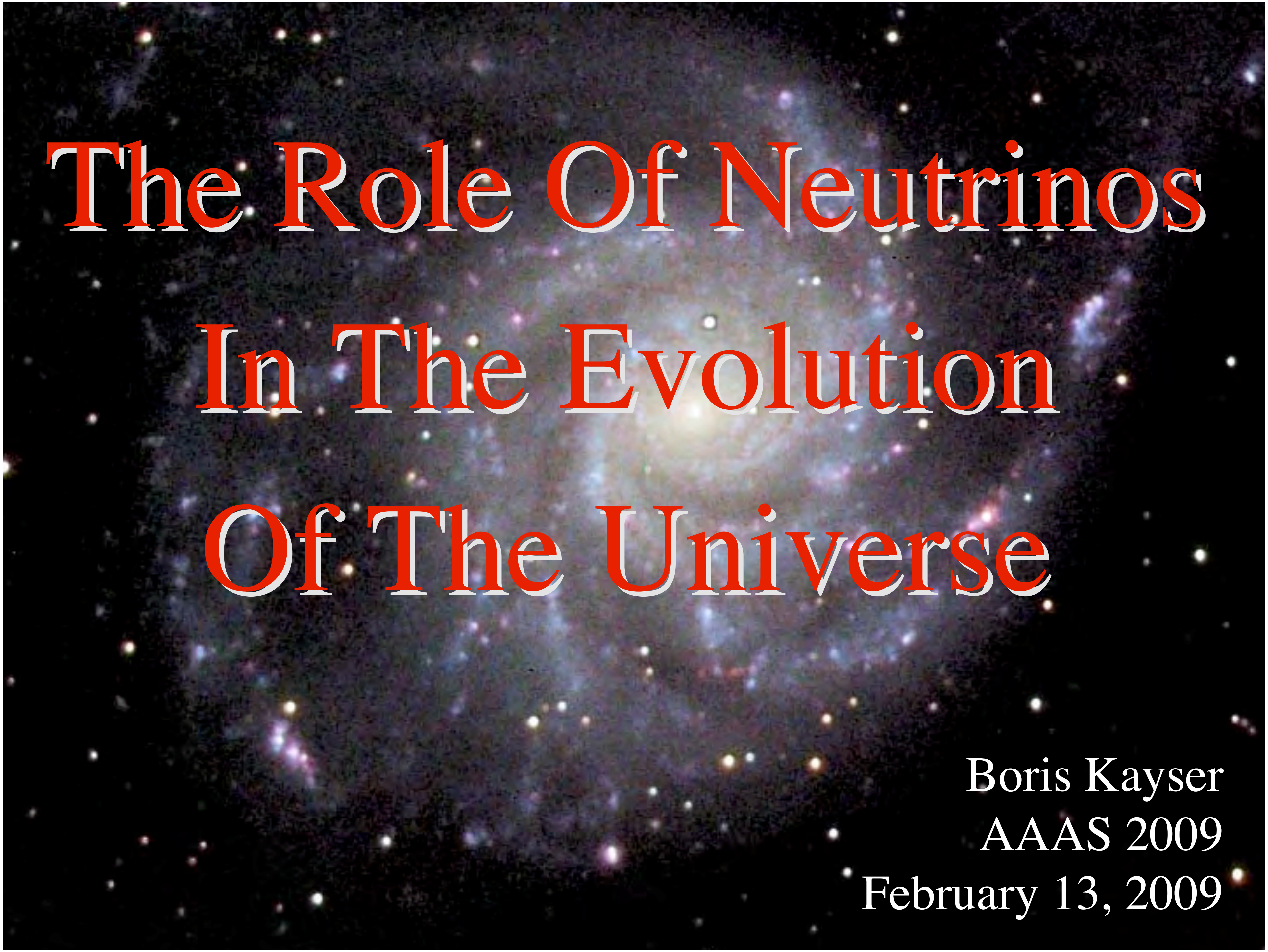


The Role Of Neutrinos In The Evolution Of The Universe

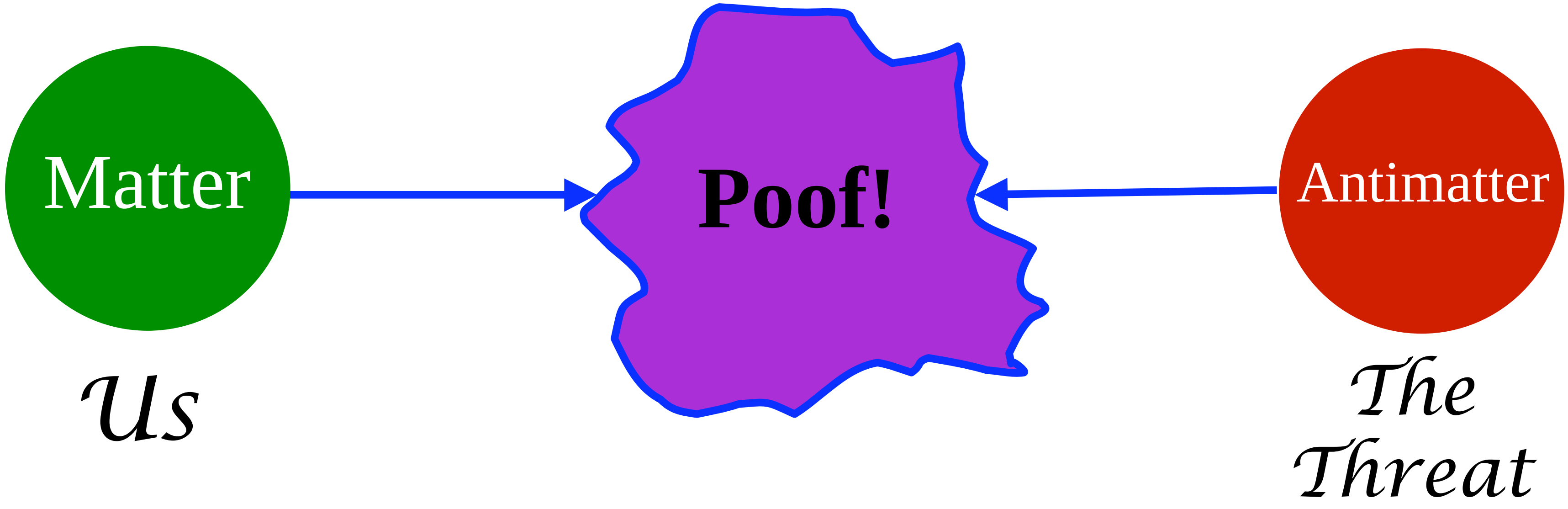
Boris Kayser

AAAS 2009

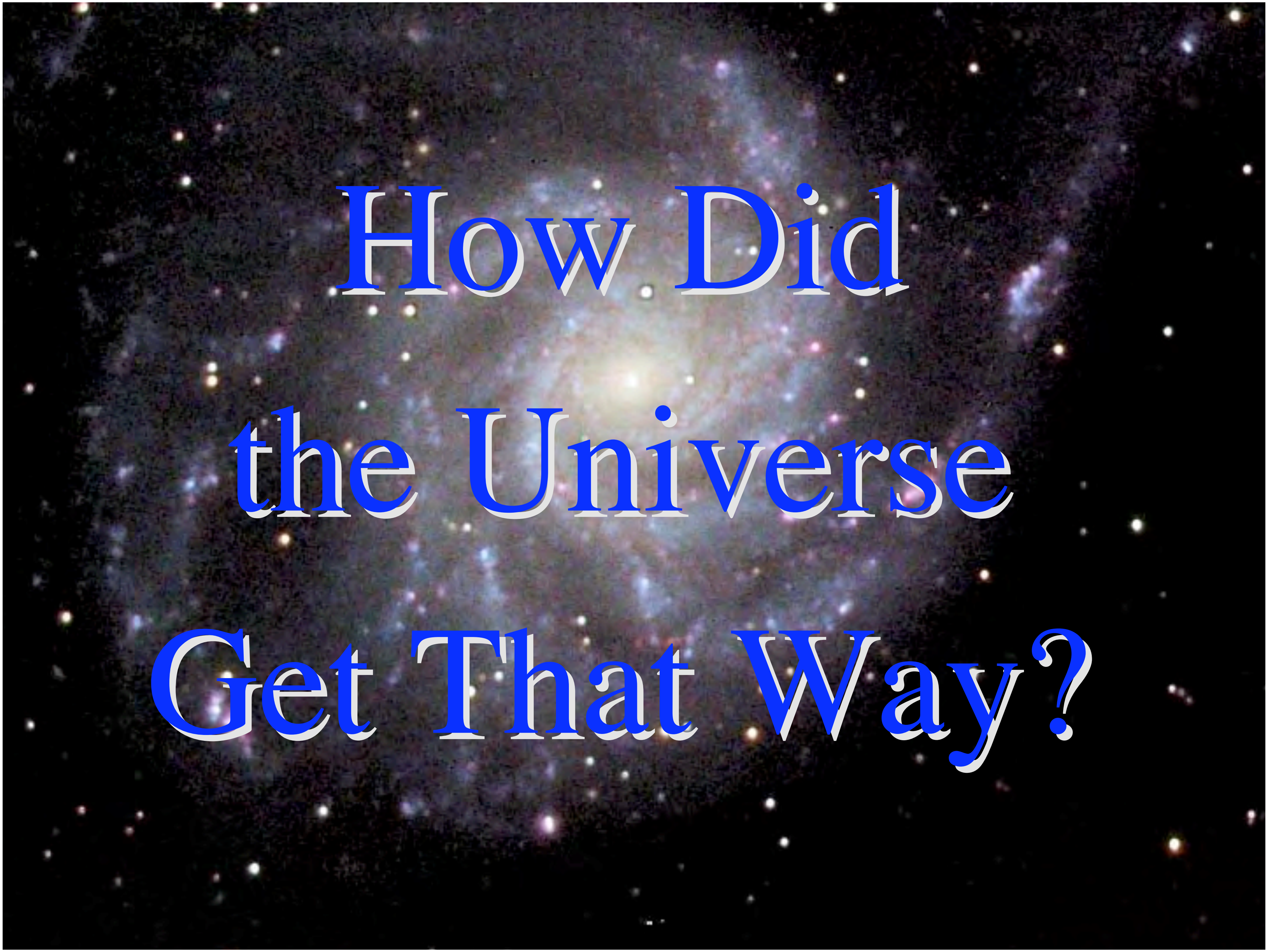
February 13, 2009

Are neutrinos the reason we exist?


STAY AWAY
FROM
ANTIMATTER



The universe is safe for life only because there is virtually no antimatter around.


How Did
the Universe
Get That Way?

Cosmologists tell us that: *In the beginning* —

The universe contained equal amounts
of **ANTIMATTER** and **MATTER** .

There were as many **ANTINUCLEONS** as **NUCLEONS** ,
as many **POSITRONS** as **ELECTRONS** , etc.

Any initial **MATTER** – **ANTIMATTER** asymmetry
would have been washed out.

Today —

The universe contains **NUCLEONS**, of which we
are made, but essentially no **ANTINUCLEONS**,
so we don't get annihilated.

The present preponderance of **Nucleons** over **Antinucleons** could not have developed unless **Matter** and **Antimatter** behave differently($\cancel{CP}$).

Experiments on K and B decays →

Quarks and **Antiquarks** do behave differently.

(Previous talk)

But: The observed difference between **Quark** and **Antiquark** behavior cannot explain the **Matter** – **Antimatter** asymmetry of the universe.

So what IS the explanation?


A Matter-Dominated
Universe
From Neutrinos

If the ***quarks*** cannot explain the universe,
maybe the ***leptons*** can.

The Leptons

	Charged		Neutrinos	
Flavors	e	(Electron)	ν_1	(Tom)
	μ	(Muon)	ν_2	(Dick)
	τ	(Tau)	ν_3	(Harry)

(R. Chast)

Perhaps ***neutrinos*** are the key to understanding the dominance of **MATTER** over **ANTIMATTER** in the universe.

Perhaps **ANTIMATTER** interacts differently with ***neutrinos*** than **MATTER** does.

The Neutrinos

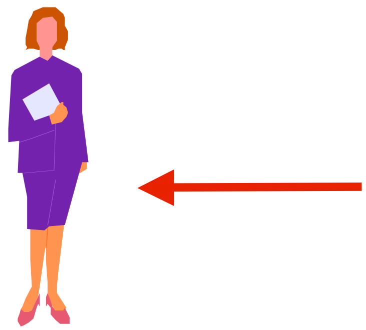
What are they, and what do we know about them?

Neutrinos are Abundant

- We humans, and all the everyday objects around us, are made of nucleons and electrons.
- But in the universe as a whole —

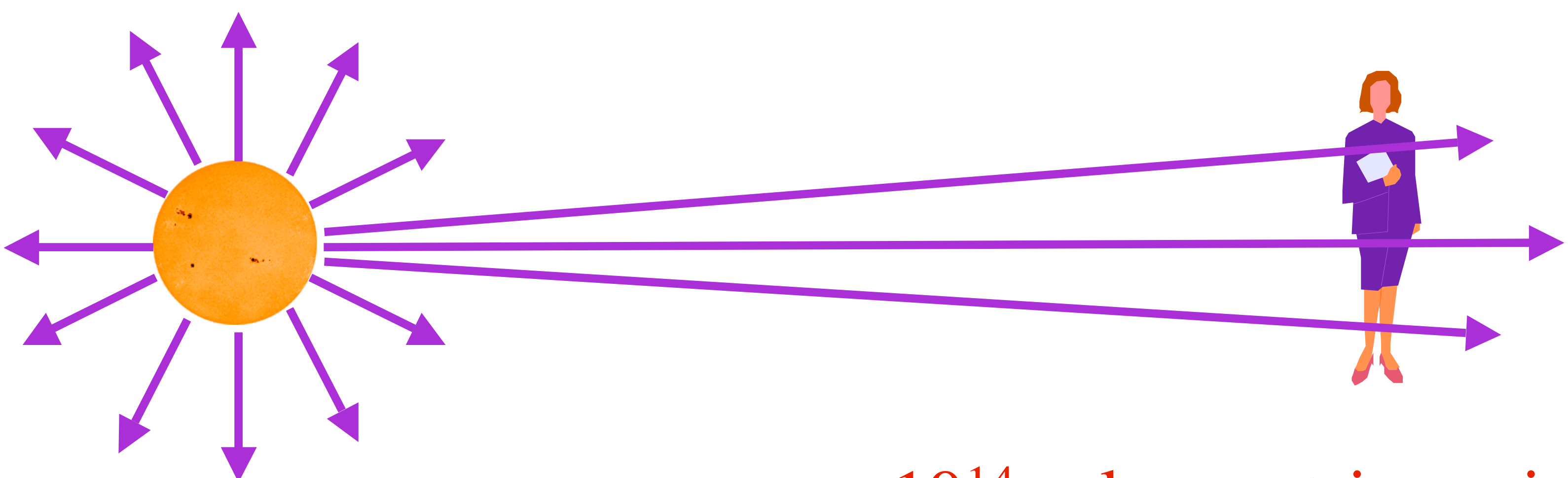
  $\sim 10^9$ neutrinos for each nucleon or electron.
- Neutrinos and photons are the most abundant particles in the universe.

Neutrinos Are Under Our Skin



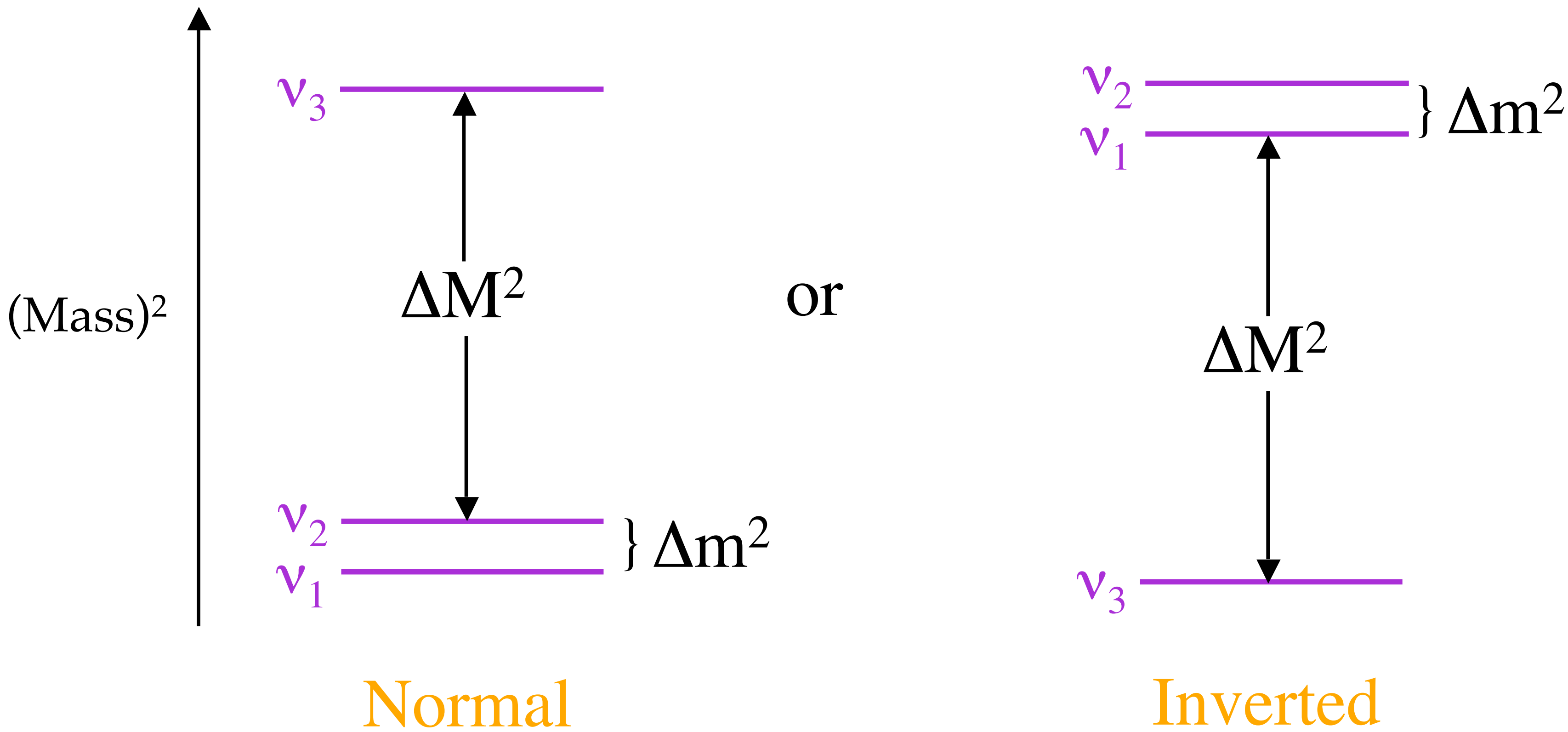
Inside each person:

$> 10^7$ neutrinos from the Big Bang



$\sim 10^{14}$ solar neutrinos zip through every second.

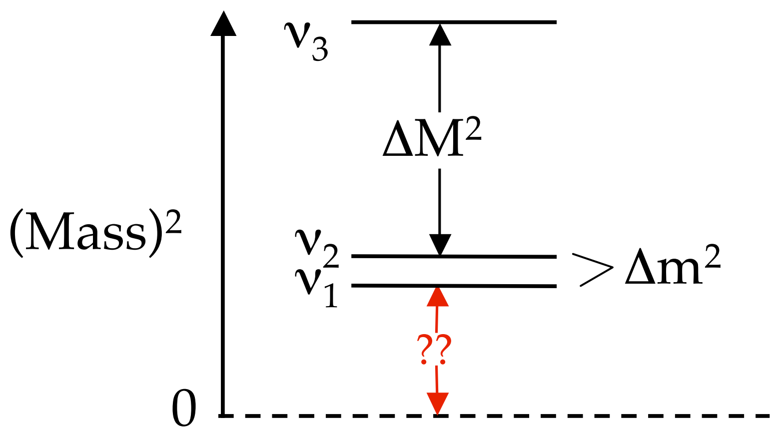
The $(\text{Mass})^2$ Spectrum



$\Delta m^2 \cong 3 \times 10^{-16}\, m_e^{\,2}$, $\quad \Delta M^2 \cong 30\, \Delta m^2$

Electron mass

What Is the Absolute Scale of Neutrino Mass?



How far above zero
is the whole pattern?

Known Splitting $\Rightarrow \sqrt{\Delta M^2} < \text{Mass}[\text{Heaviest } \nu_i]$

A Cosmic Connection

Neutrino mass affects large scale structure.

Cosmological Data + Cosmological Assumptions ⇒

$$\Sigma\, m_i < (0.33 - 2.0) \times 10^{-6}\, m_e\ .$$

Mass(ν_i)

(Seljak, Slosar, McDonald
Hannestad; Pastor)

Given the known spectrum,

$$0.08 \times 10^{-6}\, m_e < \text{Mass}[\text{Heaviest } \nu_i] < (0.11 - 0.66) \times 10^{-6}\, m_e$$

$\sqrt{\Delta M^2}$ Cosmology

Are Neutrinos Their Own Antiparticles?

For each neutrino ν_i , $i = 1, 2, 3$, does —

$$\overline{\nu}_i = \nu_i$$

or

$$\overline{\nu}_i \neq \nu_i \qquad ?$$

$e^+ \neq e^-$ since Charge(e^+) = – Charge(e^-).

But neutrinos may not carry any conserved charge-like attribute.

A conserved Lepton Number L defined by—
$L(\nu) = L(e^-) = –L(\overline{\nu}) = –L(e^+) = 1$ may not exist.

Then there may be nothing to distinguish $\overline{\nu}_i$ from ν_i .

To Determine If $\bar{\nu} = \nu$ — Seek

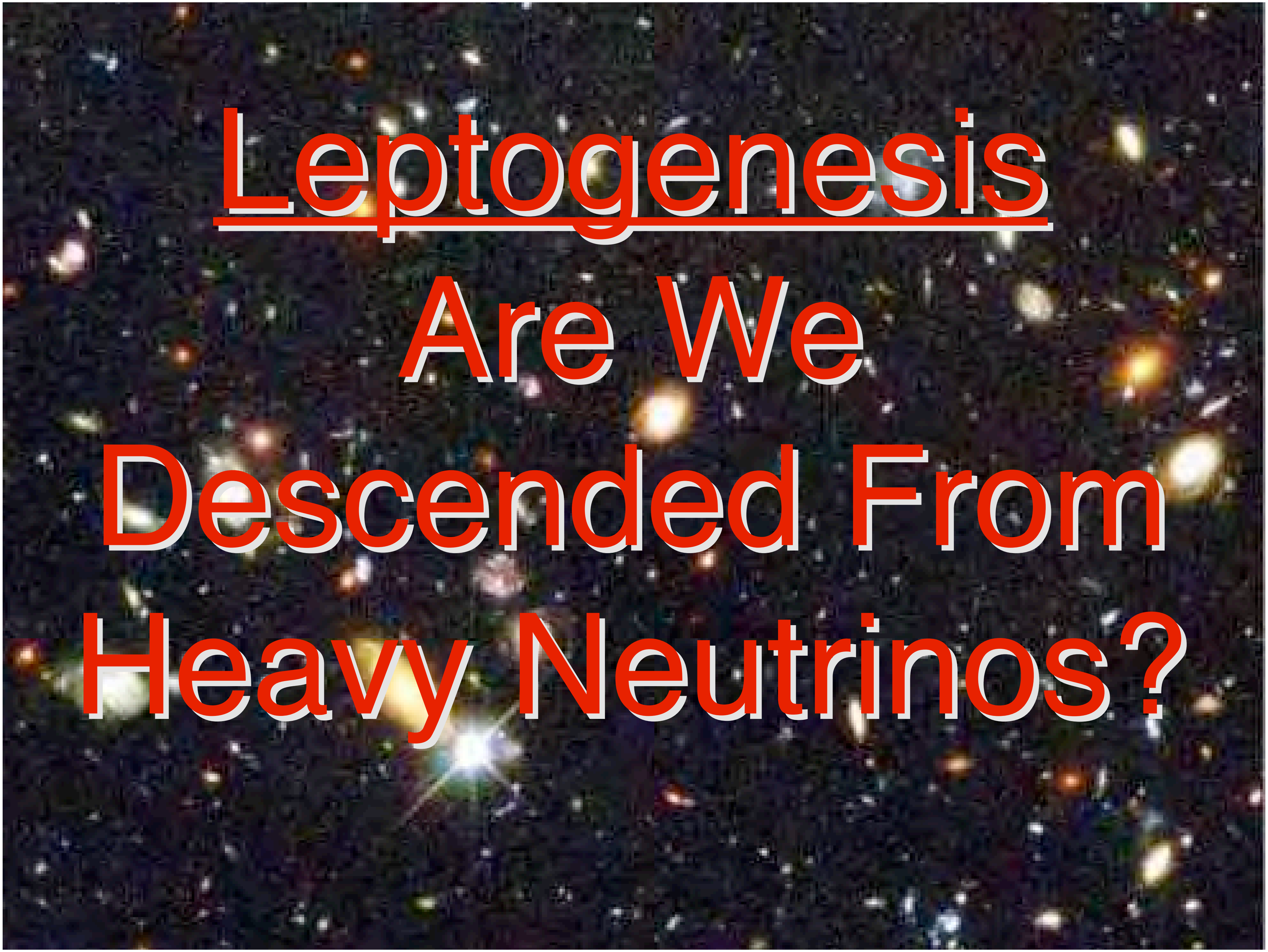
Neutrinoless Double Beta Decay

L(final) – L(initial) = 2. L is not conserved.

$\Rightarrow$ $\boldsymbol{\bar{\nu} = \nu}$

<u>Leptogenesis</u>

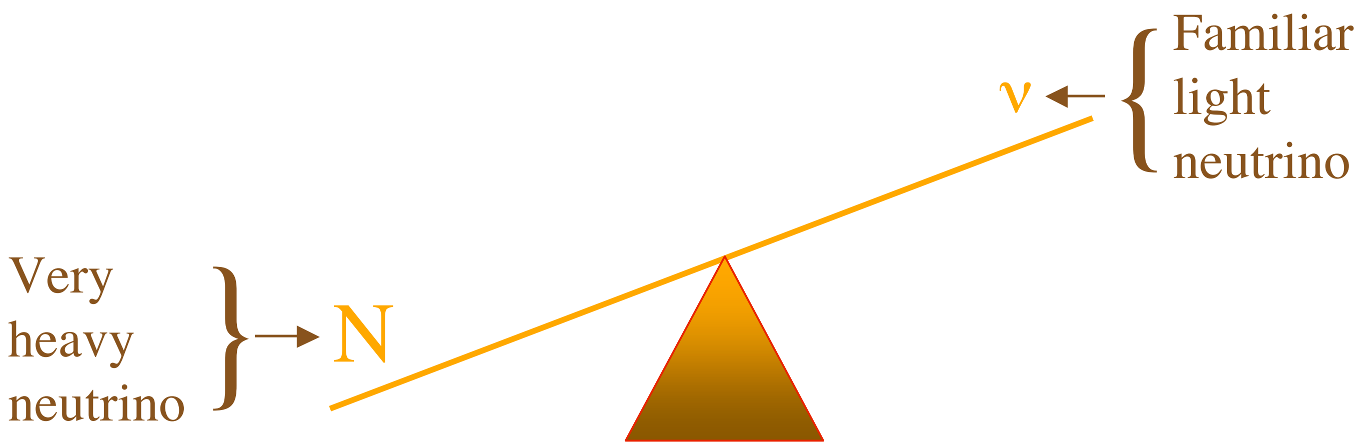
Are We Descended From Heavy Neutrinos?



Leptogenesis

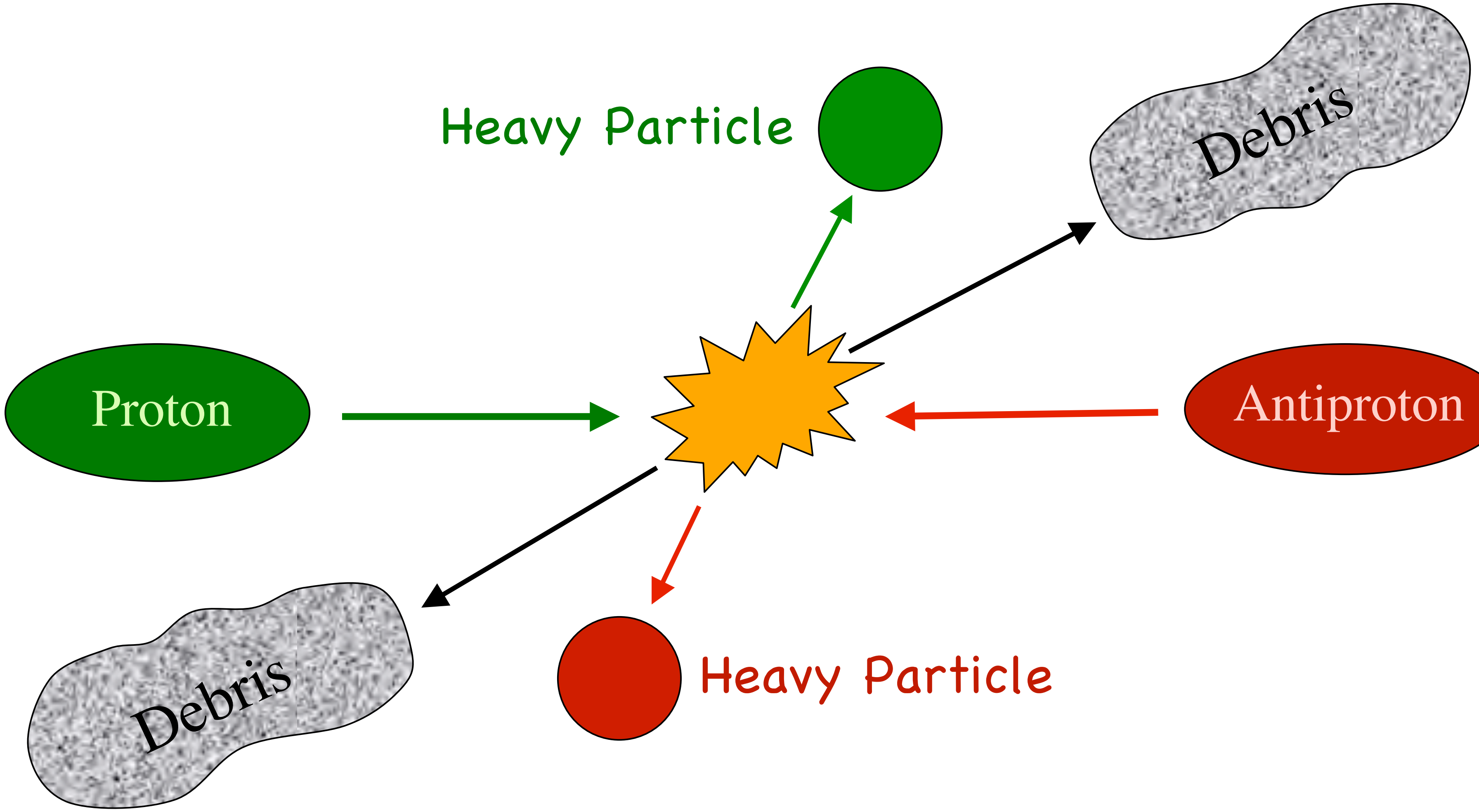
The most popular theory of why neutrinos are so light is the —

See-Saw Mechanism



The neutrinos N are ***very*** heavy —
about a billion times heavier than a proton.

At the Fermilab Tevatron Collider —



The ***energies*** *of the proton and antiproton get converted into the* ***masses*** *of the heavy particles.*

To make a heavy particle of mass m, we must give the proton an energy —

$$E = mc^2$$

Neither present nor forseeable colliders can give a proton enough energy to make $m = 1{,}000{,}000{,}000\ m_{proton}$.

But right after the Big Bang, it was very ***hot***.

Hot means the average ***energy*** of the particles was very ***large***.

Early enough, it was ***hot*** enough to make the heavy neutrinos *N*.

N Decay

The See-Saw predicts that $\bar{\nu} = \nu$ and $\bar{N} = N$.

An N is neither **MATTER** nor **ANTIMATTER** , and can decay into either an e^- or an e^+.

If **MATTER** and **ANTIMATTER** interact differently with N, then in the early universe —

$$\text{Probability } [\, N \rightarrow \underset{\substack{\uparrow \\ \textbf{MATTER}}}{e^-} + \ldots \,] \neq \text{Probability } [\, N \rightarrow \underset{\substack{\uparrow \\ \textbf{ANTIMATTER}}}{e^+} + \ldots \,]$$

This phenomenon (*Leptogenesis*) would have led to a universe containing ***unequal amounts*** of (***leptonic***) **MATTER** and **ANTIMATTER** .

From Leptons To Nucleons

The ***Standard Model***: Tremendously successful.

The ***Standard Model*** predicts:

When the universe is ***hot***:

Any **LEPTON – ANTILEPTON** asymmetry begets a **NUCLEON – ANTINUCLEON** asymmetry.

$$[\#(\mathbf{N}) - \#(\overline{\mathbf{N}})] \cong -\,(1/3)\,[\#(\mathbf{L}) - \#(\overline{\mathbf{L}})]$$

Leptogenesis very successfully explains the observed **NUCLEON – ANTINUCLEON** asymmetry.

If N decays led to the present preponderance of NUCLEONS over ANTINUCLEONS, then we are all descendants of Heavy Neutrinos.

Probing the Physics Of *Leptogenesis*

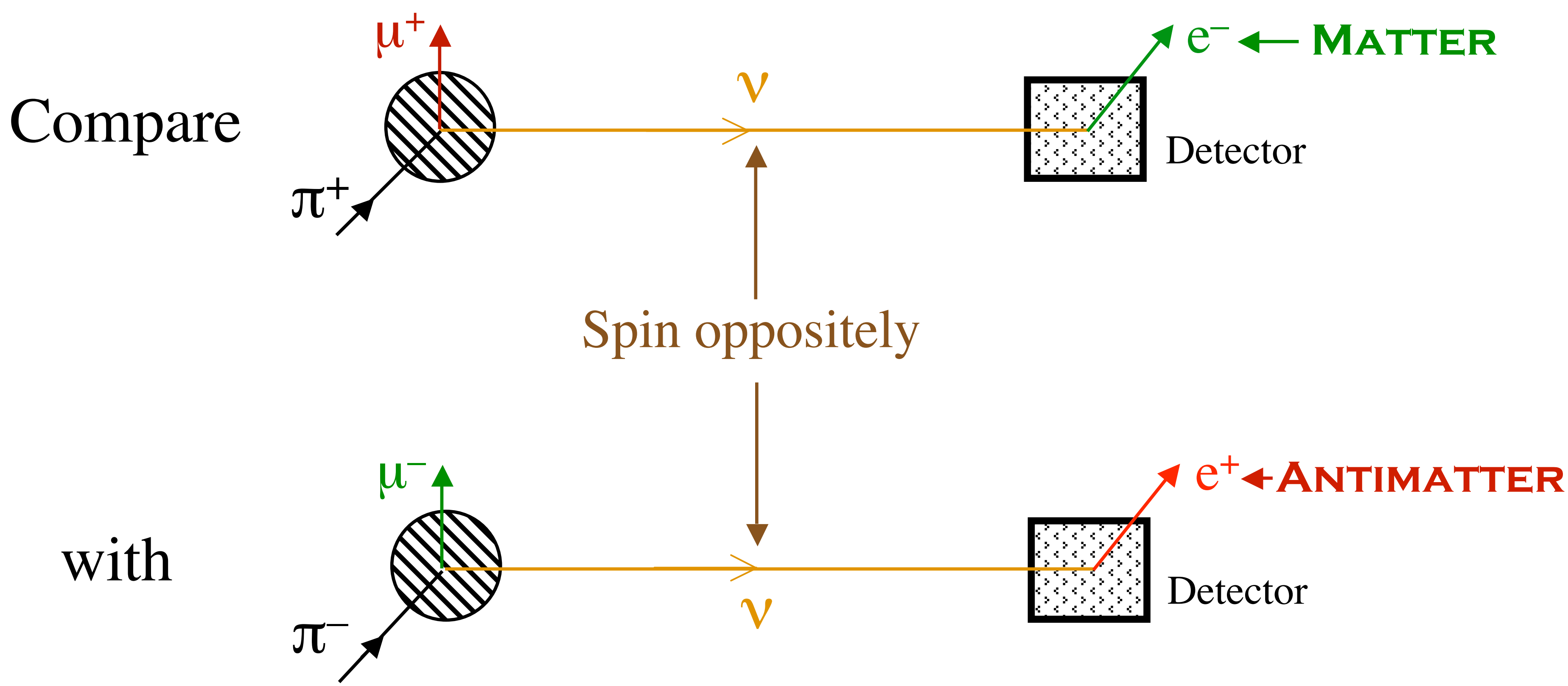
The heavy neutrinos N passed away long ago.

But today's light neutrinos ν are their See-Saw partners.

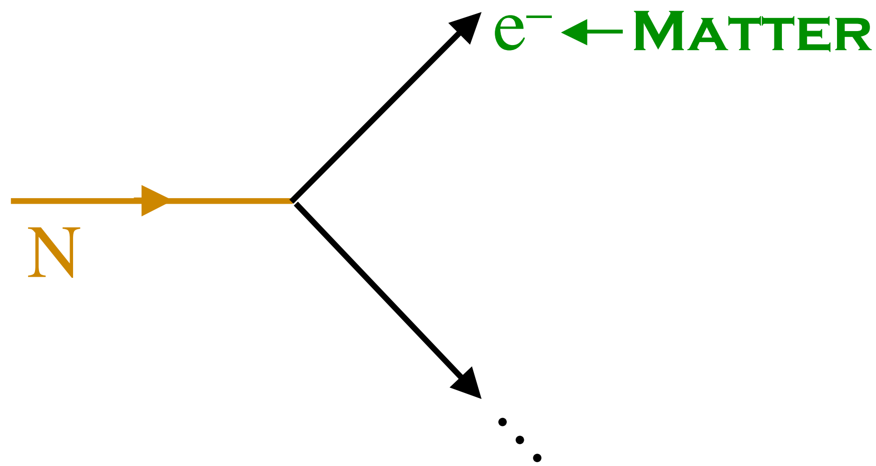
If* MATTER *and* ANTIMATTER *interact differently with the* ν*s, then quite likely they also interact differently with the N*s*.

In the See-Saw model, both of these* MATTER *-* ANTIMATTER *differences have a common origin.

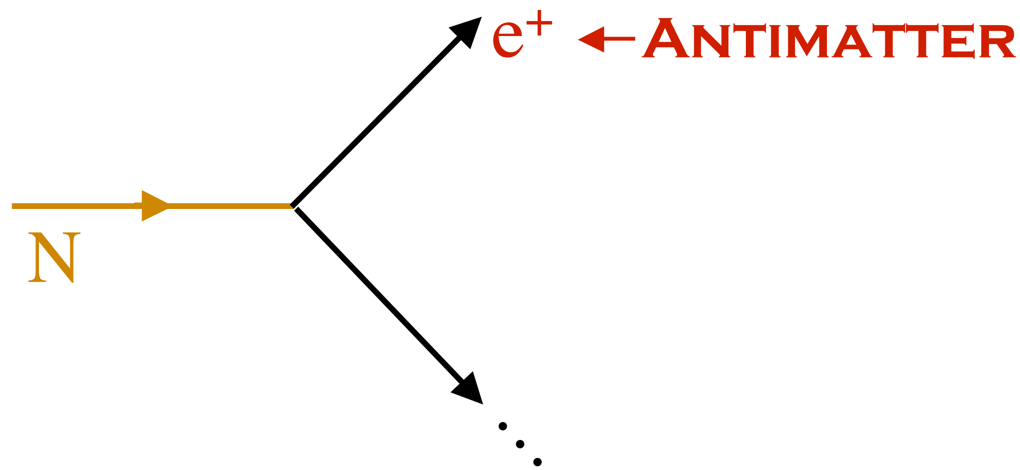
Do MATTER and ANTIMATTER Interact Differently With Light Neutrinos?



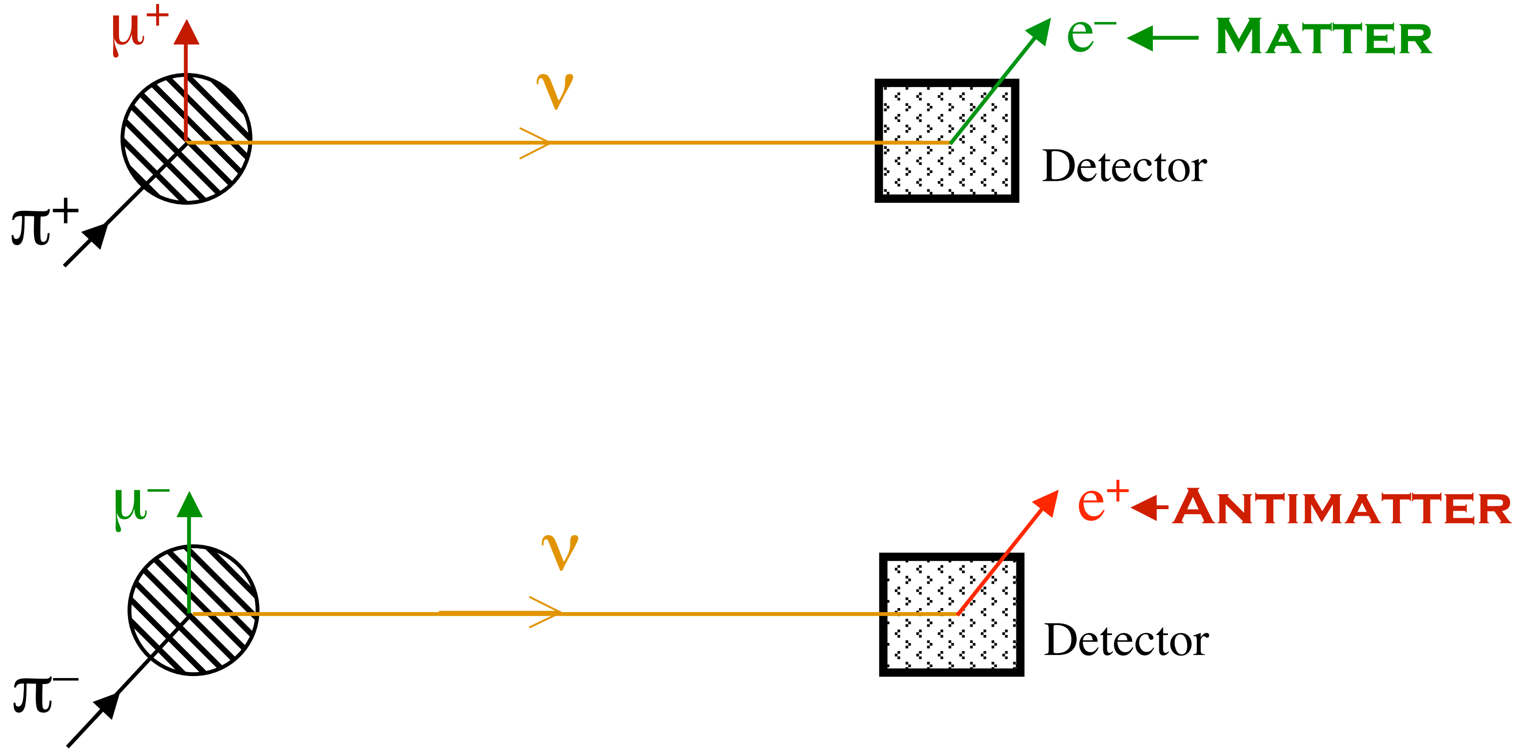
This is today's version of comparing —



with —



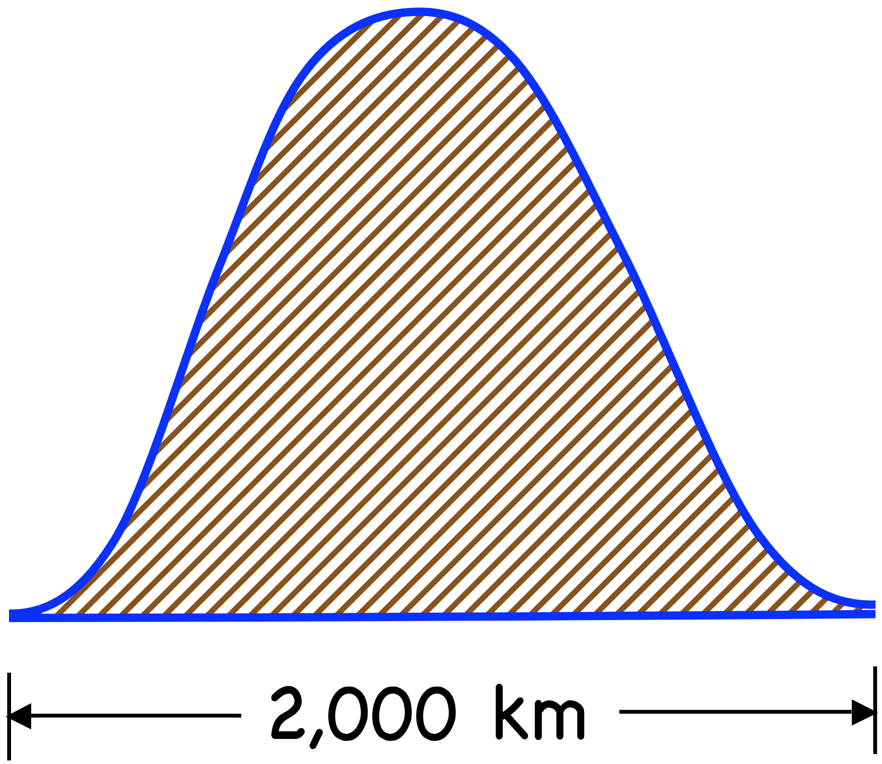
The



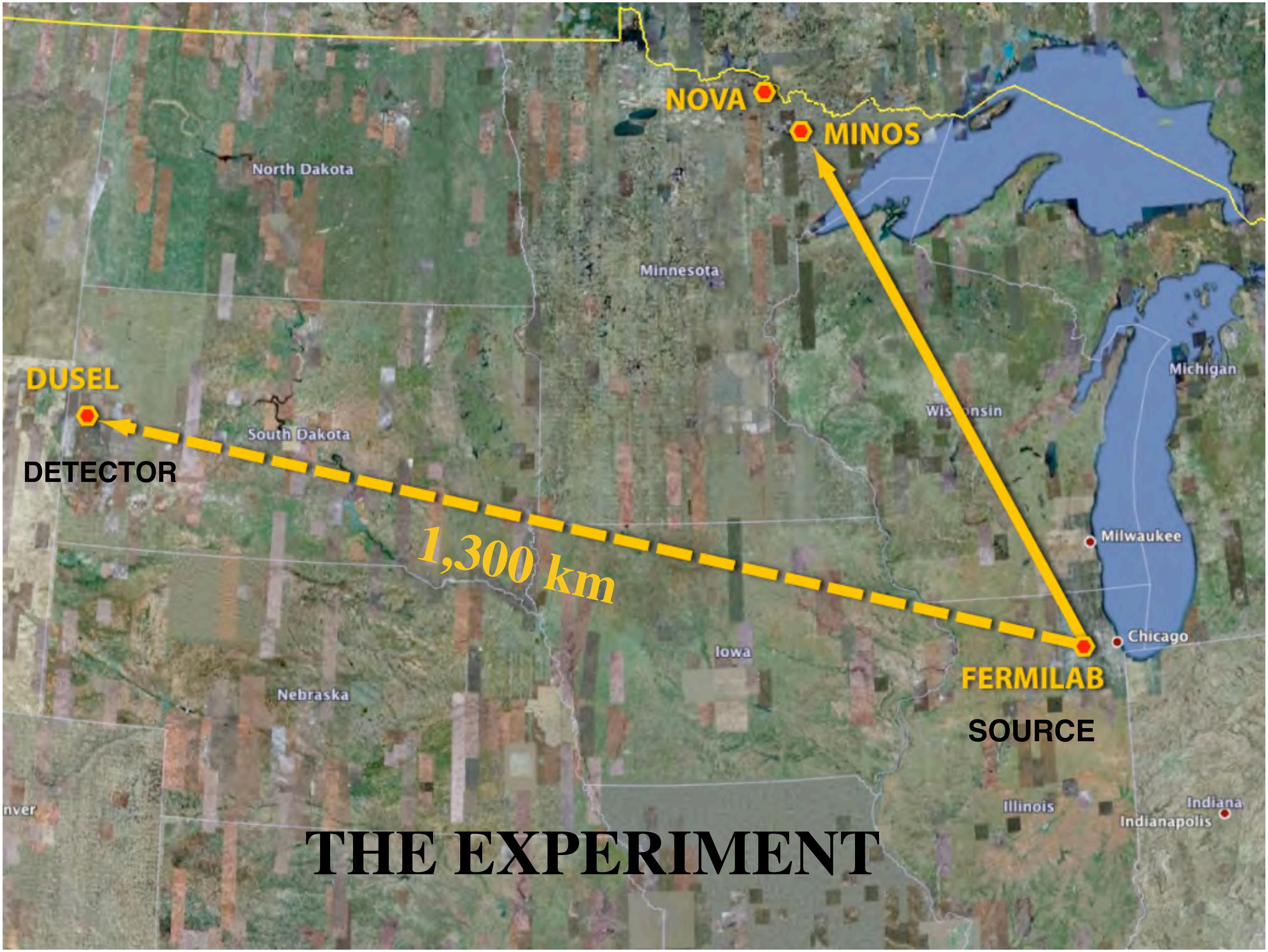
difference

comes from an interference between two waves.

The longer one:



The neutrinos must go far for us
to see the interference.


NOVA
MINOS
North Dakota
Minnesota
Michigan
DUSEL
South Dakota
DETECTOR
Milwaukee
1,300 km
Chicago
Iowa
FERMILAB
Nebraska
SOURCE
Illinois
Indiana
Indianapolis
THE EXPERIMENT

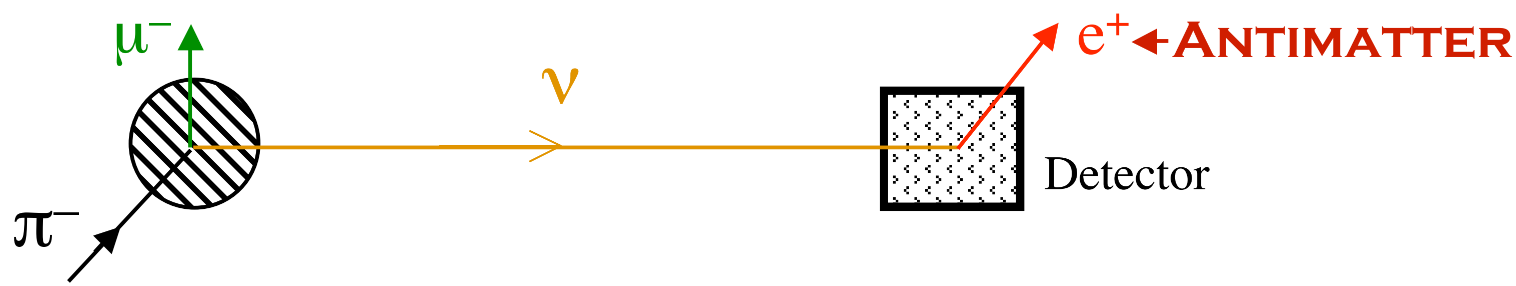
The Source: Fermilab's Project X

Y-K Kim

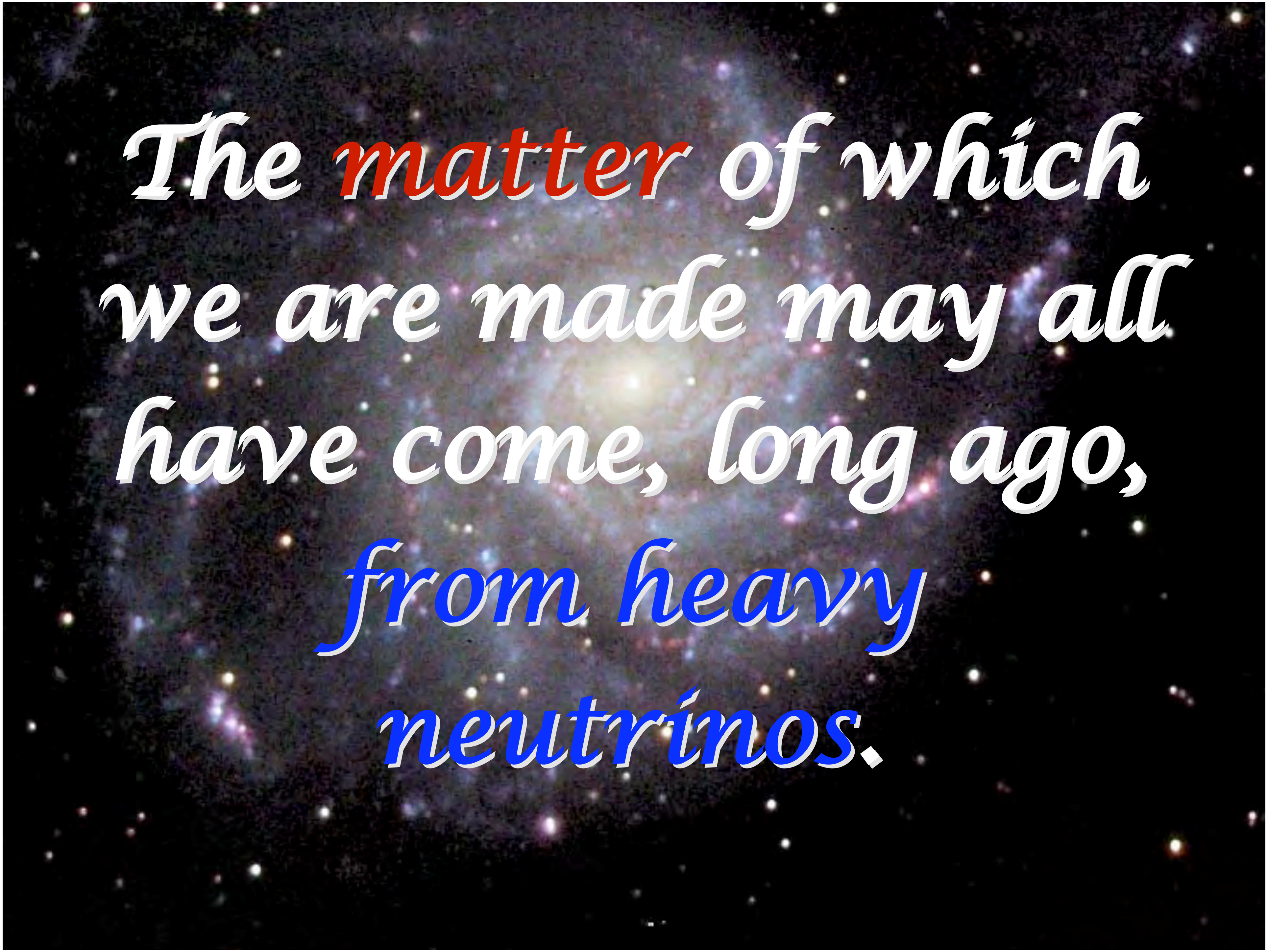
The Physics Reach

Can see the difference between —

and



even if it is only of order 10^{-3}!


The matter of which we are made may all have come, long ago, from heavy neutrinos.

Flavor and Intensity-Frontier Physics

Particle physics: A synergy between experiments at diverse frontiers.

This session: Flavor physics and the intensity frontier.

From quark and lepton flavor physics

- Discovery and understanding of CP violation
- Mystery of the missing indirect effects of New Physics
- Discovery of neutrino mass – New Physics beyond the Standard Model

Coming from the flavor & intensity frontier

- Indirect exploration of an energy regime far beyond the one LHC can observe
- Search for evidence for leptogenesis in the behavior of neutrinos
- Exploration of whether all the world's protons will eventually disappear

CERN's LHC will soon be exploring a very promising energy frontier.

The U.S. particle physics community will foster continuing energy-frontier — intensity-frontier synergy:

- Participation in the LHC
- A rich intensity-frontier program here at home