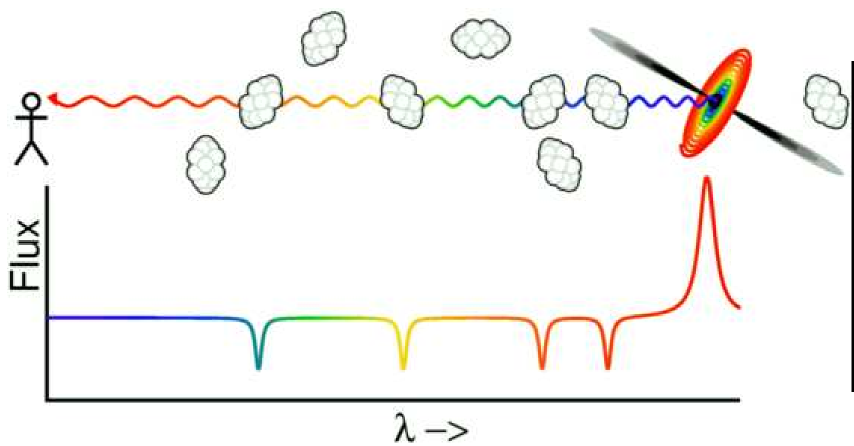
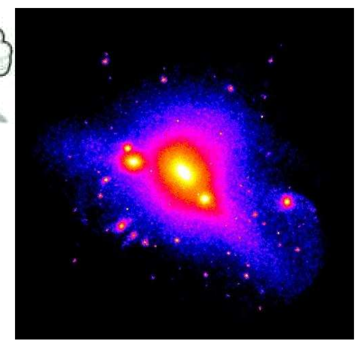
Warm dark matter

Oleg RUCHAYSKIY





Workshop on Indirect Dark Matter Detection

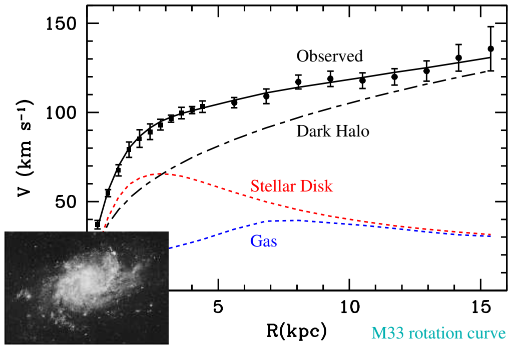
DESY. June 14, 2011

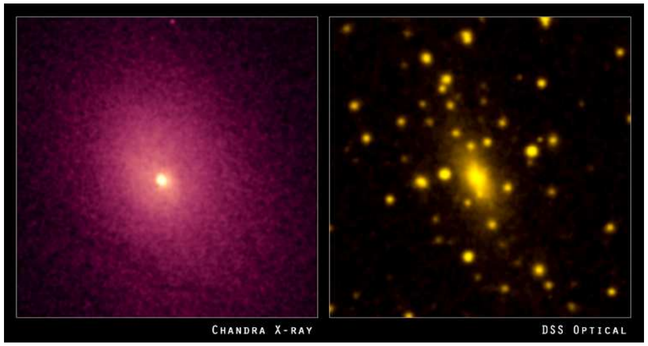
Plan

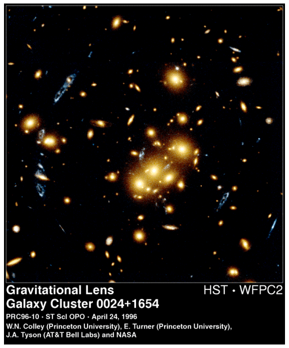
- Short introduction about dark matter in cosmology and astrophysics
- Free-streaming. **Cold**, **warm**, **hot** dark matter
- What is affected?
  - Halo mass function
  - Density profiles
  - Suppression of the matter power-spectrum
  - ...
- Existing observational data: evidence, constraints,...
- Lyman-α constraints
- Sterile neutrino – a particle that captures essence of realistic WDM candidates

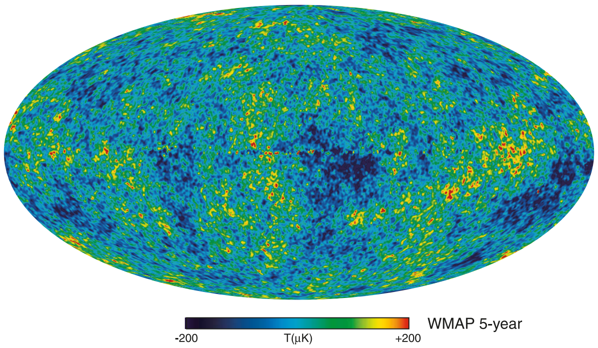
Plan

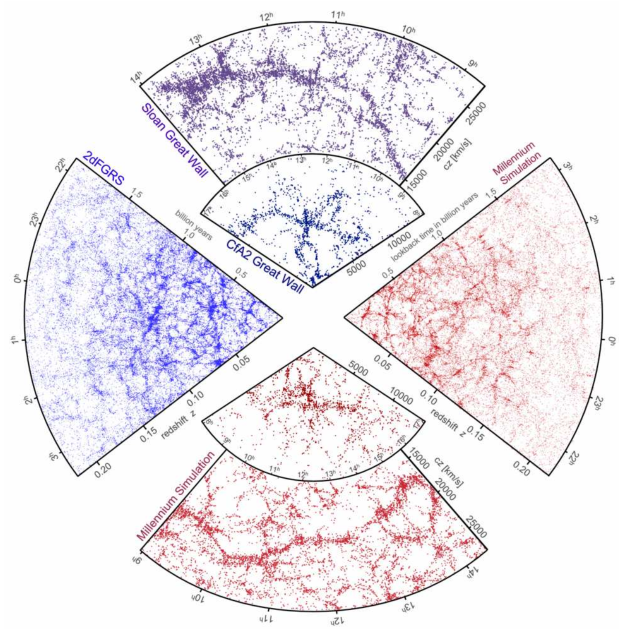
Extensive evidence for the presence of **dark, non-baryonic** matter, dominating the mass balance of the Universe at scales above 100 pc.



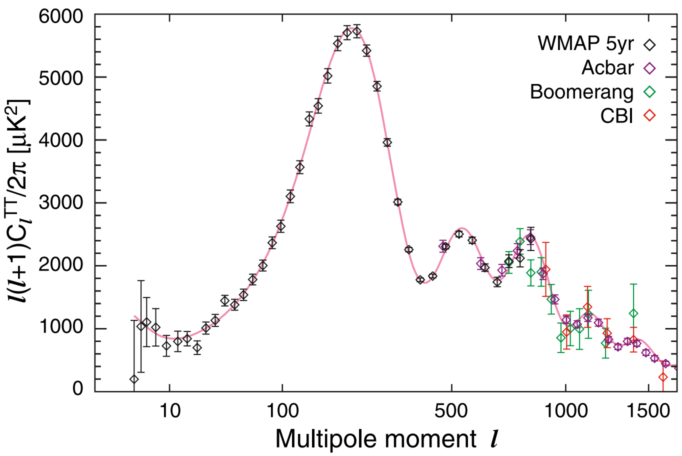


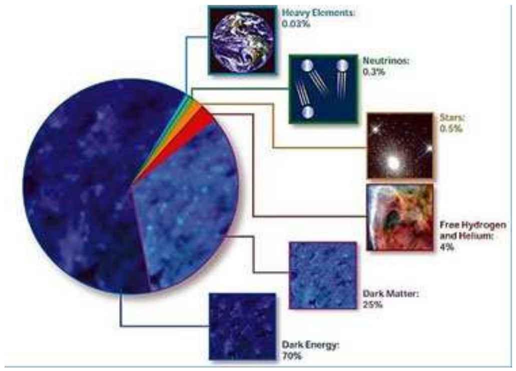


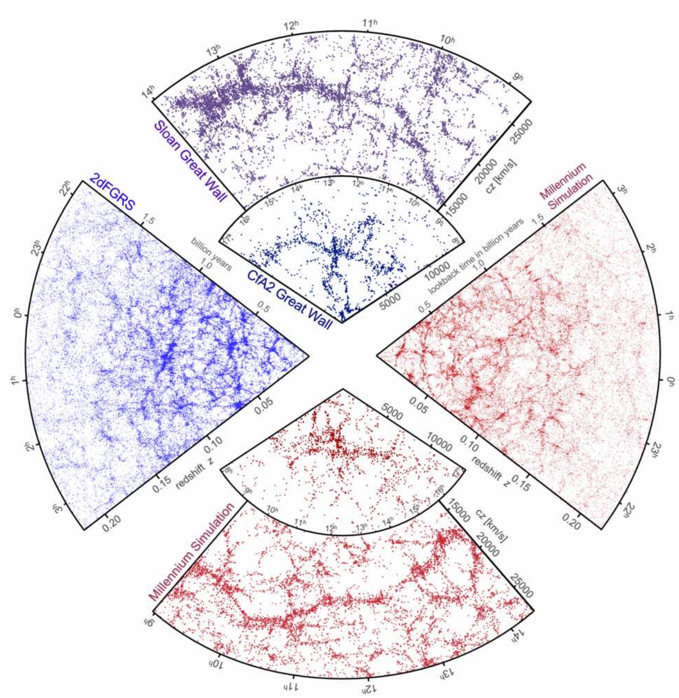




Concordance model at cosmological scales







- 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, . . .)

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. All DM models are thus divided into 3 groups:
  - **CDM** : particles were always **non-relativistic**
  - **WDM** : particles were created **relativistic**, but became non-relativistic in the **RD epoch**
  - **HDM** : particles were created **relativistic**, and became non-relativistic in or around the **MD epoch**

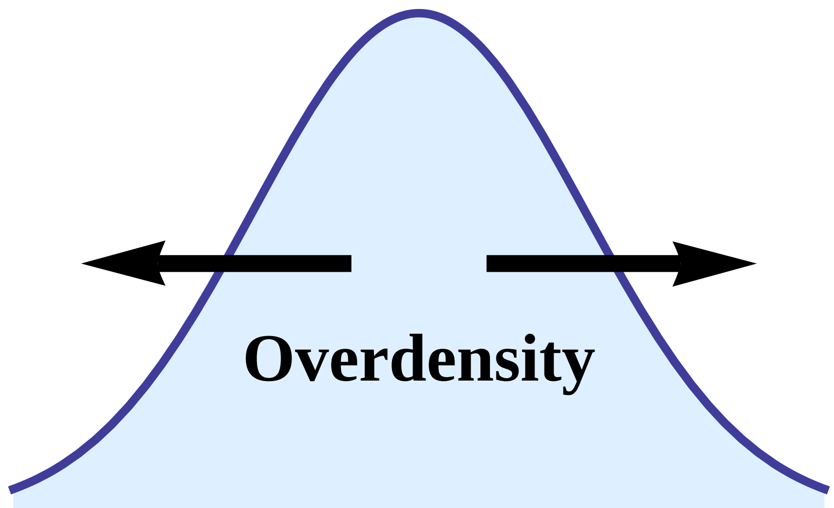
Free-streaming

- Relativistic particles **free stream** out of overdense regions and smooth primordial inhomogeneities on the scales below **free-streaming horizon**

$$\lambda_{\text{FS}}^{co} = \int_0^t \frac{v(t')dt'}{a(t')} = \int_0^{t_{nr}} \frac{dt'}{a(t')} + \int_{t_{nr}}^{t_{eq}} \frac{dt'}{a^2(t')} + \dots$$

Suppression mass scale: $M_{\text{FS}} = \frac{4\pi}{3}\bar{\rho}\left(\frac{\lambda_{\text{FS}}}{2}\right)^3$

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



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)

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

WDM affects:

- Matter power spectrum of density fluctuations $\delta(\vec{x}) = \frac{\delta\rho(\vec{x})}{\bar{\rho}}$ at scales **below the free-streaming**:

$$\mathbf{P}(\mathbf{k}) = \left|\frac{\delta\rho_k}{\rho}\right|^2 = \int d^3\vec{r}e^{ik\cdot(\vec{x}-\vec{x}')}\left\langle\delta(\vec{x})\delta(\vec{x}')\right\rangle$$

- Halo (subhalo) mass function (decrease number of halos of small mass)

$$N(>M) = \int_M^\infty dM'\frac{dn(M')}{dM}$$

- Density profile (central **core** rather than **cusp**)

$$\rho(r) = \frac{\rho_0}{(r/r_0)^\alpha(1+(r/r_0)^\beta)^\gamma}$$

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)

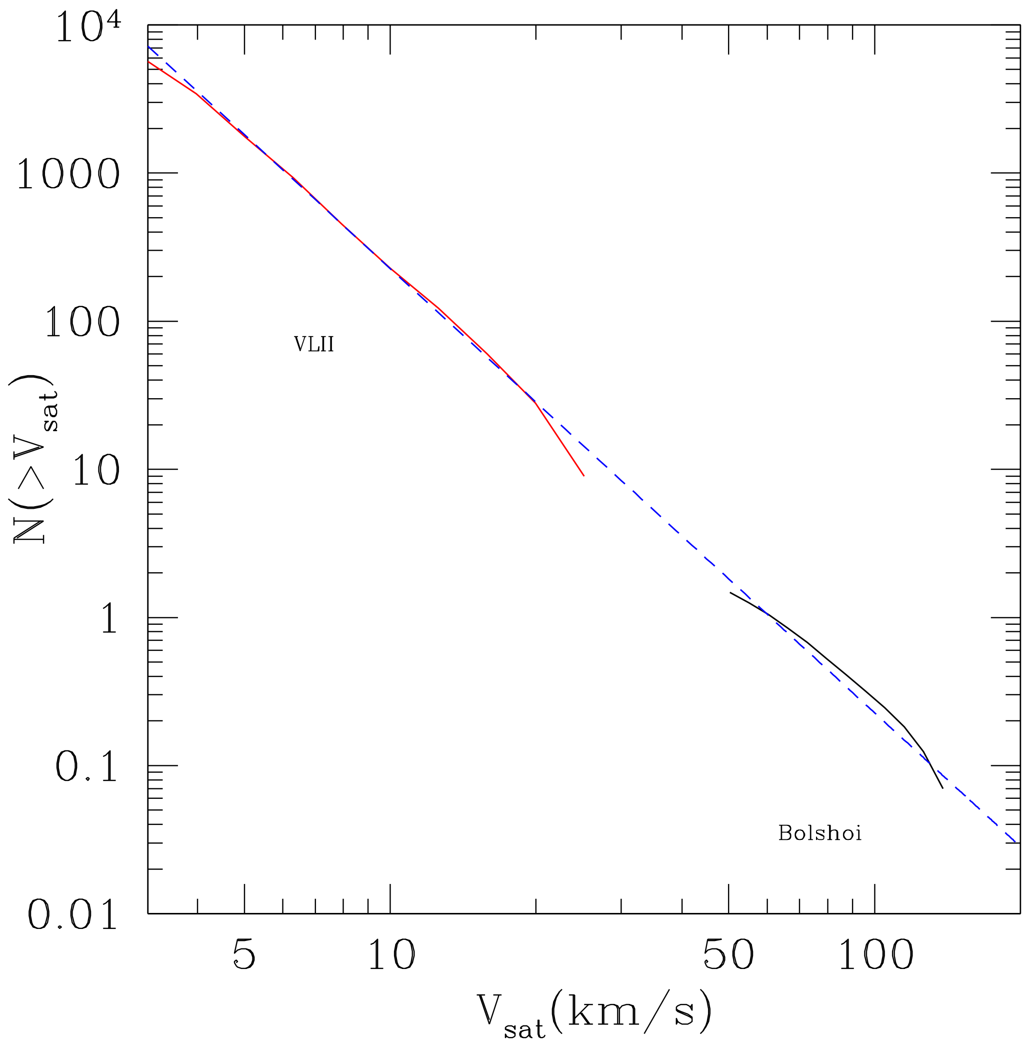
$$k \simeq \ell \times \frac{H_0}{2} = \frac{\ell}{6000} \frac{h}{\text{Mpc}}$$

- Is sensitive up to scales $k \lesssim 0.1\ h/$ Mpc

- Smaller scales? Non-linear stage of structure formation

Halo (subhalo) mass function

CDM scale-free structures

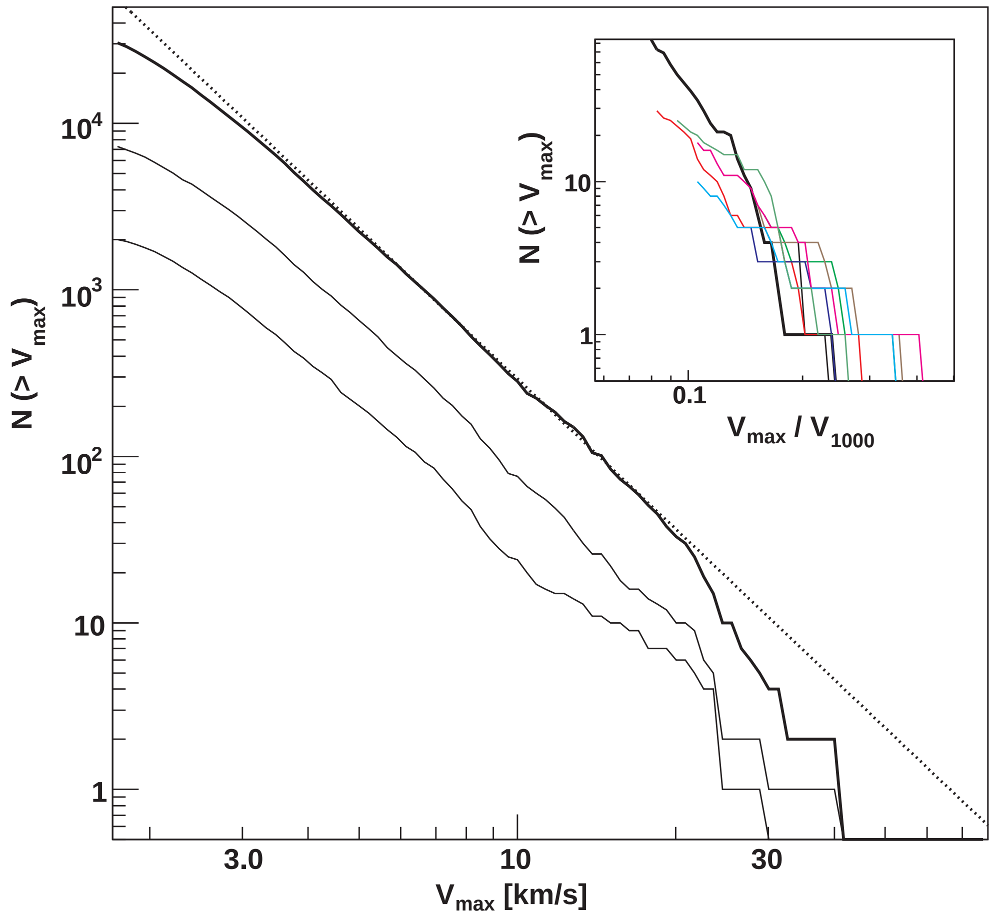


- **CDM** structures form in a scale-free manner

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

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

CDM scale-free structures

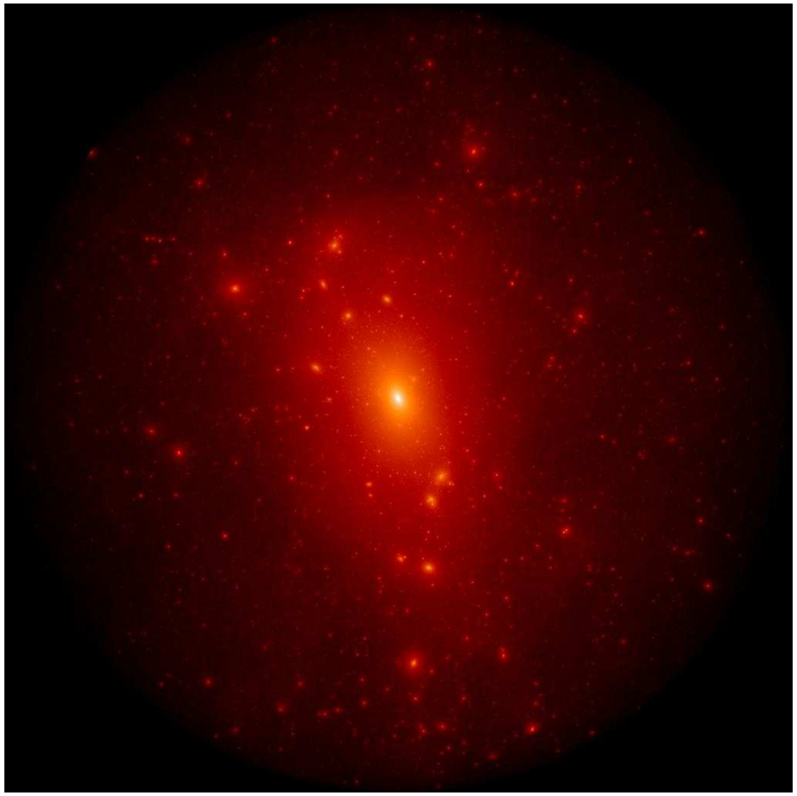


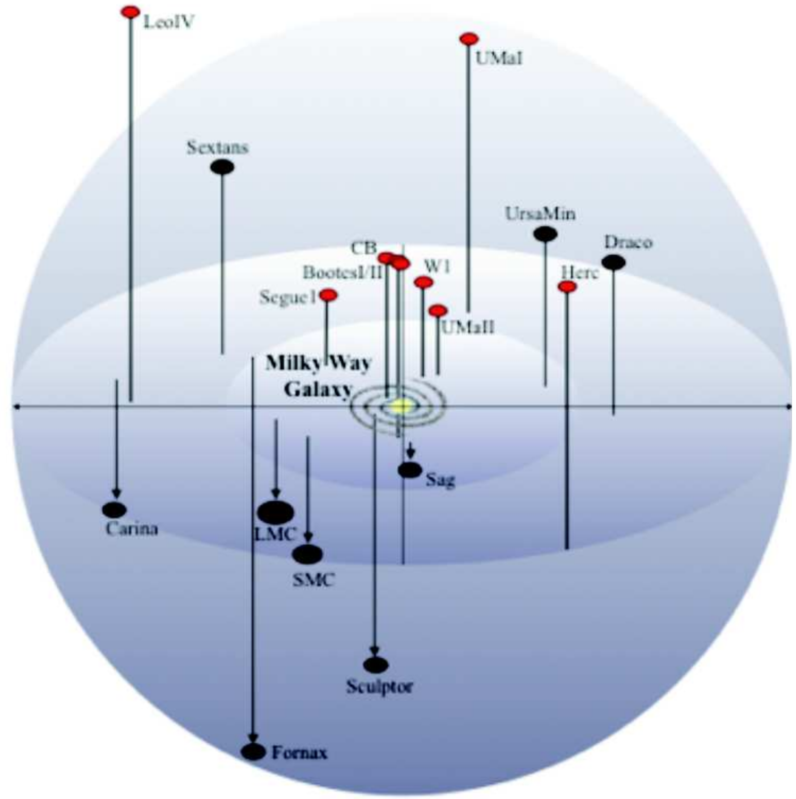
- **CDM** structures form in a scale-free manner

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

- *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

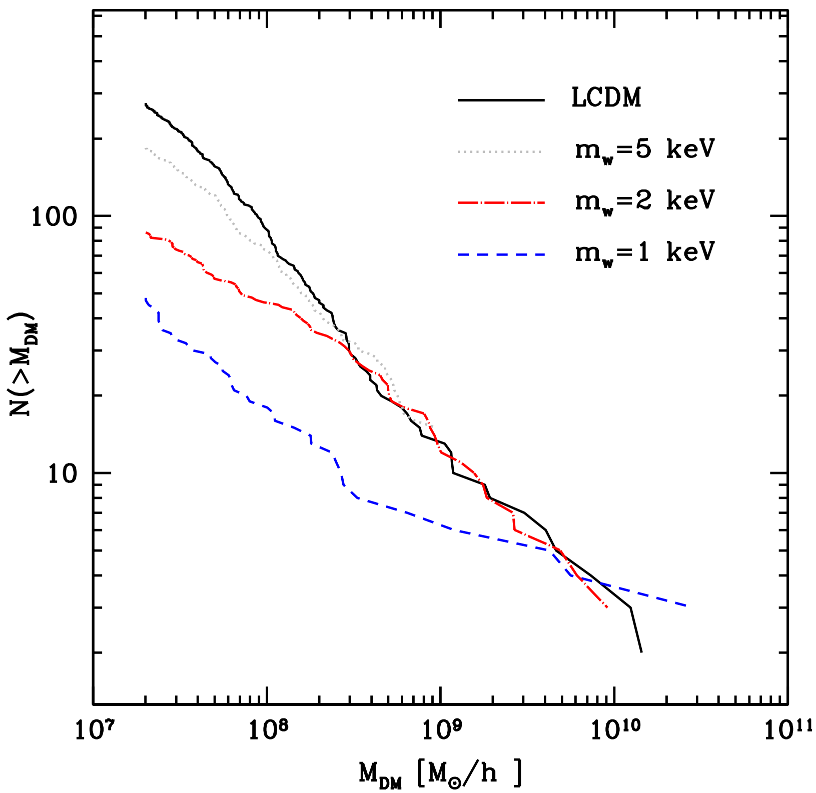
Is small number of observed substructures due to dark matter free-streaming? Moore et al. (1999), Klypin et al. (1999) and many others

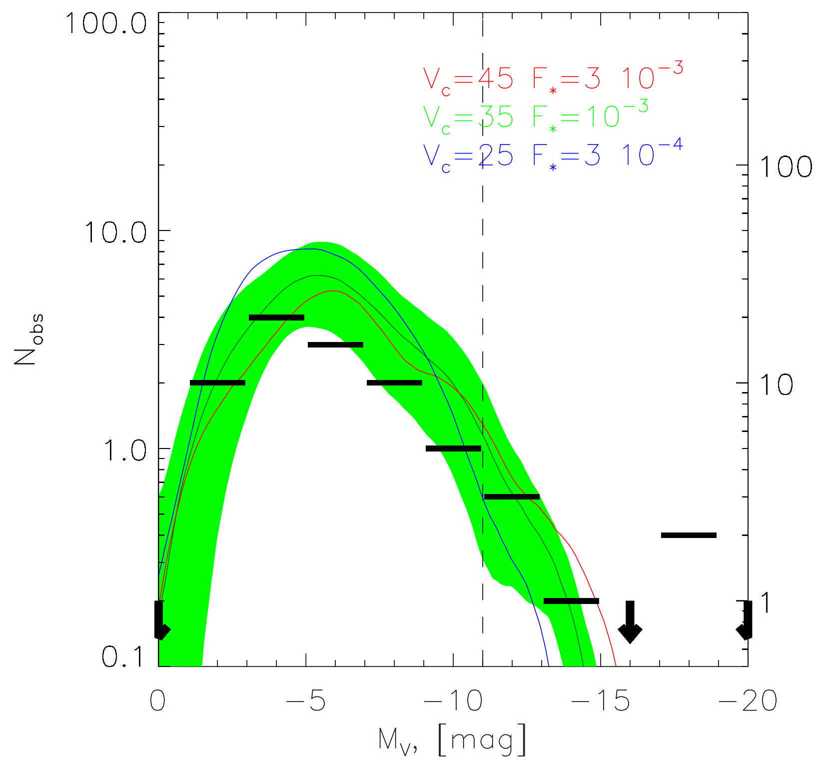
Mass vs. luminosity function

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

Bullock et al. (2000);

Benson et al. (2002)



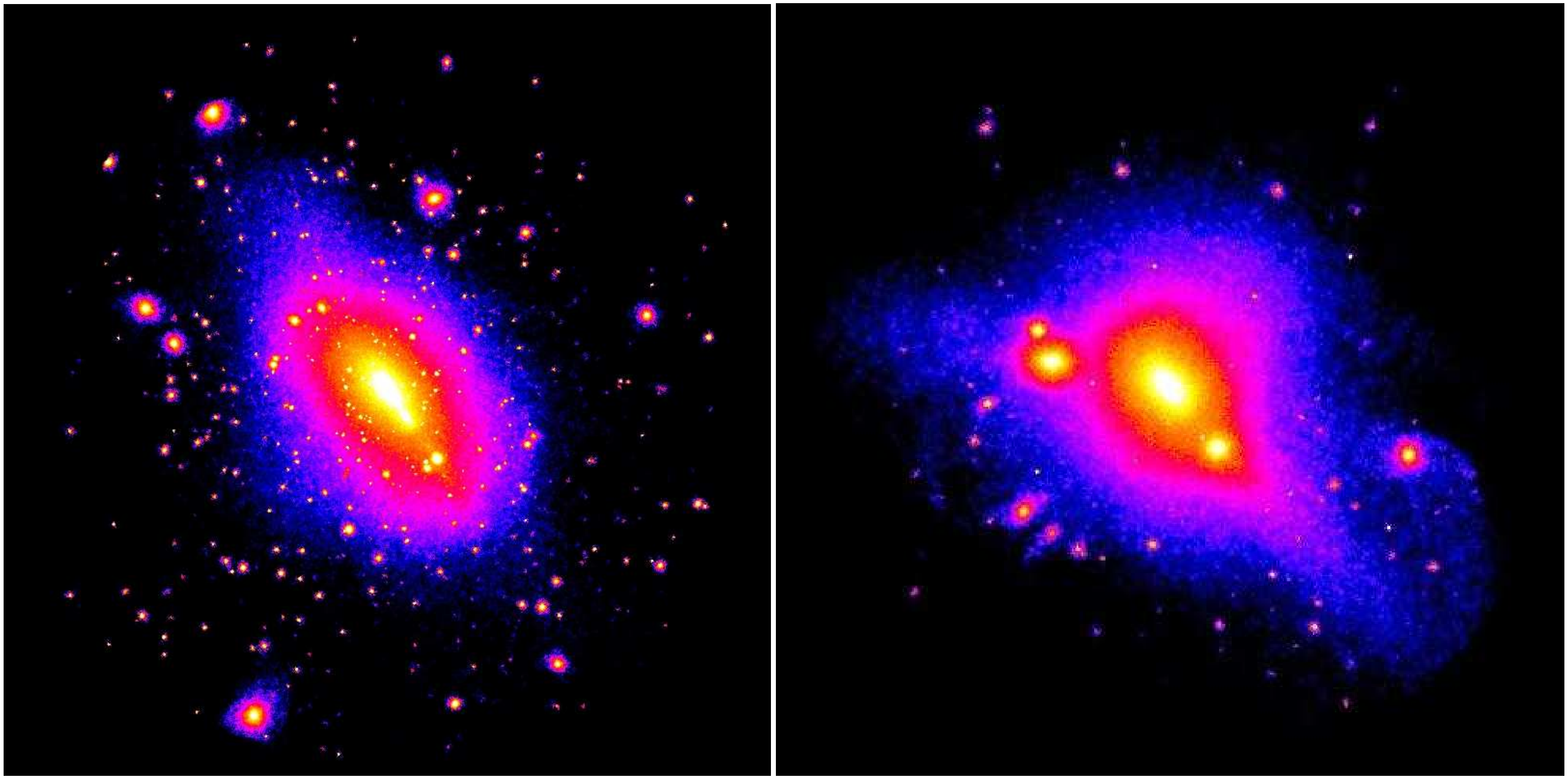


Macciò & Fontanot'09

Suppression of number of structures in WDM Universe

Koposov et al.'09

WDM substructure suppression



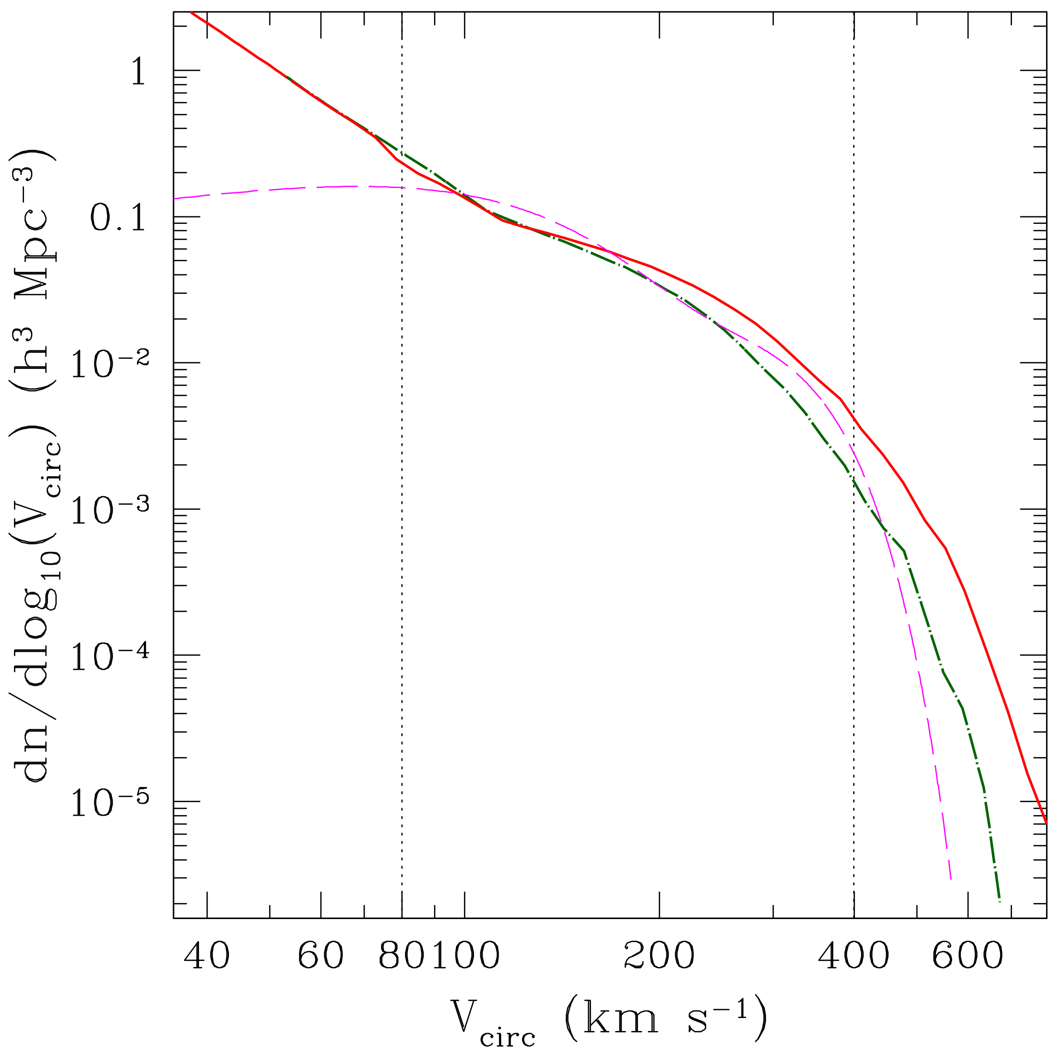
Thermal relics with mass ~ 1 keV would erase **too many substructures**. Anything "colder" would produce enough structures to explain observed Milky Way structures

Maccio & Fontanot (2009);

Polisensky & Ricotti (2010)

Another overabundance problem

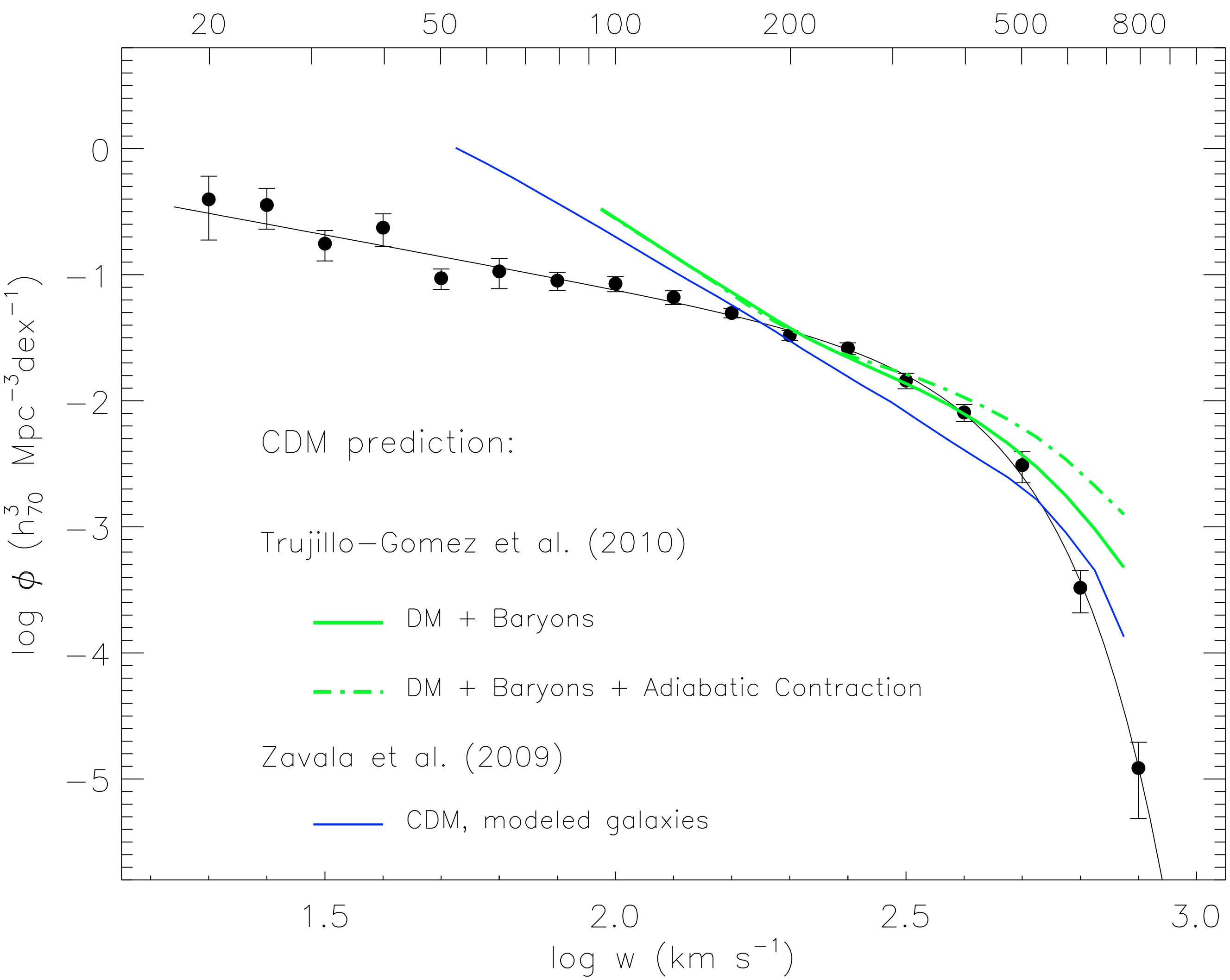
Trujillo-Gomez, Klypin, Primack et al. 2010-2011



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

ALFALFA Velocity width function vs. CDM

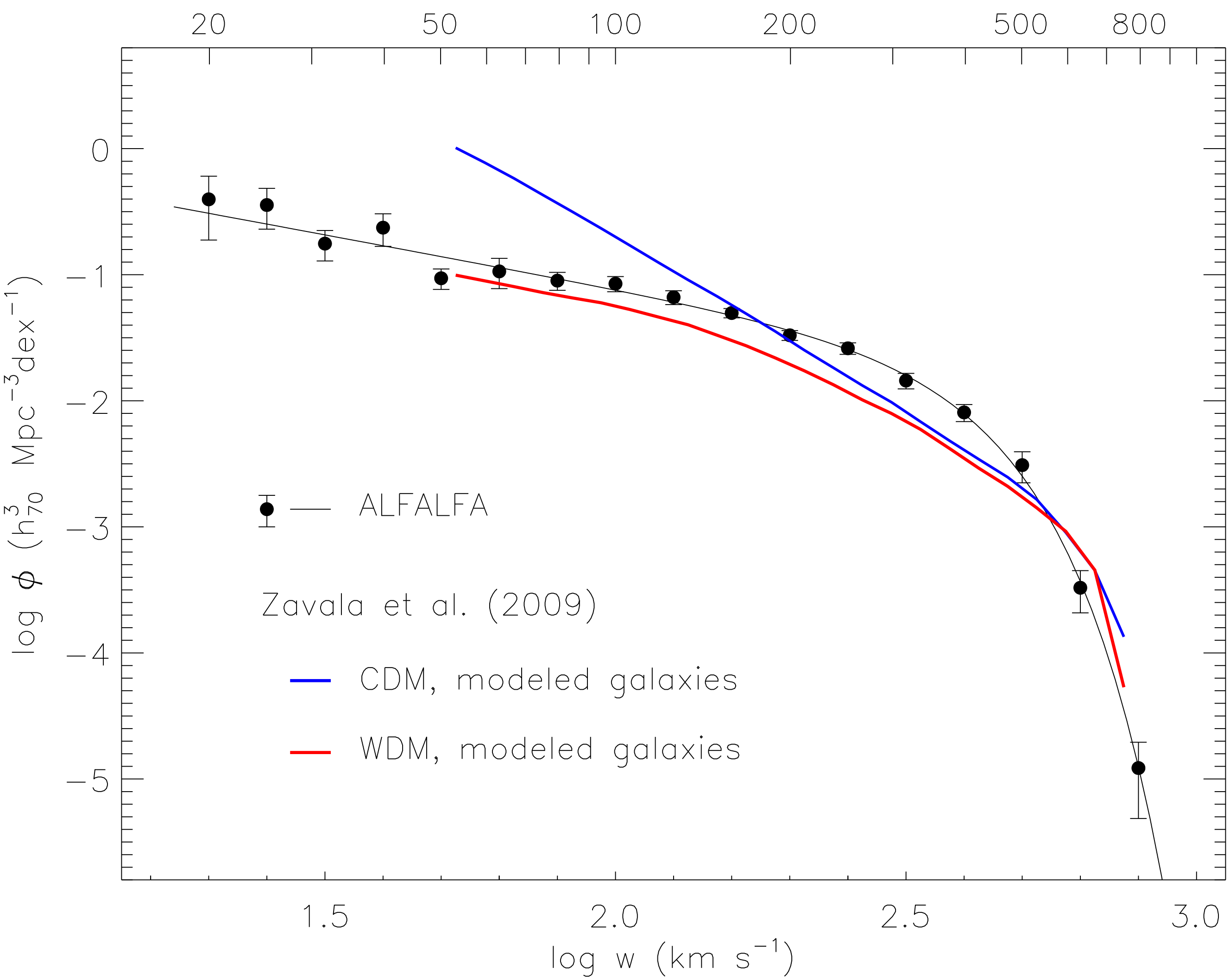
Papastergis+
[1106.0710]



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

Velocity width function vs. WDM

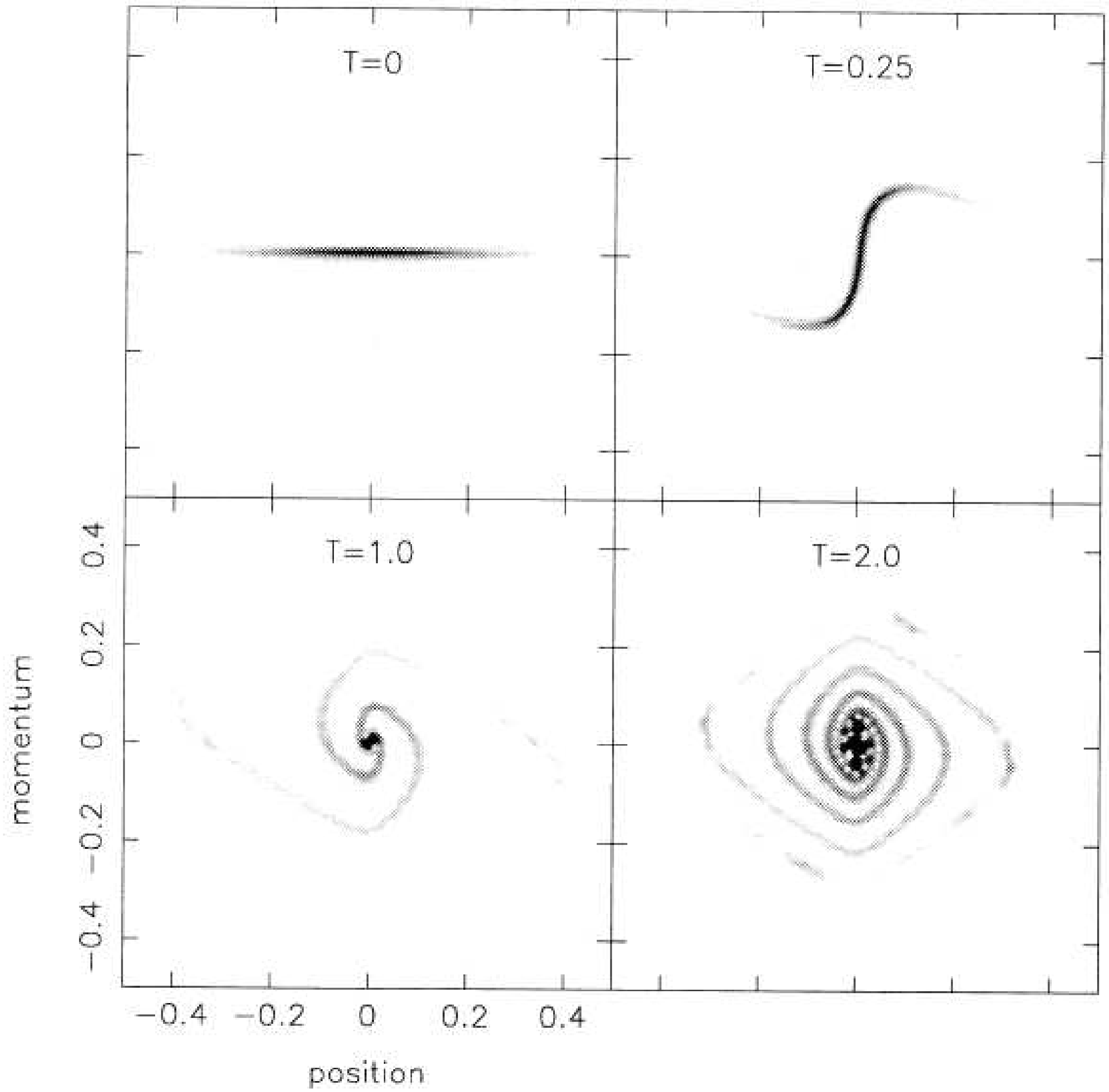
Papastergis+
[1106.0710]

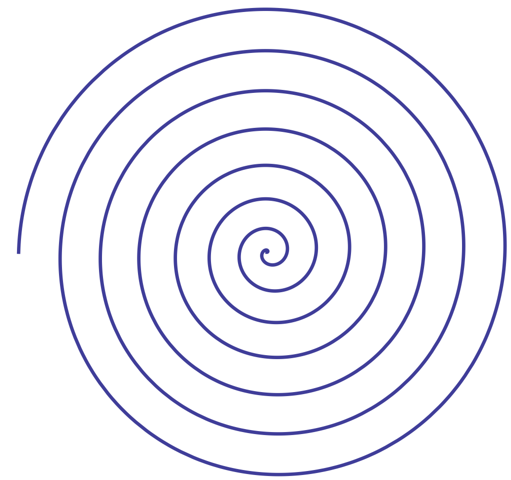


ALFALFA (HI) survey. Deviations from ΛCDM predictions for $v_{rot} \lesssim 100$ km/sec

Density profiles

WDM - finite phase-space density



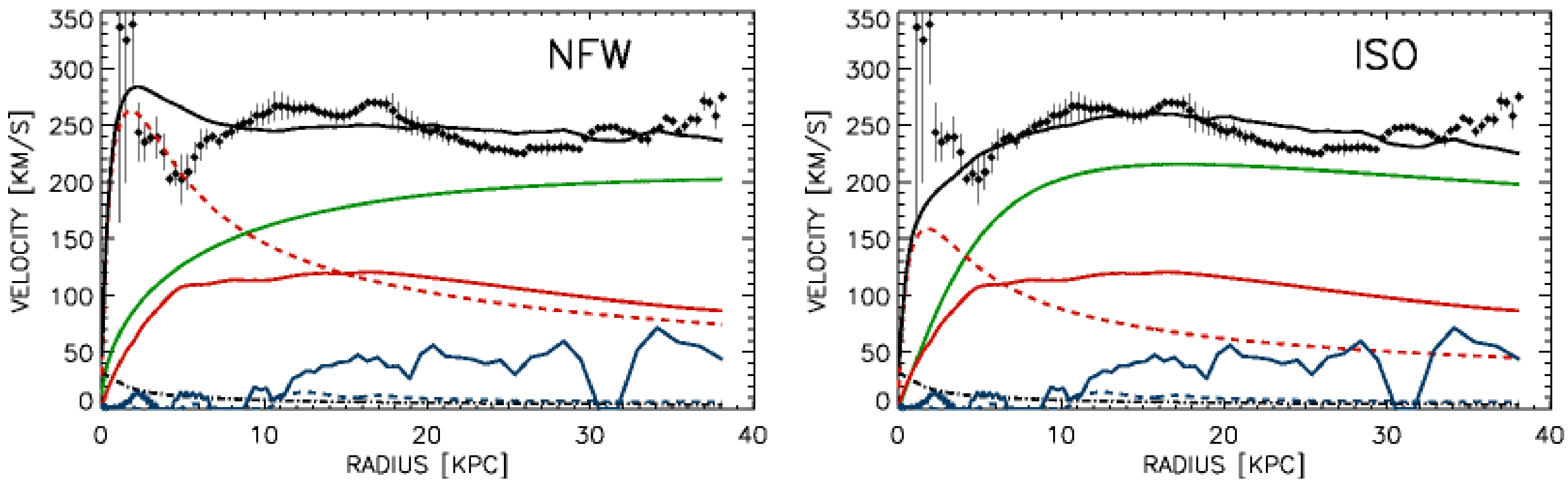


Unlike in the case of CDM, finite WDM phase-space density should lead to formation of DM **cores**

Cores in dark matter halos

- Mass distribution in galaxies and galaxy clusters can be described by different density distribution
- Highly degenerate (indirect tracers, contributions from various baryonic mass components)

Chemin et al. ApJ 2009 [0909.3846]

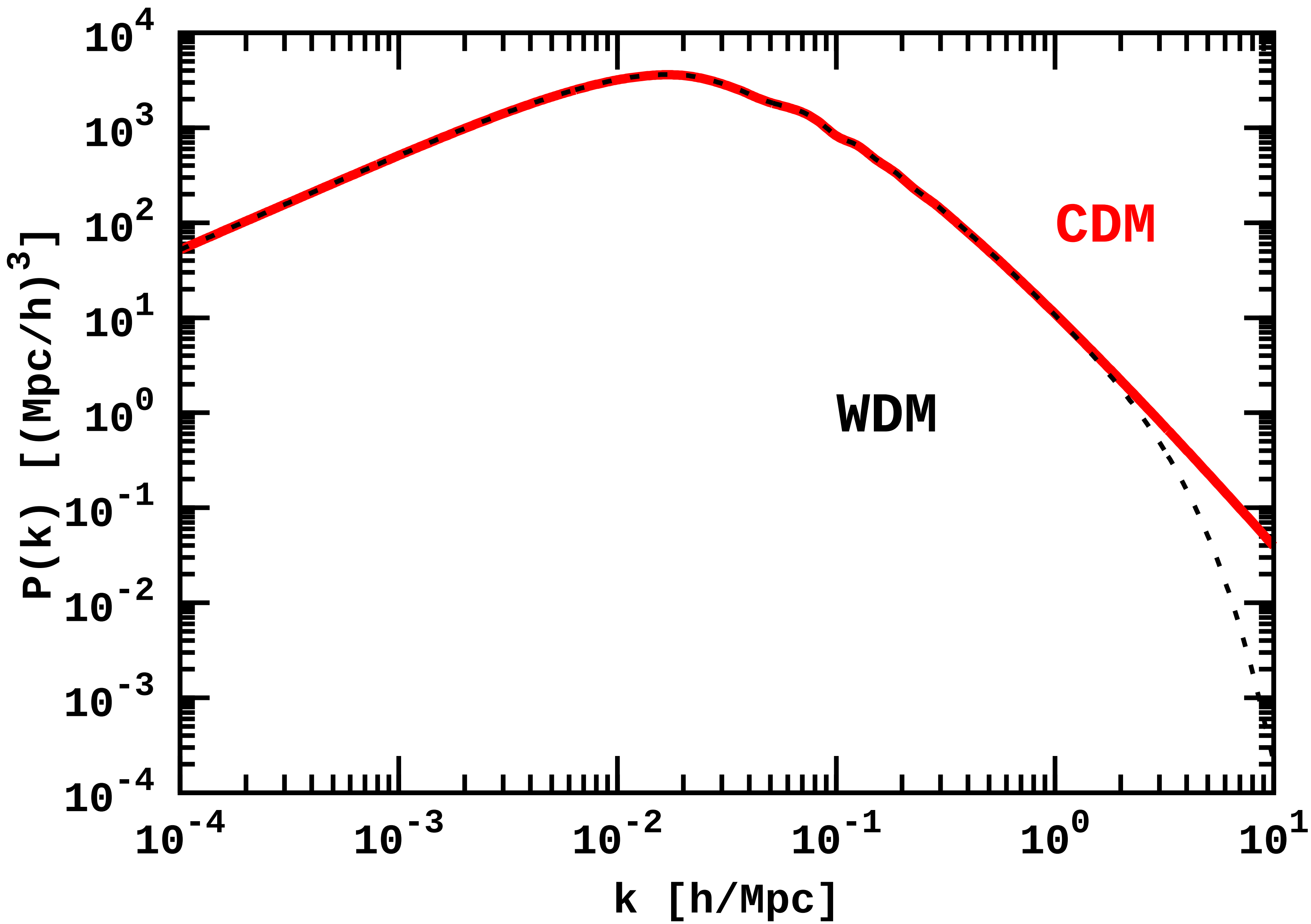


- Dwarf spheroidal galaxies – degeneracy between central slope and anisotropy parameter. Very recent works **favor cores**.

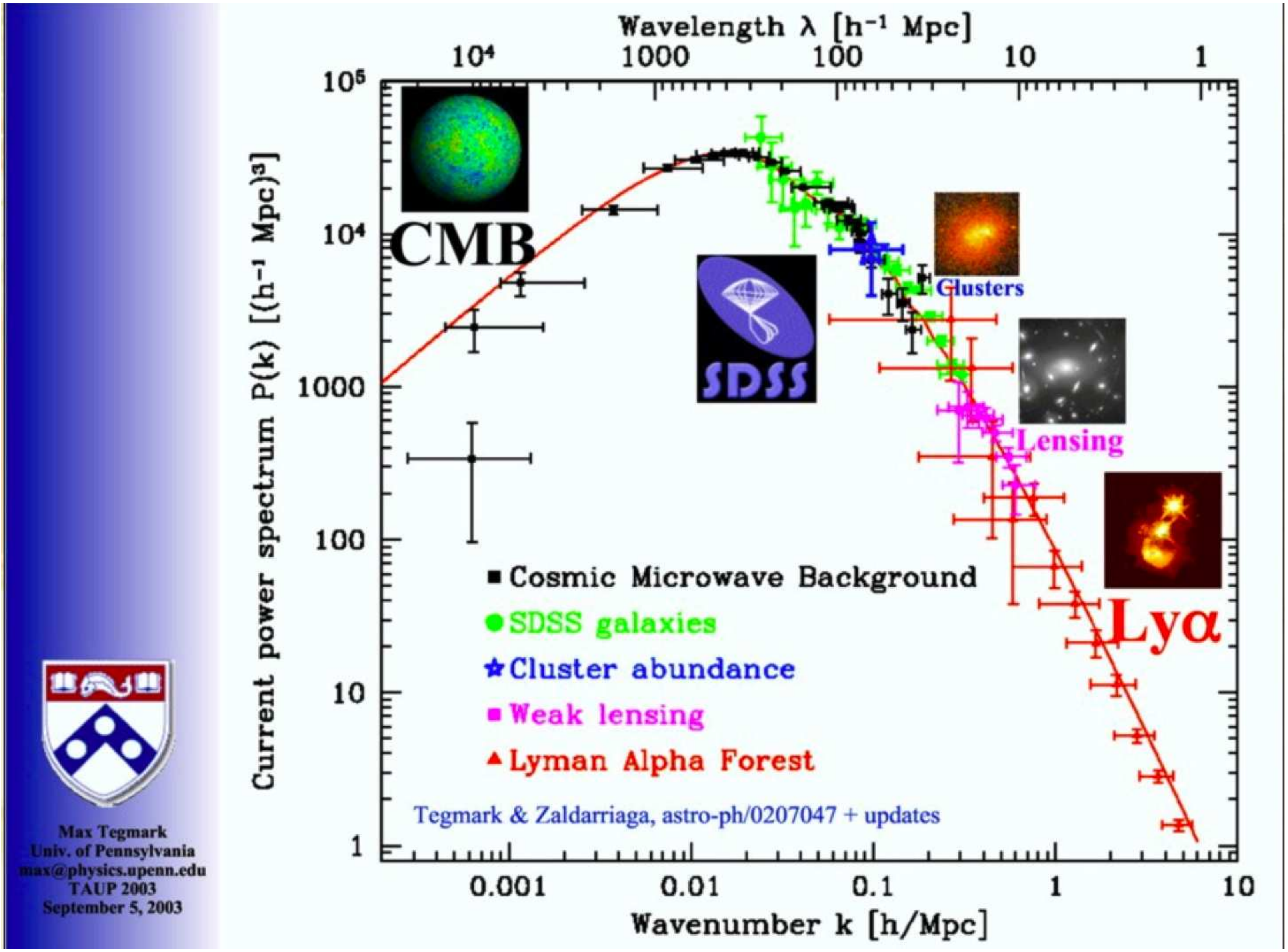
Amorisco & Evans [1106.1062]; Walker & Peñarrubia (2011)

Matter power spectrum at sub-Mpc scales

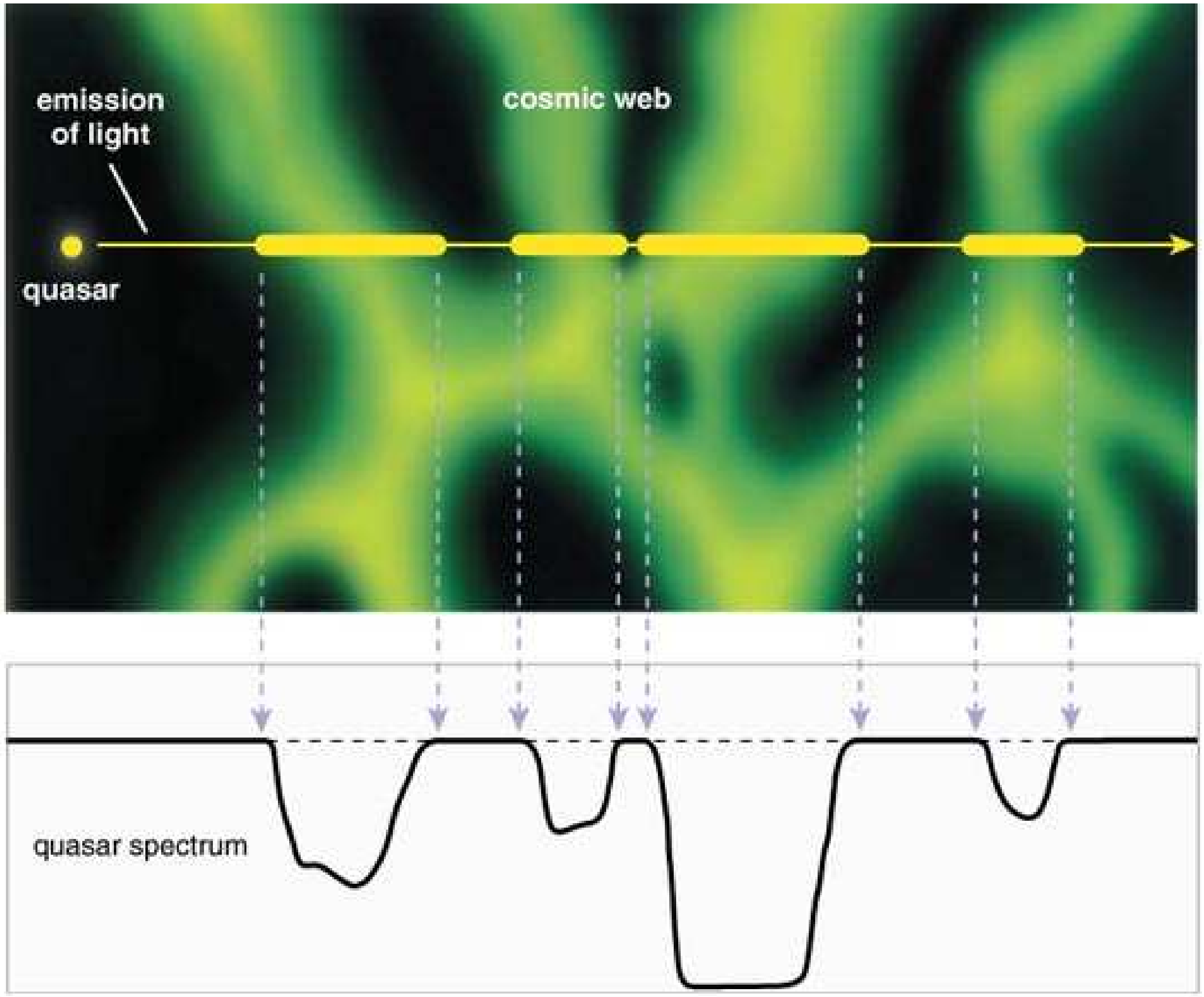
Suppression of power spectrum



How to probe 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

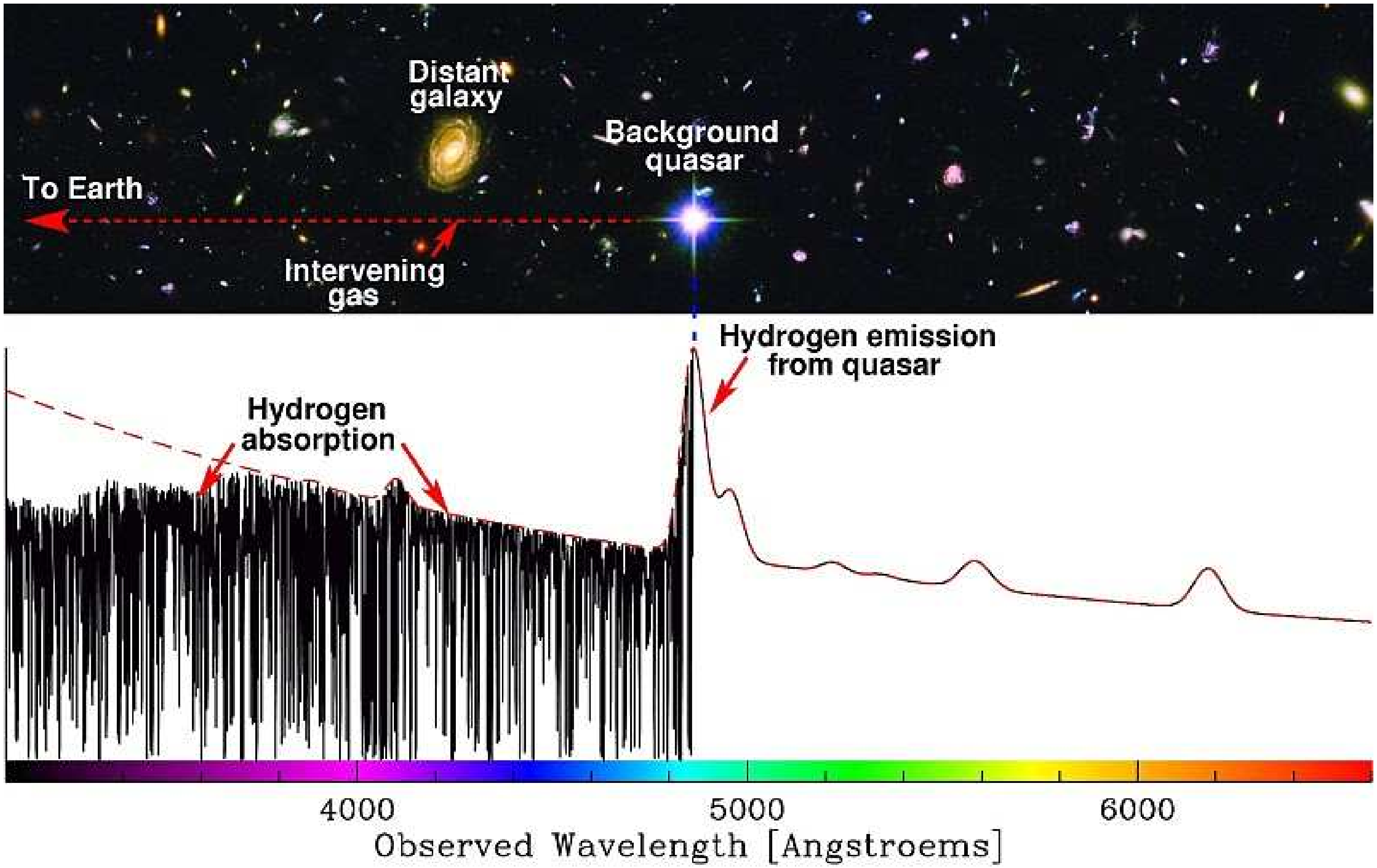


Image: Michael Murphy, Swinburne University of Technology, Melbourne, Australia

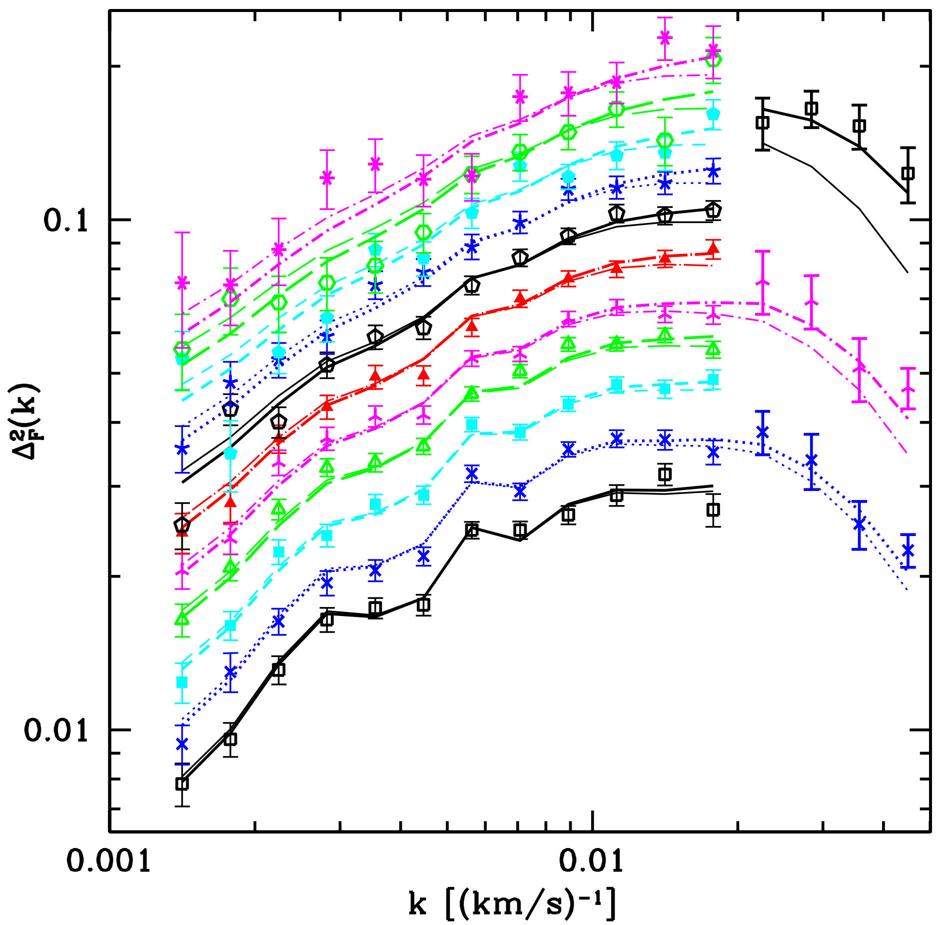
Neutral hydrogen in intergalactic medium is a tracer of overall matter density. Scales $0.3h/\text{Mpc} \lesssim k \lesssim 3h/\text{Mpc}$

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 $\ldots$ (thousands of data points, sometimes correlated)

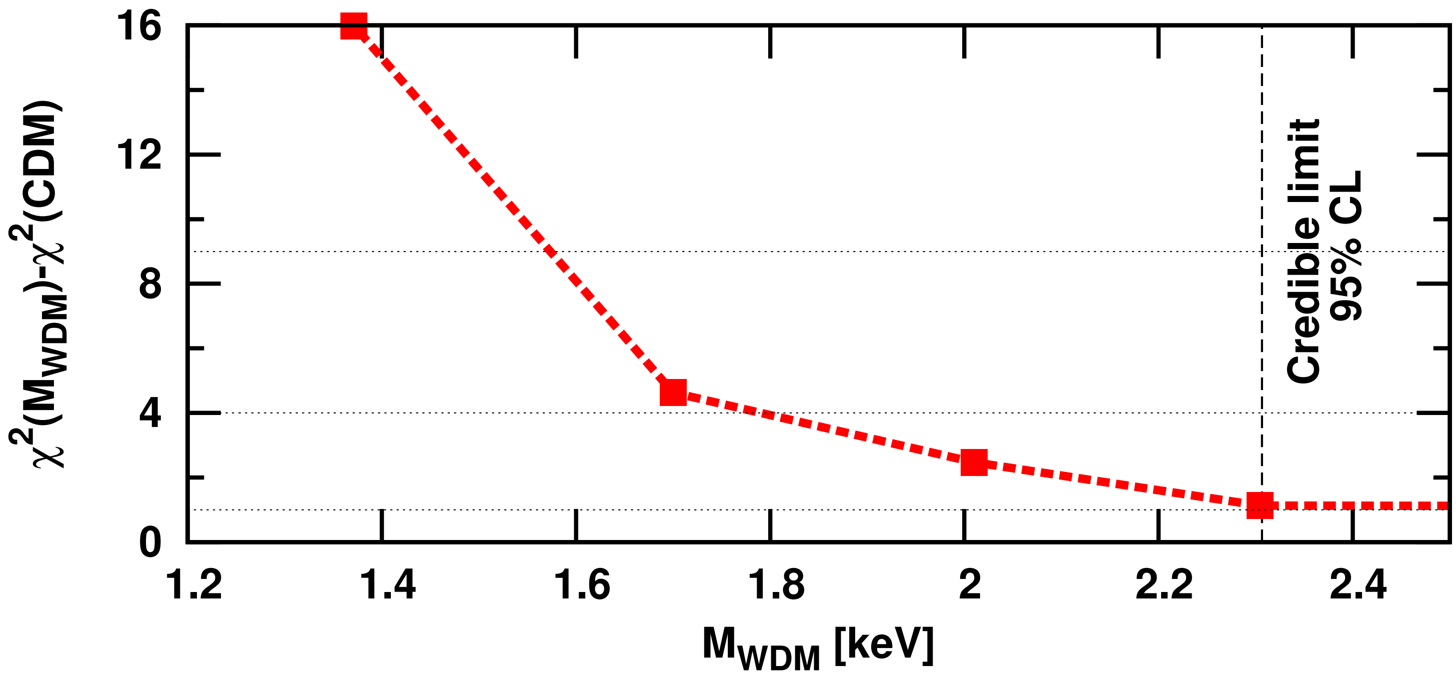
Lyman-α forest flux power spectrum

Seljak et al. '06



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

Ly-α and thermal relics



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

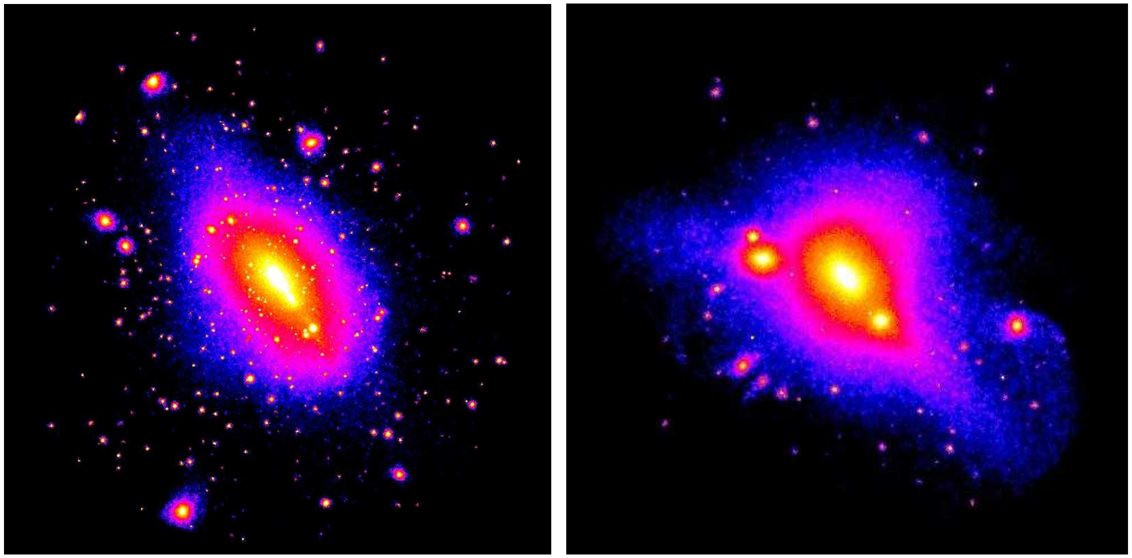
Also Viel et al. 2005-2007;

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:



- **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

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

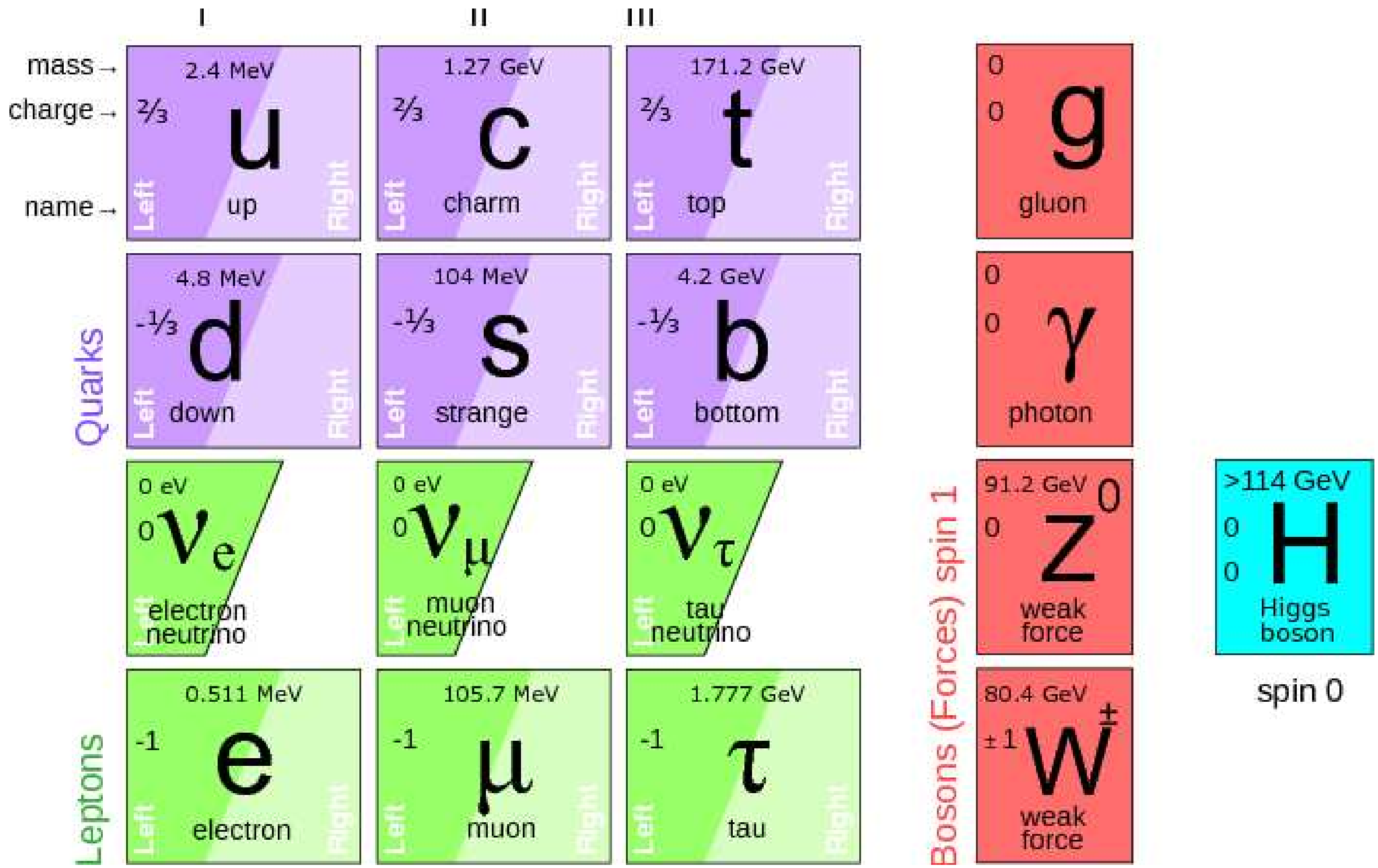
Maccio & Fontanot (2009);

Polisensky & Ricotti (2010)

Are there other WDM candidates evading these Lyman-α constraints?

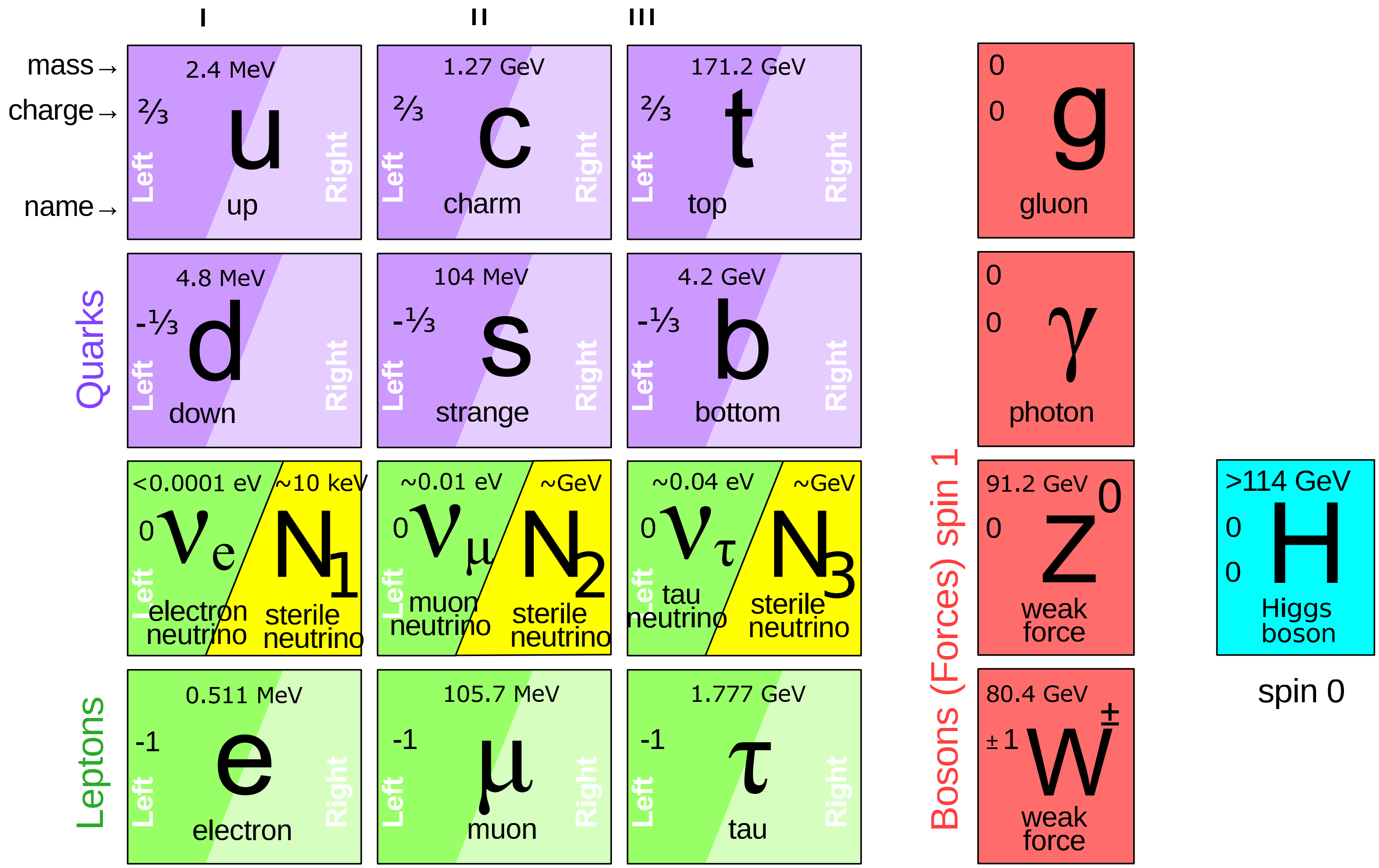
Sterile neutrino – warm dark matter candidate

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

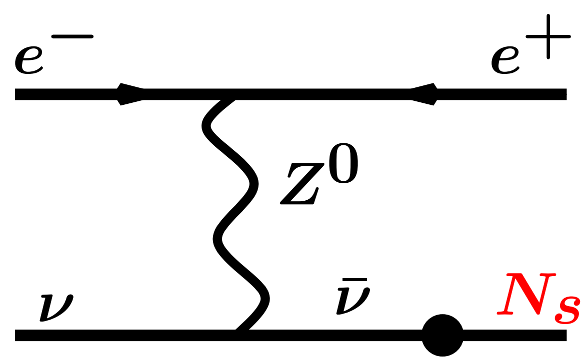
Some general properties of sterile neutrino

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: $G_F \to \theta G_F$

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

Properties of sterile neutrino DM

- Mass can be **anything** higher than ~ 300 eV

  Tremaine & Gunn (1979)

  The **smaller** is the DM mass – the **bigger** is the number of particles in a gravitationally bound object.

  The occupied phase-space density in the system with fermionic DM particles is bounded by the **maximal** phase-space density of degenerate Fermi gas $\Rightarrow$ the lower bound on the mass of any fermionic DM

- Can **decay** into the SM particles

  With the lifetime at least 8 orders of magnitude longer, than the age of the Universe

- Produced in many different ways. Have never been in thermal equilibrium in the early Universe

  Has a non-universal **non-thermal** 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 $N \to 3\nu$.

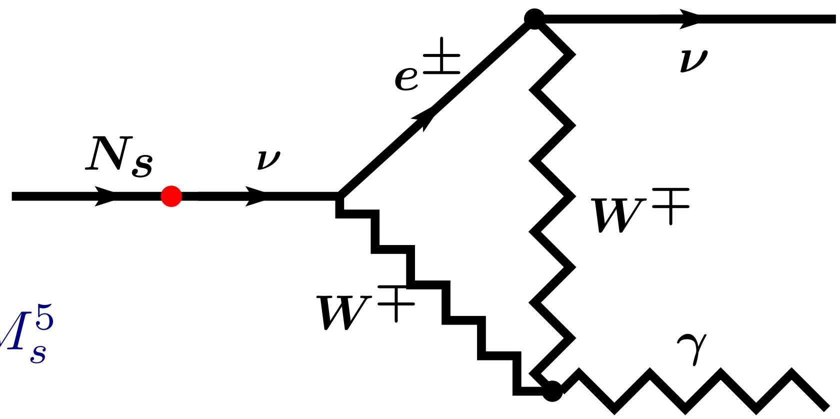
Wolfenshtein Pal (1982)

- 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

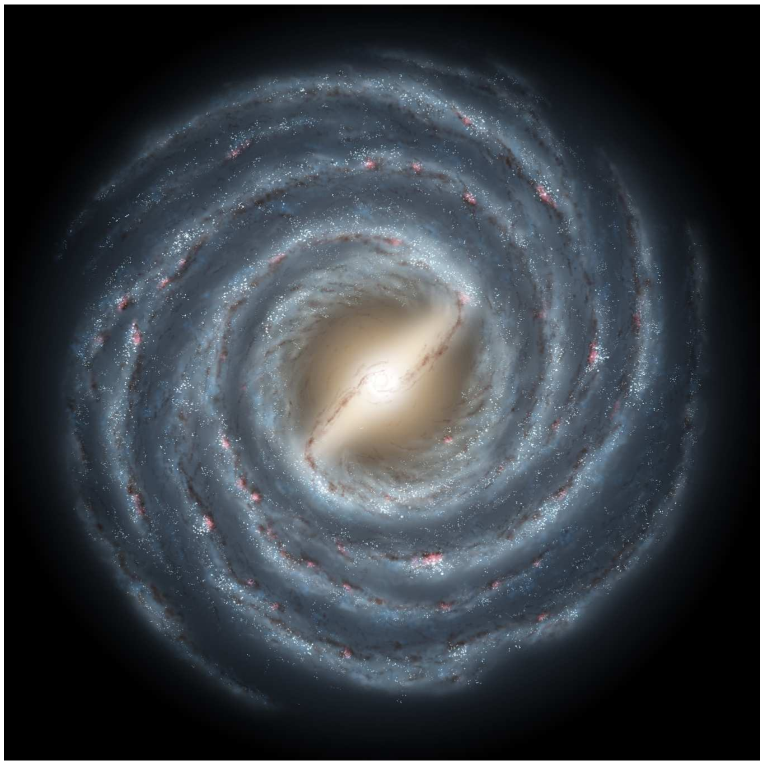
Abazajian Fuller Tucker (2001)

- 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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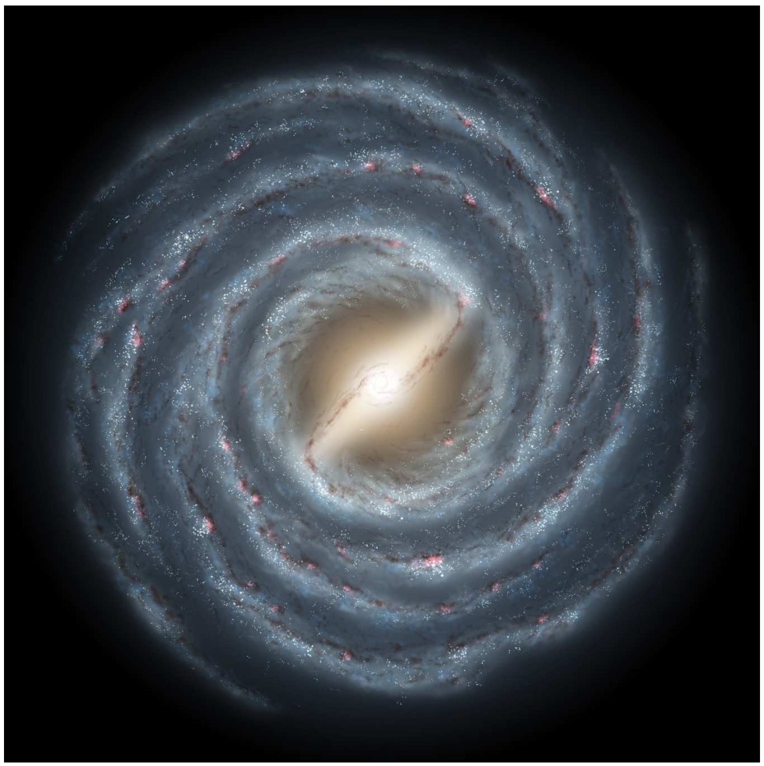
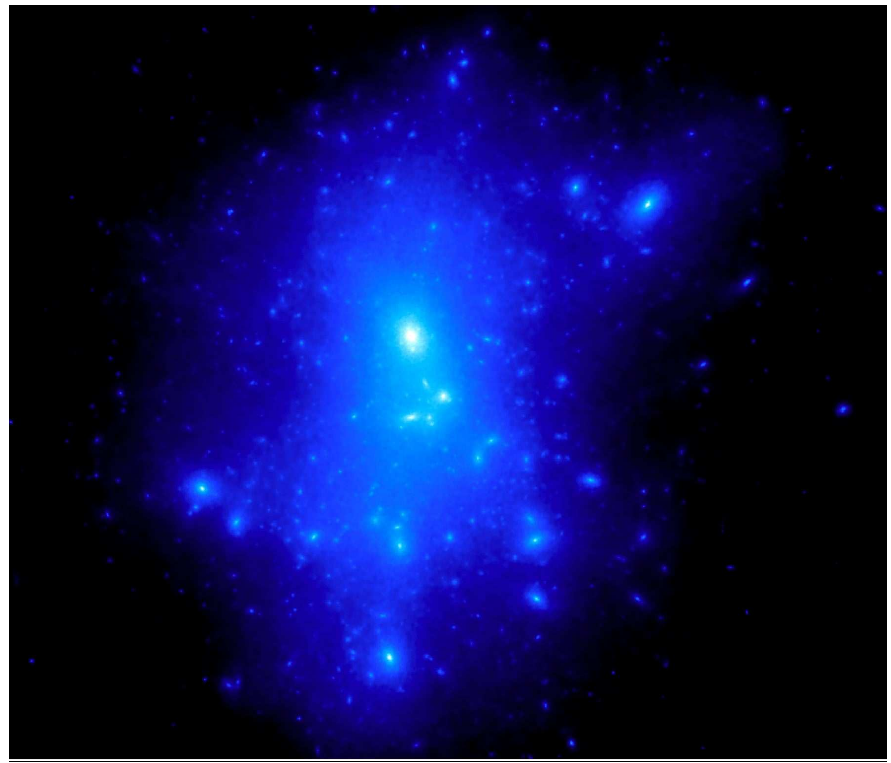
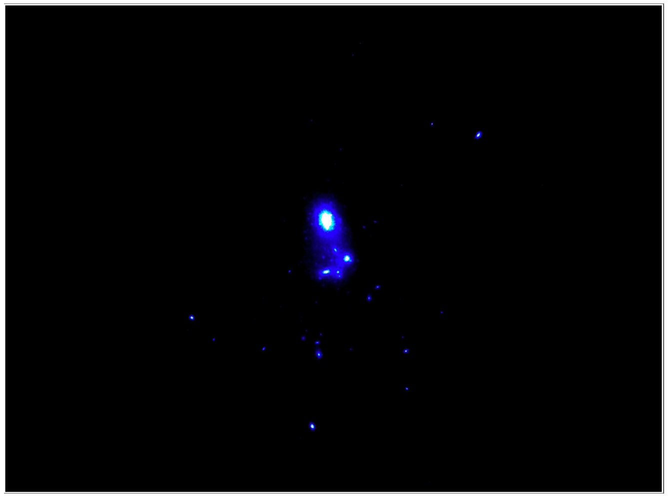




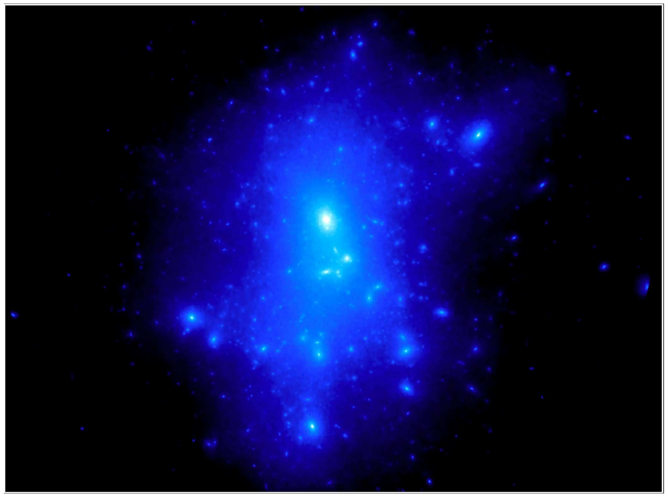
Expected signal from a galaxy at a particular energy (simulation from B. Moore)

Decay vs. annihilation

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

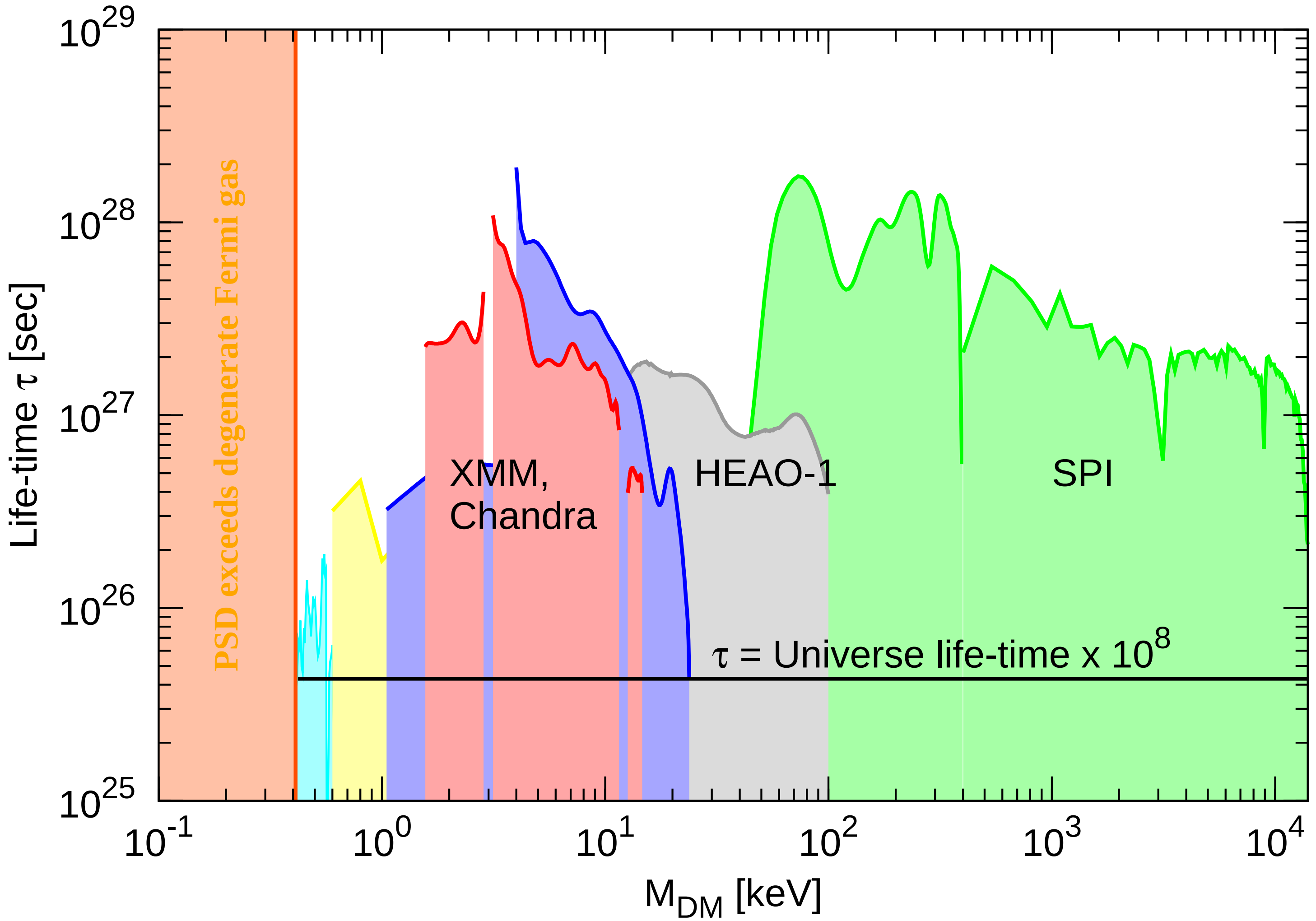


- We have a lot of freedom in choosing observation targets and, therefore, can unambiguously check DM origin of a suspicious signal.



For decaying DM "indirect" search becomes very promising!

Restrictions on life-time of decaying DM



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

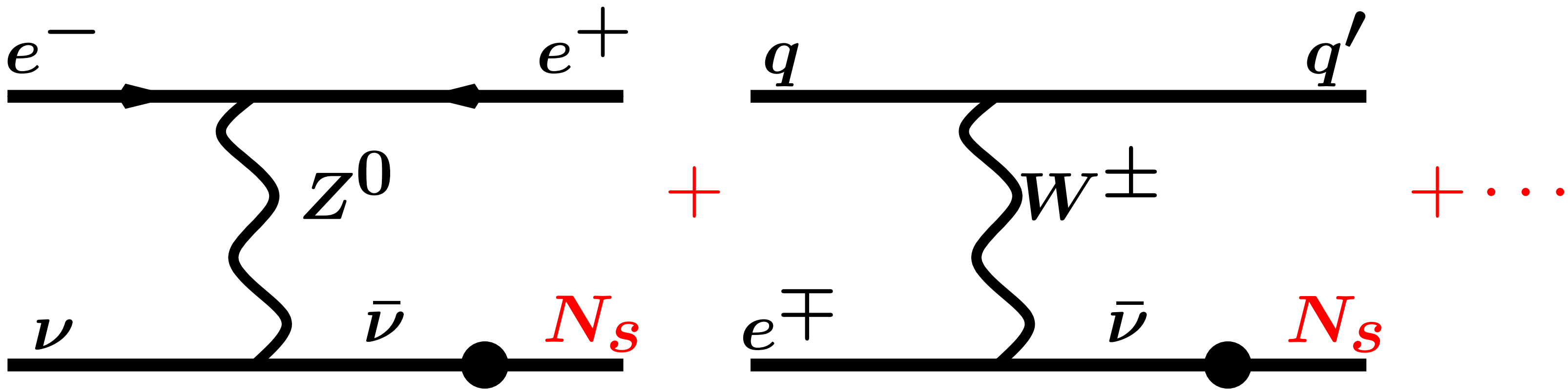
M31 Watson et al. 2006; Boyarsky et al 2007

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**

$$T_{\text{production}} \sim 130\ \text{MeV} \left(\frac{M_{\text{DM}}}{\text{keV}}\right)^{1/3}$$

- **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

Properties of sterile neutrino DM

- The interaction strength $\theta \ll 1$ $\Rightarrow$
  - Sterile neutrino DM had never been in thermal equilibrium in the early Universe
  - Sterile neutrino DM does not contribute to neutrino flavour oscillation
  - **Two more** sterile neutrinos are needed to explain dark matter and neutrino oscillation data

Dodelson & Widrow (1993)

O.R. with Boyarsky, Shaposhnikov et al. (2006), (2009)

- Sterile neutrinos have **Majorana masses** $\Rightarrow$ violate lepton number and lead to **leptogenesis**

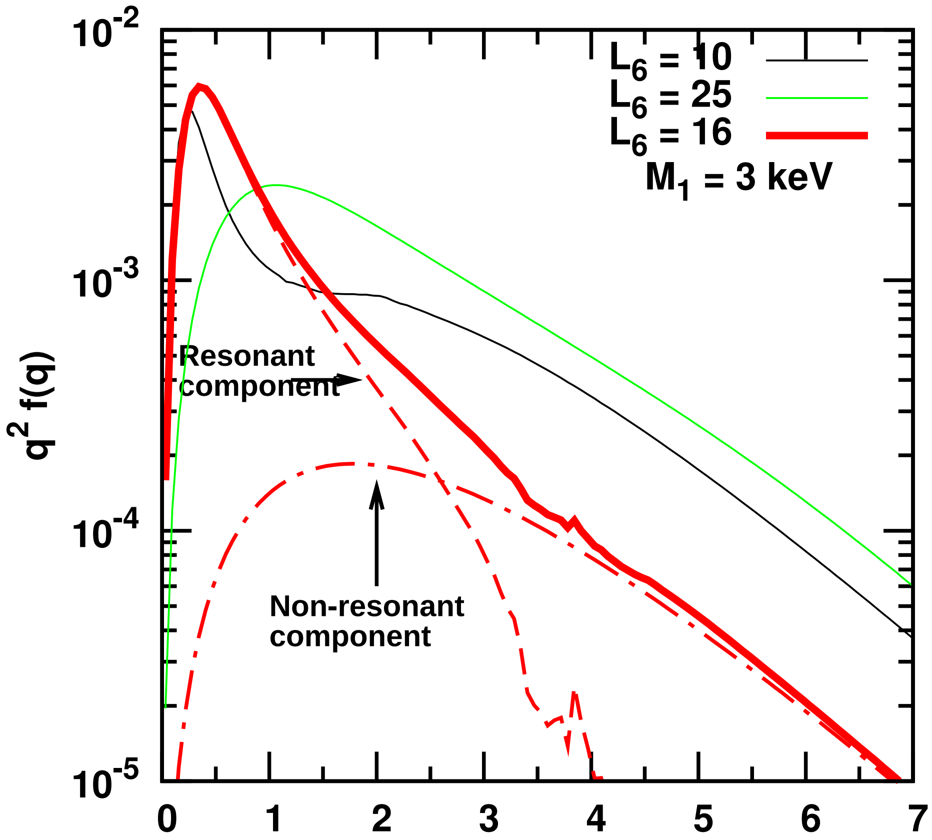
- The presence of lepton asymmetry in primordial plasma makes **active-sterile mixing** much more effective – **resonant production**

Shi Fuller'98 Laine, Shaposhnikov

RP sterile neutrino spectra

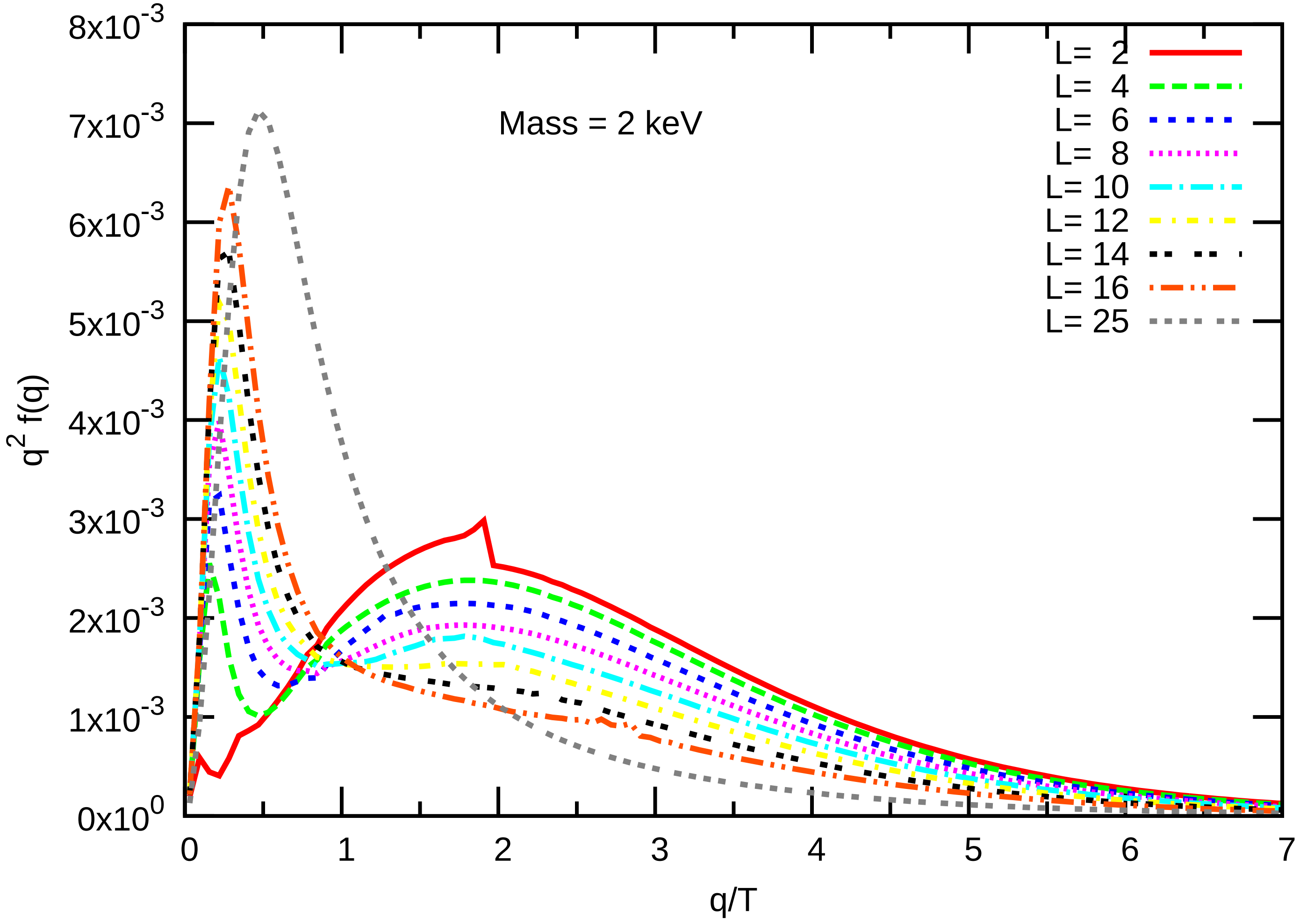
Laine, Shaposhnikov
Boyarsky, **O.R.**, Shaposhnikov

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



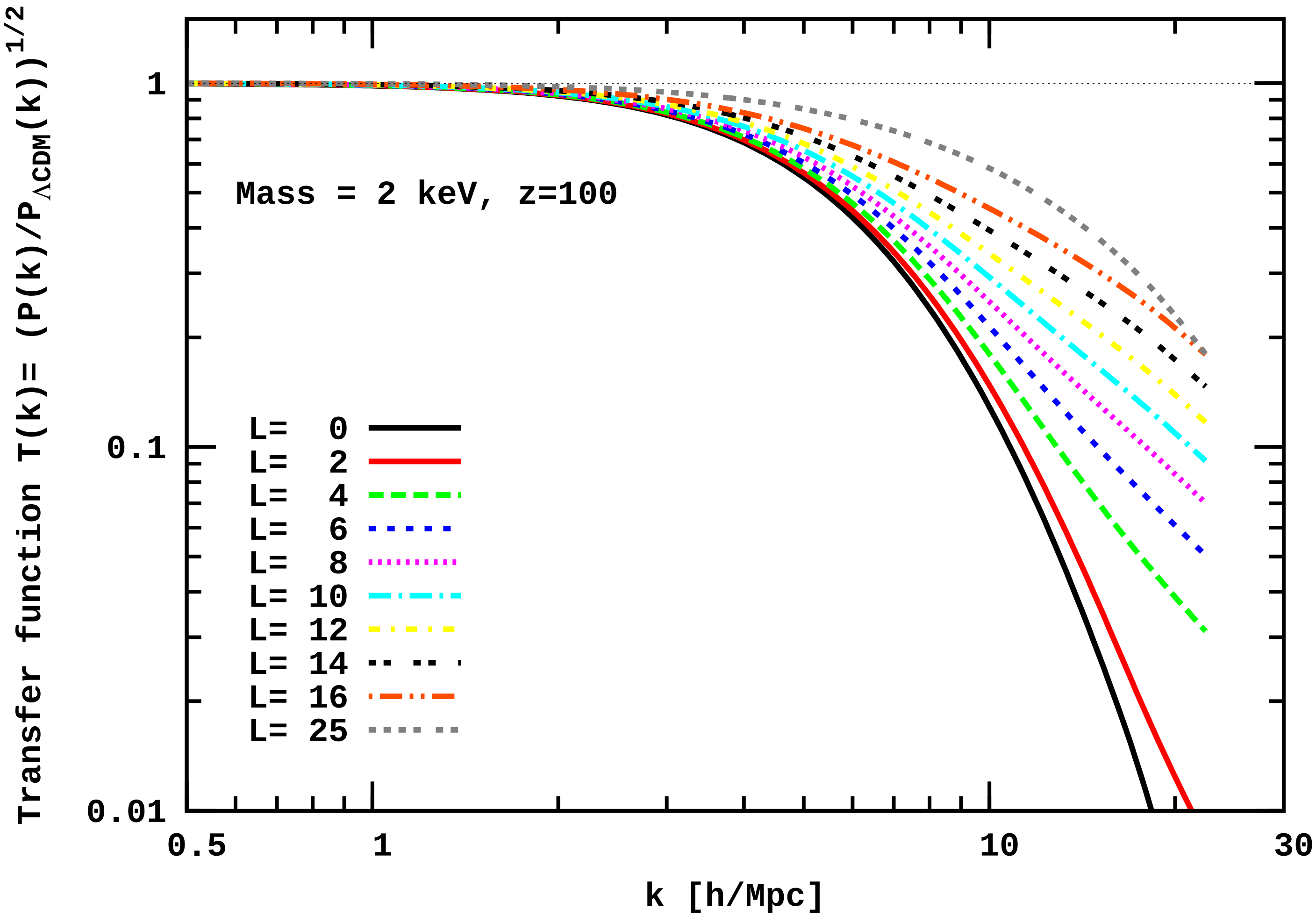
- Colder (**resonant**) component with $\langle p \rangle \ll T_\nu$)
- Warmer (**non-resonant**) component with $\langle p \rangle \sim 3T_\nu$)

Primordial velocities of sterile neutrino



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

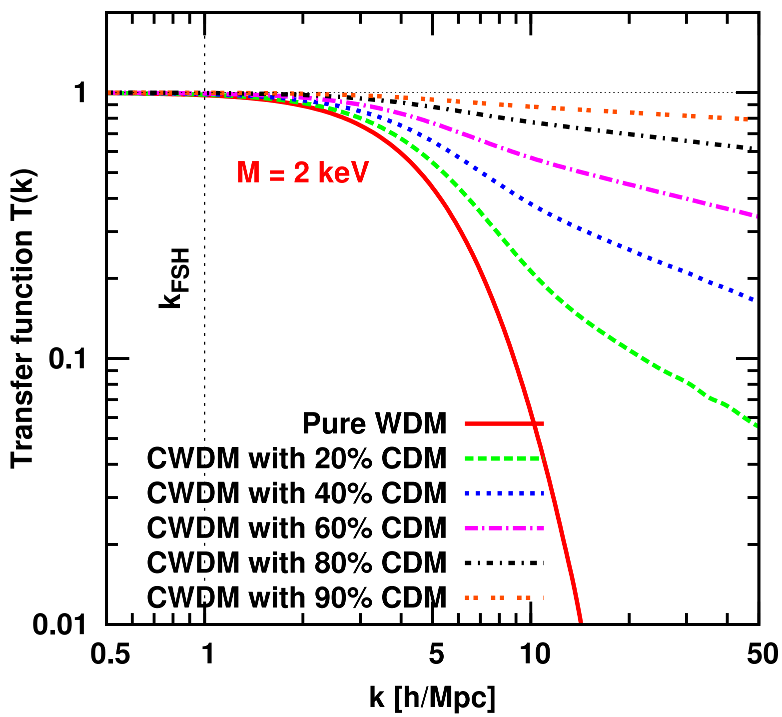
Free-streaming of sterile neutrino DM



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

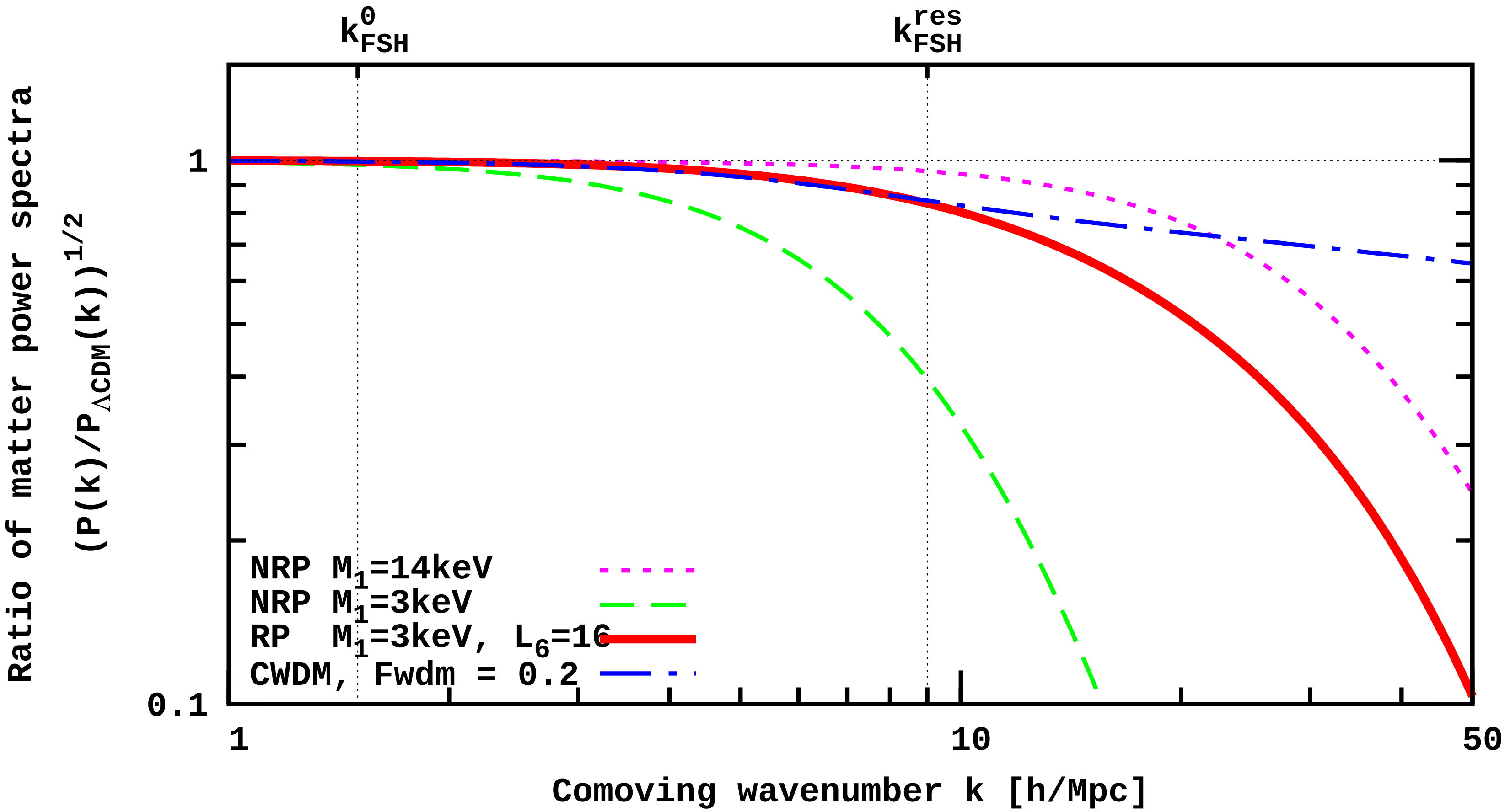
Cold+warm DM model (CWDM)

- 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



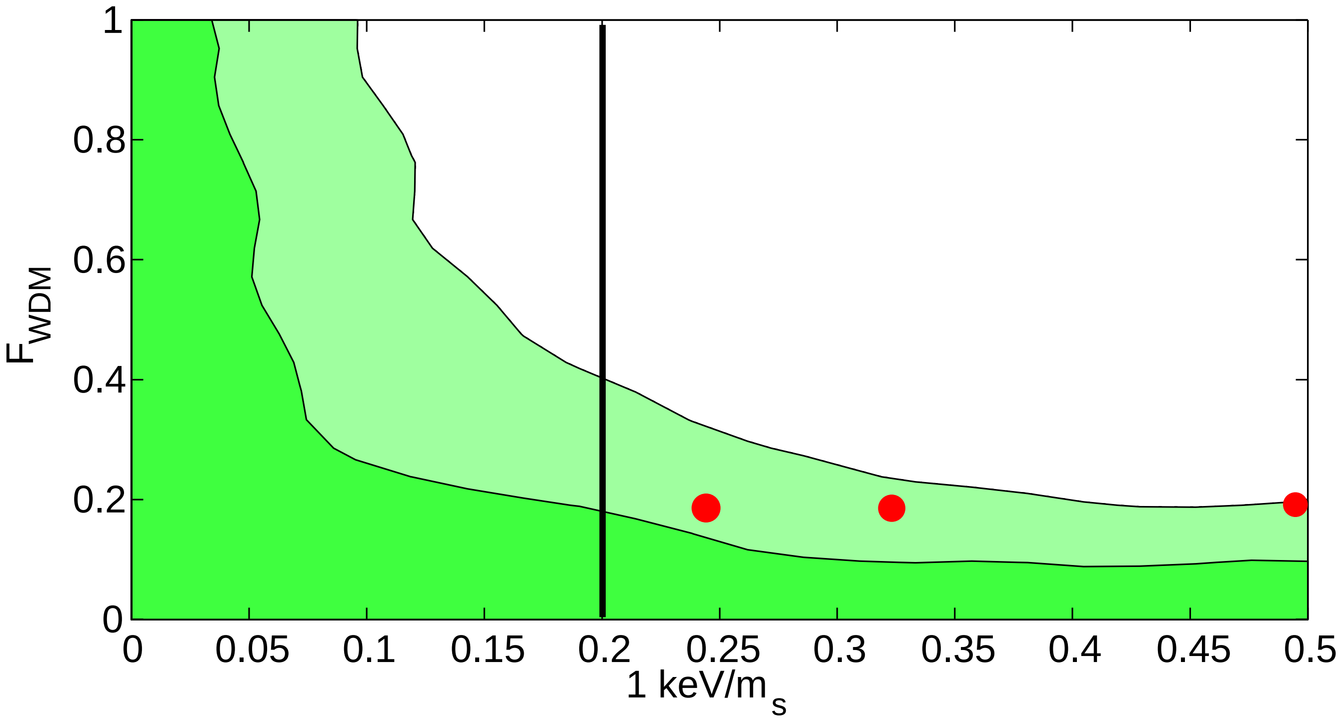
Boyarsky, Lesgourgues, **O.R.**, Viel JCAP, PRL 2009;

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

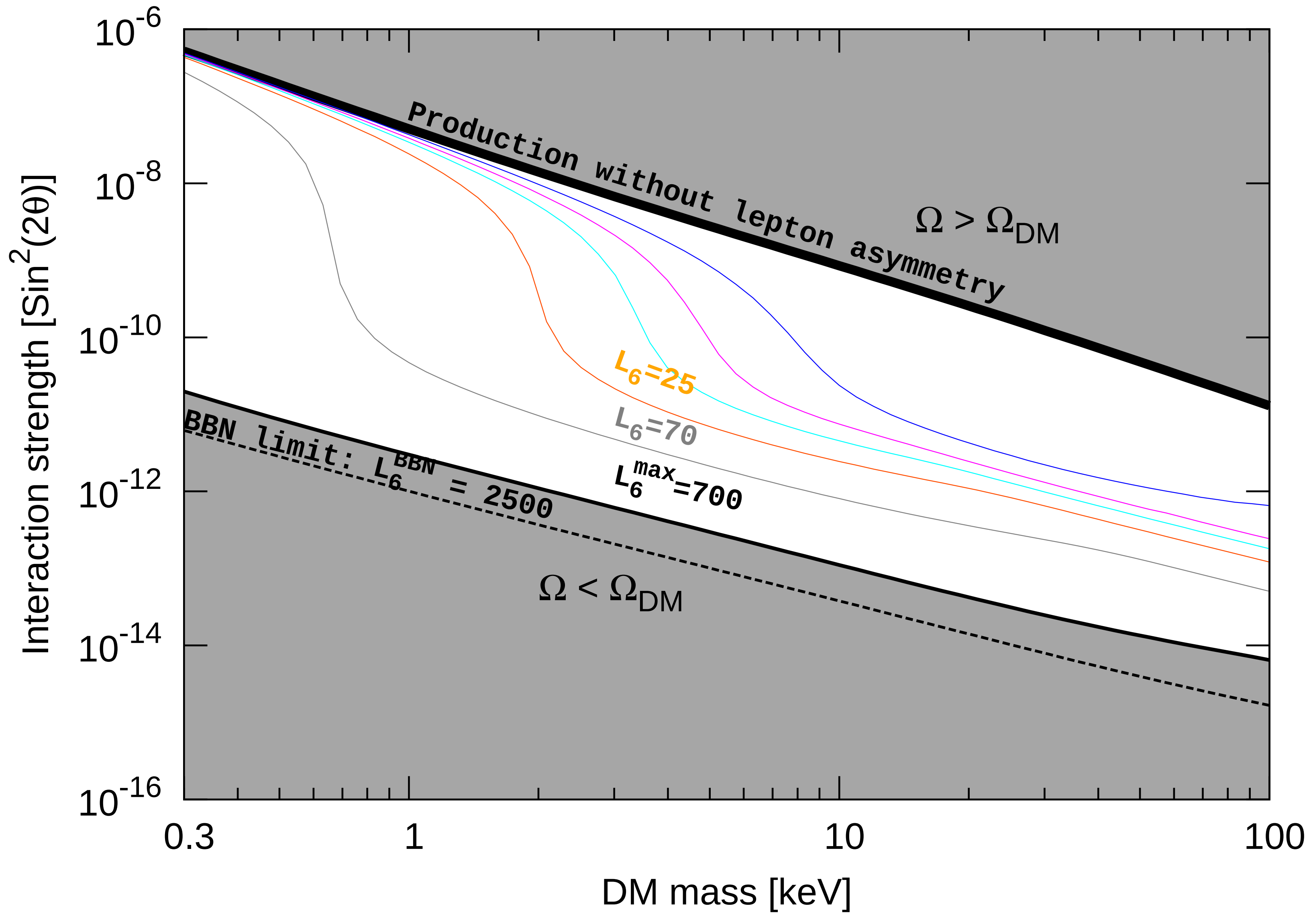
Boyarsky, **O.R.**, Lesgourgues, Viel JCAP & PRL (2009)



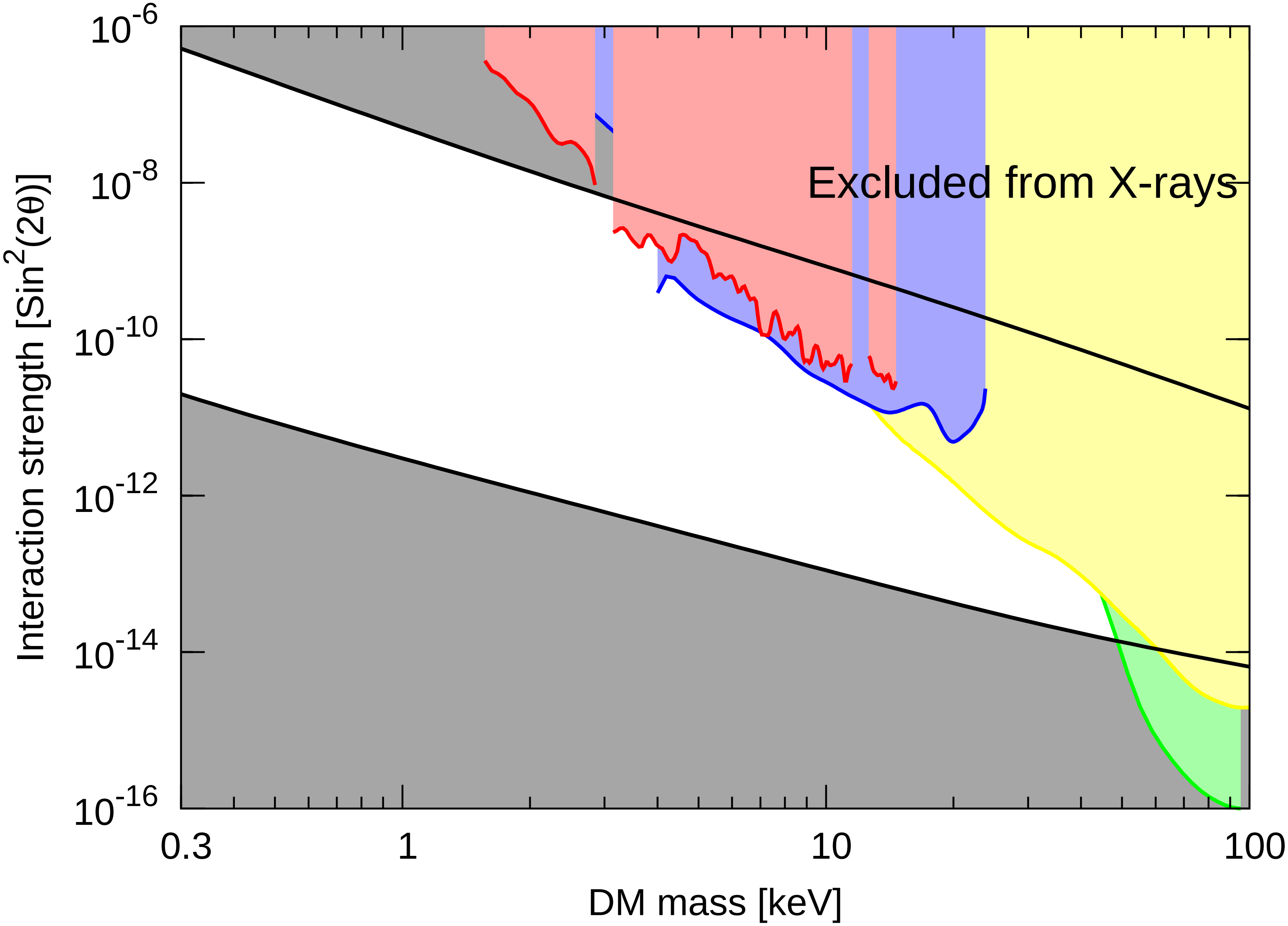
Window of parameters of sterile neutrino DM

Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov



Window of parameters of sterile neutrino DM

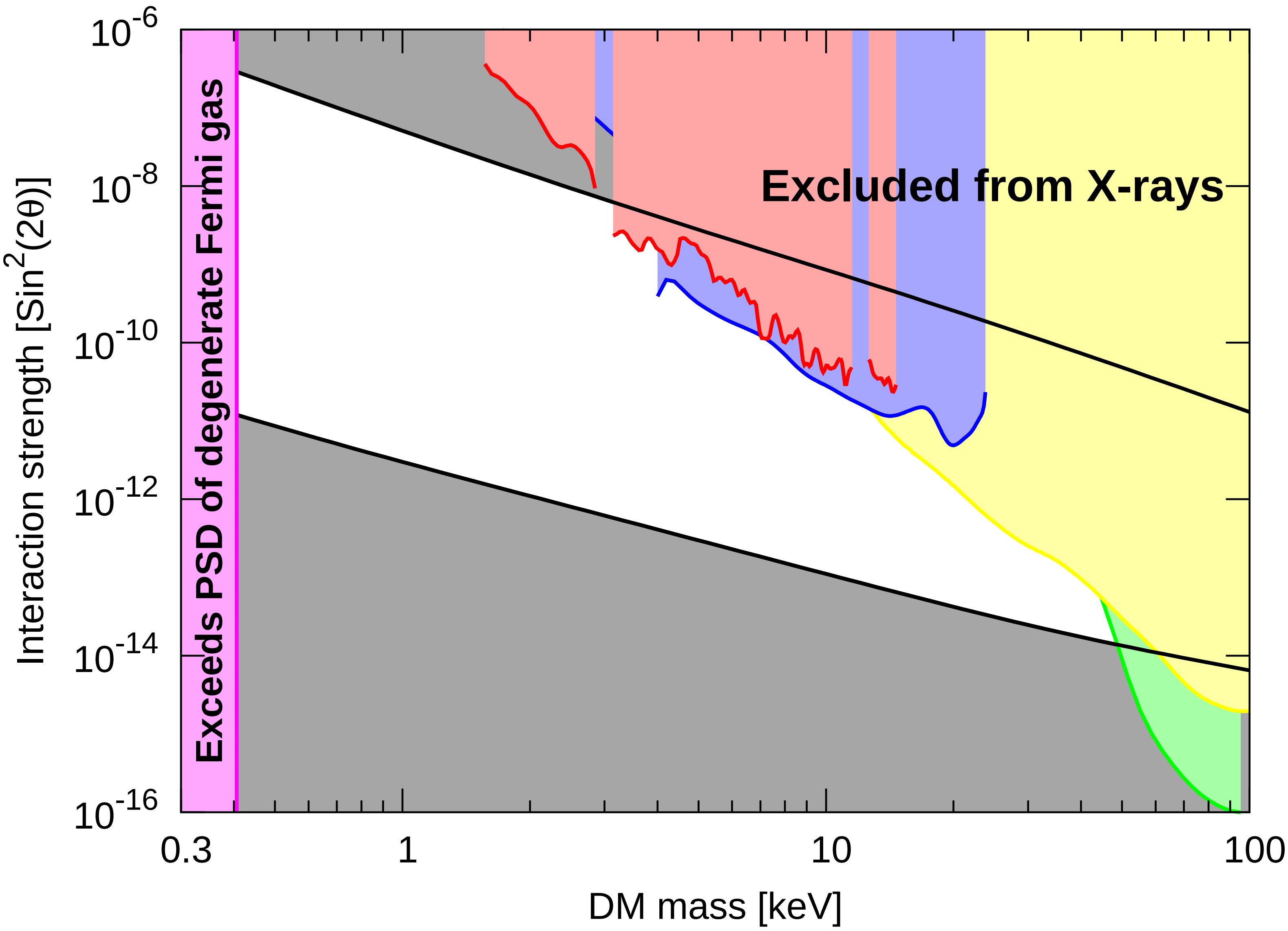


Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov

O.R. and many others 2005-2010

Window of parameters of sterile neutrino DM

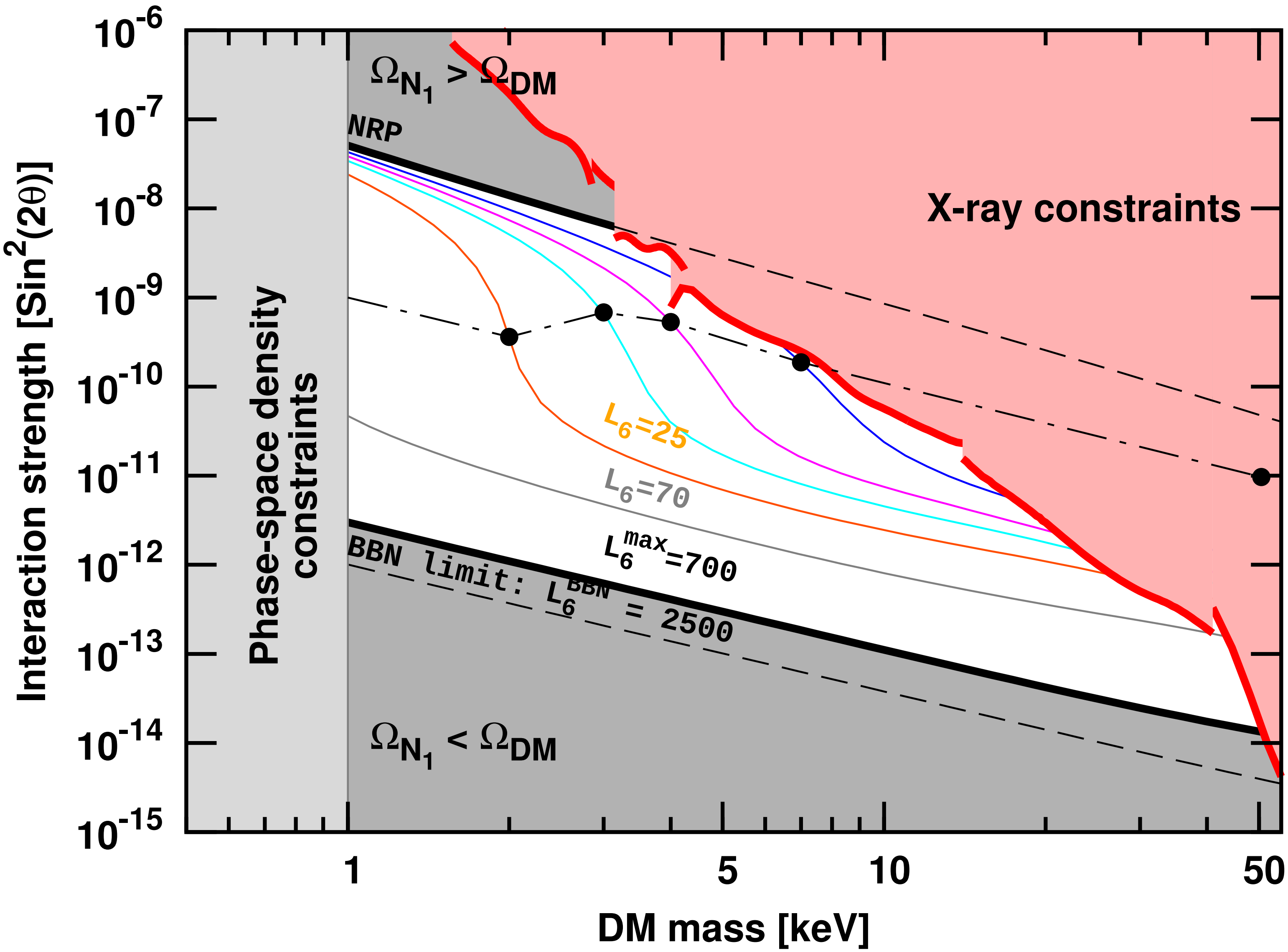


Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov

O.R. and many others 2005-2010

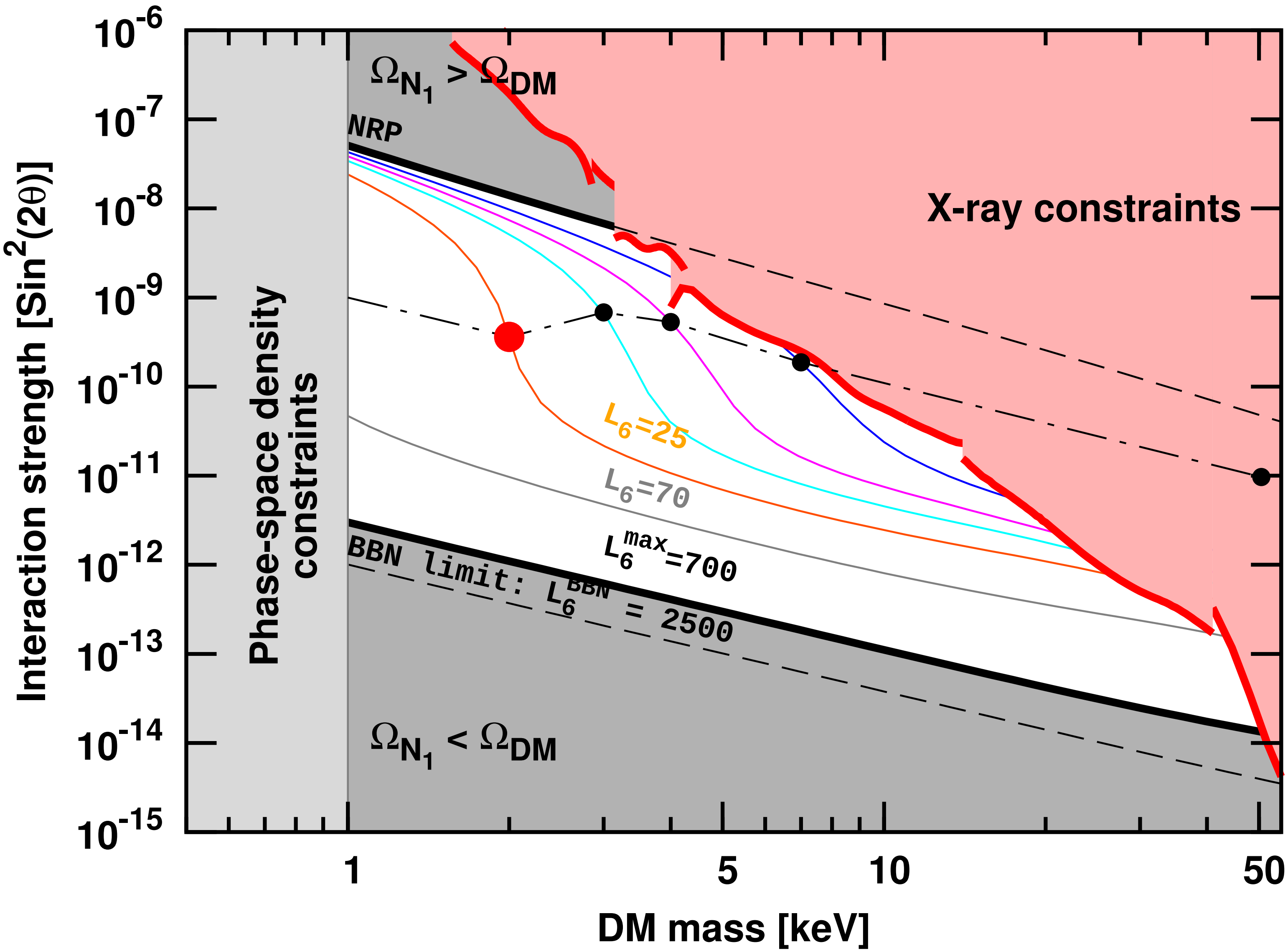
Sterile neutrino DM in the νMSM



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

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

Sterile neutrino DM in the νMSM

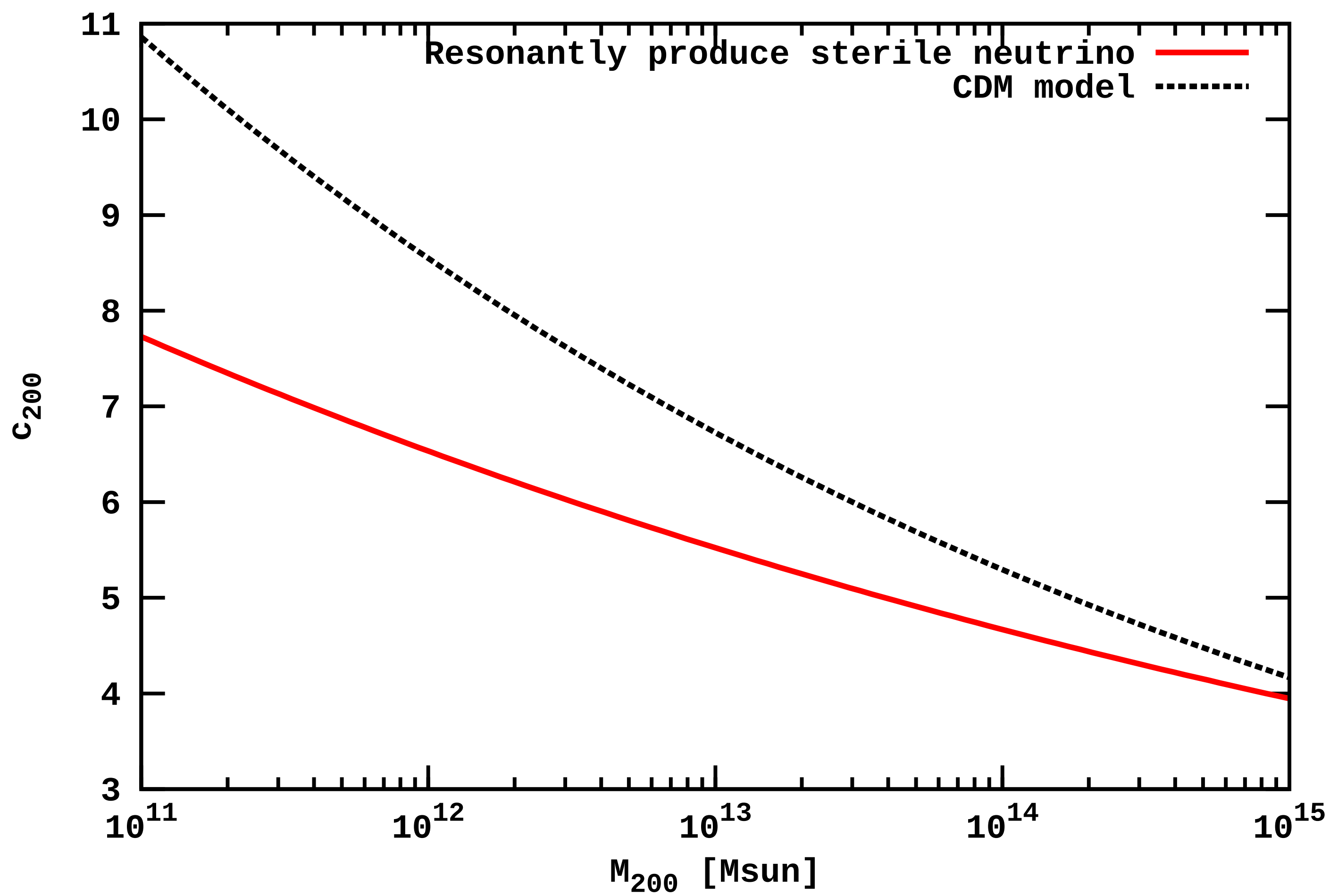


Boyarsky, **O.R.**, Lesgourgues, Viel [0812.3256]

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

c-M relation for sterile neutrino DM

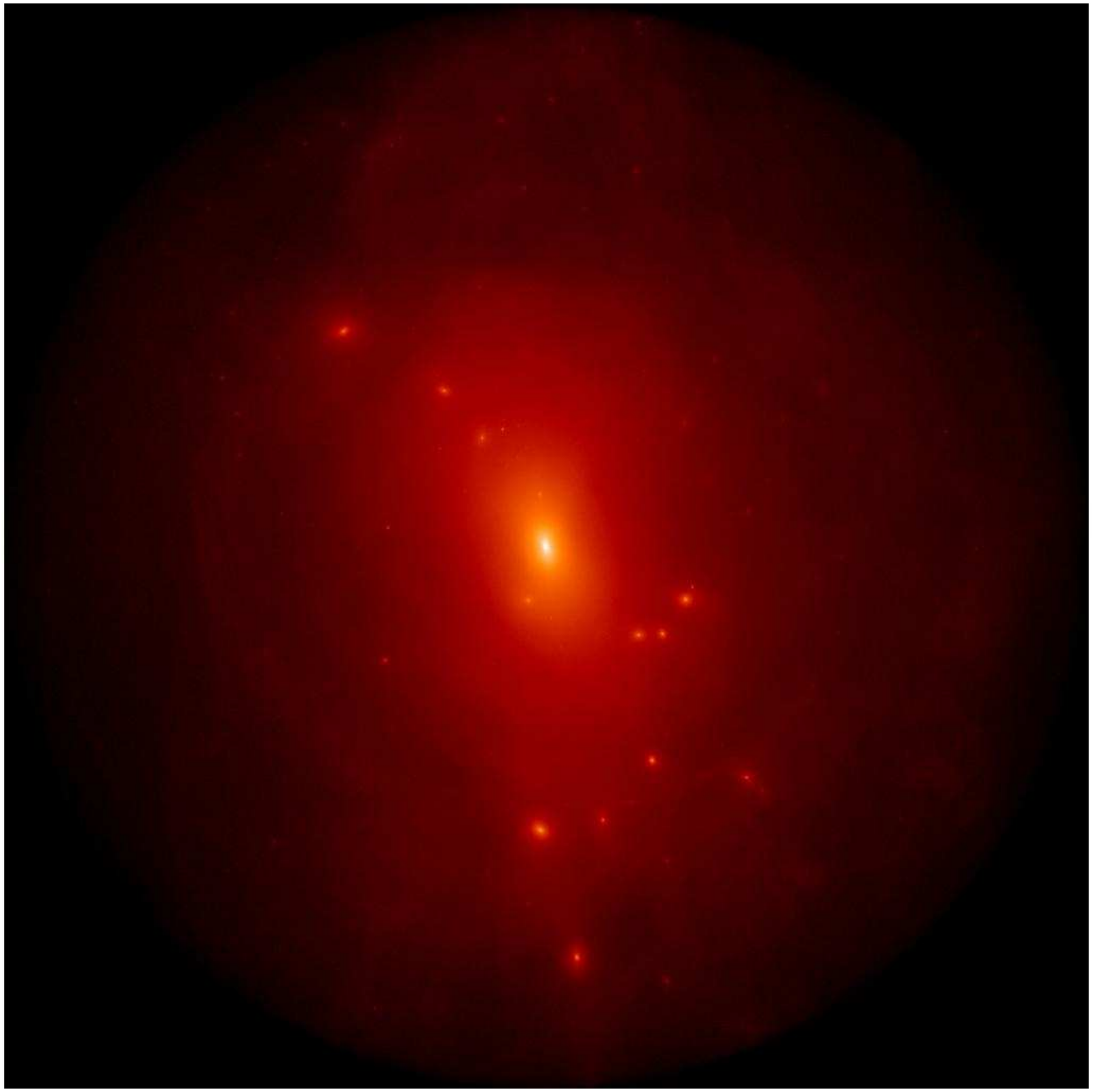
Macciò, **O.R.** et al. (2011)



Warm admixture decreases concentration of isolated halos at masses above the free-streaming mass

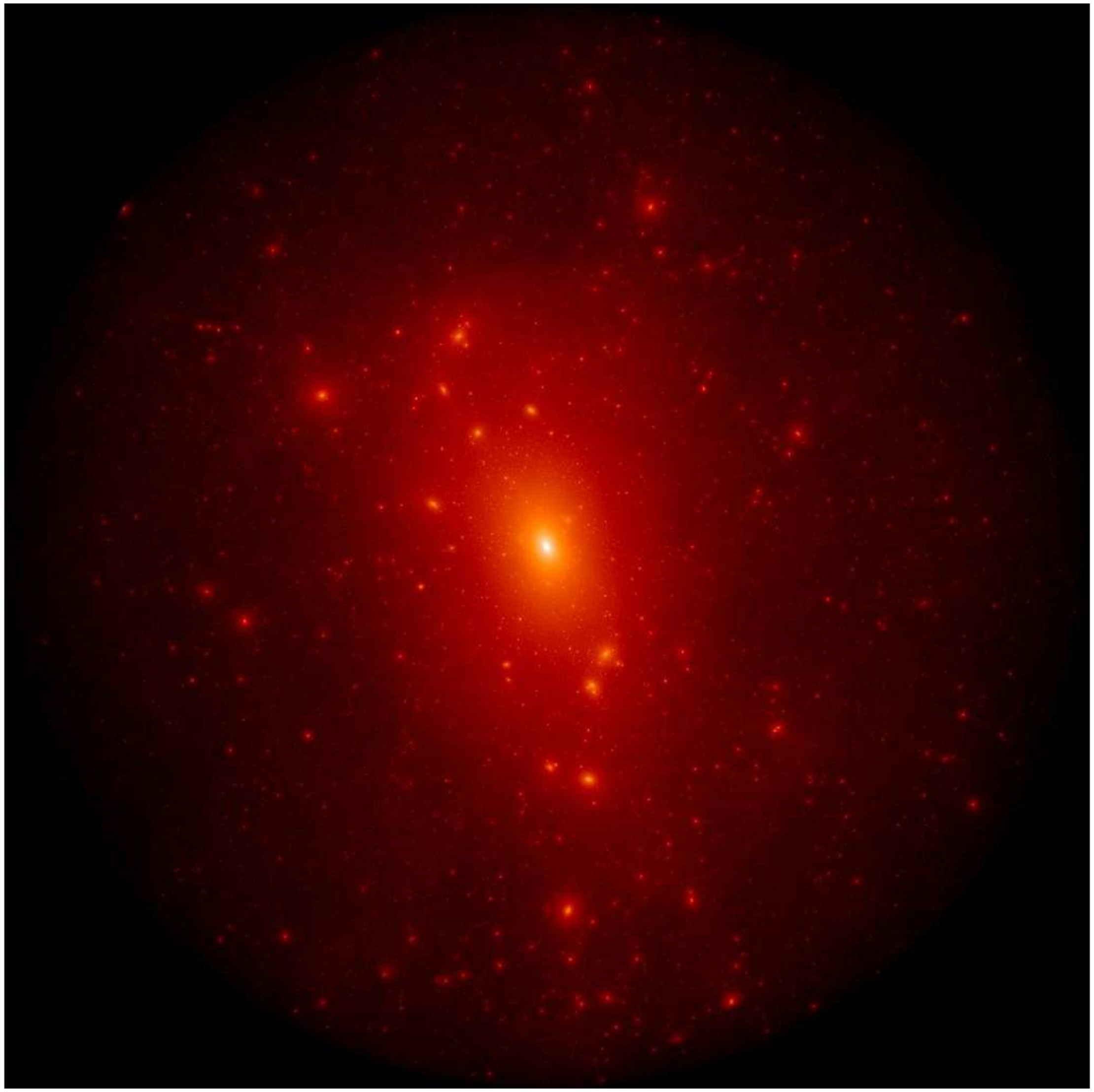
Halo substructure with sterile neutrino DM

work in progress

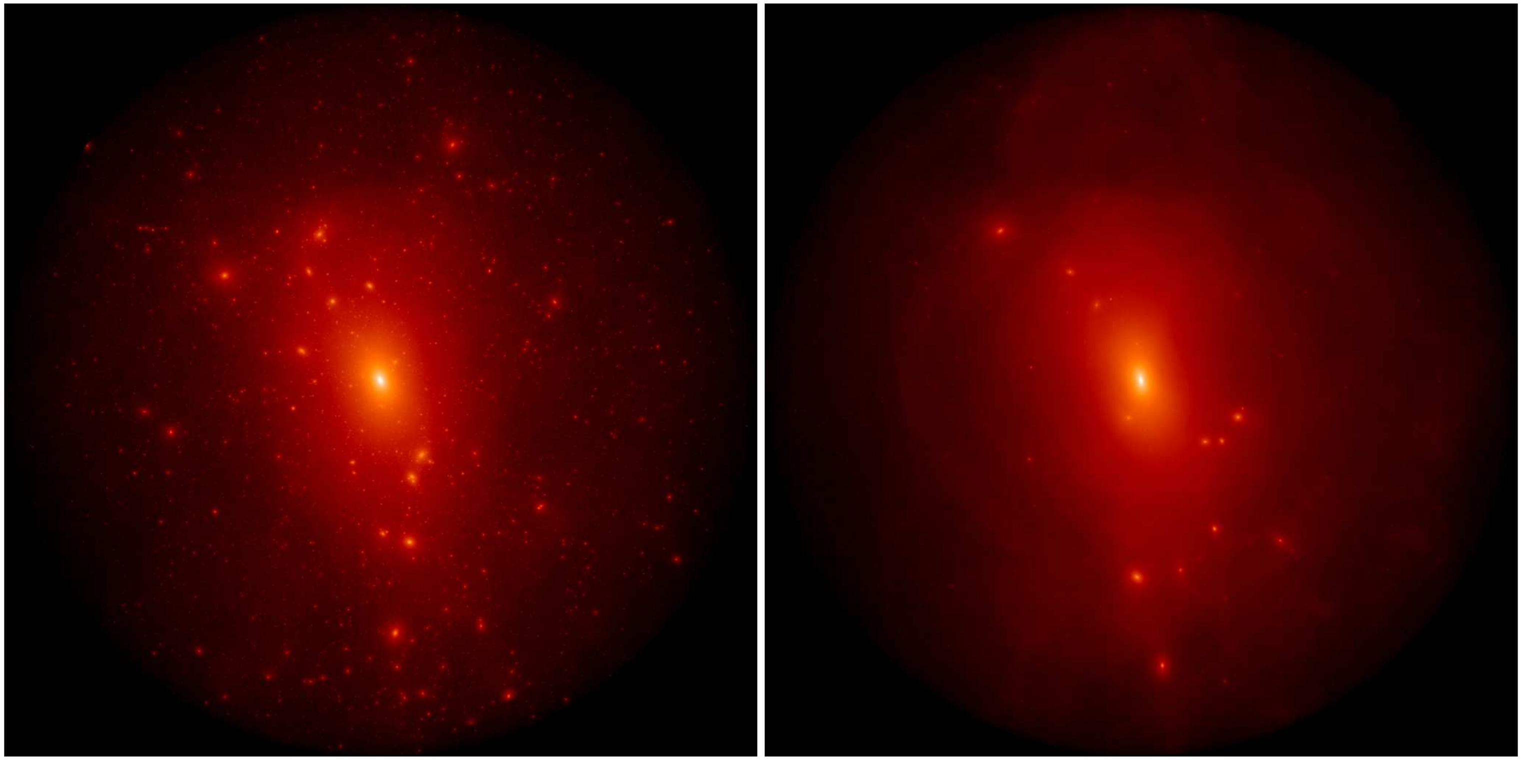


Halo substructure with CDM

Aq-A2 halo



Halo substructure with sterile neutrino DM

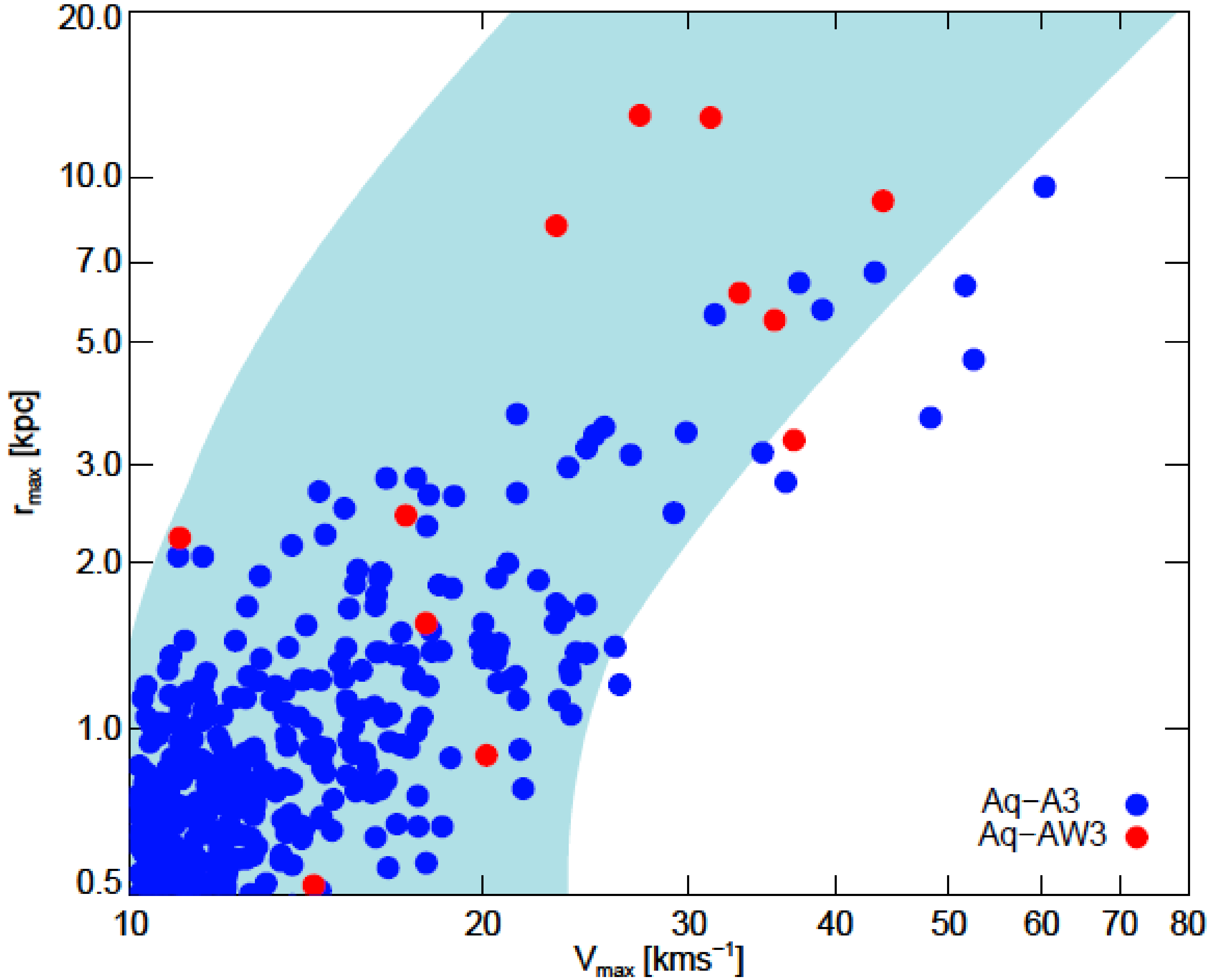


Aq-A-2 CDM halo

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

Abundance of large satellites



Strigari, Frenk White (2011)

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

Conclusions

- Warm dark matter is indistinguishable from CDM at cosmological scales and can reduce over-abundance of structures at (sub)Mpc scales
- **Thermal relics** WDM with interesting astrophysical and cosmological applications are ruled out by Lyman-α
- **Particle physics motivated WDM models remain viable**
- Adding 3 sterile neutrinos to the Standard Model of elementary particles can explain **neutrino oscillations**, provide a mechanism of generation of **matter-antimatter asymmetry** and provides a **dark matter** candidate.
- This candidate can be warm (or luke-warm) and can leave its imprints on formation of structures. It can be detected via its monochromatic decays to photons. For sterile neutrino (and other decaying DM candidates) astrophysical search is **very promising**

In short: Warm dark matter remains a viable (and exciting) possibility!

Thank you for your attention!

Sakharov conditions in the SM

Sakharov (1967)

Kuzmin, Rubakov, Shaposhnikov (1985)

Farrar & Shaposhnikov (1994)

Kajantie et al. (1996)

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

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

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

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

What changes in the νMSM?

Sakharov conditions in the νMSM

Sakharov (1967)

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

Kuzmin, Rubakov, Shaposhnikov (1985)

⊕ B-number violation $\longrightarrow$ sphalerons

Farrar & Shaposhnikov (1994)

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

Kajantie et al. (1996)

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

Lyman-α analysis in CWDM models

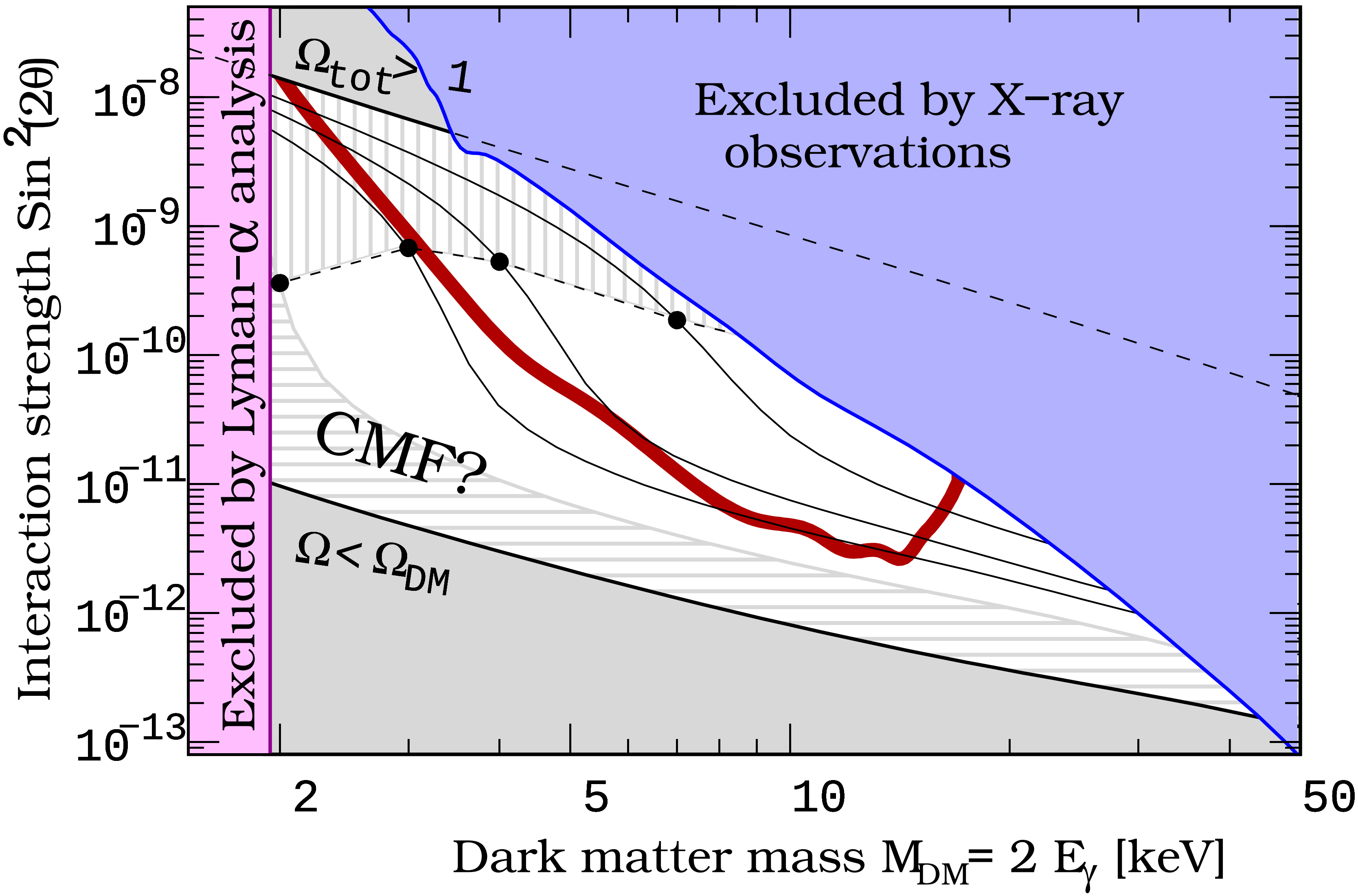
- CWDM Ly-α bounds: about 20% of DM can be rather warm
- Primordial velocities at MD epoch can be significant (~ 10 km/sec)
- Numerical simulations with velocities?

Effect of velocities is negligible at scales of interest:

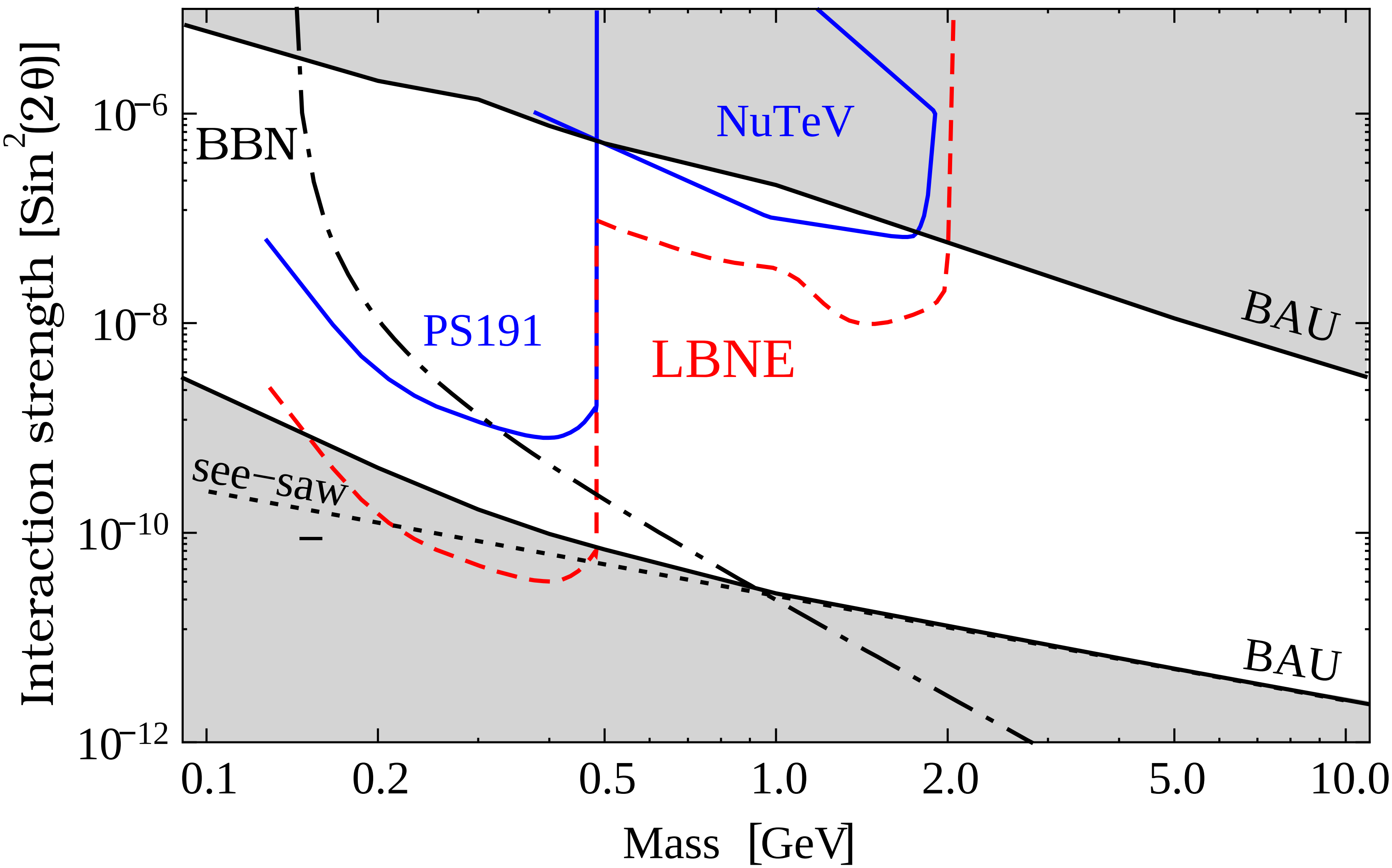
Work in progress

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

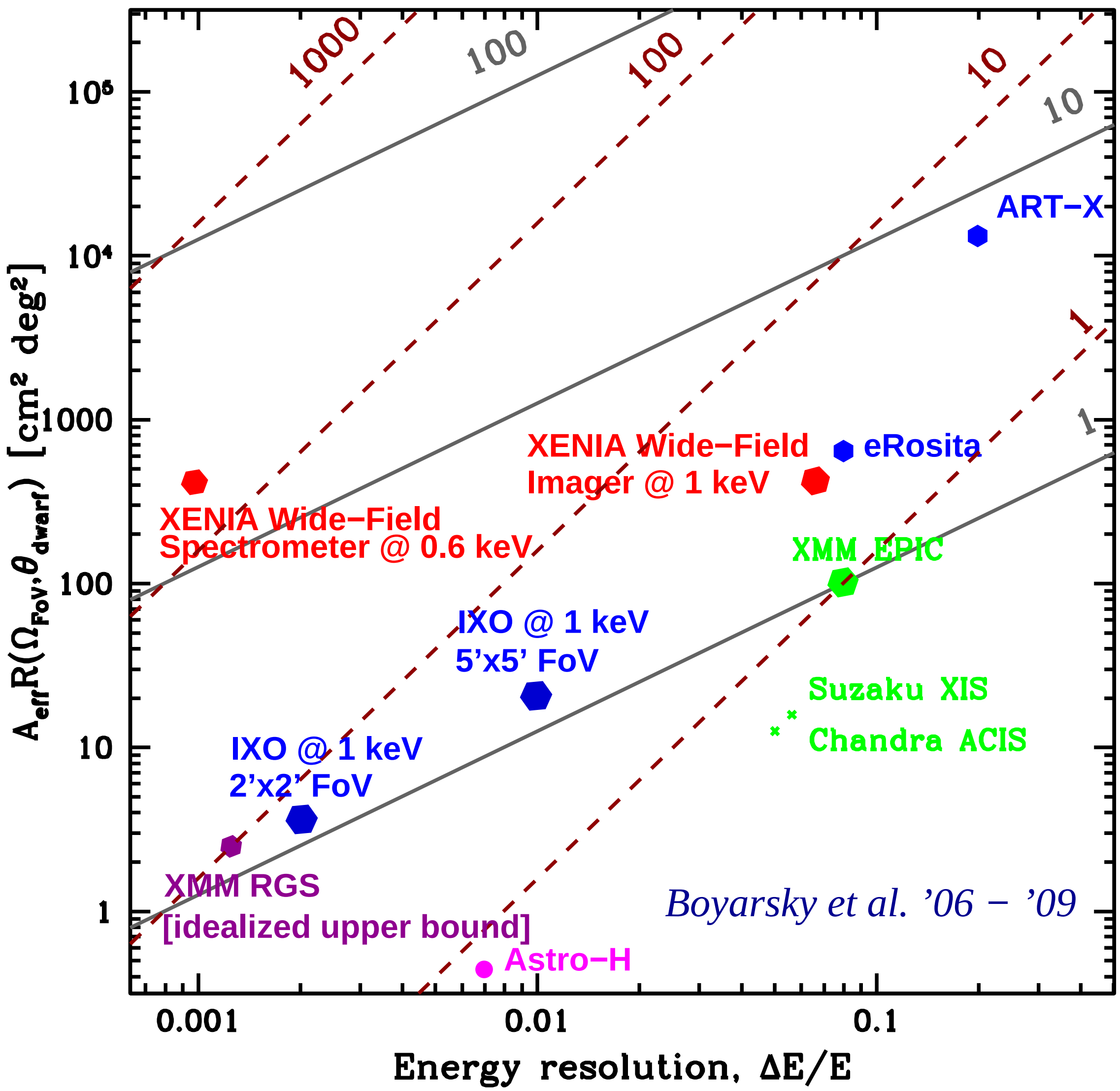
Future of sterile neutrino DM



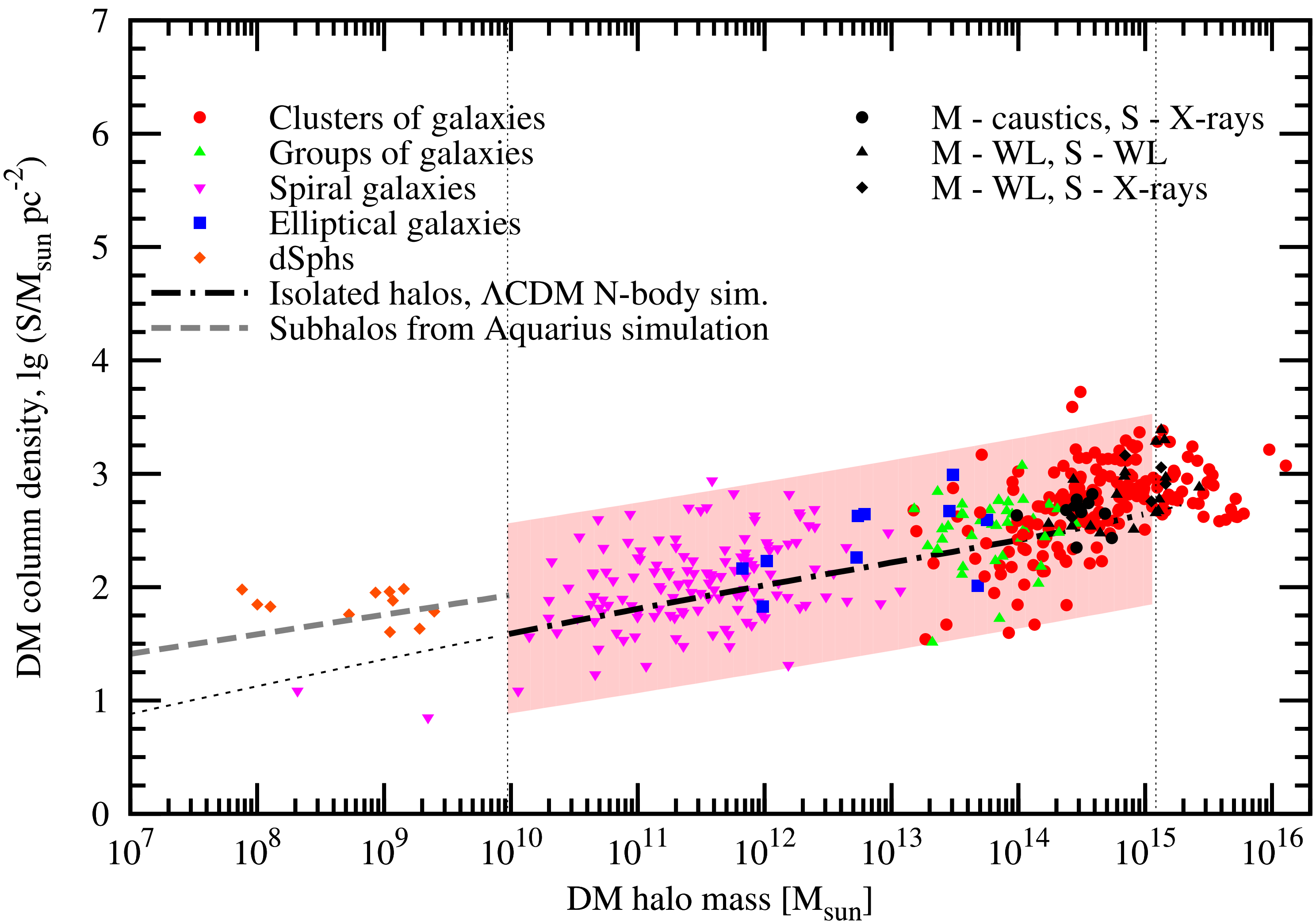
Probing other sterile neutrinos



Improved bounds on DM decay



Universality of dark matter halos



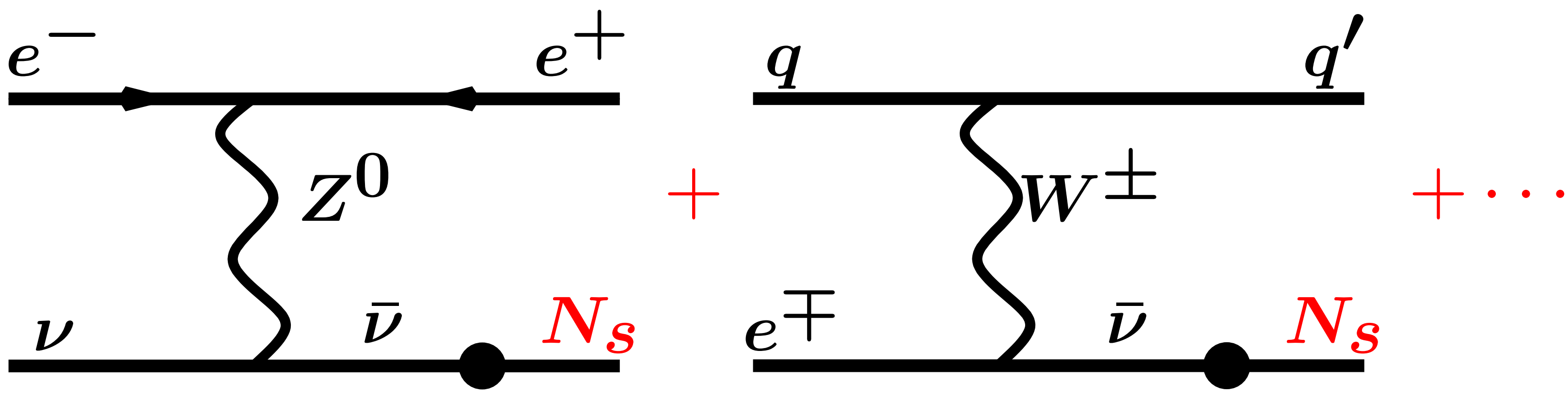
Boyarsky, **O.R.**, Macciò et al. (2009);

PRL (2010);

work in progress

Evidence for DM (rather than MOND)

Non-resonant production of sterile neutrino



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

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

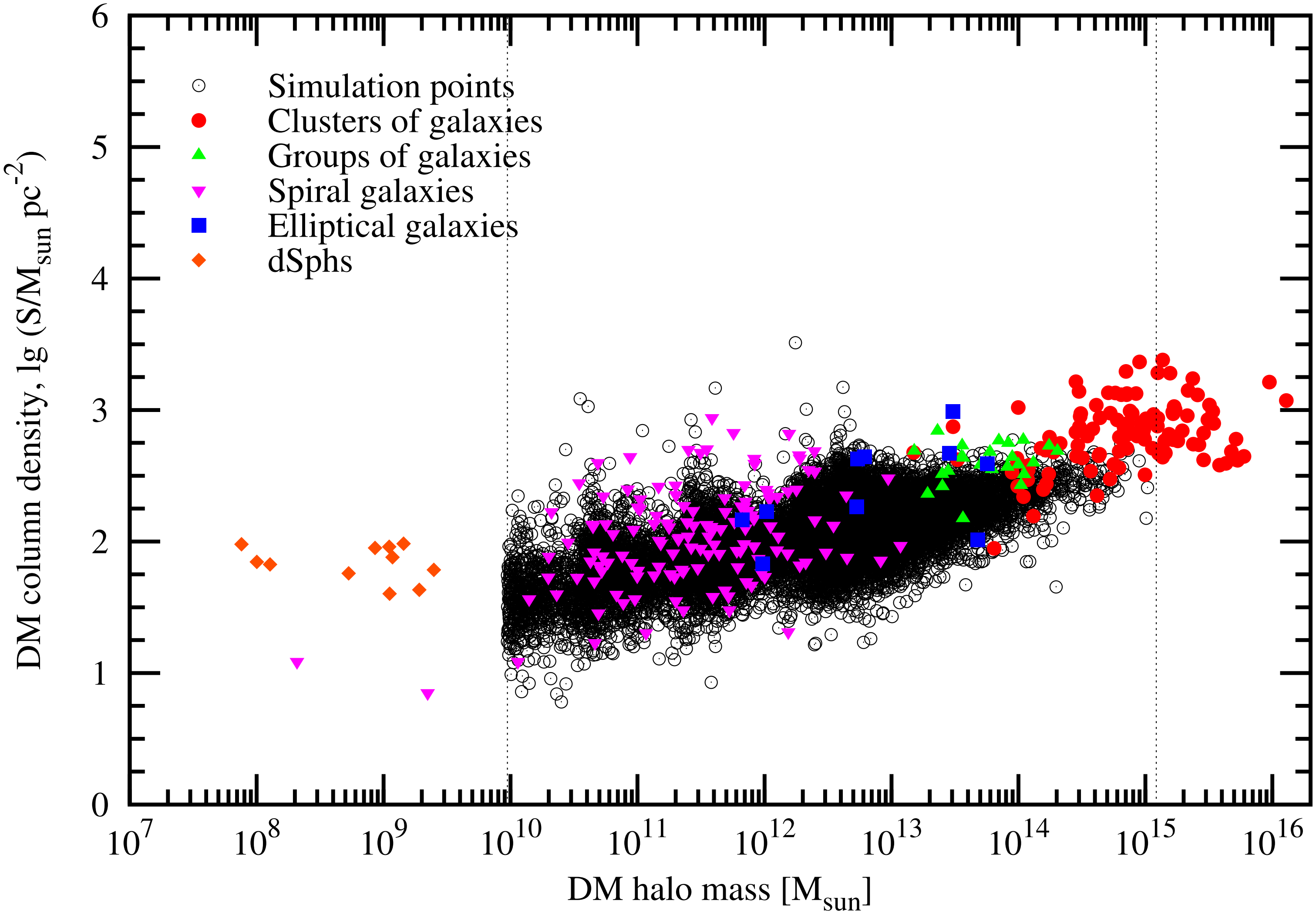
(for this distribution $\int dq\, q^2 f(q) \propto \theta^2 \lll 1$)

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

A couple of slides about dark matter surface density

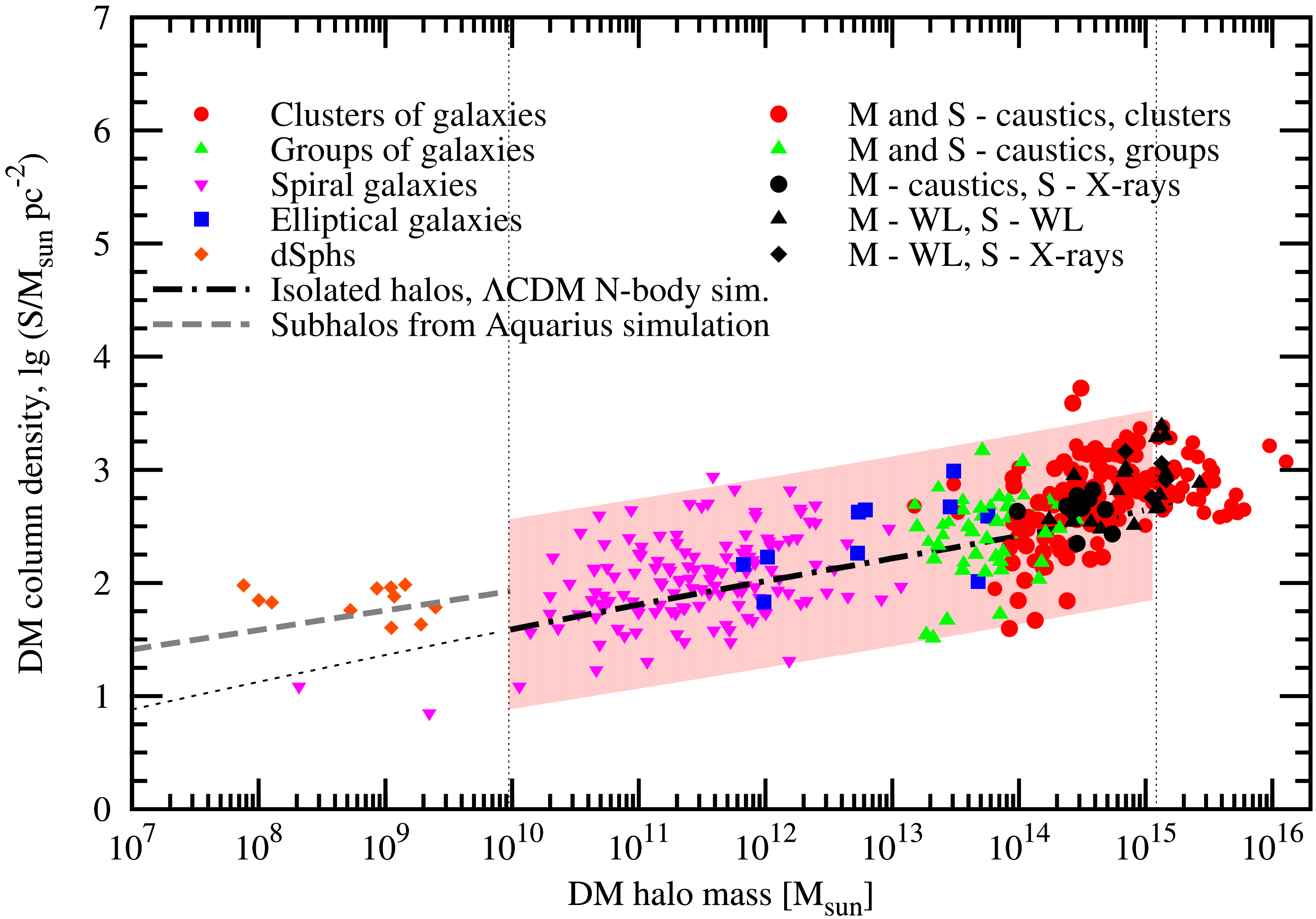
Observations vs. simulations

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**

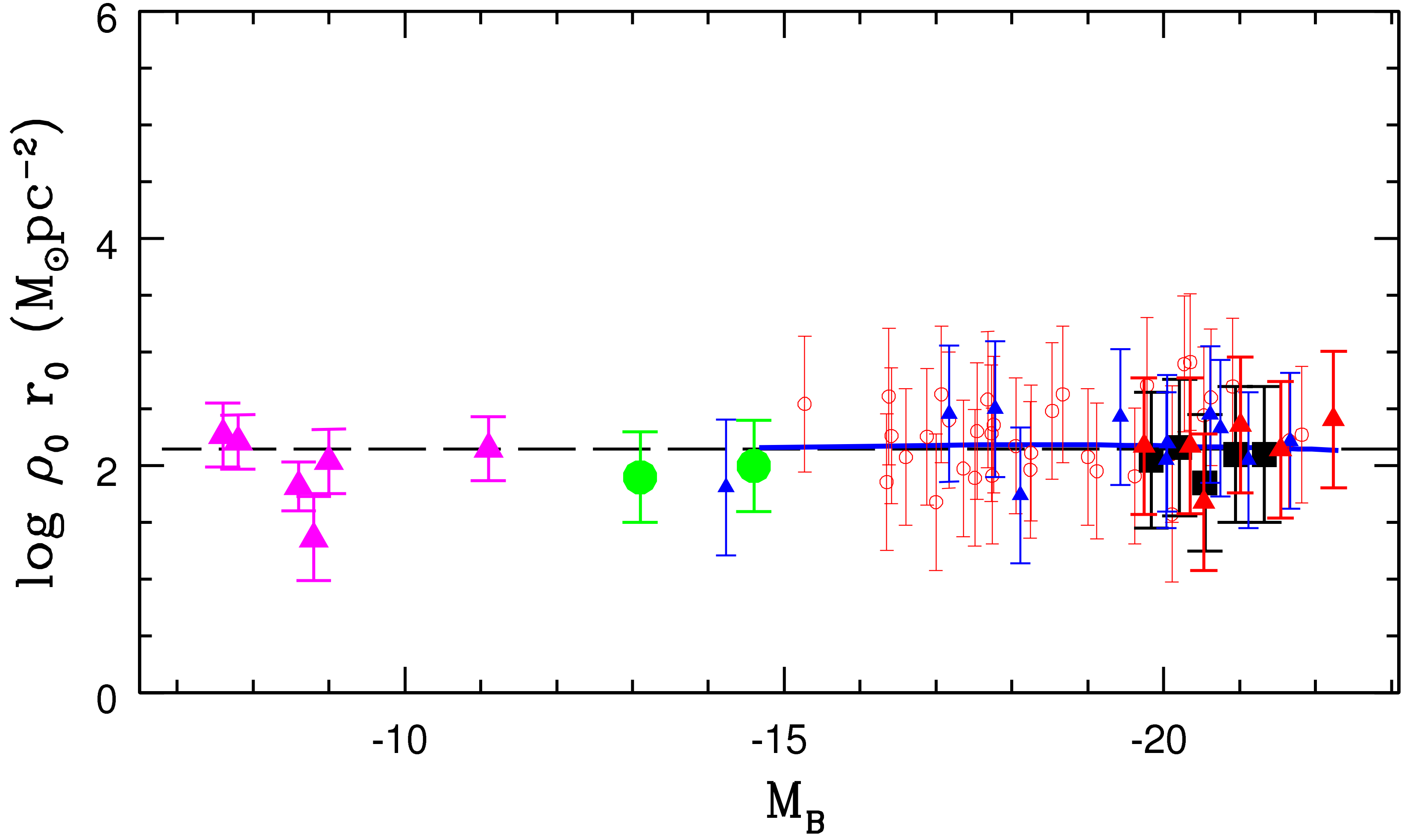
$$\mathcal{S} = \int\limits_{\text{l.o.s.}} \rho_{\text{DM}}(r) dl \propto \rho_\star r_\star$$

- $r_\star$ 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?

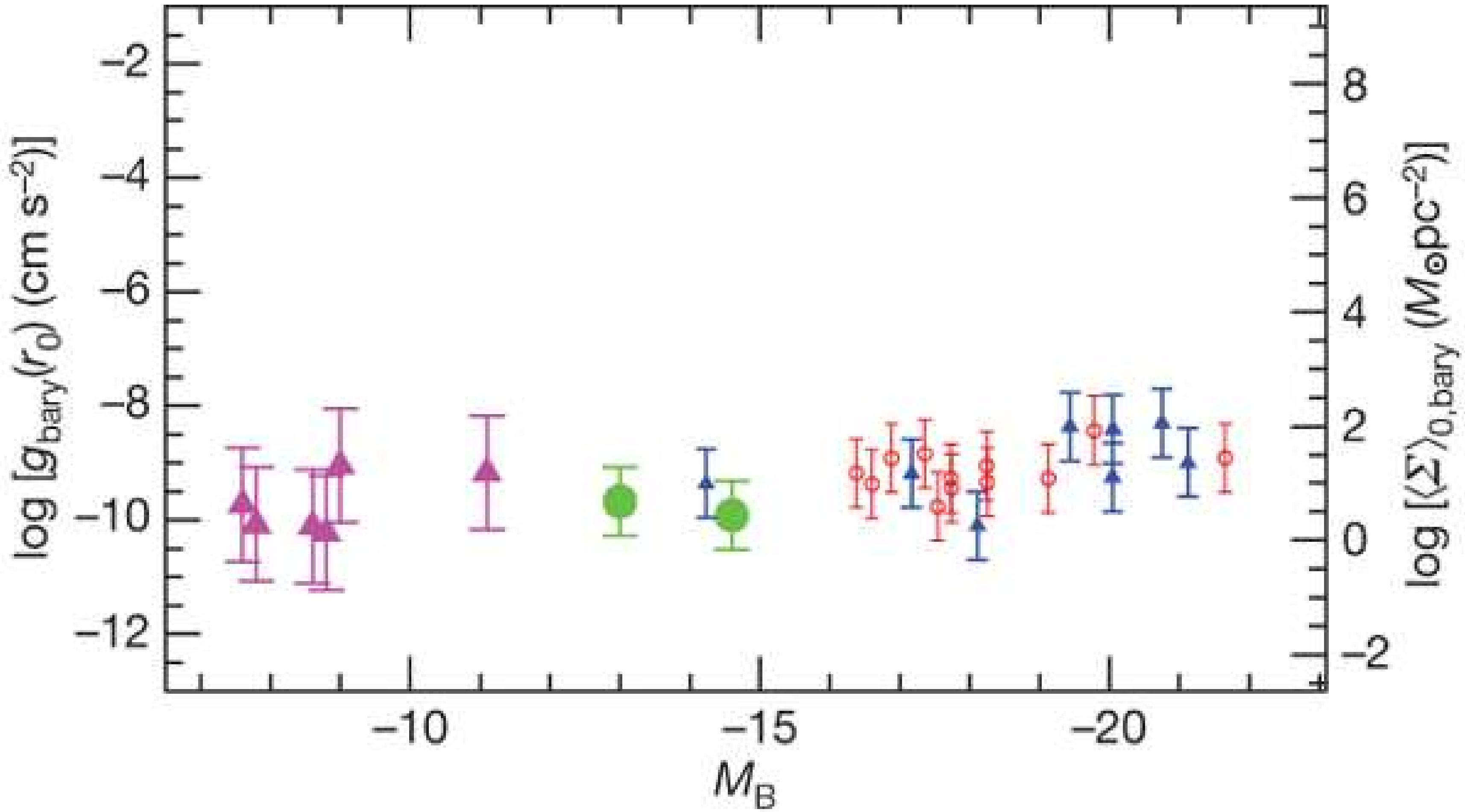
Donato et al.'09, Gentile et al.'09



DM surface density for different types of galaxies.

An evidence in favor of MOND?

Gentile et al.'09



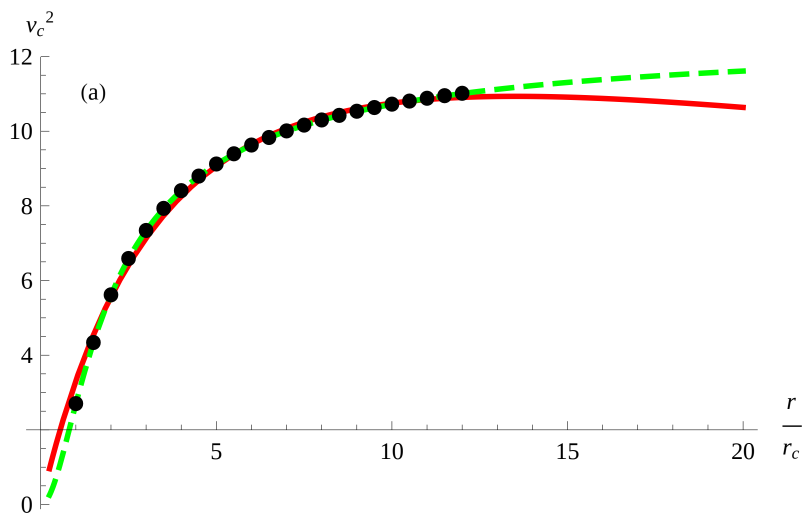
Baryonic surface density for different types of galaxies.

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

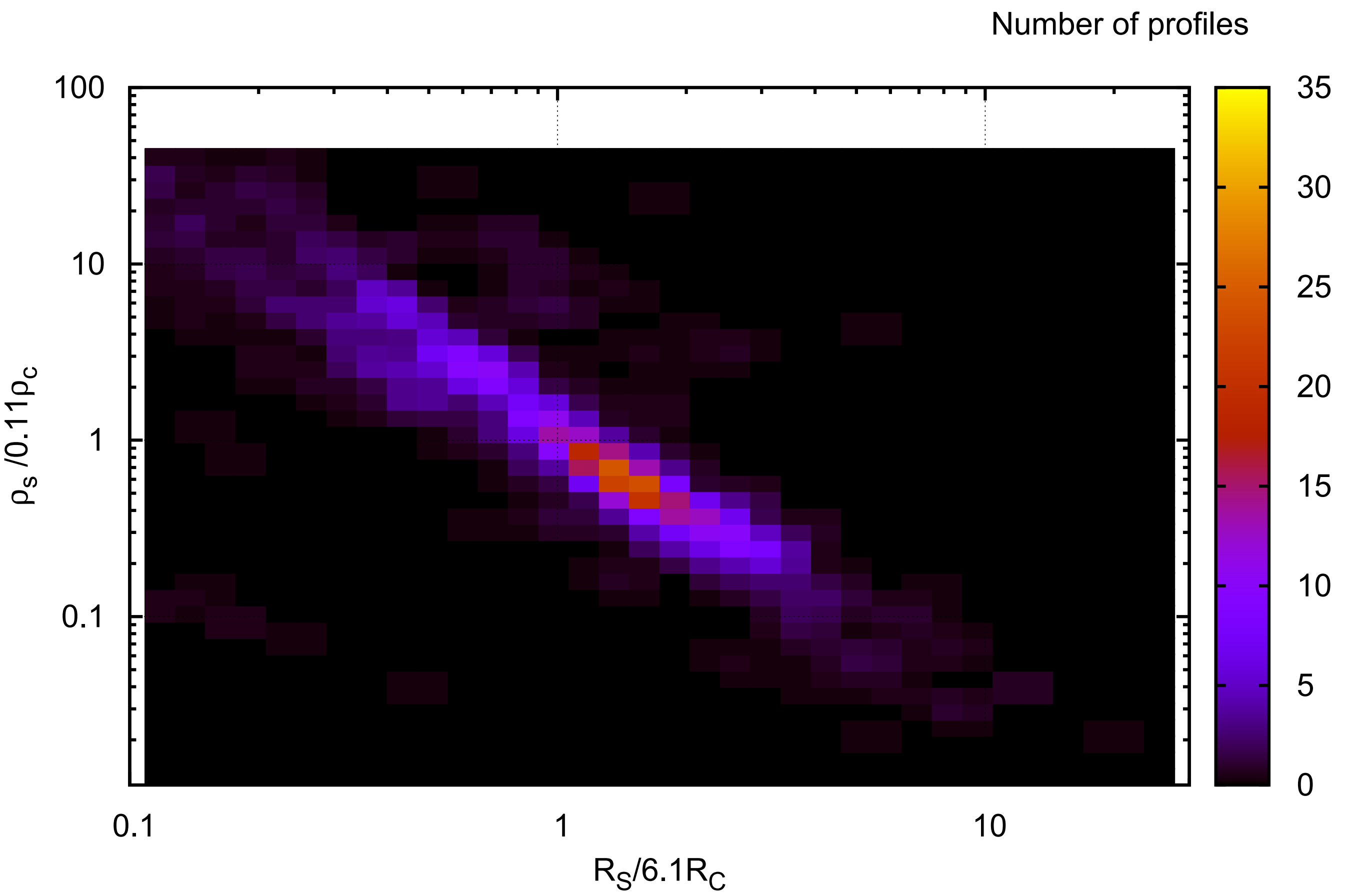


- one finds a relation between parameters of two DM density distribution, fitting the same data 0911.1774
  - NFW vs. ISO : $r_s \simeq 6.1\, r_c$; $\rho_s \simeq 0.11\, \rho_c$
  - NFW vs. BURK : $r_s \simeq 1.6 r_B$; $\rho_s \simeq 0.37 \rho_B$

- Is this relation actually observed?

NFW vs. ISO

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

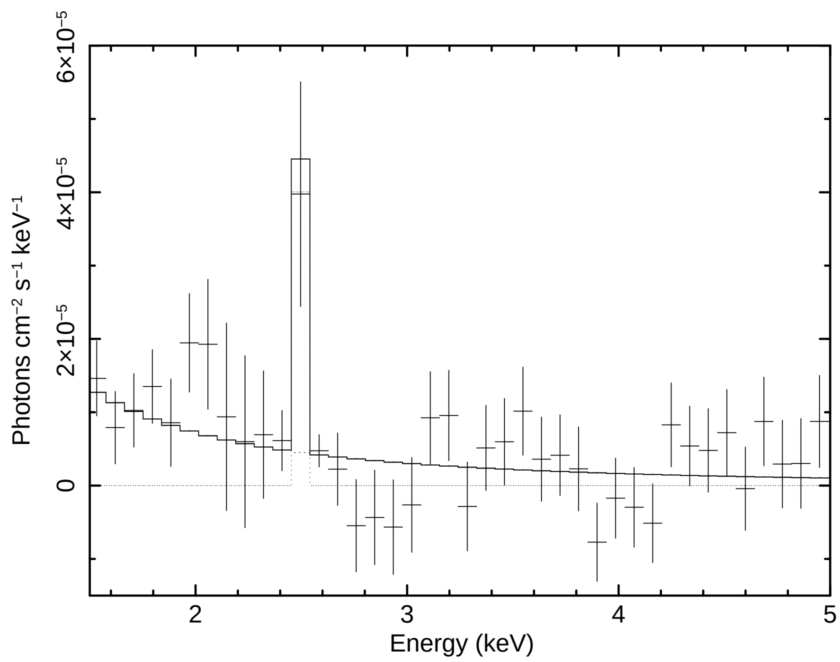


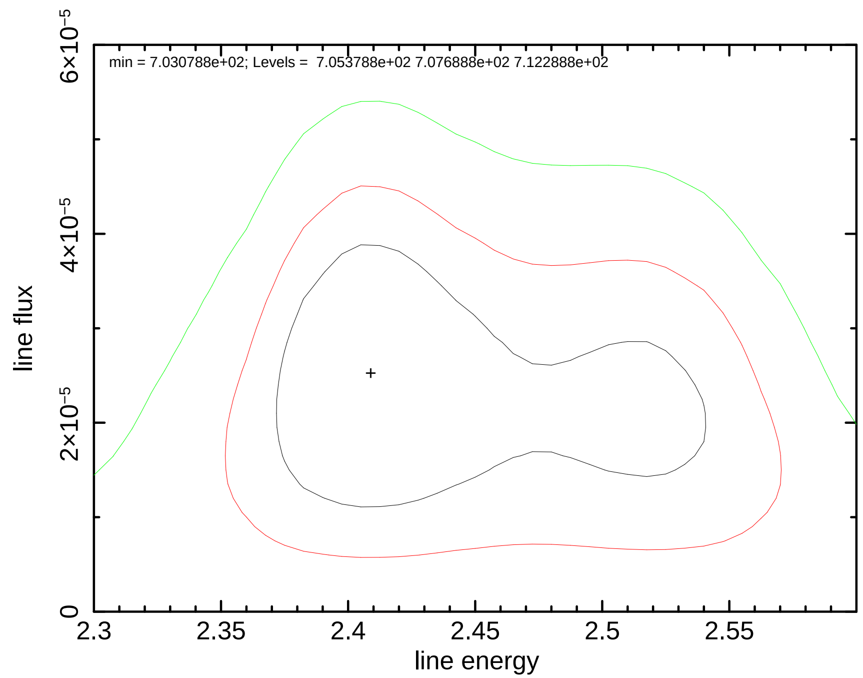
Universal scaling of DM column density

- 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)

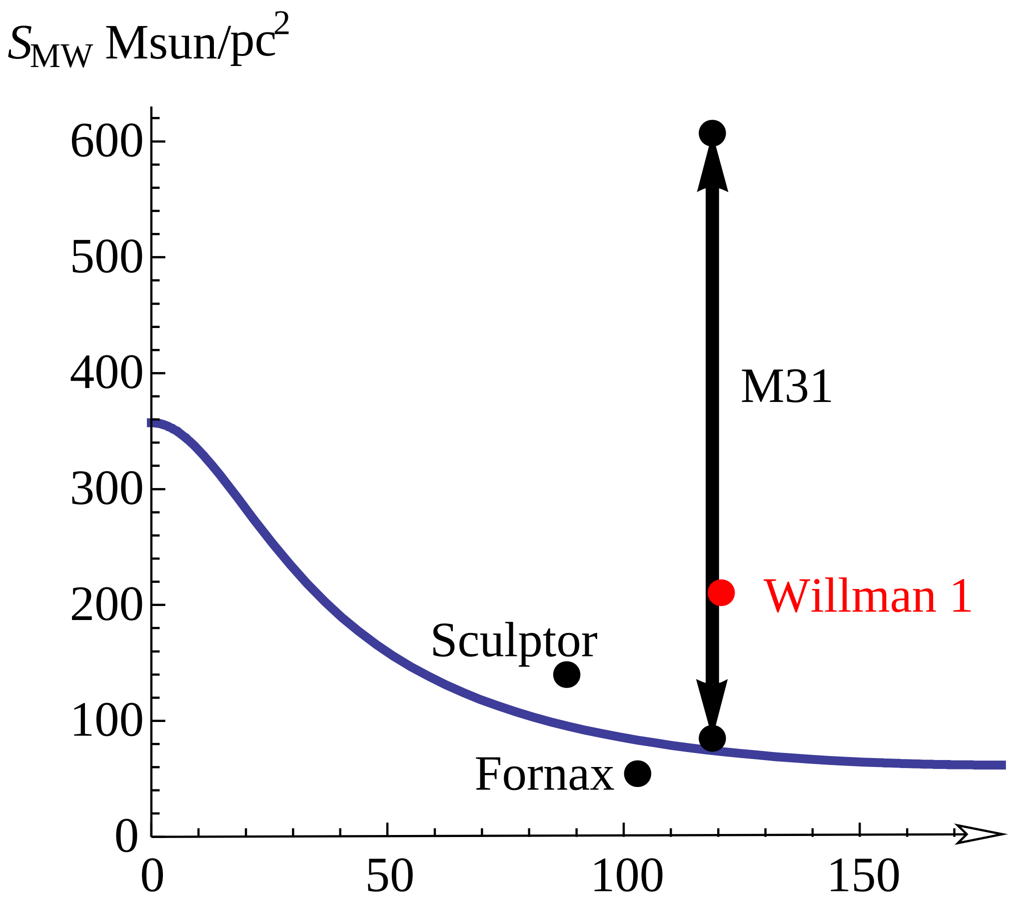




68%, 90% and 99% confidence intervals

- *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?



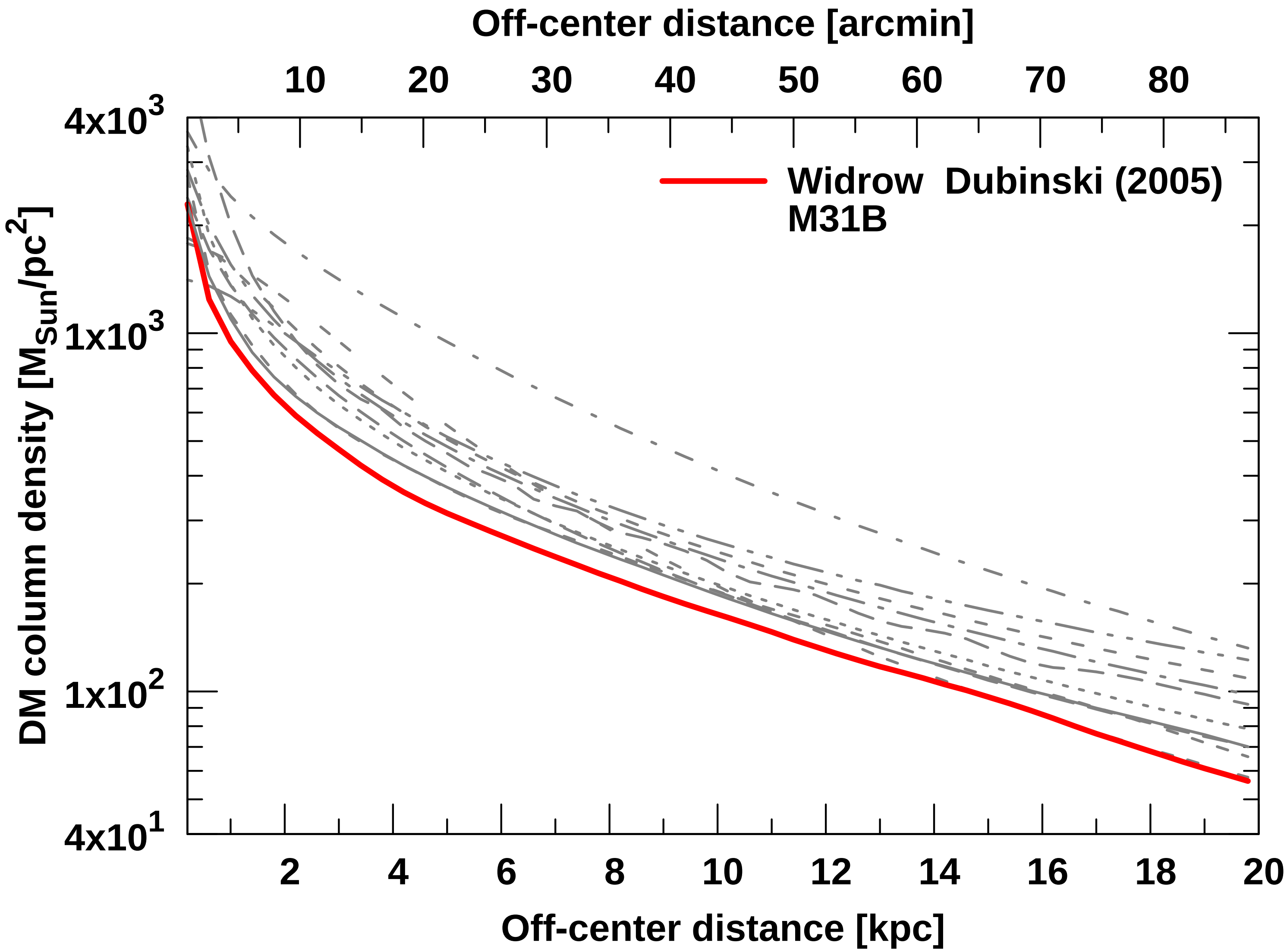
Objects with comparable expected signal for which archival data is available

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

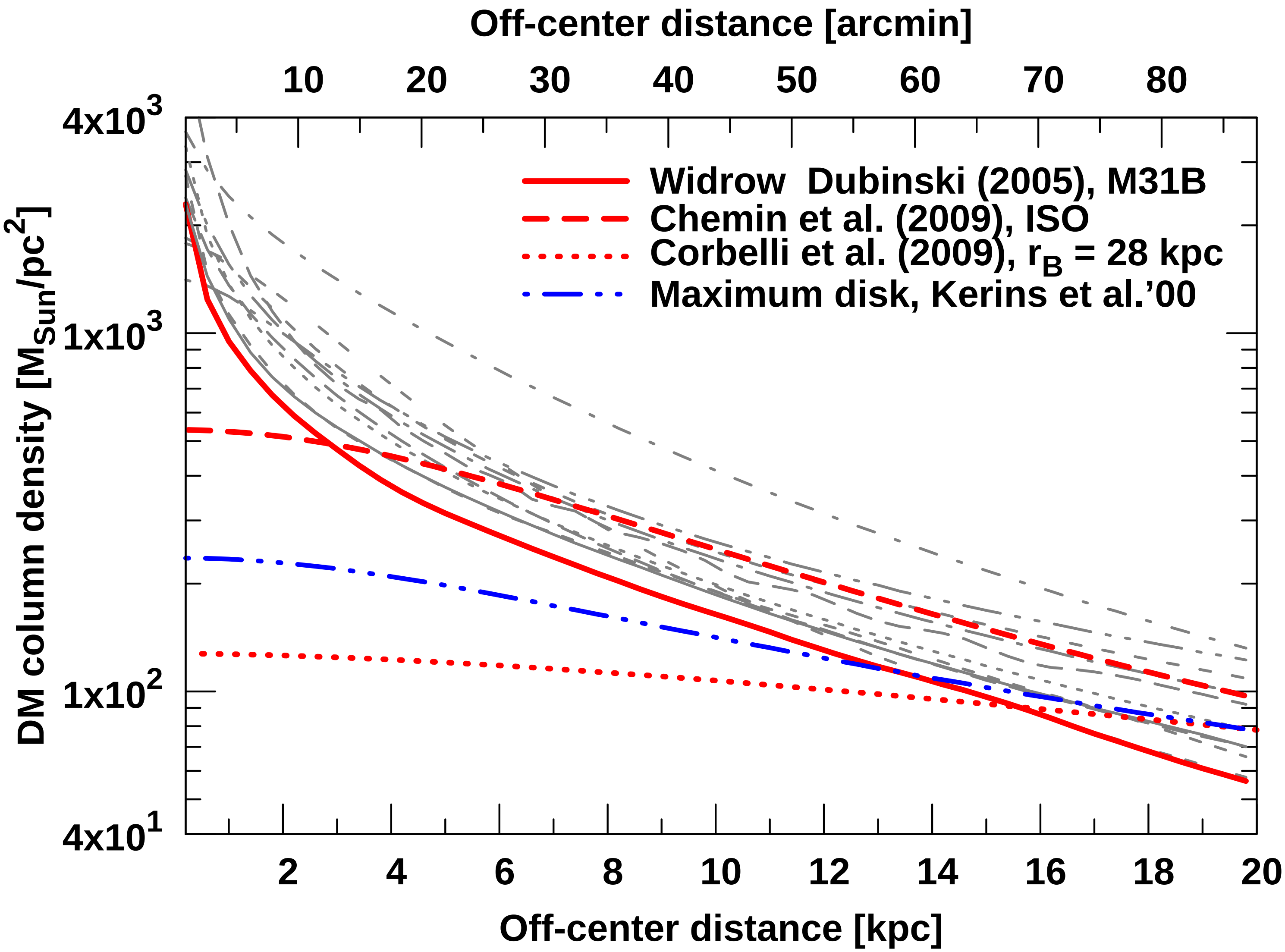
Do we see this 2.5 keV line?

DM in Andromeda galaxy (2008)

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



DM in Andromeda galaxy (2010)



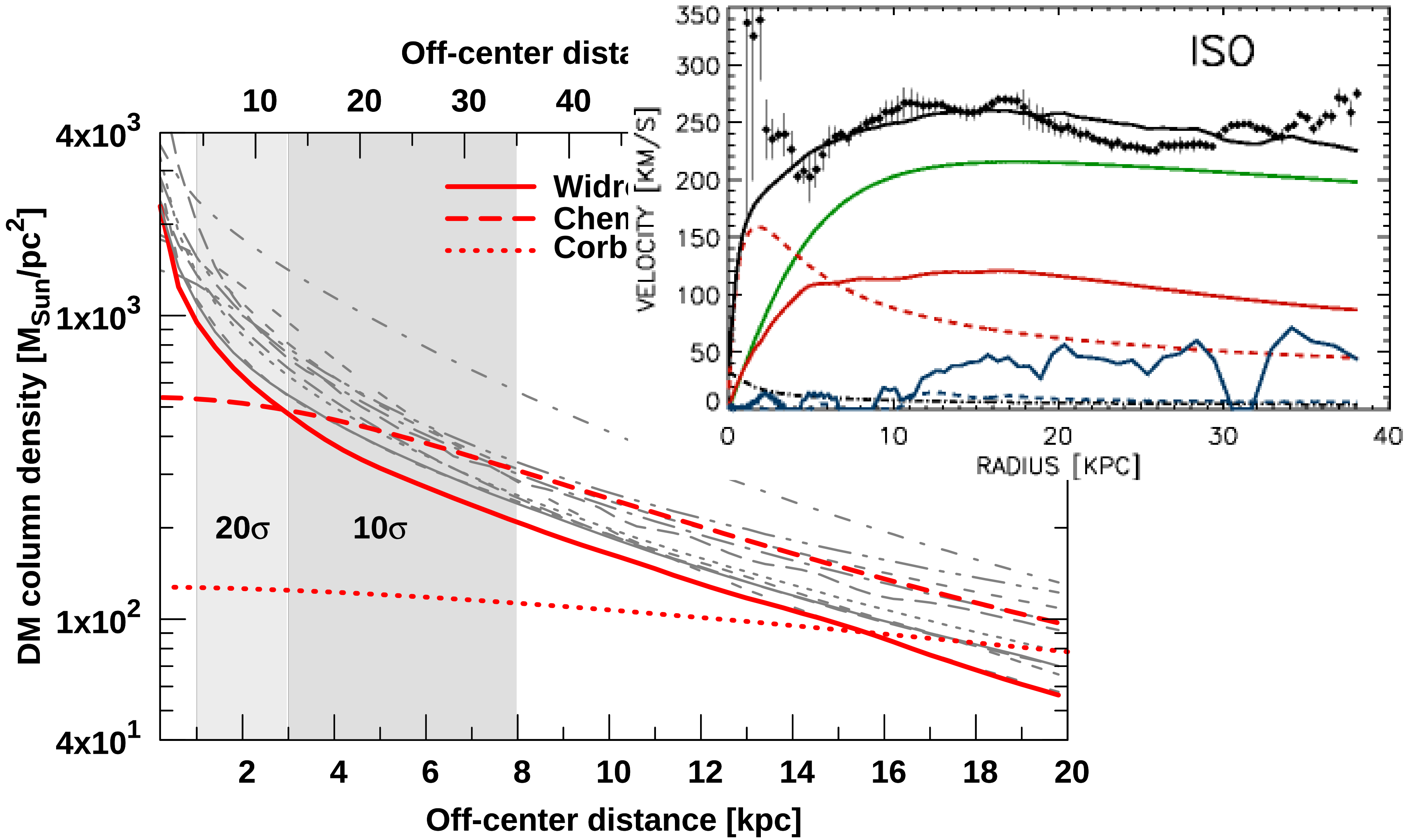
Boyarsky, O.R. et al. MNRAS'08

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

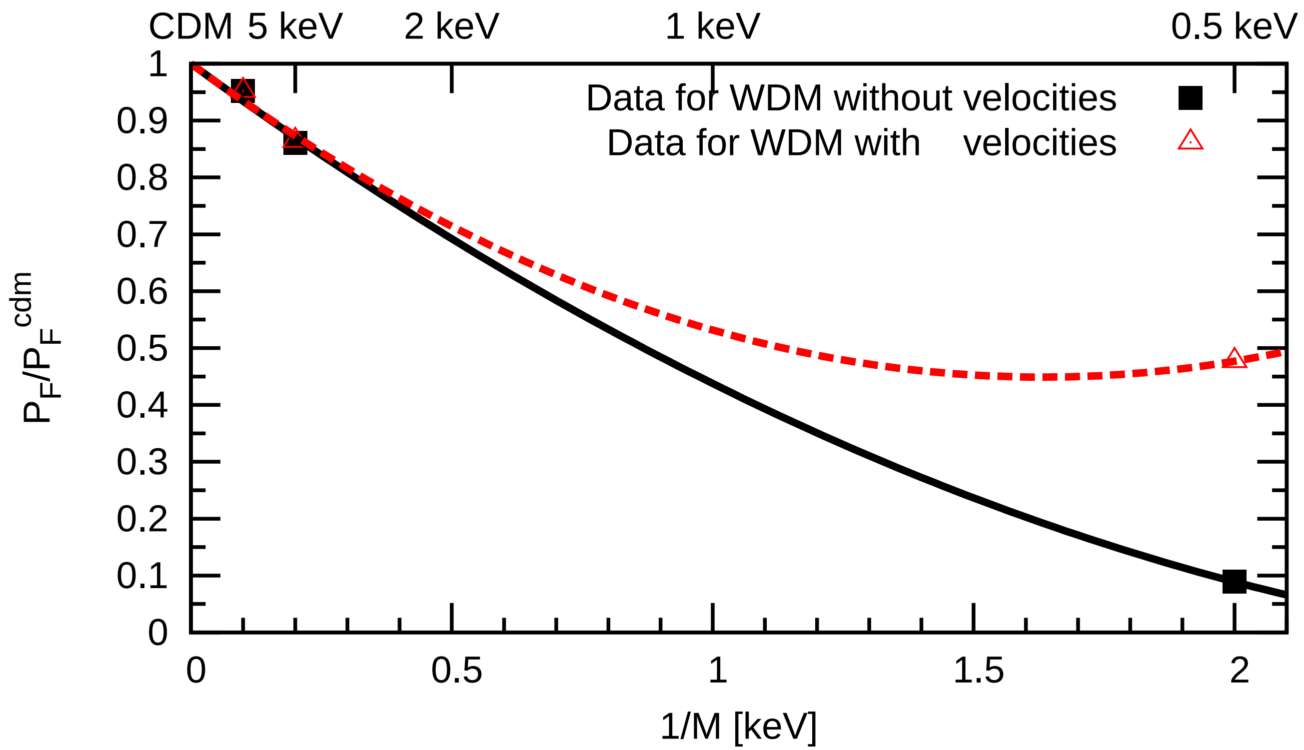
How to check DM origin of a line?

- 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



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Work in progress

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