Searching for sterile neutrino DM

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Hunt for Dark Matter Symposium

Fermilab. May 11, 2007

Based on works of...

- **Takehiko Asaka** (EPFL, Lausanne, Switzerland)
- **Steve Blanchet** (EPFL, Lausanne, Switzerland)
- **Alexey Boyarsky** (CERN, Geneva, Switzerland)
- **Jan-Willem den Herder** (SRON, Utrecht, the Netherlands)
- **Mikko Laine** (Bielefeld U., Germany)
- **Maxim Markevitch** (Harvard-Smithsonian CfA, USA)
- **Jukka Nevalainen** (Helsinki University Observatory, Finland)
- **Andrey Neronov** (INTEGRAL Science Data Center, Switzerland)
- **Oleg Ruchayskiy** (IHES, Paris, France & EPFL, Switzerland)
- **Mikhail Shaposhnikov** (EPFL, Lausanne, Switzerland)
- **Igor Tkachev** (CERN, Geneva, Switzerland)

in 2005...2007

Why go beyond the Standard Model?

Minimal Standard Model (MSM) – great success of particle physics

However MSM ***does not explain*** several important phenomena:

- neutrino oscillations
- dark matter
- absence of anti-matter (baryon asymmetry of the Universe)
- flatness and homogeneity (inflation?) **involves gravity**
- dark energy (cosmological constant problem) **involves gravity**
- CP problem, hierarchy problem **fine tuning problems**
- grand unification, quantum gravity **theoretical**

New physics is needed?

- Most models introduce *new energy scale* between the electro-weak and Planck scales to explain neutrino oscillations, Dark Matter and baryogenesis.

- However, there is a very modest and simple modification of the SM which can explain **within one consistent framework**

✓ . . . neutrino oscillations

✓ . . . baryon asymmetry of the Universe

✓ . . . provide a viable (warm or cold) dark matter candidate

✓ . . . can have a number of astrophysical applications

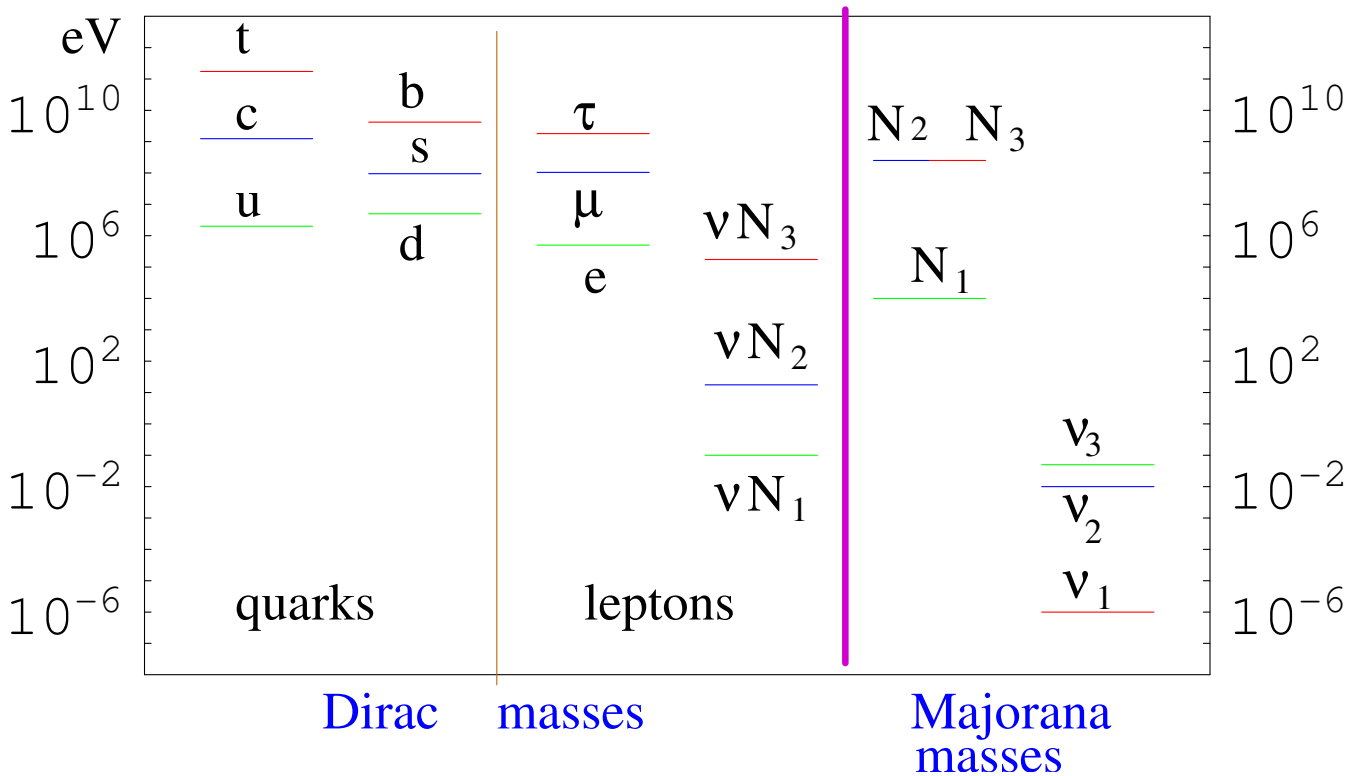
Just add 3 right-handed (sterile) neutrinos N_I to MSM:

$$\mathcal{L}_{\nu MSM} = \mathcal{L}_{MSM} + i\bar{N}^I \not{\partial} N_I - \left(\bar{L}_\alpha M^D_{\alpha I} N_I + \frac{M_I}{2} \bar{N}^c_I N_I + h.c. \right)$$

Asaka, Shaposhnikov, PLB **620**, 17 (2005)

Asaka, Blanchet, Shaposhnikov, PLB **631**, 151 (2005)

The spectrum of the νMSM



Choosing parameters of the νMSM

- νMSM adds **18 new parameters** (3 Majorana masses, 3 Dirac masses, 6 mixing angles and 6 CP-phases) to the **19 free parameters** of the MSM.

- Parameters of **two** sterile neutrinos are enough to explain baryogenesis and fit the oscillations data:
  - If $M_{2,3} \sim 150$ **MeV** $- 20$ **GeV** and $\Delta M_{2,3} \ll M_{2,3}$ νMSM explains **baryon asymmetry** of the Universe. Mixing with the rest of the matter:

    Asaka, Shaposhnikov, PLB **620**, 17 (2005)

    $$10^{-11}\left(\frac{\text{GeV}}{M_{2,3}}\right)^2 < \theta^2_{\text{heavy}} < 10^{-8}\left(\frac{\text{GeV}}{M_{2,3}}\right)^2$$

    (heavy sterile neutrinos should decay before BBN)
  - Neutrino experiments can be explained within the same choice of parameters. See-saw with masses below EW scale.

- The lightest sterile neutrino can couple with the MSM arbitrarily weakly and has mass $\ll 1$ GeV. This is **viable DM candidate**.

Properties of the DM sterile neutrino

- Cosmologically long life time:
  - Dominant decay channel for sterile neutrino (with mass below ~ 1 MeV) is $N_s \to 3\nu$.
  - Life-time $\tau = 5 \times 10^{26}\text{sec} \times \left(\frac{\text{keV}}{M_s}\right)^5 \left(\frac{10^{-8}}{\theta^2}\right)^2$

Pal, Wolfenstein (1982)

Barger Phillips Sarkar (1995)

- Can be produced in the early Universe in the right amount:
  - Via active-sterile **neutrino oscillations** (the required Yukawa coupling seems to be too large to be consistent with X-ray and Lyman-α bounds)
  - Via **resonant** active-sterile neutrino oscillations in the presence of **lepton asymmetries**. (Works well for sterile neutrinos in keV range.)
  - In light **inflaton** decays. (Can produce sterile neutrinos up to the mass of few MeV)

Dodelson Widrow'93

Asaka, Laine, Shaposhnikov (2006)

Shi, Fuller'98

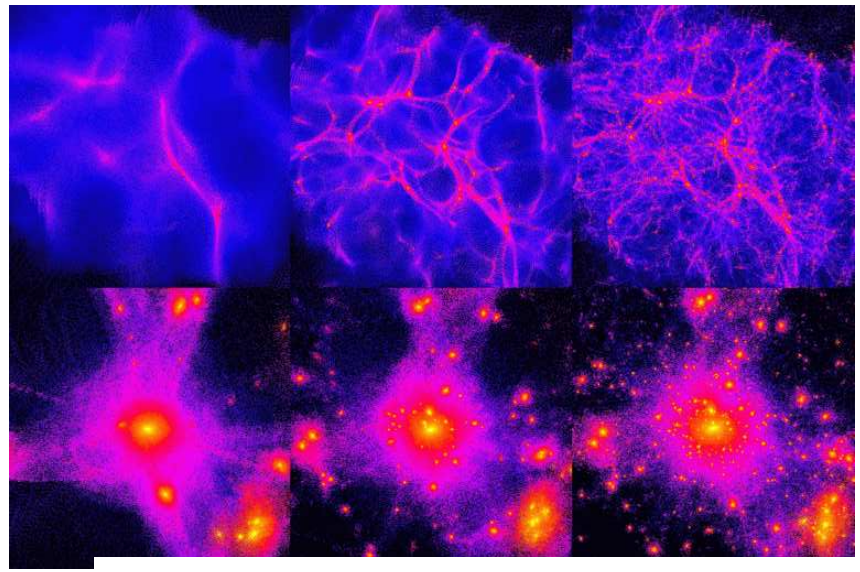
Shaposhnikov, Tkachev (2006)

- Mass can be anywhere between a lower bound ~ 300 eV and GeV. How to choose it?

Tremaine, Gunn (1979)

Sterile ν can be cold or warm DM

- □ **CDM**: no *free streaming*
- □ **WDM** : FS at galaxy scales
- □ **HDM**: FS at cosmological scales. Ruled out!



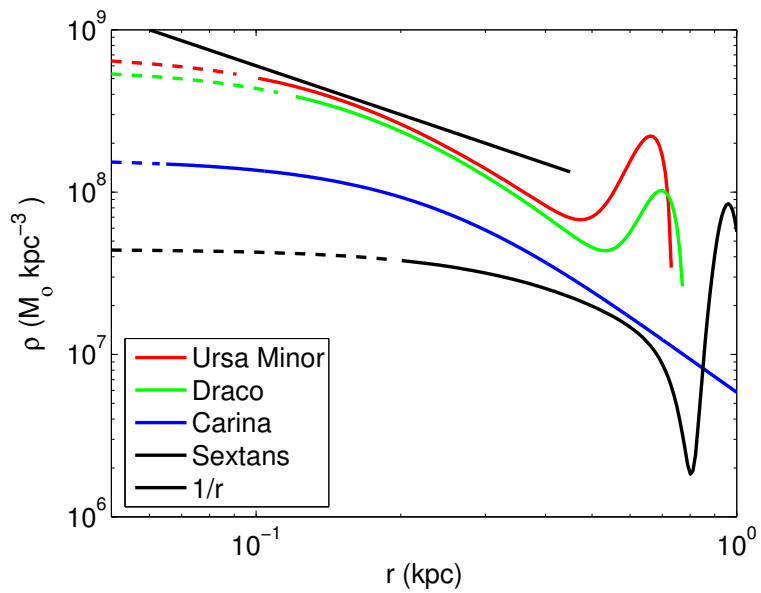
CDM: $\lambda_{\rm FS} \lesssim 10$ kpc

HDM: $\lambda_{\rm FS} \sim H^{-1}$

WDM: 10 kpc $\lesssim \lambda_{\rm FS} \ll H^{-1}$

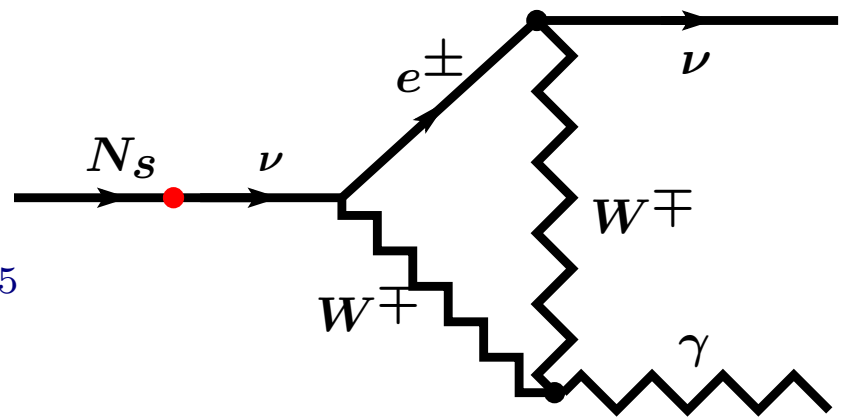
- CDM and WDM work equally well at large scales.

- CDM at galaxy scale predicts:
  - □ ***Cuspy profiles.*** Cores observed
  - □ ***Many satellites.*** Few observed
  - □ ***Could be ways out, but***
- **WDM** agrees with observations at small scale and shares success of CDM at larger scales. Interesting to have a keV DM particle!



Sterile neutrino DM is not completely dark

- Subdominant (BR $\sim \frac{1}{128}$) **radiative decay channel**
  - Photon energy: $E_\gamma = \frac{M_s}{2}$
  - Decay width
    $$\Gamma_{\text{rad}} = \frac{9\,\alpha_{\text{EM}}\,G_F^2}{256 \cdot 4\pi^4}\,\sin^2(2\theta)\,M_s{}^5$$
  - depends on two parameters



- – ***Flux from DM decay:***

$$F_{\text{DM}} = \frac{E_\gamma}{M_s}\frac{\Gamma_{\text{rad}} M_{\text{DM}}^{\text{fov}}}{4\pi D_L^2} \approx \frac{\Gamma_{\text{rad}}\Omega_{\text{fov}}}{8\pi}\int \rho_{\text{DM}}(r)\,dr$$

line of sight

$(z \ll 1,\ \Omega_{\text{fov}} \ll 1)$

Dolgov
Hansen (2000

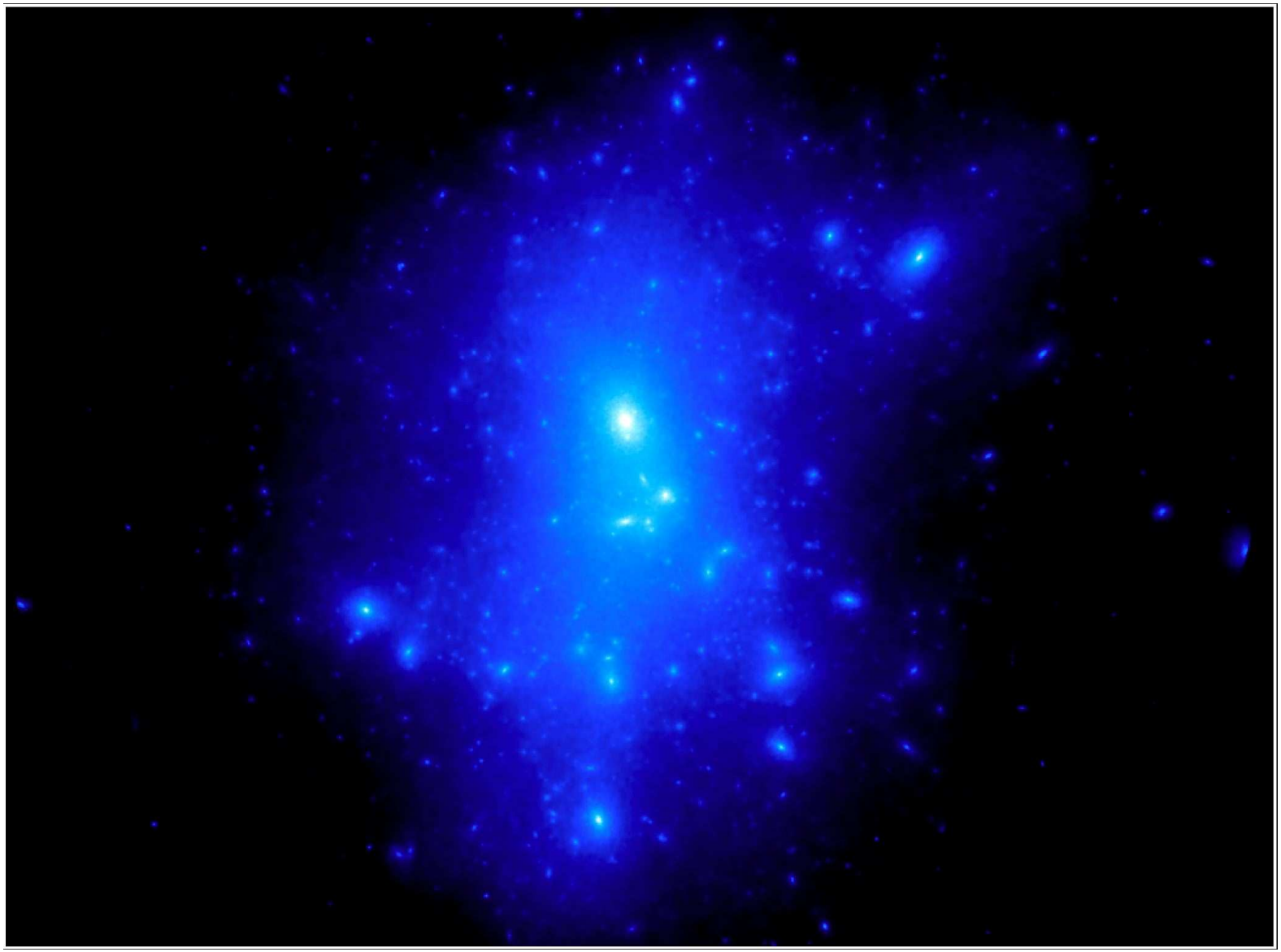
Abazajian
Fuller Tucker
(2001)

Boyarsky et al
(2006)

Decay is linear in DM density! Easy to observe, less sensitive to the profiles in the center.

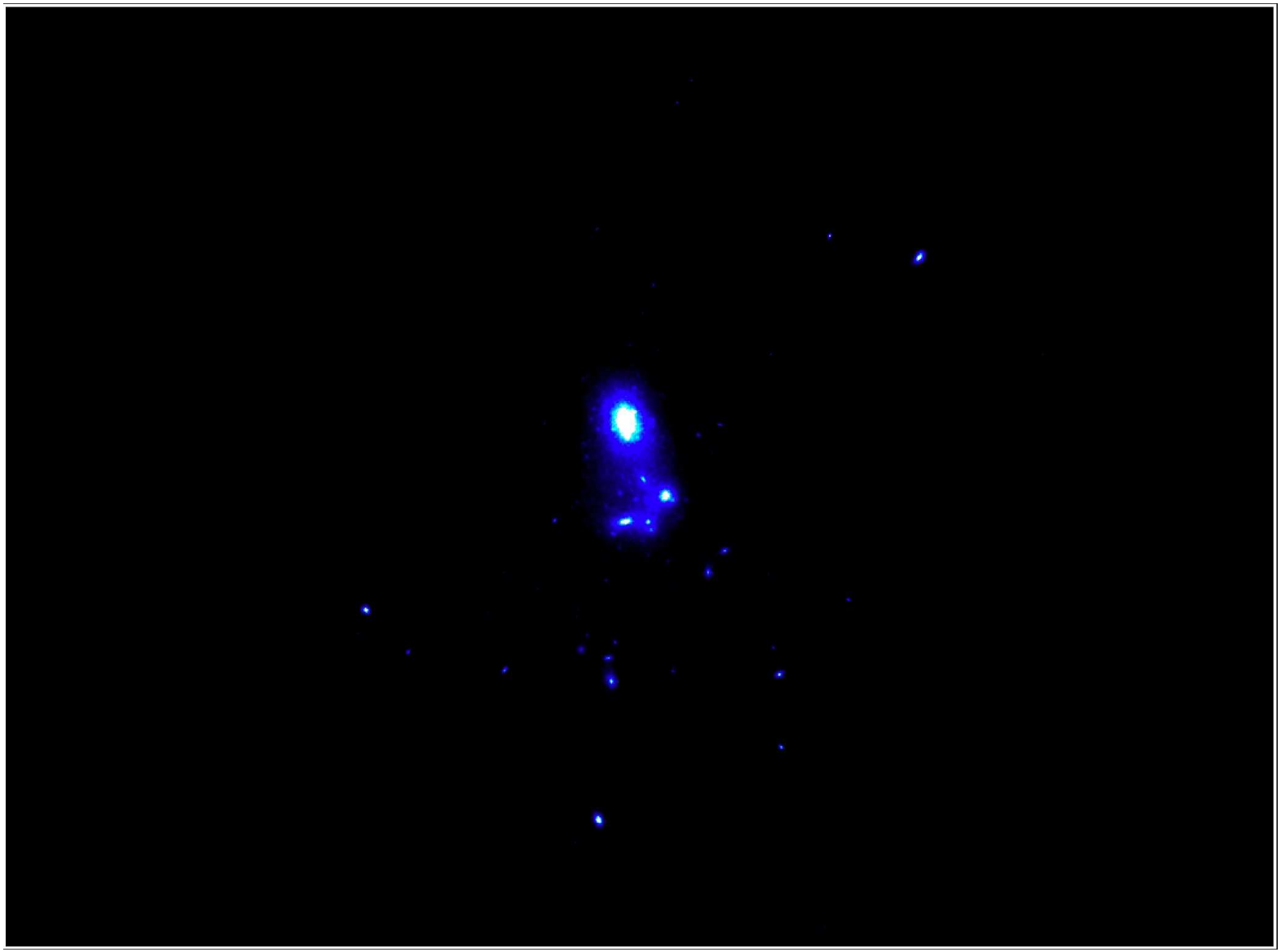
Column density in MW-sized galaxy

Moore et al. 2005



Column density squared in MW-sized galaxy

Moore et al. 2005



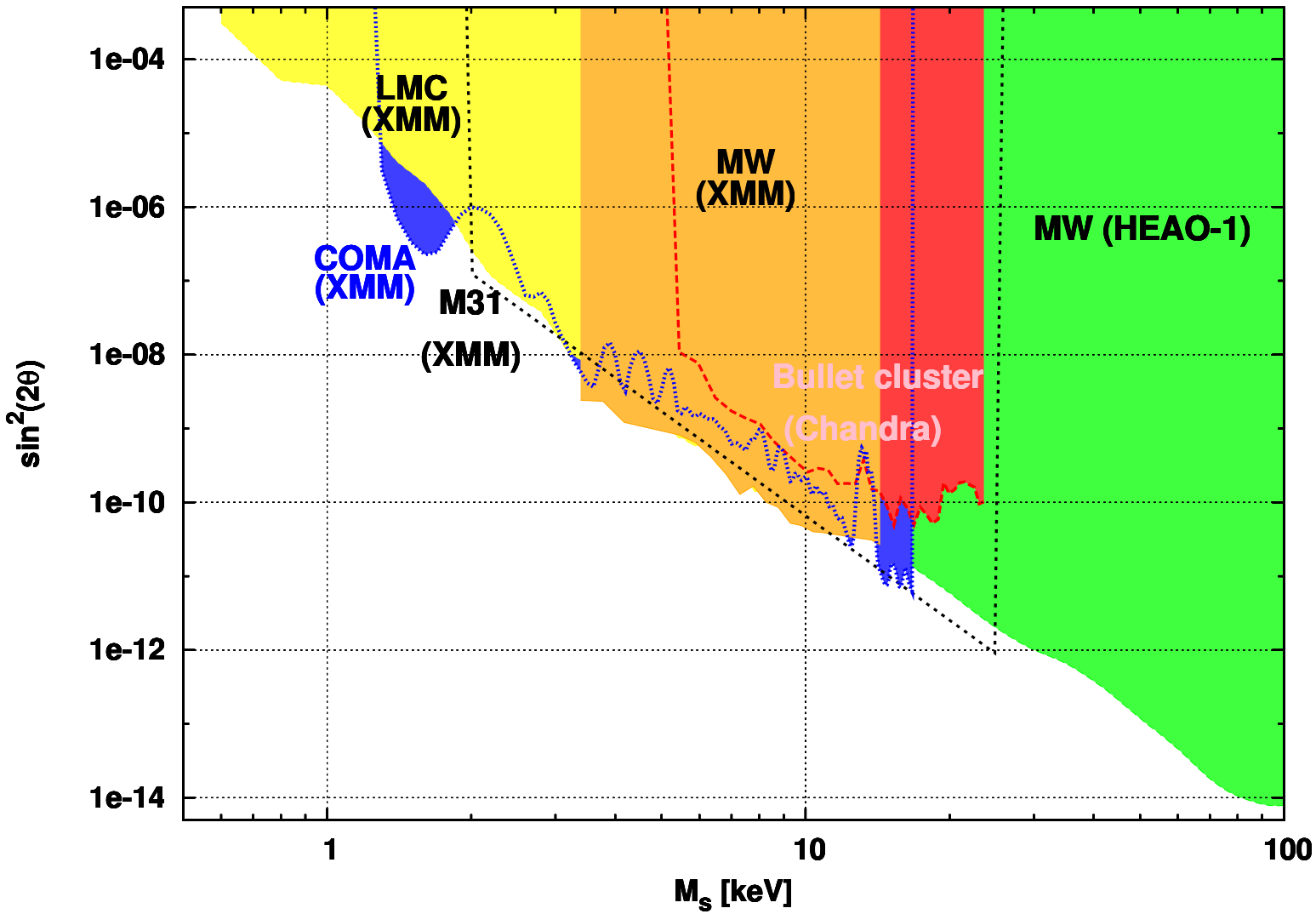
Astrophysical search for sterile neutrino and restrictions on its parameters M_s and θ

Where to look for DM decay line?

■ Extragalactic diffuse X-ray background (XRB)	**Boyarsky, Neronov, O.R., Shaposhnikov, 2005** Mapelli & Ferrara, 2005
■ Clusters of galaxies (Coma, Virgo)	Abazajian et al., 2001 **Boyarsky, Neronov, O.R., Shaposhnikov** PRD 74, 2006 [astro-ph/0603368]
■ DM halo of the Milky Way. Signal increases as we increase FoV!	**Boyarsky, Neronov, O.R., Shaposhnikov, Tkachev** PRL 2006 [astro-ph/0603660] Riemer-Sørense et al. ApJL 2006 [astro-ph/0603661] **Boyarsky, Nevalainen, O.R.** A&A 2007 [astro-ph/0610961] Abazajian et al. [PRD 75, 2007]
■ Local Group galaxies	**Boyarsky et al. astro-ph/0603660** Watson et al. PRD 74, 2006 [astro-ph/0605424]
■ "Bullet" cluster 1E 0657-56	**Boyarsky, Markevitch, O.R.** [astro-ph/0611168]
■ Soft XRB	**Boyarsky, den Herder, Neronov, O.R.** [astro-ph/0612219]

Need to find the ***best ratio*** between the DM decay *signal* and object's X-ray emission.

Parameters of sterile neutrino DM



MW (HEAO-1) Boyarsky et al 2005

Coma and Virgo clusters Boyarsky et al 2006

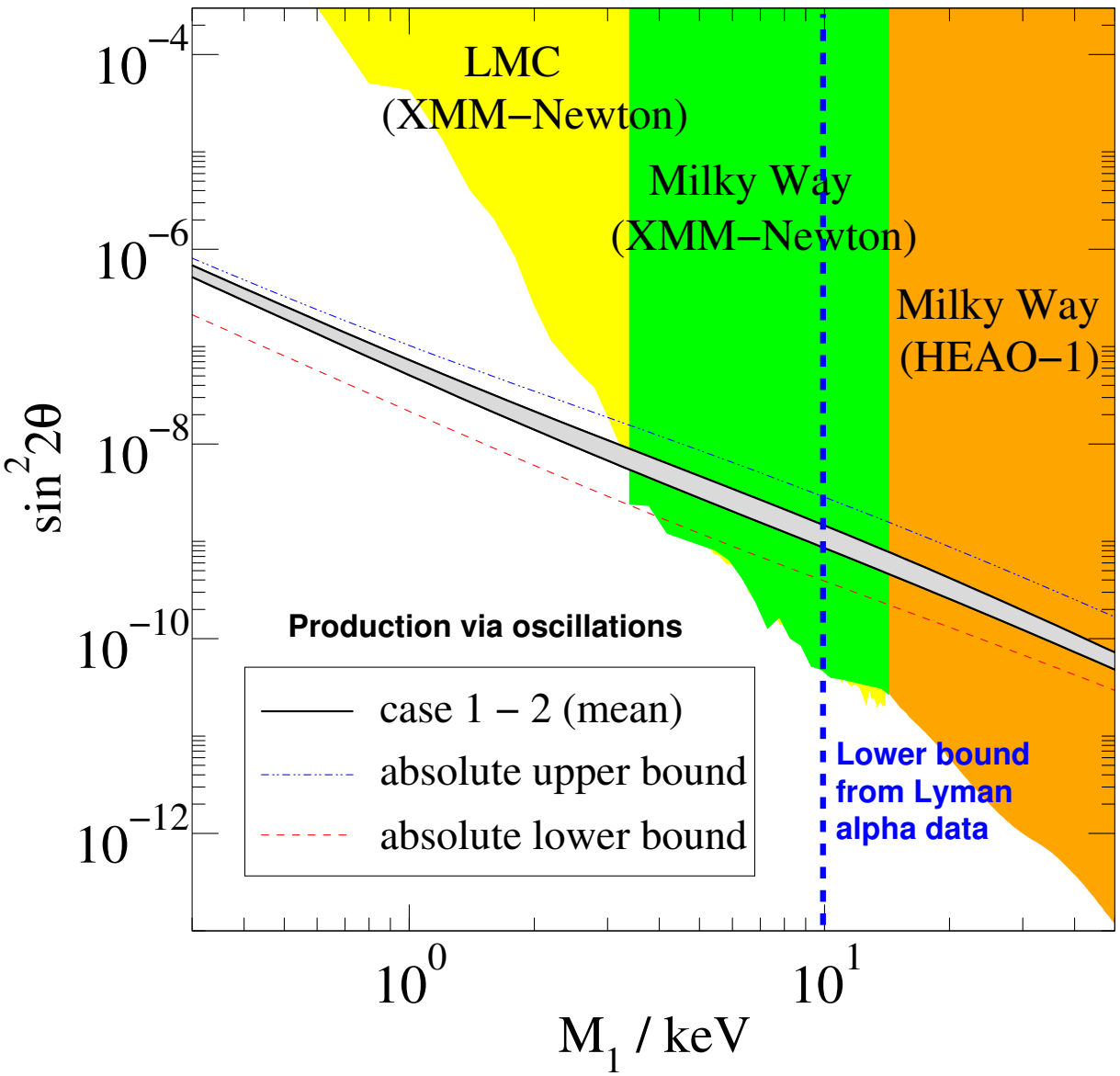
LMC+MW(XM Boyarsky et al 2006

MW (Chandra) Riemer-Sørensen et al.; Abazajian et al.

M31 Watson et al. 2006

Fine print: all results subject to intrinsic factor ~ 2 uncertainty!

Parameters of sterile neutrino DM with Ly-α



Lyman-α bound is valid for the production via oscillations ("Dodelson-Widrow") scenario. For other production mechanisms the limit can go down by as much as ***80%***.

MW (HEAO-1)
Boyarsky et al
2005

LMC+MW
Boyarsky et al
2006

Ly-α data
Viel et al.
2006;
Seljak et al.
2006

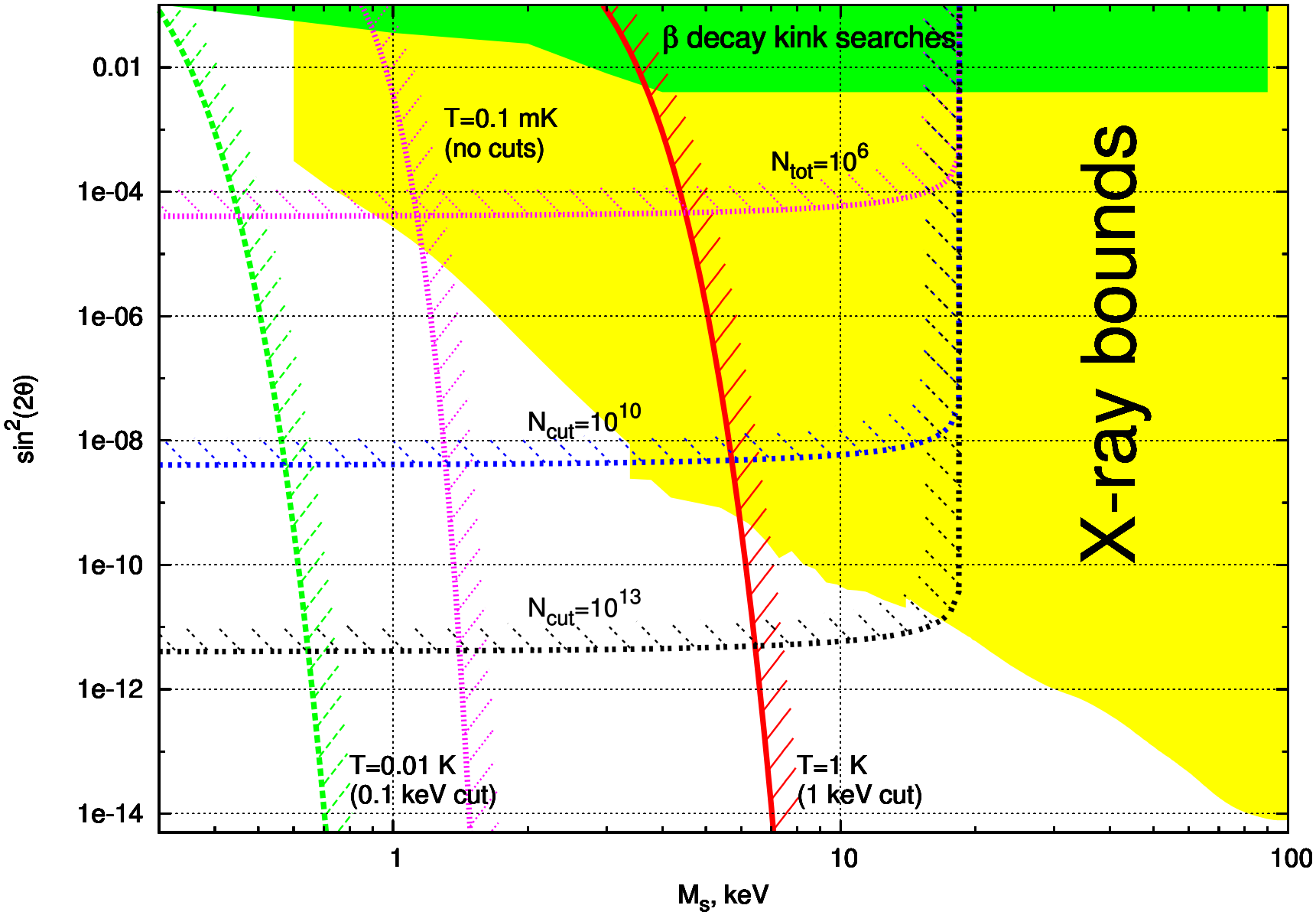
Production from oscillations
Asaka et al.
2006, 2007

Laboratory detection of sterile neutrino

- **Creation** and **detection** in the lab: suppressed by θ^4 and hopeless.
- Creation somewhere and **detection** in the lab – θ^2 effect. But the only realistic possibility is to search for radiative decays of sterile neutrino in the DM clouds – not a laboratory experiment.

  Bezrukov, Shaposhnikov PRD 2007
- **Creation** in the lab without subsequent detection – the unique option, θ^2 effect.
- Possibilities:
  - Forbidden decays, e.g. $\pi^0 \to N\nu$ – branching ratio is too small. Hopeless.
  - β-decay kinematics: ${}^3H \to {}^3He + e + \bar{\nu}_e$ is not the same as ${}^3H \to {}^3He + e + N$!
- **Full kinematics** event-by-event mass measurement: may work. ***COLTRIMS technology***

Optimistic prospects



How to detect heavy sterile neutrinos

- Missing energy signal in $K,\ D$ and B decays (θ^2 effect)
  - $M_N < M_K$: KLOE, NA48, E787
  - $M_N < 1$ GeV : charm and τ factories
  - $1\ \mathrm{GeV} < M_N < M_B$: charm, τ and B-factories (planned luminosity is not enough)

- Decay processes $N \to \mu^+\mu^-\nu$, etc (”nothing”$\to \mu^+\mu^-$) (θ^4 effect)
  - $M_N < M_K$: Any intense source of K-mesons (e.g. from proton targets of K2K, MiniBooNe or MINOS)
  - $M_N < M_D$: JPARC, MINOS, CNGS beams + very near detector

- $M_N > M_D$: extremely difficult

Summary: Sterile neutrino DM

- Sterile neutrino is a viable DM candidate. The mass can be in **keV** range providing a **WDM**

- νMSM is **not** enough to compute abundance of DM. The initial conditions (at $T \gtrsim 1$ GeV) need to be specified. Mass M_s and mixing angle $\sin^2(2\theta)$ should be treated as **independent parameters**.

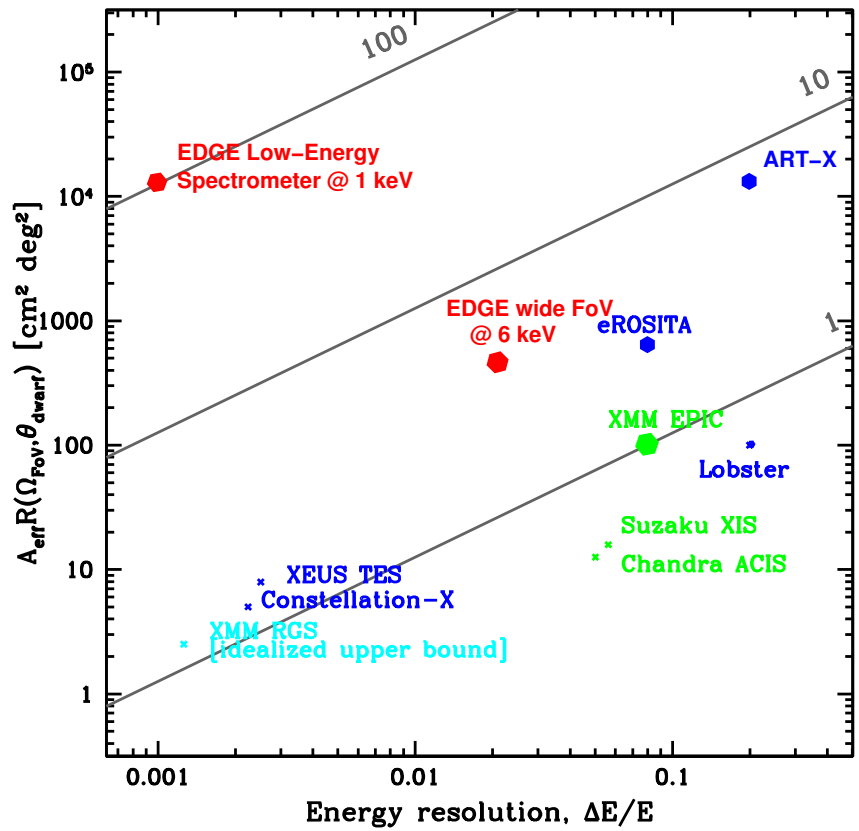
- Cosmological (Ly-α) lower bound on mass depends on the model-dependent initial momentum distribution and may be weakened

- Sterile neutrino possesses radiative **decay** channel. Restrictions from astrophysical observations are not sensitive to the presence of cusps in the DM density profiles.

- To further improve constraints – observe "dark" objects, like dwarf spheroidals. Search for "exotic" like the bullet cluster.

Outlook: Future missions

- Spectrometers with big FoV and spectral resolution $\Delta E/E \sim 10^{-3}$ are needed
- Future missions (*XEUS* or *Constellation X*) will have better spectral resolution but very small FoV
- EDGE (proposed for ESA Cosmic Vision Programme) by SRON and INAF) is very interesting from sterile neutrino DM search prospective.



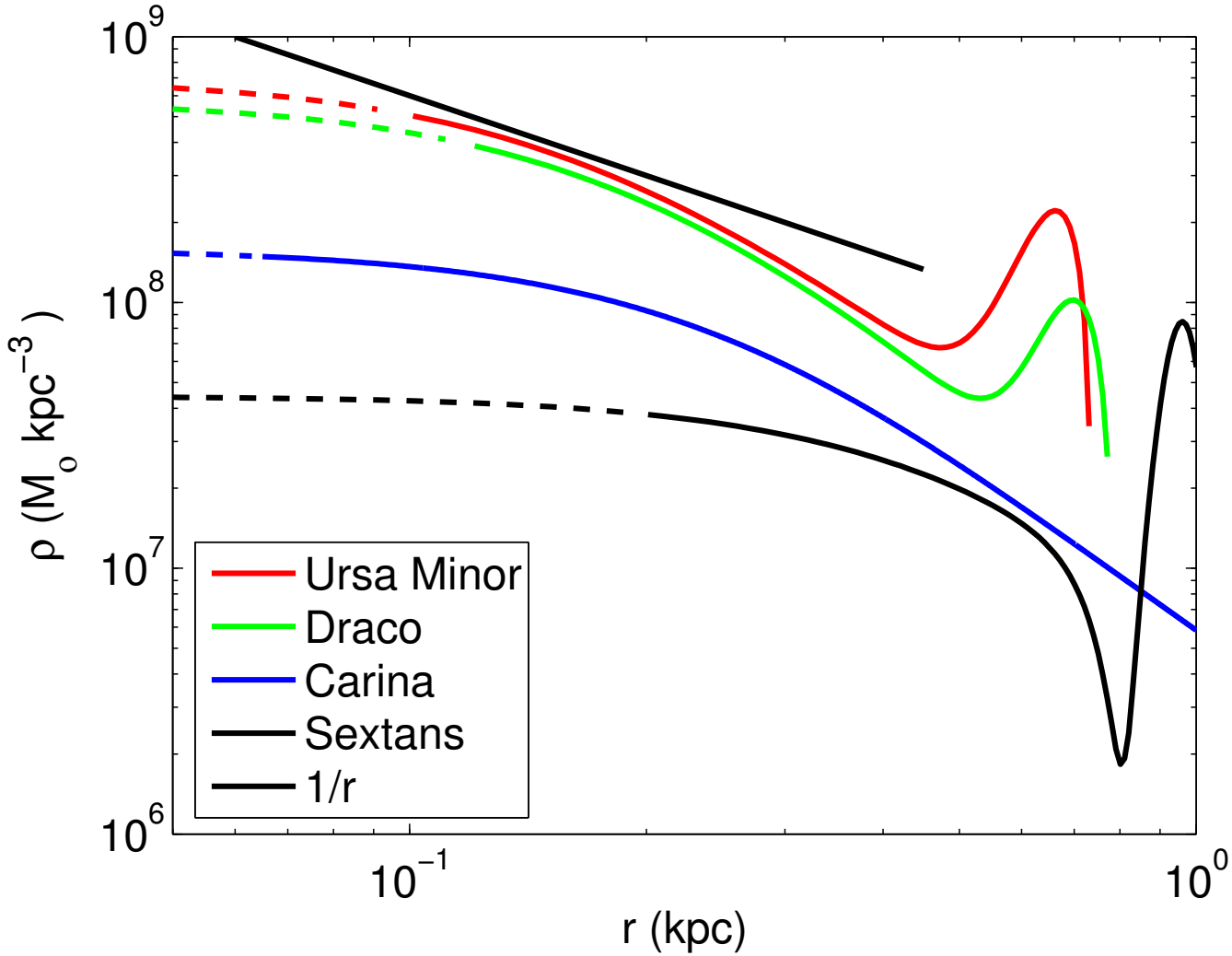
Boyarsky, den Herder, Neronov, O.R. 2006

Outlook: νMSM

- Extending the MSM by three right-handed neutrino allows
  - explain neutrino oscillations
  - explain baryogenesis
  - provide DM candidate
- All mass parameters in the νMSM are below electroweak scale – the theory is **testable**.
- The theory can be tested from various sides:
  - Laboratory experiments: detailed studies of β-decay using Cold Target Recoil Ion Momentum Spectroscopy technique
  - Particle physics experiments (decay of heavier sterile neutrinos)
  - If the lightest sterile neutrino constitutes (large fraction of) DM, νMSM can be tested in current and future astrophysical missions.
- Future experiments will allow to rule this theory out or confirm it.

Thank you for your attention

Dwarf DM profile

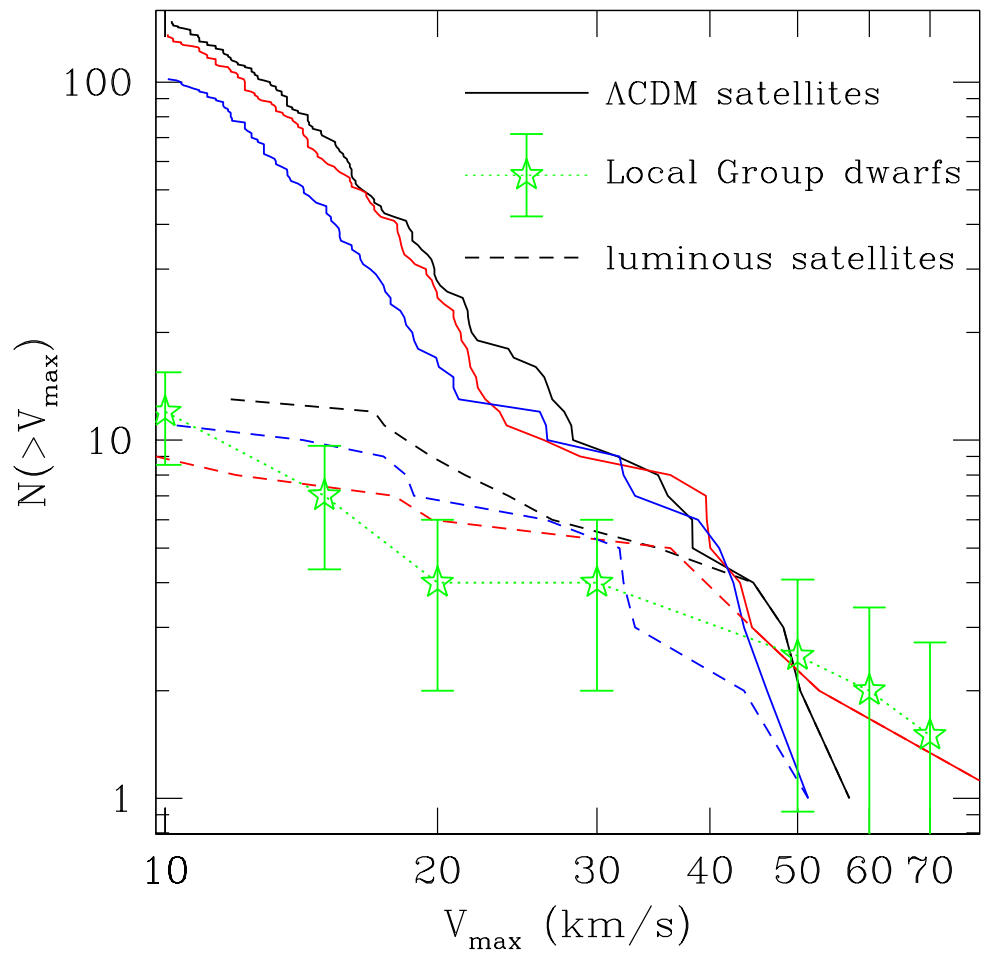


Wilkinson et al., astro-ph/0602186

Back to CDM vs. WDM

Missing satellites in ΛCDM

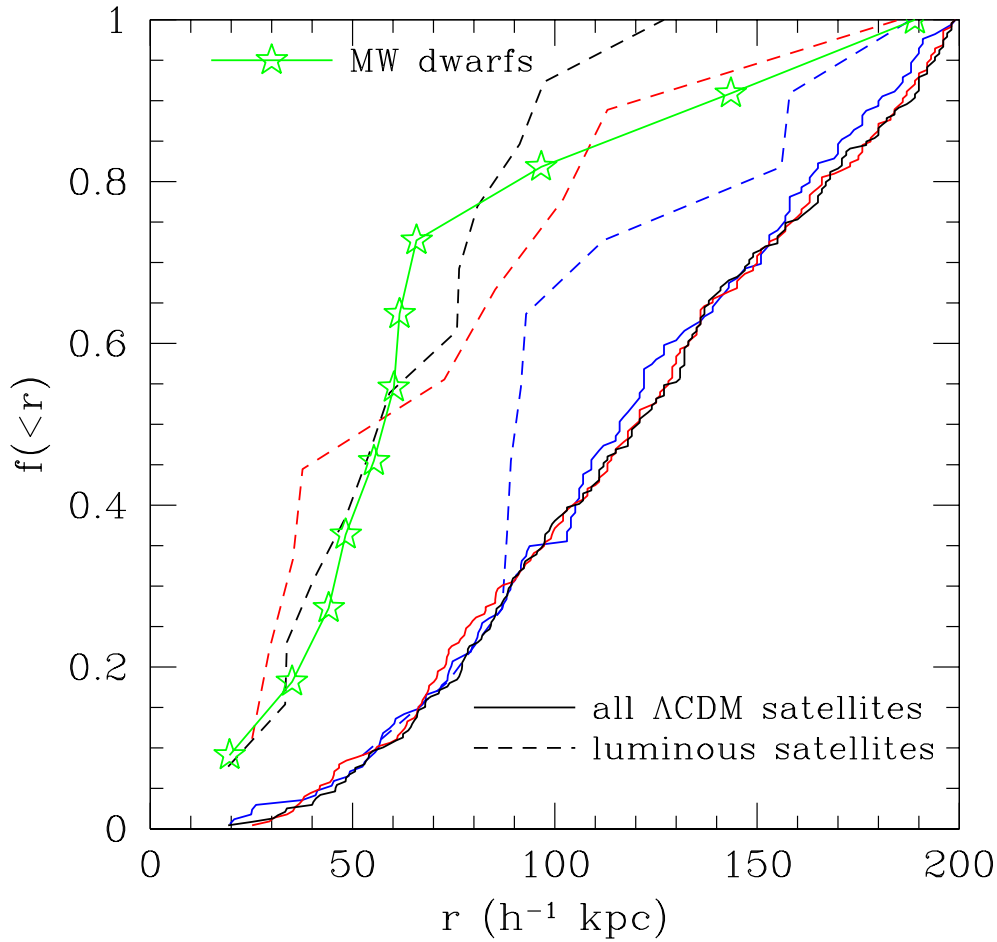
The cumulative velocity function ($\approx$ **mass distribution**) of the DM satellites in the three **simulated** galactic halos compared to that of **dwarf galaxies around the MW and Andromeda** galaxies. Both observed and simulated objects are selected within the radius of $200h^{-1}$ kpc from the center of their host. The dashed lines show the velocity function for the **luminous satellites**. The minimum stellar mass of the luminous satellites for the three hosts ranges from $\approx 10^5 M_\odot$ to $\approx 10^6 \mathrm{M}_\odot$, comparable to the observed range. ***Back to CDM vs. WDM***



Kravtsov, Gnedin, Klypin
ApJ 609 (2004) [astro-ph/0401088]

Missing dwarfs

The fraction of satellites within a certain distance from the center of their host galaxy.
Solid lines – **simulated** distributions of the ΛCDM satellites (3 galactic halos). **Stars** – distribution of dwarf galaxies around the Milky Way. The figure shows that radial distribution of observed satellites is more compact than that of the overall population of dark matter satellites. **Dashed** lines – distributions for the luminous satellites.



Back to CDM vs. WDM

Kravtsov, Gnedin, Klypin
ApJ 609 (2004) [astro-ph/0401088]

Dilution of sterile neutrino abundance

- Do Lyman-α results mean that any mass below $M_s \simeq 10$ keV ($M_s \simeq 14$ keV) are excluded for all θ and the sterile neutrino cannot be **WDM**?
- **No,** the actual result reads: $\boxed{M_{\textbf{lower limit}} = \frac{\langle p_s \rangle}{\langle p_\nu \rangle} M_{\textbf{Ly}-\alpha}}$. This ratio depends on the production history of the sterile neutrino.
- Two heavy sterile neutrino $N_{2,3}$ can decay at $T \sim \mathcal{O}(1)$ MeV (after the lightest sterile neutrino has been produced)
- This leads to the **entropy production** $S \sim \mathcal{O}(1{-}100)$.
- Entropy production leads to the **dilution** of DM sterile neutrino abundance: $\Omega_{\textbf{DM}} \to \frac{\Omega_{\textbf{DM}}}{S}$ and **red-shifting** the momentum distribution and $\langle p_s \rangle$ by $S^{1/3}$. Therefore...
- $\boxed{M_{\textbf{lower limit}} = \frac{M_{\textbf{Ly}-\alpha}}{S^{1/3}}}$ For $S \sim 100$ we have $M_s \sim 2$ **keV** and the decay line at 1 **keV**.

  Back to restrictions with Lyman-α.

Asaka et al. PLB 638 (2006)

How to choose the best object?

- **Size does not matter**: signal from the Milky way halo comparable with that of clusters like Coma or Virgo

- DM flux from e.g. **Draco** or **Ursa Minor** dSph is 3 times stronger than that of the Milky Way halo.

$$F_{\text{DM}} = \frac{E_\gamma}{M_s}\frac{\Gamma_{\text{rad}} M_{\text{DM}}^{\text{fov}}}{4\pi D_L^2} \approx \frac{\Gamma_{\text{rad}}\Omega_{\text{fov}}}{8\pi}\int_{\text{line of sight}} \rho_{\text{DM}}(r)dr$$

- Dwarf satellites of the MW are really dark (M/L ~ 100). Therefore, are rarely looked at in the X-ray

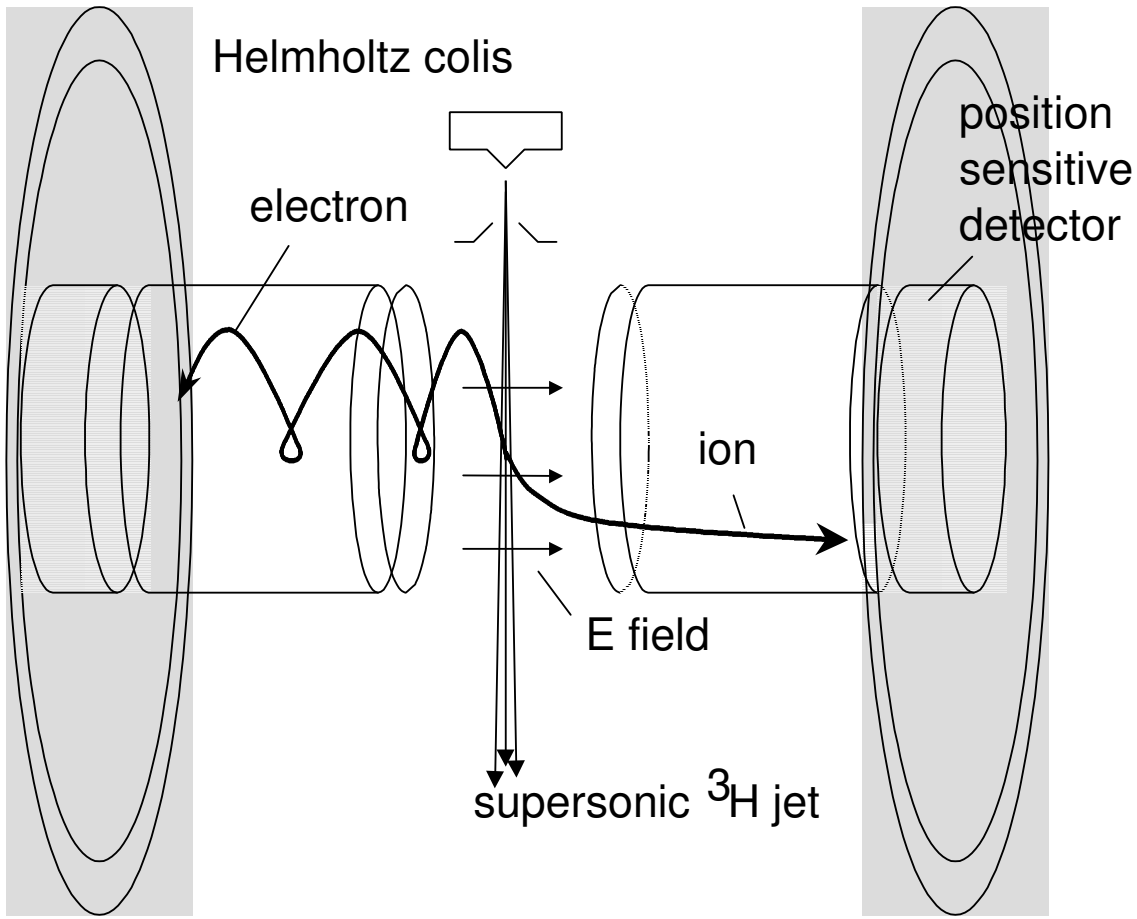
- Continuum X-ray emission from Milky Way is about 2 orders **weaker** than that of a cluster

- Feature we are looking for is **a narrow line**. Astrophysical background can be strong, yet described by a featureless spectrum (power-law). Can effectively search for a thin line against a power-law background emission

Results

COLTRIMS experiment

Cold-Target Recoil-Ion-Momentum Spectroscopy



νMSM coupled with inflaton

- To go beyond SM, one can incorporate inflation into νMSM
- Lagrangian of νMSM can be coupled with **inflaton** field χ in the natural way:

Shaposhnikov, Tkachev PLB **639**, 414 (2006)

$$\mathcal{L}_{\nu\text{MSM}} = \mathcal{L}_{\text{SM}} + i\bar{N}_I \partial\!\!\!/ N_I - F_{\alpha I}\bar{L}_\alpha \Phi N_I - \frac{f_I}{2}\chi \bar{N}_I^c N_I + \text{h.c.} - V(\Phi, \chi)$$

SM **without** Higgs potential

- Inflaton coupling generates Majorana mass M_I of sterile neutrino N_I after spontaneous breaking of scale invariance by the inflaton mass term:

$$V(\Phi, \chi) = -\frac{1}{2}M_\chi^2\chi^2 + \lambda\left(\Phi^+\Phi - \frac{\alpha}{\lambda}\chi^2\right)^2 + \frac{\beta}{4}\chi^4$$

Production via coupling with the inflaton

Shaposhnikov
Tkachev
PLB **639**, 414
(2006)

$$\mathcal{L}_{\nu\text{MSM}} = \mathcal{L}_{\text{SM}} + i\bar{N}_I \not{\partial} N_I - F_{\alpha I}\bar{L}_\alpha \Phi N_I - \frac{f_I}{2}\chi\, \bar{N}_I^c N_I + \text{h.c.} - V(\Phi, \chi)$$

- The lightest sterile neutrino production goes via $\boxed{\chi \to N_1 N_1}$
- Parameters of the model $\left(\alpha, \beta, \lambda, f_I, \langle\chi\rangle\right)$ can be chosen so that:
  - Conditions for chaotic inflation are satisfied. Inflaton potential is sufficiently flat and gives correct amplitude of scalar perturbations.
  - Correct Higgs mass is generated
  - Model allows for correct baryogenesis (large reheating temperature)
  - Decay of inflaton **produces enough light sterile neutrino** to account for all the DM

For $m_I \sim 300$ MeV correct Ω_s obtained for $M_s \sim 16-20$ keV
For $m_I \sim 100$ GeV correct Ω_s obtained for $M_s \sim 10$ MeV

Back to sterile neutrino DM properties

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