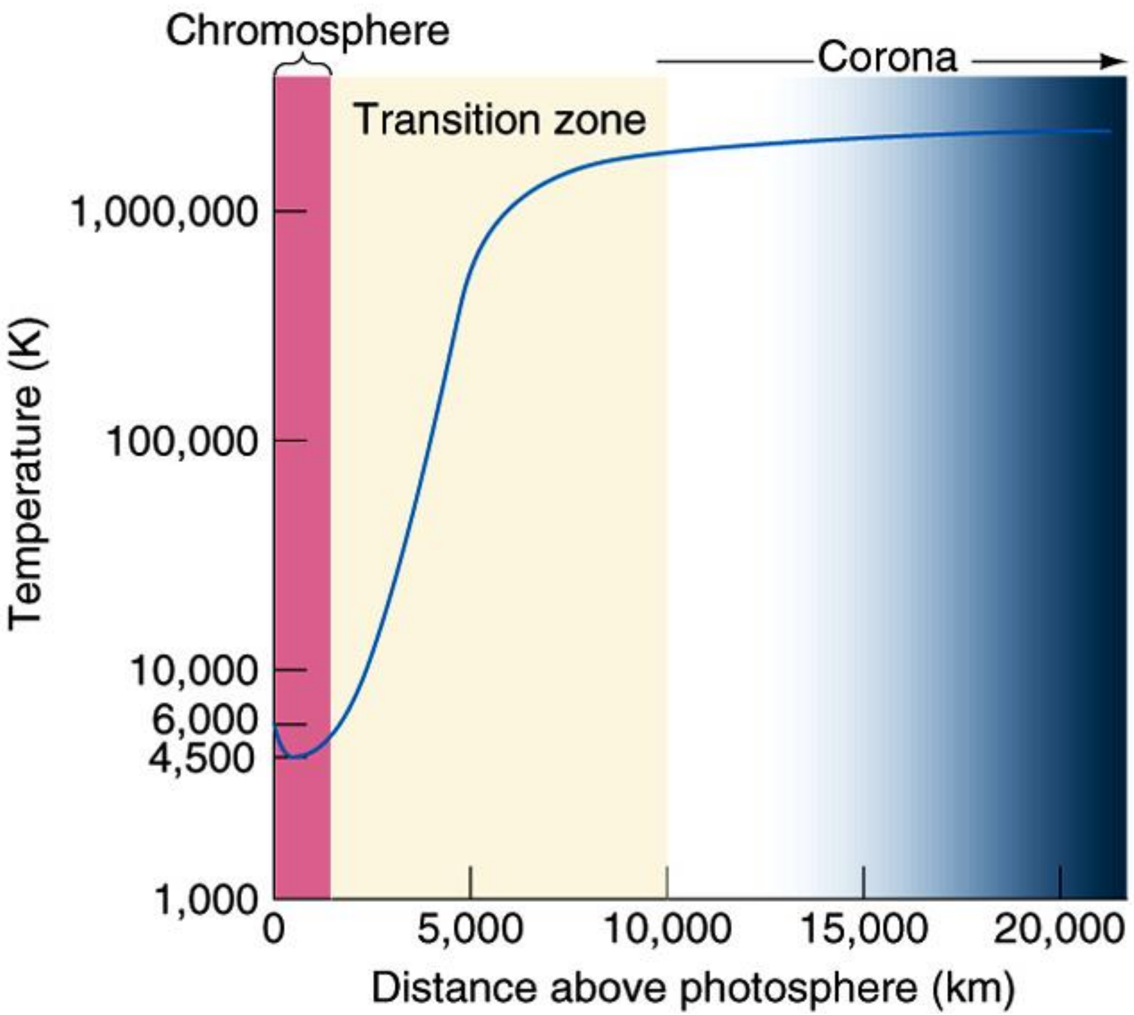
Transition Zone & Corona

Very low density, T ~ 10^6 K

We see <u>emission lines</u> from highly ionized elements (Fe^{+5} – Fe^{+13}) which indicates that the temperature here is very *HOT*



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Corona - during full Solar eclipse)

Hot coronal gas escapes the Sun $\rightarrow$ <u>Solar wind</u>

- Coronal gas has enough heat (kinetic) energy to escape the Sun’s gravity.
- The Sun is *evaporating* via this “wind”.
- Solar wind travels at ~500 km/s, reaching Earth in ~3 days
- The Sun loses about 1 million tons of matter each second!
- However, over the Sun’s lifetime, it has lost only ~0.1% of its total mass.

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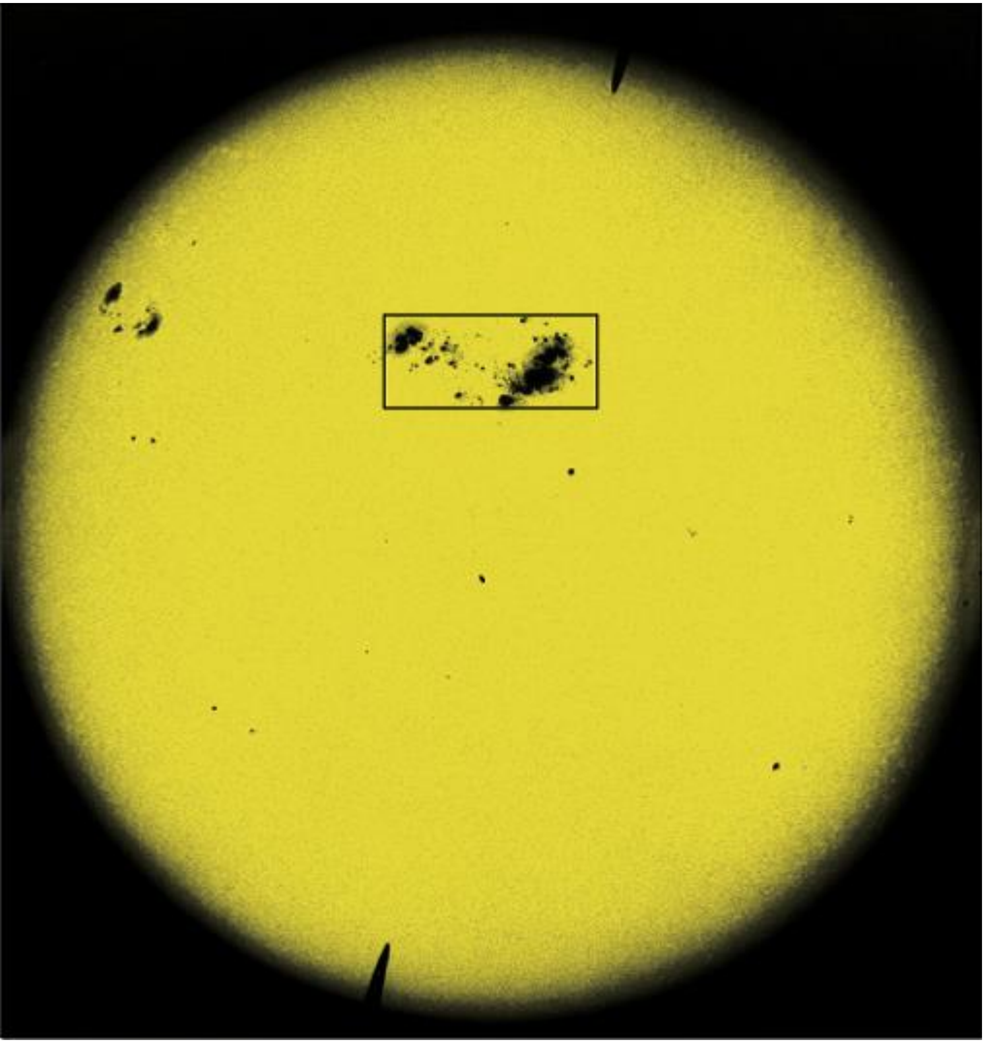
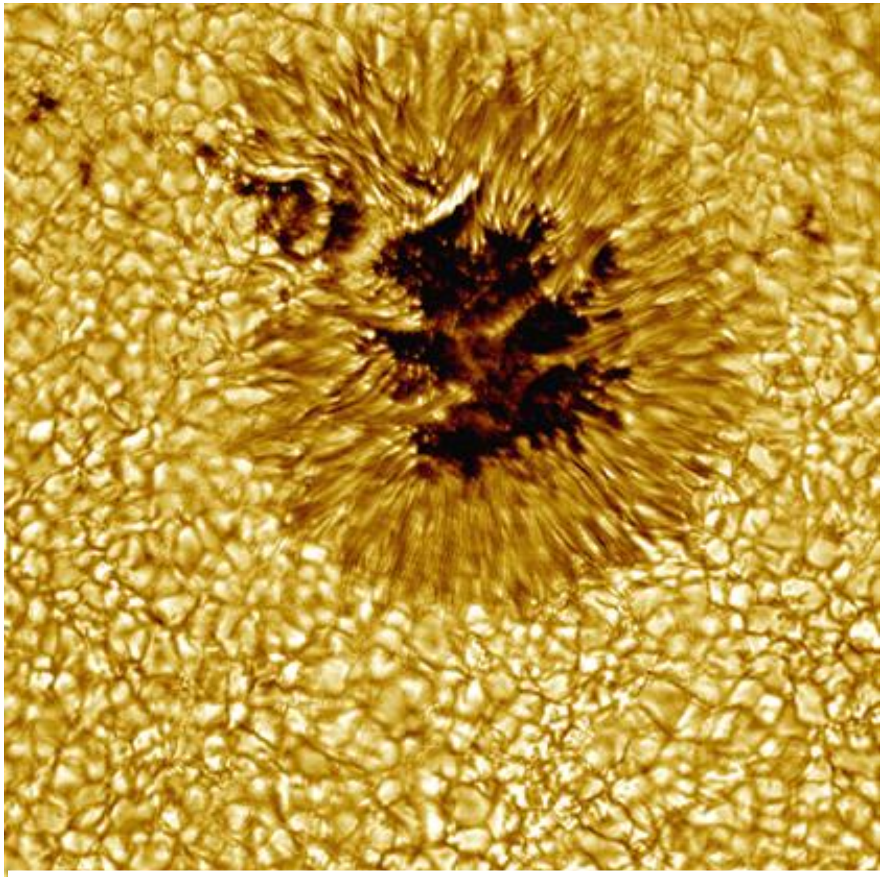
Sunspots





Granulation around sunspot

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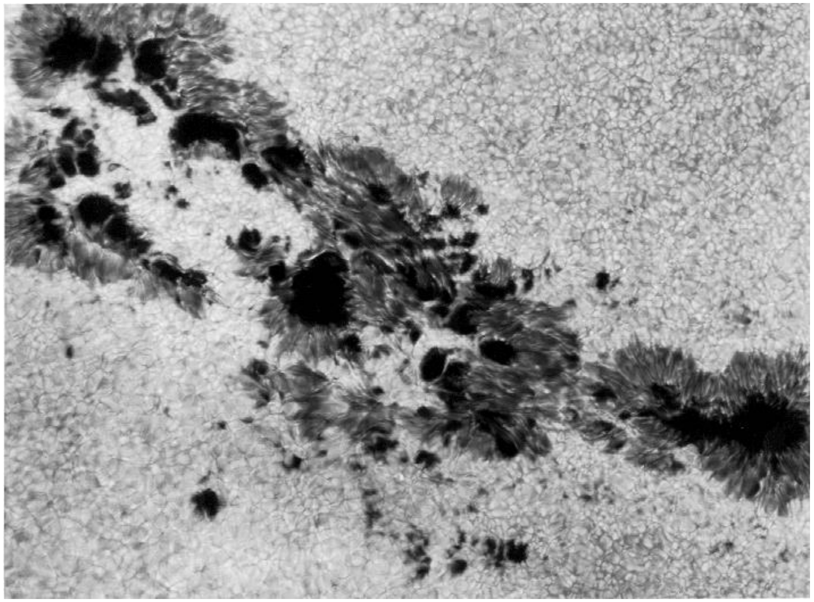
Sunspots

- Typically about 10000 km across
- At any time, the sun may have hundreds or none
- Dark color because they are cooler than photospheric gas (4500K in darkest parts)



- Each spot can last from a few days to a few months
- Galileo observed these spots and realized the sun is rotating *differentially* (faster at the poles, slower at the equator)

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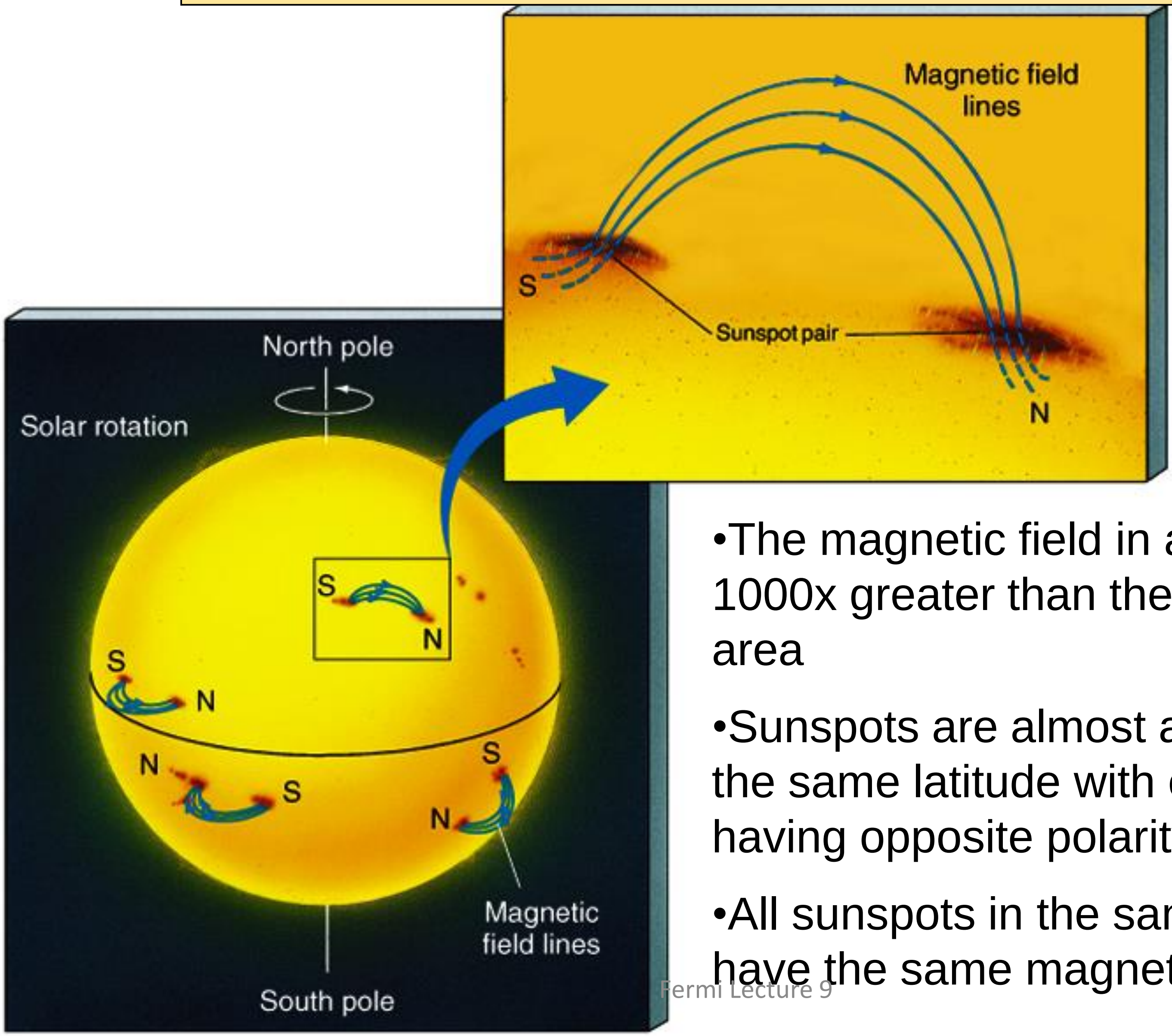
Sunspots & Magnetic Fields



- The magnetic field in a sunspot is 1000x greater than the surrounding area
- Sunspots are almost always in pairs at the same latitude with each member having opposite polarity
- All sunspots in the same hemisphere have the same magnetic configuration

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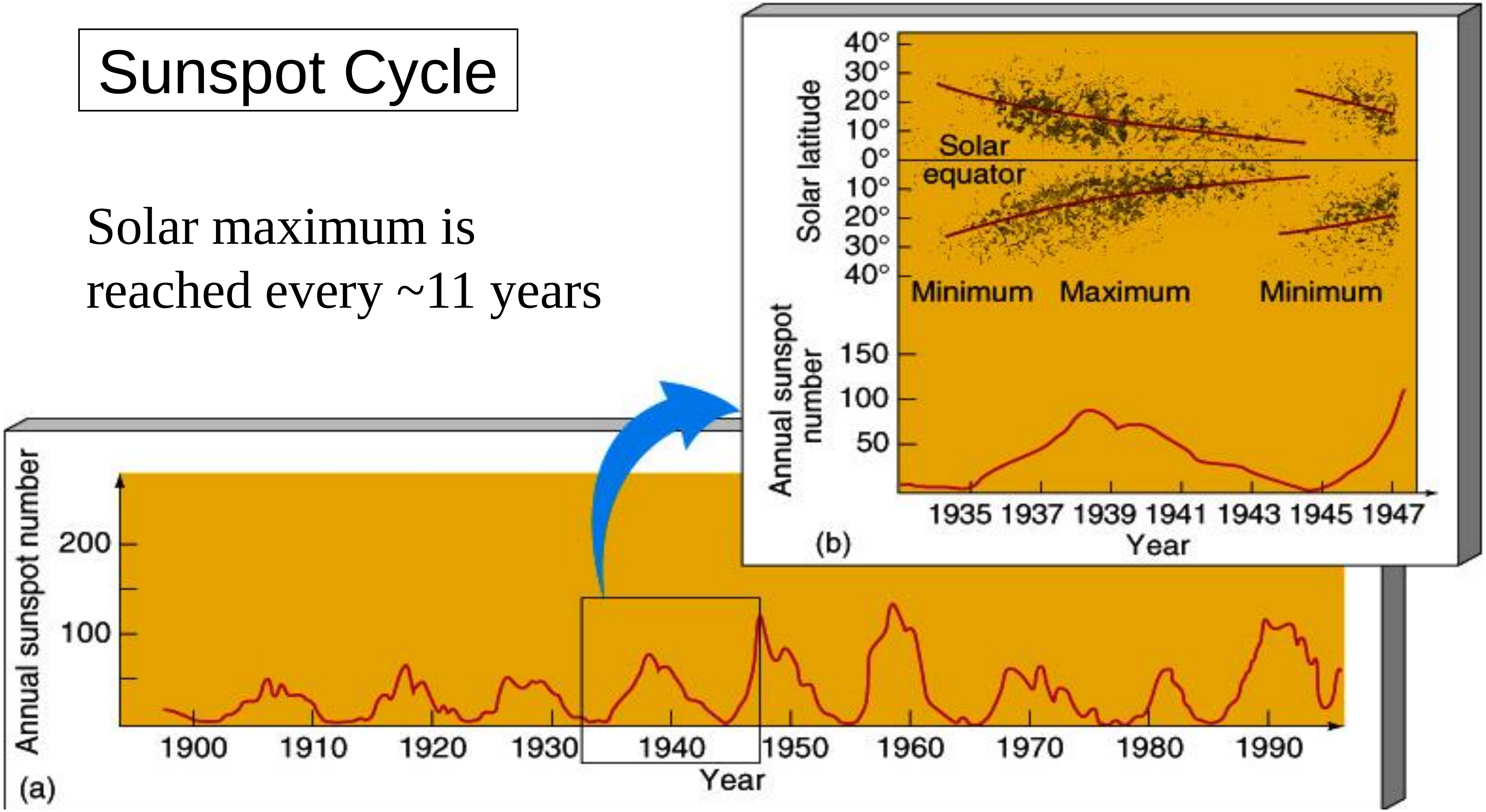
Sunspot Cycle

Solar maximum is reached every ~11 years



Solar Cycle is 22 years long – direction of magnetic field polarity flips every 11 years (back to original orientation every 22 years)

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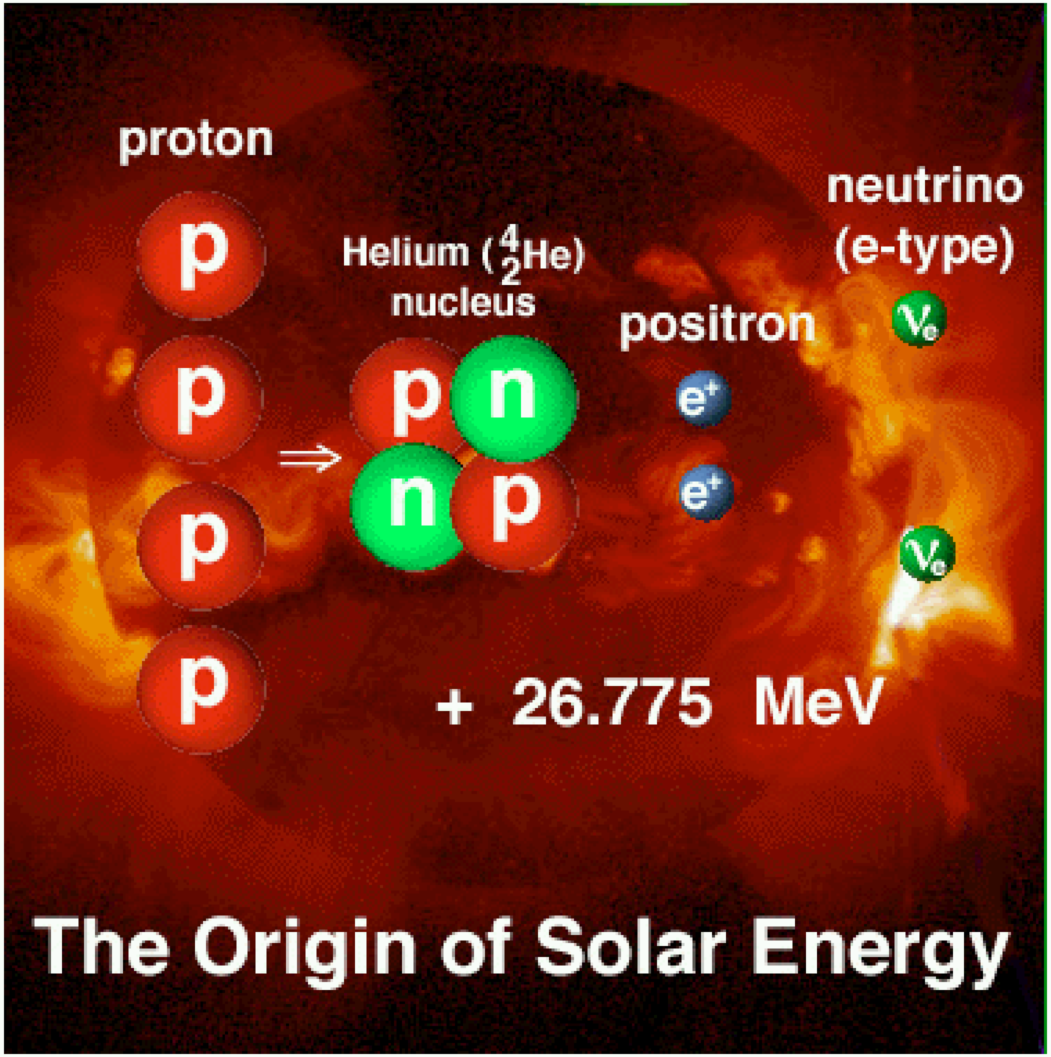
Neutrinos from the Sun: SOLAR FUSION



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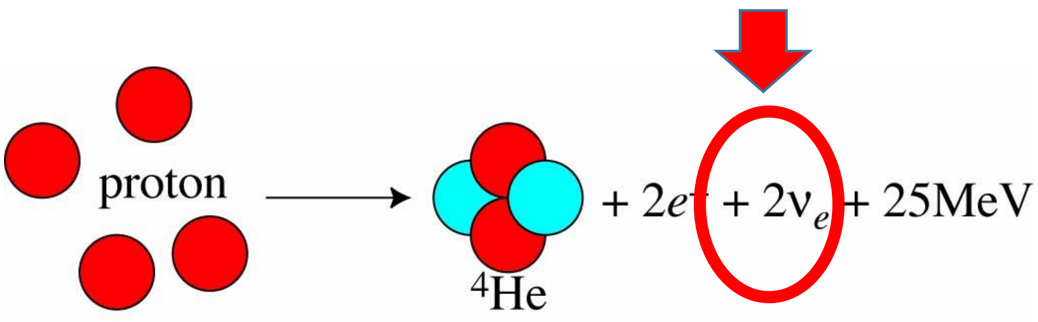
Solar Neutrinos: How the Sun burns

- **Solar neutrinos** are produced by the nuclear reactions that power the Sun. The fusion of proton plus proton (pp) to deuterium plus positron plus **neutrino** is responsible for 98% of the energy production of the sun.
- The Sun emits light because nuclear fusion produces a lot of energy



$$\Phi_\nu = \frac{2L_{\text{sun}}}{25\text{MeV}} \frac{1}{4\pi(1\text{AU})^2} = 7 \cdot 10^{10}\ \text{sec}^{-1}\ \text{cm}^{-2}$$

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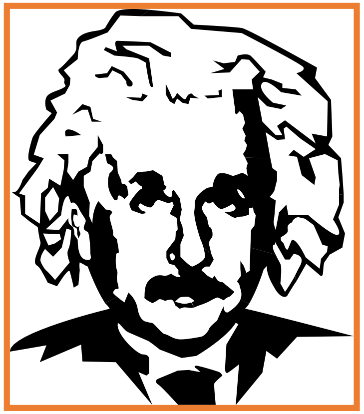
Nuclear Fusion

- Conversion of mass to energy.
- A little mass makes lots of energy

1 gram of matter $\Rightarrow$ 10^{14} Joules (J) of energy



$$E = m c^2$$

(c = speed of light)

The total mass decreases during a fusion reaction.

Mass "lost" is converted to Energy:

Mass of 4 H Atoms	**=**	**6.693** $\times 10^{-27}$ kg
Mass of 1 He Atom	**=**	6.645 $\times 10^{-27}$ kg
Difference	**=**	0.048 $\times 10^{-27}$ kg
(*% m converted to E*)	**=**	**(0.7%)**

The sun has enough mass to fuel its current energy output for another 5 billion years

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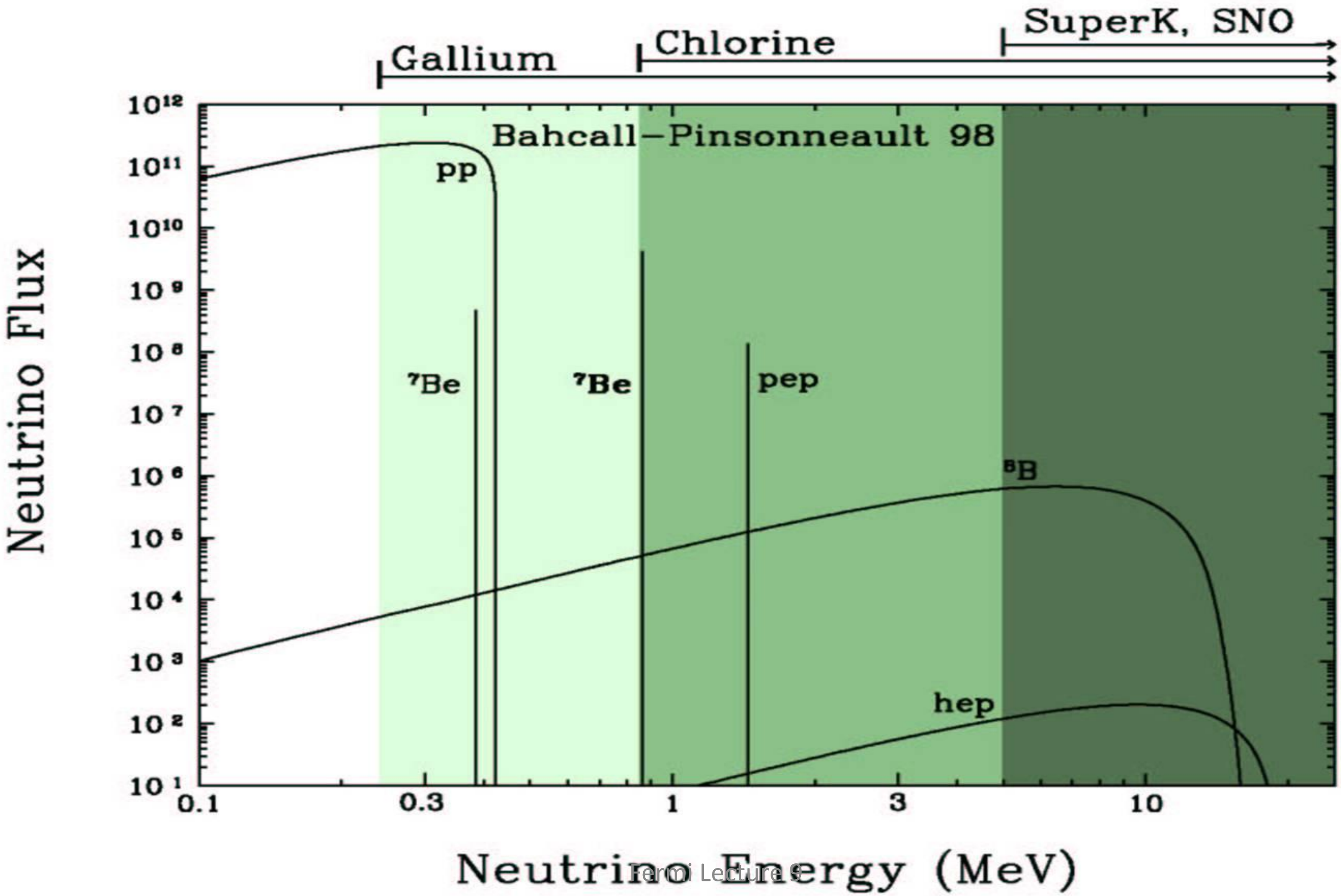
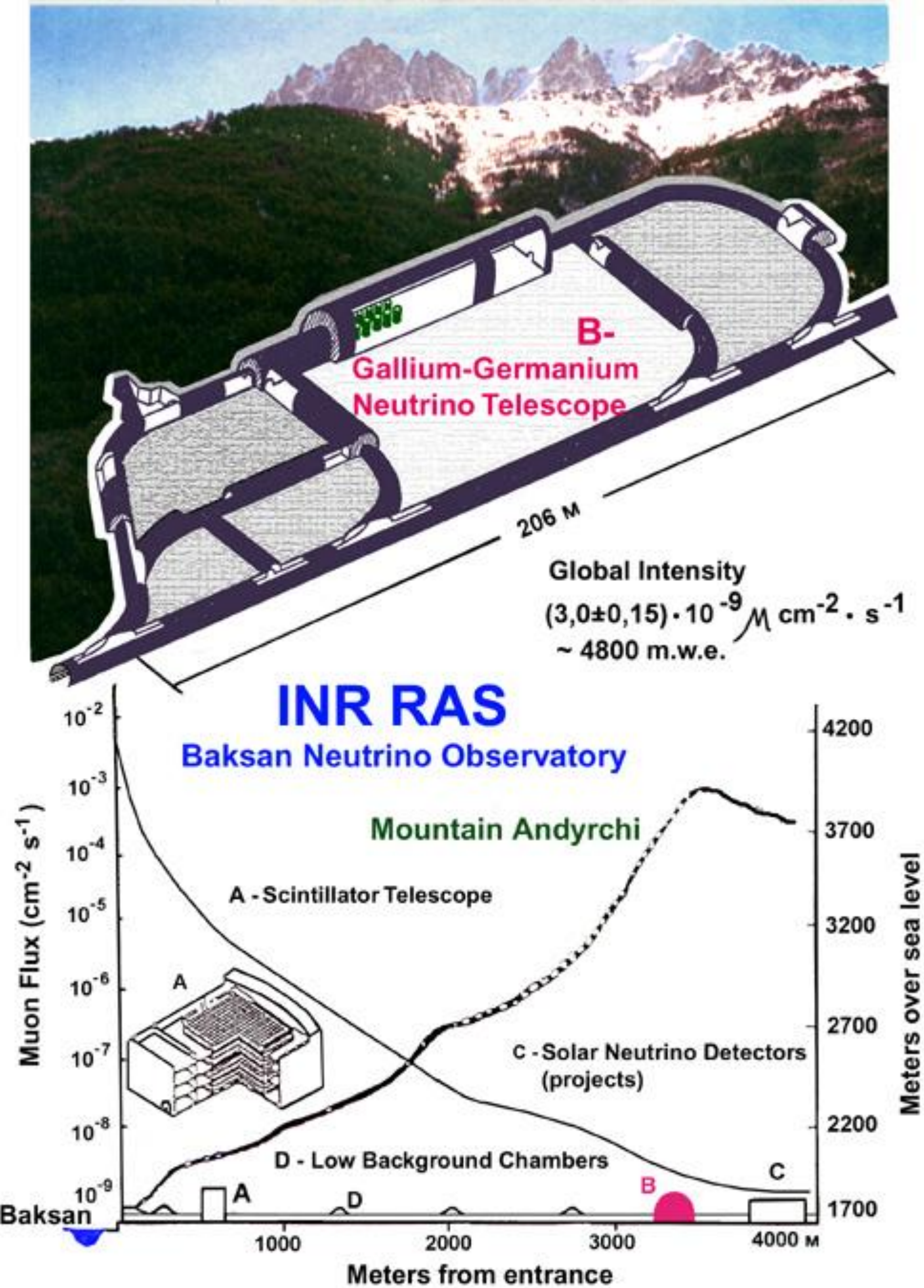
SOLAR FUSION

…within the `Standard Solar Model'





SAGE Soviet-American Gallium Experiment

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

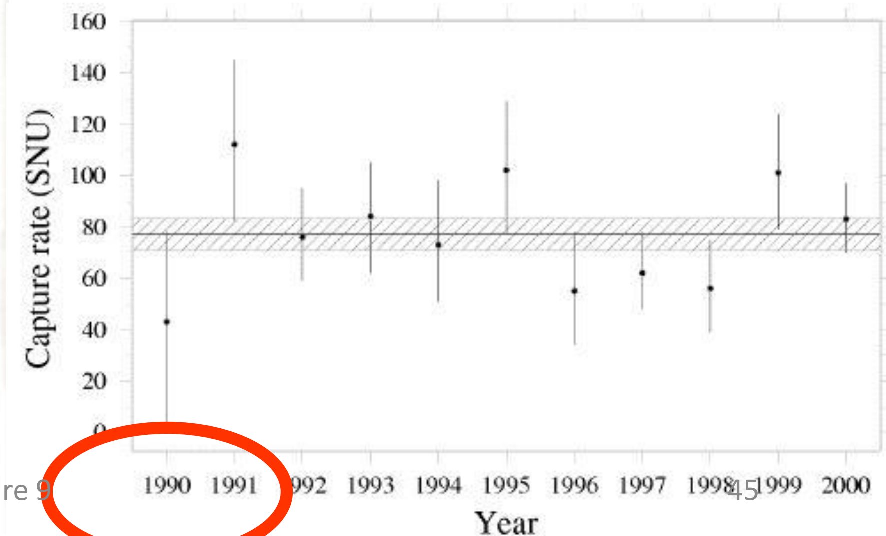
Sensitive to pp fusion in sun.

50 metric tons of Gallium

They extract a *few tens of atoms* of

Measured: 65.4± 3.1 ± 2.7 SNU

Predicted: 138 + 9 -7 SNU



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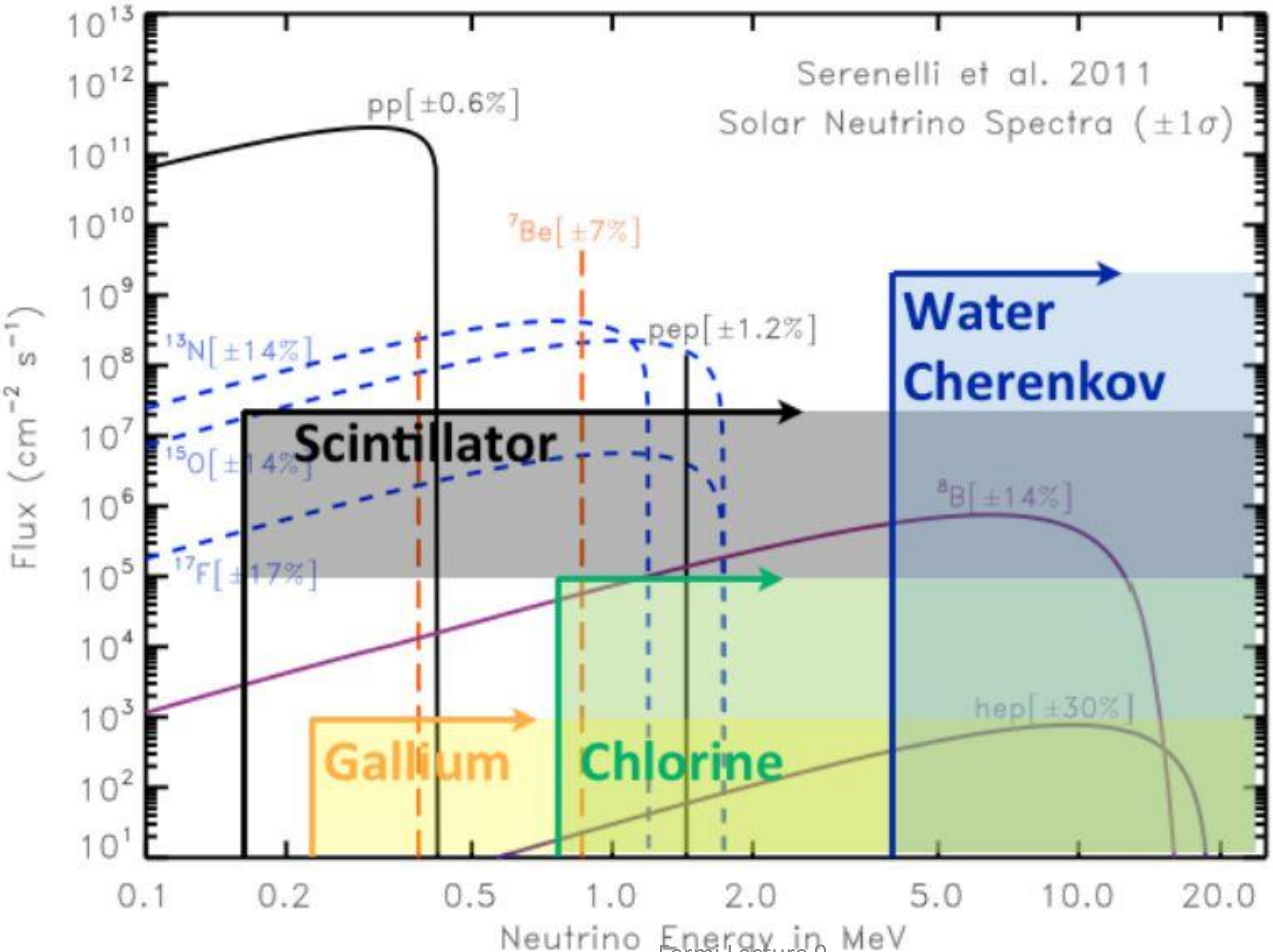
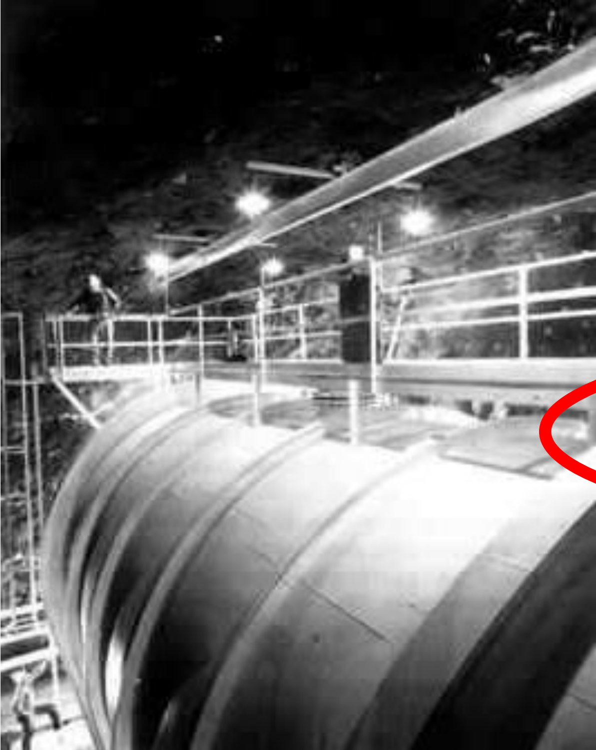


Serenelli et al. 2011
Solar Neutrino Spectra (±1σ)
pp[±0.6%]
^{7}Be[±7%]
pep[±1.2%]
^{13}N[±14%]
^{15}O[±14%]
^{17}F[±17%]
^{8}B[±14%]
hep[±30%]
Water
Cherenkov
Scintillator
Gallium
Chlorine
Flux (cm^{-2} s^{-1})
Neutrino Energy in MeV

Homestake Gold Mine



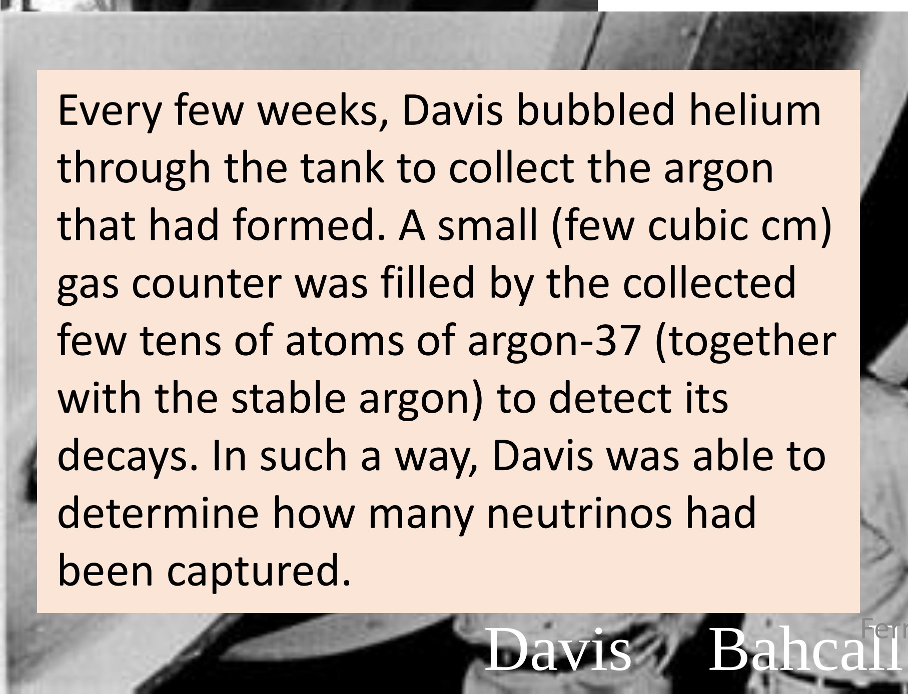
100,000 gallons of cleaning fluid: $Cl_2C{=}CCl_2$ (Tetrachloroethylene)

Expected 1.5 interactions per day
Measured 0.5 interactions per day

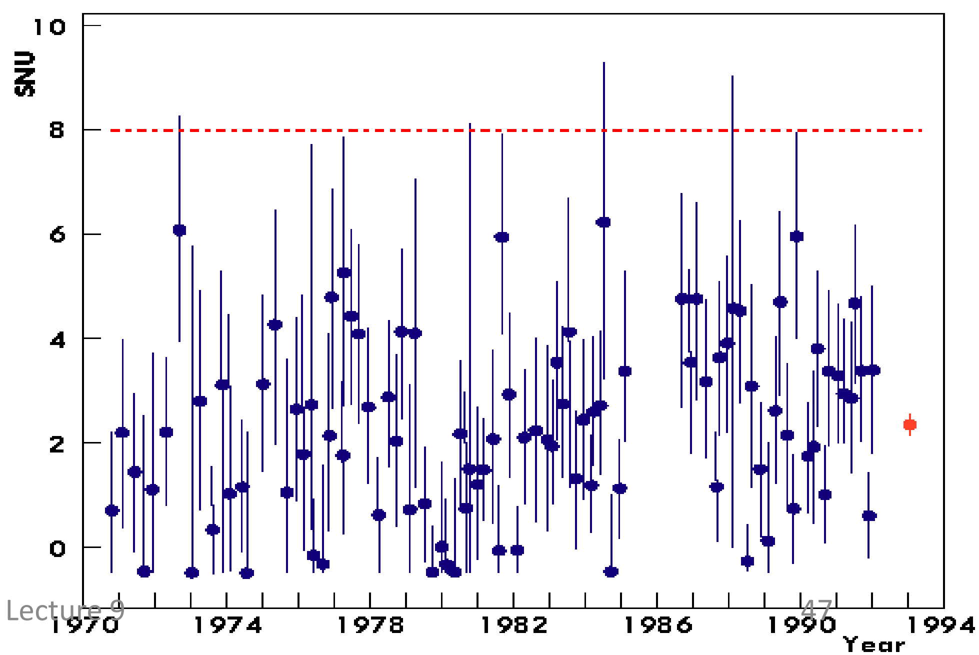
Sensitive to ^{8}B solar neutrinos only

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

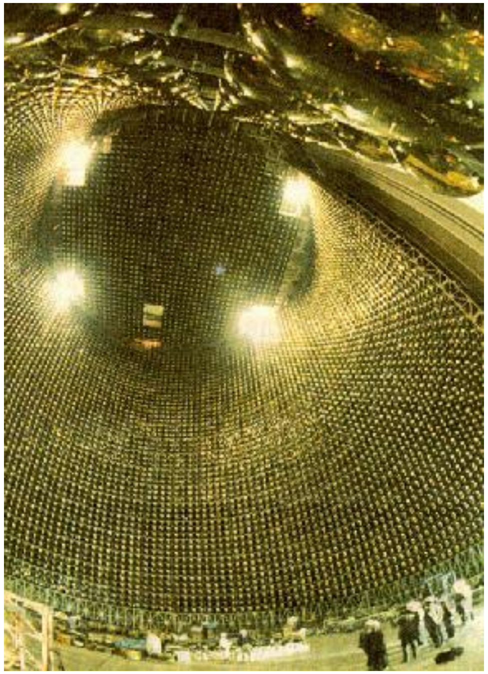
1968!



Every few weeks, Davis bubbled helium through the tank to collect the argon that had formed. A small (few cubic cm) gas counter was filled by the collected few tens of atoms of argon-37 (together with the stable argon) to detect its decays. In such a way, Davis was able to determine how many neutrinos had been captured.

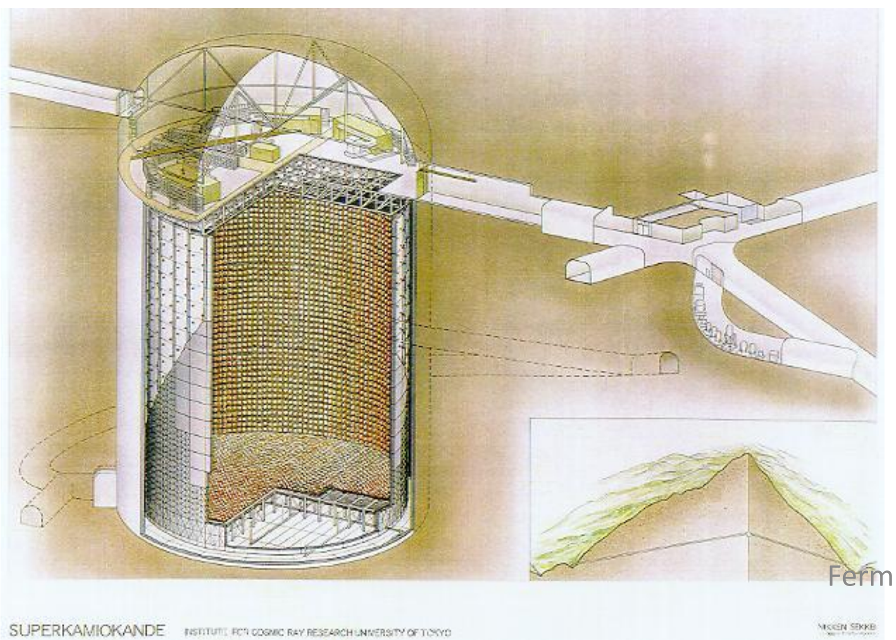


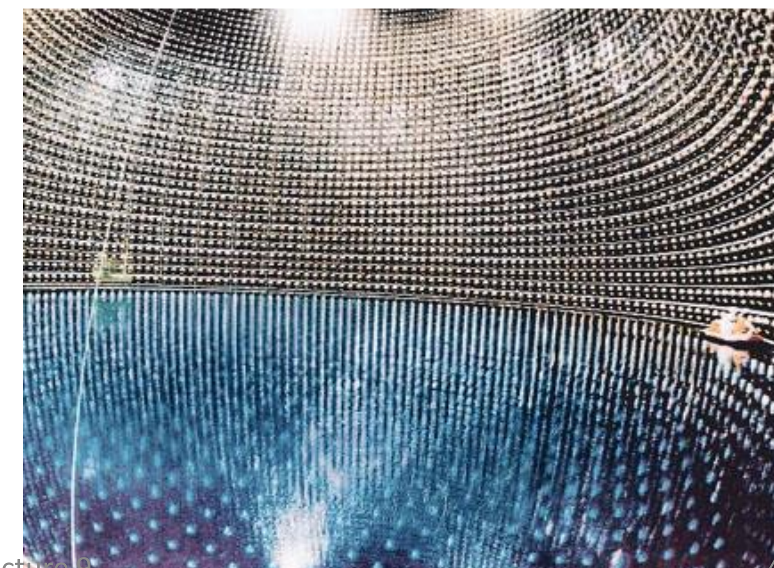
Frontiers 9



Super-Kamiokande

11 stories high
1,000 meters underground
50,000 tons of water
22,500 tons fiducial volume
11,200 photomultipliers
0.5 meter photomultiplier diameter
(old copper and zinc mine)





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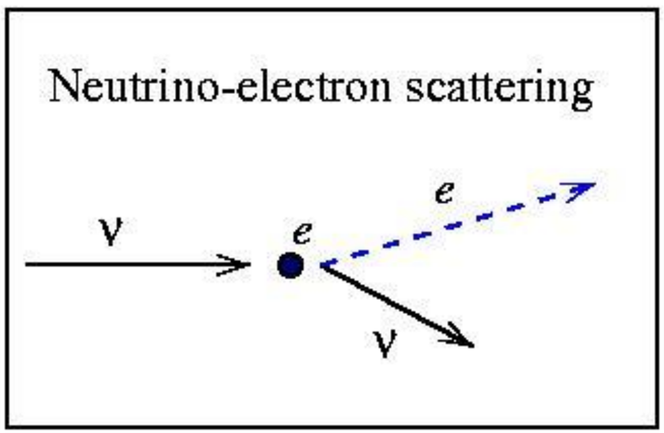
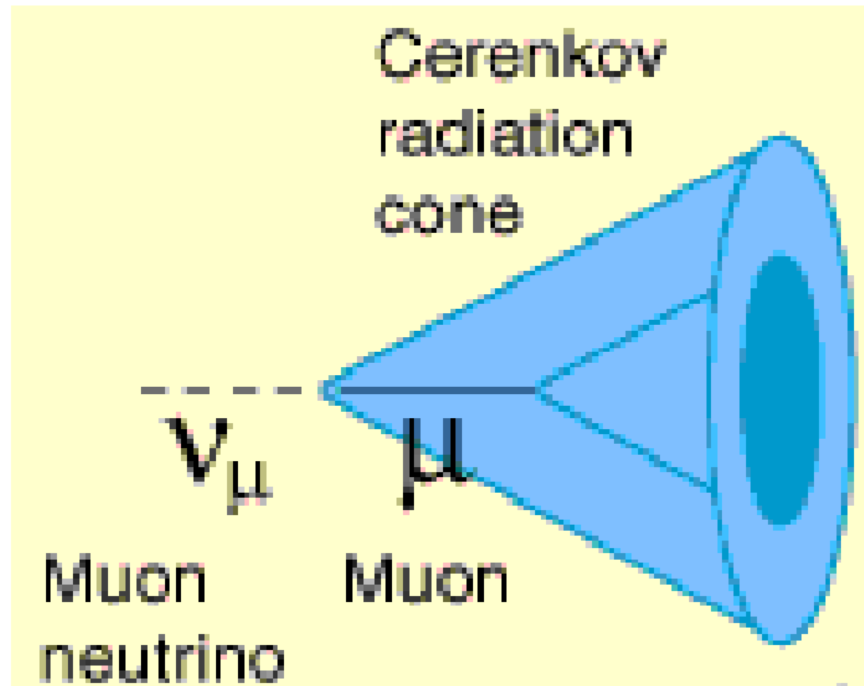
SOLAR Neutrino Experiments



$$\nu_x + e^- \longrightarrow \nu_x + e^-$$



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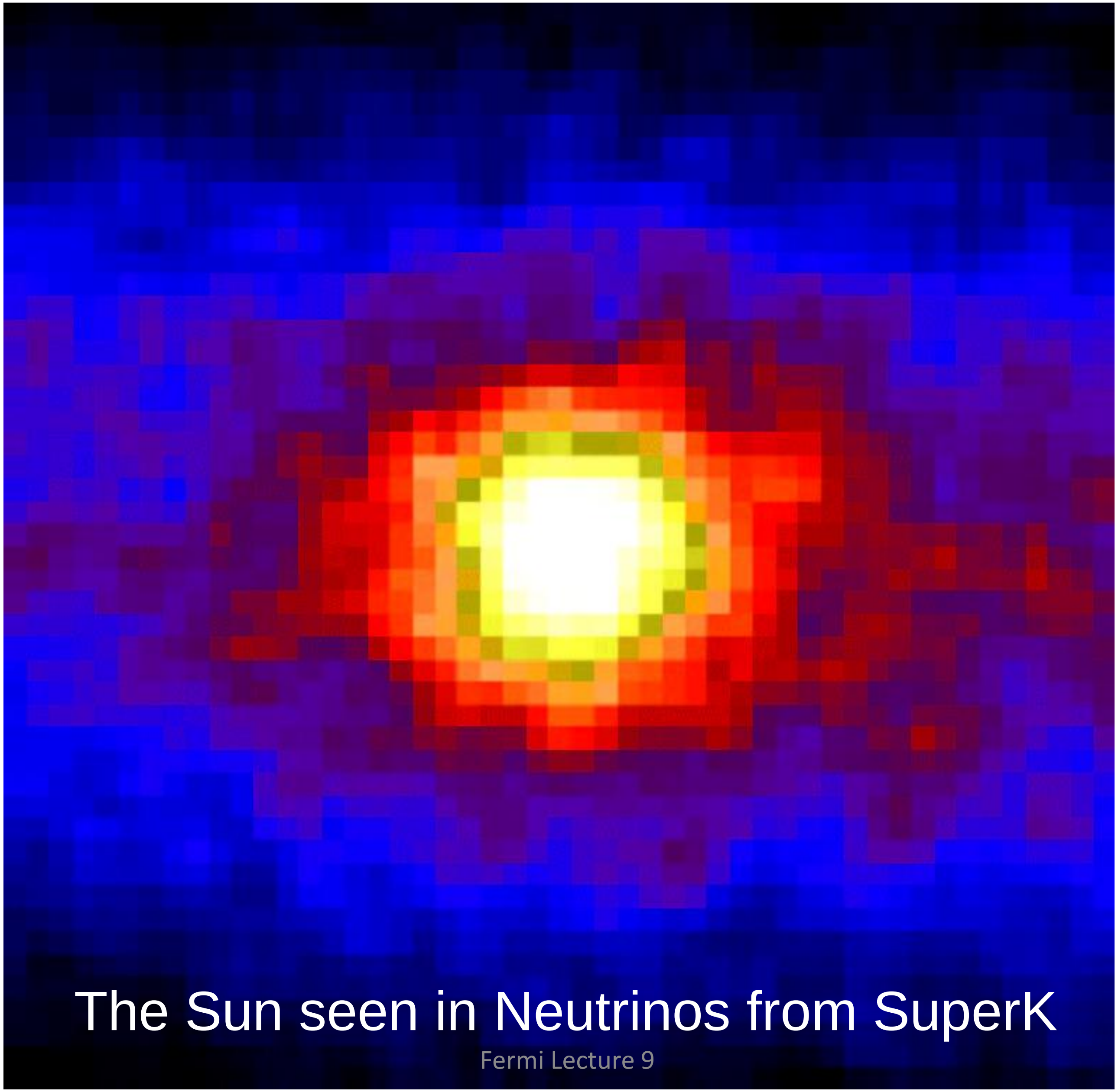
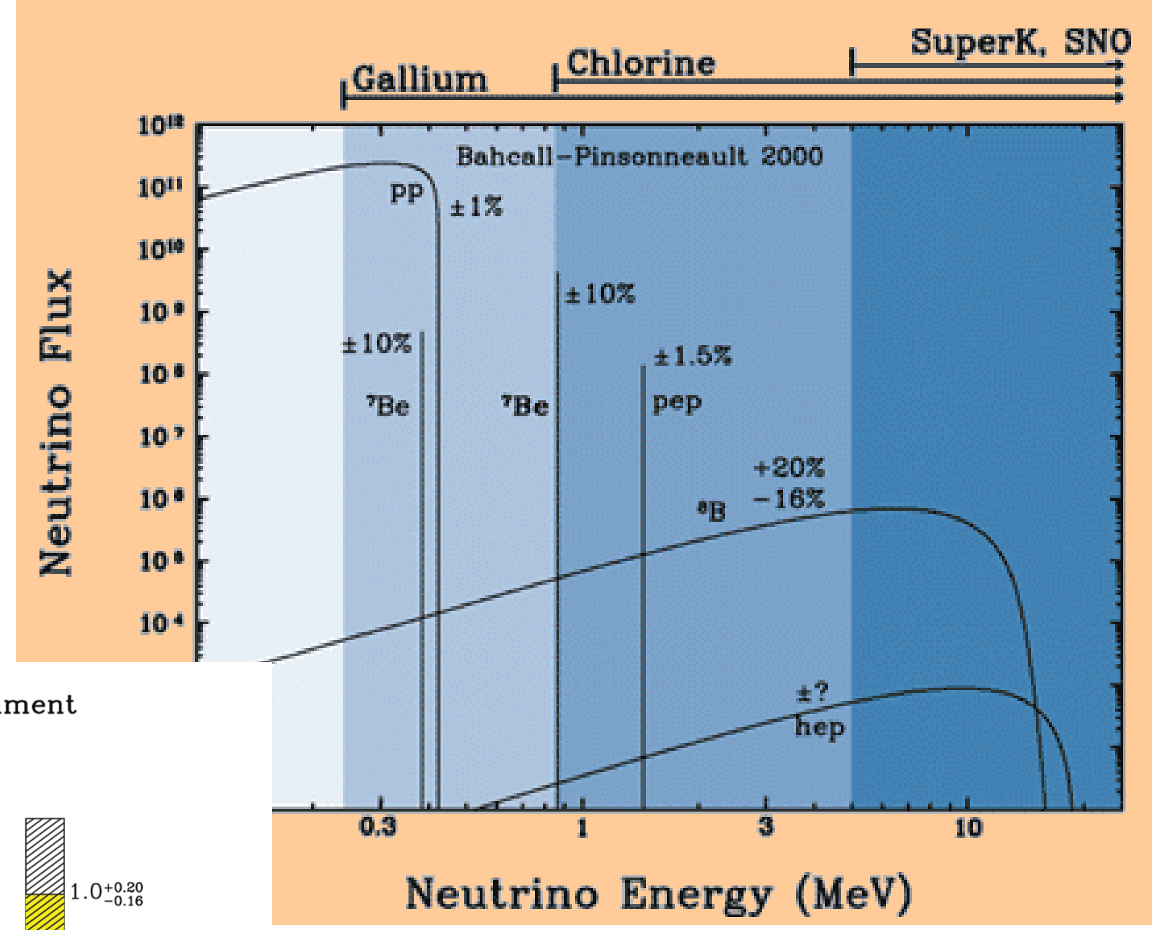
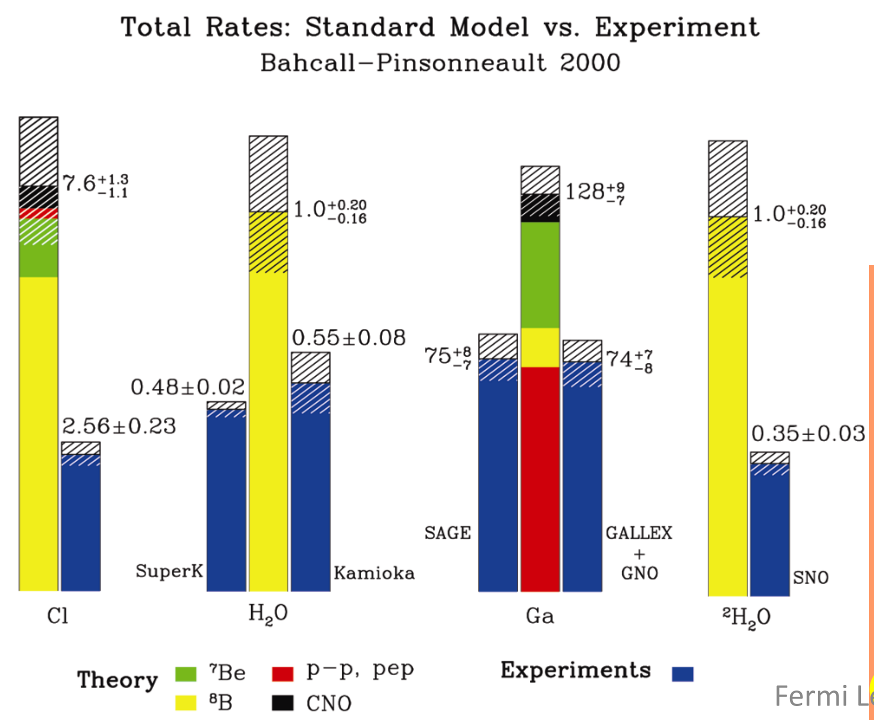


Break

Solar Neutrino Summary

Different experiments are sensitive to different solar processes.





But all experiments show a marked deficit of electron neutrinos.

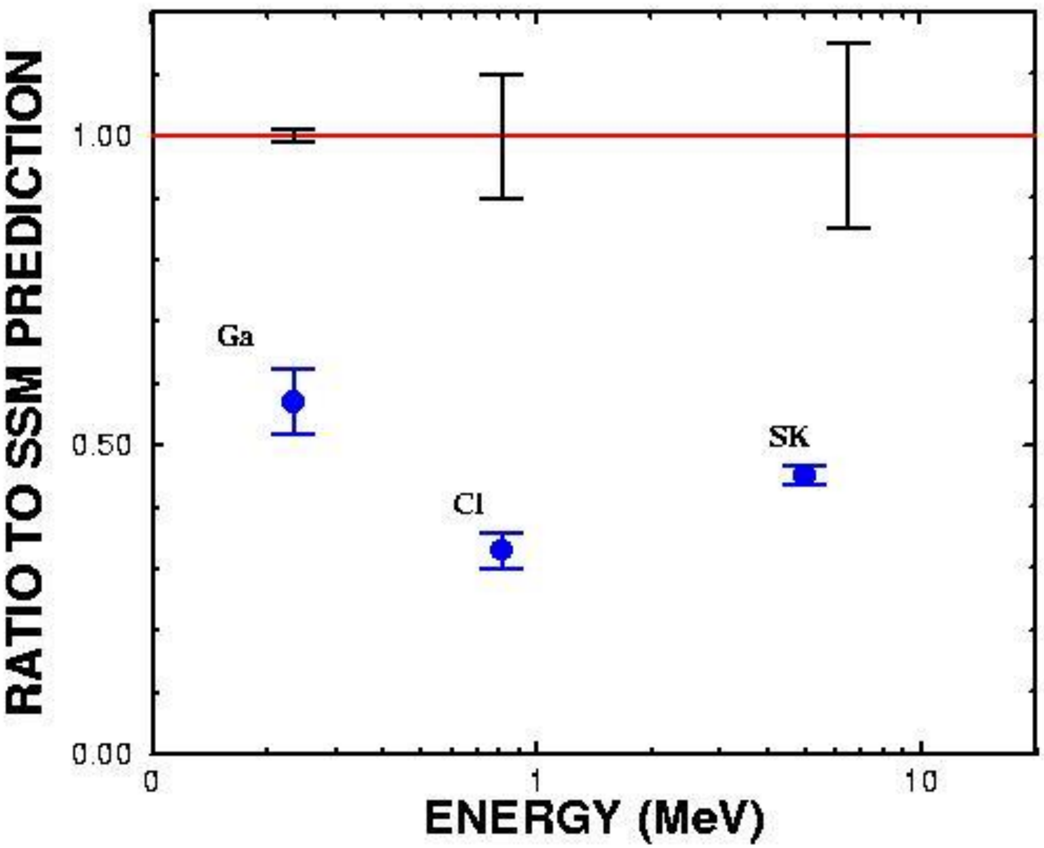
Could reflect ignorance of how the sun works?

Or Neutrino Oscillations?

Frontiers 9

Results after Six Solar ν Experiments

- 3 Gallium (Radiochemical)
- 1 Chlorine (Radiochemical)
- Kamiokande + Super-Kamiokande (Water Cerenkov)



- The Question Became
- Solar Theory Wrong?
- Or Theory of Neutrinos?

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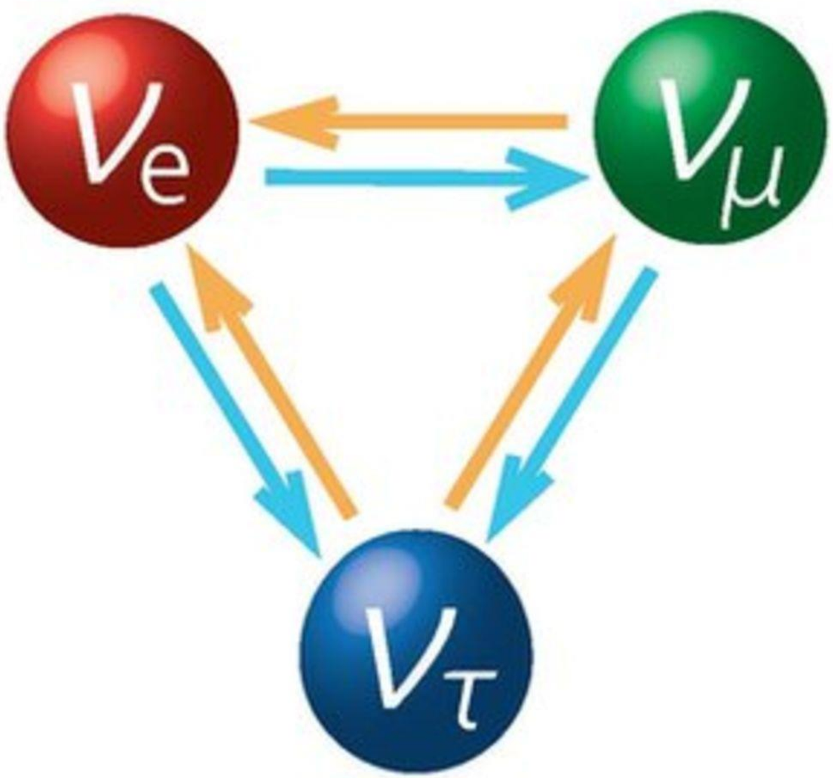
Neutrinos have mass and oscillate one to another !!

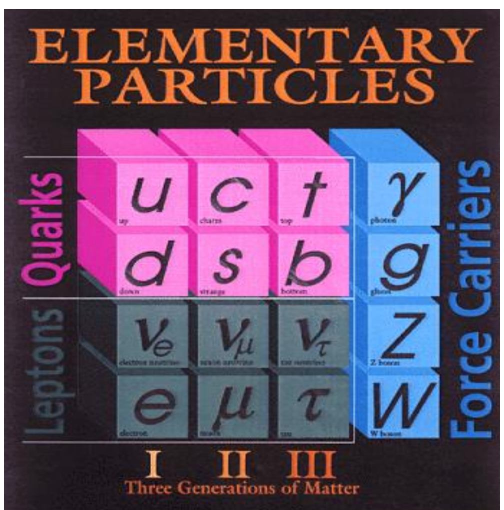


Neutrino Oscillations → Next Week

Frontiers 9

Three families – three neutrinos?

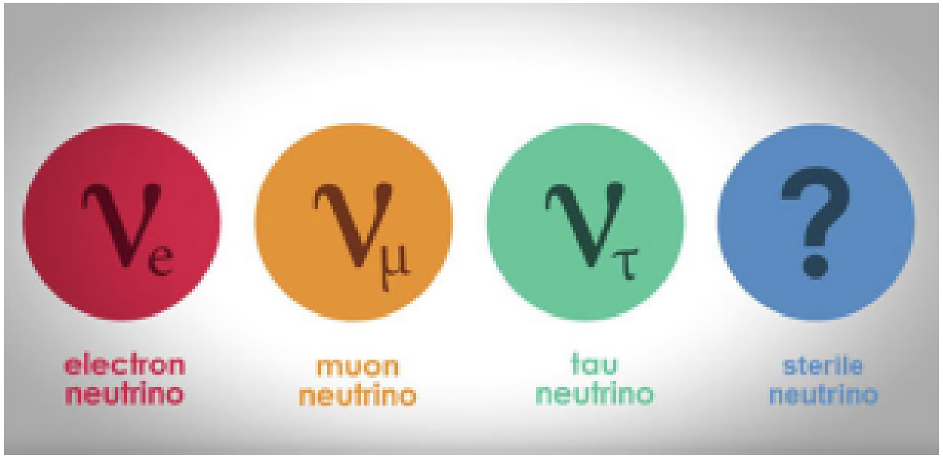
- **In fact, are there really only three neutrinos??**
- **There still could be 'sterile' neutrinos.**
- **What is a <u>sterile neutrino</u> and is there any evidence?**



A sterile neutrino are hypothetical neutral particles that interact only by gravity and do not interact via any of the fundamental interactions of the standard model.

Are there more than 3 Neutrinos?

- Is there is a 4th (5th…) neutrino then it has to be quasi-sterile, ie should not couple significantly to other fermions and bosons, as we know from measurements at LEP
- Could mix with the known neutrinos
- Some indication since more than 10 years (LSND, reactor anomalies, Gallium anomalies)
- The interpretation is still controversial/unclear..



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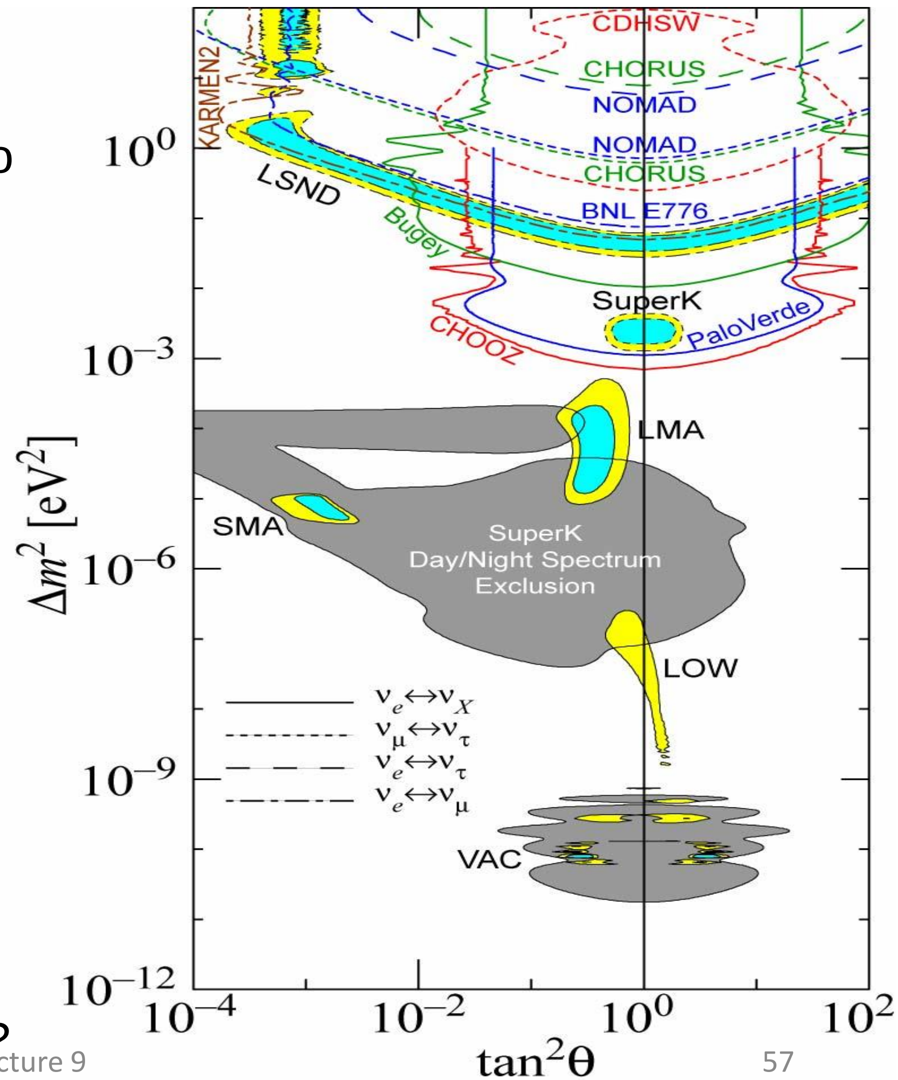
Is there any evidence for sterile neutrinos?

- **Neutrino Mass and Oscillations** (We will return to this subject)
- There is very strong evidence for neutrino oscillation from atmospheric and solar neutrinos (e.g. the three neutrinos have mass and can 'oscillate' from one to another.
- ***Sterile Neutrinos*** *– There are various theoretical hypotheses and many papers, including sterile neutrinos as dark matter particles. (Experimentally, nothing, except LSND --- 1990s)*
- *Experiment at Fermilab MiniBoone and Boone showing similar effects , BUT … only three sigma and is this confirmation?*



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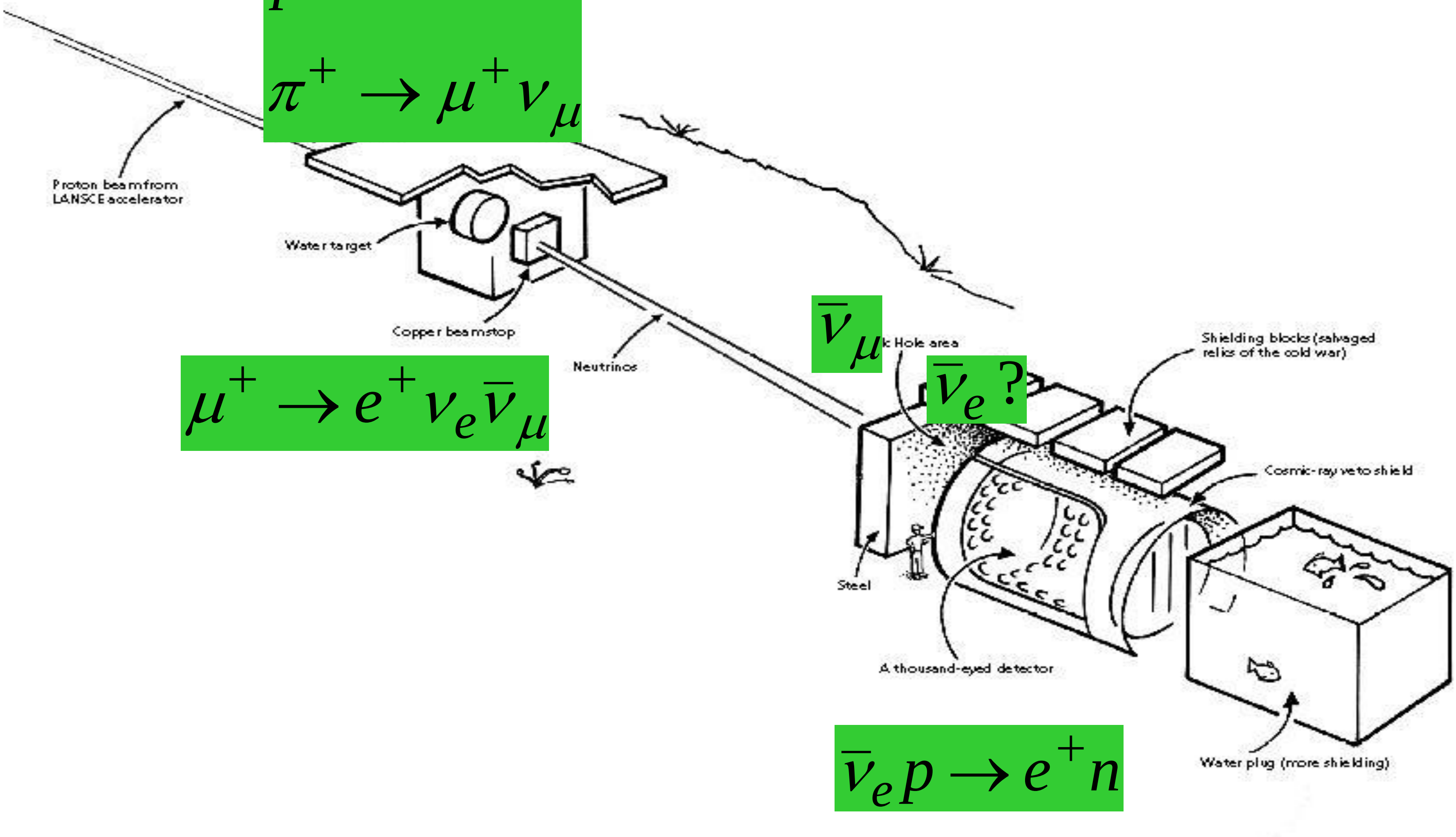
Los Alamos Experiment on LANSCE Accelerator

$$p \rightarrow \pi^+$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$



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

$$\bar{\nu}_\mu$$

$$\bar{\nu}_e \,?$$

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

Frontiers 9

Result motivated Mini-Boone & Boone

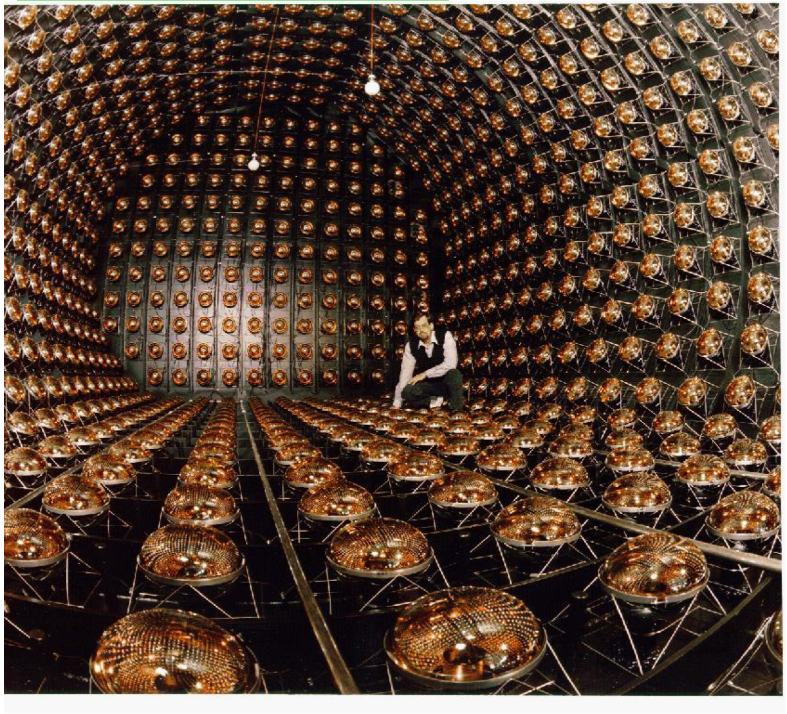
$p \to \pi^+$

Protons from the LANSCE Accelerator (Los Alamos)

$\pi^+ \to \mu^+ \nu_\mu$

<u>Pion and Muon Decay at Rest</u>, making neutrino 'beam'

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$



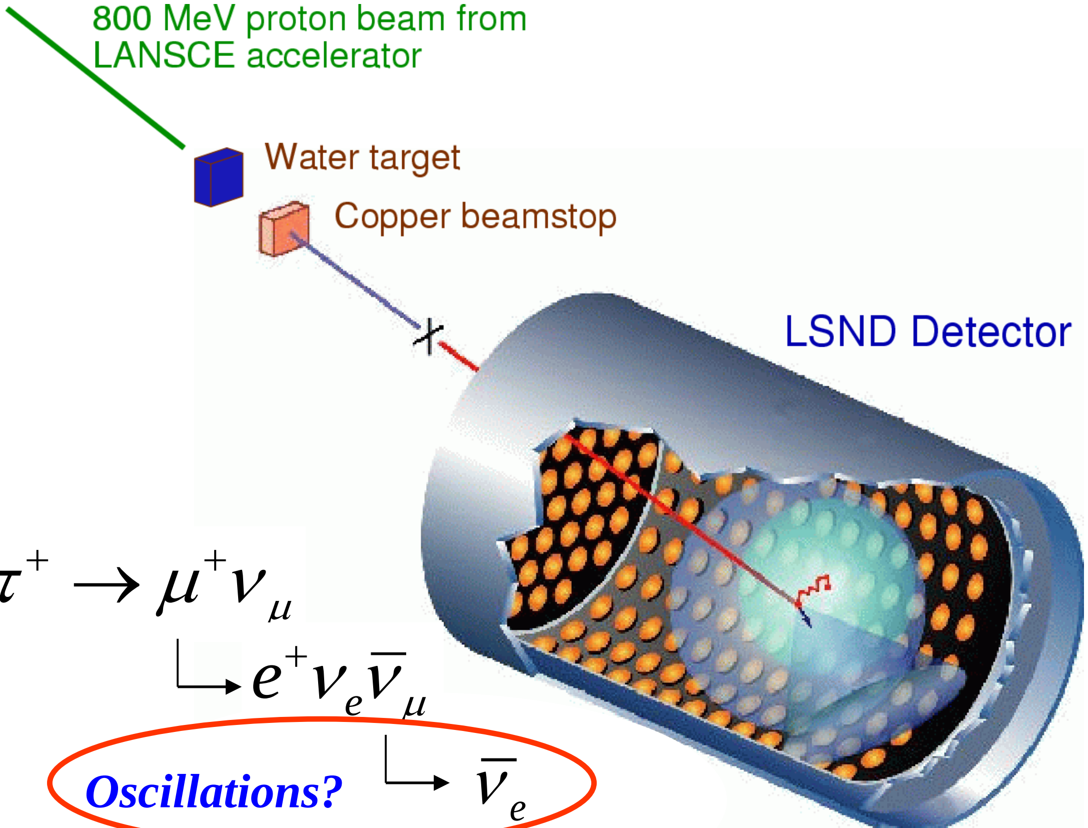
Note, no decays making $\bar{\nu}_e$?

In the detector, they observe an excess of

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

Frontiers 9

LSND Detector Parameters



$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

Oscillations? $\hookrightarrow \bar{\nu}_e$

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

n p $\rightarrow$ d γ(2.2MeV)

LSND took data from 1993-98

Nearly 49000 Coulombs of protons on target

Baseline: 30 meters

Neutrino Energy: 20-55 MeV

LSND Detector:
- **-- 1280 phototubes**
- **-- 167 tons Liquid Scintillator**

Observe an excess of $\bar{\nu}_e$:
- **-- 87.9 ± 22.4 ± 6.0 events.**

Non-Standard result

Neutrino appearance

- LSND $(\nu_\mu \rightarrow \nu_e)$

  $L = 30$ m; $20 \text{ MeV} < E_\nu < 52.8 \text{ MeV} \rightarrow \Delta m^2 \sim 1 - 10 \text{ eV}^2$

It did see ν_e appearance!

But…

$$\Delta m^2_{atm} + \Delta m^2_{sol} \neq \Delta m^2_{LSND}$$

The LSND experiment

Neutrinos are produced from pion and muon decays

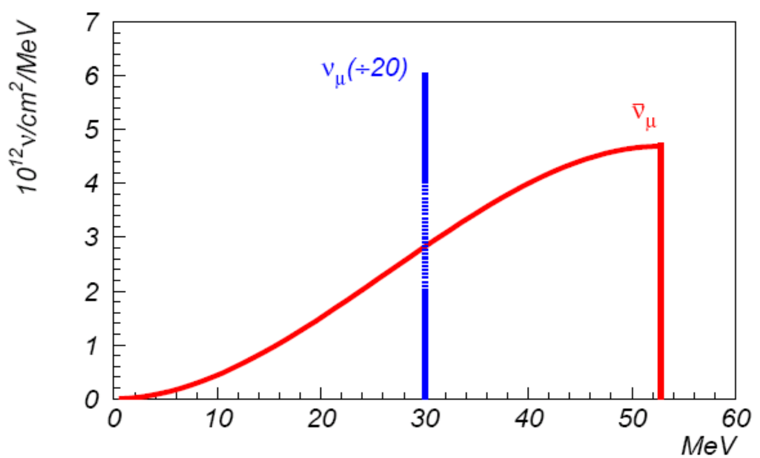
$$\pi^+ \to \mu^+ \nu_\mu \ (e^+ \nu_e) \qquad\qquad \pi^- \to \mu^- \bar{\nu}_\mu \ (e^- \bar{\nu}_e)$$

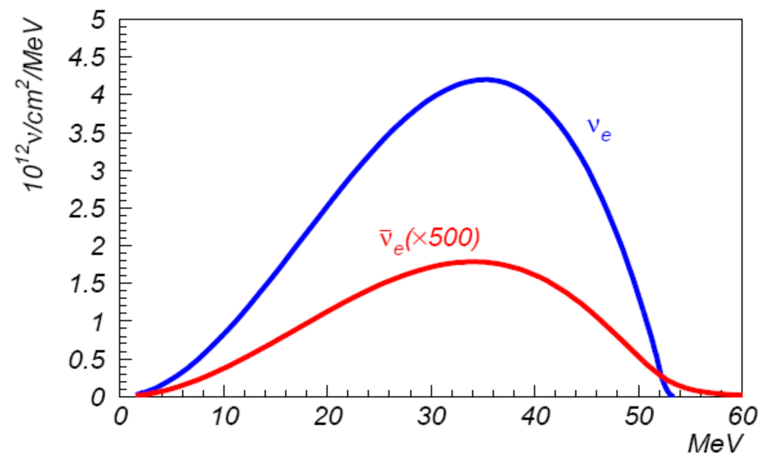
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \qquad\qquad \mu^- \to e^- \bar{\nu}_e \nu_\mu$$

$$\bar{\nu}_e$$

Most π^+ decay at rest (97%) and also most μ^+

Very few μ^- decays at rest (DAR) → 0.08% $\bar{\nu}_e$ backgrounds



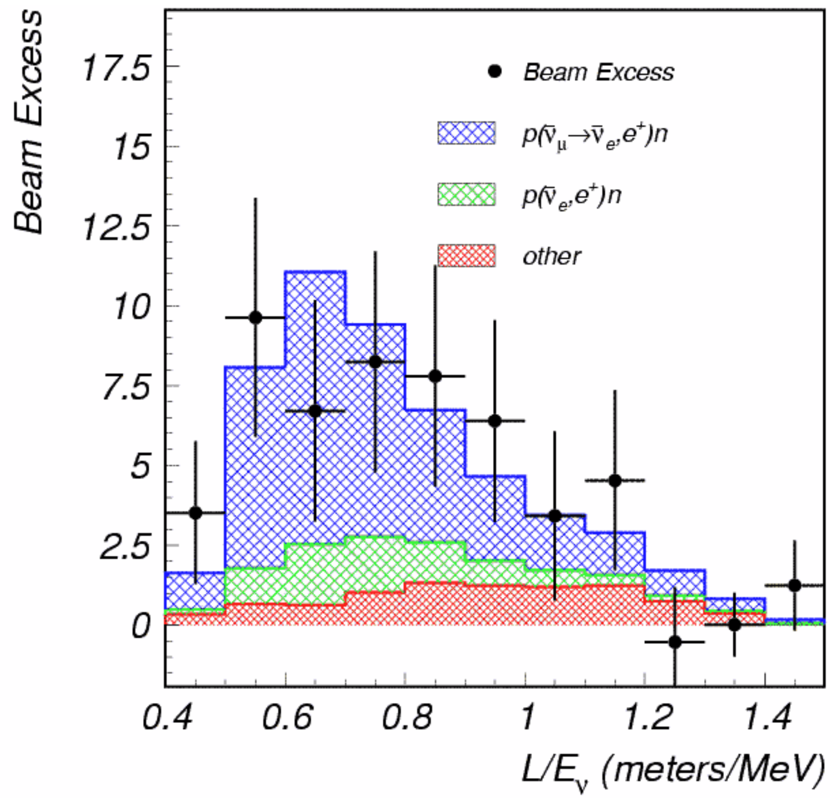


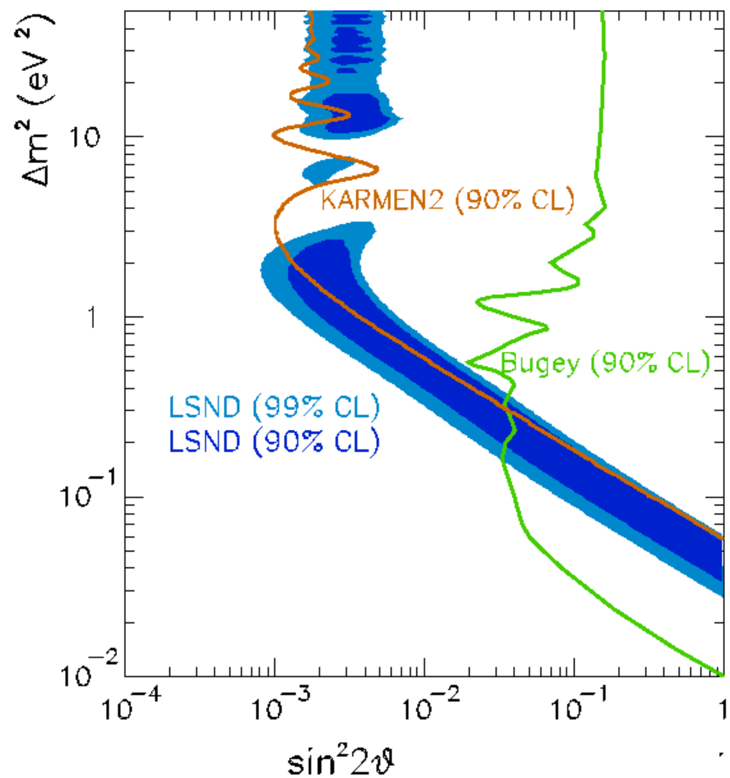
A. Aguilar *et al.*, Phys. Rev. D64:112007, 2001

Frontiers 9

LSND observed a positive signal 3.8σ

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2(2\theta)\sin^2(\frac{1.27 L\Delta m^2}{E}) = (0.264 \pm 0.067 \pm 0.045)\%$$





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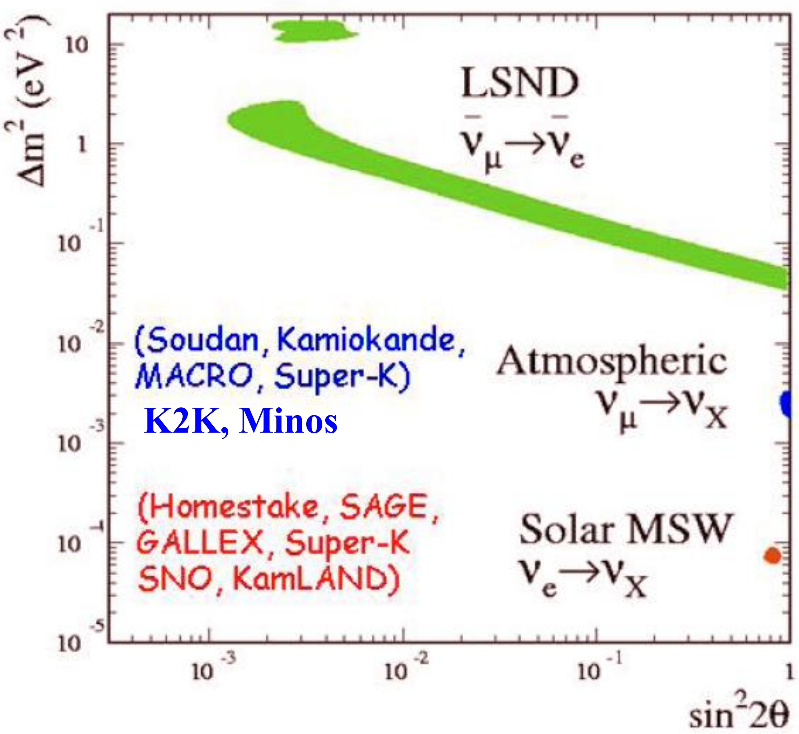
State of Oscillation Results



- Simplest model has three neutrino mass eigenstates, but…
- Data indicates 3 mass differences
  - $\Delta m^2_{atm} \sim 2\text{-}3\times10^{-3}$ eV^2
  - $\Delta m^2_{sol} \sim 7\times10^{-5}$ eV^2
  - $\Delta m^2_{LSND} \sim .1\text{-}10$ eV^2

$$\Delta m^2_{atm} + \Delta m^2_{sol} \neq \Delta m^2_{lsnd}$$

➔ If the LSND signal does exist, it implies new physics beyond SM.
➔ The MiniBooNE is designed to confirm or refute LSND oscillation result at $\Delta m^2 \sim 1.0$ eV^2 .

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How can there be 3 distinct Δm^2 ?

- **Mass Difference Equation:**

  $(m_1^2 - m_2^2) + (m_2^2 - m_3^2) = (m_1^2 - m_3^2)$

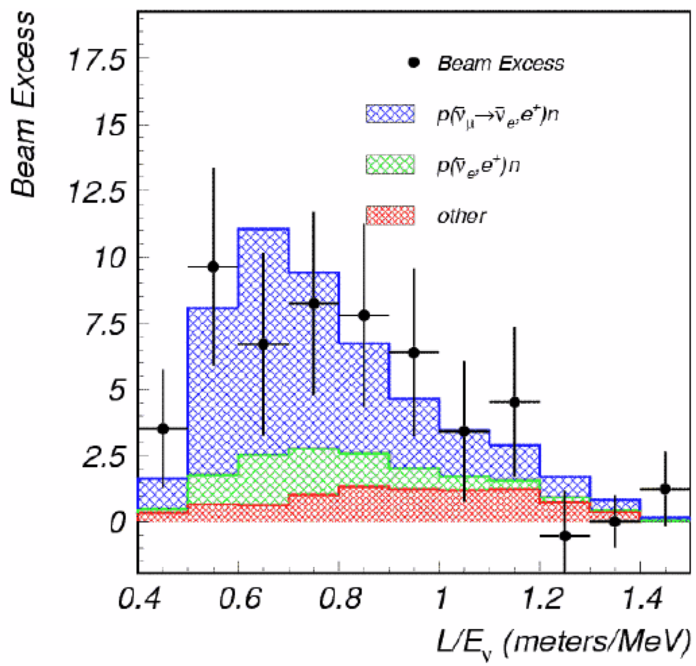
1. One of the experimental measurements is wrong
2. One of the experimental measurements is not neutrino oscillations:

   → Neutrino decay

   → Neutrino production from flavor violating decays
3. Additional "sterile" neutrinos involved in oscillation
4. CPT violation or CP violation + sterile n's allows different mixing for n's and n bars.

LSND

- Evidence for oscillations at higher Δm^2 than atmospheric and solar
- Stopped pion beam
  $$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
  $$\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- $\bar{\nu}_e$ signature: Cherenkov light from e^+ with delayed n-capture
- Excess=87.9 ± 22.4 ± 6 (3.8σ)

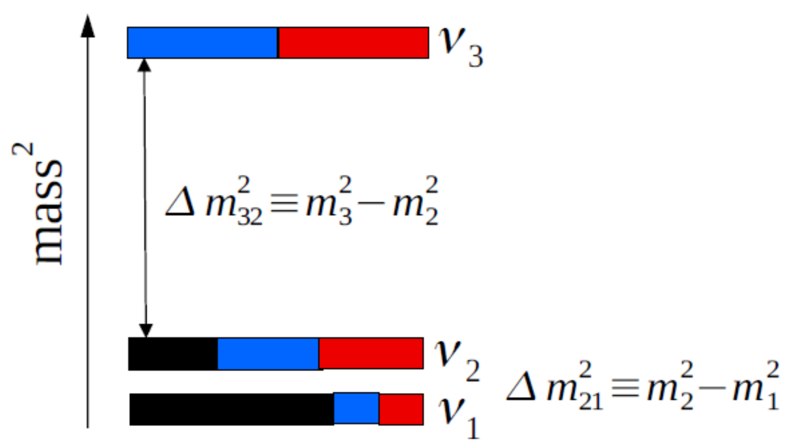


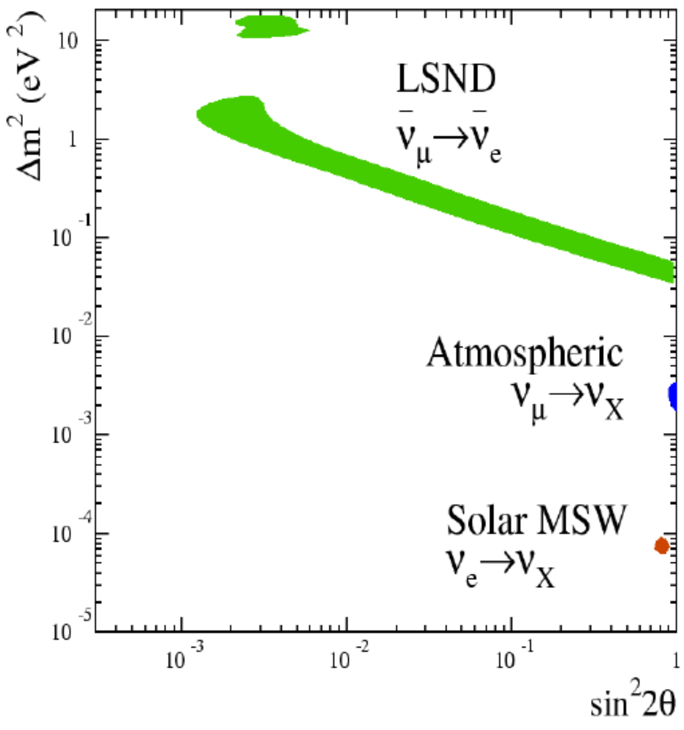
LSND signal

- Assuming two neutrino oscillations

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\ \Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

- Can't reconcile LSND result with atmospheric and solar neutrino using only 3 Standard Model neutrinos – only two independent mass splitings





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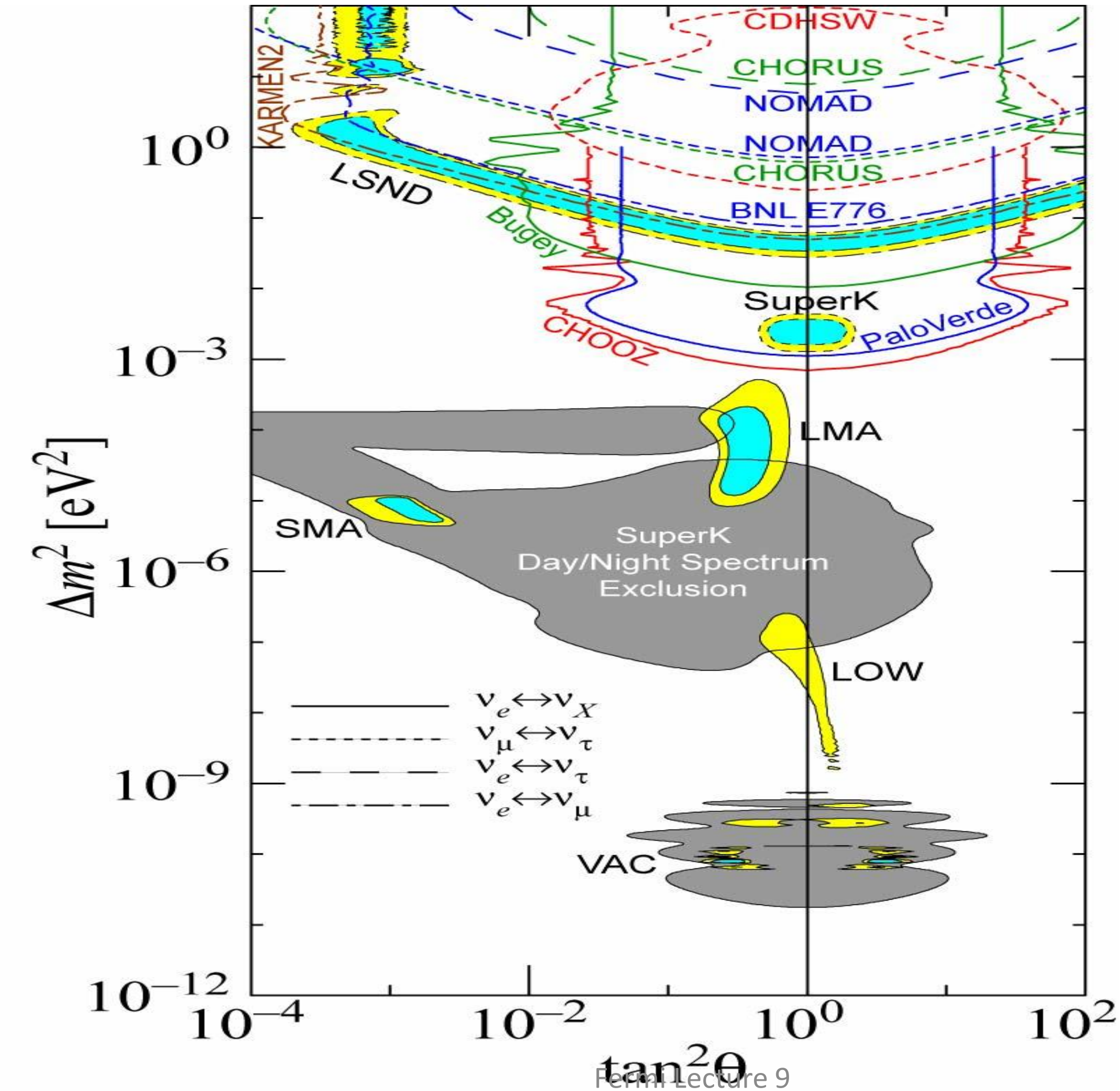
3.8σ Signal



Frontiers 9

How can there be three distinct Δm^2 ?

- **Mass Difference Equation:**

  $(m_1^2 - m_2^2) + (m_2^2 - m_3^2) = (m_1^2 - m_3^2)$

1. One of the experimental measurements is wrong
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   → Neutrino decay
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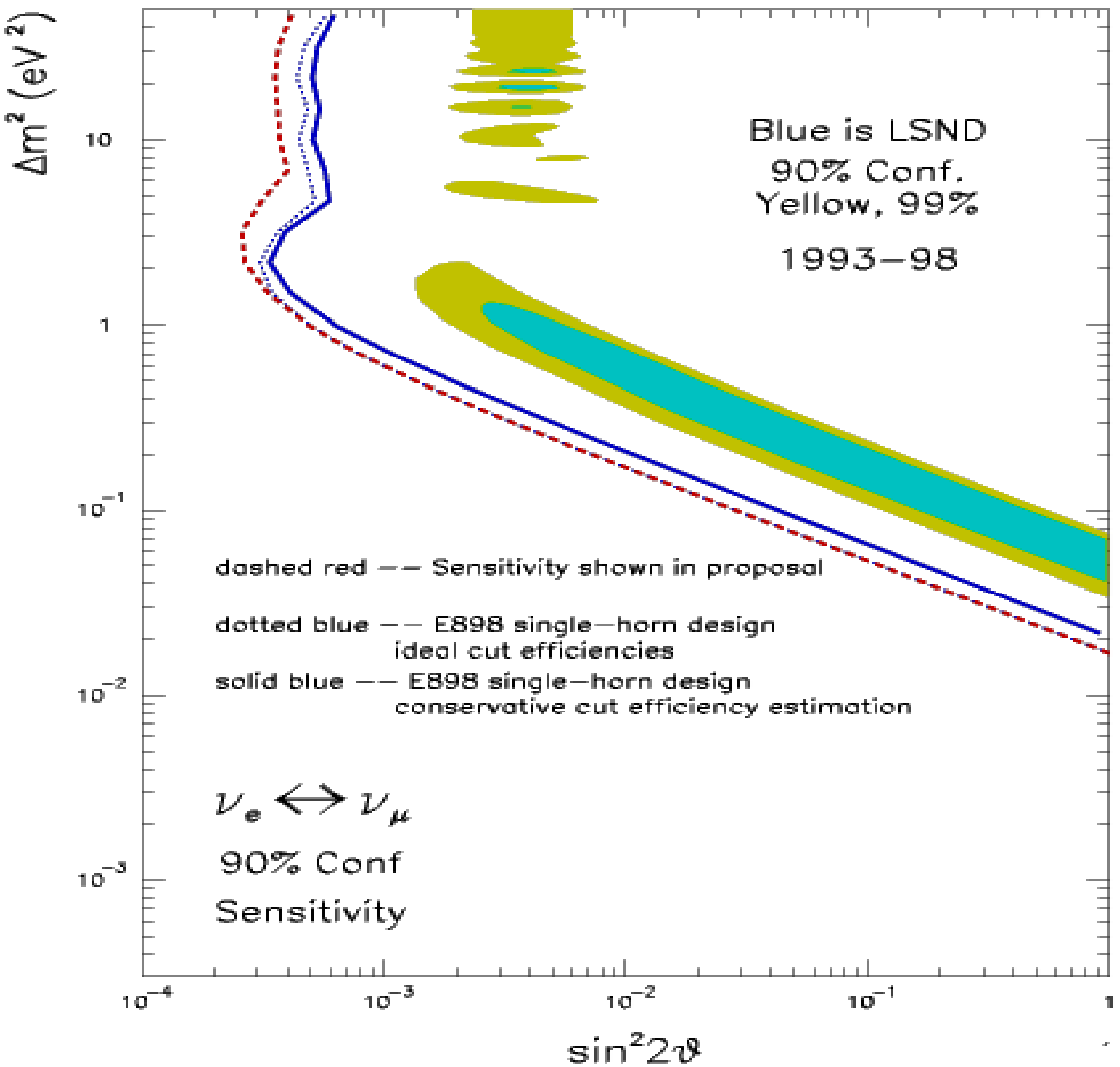
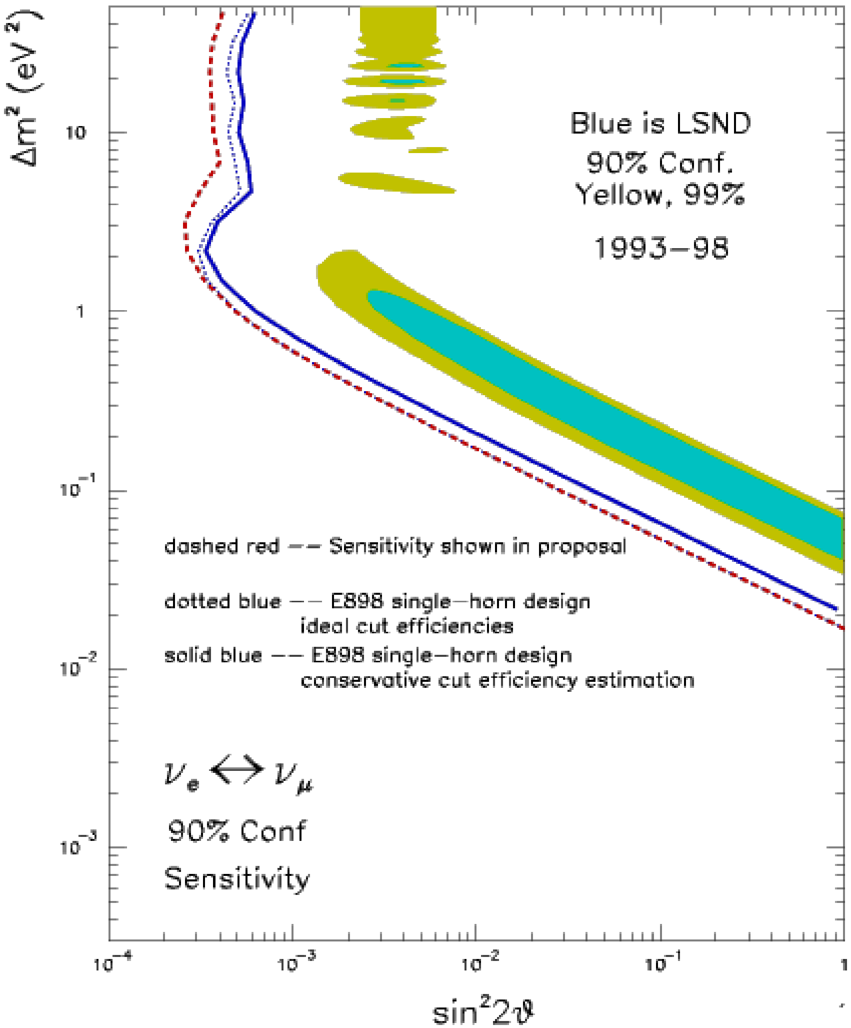
Result motivated Mini-Boone & Boone



Frontiers 9

Mini-BooNE

- Neutrino beam from Fermilab booster
- Designed specifically to prove/disprove LSND, studying $\nu_e \leftrightarrow \nu_\mu$ oscillations
- Uses Fermilab Booster and specially designed experiment



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Mini-BooNE

- Proposed in summer 1997， operating since 2002
- **The goal of the MiniBooNE Expriment: to confirm or exclude the LSND result and extend the explored oscillation parameter space**
- Similar L/E as LSND
  - Baseline: L = 451 meters, ~ x15 LSND
  - Neutrino Beam Energy: E ~ x(10-20) LSND
- Different systematics: event signatures and backgrounds different from LSND
- High statistics: ~ x5 LSND
- Expected ~ 90% C.L. for most of LSND allowed region

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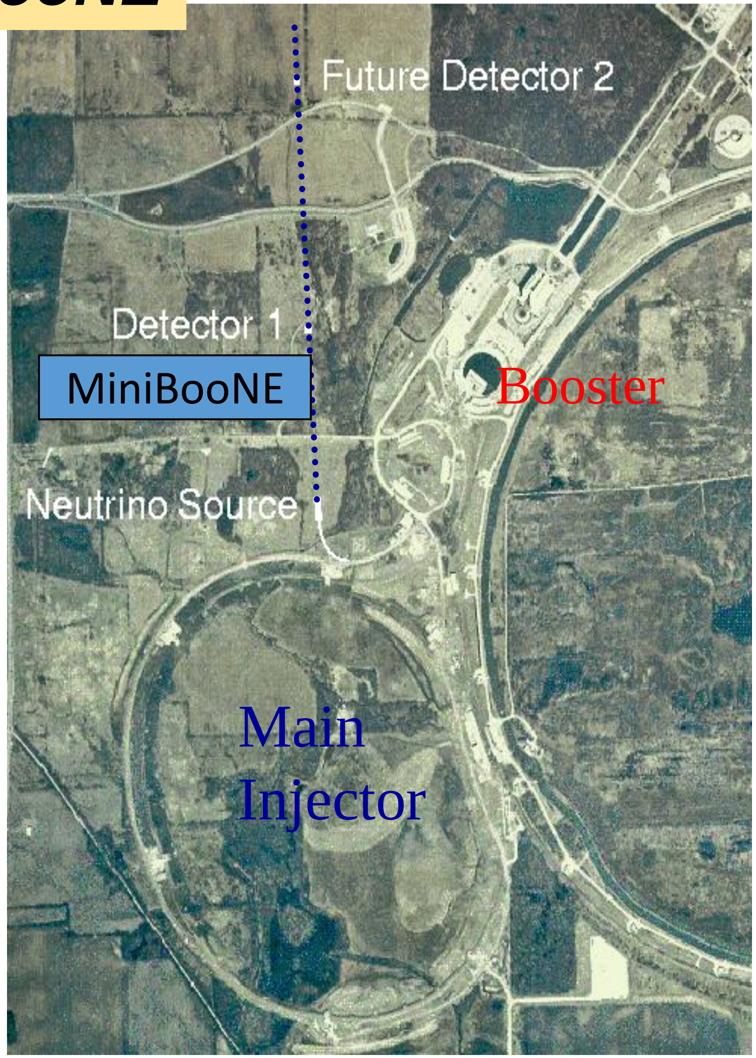
Mini-BooNE



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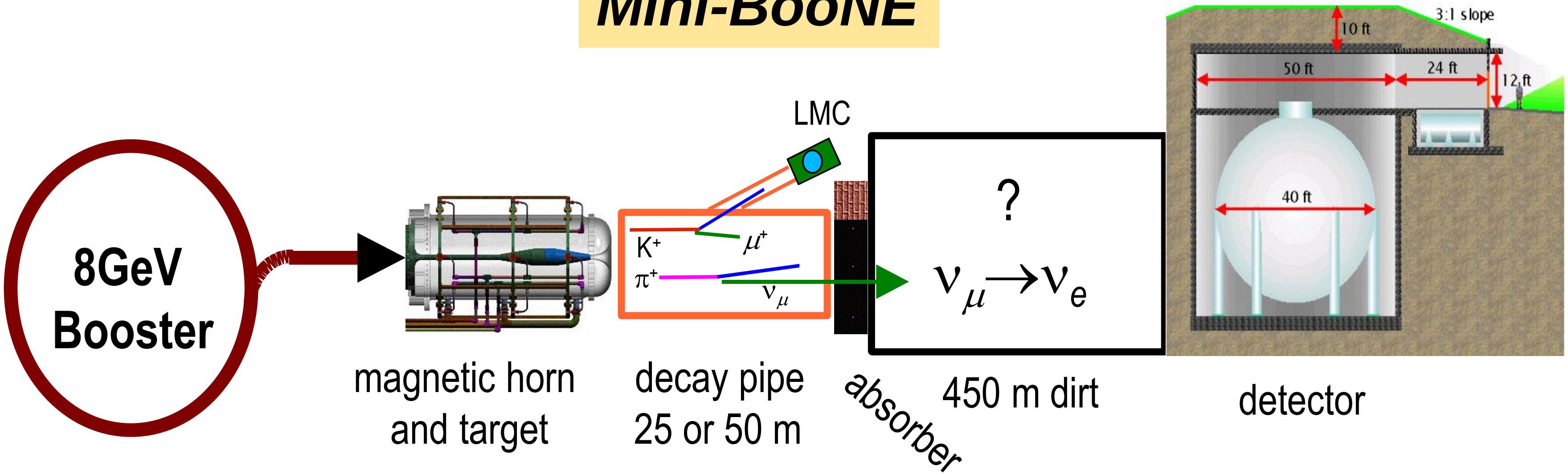
Mini-BooNE



- The FNAL Booster delivers 8 GeV protons to the MiniBooNE beamline.
- The protons hit a 71cm beryllium target producing pions and kaons.
- The magnetic horn focuses the secondary particles towards the detector.
- The mesons decay into neutrinos, and the neutrinos fly to the detector, all other secondary particles are absorbed by absorber and 450 m dirt.
- 5.579E20 POT for neutrino mode since 2002.
- Switch horn polarity to run anti-neutrino mode since January 2006.

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Mini-BooNE Flux

8 GeV protons on Be target gives:

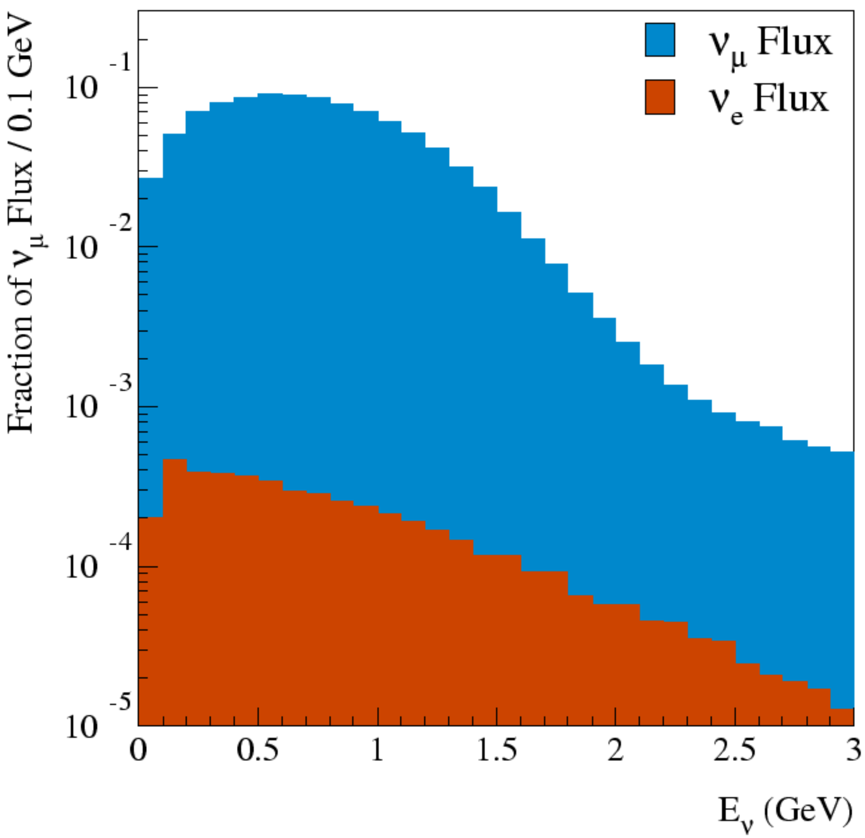
$p + Be \rightarrow \pi^+, K^+, K^0_L$

ν_μ from:

$\pi^+ \rightarrow \mu^+ \nu_\mu \quad K^+ \rightarrow \mu^+ \nu_\mu \quad K^0_L \rightarrow \pi^- \mu^+ \nu_\mu$

Intrinsic ν_e from:

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \quad K^+ \rightarrow \pi^0 e^+ \nu_e \quad K^0_L \rightarrow \pi^- e^+ \nu_e$



The intrinsic ν_e , ~0.5% of the neutrino flux, are one of the major backgrounds for $\nu_\mu \rightarrow \nu_e$ search.

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

L(m), E(MeV), Δm²(eV²)

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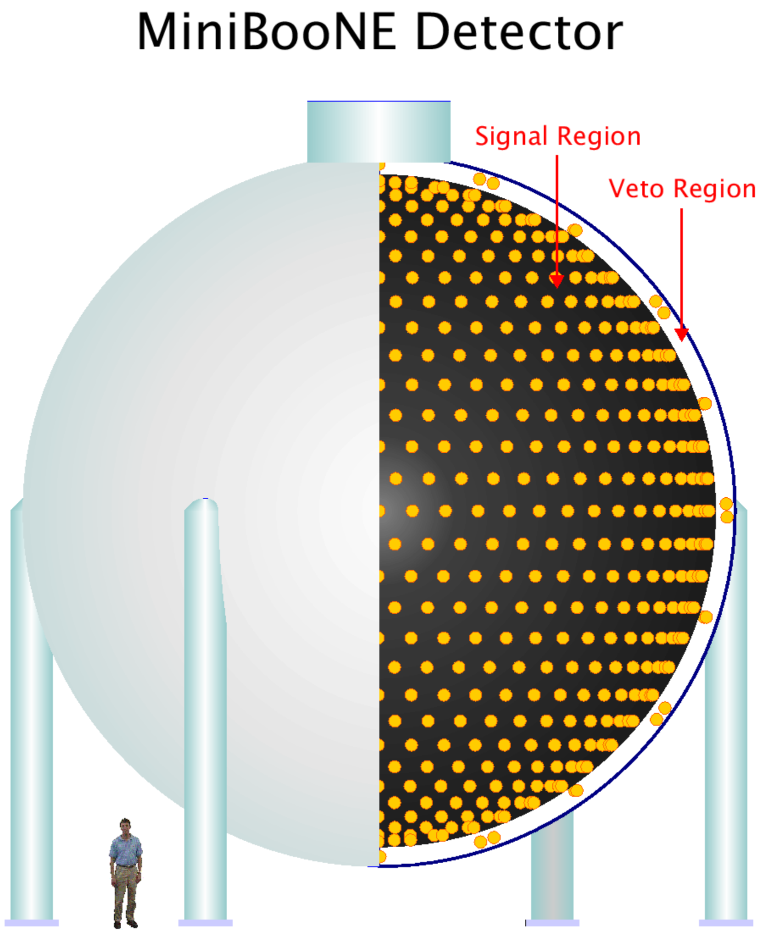
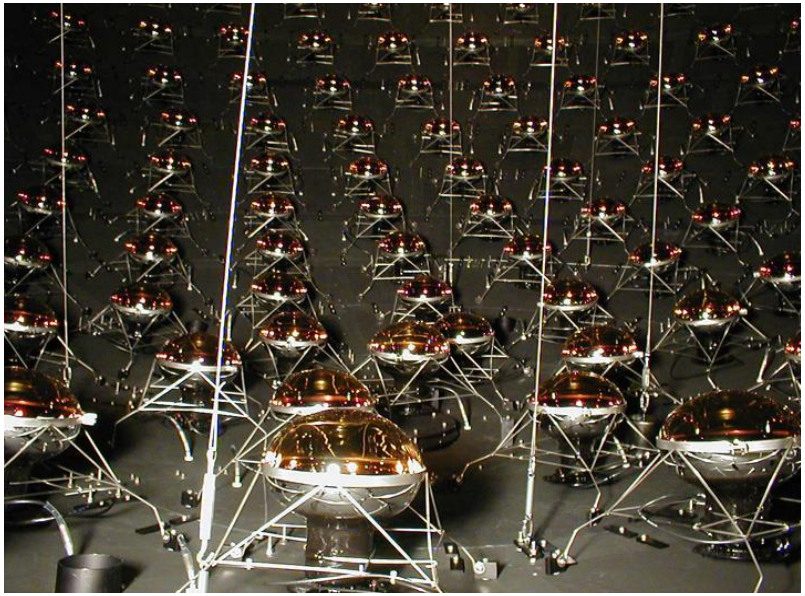
Mini-BooNE



- 12m diameter tank
- Filled with 800 tons of pure mineral oil
- Optically isolated inner region with 1280 PMTs
- Outer veto region with 240 PMTs.



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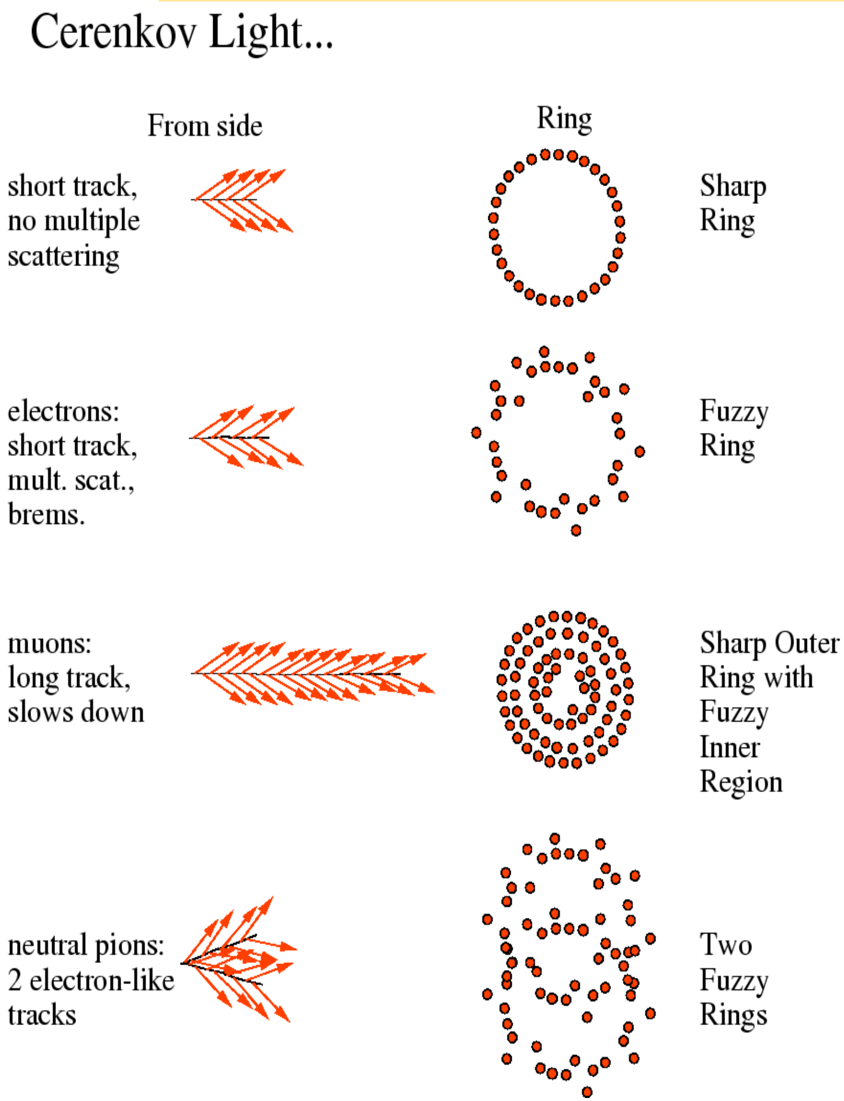
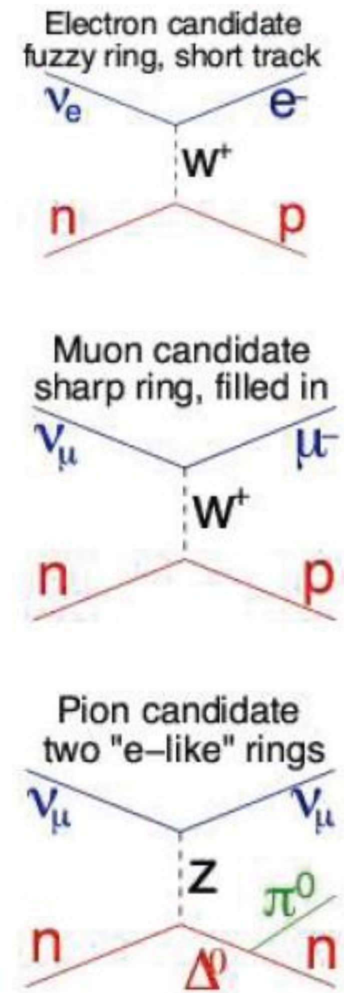
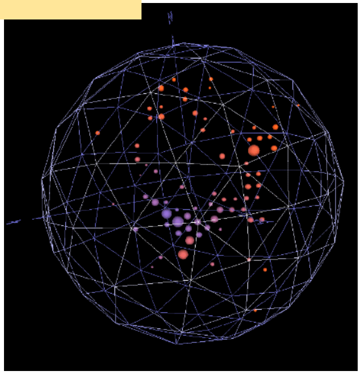
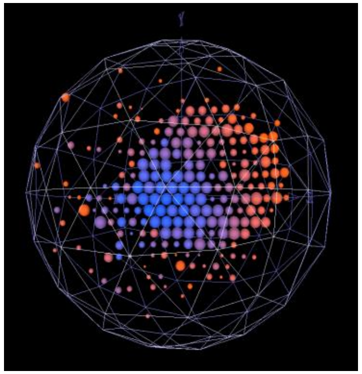
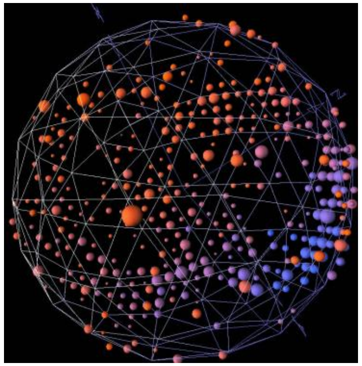
Mini-BooNE – Identifying Event Candidates











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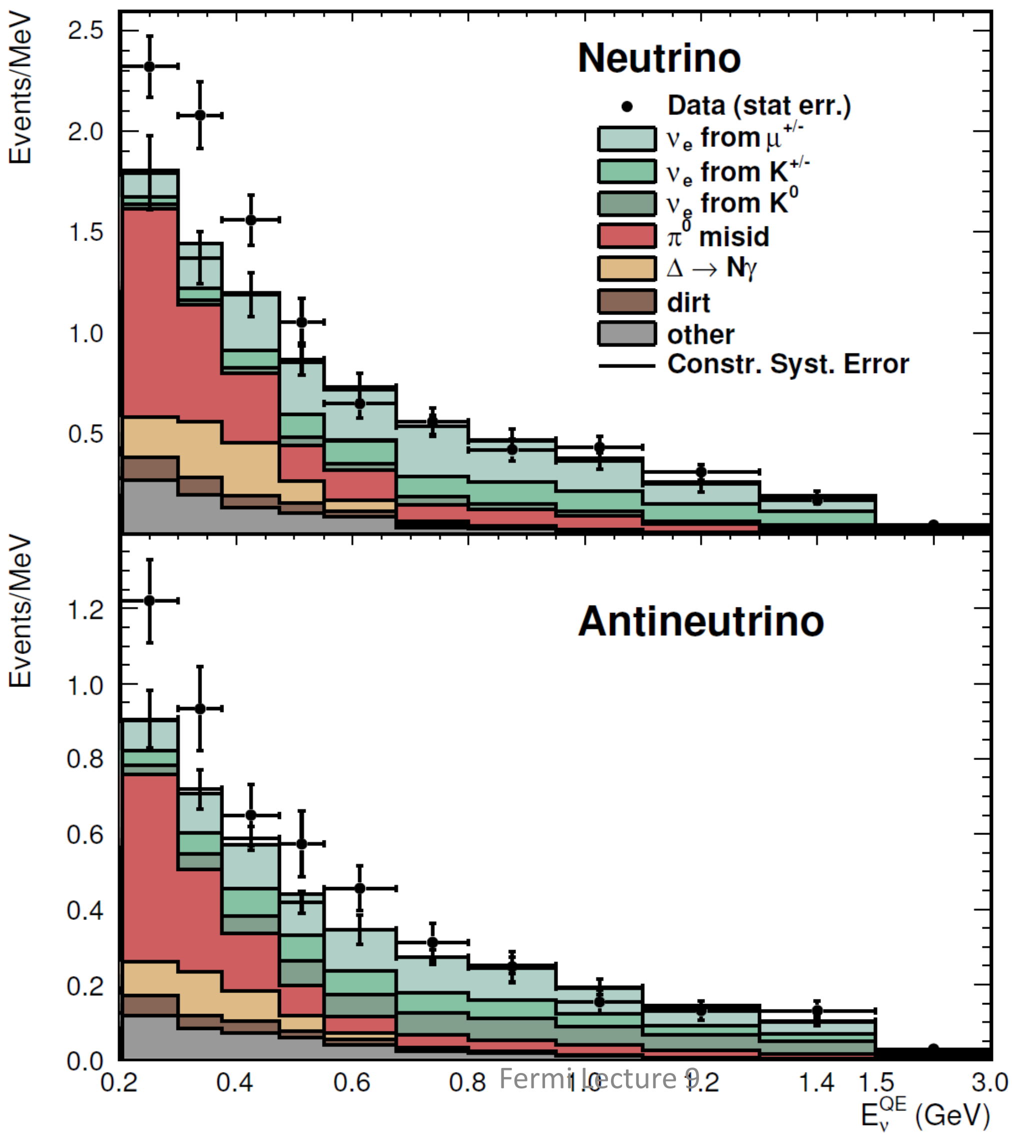
Mini-BooNE Observed Events



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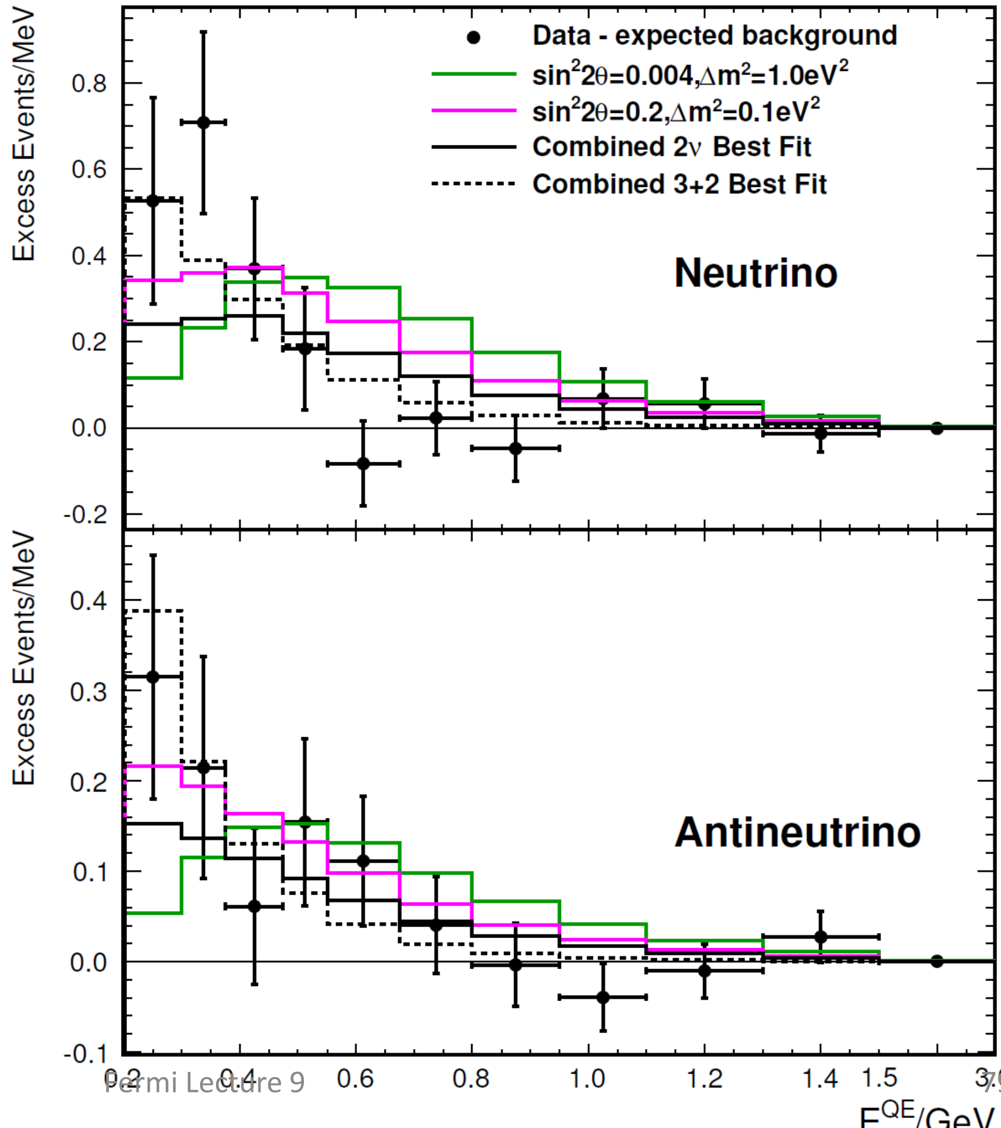
Mini-BooNE Event Excesses

Neutrino and Antineutrino event excesses as a function of E_n

Neutrino Oscillation Model Fits also shown



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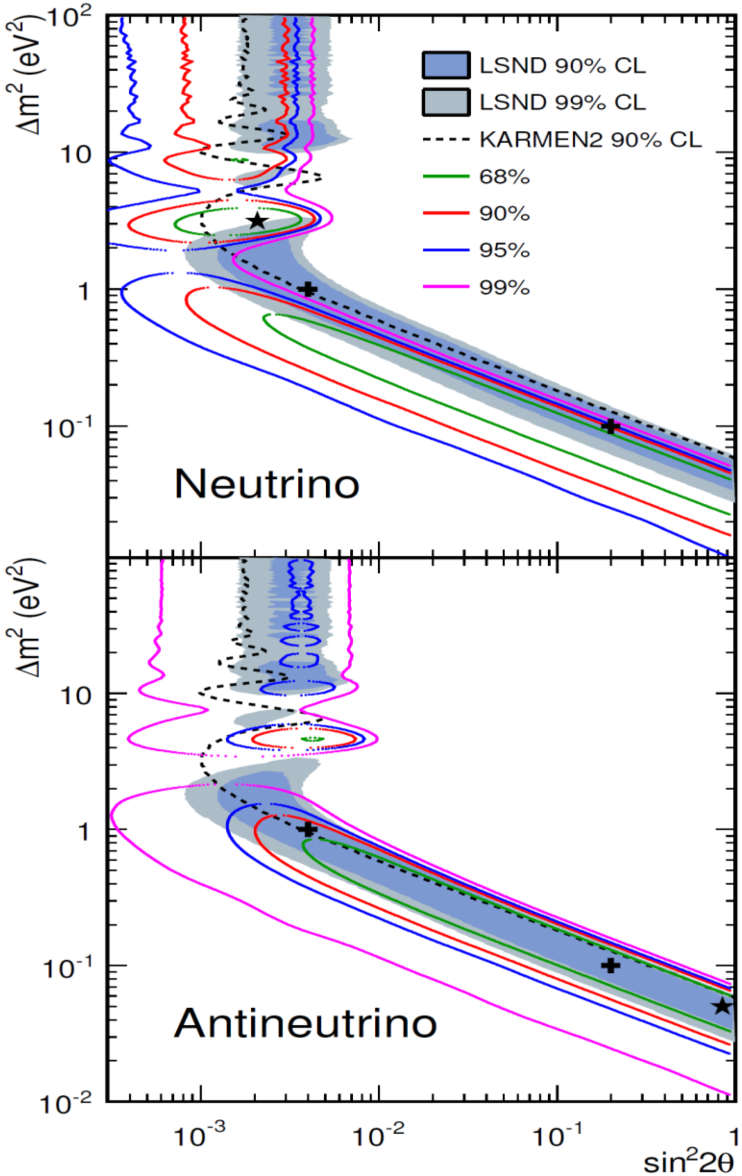
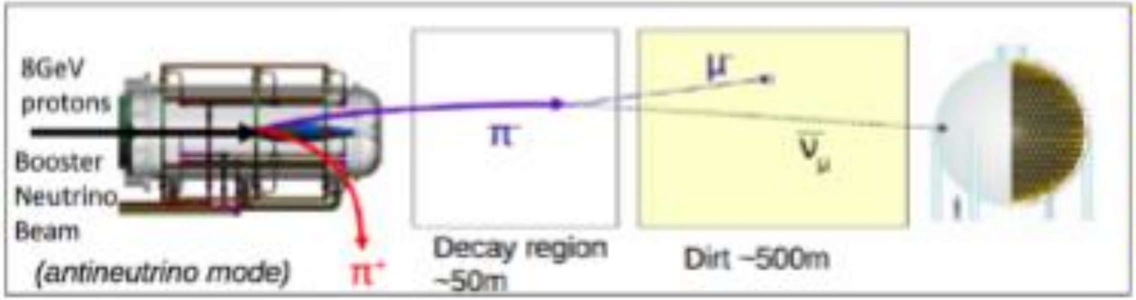
Mini-BooNE Event Excesses



- MiniBoone allowed regions in combined neutrino and antineutrino mode for events within a two neutrino $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.
- Shaded area shows LSND $\nu_\mu \rightarrow \nu_e$ allowed regions
- Black Star is best fit

MiniBooNE May 2018

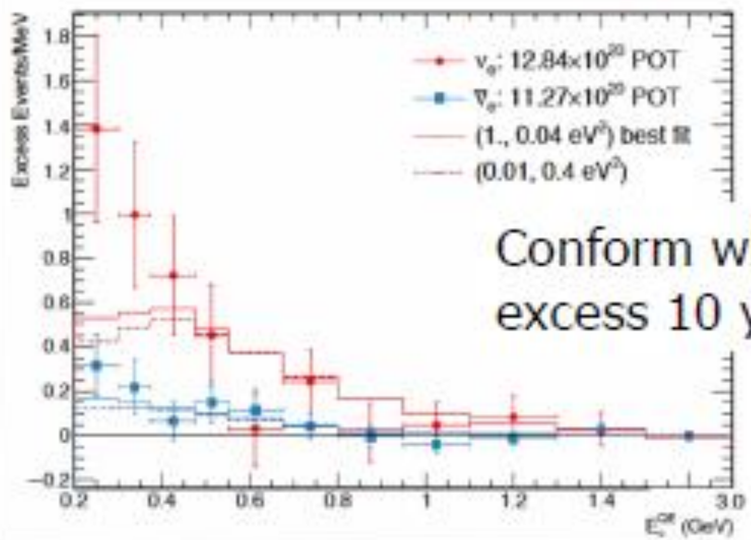
MiniBooNE



Search for electron neutrino appearance in short baseline accelerator experiment.

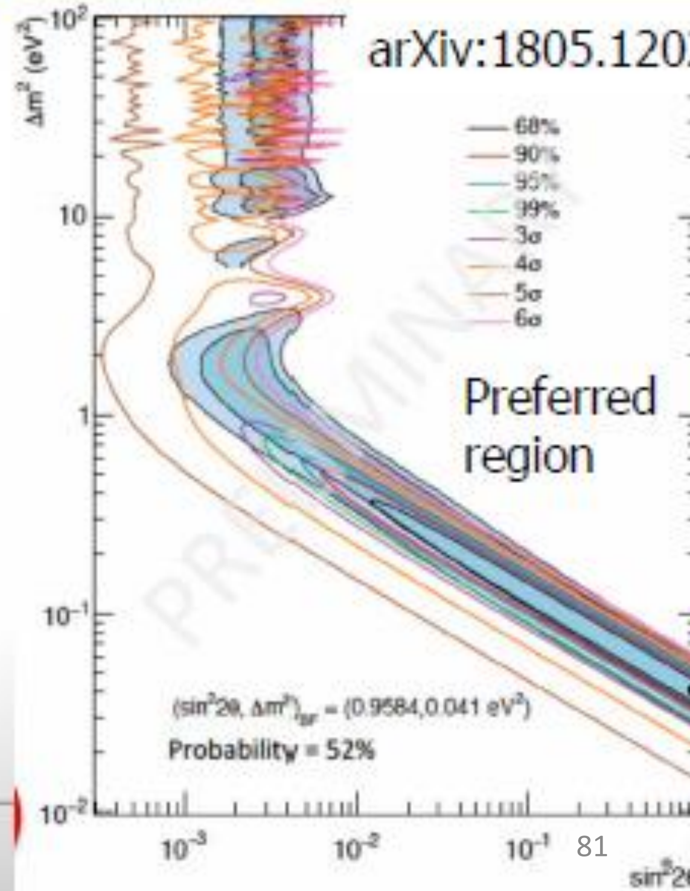
6.3 sigma excess reported combining the data with LSND

Excess of events over expectation



Conform with LSND excess 10 years ago

arXiv:1805.12028



Preferred region

Caused by a new sterile neutrino? The jury is still out..

Frontiers 9

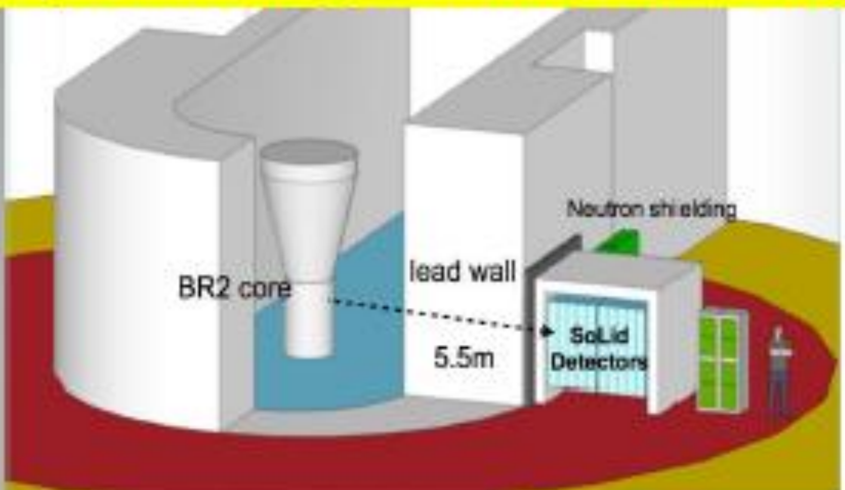
Conclusions of Experimental Spokespersons

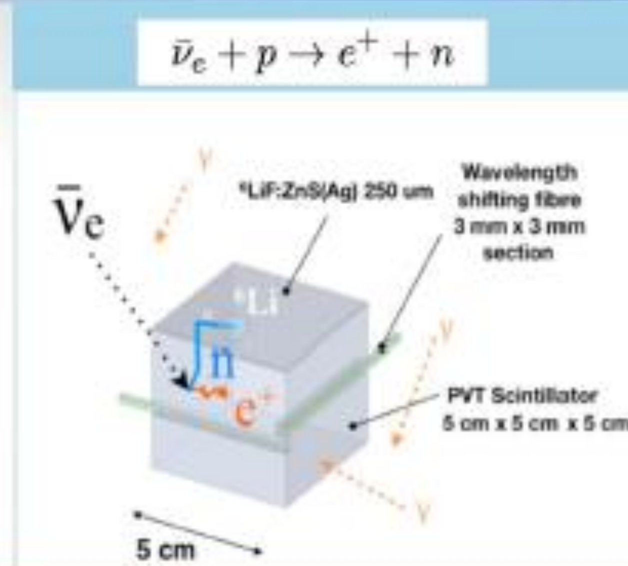
Both LSND and MiniBooNE see indications of electron neutrino/antineutrino appearance, but there are discrepancies in the energy distributions of the appearance signal that could or could not be related to oscillations. The analysis of all high Δm^2 data sets shows that models with several sterile neutrinos can give acceptable global fits. Reported incompatibility with sterile neutrino models, especially between the appearance and disappearance measurements, may be arising from the choice of test statistic, rather than an underlying discrepancy with the data sets. Investigations of high Δm^2 oscillations currently form one of the most active areas of neutrino physics and many new experiments are being mounted or considered. This future program builds on the initial measurements of LSND and MiniBooNE discussed here and aims to provide a definitive exploration of new physics signals in the neutrino sector, such as sterile neutrinos.

Conrad, Louis and Shaevitz

New Short Baseline Experiments will check!

Experiments at reactors, eg the SoLid experiment @BR2 reactor in Belgium



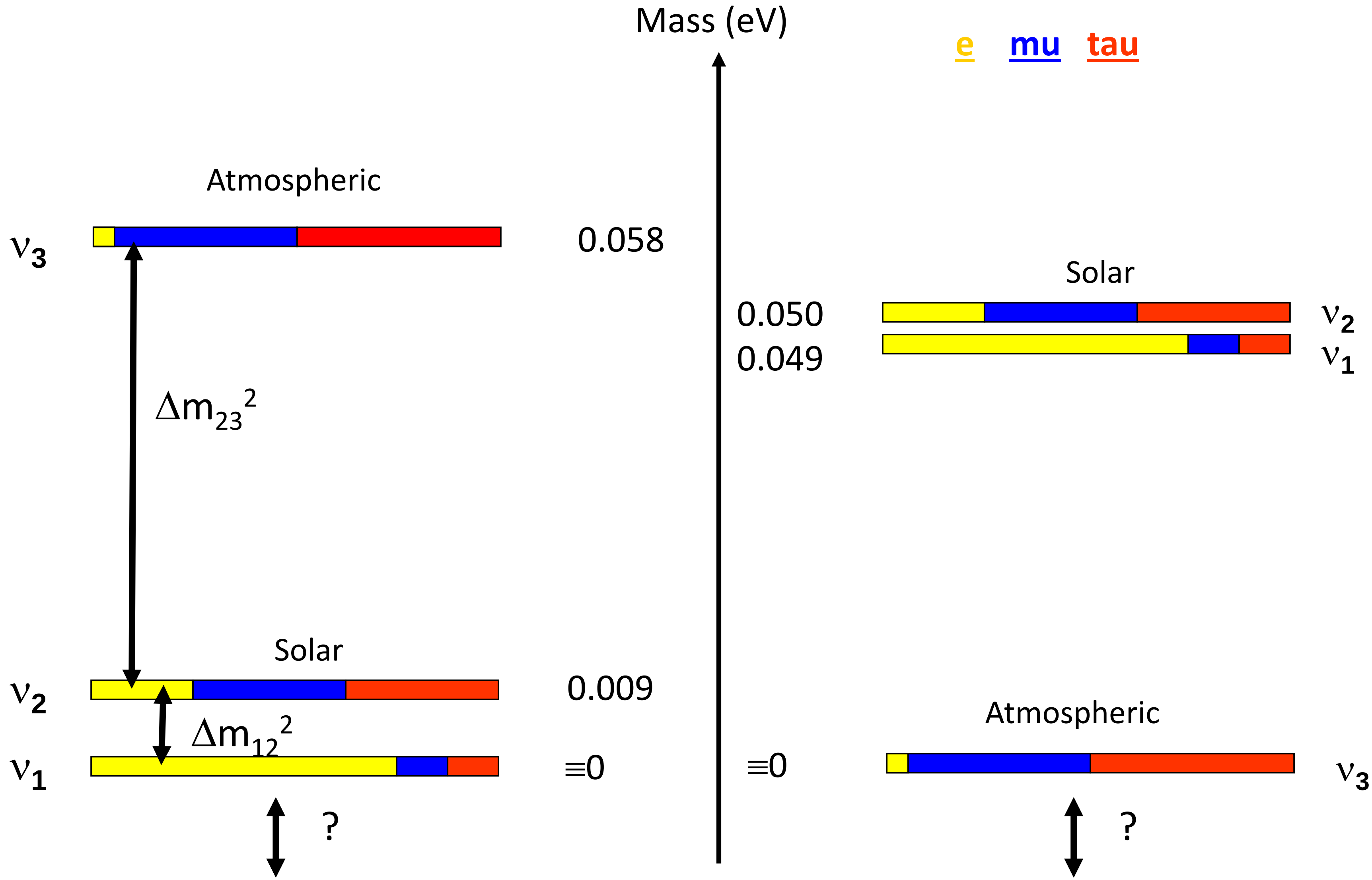


Also: Prospect, STEREO, DANSS, NEOS

FNAL Short-Baseline Neutrino programme:Neutrino beam from Booster
Start ~2019

Minimum Neutrino Masses and Flavor Content

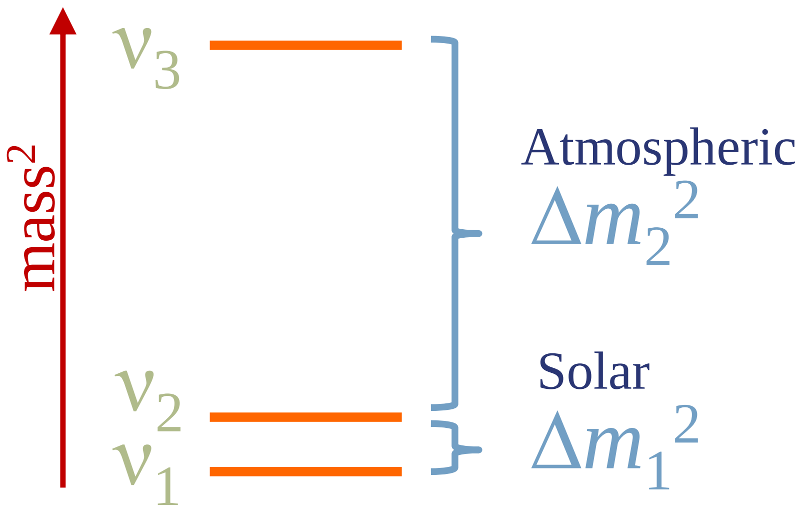
Neutrino mass spectrum and flavor content



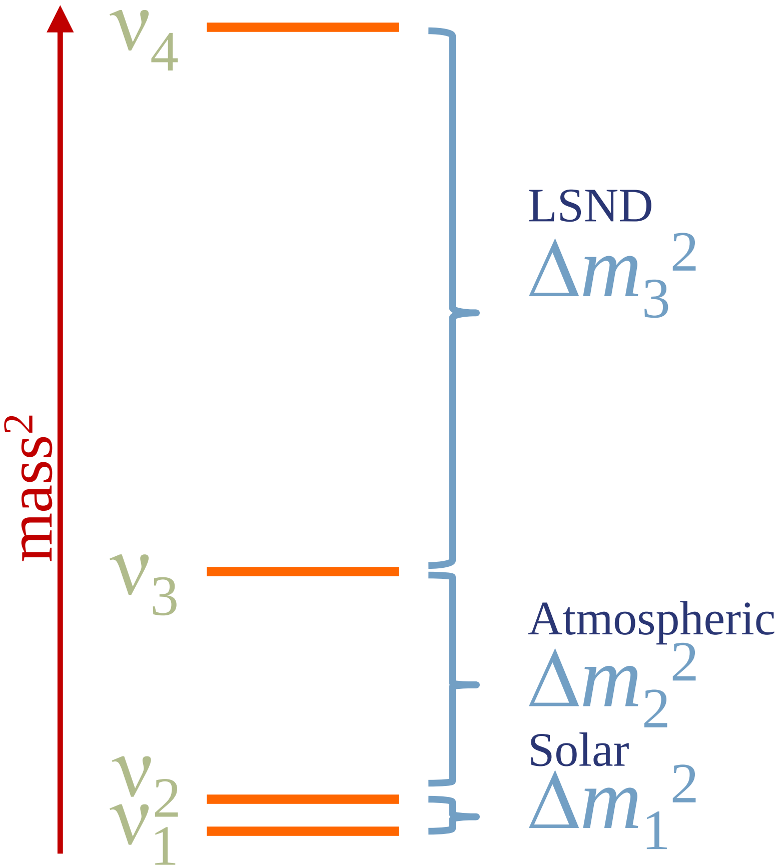
Sterile Neutrinos

A sterile neutrino is a lepton with no ordinary electroweak interaction except those induced by mixing.

Three neutrinos allow only 2 independent Δm^2 scales.

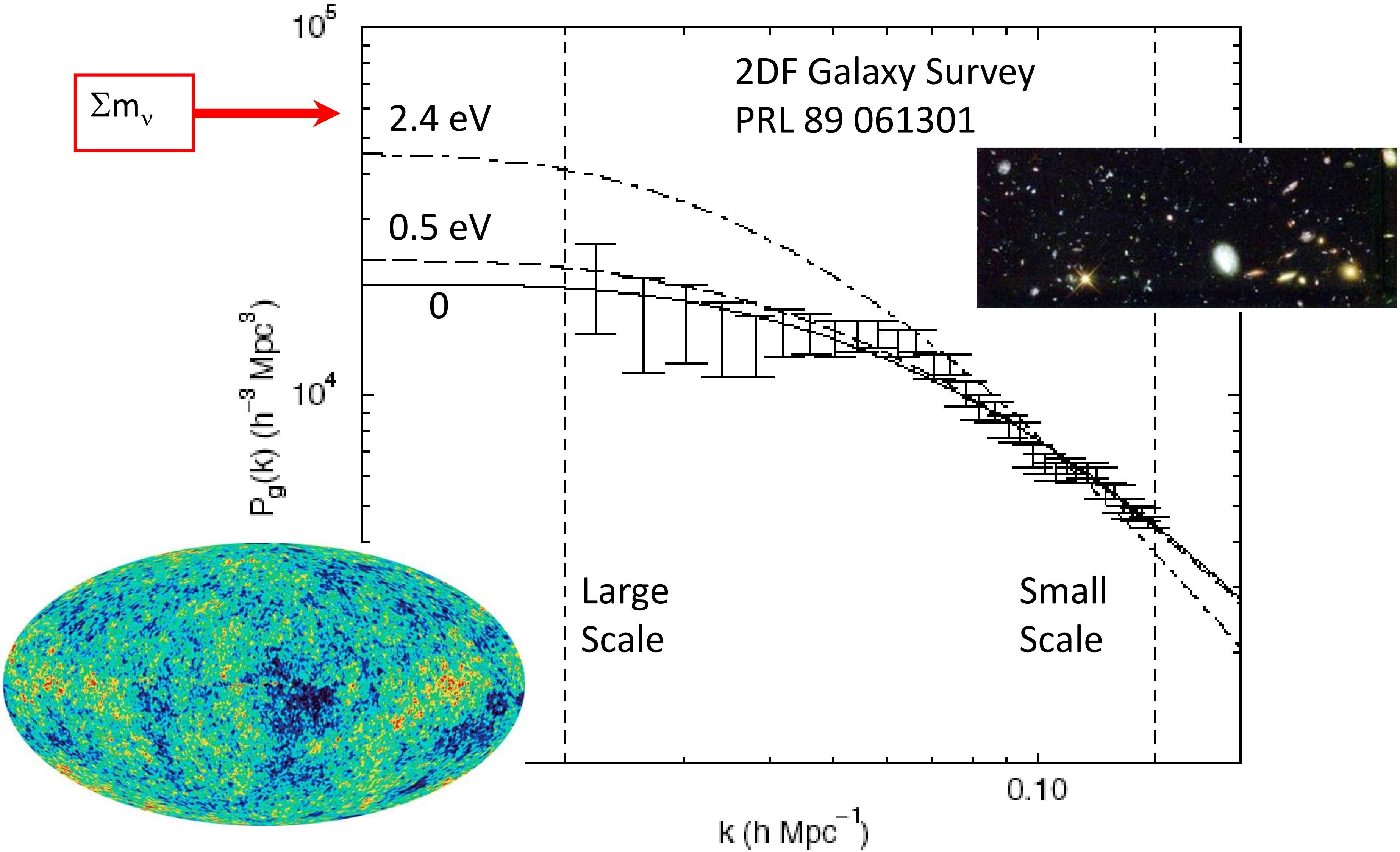


But the LSND Δm^2 is at a completely different scales.



Even small m_ν influences structure

Σm_ν



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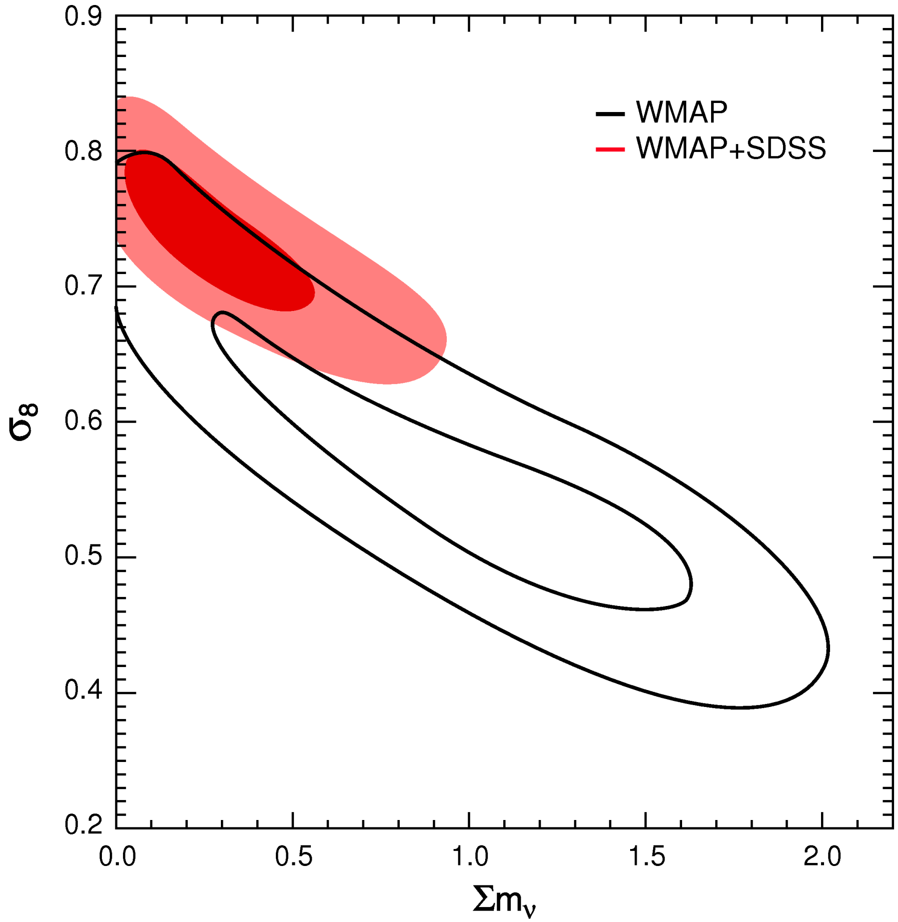
WHAT IS THE PRESENT BOUND ON THE NEUTRINO MASS?



WMAP-3 ONLY ~ 2.0 eV
WMAP + LSS 0.68 eV

COMPARE WITH WMAP-I:

WMAP-1 ONLY ~ 2.1 eV
WMAP + LSS ~ 0.7 eV
(without information on bias)

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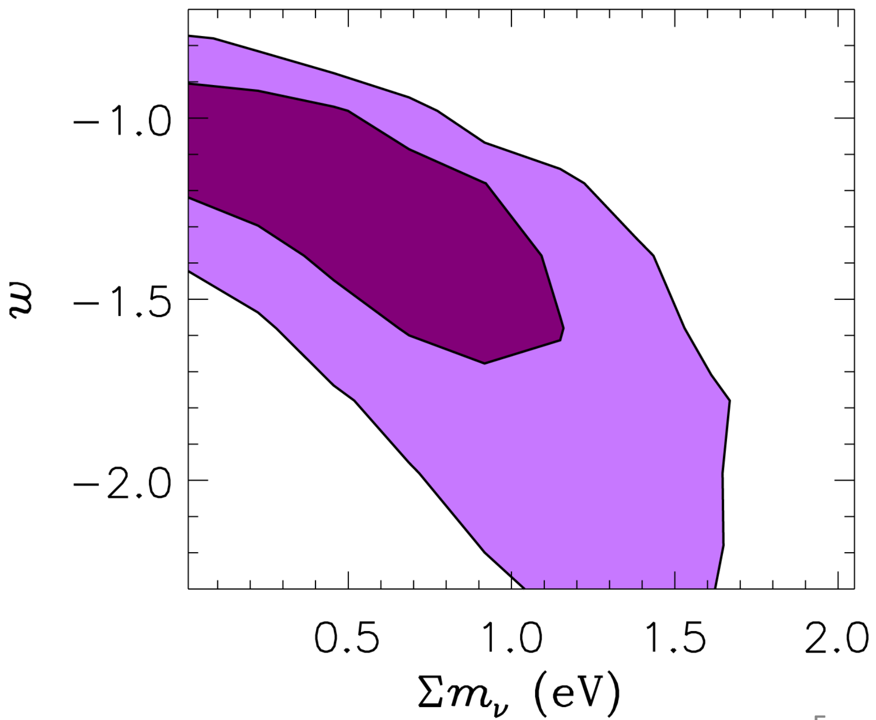
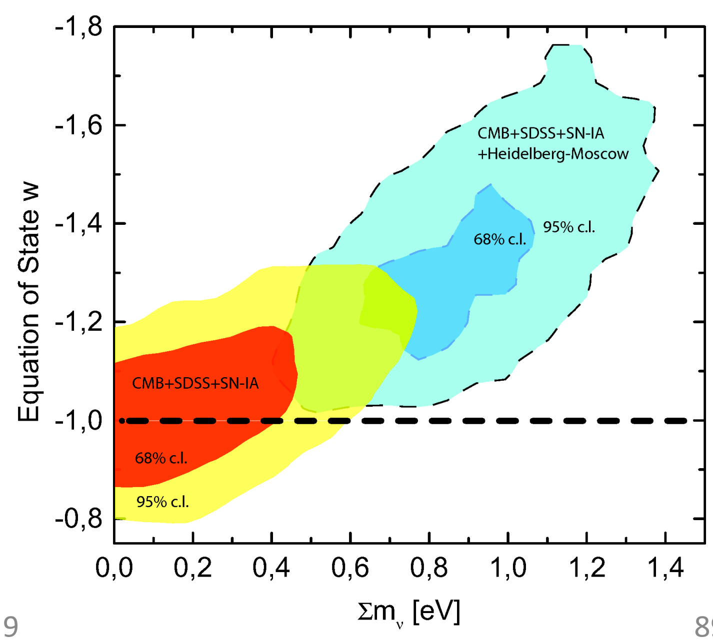
HOW CAN THE BOUND BE AVOIDED?

THERE IS A VERY STRONG DEGENERACY BETWEEN NEUTRINO MASS AND THE DARK ENERGY EQUATION OF STATE WHEN CMB, LSS AND SNI-A DATA IS USED.
THIS SIGNIFICANTLY RELAXES THE COSMOLOGICAL BOUND ON NEUTRINO MASS

IF A LARGE NEUTRINO MASS IS MEASURED EXPERIMENTALLY THIS SEEMS TO POINT TO $w < -1$





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Cosmology and the Number of Neutrinos

The energy density of neutrinos is proportional to the number of neutrino families, N_{eff}:

$$\rho_\nu \propto N_{eff}$$

The expansion rate of the radiation dominated era of the early universe depends on the density of relativistic particles.

This can be measured in:

- Large Scale Structure (LSS)
- Cosmic Microwave Background (CMB)
- Big-Bang Nucleosynthesis (BBN)

Model	Data	N_{eff}
N_{eff}	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$
	W-5+CMB+BAO+XLF+f_{gas}+H_0	$3.4^{+0.6}_{-0.5}$
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$
	W-7+ACT	5.3 ± 1.3
	W-7+ACT+BAO+H_0	4.56 ± 0.75
	W-7+SPT	3.85 ± 0.62
	W-7+SPT+BAO+H_0	3.85 ± 0.42
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41
$N_{eff}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$
	W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$
$N_{eff}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96
	W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45
$N_{eff}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43
$N_{eff}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$
$N_{eff}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$
	W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$

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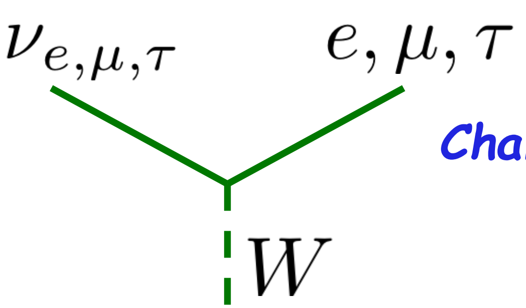
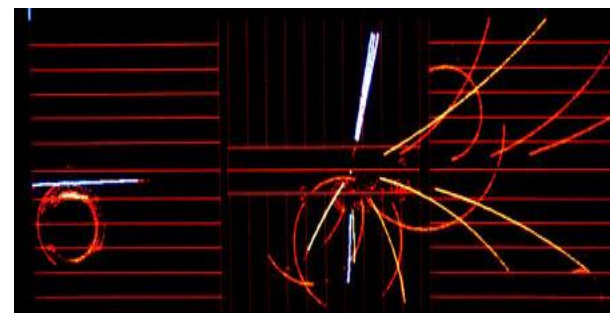
Today, after more than 70 years, several further properties have been discovered. In particular, neutrinos appear in three different "flavors", together with the corresponding leptons (e, μ, τ)

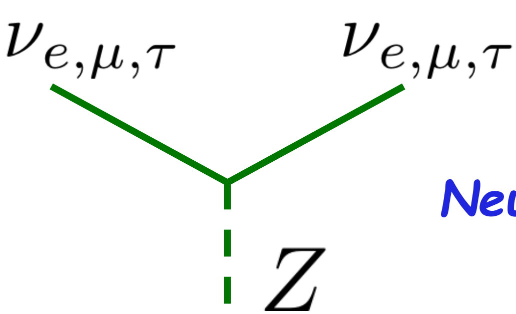
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{matrix} \leftarrow & q = 0 \\ \leftarrow & q = -1 \end{matrix} \quad (\Delta q = 1)$$

Moreover, we know that Fermi interaction proceeds through the exchange of charged vector bosons W, or a neutral vector boson Z



Charged current (Δq=1)





Neutral current (Δq=0)

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However, in spite of many considerable progresses, only recently it has been possible to attempt of answering some of the fundamental questions asked in the past century:

How small is the neutrino mass ?
(Pauli, Fermi, in the thirties)

Can a neutrino transform into its antiparticle ?
(Majorana, in the thirties)

Can a neutrino of a given flavor transform into a neutrino of a different flavor ("oscillate") ?
(Pontecorvo, Maki-Nakagawa-Sakata, in the sixties)

In particular, as we will see, it is possible to answer positively and with well-constructed arguments to the third question.

END