ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Dark matter, baryogenesis and neutrinos

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ISAPP 2011: The dark side of the Universe

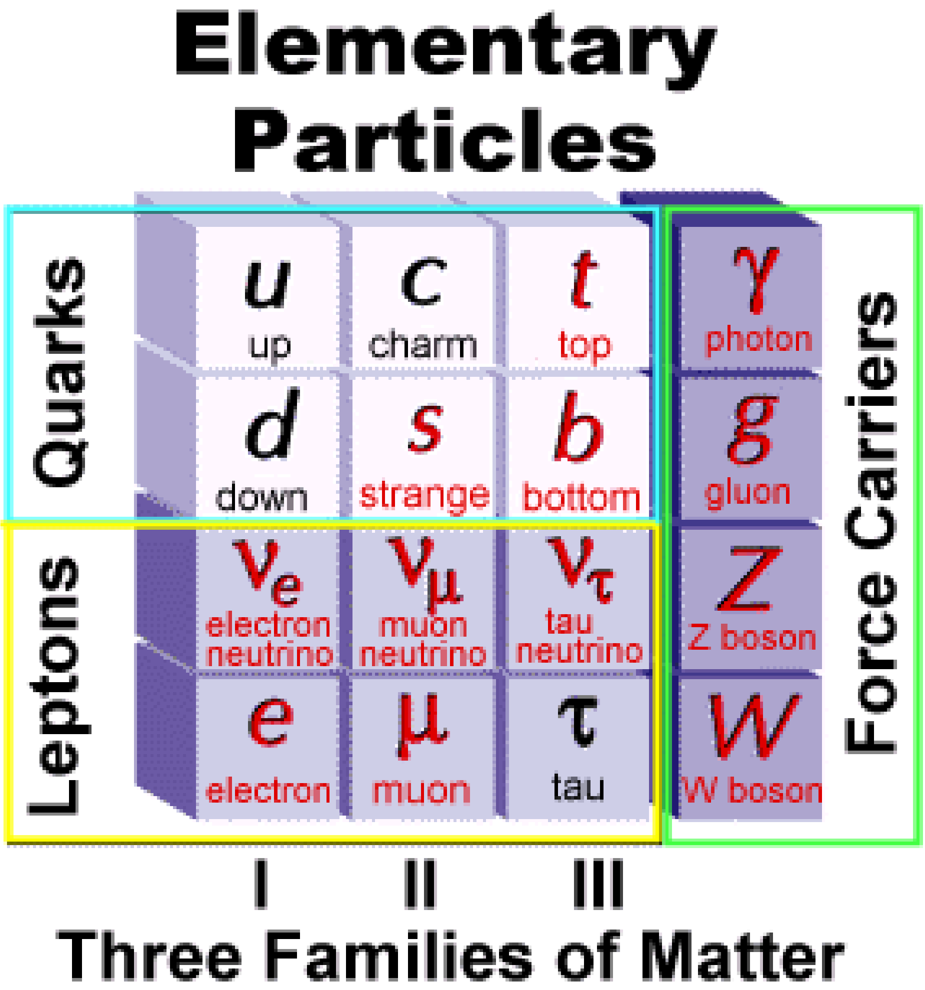
Outline 1

- Introduction: “No new scale paradigm”
- Minimal model leading to minimal solutions
- The structure of the minimal model - νMSM
- Sterile neutrino as Dark Matter
  - Elements of finite temperature field theory
  - Cosmological production of sterile neutrino
  - How to search for DM sterile neutrino

Outline 2

- Baryogenesis and neutrinos
  - Anomalous baryon and lepton number non-conservation
  - The mechanism
  - Experimental consequences
- Conclusions

Standard Model of particle interactions is in great shape: it agrees with all accelerator experiments



The only missing particle - the Higgs boson. It will be searched at the LHC

Still, the Standard Model cannot accommodate a number of cosmological observations and discoveries in neutrino physics, it also has a number of “fine tuning” problems from theory side.

The strategy

- Select the most important problems to solve (may be subjective).
- Use Ockham’s razor principle: *“Frustra fit per plura quod potest fieri per pauciora”* or ”entities must not be multiplied beyond necessity”. For particle physics: entities = new hypothetical particles and new scales different from Fermi and Planck scales.

SM problems and possible solutions

Hierarchy problem: stability of the Higgs mass against radiative corrections

Possible solutions:

- Compensation of divergent diagrams by new particles at TeV scale (supersymmetry, composite Higgs boson). Consequence: new physics at LHC

SM problems and possible solutions

- New symmetry – exact, but spontaneously broken scale invariance. Higgs mass is kept small in the same way as photon mass is kept zero by gauge invariance. Consequences: validity of the SM all the way up to the Planck scale, nothing but the Higgs at LHC in the mass interval

$$m_{\min} < m_H < m_{\max}$$

$$m_{\min} = [126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5]\ \mathrm{GeV}$$

$$m_{\max} = [173.5 + \frac{m_t - 171.2}{2.1} \times 1.1 - \frac{\alpha_s - 0.1176}{0.002} \times 0.3]\ \mathrm{GeV}$$

theory error in $m_{\min} \simeq \pm 2$ GeV. Existence of massless particle – dilaton, which can play the role of Dark Energy

Zenhausern, M.S

SM problems and possible solutions

The universe is flat, homogeneous and isotropic with high accuracy. It contained in the past small density fluctuations that lead to structure formation

Possible solution: inflation.

The inflaton (scalar particle inflating the universe) is

- new particle with the mass of the order of 10^{13} GeV and minimal coupling to gravity

Alternative

- SM Higgs boson with non-minimal coupling to gravity Bezrukov, M.S

Neutrino masses and oscillations

Possible solutions:

- See-saw mechanism: existence of several superheavy ($M \sim 10^{10}$ GeV) neutral leptons. Direct experimental consequences: none, as the mass is too large to be accessed

Alternative

- Existence of new leptonic flavours with masses similar to those of known quarks and leptons. Experimental consequence: possibility of direct experimental search

SM problems and possible solutions

Dark matter

Possible solutions:

- WIMPS with masses of the order of 100 GeV and roughly electroweak cross-sections (e.g. SUSY neutralino). Consequences: new particles at LHC, success of WIMP searches

Alternative

- Super-WIMPS with masses in keV region. Natural possibility: new neutral leptonic flavour with mass of few keV. Consequences: no DM candidates at LHC, failure of WIMP searches. Possibility of search through radiative processes $N \to \nu\gamma$ which leads to existence of narrow X-ray line in direction of DM concentrations.

SM problems and possible solutions

Baryon asymmetry of the Universe

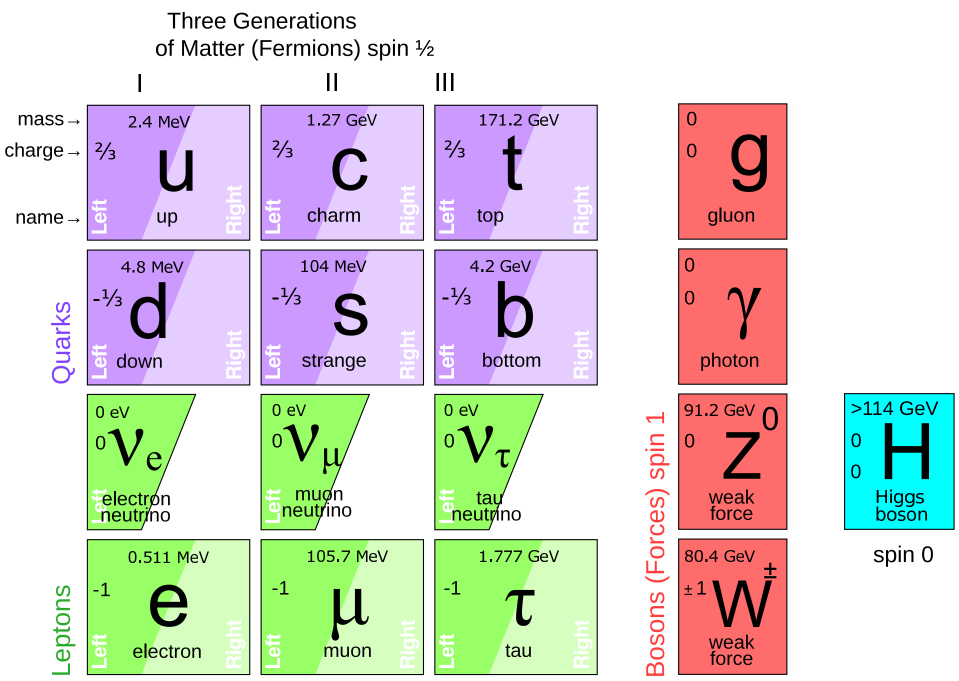
Possible solutions:

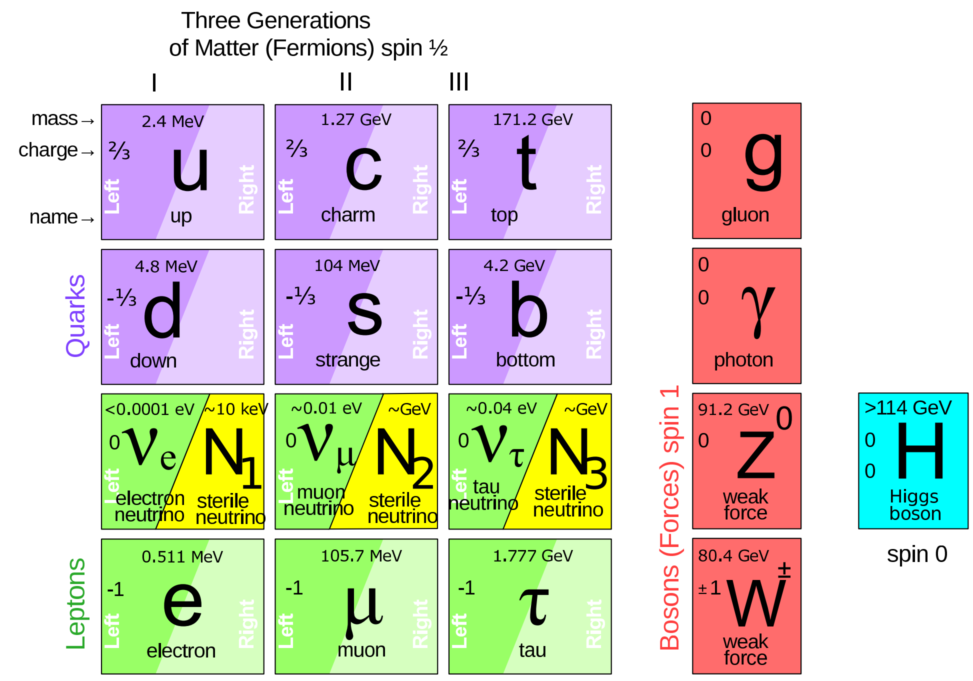
- Baryogenesis due to new physics above the electroweak scale. Potential consequences: new particles at LHC (for electroweak baryogenesis)

Alternative

- Baryogenesis due to new neutral leptonic flavours with masses in the region from 140 MeV up to few GeV. Experimental consequence: possibility of direct experimental search

Realisation: νMSM + scale-invariant unimodular gravity





Role of N_1 with mass in keV region: dark matter

Role of N_2, N_3 with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

Role of scale invariance and unimodular gravity: dilaton gives mass to the Higgs and $N_{1,2,3}$ and provides dynamical dark energy

Parameter counting: the νMSM

Most general renormalizable Lagrangian

$$L_{\nu MSM} = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\,\bar{N}_I^c N_I + h.c.,$$

Extra coupling constants:

3 Majorana masses of new neutral fermions N_i,

15 new Yukawa couplings in the leptonic sector

(3 Dirac neutrino masses $M_D = F_{\alpha I} v$, 6 mixing angles and 6 CP-violating phases),

18 new parameters in total. The number of parameters is almost doubled.

The strategy

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- Let us see therefore whether νMSM agrees with particle physics experiments, and can explain neutrino masses, dark matter, and baryon asymmetry of the Universe for some choice of parameters
- The parameters, found in this way can be used to fix the experimental strategy for search for new physics

Neutrino masses and oscillations

νMSM neutrino masses

If the Dirac neutrino masses $M_D \sim Fv \ll M_I$ (v is the VEV of the Higgs field) the see-saw formula works,

$$M_\nu = -M_D \frac{1}{M_N} [M_D]^T, \quad M_D = Fv, \;\; v = 174\,\mathrm{GeV}$$

M_ν depends on 9 physical parameters which potentially can be determined experimentally in low energy neutrino experiments. They are: 3 absolute values of ν masses, 3 mixing angles, 1 Dirac CP-violating phase and 2 Majorana phases. 4 out of these 9 are not known.

- Obvious statement: 18 new parameters of the νMSM can fit any pattern of neutrino masses and oscillations
- Another obvious statement: scale of M_N cannot be extracted from low-energy experiments:

  multiply M_D by x and M_N by x^2, M_ν does not change ($m_\nu \propto M_D^2/M_N$)

EW see-saw

Assume that the Majorana masses of N are smaller or of the same order as the mass of the Higgs boson and find Yukawa couplings from requirement that one gets correct active neutrino masses:

$$F \sim \frac{\sqrt{m_{atm} M_N}}{v} \sim (10^{-6} - 10^{-13}),$$

small F will play crucial role for dark matter and baryogenesis.

Dark matter in the universe

Problem since 1933, F. Zwicky.

Most of the matter in the universe is dark

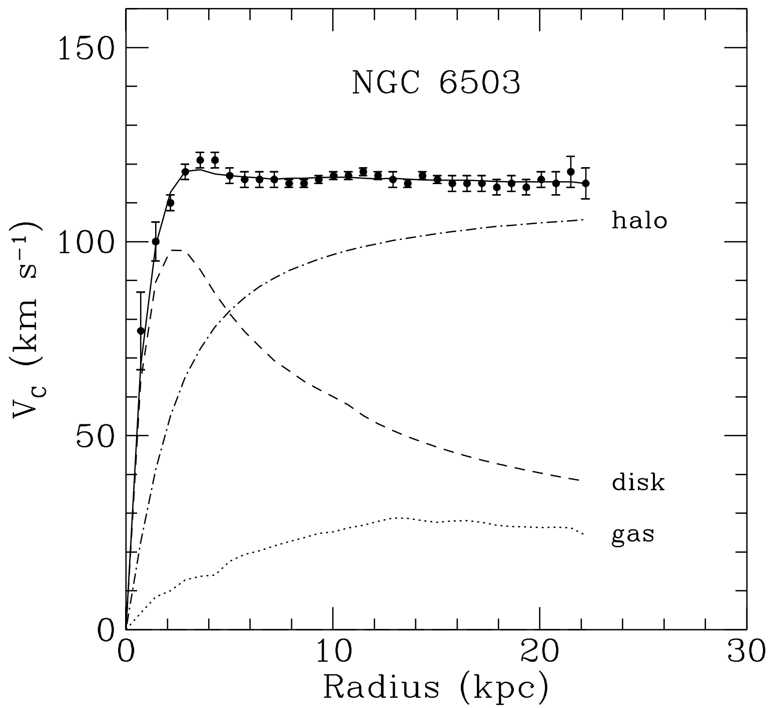
Evidence:

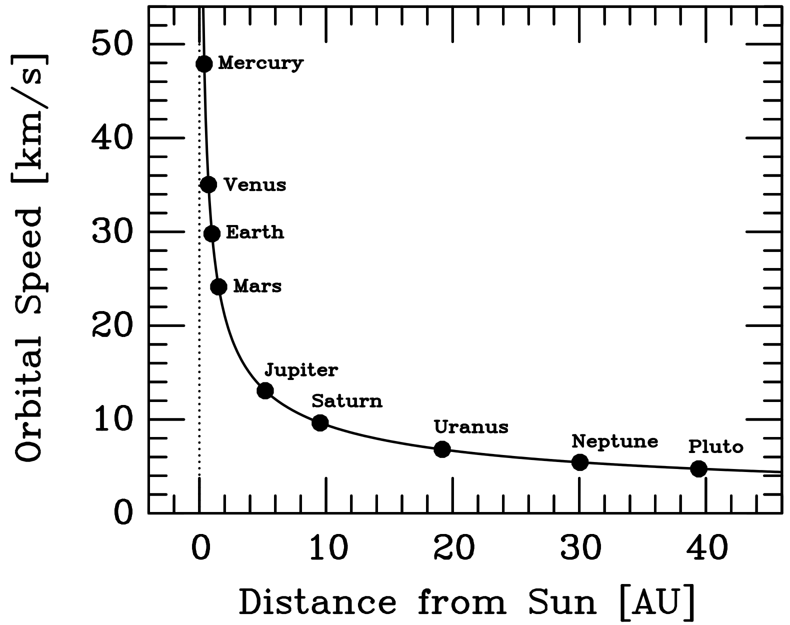
- Rotation curves of galaxies
- Big Bang nucleosynthesis
- Structure formation
- CMB anisotropies
- Supernovae observations

Non-baryonic dark matter:

$\Omega_{DM} \simeq 0.22$

SM: no particle physics candidate

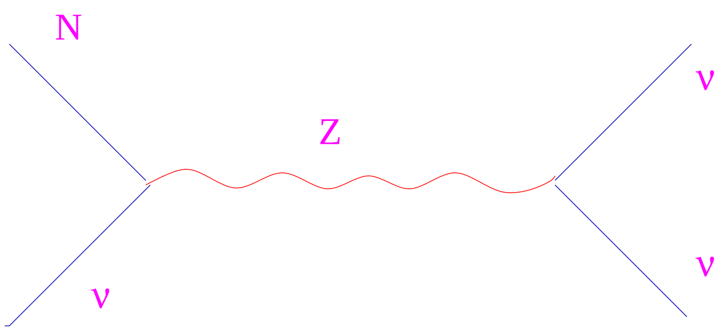




νMSM Dark matter

Dodelson, Widrow; Shi, Fuller; Dolgov, Hansen;
Abazajian, Fuller, Patel; Asaka, Laine, M.S.

Yukawa couplings are small $\rightarrow$ sterile N can be very stable.



Main decay mode: $N \to 3\nu$.

Subdominant radiative decay channel: $N \to \nu\gamma$.

For one flavour:

$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\,\text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

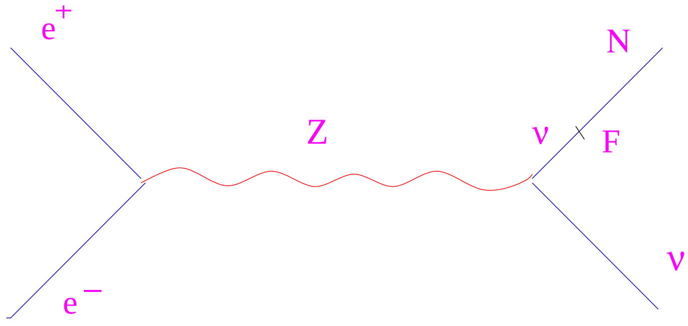
$$\theta_1 = \frac{m_D}{M_N}$$

Production via neutrino oscillations

Assumptions (Dodelson, Widrow):

- The theory is SM + just one sterile neutrino
- The abundance of sterile neutrino at $T > 1$ GeV is zero

Cosmological production is due to active - sterile neutrino oscillations:



Production via neutrino oscillations

Naive estimate: production rate

$$\Gamma \sim \sigma n v, \quad \sigma \sim G_F^2 \theta^2 T^2, \quad n \sim T^3$$

Abundance:

$$\frac{n_N}{n_\gamma} \sim G_F^2 \theta^2 M_W^3 M_{Pl}$$

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Wrong by many orders of magnitude!

Correct physics

- L. Wolfenstein, Phys. Rev. D17 (1978) 2369;
  Phys. Rev. D20 (1979) 2634
- A.D. Dolgov, Yad.Fiz. 33 (1981) 1309
- S.P. Mikheev, A.Yu. Smirnov, Yad.Fiz. 42 (1985) 1441;
  Nuovo Cim. C9 (1986) 17
- D. Notzold, G. Raffelt, Nucl.Phys. B307 (1988) 924

Correct physics

Active-sterile neutrino mixing angle is temperature dependent.

From Dolgov-Hansen:

$$\theta \to \theta_M \simeq \frac{\theta}{1 + 2.4(T/200\ \mathrm{MeV})^6(\mathrm{keV}/\mathrm{M_I})^2}$$

So, $\Gamma \propto T^{-7}$ and not T^5 !

Strong suppression of sterile neutrino production at $T > 100$ MeV!

Production temperature of sterile neutrinos:

$$T \sim 130 \left(\frac{M_I}{1\ \mathrm{keV}}\right)^{1/3}\ \mathrm{MeV}$$

To find the number of produced sterile neutrinos exactly one must know

- The rate of *sterile* neutrino production
- The equation of state of the plasma $P = F(T)$, which gives the temperature-time relation in the expanding Universe

Asaka, Laine, M.S.

Computation from first principles of QFT and statistical physics

Elements of finite temperature field theory

Master formula for sterile neutrino DM production

(Blackboard part)

Initial conditions for Big Bang

Assume: at some temperature $T \gg M_W$ we have:

- thermal equilibrium for all SM particles
- no singlet fermions present

Why?

- Yukawa couplings of singlet fermions are very small: reactions $N \leftrightarrow$ SM particles are out of thermal equilibrium at $T \gg M_W$.
- In the νMSM with non-minimal Higgs coupling the $Higgs \equiv inflaton$ energy goes to SM particles rather than singlet fermions. Yukawas are small!

Statistical physics formulation

Find $\mathrm{Tr} N \hat{\rho}(t)$ where density matrix $\hat{\rho}(t)$ satisfies:

$$i \frac{\mathrm{d}\hat{\rho}(t)}{\mathrm{d}t} = [\hat{H}, \hat{\rho}(t)]$$

$\hat{H}$ - total Hamiltonian. Initial condition:

$$\hat{\rho}(0) = \hat{\rho}_{\text{SM}} \otimes |0\rangle\langle 0|$$

where $\hat{\rho}_{\text{SM}} = Z_{\text{SM}}^{-1} \exp(-\beta \hat{H}_{\text{SM}})$, $\beta \equiv 1/T$, is the equilibrium MSM density matrix at a temperature T, and $|0\rangle$ is the vacuum state for sterile neutrinos.

Master formula

DM sterile neutrinos are never in thermal equilibrium

$$\Downarrow$$

Kinetic equations are not necessary: one can use perturbation theory on Yukawa coupling !

Result in the lowest order of perturbation theory:

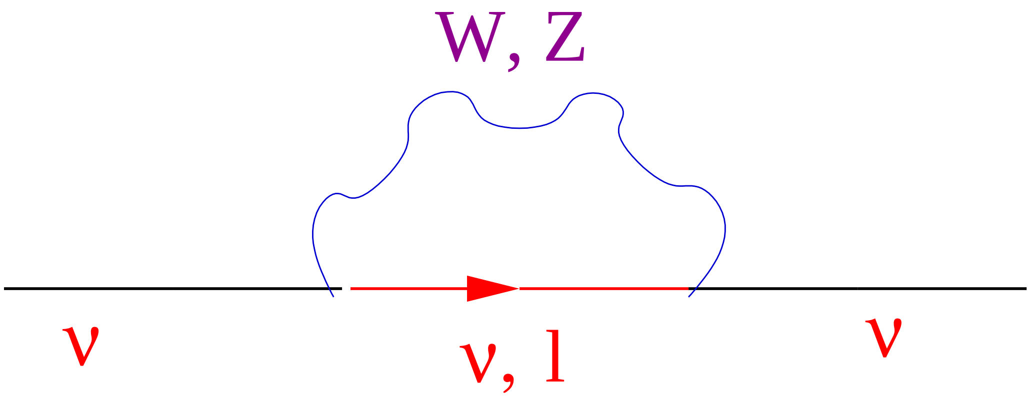
$$\frac{dN_I(x,\vec{q})}{d^4x\, d^3\vec{q}} = \frac{2n_F(q^0)}{(2\pi)^3 2q^0} \sum_{\alpha=1}^{3} |M_D|^2_{\alpha I} \mathrm{tr}\Big\{ \not{Q}\, a_L \Big[\rho_{\alpha\alpha}(-Q)+\rho_{\alpha\alpha}(Q)\Big] a_R \Big\}$$

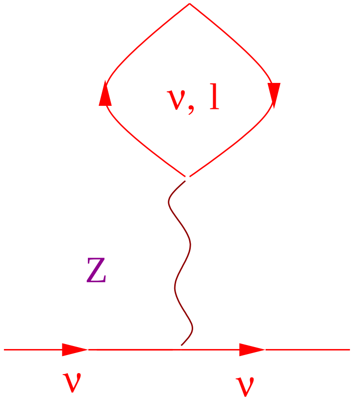
$$a_{L,R} = \frac{1}{2}(1 \pm \gamma_5)$$

Spectral function

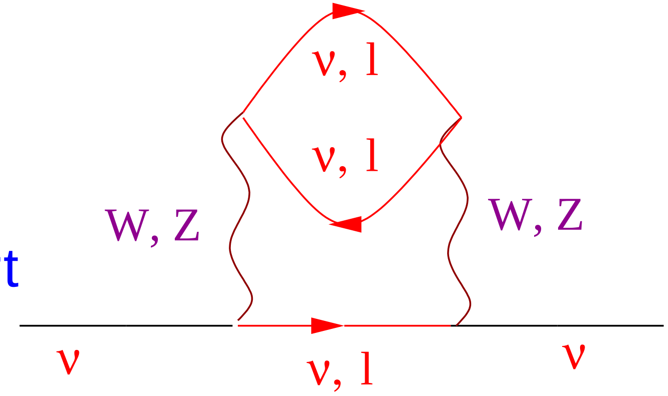
$$\rho_{\alpha\beta}(Q) \equiv \int \mathrm{d}t\, \mathrm{d}^3\vec{x}\, e^{iQ\cdot x} \left\langle \frac{1}{2}\left\{\hat{\nu}_\alpha(x), \hat{\bar{\nu}}_\beta(0)\right\}\right\rangle$$

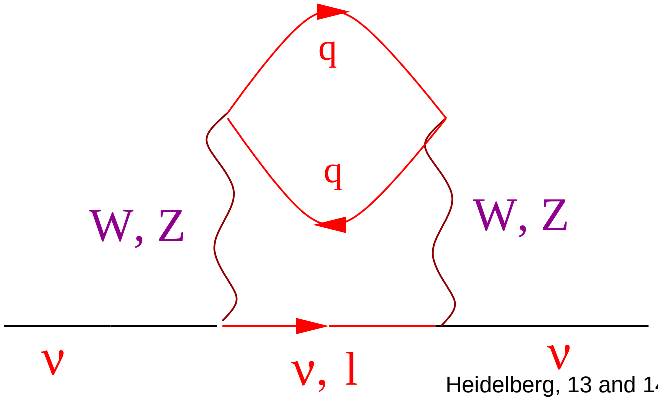
Real part





Imaginary part





Challenge: production temperature of sterile neutrinos:

$$T \sim 130 \left(\frac{M_I}{1\ \text{keV}}\right)^{1/3}\ \text{MeV}$$

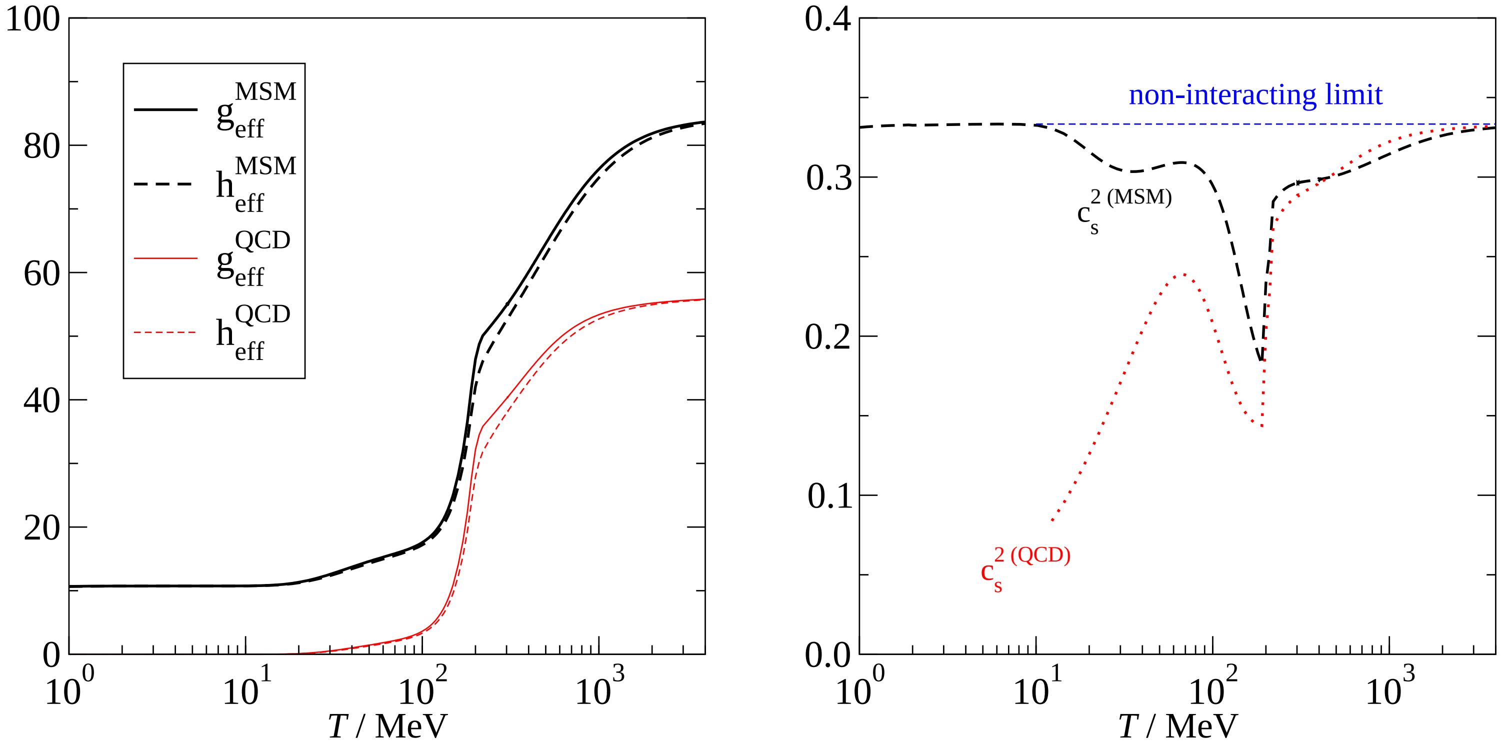
QCD interactions are strong!

The problem can be solved if one knows:

- equation of state at temperatures 10 MeV - 1 GeV
- real time correlators of vector and axial vector hadronic currents in this temperature range

Equation of state

Method: use a gas of hadronic resonances at low temperatures; the most advanced (up to resummed 4-loop level weak-coupling) results at high temperatures; and an interpolation thereof at intermediate temperatures



Scattering: imaginary part

- $T \gg \Lambda_{QCD}$: use quarks
- $T \ll \Lambda_{QCD}$: use hadrons
- Conservative upper bound on hadronic contribution: use free quarks at all temperatures
- Conservative lower bound on hadronic contribution: put $N_c = 0$
- Phenomenological mean value:

$$N_c \to N_c \frac{h_{eff}^{QCD}(T)}{58}$$

Lepton asymmetry

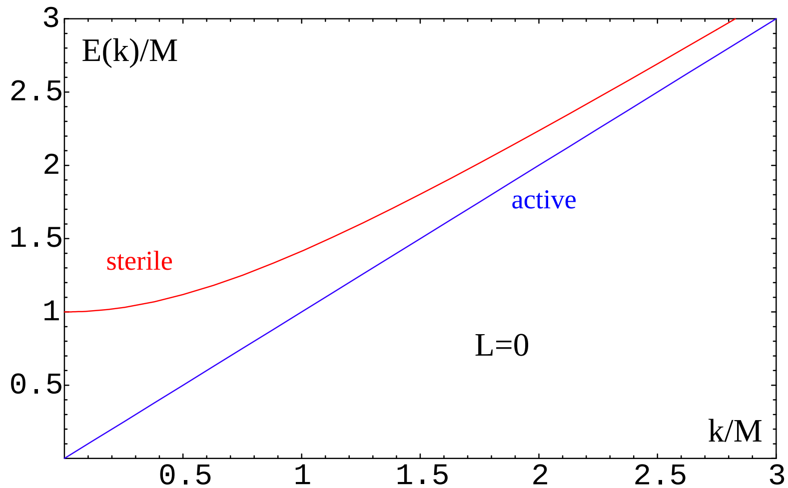
Yet another parameter: leptonic asymmetry

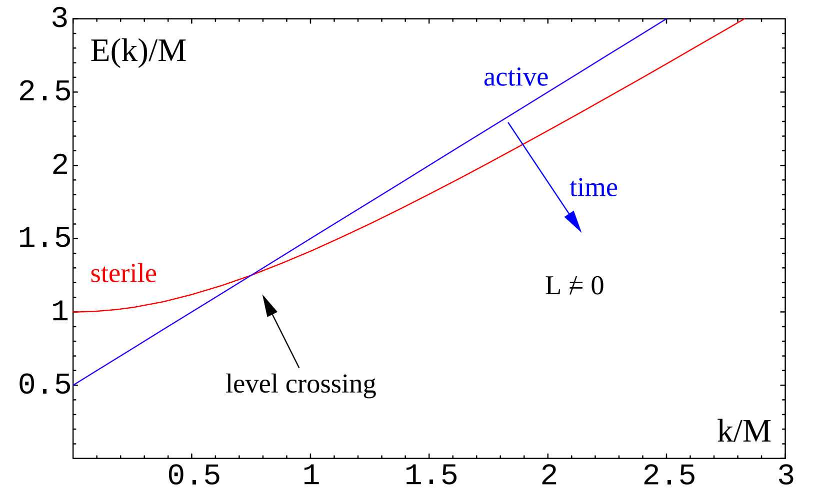
$$\Delta_L = \frac{(n_L - \bar{n}_L)}{(n_L + \bar{n}_L)}$$

in the QCD epoch

- Lepton asymmetry is created in reactions with heavier singlet fermions of the νMSM, $\Delta_L \lesssim 0.2$
- Constraints from BBN on Δ_L are weak

Dispersional relations for active and sterile neutrinos (from real part)





Transitions $\nu \rightarrow N_1$

Dodelson-Widrow

Zero lepton asymmetry

Resonant transitions

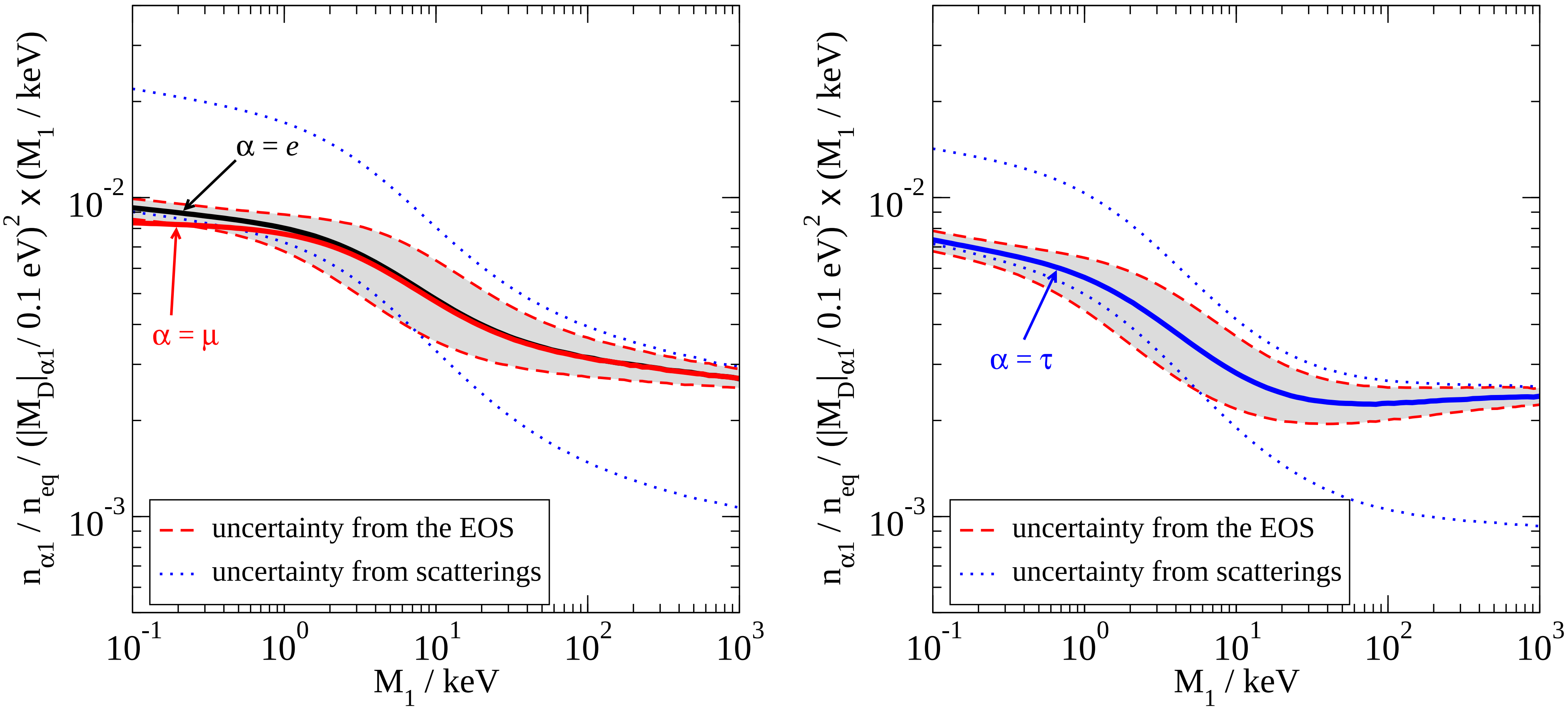
Shi-Fuller

Lepton asymmetry

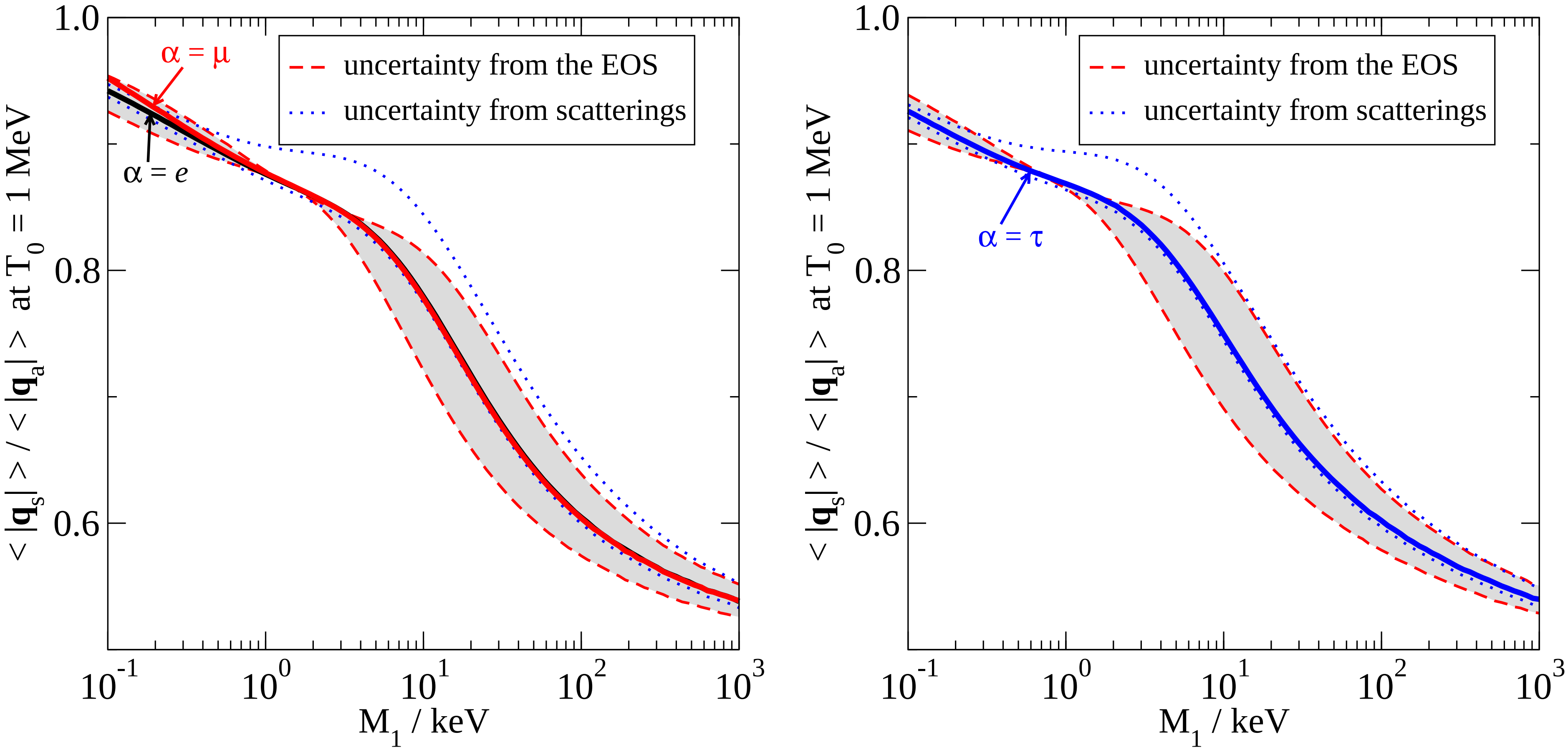
created in $N_{2,3}$ decays

Results: non-resonant case

Dark matter abundance



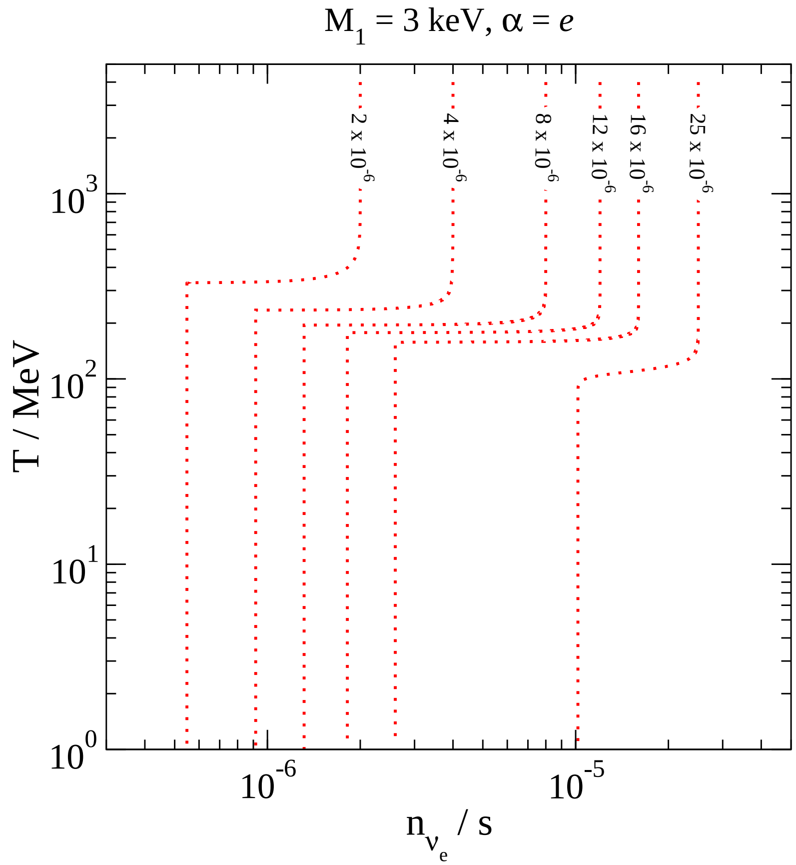
Average sterile neutrino momentum



Results: resonant case

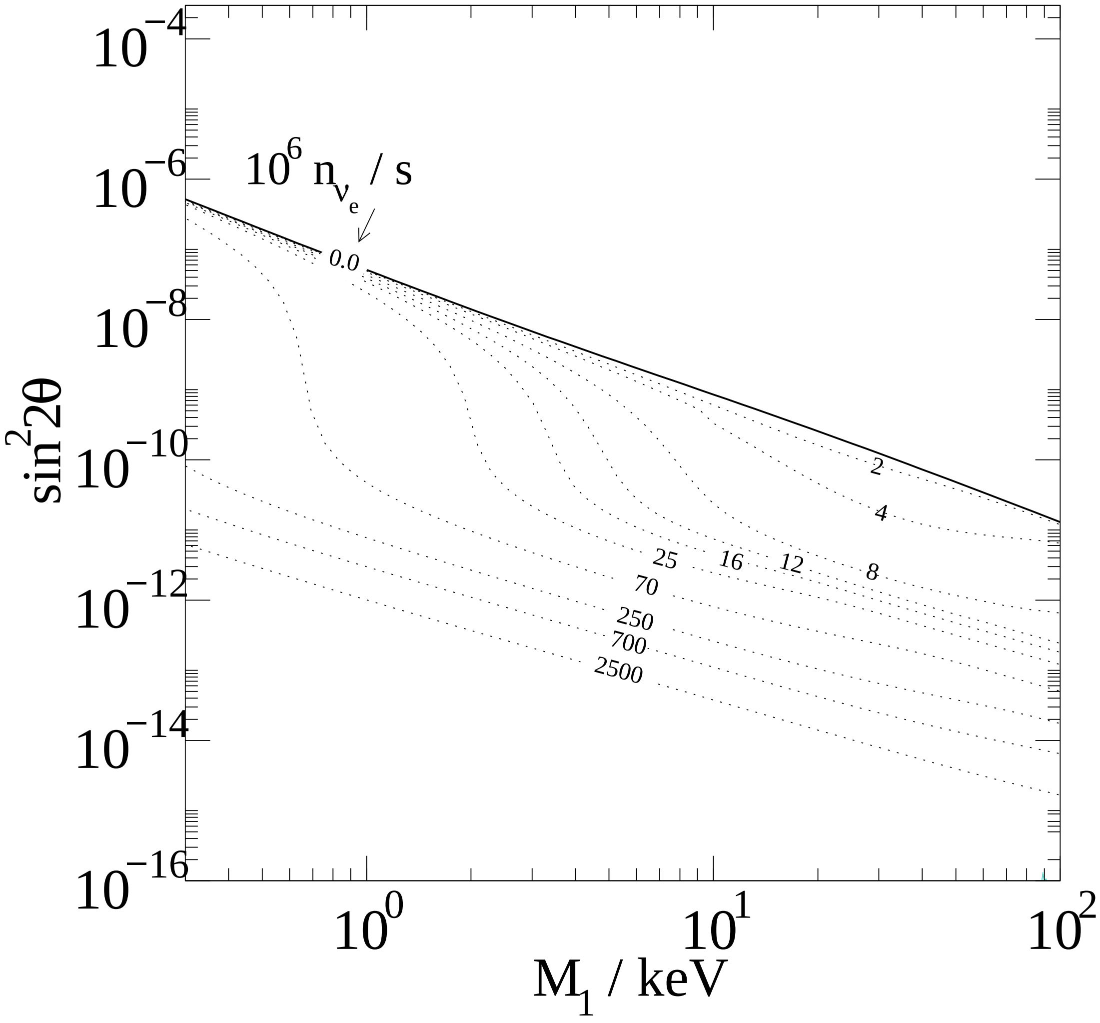
Transfer of asymmetry to DM

Large fraction of lepton asymmetry is transferred to DM

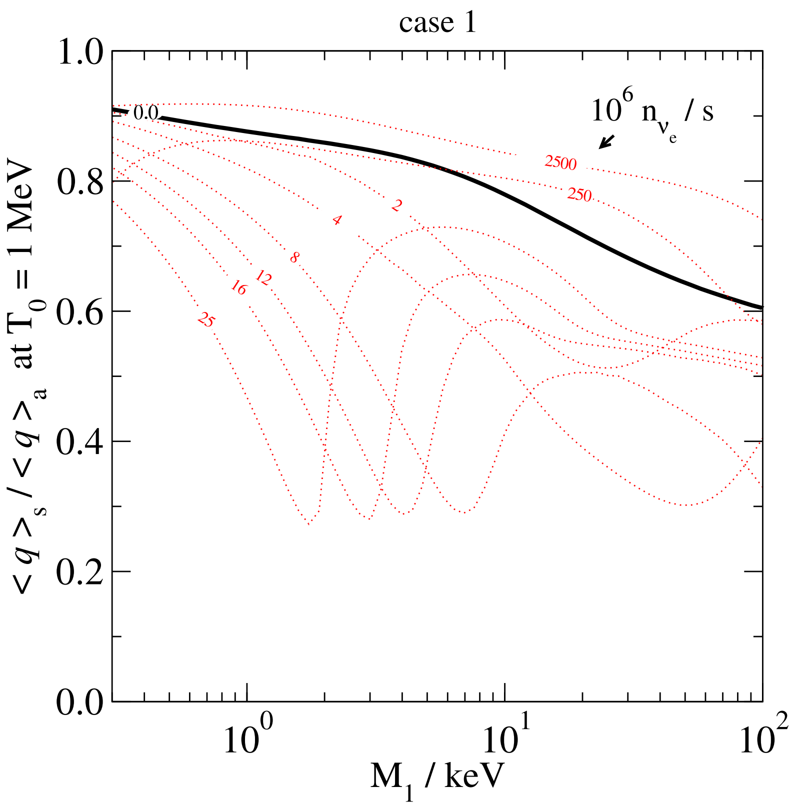


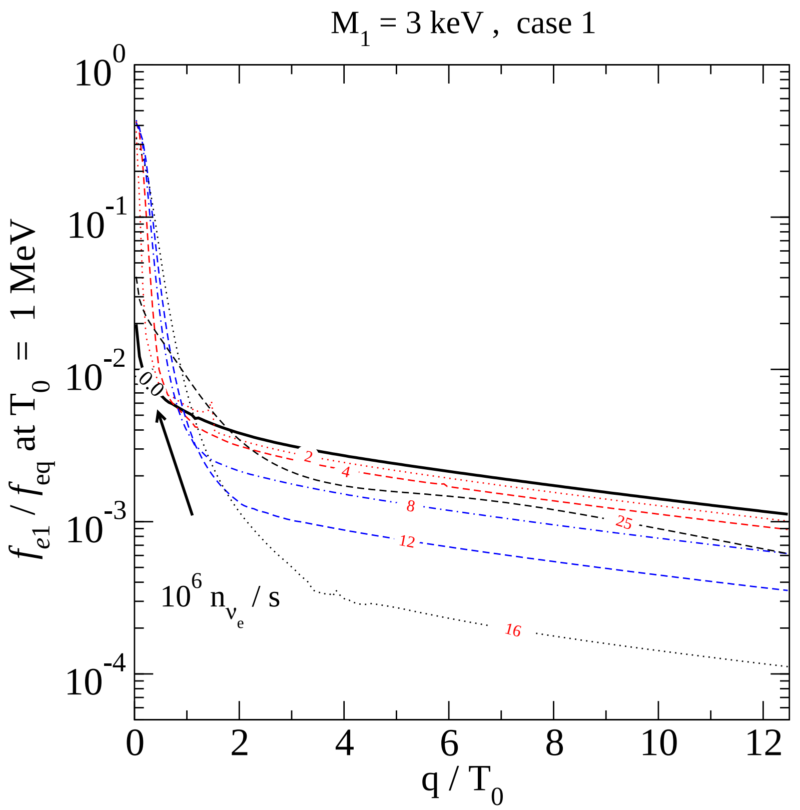
Common origin of DM and baryon asymmetry!

Explanation why $\Omega_{DM} \sim \Omega_B$?


10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
$\sin^2 2\theta$
$10^6\, n_{\nu_e} / s$
0.0
2
4
8
12
16
25
70
250
700
2500
10^0
10^1
10^2
M_1 / keV

Momentum distribution of DM

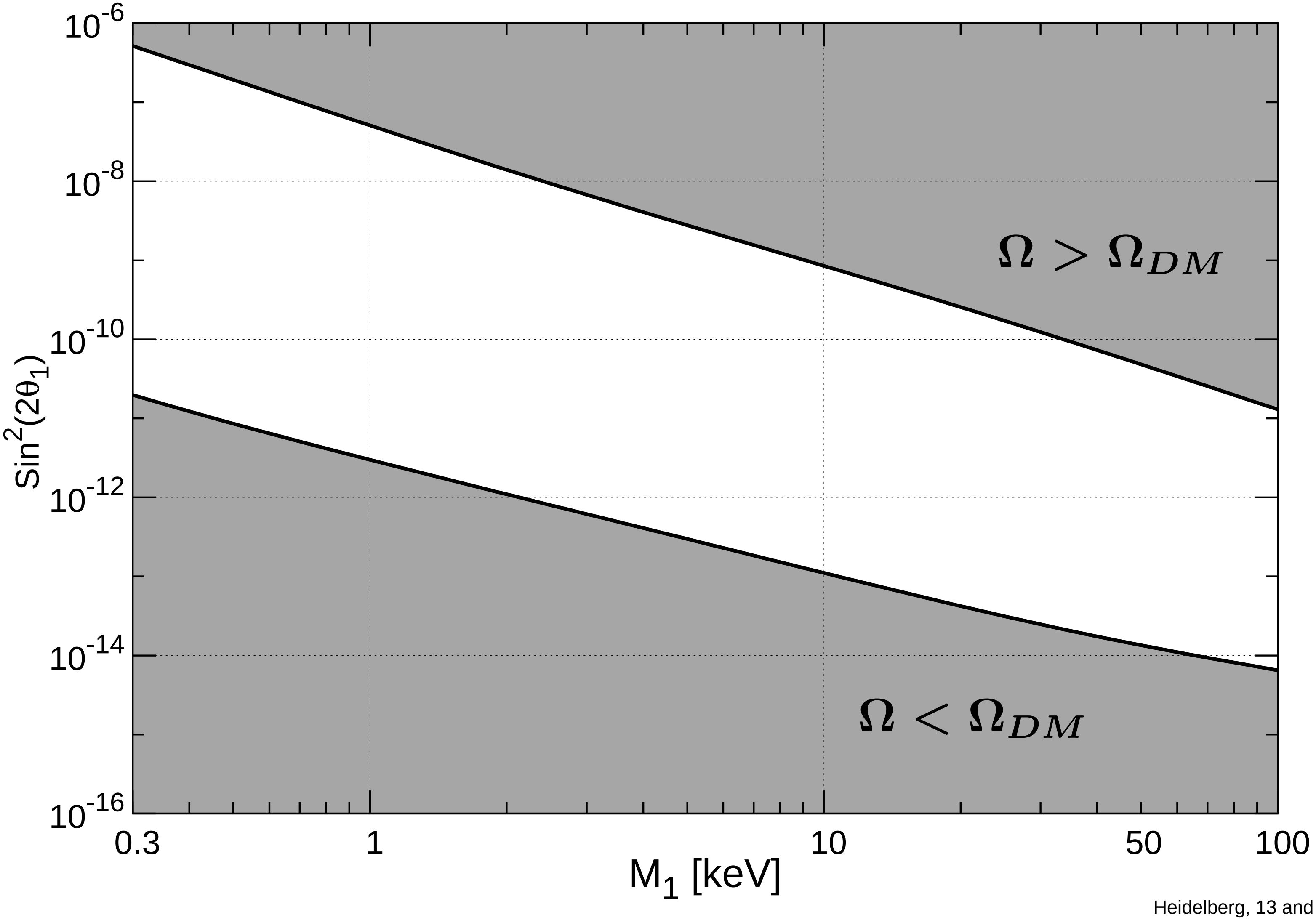




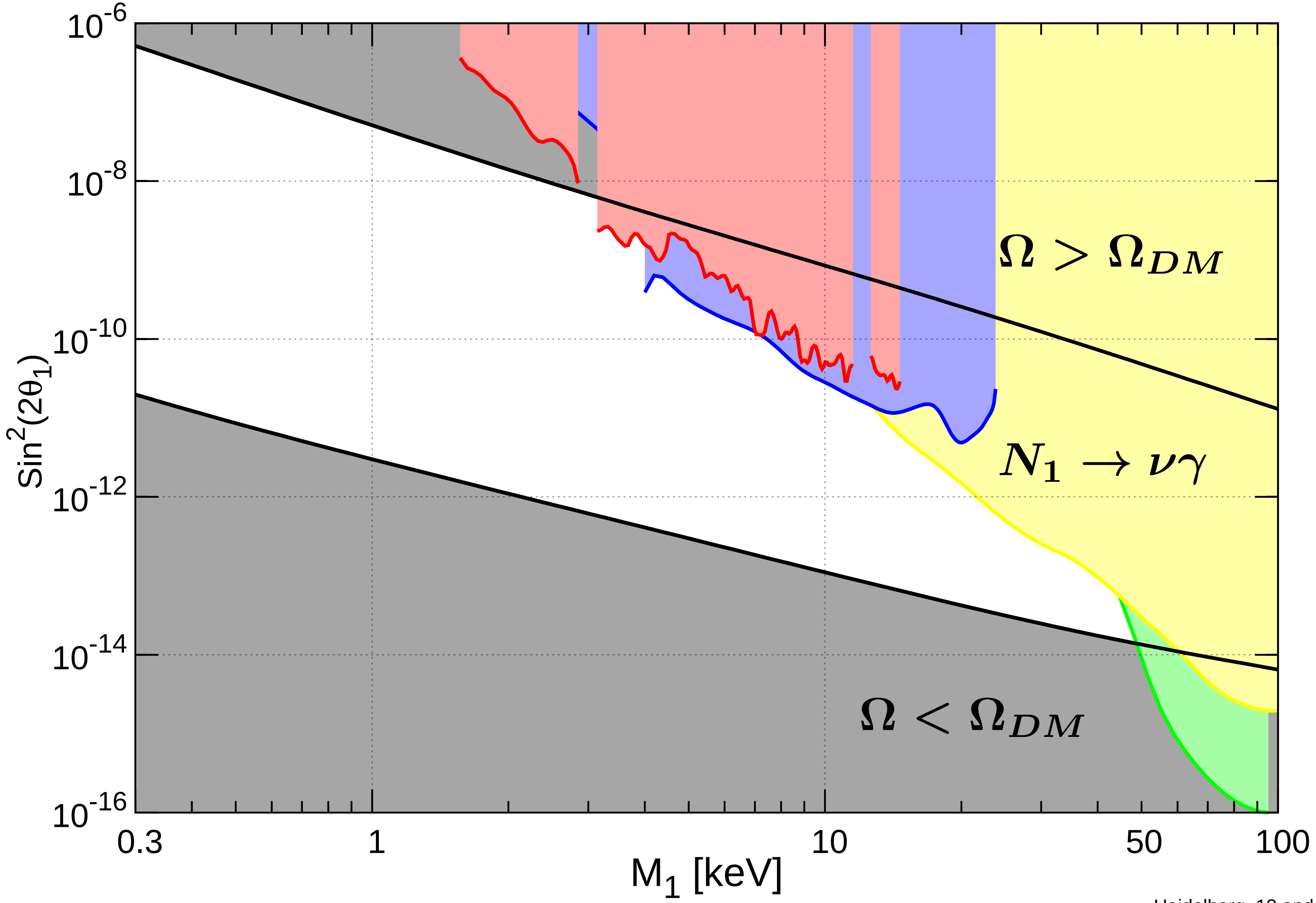
Constraints on DM sterile neutrino

- Production. N_1 are created in the early Universe in reactions $l\bar{l} \to \nu N_1, \;\; q\bar{q} \to \nu N_1$ etc. We should get correct DM abundance.
- X-rays. N_1 decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line which can be detected. This line has not been seen (yet).
- Structure formation. If N_1 is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-α forest spectra of distant quasars.

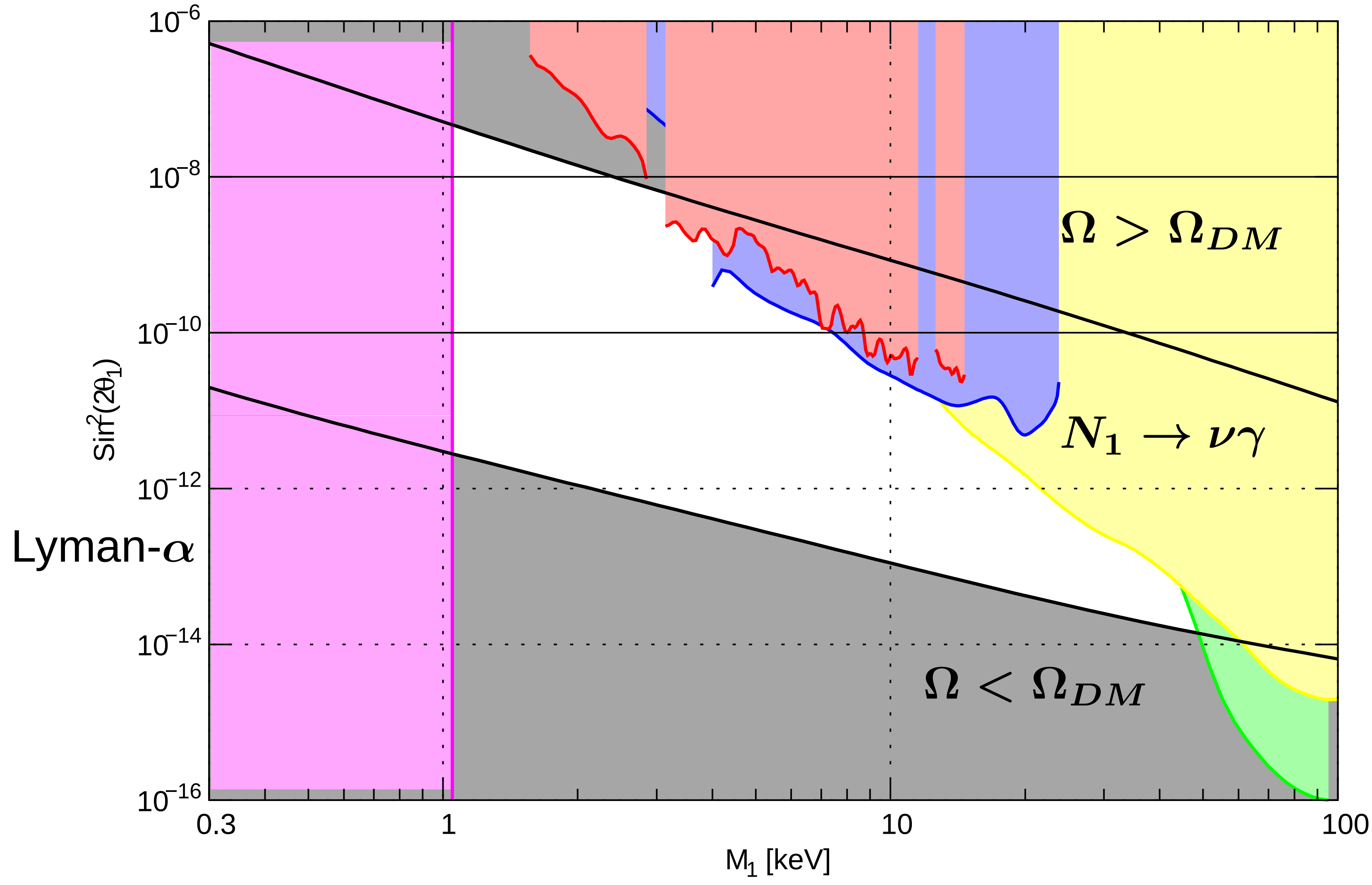
DM: production



DM: production + X-ray constraints



DM: production + X-ray constraints + Lyman-α bounds



Constraints on the mass of dark matter sterile neutrinos

Tremaine, Gunn; Lin, Faber; Hogan, Dalcanton

Rotational curves of dwarf spheroidal galaxies:

- $M_I > 0.3$ keV

Hansen et al, Viel et al

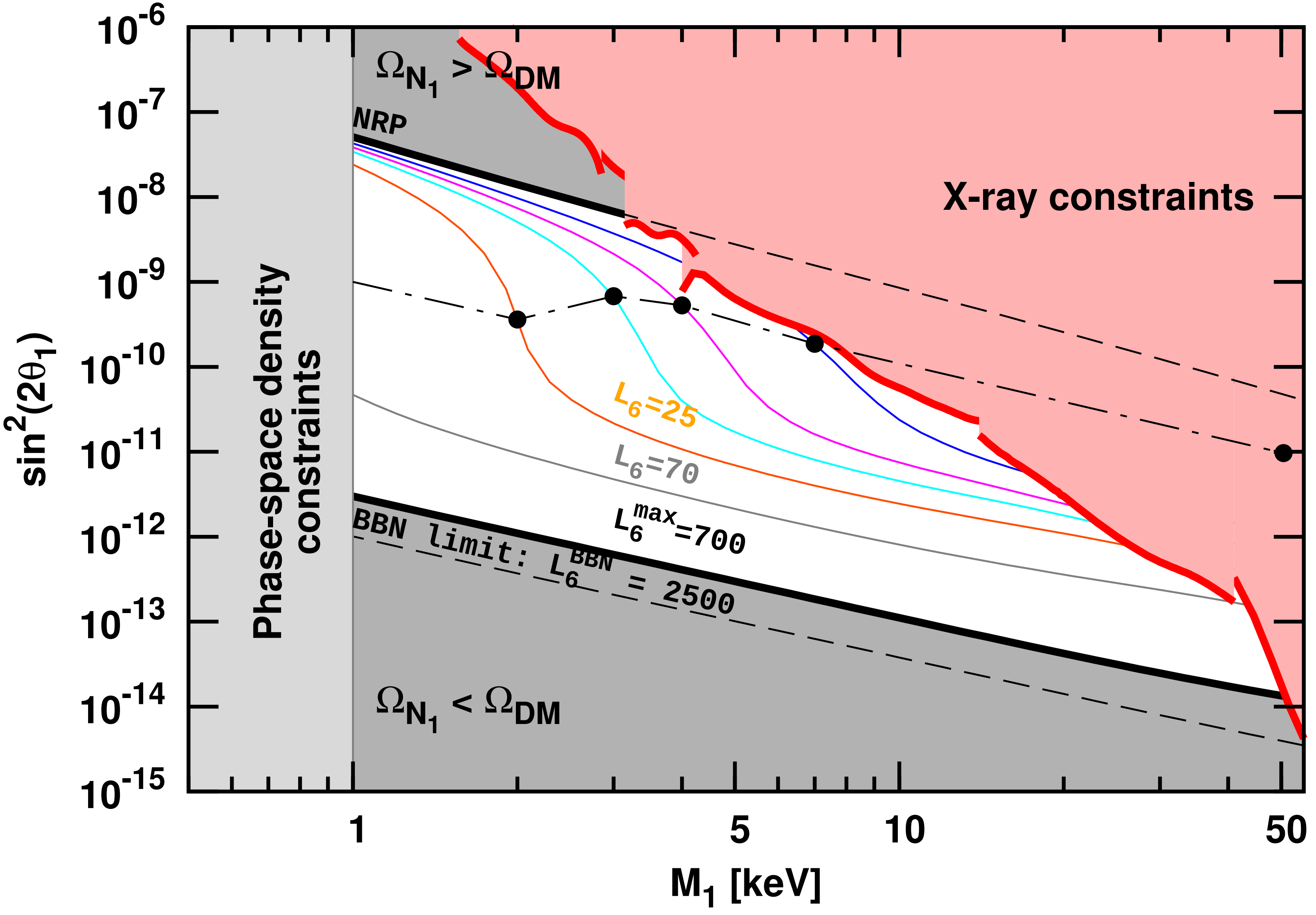
Structure formation and Lyman-α forest data:

- $M > M_0 \left(\frac{<p_s>}{<p_a>} \right)$

Viel et al: $M_{Ly\alpha} = 10$ keV

Seljak et al: $M_{Ly\alpha} = 15.4$ keV

Conservative limit, Boyarsky et al: $M_{Ly\alpha} \simeq 1$ keV



$\Omega_{N_1} > \Omega_{DM}$
NRP
X-ray constraints
Phase-space density constraints
$L_6=25$
$L_6=70$
$L_6^{max}=700$
BBN limit: $L_6^{BBN} = 2500$
$\Omega_{N_1} < \Omega_{DM}$
$\sin^2(2\theta_1)$
M_1 [keV]

Sterile neutrino free streaming length an matter-radiation equality:

$$\lambda_{FS} \simeq 1 \text{ Mpc} \left(\frac{1 \text{ keV}}{M_I}\right)\left(\frac{\langle p/T \rangle}{3.15}\right)$$

The mass inside λ_{FS}:

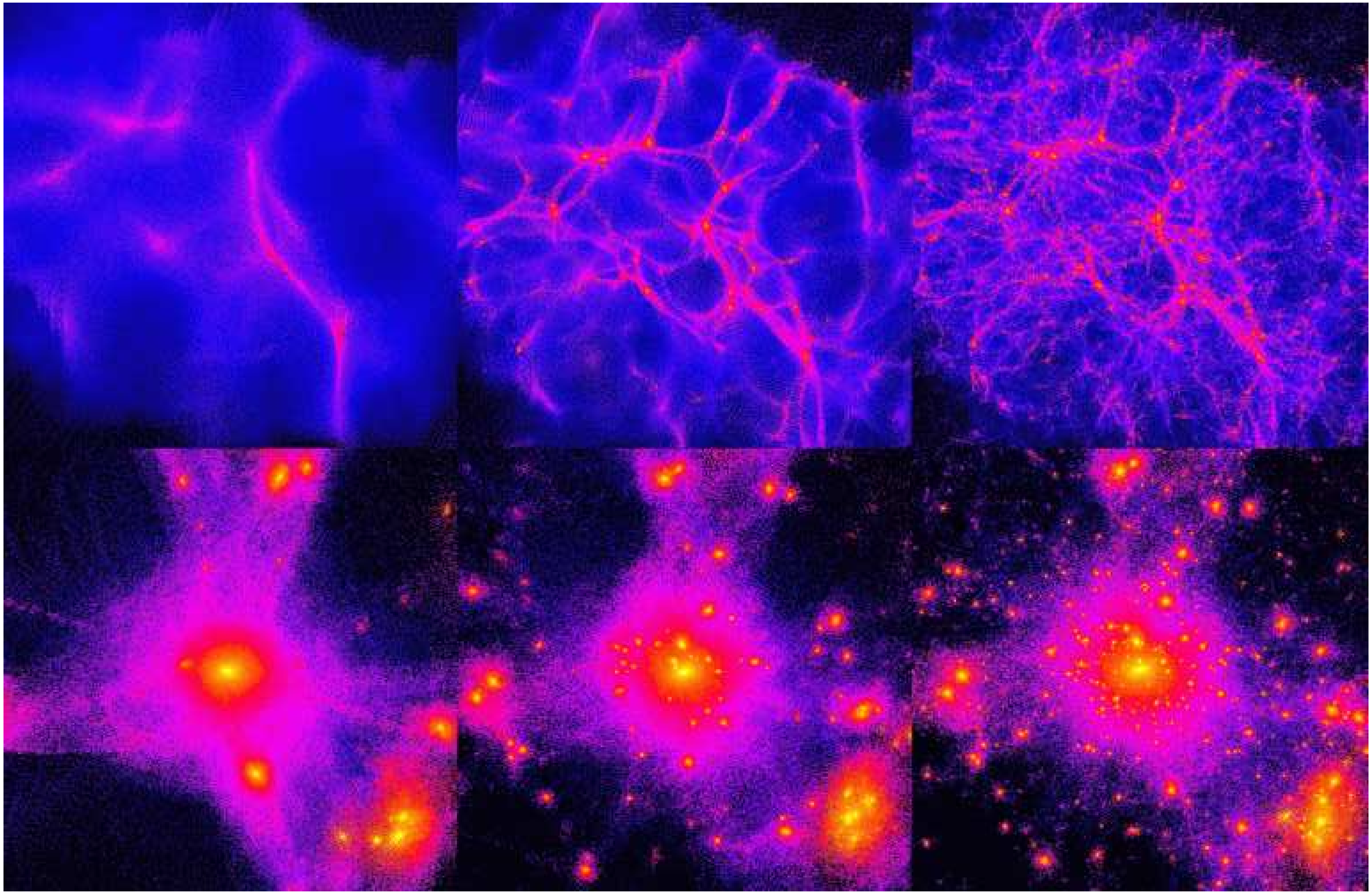
$$M_{FS} \simeq 3 \times 10^{10} M_{\odot} \left(\frac{1 \text{ keV}}{M_I}\right)^3 \left(\frac{\langle p/T \rangle}{3.15}\right)^3$$

Hot DM : $M_{FS} > 10^{14} M_{\odot}$

Warm DM : $10^5 M_{\odot} < M_{FS} < 10^{14} M_{\odot}$

Cold DM : $M_{FS} < 10^5 M_{\odot}$

Hot DM Warm DM Cold DM



Ben Moore simulations

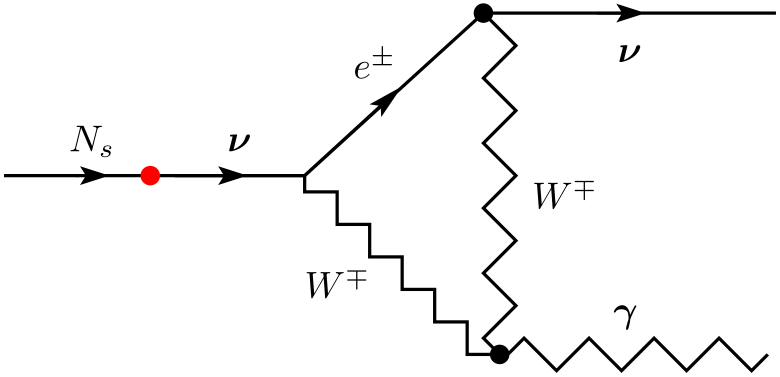
Sterile neutrino DM is not completely dark!

Dolgov, Hansen; Abazajian, Fuller, Tucker

Subdominant radiative decay channel: $N \to \nu\gamma$.

Photon energy:

$$E_\gamma = \frac{M_s}{2}$$



Radiative decay width:

$$\Gamma_{\rm rad} = \frac{9\,\alpha_{\rm EM}\,G_F^2}{256 \cdot 4\pi^4}\,\sin^2(2\theta)\,M_s^5$$

How to find DM sterile neutrino

Flux from DM decay:

$$F_{\rm dm} = \frac{\Gamma_{\rm rad} M_{\rm dm}^{\rm fov}}{8\pi D_L^2} \approx \frac{\Gamma_{\rm rad}\Omega_{\rm fov}}{8\pi} I, \quad I = \int\limits_{\text{line of sight}} \rho_{\rm dm}(r) dr$$

(Valid for small redshifts $z \ll 1$, and small fields of view $\Omega_{\rm fov} \ll 1$)

Strategy:

- Look for a narrow line against astrophysical background
- Maximize the value of integral I
- Minimize the X-ray background

Signal

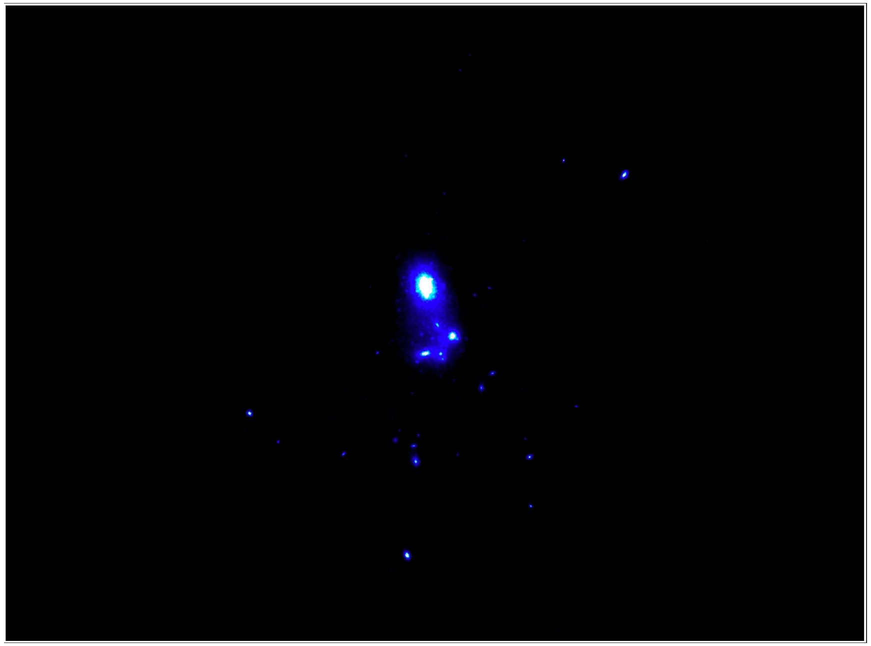
Amazing fact: the signal (value of I) is roughly the same for many astrophysical objects - from clusters to dwarf galaxies!

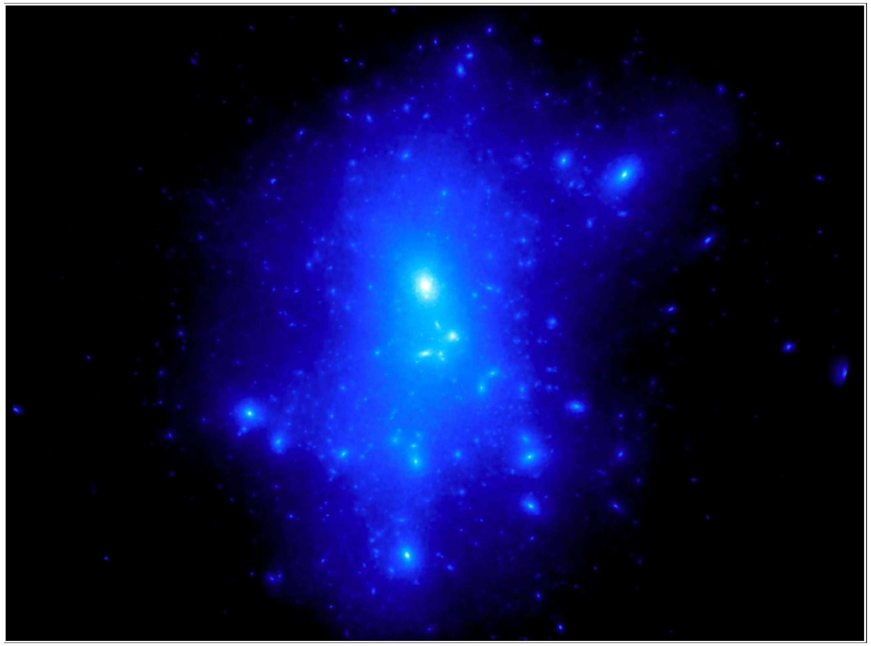
- Milky Way halo signal is comparable with that of clusters like Coma or Virgo
- DM flux from Draco or Ursa Minor dSph is 3 times stronger than that of the Milky Way halo.

Boyarsky, Neronov, Ruchayskiy, MS, Tkachev

Signal from annihilation

Signal from decay





Ben Moore simulations for cold Dark Matter

Background

Background strongly depends on the astrophysical object!

- Clusters of galaxies (e.g. Coma or Virgo) - temperature in KeV range - strong X-ray emission, atomic lines
- Continuum X-ray emission from Milky Way is about 2 orders weaker than that of a cluster
- Dwarf satellites of the MW are really dark, $M/L \sim 100$.

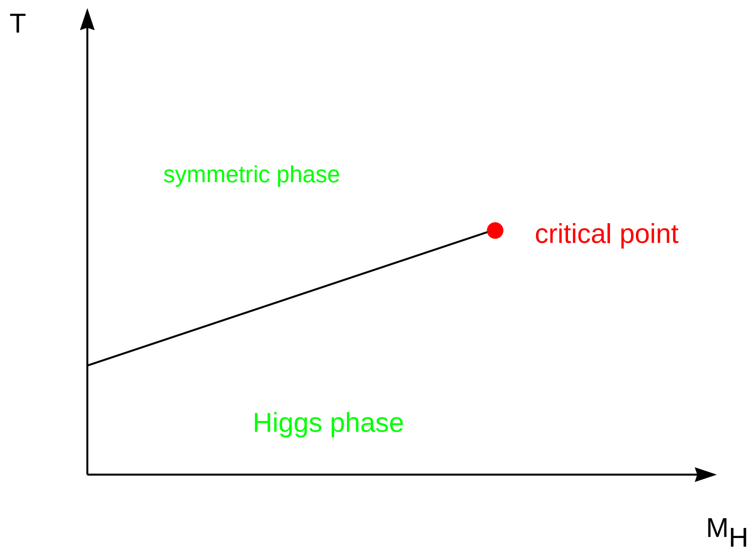
Conclusion: look at Milky Way and dwarf satellite galaxies! (Not very interesting objects for X-ray astronomers...)

Baryon asymmetry of the universe

Problem since 1930, P. Dirac.

Observational evidence: no antimatter in the Universe. Required (Sakharov):

- Baryon number non-conservation (OK)
- CP-violation (OK)
- Substantial deviations from thermal equilibrium. Present for Higgs masses larger than $\simeq$ $\mathbf{73}$ GeV (first order electroweak phase transition).



Electroweak theory

$\langle \phi^\dagger \phi \rangle \ll (250GeV)^2$

$T = 109.2 \pm 0.8GeV,$

$M_H = 72.3 \pm 0.7GeV$

$\langle \phi^\dagger \phi \rangle_{T=0} \sim (250GeV)^2$

SM: Higgs mass > 114 GeV

CP violation present but too small to accommodate observed BAU.

EW phase transition

Anomalous baryon and lepton number non-conservation

Master formula for baryon asymmetry

(Blackboard parts)

The problem

Find domain of the parameters of the νMSM, where baryon asymmetry can be consistent with observations, and which fit the neutrino data. Number of unknown constants is large - 7:

$M,\ \Delta M_M,\ \epsilon,\ \eta,\ \theta_{13}\ ,\phi,\ \alpha$

Whether $N_{2,3}$ can be found experimentally depends crucially on 2 parameters (Gorbunov, M.S.)

- their mass M
- strength of their coupling to leptons, parametrised by ϵ

So - fix M, ϵ and the degree of degeneracy ΔM_M and extremise the asymmetry as a function of other unknown parameters. Result: 3-dimensional parameter space.

Baryon asymmetry generation

Akhmedov, Rubakov, Smirnov

Asaka, MS

Idea - sterile neutrino oscillations as a source of baryon asymmetry. Qualitatively:

- Sterile neutrino are created in the early universe and oscillate in a coherent way with CP-breaking.
- The total lepton number gets unevenly distributed between active and sterile neutrinos.
- The lepton number of active left-handed neutrinos is transferred to baryons due to equilibrium sphaleron processes.

Kinetics of sterile neutrinos

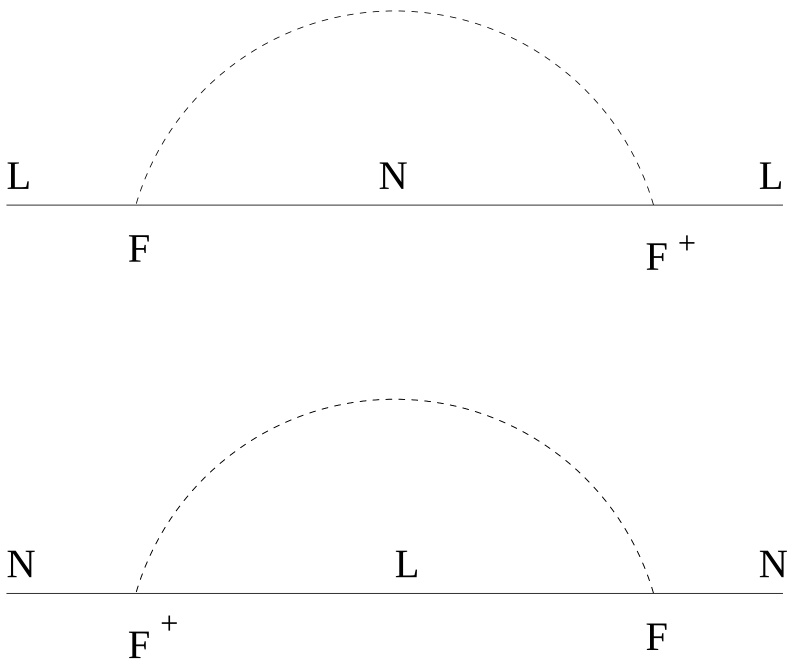
Asaka,MS

Facts to take into account:

(i) Coherence of sterile neutrino interactions $\rightarrow$ density matrix ρ_{NN} rather than concentrations.

(ii) Oscillations, creation and destruction of sterile and active neutrinos.

(iii) Dynamical asymmetries in active neutrinos and charged leptons.



Kinetics of sterile neutrinos

Sterile neutrino kinetic equation

$$i\frac{d\tilde{\rho}_{NN}}{dt} = [H^N_{int}(t), \tilde{\rho}_{NN}] - \frac{i}{2}\{\Gamma^N(t), \tilde{\rho}_{NN} - \tilde{\rho}^{eq}_{NN}\}$$

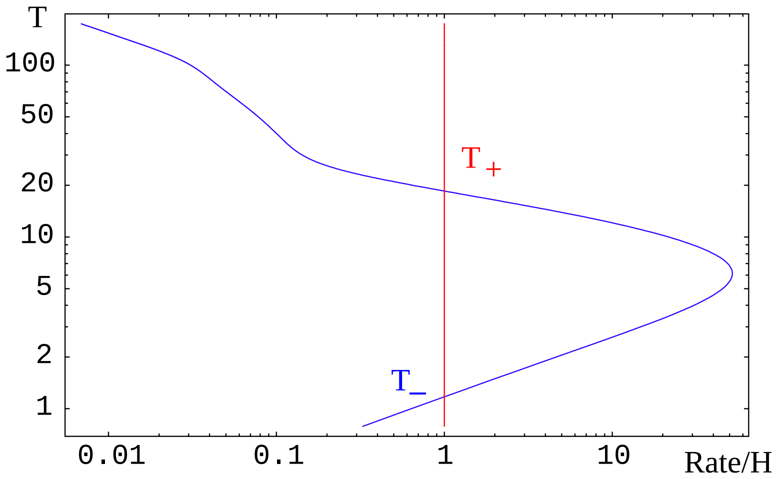
$$+i\frac{\sin\phi}{8} T\, U^\dagger(t) F^\dagger (\rho_{LL} - \rho^{eq}_{LL}) F U(t)\,.$$

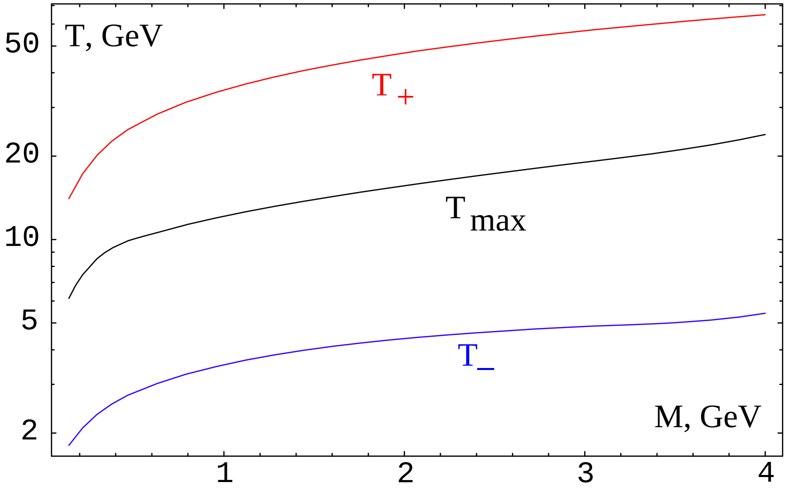
Diagonal part of the active neutrino density matrix:

$$i\frac{d\rho_{LL}}{dt} = i\frac{\sin\phi}{8} T\, F U(t)(\tilde{\rho}_{NN} - \tilde{\rho}^{eq}_{NN}) U^\dagger(t) F^\dagger$$

$$-\frac{i}{2}\{\Gamma^L(t), \rho_{LL} - \rho^{eq}_{LL}\}\,.$$

$M_N = 140$ MeV, $\epsilon = 1$





Always thermal equilibrium for $T_- < T < T_+$ and always $T_- < M_W$

Sphaleron decoupling:

$T_{EW} \simeq 130 - 175$ GeV for $M_H \simeq 114 - 200$ GeV

Source of thermal non-equilibrium: deviation of $N_{2,3}$ concentrations from equilibrium ones.

Relevant deviations from thermal equilibrium are maximal at

- $T \simeq T_{EW}$ if $T_+ < T_{EW}$
- $T \simeq T_+$ if $T_+ > T_{EW}$

Perturbative results

Analytic computation (Asaka, M.S), valid for

- Singlet fermions are out of thermal equilibrium for all temperatures above the sphaleron freeze-out, $T_+ < T_{EW}$.
- The number of singlet fermion oscillations $N_{osc} \simeq \frac{M \Delta M_M}{T_{EW}} \times \frac{M_P}{T_{EW}^2}$ is large at the electroweak temperature.
- The mass difference between two singlet fermions is much larger than the the mass difference between active neutrinos, $\Delta M_M \gg 0.04$ eV for the normal hierarchy and $\Delta M_M \gg 8 \cdot 10^{-4}$ eV for the inverted hierarchy.

Value of baryon asymmetry

$$\frac{n_B}{s} \simeq 1.7 \cdot 10^{-10} \, \delta_{\rm CP} \left(\frac{10^{-5}}{\Delta M_{32}^2 / M_3^2} \right)^{\frac{2}{3}} \left(\frac{M_3}{10 \text{ GeV}} \right)^{\frac{5}{3}} .$$

$\delta_{\rm CP} \sim 1$ is consistent with observed ν oscillations.

Non-trivial requirement: $|M_2 - M_3| \ll M_{2,3}$, i.e. heavier neutrinos must be degenerate in mass.

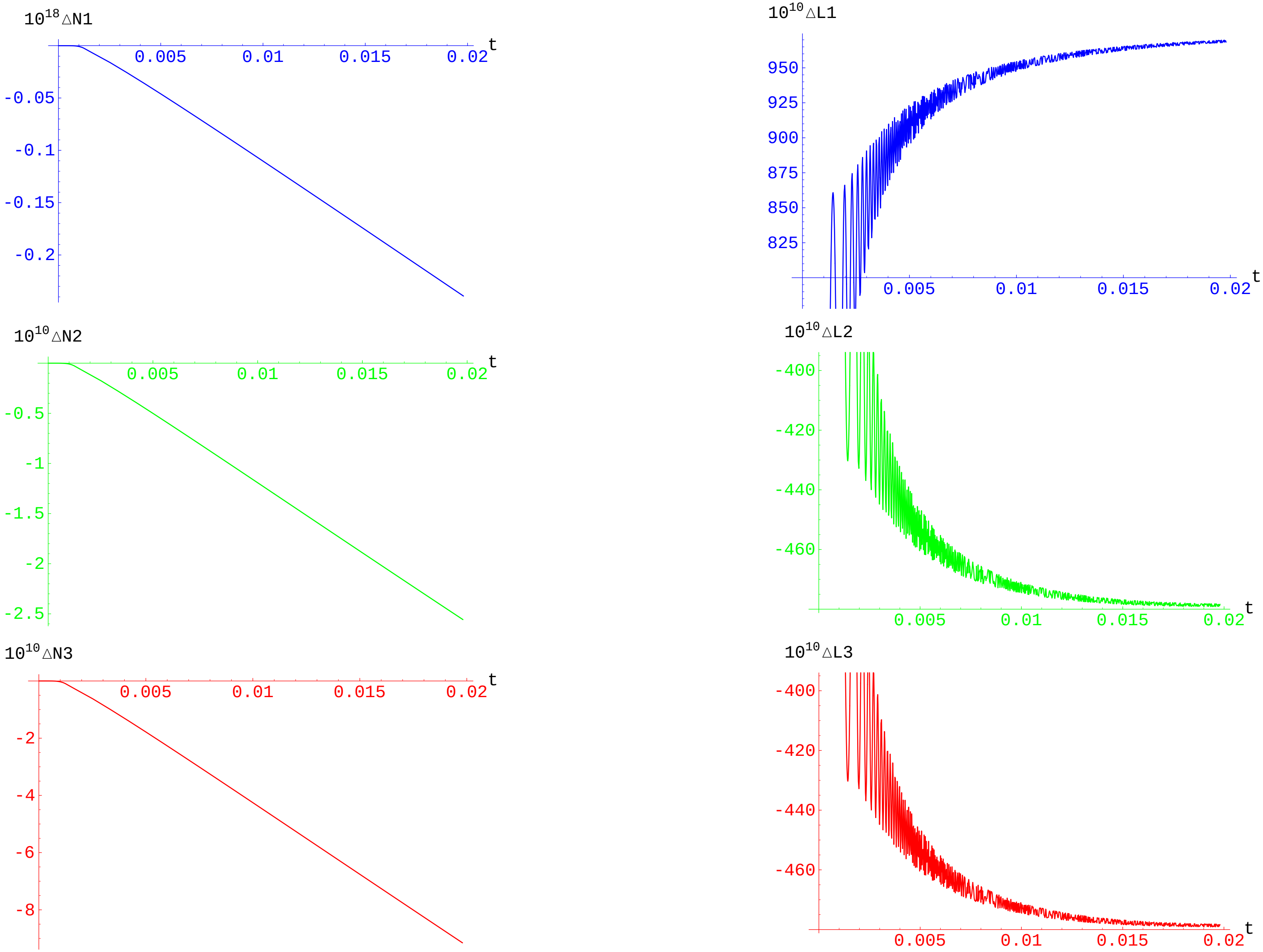
Works best (resonance) if

$$T_+ \simeq T_{EW}, \qquad N_{osc} \simeq 1$$

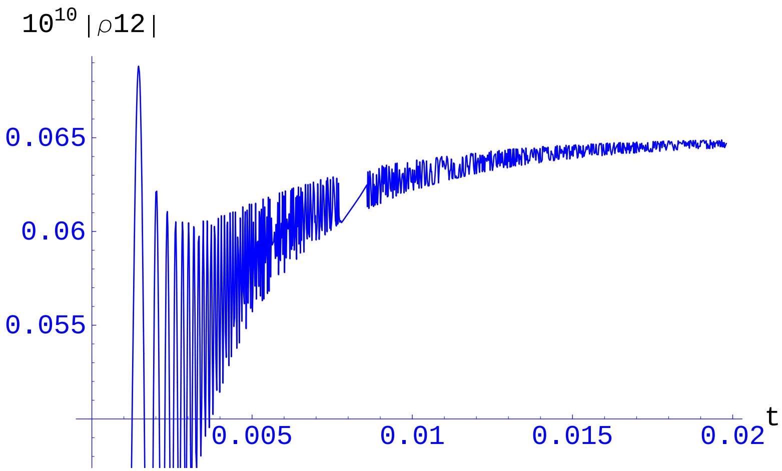
Perturbation theory does not work in this domain.

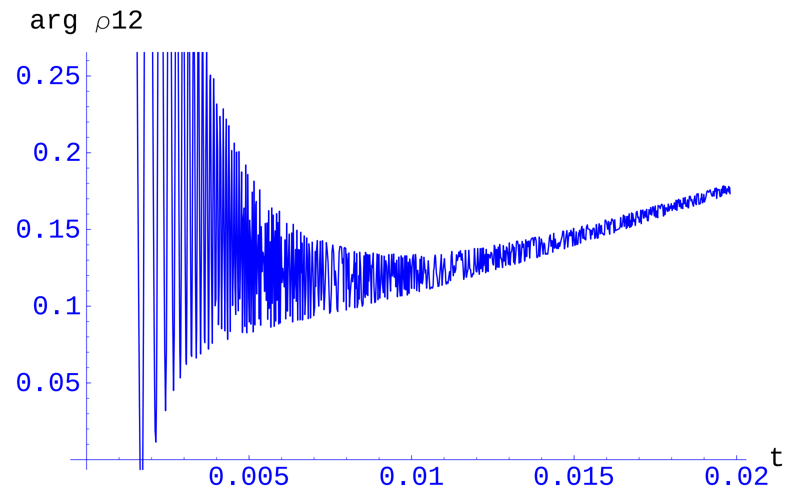
Numerical results

Asymmetry evolution

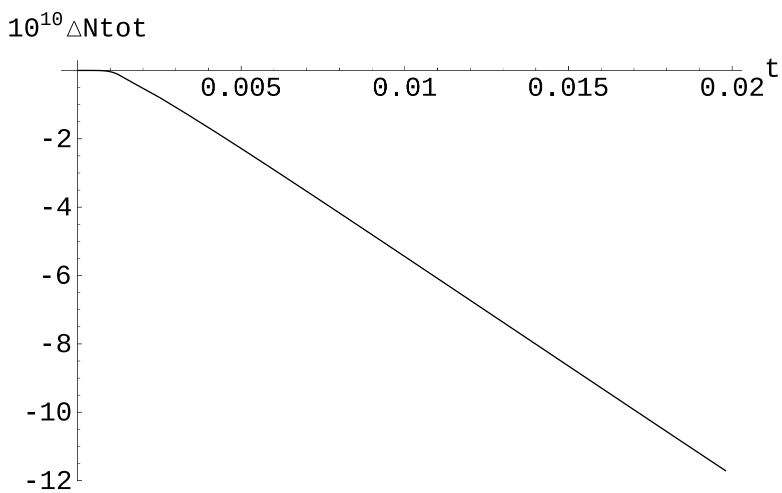


Asymmetry evolution

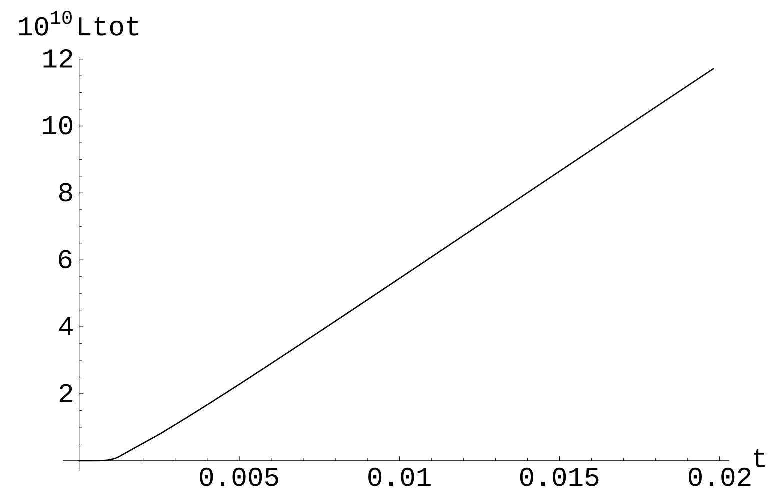




Total asymmetry in sterile sector



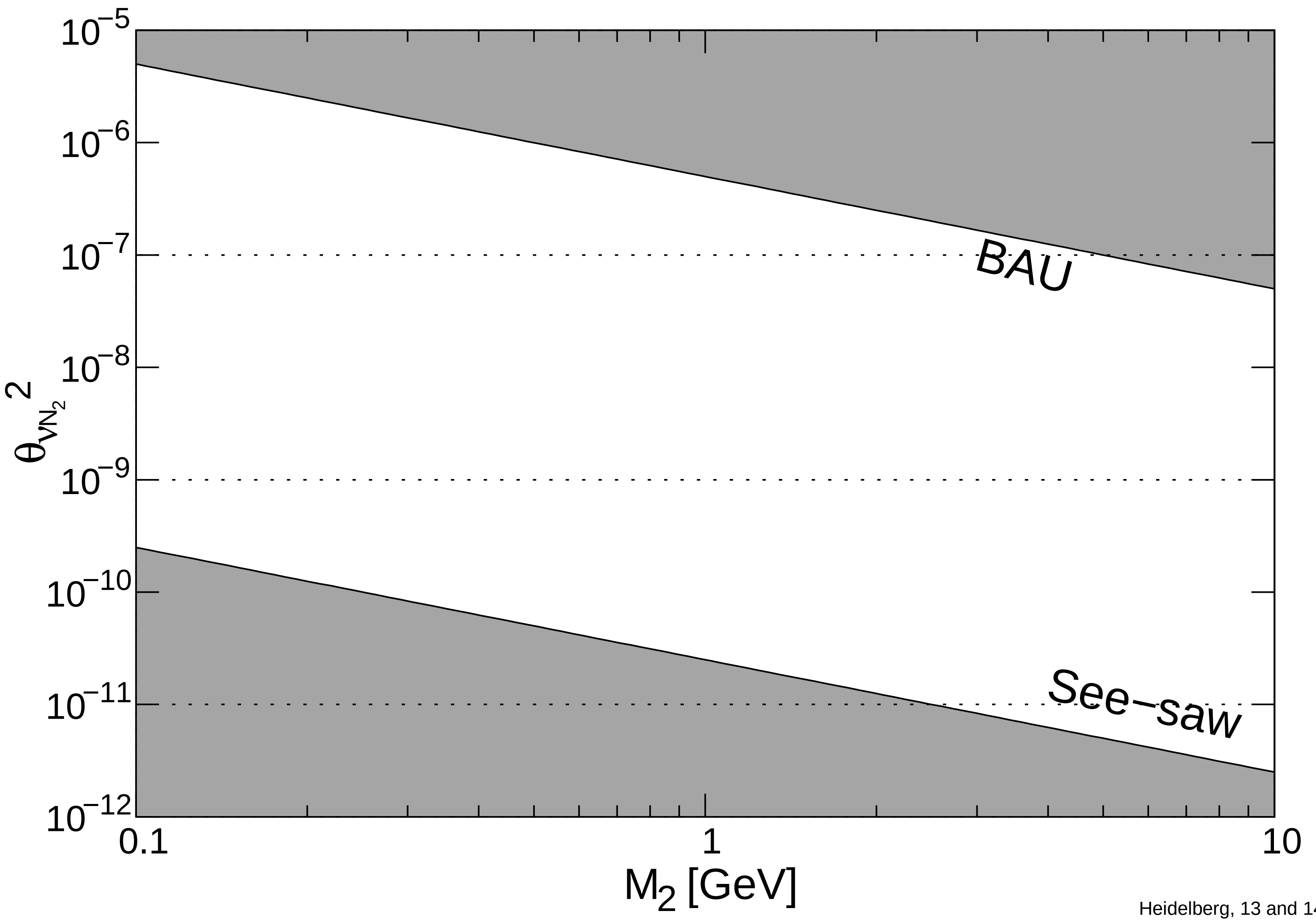
Total asymmetry in active ν



Constraints on BAU sterile neutrinos

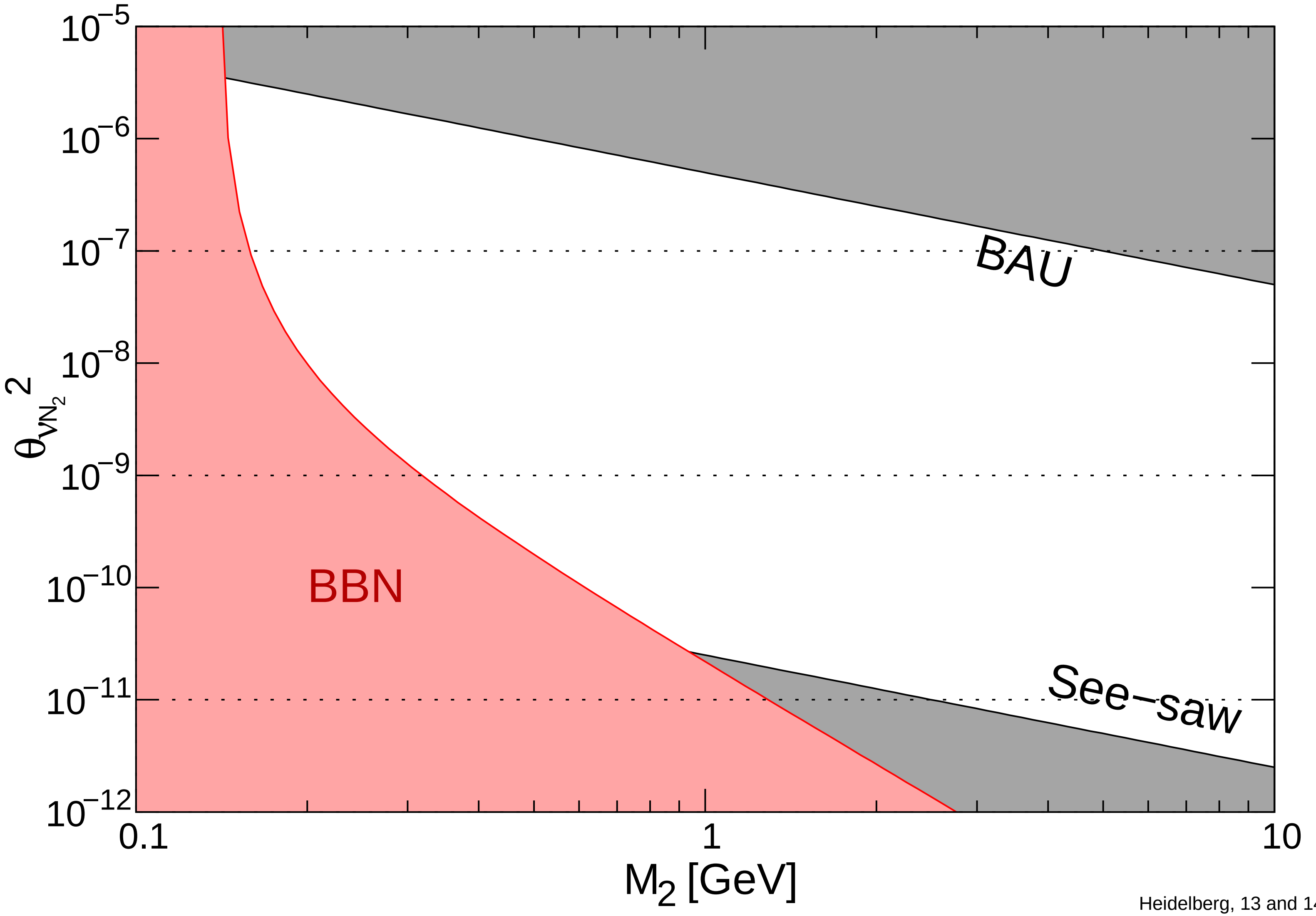
- BAU generation requires out of equilibrium: mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too small
- BBN. Decays of $\boldsymbol{N_{2,3}}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $\boldsymbol{N_{2,3}}$ have not been seen (yet).

$N_{2,3}$: BAU



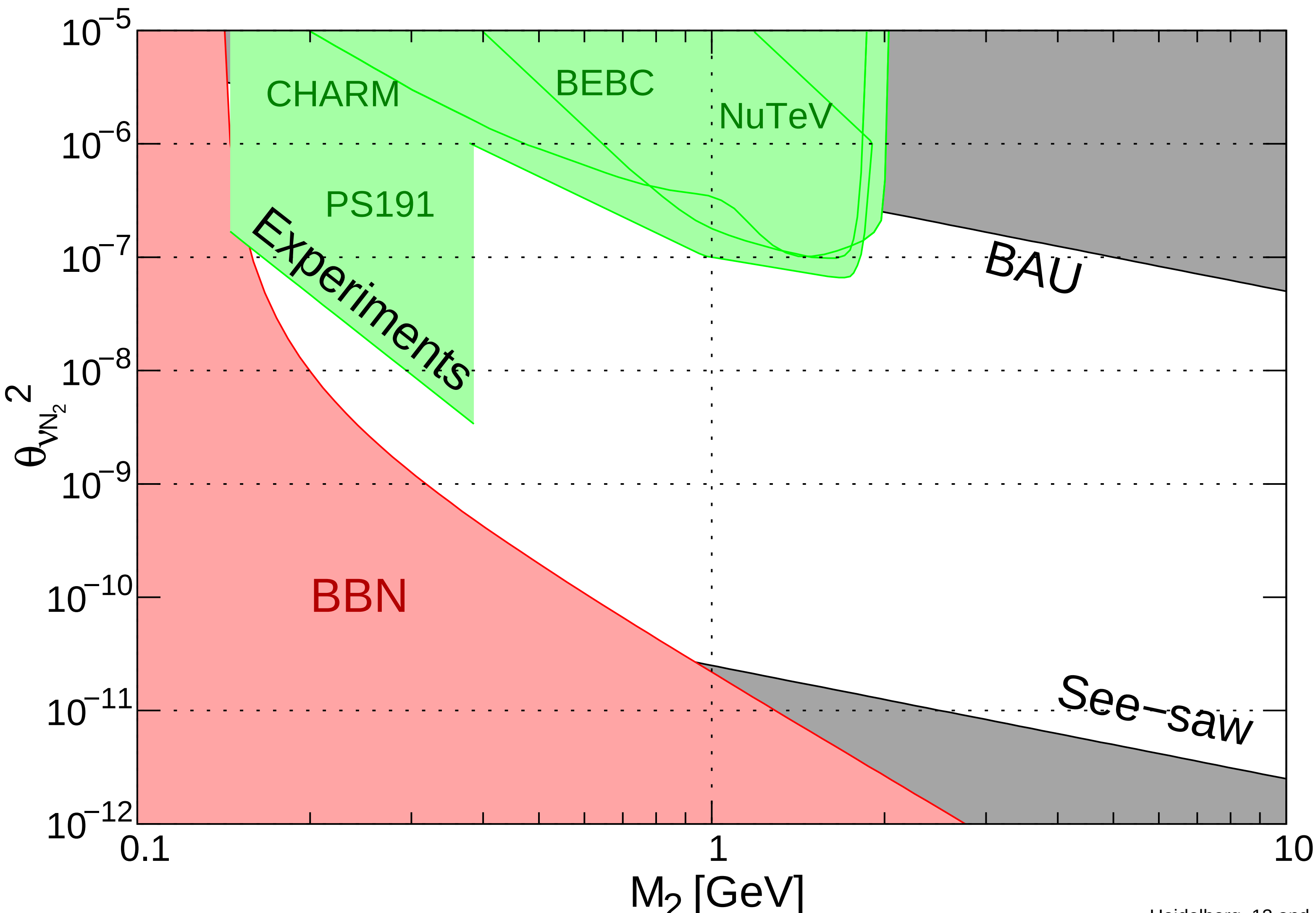
BAU
See−saw
10−5
10−6
10−7
10−8
10−9
10−10
10−11
10−12
0.1
1
10
M2 [GeV]
θνN2 2

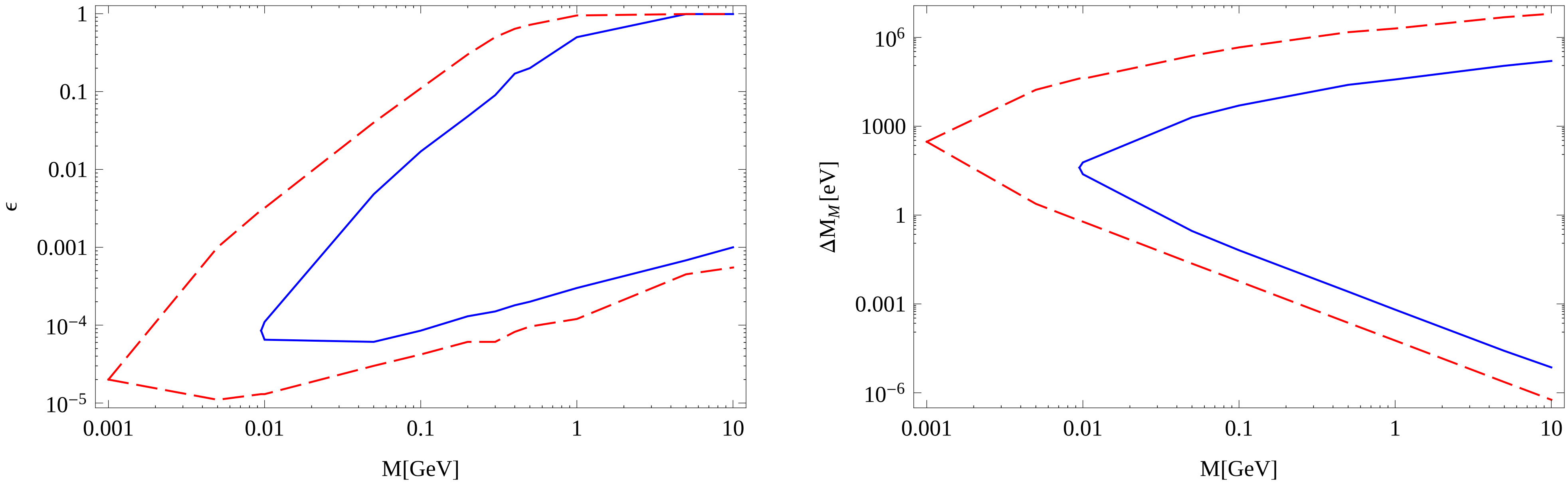
$N_{2,3}$: BAU + BBN



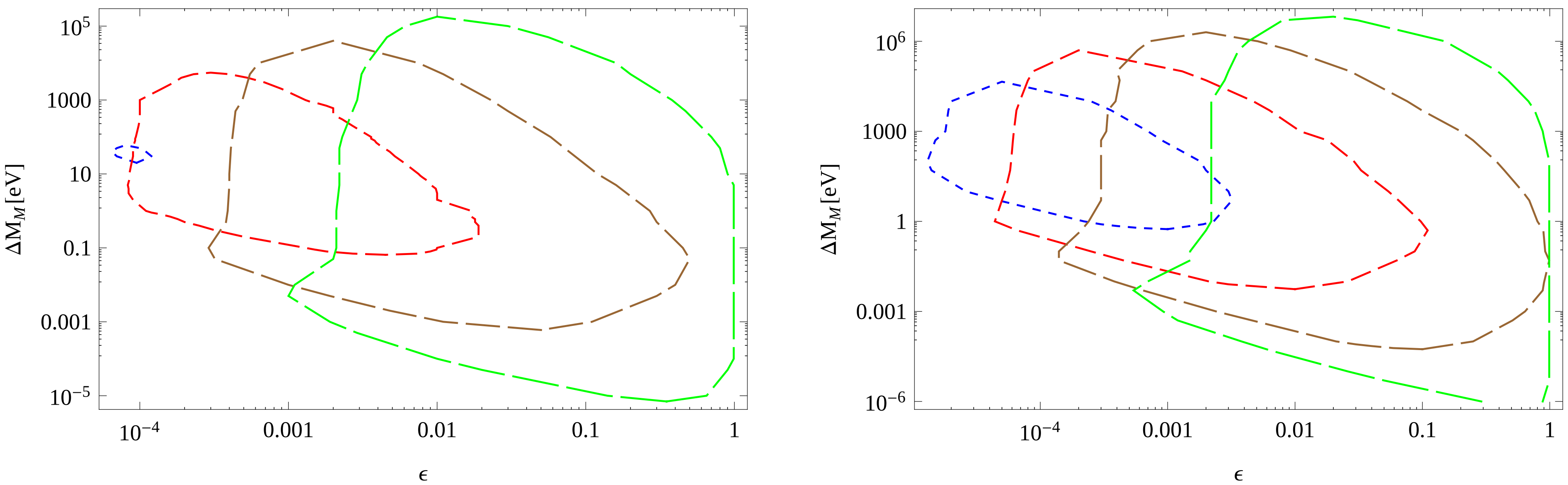
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$\theta_{\nu N_2}{}^2$
BAU
BBN
See–saw
0.1
1
10
M_2 [GeV]

$N_{2,3}$: BAU + BBN + Experiment

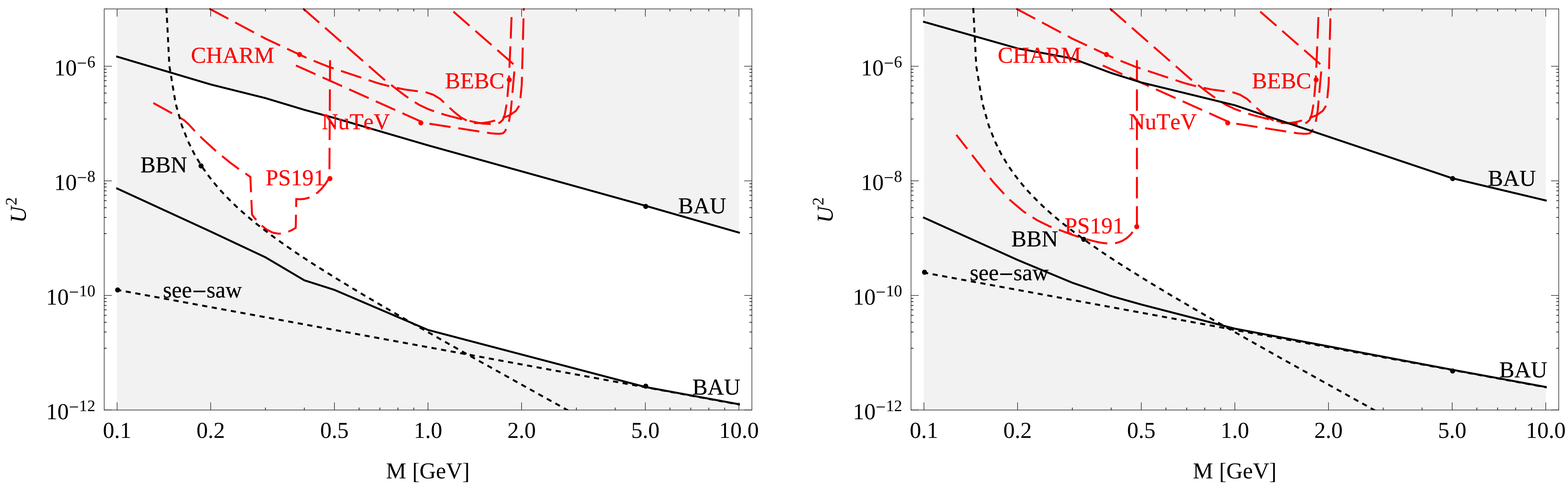




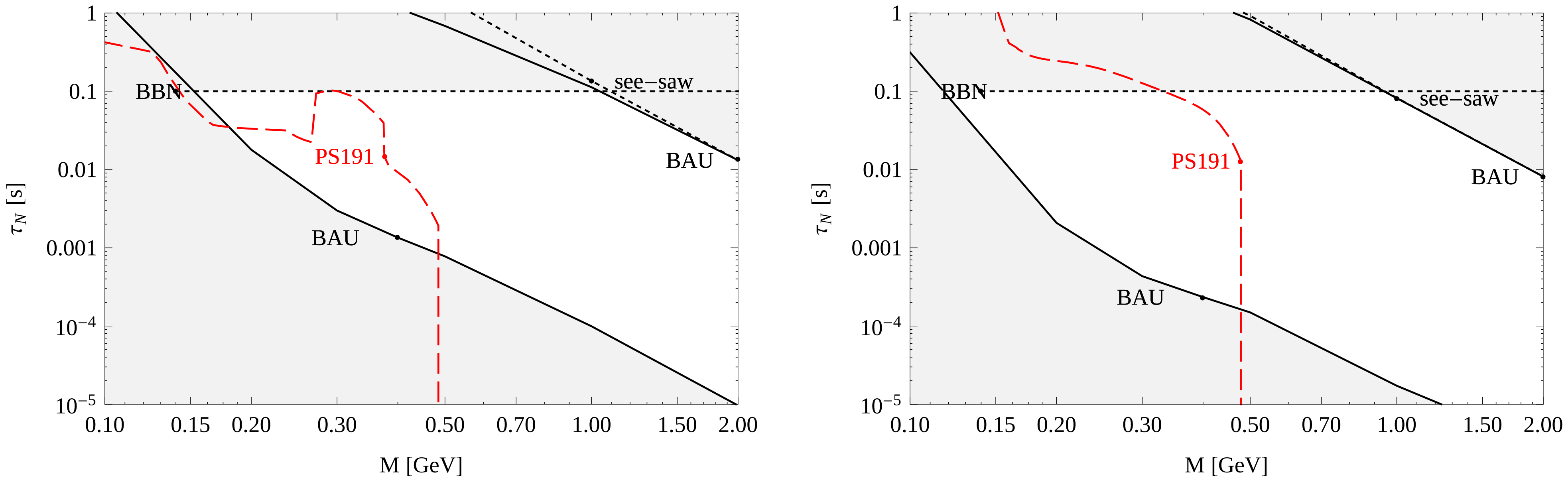
Values of ϵ - M (left panel) and ΔM_M - M (right panel) that leads to the observed baryon asymmetry for the normal hierarchy and for the inverted one.



Values of ΔM_M and ϵ that lead to the observed baryon asymmetry for different singlet fermion masses, $M = 10$ MeV, 100 MeV, 1 GeV, and 10 GeV. Left panel - normal hierarchy, right panel - inverted hierarchy.



Constraints on U^2 coming from the baryon asymmetry of the Universe (solid lines), from the see-saw formula (dotted line) and from the big bang nucleosynthesis (dotted line). Experimental searched regions are in red - dashed lines. Left panel - normal hierarchy, right panel - inverted hierarchy.



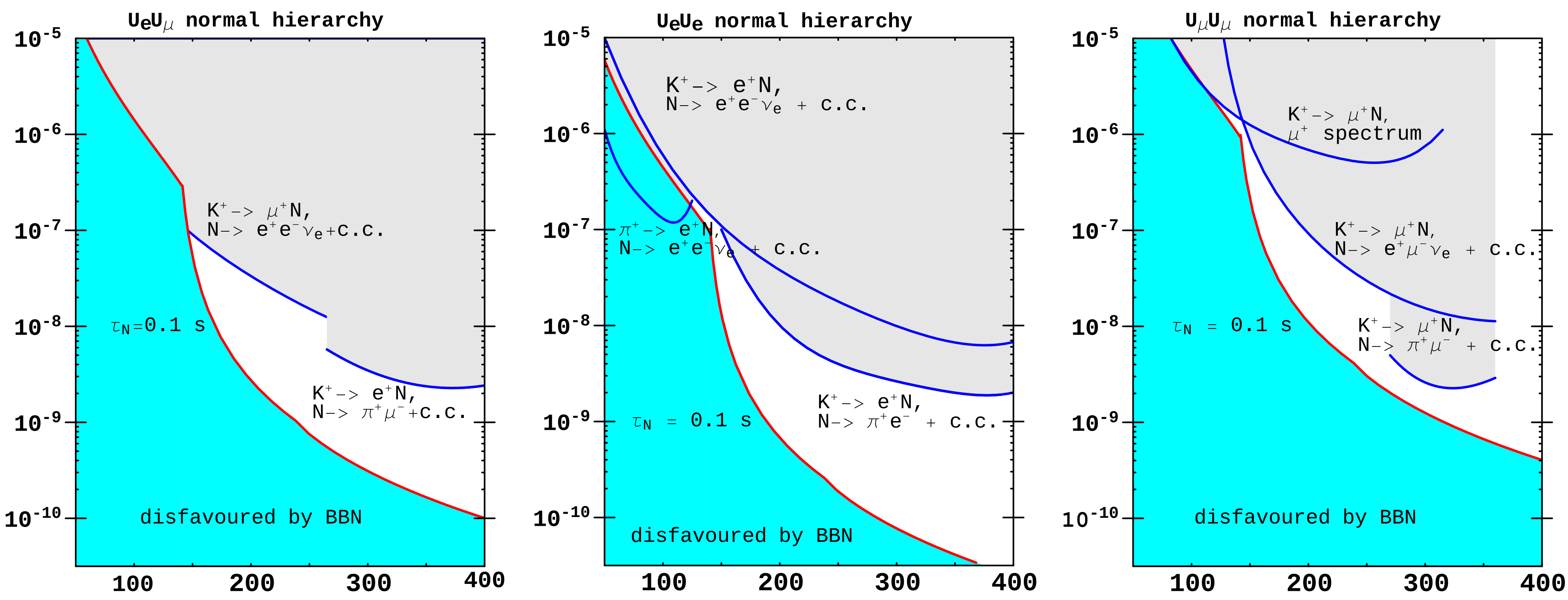
Constraints on the lifetime τ_N coming from the baryon asymmetry of the Universe (solid lines), from the see-saw formula (dotted line) and from the big bang nucleosynthesis (dotted line). Experimental constraints from PS 191 are shown in red - dashed lines. Left panel - normal hierarchy, right panel - inverted hierarchy.

Direct experimental tests: rare decays

Previous searches at CERN

- A. M. Cooper-Sarkar *et al.* [WA66 Collaboration] "Search For Heavy Neutrino Decays In The Bebc Beam Dump Experiment", 1985
- J. Dorenbosch *et al.* [CHARM Collaboration] "A search for decays of heavy neutrinos in the mass range 0.5-GeV to 2.8-GeV", 1985
- G. Bernardi *et al.* [PS191 Collaboration], "Search For Neutrino Decay", 1986;
  "Further Limits On Heavy Neutrino Couplings", 1988
- P. Astier *et al.* [NOMAD Collaboration], "Search for heavy neutrinos mixing with tau neutrinos", 2001
- P. Achard *et al.* [L3 Collaboration], "Search for heavy neutral and charged leptons in e^+e^- annihilation at LEP", 2001

CERN PS191 experiment, 1988



Conclusion: $M_{2,3} > 140$ MeV

Experimental signatures 1

Challenge - from baryon asymmetry: $\theta^2 \lesssim 5 \times 10^{-7} \left(\frac{\text{GeV}}{M}\right)$

- Peak from 2-body decay and missing energy signal from 3-body decays of K, D and B mesons (sensitivity θ^2)

  Example:

$$K^+ \to \mu^+ N, \quad M_N^2 = (p_K - p_\mu)^2 \neq 0$$

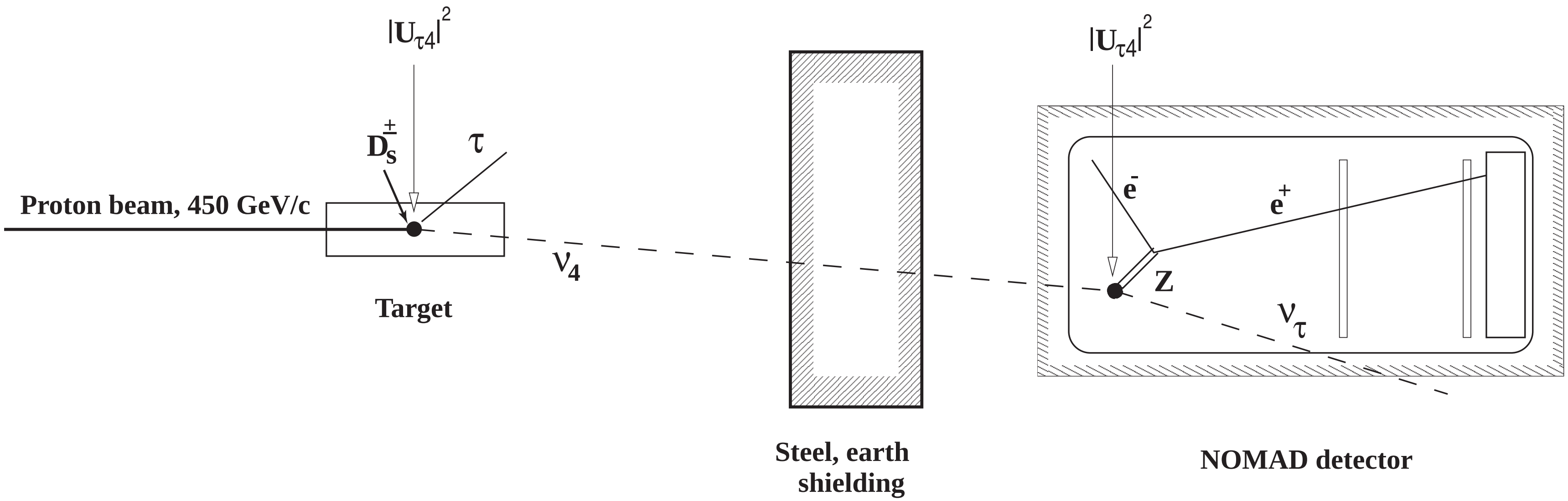
  Similar for charm and beauty.

  - $M_N < M_K$: KLOE, NA62, E787
  - $M_K < M_N < M_D$: charm and τ factories, CLEO
  - $M_N < M_B$: B-factories (planned luminosity is not enough to get into cosmologically interesting region)

Experimental signatures 2

- Two charged tracks from a common vertex, decay processes $N \to \mu^+\mu^-\nu$, etc. (sensitivity $\theta^4 = \theta^2 \times \theta^2$)
  First step: proton beam dump, creation of N in decays of K, D or B mesons: θ^2
  Second step: search for decays of N in a near detector, to collect all Ns: θ^2
  - $M_N < M_K$: Any intense source of K-mesons (e.g. from proton targets of PS.)
  - $M_N < M_D$: SPS or PS2 beam + near detector
  - $M_N < M_B$: Project X (?) + near detector
  - $M_N > M_B$: extremely difficult

$N_{2,3}$ production and decays



Type on neutrino mass hierarchy - from branching ratios of $N_{2,3}$ decays to $e, \ \mu, \tau$.

CP asymmetry can be as large as 1% - from BAU and DM

Conclusions

- New physics, responsible for neutrino masses and mixings, for dark matter, and for baryon asymmetry of the universe may hide itself below the EW scale
- New dedicated experiments in particle physics and cosmology are needed to uncover this physics

Experiments:

Particle physics

- decays of BAU singlet fermions $N_{2,3}$ created in fixed target experiments with the use of CERN SPS proton beam (or similar), e.g. $N_{2,3} \to \pi^+ \mu^-$
- precision study of kinematics of K, charm and beauty mesons, e.g. $K^+ \to \mu^+ N_{2,3}$

Astrophysics - Dark matter

- X-rays from decays of Dark Matter neutrinos $N_1 \to \nu\gamma$: X-ray spectrometer in Space with good energy resolution $\delta E/E \sim 10^{-3} - 10^{-4}$ getting signals from our Galaxy and its Dwarf satellites