Neutrinos secretly converting to lighter particles to please both KATRIN and Cosmos

Yasaman Farzan

IPM, Tehran

Outline

- Motivation for the KATRIN experiment
- Effect of neutrinos on cosmological scales and the cosmological bound on neutrino mass
- Our scenario to reconcile cosmological bounds with sizable [O(0.1 eV)] neutrino mass
- Embedding scenario in electroweak invariant models
- Results
- Summary

Neutrino oscillation

$$|\psi\rangle \rightarrow e^{-i\int H \ dt}|\psi\rangle$$

$$H = H_{vac} + H_{mat}$$

$$H_{vac} = U \cdot \mathrm{Diag}(\frac{m_1^2}{2p}\ , \frac{m_2^2}{2p}\ , \frac{m_3^2}{2p}) \cdot U^\dagger$$ → PMNS unitary matrix

$$H_{mat} = \mathrm{Diag}(\sqrt{2}G_F(N_e - N_n/2)\ , -\sqrt{2}G_F N_n/2\ , -\sqrt{2}G_F N_n/2)$$

No sensitivity to neutrino mass scale

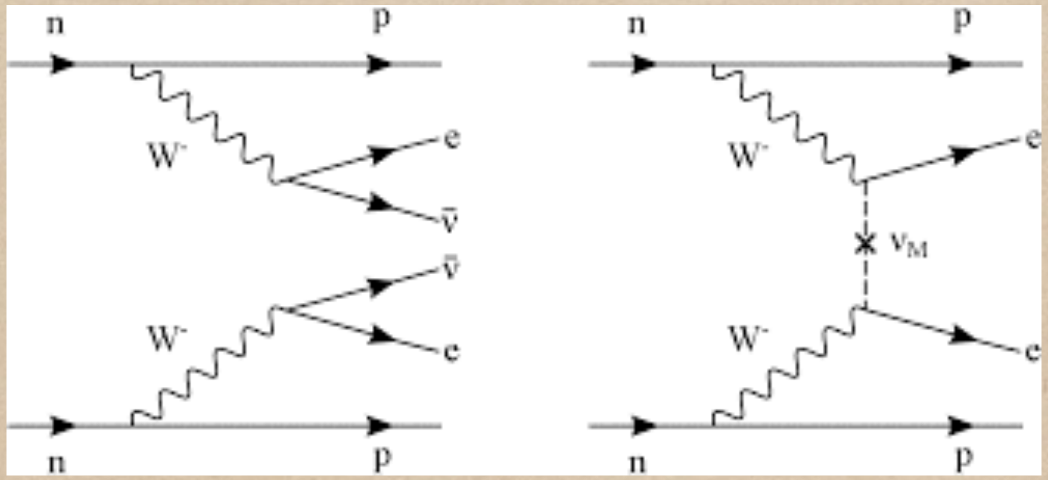
- Neutrino oscillation pattern depends only on neutrino mass splitting

$$\Delta m^2_{ij}$$

Neutrinoless double beta decay

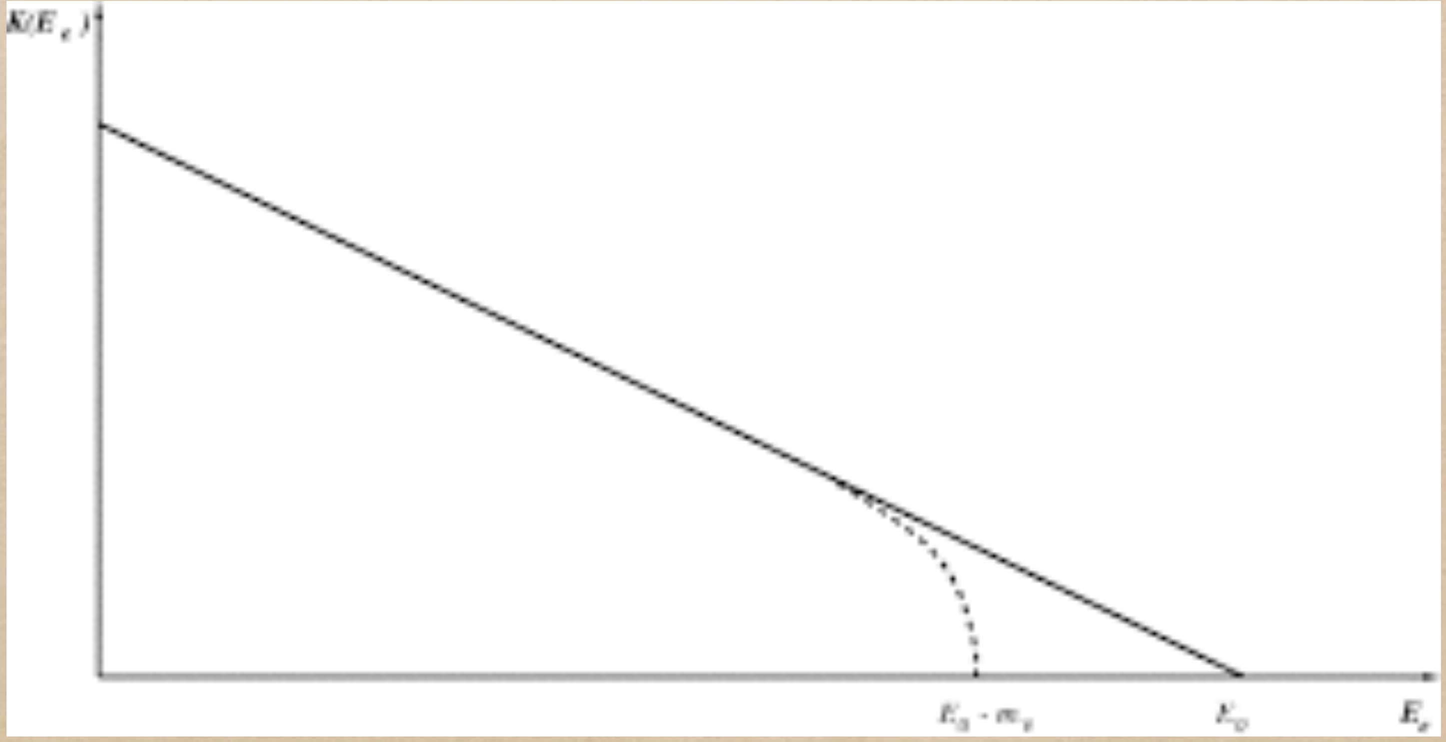
$$m_{ee} = |m_1 U_{e1}^2 + m_2 U_{e2}^2 + m_3 U_{e3}^2|$$

$$= |m_1 |U_{e1}|^2 e^{i\phi_1} + m_2 |U_{e2}|^2 e^{i\phi_2} + m_3 |U_{e3}|^2 e^{i\phi_3 + 2\delta}|$$



Beta decay experiments

$^3H \rightarrow ^3He + e + \bar{\nu}_e$



Which mass?

$$m_{\nu_e} = \sqrt{\sum_i m_i^2 |U_{ei}|^2}$$

$$m_{\nu_e} = \sum_i m_i |U_{ei}|^2$$

- Equal up to $\left(\frac{\Delta m^2}{m^2}\right)^2$

Y.F. and Smirnov, PLB557 (2003)

Previous experiments

- Mainz

J Bonn et al, Nuc Phys Supp 91 (2001) 273

$m_\nu < 2.2$ eV 95 % C.L.

- Troitsk

Troistk collaboration, PRD (2011)

KArlsruhe TRItium decay Neutrino experiment
(KATRIN)

Reach of KATRIN

- Bound in case of null result

$$0.2 \text{ eV} \quad 90\ \%\ \text{C.L.}$$

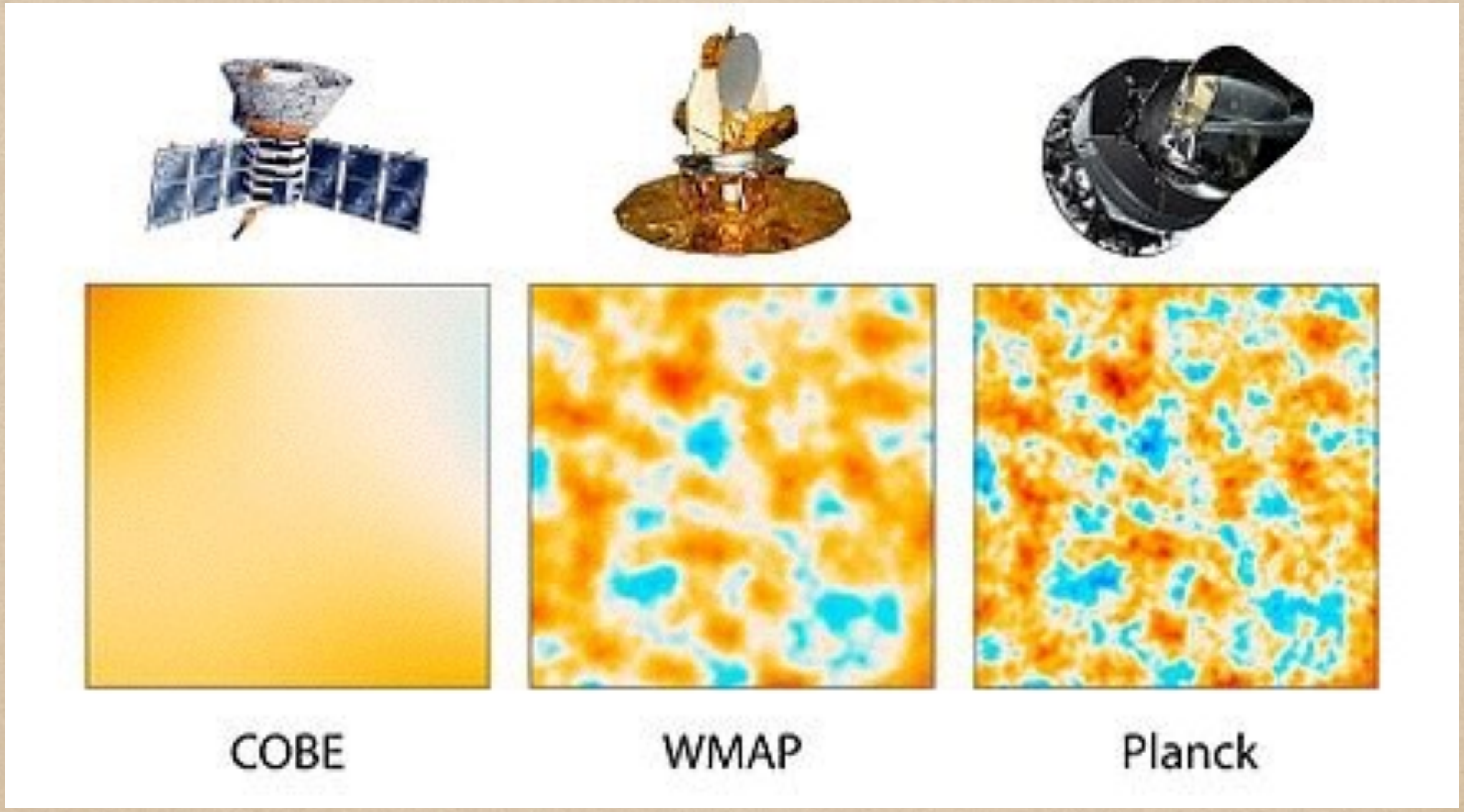
- Detection limit $0.35 \text{ eV} \quad \text{at} \ \ 5\sigma$

KATRIN spectrometer

OLD happy days before WMAP

- m_{ee} from neutrino less double beta decay
- m_1 from KATRIN
- Information on Majorana phases

PLANCK



J. Lesgourgues and S. Pastor, "Neutrino mass from cosmology," Adv High Energy Phys 2012 (2012) 608515;

arXiv:1212.6154

Neutrino effect on structure formation

free streaming wavelength and wavenumber

$$k_{FS}(t) = 0.8\frac{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}}{(1+z)^2}\left(\frac{m}{1\,\mathrm{eV}}\right) h\,\mathrm{Mpc}^{-1},$$

$$\lambda_{FS}(t) = 8\frac{1+z}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}}\left(\frac{1\,\mathrm{eV}}{m}\right) h^{-1}\mathrm{Mpc}\ ,$$

Neutrinos starting to become non-relativistic

$$m = \langle p \rangle \sim T_\nu \qquad 1 + z = 2 \times 10^3 \frac{m_\nu}{1\ \mathrm{eV}}$$

$$k_{\rm nr} \simeq 0.018\ \Omega_{\rm m}^{1/2}\left(\frac{m}{1\,\mathrm{eV}}\right)^{1/2} h\,\mathrm{Mpc}^{-1}\ .$$

effects of neutrino mass on matter power spectrum

$$P(k,z) = \left\langle \left| \frac{\delta\rho_{\rm cdm} + \delta\rho_{\rm b} + \delta\rho_\nu}{\rho_{\rm cdm} + \rho_{\rm b} + \rho_\nu} \right|^2 \right\rangle = \Omega_{\rm m}^{-2} \left\langle |\Omega_{\rm cdm}\,\delta_{\rm cdm} + \Omega_{\rm b}\,\delta_{\rm b} + \Omega_\nu\,\delta_\nu|^2 \right\rangle$$

$\delta_\nu \ll \delta_{\rm cdm}.$ $f_\nu \equiv \frac{\Omega_\nu}{\Omega_{\rm m}}.$ $(1-f_\nu)^2$

- Back reaction

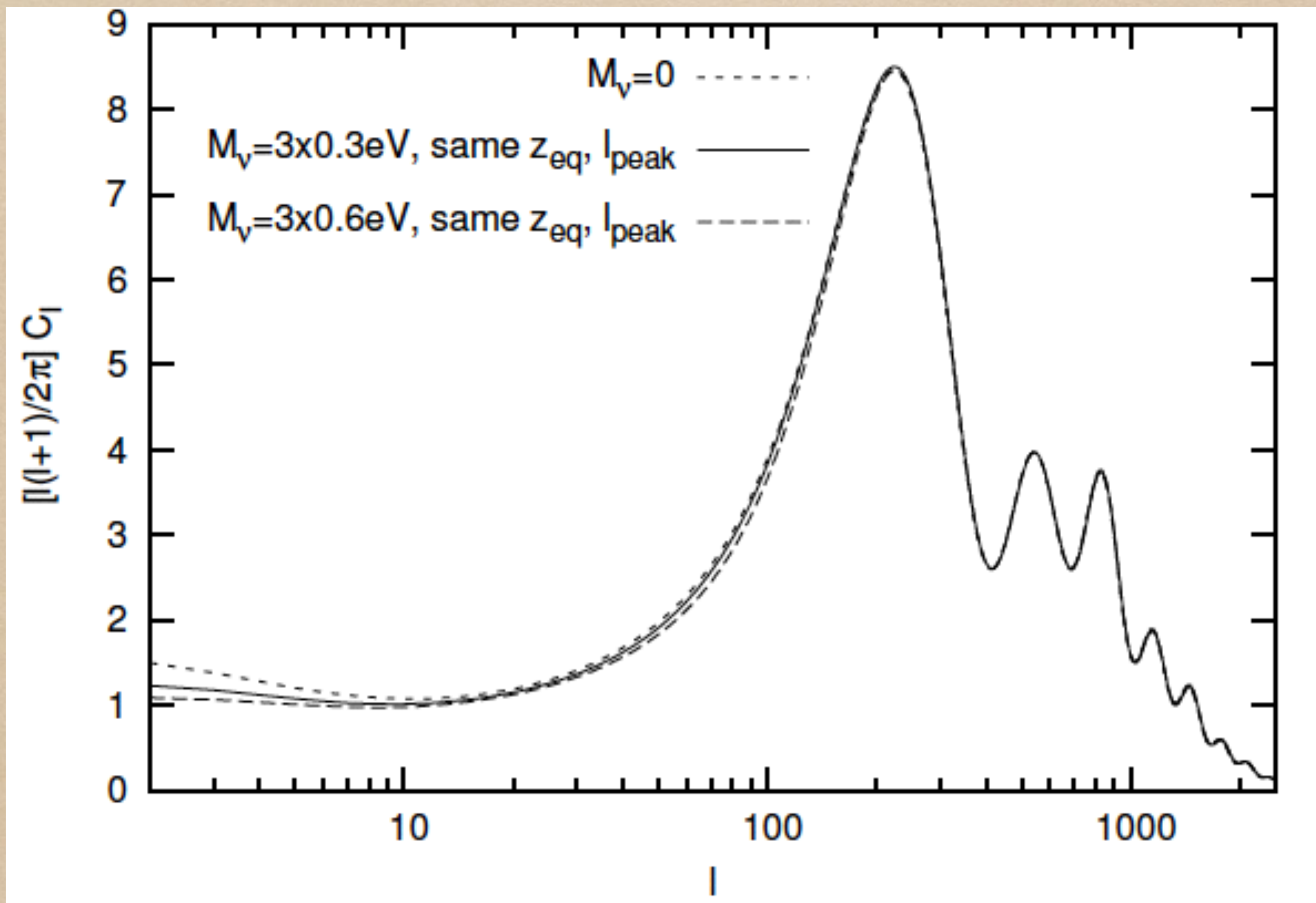
$$\delta''_{\rm cdm} + \frac{a'}{a}\delta_{\rm cdm} = -k^2\psi\,,$$

gravitational potential

Effects of neutrino mass on CMB

- At the time of recombination neutrinos were relativistic.
- Thus, their effect on CMB will be secondary and indirect through three main effects.
- Let us fix Ω_m. The z_{eq} will then depend on neutrino mass and this affects position and amplitude of CMB power spectrum peaks.

- Fixing Ω_m, the angular diameter distance to the last scattering surface $d_A(z_{dec})$varies with neutrino mass which in turn will affect the CMB spectrum feature in multipole space.
- Neutrino mass affects time evolution of matter fluctuation at late time and therefore affects Integrated Sachs-Wolfe effect, changing the slope of low-l part of CMB power spectrum.



M_ν=0
M_ν=3x0.3eV, same z_{eq}, l_{peak}
M_ν=3x0.6eV, same z_{eq}, l_{peak}
$[l(l+1)/2\pi]\ C_l$
0
1
2
3
4
5
6
7
8
9
10
100
1000
l

- Planck alone $\sum_i m_{\nu_i} < 0.71 \text{ eV}$

- Planck + BAO $\sum_i m_{\nu_i} < 0.23 \text{ eV}$

Ade et al (Planck collaboration), arXiv:1502.01589

Is there any hope for KATRIN?

- Altering cosmology
- Non-standard physics for neutrinos

Y.F and Steen Hannestad, “Neutrinos secretly converting to lighter particles to please both KATRIN and the cosmos ,” JCAP 1602 (2016) no.02, 058

Conditions

- Conversion has to be after neutrino decoupling: Below $T \sim 1$ MeV.
- During recombination neutrinos and the new particles have to freely stream.

Hannestad and Raffelt, PRD 72 (2005)

Conversion should take place when

$$1 \text{ eV} \ll T \ll 1 \text{ MeV}$$

Mechanisms for conversion

- Neutrino-Neutrino coannihilation
- Neutrino scattering off dark matter background

Neutrino mass coannihilation

- Mass of intermediate state is much higher than the temperature

$$\Gamma_{ann} \sim \frac{T^5}{m_X^4} \qquad H \sim \frac{T^2}{M_P^*}$$

- Mass of the intermediate state is much smaller than the temperature

$$\Gamma_{ann} \sim T \qquad H \sim \frac{T^2}{M_{Pl}^*}$$

Resonant conversion

$$\text{eV} < m_X < 1 \text{ MeV}$$

$$\nu + \overset{(-)}{\nu} \to X^* \to f_i + \overset{(-)}{f_i}$$

Conversion rate

$$(p_2, 0, 0, p_2)$$

$$R = \frac{1}{2p_2} \int\int\int \frac{d^3p_1}{(2\pi)^3 2p_1} \frac{1}{1+\exp^{p_1/T}} \frac{d^3k_1}{(2\pi)^3 2k_1} \frac{d^3k_2}{(2\pi)^3 2k_2} (2\pi)^4 \delta^4(p_1 + p_2 - k_1 - k_2) |M|^2$$

$$|M|^2 = \frac{\mathcal{A} f(\theta_a)}{(q^2 - m_X^2)^2 + m_X^2 \Gamma_X^2}$$

depends on properties of intermediate state

Scalar vs Vector

- Scalar intermediate state

$$\mathcal{A} = g_a^2 g_s^2 (2k_1 \cdot k_2)(2p_1 \cdot p_2)|_{resonance} = g_a^2 g_s^2 m_J^4 \quad \text{and} \quad f(\theta_a) = 1.$$

- Vector intermediate state $(X = Z')$

$$\mathcal{A} = g'^4 (e'_a e'_s)^2 m_{Z'}^4 \quad \text{and} \quad f(\theta_a) = 1 + \cos^2\theta_a.$$

Narrow width approximation

$$|M|^2 \simeq Bf(\theta_a)\delta(q^2 - m_X^2) \quad \text{where} \quad B \equiv \frac{\mathcal{A}\pi}{m_X \Gamma_X}.$$

$g_s \gg g_a$

$$\Gamma_X \simeq \frac{N g_s^2 m_J}{16\pi} \quad \text{so} \quad B = \frac{16\pi^2 g_a^2 m_J^2}{N}.$$

$e'_s \gg e'_a$

$$\Gamma_X \simeq \frac{N(g' e'_s)^2 m_{Z'}}{8\pi} \quad \text{so} \quad B = \frac{8\pi^2 (g' e'_a m_{Z'})^2}{N}$$

Condition for efficient conversion

$$R|_{T\sim m_X} \sim H|_{T\sim m_X}$$

$$g_a \text{ or } g' e'_a \gtrsim 5 \times 10^{-11}$$

No dependence on the coupling of the new light particles to X as long as $\Gamma_{Z'} \ll m_{Z'}$

$$g_a, g' e'_a < g_s, g' e'_s \lesssim \frac{0.1}{\sqrt{2}}$$

$$R = \frac{B \cdot b}{2^8 \pi^3 p_2} \int \frac{p_1^2 dp_1 d\cos\theta}{p_1} \frac{1}{1+\exp^{p_1/T}} \delta(p_1 p_2 (1-\cos\theta) - m_X^2) =$$

$$\frac{B \cdot b \cdot T}{2^8 \pi^3 p_2^2} \left(\log(1+\exp^{m_X^2/2p_2T}) - m_X^2/2p_2T \right).$$

$b = 1(4/3)$

For $p_2 T \ll m_X^2$, $R \to B \cdot b \cdot T/(2^8 \pi^3 p_2^2) \exp^{-m_X^2/2p_2T}$

For $p_2 T \gg m_X^2$, $R \to \log(2) B \cdot b \cdot T/(2^8 \pi^3 p_2^2)$.

$H = T^2/M_{Pl}^*$.

- The maximum of R/H is reached at

$$T \sim p_2 \sim m_X$$

- Maximum $\frac{R}{H} \propto \frac{M^*_{Pl}}{m_X}$

Back reaction

$\int R\, dt \gg 1$

$\int R\, dt \sim 1$

Reaction and back-reaction rate equal
similar energy distribution

$$\frac{\rho_{\rm massive,final}}{\rho_{\rm massive,initial}} = \frac{3}{3+N}$$

number of degrees of freedom that come to equilibrium with neutrinos below 1MeV

Differently possibility

- X directly decays to more than one species.
- Secondary particles decay to new particles.
- Secondary particles oscillate to new particles.

Effective number of neutrinos

- Effective number of relativistic degrees of freedom at BBN
- Effective number of relativistic degrees of freedom at recombination
- Effective number of massive neutrinos after conversion

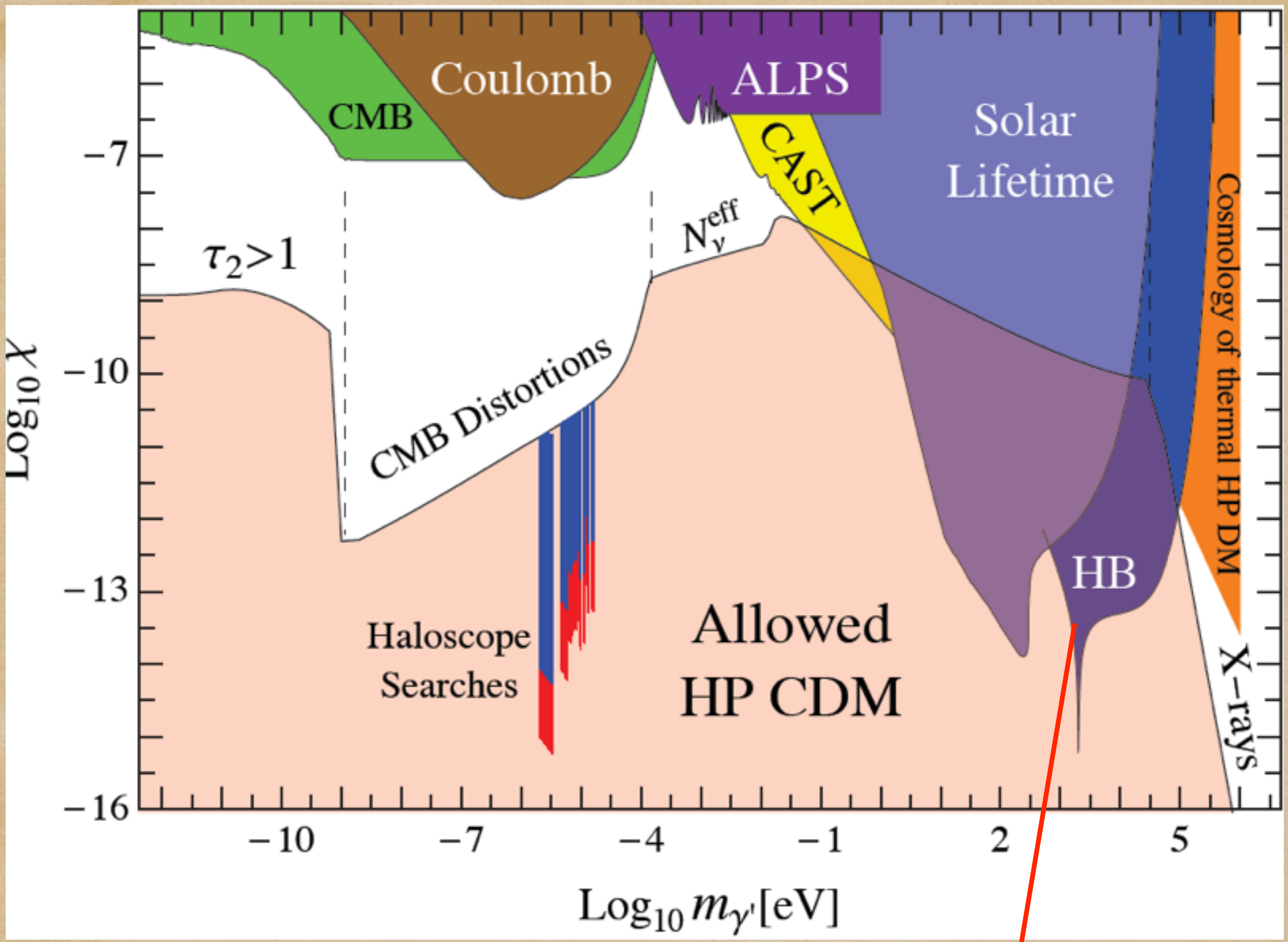
$$N_{\text{massive}} = \frac{3}{1 + N/3}$$

Gauge boson as X

$$g'(e'_a\bar{\nu}_L\gamma^\mu\nu_L + e'_s\bar{\nu}_s\gamma^\mu\nu_s)Z'_\mu$$

$$g'e'_a > 5\times 10^{-11}(\frac{m_{Z'}}{\mathrm{keV}})^{1/2}$$

- Star cooling sets a bound on coupling to electron of order of 10^{-13}



Arias et al., JCAP 1206 (2012)

Gauge boson as X

$$g'(e'_a\bar{\nu}_L\gamma^\mu\nu_L + e'_s\bar{\nu}_s\gamma^\mu\nu_s)Z'_\mu$$ $$g'e'_a > 5\times 10^{-11}(\frac{m_{Z'}}{\mathrm{keV}})^{1/2}$$

- Gauging $L_\mu - L_\tau$

$$\Delta m^2_{21}/T \gg H$$

Stueckelberg or $\langle\phi\rangle \sim m_{Z'}/(g'e'_\phi) \sim 10\ \mathrm{TeV}(e'_a/e'_\phi)$

Majoron model

$$(\frac{g_a}{2}\nu_a^T c\nu_a + \frac{g_s}{2}\nu_s^T c\nu_s)J$$

$$g_a > 5 \times 10^{-11}(m_J/\mathrm{keV})^{1/2}$$

$$\frac{g_\Delta}{2}L^T c\epsilon\Delta L + \frac{g_s}{2}J\nu_s^T c\nu_s$$

$$\frac{m_J^2}{2}J^2 + m_\Delta^2 \mathrm{Tr}[\Delta^\dagger\Delta] + \frac{\lambda_{\Delta J}}{2}H^\dagger\Delta\epsilon H^* J.$$

Mixing between triplet and singlet

$\alpha \simeq \lambda_{\Delta J} \frac{v^2}{m_\Delta^2 - m_J^2}$

$g_a \simeq g_\Delta \alpha .$

- Is hierarchy between masses of Majoron and the triplet stable?

$g_a \sim 5 \times 10^{-11}, \; g_\Delta > 0.1 \text{ and } m_\Delta \sim 1 \text{ TeV},$

↓

$\alpha^2 m_\Delta^2 \ll \text{keV}^2$

Other bounds

- Supernova cooling 10^{-7}

YF, Phys.Rev. D67 (2003) 073015

- Free streaming at recombination

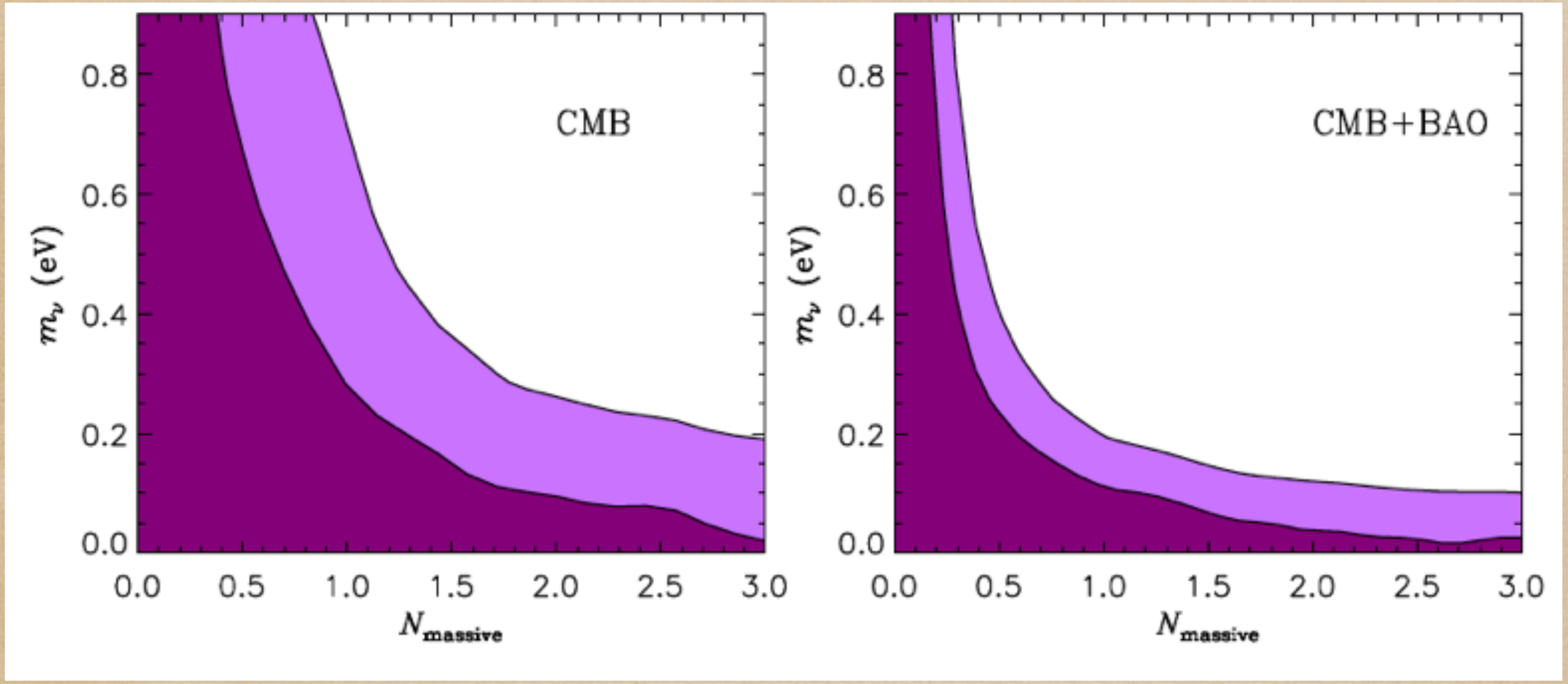
$$n_\nu \sigma_{scattering} \Delta t|_{T\sim 0.3\ \mathrm{eV}} \sim 10^9 g_s^4 \left(\frac{\mathrm{keV}}{m_J}\right)^4 . \qquad g_s \lesssim 0.005(m_J/\mathrm{keV})$$

Parameters relevant for cosmology

- Neutrino mass

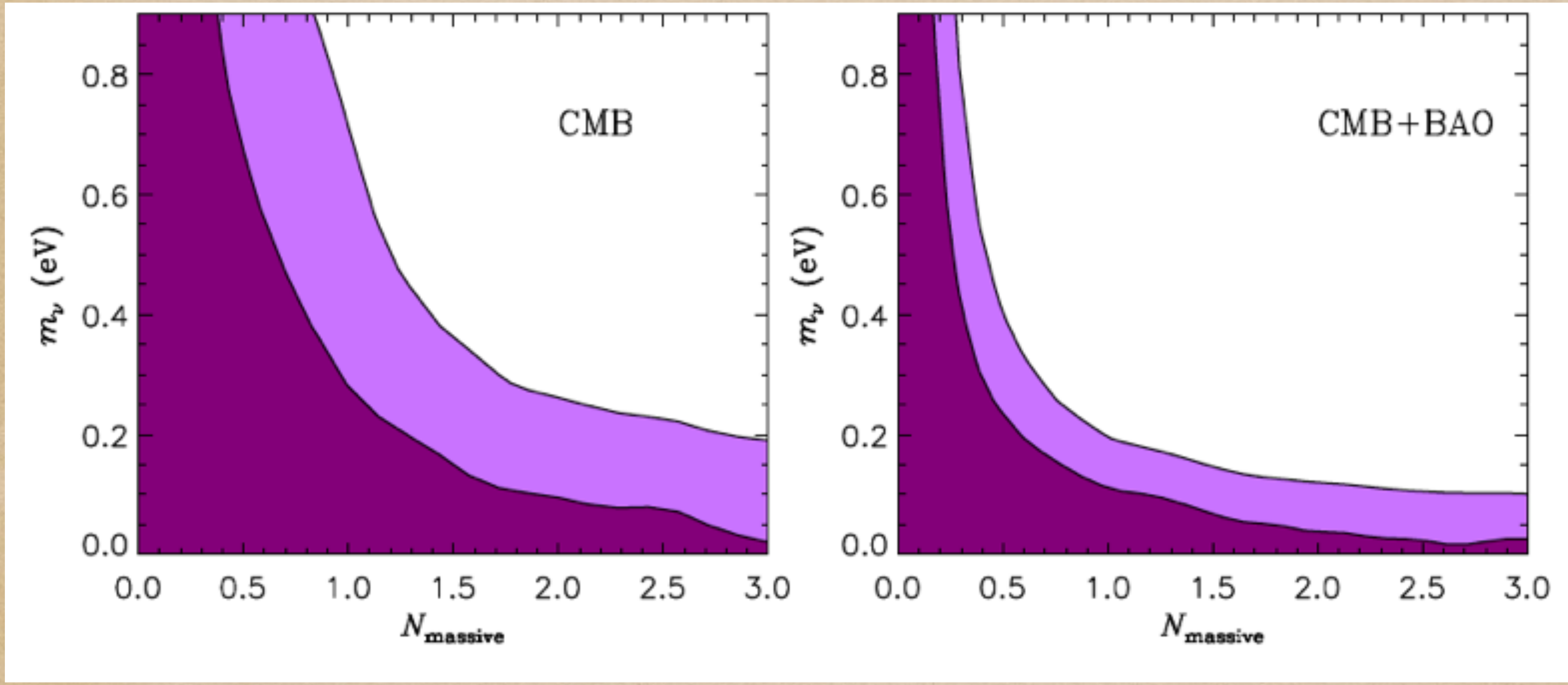
- Effective number of massive neutrinos

$$N_{\text{massive}} = \frac{3}{1 + N/3}$$



CMB
CMB+BAO
m_ν (eV)
N_{massive}
0.0
0.2
0.4
0.6
0.8
0.5
1.0
1.5
2.0
2.5
3.0

68% and 95%



If for each active neutrino there are 1 (4) lighter ones, $m_\nu = 0.35$ eV

Summary

- Scenarios that resonantly convert neutrinos to lighter particles during $T \sim m_X \sim \mathrm{keV}$
- Intermediate state can be scalar or vector boson
- Gauging $L_\mu - L_\tau$ or mixing singlet-triplet scalar
- Masses resolvable by KATRIN can be made compatible within this scenario with cosmological bounds.

Backup

We have performed a likelihood analysis of current data using `CosmoMC` [21]. Our benchmark CMB data set consists of the Planck 2015 high multipole temperature data and low multipole polarization data (PlanckTT+lowP), implemented according to the prescription of Ref. [22]. We have also performed the analysis with Baryonic Acoustic Oscillation (BAO) data,including 6dFGS [23], SDSS-MGS [24], BOSS-LOWZ BAO [25] and CMASS-DR11 [26]. The neutrino sector is described by the parameters $N_{\rm massive}$ and the physical neutrino mass m_ν.

The other cosmological parameters used in the analysis correspond to those in the standard Planck 2015 analysis of neutrino mass: The baryon density, $\Omega_b h^2$, the cold dark matter density, $\Omega_c h^2$, the angular scale of the first CMB peak, θ, the optical depth to reionization, τ, the amplitude of scalar fluctuations, A_s, and the scalar spectral index, n_s.

- Normal hierarchical scheme

$$\sum_i m_{\nu_i}\bigg|_{Min} \simeq \sqrt{\Delta m^2_{atm}} \simeq 0.06 \text{ eV}$$

- Suppression of small scale fluctuations of order of few percent to be resolved by EUCLID