Neutrinos: an open window on Fundamental physics and the **Evolution** of the **Universe**

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Departmental research event

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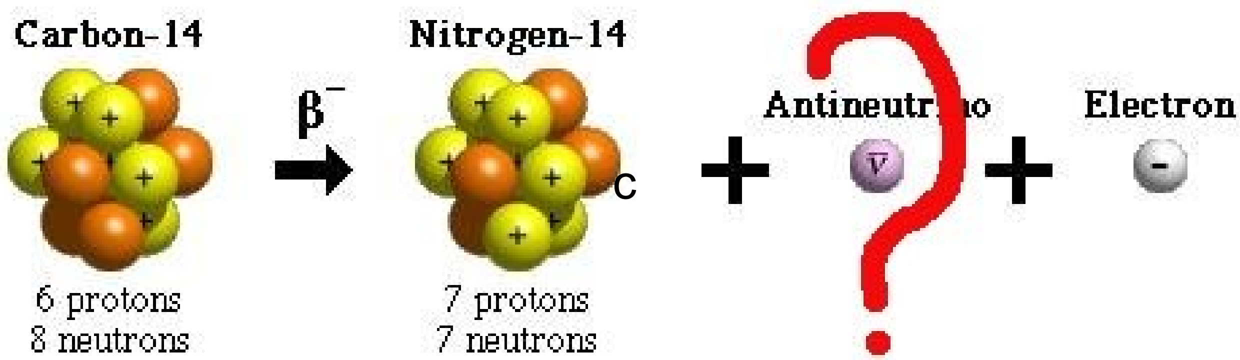
Outline

1. The Pioneering Age of Neutrino Physics (1930 - 1997)
2. The Golden Age (1998 - 2006)
3. The Precision Era (2006 -): a wide exp programme
4. Neutrino Physics and Larger Questions
   a) Open window on physics beyond the Standard Model
   b) Neutrinos as messengers from Early Universe
5. Conclusions

The **Pioneering Age** of Neutrino Physics:

Neutrino hypothesis and its discovery (1930 – 1997)



In order to explain the continuous spectrum of energy in beta decay, Pauli proposed the existence of **a very light, weakly interacting particle**: the neutron.

Fermi renamed Pauli's particle to distinguish it from the newly discovered heavy neutron: the **neutrino** (“il piccolino neutro”).

After their discovery by Cowan and Reines in 1956,
searches were performed looking for **astrophysical neutrinos**,
produced in the Sun and in the atmosphere.
The first atmospheric neutrinos were observed in 1965
by the Kolar Gold Field (KGF) and Reines' experiments.

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

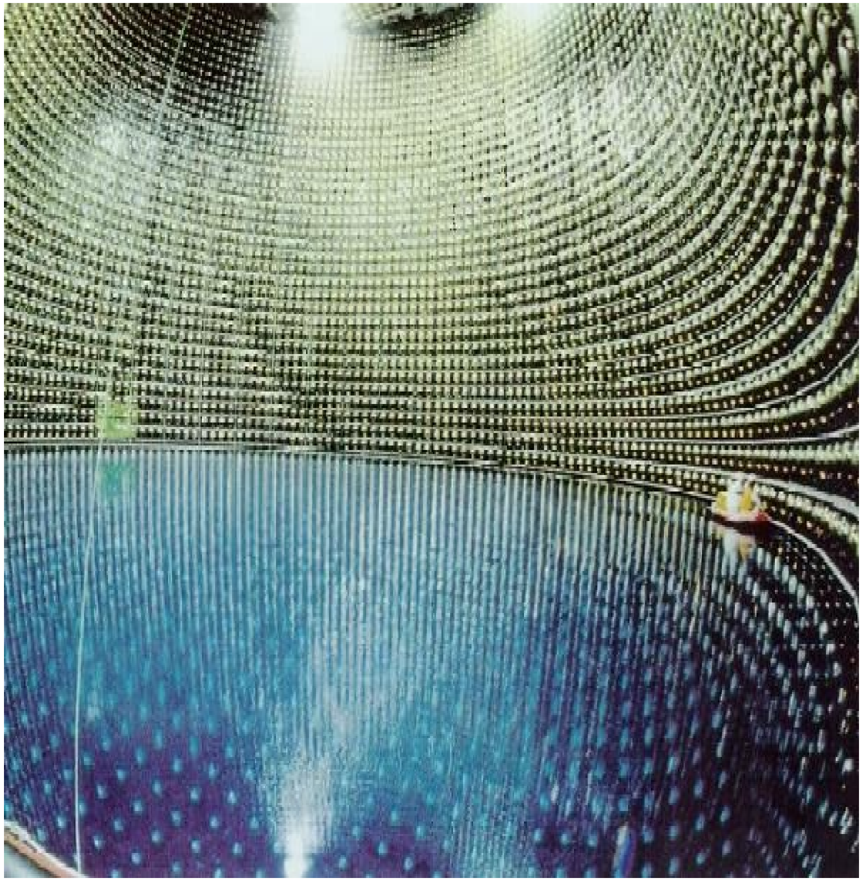
K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

The **Golden Age** of Neutrino Physics:

Evidence of neutrino oscillations (1998 - 2006)

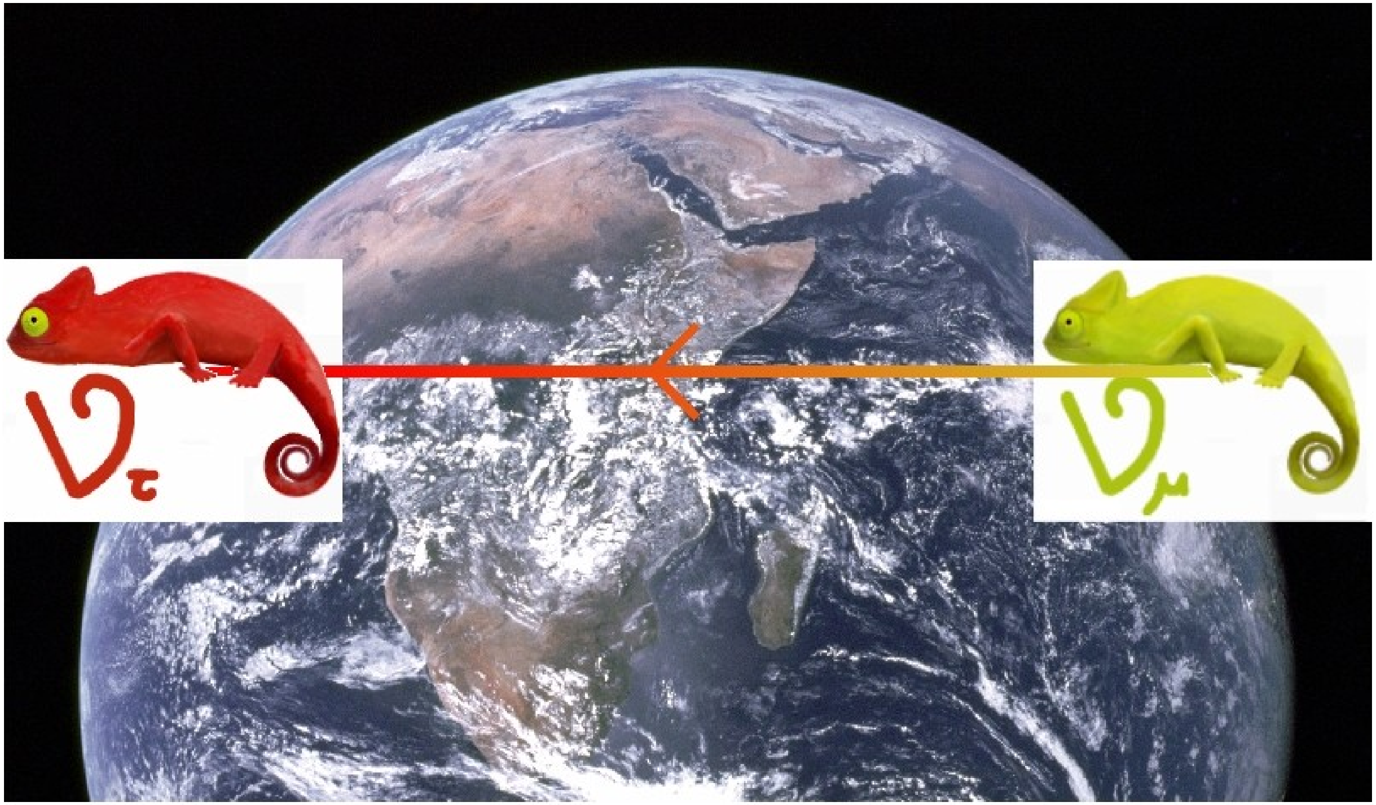


Super-Kamiokande Detector

Super-Kamiokande observed a depletion of muon-like events for **atmospheric neutrinos** which transverse the Earth. The oscillation hypothesis is supported by K2K and MINOS.

Homestake, SAGE and Gallex, SK, SNO observed a depletion of **solar neutrinos**, later confirmed by the **reactor** experiment KamLAND.

Neutrino oscillations: neutrinos are **chameleon** particles



In a SM interaction a neutrino of one type (e.g. muon) is produced.
While travelling it **changes its “flavour”** and can even become a tau neutrino.

Due to mixing, two neutrino basis: **Flavour and Massive** basis

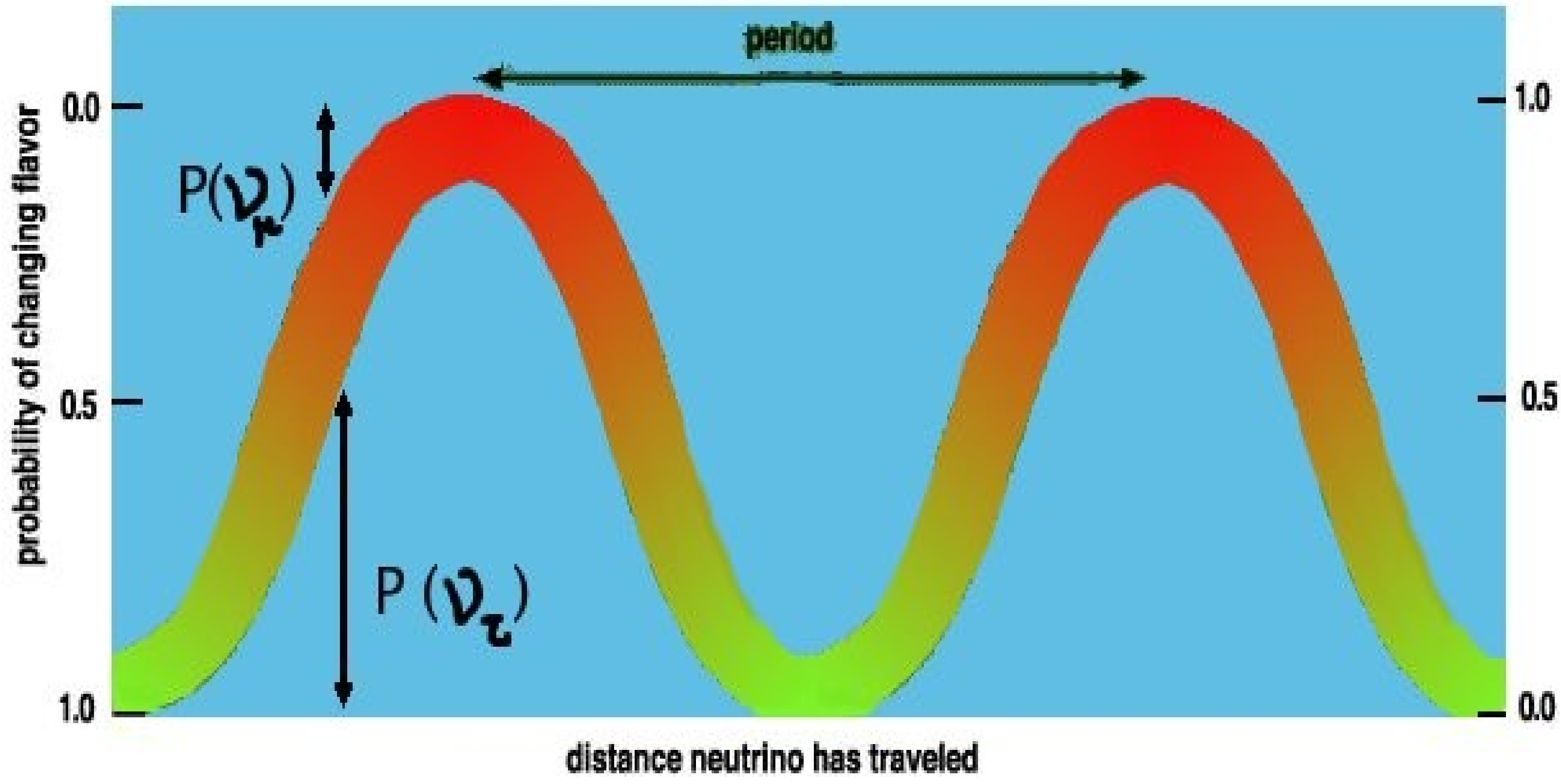
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

At t=0 an electron neutrino is produced. At a later t:

$$|\nu, t\rangle = e^{-i\mathcal{H}t}|\nu, 0\rangle = e^{-iE_1 t}\left(\cos\theta|\nu_1\rangle + e^{-i(E_2-E_1)t}\sin\theta|\nu_2\rangle\right)$$

As neutrinos are highly relativistic, $E_2 - E_1 \simeq (p + \frac{m_2^2}{2p}) - (p + \frac{m_1^2}{2p}) \simeq \frac{\Delta m^2}{2E}$

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \ \sin^2\left(\frac{\Delta m_{21}^2}{4E} L\right)$$



Neutrino oscillations imply that neutrinos have mass and they mix!

First evidence of physics beyond the Standard Model.

The **Precision Era** of Neutrinos:

Hunting for neutrino masses, mixing and their origin (2006-)

With the discovery of neutrino oscillations, a **new perspective** has opened on neutrino physics with compelling questions which await their answer:

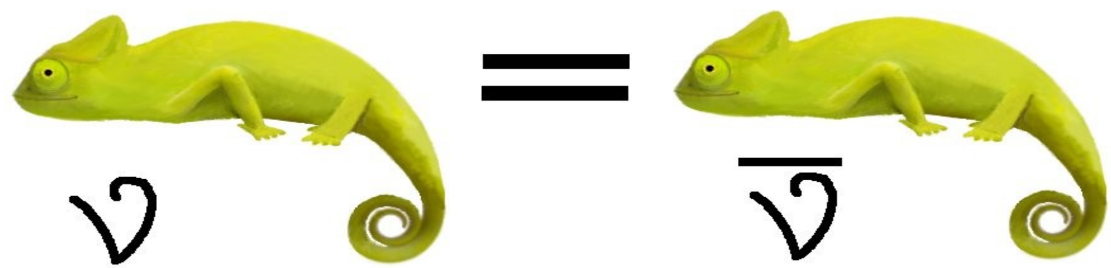
1. What is the nature of neutrinos?
2. What are the values of neutrino masses and mixing?
3. Is the charge/parity (CP) symmetry broken?
4. Are there sterile neutrinos?

A wide experimental program is going to address these questions in the next future.

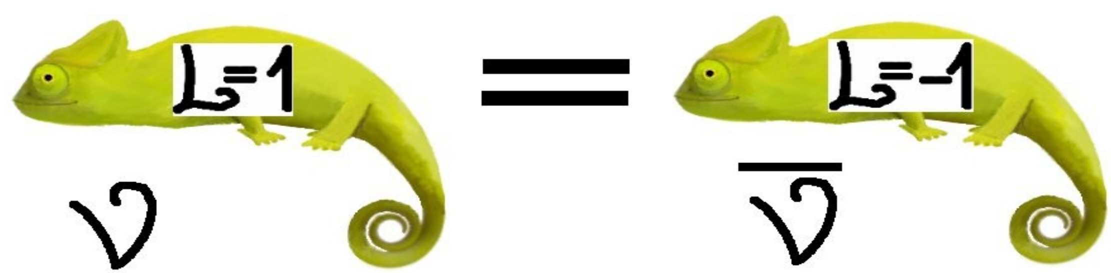
Nature of Neutrinos: Majorana vs Dirac

Neutrinos can be **Majorana** or **Dirac** particles. In the SM only neutrinos can be Majorana because they are neutral.

Majorana particles are indistinguishable from antiparticles.

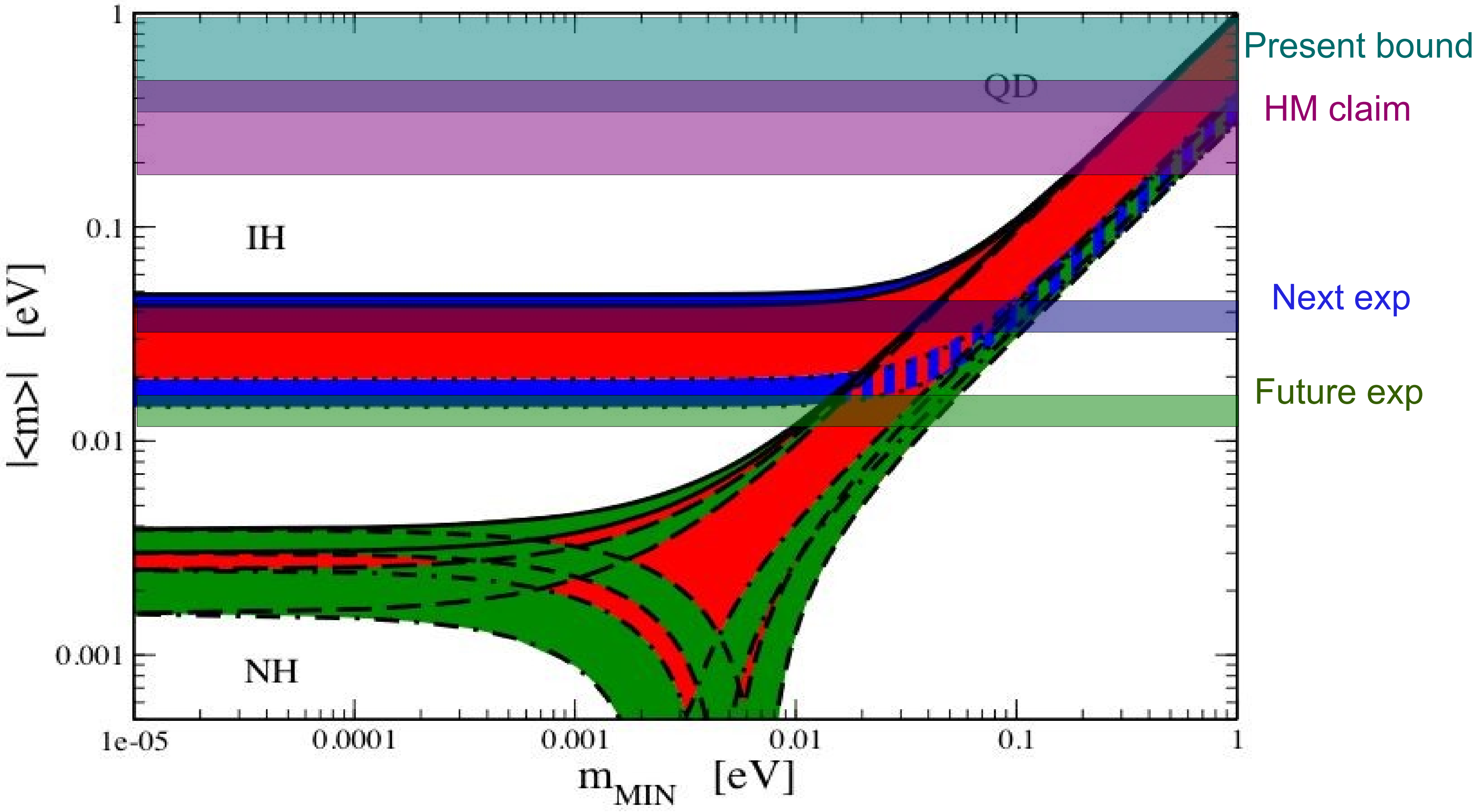


Dirac neutrinos are labelled by the lepton number.



This information is crucial in understanding the Physics BSM: with or without L-conservation?

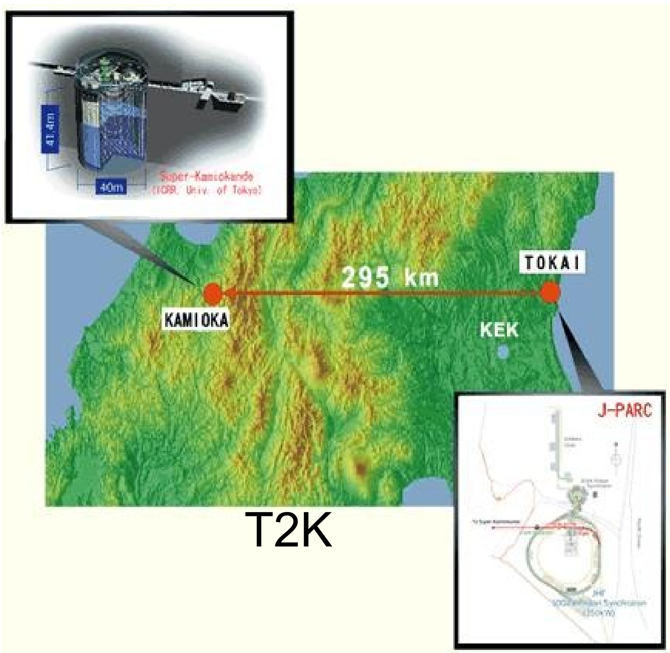
Neutrinoless double beta decay, (A, Z) → (A, Z+2) + 2 e, will test the nature of neutrinos.



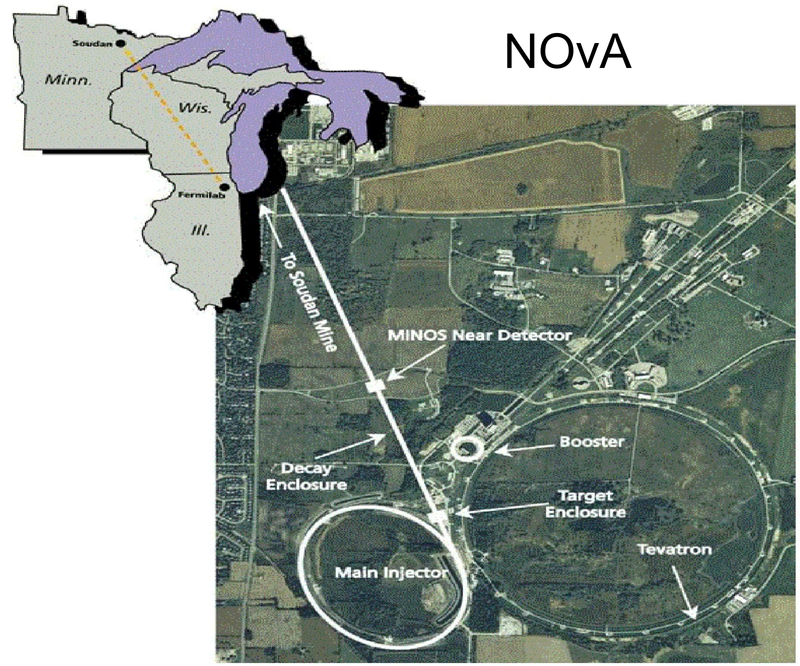
SP, S. Petcov; work in progress with S. Wong

Long baseline neutrino experiments

A wide program for long baseline experiments is under discussion (search for subdominant oscillations).



NOvA



One will get information about **neutrino masses, mixing angles and the CP-symmetry**.

The physics reach of the facilities is being actively studied in order to shape the future experimental program.

- **Superbeams**: T2K, NOvA. Use very intense muon neutrino beams and search for electron neutrino appearance. Baselines: 300 km to 1500 km.

- **Betabeams**: Use electron neutrinos from high-gamma ion decays. Baselines: 300 km to 1500 km.

- **Neutrino factory**: Use muon and electron neutrinos from high-gamma muon decays and need a magnetised detector. Baselines: 1300 km to 7000 km. High energy option and LENF.

At Durham (SP, C. Orme and T. Li), we contribute to EU design studies EUROnu, LAGUNA and lead the phenomenological efforts of IDS on nu-factory.

Neutrino Physics provides information
on the fundamental laws of Nature
and on the evolution of the Universe.

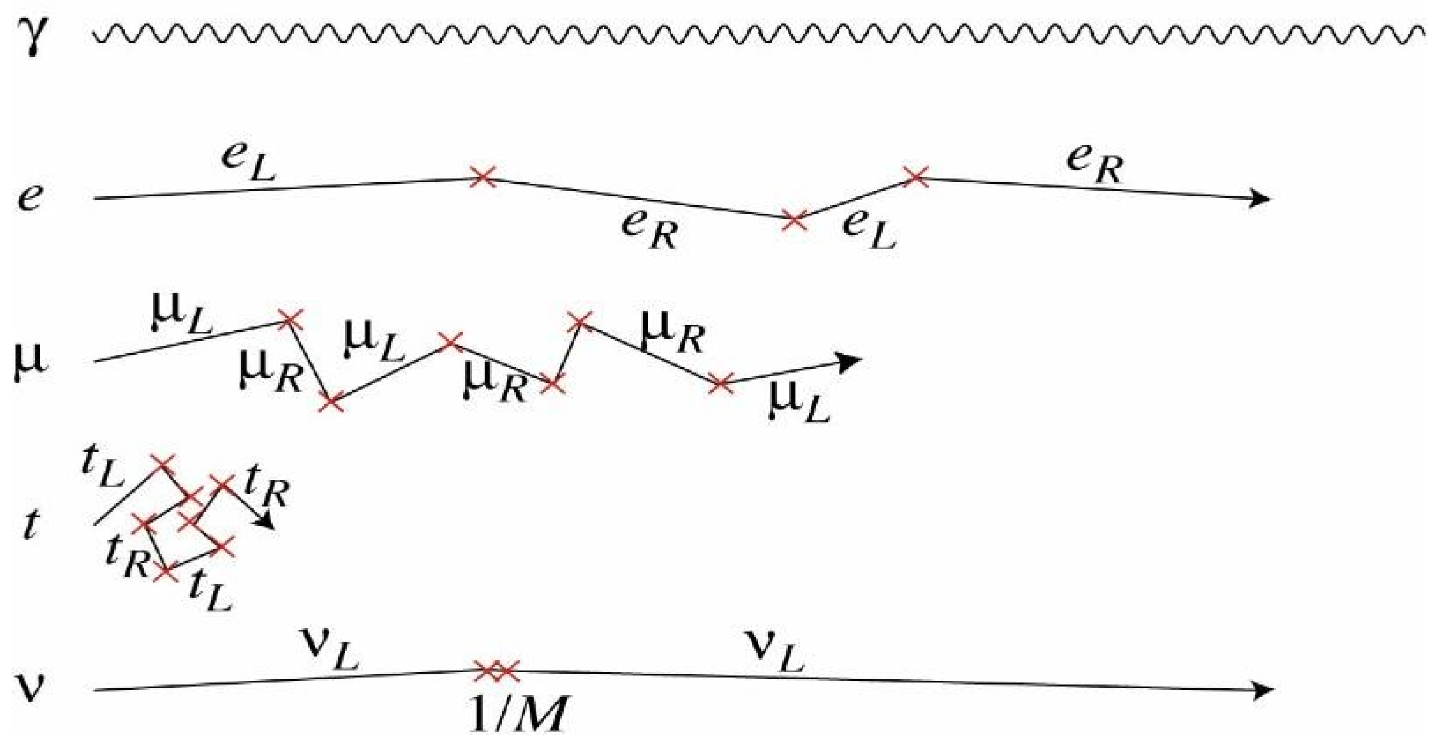
**Open window on
the Physics beyond the
SM at scales
not otherwise reachable.**

**Neutrinos are messengers
from
the Early Universe and
from Extreme Astrophysical
Environments.**

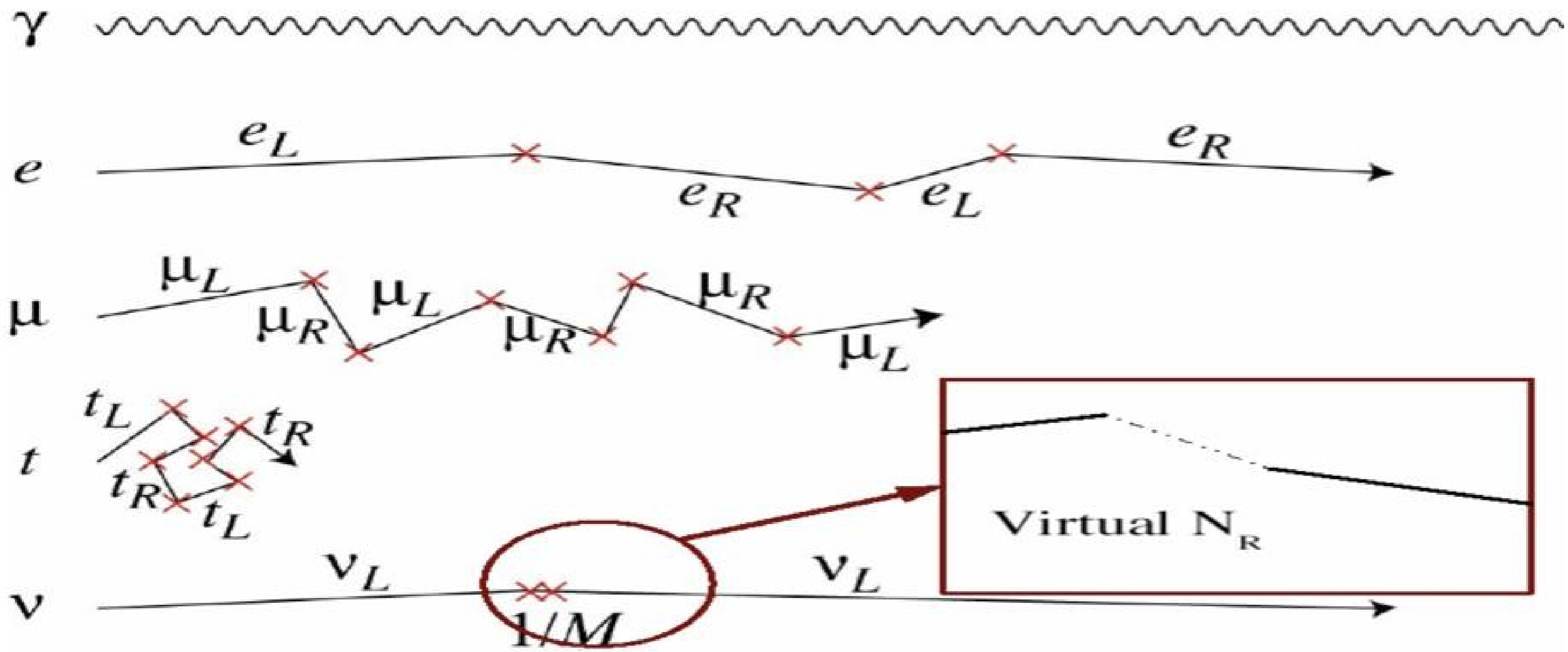
Open window on Physics beyond the SM

Neutrino masses in the sub-eV range cannot be explained naturally within the SM.

If neutrinos had the same interactions with the Higgs as the top quark, they would be **100000000000** times heavier!



Thanks to H. Murayama



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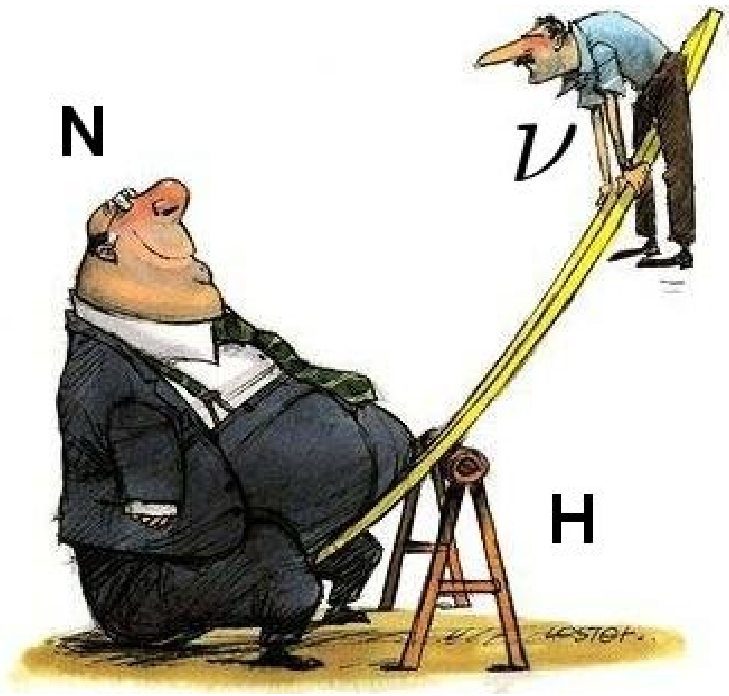
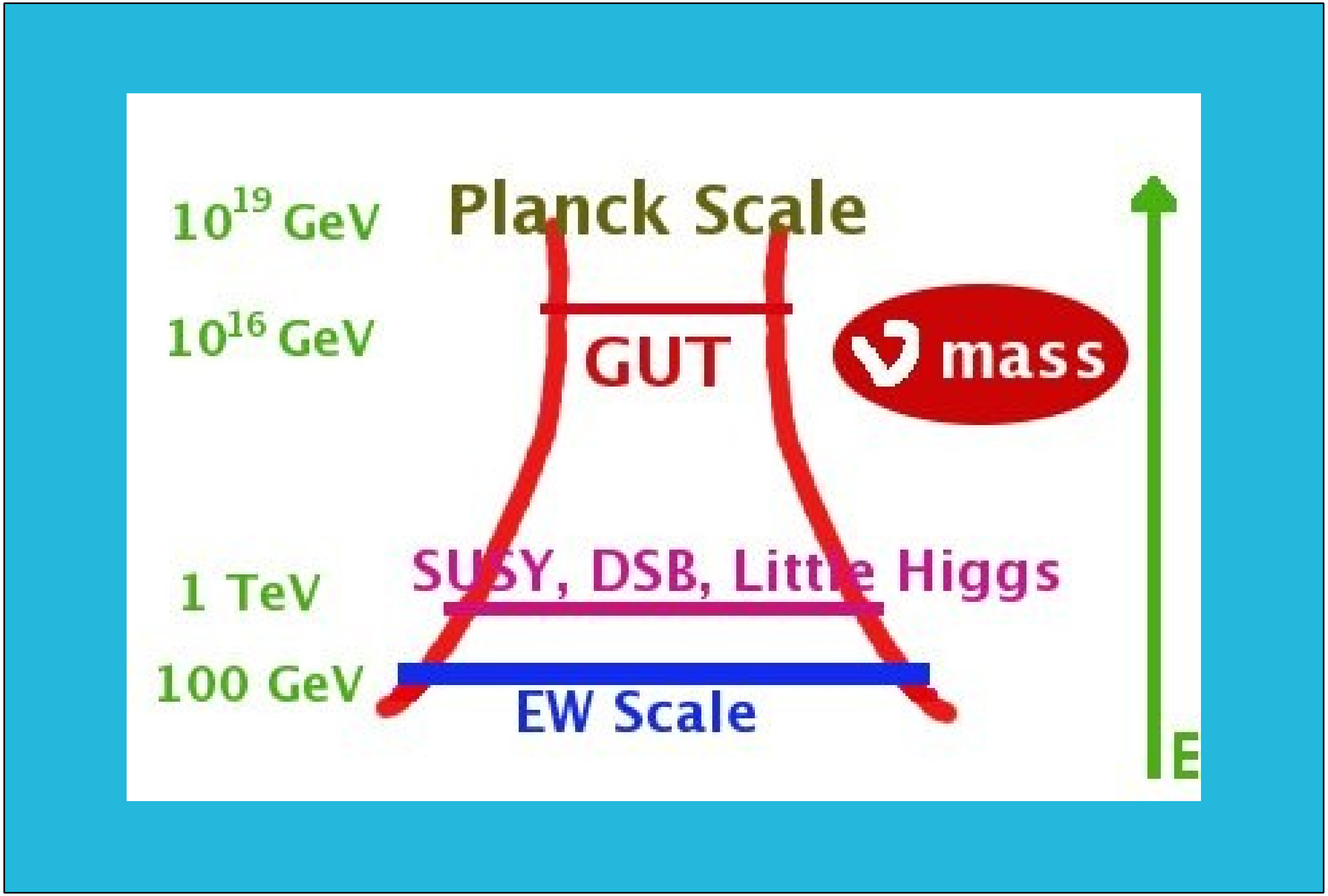
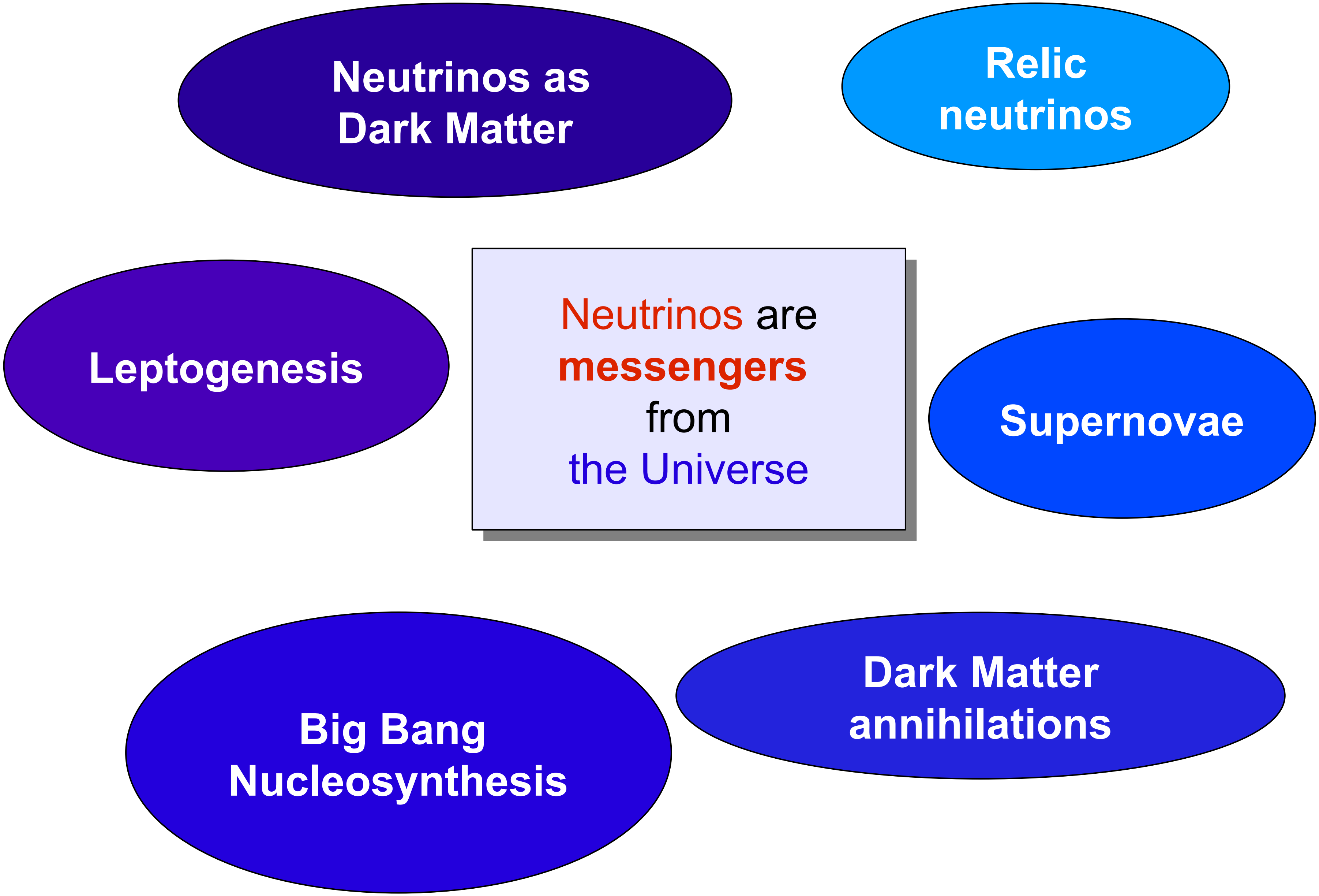


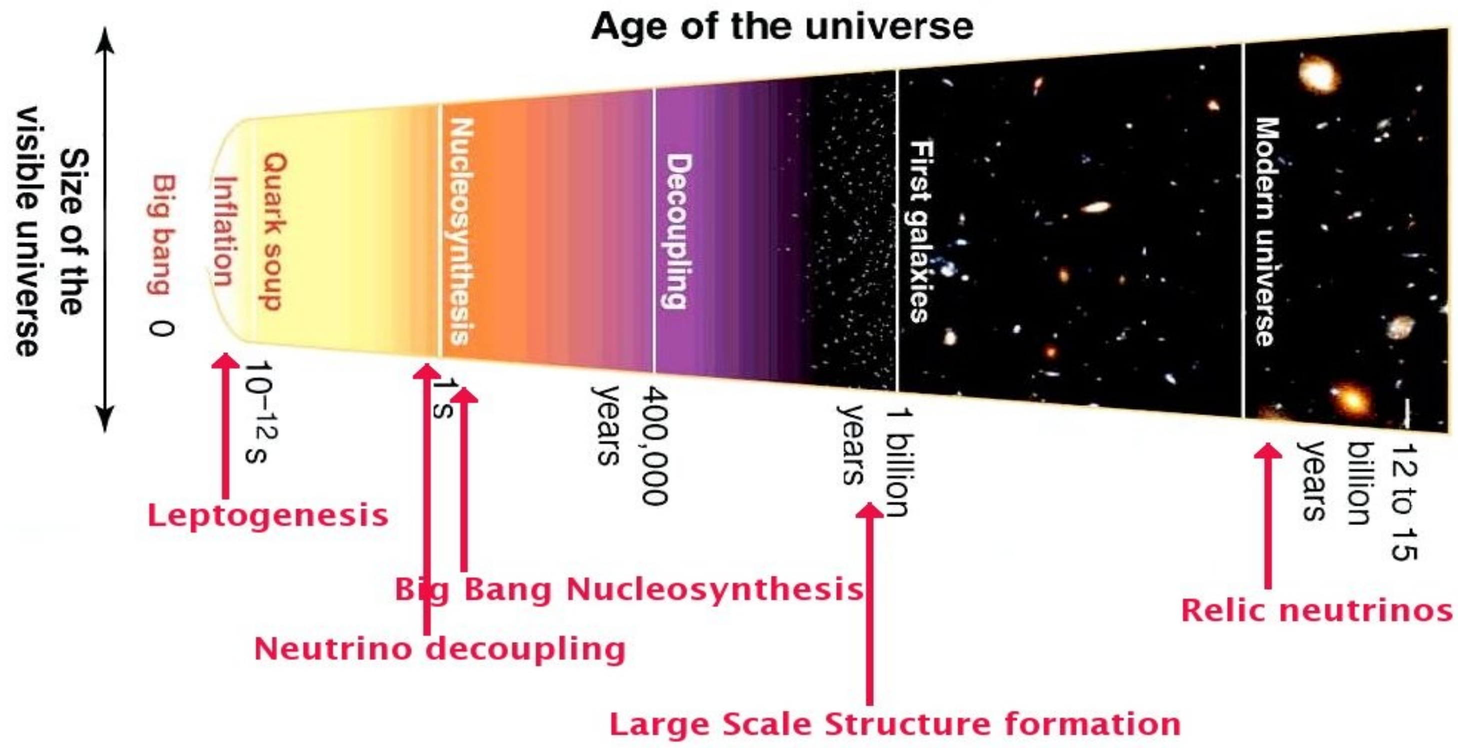
In the **see-saw mechanism,** neutrinos acquire a mass due to their interactions with **heavy sterile neutrinos N**.

$$m_\nu = \frac{\lambda^2 v^2}{M} \rightarrow M \sim 10^{14}\ \mathrm{GeV}$$



Understanding the origin of neutrino masses will shed **light** on the physics at energy scales which might not be tested directly in experiments.

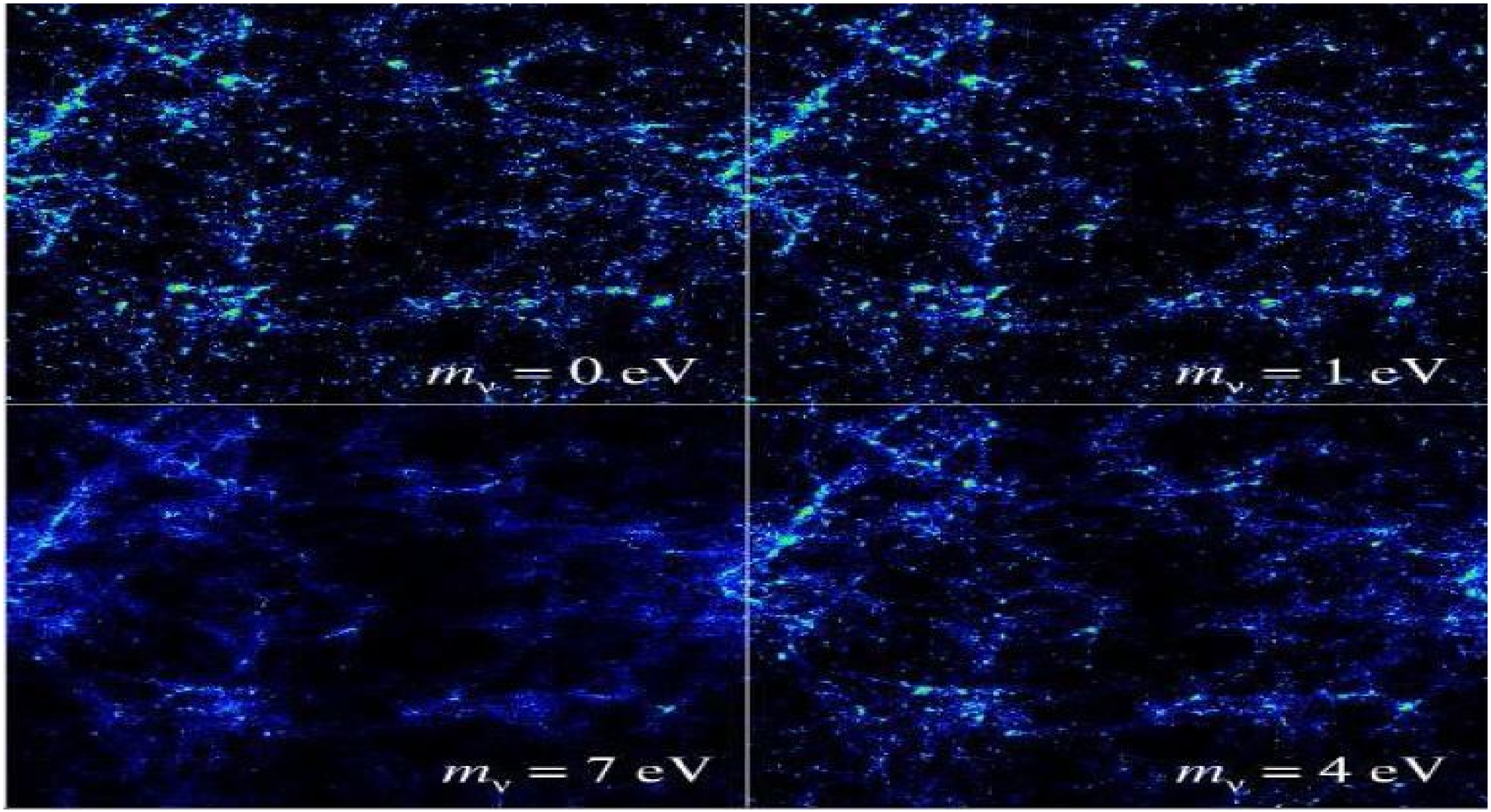

Neutrinos as Dark Matter
Relic neutrinos
Leptogenesis
Neutrinos are messengers from the Universe
Supernovae
Big Bang Nucleosynthesis
Dark Matter annihilations



How many **relic neutrinos** are in a **cup of tea**?

5600!

Neutrinos constitute a **hot dark matter** component and affect the formation of clusters of galaxies.



Need for numerical simulations of large scale structure formation.

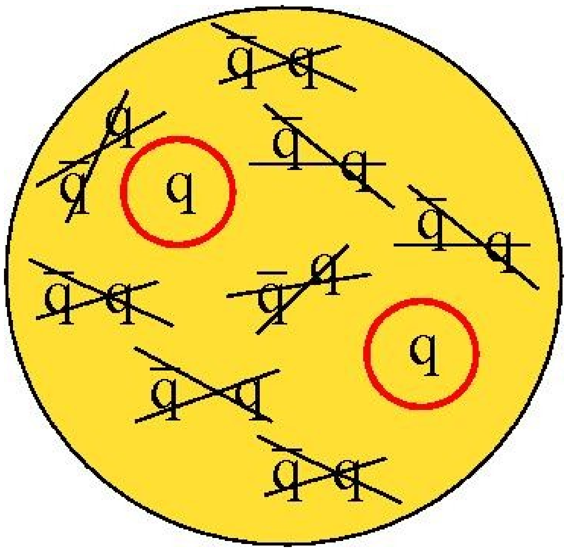
Future work with E. Jennings and C. Baugh.

Leptogenesis and the Baryon Asymmetry

10000000001 quarks

In the Early Universe

10000000000 antiquarks



As the temperature drops, only quarks are left:

$$Y_B = \frac{n_B}{n_\gamma} = (6.0 \pm 0.2) \times 10^{-10}$$

The excess of quarks can be explained by **Leptogenesis**: the heavy N responsible for neutrino masses generate a **baryon asymmetry**.

The **Diamond Era** of Neutrinos:
much harder but much brighter than before.

Our work will help in opening a new window on the fundamental laws of nature, its fundamental constituents and the evolution of the Universe.