The Standard Model of Particle Physics and Neutrino Physics

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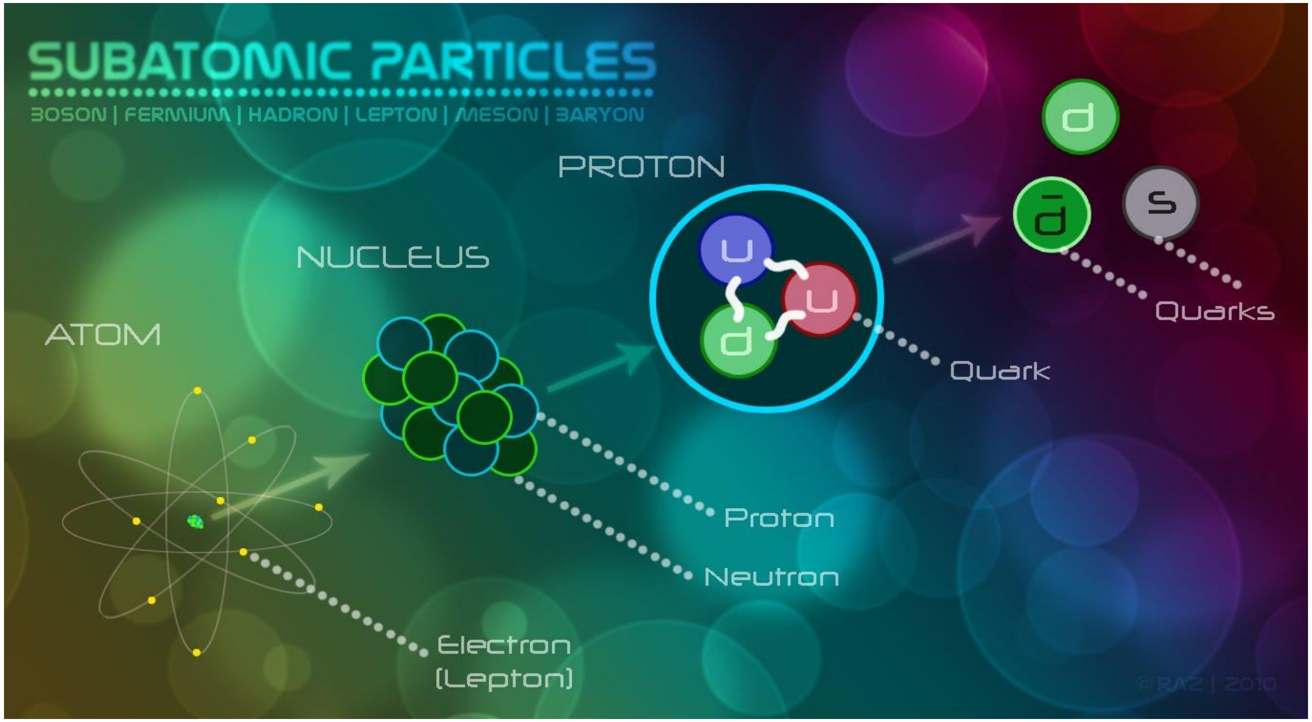
What is Particle Physics?

- Particle Physics is the study of the (subatomic) particles that constitute matter and radiation and their interactions.
- Particle Physics is the study of the really, truly, very, super-small stuff!



These are not "classical particles"

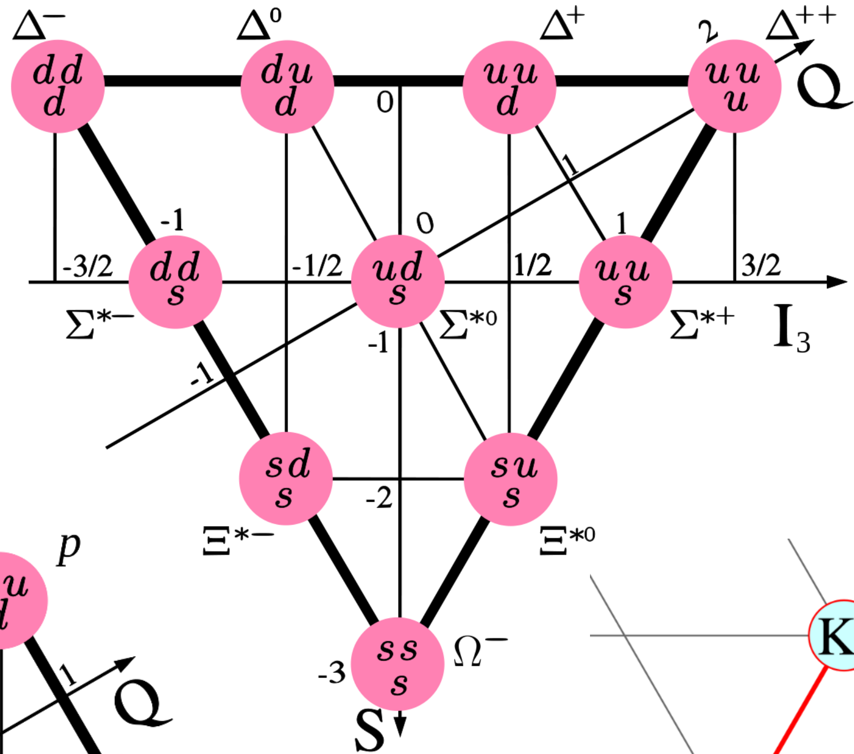
These particles obey the Principles of Special Relativity.

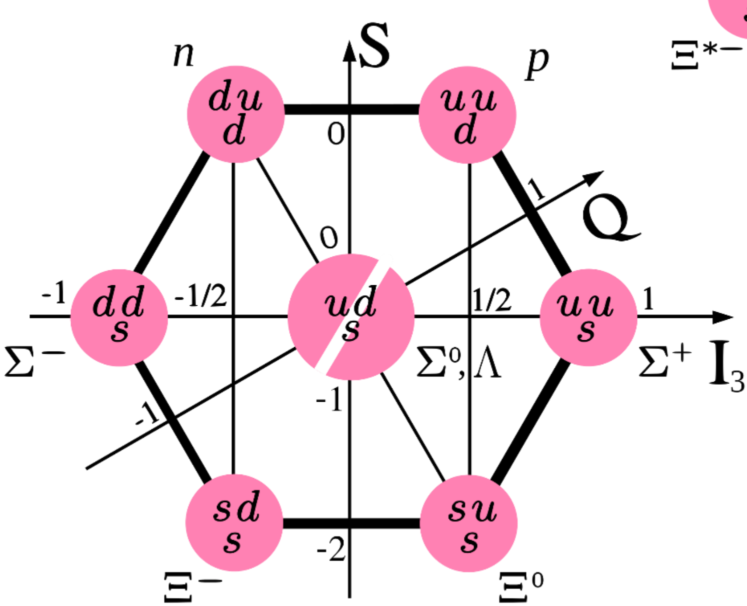
- The laws of Physics are the same in all inertial reference frames.
- The speed of light is the same in all inertial frames.

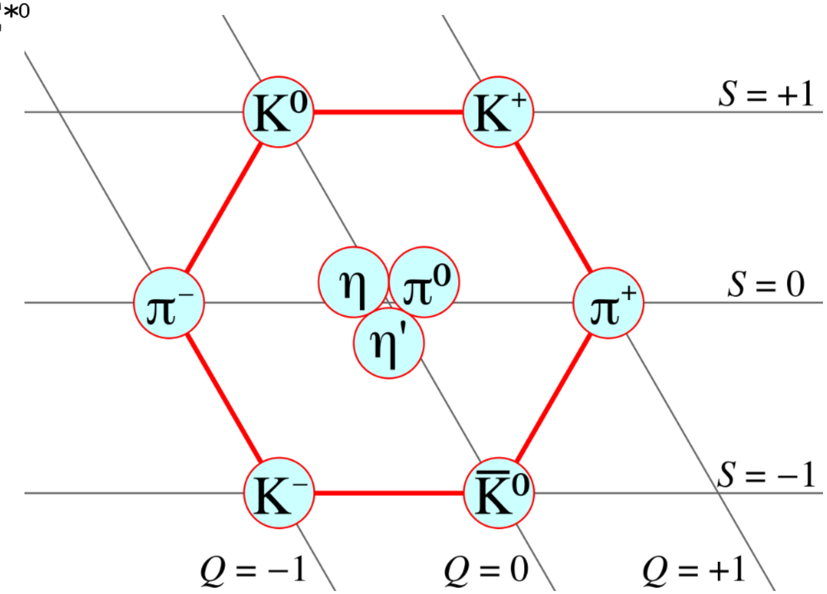
These particles obey the laws of Quantum Mechanics.

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

What particles are there?

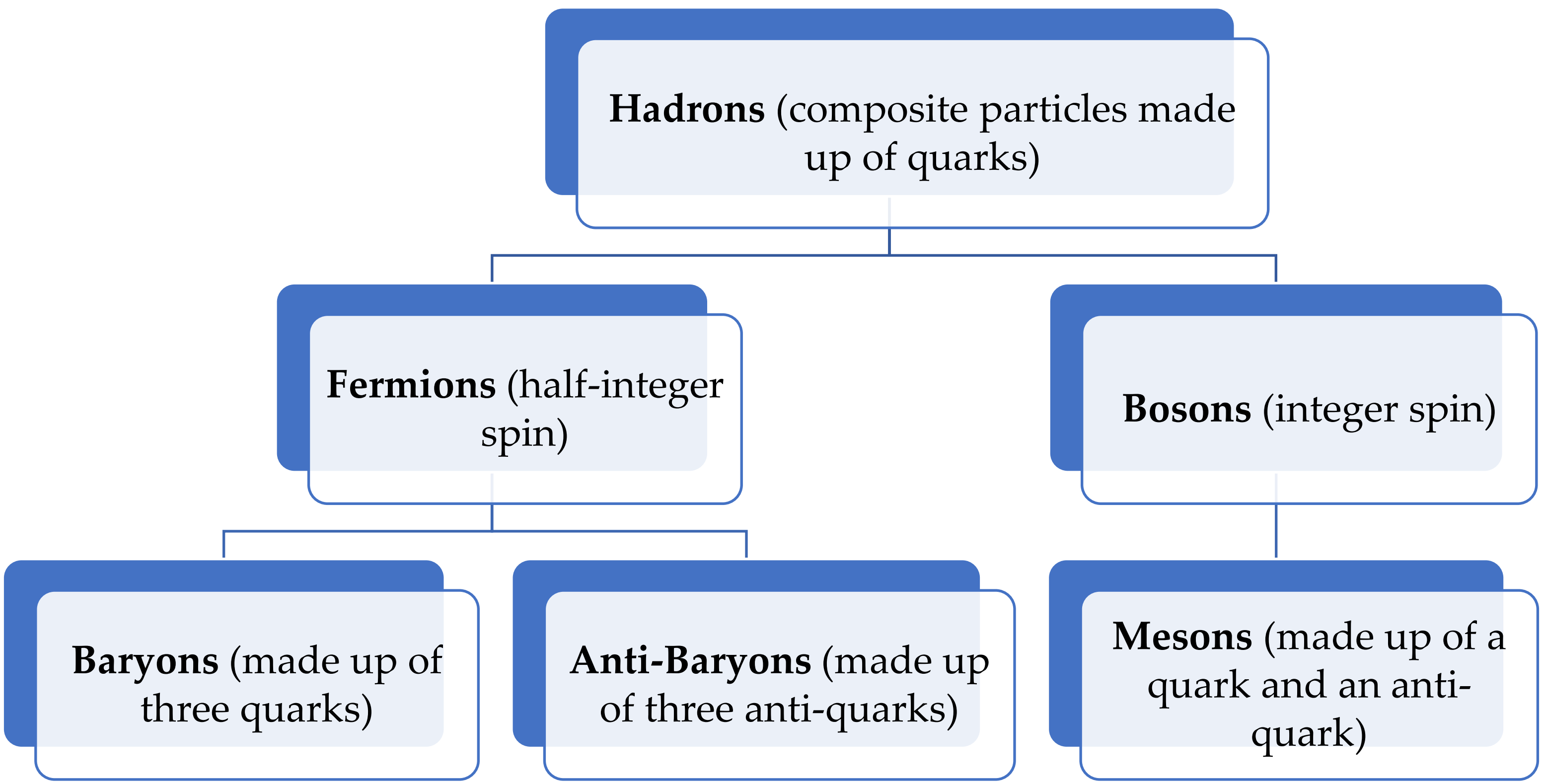




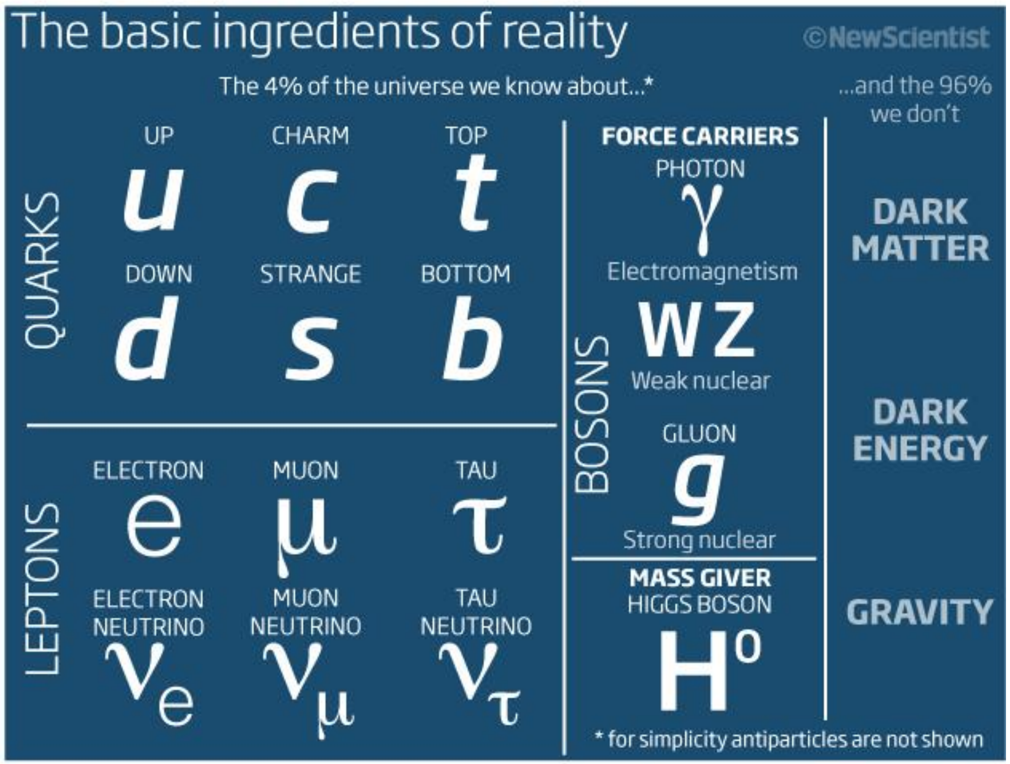


How do we classify these particles?

- The theories of Special Relativity and Quantum Mechanics allow us to classify subatomic particles as fermions or bosons according to their spin.
- Particles made up of quarks are called hadrons and can classified as baryons, anti-baryons and mesons.



The Standard Model (SM)



- This theory allows us to classify all known subatomic particles in terms of a few **elementary particles**.
- Quarks and leptons (and their anti-particles) are fermions that make up all known matter.
- The photon, gluon, W and Z are bosons that "carry" the forces.
- The higgs boson gives (most?) particles their mass.

What else does the SM do?

- The SM does more than classify particles, it is a mathematical theory that combines Special Relativity and Quantum Mechanics (our two best theories!) to explain nature at its most fundamental level.

$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}W_{\mu\nu}\cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}\cdot B^{\mu\nu} - \frac{1}{4}G_{\mu\nu}\cdot G^{\mu\nu}}_{\text{Kinetic energies and self-interactions of the gauge bosons}}$$

$$+ \underbrace{\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'Y B_{\mu}\right)L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g'Y B_{\mu}\right)R}_{\text{Kinetic energies and electroweak interactions of fermions}}$$

$$+ \underbrace{\frac{1}{2}\left|\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'Y B_{\mu}\right)\phi\right|^2 - V(\phi)}_{W^{\pm}, Z, \gamma \text{ and Higgs masses and couplings}}$$

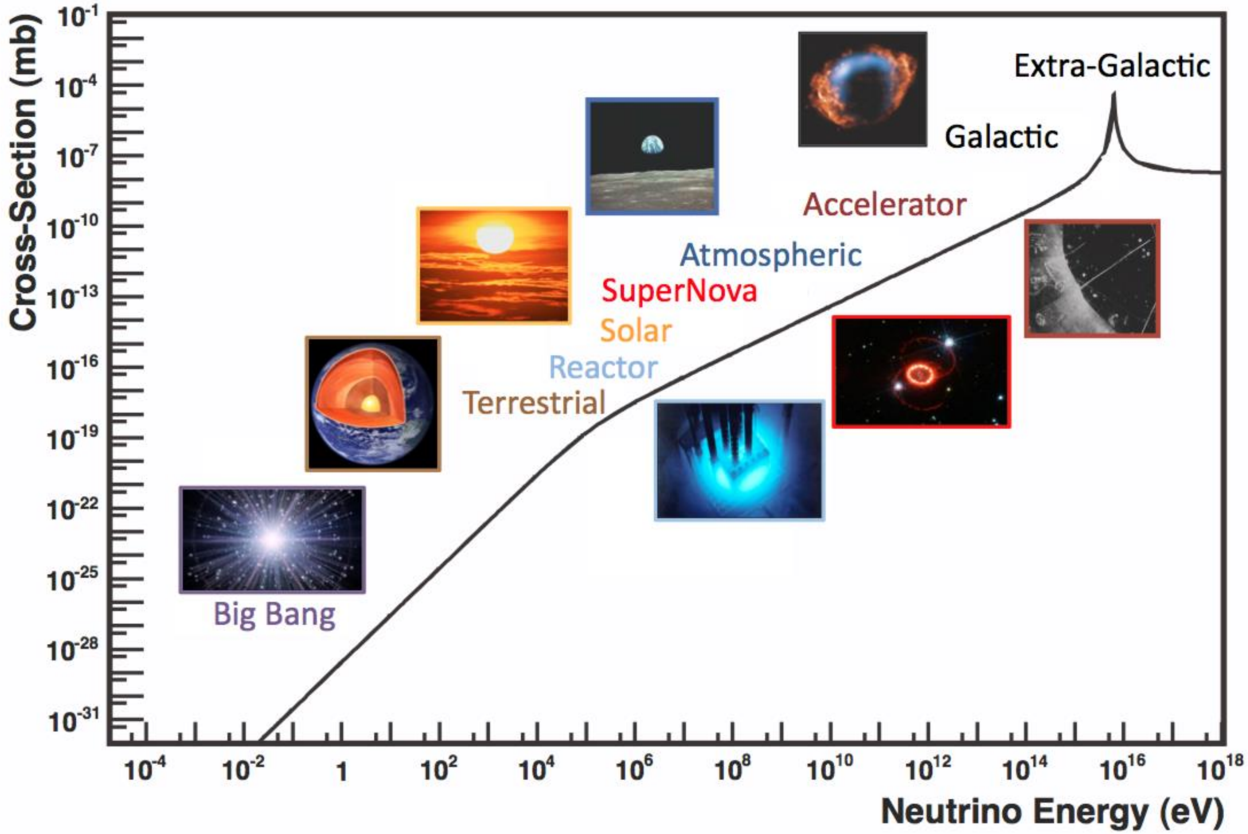
$$+ \underbrace{g''(\bar{q}\gamma^{\mu}T_a q)G_{\mu}^{a}}_{\text{interactions between quarks and gluons}} + \underbrace{(G_1\bar{L}\phi R + G_1\bar{L}\phi_c R + h.c.)}_{\text{fermion masses and couplings to Higgs}}$$

Some things we know about neutrinos

There are three types of neutrinos

- Electron neutrinos
- Muon neutrinos
- Tau neutrinos

They come from different sources



They are everywhere

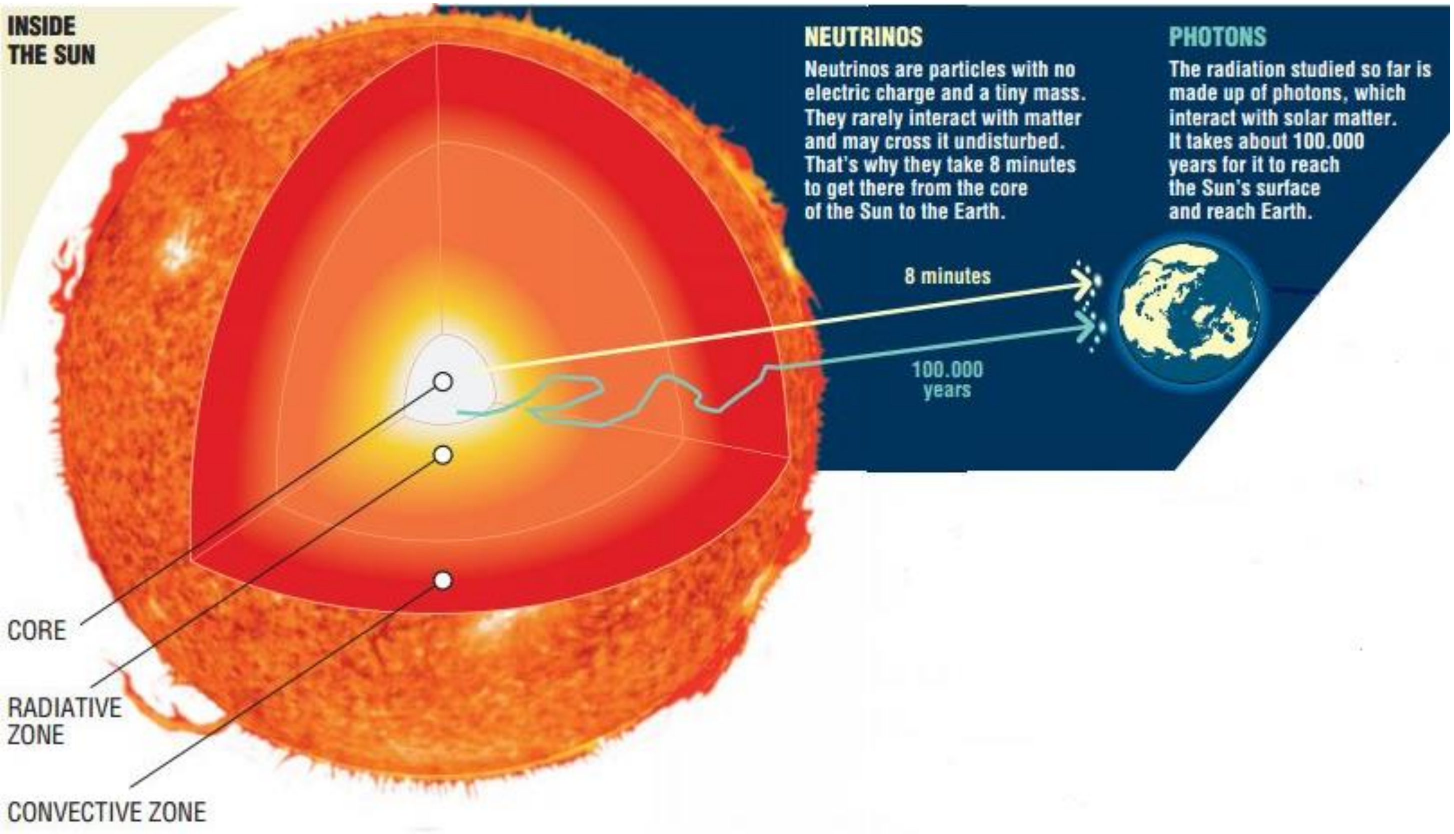
Every cm² of Earth surface is crossed every second by more than 10 billion (10^{10}) neutrinos produced in the Sun

Within your body at any instant: roughly 30 million neutrinos from the Big Bang

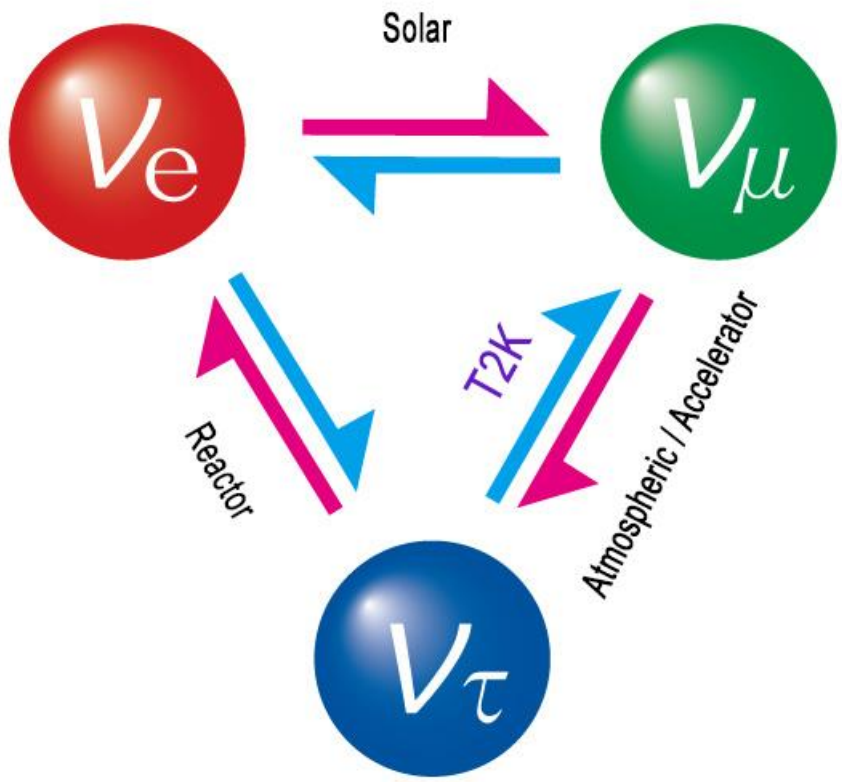
No worries!
Neutrinos do not harm us.
Our bodies are transparent to neutrinos

neutrinos are **very** weakly interacting

- No charge
- No color
- Almost no mass



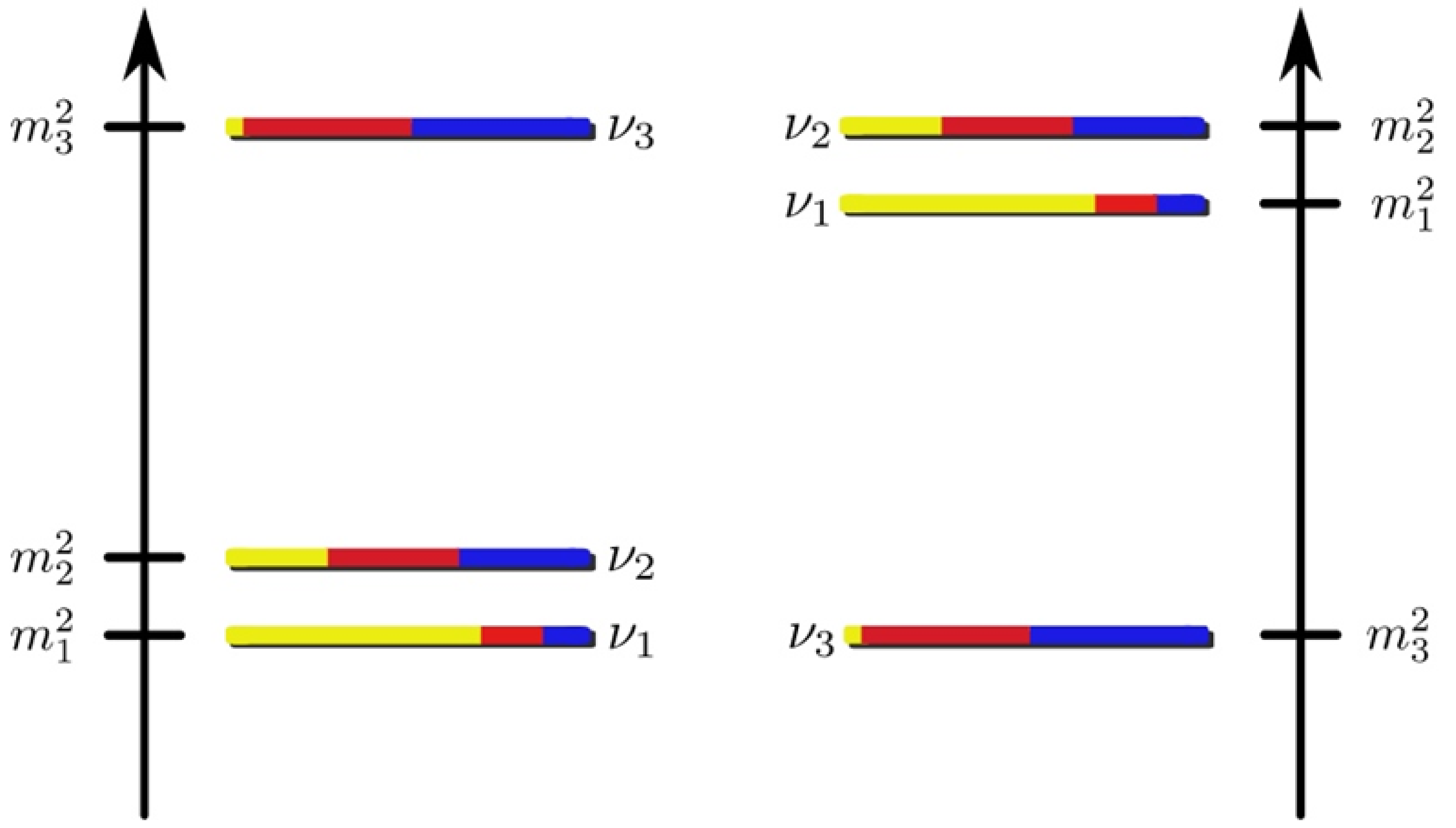
Neutrinos have (very small) mass…and oscillate!



Neutrino oscillation between three generations

(some of)
what we don’t know

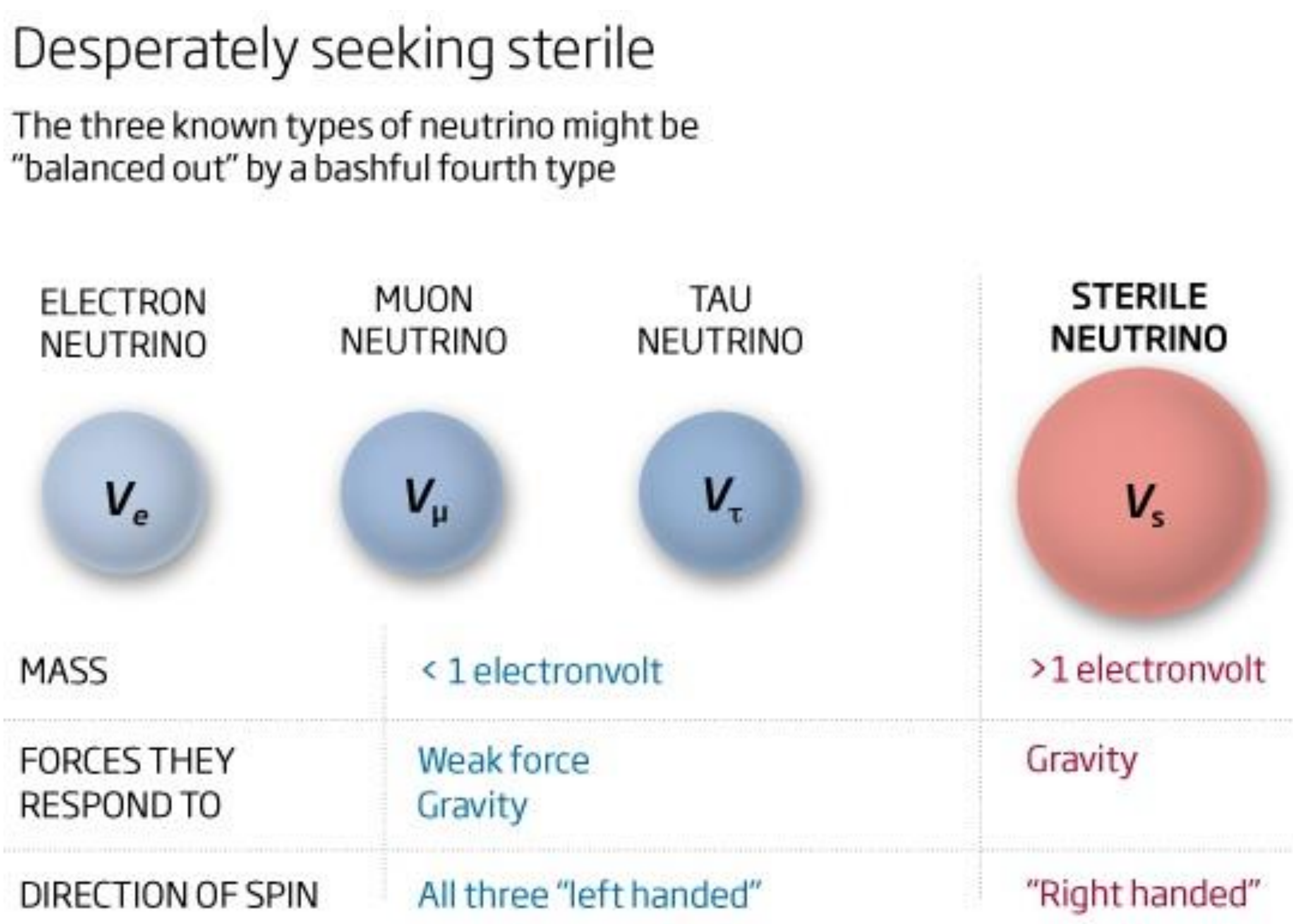
Mass Hierarchy



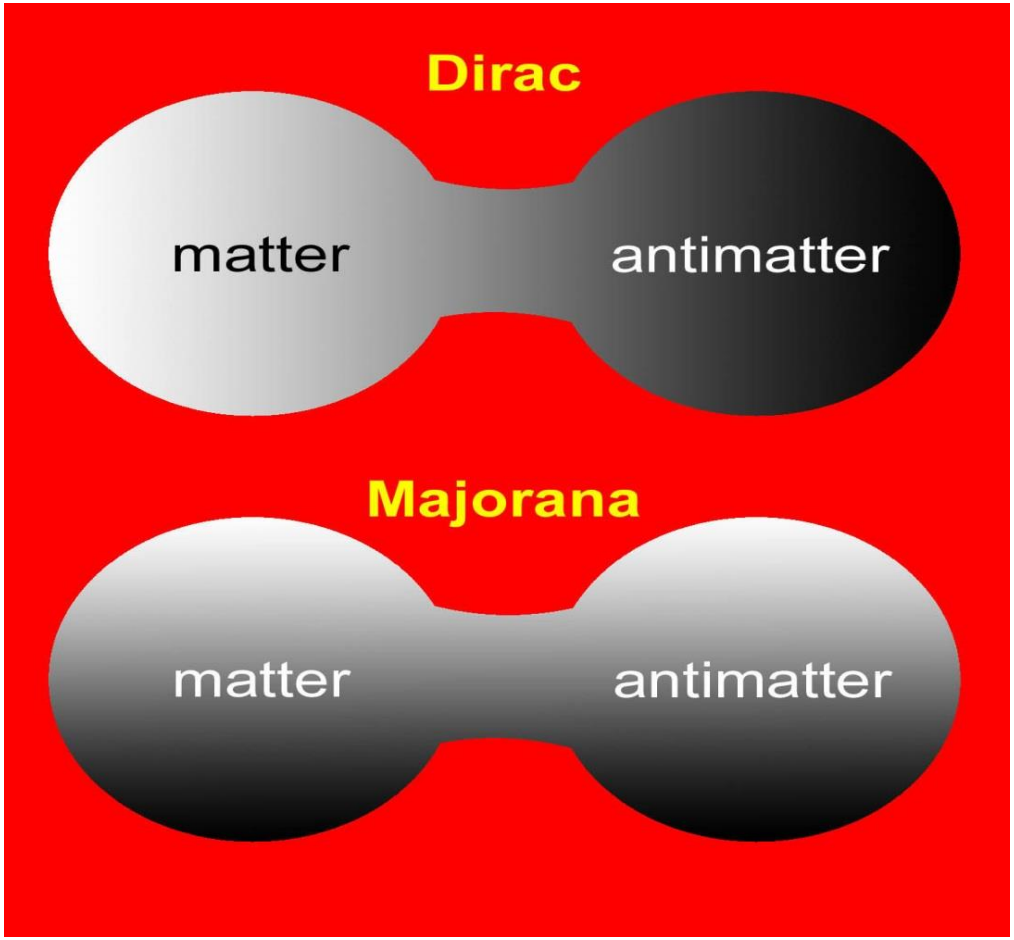
Missing parameters

$$
\begin{aligned}
U &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \\
&= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
&= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}
\end{aligned}
$$

Are there more neutrinos?

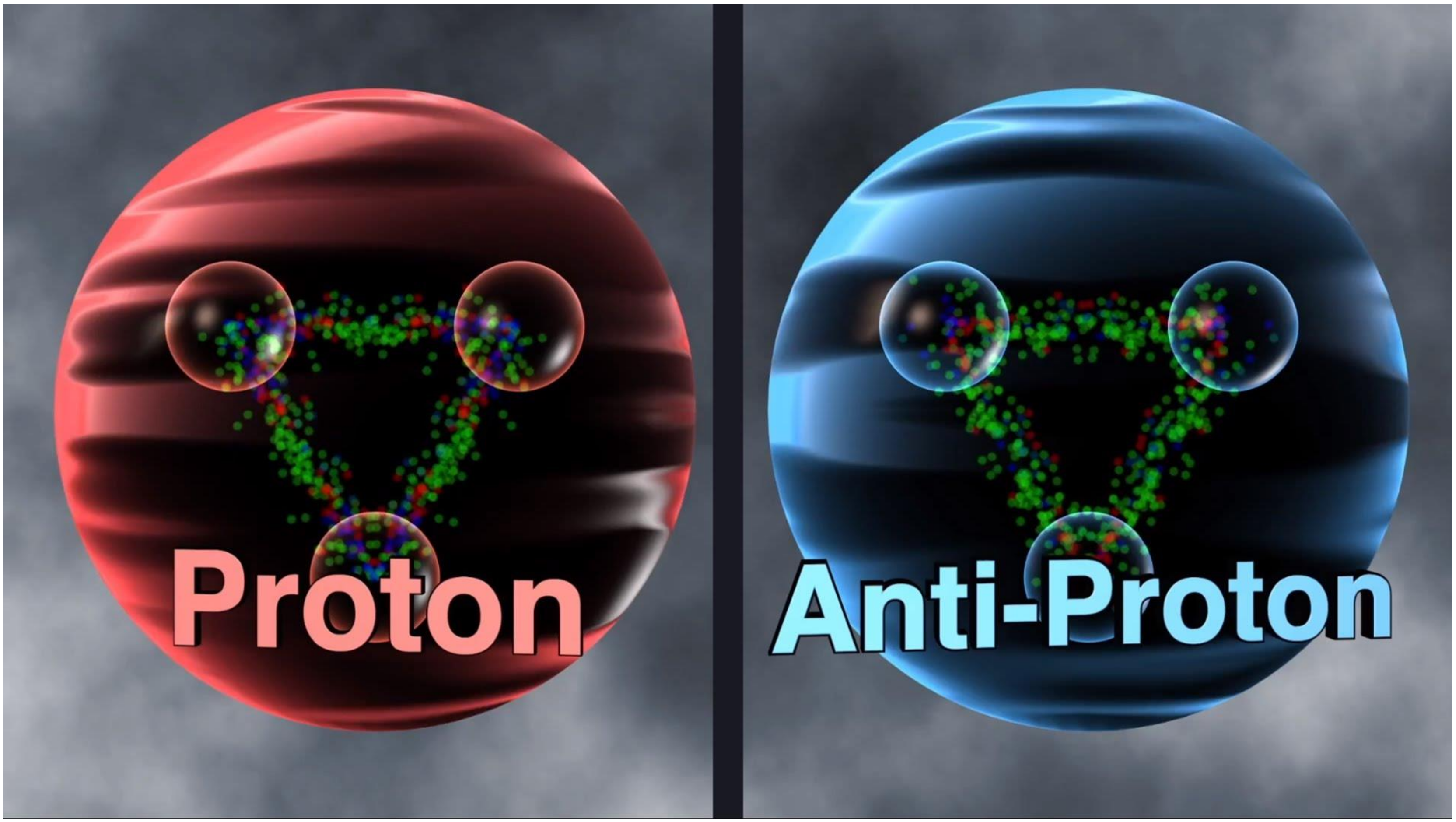


What kind of mass do they have?



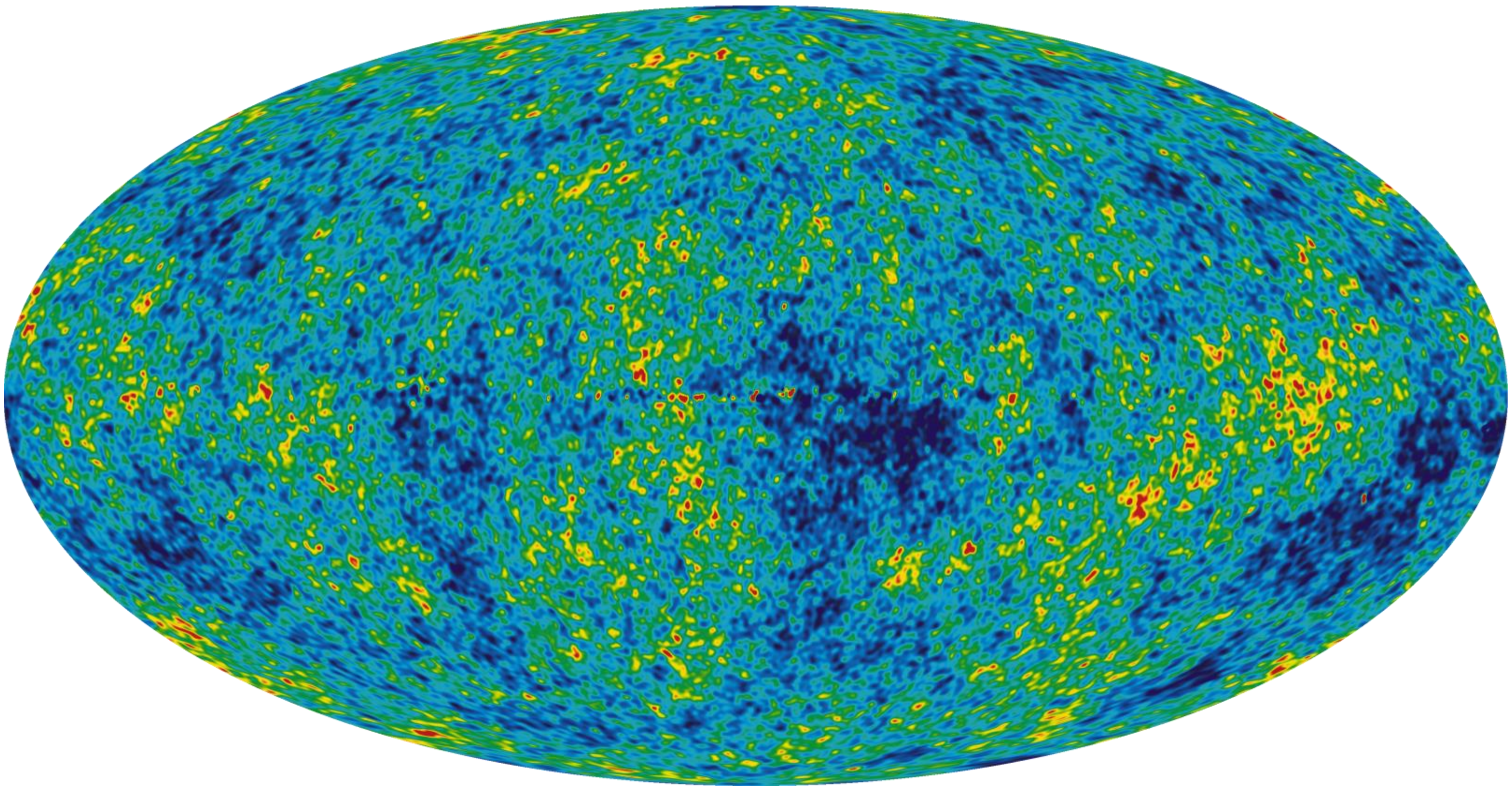
Why are neutrinos important?

Neutrinos are probably responsible for the origin of baryon asymmetry in the universe.



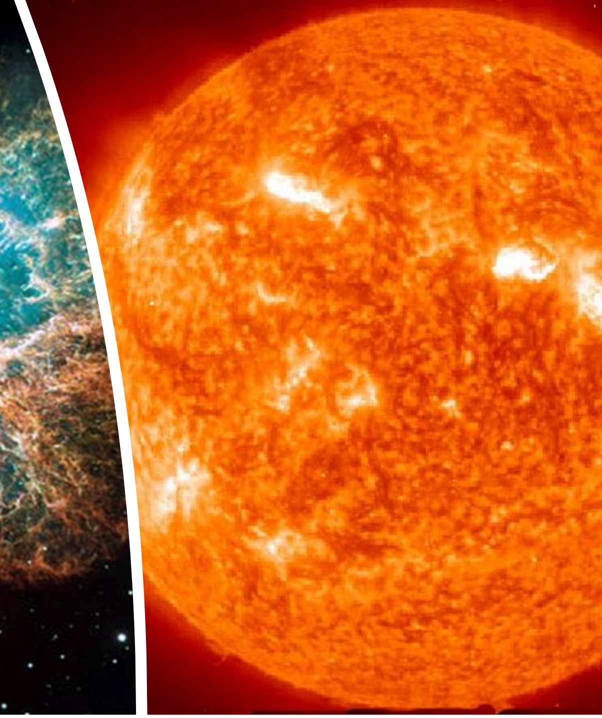
Neutrinos are important for

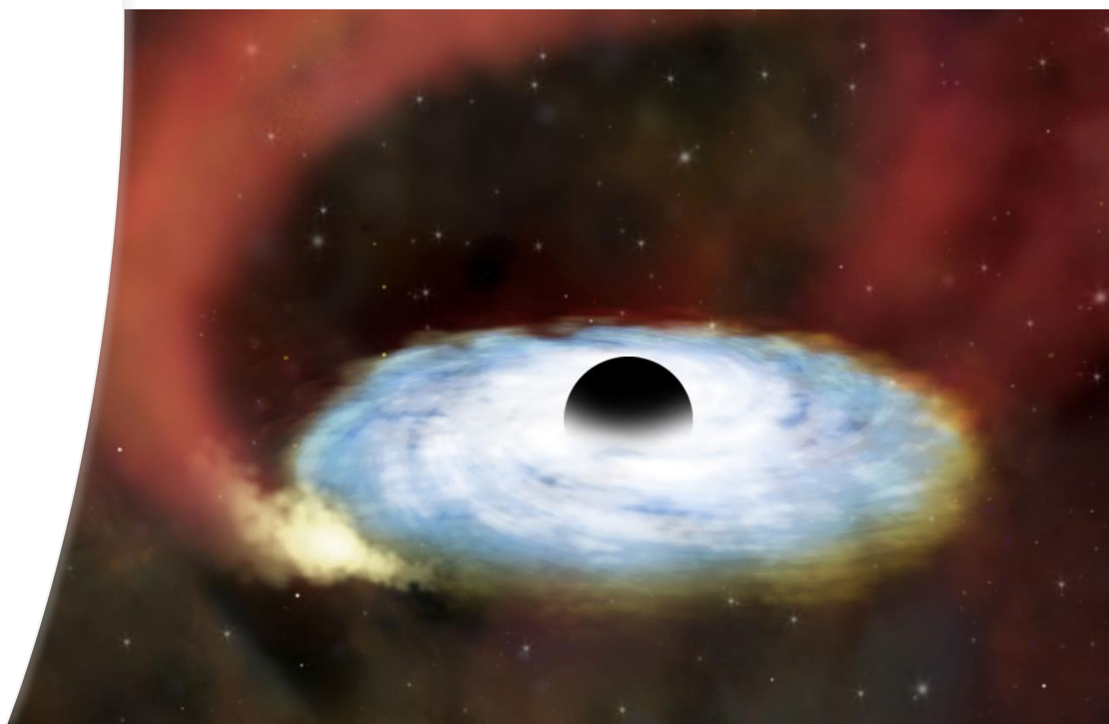
- understanding the spectrum of the CMB
- making sense of the LSS in the universe
- studying the delicate chemical equilibriums determining the light element abundances during BBN



Neutrinos could be a powerful probe of

- the dynamics of stars
- supernova collapse
- accretion disks encircling supermassive black holes.





Thank you for your attention