Sterile neutrino in astrophysics and cosmology

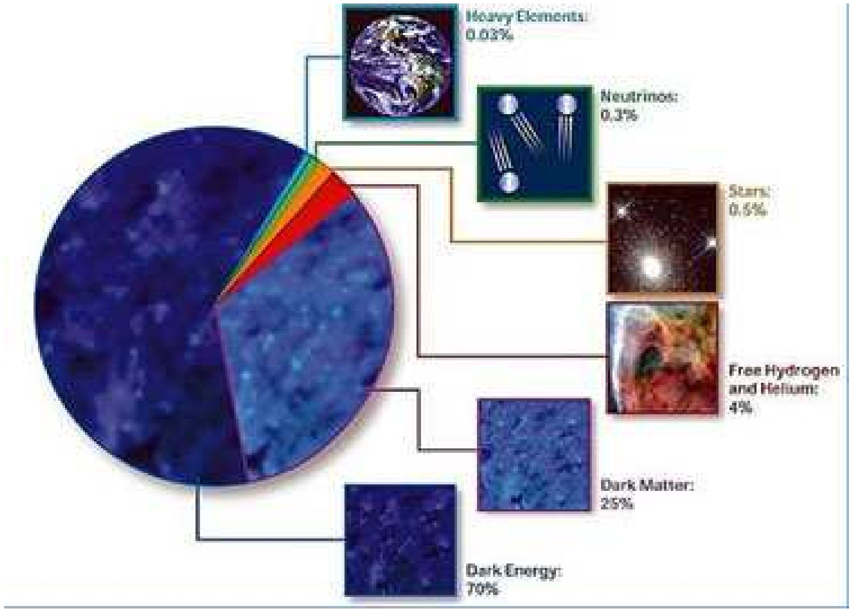
Oleg Ruchayskiy

TH Retreat. November 4, 2010

See Ann. Rev. Nucl. Part. Sci. **59** (2009) 191 for review

Why do we expect new physics?

- **The (minimal) Standard Model** (MSM) ***does not explain*** a number of important (experimentally observed) phenomena in particle physics, cosmology and astrophysics



- Minimal SM has a number of **fine-tuning problems** CP-problem, hierarchy problem, grand unification, cosmological constant problem

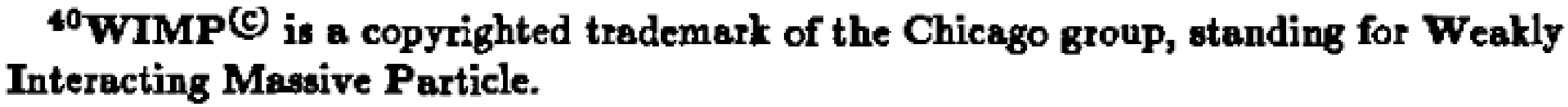
Why (and where) we expect new physics?

- **Neutrino oscillations** $m_\nu \sim \sqrt{\Delta m^2_{\rm atm}} \sim 10^{-2}$ eV.
  See-saw mechanism $m_\nu \sim v^2/\Lambda$, where $v = \langle H \rangle = 174$ GeV and **new scale** $\Lambda \sim 10^{15}$ GeV

- **Dark matter** (not a SM particle!)
  - particles with weak cross-section will have correct abundance $\Omega_{\rm DM}$ ("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.
  - **Example:** Out-of-equilibrium decay of heavy lepton χ at temperatures $M_{\rm EW} < T_{\rm decay} < M_\chi$ produces correct baryon-to-entropy ratio for $M_\chi > 10^{11}$ GeV – **new energy scale**

Example : WIMPs



[40] WIMP© is a copyrighted trademark of the Chicago group, standing for Weakly Interacting Massive Particle.

- Naturalness would require a new physics to appear around 100 GeV–10 TeV scale.
- This can lead to a DM particle: **WIMPs** – stable particles produced in *thermal freeze-out*: $\dot{n} + 3Hn = -\langle\sigma|v|\rangle(n^2 - n_{\text{eq}}^2)$
- Main properties of WIMPs:
  - Stable particles
  - Annihilate into ordinary matter (unitarity bound: annihilation cross-section is bounded $\sigma \lesssim \frac{1}{m_\chi^2}$)
  - mass : $\sim$ GeV $-$ TeV range
  - Decouple from plasma non-relativistic (“cold”)
- WIMPs can be searched in direct detection experiments (interaction of galactic WIMPs with laboratory nucleons).

Alternatives?

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

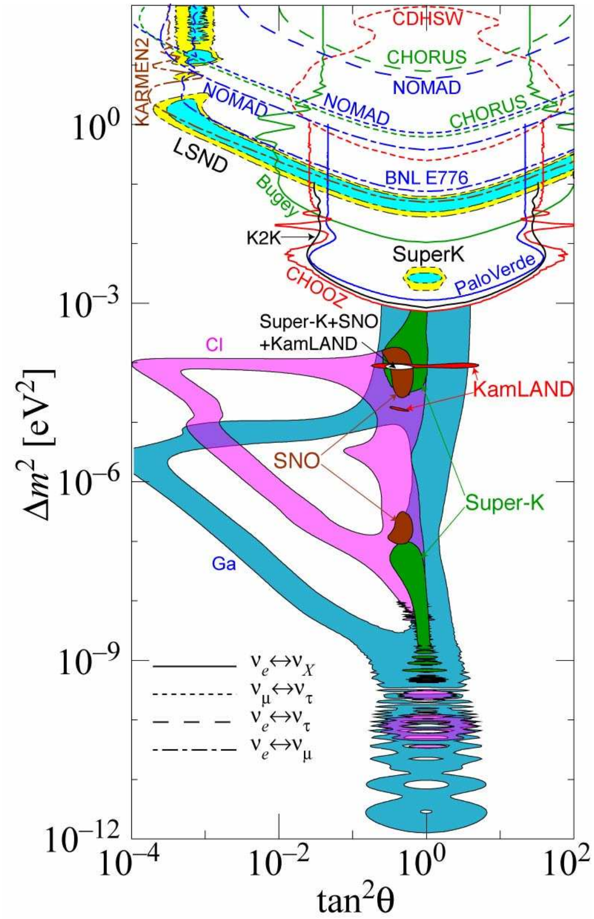
Worry about fine-tunings later

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.



http://hitoshi.berkeley.edu/neutrino

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.

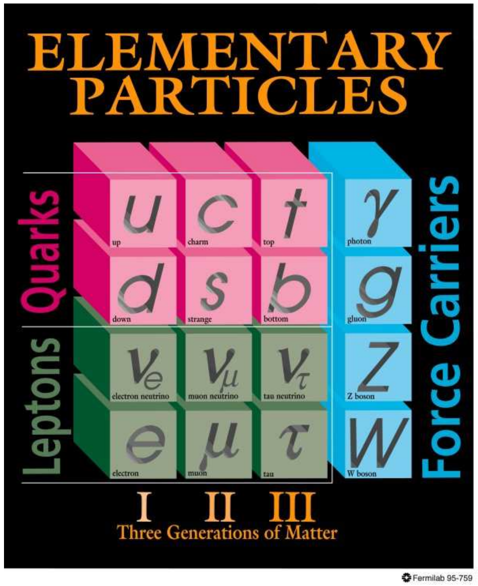
Scale of Dirac and Majorana masses is not fixed!

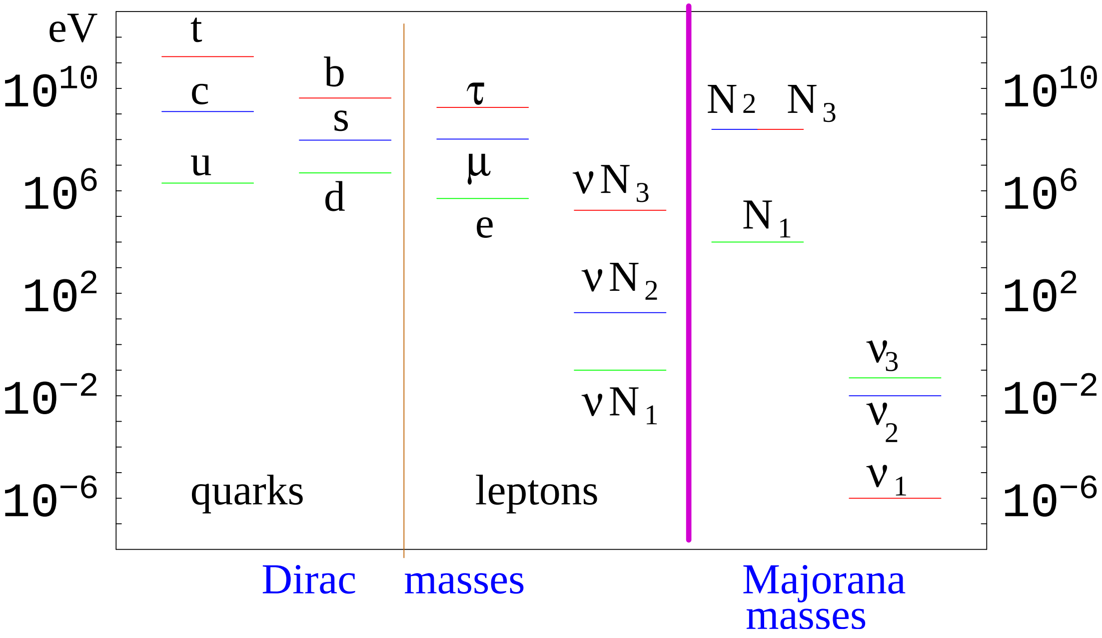
The scale of right-handed masses?

“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**
- ✓ The model allows for a **complete description** of the early Universe from reheating onward

Sterile neutrinos and early Universe

- Sterile neutrinos are **decaying particles**:
  $N_I \to \nu\nu\bar{\nu}$, $N_I \to \nu\gamma$, $N_I \to \nu e^+ e^-$, $N_I \to \pi^0\nu$
- 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:

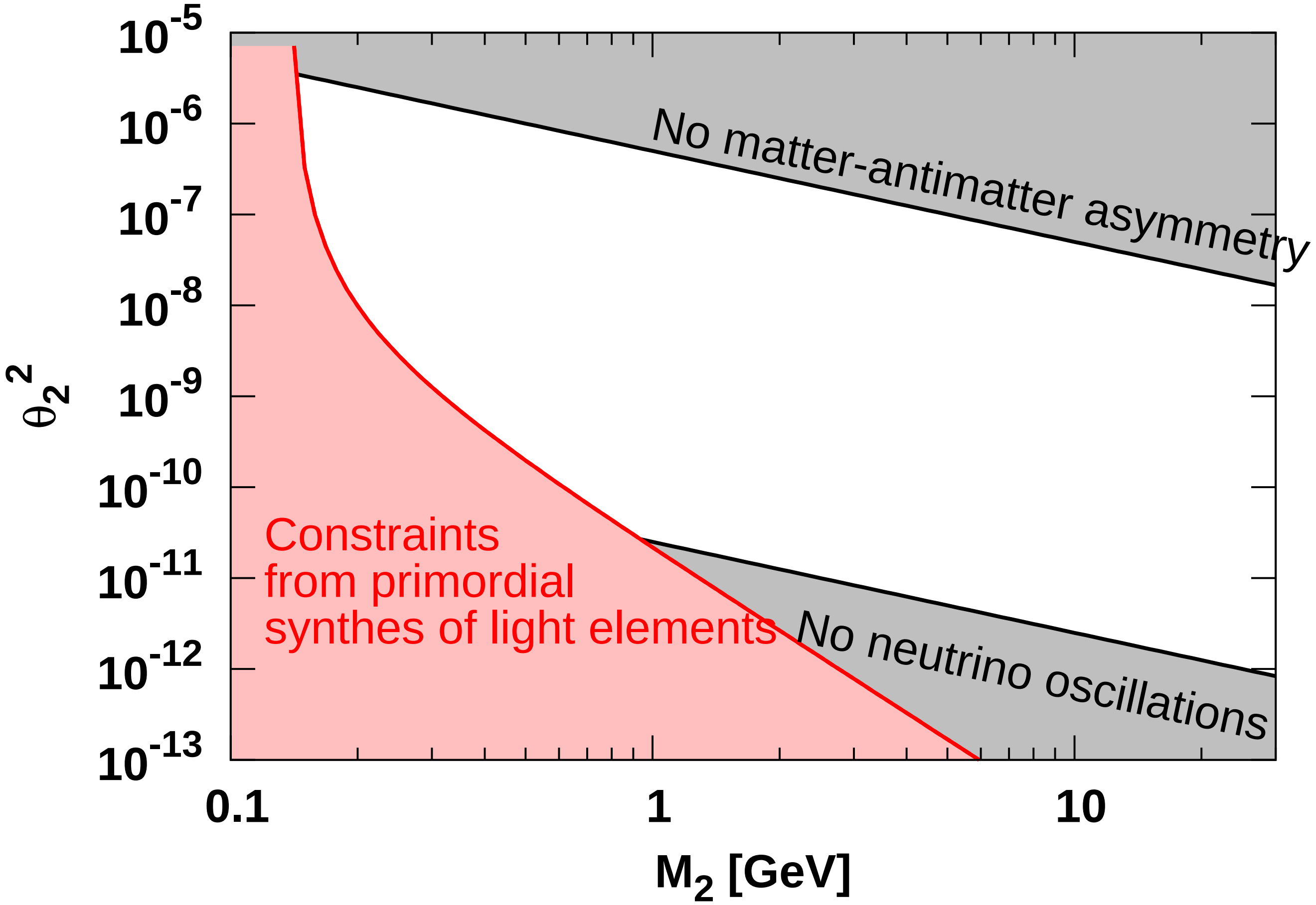
$$\theta_I^2 = \sum_{\alpha=e,\mu,\tau} \frac{|F_{\alpha I}|^2 v^2}{M_I^2} \ll 1$$

- Sterile neutrinos **can be out of equilibrium** in the early Universe

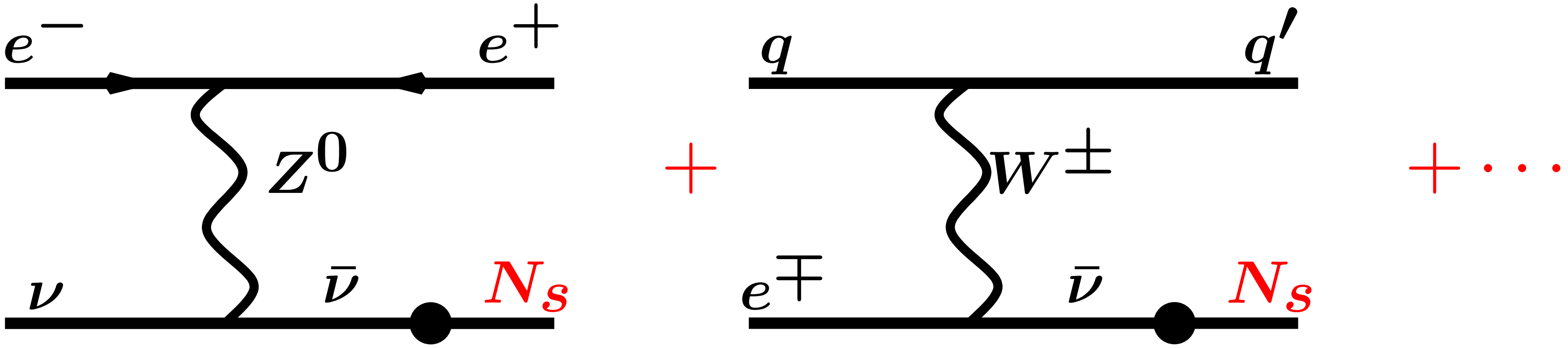
Choosing parameters of the νMSM

Two neutrinos with $\Delta M_{2,3} \ll M_{2,3}$ in the νMSM explains **baryon asymmetry** of the Universe. and neutrino flavour experiments.

Asaka, Shaposhnikov '05; Canetti, Shaposhnikov '10



Production through oscillations



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

- **Non-equilibrium spectrum of primordial velocities**

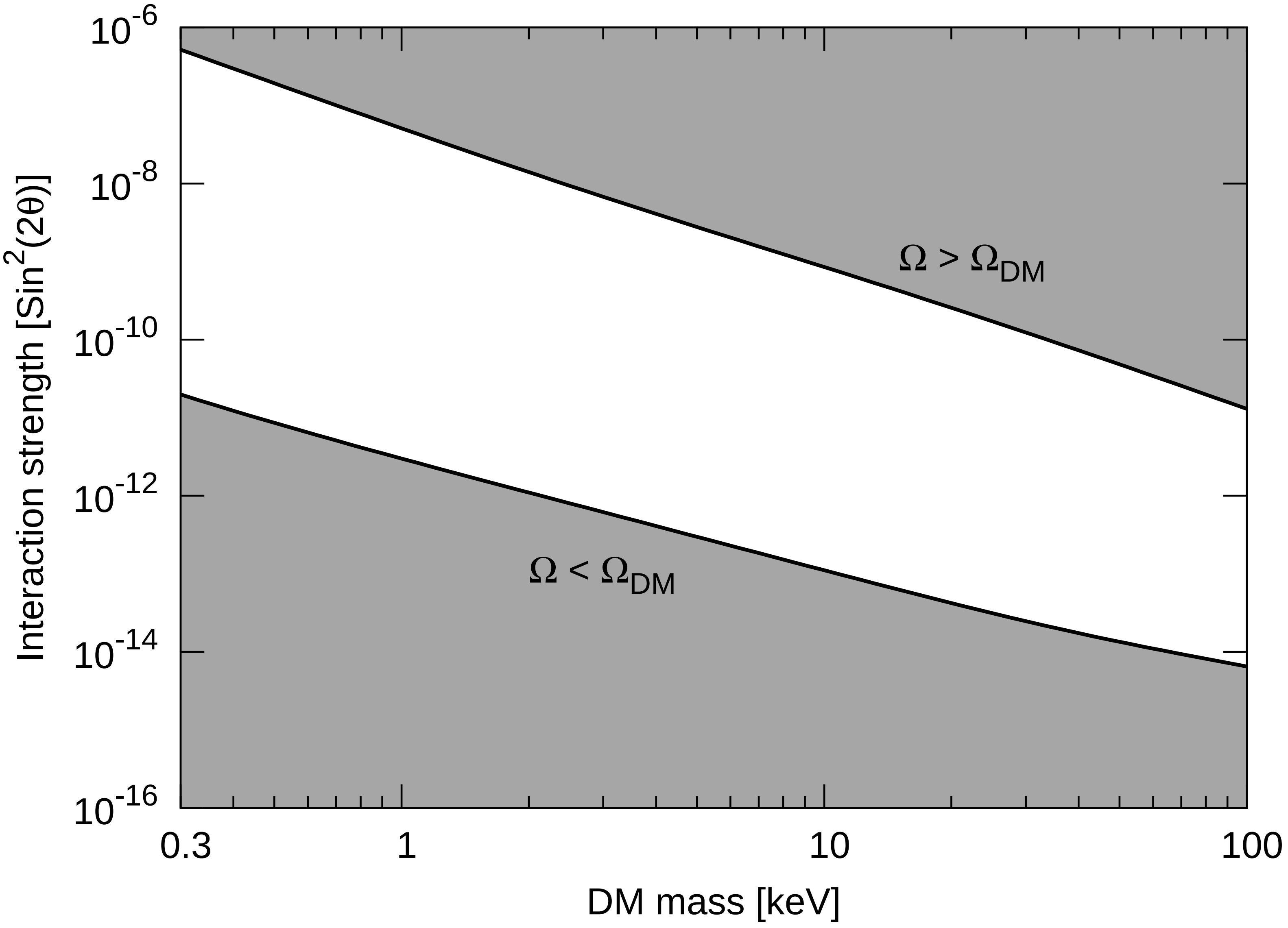
- Their amount less than that of active neutrinos

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

- Oscillations may become **resonant** in the presence of large lepton asymmetry – highly non-thermal spectrum.

Window of parameters of sterile neutrino DM

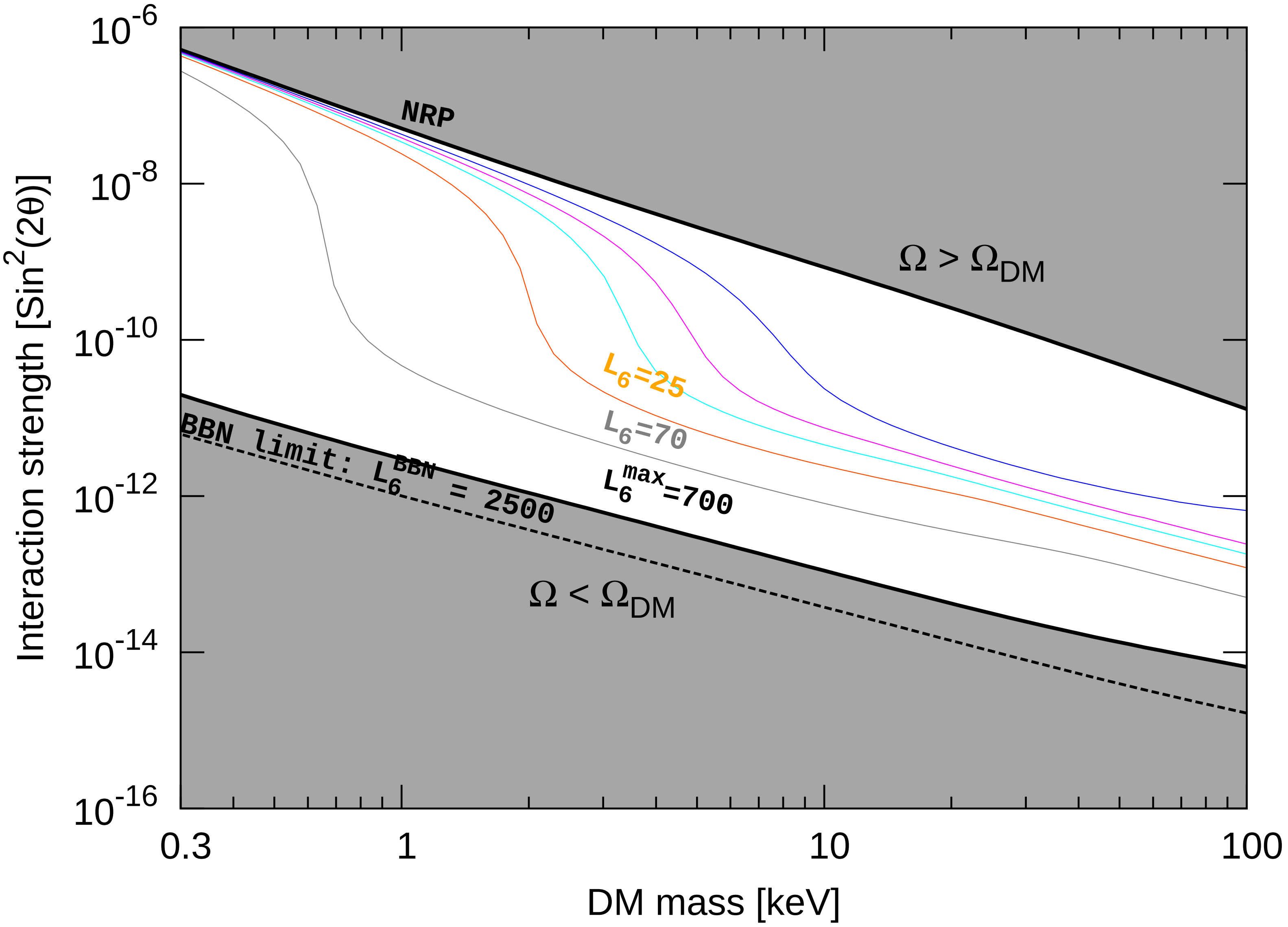
Laine, Shaposhnikov



Window of parameters of sterile neutrino DM

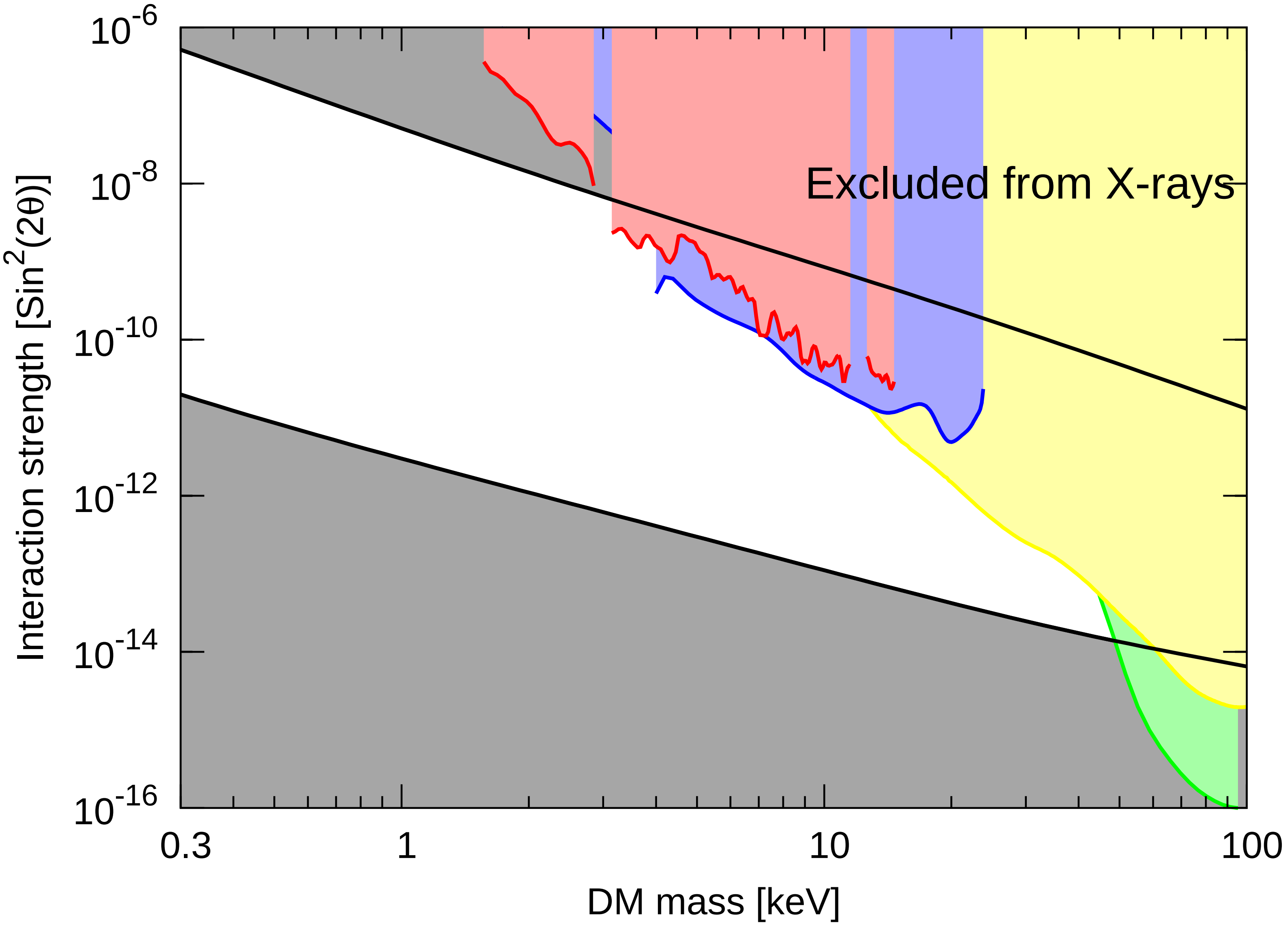
Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov

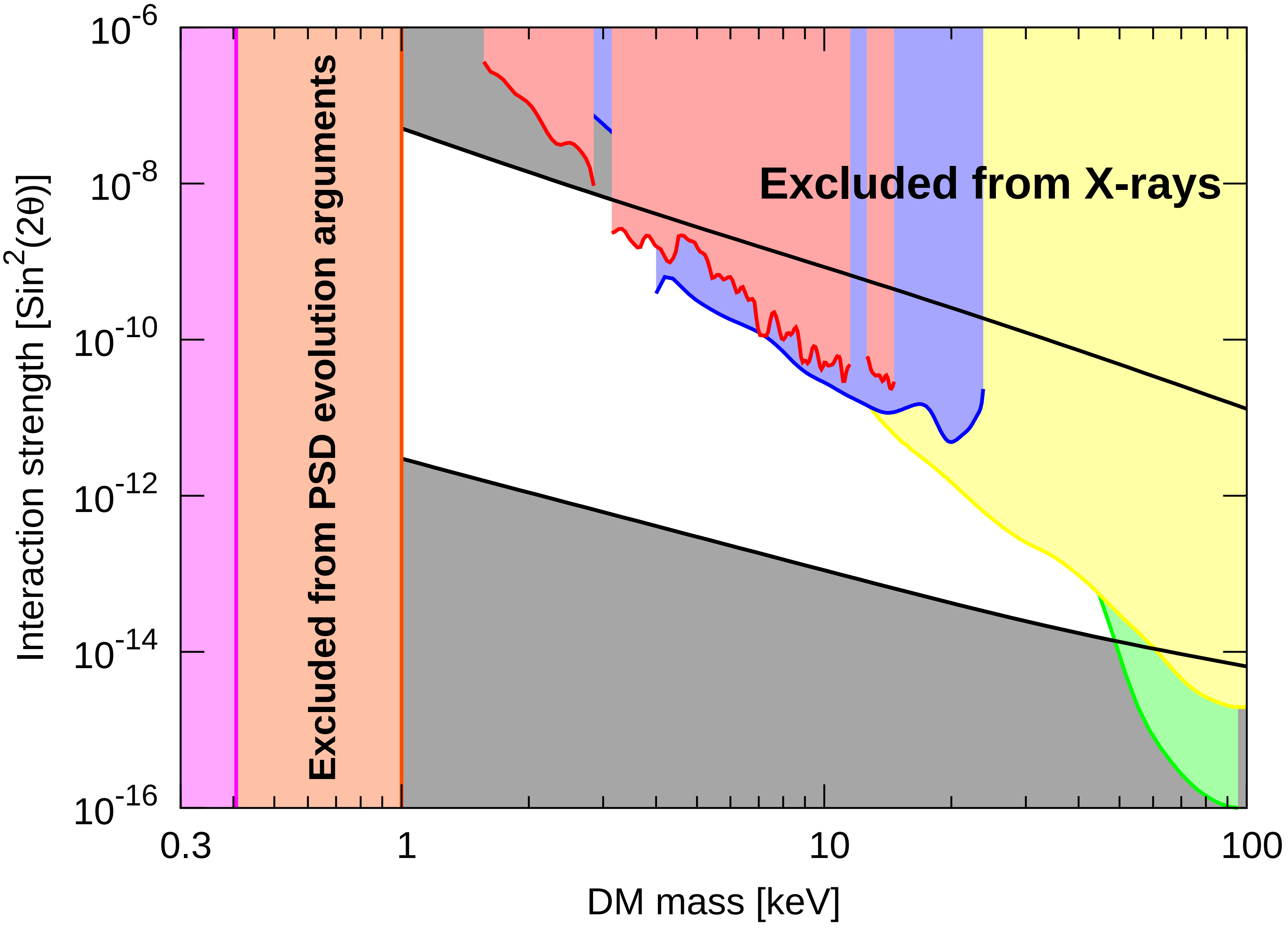


Window of parameters of sterile neutrino DM

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



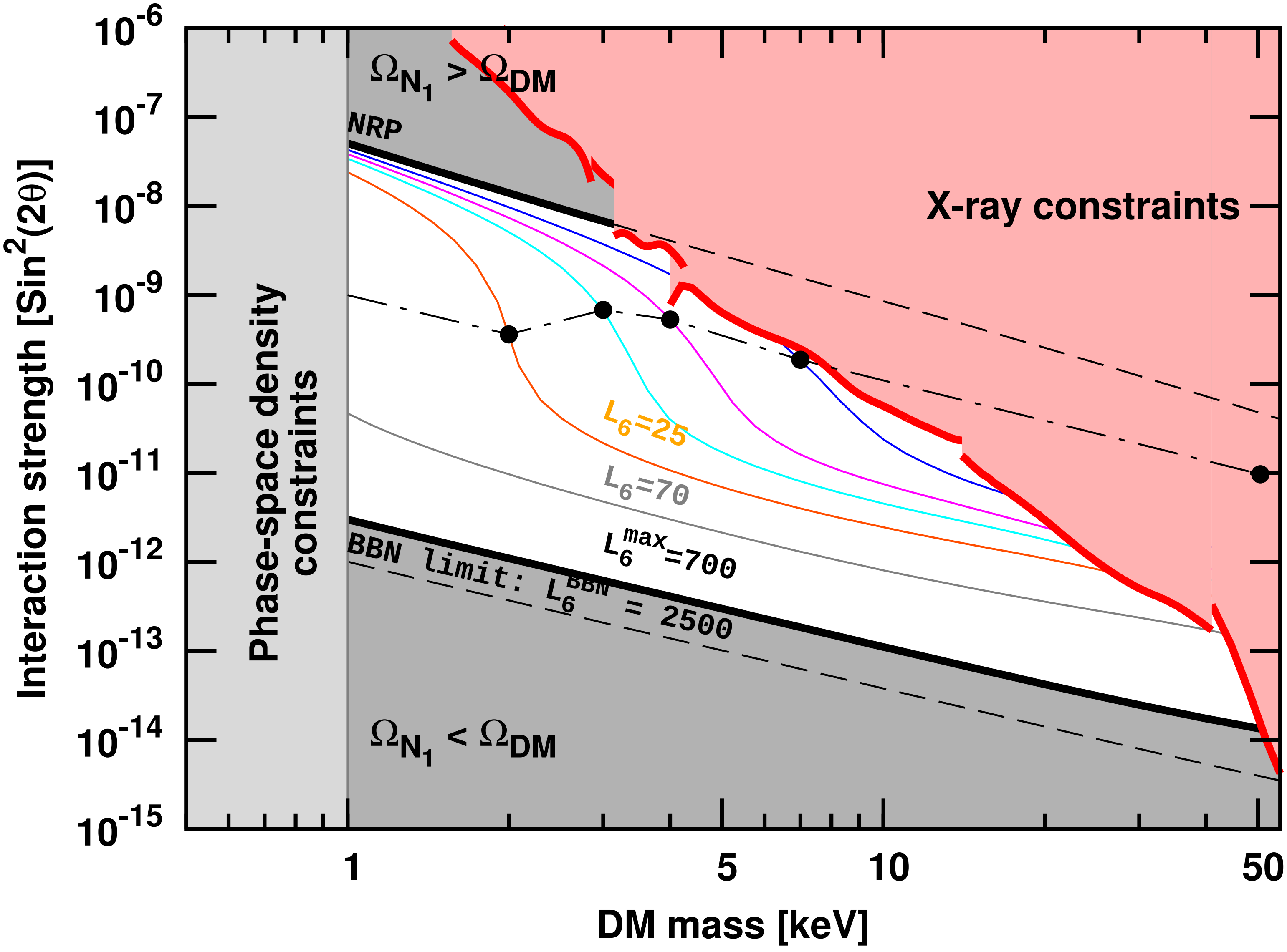
Window of parameters of sterile neutrino DM



Boyarsky, Ruchayskiy et al. 2005-2008

Boyarsky, O.R., Iakubovskyi, **2008**

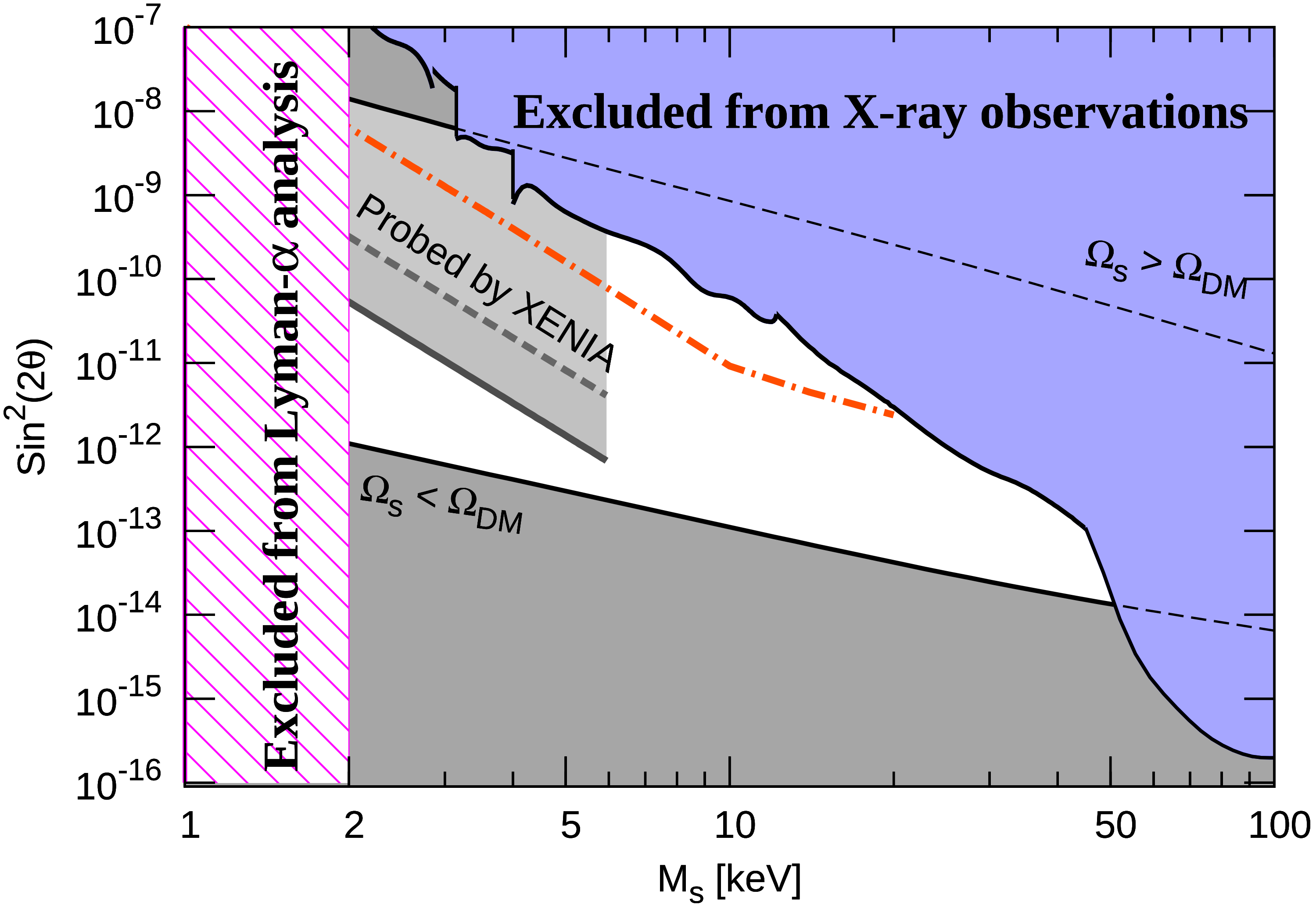
Sterile neutrino DM in the νMSM



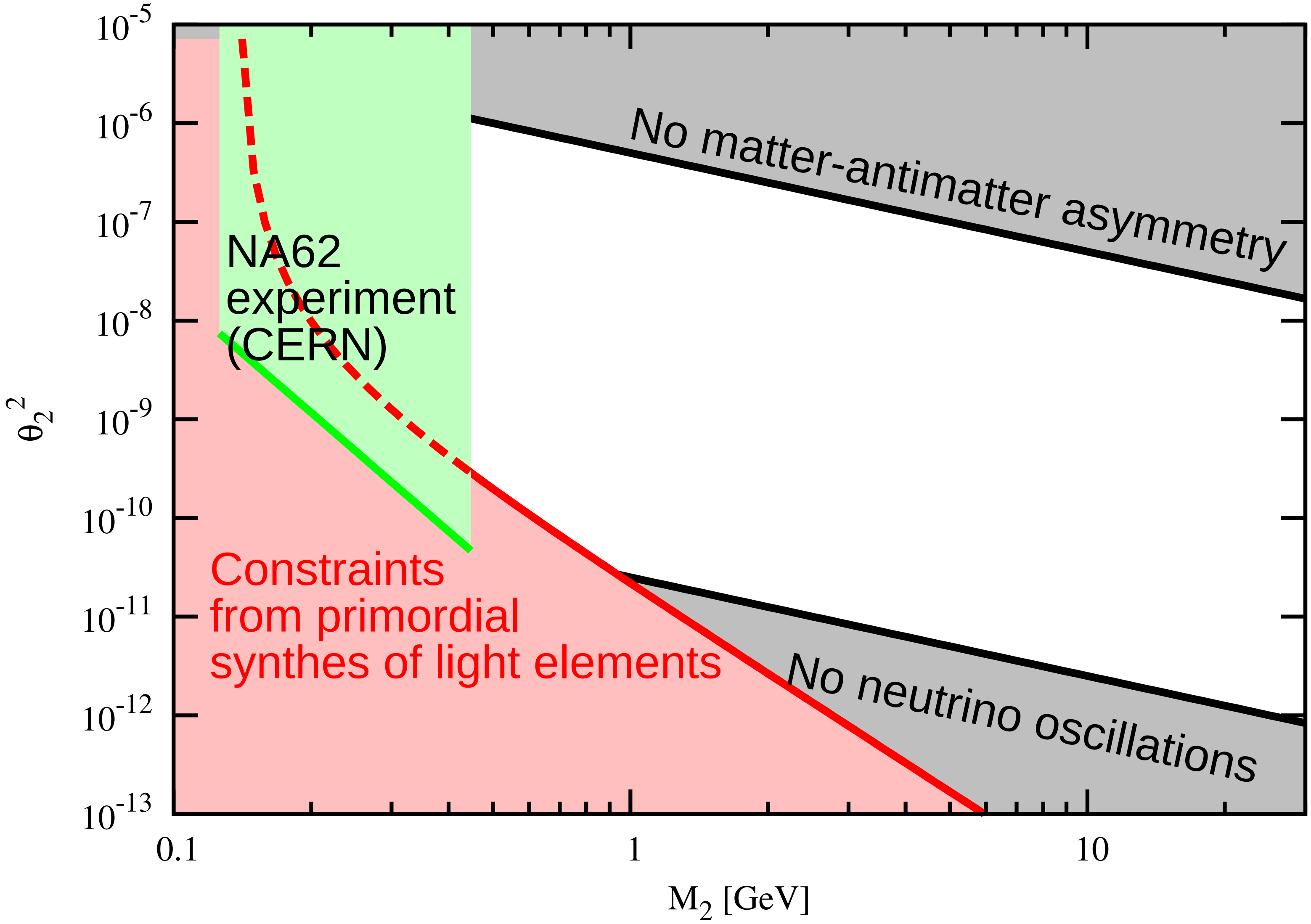
Boyarsky,
O.R.,
Lesgourgues,
Viel
[0812.3256]

Boyarsky,
O.R.,
Shaposhnikov
[0901.0011]

Improved bounds on DM decay



Probing other sterile neutrinos



Summary

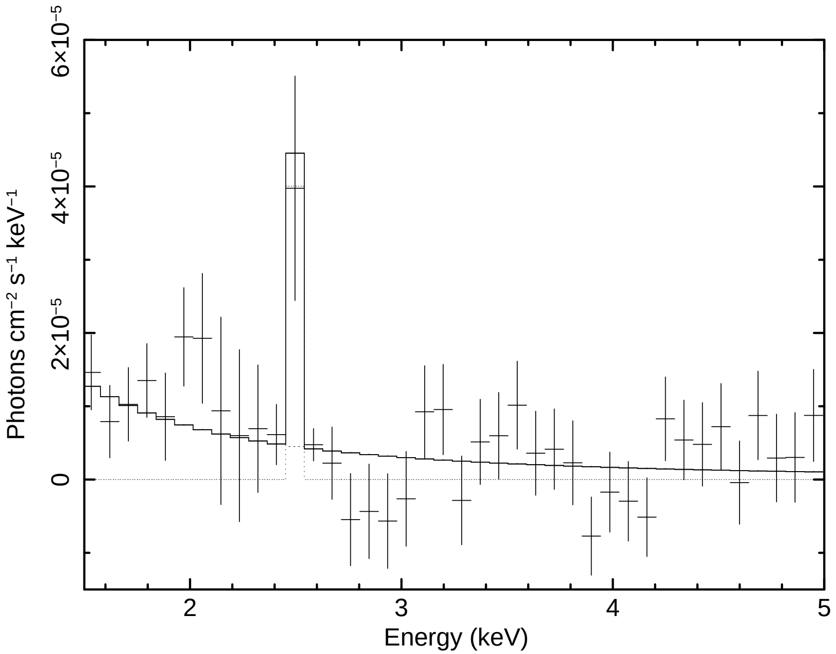
Main conclusion: superweakly interacting sterile neutrinos allow to explain several BSM problems within one consistent framework.

- neutrino oscillations
- baryogenesis
- dark matter

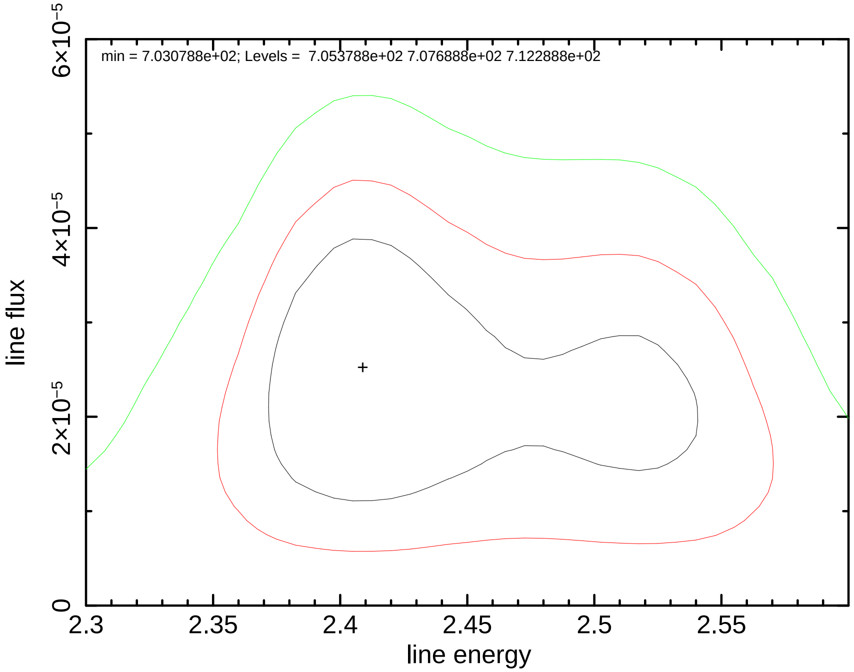
Astrophysics and cosmology are the main tools to find/rule out this model.

THANK YOU FOR YOUR ATTENTION

Example: Spectral feature in Willman 1



[Loewenstein & Kusenko [0912.0552]]



68%, 90% and 99% confidence intervals

Checking for DM line in dSphs

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

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

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

- No significant lines were found in spectra of dSphs

- We obtain the following <u>exclusions</u>

	$2.44 - 2.58$ 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 <u>worse</u>.

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	$\boxed{23.3\sigma}$

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:

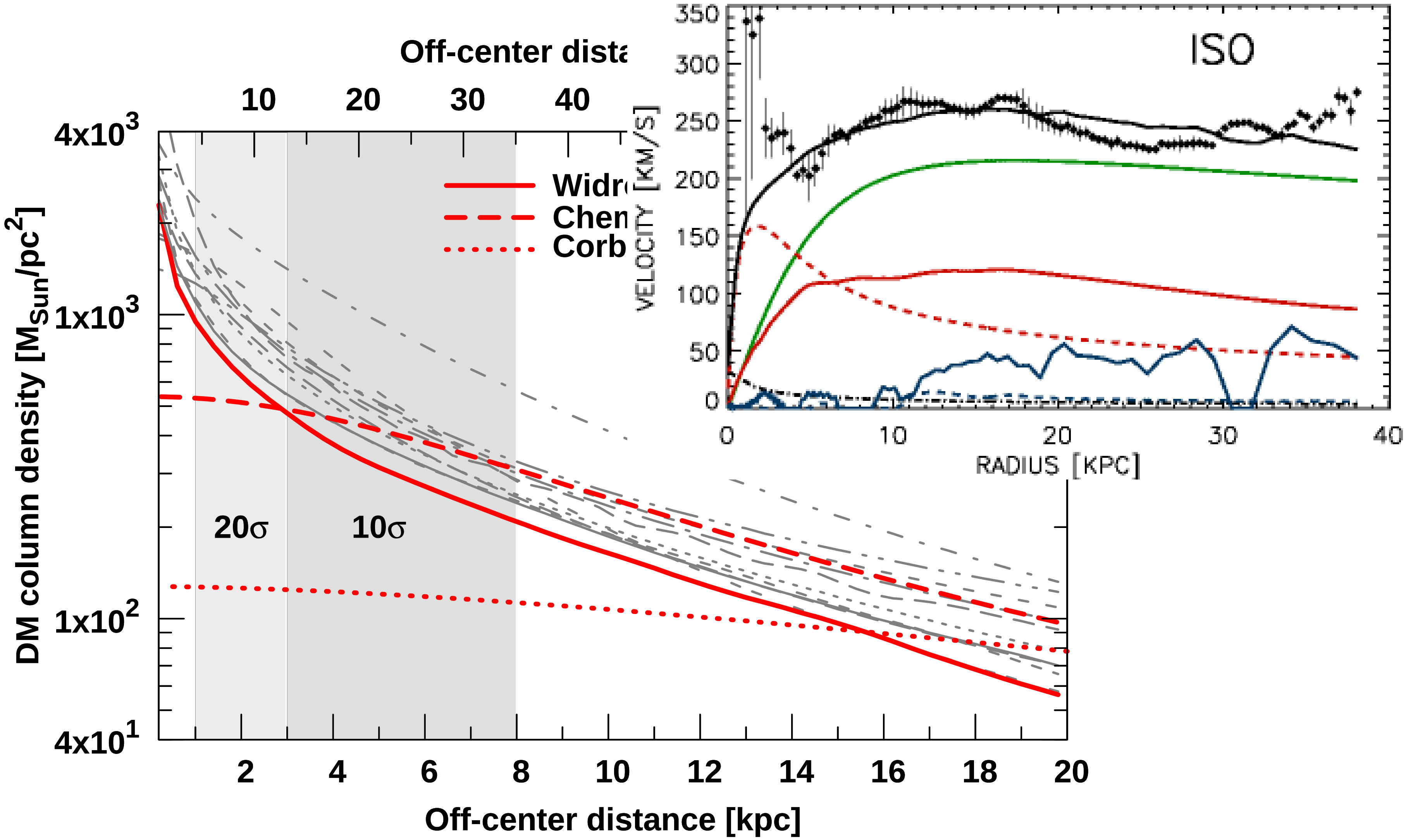
$2.44 - 2.58$ keV	$2.30 - 2.72$ keV
5.9σ	4.1σ

- 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	$\boxed{6.9\sigma}$	**[Corbelli et al.'09]**

1001.0644

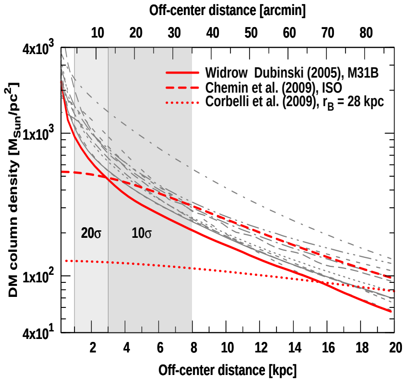
Checking for DM line in M31



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

1001.0644v2

Summary of exclusions

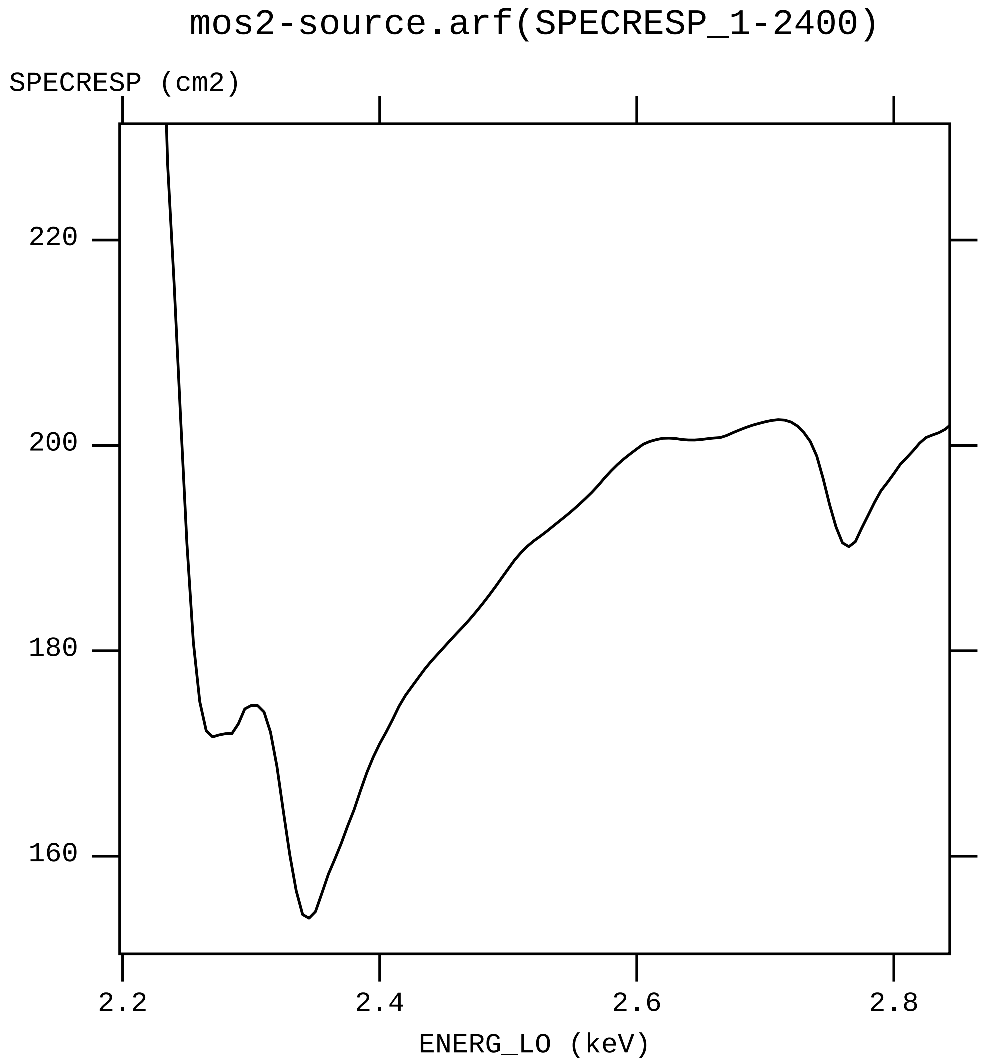
	“Consensus model” (Widrow & Dubinski, M31B)		Minimal DM amount (Corbelli et al., Burkert profile, $r_B = 28$ kpc, $M/L = 8$)	
	68%CL	99%CL	68%CL	99%CL
M31 within 8 central kpc	24.9σ	23.3σ	7.9σ	6.9σ
M31 10–20 kpc off-center	12.0σ	10.7σ	11.7σ	10.6σ
All M31 obs.	28.2σ	26.2σ	13.6σ	13.2σ
All M31 + Fornax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

68% CL:
2.44 keV – 2.58 keV

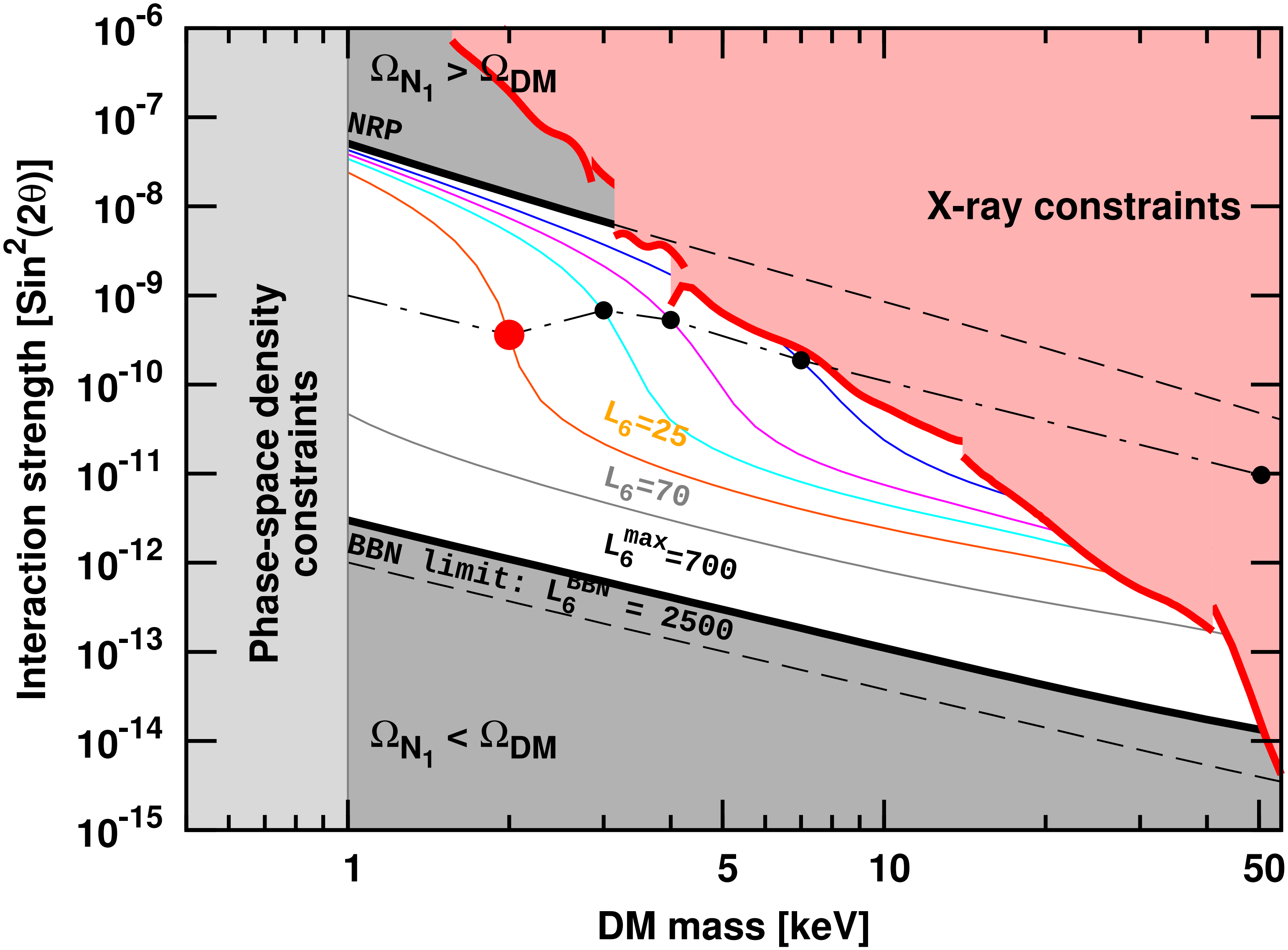
99%CL:
2.30 keV – 2.72 keV

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

Effective area around absorption edge



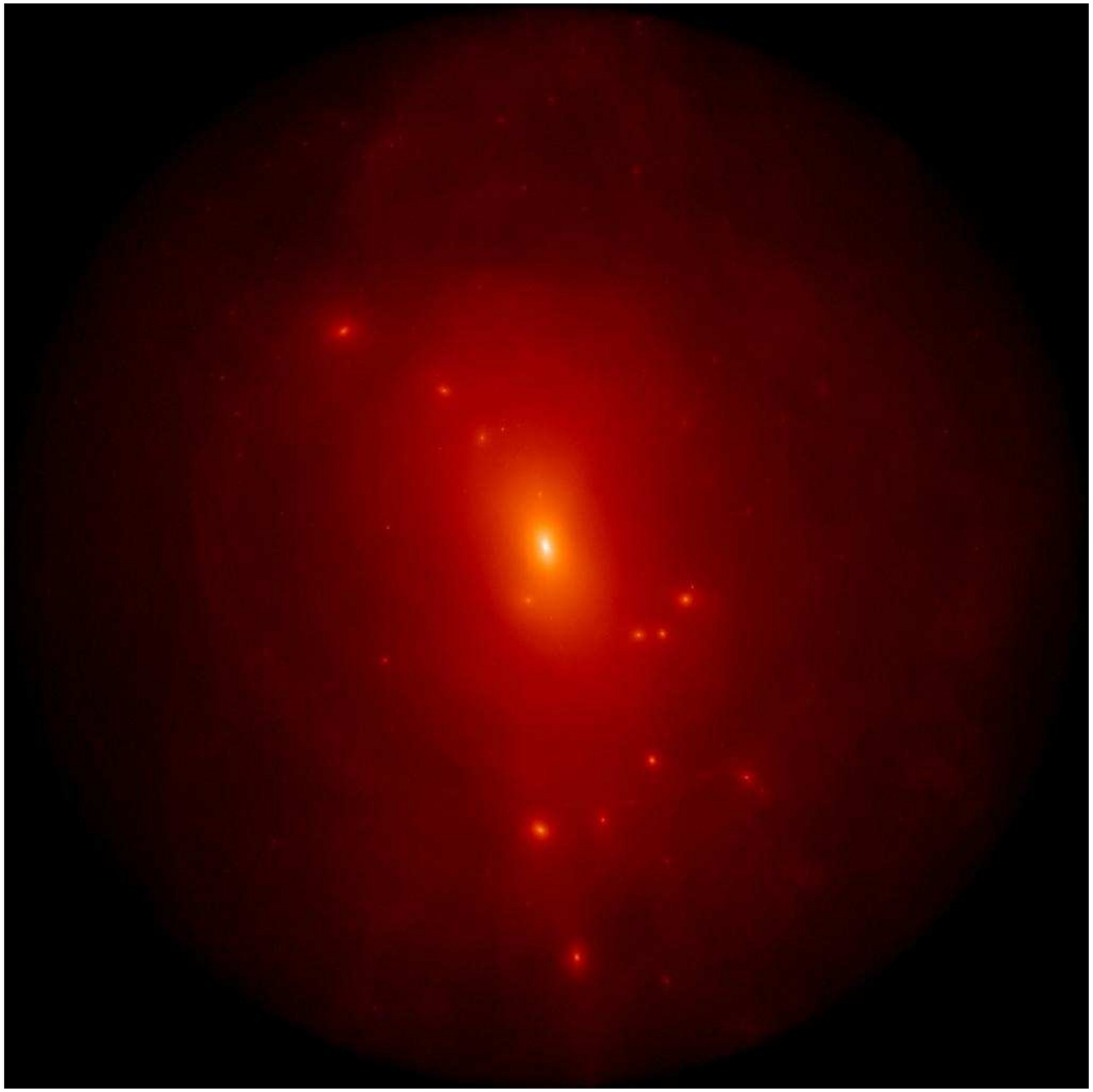
Sterile neutrino DM in the νMSM



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

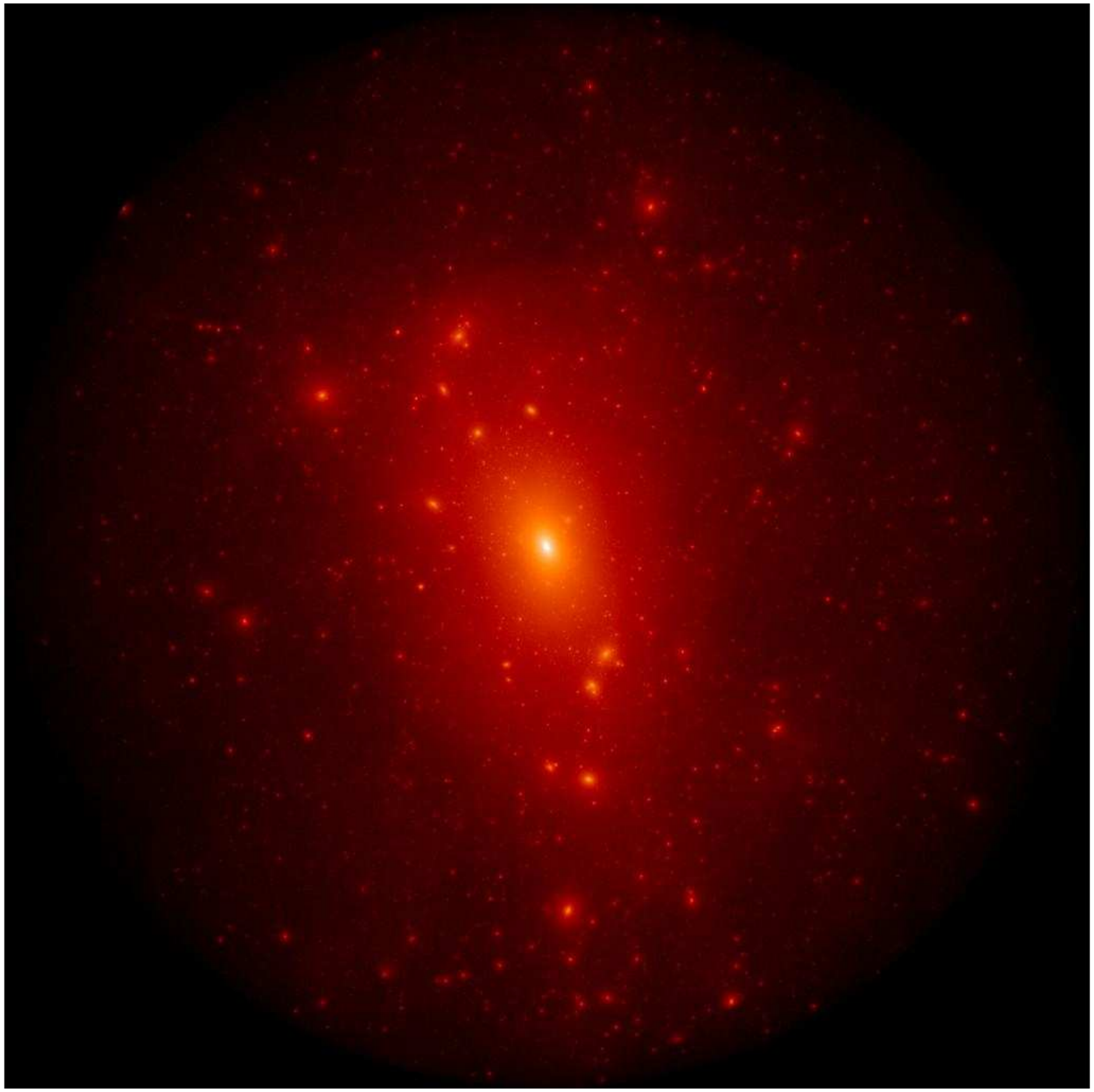
Boyarsky, **O.R.**, Shaposhnikov [0901.0011]

Halo substructure with sterile neutrino DM

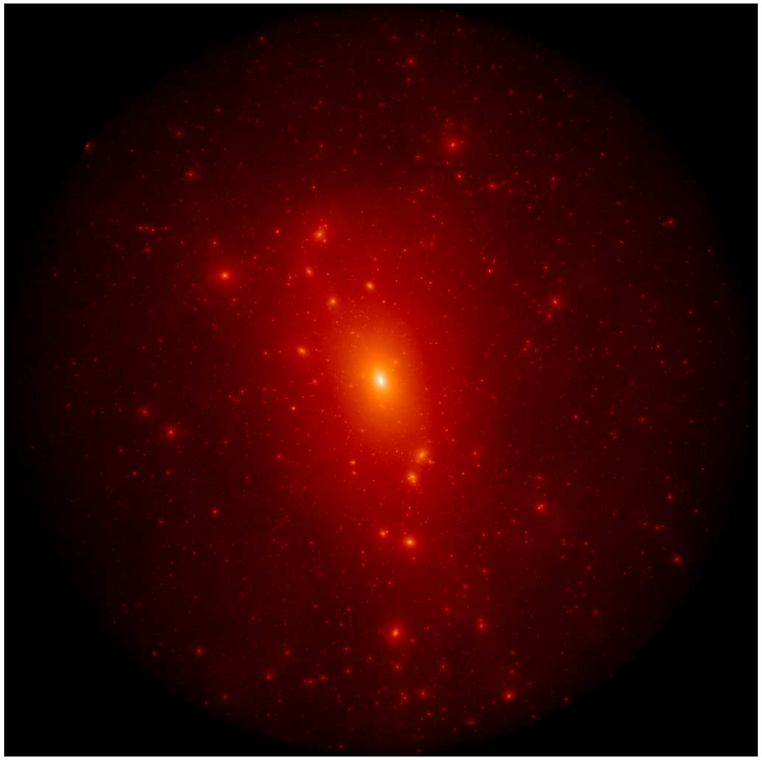


work in progress

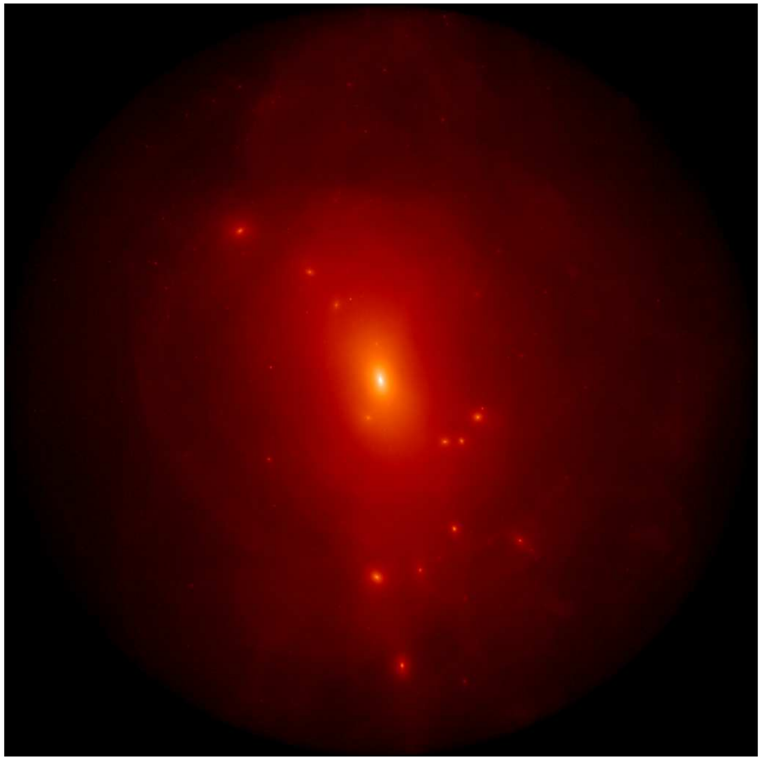
Halo substructure with CDM



Halo substructure with sterile neutrino DM



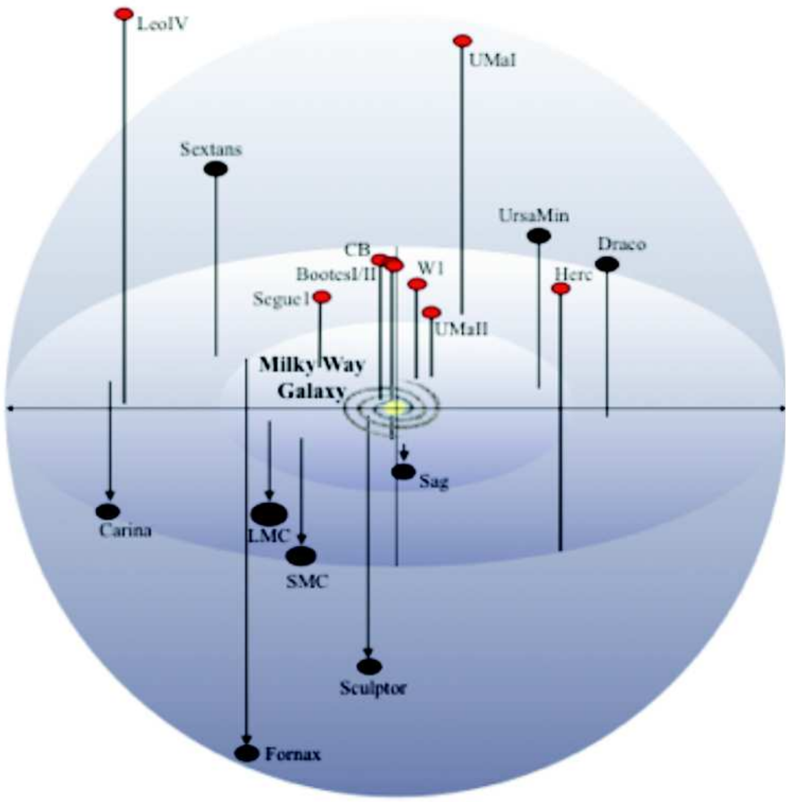
Aq-A-2 CDM halo



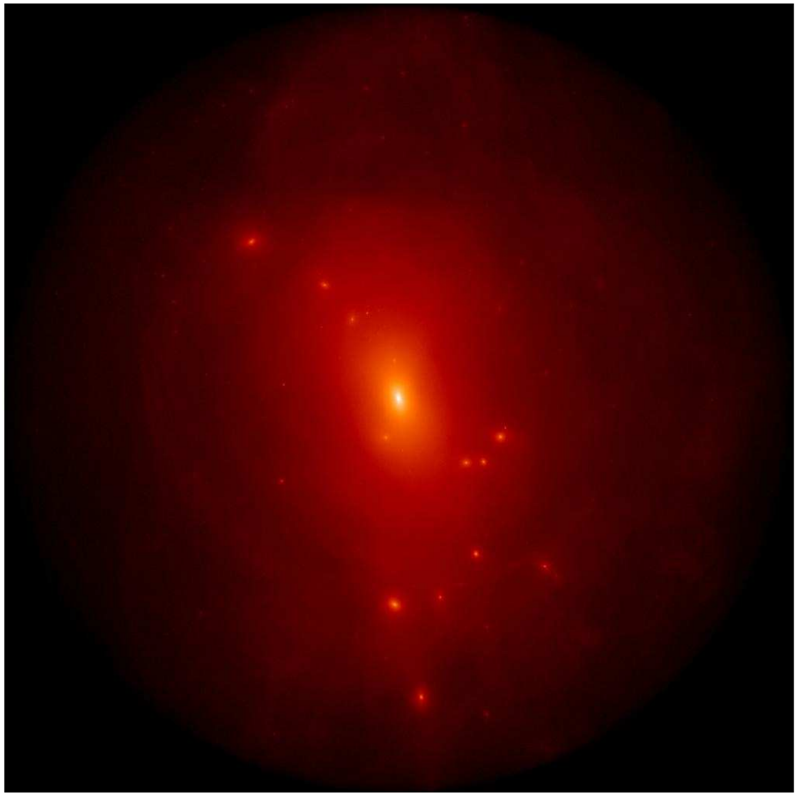
PRELIMINARY: ***Aq-A-2 halo*** made of sterile neutrino DM (Gao, Theuns, Frenk, **O.R.**, . . .)

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

Halo substructure with sterile neutrino DM



Observed substructures within our Galaxy. M. Geha 2010



PRELIMINARY: ***Aq-A-2 halo*** made of sterile neutrino DM (Gao, Theuns, Frenk, **O.R.**, . . .)

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

Parameters of Aquarius simulation

Name	m_{p} $[\mathrm{M}_{\odot}]$	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.

Springel et al.'08

Back to CDM+WDM halo simulation

TOC

TOC