Sterile neutrinos in cosmology and laboratories

Theory Division - Fermilab

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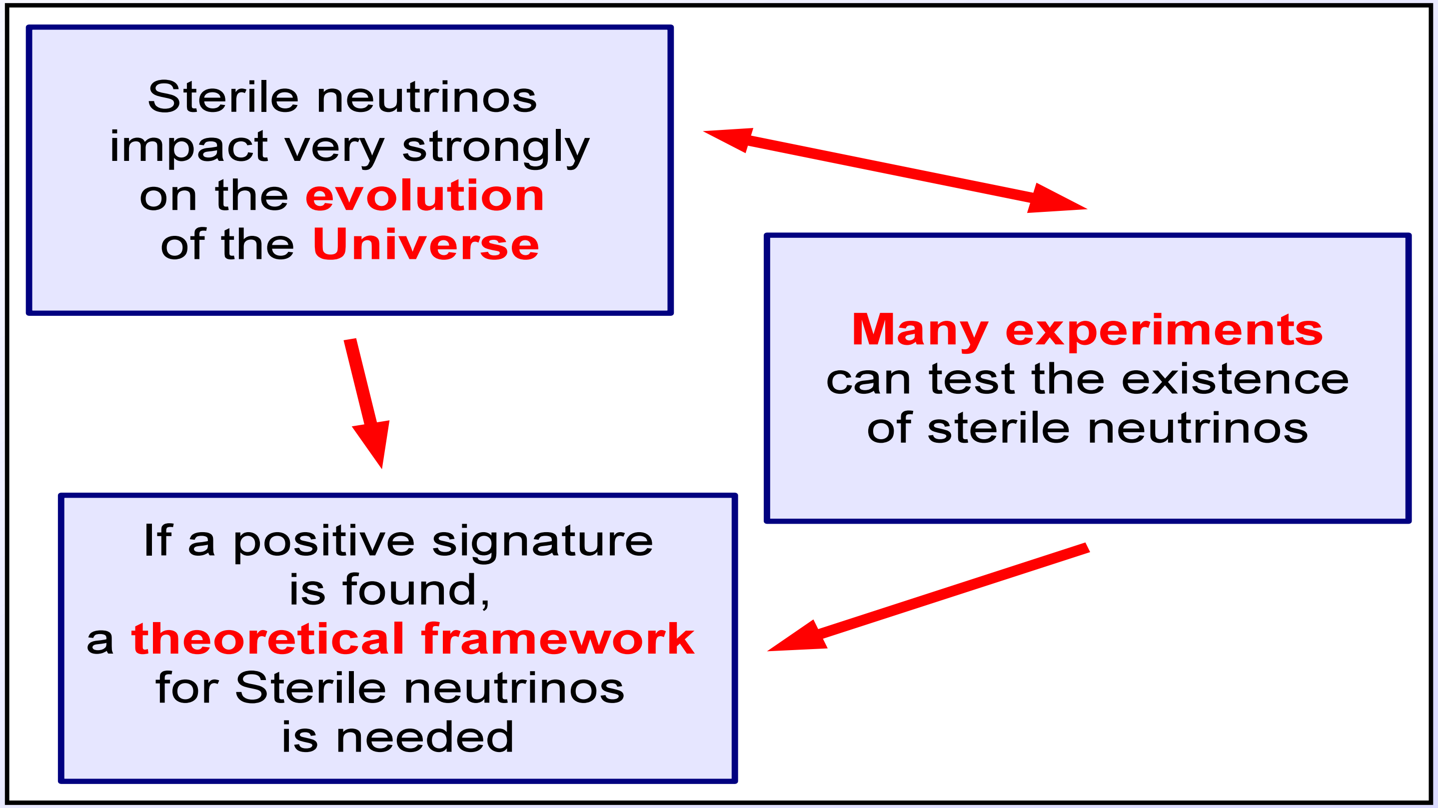
1 – Outline



- Sterile neutrinos: formalism
- Production in the Early Universe
- Cosmological constraints
- Laboratory constraints

2 – Formalism

Sterile neutrinos do not have SM interactions but can mix with the active ones:

$$\begin{cases} |\nu_1\rangle = \cos\theta|\nu_e\rangle - \sin\theta|\nu_s\rangle \\ |N_2\rangle = \sin\theta|\nu_e\rangle + \cos\theta|\nu_s\rangle \end{cases}$$

More in general we have

$$\nu_{aL} = \sum_{m=1}^{3} U_{am}\nu_{mL} + \sum_{m'=4}^{n} V_{am'} N^c_{m'L}$$

- This is the minimal extension of the Standard Model (phenomenological approach) which can account for DM (and in the νMSM also for the baryon asymmetry).

The SM Lagrangian for massive neutrinos is:

$$
\begin{aligned}
-\mathcal{L} = \quad & \left(\frac{g}{\sqrt{2}} W_\mu^+ \sum_{a=1}^{3} \overline{\nu_{aL}}\, \gamma^\mu l_L + h.c.\right) + \\
& \frac{g}{2\cos_W} Z_\mu \sum_{a=1}^{3} \overline{\nu_{aL}}\, \gamma^\mu \nu_{aL}, \\
\\
= \quad & \frac{g}{\sqrt{2}} W_\mu^+ \left(U^\dagger \overline{\nu_m} \gamma^\mu P_L \ell + V^\dagger \overline{N^c} \gamma^\mu P_L \ell \right) + h.c. \\
& + \frac{g}{2\cos_W} Z_\mu \left(U^\dagger V \overline{\nu_m} \gamma^\mu P_L N^c + h.c. \right) \\
& + \frac{g}{2\cos_W} Z_\mu \left(U^\dagger U \overline{\nu_m} \gamma^\mu P_L \nu_n + V^\dagger V \overline{N^c} \gamma^\mu P_L N^c \right).
\end{aligned}
$$

Notation: N_4 is commonly called ”sterile neutrino”, although it is a massive state.

3 – Sterile neutrino production in the EU

The simplest mechanism of ν_s production in the EU is via oscillations.

[Dodelson and Widrow, 1992]

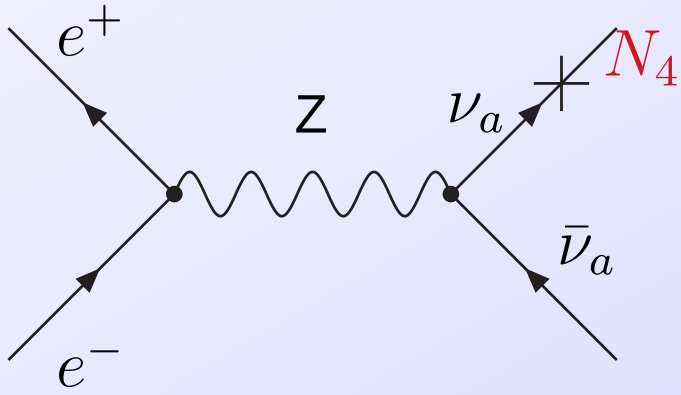
ν_a are kept in equilibrium due to the weak interaction with the other particles in the bath ($e^{\pm}$...) till

$$\boxed{\Gamma_{\rm weak} \sim H}$$

- $\Gamma_{\rm weak} = \langle\sigma\rangle n \sim G_F^2 T^2 T^3$
- $H = \sqrt{\frac{4\pi^3 g_*}{45}} \frac{T^2}{m_{\rm Pl}}$

This corresponds to a temperature: $\boxed{T_{\rm dec} \sim {\rm MeV}}$

In an interaction involving active neutrinos, a N_4 can be produced **due to loss of coherence**



The "sterile" neutrino N_4 production

- **depends on** $|V_{a4}|^2 = \sin^2\theta$
- **is controlled by** Γ_a and will stop at $T_{\rm dec}$

The probability of $N_4 \sim \nu_s$ production can be computed by looking at the evolution of the states. In the flavour basis:

$$i\frac{d}{dt}\begin{pmatrix} |\nu_a\rangle \\ |\nu_s\rangle \end{pmatrix} = \left[U\begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix}U^\dagger + \begin{pmatrix} V_a & 0 \\ 0 & 0 \end{pmatrix}\right]\begin{pmatrix} |\nu_a\rangle \\ |\nu_s\rangle \end{pmatrix}$$

One needs to diagonalise H_m using a unitary matrix given in terms of $\sin\theta_m$

$$U_m = \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix}$$

and finally the average probability of oscillation is given by

$$\langle P(\nu_a \to \nu_s; p, t)\rangle = \frac{1}{2}\langle \sin^2 2\theta_m \rangle$$

The mixing angle in the EU depends on

- **matter effects** due to an asymmetry in the weakly interacting particles

$$V_D \sim \frac{2\sqrt{2}\zeta(3)}{\pi^2} G_F T^3 (\mathcal{L} \pm \eta/4)$$

with $\mathcal{L} = (n_{\nu_a} - n_{\bar{\nu}_a})/\nu_\gamma$

- **finite temperature effects**

$$|V_T| = C_a G_F^2 T^4 E/\alpha$$

We have ($\Delta(p) = m_4^2/(2E)$)

$$\sin^2 2\theta_m = \frac{\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + D^2 + (\Delta(p)\cos 2\theta - V_D + |V_T|)^2}$$

The production of sterile neutrinos can be computed solving the Boltzmann equation

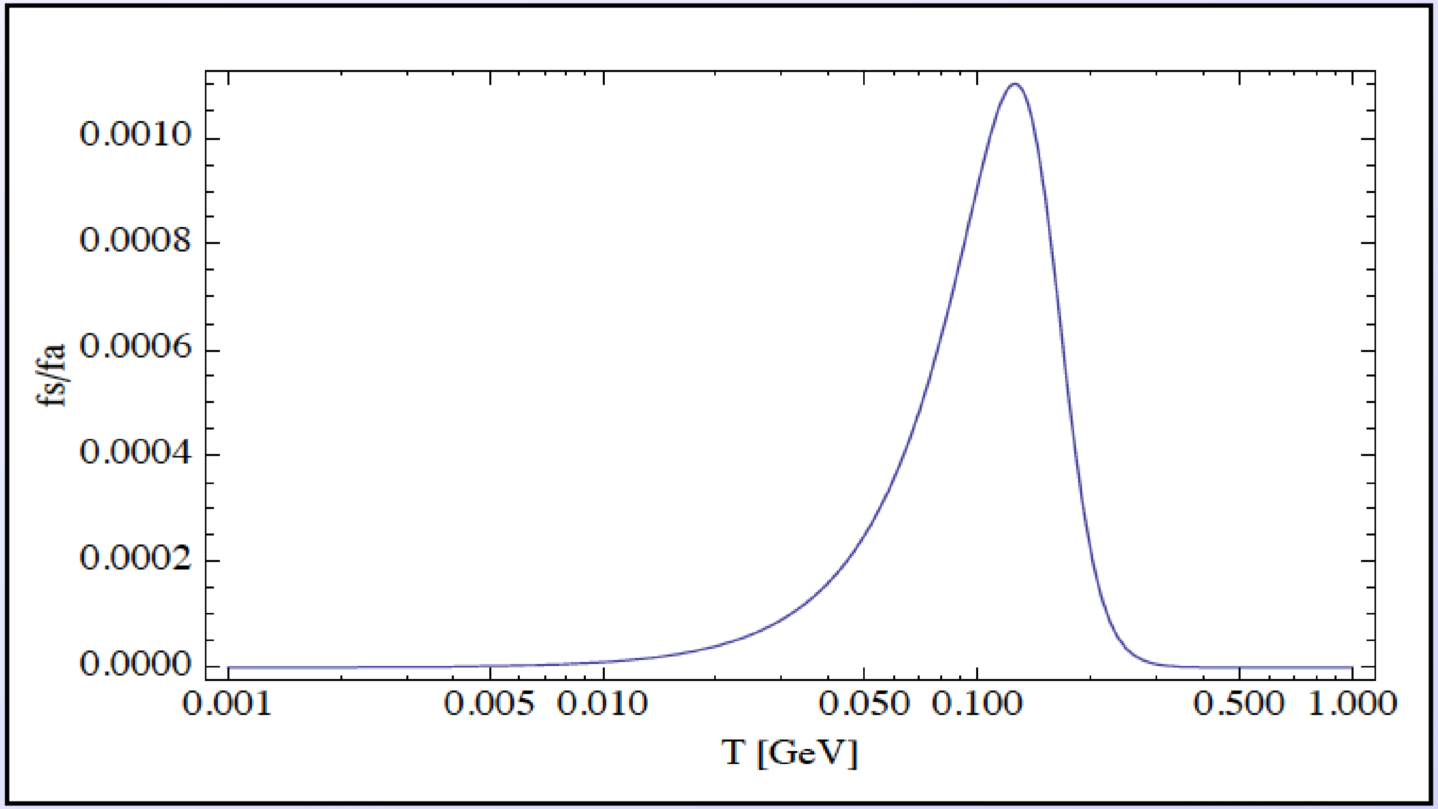
$$\frac{\partial}{\partial t} f_s(p,t) - Hp\frac{\partial}{\partial p} f_s(p,t) \simeq \frac{\Gamma_a}{2} \langle P(\nu_a \to \nu_s; p, t)\rangle \left[f_a(p,t) - f_s(p,t)\right]$$

with $\Gamma_a \sim G_F^2 p T^4$ and $f_a(p,T) = (1+e^{E/T})^{-1}$ the equilibrium distribution for ν_a.

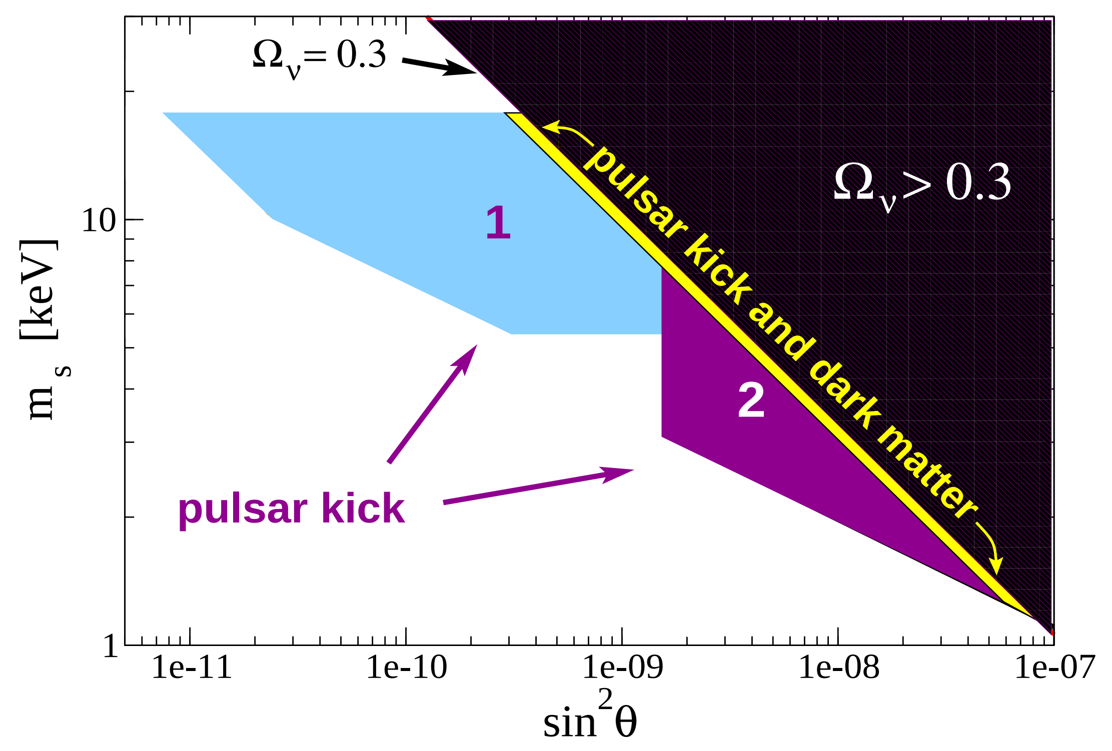
$$\boxed{\frac{\partial f_s}{\partial T}\Big|_{E/T} = -\frac{\Gamma_a}{2HT} \sin^2 2\theta_m \left[f_a(p,T) - f_s(p,T)\right]}$$

For the non-resonant production,

- at high T, the production is suppressed by $\sin^2 2\theta_m$
- at small T by $\Gamma_a \propto T^5$
- the maximum of production happens at $T_{\max} \simeq 133 \text{ MeV} \left(\frac{m_4}{1\text{keV}}\right)^{1/3}$



The final abundance is $$\Omega_4 h^2 \simeq 0.3 \frac{\sin^2 2\theta}{10^{-8}} \left(\frac{m_4}{10\mathrm{keV}}\right)^2$$



[Fuller, Kusenko, Mocioiu, S.P., 2003; see also Dodelson, Widrow, 1992; Abazajian et al. 2001]

4 – A multiflavour approach

If more than one sterile neutrino is present, ν_h, it is convenient to use the density matrix formalism, $\hat{\rho}^i_j = |\nu_i\rangle\langle\nu_j|$. The Boltzmann equation can be rewritten as

$$\dot{\rho} = i\,[H_m + V_a, \rho] - \{\Gamma, (\rho - \rho_{\rm eq})\}$$

- $H_m = U H_0 U^\dagger$
- $V_a = -C_a G_F^2 T^4 E/\alpha$
- $\{\Gamma, (\rho - \rho_{\rm eq})\}$ describes the loss of coherence responsible for ν_h production

If the typical frequency of oscillation is faster than the expansion of the Universe, the static approximation is valid $\dot{\rho}_{ah} = 0$ and $\dot{\rho}_{sp} = 0$.

One can solve a system of linear equation and find ρ_{ah}, ρ_{sp} which will be given by (for real mixing matrix and no mixing in the sterile sector):

$$\rho_{ah} \simeq \rho_{eq} \frac{\sum_i m_i^2/(2E) U_{ai} U_{hi}}{(H_{aa} - H_{hh} + i\Gamma_a)} ,$$

The density of sterile neutrino is then given by:

$$\boxed{\dot{\rho}_{hh} = -2 \sum_a H_{ha} \mathrm{Im}(\rho_{ah}) \propto \sum_a U_{ah}^2 \Gamma_a}$$

- The integration can be performed as in the 2-ν case to find

$$\Omega_h h^2 = 7 \times 10^{-1} \frac{m_h^2}{10\mathrm{keV}^2} \sum_a \frac{g_a}{\sqrt{C_a}} \frac{U_{aj}^2}{10^{-8}}$$

For mixing in the sterile sector, $\rho_{sp} \neq 0$ but an analytical approximation also holds. The growth of each ρ_{hh} can be followed separately.

- The final abundance for each sterile neutrino is the sum of the contribution of mixing with each active neutrino!!!

[Melchiorri, Mena, Palomares-Ruiz, SP, Slosar, Sorel, 2009]

5 – The low reheating case

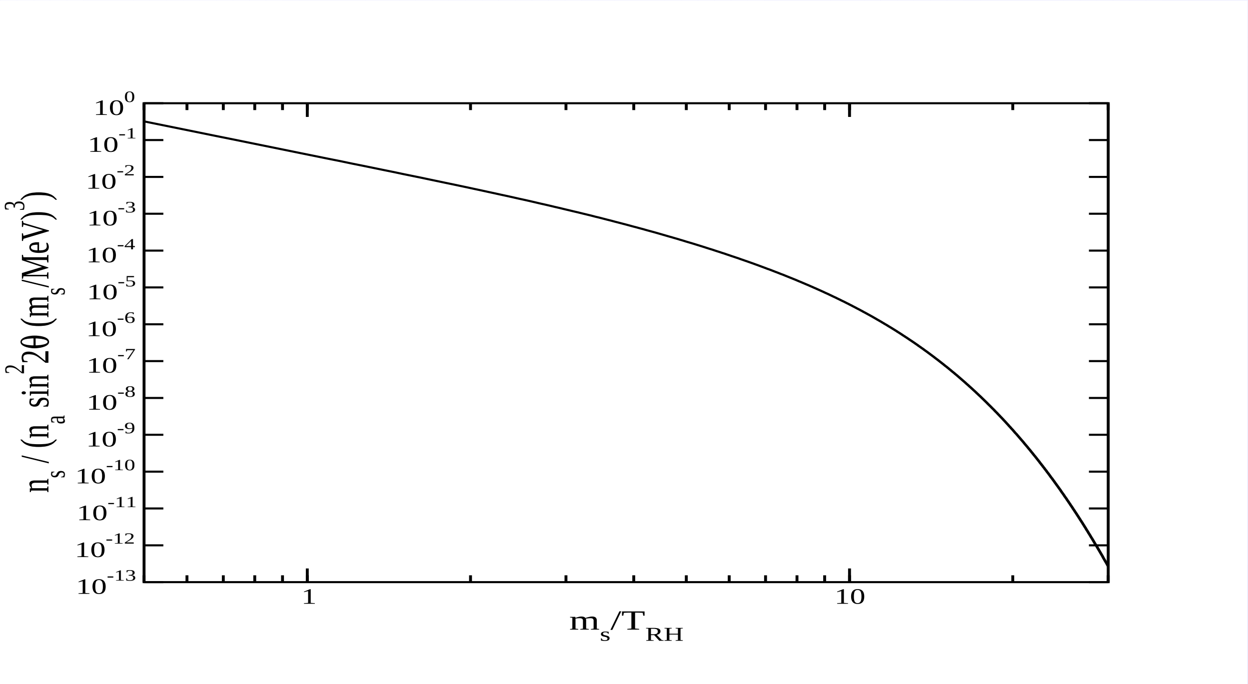
If the reheating temperature is low ($T_R \sim 5$ MeV), the production of sterile neutrinos in the Early Universe is strongly suppressed.

$$\boxed{T_R \ll T_{\rm MAX}}$$

The allowed $\sin^2\theta$ can be much larger than in the conventional case.

The sterile neutrinos can give a signature in future terrestrial experiments and astrophysical observations.

[Gelmini, Palomares-Ruiz, SP, 2005]



[Gelmini, Palomares-Ruiz, SP, 2005; Gelmini, Osoba, Palomares-Ruiz, SP, 2008]

For small masses, we have

$$\boxed{\Omega_s h^2 \simeq 0.1 \left(\frac{\sin^2 2\theta}{10^{-3}}\right) \left(\frac{m_s}{1\ \mathrm{keV}}\right)^3 \left(\frac{T_R}{5\mathrm{MeV}}\right)^3}$$

The production is significantly suppressed.

6 – Resonant sterile neutrino production

In presence of a large lepton asymmetry, $\mathcal{L} \equiv (n_\nu - n_{\bar{\nu}})/n_\gamma$, matter effects become important and the mixing angle can be resonantly enhanced. [Shi, Fuller, 1998; Kishimoto, Fuller, 2008; Abazajian et al., 2001]

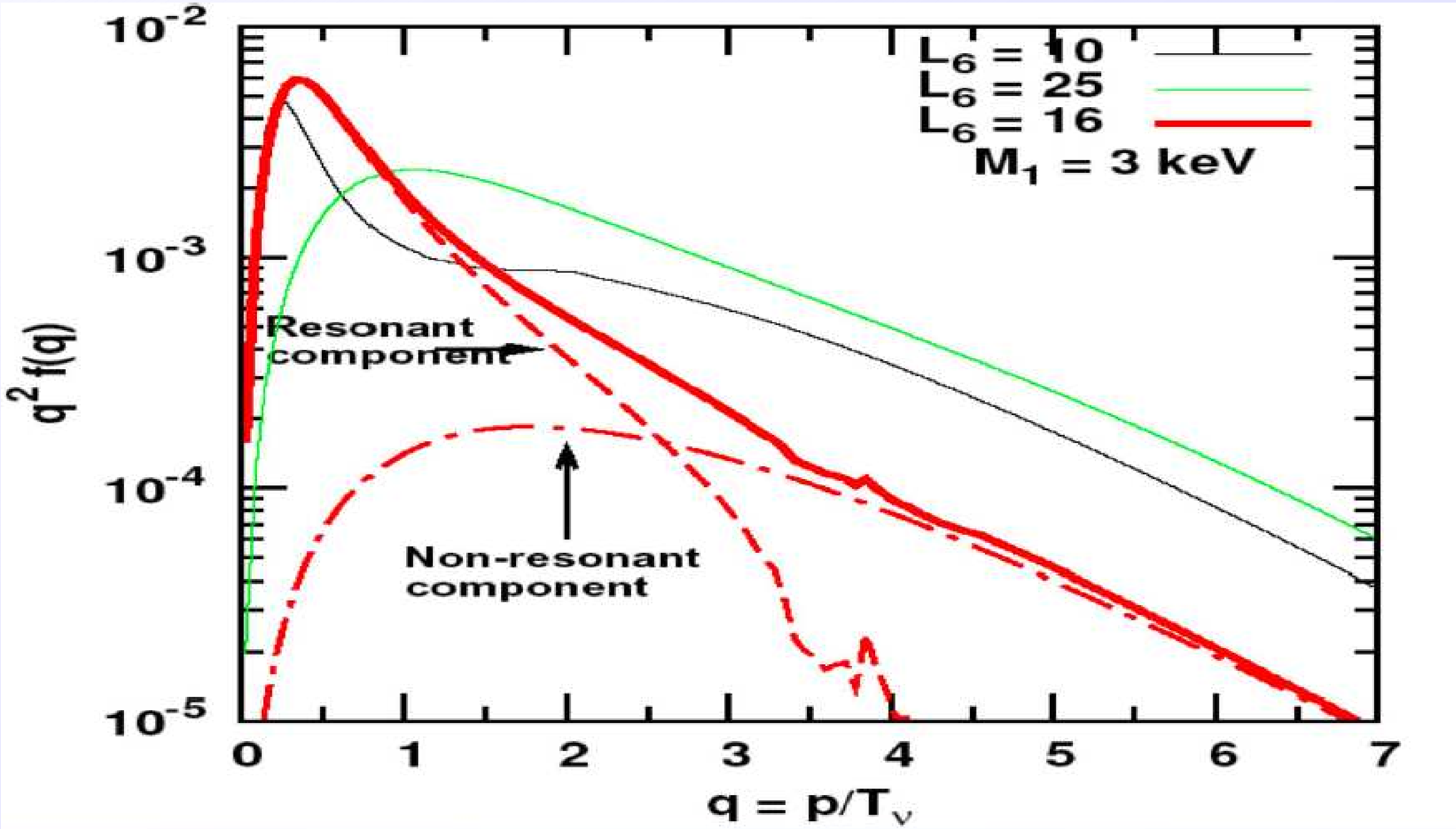
$$\sin^2 2\theta_m = \frac{\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + D^2 + \left(\Delta(p)\cos 2\theta - \frac{2\sqrt{2}\zeta(3)}{\pi^2} G_F T^3 \mathcal{L} + |V_T|\right)^2}$$

The mixing angle is maximal $\sin^2 2\theta_m = 1$ when the resonant condition is satisfied (with $\Delta(p) \equiv m_4^2/(2p)$)

$$\Delta(p)\cos 2\theta - \frac{2\sqrt{2}\zeta(3)}{\pi^2} G_F T^3 \mathcal{L} + |V_T| = 0$$

- The production (both resonant and incoherent) is enhanced with respect to the case of negligible lepton asymmetry and much smaller values of the vacuum mixing angles are required.

- The resonance enhancement of the conversion happens first for the lowest values of p/T and this results in a final distribution which is peaks at much smaller values of p/T, with $\langle p/T \rangle \sim 0.6$.



This is a "cool" dark matter candidate.

7 – Sterile neutrino production summary

A population of keV sterile neutrinos, which constitute the DM, can be produced out-of equilibrium in the EU via various mechanisms:

- non-resonant production
- resonantly enhanced oscillations
- low reheating scenario
- boson decays

For a spectrum proportional to the equilibrium one, $p/T \sim 3.15$, while for the resonant production ($p/T \sim 2$) and for a subsequent injection of entropy in the thermal plasma ($p/T \sim 0.7$) it is much colder.

8 – Cosmological constraints

The impact of ν_s in the Early Universe depends critically on their life-time.

N decay due to their mixing with active neutrinos via CC and NC:

$m_N < 1$ MeV: $N \to \nu\nu\bar{\nu}$;

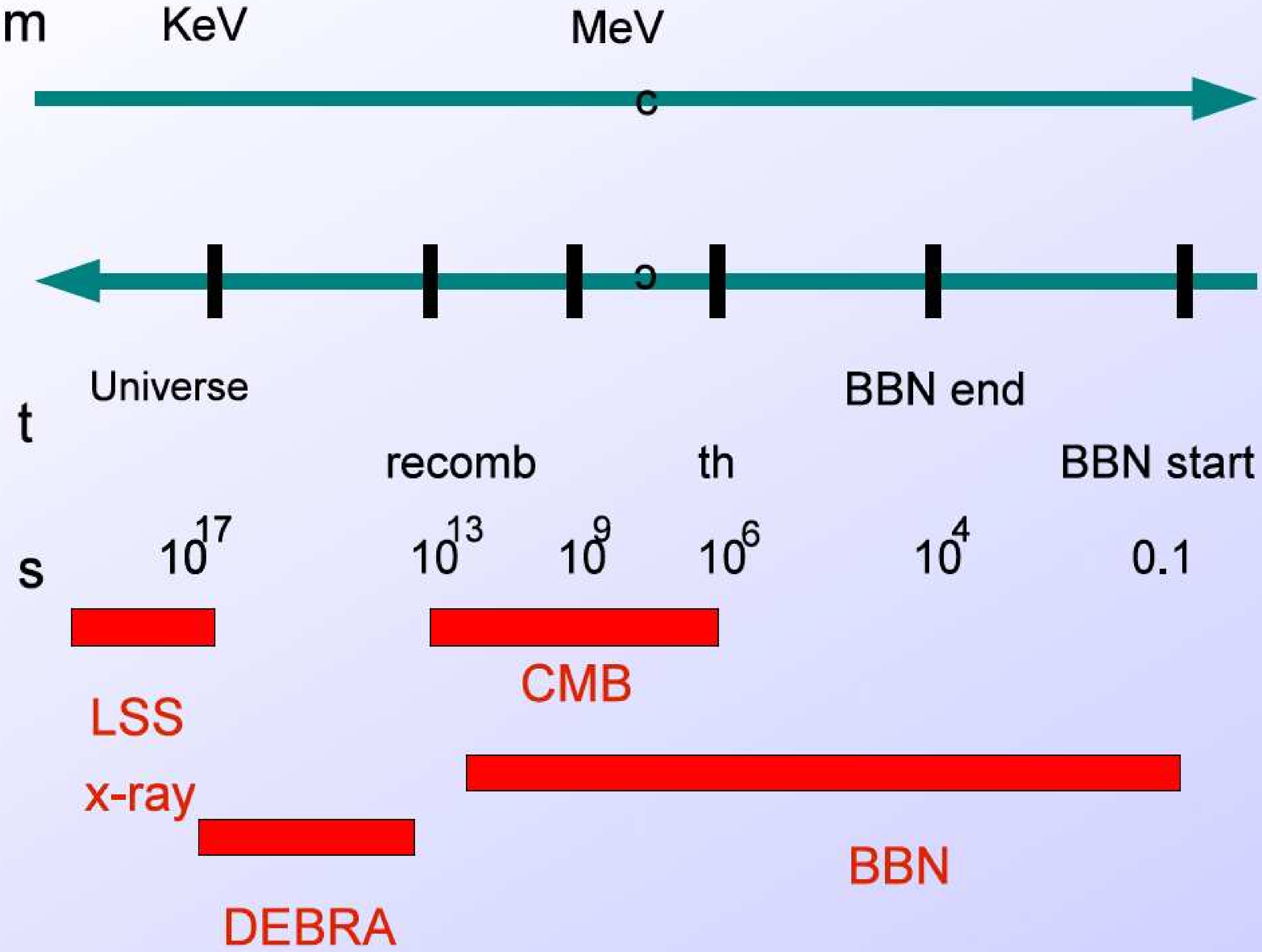
$1\,\mathrm{MeV} < m_N < m_\pi$: $N \to e^+ e^- \nu$;

$m_N > m_\pi^0$: $N \to \pi^0 \nu$...

The decay rates is given by:

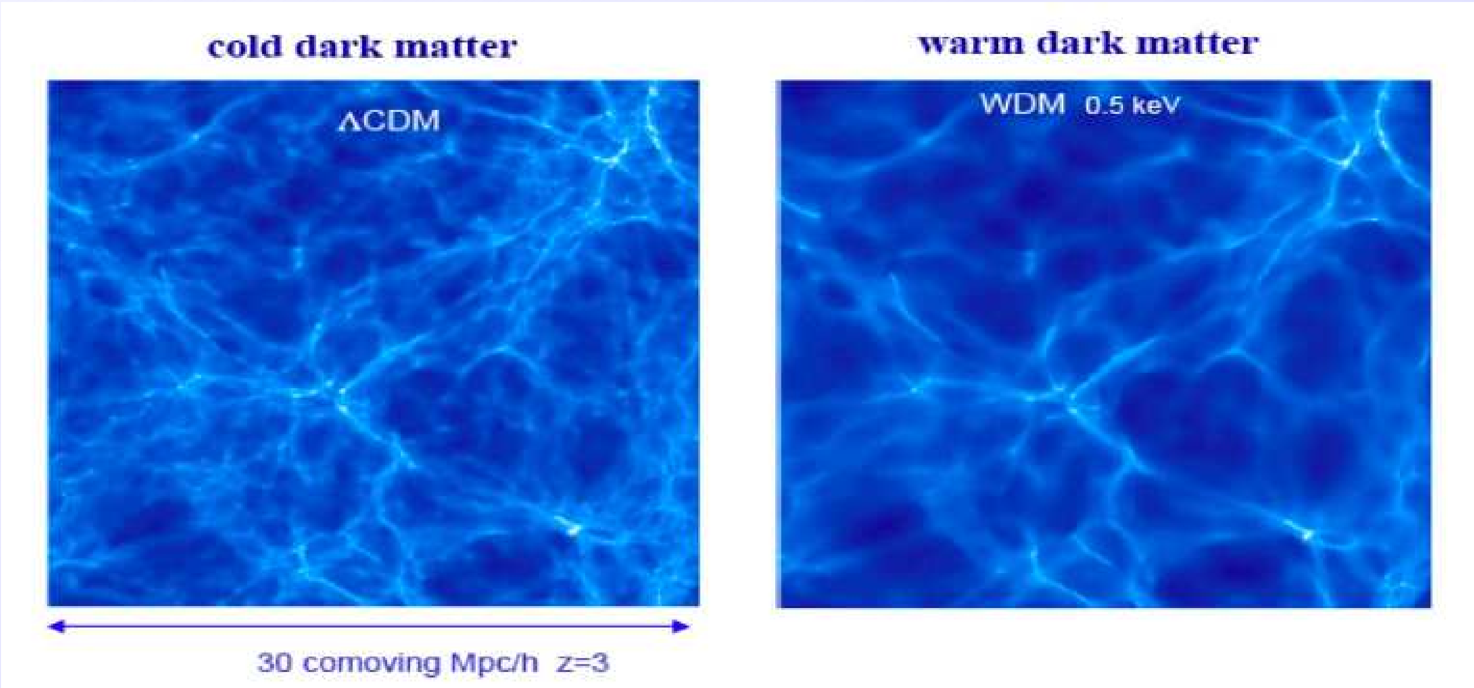
$$\Gamma^{3-\mathrm{body}} \propto \frac{1}{768\pi^3} G_F^2 m_N^5 \, |V_{l4}|^2$$

$$\Gamma^{2-\mathrm{body}} \propto \frac{1}{16\pi} G_F^2 m_N^3 \, |V_{l4}|^2$$


m
KeV
MeV
c
c
Universe
t
recomb
th
BBN end
BBN start
s
10^17
10^13
10^9
10^6
10^4
0.1
LSS
x-ray
CMB
DEBRA
BBN

9 – Large scale structure formation constraints

KeV sterile neutrinos behave as a WDM component: at large scales the formation of structure happens as for CDM but perturbations at small scales get erased due to the free-streaming.

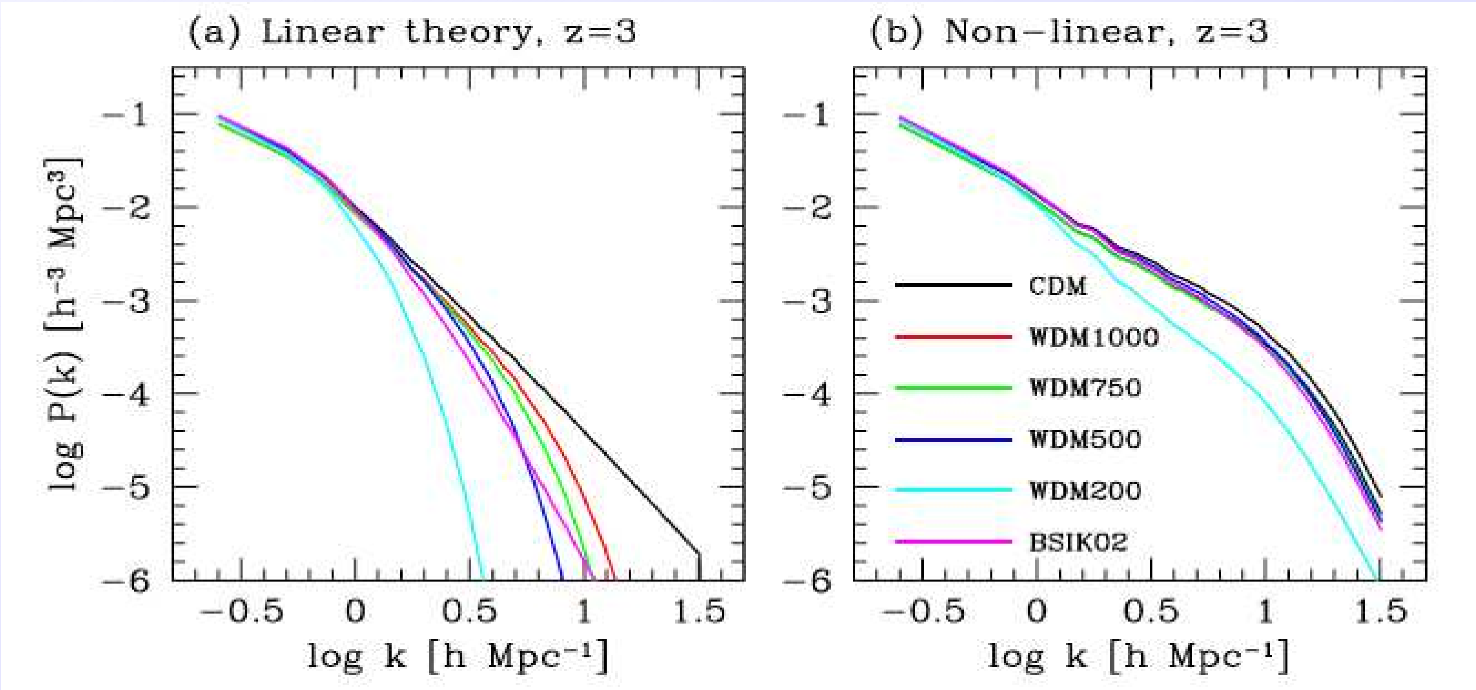


[see, e.g. Haehnelt]

The amount of structures in the Universe at a certain scale is measured by the matter power spectrum $P(k)$:

$$P(k) = \langle | \frac{\delta\rho_m}{\bar{\rho}_m} |^2 \rangle$$

This can be probed by observations of the matter distribution in the Universe.



[see e.g. Narayanan et al., 2000]

10 – Indirect searches

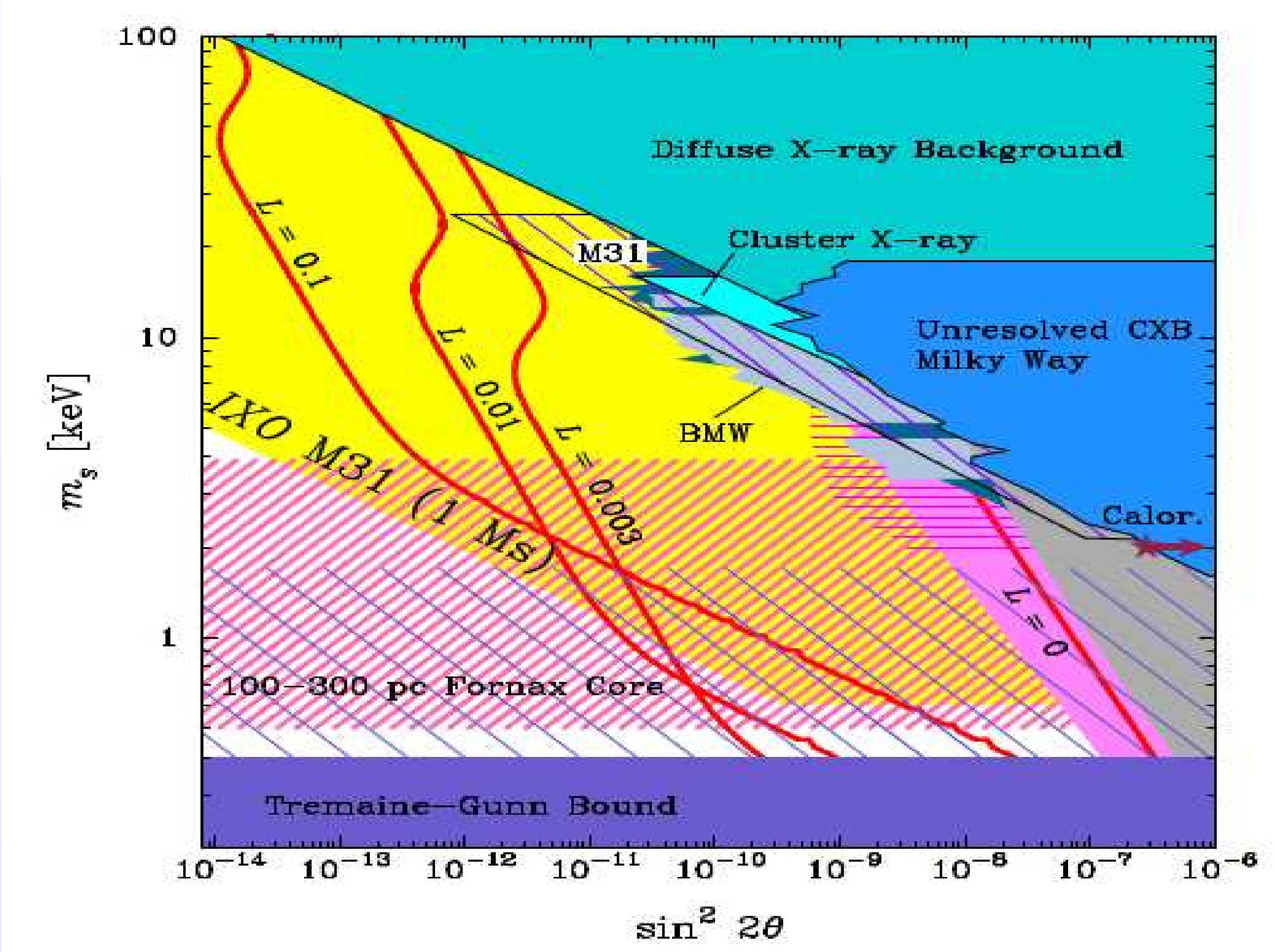
- KeV N_4: they can decay into $3\nu_a$ and $\nu_a\gamma$ due to the mixing with active neutrinos. [Boehm and Vogel, 1987; Barger et al., 1995; Pal, Wolfenstein, 1982]

The decay rate is given by

$$\Gamma_{3\nu} \simeq \sin^2 2\theta \, G_F^2 \frac{m_4^5}{768\pi^3} \sim 10^{-30}\mathrm{s}^{-1} \frac{\sin^2 2\theta}{10^{-10}} \left(\frac{m_4}{\mathrm{keV}}\right)^5$$
$$\Gamma_{\nu\gamma} \simeq \sin^2 2\theta \, \alpha G_F^2 \frac{9m_4^5}{2048\pi^4} \sim 10^{-32}\mathrm{s}^{-1} \frac{\sin^2 2\theta}{10^{-10}} \left(\frac{m_4}{\mathrm{keV}}\right)^5$$

The photon from the decay carries away an energy $E_\gamma = \frac{m_4}{2}$

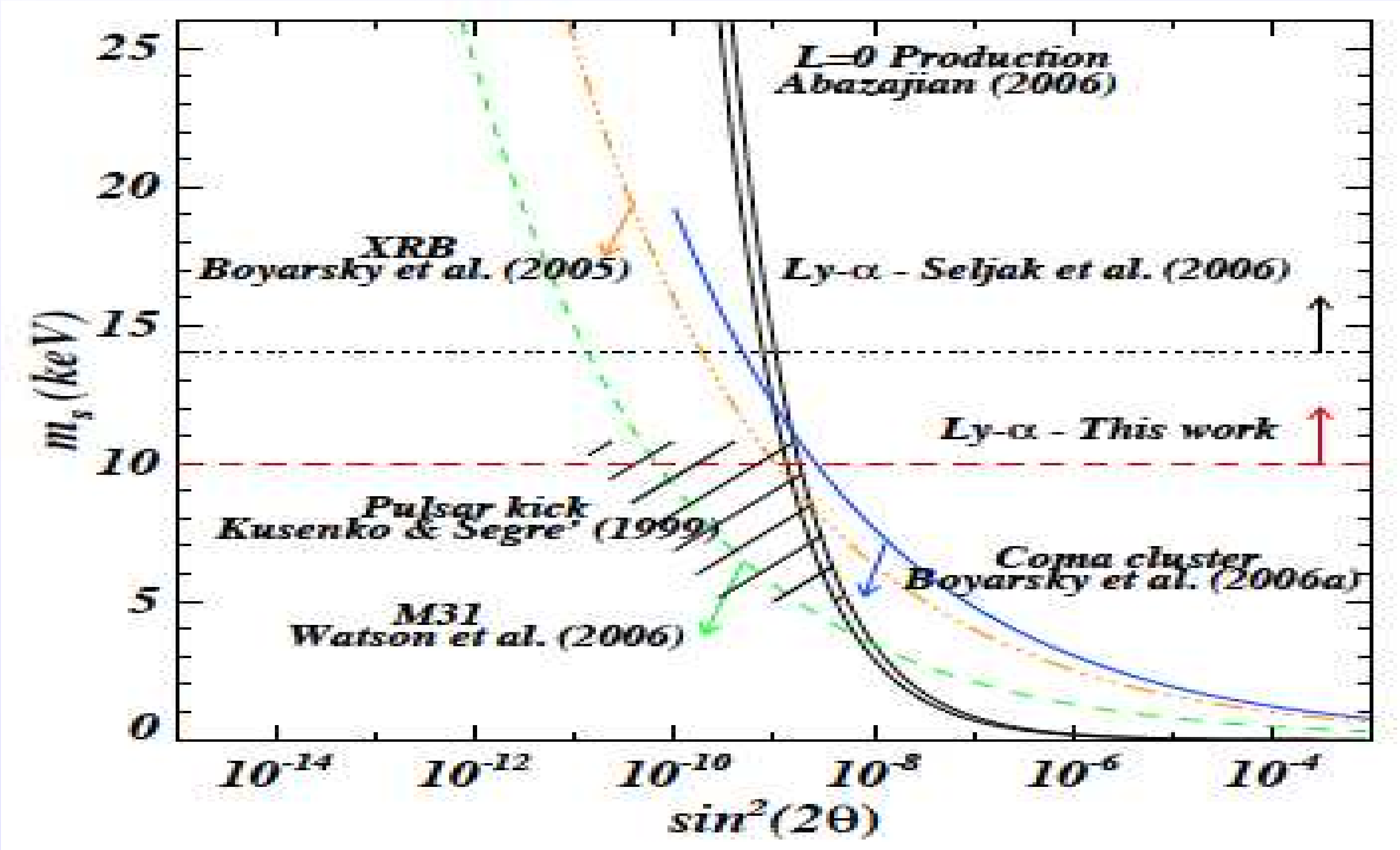
Searches of a γ line in X-ray observatories which point towards objects with DM overdensities (dwarf galaxies, M31, the center of our galaxy) or DEBRA.



[Abazajian, 0903.2040; See also Abazajian, Fuller, Patel, 2001; Abazajian, Fuller, Tucker, 200; Dolgov, Hansen, 2002; Boyarsky et al., 2006, 2007; Loewenstein et al., 2008; Watson et al., 2006]

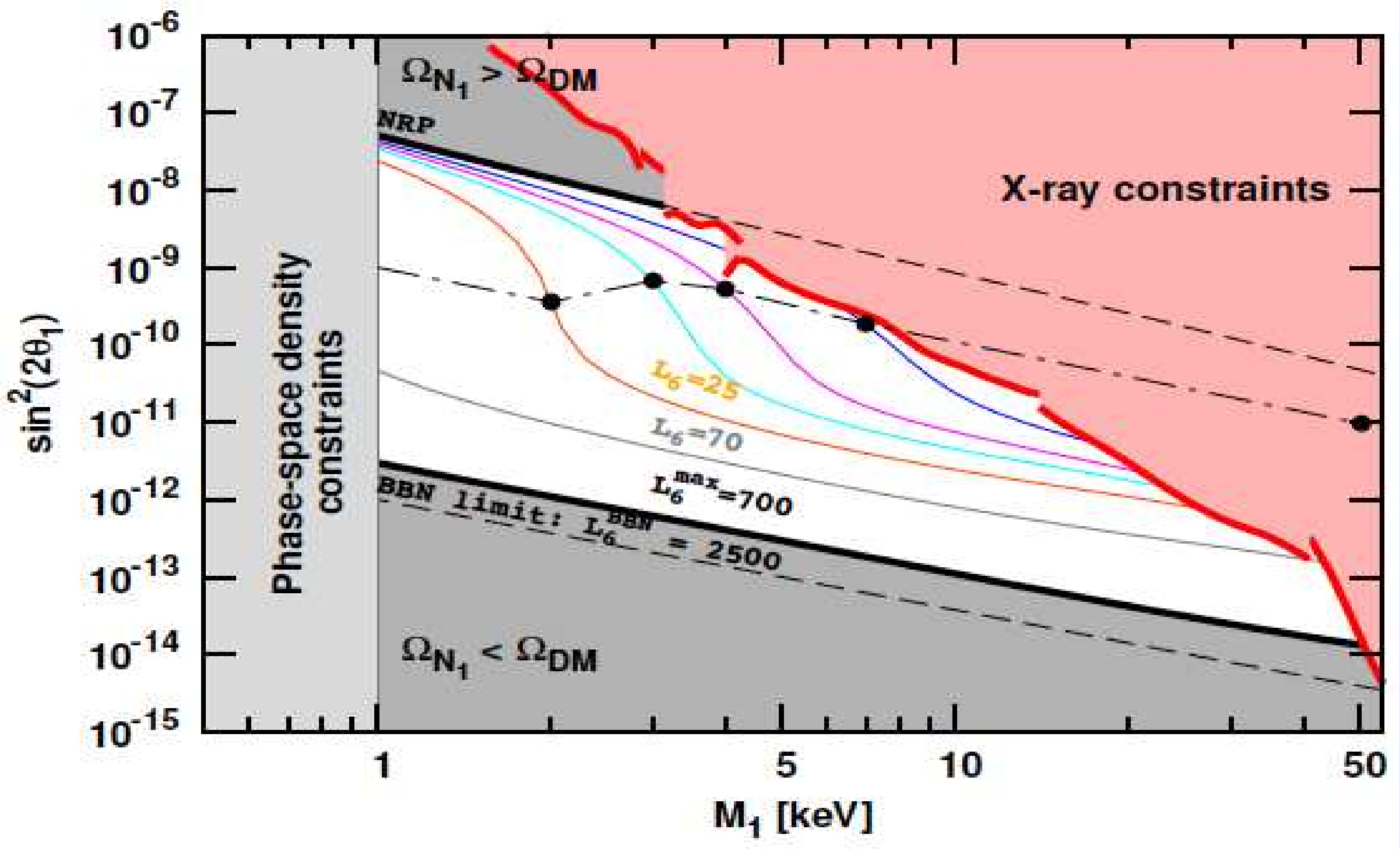
Tension between LSS and x-ray constraints

For a WDM sterile neutrino from DW non-resonant production, the lower bound on m_4 from LSS observations and the upper bound coming from x-ray searches exhibit a strong tension.



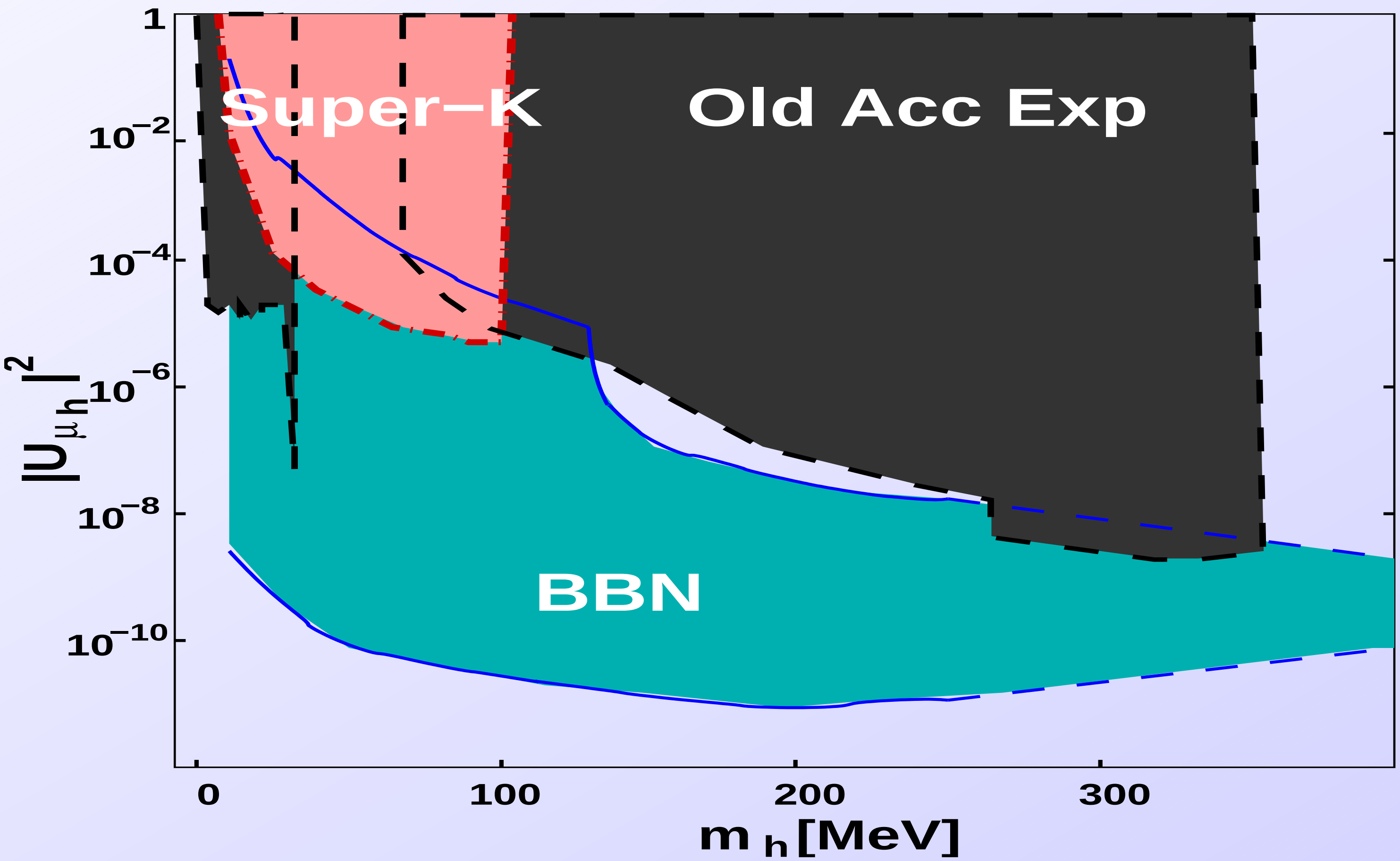
[Viel et al., 2006]

This tension can be avoided if a colder DM component is present or it the spectrum is peaked at smaller p (as in RP or boson decay).



[Boyarsky et al., 2009]

- **MeV N_4**: they produce copious amounts of γ $(N_4 \to \pi^0\nu \to \gamma\gamma\nu)$ and affects BBN.

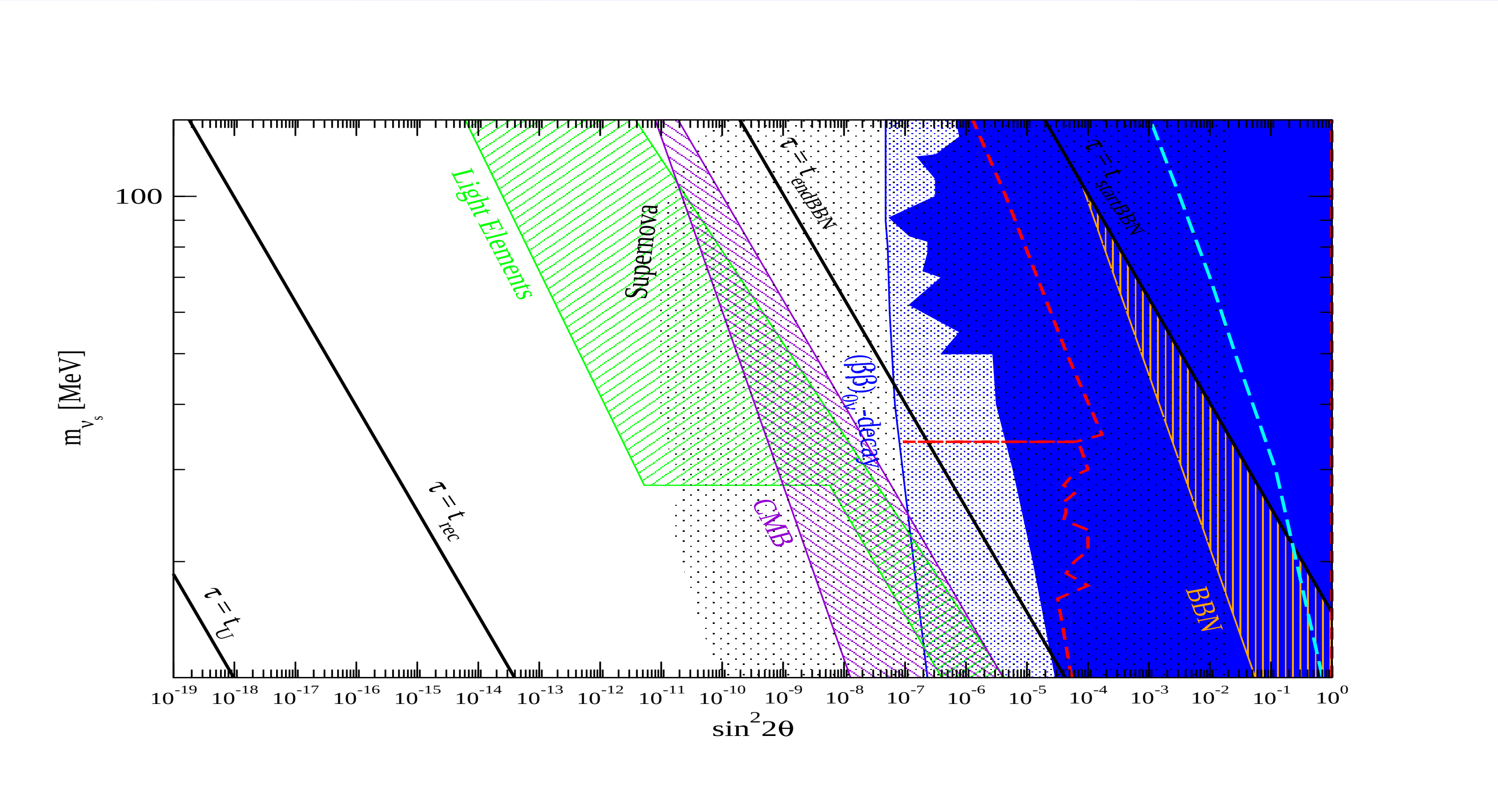


[Kusenko, SP, Semikoz, 2004]

These bounds can be avoided if

- sterile neutrinos couple predominantly to other light non-standard model particles;

- the production in the EU was suppressed by a low reheating temperature.



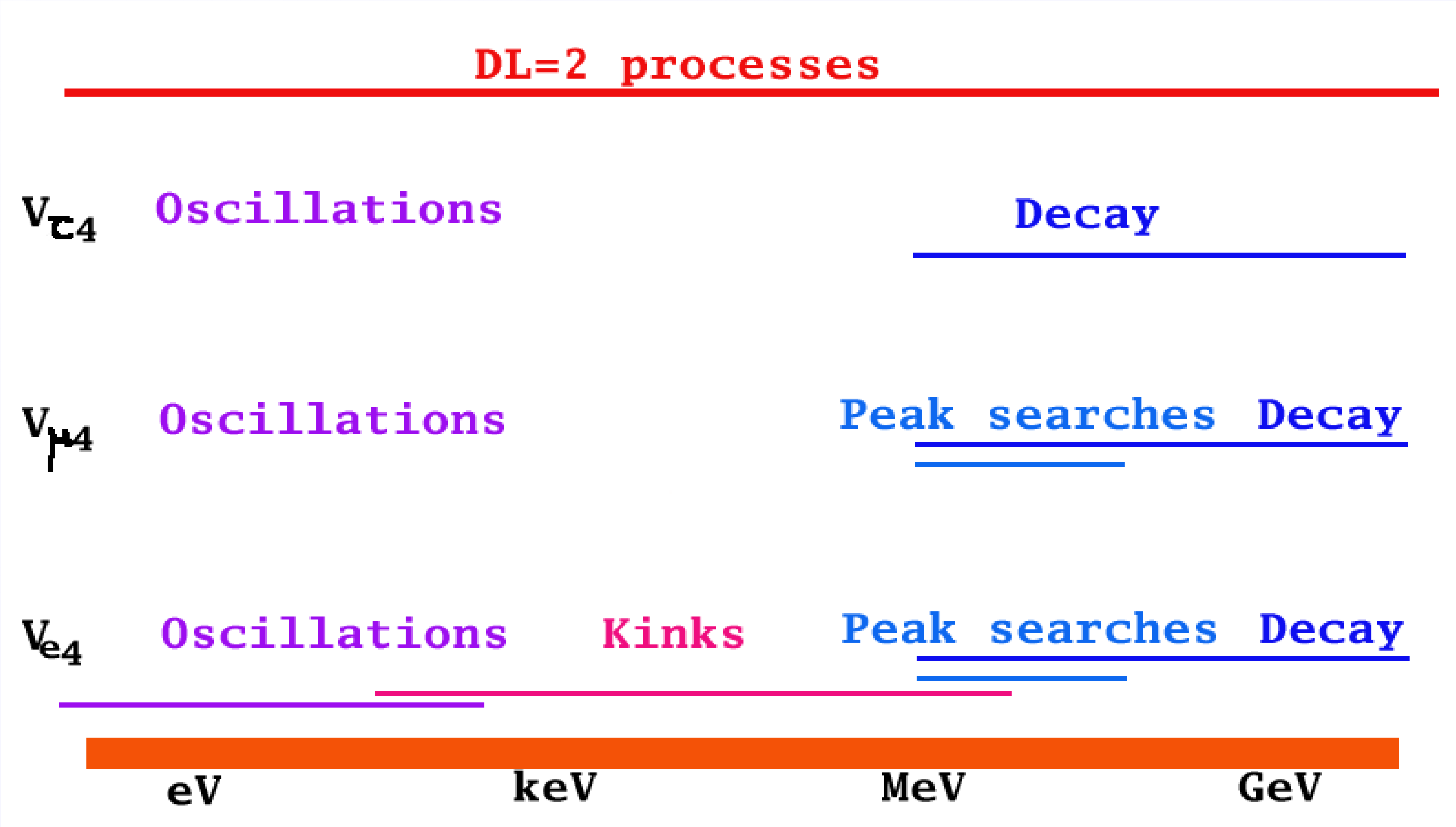
[Gelmini, Osoba, Palomares-Ruiz, SP, 2008]

11 – Summary of cosmological constraints

- Sterile neutrinos in the KeV range are a viable WDM (to CDM) candidate.
- If produced via non-resonant oscillations, tension between LSS constraints and x-ray searches.
- Other mechanisms of production (with smaller mixing angles and/or colder spectra) avoid this tension.

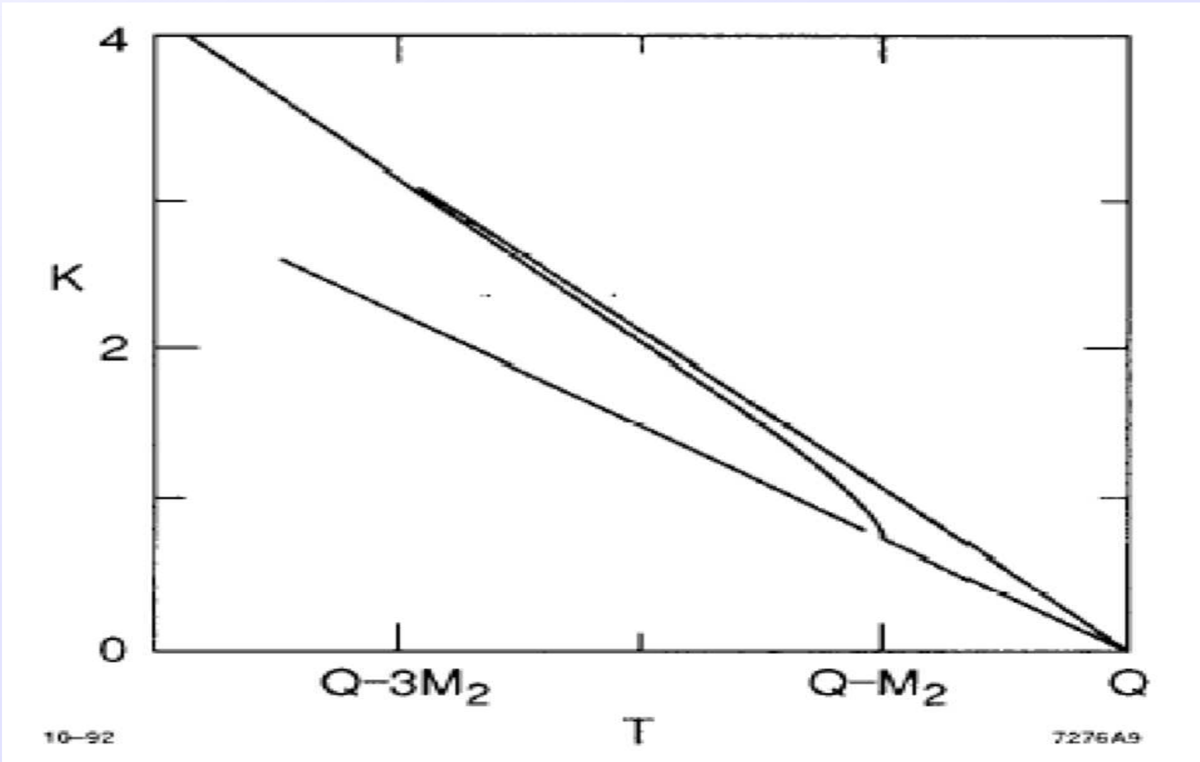
12 – Laboratory constraints

The signatures of N depend on its mass:

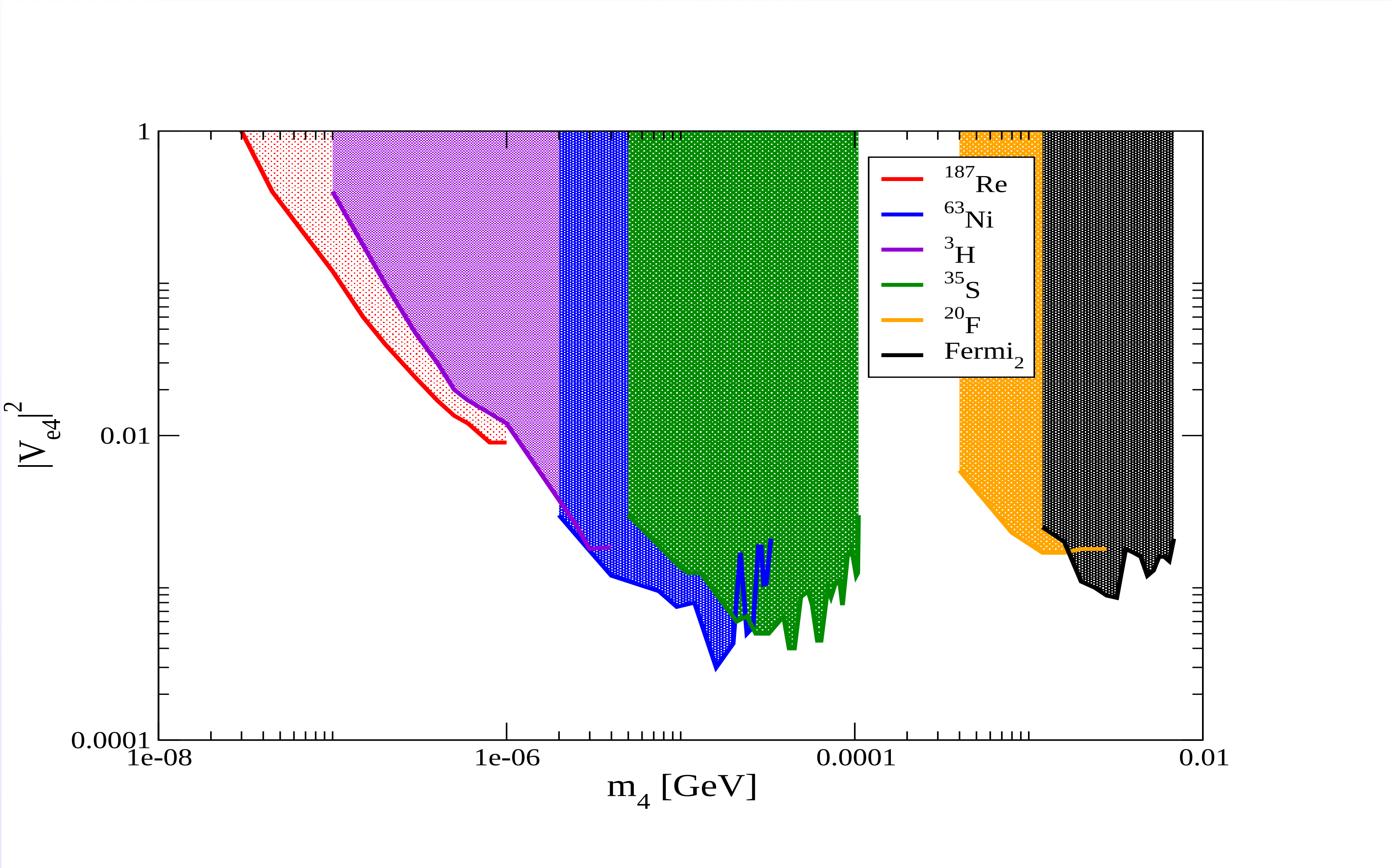


Kinks in the electron β-spectrum

For masses $m \sim 10\ \mathrm{eV}$–$1\ \mathrm{MeV}$, the search of kinks in the $\beta-$ spectrum is very sensitive to an admixture of heavy neutrinos in ν_e.



12 – Laboratory constraints

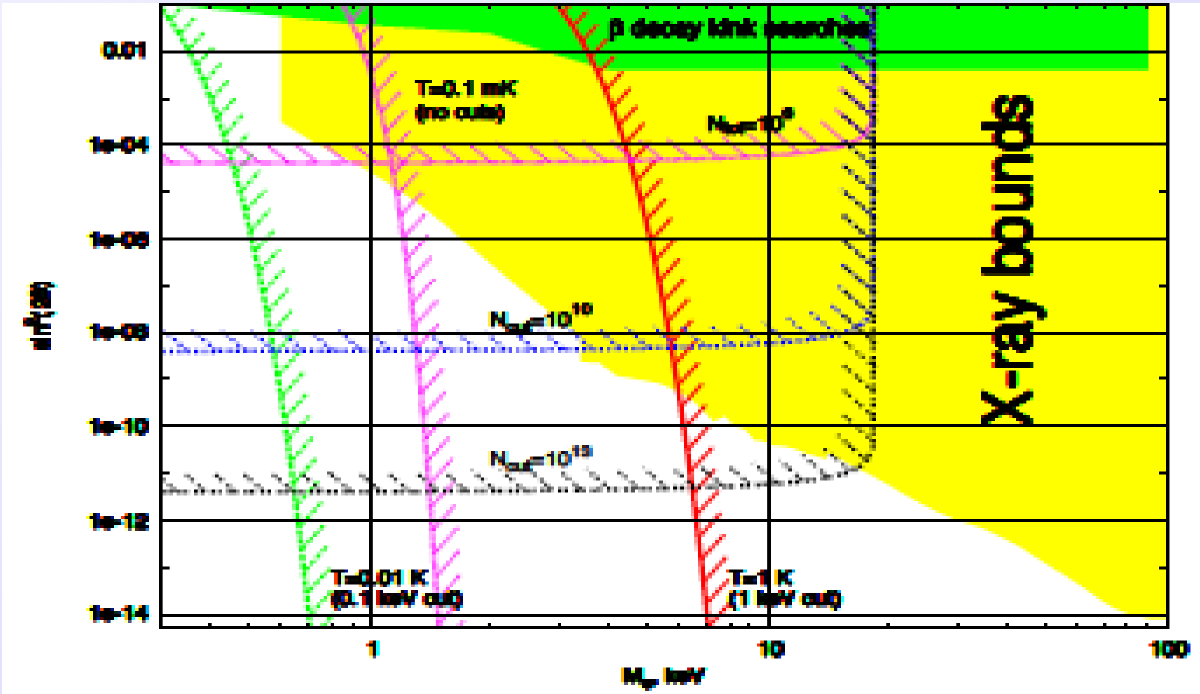


[Atre, Han, SP, Zhang, 2009]

Full kinematics in β-decay

A recent proposal is to study the full kinematics of the beta decay by reconstructing

- the momentum of the initial and final ions
- the momentum of the emitted electron

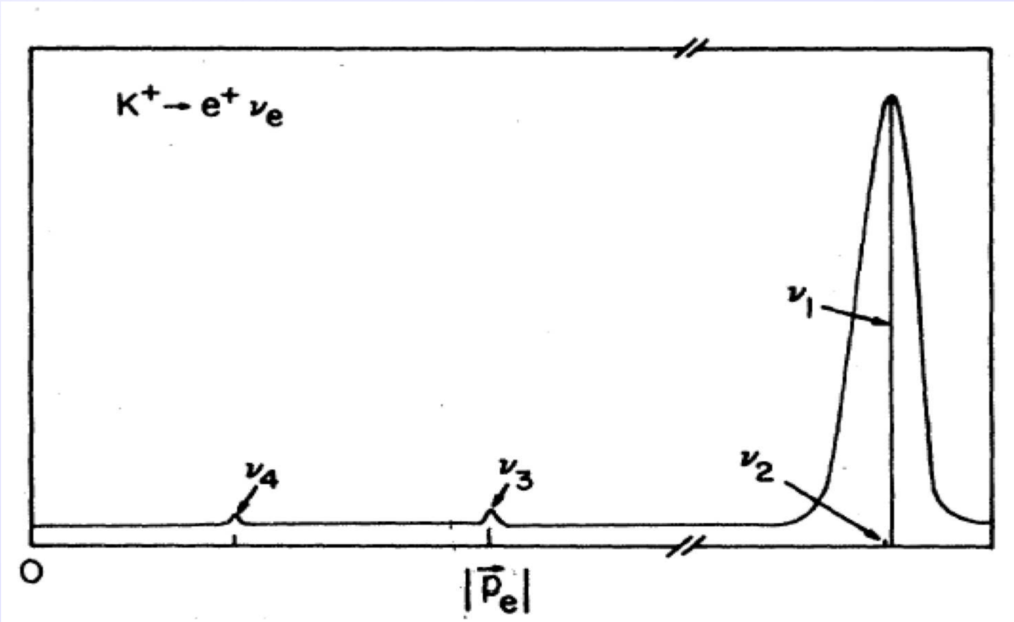


[Bezrukov, Shaposhnikov, 2006]

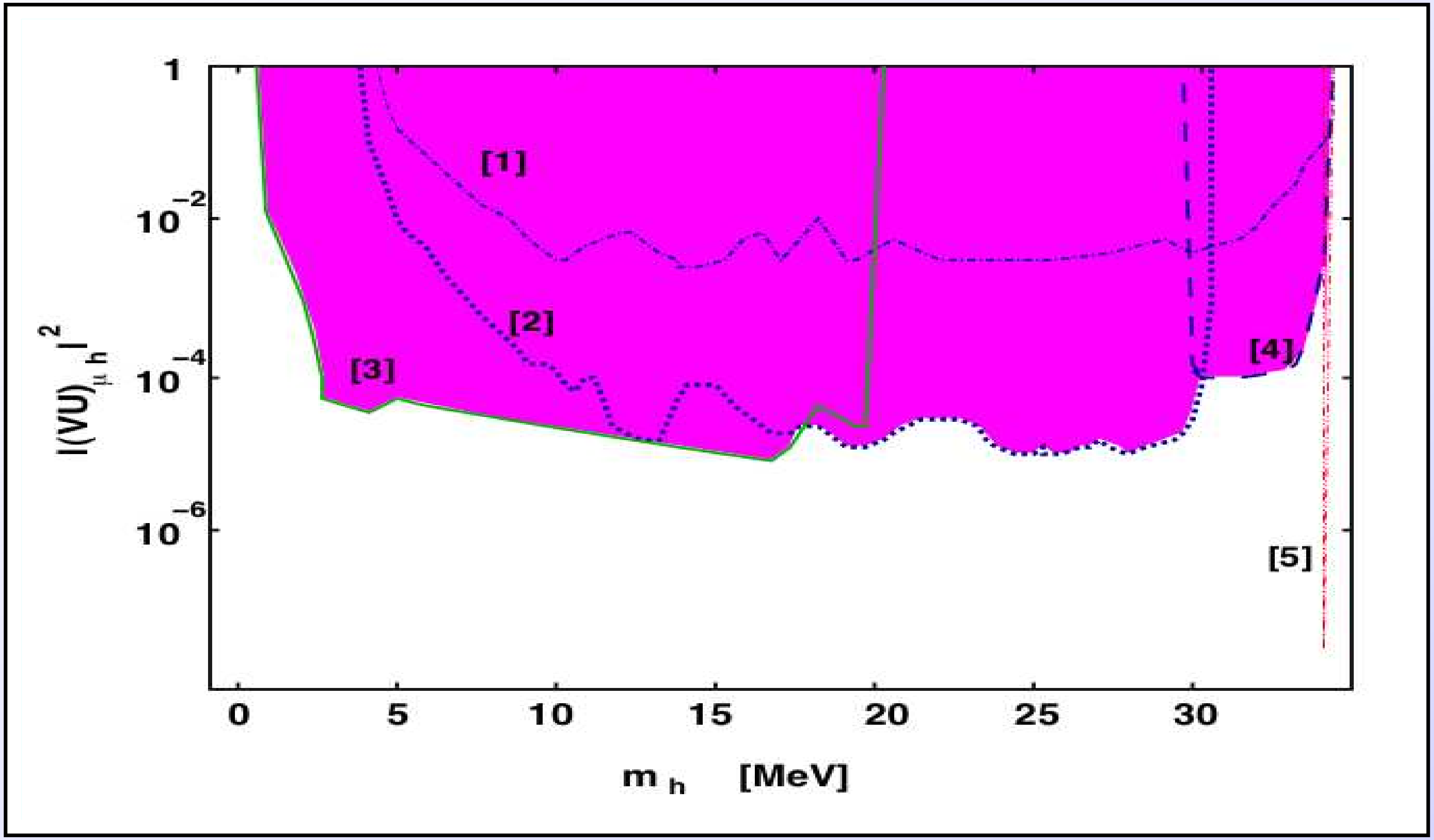
13 – Peak searches

If a heavy neutrino mixes with $\nu_{e,\mu}$, it would modify the spectrum of e and μ in meson decays. For ex., in $\pi \longrightarrow \mu\nu_\mu$ a peak would appear at

$$T_i = (m_\pi^2 + m_\mu^2 - 2m_\pi m_\mu - m_{\nu_i}^2)/2m_\pi,$$



[Shrock, PRD 1980]



[Kusenko, Pascoli and Semikoz, JHEP **0511** (2005) 028]

And similar bounds are available from K-decays.

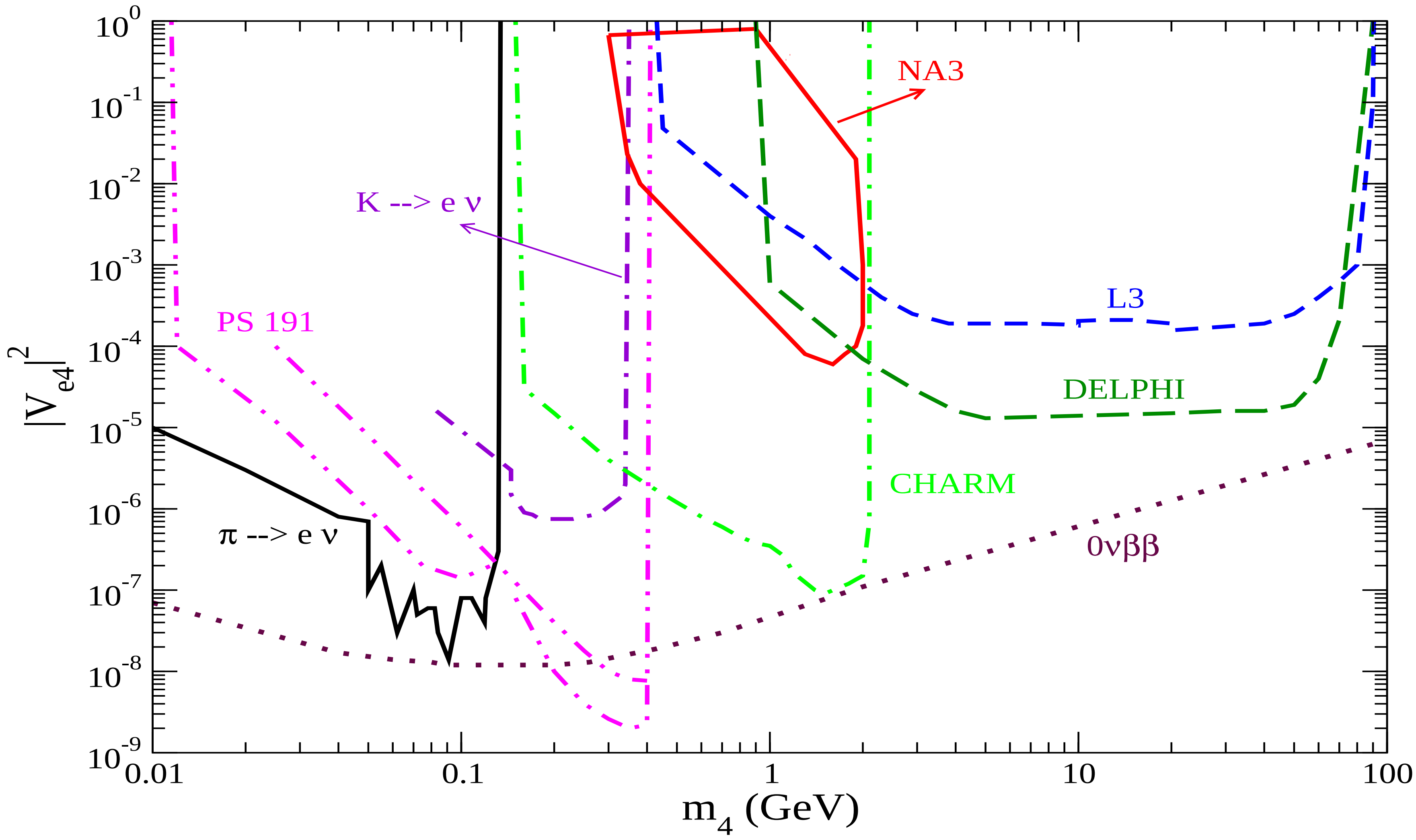
14 – N-decays searches

N decay due to their mixing with active neutrinos via CC and NC ($N \rightarrow e^+e^-\nu$, $N \rightarrow \pi^0\nu$...).

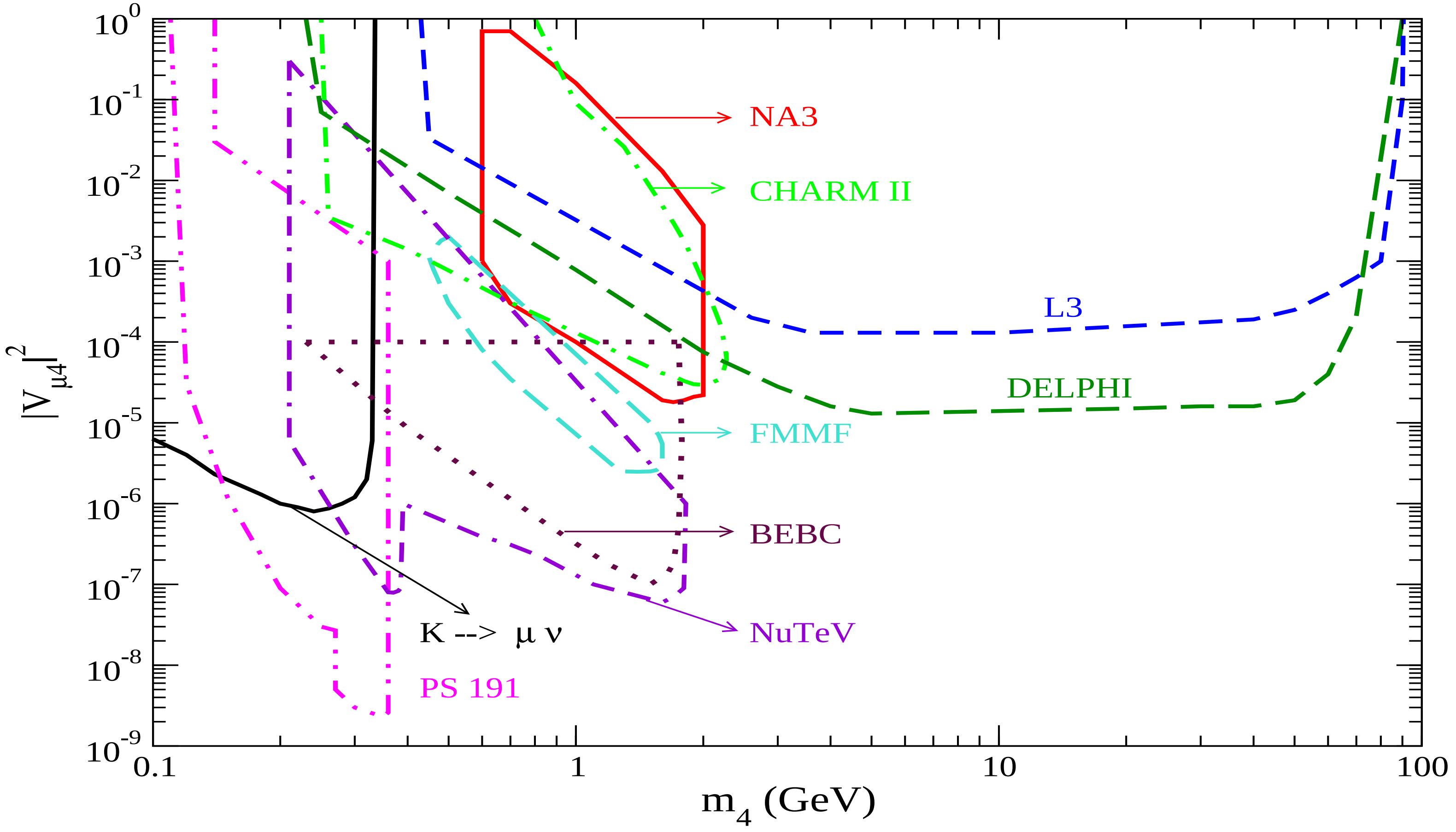
Experimentally: i) N_4 produced with $P = |V_{l4}|^2$ in ν-beams and colliders
ii) N_4 decays with $\Gamma_N(m_4, V_{l4})$
iii) search for SM decay products

- These bounds are less reliable than peak searches because in presence of non-SM decay channels they could be weakened and evaded.

- Present and future neutrino facilities could improve on these bounds, due to the large ν flux (MINOS, T2K and superbeams, neutrino factory).



[Atre et al., arXiv:0901.3589 [hep-ph]]



[Atre et al., arXiv:0901.3589 [hep-ph]]

15 – Electroweak precision tests

- The presence of N affects processes below their mass threshold (due to breaking of unitarity in U). Universality tests allow to put constraints $|V_{\ell 4}|^2 <$ few $\times 10^{-3}$.

- Indirect limits come from lepton flavour violation processes searches, as $\mu \to e\gamma$.

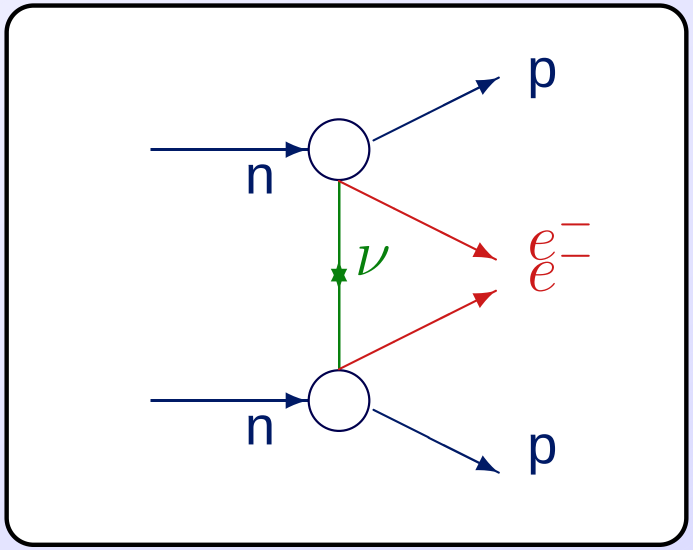
$$\mathrm{Br}(\mu \to e\gamma) \simeq \frac{3\alpha}{8\pi} \left| \sum_{m'} V_{em'} V^*_{\mu m'} \, g(m_N) \right|^2 ,$$

$\mathrm{Br}(\mu \to e\gamma) < 1.2 \times 10^{-11}$ implies

$|V_{e4} V_{\mu 4}| < 0.015 \left[1 \times 10^{-5}\right]$ for $m_N = 10 \text{ GeV} \left[1000 \text{ GeV}\right]$.

16 – $\Delta L = 2$ processes

$\Delta L = 2$ processes are sensitive to massive **Majorana** neutrinos. By far, the most sensitive is neutrinoless double beta decay: $(A, Z) \to (A, Z+2) + 2e^-$.



The half-life time, $\mathrm{T}_{0\nu}^{1/2}$, of the $(\beta\beta)_{0\nu}$-decay depends on

- small m_N: $\Gamma \propto (m_N \sin^2\theta)^2$
- large m_N: $\Gamma \propto (m_N^{-1} \sin^2\theta)^2$

For $m_N \ll 100\ \mathrm{MeV}$: $$\left[\mathrm{T}^{1/2}_{0\nu}\right]^{-1} \propto |M_F - g_A^2 M_{GT}|^2\ |{<}m{>}|^{\ 2}$$

- $|<m>|$ **is the effective Majorana mass parameter**:

$$|{<}m{>}| \equiv \left|\ \sum\nolimits_{\mathrm{light}} m_i U_{\mathrm{e}i}^2 + m_4 |U_{\mathrm{e4}}|^2 e^{i\alpha_{41}}\ \right|,$$

- The present best limit on $|{<}m{>}|$ reads:

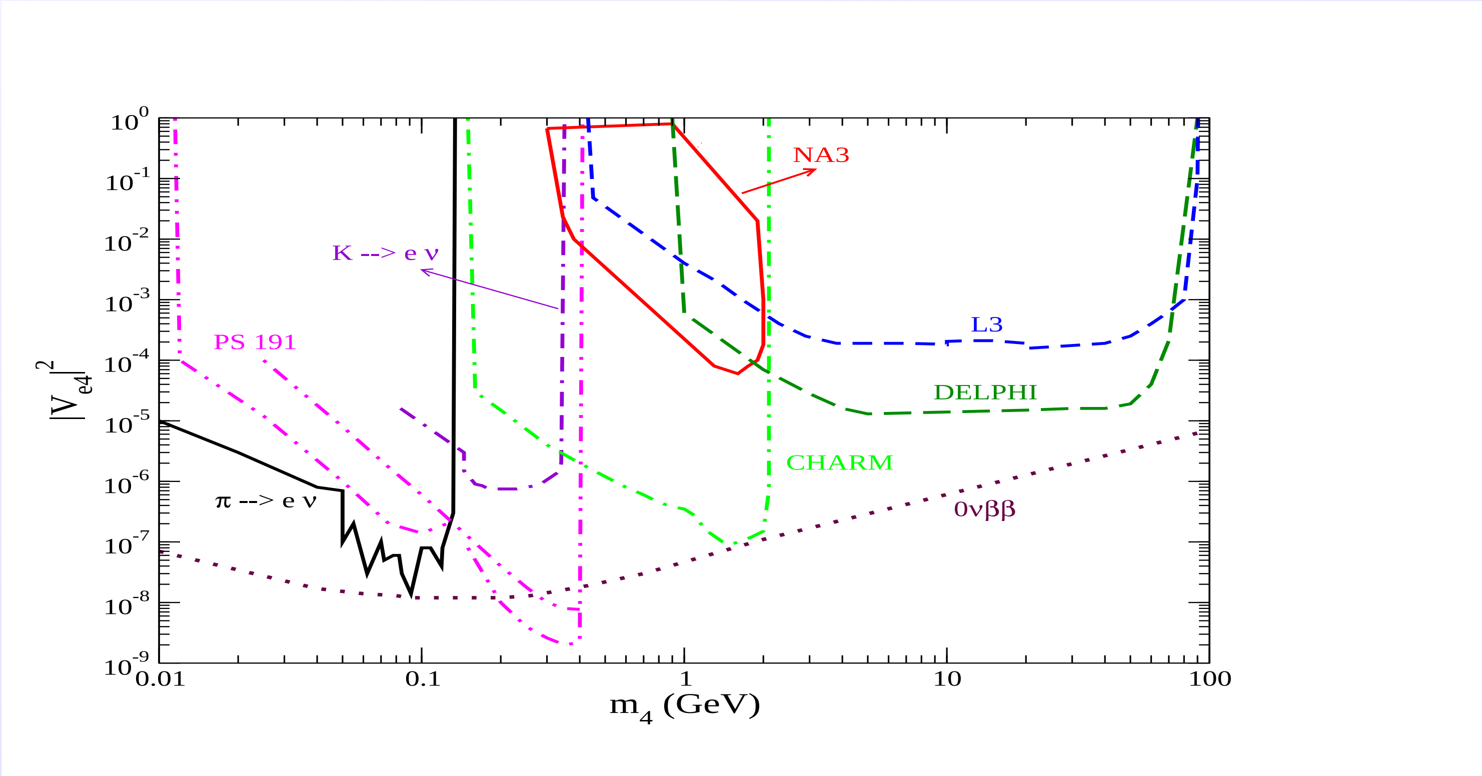
$|{<}m{>}| < (350 - 1050)\ \mathrm{meV}$	**Heidelberg-Moscow**
$|{<}m{>}| < (680 - 2800)\ \mathrm{meV}$	**NEMO3**
$|{<}m{>}| < (200 - 1050)\ \mathrm{meV}$	**CUORICINO**

- A claim of $(\beta\beta)_{0\nu}$decay discovery has been published [Klapdor-Kleingrothaus et al. 2004, 2006]. It implies $|{<}m{>}| \simeq 200 - 600\ \mathrm{meV}$.

- Future sensitivities to $|{<}m{>}| \sim 10 - 30\ \mathrm{meV}$, (CUORE, Majorana, SuperNEMO, EXO, GERDA, COBRA, NEXT).

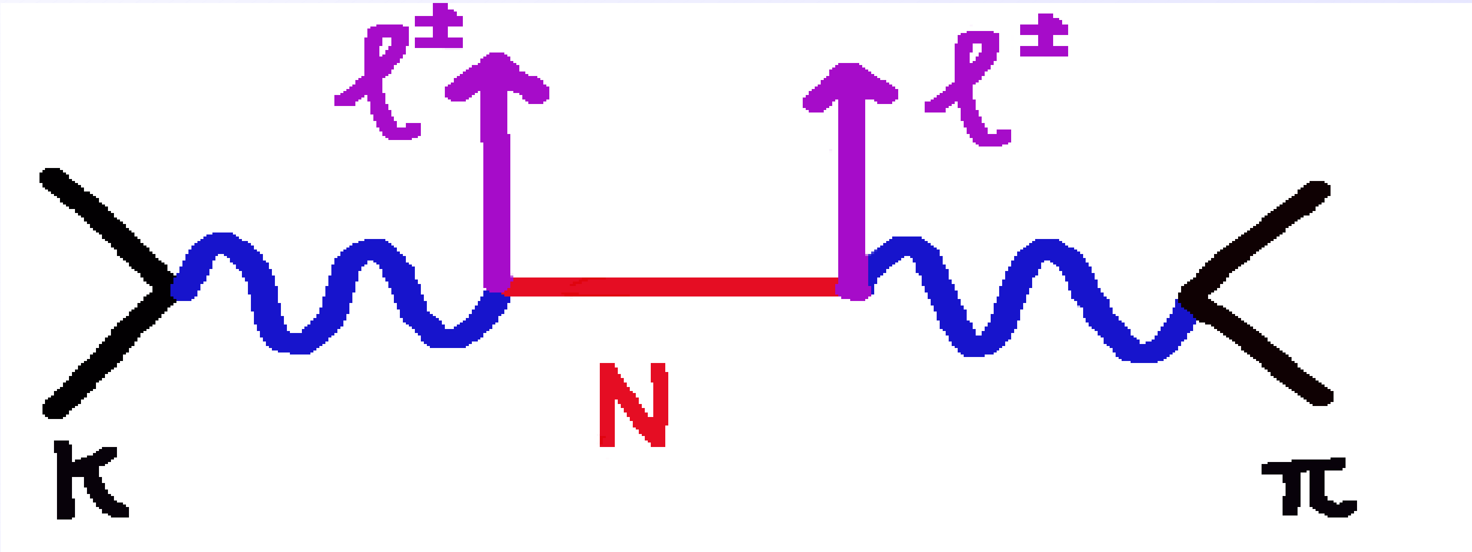
- These bounds translate into a limit on $\sin\theta$ as a function of m_4:

$$\sin^2\theta \lesssim \frac{|\langle m\rangle|}{m_4} \sim 10^{-4}\,\frac{3\text{ keV}}{m_4}$$



- For more than one sterile ν, it is possible to have cancellations among different terms and the bounds can be strongly weakened.

For heavy masses, $m_4 \sim 100\ \mathrm{MeV} - 1\ \mathrm{GeV}$, $\Delta L = 2$ processes, as rare K and τ decays can be resonantly enhanced.



The intermediate N state is a real particle which propagates before decaying. It may exit the detector and therefore give no positive signal with probability

$$\boxed{P = 1 - \exp(-L_{\mathrm{exp}}\Gamma_N)}$$

We give an estimated weaking factor for the mixing angle

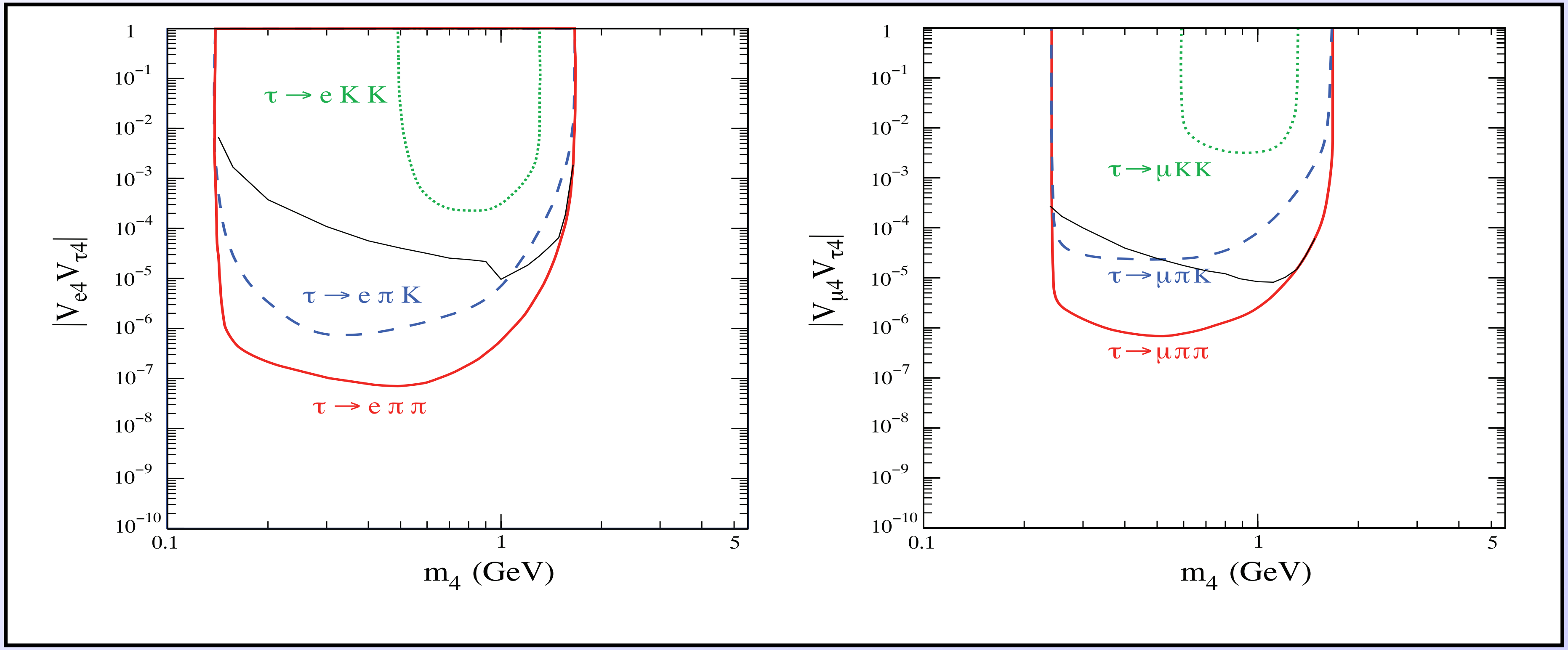
$$|V_{e4}V_{\tau 4}|(= |V_{e4}|^2) = \sqrt{|V_{e4}|^2_\infty/(L_{\mathrm{exp}}\Gamma_{N0})}$$

LNV τ decays: $\tau^- \longrightarrow \ell^+ M^- M^-$

The Branching ratio can be approximated as:

$$\mathrm{Br} \sim G_F^2 f_{M_1}^2 f_{M_2}^2 |V_{M_1}^{CKM} V_{M_2}^{CKM}|^2 |V_{\tau 4} V_{\ell 4}|^2 \left(\frac{m_N}{\Gamma_{N_4}}\right),$$

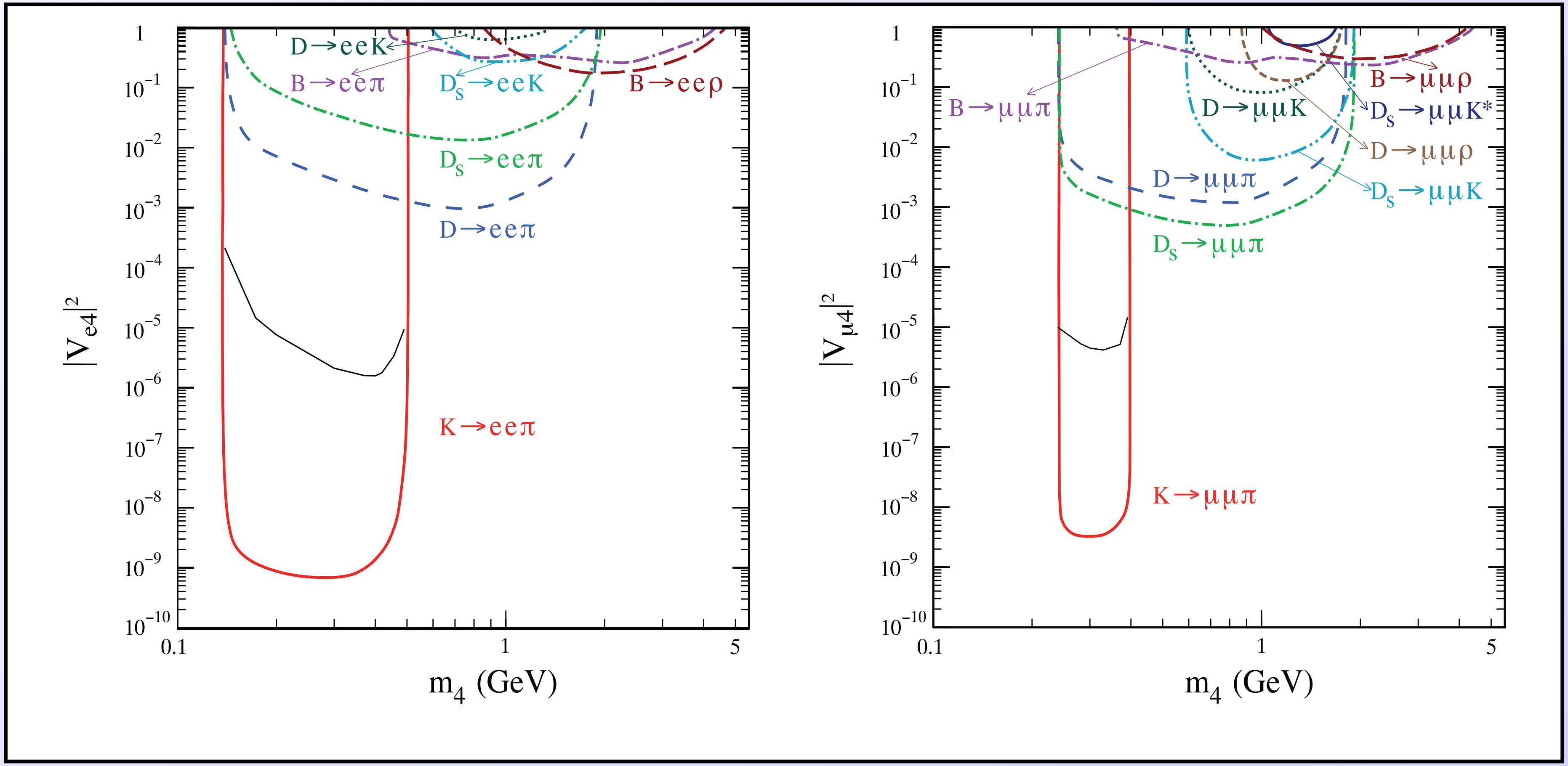
$$\sim 10^{-3} \left(\frac{\mathrm{GeV}}{m_N}\right)^4 |V_{\tau 4} V_{\ell 4}|$$



[Atre et al., arXiv:0901.3589 [hep-ph]]

LNV meson decays

$$M^- \to \ell^+ \ell^+ M^-$$

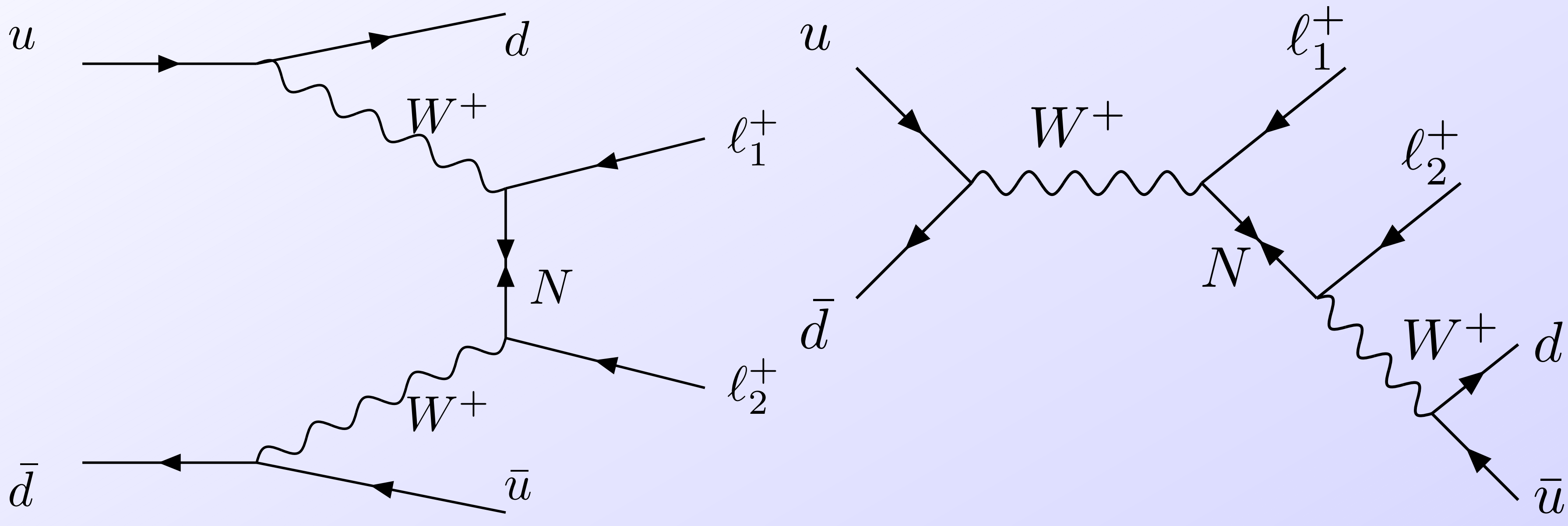


[Atre et al., arXiv:0901.3589 [hep-ph]]

17 – Collider signatures

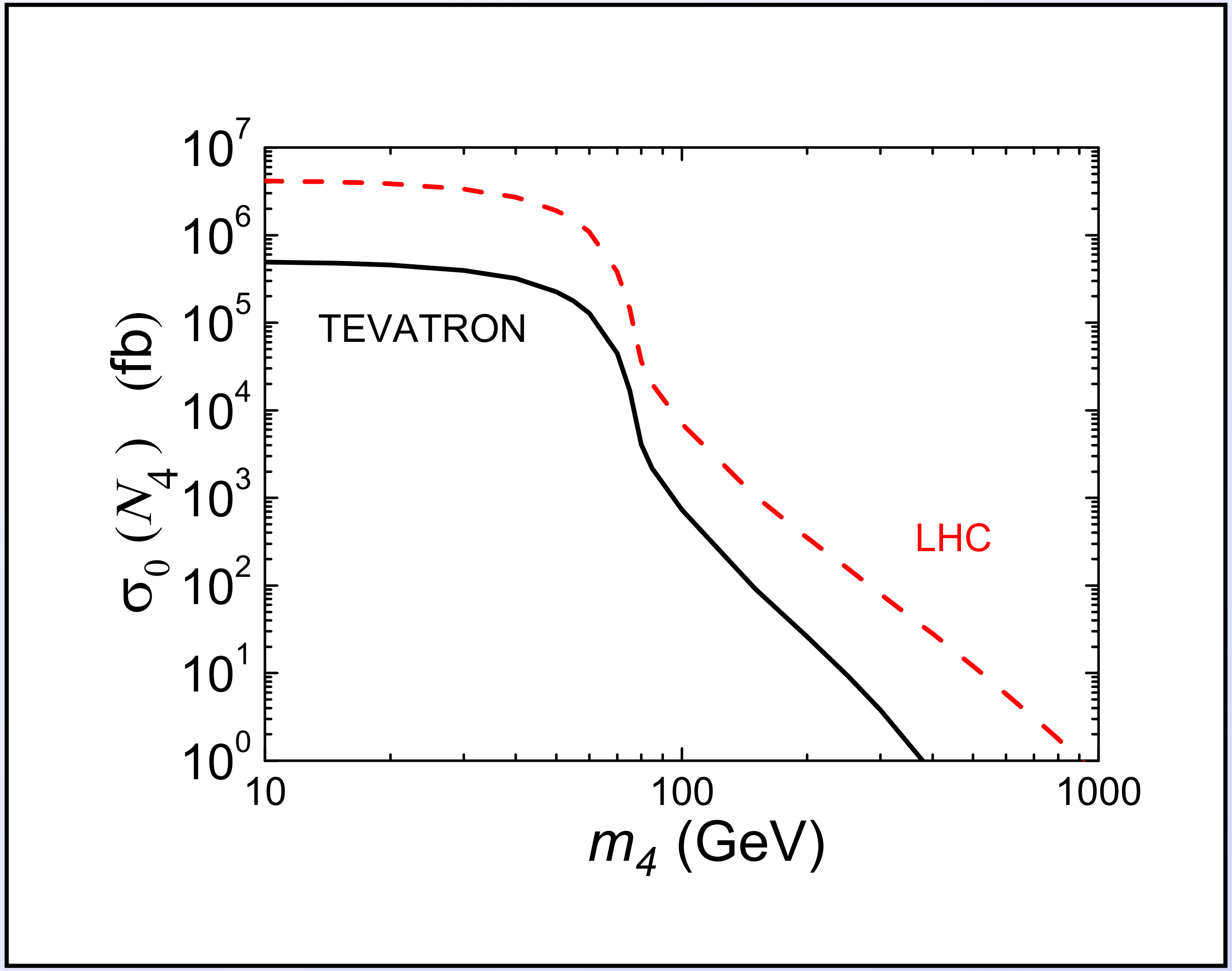
Search for like-sign di-leptons at Tevatron and LHC.

[Keung, Senjanovic PRL50; Dicus et al., PRD44; Datta et al., PRD50...]



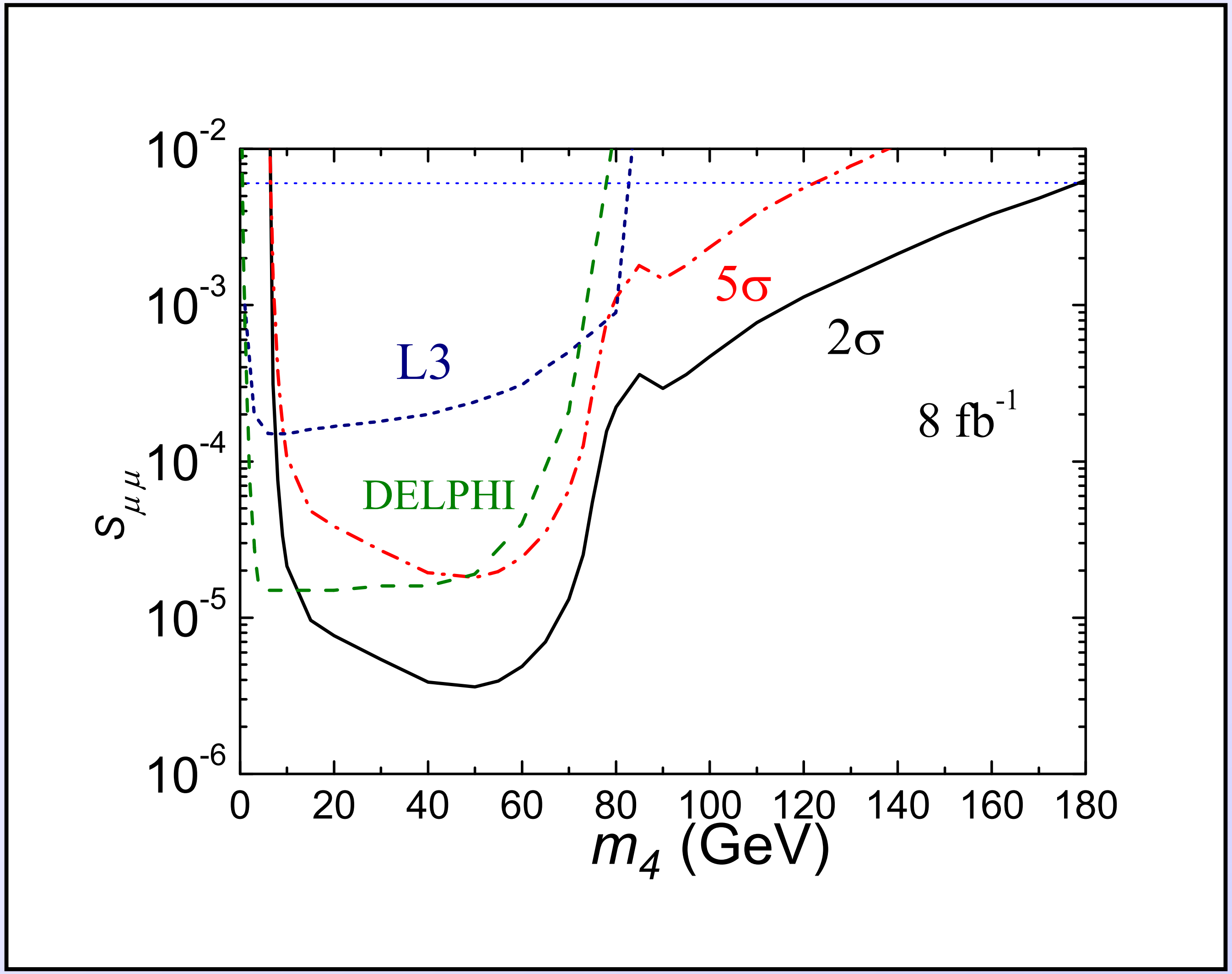
An excellent approximation for the cross section is

$$\sigma(pp \to \ell\ell W) \approx \sigma(pp \to \ell N_4) Br(N_4 \to \ell W) \simeq \frac{|V_{\ell_1 4} V_{\ell_2 4}|^2}{\sum_{\ell=e}^{\tau} |V_{\ell 4}|^2} \sigma_0$$



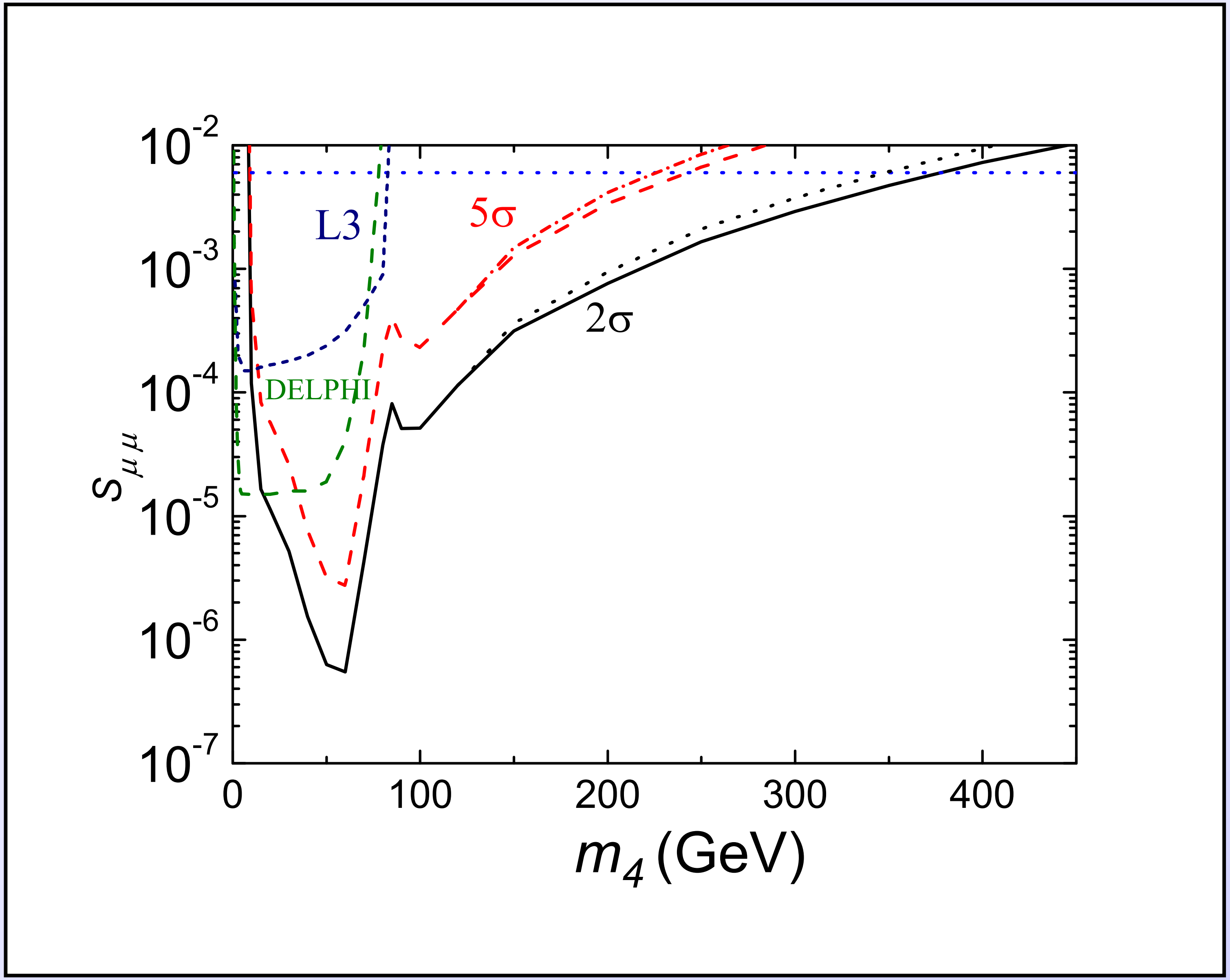
[Atre et al., arXiv:0901.3589 [hep-ph]]

At Tevatron, the most promising channels are $p\bar{p} \longrightarrow \mu^{\pm}\mu^{\pm}jjX$ ($p\bar{p} \longrightarrow \mu^{\pm}e^{\pm}jjX$):



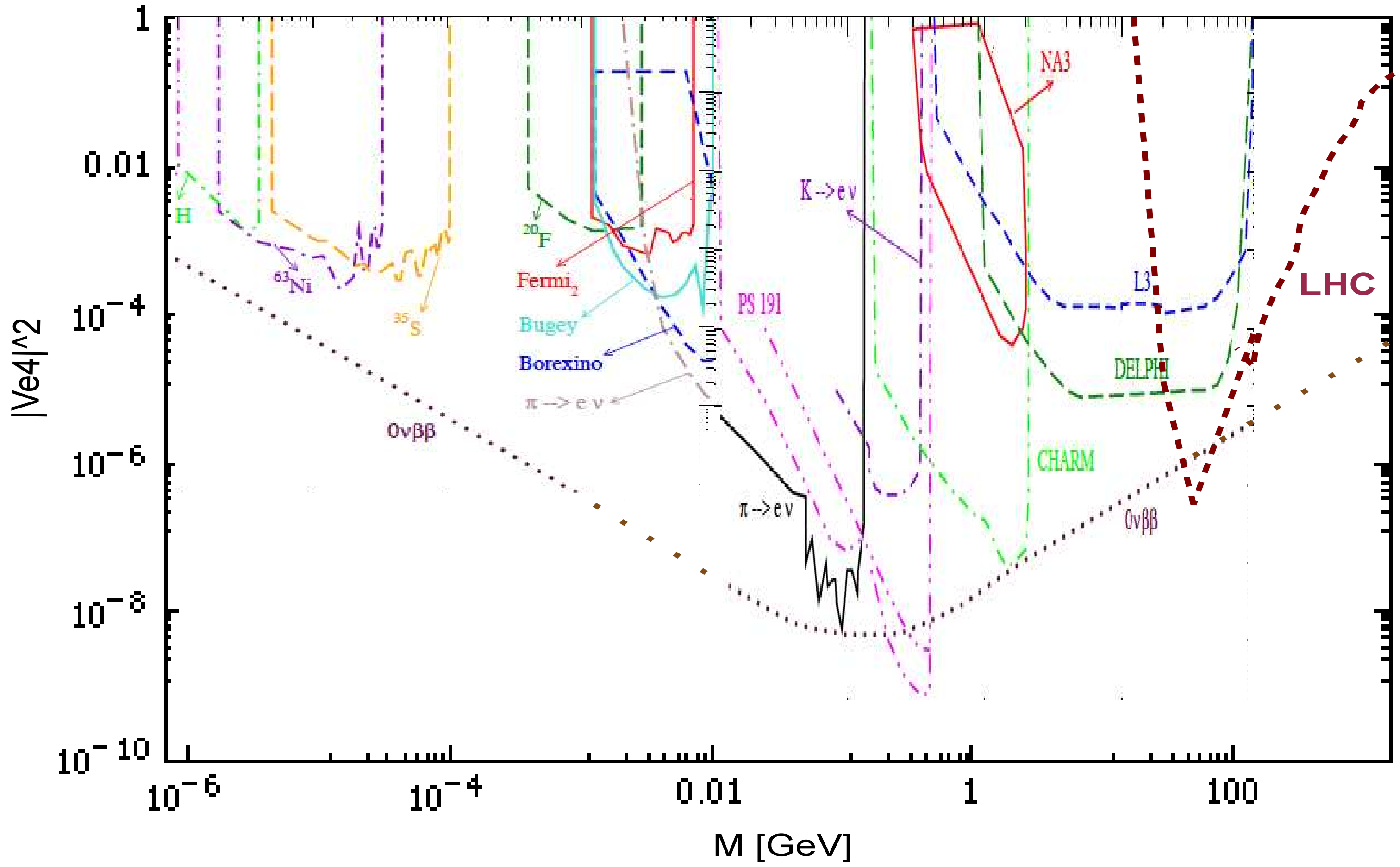
[Atre et al., arXiv:0901.3589 [hep-ph]]

At the LHC a similar analysis gives



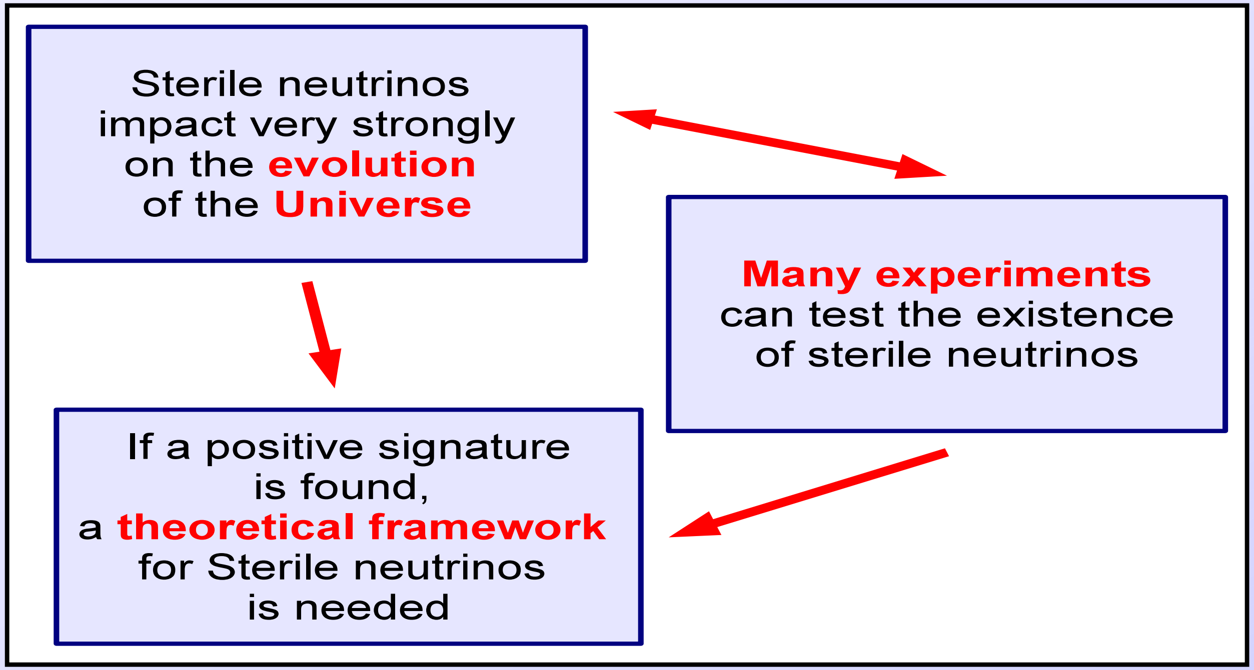
[Atre et al., arXiv:0901.3589 [hep-ph]]

18 – Summary of laboratory constraints



19 – Conclusions

- Sterile neutrinos have a rich phenomenology and can severely impact the evolution of the Universe.
- keV sterile neutrinos can constitute the DM of the Universe and can be searched for in x-ray observatories.



20 – Sterile neutrino production summary

A population of keV sterile neutrinos, which constitute the DM, can be produced out-of equilibrium in the EU via various mechanisms:

- non-resonant production
- resonantly enhanced oscillations
- low reheating scenario
- boson decays

For a spectrum proportional to the equilibrium one, $p/T \sim 3.15$, while for the resonant production ($p/T \sim 2$) and for a subsequent injection of entropy in the thermal plasma ($p/T \sim 0.7$) it is much colder.

- Production via decay of new bosons S, with $m_S \sim 100$ GeV, which couple to N_4

$$\mathcal{L}_{S\nu} = f_a S N_4 N_4$$

When $\langle S \rangle = v_S \sim 100\text{GeV}$,

- N_4 acquire a mass
- S can decay into N_4 at $T \sim m_S/\text{few}$

Because of the entropy released as the EU cools down, the density of N_4 gets diluted by a factor ~ 33 and the average momentum ~ 3.

$$\frac{\langle p \rangle}{T} \sim 0.76 \left(\frac{110}{g_*(100\text{GeV})} \right)$$

This DM is much more cold than the standard DW scenario.

[Kusenko, 2006]

The νMSM: this model is the minimal extension of the SM which incorporates DM, the baryon asymmetry and neutrino masses. It requires 3 sterile neutrinos:

- N_4 is the DM candidate with $m_4 \sim \mathrm{few\ keV}$
- N_5 and N_6 are required for baryogenesis,

$m_5 \simeq m_6 \sim 100\ \mathrm{MeV} - 100\ \mathrm{GeV}$

If N_4 are produced before N_5 and N_6 decays, the entropy release after N_4 production due to out-of-equilibrium decays of heavy sterile neutrinos cools down the DM.

[Asaka et al., 2006]

If N_4 are produced after, N_5 and N_6 decays can generate a large lepton asymmetry and the N_4 production is resonantly enhanced.

[Asaka et al., 2005; 2005; Shaposhnikov, 2008; Laine, Shaposhnikov, 2008; Asaka et al., 2007]