Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Neutrino physics

Anne Schukraft, FNAL

Hadron Collider Summer School

August 22nd, 2018

Outline

- Neutrino history
  - Discovery of the neutrino
  - What we have learned about the neutrino

- Today's challenges
  - Neutrino masses
  - Precision measurements of oscillation parameters
  - Sterile neutrinos

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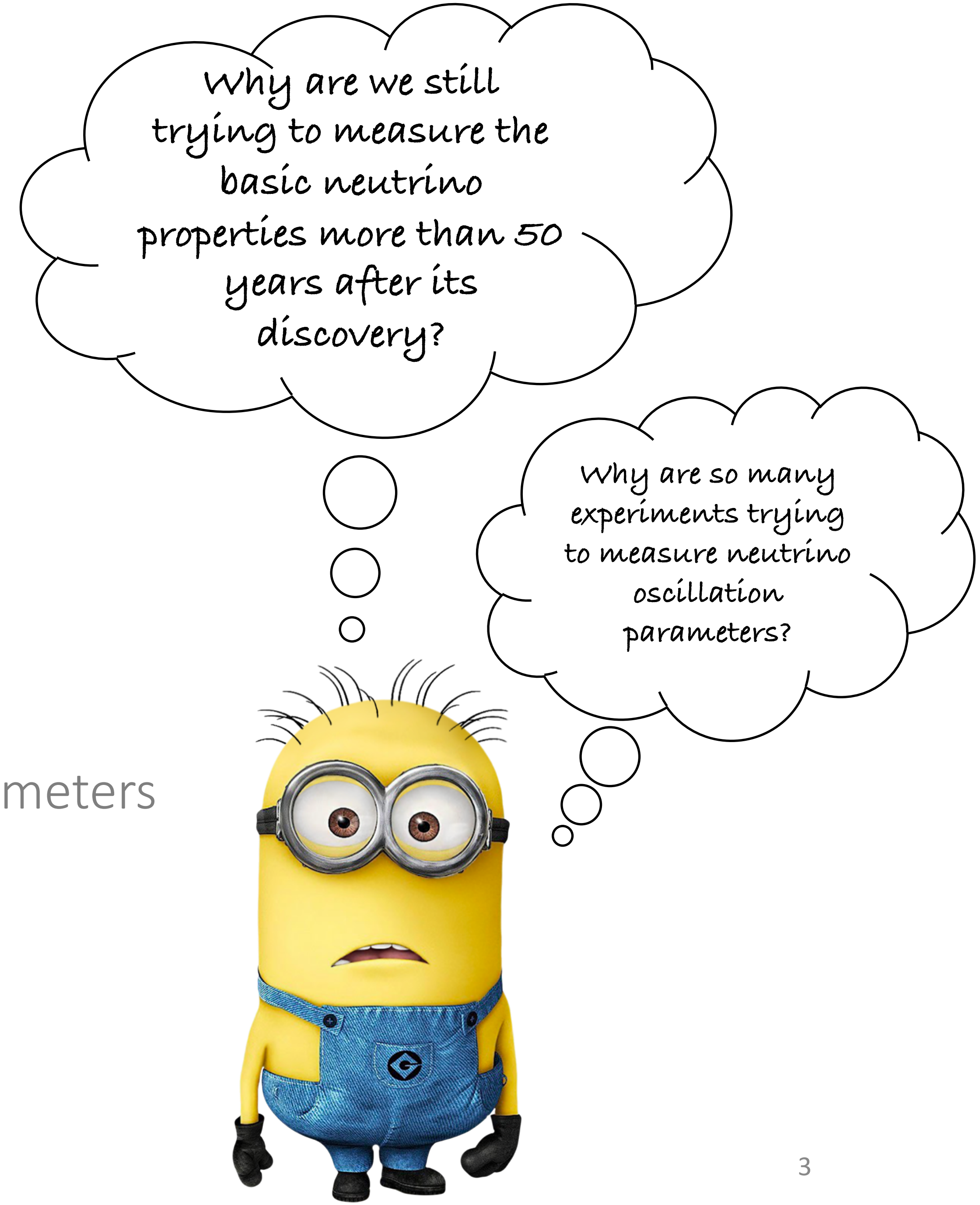
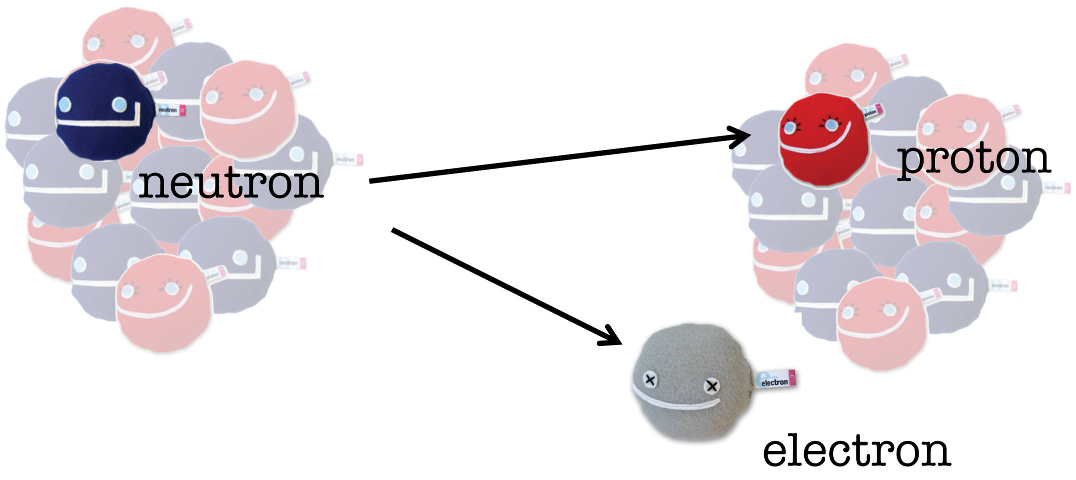
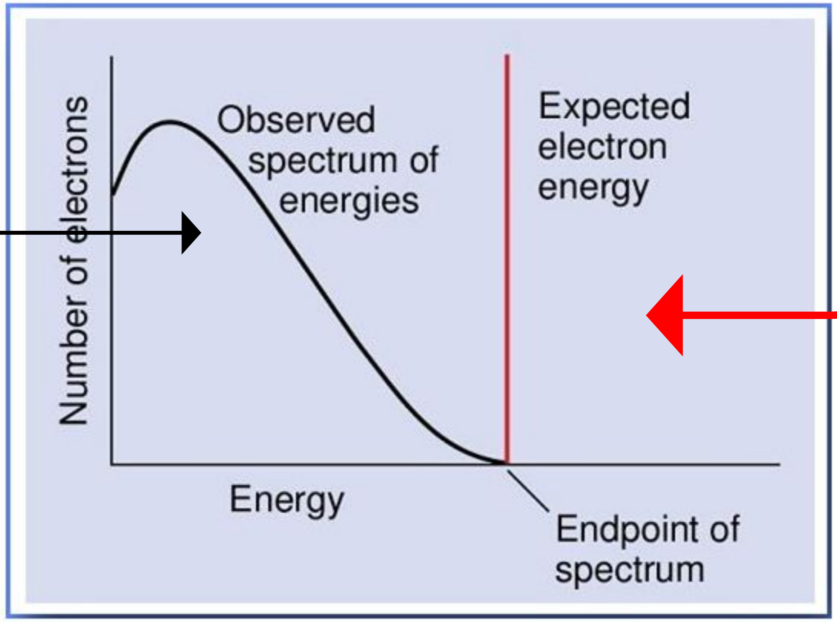


Wolfgang Pauli and the β-decay spectrum



β-decay before 1930

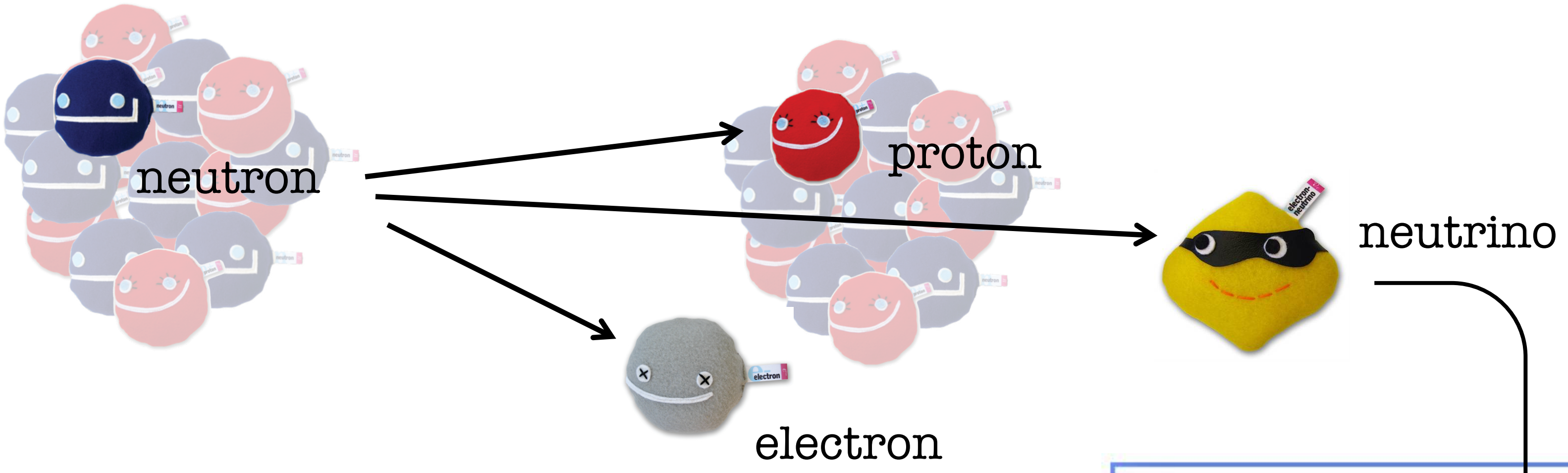
In this case, all electrons would have the same momentum, which would be the difference of the initial and final nuclear state



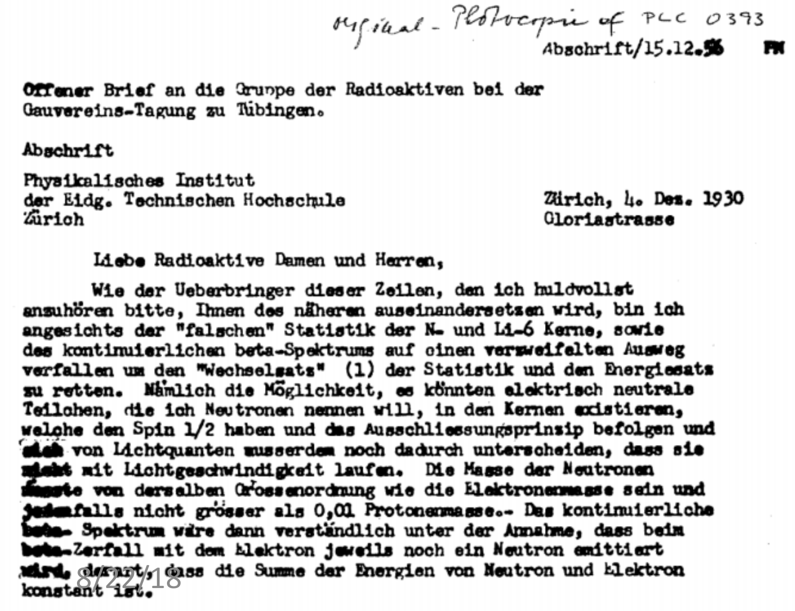
But:

Chadwick et al. observed a continuous electron momentum spectrum

Wolfgang Pauli and the β-decay spectrum



Wolfang Pauli postulated the neutrino in 1930



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Abschrift/15.12.56 FM

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

Abschrift

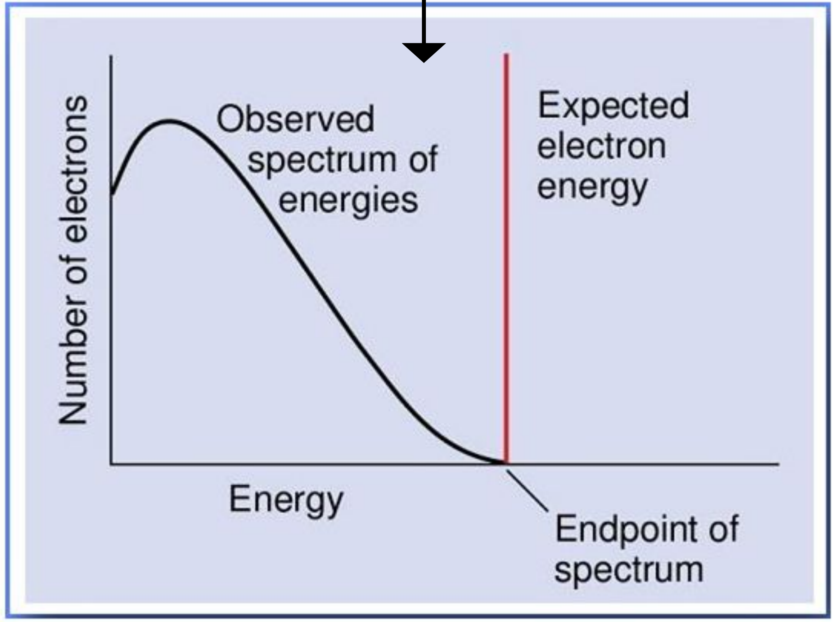
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

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

Explains the continuous decay spectrum



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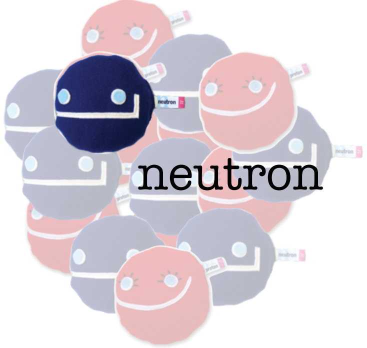
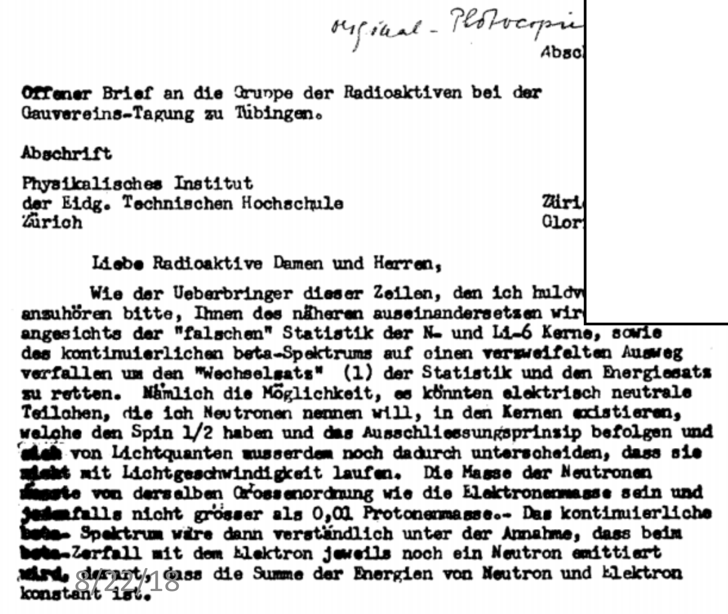


I have done a terrible thing,

I have postulated a particle

that can not be detected.



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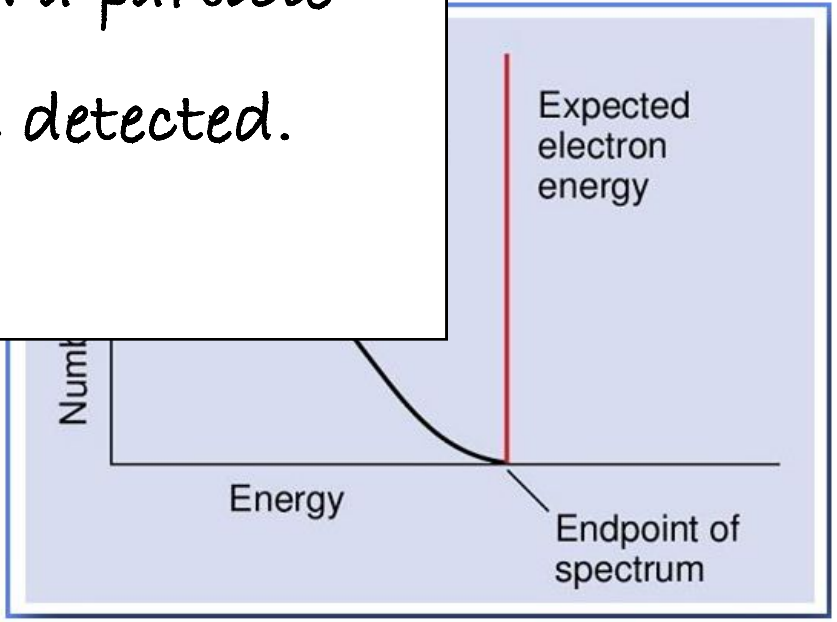
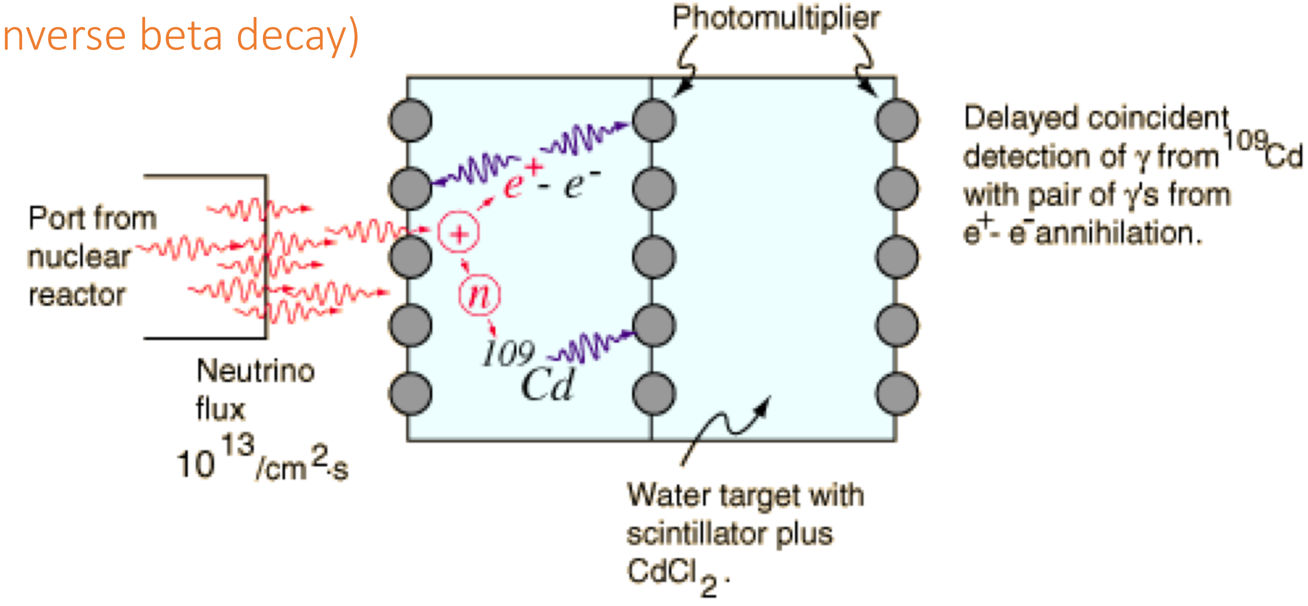
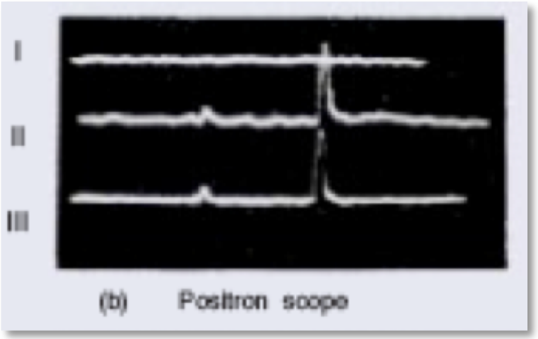
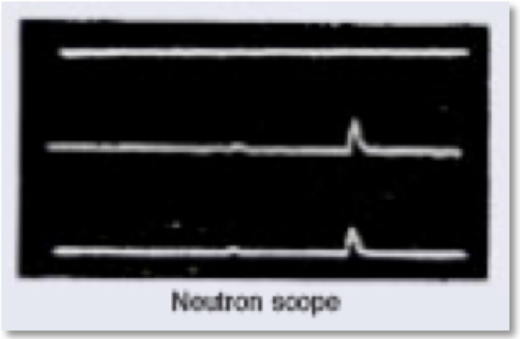


Cowan & Reines & the antineutrino discovery

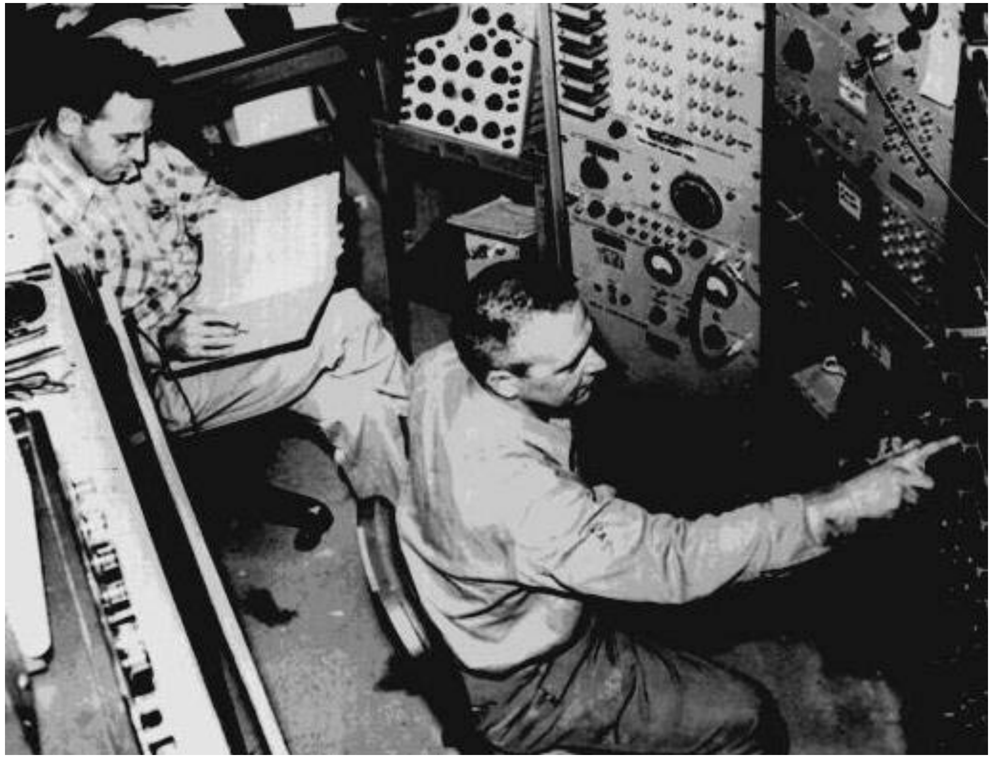
$\bar{\nu}_e + p \rightarrow e^+ + n$
(inverse beta decay)







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



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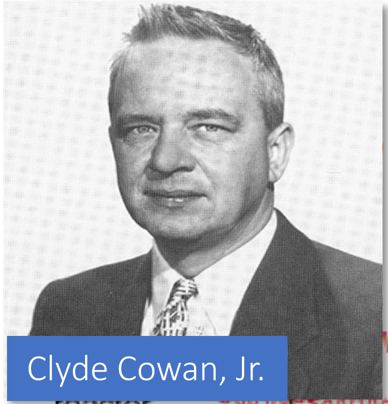
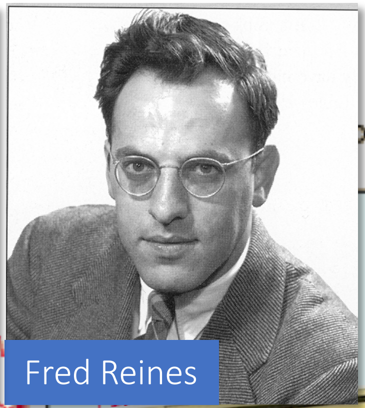
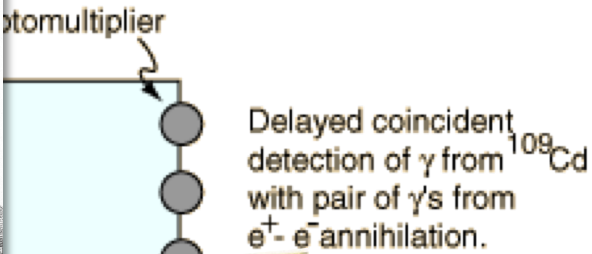
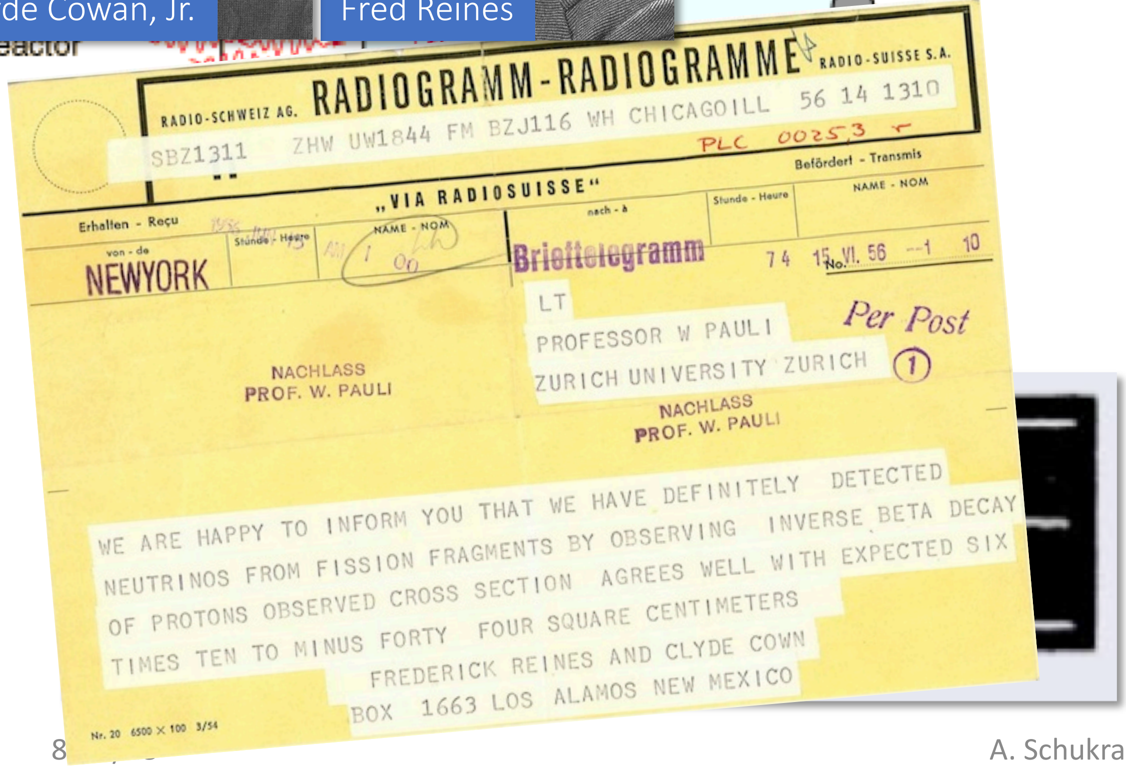

Clyde Cowan, Jr.


Fred Reines

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Per Post

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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

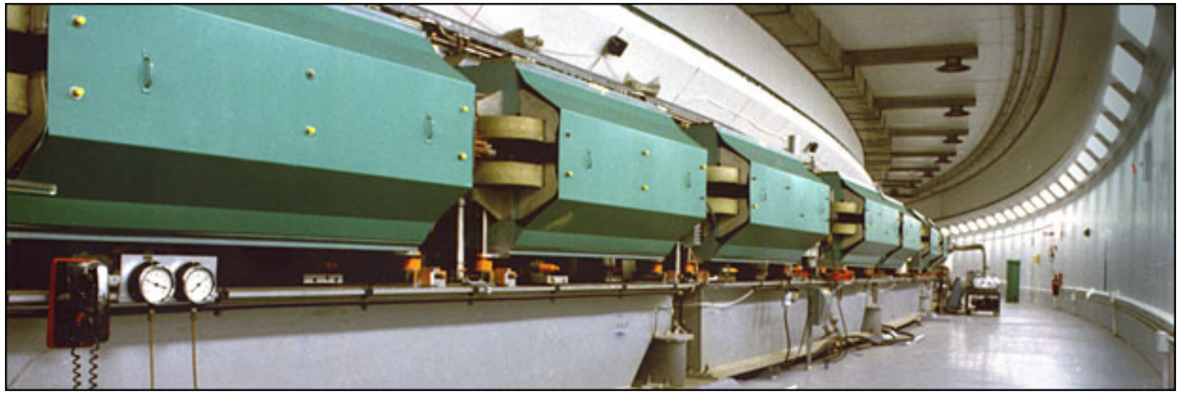
Nr. 20 6500 × 100 3/54

Cow

liquid scintillator de

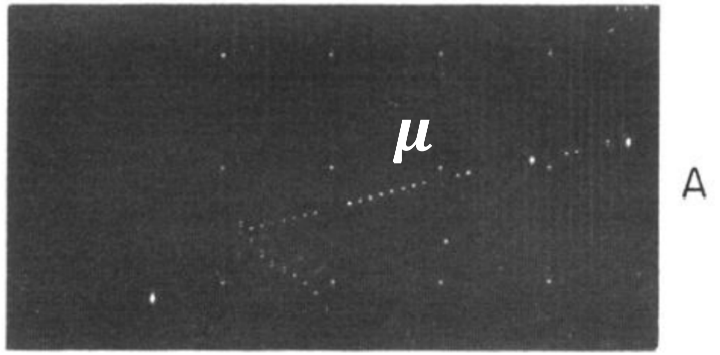
th

The discovery of the muon neutrino

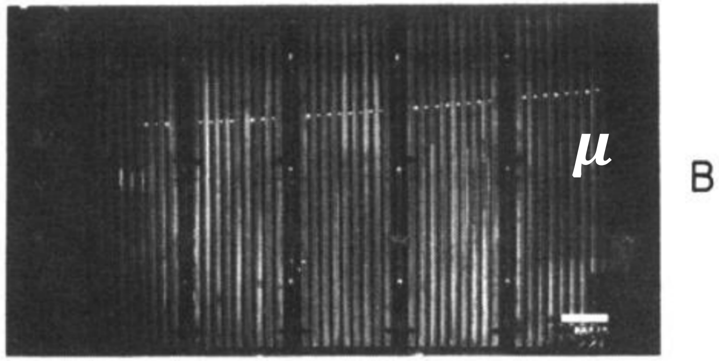


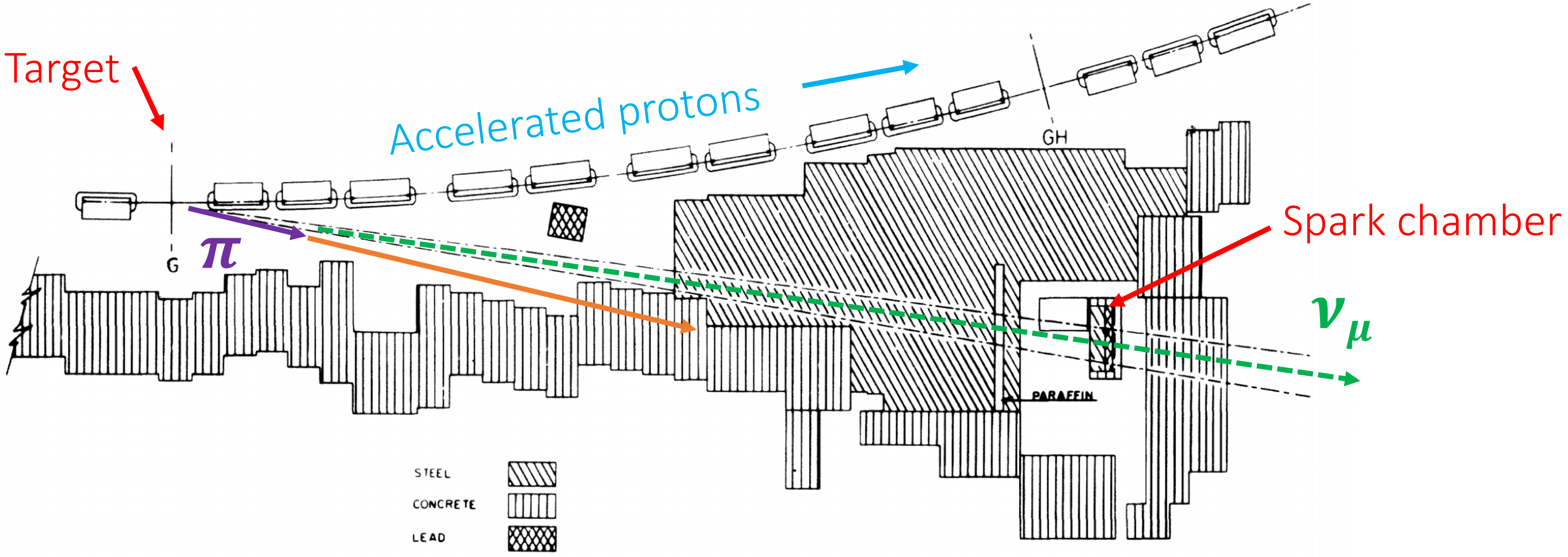
Lederman, Schwartz & Steinberger used neutrinos produced in pion decays in the BNL Alternating gradient synchrotron

“Vertex event”



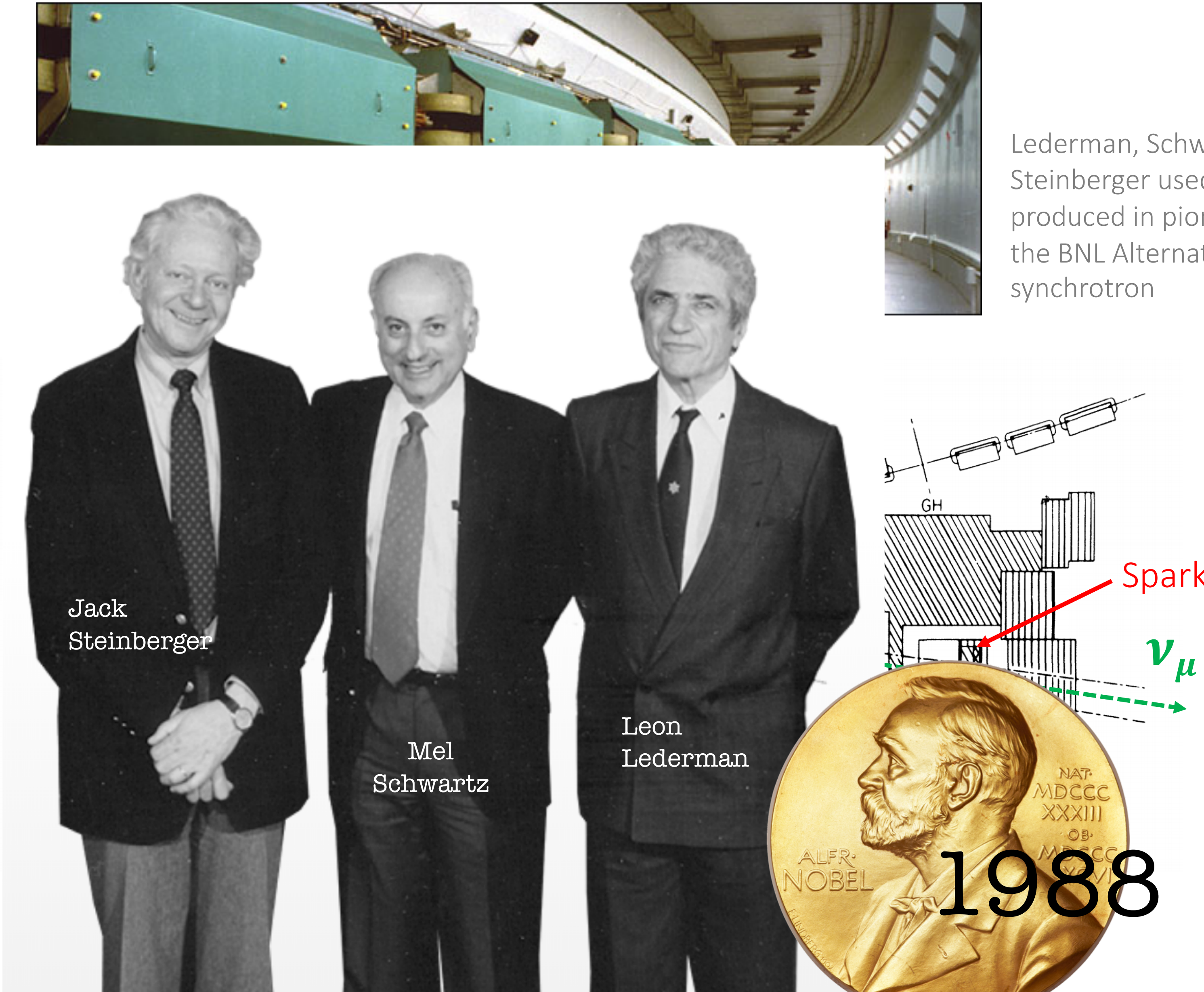
“Single muon event”





Dominantly muon events were found over electron events, indicating a new species of neutrinos (1962)

The discovery of the muon neutrino



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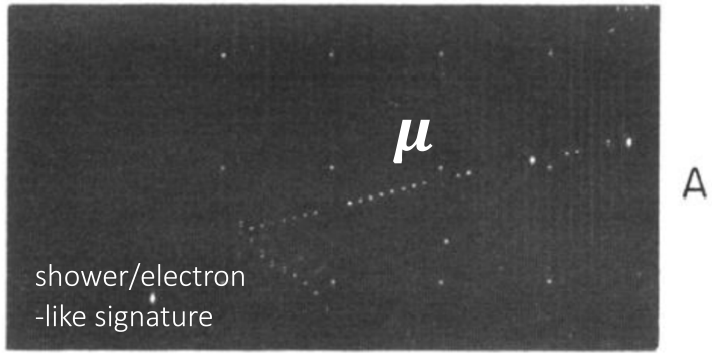

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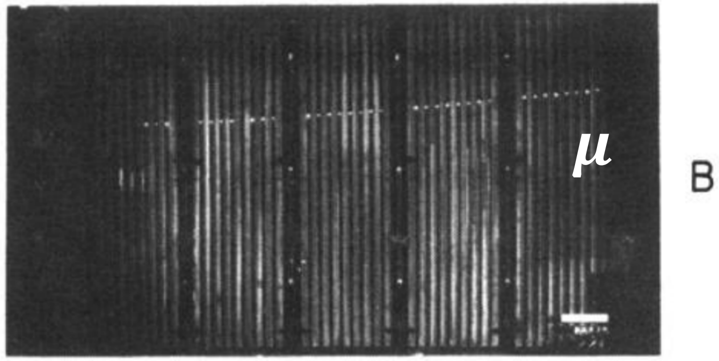

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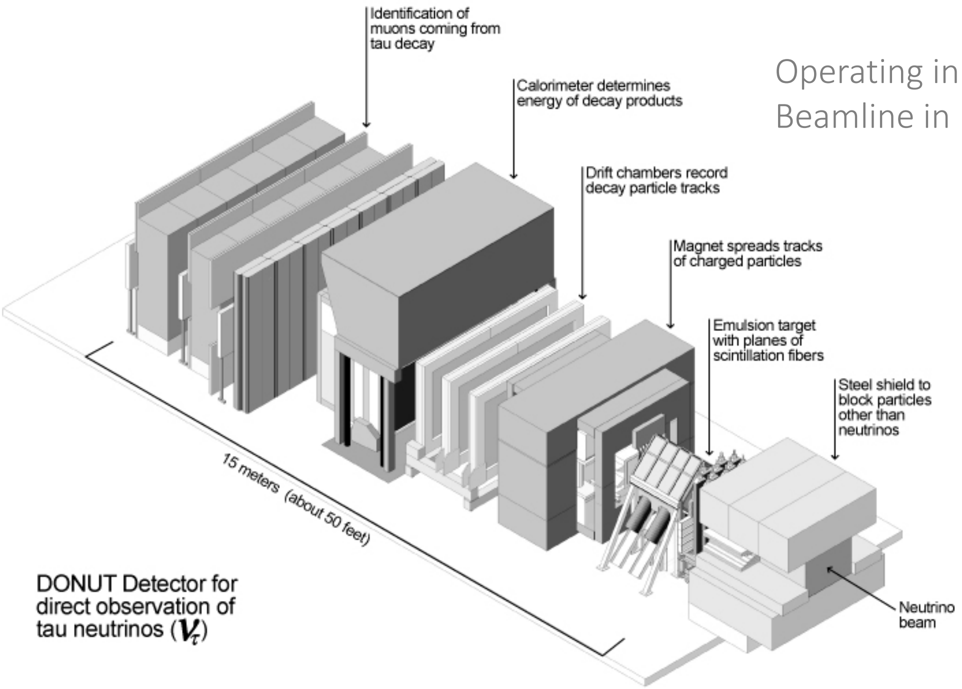
The discovery of the tau neutrino

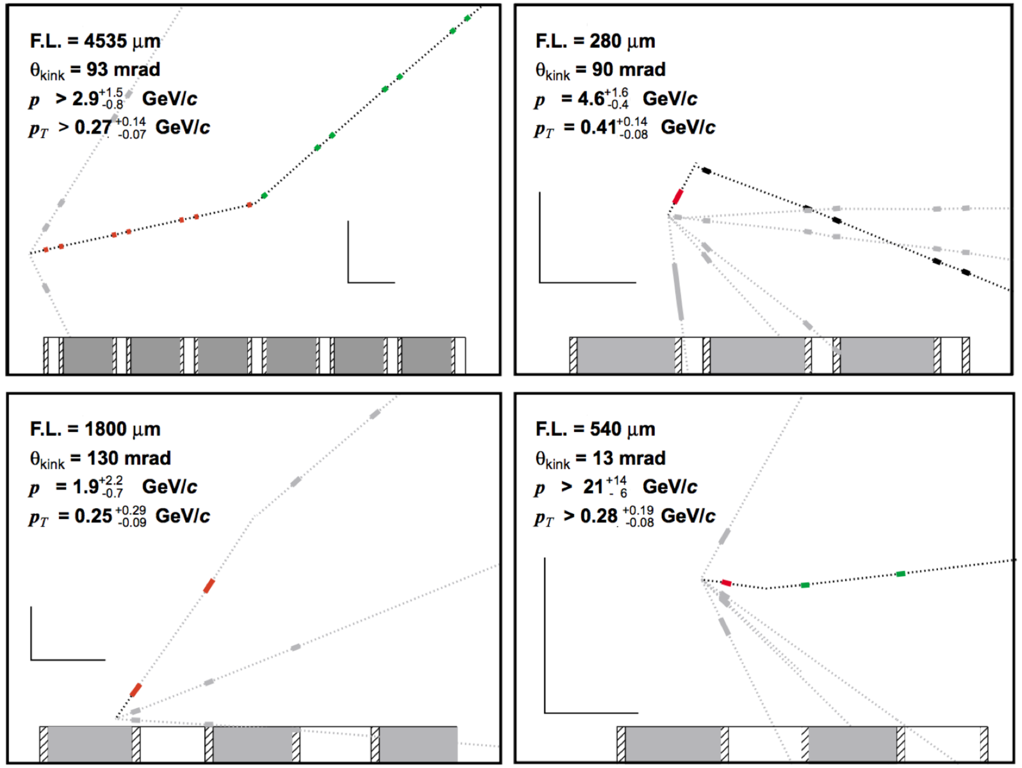
- After the discovery of the tau lepton (70s), physicists immediately expected there would also be a tau neutrino

- Challenge:
  The tau is heavy (m_τ = 1.78 GeV, m_μ = 106 MeV, m_e = 511 keV)
  $\Longrightarrow \nu_\tau$ production requires decay of charmed mesons.

DONUT Detector



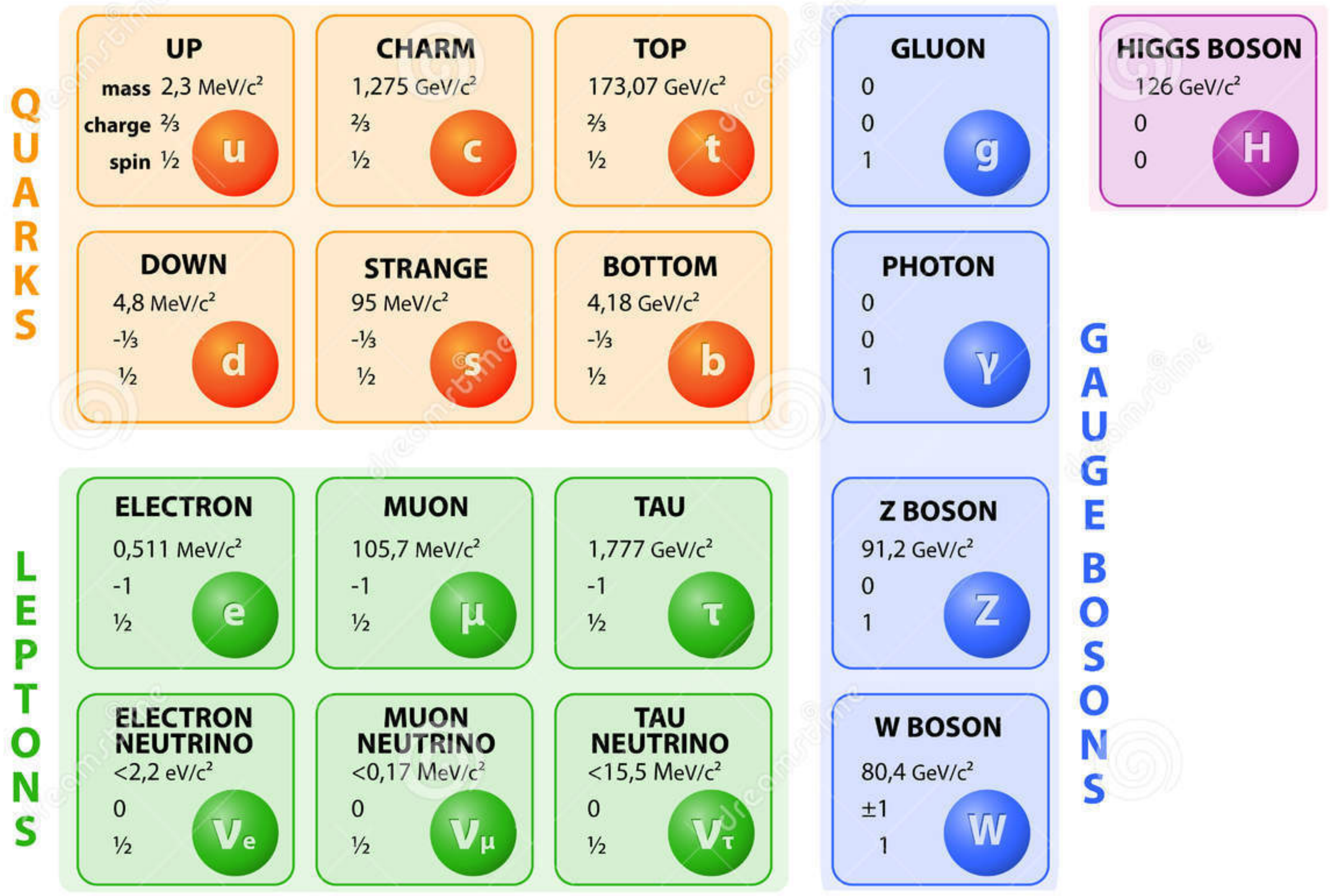
Operating in Fermilab Beamline in 1997



Four candidate events announced in 2000.
τ identified through decay into μ.
(Background expectation was only 0.2 events.)

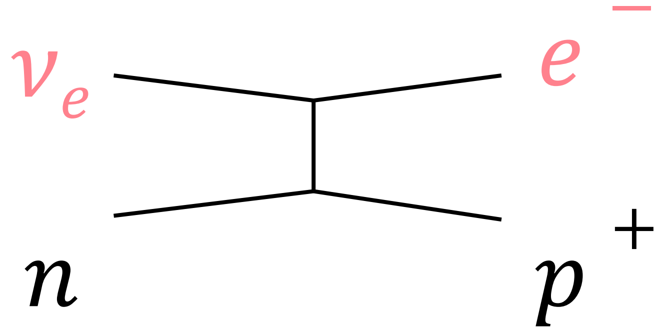
Last missing piece to the standard model besides the Higgs.

Neutrinos in the standard model

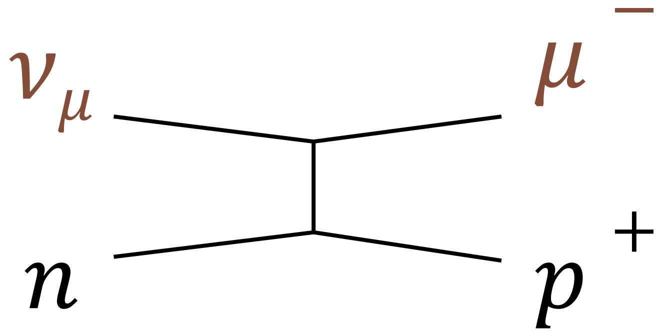


QUARKS	**UP** mass 2,3 MeV/c^2 charge ⅔ spin ½ u	**CHARM** 1,275 GeV/c^2 ⅔ ½ c	**TOP** 173,07 GeV/c^2 ⅔ ½ t	**GLUON** 0 0 1 g	**HIGGS BOSON** 126 GeV/c^2 0 0 H
	DOWN 4,8 MeV/c^2 -⅓ ½ d	**STRANGE** 95 MeV/c^2 -⅓ ½ s	**BOTTOM** 4,18 GeV/c^2 -⅓ ½ b	**PHOTON** 0 0 1 γ	
LEPTONS	**ELECTRON** 0,511 MeV/c^2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

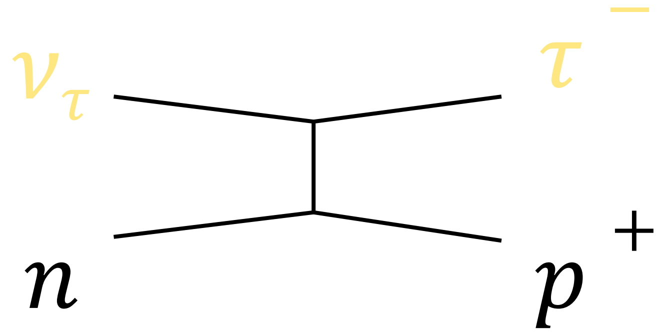
electron-neutrino



muon-neutrino



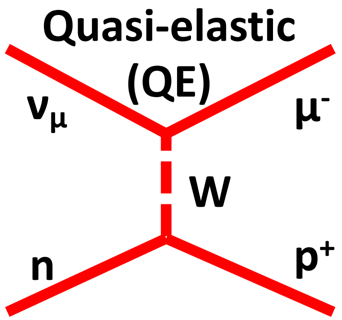
tau-neutrino

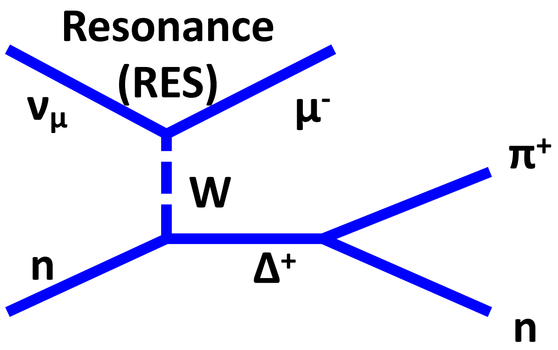


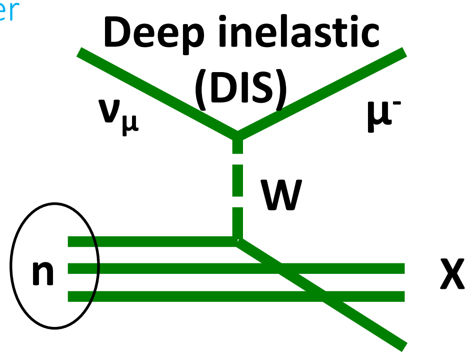
Neutrino cross sections

Neutrinos are only weakly interacting. This is a challenge for every neutrino experiment!

Dominant interaction processes at typical energies in neutrino physics

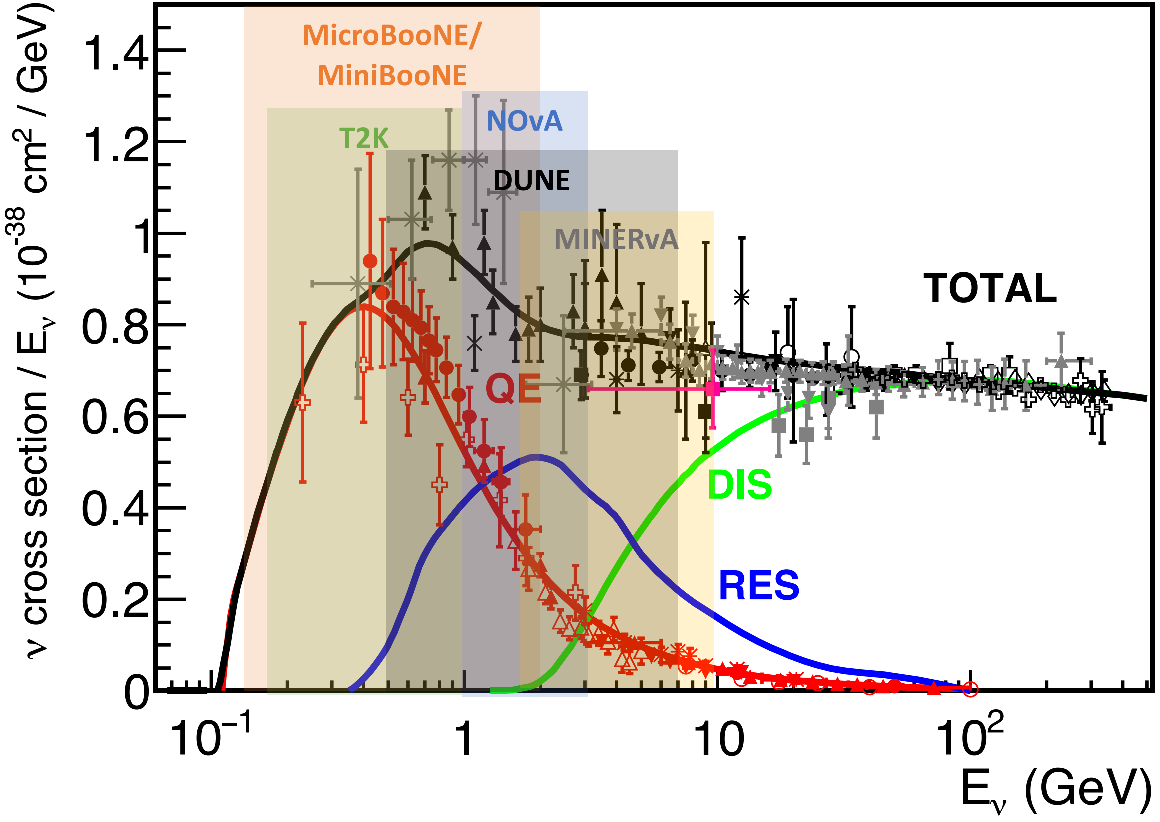






Most modern experiments use heavy nuclear target materials (C, Ar, …) and the neutrino doesn't scatter off a free nucleon. This brings is complicated nuclear physics!!! This is not easy!!!

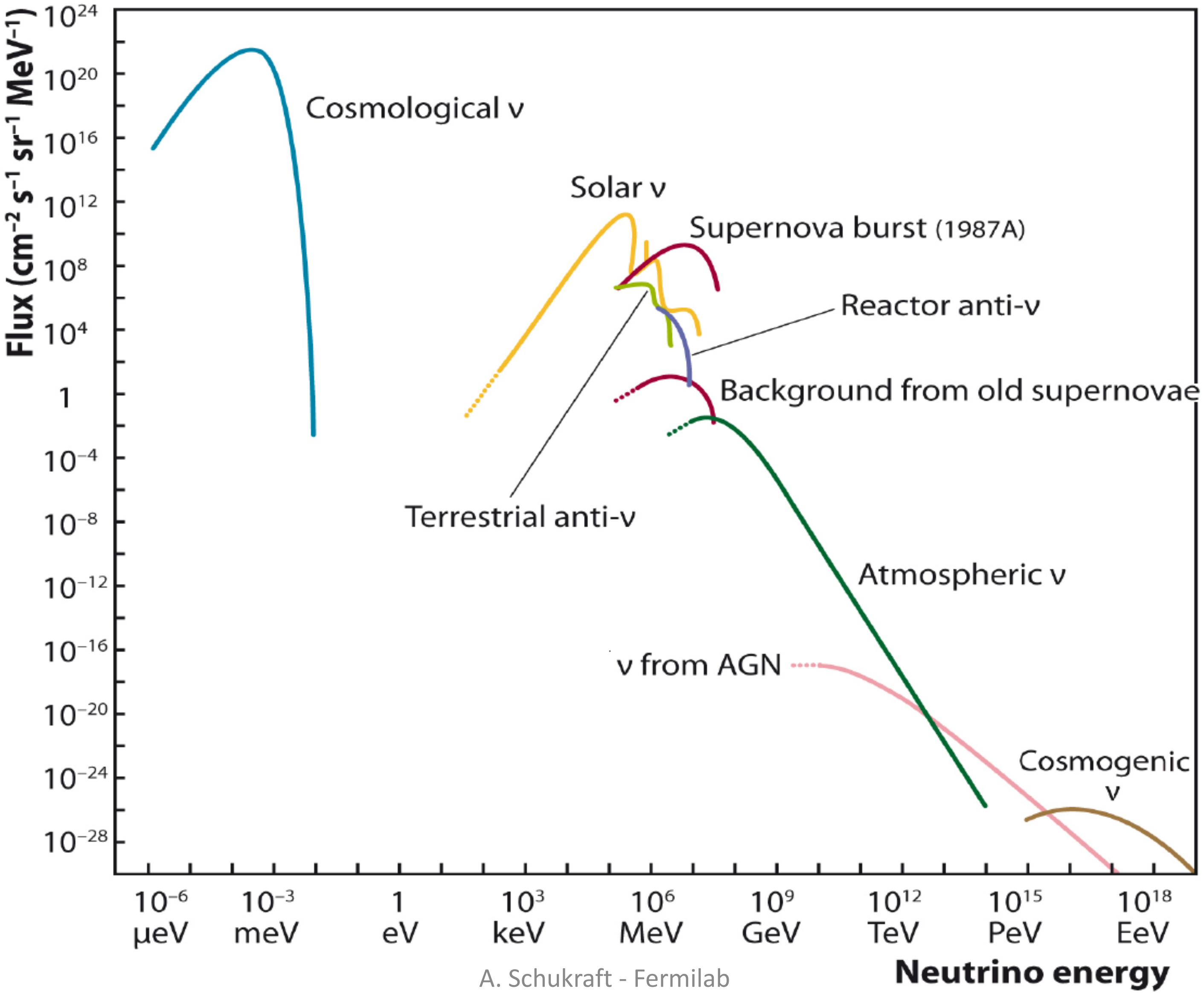
+ equivalent NC processes



A. Schukraft, G. Zeller

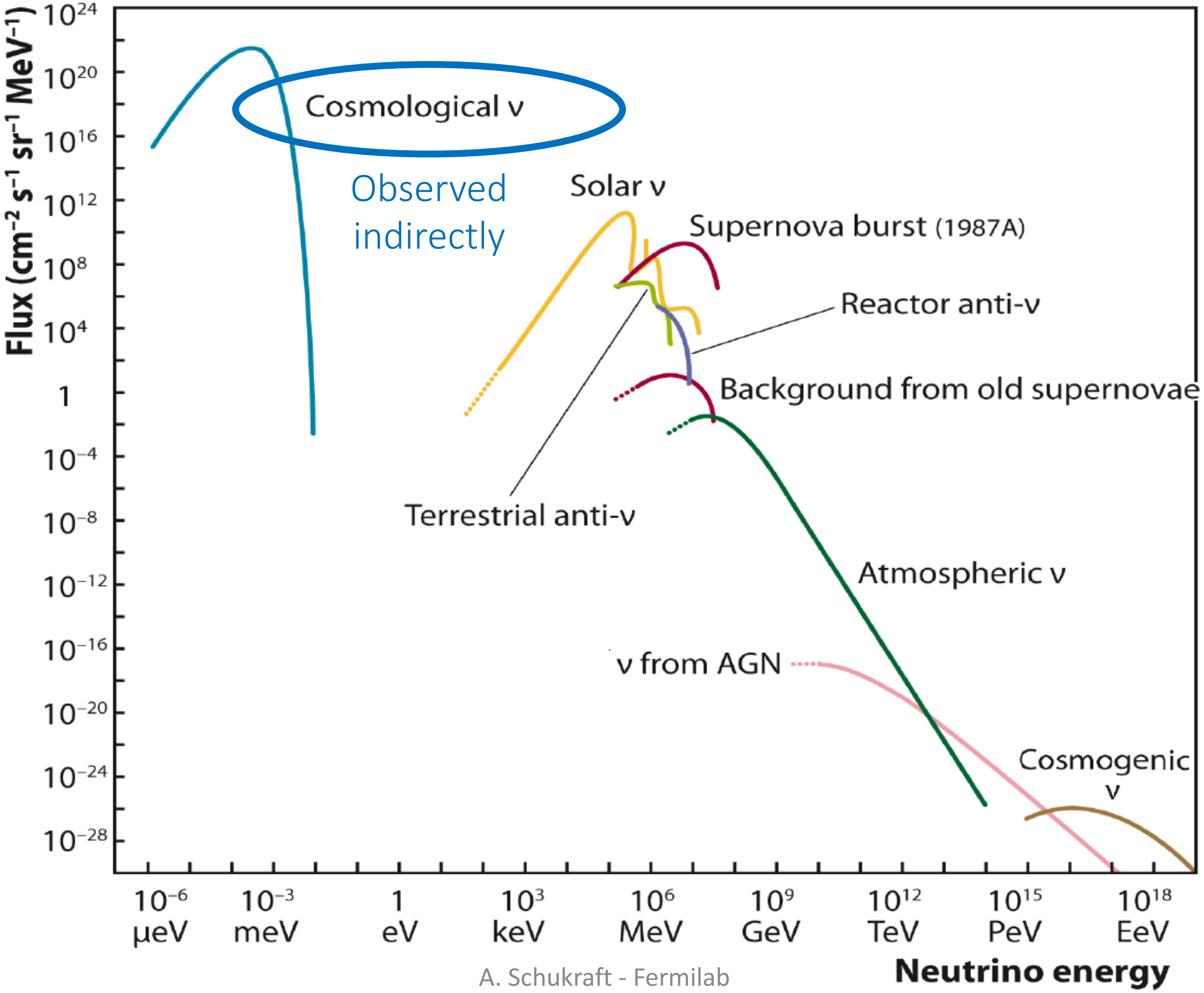
The mean free path of a 1GeV neutrino in rock is 6x10^8 km. That's 50,000 times the diameter of the Earth.

Neutrino sources



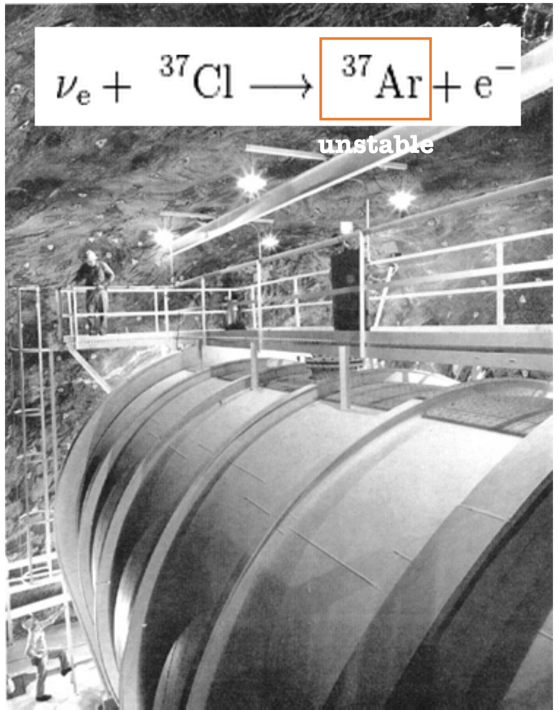
Neutrino sources

- Also called “cosmic neutrino background” or “relic neutrinos”
- Produced in the big bang, and due to low interaction probability of neutrinos still around today
- Today’s temperature: 1.95 K
  (compare to 2.7 K for CMB)
- Due to low energy, not yet directly detectable
- Observed indirectly through cosmology observations. The existence of relic neutrinos affects the anisotropy of the CMB

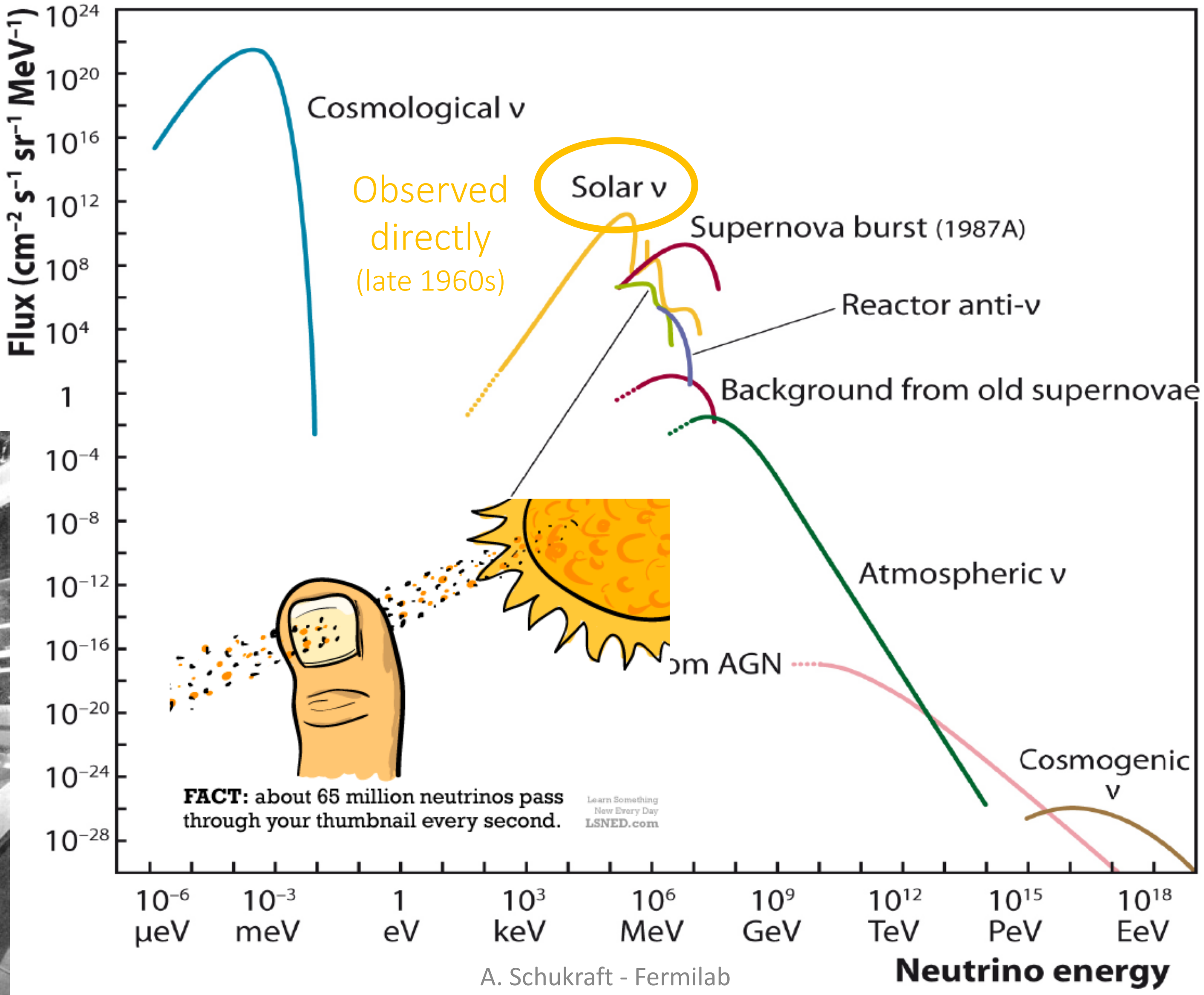


Neutrino sources

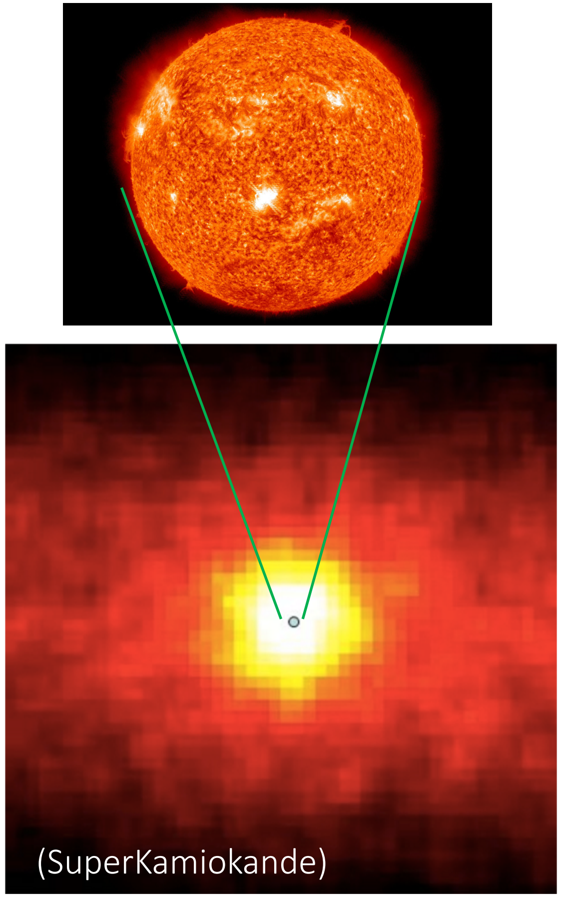
- The sun produces ν_e in nuclear fusion processes
- Strongest source in our neighborhood!
- Discovered in an experiment at Homestake Mine in South Dakota through neutrino capture:

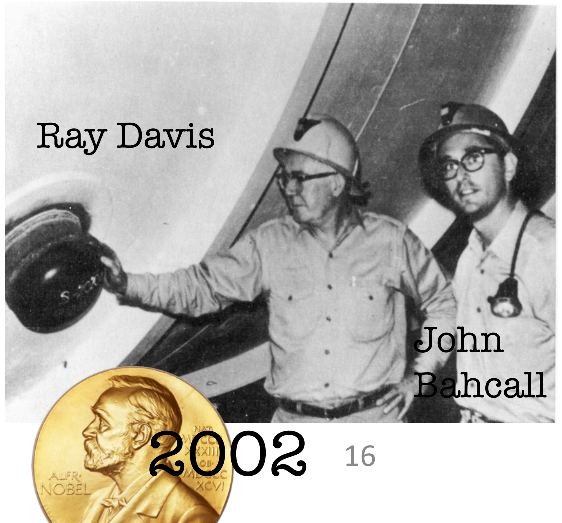


$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow \boxed{{}^{37}\mathrm{Ar}} + e^-$$



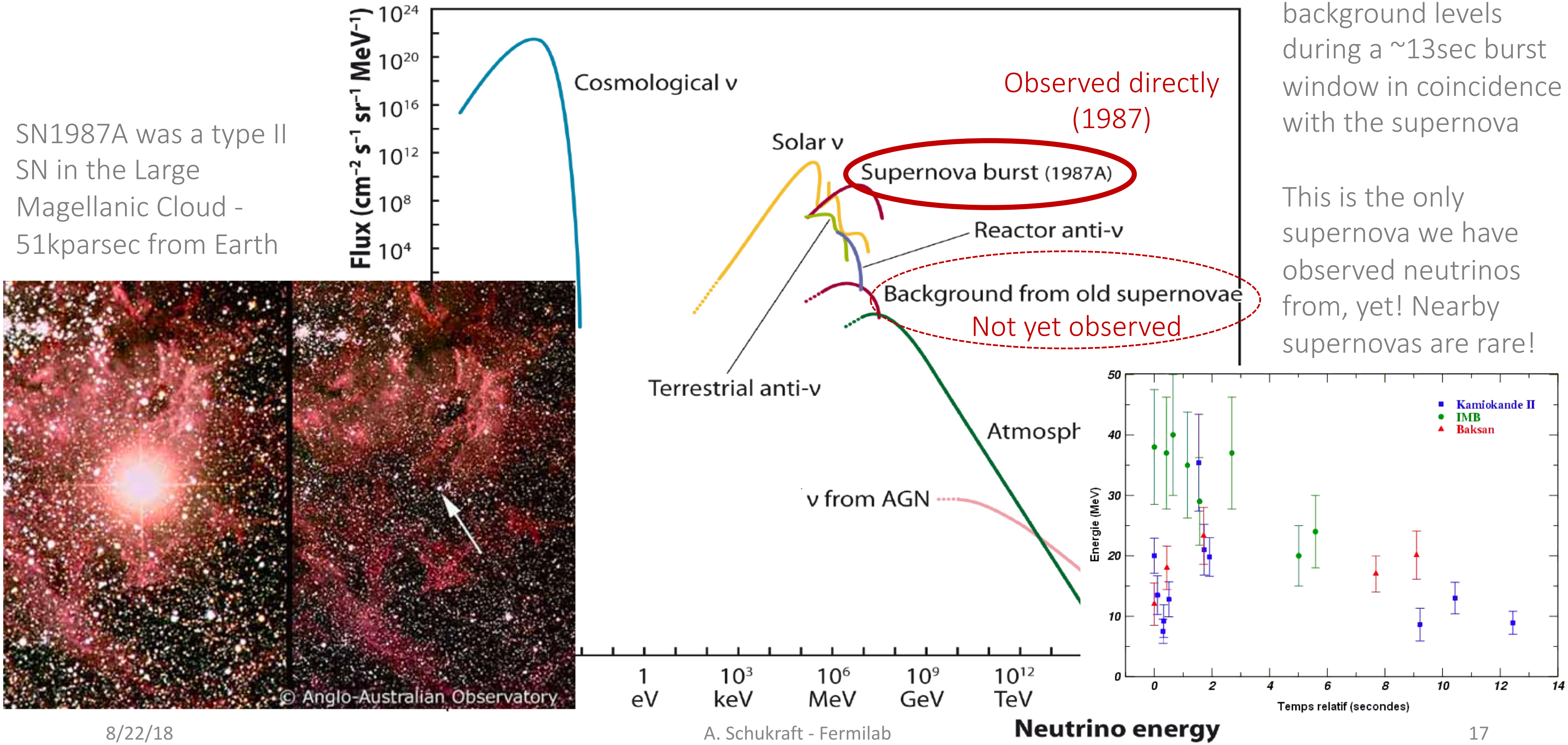
FACT: about 65 million neutrinos pass through your thumbnail every second.





Neutrino sources

SN1987A was a type II SN in the Large Magellanic Cloud - 51kparsec from Earth



Observed directly (1987)

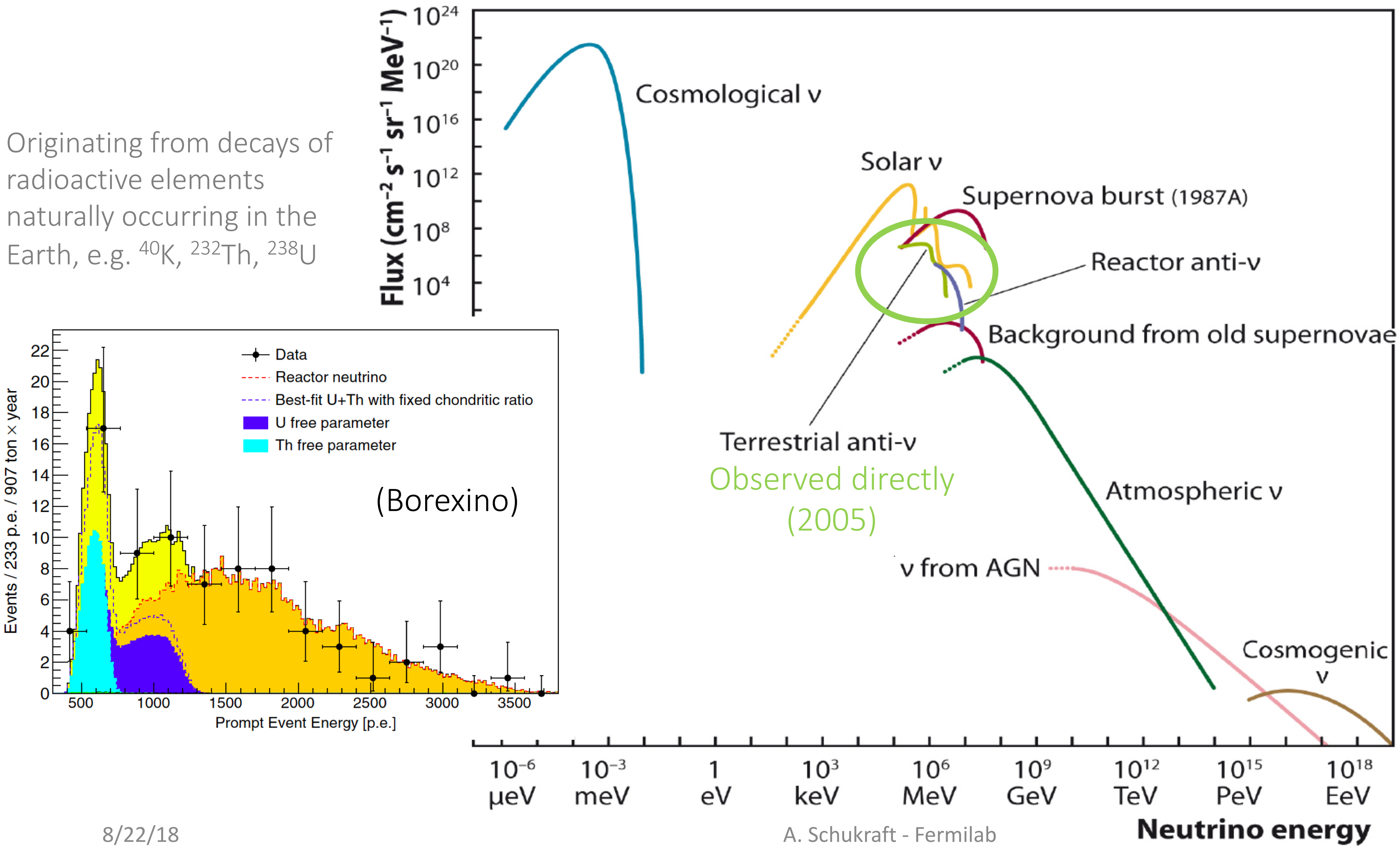
Not yet observed

Three different experiments observed a neutrino rate above background levels during a ~13sec burst window in coincidence with the supernova

This is the only supernova we have observed neutrinos from, yet! Nearby supernovas are rare!

Neutrino sources

Originating from decays of radioactive elements naturally occurring in the Earth, e.g. ^{40}K, ^{232}Th, ^{238}U



Observed directly (2005)

(Borexino)

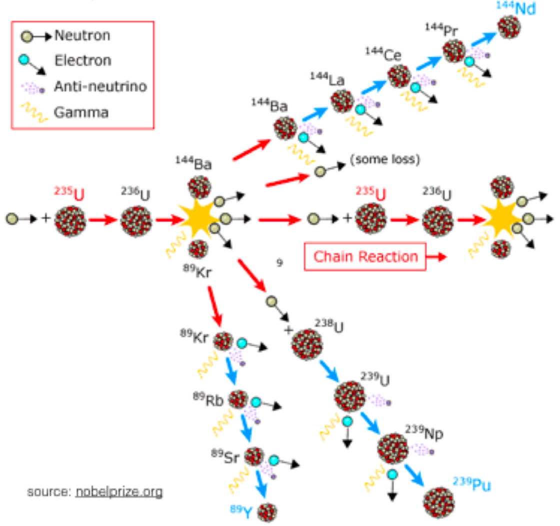
Other neutrino sources with Potassium decay:

358 mg / 100gm
-> 1 million neutrinos/day

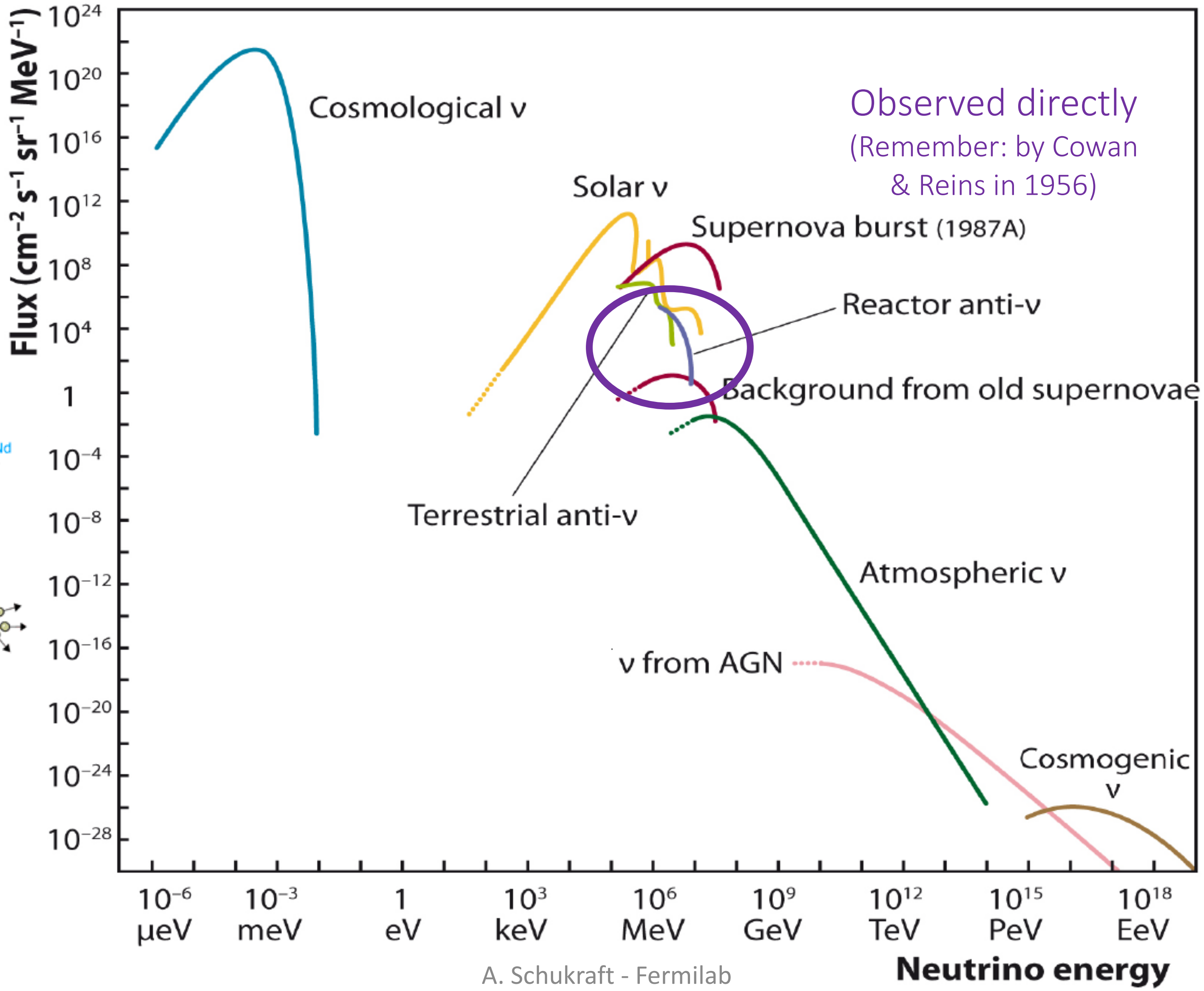
485 mg / 100gm

Neutrino sources

Electron-antineutrinos are produced in nuclear fission processes

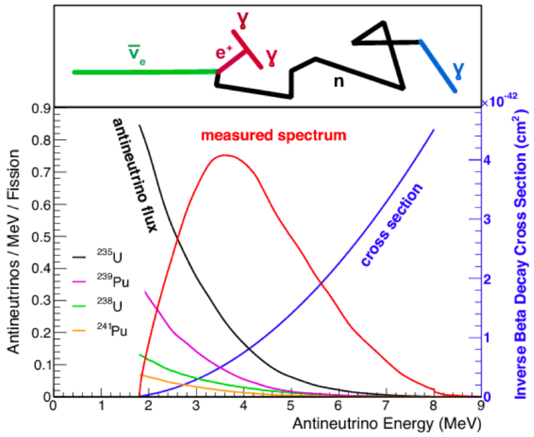

fission process in a nuclear reactor

source: nobelprize.org



Observed directly
(Remember: by Cowan & Reins in 1956)

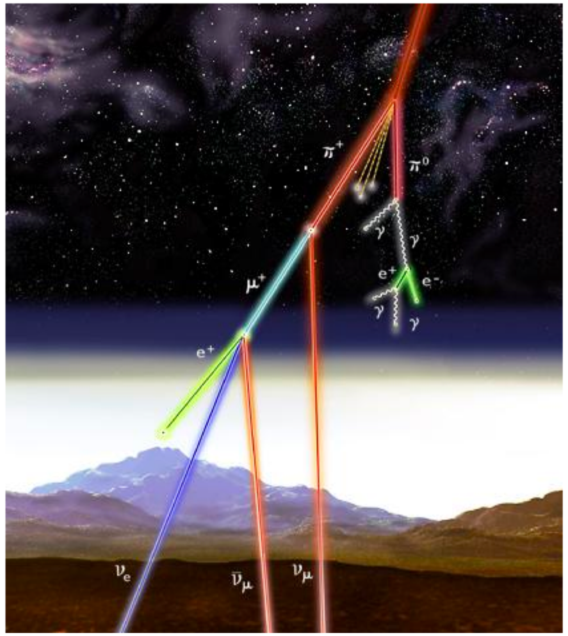
Reactors enabled the first discovery of neutrinos!

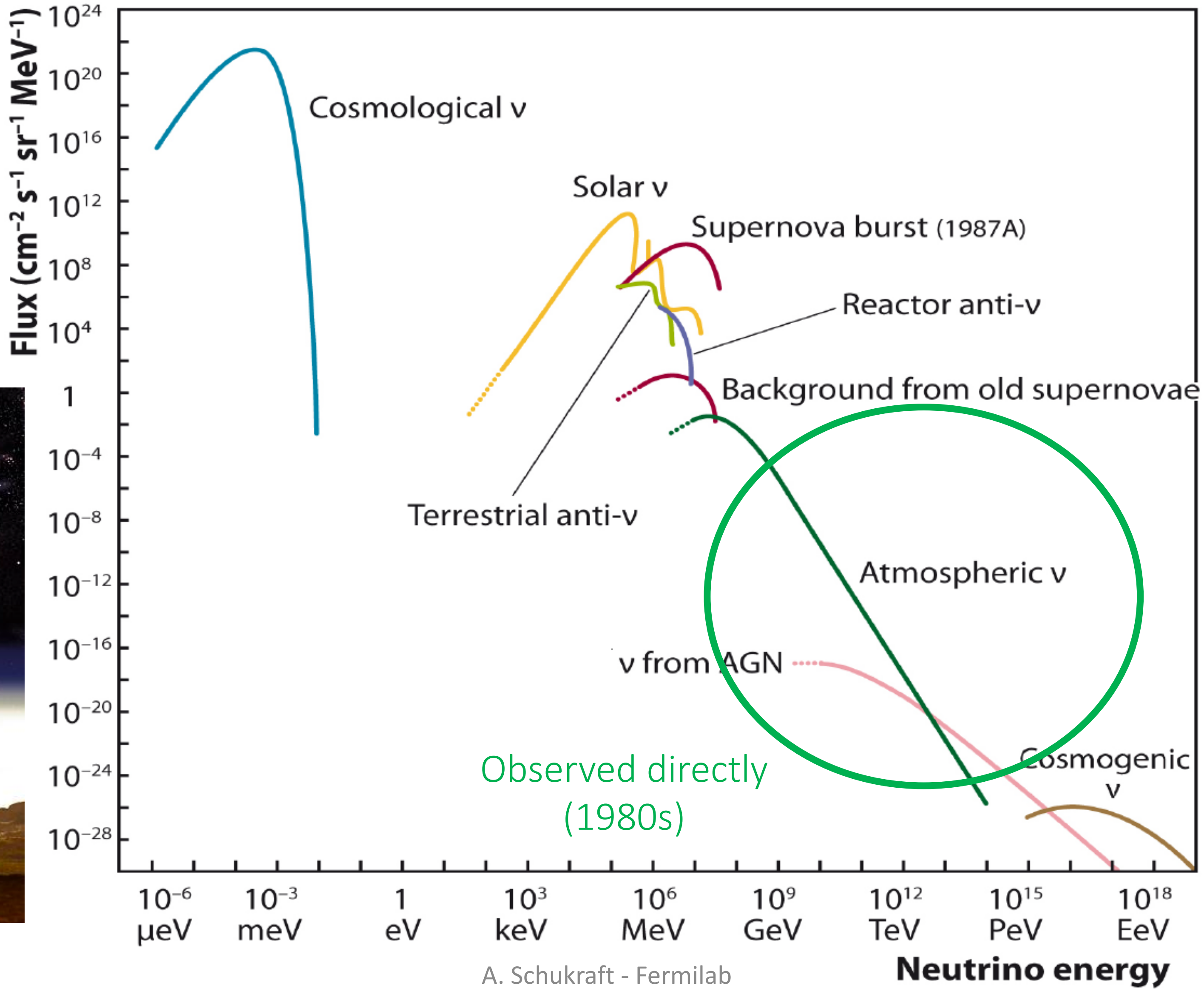


Today, we have several neutrino oscillation experiments placed nearby nuclear reactors

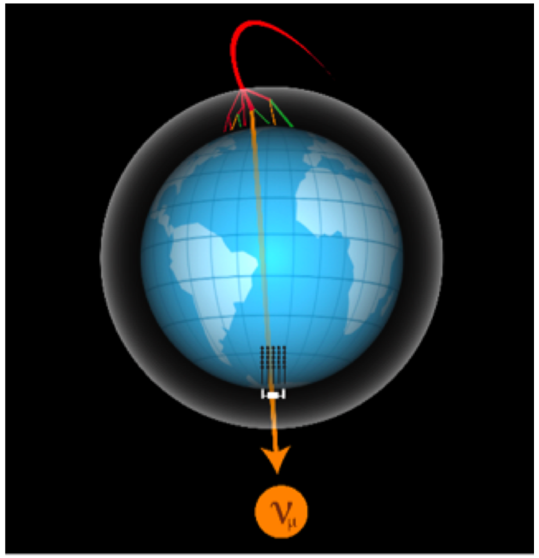
Neutrino sources

Atmospheric neutrinos (and muons) are produced when high-energy cosmic rays hit the Earth atmosphere and create a shower





Observed directly
(1980s)



To distinguish atmospheric neutrinos from atmospheric muons, experiments often look for particles coming through the entire Earth so they can be sure it is a neutrino.

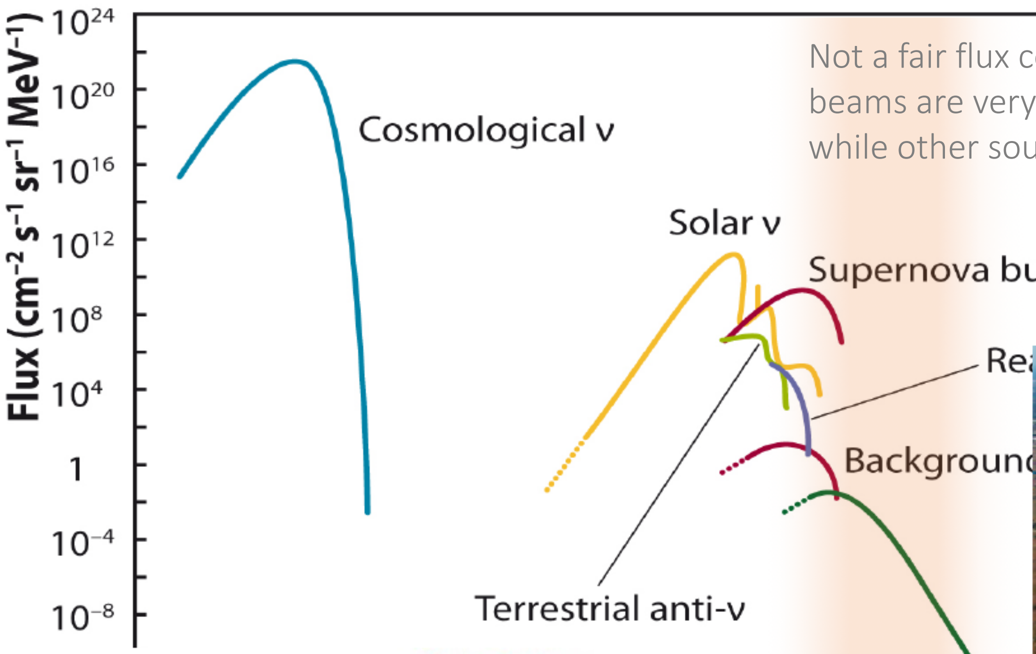
Neutrino sources

For precision
neutrino experiments
(since 1980s)

- p accelerated in accelerators and directed to a target
- High-energy π are produced and focused
- π decay into μ and ν. μ are absorbed by rock.

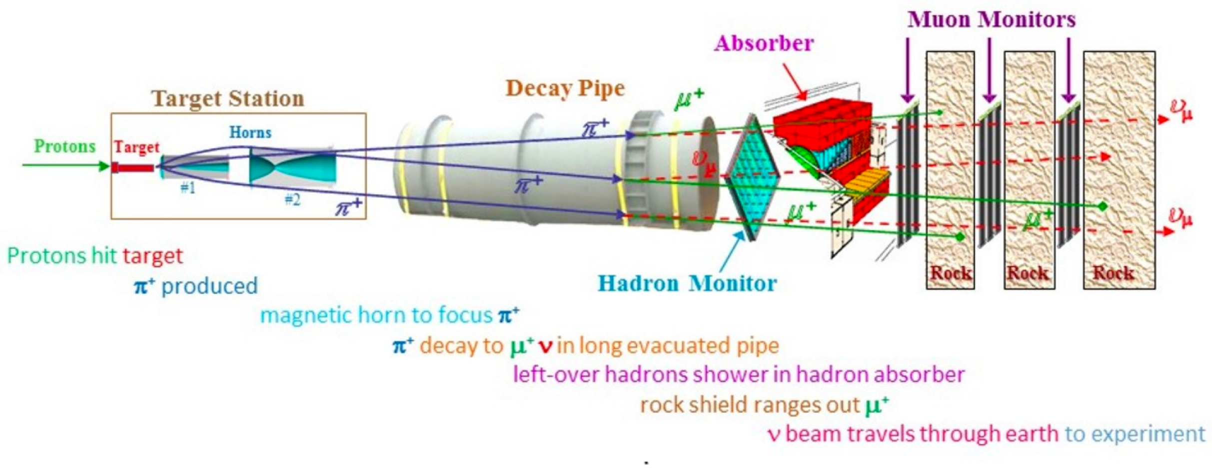
$$\pi \rightarrow \mu + \nu\mu$$

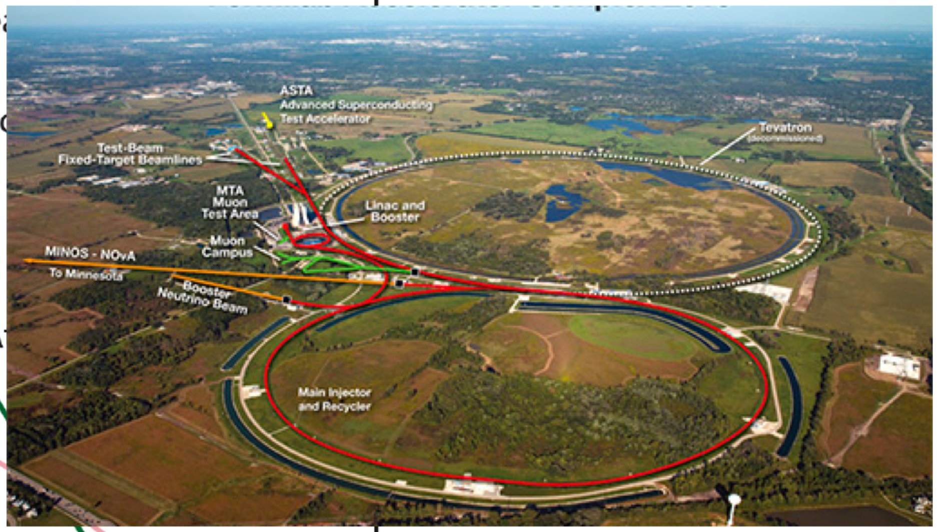
- Can be a ν_μ or anti-ν_μ beam depending on the charge of the π that are being focused!



Not a fair flux comparisons because beams are very intense but directed, while other sources are isotropic)

Fermilab currently operates two neutrino beams simultaneously (different energies)



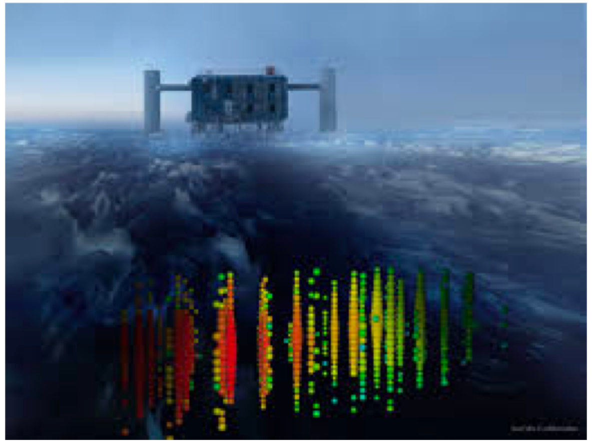


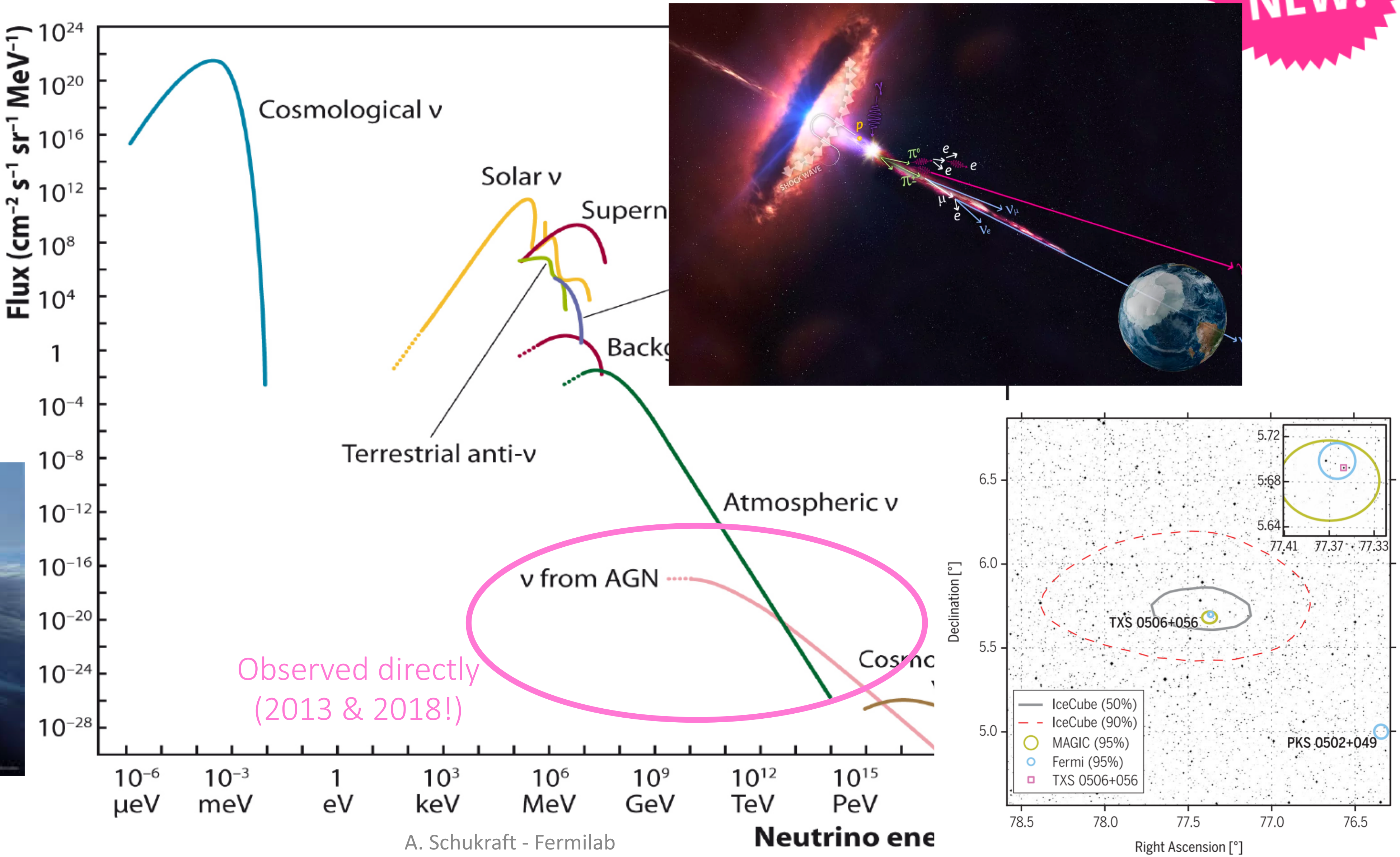
Neutrino sources

Announced
July 12th, 2018!!!

BRAND NEW!

- Ultra-high energy neutrinos were expected to be produced in the same processes as cosmic rays and high-energy gamma rays.
- First time evidence for a extragalactic neutrino flux in 2013, but sources could not yet be identified
- **First time evidence for a neutrino source in 2018!!!**





Observed directly
(2013 & 2018!)

Neutrino sources

- At energies > 5 x 10^{19} eV, it is expected that cosmic rays interact with photons of the cosmic microwave background

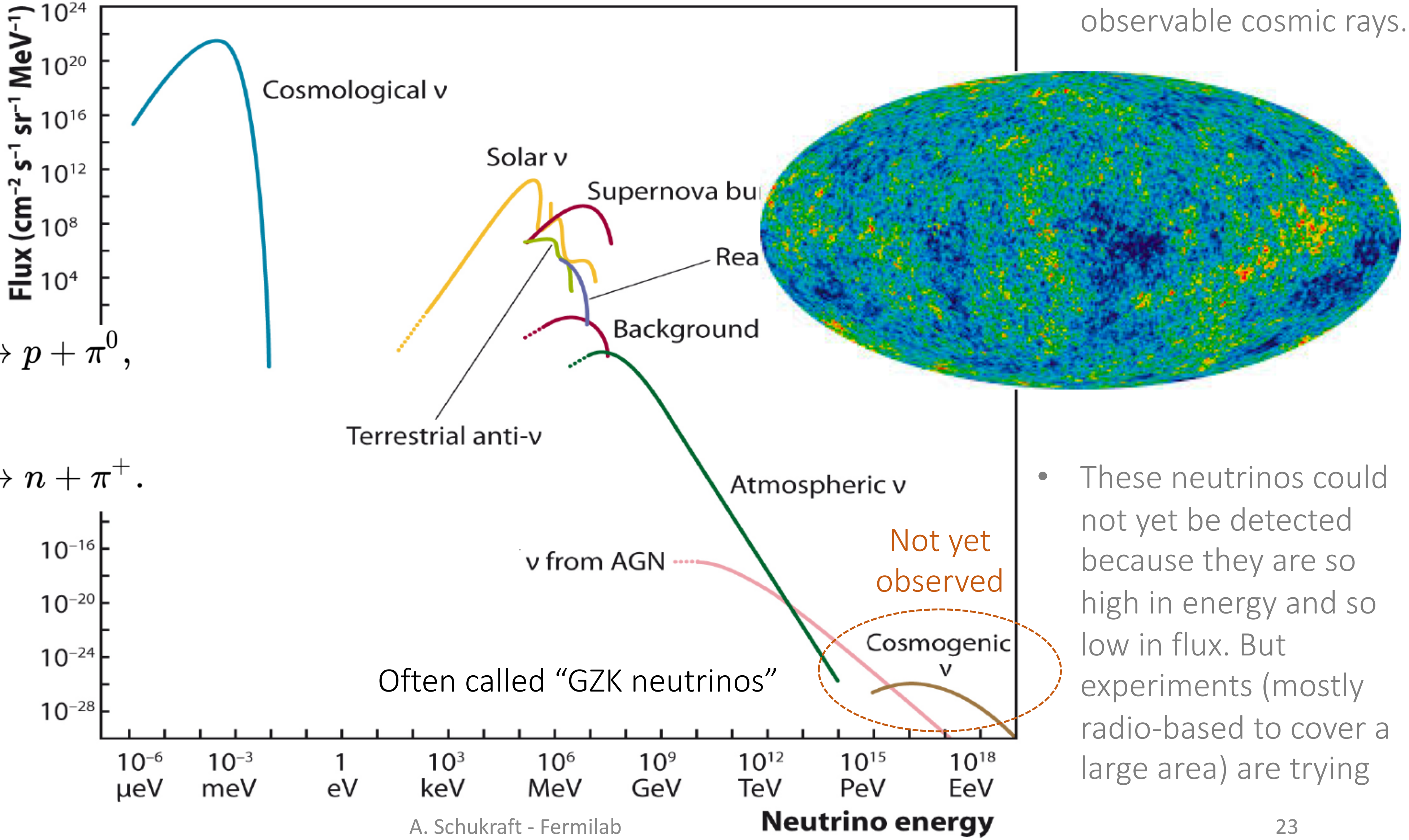
$$\gamma_{\rm CMB} + p \rightarrow \Delta^{+} \rightarrow p + \pi^{0},$$

or

$$\gamma_{\rm CMB} + p \rightarrow \Delta^{+} \rightarrow n + \pi^{+}.$$

- This reaction would produce extremely high energetic neutrinos (EeV energies)

- This also sets a limit to the energy of observable cosmic rays.

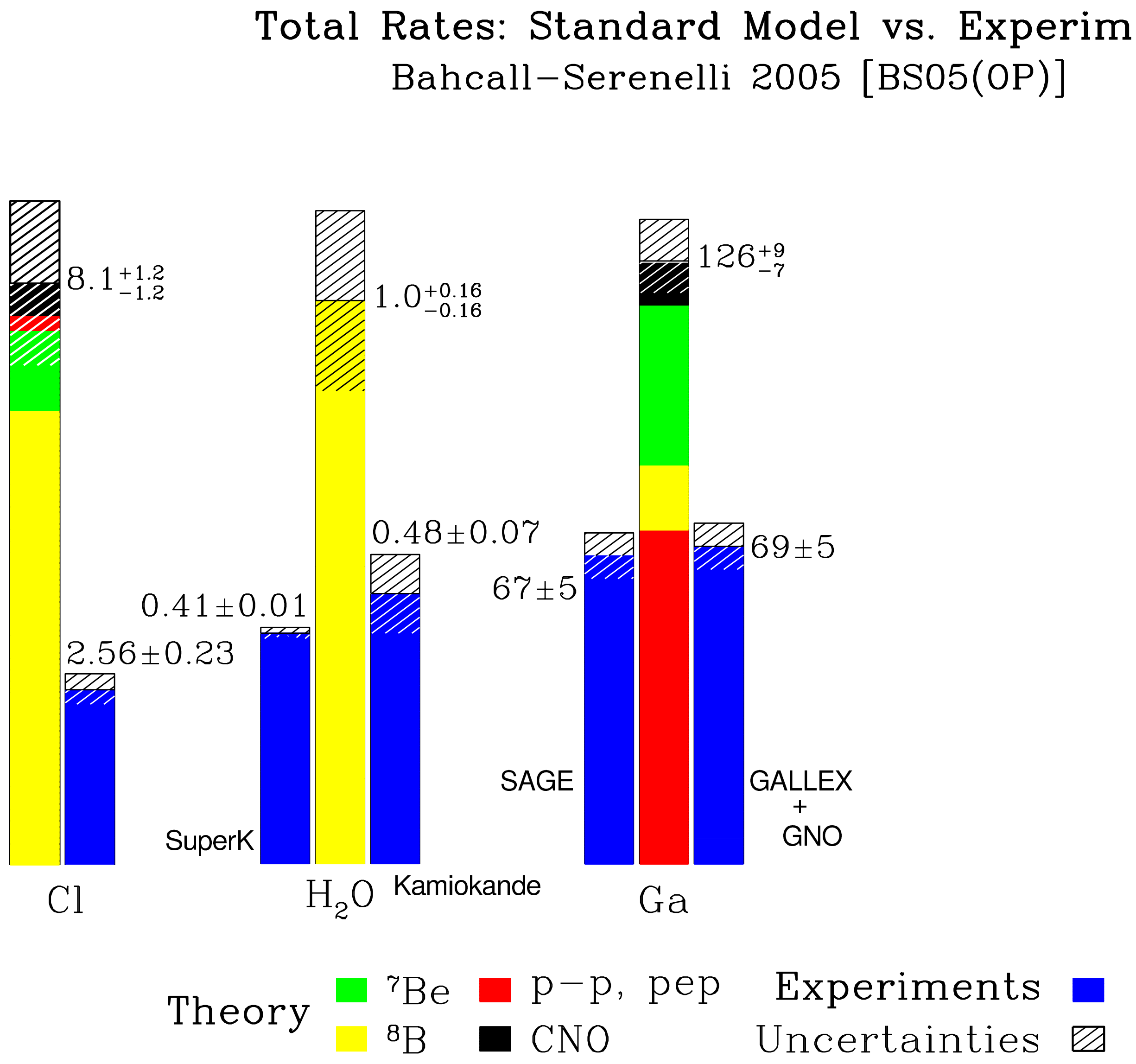


Not yet observed

Often called “GZK neutrinos”

- These neutrinos could not yet be detected because they are so high in energy and so low in flux. But experiments (mostly radio-based to cover a large area) are trying

The solar neutrino puzzle



- In the late 60s, experiments with different detection technologies measured the fluxes of solar neutrinos
- The sun produces exclusively electron neutrinos in fusion processes. The expected flux can be calculated based on our knowledge of the sun.
- All experiments measured significantly LESS neutrinos than predicted.

The proposed solution

- Neutrino flavor eigenstates are not the same as neutrino mass eigenstates.
- Neutrinos are detected as flavor eigenstates, but their propagation is described by its mass eigenstates.
- The two relate through the PMNS matrix.

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

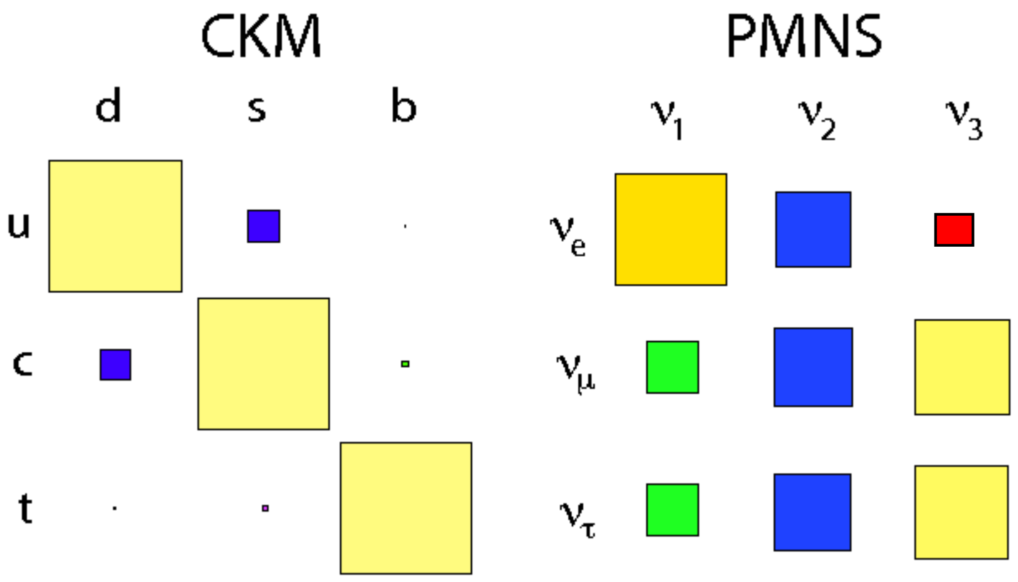
PMNS matrix

Production & Detection

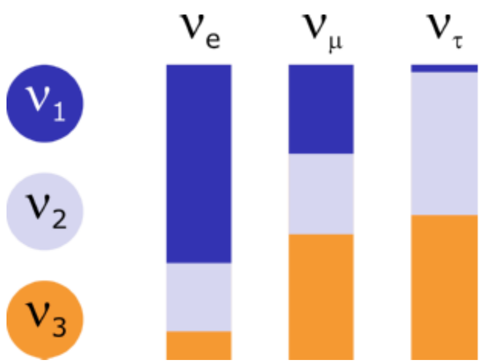
Wave function

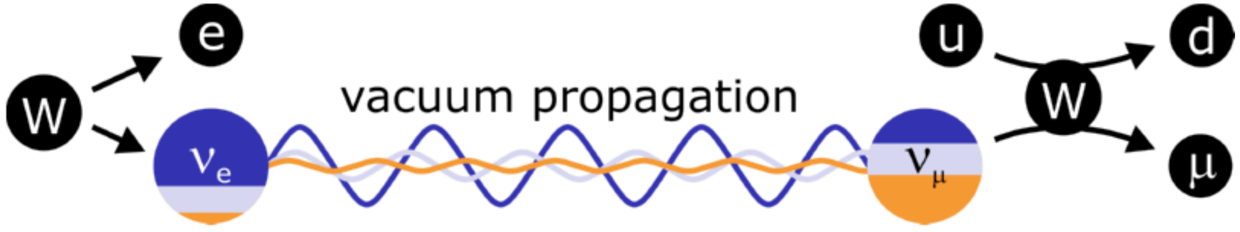
The PMNS matrix is comparable to the CKM matrix for quark mixing. However, there are open questions:

- Are the CKM and PMNS matrices related?
- Are they connected to their masses?
- They appear to be very different - why?



Neutrino oscillations





$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \underbrace{\begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}}_{\text{PMNS matrix}} \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

$$\underbrace{\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}}_{\text{Atmospheric/ Accelerator}} \underbrace{\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{bmatrix}}_{\text{Accelerator/Reactor}} \underbrace{\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}}_{\text{Solar/Reactor}}$$

3 mixing angles: θ_{12}, θ_{13}, θ_{23}

CP violating phase: δ_{CP}

+ 2 Majorana phases (not shown here)

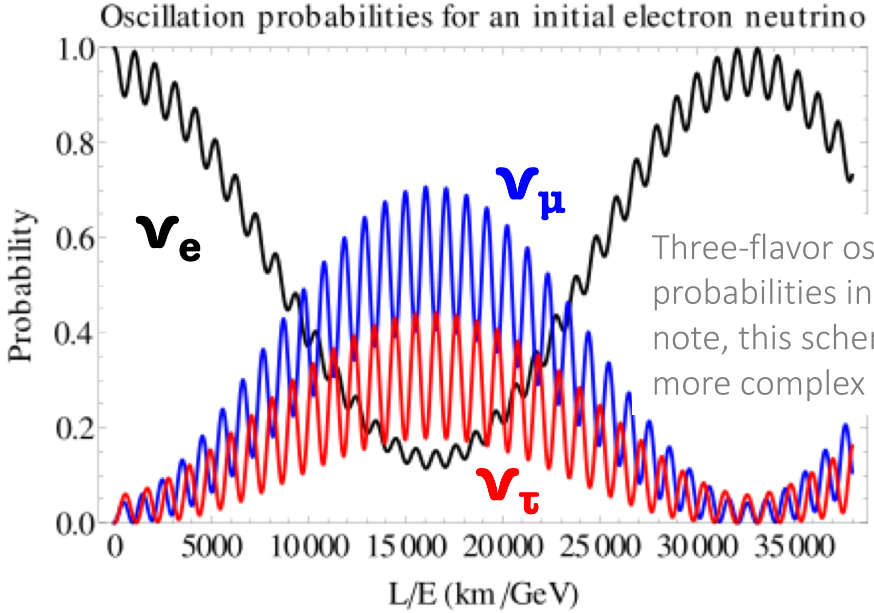
Neutrino oscillations

Neutrino experiments measure neutrino mixing parameters through appearance and/or disappearance observations

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

$$+\,2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right),$$

Appearance
$\alpha \neq \beta$
Disappearance
$\alpha = \beta$



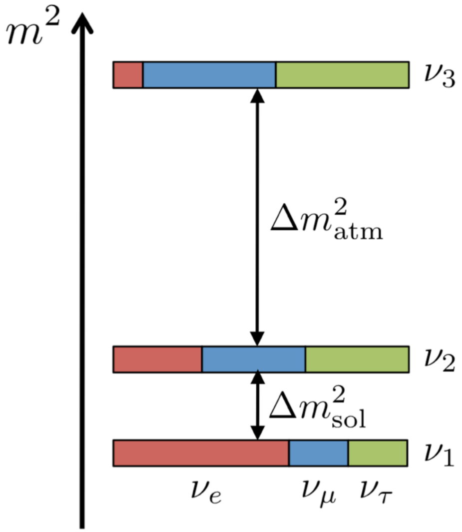
Three-flavor oscillation probabilities in vacuum – note, this scheme gets slightly more complex in matter.

Parameters characterizing the oscillation pattern need to be experimentally determined:

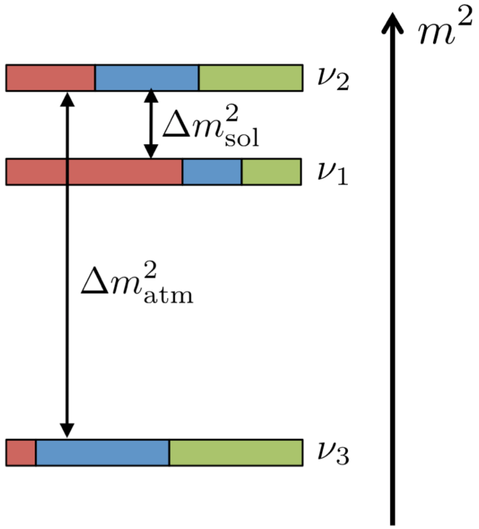
3 mixing angles: θ_{12}, θ_{13}, θ_{23}
CP violating phase: δ_{CP}

2 mass differences: Δm^2_{32}, Δm^2_{21}
Sign of Δm^2_{32}

Normal ordering

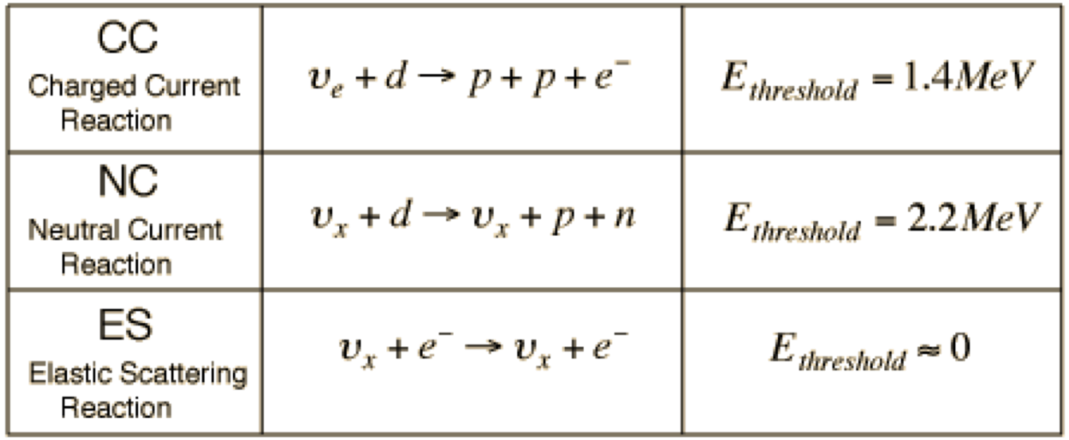


Inverted ordering



The solar neutrino puzzle solved

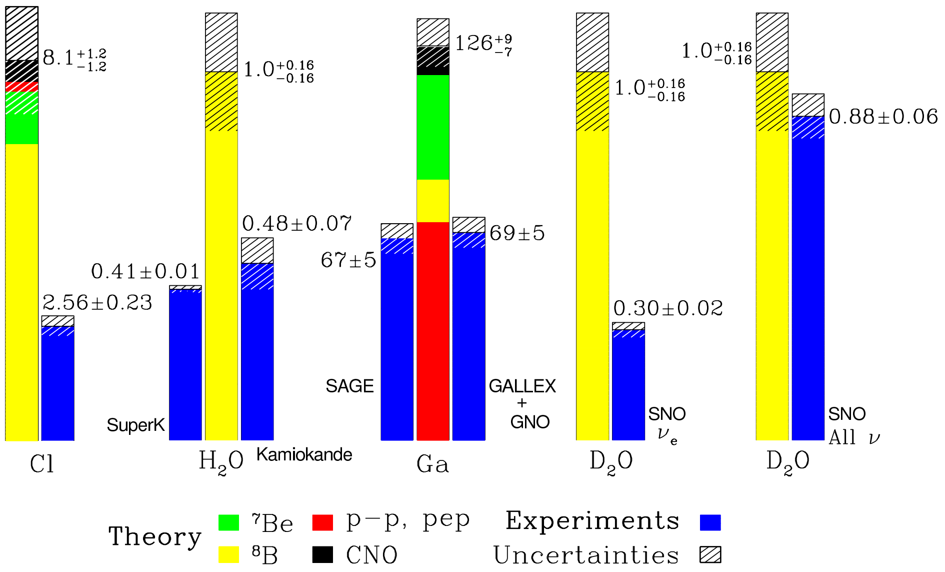
- The SNO experiment was the first experiment to be able to detect all three neutrino flavors and not just electron neutrinos.
- Looking at the some of all three neutrino flavors, the measured number of solar neutrinos matched the expectation.
- This is the first confirmation of neutrino oscillations.

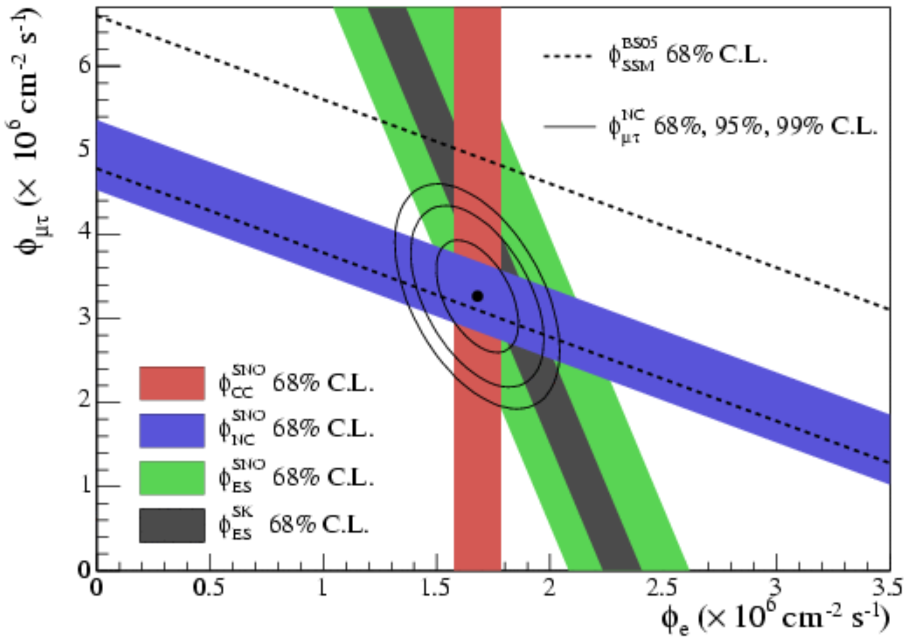


CC Charged Current Reaction	$\nu_e + d \rightarrow p + p + e^-$	$E_{threshold} = 1.4MeV$
NC Neutral Current Reaction	$\nu_x + d \rightarrow \nu_x + p + n$	$E_{threshold} = 2.2MeV$
ES Elastic Scattering Reaction	$\nu_x + e^- \rightarrow \nu_x + e^-$	$E_{threshold} \approx 0$

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

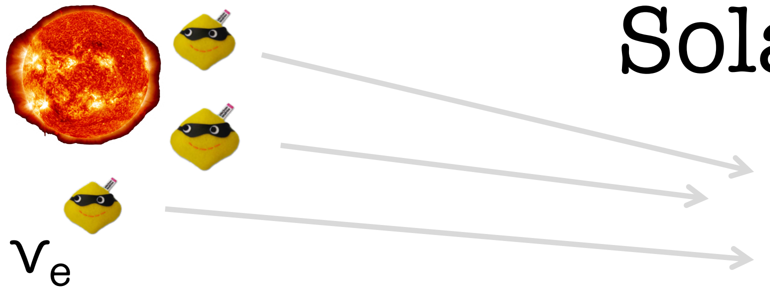
Total Rates: Standard Model vs. Experiment
Bahcall–Serenelli 2005 [BS05(OP)]

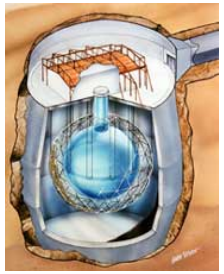




The full picture of neutrino oscillations

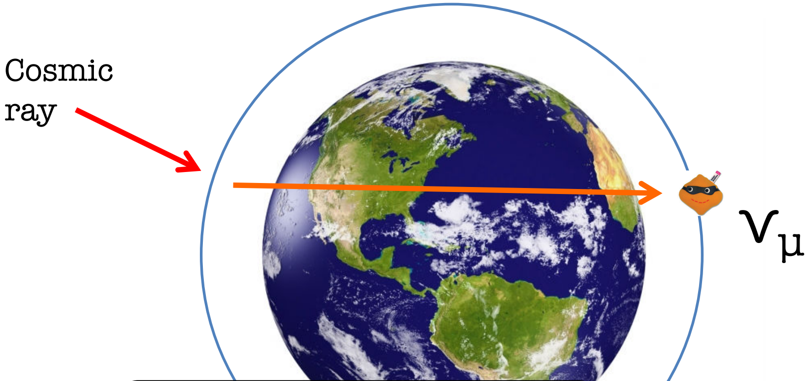
Solar





Energy: MeV
Baseline: (oscillation inside sun)

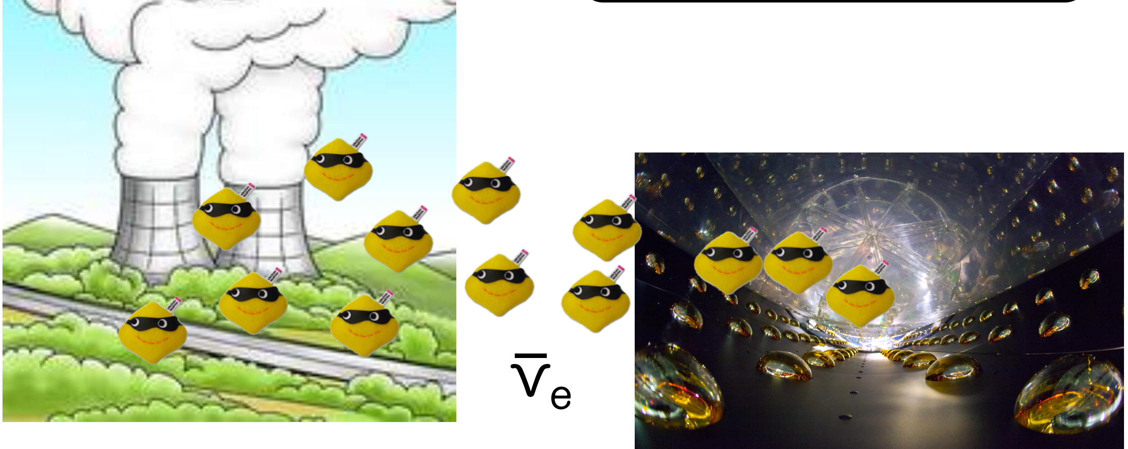
Atmospheric



Energy: GeV - TeV
Baseline: ~ 13 000 km

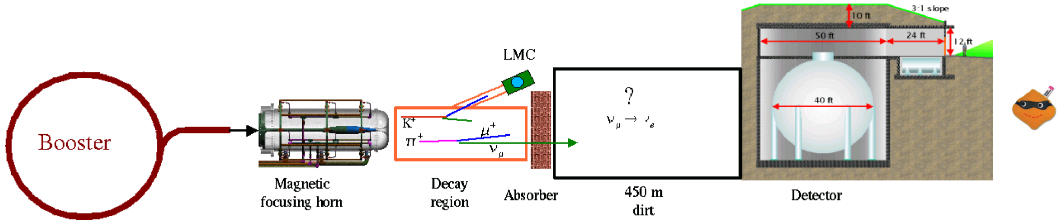
Reactor

Energy: MeV
Baseline: 10 m – 100 km



Accelerator

Energy: GeV
Baseline: 30 m – 1500 km

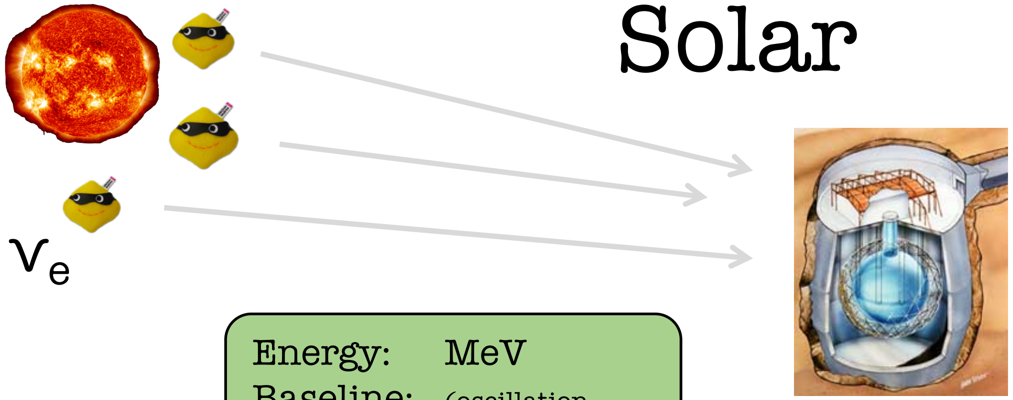


Many different sources available to test the concept of neutrino oscillations

- Natural and artificial sources
- Different energies
- Different baseline

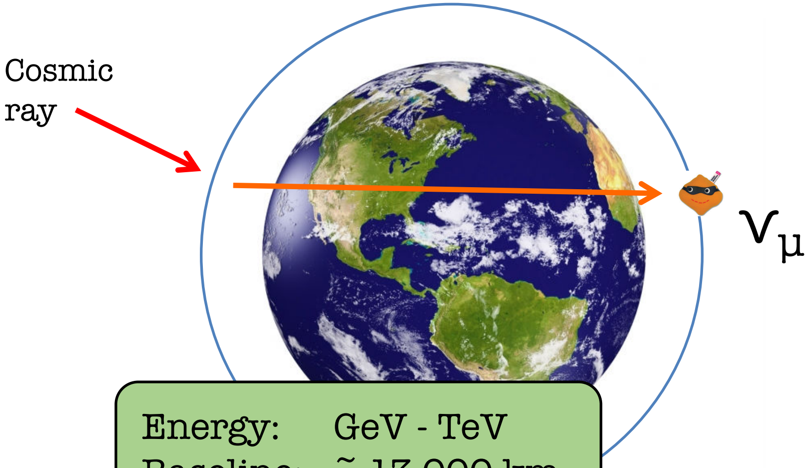
The full picture of neutrino oscillations

Solar



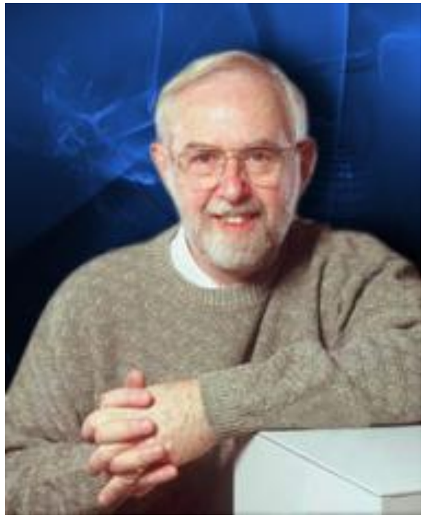
Energy: MeV
Baseline: (oscillation inside sun)

Atmospheric



Energy: GeV - TeV
Baseline: ~ 13 000 km

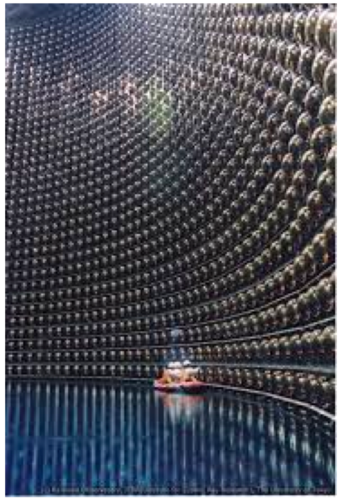
SNO experiment



Sir Arthur McDonald

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

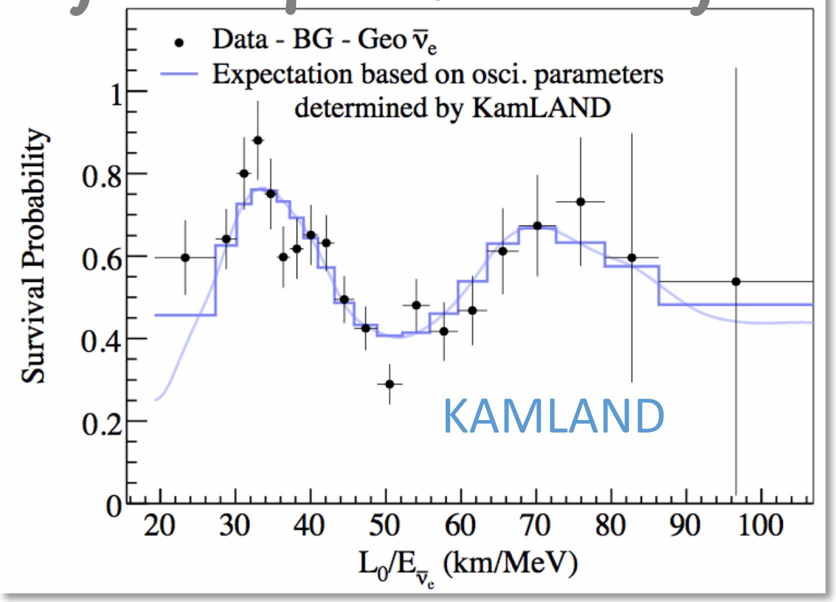
Takaaki Kajita



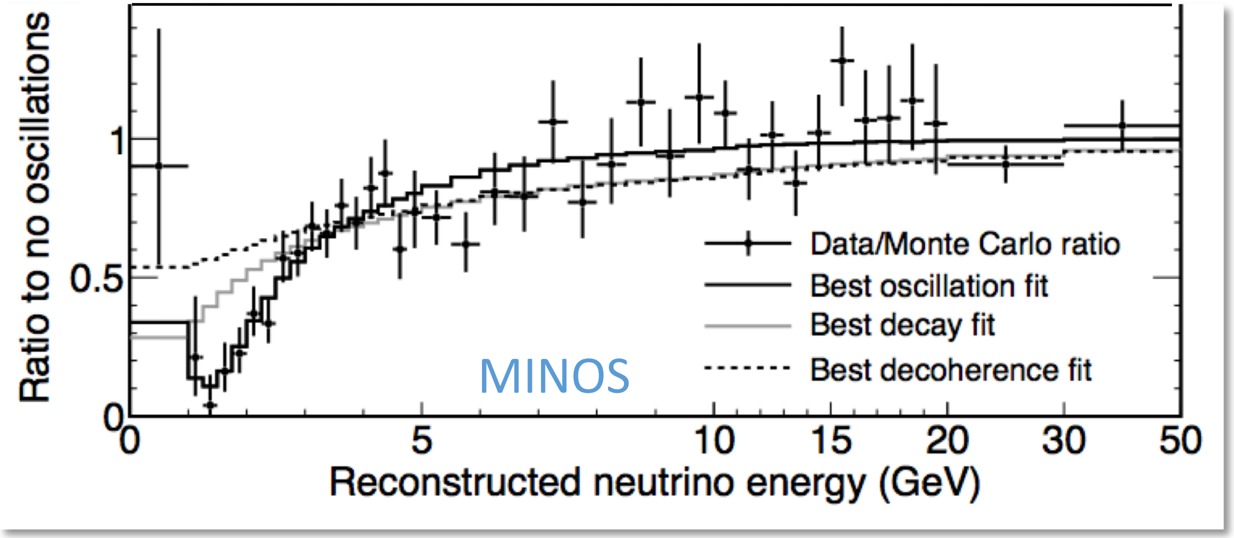
Superkamiokande

The full picture of neutrino oscillations

reactor ν's test same parameter space as **solar** ν oscillations



accelerator ν's test same parameter space as **accelerator** ν oscillations

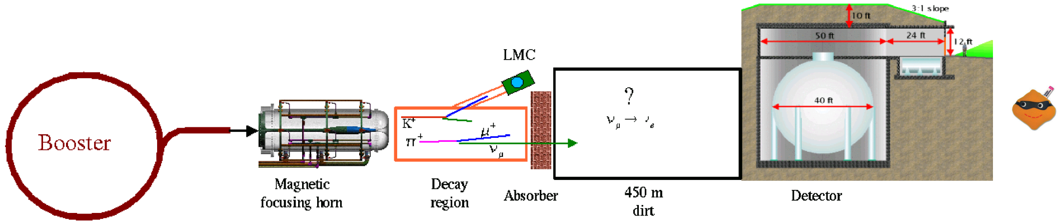


Reactor

Energy: MeV
Baseline: 10 m – 100 km

Accelerator

Energy: GeV
Baseline: 30 m – 1500 km



Outline

- Neutrino history
  - Discovery of the neutrino
  - What we have learned about the neutrino

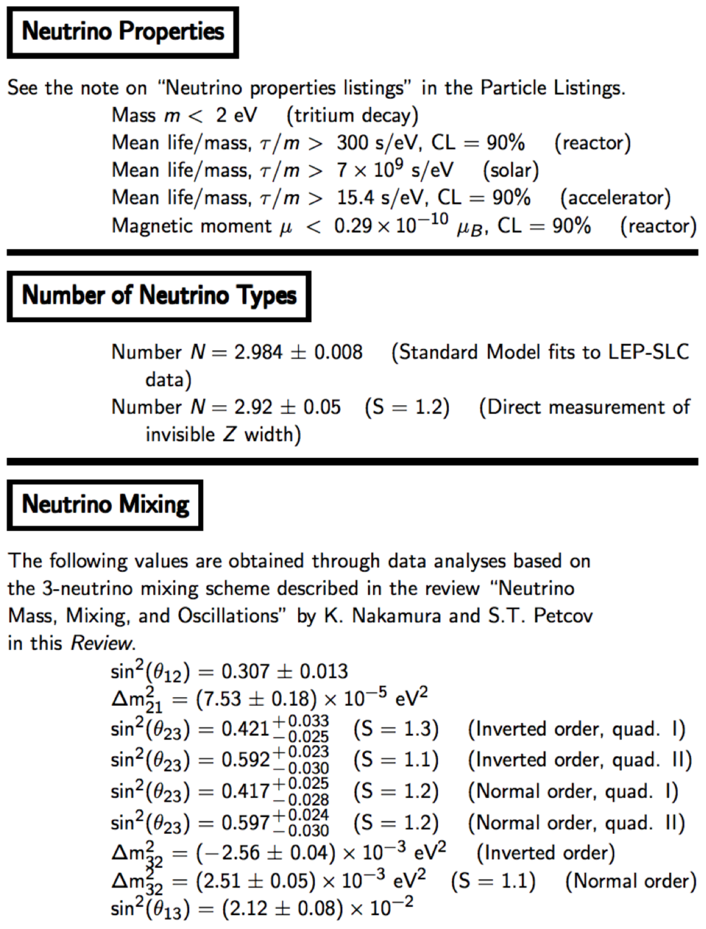
- Today's challenges
  - Neutrino masses
  - Precision measurements of oscillation parameters
  - Sterile neutrinos

Neutrinos in the standard model

In order to understand how neutrinos fit in the standard model, their properties need to be experimentally determined:

1. What is the absolute mass of the neutrinos?
2. What are the parameters that characterize the oscillations?
3. Are there only three neutrino flavors?

The PDG summary tables on neutrinos are yet short and vague:



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

Number of Neutrino Types

Number $N = 2.984 \pm 0.008$ (Standard Model fits to LEP-SLC data)
Number $N = 2.92 \pm 0.05$ (S = 1.2) (Direct measurement of invisible Z width)

Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Mass, Mixing, and Oscillations" by K. Nakamura and S.T. Petcov in this *Review*.

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$
$\sin^2(\theta_{23}) = 0.421^{+0.033}_{-0.025}$ (S = 1.3) (Inverted order, quad. I)
$\sin^2(\theta_{23}) = 0.592^{+0.023}_{-0.030}$ (S = 1.1) (Inverted order, quad. II)
$\sin^2(\theta_{23}) = 0.417^{+0.025}_{-0.028}$ (S = 1.2) (Normal order, quad. I)
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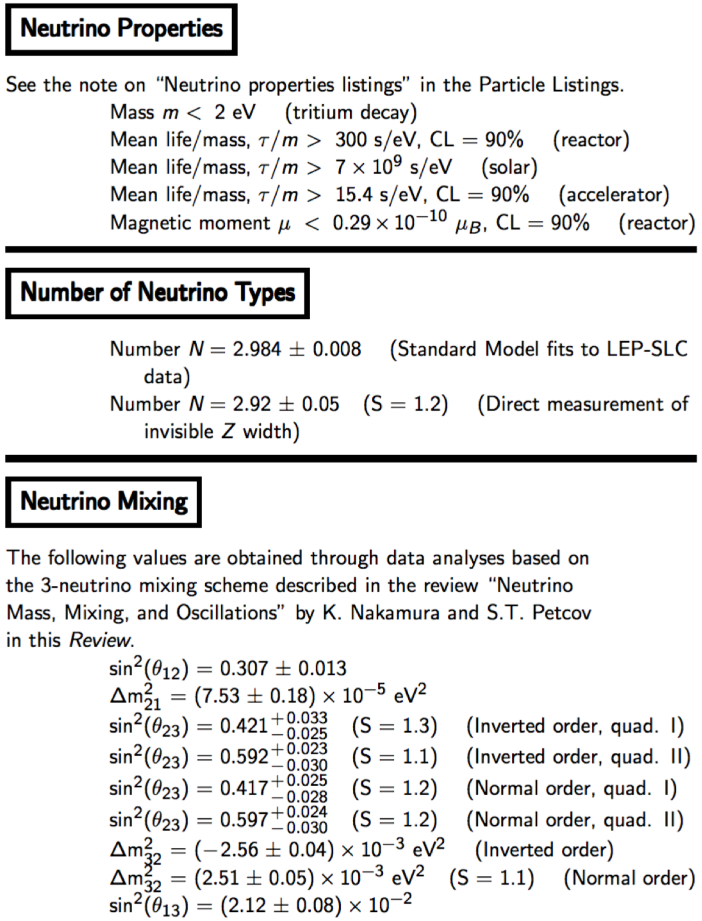

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$\sin^2(\theta_{13}) = (2.12 \pm 0.08) \times 10^{-2}$

What is the absolute mass of the neutrino?

~~What is the absolute mass of the neutrino?~~

Do neutrinos have a mass?

If the mass difference between neutrinos was zero, we wouldn't observe neutrino oscillations.

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$
$$+ 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right),$$

This implies, that not all neutrinos can be massless.

Yes

~~What is the absolute mass of the neutrino?~~

How do neutrinos get mass?

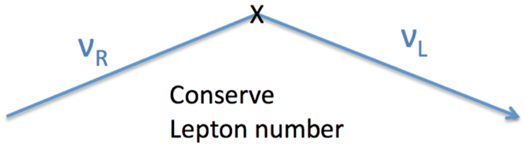
Dirac neutrinos

or

Majorana neutrinos

?

- Neutrinos get their mass from interaction with the Higgs (just like other Fermions). Lepton number is conserved.

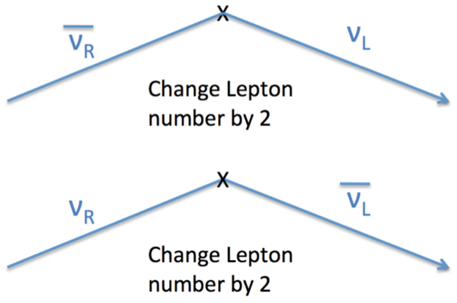


- This only works if there are right handed neutrinos, which we have not yet been observed in nature (see sterile neutrinos)

- This mechanism doesn't give us any indication why the neutrino masses are so much lighter than the charged fermion masses ("hierarchy problem").

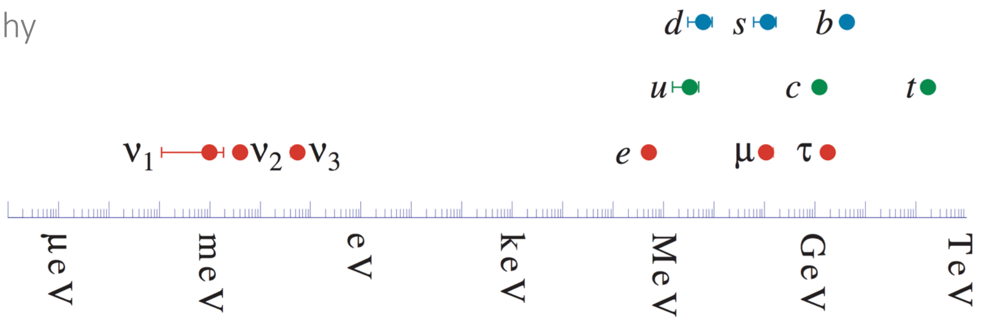
$(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	$(\mathbf{3},\mathbf{2})_{-\frac{1}{6}}$	$(\mathbf{1},\mathbf{1})_{-1}$	$(\mathbf{3},\mathbf{1})_{-\frac{2}{3}}$	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$
$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L$	$\begin{pmatrix}u^i\\ d^i\end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L$	$\begin{pmatrix}c^i\\ s^i\end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$	$\begin{pmatrix}t^i\\ b^i\end{pmatrix}_L$	τ_R	t^i_R	b^i_R

- Adding a Majorana mass term to the Lagrangian gives mass only to the neutrinos

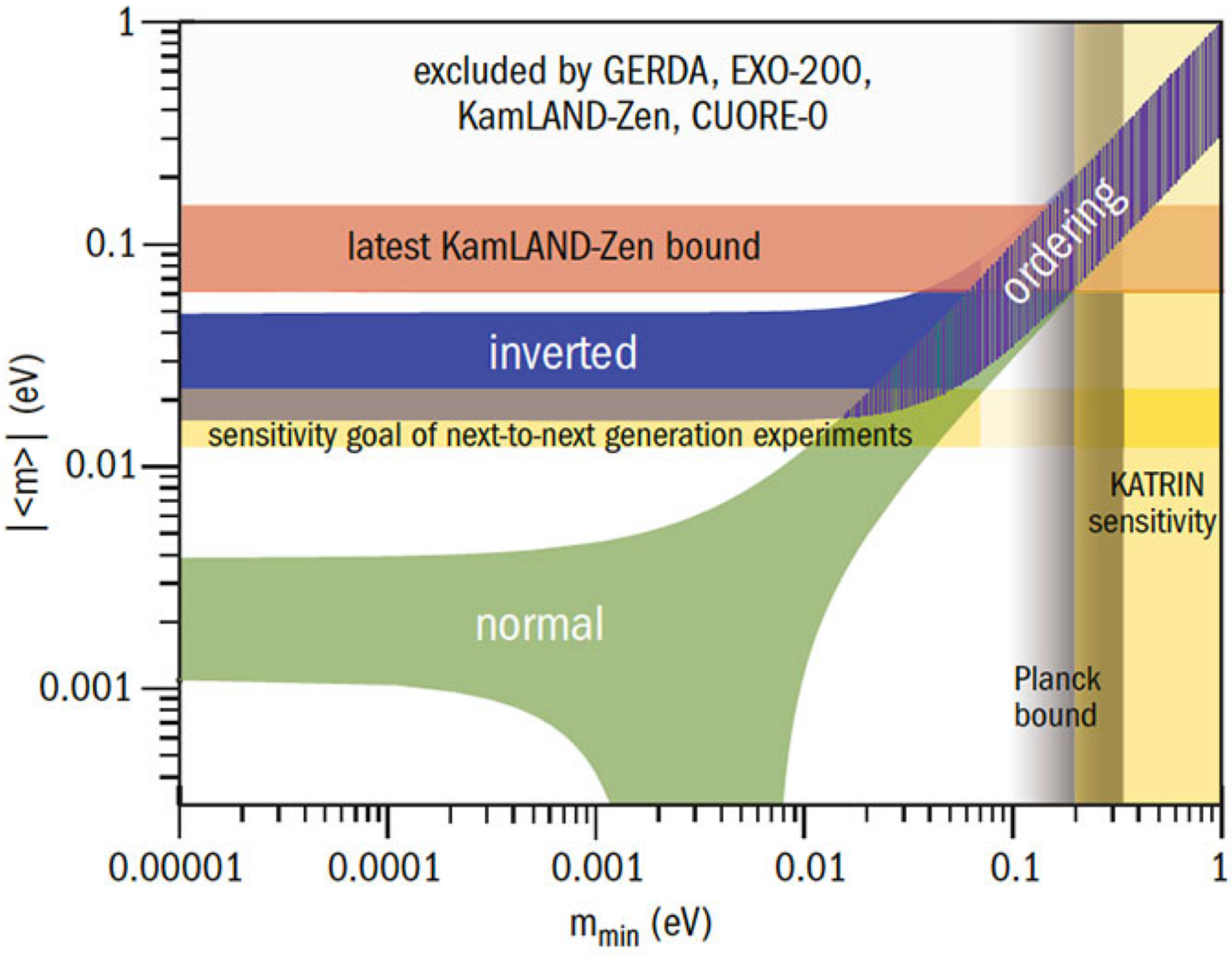


- The lepton number is NOT conserved

- The see-saw mechanism would naturally explain why the neutrinos are so much lighter than other Fermions



What is the absolute mass of the neutrino?



Mass of the lightest neutrino

Currently, the answer is:

It depends…

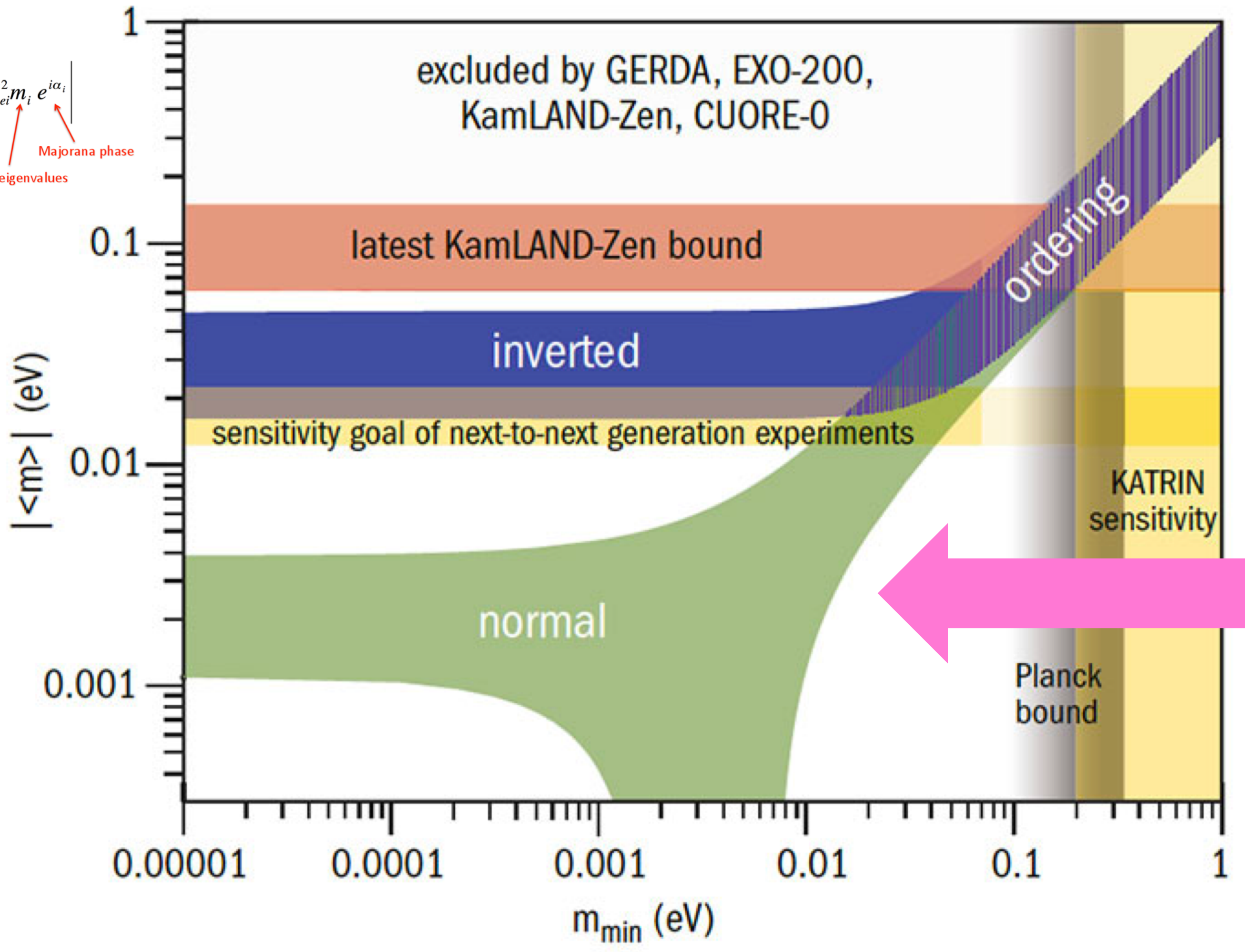
Questions we need to answer:

$$\langle m_{\beta\beta}\rangle = \left|\sum_i U_{ei}^2 m_i \, e^{i\alpha_i}\right|$$

Mixing matrix

mass eigenvalues

Majorana phase

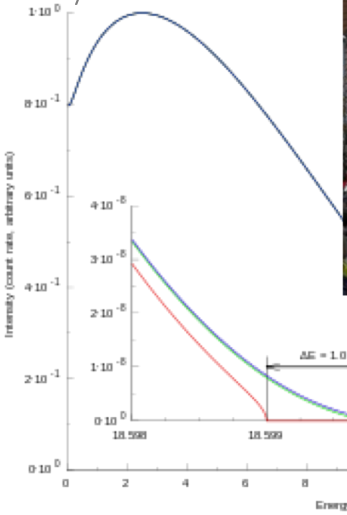


Mass of the lightest neutrino

What's the mass of the lightest neutrino?

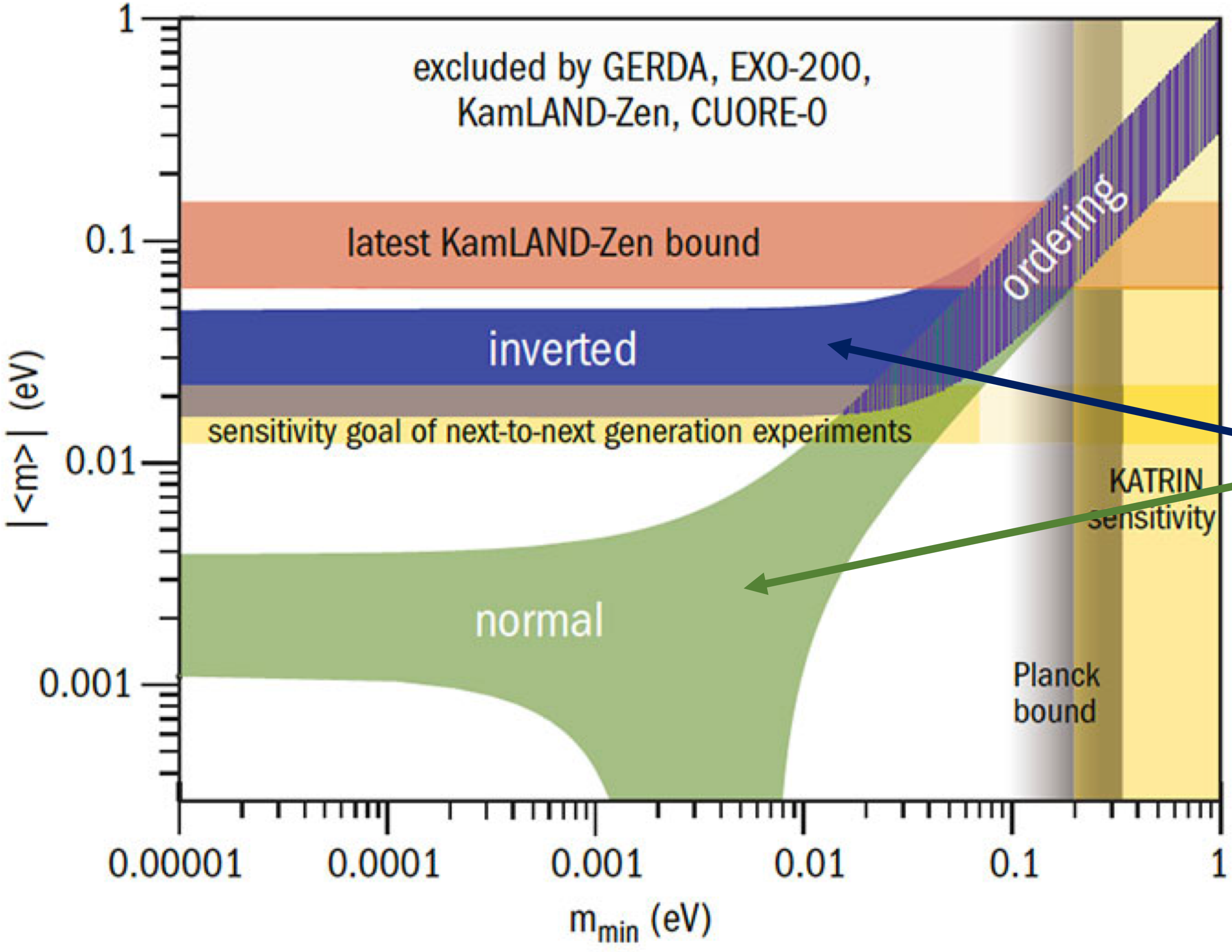
- Have bounds from cosmological measurements.
- Attempting direct mass measurements with precision measurements of beta decay

Spectrum of tritium decay electrons



KATRIN experiment

Questions we need to answer:



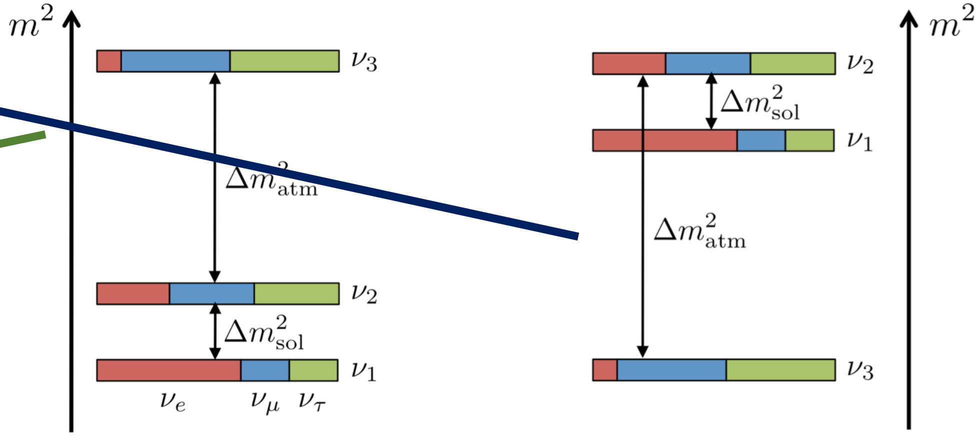
Mass of the lightest neutrino

What is the neutrino mass ordering?

- Knowing the neutrino mass ordering will tell us what branch (normal or inverted) we live on.

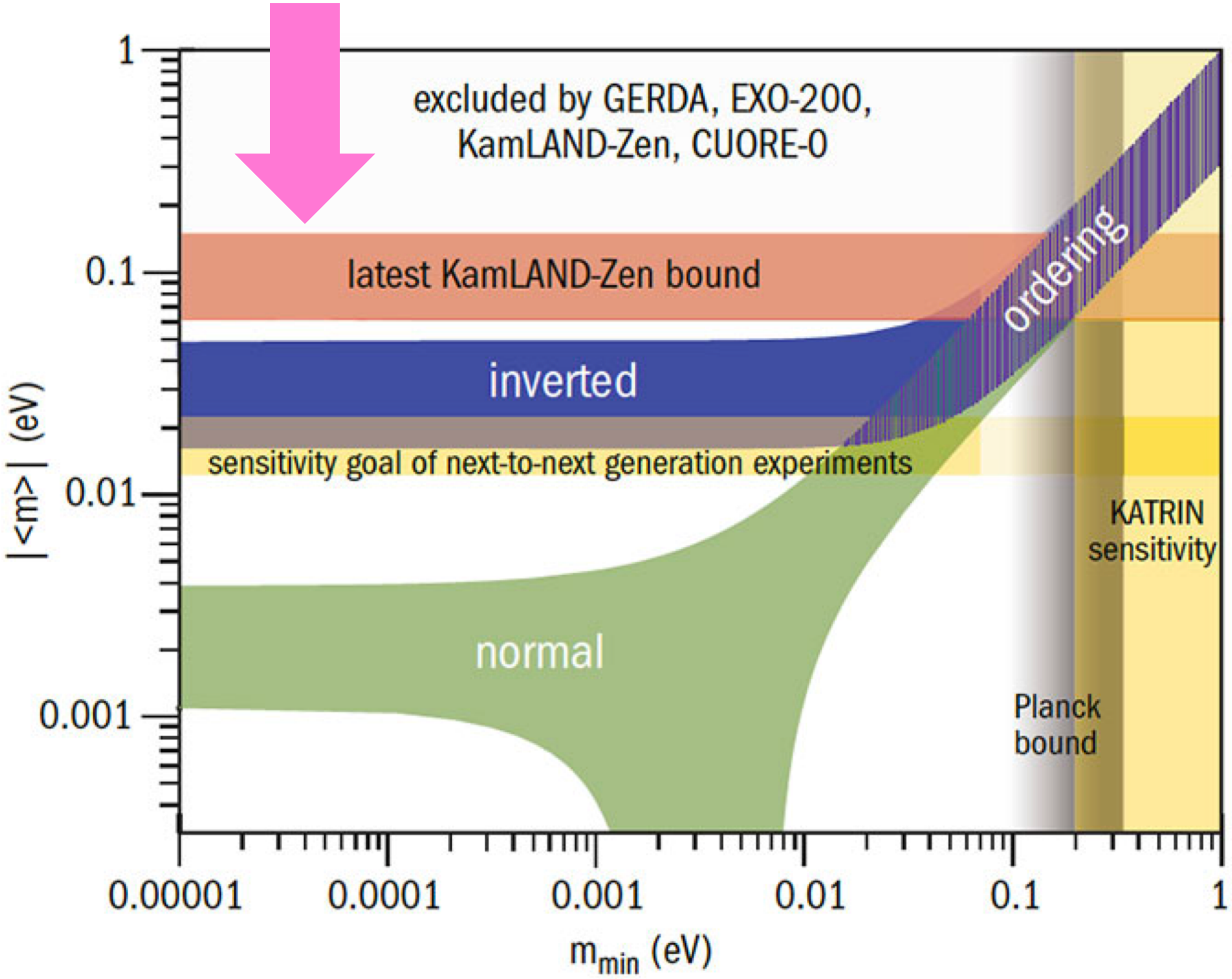
Normal ordering

Inverted ordering



- Current oscillation experiments are trying to answer this question (see later)

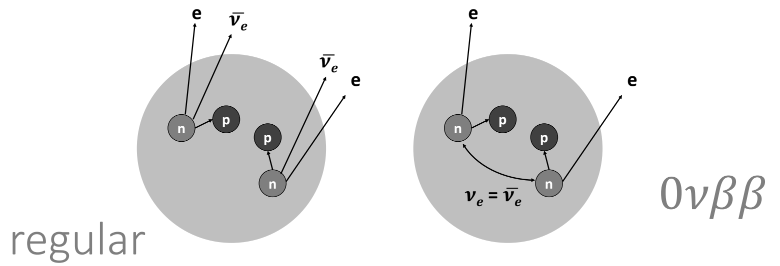
Questions we need to answer:



Mass of the lightest neutrino

Are neutrinos Dirac or Majorana particles?

- Experiments are looking for lepton number violation in neutrinoless double-beta decay



- The rate of the observed $0\nu\beta\beta$ scales with the effective mass $<m_{ee}>$:

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

0νββ decay rate

Phase Space

Matrix Element

Effective Mass

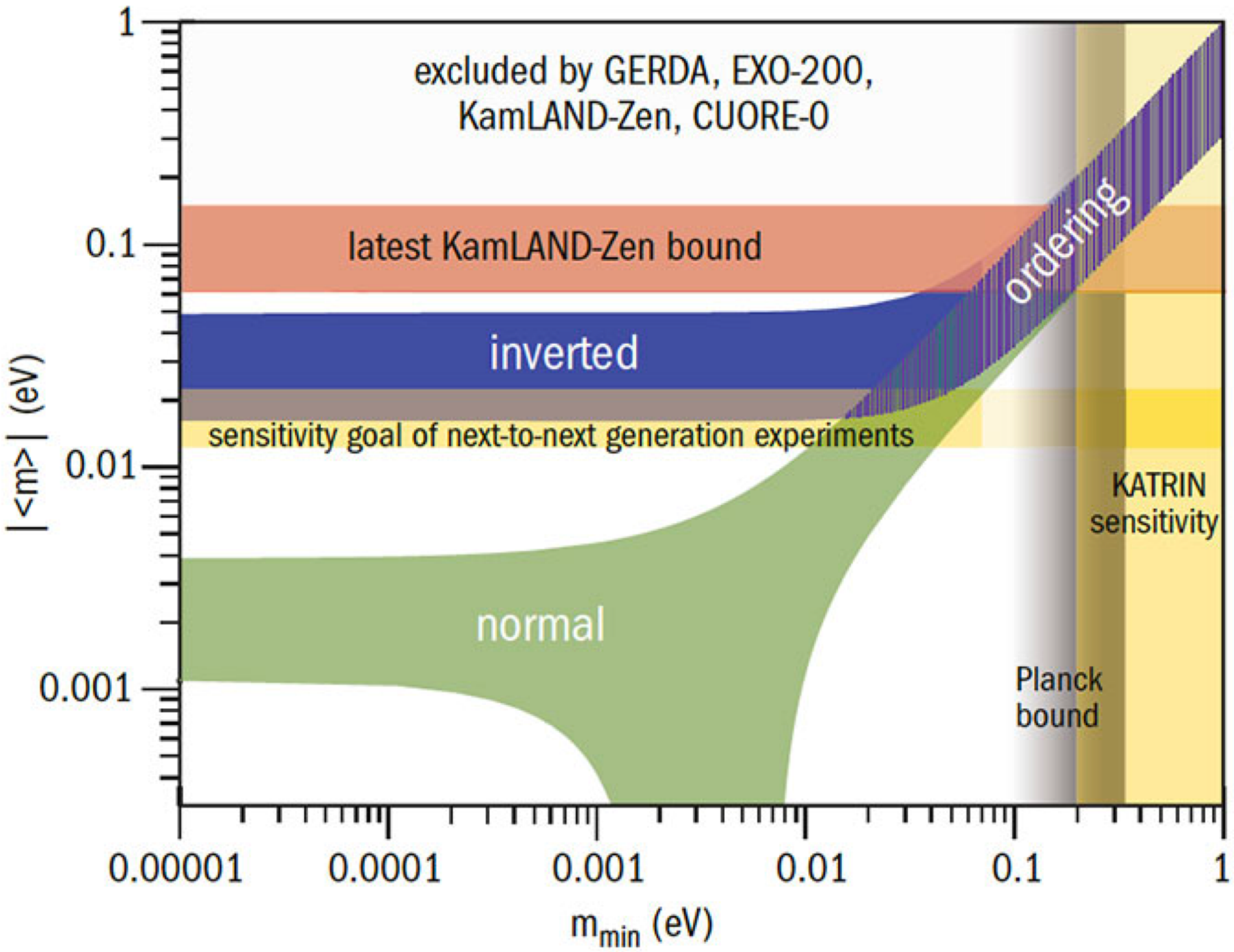
$$\langle m_{\beta\beta}\rangle = \left|\sum_i U_{ei}^2 m_i \, e^{i\alpha_i}\right|$$

Mixing matrix

Majorana phase

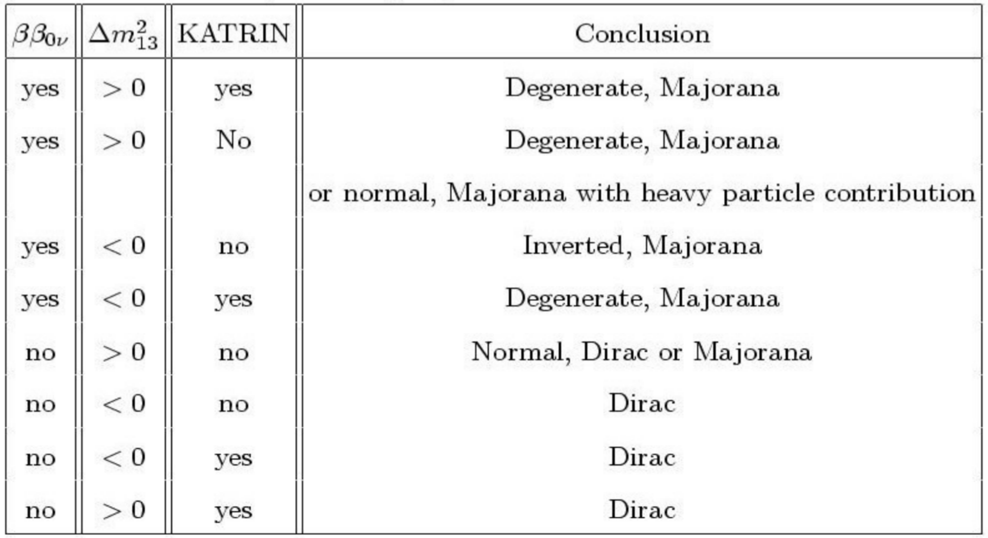
mass eigenvalues

Questions we need to answer:



Mass of the lightest neutrino

- Different experiments will be closing in on these questions in the upcoming years
- We will learn a lot from any outcome!



$\beta\beta_{0\nu}$	Δm^2_{13}	KATRIN	Conclusion
yes	> 0	yes	Degenerate, Majorana
yes	> 0	No	Degenerate, Majorana or normal, Majorana with heavy particle contribution
yes	< 0	no	Inverted, Majorana
yes	< 0	yes	Degenerate, Majorana
no	> 0	no	Normal, Dirac or Majorana
no	< 0	no	Dirac
no	< 0	yes	Dirac
no	> 0	yes	Dirac

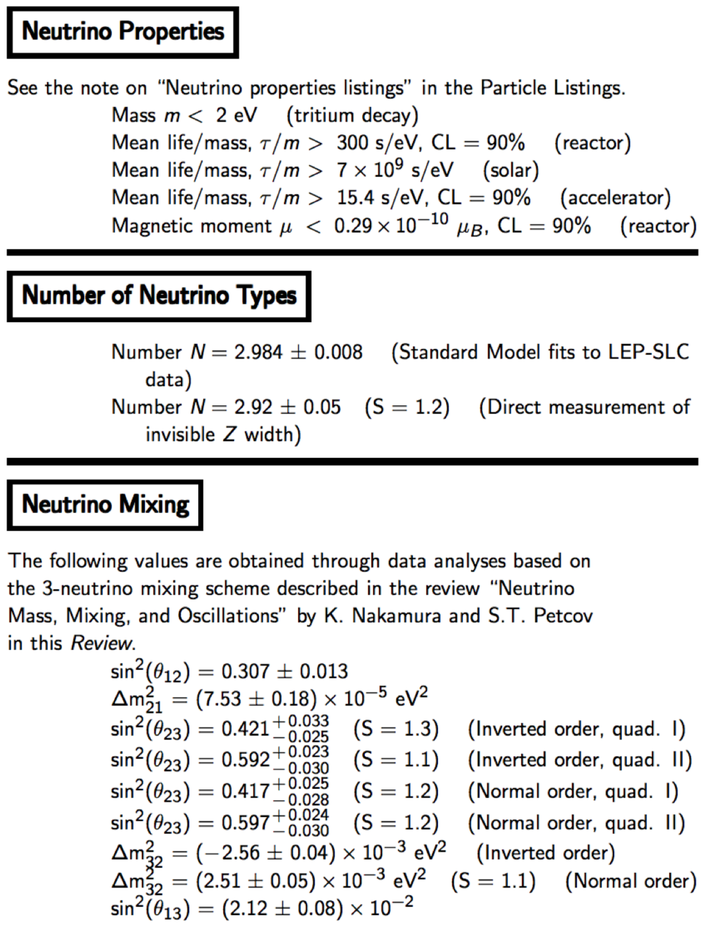
- This topic is very exciting and experimentally very challenging!
  These few slides don't do it justice.
  Please forgive me for moving on to the next topic …

Neutrinos in the standard model

In order to understand how neutrinos fit in the standard model, their properties need to be experimentally determined:

1. What is the absolute mass of the neutrinos?
2. What are the parameters that characterize the oscillations?
3. Are there only three neutrino flavors?

The pdg summary tables on neutrinos are yet short and vague:



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

Number of Neutrino Types

Number $N = 2.984 \pm 0.008$ (Standard Model fits to LEP-SLC data)
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The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Mass, Mixing, and Oscillations" by K. Nakamura and S.T. Petcov in this *Review*.

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$\Delta m^2_{32} = (2.51 \pm 0.05) \times 10^{-3}\ \mathrm{eV}^2$ (S = 1.1) (Normal order)
$\sin^2(\theta_{13}) = (2.12 \pm 0.08) \times 10^{-2}$

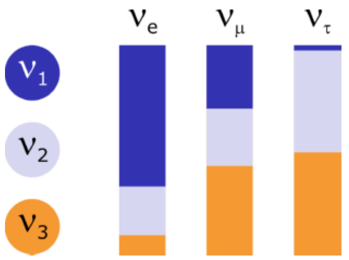
Reminder: oscillation parameters

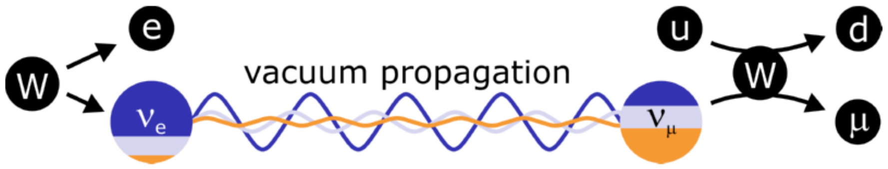
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

PMNS matrix

$$\overbrace{\underbrace{\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}}_{\text{Atmospheric/ Accelerator}}\underbrace{\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{bmatrix}}_{\text{Accelerator/Reactor}}\underbrace{\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}}_{\text{Solar/Reactor}}}$$

The mixing angles determine how much ν_1, ν_2, ν_3 is in ν_e, ν_μ, ν_τ





3 mixing angles: θ_{12}, θ_{13}, θ_{23}
CP violating phase: δ_{CP}
2 mass differences: Δm^2_{32}, Δm^2_{21}
Sign of Δm^2_{32} (through matter effects)

Appearance and Disappearance probabilities (in vacuum)

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right),$$

- Accessible for experiments is the appearance/disappearance probability P
- P depends on ALL oscillation parameters, the key is to disentangle the information
- We do this through different experiments (different energy, different baselines): different terms in P become dominant or negligible, which helps to disentangle the parameters

Status of solar parameters

θ_{12}

Δm^2_{21}

θ_{13}

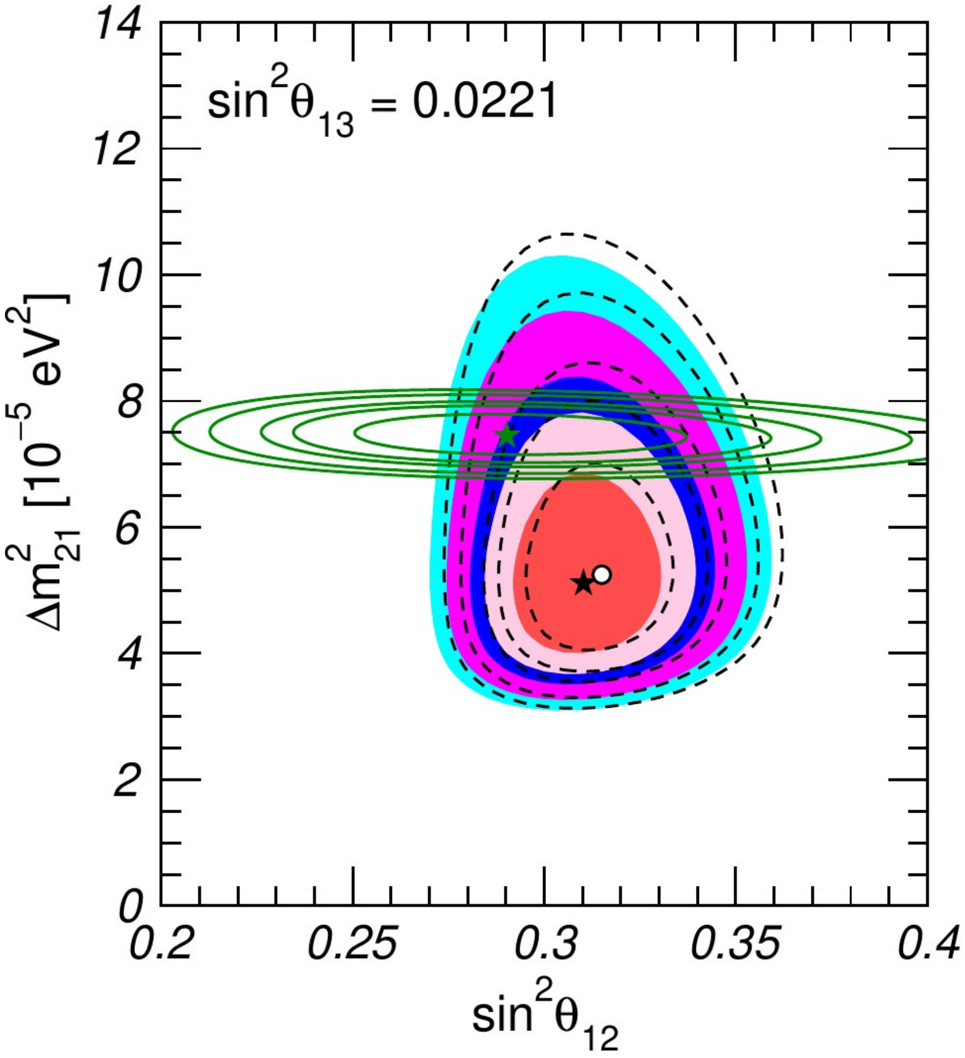
θ_{23}

Δm^2_{32}

δ_{CP}

Sign of Δm^2_{32}

- Longest history in measuring the "solar parameters"
- Relatively well known with uncertainties 2.4% (Δm^2_{21}) and 4.7% ($\sin^2\theta_{12}$)
- There is a 2σ tension between reactor and solar experiments.
- New reactor experiments (JUNO, RENO-50) will get the uncertainties below the 1% level and investigate this. Timescale 5-10 years.



Status of θ_{13}

θ_{12}

Δm^2_{21}

θ_{13}

θ_{23}

Δm^2_{32}

δ_{CP}

Sign of Δm^2_{32}

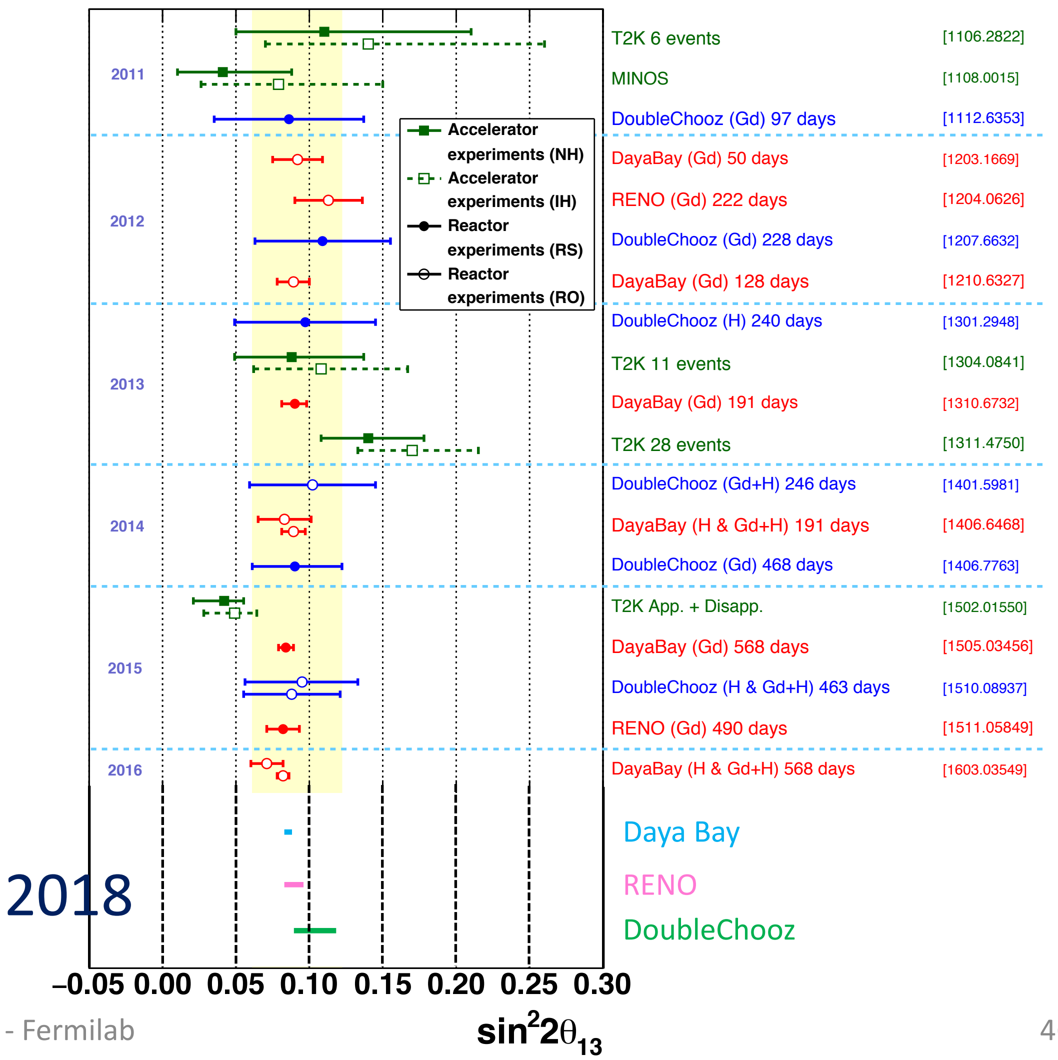
Why …should I care?

- In our parameterization of the PMNS matrix θ_{13} is a scale factor for the δ_{CP} term
- Absolute value: if θ_{13} is large, it is easier to measure δ_{CP}
- Precision: A good knowledge of θ_{13} from reactor experiments is important for determining δ_{CP} in long-baseline experiments

Accelerator/Reactor term in the PMNS matrix

$$\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix}$$

- θ_{13} went from unknown to best known mixing angle within the last ten years (3.5% uncertainty)
- θ_{13} turned out non-zero and larger than expected. This is good for us!



Long baseline accelerator experiments

There are currently two long baseline experiments operating world wide
Their goals are

- Precision measurements of the atmospheric mixing parameters
- Determination of the neutrino mass ordering
- Test of CP violation in the neutrino sector

Measure

$P_{\mu \to \mu}$ ("ν_μ disappearance")

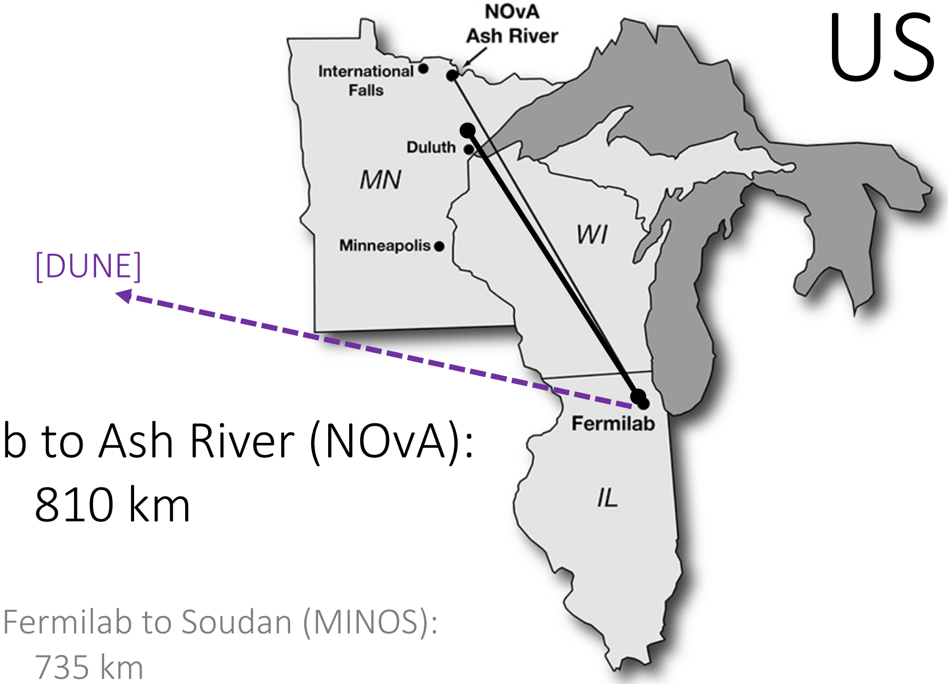
and

$P_{\mu \to e}$ ("ν_e appearance")

Japan

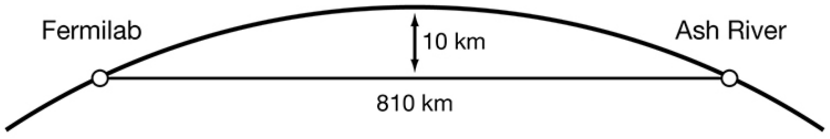
Tokai to Kamioka (T2K):
295 km

US



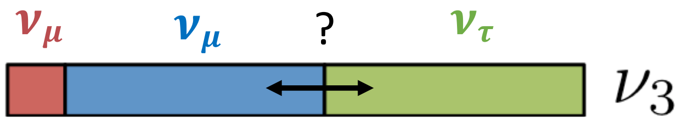
Fermilab to Ash River (NOvA):
810 km

Previously Fermilab to Soudan (MINOS):
735 km



ν_μ disappearance results

How much ν_μ is in ν_3?



θ_{12}

Δm^2_{21}

θ_{13}

θ_{23}

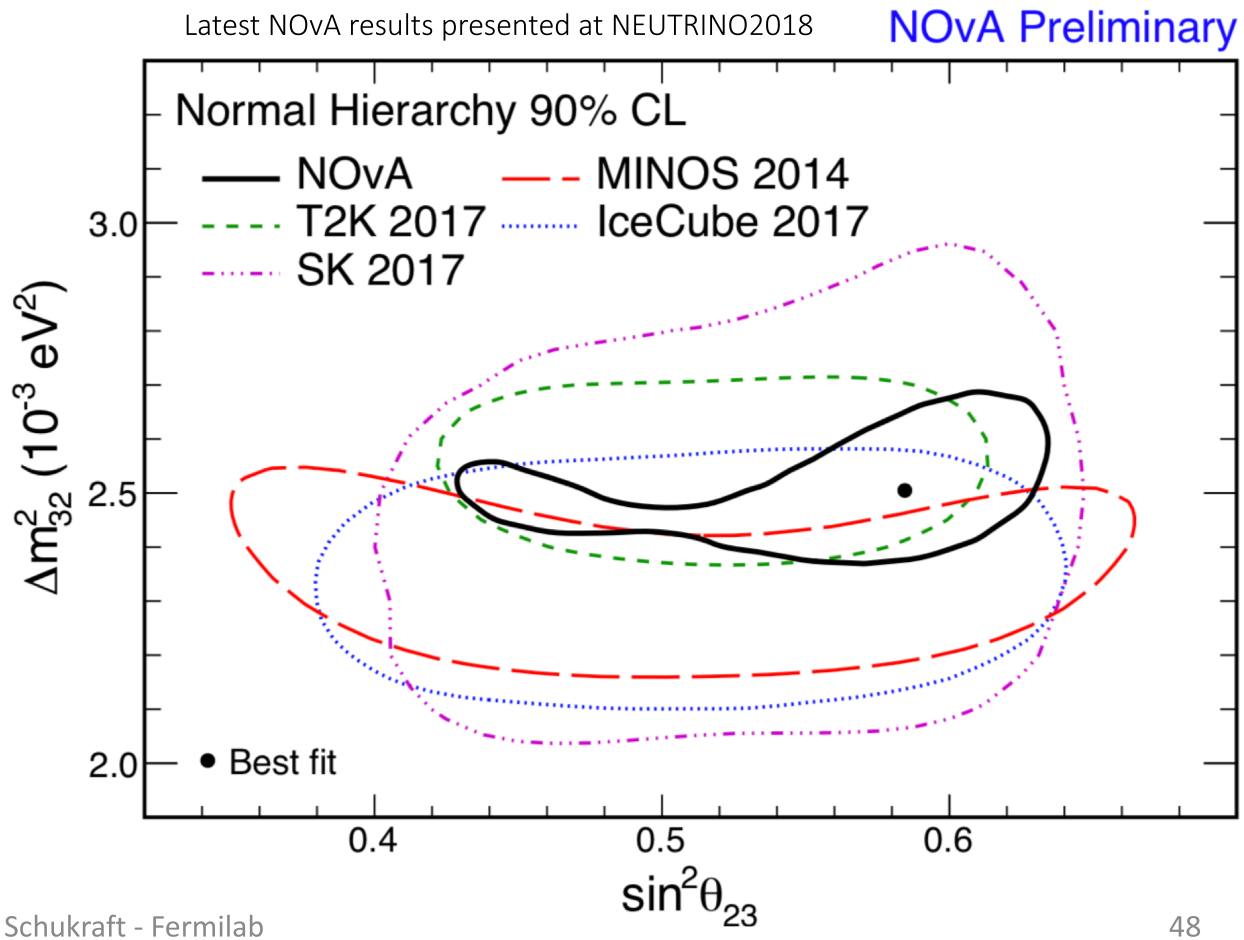
Δm^2_{32}

δ_{CP}

Sign of Δm^2_{32}

- If $\sin^2\theta_{23}$ = 0.5 (known as *maximal mixing*) it means that the same amount of ν_μ and ν_τ is in ν_3. This would be special and therefore particularly interesting!
- A challenge in determining $\sin^2\theta_{23}$ is that in leading order there are two degenerate solutions (known as *octant puzzle*).
- NOvA results seem to favor non-maximal mixing and the higher octant in both mass ordering cases. Not yet significant enough though.

Latest NOvA results presented at NEUTRINO2018



ν_e appearance results

θ_{12}

Δm^2_{21}

θ_{13}

θ_{23}

Δm^2_{32}

δ_{CP}

Sign of Δm^2_{32}

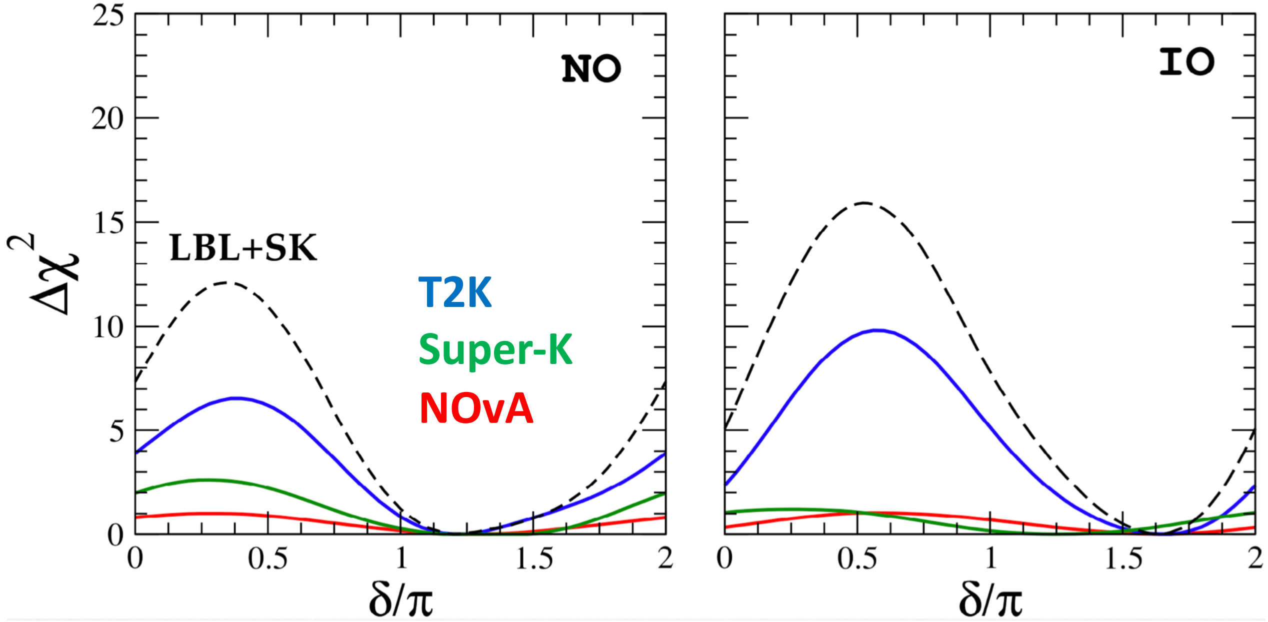
- Long baseline ν_e appearance measurements are sensitive to measuring the CP violating phase

$$P(\nu_\mu \to \nu_e) \approx \left| \sqrt{P_{\rm atm}} e^{-e(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\rm sol}} \right|^2$$

$$\approx P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm} P_{\rm sol}} \left(\cos\Delta_{32} \cos\delta_{CP} \mp \sin\Delta_{32} \sin\delta_{CP} \right)$$

$$\sqrt{P_{\rm atm}} = \sin(\theta_{23}) \sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL} \Delta_{31}$$

$\delta_{CP} = 0, \pi, 2\pi$:
No CP violation
$\delta_{CP} = \pm \pi/2$:
CP maximally violated



- All experiments favor $\pi < \delta_{CP} < 2\pi$
- These measurements typically use reactor measurements for the best constraint on θ_{13}

deSalas et al., pre-NEUTRINO2018

ν_e appearance results

θ_{12}

Δm^2_{21}

θ_{13}

θ_{23}

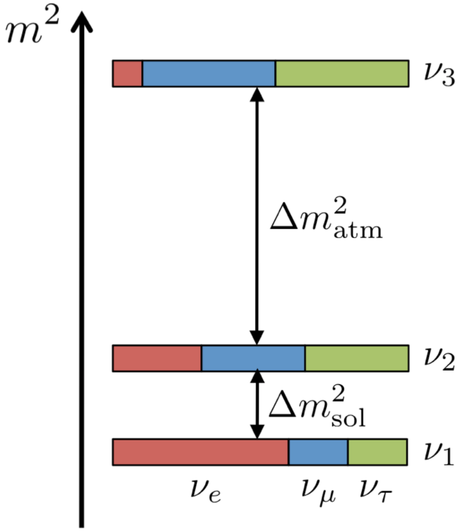
Δm^2_{32}

δ_{CP}

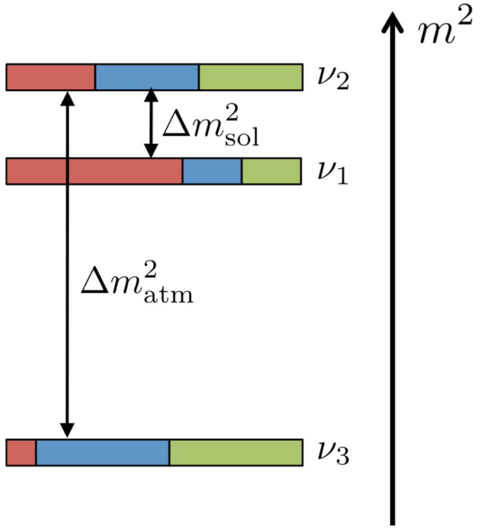
Sign of Δm^2_{32}

- Determining the mass ordering of the neutrinos is important for the questions of the absolute neutrino masses
- In vacuum, neutrino oscillations are insensitive to the mass ordering
- However, the presence of electrons in matter changes the behavior of ν_e vs the other flavors (MSW effect). This causes a difference in the oscillation probability between normal and inverted ordering.
- Experiments with long baselines (= lots of mass) are sensitive to the mass ordering

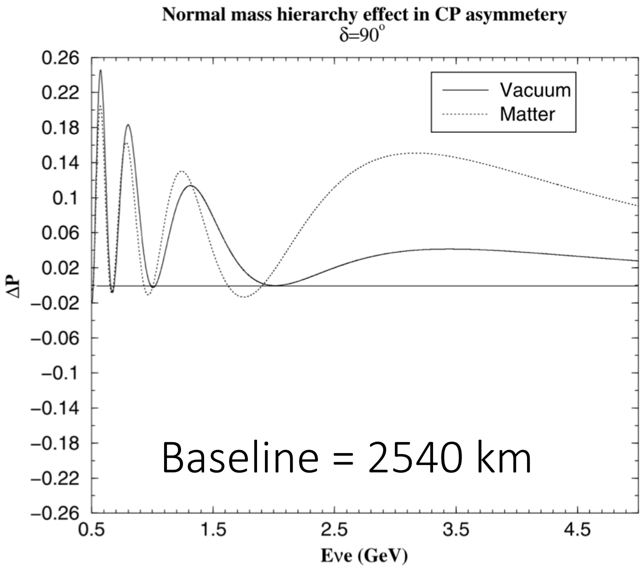
Normal ordering



Inverted ordering

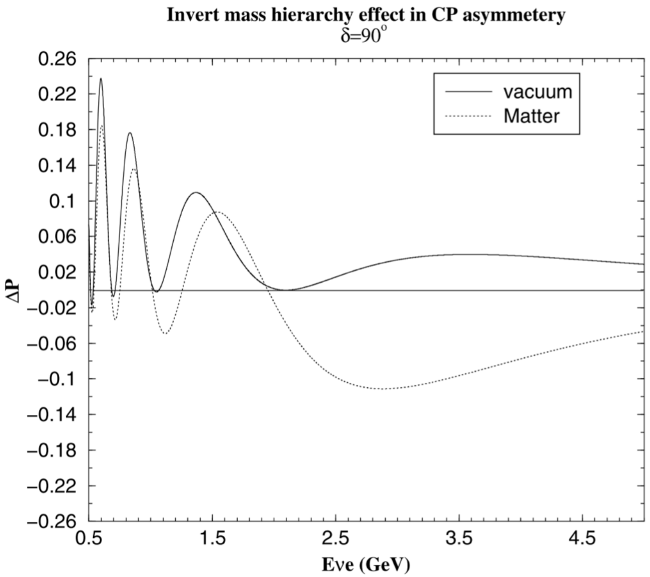


Normal mass hierarchy effect in CP asymmetery
δ=90°



Baseline = 2540 km

Invert mass hierarchy effect in CP asymmetery
δ=90°



ν_e appearance results

Latest results presented at NEUTRINO2018

θ_{12}

Δm^2_{21}

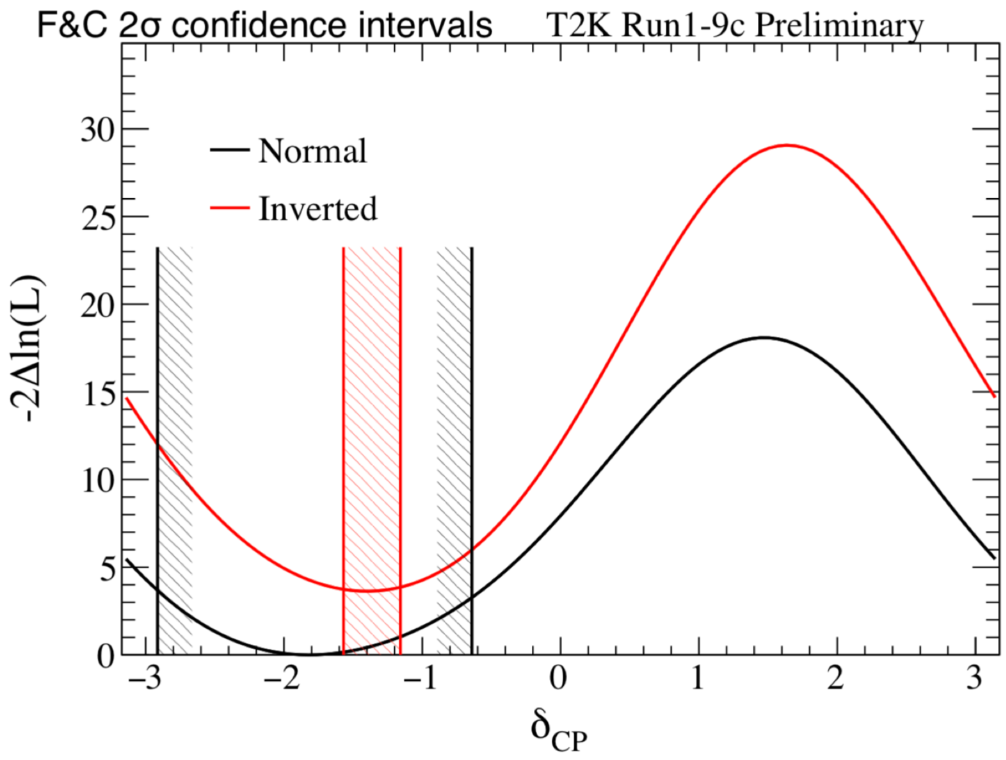
θ_{13}

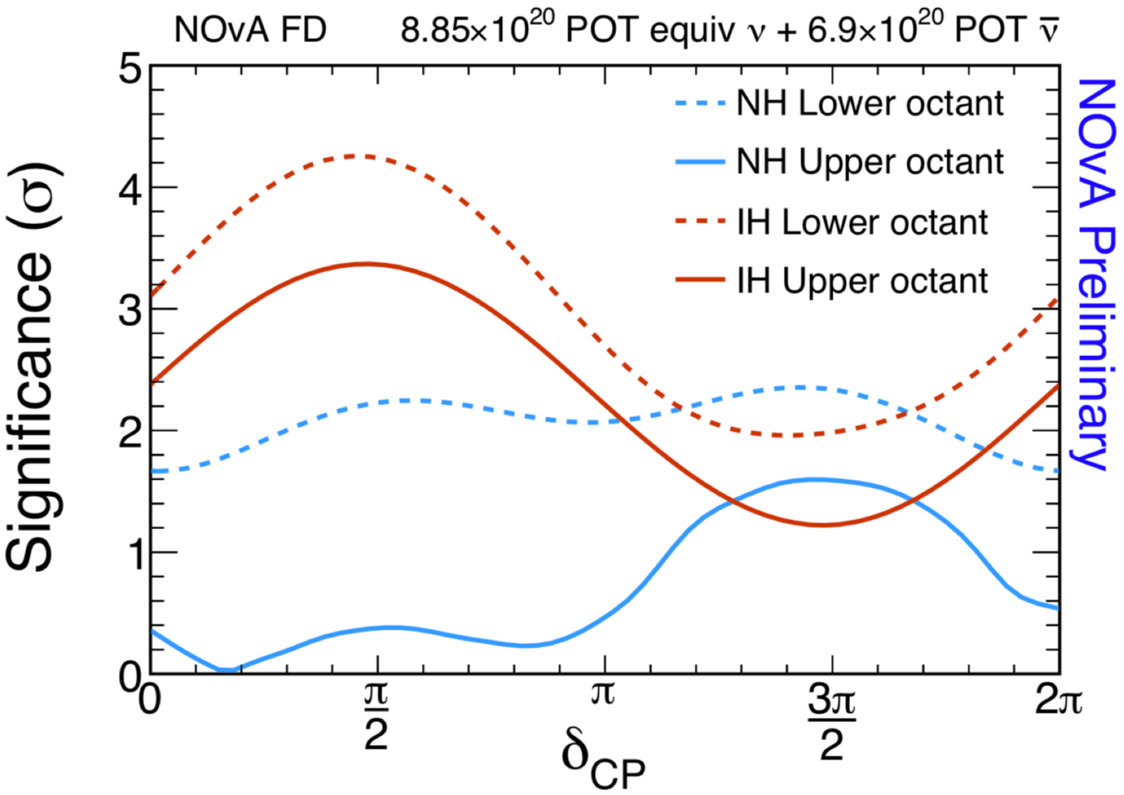
θ_{23}

Δm^2_{32}

δ_{CP}

Sign of Δm^2_{32}





- Inverse ordering disfavored at $\sim 2\sigma$

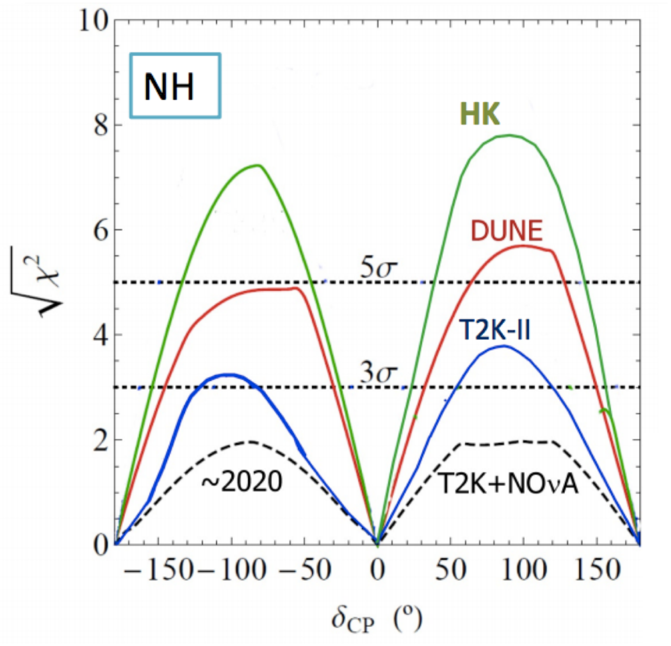
- Inverse ordering disfavored at 1.8σ

(both measurements using reactor constraints)

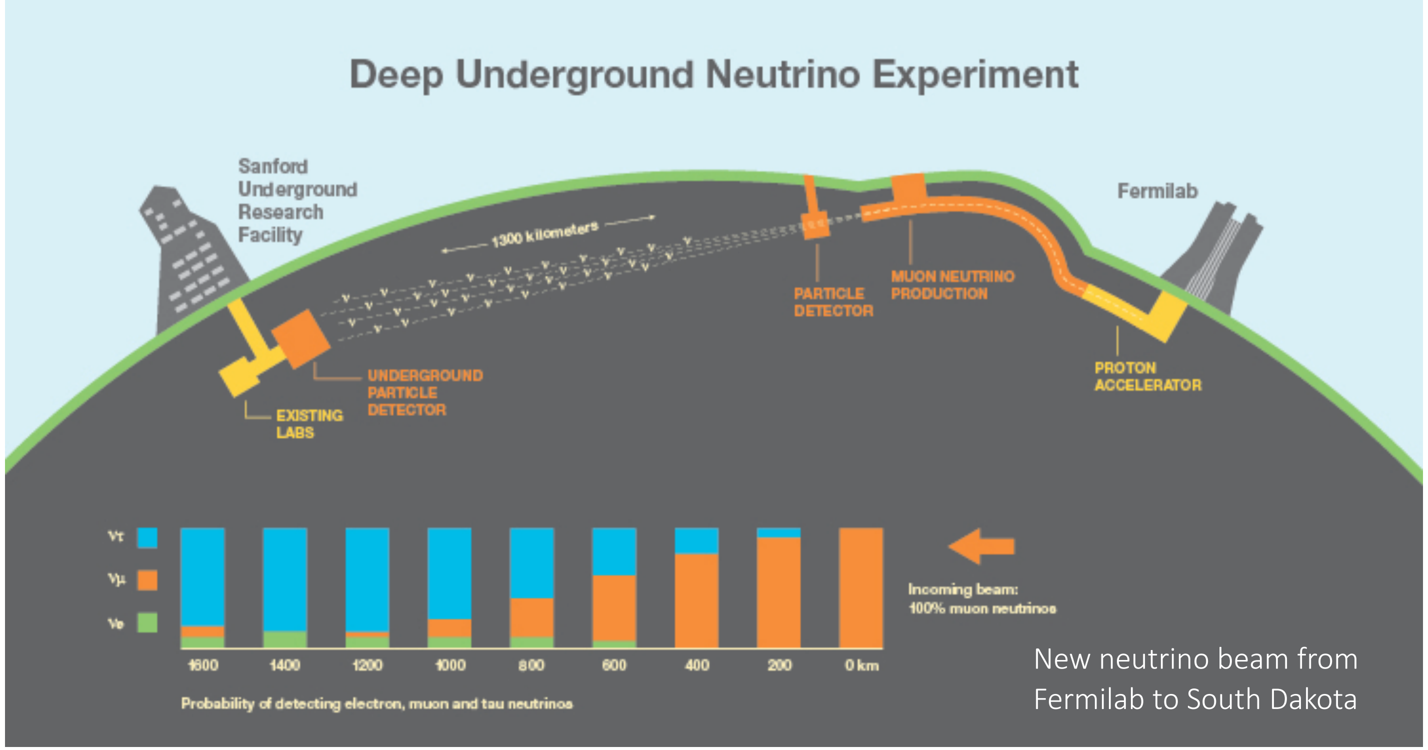
Future experiments: DUNE

- **Near future:**
  If δ_{CP} is confirmed to be maximal we are pretty lucky (again). T2K + NOvA can reach $\sim 2\sigma$ for δ_{CP}.
  NOvA has a chance to determine the mass ordering with $\sim 2-3\sigma$ if δ_{CP} is confirmed to be maximal.
  (This is roughly where we are right now.)

- A precision measurement of the CP violating phase and mass ordering requires new experiments.



Mezzetto @ NEUTRINO2016

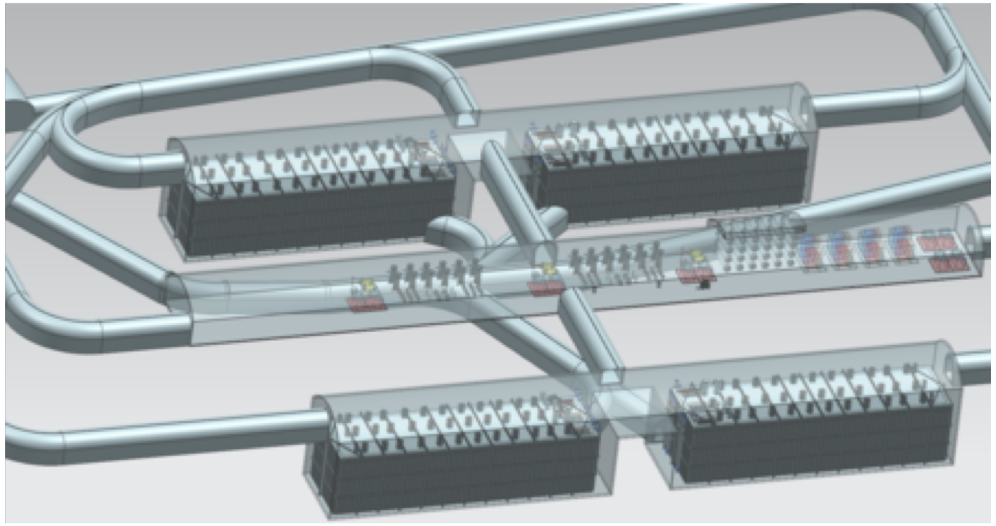


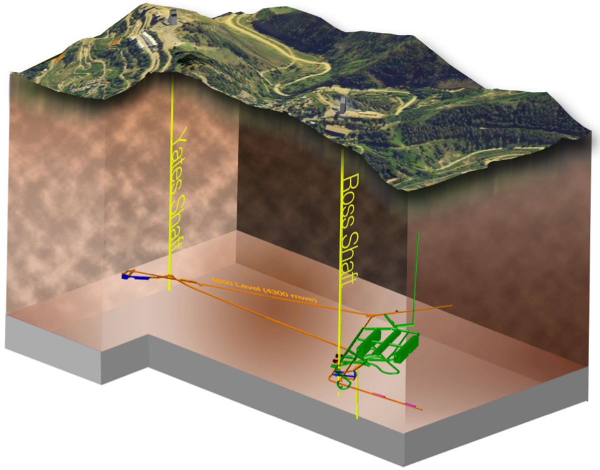
New neutrino beam from Fermilab to South Dakota

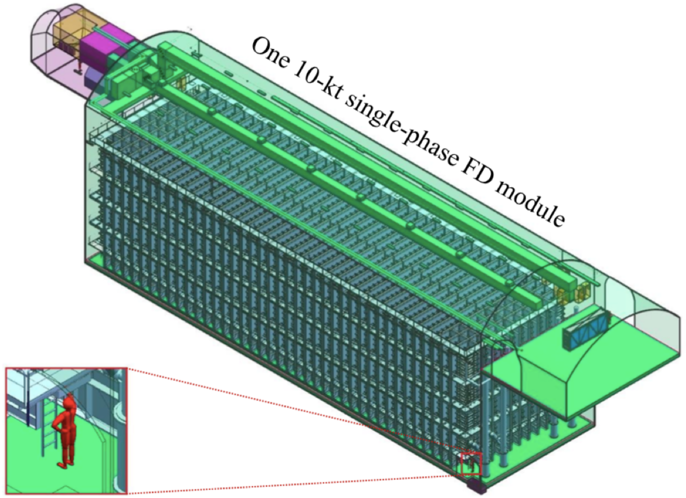
- To definitively answer these questions, we are building the DUNE experiment
- It will have a neutrino beam from Fermilab going 1300km to Homestake in South Dakota
- More than 1000 scientists from 175 institutions and 32 countries
- Planned to go fully operational within the next 10 years

The DUNE experiment

DEEP UNDERGROUND NEUTRINO EXPERIMENT







- Enormous volume:
  4 x 10kt modules filled with liquid argon
- Underground, to best reduce cosmic backgrounds
- New high intensity ν_μ and $\overline{\nu_\mu}$ beam from FNAL
- LArTPC technology provides amazing imaging capabilities

Science goals

- Determine CP violation, mass ordering, and precision measurements of mixing parameters
- Supernova neutrinos, diffuse supernova backgrounds, proton decay searches, and many more astrophysics and exotics searches possible since the detector is underground!

Neutrinos in the standard model

In order to understand how neutrinos fit in the standard model, their properties need to be experimentally determined:

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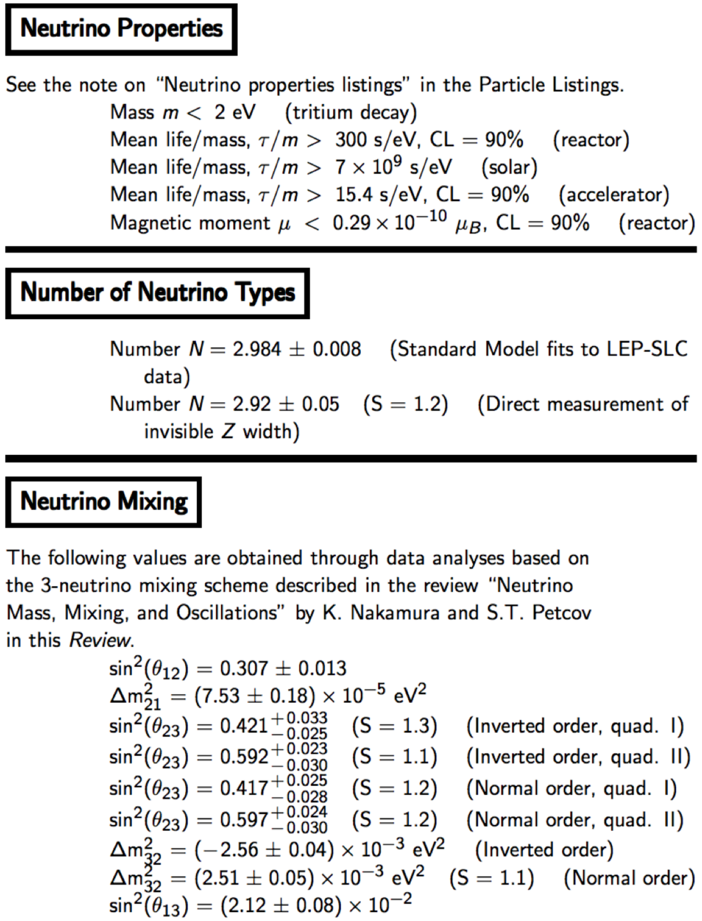

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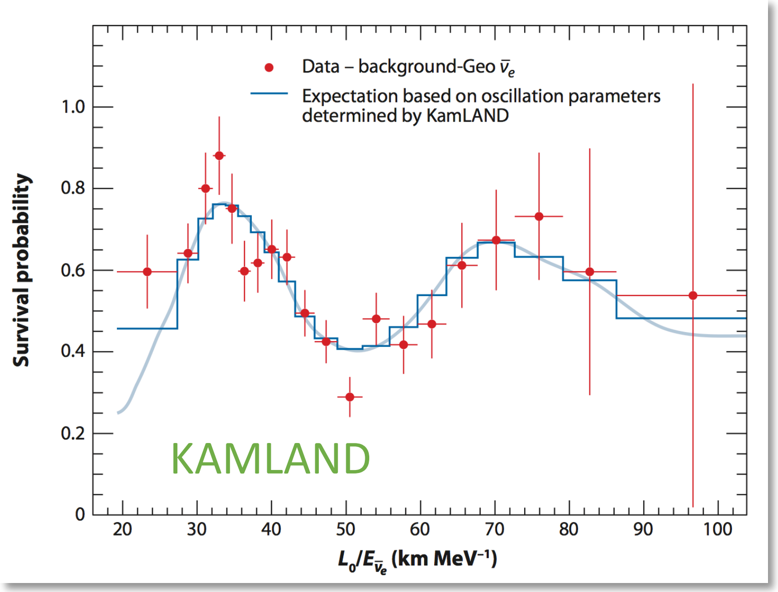
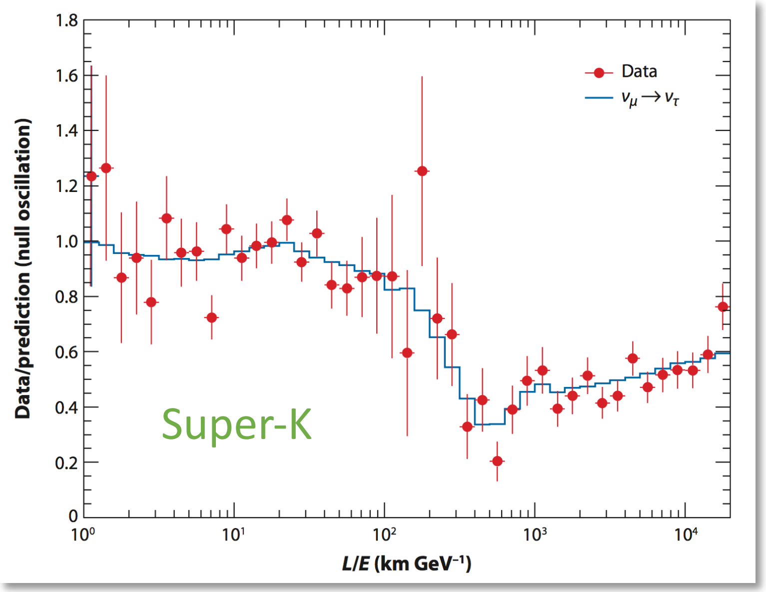
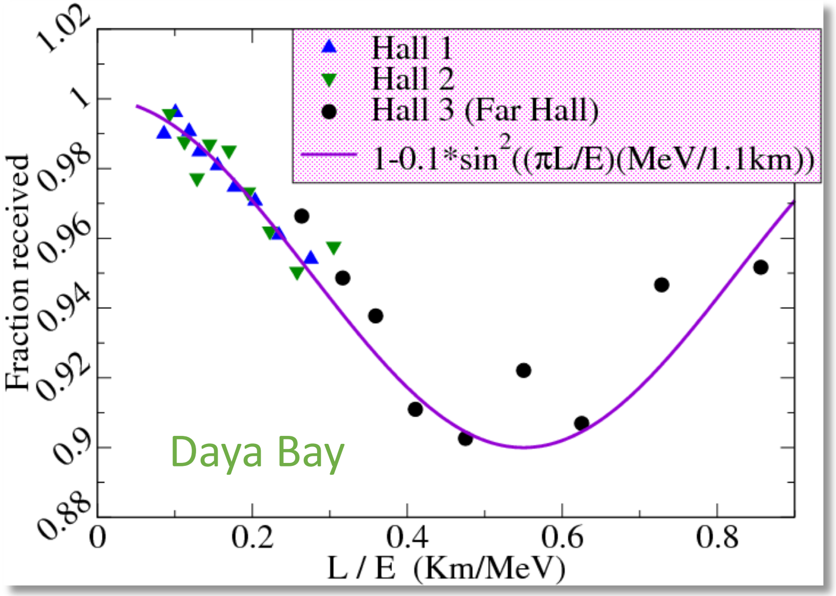
The scale of “standard three-flavor-oscillations”

“solar mixing”

“atmospheric mixing”





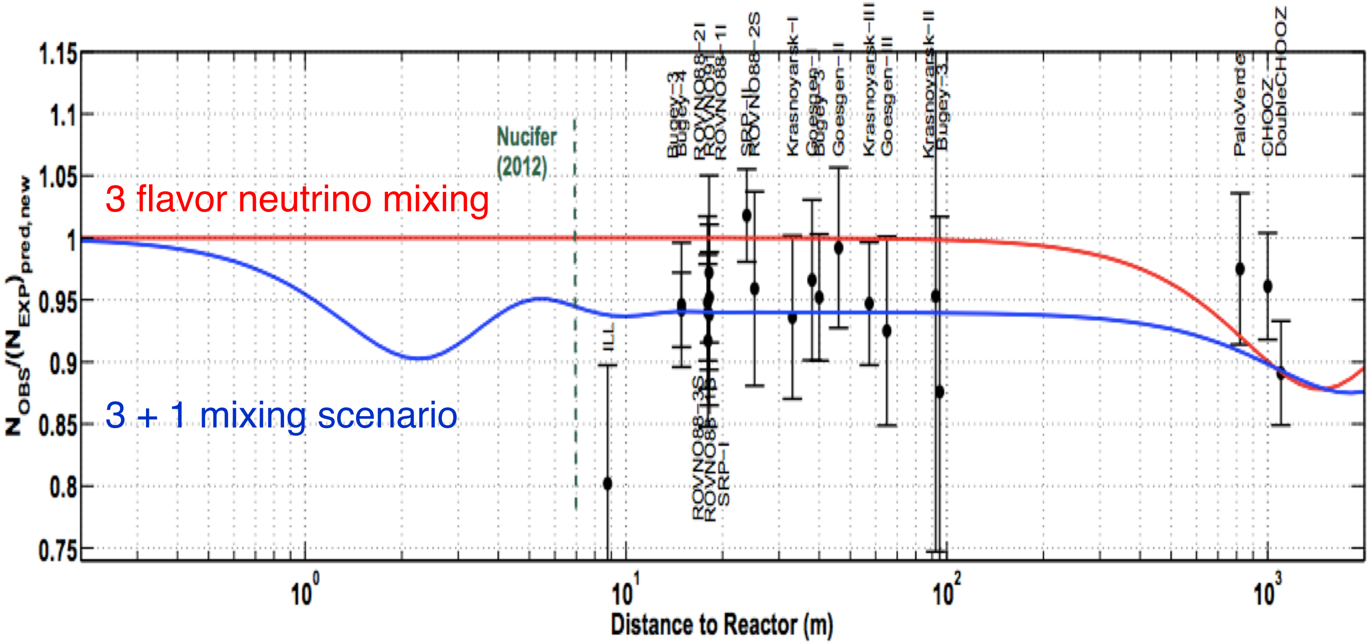


Standard model three-flavor oscillations are observed on the scale of

L/E > ~ km / MeV

The reactor neutrino anomaly

arXiv:1204.5379 [hep-ph]



Reactor $\overline{\nu}_e$ disappearance experiments

- Typical energies: few MeV
- Typical baselines: 10 – 1000m

Deficit in neutrino flux at the detector observed

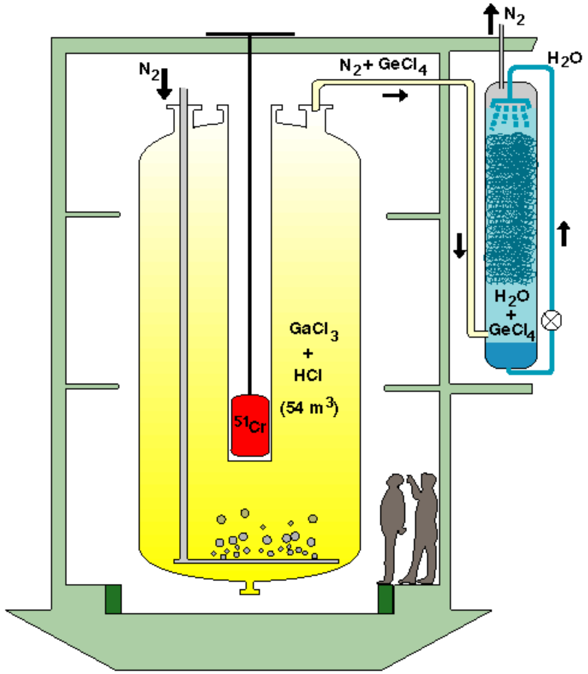
- Normalization problem?
- Oscillations on the scale of

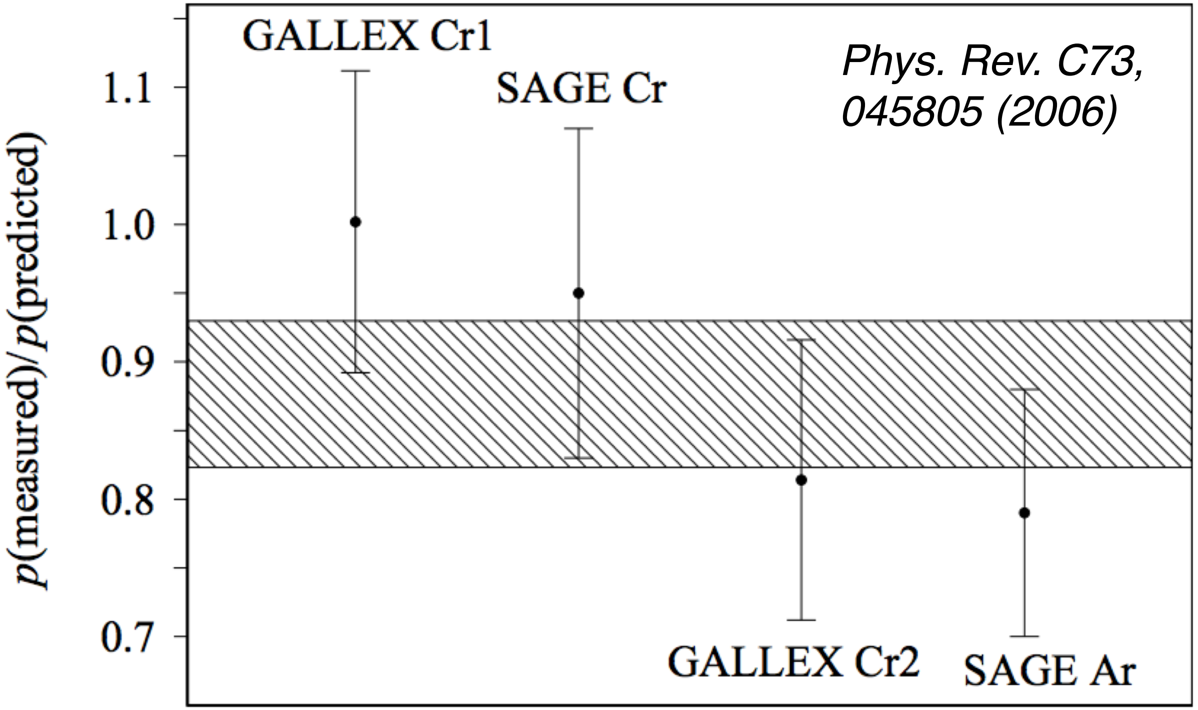
L/E > ~ m / MeV?

Radioactive source experiments

Radiochemical solar neutrino experiments GALLEX and SAGE with intense (MCi) ν_e calibration sources
(ν_e disappearance experiments)

- ν_e below the MeV scale
- Baselines on the scale of meters





Phys. Rev. C73, 045805 (2006)

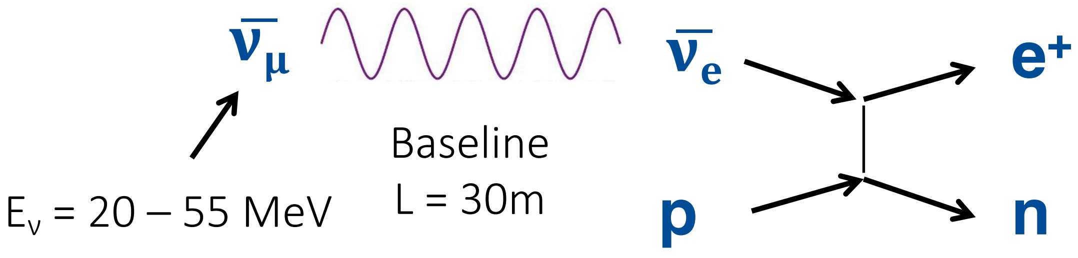
Deficit in ν_e rate observed
- Normalization problem?
- Oscillations on the scale of

L/E > ~ m / MeV?

The MiniBooNE and LSND event excess

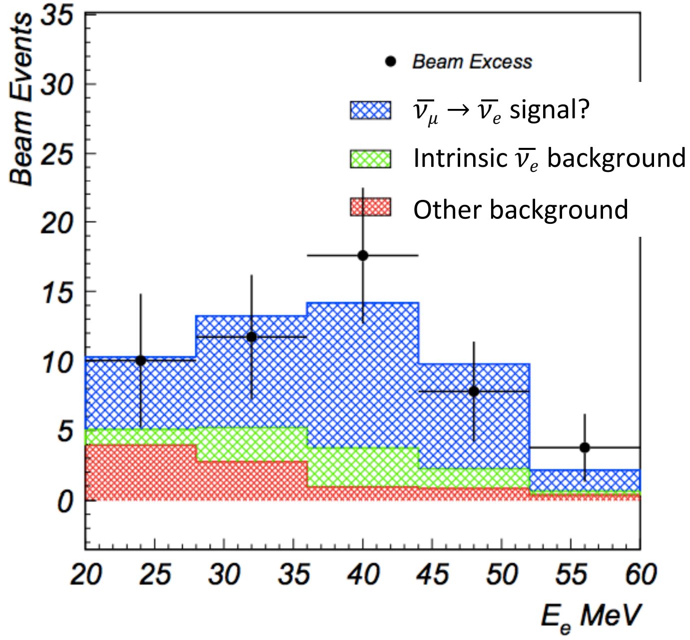
Anomalies observed in ν_e appearance experiments

LSND

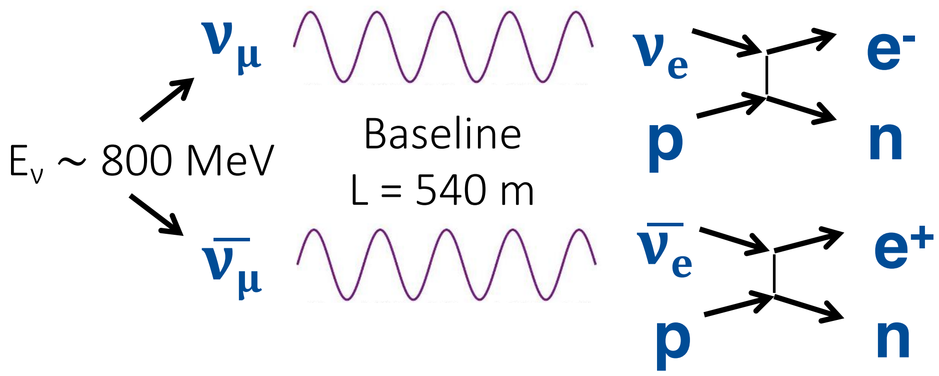


Baseline
L = 30m

E_ν = 20 – 55 MeV

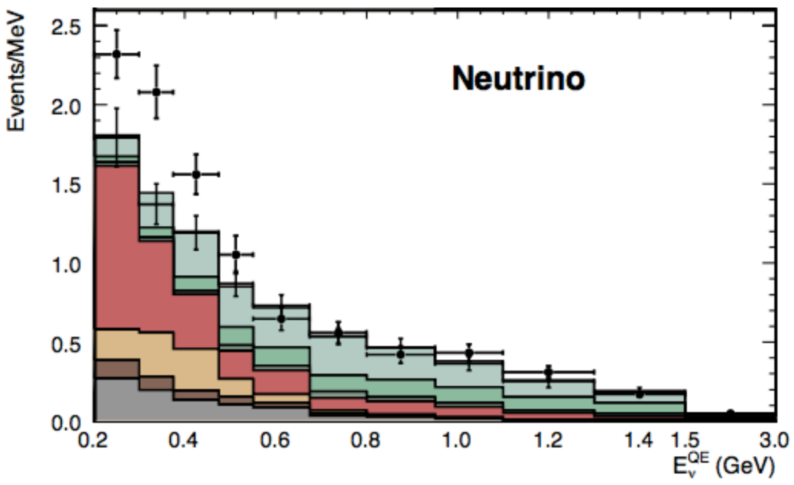


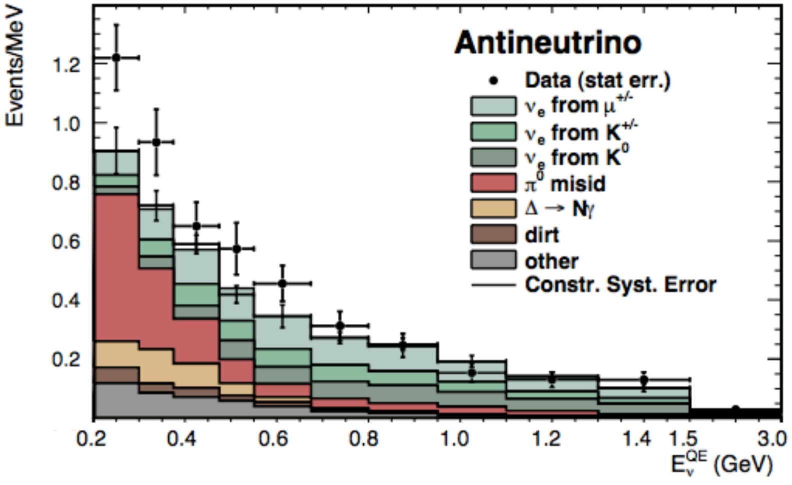
MiniBooNE



E_ν ~ 800 MeV

Baseline
L = 540 m





The MiniBooNE and LSND event excess

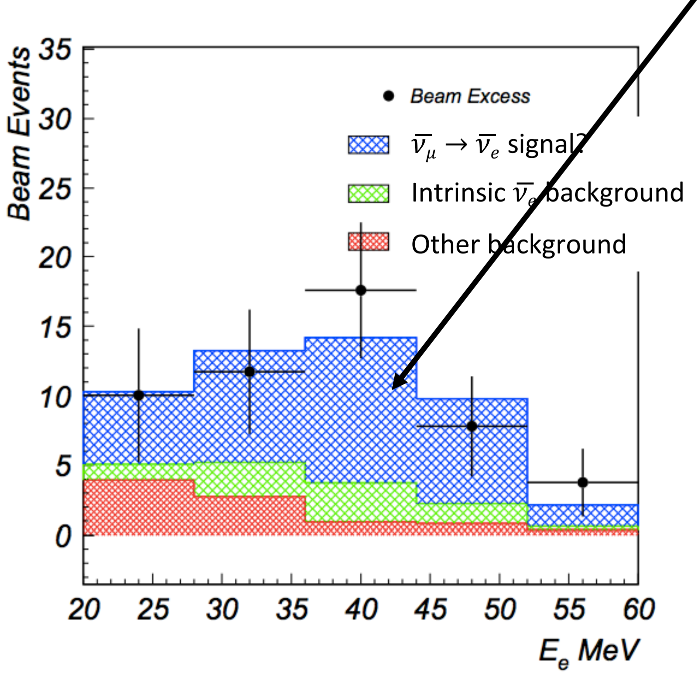
LSND

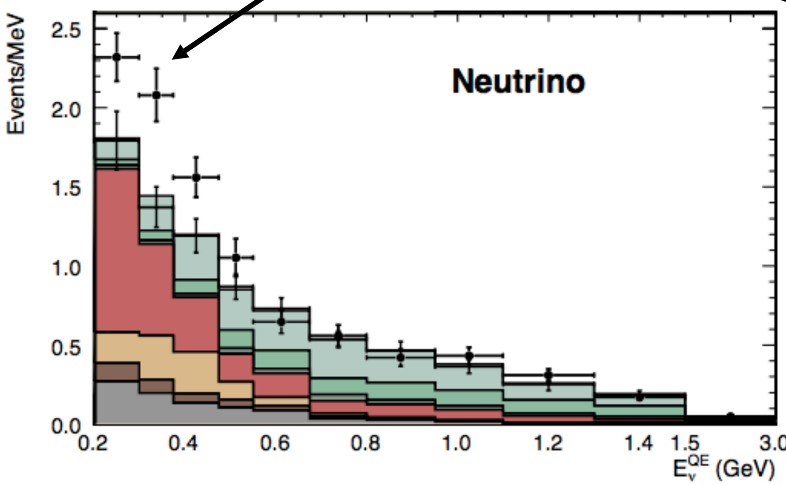
- Oscillation signal from additional sterile neutrinos?
- Unknown background?

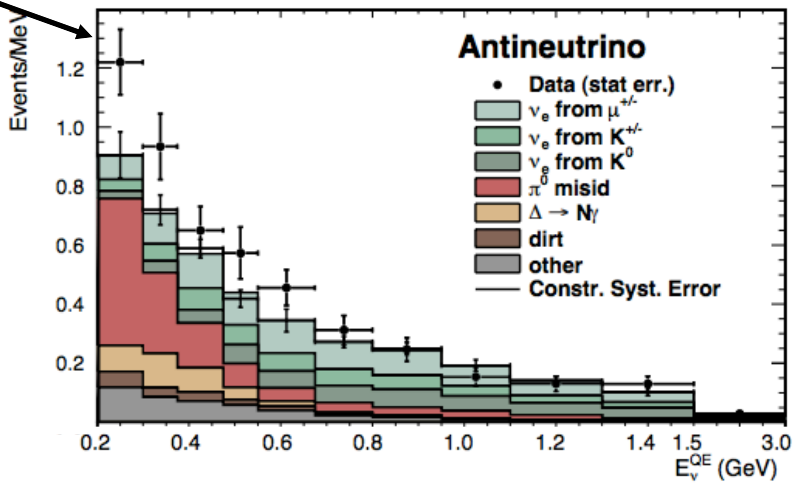
Excess of electromagnetic events on a scale of L / E ~m / MeV

MiniBooNE

- Oscillation signal from additional sterile neutrinos?
- Background from $\gamma -$ induced showers?
- Unknown background?



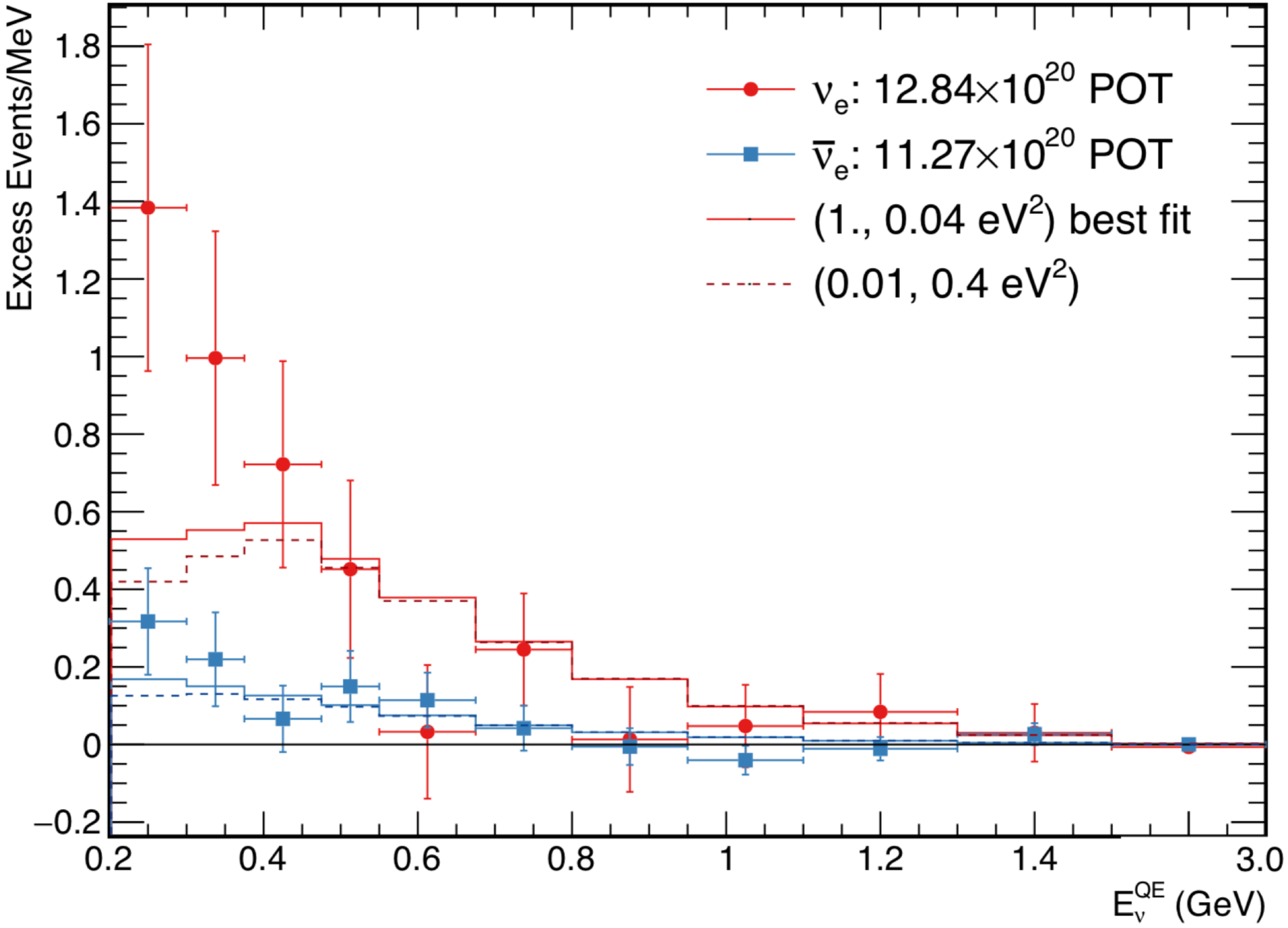




MiniBooNE 2018

- MiniBooNE was re-started data taking when MicroBooNE started operations
- With the new data MiniBooNE has doubled it's statistics in neutrino-mode running since the previous result
- Updated results were presented in June 2018
- MiniBooNE also sees an excess of low-energy electron-like events in the new data set. Combined with the previous data, the excess is at the level of 4.8σ

Presented at NEUTRINO2018



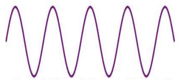
Sterile neutrinos?

Status of sterile neutrino global fits

One idea:

- "Active" neutrinos (ν_e, ν_μ, ν_τ) oscillate into "sterile" neutrinos (ν_s) on a scale of L/E ~ m/MeV

ν_e, ν_μ, ν_τ



ν_s

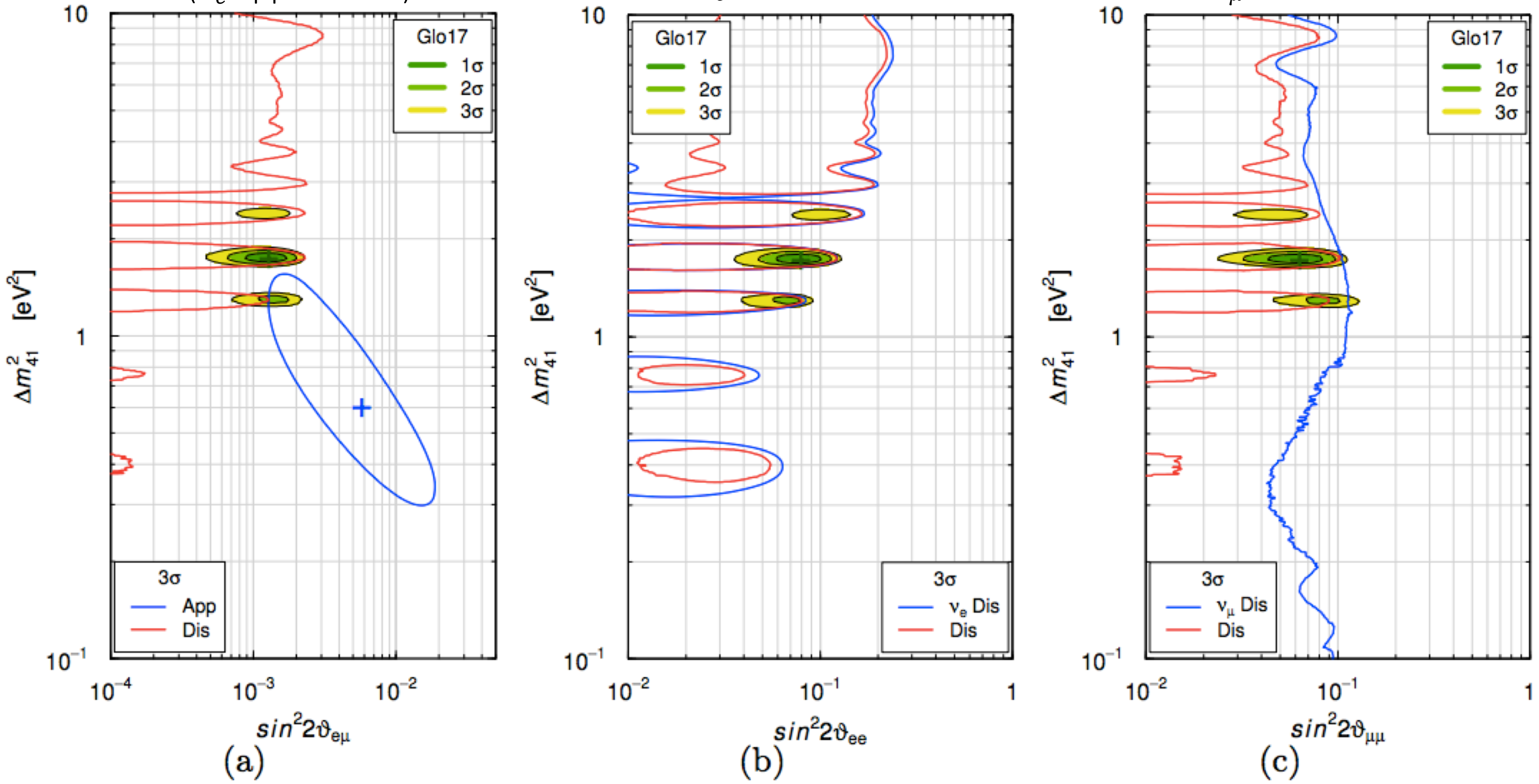
- "Sterile" neutrinos are called sterile because they are not detectable in our experiments
- There is no weak interaction process to produce a detectable lepton/hadron

(Note: Sterile neutrinos are not the only possible explanation)

$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (ν_e appearance)

$\nu_e \rightarrow \nu_e$ and $\bar{\nu}_e \rightarrow \bar{\nu}_e$ (ν_e disappearance)

$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ (ν_μ disappearance)



S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, arXiv:1703.00860

Future experiments to test ν_e disappearance

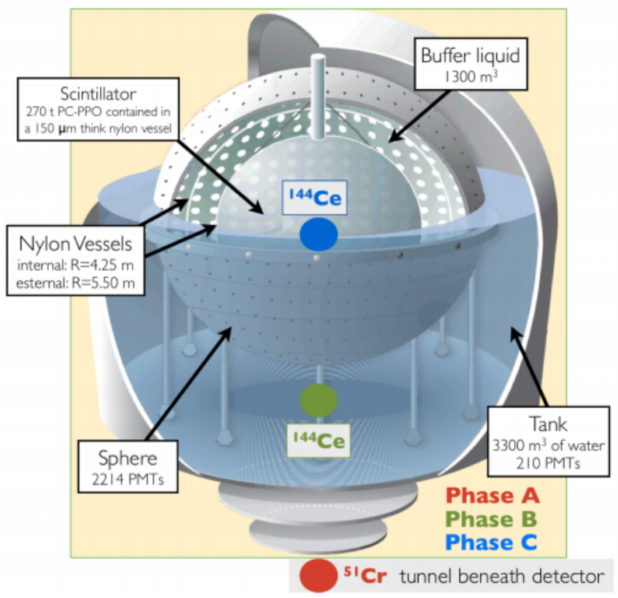
S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, arXiv:1703.00860

New generations of experiments:

- VERY short baseline (~m)

a) Radioactive source inside the detector (SOX,…)
b) Detector very close to a reactor (PROSPECT, SoLid, STEREO, …)
c) Isotope at rest decay (IsoDAR)

Example: SOX experiment (Borexino)

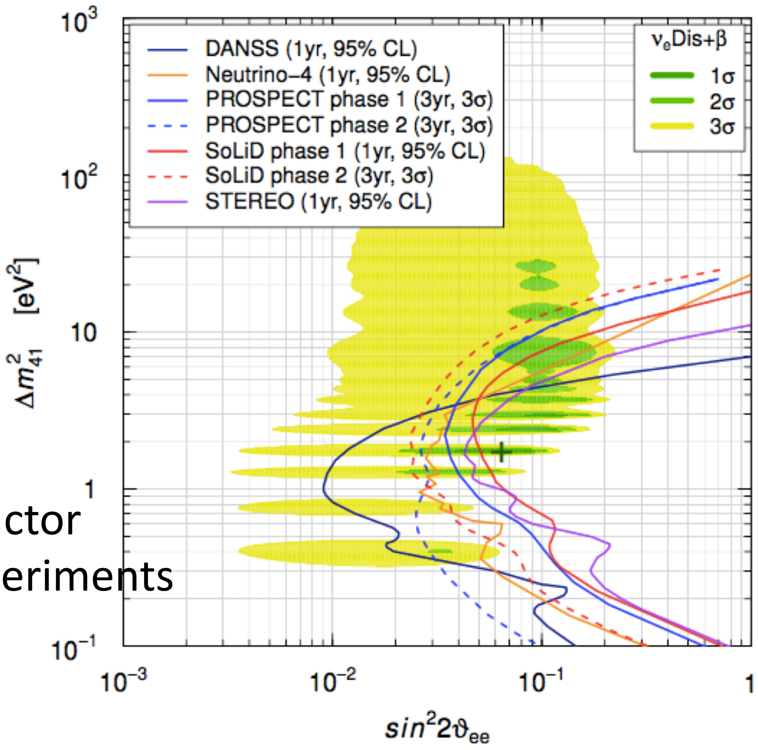


(unfortunately SOX is not going to happen)

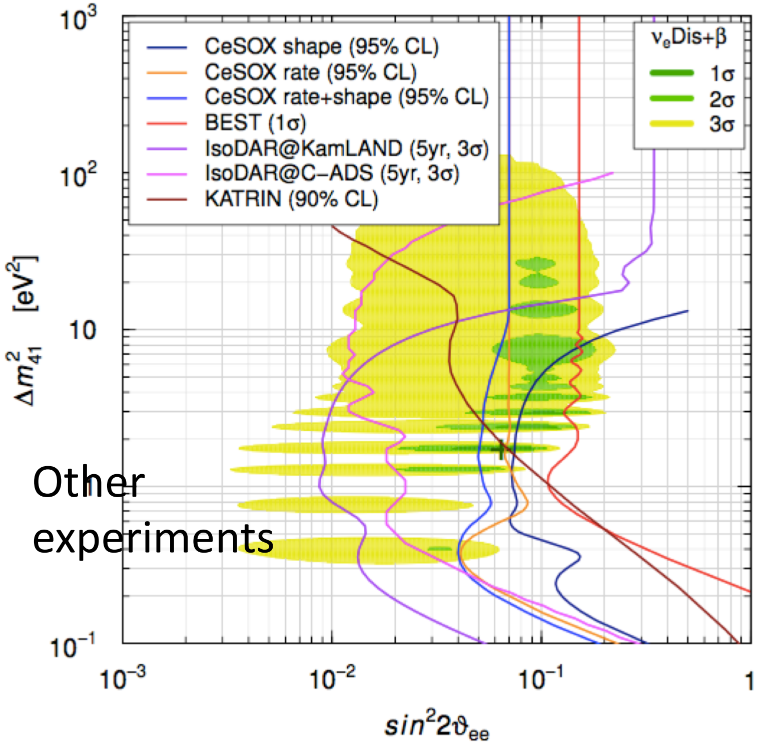
arXiv:1304.7721

Sensitivities

$\nu_e \rightarrow \nu_e$ and $\bar{\nu}_e \rightarrow \bar{\nu}_e$
(ν_e disappearance)



Reactor experiments



Other experiments

Fermilab's short baseline program: Testing ν_e appearance and ν_μ disappearance

Direct follow-up to the MiniBooNE low-energy excess result

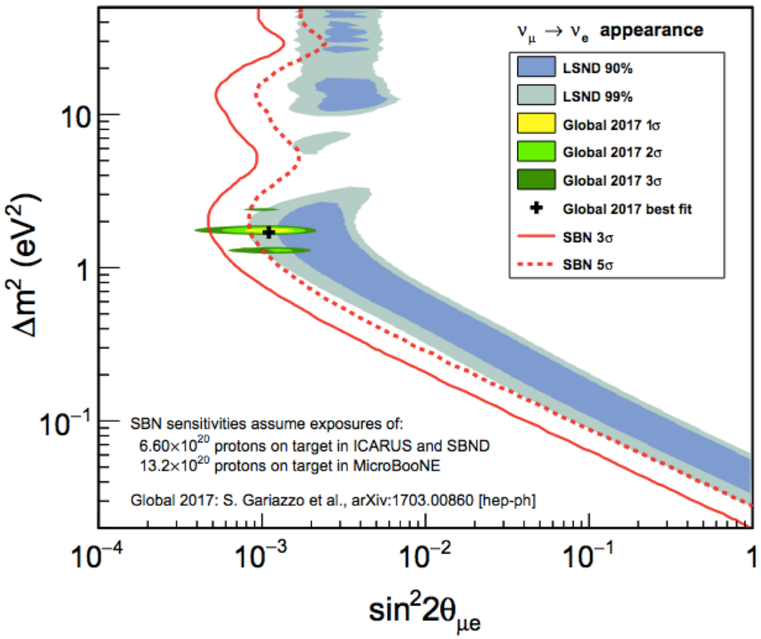
Things we are keeping the same:

- Same neutrino beam
- Similar baseline

Things we are changing:

- Three detectors instead of one, to map the spectrum at different baselines
- Different detector technology: Superior imaging capabilities and different
- ν_e appearance AND ν_μ disappearance analysis possible in the same experiment

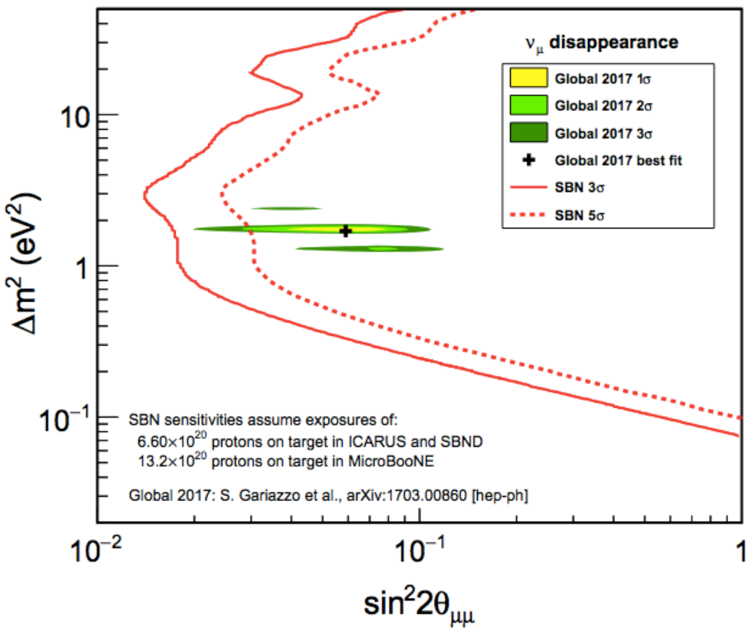
ν_e appearance



SBN sensitivities assume exposures of:
6.60×10^{20} protons on target in ICARUS and SBND
13.2×10^{20} protons on target in MicroBooNE

Global 2017: S. Gariazzo et al., arXiv:1703.00860 [hep-ph]

ν_μ disappearance

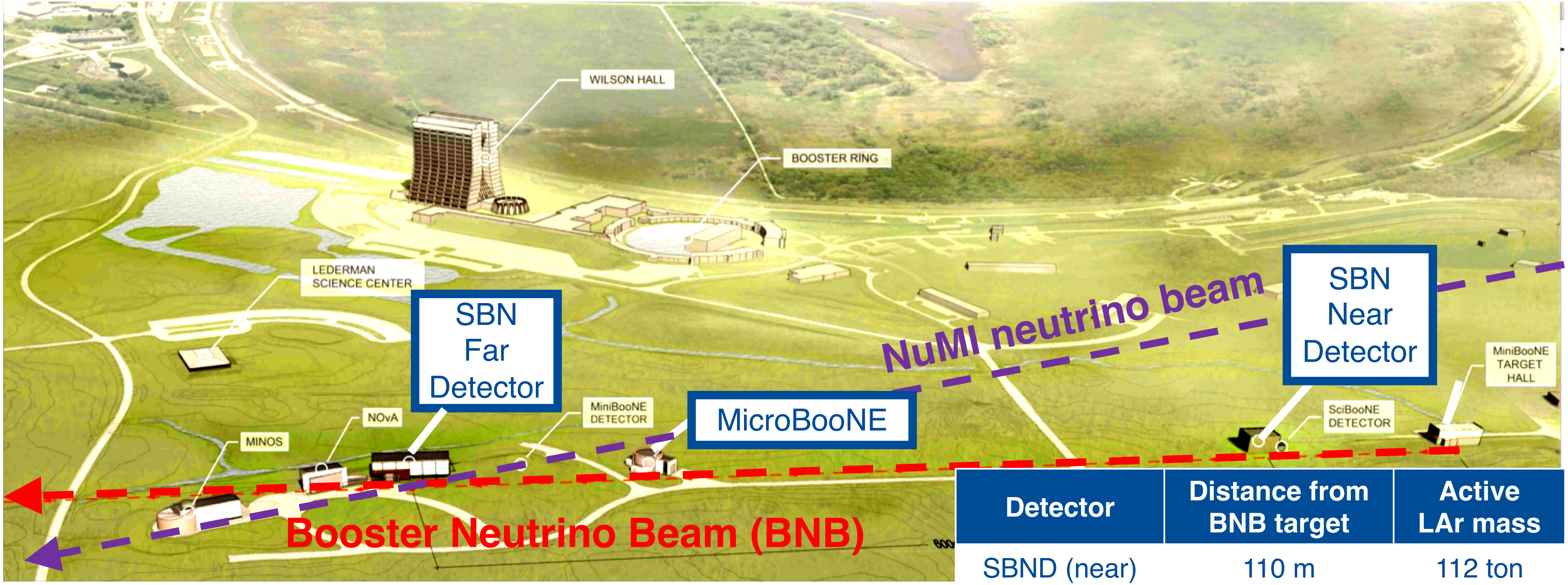


SBN sensitivities assume exposures of:
6.60×10^{20} protons on target in ICARUS and SBND
13.2×10^{20} protons on target in MicroBooNE

Global 2017: S. Gariazzo et al., arXiv:1703.00860 [hep-ph]

SBN is sensitive to the entire range of interest.

One Program – three detectors



Detector	Distance from BNB target	Active LAr mass
SBND (near)	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS (far)	600 m	476 ton

- All detectors are liquid-argon time projection chambers (LArTPC)
- Sitting on-axis in the BNB
- Receiving off-axis NuMI beam

Status of the SBN detectors

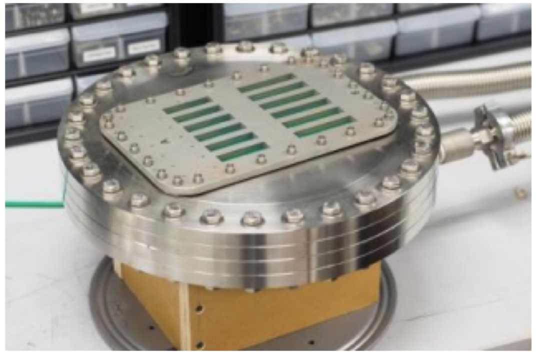
MicroBooNE

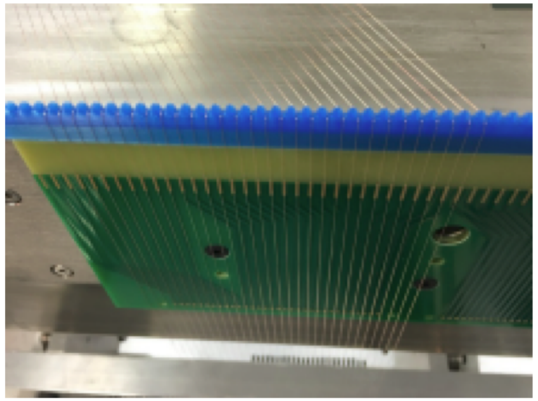
- MicroBooNE is completed and taking the data since Summer 2015
- Just bringing out first results on neutrino-Argon interactions and LArTPC properties and performances

ICARUS

- The two ICARUS vessels from CERN just moved into the building this month!
- Completion expected end of 2019.

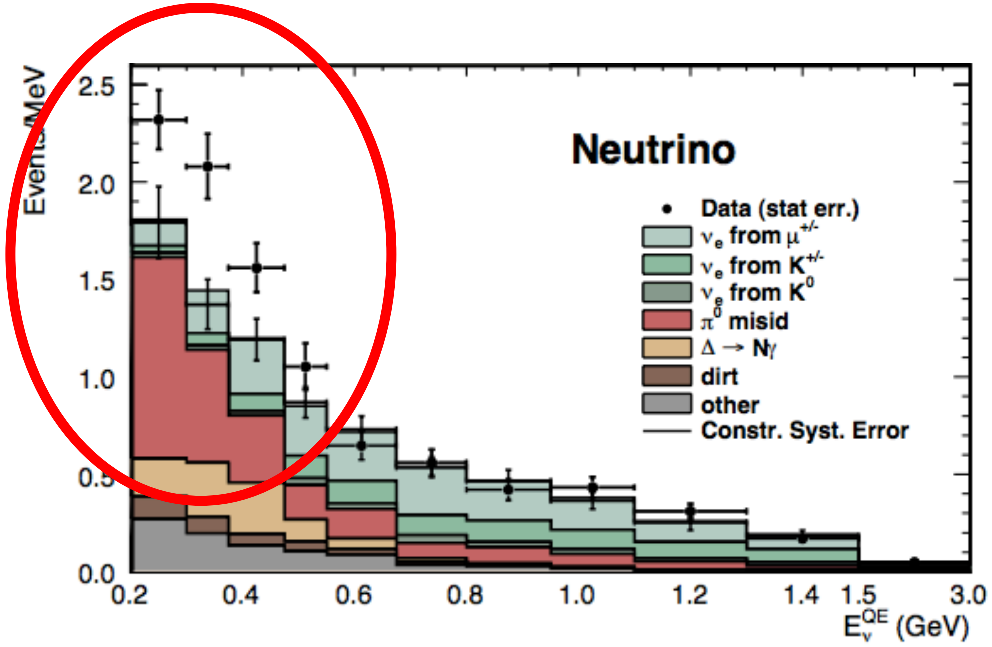
SBND

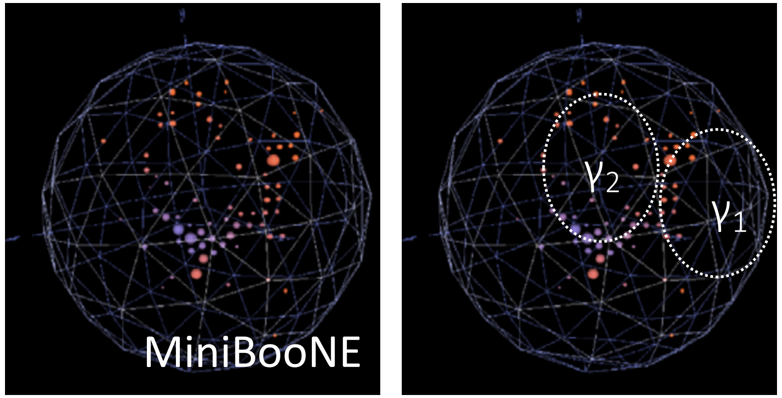




- The different parts of SBND are currently being constructed in the US, UK, and Switzerland
- Installation during 2019/2020

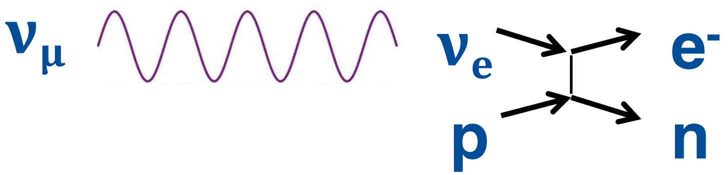
Why we want LArTPCs for the SBN program





MiniBooNE collaboration;
Phys. Rev. Lett. 110, 161801 (2013)

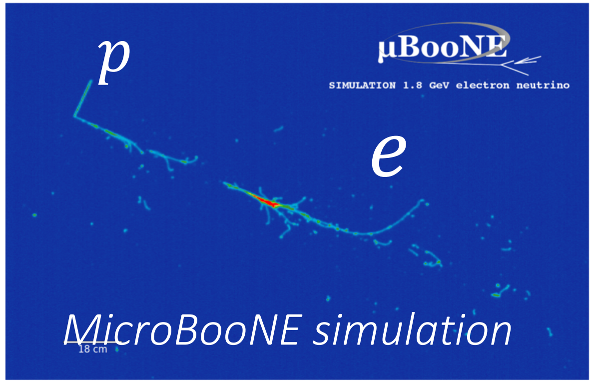
The signature we are looking for is an electron

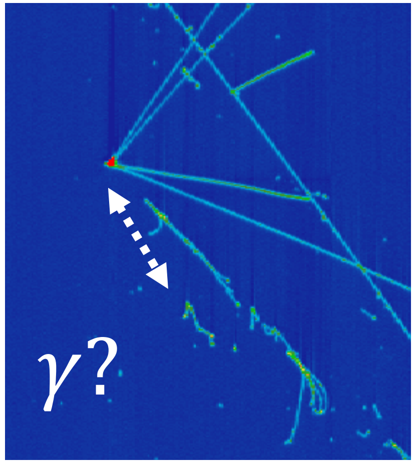


The largest background in the MiniBooNE analysis comes from photons!

For MiniBooNE it was difficult to distinguish electrons and photons.

LArTPCs are much better at this!





MicroBooNE is already taking data since October 2015. Without SBND and ICARUS, MicroBooNE will be able to tell if the event excess is electron-like or photon-like.

This is an important question!

Conclusion

- Neutrinos are an established part of the standard model, but we still have a lot of open questions in neutrino physics, like
  - What's the absolute mass of the neutrinos?
  - Are neutrinos Dirac or Majorana particles?
  - What's the neutrino mass ordering?
  - Is CP symmetry violated in the neutrino sector?
  - Are there more than three neutrino flavors?
  - What role do neutrinos play in the standard model and in the evolution of the Universe?

- Neutrino detection is challenging. We have a very diverse range of experiments – different technologies are needed for different flavors, energy ranges, source intensities, baselines

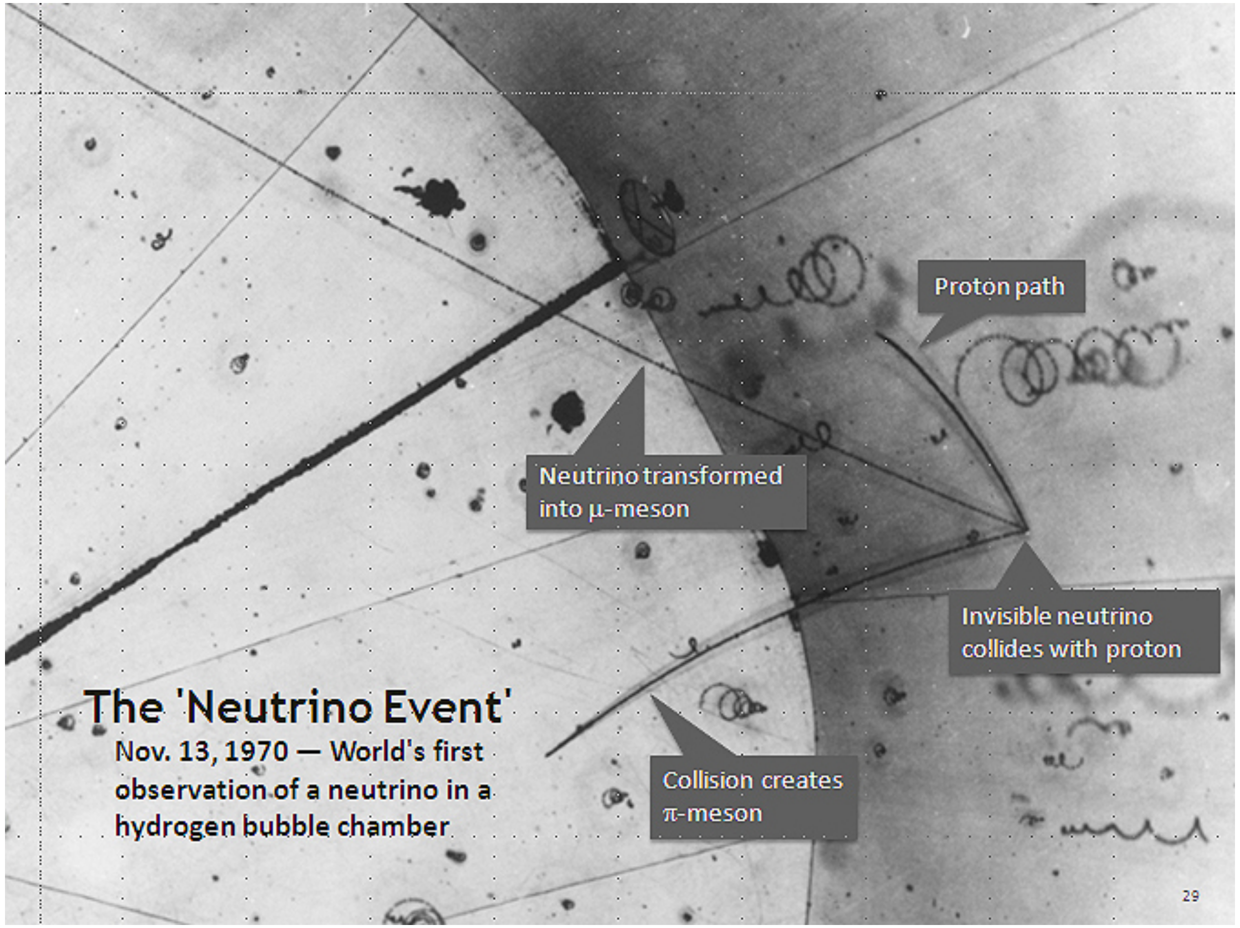
- A lot of new experiments designed to bring us a huge step further in our understanding of neutrinos are being started at the moment. In 5 years we should know a lot more!

- Last but not least: Neutrinos have always been good for a surprise – we are excited to see what the future holds!

Backup

Why liquid-argon detectors?

- a brief excursion through the history of neutrino detection



Bubble chambers

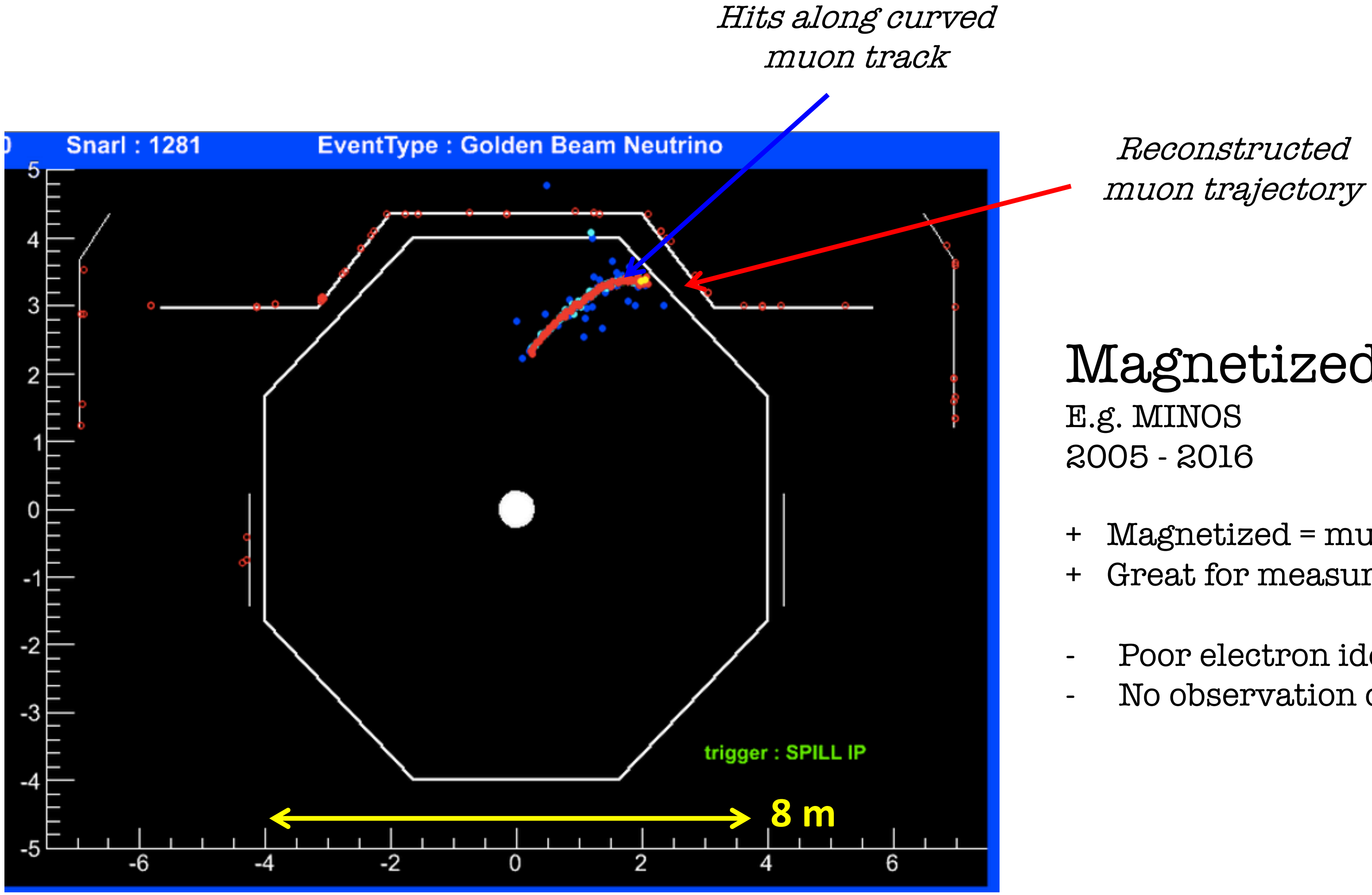
1960's and onward

\+ Beautiful resolution!

- Not self-triggered
- Not digitized
- No calorimetric information

Why liquid-argon detectors?

- a brief excursion through the history of neutrino detection



Magnetized steel/plastic scintillator

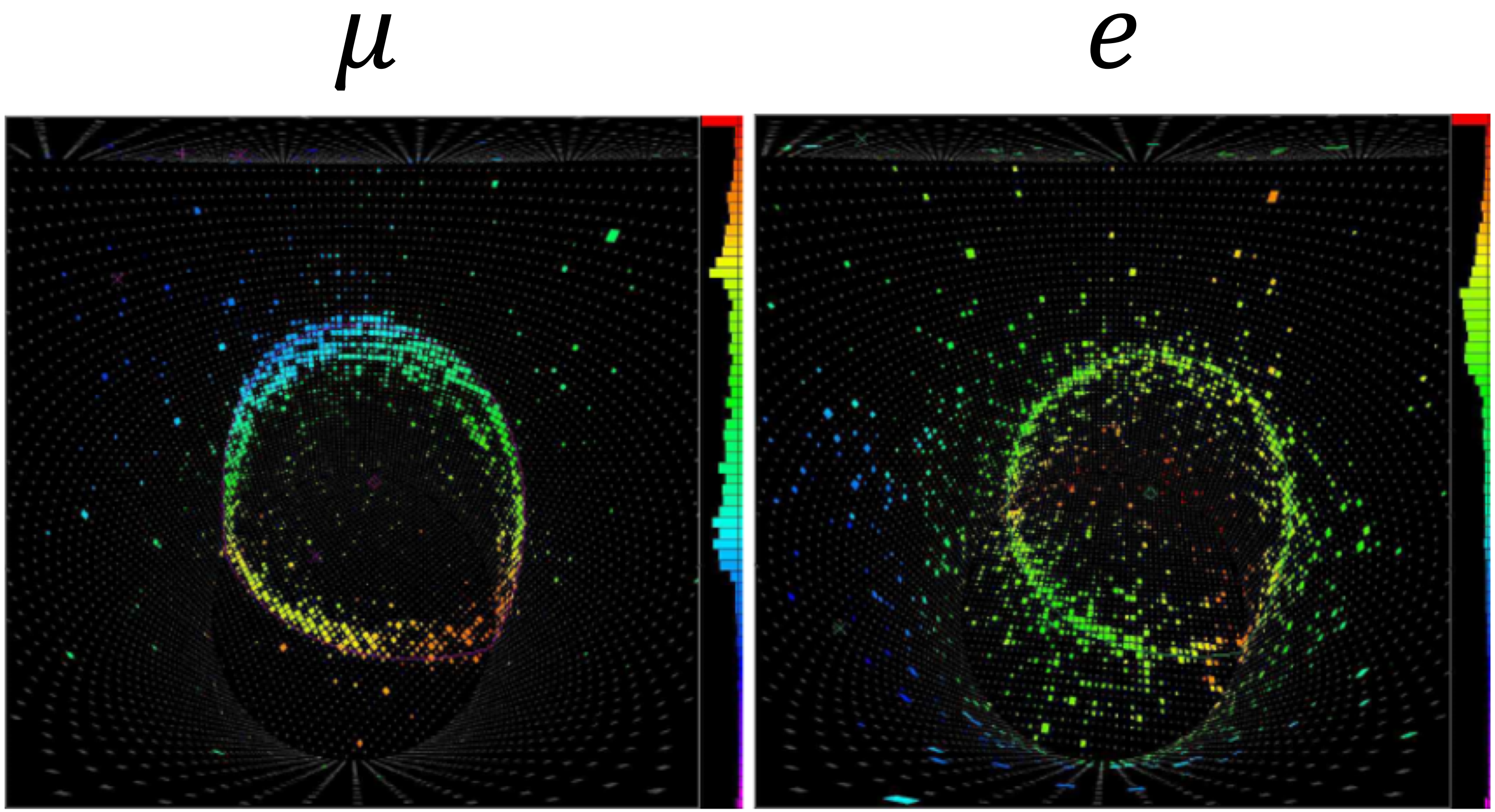
E.g. MINOS
2005 - 2016

- \+ Magnetized = muon charge and momentum measurements
- \+ Great for measurement of atmospheric mixing angles

- Poor electron identification
- No observation of hadrons in the final state

Why liquid-argon detectors?

- a brief excursion through the history of neutrino detection



SuperK, simulation

Cherenkov detectors

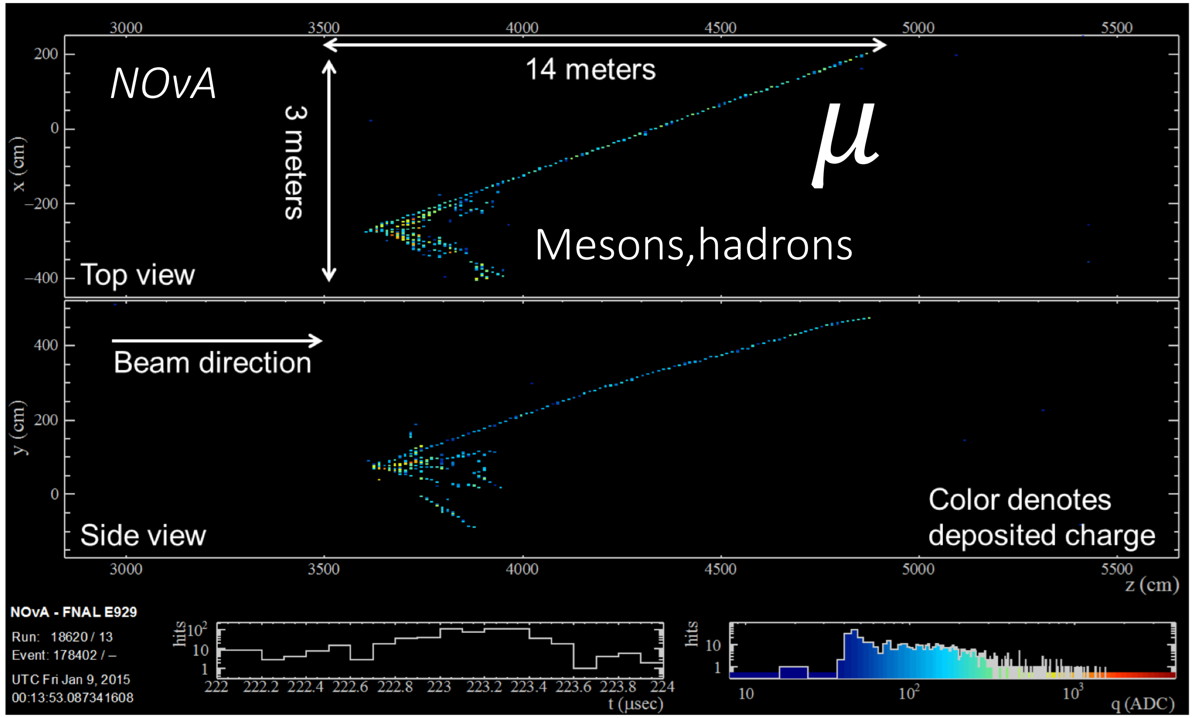
e.g. SuperKamiokande (T2K FD),
MiniBooNE
1996 – today!

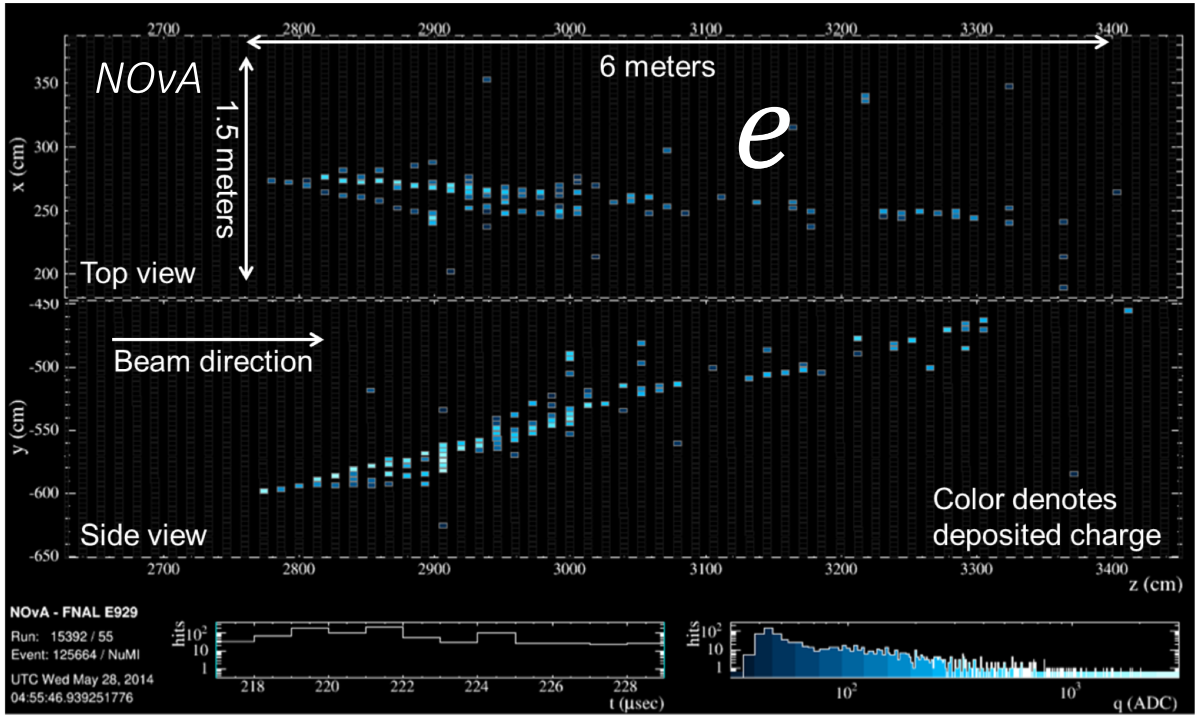
+ Can instrument a large volume at relatively low cost

- Observation of electrons possible, but difficult due to π^0 backgrounds
- No observation of hadrons in the final state

Why liquid-argon detectors?

- a brief excursion through the history of neutrino detection





Liquid/solid scintillator strip detectors

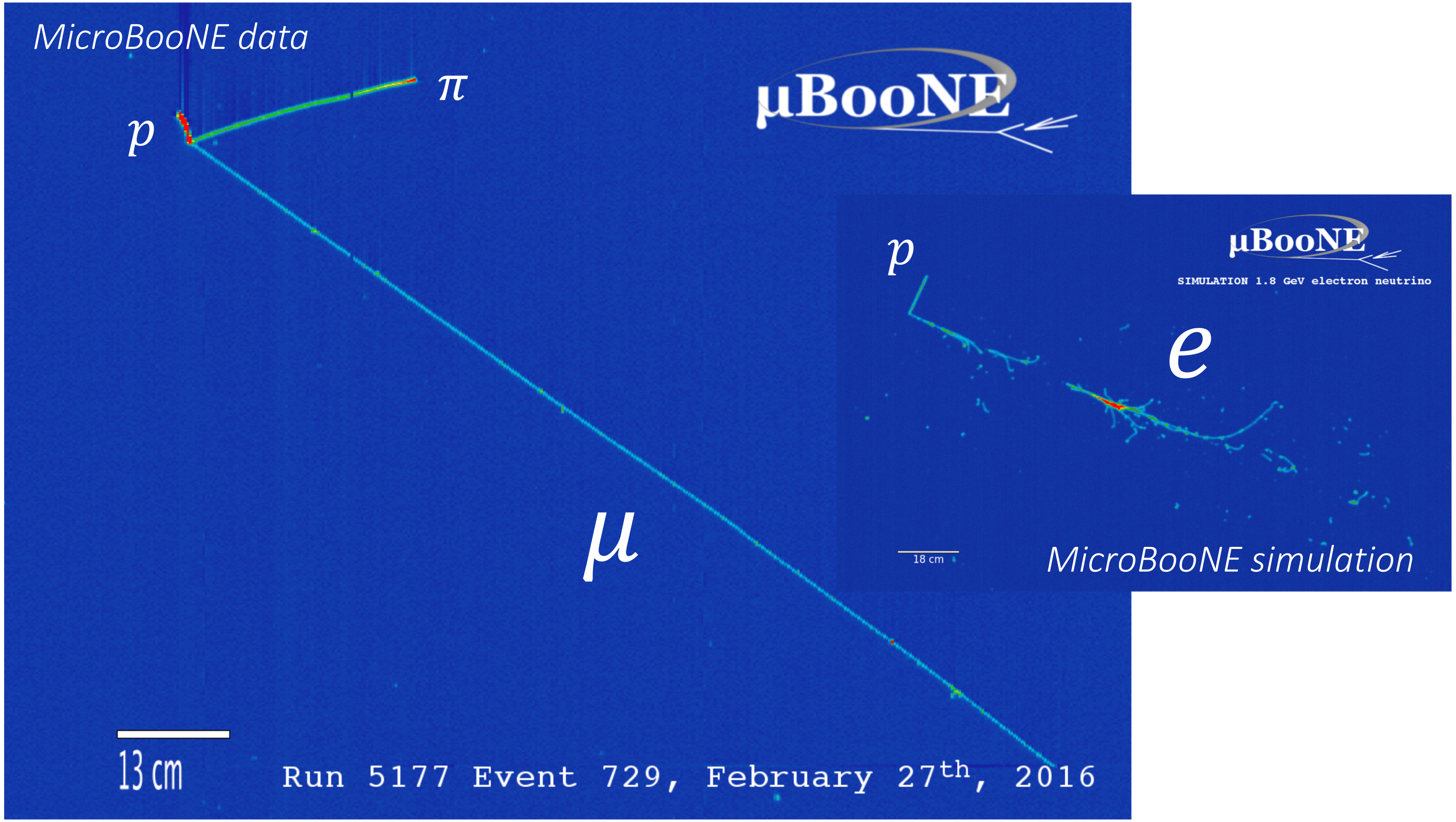
e.g. MINERvA, NOvA
2010 – today!

+ Improved observation of electrons and hadrons
+ Calorimetric information

- Limited resolution

Why liquid-argon detectors?

- a brief excursion through the history of neutrino detection



LArTPCs

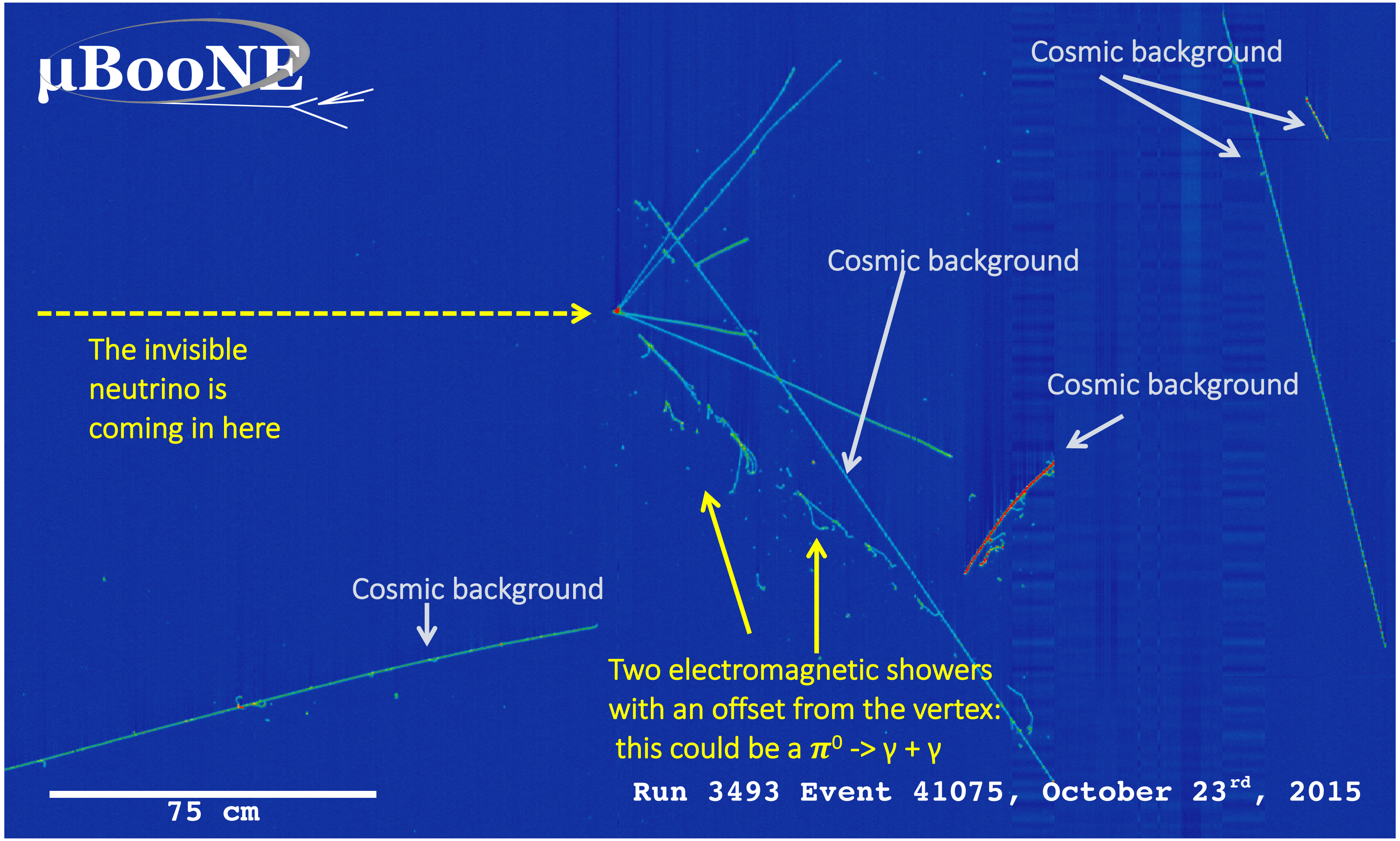
e.g. ICARUS, ArgoNeuT, MicroBooNE
and many more to come
The 21st century

+ almost Bubble-chamber image quality
+ self triggered
+ fully digitized
+ calorimetric information

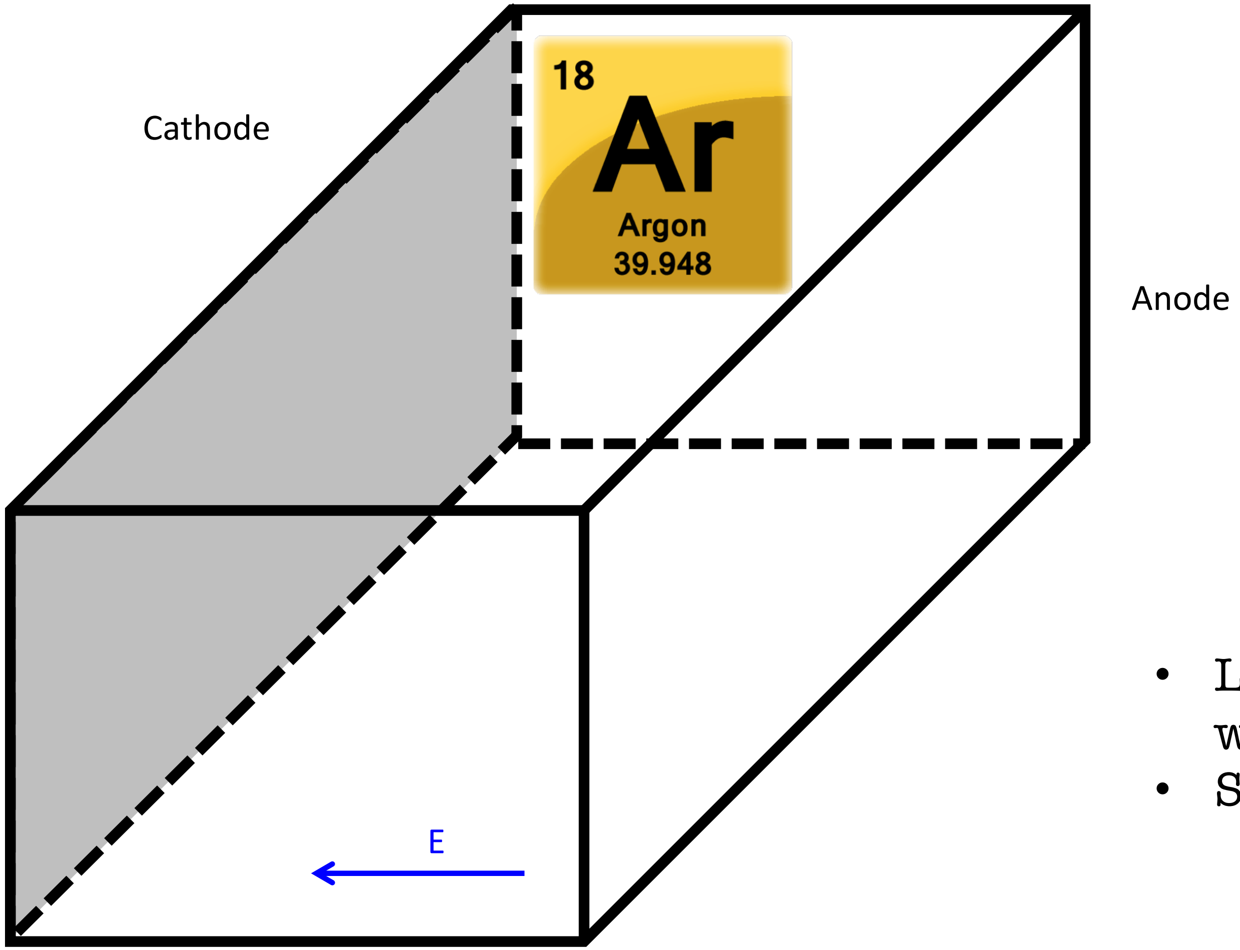
- Challenging technology!
- Not (yet) magnetizable

The amazing things you can do with a LArTPC

- Better knowledge on the final state products
- Better particle ID capabilities
- Allows more precise and less model dependent reconstruction of the initial neutrino energy!
  (needed for oscillation physics!)
- Proton observation allows us to study nuclear effects in ν-Argon scattering
  (reduces systematic errors in oscillation analyses)

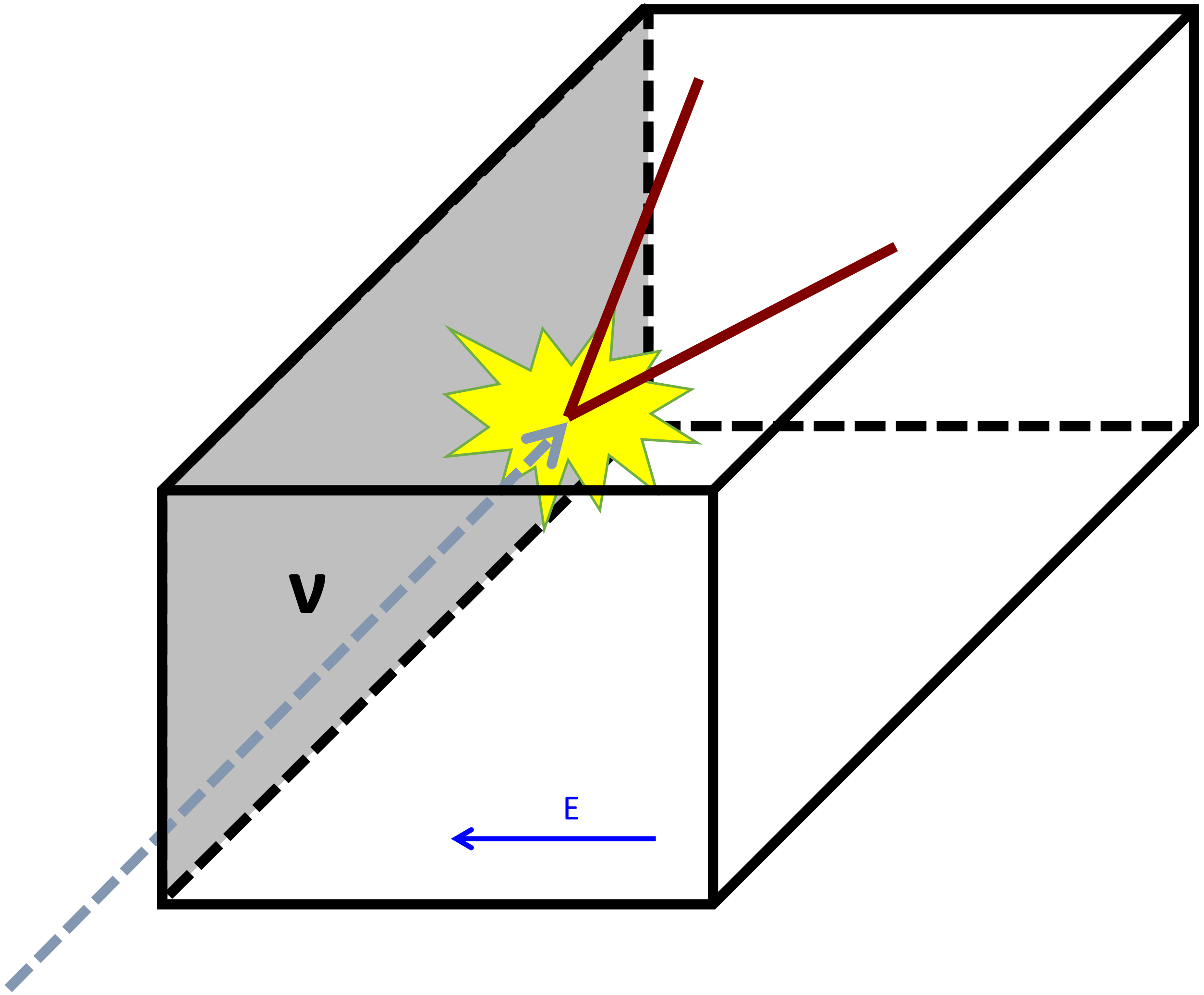


The principle of a liquid-argon Time Projection Chamber



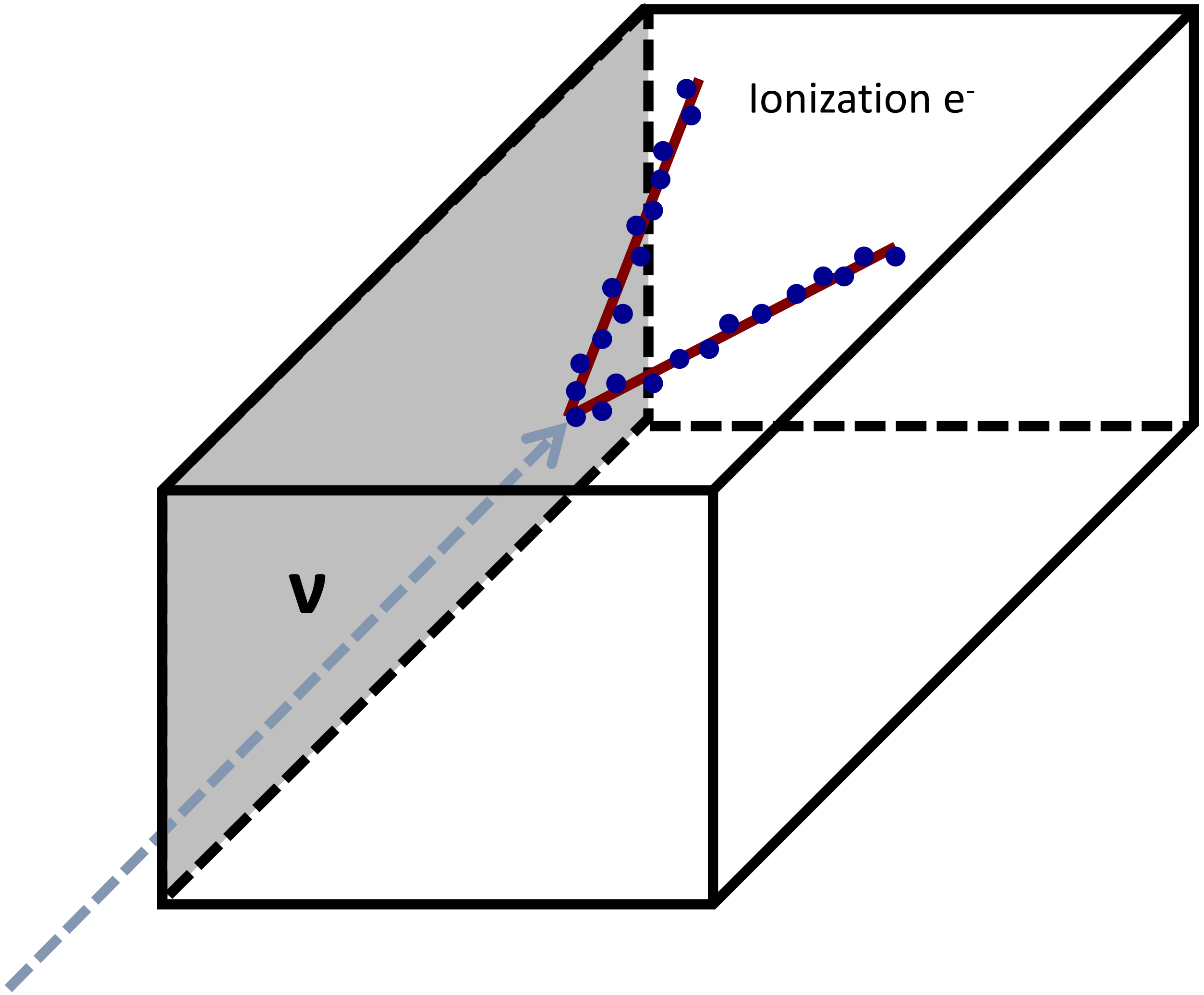
- Large volume filled with liquid-argon
- Strong electric field

The principle of a liquid-argon Time Projection Chamber



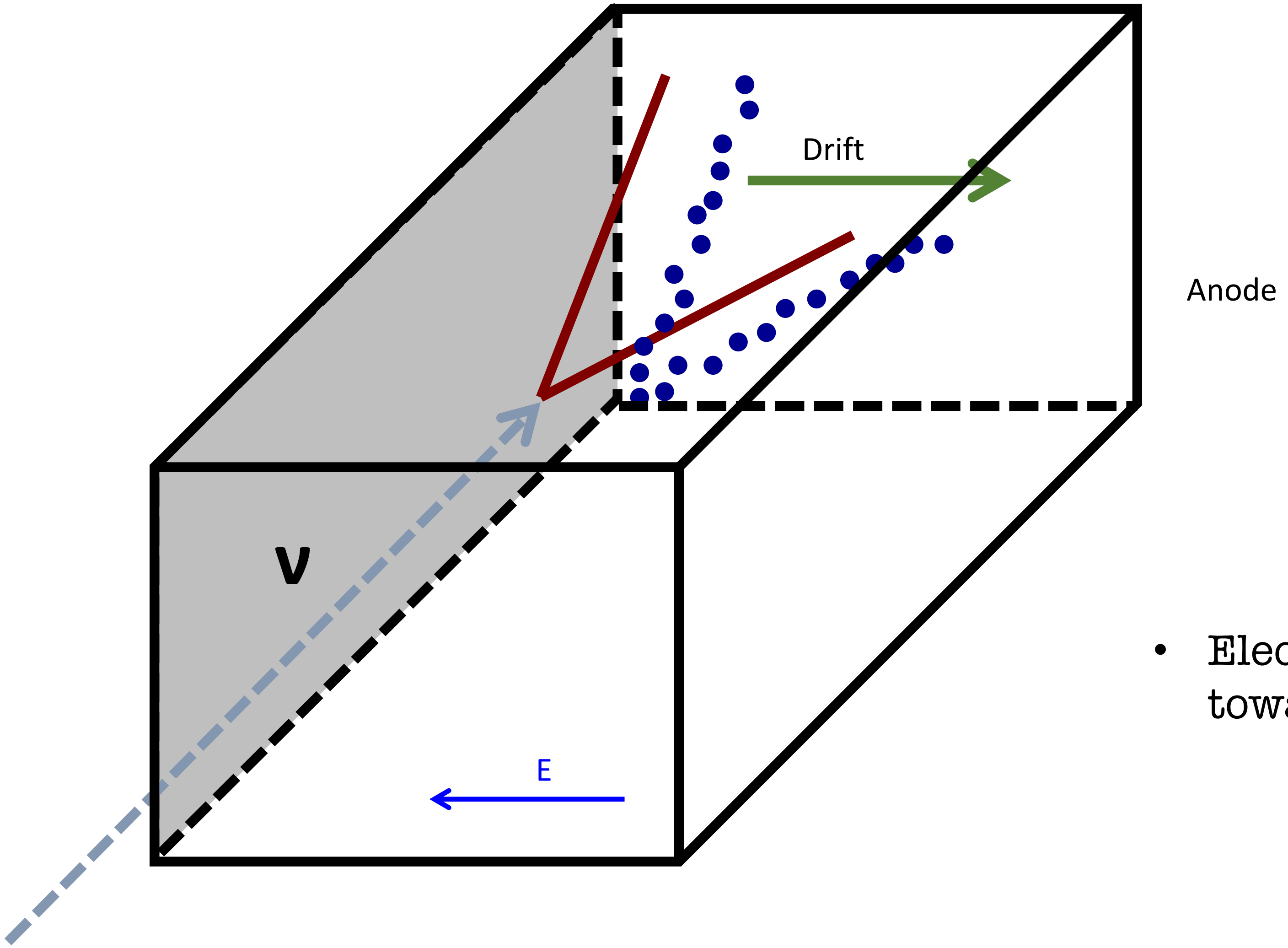
- Neutrinos interact within the liquid argon volume
- Scintillation light production

The principle of a liquid-argon Time Projection Chamber



- Production of ionization electrons

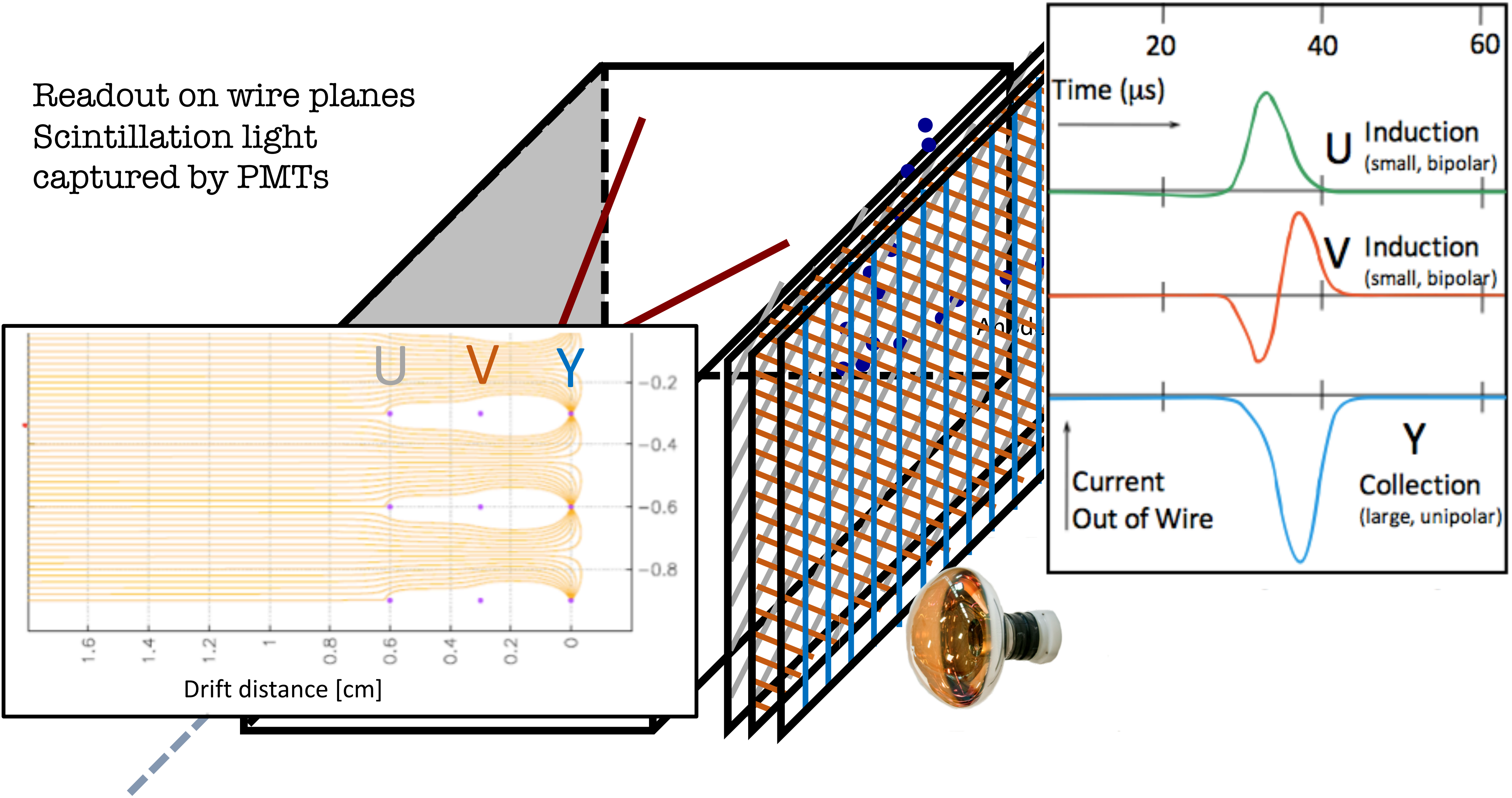
The principle of a liquid-argon Time Projection Chamber



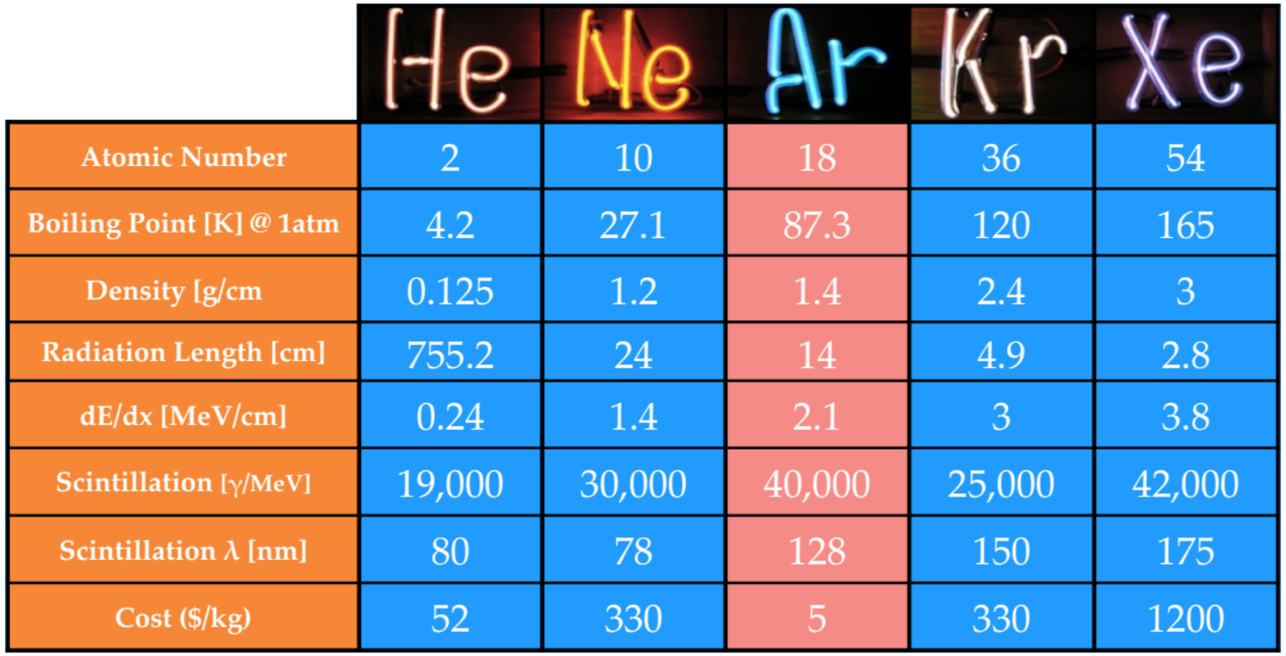
- Electrons drift towards anode plane

The principle of a liquid-argon Time Projection Chamber

- Readout on wire planes
- Scintillation light captured by PMTs

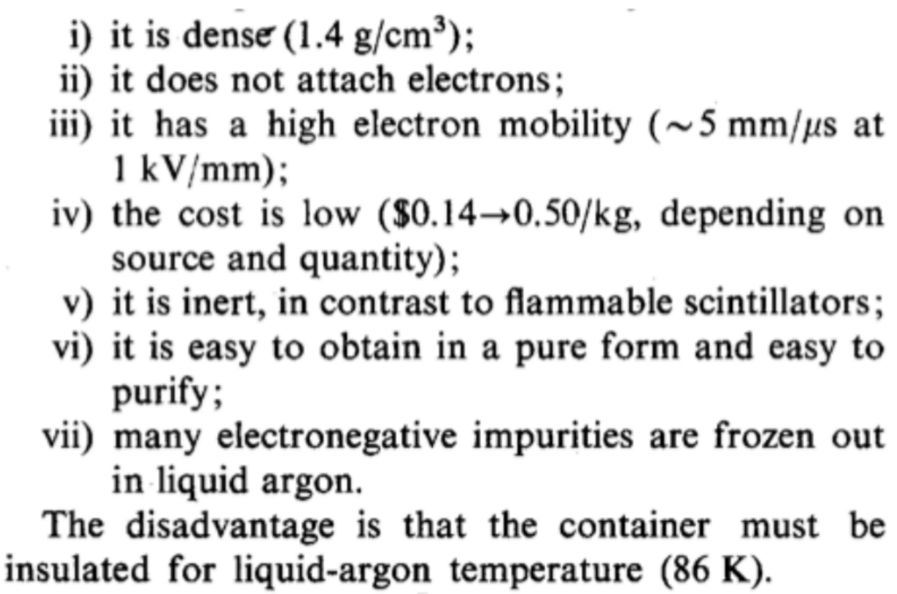


Why argon?



	He	Ne	Ar	Kr	Xe
Atomic Number	2	10	18	36	54
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120	165
Density [g/cm	0.125	1.2	1.4	2.4	3
Radiation Length [cm]	755.2	24	14	4.9	2.8
dE/dx [MeV/cm]	0.24	1.4	2.1	3	3.8
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000
Scintillation λ [nm]	80	78	128	150	175
Cost ($/kg)	52	330	5	330	1200

Credit: Mitch Soderberg



i) it is dense (1.4 g/cm^3);
ii) it does not attach electrons;
iii) it has a high electron mobility (~5 mm/μs at 1 kV/mm);
iv) the cost is low ($0.14→0.50/kg, depending on source and quantity);
v) it is inert, in contrast to flammable scintillators;
vi) it is easy to obtain in a pure form and easy to purify;
vii) many electronegative impurities are frozen out in liquid argon.

The disadvantage is that the container must be insulated for liquid-argon temperature (86 K).

Willis & Radeka, NIM 120 (1974)