Neutrino Physics

Where We Are & Where We're Going

The Physics of Neutrinos: Progress and Puzzles

The 87th Compton Lecture Series

Enrico Fermi Institute, University of Chicago

Andrew T. Mastbaum

June 2, 2018

The Physics of Neutrinos: Progress and Puzzles

The 87th Compton Lecture Series

Agenda

March 31	Little, Neutral, Mysterious: An Introduction to Neutrino Physics
April 7	Lost and Found: Solar Neutrinos and Oscillations
April 14	Supernova Neutrinos: Neutrinos From the Beyond the Solar System
April 21	Neutrinos in Cosmology (Dr. Marco Raveri, KICP)
April 28	Gone Fission': Neutrinos at Nuclear Reactors
May 5	The Small Things: Neutrino Mass and Neutrinoless Double-Beta Decay
May 12	How Many Neutrinos Are There? Sterile Neutrinos
May 19	Neutrinos, the Universe, and CP Violation
May 26	*No lecture*
June 2	Neutrino Physics: Where We Are & Where We're Going

Neutrinos Everywhere!

ν

Neutrinos Everywhere!

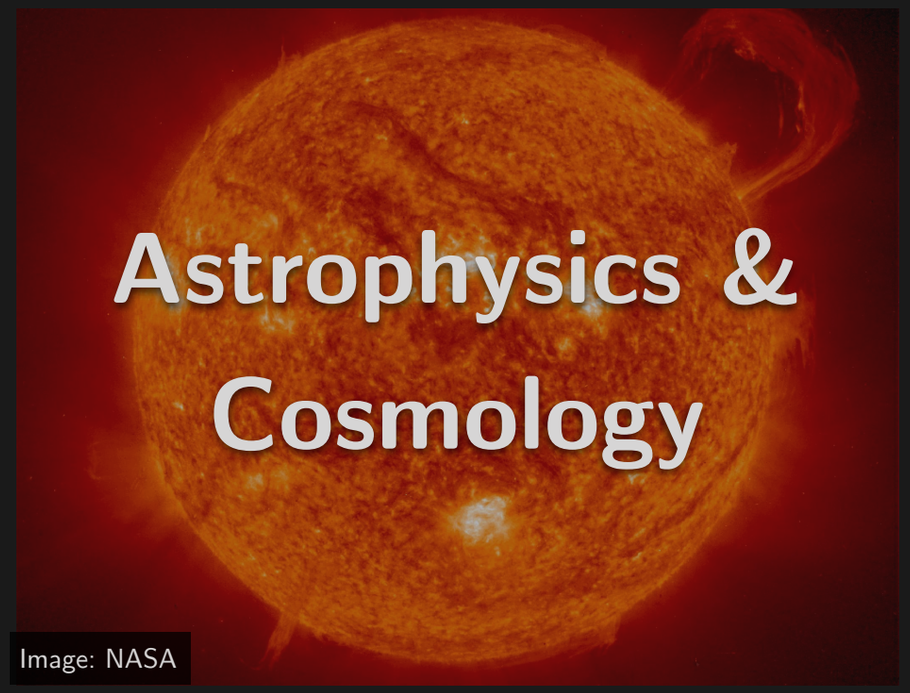


Image: NASA

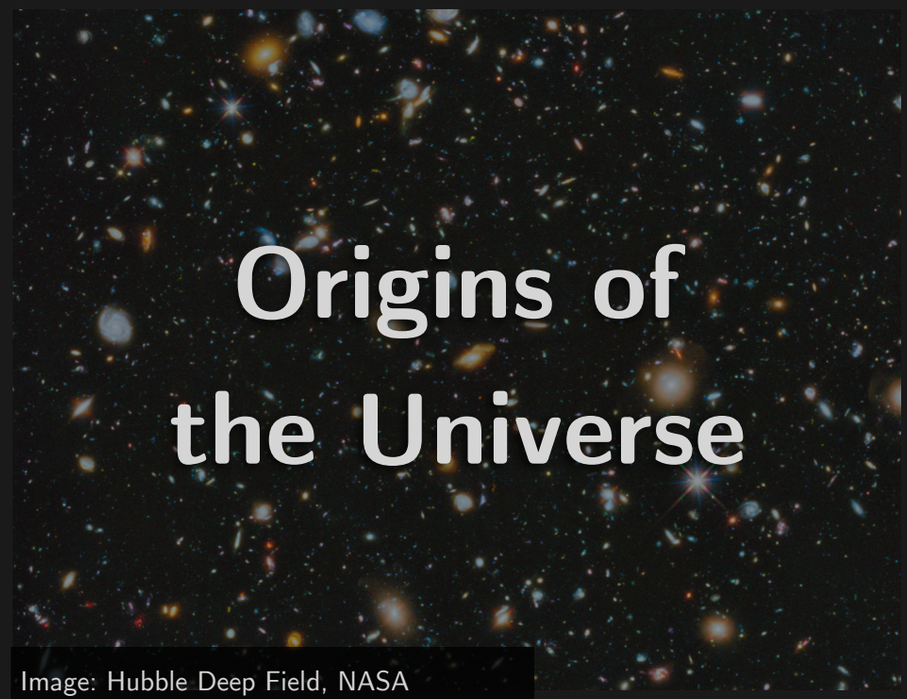
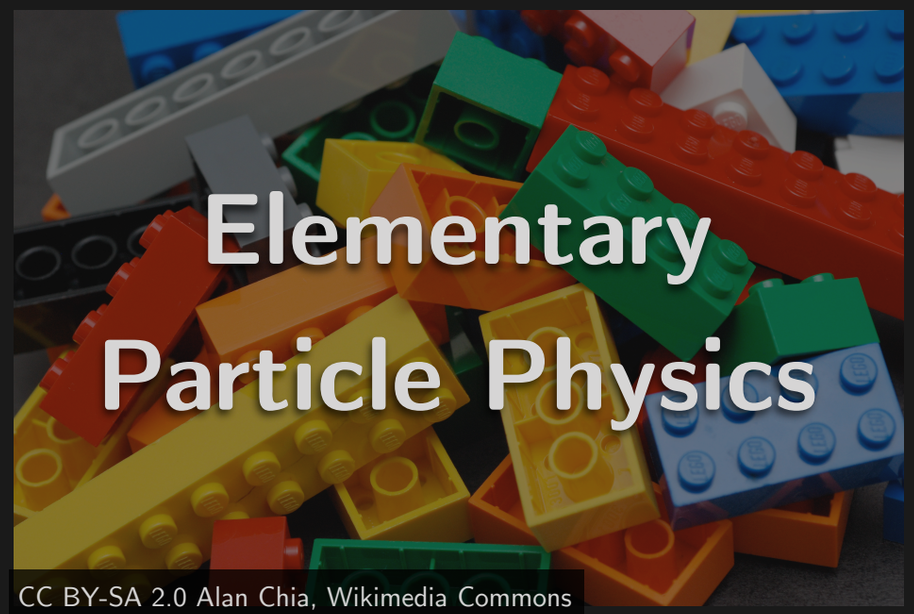


Image: Hubble Deep Field, NASA

ν

Image: NRC



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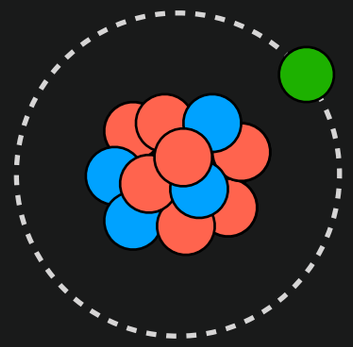
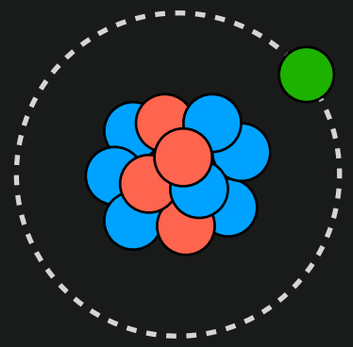


$$n \rightarrow p + e^-$$



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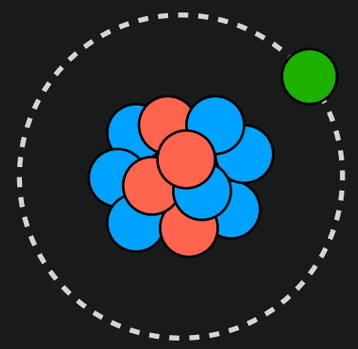


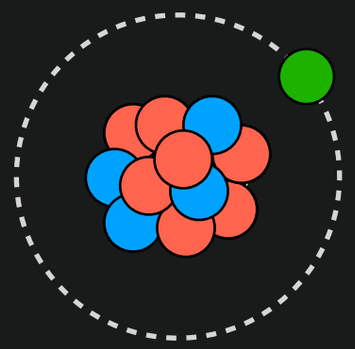
$$n \rightarrow p + e^-$$

Wolfgang Pauli

1930: A bold proposal...

Dear Radioactive Ladies and Gentlemen,

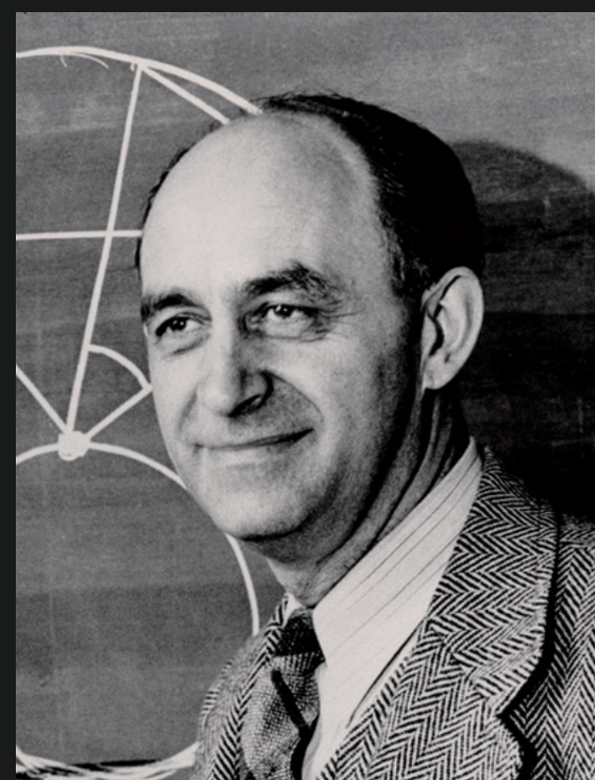
I have hit upon a **desperate remedy** ... there could exist electrically-neutral particles [emitted in beta decay] ...



$$n \rightarrow p + e^- + \nu$$

...and a theory to match

Enrico Fermi



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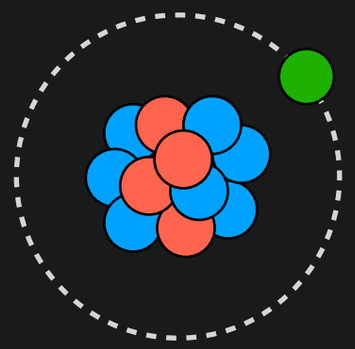

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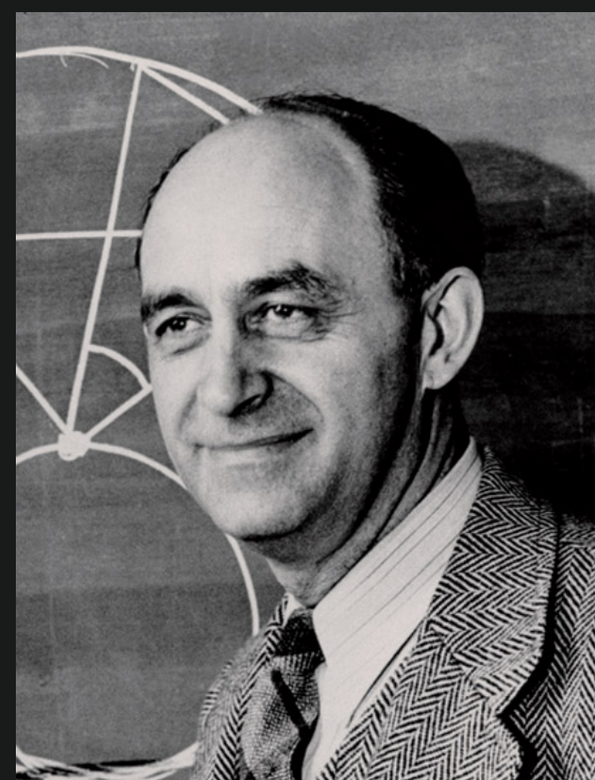
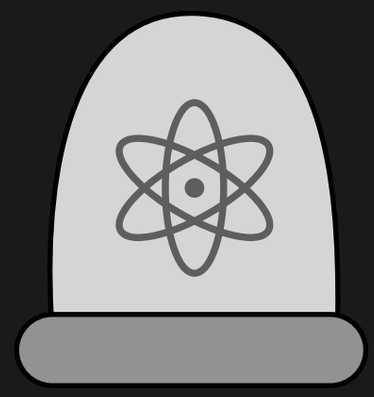
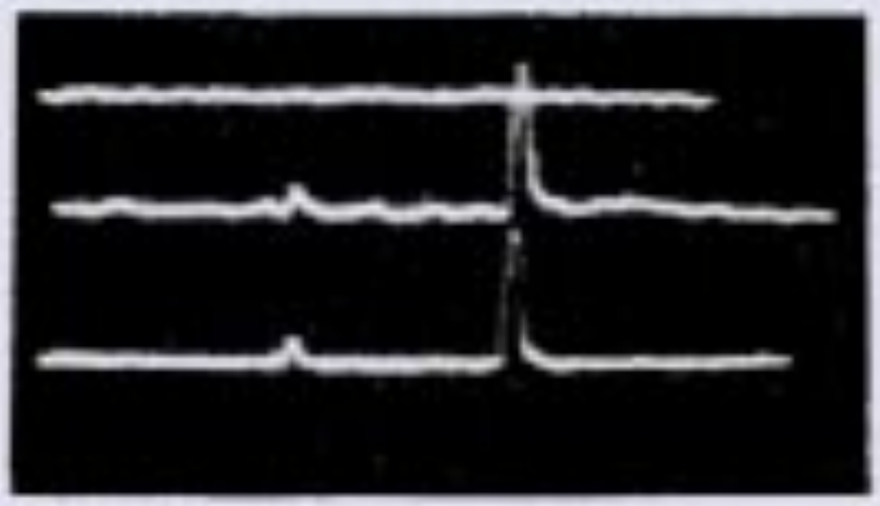
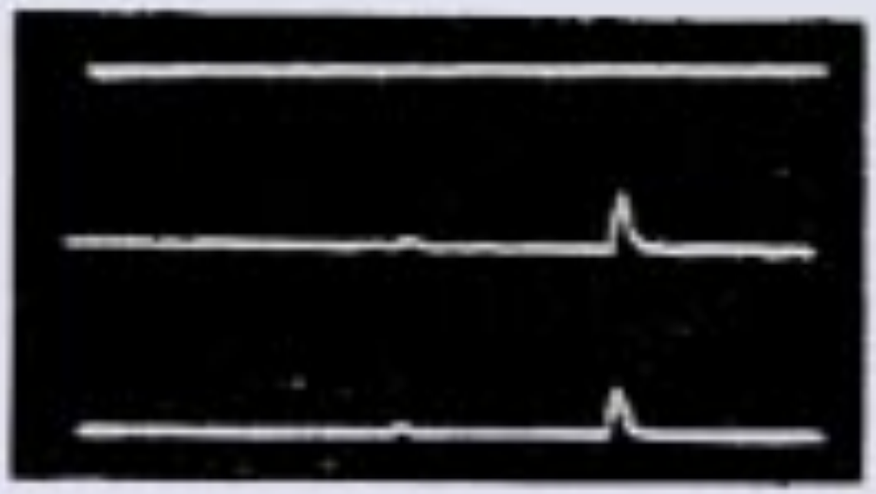


Cowan & Reines

In **1956**, neutrinos are first observed: antineutrinos from a nuclear reactor at Savannah River

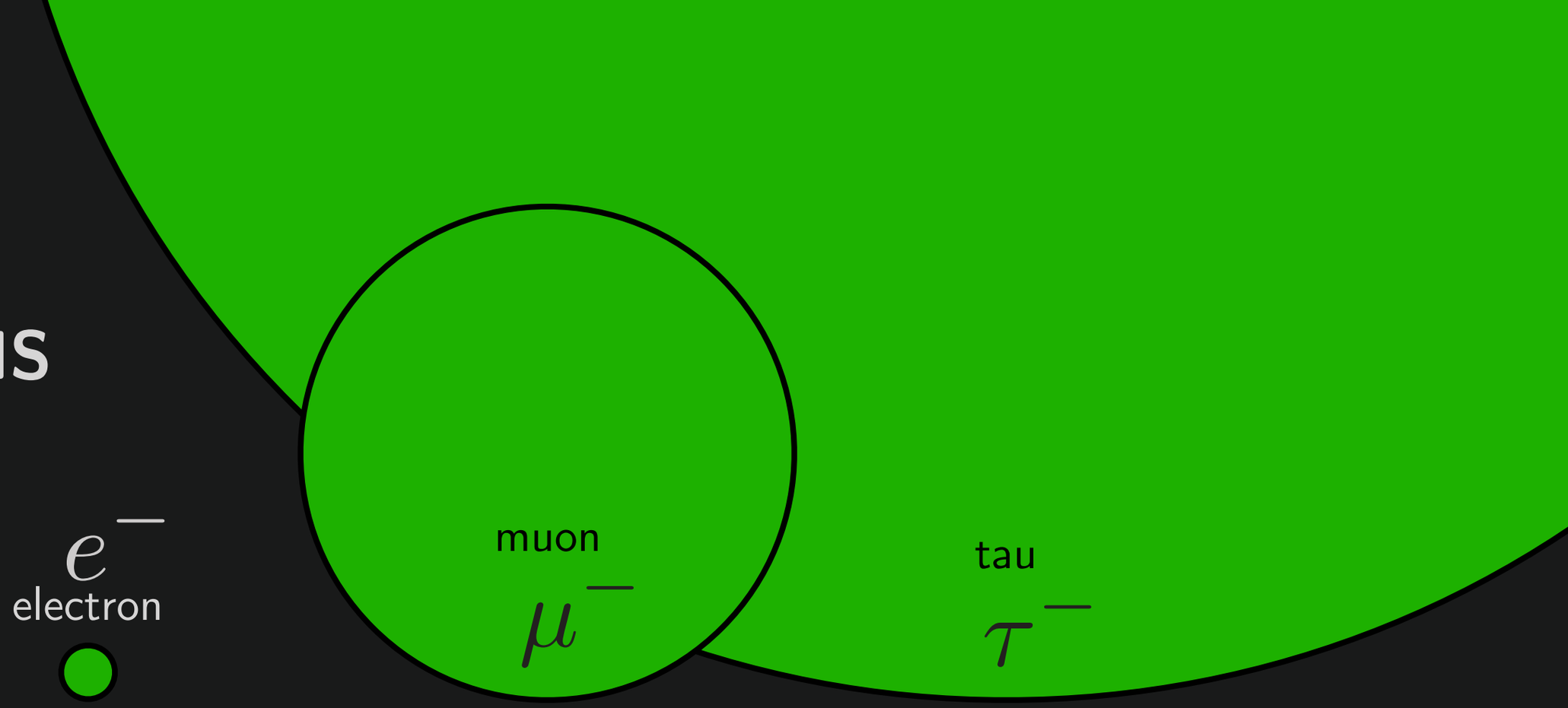






LEPTONS

LEPTONS



LEPTONS

electron
e^-

muon
μ^-

tau
τ^-

electron neutrino
ν_e

muon neutrino
ν_μ

tau neutrino
ν_τ

LEPTONS

e^-
electron

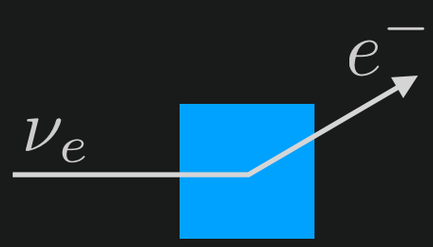
muon
μ^-

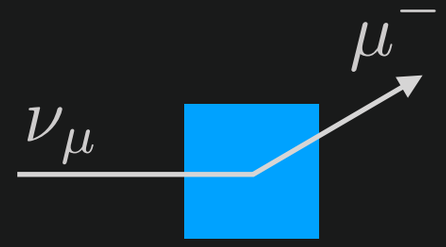
tau
τ^-

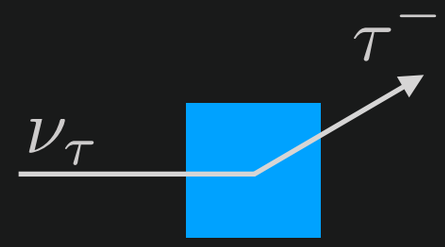
electron neutrino
ν_e

muon neutrino
ν_μ

tau neutrino
ν_τ







ANTI LEPTONS

ANTI LEPTONS

e^+
positron

anti-muon
μ^+

anti-tau
τ^+

ANTI LEPTONS

e^+
positron

anti-muon
μ^+

anti-tau
τ^+

electron antineutrino
$\bar{\nu}_e$

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

tau antineutrino
$\bar{\nu}_\tau$

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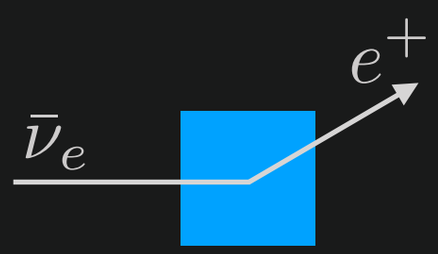

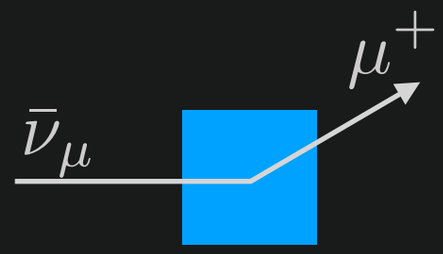

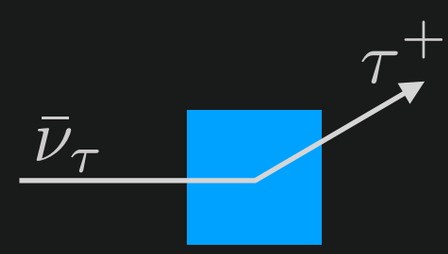

Standard Model of Particle Physics

	I	II	III	
QUARKS	u up 0.003 GeV/c^2 +2/3	c charm 1.3 GeV/c^2 +2/3	t top 175 GeV/c^2 +2/3	γ photon 0 0
	d down 0.006 GeV/c^2 -1/3	s strange 0.1 GeV/c^2 -1/3	b bottom 4.3 GeV/c^2 -1/3	g gluon 0 0
LEPTONS	ν_e electron neutrino $<10^{-8}$ GeV/c^2 0	ν_μ muon neutrino $<10^{-4}$ GeV/c^2 0	ν_τ tau neutrino <0.02 GeV/c^2 0	$W^\pm$ W boson 80.4 GeV/c^2 ±1
	e^- electron 511 keV/c^2 -1	μ^- muon 0.106 GeV/c^2 -1	τ^- tau 1.78 GeV/c^2 -1	Z^0 Z boson 91.2 GeV/c^2 0
				H Higgs boson 125 GeV/c^2 0

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QUARKS → EM, strong, weak, Higgs

LEPTONS → EM, weak, Higgs

Electromagnetic force

Strong nuclear force

Weak nuclear force

Particle masses

Standard Model of Particle Physics

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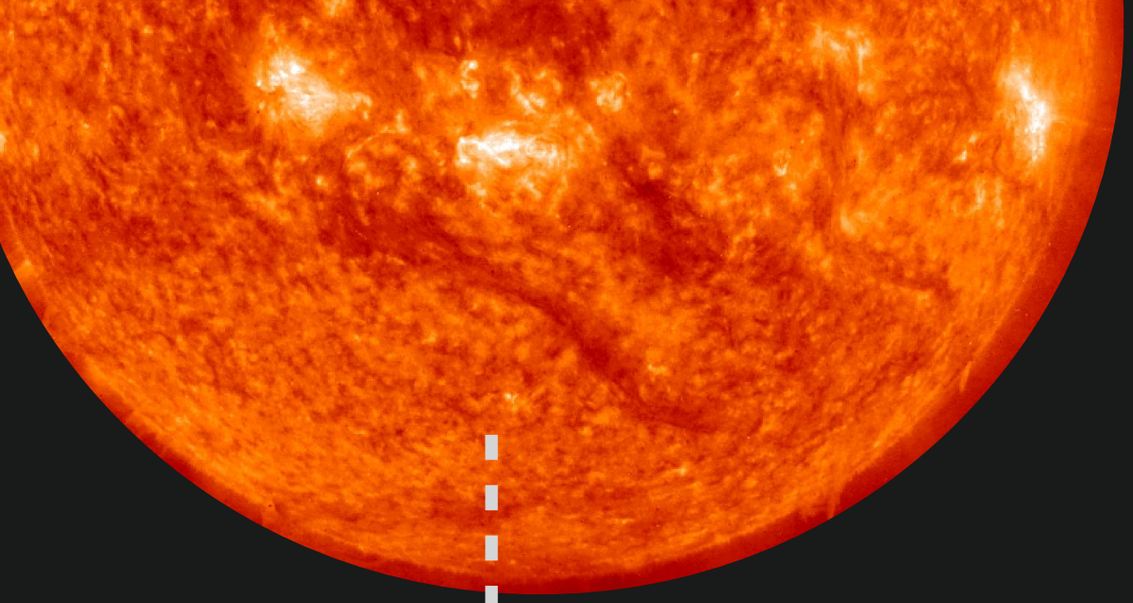
	e^- electron, -1, 511 keV/c^2	μ^- muon, -1, 0.106 GeV/c^2	τ^- tau, -1, 1.78 GeV/c^2
	EM, weak, Higgs		

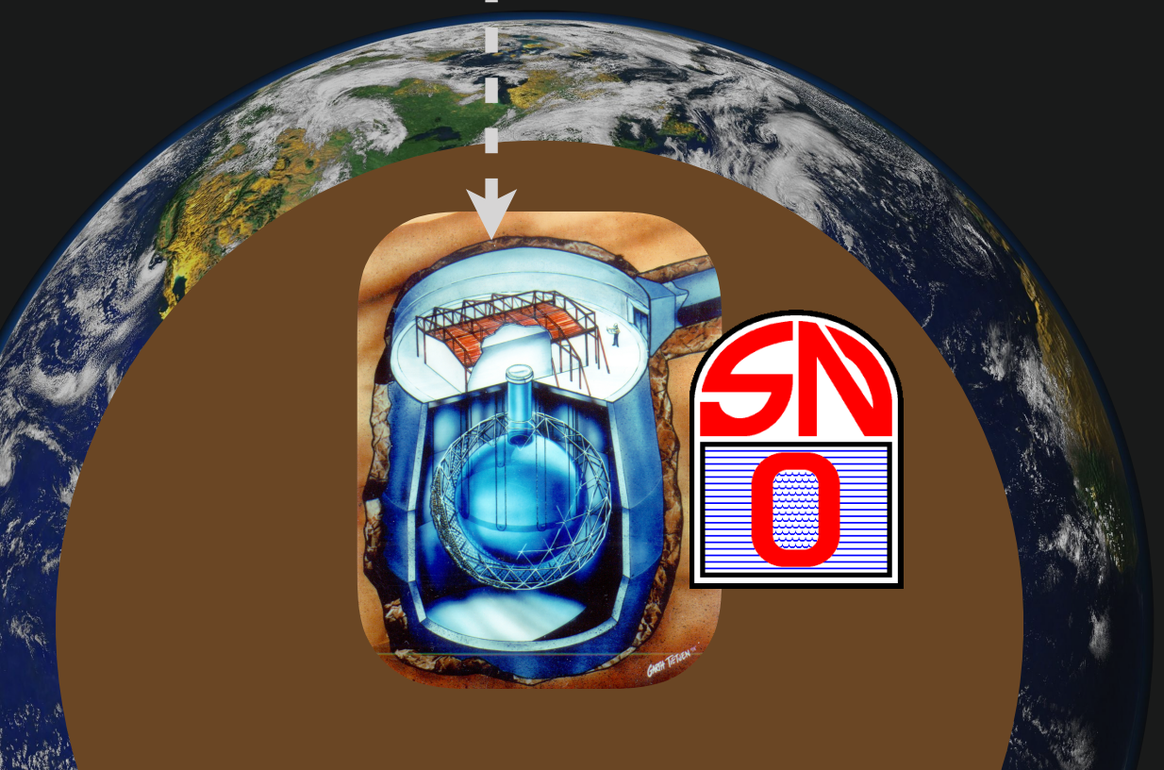
γ photon, 0, 0	Electromagnetic force
g gluon, 0, 0	Strong nuclear force
$W^\pm$ W boson, ±1, 80.4 GeV/c^2	Weak nuclear force
Z^0 Z boson, 0, 91.2 GeV/c^2	Weak nuclear force
H Higgs boson, 0, 125 GeV/c^2	Particle masses

Neutrinos seem
to be missing!



ν_e

Solar Neutrino Problem

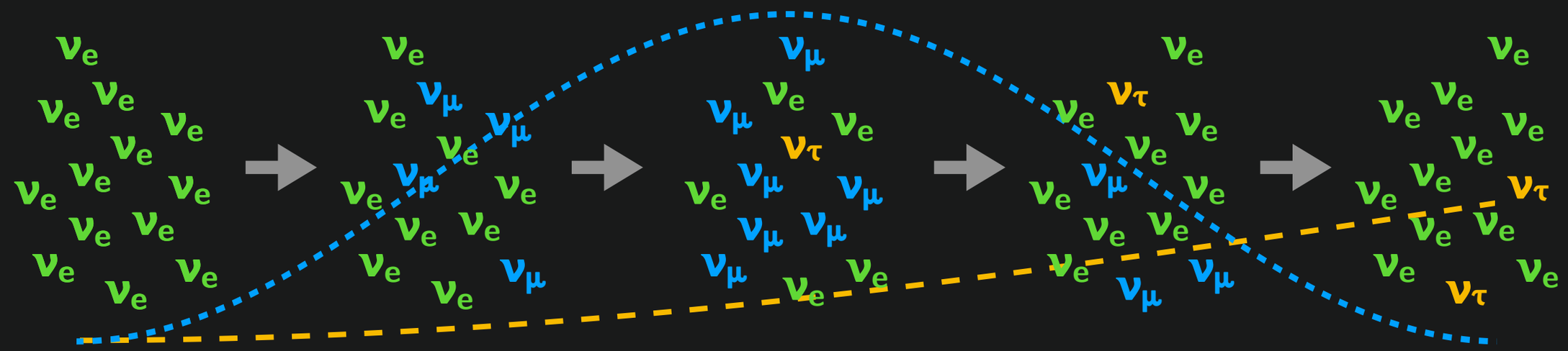


ν_μ

Atmospheric Neutrino Anomaly

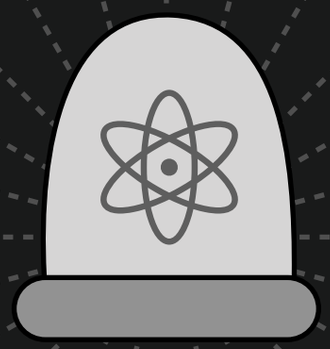
Neutrino Oscillations

Neutrinos can change type in flight if they have a small but nonzero mass!



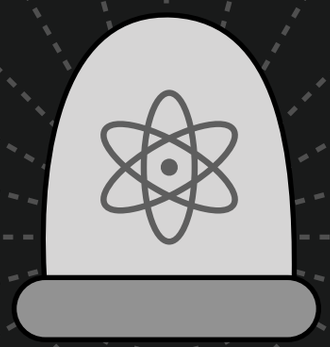
Oscillation Experiments

Oscillation Experiments



Nuclear Reactors

Oscillation Experiments



Nuclear Reactors

Chooz

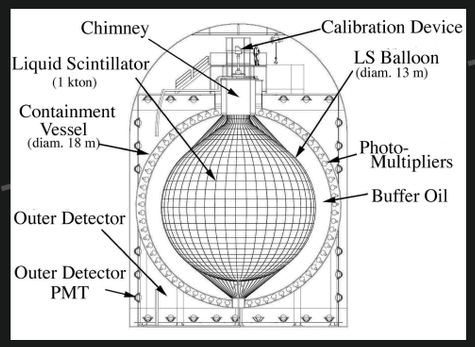
Bugey Rovno

Savannah River

ILL Goesgen

Palo Verde

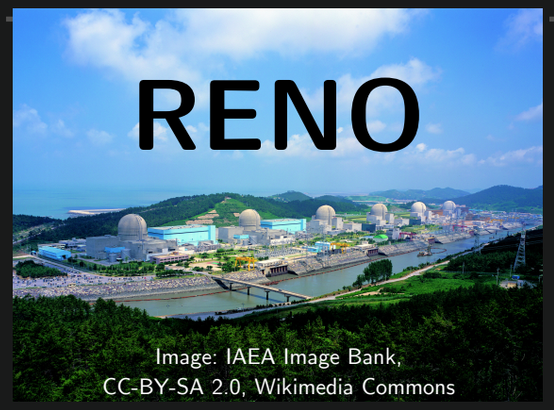
Krasnoyarsk



KamLAND

Photo: Thierry Lasserre, CEA/irfu

& more!



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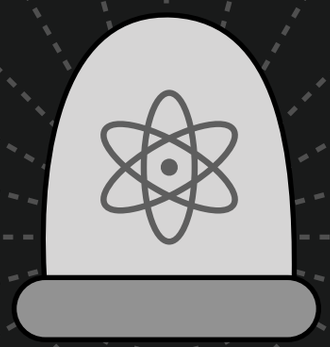
Oscillation Experiments



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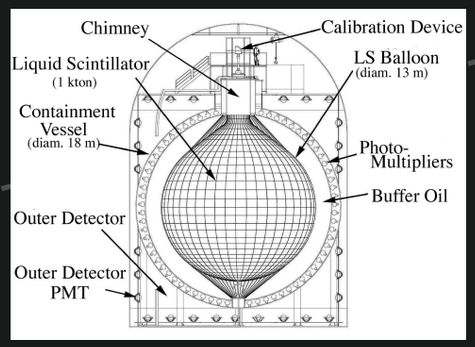

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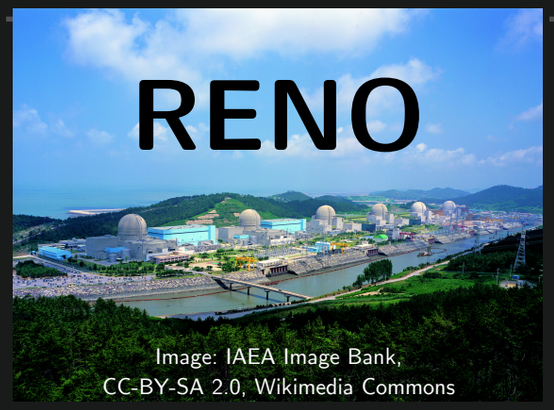

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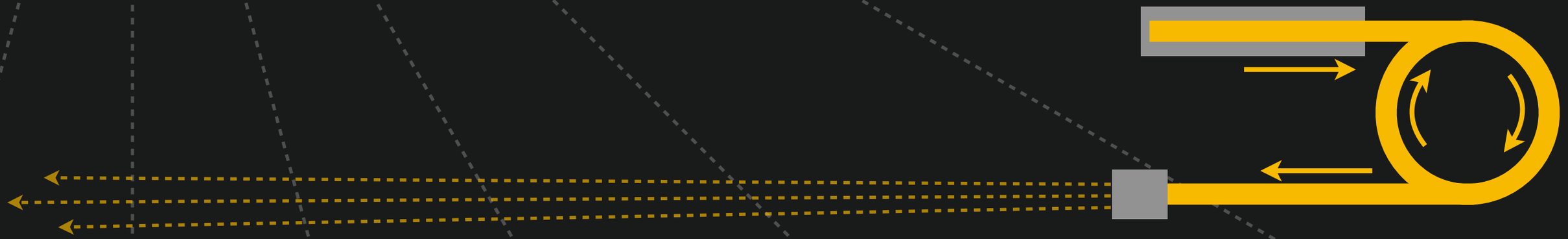
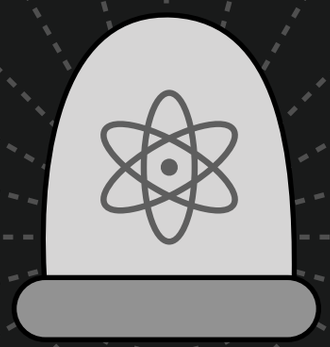


Particle Accelerators

Oscillation Experiments



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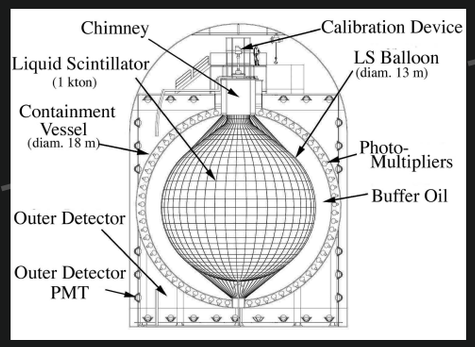

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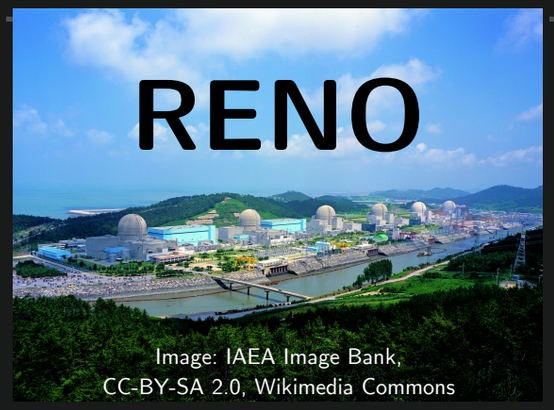

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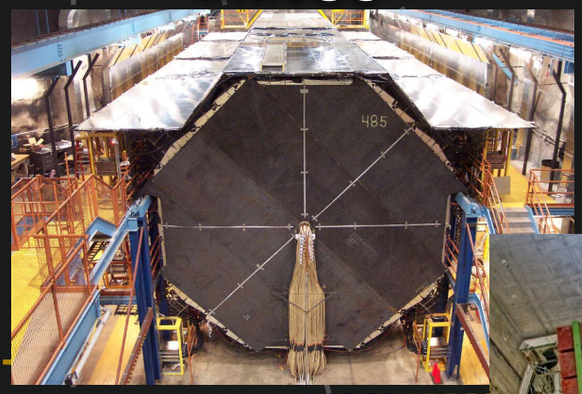
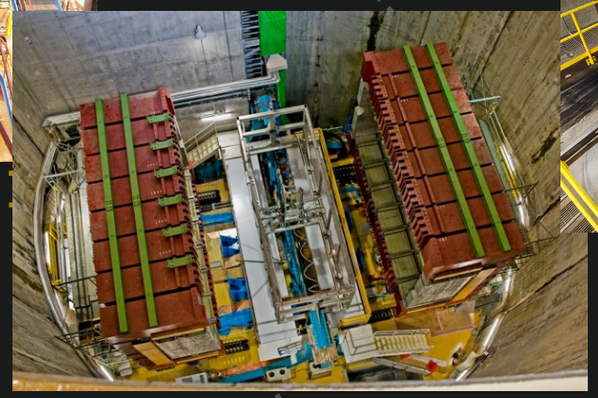
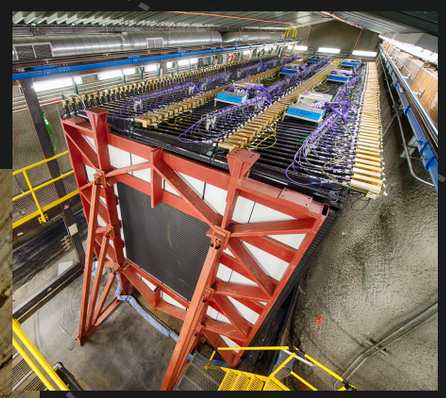
MINOS



T2K



NOvA



& more!

Particle Accelerators

Neutrino Oscillations

Probability that a neutrino of one type ends up as another:

$$P(\nu_e \to \nu_e) \quad P(\nu_\mu \to \nu_\tau)$$
$$P(\nu_\mu \to \nu_e) \quad P(\bar{\nu}_\mu \to \bar{\nu}_e)$$
$$P(\bar{\nu}_e \to \bar{\nu}_e) \quad \ldots$$

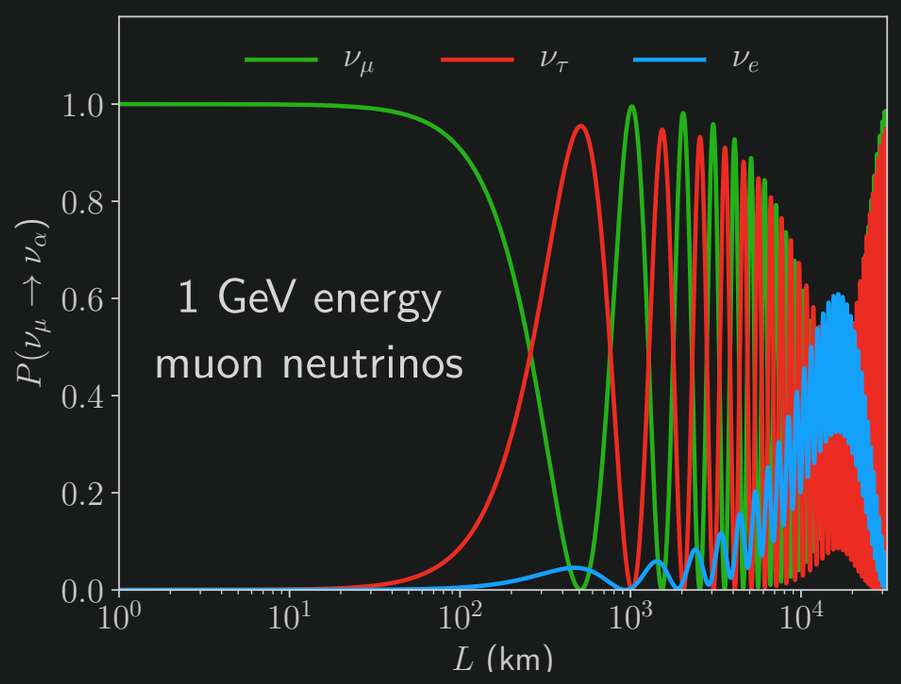
Depends on neutrino energy, time it's been propagating, and a few constants of nature:

Overall probability $\theta_{12}, \theta_{13}, \theta_{23}$

Mass differences $\Delta m^2_{12}, \Delta m^2_{23}$

CP Violation δ_{CP}

(neutrinos & antineutrinos oscillate differently)



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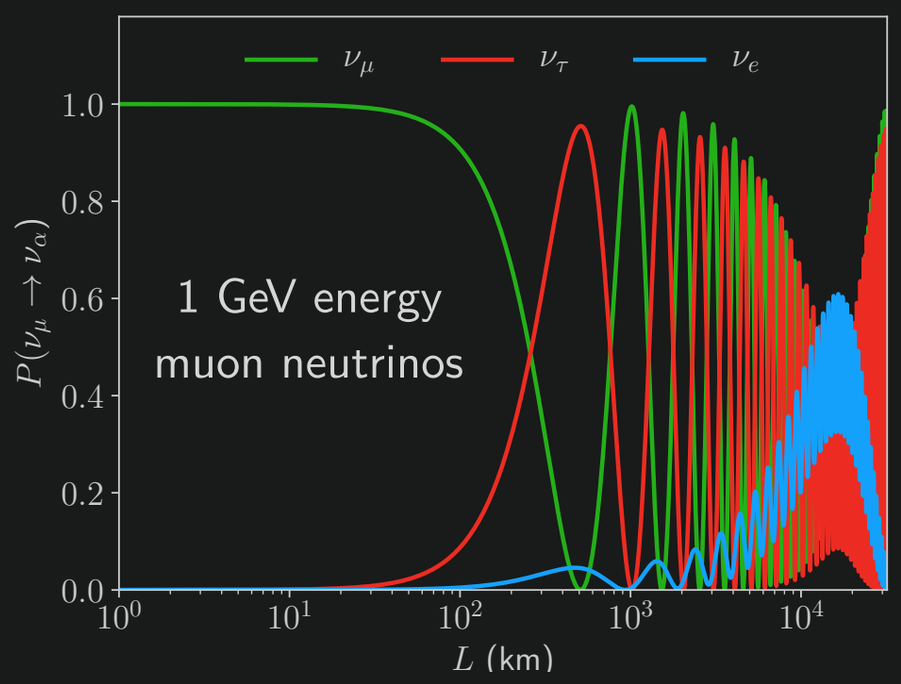
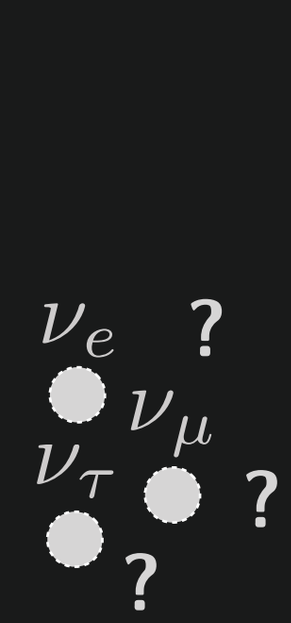
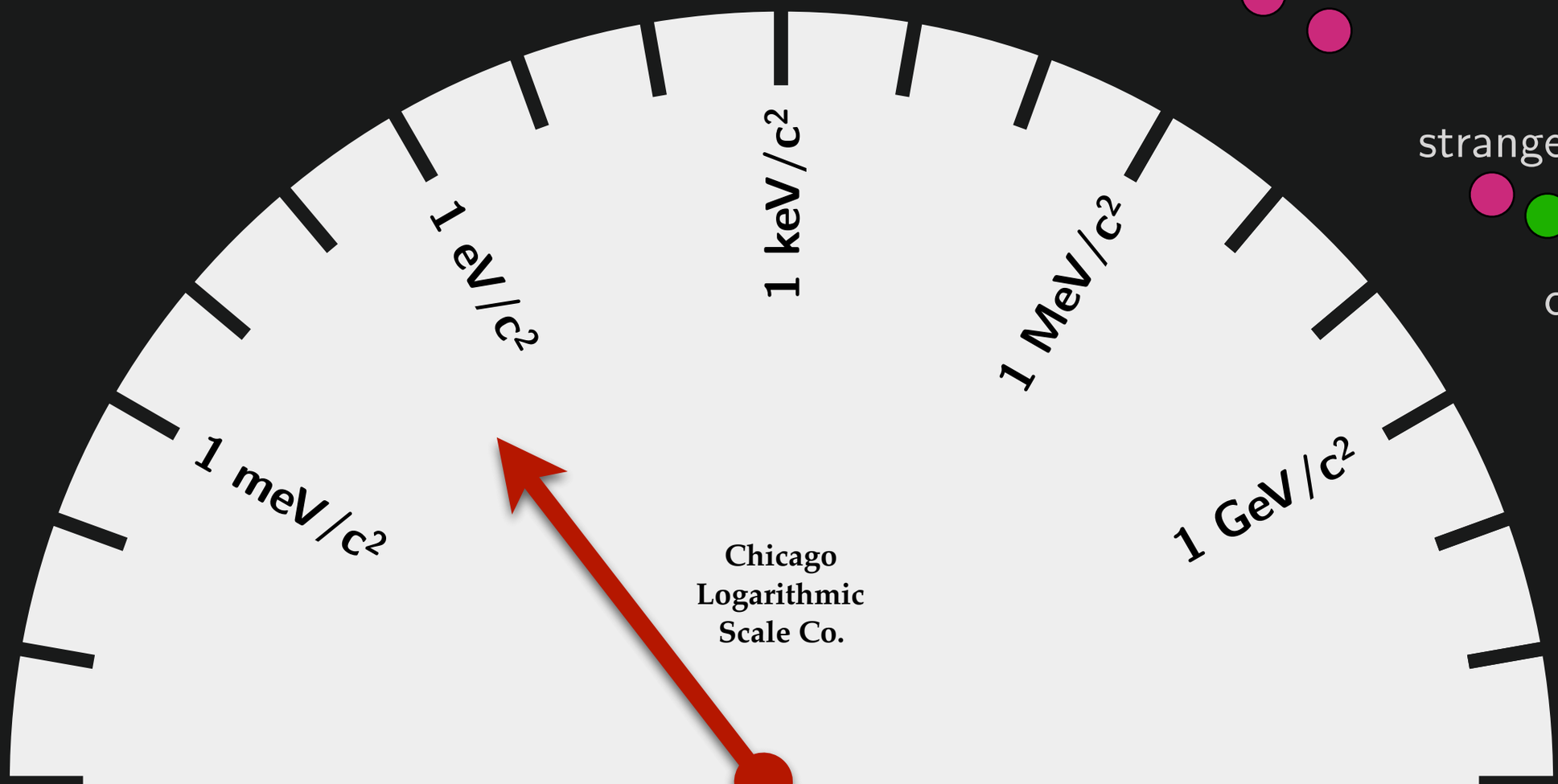


Neutrino Puzzles

Neutrino Mass

Neutrino oscillations require that neutrinos have mass.
But what are the masses, and *why are they so small?*





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$\sum U_{ei}^2 m_i$

Neutrinoless Double Beta Decay*

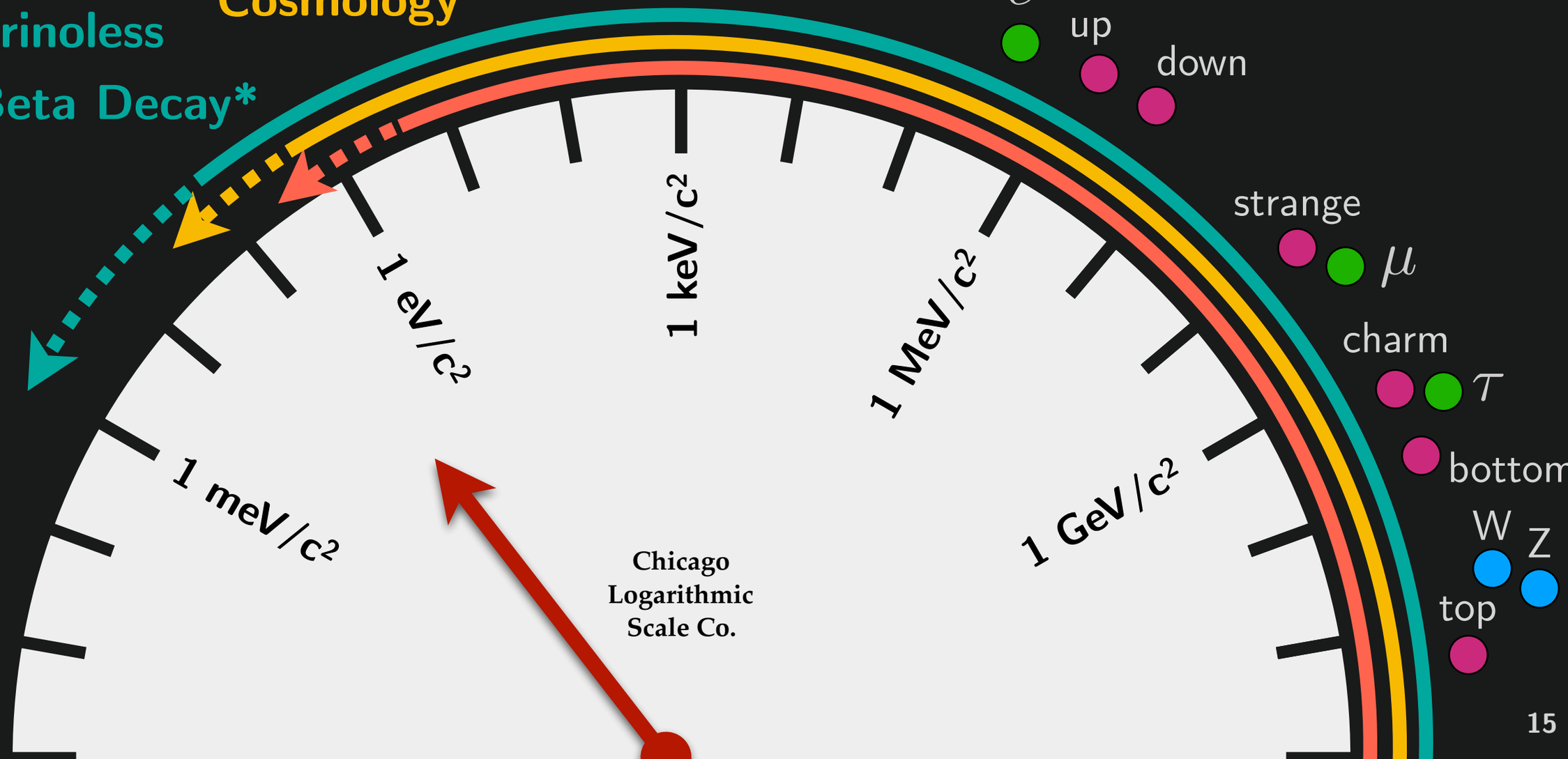
$\sum m_i$

Cosmology

$m(\nu_e)$

Beta Decay

ν_e ? ν_μ ν_τ ? ?



e up down

strange μ

charm τ

bottom

W Z

top

Neutrino Mass

Neutrino Mass

Neutrino **Cosmology**

with neutrinos **no neutrinos**

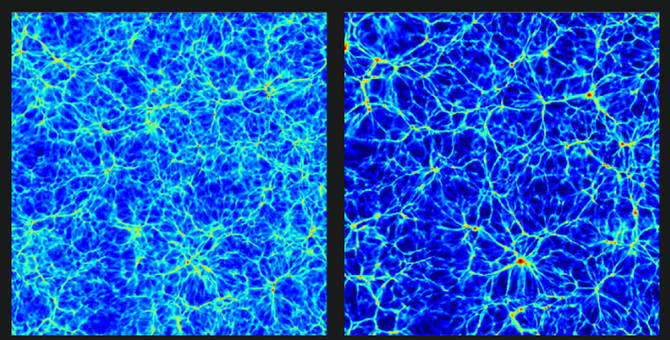


Image: Agarwal and Feldman

Weighing neutrinos using the universe as a scale

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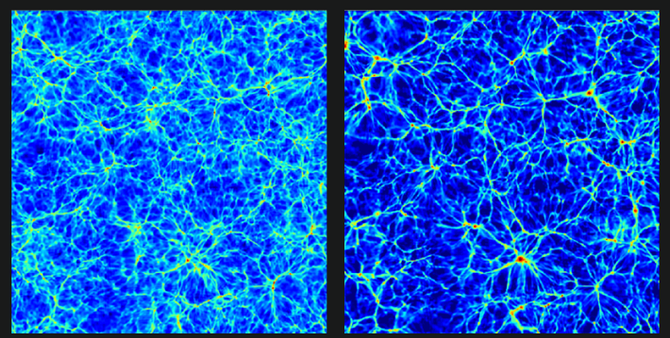

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Beta Decay

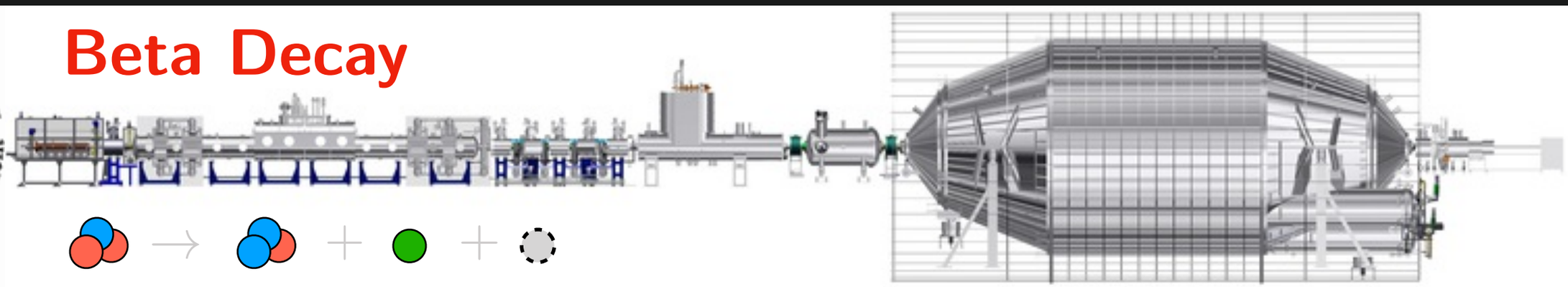

Image: Karlsruhe Tritium Neutrino Experiment

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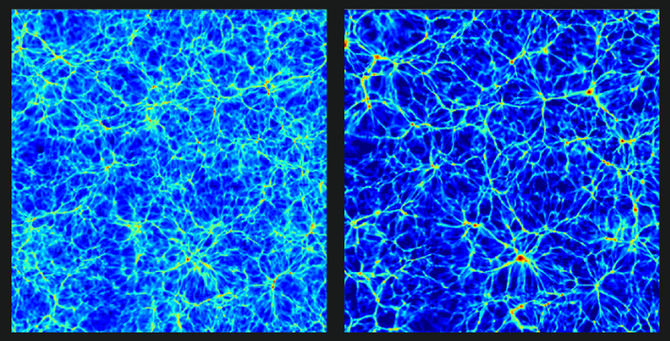

Image: Agarwal and Feldman

Weighing neutrinos
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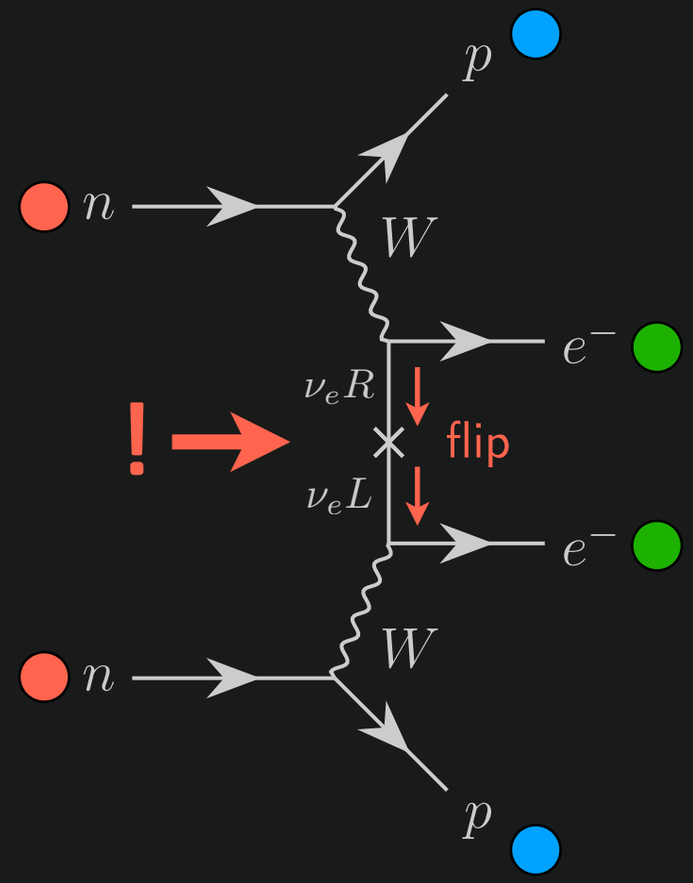
Neutrinoless Double Beta Decay

A rare form of
nuclear decay,
so far never
observed

Only if neutrino is
its own antiparticle



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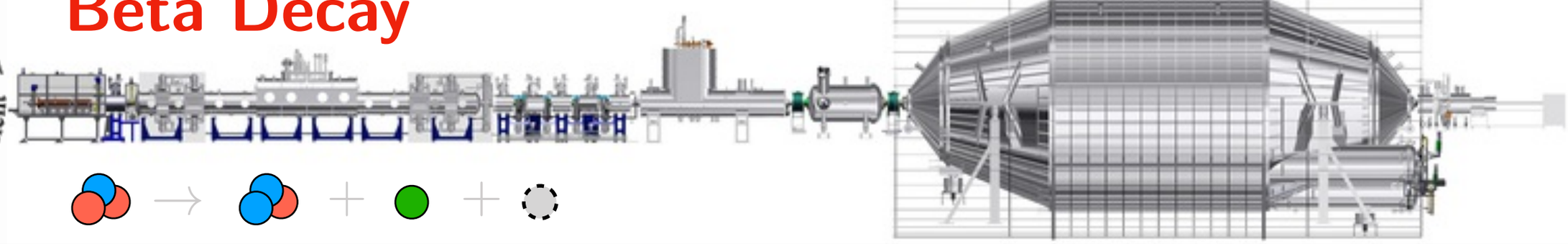

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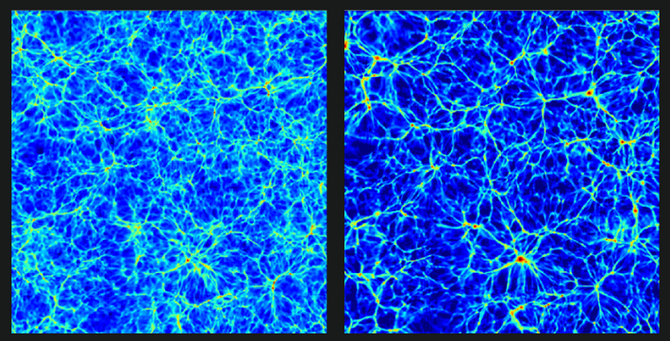

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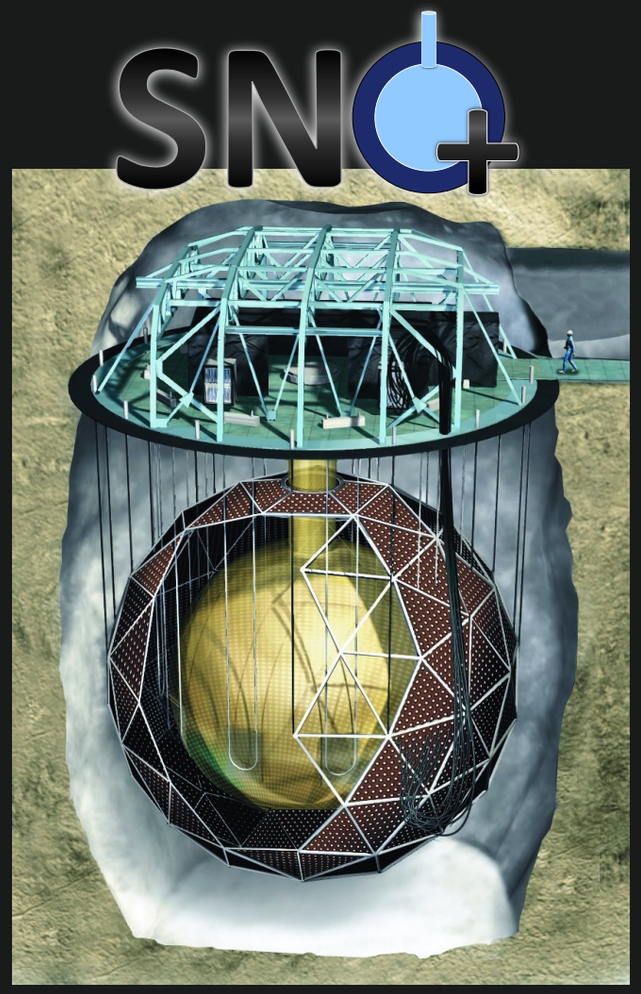

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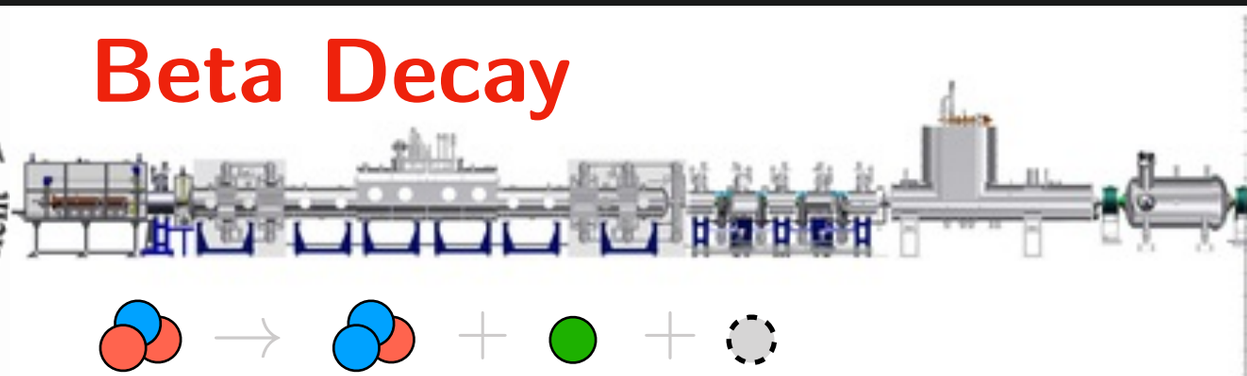


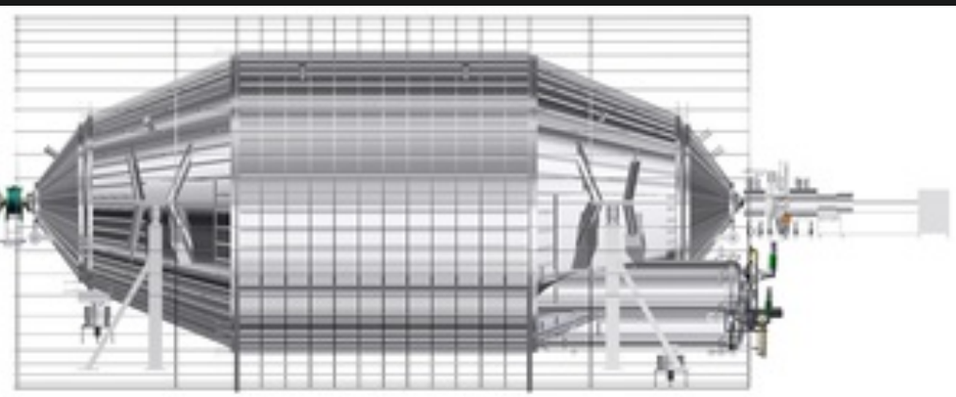
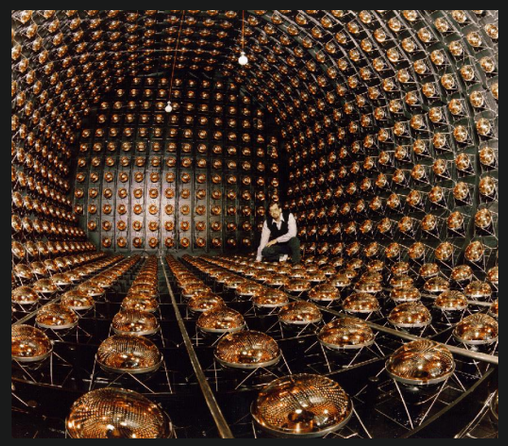


Image: Karlsruhe Tritium Neutrino Experiment

How Many Neutrinos?

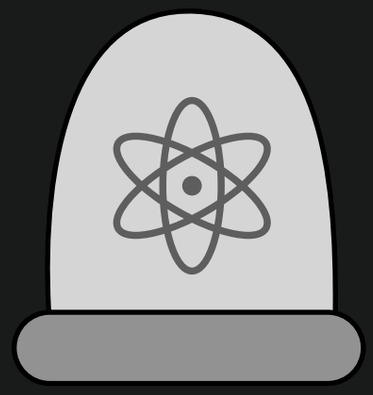
Several neutrino oscillation experiments hinting at a **new, fourth neutrino type**:



LSND

Liquid Scintillator Neutrino Detector

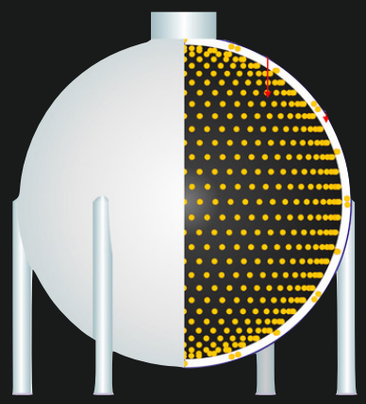
ν_e appearance in a ν_μ beam



Reactors

Updated reactor flux calculations

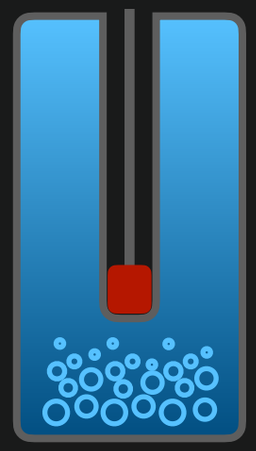
ν_e disappearance at small distances



MiniBooNE

An independent check of LSND

ν_e appearance in a ν_μ beam



Gallium

Solar neutrino experiment calibrations

ν_e disappearance at small distances

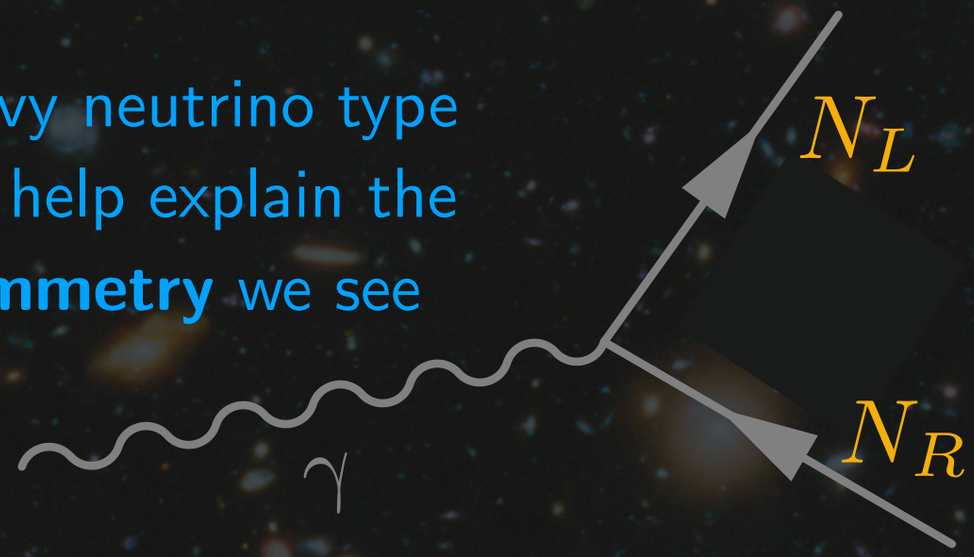
☞ Sterile Neutrinos ☜

δ_{CP}

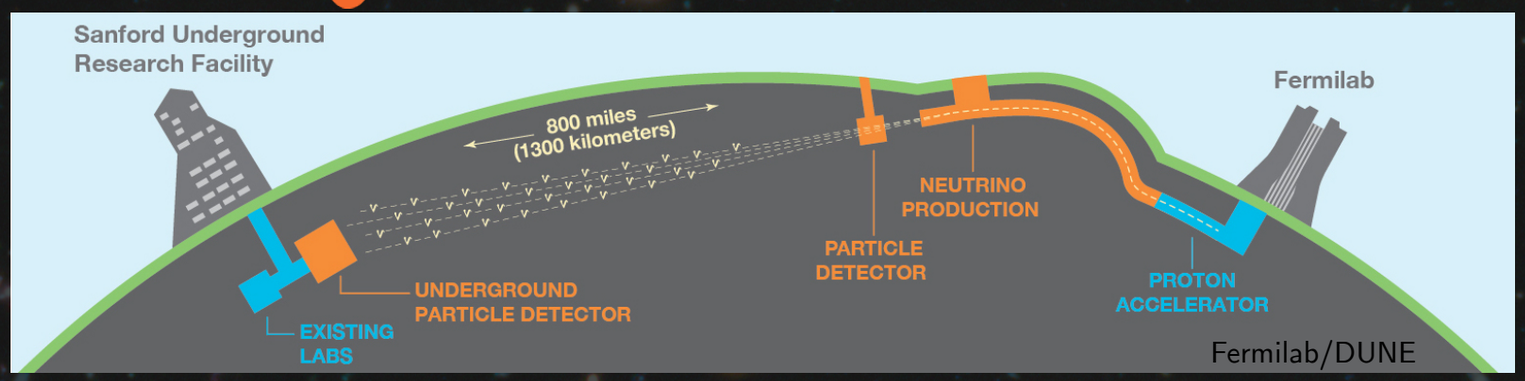
CP Violation

We don't know whether neutrinos and antineutrinos interact differently (CP Violation)

If so, decays of a new, heavy neutrino type in the early universe could help explain the **matter/antimatter asymmetry** we see today



DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



A major international effort to measure this effect, using neutrino beam from Fermilab to South Dakota (SURF)

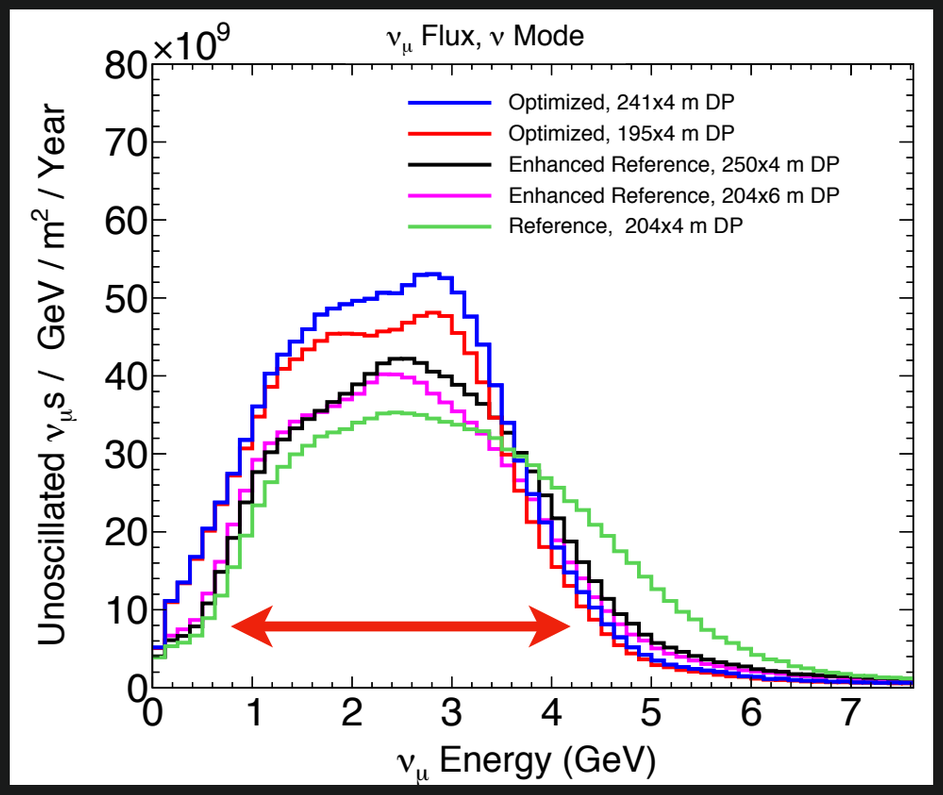
Image: Hubble Deep Field, NASA

Neutrino Interactions

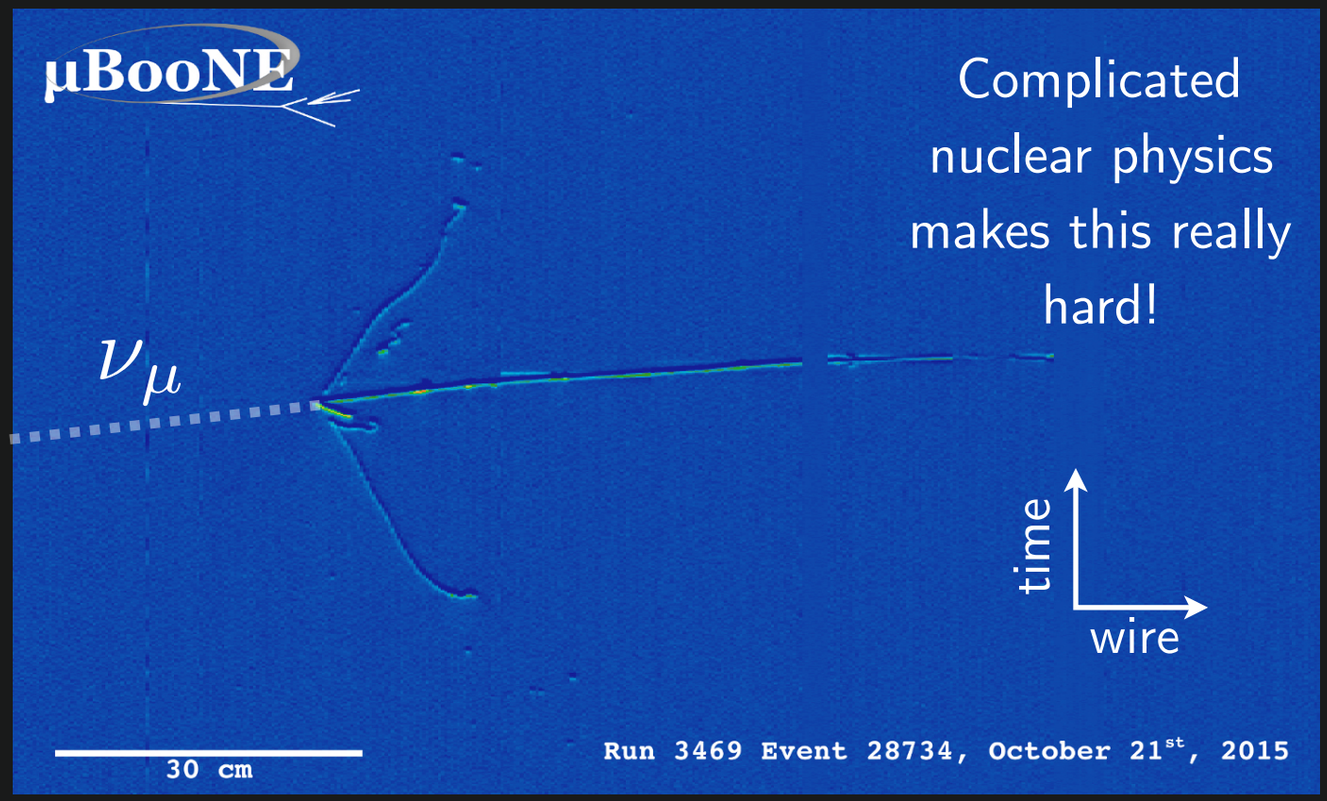
$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{E}\right)$$

To measure oscillations, you need to know the neutrino energy

We typically can only produce neutrinos with a broad range of energies

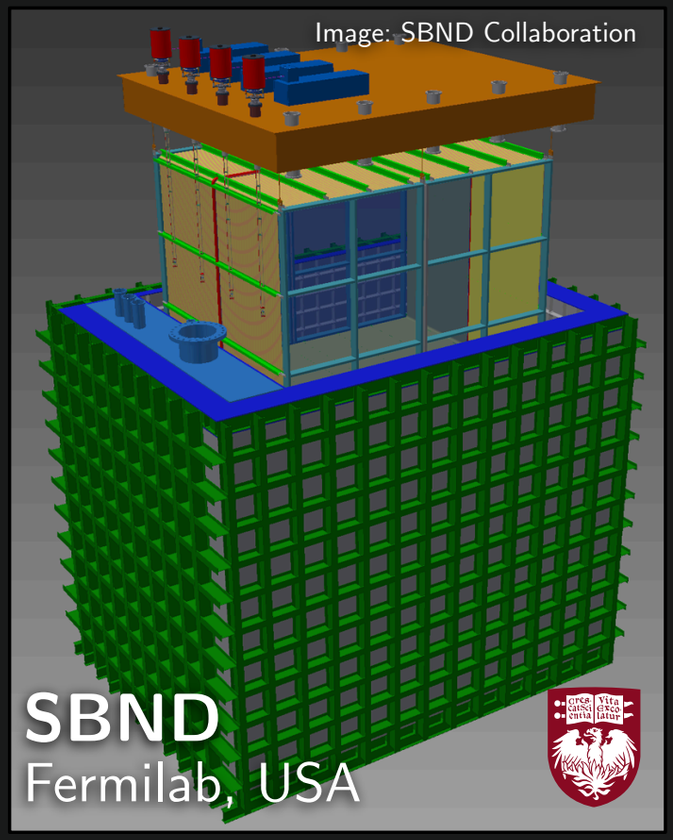


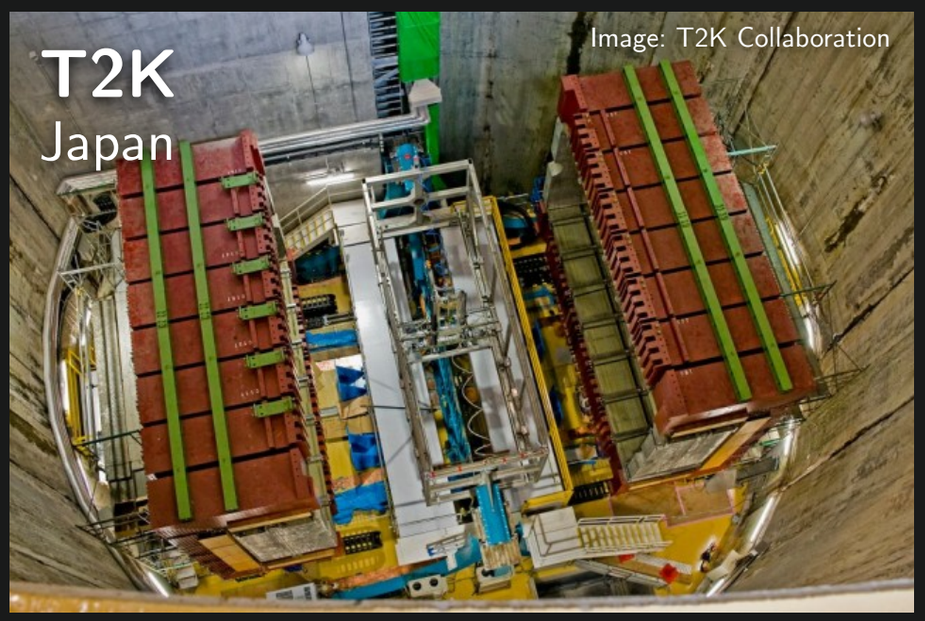
We can only measure the neutrino energy indirectly, based on what comes out

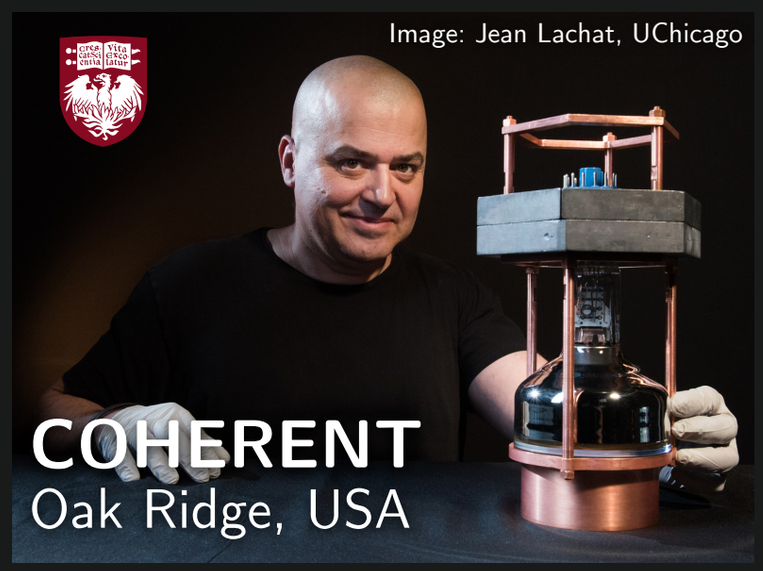


We need a better understanding of neutrino interactions: theory & experiment

Neutrino Interactions



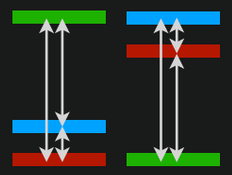




A worldwide effort aimed at better understanding neutrino interactions, required for higher-precision experiments!

Big Open Questions

What is the mass of the neutrino, and why is it so small?



What is the ordering of the neutrino masses?

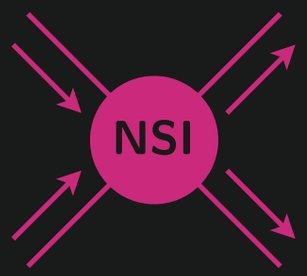
$\nu \stackrel{?}{=} \bar{\nu}$

Is the neutrino its own antiparticle?

Could CP violation in neutrino interactions explain the matter/antimatter asymmetry?

ν_s

Are there additional neutrinos beyond the known three types?



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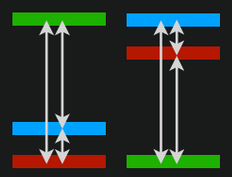

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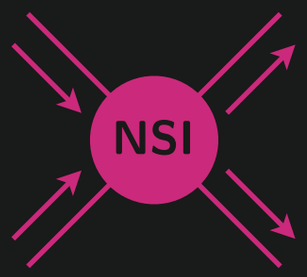

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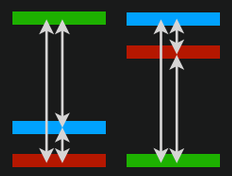

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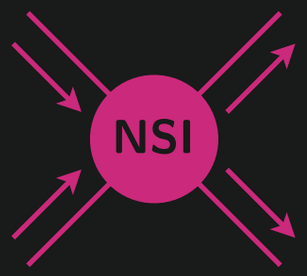

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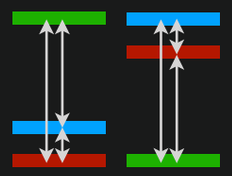

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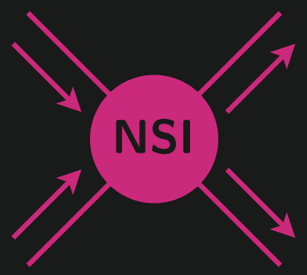

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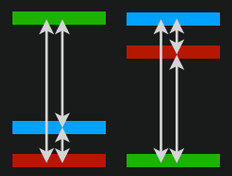

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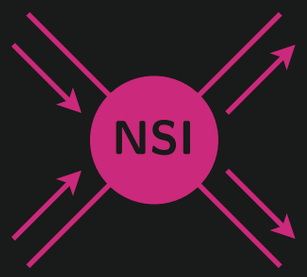

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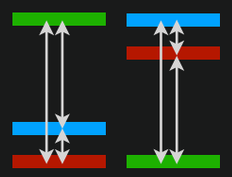

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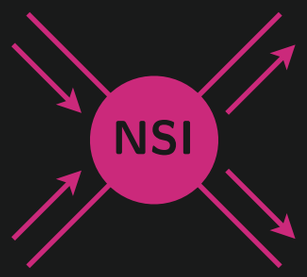

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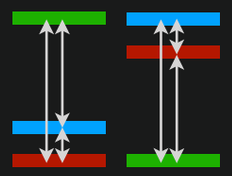

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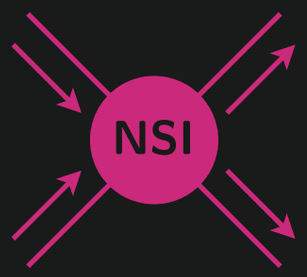
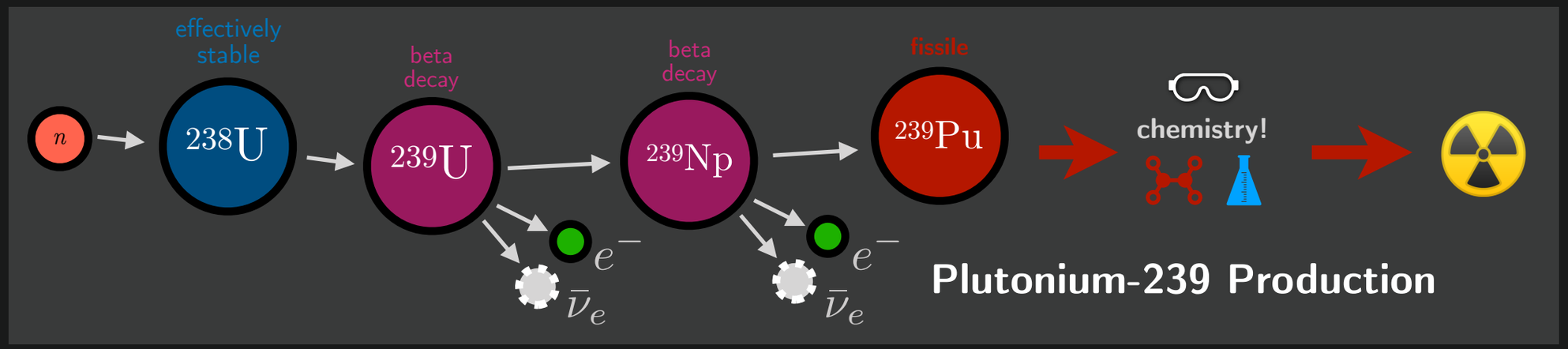


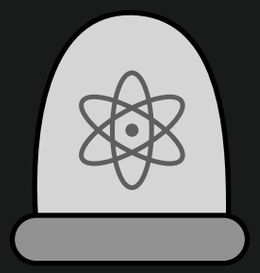
Additional interactions we could discover via neutrinos?

$\longrightarrow$ Solar neutrinos, long-baseline oscillations (e.g. DUNE)

Neutrinos as Tools

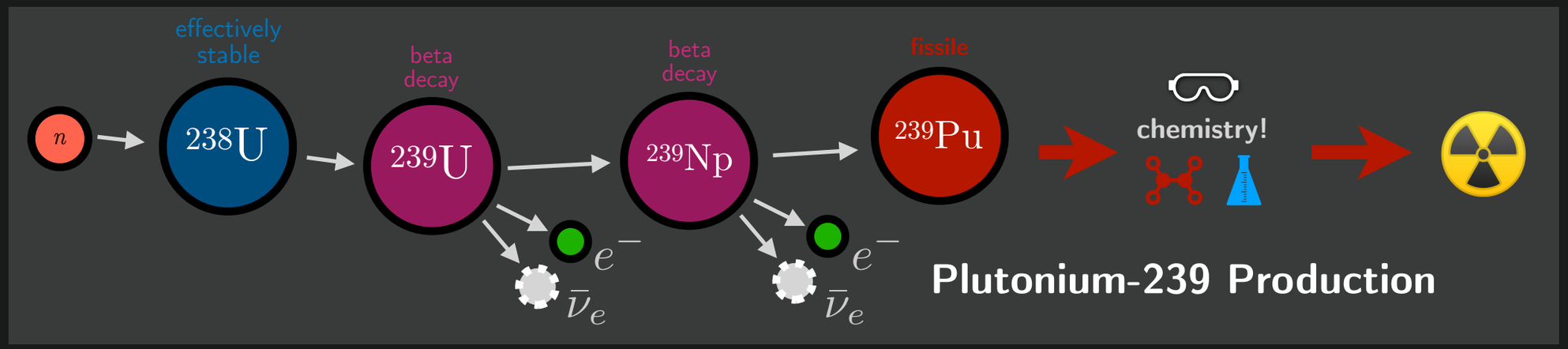
Nuclear Reactor Monitoring

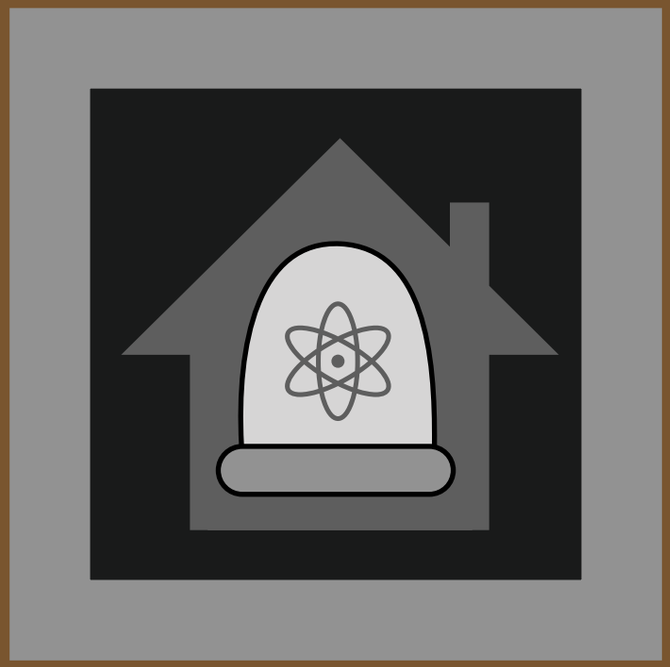




Upper figure based on http://svoboda.ucdavis.edu/experiments/watchman/

Nuclear Reactor Monitoring





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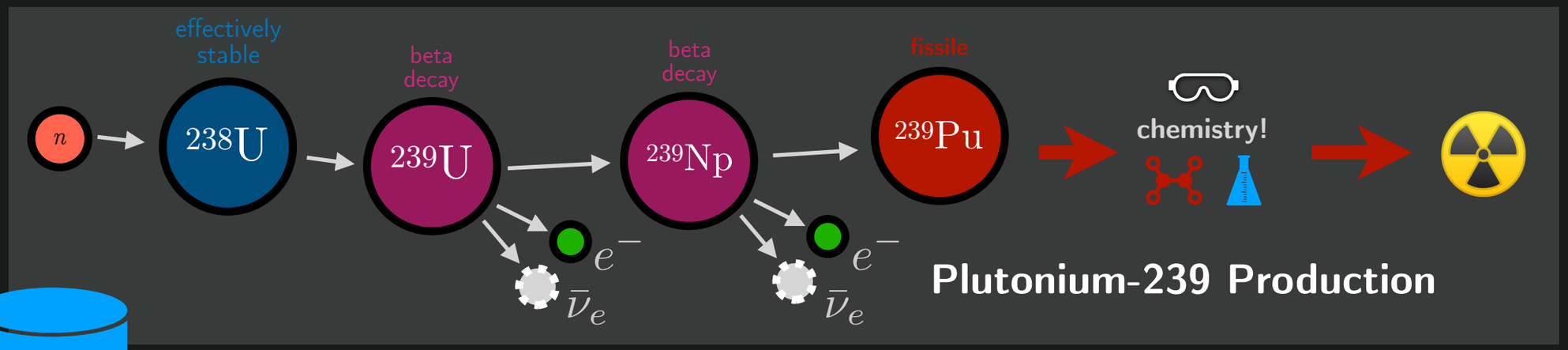
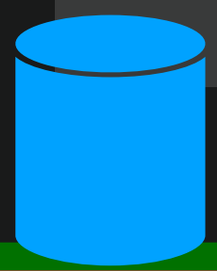




You can't shield neutrinos!

Upper figure based on http://svoboda.ucdavis.edu/experiments/watchman/

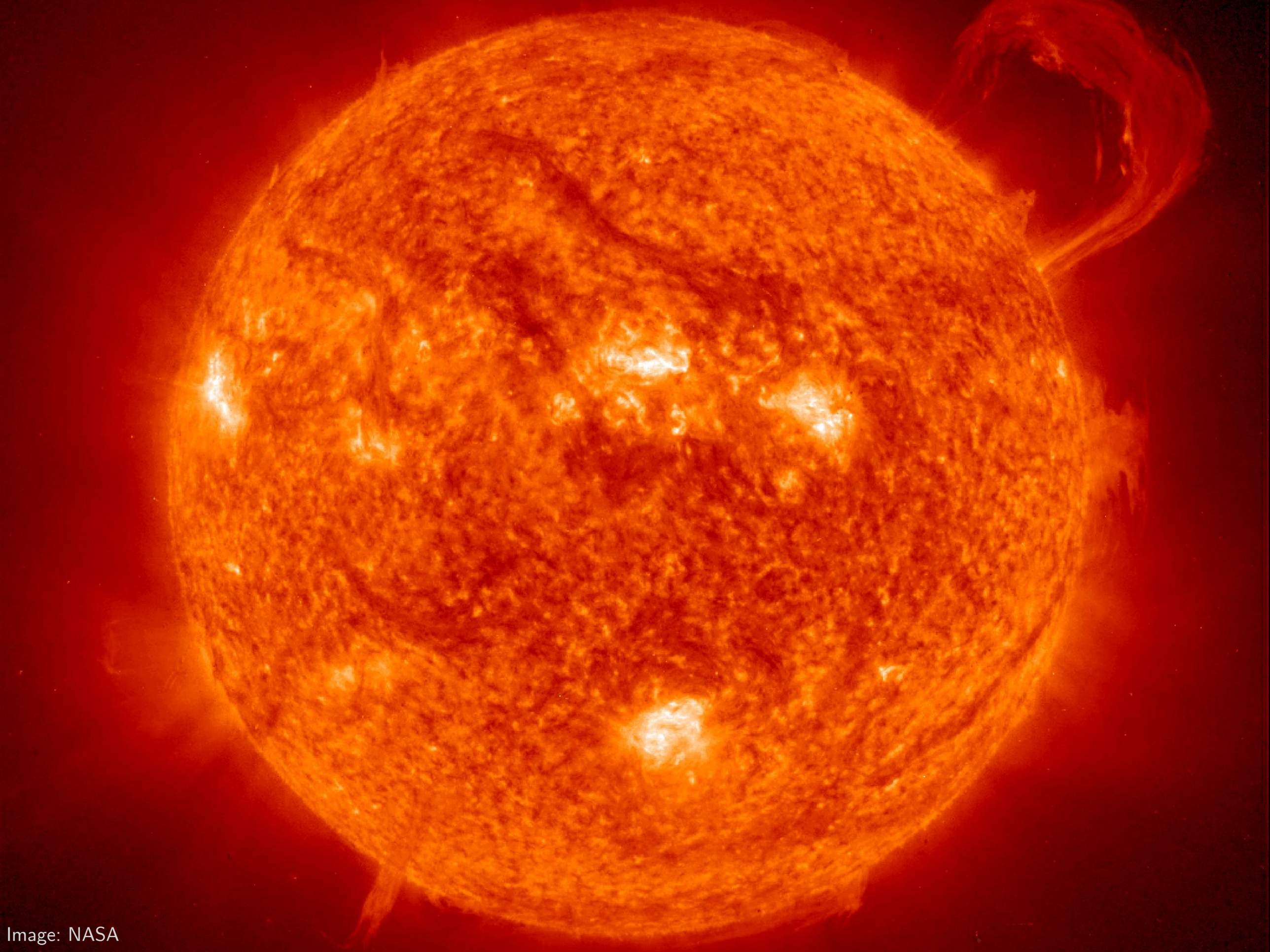
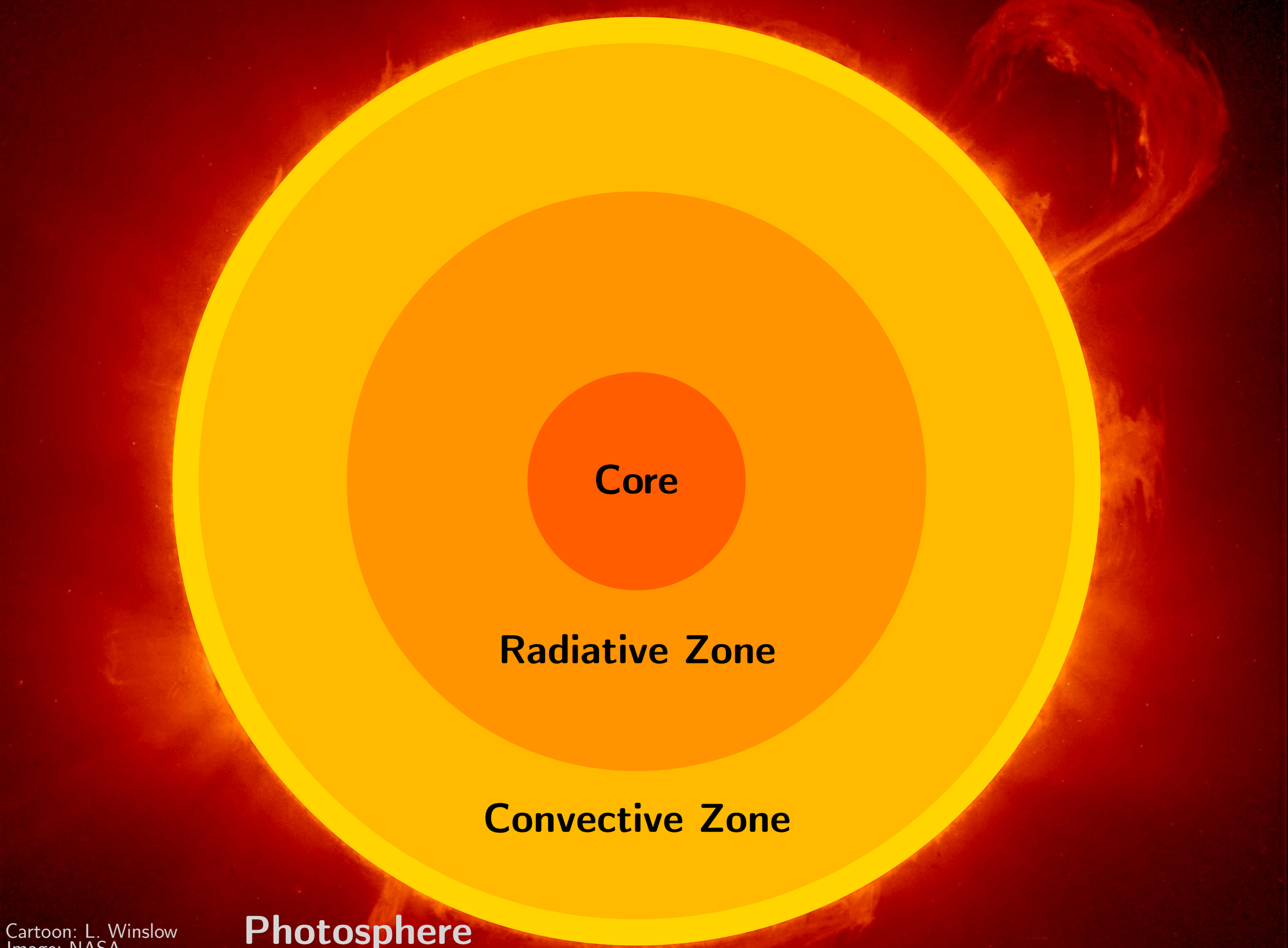
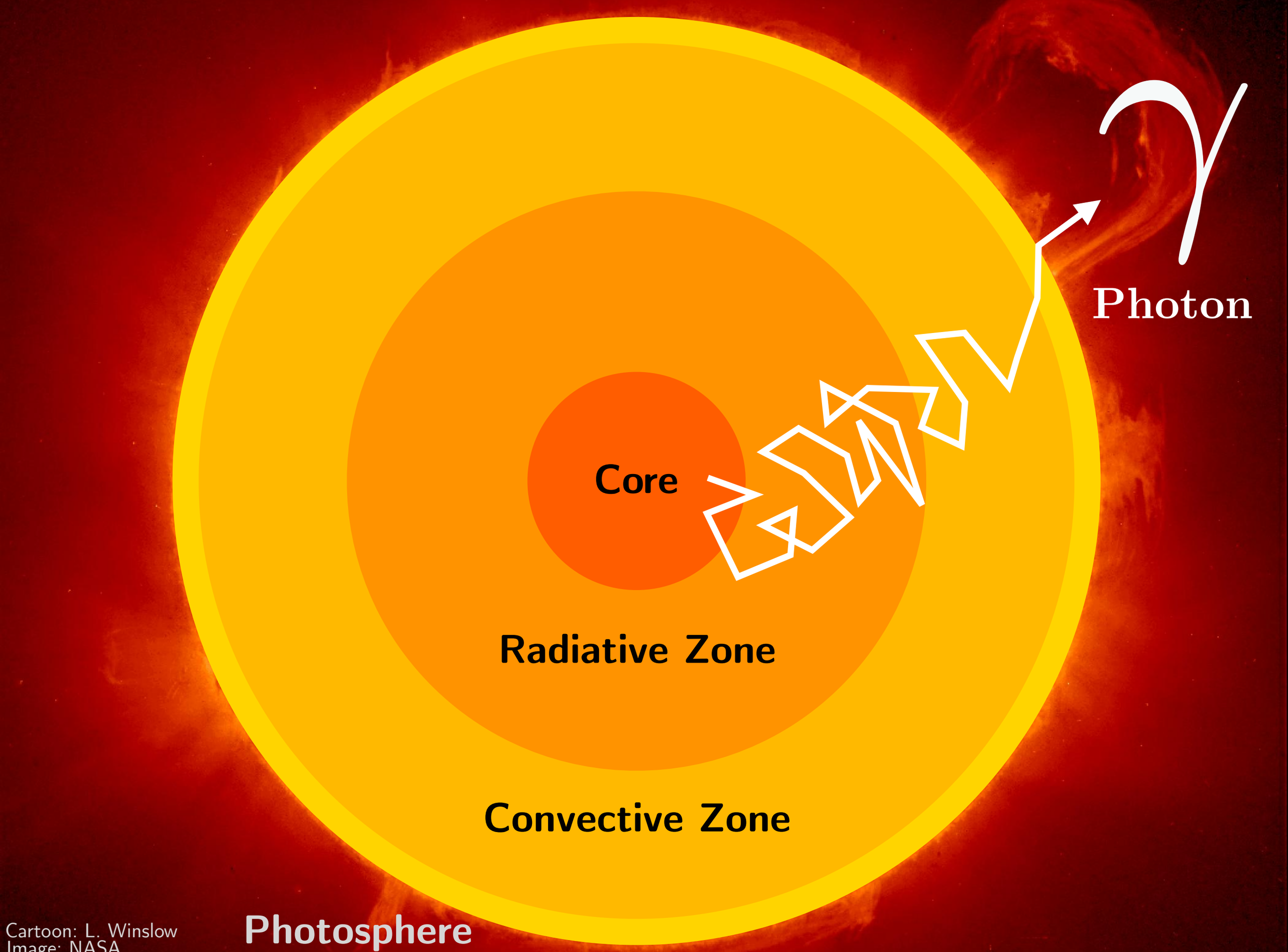


Image: NASA


Core
Radiative Zone
Convective Zone
Photosphere
Cartoon: L. Winslow
Image: NASA



Cartoon: L. Winslow
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ν

Neutrino

γ

Photon

Core

Radiative Zone

Convective Zone

Photosphere

Cartoon: L. Winslow
Image: NASA

Credit: ALMA (ESO/NAOJ/NRAO)/A. Angelich. Visible light image: the NASA/ESA Hubble Space Telescope. X-Ray image: The NASA Chandra X-Ray Observatory

SN1987A

February 23, 1987

Large Magellanic Cloud

(170,000 light years away)

Type II Supernova

Credit: ALMA (ESO/NAOJ/NRAO)/A. Angelich. Visible light image: the NASA/ESA Hubble Space Telescope. X-Ray image: The NASA Chandra X-Ray Observatory

Relic Neutrinos

Can we detect neutrinos left over from the Big Bang?

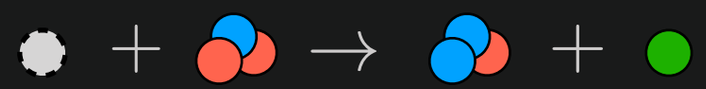
PTOLEMY aims to detect these low-energy neutrinos when they interact and produce an electron

Beta Decay

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$$

Neutrino Capture

$$\nu_e + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$$



PTOLEMY Prototype

Princeton Plasma Physics Laboratory, USA

Image: Elle Starkman, PPPL Office of Communications

Ultra-High Energy Sources

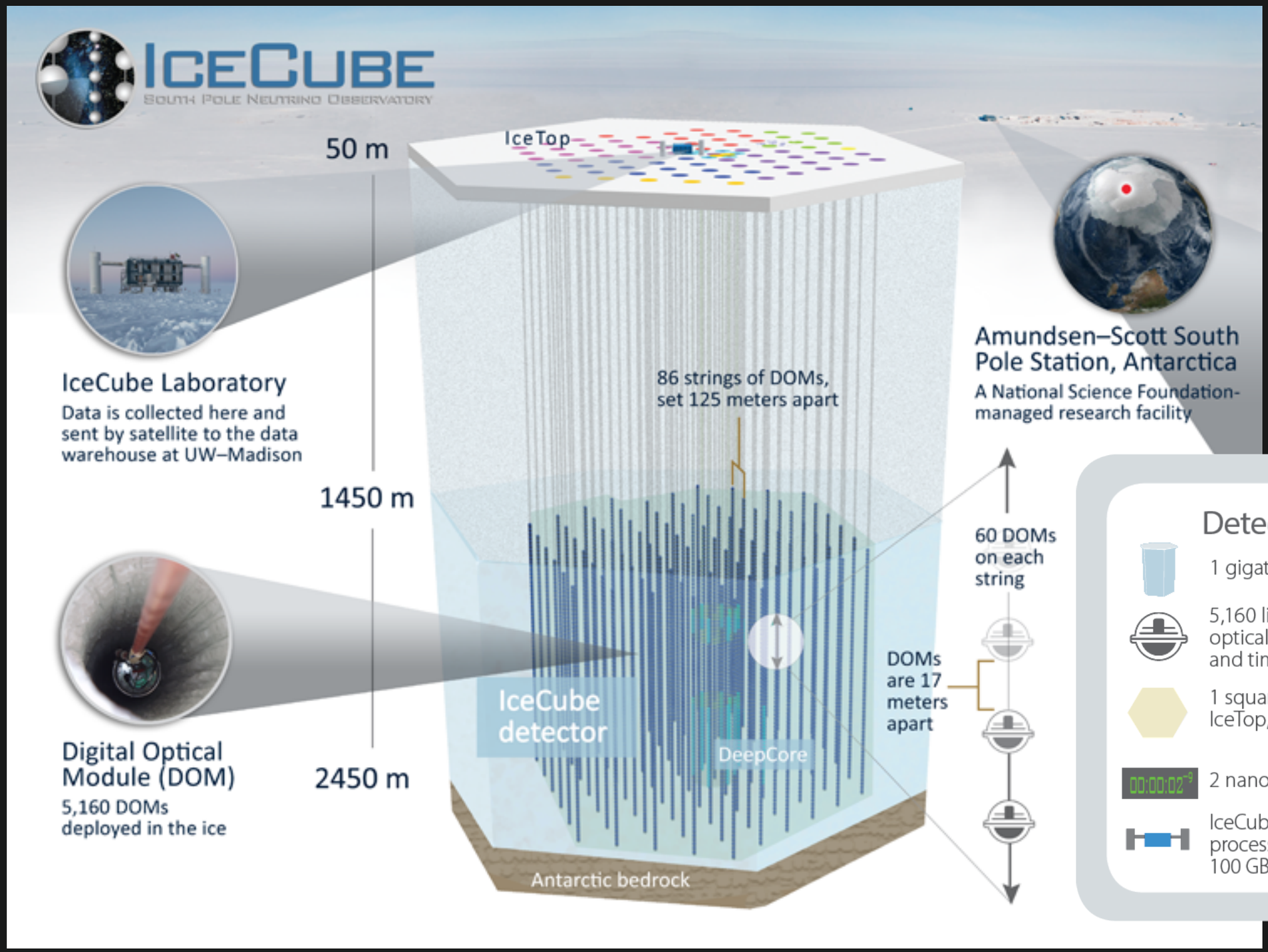
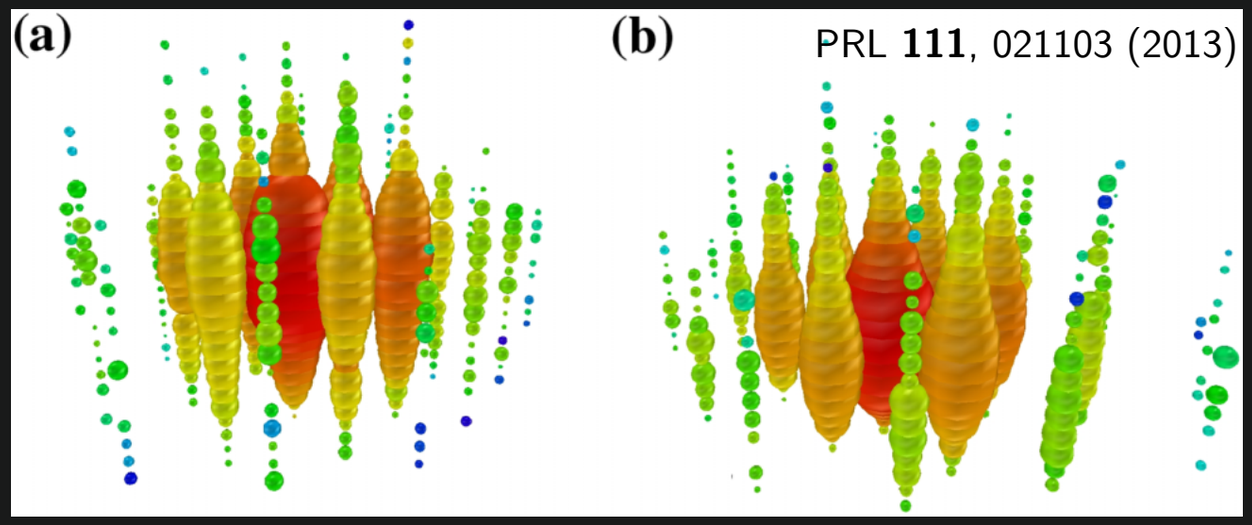


Image: IceCube/NSF/University of Wisconsin-Madison

https://icecube.wisc.edu/science/icecube/detector

Ultra-High Energy Sources

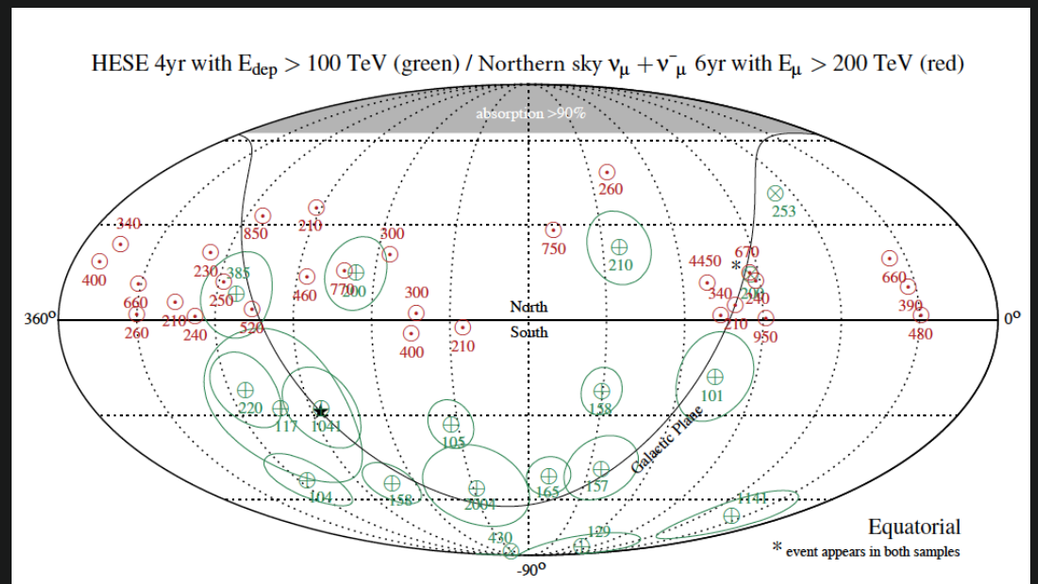


Bert
August 8, 2011
Energy: 1.04 PeV

Ernie
January 3, 2012
Energy: 1.14 PeV

PeV: 100,000,000× more energy than solar neutrinos
100× more energy than the LHC

Today, IceCube has detected over 80 Ultra-High Energy neutrinos



https://icecube.wisc.edu/science/highlights/neutrino_astronomy

The source of these high-energy neutrinos is currently unknown!

IceCube works to correlate these events with other astrophysical observations
e.g., gamma ray sources or gravity waves

Neutrinos are an essential building block of matter
we've come to understand over the past several decades

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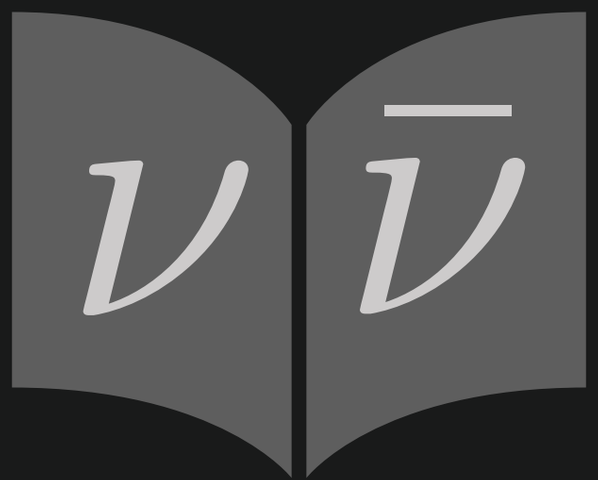
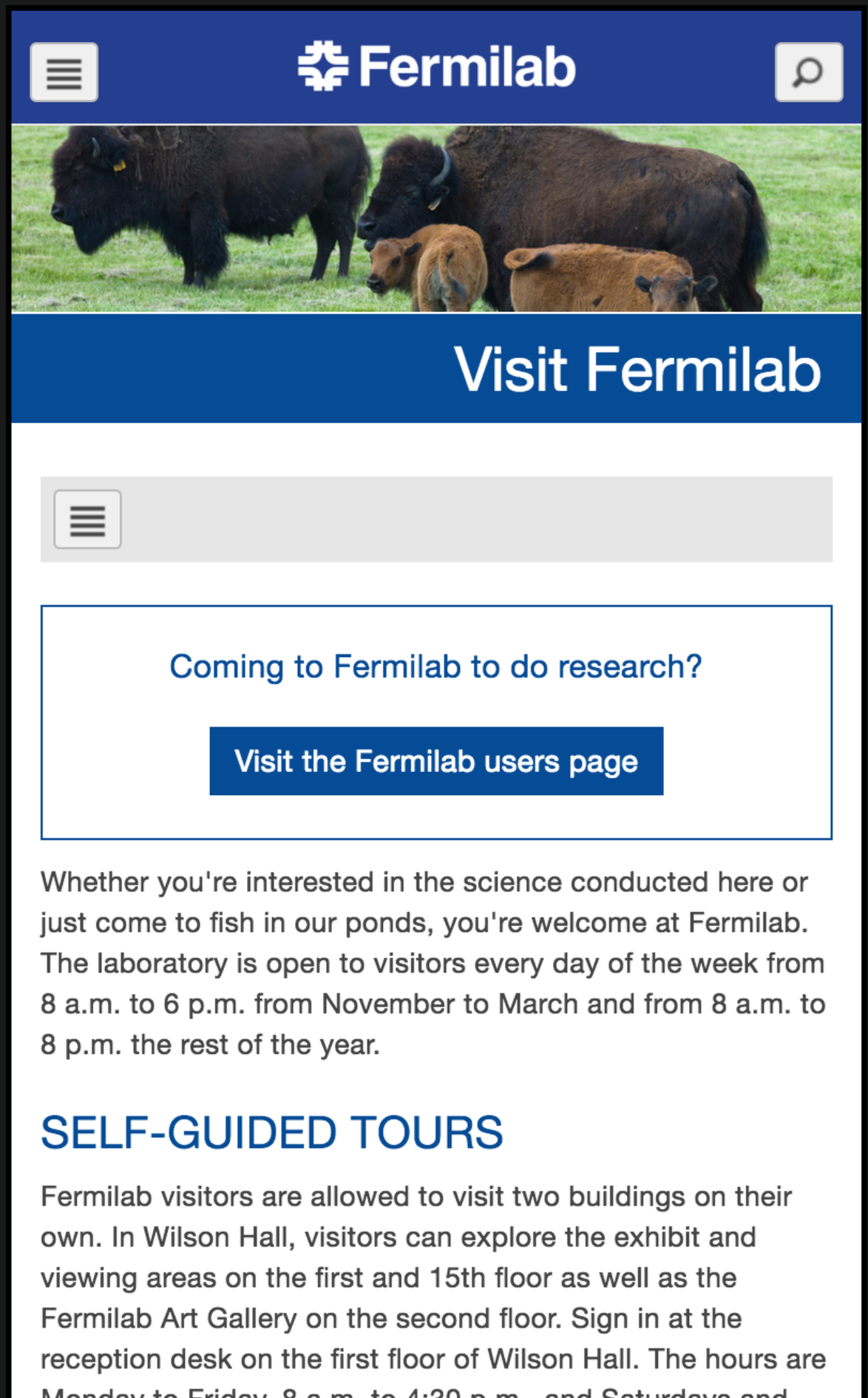
A number of unexplained results and fundamental open questions make neutrino physics an exciting area, ripe for important discoveries!

Meanwhile, neutrinos are a powerful tool for discovery, giving us a window into otherwise inaccessible systems like the interiors of stars or supernovae



Learning More



Pay a Visit to Fermilab!

Your Neighborhood Physics Lab

Colloquium Lecture Series
4 PM, Wednesdays

Ask A Scientist
1-4 PM, first Sundays

"Get to Know" Tours
Wednesdays, summer Sundays

Tevatron and D0 Tours
First Tuesday

Schedule and registration online:

https://www.fnal.gov/pub/visiting

Sign up for the Fermilab Frontiers email newsletter

Web & Social Media!

Many neutrino experiments are active on Twitter

Lots have pages to follow on Facebook

Websites with lots more details and information

Great Science Journalism!

Science News
sciencenews.org

ScienceNews

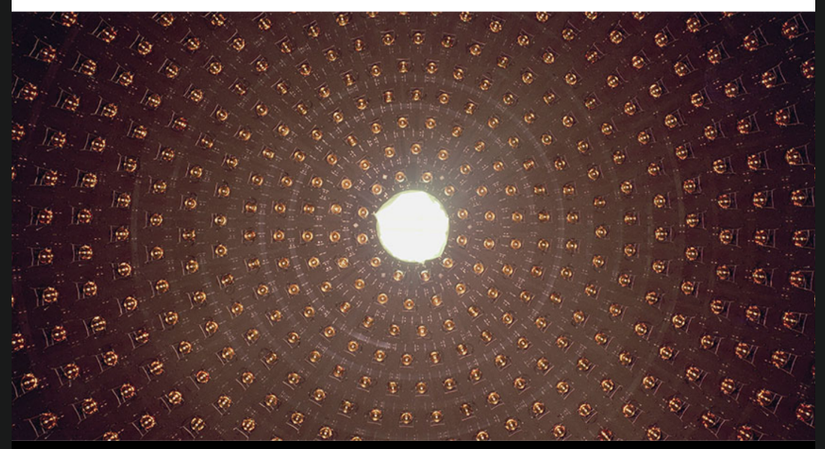
NEWS PARTICLE PHYSICS

Mysterious neutrino surplus hints at the existence of new particles

The MiniBooNE experiment found more interactions of the subatomic particles than expected

BY EMILY CONOVER 3:45PM, JUNE 1, 2018

SHARE ARTICLE



NEW NEUTRINO? The particle detector MiniBooNE (shown) observed an excess of neutrino interactions, which may hint at the existence of a new type of neutrino.

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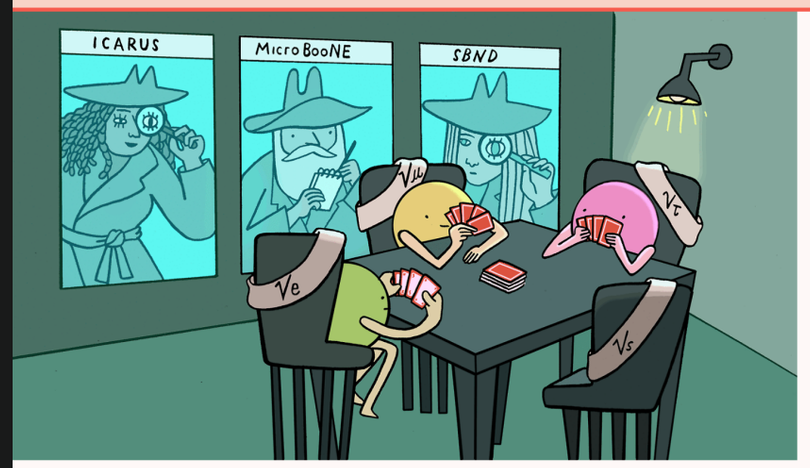

Artwork by Sandbox Studio, Chicago with Corinne Mucha

Sterile neutrino sleuths

01/30/18 | By Tom Barratt and Leah Poffenberger

Meet the detectors of Fermilab's Short-Baseline Neutrino Program, hunting for signs of a possible fourth type of neutrino.

Neutrinos are not a sociable bunch. Every second, trillions upon trillions of the tiny

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The New Era of Multimessenger Astronomy

Astronomers' newfound ability to see the same cosmic events in light, particles and gravitational waves—a synthesis called multimessenger astronomy—gives them a fuller picture of some of the universe's most mysterious phenomena

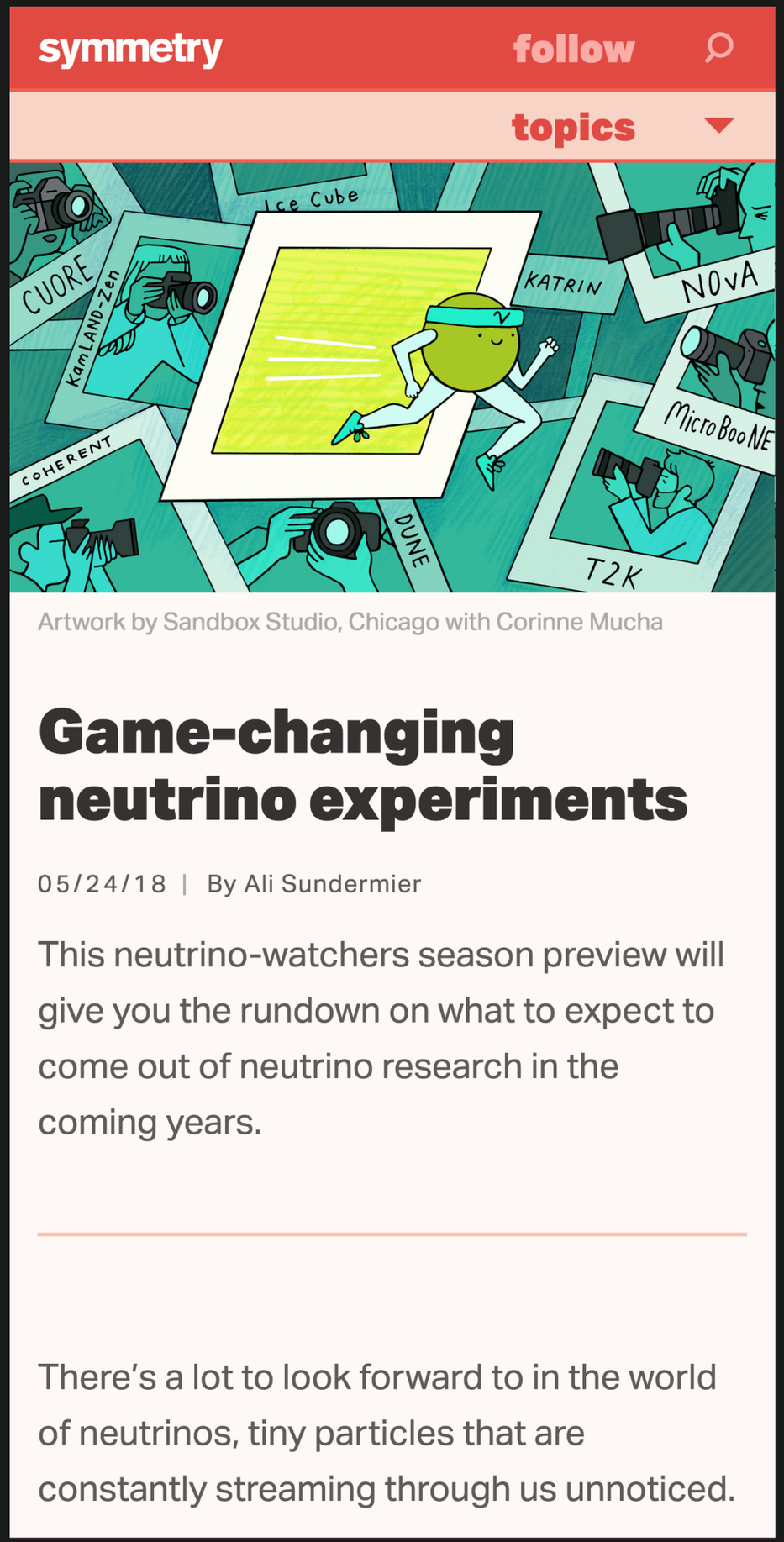
By Ann Finkbeiner

A neutrino hit on September 22, 2017, at 4:54 P.M. Eastern time. the nearly massless elementary particle barreled through the sensors of the IceCube Neutrino Observatory, an experiment buried in the Antarctic ice. This neutrino was rare, carrying an energy of more than 100 tera electron volts, about 10 times the energy reachable by particles inside the most powerful accelerators on Earth. Thirty seconds later IceCube's computers sent out an alert with the neutrino's energy, the time and date, and roughly where it came from in the sky.

Great Science Journalism

Great article this week anticipating new results at an important international conference next month

symmetrymagazine.org/article/game-changing-neutrino-experiments



Artwork by Sandbox Studio, Chicago with Corinne Mucha

Game-changing neutrino experiments

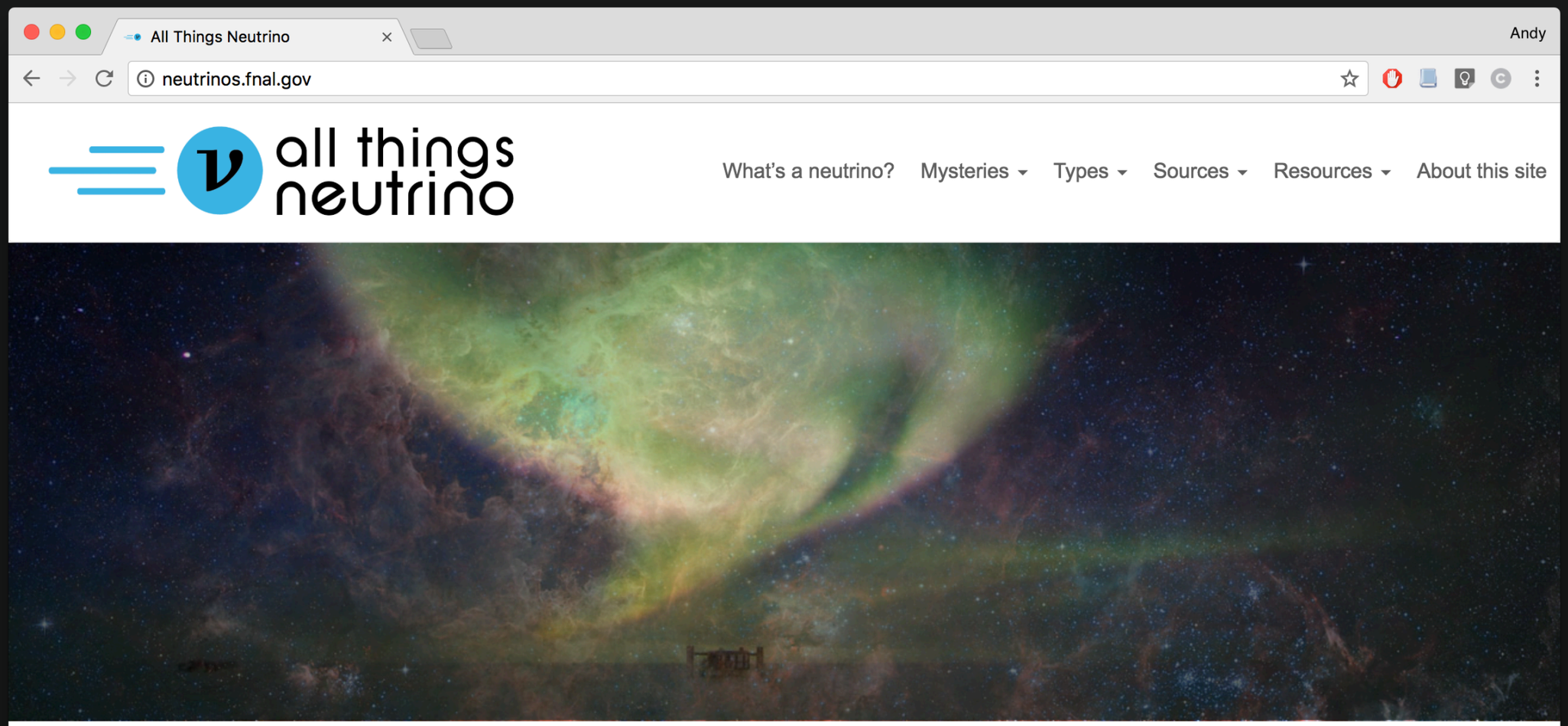
05/24/18 | By Ali Sundermier

This neutrino-watchers season preview will give you the rundown on what to expect to come out of neutrino research in the coming years.

There's a lot to look forward to in the world of neutrinos, tiny particles that are constantly streaming through us unnoticed.

New! neutrinos.fnal.gov

Fermilab



Thank You!

Image: Hubble Deep Field, NASA