ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

# How to find dark matter sterile neutrino ?

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# Outline

- Dark matter: the case of sterile neutrino

  DM sterile neutrino $\neq$ LSND sterile neutrino
- Search for sterile neutrino in the universe
- Search for sterile neutrino in laboratory
- Conclusions

## Observational Problems of the Minimal Standard Model

- Contradiction with neutrino physics.
- No particle physics candidate for DM.
- No baryogenesis.
- Contradiction with cosmological observations: flatness of the Universe, density perturbations. Perhaps, not a particle physics problem, since gravity is involved.
- Accelerated expansion of the Universe – dark energy. Perhaps, not a particle physics problem, since gravity is involved.

So: MSM is unlikely to be a good effective field theory up to the Planck scale

# Proposal:

a minimal extention of the standard model, called $\nu$MSM, is a viable effective field theory up to the Planck scale

# the MSM

There are 36 quark states: left fermionic doublets:

$(u\ \ , d)_L,\ (c\ \ , s)_L,\ (t\ \ , b)_L$ and $u_R\ ,\ d_R,\ c_R\ ,\ s_R,\ t_R\ ,\ b_R$

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9 + 0 leptonic states

$(\nu_e, e)_L,\ (\nu_\mu, \mu)_L,\ (\nu_\tau, \tau)_L$ and $\quad\ ,\ e_R, \quad\ ,\ \mu_R, \quad\ ,\ \tau_R$

12 $SU(3) \times SU(2) \times U(1)$ gauge bosons (8+3+1)

and one Higgs doublet,

in total $(3 \times 2 + 3 \times 2 + 2 + 1 + 0) \times 3 \times 2 = 90$ fermionic and

$(8 + 3 + 1) \times 2 + 4 = 28$ bosonic degrees of freedom

# the $\nu$MSM

There are 36 quark states: left fermionic doublets:

$(u\ ,d)_L,\ (c\ ,s)_L,\ (t\ ,b)_L$ and $u_R\ ,\ d_R,\ c_R\ ,\ s_R,\ t_R\ ,\ b_R$

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$(u\ ,d)_L,\ (c\ ,s)_L,\ (t\ ,b)_L$ and $u_R\ ,\ d_R,\ c_R\ ,\ s_R,\ t_R\ ,\ b_R$,

9 + 3 leptonic states

$(\nu_e, e)_L,\ (\nu_\mu, \mu)_L,\ (\nu_\tau, \tau)_L$ and $N_D,\ e_R,\ N_C,\ \mu_R,\ N_B,\ \tau_R$

12 $SU(3) \times SU(2) \times U(1)$ gauge bosons (8+3+1)

and one Higgs doublet,

in total $(3 \times 2 + 3 \times 2 + 2 + 1 + 1) \times 3 \times 2 = 96$ fermionic and

$(8 + 3 + 1) \times 2 + 4 = 28$ bosonic degrees of freedom

# Parameter counting: the $\nu$MSM

Most general renormalizable Lagrangian

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

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.

Require: $M_I < M_W$ (No see-saw)

## There is no indication of the existence of GUT scale from neutrino oscillations!

Consequence: small Yukawa couplings,

$$F_{\alpha I} \sim \frac{\sqrt{m_{atm} M_I}}{v} \sim (10^{-6} - 10^{-13}),$$

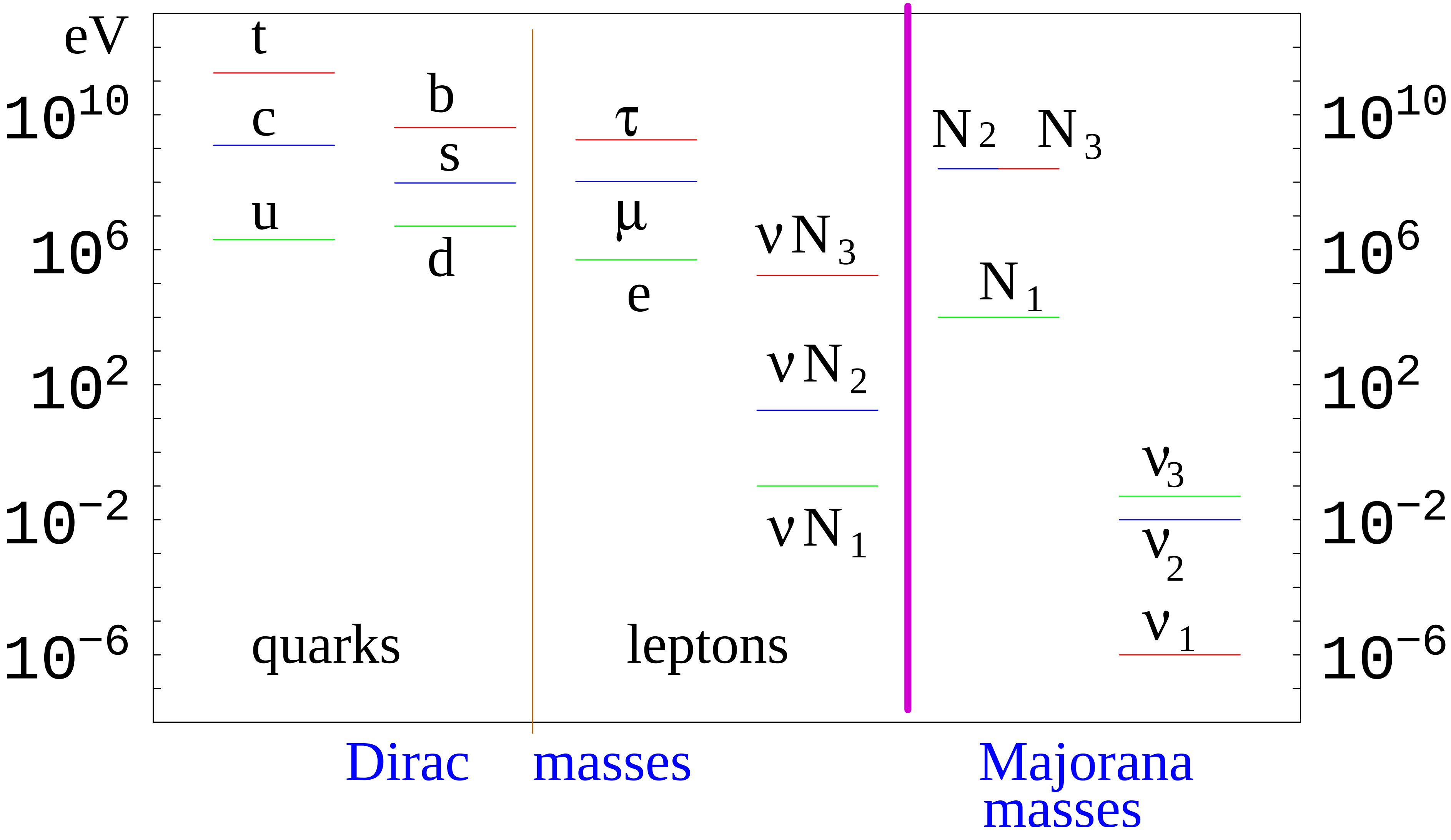
here $v \simeq 174$ GeV is the VEV of the Higgs field,

$m_{atm} \simeq 0.05$ eV is the atmospheric neutrino mass difference.

# Highlights of the $\nu$MSM

- The theory has just one energy scale, $\sim M_W$. No gauge coupling unification: no Grand Unification $\longrightarrow$ no gauge hierarchy problem in quantum field theory sense
- Consistent description of neutrino masses and oscillations: for Dirac neutrino masses $M_D \sim Fv \ll M_I$ the see-saw formula works, $M_\nu = -M_D \frac{1}{M_I} M_D^T$ . Scale of $M_I$ does not matter!
- Can explain dark matter in the universe
- Can explain baryon asymmetry of the Universe
- $M_I$ are small: all parameters can potentially be determined experimentally!
- Absolute mass scale of active neutrinos is fixed: $m_{smallest} < 10^{-5}$ eV.

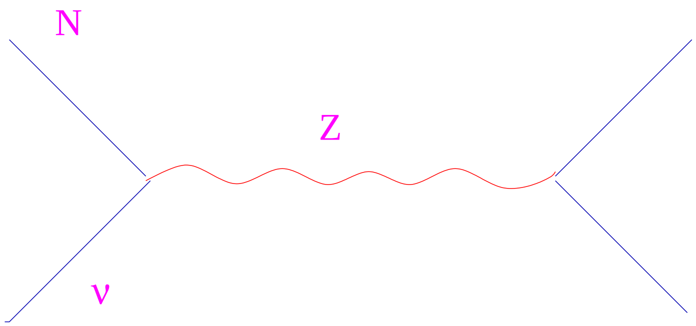
# The spectrum of the νMSM



# DM candidate: the lightest Majorana $\nu$

Dodelson, Widrow; Shi, Fuller; Dolgov, Hansen; Abazajian, Fuller, Patel

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




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

For one flavour:

$$\tau_{N_1} = 5 \times 10^{26}\,\text{sec}\left(\frac{1\text{keV}}{M_I}\right)^5\left(\frac{10^{-8}}{\theta^2}\right)$$

$$\theta = \frac{m_D}{M_I}$$

# 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-$\alpha$ forest data:

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

Viel et al: $M_{Ly\alpha} = 11$ keV

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

Conservative limit, Viel et al: $M_{Ly\alpha} \simeq 2$ keV

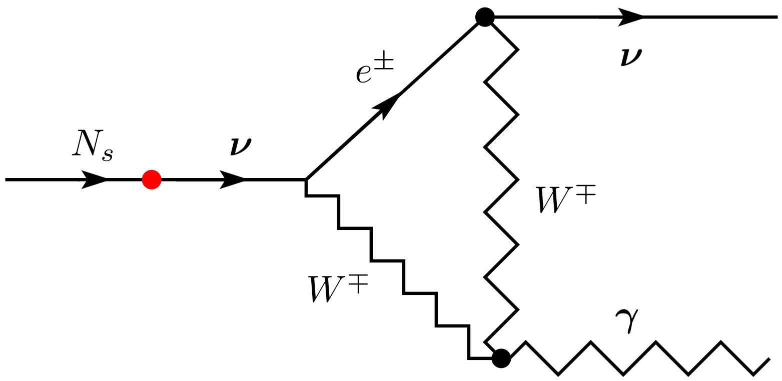
# Sterile neutrino DM is not completely dark!

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: astrophysics

Flux from DM decay:

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

(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

# 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...)

Earlier proposals: X-ray background (Dolgov, Hansen) ; clusters of galaxies and galaxies (Abazajian, Fuller, Tucker)

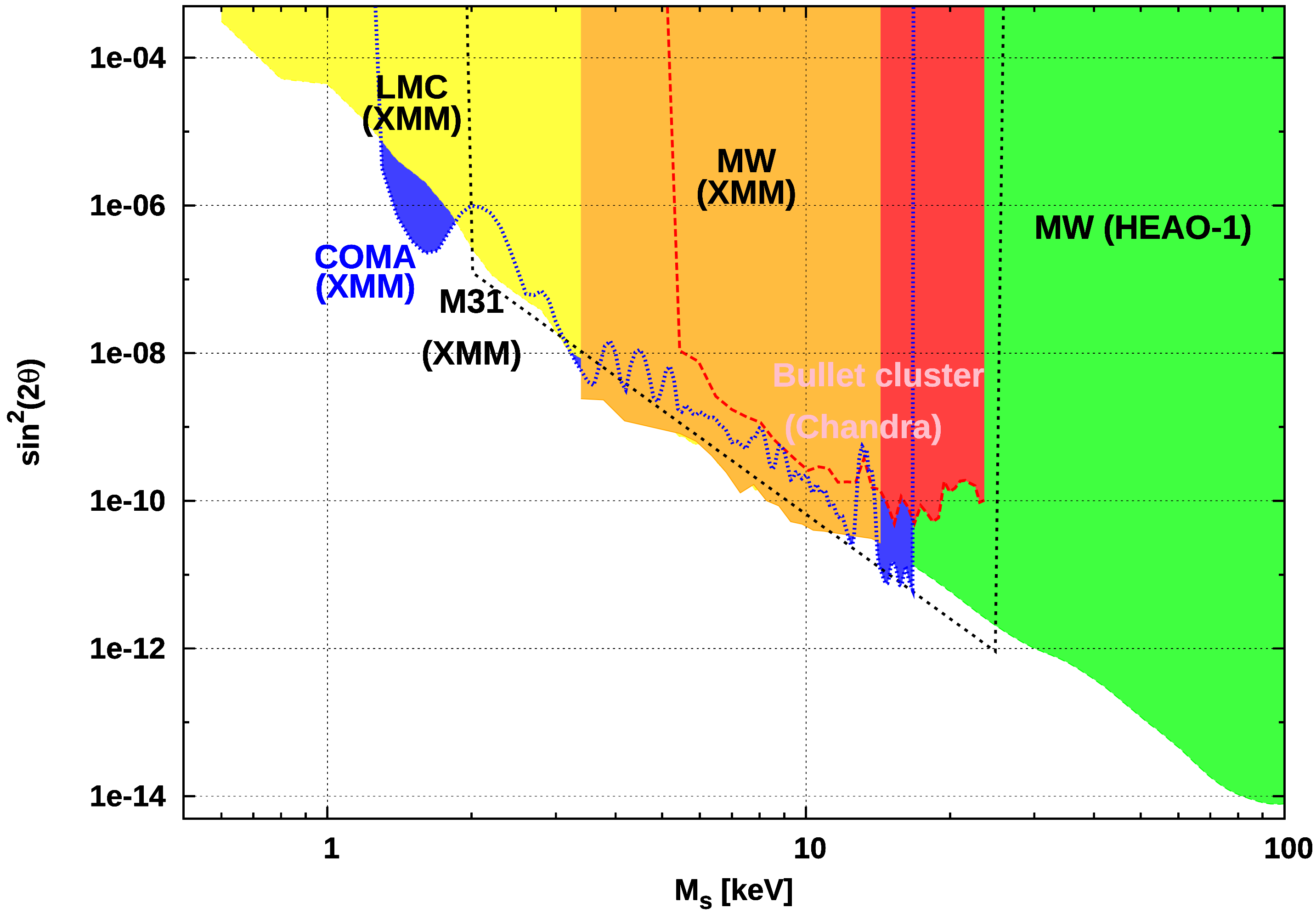
**MW (HEAO-1):** Boyarsky et al. 2005

**Coma and Virgo clusters:** Boyarsky et al.

**LMC+MW(XMM):** Boyarsky et al.

**MW (Chandra):** Riemer-Søorensen et al.; Abazajian et al.

**M31:**Watson et al.




Fine print: all results subject to intrinsic factor $\sim 2$ uncertainty!

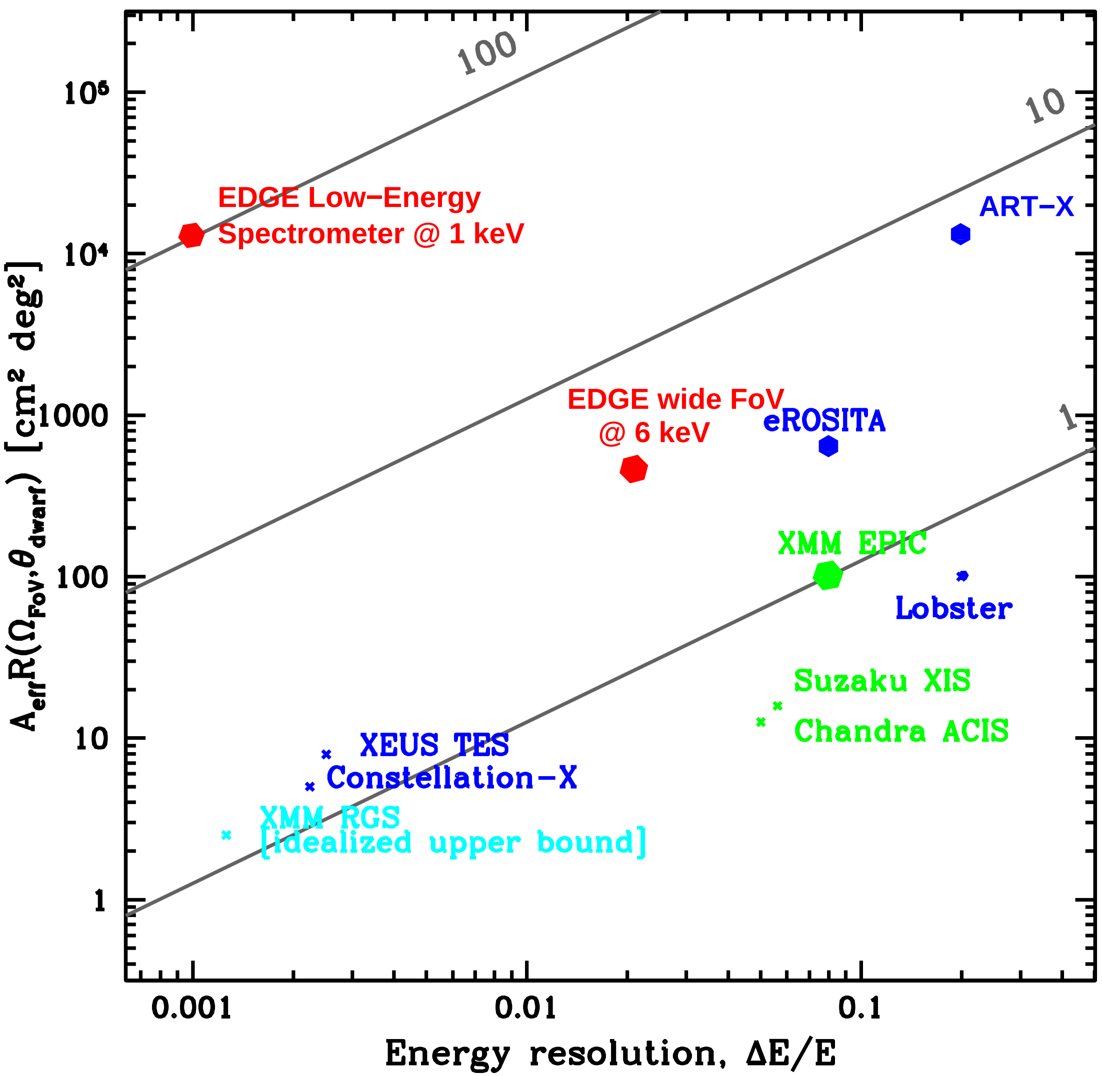
# Cosmological production of sterile neutrinos

- Via active-sterile neutrino oscillations (Dodelson, Widrow)
  Most probably, this is ruled out: the required Yukawa coupling is too large to be consistent with X-ray and Lyman-$\alpha$ constraints.
- Via resonant active-sterile neutrino oscillations in the presence of lepton asymmetries (Shi, Fuller). Works well for sterile neutrinos in keV range.
- In inflaton (or any neutral scalar) decays (M.S., Tkachev). Can produce sterile neutrinos up to the mass of few MeV.

Over the last year restrictions on sterile neutrino parameters were improved by several orders of magnitude.

The new data from *Chandra* and *XMM-Newton* can hardly improve constraints by more than a factor $10$. One needs:

- Improvement of spectral resolution up to the natural line width ($\Delta E/E \sim 10^{-3}$).
- FoV $\sim 1^\circ$ (size of a dSph).
- Wide energy scan, from $\mathcal{O}(100)$ eV to $\mathcal{O}(10)$ MeV.



# How to find DM sterile neutrino: laboratory

Bezrukov, MS

In general, 3 possibilities:

- Creation and detection in the lab: suppressed by $\theta^4$ and hopeless.
- Creation somewhere and detection in the lab: the only posibility is to search for radiative decays of $N$ in the DM clouds – not a laboratory experiment.
- Creation in the lab without subsequent detection – the unique option, $\theta^2$ effect.

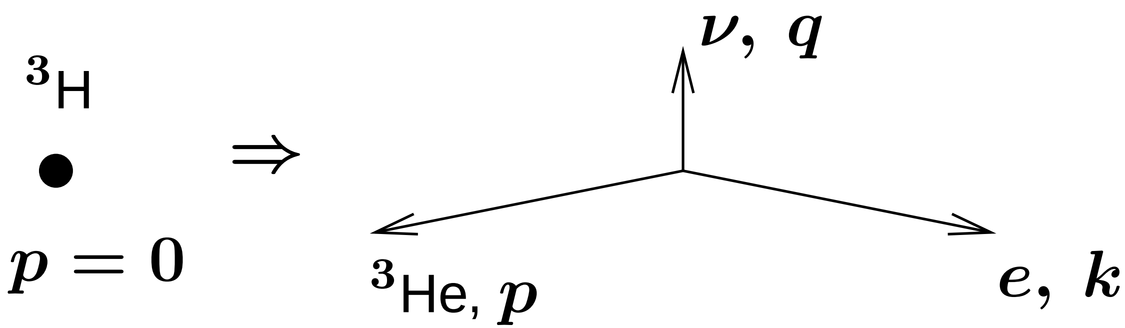
# Possibilities:

- Forbidden decays, e.g. $\pi^0 \longrightarrow N\nu$ – branching ratio is too small. Hopeless.
- $\beta$-decay kinematics: $^3H \longrightarrow {}^3He + e + \bar{\nu}_e$ is not the same as $^3H \longrightarrow {}^3He + e + N$!
  - Partial kinematics: kink search in electron $\beta$-decay spectrum. Hopeless:

    (i) Extremely large statistics to see the effect is needed ($\sqrt{N}$ statistical error)

    (ii) Exact theoretical knowledge of the decay spectrum is needed (c.f. 17 keV neutrino "discovery")
  - Full kinematics event-by-event mass measurement: may work.

# Beta decay kinematics




Neutrino mass is reconstructed from observed momenta

$$m_\nu^2 = (Q - E_p^{\rm kin} - E_e^{\rm kin})^2 - (p + k)^2$$

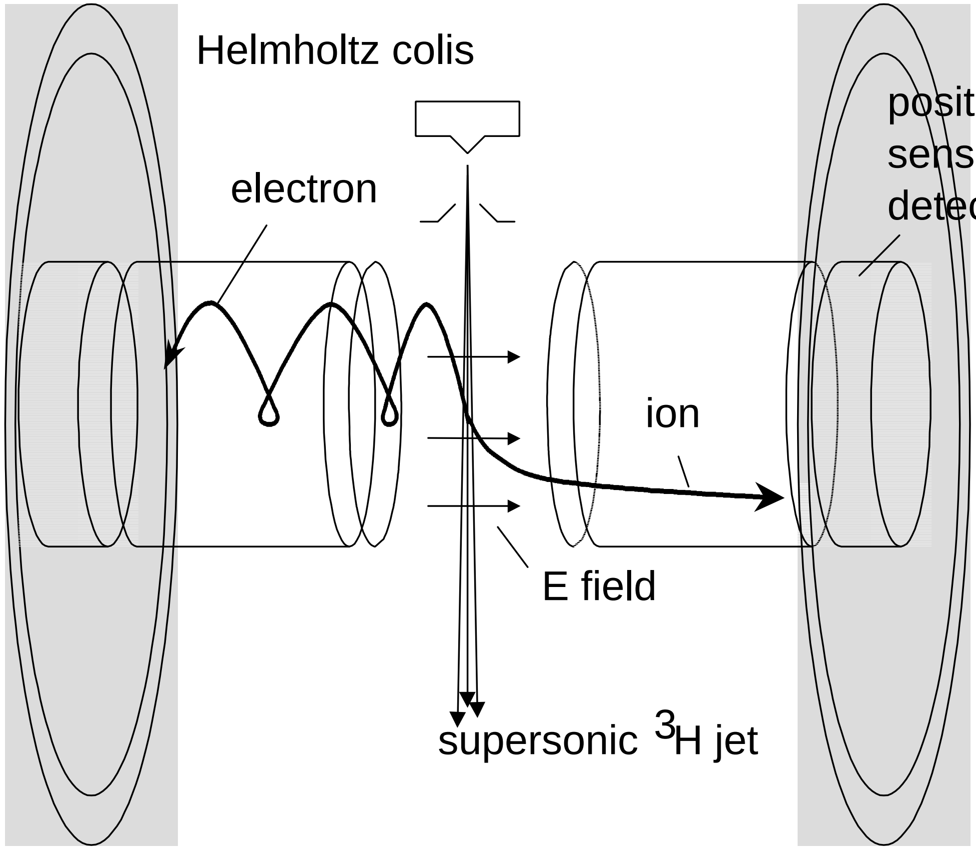
For $^3H$: $Q = 18.591$ keV

- Typical ion energy $E_p^{\rm kin} \sim 1$ eV or $|p| \sim 100$ keV $\Rightarrow$ speed $v \sim 10^4\ {\rm m/s}$
- Typical electron energy $E_e^{\rm kin} \sim 10$ keV

Time of flight measurement of ion momenta!

# COLTRIMS setup

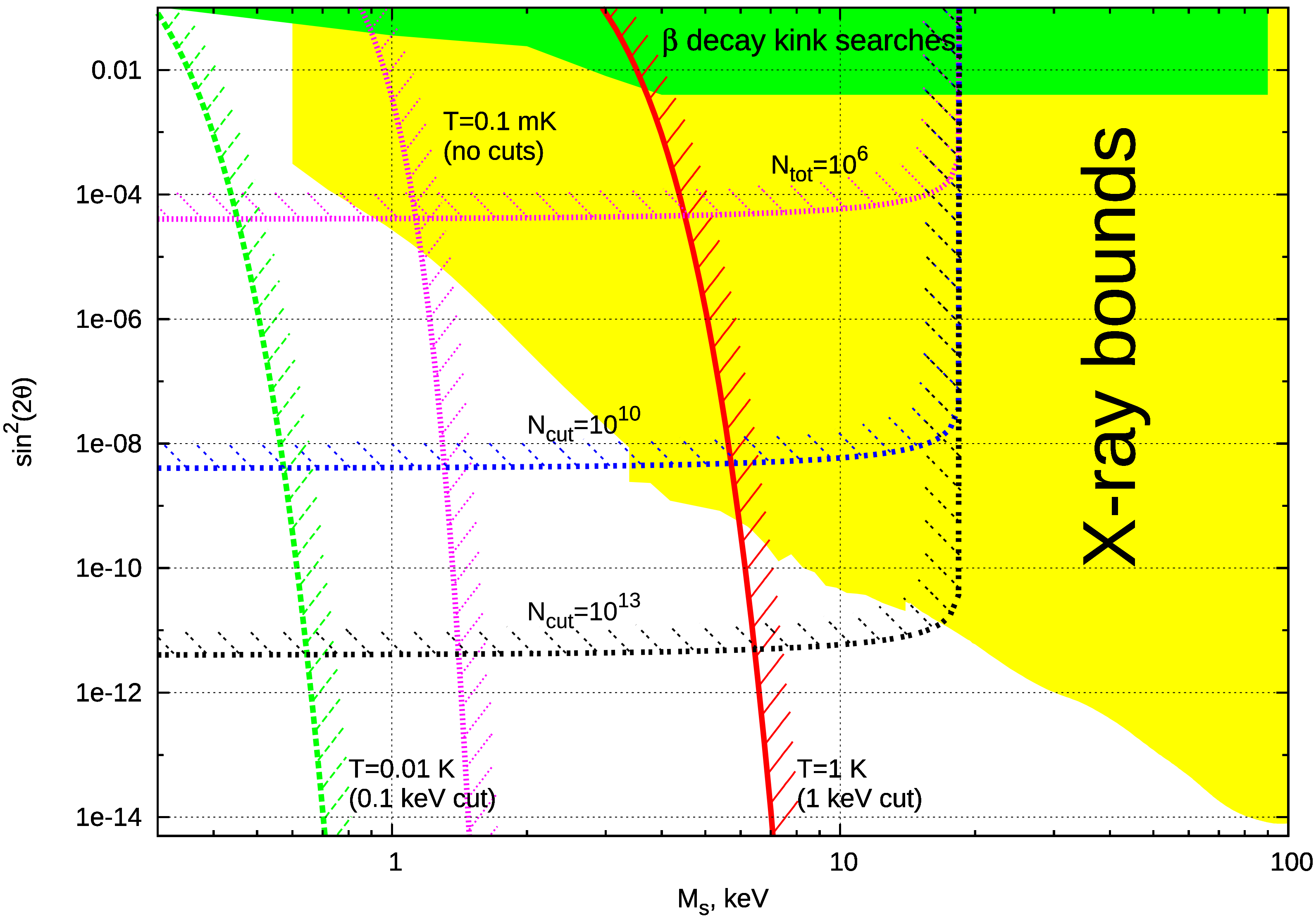
Cold-Target Recoil-Ion-Momentum Spectroscopy



# COLTRIMS & MOTRIMS abilities

- Detection precision
  - 0.2 keV momentum resolution for ions!
  - for electrons — electrostatic spectrometers allow for similar resolution (for TOF measurement electrons may be too energetic)
- Source cooling
  - Supersonic gas-jets (COLTRIMS) — expansion of gas into vacuum with subsequent jet collimation — $T < 1$ K, density $10^{11} - 10^{12}\mathrm{cm}^{-3}$.
  - Magneto optic traps (MOTRIMS) — laser cooling — $T \sim 100$ $\mu$K, density $10^{10}\mathrm{cm}^{-3}$.

# Optimistic prospects



# Experimental problems

- Ion momenta are in fact *much larger* than for usual COLTRIMS
- Electron spectrometry is difficult because of large energy
- Backgrounds form tritium molecule dissociation?
- Source densities (high statistics, no scattering)

Variations:

- Other isotopes
- Electron capture instead of beta decay

# Conclusions

Physics at the electroweak scale ($\nu$MSM ) can explain a number of experimental and observational facts that do not fit to the Standard Model:

- neutrino masses and oscillations
- baryon asymmetry of the Universe
  Non-zero asymmetry for zero $\theta_{13}$
- dark matter in the Universe

# What $\nu$MSM cannot explain

- Potential observation of lepton number non-conservation in neutrino-less double beta decay by a part of Heidelberg-Moscow collaboration (Klapdor Kleingrothaus et all, $m^{\nu}_{Majorana} \simeq 0.4$ eV). Could be checked in future neutrino experiments.
- Potential observation of $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions by the LSND experiment, leading to $\Delta m^2 \simeq 1$ eV. Will be checked by the MiniBoone experiment.
- Potential observation of WIMPs by DAMA

# Crucial tests and experiments

Astrophysics

- X-rays from decays of Dark Matter neutrinos: 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

Particle physics

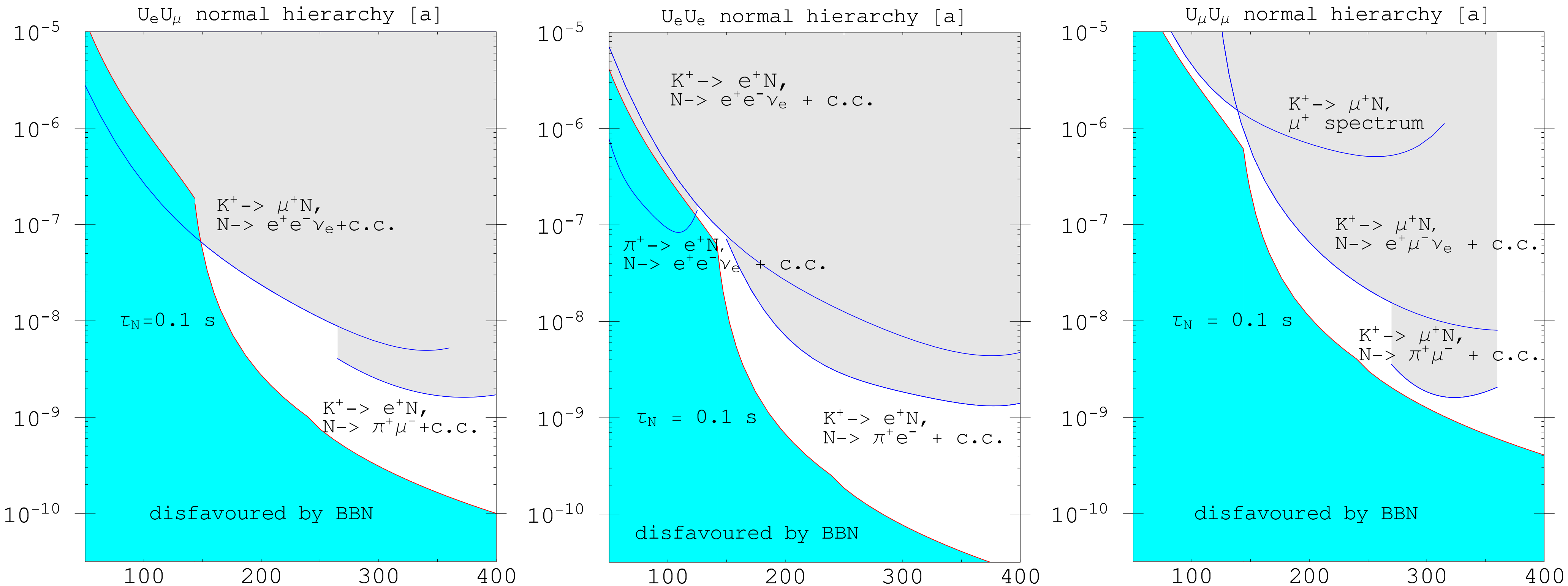
- Search for DM sterile neutrino in nuclear $\beta$-decays (e.g. COLTRIMS)
- LHC : nothing but the Higgs

Baryogenesis + active neutrino mixing: $M_N < 20$ GeV,

$\Delta M/M < 10^{-5}$, $10^{-11}\left(\frac{\mathrm{GeV}}{M}\right) < \theta^2 < 10^{-8}\left(\frac{\mathrm{GeV}}{M}\right)^2$.

Lepton number symmetry: preference for small $M_N$.

Constraints from BBN and CERN PS191 experiment (1988)



## Where to look for N

- Missing energy signal in $K,\ D$ and $B$ decays ($\theta^2$ effect)
  - $M_N < M_K$: KLOE, NA48, E787
  - $M_N < M_D$: charm and $\tau$ factories (planned luminosity is not enough)
  - $M_N < M_B$: B-factories (planned luminosity is not enough)
- Decay processes $N \to \mu^+\mu^-\nu$, etc ("nothing"$\to \mu^+\mu^-$) ($\theta^4$ effect)
  - $M_N < M_K$: Any intense source of K-mesons (e.g. from proton targets of K2K, MiniBooNe or MINOS)
  - $M_N < M_D$: MINOS beam + very near detector
  - $M_N < M_B$: CNGS beam + very near detector
- $M_N > M_B$: extremely difficult