Secret neutrino interactions with ultralight dark matter

Jim Cline, McGill University

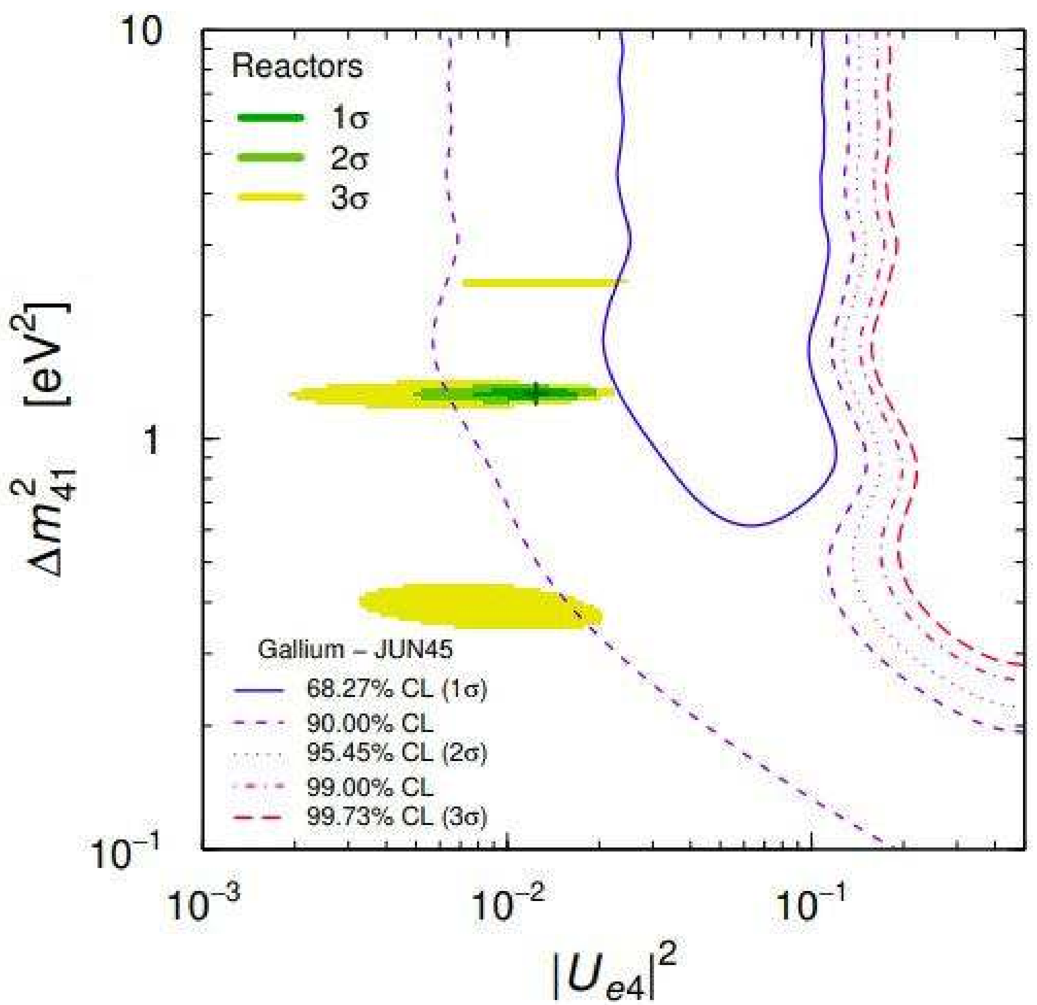
CERN Neutrino Platform Week 2019: Hot Topics in Neutrino Physics,

10 Oct., 2019

Short baseline anomalies suggest ν_s

Missing ν_e from reactors and low-energy solar flux (Gallium anomaly) suggests mixing with sterile ν_s

Giunti *et al.*, 1210.5715, 1212.3805; Kopp *et al.*, 1303.3011; Dentler *et al.*, 1803.10661; Diaz *et al.*, 1906.00045

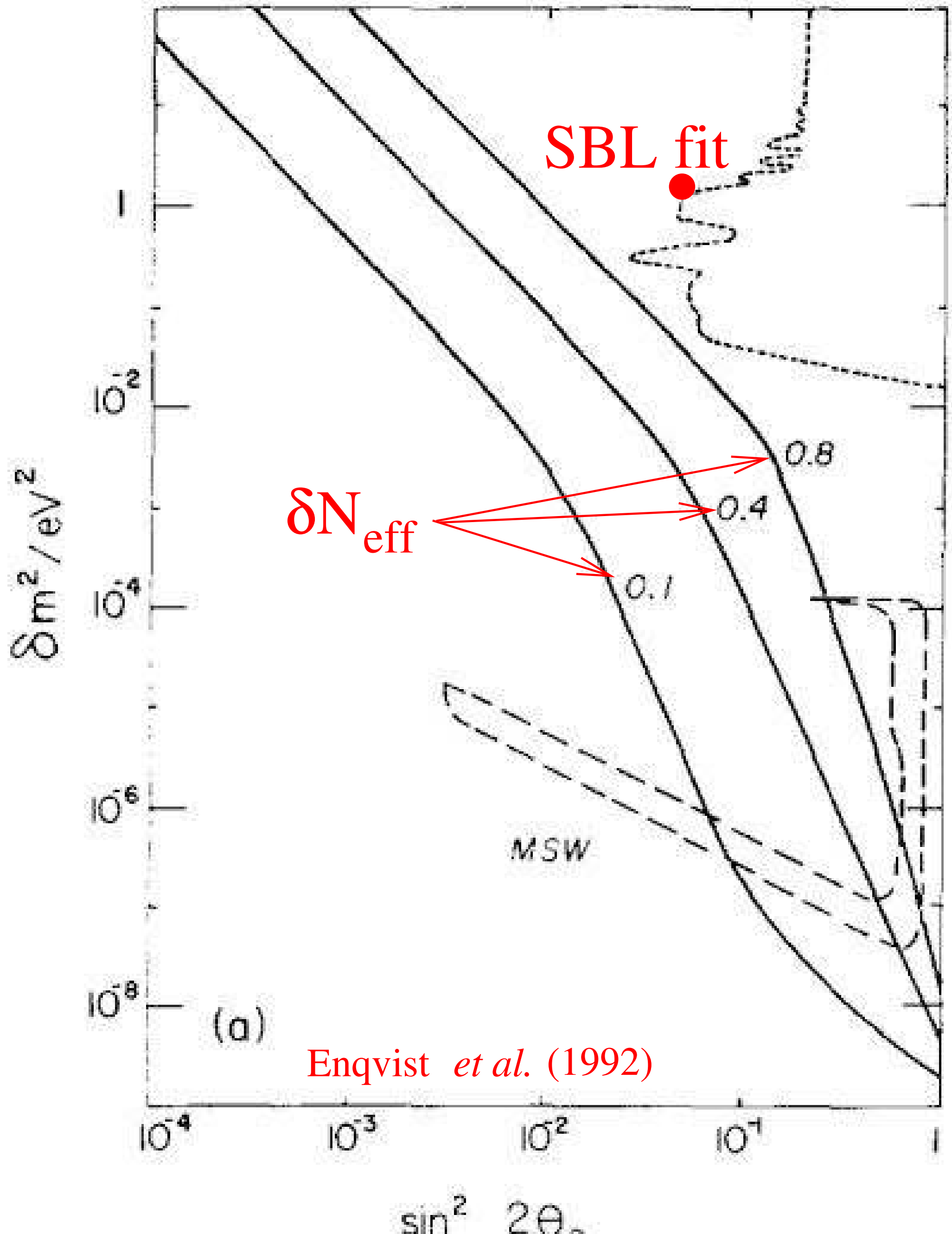


Kostensalo *et al.*, 1906.10980 fit to reactor data (NEOS, DANSS, PROSPECT) and find preferred regions from Gallium data, in $1+1$ mixing scenario.

Best fit by

$$m_4 = 1.1\,\mathrm{eV}, \quad U_{e4} = 0.11$$

Cosmological production of ν_s



But such oscillation parameters are strongly excluded by BBN and CMB constraints on extra neutrinos ($N_{\rm eff}$)

Enqvist, Kainulainen, Thomson (1992); Dolgov, Villante hep-ph/0308083; Gariazzo, de Salas, Pastor, 1905.11290

$\Longleftarrow$ Enqvist *et al.*, contours of $\delta N_{\rm eff}$ from ν_e-ν_s oscillations in early universe

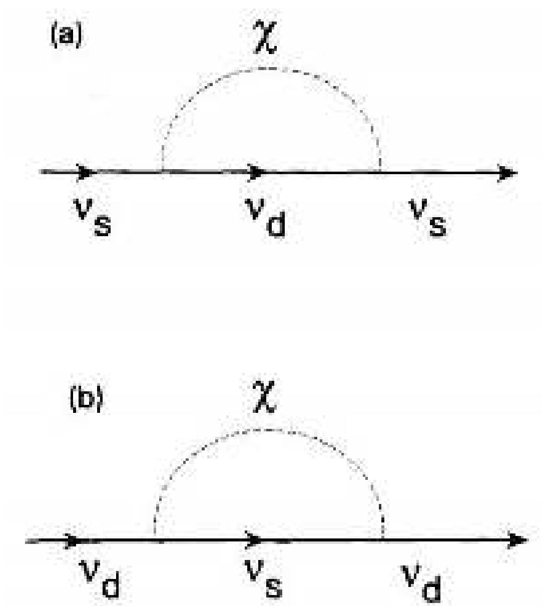
Secret ν_s interactions

Suppressing ν_s oscillations by new interactions is an old idea, in the context of Simpson's 17 keV neutrino

Babu, Rothstein (1992)

Enqvist, Kainulainen, Thomson (1992)

JC (1992)



Coupling to Majoron induces thermal self-energies $V_{d,s}$ whose difference $V_d - V_s$ can suppress oscillations in early universe

$$
\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_d\\ \nu_s\end{pmatrix} = \begin{bmatrix} \dfrac{c^2m_1^2+s^2m_2^2}{2E}+V_d & cs\Delta \\ cs\Delta & \dfrac{s^2m_1^2+c^2m_2^2}{2E}+V_s \end{bmatrix}\begin{pmatrix}\nu_d\\ \nu_s\end{pmatrix},
$$

Secret interactions revived

A similar idea was proposed for the SBL oscillations,

How secret interactions can reconcile sterile neutrinos with cosmology

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(Dated: October 23, 2013)

A ménage à trois of eV-scale sterile neutrinos, cosmology, and structure formation

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(Dated: December 11, 2013)

Though PRL did not like the original titles . . .

How Self-Interactions can Reconcile Sterile Neutrinos with Cosmology

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Cosmologically Safe eV-Scale Sterile Neutrinos and Improved Dark Matter Structure

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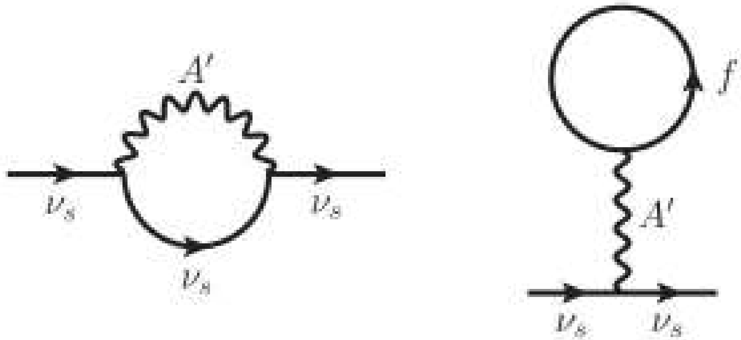
(Received 29 October 2013; published 22 January 2014)

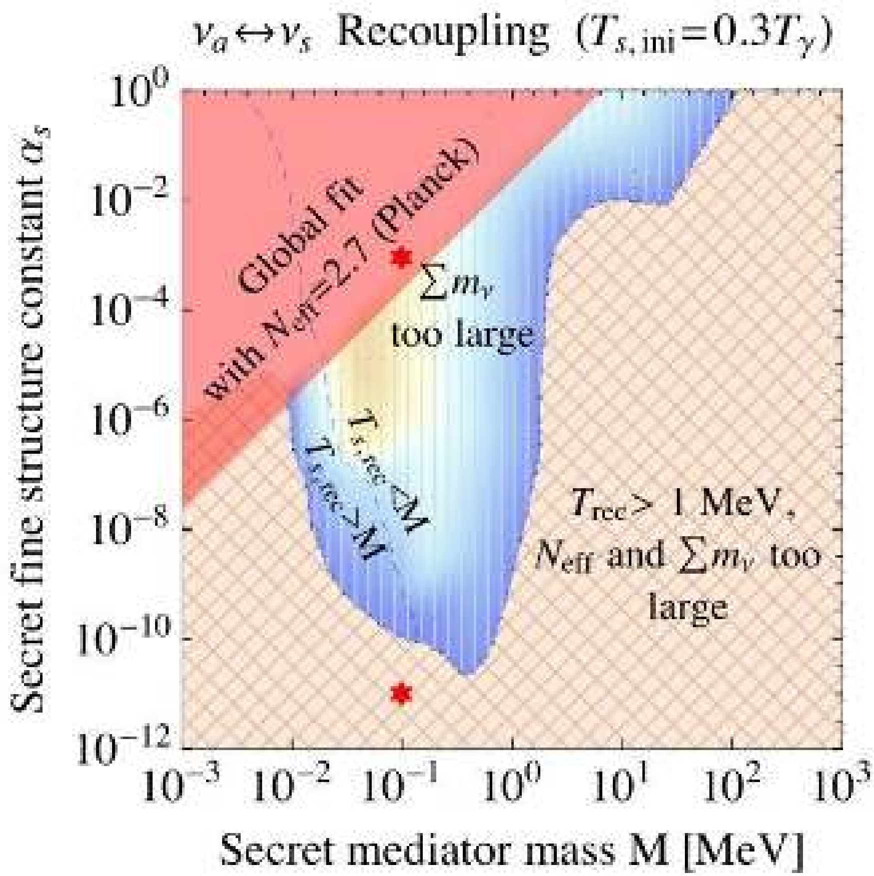
A'-mediated secret interactions

The new papers proposed an A' gauge boson interacting with ν_s



Thermal propagators used for A' (left) and fermion f (right).

These generate self-energy V_s for ν_s to suppress oscillations that disturb BBN.



Problem: the oscillations become unsuppressed at lower T, causing $\nu_e \to \nu_s$ in violation of CMB bounds on $\sum m_\nu$,

$$\sum m_\nu < 0.23\,\mathrm{eV}$$

Chu, Dasgupta, Dentler, Kopp, Saviano 1806.10629

Secret interactions with ultralight DM

Y. Farzan (1907.04271) proposed a robust mechanism: couple ν_s to ultralight scalar dark matter,

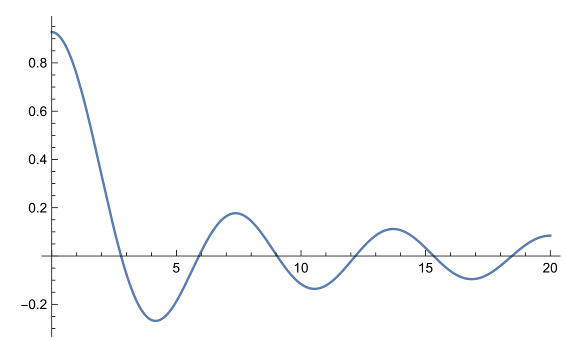
$$\mathcal{L}_{\rm int} = \tfrac{1}{2}\lambda\bar\nu_s\phi\nu_s$$

For $H > m_\phi$, the VEV of ϕ is frozen, and gives extra mass to ν_s,

$$m_{s,0} = \lambda\phi_0$$

that can suppress oscillations. Later ϕ starts to oscillate and redshift,

$$\phi(t) \cong 1.08\,\phi_0 \frac{J_{1/4}(m_\phi t)}{(m_\phi t)^{1/4}} \equiv \phi_0\,\hat\phi(t)$$



and eventually ν_s-ν_e oscillations become unsuppressed.

Why "robust"?

For $t \gg m_\phi^{-1}$ (during radiation domination),

$$\rho_\phi \cong 0.37\, \frac{m_\phi^2 \phi_0^2}{(m_\phi t)^{3/2}}$$

By matching to observed DM density, ultralight DM has large initial VEV,

$$\phi_0 = 1.0 \times 10^{15}\,\mathrm{GeV} \left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\right)^{1/4}$$

(*e.g.*, axion misalignment). It's easy to get large effective mass for ν_s until desired epoch. Needs only a small coupling

$$\lambda \gtrsim 10^{-22} \times \left(\frac{m_\phi}{10^{-15}\,\mathrm{eV}}\right)^{1/4}$$

to satisfy CMB bounds. "Secret interaction" name is very appropriate here!

Also quite economical

This model has only two important parameters,

$$m_\phi, \qquad m_{s,0} = \lambda\phi_0$$

What is the allowed parameter space?

Need to solve the oscillation problem for the Hamiltonian

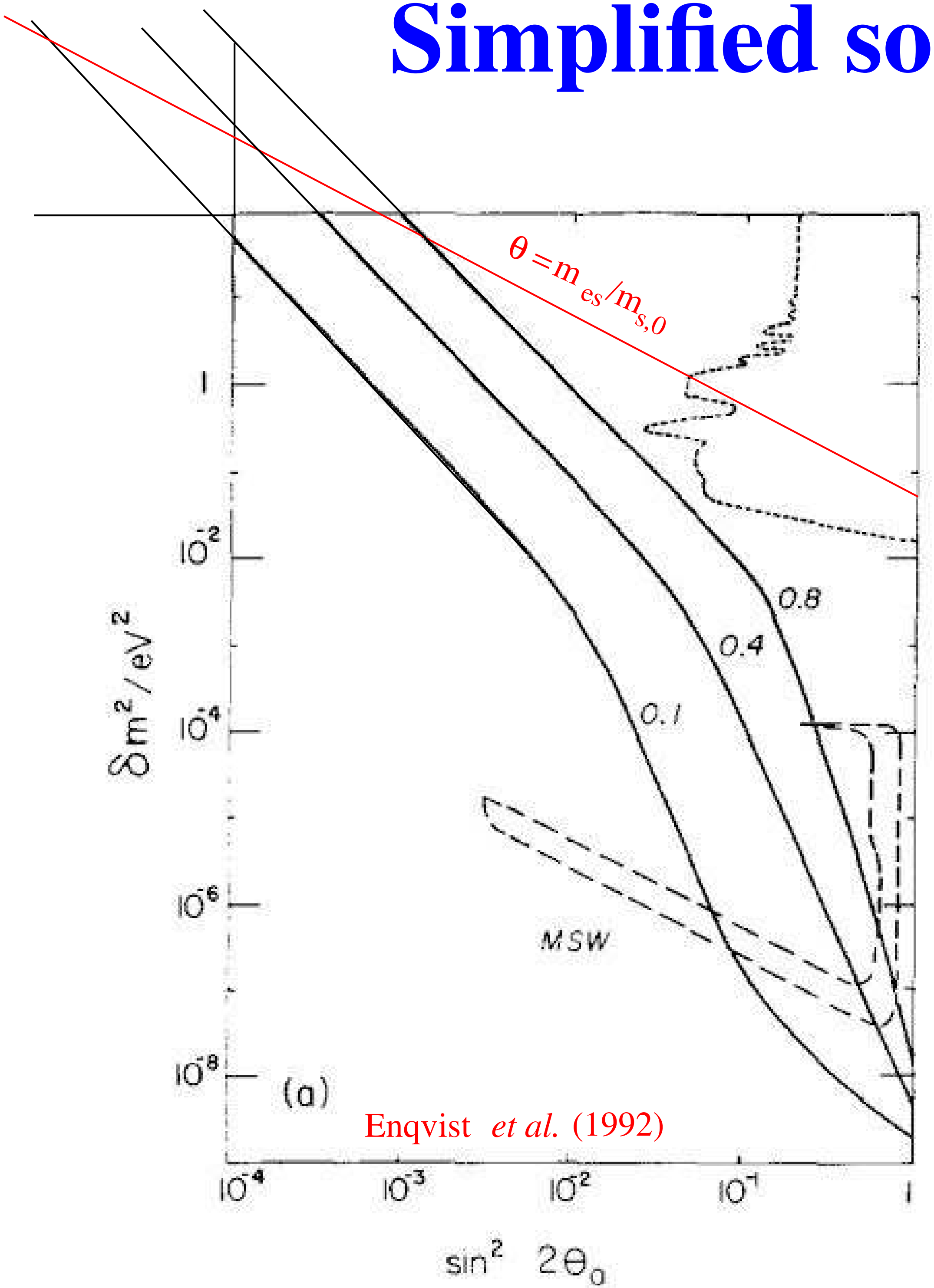
$$\mathcal{H} = \begin{pmatrix} m_{ee} & m_{es} \\ m_{es} & m_{ss}(t) \end{pmatrix}$$

with $m_{ss}(t) = m_{ss} + \lambda\phi(t)$.

Simplified version: treat $m_{ss}(t)$ as constant $m_{s,0}$ for $t < m_\phi^{-1}$ and solve vacuum mixing problem, with

$$\theta \cong \frac{m_{es}}{m_{s,0}}, \quad m_{es} \cong 0.12\,\mathrm{eV}, \quad \delta m^2 \cong m_{s,0}^2$$

Simplified solution



Putting $\theta = 2m_{es}/m_{s,0}$ on exclusion plot and extrapolating, we would get

$$m_{s,0} \gtrsim \mathrm{keV}$$

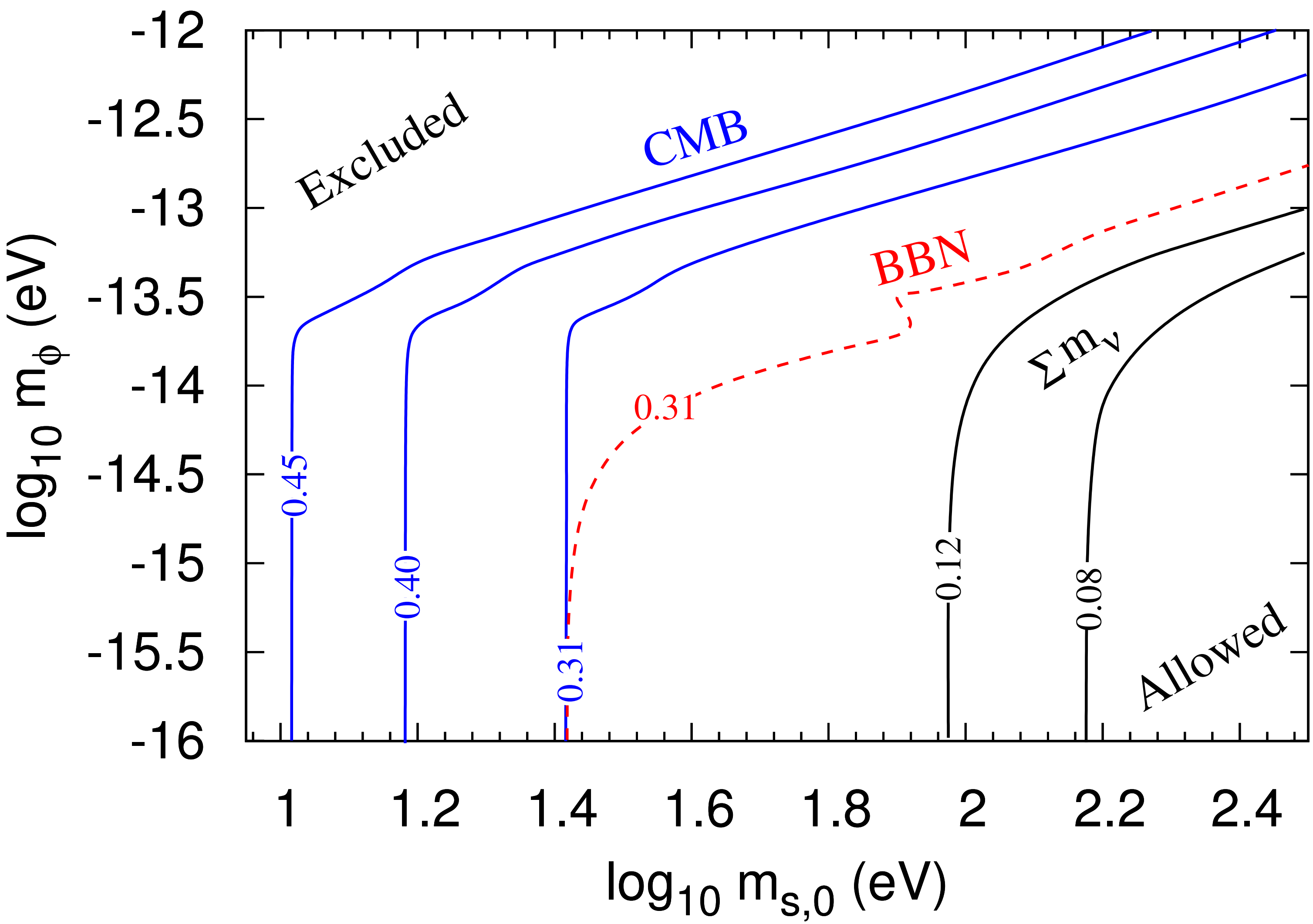
to get $\delta N_{\rm eff} \lesssim 0.1$

If $m_\phi < 10^{-14}\,\mathrm{eV}$, then oscillations start at $T < 3.2\,\mathrm{MeV}$, below ν_e decoupling temperature, so $N_{\rm eff}$ is not increased.

But couldn't even larger $m_{s,0}$ inhibit ν_s-ν_e oscillations, for $m_\phi > 10^{-14}\,\mathrm{eV}$?

The full solution

I derive the more general result



using a simplified oscillation formalism

Density matrix formalism

The rigorous method is to solve Boltzmann equation for 2×2 neutrino density matrix in thermal background

Stodolsky (1986), Enqvist, Maalampi, Kainulainen (1991), Sigl, Raffelt (1993)

Defining

$$p_{ab}(k,t) = (1 + \vec{P} \cdot \vec{\sigma})_{ab}, \quad \mathcal{H} = \tfrac{1}{2}\vec{V} \cdot \vec{\sigma}$$

the time evolution is given by

$$\frac{d\vec{P}}{dt} = \vec{V} \times \vec{P} - D\vec{P}_T$$

with $D =$ rate of damping by elastic scattering, $\vec{P}_T = \vec{P} - (\hat{z} \cdot \vec{P})\hat{z}$

Oscillation probabilities given by diagonal elements of p_{ab}.

I prefer a more intuitive approach ...

Intuitive approach

Barbieri, Dolgov (1990); Kainulainen (1990); JC (1992); Doldelson, Widrow (1993)

The probability for $\nu_e \to \nu_s$ by oscillations is related to matter mixing angle

$$P_{\nu_e \to \nu_s}(p) = \sin^2\theta_m \cong \frac{m_{es}^2}{4m_{es}^2 + [m_{ss}(t) + 2V_e p/m_{ss}(t)]^2}$$

where V_e is the Wolfenstein potential

$$V_e = \frac{7\pi}{90\alpha}\sin^2(2\theta_W) G_F^2 T^4 p$$

for ν_e of momentum p. The rate of conversions by "measurement" of ν flavor through elastic scattering is

$$\Gamma = \tfrac{1}{2}\Gamma_{\rm el}\, P_{\nu_e\to\nu_s} = \left(\frac{7\pi}{24}G_F^2 T^4 p\right) P_{\nu_e\to\nu_s}$$

Solution of Boltzmann equation for final ratio of ν_s to ν_e at momentum p is

$$R(T,p) \equiv \frac{n_{\nu_s}}{n_{\nu_e}} = \frac{1}{2}\left(1 - \exp\left[-2\int_T^{T_i}\left(\frac{\Gamma\sin^2\theta_m}{HT'}\right)dT'\right]\right).$$

We reduce the problem to doing an integral. (See JC 1992 PRL for detailed derivation.)

Contribution to $N_{\rm eff}$

From $R(T,p)$ we get $\delta N_{\rm eff}$ at a given temperature, In general, we need to average over momentum

$$\delta N_{\rm eff}(T) = \frac{\int d^3p\, f(p)\, R(T,p)}{\int d^3p\, f(p)}$$

If $m_\phi \lesssim 10^{-14}\,{\rm eV}$, the ν_s mass is time-independent, we can do integral over T' and get analytic expression for R. Leads to

$$\delta N_{\rm eff} \cong \frac{1}{2}\left[1 - \exp\left(-\frac{5\sqrt{7}\,\alpha^{1/2} G_F M_p m_{es}^2}{64\, s_W c_W g_*^{1/2} m_{s,0}}\right)\right]$$

independent of T, p for $T < 1\,{\rm MeV}$.

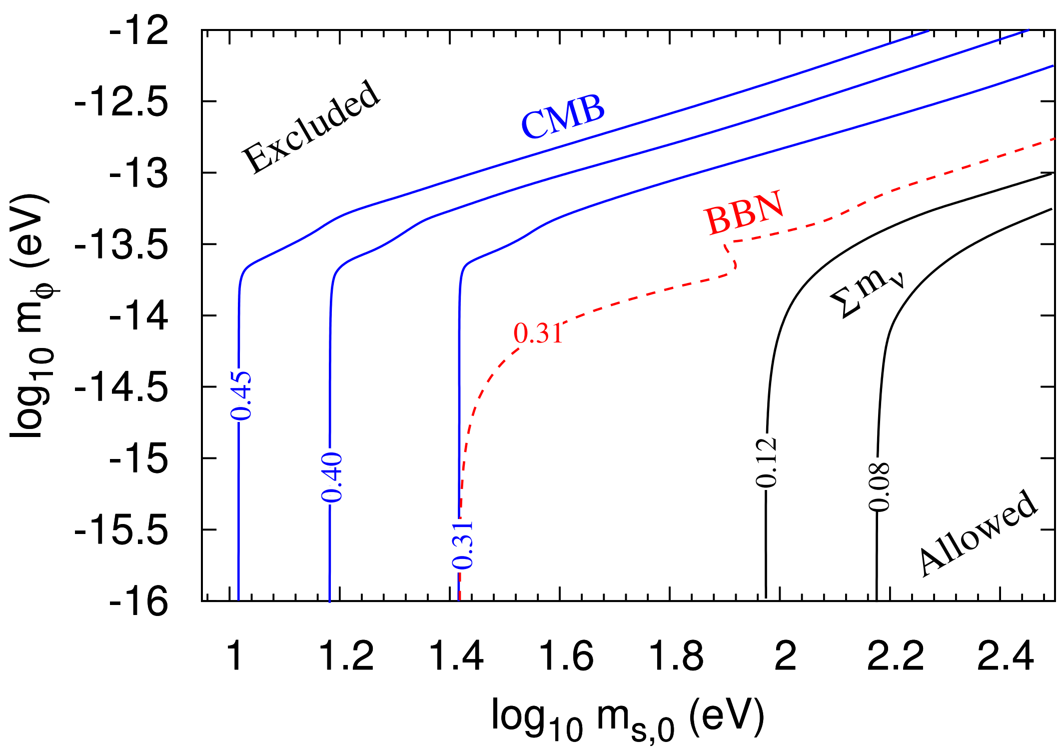
For $m_\phi > 10^{-14}\,{\rm eV}$, must do all the integrals numerically

Big bang nucleosynthesis

For $\delta N_{\rm eff}$, we can evaluate at ν_e decoupling, $T = 3.2\,{\rm MeV}$. But conversions $\nu_e \to \nu_s$ can still affect BBN by changing $p \leftrightarrow n$ equilibrium. This can be parametrized by (Dolgov, Villante, hep-ph/0308083)

$$\delta N_{\rm eff}^{BBN} = \frac{4}{7}\left(\frac{4g_* + 7\delta N_{\rm eff}}{(1+Y_{\nu_e})^2} - g_*\right)$$

by considering $\nu_e \to \nu_s$ between $T = 3.2\,{\rm MeV}$ and $T = 0.1\,{\rm MeV}$



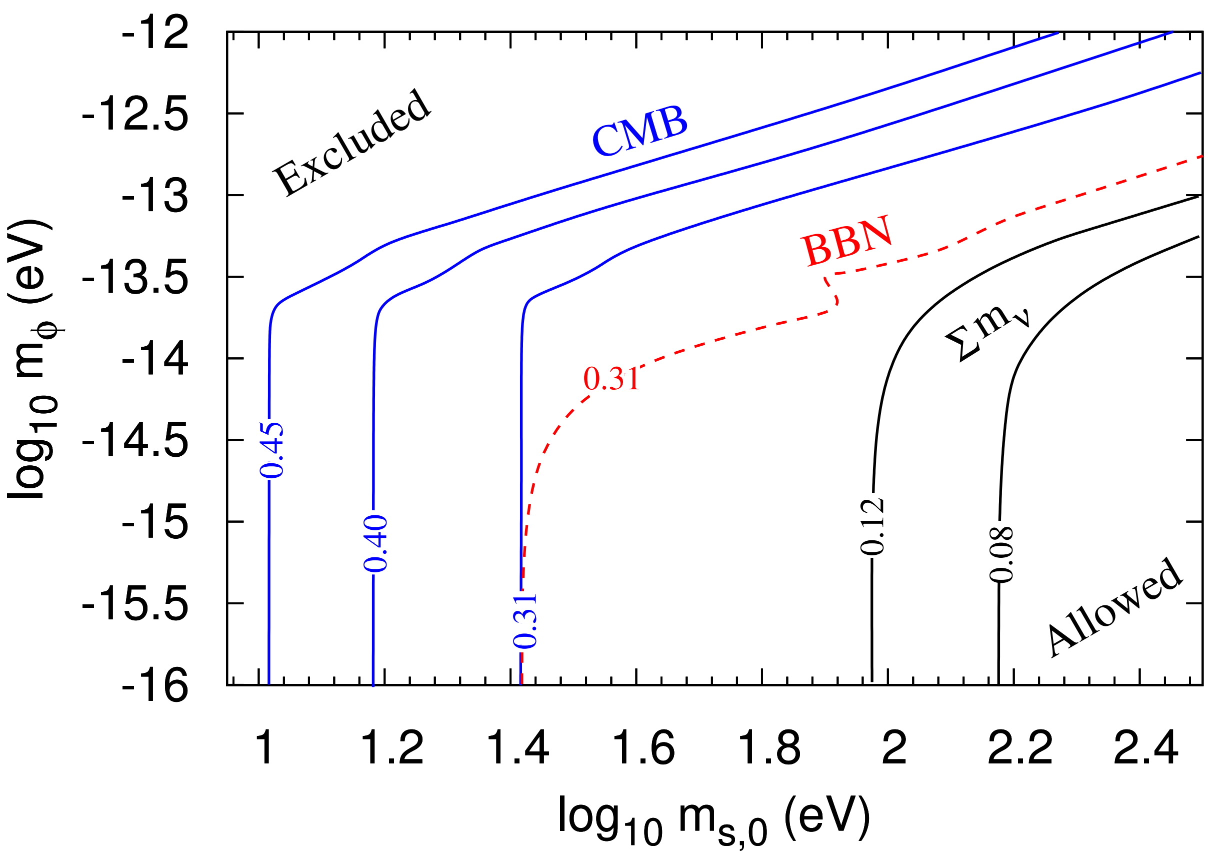
CMB $\sum m_\nu$

Further conversions $\nu_e \to \nu_s$ before $T \sim 1\,\mathrm{eV}$ increase the effective ν mass sum probed by CMB,

$$\sum m_\nu \cong [0.06\,\mathrm{eV} + m_4\,\delta N_{\mathrm{eff}}] < 0.145^*$$

* Choudhury, Hannestad 1907.12598

constraining $\delta N_{\mathrm{eff}} < 0.08$, and giving the strongest bound.



(This is fake δN_{eff} that doesn't account for reduction in ν_e.)

Remarks on ultralight DM

Favored mass for ϕ is $m_\phi \sim 10^{-22}\,\mathrm{eV}$ to solve small-scale structure problems of ΛCDM

(Hu, Barkana, Gruzinov astro-ph/0003365; Hui, Ostriker, Tremaine, Witten 1610.08297)

Interesting time scale:

$$[10^{-22}\,\mathrm{eV}]^{-1} \cong 0.7\,\mathrm{yr}$$

$m_{ss}(t)$ could be modulating on time scales relevant for SBL experiments, leading to confusing results (if interpreted assuming constant m_{ss}).

Such effects on active ν oscillations have been considered

Berlin, 1608.01307; Krnjaic, Machado, Necib, 1908.02278; Brdar, Kopp, Liu, Prass, Wang, 1705.09455

but not ν_s oscillations

Backup slides

Derivation of ν_s production

JC, Phys. Rev. Lett. 68,3137 (1992)

Starting from Hamiltonian including matter effect, solve Schrödinger eq. for amplitude to oscillate $U(t_0;t)$ between t_0 and t. Square it to get probability:

$$P(t_0;t) = |U_{RL}(t_0;t)|^2 = s_t^2 c_{t_0}^2 \exp\left(-\int_{t_0}^{t} \Gamma c_\tau^2\, d\tau\right) + s_{t_0}^2 c_t^2 \exp\left(-\int_{t_0}^{t} \Gamma s_\tau^2\, d\tau\right)$$

plus oscillatory terms that average to zero. Number of ν_s produced by time t is

$$N_s(t) = \int_{t_i}^{t} dt_0\, P(t_0;t)\, dN_{\rm prod}/dt_0 + P(t_i;t)\, N_a(t_i)$$

Since active ν is in equilibrium, its production rate is

$$dN_{\rm prod}/dt = \Gamma N_a(t)$$

Can solve for N_s/N_a explicitly,

$$\frac{N_s(T)}{N_a(T)} \cong 1 - \exp\left[-\int_T^{T_i} \left(\frac{s_T^2 \Gamma}{HT}\right) dT\right]$$

Taking account of back reaction,

$$\frac{N_s(T)}{N_a(T)} \cong \left[1 - \exp\left[-2\int_T^{T_i} \left(\frac{s_T^2 \Gamma}{HT}\right) dT\right]\right] \times \frac{1}{2}$$

Comparison of formalisms

The simplified decoherent oscillation formalism agrees very well with the matrix Boltzmann formalism.

We showed this recently in a different context, baryogenesis via neutron-DM oscillations (Bringmann, JC, Cornell, 1810.0821)