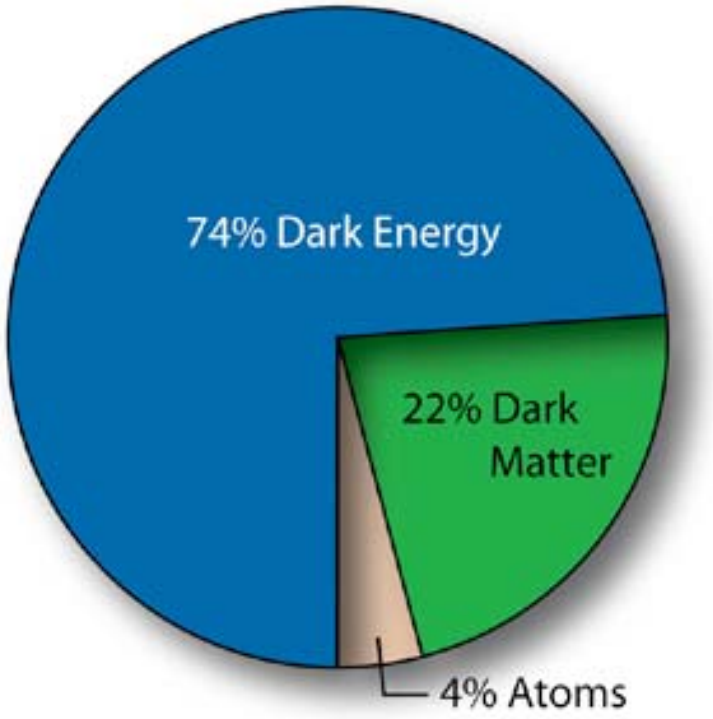
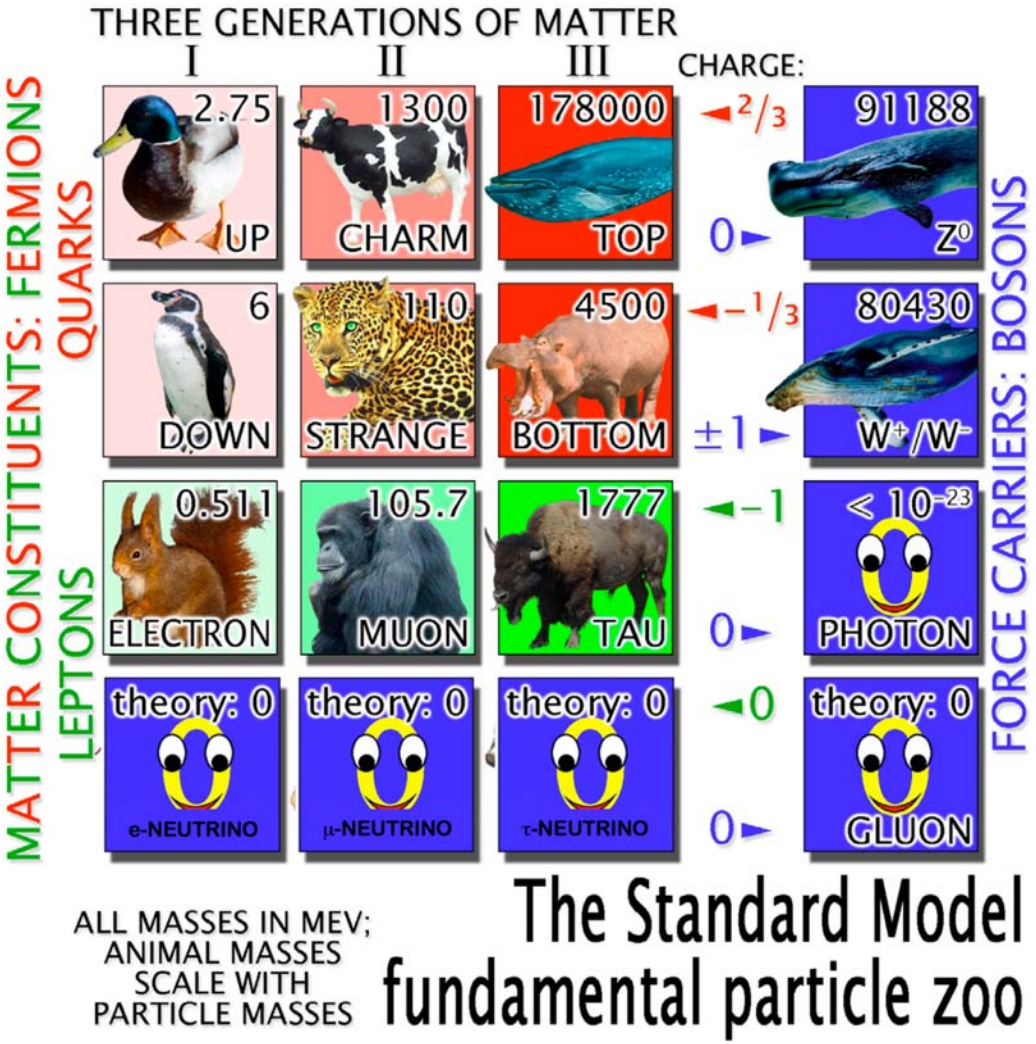
Dark Matter-Candidate Sterile Neutrinos



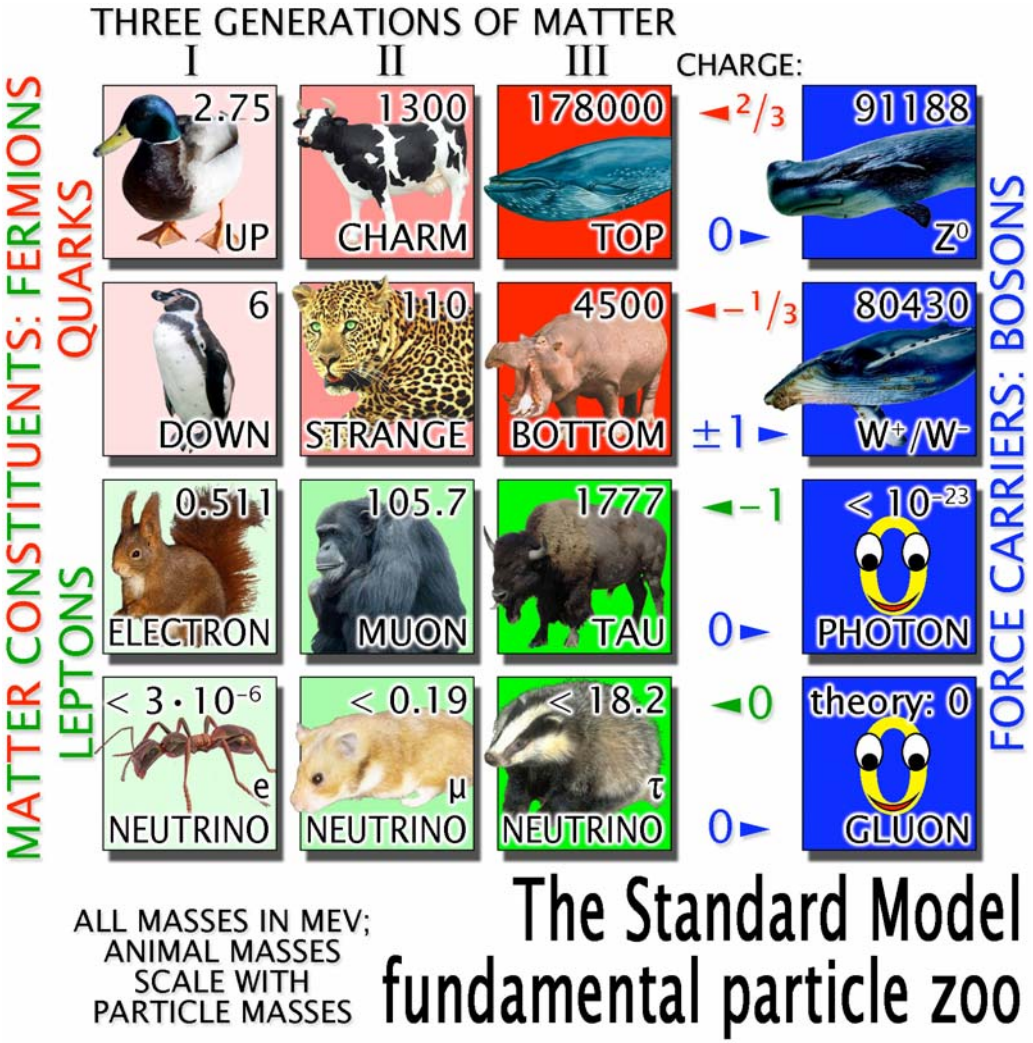
Chad Kishimoto

University of California, San Diego

UDiG; October 17, 2008

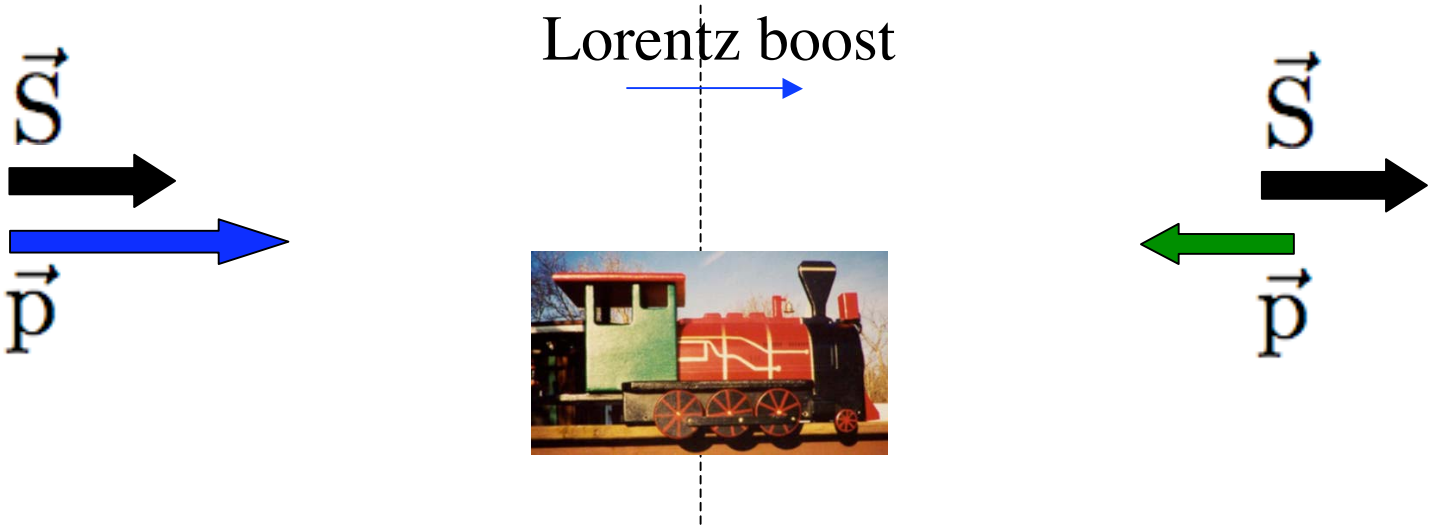


- Massless neutrinos
- Left-handed neutrinos
- Right-handed anti-neutrinos

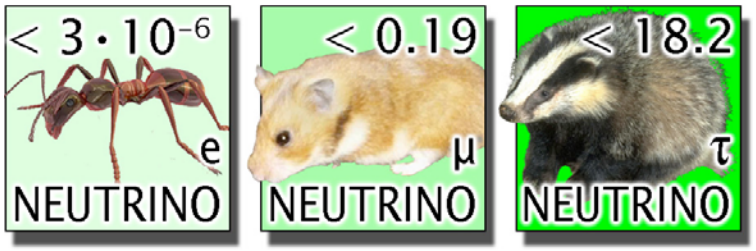


- ~~Massless neutrinos~~
- Left-handed neutrinos
- Right-handed anti-neutrinos

Helicity is not relativistically invariant (for massive particles)



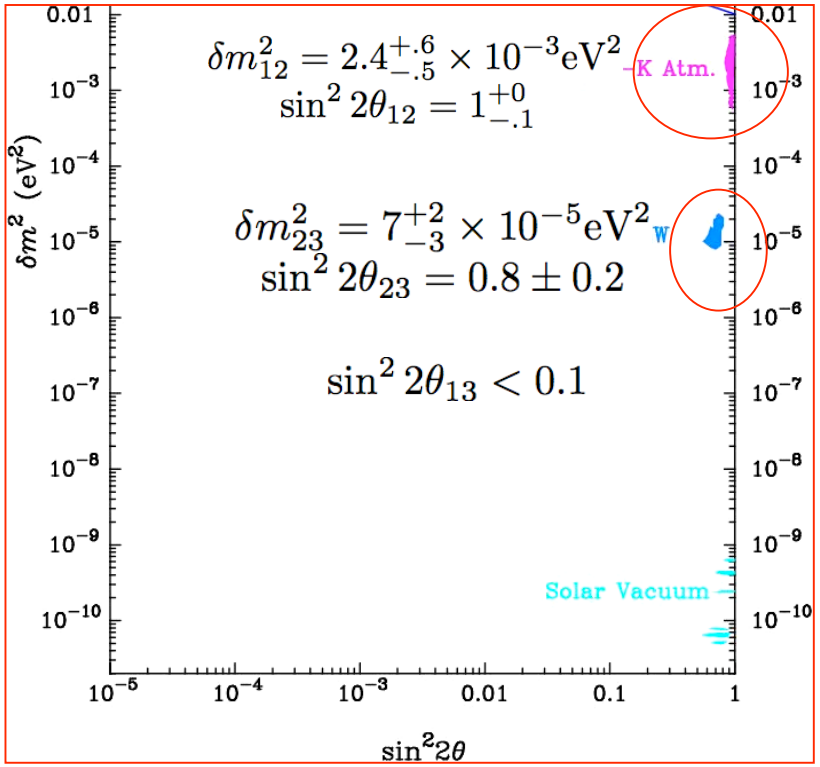
Left-handed neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ and Right-handed antineutrinos $(\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau)$ do not solve the Dirac equation.



Mass Eigenstates
Solutions to the Dirac equation

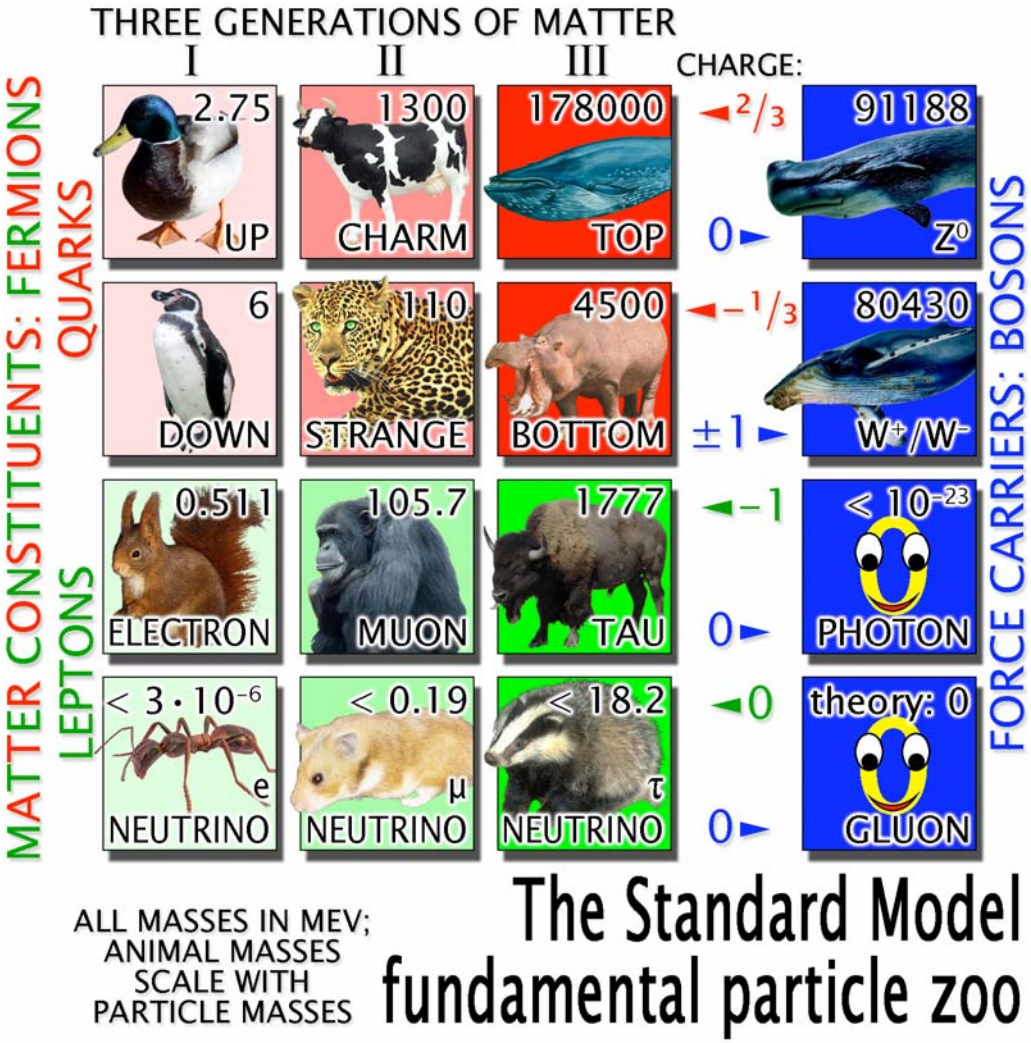
$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} \\ U^\dagger \\ \\ \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

Active Neutrinos
Weak Interaction Eigenstates

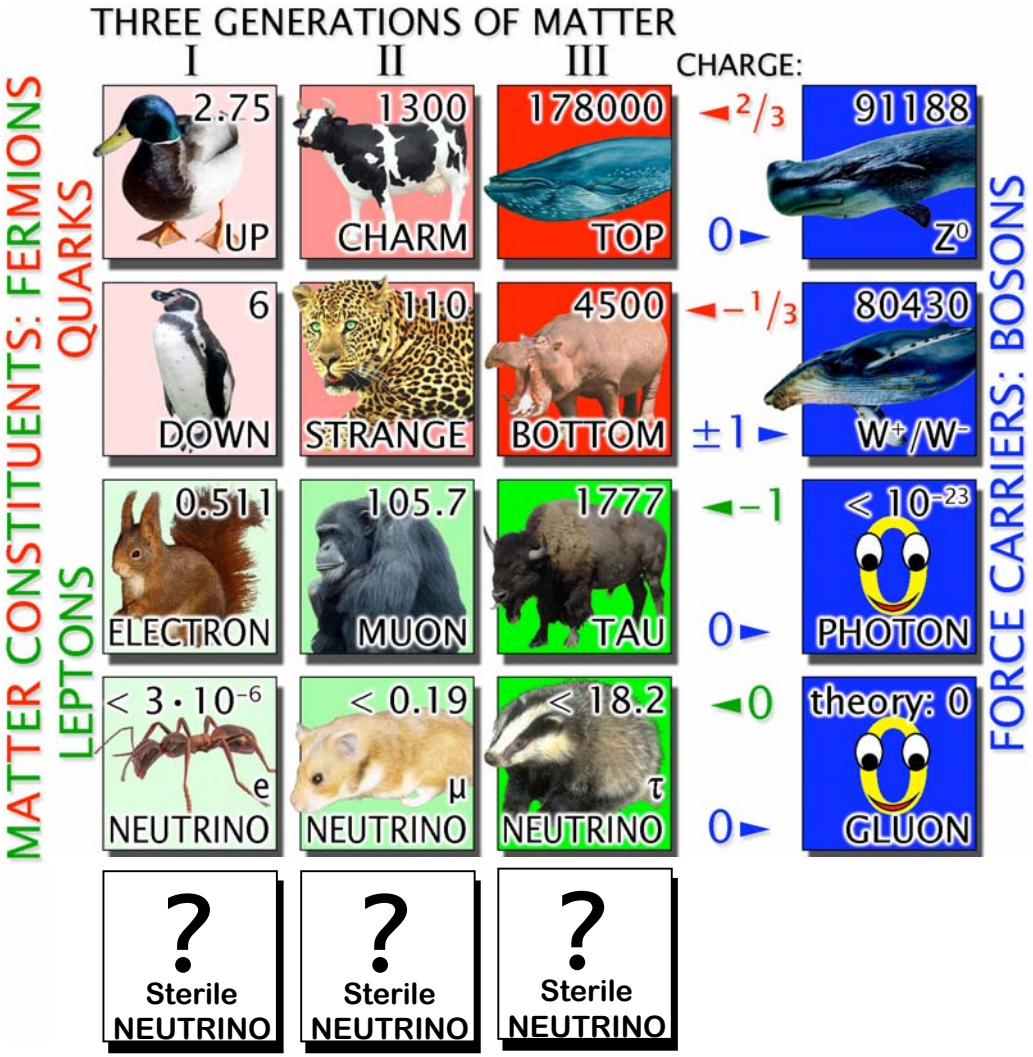


Maki-Nakagawa-Sakata matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



- ~~Massless neutrinos~~
- Left-handed neutrinos
- Right-handed anti-neutrinos



- Right-handed neutrinos
- Left-handed anti-neutrinos
- No weak, strong, or electromagnetic interactions

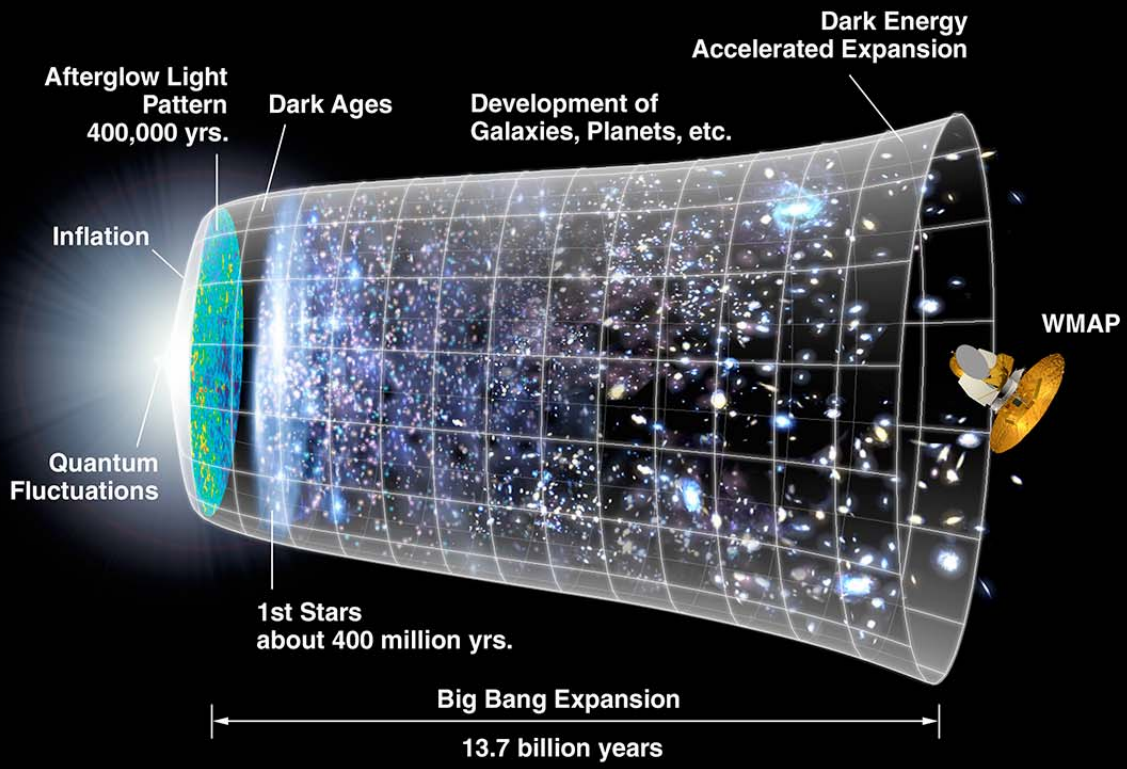
Sterile Neutrinos

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_s\rangle \\ |\nu'_s\rangle \\ |\nu''_s\rangle \end{pmatrix} = \begin{pmatrix} & & \\ & U^\dagger & \\ & & \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \\ |\nu_5\rangle \\ |\nu_6\rangle \end{pmatrix}$$

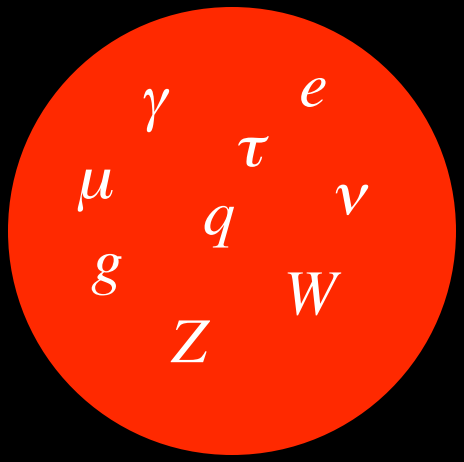
Because of oscillations with active states, “sterile” neutrinos aren’t actually sterile.

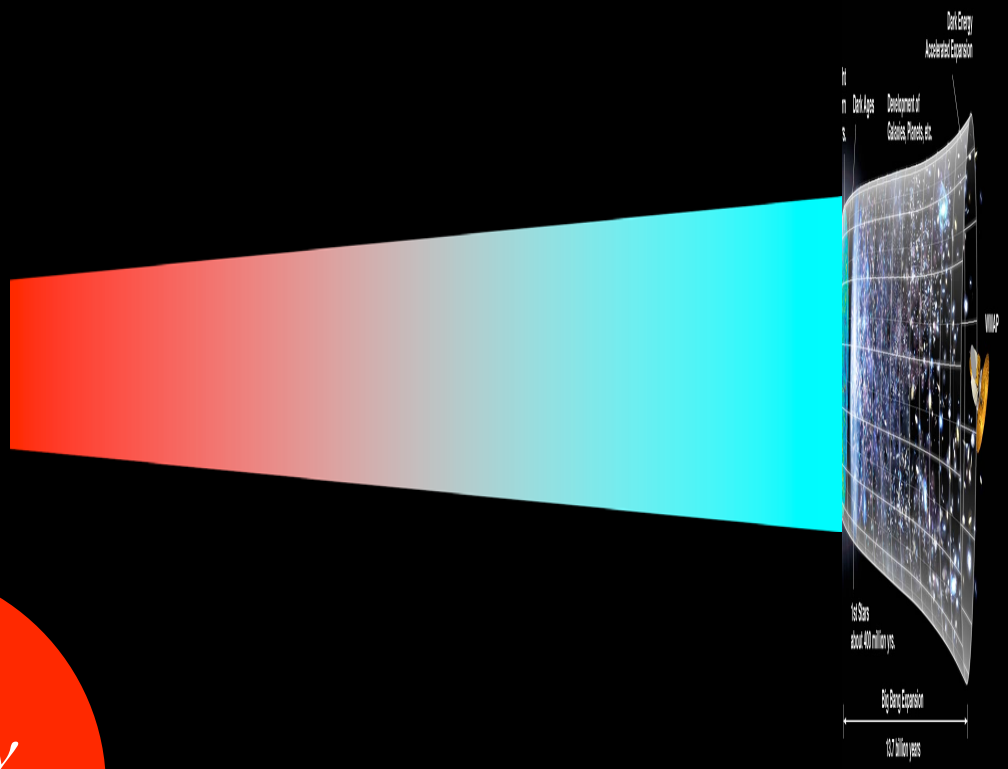
Weak interaction strength $\sim G_F^2$

Sterile neutrino interaction strength $\sim G_F^2 \sin^2 2\theta$



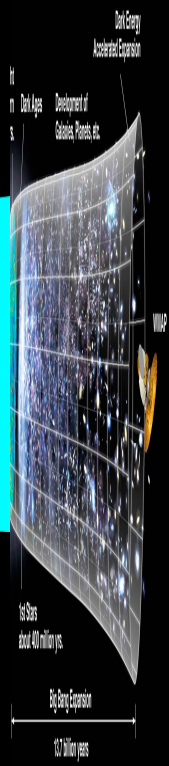
NASA/WMAP Science Team

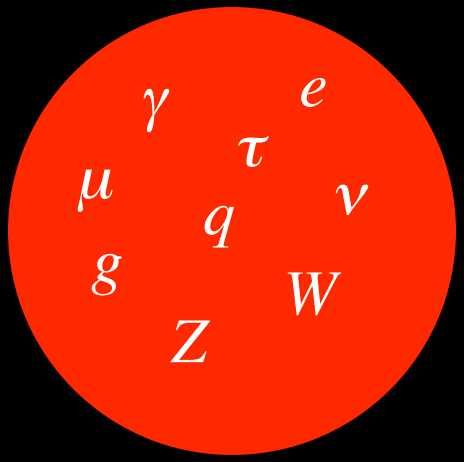

γ
e
τ
μ
ν
q
g
W
Z


Dark Energy
Accelerated Expansion
Dark Ages
Development of
Galaxies, Planets, etc.
WMAP
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 Billion years

Electroweak transition

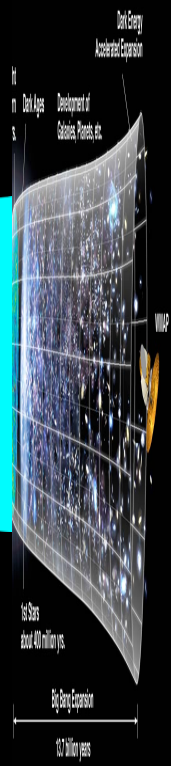
100 GeV

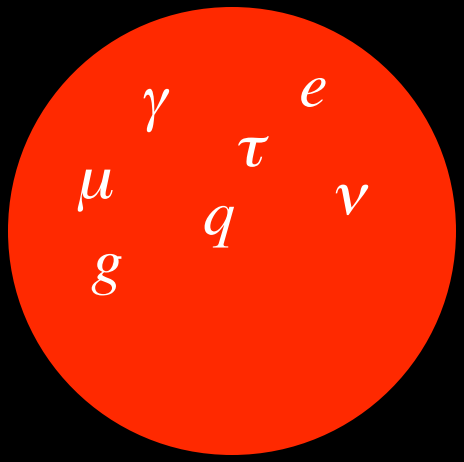




Electroweak transition

170 MeV





QCD transition

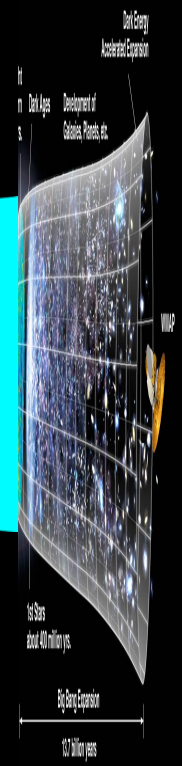
n

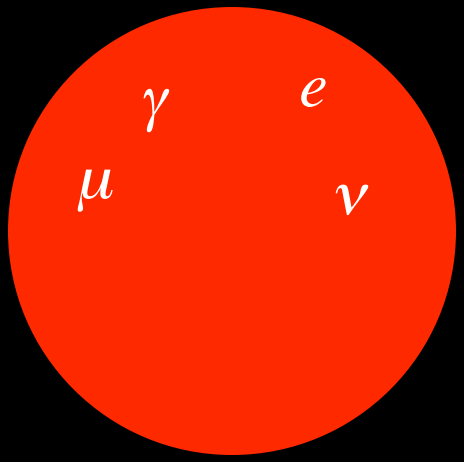
p

neutrinos decouple

Electroweak transition

3 MeV



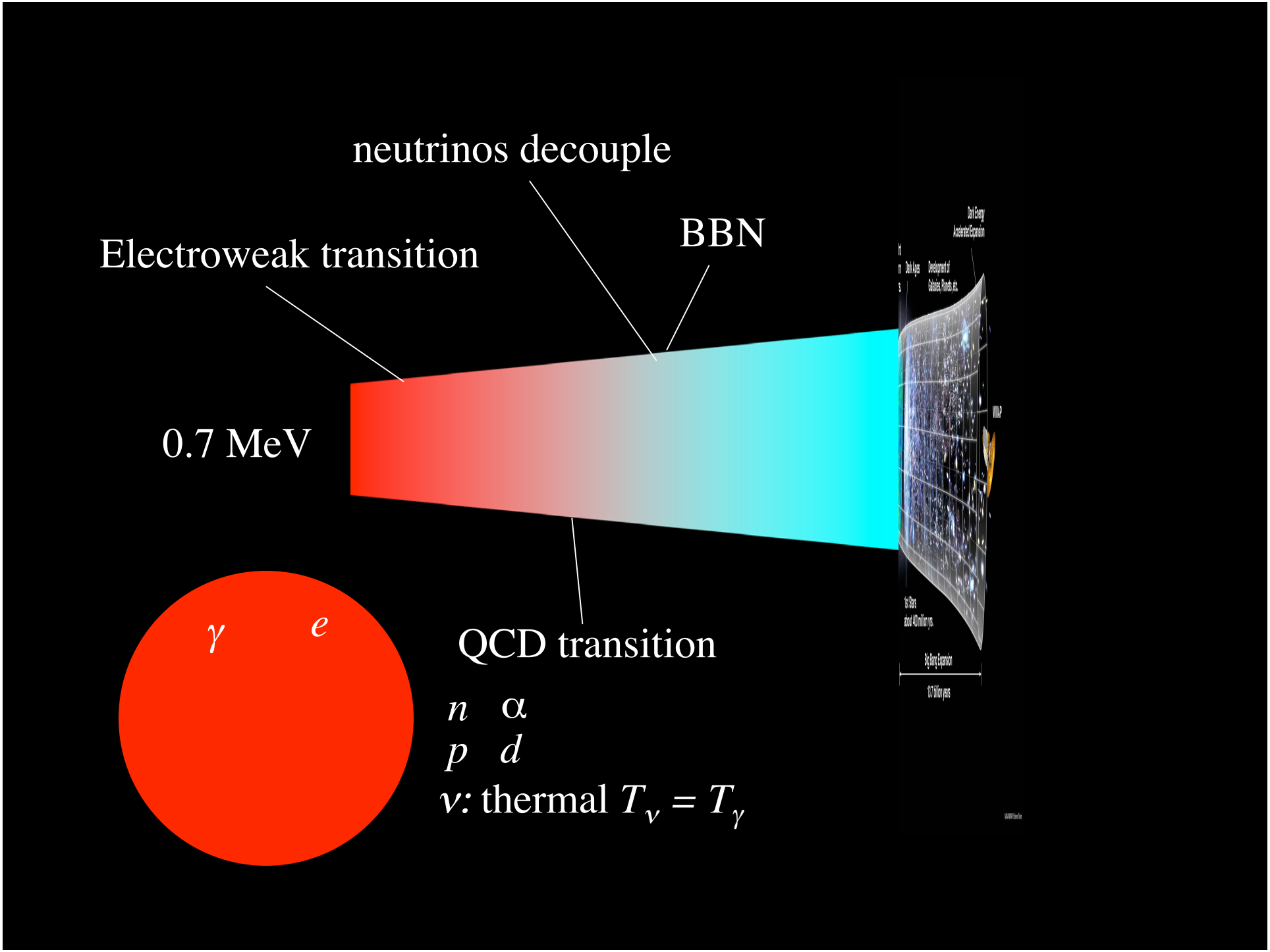


QCD transition

n

p

ν: thermal $T_\nu = T_\gamma$

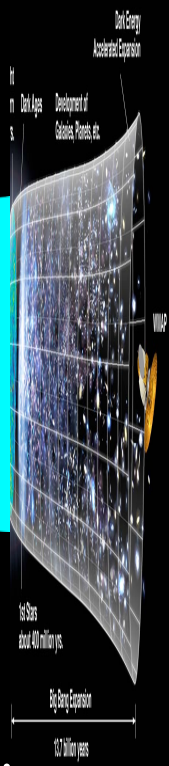

neutrinos decouple
BBN
Electroweak transition
0.7 MeV
QCD transition
γ e
n α
p d
ν: thermal $T_\nu = T_\gamma$

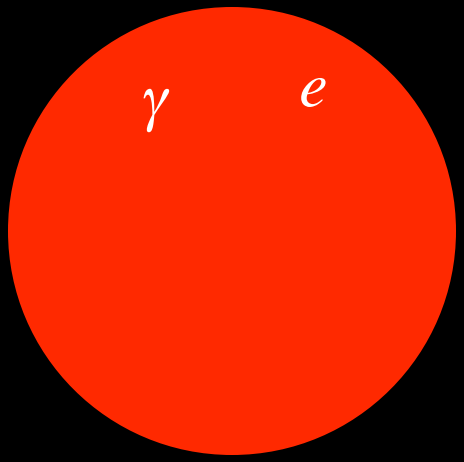
neutrinos decouple

Electroweak transition

BBN

500 keV





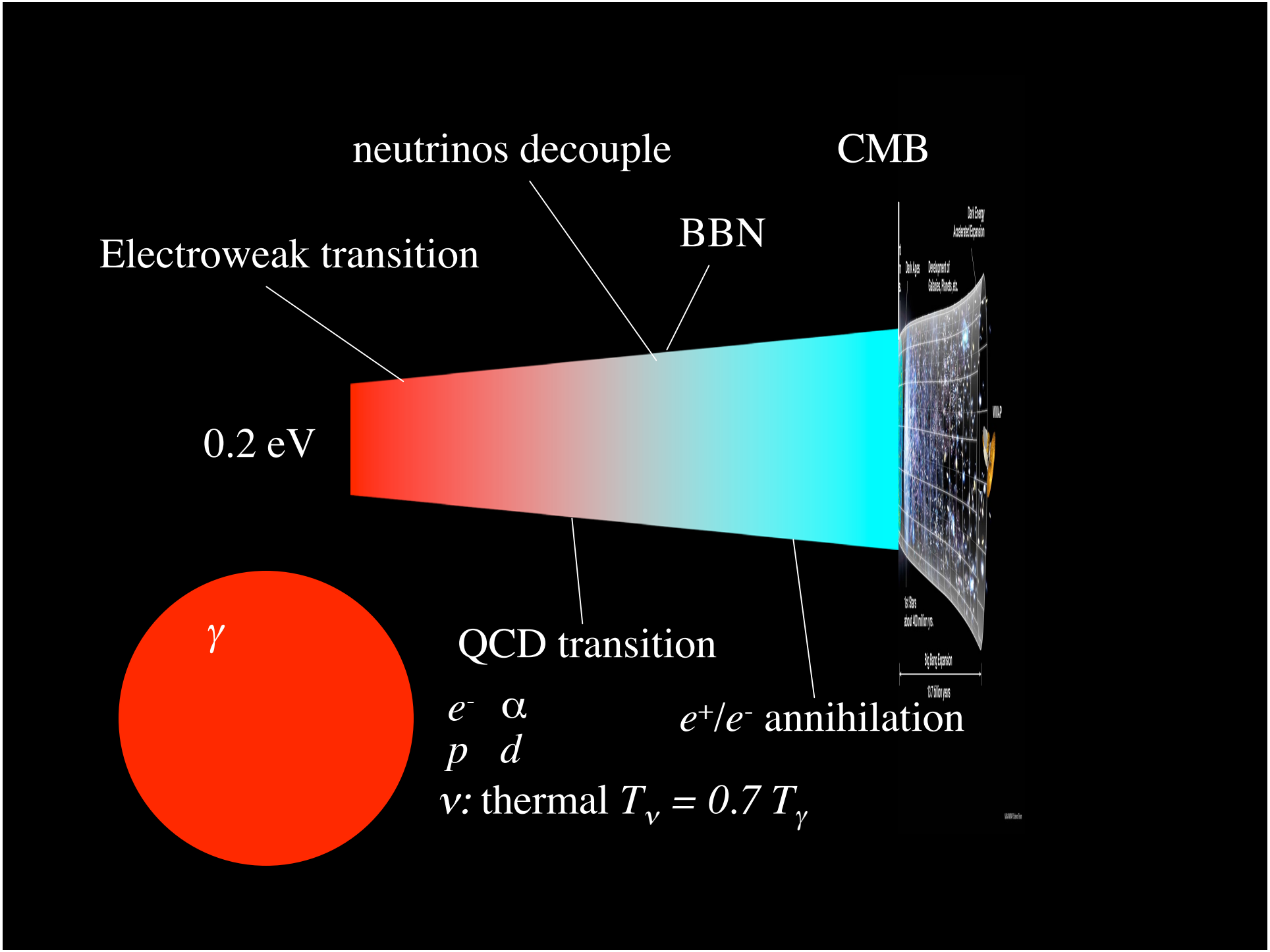
QCD transition

e^- α

p d

e^+/e^- annihilation

ν: thermal $T_\nu = 0.7\ T_\gamma$


neutrinos decouple
CMB
BBN
Electroweak transition
0.2 eV
γ
QCD transition
e- α
p d
e+/e- annihilation
ν: thermal T_ν = 0.7 T_γ

Sterile Neutrino Dark Matter

Sterile neutrino parameters:

m_s = 64 keV $\qquad\qquad$ $\sin^2 2\theta = 10^{-10}$

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_s\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

Initial lepton numbers:

$L_{e0} = L_{\mu 0} = L_{\tau 0} = 1.1 \times 10^{-3}$

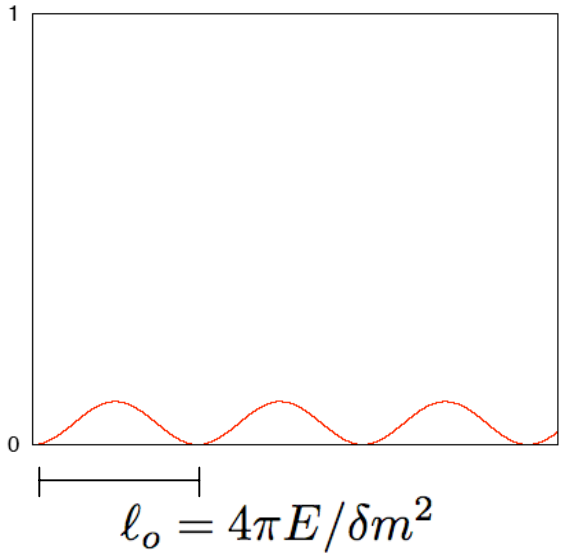
$$L_\alpha = \frac{n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{n_\gamma}$$

Neutrino Oscillations

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$
$$|\nu_s\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

$|\nu_1\rangle$ picks up $e^{-i\varepsilon_1 t}$; $|\nu_2\rangle$ picks up $e^{-i\varepsilon_2 t}$

$$\varepsilon_i = \sqrt{p^2 + m_i^2}$$



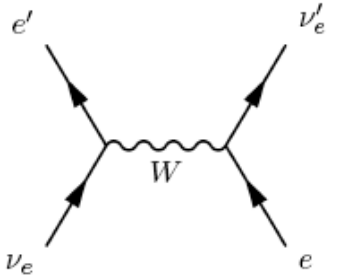
$\sin^2 2\theta$

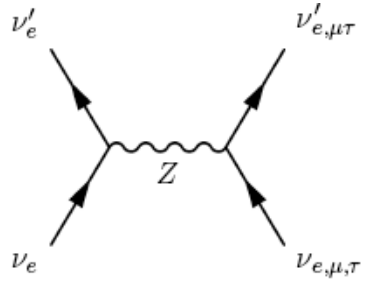
$$\mathcal{P}(\nu_e \to \nu_s) = \sin^2 2\theta \sin^2\left(\frac{\delta m^2}{4E}t\right)$$

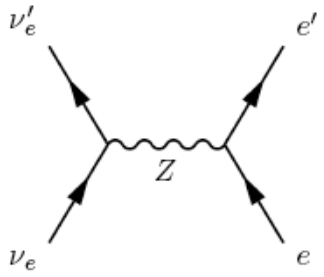
Matter-Enhanced Neutrino Oscillations

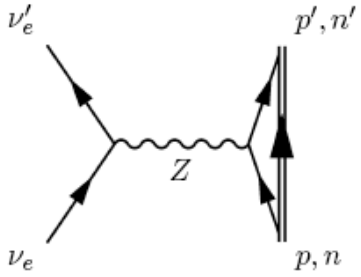
$$\mathcal{H}_e|\nu_e\rangle = V_e\,|\nu_e\rangle$$

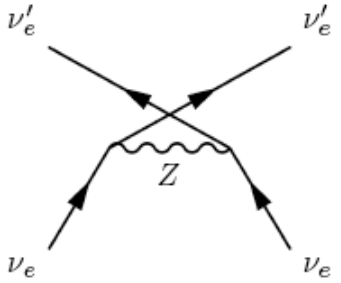
$$\mathcal{H}_e|\nu_s\rangle = 0$$





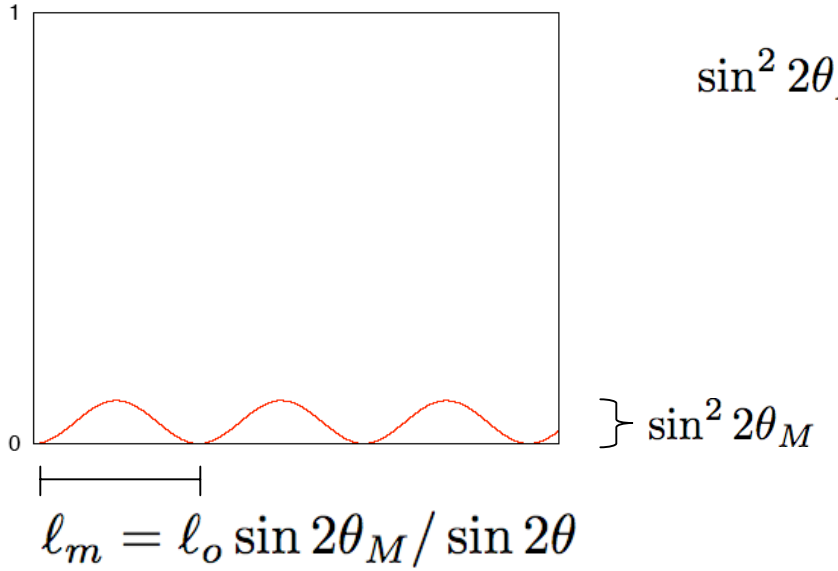






Matter-Enhanced Neutrino Oscillations

$$|\nu_e\rangle = \cos\theta_M\,|\nu_1'\rangle + \sin\theta_M\,|\nu_2'\rangle$$
$$|\nu_s\rangle = -\sin\theta_M\,|\nu_1'\rangle + \cos\theta_M\,|\nu_2'\rangle$$



$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - 2EV_e/\delta m^2)^2}$$

$$\mathcal{P} = \sin^2 2\theta_M \sin^2(2\pi t/\ell_m)$$

Decoherent Sterile Neutrino Production

Mean Free Path

$$\lambda_{\rm mfp} = \Gamma_e^{-1} \sim G_F^{-2} T^{-5}$$

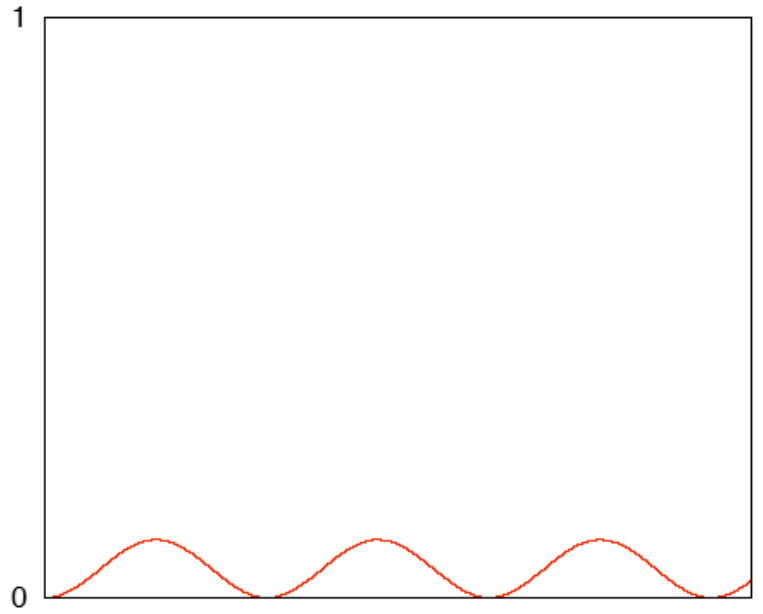
Horizon Size

$$d_{\rm H} \sim H^{-1} = \sqrt{\frac{45}{4\pi^2}} g^{-1/2} \frac{m_{\rm PL}}{T^2}$$

For $T \gtrsim 3\,\mathrm{MeV}$, the mean free path of neutrinos in the early universe is short compared to the size of the universe. As a result, scattering dominates the quantum dynamics of the neutrinos.

Decoherent Sterile Neutrino Production

$$\mathcal{P}(\nu_e \to \nu_s) = \sin^2 2\theta_M \sin^2(2\pi t/\ell_m)$$



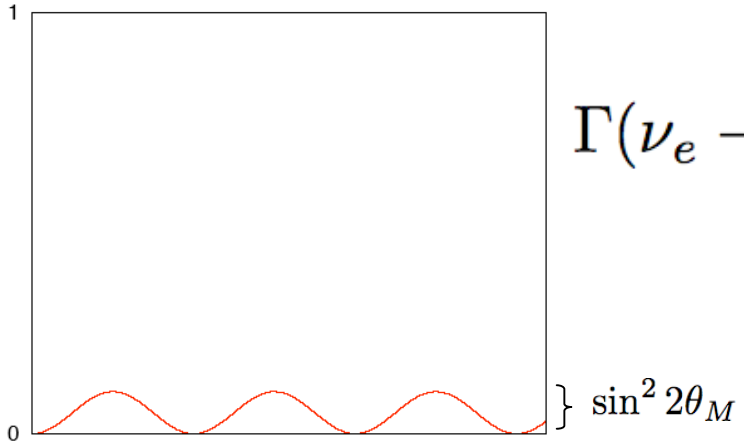
$$\Gamma(\nu_e \to \nu_s) = \frac{1}{2}\Gamma_e \sin^2 2\theta_M$$

Decoherent Sterile Neutrino Production

Quantum Zeno Effect

"a watched pot never boils"

$$\mathcal{P}(\nu_e \to \nu_s) = \sin^2 2\theta_M \sin^2(2\pi t/\ell_m)$$



$$\Gamma(\nu_e \to \nu_s) = \frac{1}{2}\Gamma_e \langle \sin^2 2\theta_M \rangle$$
$$= \frac{1}{4}\Gamma_e \sin^2 2\theta_M \frac{1}{1 + \Gamma_e^2 \ell_m^2}$$

$$\frac{D}{Dt} f_s(E,t) = \Gamma(\nu_e \to \nu_s)(f_e(E,t) - f_s(E,t))$$

Sterile Neutrino Dark Matter

$$\frac{D}{Dt} f_s(E,t) = \frac{1}{4}\Gamma_e \sin^2 2\theta_M \frac{1}{1+\Gamma_e^2 \ell_m^2}(f_e(E,t) - f_s(E,t))$$

Sterile neutrino parameters:

m_s = 64 keV $\qquad\qquad$ $\sin^2 2\theta = 10^{-10}$

Initial lepton numbers:

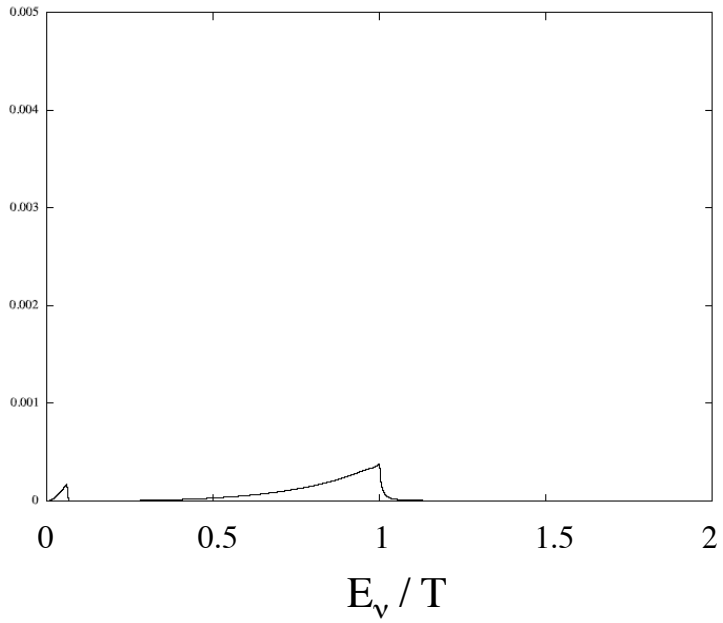
$L_{e0} = L_{\mu 0} = L_{\tau 0} = 1.1 \times 10^{-3}$

Sterile Neutrino Dark Matter

$$\frac{D}{Dt} f_s(E,t) = \frac{1}{4}\Gamma_e \sin^2 2\theta_M \frac{1}{1+\Gamma_e^2 \ell_m^2}(f_e(E,t) - f_s(E,t))$$

m_s = 64 keV, $\sin^2 2\theta = 10^{-10}$, $L_{e0} = 1.1 \times 10^{-3}$

T = 1200 MeV

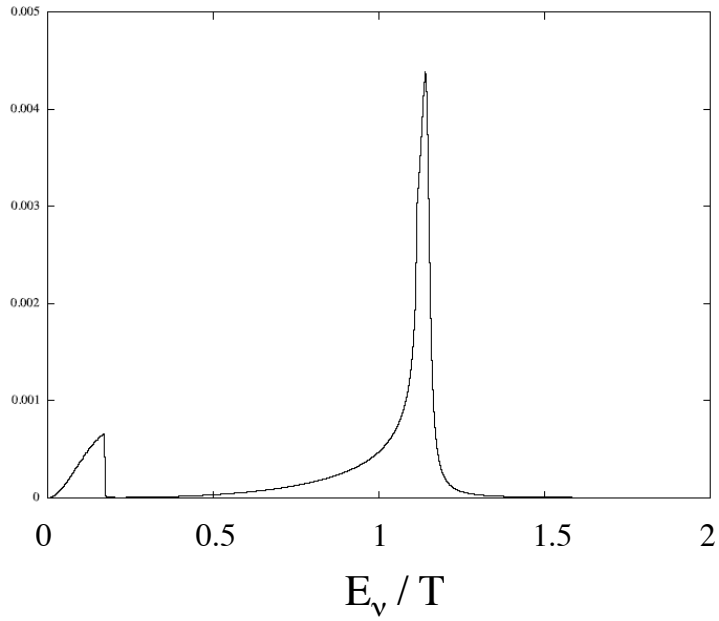


Sterile Neutrino Dark Matter

$$\frac{D}{Dt} f_s(E,t) = \frac{1}{4}\Gamma_e \sin^2 2\theta_M \frac{1}{1+\Gamma_e^2 \ell_m^2}(f_e(E,t) - f_s(E,t))$$

m_s = 64 keV, $\sin^2 2\theta = 10^{-10}$, $L_{e0} = 1.1 \times 10^{-3}$

T = 1000 MeV

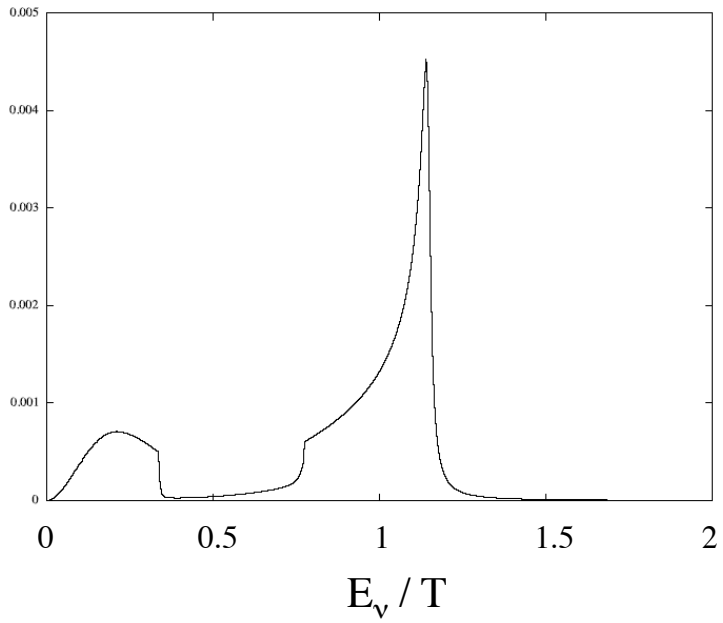


Sterile Neutrino Dark Matter

$$\frac{D}{Dt} f_s(E,t) = \frac{1}{4}\Gamma_e \sin^2 2\theta_M \frac{1}{1+\Gamma_e^2 \ell_m^2} (f_e(E,t) - f_s(E,t))$$

m_s = 64 keV, $\sin^2 2\theta = 10^{-10}$, $L_{e0} = 1.1 \times 10^{-3}$

T = 950 MeV

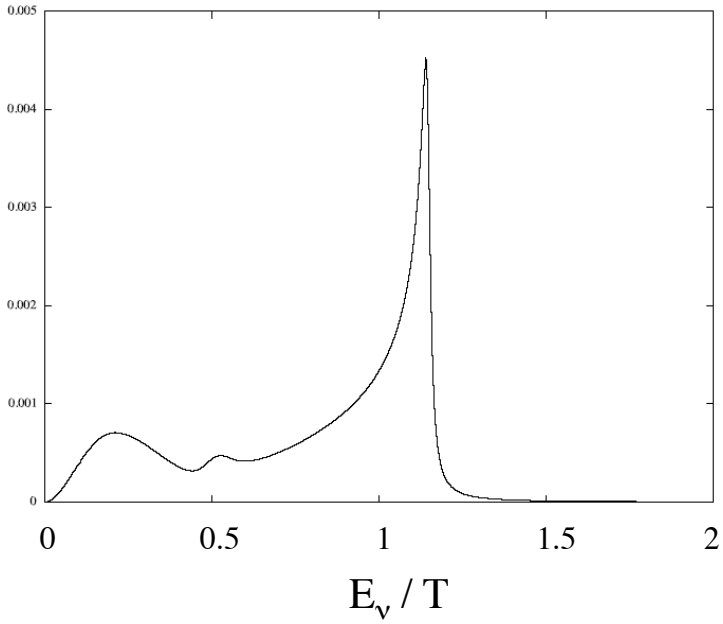


Sterile Neutrino Dark Matter

$$\frac{D}{Dt} f_s(E,t) = \frac{1}{4}\Gamma_e \sin^2 2\theta_M \frac{1}{1+\Gamma_e^2 \ell_m^2}(f_e(E,t) - f_s(E,t))$$

m_s = 64 keV, $\sin^2 2\theta = 10^{-10}$, $L_{e0} = 1.1 \times 10^{-3}$

T = 900 MeV

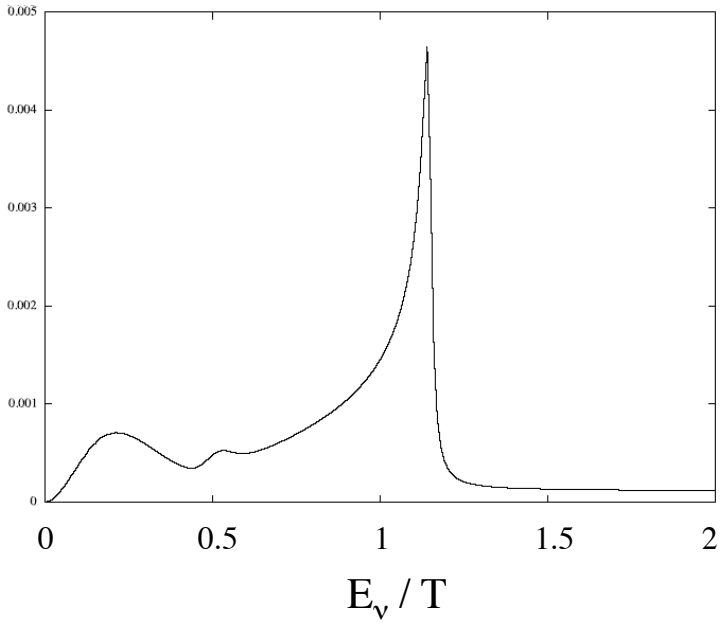


Sterile Neutrino Dark Matter

$$\frac{D}{Dt} f_s(E,t) = \frac{1}{4}\Gamma_e \sin^2 2\theta_M \frac{1}{1+\Gamma_e^2 \ell_m^2}(f_e(E,t) - f_s(E,t))$$

m_s = 64 keV, $\sin^2 2\theta = 10^{-10}$, $L_{e0} = 1.1 \times 10^{-3}$

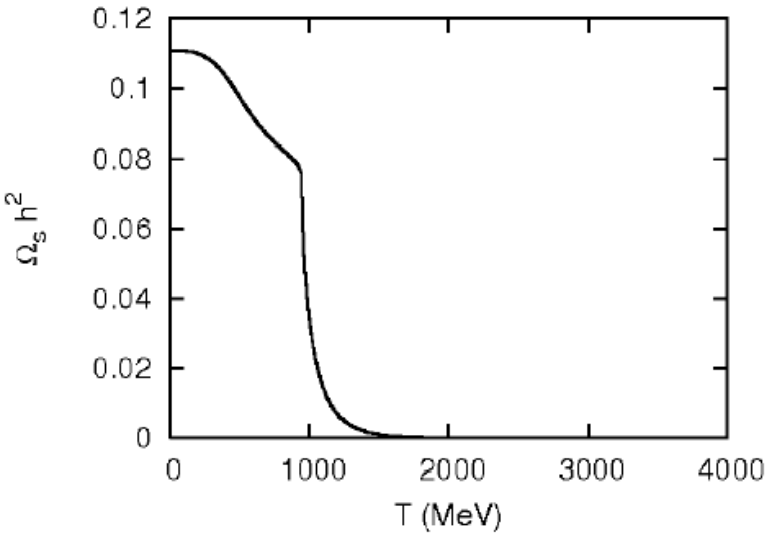
T = 20 MeV

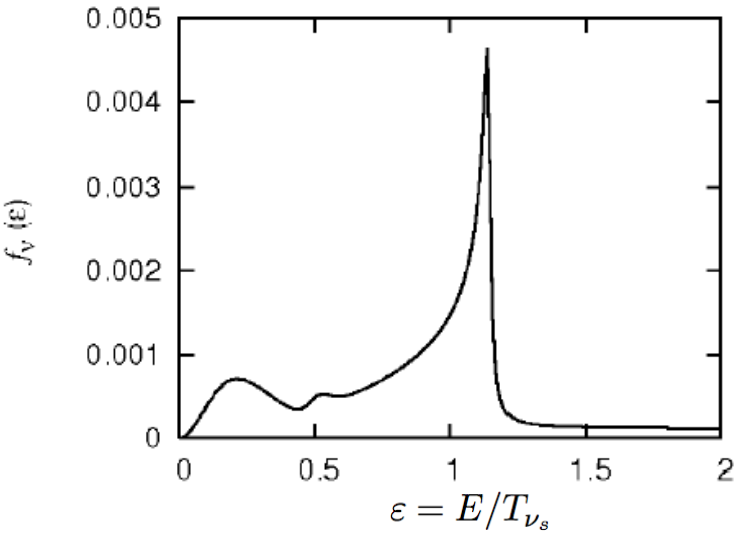


Sterile Neutrino Dark Matter

$$\frac{D}{Dt} f_s(E,t) = \frac{1}{4}\Gamma_e \sin^2 2\theta_M \frac{1}{1+\Gamma_e^2 \ell_m^2}(f_e(E,t) - f_s(E,t))$$

m_s = 64 keV, $\sin^2 2\theta = 10^{-10}$, $L_{e0} = 1.1 \times 10^{-3}$

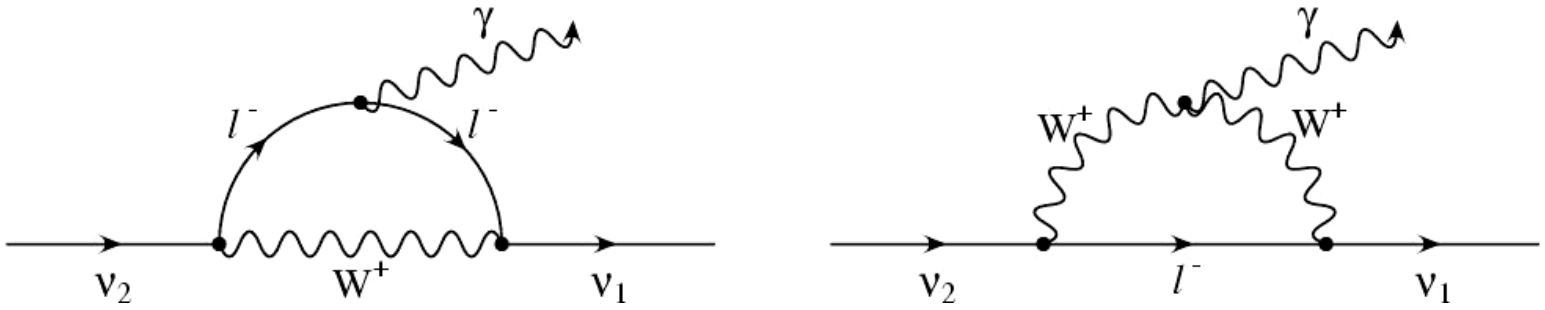




$$T_{\nu_s} \approx T_\gamma / 3$$

Sterile Neutrino Dark Matter

As a dark matter candidate, sterile neutrinos aren't as dark as they ought to be.



$$\Gamma_\gamma \approx 6.8 \times 10^{-33}\ \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_s}{\mathrm{keV}}\right)^5$$

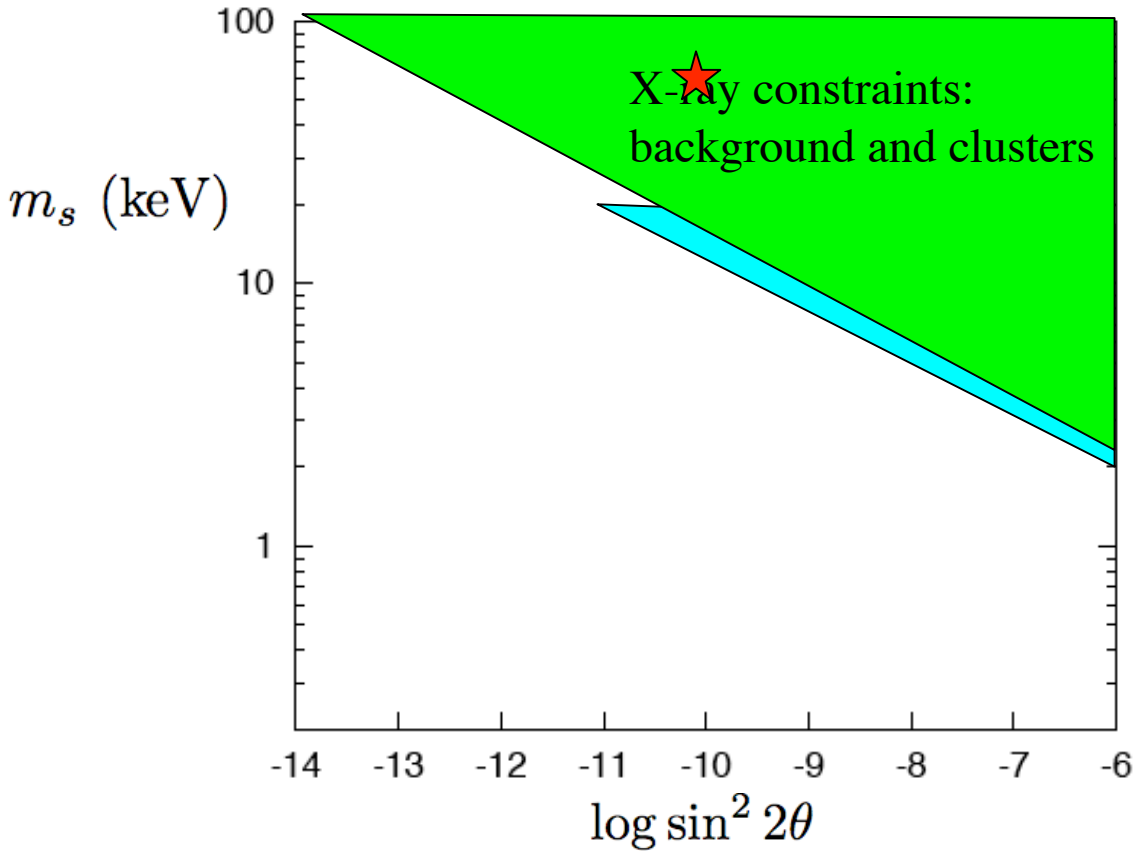
$$H_0^{-1} \approx 4 \times 10^{17}\,\mathrm{s}$$

$$\frac{M_{\mathrm{DM}}}{m_s} \approx 10^{78} \frac{M_{\mathrm{DM}}}{10^{15} M_\odot} \frac{\mathrm{keV}}{m_s}$$


Chandra X-Ray Observatory

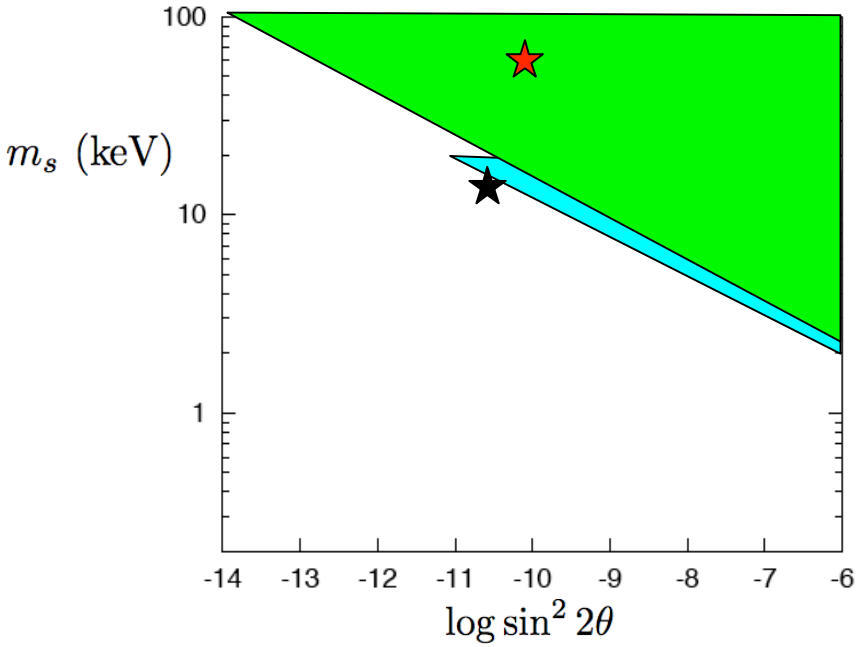
Sterile Neutrino Dark Matter: Astrophysical Constraints

Constraints on sterile neutrino mass and mixing angle with active neutrinos.



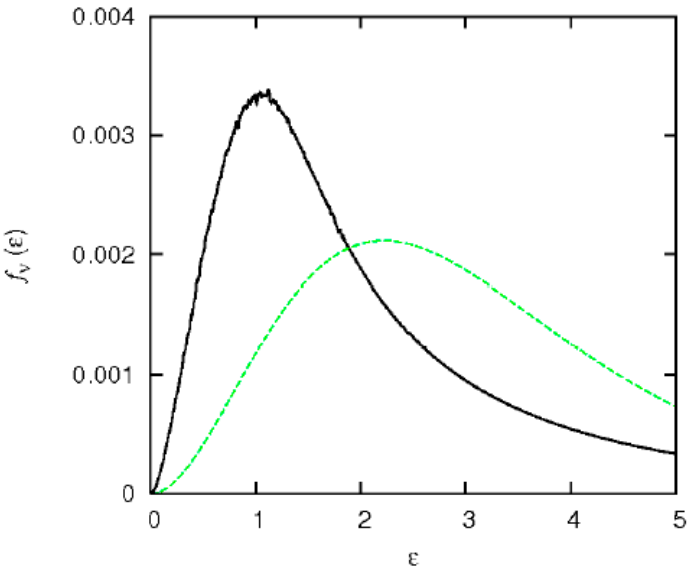
Sterile Neutrino Dark Matter: Astrophysical Constraints

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m_s = 12 kev, sin^2 2θ = $10^{-10.5}$

L_{e0} = 4.8 x 10^{-3}



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Lepton-number-driven sterile neutrino production in the early universe

Chad T. Kishimoto and George M. Fuller

Department of Physics, University of California, San Diego, La Jolla, California 92093-0319, USA

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We examine medium-enhanced, neutrino scattering-induced decoherent production of dark matter candidate sterile neutrinos in the early universe. In cases with a significant net lepton number we find two resonances, where the effective in-medium mixing angles are large. We calculate the lepton number depletion-driven evolution of these resonances. We describe the dependence of this evolution on lepton numbers, sterile neutrino rest mass, and the active-sterile vacuum mixing angle. We find that this resonance evolution can result in relic sterile neutrino energy spectra with a generic form which is sharply peaked in energy. We compare our complete quantum kinetic equation treatment with the widely-used quantum Zeno ansatz.

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