Sterile neutrino dark matter

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The Dark Matter connection: Theory & Experiment

GGI Florence
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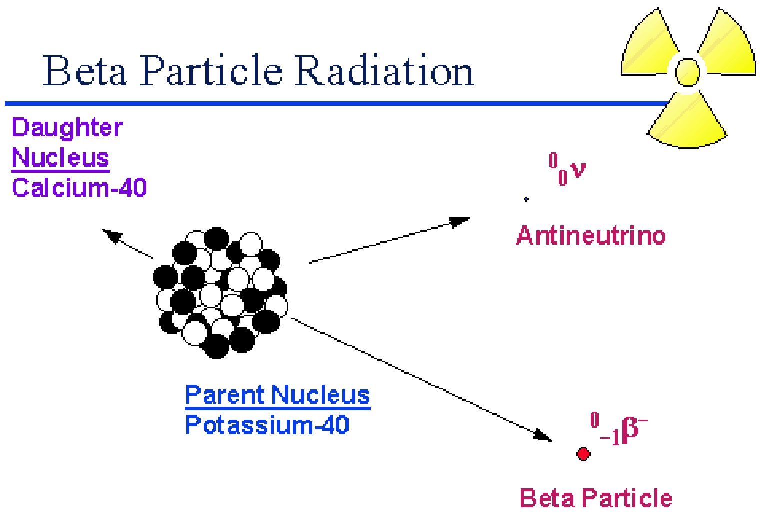
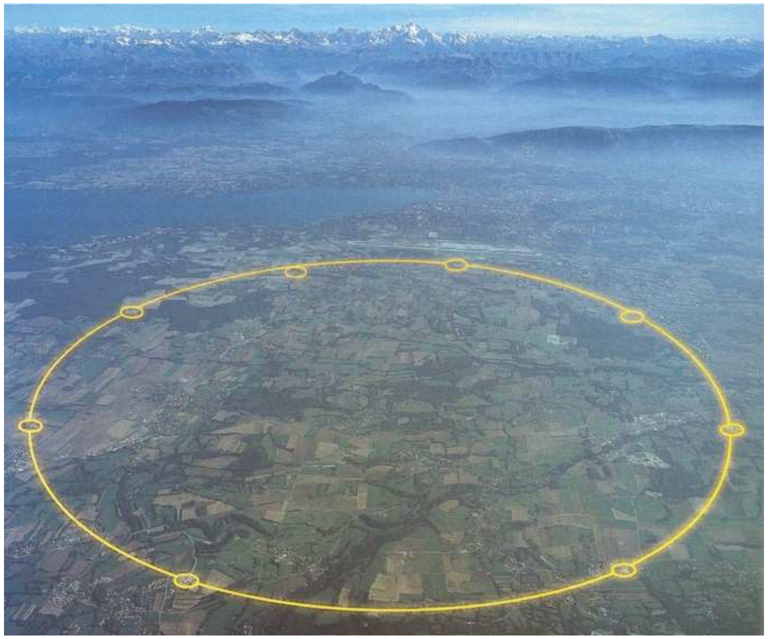
Standard Model of Elementary Particles

The Standard Model of elementary particle physics: from understanding the β-decay to the Large Hadron Collider.





Is there a new physics beyond the Standard Model?

Why (and where) we expect new physics?

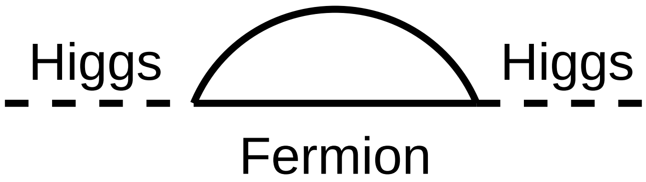
- **Dark matter** (not a SM particle!)
  - particles with weak cross-section will have correct abundance Ω_{DM} ("WIMP miracle"). **New scale** ~ 1 TeV
  - Axions. **New scale** $10^{10} - 10^{12}$ GeV.

- **Baryon asymmetry of the Universe**: what ensured that for each 10^{10} anti-protons there was $10^{10} + 1$ proton in the early Universe?
  - **Sakharov conditions:** CP-violation; B-number violation; out-of-equilibrium particles.
  - Out-of-equilibrium decay of heavy lepton χ at temperatures $M_{\mathrm{EW}} < T_{\mathrm{decay}} < M_\chi$ produces correct baryon-to-entropy ratio for $M_\chi > 10^{11}$ GeV – **new energy scale**

- **Fine-tuning problems:** CP-problem, hierarchy problem, grand unification, cosmological constant problem

Hierarchy problem

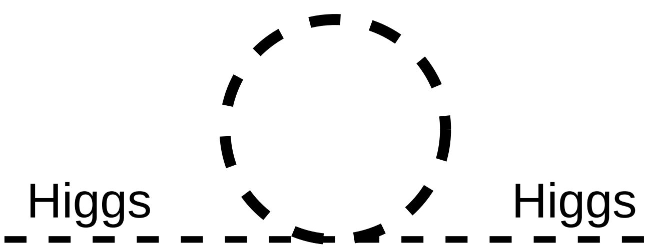
Quantum corrections to the Higgs mass:



? $\Downarrow$

100 GeV $< M_H < 300$ GeV

$\Uparrow$



- Masses of fermions are provided by the Higgs field
- Fermion corrections to the Higgs mass are proportional to their mass M_f^2.
- Contributions from heavy fermions ($M_f \gg 100$ GeV) would make Higgs mass heavy $M_H \sim M_f$
- To keep Higgs boson light, one should **fine-tune** the parameters of the model to cancel fermions' contribution by that of Higgs

Alternatives?

Build a model that resolves several BSM phenomena within its framework.

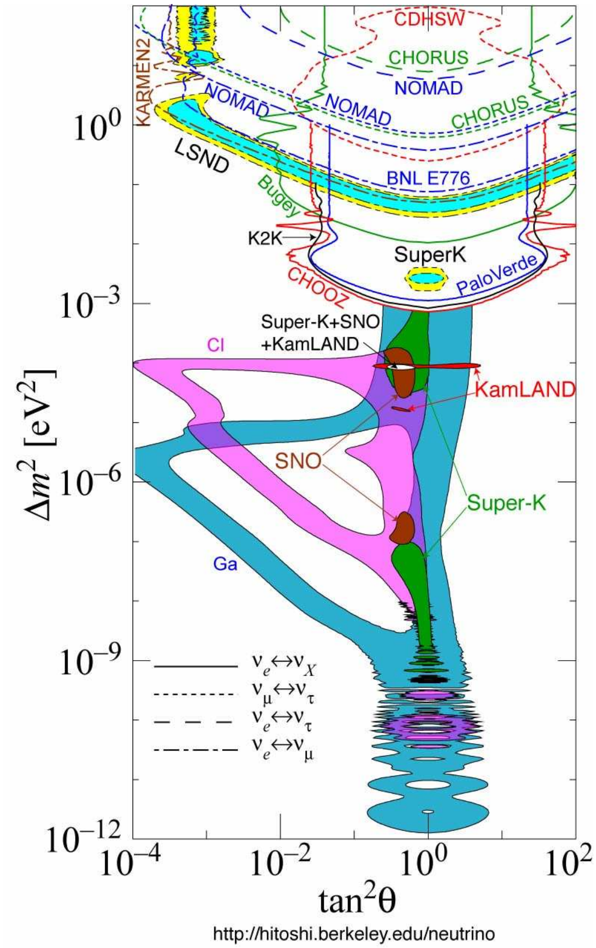
Worry about fine-tunings later

Neutrino oscillations

- Experiments on neutrino oscillations determined **two** mass differences between neutrino mass states

- **Sterile (right-handed) neutrinos** provide the simplest and natural extension of the Minimal SM that describe oscillations.

- Make leptonic sector of the SM symmetric.



See-saw Lagrangian

Add right-handed neutrinos N_I to the Standard Model

$$\mathcal{L}_{\text{right}} = i\bar{N}_I \partial\!\!\!/ N_I + \begin{pmatrix} \bar{\nu}_e \\ \bar{\nu}_\mu \\ \bar{\nu}_\tau \end{pmatrix} \underbrace{\begin{pmatrix} F\langle H\rangle \end{pmatrix}}_{\text{Dirac mass } M_D} \begin{pmatrix} N_1 \\ N_2 \\ \dots \end{pmatrix} + \begin{pmatrix} N_1^c \\ N_2^c \\ \dots \end{pmatrix} \underbrace{\begin{pmatrix} M \end{pmatrix}}_{\text{Majorana mass}} \begin{pmatrix} N_1 \\ N_2 \\ \dots \end{pmatrix}$$

$\nu_\alpha = \tilde{H} L_\alpha$, where L_α are left-handed lepton doublets

- Active masses are given via usual **see-saw formula**:

$$(m_\nu) = -M_D \frac{1}{M_I} M_D^T \qquad ; \qquad M_D \ll M_I$$

- Neutrino mass matrix – **7 parameters**. Dirac+Majorana mass matrix – **11 (18) parameters** for 2 (3) sterile neutrinos. **Two** sterile neutrinos are enough to fit the neutrino oscillations data.

Scale of Dirac and Majorana masses is not fixed!

Some general properties of sterile neutrino

- Sterile neutrinos are **decaying particles**

$M_I < 1$ MeV	$M_I > 1$ MeV	$M_I > 150$ MeV	$\ldots$
$N_I \to \nu\nu\bar{\nu}$	$N_I \to \nu e^+ e^-$	$N_I \to \pi^\pm e^\mp$	
$N_I \to \nu\gamma$		$N_I \to \pi^0 \nu$	

- Short lifetime – decay in the early Universe. Can have CP-violating phases. Leptogenesis? Affects BBN?

- Lifetime $\tau \propto \theta_I^{-2} M_I^{-5}$. (Cosmologically) long lifetime – dark matter candidate?

- **Mixing angle** θ_I:

$$\theta_I^2 = \sum_{\alpha=e,\mu,\tau} \frac{|F_{\alpha I}|^2 v^2}{M_I^2} \ll 1$$

The scale of right-handed masses?

“Popular” choices of see-saw parameters

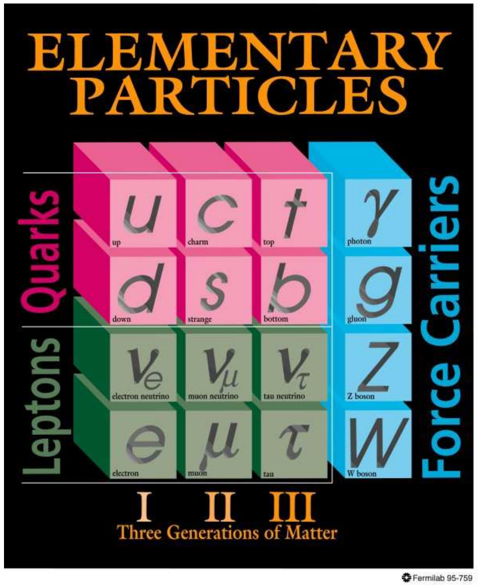
- Yukawa couplings $F_{\alpha I} \sim 1$, i.e. Dirac masses $M_D \sim M_t$. Majorana masses $M_I \sim 10^{15}$ GeV.

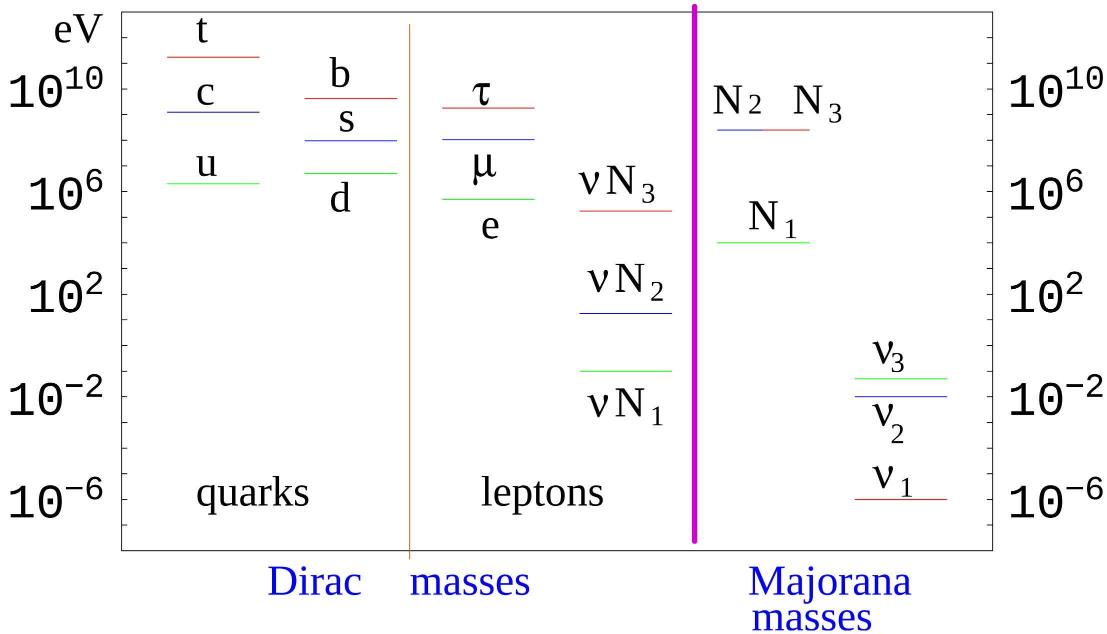
- Attractive features:
  - Provides a mechanism of baryon asymmetry of the Universe
  - Scale of Majorana masses is possibly related to GUT scale

- This model **does not provide the dark matter particle**

- Alternative? Choose Majorana masses M_I of the order of masses of other SM fermions and make Yukawa couplings small

Neutrino minimal Standard Model (νMSM)





The model solves several *beyond the Standard Model problems*

✓ . . . explains neutrino oscillations

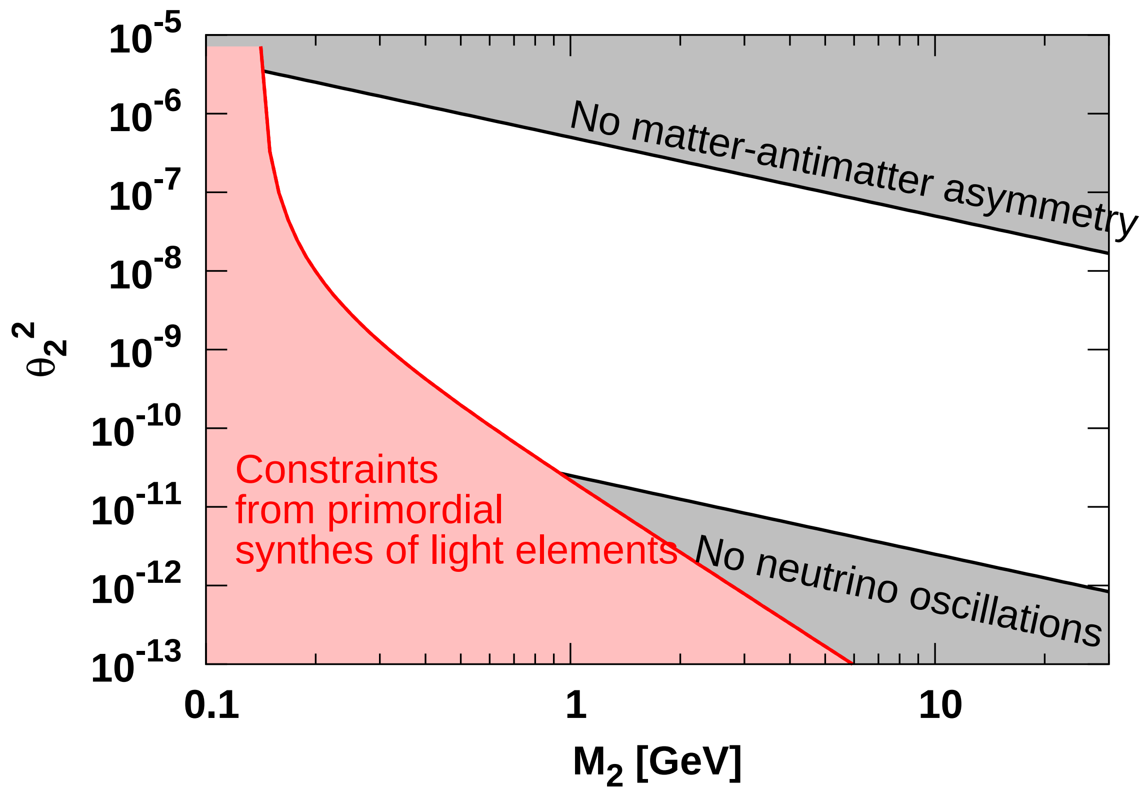
✓ . . . matter-antimatter asymmetry of the Universe

✓ . . . provides a viable dark matter candidate that can be cold, **warm** or **mixed** (cold+warm)

Choosing parameters of the νMSM

- If $M_{2,3} \sim 100$ **MeV** $- 20$ **GeV** and $\Delta M_{2,3} \ll M_{2,3}$ νMSM explains **baryon asymmetry** of the Universe.
- Neutrino experiments can be explained within the same choice of parameters.

Asaka, Shaposhnikov '05



Parameters of the third sterile neutrino?

- The third sterile neutrino can couple to the SM arbitrarily weakly. **Dark matter candidate?**
- Any DM candidate must be
  - Produced in the early Universe and have correct relic abundance
  - Be stable or cosmologically long-lived
  - Very weakly interacting with electromagnetic radiation ("dark")
  - Allow to explain the observed large scale structure

Mass of sterile neutrino DM?

- The model-independent lower limit on the mass of **fermionic** DM

Tremaine, Gunn (1979)

- The smaller is the DM particle mass – the bigger is the number of particles within some region of phase-space density (defined by velocity dispersion σ and size R)
- For fermions Pauli principle restricts number of fermions
- Objects with highest phase-space density – dwarf spheroidal galaxies – lead to the **lower bound** on the DM mass $m > 300$ eV
- New dSph's are very dense $Q_{obs} = 10^4 - 10^5\ M_\odot$ kpc^{-3}[km s^{-1}]$^{-3}$.
- Bound on any fermionic DM improved to become $M_s > 0.41$ **keV**

Boyarsky, **O.R.**, Iakubovskyi'08

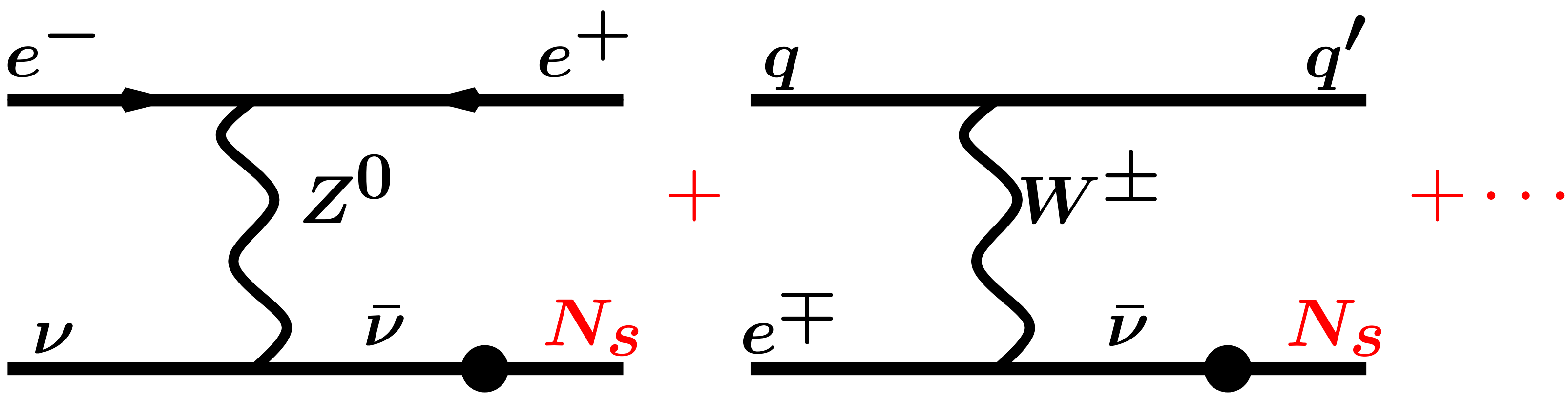
- Can be further improved if production model of sterile neutrinos is specified

How sterile neutrino DM is produced?

- Phenomenologically acceptable values of θ_1 are so small, that the rate of this interaction Γ of sterile neutrino with the primeval plasma is much slower than the expansion rate ($\Gamma \ll H$)
  $\Rightarrow$ Sterile neutrino are never in **thermal equilibrium**

- **Simplest scenario:** sterile neutrino in the early Universe interact with the rest of the SM matter via ***neutrino oscillations:***

Dodelson Widrow'93
Asaka, Laine, Shaposhnikov



- Production is sharply peaked at

$$T_{\text{max}} \simeq 130 \left(\frac{M_s}{\text{keV}}\right)^{1/3} \text{ MeV}$$

Production through oscillations

- Sterile neutrinos have non-equilibrium spectrum of primordial velocities, roughly proportional to the spectrum of active neutrinos

$$f_s(p) \propto \frac{\theta^2}{\exp(\frac{p}{T_\nu}) + 1}$$

- Their amount less than that of active:

$$\Omega_s h^2 \propto \theta^2 \frac{M_s}{94\text{ eV}} \qquad \text{recall: SM neutrinos } \Omega_\nu h^2 = \frac{\sum m_\nu}{94\text{ eV}}$$

- Average momentum $\langle p_s \rangle \sim \langle p_\nu \rangle \gg M_s$ – **sterile neutrinos are produced relativistic**

Resonant production

- The presence of lepton asymmetry makes this production much more effective – **resonant production**

Shi Fuller'98
Laine, Shaposhnikov

- To be effective this mechanism requires lepton asymmetry of the order $\frac{n_\nu - n_{\bar\nu}}{s} \gtrsim 10^{-6}$ (compare with $\eta_B = \frac{n_b - n_{\bar b}}{s} \sim 10^{-10}$)

- Typically, one expect the lepton asymmetry to be $\sim \eta_B$ (sphalerons equilibrate the two)

- In the νMSM one can generate the lepton asymmetry **below** the sphaleron scale thus making it significantly large than η_B

Shaposhnikov

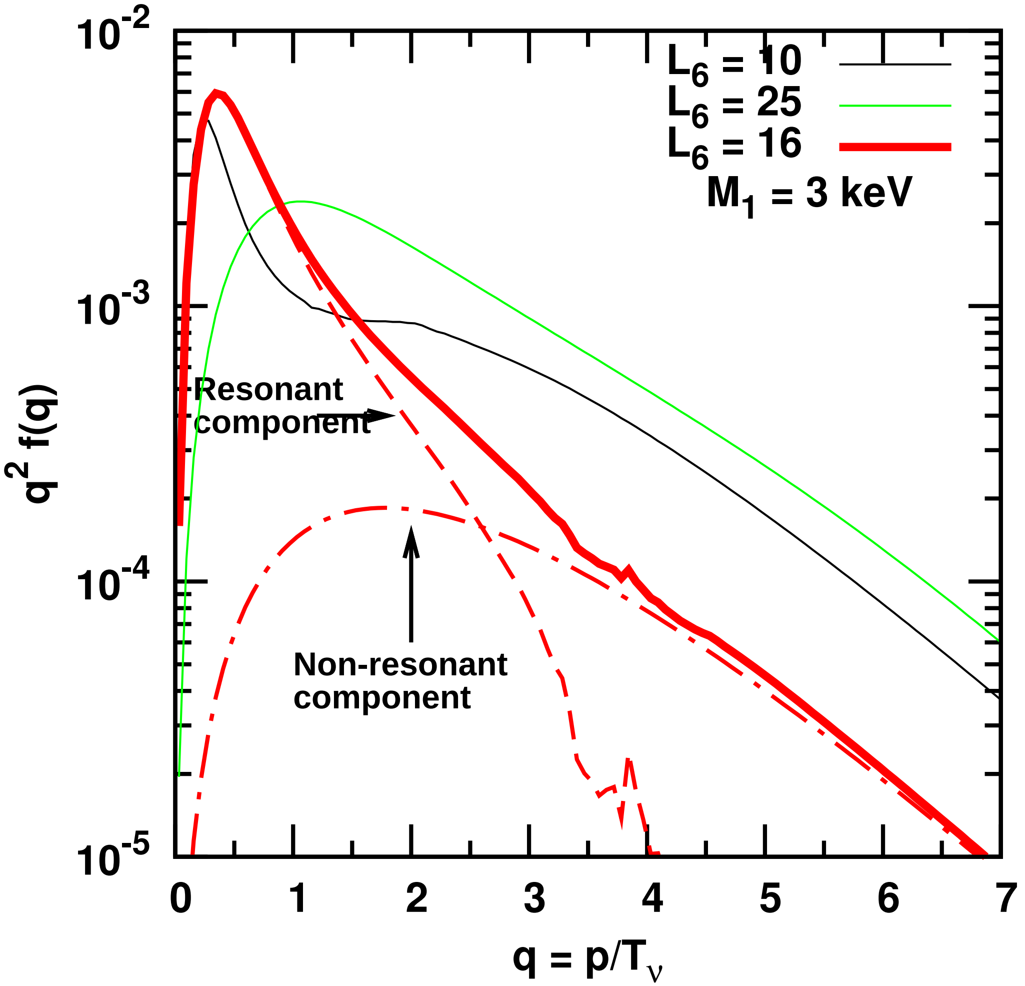
- The value of lepton asymmetry can be as large as

$$L_6 \equiv 10^6 \frac{n_{\nu_e} - n_{\bar\nu_e}}{s} \lesssim 700$$

(present BBN bound $L_6^{\text{BBN}} \lesssim 2500$)

Serpico, Raffelt'05

RP sterile neutrino spectra



Laine, Shaposhnikov'08; Boyarsky, **O.R.**, Shaposhnikov'09

Sterile neutrinos and structure formation

- Sterile neutrinos are ultra-relativistic at production

$$\lambda_{FS}^{co} = \int_0^t \frac{v(t')dt'}{a(t')}$$

- DM particles erase primordial spectrum of density perturbations on scales up to the DM particle horizon – **free-streaming length**

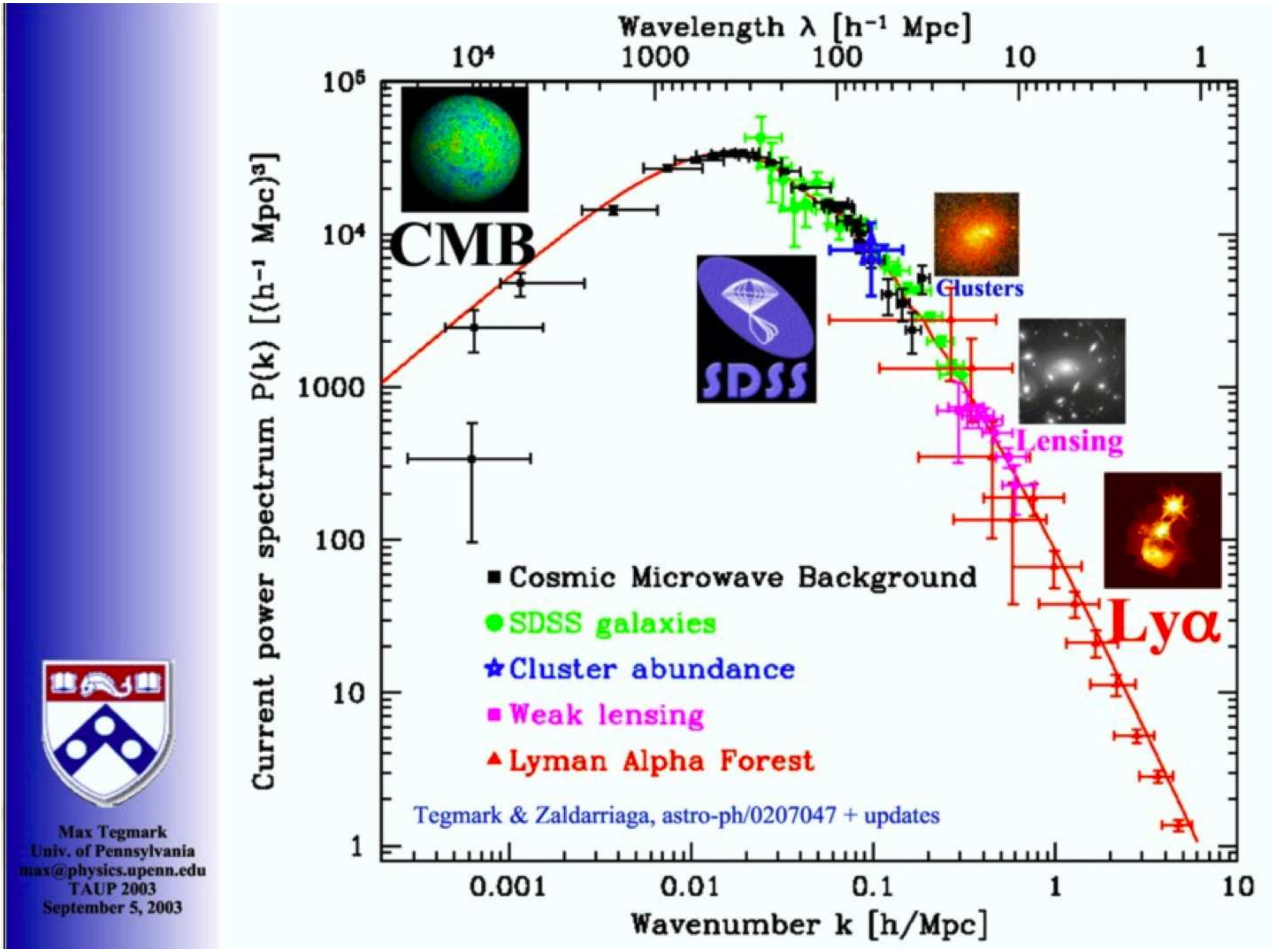
- Comoving free-streaming lengths peaks around $\boldsymbol{t_{nr}}$ when $\langle \boldsymbol{p} \rangle \sim \boldsymbol{m}$

- Free-streaming horizon determines suppression scale of power spectrum of density perturbations.

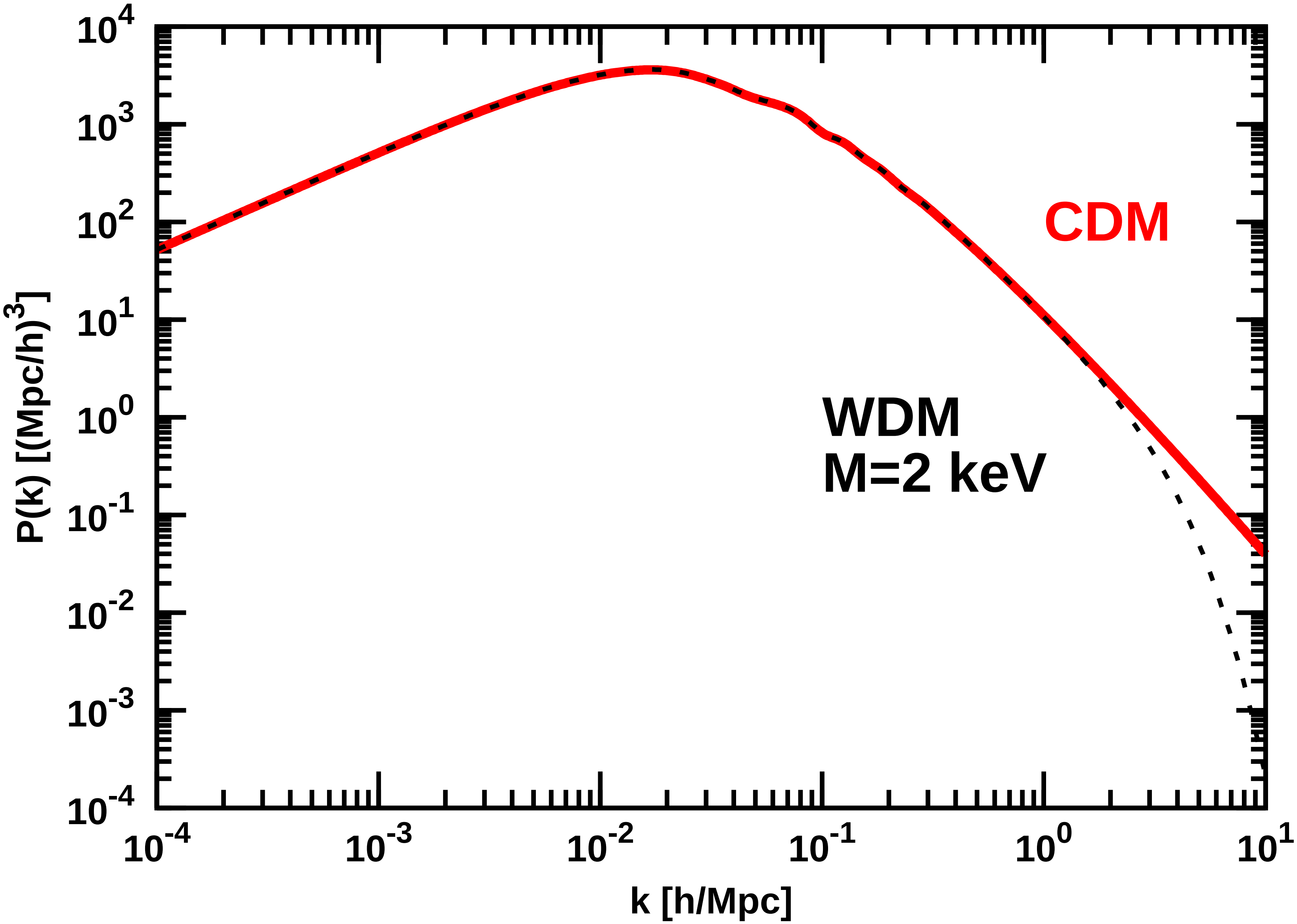
- An order of magnitude estimate for the free-streaming scale?

$$\lambda_{\text{FS}}^{co} \sim 1\,\text{Mpc}\left(\frac{\text{keV}}{M_s}\right)\frac{\langle p_s \rangle}{\langle p_\nu \rangle}$$

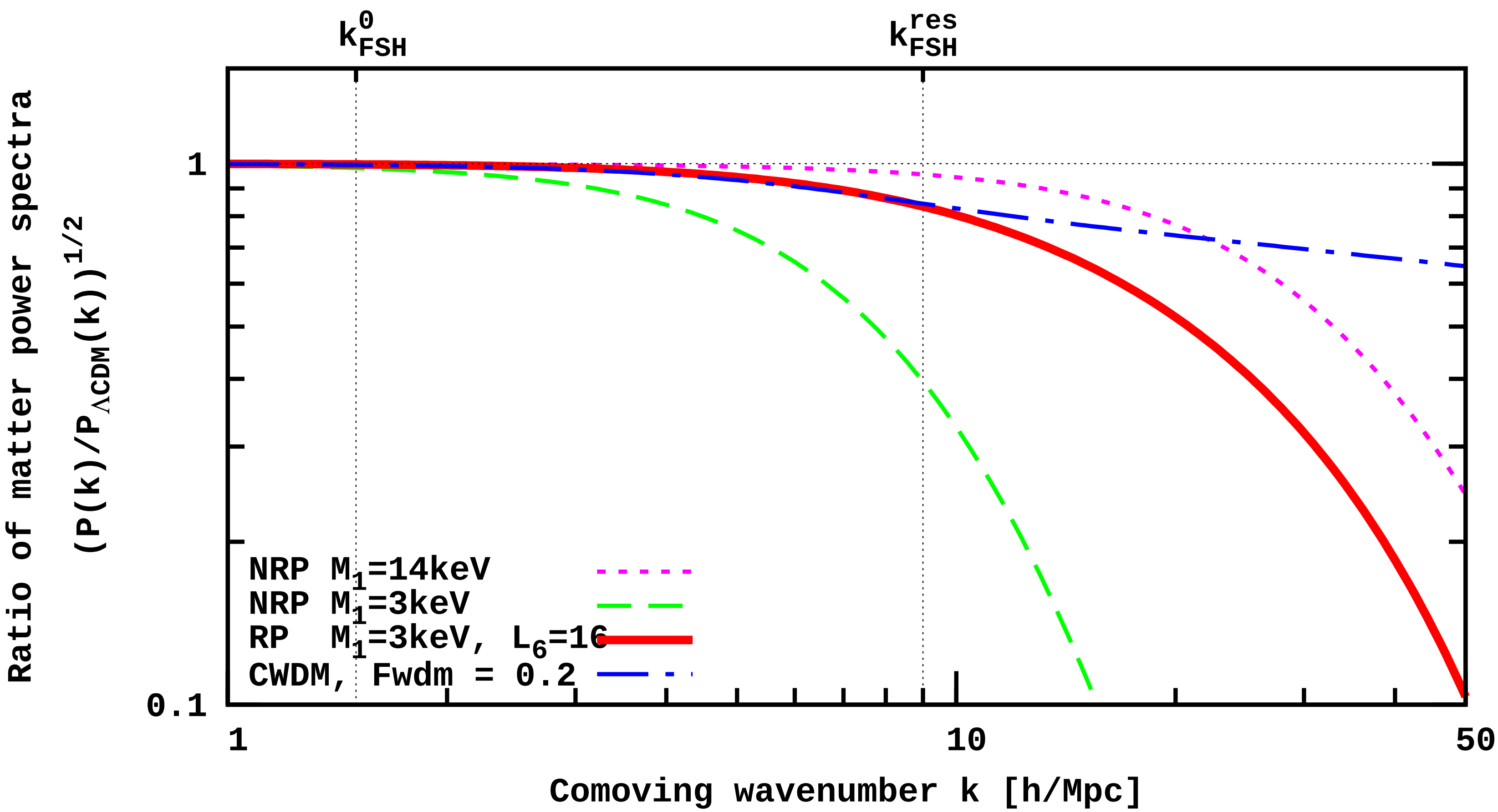
Power spectrum of density fluctuations



Influence of primordial velocities



Power spectrum for sterile neutrinos



Boyarsky, Lesgourgues, **O.R.**, Viel JCAP, PRL 2009;

Boyarsky, **O.R.**, Shaposhnikov Ann. Rev. Nucl. Part. Sci. 2009

Lyman-α forest and cosmic web

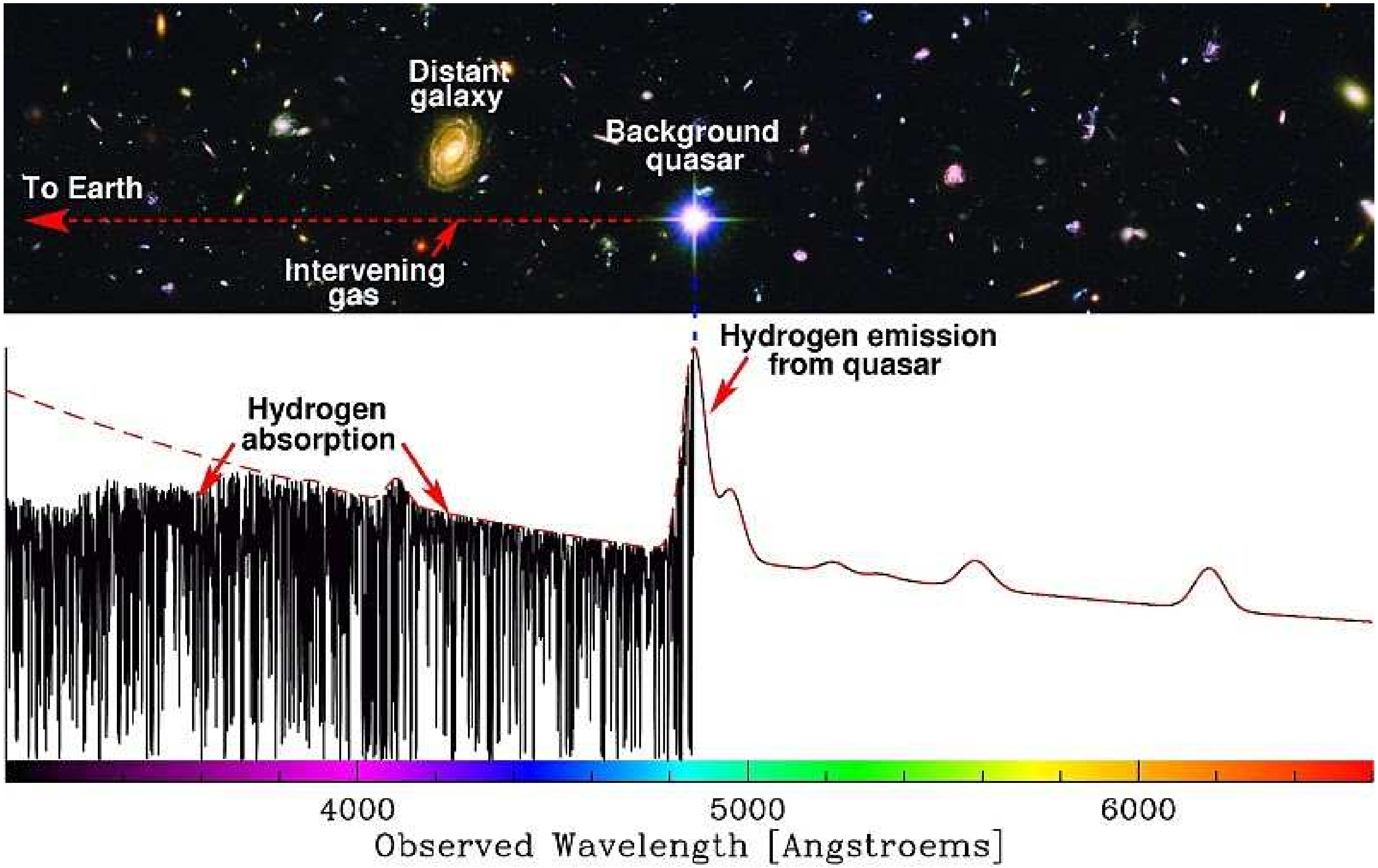


Image: Michael Murphy, Swinburne University of Technology, Melbourne, Australia

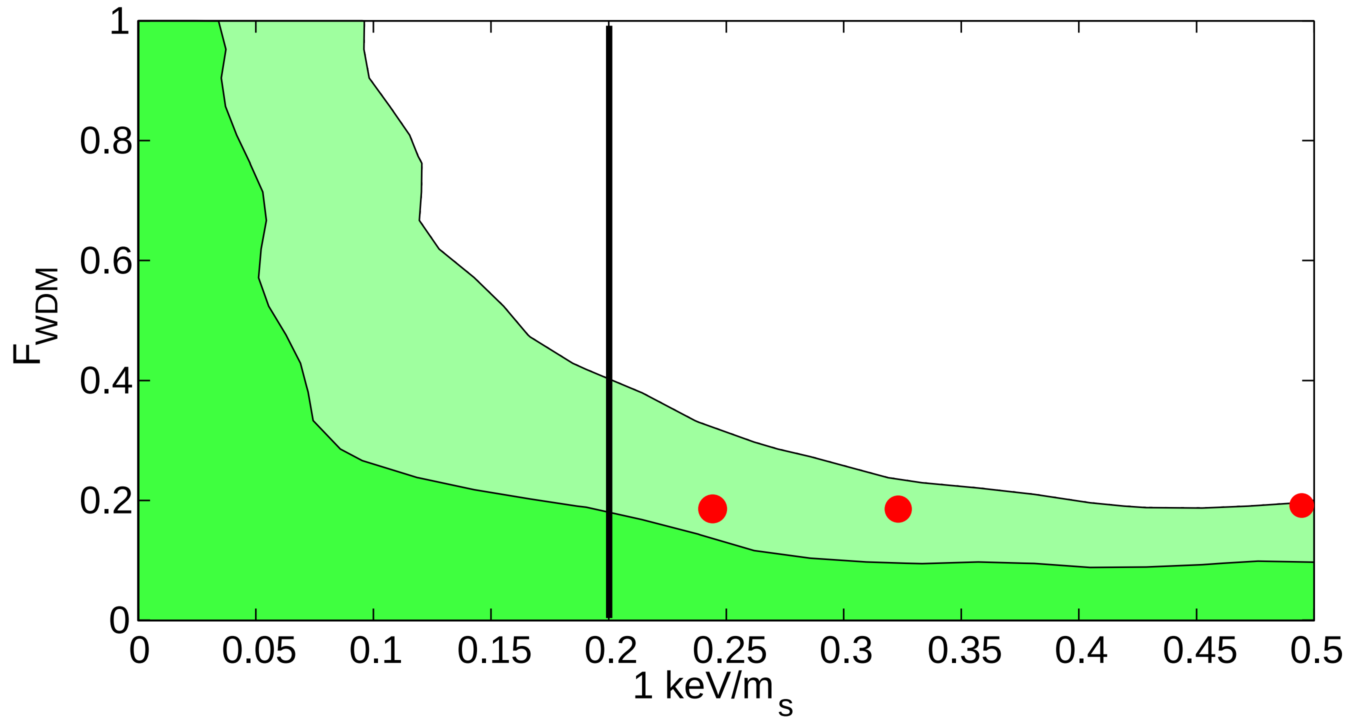
Neutral hydrogen in intergalactic medium is a tracer of overall matter density. Scales $0.3h/\text{Mpc} \lesssim k \lesssim 3h/\text{Mpc}$

The Lyman-α method includes

- Astronomical data analysis of quasar spectra
- Astrophysical modeling of hydrogen clouds
- N-body+hydrodynamical simulations of DM clustering at non-linear stage
- Simultaneous fit of cosmological parameters ($\Omega_b, \Omega_M, n_s, h, \sigma_8 \ldots$) . Astrophysical parameters, describing IGM, are not known and should be fitted as well (another $20+$ parameters)
- The data: Lyman-$\alpha+$ CMB $+$ maybe LSS $\ldots$ (thousands of data points, sometimes correlated)

Main challenge: reliable estimate of systematic uncertainties

Lyman-α bounds on CDM+WDM mixture



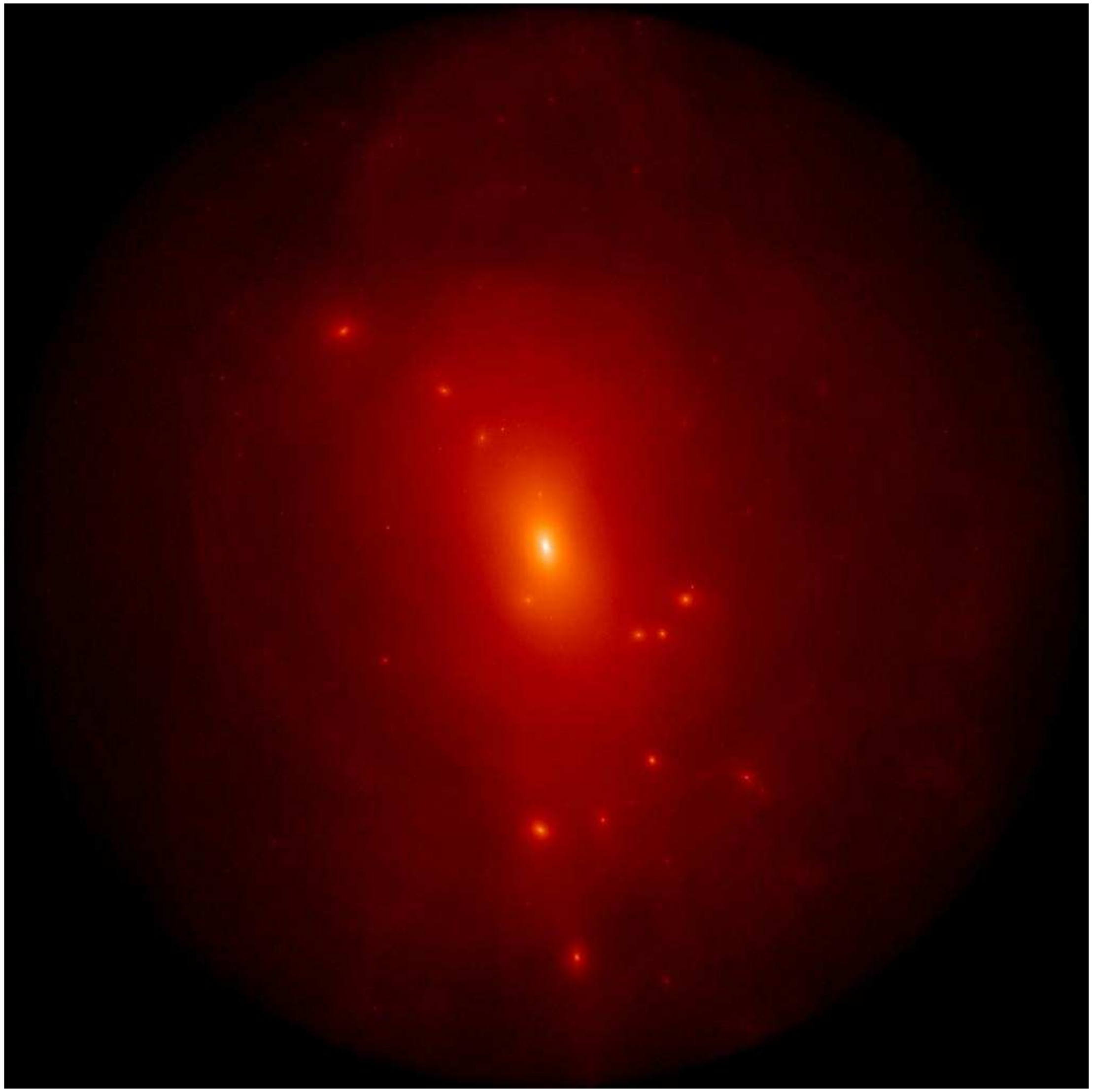
JCAP'09; PRL'09

$$F_{\text{WDM}} = \frac{\Omega_{\text{WDM}}}{\Omega_{\text{WDM}} + \Omega_{\text{CDM}}}$$

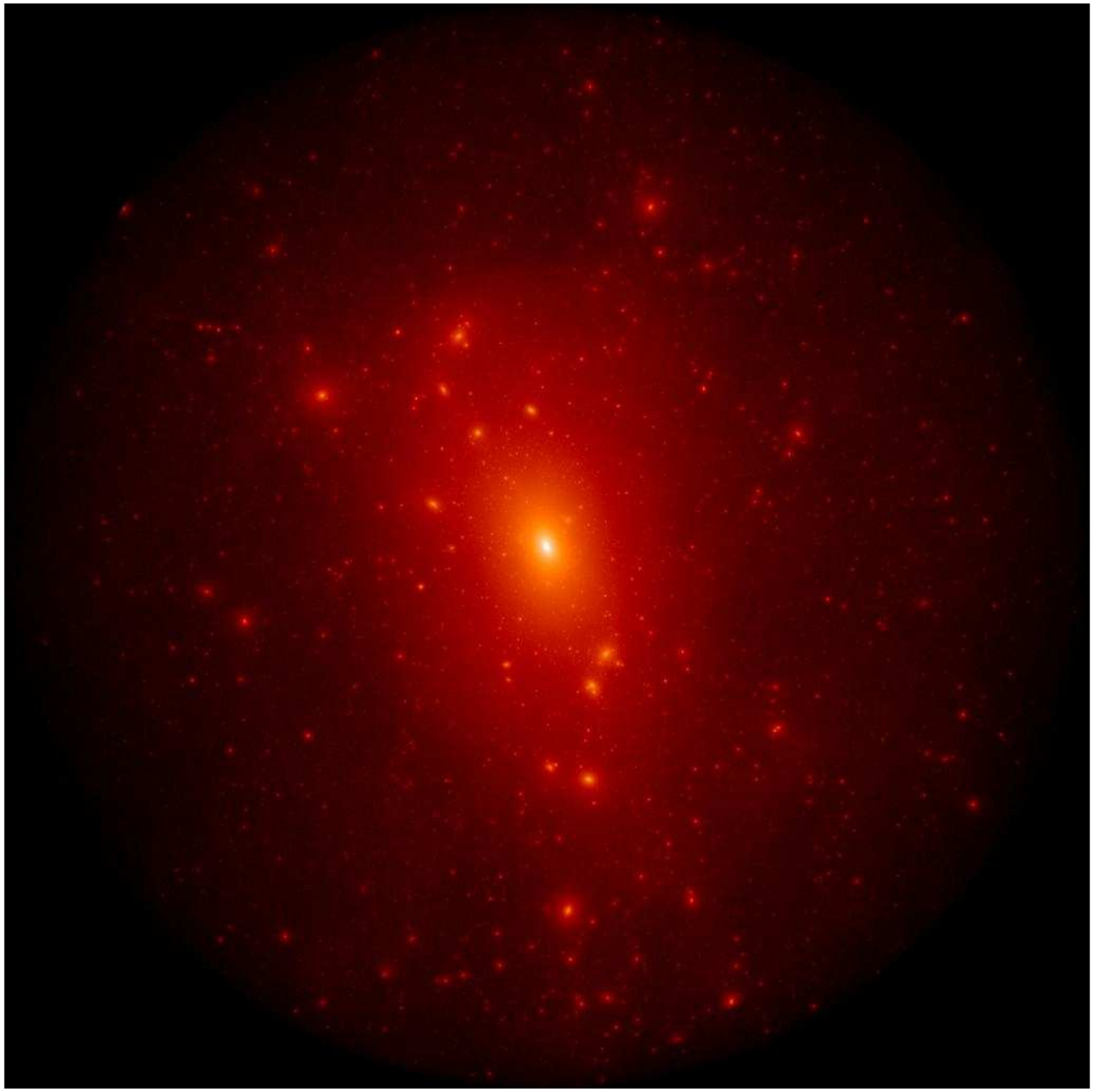
Lyman-α allows to restrict the shape of primordial velocity spectrum, rather than free-streaming (for example, a fraction of warm DM (F_{WDM}) for given mass)

Halo substructure with sterile neutrino DM

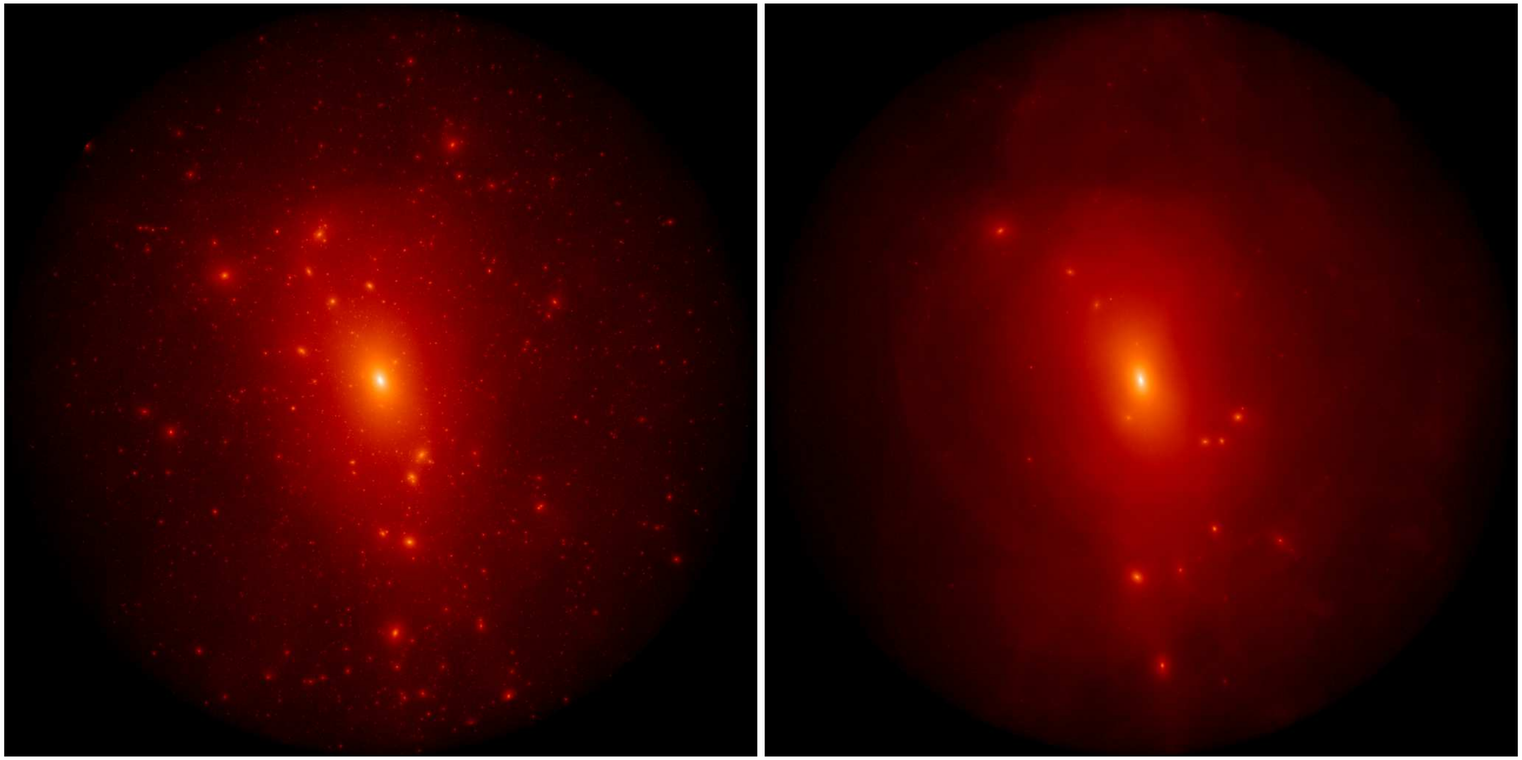
work in progress



Halo substructure with CDM



Halo substructure with sterile neutrino DM



PRELIMINARY: ***Aq-A-2 halo*** in CDM and CDM+WDM simulations (Gao, Theuns, Frenk, **O.R.**, . . .)

- Simulated CWDM model (right) is fully compatible with the Lyman-α forest data but provides a structure of Milky way-size halo different from CDM (left)

Lifetime of sterile neutrino DM candidate

- Dominant decay channel for sterile neutrino (for $M_s < 1$ MeV) is $N \to 3\nu$.

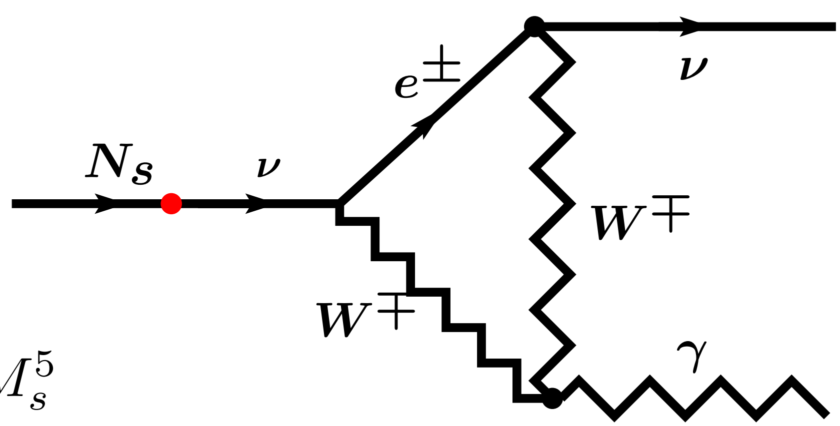
Wolfenshtein Pal (1982)

- Life-time $\tau = 5 \times 10^{26}\text{sec} \times \left(\frac{\text{keV}}{M_s}\right)^5 \left(\frac{10^{-8}}{\theta^2}\right)^2$

Barger Phillips Sarkar (1995)

- Subdominant **radiative decay channel**
  - Photon energy: $E_\gamma = \frac{M_s}{2}$
  - Radiative decay width:

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



Dolgov Hansen (2000

Abazajian Fuller Tucker (2001)

- Sterile neutrino DM **is not completely dark**. Its decay signal can be searched for in the spectra of astrophysical objects.

Boyarsky, **O.R** et al. (2006-2009)

A DM column density

- Flux from DM decay:

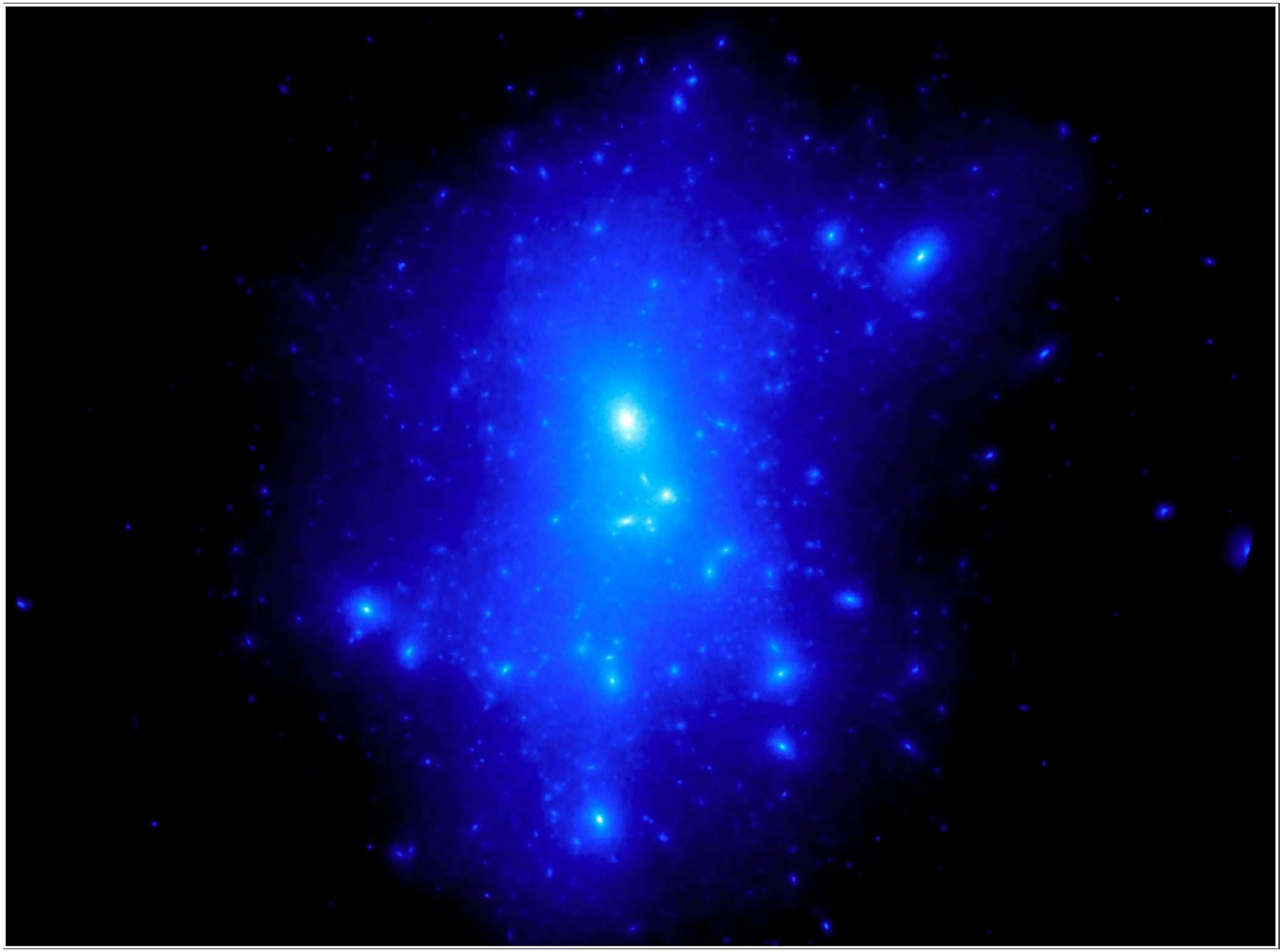
$$F_{\text{DM}} = \Gamma_{\text{rad}} \frac{E_\gamma}{M_s} \int\limits_{\text{fov cone}} \frac{\rho_{\text{DM}}(\vec{r})}{4\pi|\vec{D}_L + \vec{r}|^2} d^3\vec{r} \approx \frac{\Gamma_{\text{rad}}\Omega_{\text{fov}}}{8\pi} \mathcal{S}$$

- **DM column density**

$$\mathcal{S} = \int\limits_{\Omega_{\text{fov}}} \rho_{\text{DM}}(r) dr$$

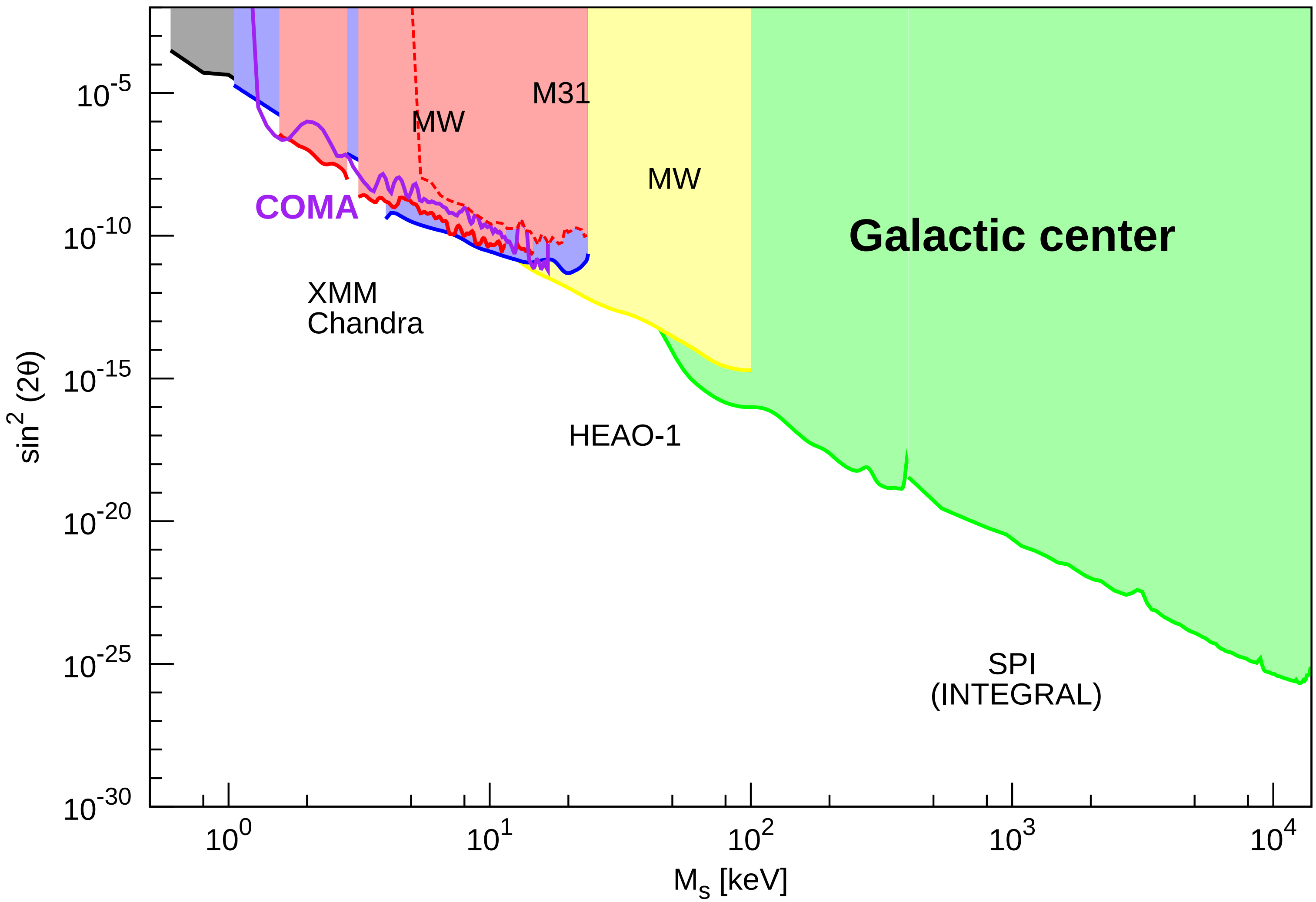
– integral along the line-of-sight, averaged within the instrument's field-of-view

Decay signal from MW-sized galaxy



Simulations: B.Moore et al. 2005

Bounds on decaying DM from varios objects



MW (HEAO-1) Boyarsky, **O.R.** et al. 2005

Coma and Virgo clusters Boyarsky, **O.R.** et al.

Bullet cluster Boyarsky, **O.R.** et al. 2006

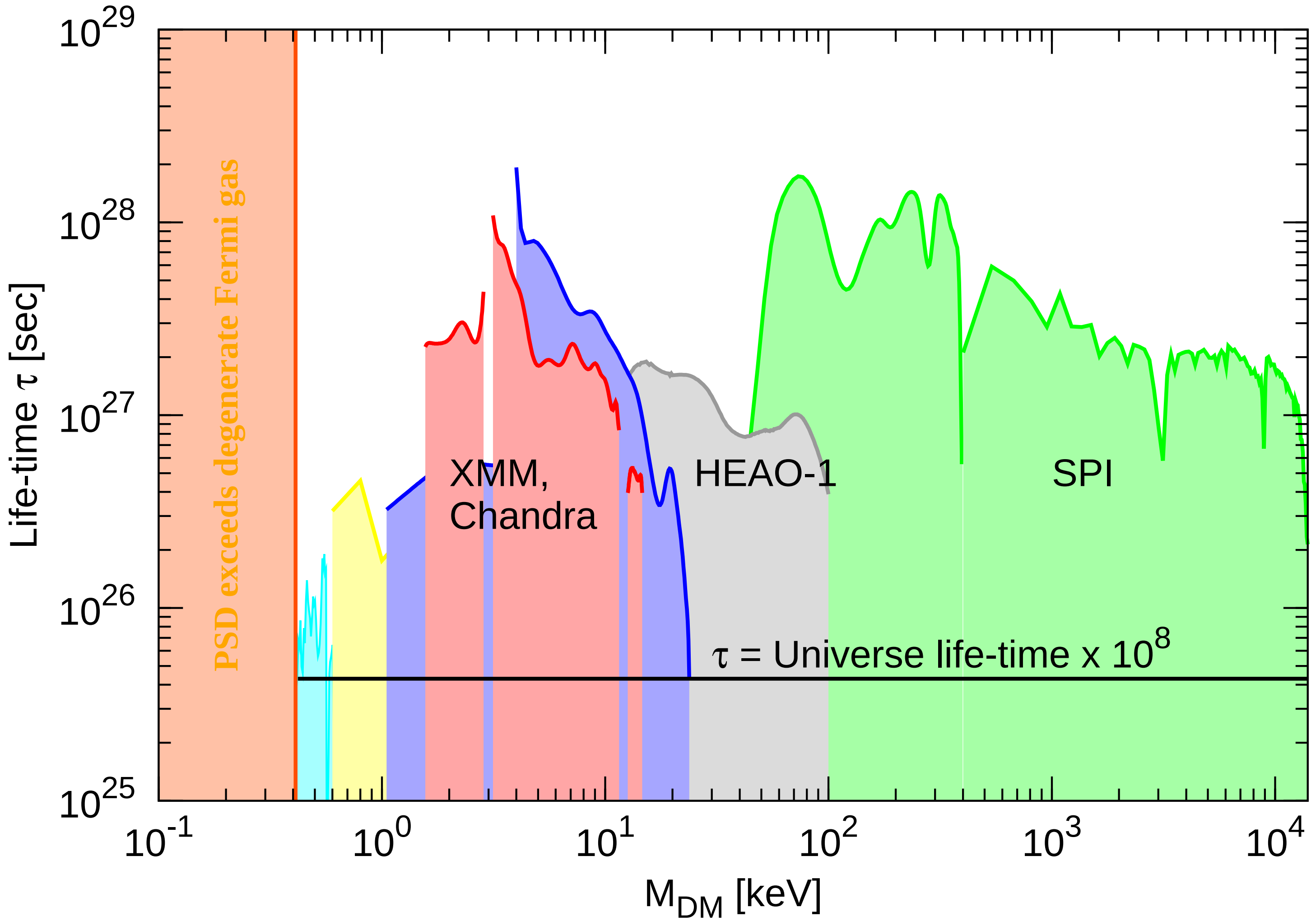
LMC+MW(XMM) Boyarsky, **O.R.** et al. 2006

MW Riemer-Sørensen et al.; Abazajian et al.

MW (XMM) Boyarsky, **O.R.** et al. 2007

M31 Watson et al. 2006; Boyarsky et al. 2007

Restrictions on life-time of decaying DM



XRB **HEAO-1** 2005;

Bullet cluster **Chandra** 2006;

LMC **XMM**

MW **XMM** 2006-2007

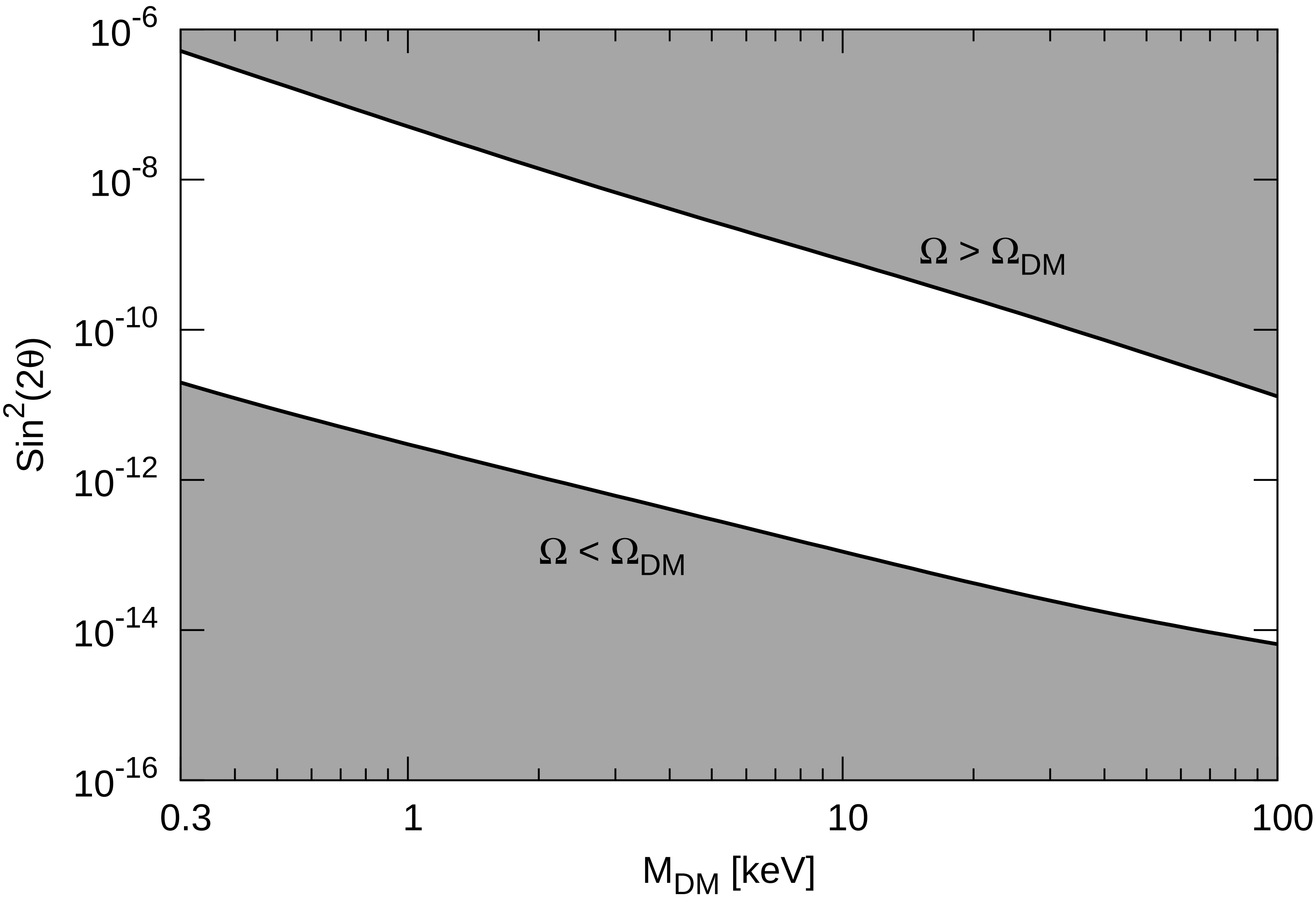
MW **Chandra** **M31** 2006-2007

dSps, **Suzaku, Chandra, XMM** 2006,2008-2010.

Results of almost **20** published works.

Window of parameters of sterile neutrino DM

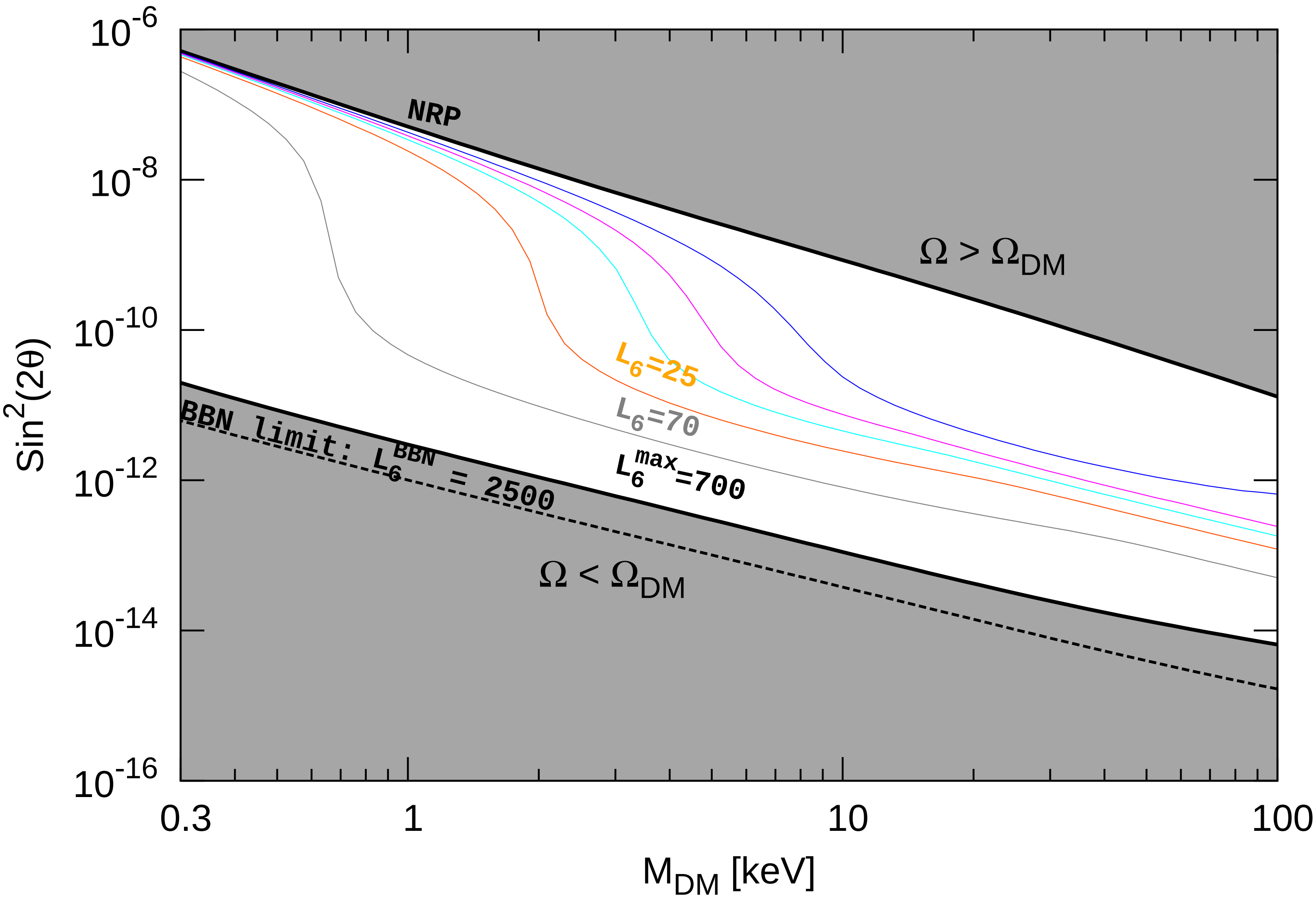
Laine, Shaposhnikov



Window of parameters of sterile neutrino DM

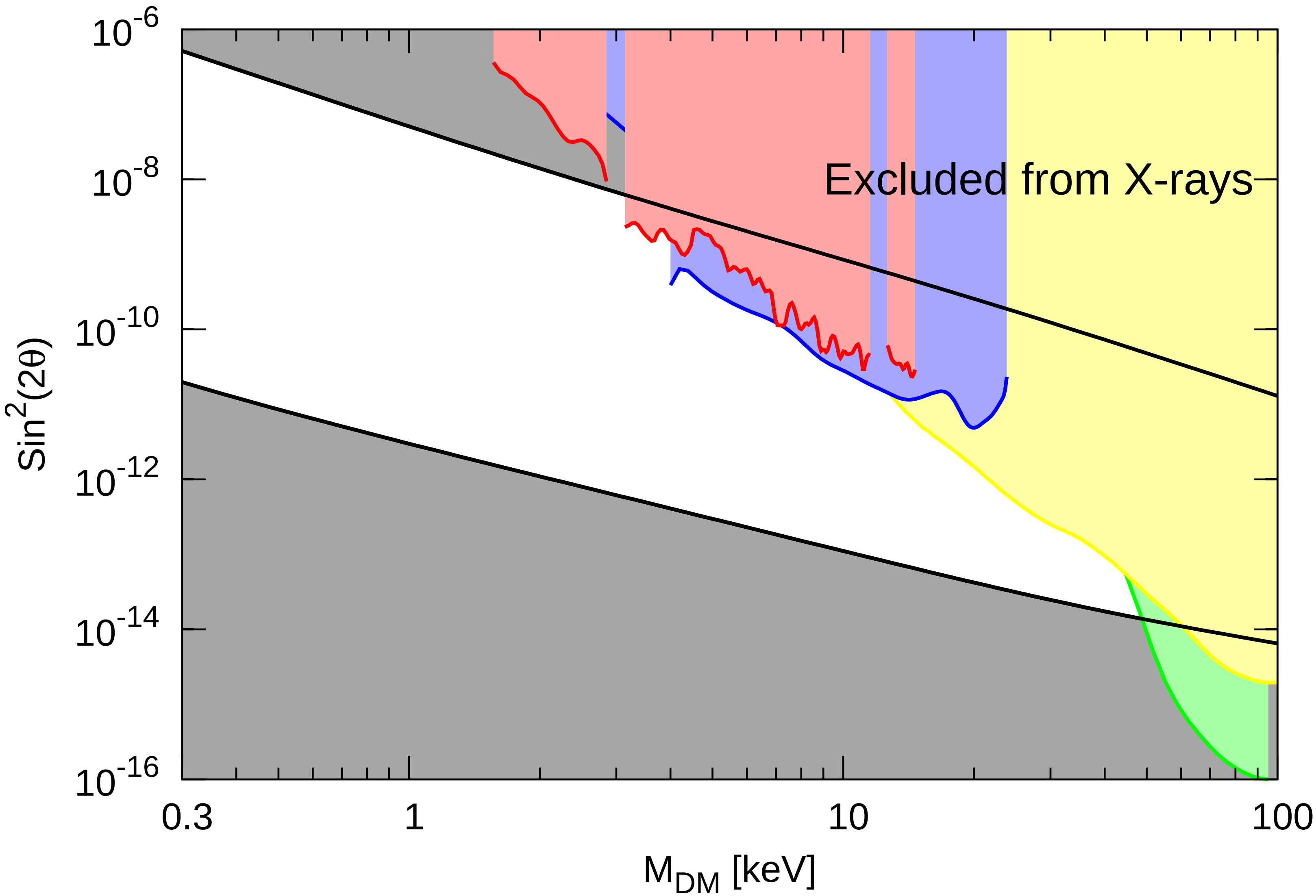
Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov



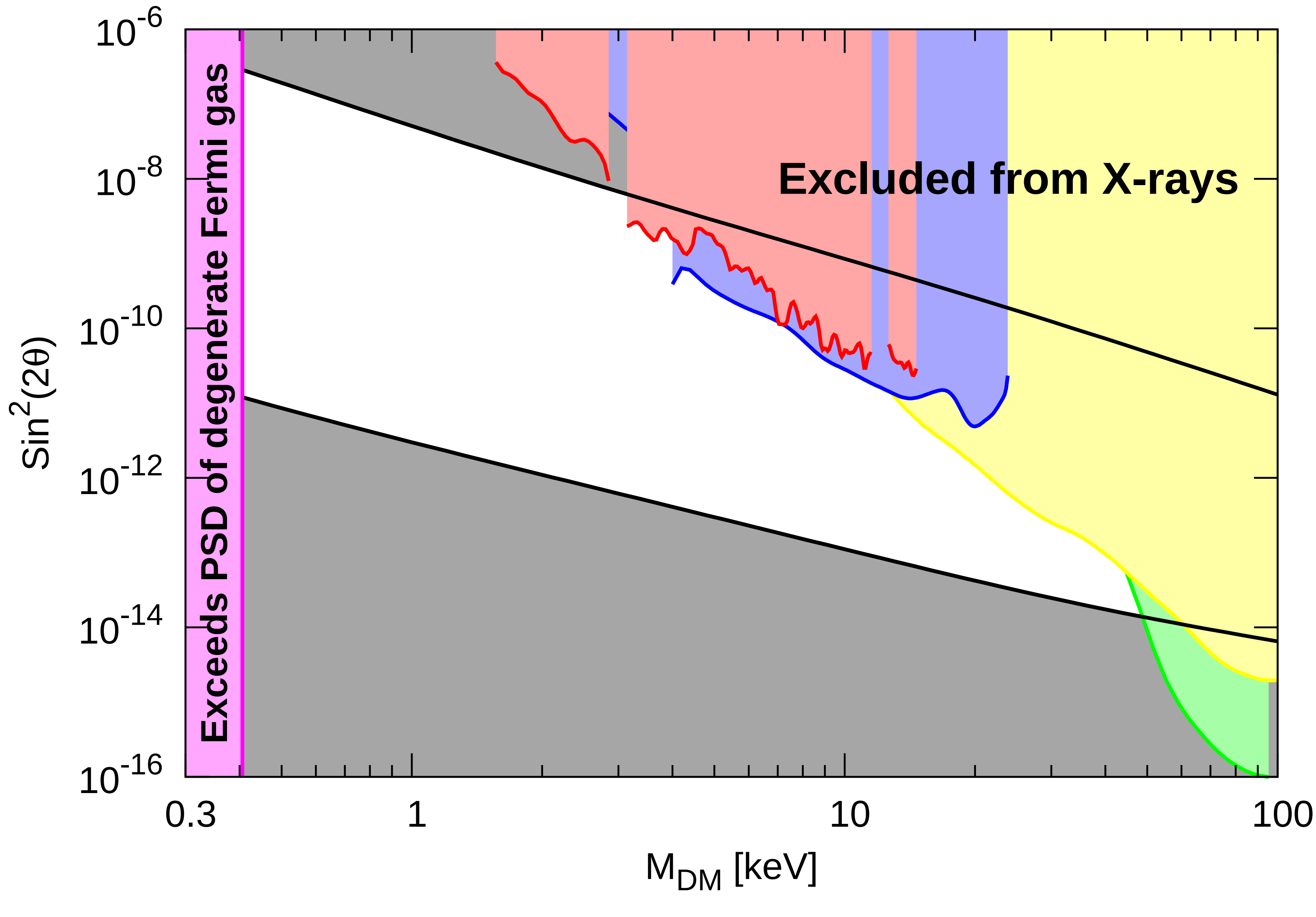
Window of parameters of sterile neutrino DM

Boyarsky, **O.R** et al. 2005-2008

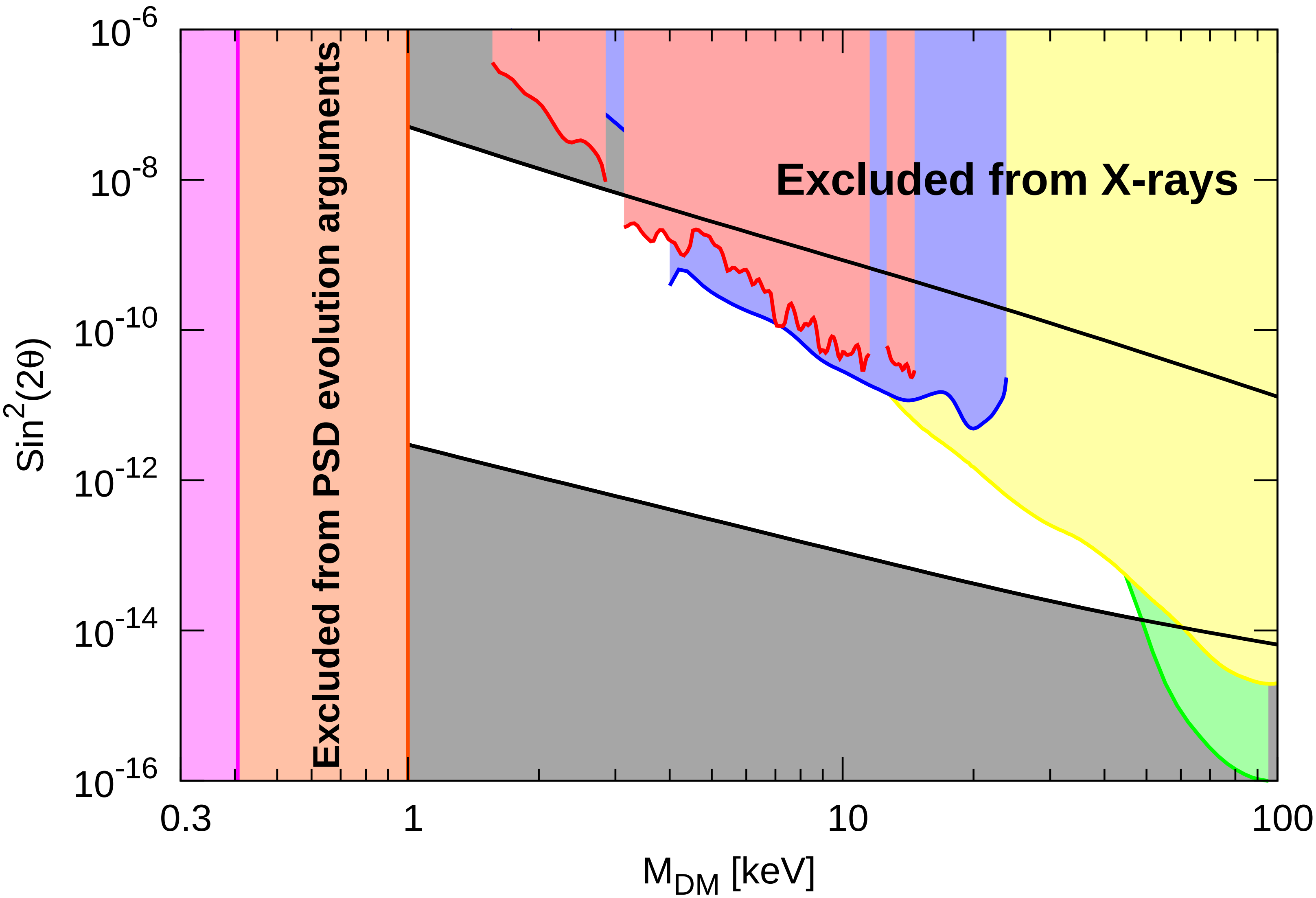


Window of parameters of sterile neutrino DM

Boyarsky, Ruchayskiy et al. 2005-2008



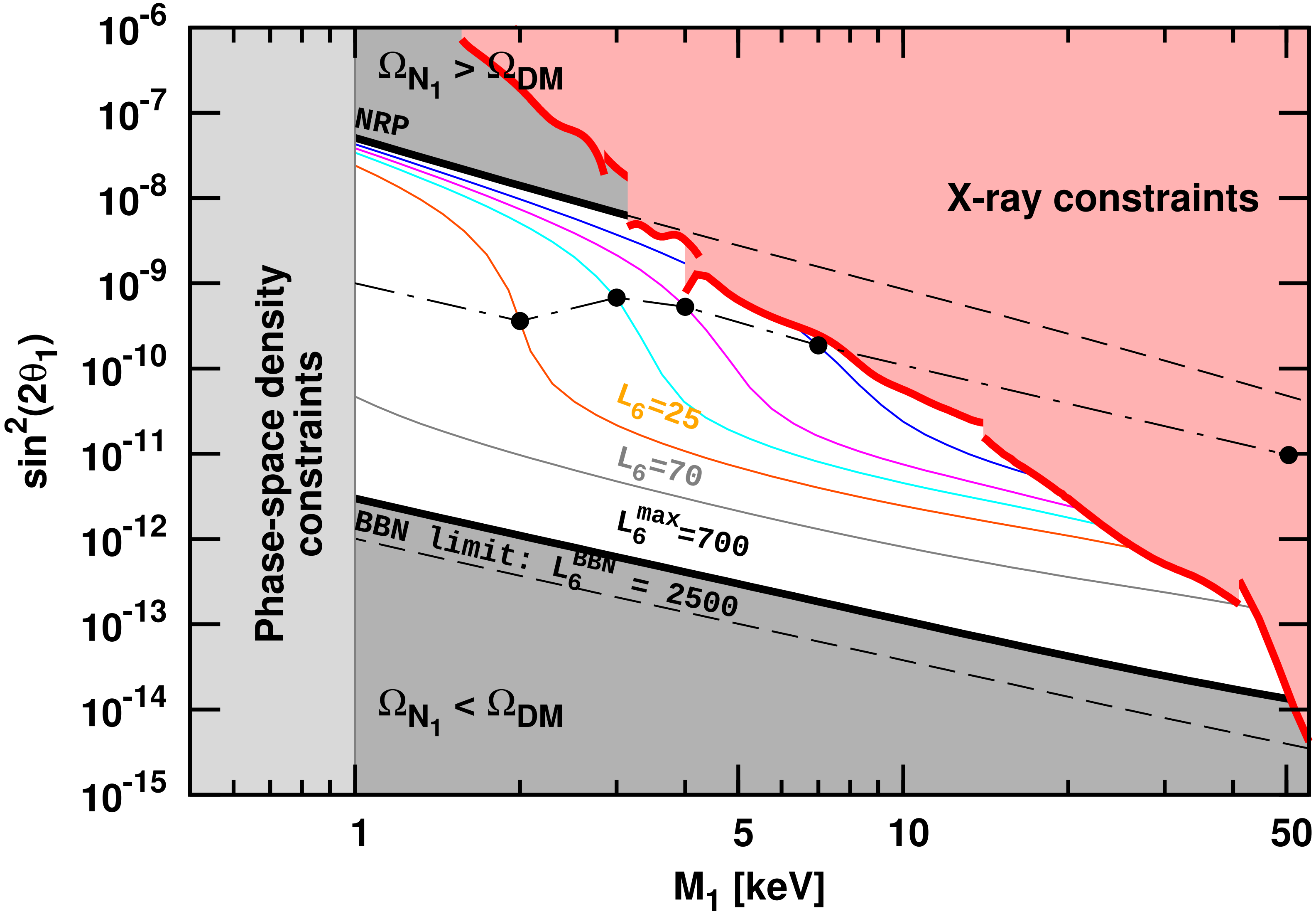
Window of parameters of sterile neutrino DM



Boyarsky, Ruchayskiy et al. 2005-2008

Boyarsky, O.R., Iakubovskyi,**20**

Sterile neutrino DM in the νMSM



Boyarsky, **O.R.**, Lesgourgues, Viel [0812.3256]

Boyarsky, **O.R.**, Shaposhnikov [0901.0011]

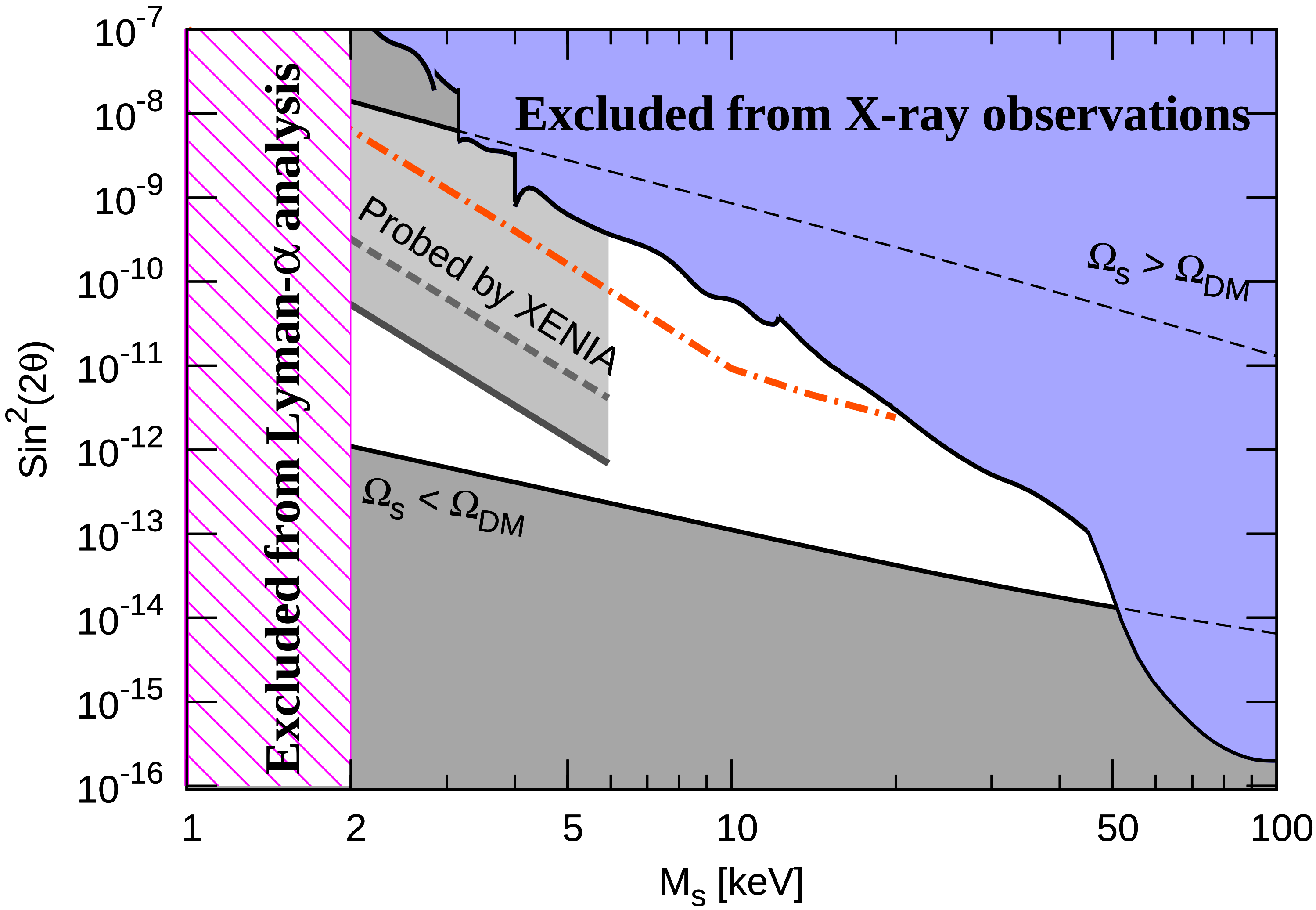
Astrophysical searches for decaying DM

- Sterile neutrino DM candidates are hard to search in labs

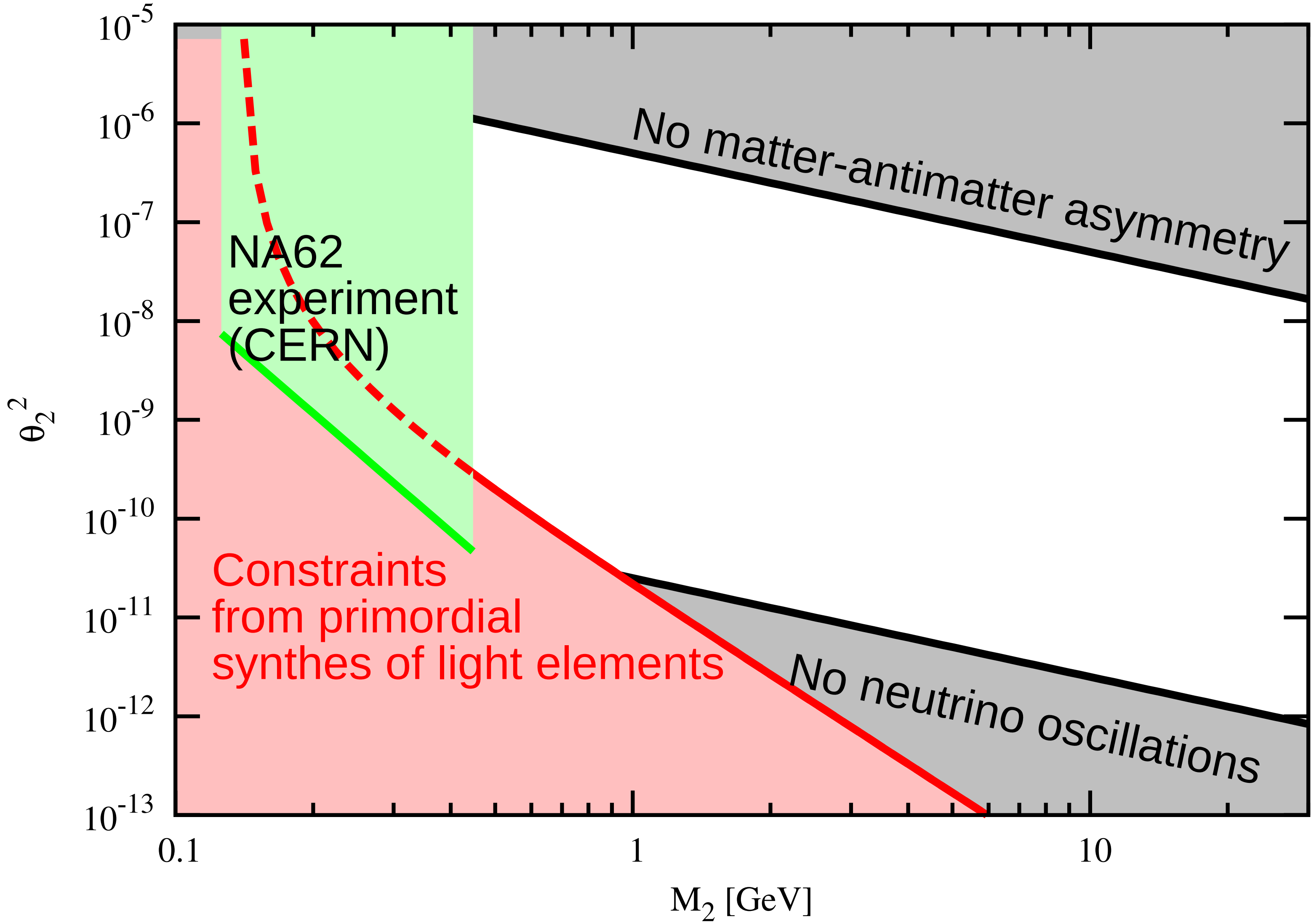
Bezrukov, Shaposhnikov

- The decaying dark matter is a unique all-sky signal, with variations, correlated with the distribution of galaxies/galaxy clusters
- If any candidate decay line is found, the distribution of its intensity over the sky can be predicted and checked against observations.
- This makes the search for decaying dark matter a **direct detection experiment**
- New instruments (EDGE/XENIA) – White paper for ESA's call for Fundamental physics roadmap

Improved bounds on DM decay

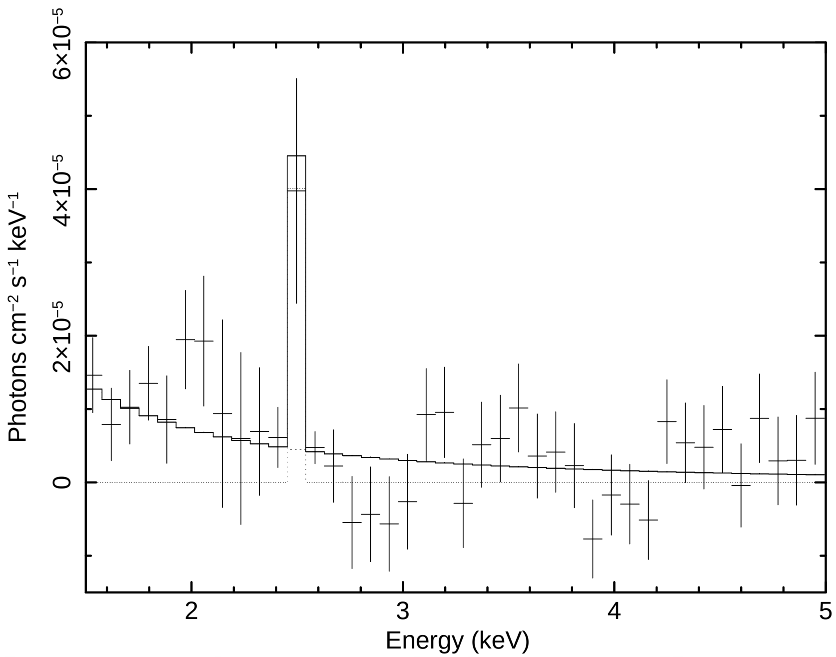


Probing other sterile neutrinos

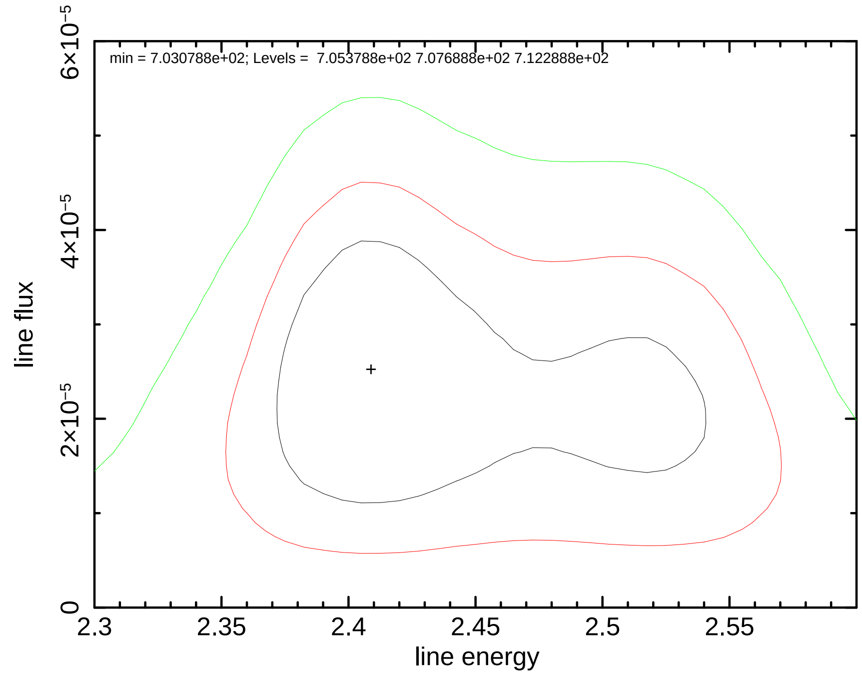


Main conclusion: sterile neutrino remains viable dark matter candidate

Example: Spectral feature in Willman 1



[Loewenstein & Kusenko [0912.0552]]



68%, 90% and 99% confidence intervals

Checking for DM line in dSphs

- $E_{\text{line}} = (2.51 \pm 0.07)$ **keV**

  2.44 keV – 2.58 keV (1σ)
  2.30 keV – 2.72 keV (3σ)

- **Line flux** $F_{\text{Wil 1}} = (3.53 \pm 1.95) \times 10^{-7}$ **photons/cm^2/sec** (68% CL)

- No significant lines were found in spectra of dSphs

- We obtain the following exclusions

	$2.44 - 2.58$ keV	$2.30 - 2.72$ keV
Fornax dSph:	5.1σ	3.3σ
Sculptor dSph:	3.0σ	2.5σ
Fornax + Sculptor	5.9σ	4.1σ

- In case of the DM decay origin of the line we were expecting about 4σ detection from Fornax. However adding the line makes fit worse.

Checking for DM line in M31

Exclusion from Fornax + Sculptor dSph:	$2.44 - 2.58$ keV	$2.30 - 2.72$ keV
	5.9σ	4.1σ

Andromeda galaxy

- Diffuse spectrum above 2 keV is a featureless power law

MNRAS'08 [0709.2301]

	$2.44 - 2.58$ keV	$2.30 - 2.72$ keV
M31, 1kpc $< R <$ 3kpc:	22.7σ	20.1σ
M31, 5 kpc off-center: circle radius 3 kpc	10.4σ	10.4σ
M31, both regions	24.9σ	23.3σ

1001.0644

- Extremely significant exclusion from central 8 kpc of Andromeda!
- All bounds are based on the conservative DM estimate from **[Widrow & Dubinski'05]**!

Checking for DM line in M31

- Exclusion from Fornax and Sculptor dSphs:

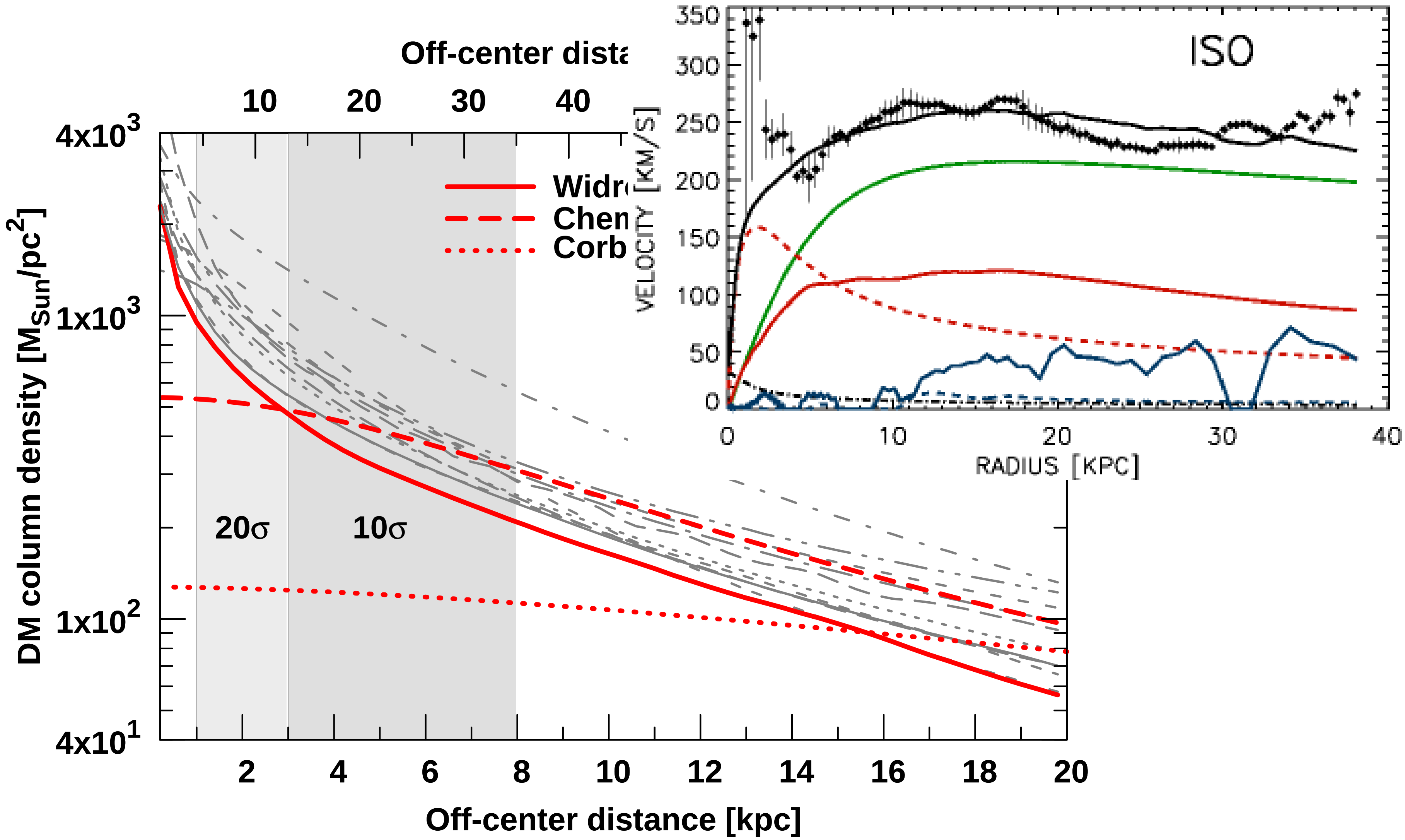
$2.44-2.58$ keV	$2.30-2.72$ keV
5.9σ	4.1σ

- Exclusion from **central 8 kpc of Andromeda**:

$2.44-2.58$ keV	$2.30-2.72$ keV	DM model
24.9σ	23.3σ	**[Widrow & Dubinski'05]**
7.9σ	6.9σ	**[Corbelli et al.'09]**

1001.0644

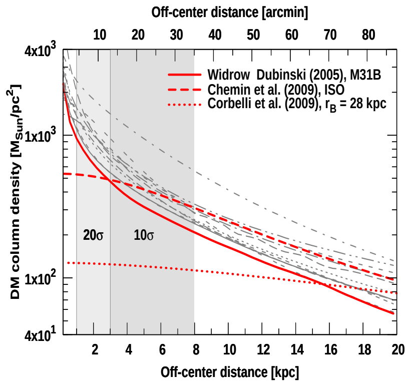
Checking for DM line in M31



In the final version of the paper we processed observations in the region $10-20$ kpc

1001.0644v2

Summary of exclusions



	"Consensus model" (Widrow & Dubinski, M31B)		Minimal DM amount (Corbelli et al., Burkert profile, $r_B = 28$ kpc, $M/L = 8$)	
	68%CL	99%CL	68%CL	99%CL
M31 within 8 central kpc	24.9σ	23.3σ	7.9σ	6.9σ
M31 10–20 kpc off-center	12.0σ	10.7σ	11.7σ	10.6σ
All M31 obs.	28.2σ	26.2σ	13.6σ	13.2σ
All M31 + Fornax	29.0σ	26.7σ	15.2σ	14.0σ

68% CL: 2.44 keV – 2.58 keV

99%CL: 2.30 keV – 2.72 keV

- The DM origin of the spectral feature in Willman 1 at ~ 2.5 keV is **excluded with 14σ significance**!

Parameters of Aquarius simulation

Name	m_p $[M_\odot]$	ϵ [pc]	N_{hr}	N_{lr}	N_{50}
Aq-A-1	1.712×10^3	20.5	4,252,607,000	144,979,154	1,473,568,512
Aq-A-2	1.370×10^4	65.8	531,570,000	75,296,170	184,243,536
Aq-A-3	4.911×10^4	120.5	148,285,000	20,035,279	51,391,468

Basic parameters of the Aquarius simulations. m_p is the particle mass, ϵ is the gravitational softening length, N_{hr} is the number of high resolution particles, and N_{lr} the number of low resolution particles filling the rest of the volume. $M_{200} = 1.839 \times 10^{12} M_\odot$ is the virial mass of the halo, defined as the mass enclosed in a sphere with mean density 200 times the critical value. $r_{200} = 245$ kpc gives the corresponding virial radius. $M_{50} = 2.524 \times 10^{12} M_\odot$. Finally, N_{50} gives the number of simulation particles within $r_{50} = 433$ kpc.

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