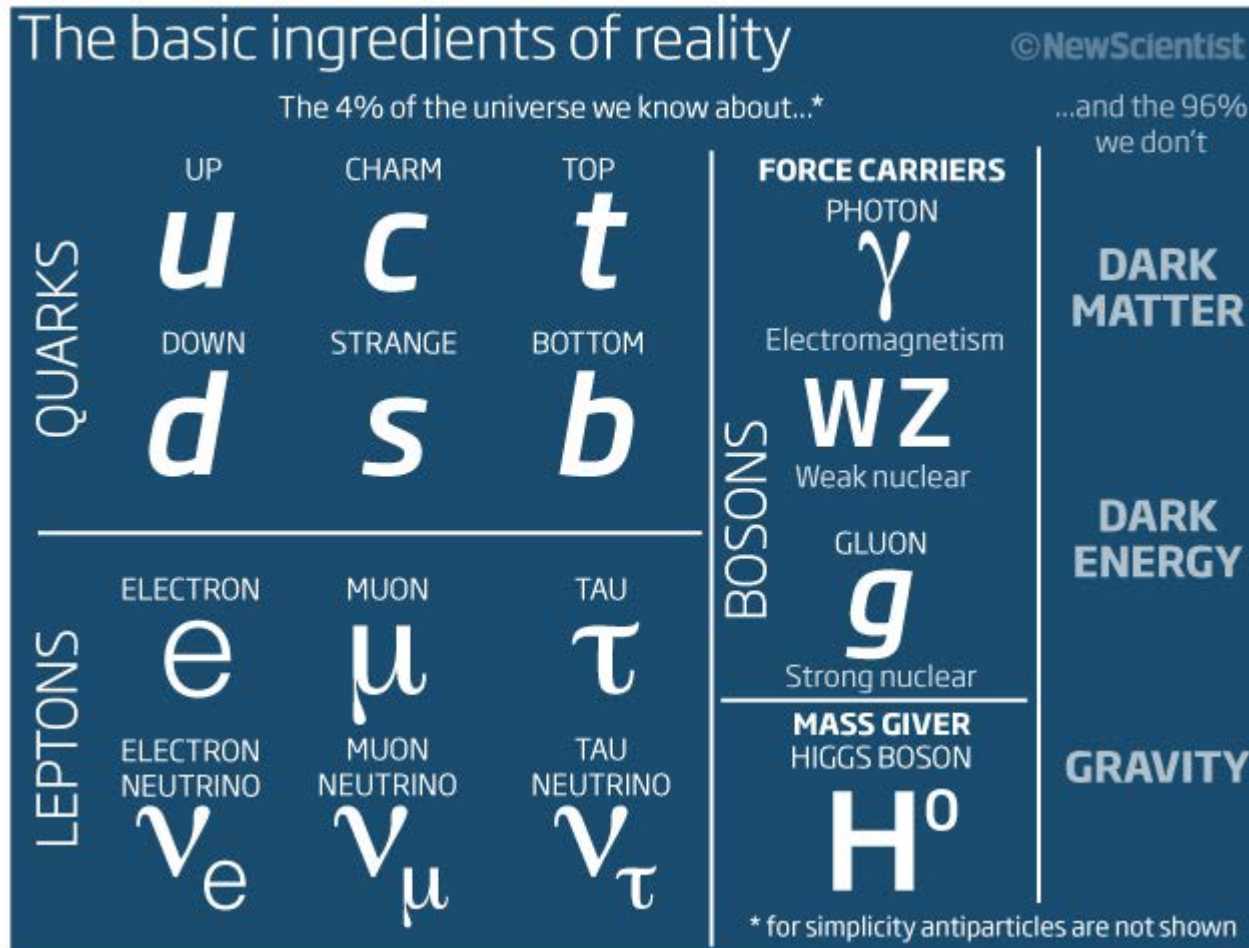


Neutrino Physics

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The Standard Model



These are not
“classical
particles”

These particles obey the Principles of Special Relativity

- The laws of Physics are the same in all inertial reference frames.
- The speed of light is the same in all inertial frames.

These particles obey the laws of Quantum Mechanics

- The Heisenberg Uncertainty Principle.
- Probabilistic nature, subjective properties.
- Described by a wavefunction.

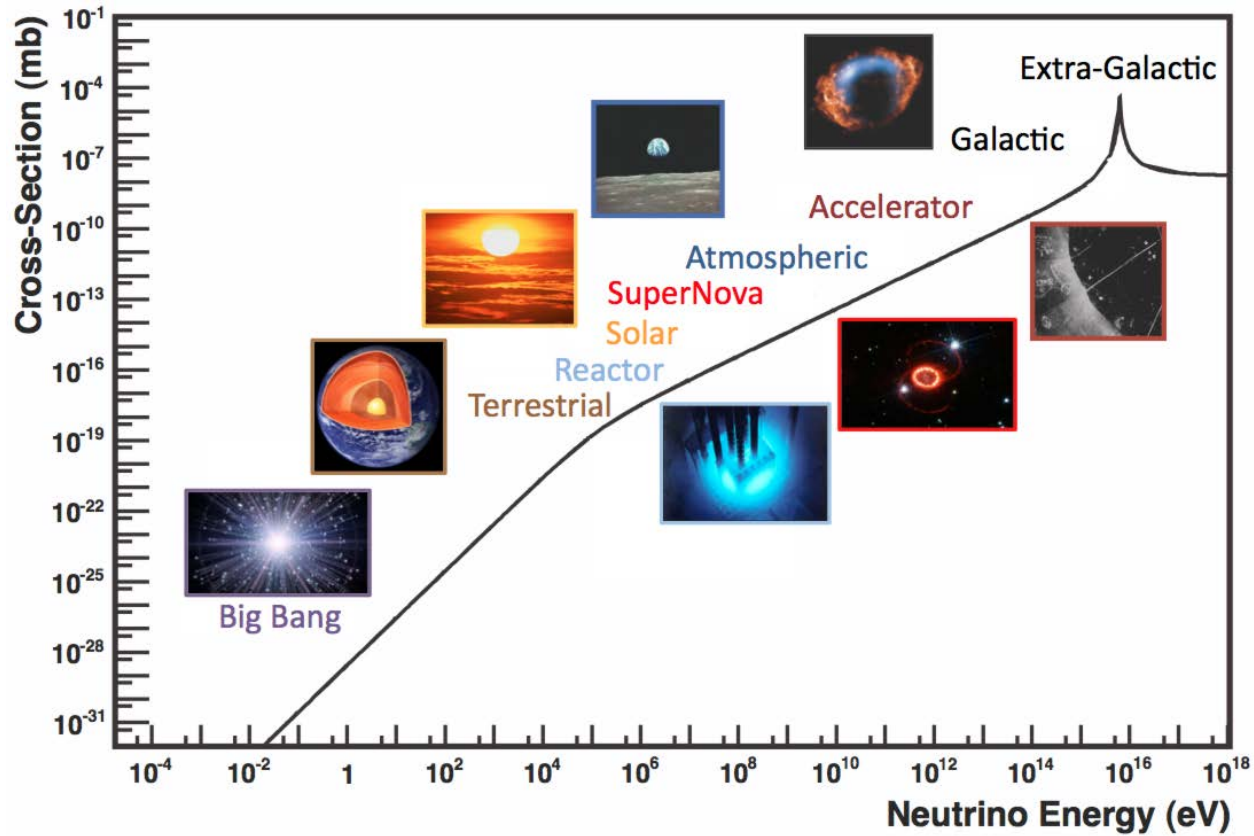


Some things we know
about neutrinos



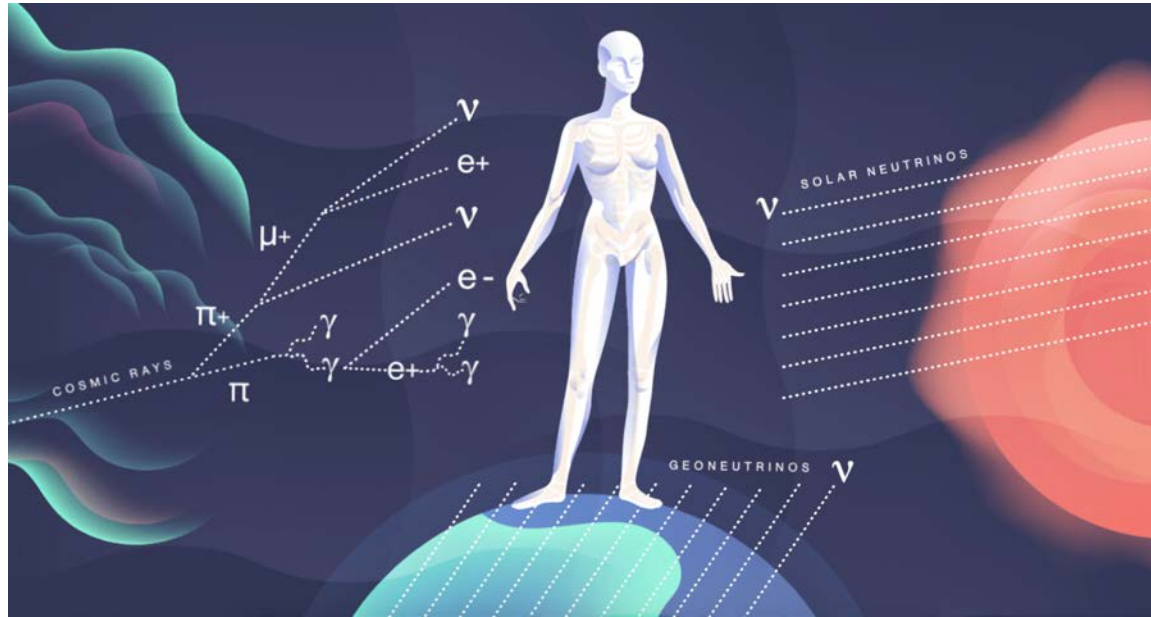
- Electron neutrinos
- Muon neutrinos
- Tau neutrinos

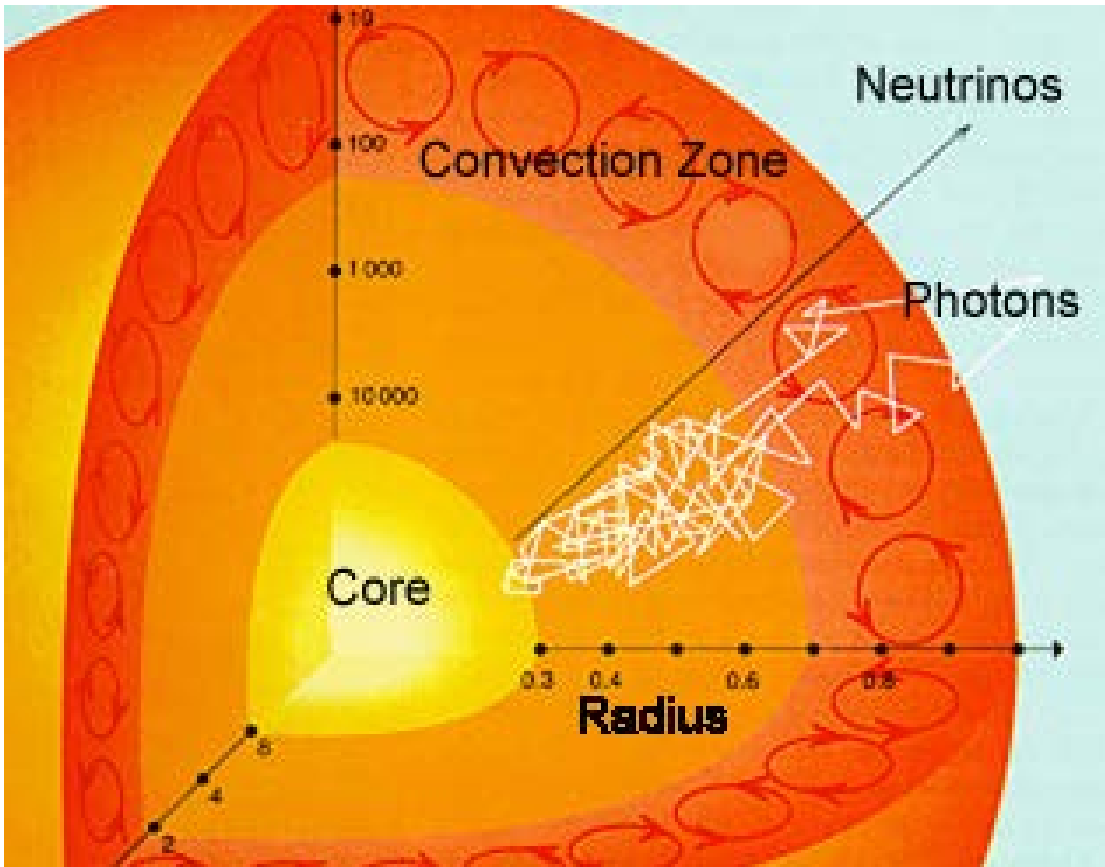
There are three types
of neutrinos



They come from different sources

They are
everywhere

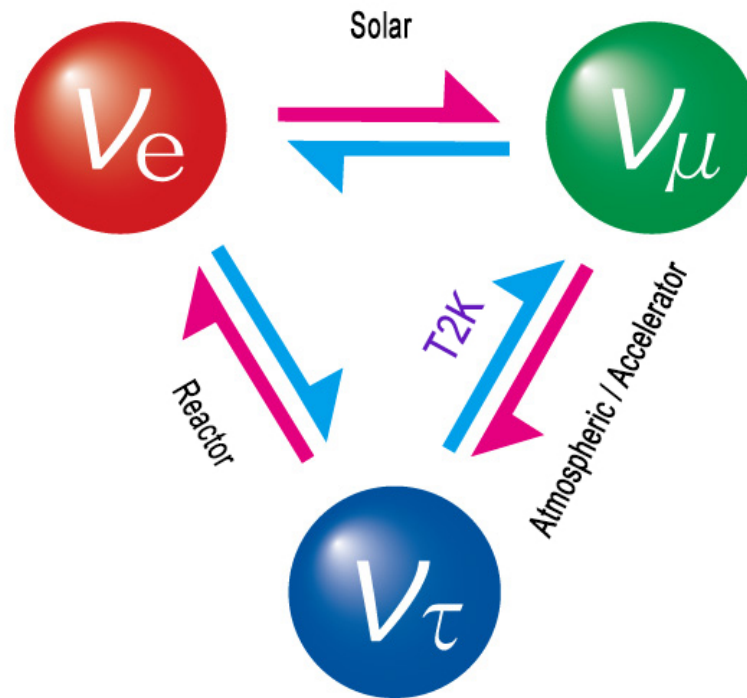




neutrinos are **very**
weakly interacting

- No charge
- No color
- Almost no mass

Neutrinos have (very small) mass...and oscillate!

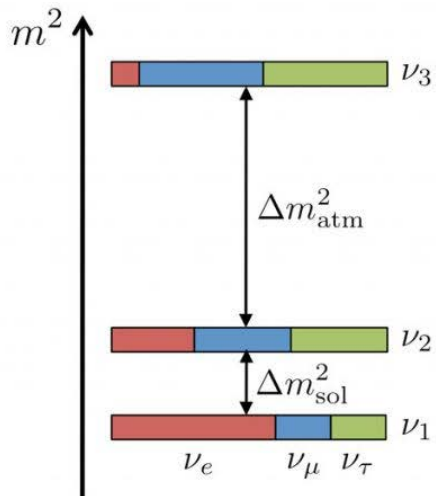


Neutrino oscillation between three generations

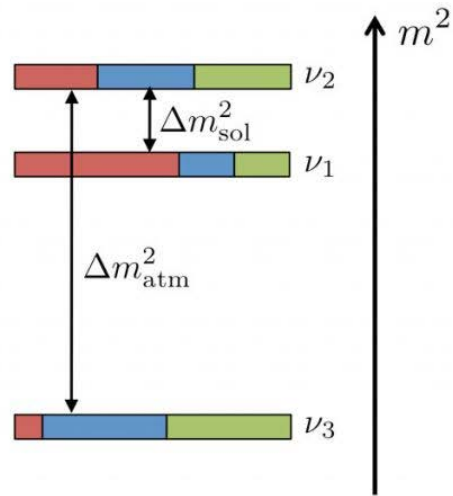
(some of)
what we don't know



normal hierarchy (NH)



inverted hierarchy (IH)







Mass Hierarchy

Missing parameters

$$\begin{aligned}
 U &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \\
 &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
 &= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}
 \end{aligned}$$

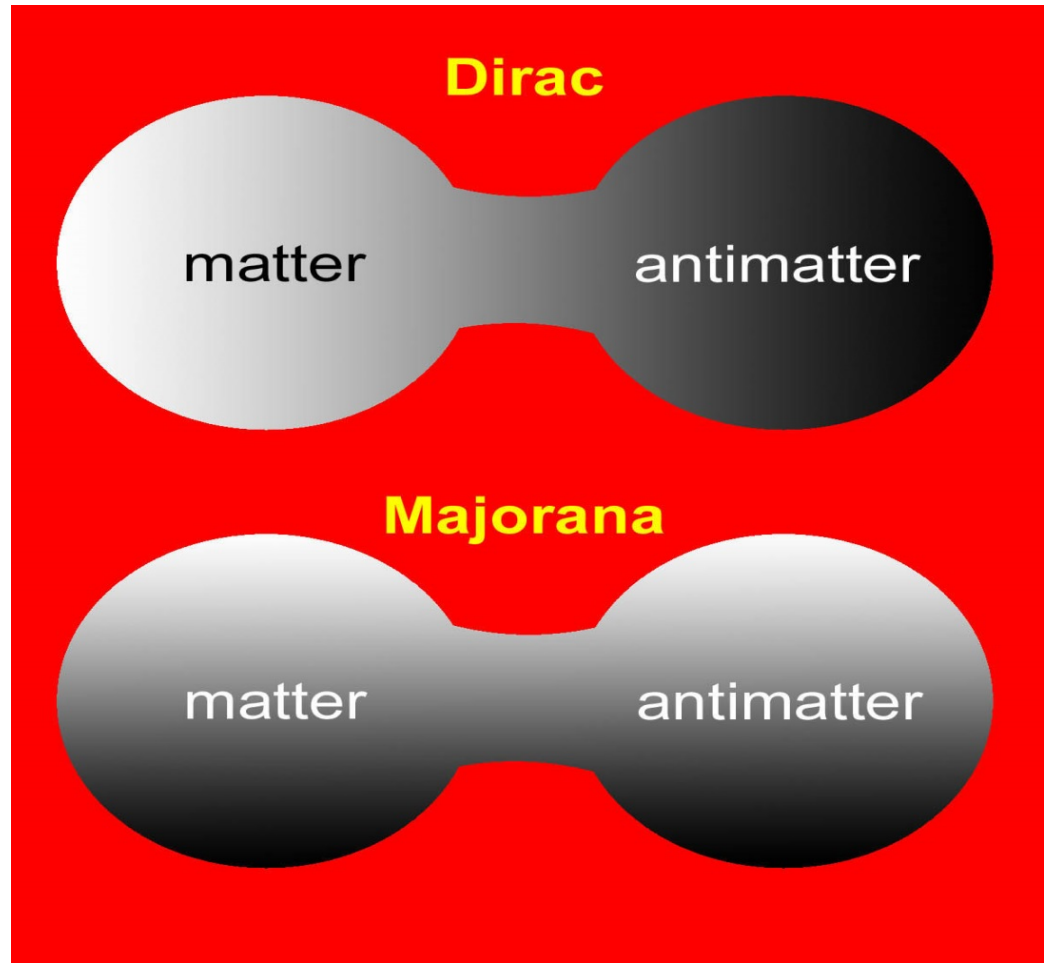
Desperately seeking sterile

The three known types of neutrino might be "balanced out" by a bashful fourth type

ELECTRON NEUTRINO	MUON NEUTRINO	TAU NEUTRINO	STERILE NEUTRINO
			
MASS	< 1 electronvolt		> 1 electronvolt
FORCES THEY RESPOND TO	Weak force Gravity		Gravity
DIRECTION OF SPIN	All three "left handed"		"Right handed"

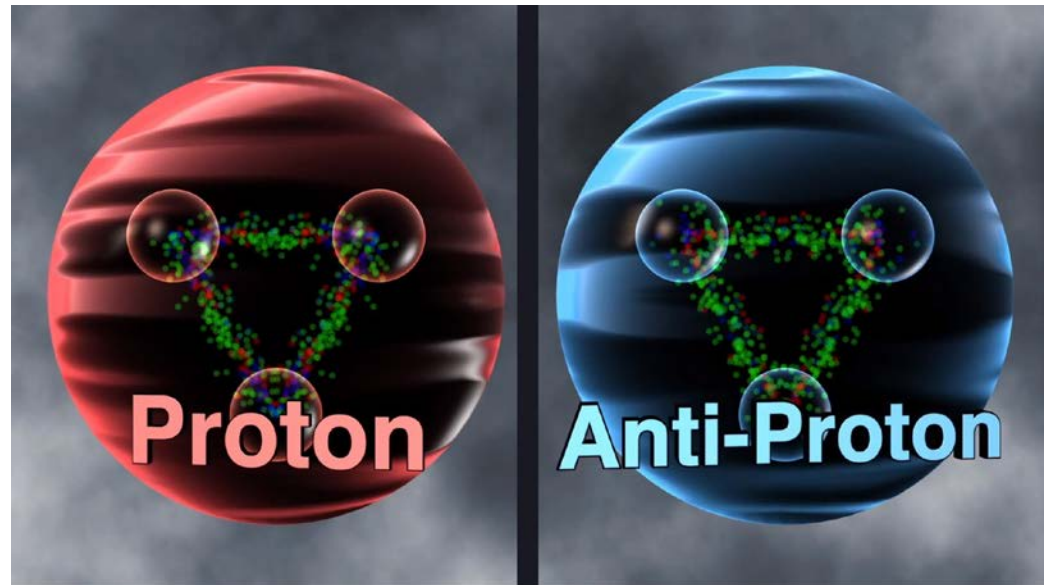
Are there more neutrinos?

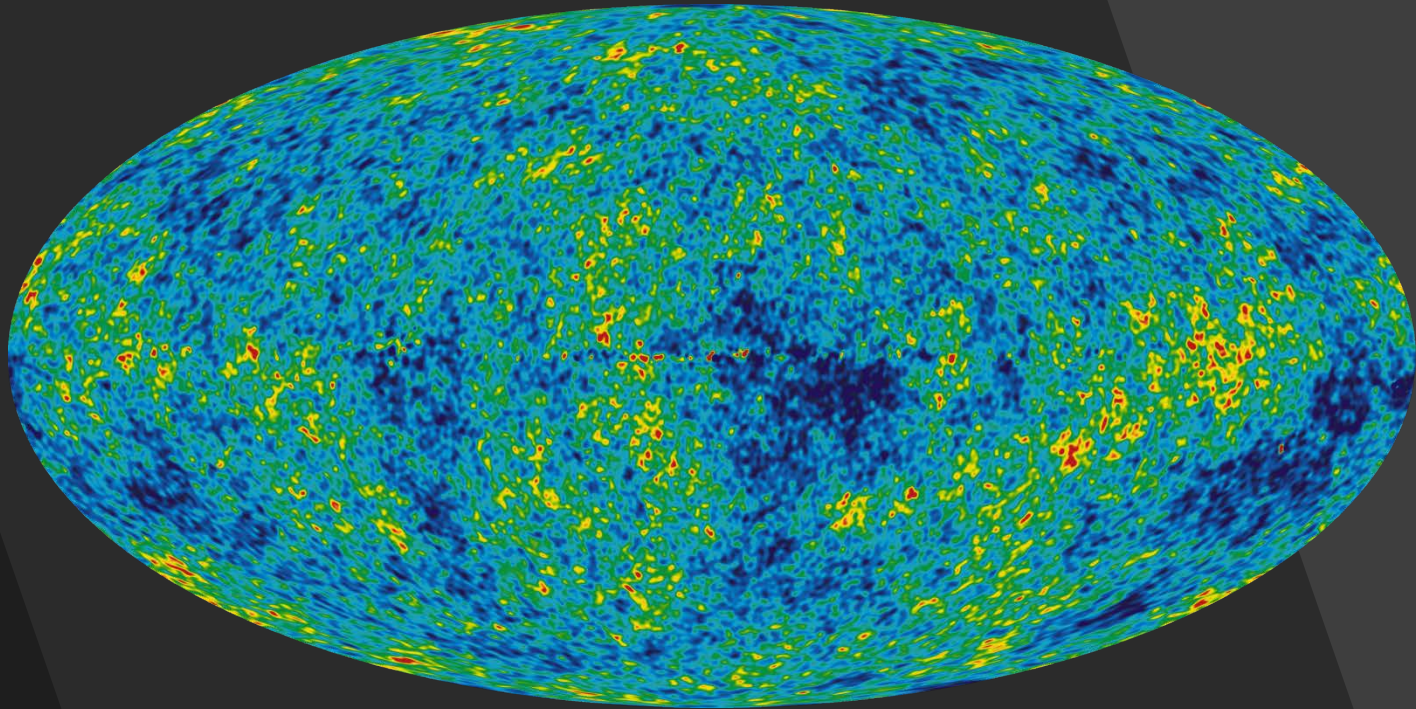
What kind
of mass do
they have?



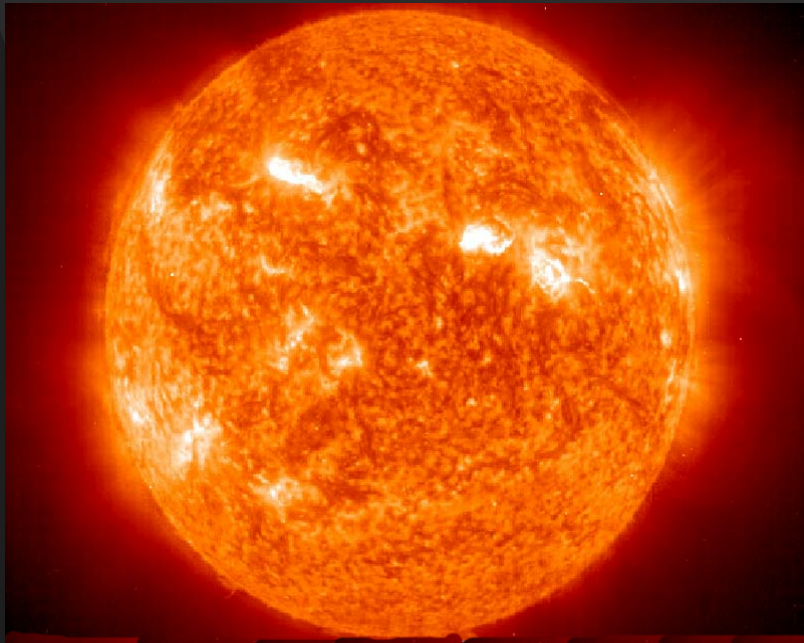
Why are neutrinos
important?

Could be responsible for the origin of Baryon asymmetry in the universe.

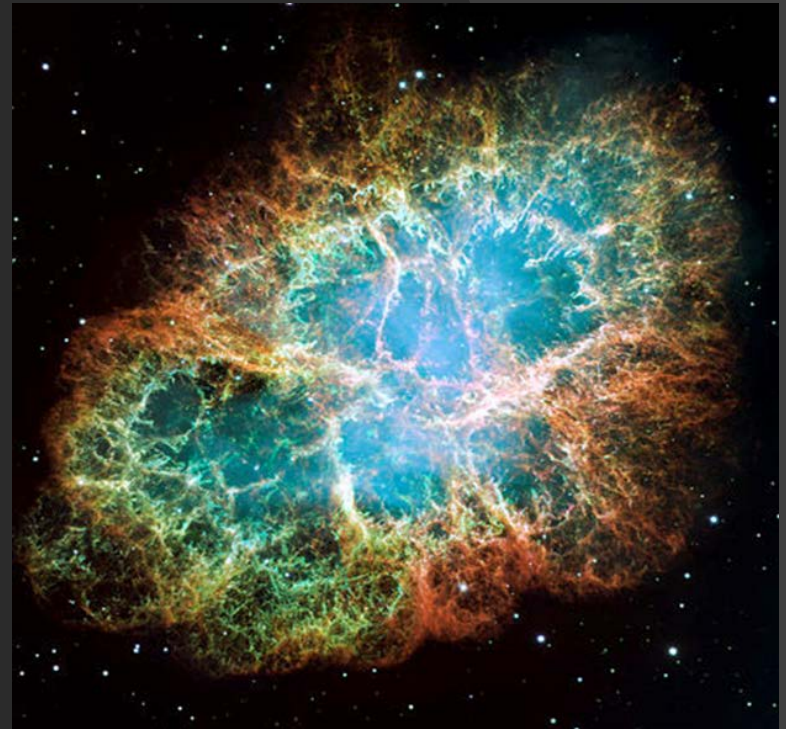




- Enter in the determination of
 - the spectrum of the CMB
 - the LSS in the universe
 - the delicate chemical equilibriums determining the light element abundances during BBN



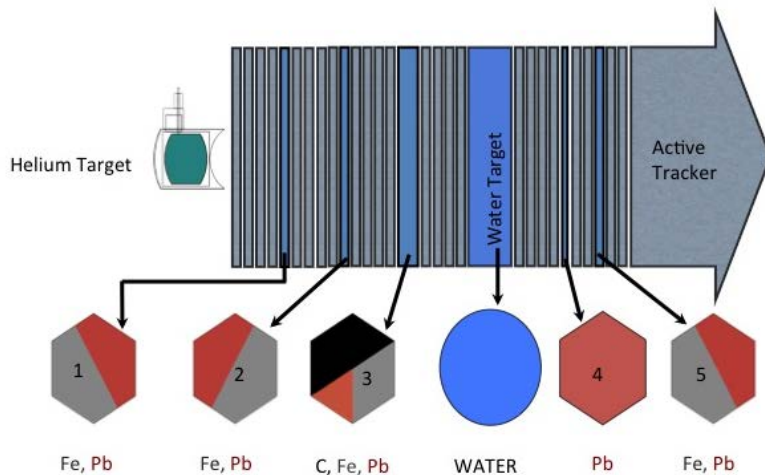
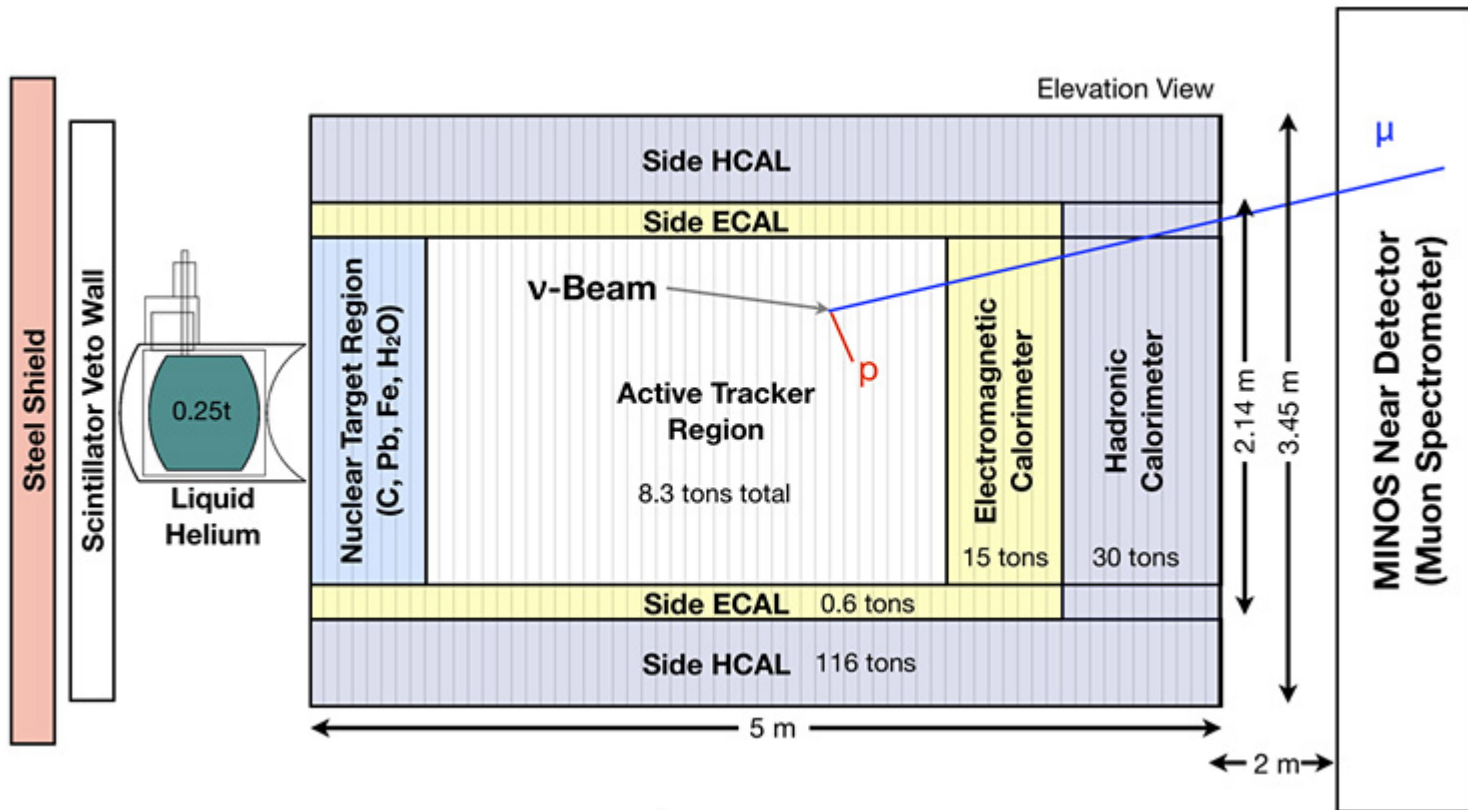
They represent a powerful probe of the dynamics of stars, supernova collapse and accretion disks encircling supermassive black holes.



Thank you for your
attention

MINERvA: Bringing neutrinos into sharp focus

- Uses the NuMI (Neutrinos at the Main Injector) beamline to study neutrino interactions with five different nuclei (He, C, Pb, Fe, H₂O).
- Results will be used as inputs for current and future neutrino oscillation experiments.
- Provides information on the structure of protons and neutrons and the strong force dynamics that affects neutrino – nucleon interactions.
- A better understanding of neutrinos can potentially help unlock the mysteries of dark matter and dark energy.



- $\nu_{\mu} + n \rightarrow \mu^{-} + p$
- $\nu_{\mu} + e^{-} \rightarrow \nu_{\mu} + e^{-}$
- $\nu_{\mu} + p \rightarrow \mu^{-} + \Delta^{++}$
 $\Delta^{++} \rightarrow p + \pi^{+}$
- Deep inelastic scattering