Neutrinos

in Astrophysics and Cosmology

Cosmological Neutrinos 3

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- **How Many Neutrinos?**
  (Dark radiation/sterile neutrinos?)

- **Absolute mass determination and limits**

- **Big Bang Nucleosynthesis – BBN**
  (Origin of light elements)

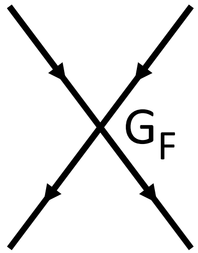
- **Leptogenesis**
  (Origin of Matter Abundance)

Neutrino Thermal Equilibrium

Neutrino reaction rate

Examples for neutrino processes

$$e^+ + e^- \leftrightarrow \overline{\nu} + \nu$$
$$\overline{\nu} + \nu \leftrightarrow \overline{\nu} + \nu$$
$$\nu + e^\pm \leftrightarrow \nu + e^\pm$$



Dimensional analysis of reaction rate

in a thermal medium for $T \ll m_{W,Z}$

$$\Gamma \sim G_F^2 T^5$$

Cosmic expansion rate

Friedmann equation (flat universe)

$$H^2 = \frac{8\pi}{3} \frac{\rho}{m_{Pl}^2} \qquad \left(G_N = \frac{1}{m_{Pl}^2} \right)$$

Radiation dominates

$$\rho \sim T^4$$

Expansion rate

$$H \sim \frac{T^2}{m_{Pl}}$$

Condition for thermal equilibrium: $\Gamma > H$

$$T > \left(m_{Pl} G_F^2 \right)^{-1/3} \sim [10^{19} \mathrm{GeV}\, (10^{-5} \mathrm{GeV}^{-2})^2]^{-1/3} = 1\ \mathrm{MeV}$$

Neutrinos are in thermal equilibrium for $T \gtrsim 1$ MeV
corresponding to $t \lesssim 1$ sec

Dirac vs Majorana Neutrinos

ν_e ν_μ ν_τ


Paul Dirac

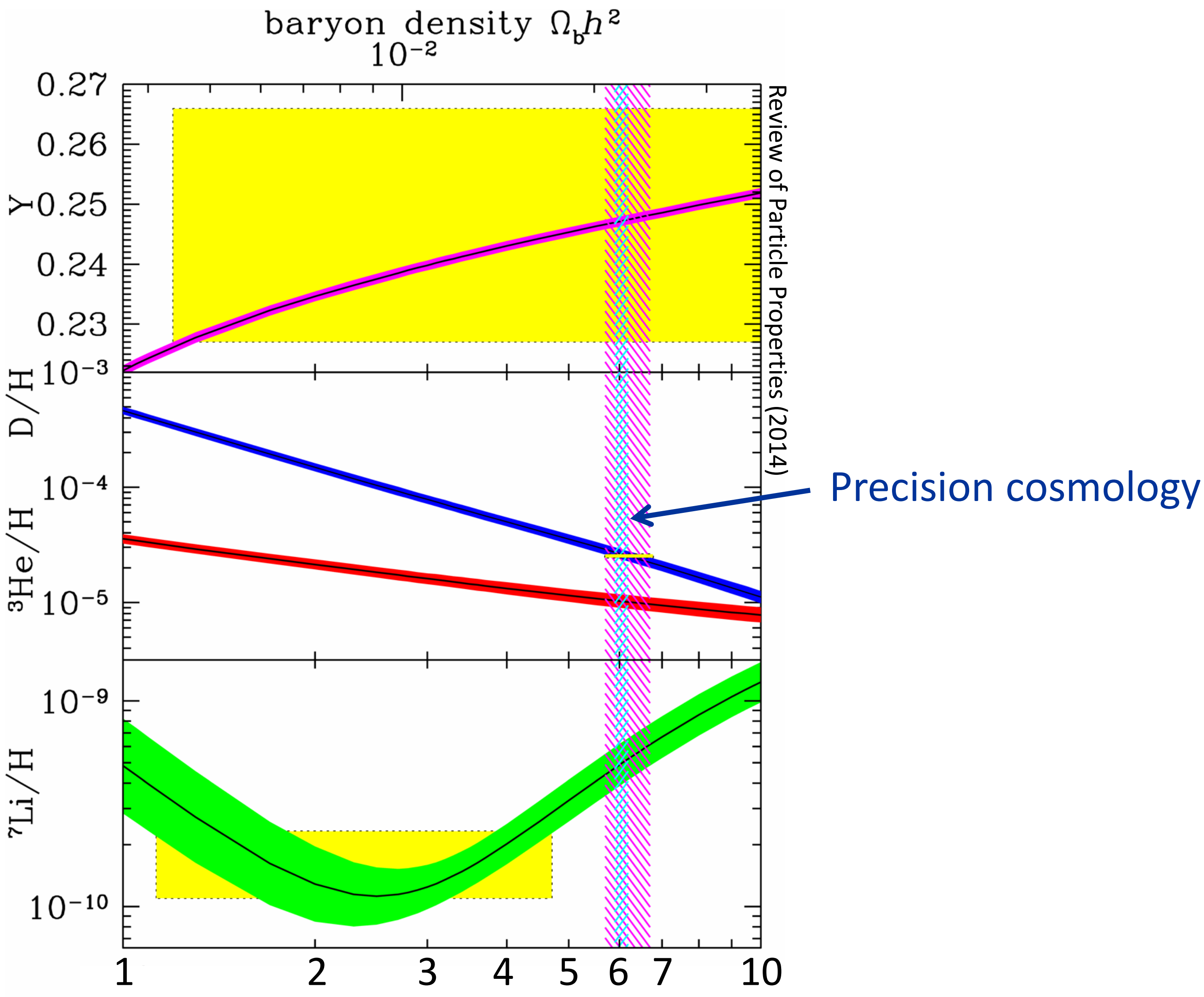
4 states per flavor
Twice the radiation density?

Not thermalized


Ettore Majorana

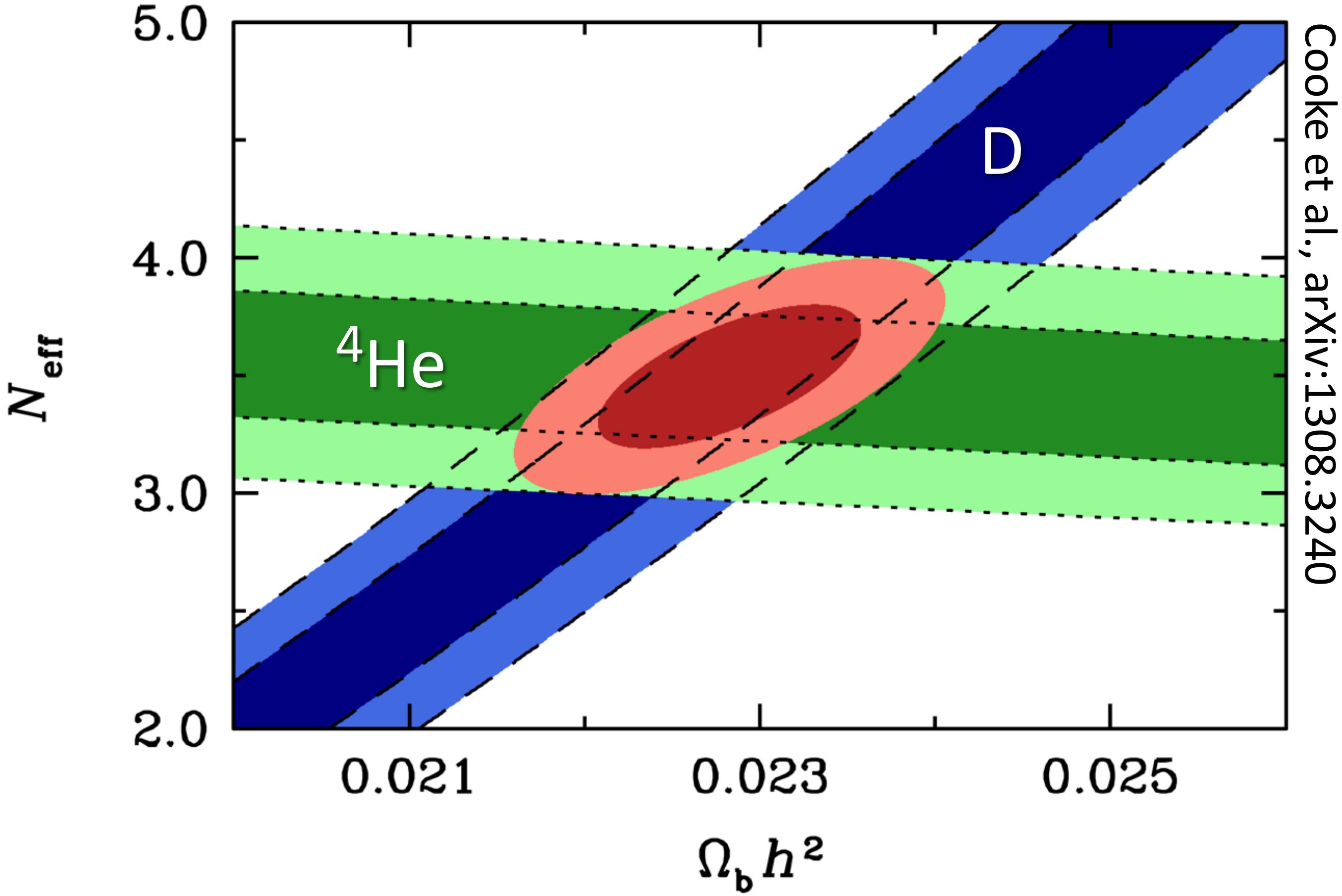
2 states per flavor
Standard assumption in cosmology

BBN Theory vs Observations



Baryon/Photon $\eta \times 10^{10}$

Baryon and Radiation Density from BBN



D abundance from Cook et al. (2013) and He-4 from Izotov et al. (2013)

BBN hint for extra radiation (evidence driven by He abundance)

What is wrong with neutrino dark matter?

Galactic Phase Space ("Tremaine-Gunn-Limit")

Maximum mass density of a degenerate Fermi gas

$$\rho_{\max} = m_\nu \underbrace{\frac{p_{\max}^3}{3\pi^2}}_{n_{\max}} = \frac{m_\nu \left(m_\nu v_{\text{escape}}\right)^3}{3\pi^2}$$

Spiral galaxies

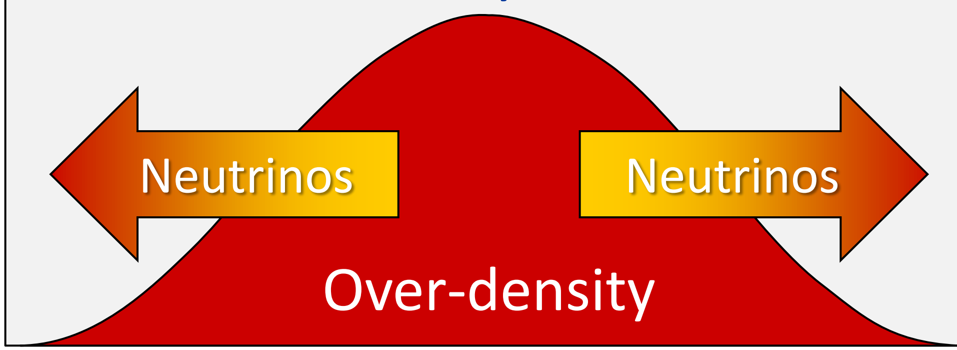
m_ν > 20–40 eV

Dwarf galaxies

m_ν > 100–200 eV

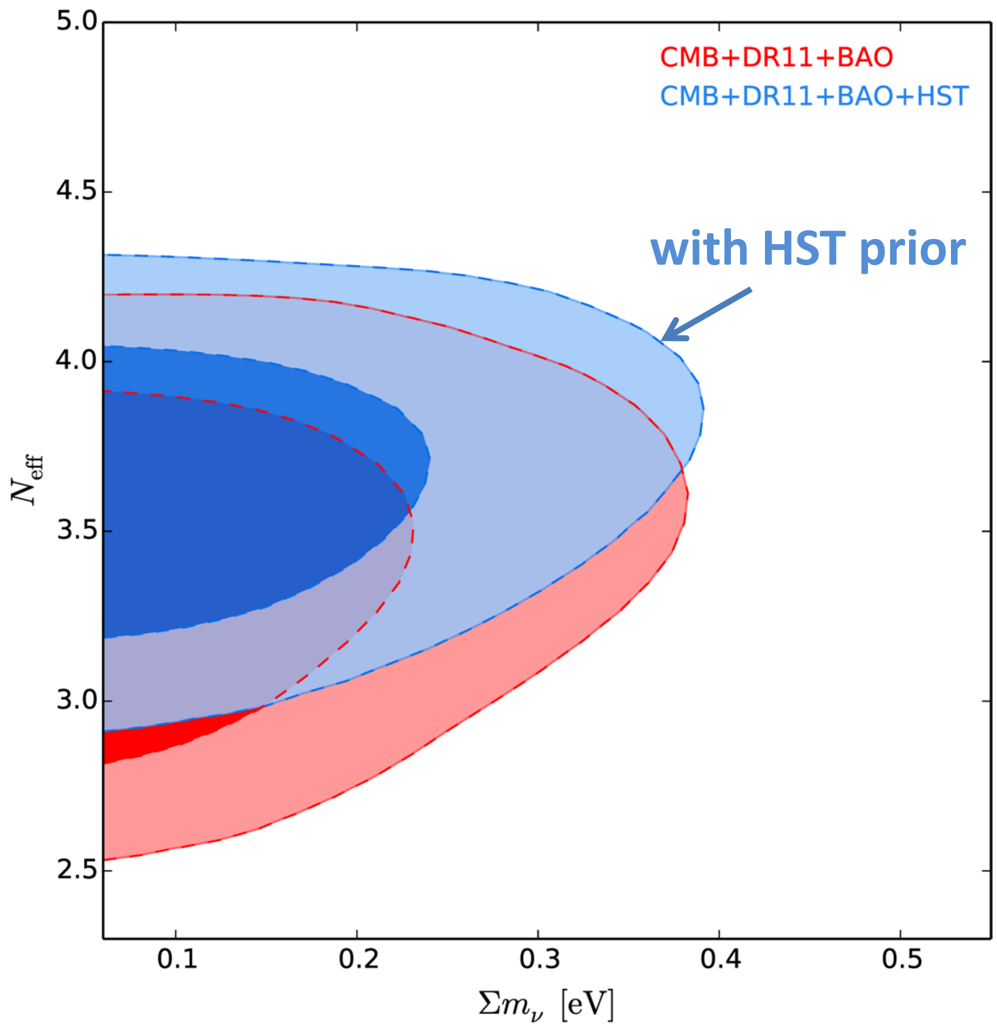
Neutrino Free Streaming (Collisionless Phase Mixing)

- At $T < 1$ MeV neutrino scattering in early universe is ineffective
- Stream freely until non-relativistic
- Wash out density contrasts on small scales



- Neutrinos are "Hot Dark Matter"
- Ruled out by structure formation

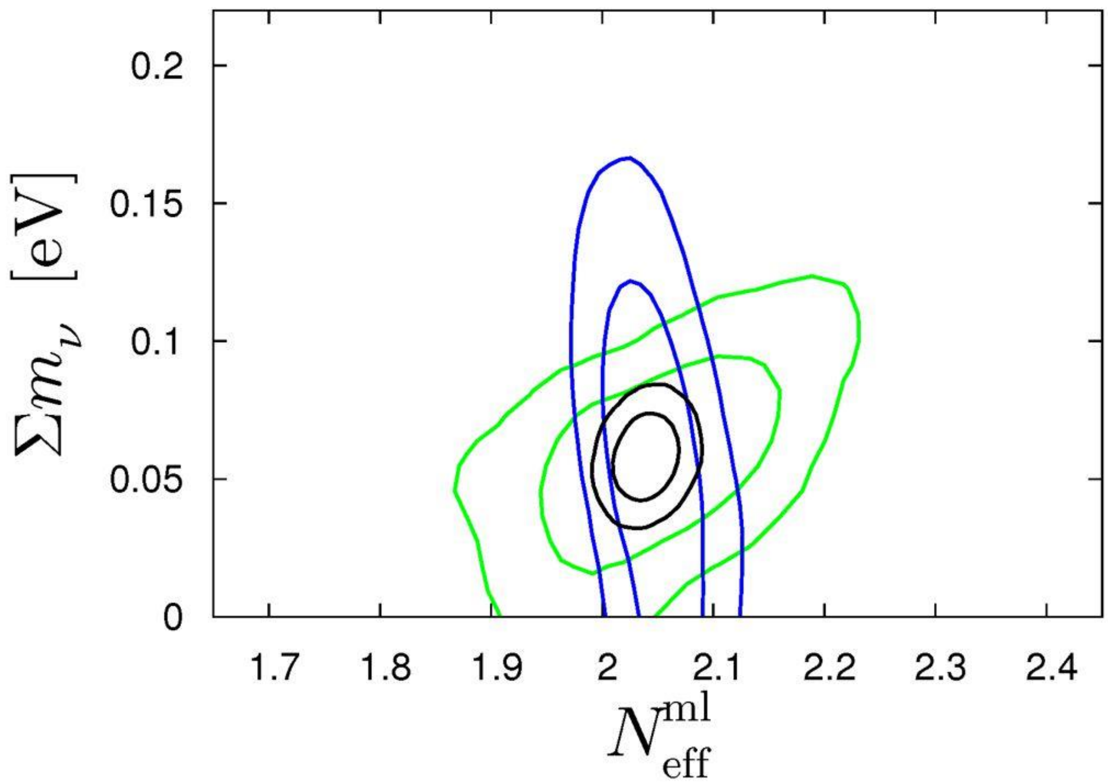
Neutrino Mass and N_{eff} Limits

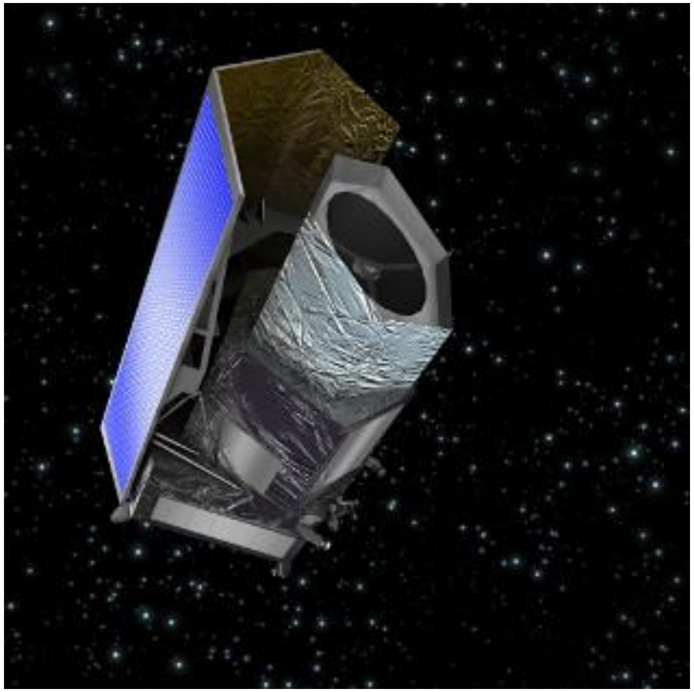


Giusarma, Di Valentino, Lattanzi, Melchiorri & Mena, arXiv:1403.4852

Future Cosmological Neutrino Mass Sensitivity

Pin down the neutrino mass in the sky!





ESA's Euclid satellite to be launched in 2020
Precision measurement of the universe out to redshift of 2

Basse, Bjælde, Hamann, Hannestad & Wong, arXiv:1304.2321:
Dark energy and neutrino constraints from a future EUCLID-like survey

Sterile Neutrinos

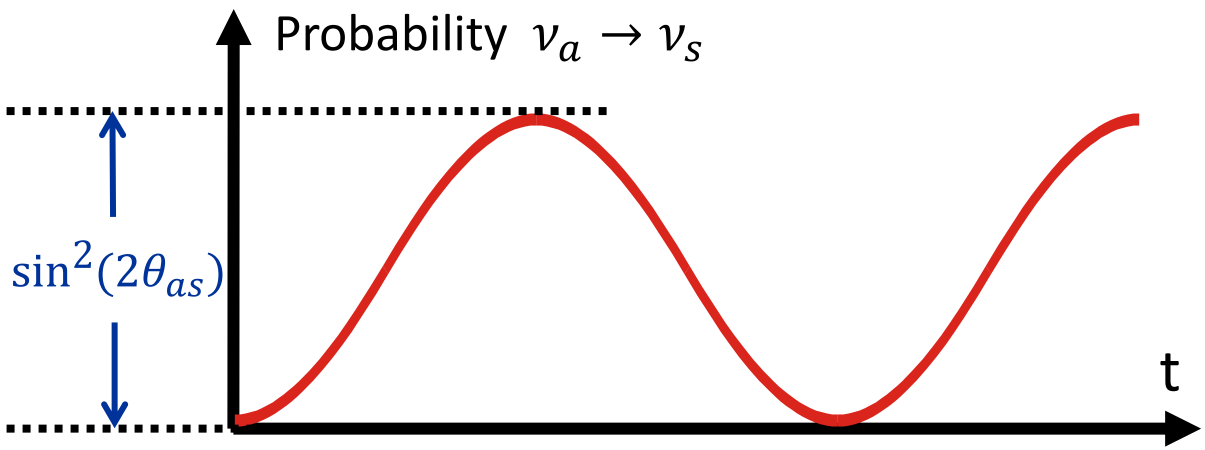
Sterile Neutrino Oscillations

Sterile (right-handed) neutrinos ν_s may exist that are not the Dirac partner to an ordinary (active) neutrino $\nu_a = \nu_e, \nu_\mu$, or ν_τ (White Paper arXiv:1204.5379)

- Unknown mass m_s
- Unknown mixing angles with ordinary neutrinos Θ_{es}, $\Theta_{\mu s}$, and $\Theta_{\tau s}$
- Some experimental "anomalies" explained by ν_s
- Experimental constraints imply that mixing angle must be small

Production in the early universe?

- Naïve average population $\langle p_{\nu_a \to \nu_s} \rangle = \frac{1}{2} \sin^2(2\theta_{as}) \ll 1$ (ignoring matter effects)

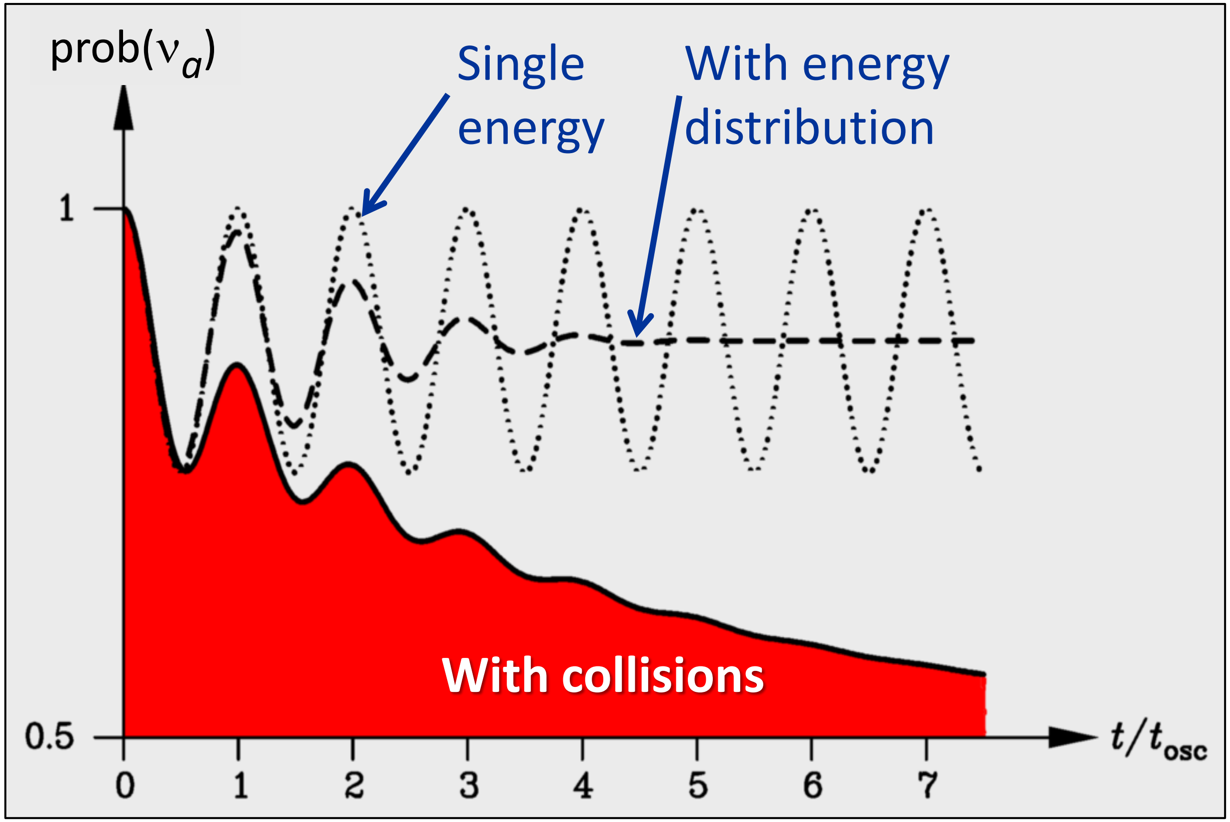


Flavor Relaxation in a Medium

Active neutrinos suffer collisions in a medium (rate Γ), but not ν_s

- Mixed state "collapses" to ν_a or ν_s
- Flavor content is "measured" by the medium at intervals $\tau \sim \Gamma^{-1}$
- Oscillations begin from scratch
- Average oscillation probability ${}^1\!/_2 \sin^2(2\Theta)$

} Flavor conversion rate $\frac{1}{2}\sin^2(2\Theta)\ \Gamma$



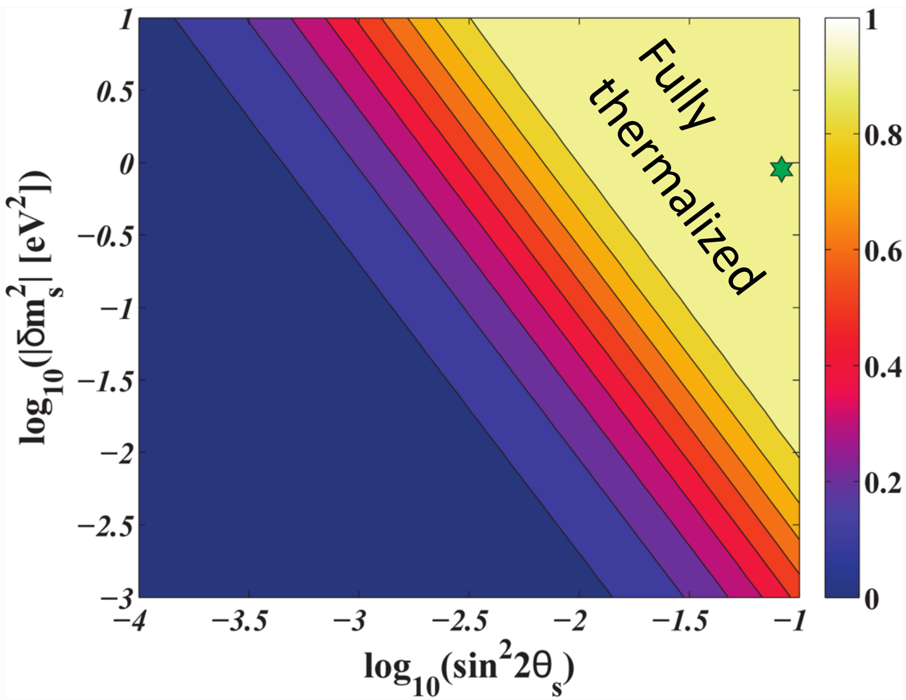
Parameters for Thermalisation

Matter effect implies that thermalisation depends on mass ordering

ν_s

$m_s > m_a$

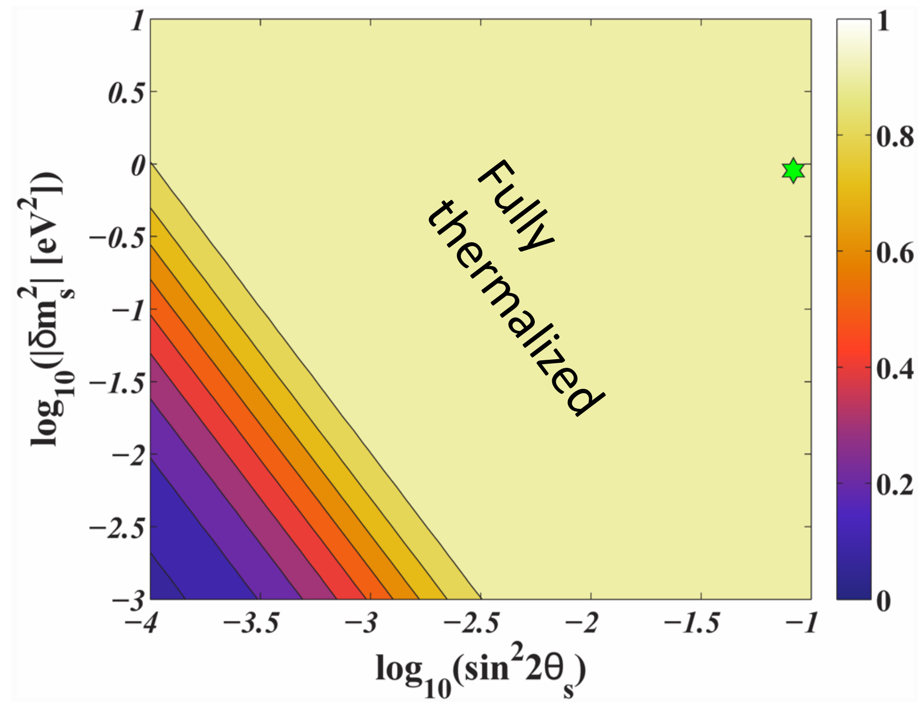
ν_a



ν_a

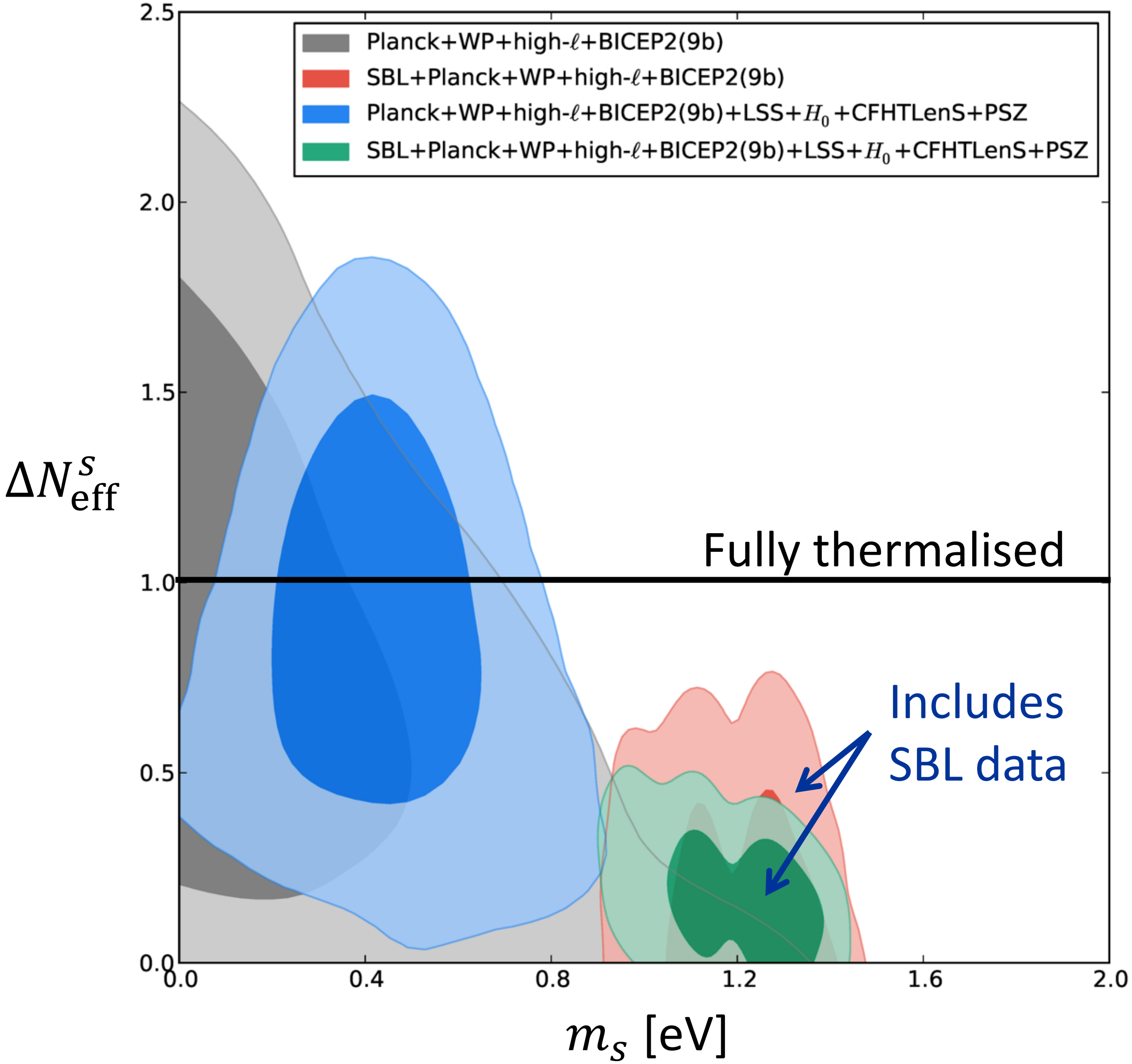
$m_s < m_a$

ν_s



Hannestad, Tamborra and Tram, arXiv:1204.5861

Constraints on Light Sterile Neutrinos

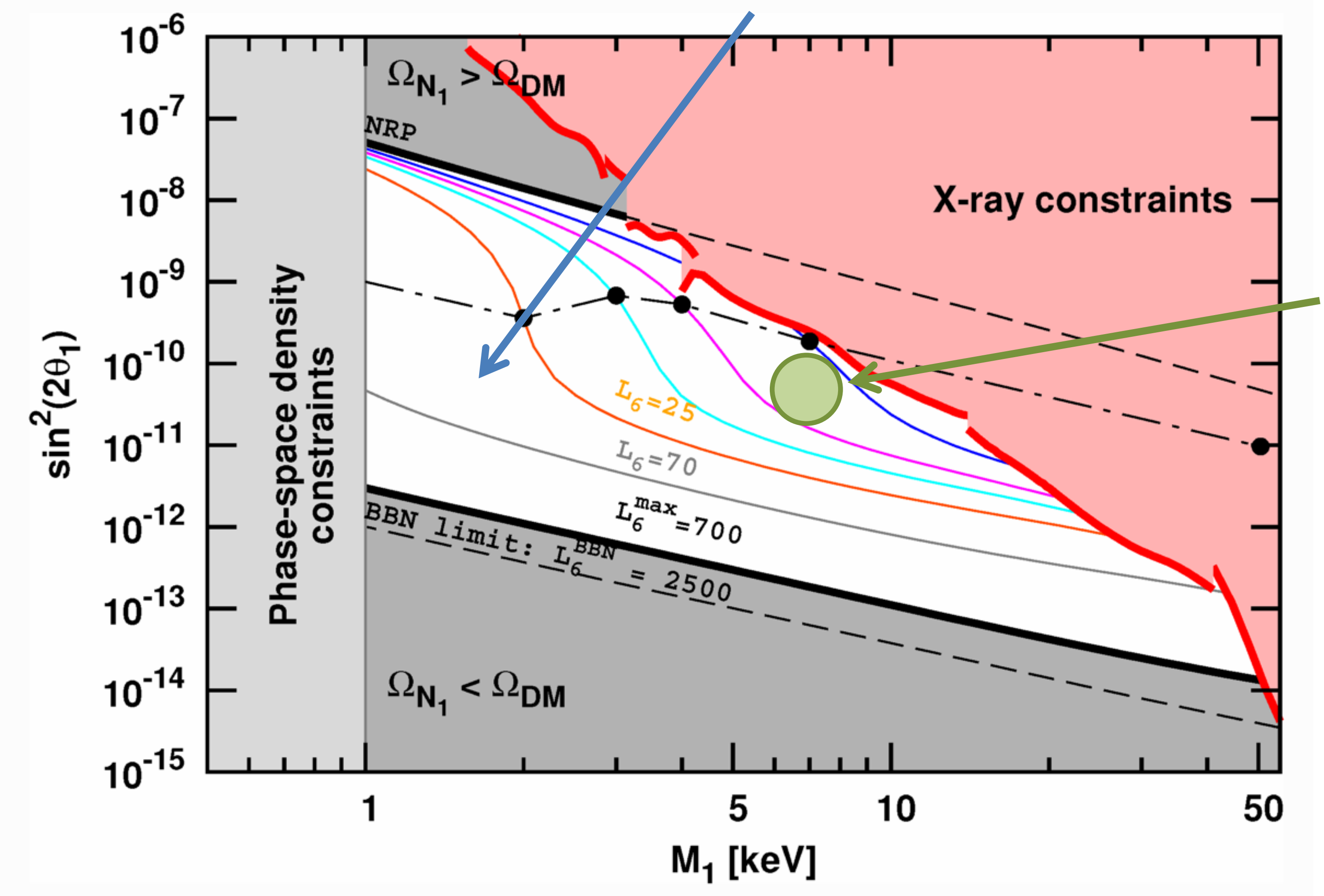


Sterile neutrinos with parameters favored by short-baseline (SBL) experiments are in conflict with cosmology unless their thermalisation is not complete (e.g. suppressed by matter effect from new interactions or by neutrino asymmetries or by other effects)

Archidiacono, Fornengo, Gariazzo, Giunti, Hannestad, Laveder, arXiv:1404.1794

Sterile Neutrino Dark Matter

Resonant production, requires large lepton asymmetry caused by other sterile neutrinos flavors



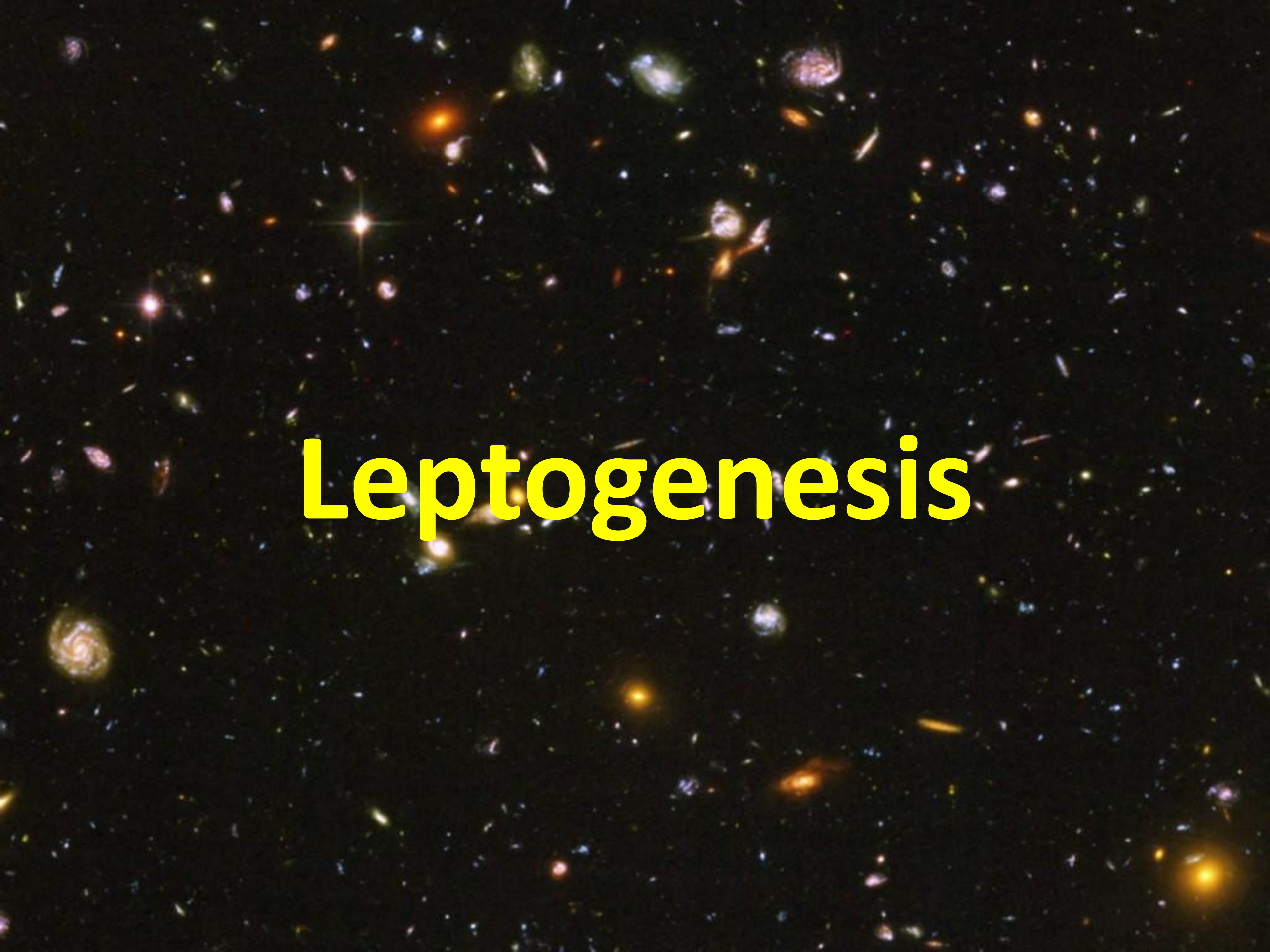
Unidentified tentative x-ray line (3.55 keV) arXiv:1402.2301 & 1402.4119

Sterile Neutrino White Paper, arXiv:1204.5379

Sterile Neutrino Summary

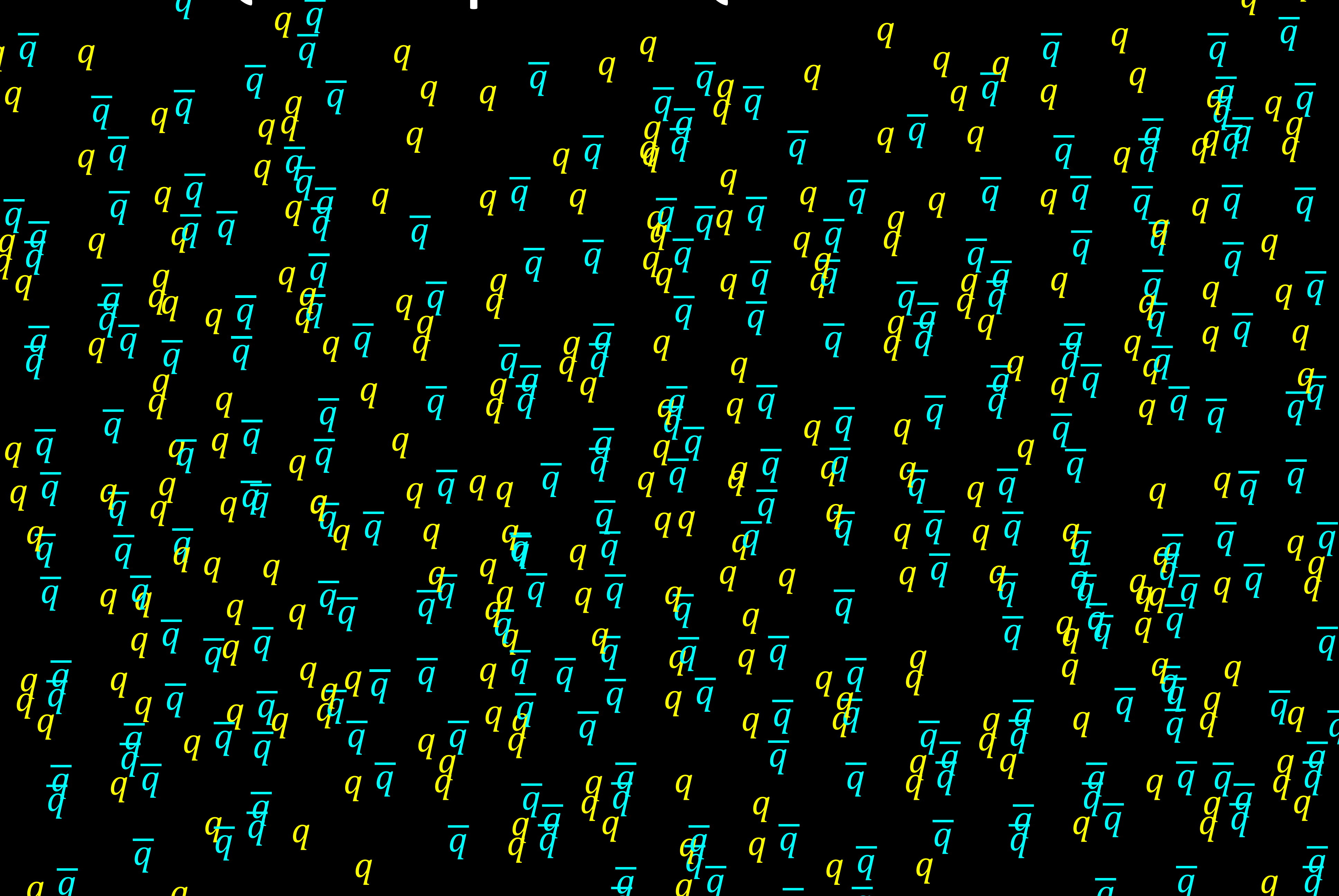
- Fully thermalised sterile neutrino (eV-mass) excluded
- Partially thermalised allowed or even favored, needs new ingredients
- keV-range sterile neutrinos possible as dark matter
- 3.55 keV x-ray line hint for this scenario?

Leptogenesis

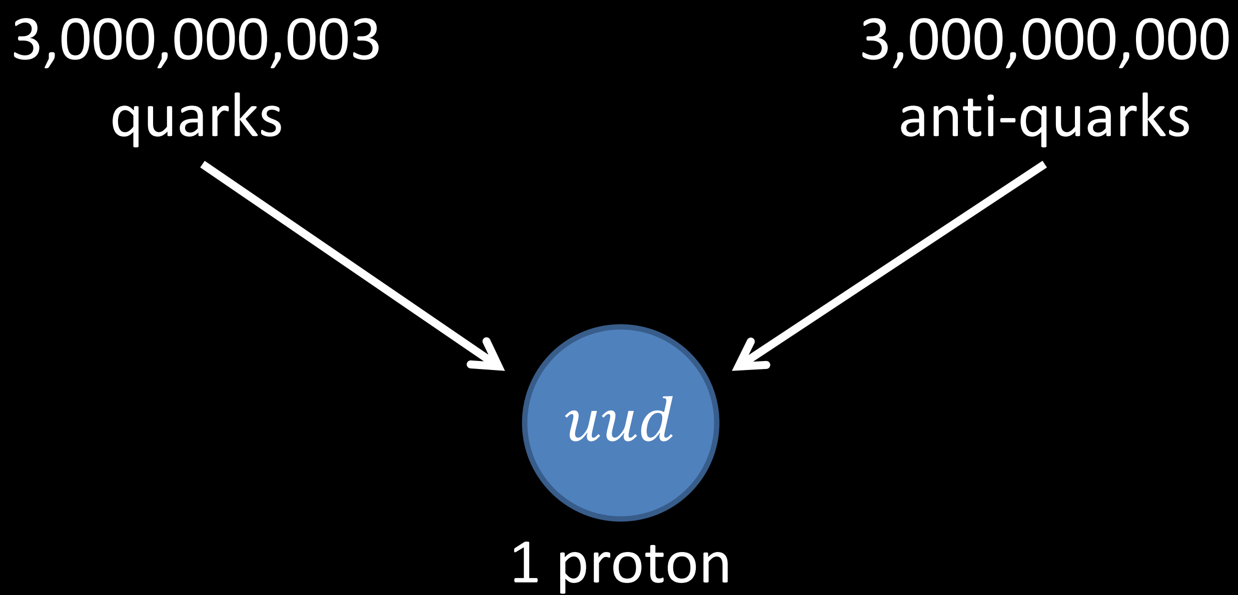


- More matter than anti-matter in the universe (BAU – Baryon Asymmetry of the Universe)
- Not from initial conditions (inflationary universe)
- Should be generated by physical processes: “Baryogenesis”
- Requires an absolute difference between matter and anti-matter in physical laws

Quark Soup Before QCD Confinement



After QCD Confinement



Initial Asymmetry $\sim 10^{-9}$ (Baryon-to-Photon-Ratio)

Baryogenesis in the Early Universe

Andrei Sakharov
1921–1989

Sakharov conditions for creating the Baryon Asymmetry of the Universe (BAU)
- C and CP violation
- Baryon number violation
- Deviation from thermal equilibrium

Particle-physics standard model
- Violates C and CP
- Violates B and L by EW instanton effects (B – L conserved)

- However, electroweak baryogenesis not quantitatively possible within particle-physics standard model
- Works in SUSY models for small range of parameters

A.Riotto & M.Trodden: Recent progress in baryogenesis
Ann. Rev. Nucl. Part. Sci. 49 (1999) 35

CP Violation in Particle Physics

Discrete symmetries in particle physics

C – Charge conjugation, transforms particles to antiparticles
violated by weak interactions

P – Parity, changes left-handedness to right-handedness
violated by weak interactions

T – Time reversal, changes direction of motion (forward to backward)

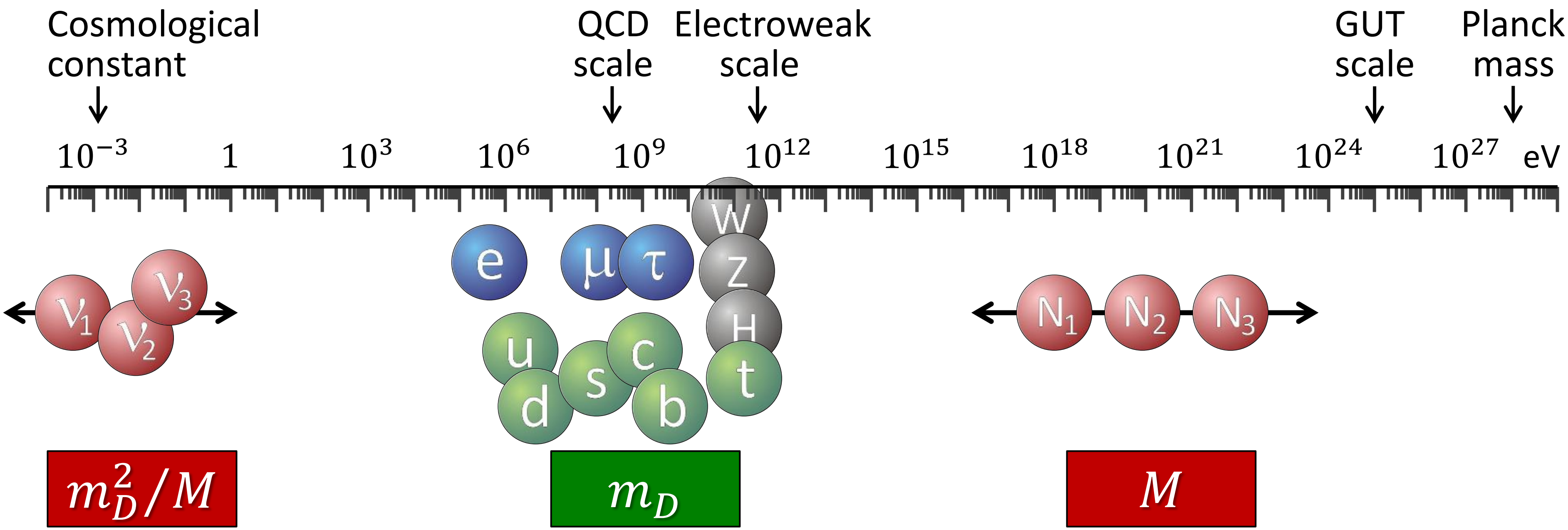
CPT – exactly conserved in quantum field theory

CP – conserved by all gauge interactions
violated by three-flavor quark mixing matrix

Physics Nobel Prize 2008

- All measured CP-violating effects derive from a single phase in the quark mass matrix (Kobayashi-Maskawa phase), i.e. from complex Yukawa couplings
- Cosmic matter-antimatter asymmetry requires new ingredients

See-Saw Model for Neutrino Masses



Mass matrix for one family of ordinary and heavy r.h. neutrinos

$$\left(\overline{\nu}'_L, \overline{N}'_R\right)\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu'_L \\ N'_R \end{pmatrix}$$

Diagonalization

$$\left(\overline{\nu}_L, \overline{N}_R\right)\begin{pmatrix} m_D^2/M & 0 \\ 0 & M \end{pmatrix}\begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

One light and one heavy Majorana neutrino

Volume 174, number 1 PHYSICS LETTERS B 26 June 1986

BARYOGENESIS WITHOUT GRAND UNIFICATION

M. FUKUGITA

Research Institute for Fundamental Physics, Kyoto University, Kyoto 606, Japan

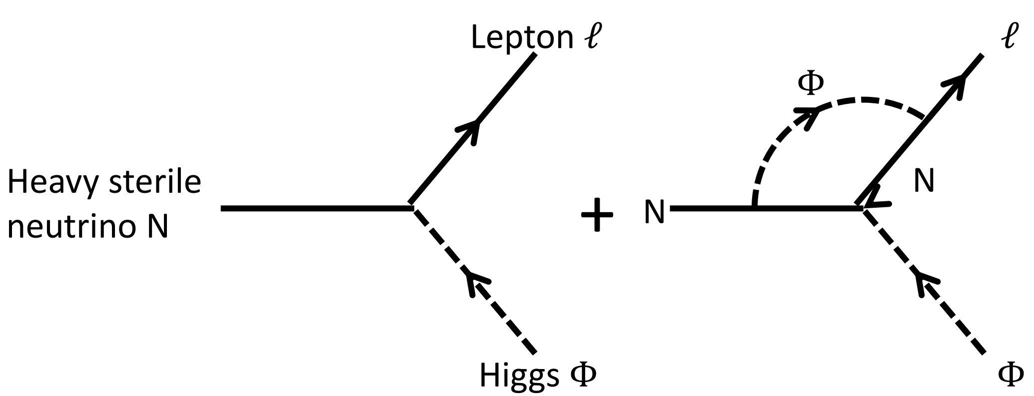
and

T. YANAGIDA

Institute of Physics, College of General Education, Tohoku University, Sendai 980, Japan and Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg, Fed. Rep. Germany

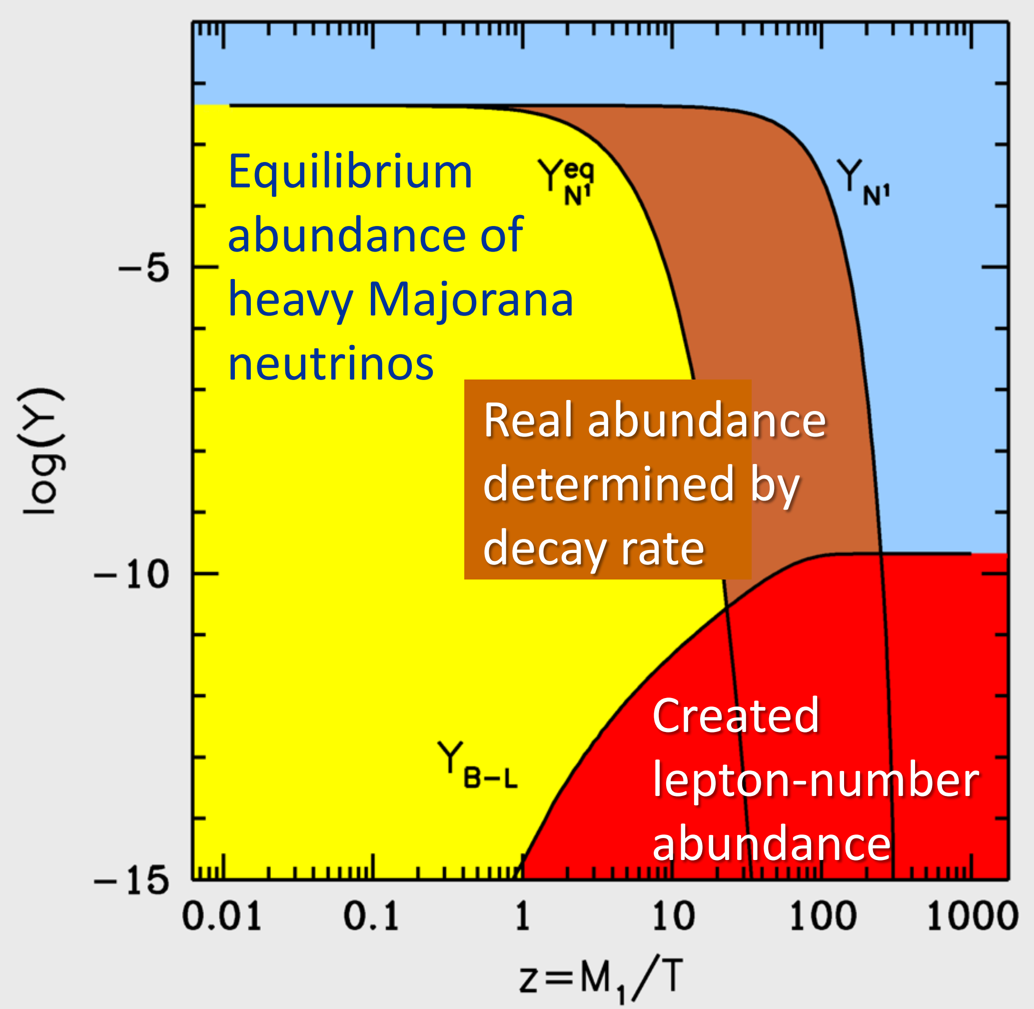
Received 8 March 1986

A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories. The lepton number excess originating from Majorana mass terms may transform into the baryon number excess through the unsuppressed baryon number violation of electroweak processes at high temperatures.



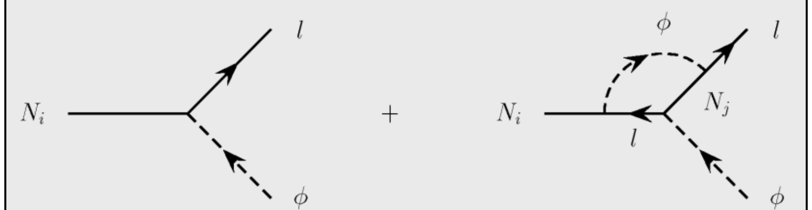
CP-violating decays of heavy sterile neutrinos by interference of tree-level with one-loop diagram

Leptogenesis by Out-of-Equilibrium Decay



M. Fukugita & T. Yanagida: Baryogenesis without Grand Unification
Phys. Lett. B 174 (1986) 45

CP-violating decays by interference of tree-level with one-loop diagram

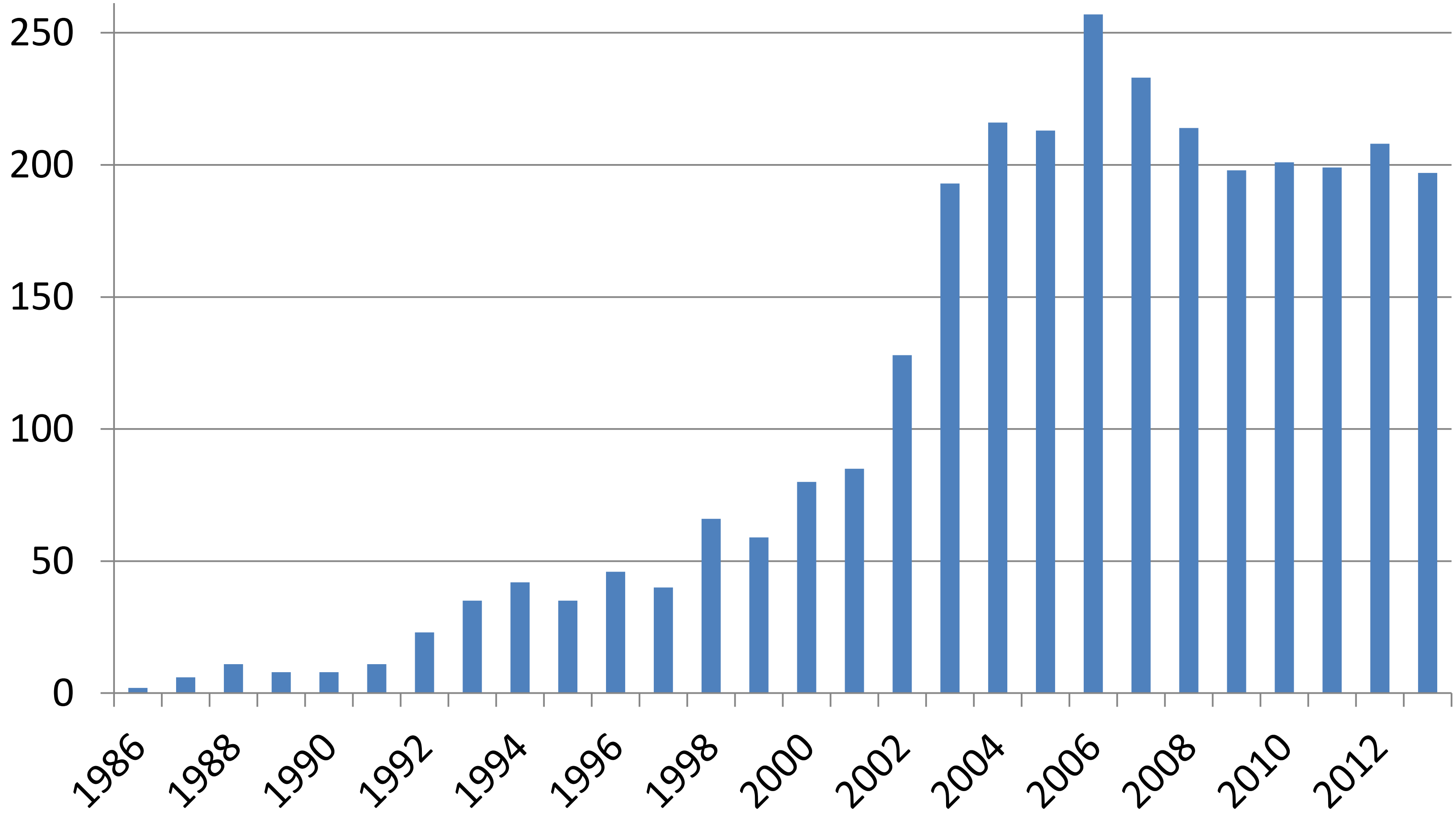


$$\Gamma_{\text{Decay}} = g_\nu^2 \frac{M}{8\pi}$$

W. Buchmüller & M. Plümacher: Neutrino masses and the baryon asymmetry
Int. J. Mod. Phys. A15 (2000) 5047-5086

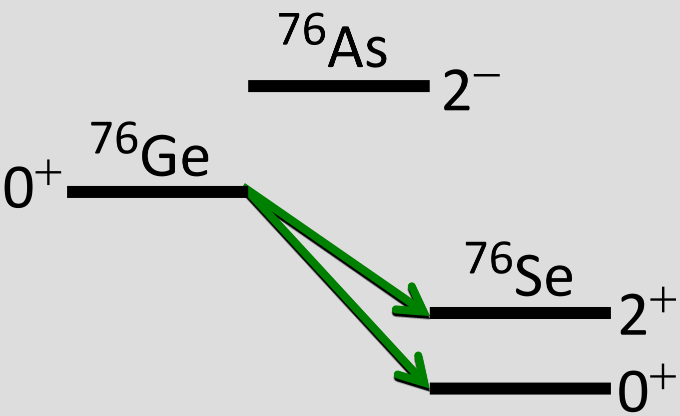
Dow Jones Index for Leptogenesis

inSPIRE: Citations of Fukugita & Yanagida, PLB 174 (1986) 45
or “Leptogenesis” in title

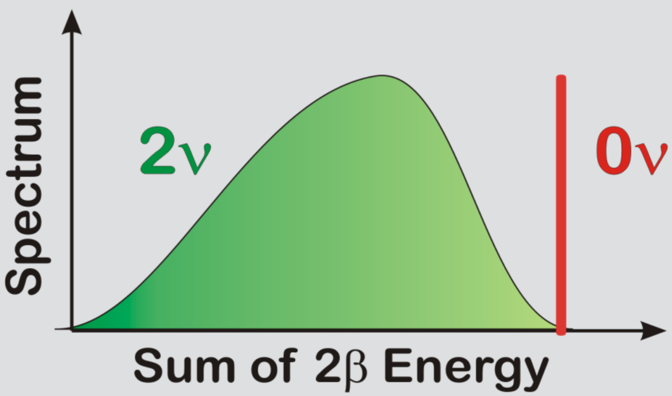


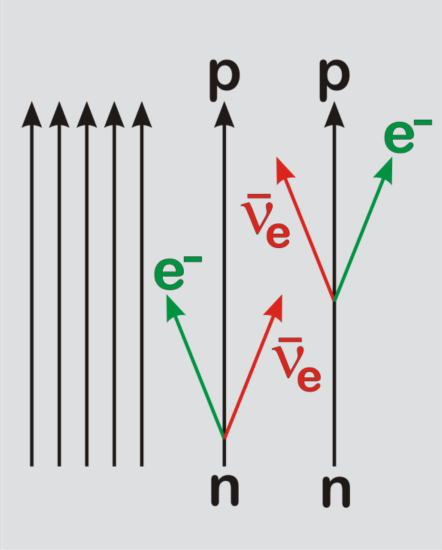
Neutrinoless ββ Decay

Some nuclei decay only by the ββ mode, e.g. Ge-76

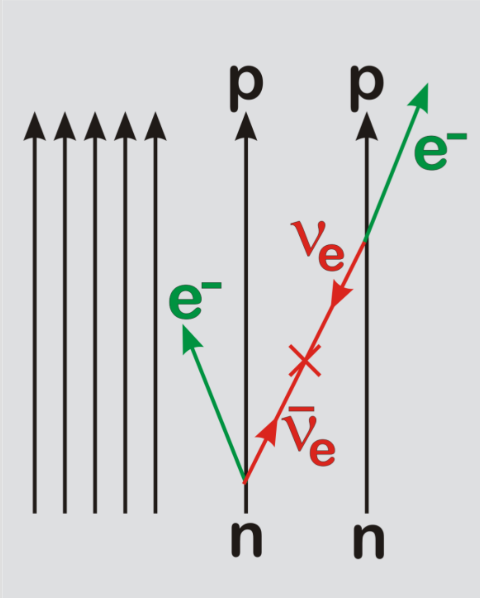


Half life $\sim 10^{21}$ yr





Standard 2ν mode



0ν mode, enabled by Majorana mass

Measured quantity

$$|m_{ee}| = \left| \sum_{i=1}^{N} \lambda_i |U_{ei}|^2 m_i \right|$$

Best limit from ^{76}Ge

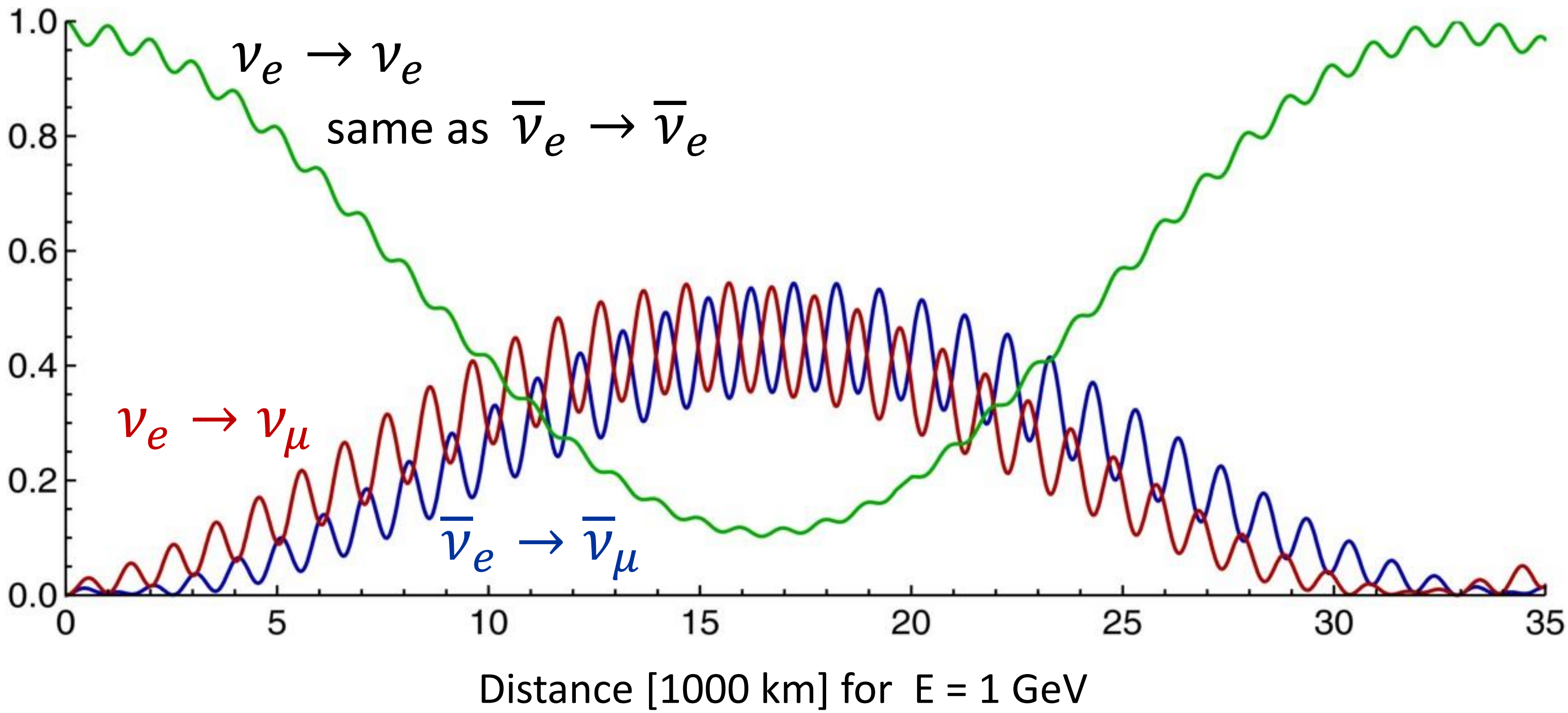
$$|m_{ee}| < 0.35 \text{ eV}$$

Antineutrino Oscillations Different from Neutrinos?

$$\nu_e = c_{12}c_{13}\,\nu_1 + s_{12}c_{13}\,\nu_2 + s_{13}e^{-i\delta}\,\nu_3$$

$$\overline{\nu}_e = c_{12}c_{13}\,\overline{\nu}_1 + s_{12}c_{13}\,\overline{\nu}_2 + s_{13}e^{+i\delta}\,\overline{\nu}_3$$

Dirac phase causes different 3-flavor oscillations for neutrinos and antineutrinos



Leptogenesis Summary

- See-saw model for small Majorana masses provides a generic way for BAU generation
- Observing lepton-number violation (neutrinoless double beta decay) and leptonic CP violation (LBL oscillation) would provide strong support (not proof) for this scenario