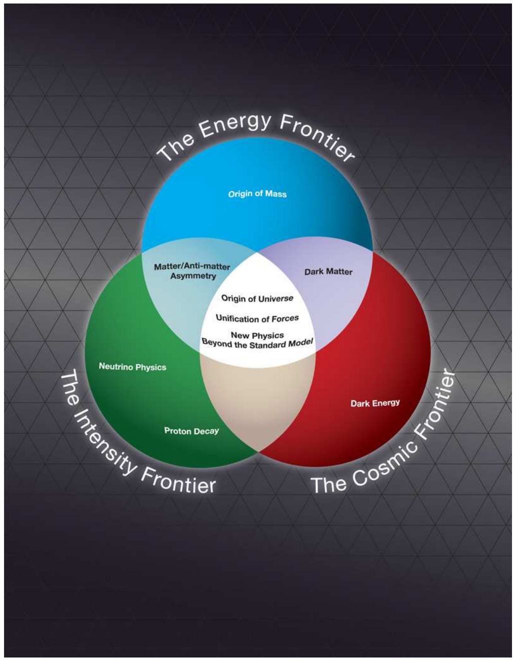
Sterile neutrinos as dark matter



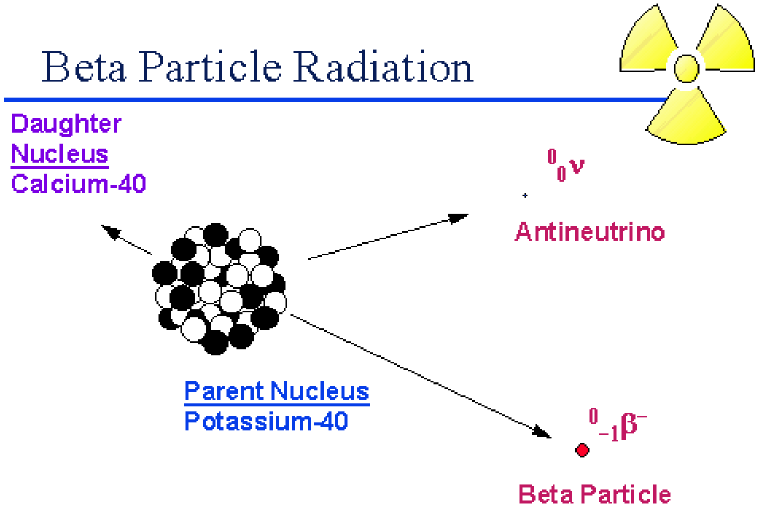
Oleg RUCHAYSKIY

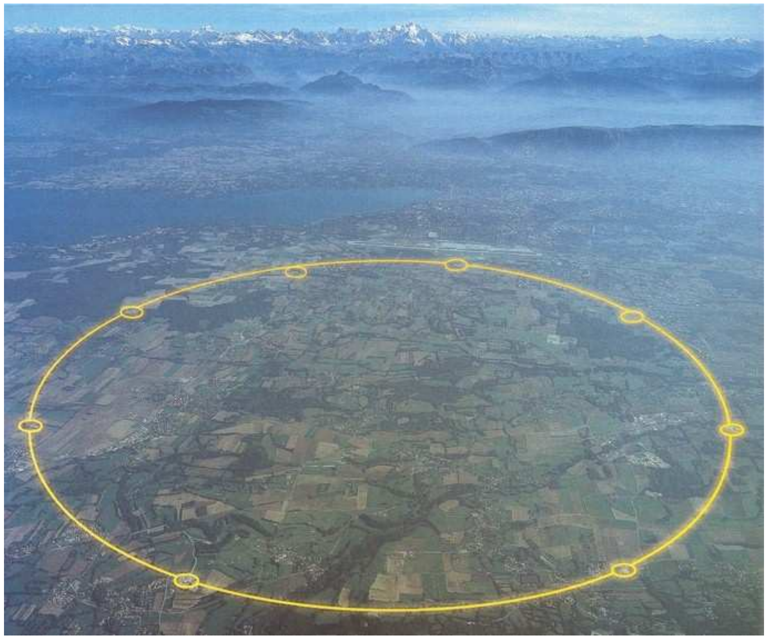
CERN

Dark matter underground
and in the heavens

Higgs - last unseen element of the SM

The quest that started from attempts to explain atomic and nuclear physics, taking into account Quantum Mechanics and Relativity resulted in construction of the **Standard Model of elementary particles**





BSM physics

Already now we know a number of observational **beyond the Standard Model phenomena**:

- ⟶ **Neutrino oscillations**: transition between neutrinos of different flavours (ν_e, ν_μ, ν_τ) means violation of lepton flavour symmetries (but not total lepton number!)
- ⟶ existence of **dark matter** (why observed gravity of galaxies and clusters is so strong?)
- ⟶ the **absence of anti-matter** in the Universe
- ⟶ inflation (homogeneity of the observed Universe seem to require correlated initial conditions for causally non-connected regions)
- ⟶ dark energy (If it will be shown that accelerated expansion of the Universe is caused not by a small cosmological constant, but by some other unknown substance – what is this substance?)

Fine-tuning problems

- Important direction of the theoretical particle physics research of the last decades is the problem of “naturalness” – understanding the structure of the Standard Model, small values of some parameters, symmetries, etc:
  - **Gauge hierarchy** problem (why the Higgs mass is small and stable against radiative corrections)
  - **CP problem** (why neutron electrical dipole moment is so small?)
  - **Cosmological constant** problem (why is cosmological constant zero or almost zero?)

Where can we expect new physics?

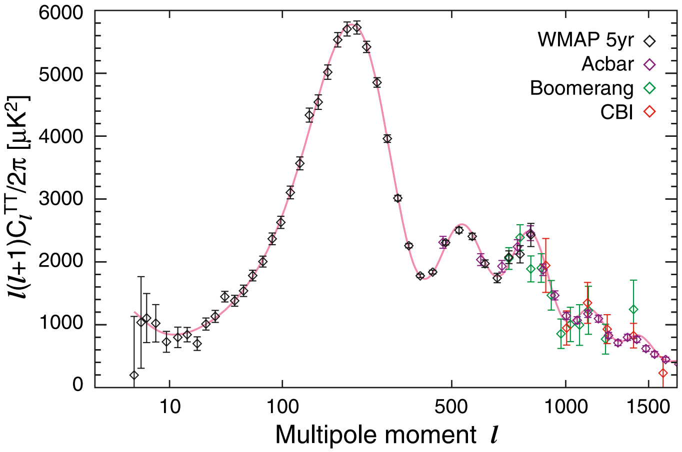
- **Neutrino oscillations** $m_\nu \sim \sqrt{\Delta m^2_{\rm atm}} \sim 10^{-2}$ eV.
  See-saw mechanism $m_\nu \sim v^2/\Lambda$, where $v = \langle H\rangle = 174$ GeV and **new scale** $\Lambda \sim 10^{15}$ GeV

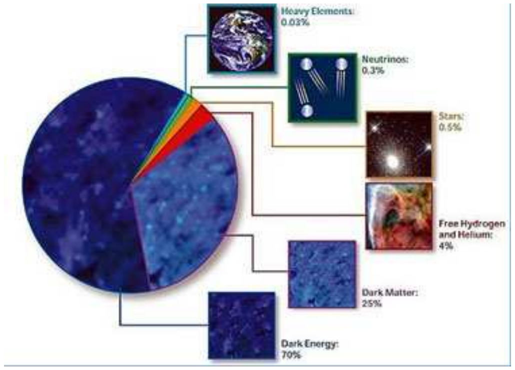
- **Dark matter**
  - particles with weak cross-section will have correct abundance Ω_{DM} ("WIMP miracle"). **New scale** ~ 1 TeV
  - Axions. **New scale** $10^{10} - 10^{12}$ GeV.

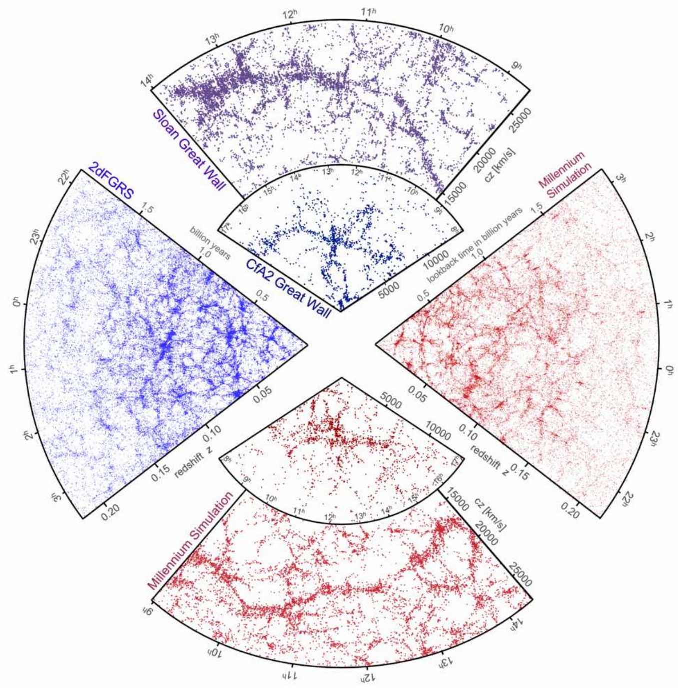
- **Fine-tuning problems:**
  - hierarchy problem: ~ 1 TeV
  - grand unification: $\sim 10^{15}$ GeV
  - CP-problem: $10^{10} - 10^{12}$ GeV (if provided by axion)

- . . .

Dark matter in the Universe







- ΛCDM: about 20% of total energy density is in the form of **non-baryonic** matter

- This dark matter is **scale-free** (non-interacting, “cold”, . . .)

Sterile neutrino dark matter

- Massive neutrinos – probably the first DM candidate. Did not work – particles remain relativistic for too long. ⇒ **Standard Model neutrinos** do not contribute significantly to the Universe mass balance at matter-dominated epoch (CMB, LSS, . . .)

Dodelson & Widrow (1993

- Sterile neutrinos (right-handed counterparts of SM neutrinos): heavier (“colder”) than ordinary neutrinos and couple to the Standard Model super-weakly. ⇒ **Dark matter candidate**

Shi & Fuller (1998)

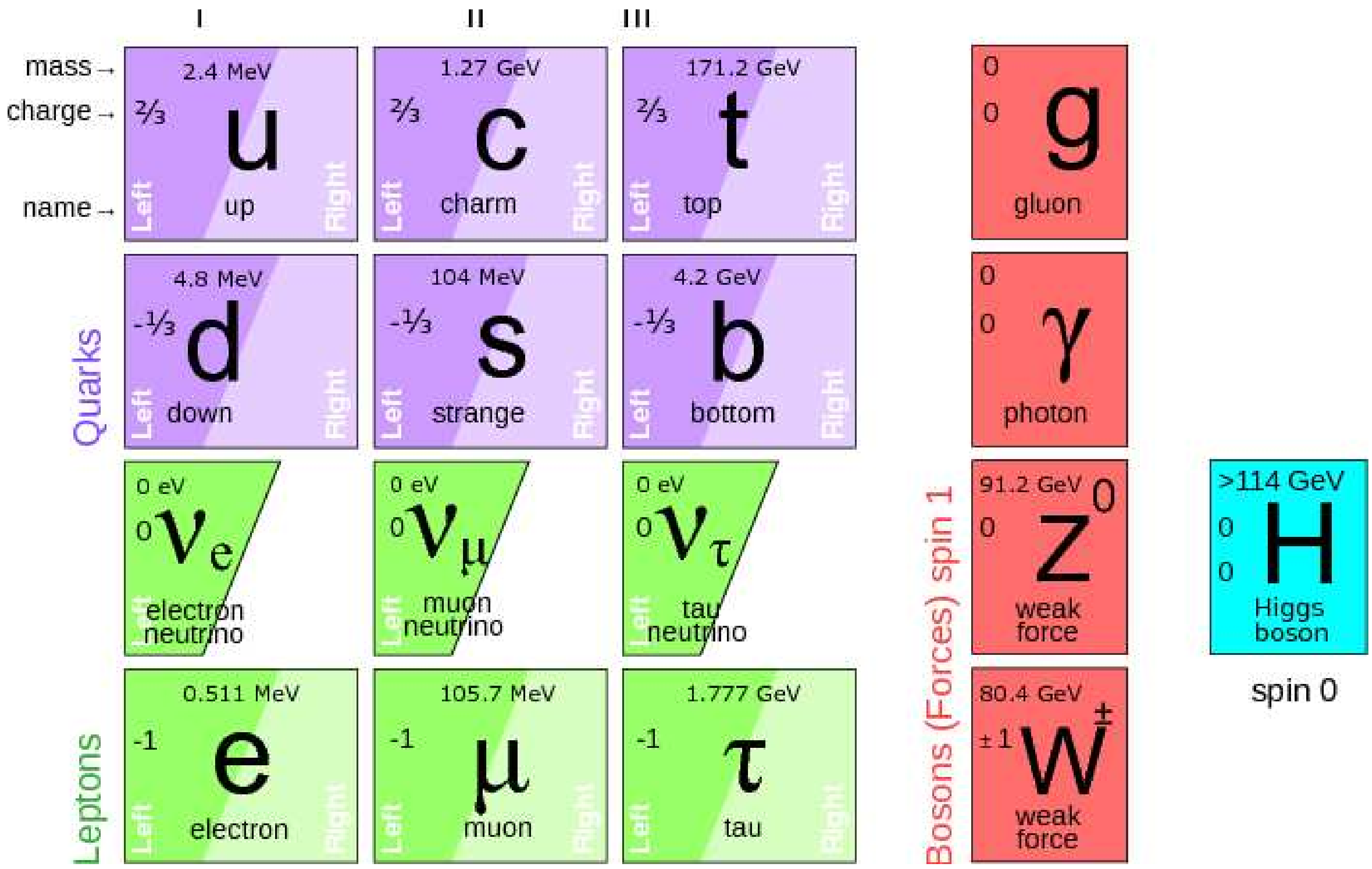
Abazajian et al. 2001-2005

- DM sterile neutrino does not contribute to the neutrino oscillations ⇒ two more particles are needed.

Asaka, Shaposhnikov et al. 2005-. . .

- To be a DM candidate sterile neutrino should couple super-weakly to the Standard Model particles ⇒ its properties (abundance, primordial velocities, etc.) are sensitive to the content of primordial plasma

Standard Model



Standard Model neutrinos are **strictly massless**

Right-chiral particles

- Massless fermions can be left and right-chiral (left and right moving):

$$(i\gamma^\mu\partial_\mu - \cancel{m})\psi = \begin{pmatrix} \cancelto{0}{-m} & i(\partial_t+\vec{\sigma}\cdot\vec{\nabla}) \\ i(\partial_t-\vec{\sigma}\cdot\vec{\nabla}) & \cancelto{0}{-m} \end{pmatrix}\begin{pmatrix}\psi_L \\ \psi_R\end{pmatrix} = 0$$

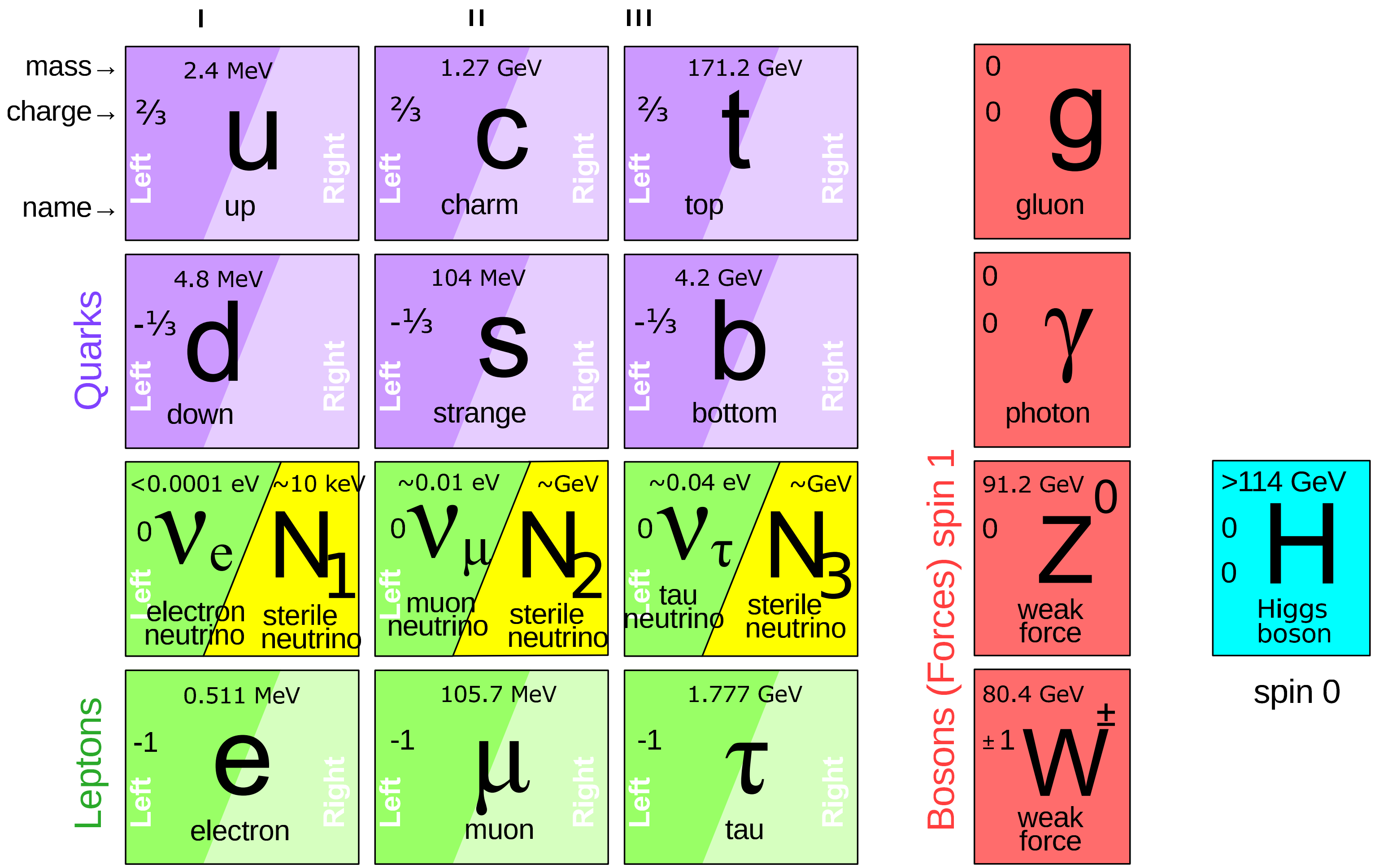
  where $\gamma_5\psi_{R,L} = \pm\psi_{R,L}$ and $\gamma_5 = i\gamma_0\gamma_1\gamma_2\gamma_3$

- Mass term mixes left and right movers

- To make neutrinos massive, we can add **right-chiral** counterparts N_I

$$\mathcal{L}_{\text{neutrino mass}} = i\bar{N}_I\not{\partial}N_I + \underbrace{\begin{pmatrix}\bar{\nu}_e - N_I \\ \bar{\nu}_\mu - N_J \\ \dots\end{pmatrix}}_{\text{left-right mixing}} + ????$$

Right-chiral neutrino counterparts?



mass →
charge →
name →

	I	II	III	Bosons (Forces) spin 1	
Quarks	2.4 MeV $\frac{2}{3}$ u up Left Right	1.27 GeV $\frac{2}{3}$ c charm Left Right	171.2 GeV $\frac{2}{3}$ t top Left Right	0 0 g gluon	
Quarks	4.8 MeV $-\frac{1}{3}$ d down Left Right	104 MeV $-\frac{1}{3}$ s strange Left Right	4.2 GeV $-\frac{1}{3}$ b bottom Left Right	0 0 γ photon	
Leptons	<0.0001 eV ~10 keV 0 ν_e N_1 electron neutrino, sterile neutrino Left	~0.01 eV ~GeV 0 ν_μ N_2 muon neutrino, sterile neutrino Left	~0.04 eV ~GeV 0 ν_τ N_3 tau neutrino, sterile neutrino Left	91.2 GeV 0 Z^0 weak force	>114 GeV 0 0 H Higgs boson spin 0
Leptons	0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right	80.4 GeV ±1 $W^\pm$ weak force	

The most natural explanation of neutrino experiments – adding right-chiral counterparts to the Standard Model

Properties of right-chiral neutrinos

- Charges of right neutrinos?
  - SU(3) : **singlets**
  - SU(2) : **singlets** ($\nu = L\tilde{H}$ – singlet combination)
  - U$_Y$(1) : **singlets** ($Y(\nu) = Y($Higgs$)$)

- Right-chiral neutrinos **carry no charge** under the Standard Model interactions $\Rightarrow$ **sterile neutrinos**

- Can add for them a **Majorana mass**

$$\boldsymbol{\mathcal{L}}_{\text{see-saw}} = i\bar{N}_I \not{\partial} N_I + \underbrace{\begin{pmatrix}\text{mixing matrix}\\ \bar{\nu}_e - N_I\\ \bar{\nu}_\mu - N_J\\ \dots\end{pmatrix}}_{\text{Dirac mass } M_D} + \underbrace{\begin{pmatrix} N - N\\ \text{mixing}\end{pmatrix}}_{\text{Majorana mass } M_I}$$

- See-saw Lagrangian violate **flavour** and **total** lepton numbers

See saw Lagrangian

$$\mathcal{L}_{\text{see-saw}} = i\bar{N}_I \partial\!\!\!/ N_I + \underbrace{\begin{pmatrix} \bar{\nu}_e - N_I \\ \bar{\nu}_\mu - N_J \\ \ldots \end{pmatrix}}_{\text{Dirac mass } M_D} + \underbrace{\begin{pmatrix} N - N \\ \text{mixing} \end{pmatrix}}_{\text{Majorana mass } M_I}$$

- Standard Model neutrino masses are given by **see-saw formula**:

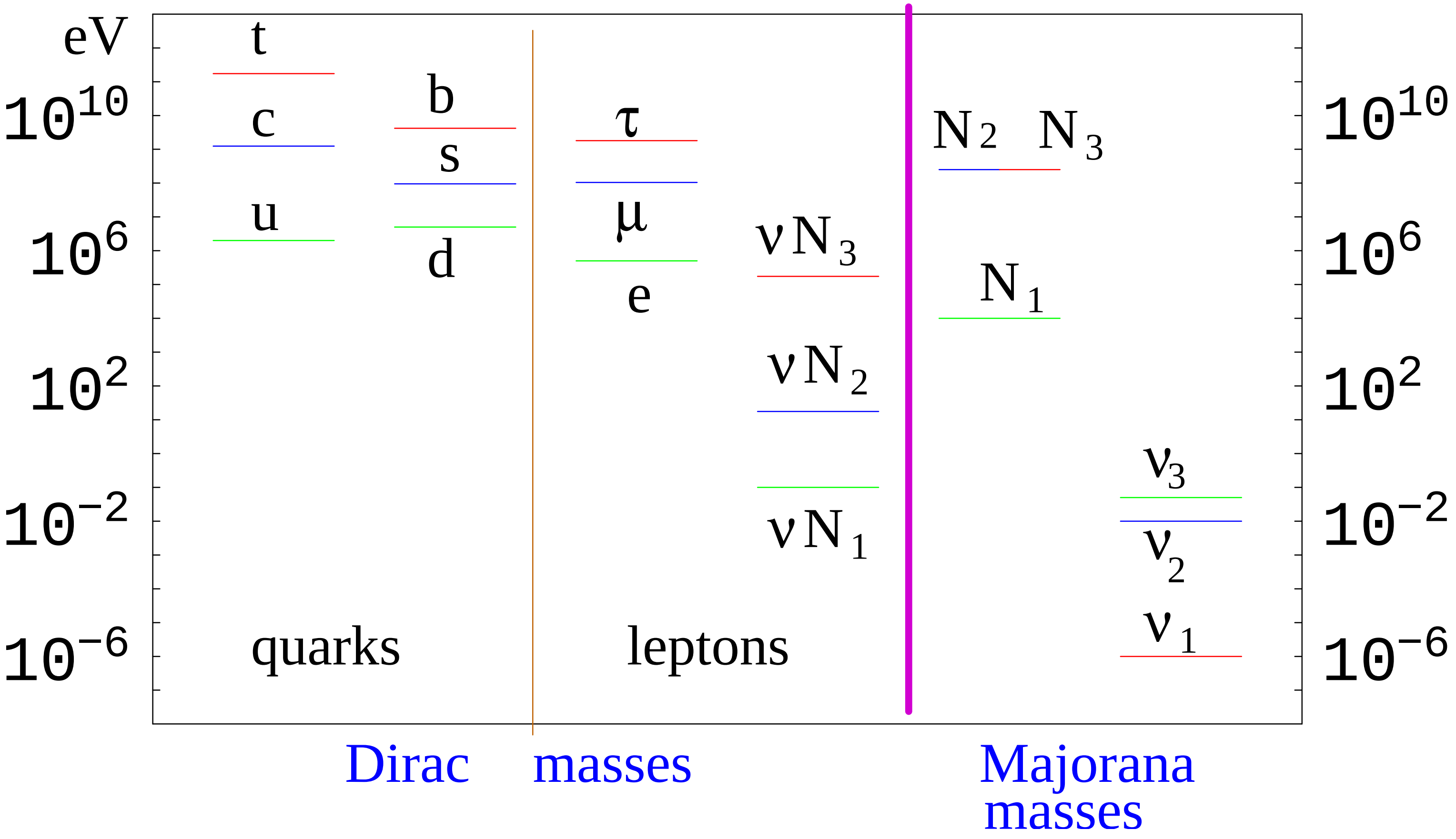
$$\textbf{Neutrino mass matrix} = -M_{\text{Dirac}} \frac{1}{M_{\text{Majorana}}} M^T_{\text{Dirac}}$$

- Neutrino mass matrix – **9 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!

Neutrino Minimal Standard Model



Mass spectrum of the νMSM

Yukawa couplings of sterile neutrinos $\ll 1$

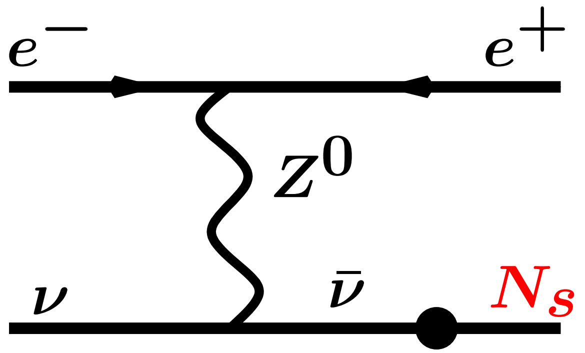
Some general properties of sterile neutrino

Sterile neutrinos behave as **superweakly interacting** heavy neutrinos

$M_I < 1$ MeV	$M_I \gtrsim 1$ MeV	$M_I \gtrsim 140$ MeV	$\ldots$
$N_I \to \nu\nu\bar{\nu}$	$N_I \to \nu e^+ e^-$	$N_I \to \pi^\pm e^\mp$	
$N_I \to \nu\gamma$		$N_I \to \pi^0\nu$	

Mixing angle with usual neutrinos θ_I:

$$\theta_I^2 = \sum_{\alpha=e,\mu,\tau} \frac{M^2_{\text{Dirac},\alpha I}}{M^2_{\text{Majorana},I}} \ll 1$$



Fermi constant: $\boxed{G_F \to \theta G_F}$

Lifetime $\tau \propto \theta_I^{-2} M_I^{-5}$. Can be cosmologically long

Mixing angle $\theta \ll 1$ means that sterile neutrinos can be out of equilibrium in the early Universe

Entire history of the Universe

Neutrino Minimal Standard Model (νMSM) solves several *beyond the Standard Model problems*

Asaka, Shaposhnikov (2005)

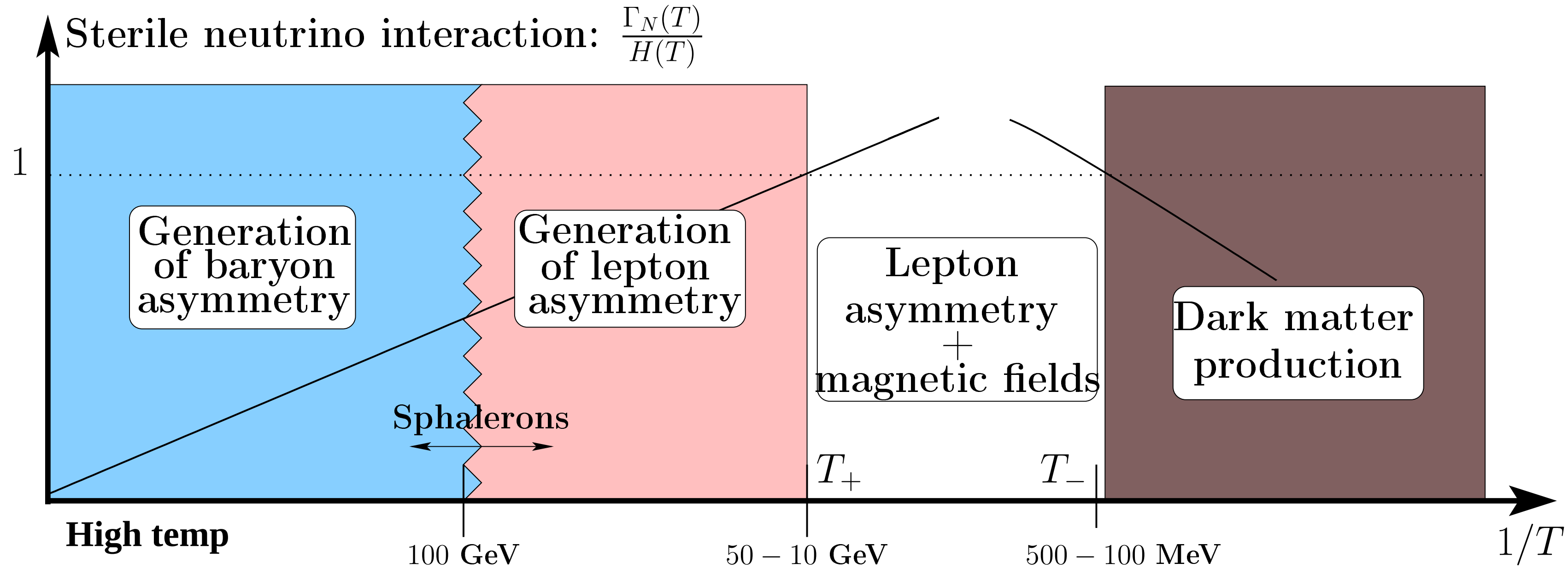
- ✓ . . . explains neutrino oscillations
- ✓ . . . matter-antimatter asymmetry of the Universe
- ✓ . . . provides a viable dark matter candidate that can be cold, **warm** or **mixed** (cold+warm)

- ■ The νMSM is self-consistent and does not require any other particles ⇒ we have a **complete description of the Universe** from the time of reheating
- ■ Coupled with Higgs inflation the νMSM is a complete and self-consistent theory up to the Planck scale

Bezrukov & Shaposhnikov (2008)

Thermal history of the νMSM

- Two sterile neutrinos are responsible for neutrino oscillations.
- They determine the properties of the third (DM) sterile neutrino
- Physics of the early Universe with (out-of-equilibrium) sterile neutrinos



Sakharov conditions in the SM

Sakharov (1967)

Quick reminded: necessary conditions for generation of baryon asymmetry of the Universe (**Sakharov conditions**):

Kuzmin, Rubakov, Shaposhnikov (1985)

⊕ B-number violation → sphalerons

Farrar & Shaposhnikov (1994)

? CP (and C) non-conservation → phase of the CKM matrix

Kajantie et al. (1996)

⊖ Out-of-equilibrium processes → no phase transition in the SM for $m_H > 72$ GeV!

What changes in the νMSM?

Sakharov conditions in the (ν)MSM

Necessary conditions for generation of baryon asymmetry of the Universe (**Sakharov conditions**):

Sakharov (1967)

- ⊕ B-number violation → sphalerons

Kuzmin, Rubakov, Shaposhnikov (1985)

- ⊕ CP (and C) non-conservation → phase of the CKM matrix **plus additional CP phases in the Dirac mass matrix of sterile neutrinos**

Farrar & Shaposhnikov (1994)

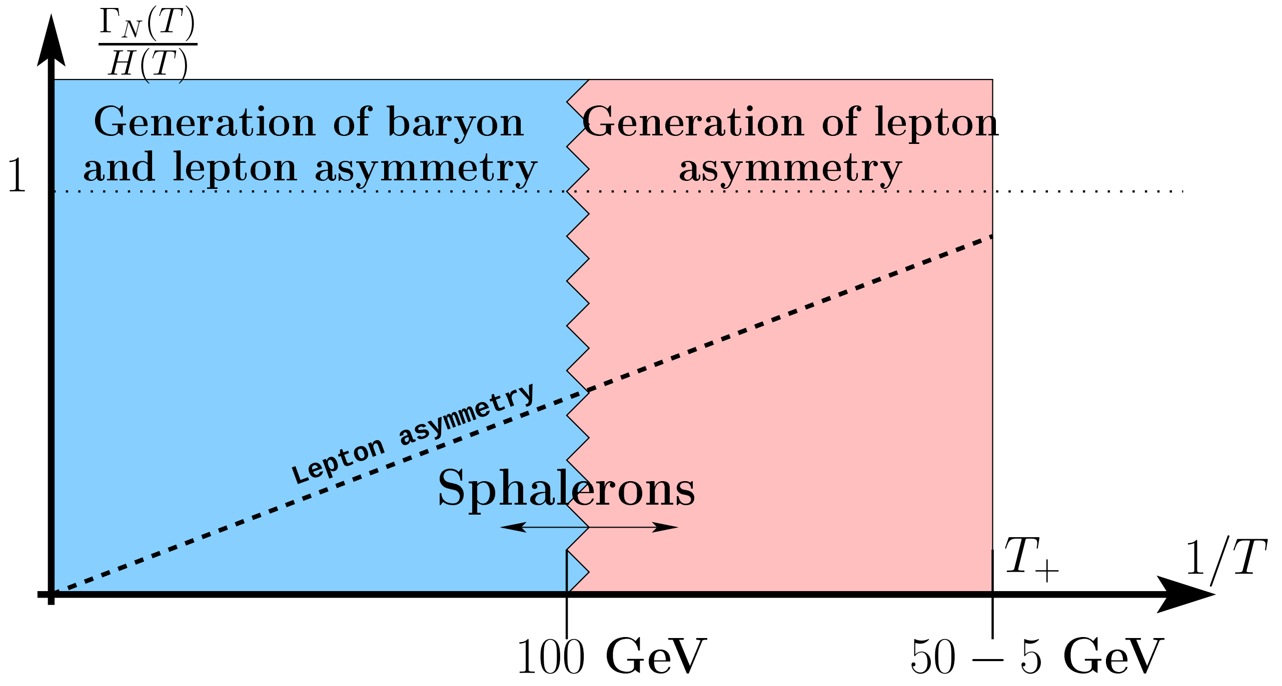
Kajantie et al. (1996)

- ⊕ Out-of-equilibrium processes → no phase transition in the νMSM for $m_H > 72$ GeV! **but Yukawa couplings of sterile neutrinos are small enough to keep them out of thermal equilibrium at $T \sim 100$ GeV**

Asaka, Shaposhnikov (2005)

Baryogenesis in the νMSM goes through leptogenesis

Baryo- and lepto-genesis in the νMSM

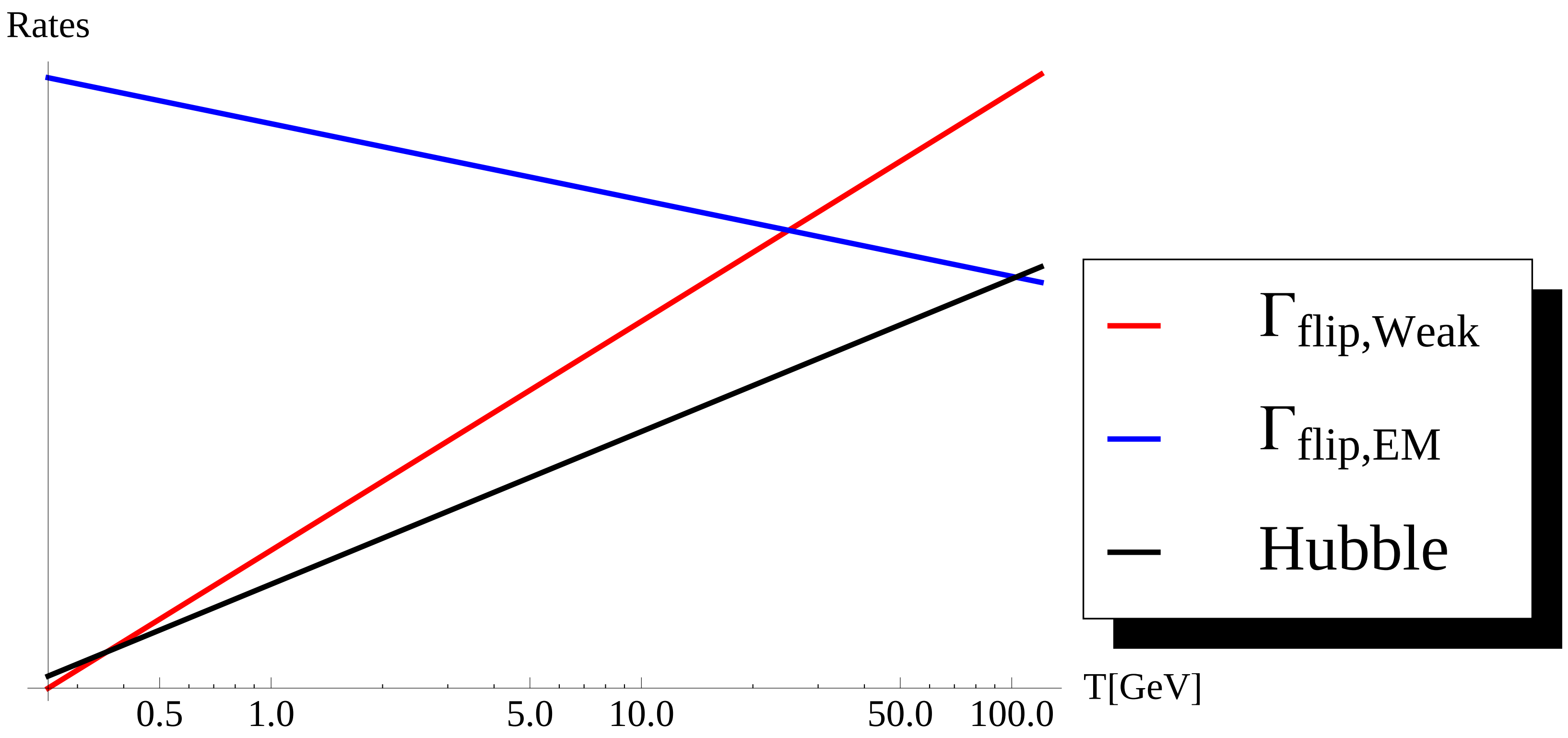


- At $T > T_{\rm sph}$ lepton asymmetry **gets converted** “on-the-fly” to baryon asymmetry by sphalerons — **baryogenesis**
- At $T_{\rm sph} > T > T_+$ lepton asymmetry **continues to be generated** (where $|F|^2 T_+ = \frac{T_+^2}{M}$ and the Yukawa coupling $|F|^2 \sim \frac{M m_{\rm atm}}{v^2}$)
- $\Rightarrow$ In the νMSM $L_{\rm tot}(T_+) \gg B_{\rm tot}(T_{\rm sph})$

Left-right asymmetry in primordial plasma

- Classically, the number of **left** and **right** massless fermions is conserved **independently** (in particular, number of left and right **electrons** at high temperatures)
- Introduce a **chemical potential** $\mu_{L,R}$ for each conserved quantity. The **density matrix** is $\hat{\varrho} = \exp\left(-\frac{\hat{\mathcal{H}}}{T} + \mu_R \hat{N}_R + \mu_L \hat{N}_L\right)$ Equilibrium value of *any* quantity is determined by these numbers (T, μ_L, μ_R)
- Left-handed **electrons** $e_L, \bar{e}_L$ – inherit lepton asymmetry $n_{e_L} \neq n_{\bar{e}_L}$ from active neutrinos through weak processes $(\Gamma_{\text{Weak}} \gg \text{Hubble})$
- The **difference of chemical potentials** $\boxed{\Delta\mu = \mu_L - \mu_R}$ in the electron sector **appears**

Chirality flipping rates in the SM



$$\Gamma_{\textbf{EM}} \propto \alpha^2 T \left(\frac{m}{3T}\right)^2 \qquad \Gamma_{\textbf{W}} \propto G_F^2 T^5 \left(\frac{m}{3T}\right)^2 \qquad H(T) = \frac{T^2}{M_*}$$

$$\frac{\partial \Delta\mu}{\partial t} = -\Gamma_{\text{flip}} \Delta\mu \Rightarrow \Delta\mu \propto e^{-\Gamma_{\text{flip}} t}$$

Source of asymmetry?

- Evolution of the **difference** of chemical potential:

$$\frac{\partial \Delta\mu}{\partial t} = -\underbrace{\boxed{\Gamma_{\mathrm{flip}}}}_{\text{Chirality flipping rate}} \Delta\mu + \underbrace{\boxed{\mathcal{S}(t)}}_{\text{Source of left-right asymmetry}} + \dots$$

- The situation when $\Gamma \gg H$ implies **source-tracking solution** (system forgets initial conditions)

$$\Delta\mu \approx \frac{\mathcal{S}(t)}{\Gamma}$$

works if $\frac{\partial \log \mathcal{S}(t)}{\partial t} \ll \Gamma_{\mathrm{flip}}$ – the faster chirality flipping the better

Maxwell equations

- The presence of different number of left and right fermions leads to additional terms in the effective Lagrangian for gauge fields

- As a result Maxwell equations get term current, proportional to $\Delta\mu$:

Vilenkin (1978)

Redlich & Wijewardhana (1985);

Fröhlich et al. (2000–2001)

$$\begin{aligned}
\mathrm{curl}\,\vec{E} &= -\frac{\partial \vec{B}}{\partial t}\\
\mathrm{curl}\,\vec{B} &= \sigma\vec{E} + \frac{e^2}{4\pi}\Delta\mu\vec{B}\\
\frac{\partial\Delta\mu}{\partial t} &\propto \boxed{\frac{e^2}{16\pi^2}\vec{E}\cdot\vec{B}} - \Gamma_{\mathrm{flip}}\Delta\mu
\end{aligned}$$

Chiral anomaly

Joyce & Shaposhnikov

Giovannini & Shaposhnikov (1998

- If $\Delta\mu$ is a function of t **only** Maxwell equations have an **exponentially growing solution** for **one of the two** circular polarizations ⇒ **helical magnetic fields**

CMF instability in the νMSM

- At $T \geq T_+$ lepton asymmetry in the left neutrino + left-electron sector $\Rightarrow$ $\Delta\mu$ between left and right electrons appears…
- …and instability quickly develops: $B \propto e^{\lambda_k(t)}$ with

$$\lambda_{\max} = \left(\frac{\alpha\bar\mu/T}{2\pi}\right)^2 \frac{\eta(T)}{\sigma/T} \approx 5 \left(\frac{\bar\mu/T}{10^{-4}}\right)^2 \frac{100\text{ GeV}}{T}$$

- …generating **maximally helical** magnetic fields …
- …with the total energy

$$\frac{\rho_B}{T^4} = \left(\frac{\bar\mu}{T}\right)^3 \frac{\pi^{3/2}}{\lambda_{\max}^{1/2}} e^{\lambda_{\max}/4}$$

- …in the wide range of length scales

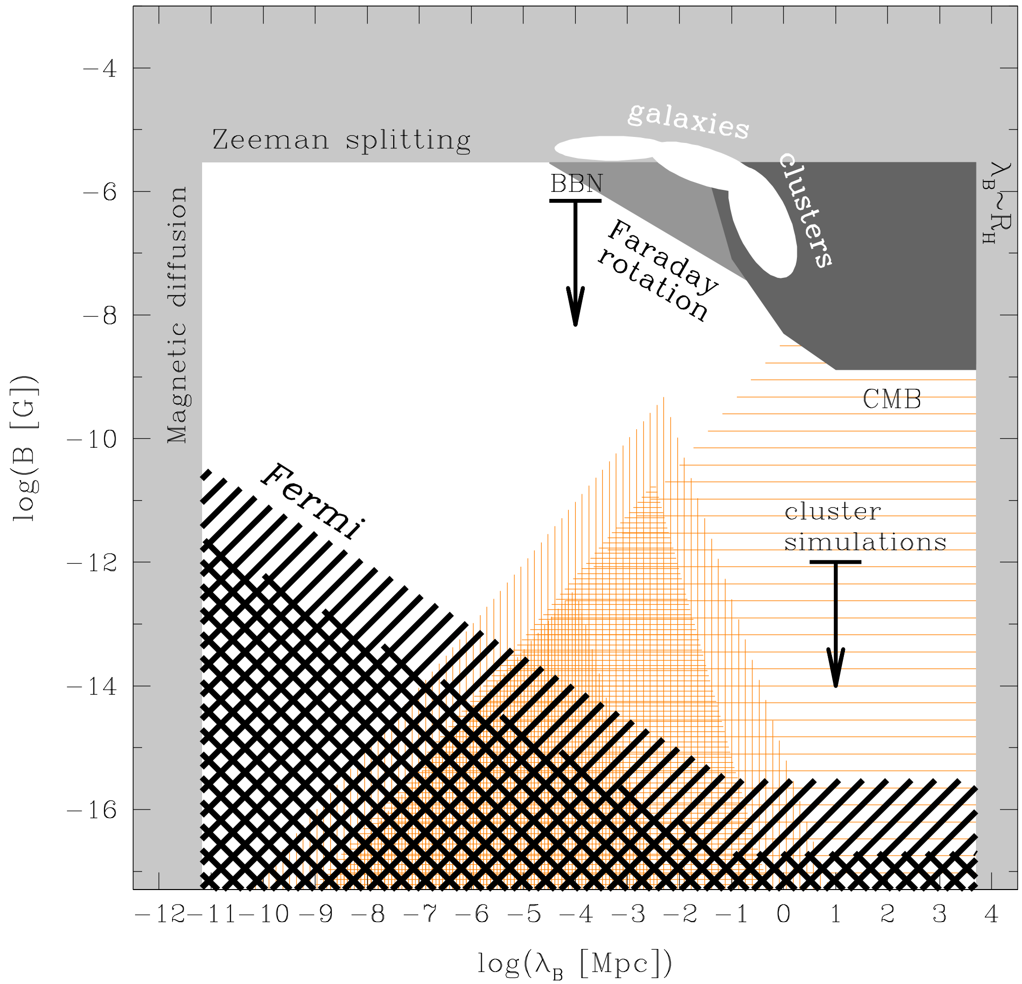
Magnetic fields in the νMSM

- Magnetic fields, generated in the νMSM *below* 100 GeV are:
  - Maximally helical (sign of helicity determined by the sign of baryon asymmetry)
  - Energetic (magnetic energy density can be $\sim$ total radiation density)
  - The generation occurs on subhorizon scales, but modes up to 10^{-4} of the horizon (at $T \sim 10$ GeV) can be generated)
- Their survival until today is a matter of complicated magneto-hydrodynamical evolution

The leptogenesis in the νMSM thus leads to the **baryogenesis** and generation of **potentially observable** cosmological magnetic fields

Evidence for magnetic fields in voids?

Our **very preliminary** estimates show that the fields with $B \sim 10^{-16} - 10^{-13}$ G and correlation scale $1\,\mathrm{pc} - 1$ kpc can survive in the νMSM



Banerjee & Jedamzik (2004)

Jedamzik & Sigl (2010)

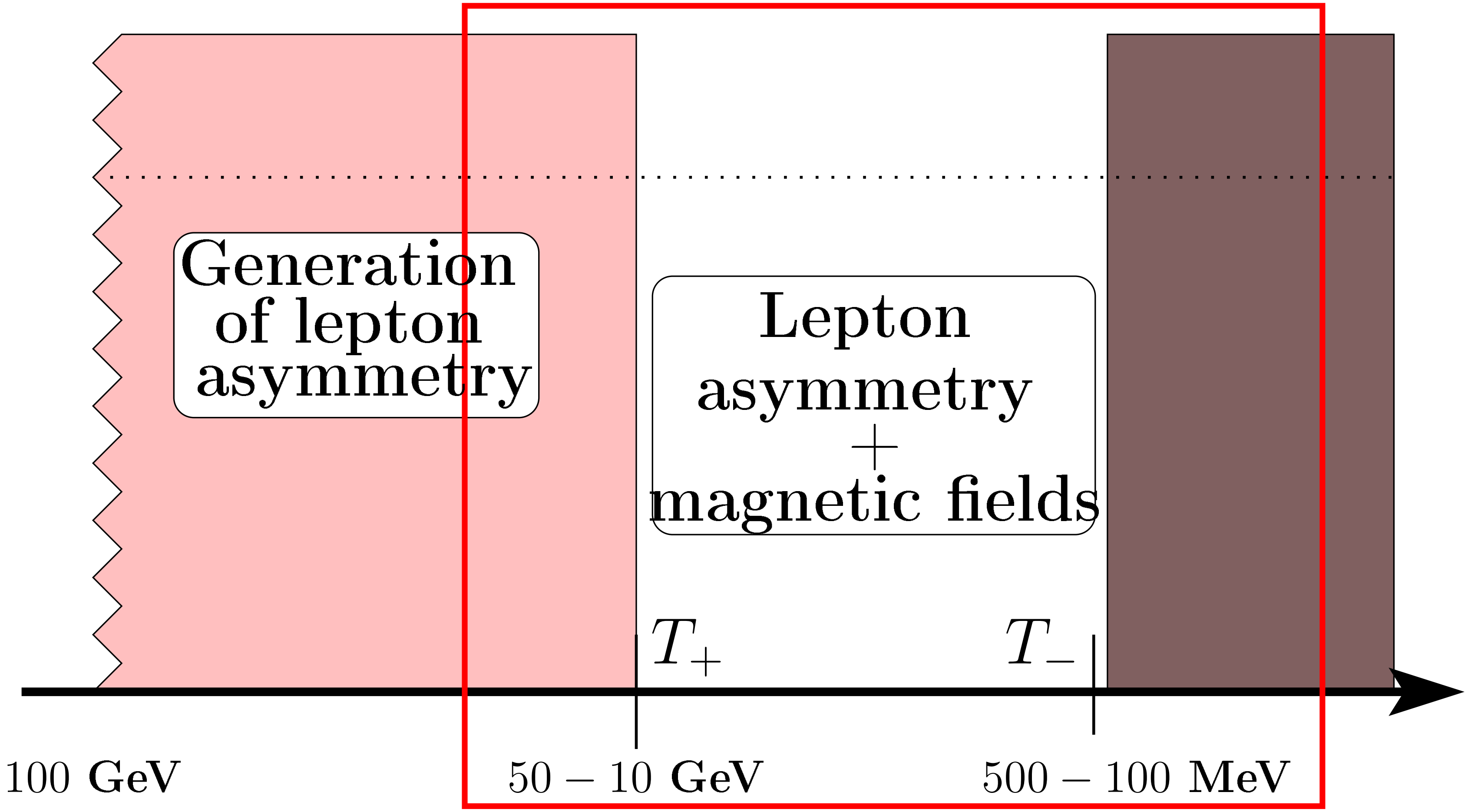
Boyarsky, **O.R**
in progress

Neronov & Vovk, Science (2010);

Dolag et al. (2010);

Tavecchio et al. (2011)

Magnetic fields and chiral asymmetry



Magnetic fields and chiral asymmetry

- At $T = T_+ \sim \mathcal{O}(1)$ GeV sterile neutrino enter equilibrium with primordial plasma and the source of lepton asymmetry disappears

- The presence of **helical magnetic fields re-**generates lepton asymmetry in plasma

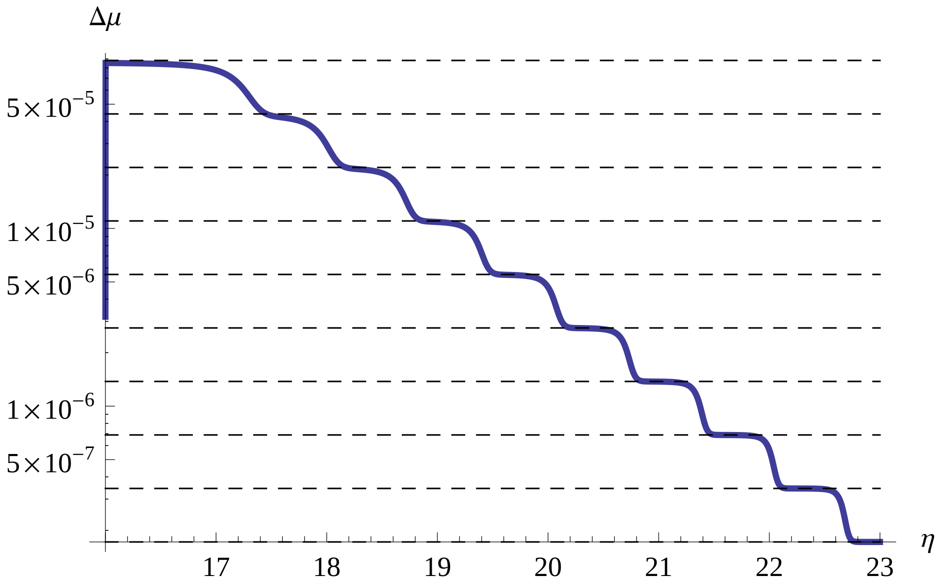
$$\begin{aligned} \frac{\partial B}{\partial t} &= \frac{1}{\sigma}\nabla^2 B + \frac{\alpha\Delta\mu}{\sigma}\operatorname{curl} B \\ \frac{\partial\Delta\mu}{\partial t} &\propto \frac{1}{\alpha}\frac{B\times\operatorname{curl} B}{\sigma} - \frac{\alpha\Delta\mu B^2}{\sigma} - \Delta\mu\Gamma_{\text{flip}} \end{aligned}$$

- Chemical potential settles at the level

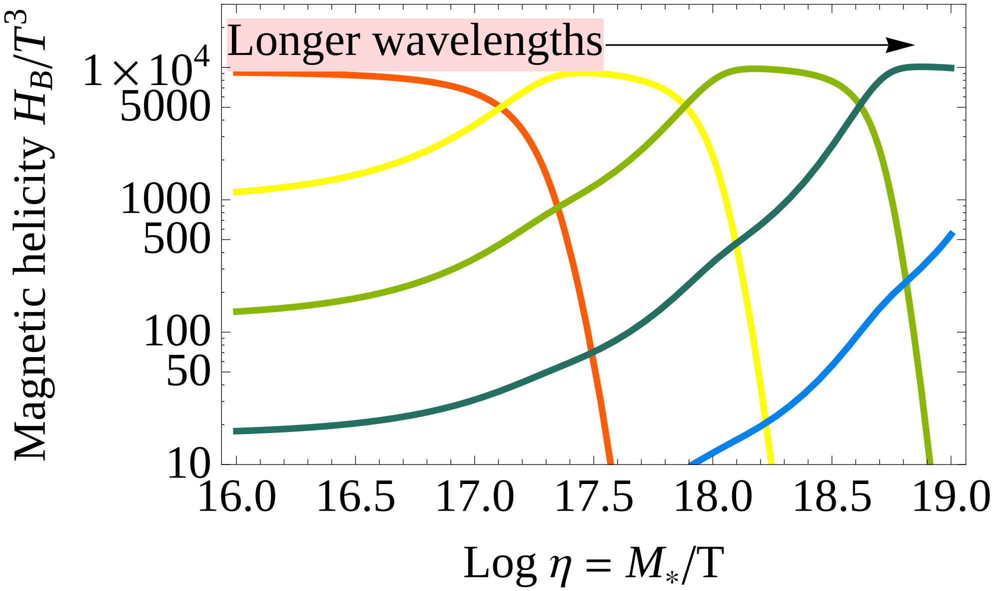
$$\Delta\mu \approx \frac{B\times\operatorname{curl} B}{B^2 + \sigma\Gamma_{\text{flip}}}$$

- Creates **negative feedback loop** – opposes magnetic diffusion

Chemical potential/helicity evolution

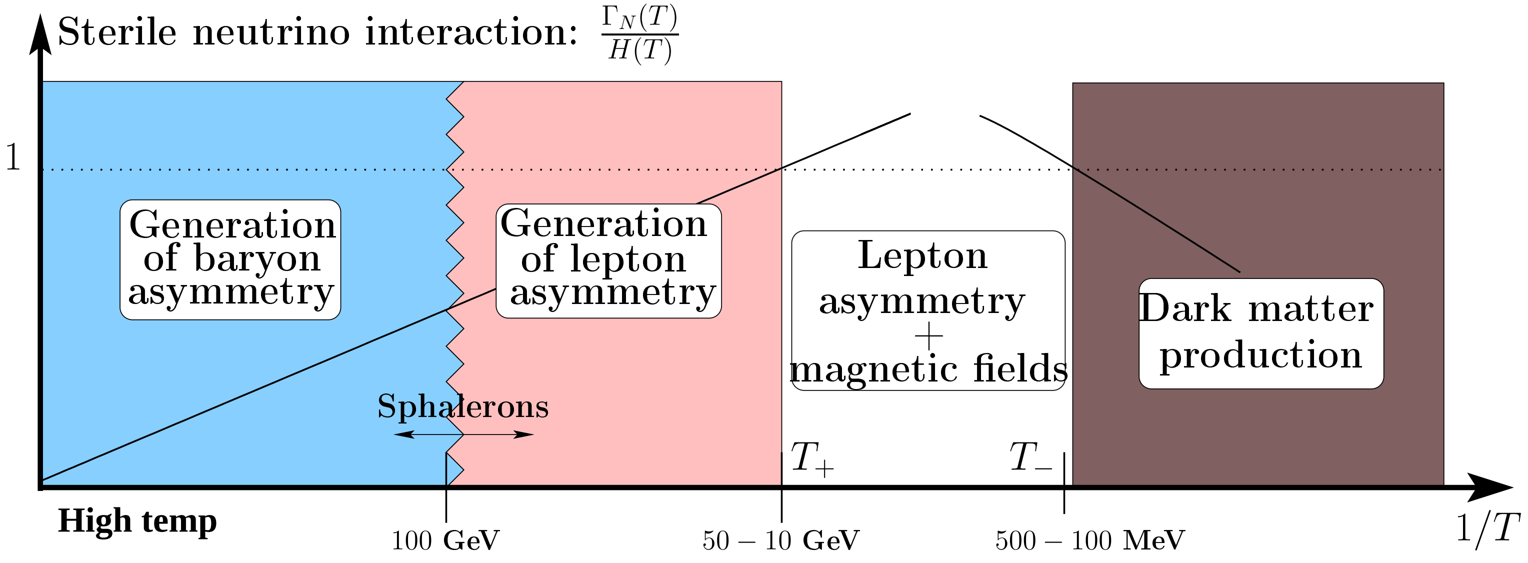


- Chemical potential is generated fast from $\Delta\mu \approx 0$
- Then it decreases slowly in time
- Its presence undoes effects of *magnetic diffusion*



Helicity gets pumped into longer and longer modes (from red to blue colors)

Chemical potential/helicity evolution



- Chemical potential is generated from helical magnetic fields and **survives** till temperatures $\mathcal{O}(100)$ MeV
- Dissipation due to magnetic diffusion is **much slower than exponential** ⇒ Helicity and magnetic energy survive for longer. The magnetic energy/helicity spectrum **reddens**
- This whole process stops when **chirality flipping reactions** become too fast (as compared to magnetic energy density)

Properties of sterile neutrino DM

- The third sterile neutrino is a **dark matter** particle in the νMSM
- Mass can be **anything** higher than ~ 300 eV
- Can **decay** into the SM particles (with the lifetime at least 10^{26} sec)
- Sterile neutrino DM never been in thermal equilibrium in the early Universe (Has a non-universal **non-thermal** spectrum of primordial velocities)
- Production sensitive to the presence of **lepton asymmetry** in plasma
- Modifies formation of structures at sub-Mpc scales (warm dark matter)

Tremaine & Gunn (1979)

Boyarksy, **O.R** et al. (2008)

Lifetime of sterile neutrino DM candidate

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

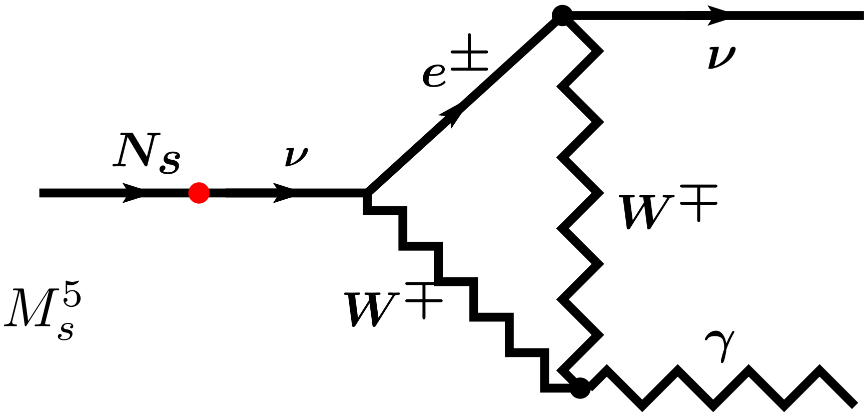
Wolfenshtein
Pal (1982)

- 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

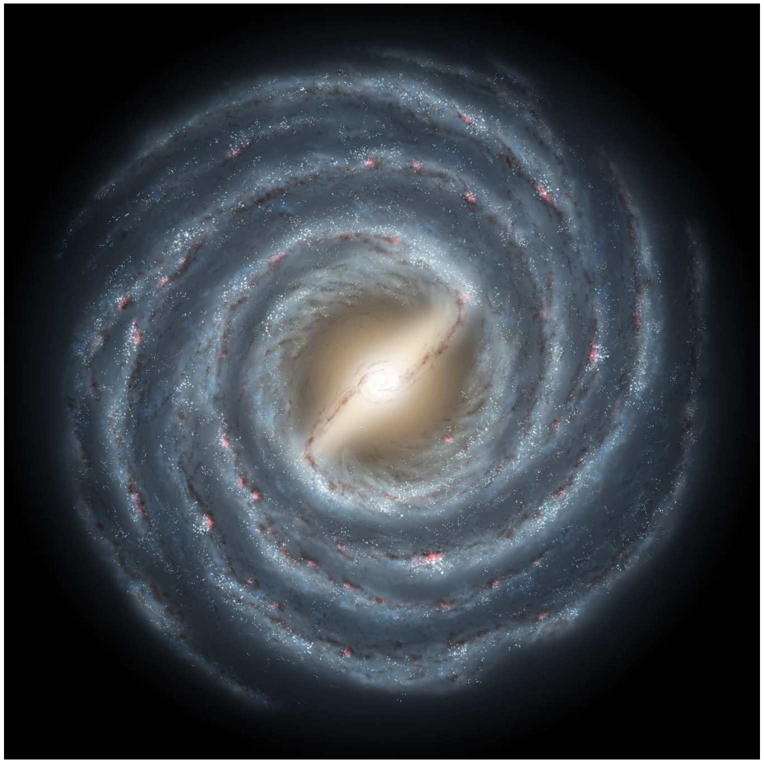
Abazajian
Fuller Tucker
(2001)

- 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)

Decay of sterile neutrino DM

- DM may be decaying with a cosmologically long life-time (age of the Universe or even longer). Can we detect such decay?
- **Yes!** if you multiply a small number (probability of decay) with a large number (typical amount of DM particles in a galaxy $\sim 10^{70}$–10^{100})



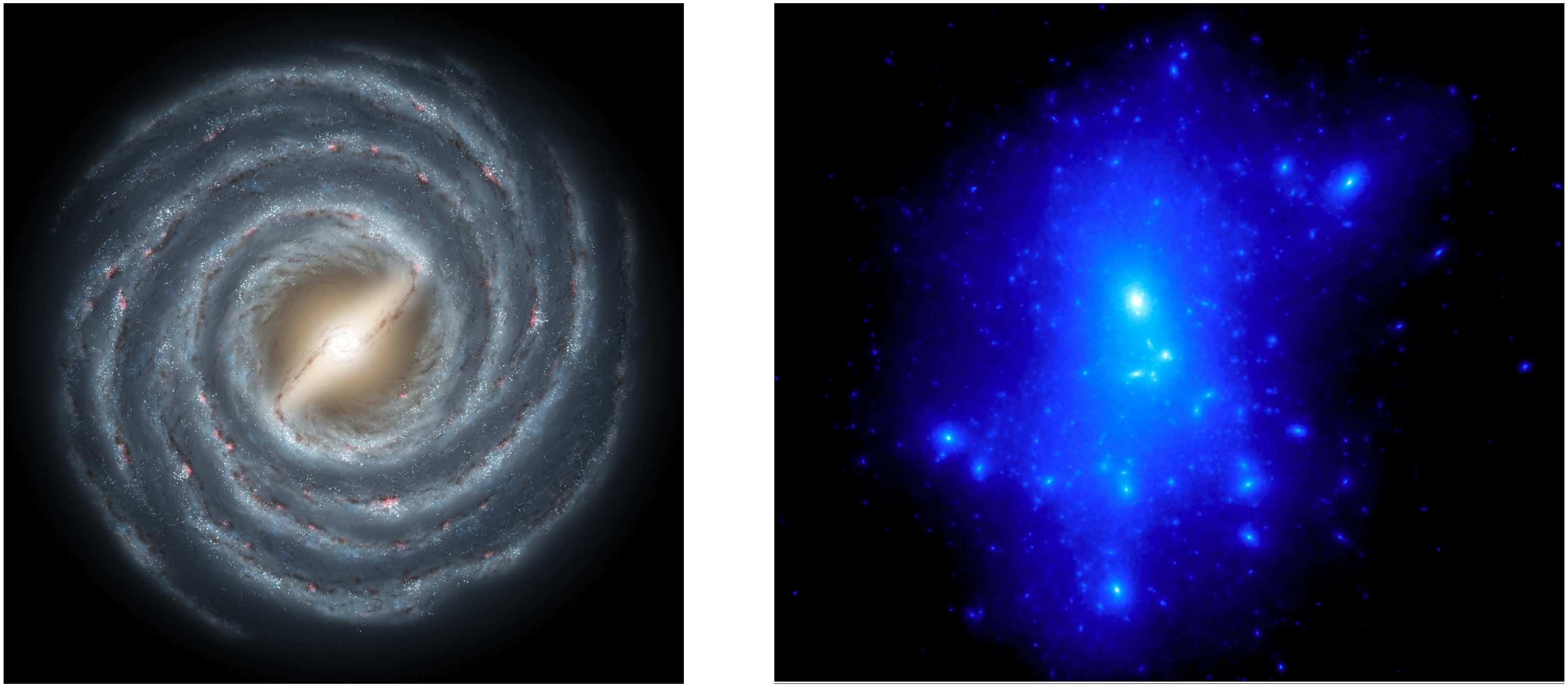
$$\text{Signal} \propto \int_{\text{line of sight}} \rho_{\text{DM}}(r)\,dl$$

Expected signal from the galaxy at a particular energy

Decay of sterile neutrino DM

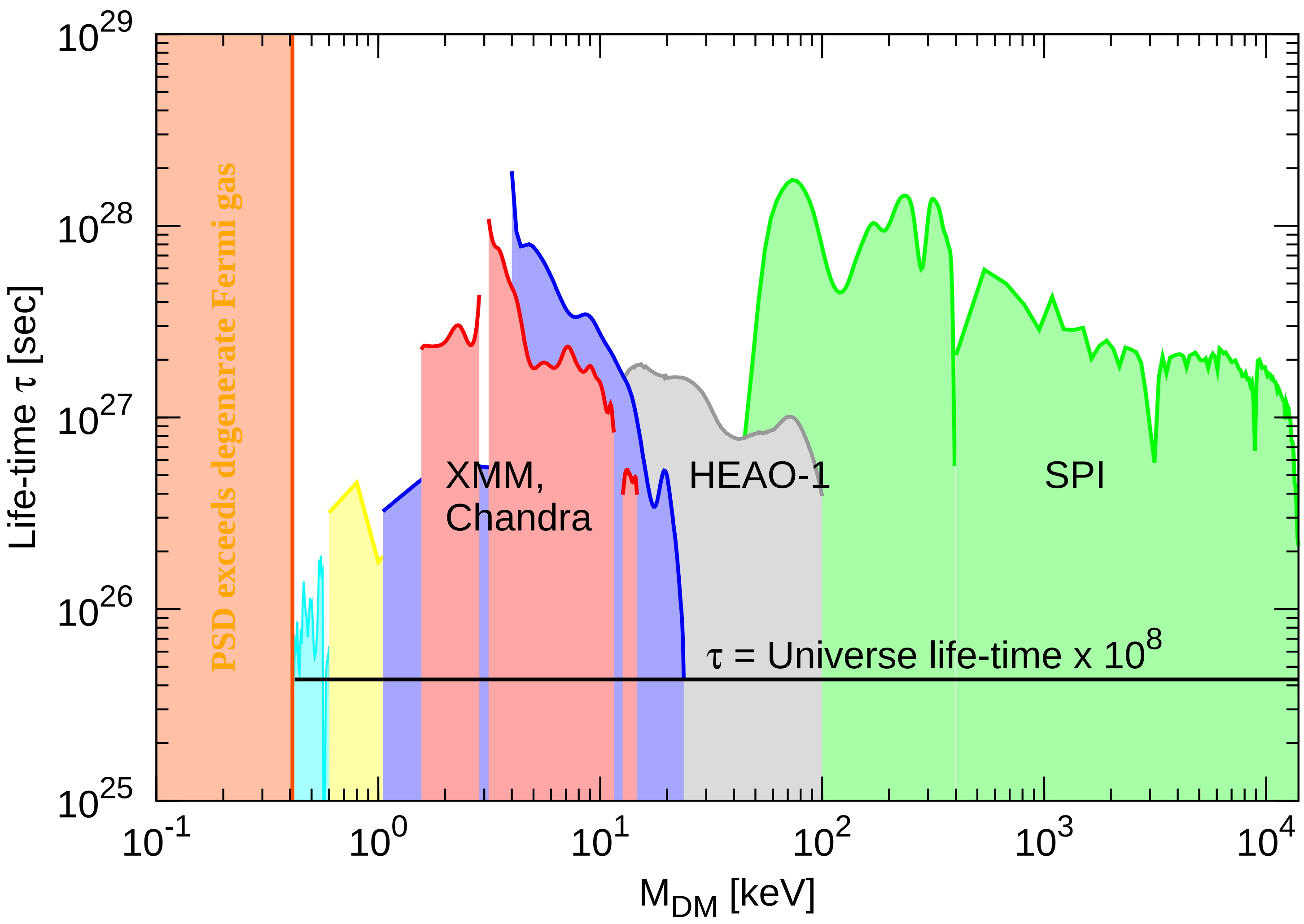
- DM may be decaying with a cosmologically long life-time (age of the Universe or even longer). Can we detect such decay?

- **Yes!** if you multiply a small number (probability of decay) with a large number (typical amount of DM particles in a galaxy $\sim 10^{70}$–10^{100})



Expected signal from a galaxy at a particular energy (simulation from B. Moore)

Restrictions on life-time of decaying DM



Results of almost **20** published works.

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

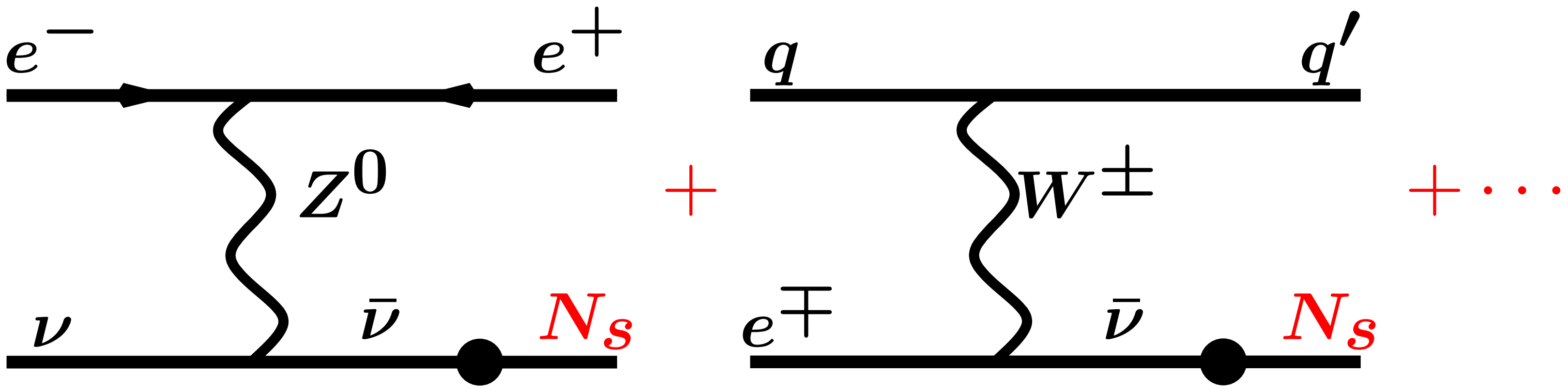
LMC+MW(XM
Boyarsky, **O.R**
et al. 2006

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

Production through mixing



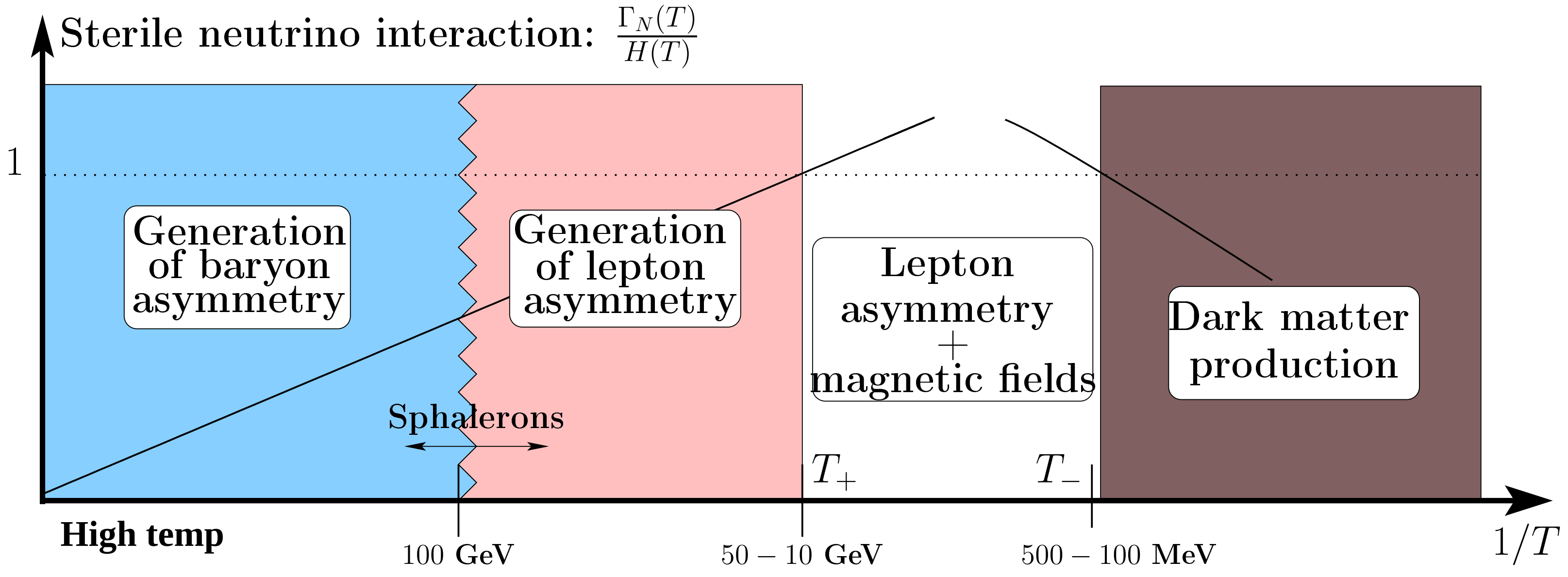
- Sterile neutrinos have **non-equilibrium spectrum of primordial velocities**, roughly proportional to the spectrum of active neutrinos

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

- Production is sharply peaked at

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

Resonant production



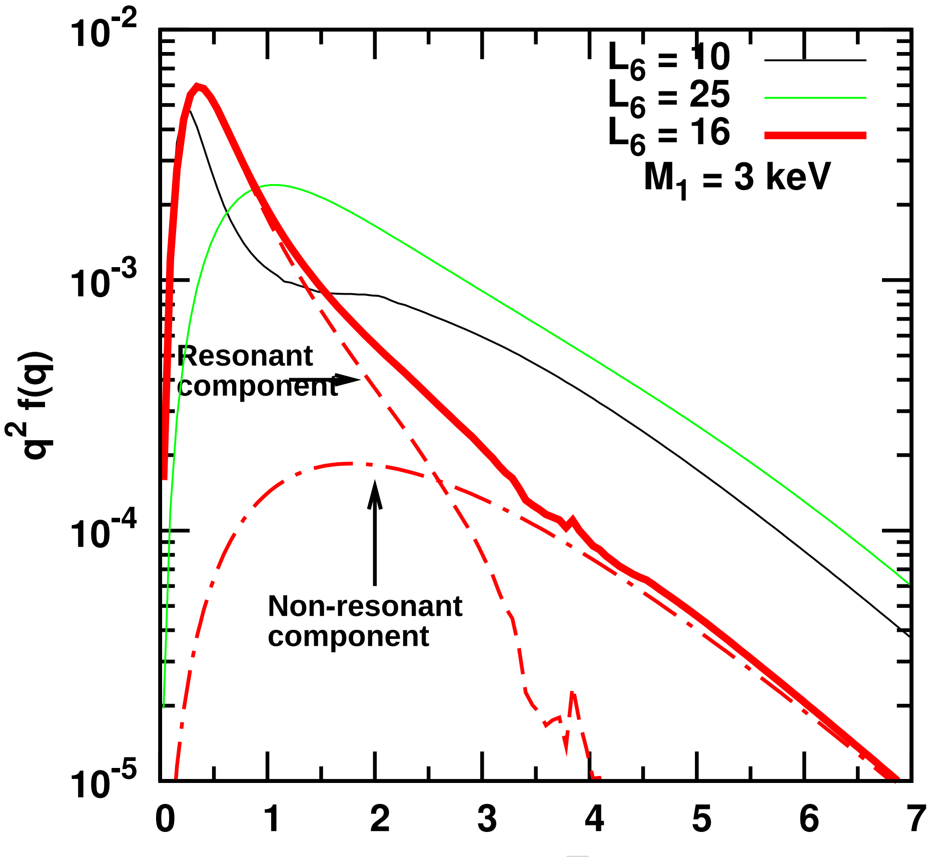
- The lepton asymmetry gets carried over to by magnetic fields
- The presence of lepton asymmetry in primordial plasma at $T \sim \mathcal{O}(100)$ MeV makes active-sterile mixing much more effective – **resonant production** of sterile neutrino dark matter

Shi Fuller'98
Laine, Shaposhnikov

RP sterile neutrino spectra

In the minimal model explaining neutrino oscillations and dark matter (3 sterile neutrinos and nothing more), sterile neutrino DM has spectrum with **two components**:

Laine, Shaposhnikov
Boyarsky, **O.R.**, Shaposhnikov



- Maximal amount of DM produced resonantly:

$$\Omega_{\text{RP}} h^2 \propto M_{\text{DM}} \times \frac{n_\nu - n_{\bar\nu}}{n_\nu + n_{\bar\nu}}$$

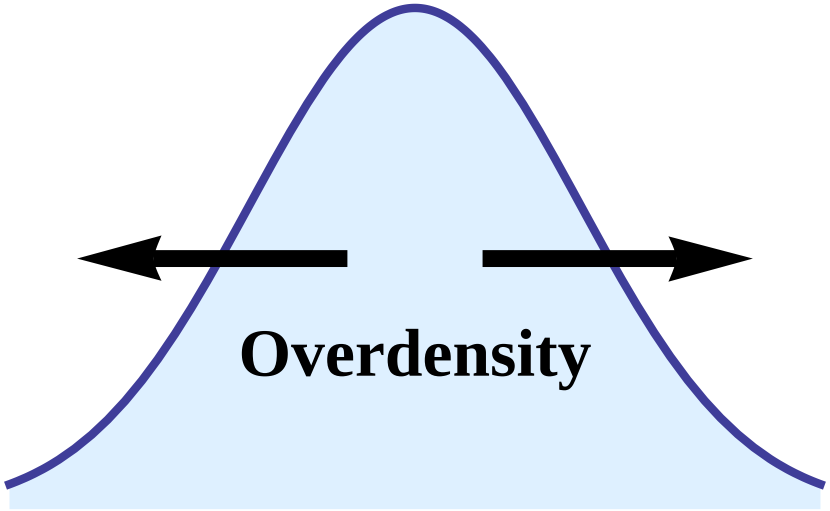
- Colder (**resonant**) component with $\langle p \rangle \ll T_\nu$
- Warmer (**non-resonant**) component with $\langle p \rangle \sim 3T_\nu$

Free-streaming

- Sterile neutrino DM is produced at temperatures $T \sim 100$ MeV (for masses $\sim$ keV – created relativistic $\Rightarrow$ **warm dark matter**
- Relativistic particles **free stream** out of overdense regions and smooth primordial inhomogeneities

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

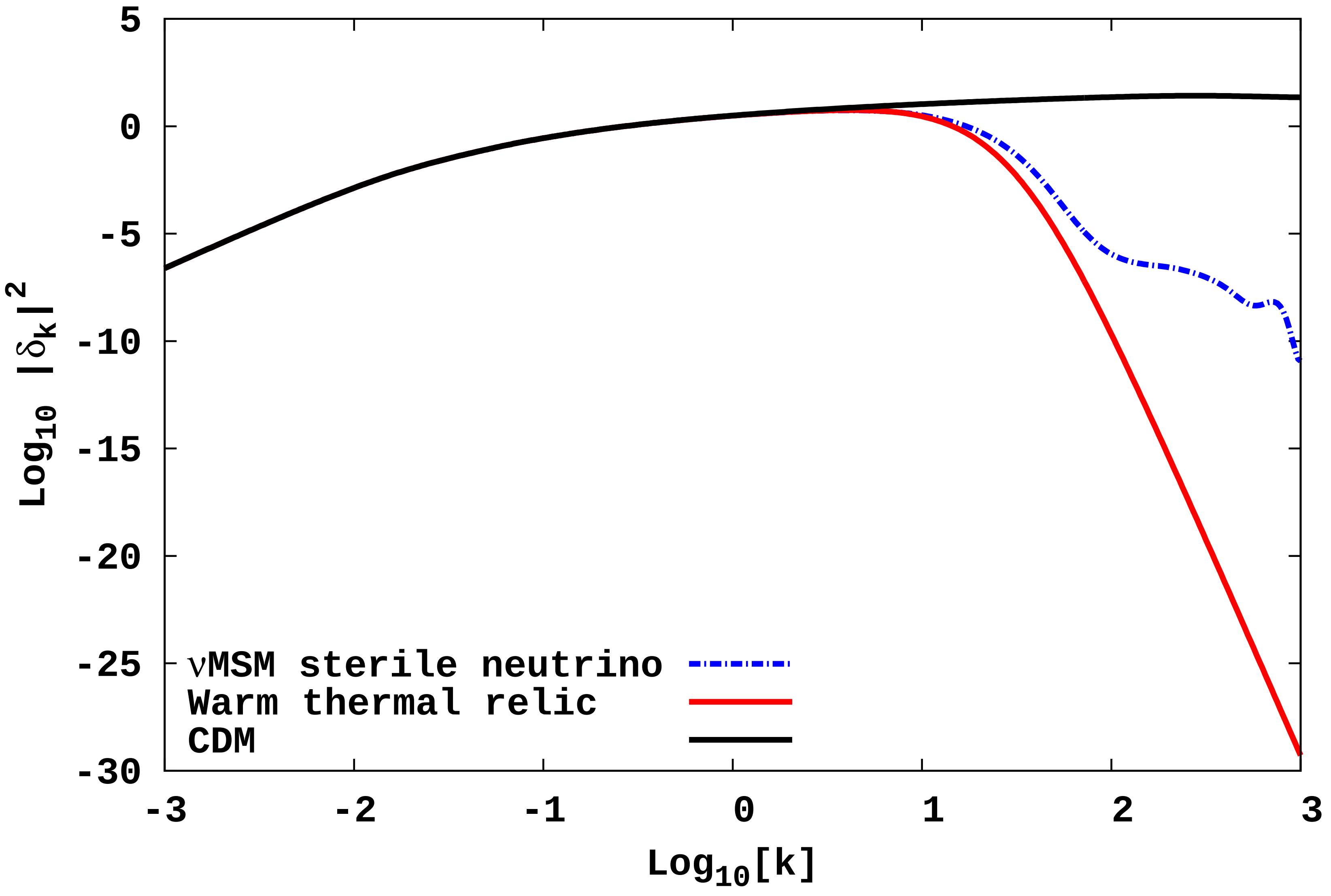
- Power spectrum of primordial density perturbations is suppressed at scales below **free-streaming horizon**



- Scales of interest:

$$\lambda_{FS}^{co} \sim 1\ \text{Mpc} \left(\frac{\text{keV}}{M_{\text{sterile}}}\right)$$

Suppression of power spectrum



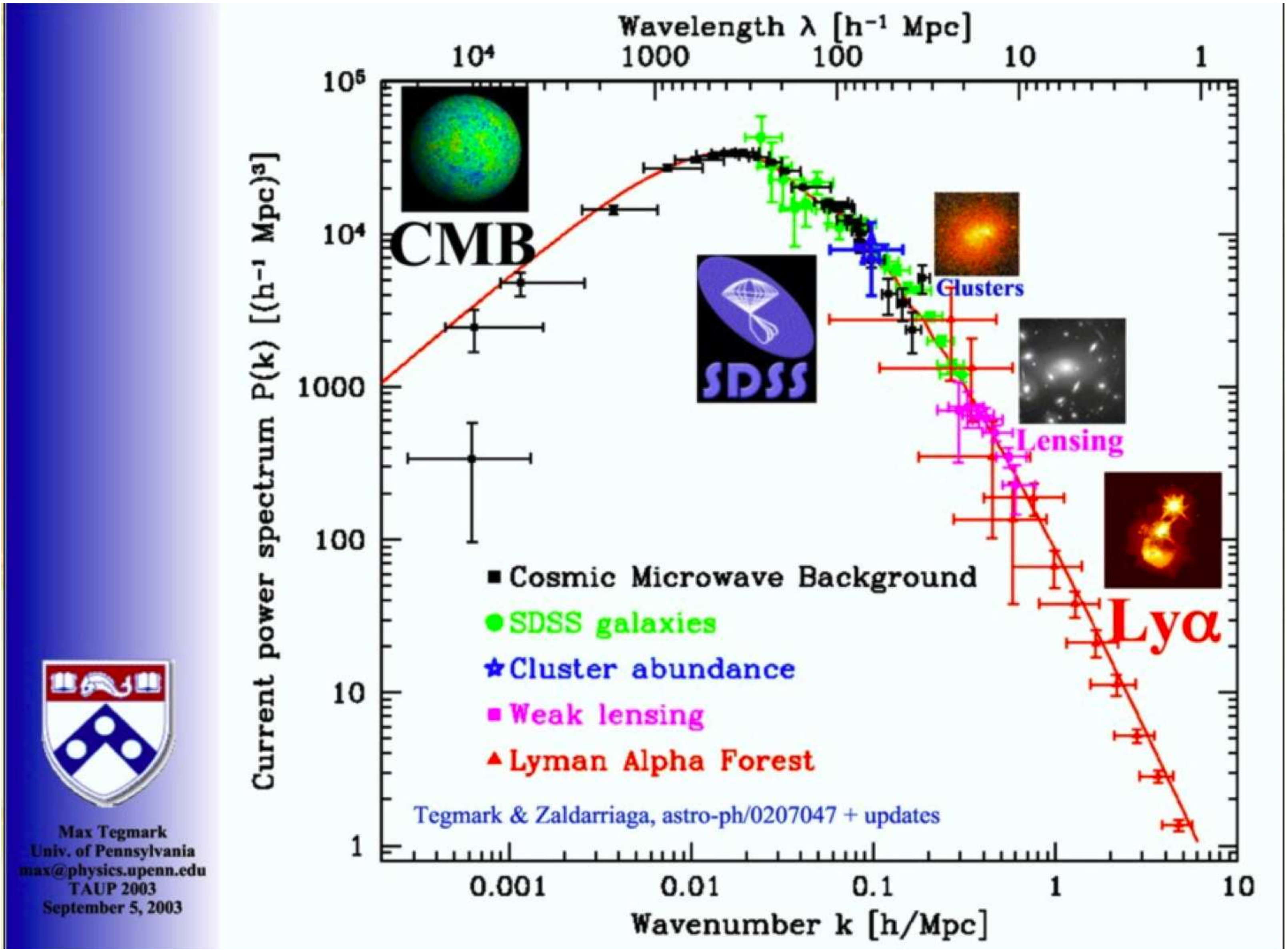
How to probe primordial velocities?

- Primordial velocities **affect**:
  - **Power-spectrum** of density fluctuations (suppress normalization at large scale)
  - **Halo mass function** (number of halos of small mass decreases)
  - Dark matter **density profiles** in individual objects
- Scales probed by CMB and LSS experiments (linear regime of perturbation growth)

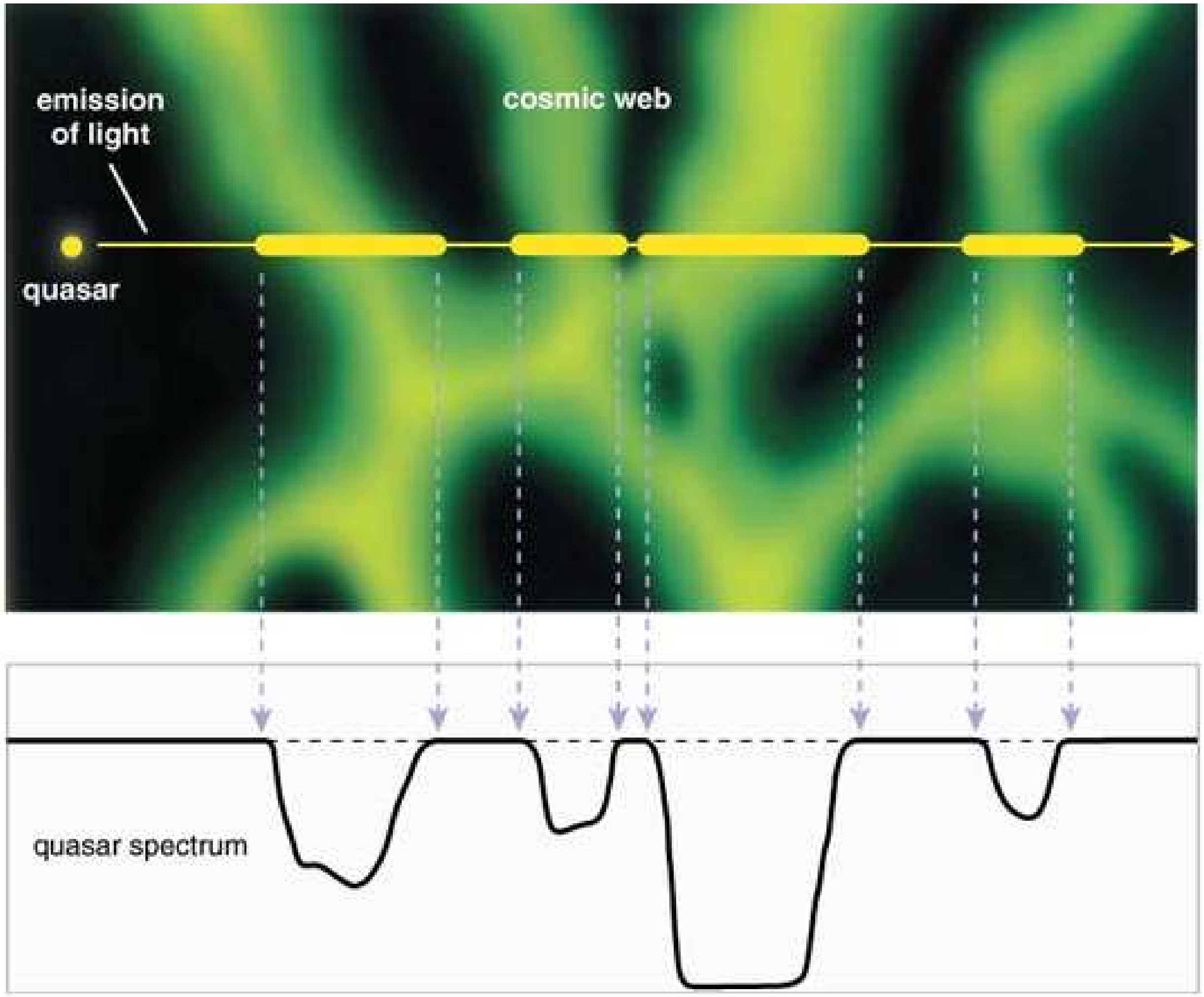
$$k \simeq \ell \times \frac{H_0}{2} = \frac{\ell}{6000} \frac{h}{\text{Mpc}}$$

- Is sensitive up to scales $k \lesssim 0.1\ h/$ Mpc
- Smaller scales? Non-linear stage of structure formation

How to measure power spectrum

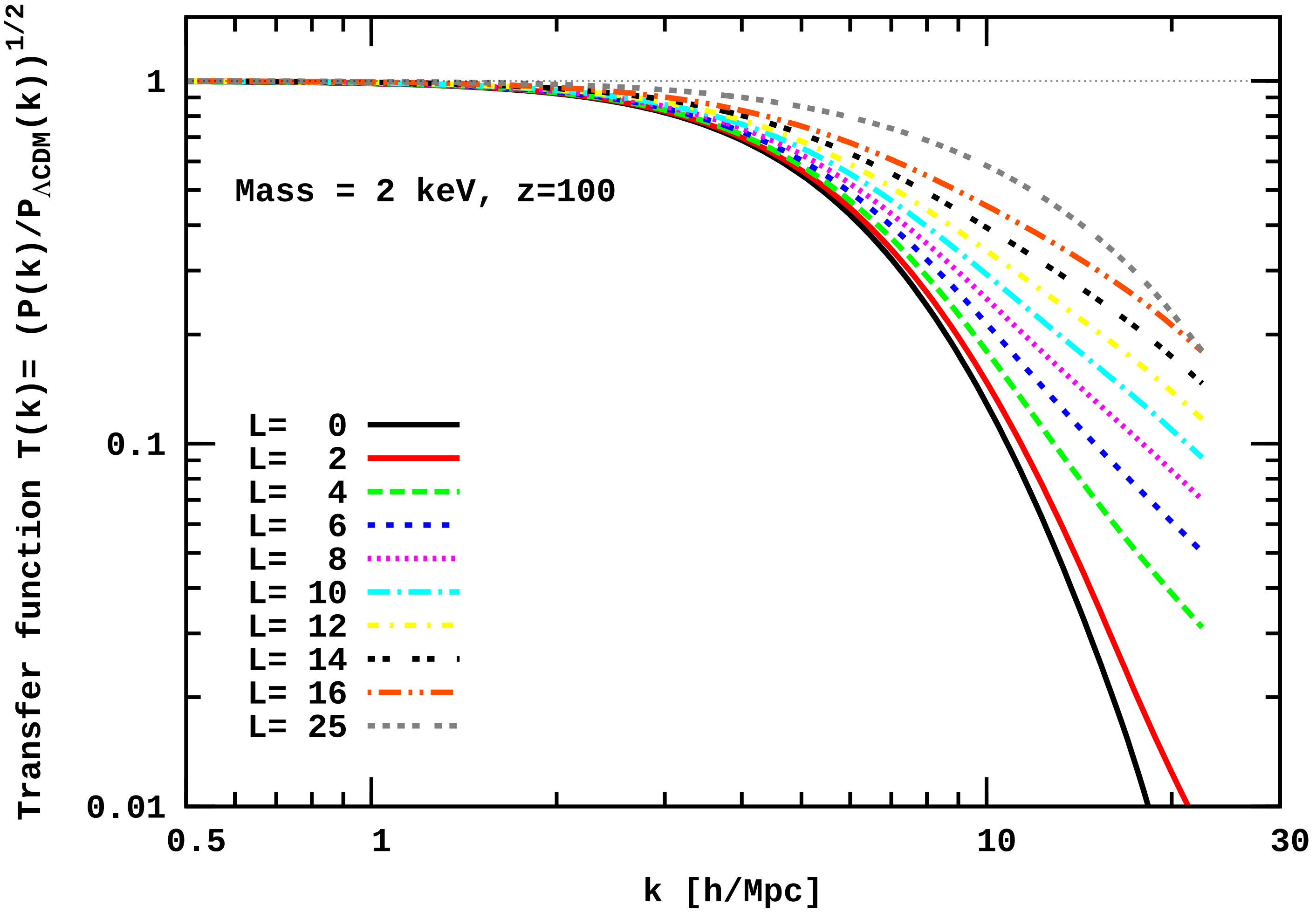


Lyman-α forest and cosmic web



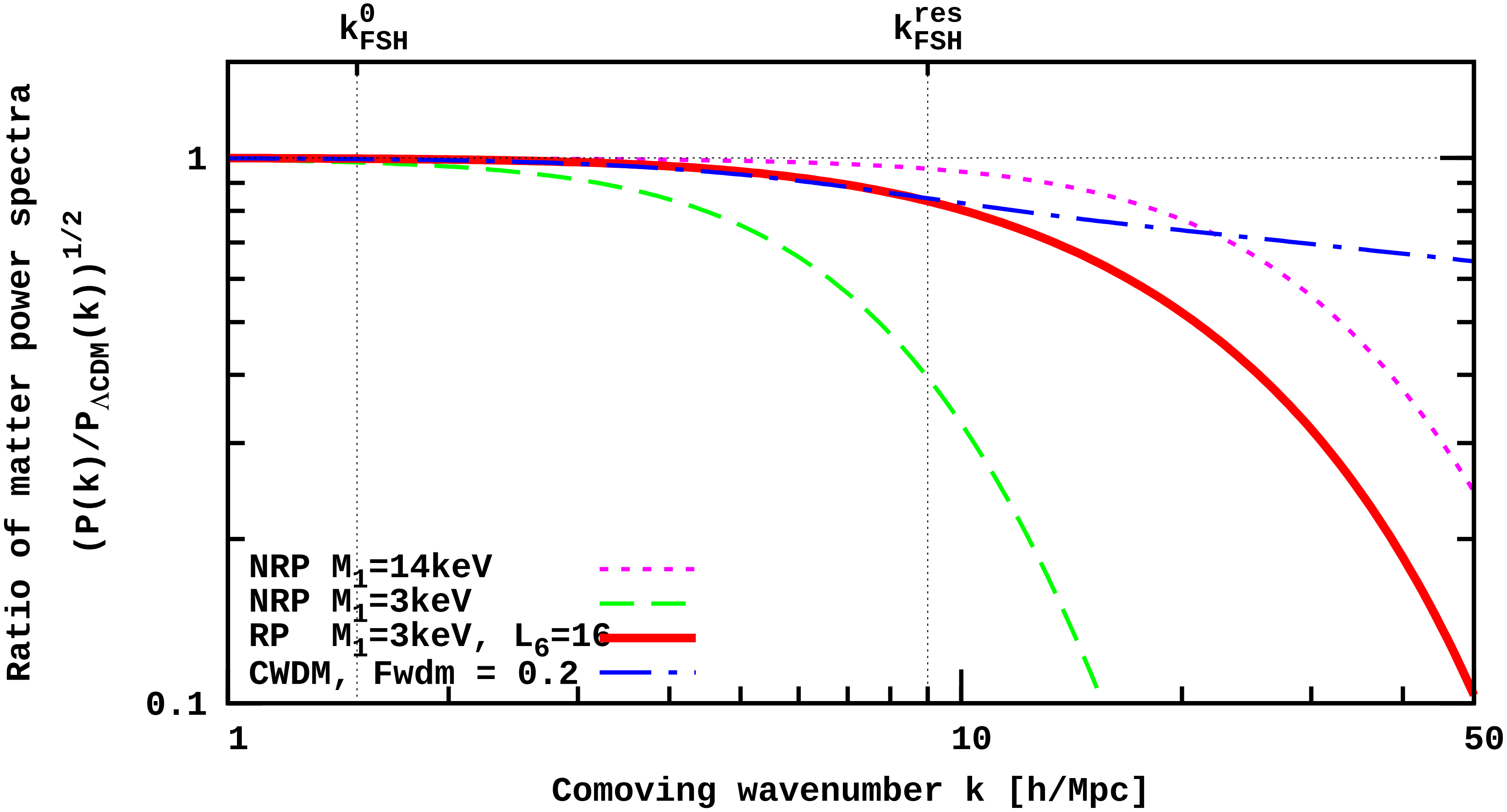
Neutral hydrogen in intergalactic medium is a tracer of overall matter density. Scales $0.3h/$Mpc $\lesssim k \lesssim 3h/$Mpc

Free-streaming of sterile neutrino DM



Transfer functions of resonantly produce sterile neutrinos with the mass 2 keV, produced at different lepton asymmetries

Power spectrum for sterile neutrinos



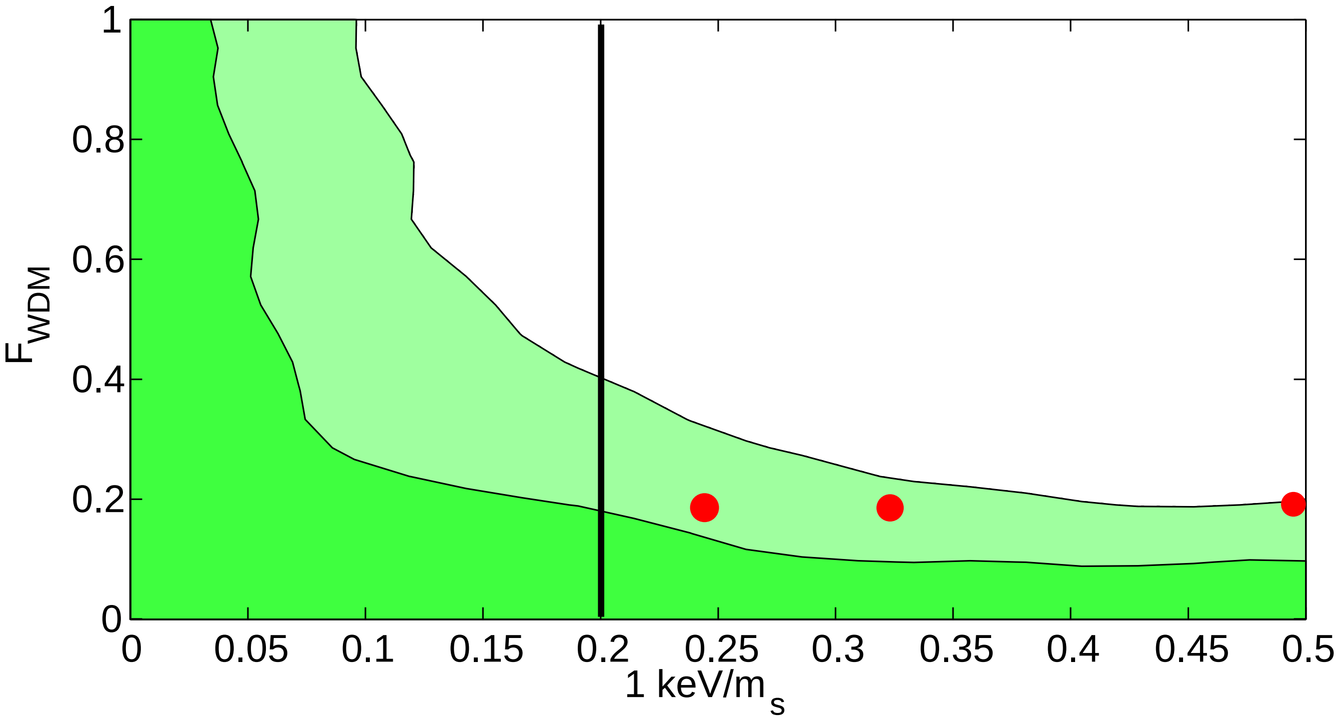
Boyarsky, Lesgourgues, **O.R.**, Viel JCAP, PRL 2009;

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

Lyman-α bounds for sterile neutrinos

- Revised version of these bounds in CDM+WDM (mixed, CWDM) models demonstrates that
  - The primordial spectra **are not described by free-streaming**
  - There exist viable models with the masses as low as 2 keV

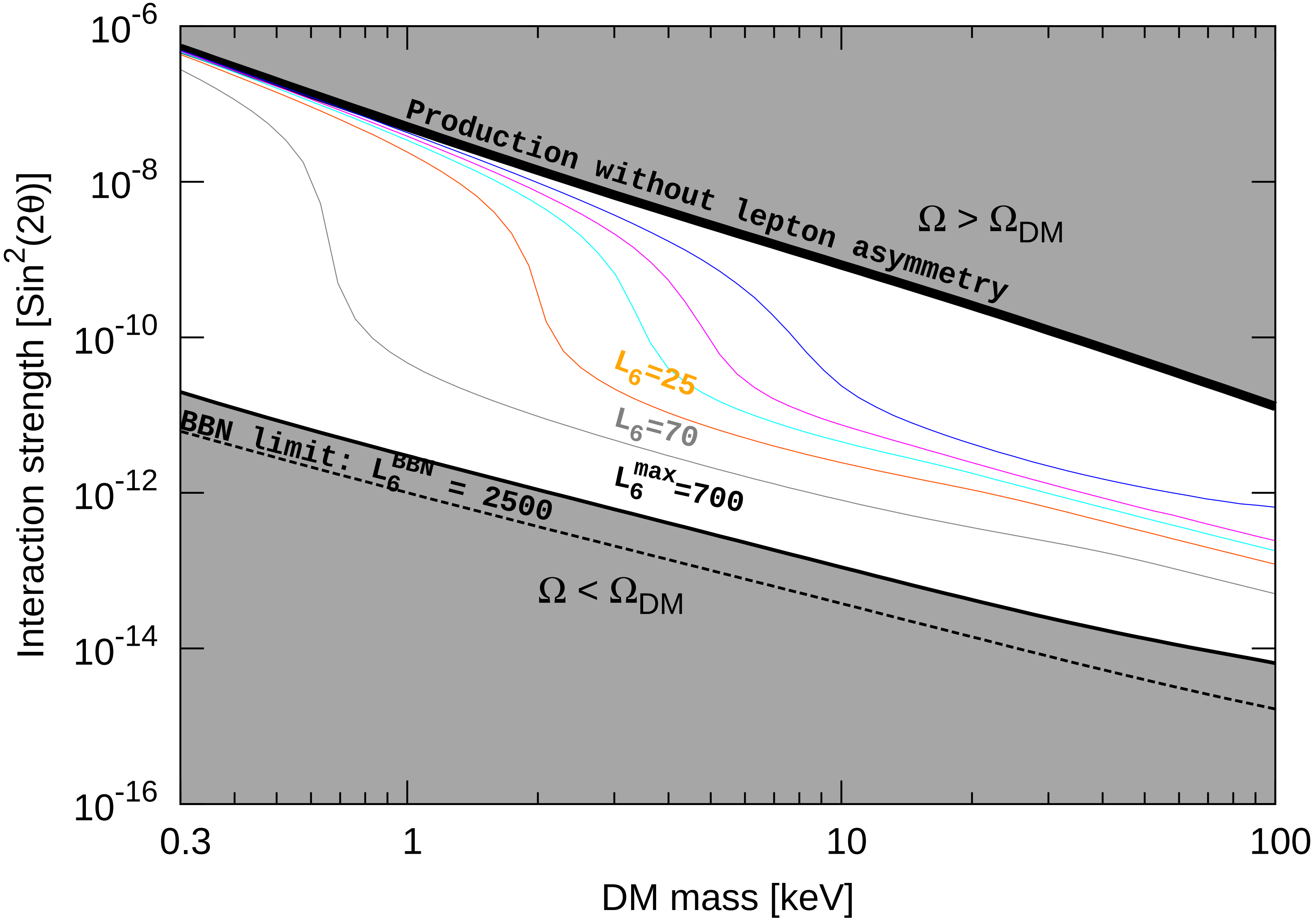
Boyarsky, **O.R.**, Lesgourgues, Viel JCAP & PRL (2009)



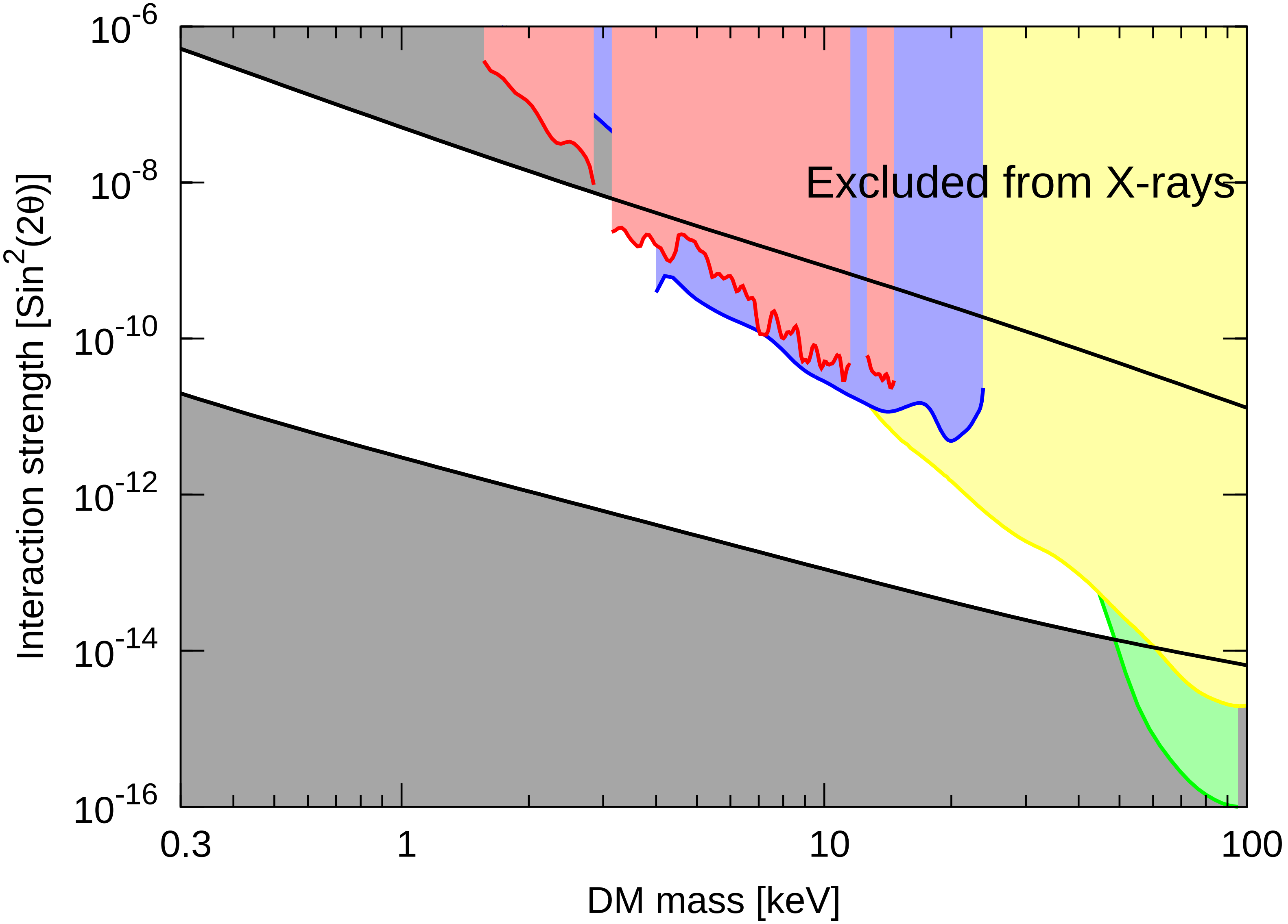
Window of parameters of sterile neutrino DM

Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov



Window of parameters of sterile neutrino DM

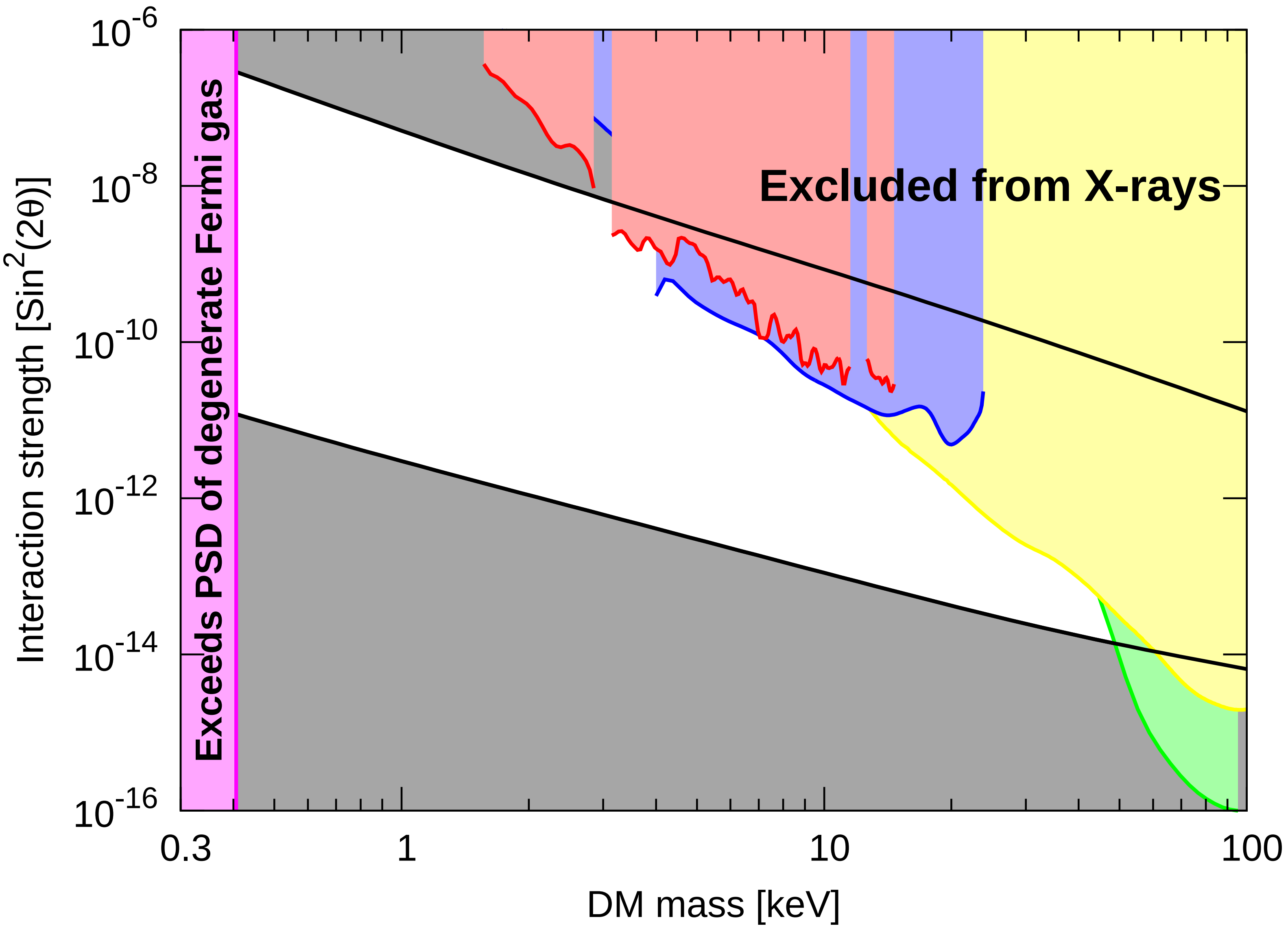


Asaka, Laine,
Shaposhnikov

Laine,
Shaposhnikov

O.R. and
many others
2005-2010

Window of parameters of sterile neutrino DM

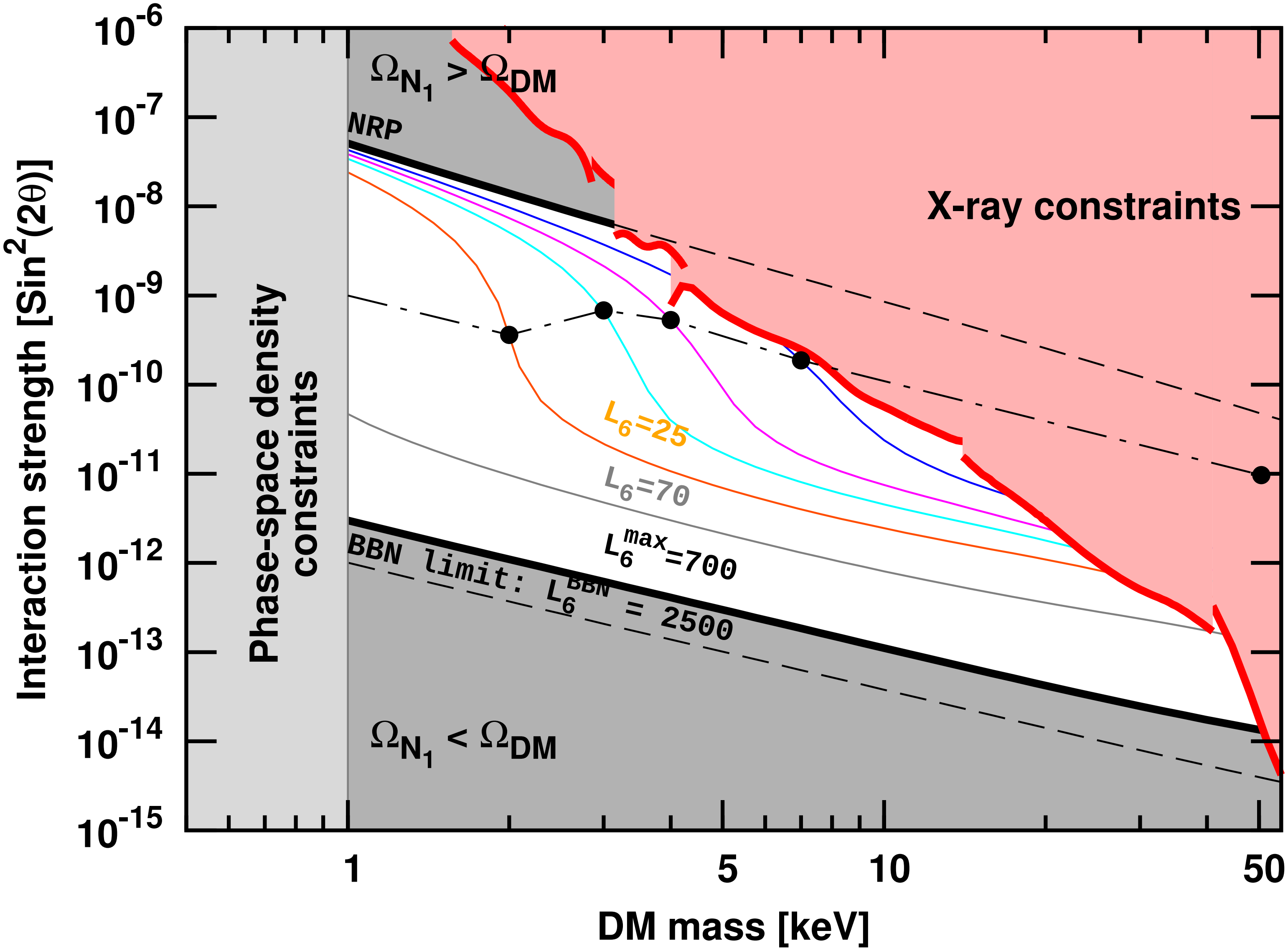


Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov

O.R. and many others 2005-2010

Sterile neutrino DM in the νMSM



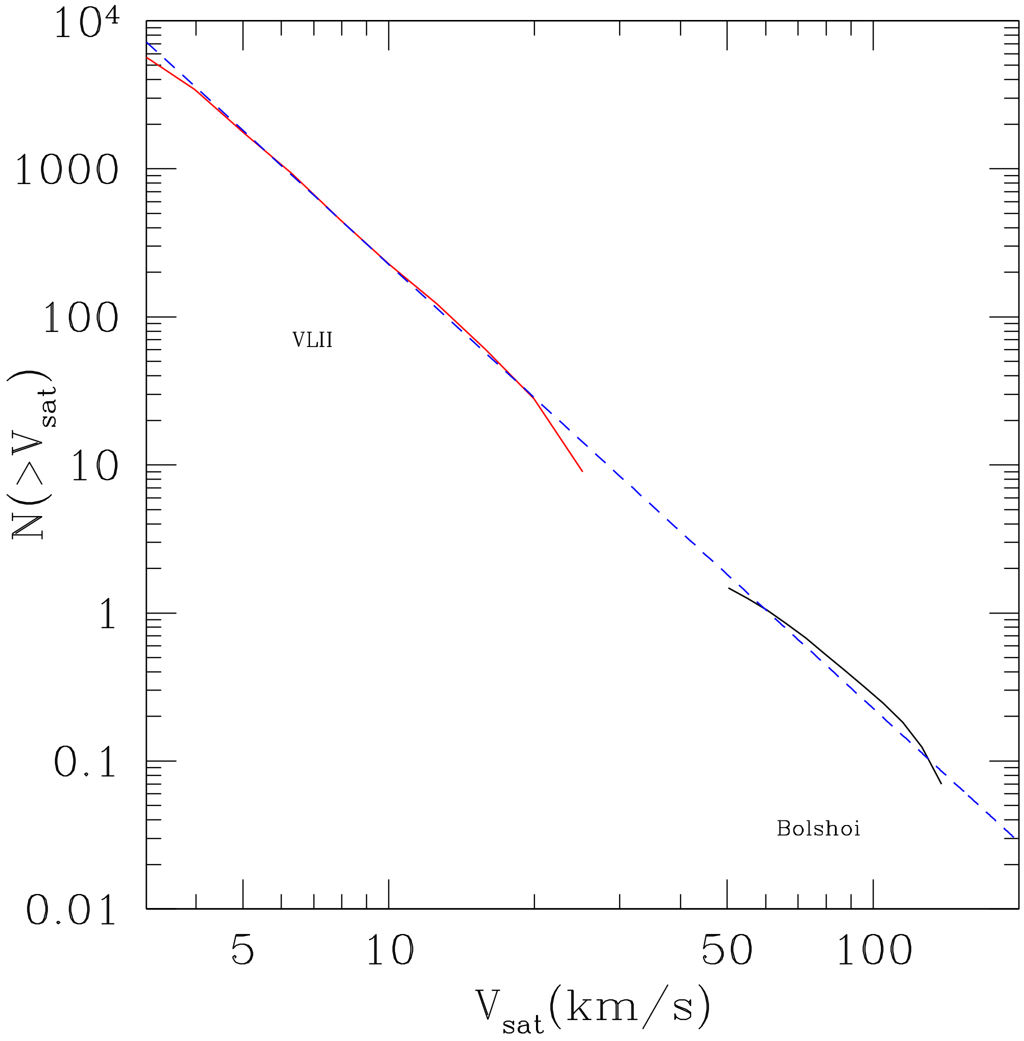
Boyarsky,
O.R.,
Lesgourgues,
Viel
[0812.3256]

Boyarsky,
O.R.,
Shaposhnikov
[0901.0011]

(Sub)halo mass function

Number of small dark matter halos
((Sub)Halo mass function)

CDM scale-free structures

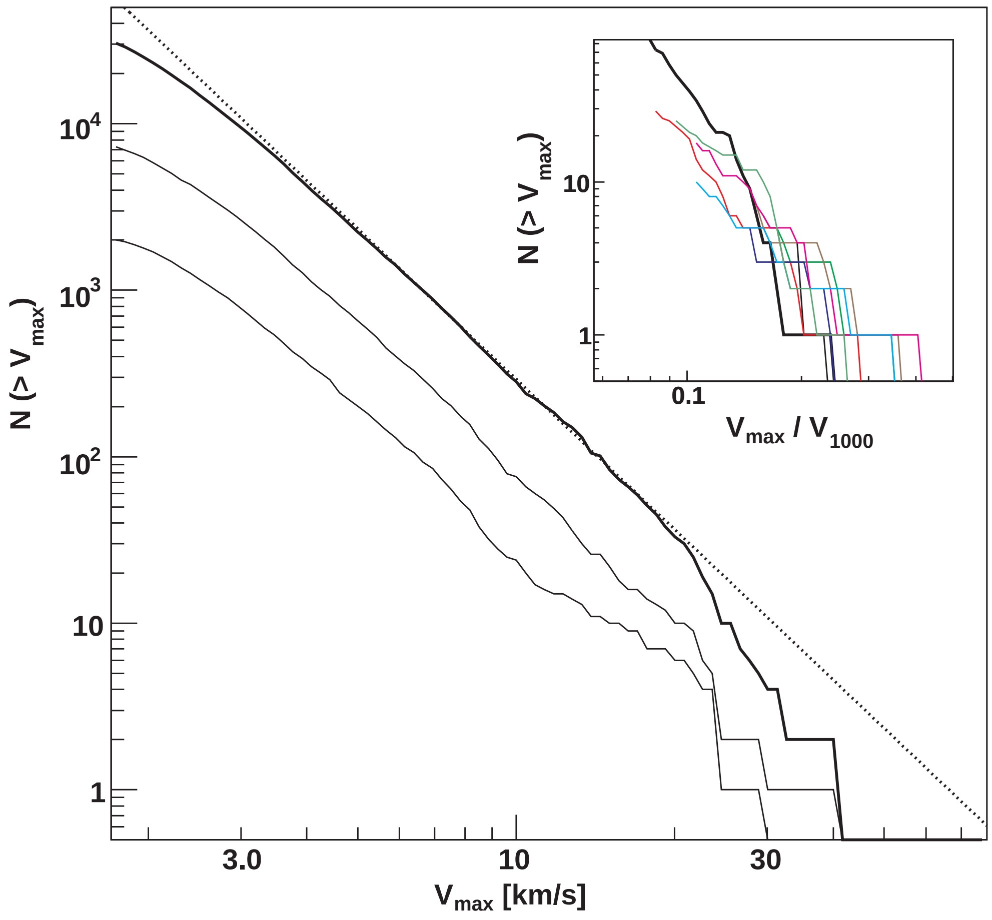


- **CDM** structures form in a scale-free manner

$$\frac{dn}{dM} \propto M^{-2}$$

- *Bolshoi* + *Via Lactea-II* simulations
- Subhlo mass function

CDM scale-free structures

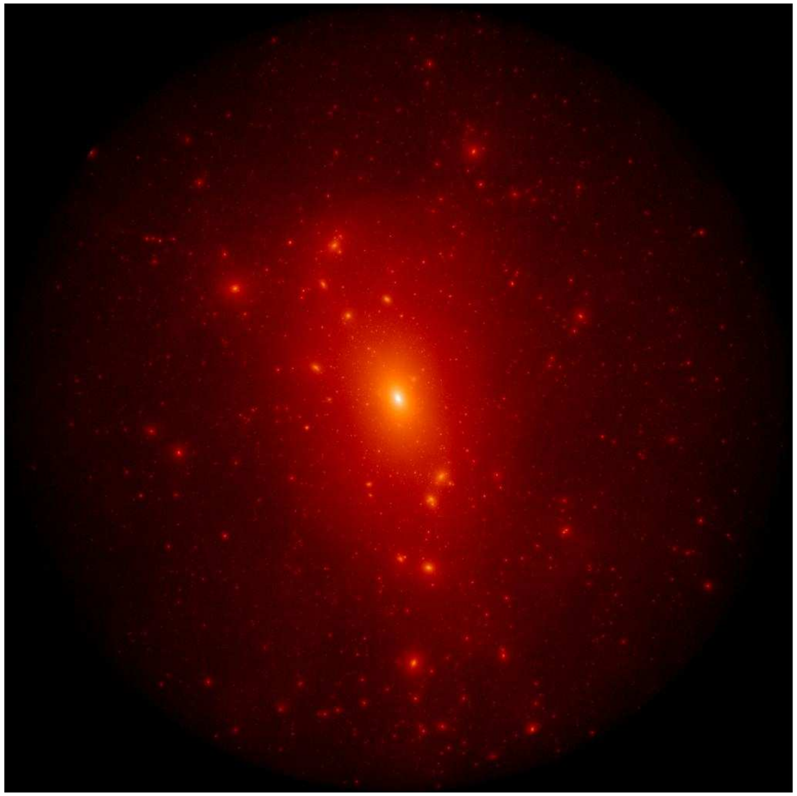


- **CDM** structures form in a scale-free manner

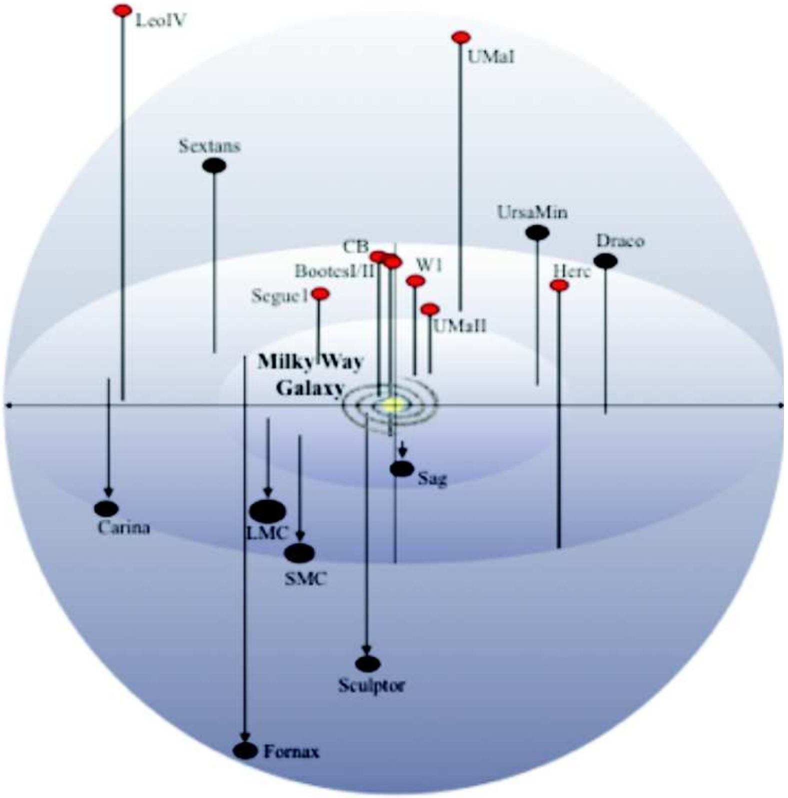
$$\frac{dn}{dM} \propto M^{-\alpha}, \qquad \alpha \approx 2$$

- *Via Lactea-II* simulations
- Subhlo mass function
- Sub-subhalo mass function is the same as for subhalos

Halo substructure in "cold" DM universe



45×10^3 substructures (Aquarius simulation)



~ 30 observed substructures within our Galaxy. M. Geha 2010

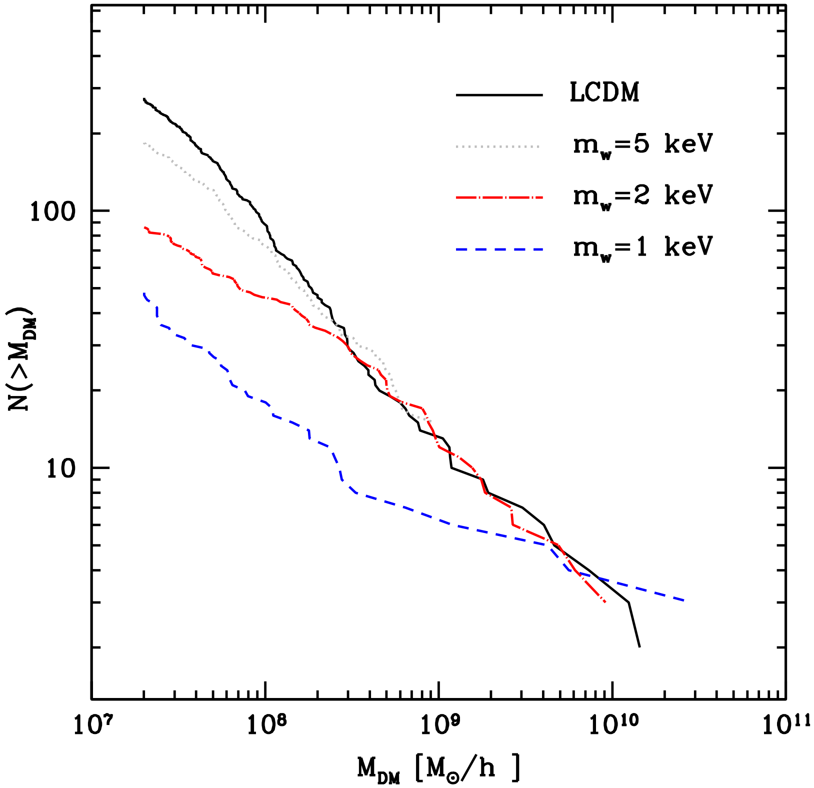
Is small number of observed substructures due to dark matter free-streaming? Moore et al. (1999), Klypin et al. (1999) and many others

Mass vs. luminosity function

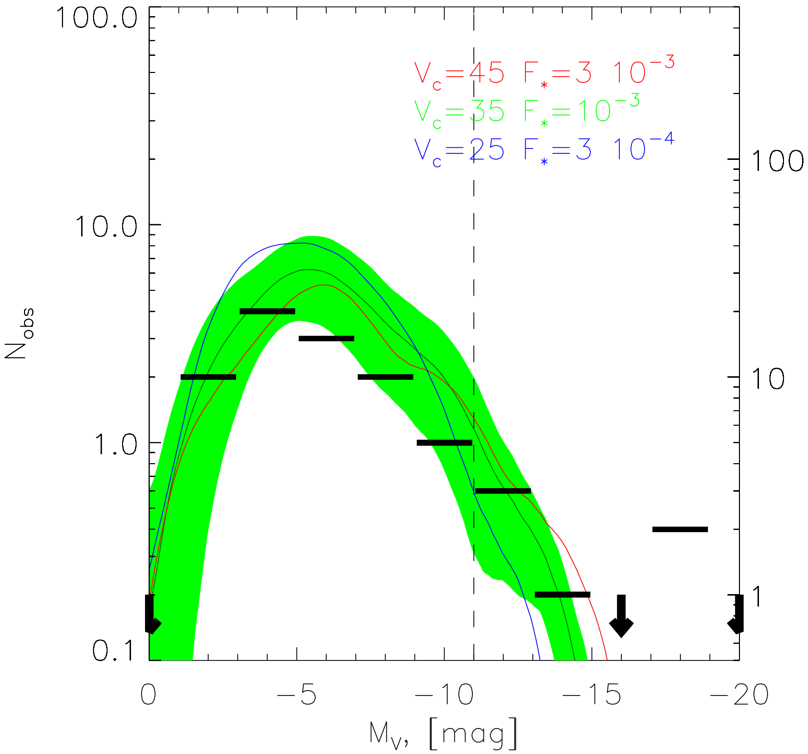
There can be a large bias between satellite **luminosity function** and satellite **mass function** in ΛCDM?

Bullock et al. (2000);

Benson et al. (2002)



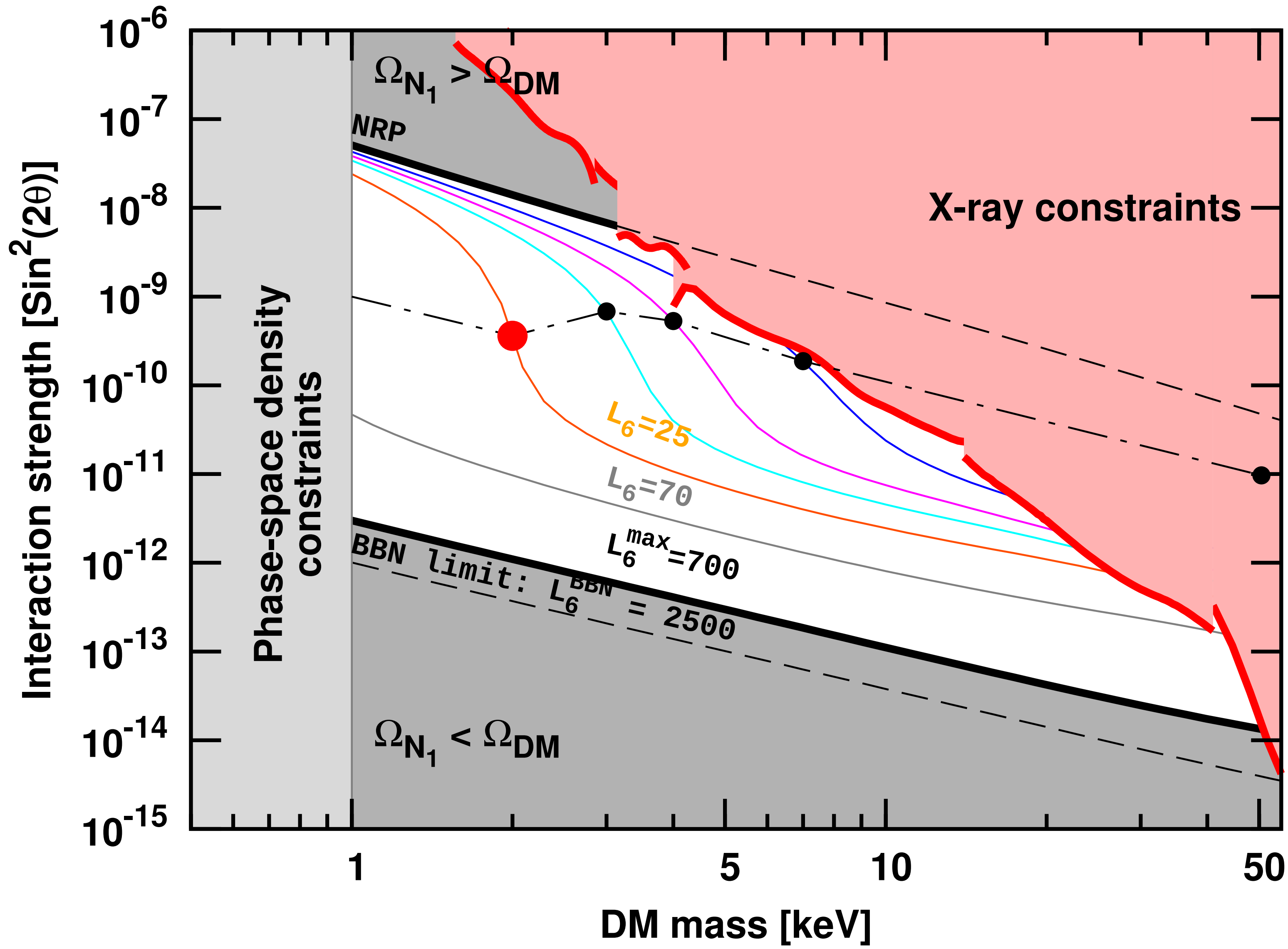
Macciò & Fontanot'09



Koposov et al.'09

Suppression of number of structures in WDM Universe

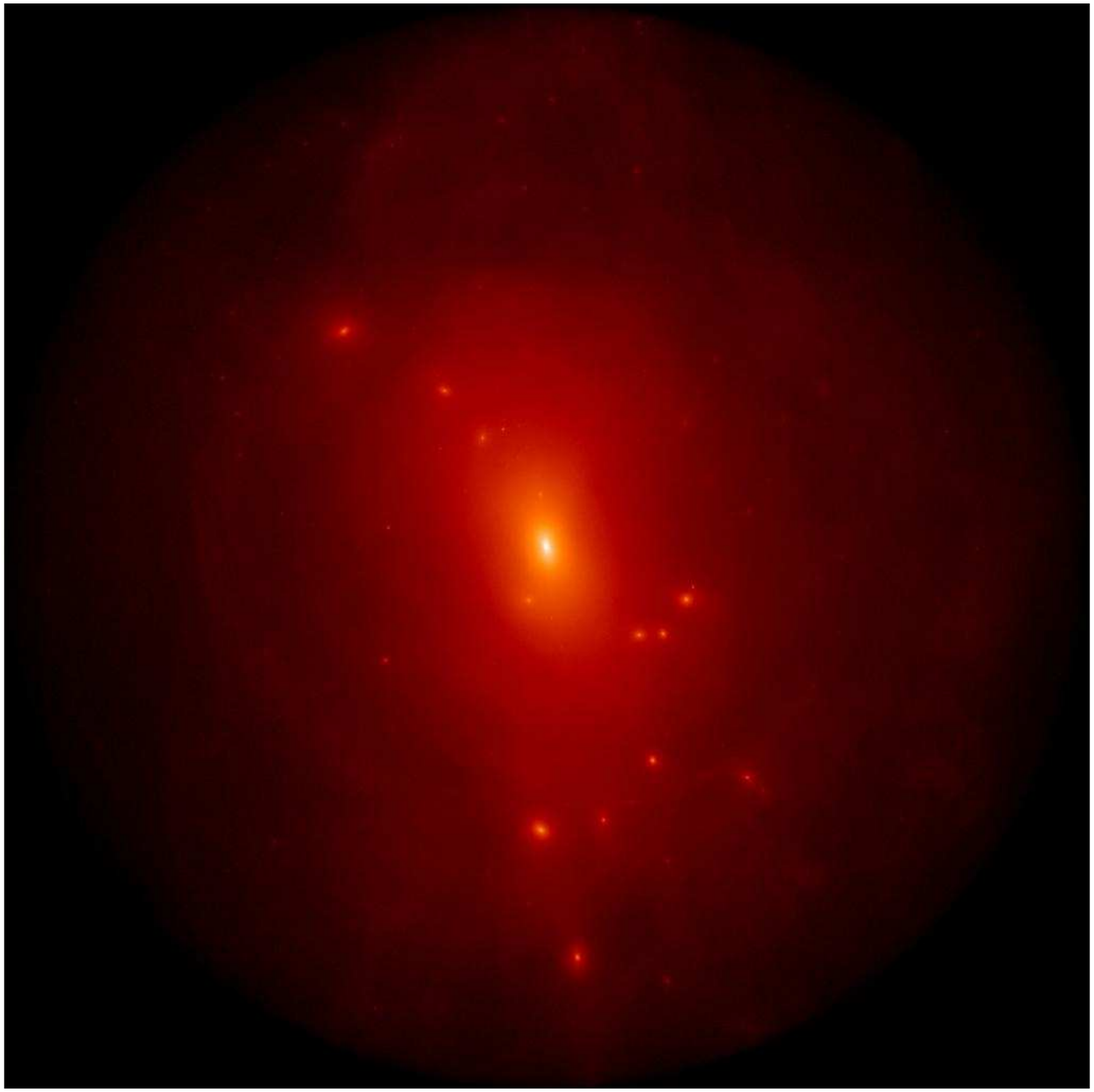
Sterile neutrino DM in the νMSM



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

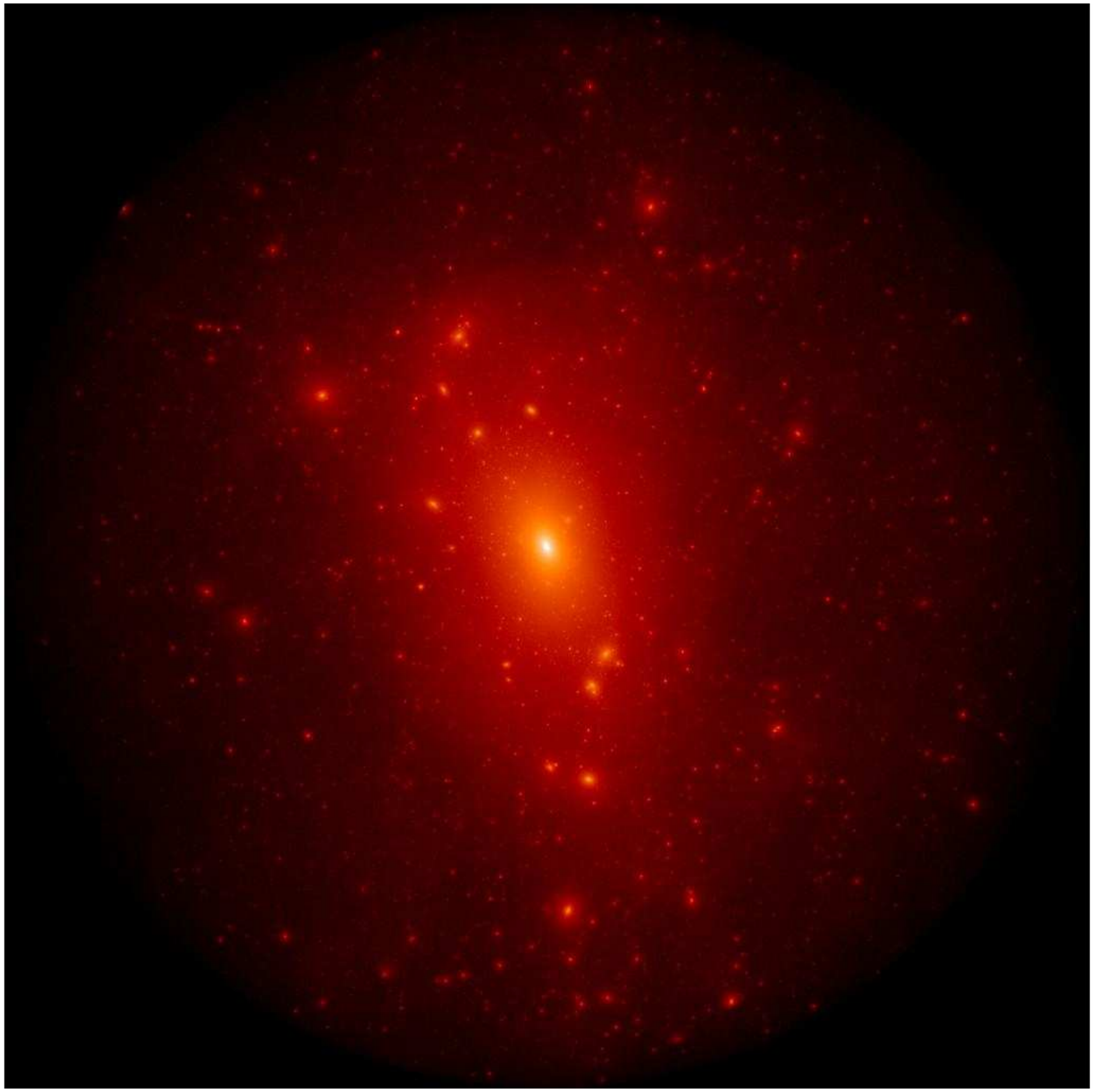
Boyarsky,
O.R.,
Shaposhnikov
[0901.0011]

Halo substructure with sterile neutrino DM



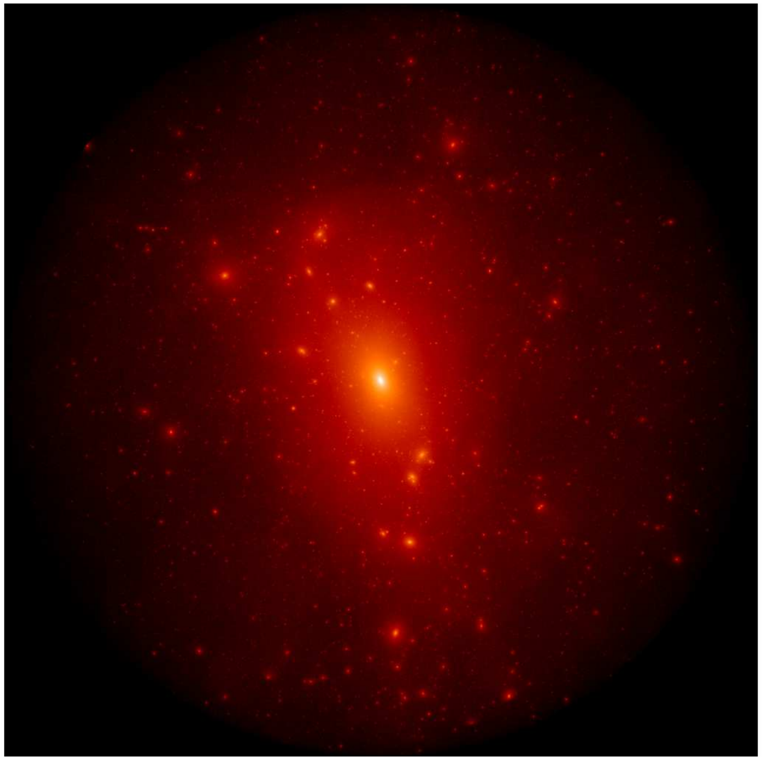
Lovell, Frenk,
Eke, . . . ,
Boyarsky,**O.R.**
1104.2929
[astro-ph.CO]

Halo substructure with CDM

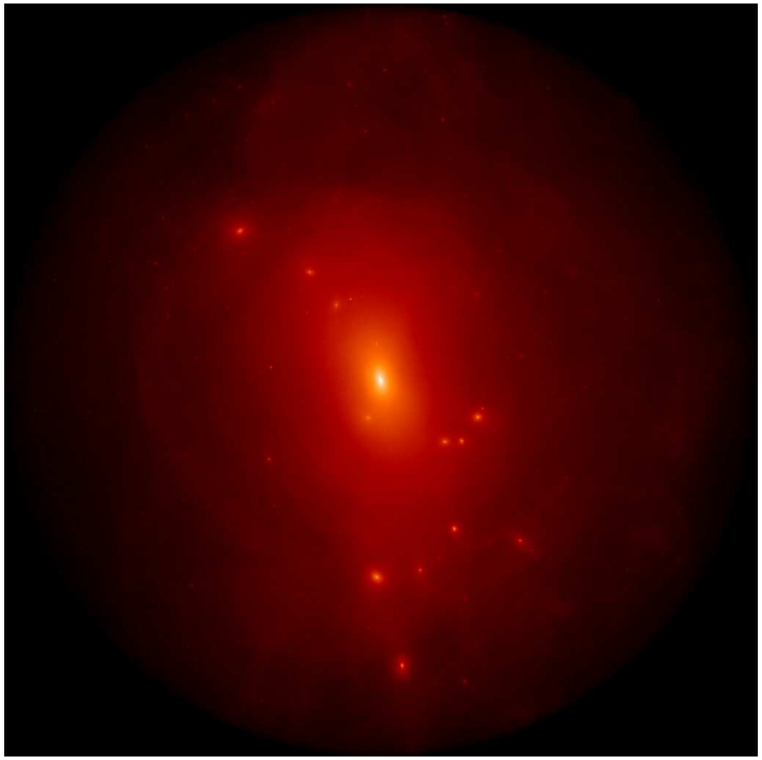


Aq-A2 halo

Halo substructure with sterile neutrino DM



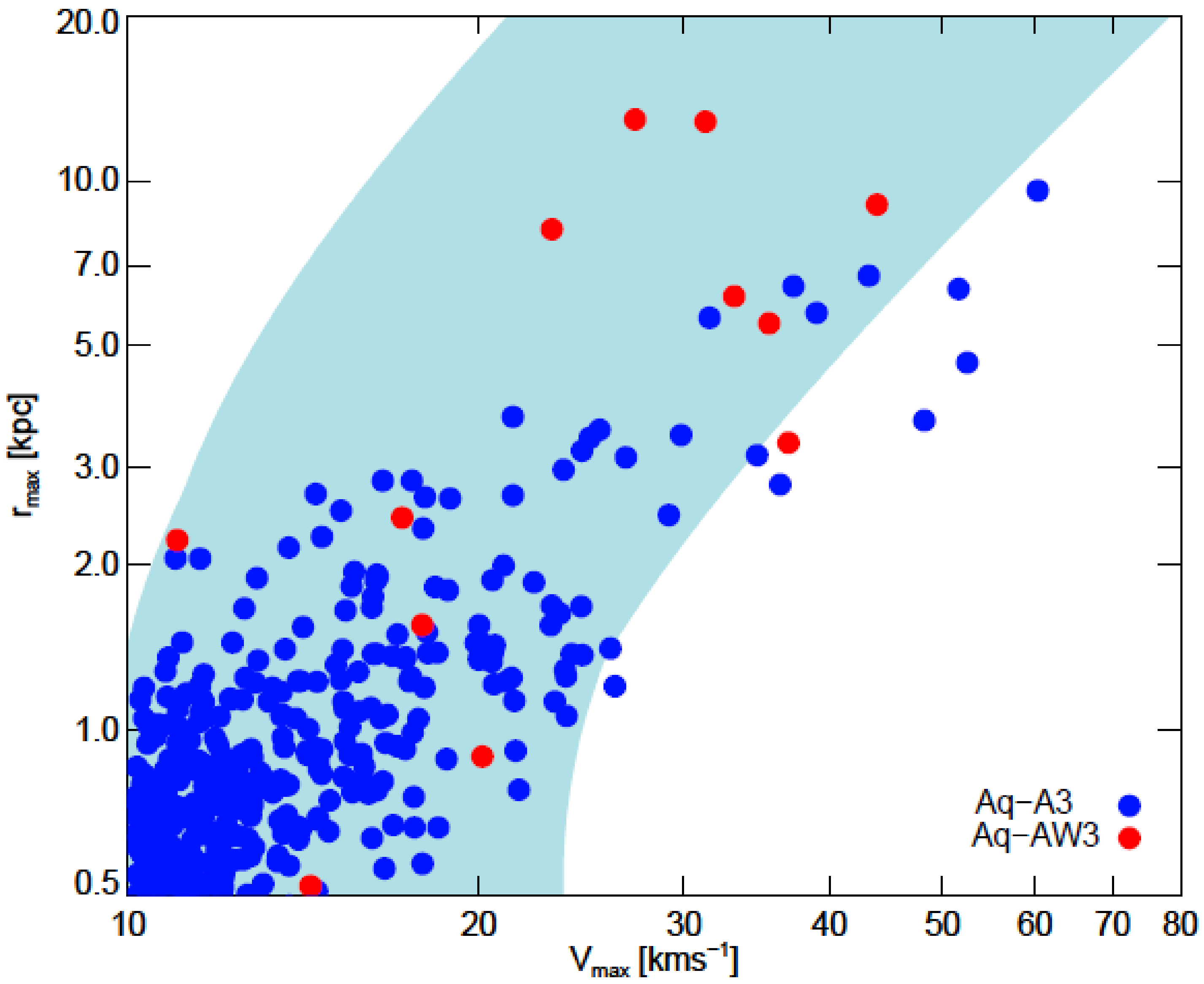
Aq-A-2 CDM halo



Aq-AW-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

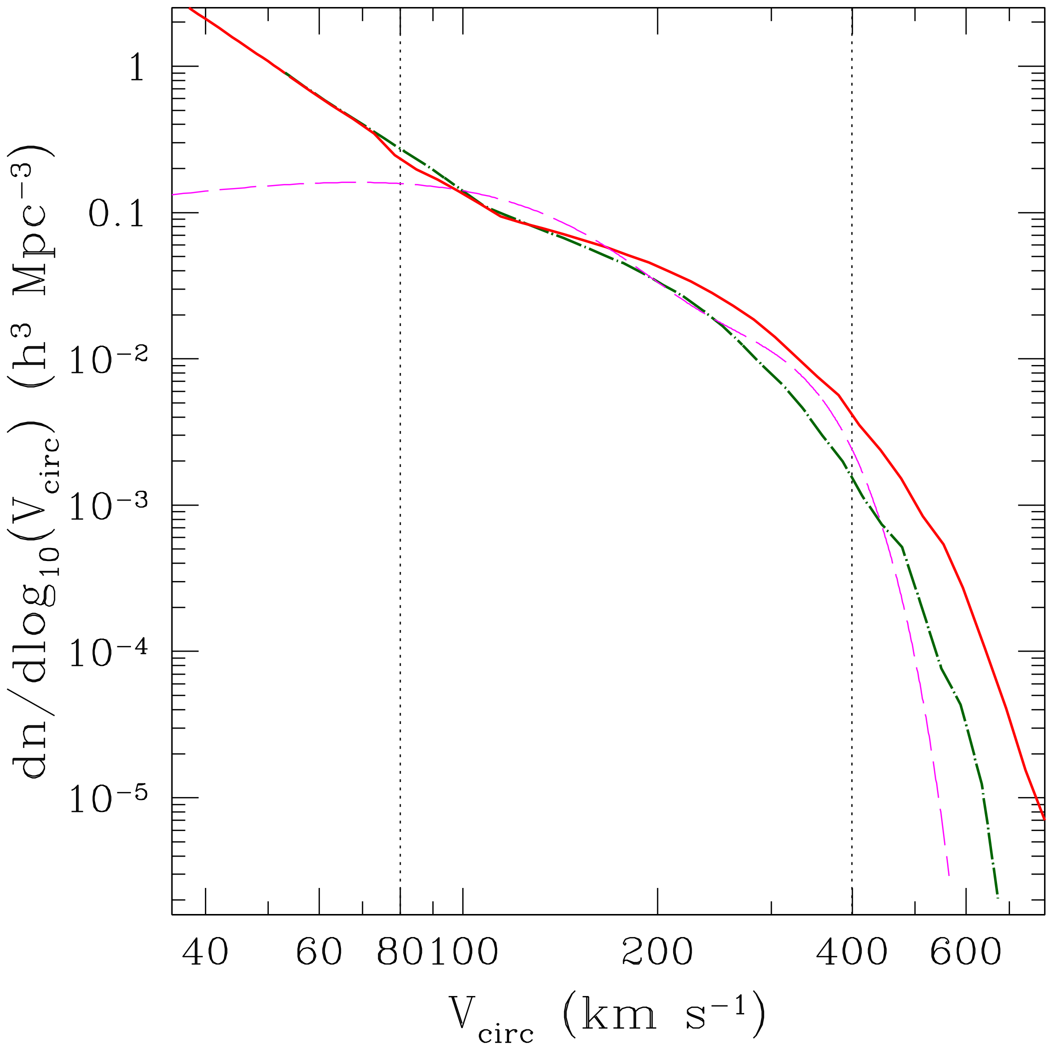
Abundance of large satellites



Strigari, Frenk
White (2011)

Lovell, Frenk,
Eke, . . . ,
Boyarsky,**O.R.**
1104.2929
[astro-ph.CO]

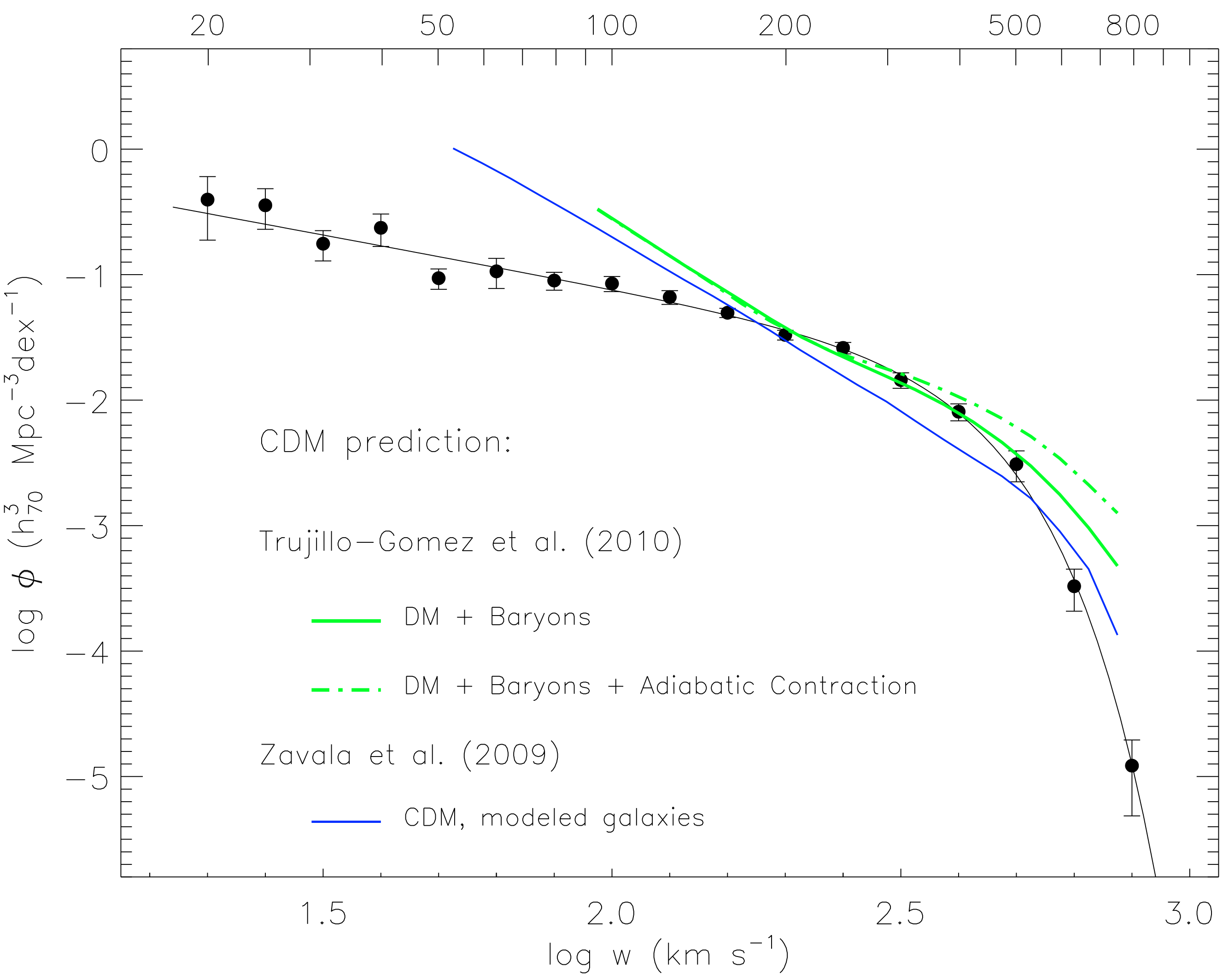
Another overabundance problem



Observed number of **isolated** halos with circular velocities below ~ 100 km/sec is smaller than predicted by ΛCDM simulations, assuming *linear bias*

Trujillo-Gomez, Klypin, Primack et al. 2010-2011

ALFALFA Velocity width function vs. CDM

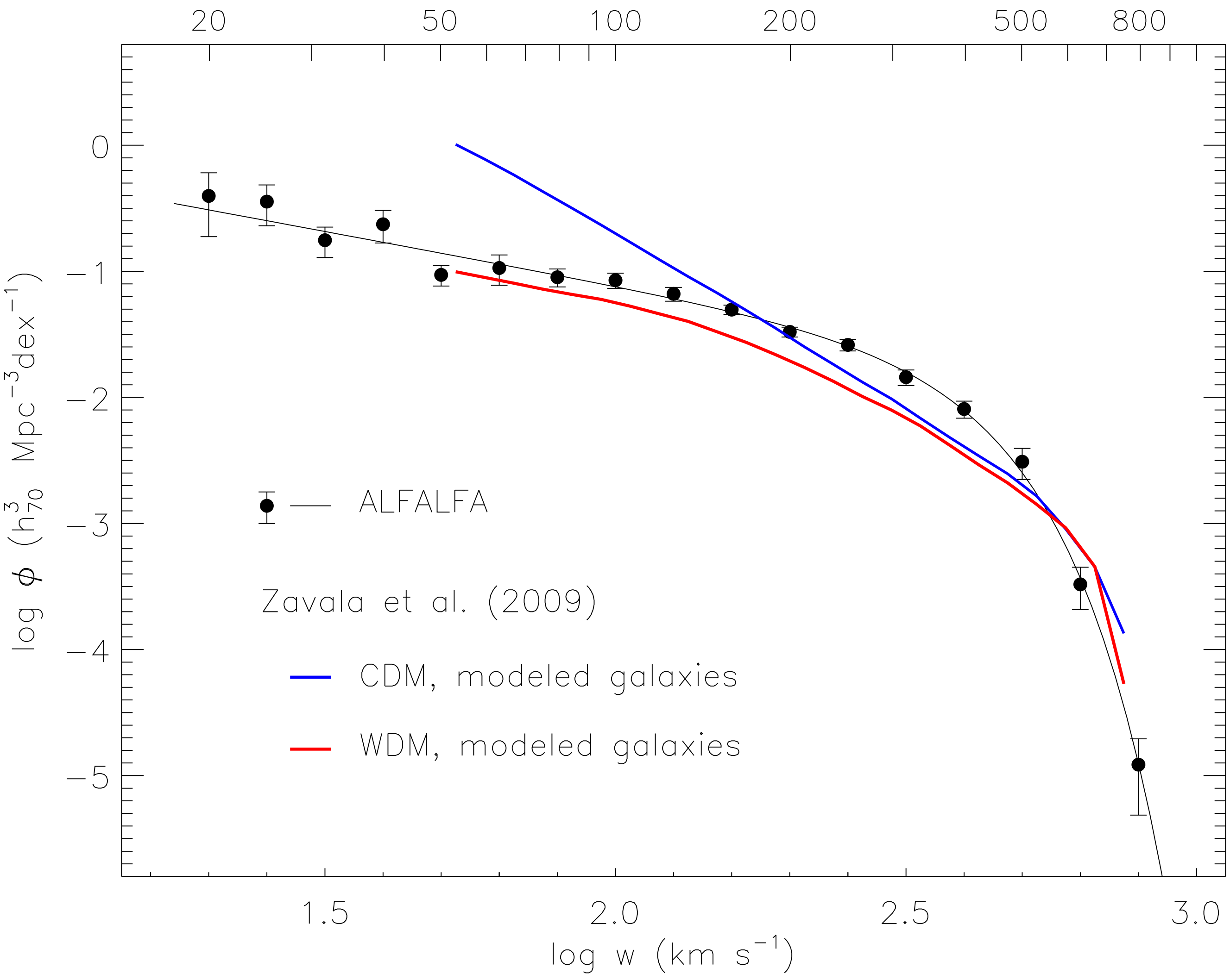


Papastergis+ [1106.0710]

ALFALFA (HI) survey. Deviations from ΛCDM predictions for $v_{rot} \lesssim 100$ km/sec

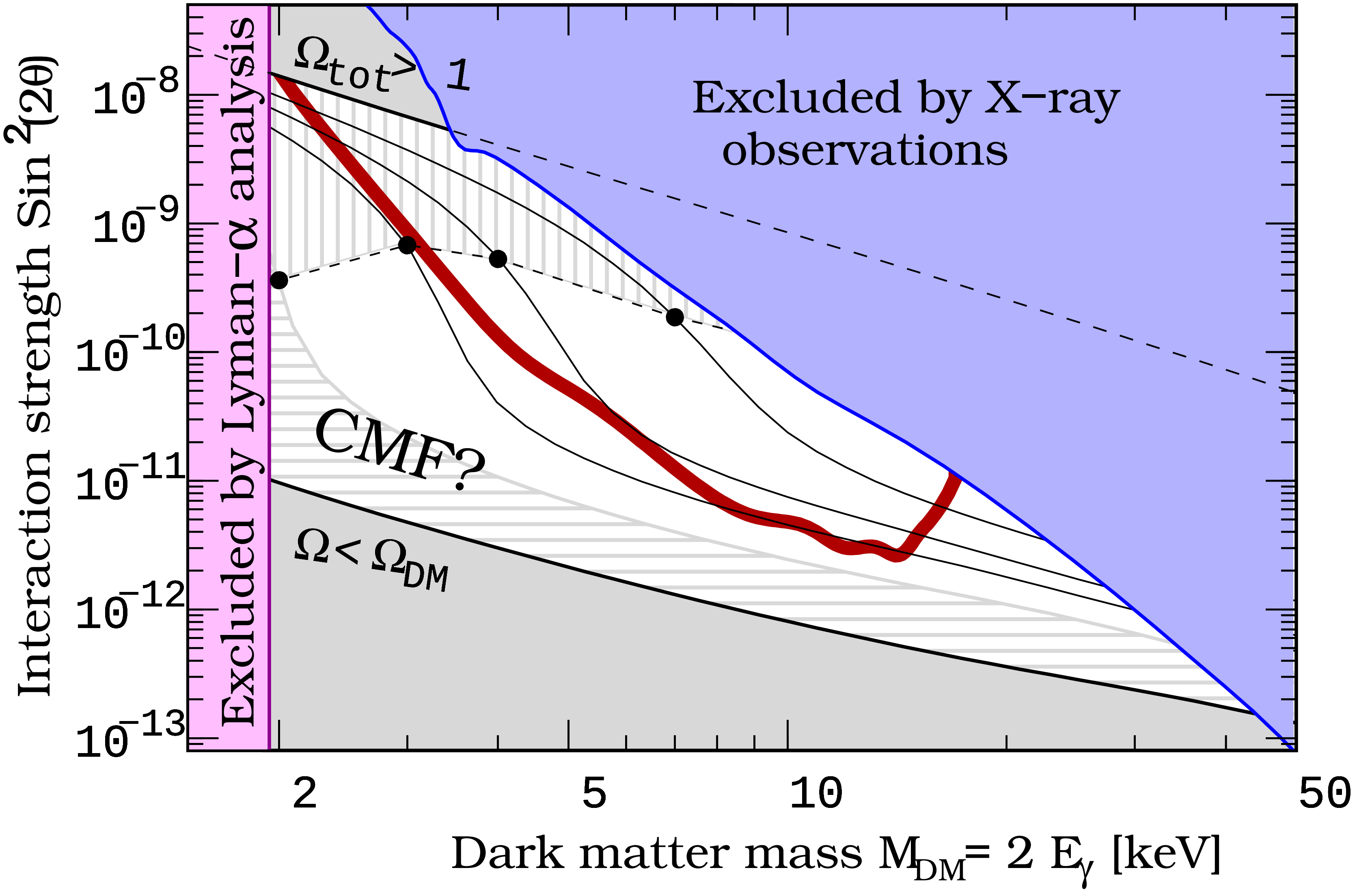
Velocity width function vs. WDM

Papastergis+ [1106.0710]



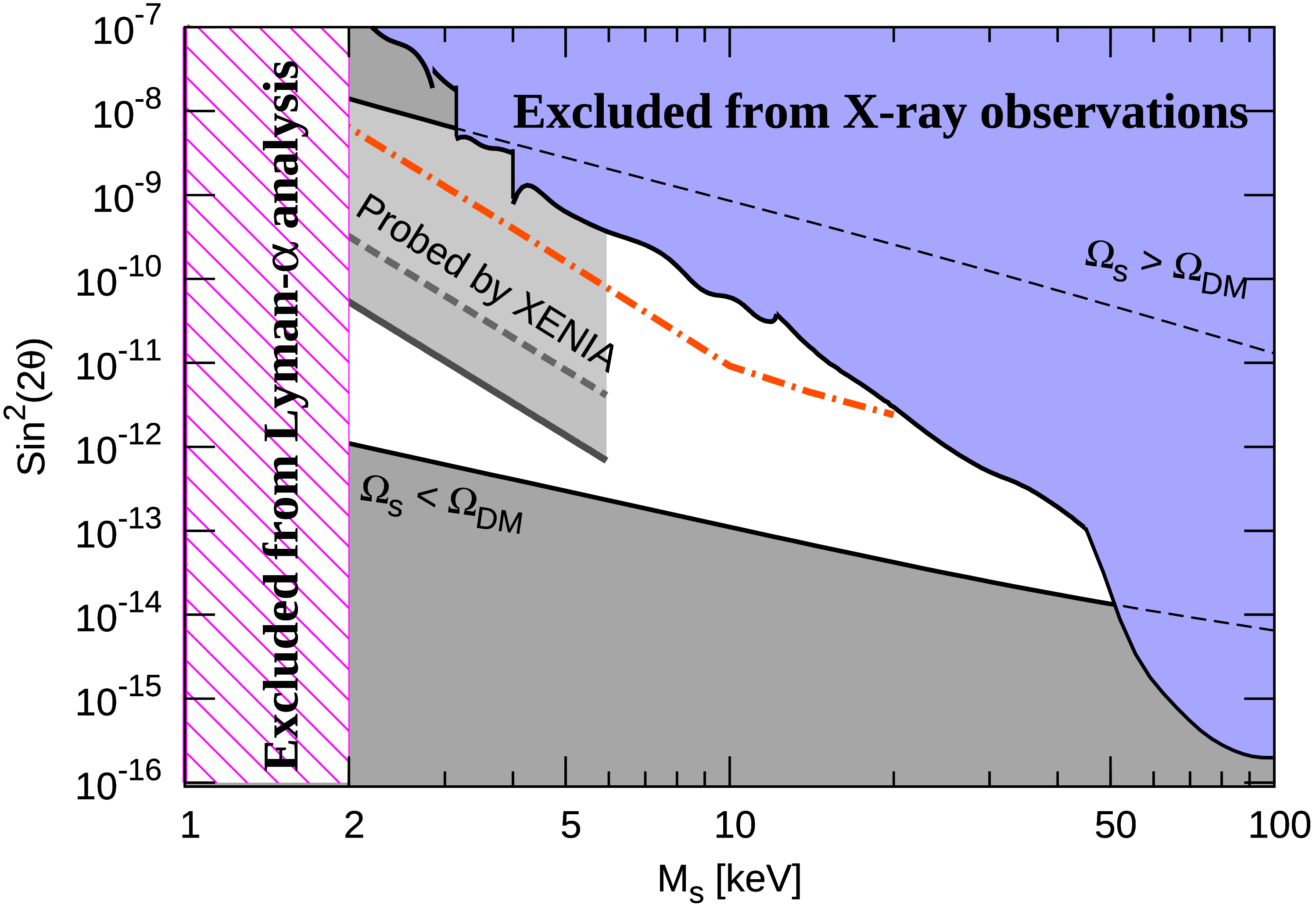
ALFALFA (HI) survey. Deviations from ΛCDM predictions for $v_{rot} \lesssim 100$ km/sec

Future?



$\Omega_{tot} > 1$
Excluded by X-ray observations
Excluded by Lyman-α analysis
CMF?
$\Omega < \Omega_{DM}$
Interaction strength $\mathrm{Sin}^2(2\theta)$
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
2
5
10
50
Dark matter mass $M_{DM} = 2\,E_\gamma$ [keV]

Improved bounds on DM decay

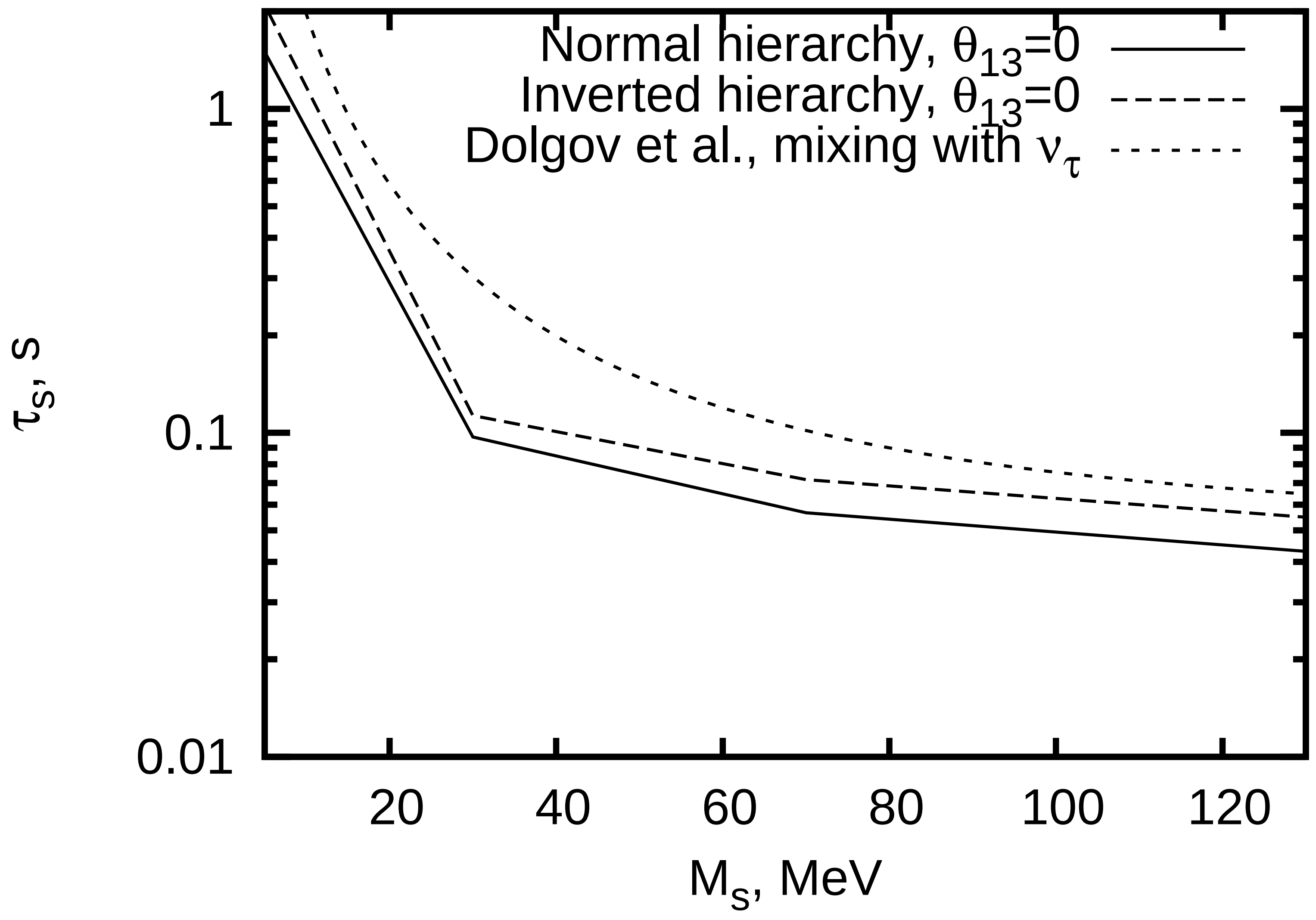


Proposal submitted for ESA M3 mission

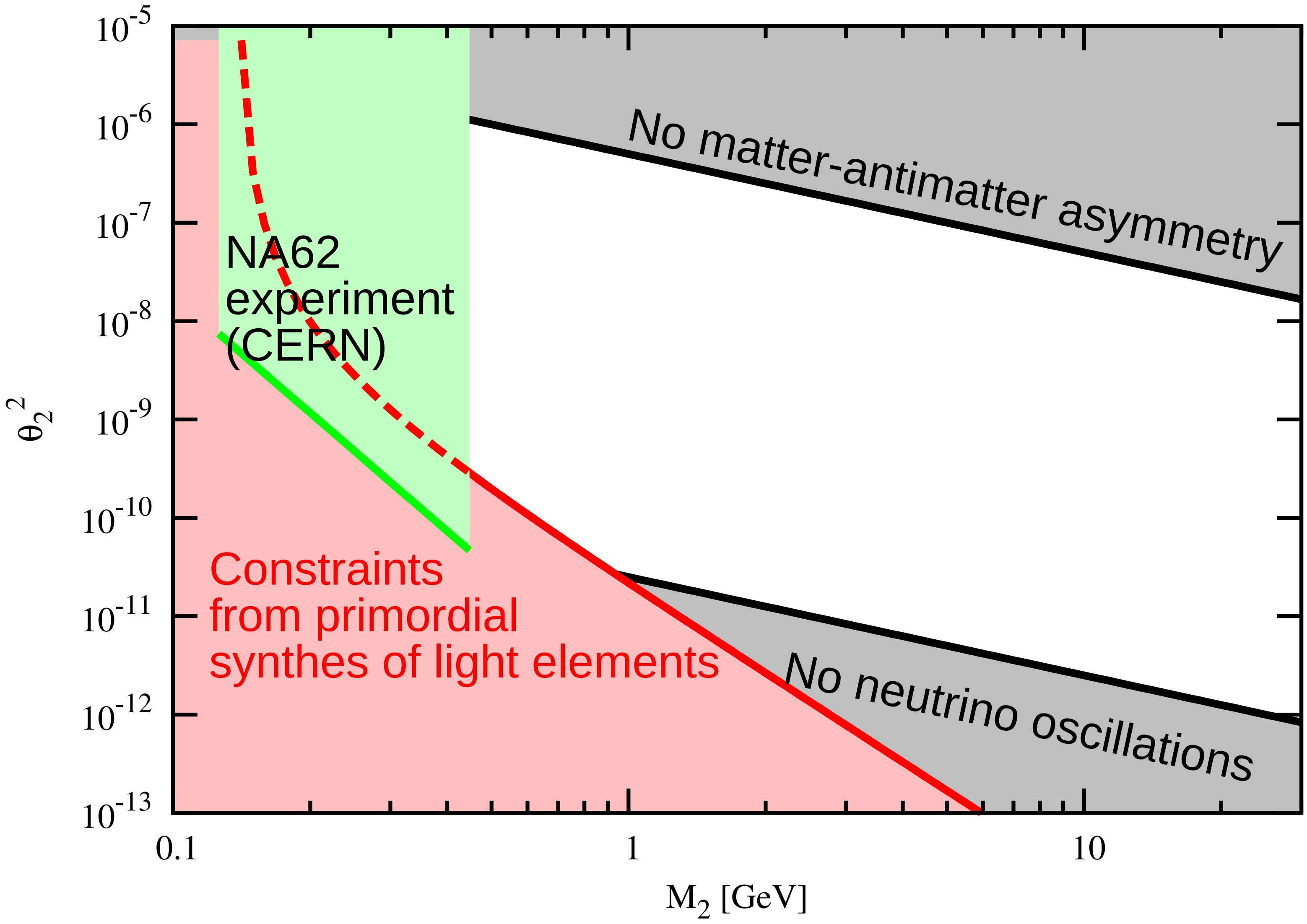
BBN constraints

Dolgov, Semikoz et al. (2000–2001);

O.R., Ivashko et al. (2011)



Probing other sterile neutrinos



Conclusion

- νMSM demonstrates that the BSM phenomena can find their explanation without introduction of new energy scale
- Neutrino Minimal Standard Model (ν**MSM**) provides resolution of all major observational BSM problems and gives a **complete history of the Universe** from inflationary era till today
- Sterile neutrino dark matter can leave its imprints on formation of structures and can be detected via its monochromatic decays to photons
- Heavier sterile neutrino particles can be probed with this generation of **intensity frontier** experiments

Thank you for your attention!

Thermal relics

- The simplest WDM model – **thermal relics**. Particles that freeze-out relativistic at temperature T_d

Bode et al. (2001)

$$f(v) = \frac{1}{\exp\left\{\frac{M_{\text{DM}} v}{T_d(t)}\right\} + 1}$$

- Decoupling temperature determines abundance:

$$\Omega_{\text{DM}} h^2 = \left(\frac{T_d}{T_\nu}\right)^3 \frac{M_{\text{DM}}}{94\ \text{eV}} \quad \text{where} \quad \left(\frac{T_d}{T_\nu}\right)^3 = \frac{10.75}{g_*(T_d)}$$

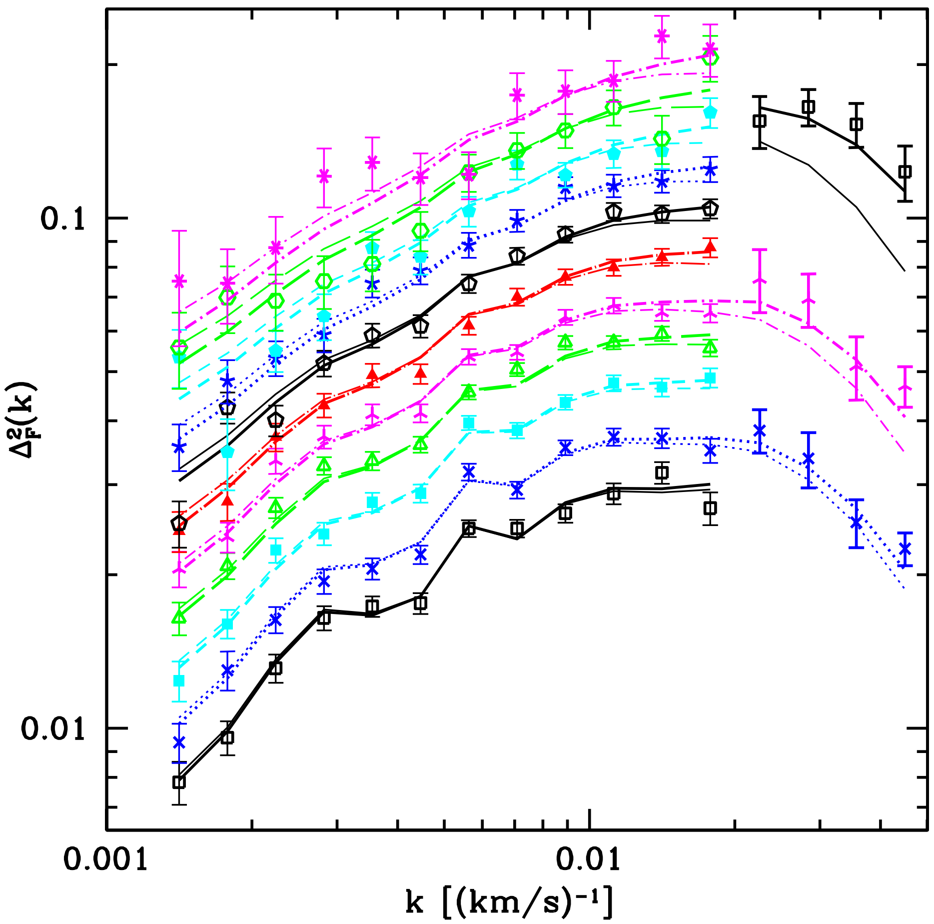
- The suppression of the power-spectrum is strong

Viel et al. (2005)

$$T(k) \equiv \sqrt{\frac{P(k)}{P_{\Lambda\text{CDM}(k)}}} \propto \left(\frac{k_c}{k}\right)^{10} \qquad k_c \sim 20 \frac{h}{\text{Mpc}} \frac{M_{\text{DM}}}{\text{keV}}$$

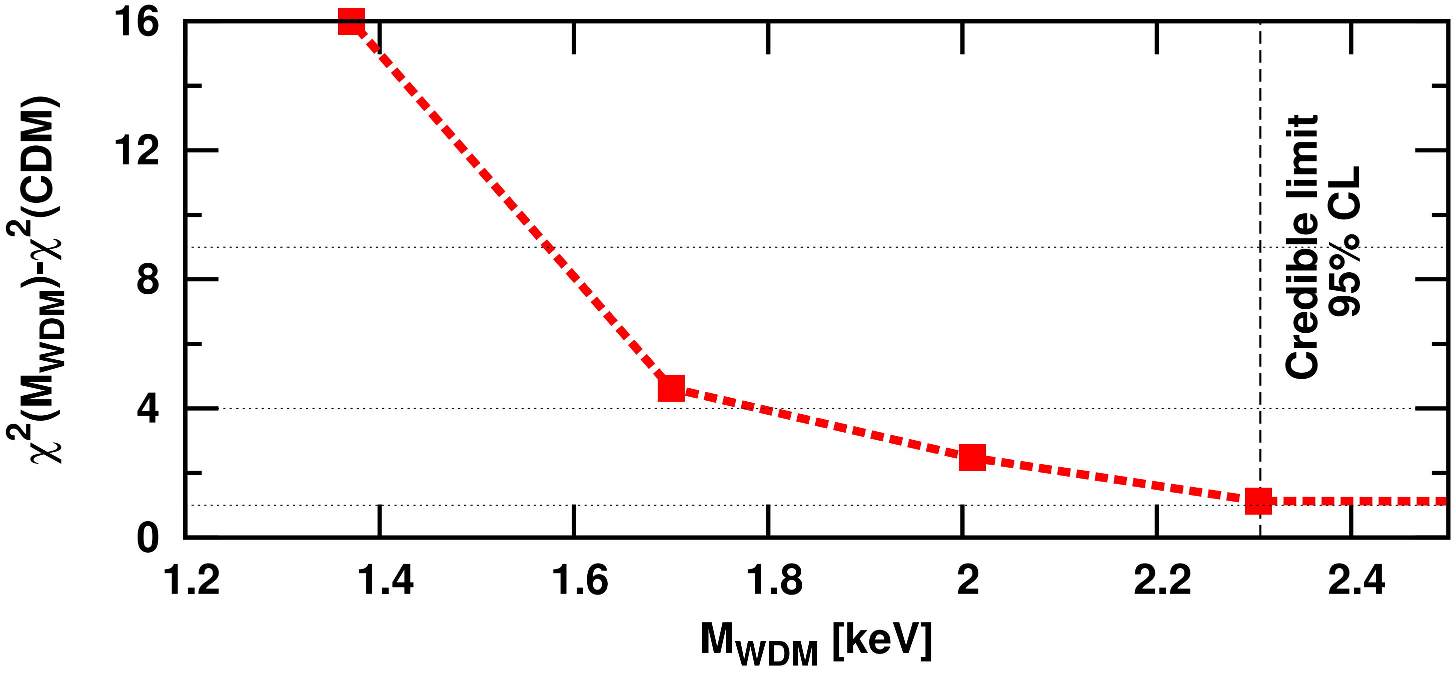
Lyman-α forest flux power spectrum

Seljak et al. ’06



Measured flux power spectrum is compared against CDM and non-CDM models

Ly-α and thermal relics



Boyarsky, Lesgourgues, **O.R.**, Viel [0812.0010] (JCAP 2009)

Also Viel et al. 2005-2007;

Seljak et al. (2006)

*These bounds are for **thermal relics** only!*

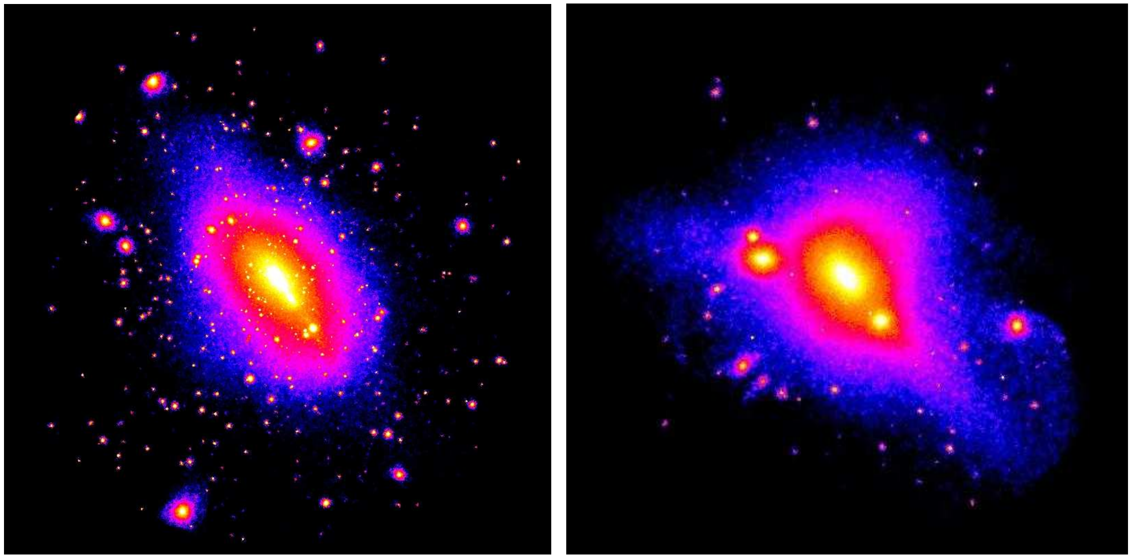
Lyman-α forest and warm DM

- Previous works put bounds on free-streaming $\lambda_{FS} \lesssim 150$ kpc ("WDM mass" > 2.3 keV)
- The simplest **WDM** with such a free-streaming would not modify visible substructures:

Viel et al. 2005-2007; Seljak et al.(2006)

Maccio & Fontanot (2009);

Polisensky & Ricotti (2010)

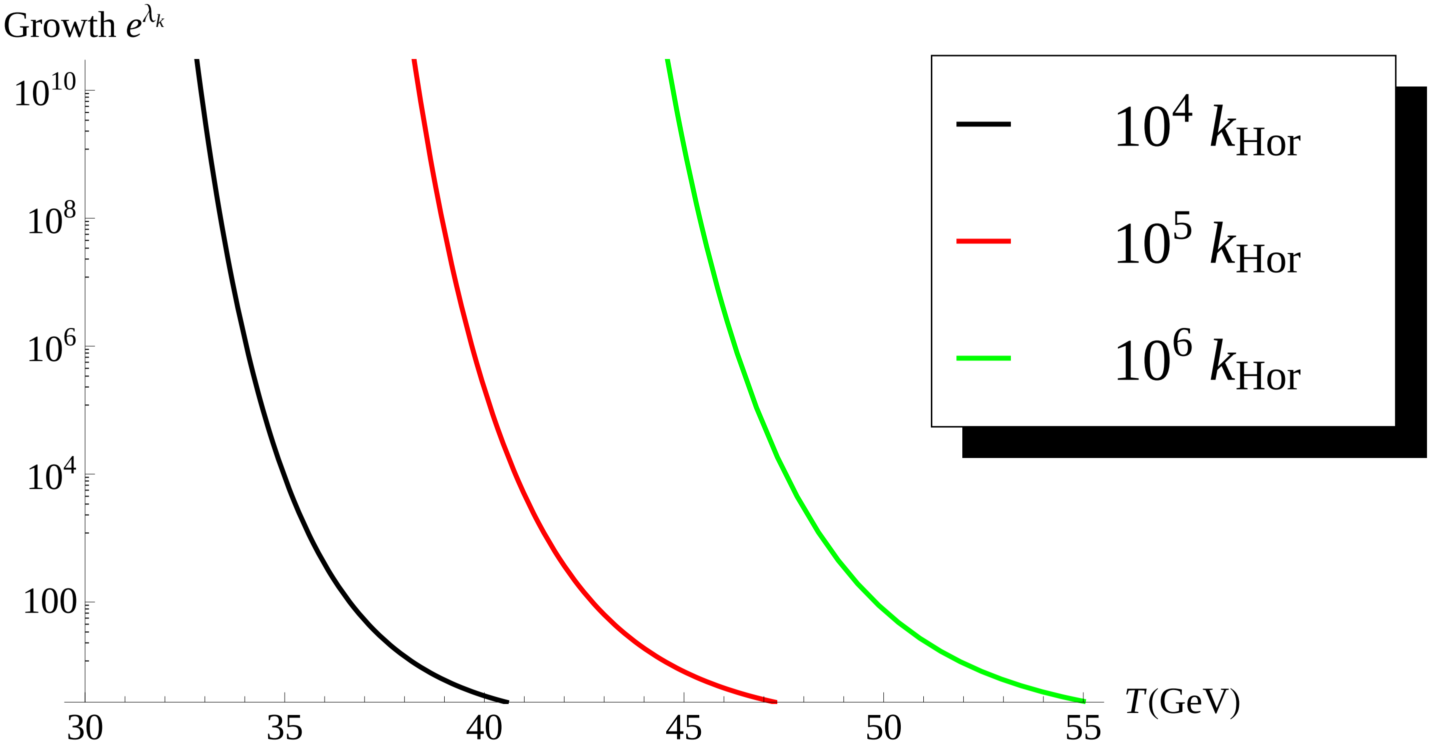


- **Thermal relic** with exponential cut-off ~ 1 Mpc would erase **too many substructures**. Anything "colder" would produce enough structures to explain observed Milky Way structures

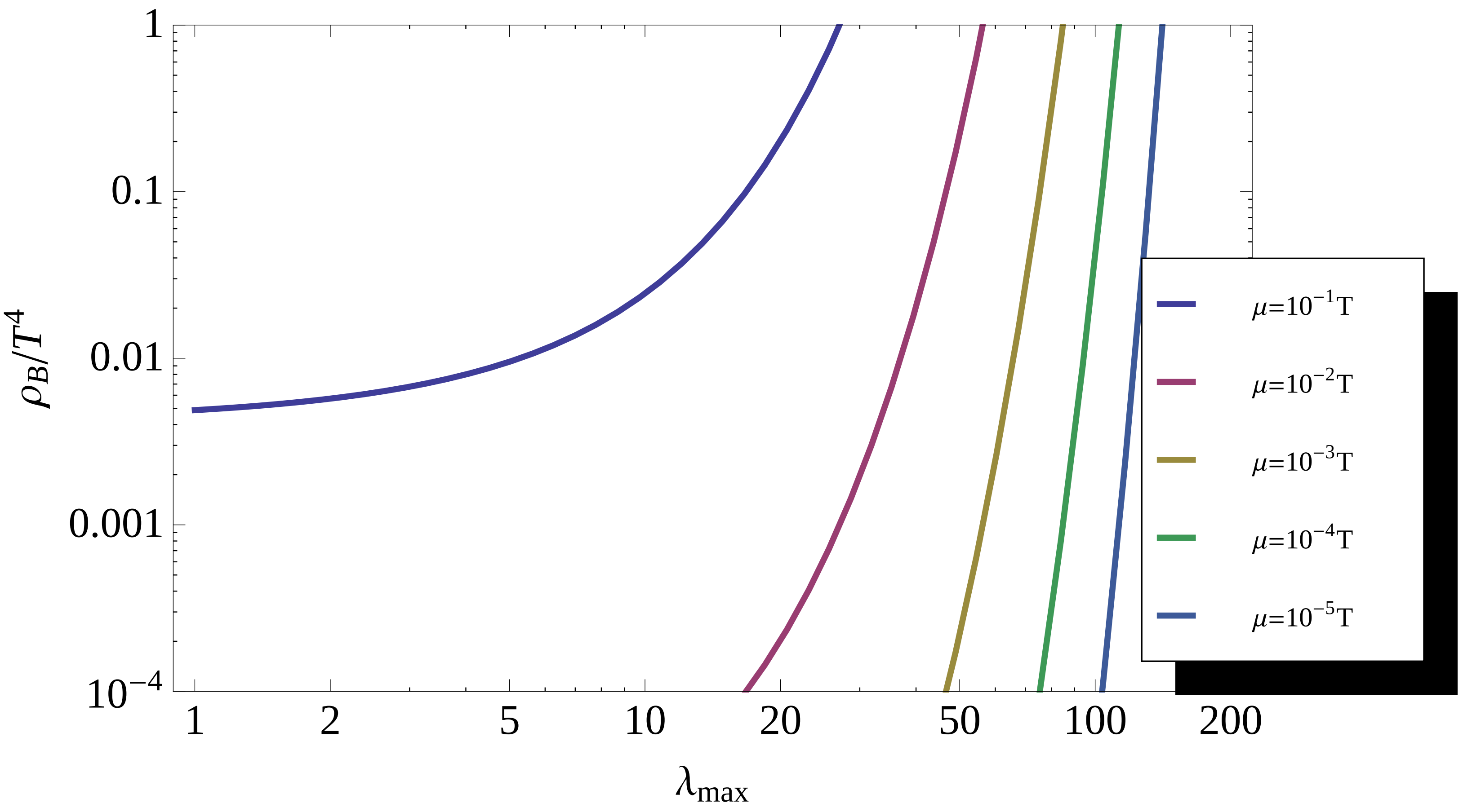
CMF instability in the νMSM

The **longest wave-length** that has experienced instability at temperature T is

$$k_{min} = H(T)\frac{\sigma}{\alpha\bar{\mu}} \sim \frac{H(T)}{\alpha^2 \log(1/\alpha)\bar{\mu}(T)}$$



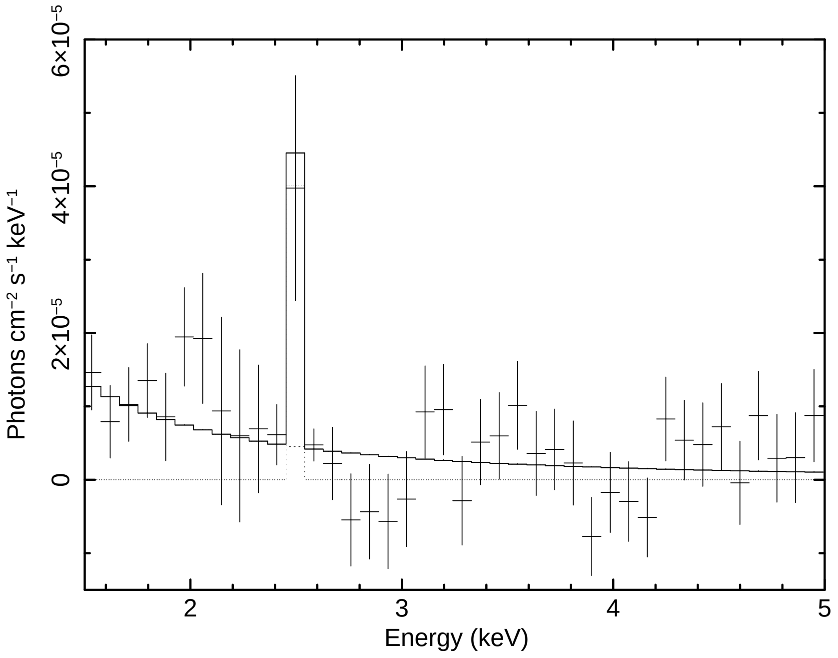
Energy in the magnetic field

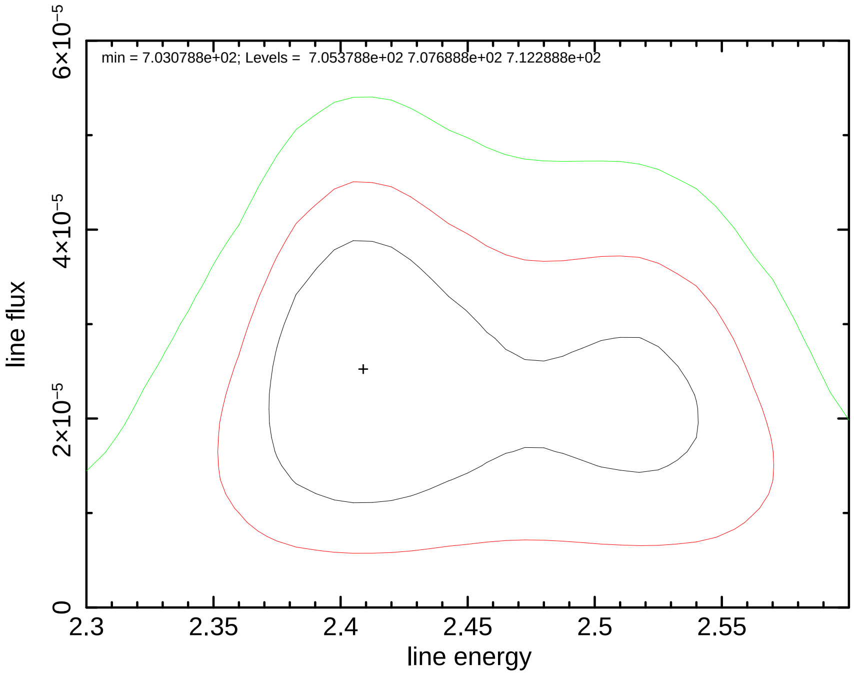


Checking DM origin of a line

- *Dark Matter Search Using Chandra Observations of Willman 1, and a Spectral Feature Consistent with a Decay Line of a 5 keV Sterile Neutrino*

Loewenstein &
Kusenko
(Dec'2009)



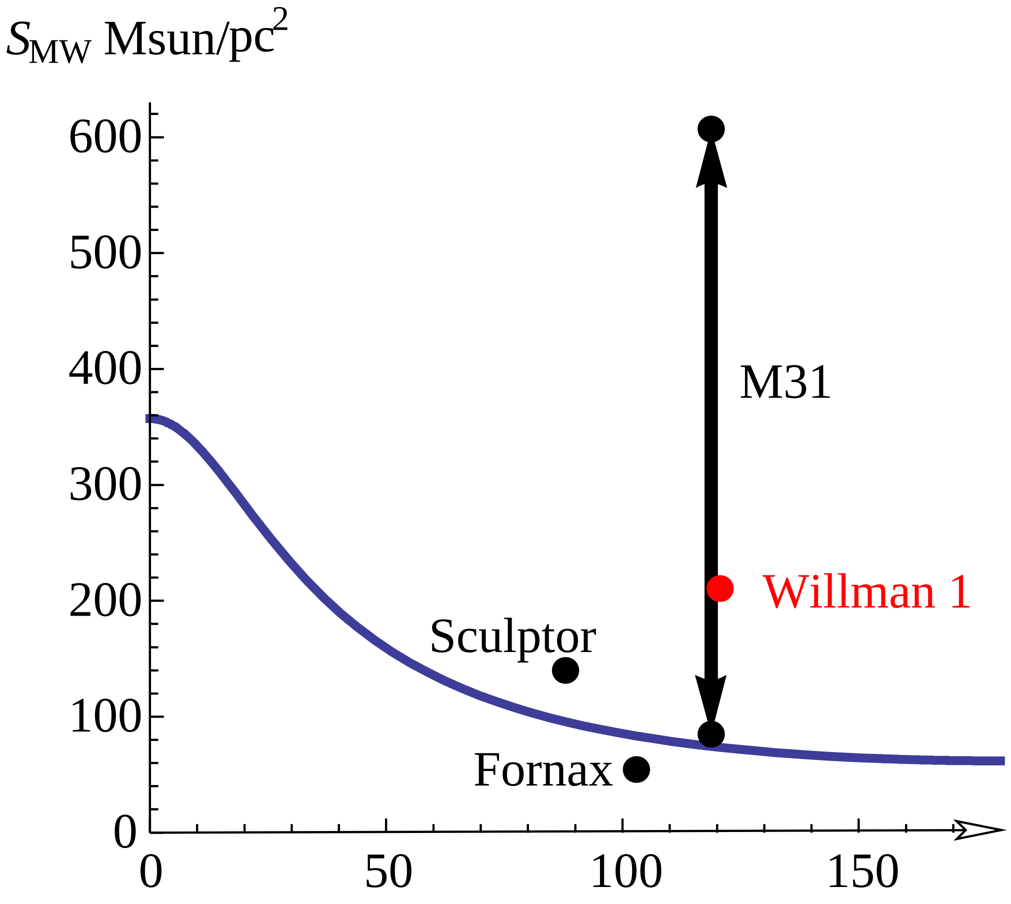


68%, 90% and 99% confidence intervals

- *Can the excess in the FeXXVI Ly gamma line from the Galactic Center provide evidence for 17 keV sterile neutrinos?*

Prokhorov &
Silk (Jan'2010

Do we see this line anywhere else?



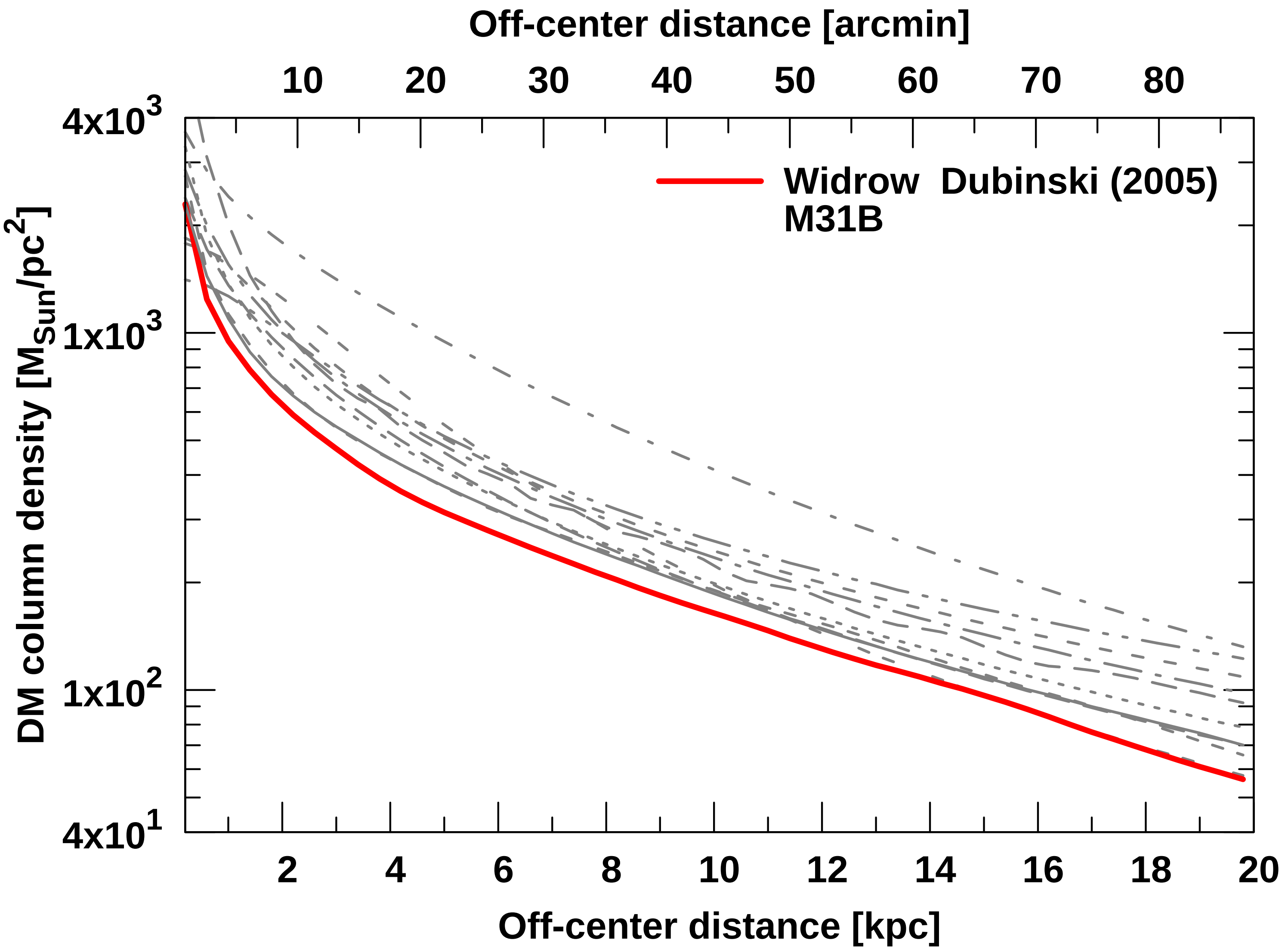
Objects with comparable expected signal for which archival data is available

- **Fornax dSph** (XMM)
  $\mathcal{S}_F = 54.4 M_\odot \mathrm{pc}^{-2}$
- **Sculptor dSph** (Chandra)
  $\mathcal{S}_{Sc} = 140 M_\odot\,\mathrm{pc}^{-2}$
- **Andromeda galaxy (M31)** :
  $\mathcal{S}_{M31} \sim 100 - 600 M_\odot/\mathrm{pc}^2$

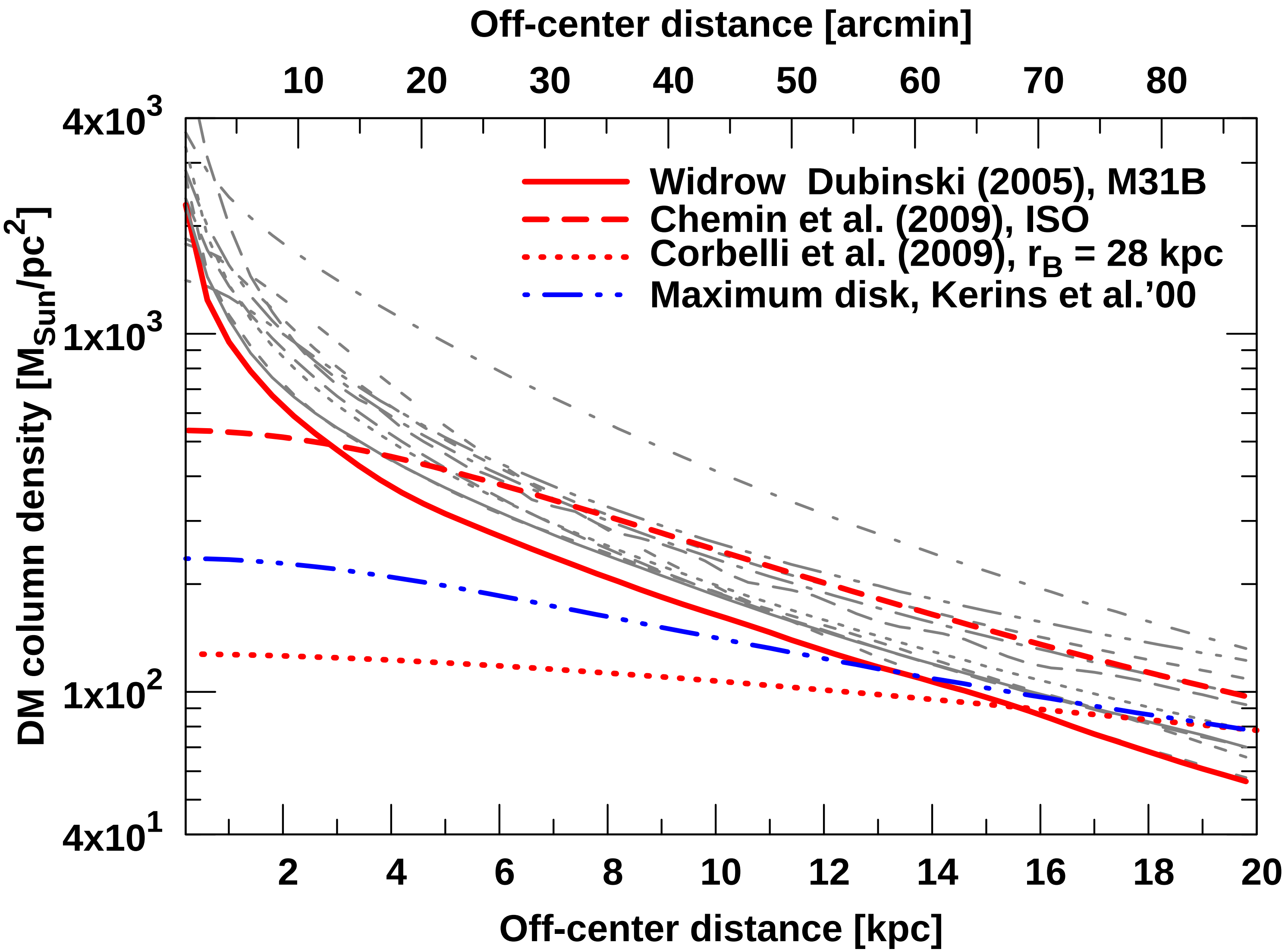
Do we see this 2.5 keV line?

DM in Andromeda galaxy (2008)

Boyarsky,
O.R. et al.
MNRAS'08



DM in Andromeda galaxy (2010)



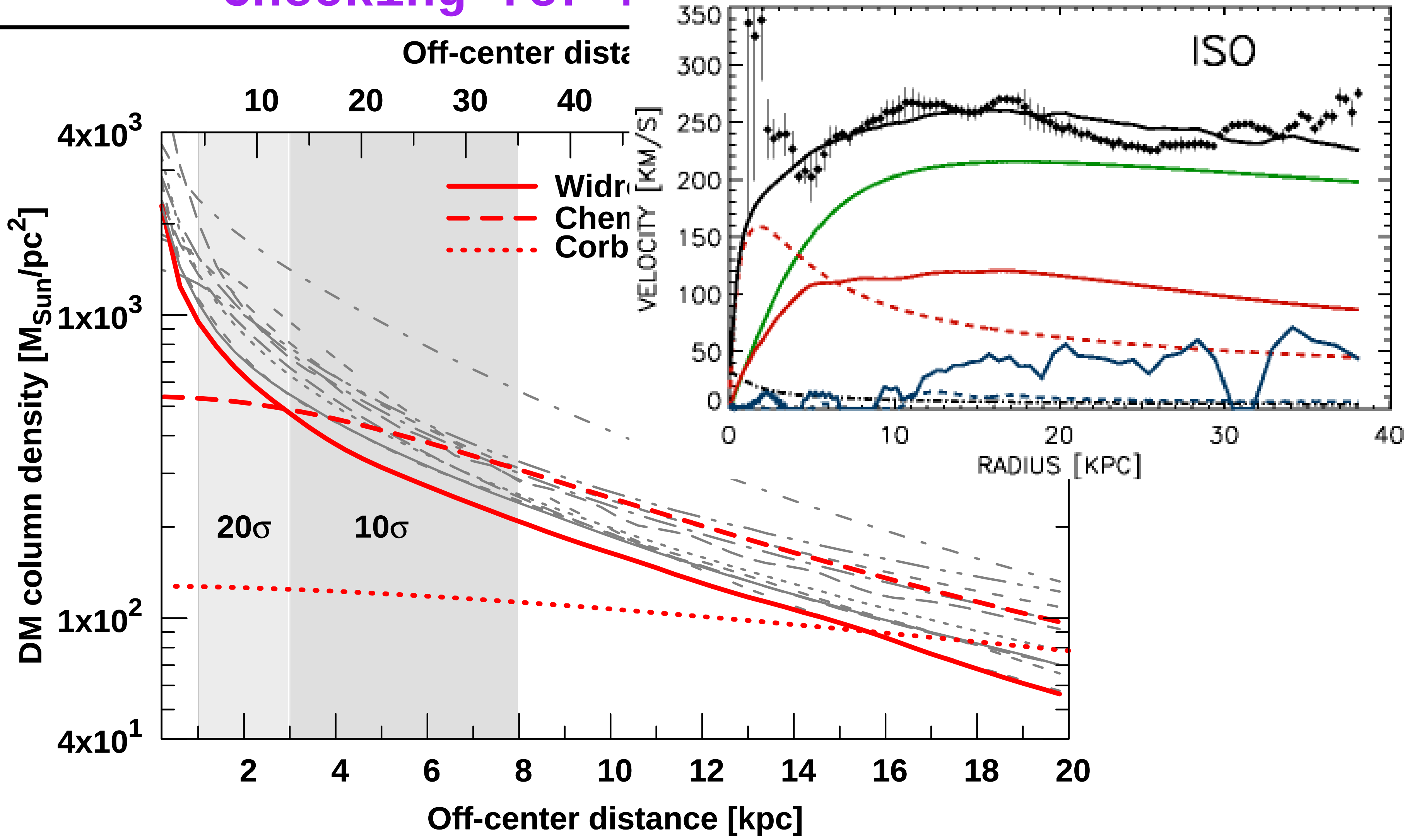
Boyarsky, O.R. et al. MNRAS'08

Chemin et al. 0909.3846

Corbelli et al. 0912.4133

Kusenko & Loewenstein 1001.4055

Checking for DM line in M31



Willman 1 spectral feature excluded with high significance from archival observations of M31 and Fornax and Sculptor dSphs