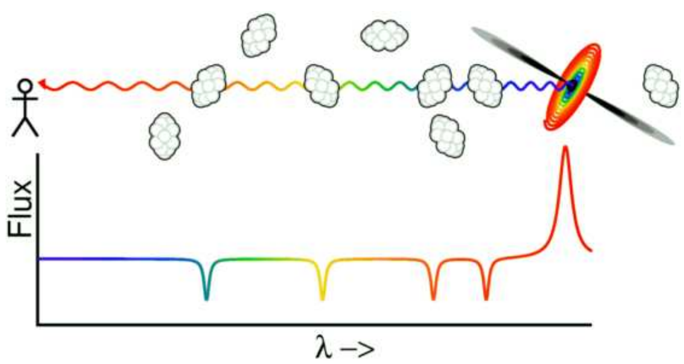
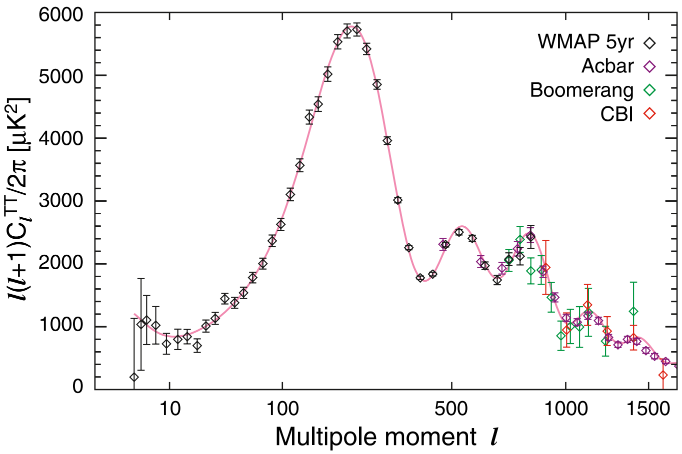
Sterile neutrino dark matter and constraints on its properties from astrophysics and cosmology

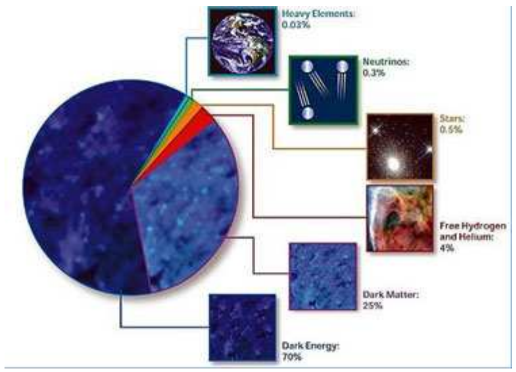
Oleg RUCHAYSKIY (CERN)

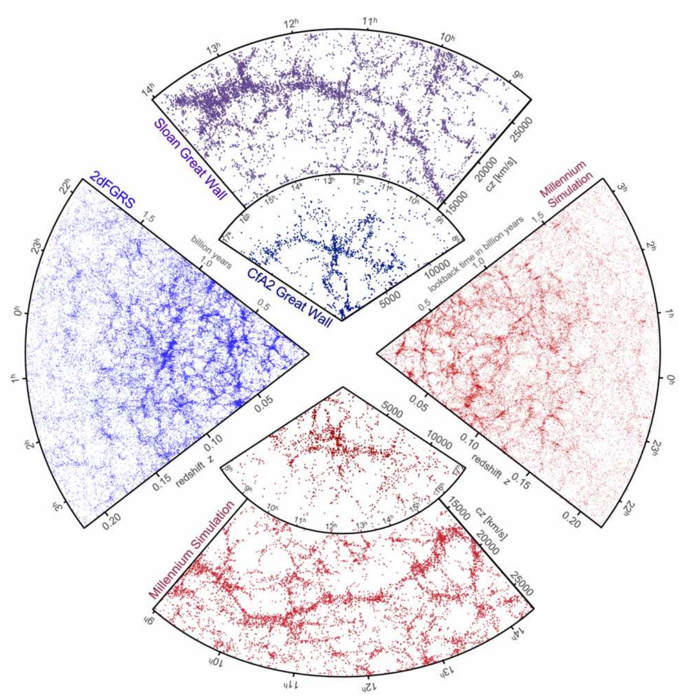


Warm Dark Matter Workshop. Meudon**.** June 9, 2011

Concordance model at cosmological scales

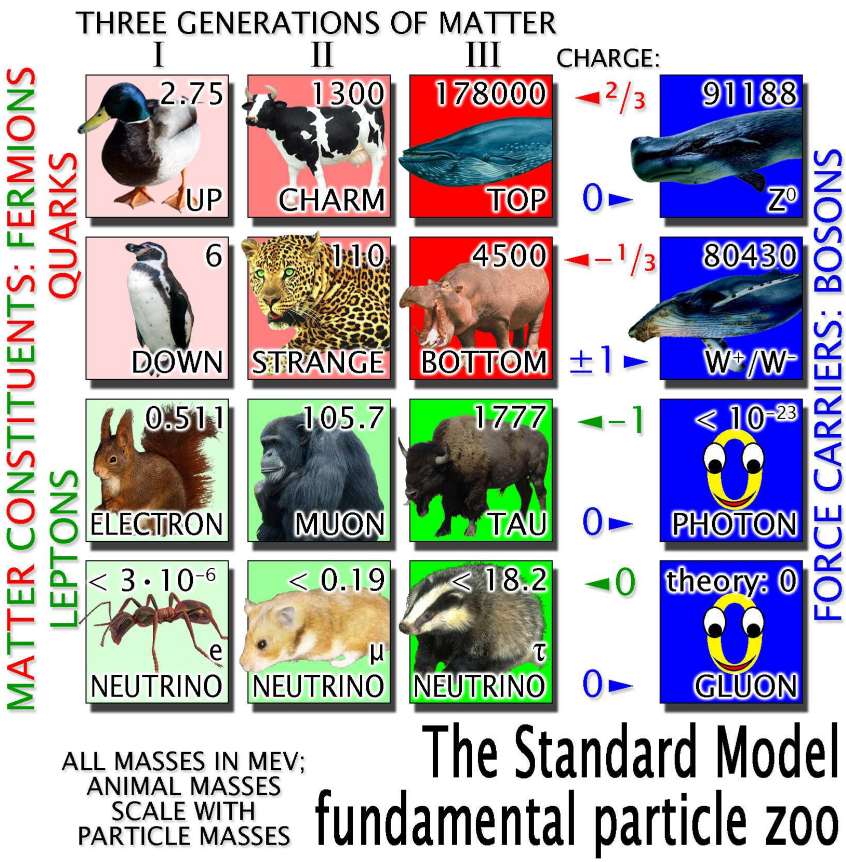






- ΛCDM: about 20% of total energy density is in the form of non-baryonic matter
- This dark matter is scale-free (non-interacting, "cold", . . .)
- Standard Model neutrinos do not contribute significantly to the Universe mass balance at matter-dominated epoch (CMB, LSS, . . .)

Dark matter - a fundamental physics problem

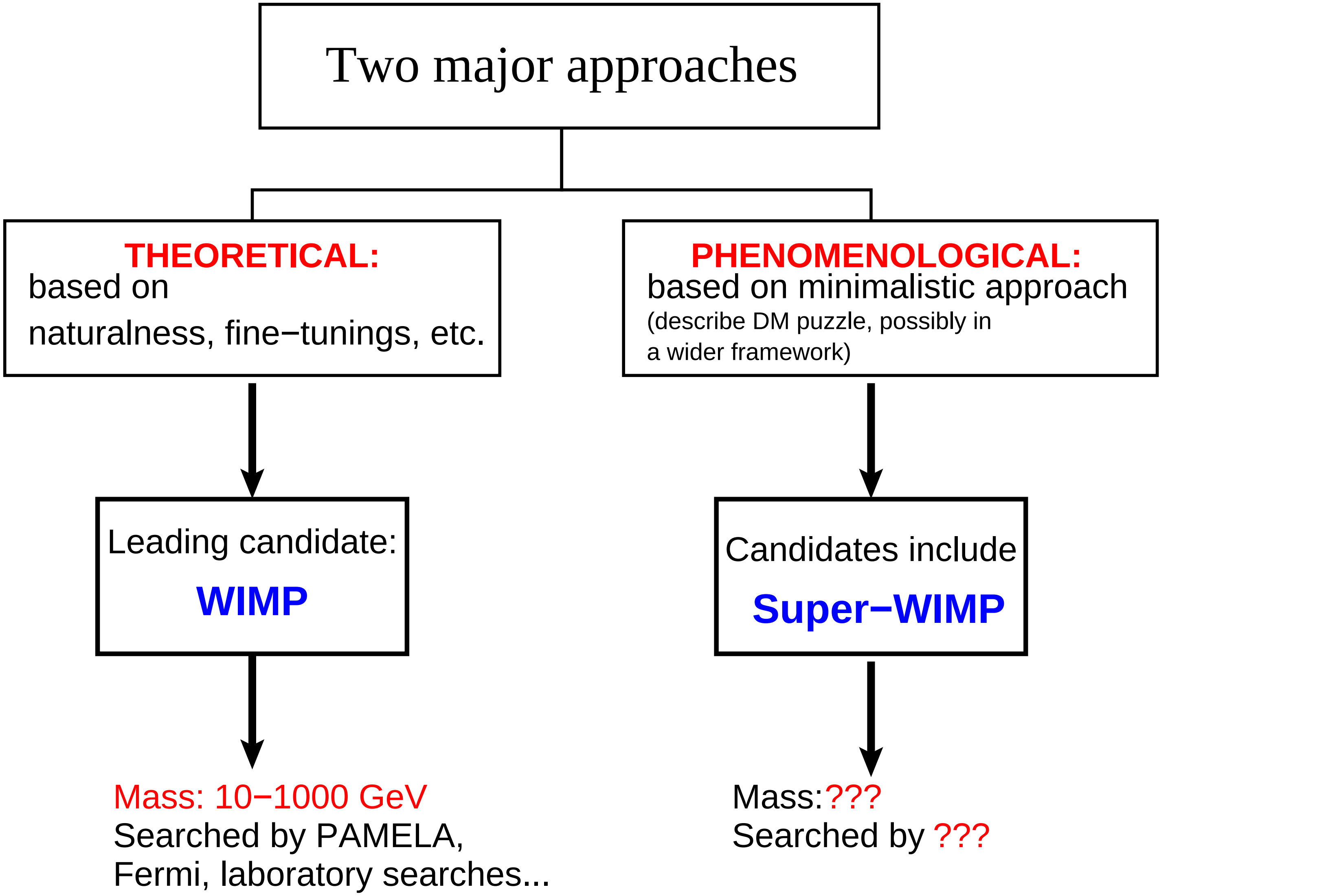


- Is evidence for DM convincing? — **yes**
- Is DM made up of particles? — **most plausible assumption**
- Is DM baryonic? — **no** (MACHO searches; BBN constraints; structure formation problems)
- Is DM made from neutrinos? — **no** (neutrino DM would contradict the observed LSS)

Properties of dark matter candidates

- Any DM candidate must be produced in the early Universe before matter-radiation equality and have correct relic abundance
- It should be stable or cosmologically long-lived
- Its non-gravitational interaction with ordinary matter or electromagnetic radiation should be feeble (to be “dark”)
- Its clustering properties should allow to explain the observed large scale structure

DM candidates. What do we expect?



Super-Weakly Interacting Massive Particles

- Phenomenologically we know little about the properties of dark matter particles
- Theoretical bias aside, dark matter particles should generically have "weaker-than-weak" interaction strength with the Standard Model sector (***super-weakly interacting*** particles)
- Such DM candidates indeed appear in many extensions of the Standard Model (sterile neutrinos, gravitino, axion, axino, Majoron,. . .)
- For super-weakly interacting particles laboratory "*direct* detection" methods may be quite challenging $\Longrightarrow$

> For Super-WIMPs astrophysics and cosmology may be our main tools to discover the true nature of dark matter particles

Example of super-weakly interacting particles: sterile neutrinos

Why (and where) we expect new physics?

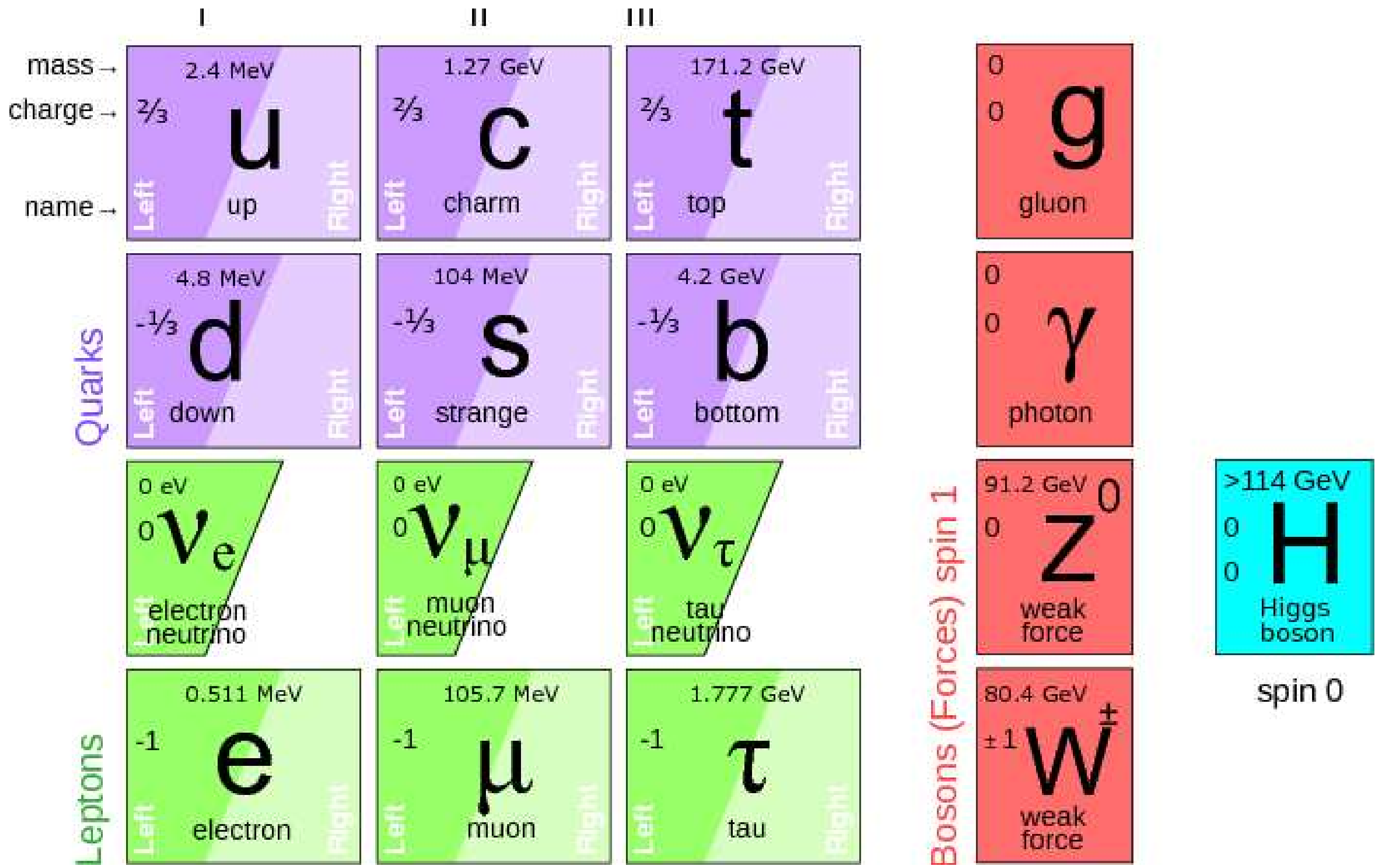
- **Neutrino oscillations**: $m_\nu \sim \sqrt{\Delta m^2_{\rm atm}} \sim 10^{-2}$ eV.
  See-saw mechanism $m_\nu \sim v^2/\Lambda$, where $v = \langle H\rangle = 174$ GeV and **new scale** $\Lambda \sim 10^{15}$ GeV

- **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 processes (leptogenesis, phase transitions, etc.)

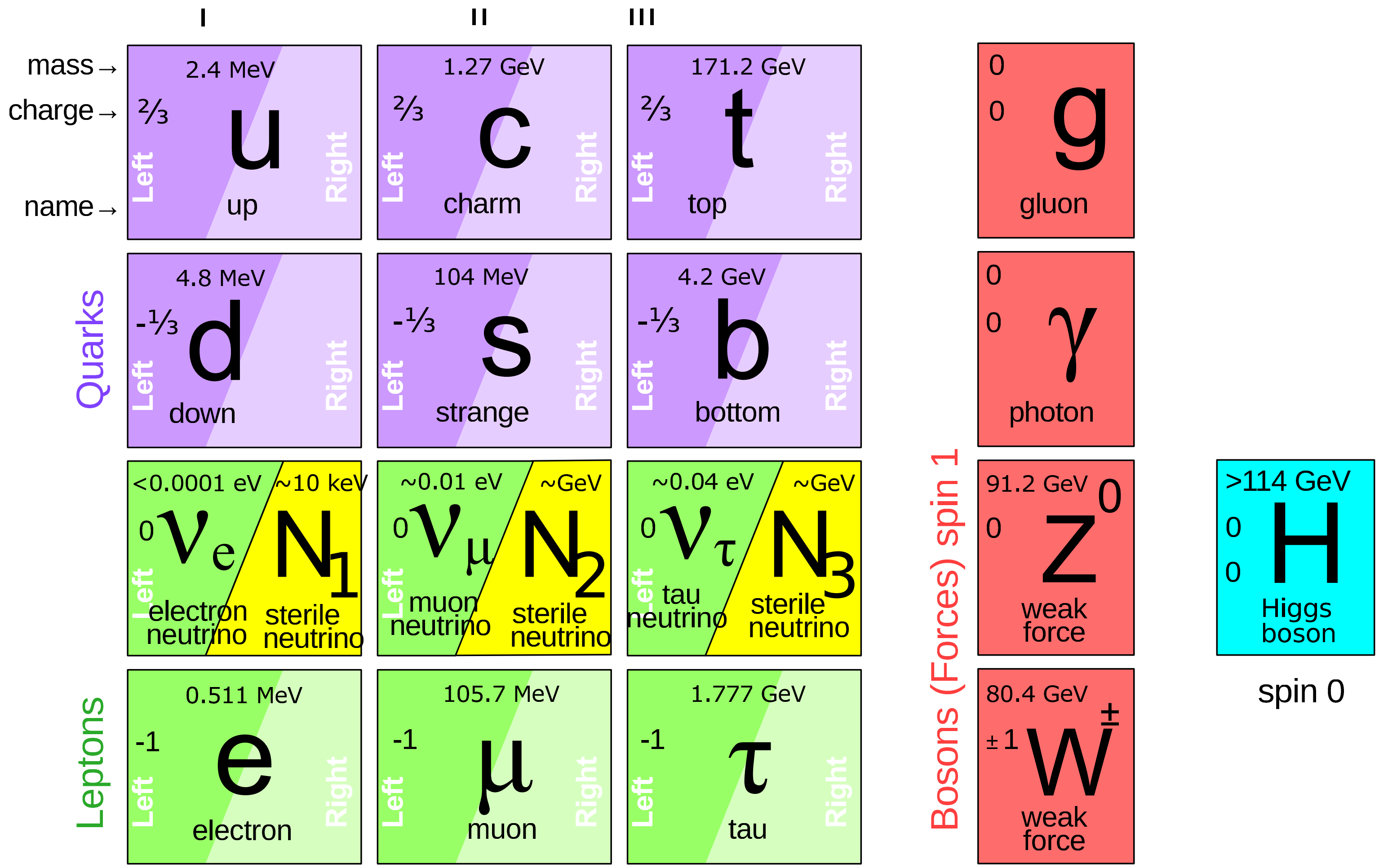
- **Fine-tuning problems:** CP-problem, hierarchy problem, grand unification, cosmological constant problem

Standard Model



Standard Model neutrinos are **strictly massless**

Right-chiral neutrino counterparts?



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)
  - $\mathrm{U}_Y(1)$: **singlets** ($Y(\nu) = Y(\text{Higgs})$)

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

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

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

See saw Lagrangian

- 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 by neutrino oscillation data!

The scale of right-handed masses?

"Popular" choices of see-saw parameters

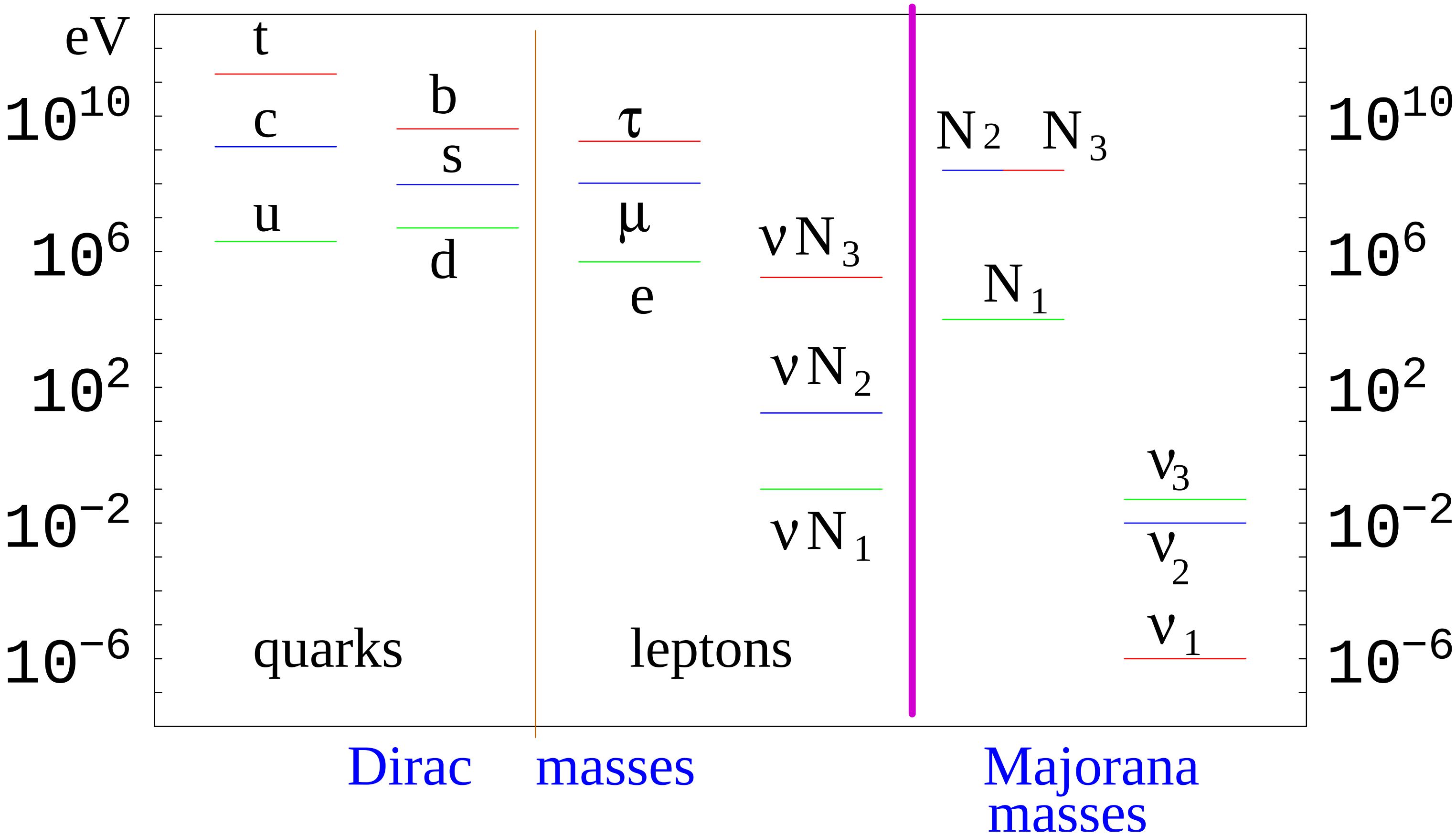
- Yukawa couplings $F_{\alpha I} \sim 1$, i.e. Dirac masses $M_D \sim M_t$. Majorana masses $M_I \sim 10^{15}$ GeV.

- 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



Mass spectrum of the νMSM

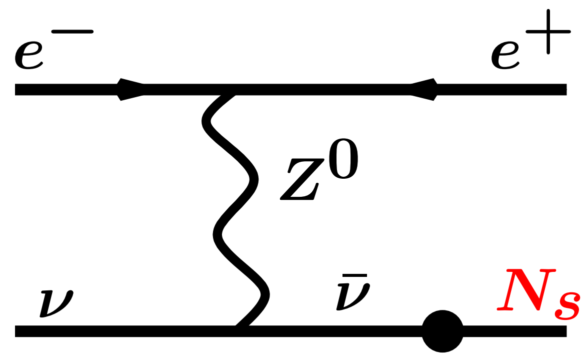
Some general properties of sterile neutrino

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

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

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: $G_F \to \boldsymbol{\theta} G_F$

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, Laine, **O.R.**, Boyarsky et al (2005-2011)

✓ . . . 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 $\Rightarrow$ 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)

Properties of sterile neutrino DM

- Mass not restricted to the GeV range
- Can **decay** into the SM particles
- Produced in many different ways, **non-thermally**. Have non-universal spectrum of primordial velocities
- Can be **warm** or **cold**

Lifetime of sterile neutrino DM candidate

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

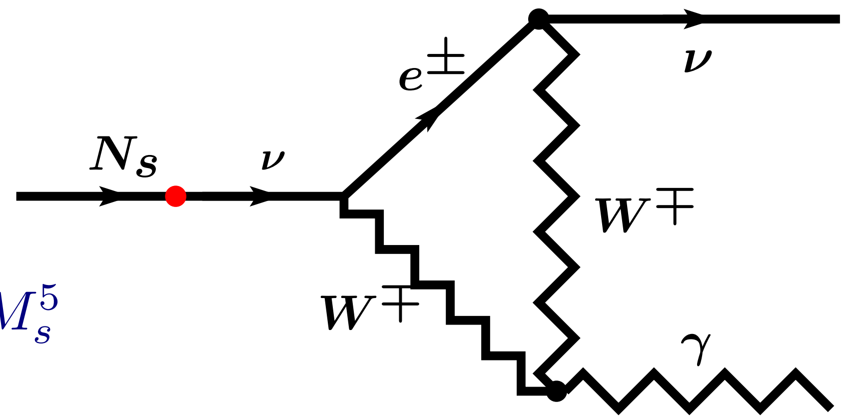
Wolfenshtein Pal (1982)

- 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)

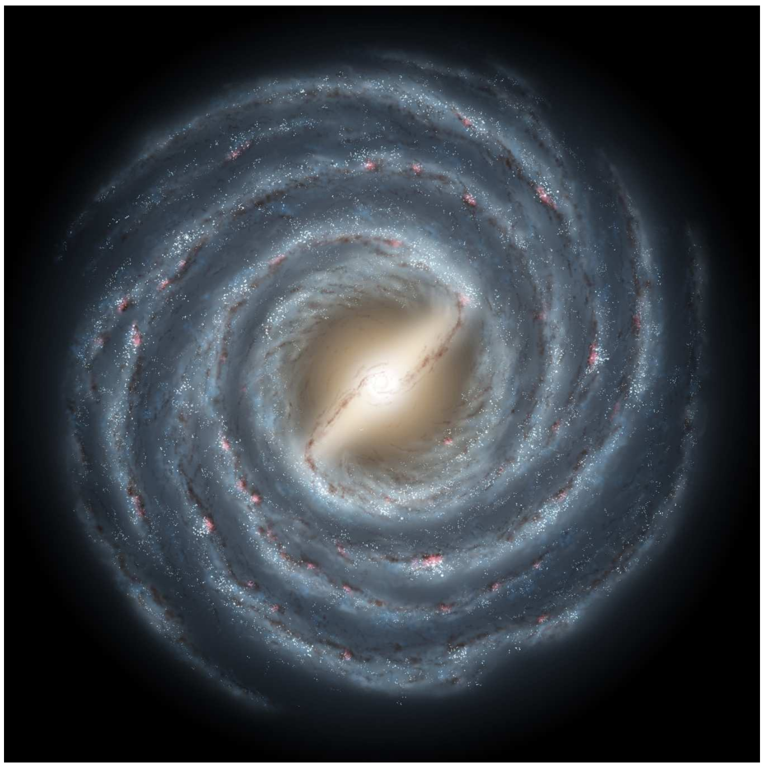
Abazajian Fuller Tucker (2001)

- 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)

Search for dark matter particles

- 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

Search for dark matter particles

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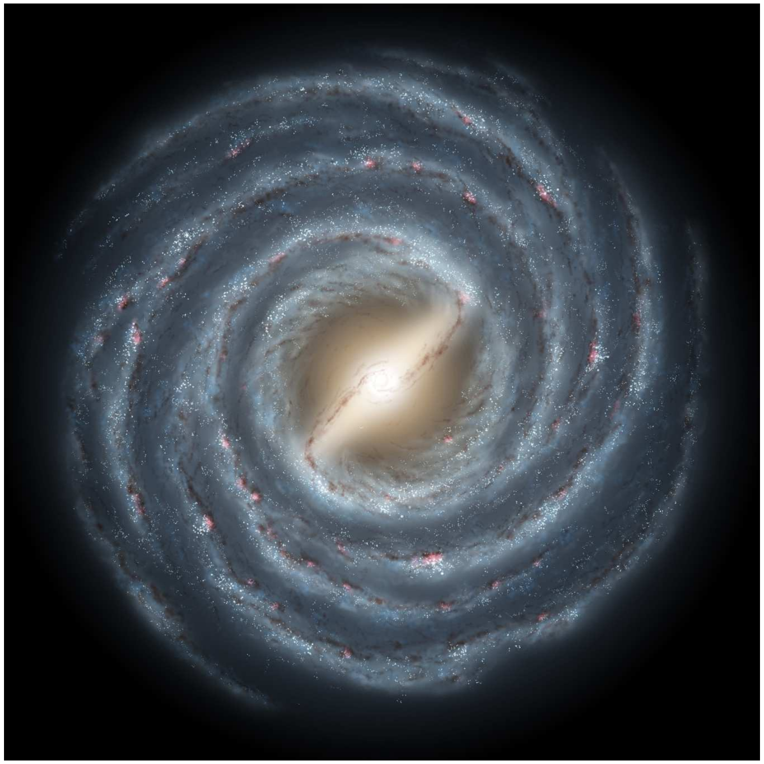
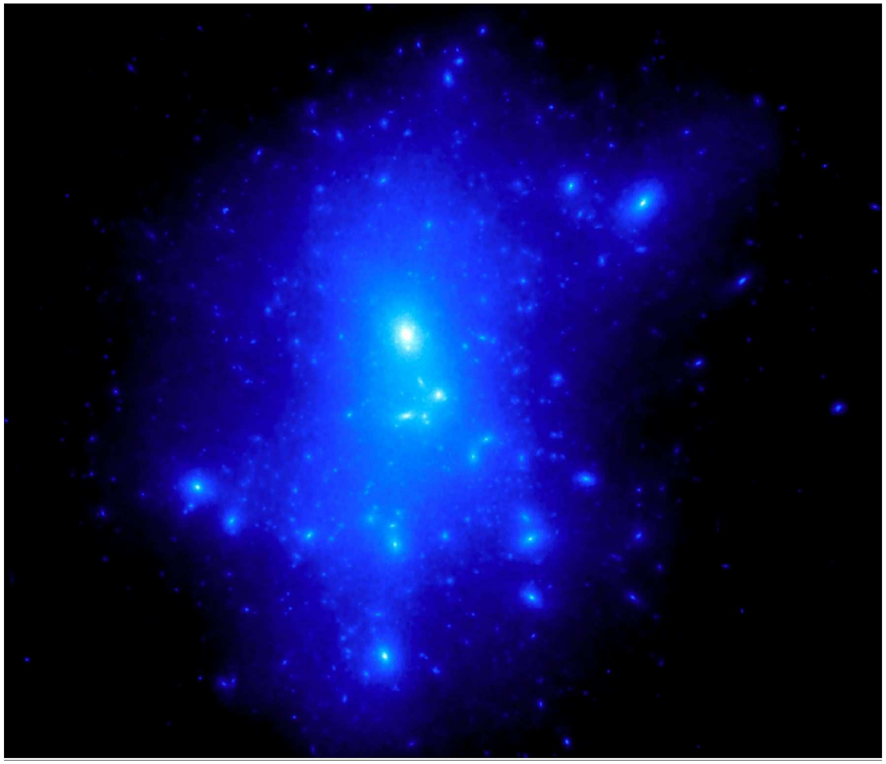
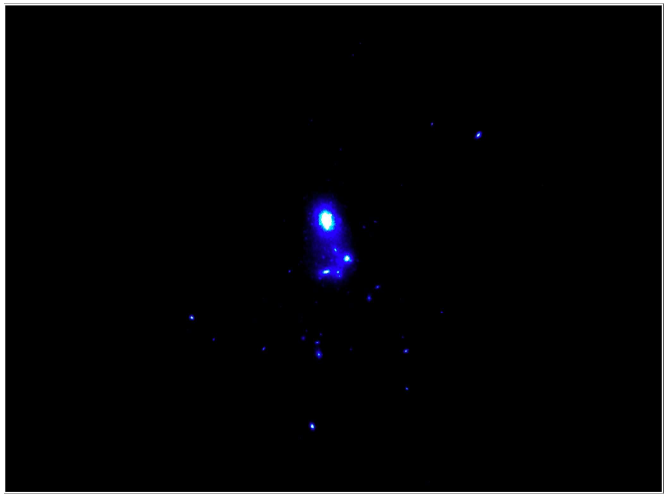




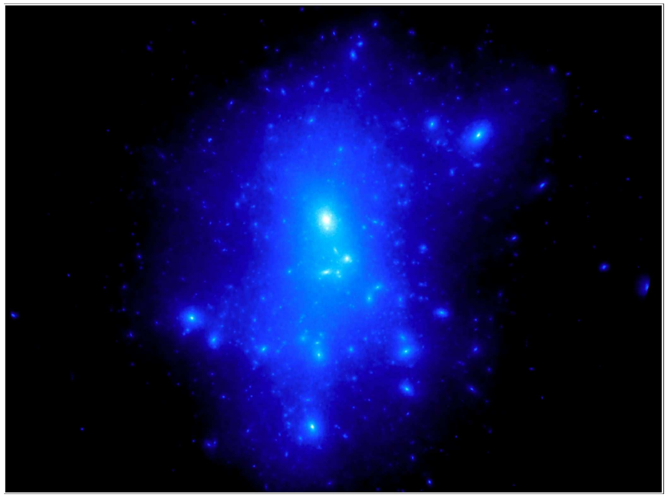
Expected signal from a galaxy at a particular energy

Decay vs. annihilation

- In the case of decaying Dark Matter the signal, if detected, is easy to distinguish from astrophysical backgrounds

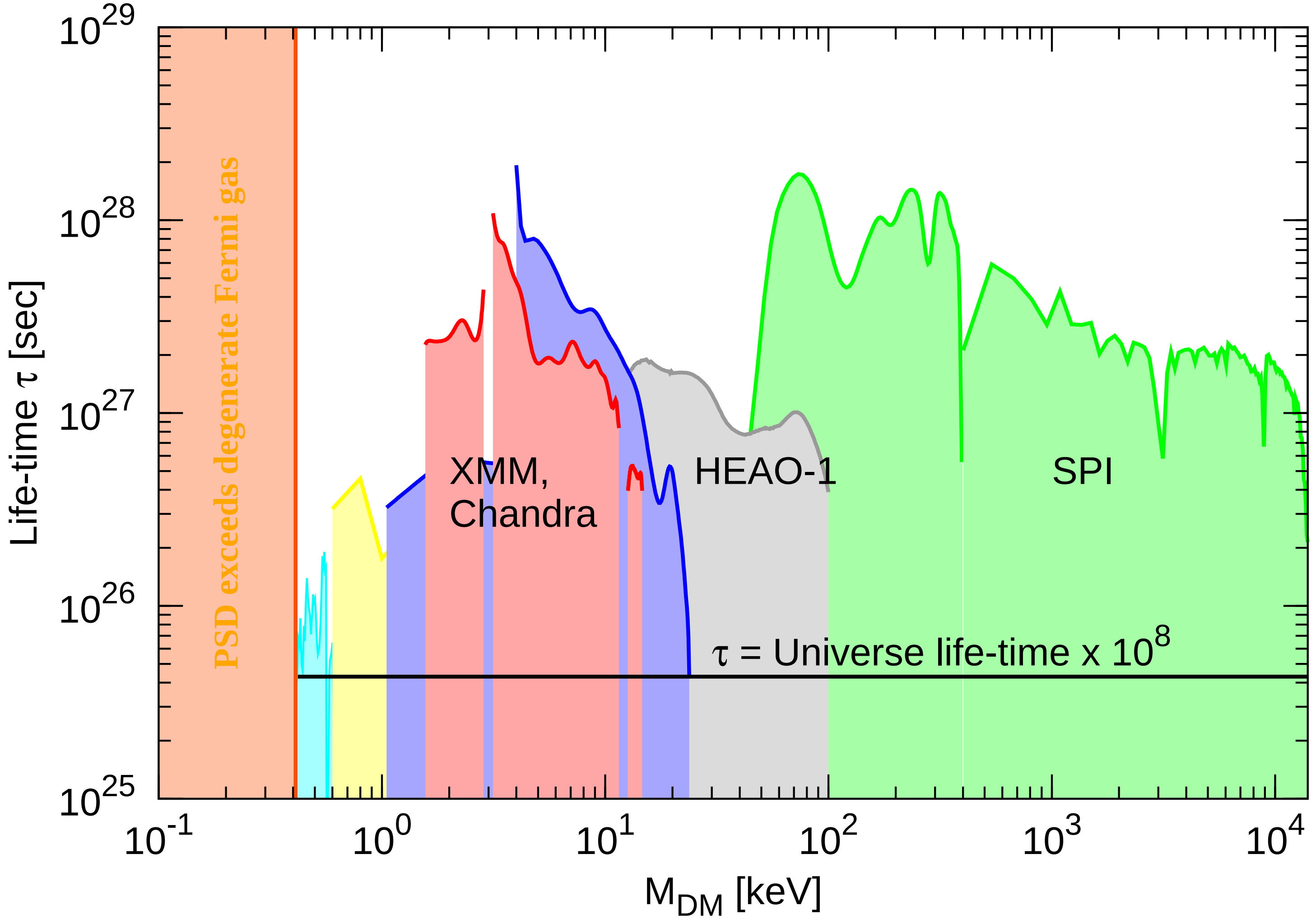


- We have a lot of freedom in choosing observation targets and, therefore, can unambiguously check DM origin of a suspicious signal.



For decaying DM "indirect" search becomes very promising!

Restrictions on life-time of decaying DM



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.

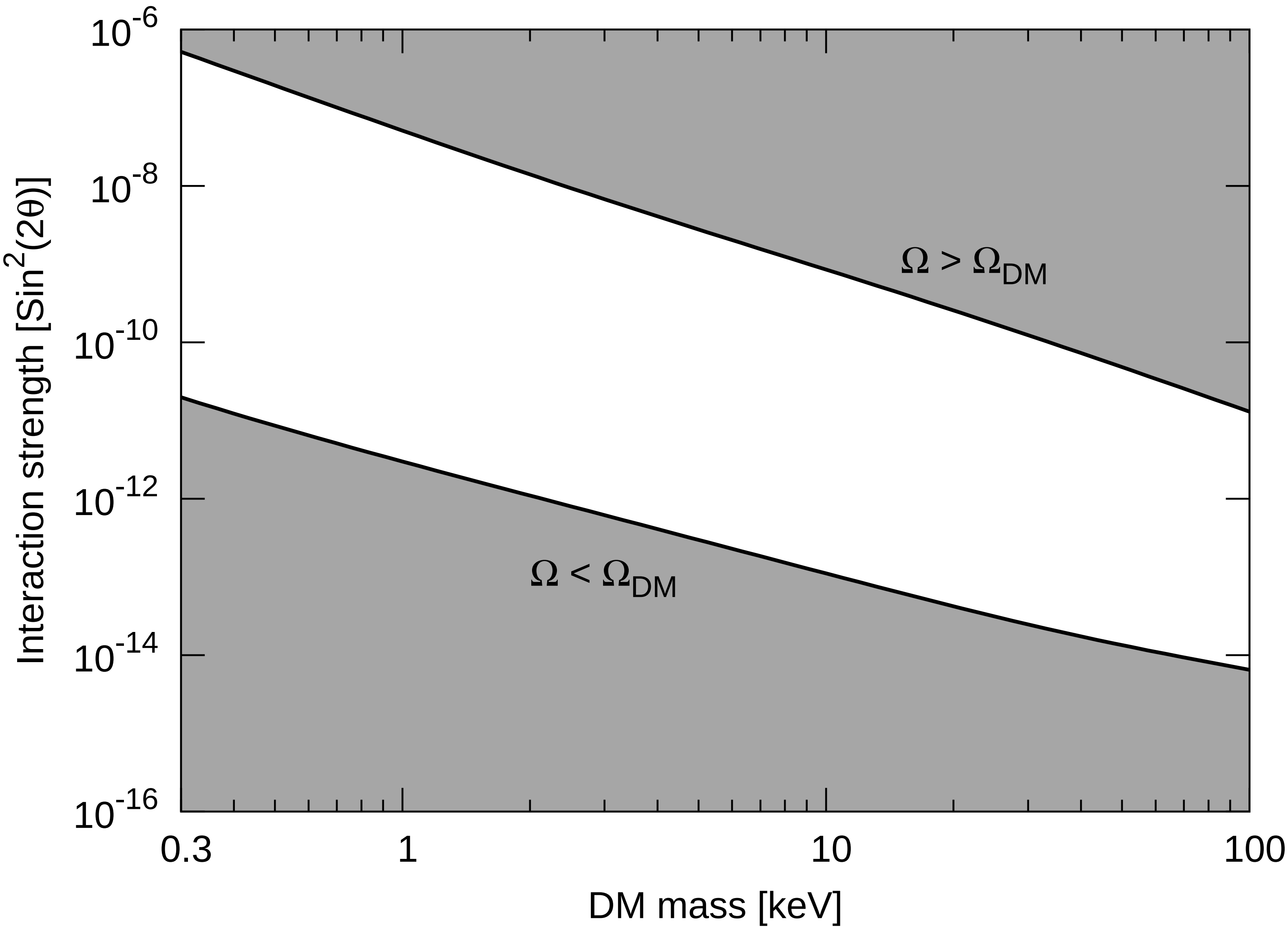
MW (XMM) Boyarsky, **O.R** et al. 2007

M31 Watson et al. 2006; Boyarsky et al 2007

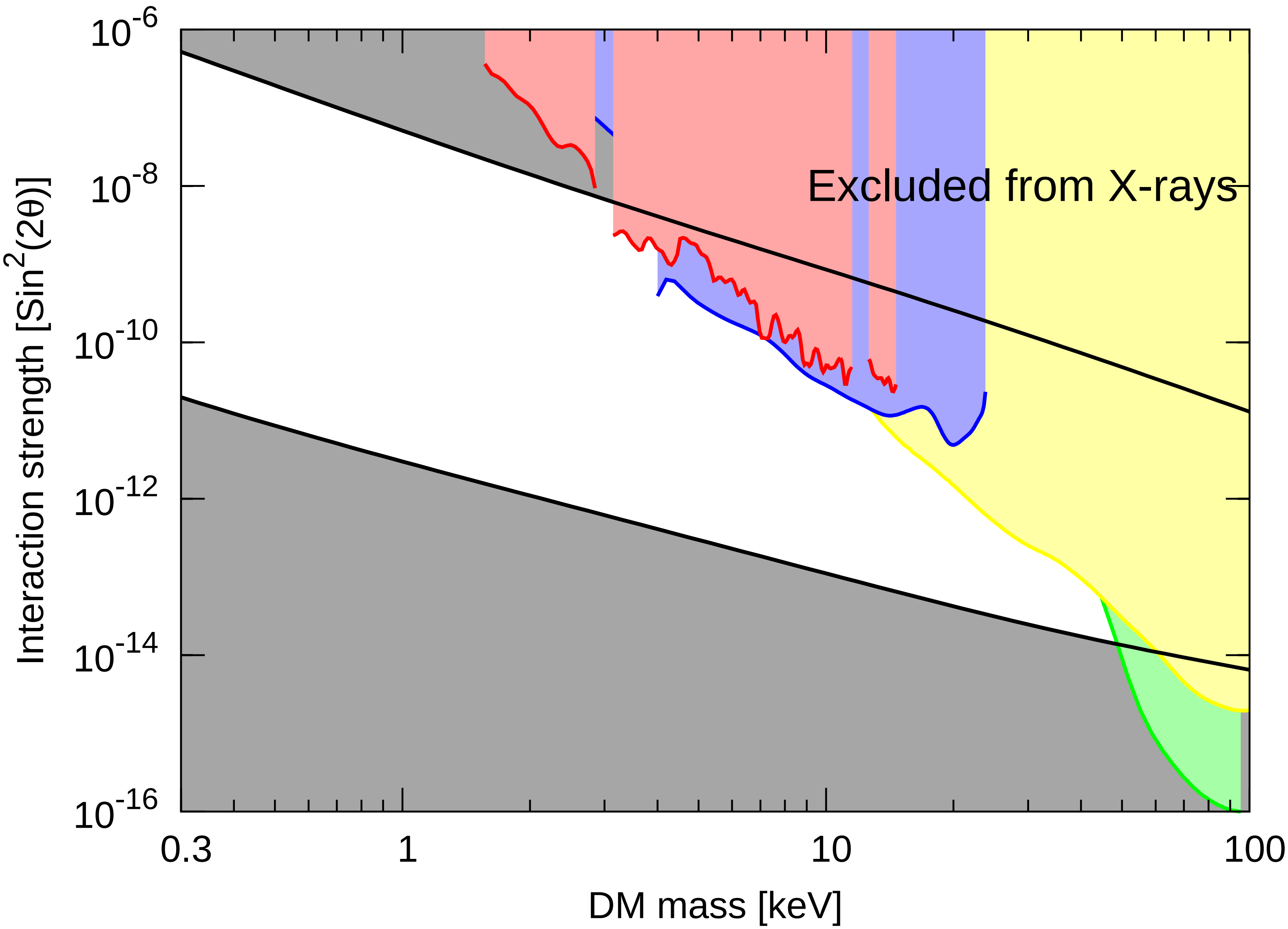
Results of almost **20** published works.

Window of parameters of sterile neutrino DM

Laine, Shaposhnikov



Window of parameters of sterile neutrino DM

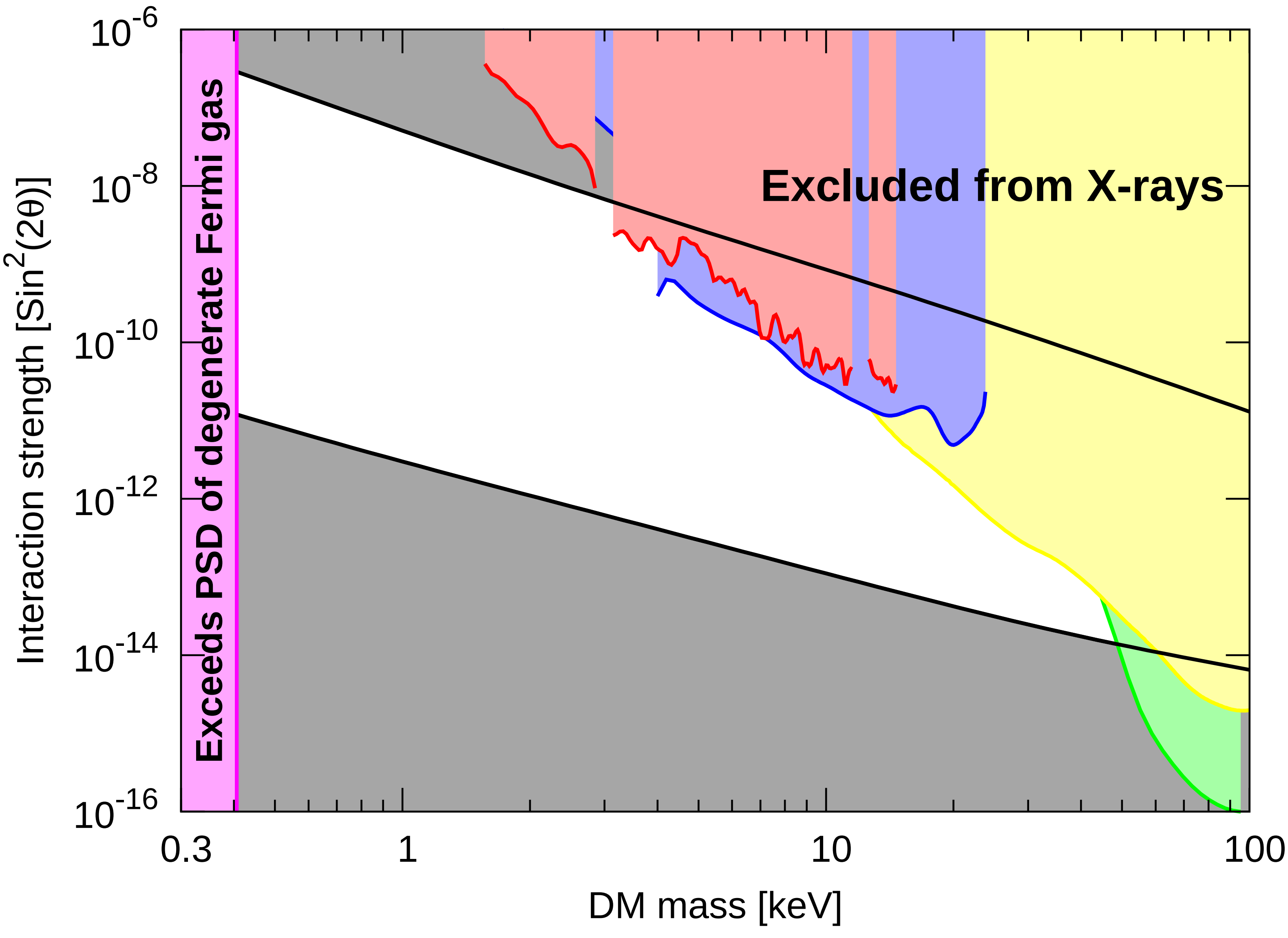


Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov

O.R. and many others 2005-2010

Window of parameters of sterile neutrino DM



Asaka, Laine, Shaposhnikov

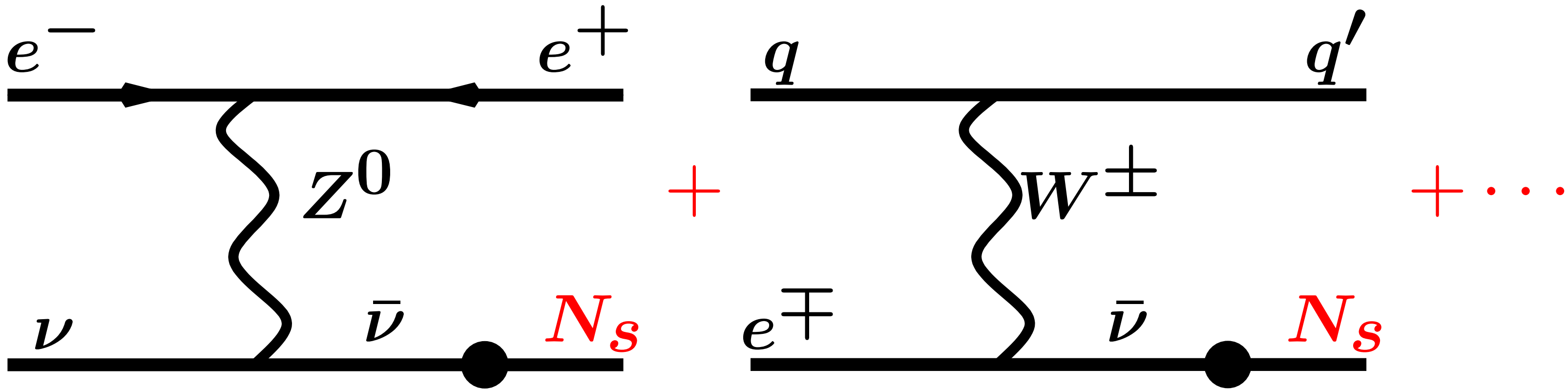
Laine, Shaposhnikov

O.R. and many others 2005-2010

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**

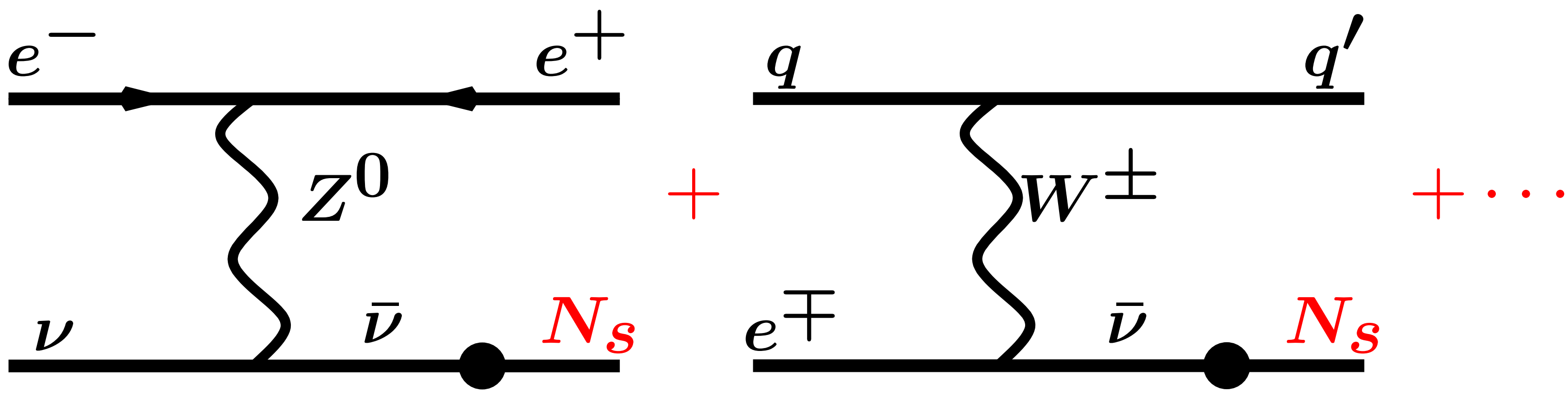
- **Simplest scenario:** sterile neutrino in the early Universe interact with the rest of the SM matter via ***neutrino oscillations:***



Dodelson & Widrow'93

Asaka, Laine, Shaposhnikov

How sterile neutrino DM is produced?



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

$$f_s(p) \propto \frac{\theta^2}{\exp(\frac{p}{T_\nu(t)})+1} \qquad \Omega_s h^2 \sim \theta^2 M_s$$

(for this distribution $\int dq\, q^2 f(q) \propto \theta^2 \lll 1$)

- Average momentum $\langle p\rangle \approx 3T_{max} \gg M_s$
- **Sterile neutrinos are produced highly relativistic**

Probing primordial velocities of dark matter particles

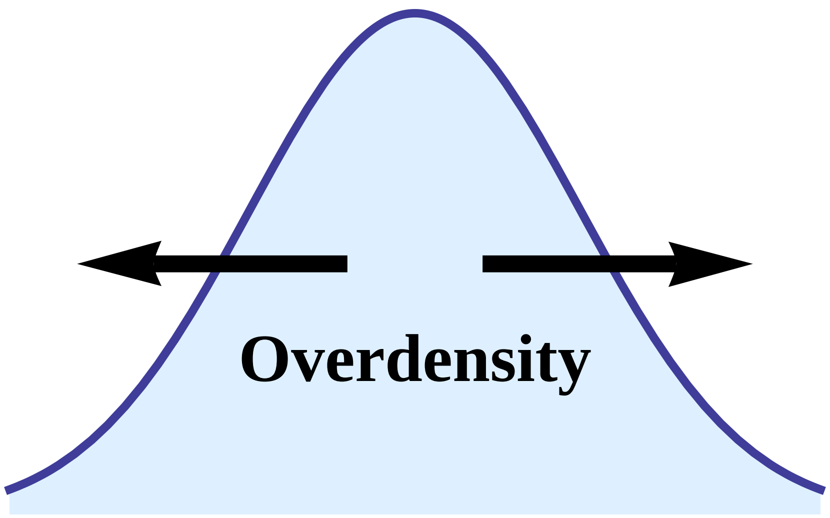
Free-streaming

- Sterile neutrino DM is produced at temperatures $T \sim 100$ MeV (for masses $\sim$ keV – created relativistic $\Rightarrow$ **warm dark matter**

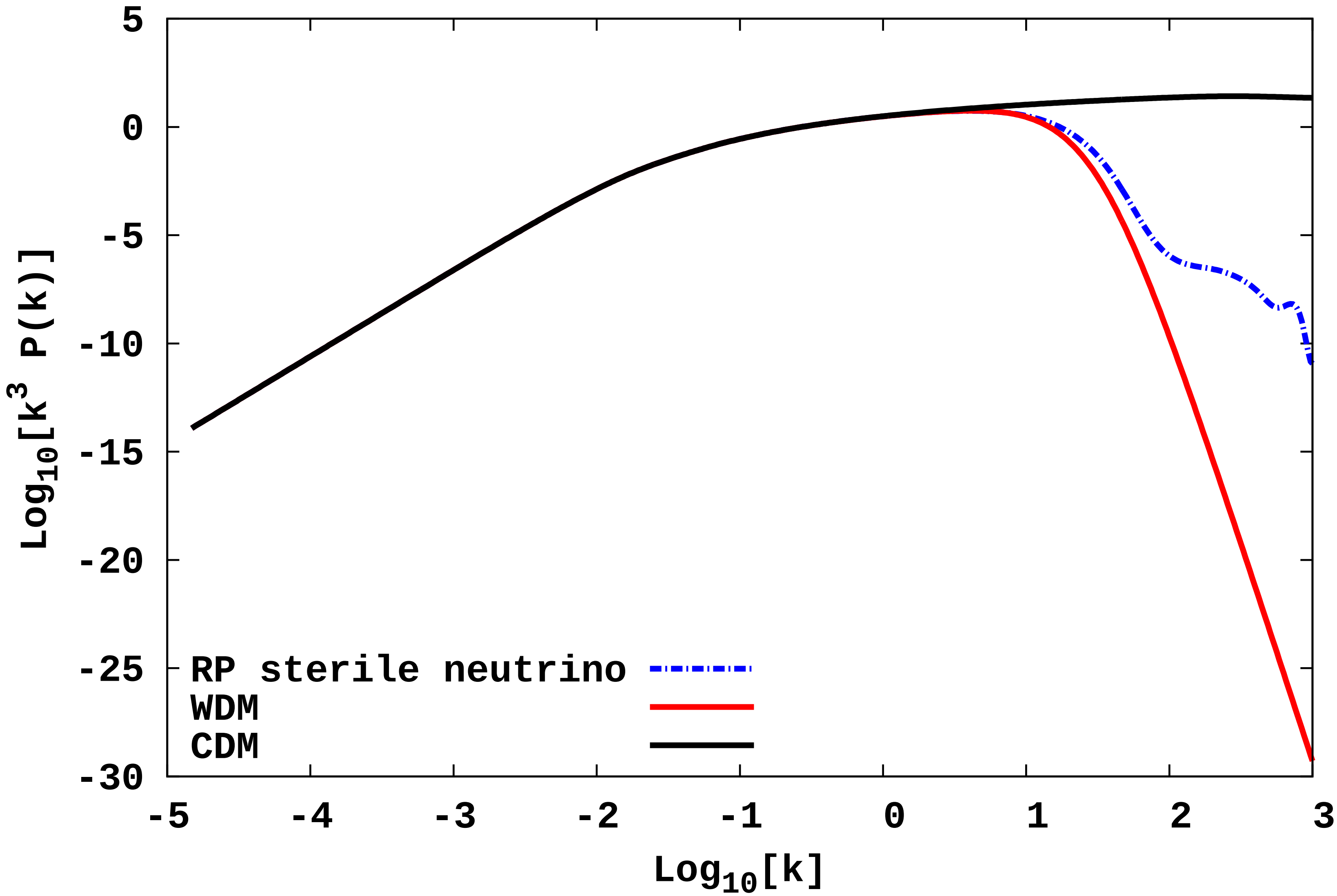
- Relativistic particles **free stream** out of overdense regions and smooth primordial inhomogeneities

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

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



Suppression of power spectrum



Thermal relics

- Free-streaming horizon determines power spectrum suppression scale. (i.e. by the time of matter-radiation equality certain small scale primordial perturbations are suppressed/erased)
- For particle with Fermi-Dirac spectrum – (**thermal relics**)

Bode et al. 2001

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

this suppression is strong:

$$T(k) \equiv \sqrt{\frac{P(k)}{P_{\Lambda\mathrm{CDM}(k)}}} \propto \left(\frac{k_{\mathsf{FS}}}{k}\right)^{10} \qquad k_{\mathsf{FS}} \sim 0.5 \frac{h}{\mathsf{Mpc}} \frac{M_{\mathsf{DM}}}{\mathsf{keV}}$$

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

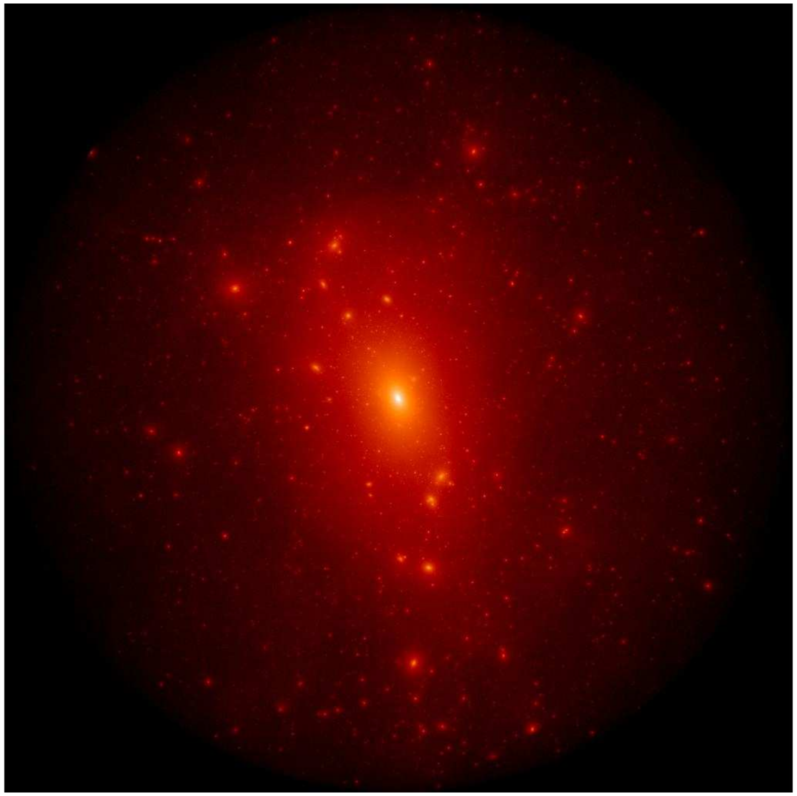
- Scales probed by CMB and LSS experiments (linear regime of perturbation growth)

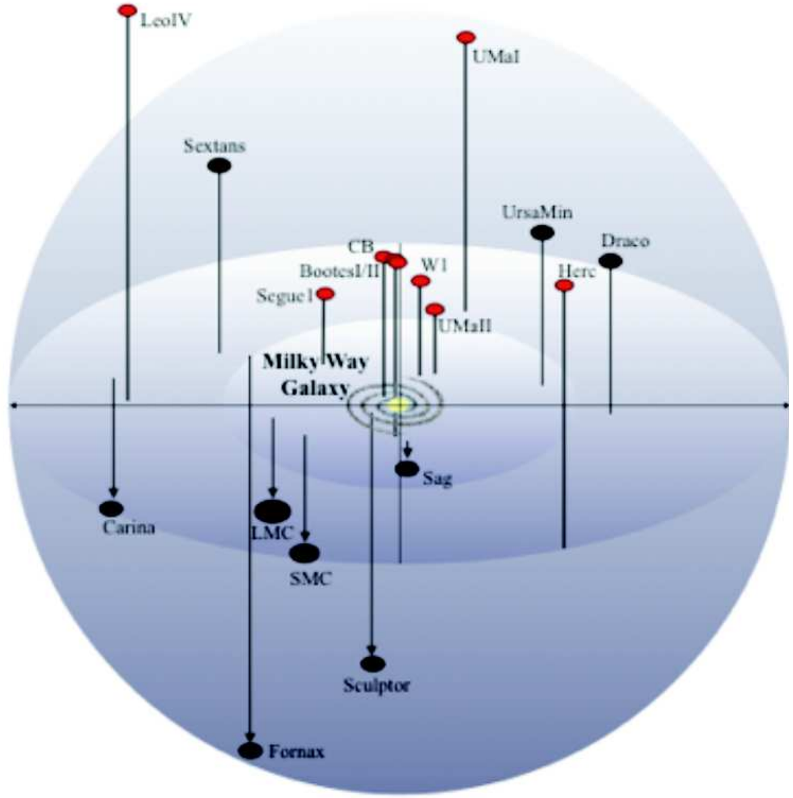
$$k \simeq \ell \times \frac{H_0}{2} = \frac{\ell}{6000} \frac{h}{\text{Mpc}}$$

- Is sensitive up to scales $k \lesssim 0.1\ h/$ Mpc (See the next talk by Katarina Markovic about future sensitivity of LSS probes)

- Smaller scales? Non-linear stage of structure formation

Halo substructure in "cold" DM universe



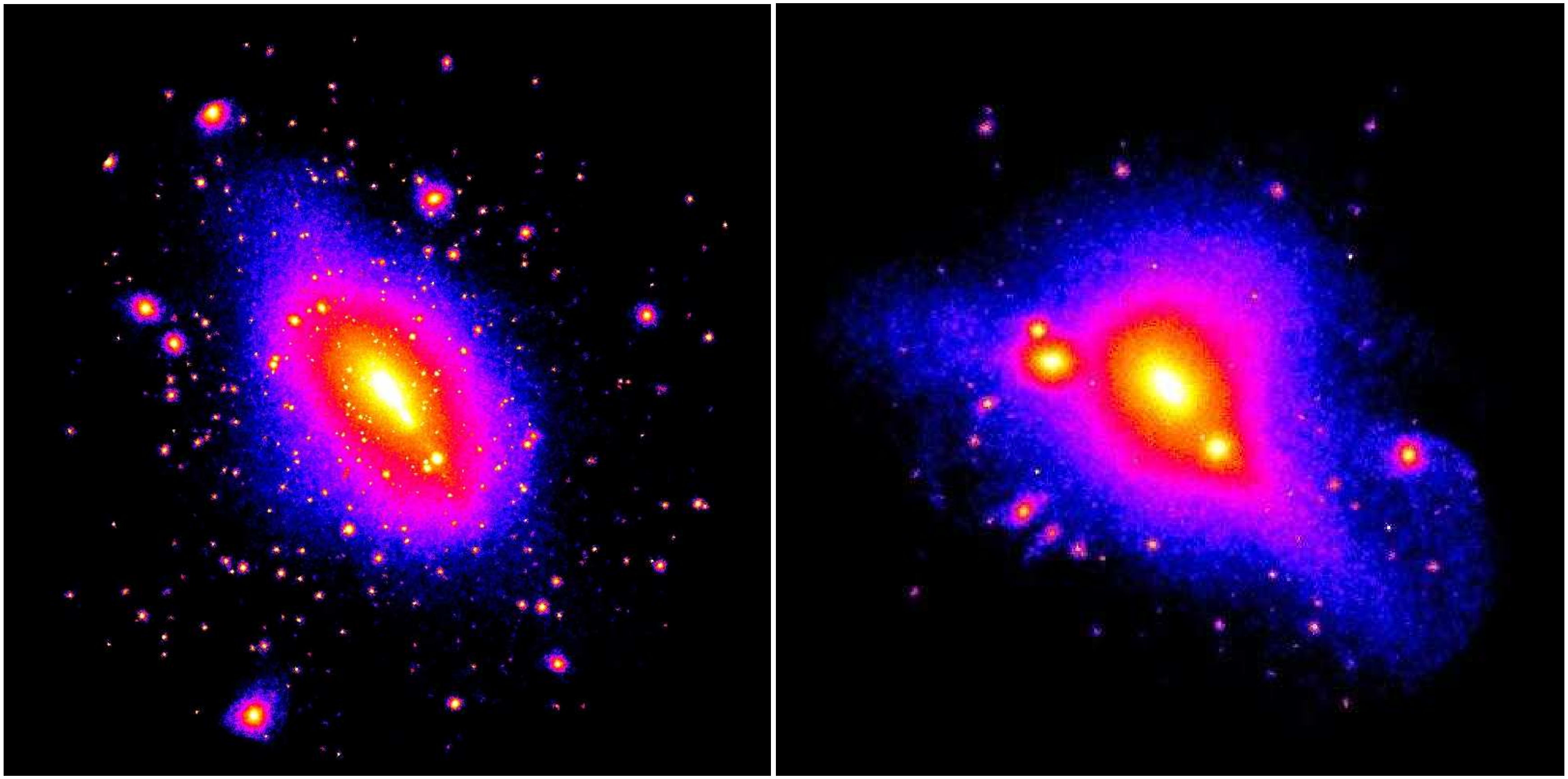


45×10^3 substructures (Aquarius simulation)

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

Is small number of observed substructures due to dark matter free-streaming?

WDM substructure suppression

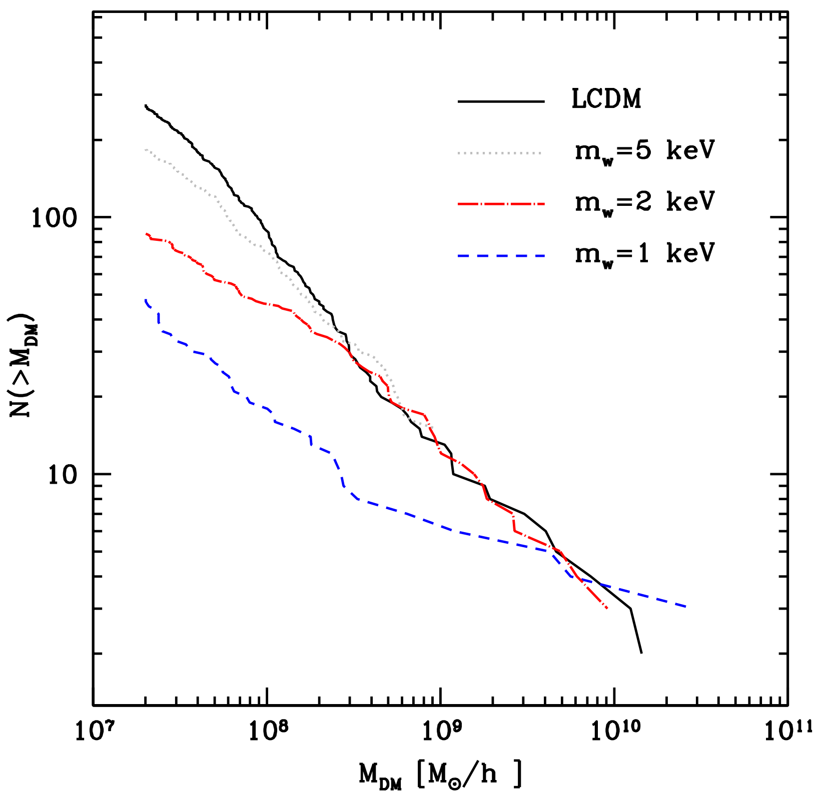


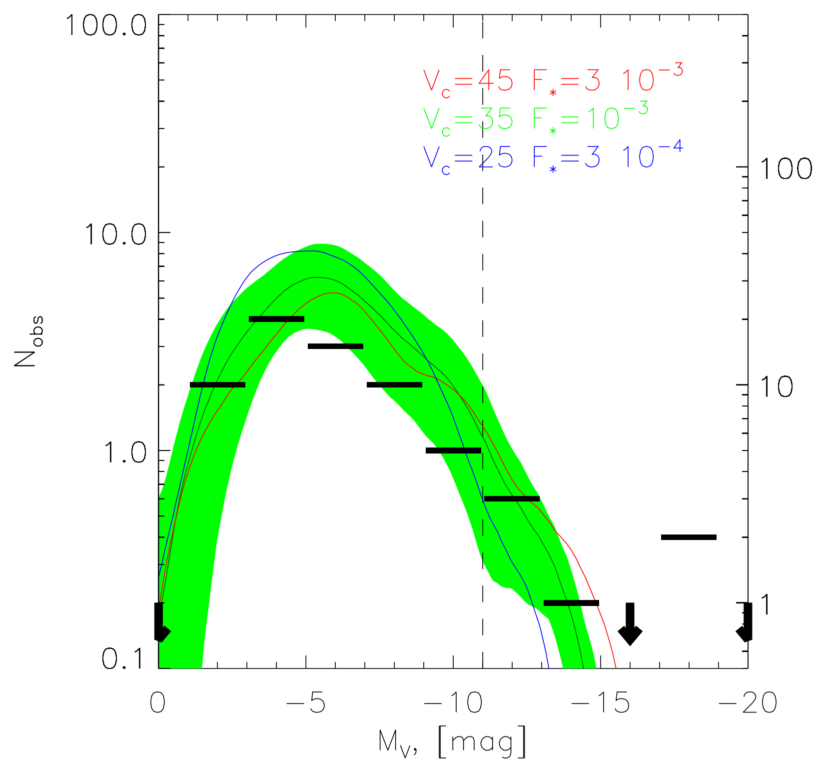
Thermal relics with mass ~ 1 keV would erase **too many substructures**. Anything "colder" would produce enough structures to explain observed Milky Way structures

Maccio & Fontanot (2009);

Polisensky & Ricotti (2010)

Luminosity vs. mass function





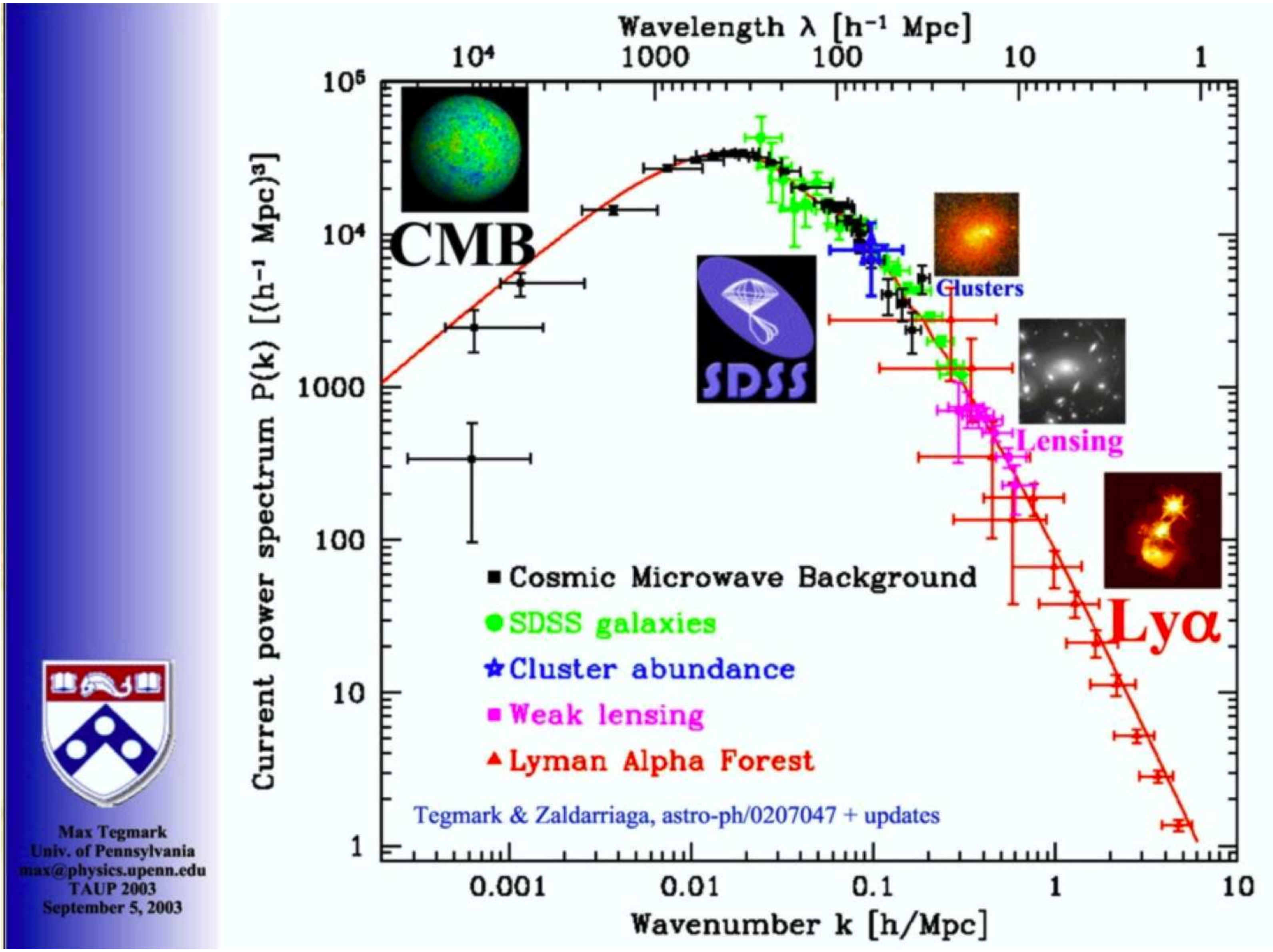
Macciò & Fontanot'09

Suppression of number of structures due to the **free-streaming**?

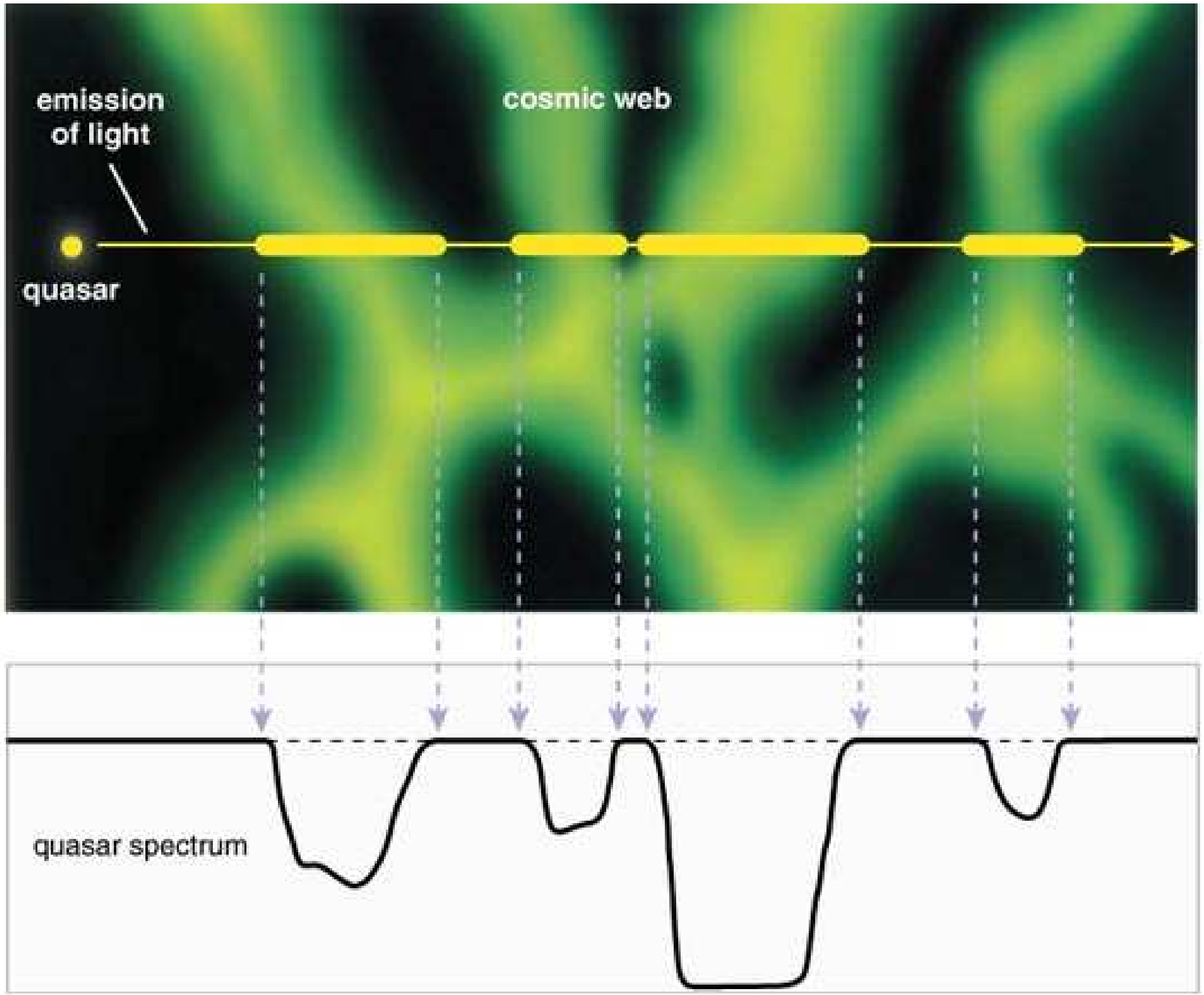
Koposov et al.'09

Bias between satellite luminosity function and halo mass function in ΛCDM?

How to measure power spectrum



Lyman-α forest and cosmic web



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

Lyman-α forest and cosmic web

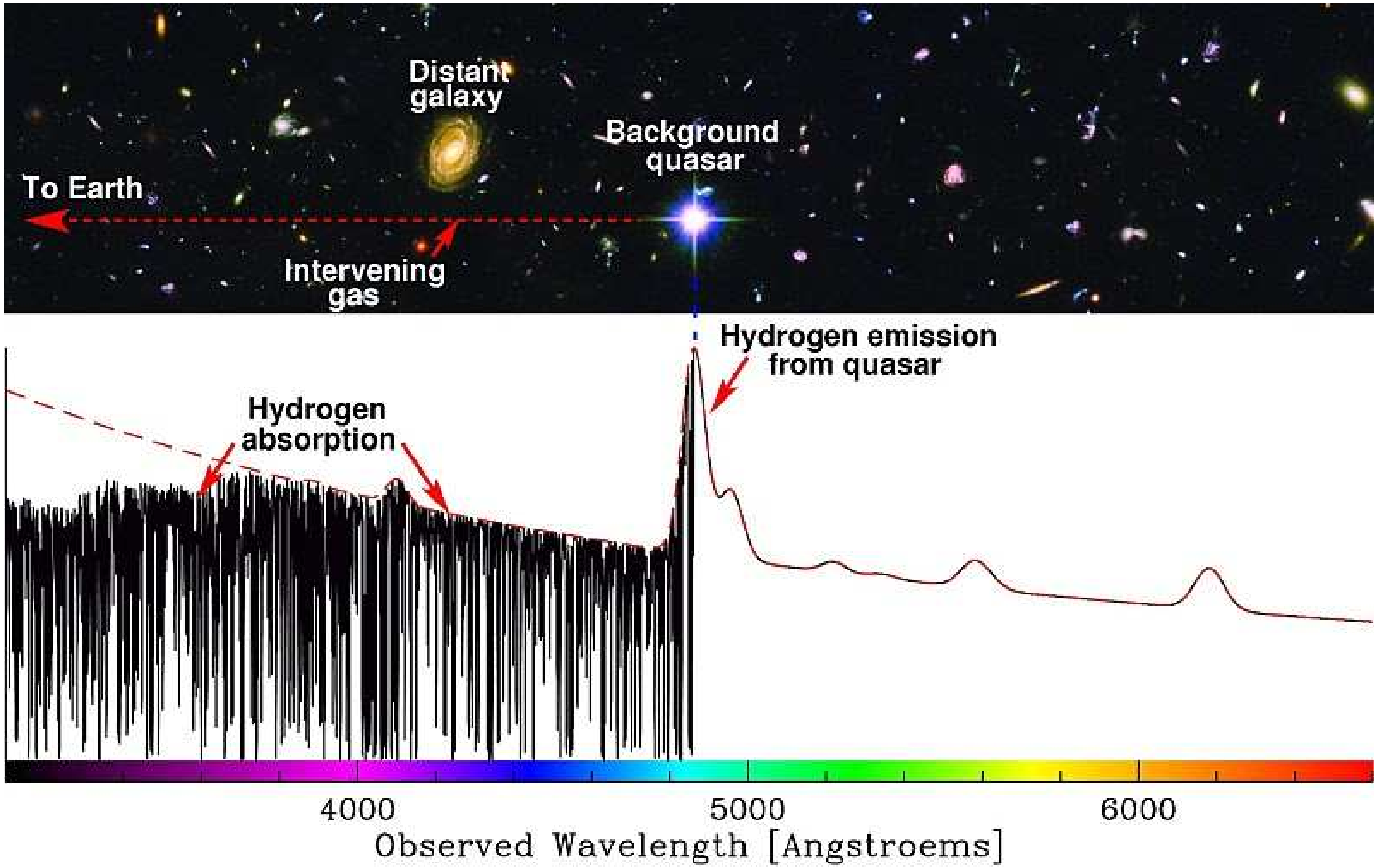


Image: Michael Murphy, Swinburne University of Technology, Melbourne, Australia

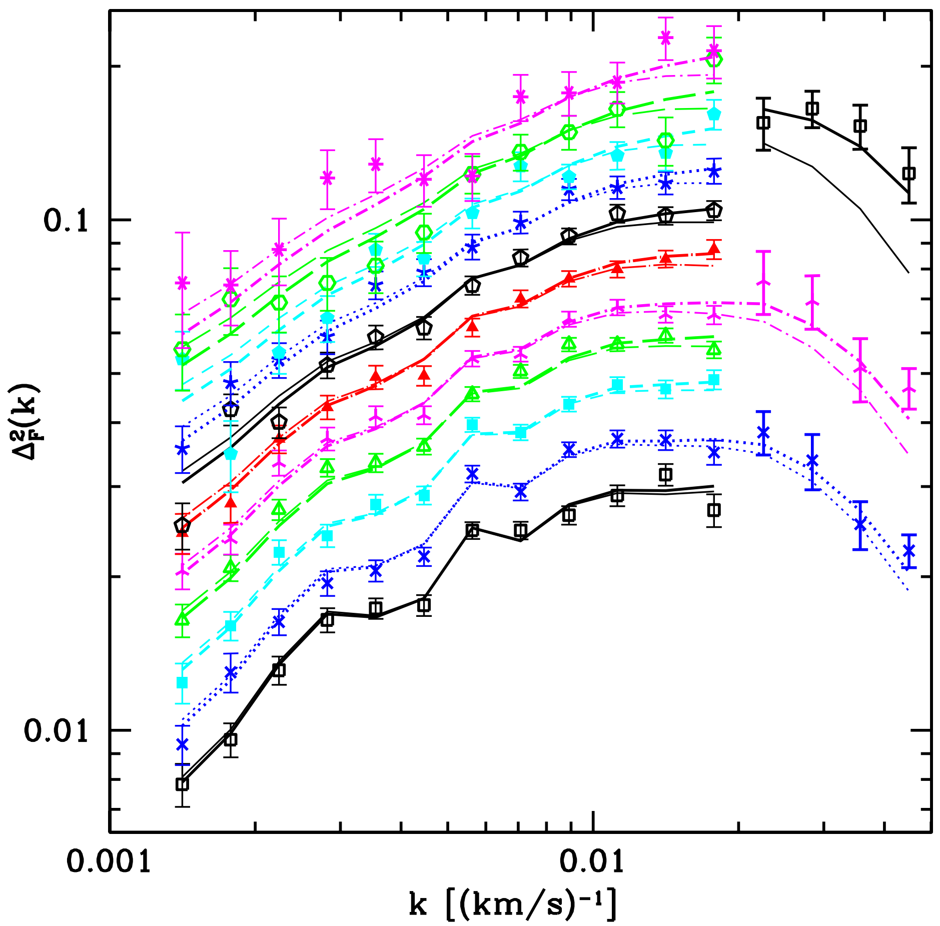
Neutral hydrogen in intergalactic medium is a tracer of overall matter density. Scales $0.3h/\text{Mpc} \lesssim k \lesssim 3h/\text{Mpc}$

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-α+ CMB $+$ maybe LSS ... (thousands of data points, sometimes correlated)

Lyman-α forest flux power spectrum

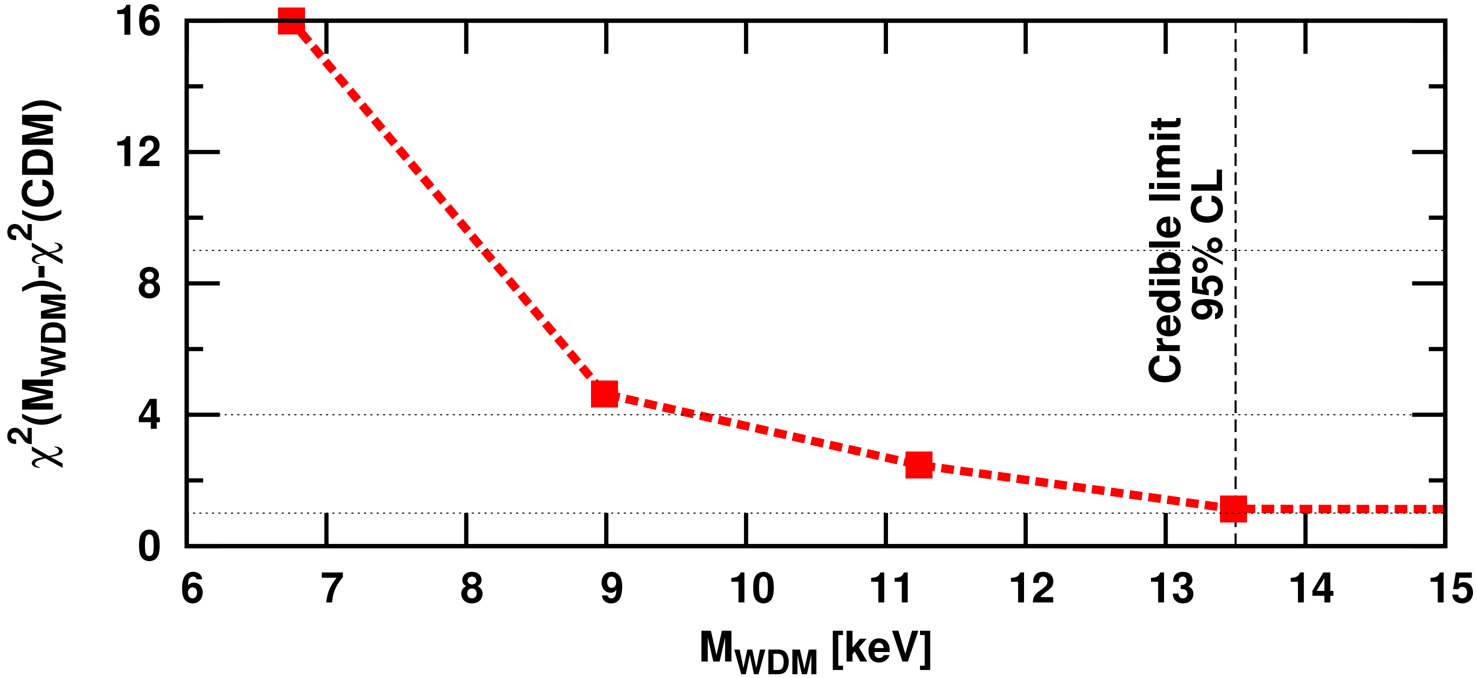
Seljak et al. '06



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

Ly-α and non-resonant sterile neutrino

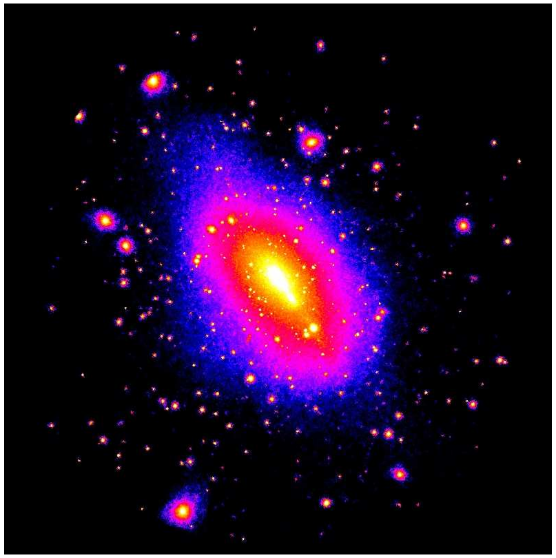
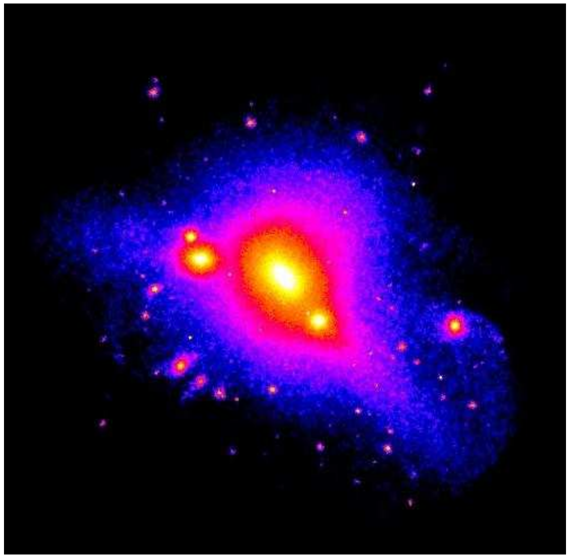
O.R. and others, 0812.0010 (JCAP 2009)



*These bounds are for **non-resonantly produced** sterile neutrinos or **thermal relics** only!*

Lyman-α forest and warm DM

- Previous works put bounds on free-streaming $\lambda_{FS} \lesssim 150$ kpc ("WDM mass" > 8 keV)
- The simplest **WDM** with such a free-streaming would not modify visible substructures:

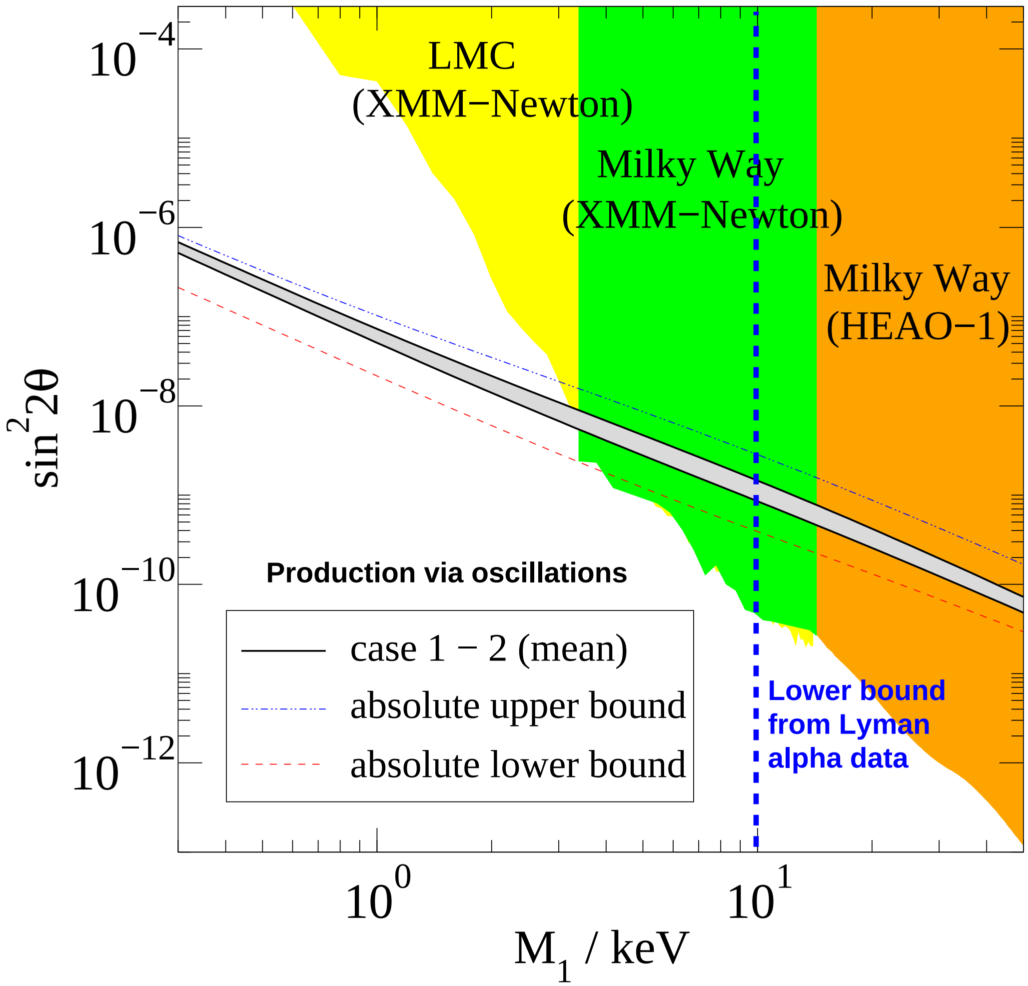
- **Thermal relic** with exponential cut-off ~ 1 Mpc (= NRP sterile neutrino with the mass ~ 4.5 keV) would erase **too many substructures**. Anything "colder" would produce enough structures to explain observed Milky Way structures

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

Maccio & Fontanot (2009);

Polisensky & Ricotti (2010)

Lyman-α forest and sterile neutrinos

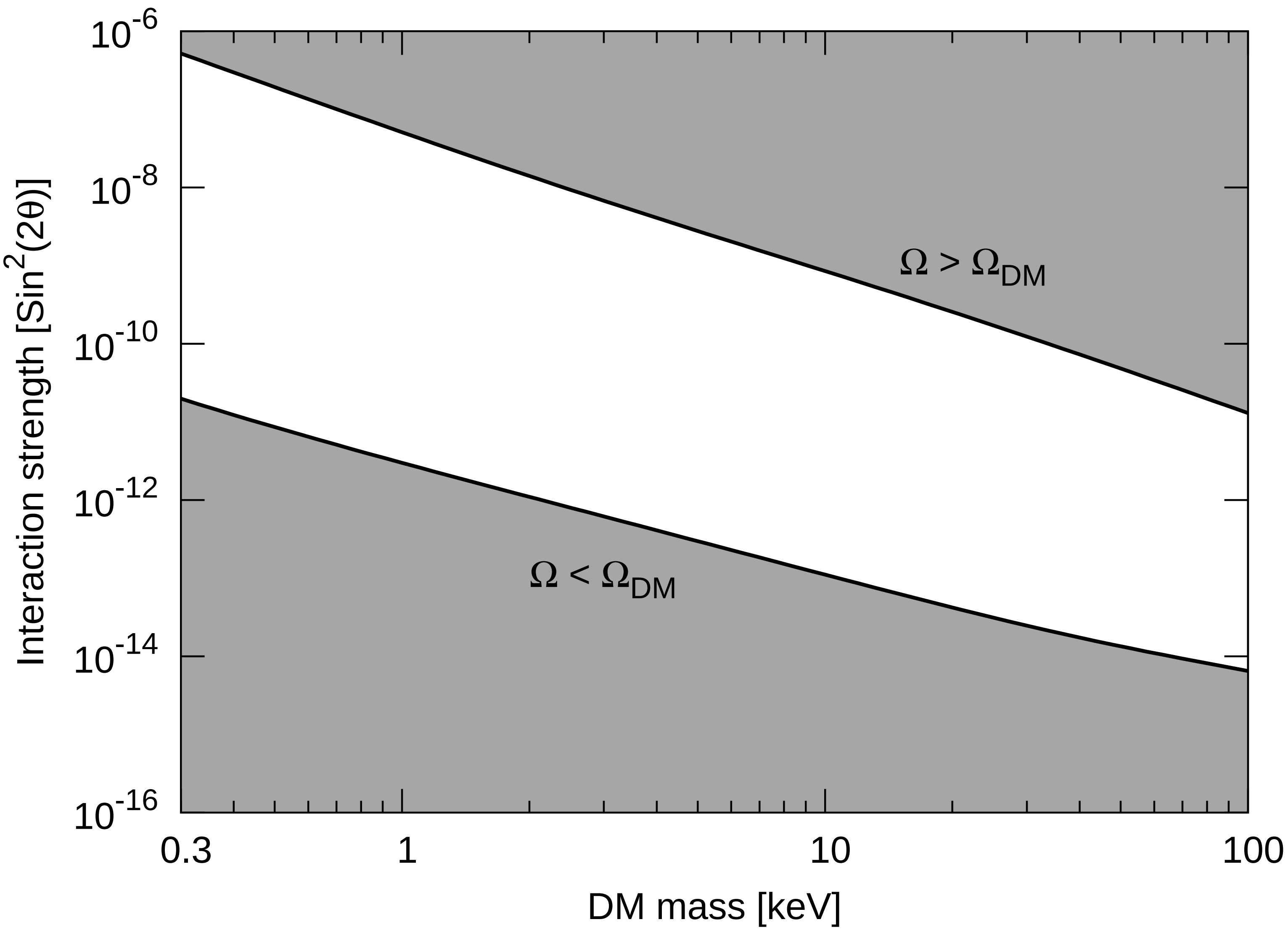


Does this mean that sterile neutrino dark matter *ruled out*? – No!

Window of parameters of sterile neutrino DM

Laine, Shaposhnikov

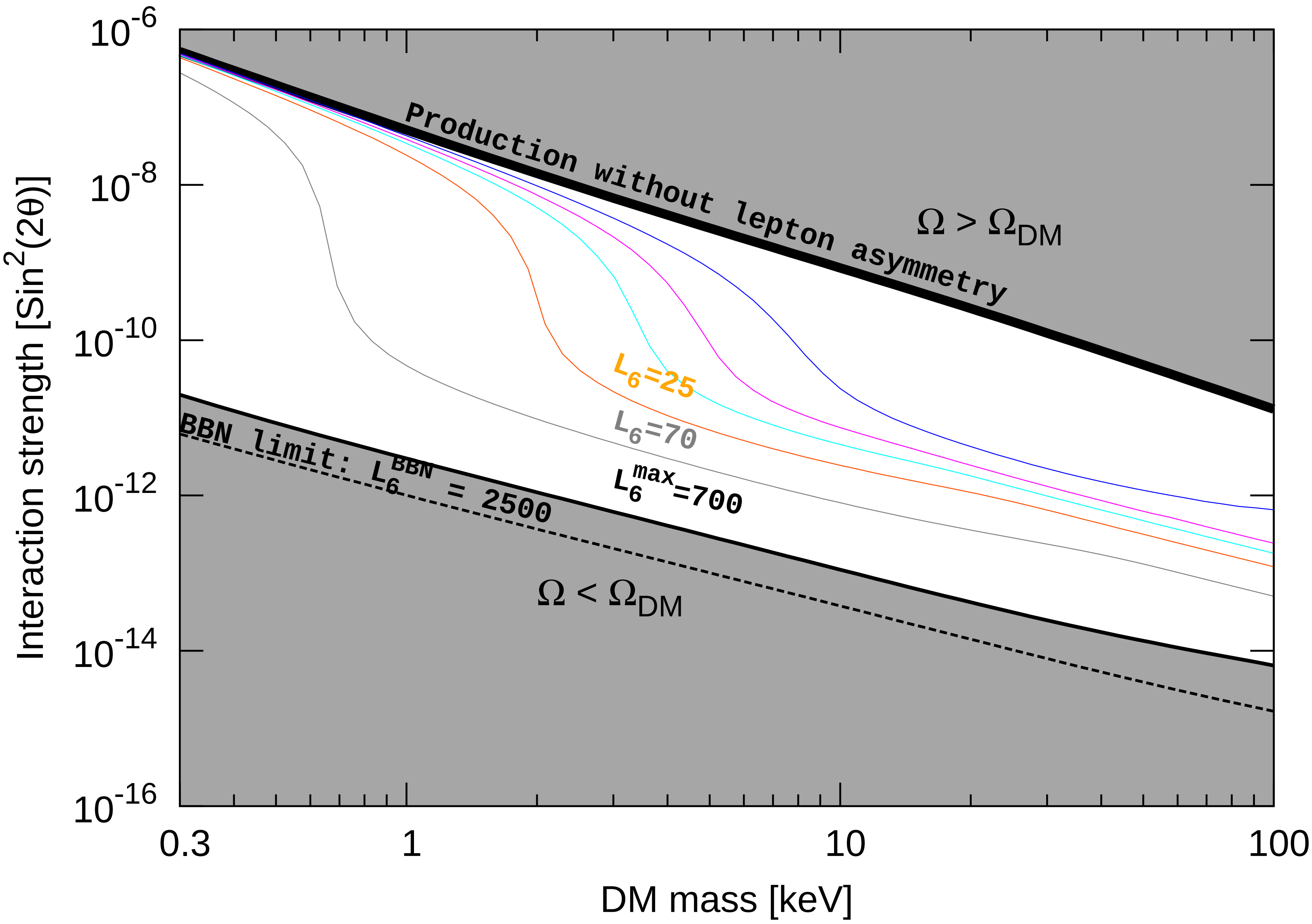
Once again:



Window of parameters of sterile neutrino DM

Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov



Sakharov conditions in the SM

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

Sakharov (1967)

Kuzmin, Rubakov, Shaposhnikov (1985)

(+) B-number violation $\longrightarrow$ sphalerons

Farrar & Shaposhnikov (1994)

(?) CP (and C) non-conservation $\longrightarrow$ phase of the CKM matrix

Kajantie et al. (1996)

(−) Out-of-equilibrium processes $\longrightarrow$ no phase transition in the SM for $m_H > 72$ GeV!

What changes in the νMSM?

Sakharov conditions in the νMSM

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

Sakharov (1967)

⊕ B-number violation $\rightarrow$ sphalerons

Kuzmin, Rubakov, Shaposhnikov (1985)

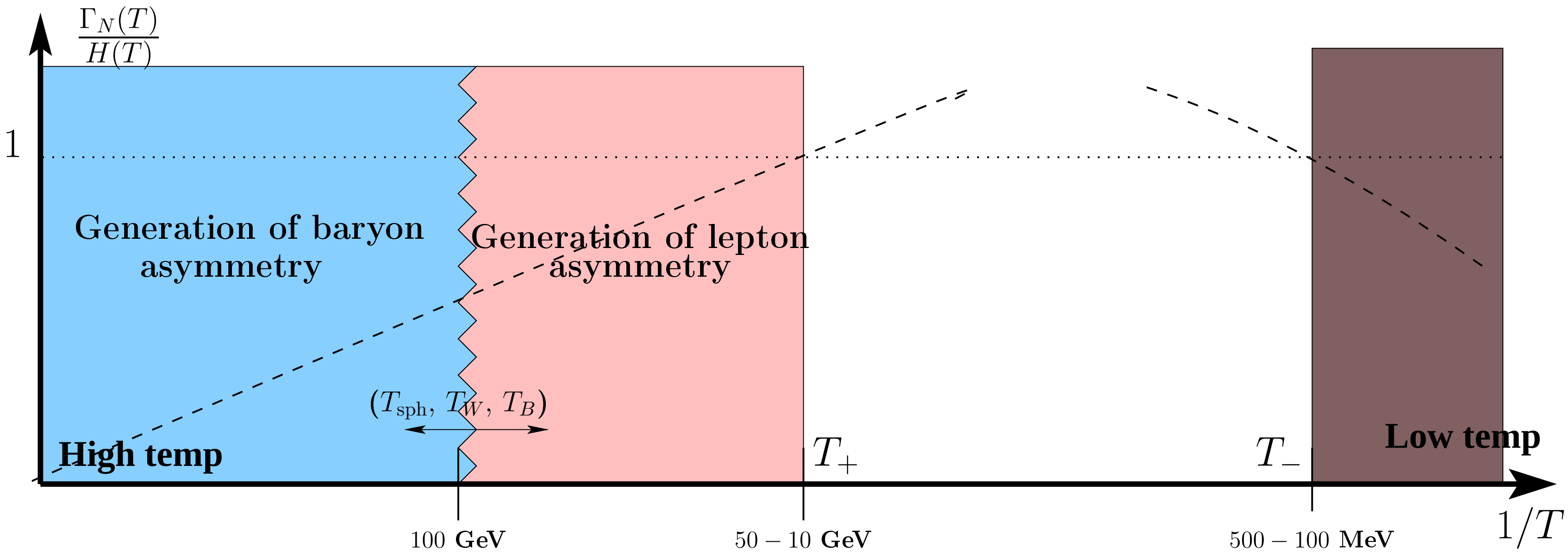
? CP (and C) non-conservation $\rightarrow$ phase of the CKM matrix **plus additional CP phases in the Dirac mass matrix of sterile neutrinos**

Farrar & Shaposhnikov (1994)

⊖ Out-of-equilibrium processes $\rightarrow$ 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**

Kajantie et al. (1996)

Baryo- and lepto-genesis in the νMSM

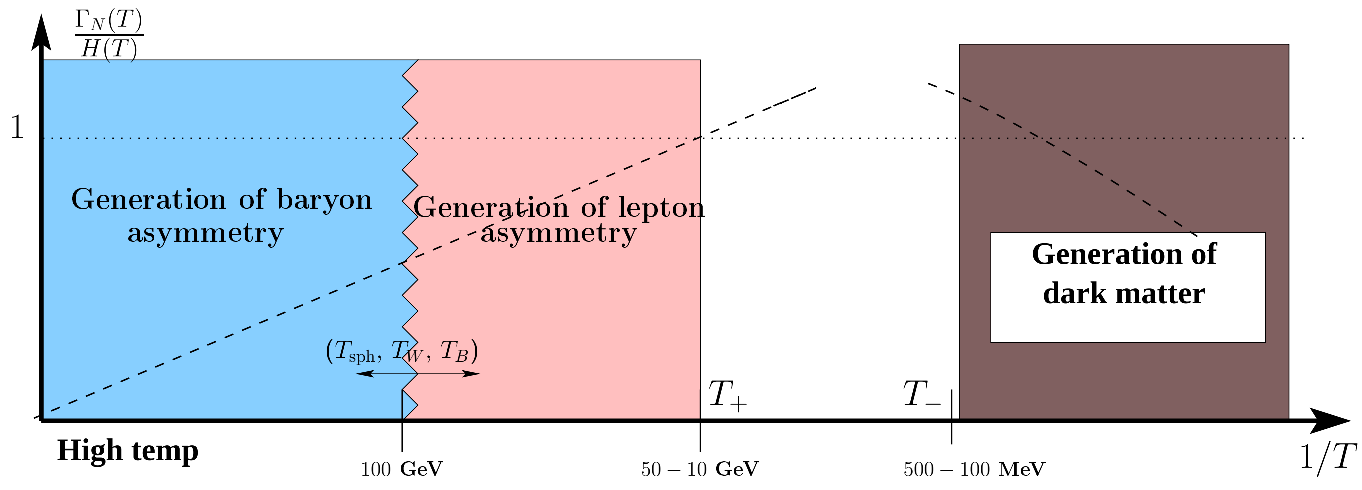


- At $T > T_{\rm sph}$ lepton asymmetry gets converted to baryon asymmetry by sphalerons — **baryogenesis**

- At $T_{\rm sph} > T > T_+$ lepton asymmetry **continues to be generated**

  where $|F|^2 T_+ = \frac{T_+^2}{M}$ (the Yukawa coupling $|F|^2 \sim \frac{M m_{\rm atm}}{v^2}$ from neutrino oscillations)

Resonant production



- The presence of lepton asymmetry in primordial plasma makes **active-sterile mixing** much more effective – **resonant production**

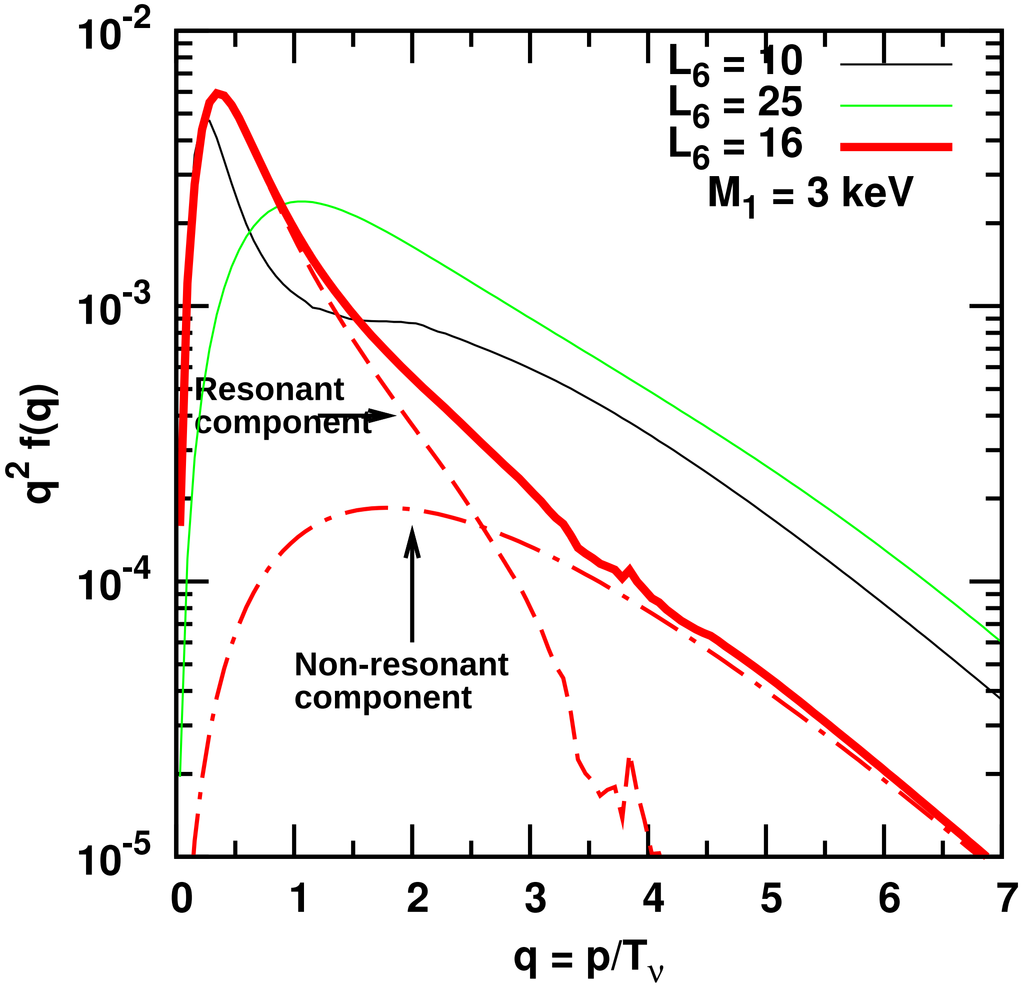
Shi Fuller'98
Laine, Shaposhnikov

- Maximal amount of DM produced resonantly:

$$\Omega_{\rm RP} h^2 \propto M_s L_6$$

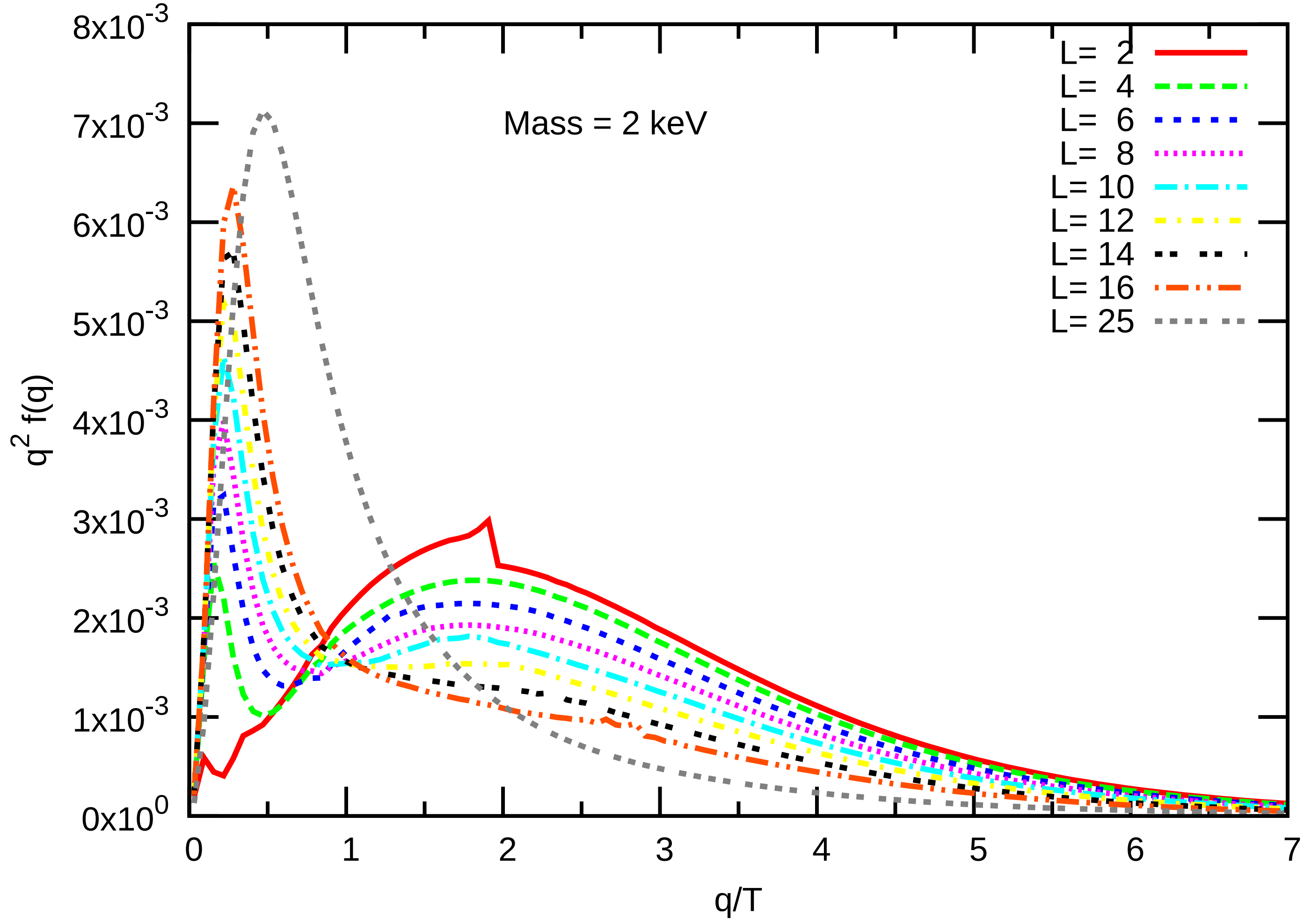
— independent of the mixing angle!

RP sterile neutrino spectra



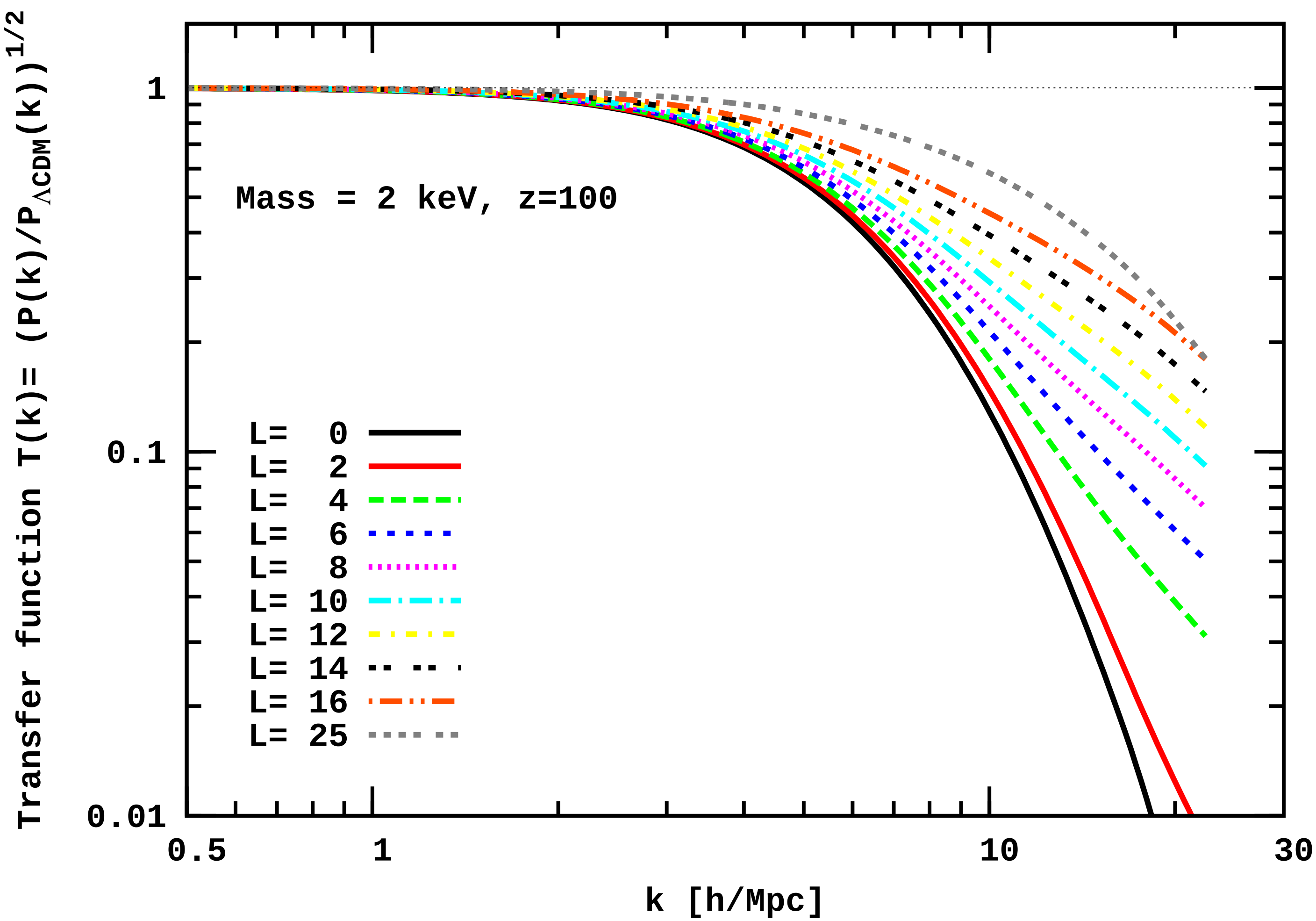
Laine, Shaposhnikov'08; Boyarsky, **O.R.**, Shaposhnikov'09

Primordial velocities of sterile neutrino



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

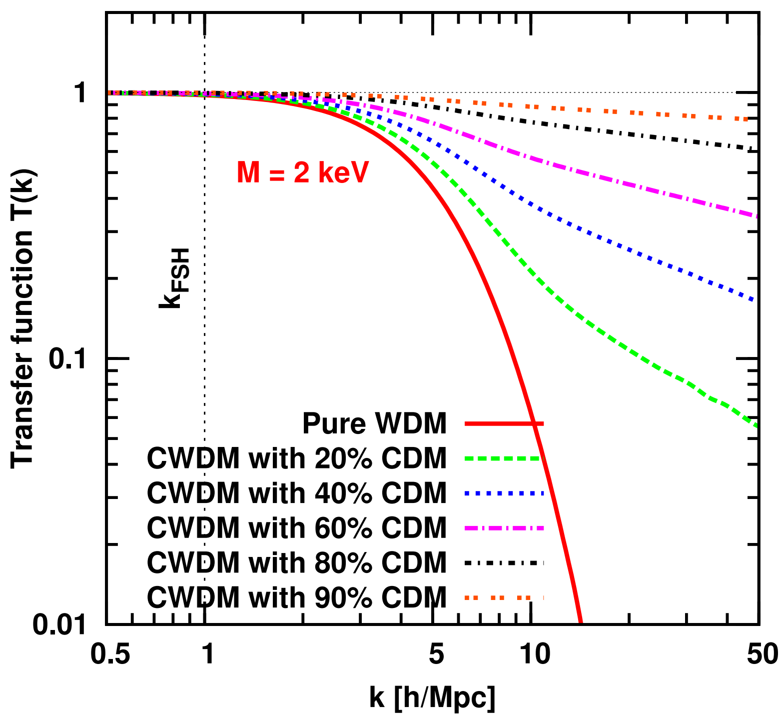
Free-streaming of sterile neutrino DM



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

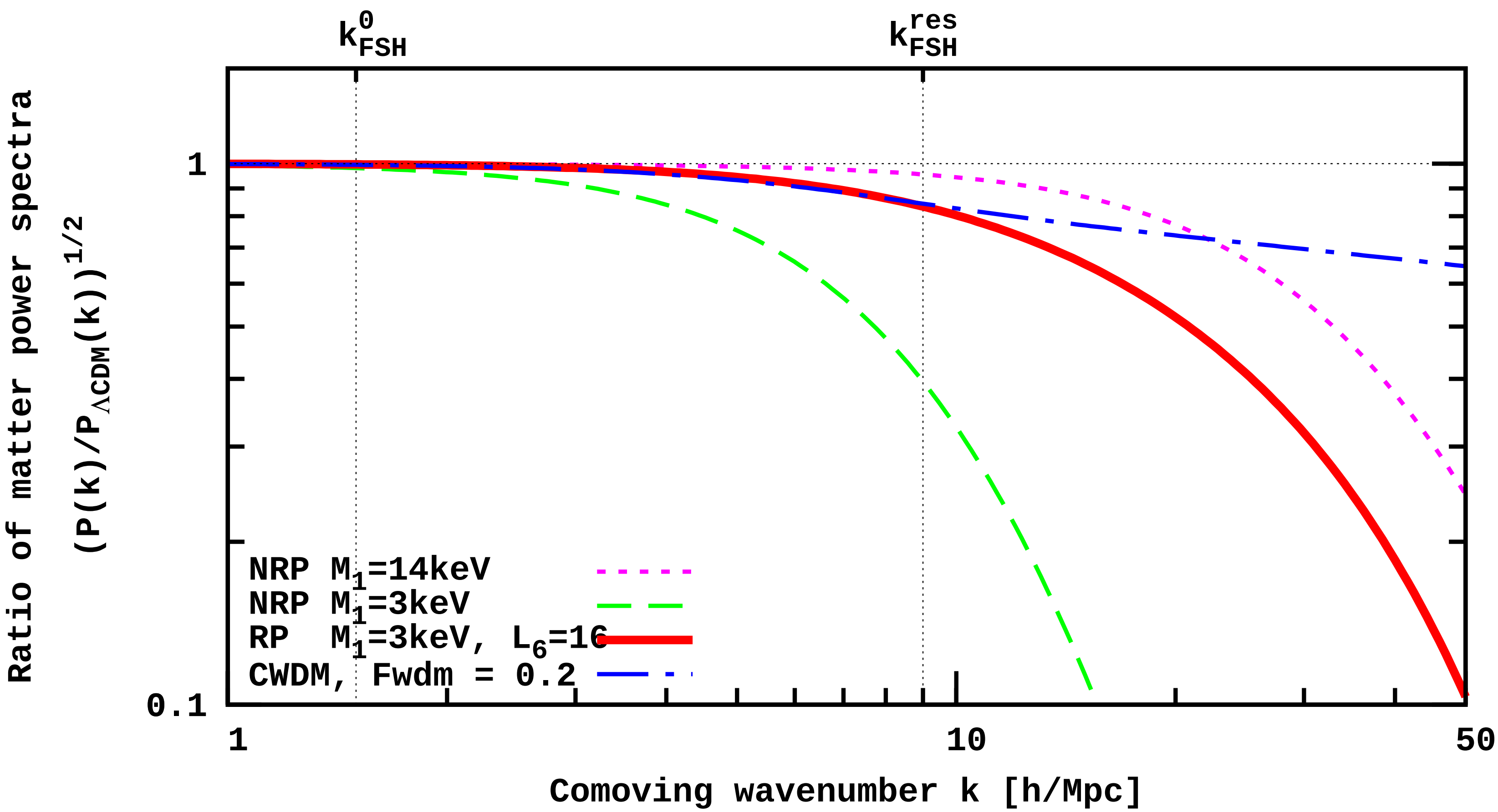
Cold+warm DM model (CWDM)

- Models with admixture of cold DM component (relevant for resonantly produced sterile neutrino DM, gravitino DM)



- k_{FSH} depends on mass, does not depend on WDM fraction
- $T(k)$ falls slower if more CDM
- For small WDM fraction $T(k)$ cannot be distinguished from CDM within the precision of the data

Power spectrum for sterile neutrinos



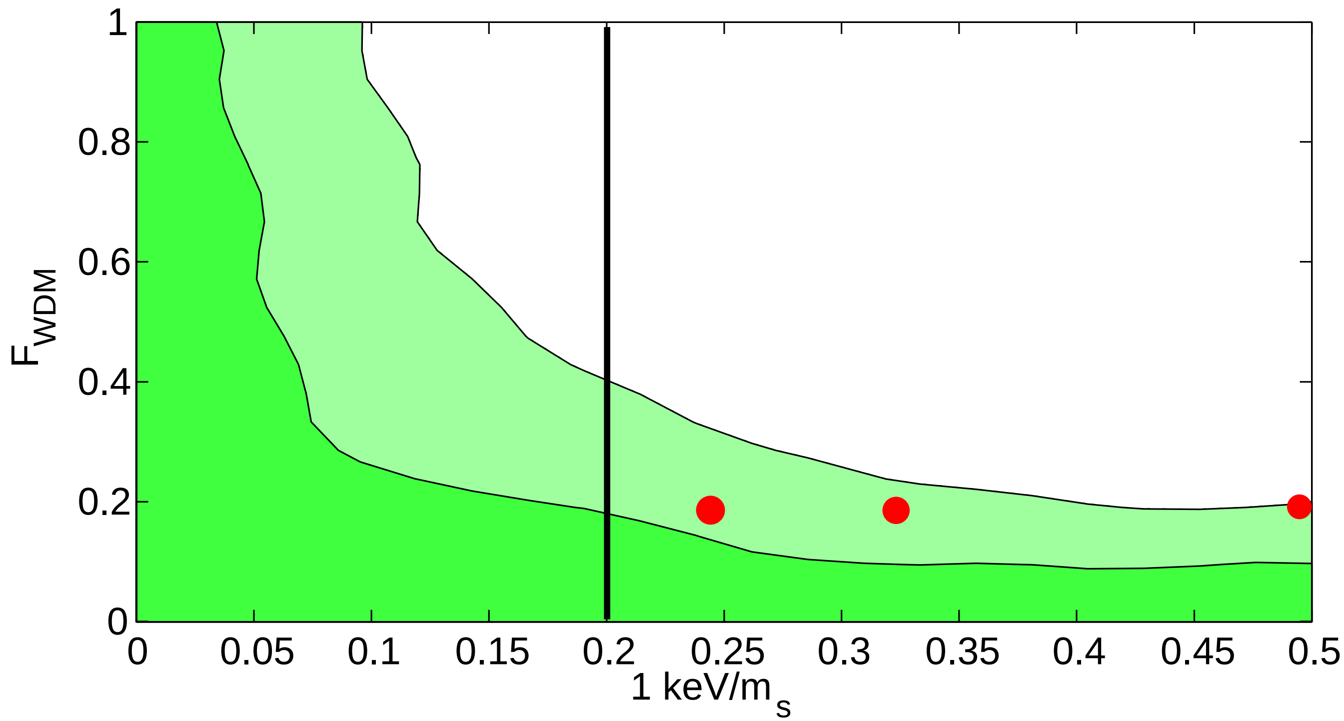
Boyarsky, Lesgourgues, **O.R.**, Viel JCAP, PRL 2009;

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

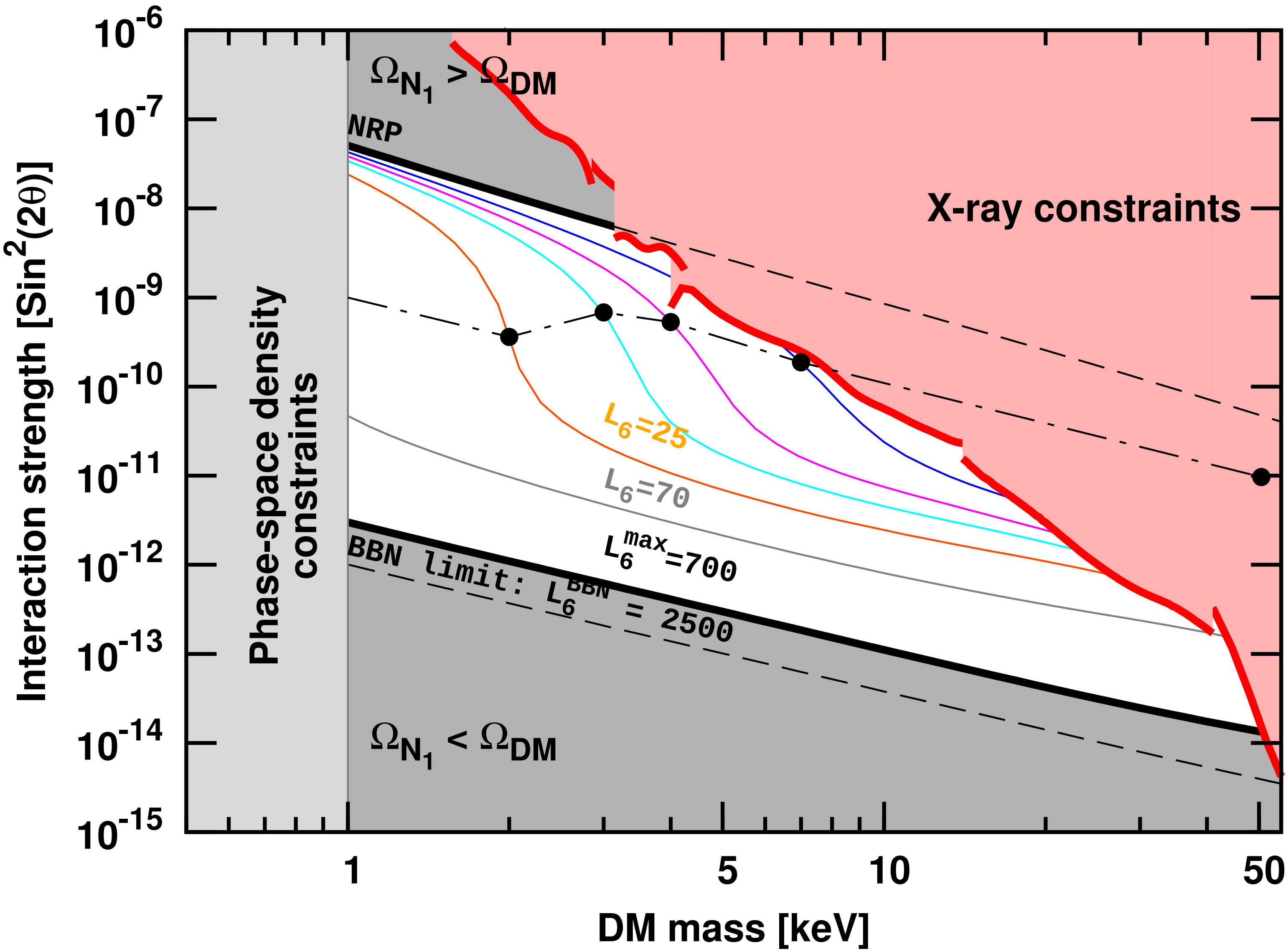
Lyman-α bounds for sterile neutrinos

- 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)



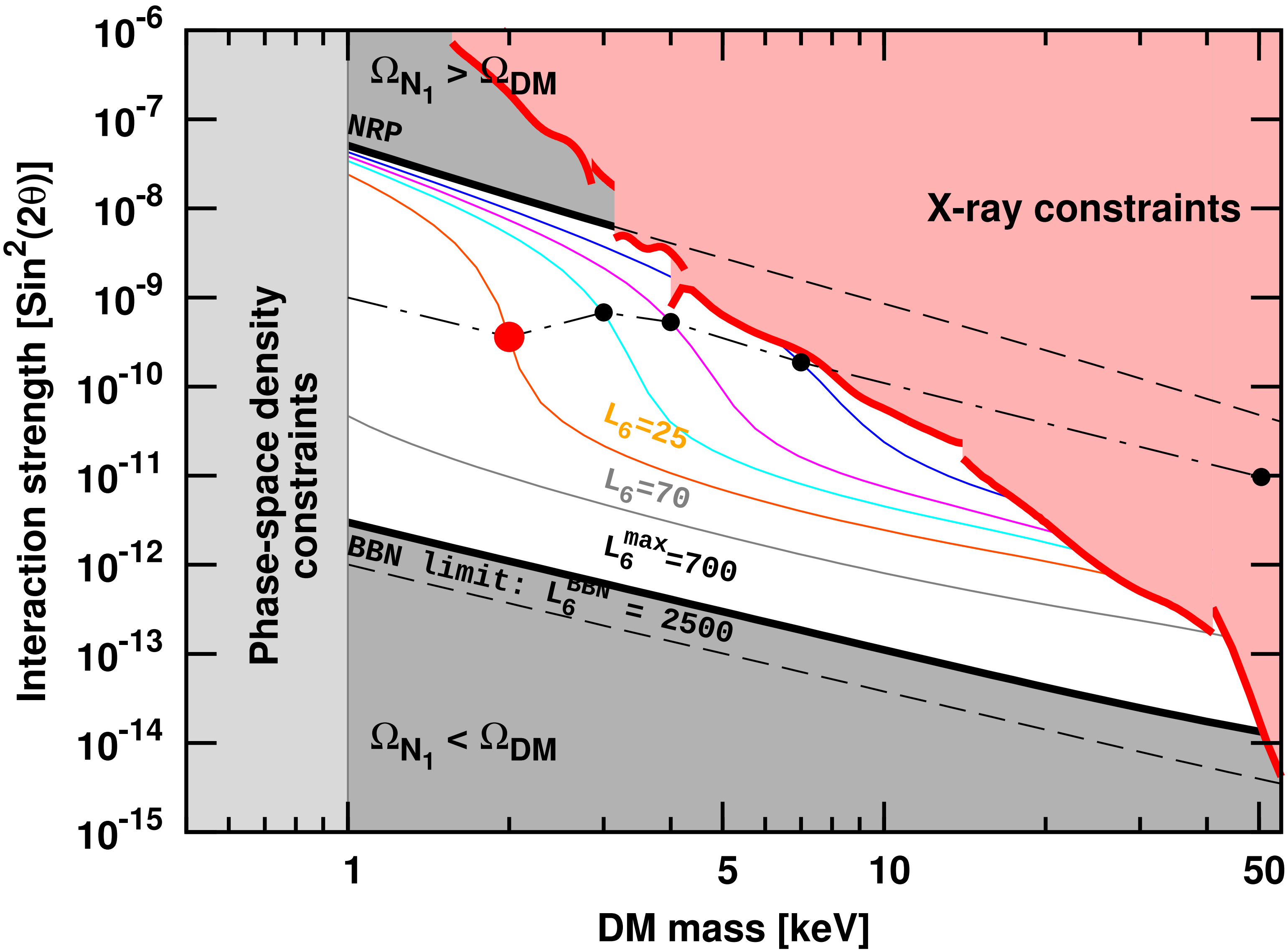
Sterile neutrino DM in the νMSM



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

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

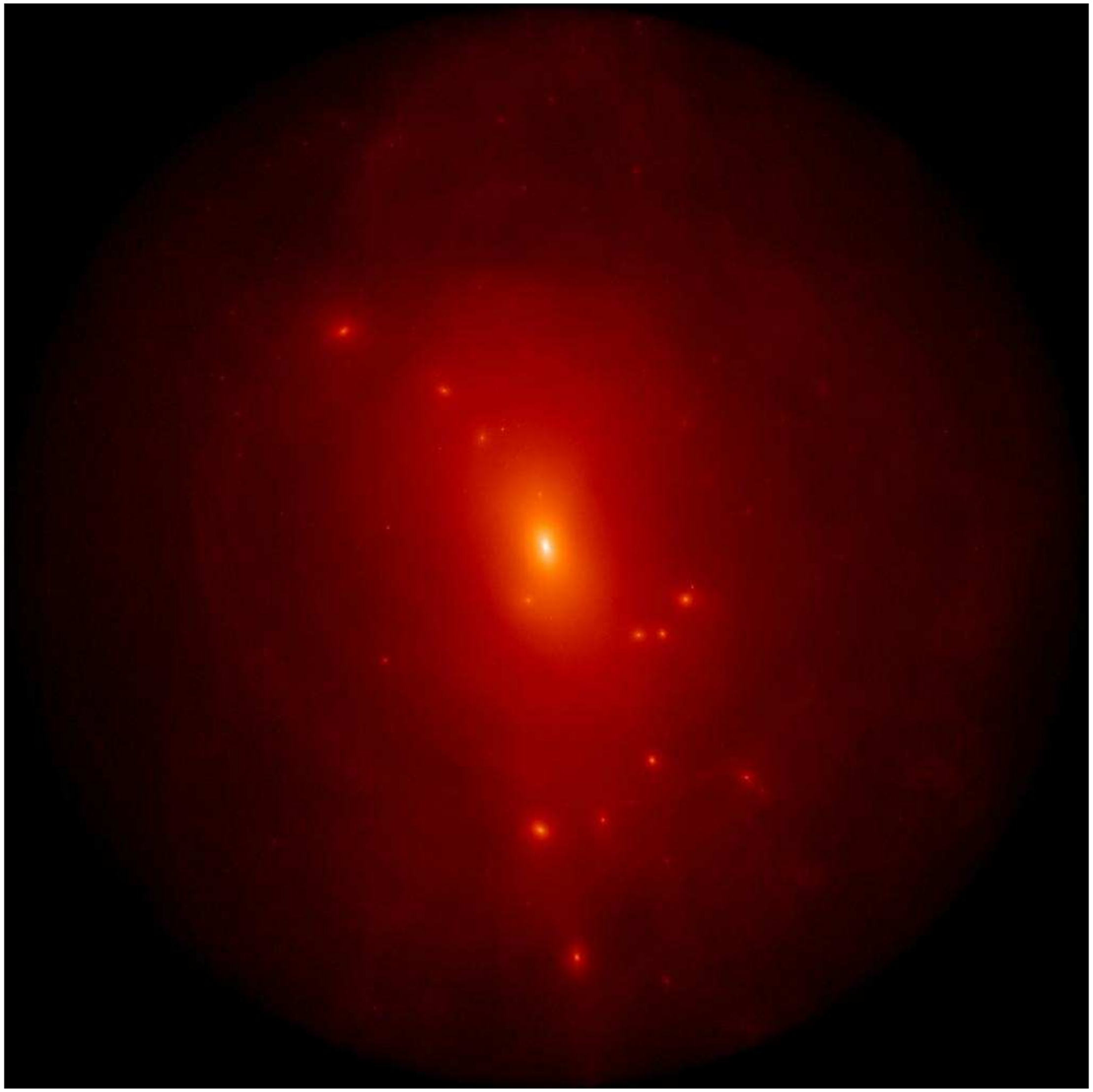
Sterile neutrino DM in the νMSM



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

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

Halo substructure with sterile neutrino DM

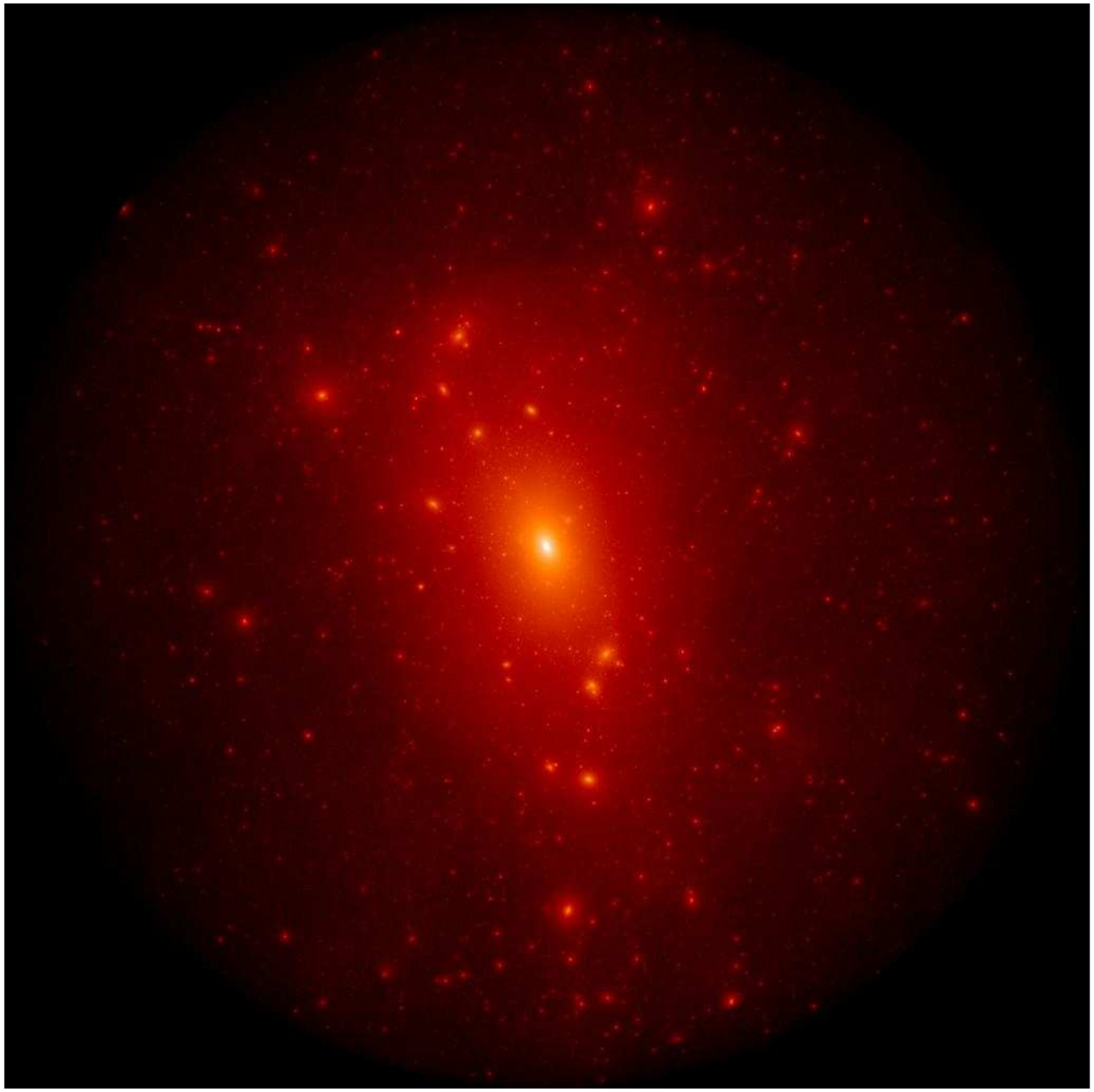


Lovell, Frenk, Theuns, **O.R** and others, 2011

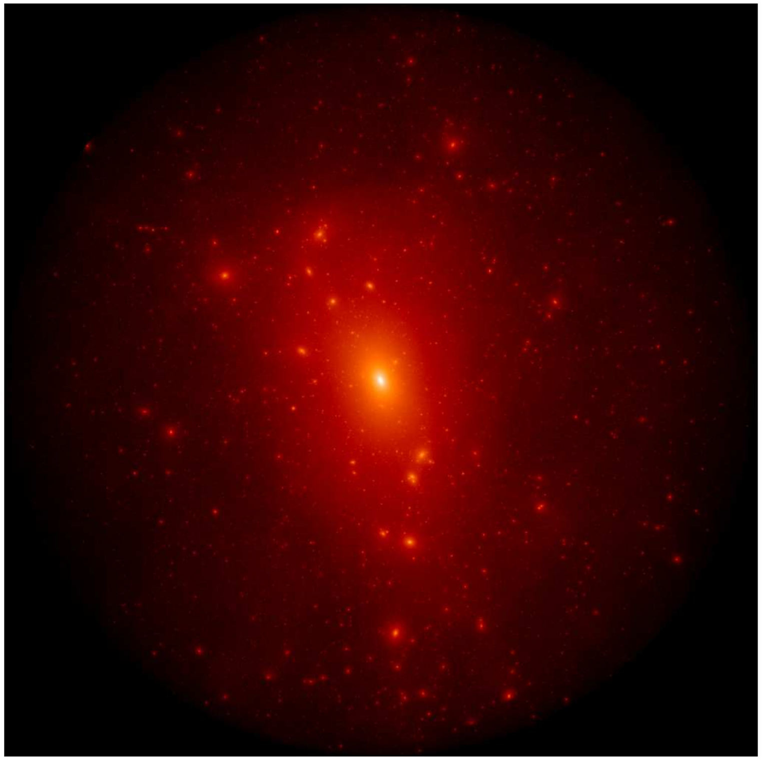
work in progress

Halo substructure with CDM

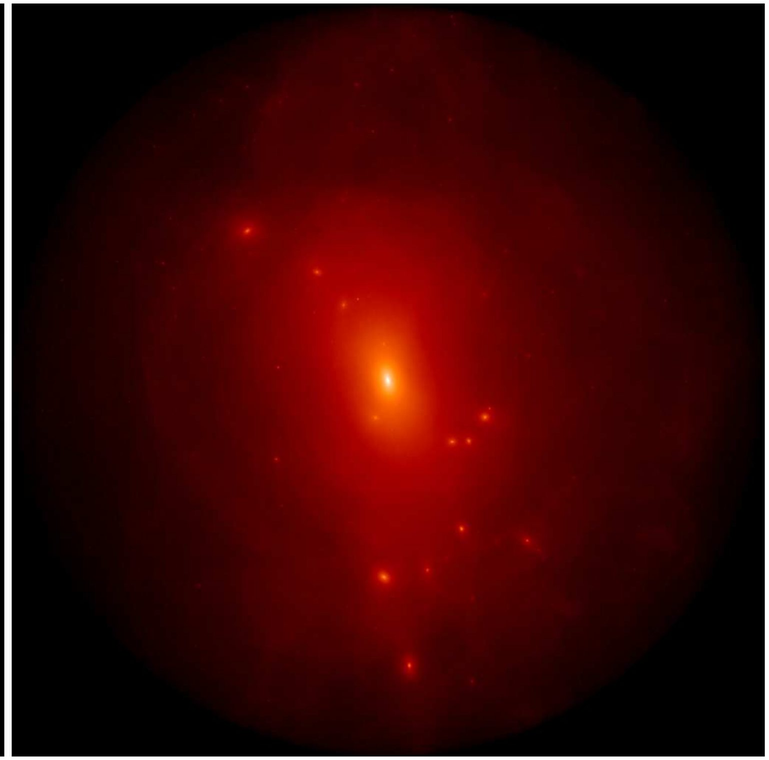
Aq-A2 halo



Halo substructure with sterile neutrino DM



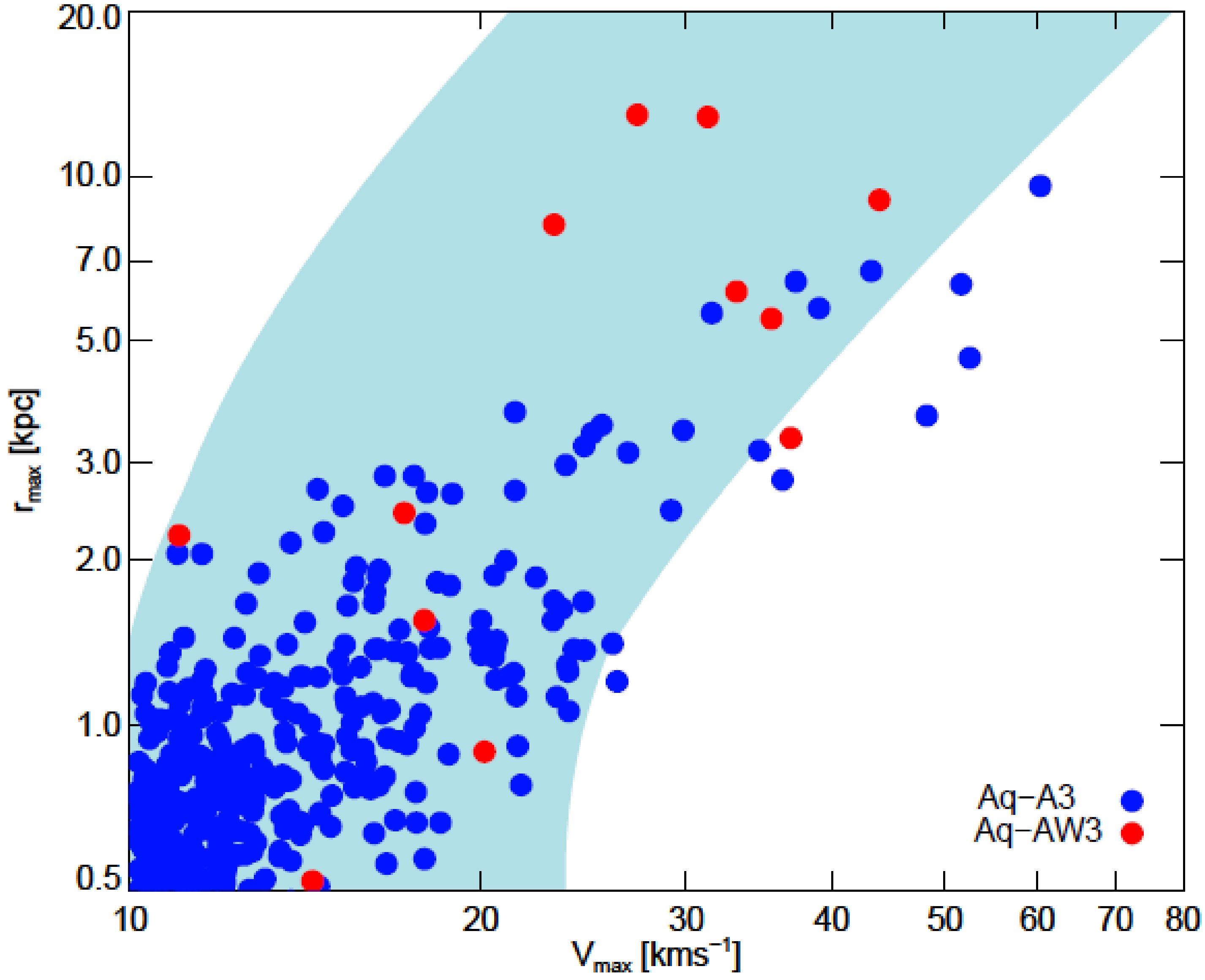
Aq-A-2 CDM halo



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

Large satellites

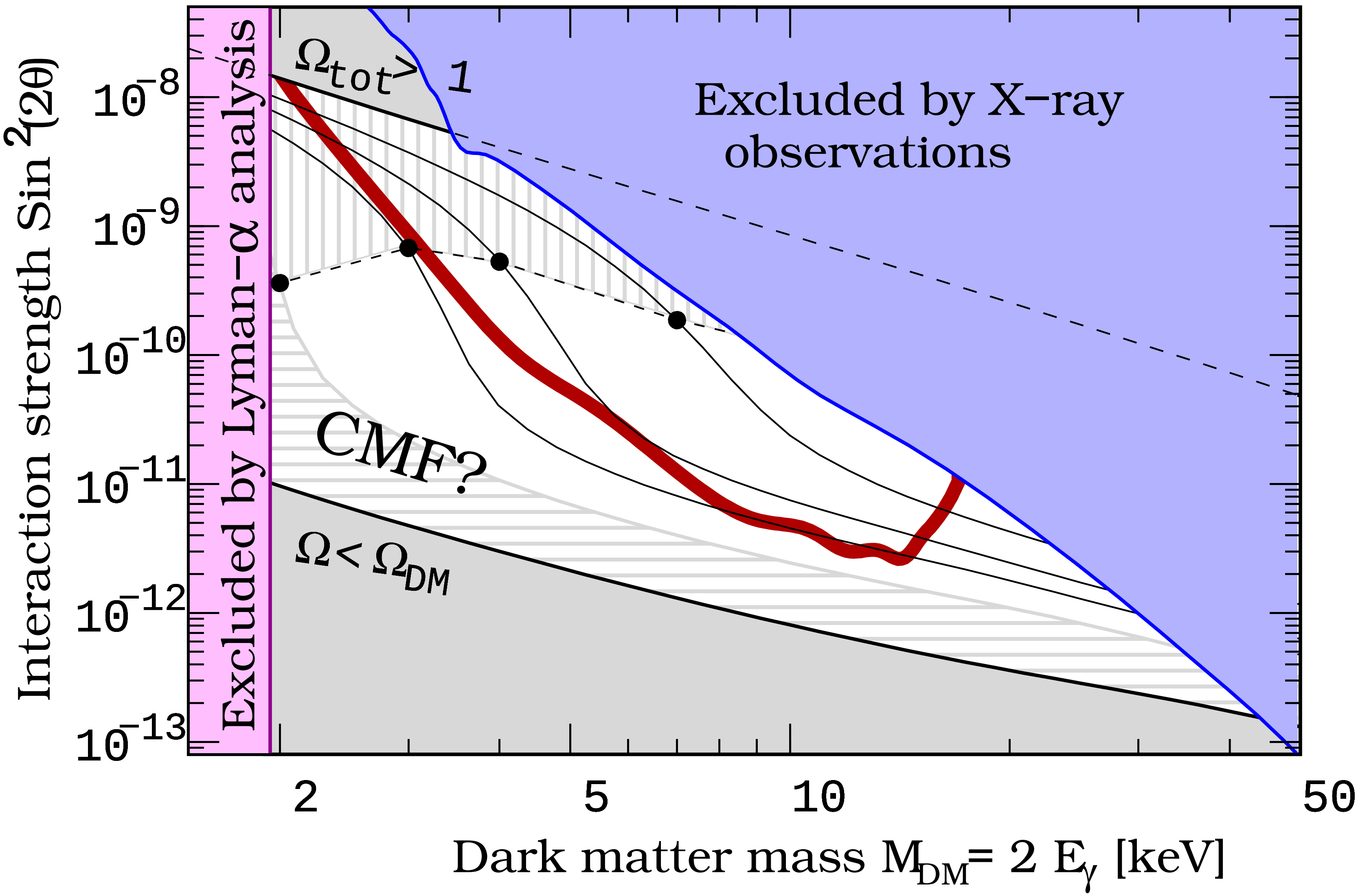


Lovell, Frenk, Eke, . . . , **O.R.** 1104.2929 [astro-ph.CO]

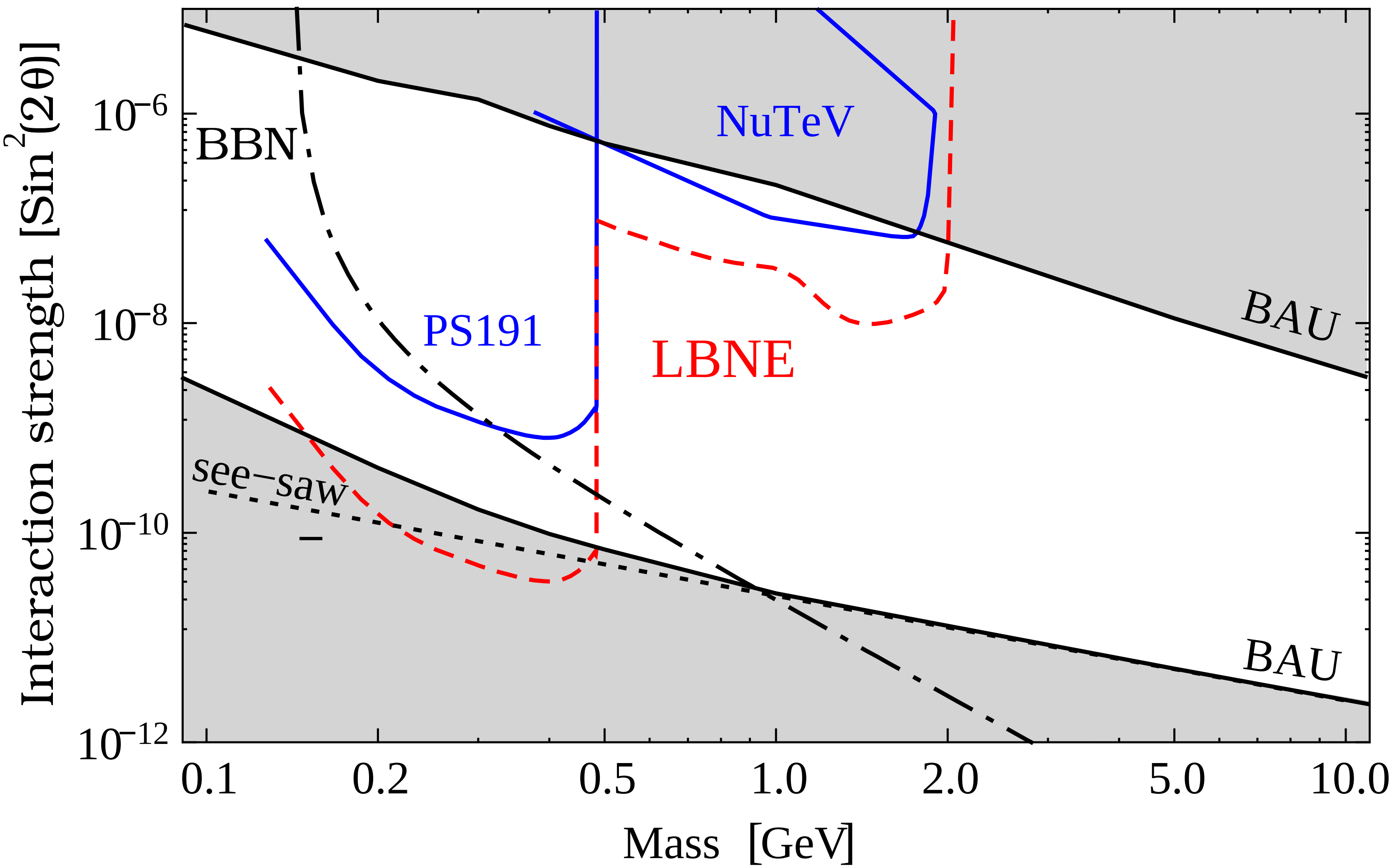
Conclusions

- 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
- **Thermal relics** WDM with interesting astrophysical and cosmological applications are ruled out by Lyman-α
- Sterile neutrino dark matter (as a part of the νMSM model) is a viable dark matter candidate, consistent with the Lyman-α constraints within a wide range of the model parameters.

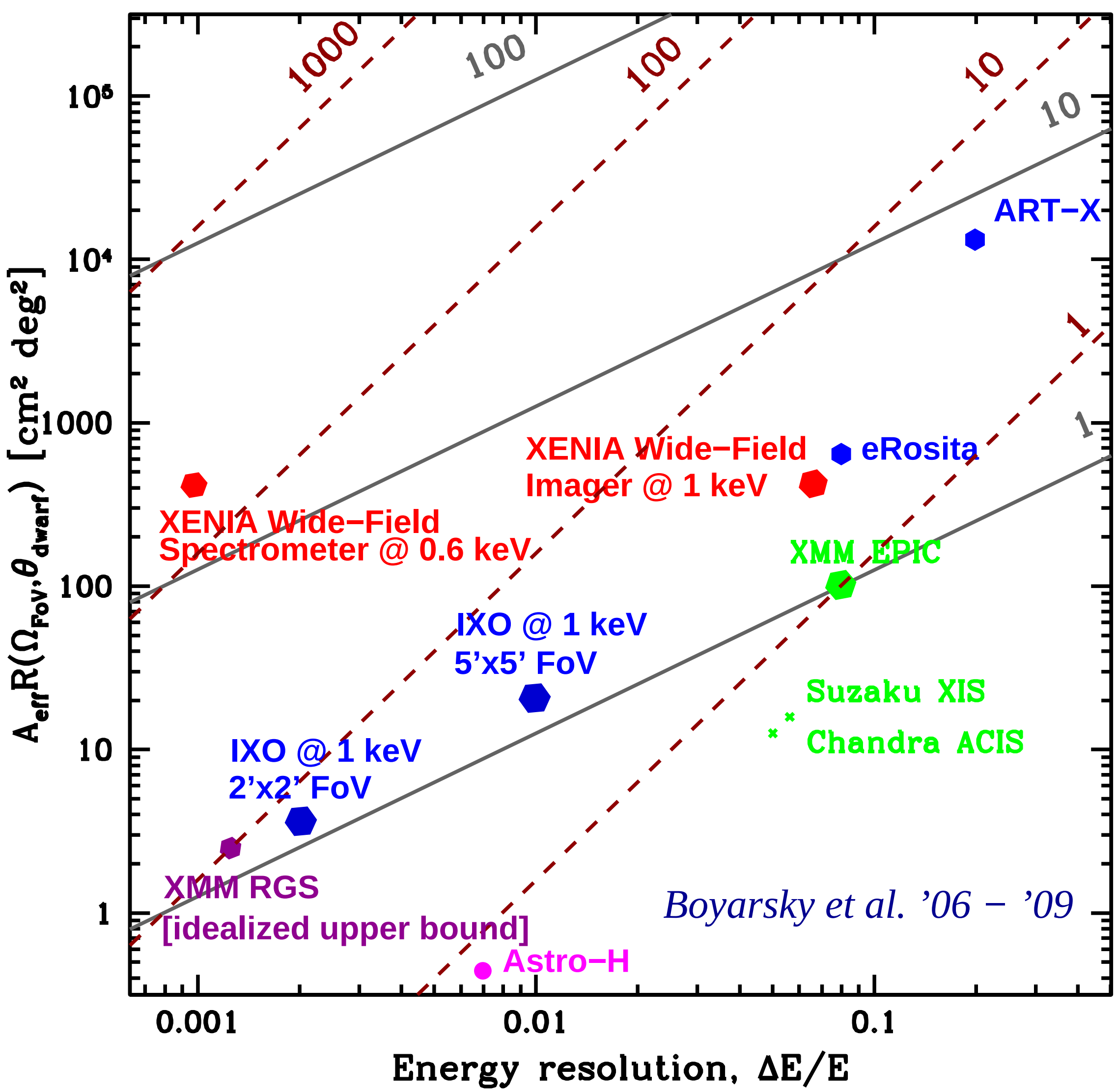
Future of sterile neutrino DM



Probing other sterile neutrinos



Improved bounds on DM decay

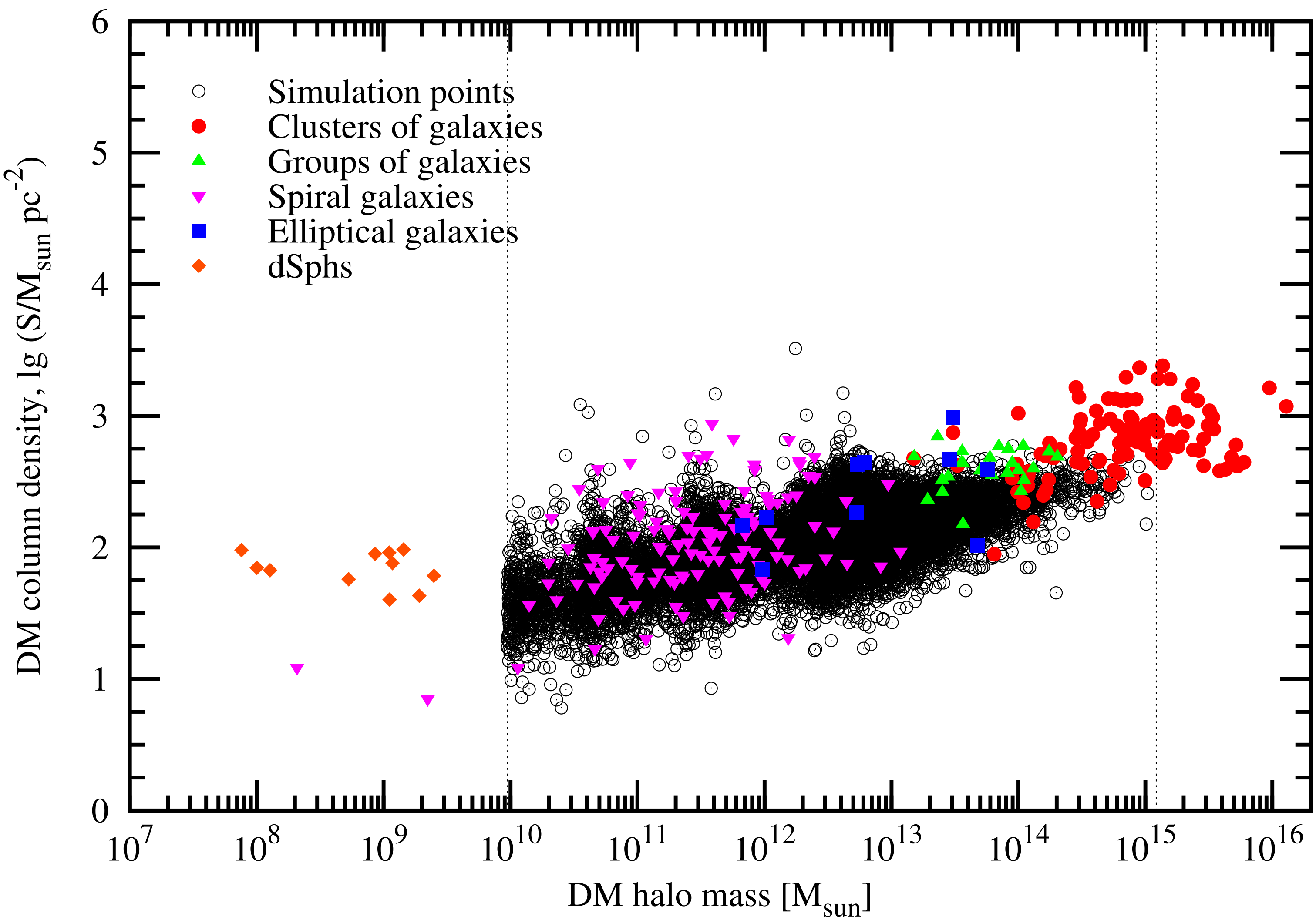


Thank you for your attention!

A couple of slides about dark matter surface density

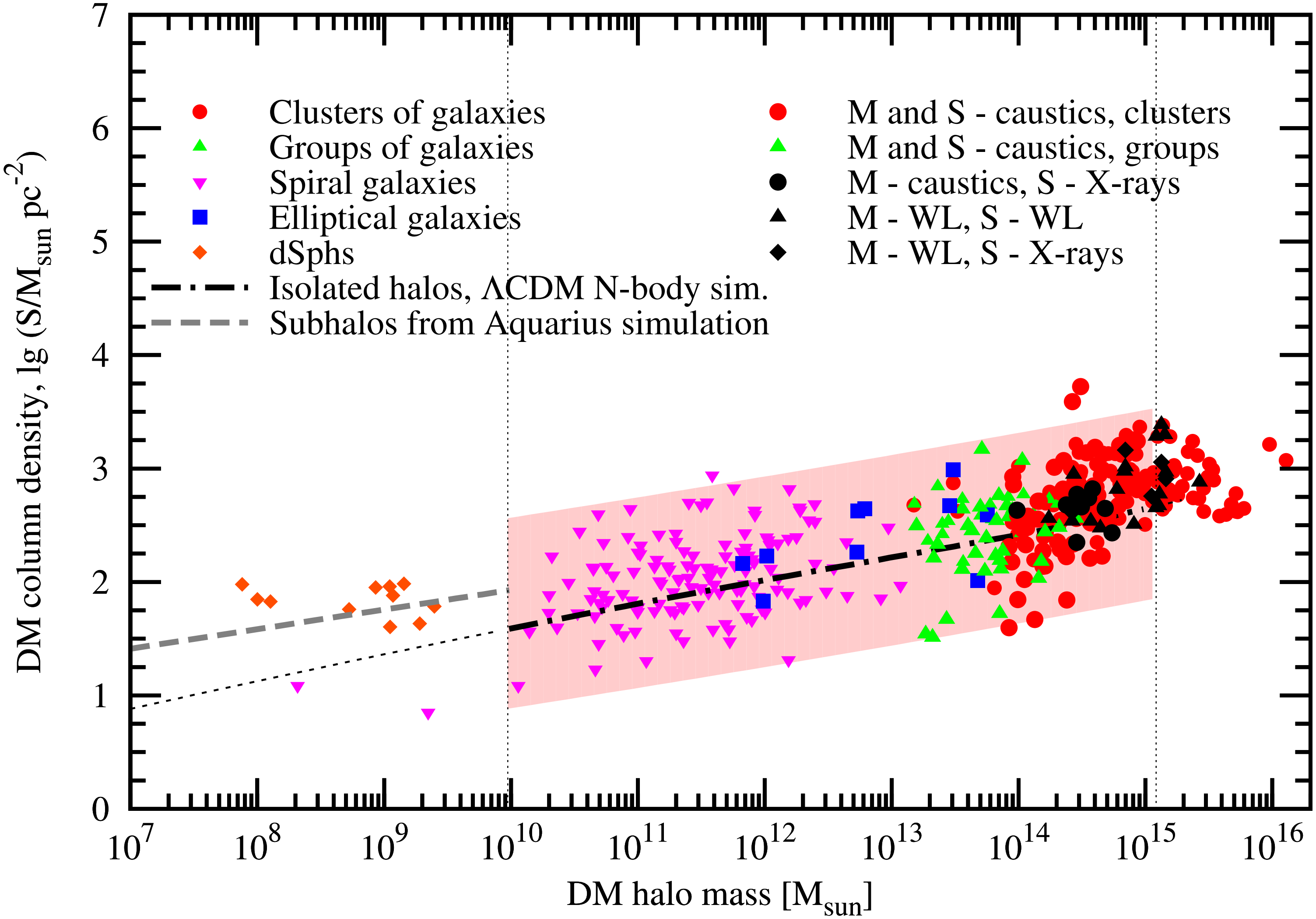
Observations vs. simulations

Boyarsky, **O.R.**, Macciò and others, **0911.1774**



Dark matter surface density

work in progress



DM column density

- More than half of all objects obey the derived relation between parameters of DM density profiles
- For most of them $\rho_s r_s \propto \rho_c r_c$
- Observable not sensitive to the choice of dark matter density profile?
- **Dark matter column density**

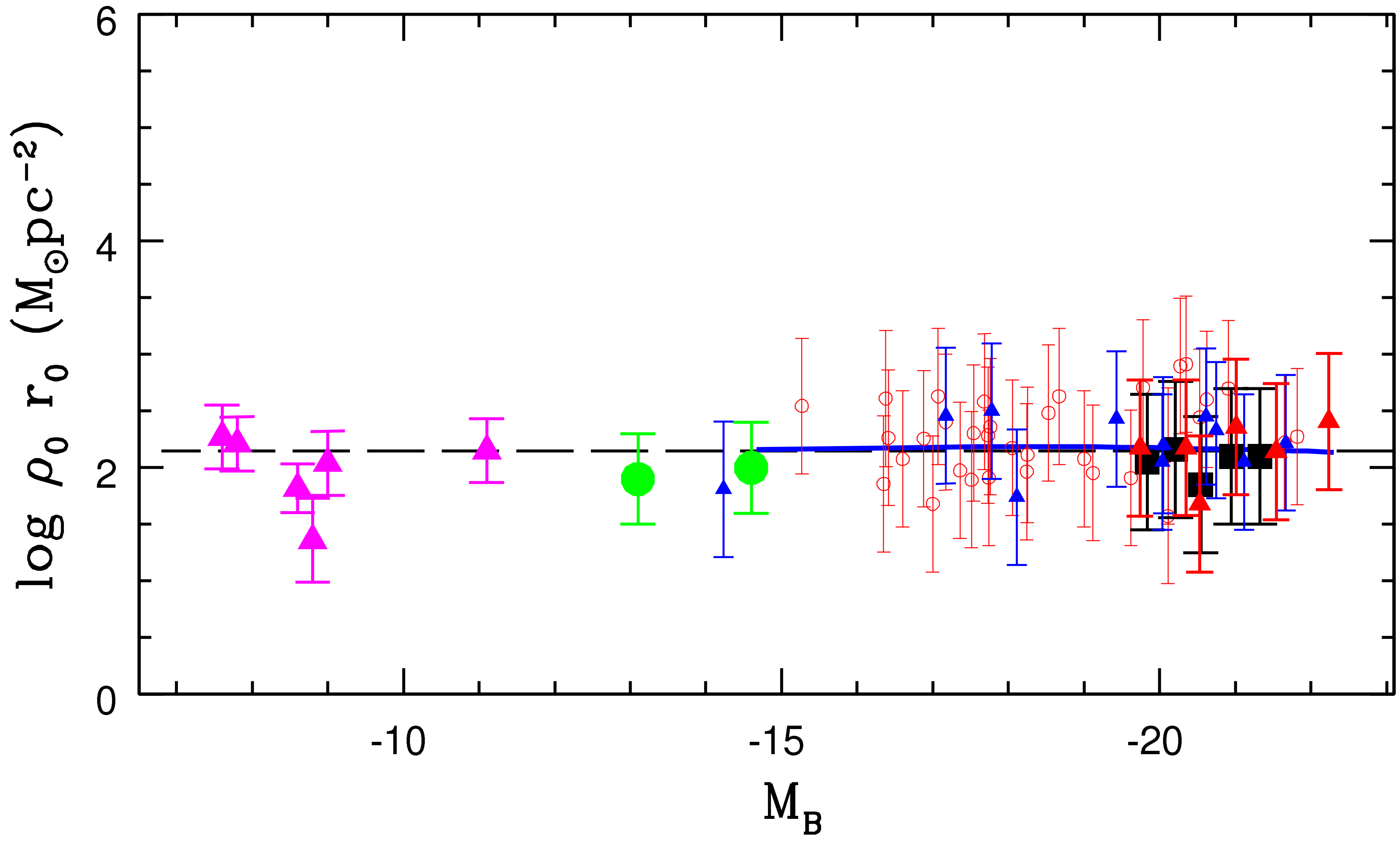
$$\mathcal{S} = \int\limits_{\text{l.o.s.}} \rho_{\text{DM}}(r) dl \propto \rho_\star r_\star$$

- $r_\star$ is a characteristic scale ($r_\star = r_s$ for NFW, $r_\star = 6.1 r_c$ for ISO).

  $\rho_\star$ – average density inside $r_\star$

Constant surface density?

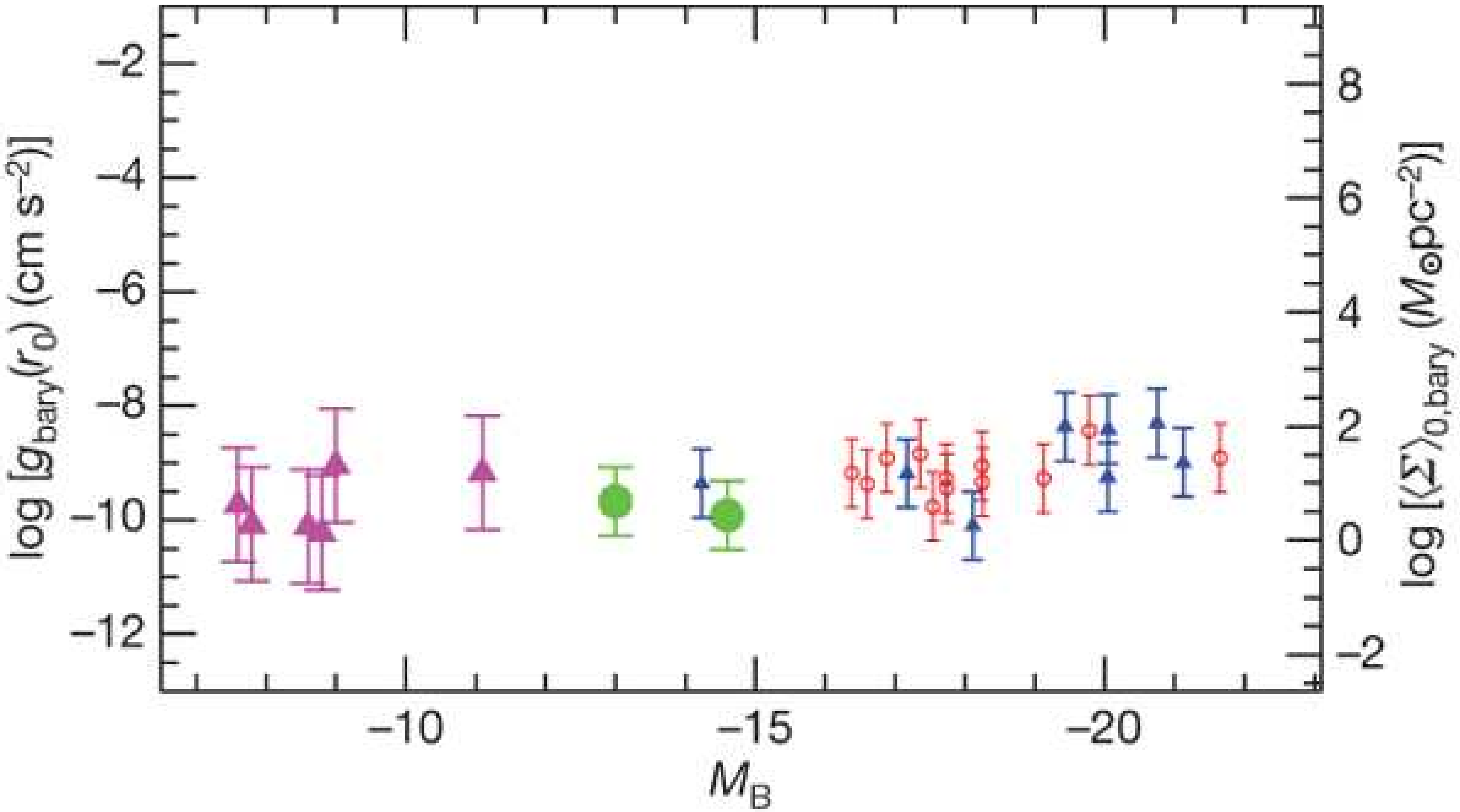
Donato et al.'09, Gentile et al.'09



DM surface density for different types of galaxies.

An evidence in favor of MOND?

Gentile et al.'09



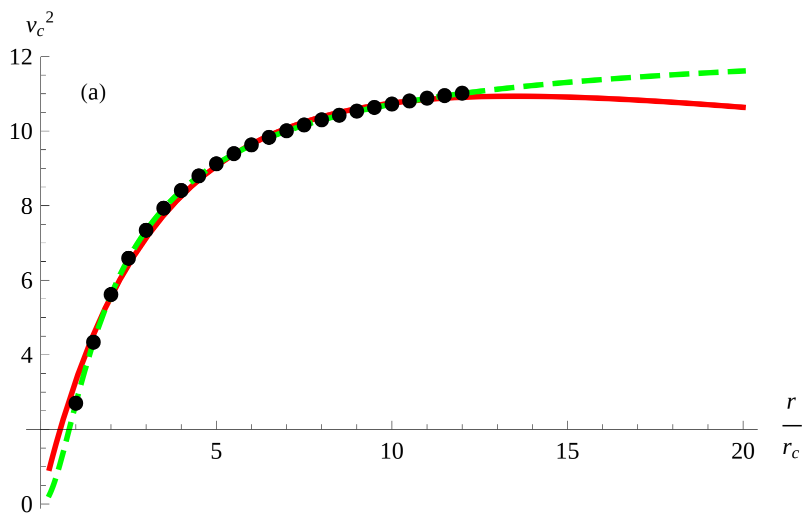
Baryonic surface density for different types of galaxies.

Comparing DM density profiles

- There exist many works on dark matter distribution in individual objects
- Going through the literature we collected a "catalog" of $\sim$**1000** DM density profiles for $\sim$**300** individual objects, ranging from dwarf spheroidal satellites of the Milky Way to galaxy clusters **0911.1774**
- Different groups of astronomers use different dark matter profiles to fit the mass distribution (ISO, NFW, BURK, . . .)
- Often fits to different DM density profiles exist for the same object. How to relate their parameters?

Comparing DM density profiles

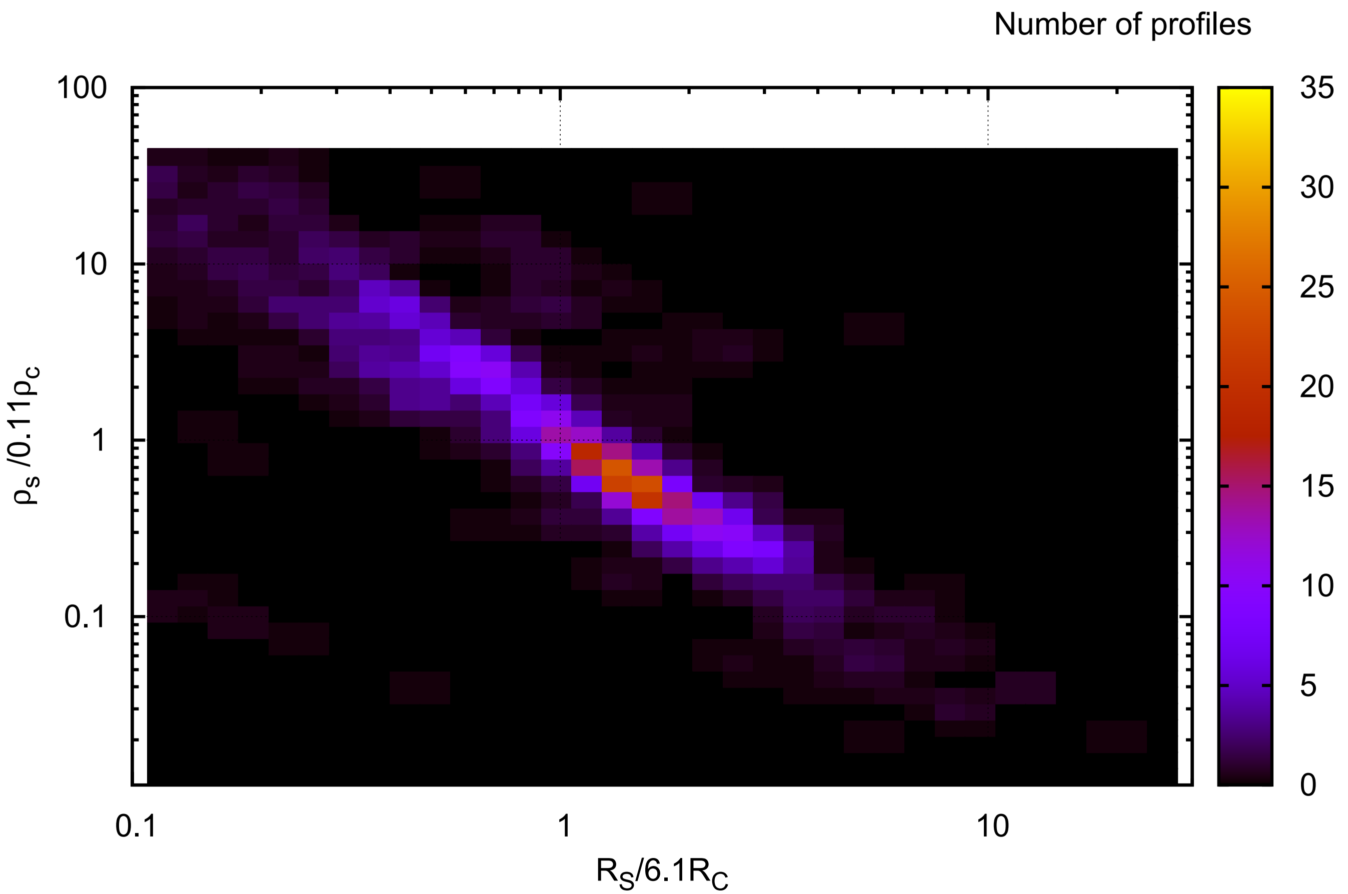
- Fitting the same (simulated) data with two different profiles



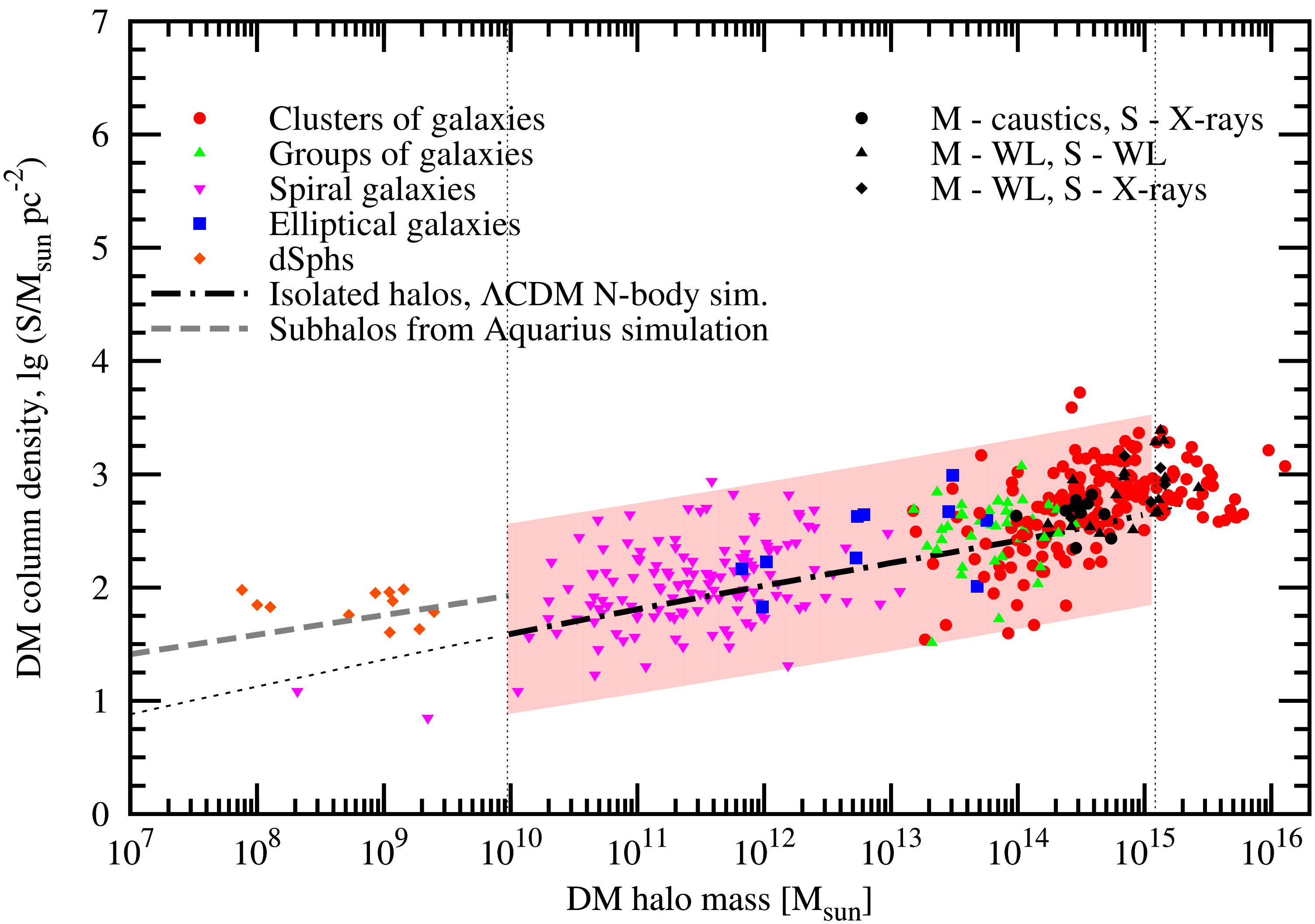
- one finds a relation between parameters of two DM density distribution, fitting the same data 0911.1774
  - NFW vs. ISO : $r_s \simeq 6.1\, r_c$; $\rho_s \simeq 0.11\, \rho_c$
  - NFW vs. BURK : $r_s \simeq 1.6 r_B$; $\rho_s \simeq 0.37 \rho_B$
- Is this relation actually observed?

NFW vs. ISO

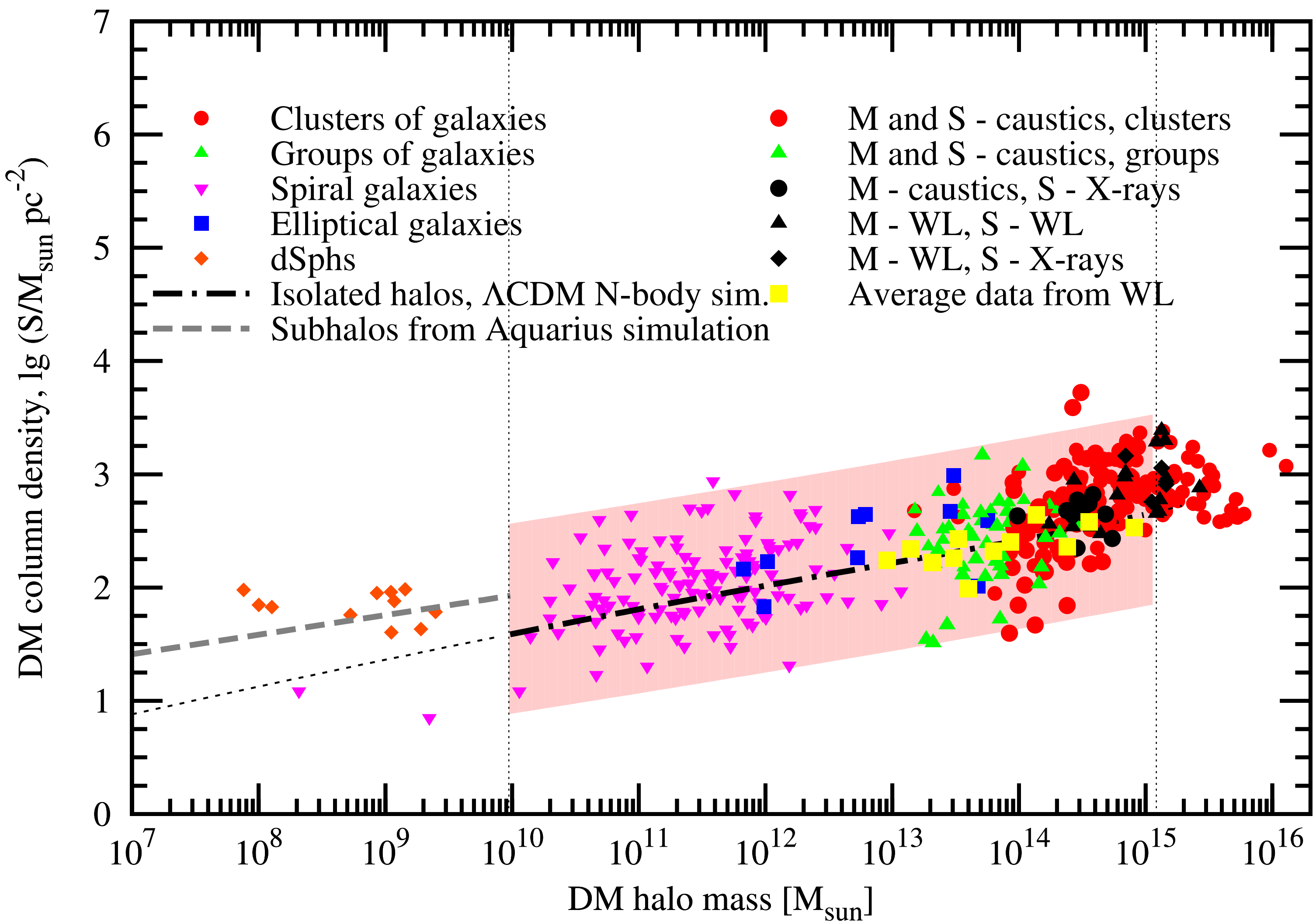
About **60** objects with both NFW and ISO profiles



Independent determination of mass



Independent determination of mass

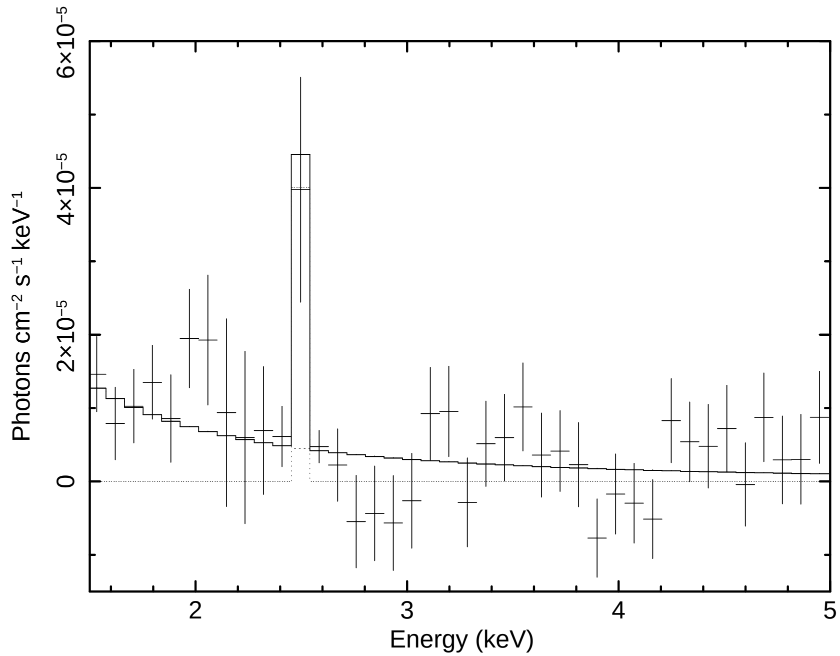


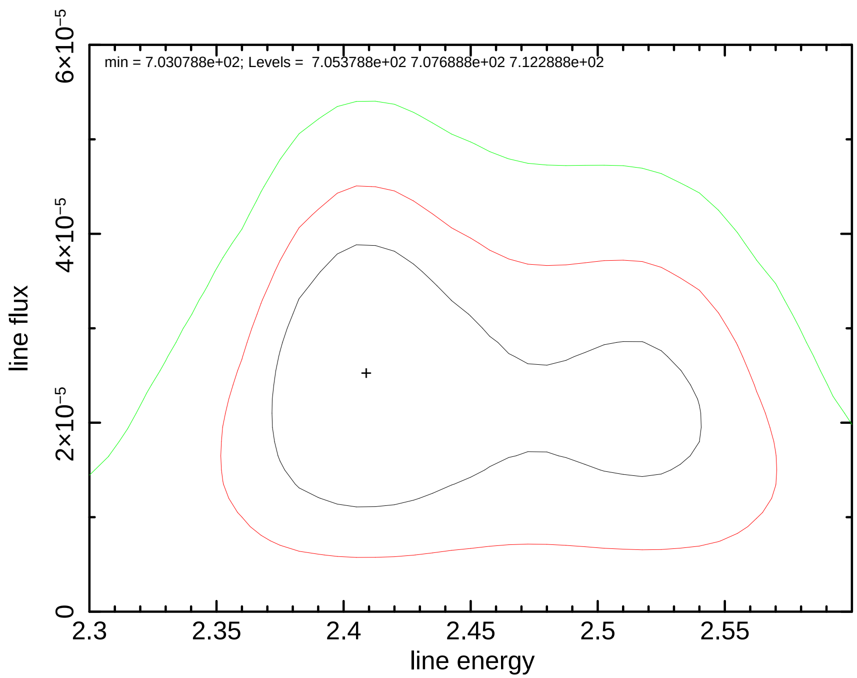
Universal scaling of DM column density

- The data spans many orders of magnitude in halo masses ($10^8 M_\odot$ – $10^{15} M_\odot$)
- The relation between $\mathcal{S}$ and M_{halo} is observed for halos of all scales
- Actual observed halos reproduce concentration-mass relation known in simulations for decades but never probed before over such a large mass scale
- Its median value and scatter coincide remarkably well with **pure dark matter** numerical simulations
- Separately the slope of subhalos is reproduced
- No visible features – universal (**scale-free**) dark matter down to the lowest observed scales and masses?

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)

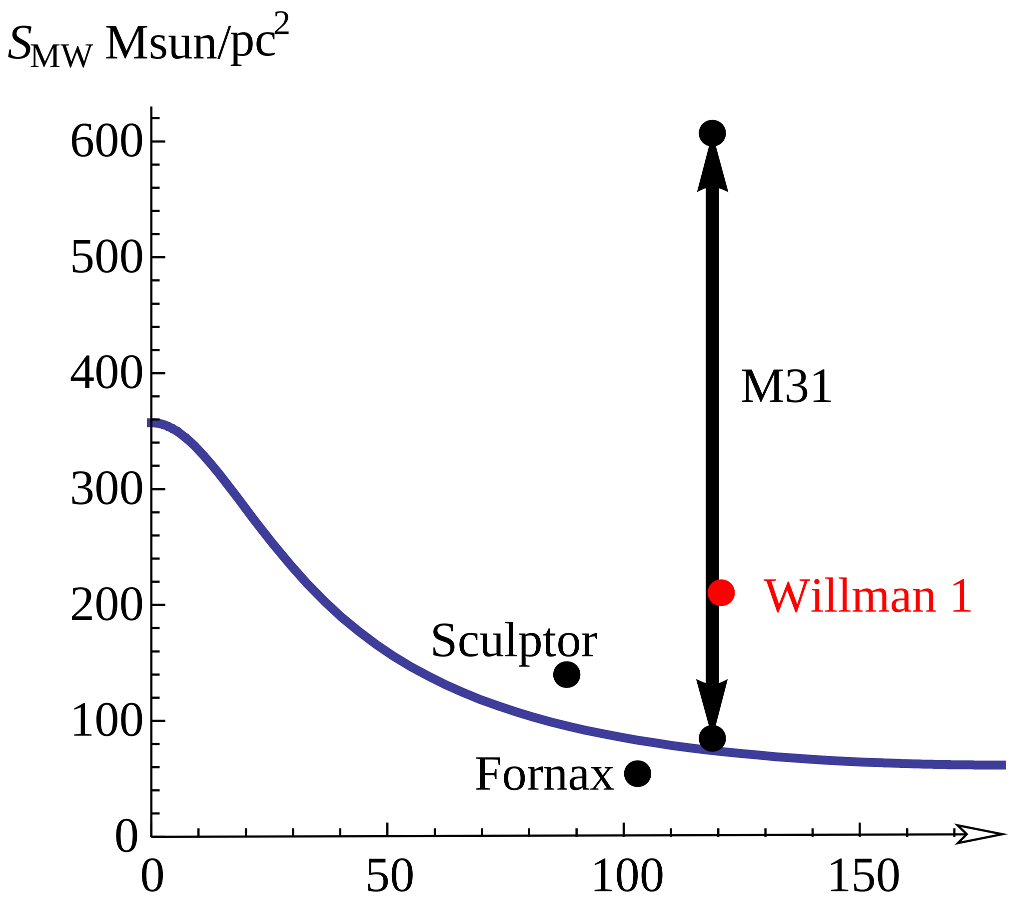




68%, 90% and 99% confidence intervals

- *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?



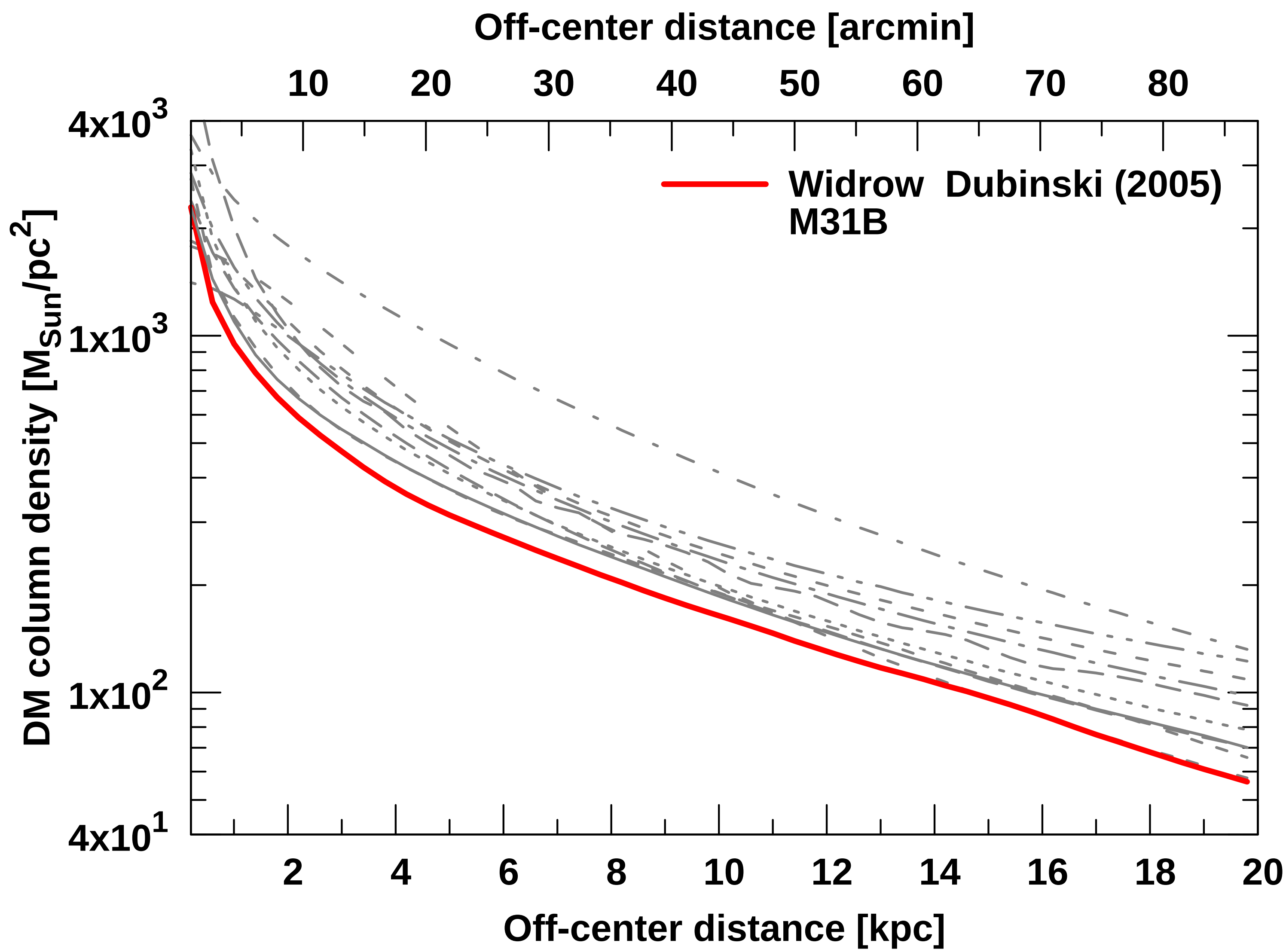
Objects with comparable expected signal for which archival data is available

- **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)** :
  $\mathcal{S}_{M31} \sim 100 - 600 M_\odot/\mathrm{pc}^2$

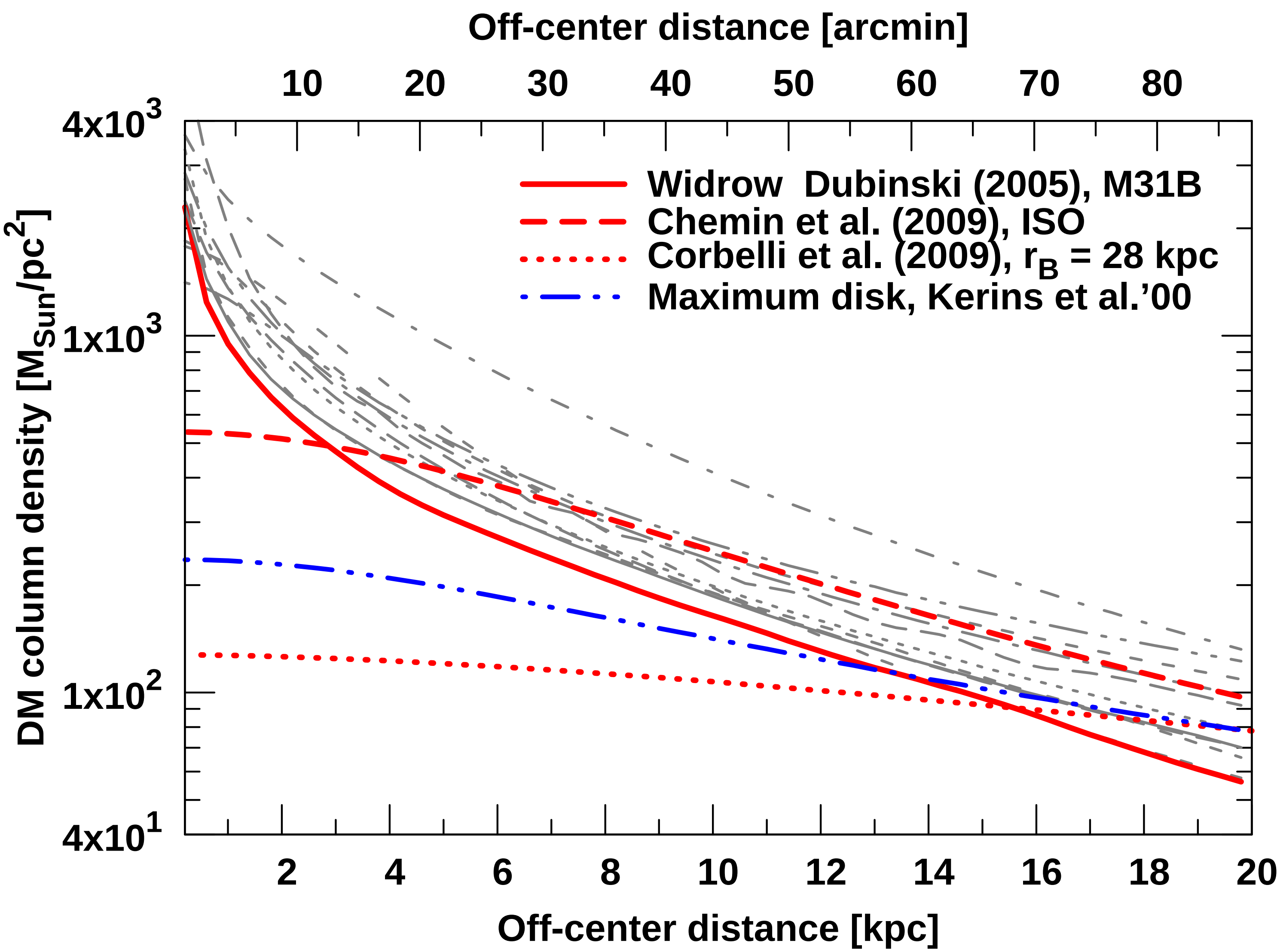
Do we see this 2.5 keV line?

DM in Andromeda galaxy (2008)

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



DM in Andromeda galaxy (2010)



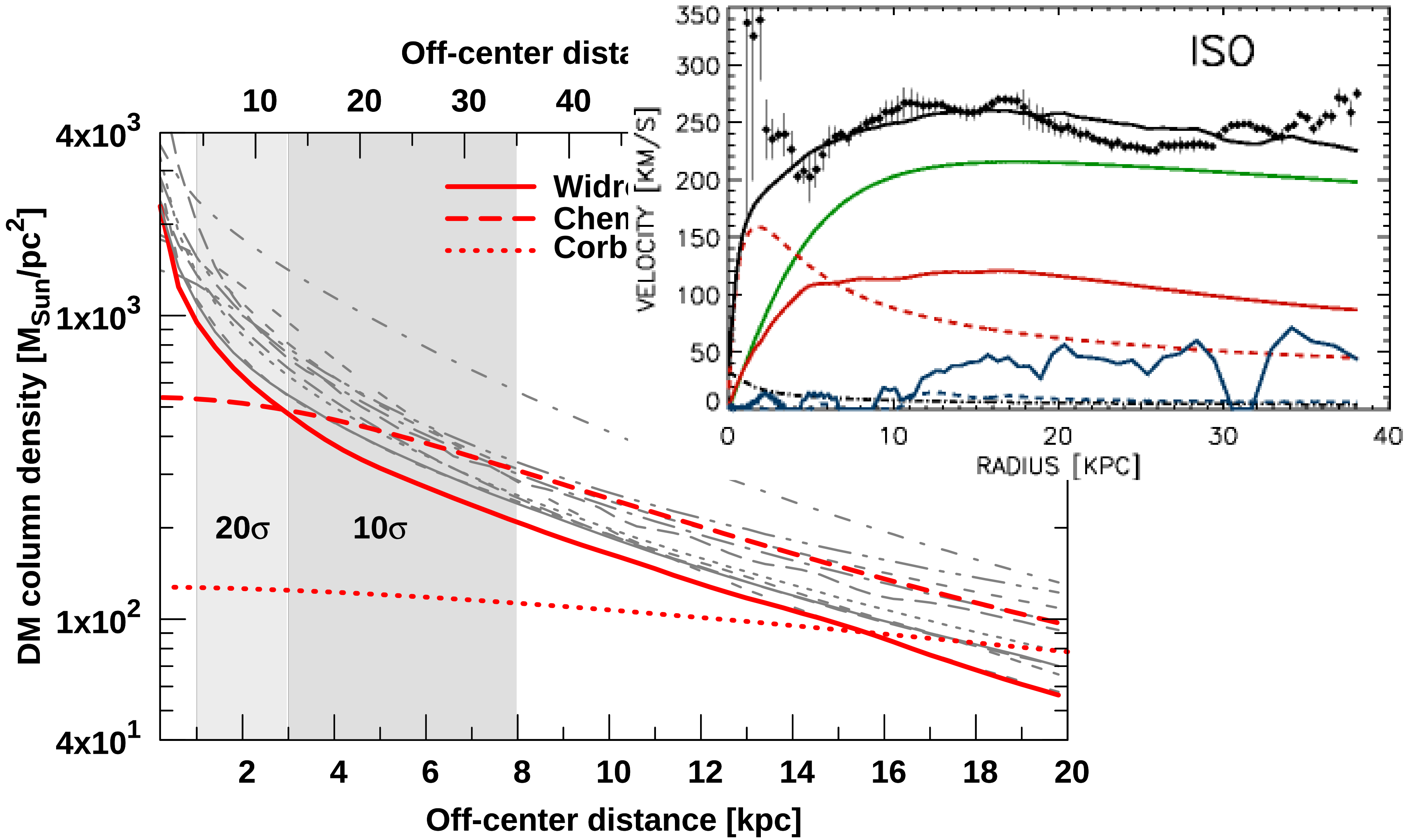
Boyarsky, O.R. et al. MNRAS'08

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

How to check DM origin of a line?

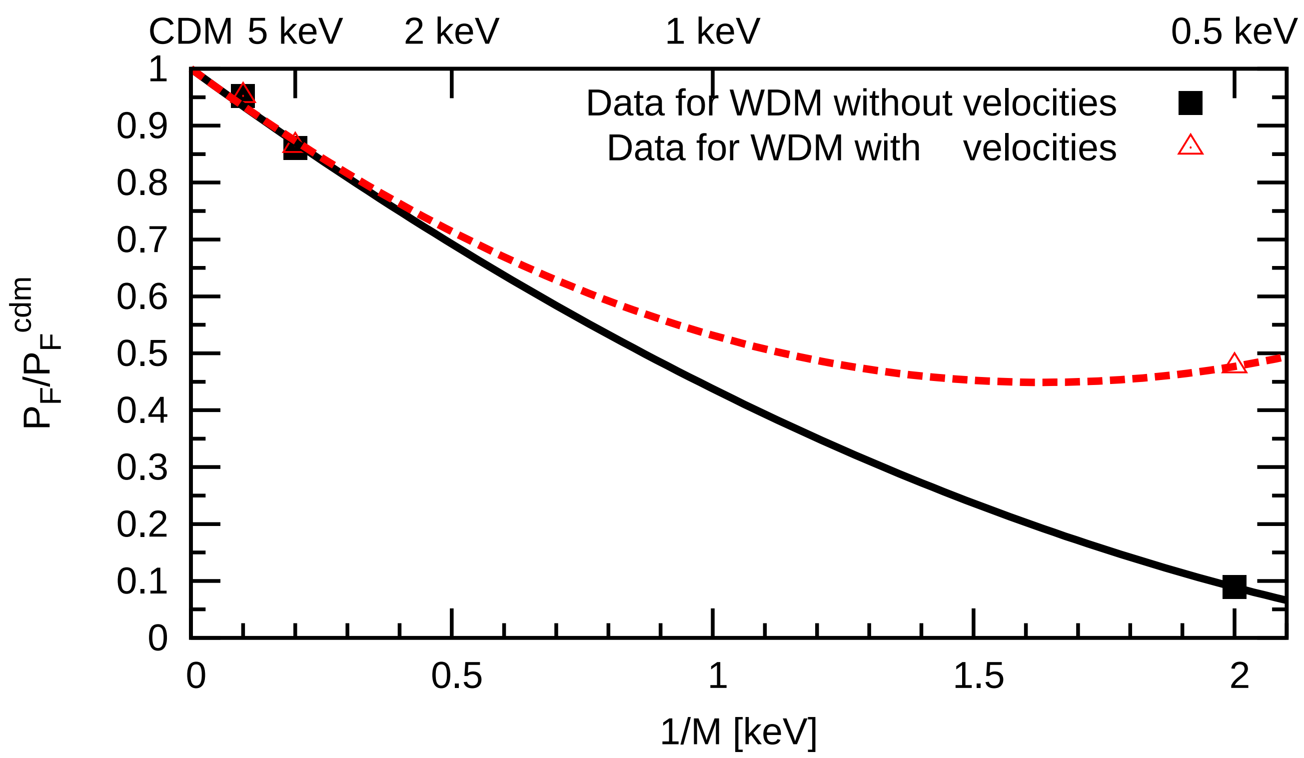
- Many DM-dominated objects would provide comparable decay signal. Freedom in choosing observation targets that optimize the signal-to-noise ratio (with well-controlled astrophysical backgrounds).

- Candidate line can be distinguish from astrophysical backgrounds by studying its **surface density** and **sky distribution**.

For decaying dark matter indirect search becomes direct!

Lyman-α analysis in CWDM models

- CWDM Ly-α bounds: about 20% of DM can be rather warm
- Primordial velocities at MD epoch can be significant (~ 10 km/sec)
- Numerical simulations with velocities? Require high resolution



Lyman-α analysis in CWDM models

- CWDM Ly-α bounds: about 20% of DM can be rather warm
- Primordial velocities at MD epoch can be significant (~ 10 km/sec)
- Numerical simulations with velocities?

Effect of velocities is negligible at scales of interest:

Work in progress

$$\frac{\Delta P(k,z)}{P(k,z)} \simeq -3.2\times 10^{-6}\left(\frac{k}{h\,\text{Mpc}^{-1}}\right)^2\left(\frac{\text{keV}}{M_s}\right)^2\left(\frac{0.27}{\Omega_M}\right)(1+z_i)$$

TOC

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