# Sterile Neutrinos and Low Reheating Temperature

**DISCRETE '08**

**Symposium on Prospects in the Physics of Discrete Symmetries**

11–16 December 2008, IFIC, Valencia, Spain

# Active Neutrinos (Standard Cosmology)

- Gerstein-Zeldovich-Cowsik-McClelland bound: neutrinos should not overclose the Universe

$\rho_\nu = \sum m_{\nu_i} n_\nu < \rho_c \Omega_{DM}$

$\rho_c = 3 H^2 m_{Pl} / 8 \pi = 10.54\, h^2$ KeV cm$^{-3}$ $\quad n_\nu = 112$ cm$^{-3}$

$\sum m_{\nu_i} < 94.1\, \Omega_{DM} h^2$ eV $= 12.7$ eV $\rightarrow$ **Hot Dark Matter**

- Problems:
  - Free-streaming length too large: structure forms in a top-down scenario with galaxies and clusters forming (TOO late) via fragmentation
  - Low amplitude of the CMB fluctuations: HDM spectrum becoming non-linear in the present epoch

- LSS and WMAP3: $\sum m_{\nu_i} < 0.62$ eV (95% CL) $\rightarrow \Omega_\nu < 5\%\ \Omega_{DM}$

S. Hannestad and G. Raffelt, JCAP 0611:016,2006

# Sterile Neutrinos (Standard Cosmology)

- Dodelson and Widrow: **Sterile neutrinos as WDM**
  First analytical estimate of the relic sterile neutrino abundance produced via oscillations

  S. Dodelson and L. Widrow, Phys. Rev. Lett. 72:17, 1994

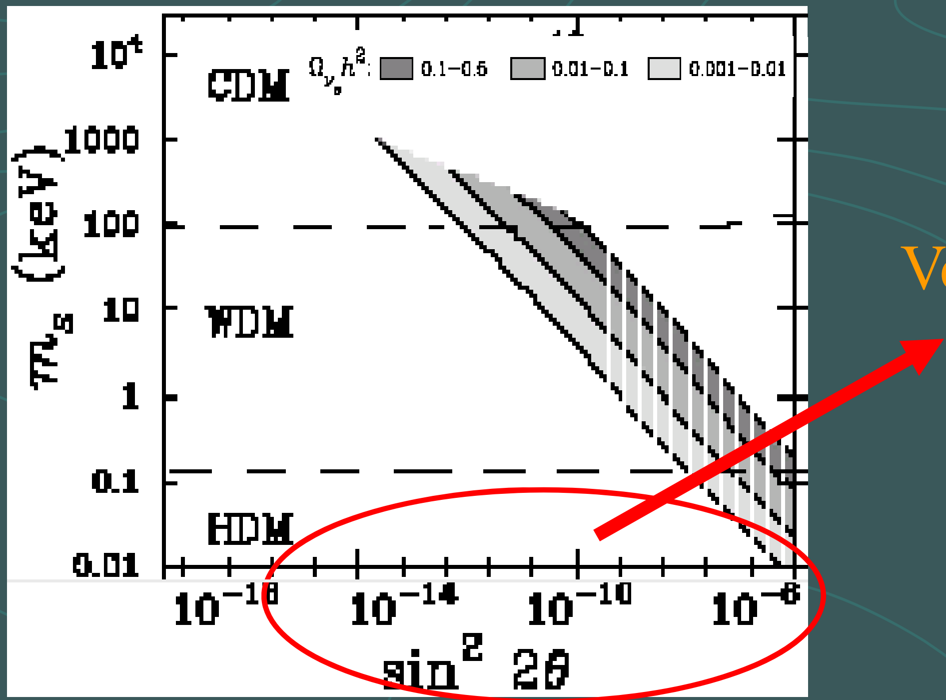
- They assumed negligible lepton asymmetry, so sterile neutrinos are produced non-resonantly

$$\left(\frac{\partial}{\partial t} - HE\frac{\partial}{\partial E}\right) f_s = \frac{\Gamma}{2}\sin^2 2\theta_m f_a \longrightarrow f_s \simeq \left(\frac{m_s}{1\,\mathrm{keV}}\right)\left(\frac{\sin^2 2\theta}{10^{-8}}\right) f_a$$

- The temperature of maximum production is:

  $T_{max} \sim 133\ (m_s/\mathrm{keV})^{1/3}$ MeV

# Sterile Neutrinos (Standard Cosmology)




Very small mixing!

K. Abazajian *et al.,* Phys. Rev. D 64:023501, 2001

# Active Neutrinos (Non-Standard Cosmology)

- In inflationary models, the maximum temperature during the last radiation-dominated era is referred to as "Reheating Temperature", $T_R$

- If $T_R < T_{max}$ , thermal scatterings do not bring neutrinos into chemical equilibrium → their number density is smaller than in the standard case

- m ~ few KeV → Problem: inconsistent with data

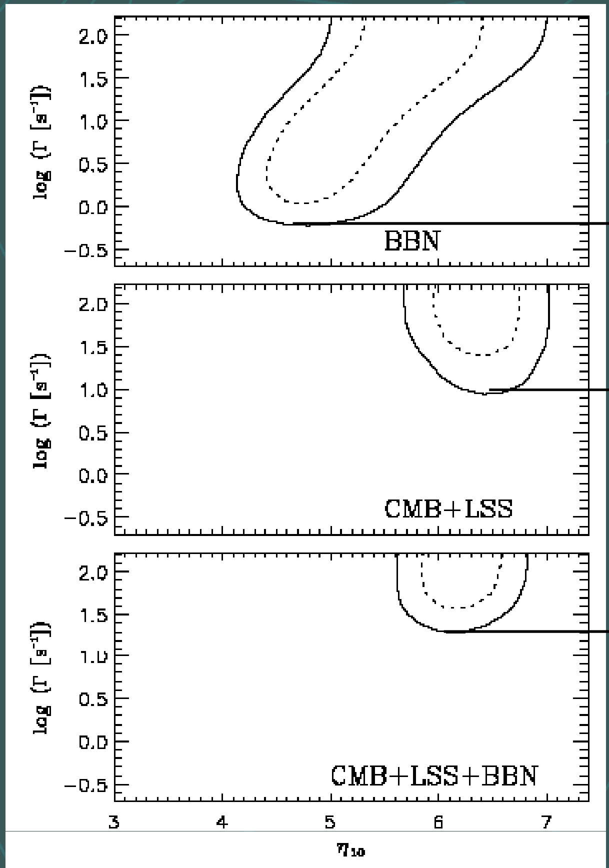
Bounds on $m_\nu$ from direct searches and oscillations:

$m_\nu > 0.05$ eV and $m_\nu < 2.2$ eV

| | Standard Cosmology | Non-Standard Cosmology: Low Reheating Temperature |
|---|---|---|
| Active neutrinos | **HDM: $\Omega_\nu$ < 5% $\Omega_{DM}$** | **WDM: Inconsistent with present data** |
| Sterile neutrinos | **Very small mixing** | **This talk** |

# Sterile Neutrinos (Non-Standard Cosmology)

- If $T_R < T_{max}$ → the production of $\nu_s$ is suppressed → larger mixings are possible
- What is the lowest possible $T_R$?




$\Gamma_{s^{-1}} \sim 2\, T_R{}^2{}_{MeV}$

$T_R > 0.5$ MeV

$T_R > 2.2$ MeV

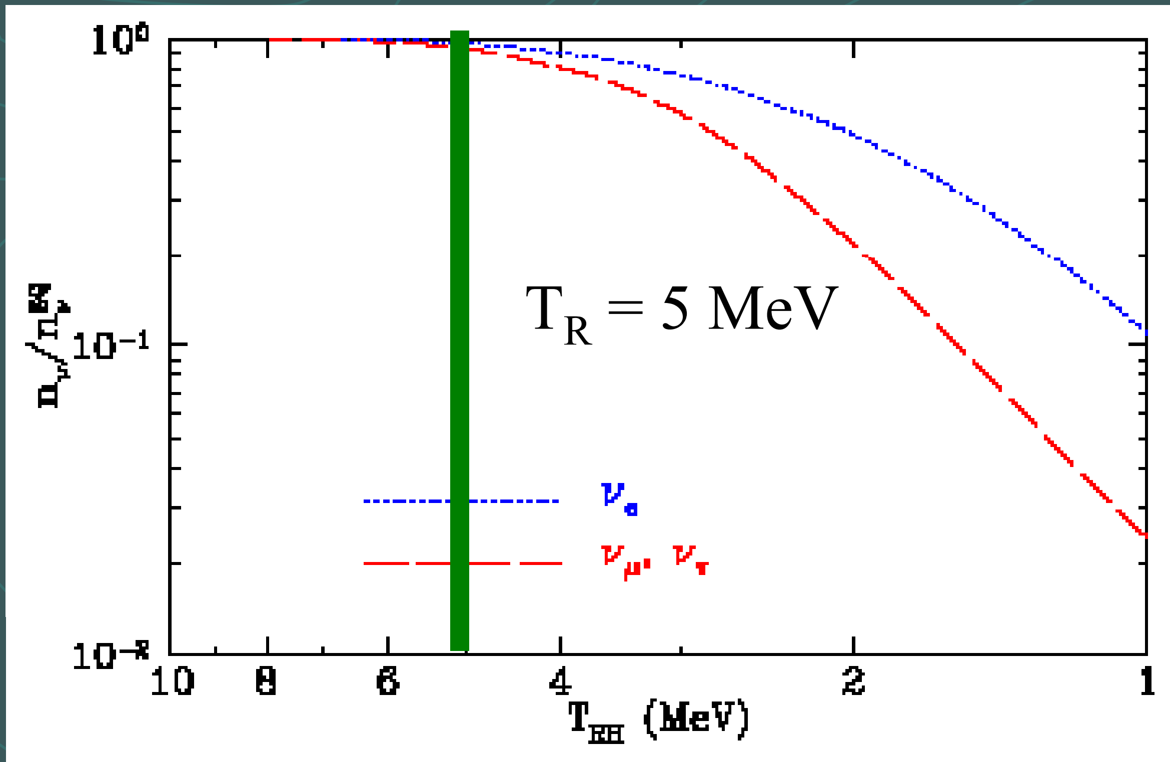
$T_R > 3.2$ MeV


S. Hannestad, Phys.Rev.D70:043506,2004

M. Kawasaki *et al.,* Phys. Rev. Lett. 82:4168, 1999
and Phys. Rev. D62: 0203506, 2000
K. Ichikawa *et al.,* Phys.Rev. D72:043522,2005

- In the calculation, active neutrinos are assumed to have a thermal equilibrium distribution,

$$f_a = \frac{1}{e^{E/T}+1}$$




G. Giudice *et al.*, Phys. Rev. D 64:043512, 2001

# Masses below 1 MeV

Main decay into 3 neutrinos

$$\tau \simeq 5 \times 10^{20}\,\mathrm{s}\left(\frac{1}{\sin^2 2\theta}\right)\left(\frac{\mathrm{keV}}{m_s}\right)^5$$

0.78% decays into neutrino + photon

G. Gelmini, SPR and S. Pascoli, Phys. Rev. Lett. 93:081302, 2004

G. Gelmini, SPR and S. Pascoli, Phys. Rev. Lett. 93:081302, 2004

- For T ~ few MeV [illegible]

- For the relevant temperatures, neutrino oscillations take place as in vacuum

[illegible] $\longrightarrow$ $f = \frac{n_s}{n_e} \simeq \left(\frac{\sin^2 2\theta}{10}\right)\left(\frac{T_R}{5\,\mathrm{MeV}}\right)^3$

**Independent of the neutrino mass**
**Hotter spectrum**

**Larger mixing allowed**

[illegible]

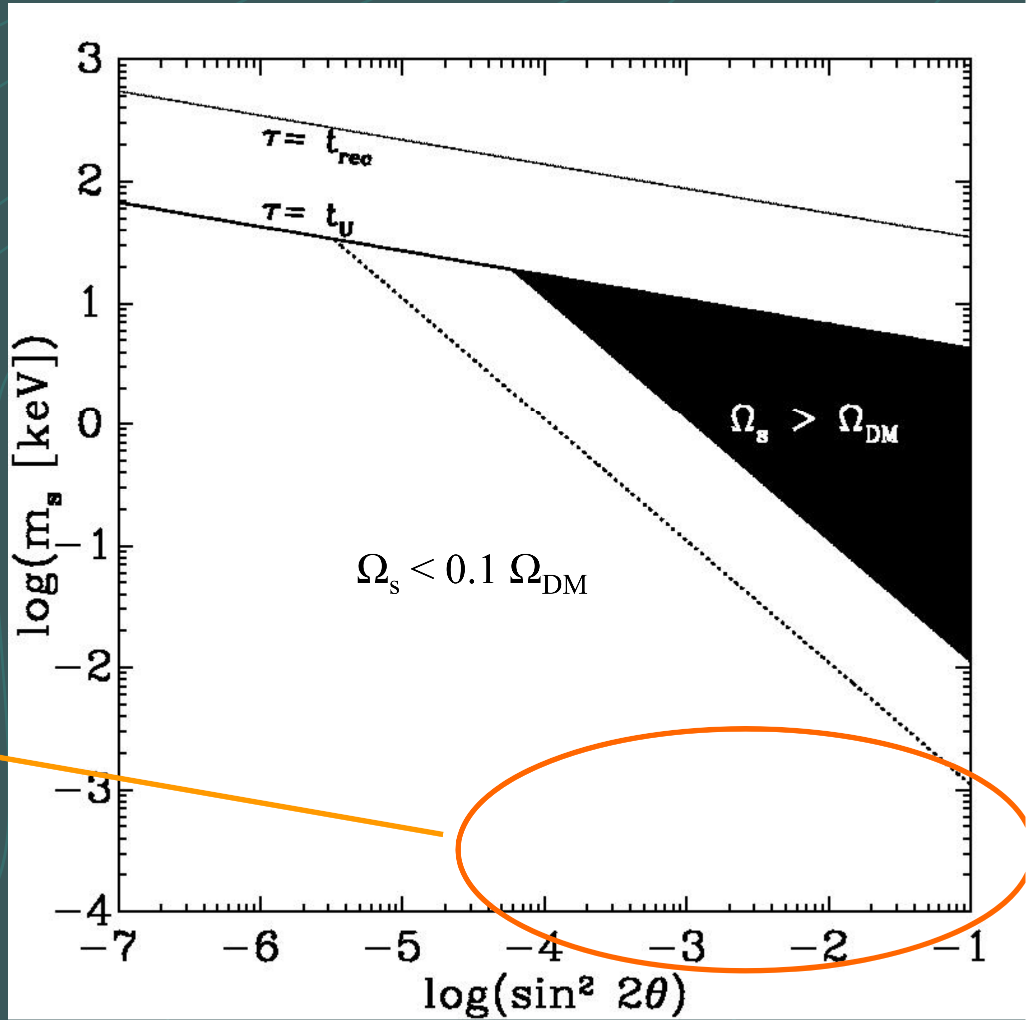
Agrees well (within an order of magnitude) with more accurate calculations

C. E. Yaguna, JHEP 0706:002,2007

To compare with: [illegible]

- For $m_s$ < 1 MeV the dominant decay mode of the mostly-sterile ν is into three neutrinos

Larger Mixings!



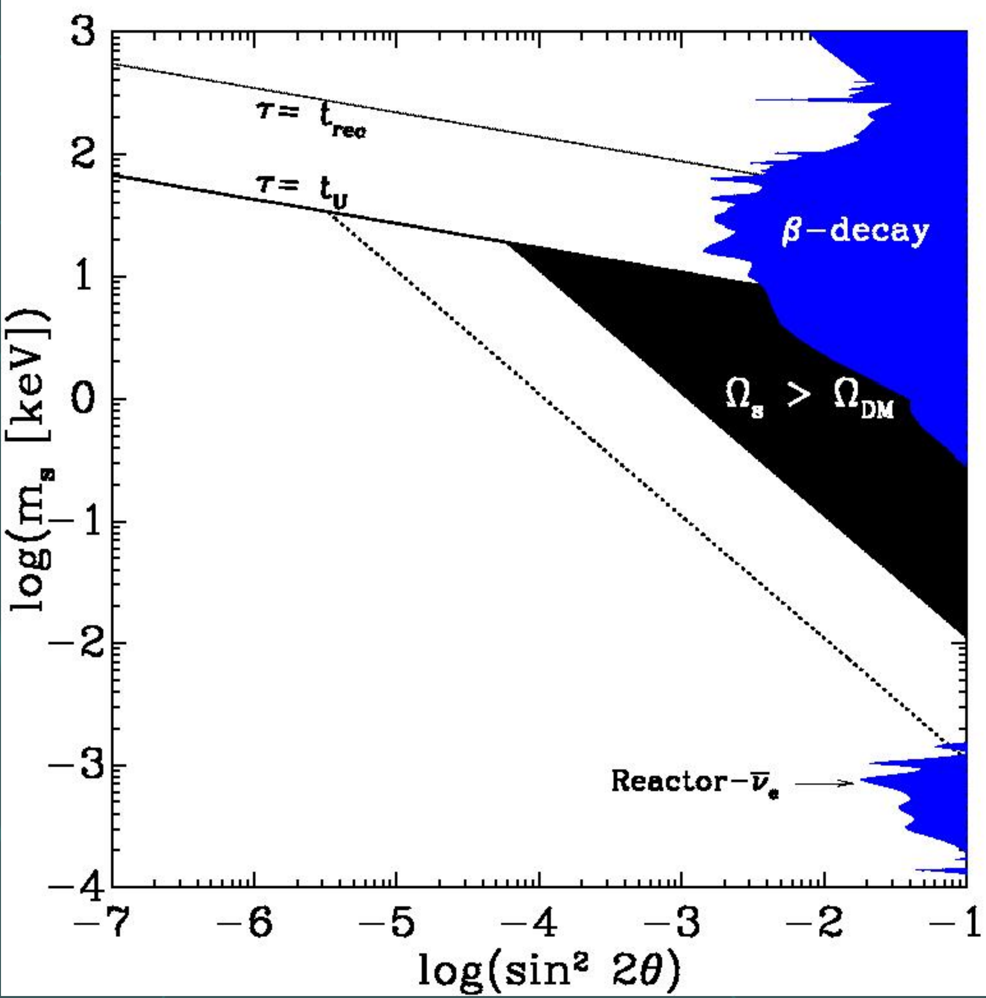

G. Gelmini, SPR and S. Pascoli,
Phys. Rev. Lett. 93:081302, 2004

# Experimental bounds
## (for $\nu_e \rightarrow \nu_s$ )

- Reactor experiments CHOOZ and Bugey: dissappearance experiments constrain the mixing angle in $\bar{\nu}_e \rightarrow \bar{\nu}_s$ conversions

- β-decay experiments searching for kinks in the energy spectra of the emitted electron: negative results so far → constraints in the mixing angle

G. Gelmini, SPR and S. Pascoli, Phys. Rev. Lett. 93:081302, 2004



# Cosmological bounds
## (for $\nu_e \rightarrow \nu_s$ )

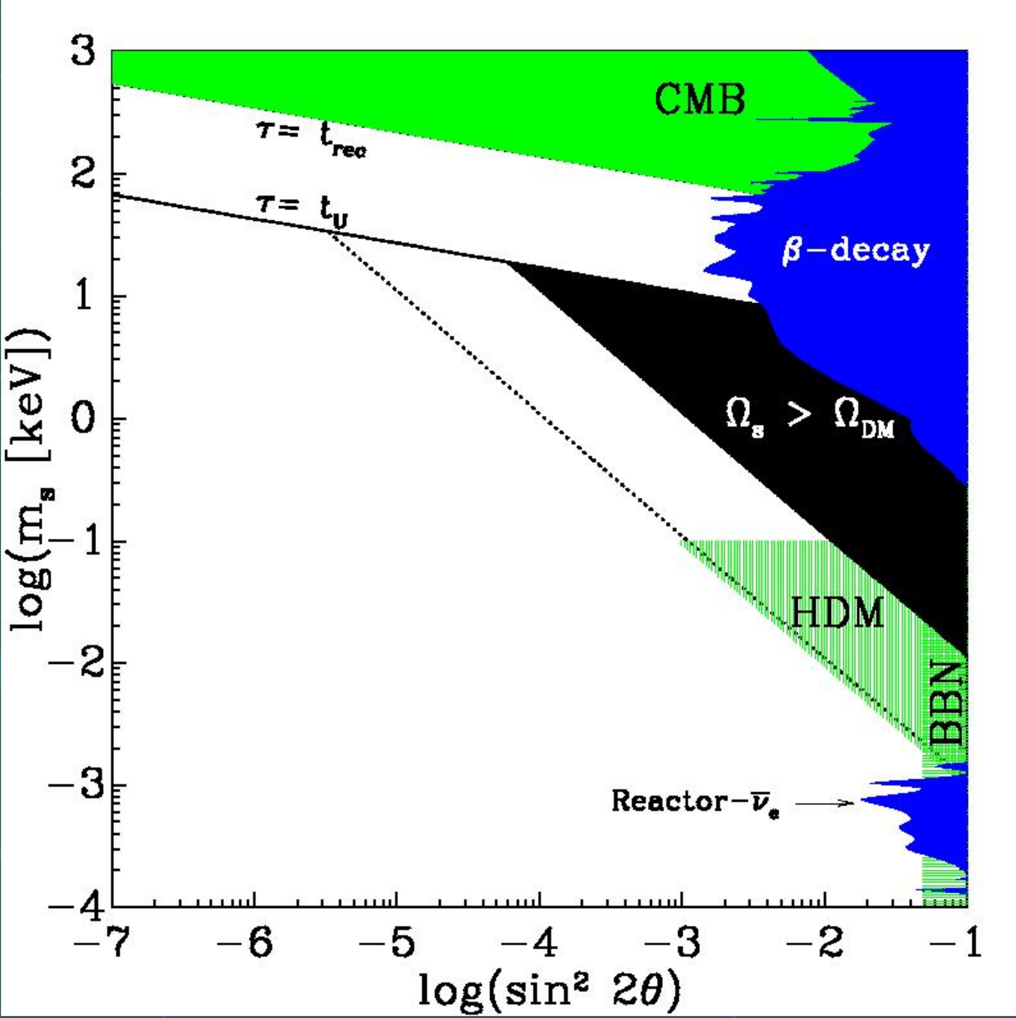
- LSS and WMAP3 →
  $\sum m_{\nu_i} + f \; m_s < 0.62$ eV

Assuming normal hierarchy:

$m_s \sin^2 2\theta < 0.1 \, (T_R/5 \text{ MeV})^{-3}$ eV

- BBN bound on $\Delta N_\nu < 0.73$
  $\sin^2 2\theta < 0.06 \, (T_R/5 \text{ MeV})^{-3}$

- The decay mode into a neutrino and a photon happens with a branching ratio B = $0.78 \times 10^{-2}$ : lack of distortions in the CMB spectrum imposes another bound




G. Gelmini, SPR and S. Pascoli, Phys. Rev. Lett. 93:081302, 2004

# Astrophysical bounds
## (for $\nu_e \longrightarrow \nu_s$ )

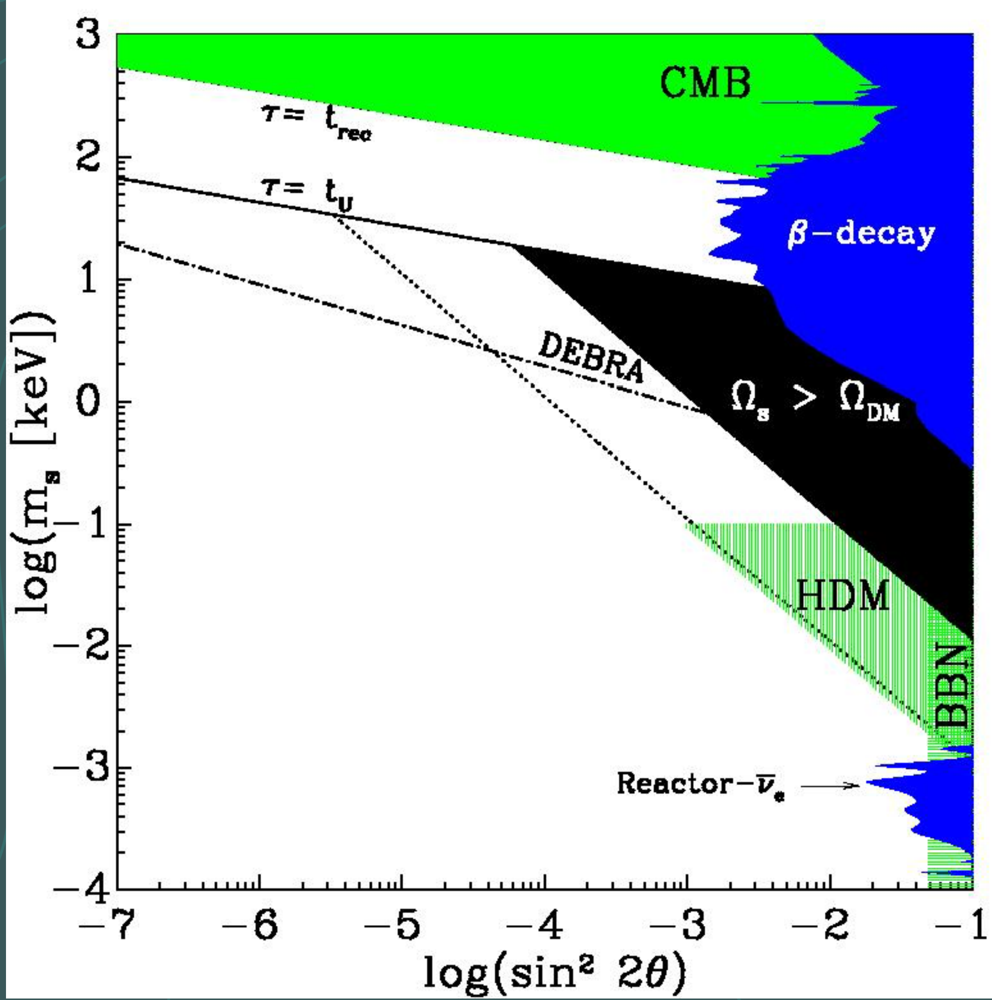
- The diffuse extragalactic background radiation (DEBRA) imposes a bound on the differential photon flux

$I_\gamma < (E/0.05\ \mathrm{MeV})^{-1}\ (\mathrm{cm}^2\ \mathrm{sr}\ \mathrm{s})^{-1}$

For $\tau > t_U$

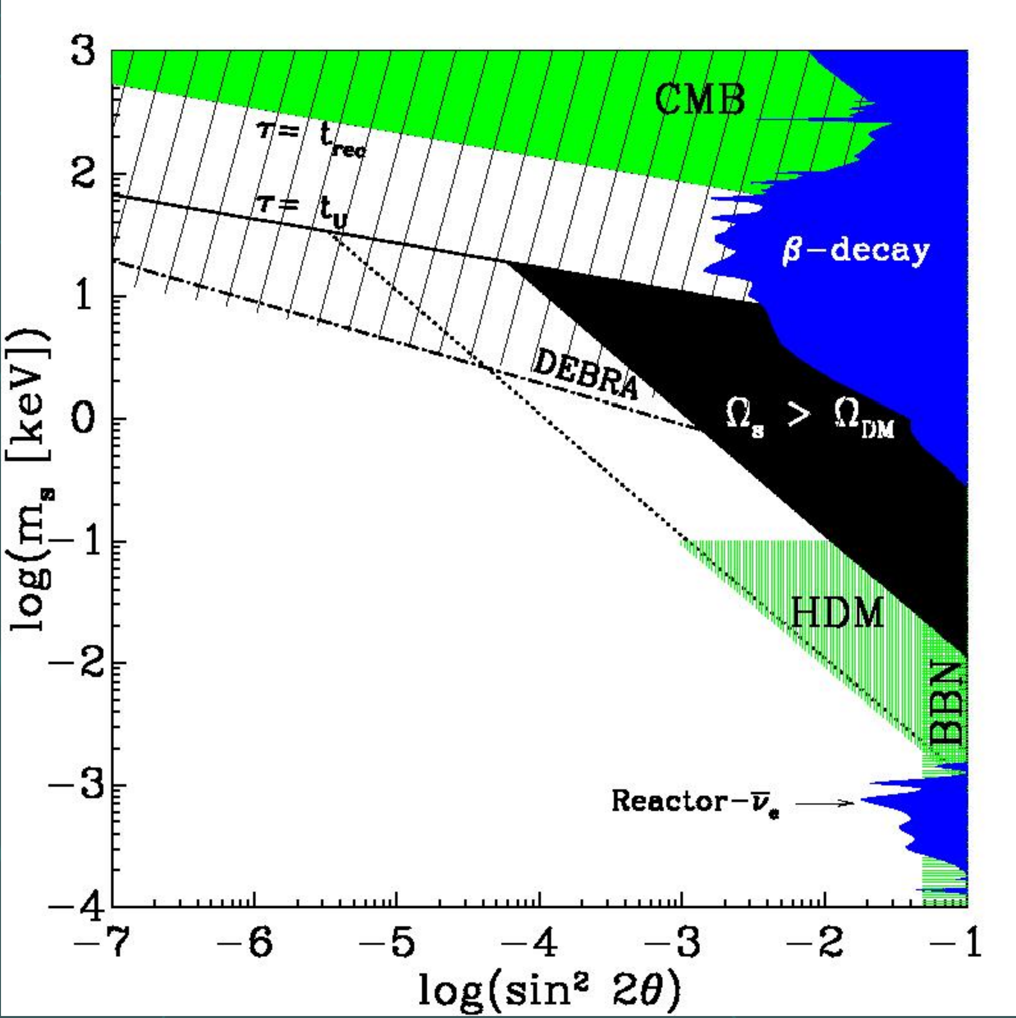
$m_s < 0.1\ (T_R/5\ \mathrm{MeV})^{-1/2}\ (\sin^2 2\theta)^{-1/3}\ \mathrm{keV}$

G. Gelmini, SPR and S. Pascoli, Phys. Rev. Lett. 93:081302, 2004



# Astrophysical bounds
## (for $\nu_e \rightarrow \nu_s$ )

- Supernova energy-loss arguments (using typical values)
- For large masses ($m_s$ > 45 keV) matter effects are negligible → Vacuum oscillations
  $7 \times 10^{-10} < \sin^2 2\theta < 0.02$
- For smaller masses, matter suppresses oscillations
$0.22 \text{ keV} < m_s (\sin^2 2\theta)^{1/4} < 17 \text{ keV}$
- However, due to deleptonization a much more detailed consideration of the cooling history of the SN core is required

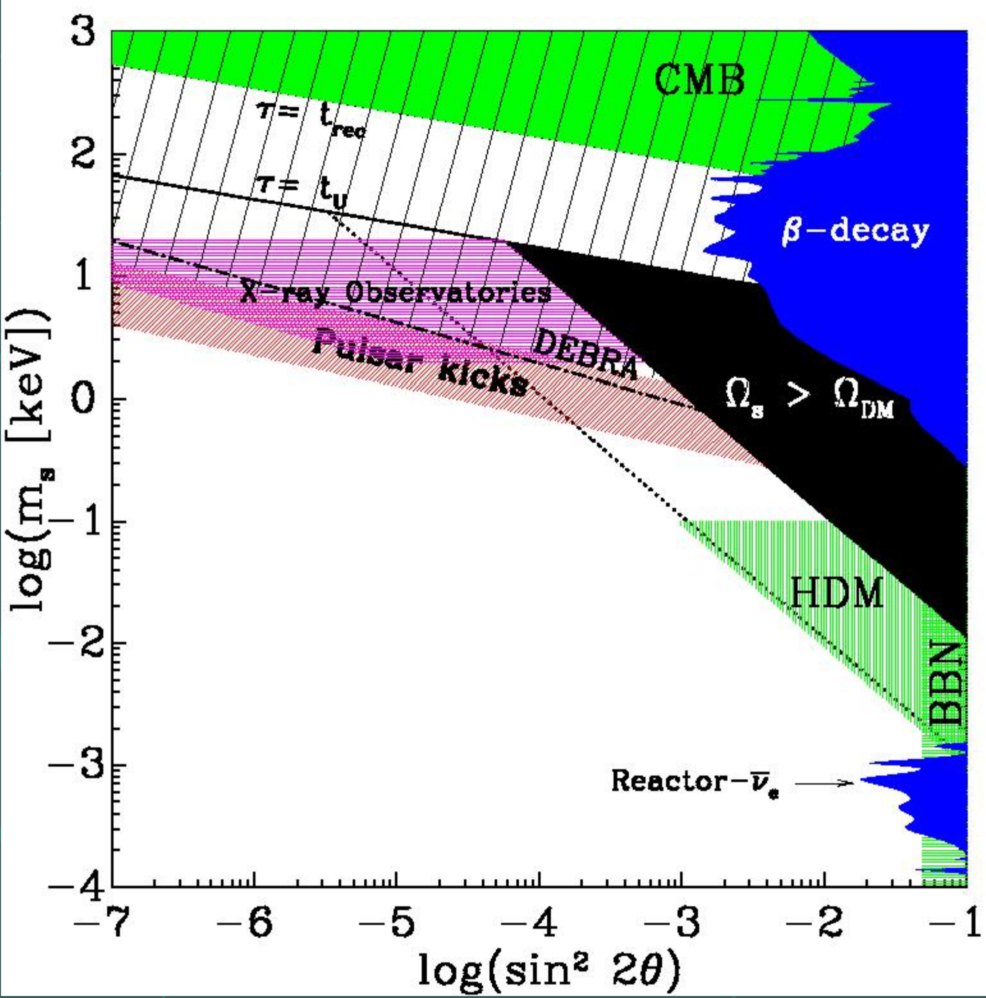



G. Gelmini, SPR and S. Pascoli, Phys. Rev. Lett. 93:081302, 2004

# Sensitivity regions
## (for $\nu_e \to \nu_s$ )

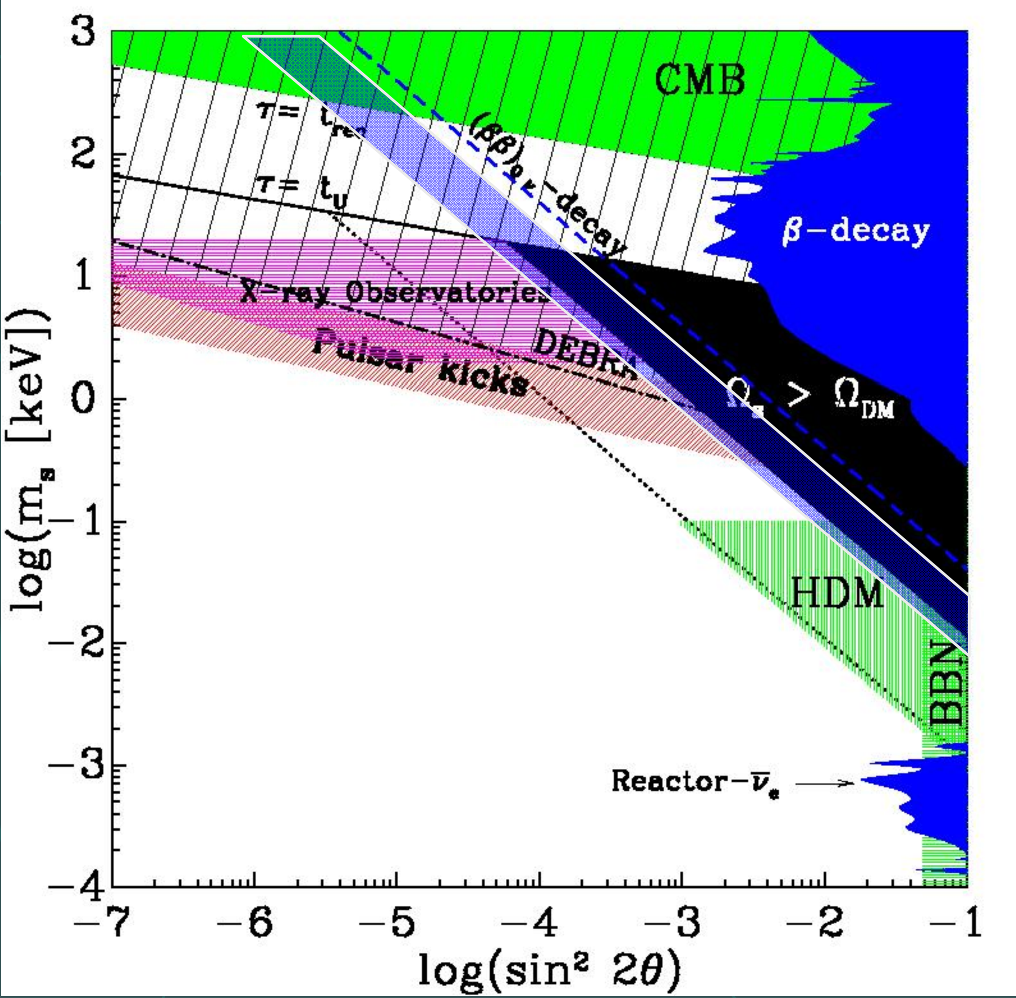
- X-ray observatories with high sensitivity for photon detection of ~ 1-10 keV → monochromatic signal for ~ 2 keV < $m_s$ < 20 keV
- Asymmetric emission of $\nu_s$ due to a strong magnetic field inside the SN → explanation for large velocities of pulsars

G. Gelmini, SPR and S. Pascoli,
Phys. Rev. Lett. 93:081302, 2004



# Majorana neutrinos
## (for $\nu_e \rightarrow \nu_s$ )

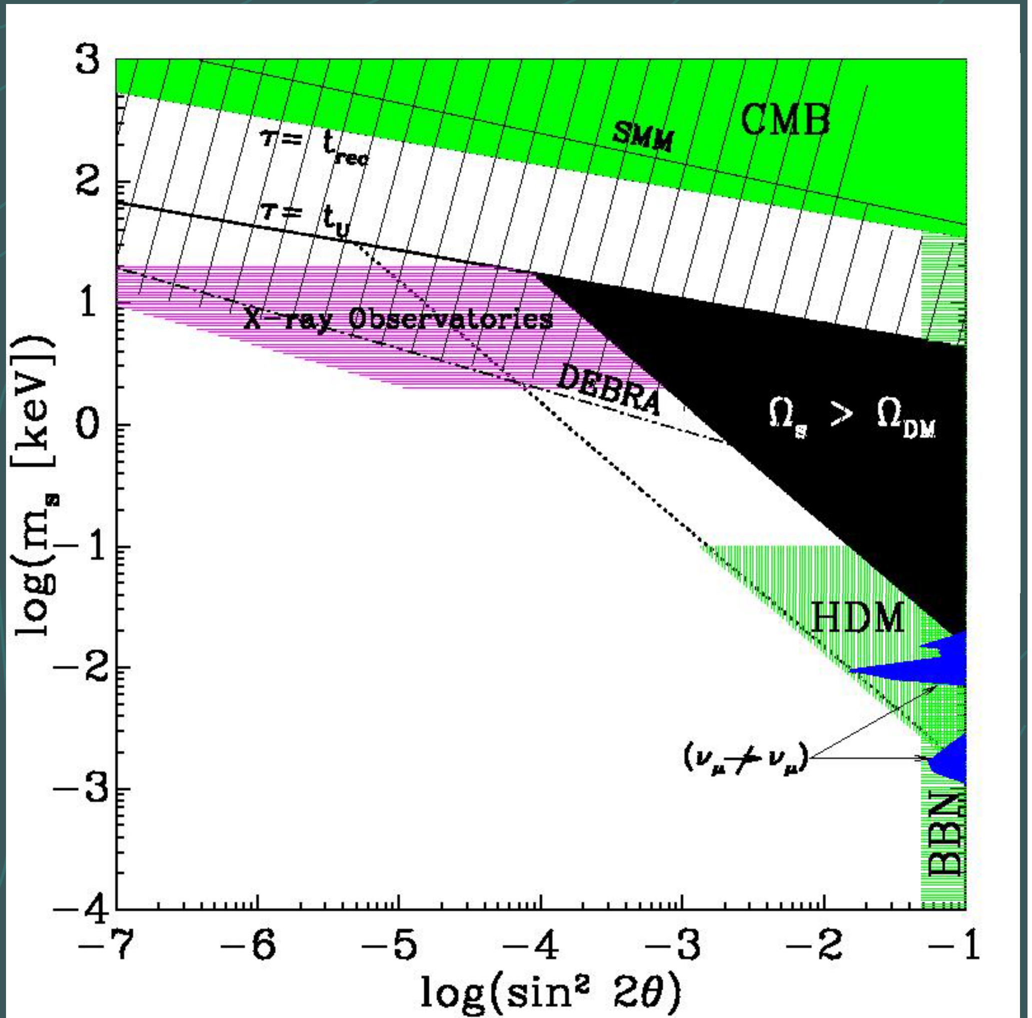
- $(\beta\beta)_{0\nu}$ – decay is allowed
- Contribution of the mostly-sterile neutrino:
  $|\langle m\rangle_s| = m_s \sin^2\theta$
- Experimental bound:
  $|\langle m\rangle| < 0.35 - 1.05$ eV $\rightarrow$
  $m_s \sin^2 2\theta < 4$ eV
- Klapdor's claim: $|\langle m\rangle| = 0.24 - 0.58$ (4.2$\sigma$)




G. Gelmini, SPR and S. Pascoli, Phys. Rev. Lett. 93:081302, 2004

# For $\nu_{\mu,\tau} \rightarrow \nu_s$

- Bounds from accelerator dissapearance experiments (CDHS)




G. Gelmini, SPR and S. Pascoli, Phys. Rev. Lett. 93:081302, 2004

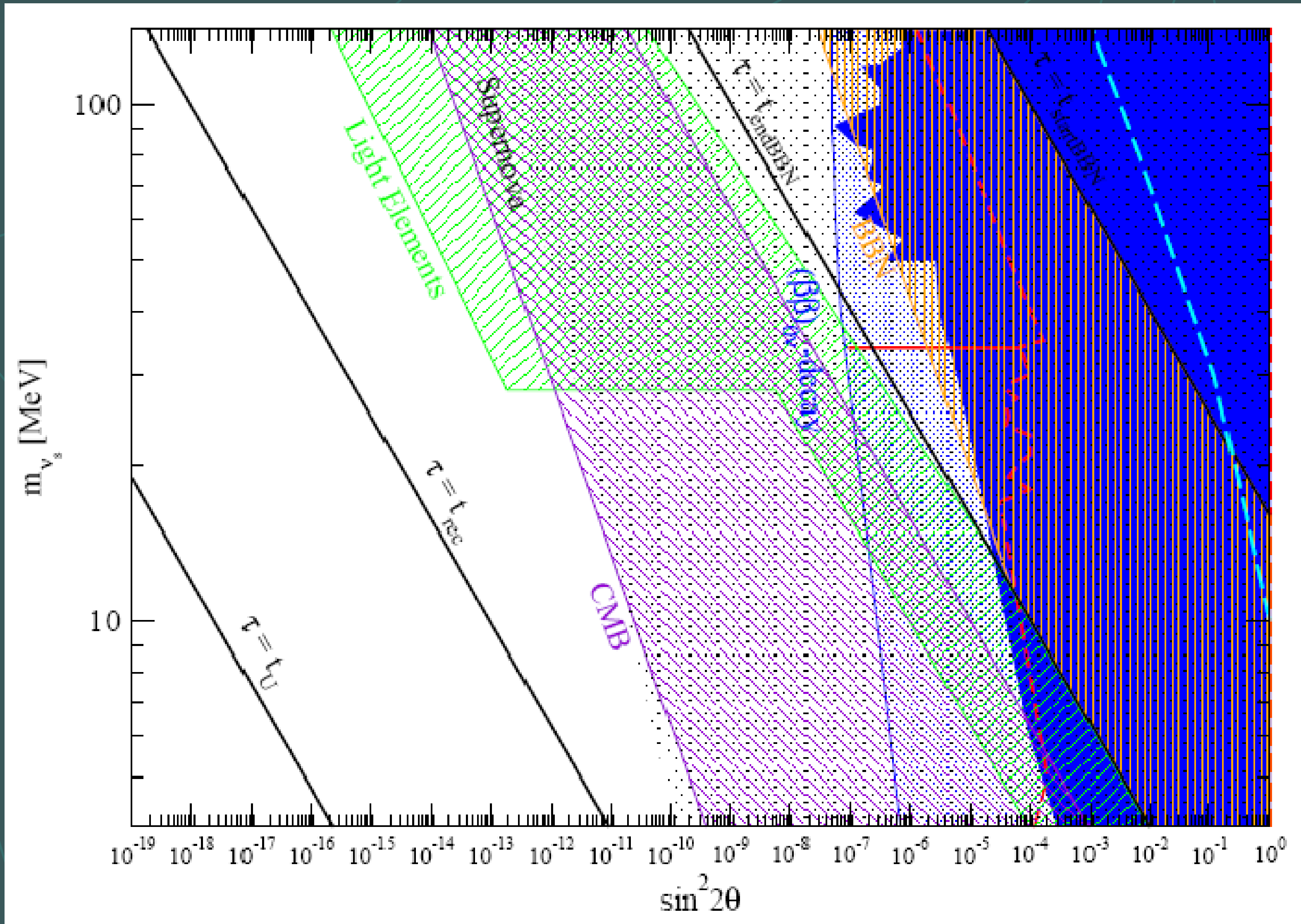
# Masses above 1 MeV and below 140 MeV

Main decay into 1 neutrino + 2 leptons

$$\tau_s = \frac{1.0\ \mathrm{sec}}{\sin^2 2\theta}\left(\frac{10\ \mathrm{MeV}}{m_s}\right)^5$$

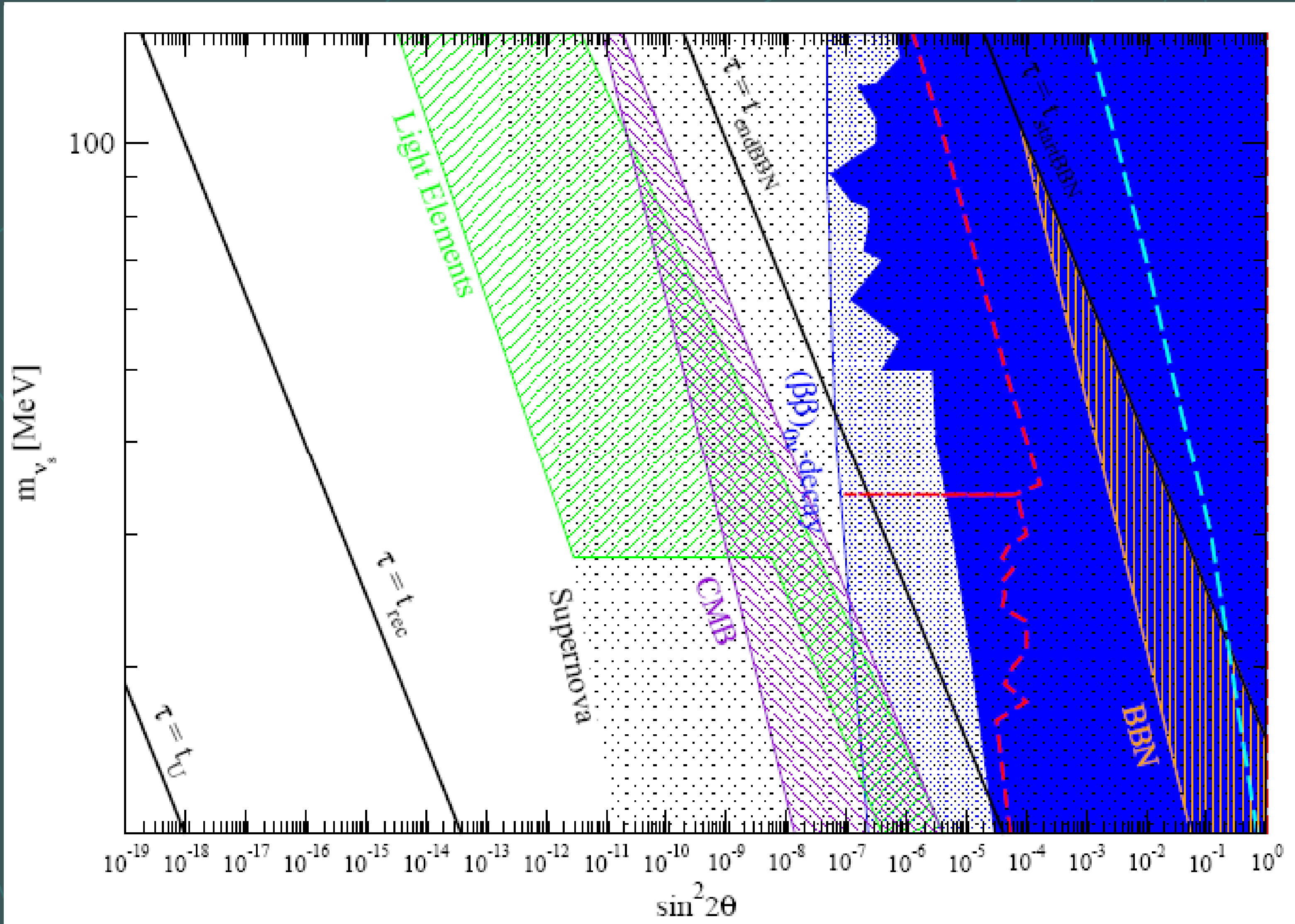
G. Gelmini, E. Osoba, SPR and S. Pascoli, JCAP 0810:029,2008

# $T_R$ = m



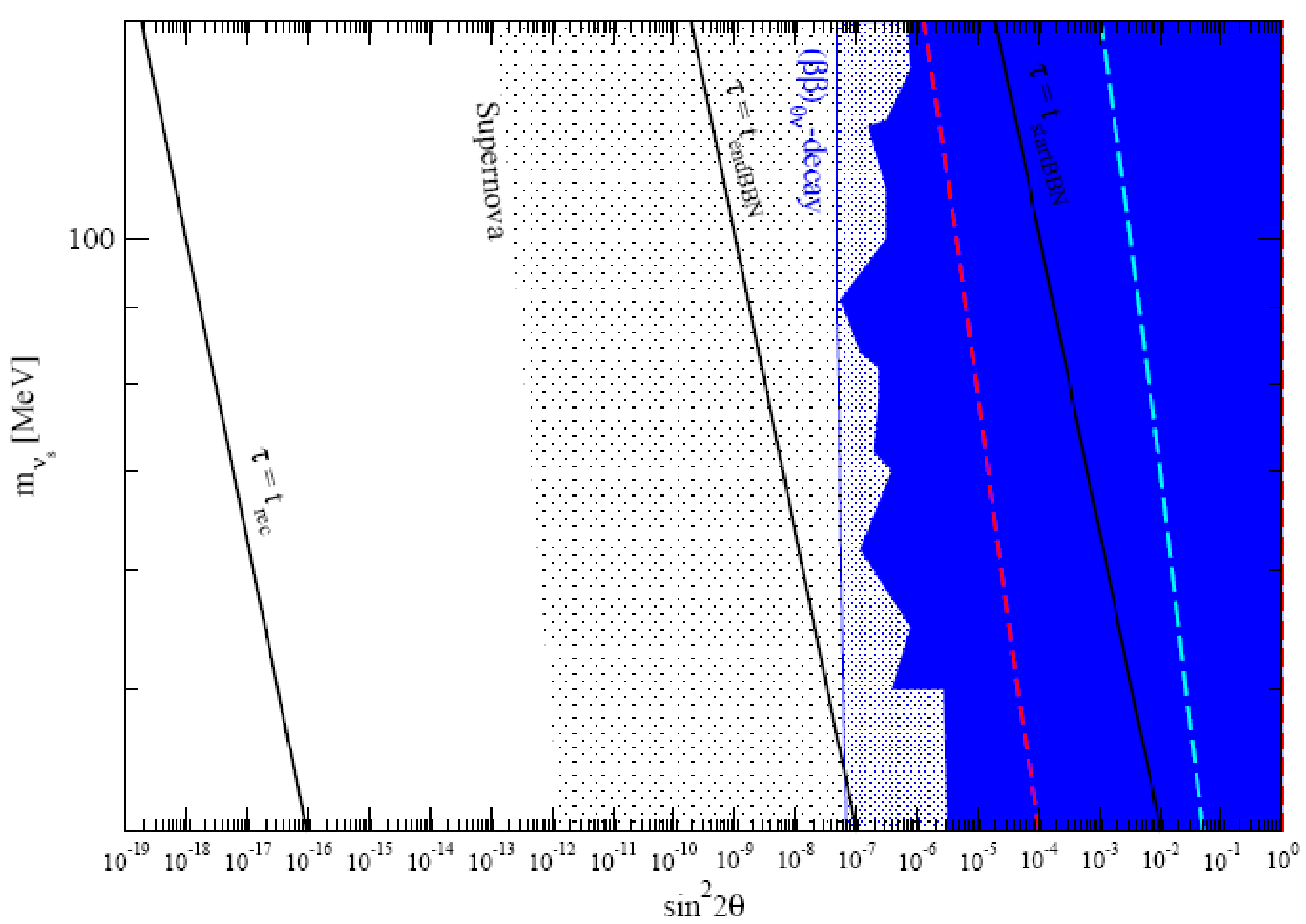

G. Gelmini, E. Osoba, SPR and S. Pascoli, JCAP 0810:029,2008

# $T_R = m/3$



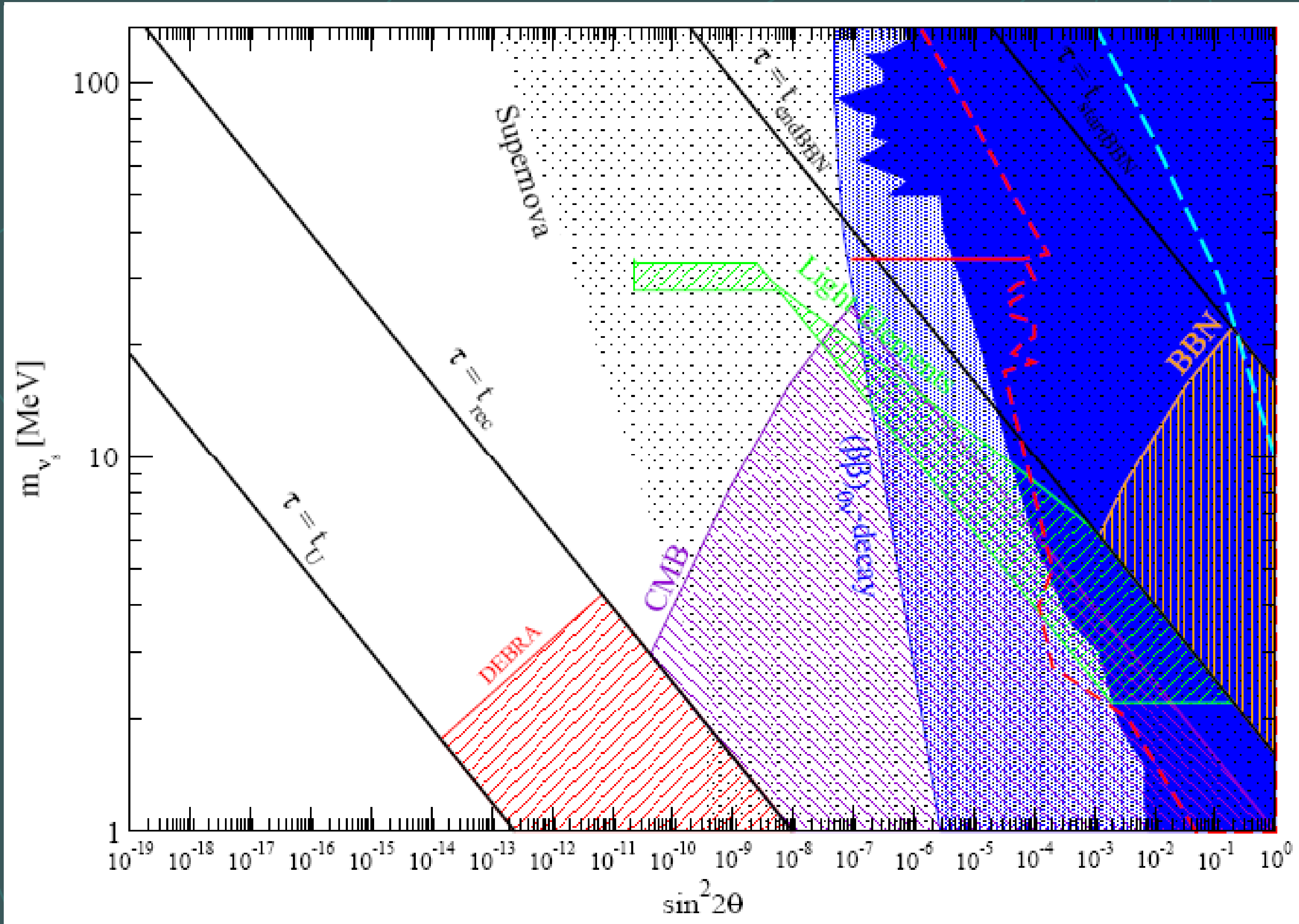

G. Gelmini, E. Osoba, SPR and S. Pascoli, JCAP 0810:029,2008

# $T_R$ = m/10




G. Gelmini, E. Osoba, SPR and S. Pascoli, JCAP 0810:029,2008

# $T_R$ = 5 MeV




G. Gelmini, E. Osoba, SPR and S. Pascoli, JCAP 0810:029,2008

# Conclusions

- A scenario with low reheating temperature would open up a new window for sterile neutrinos
- Larger mixings would be allowed, rendering sterile neutrinos to be potentially detectable in future experiments
- For example, the LSND neutrino would not have cosmological problems and then could be the "visible sterile" neutrino
- In this NSC, the bulk of DM (if not neutrinos) should consist of other non-thermally produced particles