# Cosmic rays and neutrinos: windows into the ultra-high-energy Universe

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# A story more than 100 years old

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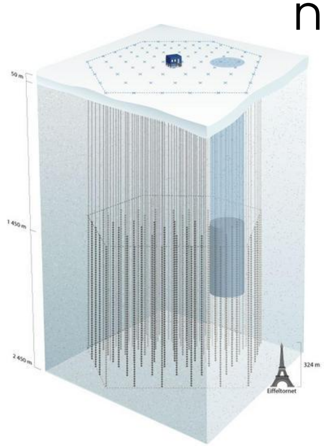
These are the **most energetic** particles in the known Universe

– are they jointly created in cosmic accelerators?

**2013:** ultra-high-energy neutrinos

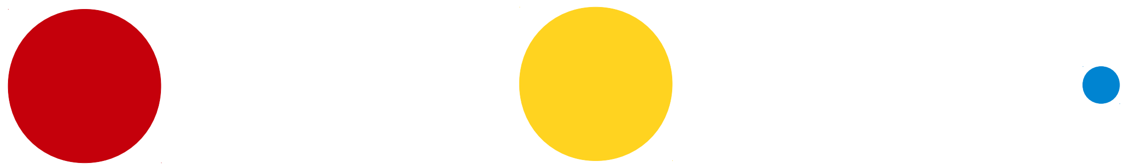


**1962:** ultra-high-energy CRs

**1956:** neutrino discovered

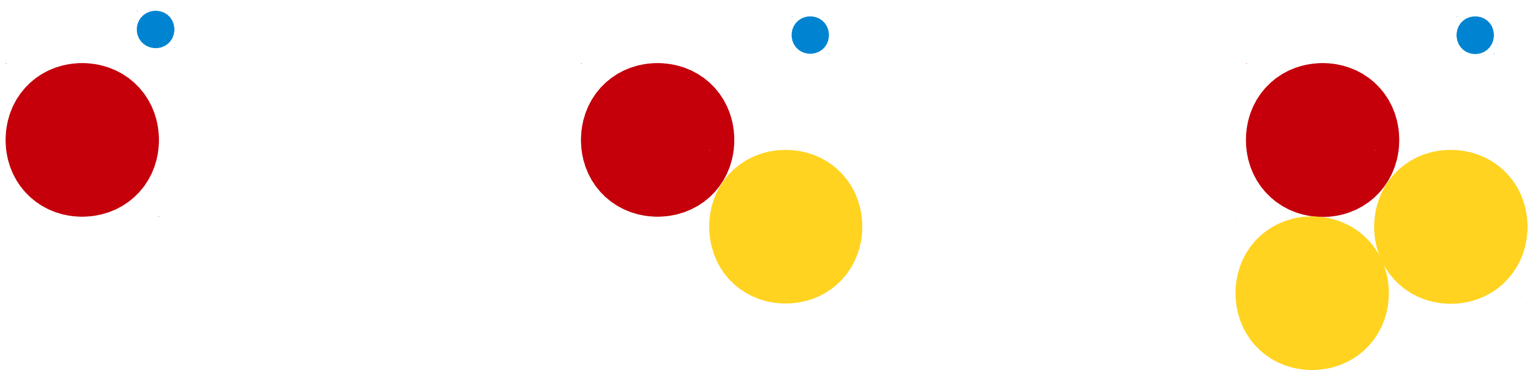
# Some atoms are not made to last

The actors:



| proton | neutron | electron |
|---|---|---|
| charge +1 | no charge | charge -1 |

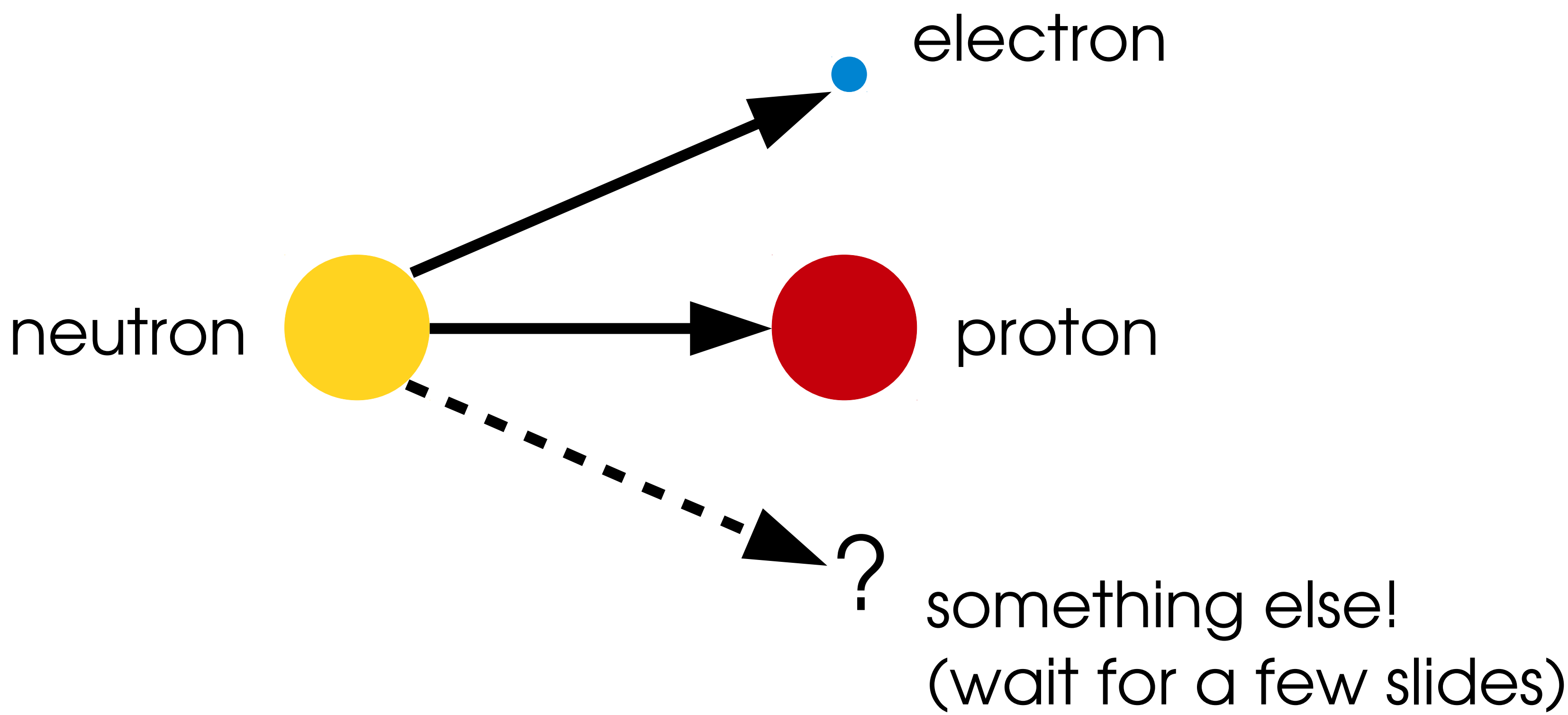
Different types (isotopes) of hydrogen:



| $^{1}_{1}H$ | deuterium $^{2}_{1}H$ | tritium $^{3}_{1}H$ |
|---|---|---|
| stable | stable | unstable! |

# Radioactivity: beta decay

A neutron in the wild will disappear after about 15 minutes



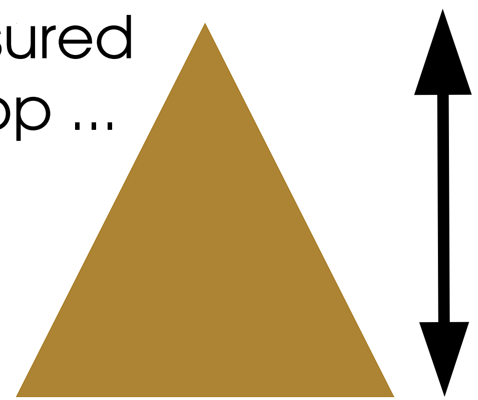
# Cosmic rays discovered

The state at the beginning of the 20th century:

(1) ambient radiation was already known to exist
(2) believed to be mainly coming from the ground

ambient radiation measured
lower at the top ...

… than at ground level

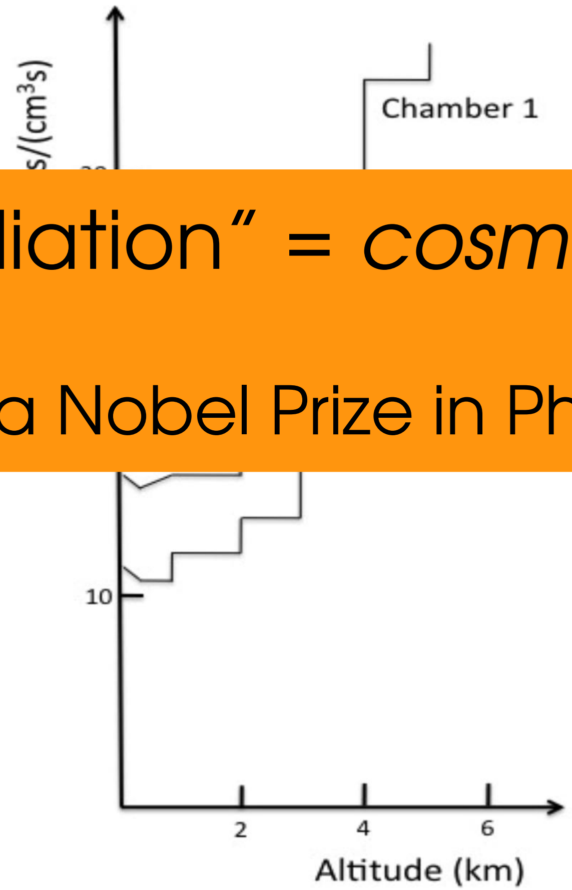


1 km tall mountain
(badly drawn)

Problem: they had measured *only* up to ~1 km of altitude

# Physics is a risky business

Victor Hess – 1911-1913, balloon flights up to 5.3 km

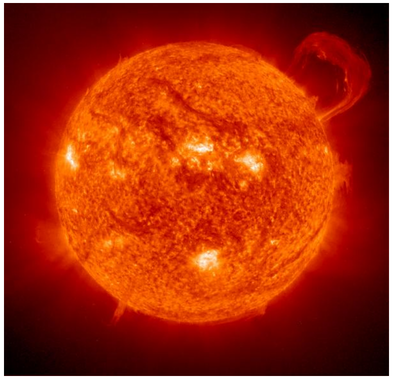



"Unknown penetrating radiation" = *cosmic rays*

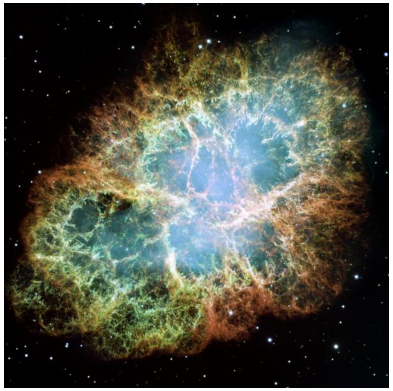
… and that's one way to get a Nobel Prize in Physics

Conclusion: an unknown penetrating form of radiation was reaching the atmosphere from beyond Earth

# So what *are* cosmic rays?



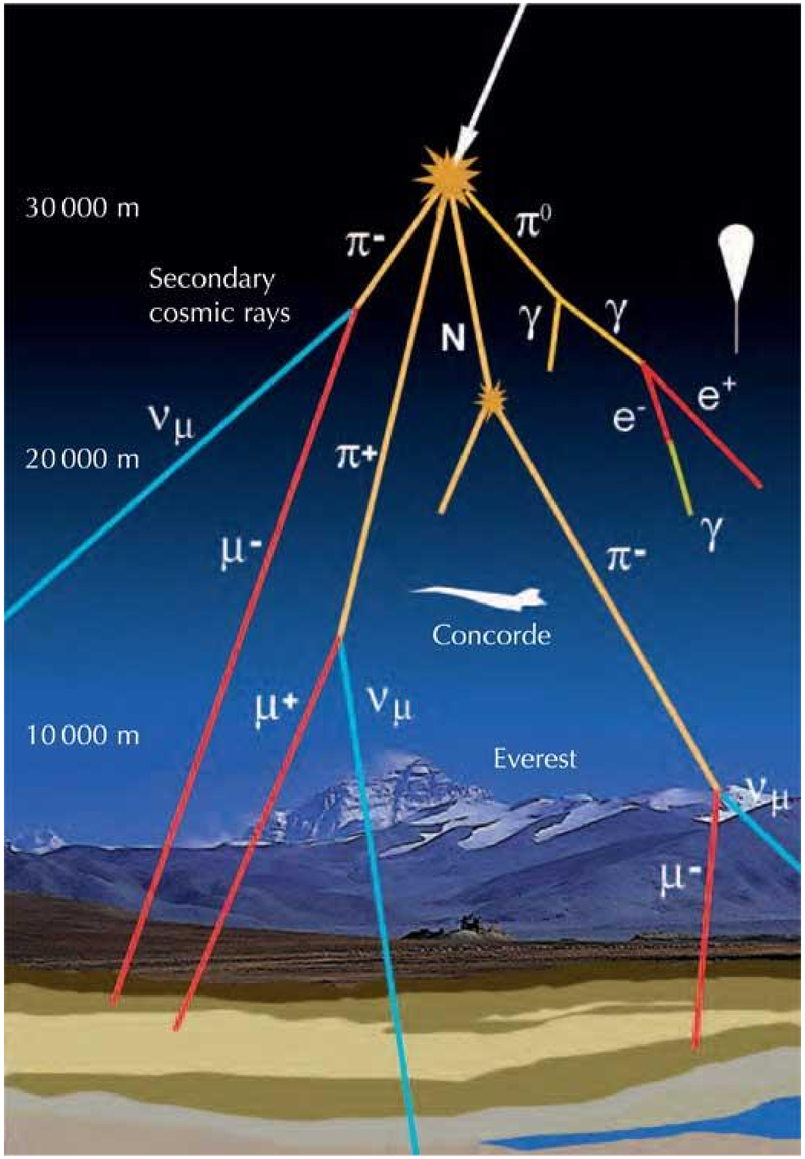
Low energies: from the Sun
– mostly electrons + protons

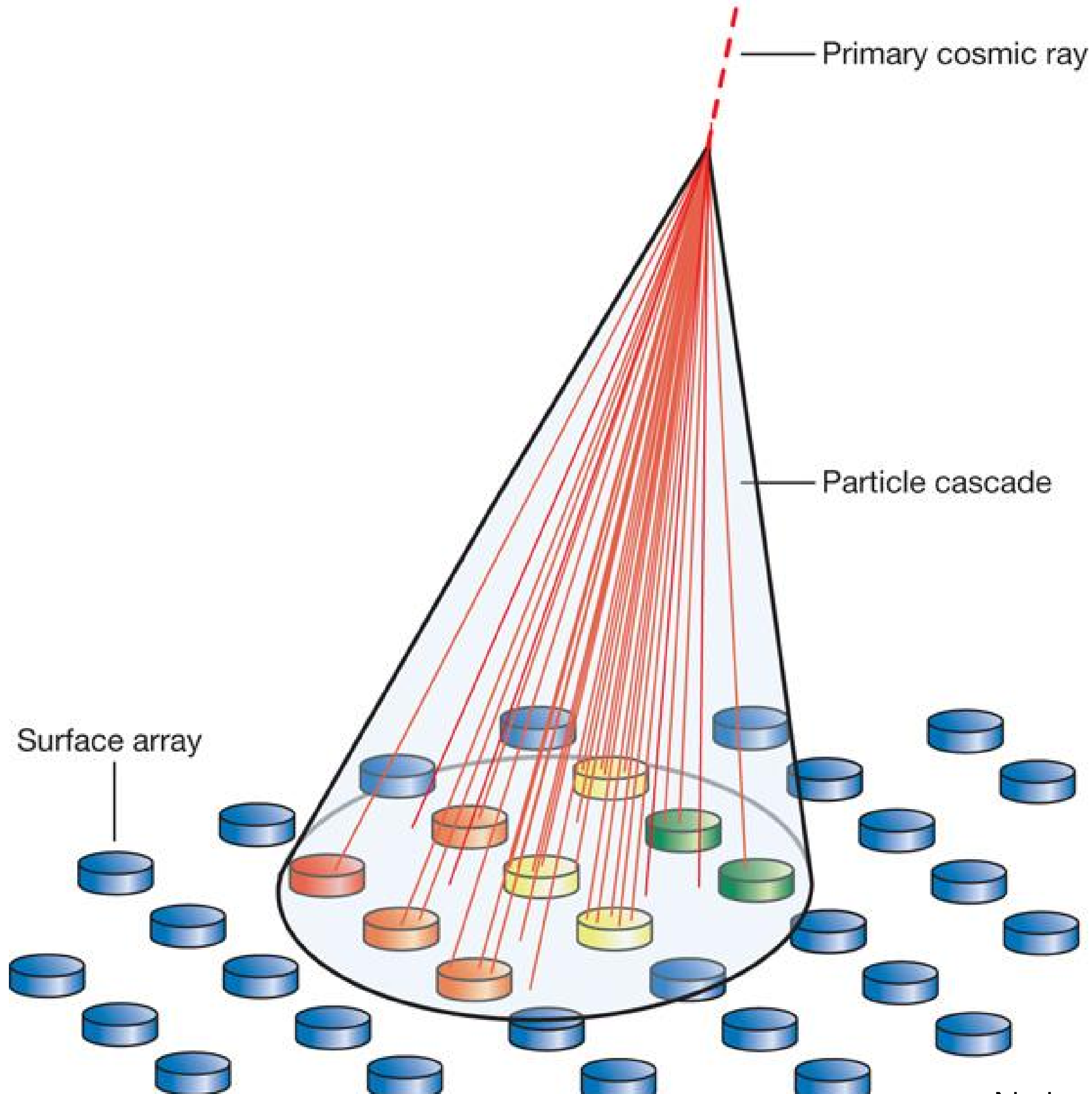


Higher energies: from supernovae inside the Milky Way
– mostly protons

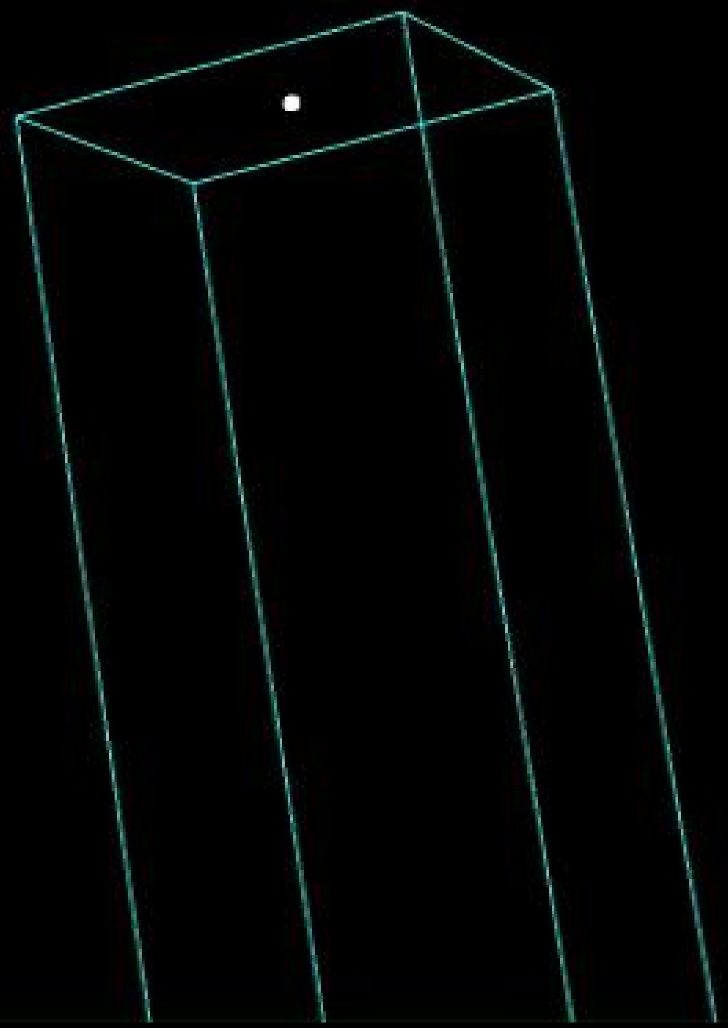
Highest energies: from beyond the Milky Way
– protons + (maybe) heavier nuclei

# Seeing the particle showers




Nature



Cosmus

# The most energetic particles!

1962: Volcano Ranch Experiment, New Mexico

Discovery of the first **ultra-high-energy** cosmic rays

# Just how energetic are they?

"Oh my God particle": Fly's Eye Experiment, Utah, 1991

Its (kinetic) energy was equivalent to...

… a baseball (142 g) flying at 94 km/h, or
… a football (410 g) flying at 55 km/h,

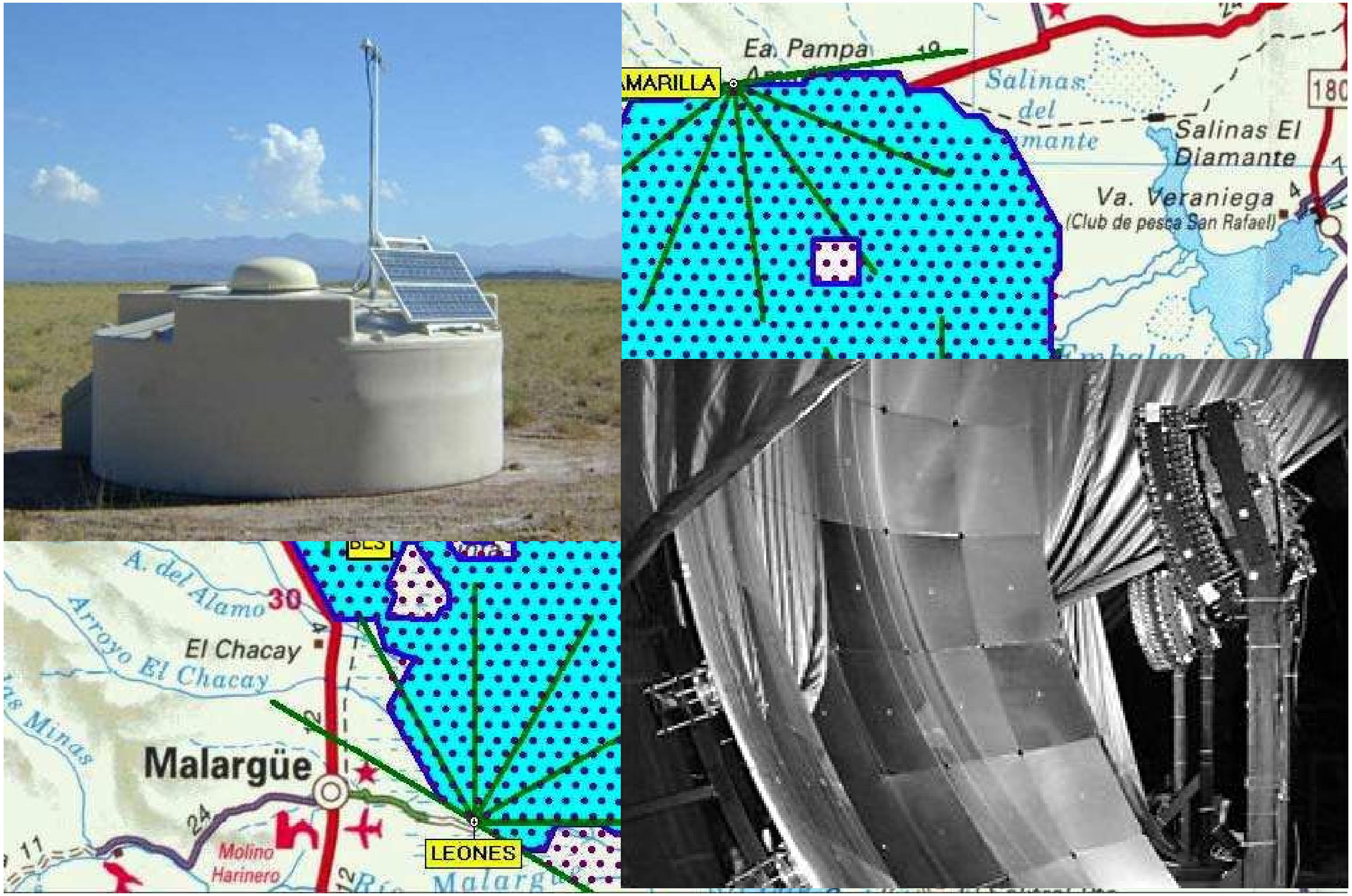
but **concentrated within the size of a proton**, $10^{-15}$ m

~40 million times more energetic than protons of the Large Hadron Collider

They are *very rare* – we have only seen ~200 of them

# Detecting cosmic rays *today*

We use arrays of thousands of water tanks
– largest experiment: Pierre Auger Observatory, Argentina

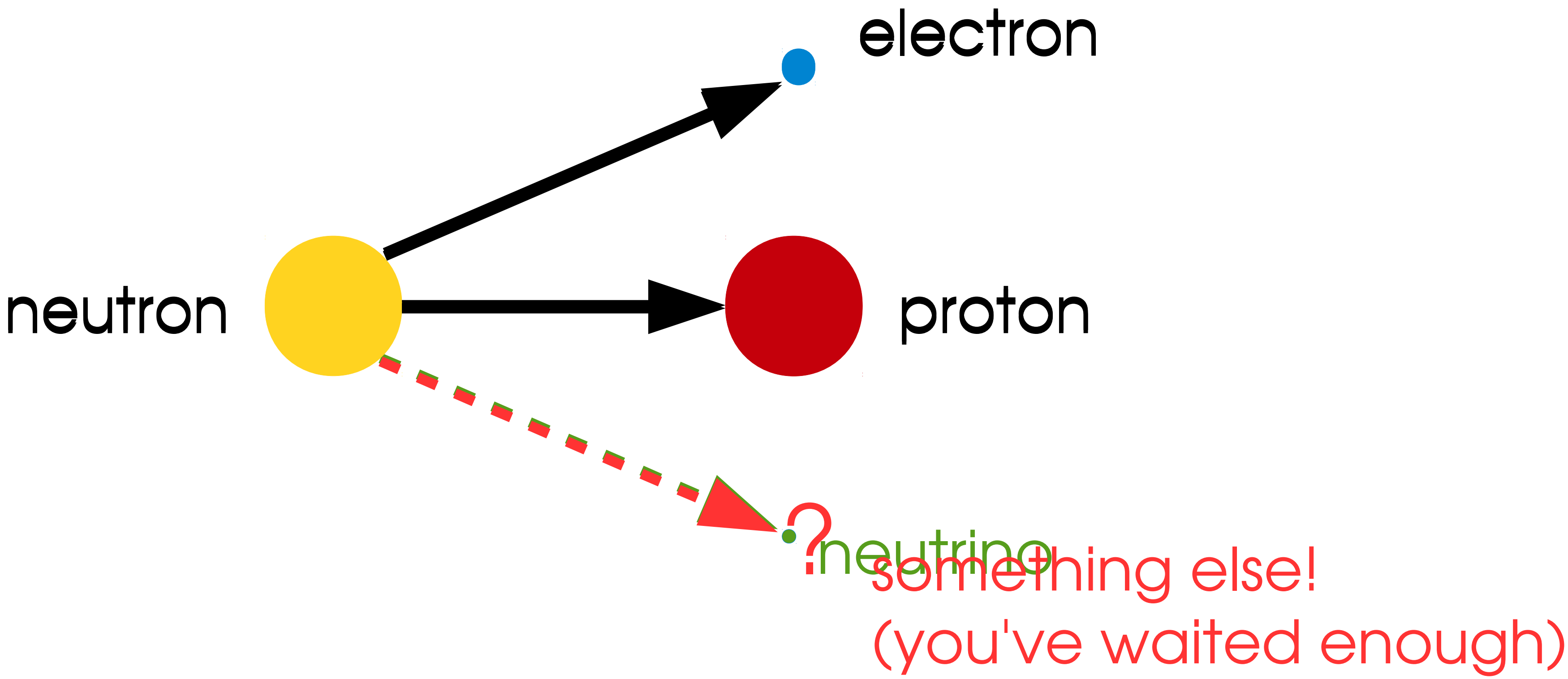


# Back up about 75 years

It's 1930 and most of you haven't been born

# Neutrinos, pesky little neutrinos

Recall the beta decay of the neutron:

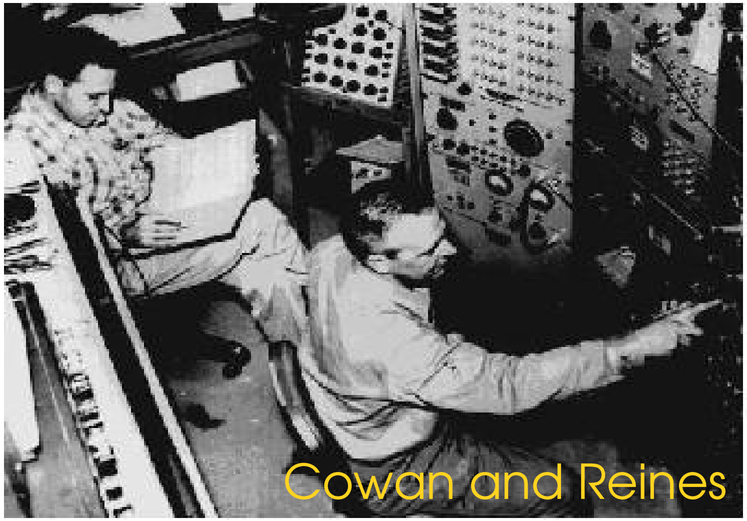


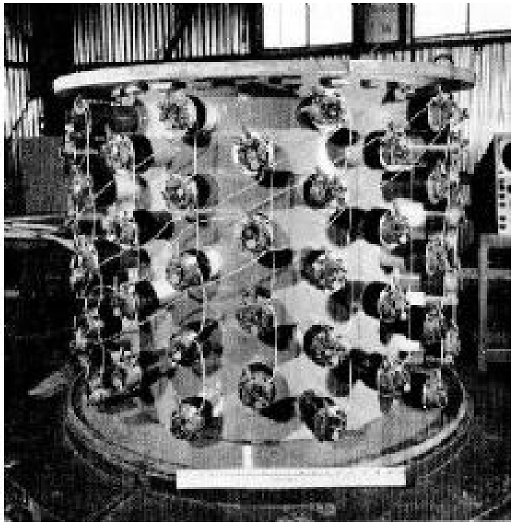

<1930: problems with energy conservation in **beta decay**

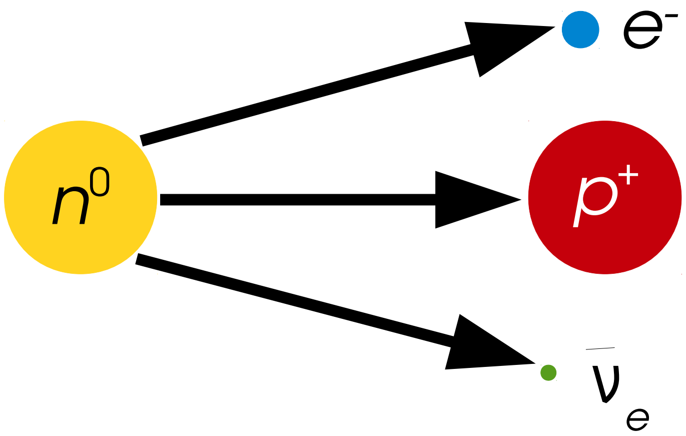
**Neutrino:** proposed in 1930 to make sense of **beta decay**

# Neutrinos are real

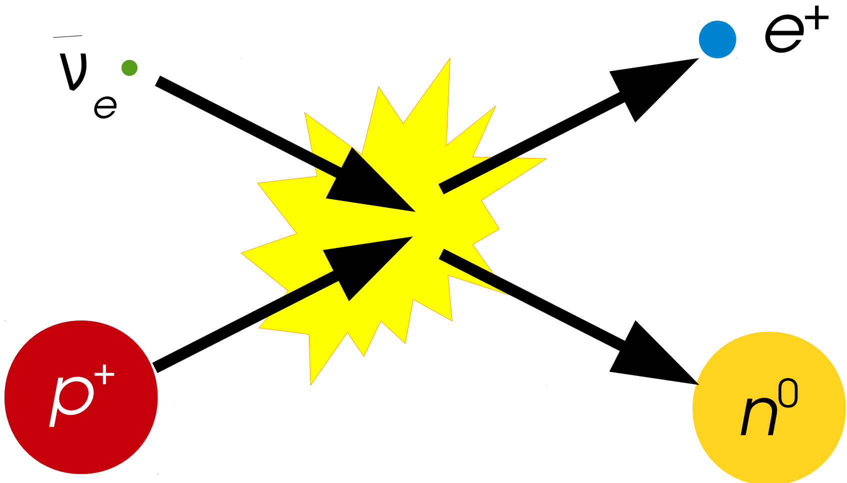
They were proposed in 1930, but detected only in 1956






beta decay




*inverse* beta decay

# Back to the present

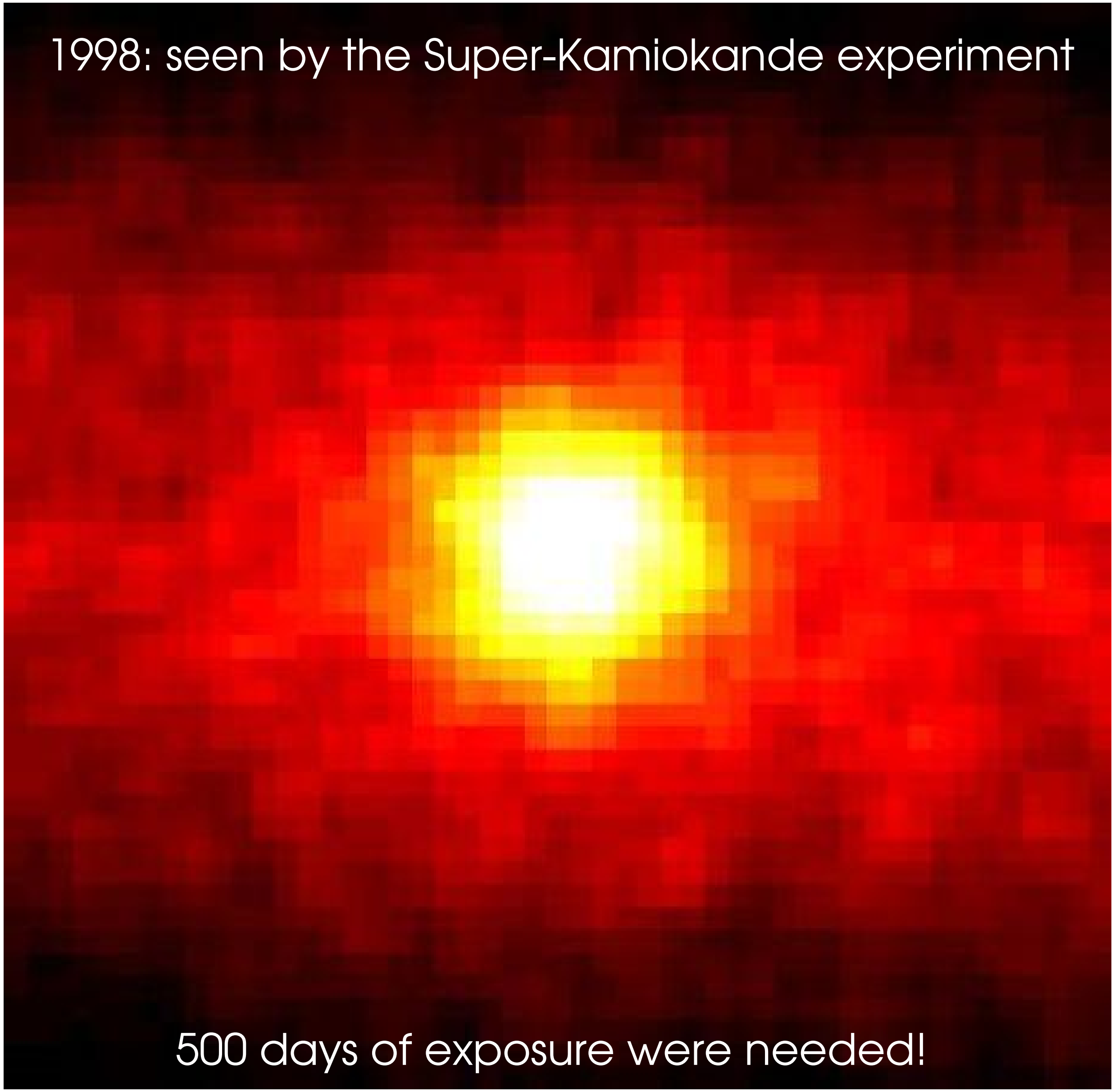
It's 2015 and you are drinking wine

# Neutrinos are wonderfully weird

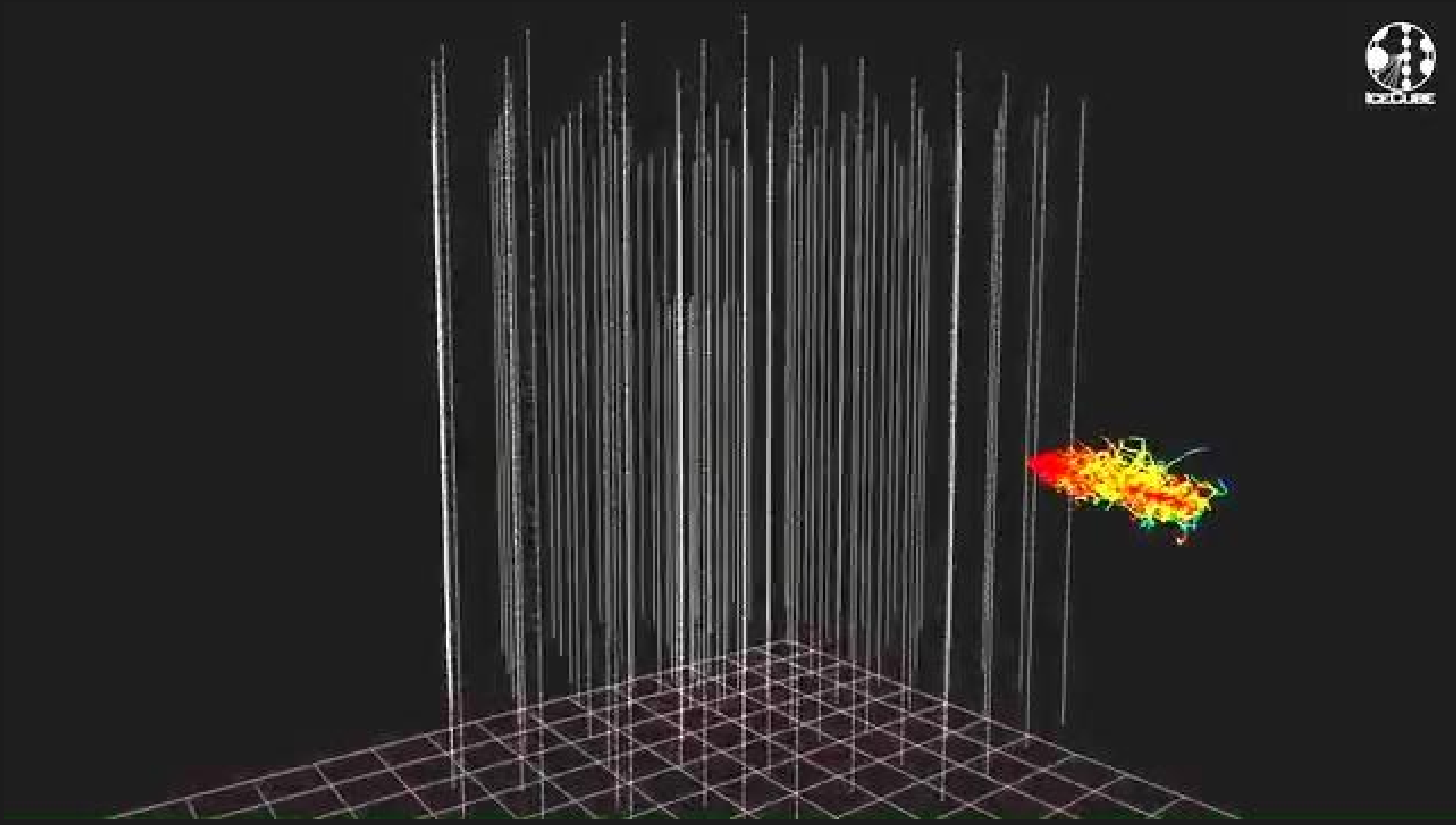
1. They are ubiquitous and extremely abundant
2. They are the lightest particles that we know of
   – we thought they were massless until 2001!
3. They hardly ever interact with other stuff
   – we call them *weakly interacting*
4. They come in three different types ("flavors")
   – and they can change ("oscillate") into one another

Like cosmic rays, some of their fundamental properties are still unknown (but we are getting there...)

# The Sun... seen in neutrinos



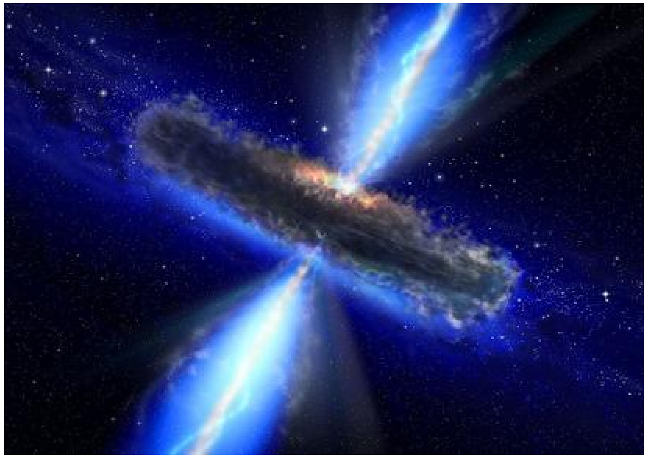
# Are there UHE neutrinos?



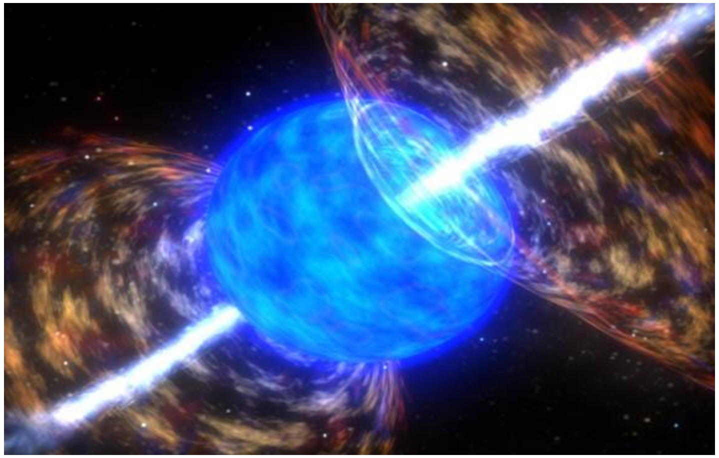
# CRs & neutrinos: common origin?

They have comparable energies, so they might have been produced in the same processes

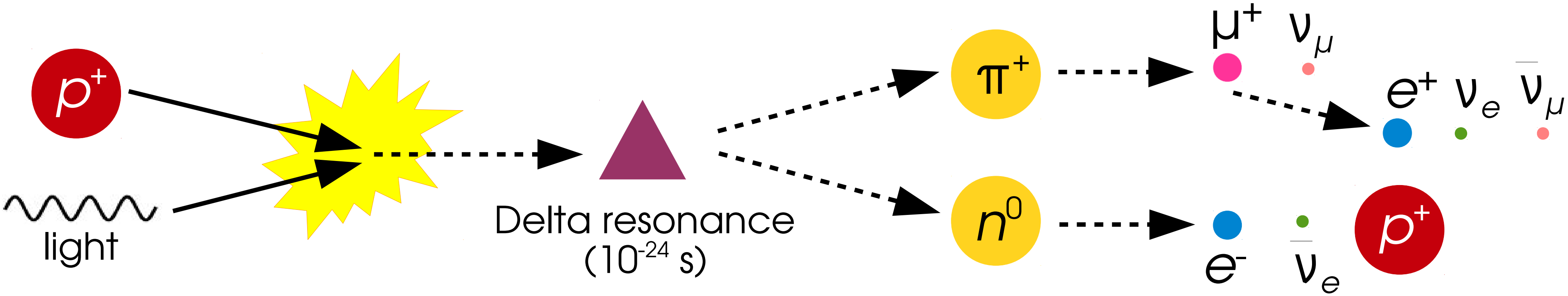
Possible sources: cosmic accelerators



active galactic nuclei

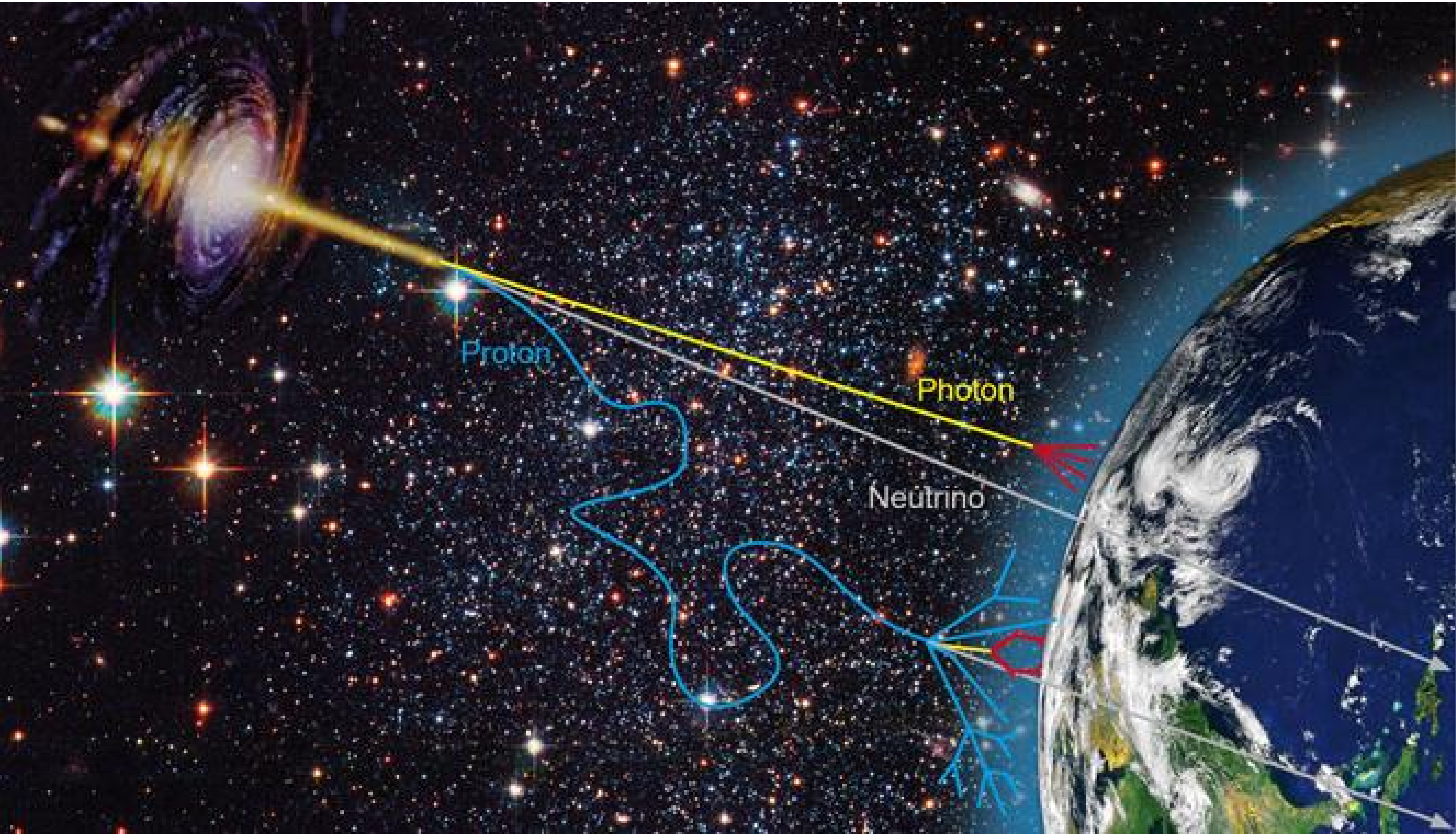


gamma-ray bursts



A long time ago in a galaxy far,
far away. . . .

# The ultra-high-energy Universe

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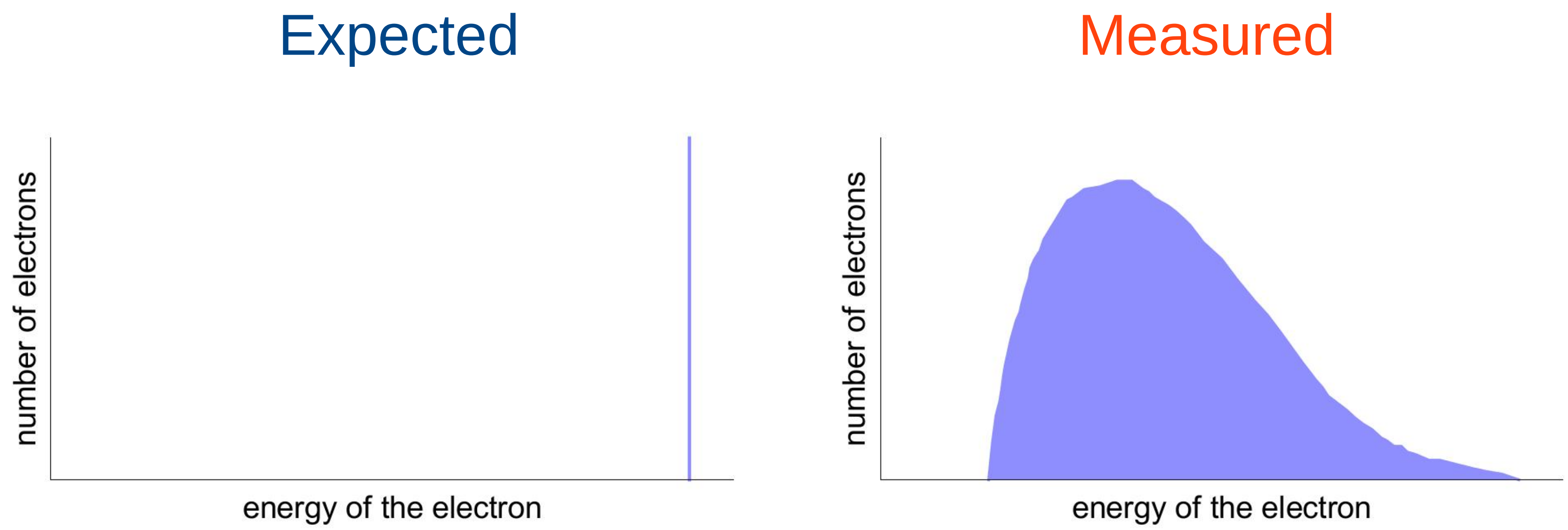
# Backup slides

# The problem with beta decay

Circa 1930: observed discrepancy in the distribution on electrons produced in beta decay:

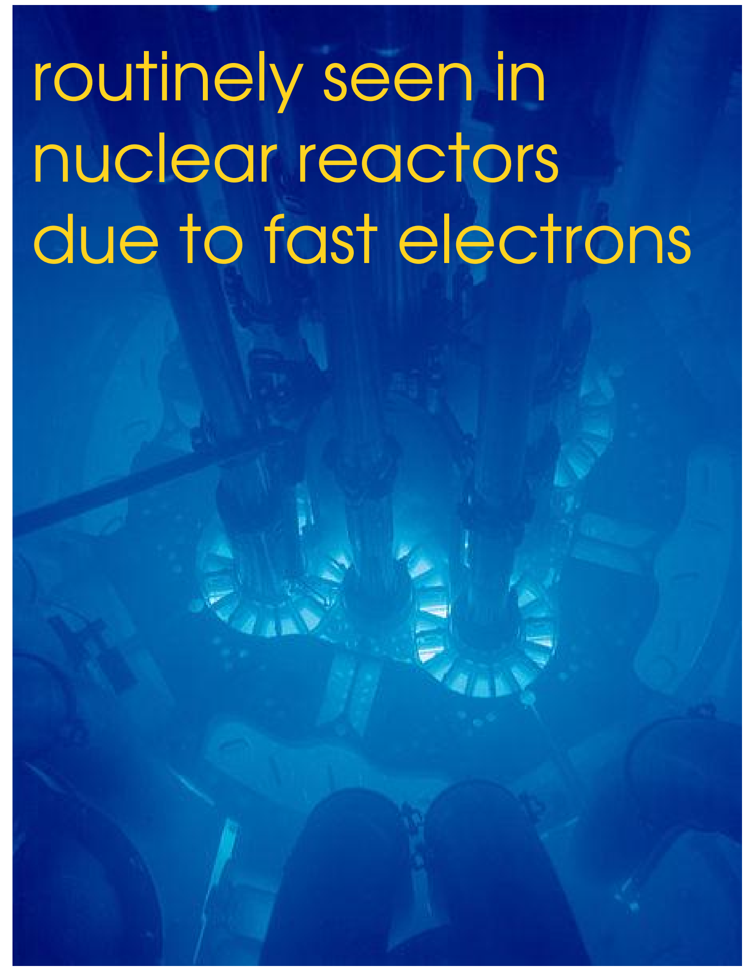



The neutrino was proposed to solve this discrepancy

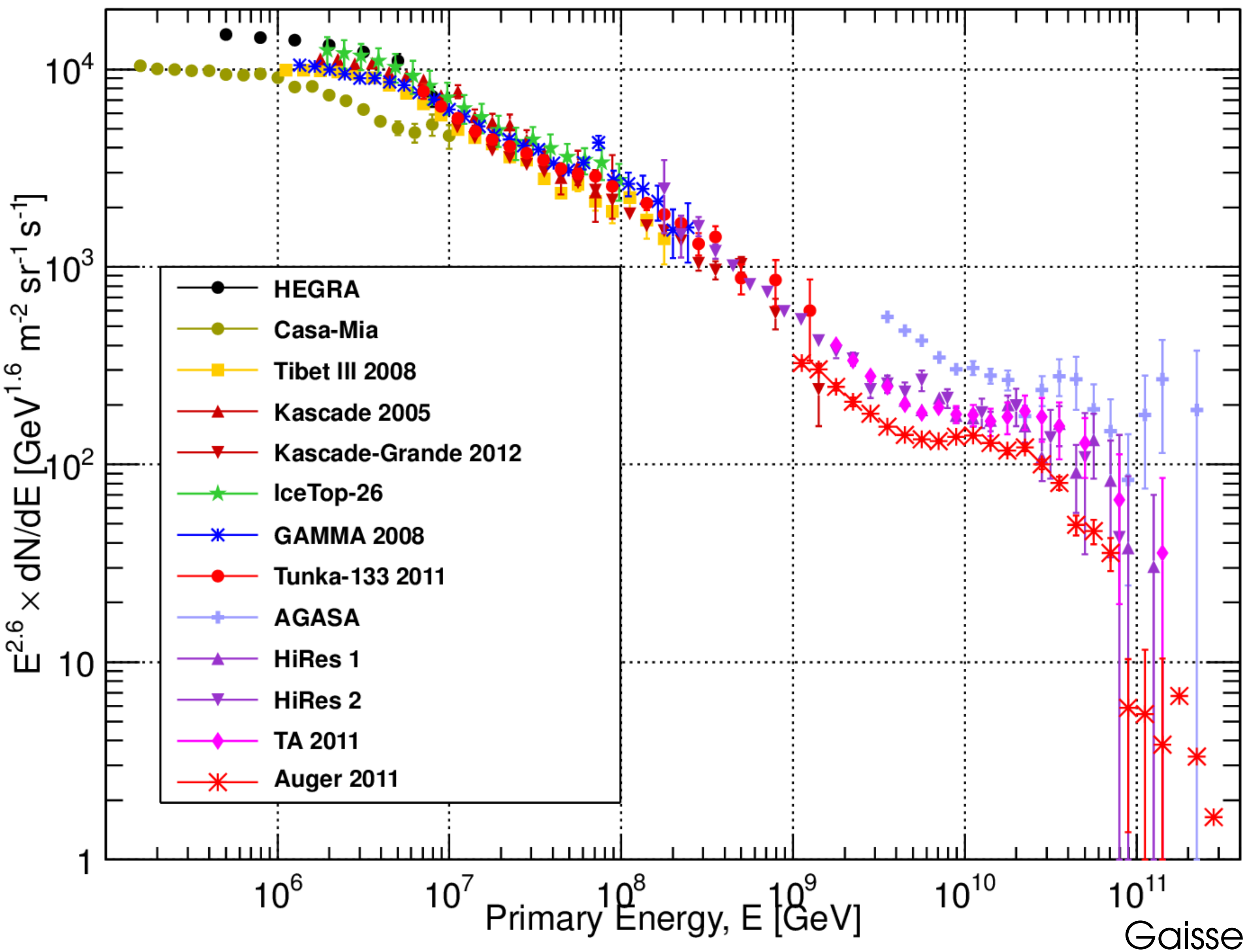
# Cherenkov radiation

It occurs when a particle in a medium travels faster than light (in that medium)

analogous to the "sonic boom" of a plane reaching Mach 1

# The cosmic ray spectrum




Gaisser et al. 2013