

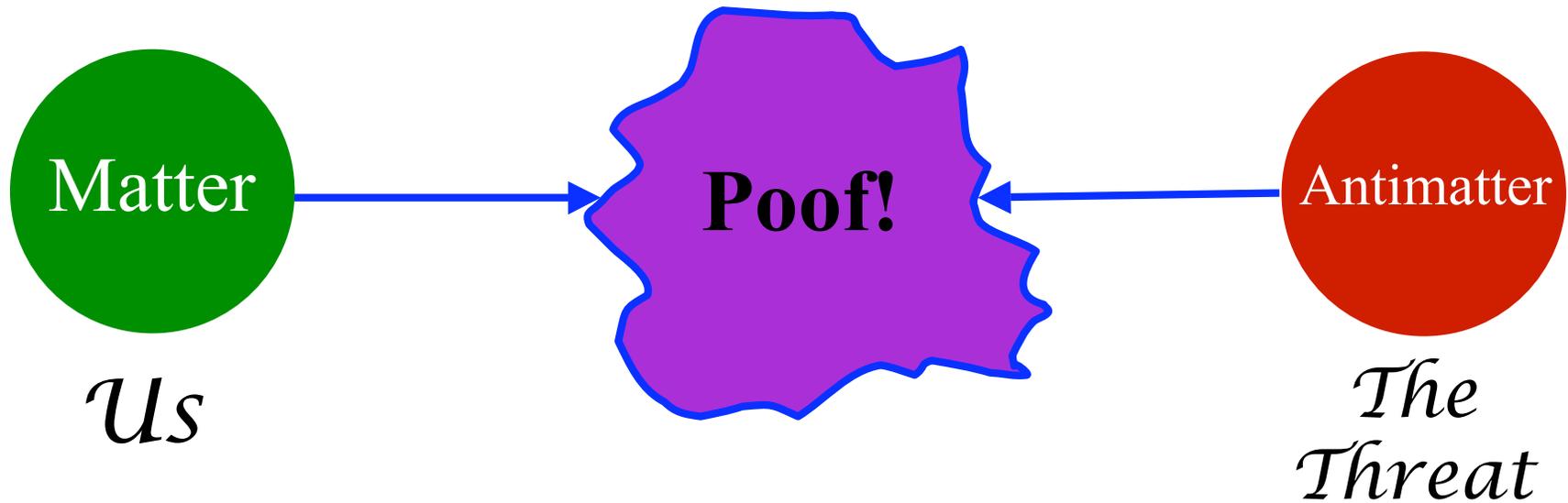
The Role Of Neutrinos In The Evolution Of The Universe

Boris Kayser
AAAS 2009
February 13, 2009

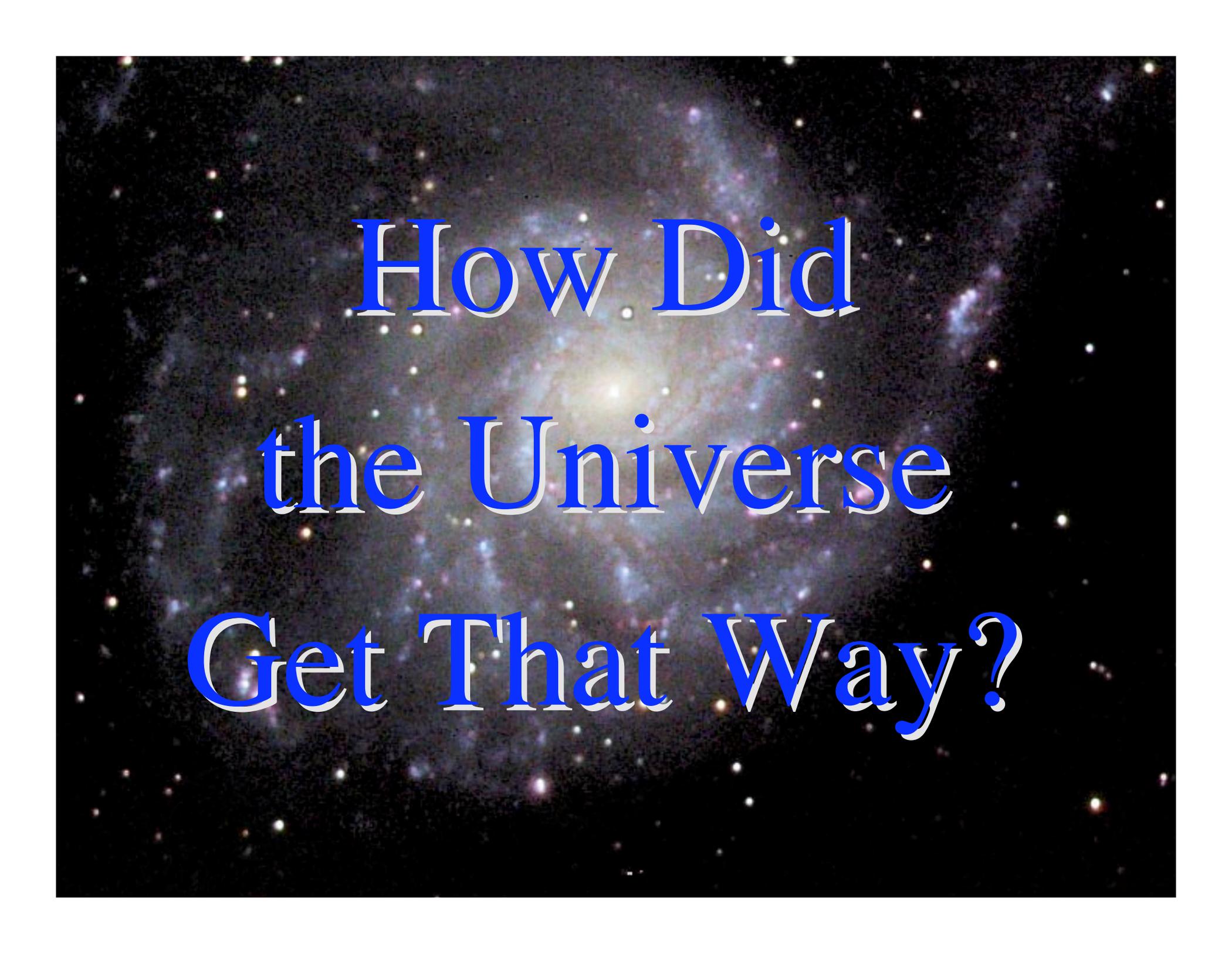
*Are neutrinos the
reason we exist?*



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(~~CP~~).

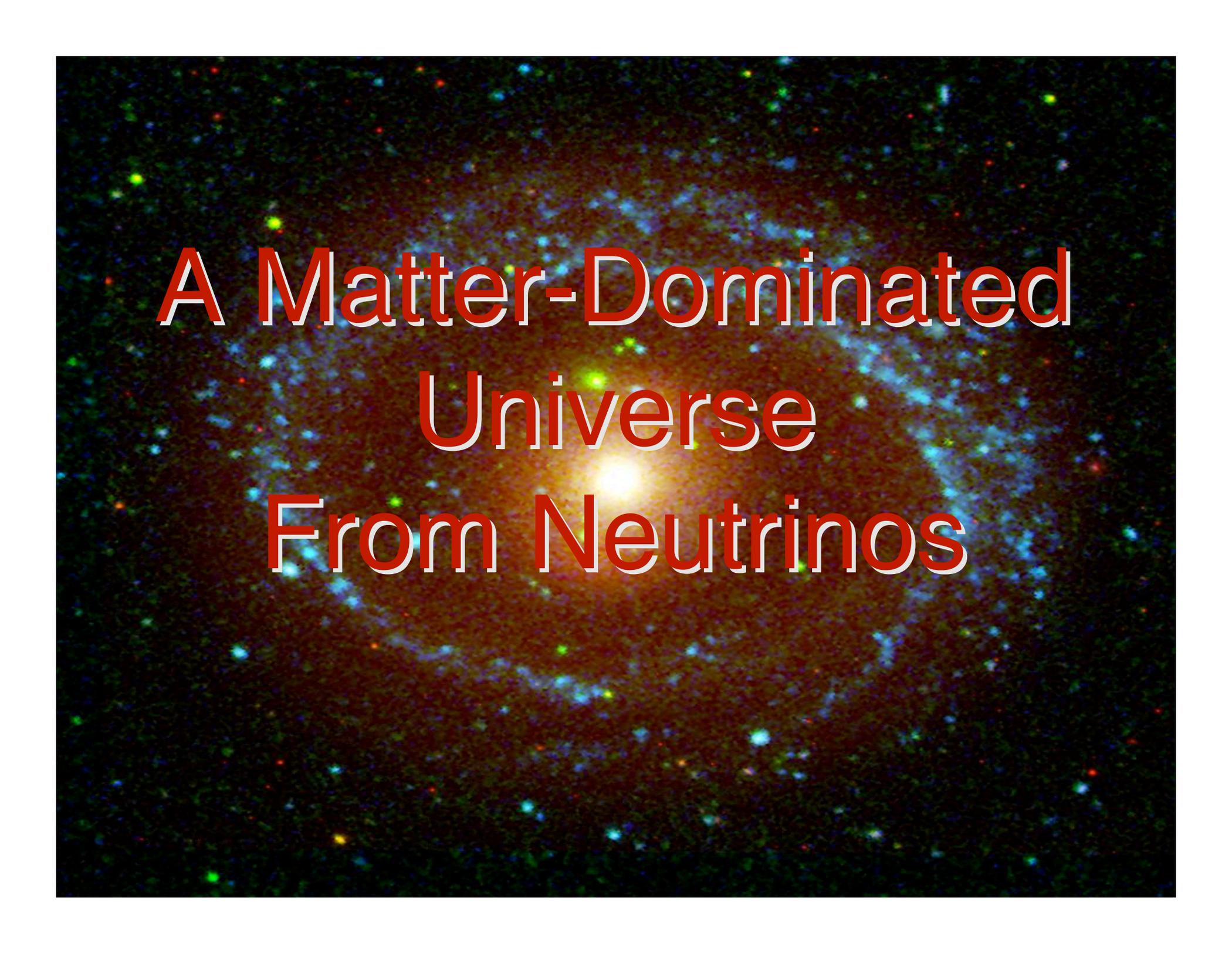
Experiments on K and B decays 

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

	<u>Charged</u>	<u>Neutrinos</u>
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?

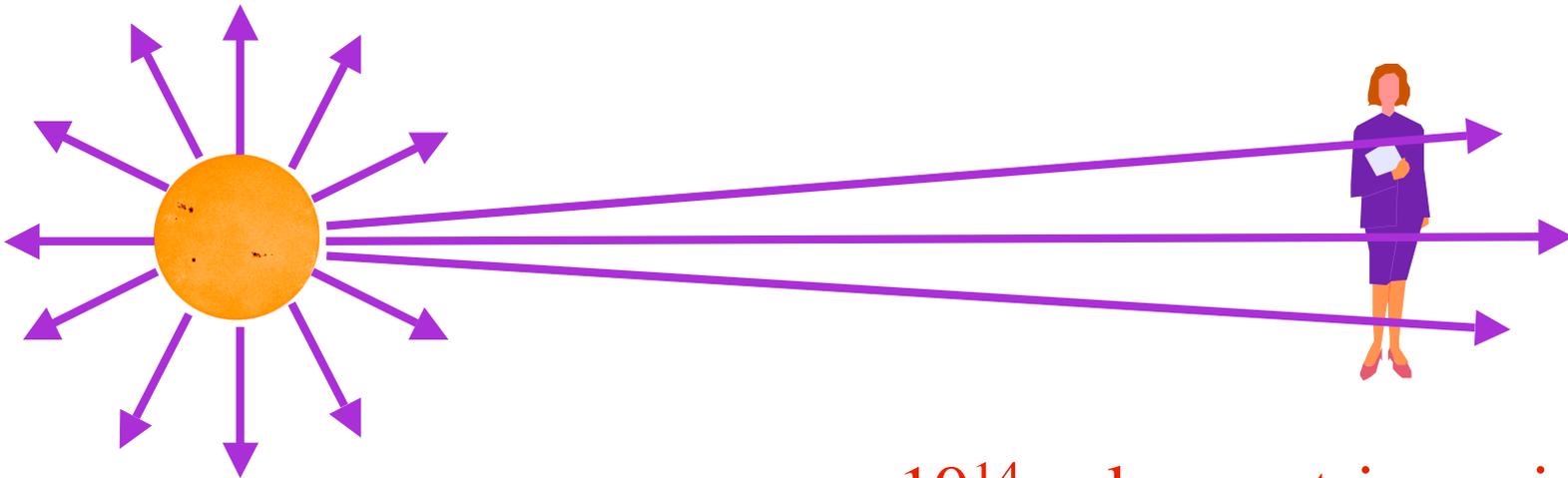
Neutrinos are Abundant

- We humans, and all the everyday objects around us, are made of nucleons and electrons.
- But in the universe as a whole —
 - ~ 10^9 neutrinos for each nucleon or electron.
- Neutrinos and photons are the most abundant particles in the universe.

Neutrinos Are Under Our Skin

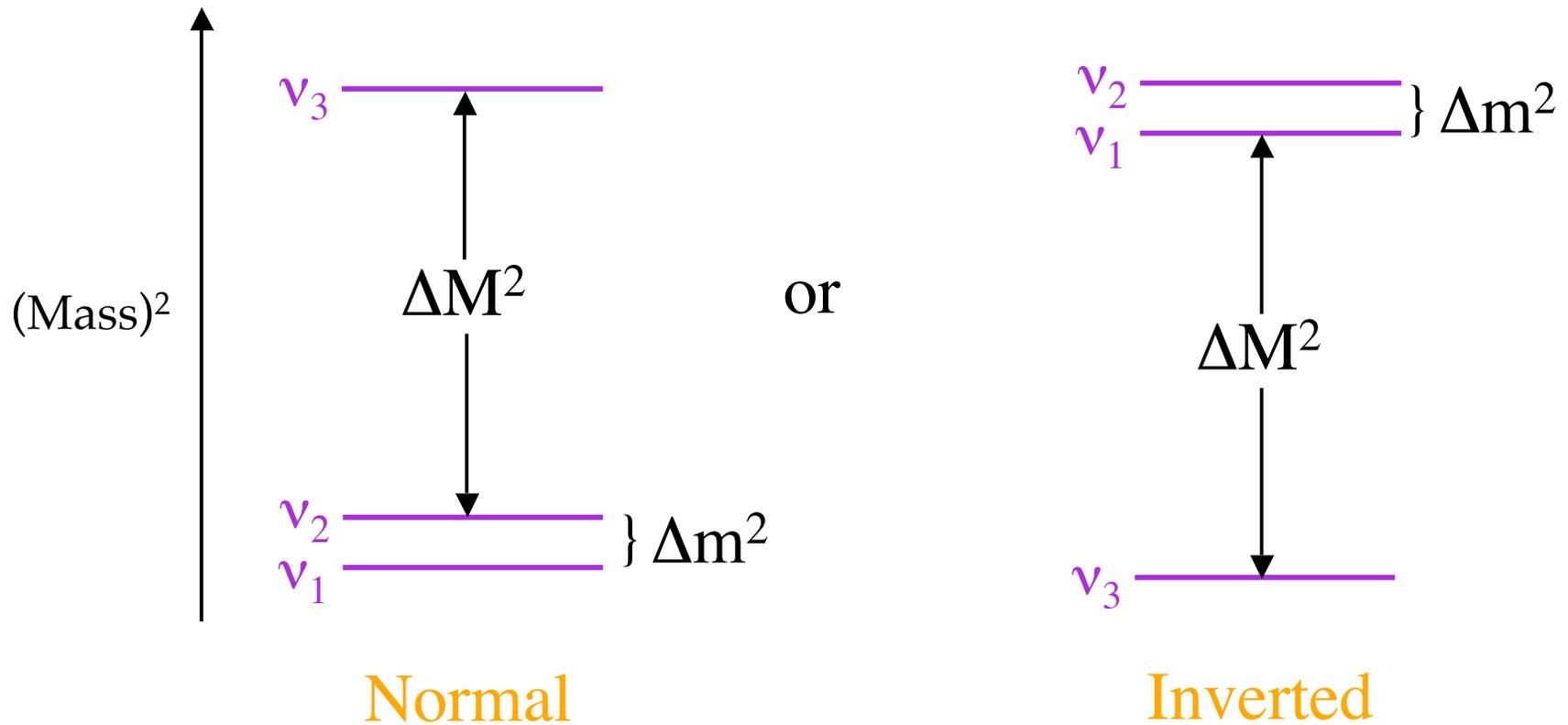


Inside each person:
> 10^7 neutrinos from the
Big Bang



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

The (Mass)² Spectrum

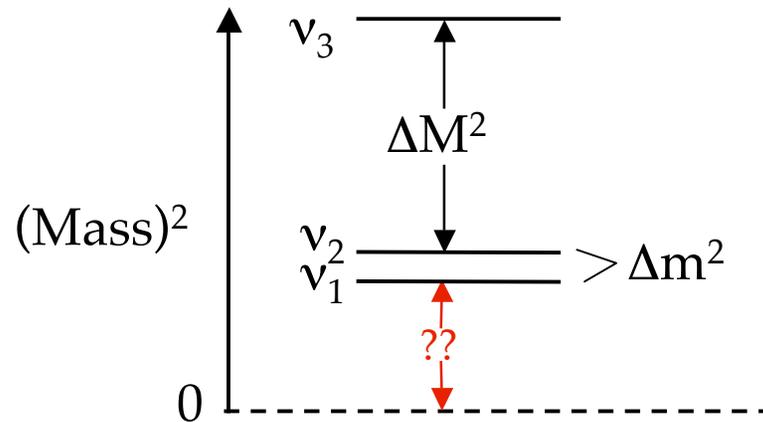


$$\Delta m^2 \cong 3 \times 10^{-16} m_e^2,$$

Electron mass \nearrow

$$\Delta M^2 \cong 30 \Delta m^2$$

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** \Rightarrow

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

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 —

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

or

$$\bar{\nu}_i \neq \nu_i \quad ?$$

$e^+ \neq e^-$ since $\text{Charge}(e^+) = -\text{Charge}(e^-)$.

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

A conserved **Lepton Number L** defined by—

$$L(\nu) = L(e^-) = -L(\bar{\nu}) = -L(e^+) = 1 \text{ may not exist.}$$

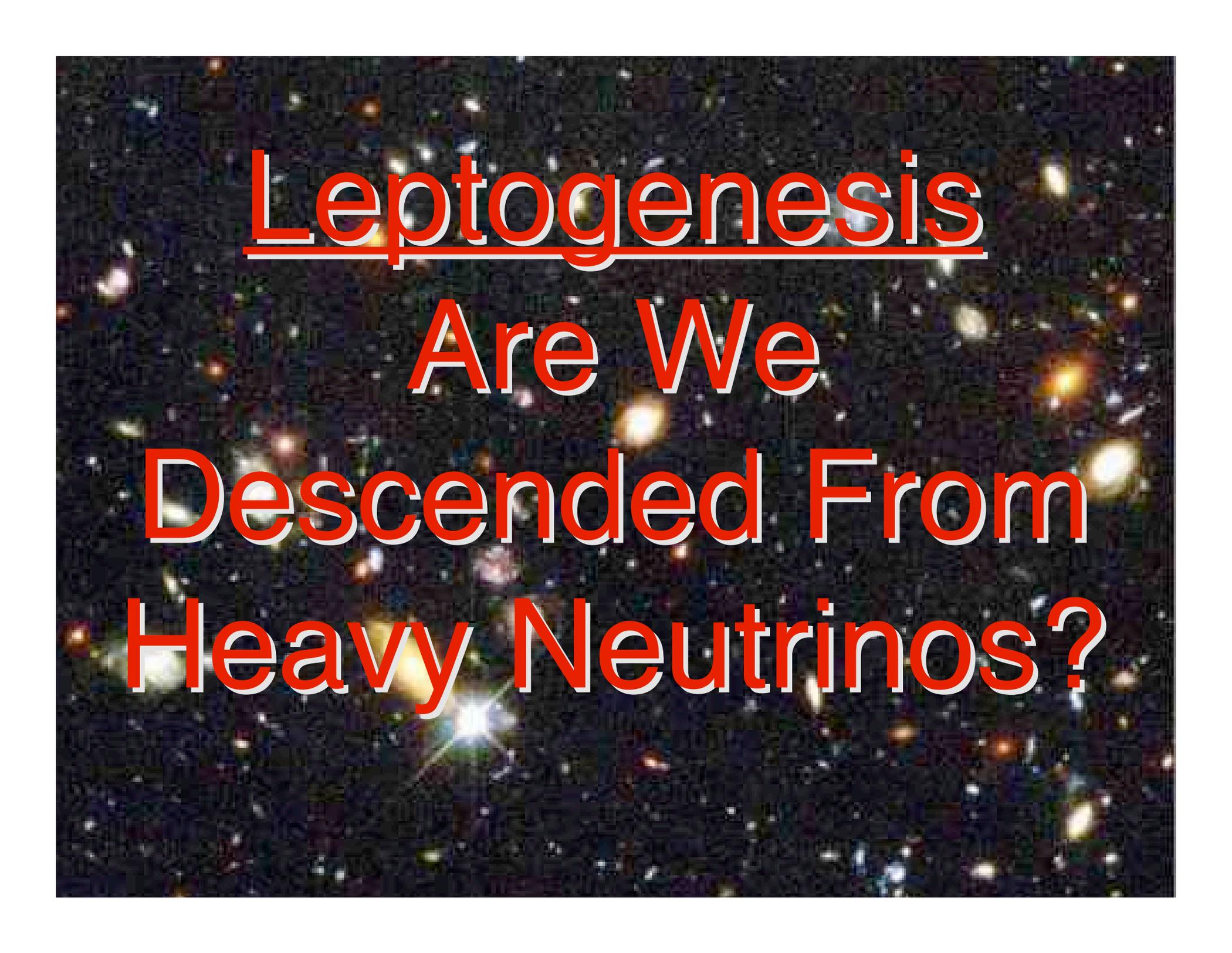
Then there may be nothing to distinguish $\bar{\nu}_i$ from ν_i .

To Determine If $\bar{\nu} = \nu$ — Seek
Neutrinoless Double Beta Decay



$L(\text{final}) - L(\text{initial}) = 2$. L is not conserved.

→ $\bar{\nu} = \nu$

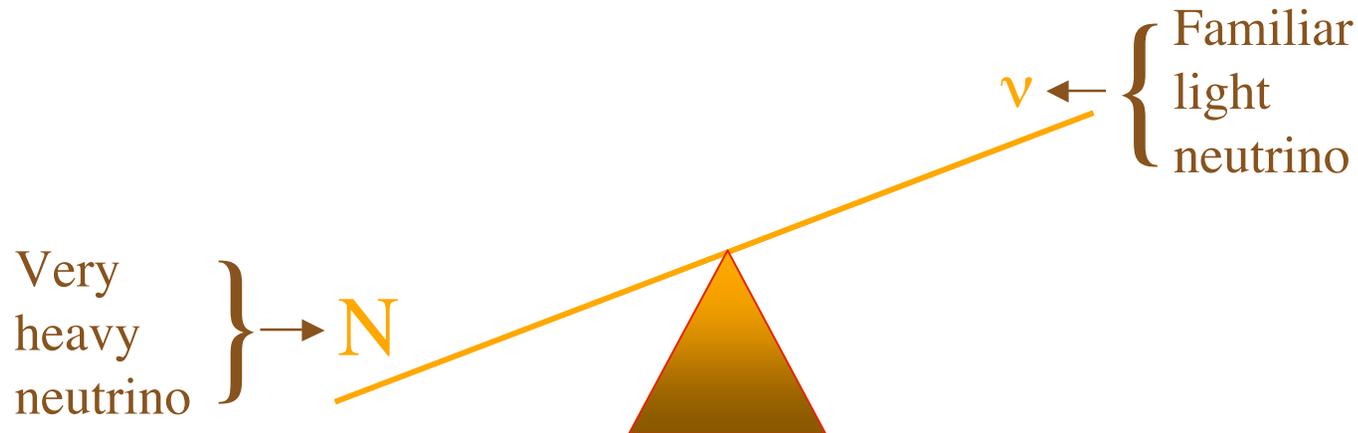


Leptogenesis
Are We
Descended From
Heavy Neutrinos?

Leptogenesis

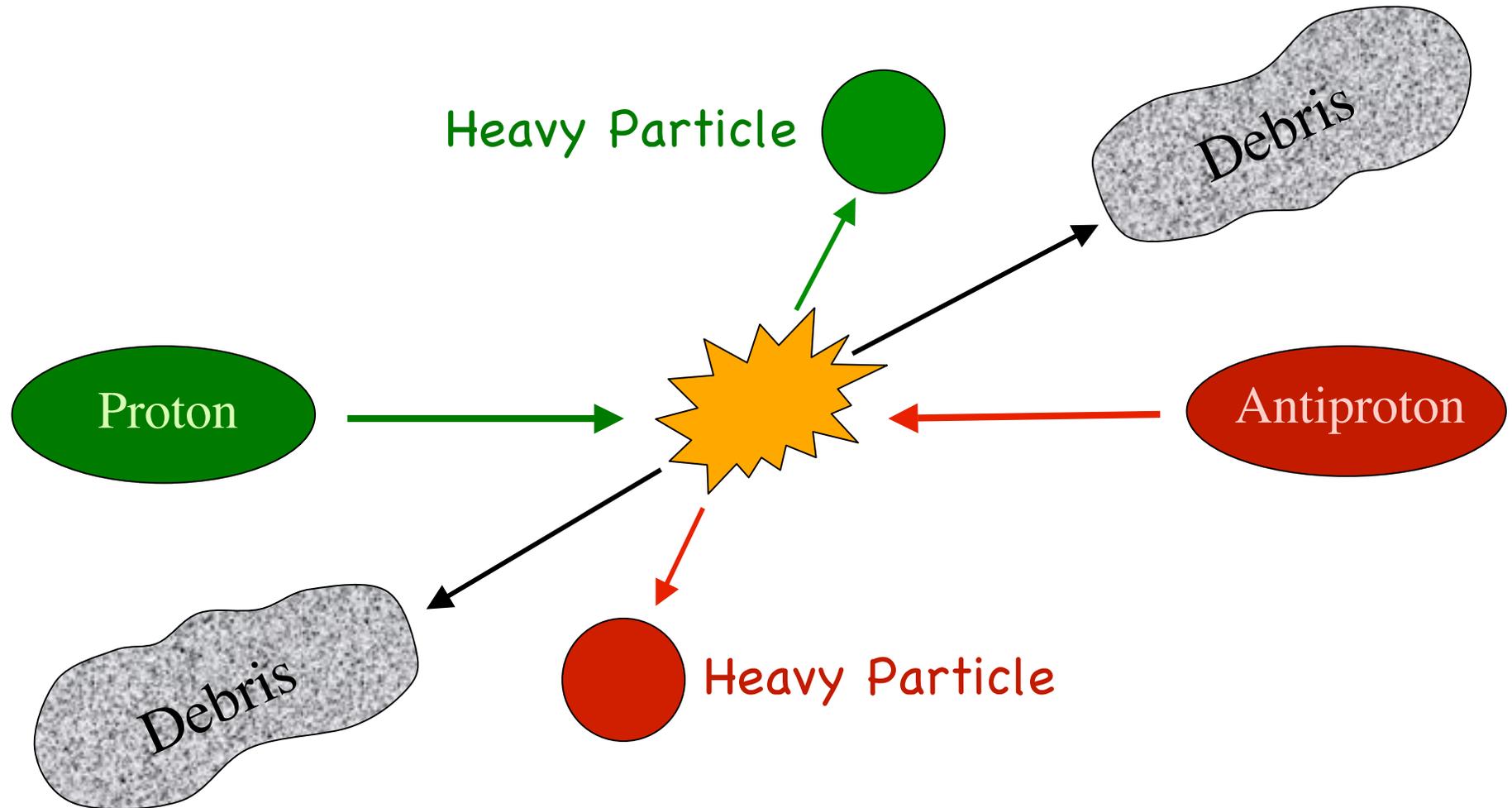
The most popular theory of why neutrinos are so light is the —

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 foreseeable colliders can give a proton enough energy to make $m = 1,000,000,000 m_{\text{proton}}$.

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* .

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*

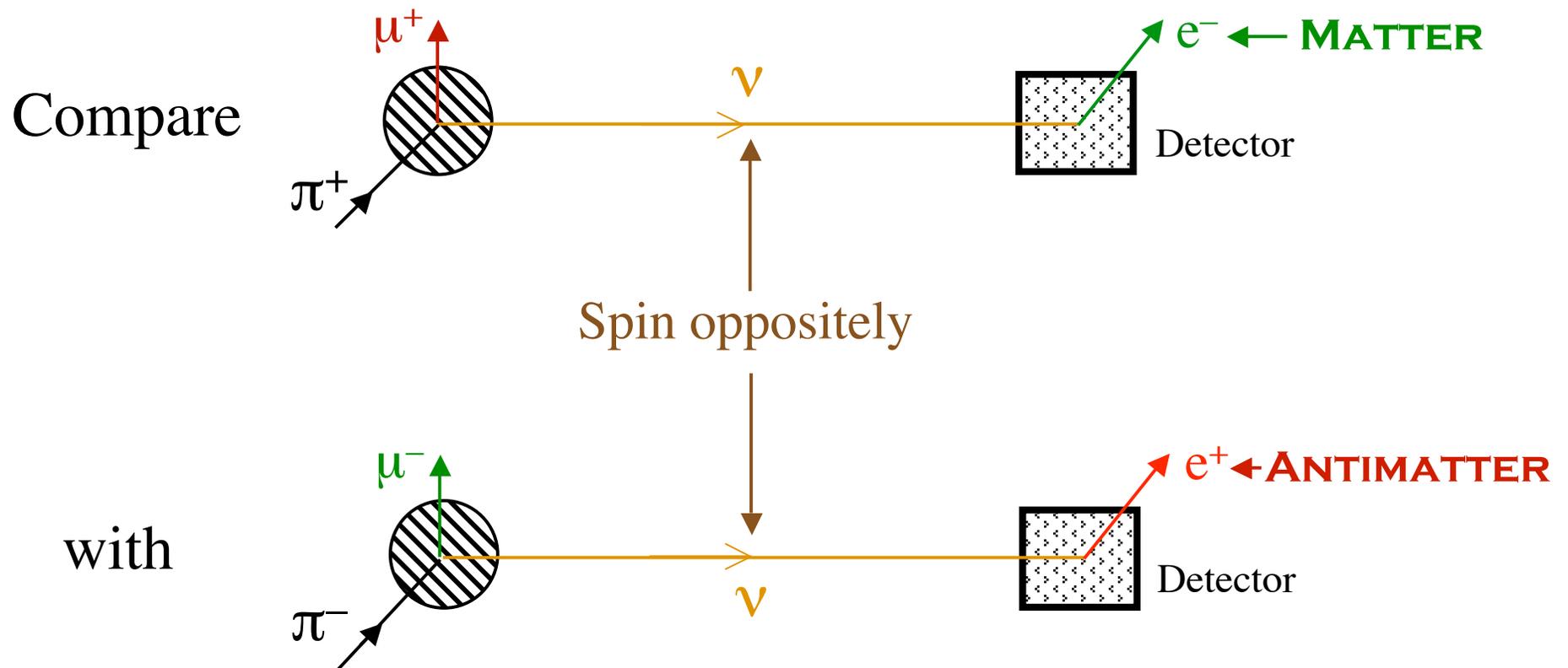
The heavy neutrinos **N** passed away long ago.

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

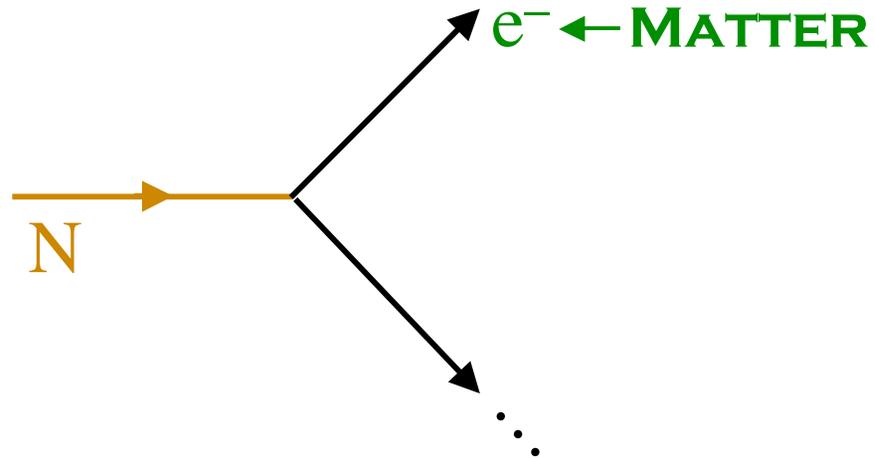
*If **MATTER** and **ANTIMATTER** interact differently with the **ν s**, then quite likely they also interact differently with the **Ns**.*

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

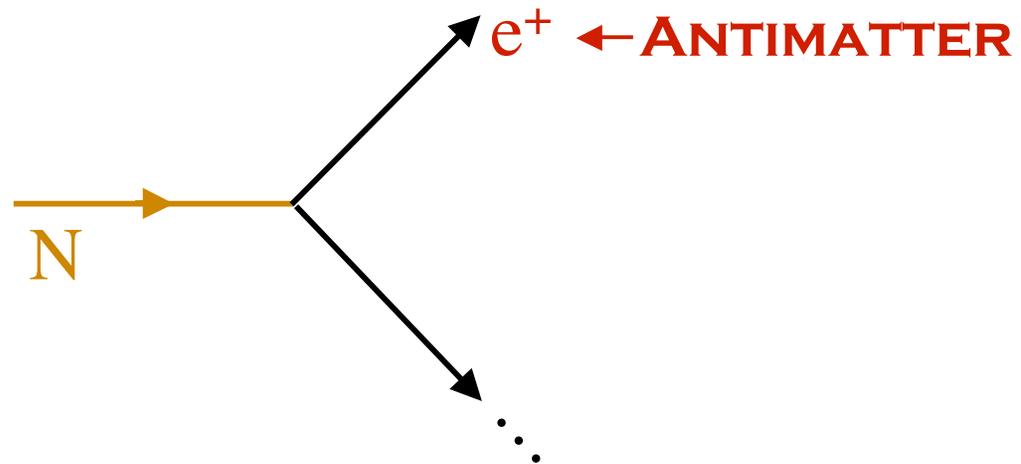
Do **MATTER** and **ANTIMATTER** Interact Differently With Light Neutrinos?



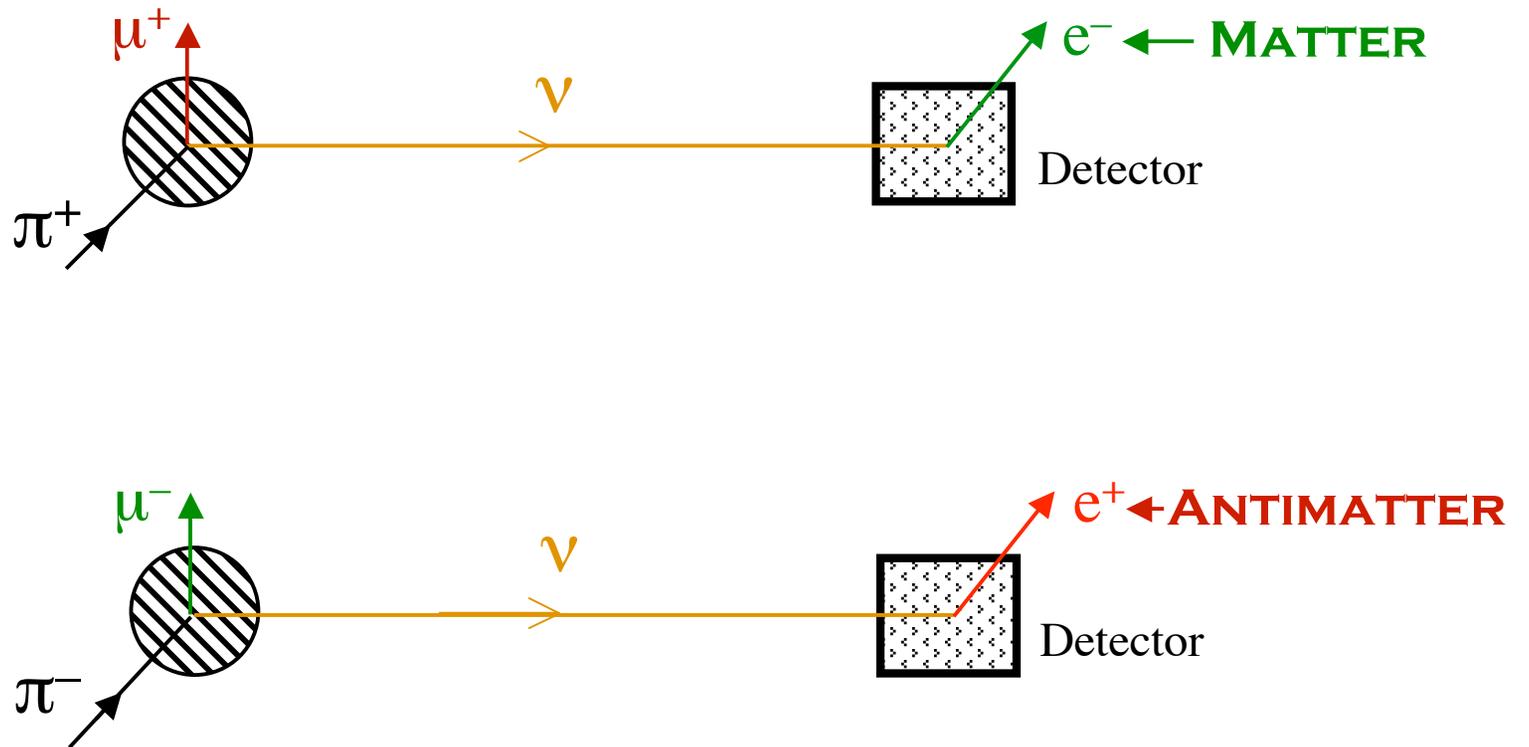
This is today's version of comparing —



with —



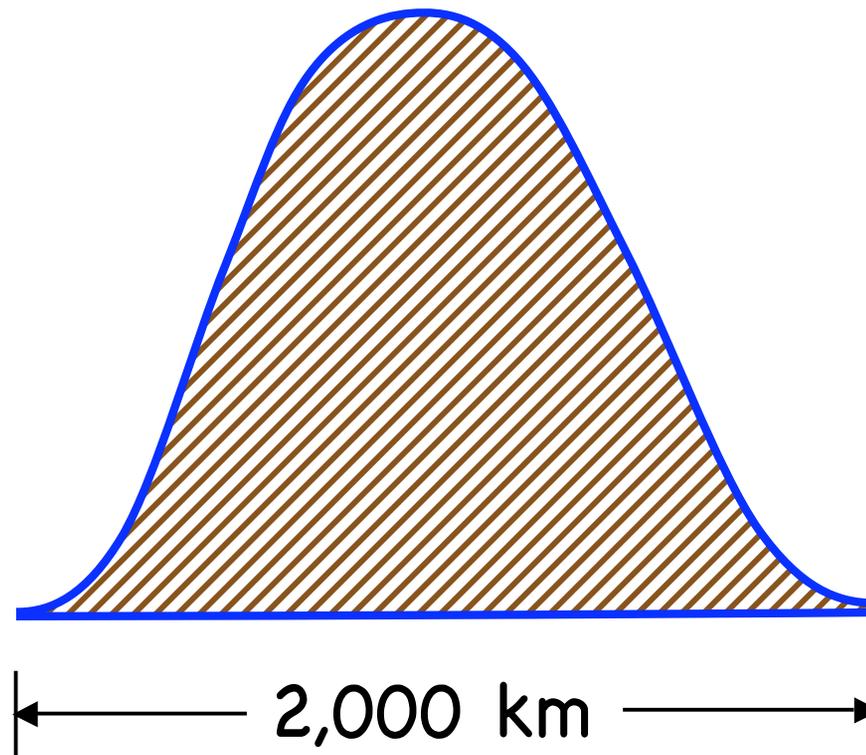
The



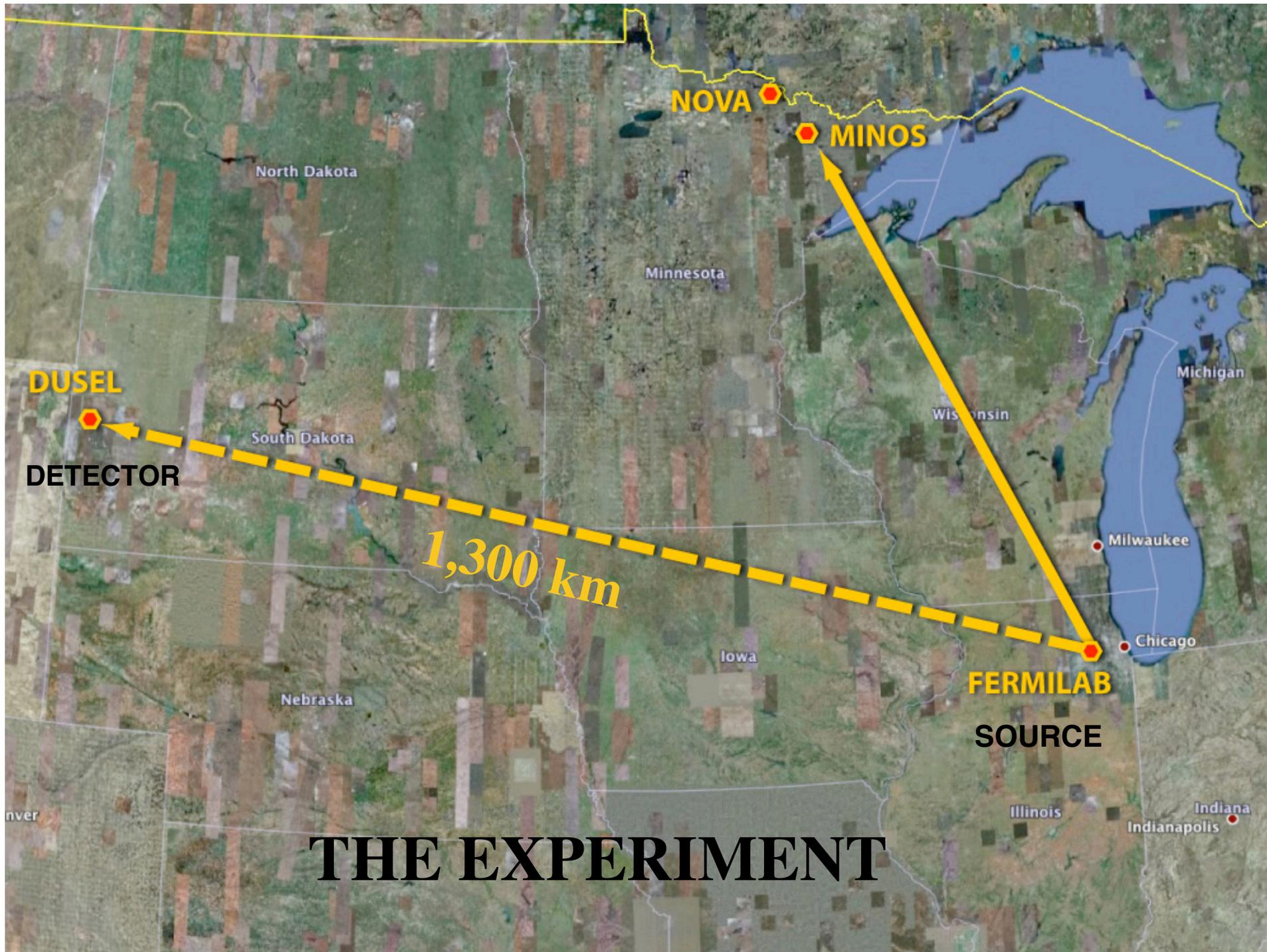
difference

comes from an **interference** between two waves.

The longer one:



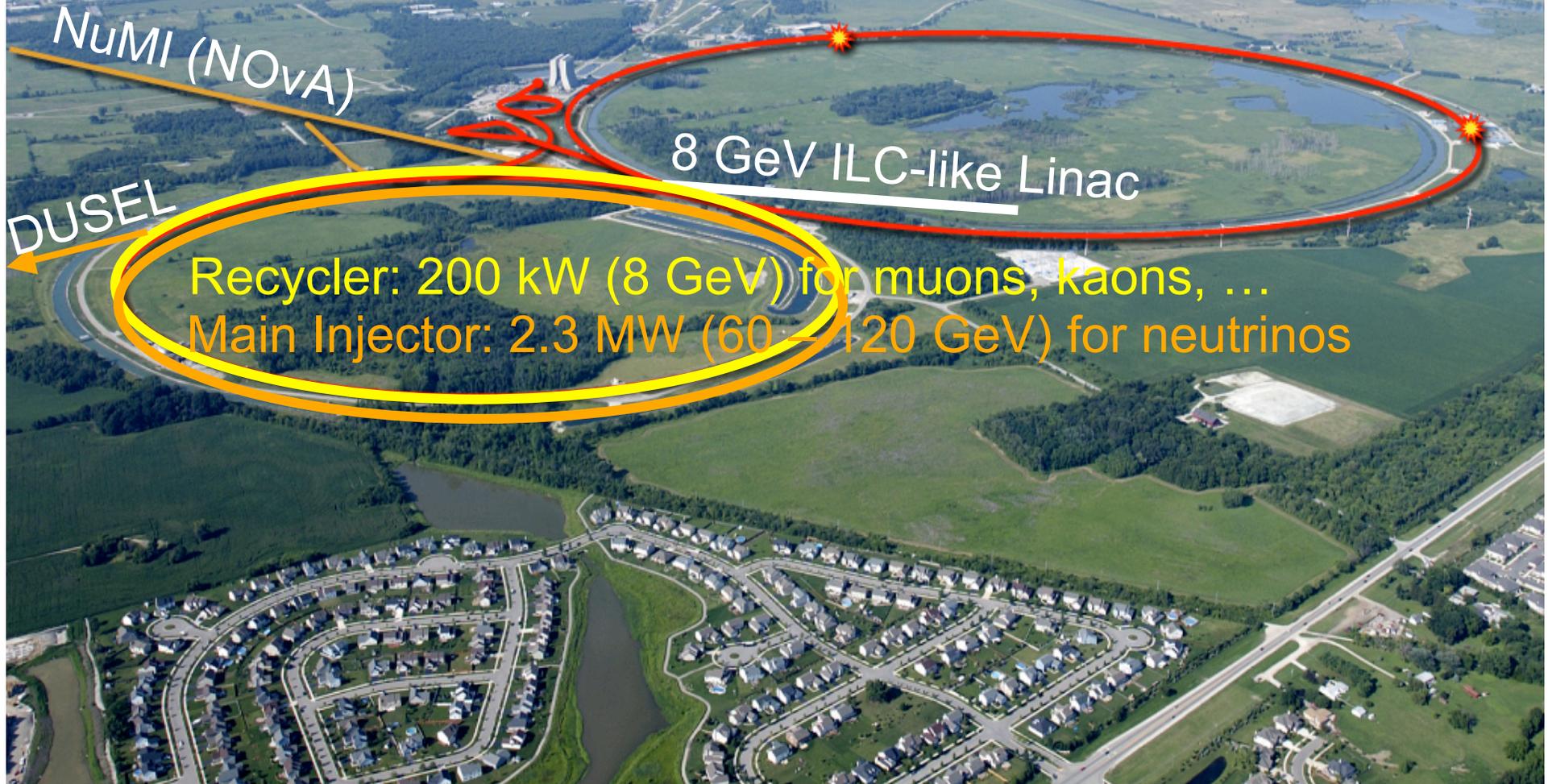
The neutrinos must go far for us
to see the interference.



THE EXPERIMENT

The Source: Fermilab's Project X

Y-K Kim

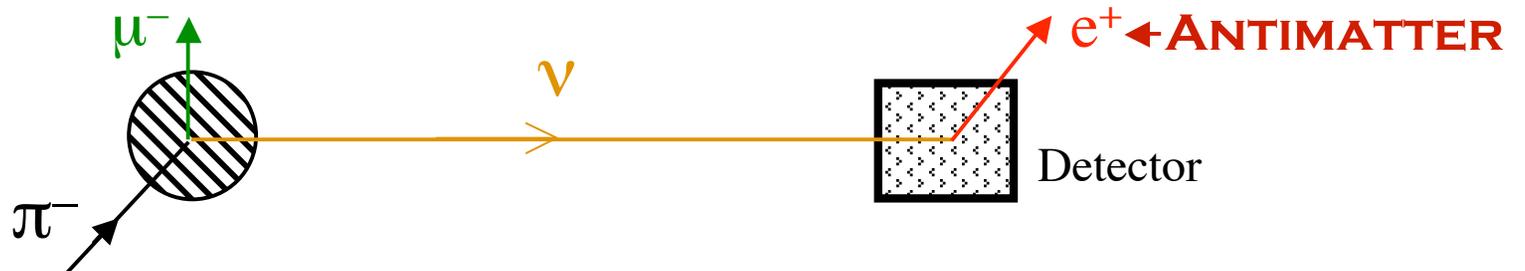


The Physics Reach

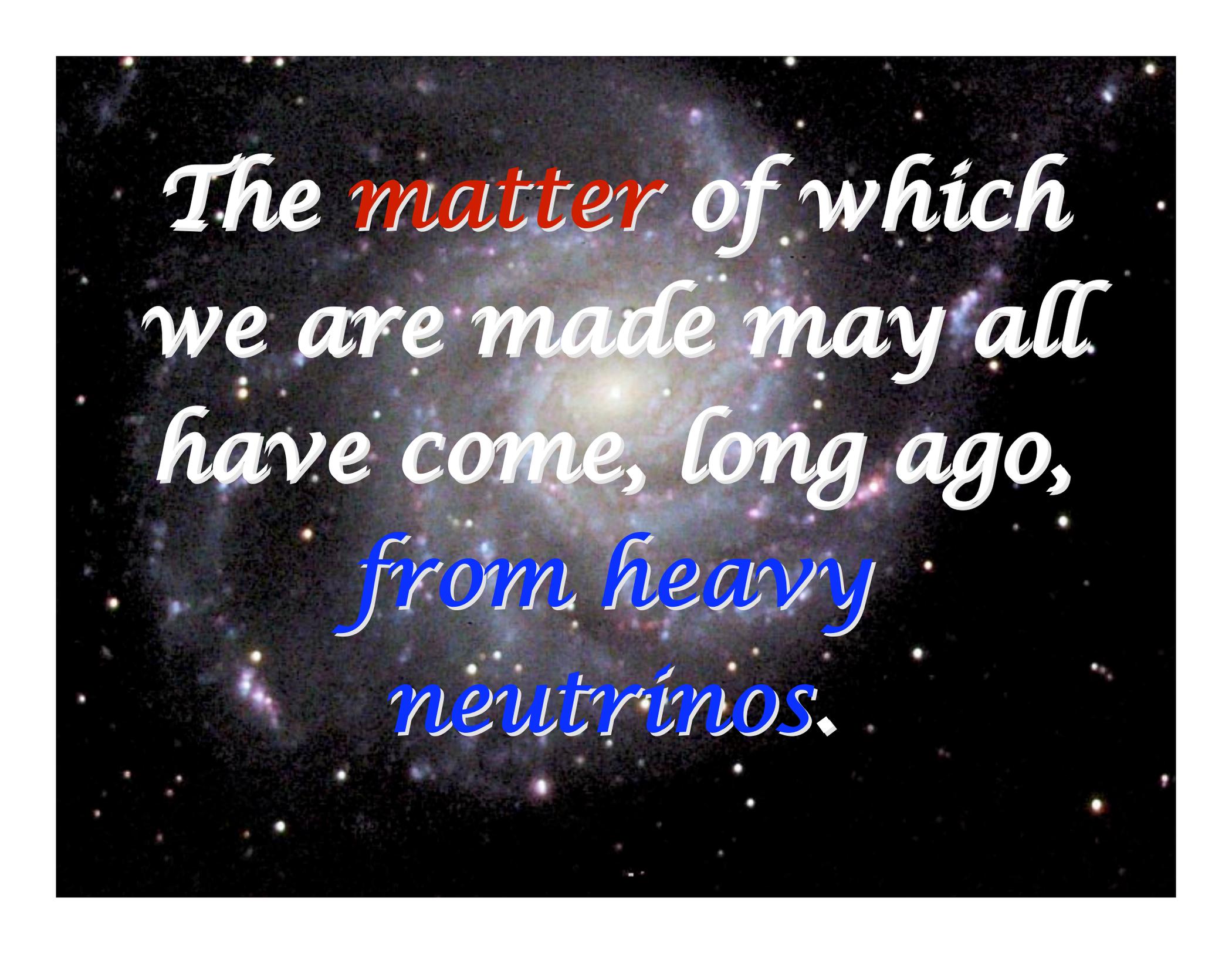
Can see the difference between –



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