Heavy Neutral Leptons

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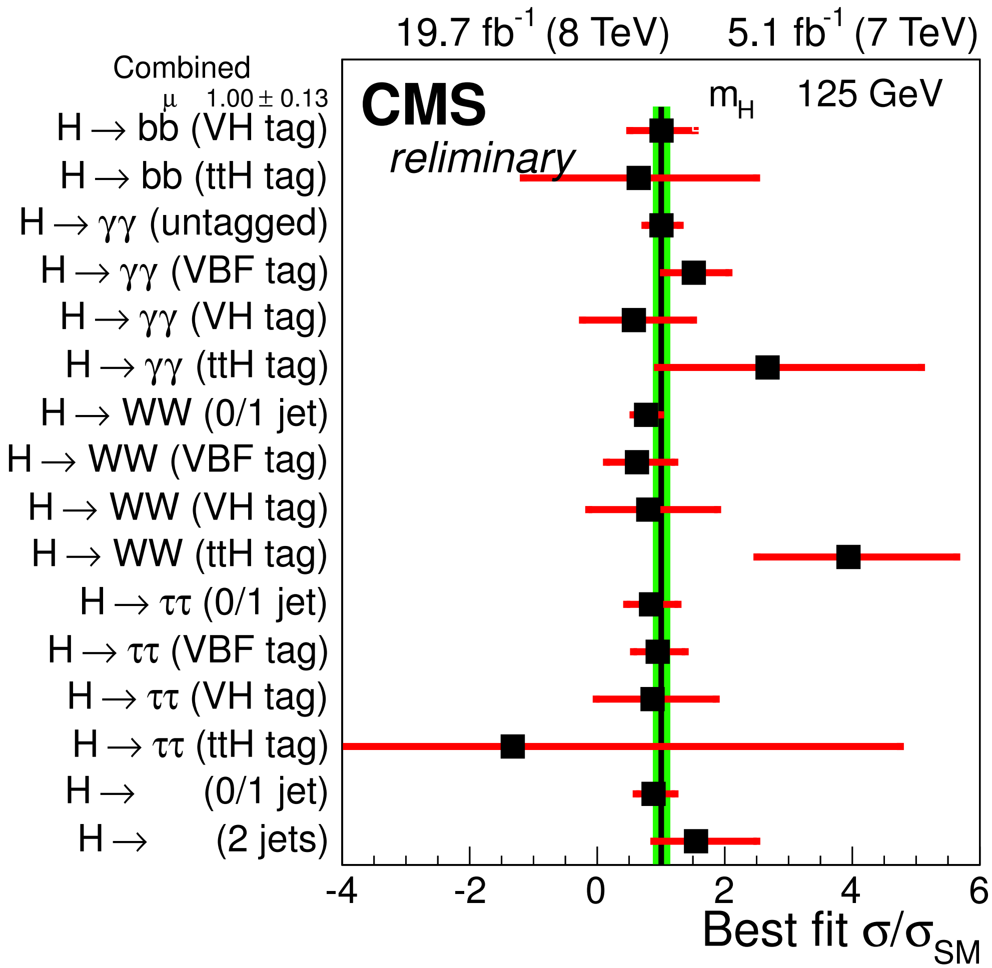
Where do we go?

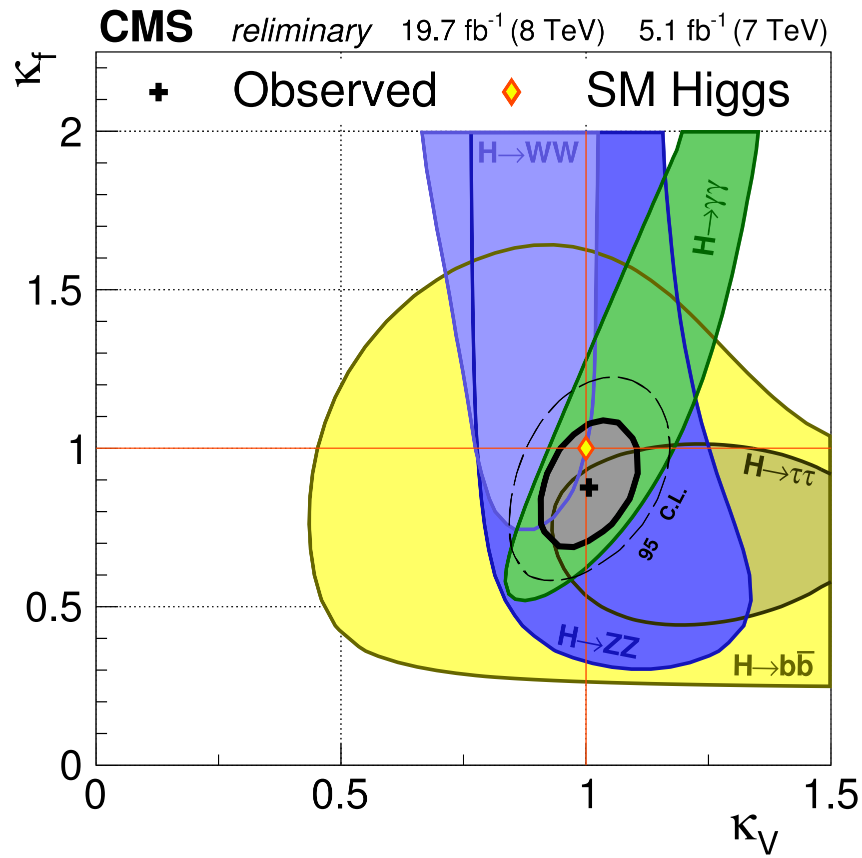
As a particle physicists we want to build "**The Theory**" such that

- ▷ All observed phenomena are explained
- ▷ All predicted particles are discovered
- ▷ The resulting theory is self-consistent

Are we there yet?

All predicted particles are found!





Century long quest came to its end – all predicted particles have been found!

All discovered phenomena explained? – No

Particle physics: neutrino oscillations

Cosmology and astrophysics: particle physics (coupled to Einstein gravity) applied to the Universe as a whole faces the challenges of

– dynamics of gravitating objects at scales from galactic to cosmological (**dark matter**?)
– absence of primordial baryon asymmetry of the Universe

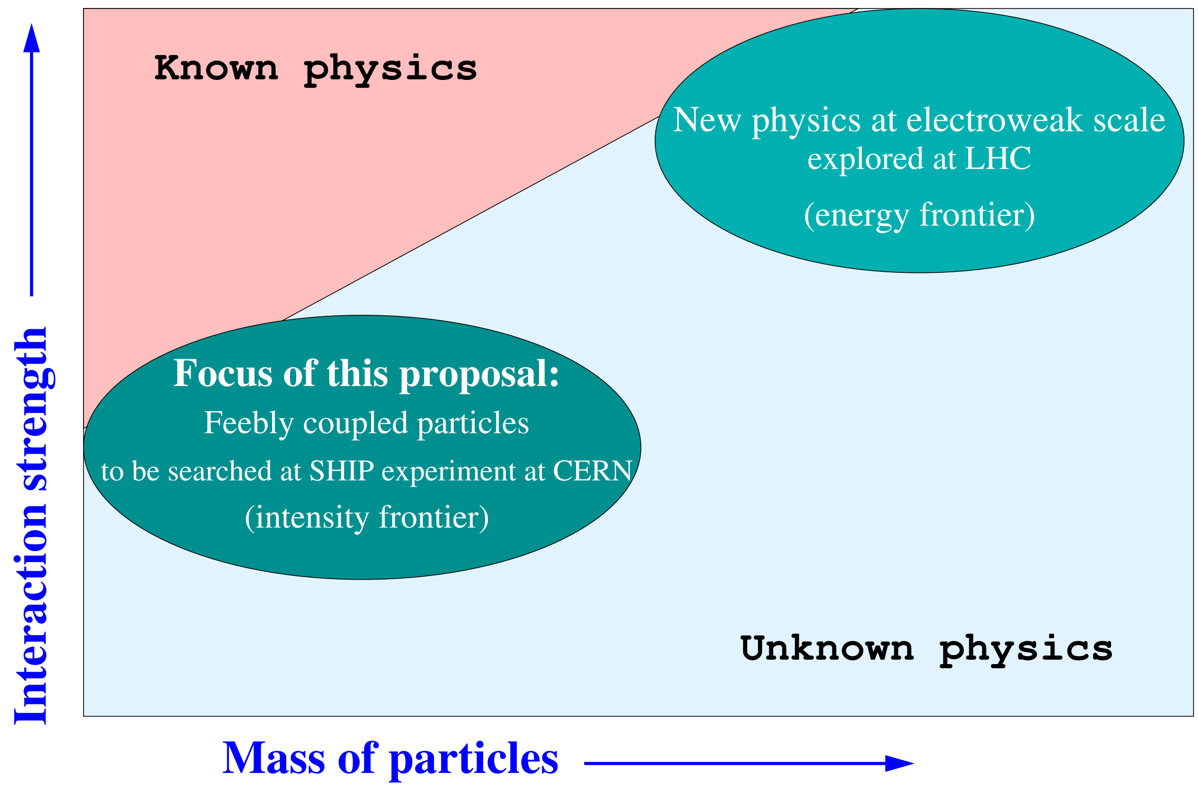
Possibly

– initial conditions for the Universe (**inflation**?)
– accelerated expansion of the Universe (**dark energy**?)

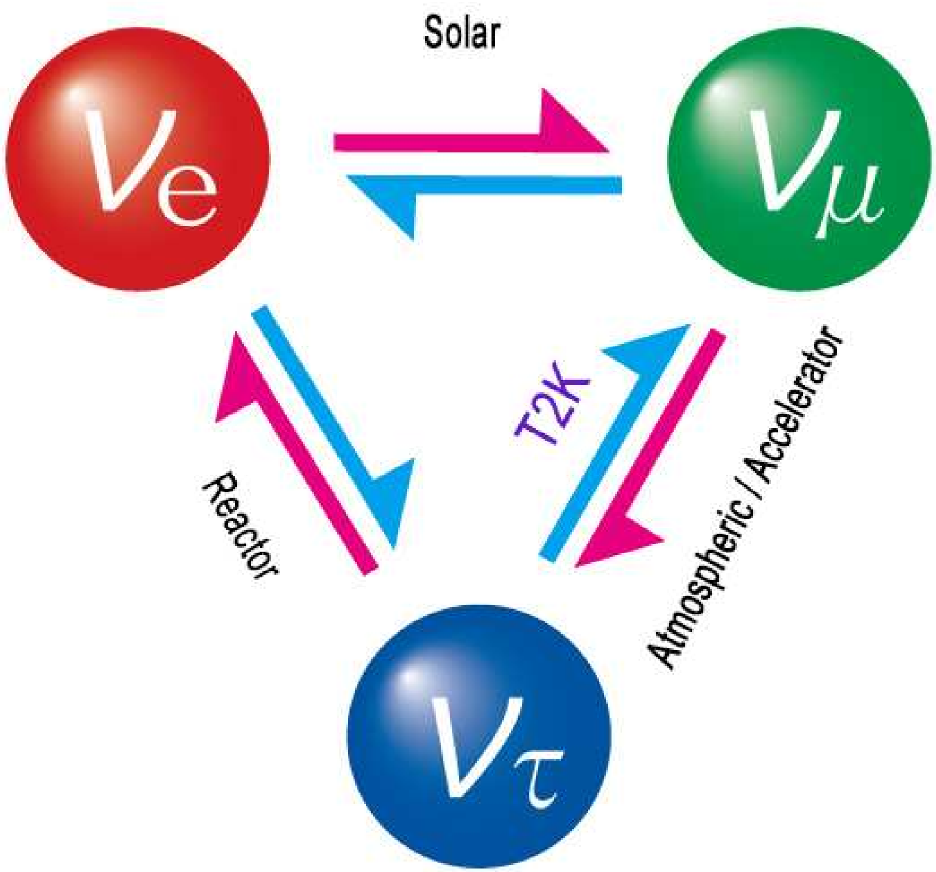
Heavy or light?

- Unsolved problems ⇒ **new particles should exist**
- We did not detect them ⇒ they are ~~heavy~~ light but **very weakly interacting**

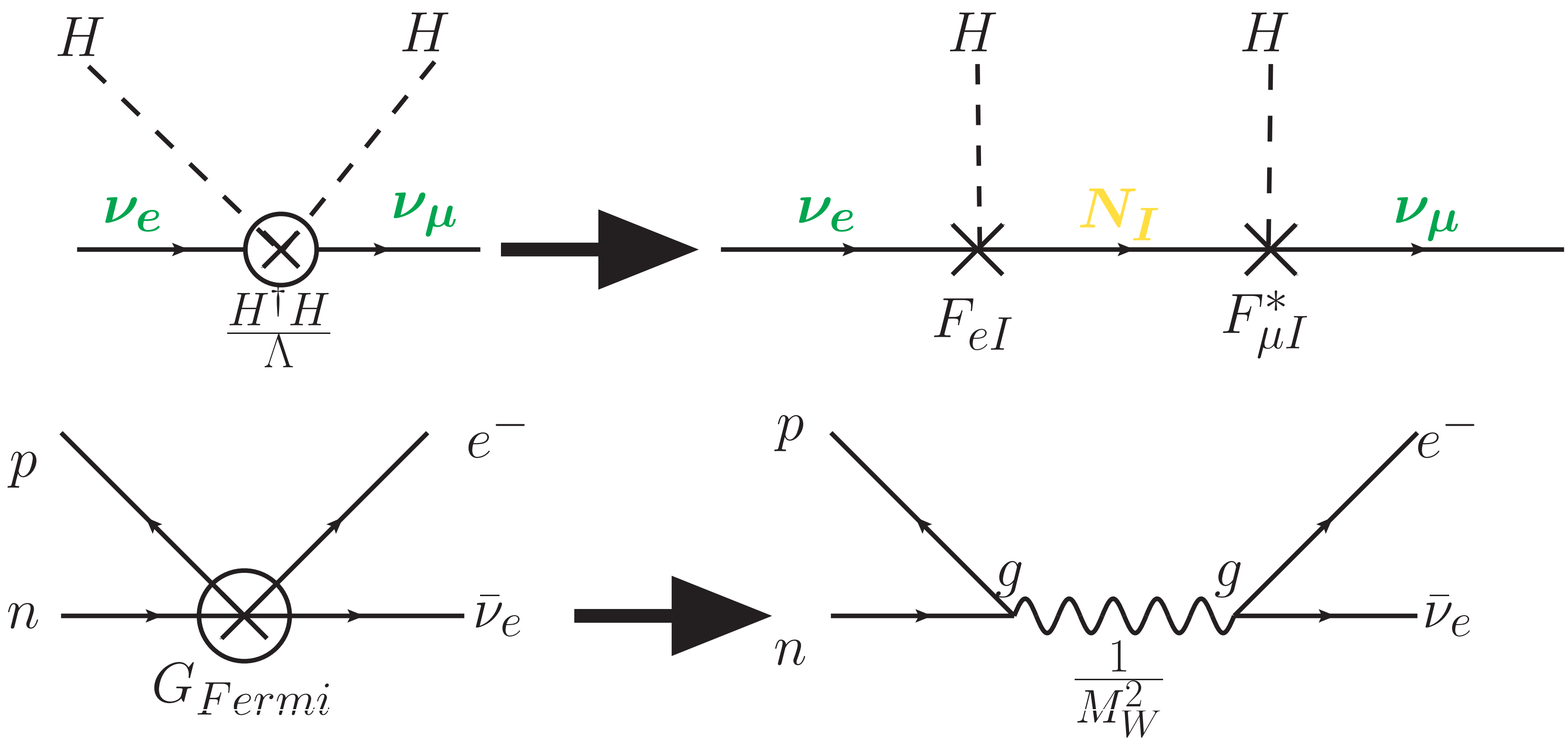
Is it possible to resolve the BSM problems with light very weakly interacting particles?



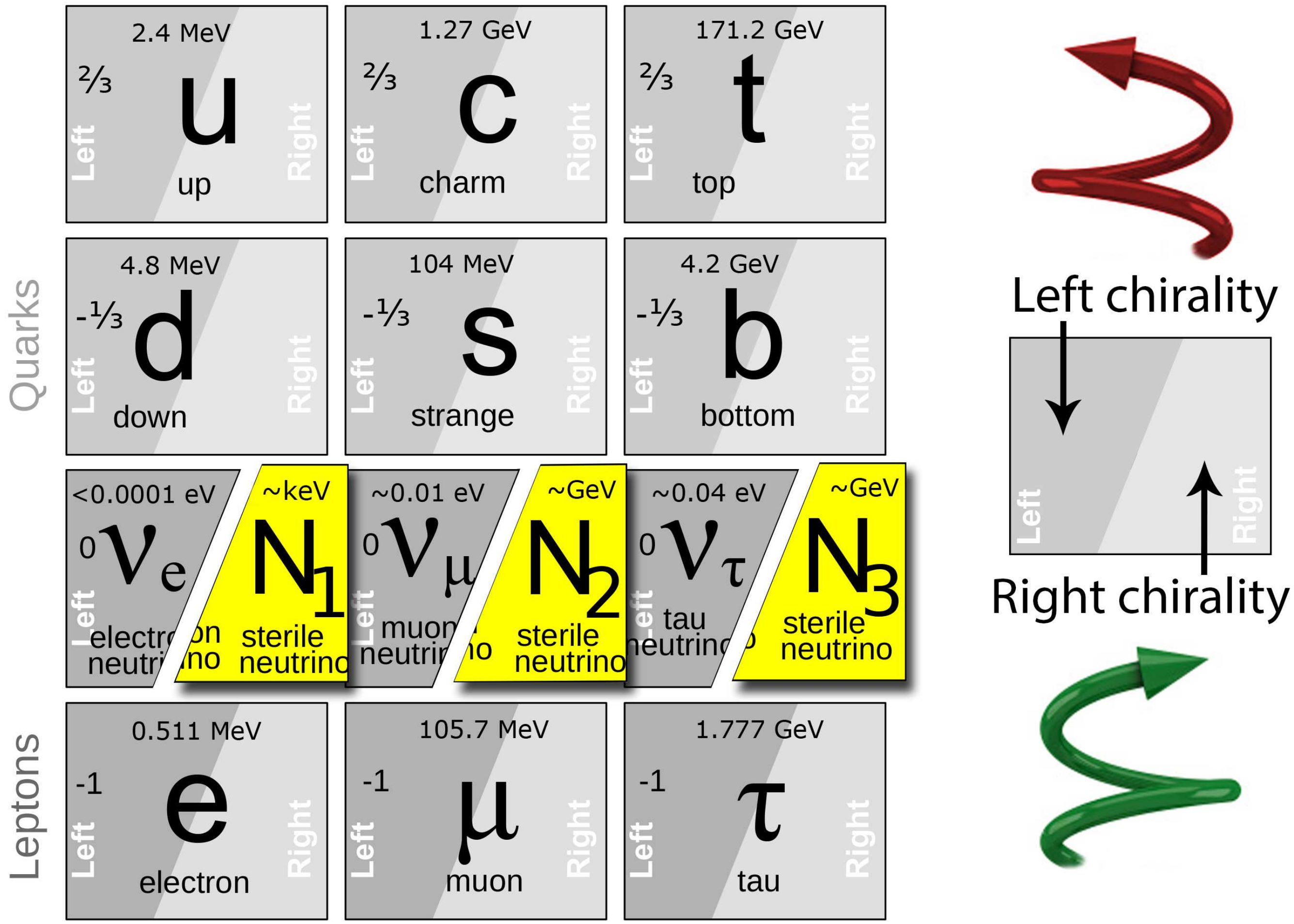
Neutrino oscillations



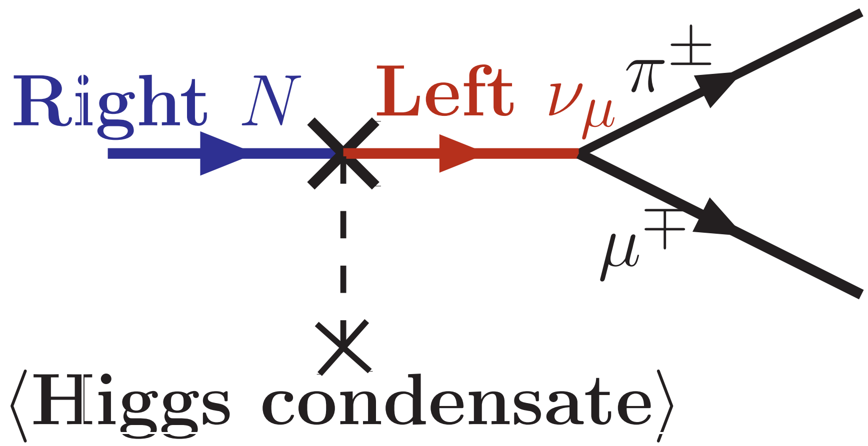
Neutrino oscillation between three generations

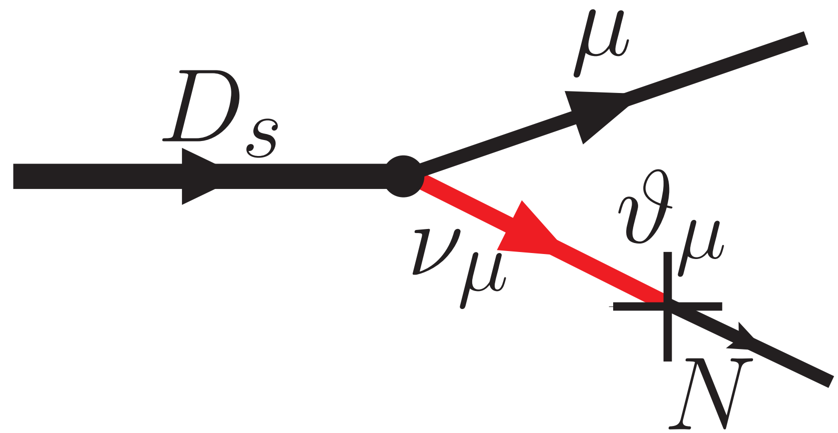


Neutrino oscillations indicate existence of new particles!



Right components of neutrinos?!





Right-handed neutrinos behave as **superweakly interacting** massive Majorana neutrinos with a smaller Fermi constant $\boxed{\vartheta \times G_F}$

- ϑ is called **mixing strength** or **mixing angle**
- Another name for these particles: **heavy neutral leptons** (or **HNL**) or **sterile neutrinos**

Dark matter and neutrino oscillations

- Right-handed neutrino N_1 with mass $M_N \sim$ keV is a viable Dark Matter candidate.
  Recent discovery of the $E_\gamma = 3.5$ keV line in cosmic X-rays is naturally explained by the decay $N_1 \to \gamma\nu$, where $M_N = 7$ keV
  see the talk by Jeroen Franse at this conference
- Can this particle N_1 describe neutrino oscillations?

Bulbul et al. 1402.2301

Boyarsky et al 1402.4119

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- Can this particle N_1 describe neutrino oscillations?
- No! On the one hand, X-ray observations imply small mixing angle Boyarsky et al 1402.4119

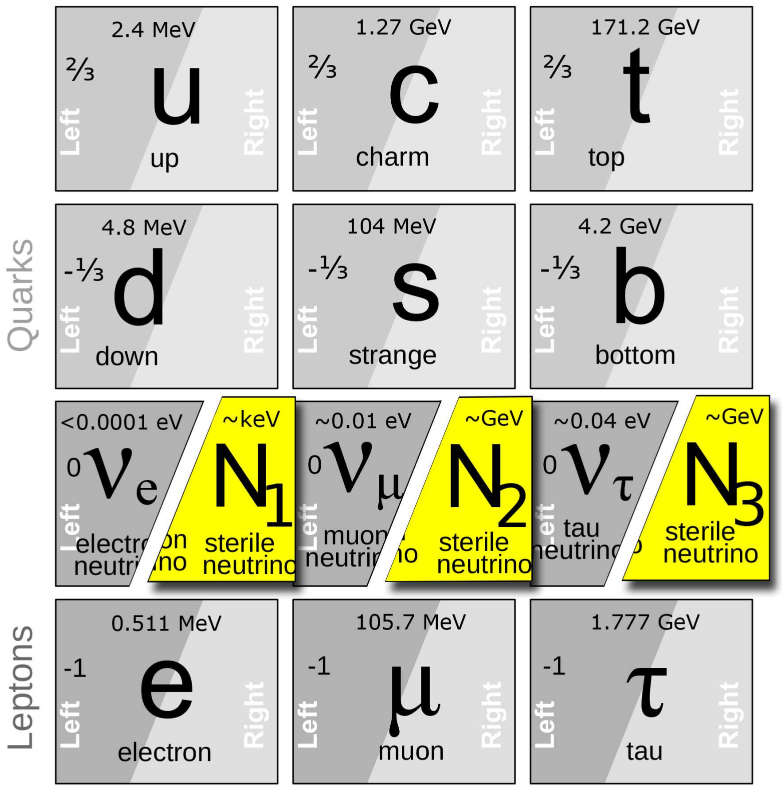
$$\vartheta^2 \simeq 10^{-11}$$

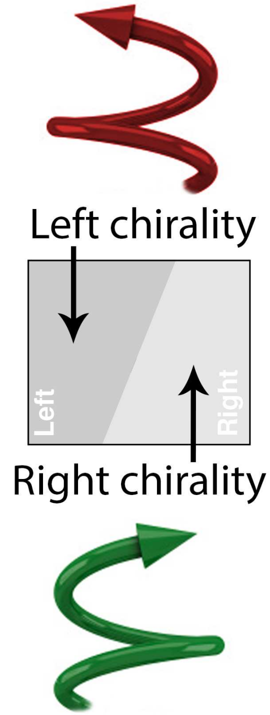
It implies that the interaction of the HNL with ordinary neutrinos is very suppressed. As a result, the neutrino masses, given by the **see-saw** formula

$$\Delta m \sim \frac{M_{\text{Dirac}}^2}{M_N} \sim \vartheta^2 M_N \simeq 10^{-7}\ \text{eV}$$

are very small, compared to the observed values $\Delta m \gtrsim 10^{-2}$ eV, which come from the oscillation experiments

Dark matter and neutrino oscillations





Two neutrino mass splittings $\Rightarrow$ need (at least) two additional sterile neutrinos, N_2 and N_3.

The heavier particles $N_{2,3}$ have relatively short lifetime

$$\tau_N \lesssim 10^4 \text{ sec} \left(\frac{100 \text{ MeV}}{M_N}\right)^4$$

and have decayed long time ago

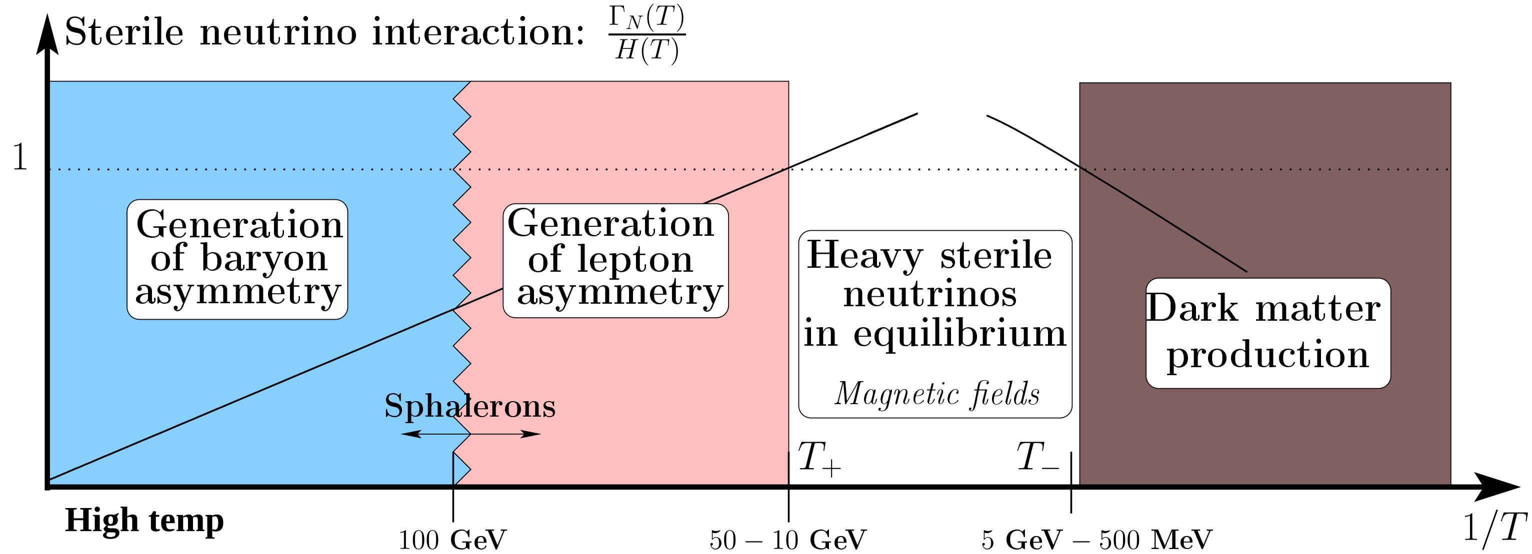
If sterile neutrinos exist – how to find them?

Ya. Zel'dovich: *The Universe is the poor man's accelerator: experiments don't need to be funded, and all we have to do is to collect the experimental data and interpret them properly*

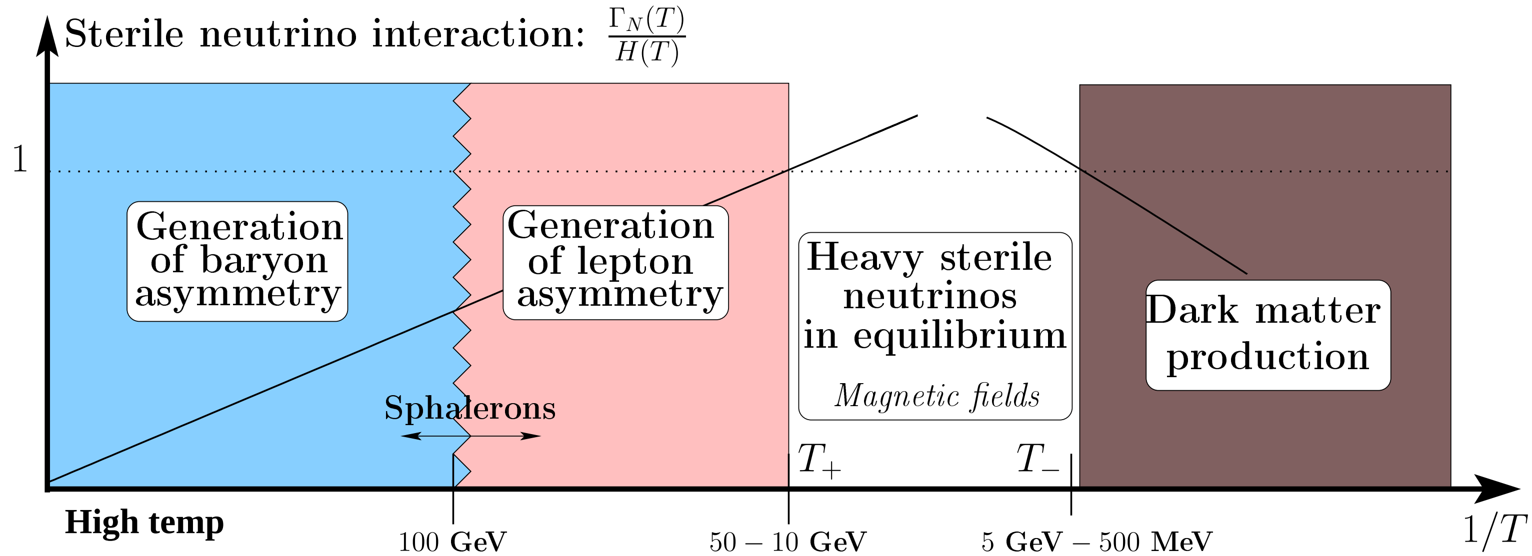
Why?

⇒Primordial plasma could have reached the densities and temperatures unachievable in the lab

This state could last sufficiently long $\Rightarrow$ even rare processes (with $N_{2,3}$) have time to take place



- At higher temperatures HNLs are produced in $\nu\nu \to \nu N$
- Some fraction of N decays, with **different** probabilities into leptons and antileptons (CP-violation)
- The produced lepton asymmetry is converted into baryon asymmetry (sphalerons)



- At $T \lesssim$ GeV the Dark Matter particle is produced
- Lepton asymmetry **enhances strongly** its production, and is **needed** to describe all observed properties of Dark Matter

N_1 is a viable dark matter candidate in a model with **at least two other** sterile neutrinos

the model is called the νMSM, see the review
Boyarsky, Ruchayskiy, Shaposhnikov
Ann.Rev.Nucl.Part.Sci. 59 (2009)

Direct experimental searches

Alternative to studies of the early Universe is the direct search at accelerators

In the past, two types of experiments were realized:

Atre et al. 0901.3589

Peak searches: In two-body decays of mesons

recent reanalysis in Ruchayskiy, Ivashko 1112.3319

$$\pi^+ \to e^+ \nu, \quad \pi^+ \to e^+ N_2$$

the energies of the decay products are fixed, leading to the peak in energy of e^+. The peak from HNLs is separated from the peak of usual neutrinos, and is a signature of the new physics.

Fixed-target searches: High-energy protons hit the target and produce neutrino beam. Most neutrinos are left-handed, but small fraction of the beam (of order θ^2) consists of HNLs. Placing large detector volume in the way of the neutrino beam, we may detect subsequent decays of HNLs.

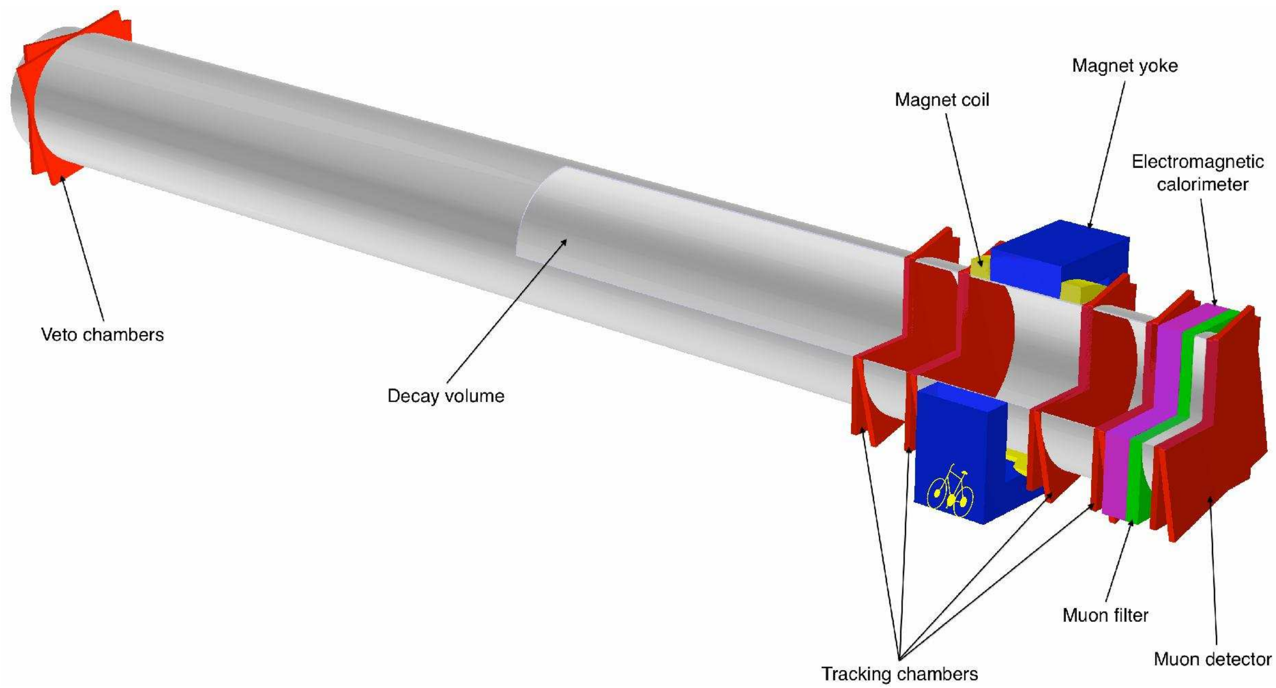
A dedicated fixed-target experiment

W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, O. Ruchayskiy, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille

arXiv: 1310.1762

Proposal to Search for Heavy Neutral Leptons at the SPS

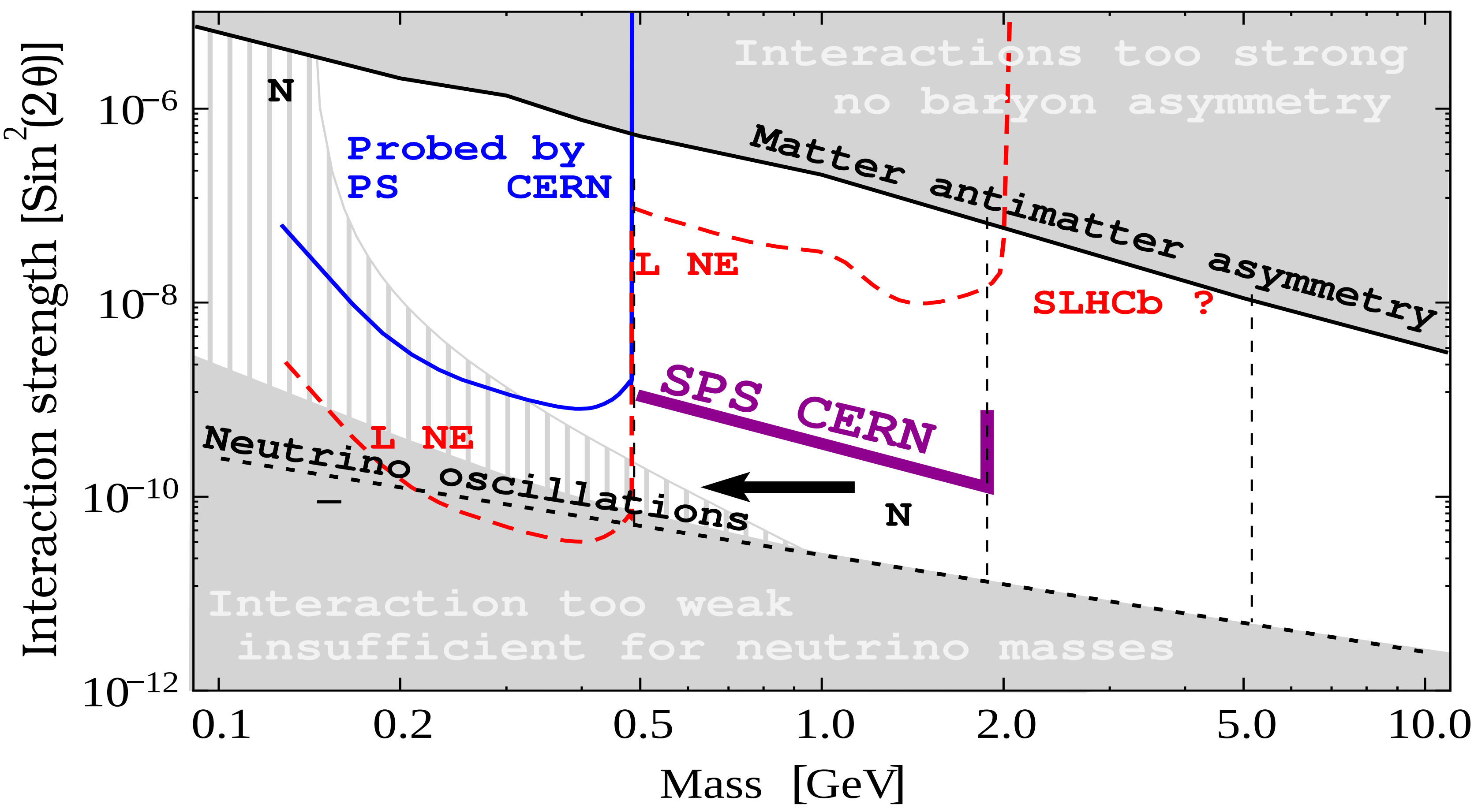
Expression of Interest. Endorsed by the CERN SPS council



SHIP - Search for HIdden Particles

http://ship.web.cern.ch/

Accelerator and cosmological bounds together:



Asaka, Canetti, Gorbunov, Shaposhnikov, 2005–2011;

Ruchayskiy, Ivashko [1112.3319] – revised accelerator bounds

LBNE white paper [1110.6249]

Conclusions

- ▷ Observable beyond-the-Standard-Model puzzles ask for new particles
- ▷ These particles can be either **heavy** or **super-weakly interacting**
- ▷ Neutrino oscillations suggest that sterile neutrinos (heavy neutral leptons) can exist
- ▷ Such particles can explain baryon asymmetry of the Universe, provide dark matter candidate and explain neutrino oscillations
- ▷ The resulting model (the νMSM) looks like Standard Model from the point of view of todays' experiments
- ▷ To distinguish $\Rightarrow$ intensity frontier experiments and "poor man's accelerator"

Thank you for your attention

Additional slides

List of the past experiments

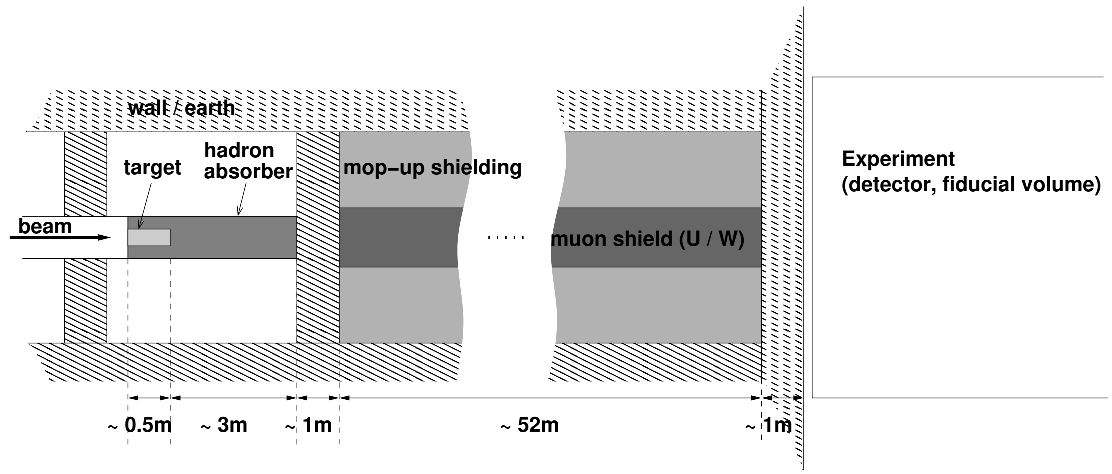
Peak searches:

- SIN $\pi M3$, Switzerland – 1981
- KEK K3, Japan – 1982
- TRIUMF M13, Canada – 1992
- TRIUMF PIENU, Canada – 2011-date 1106.4055

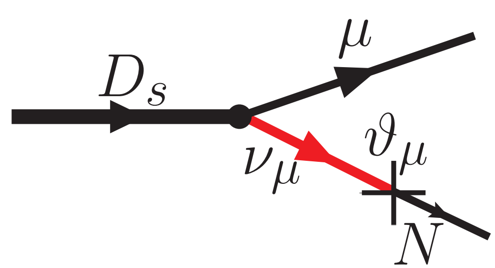
Fixed-target searches:

- PS191, CERN – 1984
- CHARM, CERN – 1985
- NuTeV, Fermilab – 1996-1997

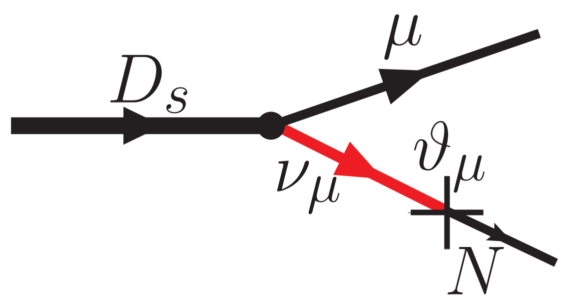
Setup:



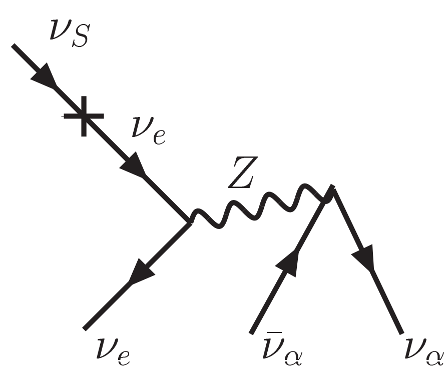
- 10^{20} protons from the SPS accelerator with energy 400 GeV hits th target
- and produces D-mesons, which decay into ordinary neutrinos, which subsequently oscillate into heavy neutral leptons due to active-sterile mixing.



The masses of D-mesons are $M_D \approx 2$ GeV, therefore the energy conservation law implies that we **can only probe** $M_N < 2$ GeV.



The same oscillation mechanism leads to the subsequent decay of N, leading to a **measurable signal** inside the detector volume.

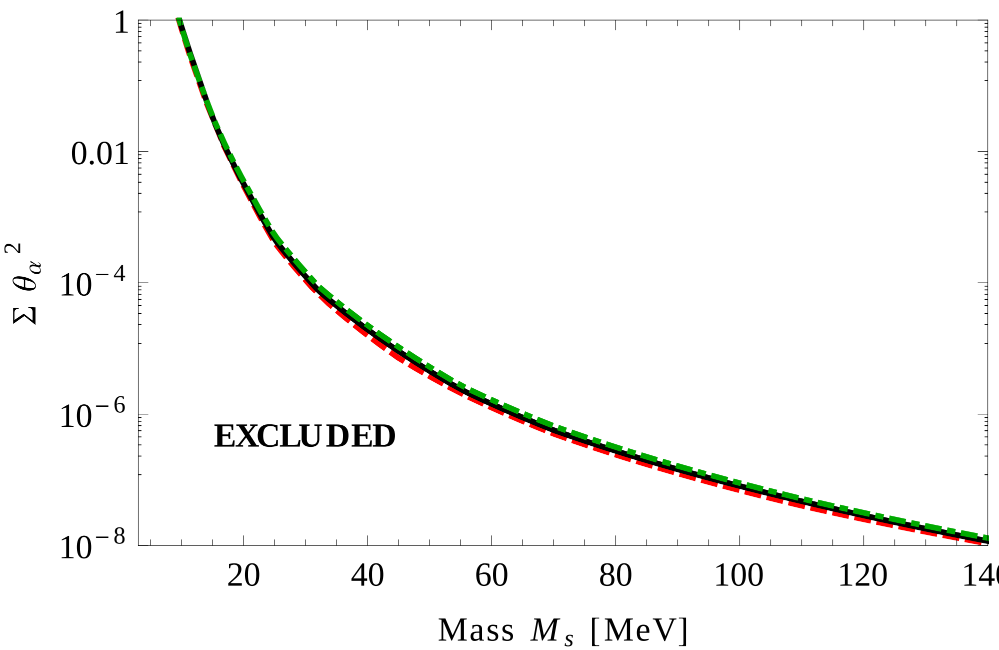


Alternative probes of Heavy Neutral Leptons

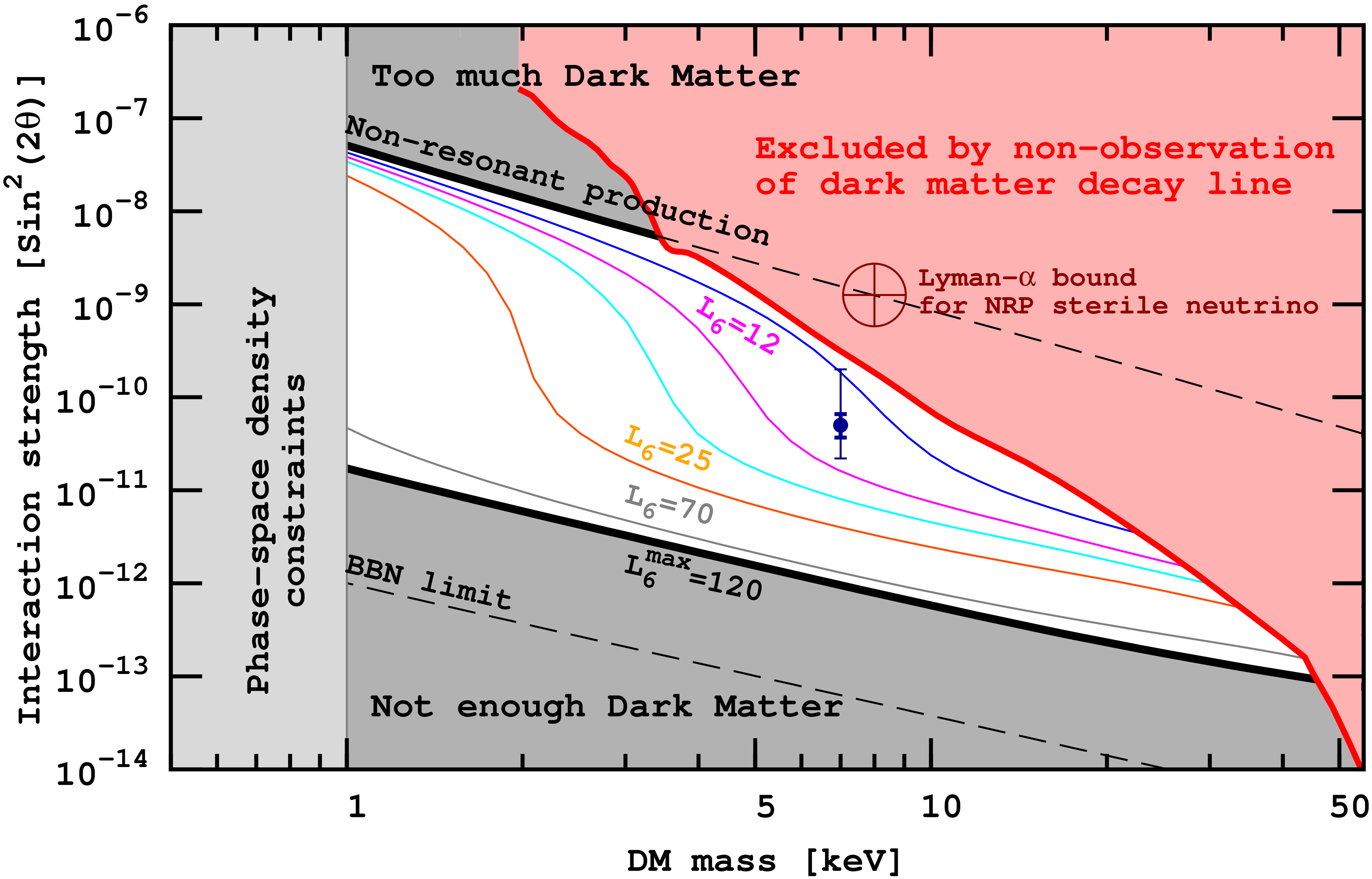
In order to increase the effectiveness of the experiment, the available parameter space of Heavy Neutral Leptons should be constrained in **other ways**, as much as possible.

In the region of smaller masses M_N, the Big-Bang Nucleosynthesis provides the most tight **lower bound on the interaction strength** θ.

Ruchayskiy, Ivashko 1202.2841



Sterile neutrino and 3.5 keV line



X-rays:
Boyarsky, **O.R** et al.

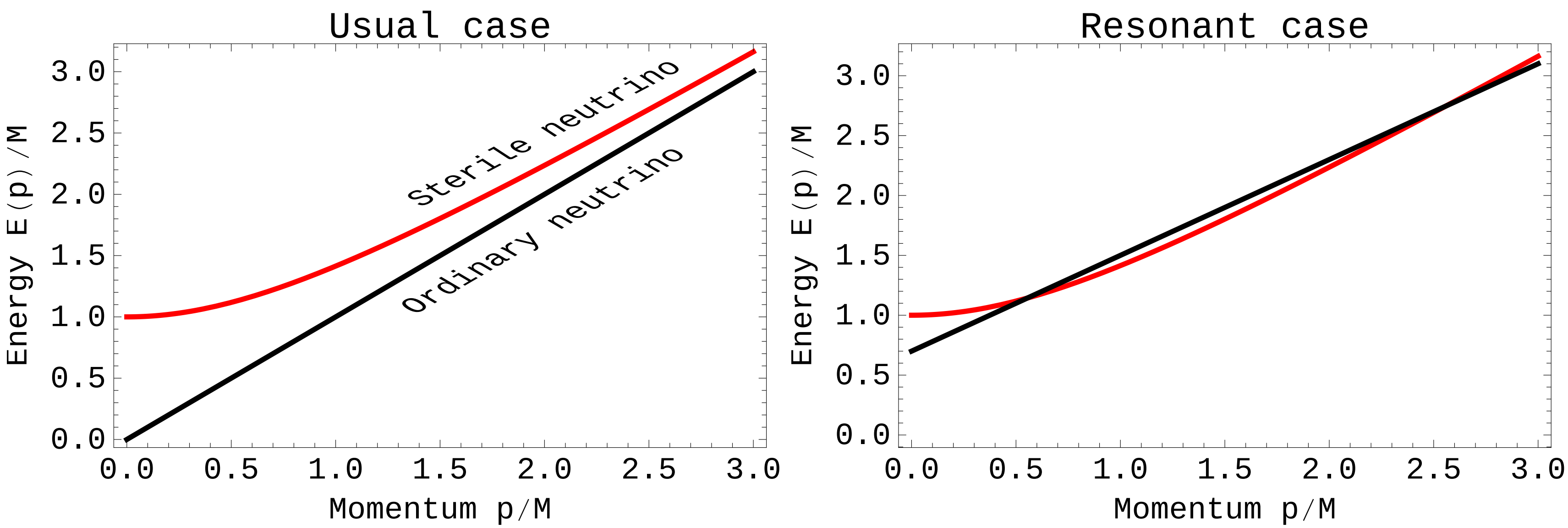
Production:
Laine & Shaposhnikov (2008)

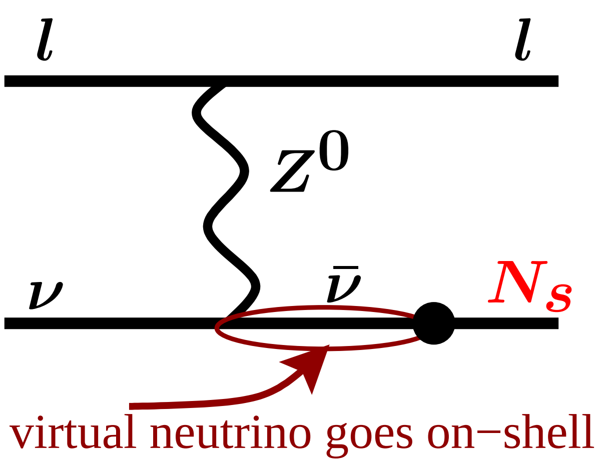
Lyman-α:
Boyarsky, Lesgourgues, **O.R.** et al.

Sterile neutrino and 3.5 keV line

Sterile neutrino DM with such parameters is not completely cold and would leave its imprints in the formations of structures

Resonant enhancement





Conversion of ν to N is enhanced whenever "levels" cross and virtual neutrino goes "on-shell" (analog of MSW effect but for active-sterile mixing)

Shi & Fuller [astro-ph/9810076]

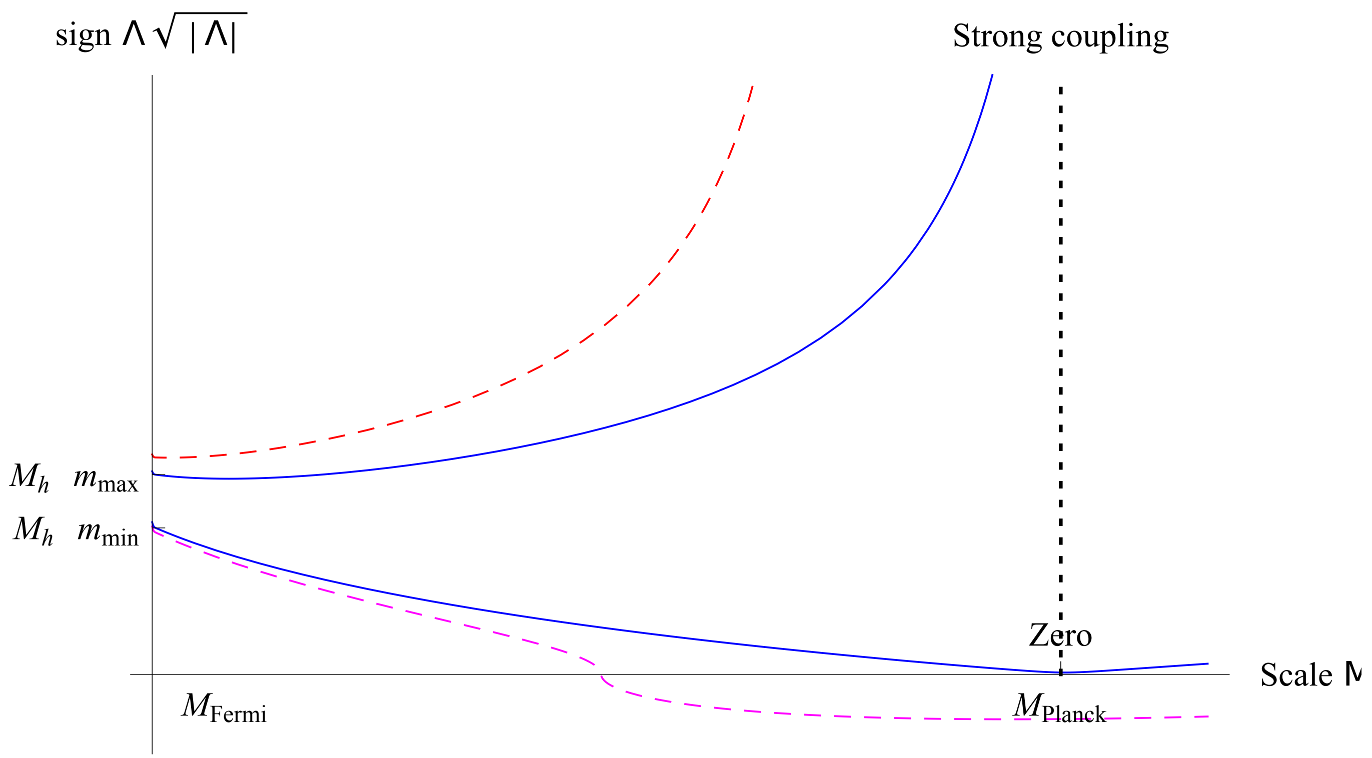
Laine & Shaposhnikov [0804.4543]

Heavy Neutral Leptons affect the production of Dark Matter

The properties of Heavy Neutral Leptons are related to the production of Dark Matter particle N_1 in the early Universe.

For example, if the X-ray 3.5 keV line will be confirmed to originate from the Dark Matter decay, it will lead to the bound $M_N \lesssim 2$ GeV (according to preliminary estimates). It is precisely the range of the searches at SHIP.

Theory is mathematically consistent!



Mass of the Higgs boson ~ 126 GeV means that the Standard Model is a consistent weakly-coupled theory up to very high scales (probably to the Planck scale)

Bezrukov et al. "*Higgs boson mass and new physics*" [1205.2893]

Also Degrassi et al. [1205.6497]

Maxwell equations

- The presence of difference of chemical potential of left and right fermions leads to additional terms in the effective Lagrangian for electromagnetic fields – **Chern-Simons term**
- As a result Maxwell equations contain current, **proportional to** μ_5 — MHD turns into **chiral MHD**:

Kharzeev'11

Vilenkin (1980)

Redlich & Wijewardhana (1985);

Fröhlich et al. (1998–2001)

Joyce & Shaposhnikov (1997)

$$\begin{aligned} \nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\ \nabla \times \vec{B} &= \sigma \vec{E} + \frac{2\alpha}{\pi}\mu_5 \vec{B} \end{aligned}$$

Chiral magnetic effect

- **In addition**, μ_5 should be allowed to **become dynamical**: because $\partial_\mu j_5^\mu \propto E \cdot B$

Boyarsky, Fröhlich, Ruchayskiy, PRL (2012)

$$
\begin{aligned}
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\
\nabla \times \vec{B} &= \sigma \vec{E} + \frac{2\alpha}{\pi} \Delta\mu \vec{B}
\end{aligned}
$$

Chiral magnetic effect

$$
\frac{\partial \mu_5}{\partial t} \propto \frac{2\alpha}{\pi} \int d^3x\, \vec{E} \cdot \vec{B} - \Gamma_{\text{flip}} \mu_5
$$

Chiral anomaly

- **Naively:**
  - Without B chirality flipping reactions drive $\mu_5 \to 0$
  - Without μ_5 finite conductivity drives $B \to 0$

Instability

- Maxwell equations with μ_5 are **unstable**:

$$\frac{\partial B}{\partial t} = \frac{1}{\sigma}\nabla^2 B + \frac{\alpha\mu_5}{\pi}\nabla \times B$$

magnetic diffusion

- Exponential growth for $k < \mu_5$ (for one of the circular polarizations depending on the sign of $\Delta\mu$) — **generation of helical magnetic fields**

$$B_\pm = B_0 \exp\left(-\frac{k^2}{\sigma}t \pm \frac{\alpha}{\pi}\frac{k\mu_5}{\sigma}t\right)$$

- Exponential growth for $k < \frac{\alpha}{\pi}\mu_5$

Helical magnetic fields in presence of μ_5

- If there are electromagnetic fields in plasma we have

$$\frac{\partial \vec{B}}{\partial t} = \frac{1}{\sigma}\nabla^2 \vec{B} + \frac{\alpha}{\pi}\frac{\mu_5}{\sigma}\nabla \times \vec{B}$$

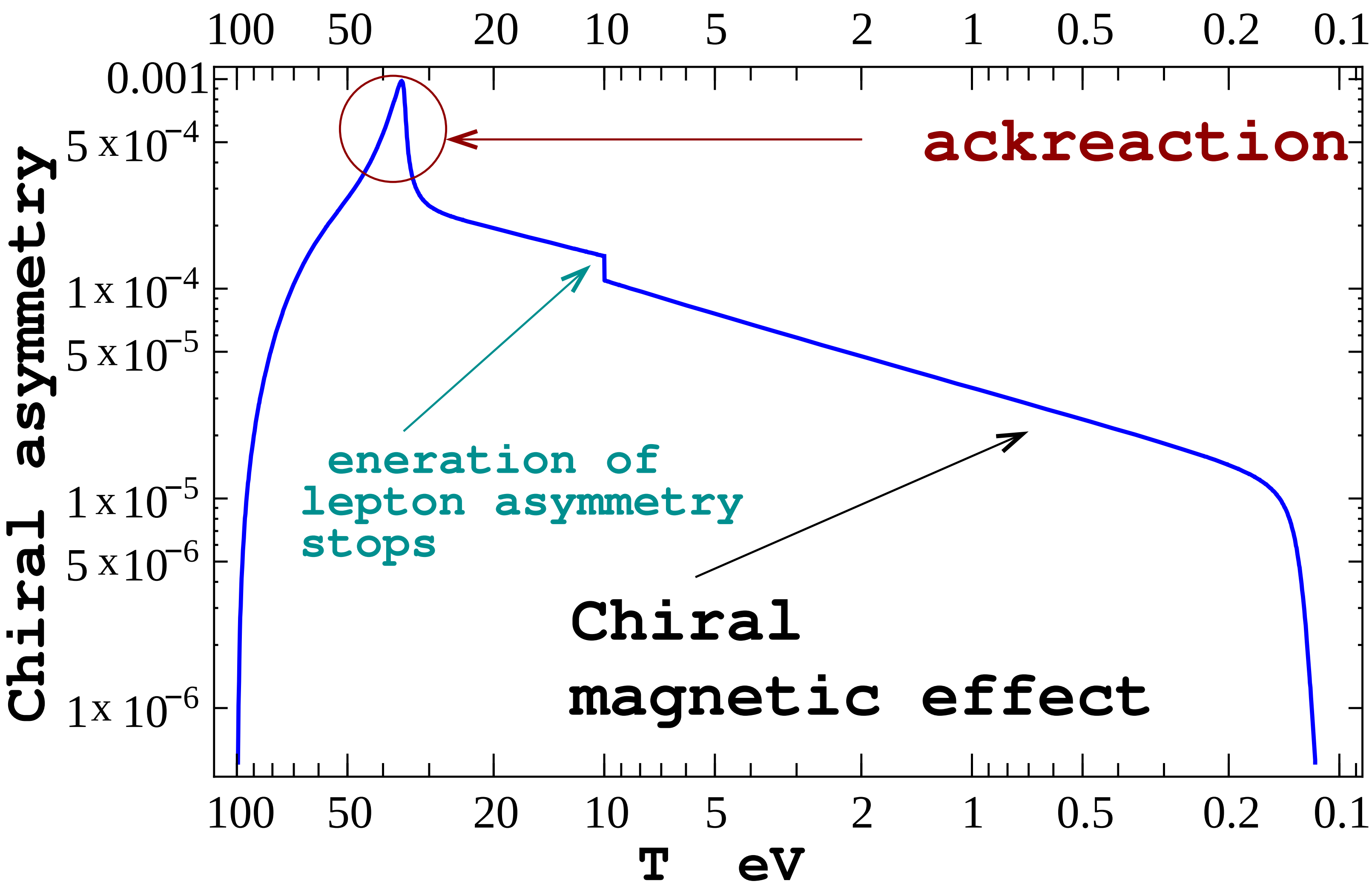
- If $\mu_5 \neq 0$ – magnetic field grows and

$$\frac{d(\mu_5)}{dt} = -(c_\Delta \alpha)\frac{2}{V}\int_V d^3x\, \vec{E}\cdot\vec{B} - \Gamma_{\text{flip}}\mu_5$$

A. Boyarsky, O. Ruchayskiy, J. Fröhlich PRL (2012)

- One cannot have $\mu_5 = 0$ if $\int \vec{E}\cdot\vec{B} \neq 0$ (i.e. **if magnetic helicity changes**)

Evolution of chiral asymmetry in νMSM



A. Boyarsky, J. Fröhlich & O.Ruchayskiy

Neutrinoless double-beta decay predictions

Effective Majorana mass is

$$1.3\text{meV} < m_{\beta\beta} < 3.4\text{meV}$$

in normal hierarchy, and

$$13\text{meV} < m_{\beta\beta} < 50\text{meV}$$

in inverted hierarhy