#SOMOSUA

Some aspects of
Neutrino Physics and Experiments

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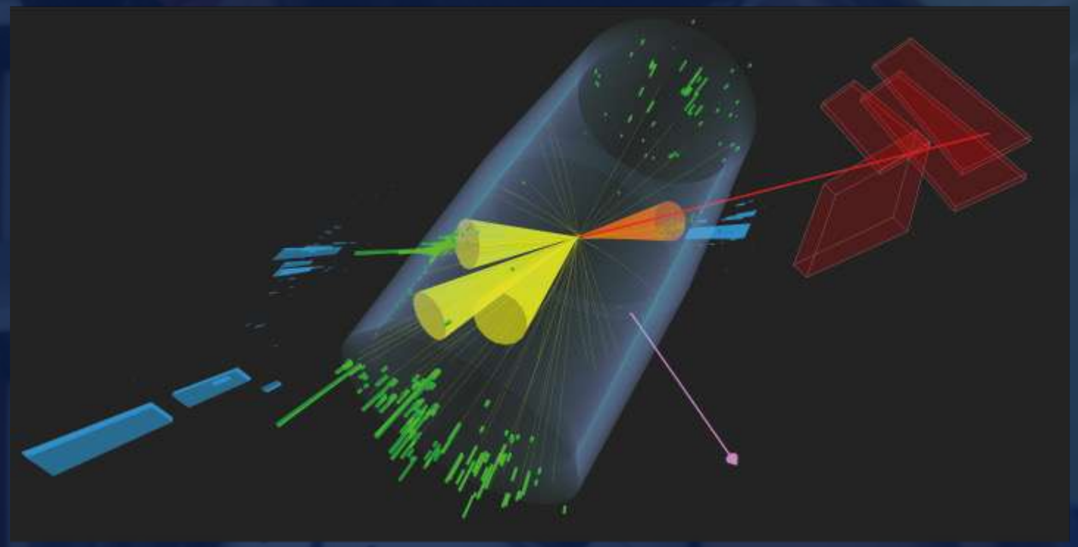
Universidad de Los Andes, Bogotá, Colombia
December 7, 2022

Universidad de los Andes Colombia



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ACREDITACIÓN INSTITUCIONAL DE ALTA CALIDAD 2019 - 2023

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WHY…

In order to understand the universe that we live in, it looks like we'll need to understand the neutrino

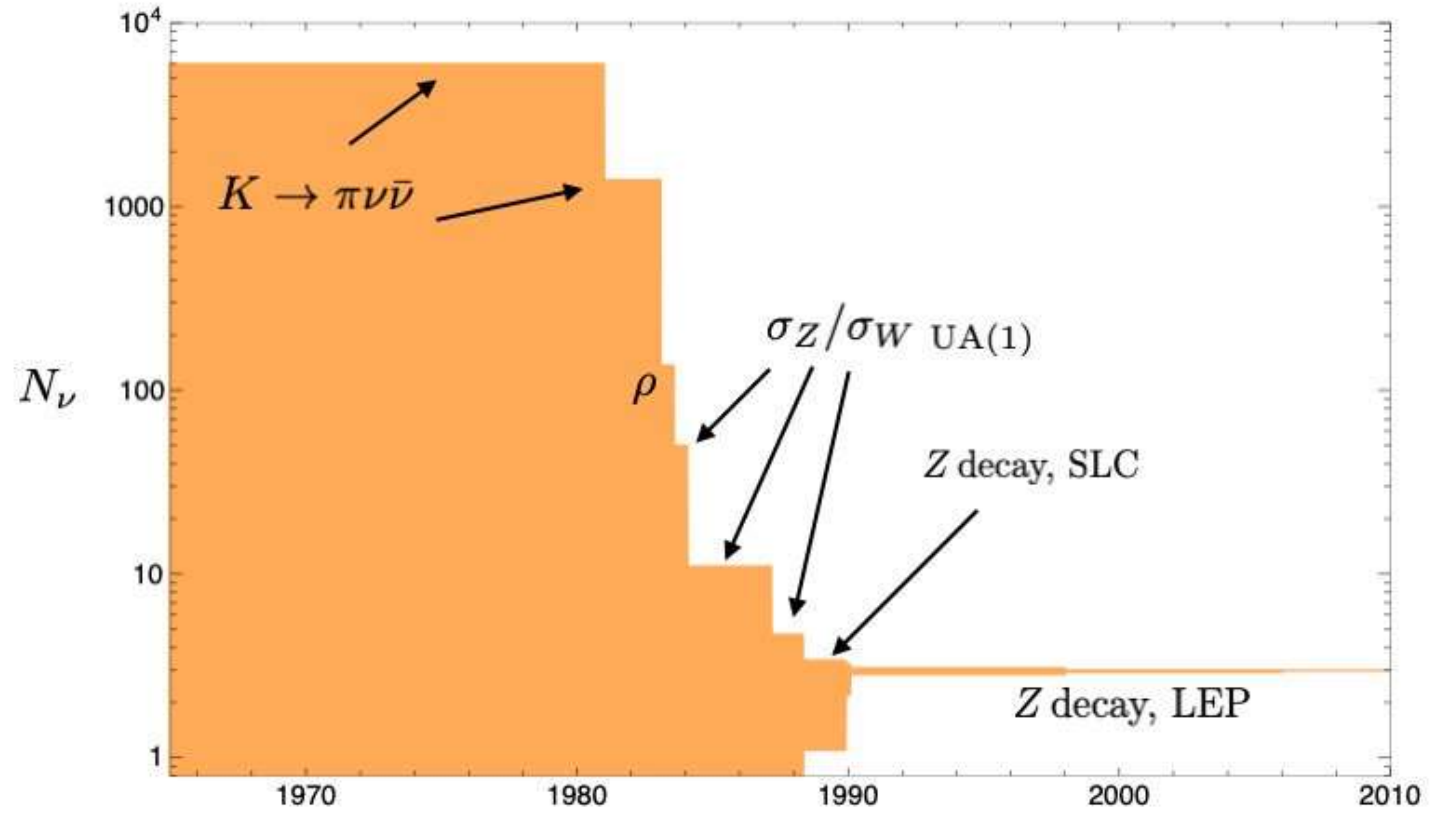
Dave Schmitz, Fermilab

[CTEQ Summer School 2011]

Kimy Agudelo's Motivation!

YEARS OF ASKING…

[M. Bauer, @martinbawer (2022)]

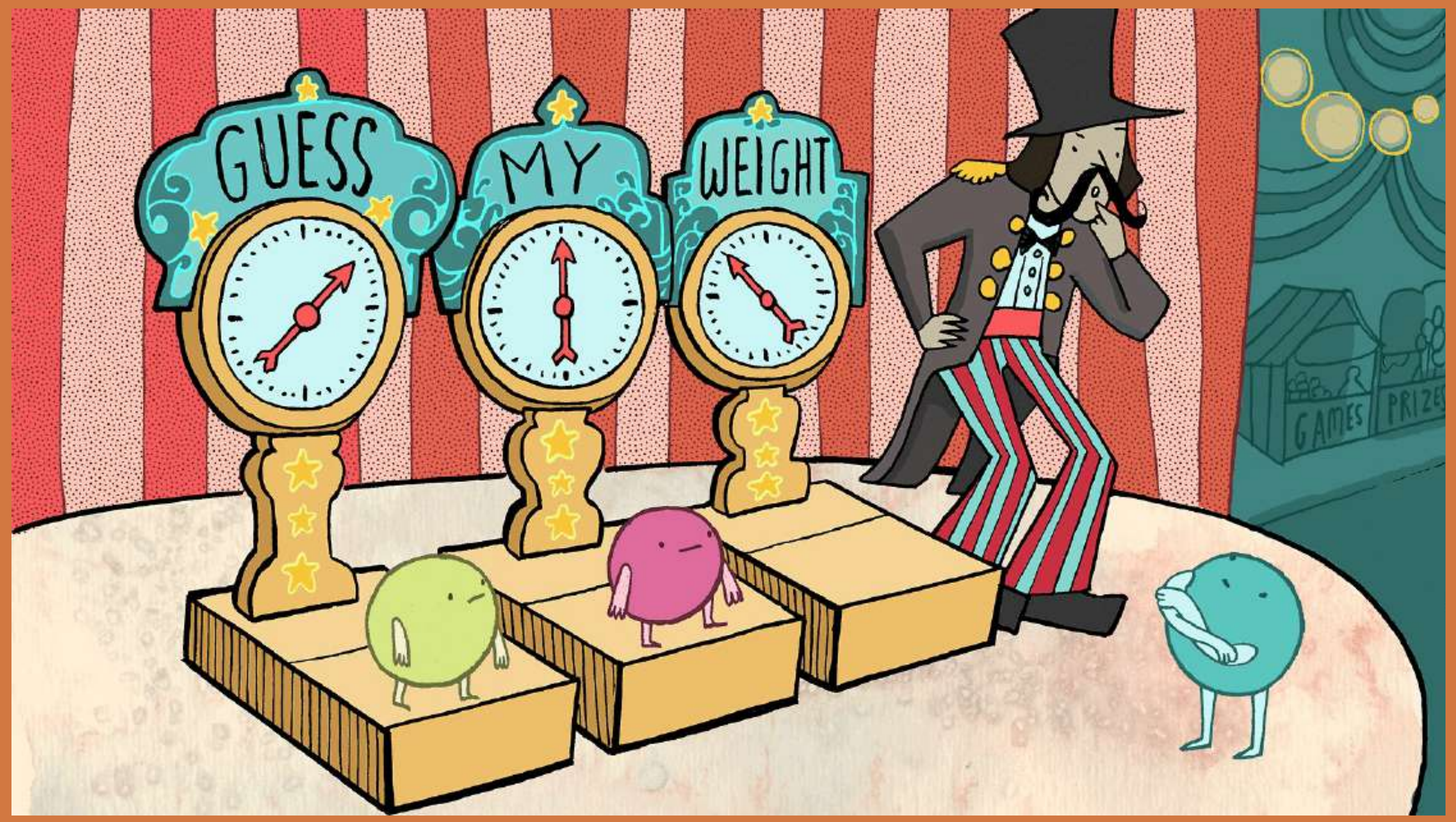


WE KNOW WE DON'T KNOW…

Is there maximal mixing?
Is CP violated?
How many neutrinos are there?

Answers may come from Neutrino Oscillations

Which neutrino is the heaviest?
How light is the lightest neutrino?
Are neutrinos and antineutrinos different particles?



[Symmetry Magazine
Artwork by Sandbox Studio, Chicago with Corinne Mucha]

All Things Neutrino
https://neutrinos.fnal.gov/

Outline

We'll be talking about…

- What is a neutrino
- The history
- Some neutrino sources (and experiments)
- Phenomenology
  - oscillations – 2 and 3 neutrinos
- Open questions
  - "Nature"
  - Mass (scale and ordering)
  - Mixture (octant -atmospheric sector-)
  - Number of neutrinos (sterile)
- Summary

What a Neutrino is

A “definition” and some basic facts

A neutrino is…

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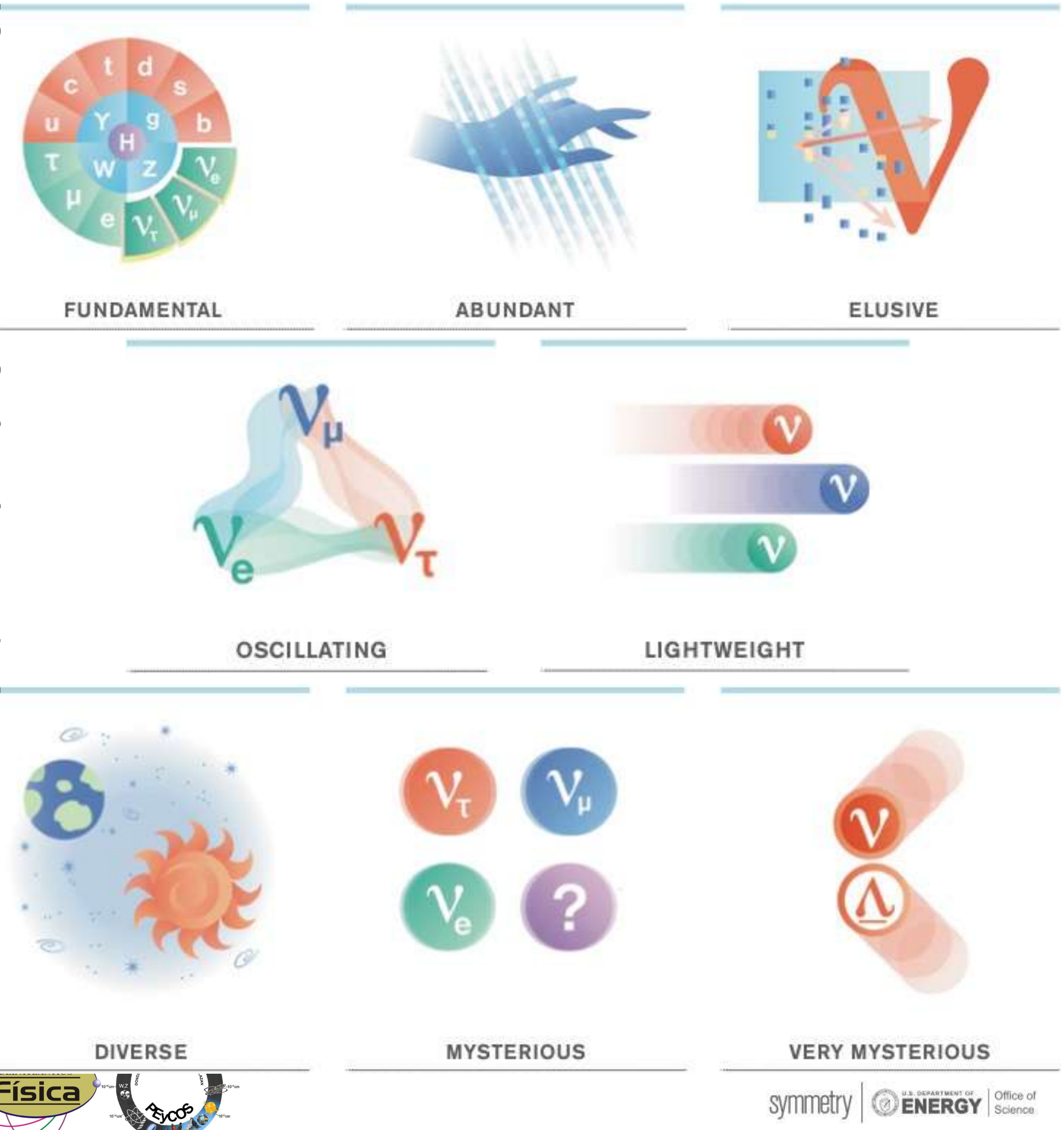
Different ways to define it



[Adapted from: Symmetry Magazine / Sandbox Studio, Chicago]

Neutrino: Uncharged elementary particle with a very small mass, that has any of three forms and that interacts only rarely with othe particles.

"Every particle and every wave in the Universe is simply and excitation of a quantum field that is defined over all space and time"

T. Lancaster, S.J. Blundell

Could be the reason why matter exists in the universe

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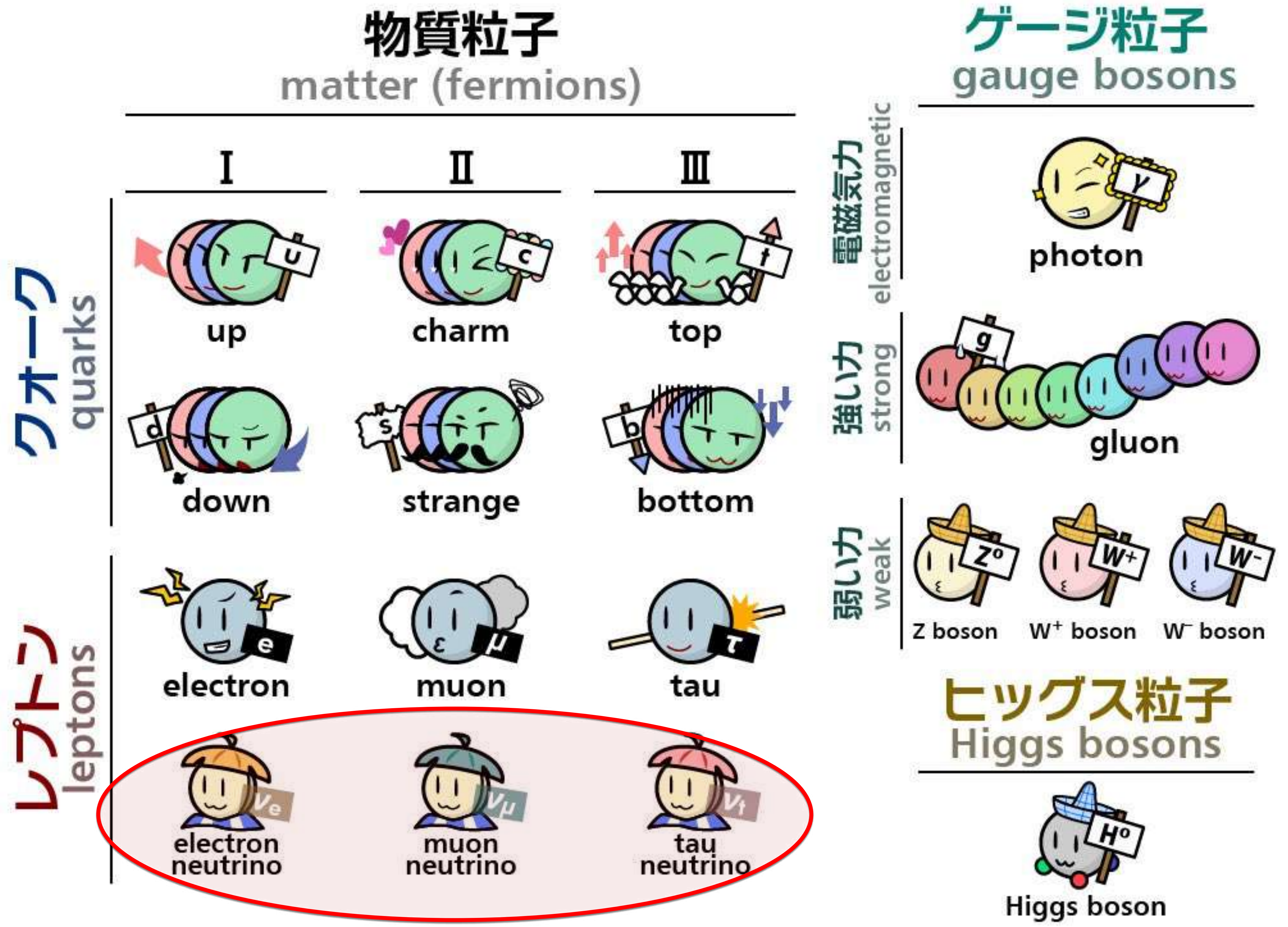
A neutrino is…

Some facts about neutrinos

The Standard Model



- Most abundant (massive) particle
- Some contribution to Dark Matter
- Effects on the structure formation of the universe
- Many sources

Neutrinos interact

Within the Standard Model

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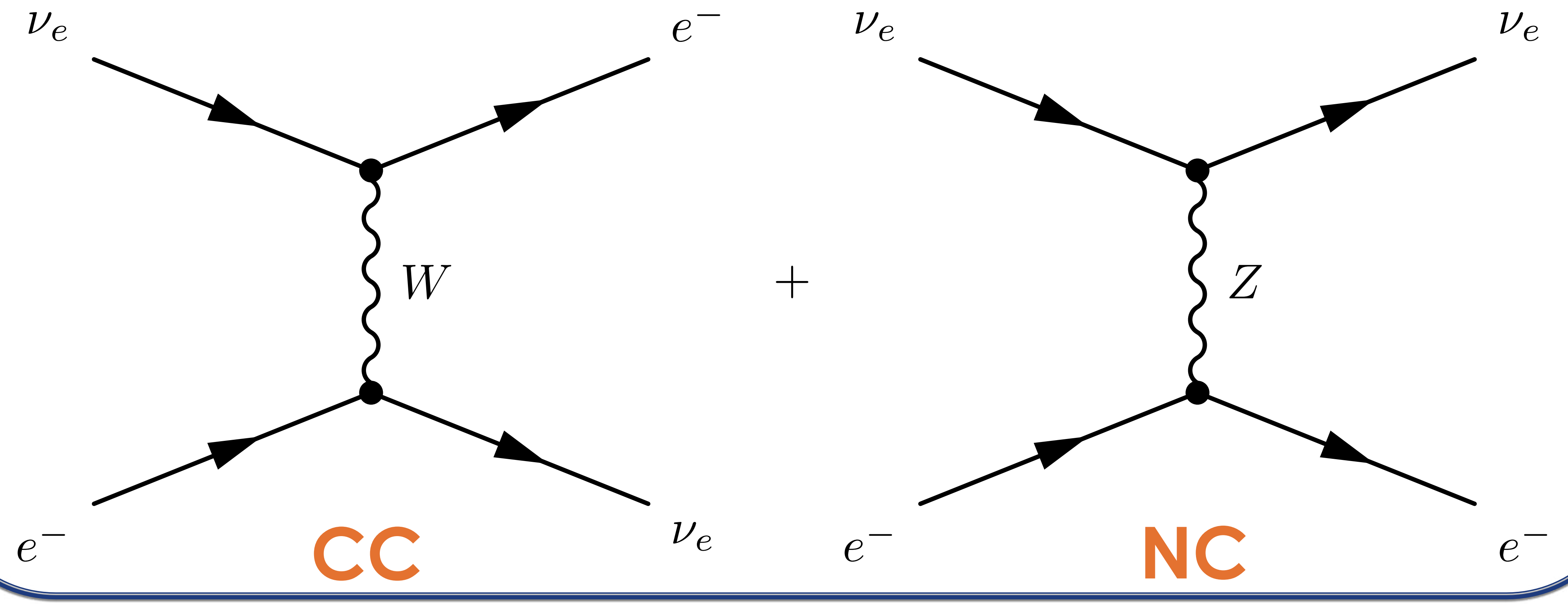
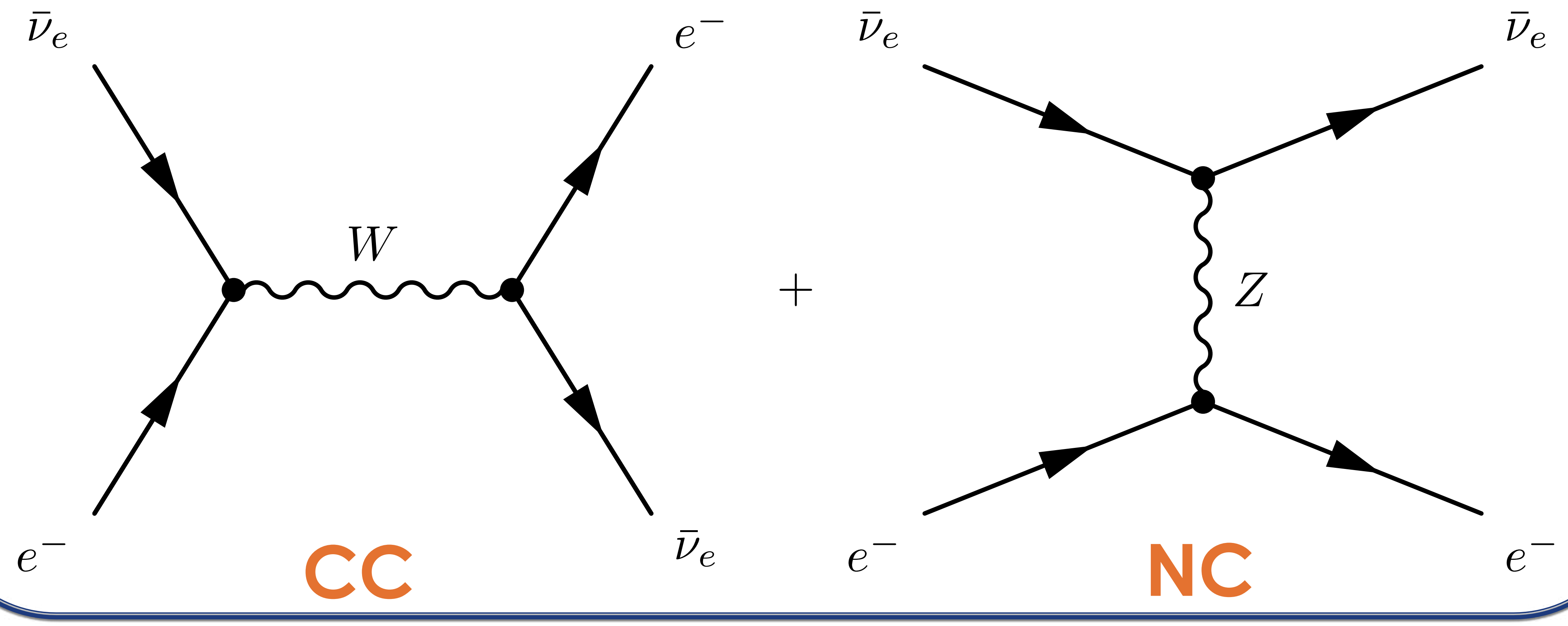
The Interactions: neutrino – electron

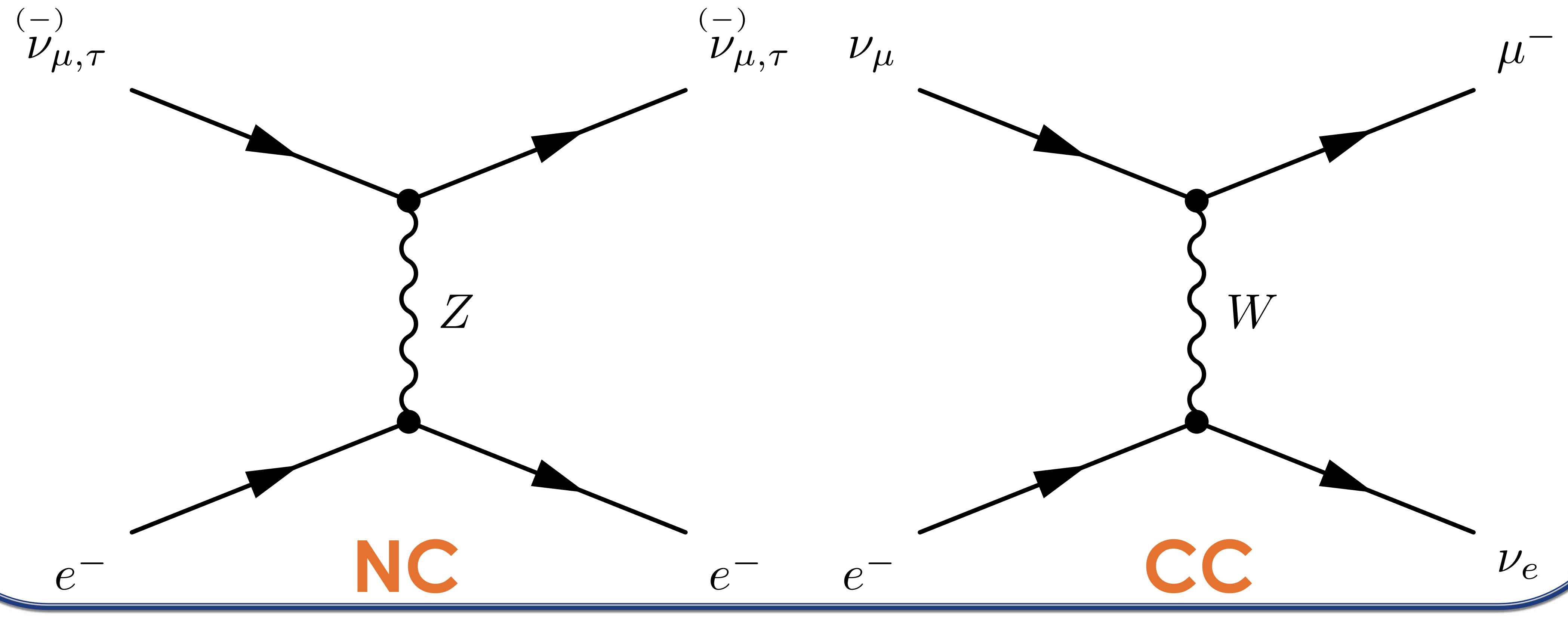
$$\nu_e + e^- \rightarrow \nu_e + e^-$$



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



$$\overset{(-)}{\nu}_{\mu,\tau} + e^- \rightarrow \overset{(-)}{\nu}_{\mu,\tau} + e^-$$



Neutrinos interact

Within the Standard Model

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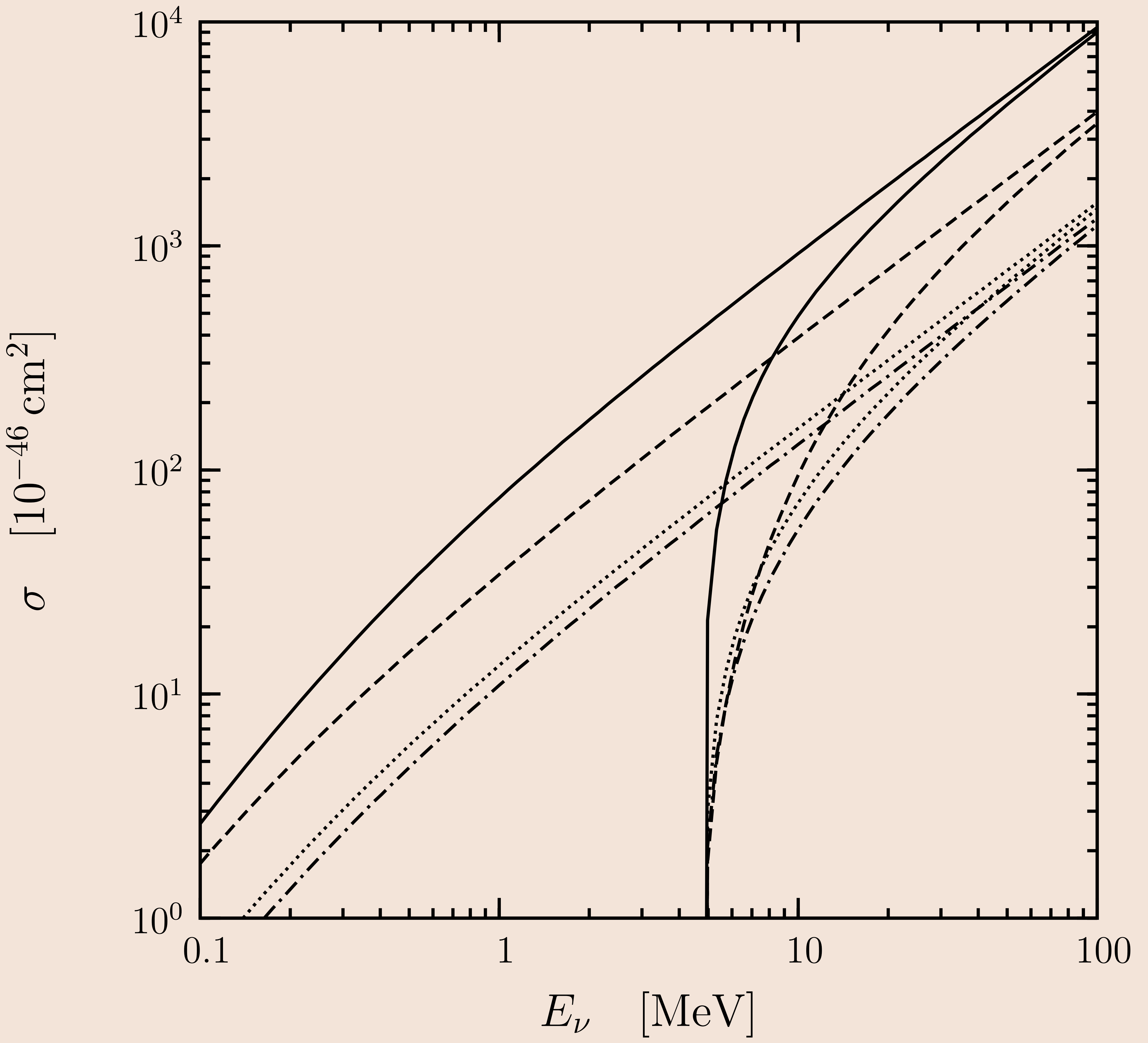
The Cross Section: neutrino – electron



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

$$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$$

$$\overset{(-)}{\nu}_{\mu,\tau} + e^- \to \overset{(-)}{\nu}_{\mu,\tau} + e^-$$

[C. Giunti & C.W. Kim, Funds. of Neutrinos Physics and Astrophysics (2007)]

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Neutrinos interact

Within the Standard Model

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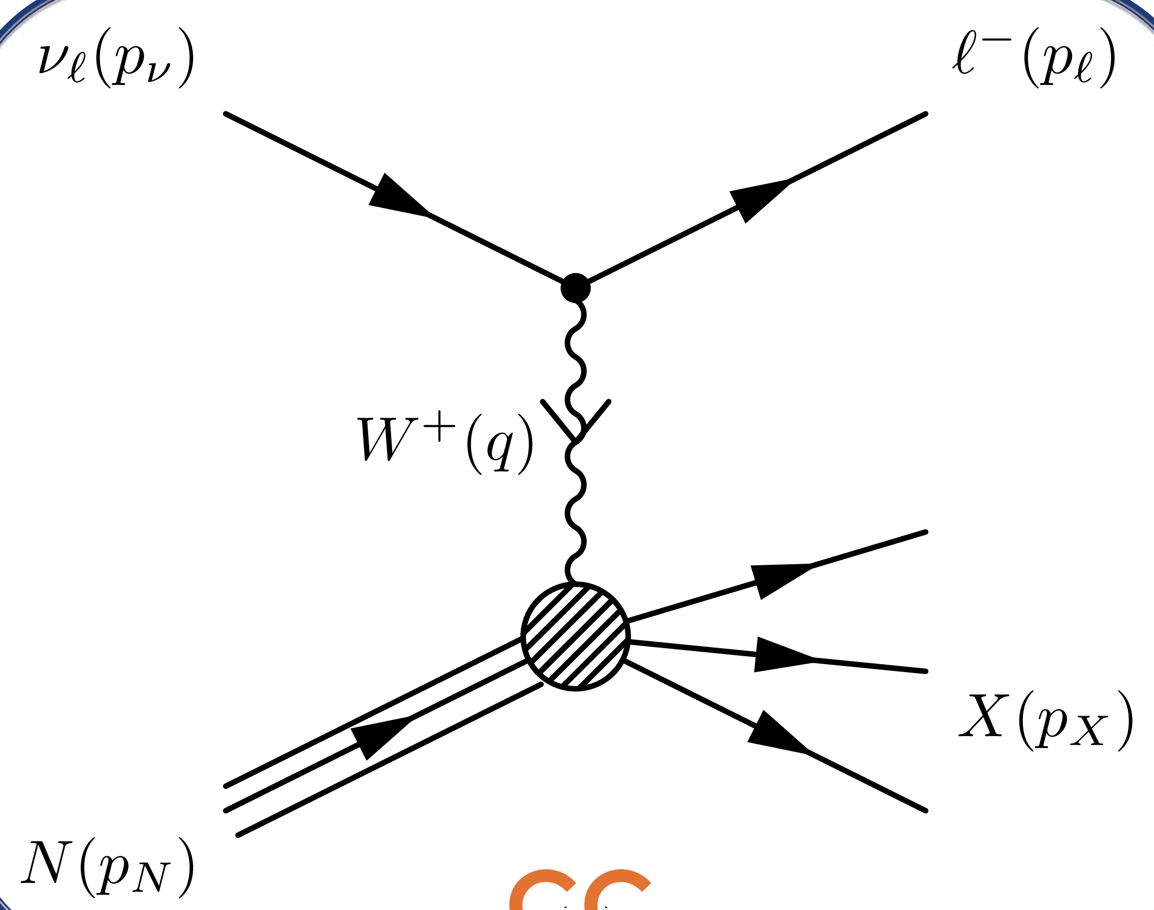
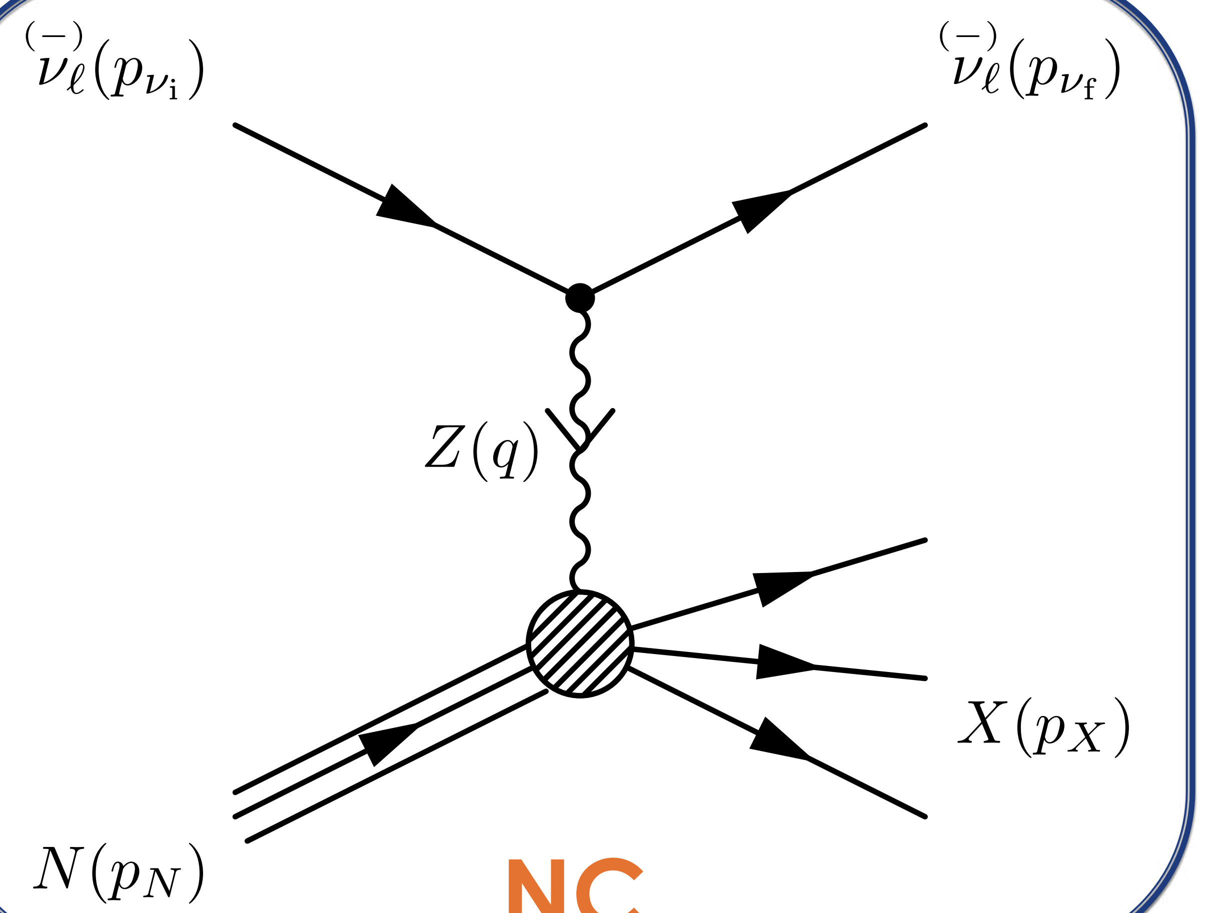
The Interactions: neutrino – nucleon DIS



CC

$$\nu_l(p_\nu) + N(p_N) \to l^-(p_l) + X(p_X)$$
$$N = p, n$$

$$\overset{(-)}{\nu}_l(p_{\nu_i}) + N(p_N) \to \overset{(-)}{\nu}_l(p_{\nu_f}) + X(p_X)$$
$$N = p, n$$



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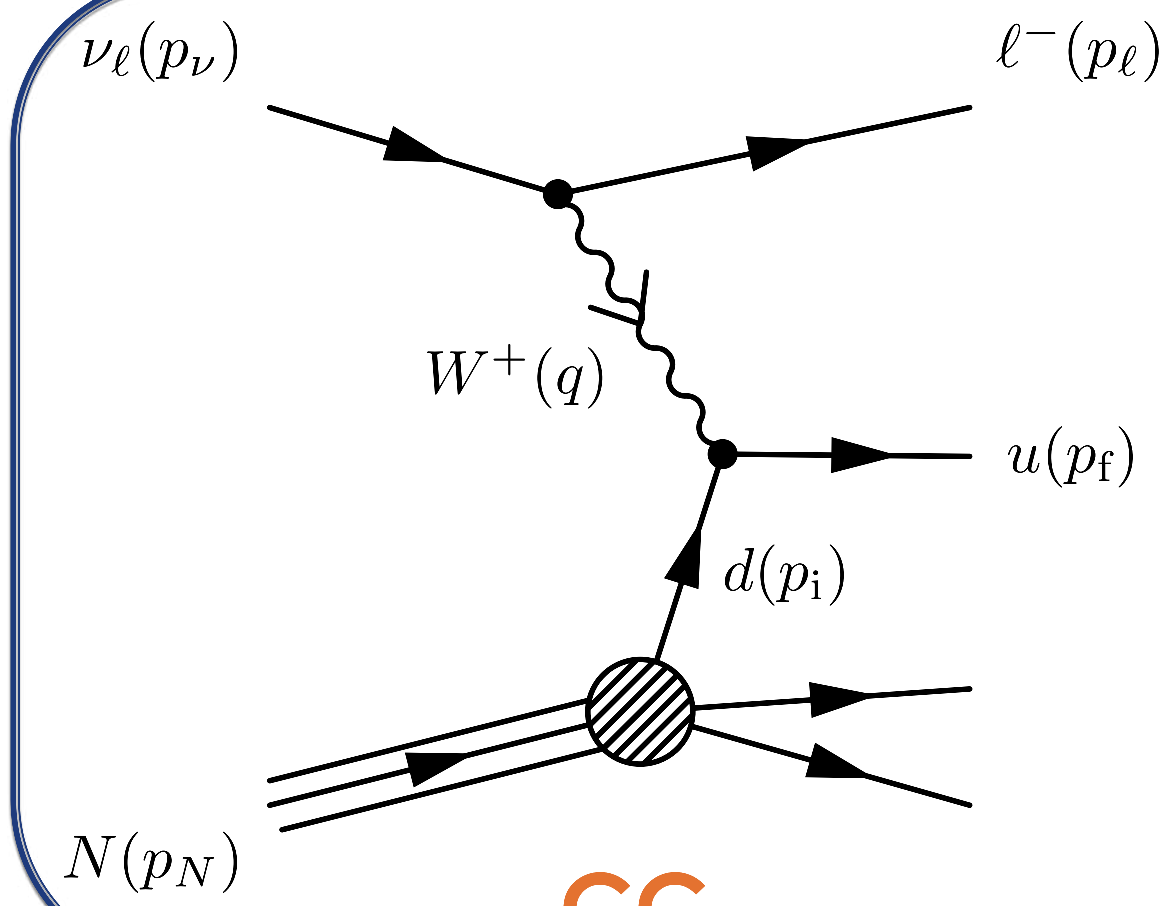
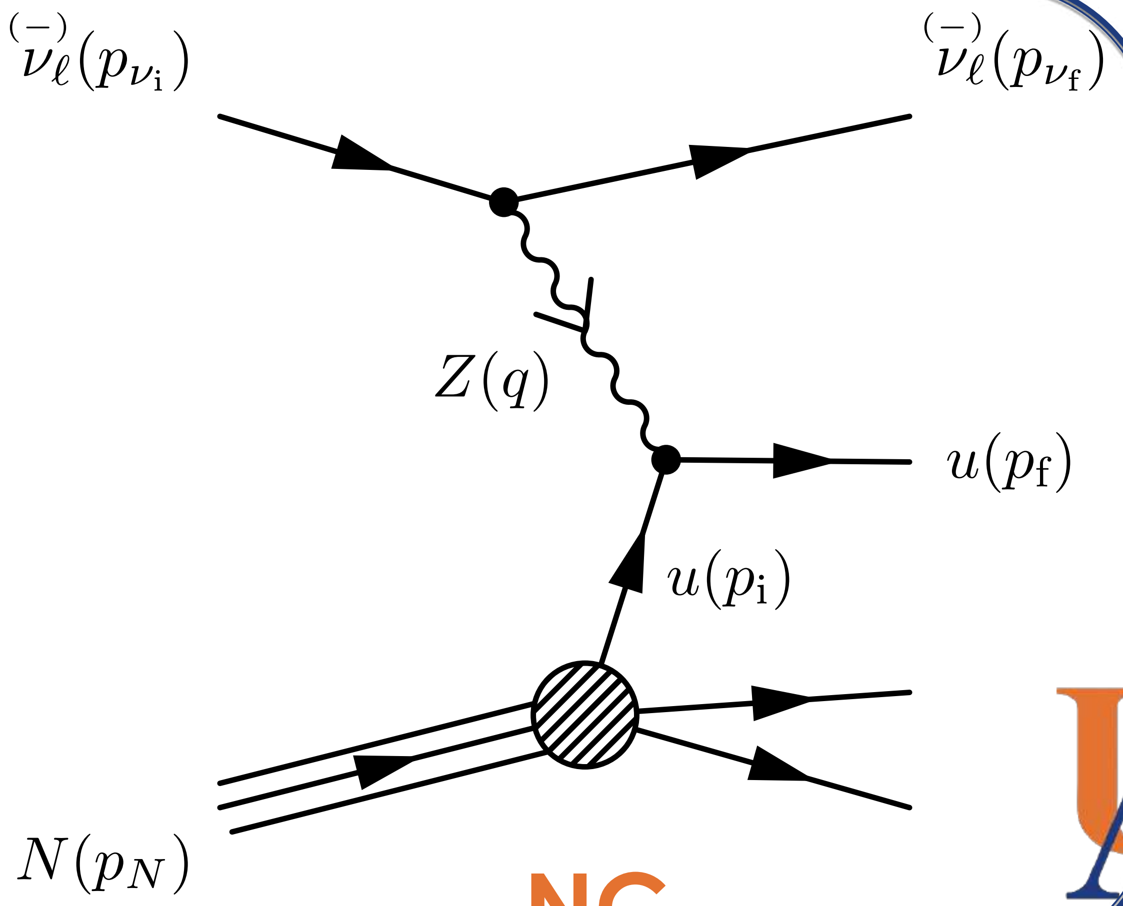
Quark-Parton Model



CC



NC

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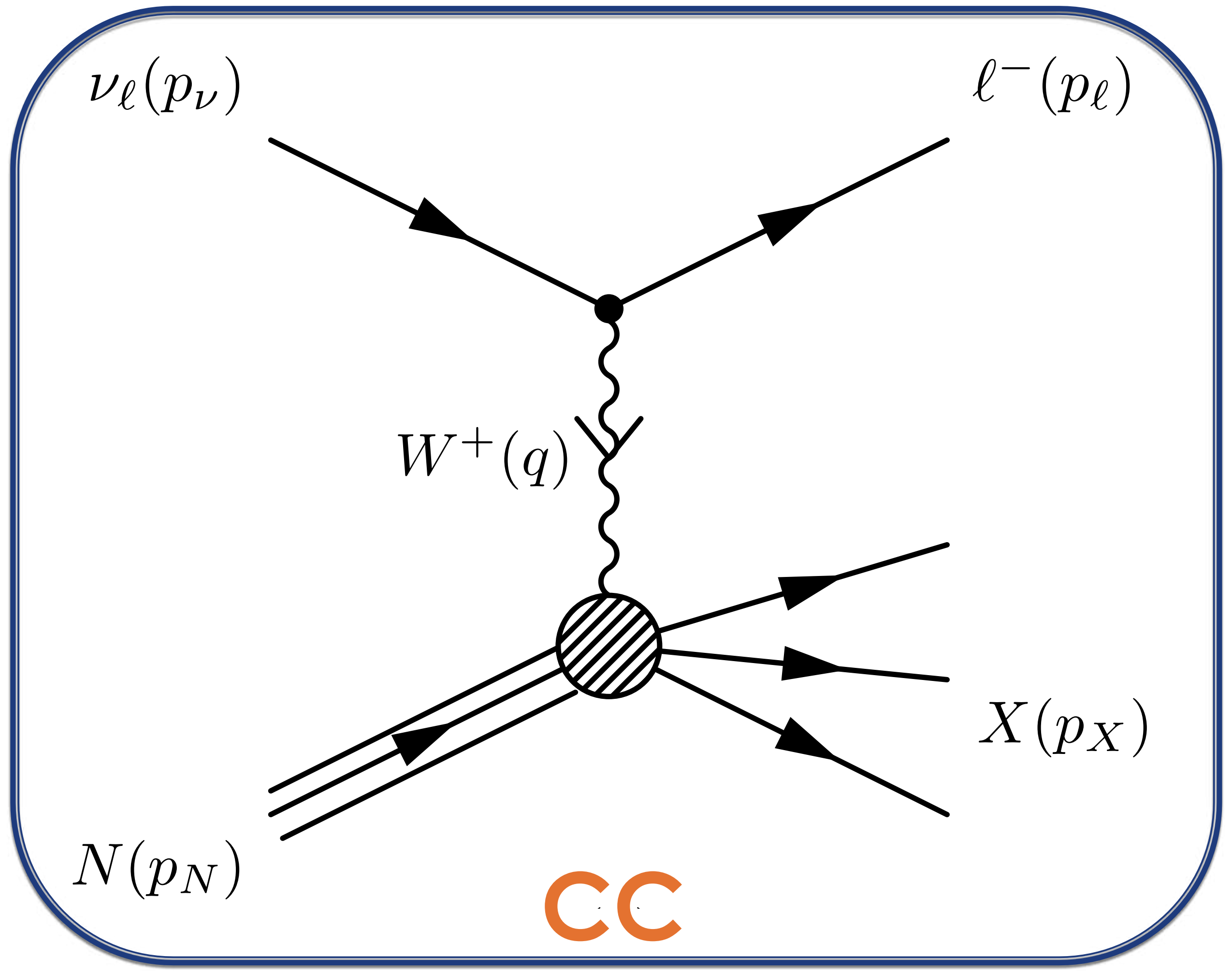
Neutrinos interact

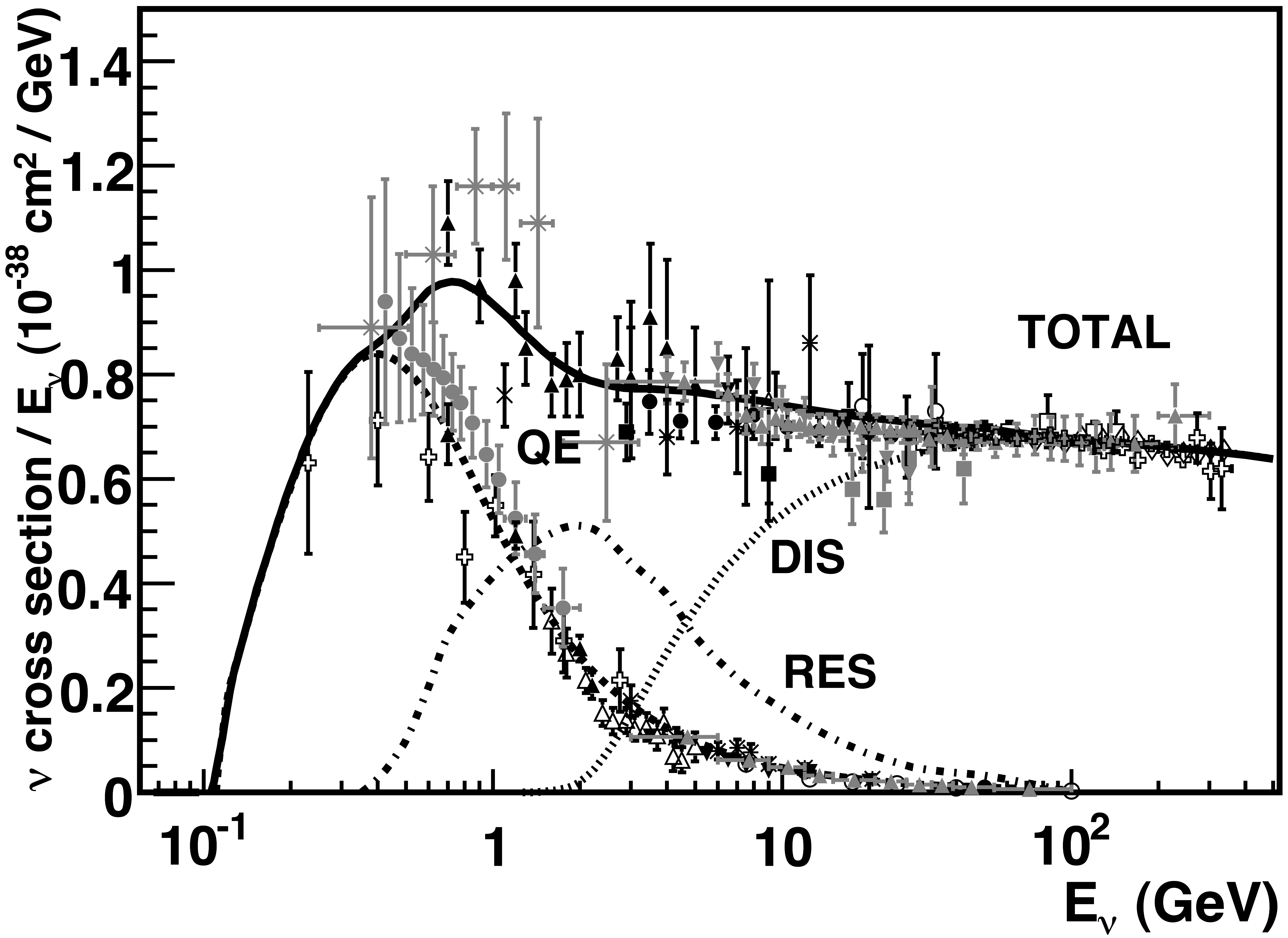
Within the Standard Model

The Interactions: neutrino – nucleon DIS



$$\nu_l(p_\nu) + N(p_N) \to l^-(p_l) + X(p_X)$$
$$N = p, n$$

[J.A. Formaggio & G.P. Zeller, Rev.Mod.Phys. 84 (2012)]



Total CC cross section

- QE: Quasi-Elastic
- RES: Resonance production
- DIS: Deep Inelastic Scattering

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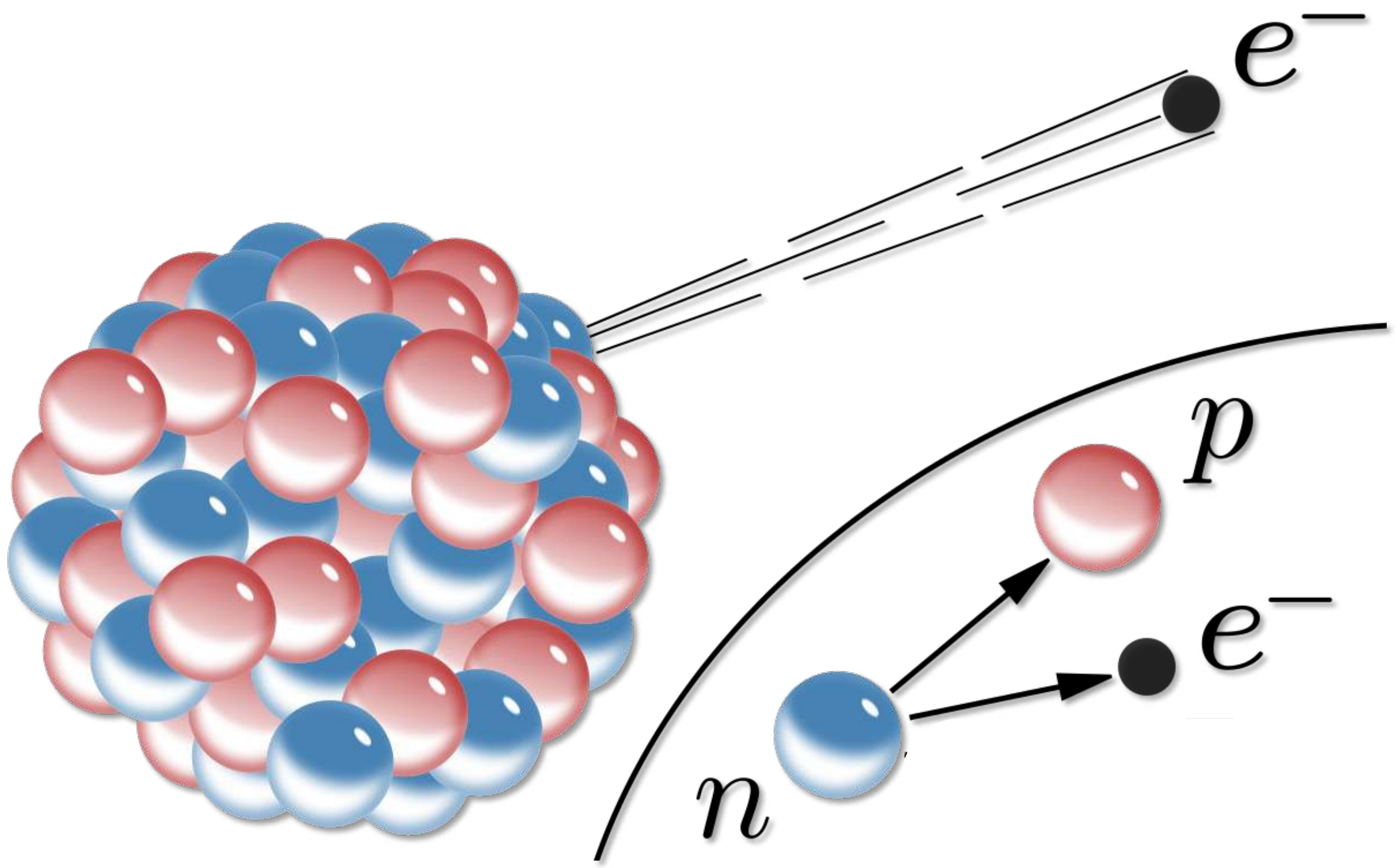
Neutrino History

How we got here…

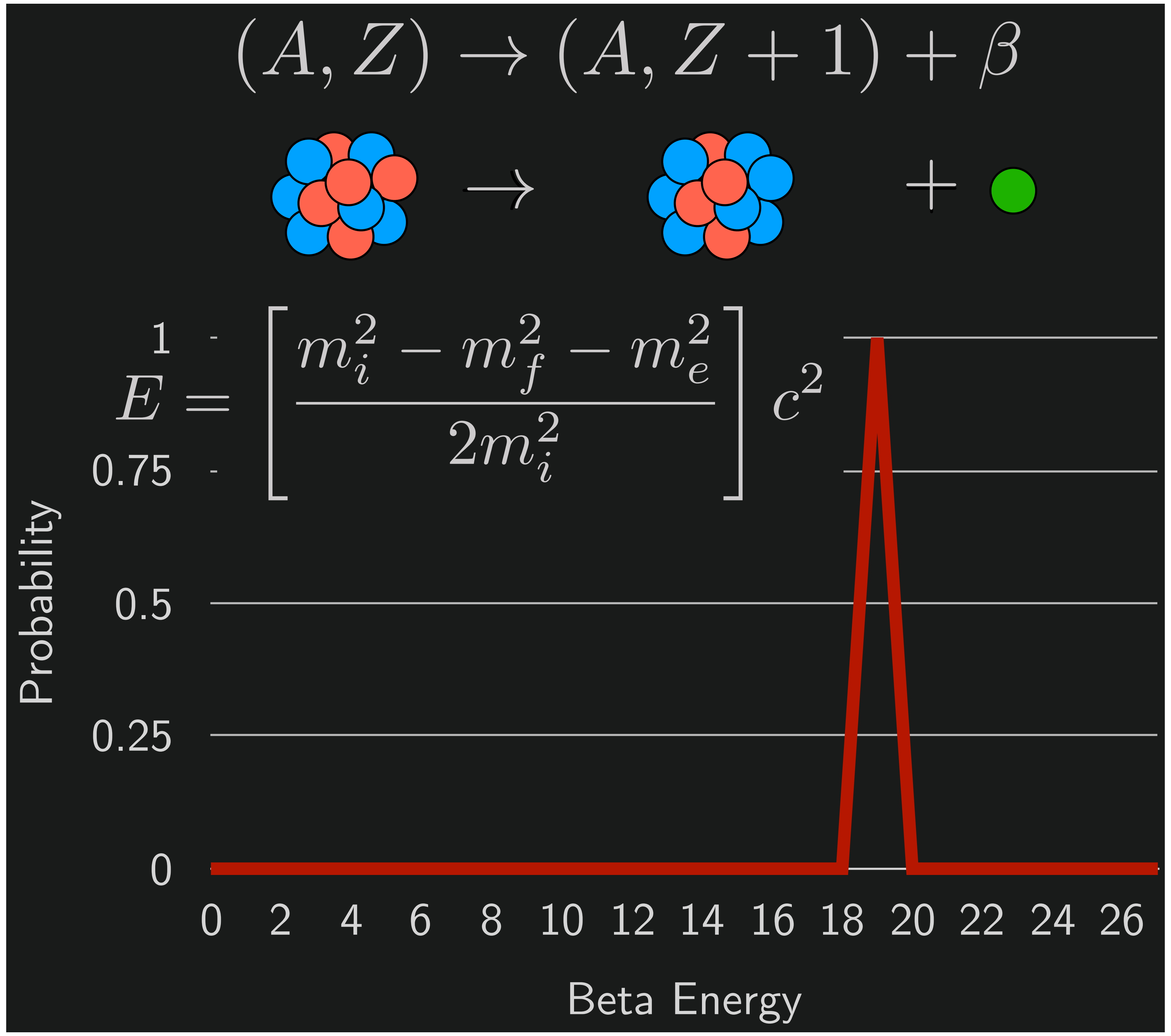
A historic review

The initial problem

Beta Decay



Expectation: *two-body decay energy spectrum*

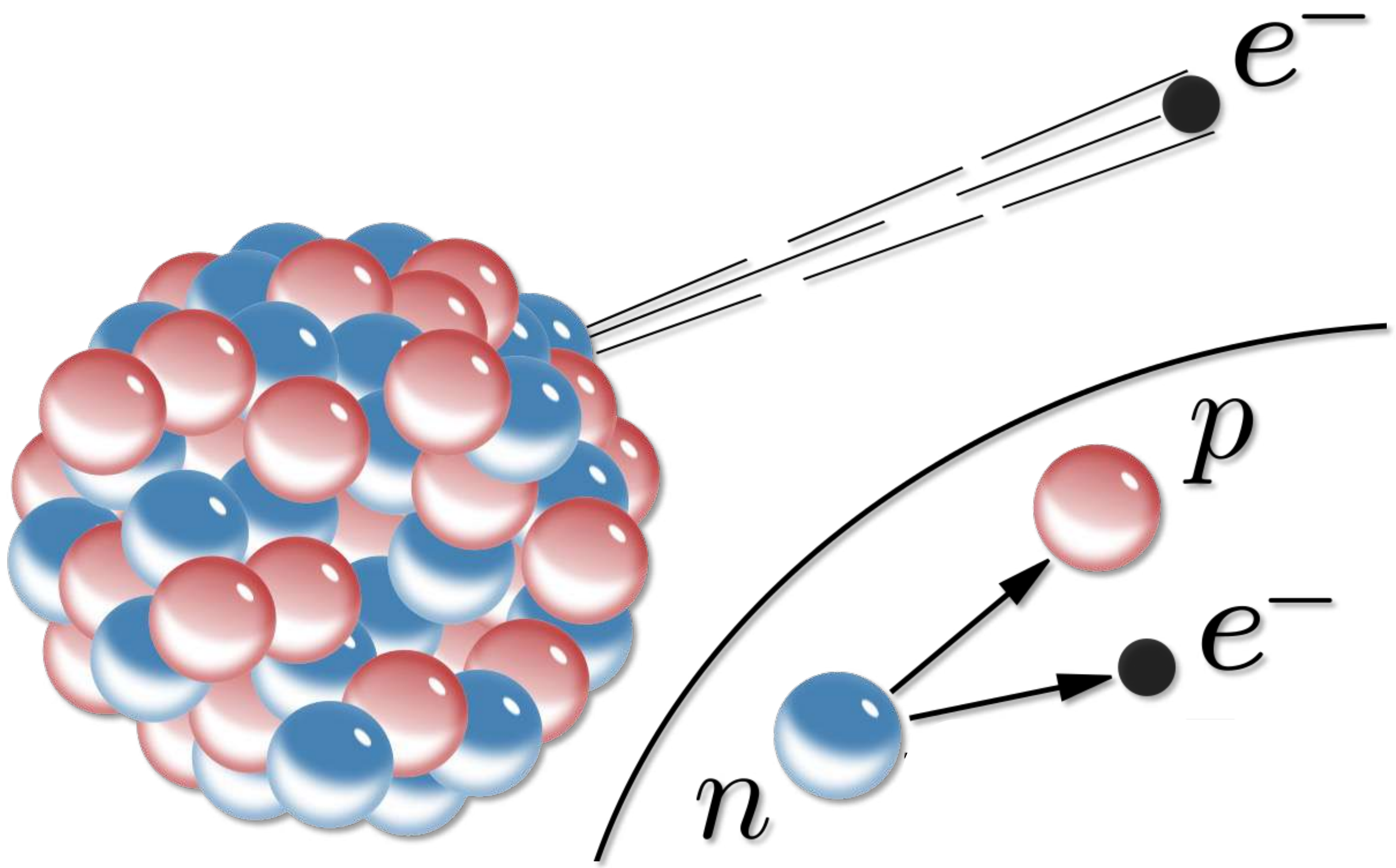


[A.T. Mastbaum, 87th Arthur H. Compton Lecture Series (2018)]

A historic review

The initial problem

Beta Decay



"Energy is not conserved."

N. Bohr

Measurement: *two-body decay energy spectrum?*

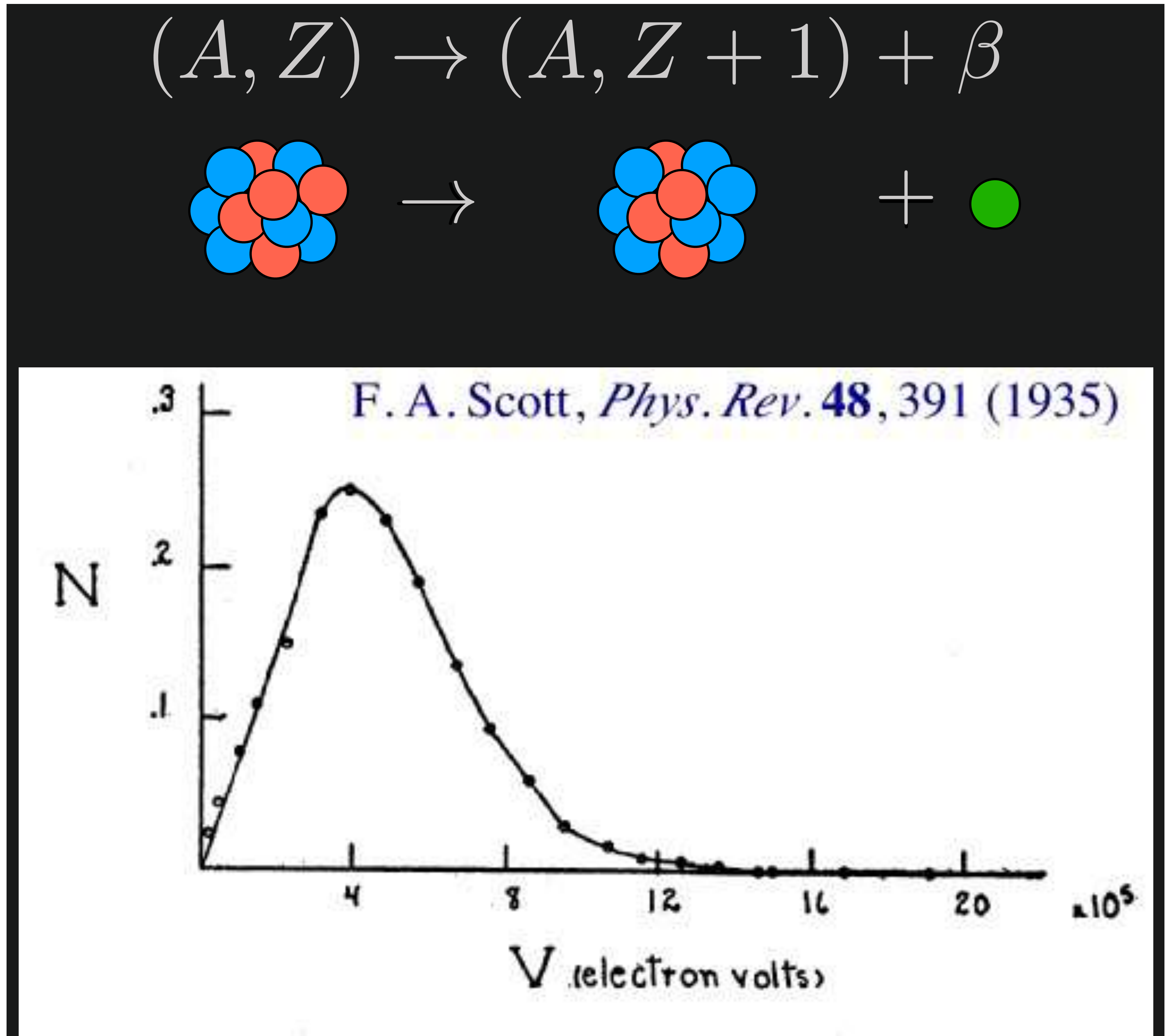


FIG. 5. Energy distribution curve of the beta-rays.

[A.T. Mastbaum, 87th Arthur H. Compton Lecture Series (2018)]

A historic review

A proposal

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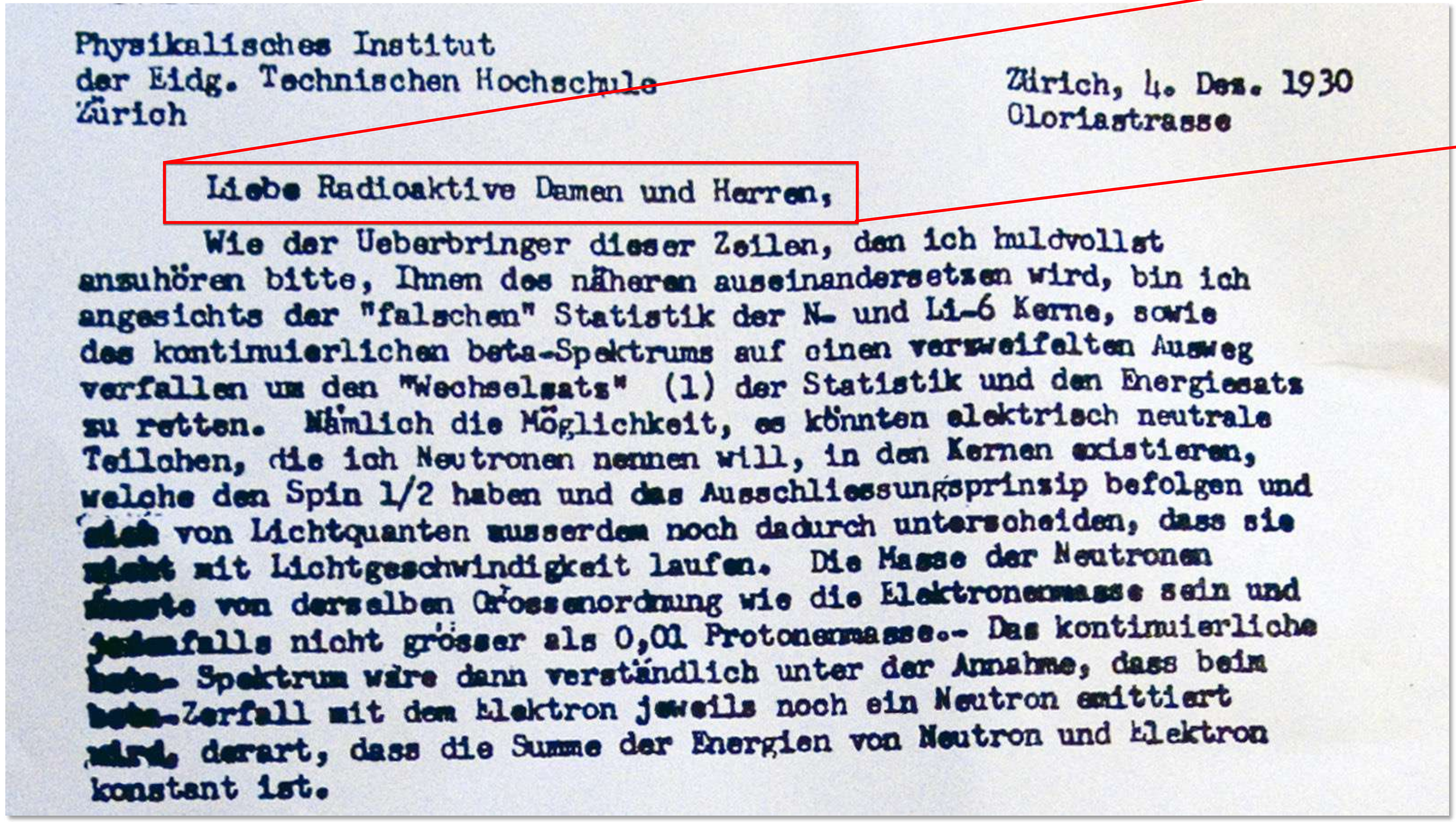
"Dear Radioactive Ladies and Gentlemen"

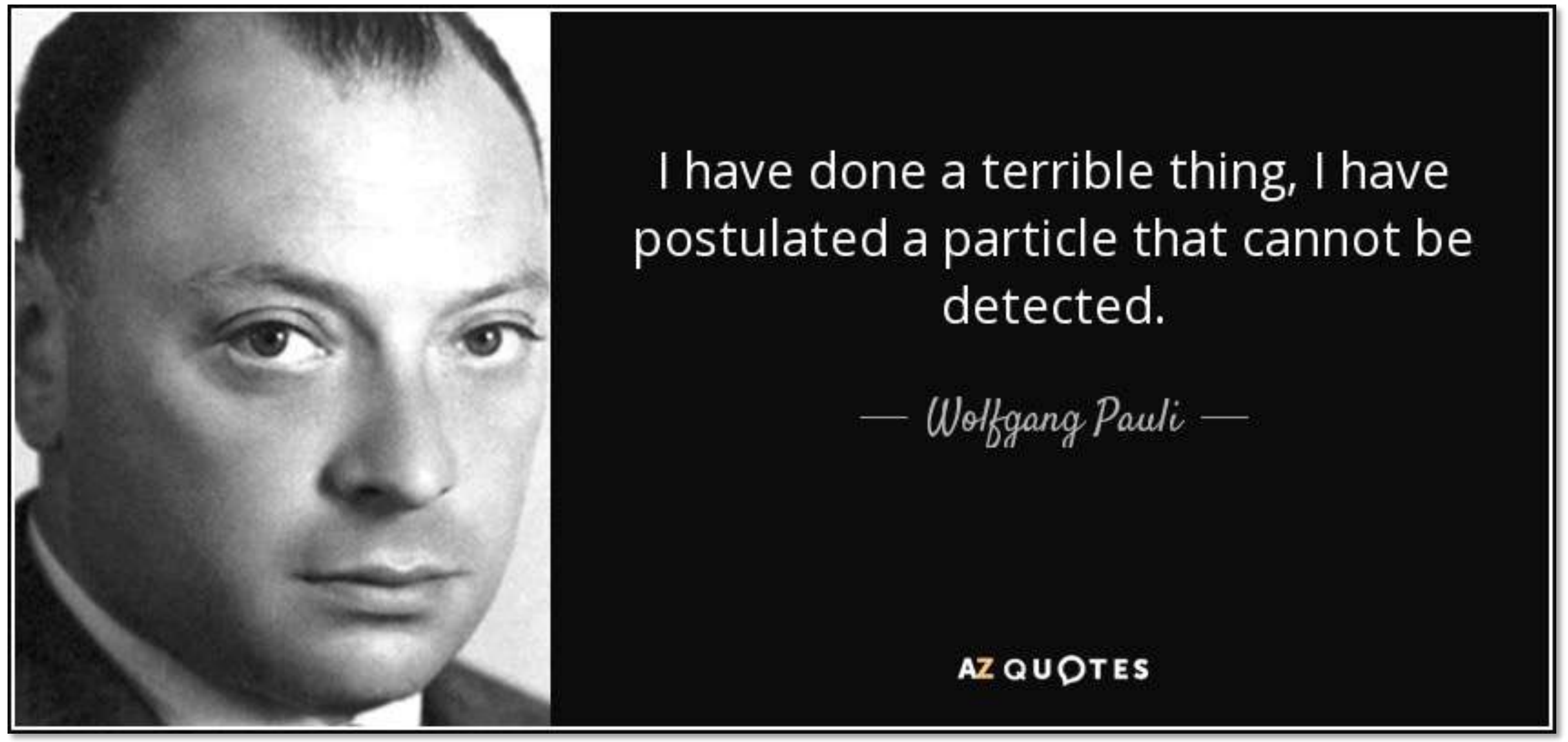


Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

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.



gez. W. Pauli

"(…), the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light."

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A historic review

The solution

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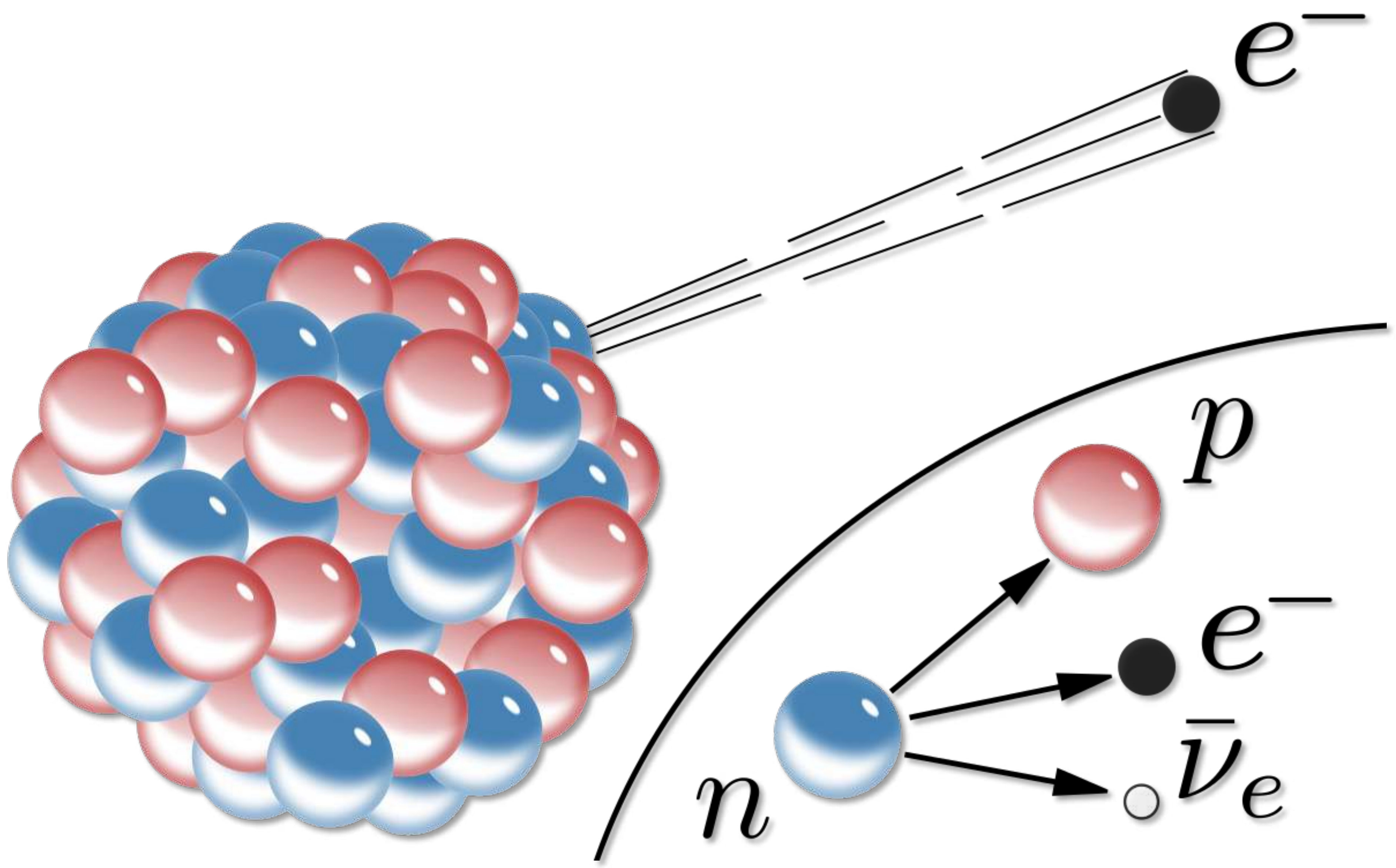
Beta Decay



Energy is conserved!

Observation: *energy spectrum is continuous!*

$$(A, Z) \to (A, Z+1) + \beta + \bar{\nu}_e$$

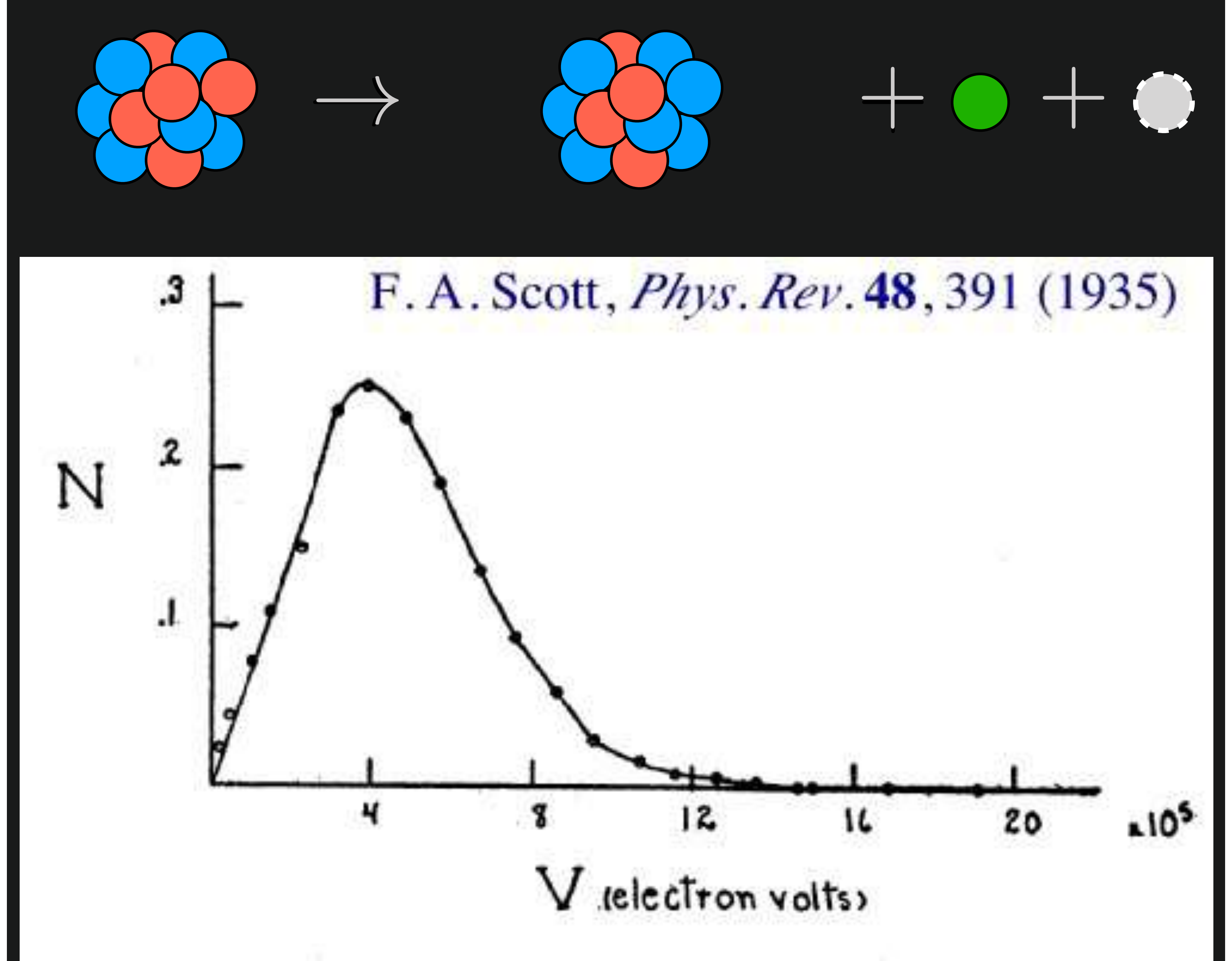


FIG. 5. Energy distribution curve of the beta-rays.

[A.T. Mastbaum, 87th Arthur H. Compton Lecture Series (2018)]

A historic review

Theory and Experiment

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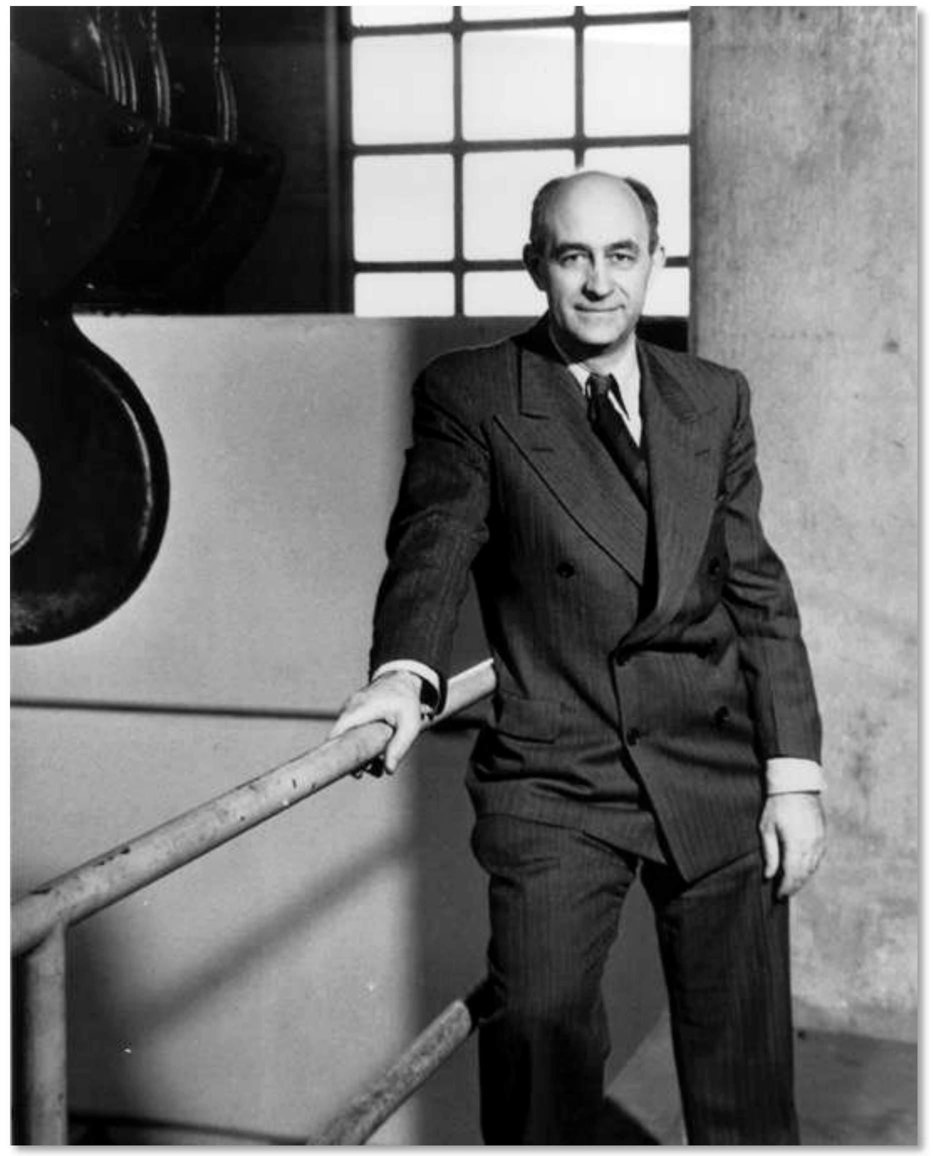
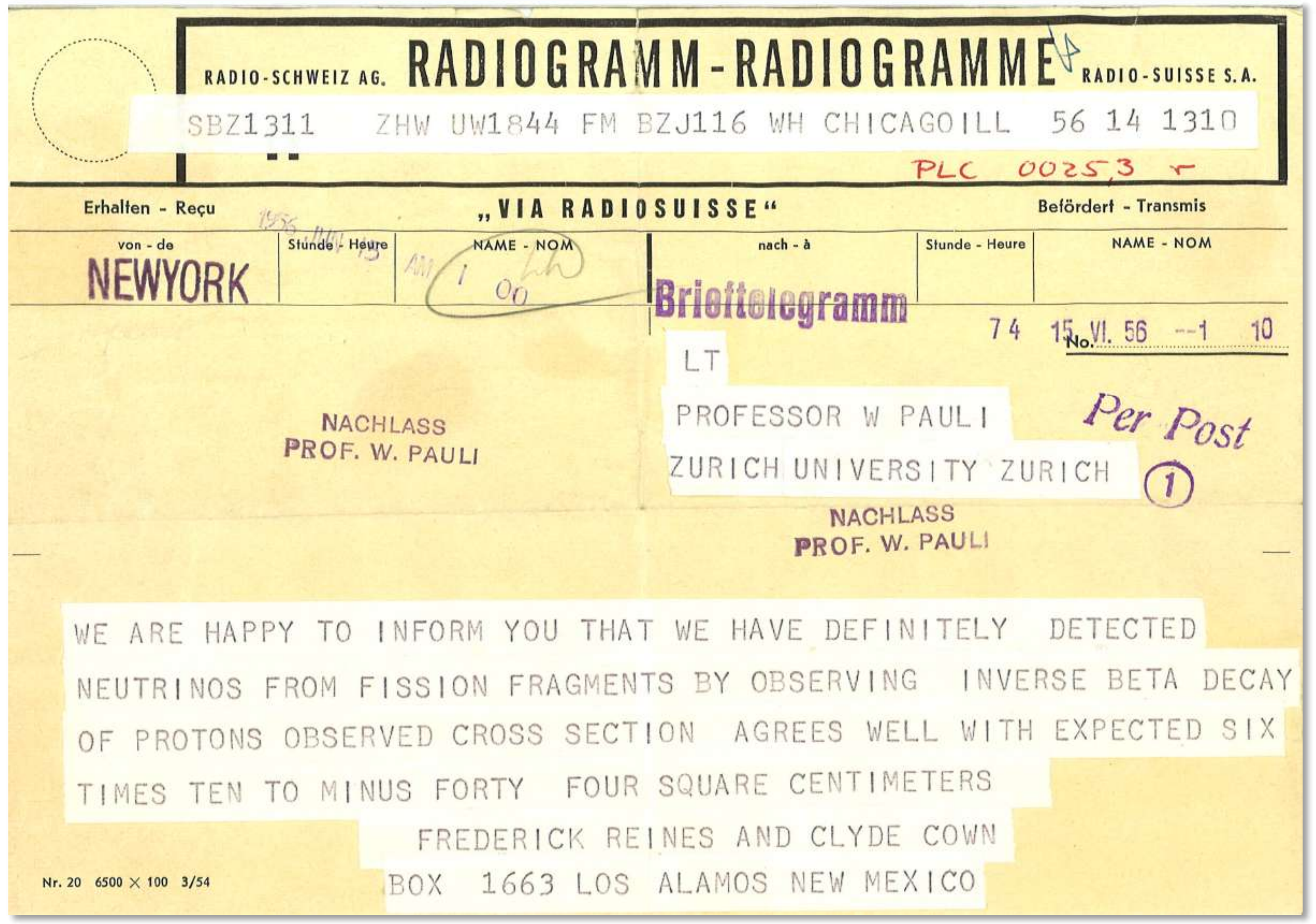
[All Things Neutrino, http://neutrinos.fnal.gov/history/]





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ZURICH UNIVERSITY ZURICH

Per Post

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 X 100 3/54

Enrico Fermi
- Effective theory of week interactions (1934)
- Neutrino (*little neutral one*) got his name!

Hans Bethe and Rudolf Peierls
- Cross section calculations $(\sigma < 10^{-44}\ \mathrm{cm}^2)$

Ettore Majorana
- Neutrinos could be their own antiparticles (1937)

Frederick Reines and Clyde Cowan Jr.
- First evidence of neutrinos (1956) – Savannah River Nuclear Reactor Plant

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A historic review

Theory and Experiment

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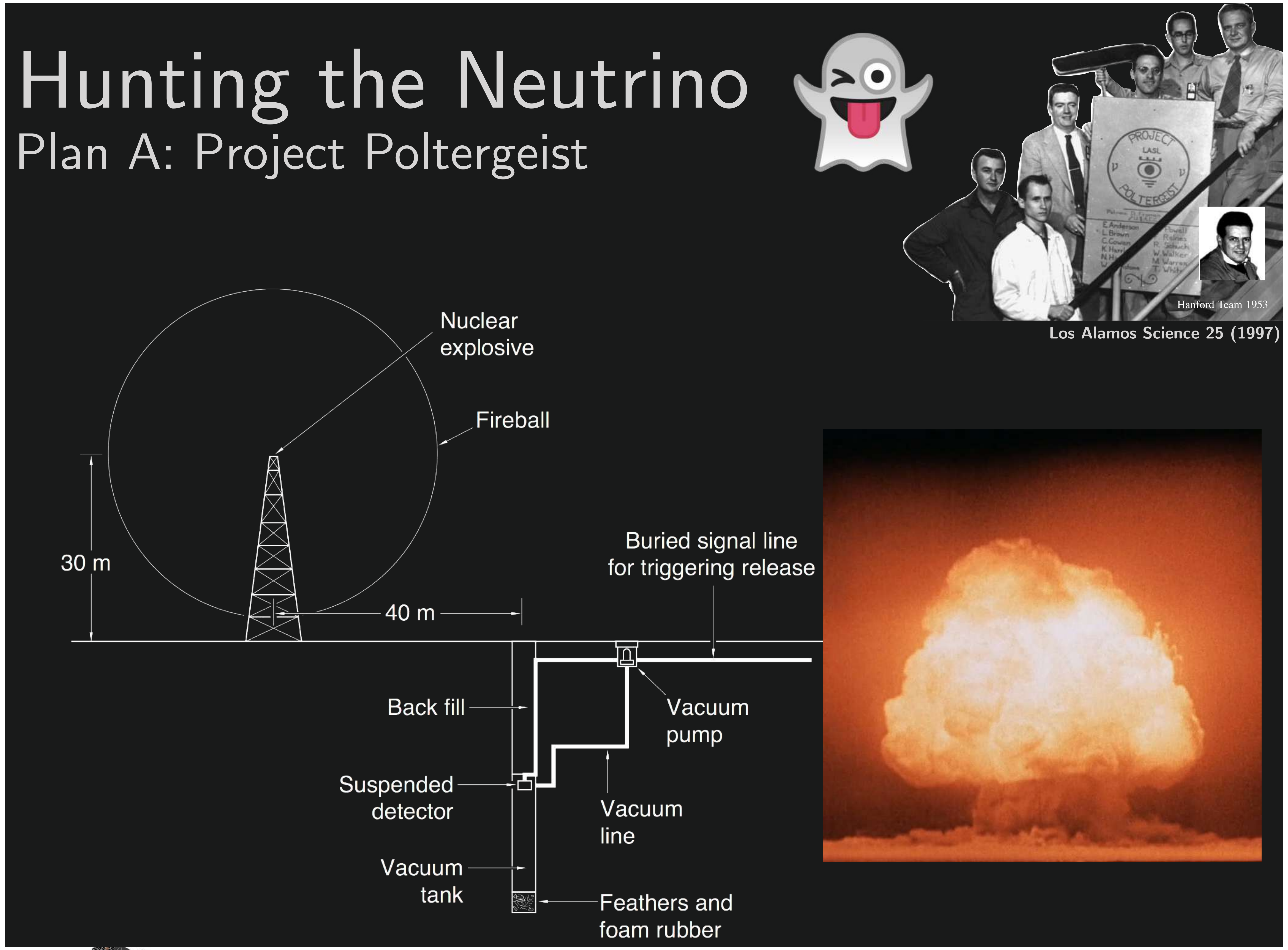
[A.T. Mastbaum, 87th Arthur H. Compton Lecture Series (2018)]



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A historic review

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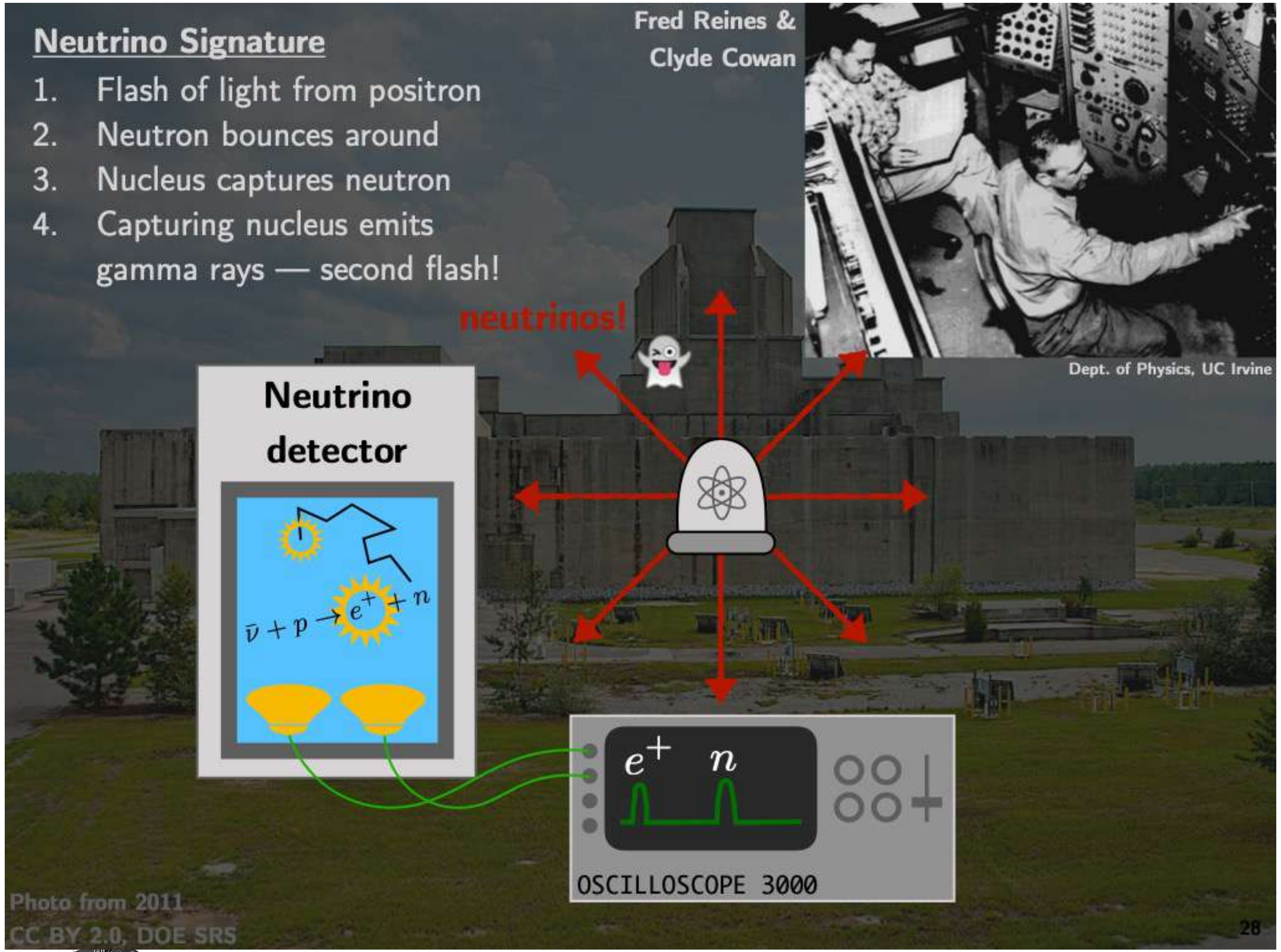

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A historic review

The recognitions


Photo from the Nobel Foundation archive.
Leon M. Lederman


Photo from the Nobel Foundation archive.
Melvin Schwartz

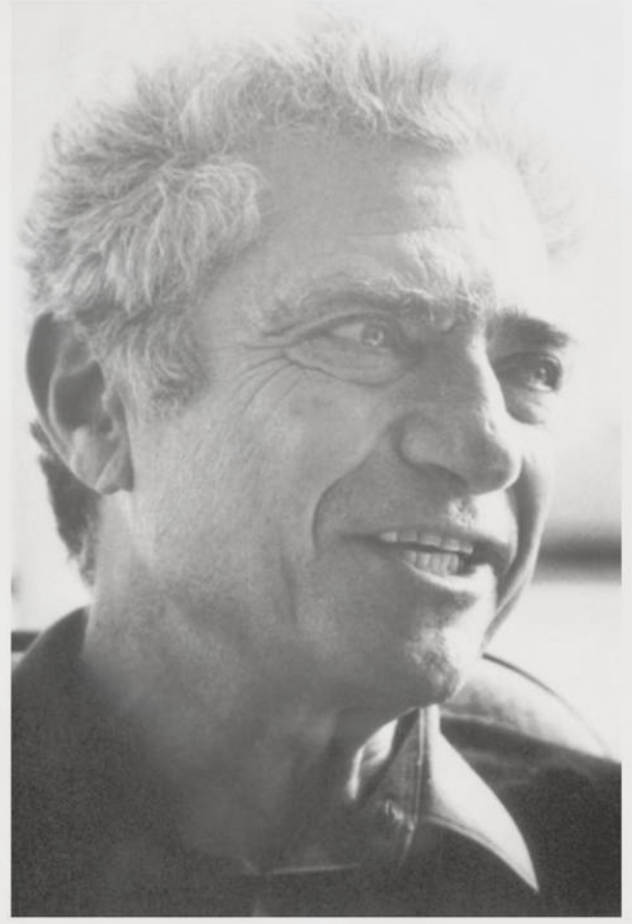
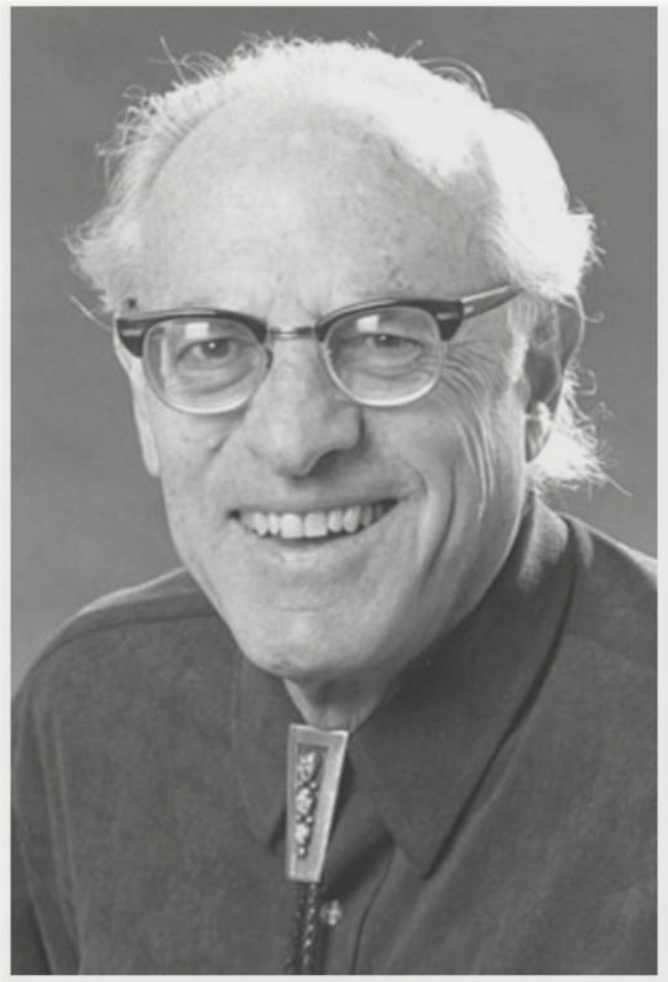


Photo from the Nobel Foundation archive.
Jack Steinberger

1988: "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino."

1995: "for the detection of the neutrino."


© University of California Regents
Frederick Reines

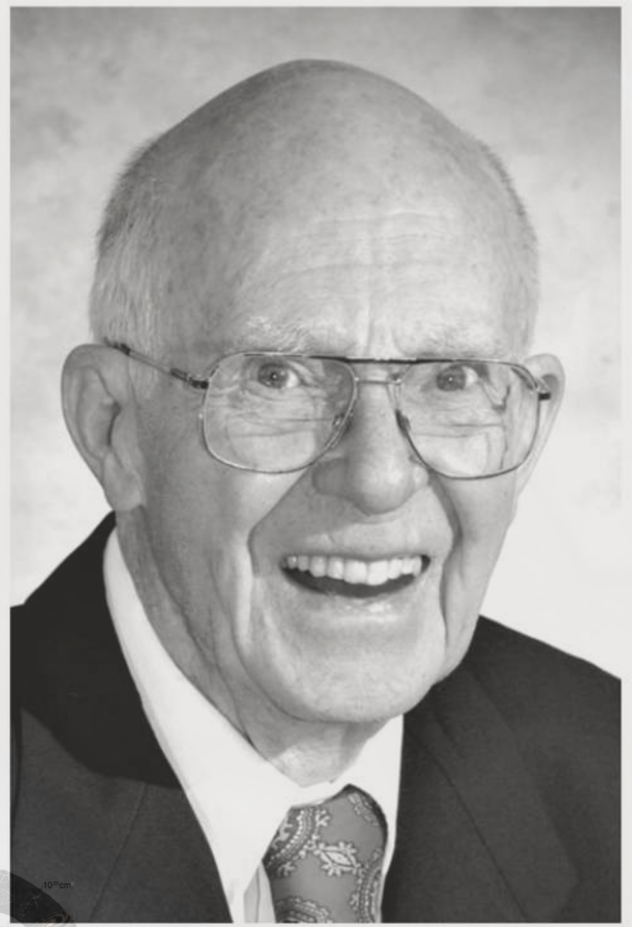


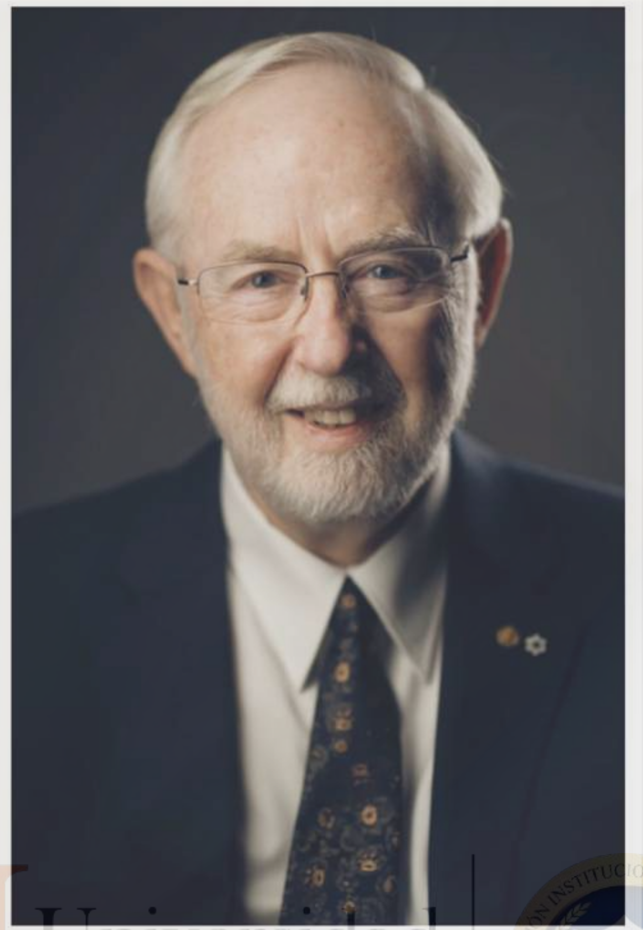
Photo from the Nobel Foundation archive.
Raymond Davis Jr.


Photo from the Nobel Foundation archive.
Masatoshi Koshiba

2002: "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

2015: "for the discovery of neutrino oscillations, which shows that neutrinos have mass."


© Nobel Media AB. Photo: A. Mahmoud
Takaaki Kajita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Arthur B. McDonald

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Neutrino Sources

Where do they come from?

Where they come from

Sources

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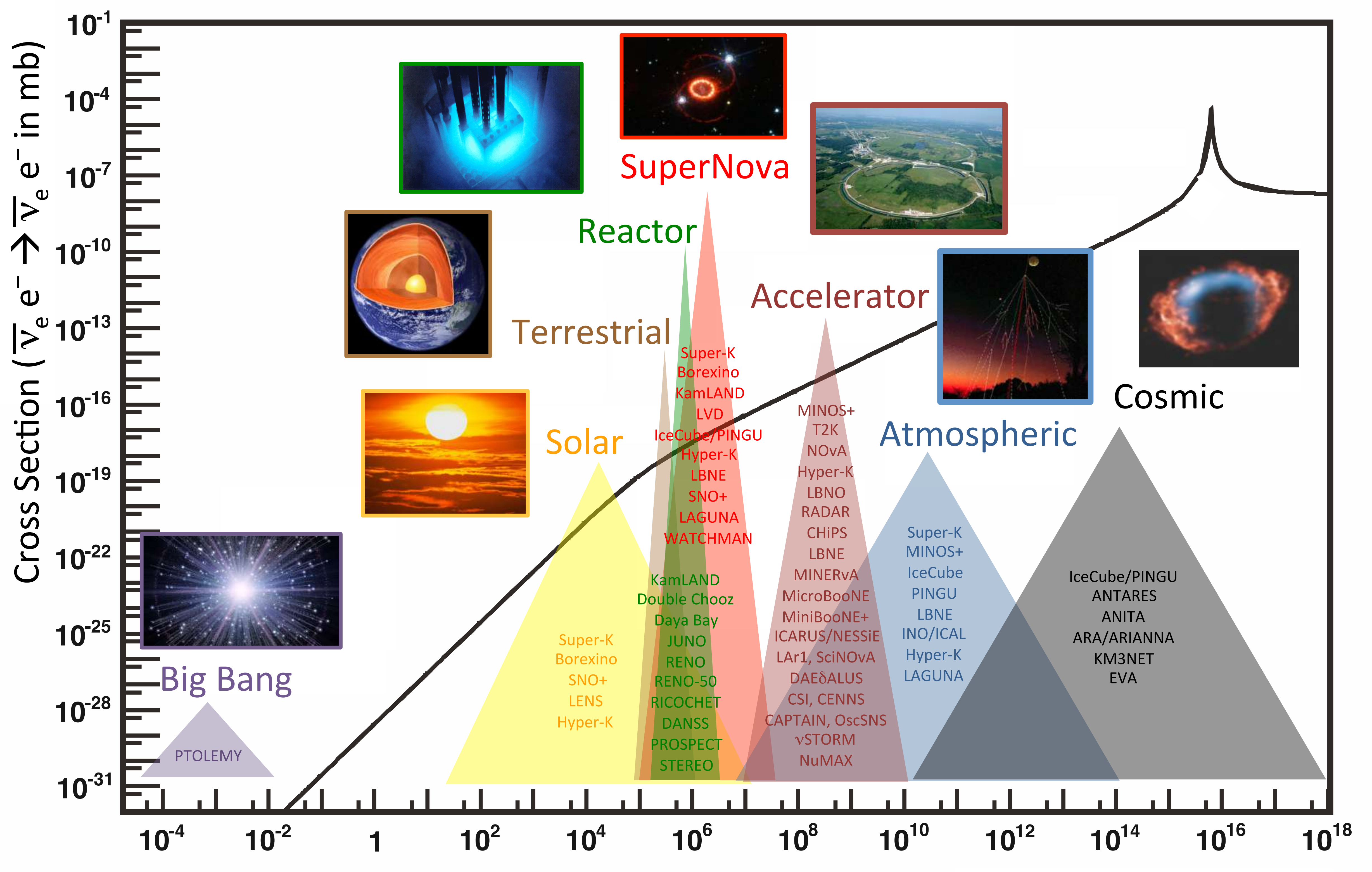
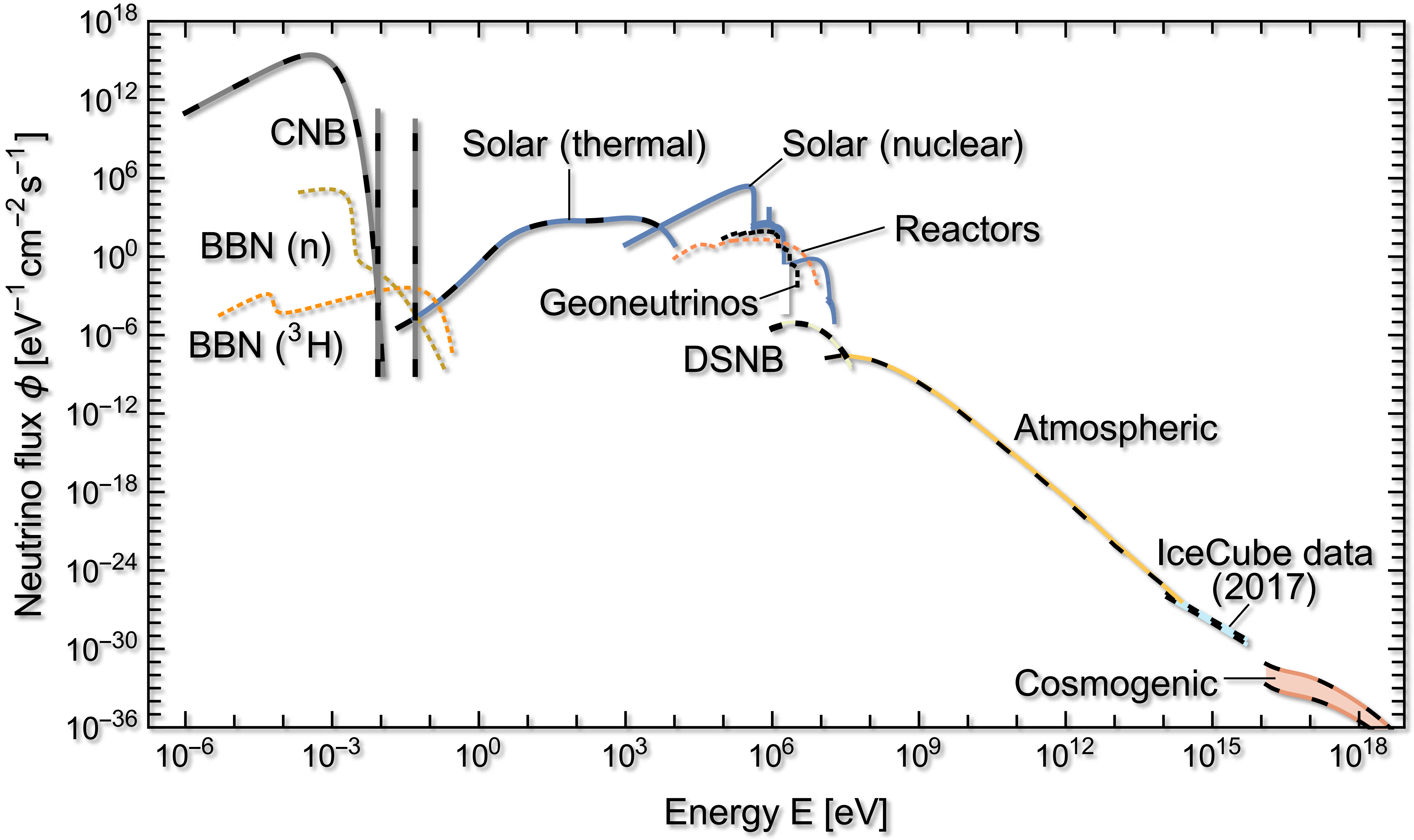


[J.L. Hewett et al., arXiv:1401.6077 (2014)]

- Many sources



[E. Vitagliano, I. Tamborra, G. Raffelt, Rev.Mod.Phys.92 (2020)]

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Sources

Where neutrinos are produced

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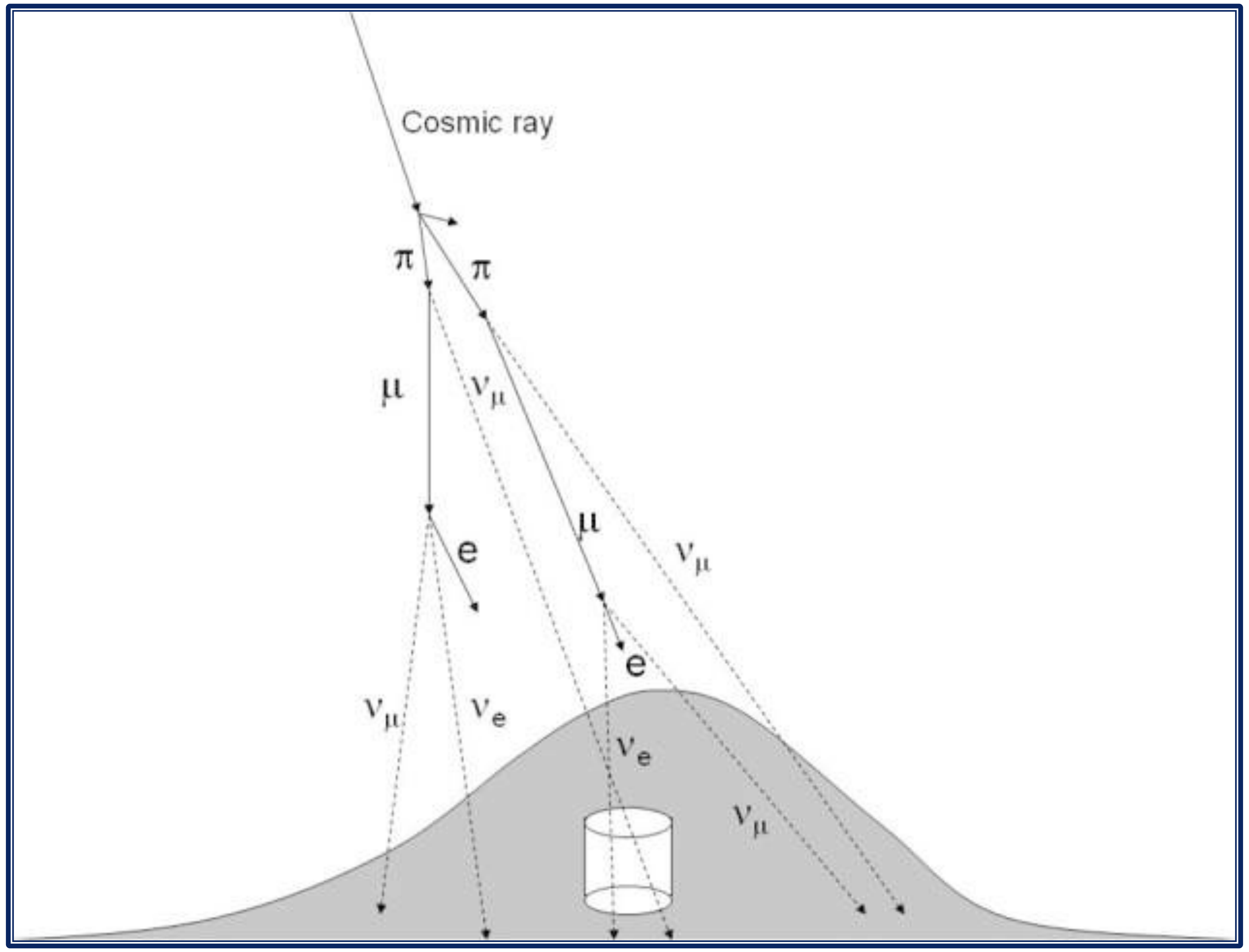
Atmospheric Neutrinos



[T. Kajita, Proc Jpn Acad Ser B Phys Biol Sci. (2010)]

Cosmic rays: protons (other heavy nuclei)

Interactions with the nuclei in the atmosphere

Pions

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

Sources

Where neutrinos are produced

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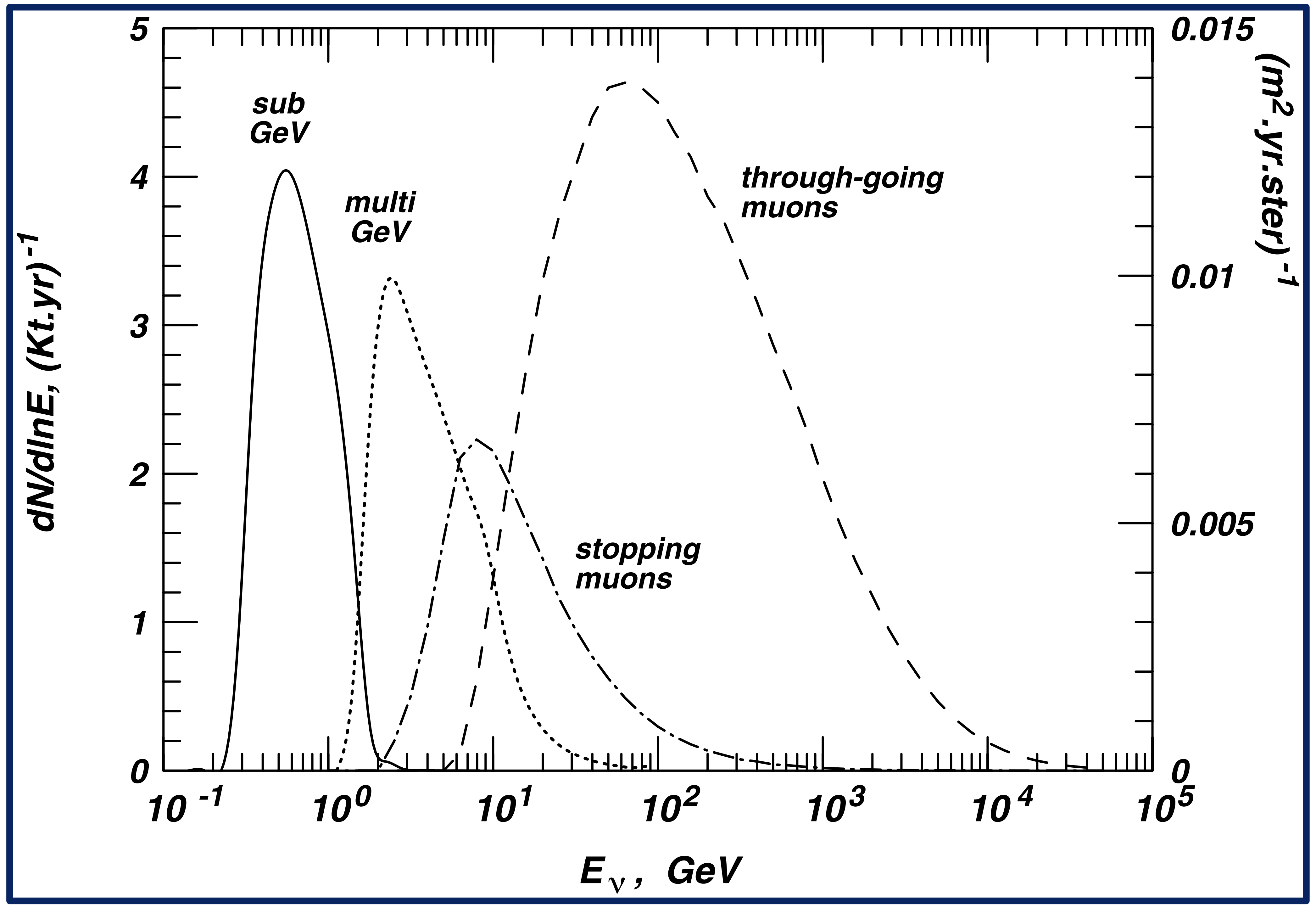
Atmospheric Neutrinos – Flux Measurement

[C. Giunti & C.W. Kim, Funds. of Neutrinos Physics and Astrophysics (2007)]



Wide range energy spectrum

Flux is measured by detecting charged leptons

$$\nu_l + N \to l^- + X \qquad \bar{\nu}_l + N \to l^+ + X \qquad (l = e, \mu, \tau)$$

Contained Events: neutrinos inside the detector

Stopping Muons: tracks of muons stop in the detector from neutrinos in the rock outside the detector

Through-Going Muons: tracks of muons traverse the detector from neutrinos in the rock outside the detector

Sources

Where neutrinos are produced

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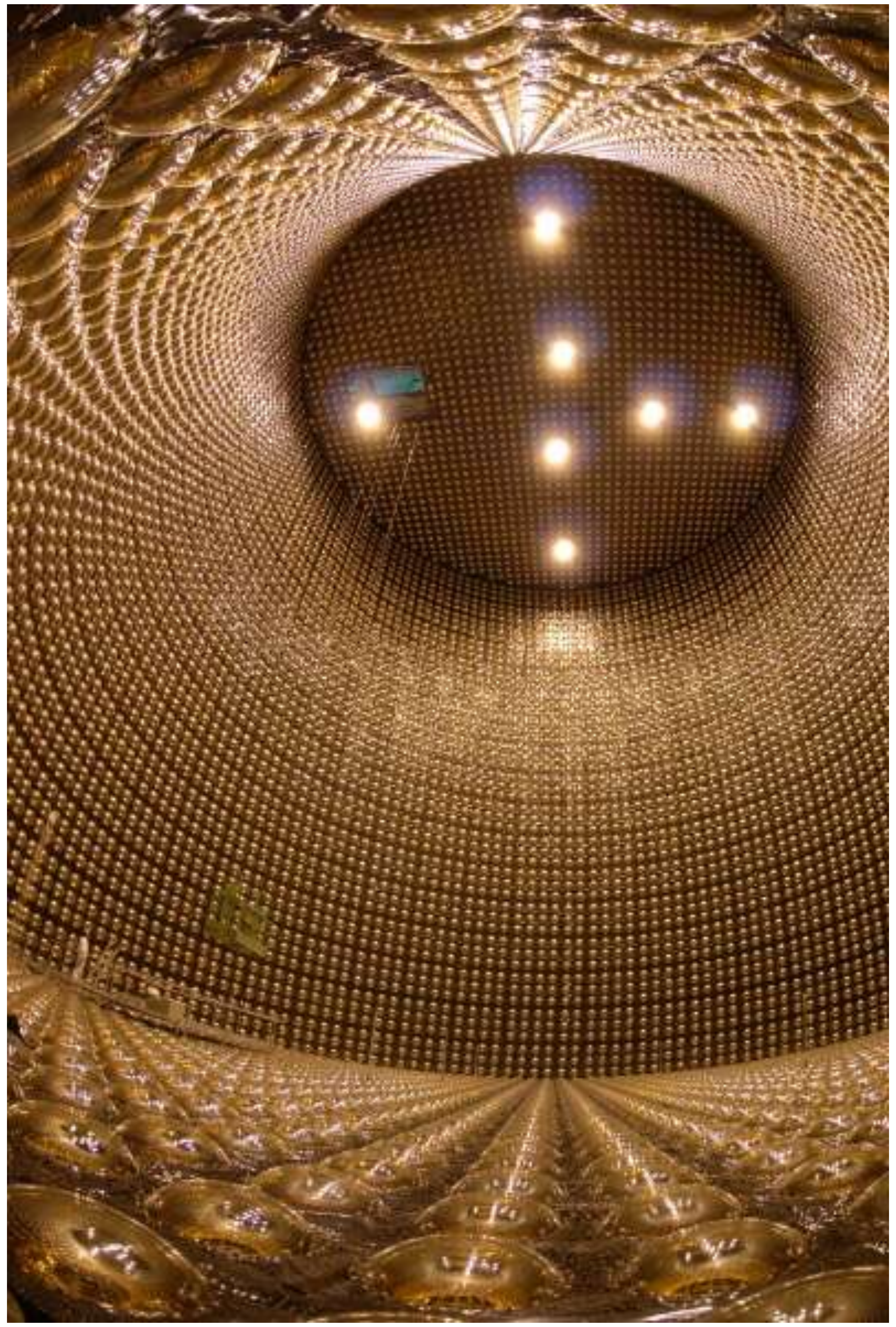
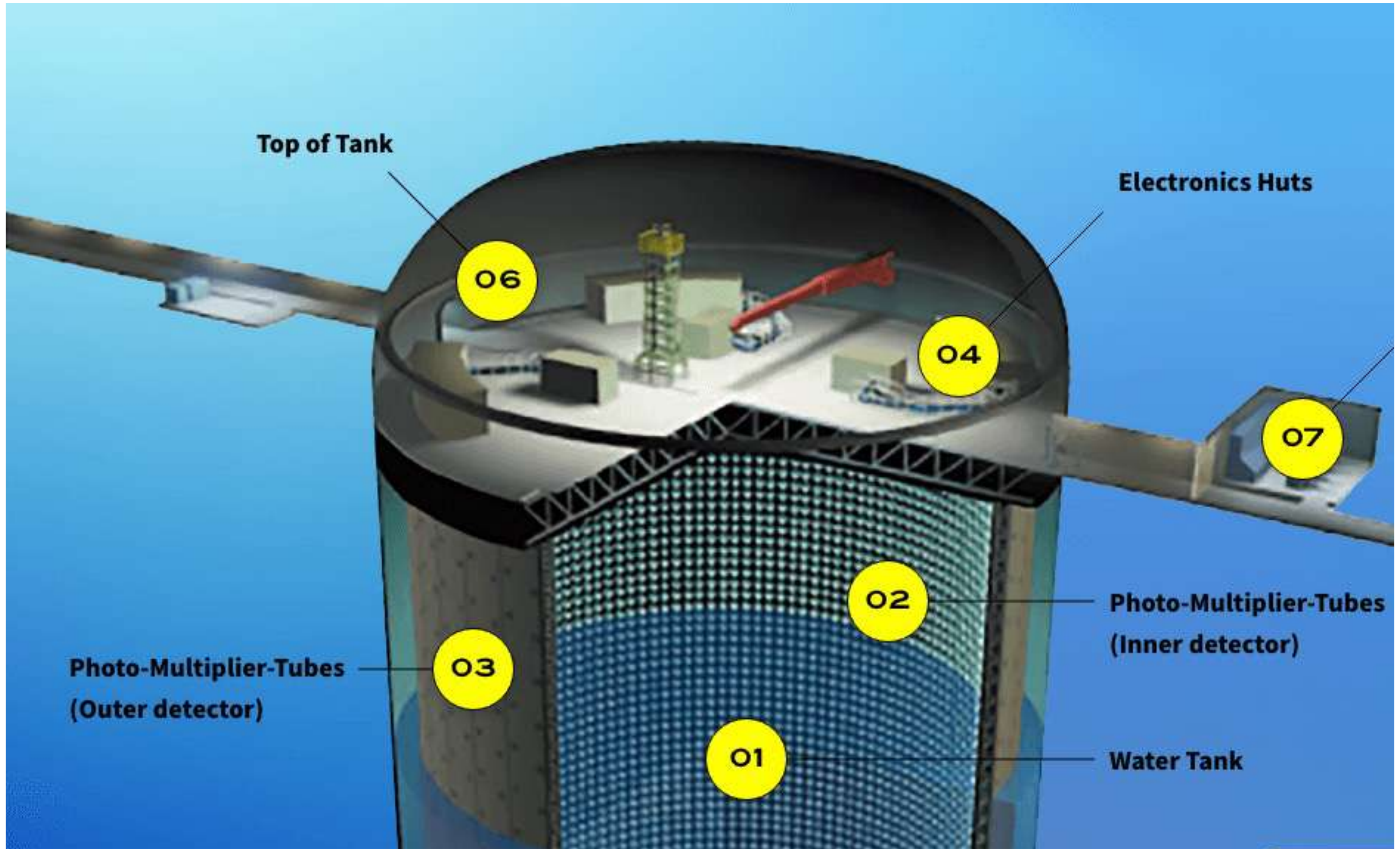
Atmospheric Neutrinos

Kamiokande and Super-Kamiokande



[Super-Kamiokande home page]



[Super-Kamiokande home page]

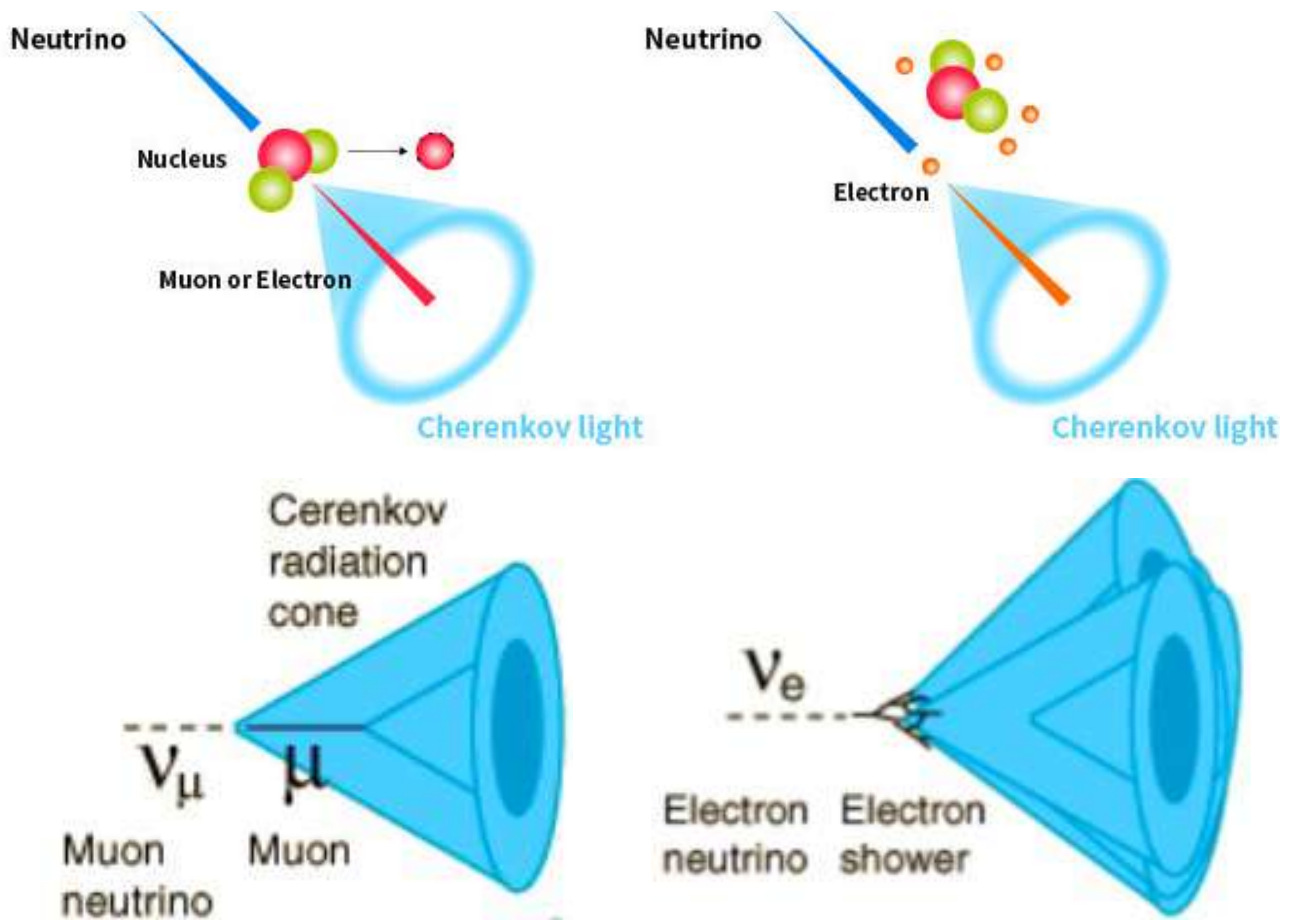
Observes neutrinos using a huge water tank with ~13000 PMTs.
When a neutrino enters the detector and interacts with water, Cherenkov light is emitted.

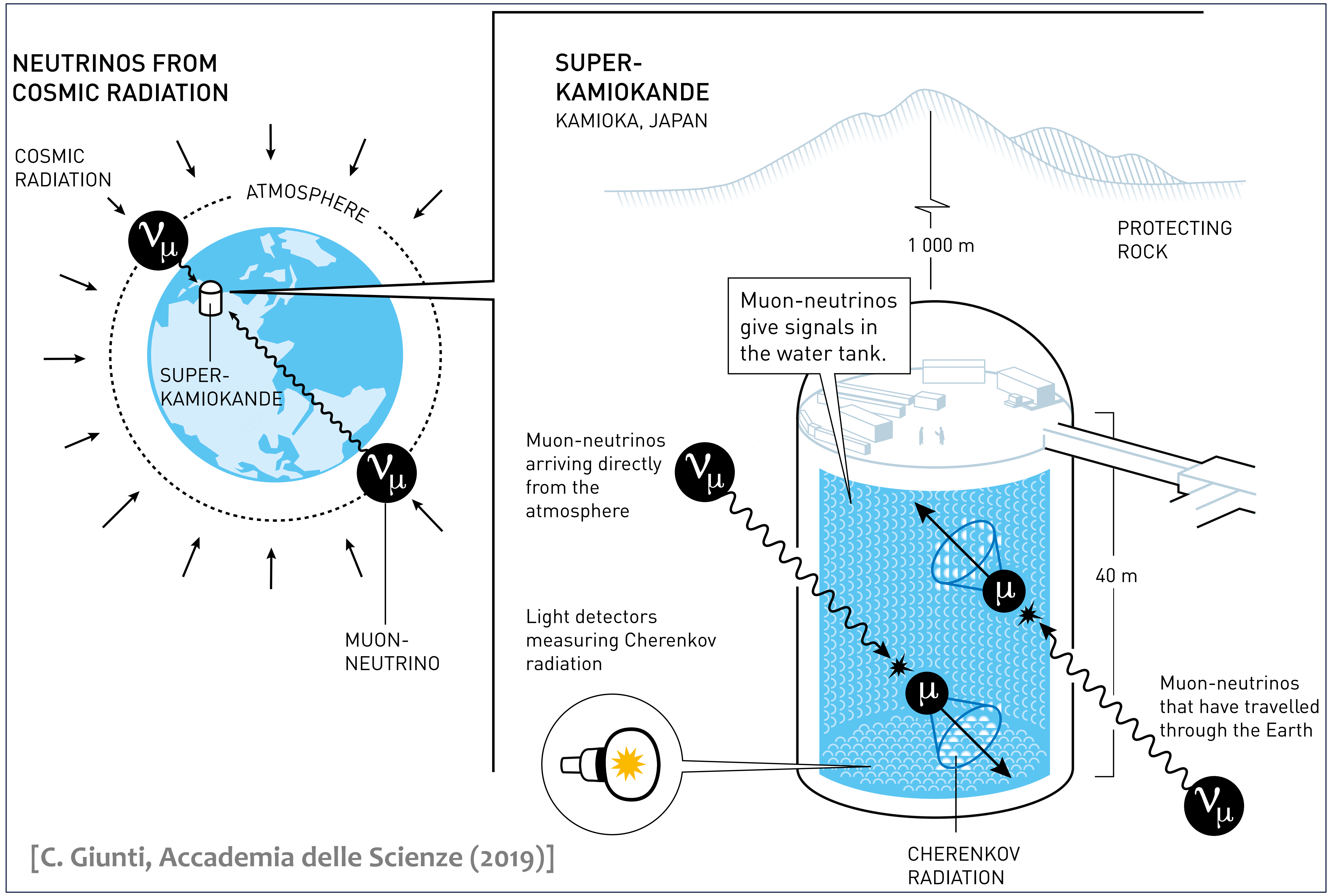
Sources

Where neutrinos are produced

Atmospheric Neutrinos

Kamiokande and Super-Kamiokande





[C. Giunti, Accademia delle Scienze (2019)]

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Sources

Where neutrinos are produced

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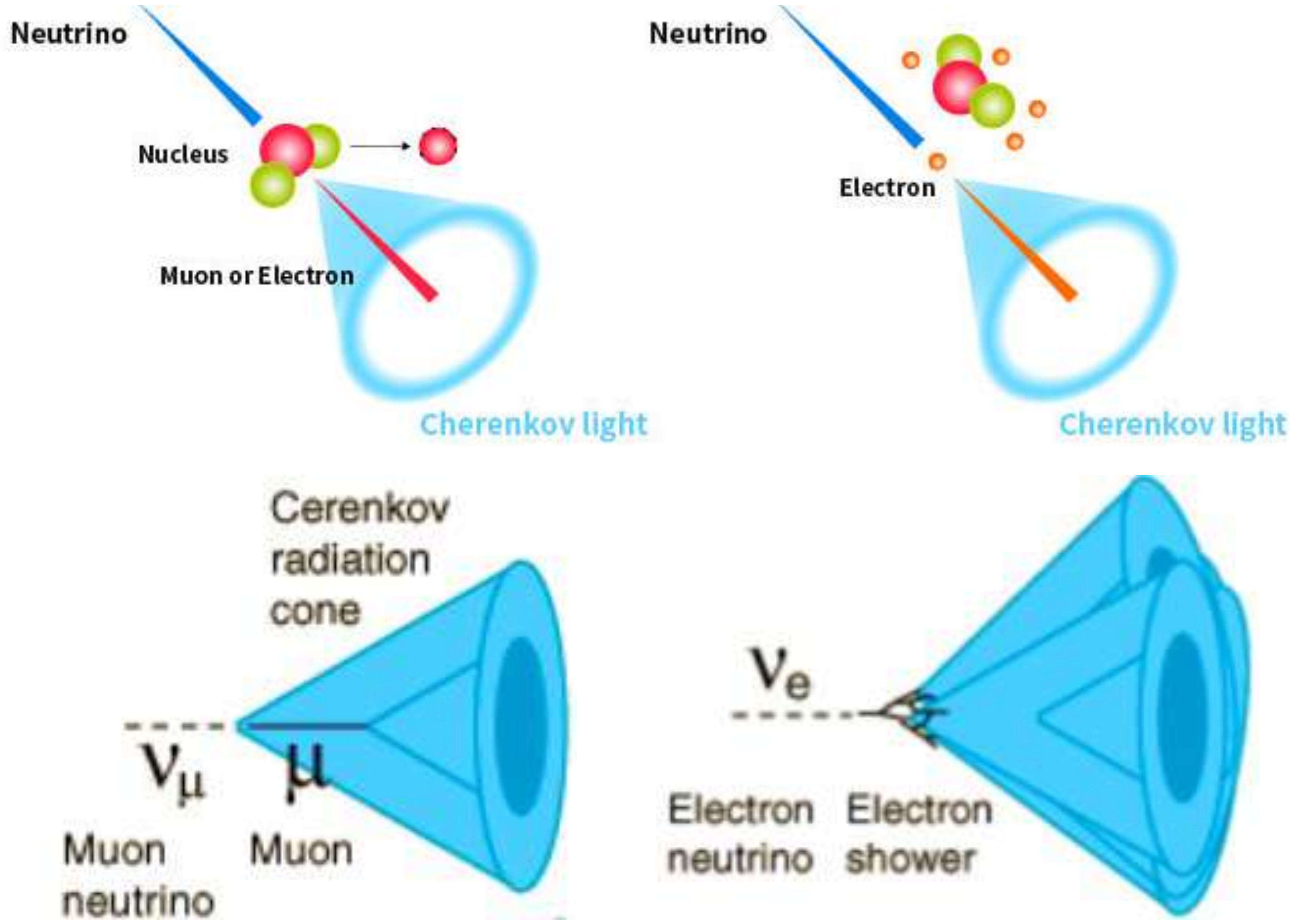
Atmospheric Neutrinos

IceCube

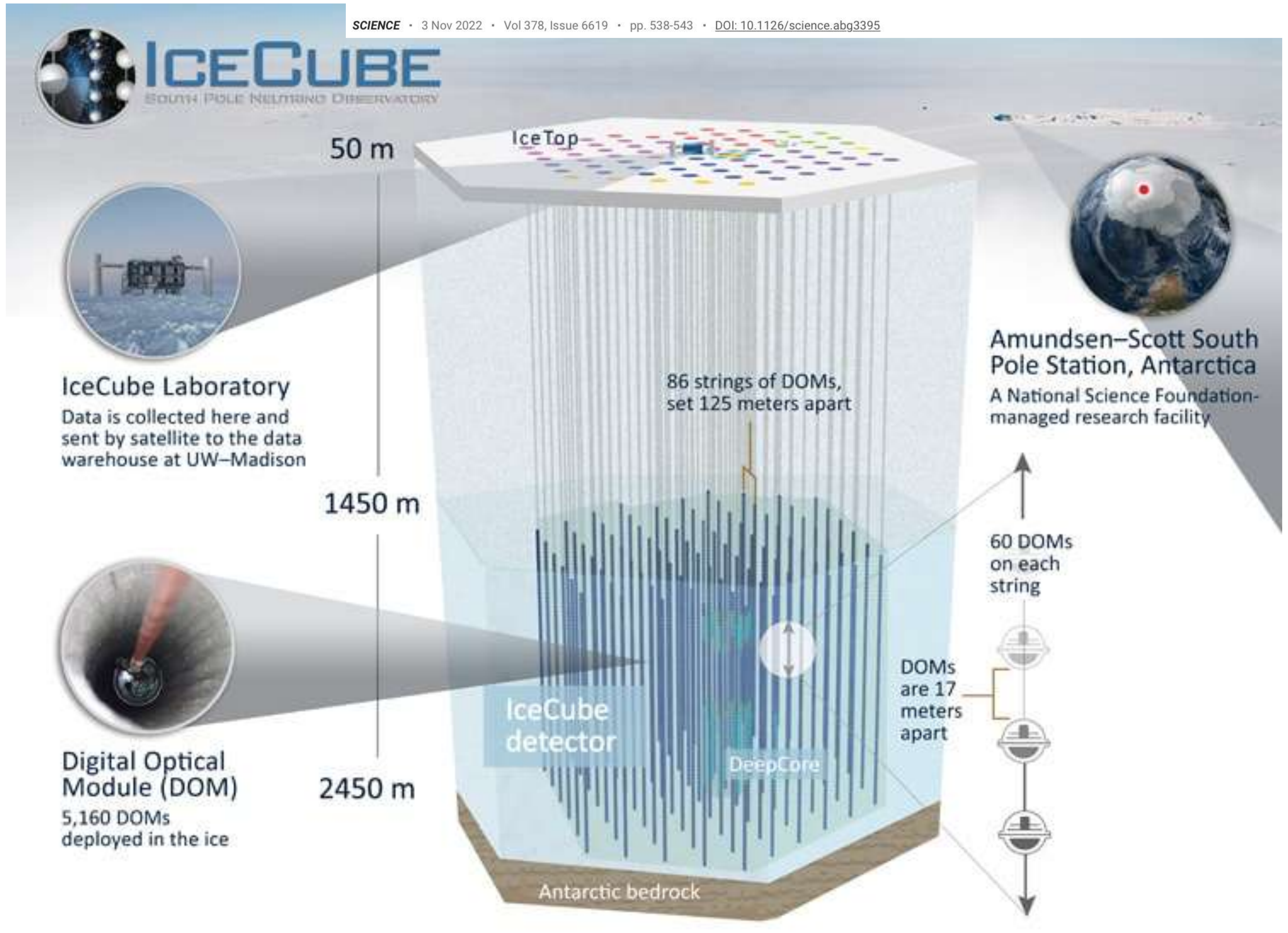


Evidence for neutrino emission from the nearby active galaxy NGC 1068

ICECUBE COLLABORATION*†, R. ABBASI, M. ACKERMANN, J. ADAMS, J. A. AGUILAR, M. AHLERS, M. AHRENS, J. M. ALAMEDDINE, C. ALISPACH, [...], AND P. ZHELNIN

+376 authors Authors Info & Affiliations

SCIENCE • 3 Nov 2022 • Vol 378, Issue 6619 • pp. 538-543 • DOI: 10.1126/science.abg3395



IceCube (Very) High energy neutrinos – Source searches
https://icecube.wisc.edu/

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Sources

Where neutrinos are produced

#SOMOSUA

Atmospheric Neutrinos

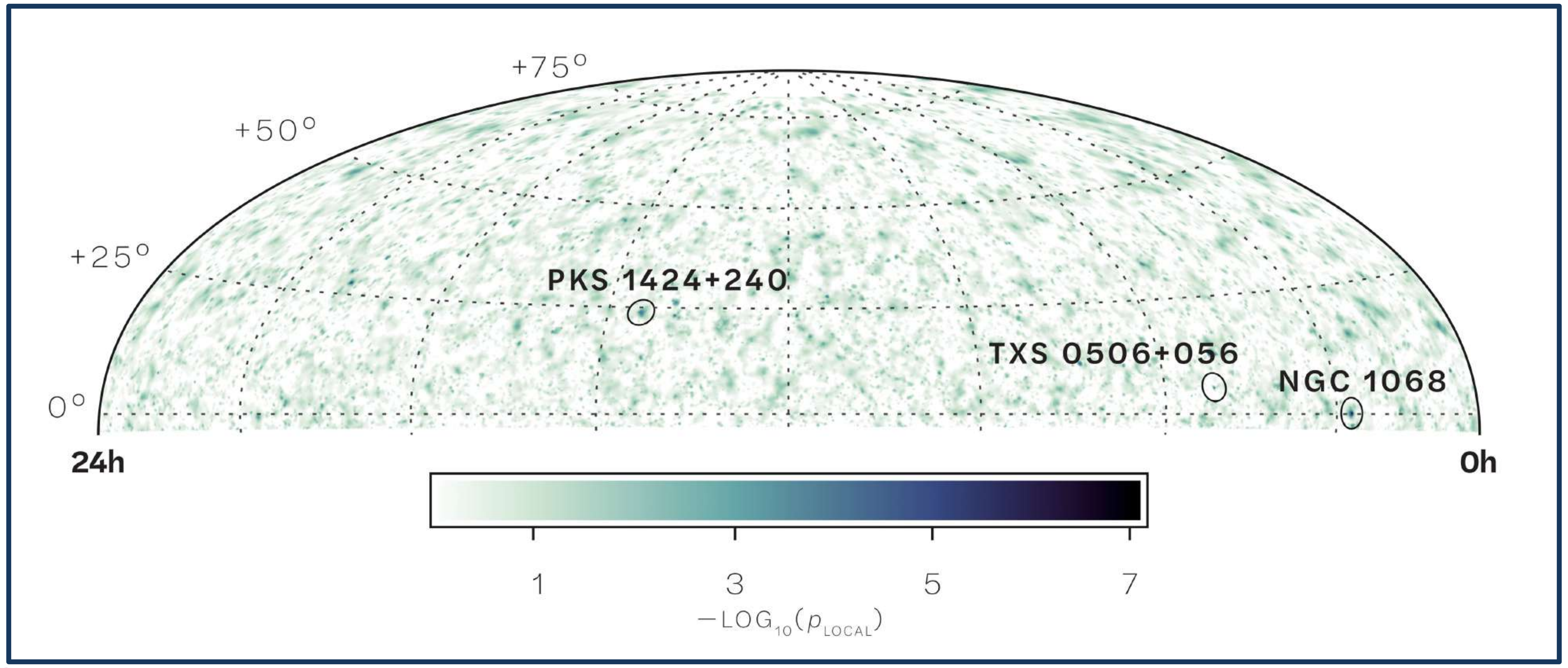
IceCube

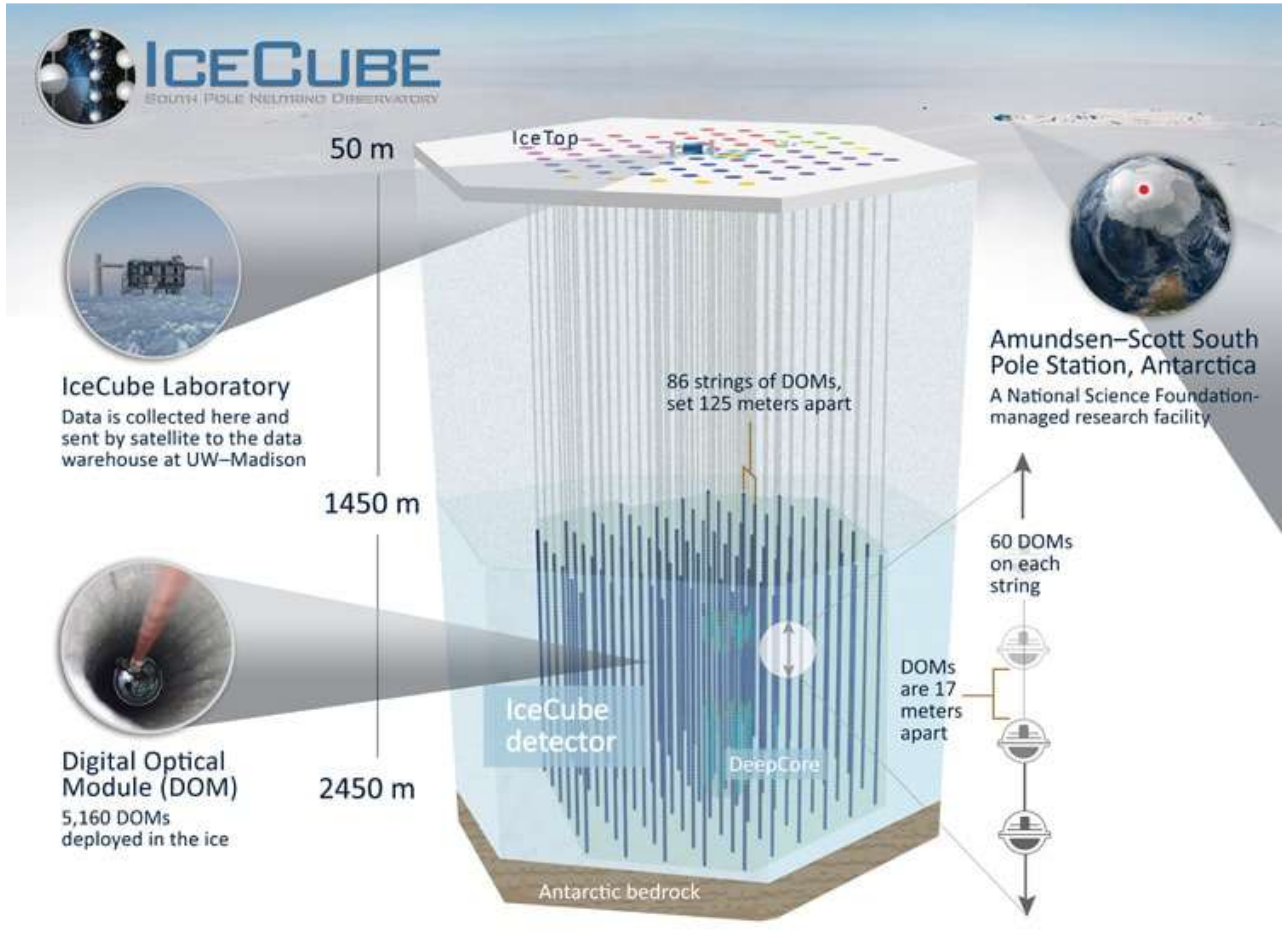
Evidence for neutrino emission from the nearby active galaxy NGC 1068

ICECUBE COLLABORATION*†, R. ABBASI, M. ACKERMANN, J. ADAMS, J. A. AGUILAR, M. AHLERS, M. AHRENS, J. M. ALAMEDDINE, C. ALISPACH, [...], AND P. ZHELNIN

+376 authors Authors Info & Affiliations

SCIENCE • 3 Nov 2022 • Vol 378, Issue 6619 • pp. 538-543 • DOI: 10.1126/science.abg3395





IceCube (Very) High energy neutrinos – Source searches
https://icecube.wisc.edu/

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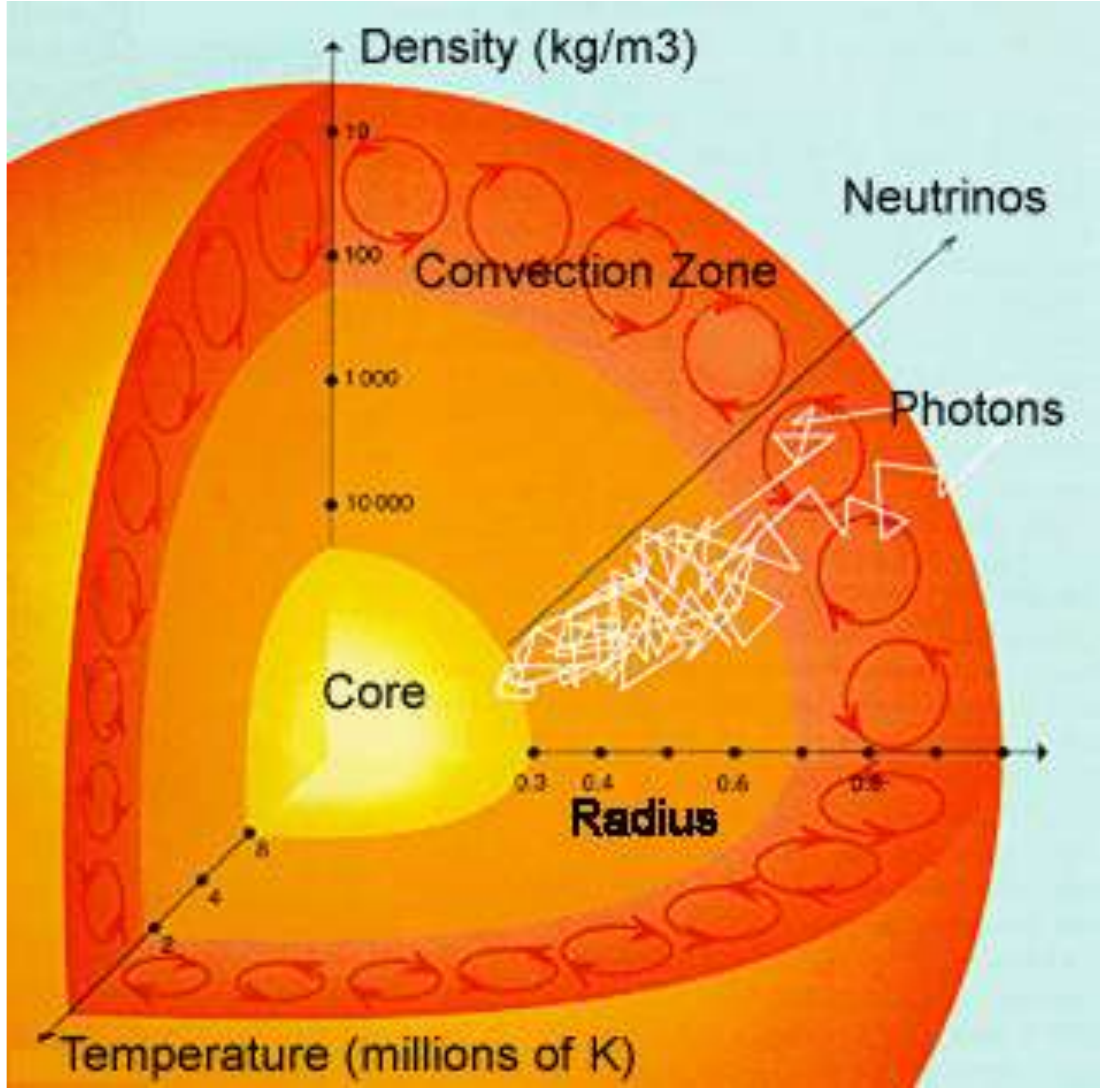
Sources

Where neutrinos are produced

#SOMOSUA

Solar Neutrinos

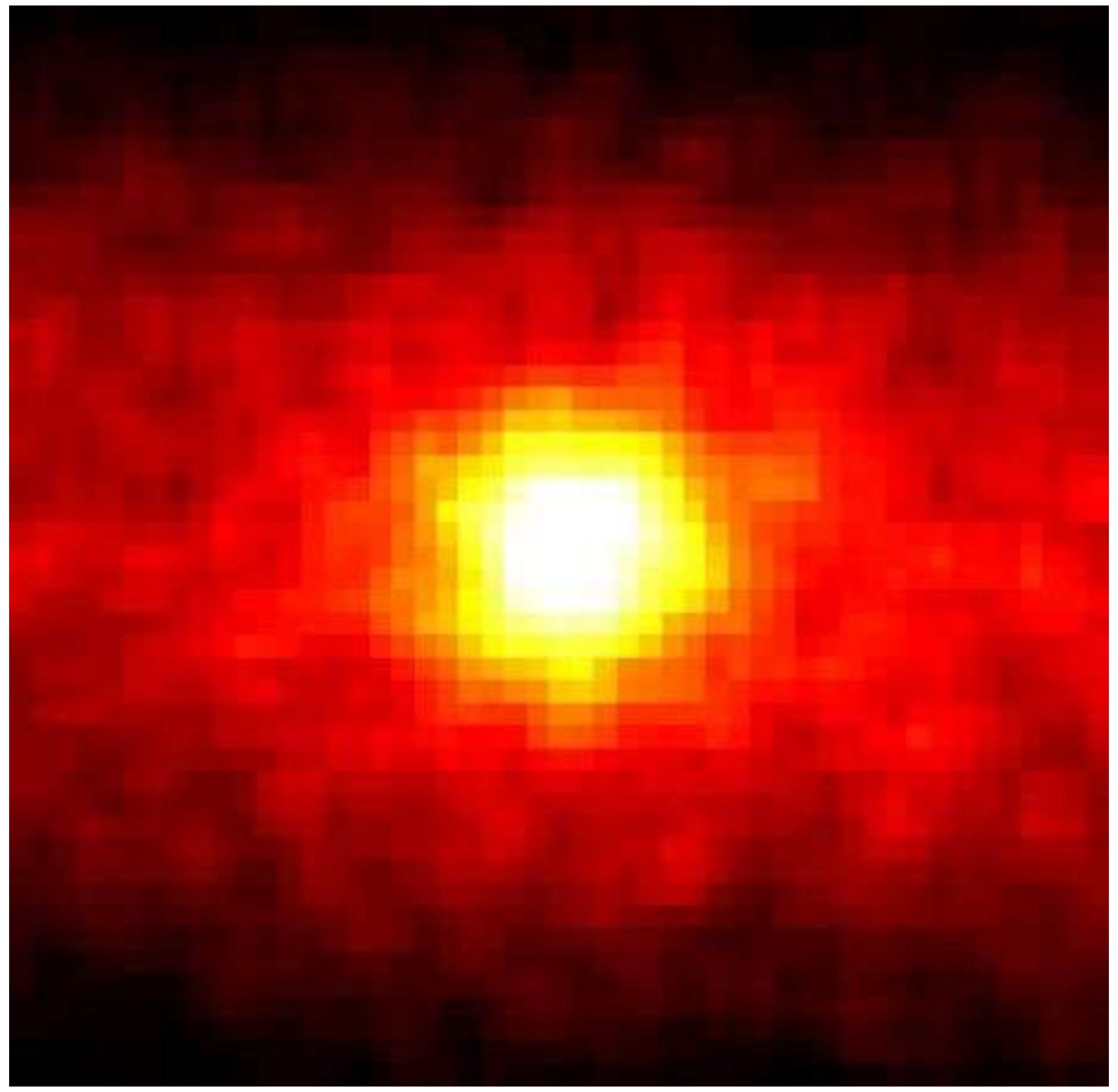
[Andromeda Geek (2015)]



Sun powered by thermonuclear reactions:

pp chain – **CNO** cycle

$$4\,p + 2\,e^- \;\rightarrow\, {}^4\mathrm{He} + 2\,\nu_e + Q$$

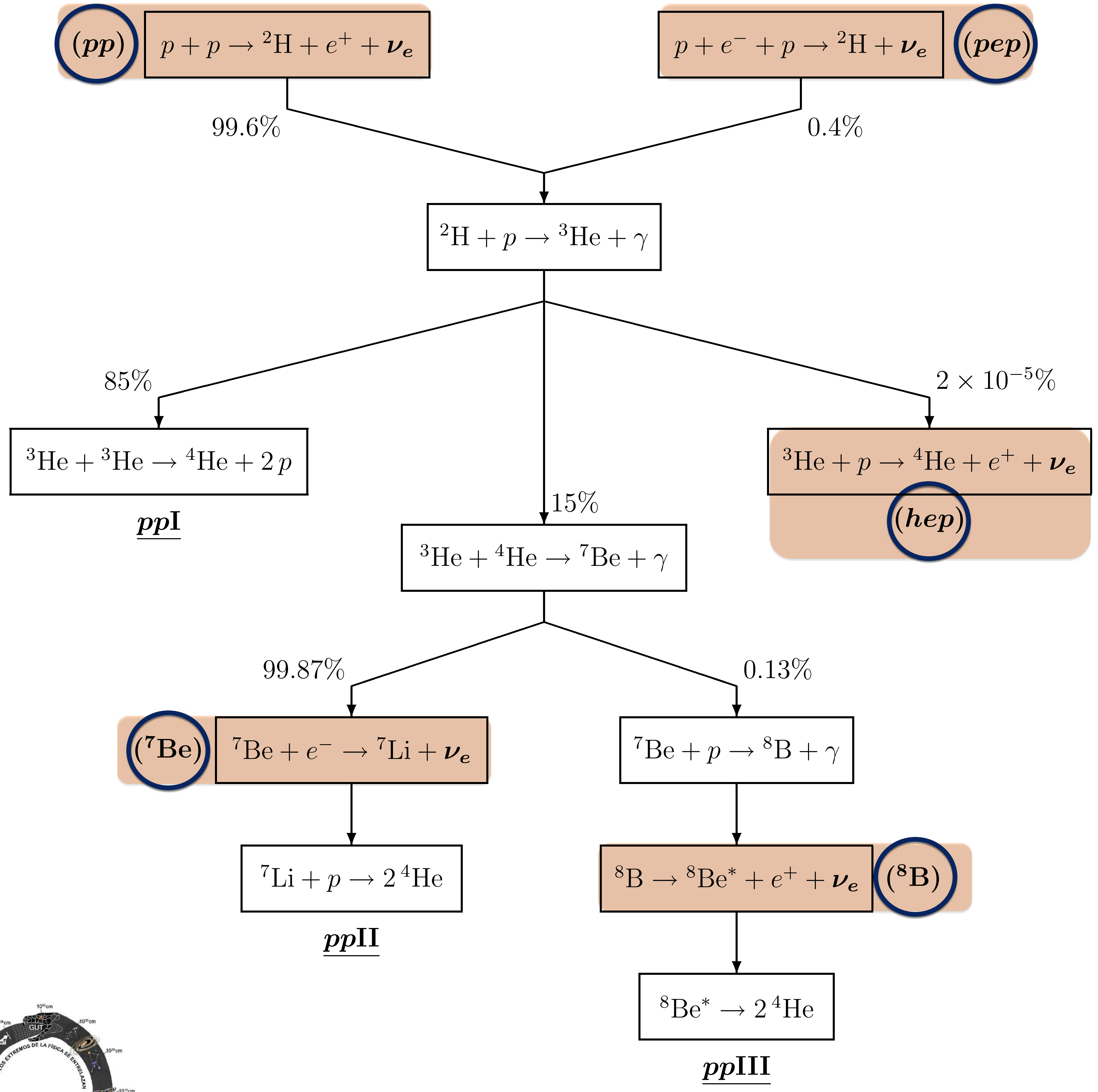


The Sun with neutrinos

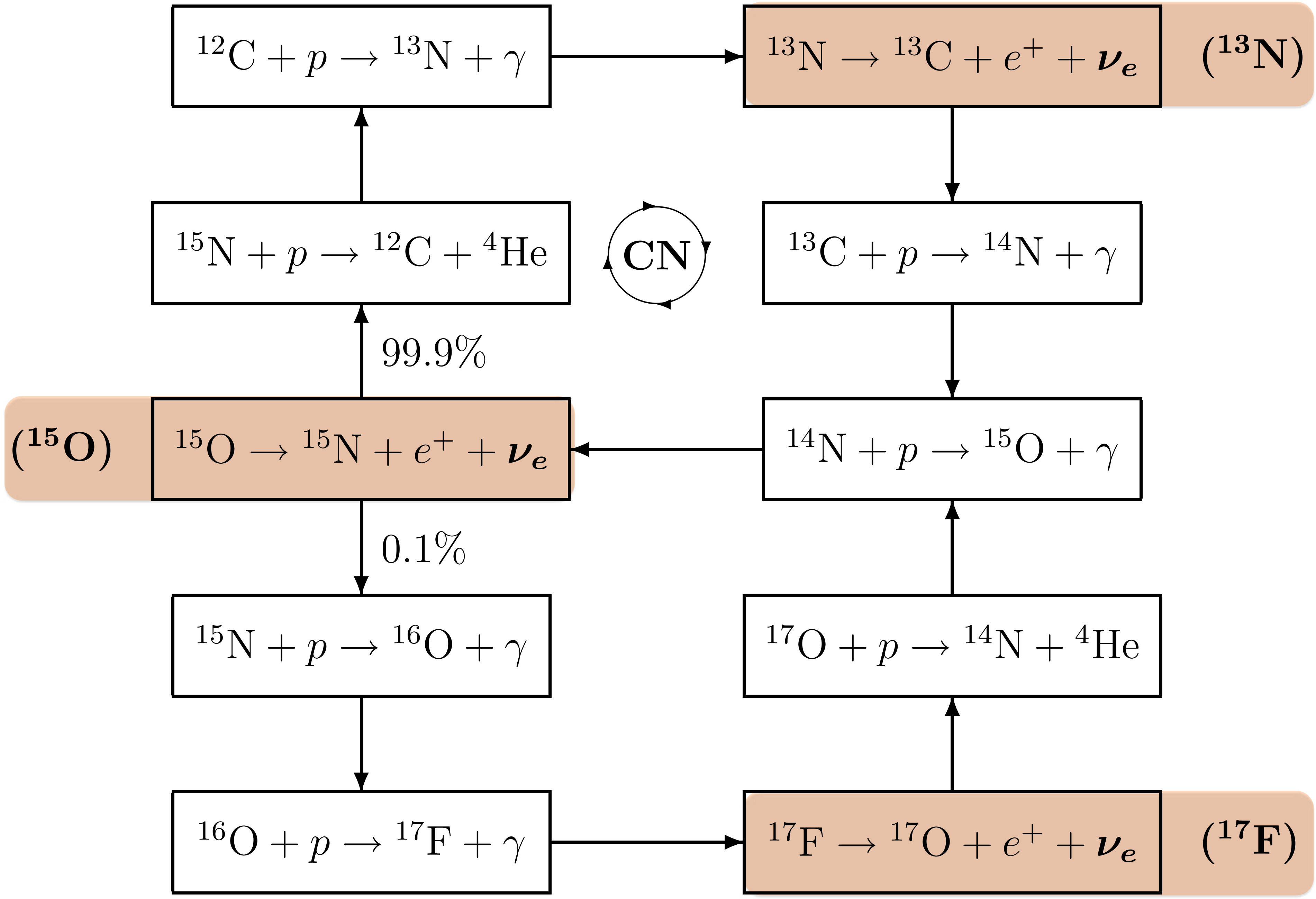
Sources

Where neutrinos are produced

Solar Neutrinos pp chain



CNO cycle



[C. Giunti & C.W. Kim, Funds. of Neutrinos Physics and Astrophysics (2007)]

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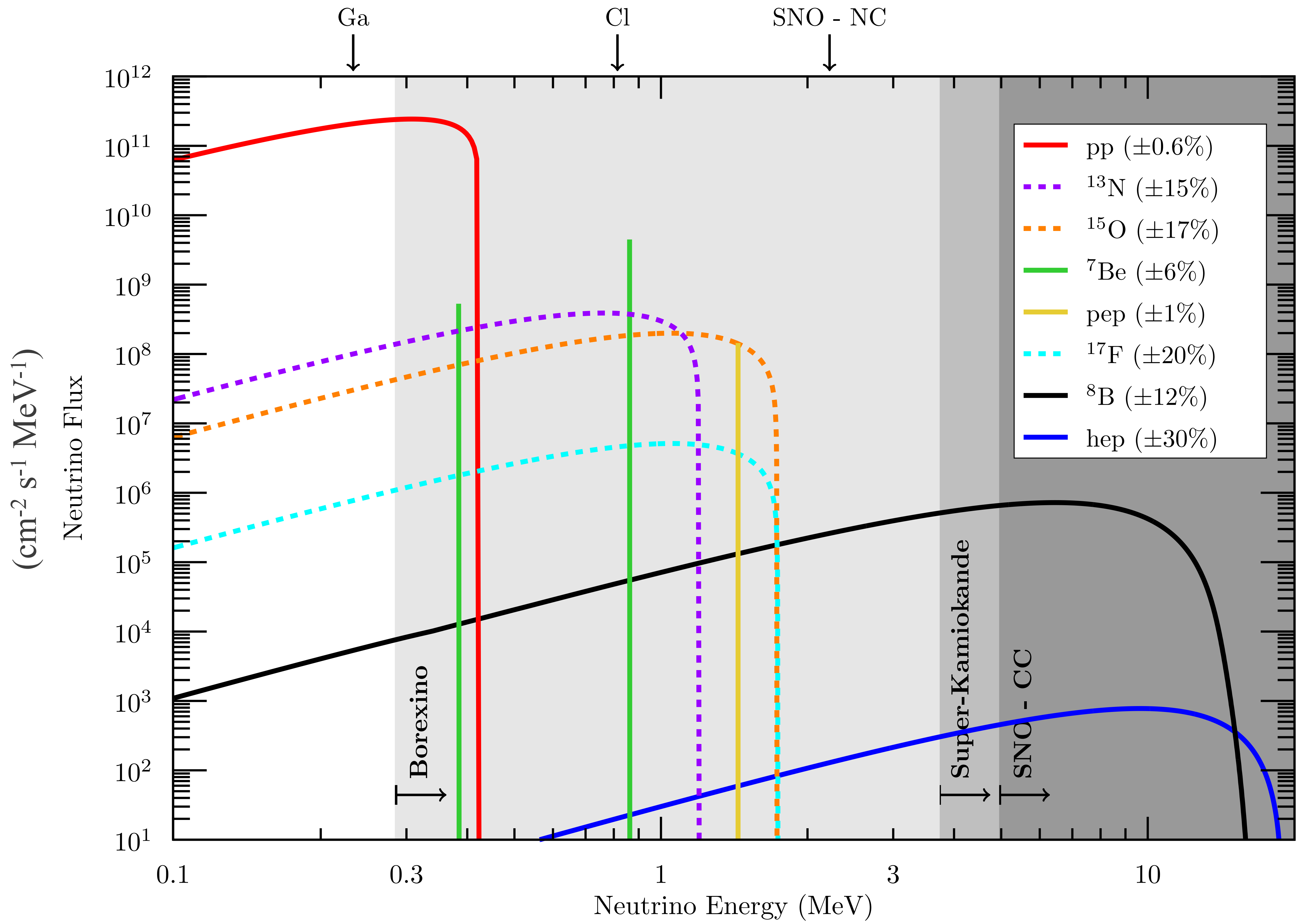
Sources

Where neutrinos are produced

#SOMOSUA

Solar Neutrinos Fluxes according to the SSM



[A. Gallo Rosso *et al.*, Eur.Phys.J. Plus 133 (2018)]

The experiments

Borexino	Liquid Scintillator Detector
GALLEX GNO SAGE	Radioactive Experiment
Homestake Kamiokande Super-Kamiokande SNO – SNO+	Water Cherenkov Detector

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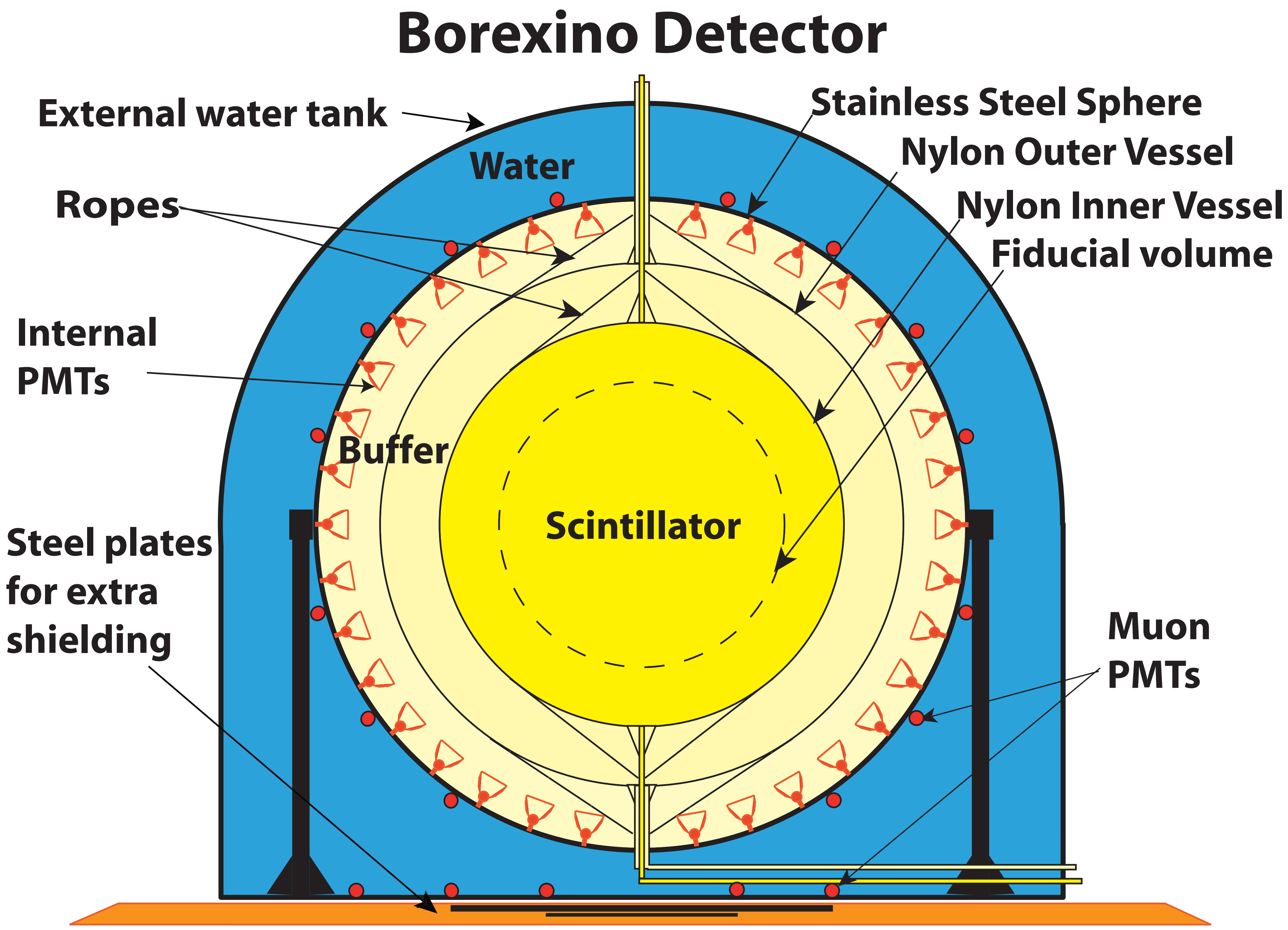
Sources

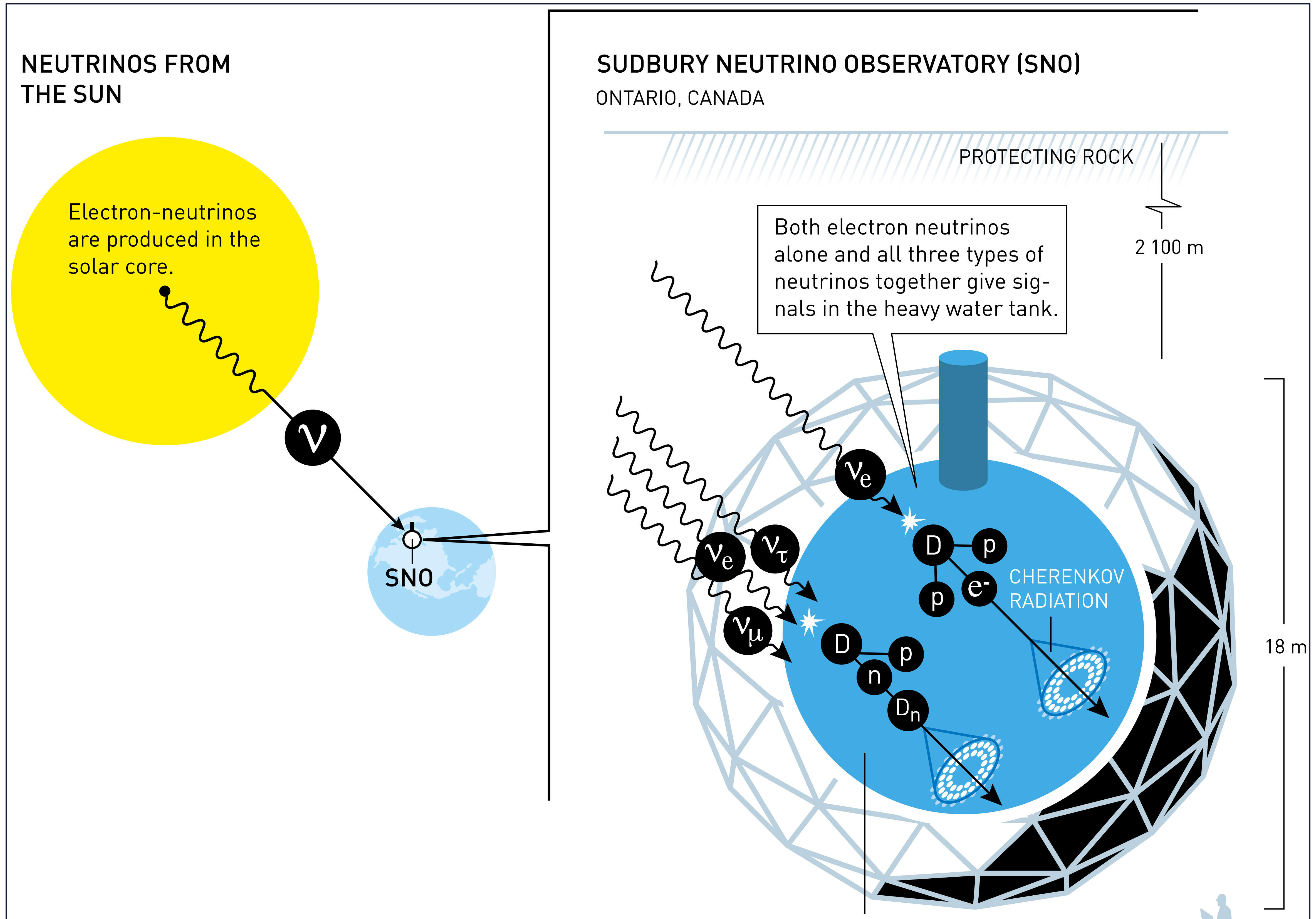
Where neutrinos are produced

#SOMOSUA

Solar Neutrinos Borexino



[The Borexino Coll., NIMA 600 (2009)]



[C. Giunti, Accademia delle Scienze (2019)]

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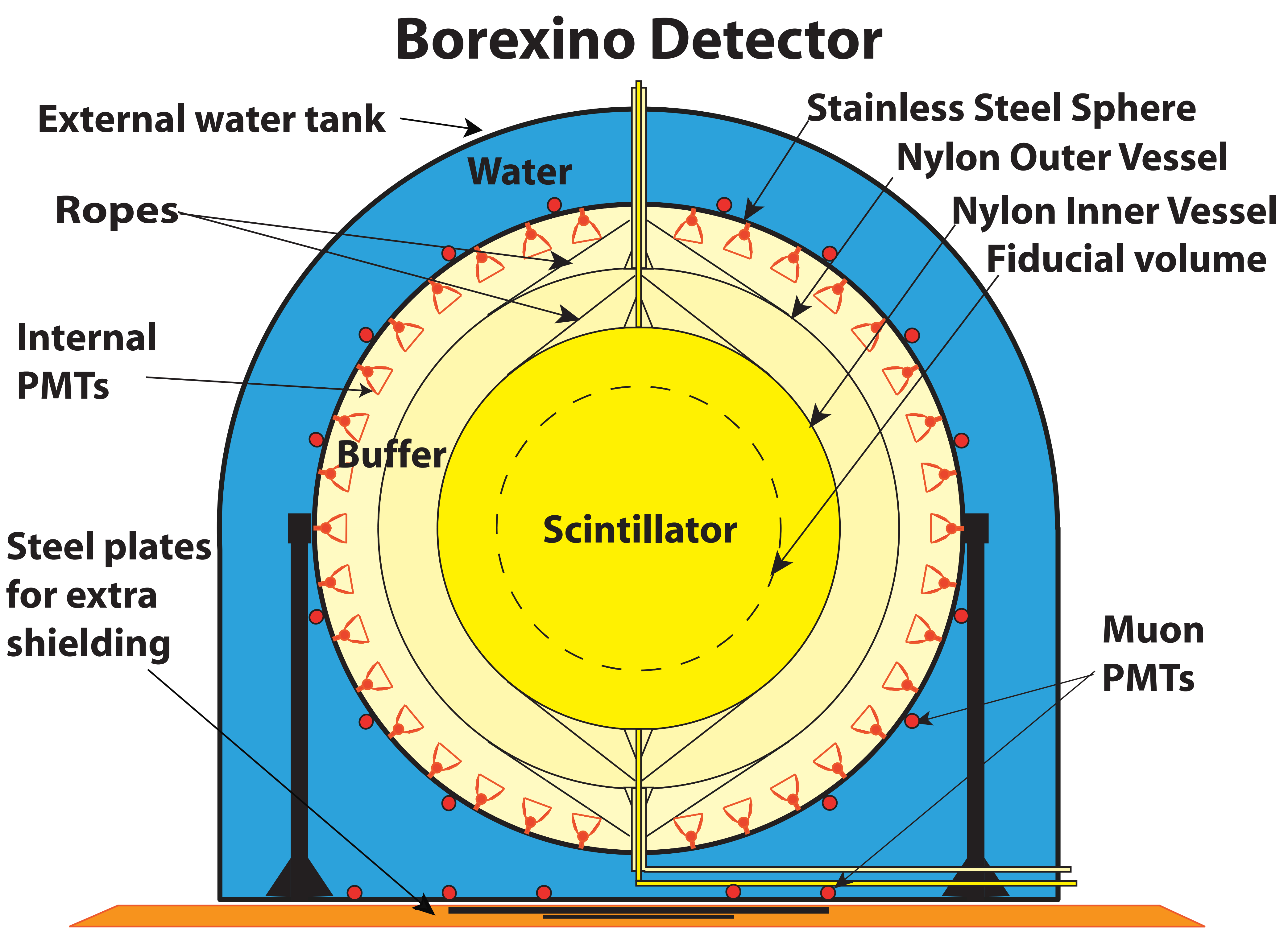
Sources

Where neutrinos are produced

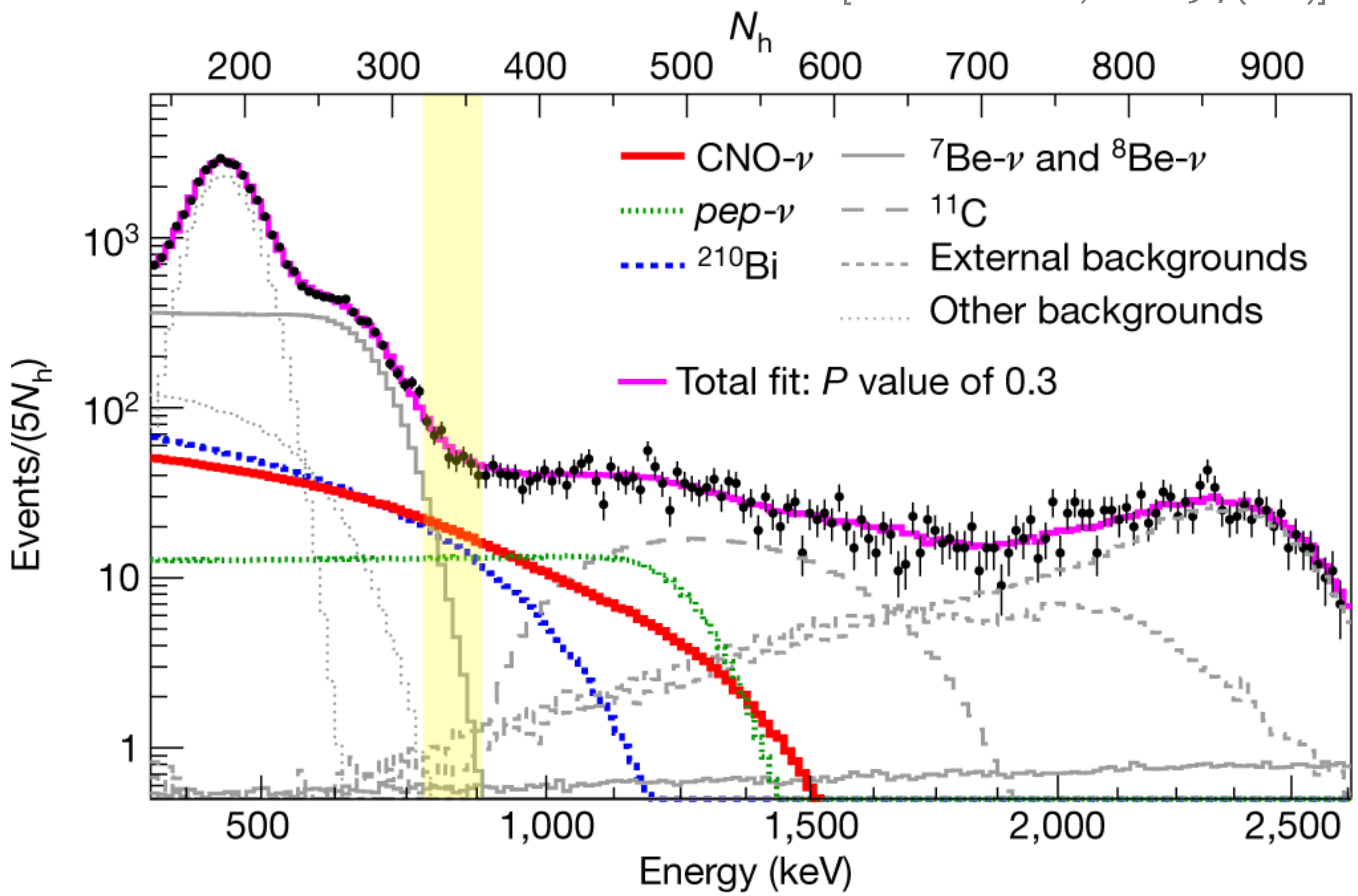
#SOMOSUA

Solar Neutrinos Borexino



[The Borexino Coll., NIMA 600 (2009)]

[The Borexino Coll., Nature 587 (2020)]

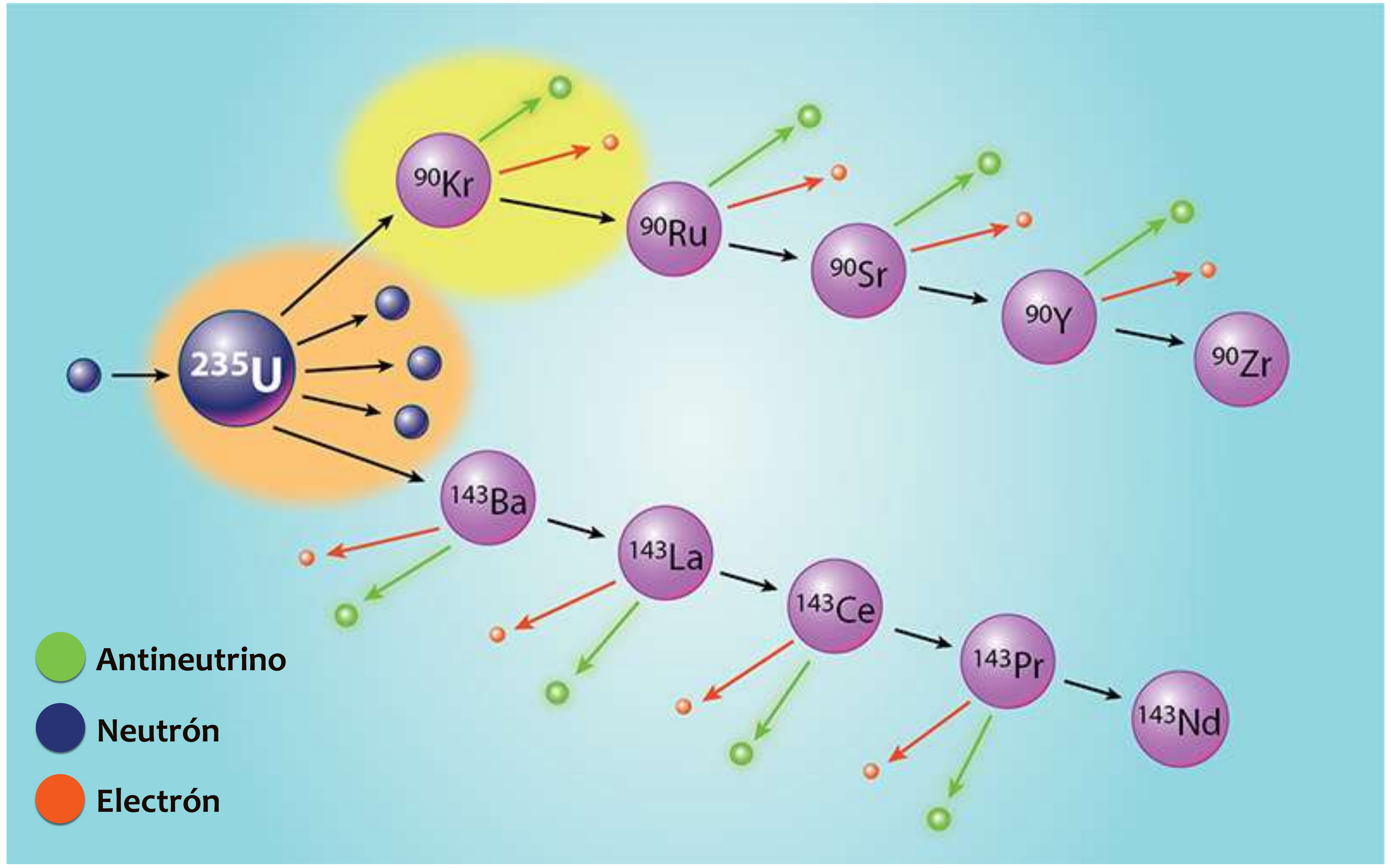


Sources

Where neutrinos are produced

#SOMOSUA

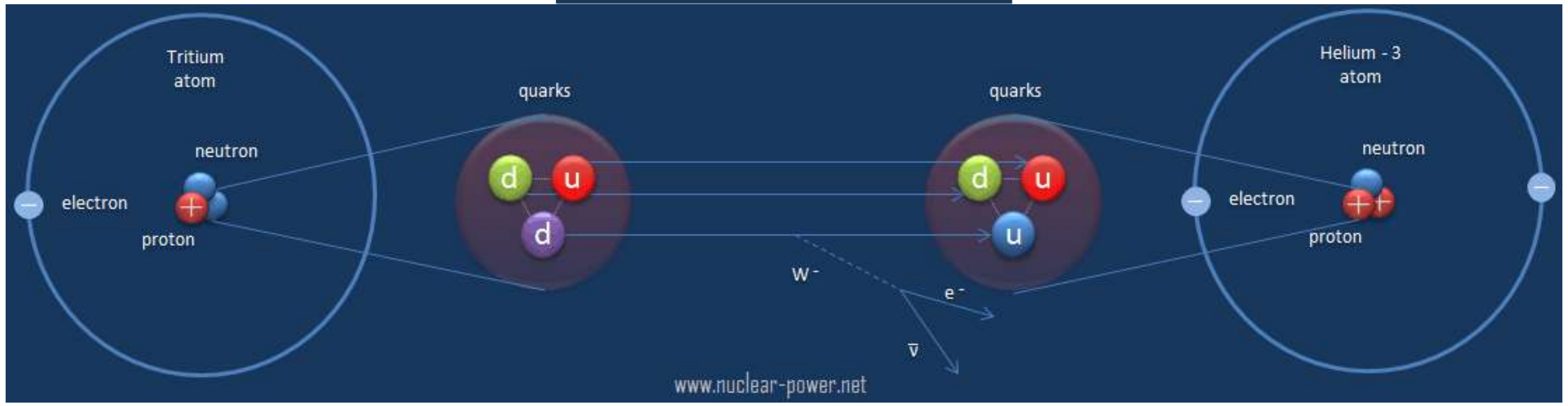
Reactor Neutrinos Electron antineutrinos: beta-decay chain of the fission products

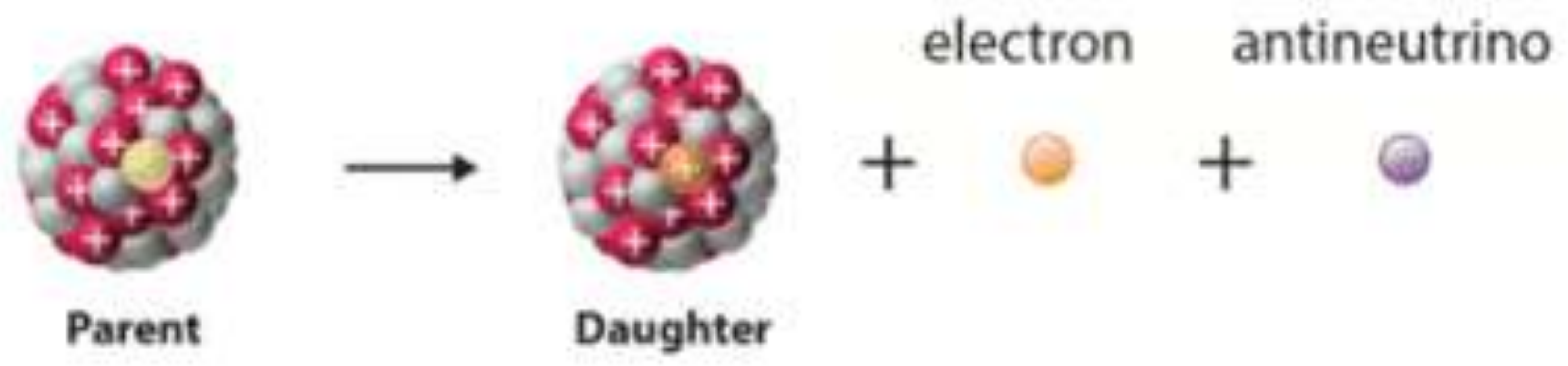


[K. Wright Physics 13 (2020)]

$$^{235}\mathrm{U}\ (56\%),\ ^{238}\mathrm{U}\ (8\%),\ ^{239}\mathrm{Pu}\ (30\%),\ ^{241}\mathrm{Pu}\ (6\%)$$

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





$$^{A}_{Z}X \to\ ^{A}_{Z+1}Y + \beta^- + \bar{\nu}_e$$

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Where neutrinos are produced

#SOMOSUA

Reactor Neutrinos Electron antineutrinos detection: inverse neutron decay

Visible Energy $E_e + m_e$, and the positron annihilates with a surrounding electron.

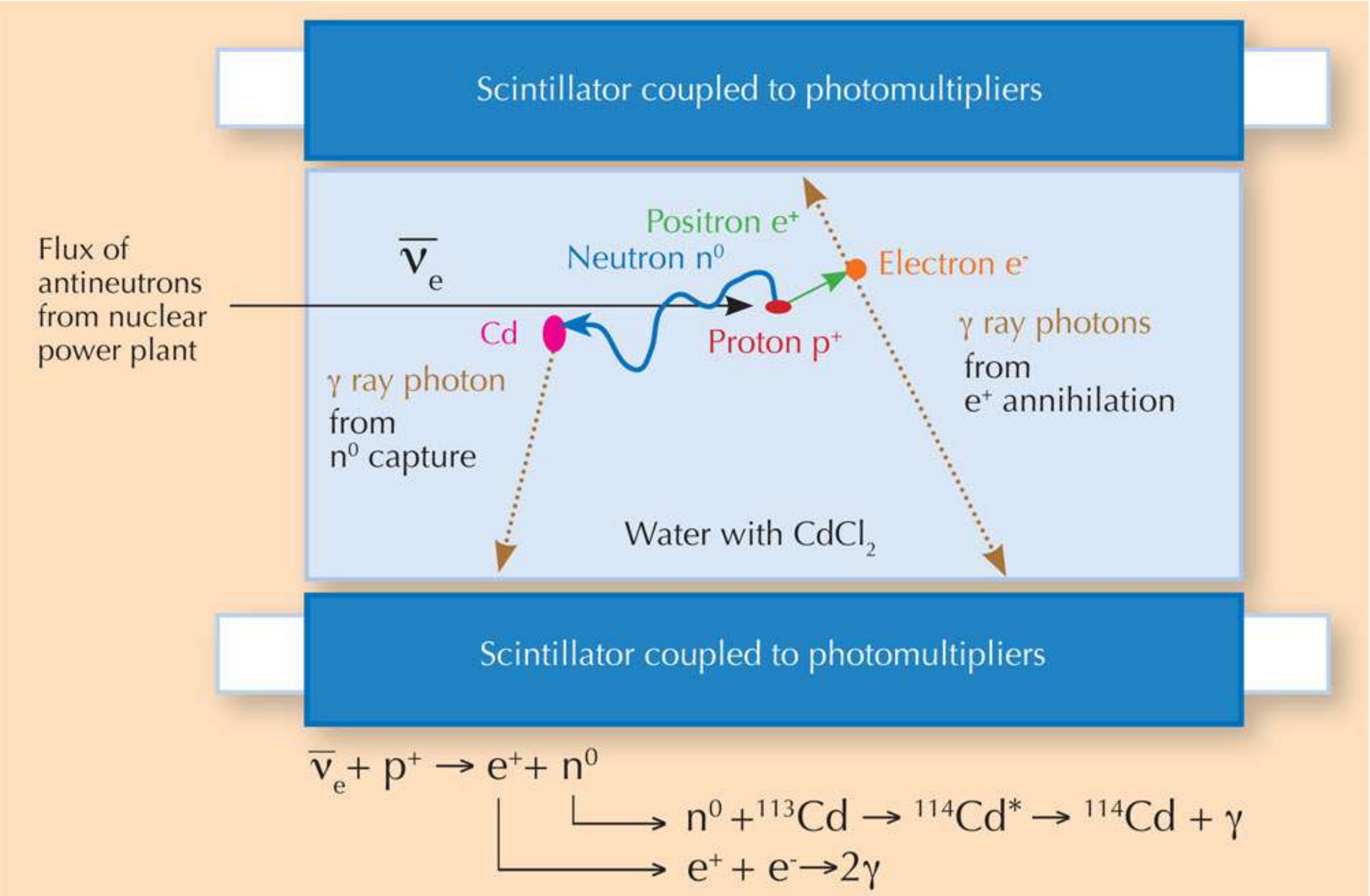
Events vs. Background: Coincidence
- Prompt positron signal
- Neutron nuclear capture (delayed)

Neutrino – Positron energy relation

$$E_\nu = E_e + T_n + m_n - m_p \simeq E_e + 1.293\ \text{MeV}$$

Threshold energy

$$E_\nu^{th} = \frac{(m_n + m_e)^2 - m_p^2}{2\, m_p} \simeq 1.806\ \text{MeV}$$



[S. Cebrián, Science in School 19 (2011)]

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Where neutrinos are produced

#SOMOSUA

Reactor Neutrinos Some experiments

Flux measurements compared to expectation

- ILL
- Gosgen
- Rovno
- Krasnoyarsk
- Bugey
- Savanah River

} Short Baseline

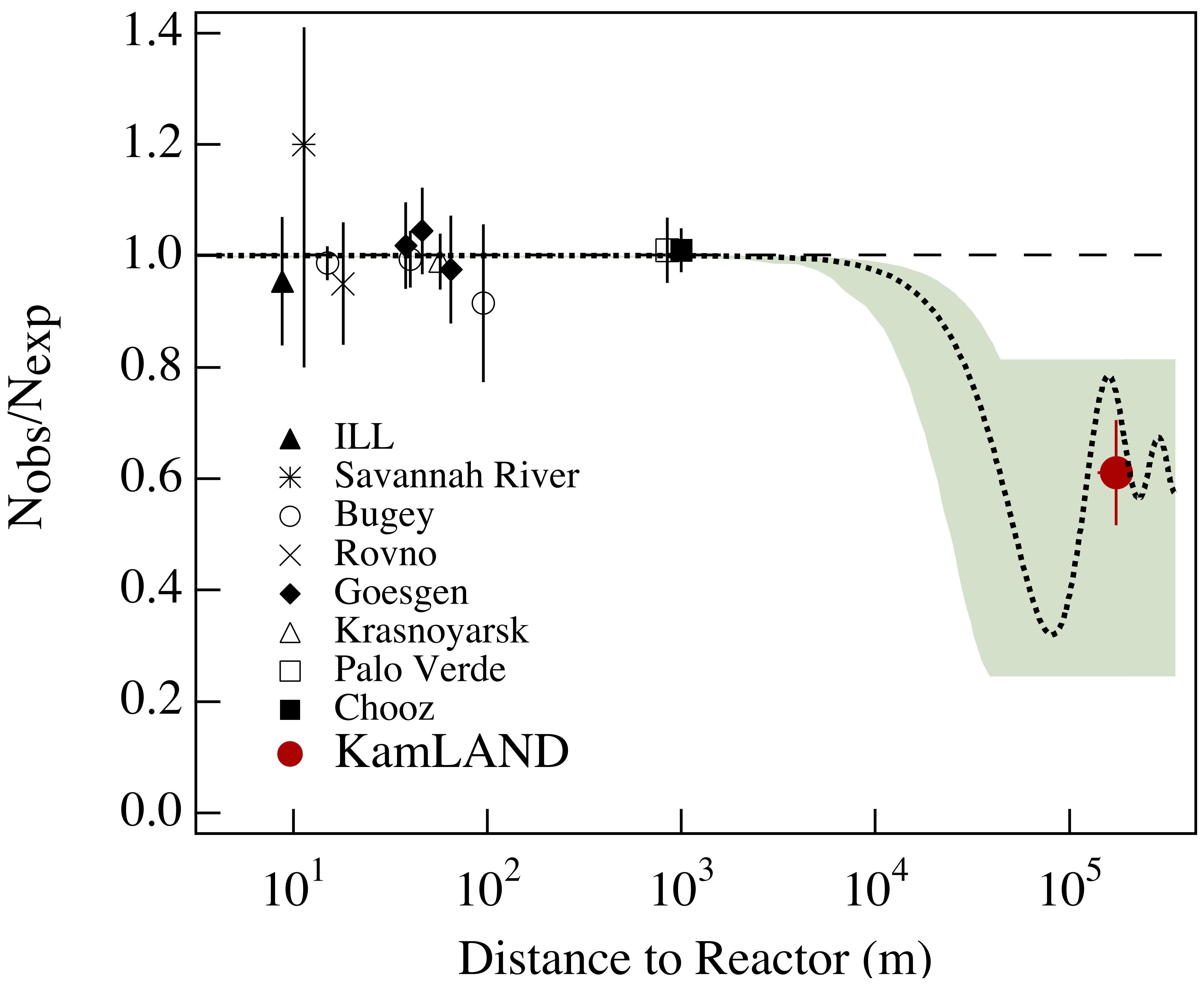
- CHOOZ
- Palo Verde

} Long Baseline

- KamLAND

} Very Long Baseline

Electron Antineutrino disappearance!



[KamLAND Collaboration, PRL 90 (2003)]

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Where neutrinos are produced

#SOMOSUA

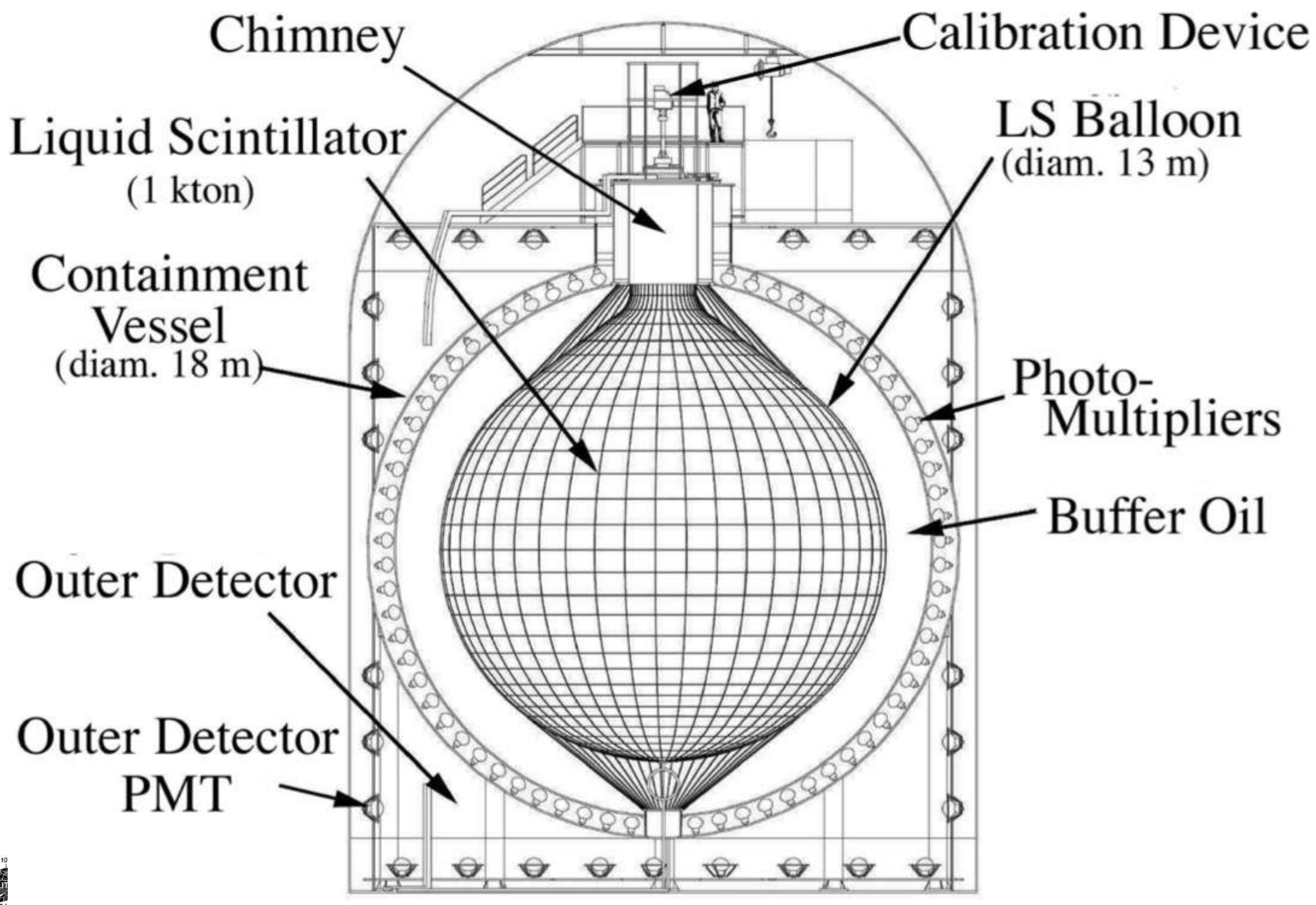
Reactor Neutrinos Some experiments

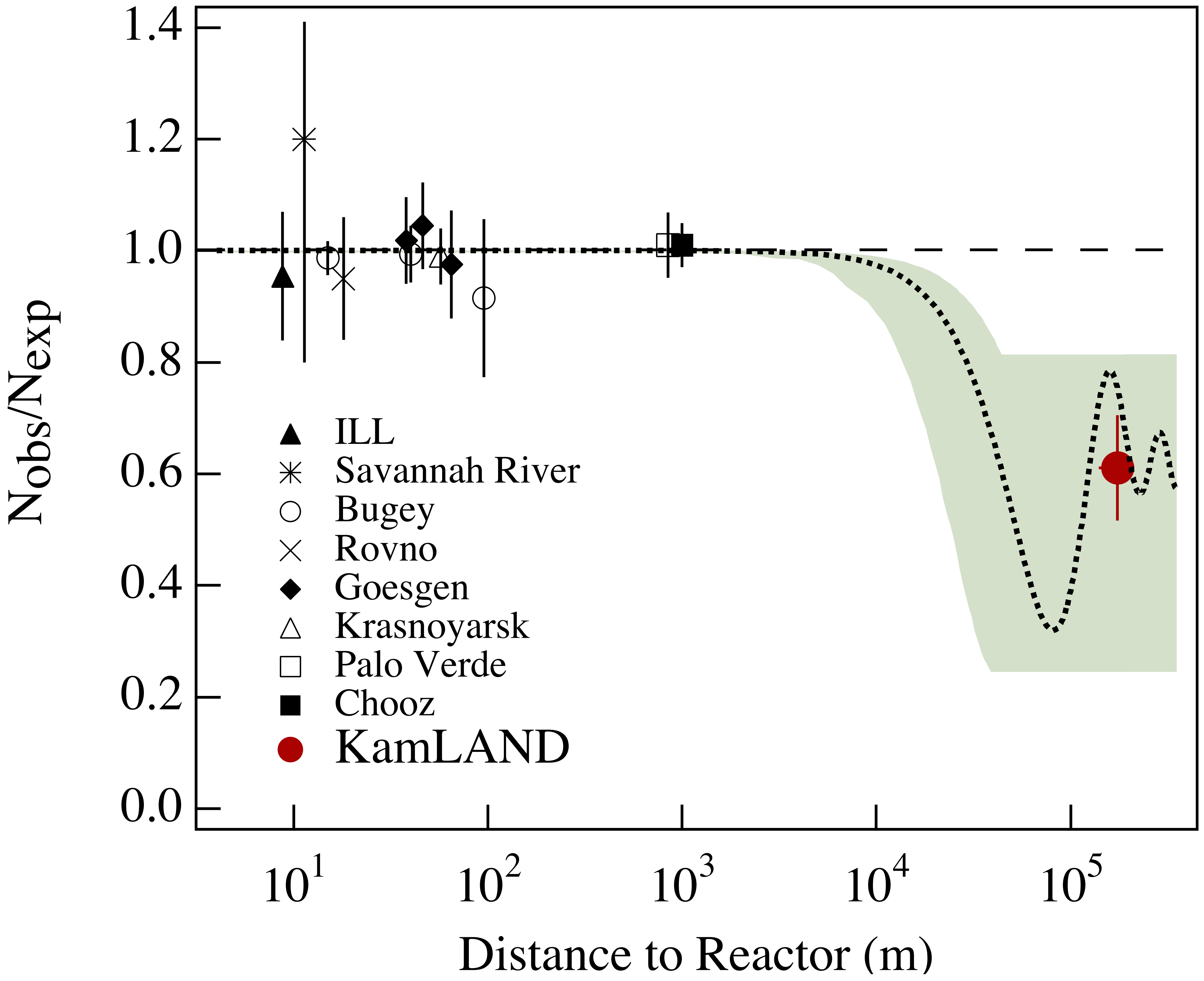
Flux measurements compared to expectation

- KamLAND

Electron Antineutrino disappearance!

[KamLAND Collaboration, PRL 90 (2003)]





[KamLAND Collaboration, PRL 90 (2003)]

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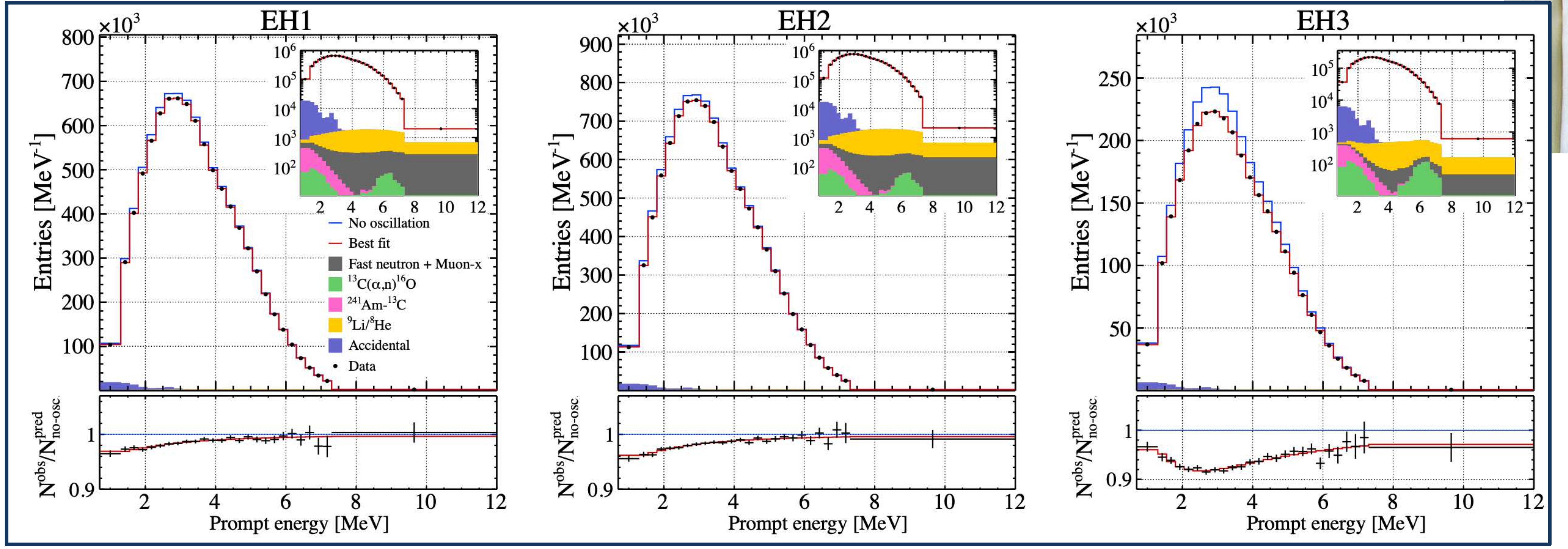
Where neutrinos are produced

Reactor Neutrinos Some experiments

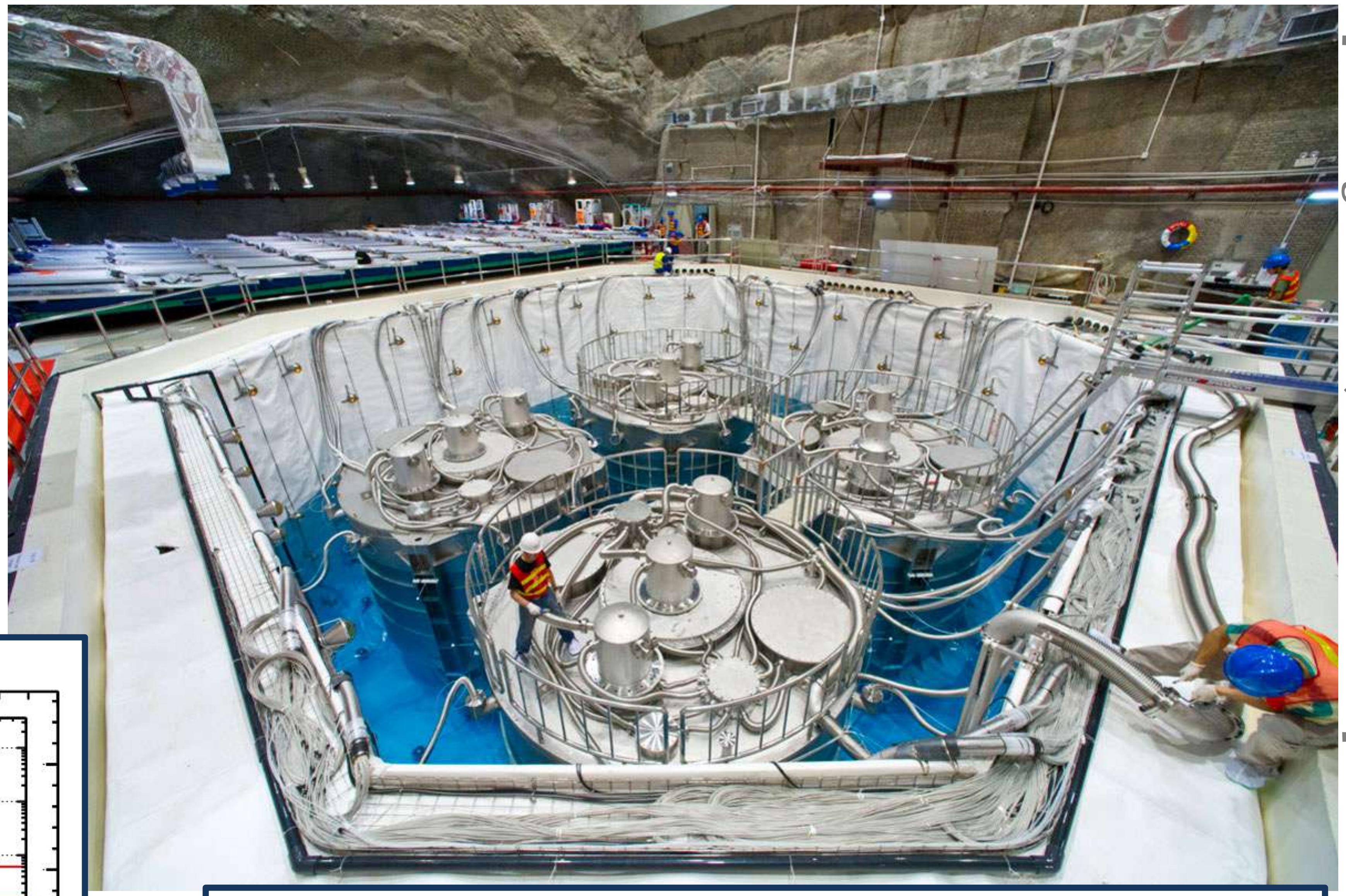
Flux measurements compared to expectation

- Daya Bay

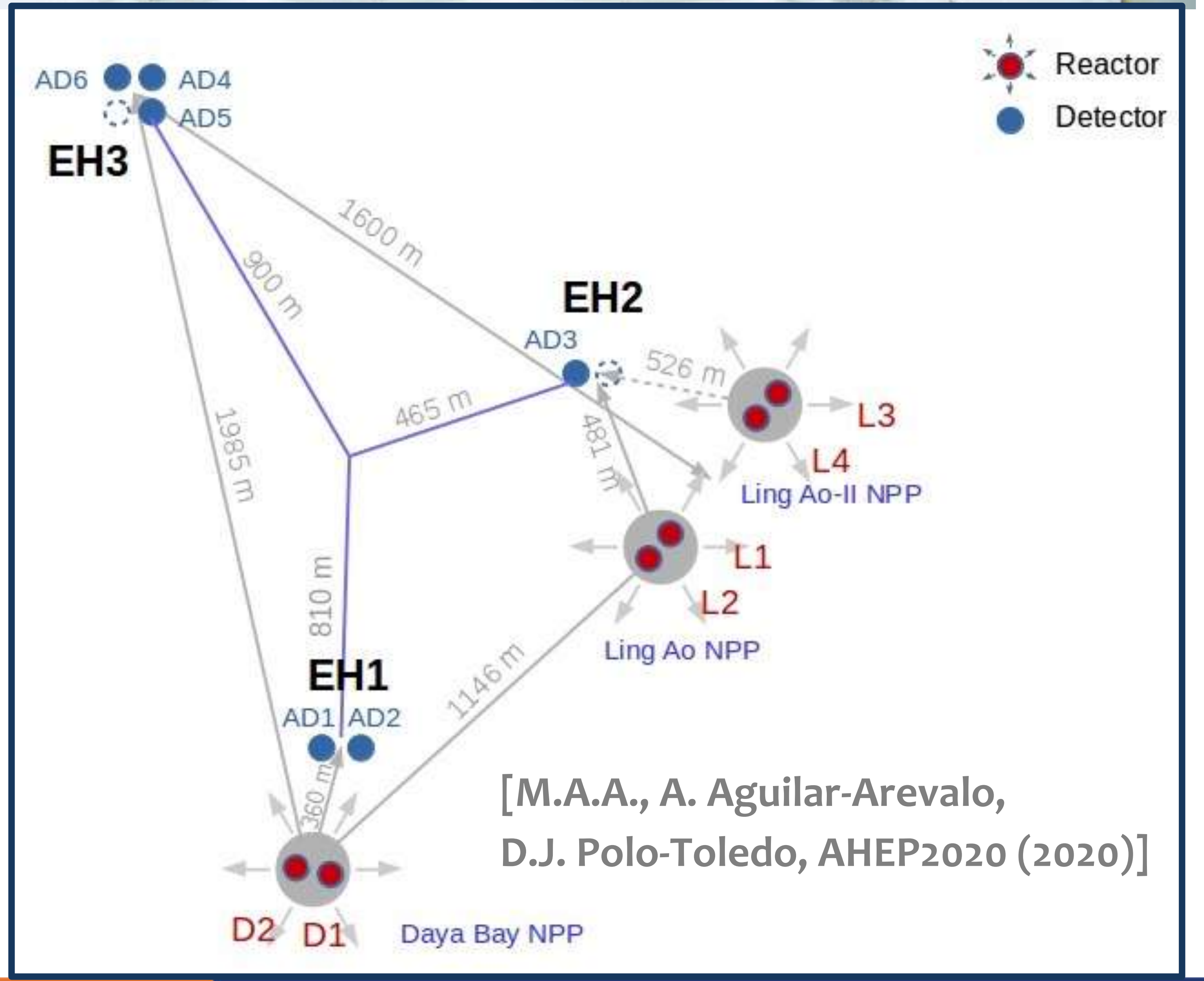
Electron Antineutrino disappearance!



[Daya Bay Collaboration, arxiv:2211.14988 (2022)]



[All Things Neutrino, Reactor Neutrinos]



[M.A.A., A. Aguilar-Arevalo, D.J. Polo-Toledo, AHEP2020 (2020)]

Sources

Where neutrinos are produced

#SOMOSUA

Reactor Neutrinos Flux around the World

An important tool for the control of Nuclear Proliferation

(Inter)National Security

Colloquium: Neutrino detectors as tools for nuclear security

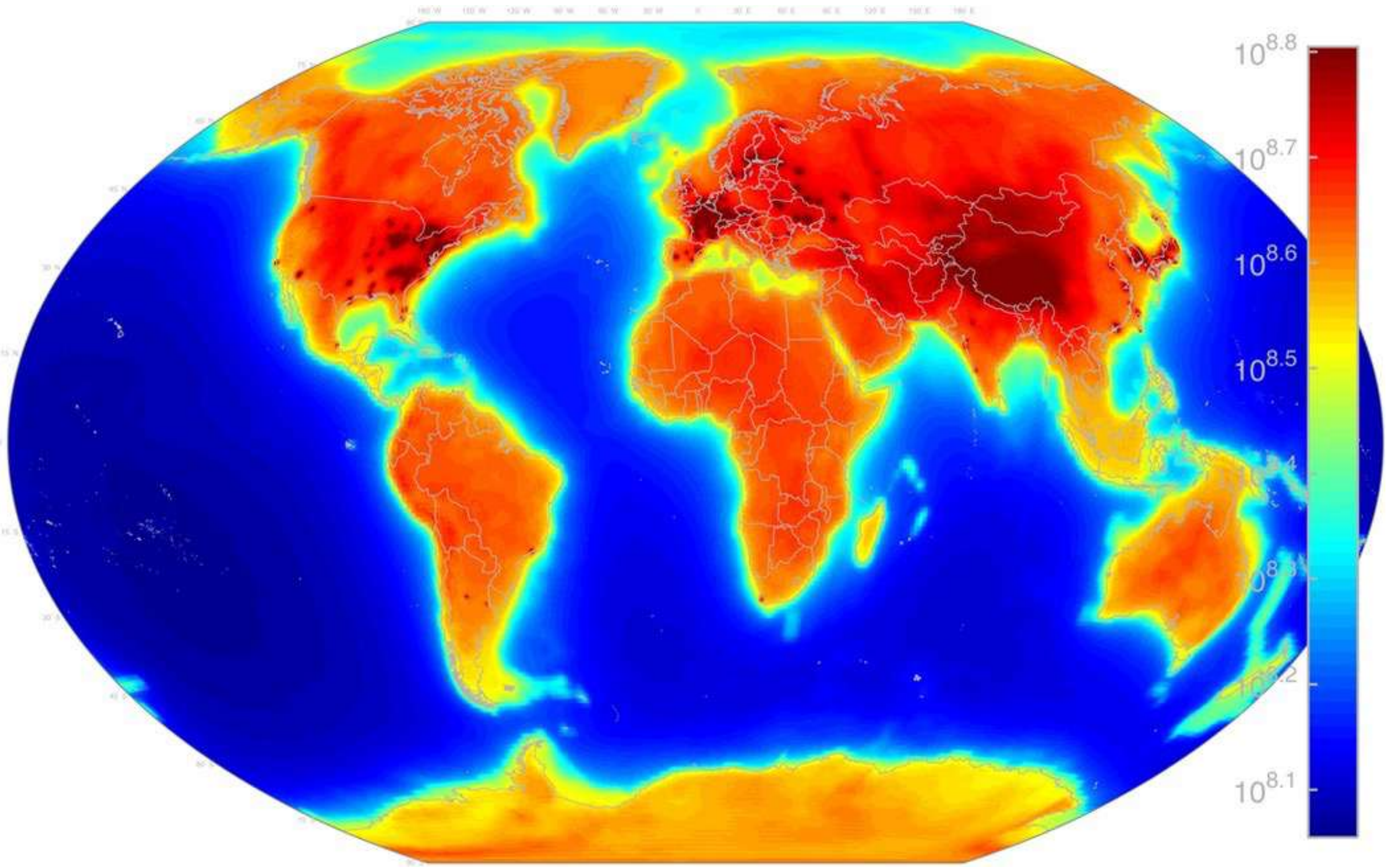
Adam Bernstein, Nathaniel Bowden, Bethany L. Goldblum, Patrick Huber, Igor Jovanovic, and John Mattingly
Rev. Mod. Phys. **92**, 011003 – Published 12 March 2020

[Review of Modern Physics (2020)]

Neutrino-Based Tools for Nuclear Verification and Diplomacy in North Korea

Rachel Carr, Jonathon Coleman, Mikhail Danilov, Giorgio Gratta, Karsten Heeger, Patrick Huber, ...show all
Pages 15-28 | Received 19 Dec 2018, Accepted 06 Mar 2019, Published online: 05 Jun 2019

[Science and Global Security (2018)]



[S.M. Usman *et al.*, Scientific Reports (2015)]

Nu Tools
Exploring Practical Roles for **Neutrinos** in **Nuclear Energy and Security**

[Nu Tools Executive Group, 2112.12593 (2021)]

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Sources

Where neutrinos are produced

#SOMOSUA

Accelerator Neutrinos

Different ways to produce neutrinos

Pion Decay In Flight (DIF)
CDHSW, CHARM, LSND, NuTeV

$$\pi^+ \to \mu^+ + \nu_\mu \quad \downarrow \quad e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu \quad \downarrow \quad e^- + \bar{\nu}_e + \nu_\mu$$

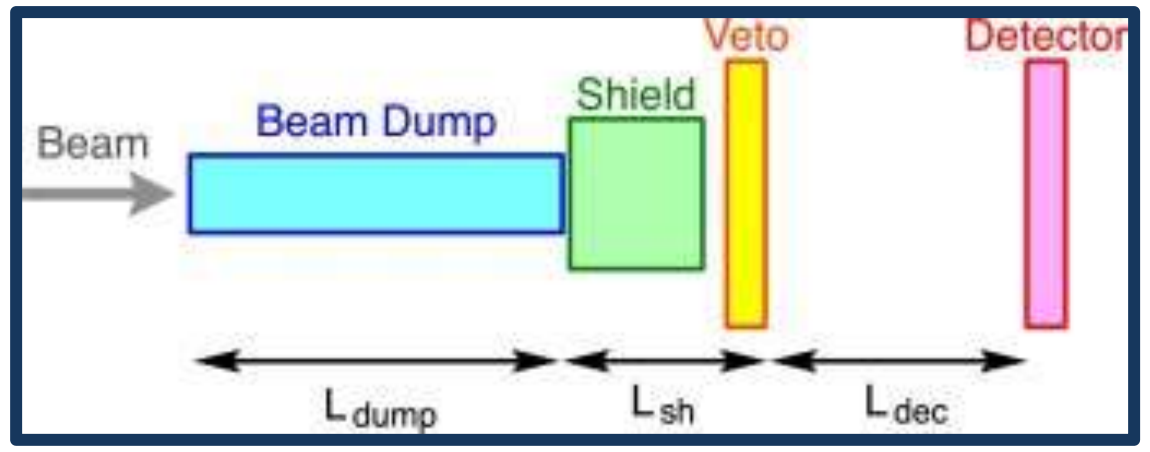
Typical Energy: ~1 GeV

Muon Decay at Rest (DAR)
LSND, KARMEN

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

Typical Energy: $O(10^1)$ MeV

Beam Dump
CDHSW, CHARM



Typical Energy: $O(10^2)$ GeV

Short Baseline (SBL)
$O(10^1 – 10^3)$ m

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Where neutrinos are produced

#SOMOSUA

Accelerator Neutrinos

Different ways to produce neutrinos

Pion Decay In Flight (DIF)

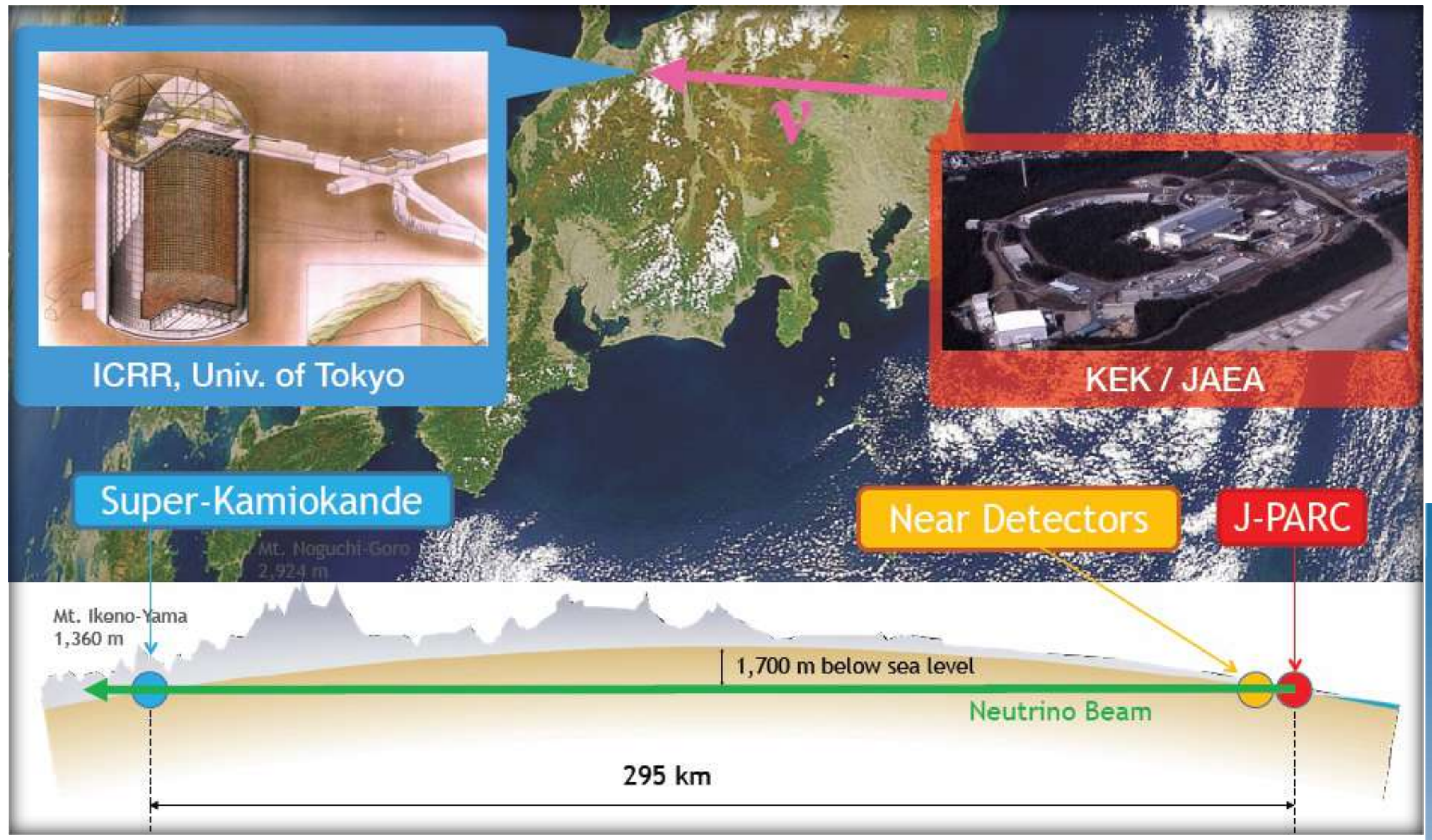
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \\ \downarrow \\ e^+ + \nu_e + \bar{\nu}_\mu$$

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

Typical Energy: ~1 GeV

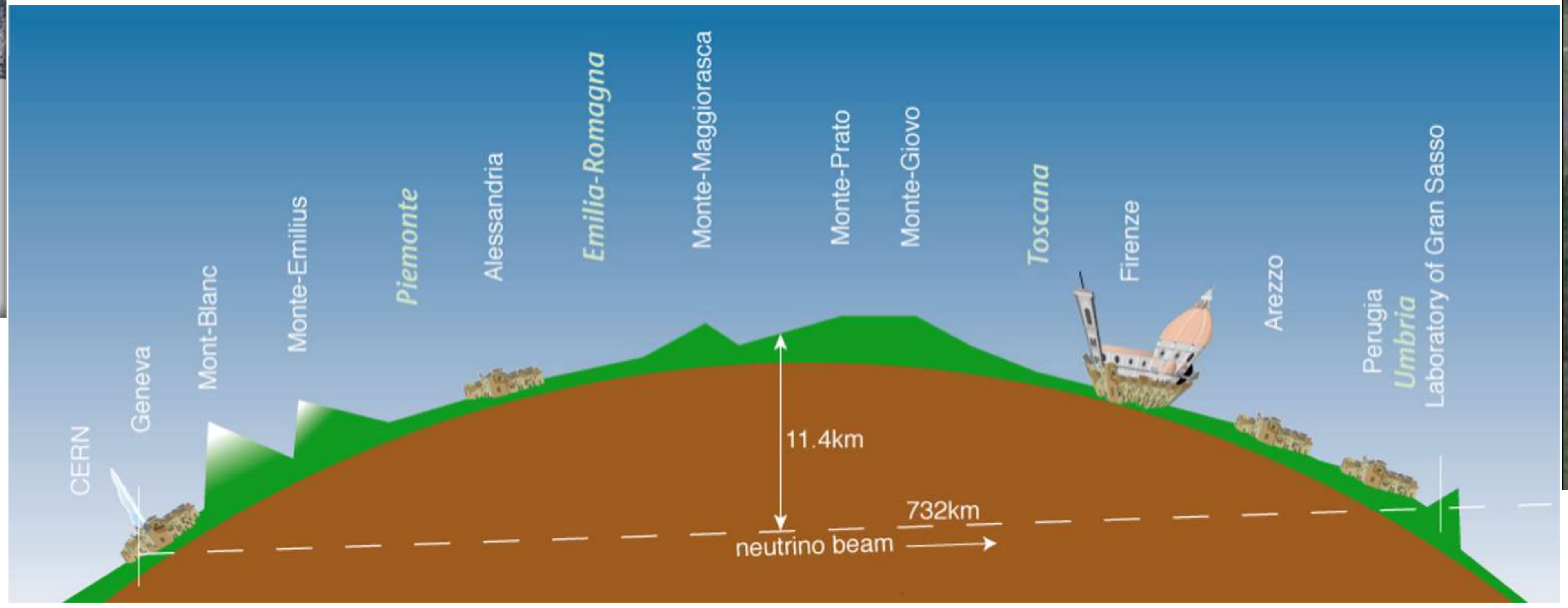
Long Baseline (LBL)

$O(10^2 – 10^3)$ km

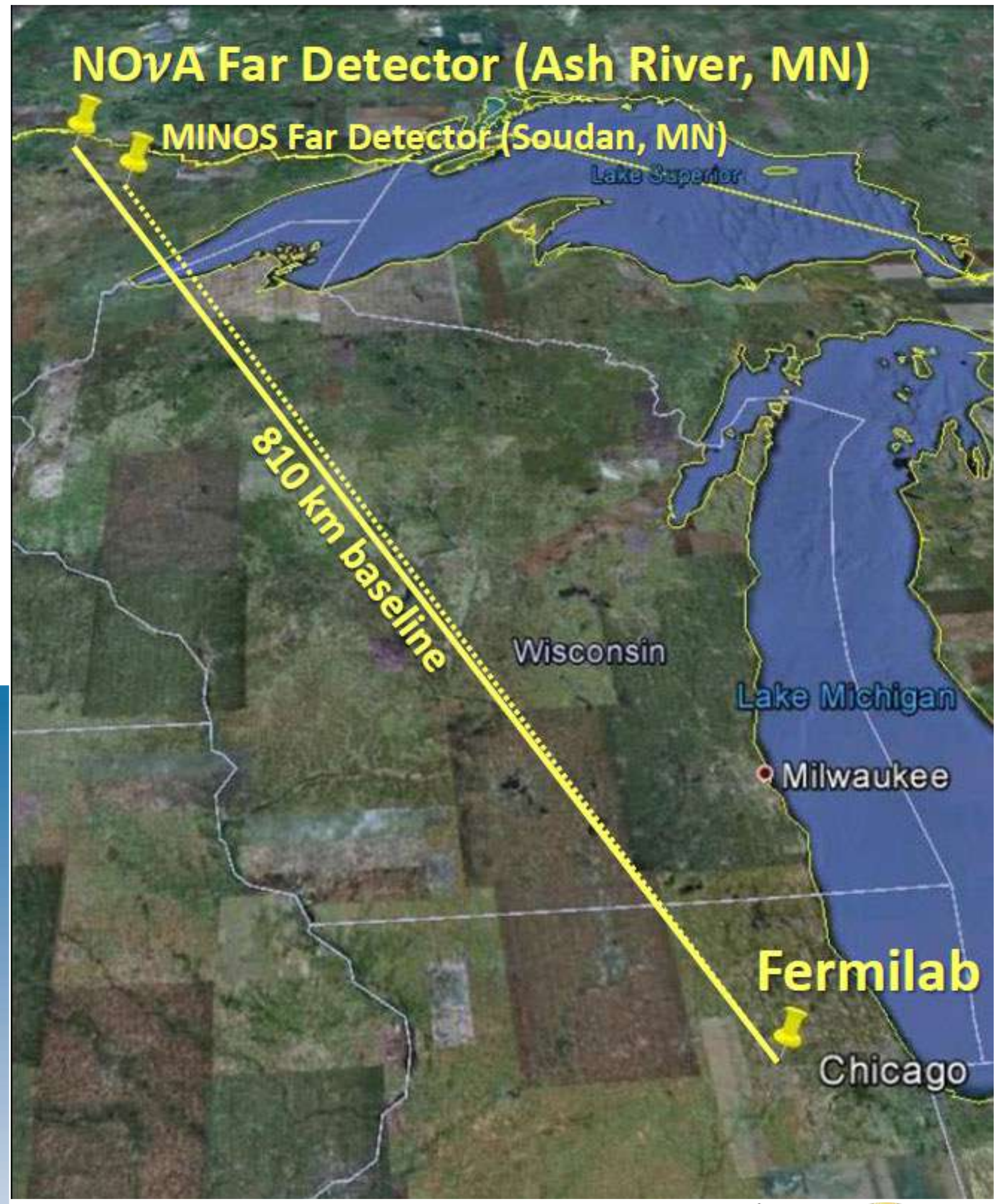


T2K

OPERA



NOvA



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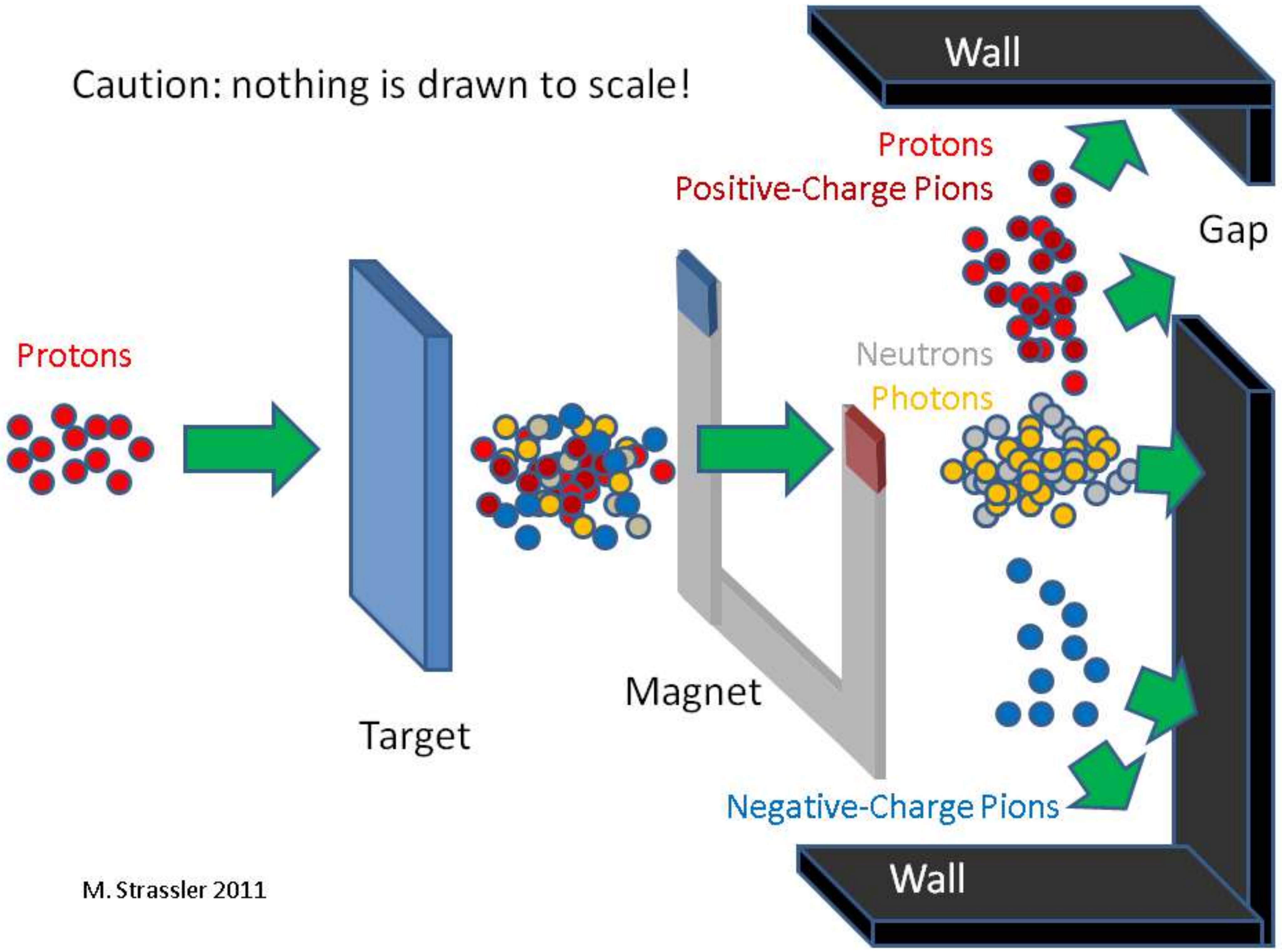
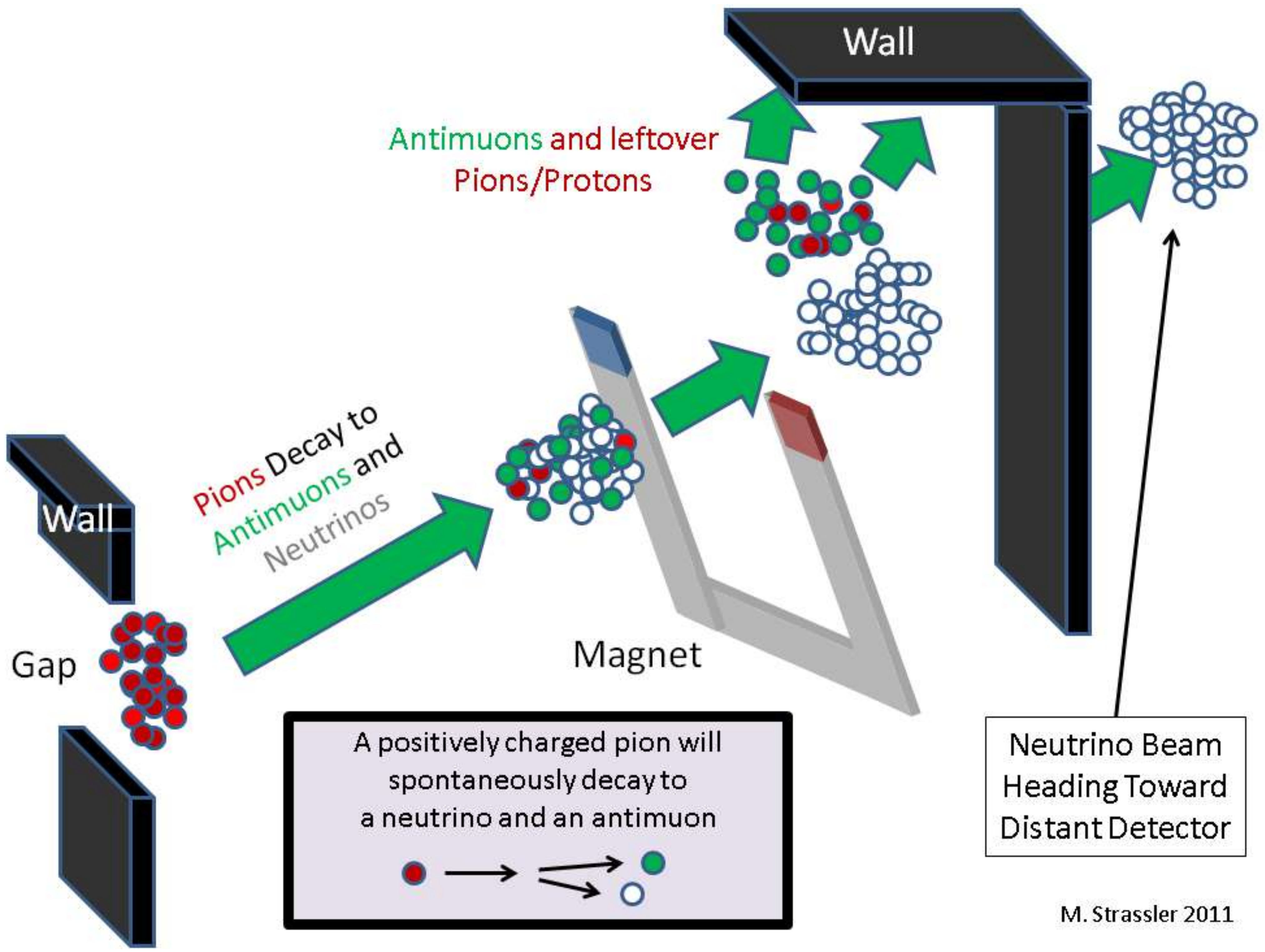
Sources

How neutrinos are produced

#SOMOSUA

Accelerator Neutrinos Producing a neutrino Beam





[M. Strassler, Of Particular Significance (2011)]

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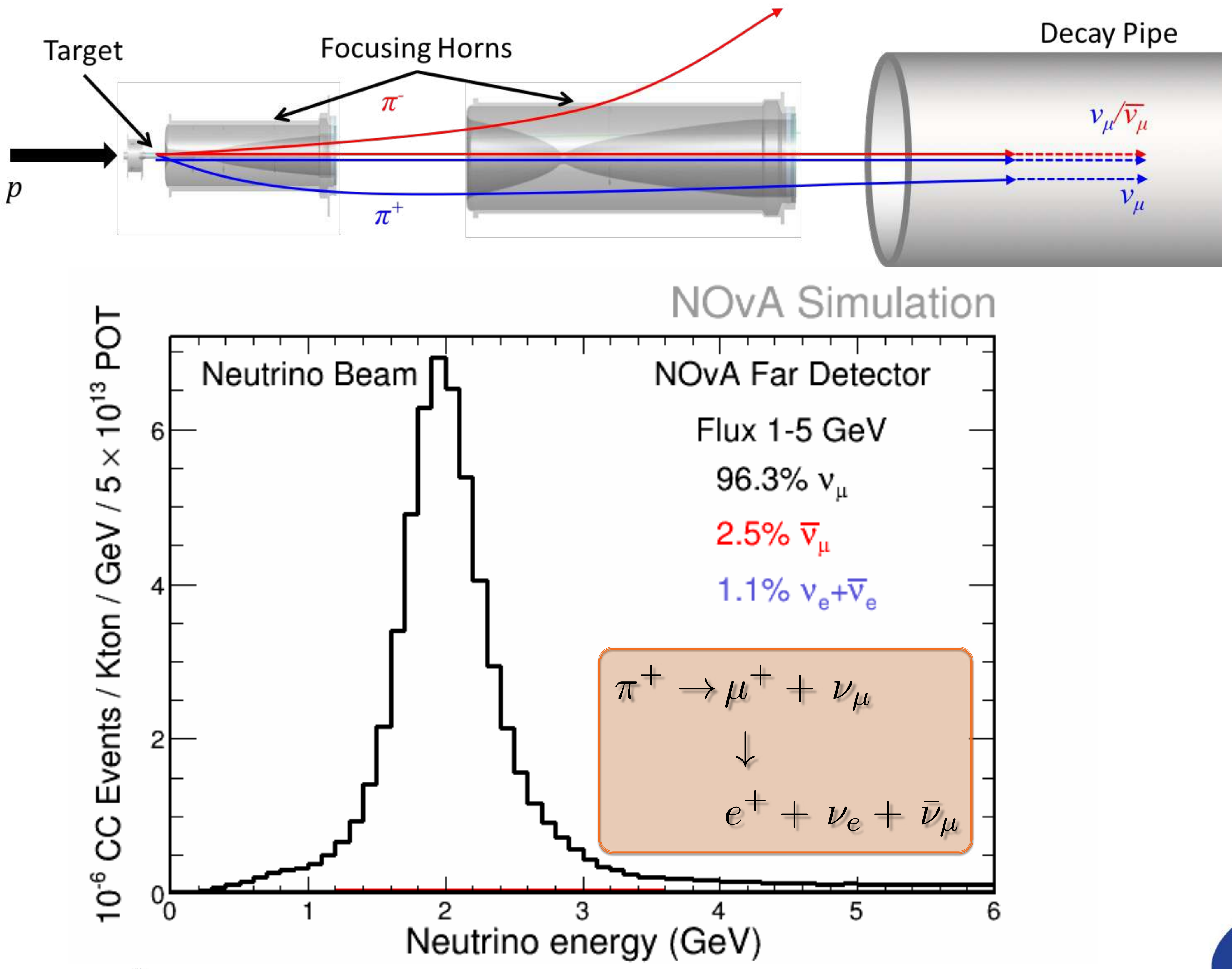
Sources

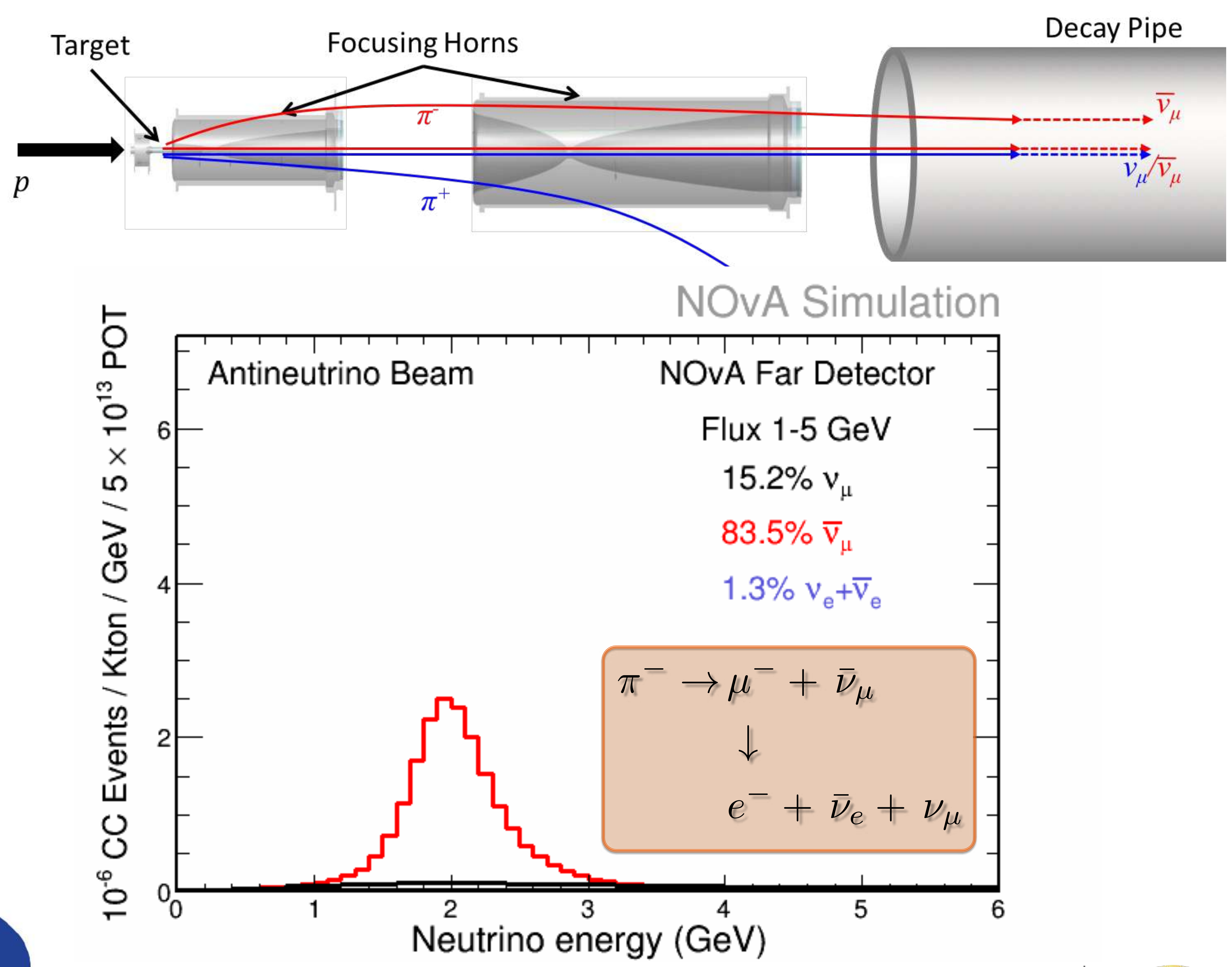
How neutrinos are produced

#SOMOSUA

Accelerator Neutrinos

Producing a neutrino Beam (in NOvA)



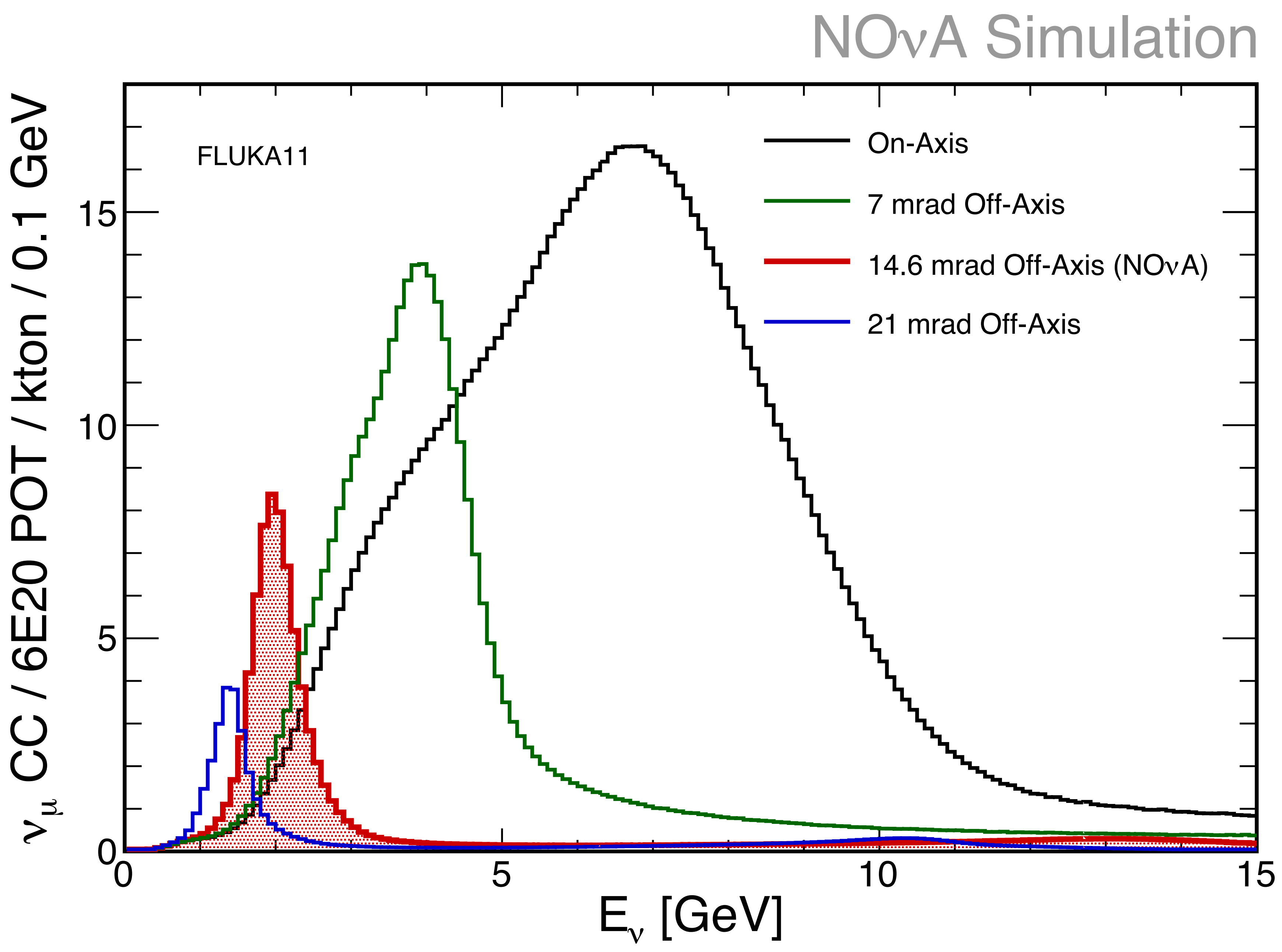


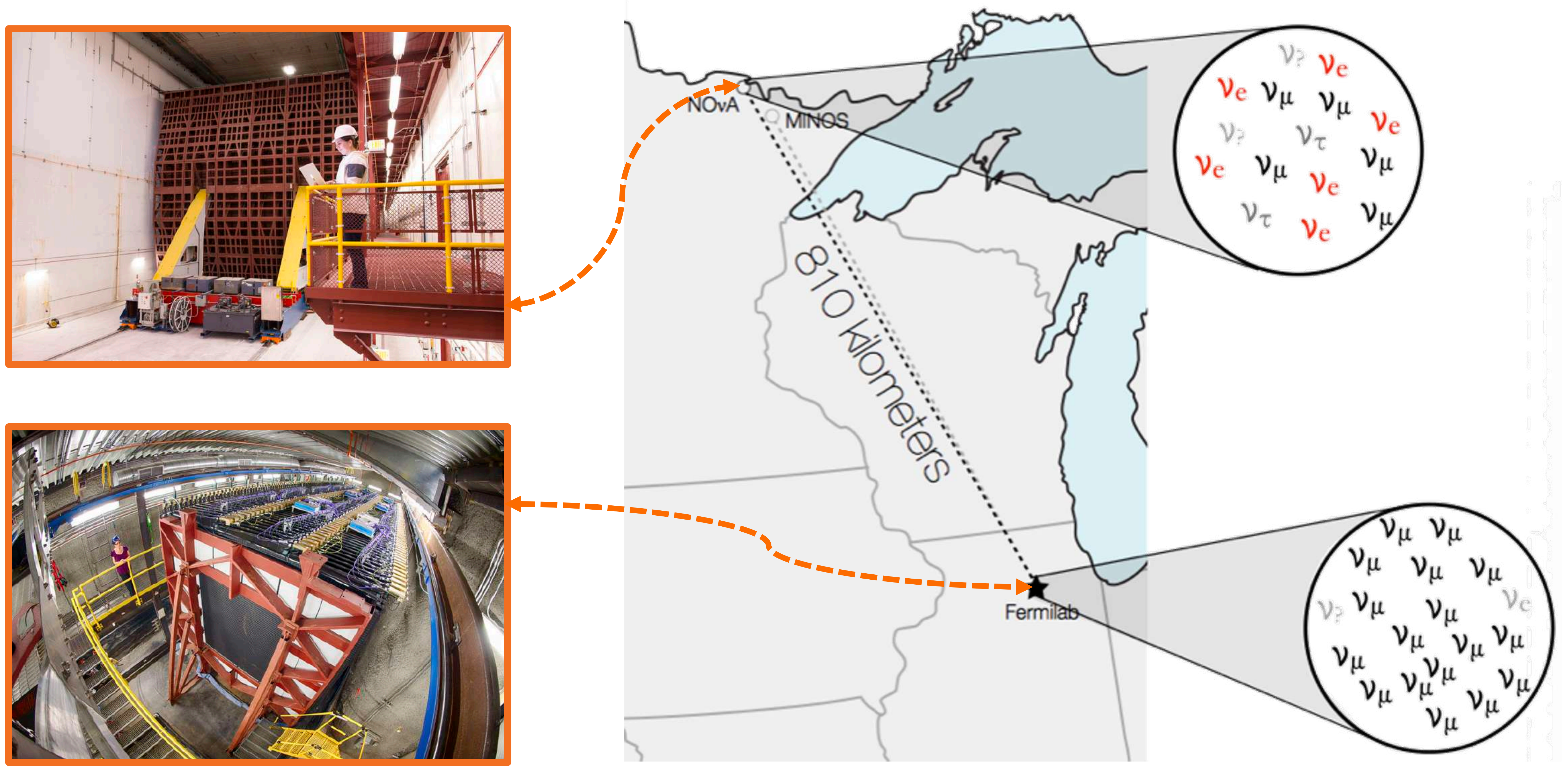
Sources

A special experiment

Accelerator Neutrinos

NOνA





Off-axis position (beam peaks at ~2 GeV)

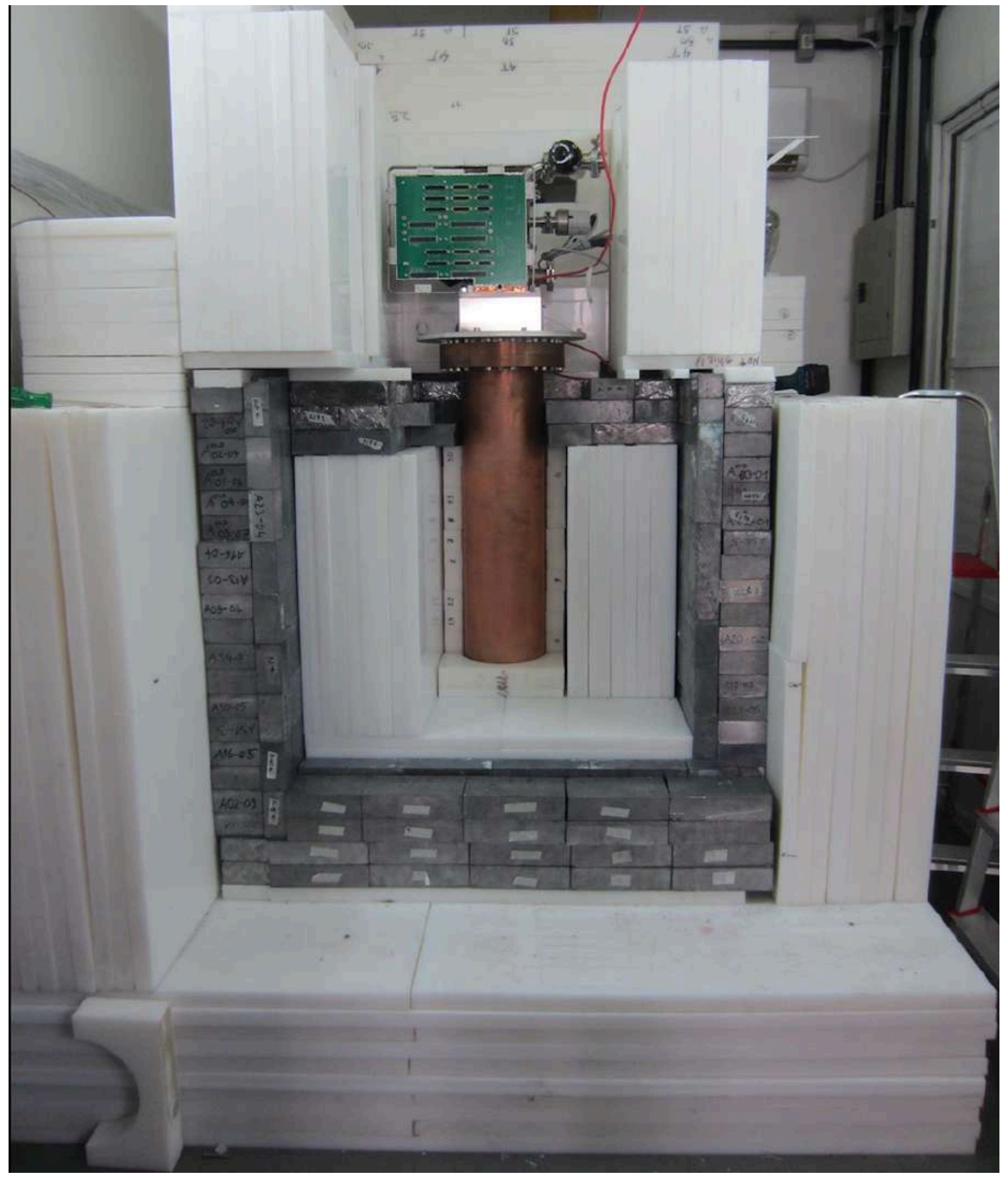
More Experiments

Currently taking data

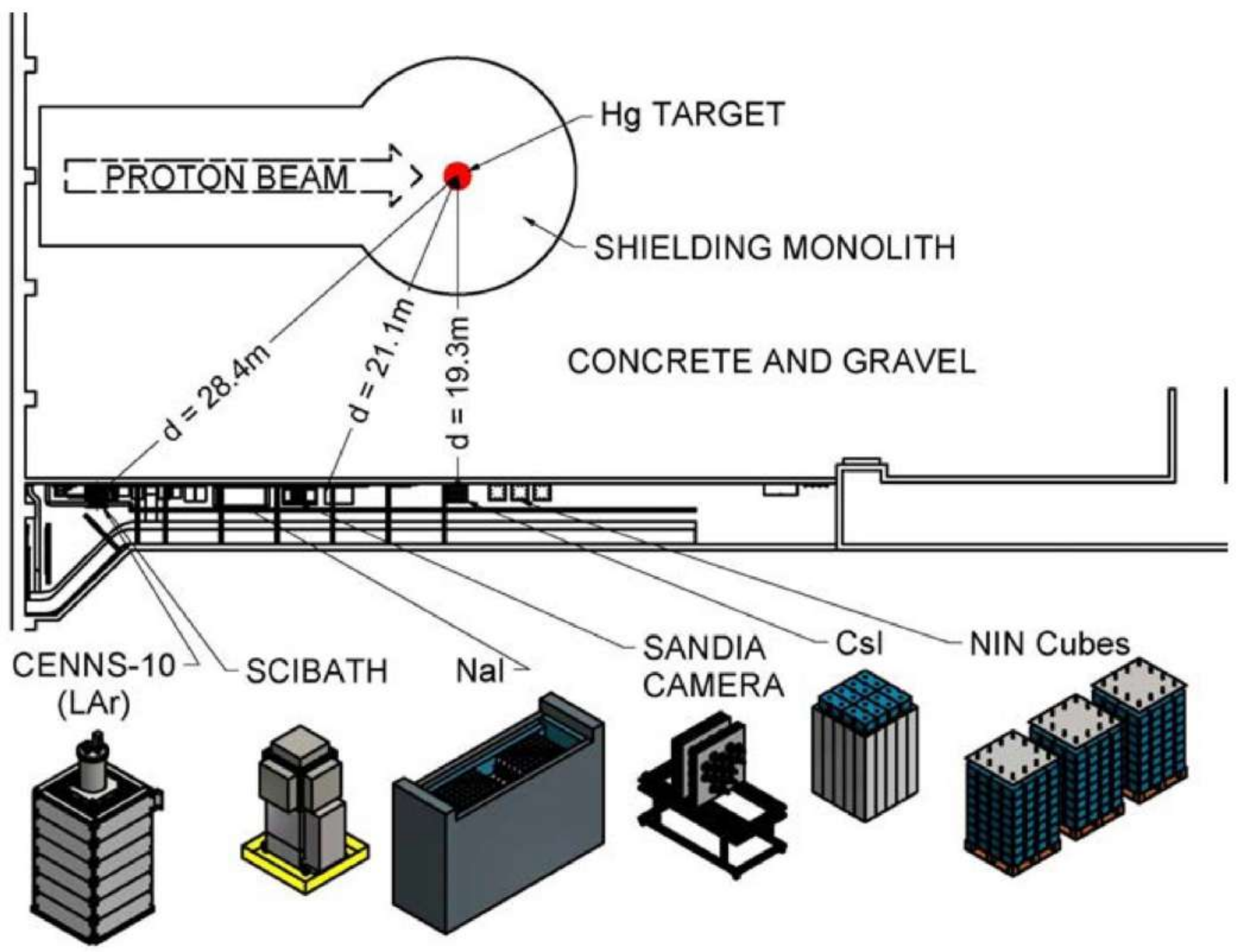
A long list of experiments studying neutrinos and related physics

- Atmospheric
- Solar
- Reactor (SBL and LBL)
- Accelerator (SBL and LBL)
- $0\nu\beta\beta$-Decay
- Astrophysics
- Supernova

http://www.nu.to.infn.it/exp



CONNIE CEvNS from reactor neutrinos
Phys.Rev.D 100 (2019) 9, 092005



COHERENT CEvNS
Science 357 (2017) 6356, 1123-1126

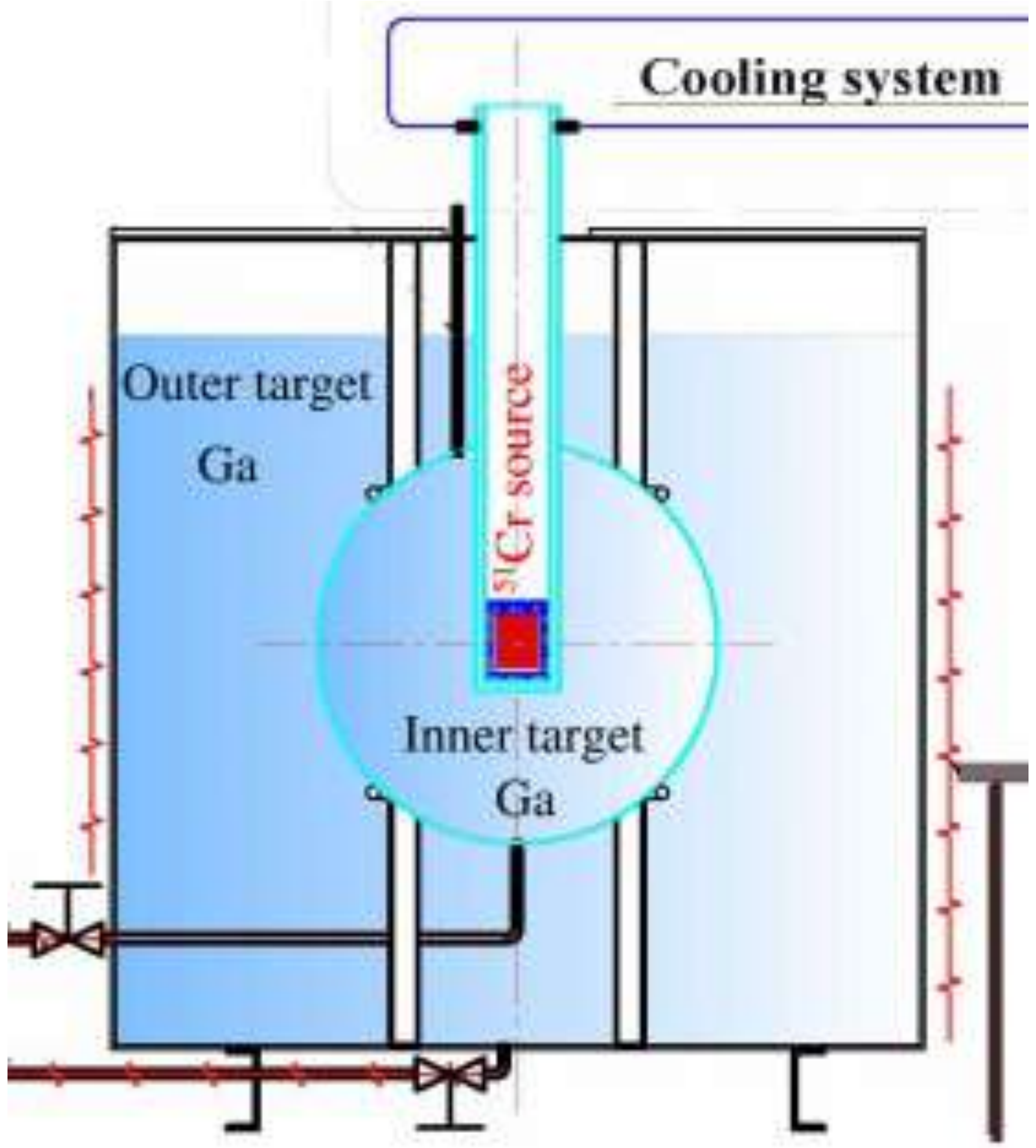
More Experiments

Currently taking data

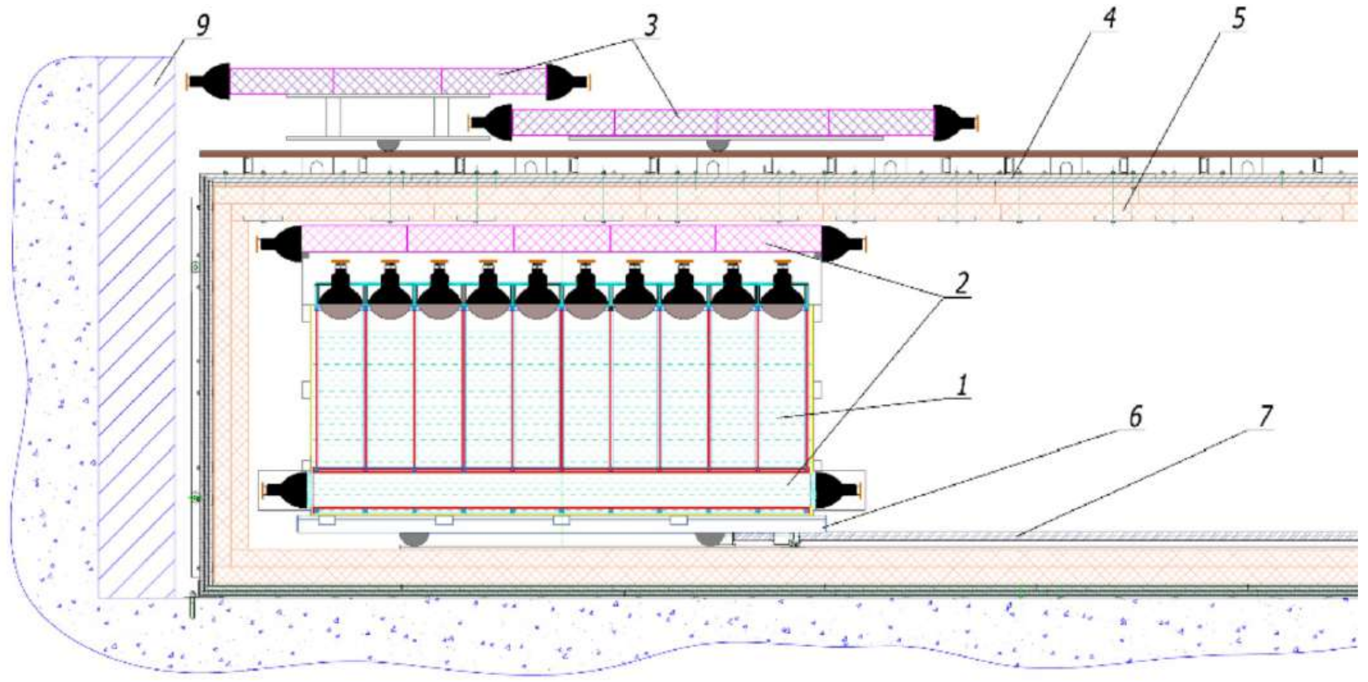
A long list of experiments studying neutrinos and related physics

- Atmospheric
- Solar
- Reactor (SBL and LBL)
- Accelerator (SBL and LBL)
- $0\nu\beta\beta$-Decay
- Astrophysics
- Supernova

http://www.nu.to.infn.it/exp



BEST Sterile neutrino Ga Anomaly
Phys. Rev. C 105, 065502 (2022)



Neutrino-4 Sterile neutrino RAA
A Serebrov et al 2017 J. Phys.: Conf. Ser. 934 012010

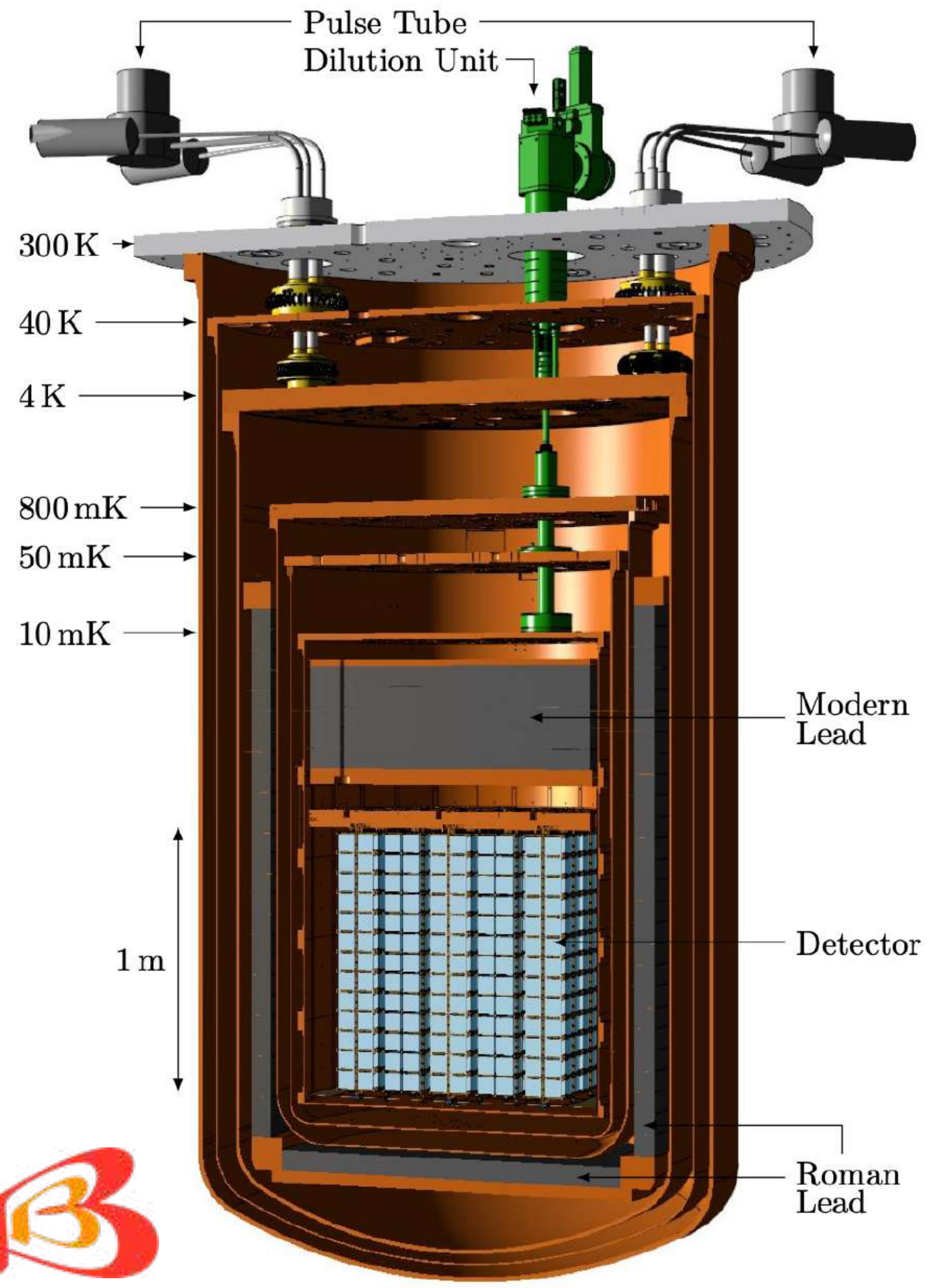
More Experiments

Currently taking data

A long list of experiments studying neutrinos and related physics

- Atmospheric
- Solar
- Reactor (SBL and LBL)
- Accelerator (SBL and LBL)
- $0\nu\beta\beta$-Decay
- Astrophysics
- Supernova

http://www.nu.to.infn.it/exp

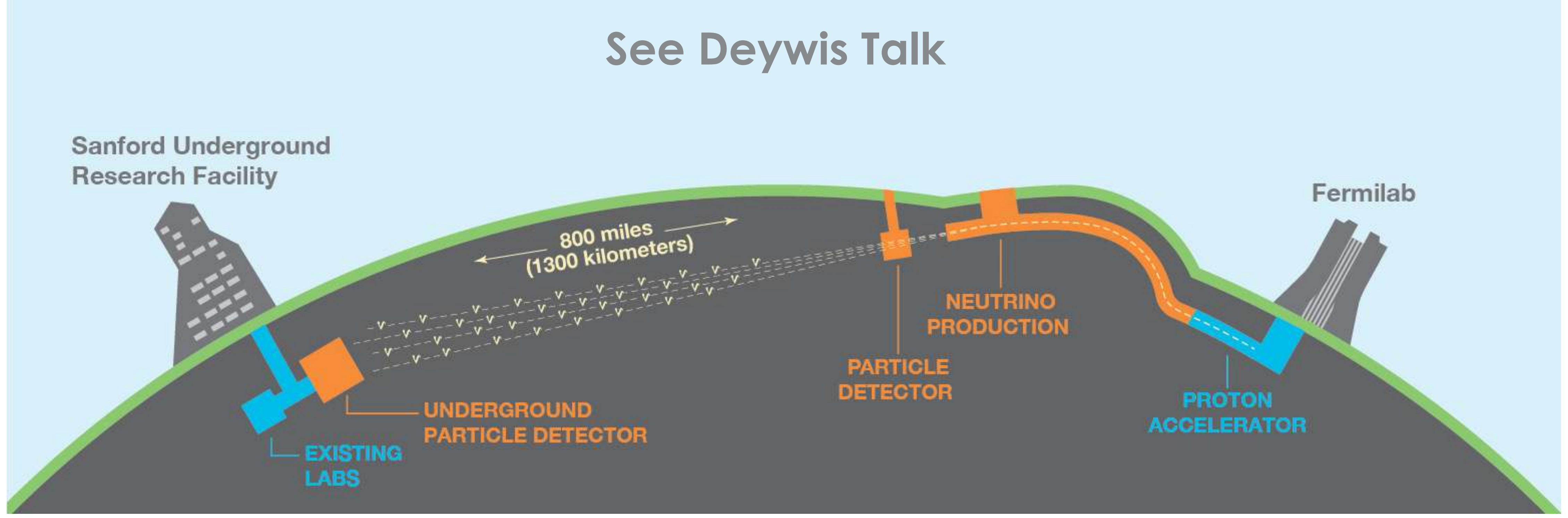


CUORE $0\nu\beta\beta$-Decay
Nature 604, 53 (2022)
https://cuore.lngs.infn.it/en/

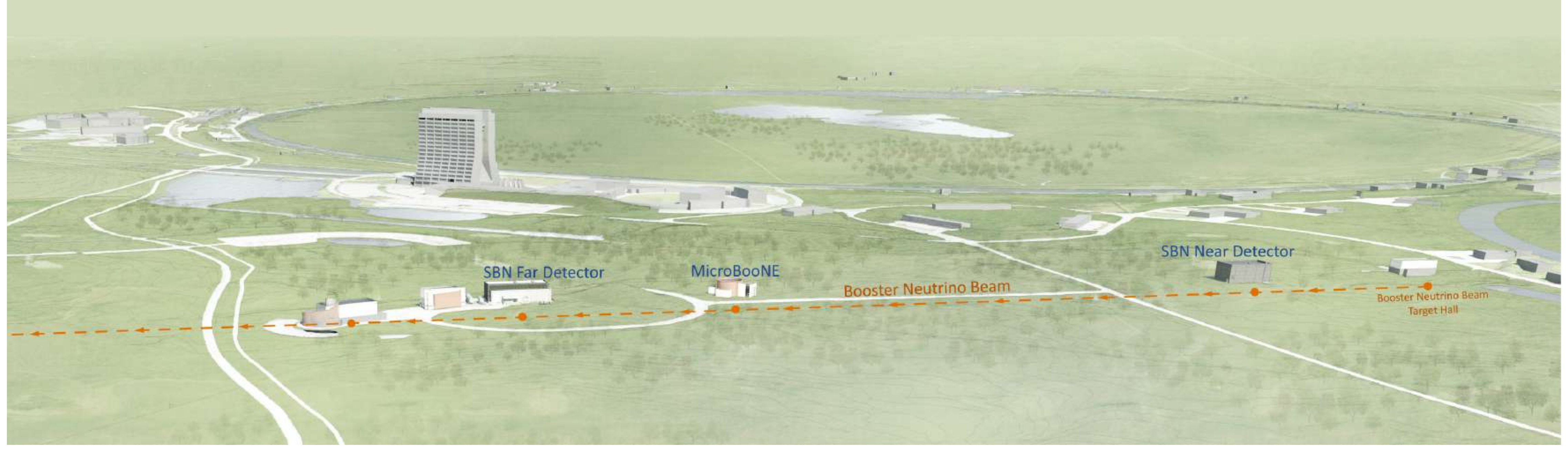
KATRIN Absolute mass scale of neutrinos
https://www.katrin.kit.edu

More Experiments

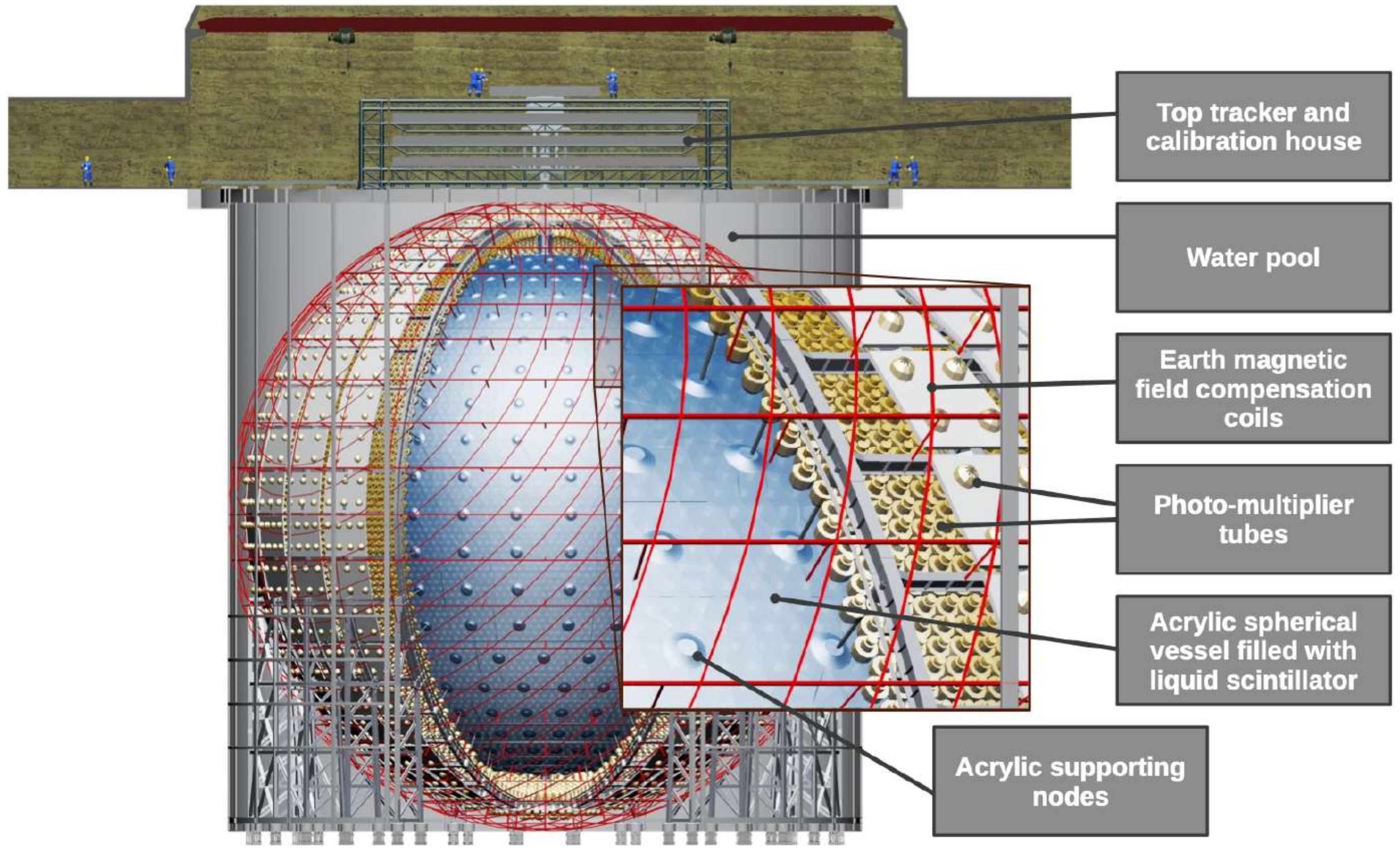
The Future



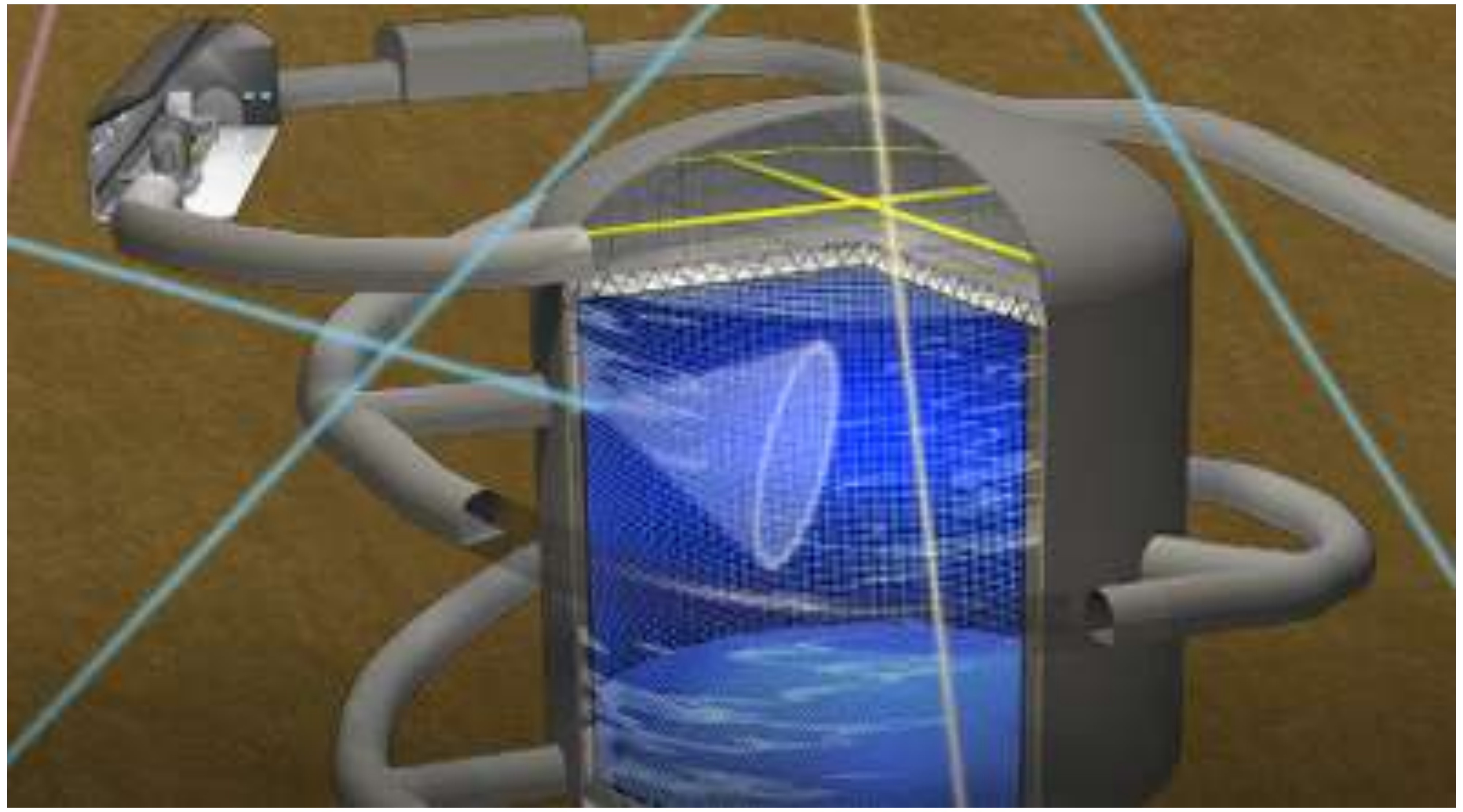
DUNE Mass hierarchy – Oscillations – Supernova – Atmospheric – Solar – Exotic searches – Proton decay studies
https://www.dunescience.org



SBN @ Fermilab Neutrino properties
https://sbn.fnal.gov/sbn-about.html



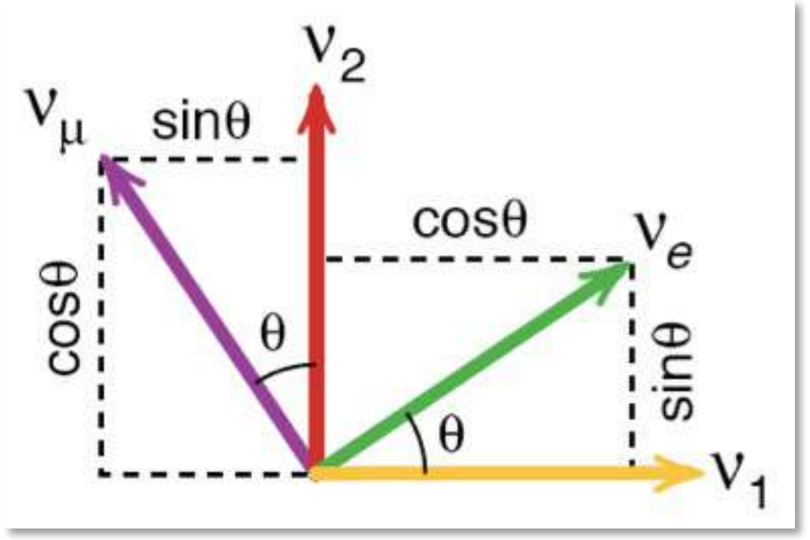
JUNO Mass hierarchy – Oscillations – Supernova – Atmospheric – Solar – Geo – Exotic searches
PoS NuFact2021 (2022) 005



Hyper-K CP violation – Solar – Supernova
https://www.hyperk.org

Neutrino Phenomenology

Some aspects…



Neutrino Oscillations

The 2-neutrino approximation (vacuum)

#SOMOSUA

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} \\ -\sin\theta_{12} & \cos\theta_{12} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Flavor states **Mass states**

$$\begin{aligned} P(\nu_e \to \nu_\mu) &= |\langle \nu_\mu | \nu(t) \rangle|^2 \\ &= \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right) \qquad \Delta m_{21}^2 \equiv m_2^2 - m_1^2 \\ &= \sin^2 2\theta_{12} \sin^2\left(1.27 \frac{\Delta m_{21}^2[\mathrm{eV}^2] L[\mathrm{km}]}{E[\mathrm{GeV}]}\right) \end{aligned}$$

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Neutrino Oscillations

The 2-neutrino approximation (vacuum)

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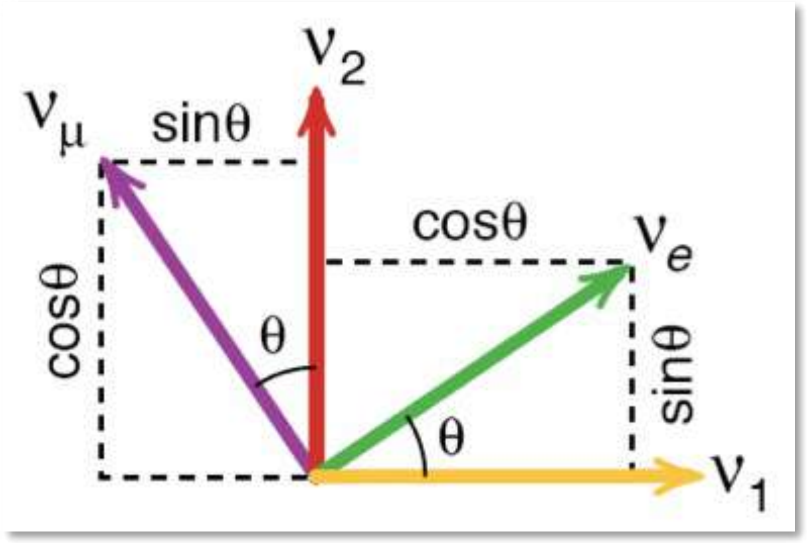

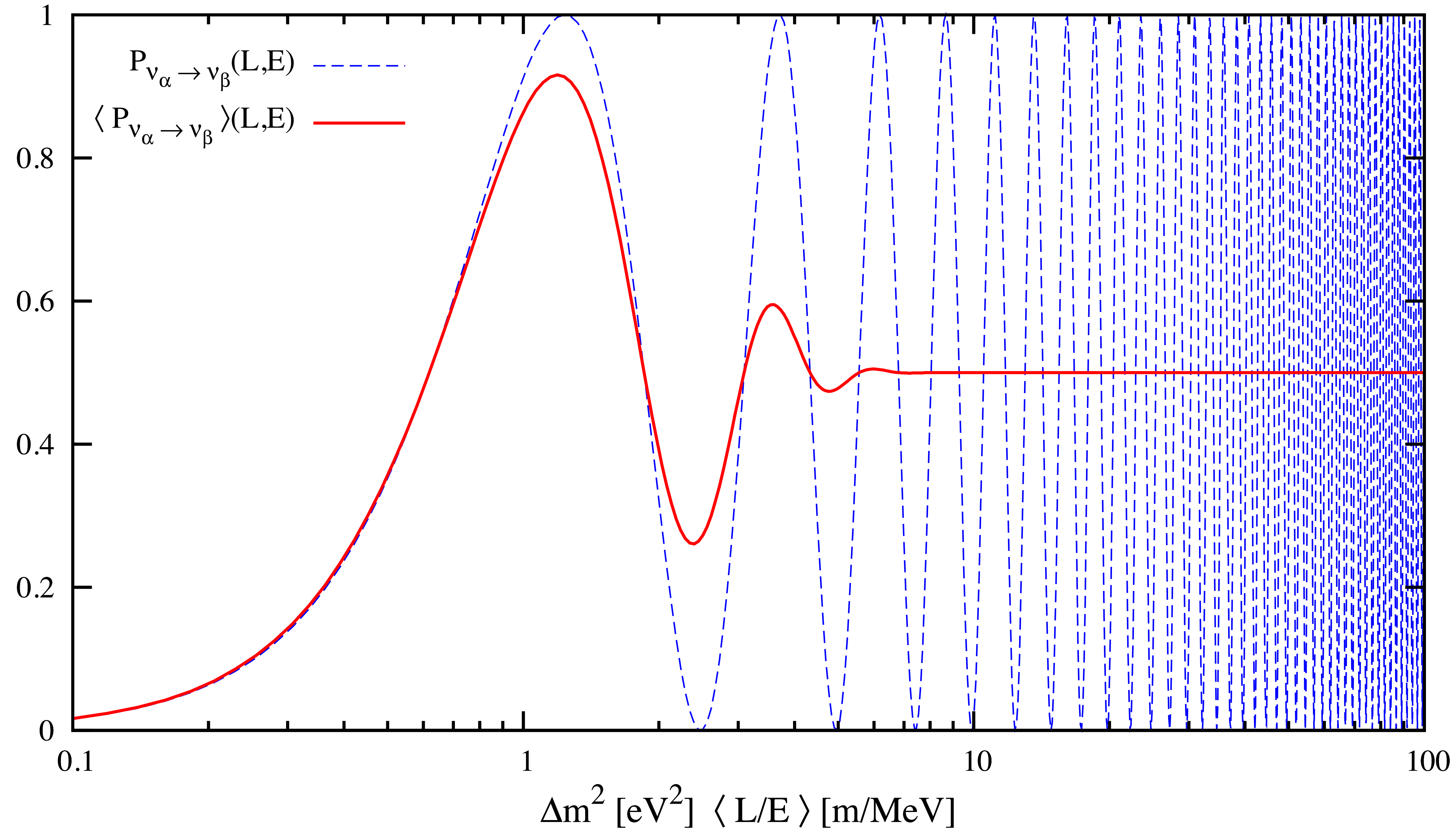

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta_{12} \sin^2\left(1.27 \frac{\Delta m^2_{21}[\mathrm{eV}^2] L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

Type of experiment	L	E	Δm^2 sensitivity
Reactor SBL	$\sim 10\,\mathrm{m}$	$\sim 1\,\mathrm{MeV}$	$\sim 0.1\,\mathrm{eV}^2$
Accelerator SBL (Pion DIF)	$\sim 1\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 1\,\mathrm{eV}^2$
Accelerator SBL (Muon DAR)	$\sim 10\,\mathrm{m}$	$\sim 10\,\mathrm{MeV}$	$\sim 1\,\mathrm{eV}^2$
Accelerator SBL (Beam Dump)	$\sim 1\,\mathrm{km}$	$\sim 10^2\,\mathrm{GeV}$	$\sim 10^2\,\mathrm{eV}^2$
Reactor LBL	$\sim 1\,\mathrm{km}$	$\sim 1\,\mathrm{MeV}$	$\sim 10^{-3}\,\mathrm{eV}^2$
Accelerator LBL	$\sim 10^3\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 10^{-3}\,\mathrm{eV}^2$
ATM	$20\text{–}10^4\,\mathrm{km}$	$0.5\text{–}10^2\,\mathrm{GeV}$	$\sim 10^{-4}\,\mathrm{eV}^2$
Reactor VLB	$\sim 10^2\,\mathrm{km}$	$\sim 1\,\mathrm{MeV}$	$\sim 10^{-5}\,\mathrm{eV}^2$
Accelerator VLB	$\sim 10^4\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 10^{-4}\,\mathrm{eV}^2$
SOL	$\sim 10^{11}\,\mathrm{km}$	$0.2\text{–}15\,\mathrm{MeV}$	$\sim 10^{-12}\,\mathrm{eV}^2$

[C. Giunti, C.W. Kim, *Fundamental of neutrino Physics and Astrophysics* (2007)]

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Neutrino Oscillations

The experimental results

#SOMOSUA

The experimental results

- **Solar** (SNO, Borexino, Super-K, GALLEX/GNO, SAGE, Kamiokande) $\nu_e \to \nu_\mu, \nu_\tau$
- **Reactors** (KamLAND, Daya Bay, RENO, Double Chooz) $\bar{\nu}_e \to \bar{\nu}_\mu, \bar{\nu}_\tau$

$$\Delta m^2_{\rm Sol} \simeq 7.42 \times 10^{-5}\ {\rm eV}^2$$
$$\sin^2\theta_{\rm Sol} \simeq 0.30$$
$$\sin^2\theta_{\rm Rea} \simeq 0.02$$

[NuFIT 5.1 (2021)]

- **Atmorpheric** (Super-K, Kamiokande, IMB, MACRO, Soudan-2, IceCube) $\nu_\mu \to \nu_\tau, \bar{\nu}_\mu \to \bar{\nu}_\tau$
- **Accelerators** (K2K, MINOS, T2K, NOvA, Opera) $\nu_\mu \to \nu_{e,\tau}, \bar{\nu}_\mu \to \bar{\nu}_{e,\tau}$

$$\Delta m^2_{\rm Atm} \simeq 2.51 \times 10^{-3}\ {\rm eV}^2$$
$$\sin^2\theta_{\rm Atm} \simeq 0.45$$

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Neutrino Oscillations

The other experimental results

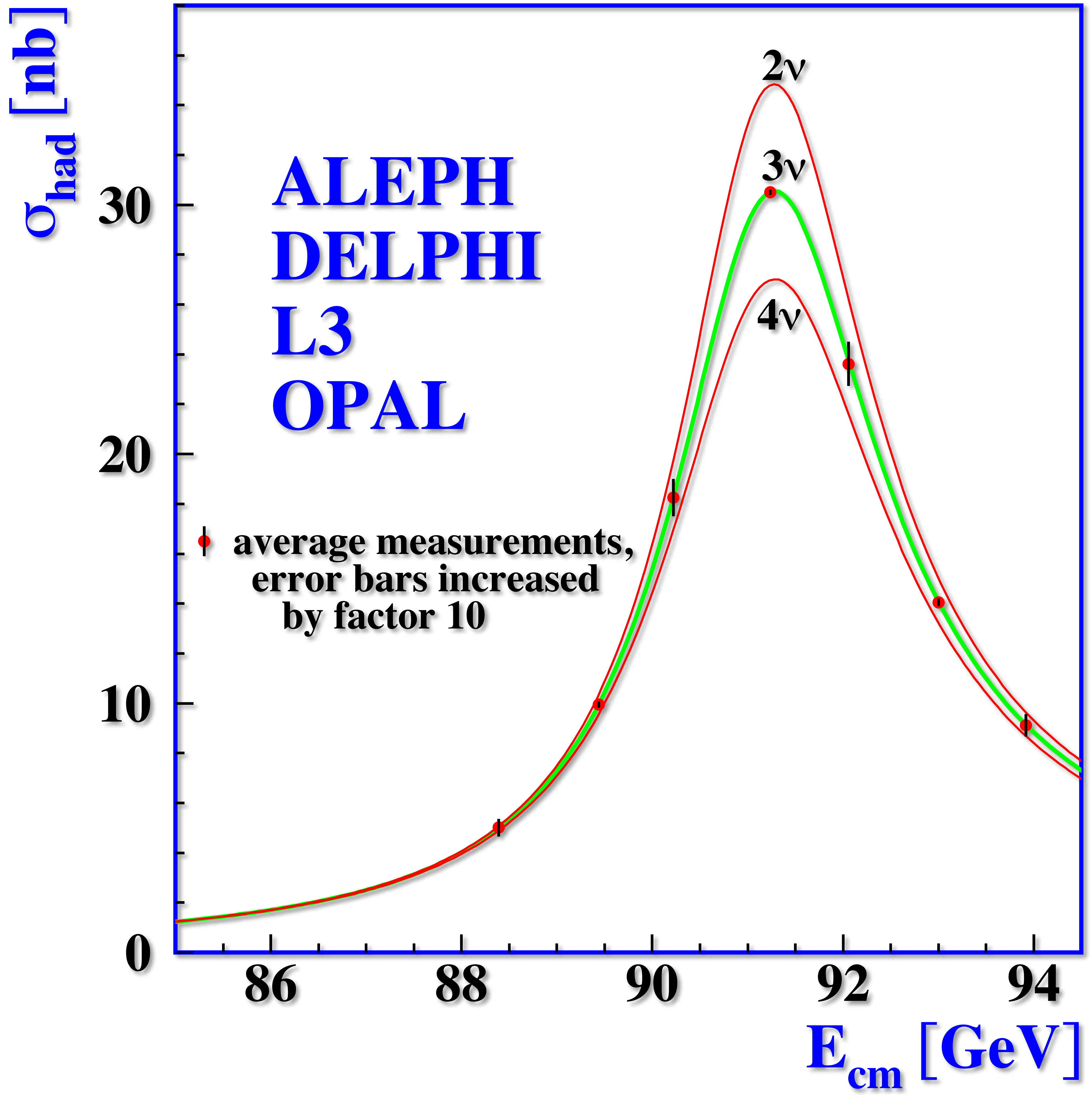
The (real-life) 3-neutrino model

Only 3 neutrinos contribute to the Z width

- 3 neutirno families are connected to the weak interaction

Number of light neutrino species:

$$N_\nu = 2.9840 \pm 0.0082$$



[S. Shael et al., Phys. Rept 427 (2006)]

Neutrino Oscillations

The 3-neutrino mixing

#SOMOSUA

The (real-life) 3-neutrino model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})}_{\text{Mixing matrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Interaction eigenstates (creation and detection)

Mass eigenstates (propagation)

$$R(\theta_{23}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \quad R(\theta_{12}) = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric/Accelerators

Solar

Reactor

$$R(\theta_{13}, \delta_{CP}) = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\,\mathrm{e}^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\,\mathrm{e}^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix}$$

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Neutrino Oscillations

The 3-neutrino mixing

#SOMOSUA

The (real-life) 3-neutrino model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^\dagger \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P_{\nu_\alpha \to \nu_\beta} = \left| \sum_k U^*_{\beta k} \exp\left(-i\frac{m_k^2 L}{2E}\right) U_{\alpha k} \right|^2$$

$$= \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i\frac{\Delta m_{kj}^2 L}{2E}\right)$$

$$\theta_{12} = 33.44^\circ$$

$$\theta_{13} = 8.57^\circ$$

$$\theta_{23} = 49.2^\circ$$

$$\Delta m_{31}^2 = 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

$$\Delta m_{21}^2 = 7.4 \times 10^{-5}\ \mathrm{eV}^2$$

[I. Esteban et al., JHEP 09 178 (2020)]
[NuFIT 5.0 (2021), http://www.nu-fit.org/]

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Neutrino Oscillations

The 3-neutrino mixing

#SOMOSUA

All this comes from the neutrino evolution:

$$\mathcal{H}_0 \left|\nu_k\right\rangle = E_k \left|\nu_k\right\rangle , \quad \left|\nu_\alpha\right\rangle = \sum_k U^*_{\alpha k} \left|\nu_k\right\rangle , \quad E_k = \sqrt{\mathbf{p}^2 + m_k^2}$$

Vacuum Hamiltonian

But neutrinos intecact with matter

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_I, \qquad \mathcal{H}_I \left|\nu_\alpha\right\rangle = V_\alpha \left|\nu_\alpha\right\rangle$$

Effective potential

$$V_\alpha = V_{CC}\delta_{\alpha e} + V_{NC} = \sqrt{2}G_F \left(N_e \delta_{\alpha e} - \frac{1}{2} N_n \right)$$

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Neutrino Oscillations

The 3-neutrino oscillations in matter

#SOMOSUA

Evolution in matter is governed by an *effective* Hamiltonian

$$\mathcal{H}_F = \frac{1}{2E}\left(U\mathbb{M}^2U^\dagger + \mathbb{A}\right)$$

$$\mathbb{M} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} \qquad \mathbb{A} = \begin{pmatrix} A_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Leading to the well-known ***Mikheev-Smirnov-Wolfenstein*** **(MSW)** effect

Open questions

We don't know it all, yet

How relevant these questions are?

Ask an average **"hardcore" BSM** folk:

Neutrino physics is done, these questions are marginal (irrelevant), in the best case

[D. Aristizabal, VII *COMHEP* (2022)]

Ask an average **"hardcore" neutrino** folk

These questions are of the upmost relevance in particle physics (physics)

Open questions

We don't know it all, yet

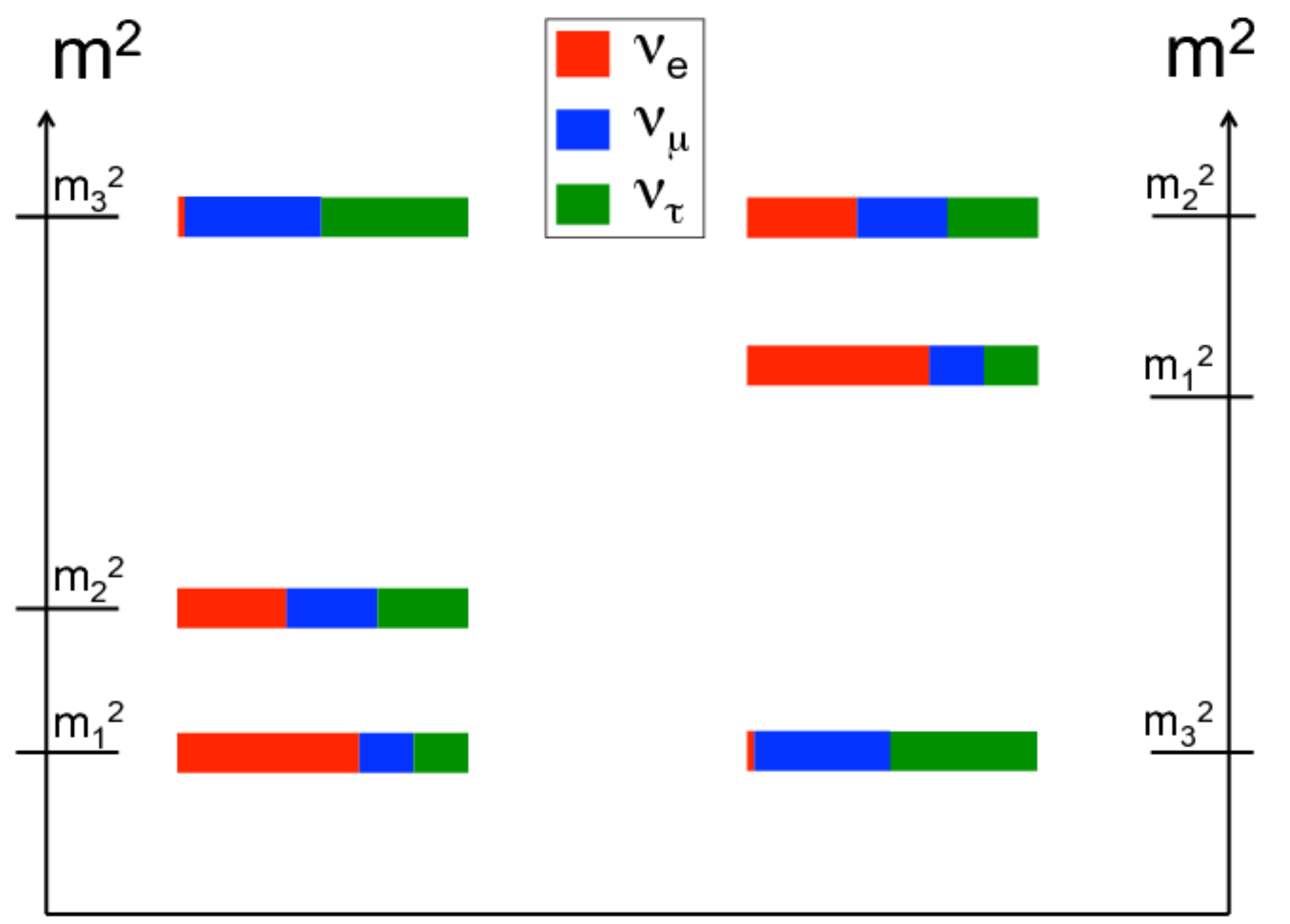
Neutrino Oscillations

Parameter values

#SOMOSUA

The (real-life) 3-neutrino model – **Not all is well known**, though.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Neutrino Oscillations

Parameter values

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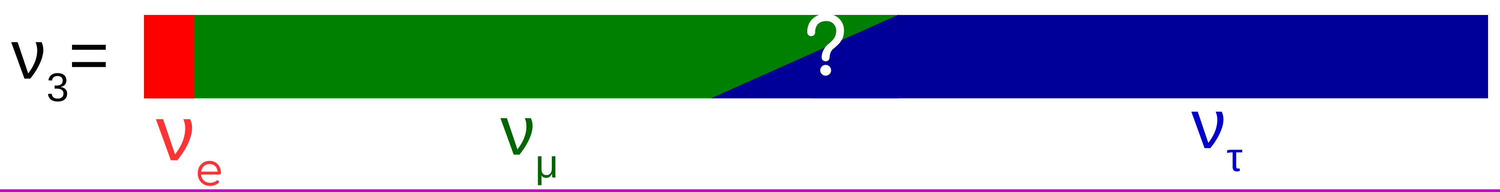
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Maximal Mixing?

(2) Is there a **symmetry** governing the ν_μ/ν_τ mixing into the 2nd and 3rd mass states?

i.e.: is θ_{23} "maximal" = 45°?



CP violation

(3) **Is δ_{CP}/π non-integral?**

If it is, neutrinos — and thus leptons — violate CP **symmetry.**

Related to wider matter/antimatter asymmetry in universe???

[J. Wolcott, Fermilab W&C (2020)]

Neutrino Oscillations

Parameter values

#SOMOSUA

The (real-life) 3-neutrino model – **Not all is well known**, though.

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Maximal Mixing? CP violation

Mass ordering (Hierarchy)

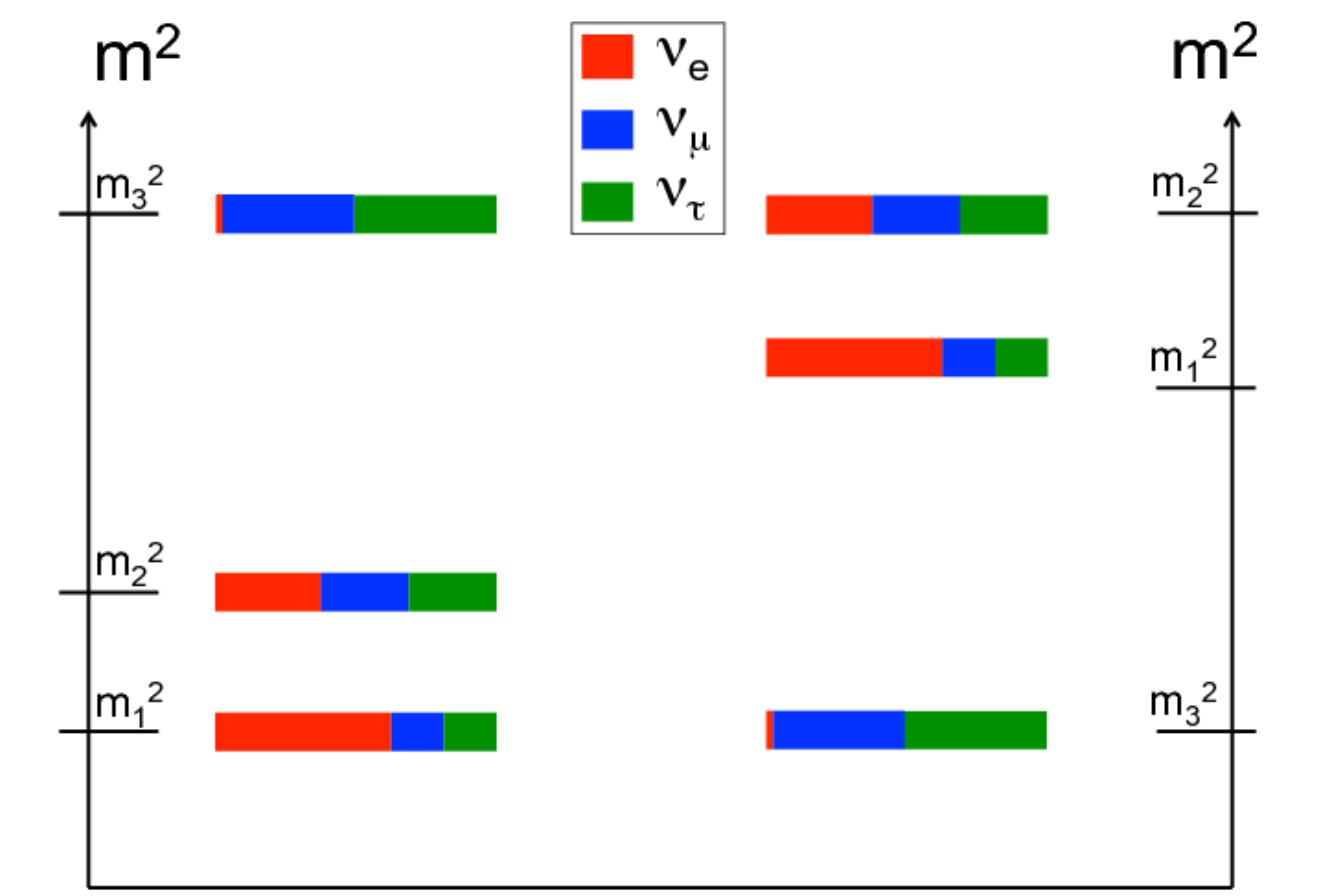
① Is there a symmetry governing the ordering of the lepton mass states?

Is the most electron-like state the lightest one, like with the charged leptons?

[J. Wolcott, Fermilab W&C (2020)]

$$\Delta m^2_{32} > 0$$

$$\Delta m^2_{32} < 0$$



Neutrino Mass

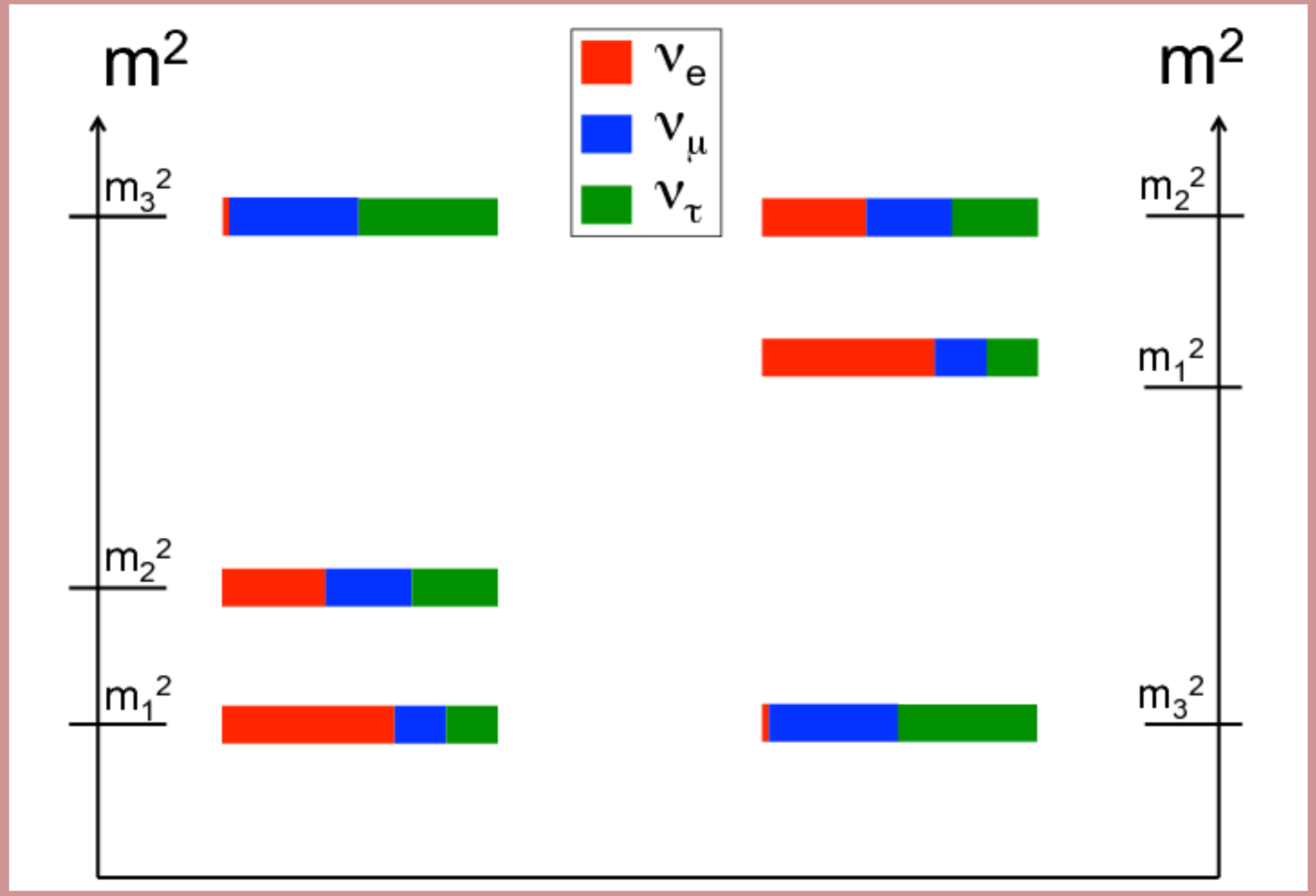
It's light but, how much?

#SOMOSUA

Not all is well known.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Maximal Mixing? CP violation

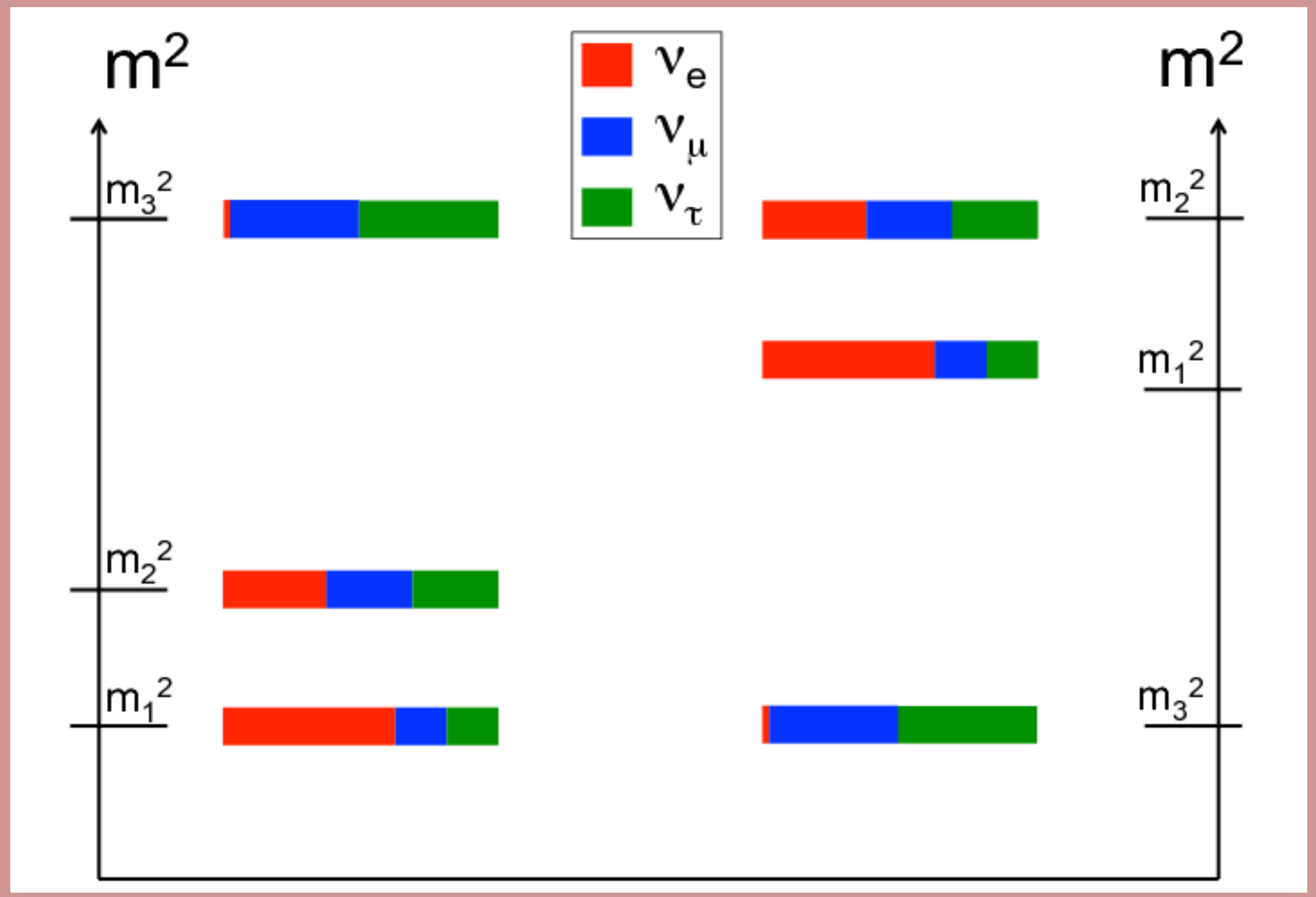


Absolute neutrino mass?

Neutrino Mass

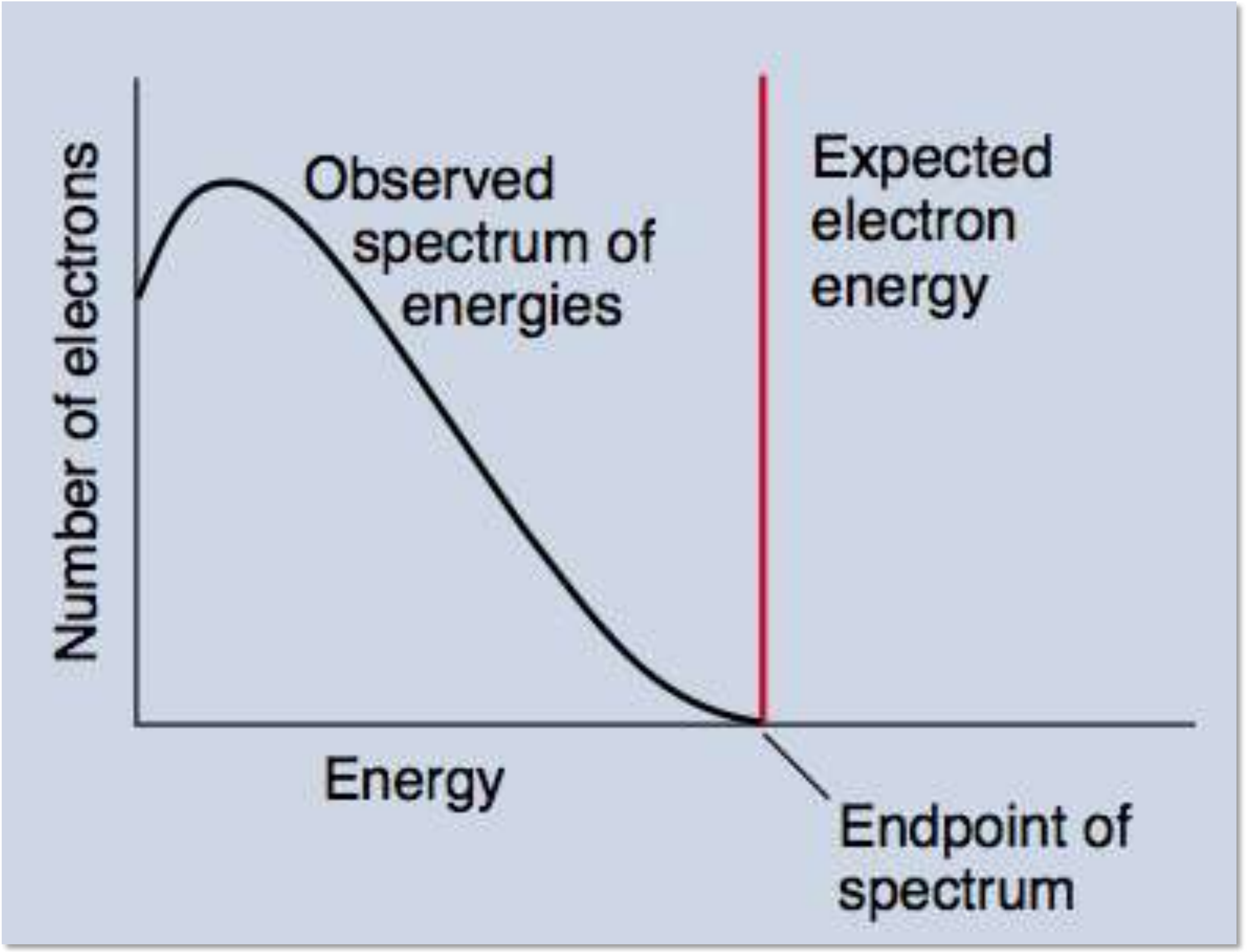
It's light but, how much?

Not all is well known.



Absolute neutrino mass?

Beta Spectrum

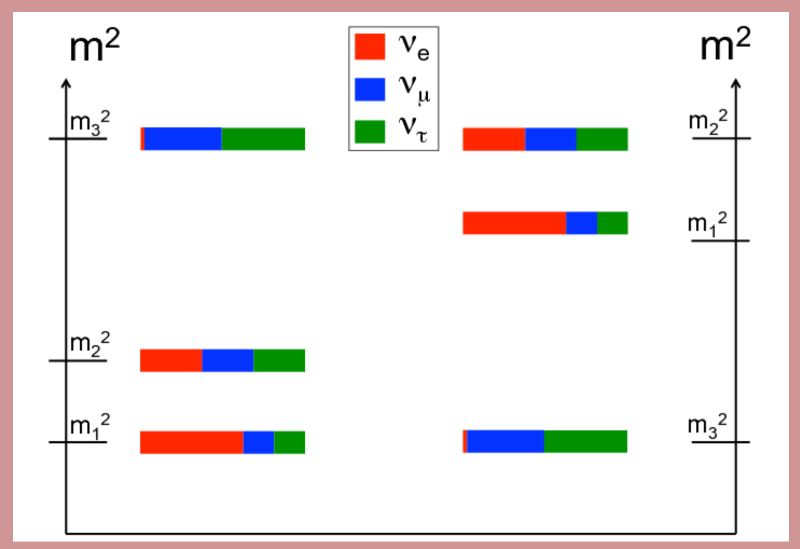


Neutrino Mass

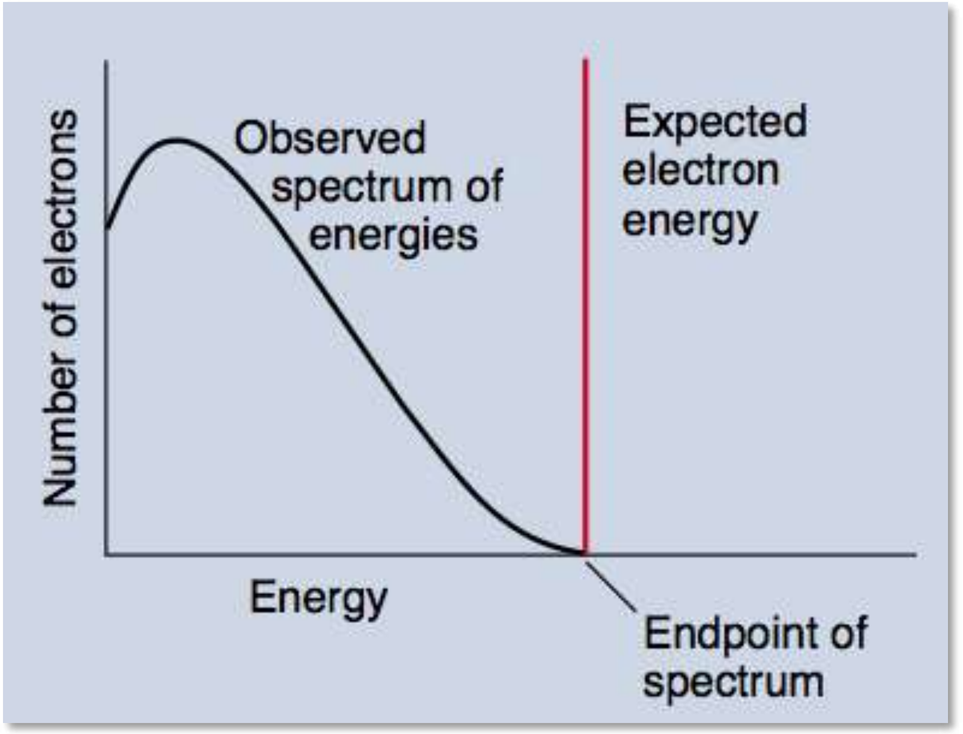
It's light but, how much?

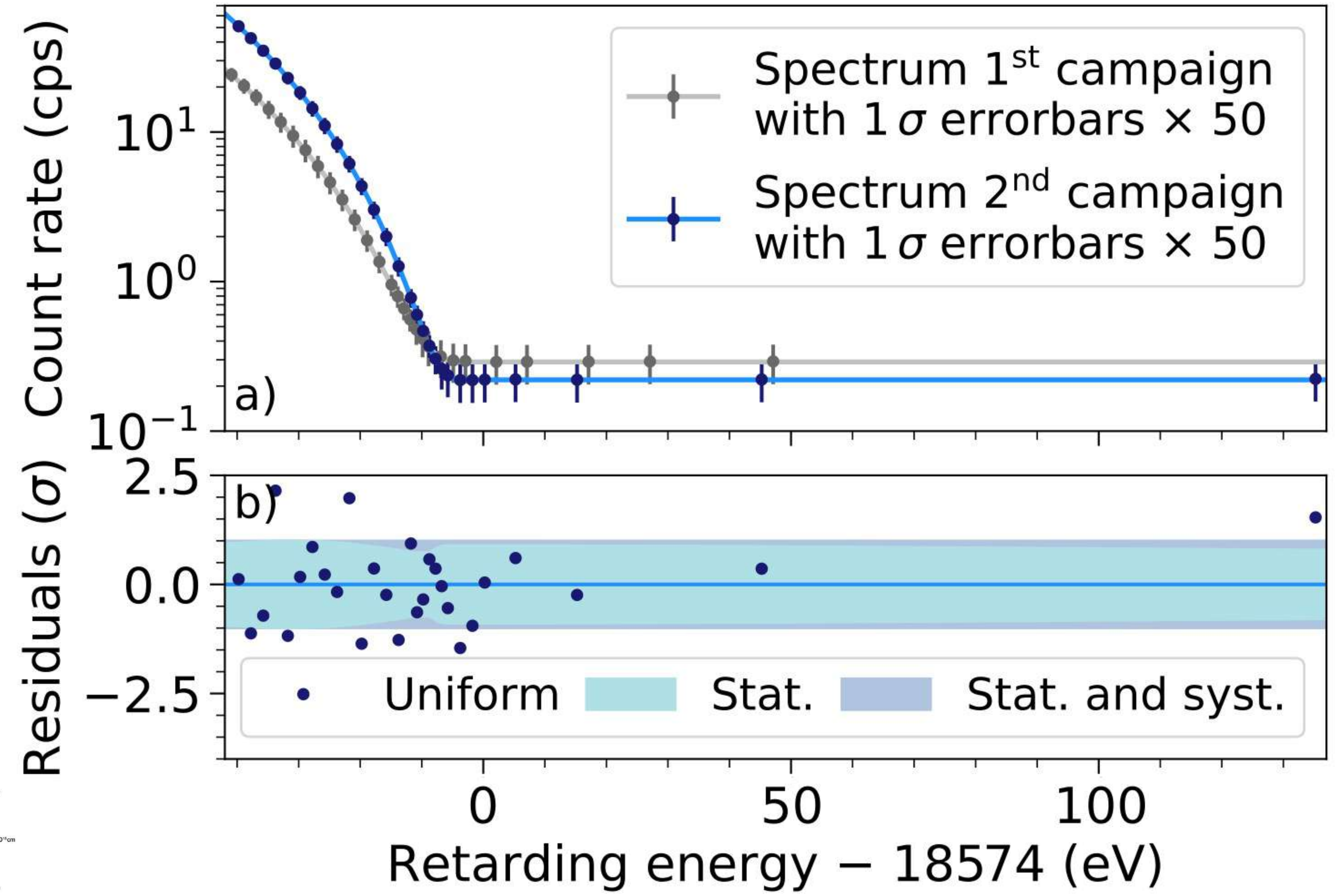
#SOMOSUA

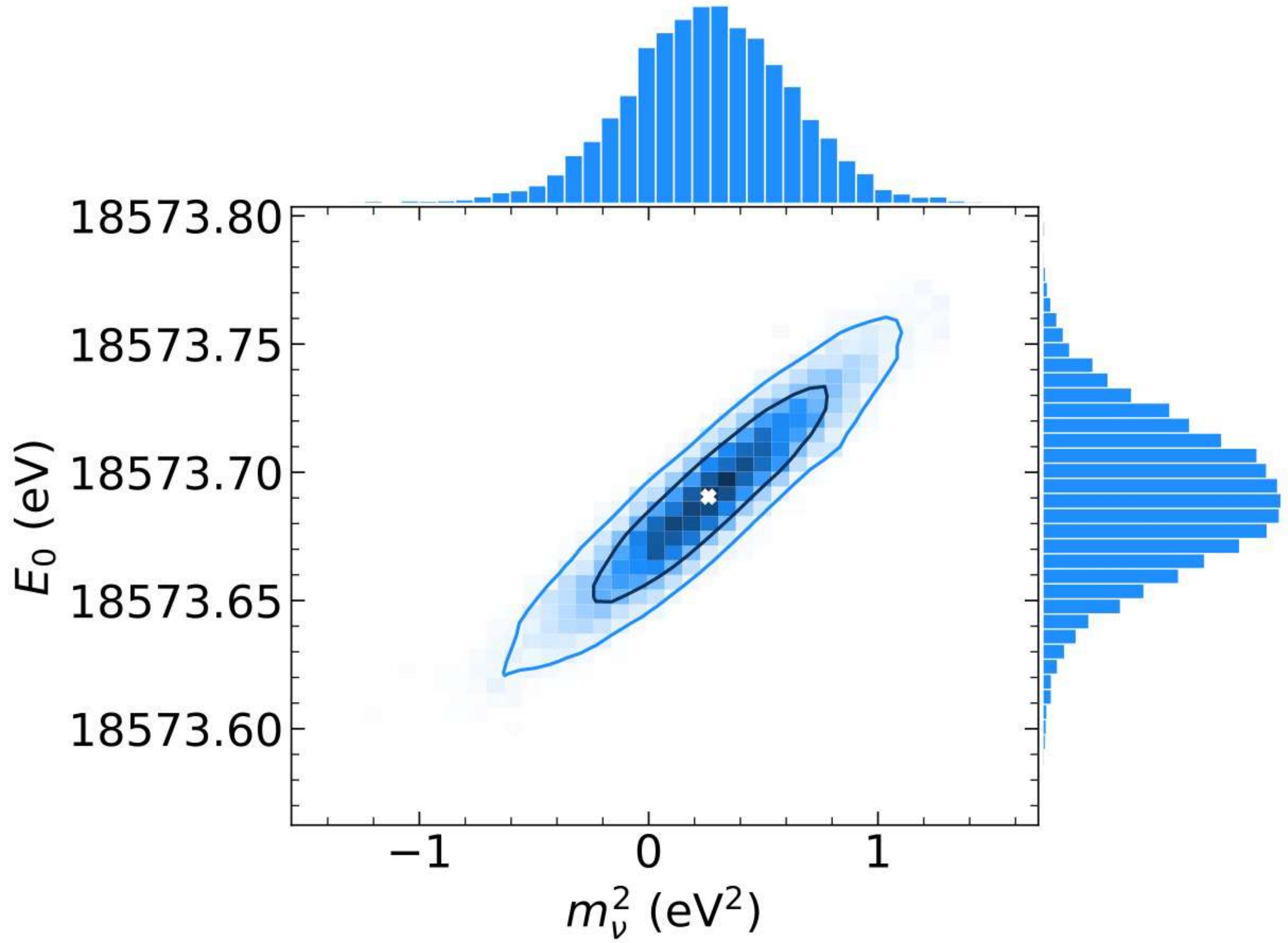
Not all is well known.



Absolute neutrino mass?







$$m_\nu^2 = (-0.26 \pm 0.34)\,\mathrm{eV}^2/\mathrm{c}^4$$

$$m_\nu < 0.9\,\mathrm{eV}^2/\mathrm{c}^2 \;\; (90\%\ \mathrm{C.L.})$$

[KATRIN, Nature 18 (2022)]

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Number of neutrinos

Are there more flavor neutrinos?

Not all is well known

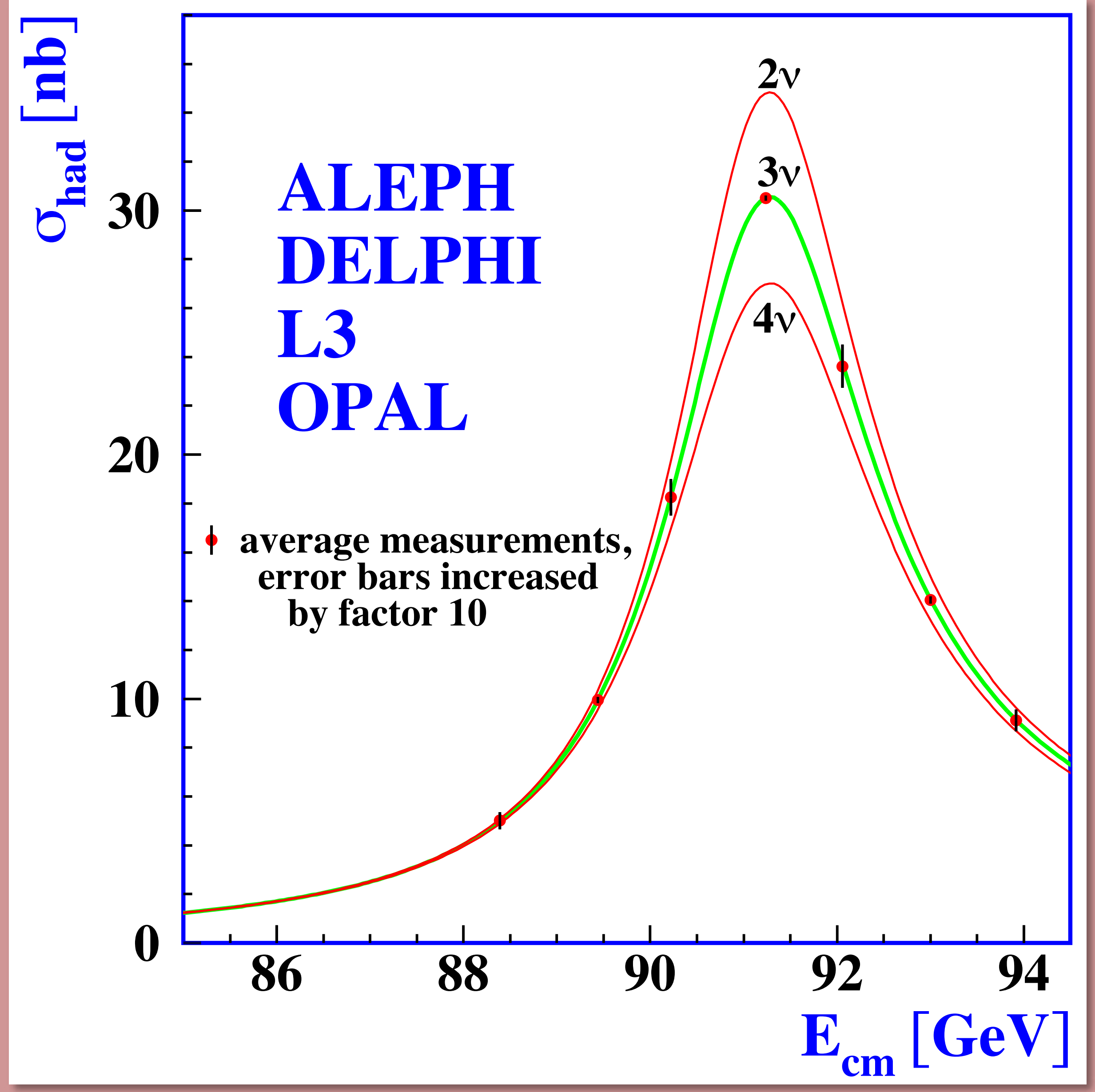
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Maximal Mixing?

CP violation

Absolute neutrino mass?

Only 3 flavors?



[S. Shael et al., Phys. Rept 427 (2006)]

These are neutrinos which *feel* the week nuclear force. Couple to the Z boson.

Number of neutrinos

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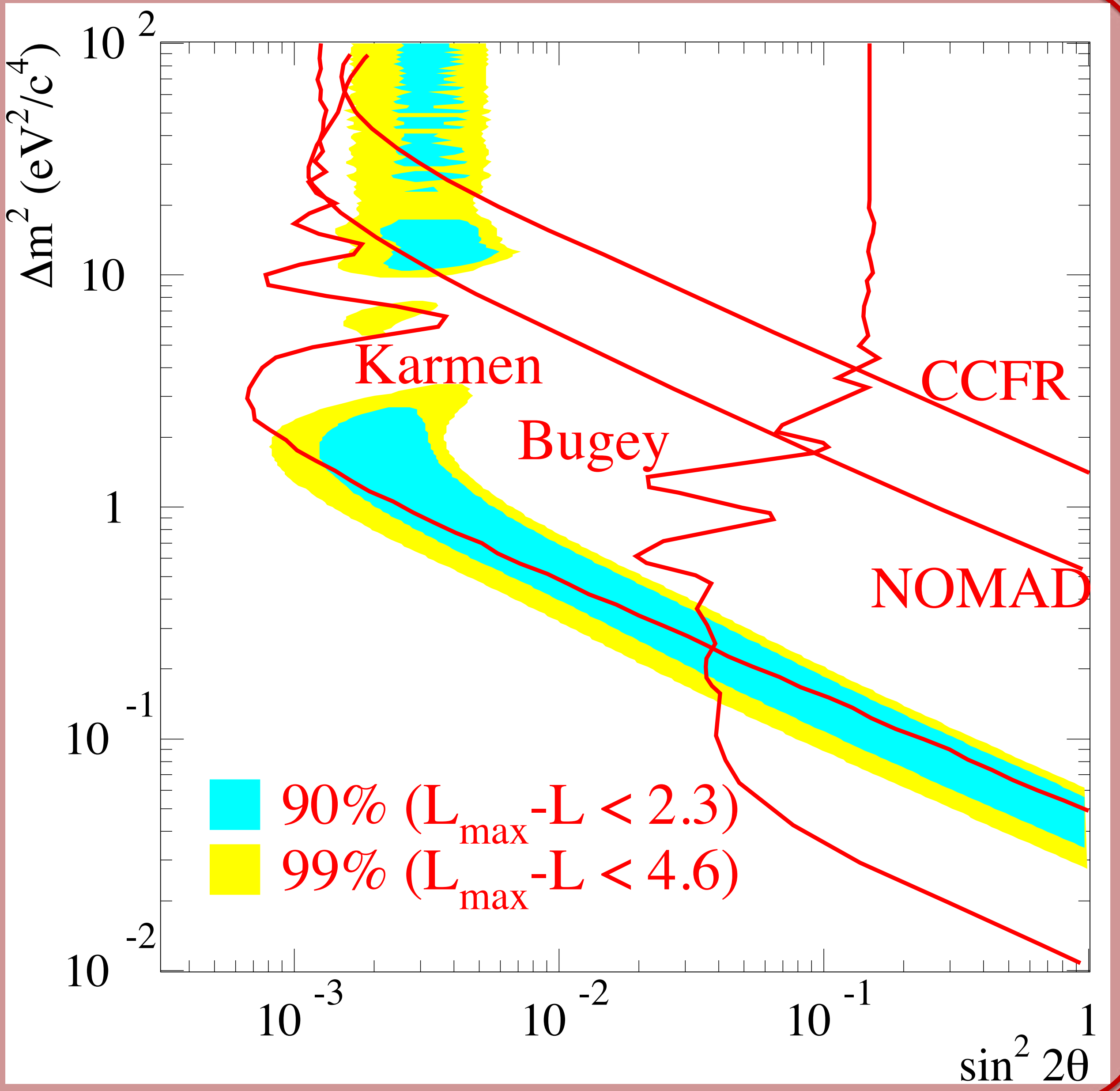
Maximal Mixing?

CP violation

Absolute neutrino mass?

Only 3 flavors?

[LSND. Aguilar et al. PRD64 (2001)]



Signals of the existence of (a) sterile neutrinos?

Number of neutrinos

Are there more flavor neutrinos?

#SOMOSUA

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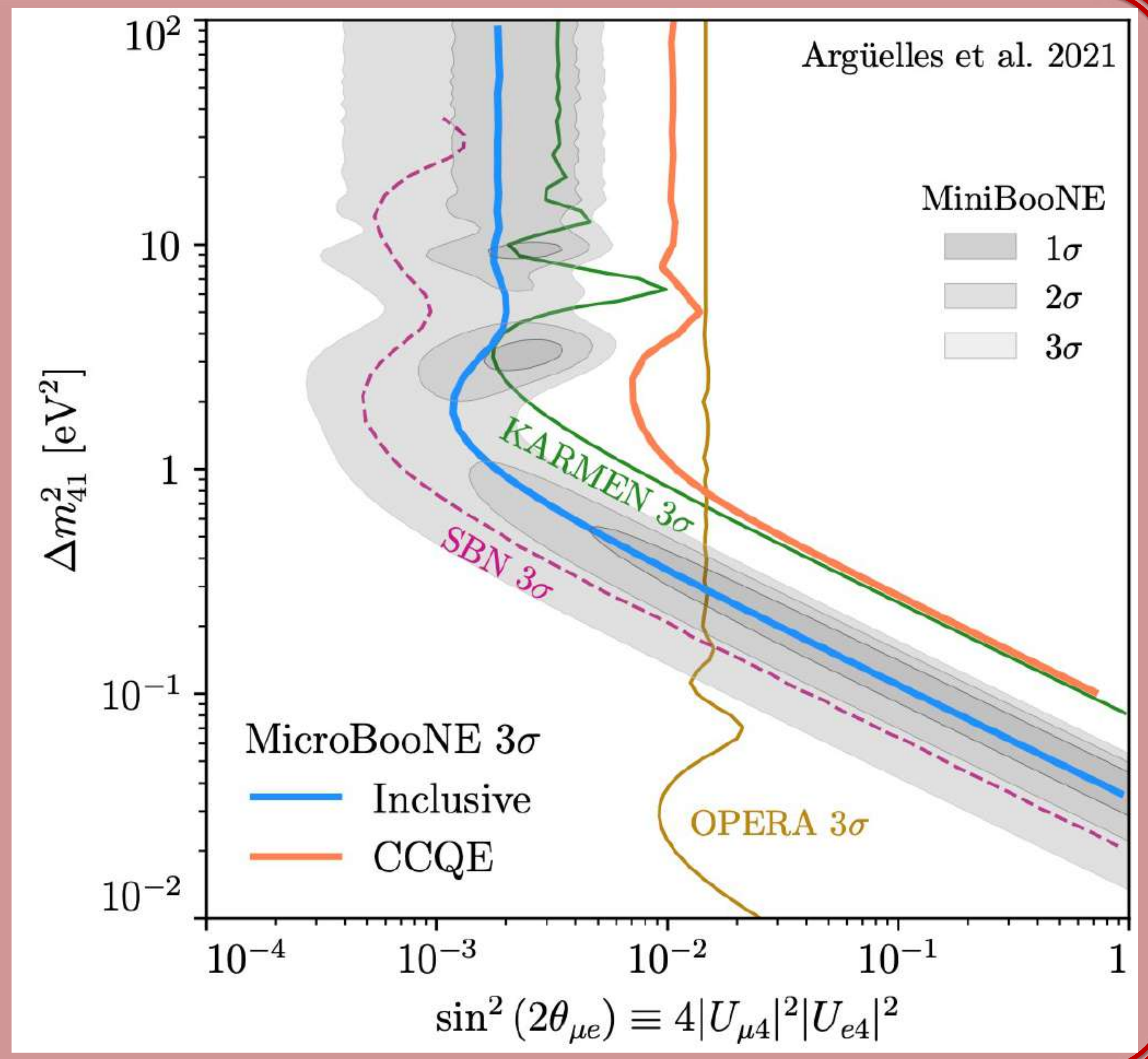
Maximal Mixing?

CP violation

Absolute neutrino mass?

Only 3 flavors?

[Argüelles et al. PRL128 (2022)]



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Maximal Mixing?

CP violation

Absolute neutrino mass?

Only 3 flavors?

More interesting results which don't fit in a 3ν framework:

- Reactor Antineutrino Anomaly
- Gallium Anomaly

White paper: **2203.07323**

Signals of the existence of (a) sterile neutrinos?

Nature of neutrinos

Dirac or Majorana?

#SOMOSUA

Not all is well known

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Only 3 Flavors?

Maximal Mixing?

CP violation

Absolute neutrino mass?

Are neutrinos their own antiparticle?	$\bar{\nu} \neq \nu$	Dirac
	$\bar{\nu} = \nu$	Majorana

How do we know?

Nature of neutrinos

Dirac or Majorana?

Not all is well known

Are neutrinos their own antiparticle?	$\bar{\nu} \neq \nu$	Dirac
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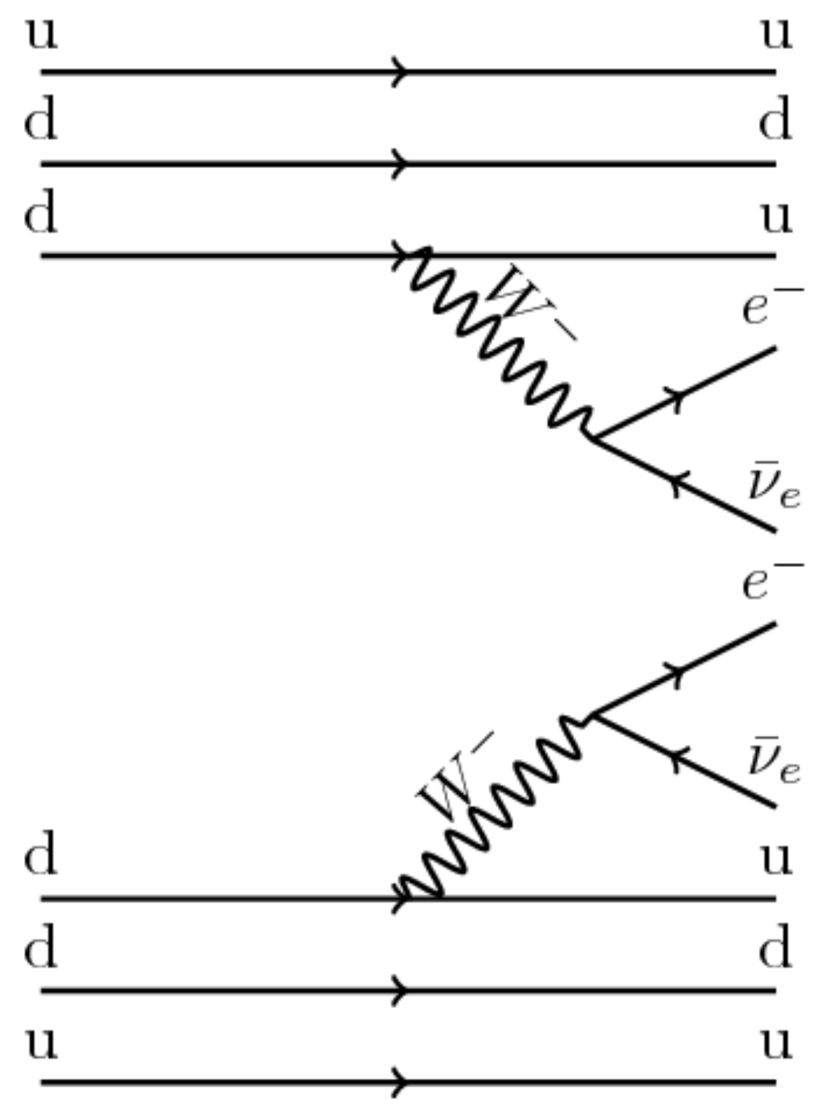
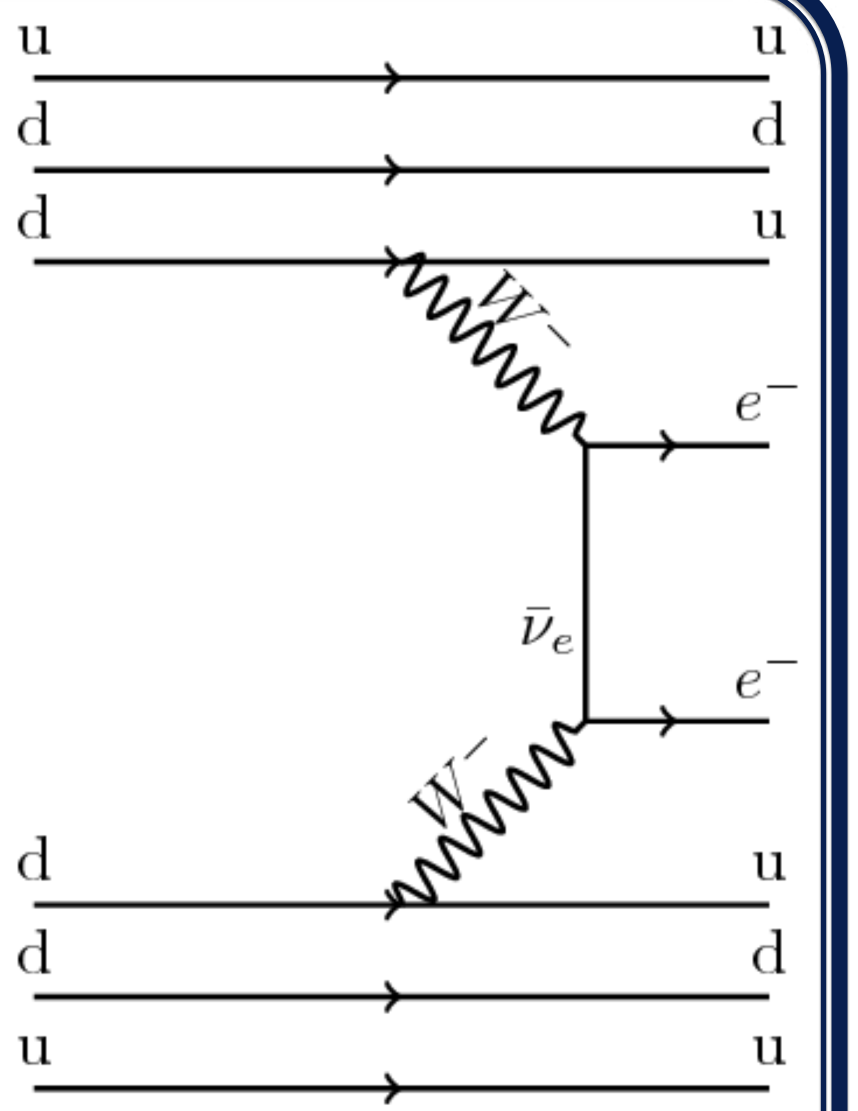
How do we know?

Double beta Decay with and without neutrinos



$2n \to 2p + 2e^- + 2\bar{\nu}_e$



$2n \to 2p + 2e^-$

Nature of neutrinos

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Not all is well known

Are neutrinos their own antiparticle?	$\bar{\nu} \neq \nu$	Dirac
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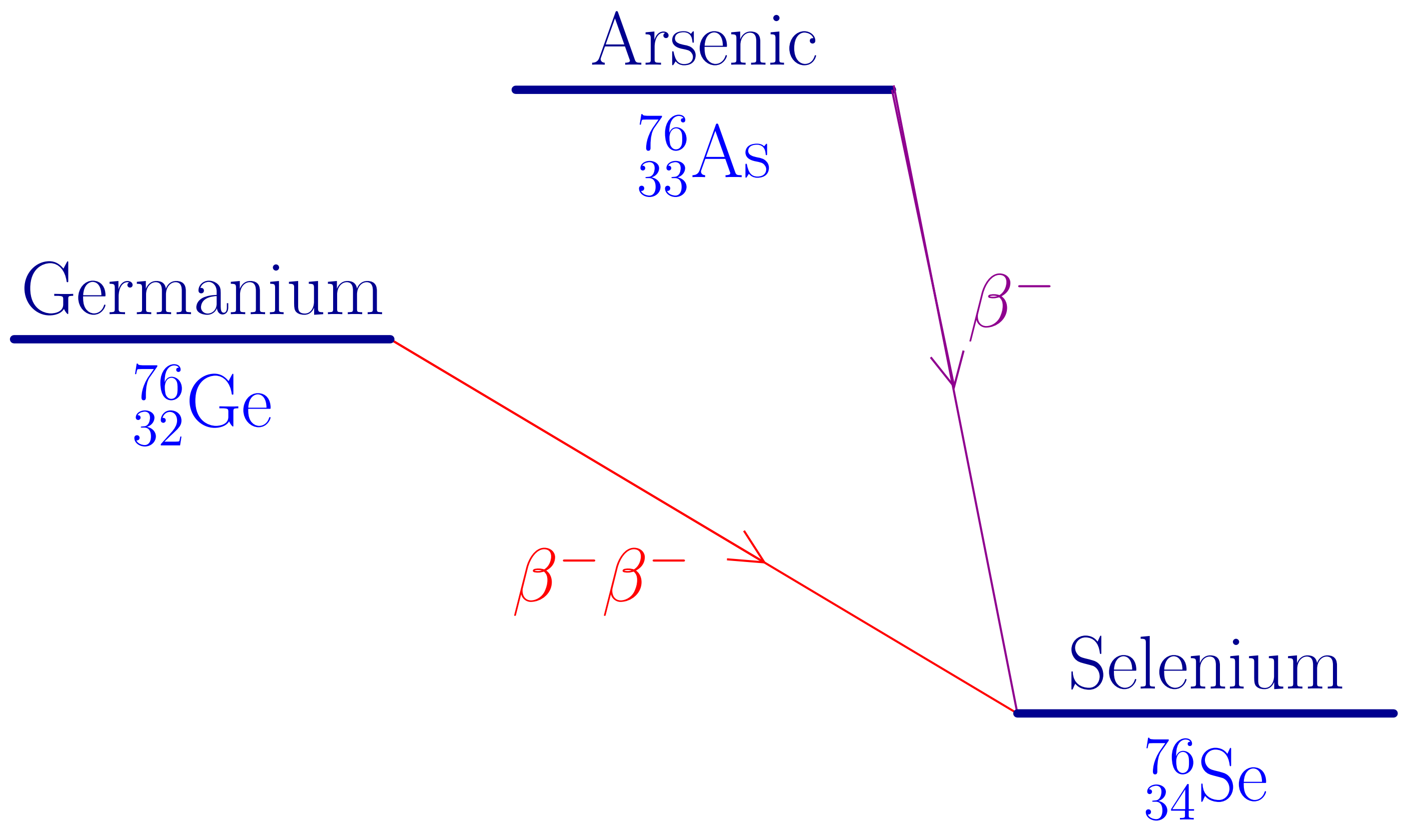
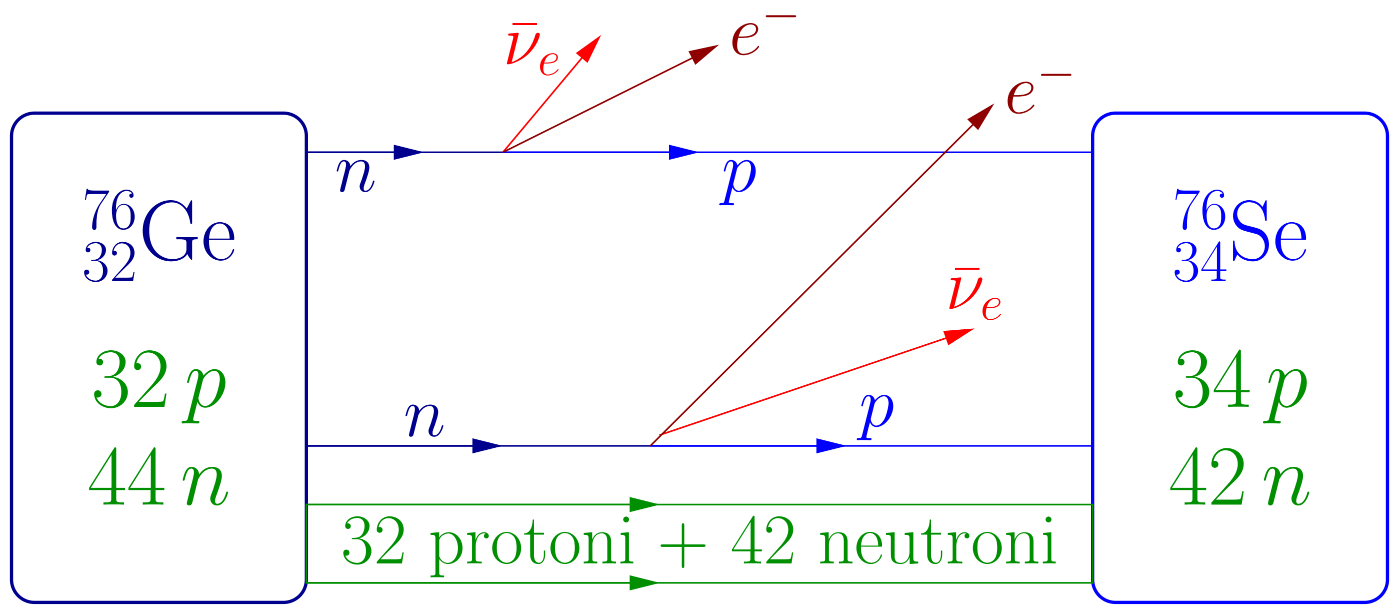
How do we know?

$$^{76}_{32}\mathrm{Ge} \to {}^{76}_{34}\mathrm{Se} + 2\,\mathrm{e}^- + 2\,\bar{\nu}_\mathrm{e}$$

Double beta Decay with and without **neutrinos**





[C. Giunti, Accademia delle Scienze (2019)]

Nature of neutrinos

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Not all is well known

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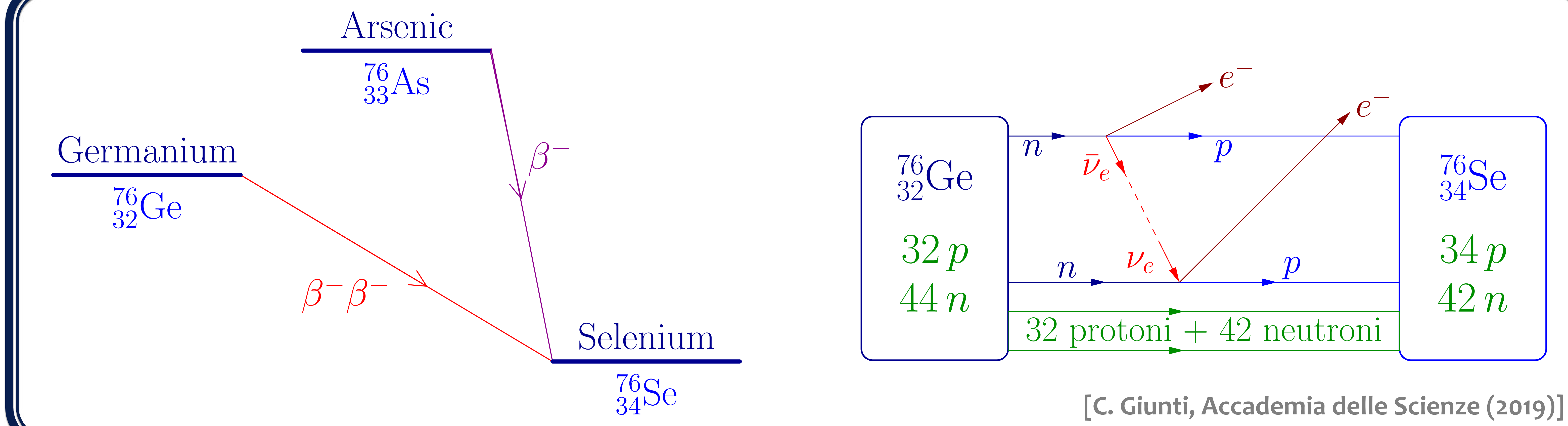
How do we know?

$$^{76}_{32}\mathrm{Ge} \to {}^{76}_{34}\mathrm{Se} + 2\,\mathrm{e}^-$$

Double beta Decay with and **without neutrinos**



[C. Giunti, Accademia delle Scienze (2019)]

$$m_{\beta\beta} = \sum_k U_{ek}^2\, m_k$$

Nature of neutrinos

Dirac or Majorana?

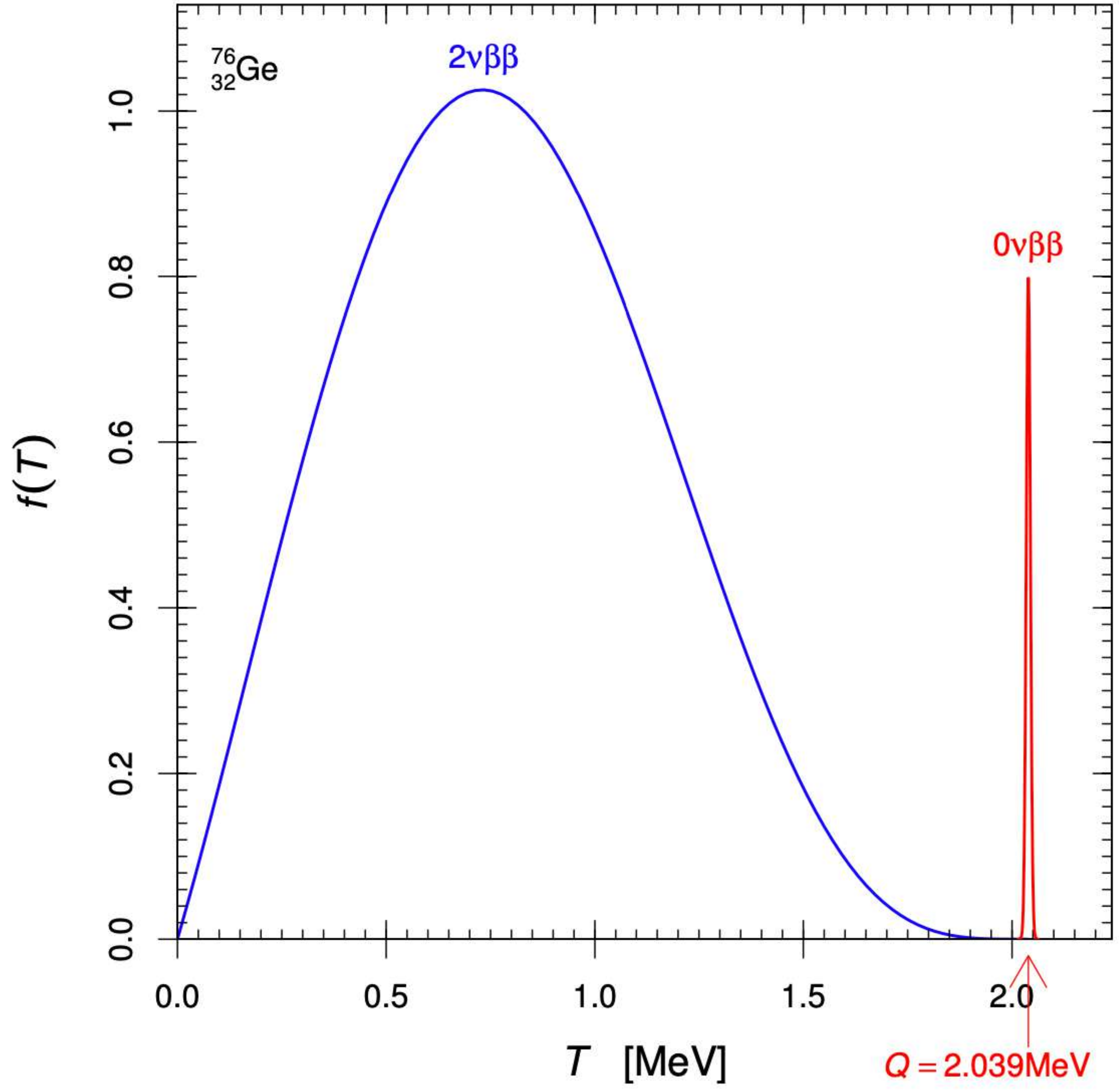
Not all is well known

Are neutrinos their own antiparticle?	$\bar{\nu} \neq \nu$	Dirac
	$\bar{\nu} = \nu$	Majorana

Double beta Decay with and without neutrinos

$${}^{76}_{32}\mathrm{Ge} \to {}^{76}_{34}\mathrm{Se} + 2\,\mathrm{e}^- + 2\,\bar{\nu}_e$$

$${}^{76}_{32}\mathrm{Ge} \to {}^{76}_{34}\mathrm{Se} + 2\,\mathrm{e}^-$$



[C. Giunti, Accademia delle Scienze (2019)]

Nature of neutrinos

Dirac or Majorana?

#SOMOSUA

Not all is well known

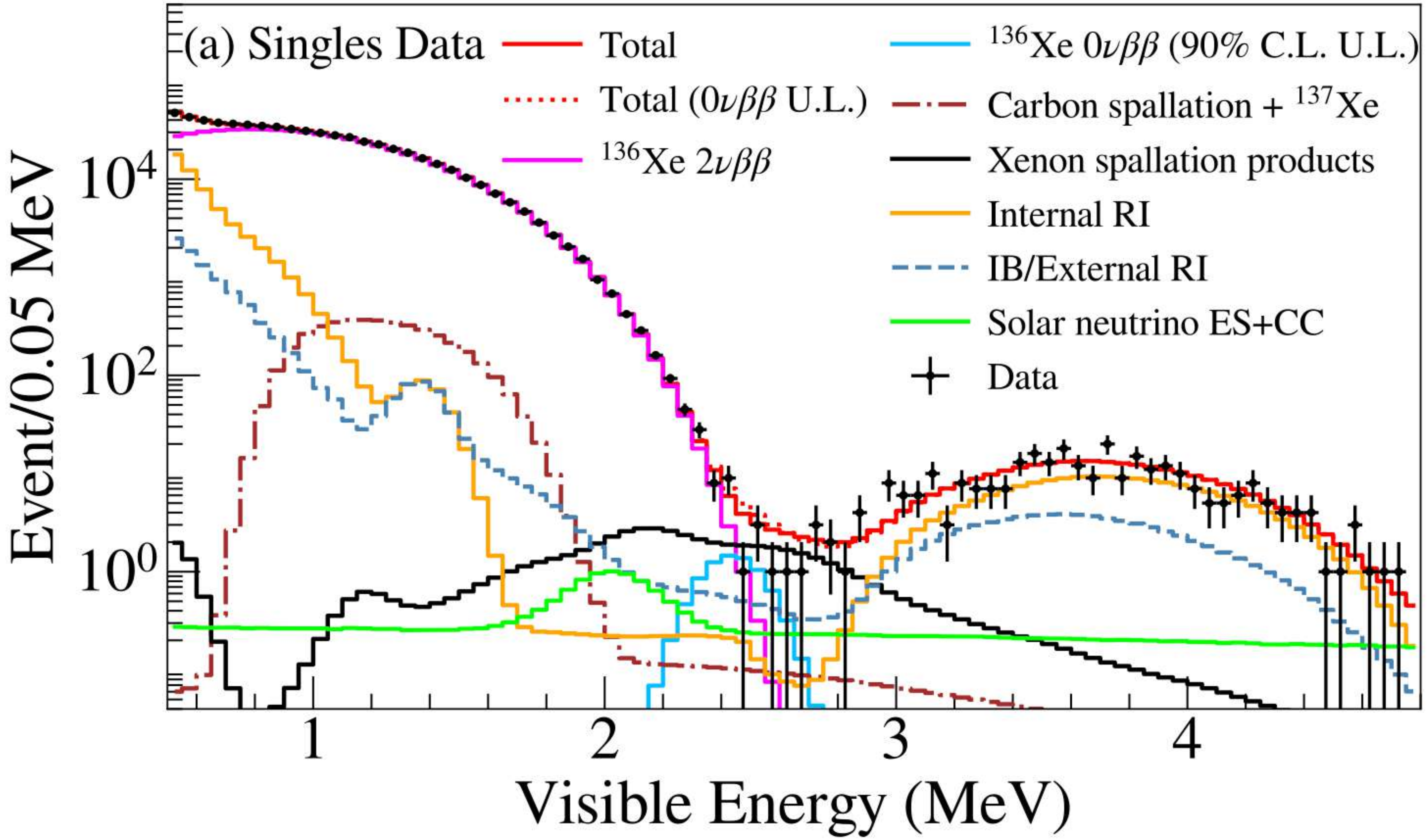
Are neutrinos their own antiparticle?

$$\bar{\nu} \neq \nu$$

$$\bar{\nu} = \nu$$

$$m_{\beta\beta} \in (36, 156)\ \text{meV}$$

[KamLAND 2203.02139 (2022)]



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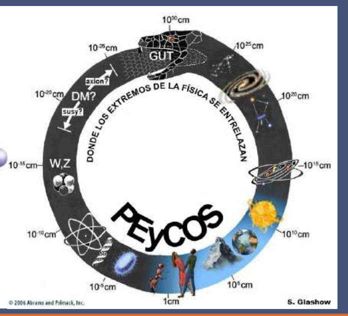
As a summary…

FACTS:

- Neutrinos exist and are massive!
- Neutrinos oscillate (and we understand the phenomenon rather well).
- There are many neutrinos and sources: we can study them with several beautiful experiments!

Exciting questions! Important implications!

- Are there symmetries?
- How many flavors?
- What is the mass, and which is the lightest?
- Dirac or Majorana?



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THANKS!

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2019 -2023

¡GRACIAS!

Backup

Sources

Where neutrinos are produced

#SOMOSUA

Reactor Neutrinos Electron antineutrinos detection: inverse neutron decay

Visible Energy $E_e + m_e$, and the positron annihilates with a surrounding electron.

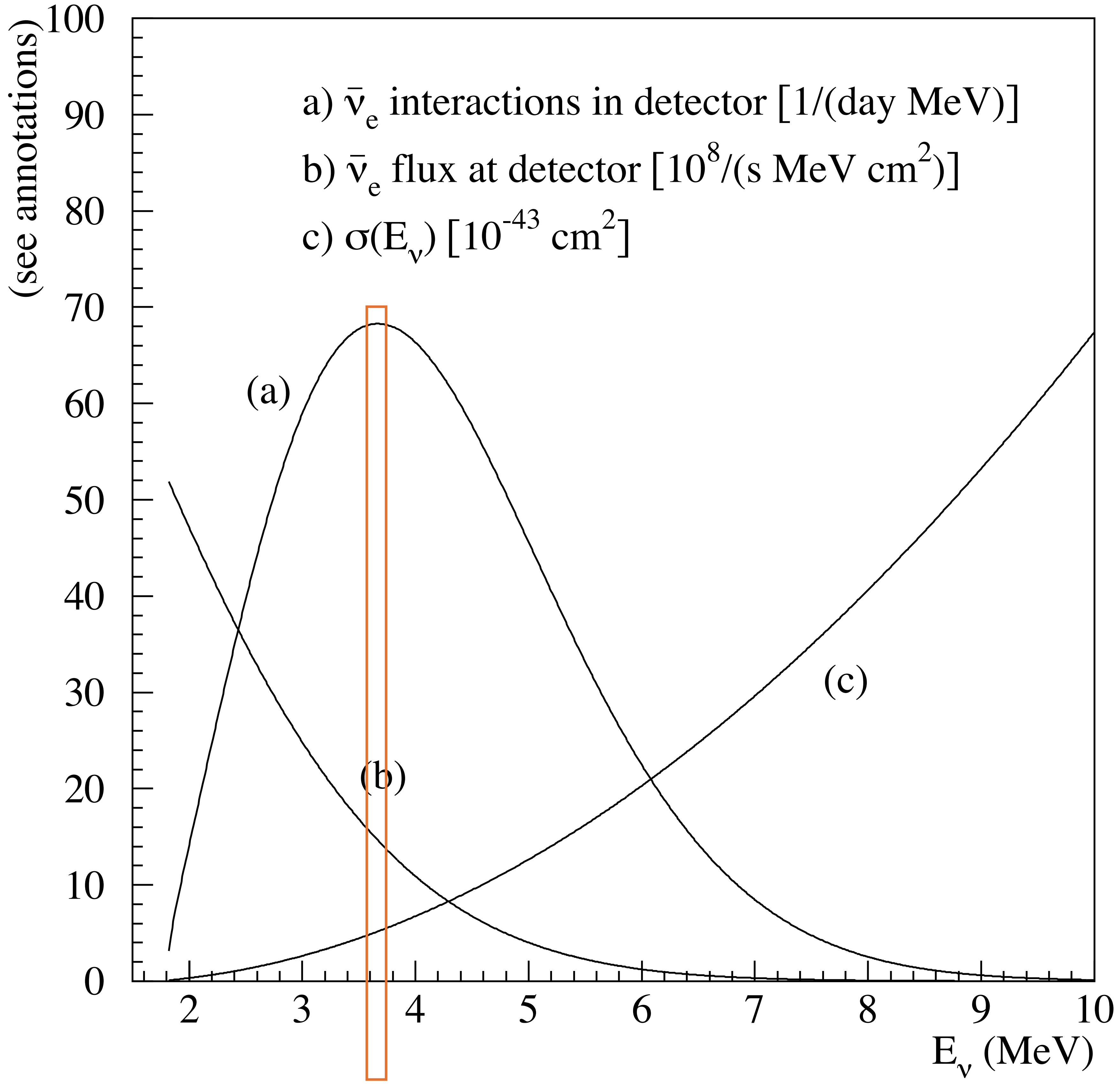
Events vs. Background: Coincidence
- Prompt positron signal
- Neutron nuclear capture (delayed)

Neutrino – Positron energy relation

$$E_\nu = E_e + T_n + m_n - m_p \simeq E_e + 1.293 \text{ MeV}$$

Threshold energy

$$E_\nu^{th} = \frac{(m_n + m_e)^2 - m_p^2}{2\, m_p} \simeq 1.806 \text{ MeV}$$



~3.6 MeV

[C. Giunti & C.W. Kim, Funds. of Neutrinos Physics and Astrophysics (2007)]

Neutrino Oscillations

Phenomenology

[Adapted from D. Schmitz, CTEQ Summer School 2011]

The neutrino of **flavor** α is the one created in W boson decay together with the charged lepton of flavor α.

And creates a charged lepton of **flavor** α when it undergoes a charged-current interaction.

Neutrino Oscillations

Phenomenology

Flavor may change…

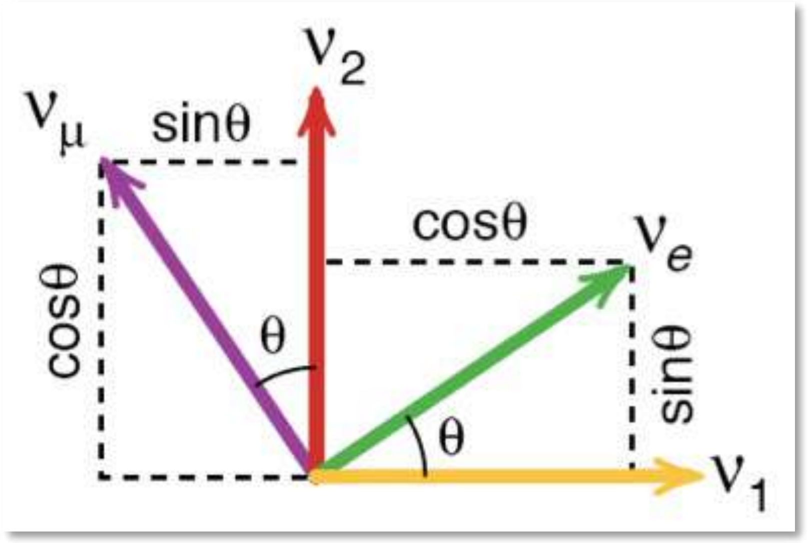
[Adapted from D. Schmitz, CTEQ Summer School 2011]

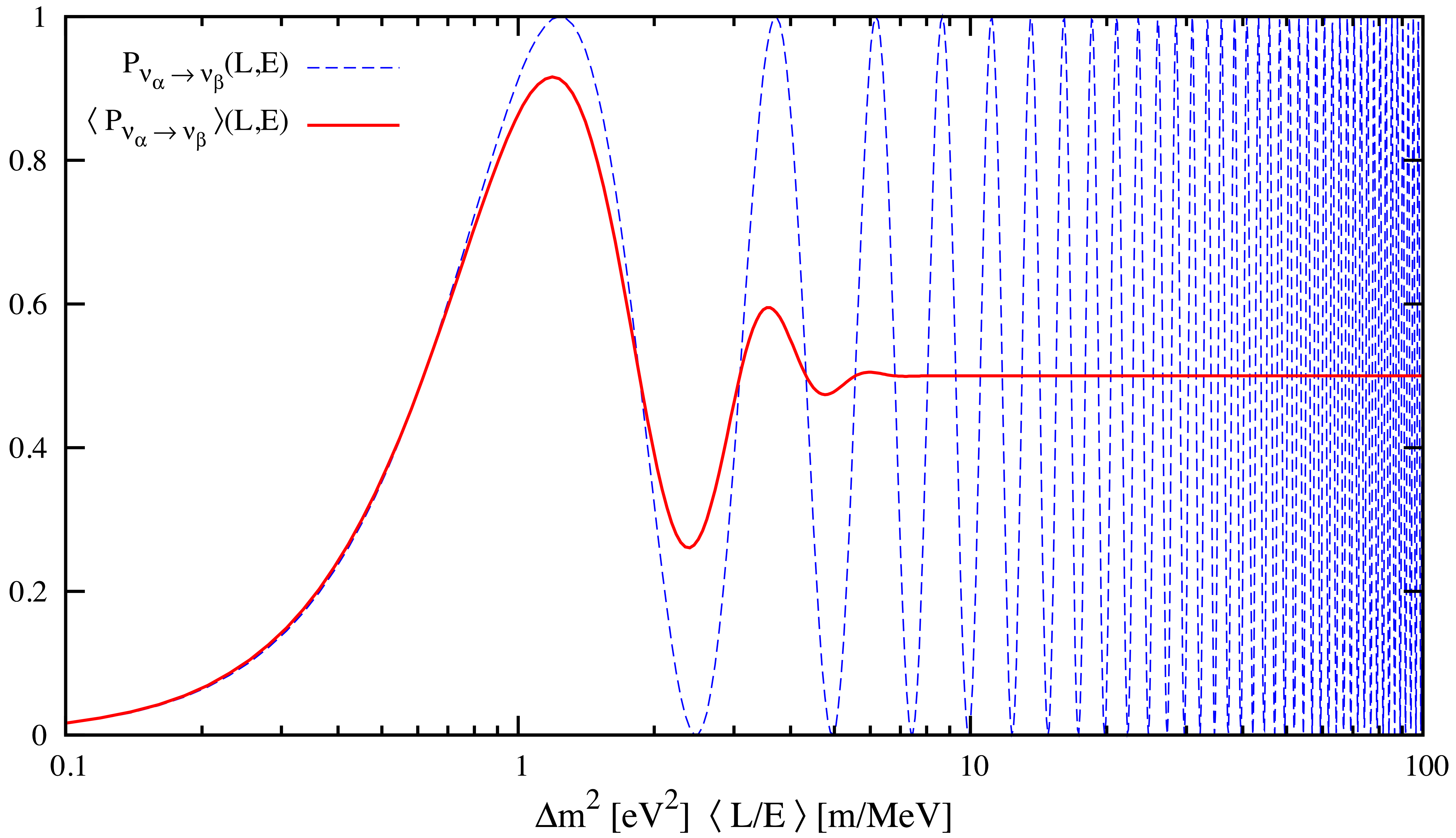
… if neutrinos have ***mass and mix***

Neutrino Oscillations

The 2-neutrino approximation (vacuum)

#SOMOSUA





$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta_{12} \sin^2 \left(1.27 \frac{\Delta m^2_{21} [\mathrm{eV}^2] L[\mathrm{km}]}{E[\mathrm{GeV}]} \right)$$