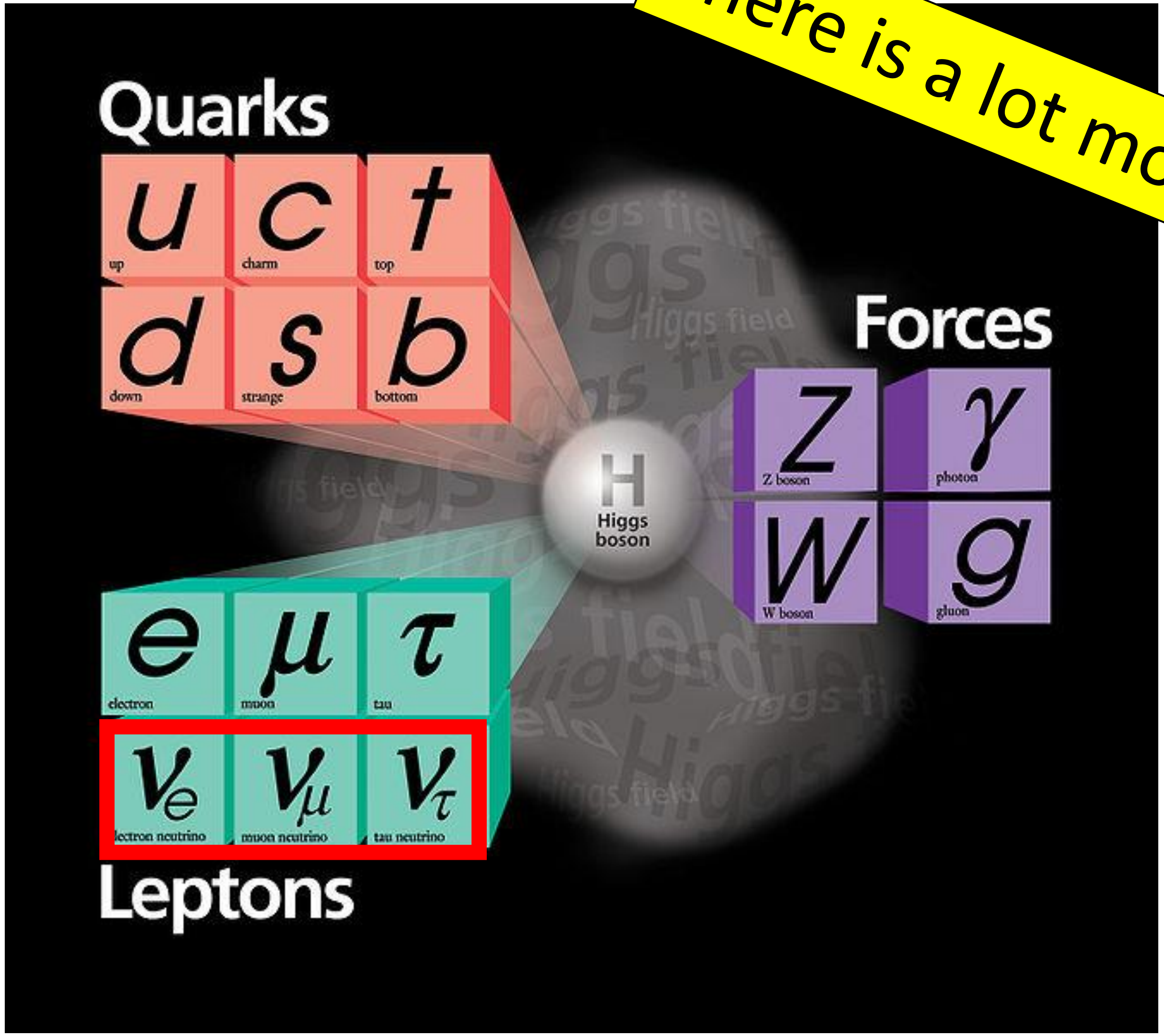
Neutrinos

The illusive little neutral ones

The Standard Model of Particle Physics

There is a lot more to this story!



Particle Contents

- Quarks and Leptons: matter particles
- Gauge Bosons: Force mediators
- Boson: Excitation of the Higgs field which gives
  - les, neutrinos?
  - W a of the weak force
- Characterized b rinsic properties, charge(s), chirality (~spin)
- Quantum fields: wavelike entities…

Neutrinos

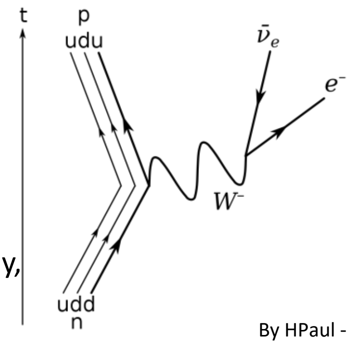
- Matter particles, spin ½ ferminons
- Three flavors: electron, muon, tau
- Charged only with weak isospin (one of 3 types of charges known)
- Massless (in original Standard Model)

- Most abundant particle with mass in the universe
- Trillions go through your body every second

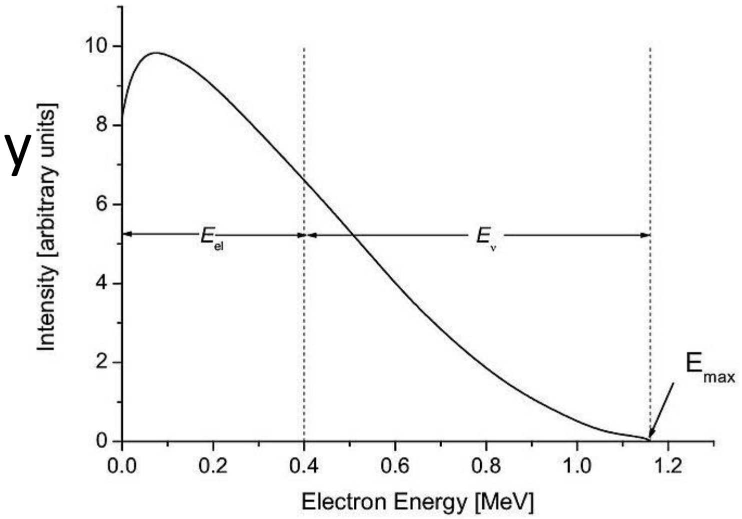
Neutrinos

Wolfgang Pauli 1900 – 1958: circa 1930

- Radioactivity, discovered in 1896, by Becquerel in U, later Rutherford separated into $\alpha, \beta, \text{and } \gamma$ radiation based on penetration depth
  - α are He nuclei 2n2p,
  - $\beta^{\pm}$, are electrons/positrons
  - γ are high energy photons, particles of light
- Problem:
  - In α and γ decays the γ, α particles are emitted in a narrow energy distribution
    - Example α: ${}^{235}_{92}\text{U} \rightarrow {}^{231}_{90}\text{Th} + \alpha({}^{4}_{2}\text{He})$,
    - Example γ: ${}^{60}_{27}\text{Co} \xrightarrow{beta} {}^{60}_{28}\text{Ni}^* \rightarrow {}^{60}_{28}\text{Ni} + \gamma(1.33\text{MeV})$
  - Not so in β decay, where emitted e in broad (cont.) energy spectrum
- Neutrino proposed by W. Pauli (1930) to fix nuclear beta decay
  - Preserve conservation of energy and momentum, whew!
  - ${}^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{C} + e^- + \bar{\nu}_e$
  - $n \rightarrow \ p + e^- + \bar{\nu}_e$
  - ${}^{14}_{6}\text{Mg} \rightarrow {}^{14}_{7}\text{Na} + e^+ + \nu_e$



Feynman Diagram of neutron decay, the basic diagram in beta decay



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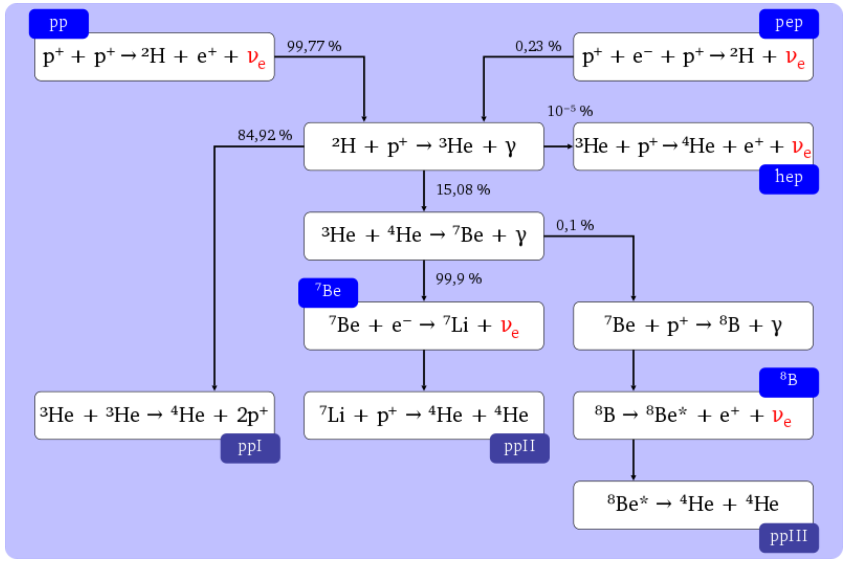
Neutrino Sources

- The most abundant massive particle known to exist
- Primordial neutrinos, relic CνB aka CNM (vs. CMB)
  - Created in processes like $e^- + e^+ \rightarrow \nu_e + \bar{\nu}_e$
  - Decoupled from the rest of matter at about 1 second after the BB
  - Used by astrophysics to pin down ν properties such as: masses, generations…
- In stellar cores (Standard Solar Model)
  - *pp* process: $p^+ + p^+ \rightarrow {}^2\mathrm{H} + e^+ + \boxed{\nu_e}$: 91%, $E_\nu < 0.42$ MeV
  - Other nuclear reactions create ${}^3\mathrm{He}$, ${}^4\mathrm{He}$ that lead to creation of Beryllium and Boron $+\nu_e$
    - Beryllium pro.: ${}^7\mathrm{Be} + \mathrm{e}^- \rightarrow {}^7\mathrm{Li} + \boxed{\nu_e}$: 7%, E_ν =0.86/0.36 MeV
    - Boron pro.: ${}^7\mathrm{Be} + \mathrm{p}^+ \rightarrow {}^8\mathrm{B} + \gamma \rightarrow {}^8\mathrm{Be}^* + e^+ + \boxed{\nu_e}$: 0.02%, $E_\nu < 15$ MeV
- In Cosmic rays
  - Primary Cosmic rays are mostly p^+, α^{++}
  - Secondary CRs are low mass hadron (pions, kaons)

$$p + N \rightarrow \begin{cases} \pi^- \rightarrow \mu^- + \boxed{\bar{\nu}_\mu}\ , \mu^- \rightarrow e^- + \boxed{\nu_e} + \boxed{\nu_\mu} \\ \pi^+ \rightarrow \mu^+ + \boxed{\nu_\mu}\ , \mu^+ \rightarrow e^+ + \boxed{\nu_e} + \boxed{\bar{\nu}_\mu} \end{cases}$$

  - Note that muon neutrinos are 2x electron neutrinos
- Man made: Fission reactors and Particle accelerators

By Dorottya Szam - file:Proton proton cycle.png, CC BY-SA 2.5, https://commons.wikimedia.org/w/index.php?curid=23213257



pp

$p^+ + p^+ \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

99,77 %

0,23 %

pep

$p^+ + e^- + p^+ \rightarrow {}^2\mathrm{H} + \nu_e$

10^{-5} %

84,92 %

${}^2\mathrm{H} + p^+ \rightarrow {}^3\mathrm{He} + \gamma$

${}^3\mathrm{He} + p^+ \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

hep

15,08 %

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

0,1 %

99,9 %

${}^7\mathrm{Be}$

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

${}^7\mathrm{Be} + p^+ \rightarrow {}^8\mathrm{B} + \gamma$

${}^8\mathrm{B}$

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p^+$

ppI

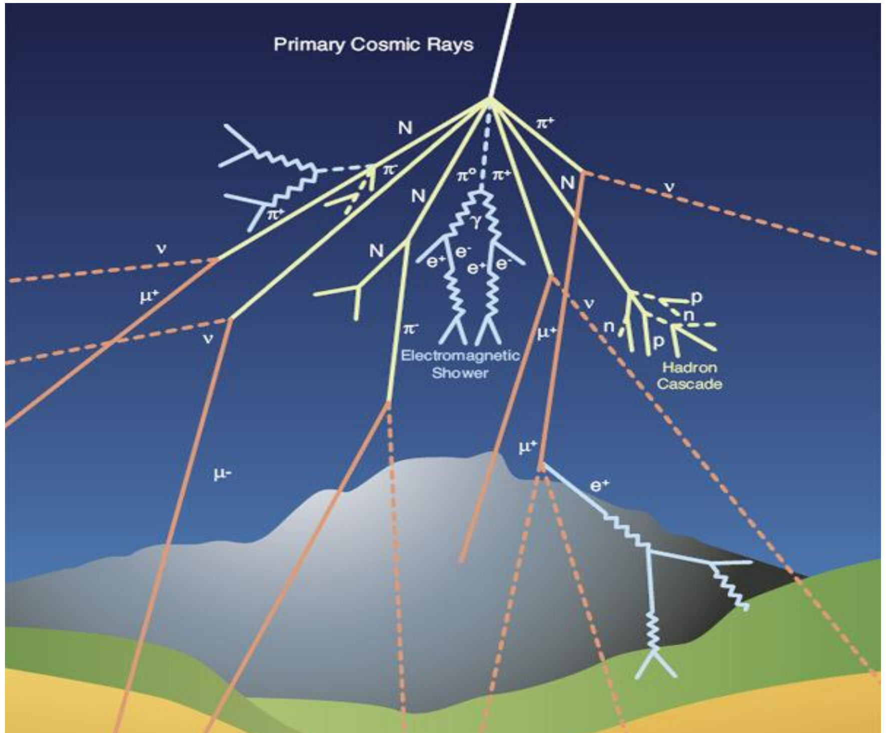
${}^7\mathrm{Li} + p^+ \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$

ppII

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$

${}^8\mathrm{Be}^* \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$

ppIII



Neutrinos Interactions

- Neutrinos, hardly interact with ordinary matter
  - Cross-section is $\sigma(\nu N)\sim 10^{-38}\ cm^2$Cross-section is $\sigma(\nu N)\sim 10^{-38}\ cm^2$, $\sigma(pp)\sim 10^{-26}\ cm^2$

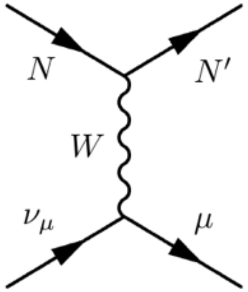
$$\sigma(\nu N) = \frac{n_{Collisions}}{\mathrm{T}_N \Phi_{\nu_{beam}}}$$

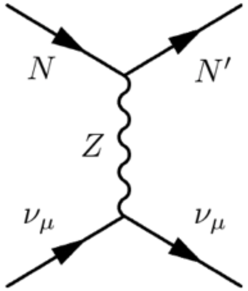
Need ~½ light years thick hunk of iron to have a 50% chance of an interaction

  - Carry only Weak isospin, (a kind of charge that **is neither** electric or color)
- Interactions with ordinary matter:
  - Via charge or neutral current (exchange $W^{\pm}$ or Z^0 boson)
  - Different kinds of interactions used to tag the flavor of incident neutrino
  - Decay products (charged particles) used to establish ν kinematics

- Particle detection 101

  Ordinary matter detectors can detect only “stable”, “charged” things
    - $p^{\pm}$, $e^{\pm}$, γ (E&M and stable)
    - $\mu^{\pm}$,$\pi^{\pm}$, $K^{\pm}$ (E&M and not as stable $\tau\sim 10^{-6-8}$s), n^0 (~900s)



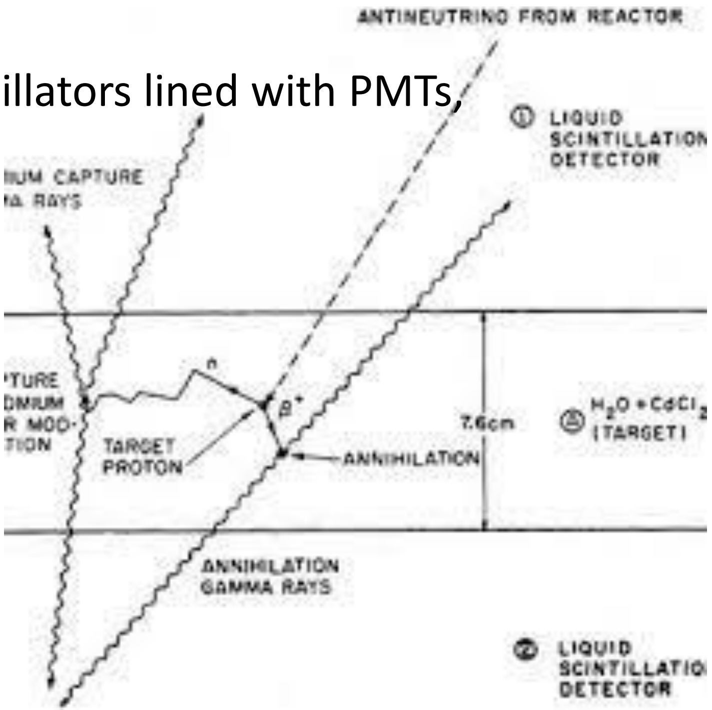


Neutrino Detectors

- Solar, reactor, atmospheric neutrinos (different energies)
- Large volume of active detector material ($\mathrm{H_2O}$…), instrumented with electronic sensors, usually light detectors (PMTs)

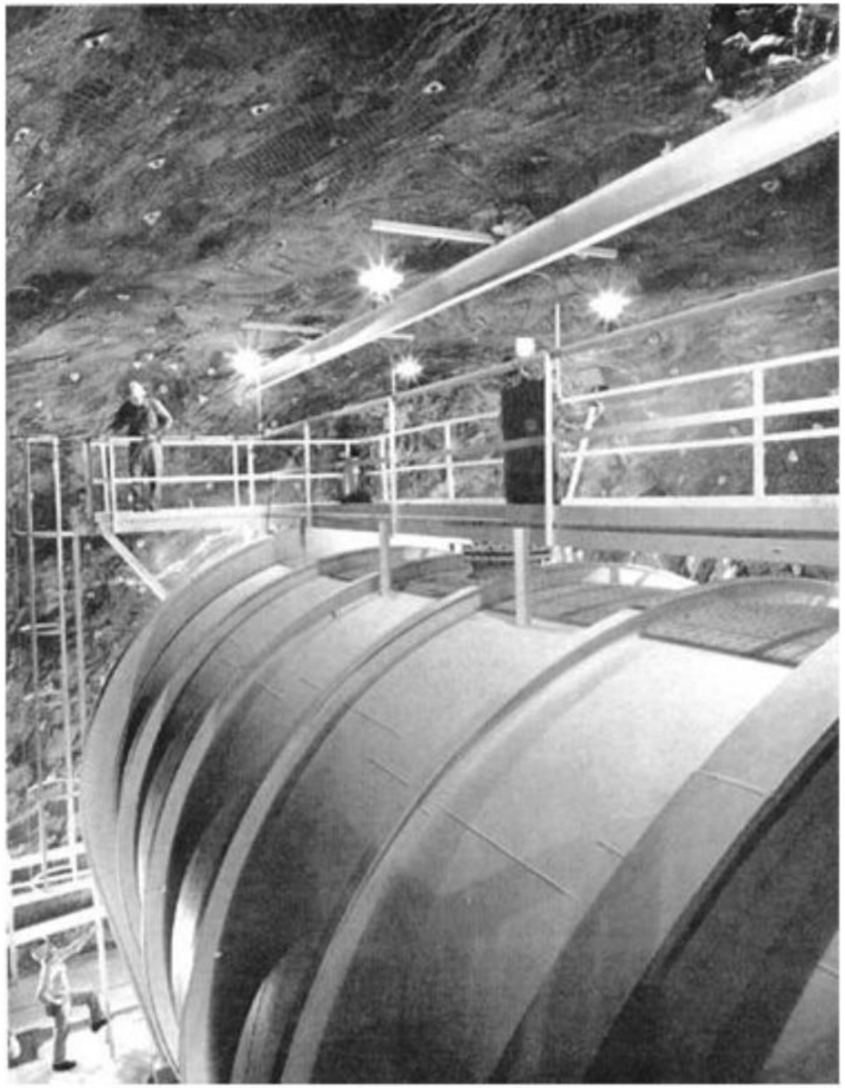
Pioneering Neutrino Experiment

- First neutrino detector (1953): Reines and Cowan, uses the inverse beta decay process
  - Rare interaction with tiny cross-section but interaction signatures are quite unique
  - Two large tanks of 200 L of $\mathrm{H_2O}$ with 40 kg of dissolved CdCl$_2$. Water tanks btw scintillators lined with PMTs, underground near a Savannah River reactor (*originally near A-bomb explosion*)
  - $(\bar{\nu}_e + p^+ \rightarrow n + e^+)\ (e^-)\ ({}^{108}_{48}\mathrm{Cd}) \Rightarrow ({}^{109}_{48}\mathrm{Cd}^* \rightarrow {}^{109}_{48}\mathrm{Cd} + \gamma), (e^+ + e^- \rightarrow \gamma + \gamma)$
  - Look for back-to-back 0.5 MeV γ, in coincidence with decay of ${}^{109}_{48}\mathrm{Cd}^*$ a few μs later



- Result : $\sigma(\bar{\nu}p) = 6.3 \times 10^{-44}\mathrm{cm}^2$ (close to prediction)

Homestake and the Solar Neutrino Problem

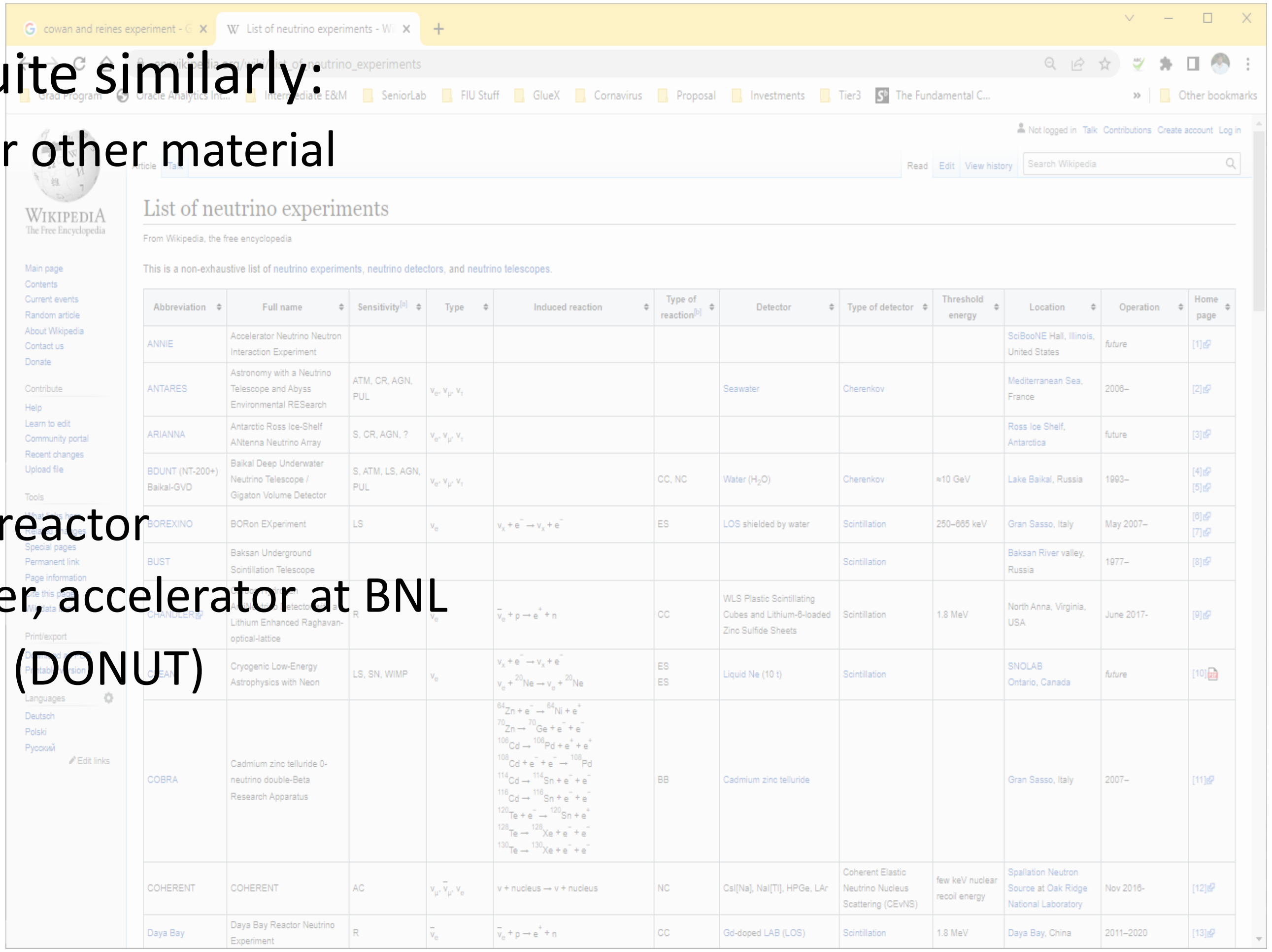


- Pioneering Solar Neutrino experiment
  - Giant (swimming pool size) vat of Cleaning fluid C_2Cl_4, in the Homestake mine, in South Dakota 5,000 ft underground
  - Radio-chemical experiments designed by R. Davis with J. Bahcall (theorist)
  - Reaction $\nu_e + {}^{37}\mathrm{CL} \rightarrow e^-$ + ${}^{37}\mathrm{Ar}$ $(E_{th} = 0.814\ \mathrm{MeV})$
  - But ${}^{37}\mathrm{Ar}$ has a half life of 35 days, expect 1.5 atoms per day
  - Extract N_ν by counting the number of argon atoms collected every few weeks
- Concluded: about 30% of the expected rate observed
  - The solar neutrino problem!
  - Confirmed by other experiments GALLEX, SAGE, IMB, SuperKamiokande…
  - Stood for +20 years

- Neutrino oscillations, $\nu_e \rightarrow \nu_{\mu,\tau}$

Neutrino Detectors

- Today neutrino experiments follow along quite similarly:
  1. Use huge volumes of active material, water, or other material
  2. Surround volume with sensors, usually PMTs
  3. Do clever things with data analysis…
  4. Publish results
- Neutrino Discoveries
  - ν_e : 1953 by Cowans and Reines, Savanah River reactor
  - ν_μ : 1962 by Lederman, Schwartz and Steinberger, accelerator at BNL
  - ν_τ : 2000 by E872, Direct Observation of NU Tau (DONUT) collaboration, Tevatron accelerator at FNAL



List of neutrino experiments

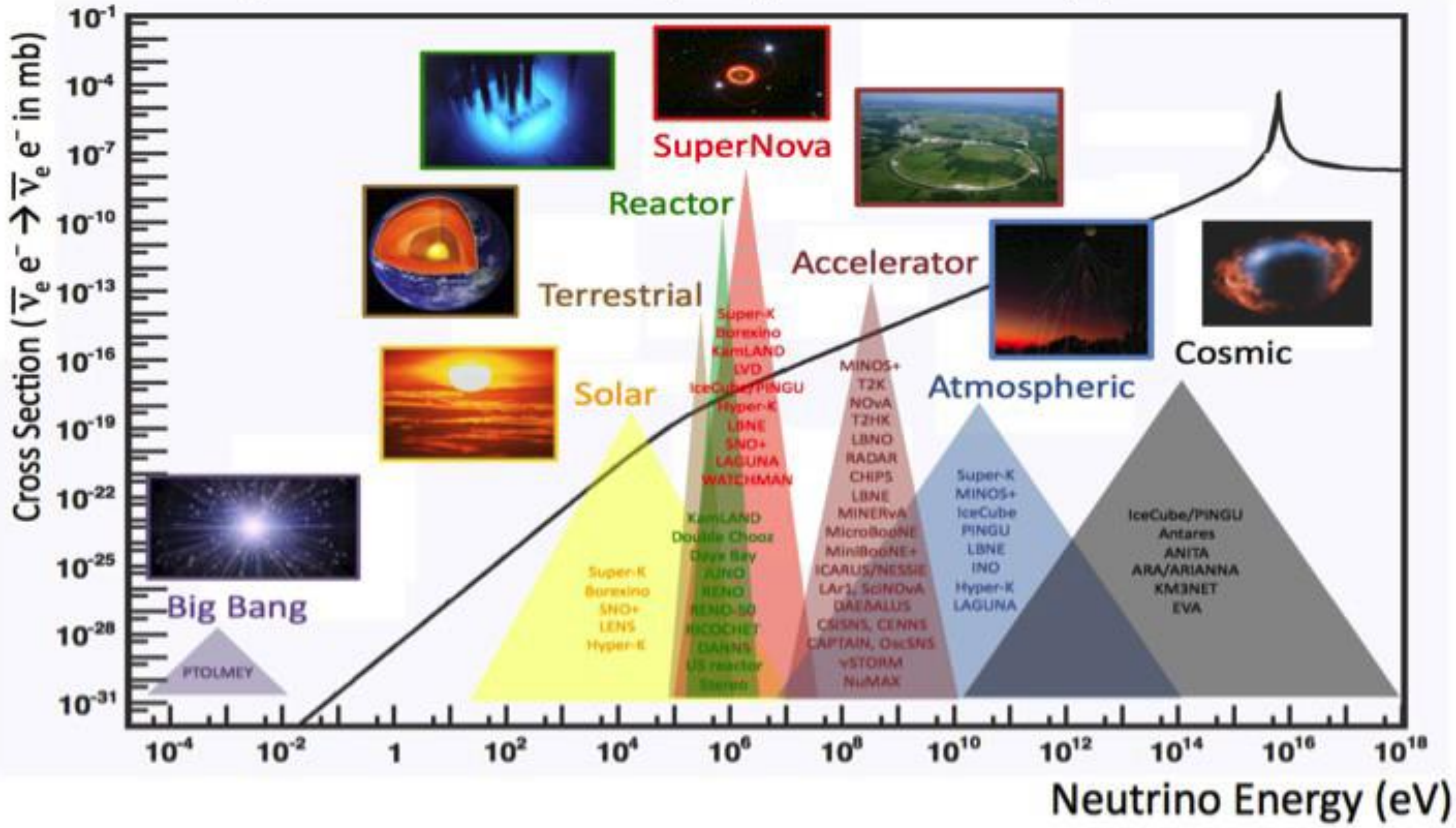
From Wikipedia, the free encyclopedia

This is a non-exhaustive list of neutrino experiments, neutrino detectors, and neutrino telescopes.

Abbreviation	Full name	Sensitivity[a]	Type	Induced reaction	Type of reaction[b]	Detector	Type of detector	Threshold energy	Location	Operation	Home page
ANNIE	Accelerator Neutrino Neutron Interaction Experiment								SciBooNE Hall, Illinois, United States	*future*	[1]
ANTARES	Astronomy with a Neutrino Telescope and Abyss Environmental RESearch	ATM, CR, AGN, PUL	ν_e, ν_μ, ν_τ			Seawater	Cherenkov		Mediterranean Sea, France	2006–	[2]
ARIANNA	Antarctic Ross Ice-Shelf ANtenna Neutrino Array	S, CR, AGN, ?	ν_e, ν_μ, ν_τ						Ross Ice Shelf, Antarctica	future	[3]
BDUNT (NT-200+) Baikal-GVD	Baikal Deep Underwater Neutrino Telescope / Gigaton Volume Detector	S, ATM, LS, AGN, PUL	ν_e, ν_μ, ν_τ		CC, NC	Water (H_2O)	Cherenkov	≈10 GeV	Lake Baikal, Russia	1993–	[4] [5]
BOREXINO	BORon EXperiment	LS	ν_e	$\nu_x + e^- \rightarrow \nu_x + e^-$	ES	LOS shielded by water	Scintillation	250–665 keV	Gran Sasso, Italy	May 2007–	[6] [7]
BUST	Baksan Underground Scintillation Telescope						Scintillation		Baksan River valley, Russia	1977–	[8]
CHANDLER	Carbon Hydrogen AntiNeutrino Detector with a Lithium Enhanced Raghavan-optical-lattice	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	WLS Plastic Scintillating Cubes and Lithium-6-loaded Zinc Sulfide Sheets	Scintillation	1.8 MeV	North Anna, Virginia, USA	June 2017-	[9]
CLEAN	Cryogenic Low-Energy Astrophysics with Neon	LS, SN, WIMP	ν_e	$\nu_x + e^- \rightarrow \nu_x + e^-$ $\nu_e + {}^{20}Ne \rightarrow \nu_e + {}^{20}Ne$	ES ES	Liquid Ne (10 t)	Scintillation		SNOLAB Ontario, Canada	*future*	[10]
COBRA	Cadmium zinc telluride 0-neutrino double-Beta Research Apparatus			${}^{64}Zn + e^- \rightarrow {}^{64}Ni + e^+$ ${}^{70}Zn \rightarrow {}^{70}Ge + e^- + e^-$ ${}^{106}Cd \rightarrow {}^{106}Pd + e^+ + e^+$ ${}^{108}Cd + e^- + e^- \rightarrow {}^{108}Pd$ ${}^{114}Cd \rightarrow {}^{114}Sn + e^- + e^-$ ${}^{116}Cd \rightarrow {}^{116}Sn + e^- + e^-$ ${}^{120}Te + e^- \rightarrow {}^{120}Sn + e^+$ ${}^{128}Te \rightarrow {}^{128}Xe + e^- + e^-$ ${}^{130}Te \rightarrow {}^{130}Xe + e^- + e^-$	BB	Cadmium zinc telluride			Gran Sasso, Italy	2007–	[11]
COHERENT	COHERENT	AC	ν_μ, $\bar{\nu}_\mu$, ν_e	ν + nucleus → ν + nucleus	NC	CsI[Na], NaI[Tl], HPGe, LAr	Coherent Elastic Neutrino Nucleus Scattering (CEvNS)	few keV nuclear recoil energy	Spallation Neutron Source at Oak Ridge National Laboratory	Nov 2016-	[12]
Daya Bay	Daya Bay Reactor Neutrino Experiment	R	$\bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	Gd-doped LAB (LOS)	Scintillation	1.8 MeV	Daya Bay, China	2011–2020	[13]

https://en.wikipedia.org/wiki/List_of_neutrino_experiments

many sources ➔ many experimental opportunities



Neutrino Physics

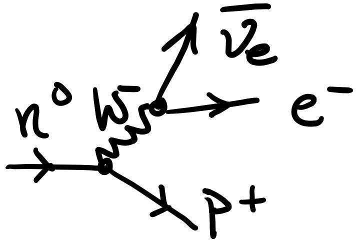
- Astrophysics: A way to “see” without using photons
  - Properties that make them difficult to detect allow us to use them as “microscopes”
  - Early Universe, ν decoupling occurred ~1 second after the Big Bang
    (CMB γ decoupled ~380,000 years after the Big Bang)
  - Observation of supernova events
  - The physics of stellar cores, neutron stars, The standard solar model
- Particle Physics: They are fundamental particles after all
  - Masses are at different scale ⇒ likely a non-Higgs phenomena
  - Possible source of *CP* violation ⇒ matter/anti-matter asymmetry
  - Why are all $\bar{\nu}/\nu$ right/left-handed? ⇒ Weak interaction maximal parity violating
  - Sterile neutrinos, do they exist? are neutrinos their own anti-particles?
  - Neutrino oscillations, purely quantum mechanical, somewhat complicated
    - Solar neutrino problem: only 33% of expected detected
    - Atmospheric neutrino problem: 50% of expected detected
    - Resolved: $\nu_e \to \nu_\mu \to \nu_\tau \to \nu_e \to \nu_\mu \to \nu_\tau \to \nu_e \to \nu_\mu \to \nu_\tau$
- Worthy of Nobel Prizes:
  - 1995 Nobel in Physics: ½ Reines (& Cowan) for the detection of ν_e in 1953
  - 1988 Nobel in Physics: Lederman, Schwartz and Steinberger, detection of 2 types of ν (ν_μ) in ν beams, 1962 at BNL
  - 2002 Nobel in Physics: ½ Koshiba, and Davis, detection of ν in cosmic rays, 1970s at Kamiokande and Homestake
  - 2015 Nobel in Physics: McDonald and Kajita, detector could resolve the 3 ν flavor, $\nu_e\ \nu_\mu\ \nu_\tau$, observed the flavor changing mechanism, 1980s SNO and SuperKamiokande

$$n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$$

$B \quad 1 = 1 + 0 + 0$ ✓

$C \quad 0 = +1 - 1 + 0$ ✓

$L \quad 0 = 0 + 1 + -1$



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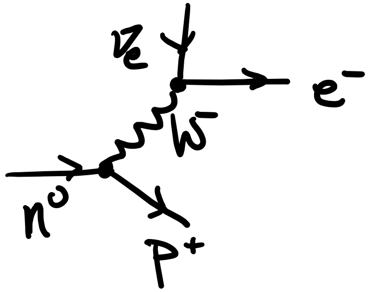

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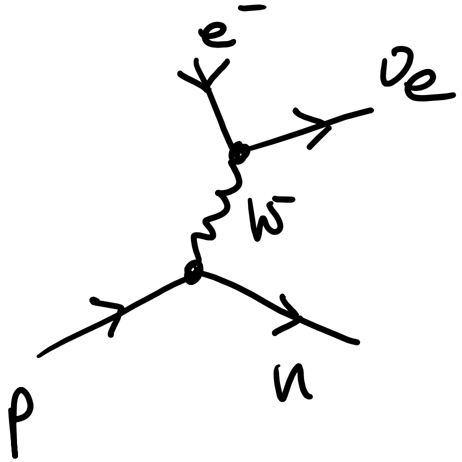
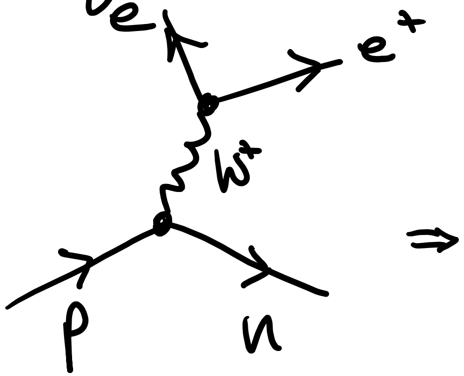


$$p^+ \rightarrow n^0 + e^+ + \nu_e$$

$B \quad 1 = 1 \quad 0 \quad 0$ ✓

$C \quad +1 = 0 \quad +1 \quad 0$ ✓

$L \quad 0 = 0 \quad -1 \quad +1$ ✓



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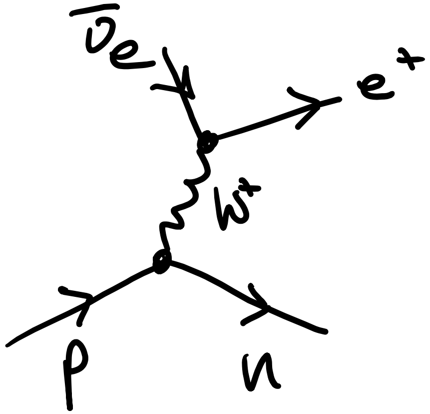

but ≠