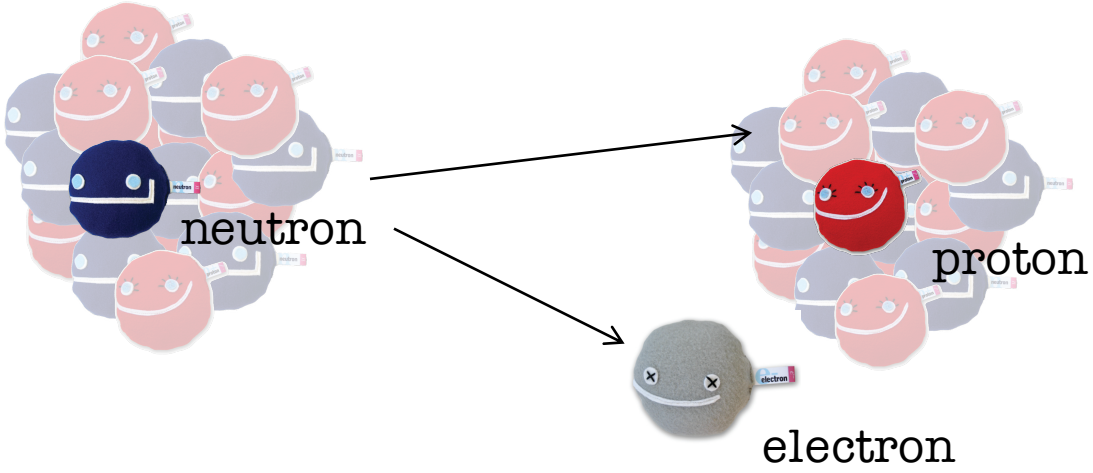
Neutrinos

Anne Schukraft
Fermilab
Undergraduate lecture series, June 16, 2016

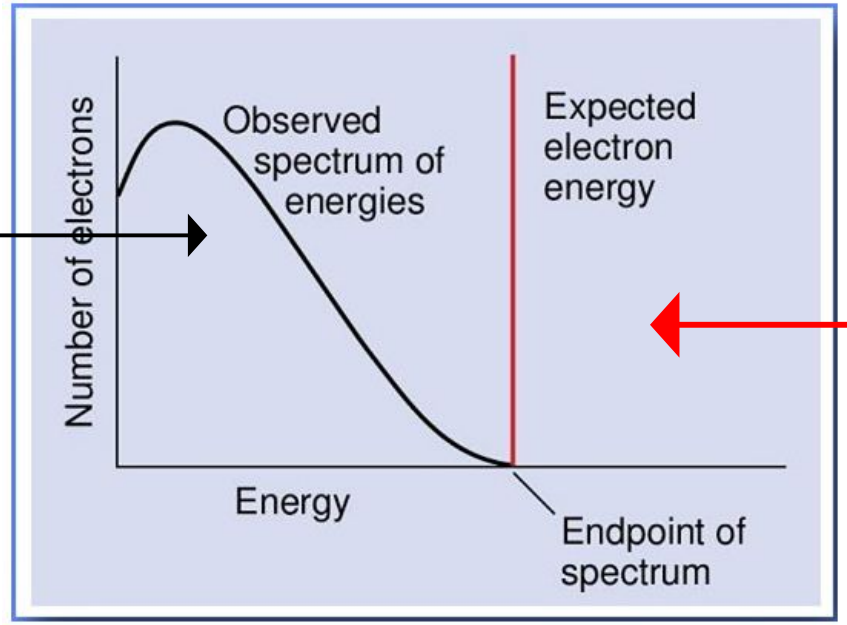
Fermilab

Wolfgang Pauli and the β-decay spectrum



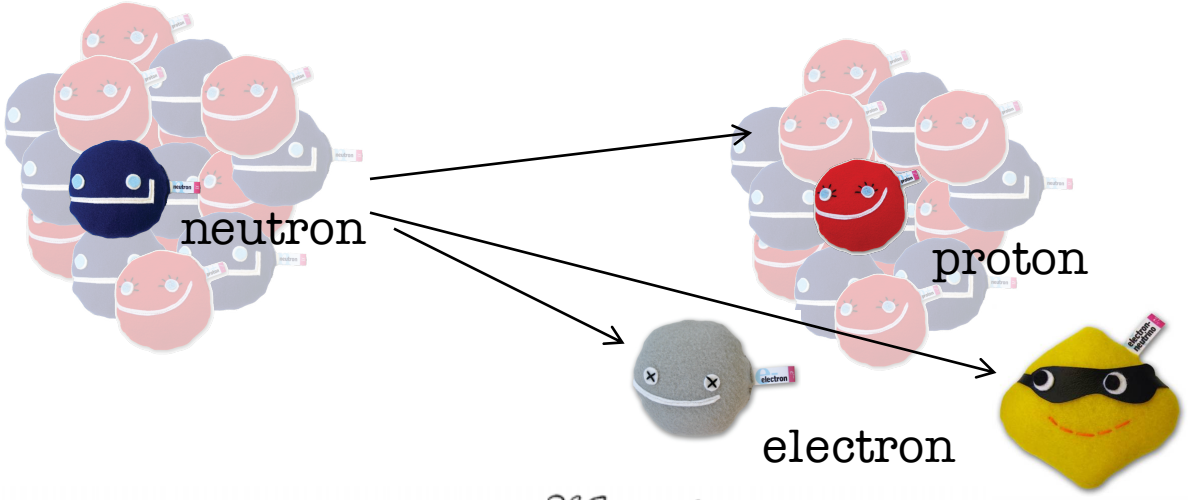
β-decay before 1930

In this case, all electrons would have the same momentum, which would be the difference of the initial and final nuclear state



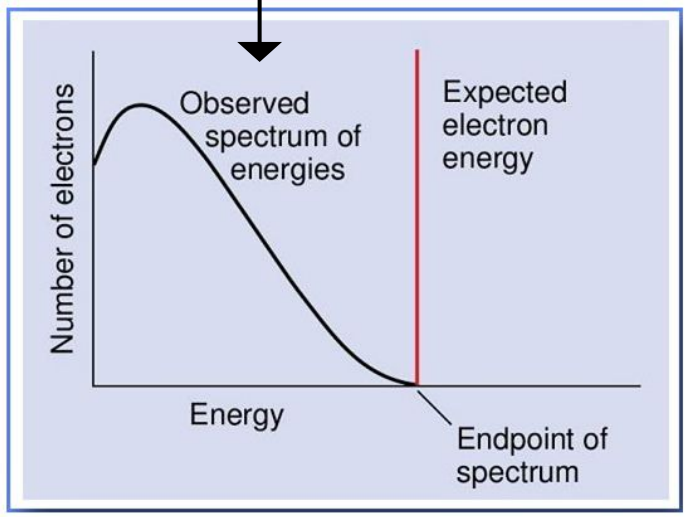
But:
Chadwick et al. observed a continuous electron momentum spectrum

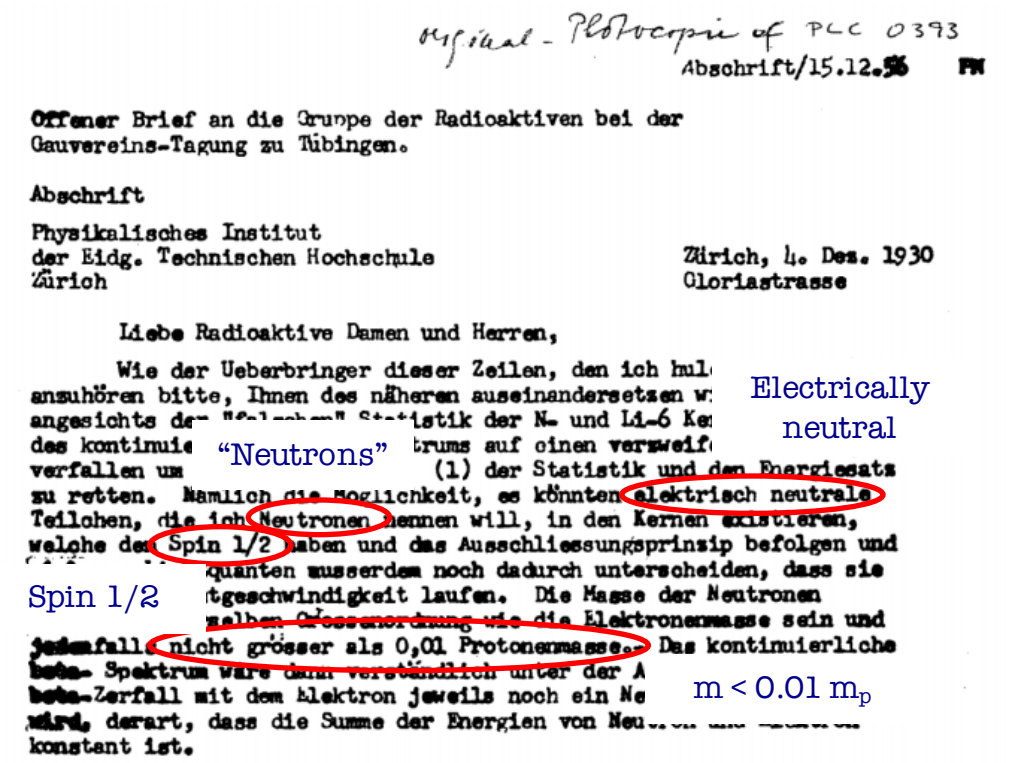
Wolfgang Pauli and the β-decay spectrum



Wolfang Pauli postulated the neutrino in 1930

Explains the continuous decay spectrum





Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich hul
ansuhören bitte, Ihnen des näheren auseinandersetzen w
angesichts der "falschen" Statistik der N- und Li-6 Ke
des kontinuie trums auf einen verzweif
verfallen un (1) der Statistik und den Energiesats
zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale
Teilchen, die ich Neutronen nennen will, in den Kernen existieren,
welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und
quanten ausserdem noch dadurch unterscheiden, dass sie
tgeschwindigkeit laufen. Die Masse der Neutronen
selben Grossenordnung wie die Elektronenmasse sein und
jedenfalls nicht grösser als 0,01 Protonenmasse. Das kontinuierliche
beta- Spektrum wäre dann verständlich unter der A
beta-Zerfall mit dem Elektron jeweils noch ein Ne
wird, derart, dass die Summe der Energien von Neu
konstant ist.

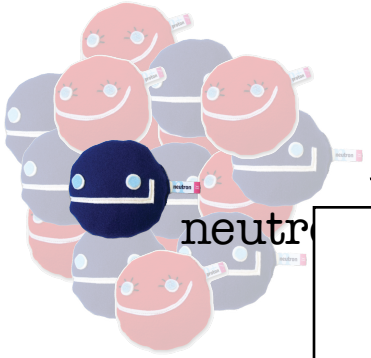
"Neutrons"

Electrically neutral

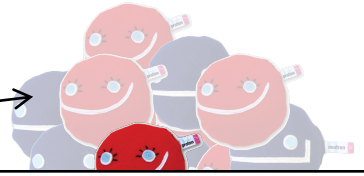
Spin 1/2

$m < 0.01\ m_p$

Wolfgang Pauli and the β-decay spectrum



neutr



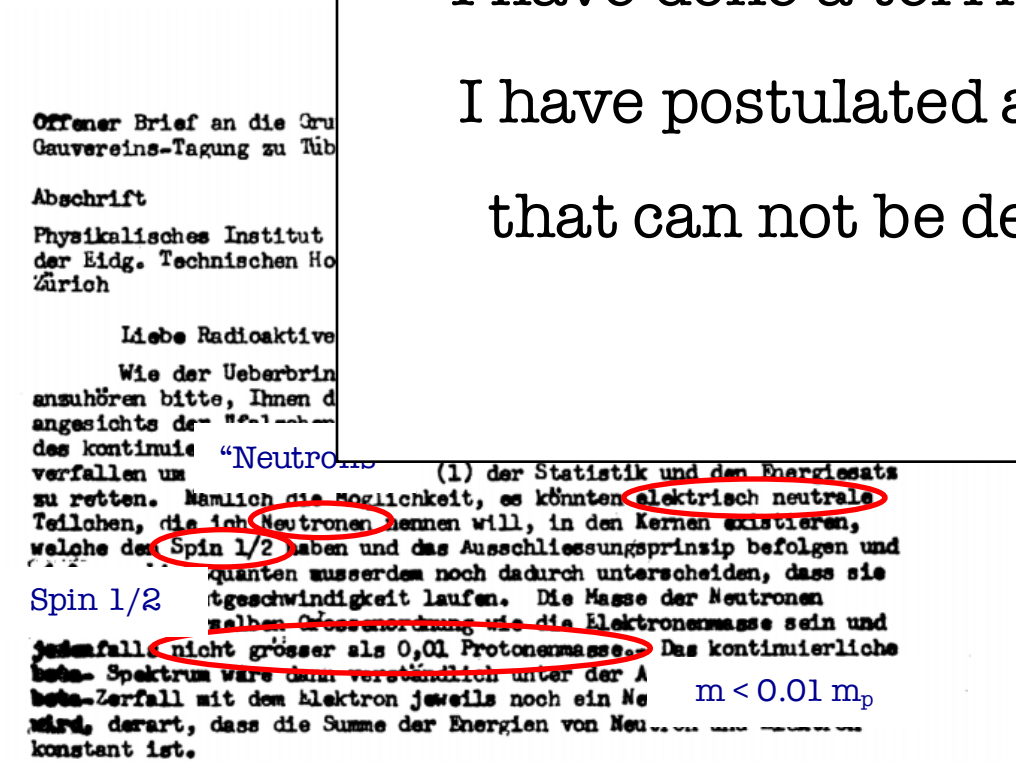
ang Pauli postulated
e neutrino in 1930

Explains the
continuous decay
spectrum

I have done a terrible thing,

I have postulated a particle

that can not be detected.



Offener Brief an die Gru
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Abschrift

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Liebe Radioaktive

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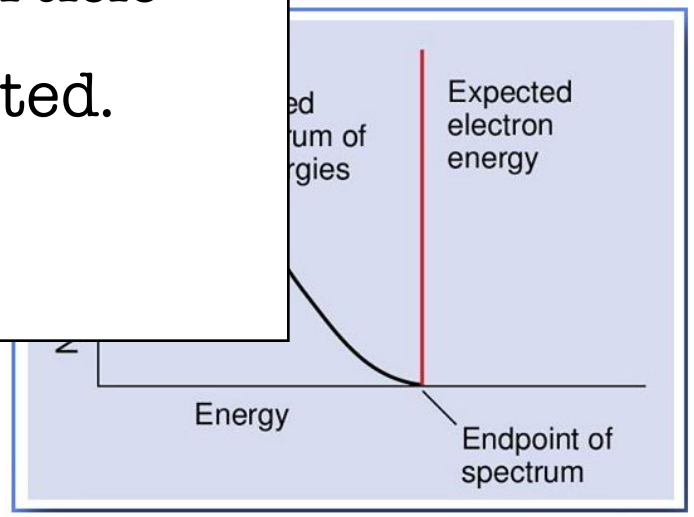
"Neutrons"

(1) der Statistik und den Energiesatz

Spin 1/2

$m < 0.01\ m_p$

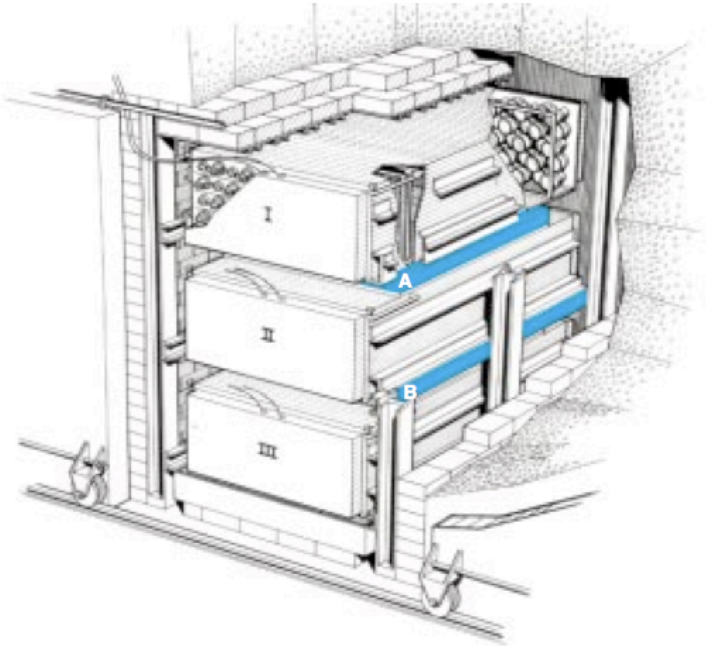


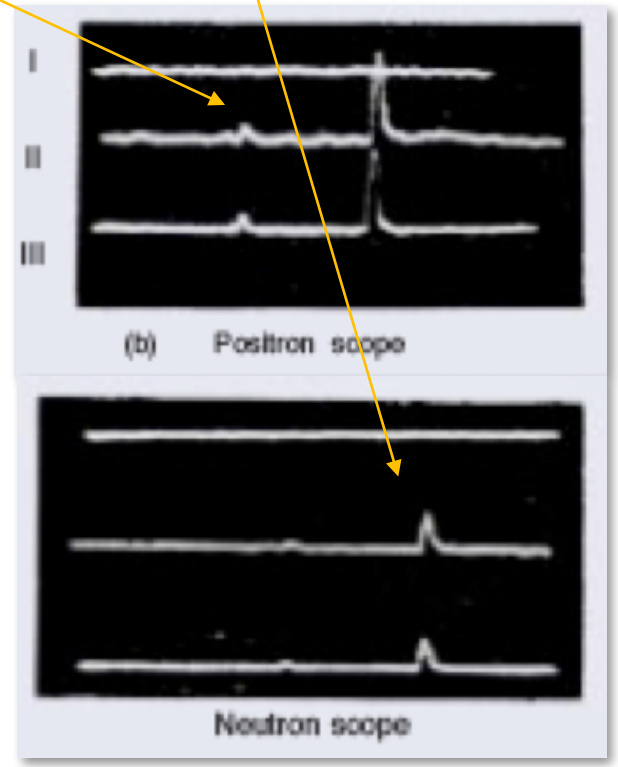
Cowan & Reines & the antineutrino discovery

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

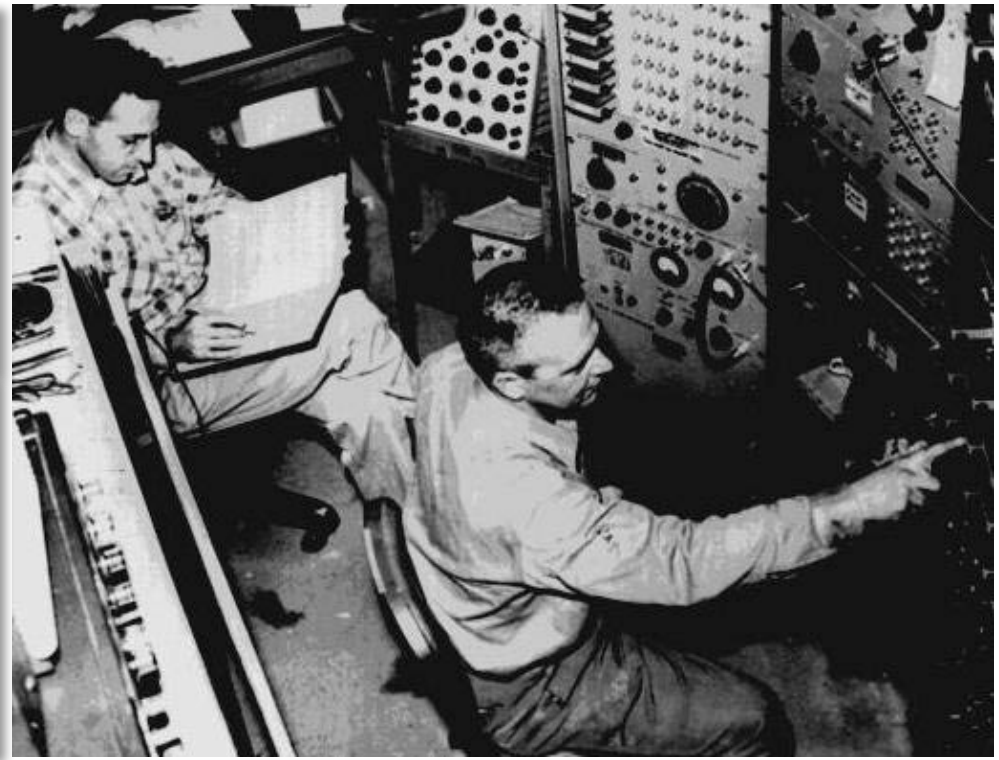
Anti-electron-neutrino | Proton | Positron | Neutron

(inverse beta decay)

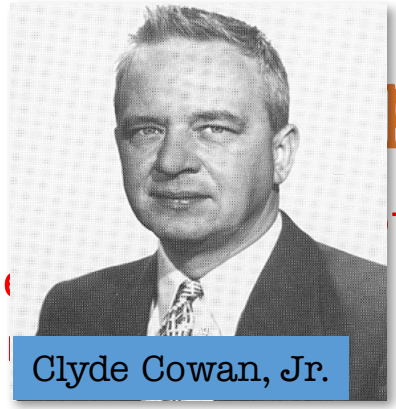




Cowan and Reines built a liquid scintillator detector and discovered the antineutrino in 1956



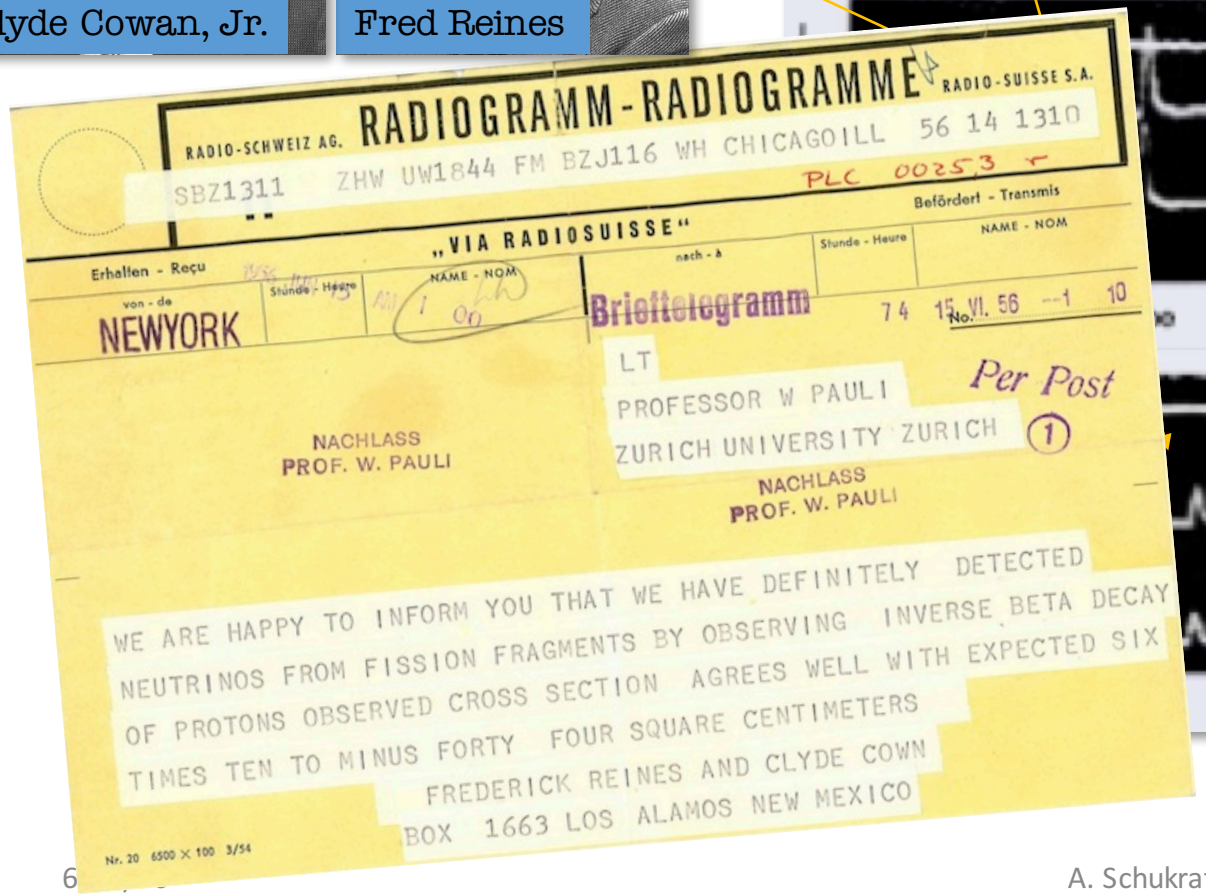
Cowan & Reines & the antineutrino discovery


Clyde Cowan, Jr.

Fred Reines

$e^+ + n$

ron Neutron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NAME - NOM

Brieftelegramm

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LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

1

NACHLASS PROF. W. PAULI

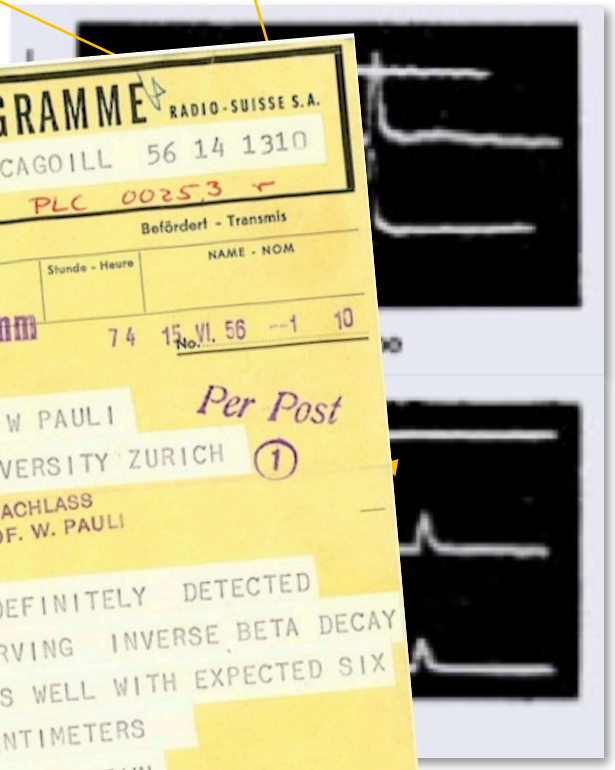
NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

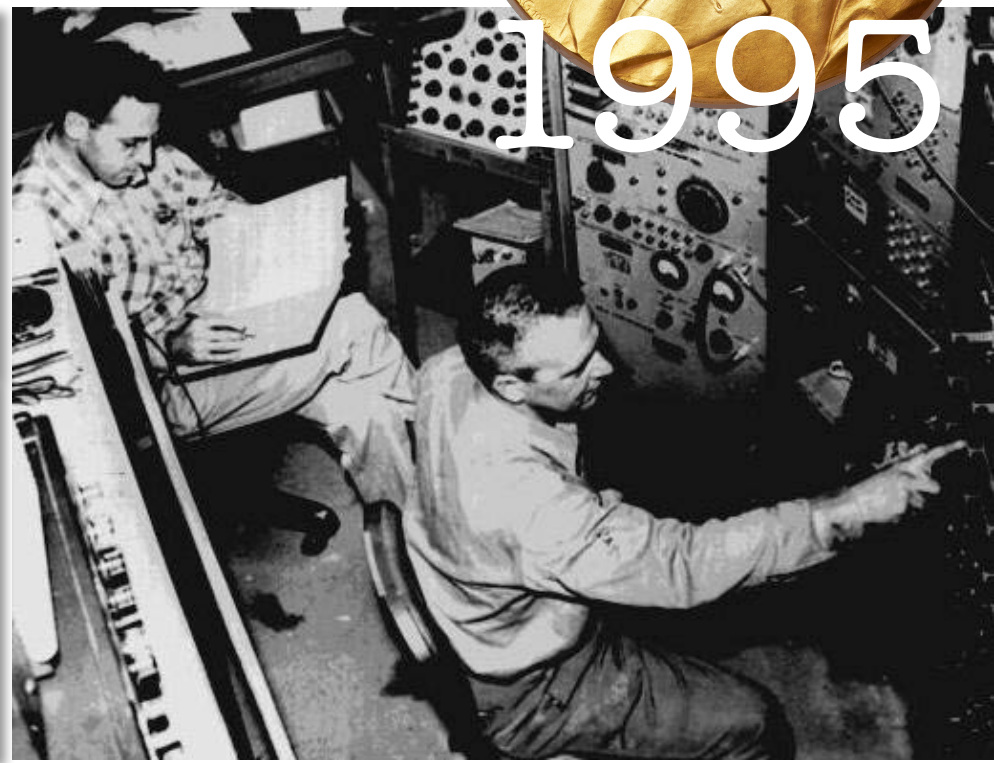
BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 × 100 3/54

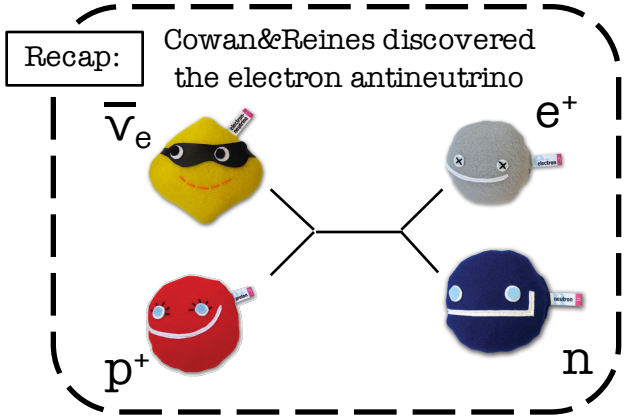


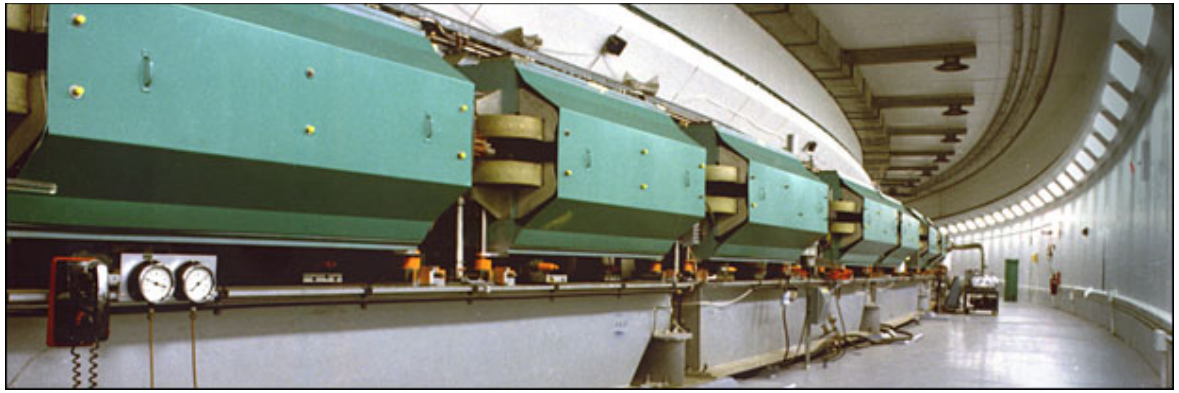
Cowan and
scintillator dete
the an

1995



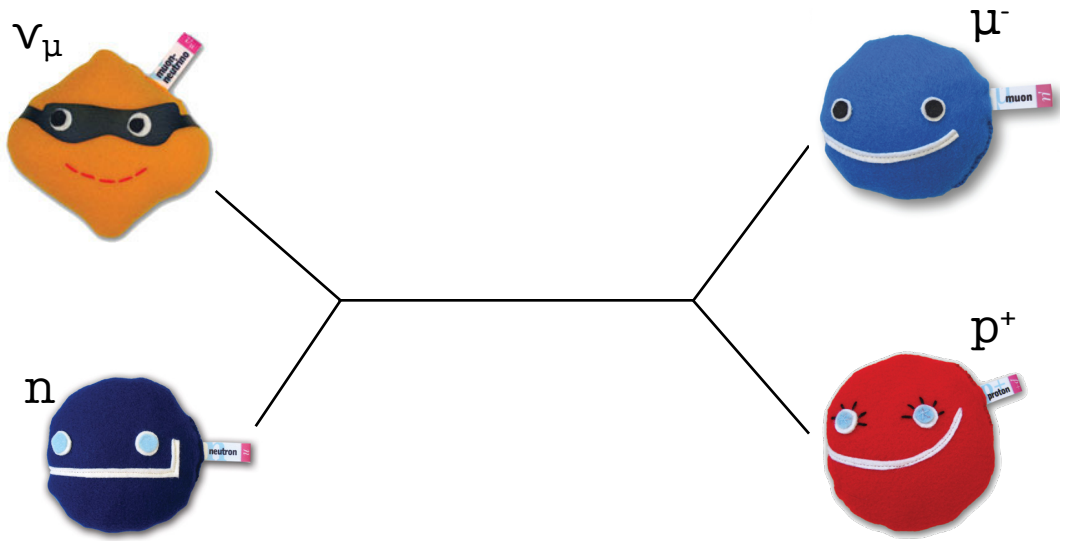
An additional type of neutrino





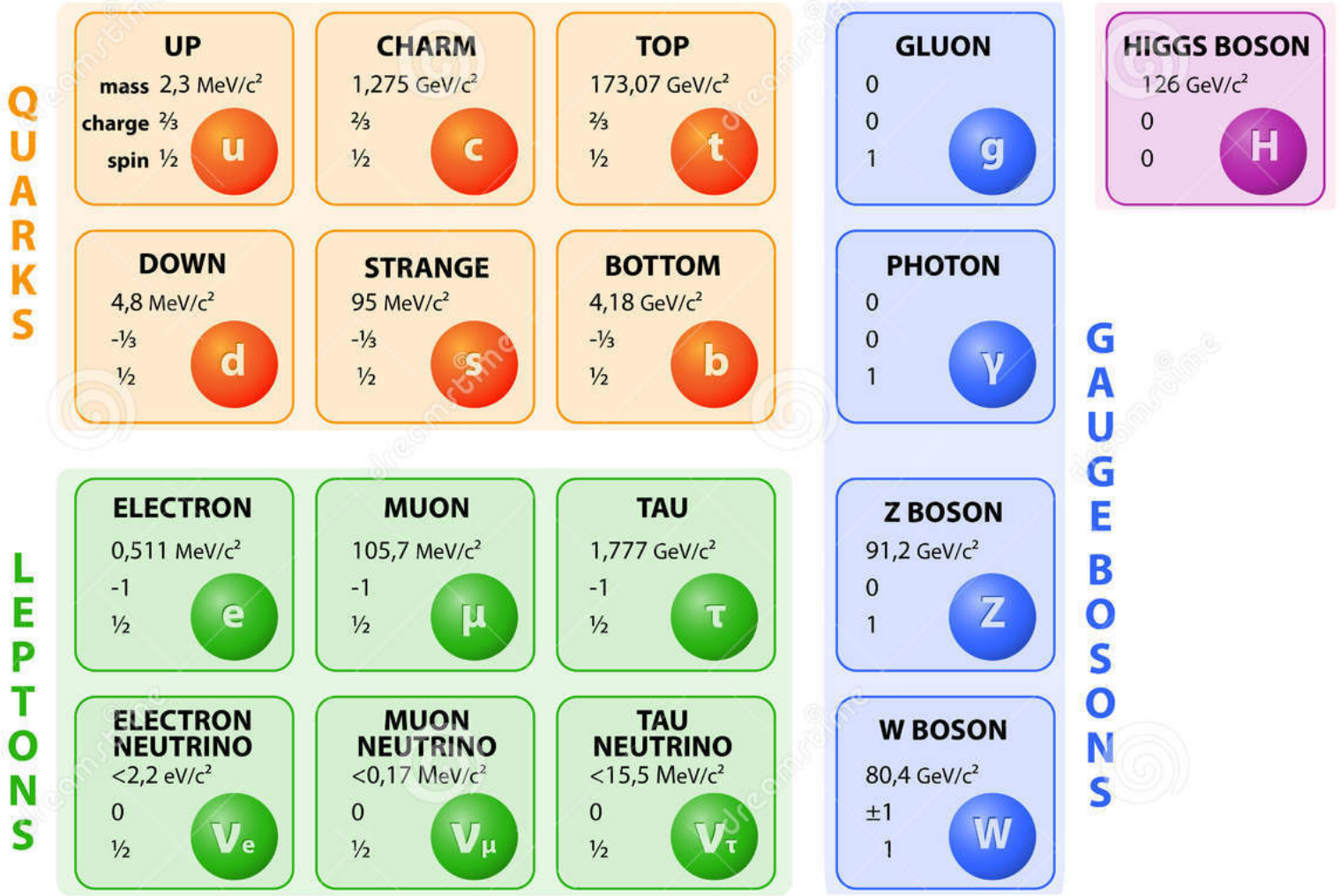
Lederman, Schwartz & Steinberger used neutrinos produced in pion decays in the BNL Alternating gradient synchrotron

1988



These neutrinos produce muons when interacting with matter. They are a different **neutrino flavor**!

STANDARD MODEL OF ELEMENTARY PARTICLES



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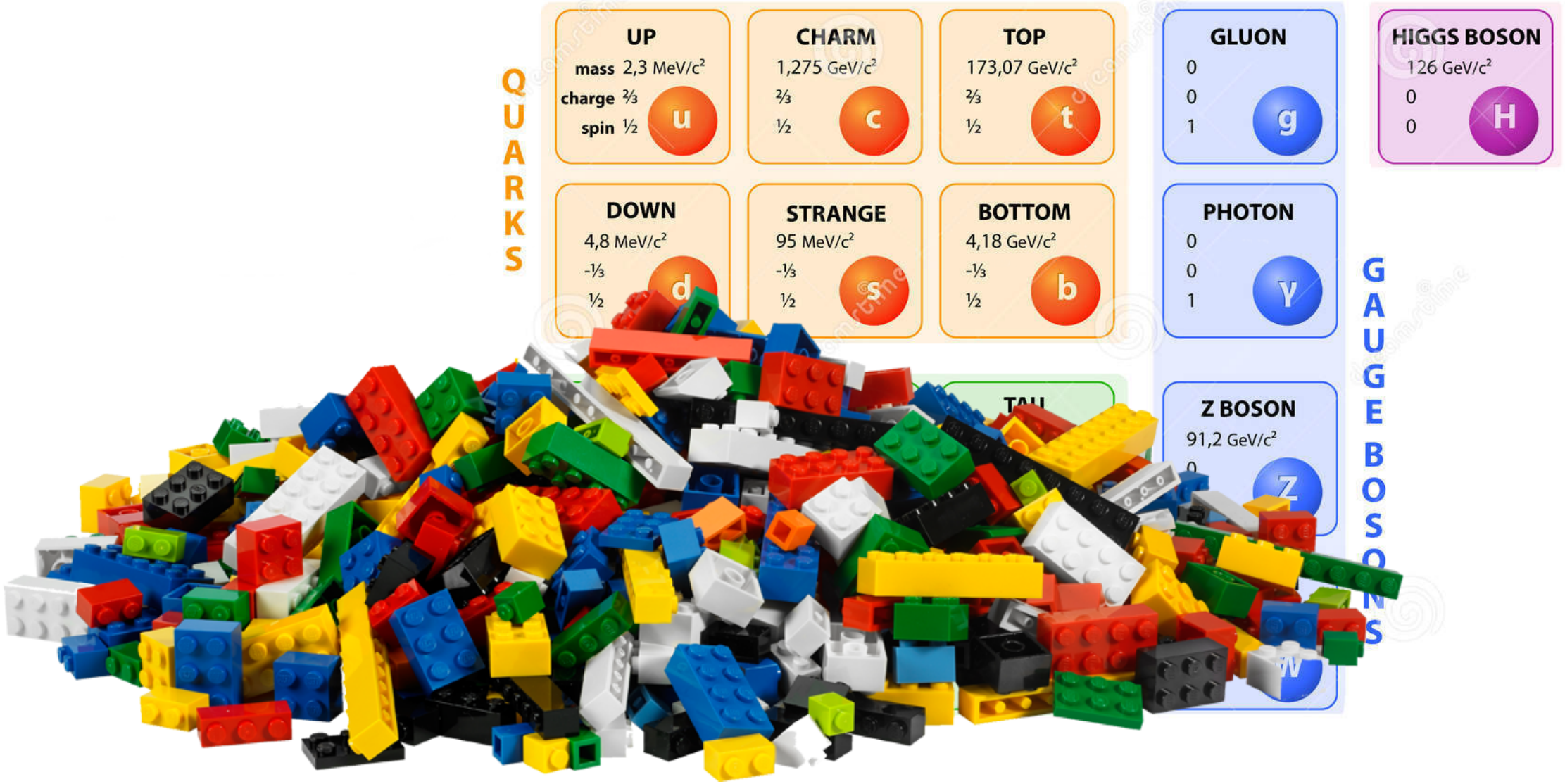

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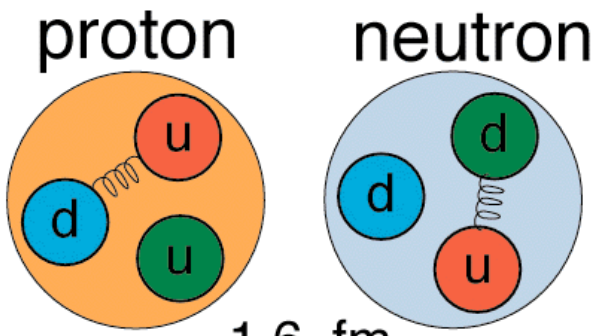
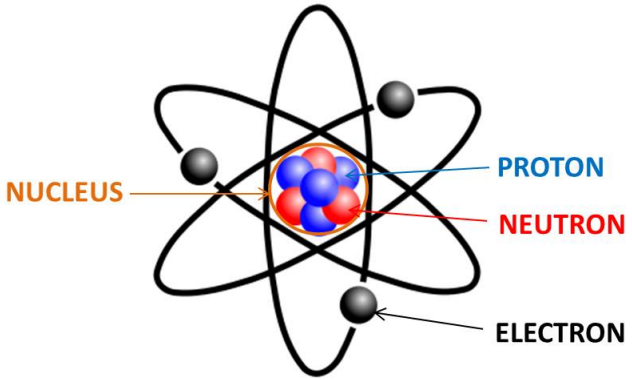


1.6 fm

= 1.6×10^{-15}



QUARKS	UP mass 2,3 MeV/c² charge ⅔ spin ½ u	CHARM 1,275 GeV/c² ⅔ ½ c	TOP 173,07 GeV/c² ⅔ ½ t	GLUON 0 0 1 g	HIGGS BOSON 126 GeV/c² 0 0 H	
	DOWN 4,8 MeV/c² -⅓ ½ d	STRANGE 95 MeV/c² -⅓ ½ s	BOTTOM 4,18 GeV/c² -⅓ ½ b	PHOTON 0 0 1 γ		GAUGE BOSONS
LEPTONS	ELECTRON 0,511 MeV/c² -1 ½ e	MUON 105,7 MeV/c² -1 ½ μ	TAU 1,777 GeV/c² -1 ½ τ	Z BOSON 91,2 GeV/c² 0 1 Z		
	ELECTRON NEUTRINO <2,2 eV/c² 0 ½ ν_e	MUON NEUTRINO <0,17 MeV/c² 0 ½ ν_μ	TAU NEUTRINO <15,5 MeV/c² 0 ½ ν_τ	W BOSON 80,4 GeV/c² ±1 1 W		

Neutrinos come in three flavors

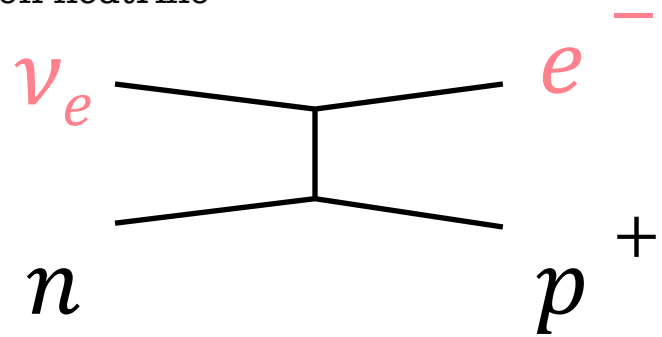
electron-neutrino ν_e

muon-neutrino ν_μ

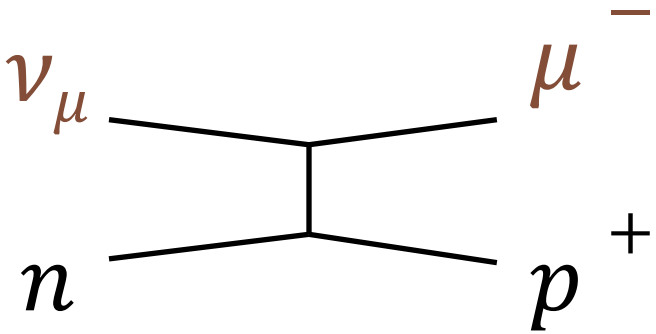
tau-neutrino ν_τ

How we distinguish them

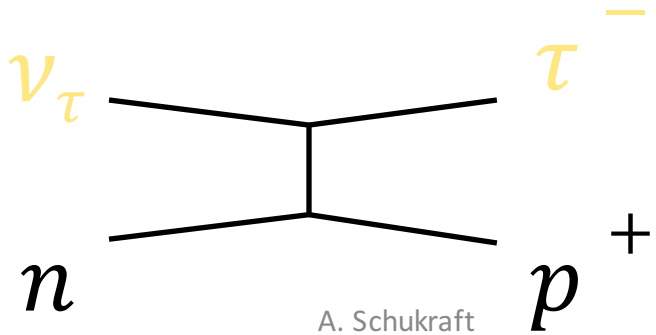
electron-neutrino



muon-neutrino

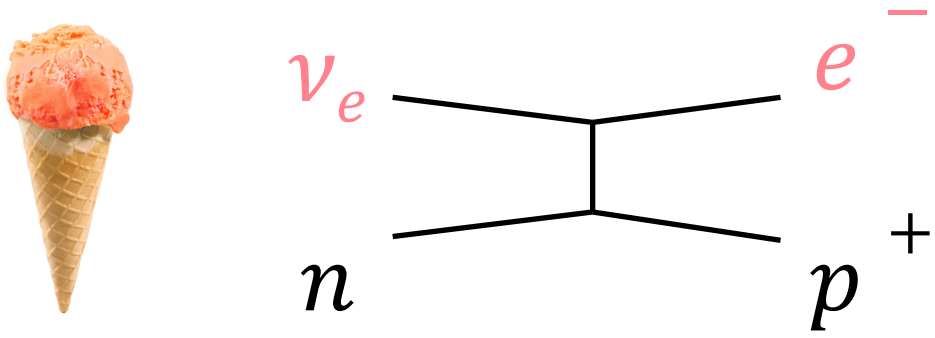


tau-neutrino

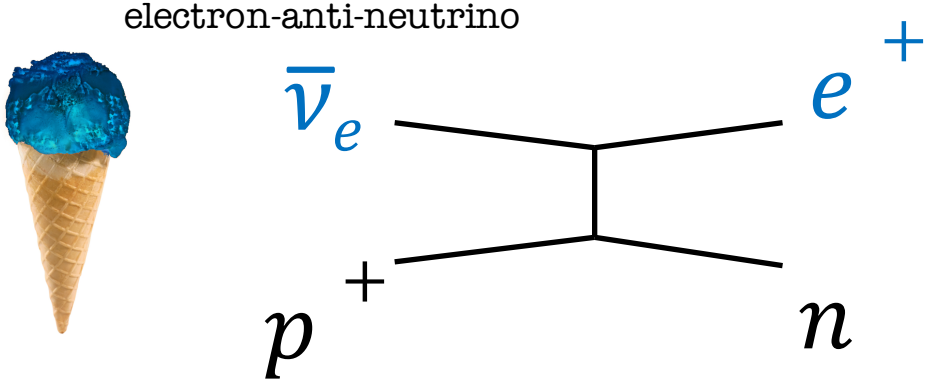


Same for anti-particles

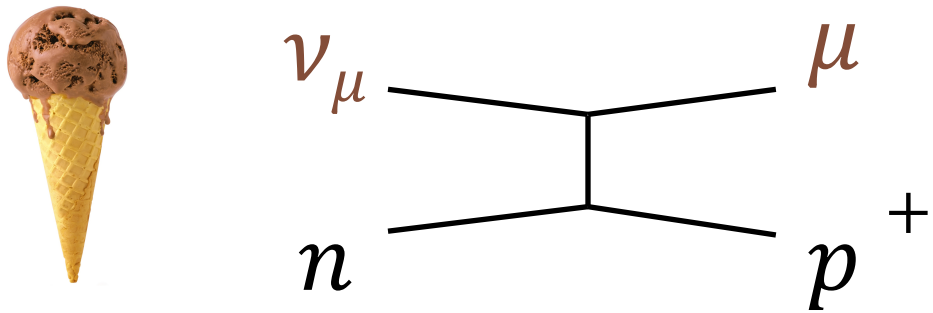
electron-neutrino



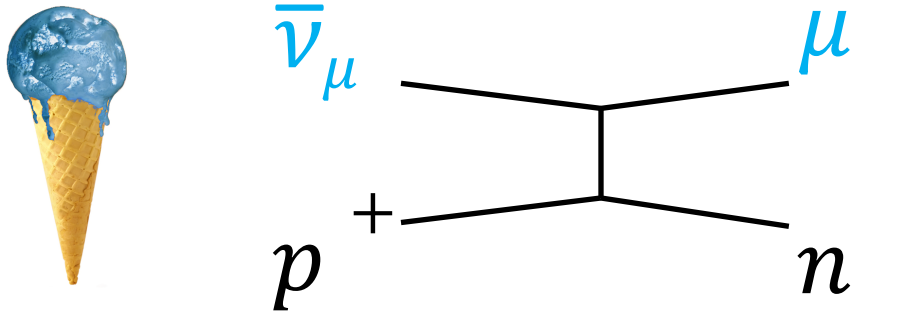
electron-anti-neutrino



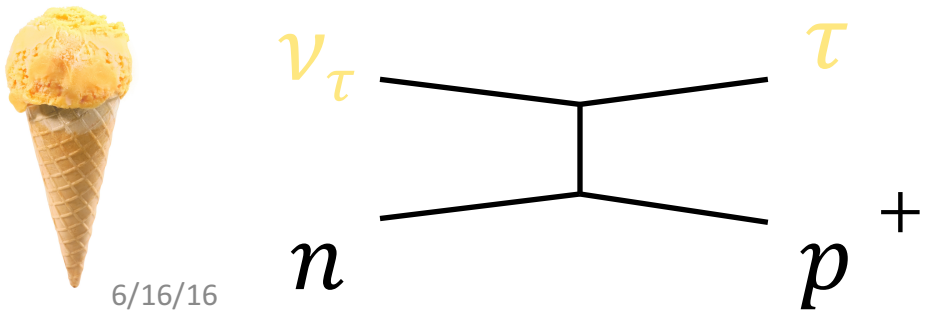
muon-neutrino



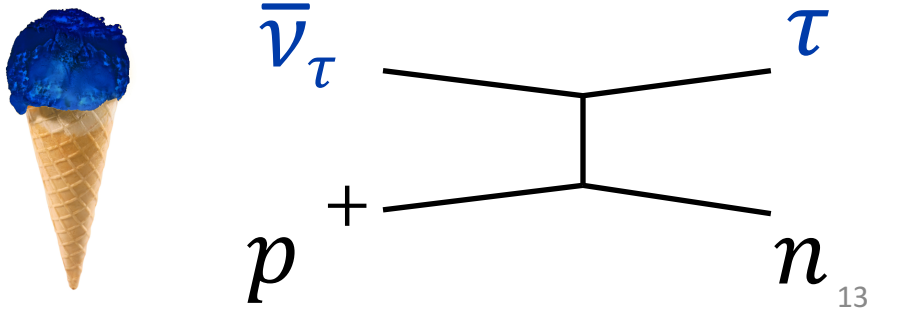
muon-anti-neutrino



tau-neutrino



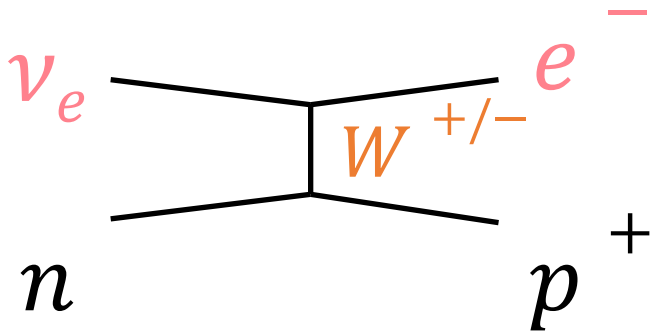
tau-anti-neutrino



charged-current versus neutral-current

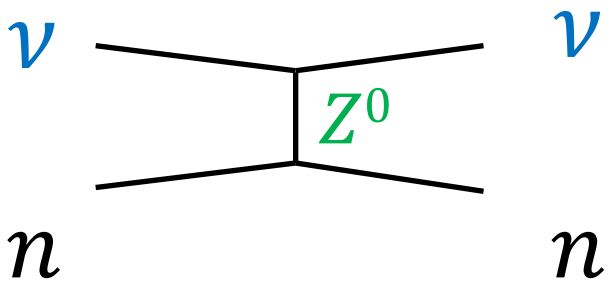
charged-current

electron-neutrino



$W^{+/-}$ = charged boson

neutral-current

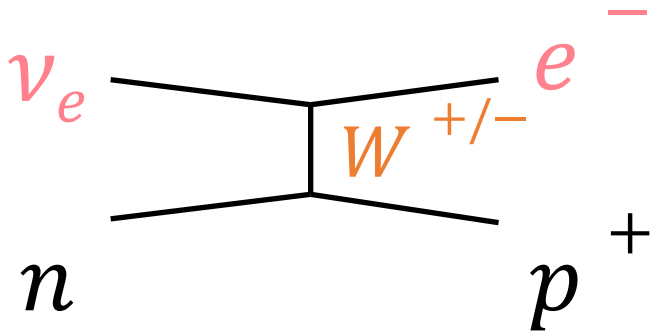


Z^0 = neutral boson

charged-current versus neutral-current

charged-current

electron-neutrino



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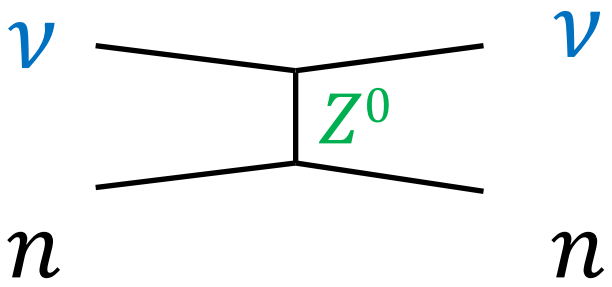
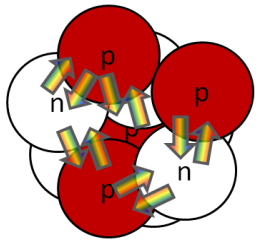
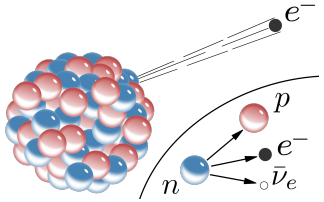
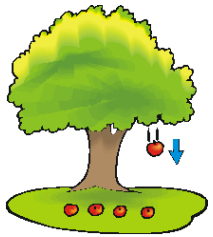


Z^0 = neutral boson

Oh no! We don't know what type of neutrino it was and we will never find out...

Neutrinos and forces

Do neutrinos interact via…

		Strength	Range	Force carrier
…strong force?		1	10^{-15} m (diameter of medium nucleus)	gluons g
…electro magnetism?		1/137	infinite	photon γ
…weak force?		10^{-6}	10^{-18} m (0.1% of proton diameter)	W&Z bosons
…gravity?		6×10^{-39}	infinite	?

Neutrinos and forces

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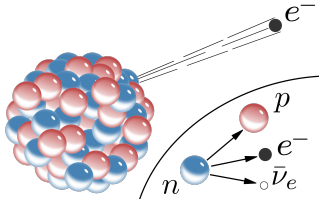
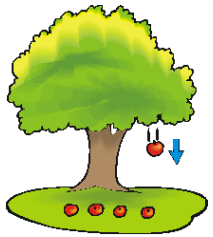
…weak force?		10^{-6}	10^{-18} m (0.1% of proton diameter)	W&Z bosons
…gravity?		6×10^{-39}	infinite	?

Neutrinos and forces

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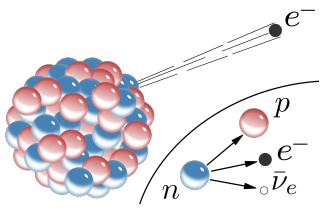
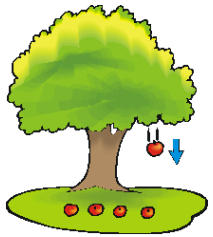
…weak force!		10^{-6}	10^{-18} m (0.1% of proton diameter)	W&Z bosons
…gravity?		6×10^{-39}	infinite	?

Neutrinos and forces

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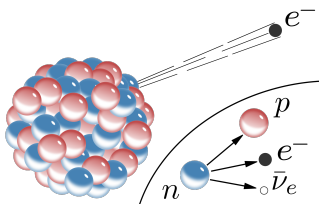
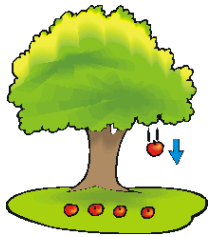
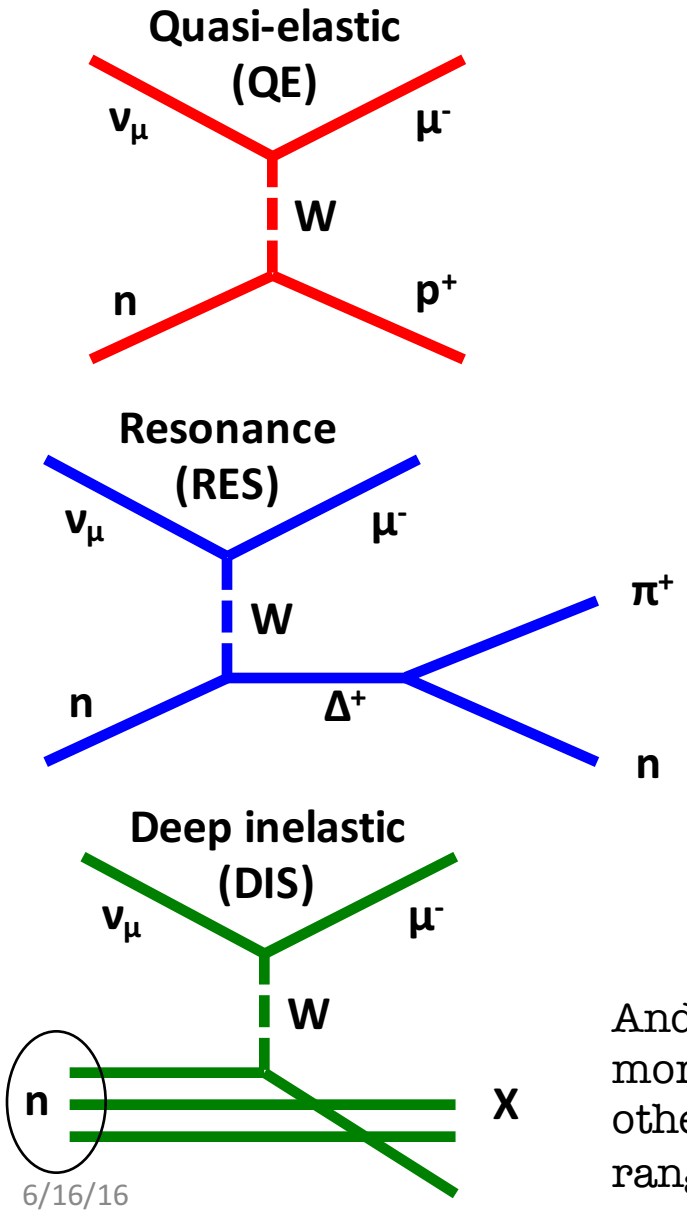
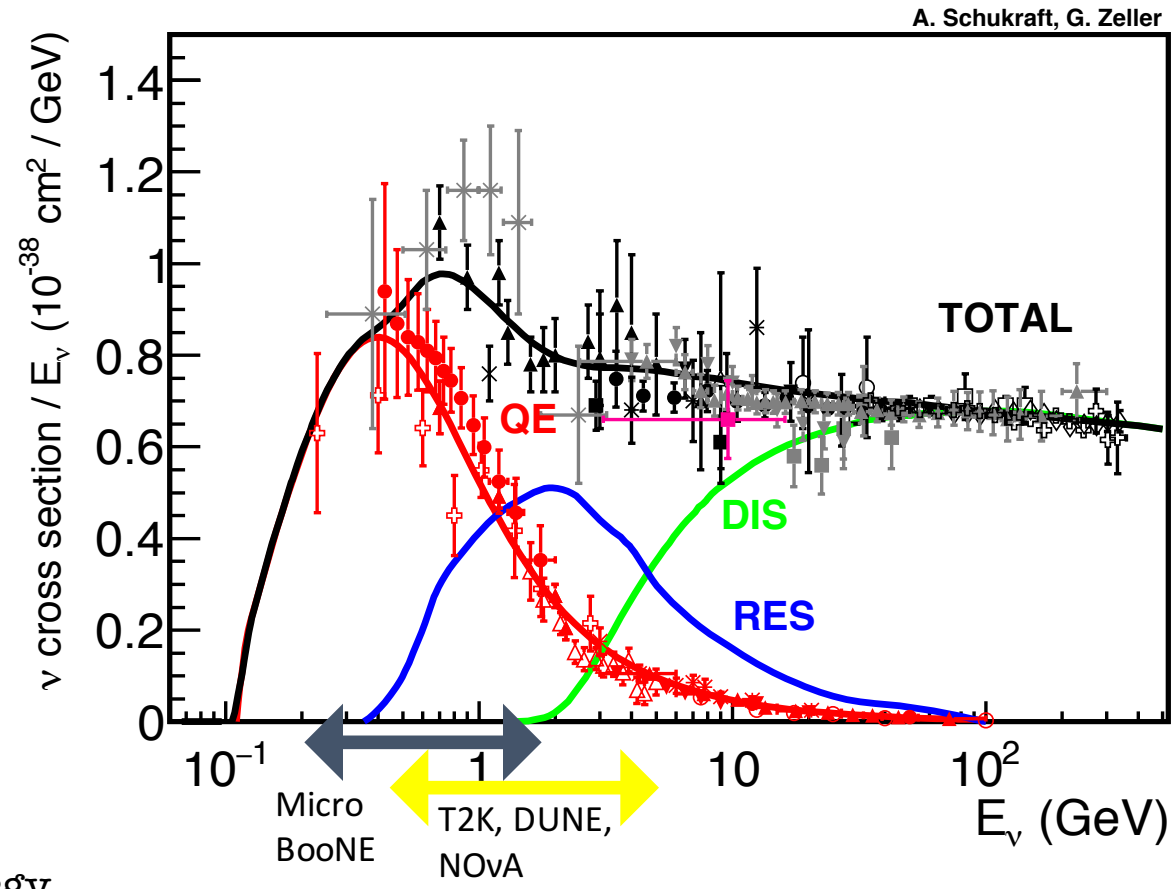
		Strength	Range	Force carrier
...weak force!		10^{-6}	10^{-18} m (0.1% of proton diameter)	W&Z bosons
...gravity!		6×10^{-39}	infinite	?

Neutrino cross sections



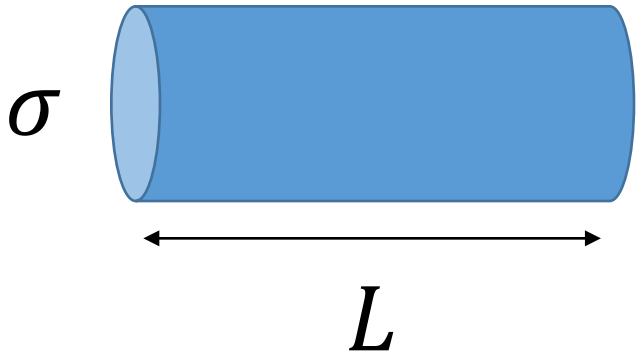
From Wikipedia:

The **cross section** is an effective area that quantifies the intrinsic likelihood of a scattering event when an incident beam strikes a target object, made of discrete particles. The cross section of a particle is the same as the cross section of a hard object, if the probabilities of hitting them with a ray are the same. It is typically denoted σ and measured in units of area.



And some more for other energy ranges...

How far does a neutrino travel?



"mean free path"

Volume swept out: $$V_s = \sigma \times L$$

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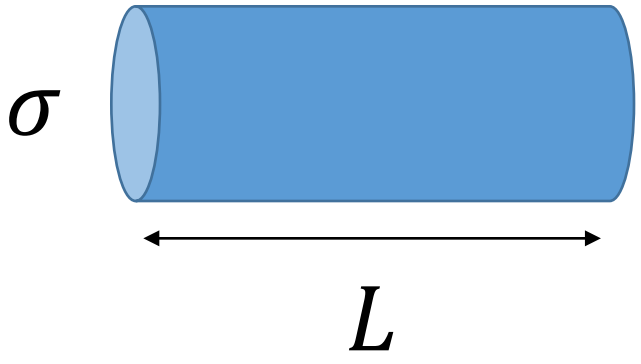

"mean free path"

Volume swept out: $V_s = \sigma \times L$

Volume per nucleon: $V_N = m_p / \rho$

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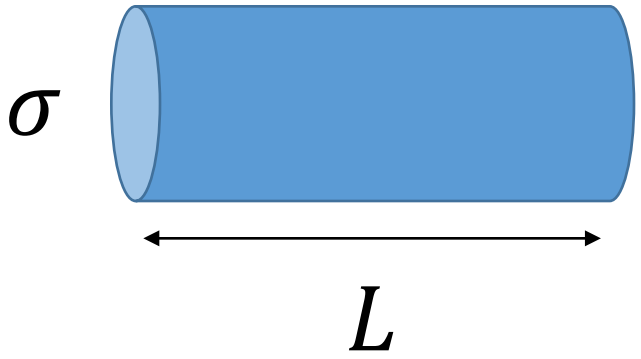

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$$V_s = VN \rightarrow L = mp / (\rho \times \sigma)$$

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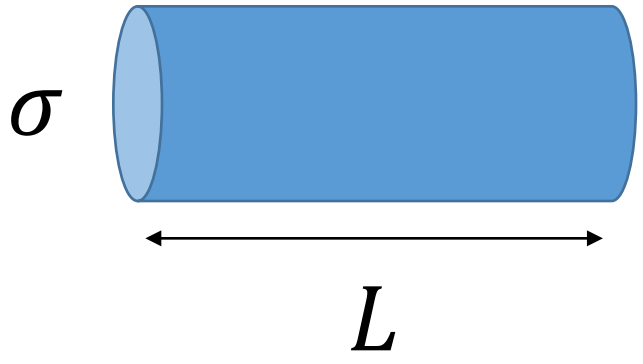


"mean free path"

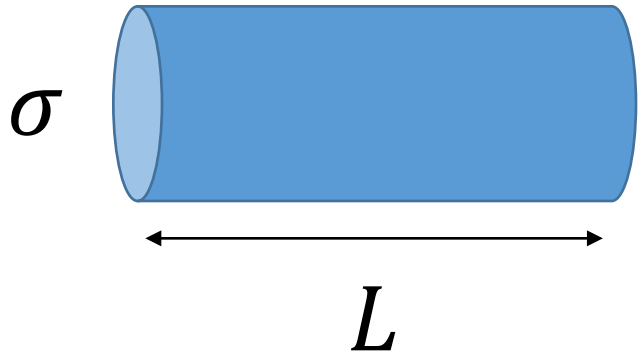
Volume swept out: $V_s = \sigma \times L$

Volume per nucleon: $V_N = m_p / \rho$

$$V_s = VN \rightarrow L = mp / (\rho \times \sigma)$$

$m_p = 1.67 \text{ x } 10^{-24}\, g$
$\rho = 2.7 \frac{g}{cm^3}$ (for rock)
$\sigma = 10^{-38}\, cm^2$ (@ 1GeV)

How far does a neutrino travel?



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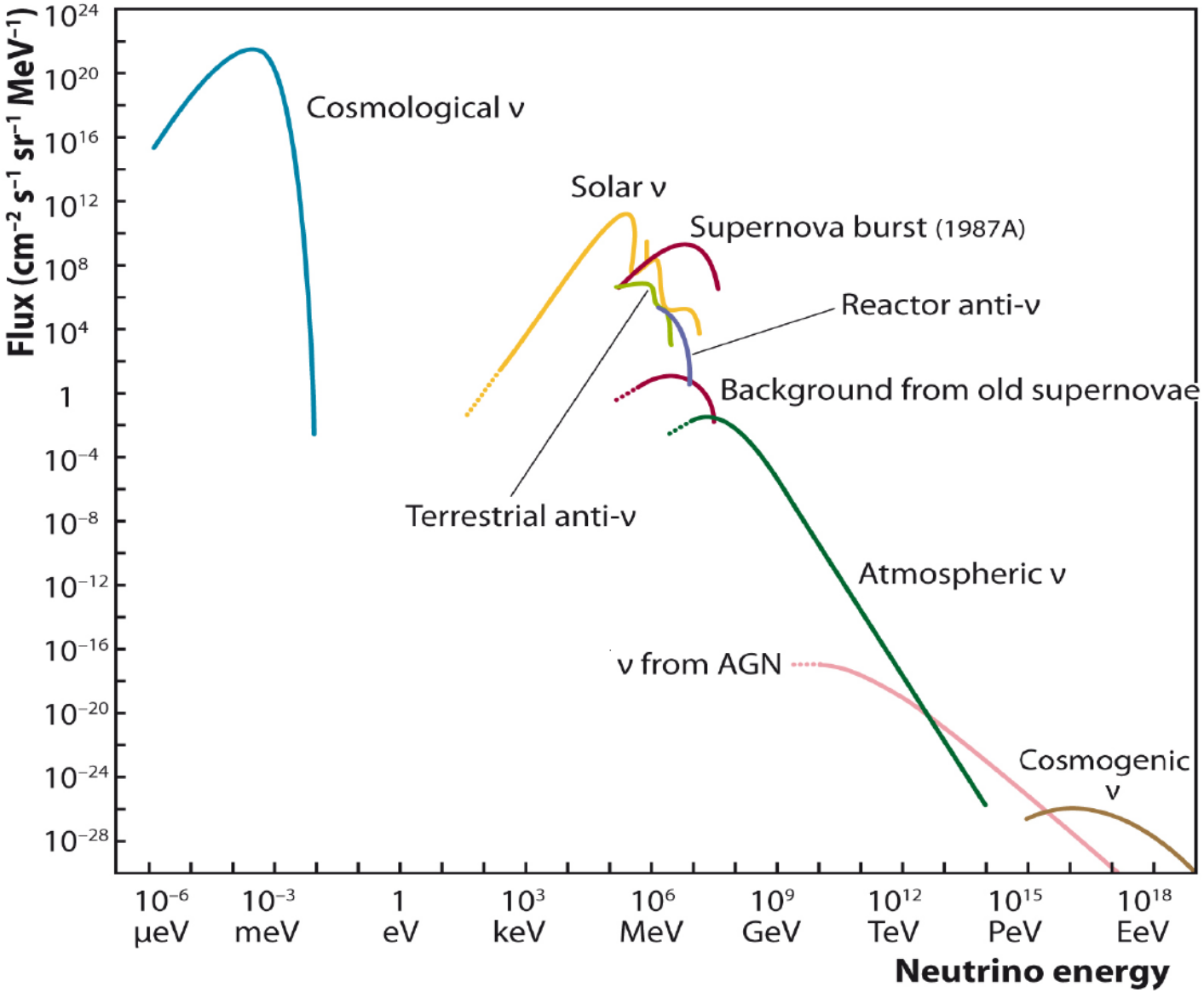
$\rho = 2.7 \frac{g}{cm^3}$ (for rock)
$\sigma = 10^{-38}\, cm^2$ (@ 1GeV)

$$L = 6 \text{ x } 10^8 \text{ km}$$

(Diameter of the Earth: ~ 13 000 km)

Where are neutrinos coming from?

Flux: neutrinos per surface area, time, solid angle and energy



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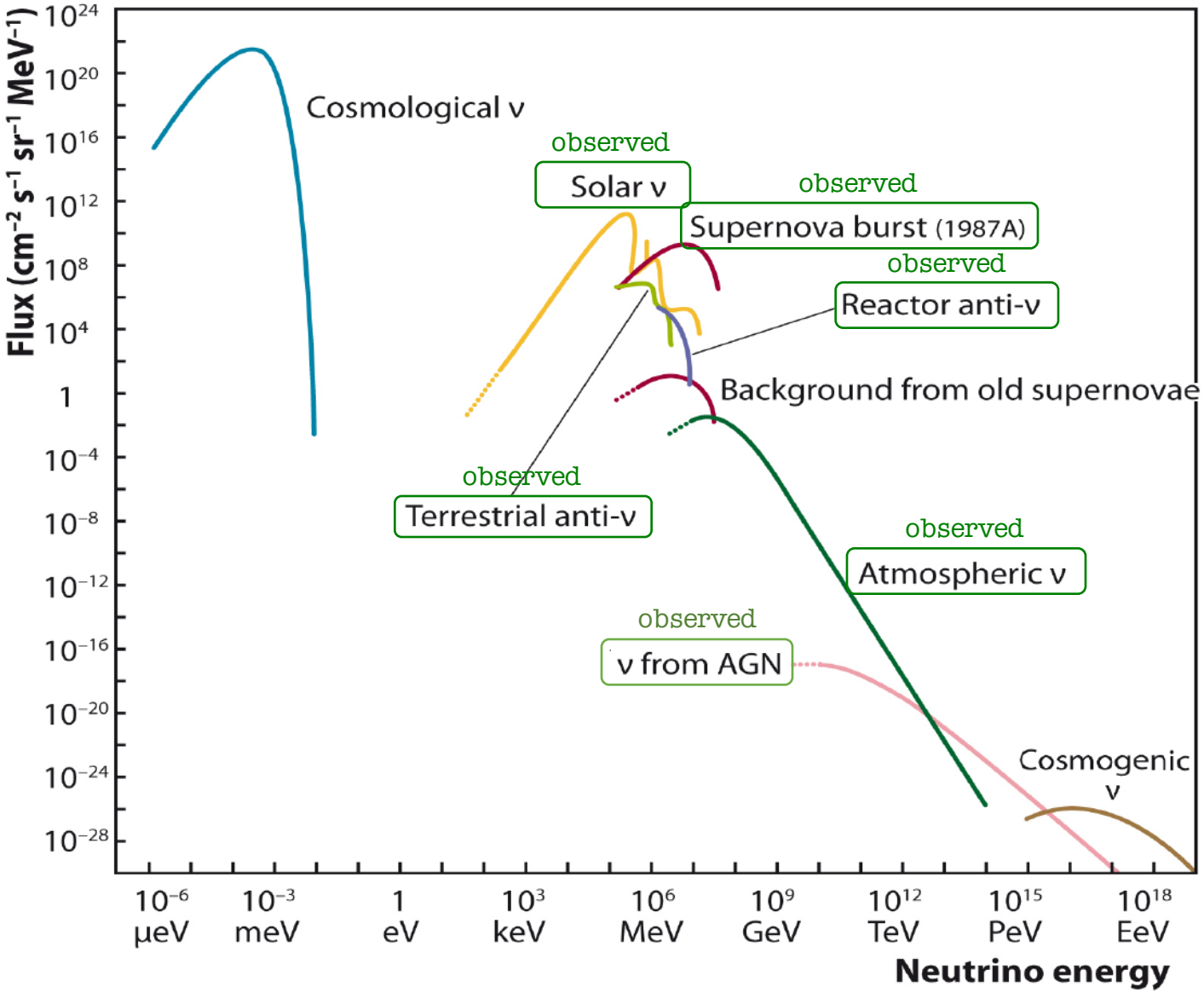

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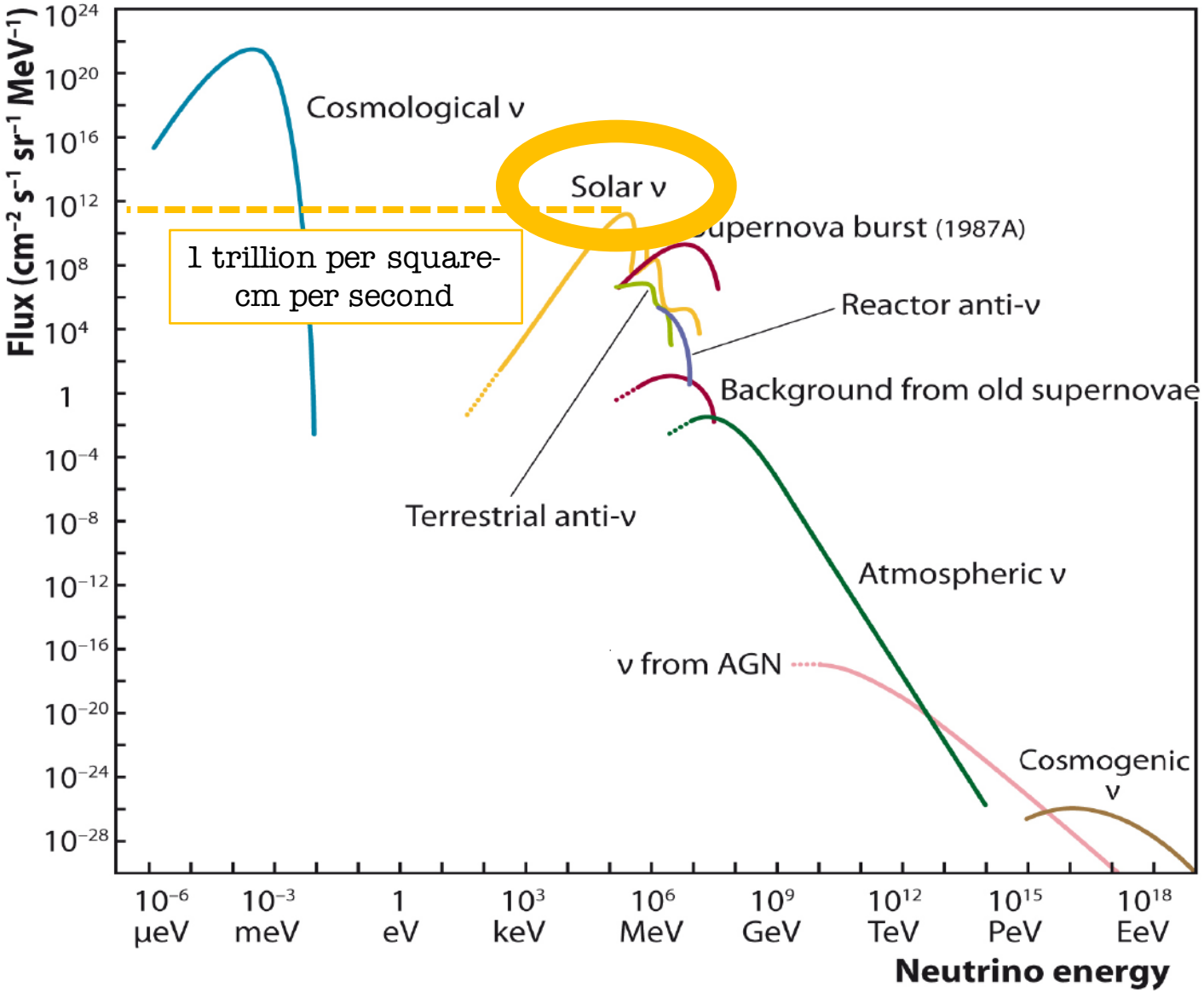
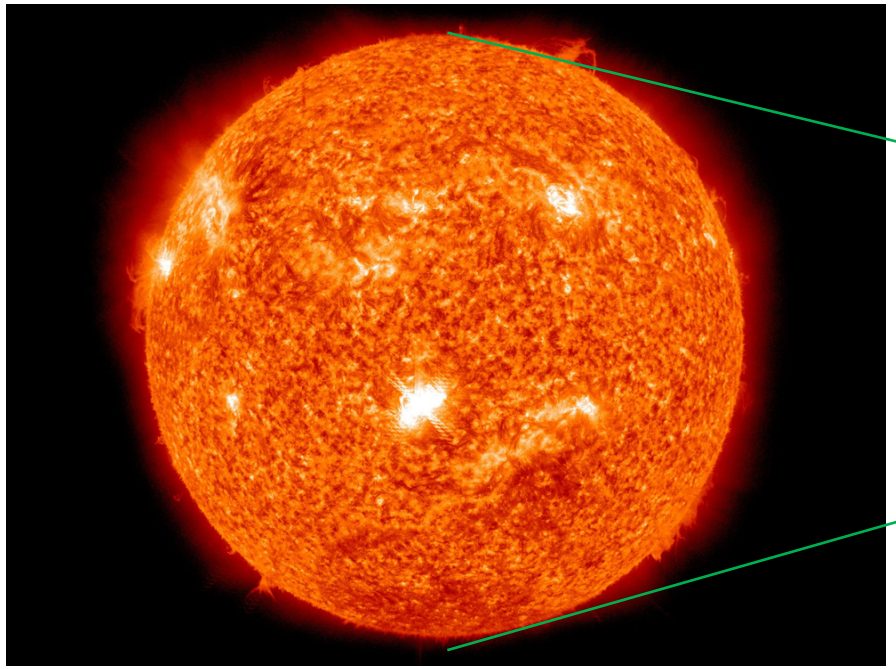
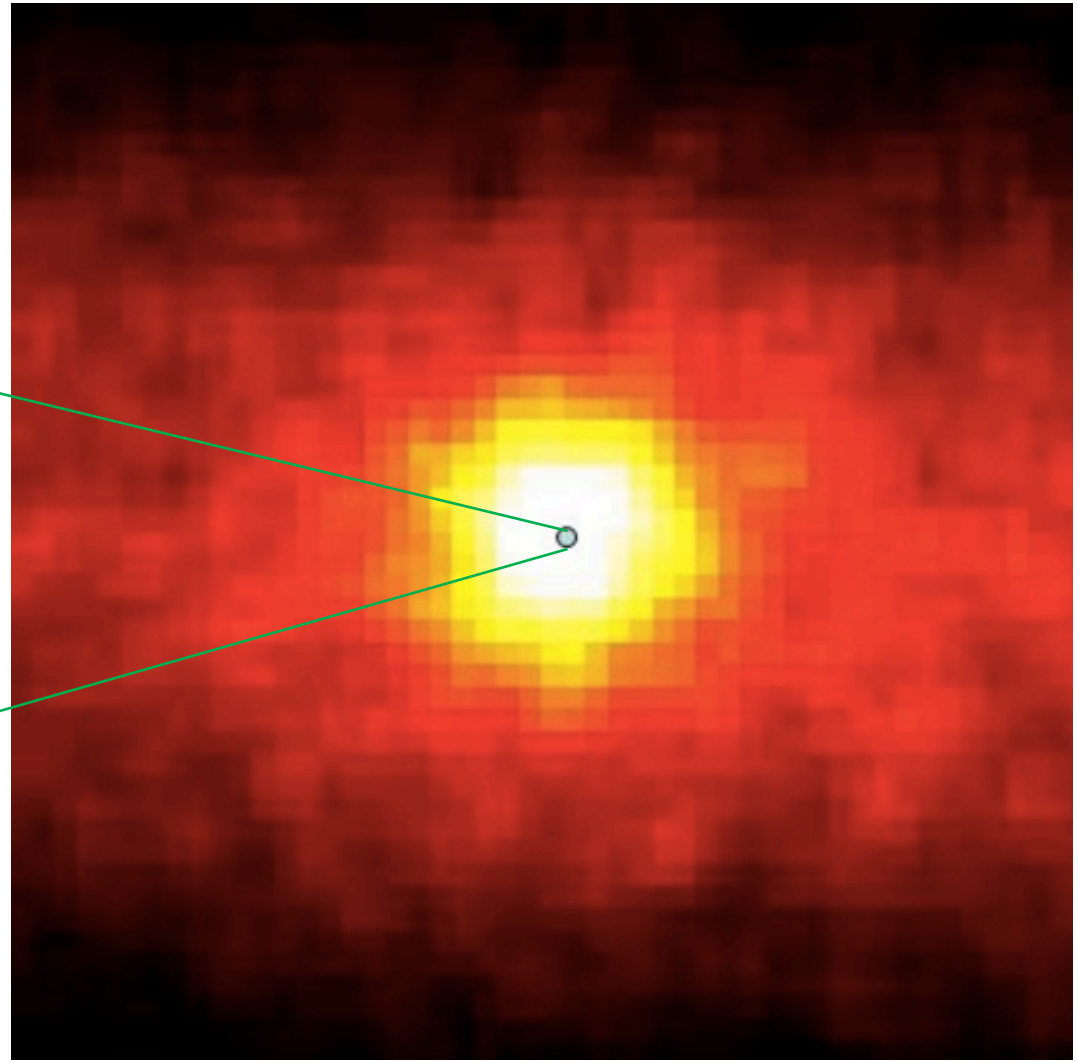


Solar neutrinos

Our sun produces
electron neutrinos in nuclear fusion

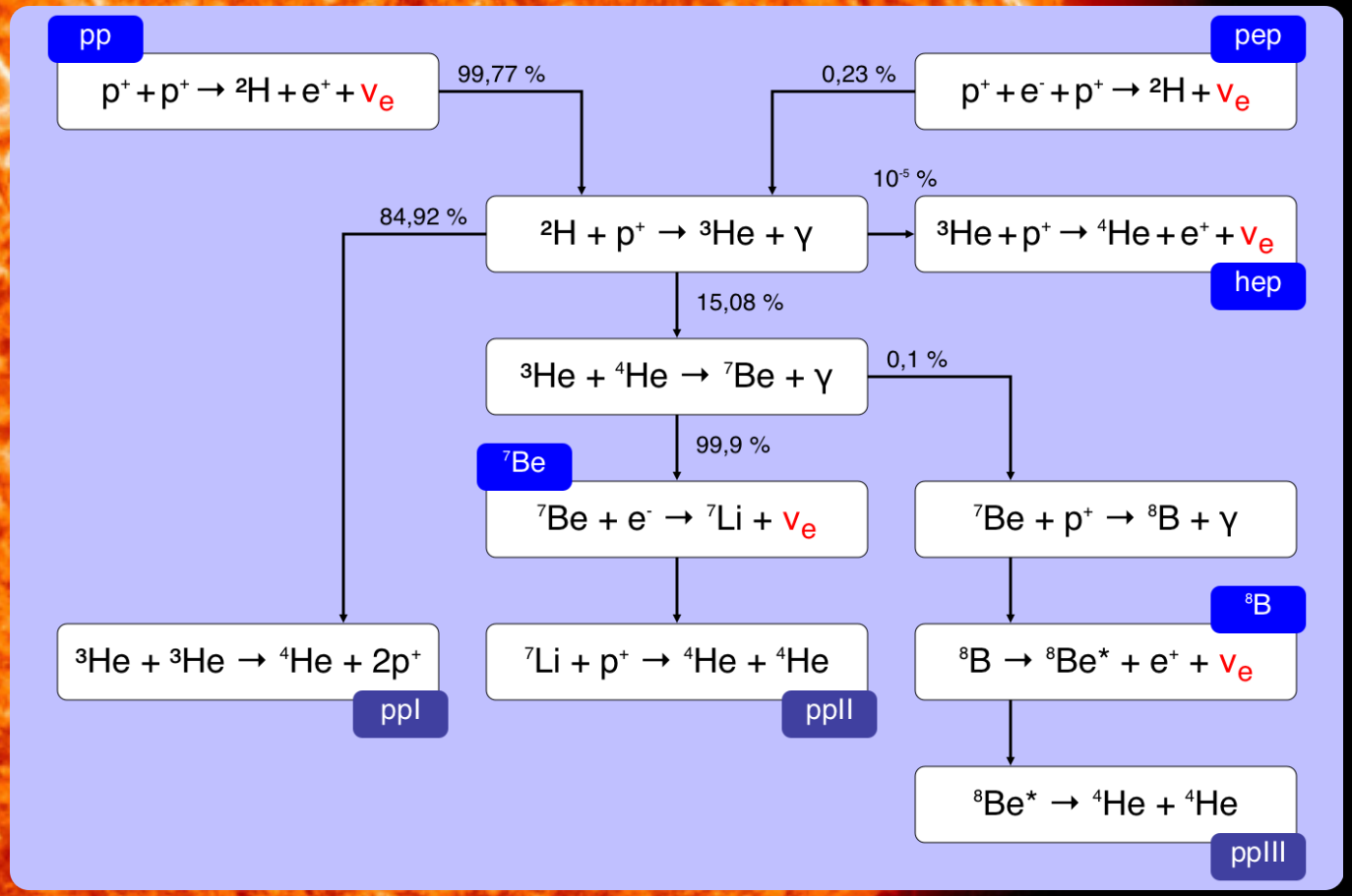


The sun in neutrinos



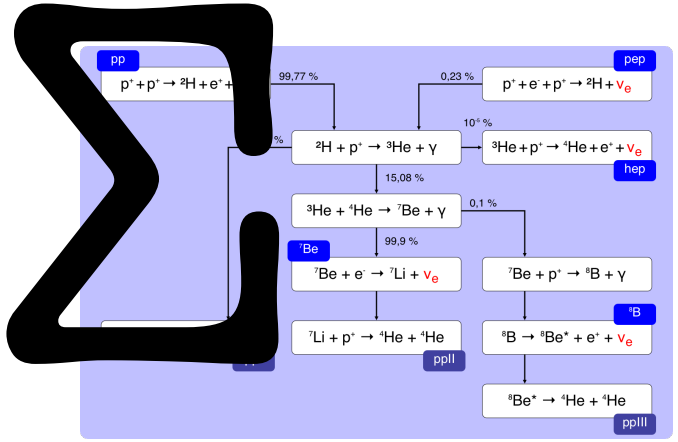
Solar neutrinos

All these are electron neutrinos!



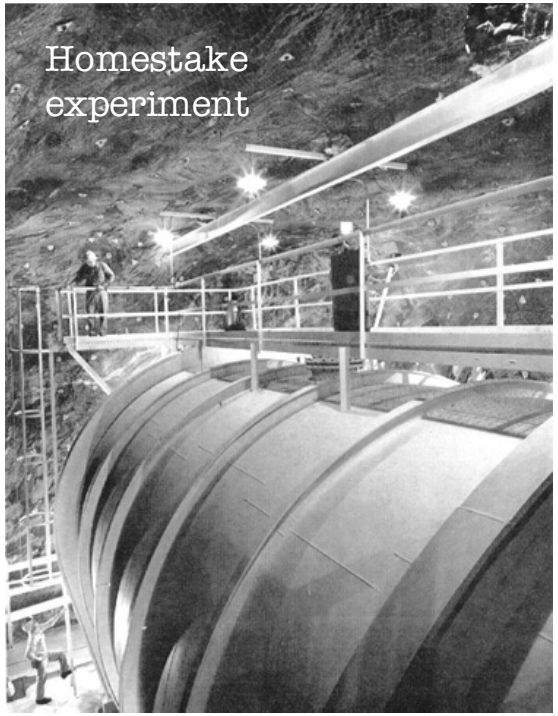
The solar neutrino problem (late 1960's)

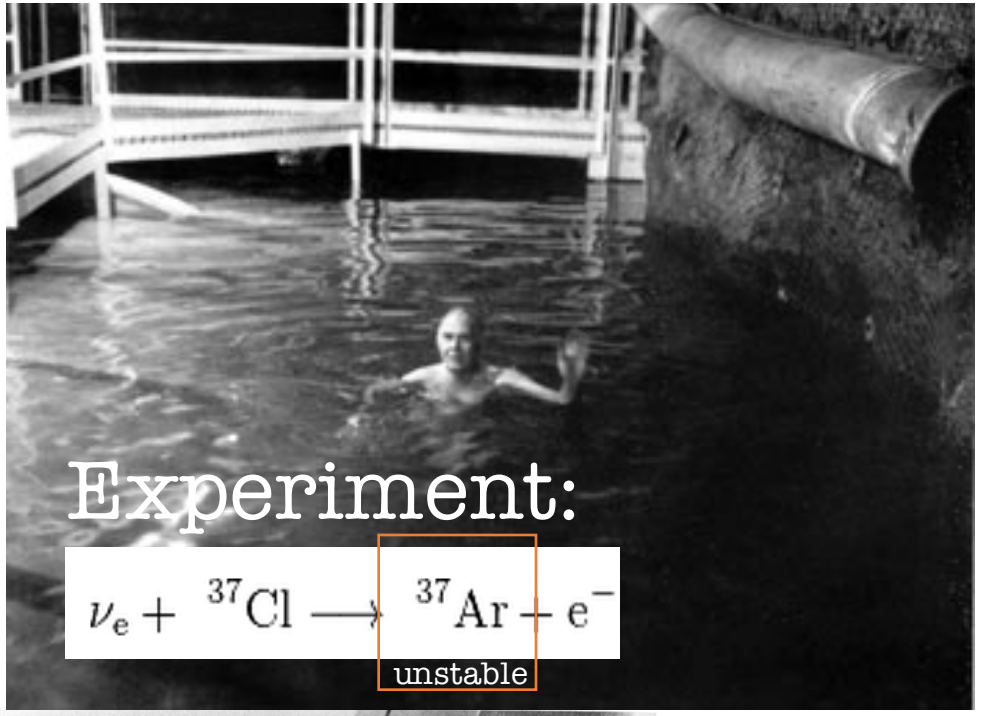
Theory:



$$= \Phi_{\nu,\mathrm{solar}}$$

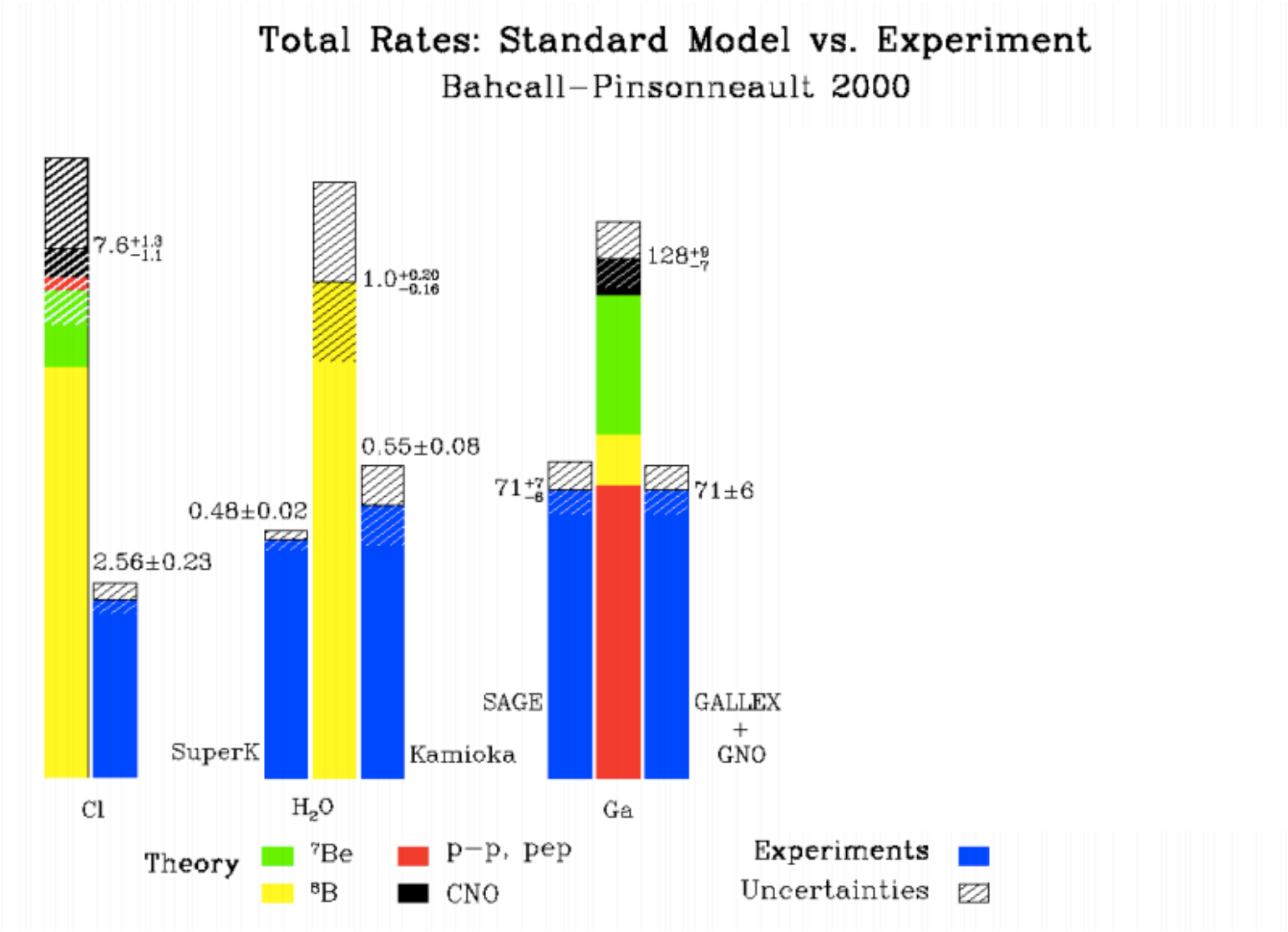
Flux: neutrinos per time and surface area



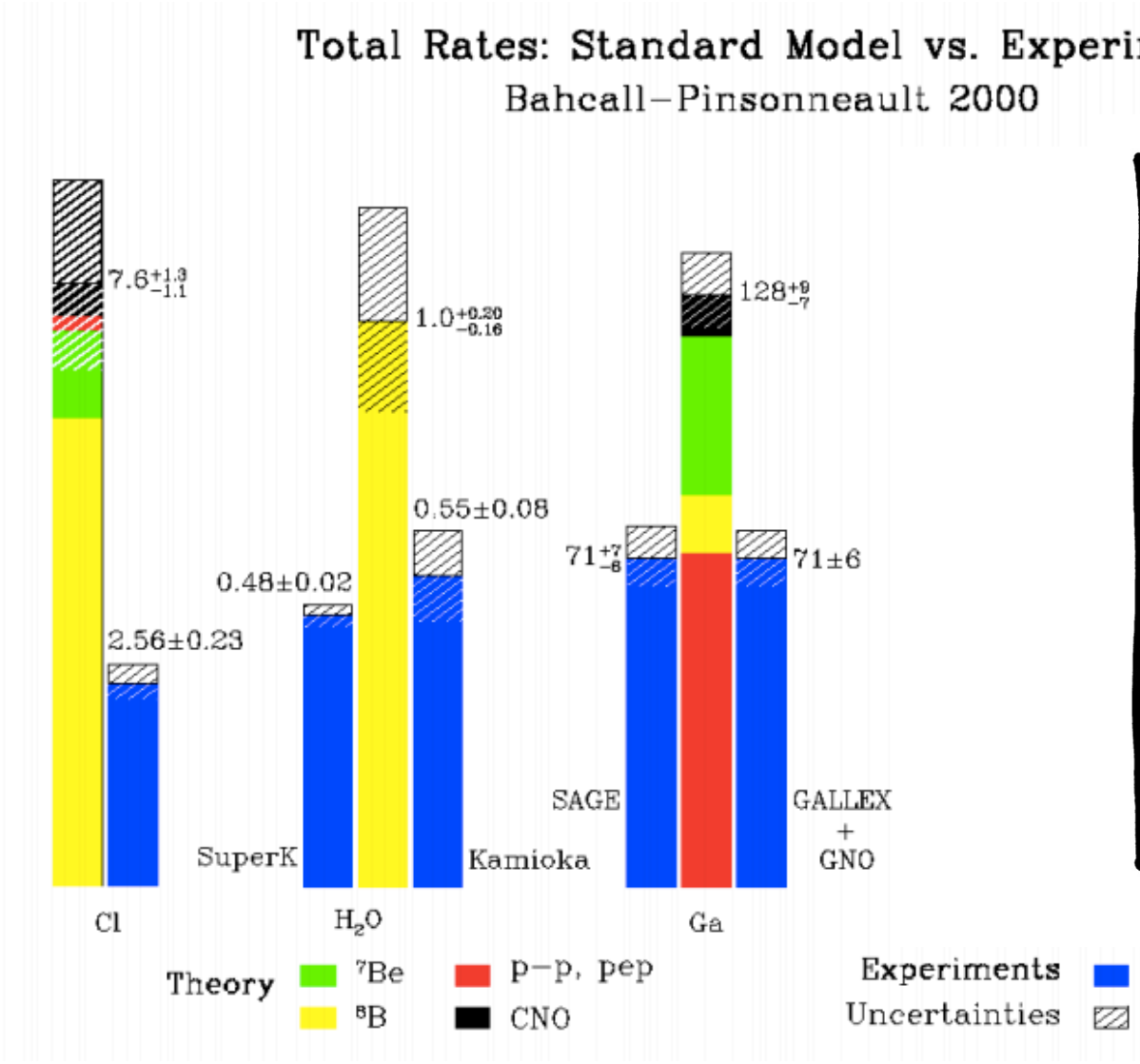


Observed:
1/3 $\Phi_{\nu,\mathrm{solar}}$

The solar neutrino problem



The solar neutrino problem

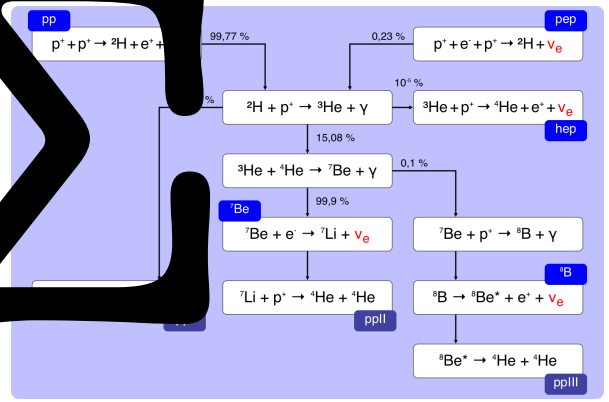


The Infamous "Neutrino-burglar"

The solar neutrino problem (late 1960's)

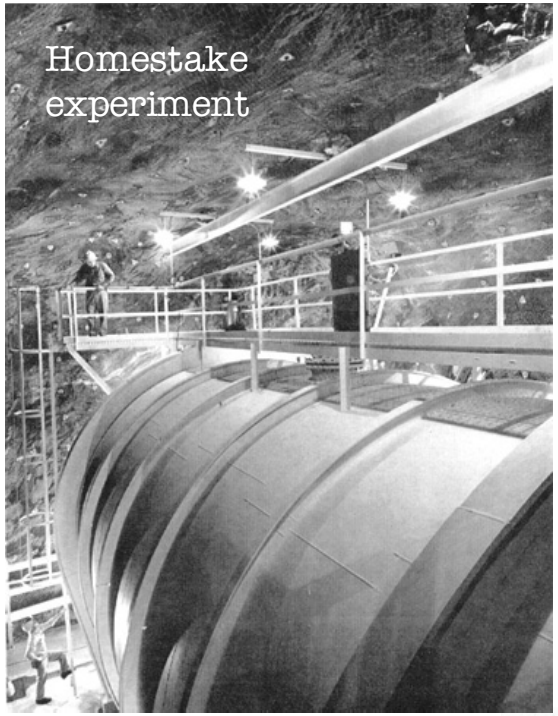
Theory:

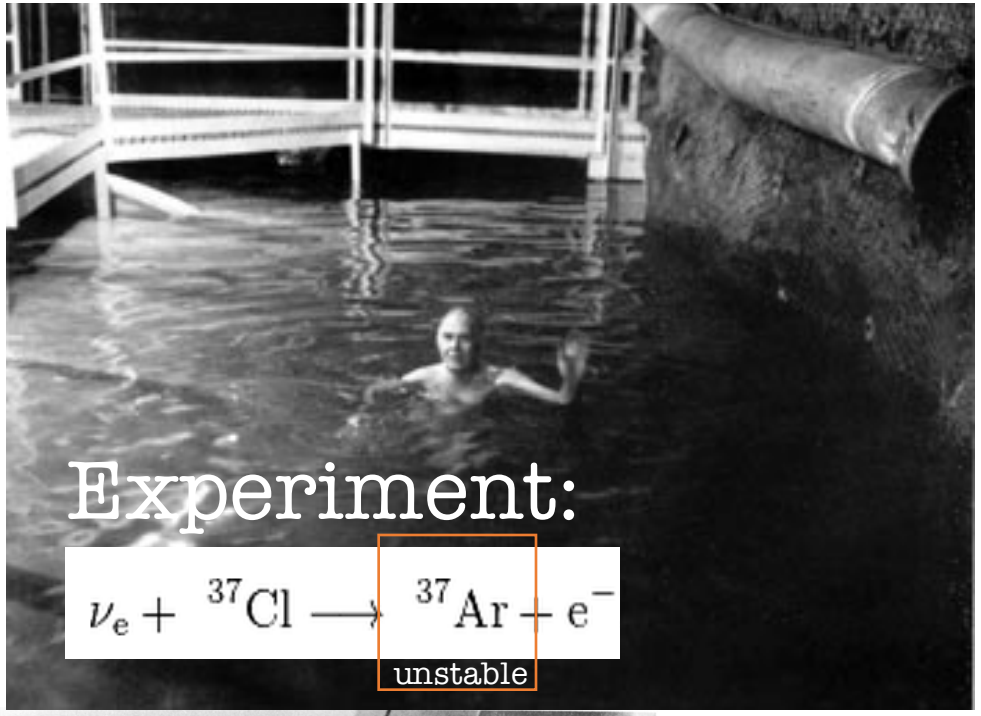
$\sum$



$$= \Phi_{\nu,\mathrm{solar}}$$

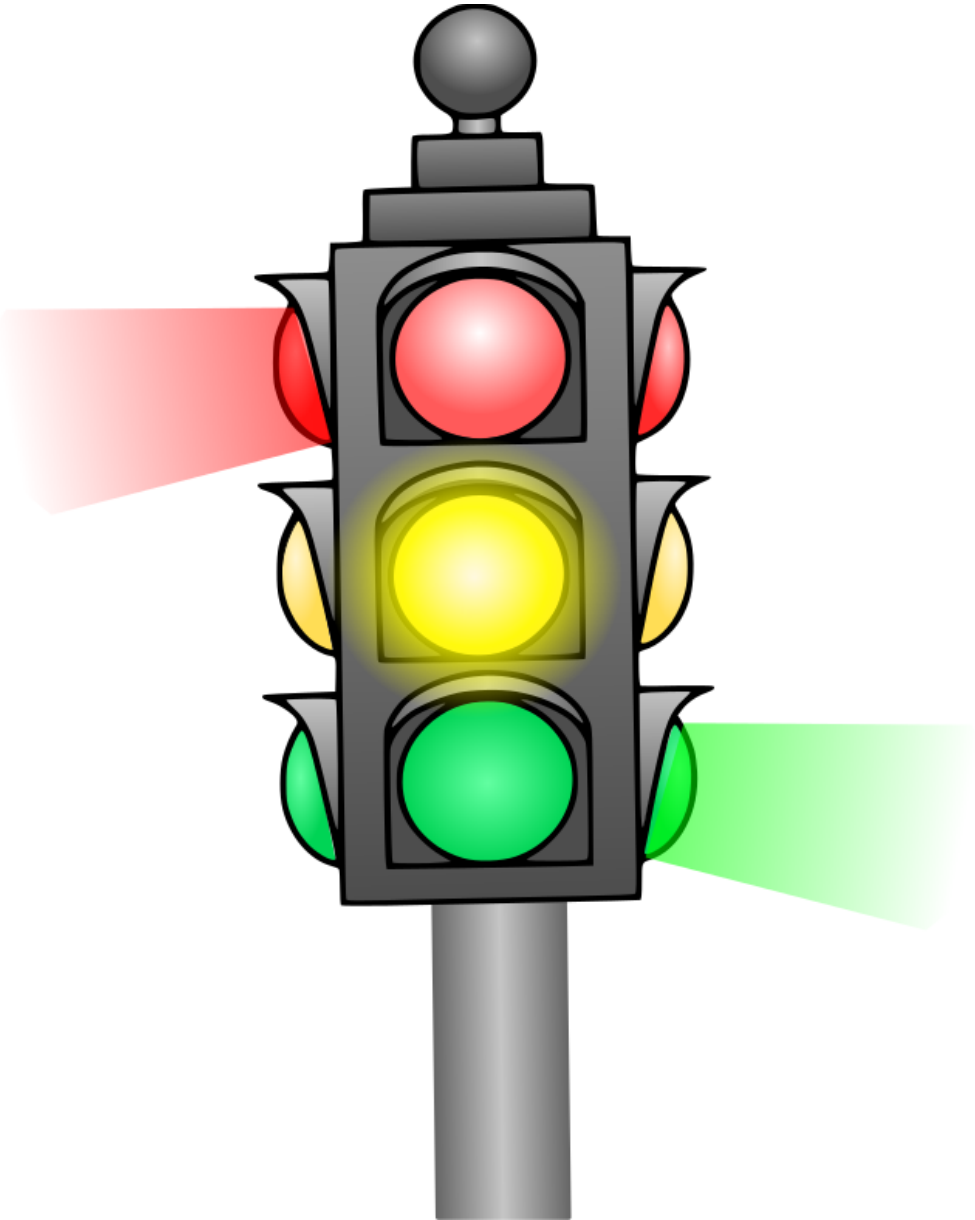
Flux: neutrinos per time and surface area





Neutrino oscillations

Neutrino oscillations



Neutrino oscillations

Neutrino oscillations

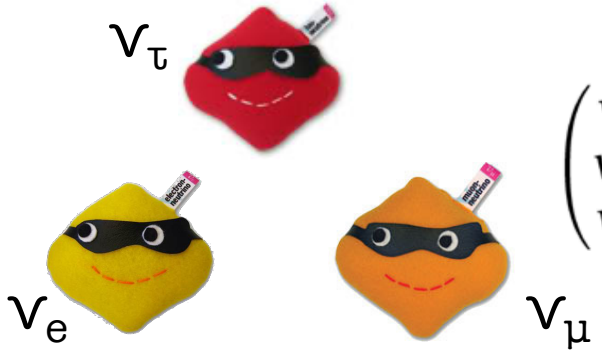
Let's introduce some math

The sun is emitting electron neutrinos...

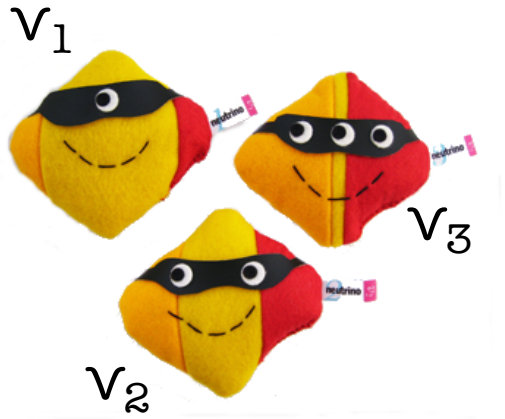
... on the way, these might change into muon neutrinos...

... and eventually change back

Flavor eigenstates $\neq$ Mass eigenstates



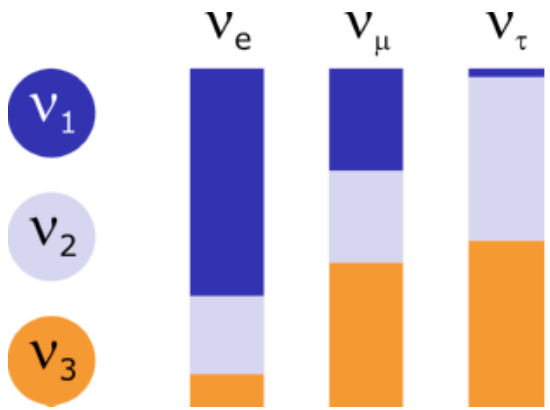
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

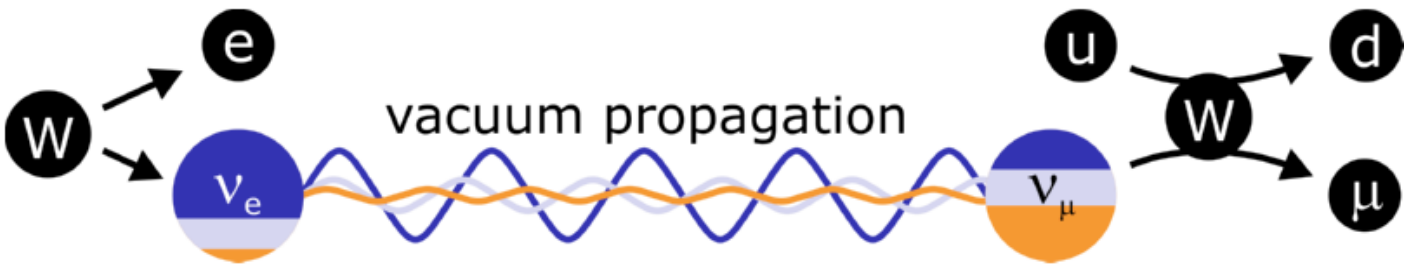


When neutrinos interact, we see the flavor eigenstate

But they travel (wave function) as a mass eigenstate

Neutrino mixing





Neutrino oscillations

This is not difficult!
Wikipedia can help you get through it!
You should try!

Propagation of mass eigenstates ν_i is described by the plane wave equation:

$$|\nu_i(t)\rangle = e^{-i(E_i t - \vec{p}_i \cdot \vec{x})}|\nu_i(0)\rangle$$

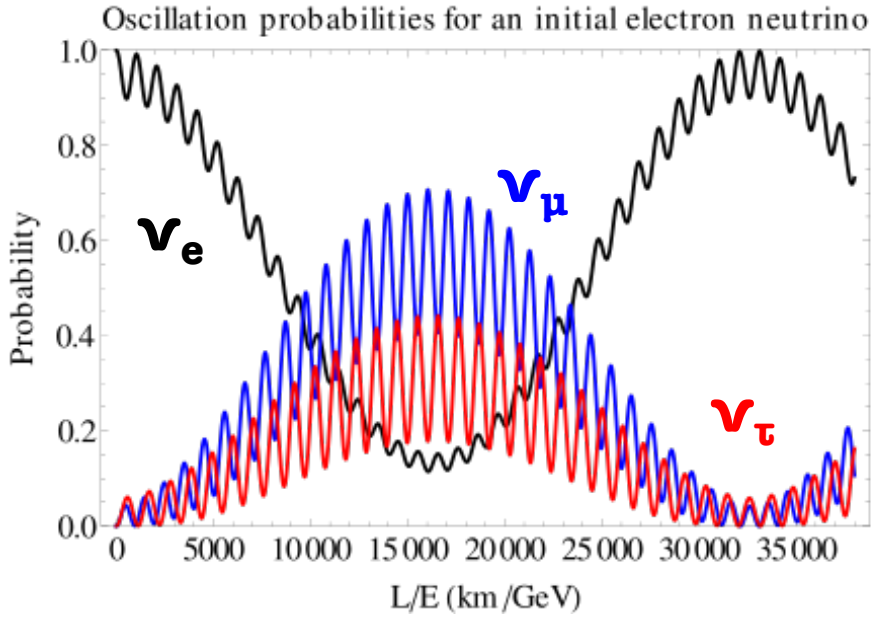
Or as a function of travel distance L:

$$|\nu_i(L)\rangle = e^{-im_i^2 L/2E}|\nu_i(0)\rangle$$

Probability of:
Sending flavor α,
and detecting flavor β

$$P_{\alpha\to\beta} = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

Function of:
- Mass m_i
- Energy E
- Distance L



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Function of:
- Mass m_i
- Energy E
- Distance L

"Two–flavor approximation"

(assume there are only 2 flavors -> makes the matrix 2x2)

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

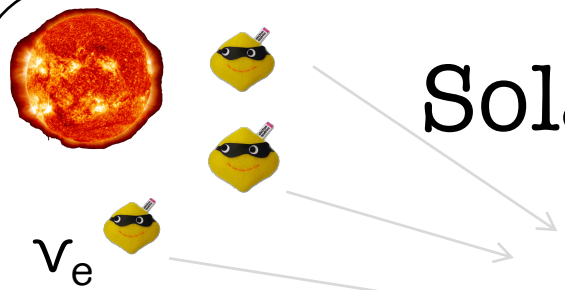
Oscillation is a function of

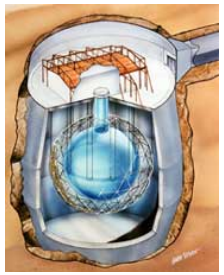
$$\frac{L}{E} = \frac{\text{baseline}}{\text{energy}}$$

Characteristic parameters:
- Mass difference: $\Delta m^2 = m_i^2 - m_j^2$
- Mixing angle: θ_{ij}

4 approaches to measure neutrino oscillations

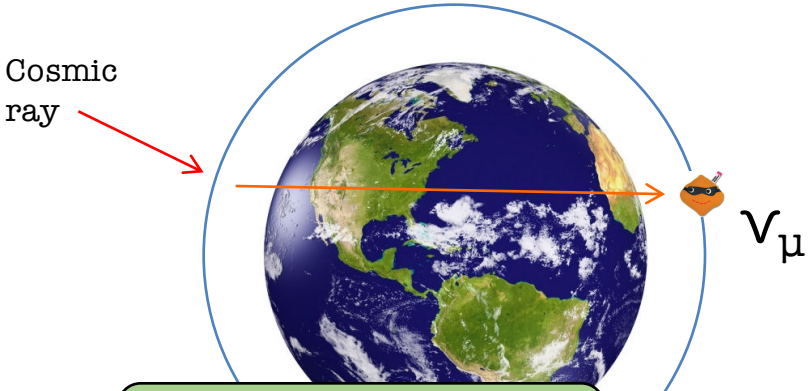
Solar





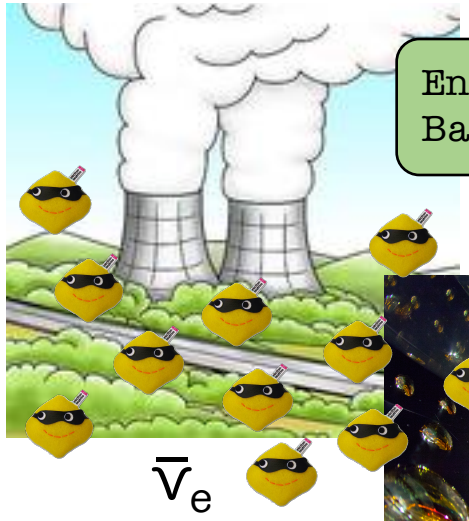
Energy: MeV
Baseline: (oscillation inside sun)

Atmospheric

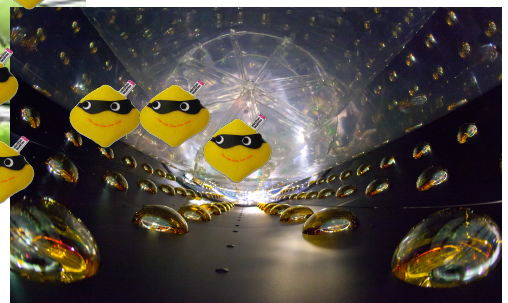


Energy: GeV - TeV
Baseline: ~ 13 000 km

Reactor

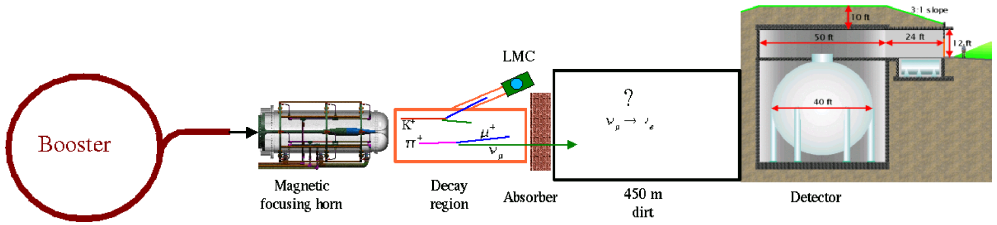


Energy: MeV
Baseline: 10 m – 100 km

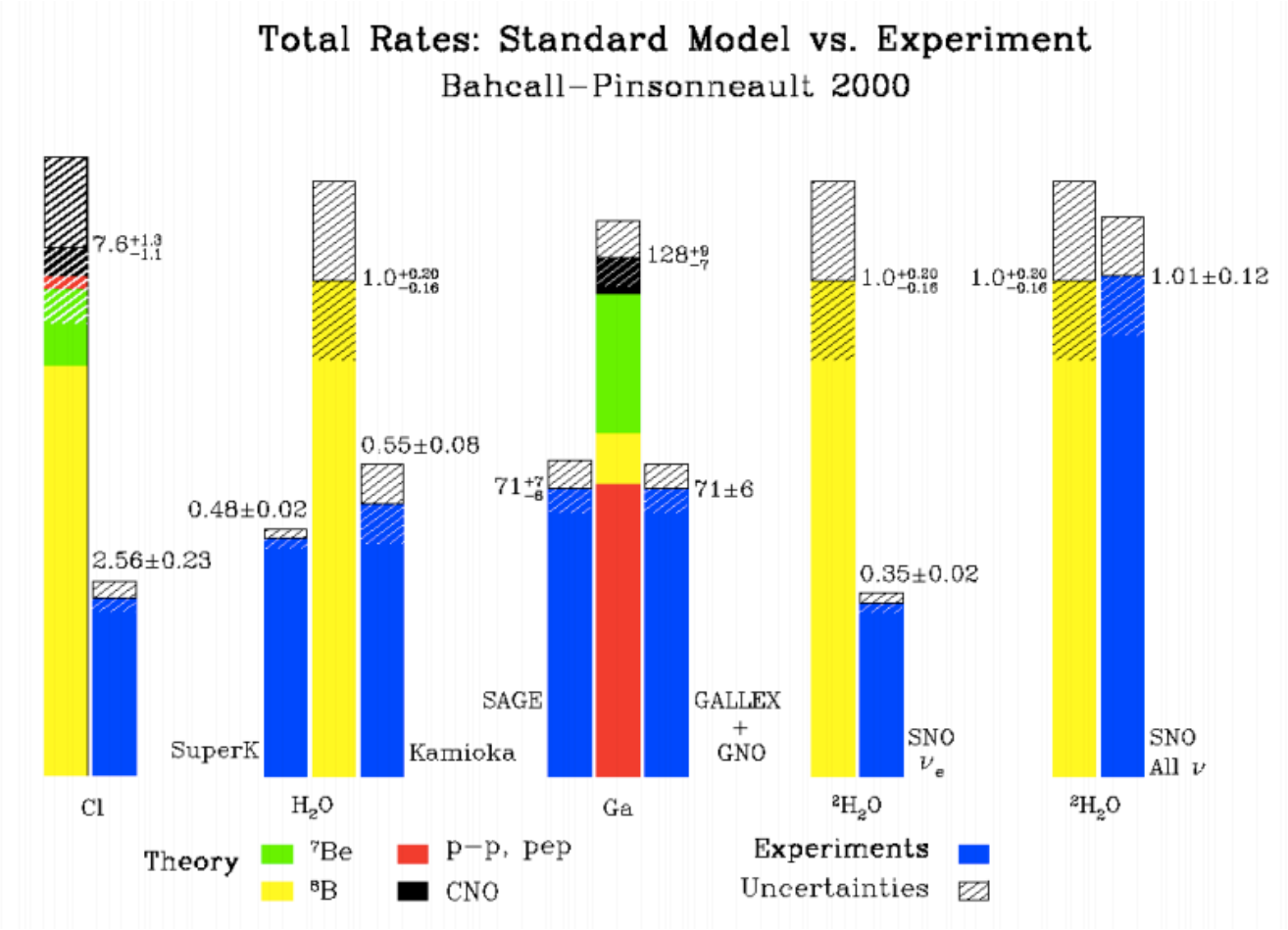


Accelerator

Energy: GeV
Baseline: 30 m – 1500 km

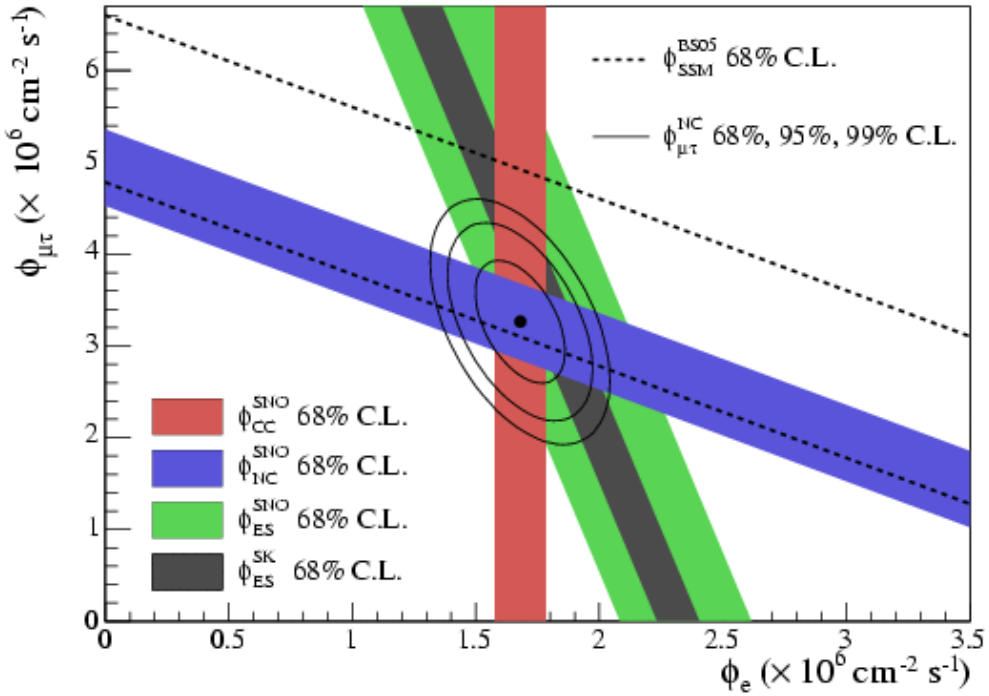


Neutrino oscillations in SNO

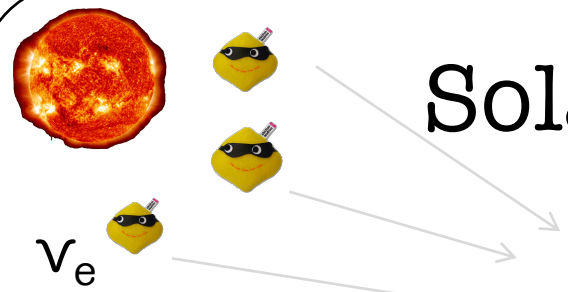


CC Charged Current Reaction	$\upsilon_e + d \rightarrow p + p + e^-$	$E_{threshold} = 1.4MeV$
NC Neutral Current Reaction	$\upsilon_x + d \rightarrow \upsilon_x + p + n$	$E_{threshold} = 2.2MeV$
ES Elastic Scattering Reaction	$\upsilon_x + e^- \rightarrow \upsilon_x + e^-$	$E_{threshold} \approx 0$

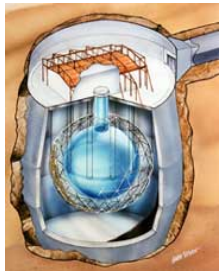
x denotes that this reaction will take place with any neutrino.



Confirmation with solar and atmospheric neutrinos

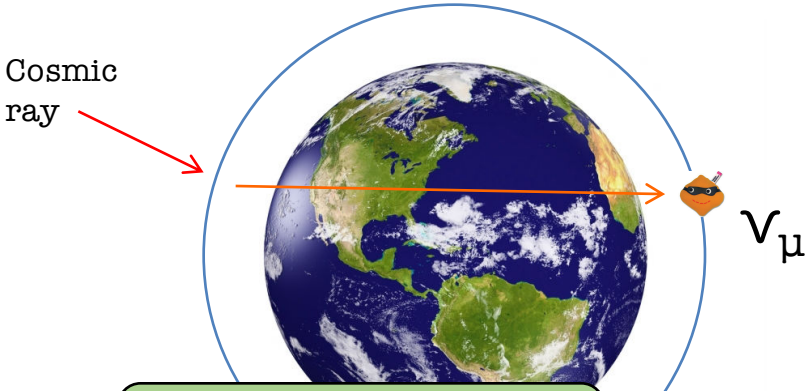


Solar

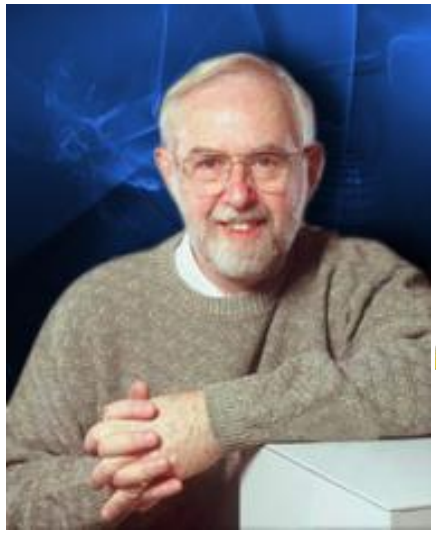


Energy: MeV
Baseline: (oscillation inside sun)

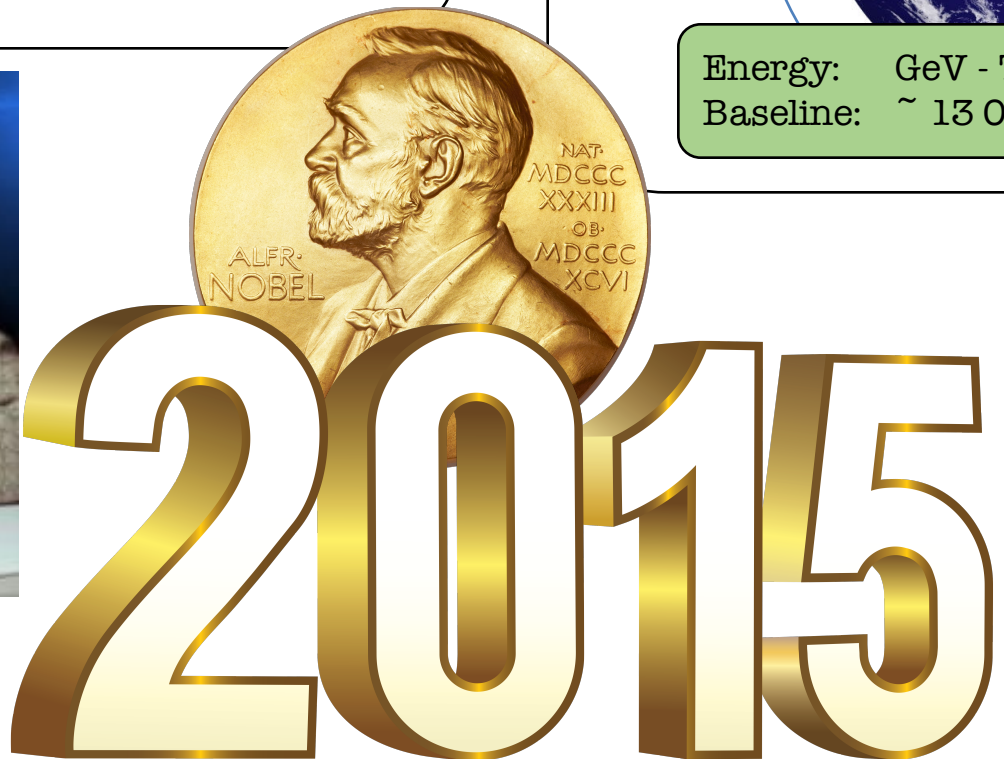
Atmospheric



Energy: GeV - TeV
Baseline: ~ 13 000 km

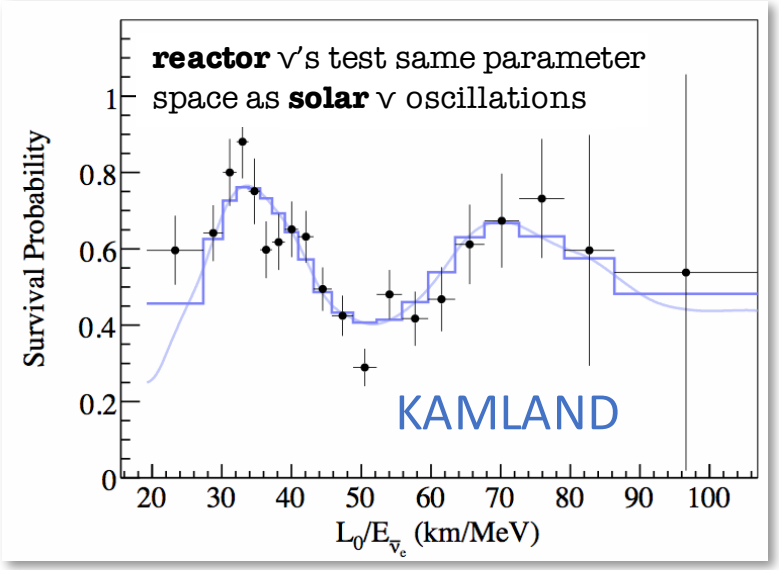


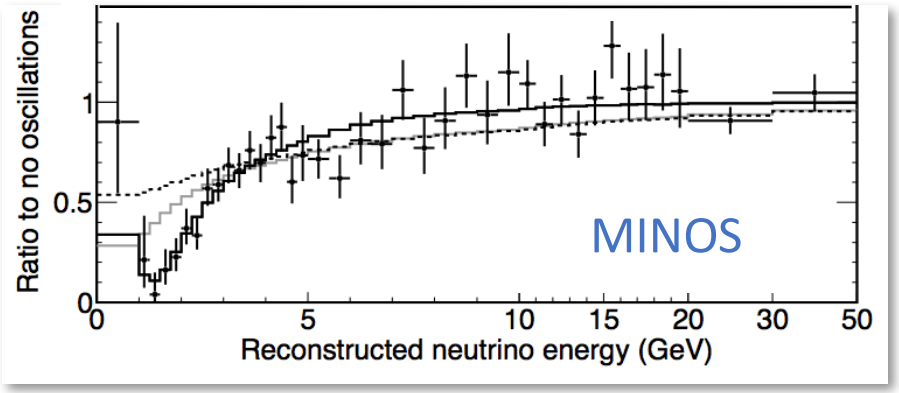
Sir Arthur McDonald



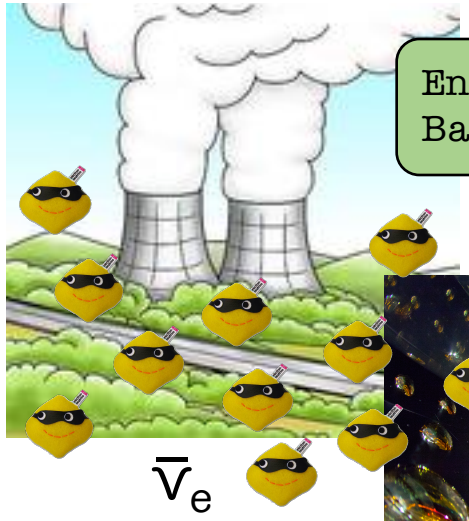
Takaaki Kajita

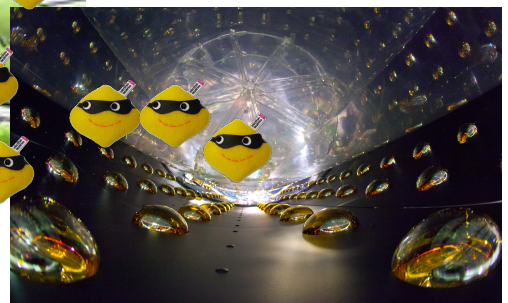
Confirmation with reactor and accelerator neutrinos





Reactor

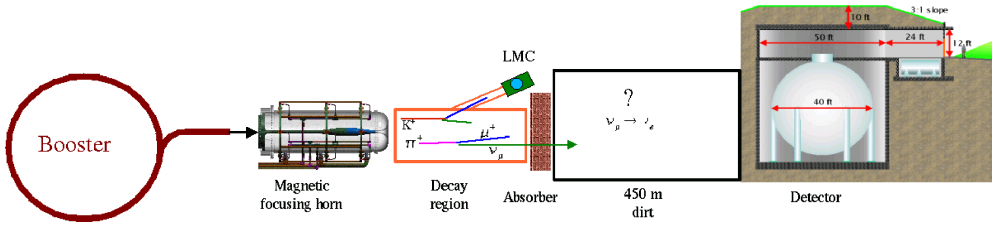




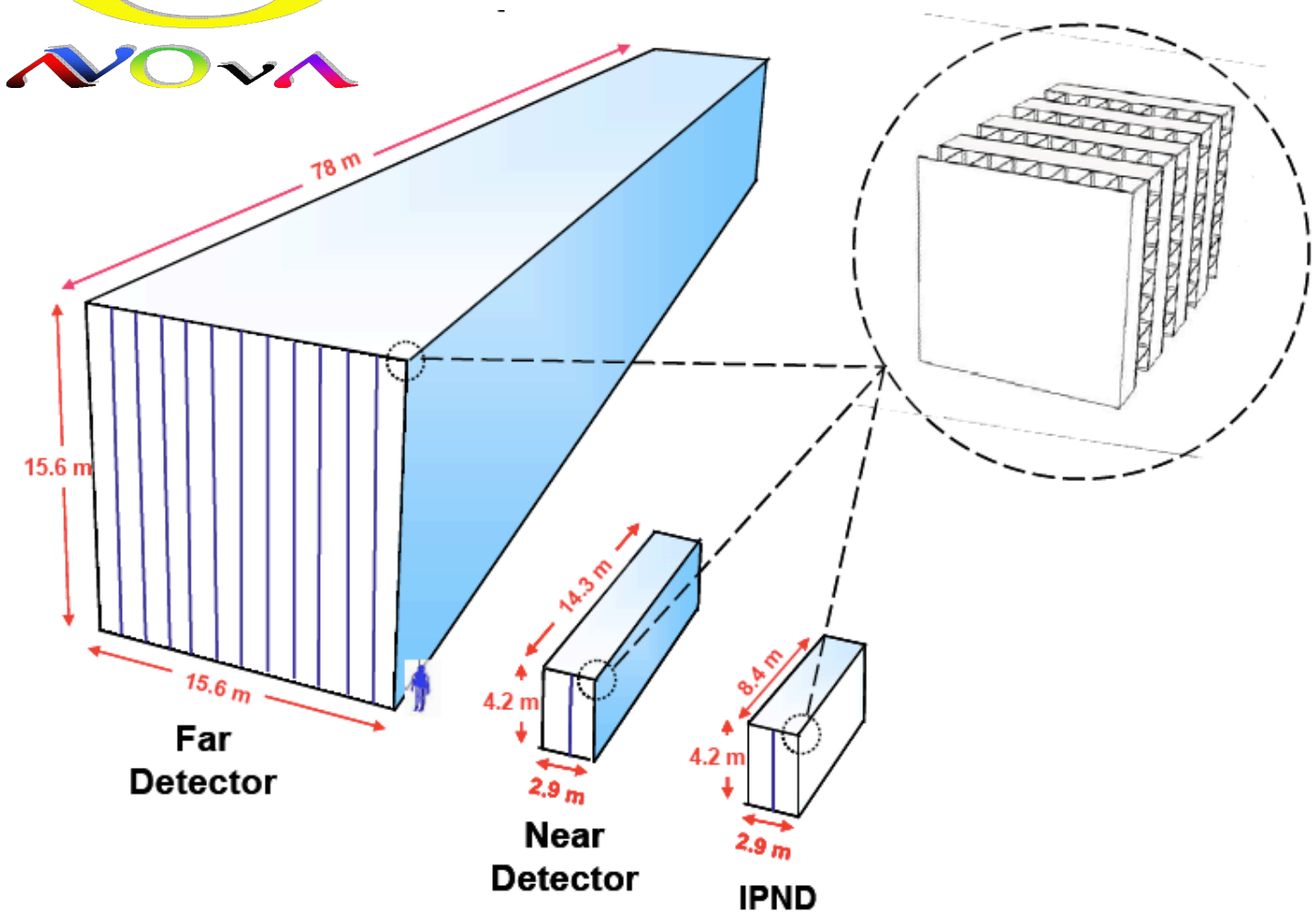
Energy: MeV
Baseline: 10 m – 100 km

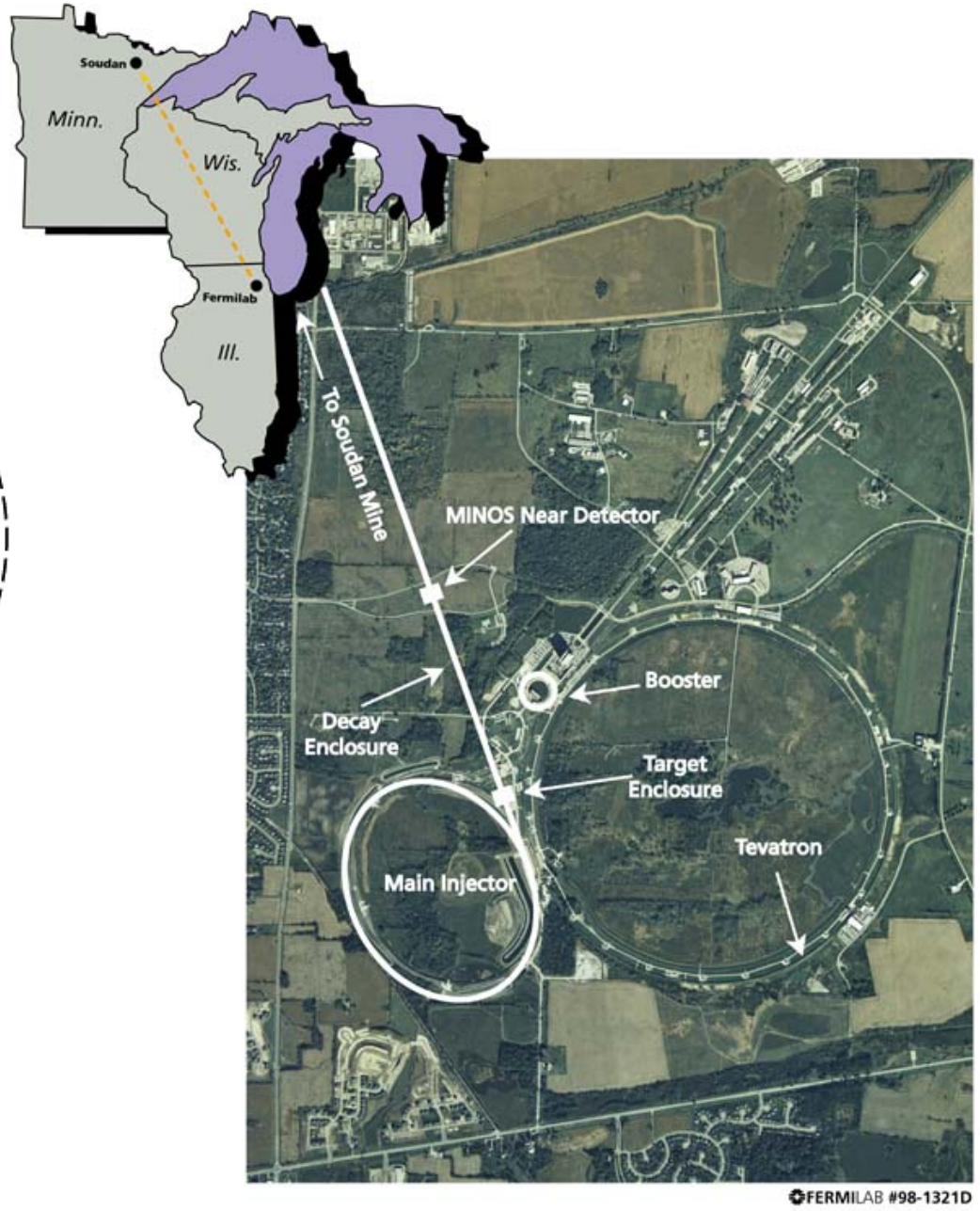
Accelerator

Energy: GeV
Baseline: 30 m – 1500 km



Neutrino oscillations at Fermilab





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Let's make it easy and assume two flavor oscillation

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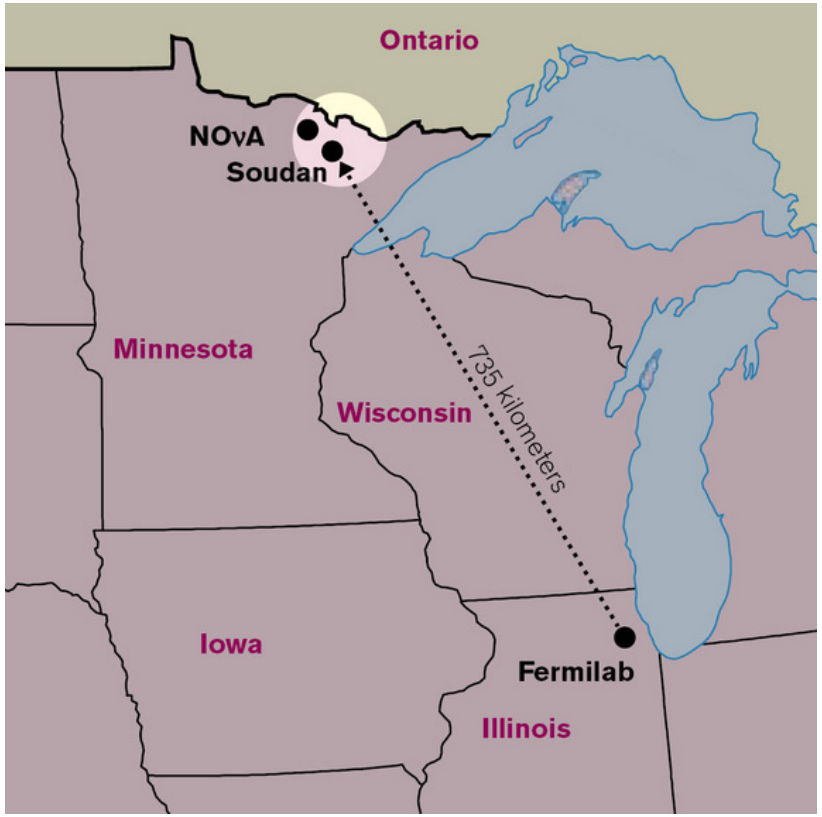

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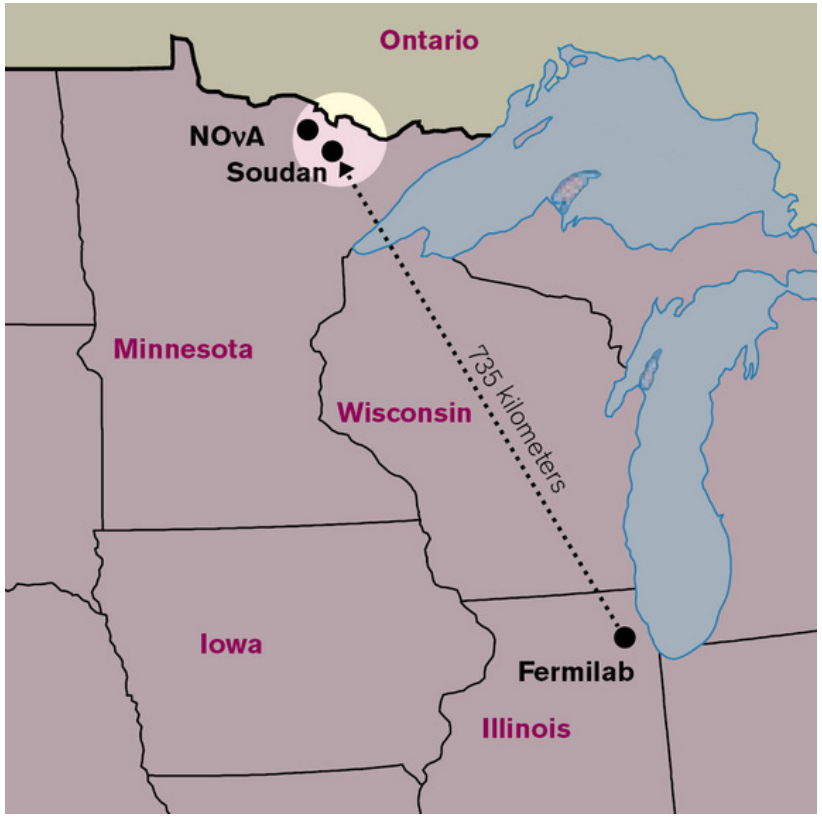

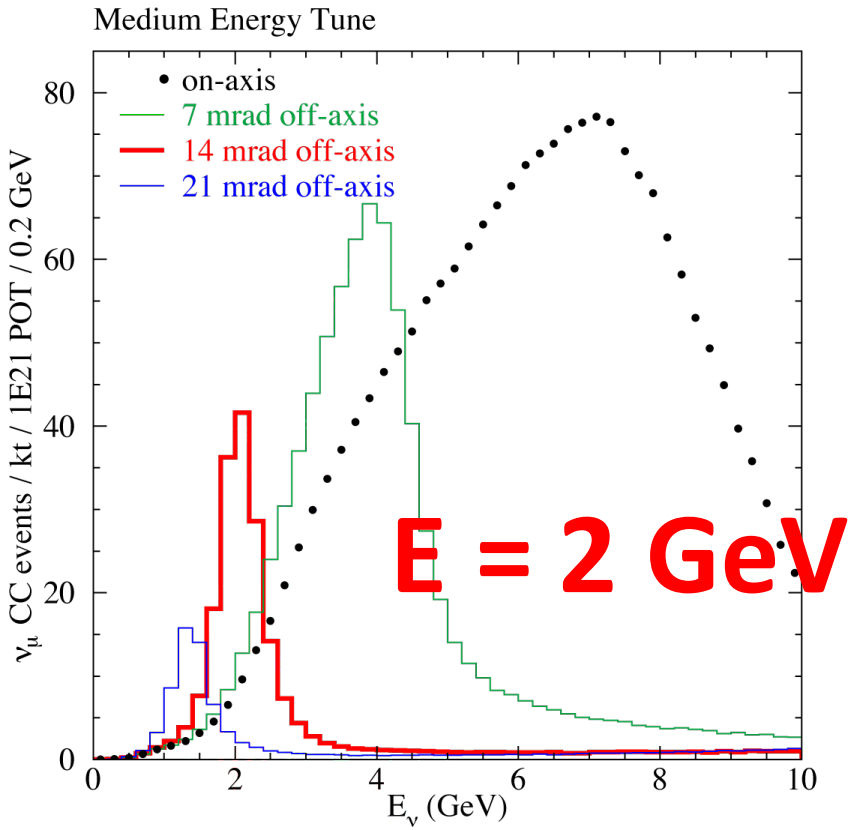

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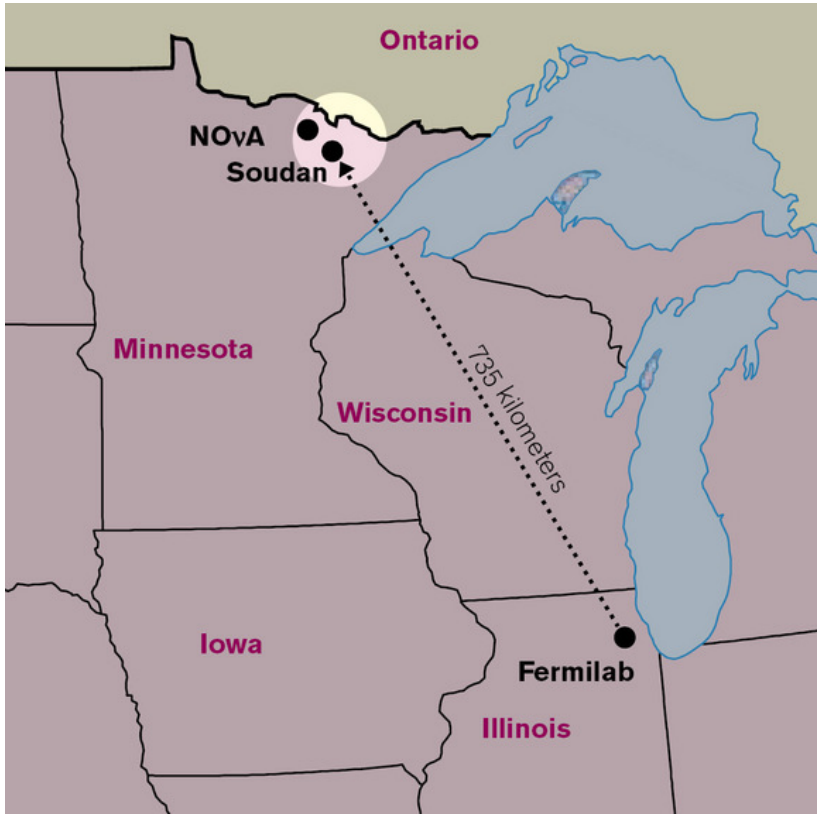

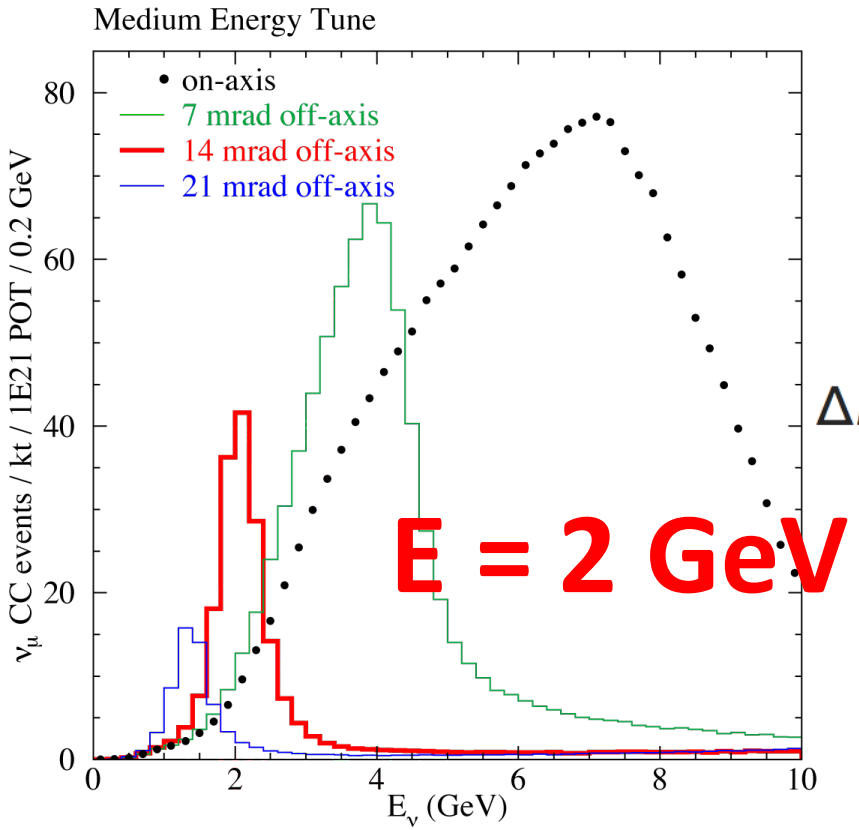

$$\sin^2 2\theta_{23} = 0.97$$

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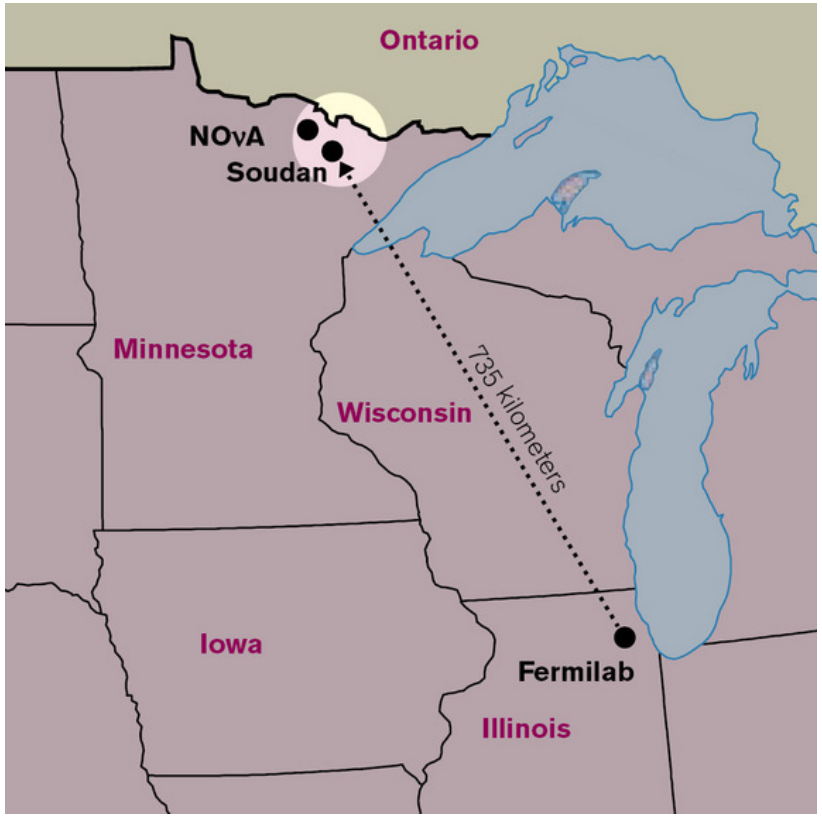

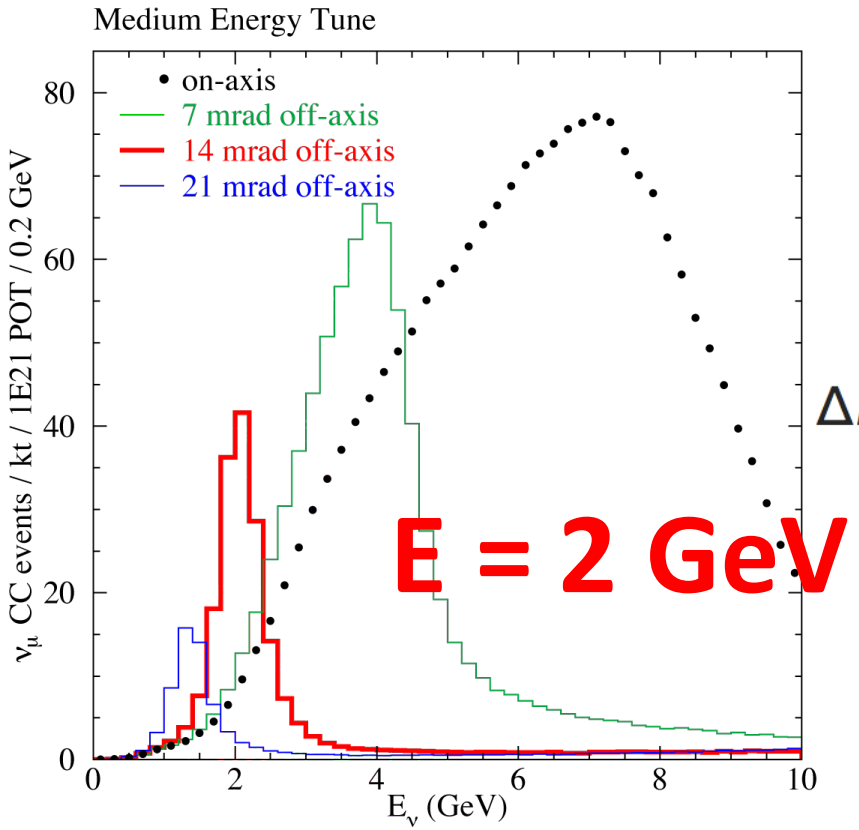

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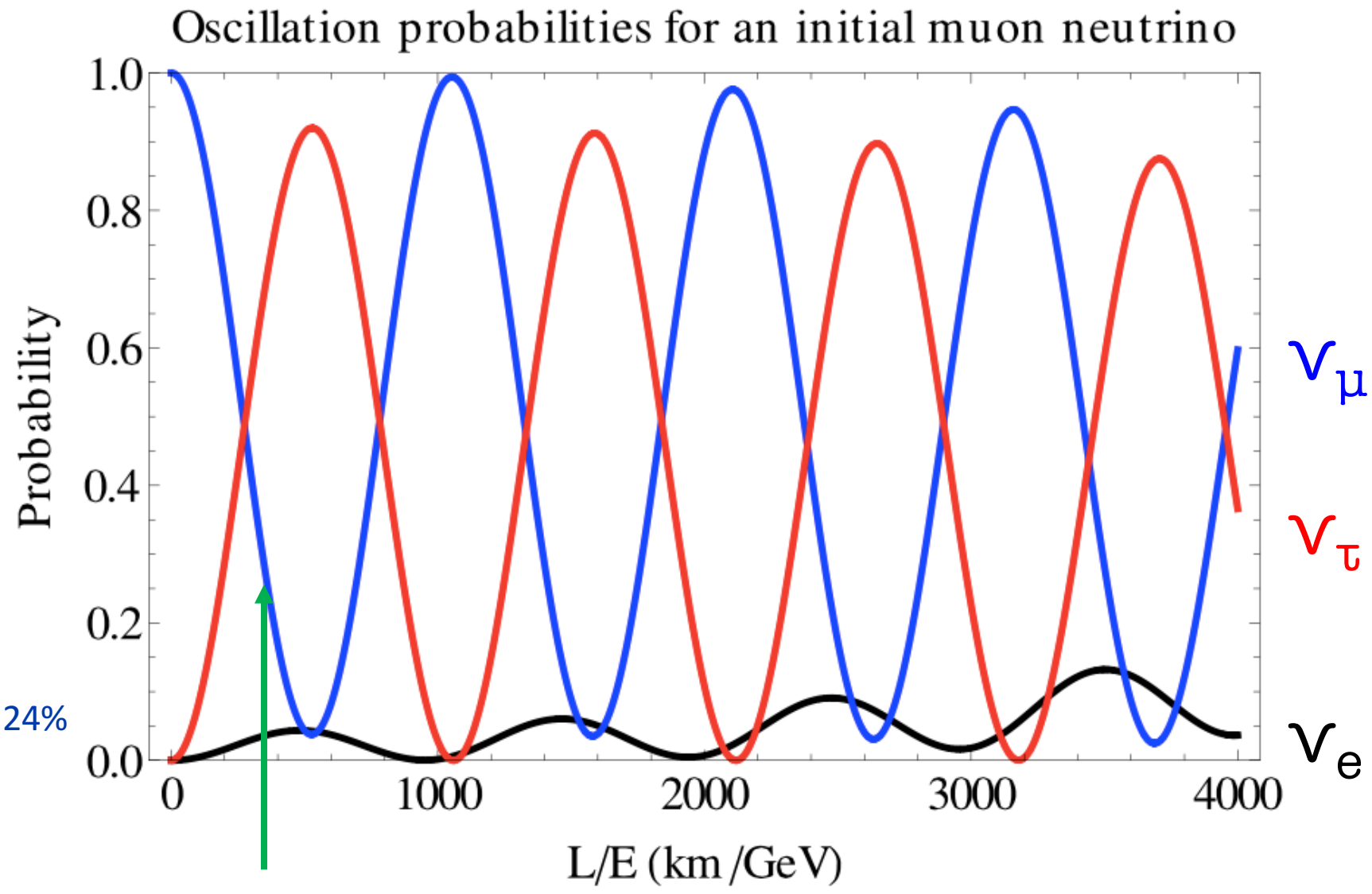
E = 2 GeV

P = 24%

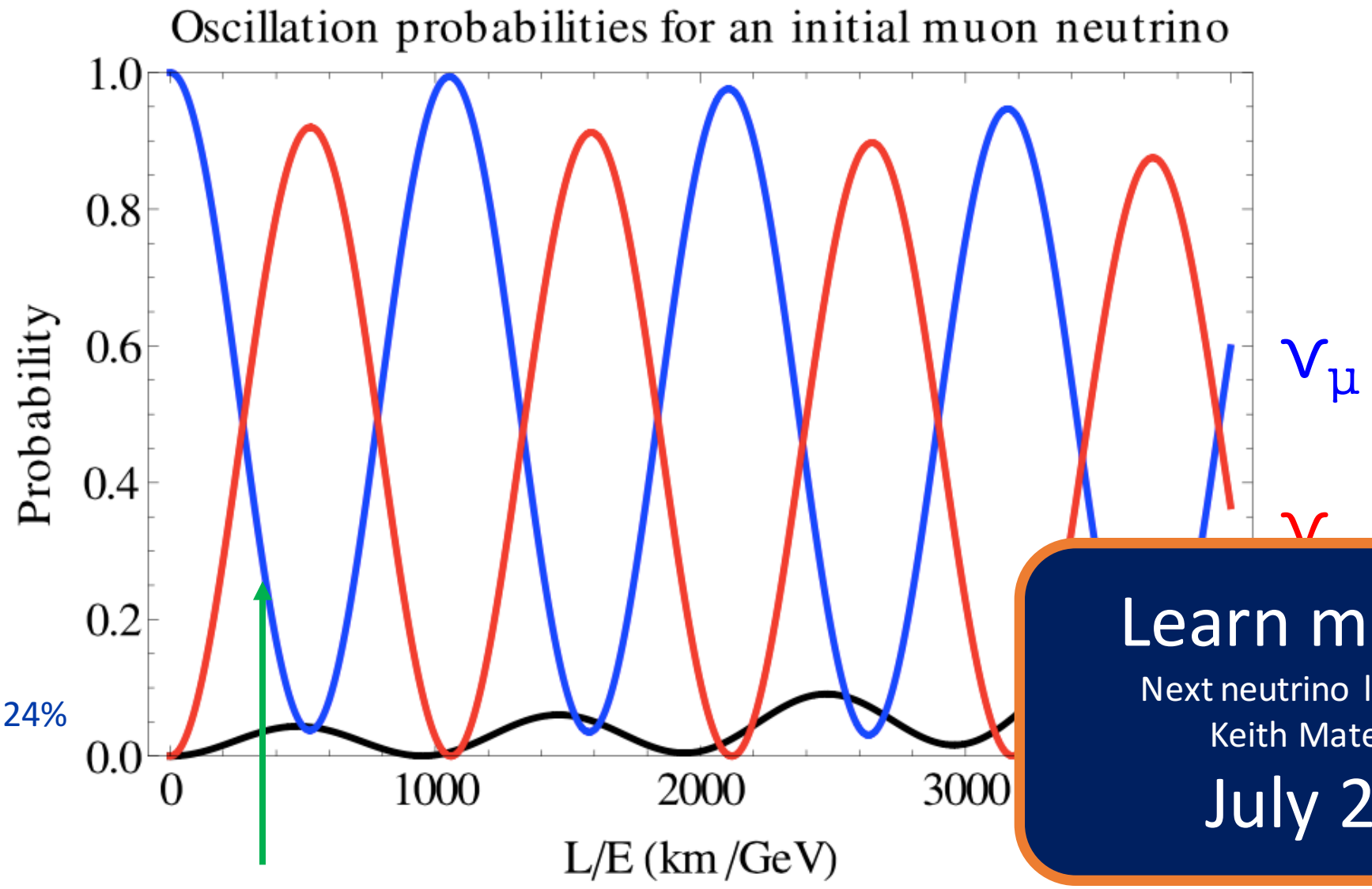
Cross check with three-flavor calculation



Two-flavor approximation: P = 24%

735 km / 2 GeV

Cross check with three-flavor calculation



Two-flavor approximation: P = 24%

735 km / 2 GeV

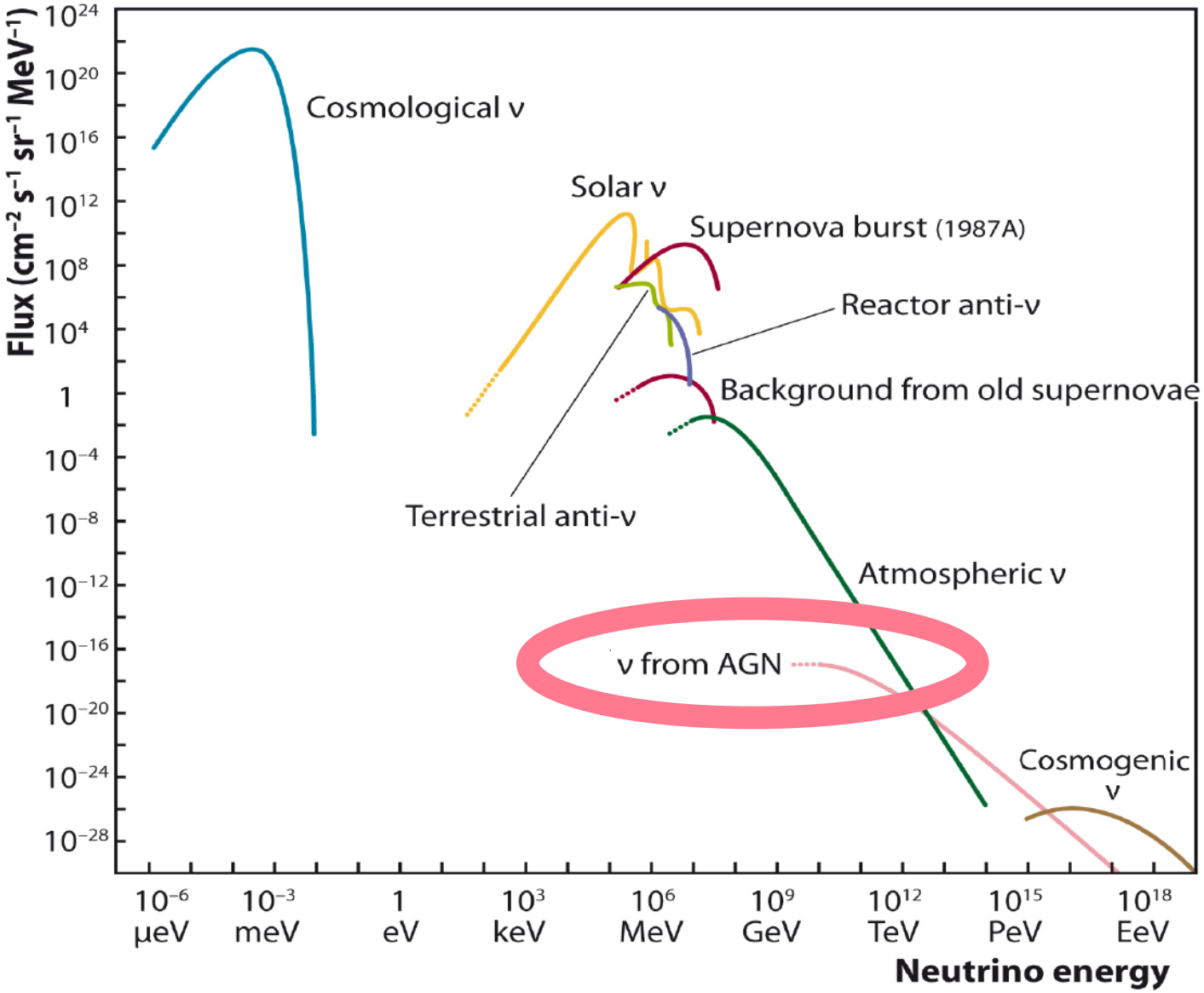
Learn more!

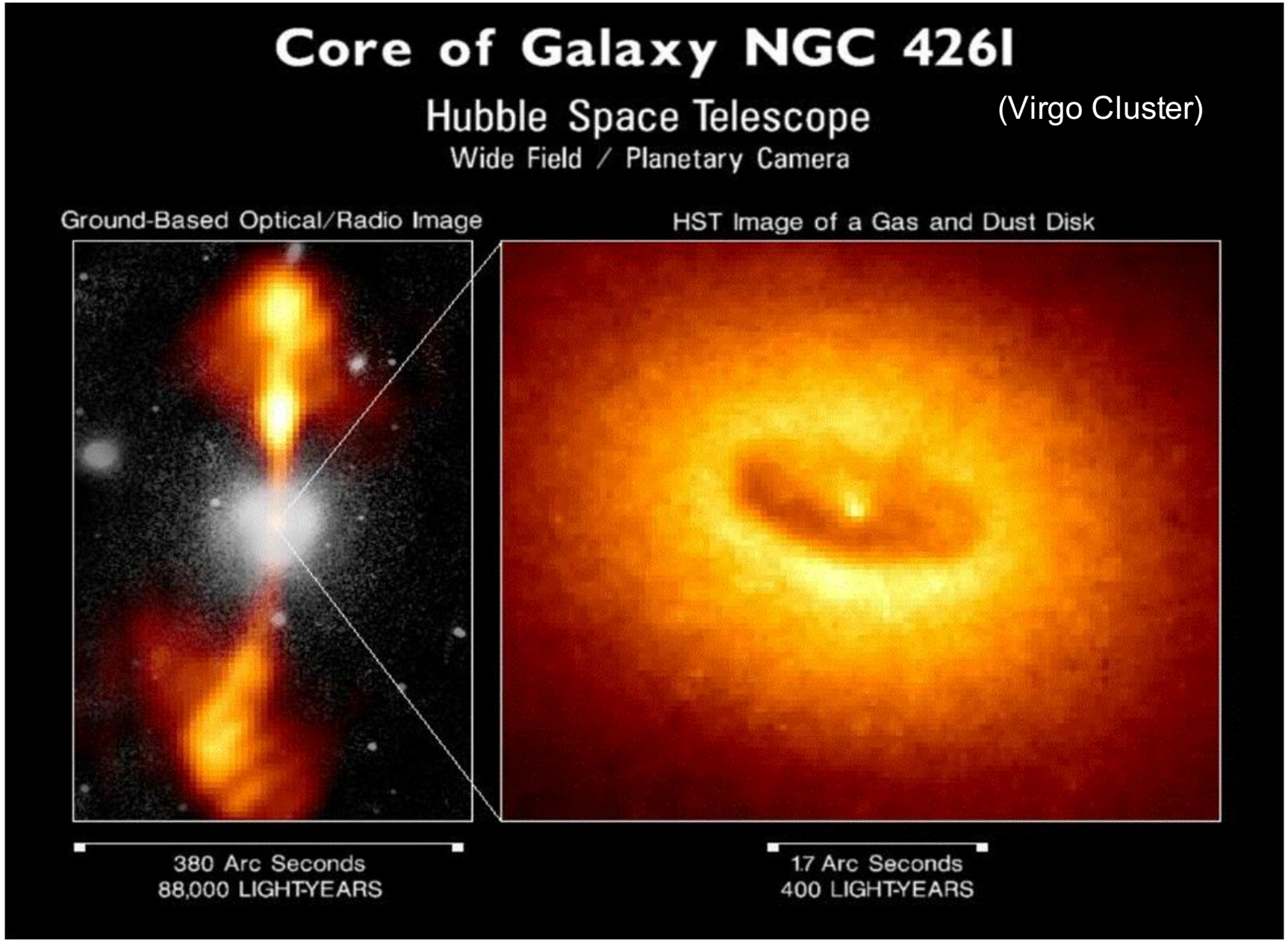
Next neutrino lecture:
Keith Matera

July 26

Where are neutrinos coming from?

Flux: neutrinos per surface area, time, solid angle and energy

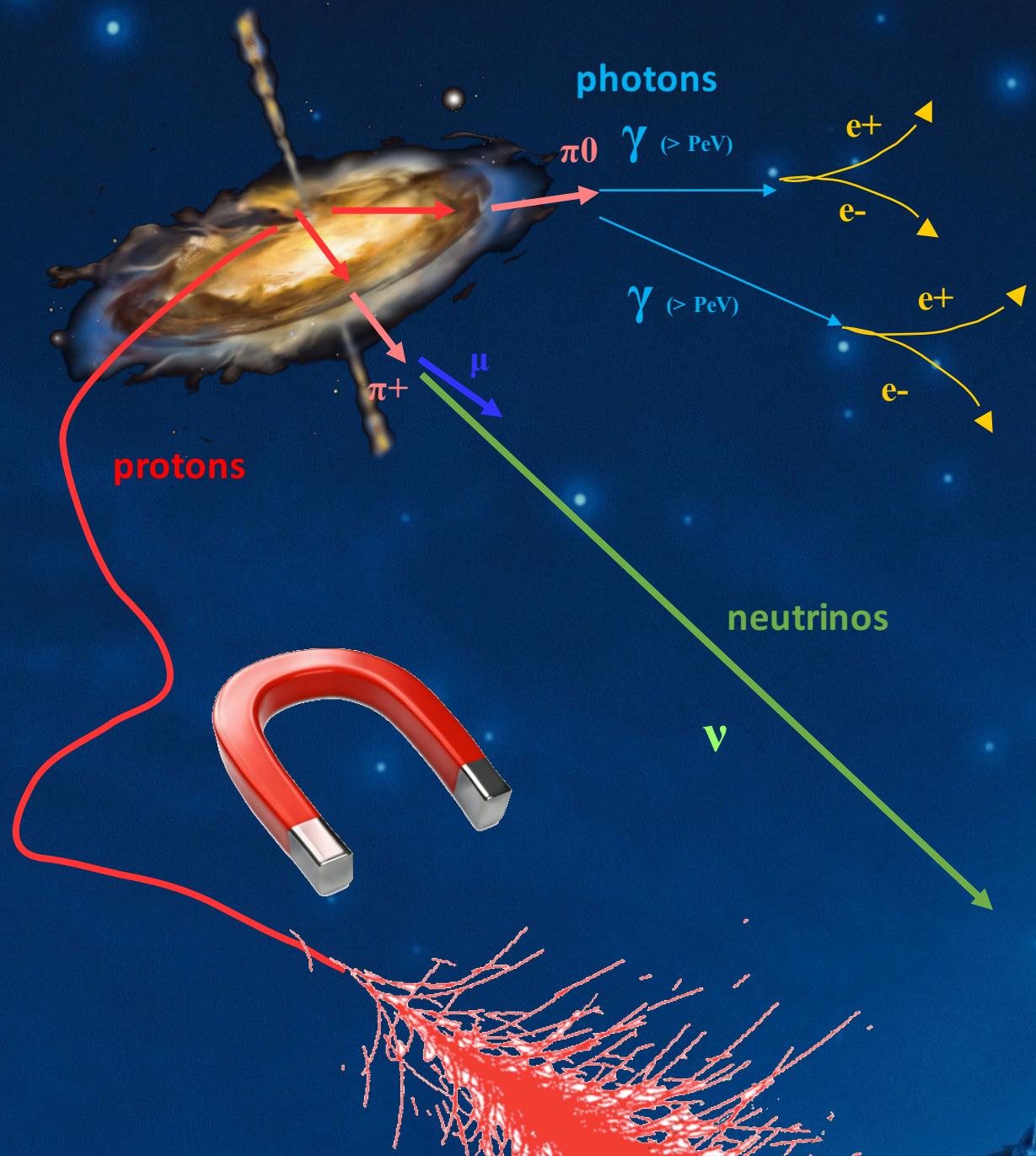




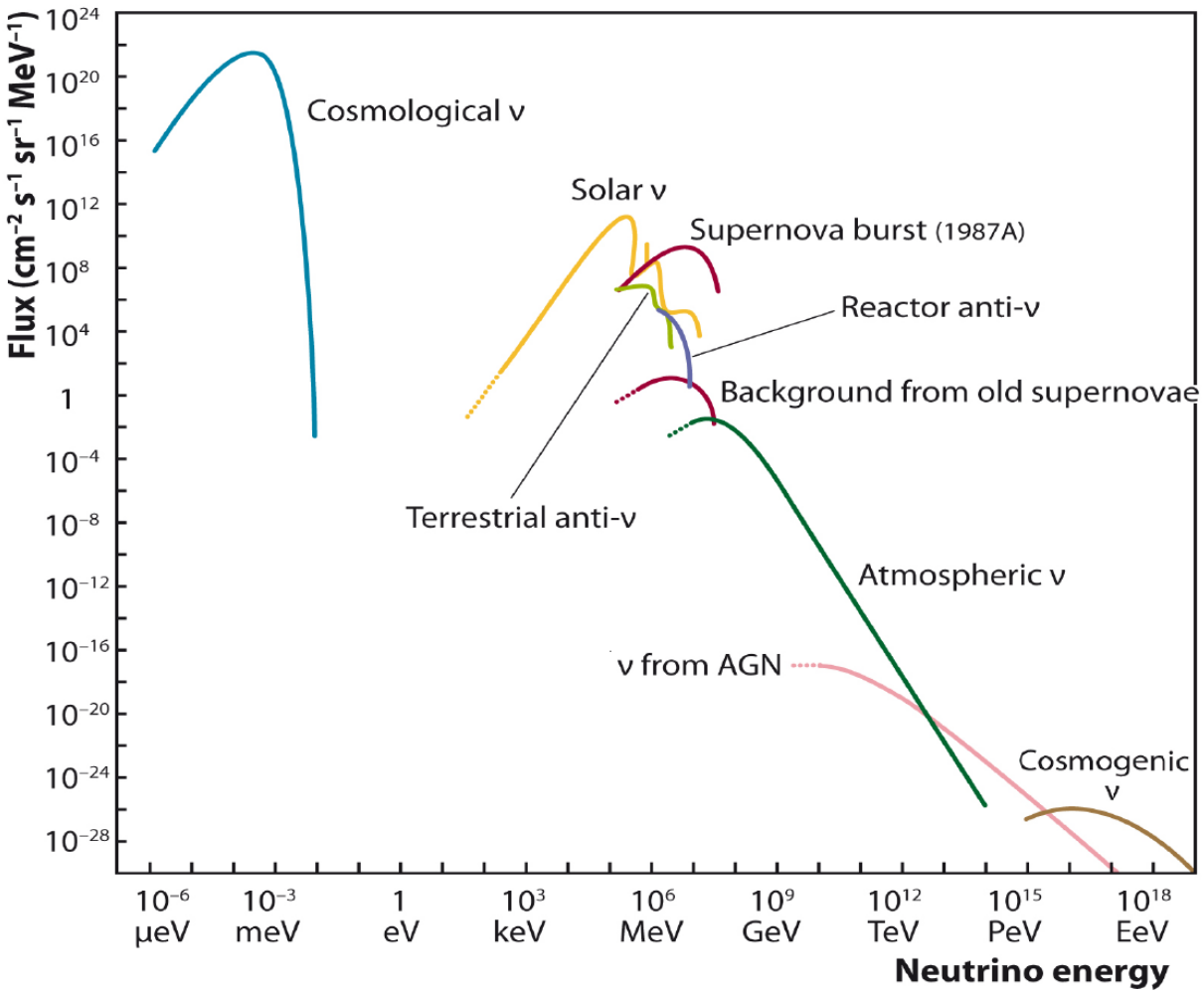
- Supermassive black holes in the center of galaxies
- Supermassive means $> 10^9$ solar masses
- Forms an accretion disk of matter around itself
- Eats ~ 1 solar mass/year!
- Ejects matter and radiation perpendicular to the accretion disk
- Ideal environment for shock acceleration!

There exist different types of AGN out in the Universe and they are very abundant!

Multimessenger astronomy

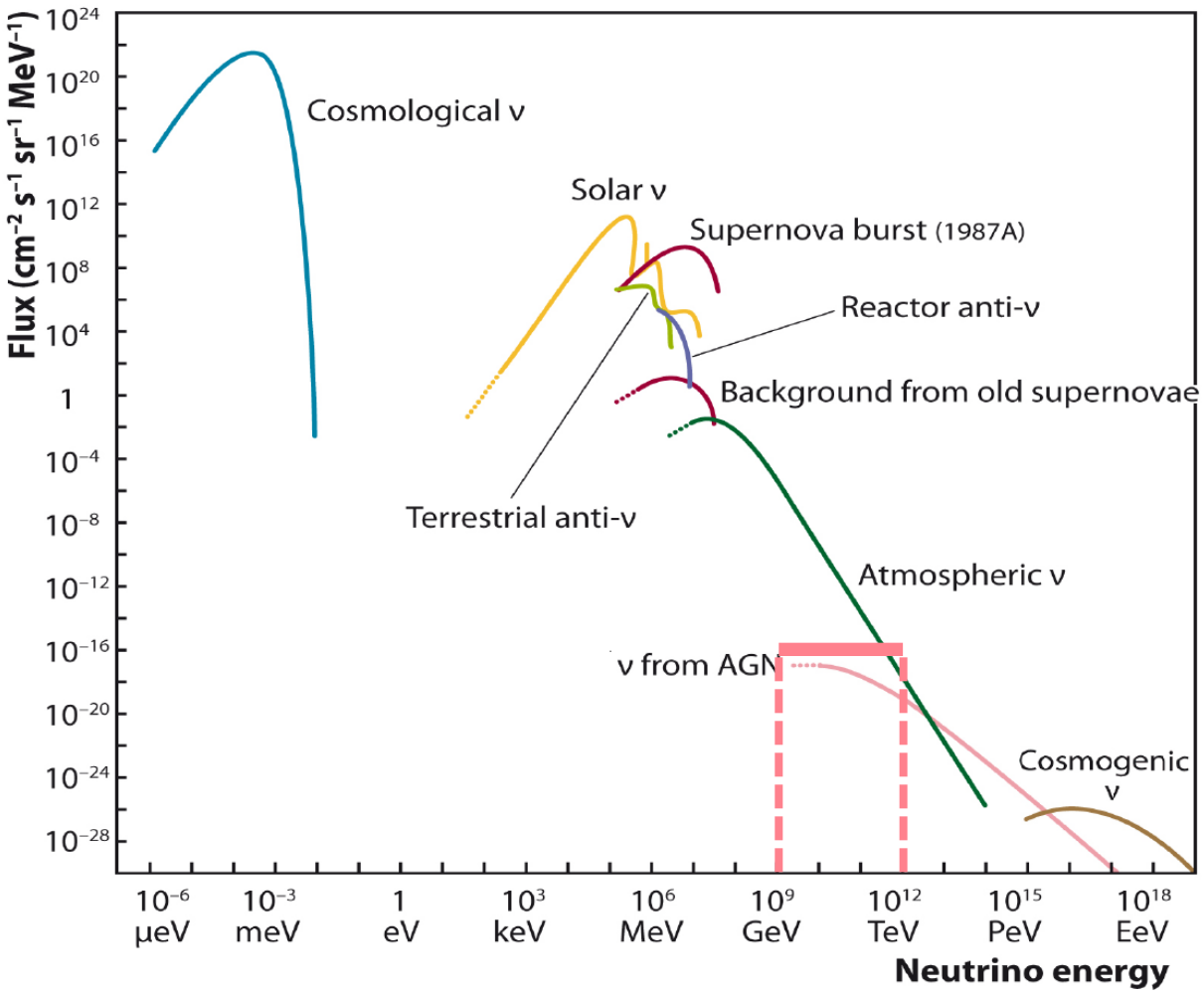


How long do you have to wait to see a neutrino from an AGN if you detector is 1m^3 of water?



How long do you have to wait to see a neutrino from an AGN if you detector is 1m^3 of water?

- Flux = 10^{-16} / cm^2 / s / sr / MeV
- Energy range: 10^9 to 10^{12} eV
- Angular coverage 4π



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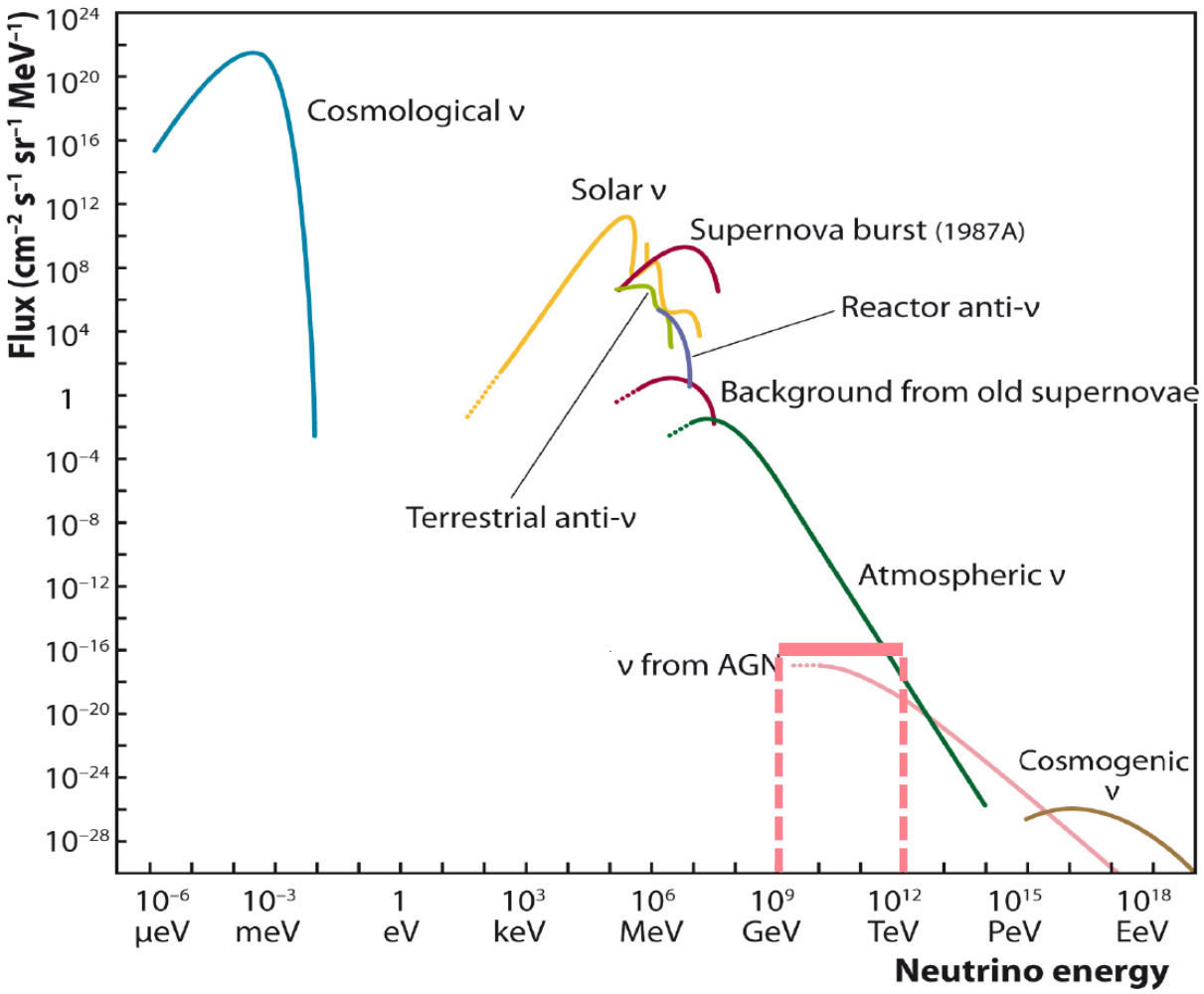
Going through the detector:

Rate: $\sim\ 10^{-5}\ /s$

This is about one per day.



How likely is it that this neutrino is going to INTERACT with your $1\mathrm{m}^3$ water detector?

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Going through the detector:

Rate: $\sim 10^{-5} /s$

This is about one per day.

Remember: neutrino mean free path

$$V_s = VN \rightarrow L = mp / (\rho \times \sigma)$$

$m_p = 1.67 \, x \, 10^{-24} \, g$
$\rho = 1 \frac{g}{cm^3}$ (for ice)
$\sigma = 10^{-35} \, cm^2$ (@ 1TeV)

$$L = 2 \, x \, 109 \, m$$

Or:
1 in $2x10^9$ neutrinos will interact during crossing a 1m water detector

How likely is it that this neutrino is going to INTERACT with your $1m^3$ water detector?

Going through the detector:

Rate: $\sim 10^{-5}\ /s$

This is about one per day.

You have to wait 10^6 years to detect such a neutrino!

Remember: neutrino mean free path

$$V_s = VN \rightarrow L = mp\ /\ (\rho \times \sigma)$$

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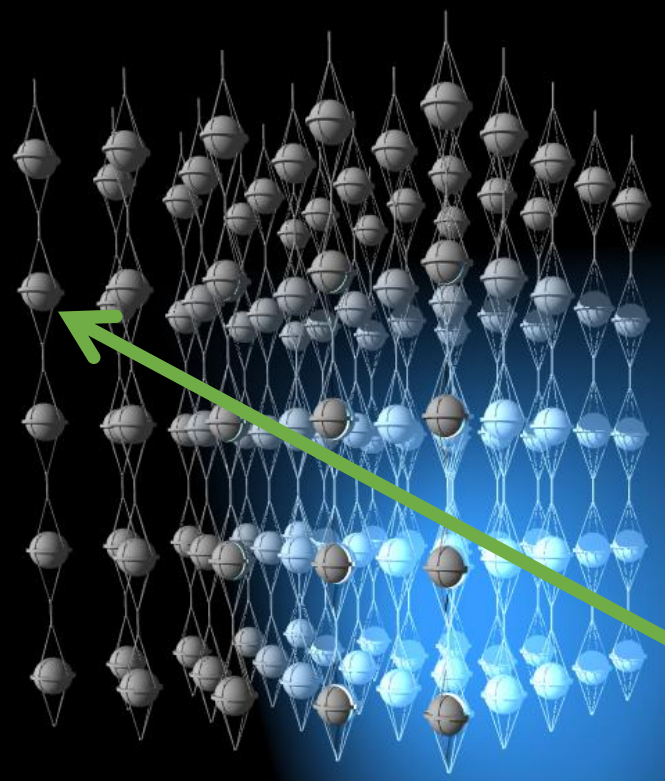
1 in $2x10^9$ neutrinos will interact during crossing a 1m water detector

GEOGRAPHIC
SOUTH POLE
ROALD AMUNDSEN
DECEMBER 14, 1911
"So we arrived and were able to plant our flag at the geographical South Pole."
ROBERT F. SCOTT
JANUARY 17, 1912
"The Pole. Yes, but under very different circumstances from those expected."
ELEVATION 9,301 FT.
ANNE SCHUKRAFT

Cherenkov detectors



High energy muons can travel several kilometers in water, ice (and other media)

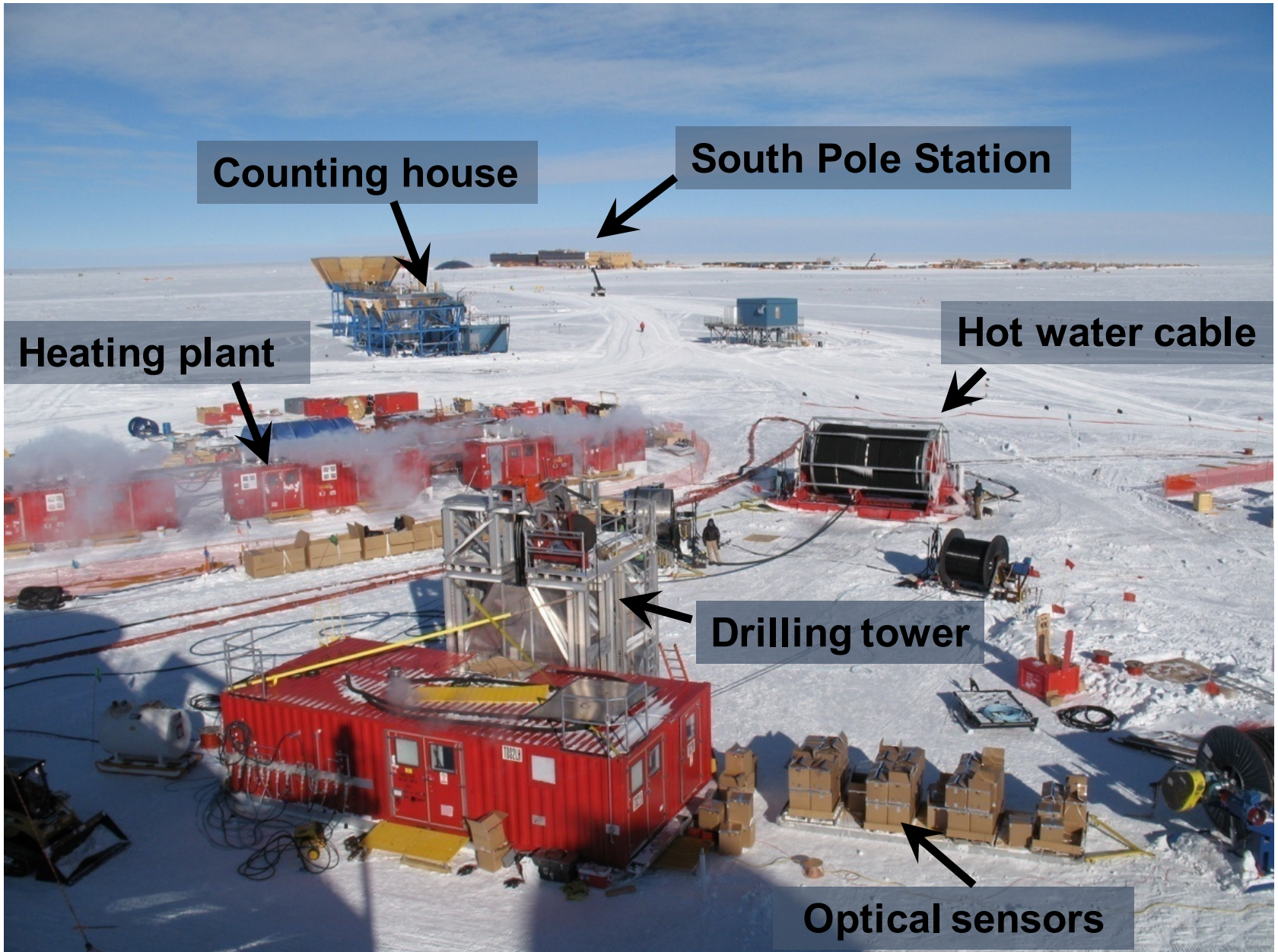
μ^-

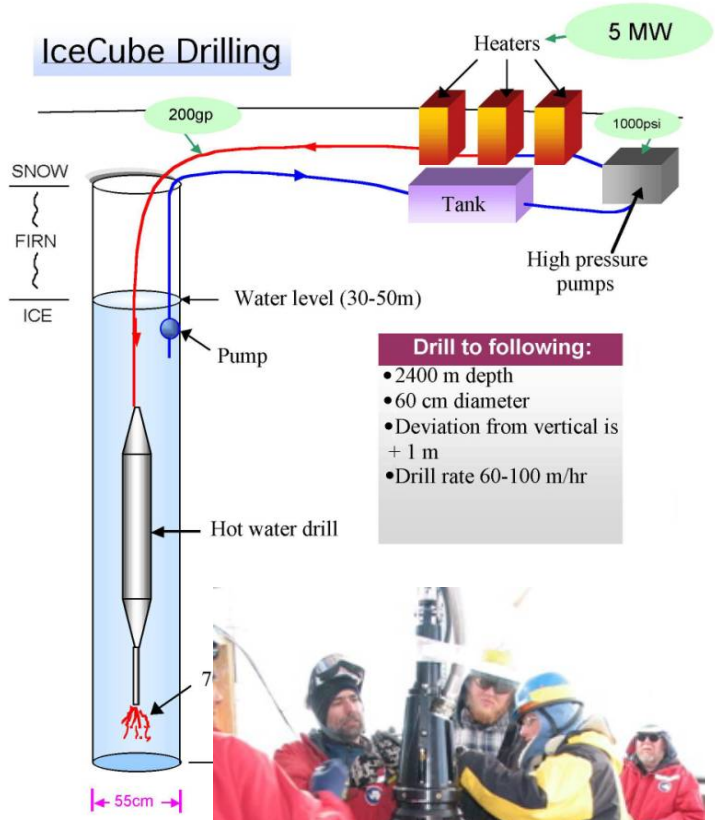
Light sensors

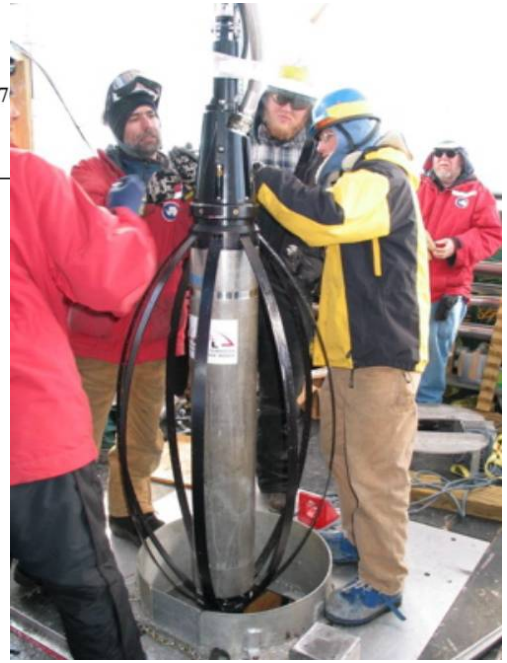
Cherenkov light cone

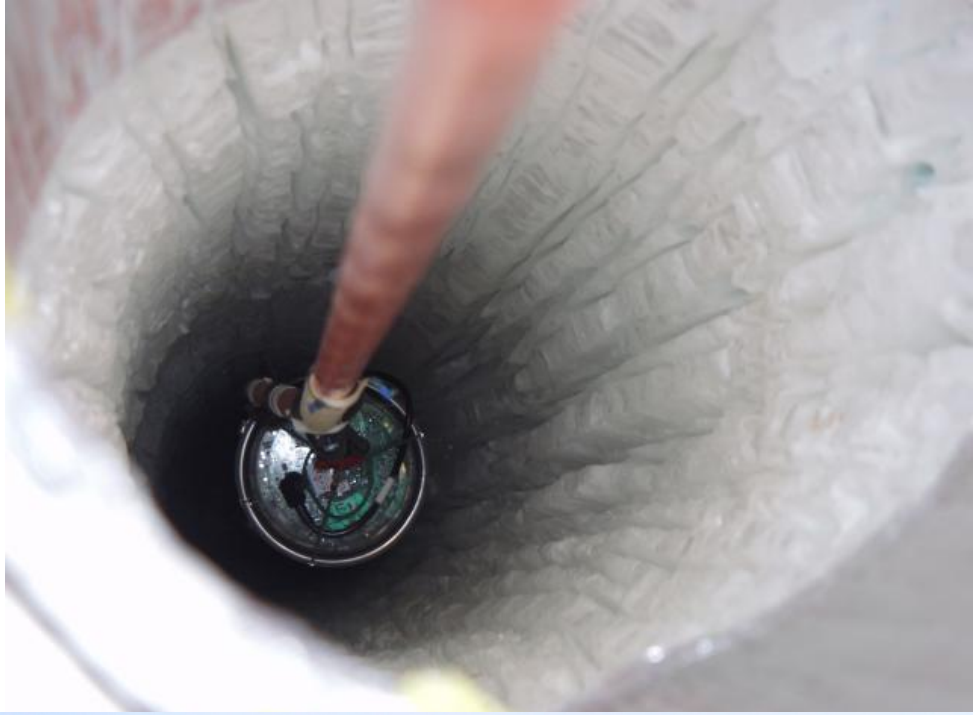
ν_μ

Hot water drilling

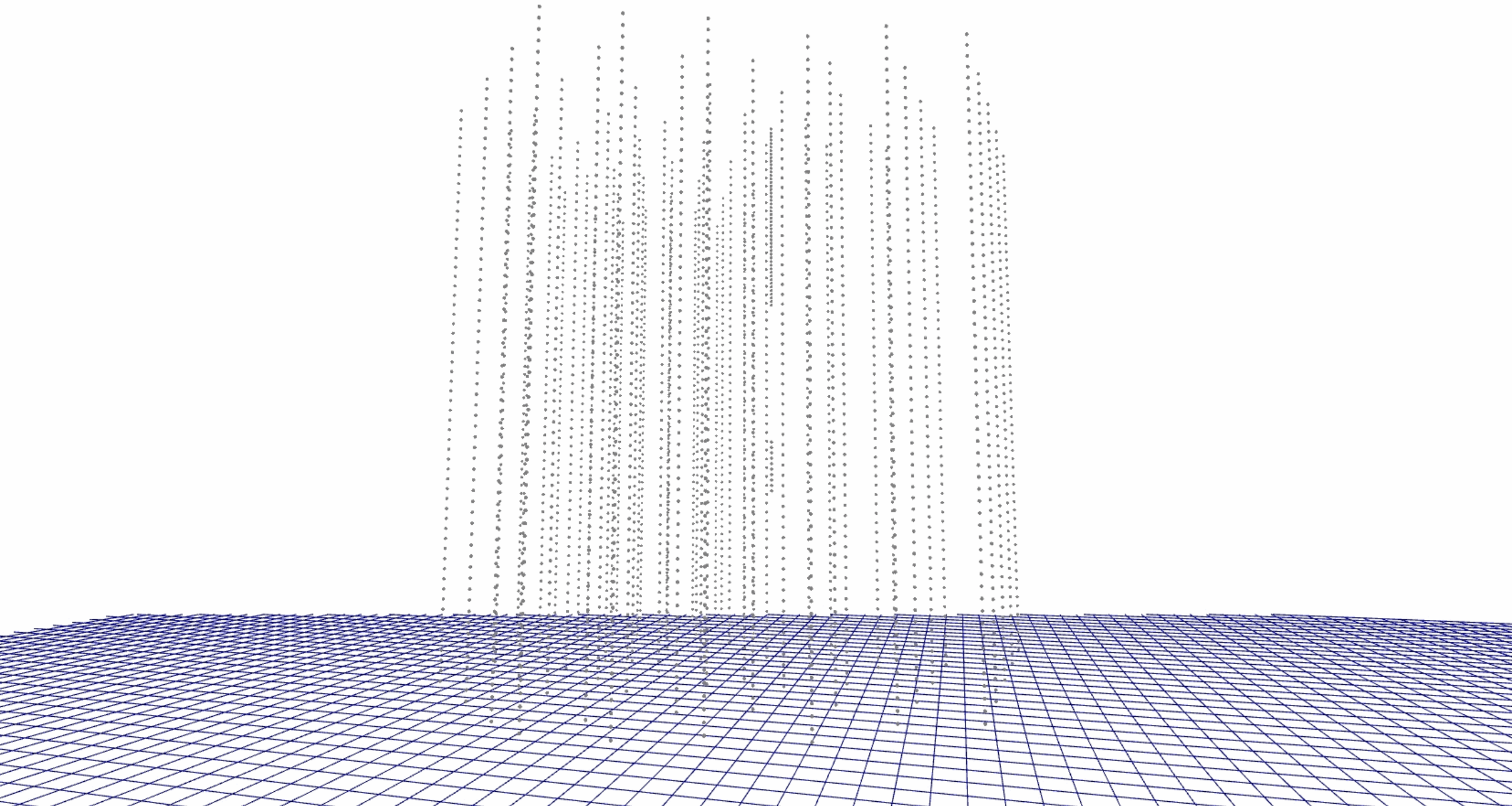


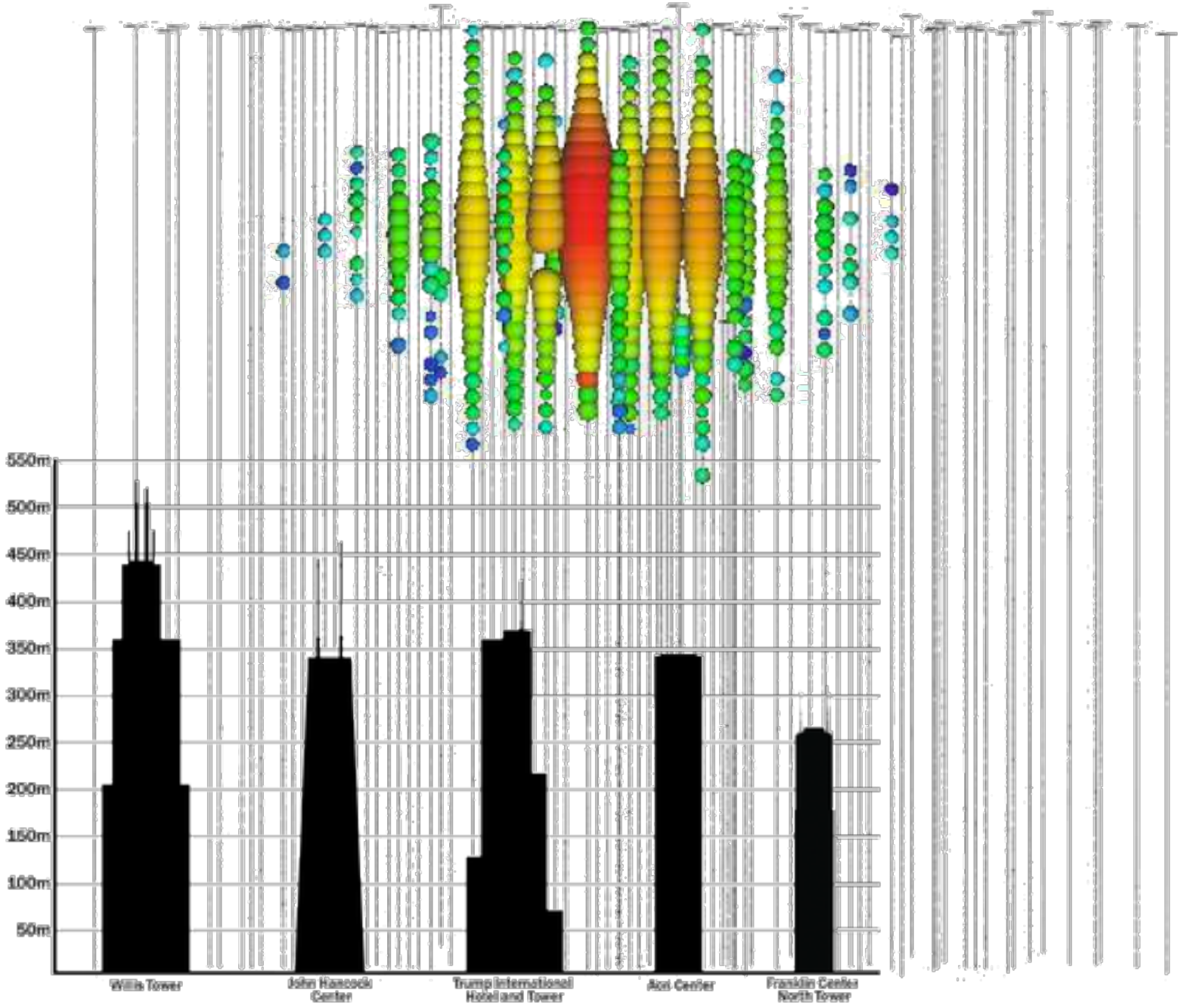




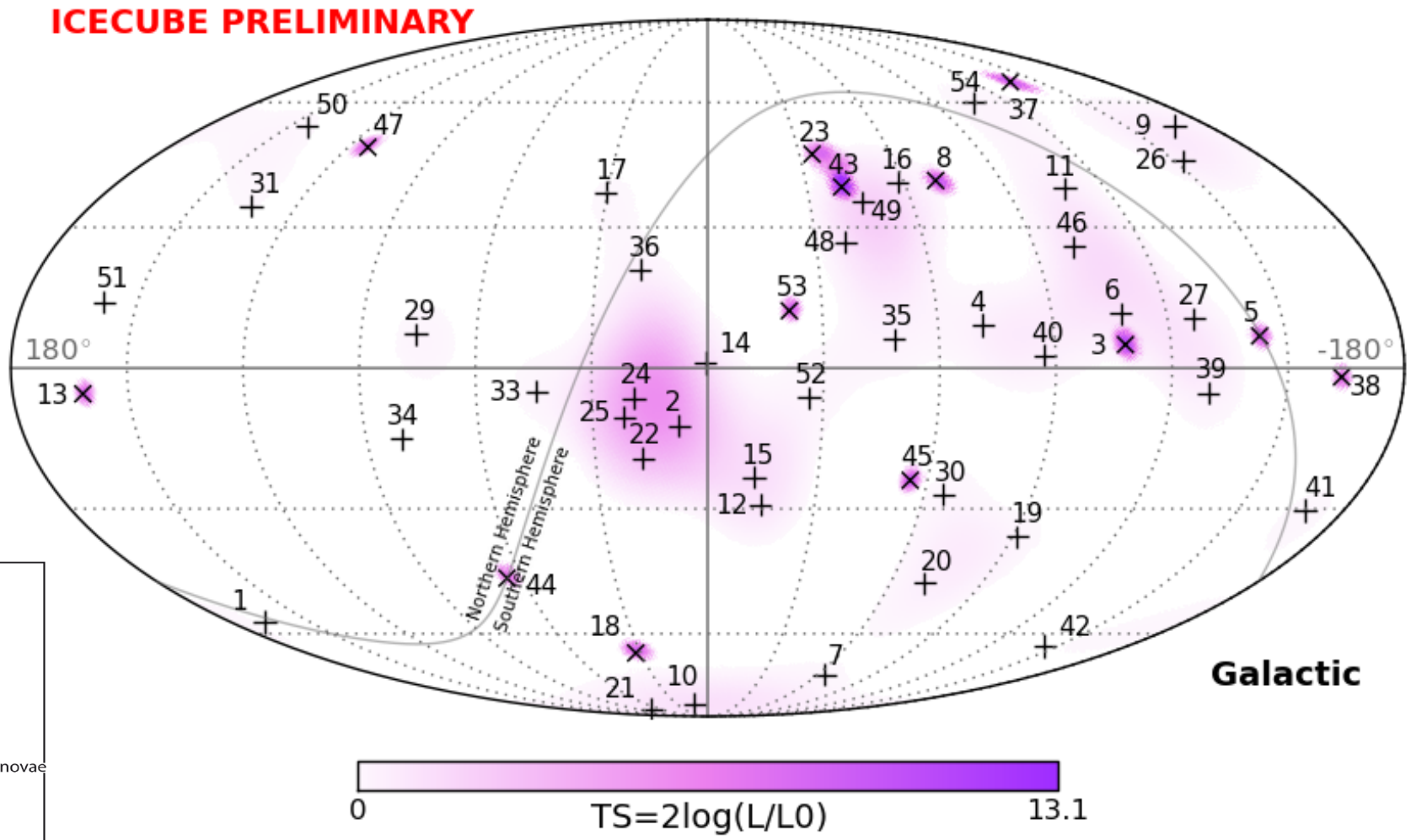


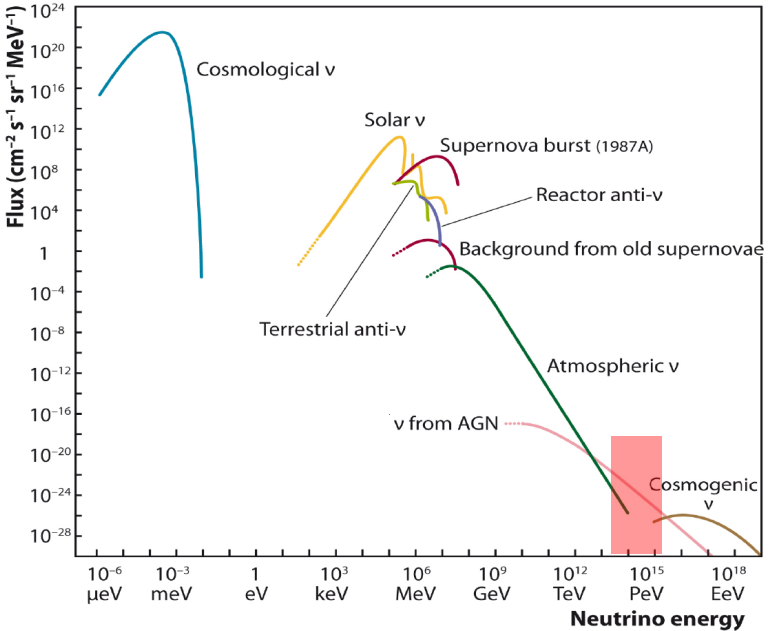
data cable: 2500 m, ~6 tons
11180 LBS



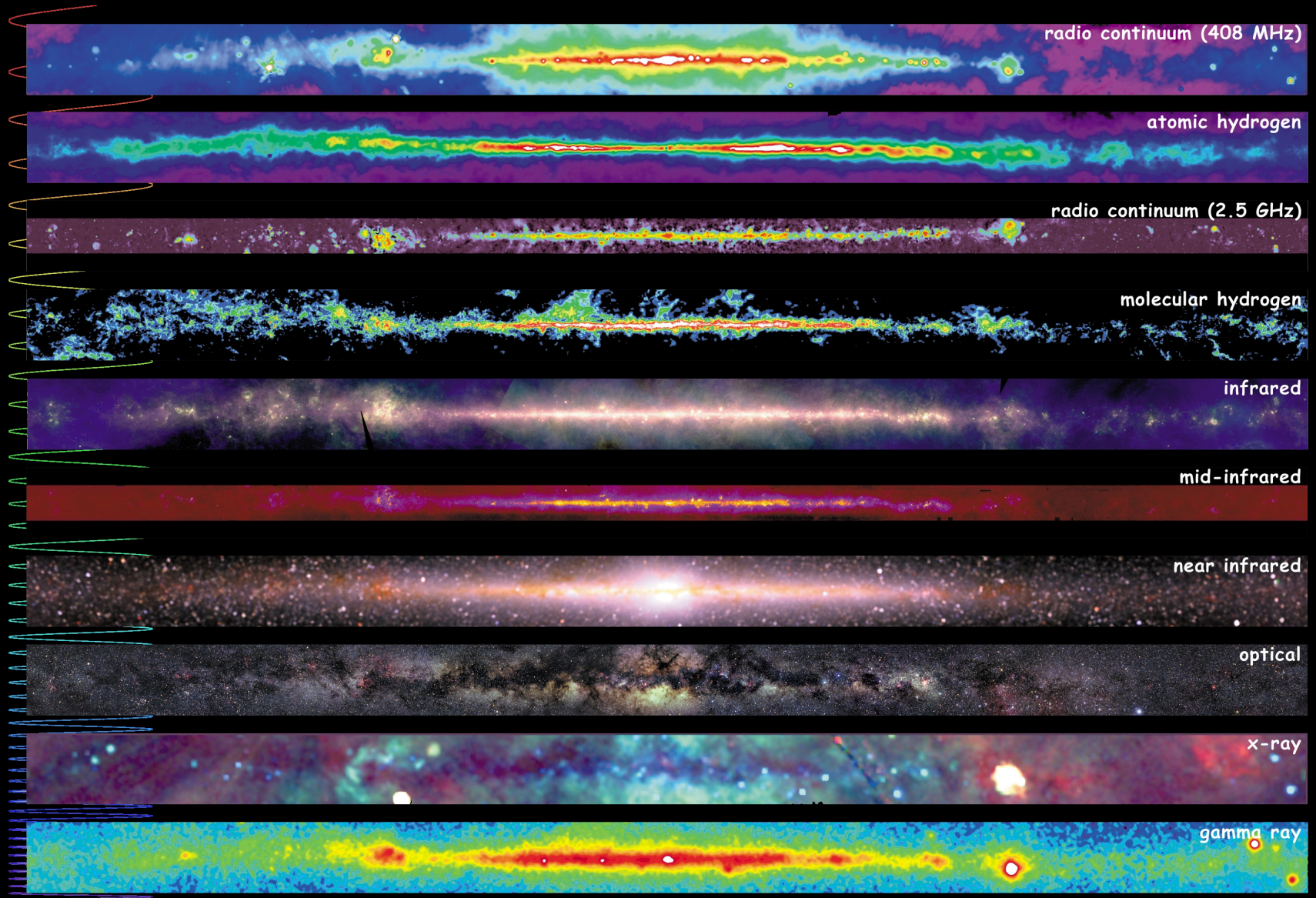

550m
500m
450m
400m
350m
300m
250m
200m
150m
100m
50m
Willis Tower
John Hancock Center
Trump International Hotel and Tower
Aon Center
Franklin Center North Tower

The Universe in neutrinos





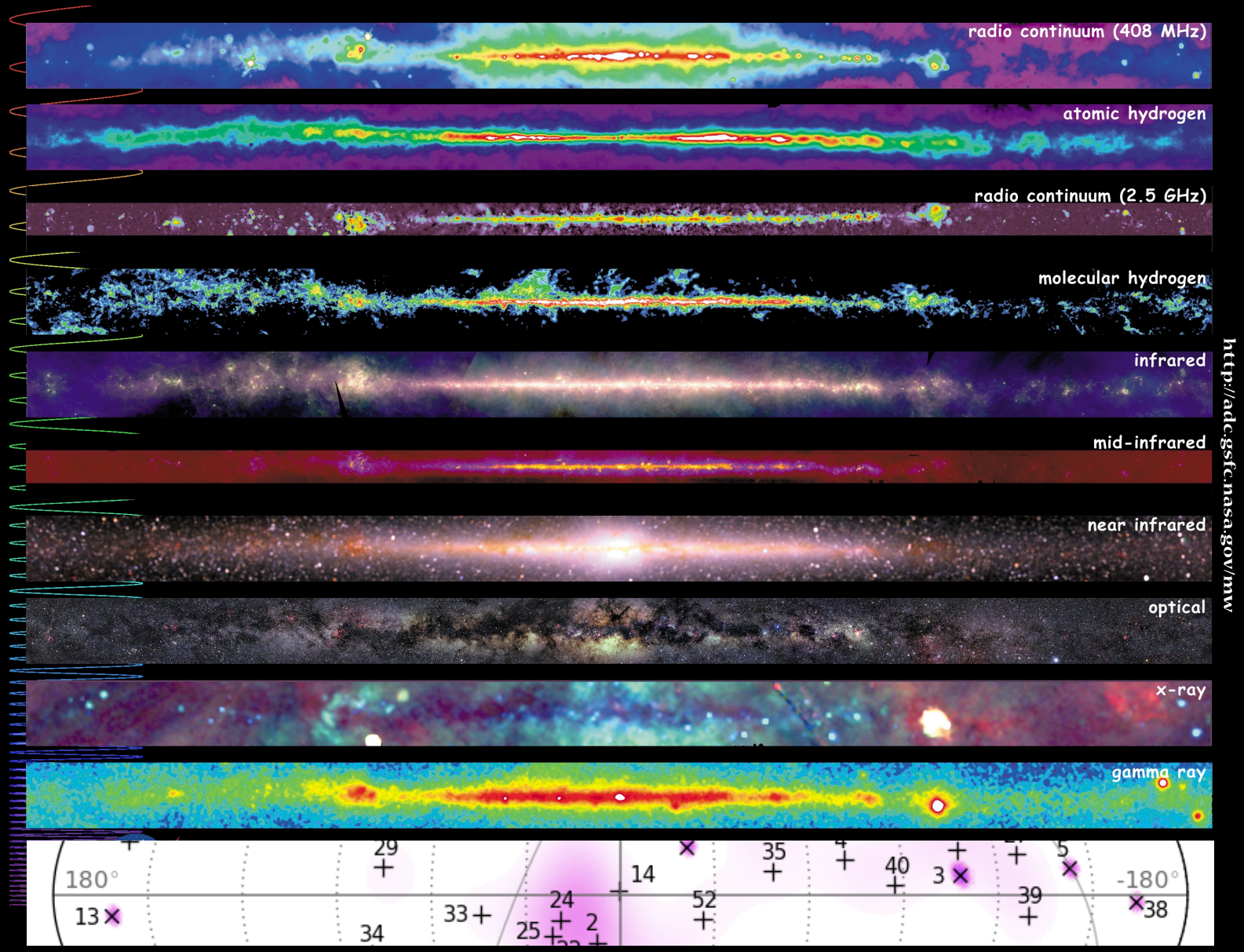
The multiwavelength Universe



http://adc.gsfc.nasa.gov/mw

Multiwavelength Milky Way

The multiwavelength Universe



http://adc.gsfc.nasa.gov/mw

?

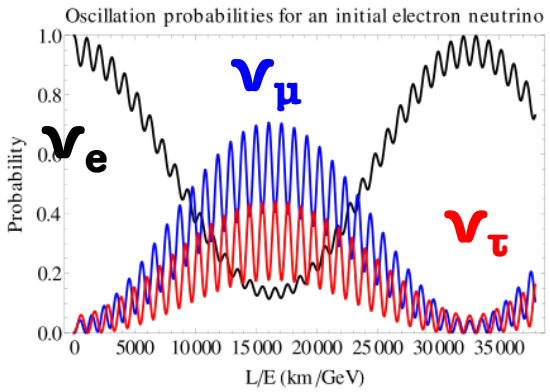
All solved?

All solved?

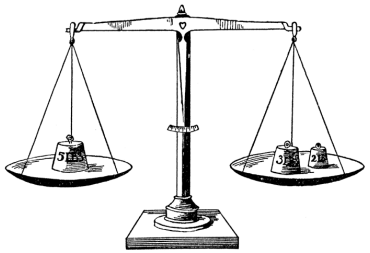
Neutrinos exist!

They exist in three flavors.

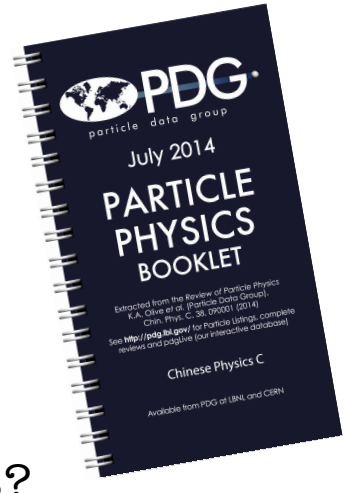
They oscillate.



They are not massless.



Not yet!



Neutrino Properties

See the note on "Neutrino properties listings" in the Particle Listings.

Mass $m <$ 2 eV (tritium decay)
Mean life/mass, $\tau/m >$ 300 s/eV, CL = 90% (reactor)
Mean life/mass, $\tau/m >$ 7×10^9 s/eV (solar)
Mean life/mass, $\tau/m >$ 15.4 s/eV, CL = 90% (accelerator)
Magnetic moment $\mu < 0.29 \times 10^{-10}$ μ_B, CL = 90% (reactor)

- What is the neutrino mass?
- What is the neutrino mass ordering?
- Are there more neutrino flavors than 3?
- Do neutrinos behave the same as anti-neutrinos?
- Are neutrinos their own antiparticles?
- Do neutrinos contribute to dark matter?

Next neutrino lecture:
Keith Matera
July 26