What astrophysics and cosmology tell us about properties of dark matter particles?

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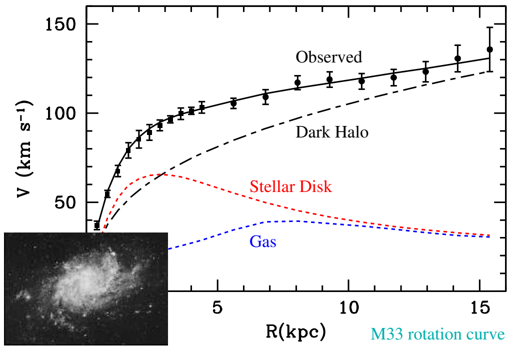
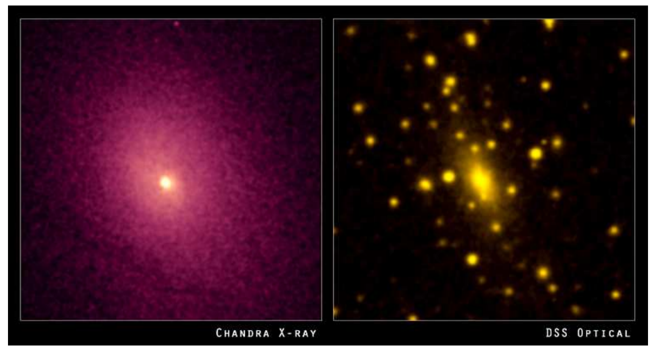
Fermilab

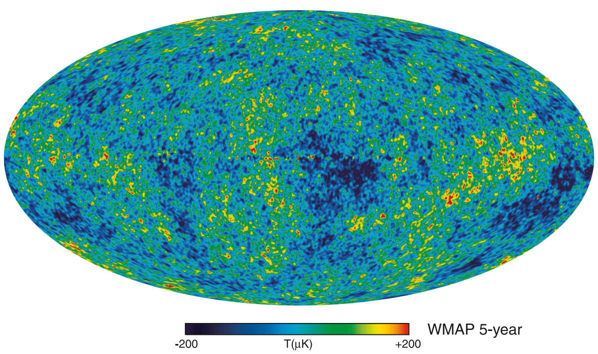
March 21, 2011

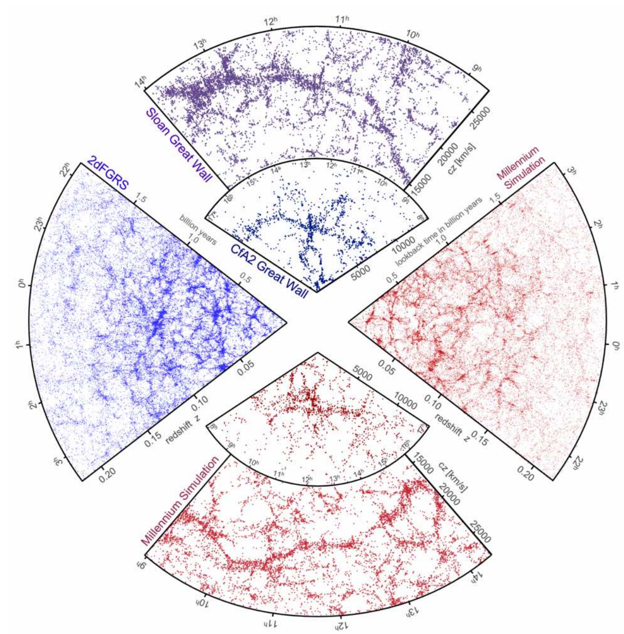
Dark Matter in the Universe

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



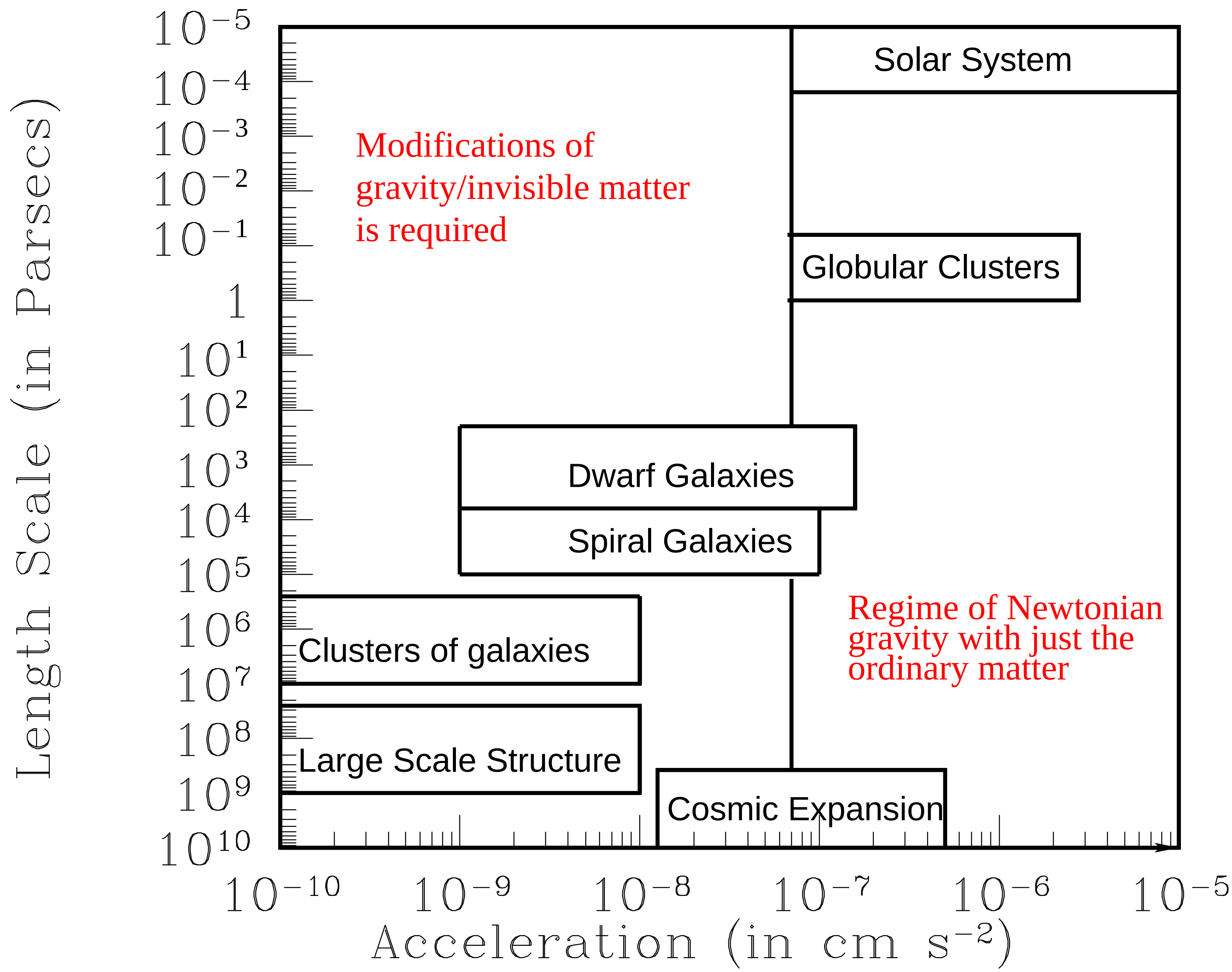






DM as change of gravity laws?

From Ferreira & Starkman 0911.1212

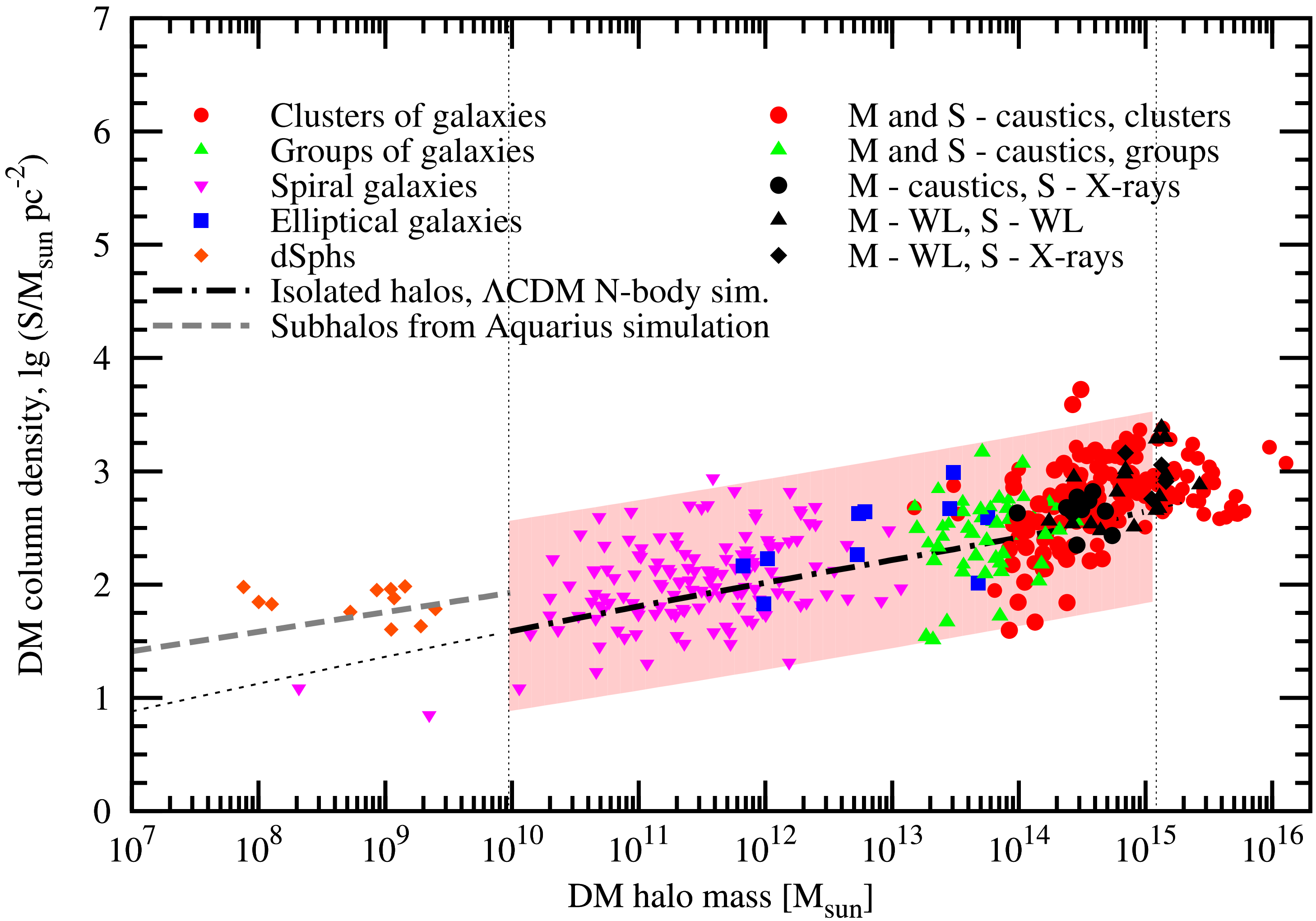


In this talk I assume that DM is made of particles and the gravity is not modified.

Universality of DM halos

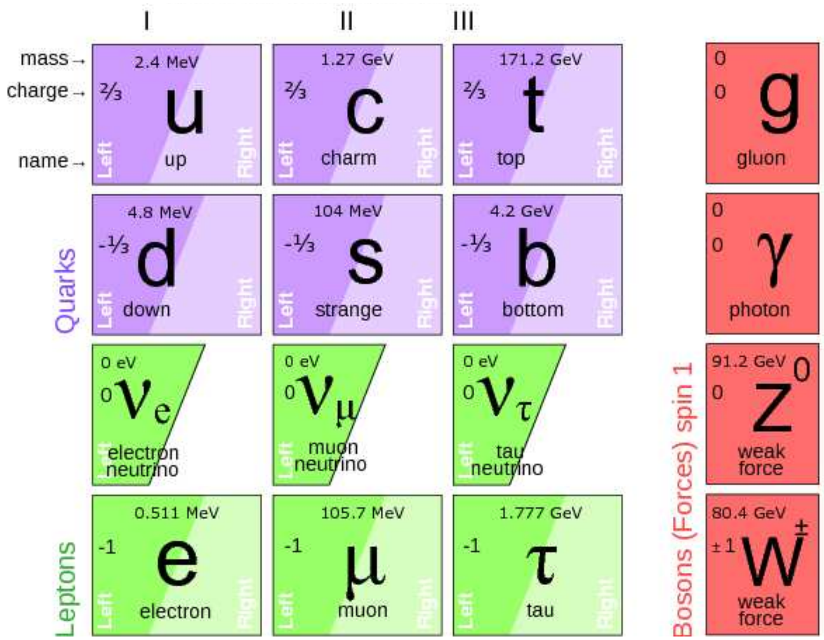
O.R.+ PRL 2010

work in progress



Evidence for DM (rather than MOND)

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)

Astrophysics and cosmology are the tools to learn about the fundamental physics

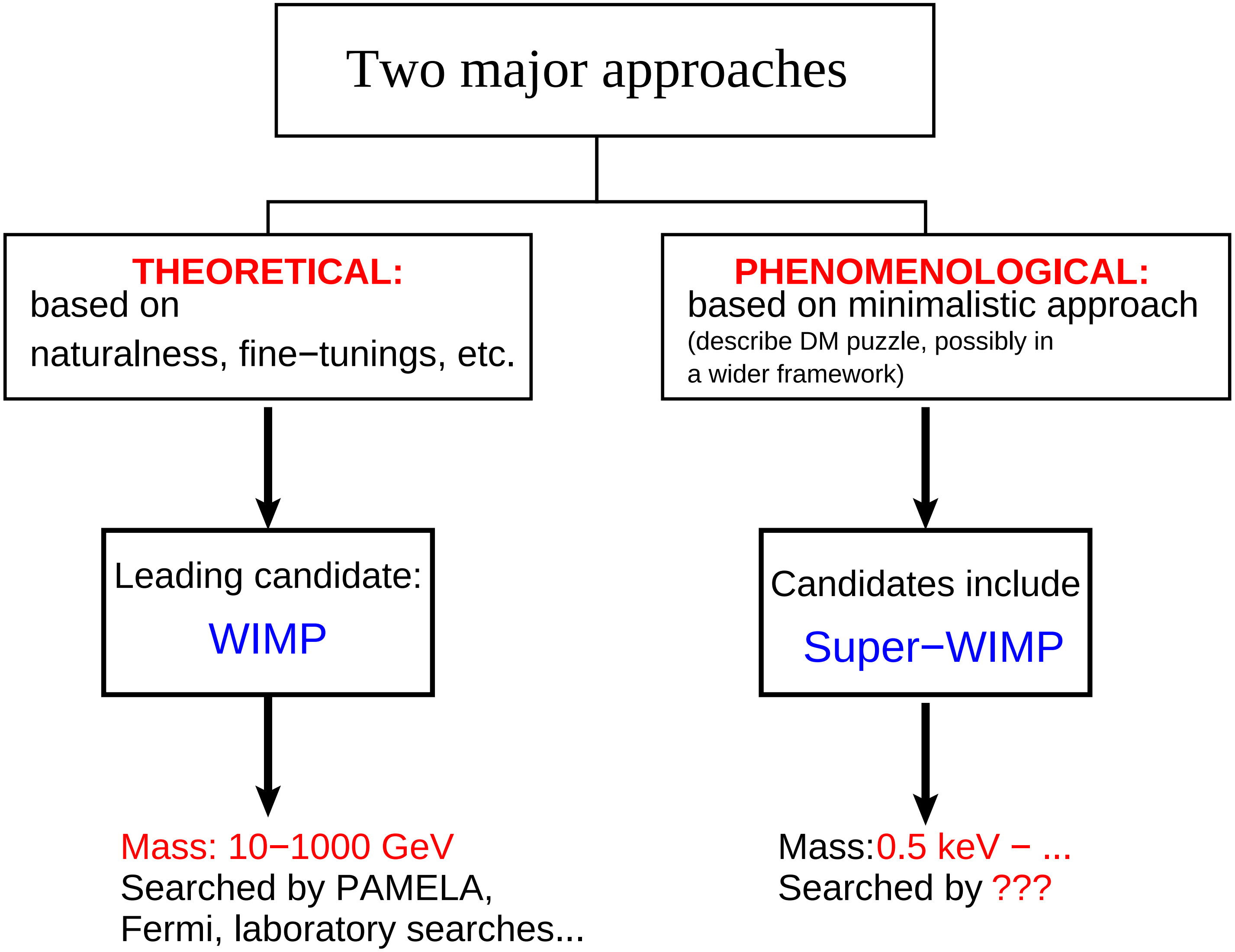
DM properties: what can be learned?

- Dark matter particle **mass**
  (Tremaine-Gunn bound, . . .)

- Dark matter **primordial velocities** (characterize the way the dark matter particles were produced and be studied by their imprints on structure formation)
  (CMB+LSS, Lyman-α, halo statistics, . . .)

- Dark matter particle **interactions** (self-interaction, inelastic scattering, annihilation/decay into ordinary matter, . . .) and **interaction strength**
  (search for decay/annihilation products, bullet cluster, . . .)

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

Interaction of dark and ordinary matter

Astrophysical dark matter search

Mass of DM particles?

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

Tremaine, Gunn (1979)

- The smaller is the DM mass – the bigger is the number of particles in an object with some velocity dispersion σ
- For fermions there is a **maximal** phase-space density (degenerate Fermi gas) $\Rightarrow$ observed phase-space density restricts number of fermions
- Objects with highest phase-space density – dwarf spheroidal galaxies – lead to the lower bound on the DM mass:

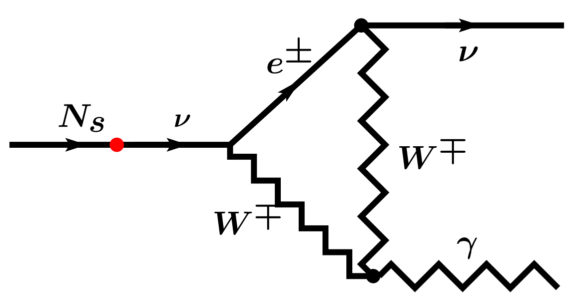
Mass of DM particle $\gtrsim 400$ eV

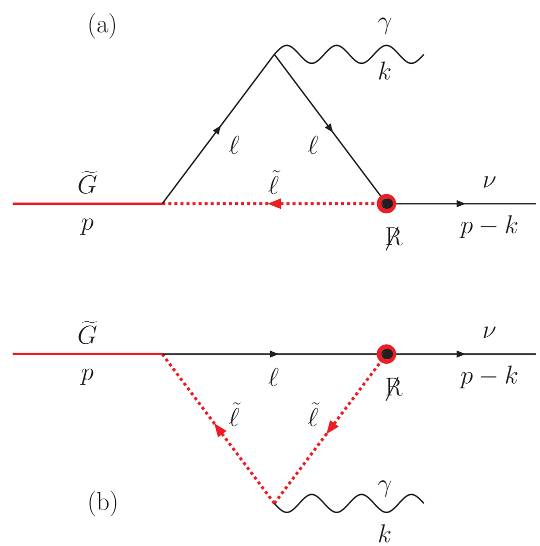
O.R.+ 2008

- Active neutrinos with $m \sim 300$ eV have **primordial** phase-space density $Q \sim Q_{obs}$. Neutrino DM abundance $\Omega_\nu h^2 = \frac{m_\nu}{94\ \mathbf{eV}}$ $\Rightarrow$ Active neutrinos cannot constitute 100% of DM

Interactions of super-WIMPs

- From a theorist's point of view DM particles should generically be **decaying** (unless some exact global symmetry protects them)
- Weakly interacting dark matter should be stable ($n \to p + e + \bar{\nu}_e$). WIMPs interact with SM particles via annihilation only. Expected signals: anti-matter excess, flux from the Galactic center, dwarfs, ...
- Expected decay channels (especially below 1 MeV): (DM $\to \gamma + \nu,\ \gamma + \gamma, \ldots$) – to neutrinos and photons





- Signature of radiative decay: monochromatic line from all dark matter overdensities. The energy $E_\gamma = \frac{1}{2} M_{\text{DM}} c^2$

- Flux from DM decay:

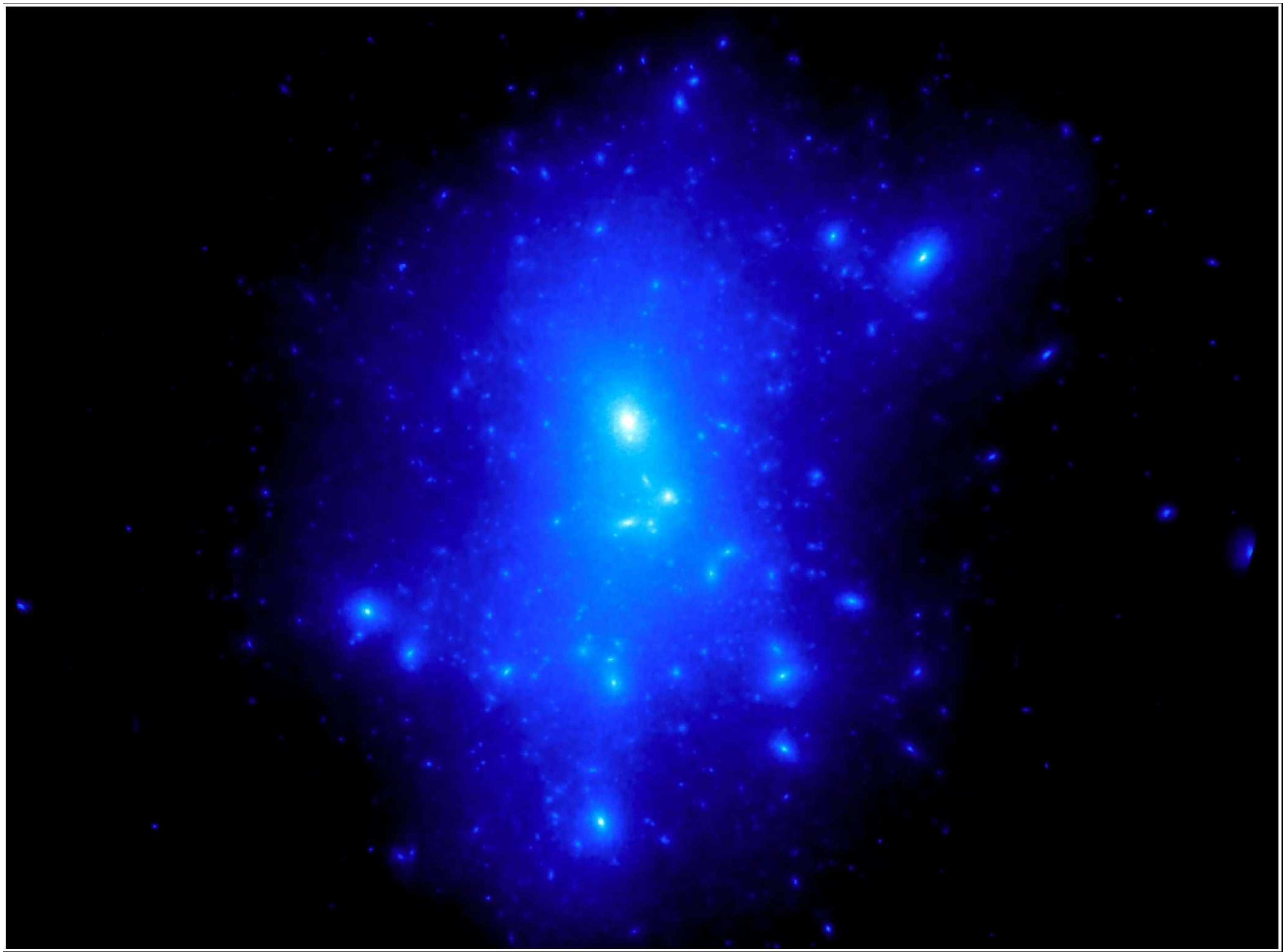
$$F_{\text{DM}} = \Gamma_{\text{rad}} \frac{E_\gamma}{M_{\text{DM}}} \int_{\text{fov cone}} \frac{\rho_{\text{DM}}(\vec{r})}{4\pi |\vec{D}_L + \vec{r}|^2} d^3\vec{r} \approx \frac{\Gamma_{\text{rad}} \Omega_{\text{fov}}}{8\pi} \mathcal{S}$$

- **DM column density**

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

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

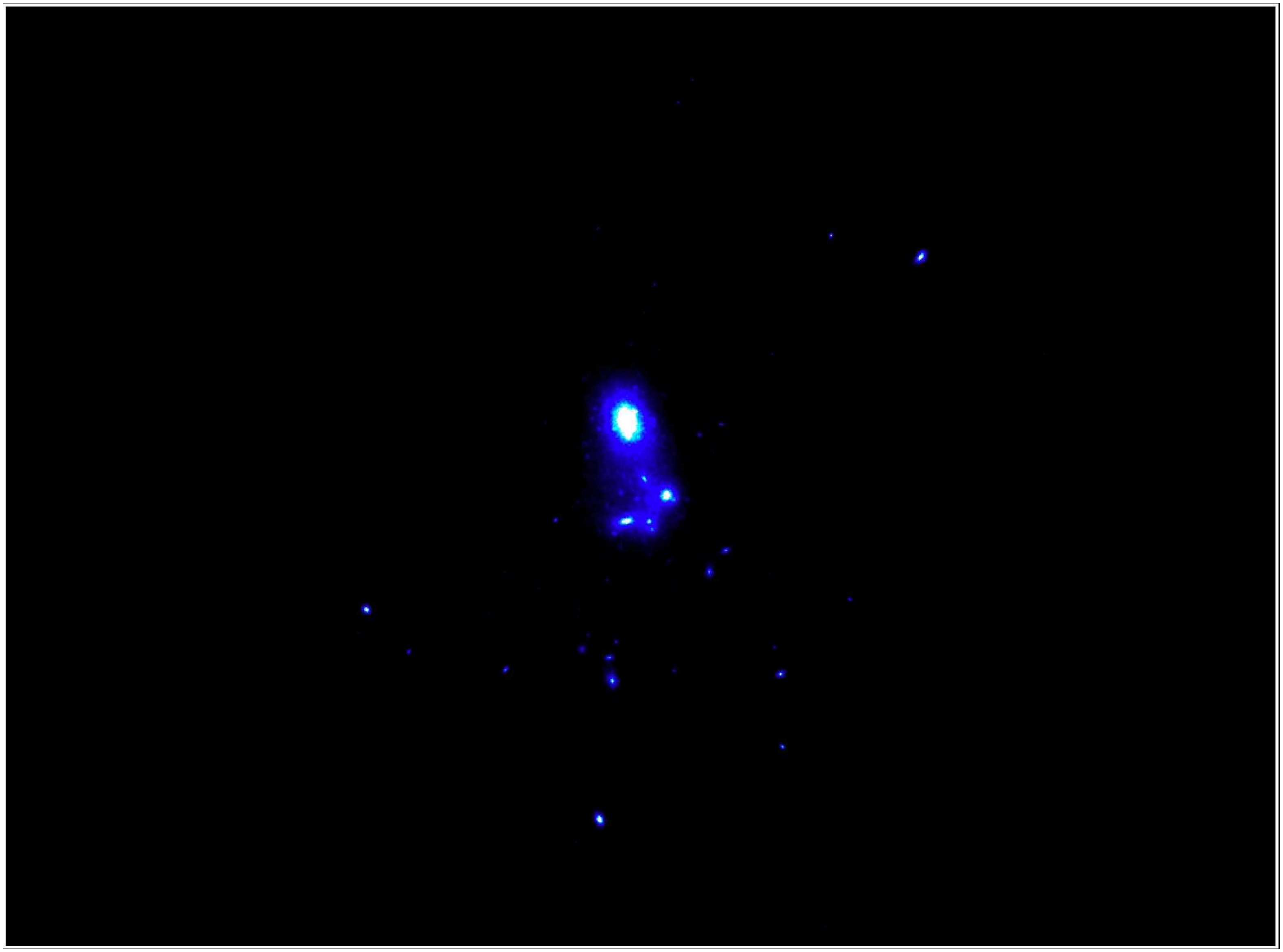
Decay signal from MW-sized galaxy



Moore et al. 2005

$$\int \rho_{\text{DM}}(r)dr$$

Annihilation signal from MW-sized galaxy



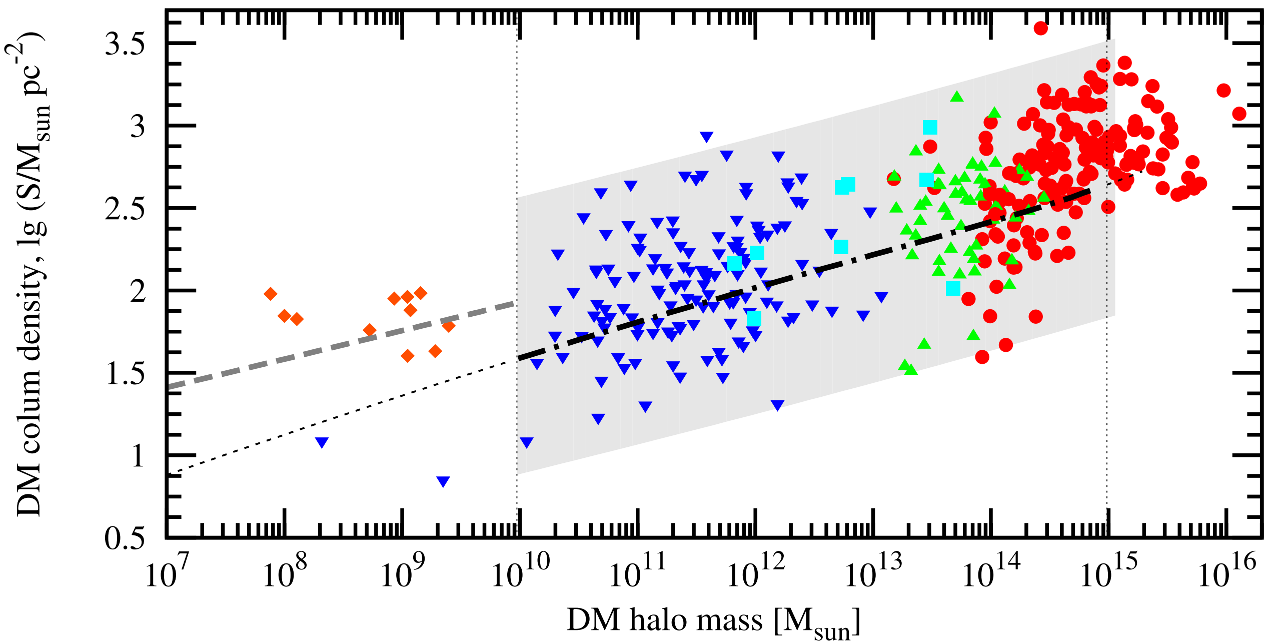
Moore et al. 2005

$$\int \rho^2_{\text{DM}}(r)dr$$

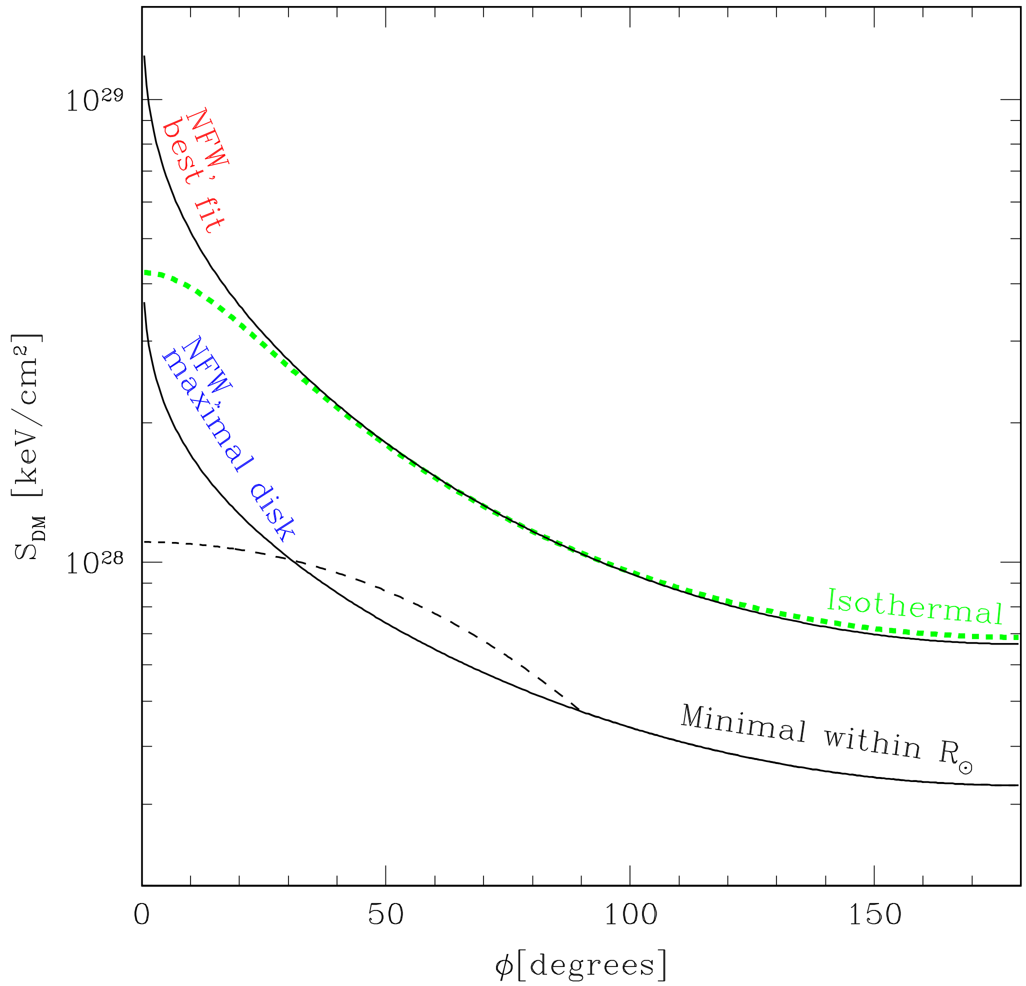
How to check DM origin of a line?

- 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**.

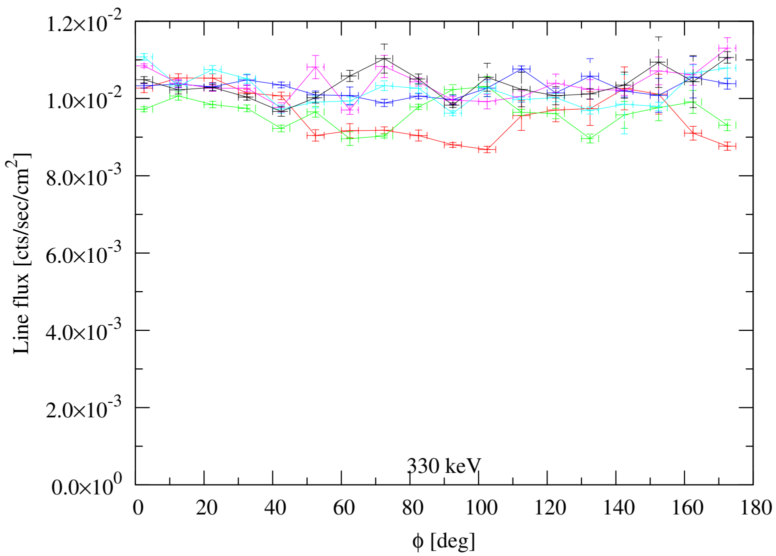


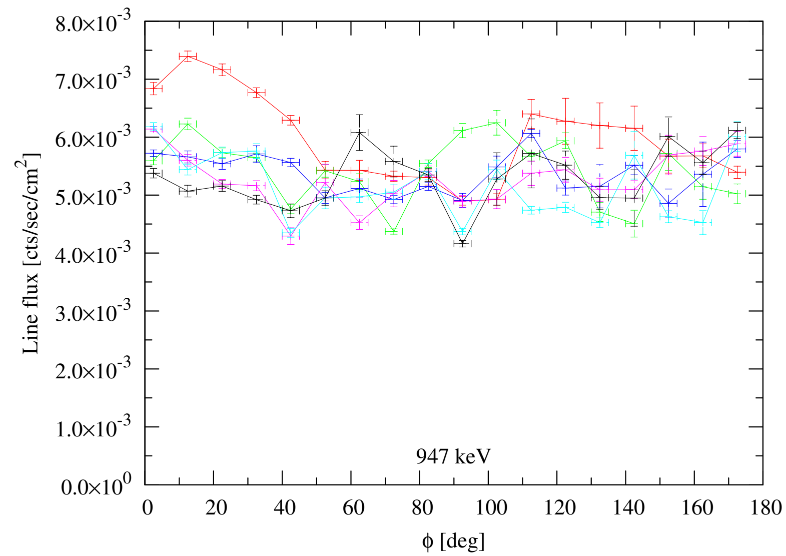
All-sky source

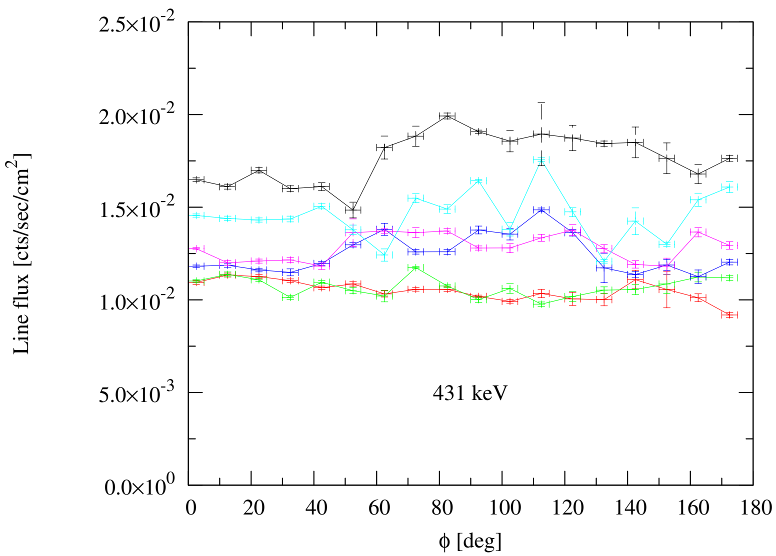


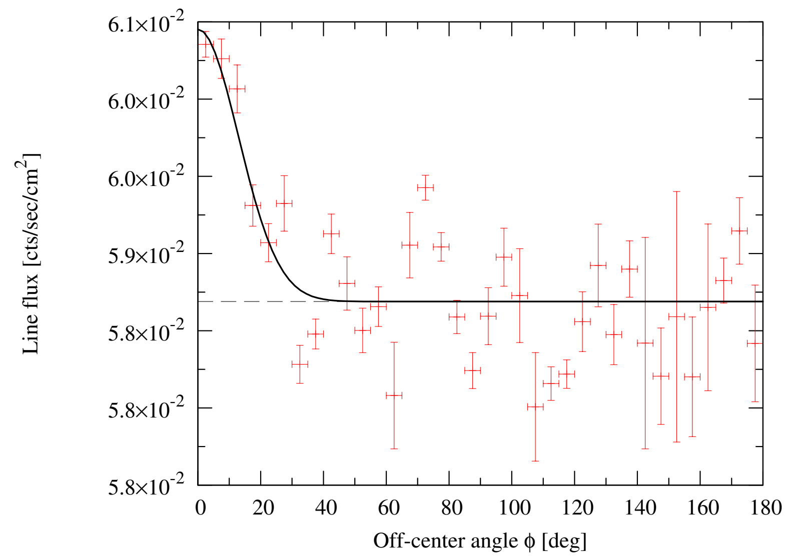
- DM is an all-sky source
- Its variability over the sky can be as low as factor of 3

SPI: spatial profile of lines



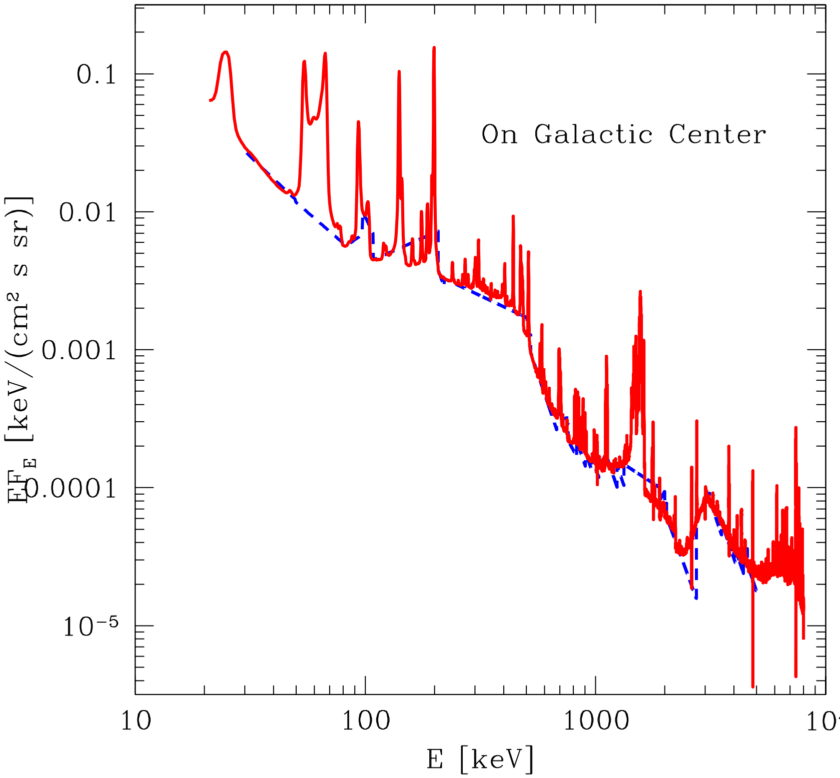


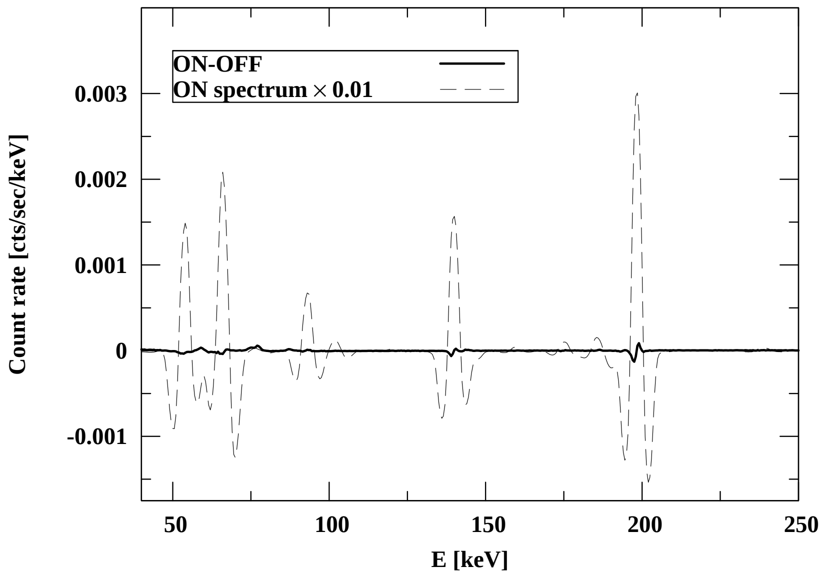




Search for decaying DM: main challenges

- **Control of astrophysical and instrumental background** (of instruments like XMM-Newton, Chandra, Suzaku, INTEGRAL, . . .)

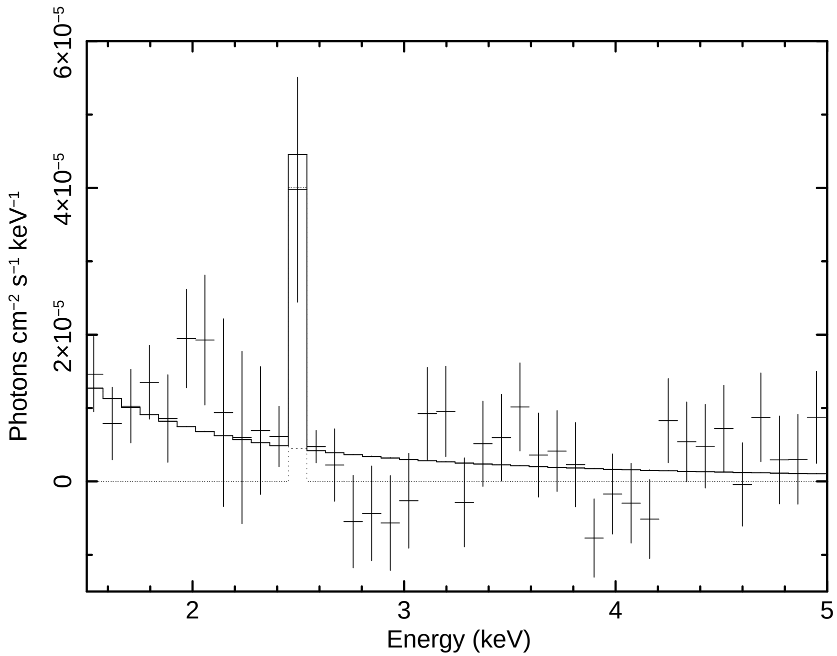


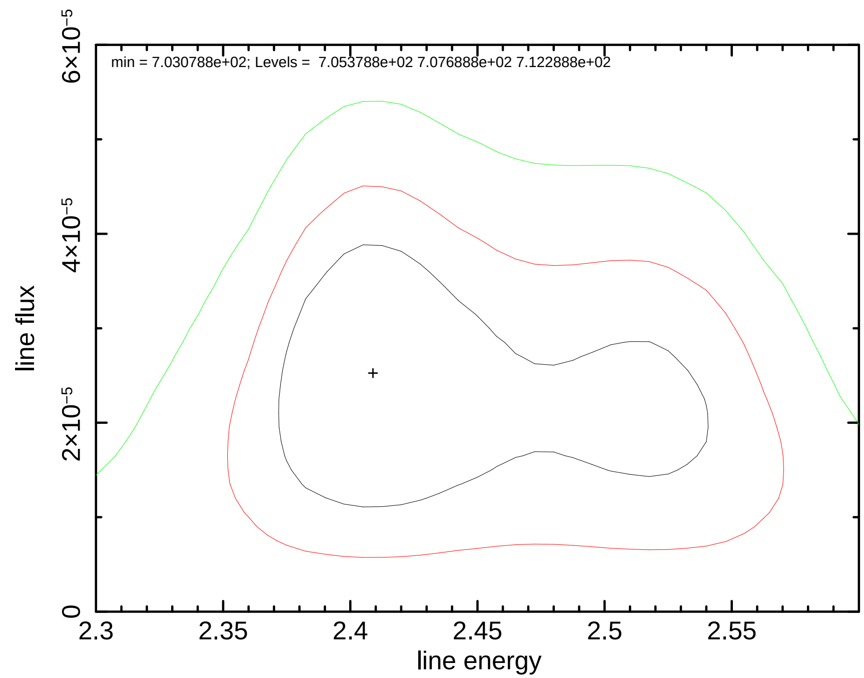


- **Reliable determination of dark matter content of an object**

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)

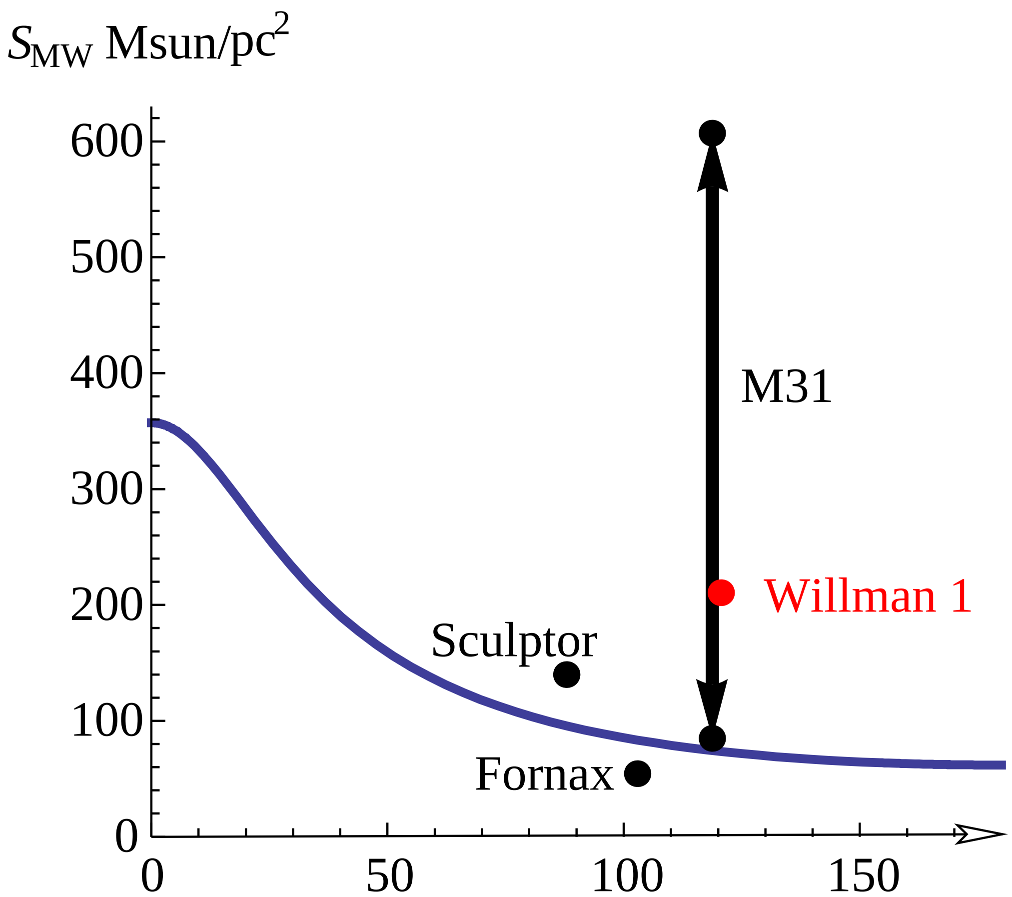




68%, 90% and 99% confidence intervals

- *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?



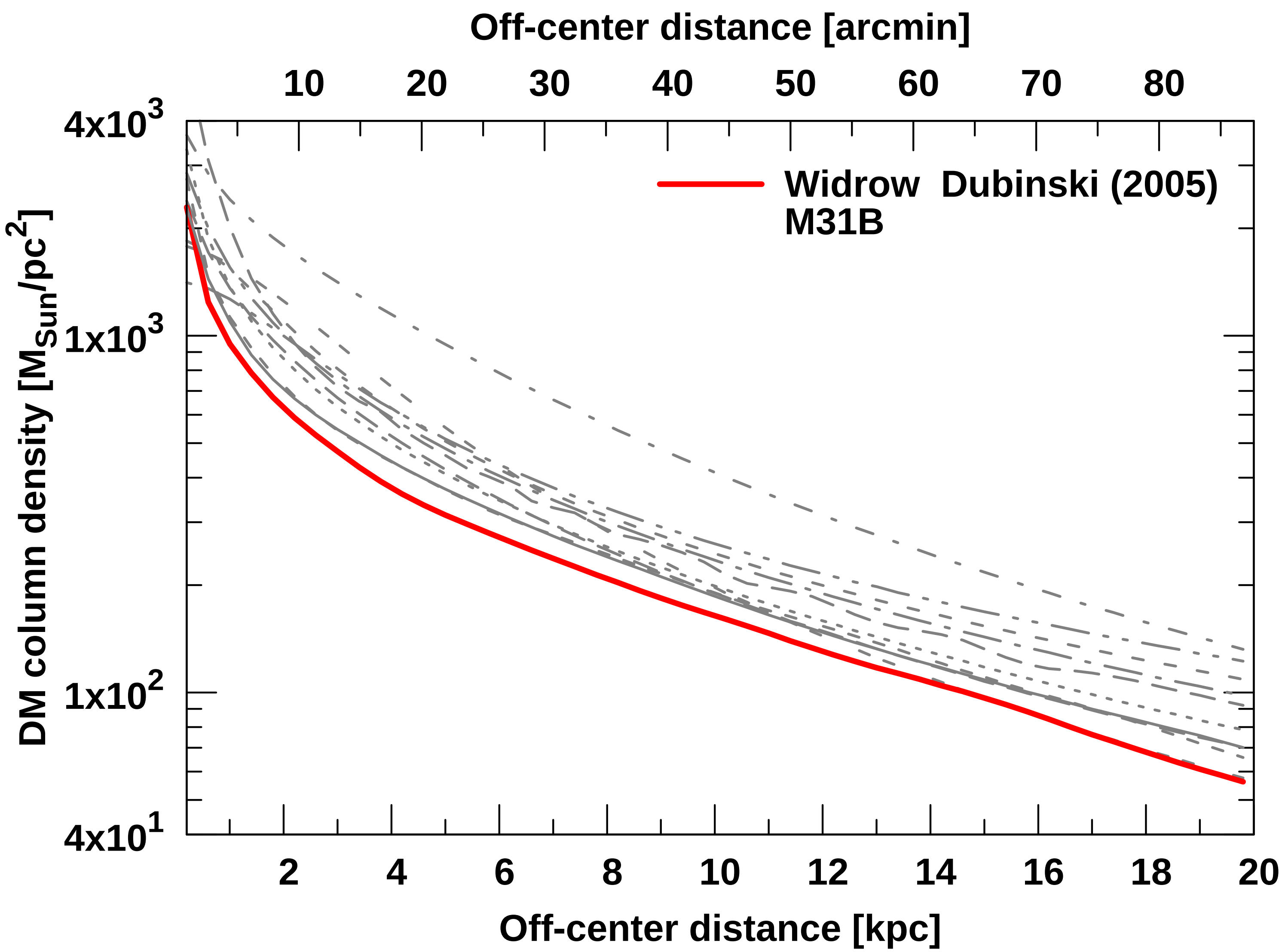
Objects with comparable expected signal for which archival data is available

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

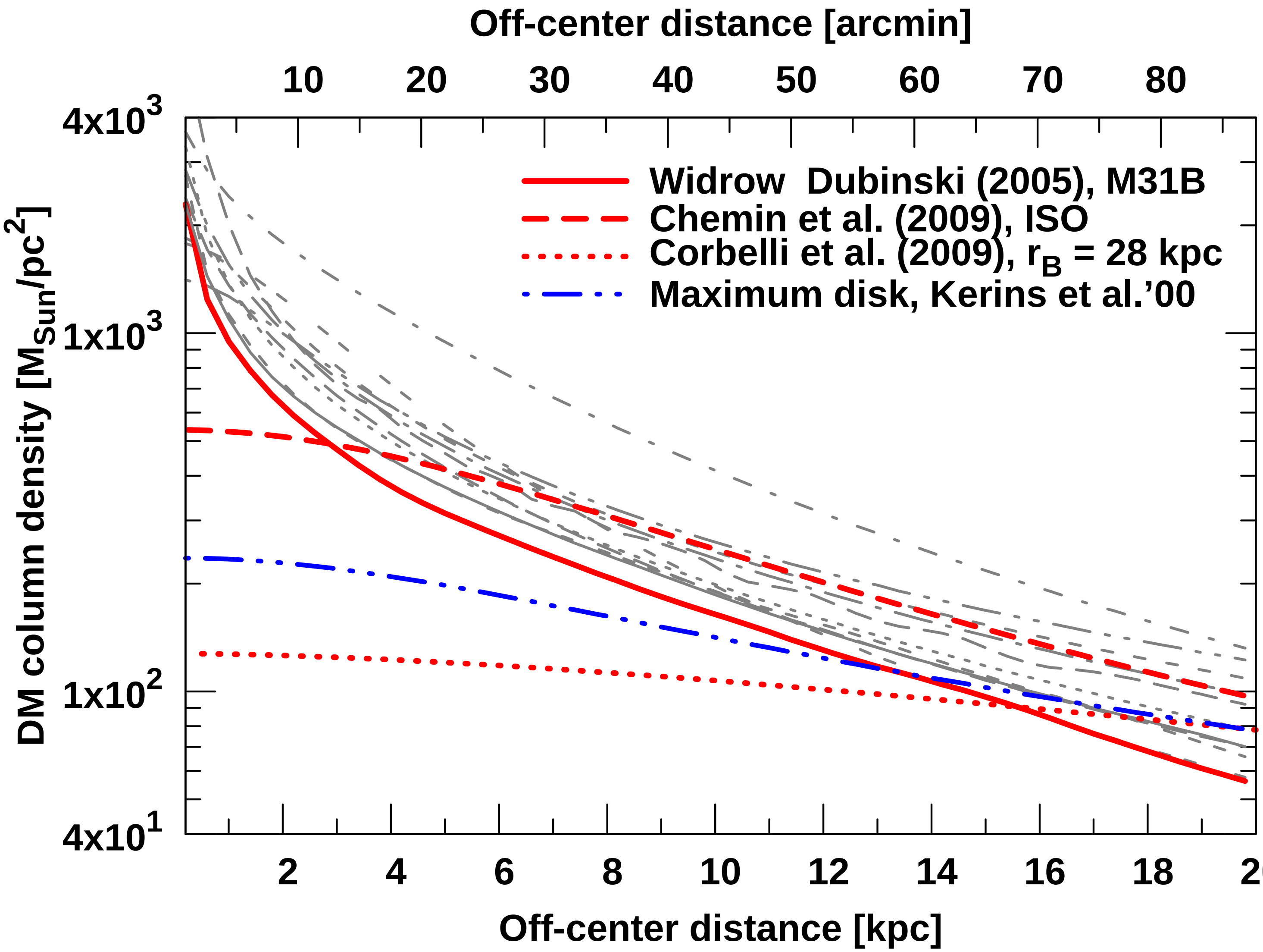
Do we see this 2.5 keV line?

DM in Andromeda galaxy (2008)

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



DM in Andromeda galaxy (2010)



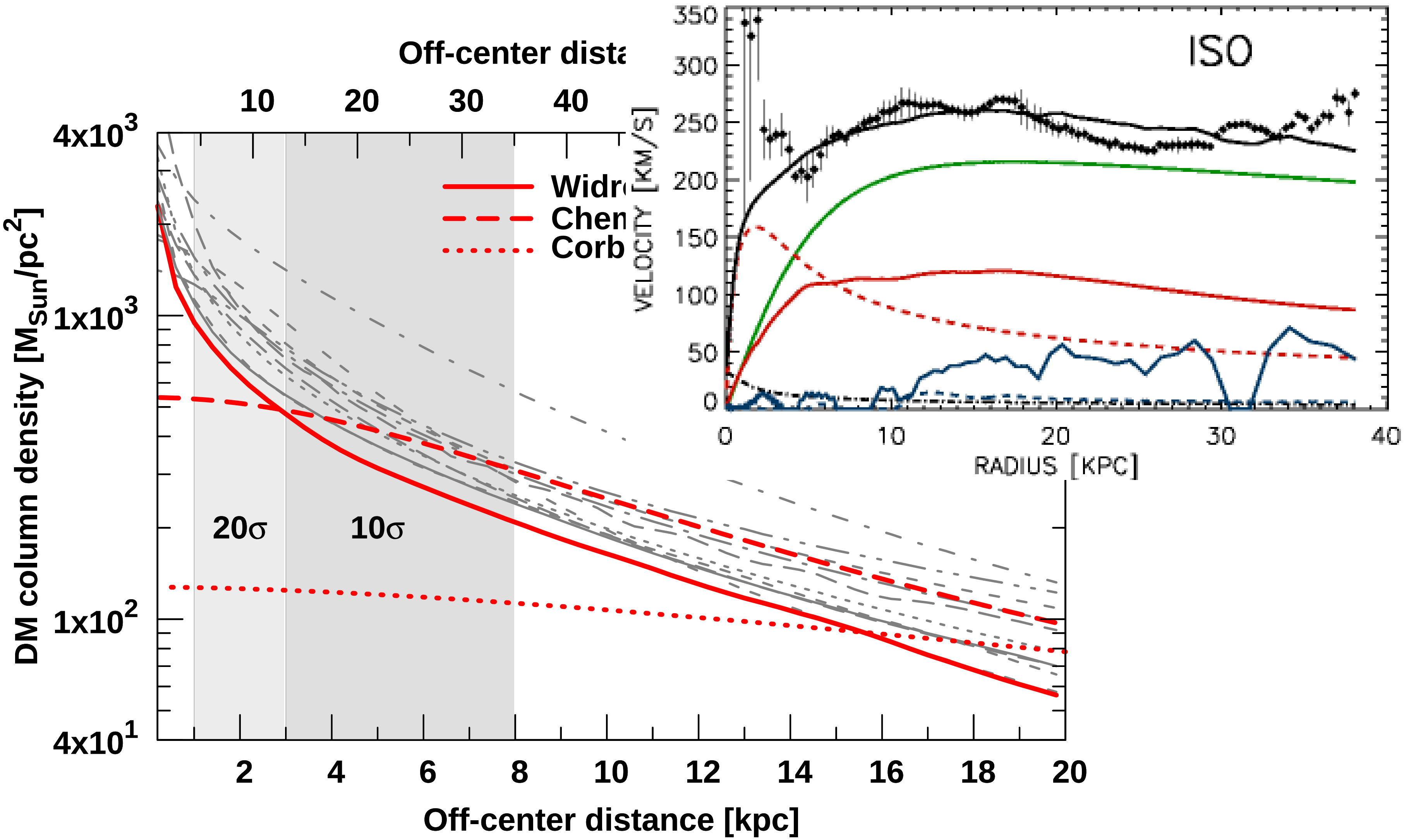
Boyarsky, O.R. et al. MNRAS'08

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?

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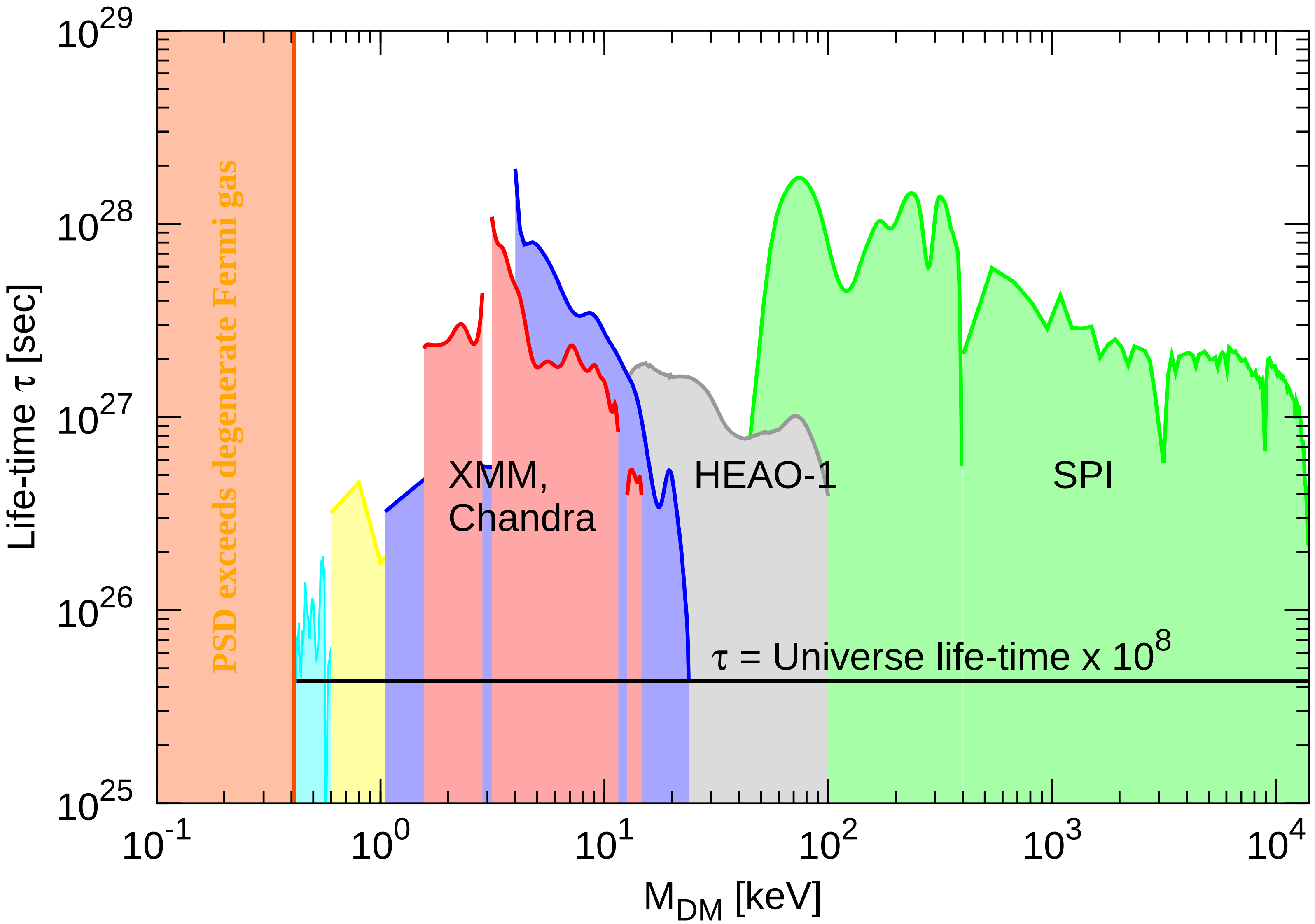
- Candidate line can be distinguish from astrophysical backgrounds by studying its **surface density** and **sky distribution**.

For decaying dark matter indirect search becomes direct!

Restrictions on life-time of decaying DM

Many groups, incl. **O.R.** with collaborators 2005-2010



Restrictions on life-time of decaying DM

- Is $10^{25} - 10^{26}$ sec a long lifetime? Is it something to be expected?
- In what situations an upper bound on the lifetime of DM can exist? Should we continue to search?
- We need some reference model to answer these questions

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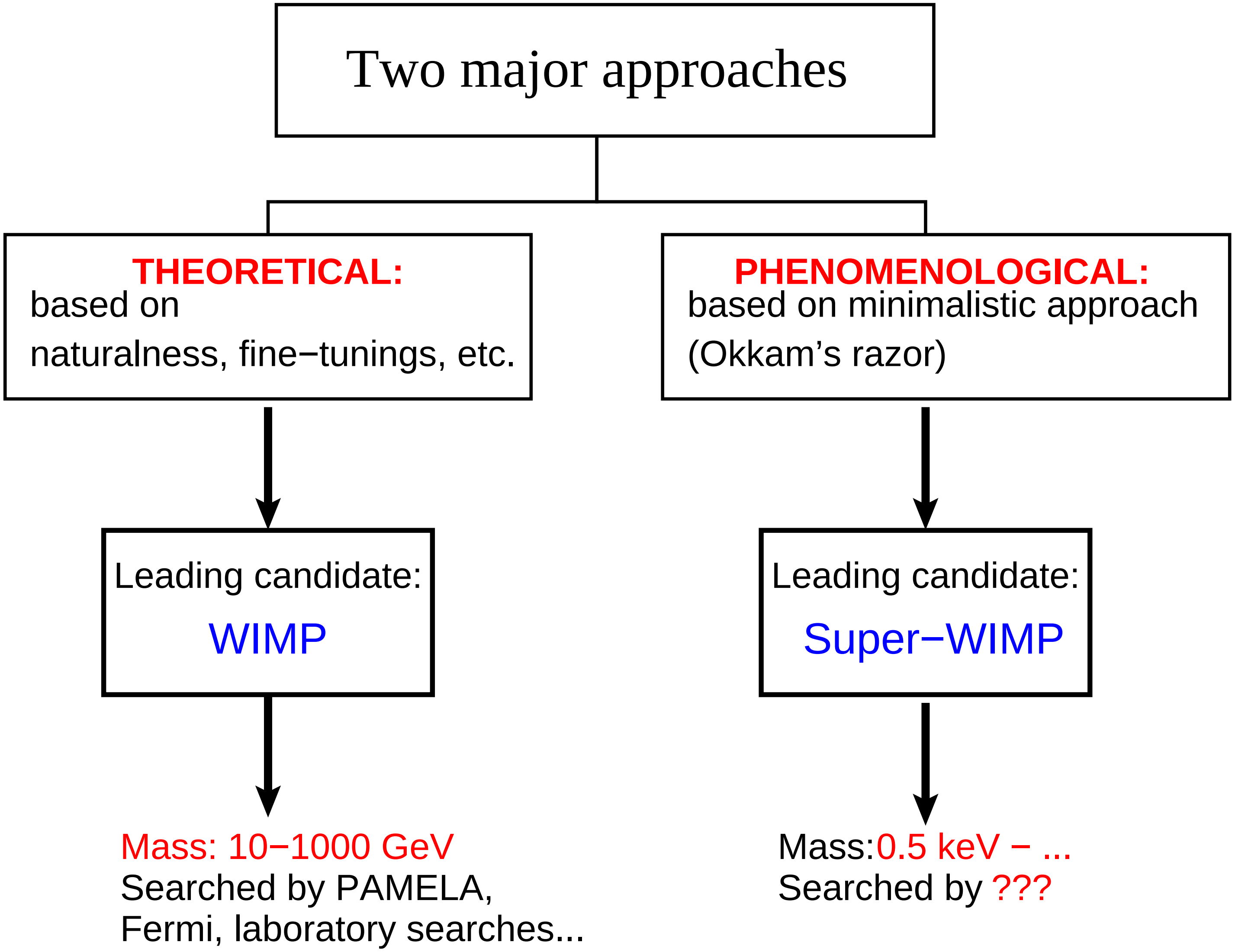
Let us look at a particular super-WIMP dark matter model

DM candidates. What do we expect?



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

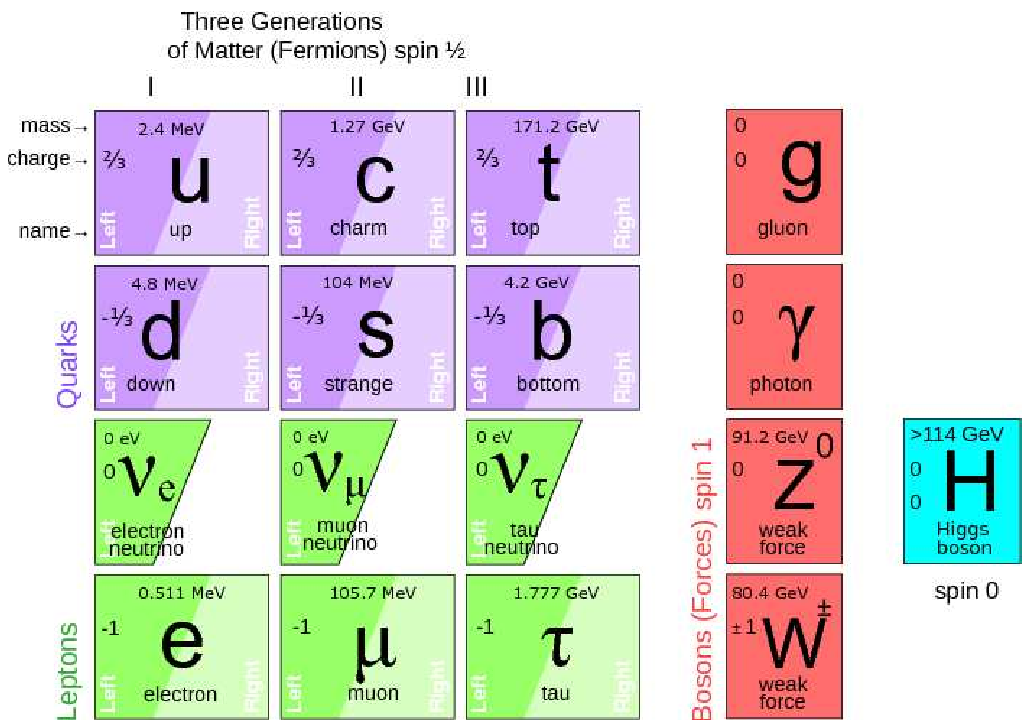
- **Dark matter** (not a SM particle!)
  – particles with weak cross-section will have correct abundance $\Omega_{\rm DM}$ ("WIMP miracle"). **New scale** ~ 1 TeV
  – Axions. **New scale** $10^{10} - 10^{12}$ GeV.

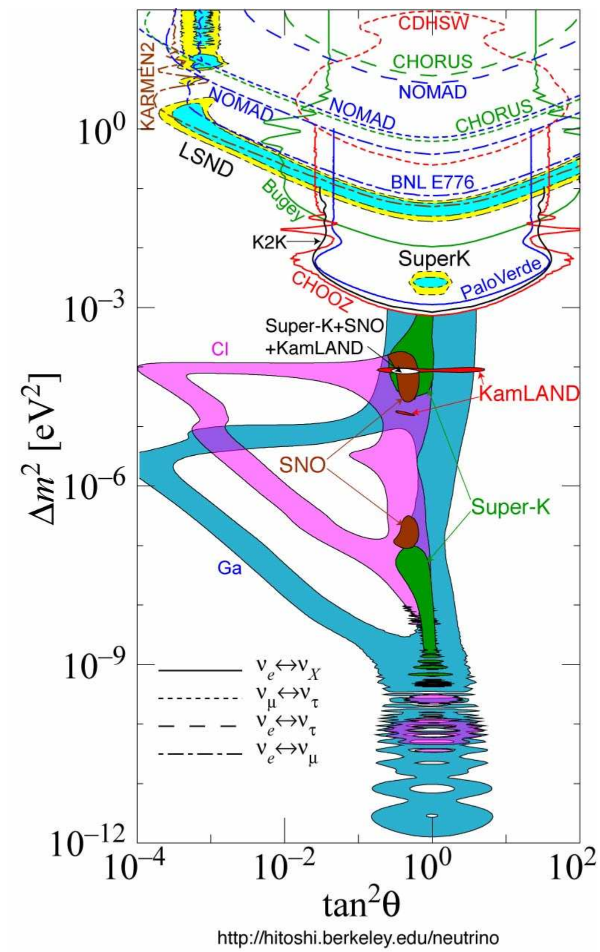
- **Baryon asymmetry of the Universe**: what ensured that for each 10^{10} anti-protons there was $10^{10} + 1$ proton in the early Universe?
  – **Sakharov conditions:** CP-violation; B-number violation; out-of-equilibrium processes (leptogenesis, phase transitions, etc.)

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

Neutrino oscillations

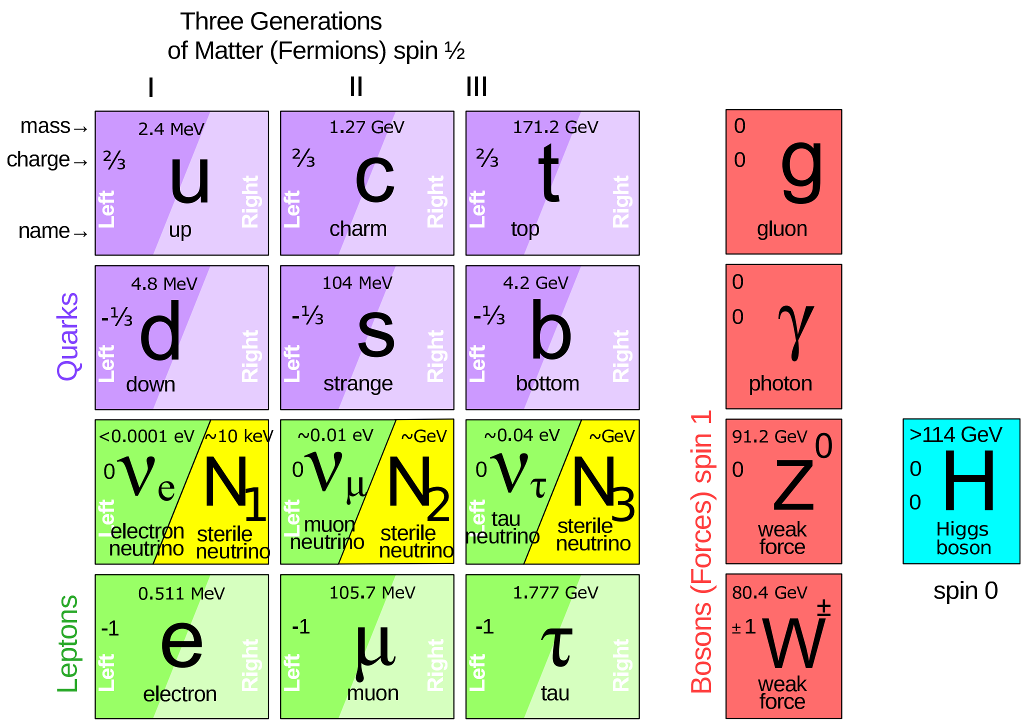
Experiments on neutrino oscillations determined **two** mass differences between neutrino mass states.

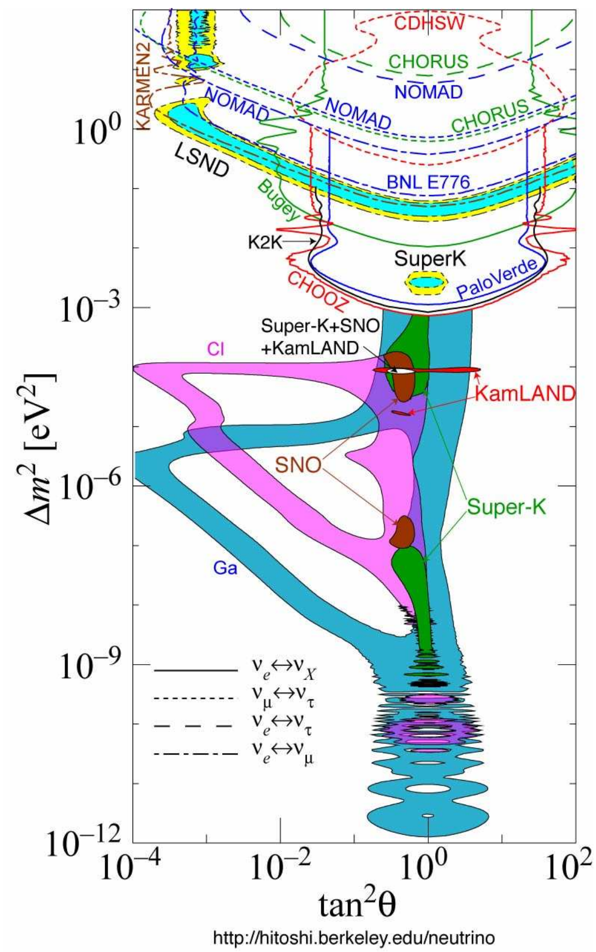




Sterile neutrinos?

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





The most natural explanation of neutrino experiments – right-chiral neutrinos in the Standard Model

See-saw Lagrangian

Add right-handed neutrinos N_I to the Standard Model

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

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

$$(m_\nu) = -M_{\text{Dirac}} \frac{1}{M_{\text{Majorana}}} M^T_{\text{Dirac}} \quad ; \quad M_{\text{Dirac}} \ll M_{\text{Majorana}}$$

- 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!

Some general properties of sterile neutrino

- Sterile neutrinos are **decaying particles**

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

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

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

- **Mixing angle** θ_I:

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

The scale of right-handed masses?

"Popular" choices of see-saw parameters

- Yukawa couplings $F_{\alpha I} \sim 1$, i.e. Dirac masses $M_D \sim M_t$. Majorana masses $M_I \sim 10^{15}$ GeV.
- Attractive features:
  - Provides a mechanism of baryon asymmetry of the Universe
  - Scale of Majorana masses is possibly related to GUT scale
- This model **does not provide the dark matter particle**
- Alternative? Choose Majorana masses M_I of the order of masses of other SM fermions and make Yukawa couplings small

Alternative: νMSM

- An alternative choice of parameters: make the masses of new fermions of the same order as those of other leptons in the SM
- Such a model is called **Neutrino (extended) Minimal Standard Model** – νMSM for short

The model solves several *beyond the Standard Model problems*

✓ ...explains neutrino oscillations

✓ ...matter-antimatter asymmetry of the Universe

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

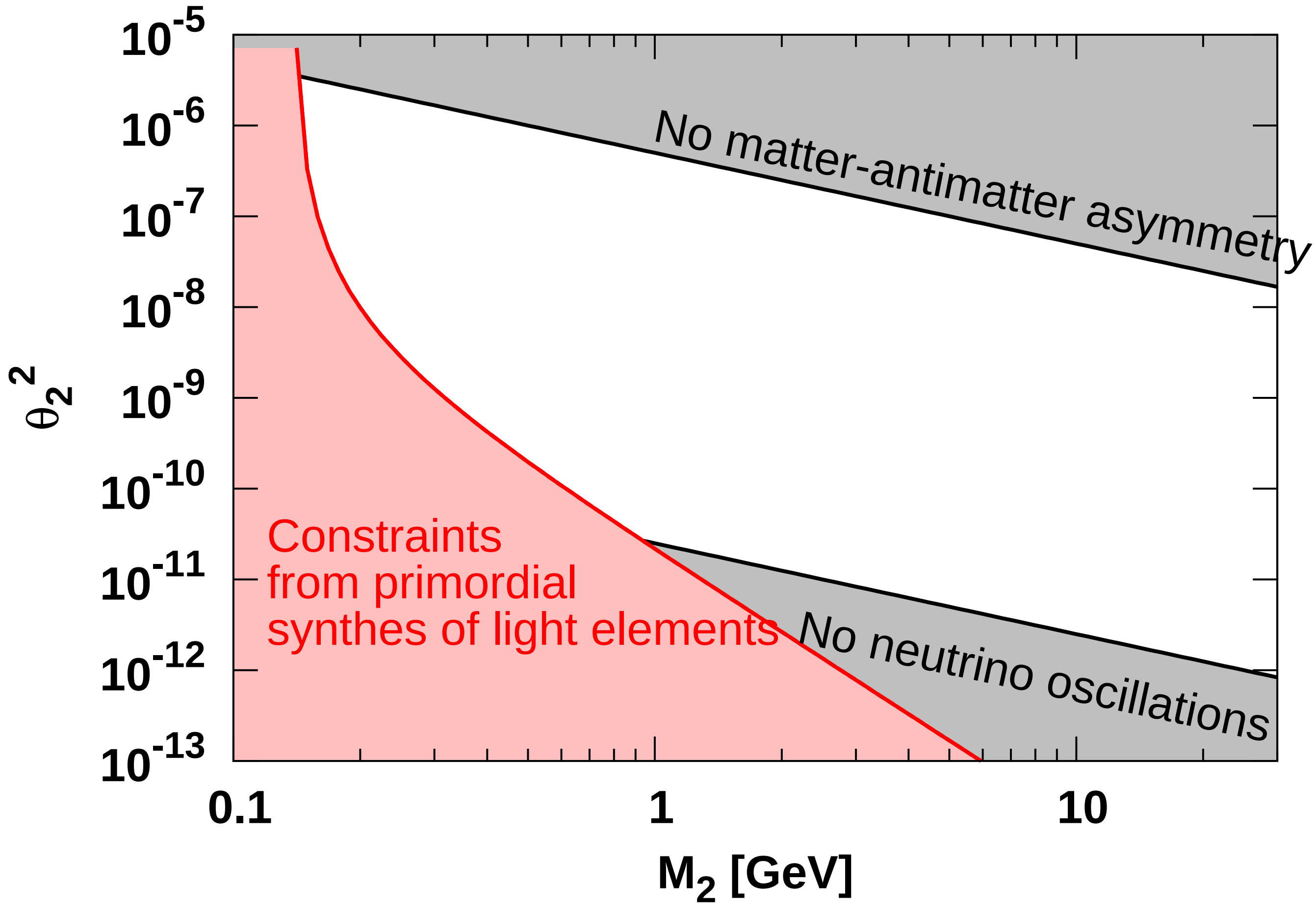
✓ **Provides complete description of the Universe history from inflation till today**

Choosing parameters of the νMSM

Asaka & Shaposhnikov (2005);

Canetti & Shaposhnikov (2010)

- Two sterile neutrinos with $\Delta M \ll M$ can explain neutrino oscillations and provide baryogenesis mechanism



Parameters of the third sterile neutrino?

- The third sterile neutrino can couple to the SM arbitrarily weakly. **Dark matter candidate?**

Dodelson & Widrow (1993)

- Any DM candidate must be
  - Produced in the early Universe and have correct relic abundance
  - Be stable or cosmologically long-lived
  - Very weakly interacting with electromagnetic radiation (“dark”)
  - Allow to explain the observed large scale structure

Shi & Fuller (1998)

Abazajian et al. 2001-2005

Asaka, Shaposhnikov et al. 2005-...

- Sterile neutrino interaction : similar to Standard Model neutrinos but the interaction strength is suppressed by the *mixing angle* θ

$$\theta^2 = \frac{M_D^2}{M_s^2}$$

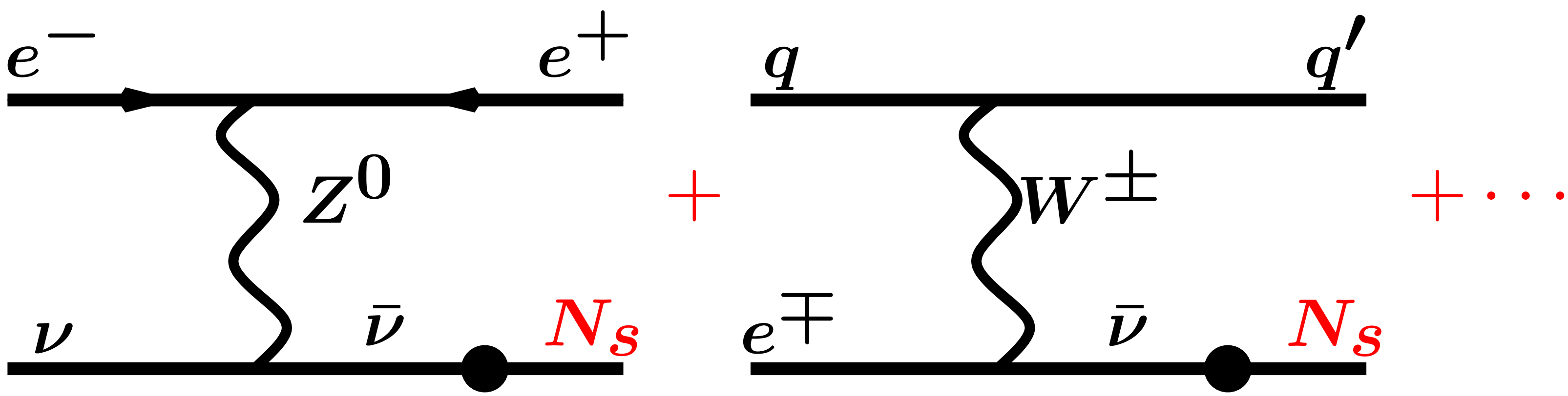
How sterile neutrino DM is produced?

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

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

Dodelson & Widrow'93

Asaka, Laine, Shaposhnikov



- Production is sharply peaked at

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

Production through oscillations

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

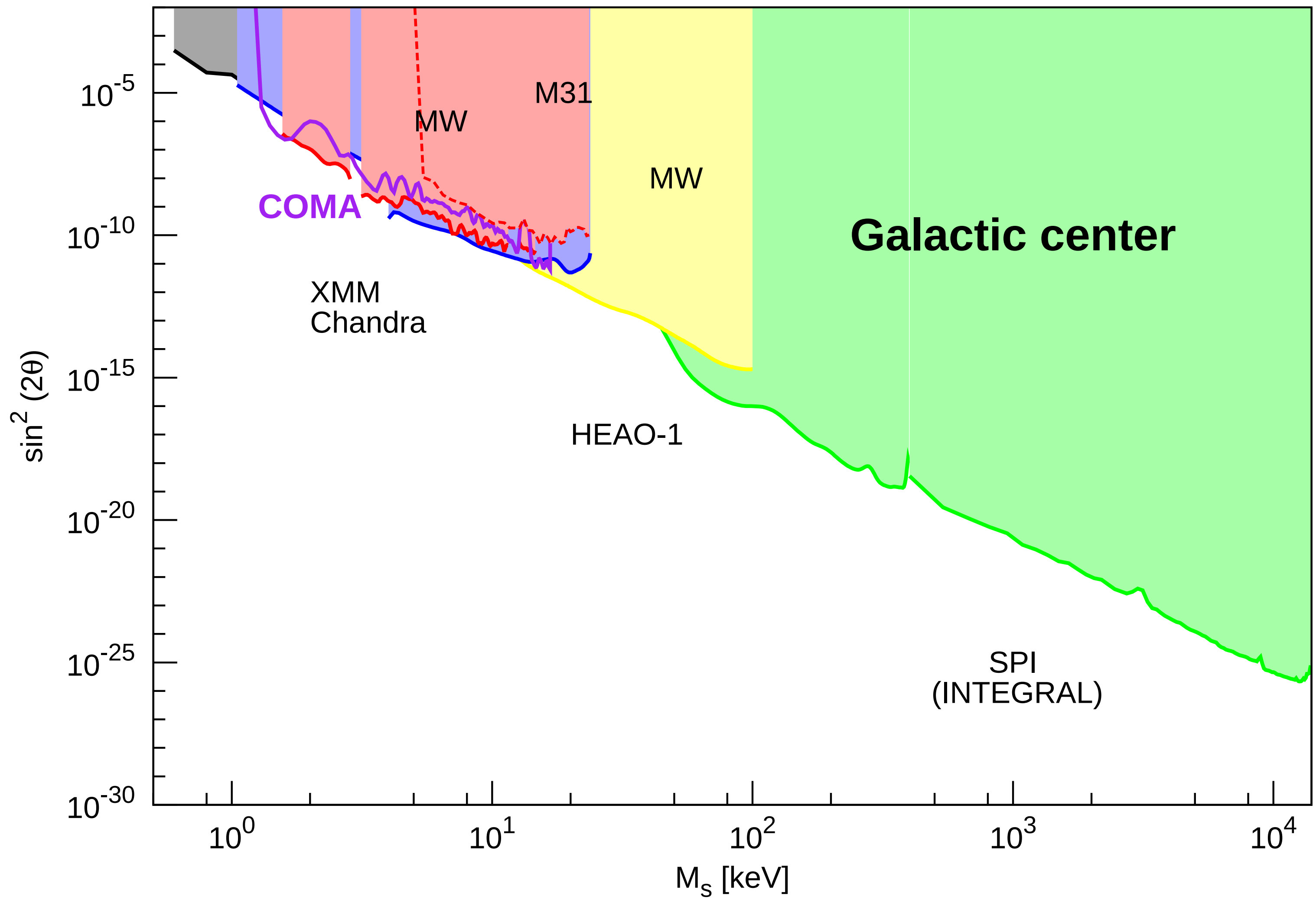
$$f_s(p) \propto \frac{\theta^2}{\exp(\frac{p}{T_\nu}) + 1}$$

- Their amount less than that of active neutrinos

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

- Sterile neutrino decay: ($N \to \nu\nu\bar{\nu}$ or $N \to \nu\gamma$)
- Decay rate: $\Gamma \propto \alpha G_F^2 \sin^2(2\theta) M_s^5$

Bounds on decaying DM from varios objects



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

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

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

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

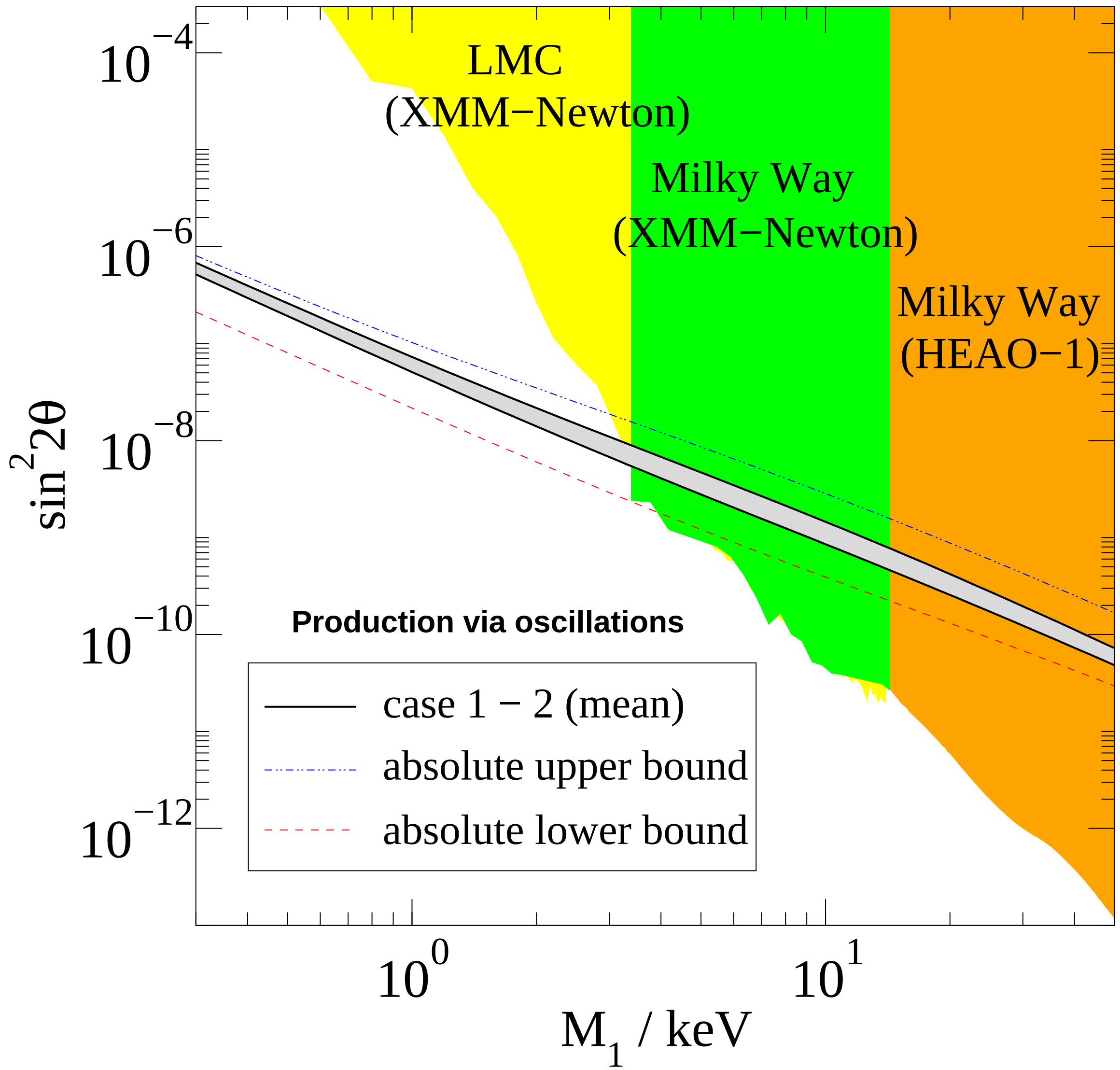
MW Riemer-Sørensen et al.; Abazajian et al.

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

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

Bounds on sterile neutrino mass

Asaka et al. (2006)



Resonant production

- The presence of lepton asymmetry in primordial plasma makes **active-sterile mixing** much more effective (as in MSW effect). Shi & Fuller (1998)

- Lepton asymmetry for this to be effective should be large Laine & Shaposhnikov (2008)

$$L_6 \equiv 10^6 \frac{n_{\nu_e} - n_{\bar{\nu}_e}}{s} \gtrsim 1$$

(present BBN bound $L_6^{\text{BBN}} \lesssim 2500$) Serpico & Raffelt (2005)

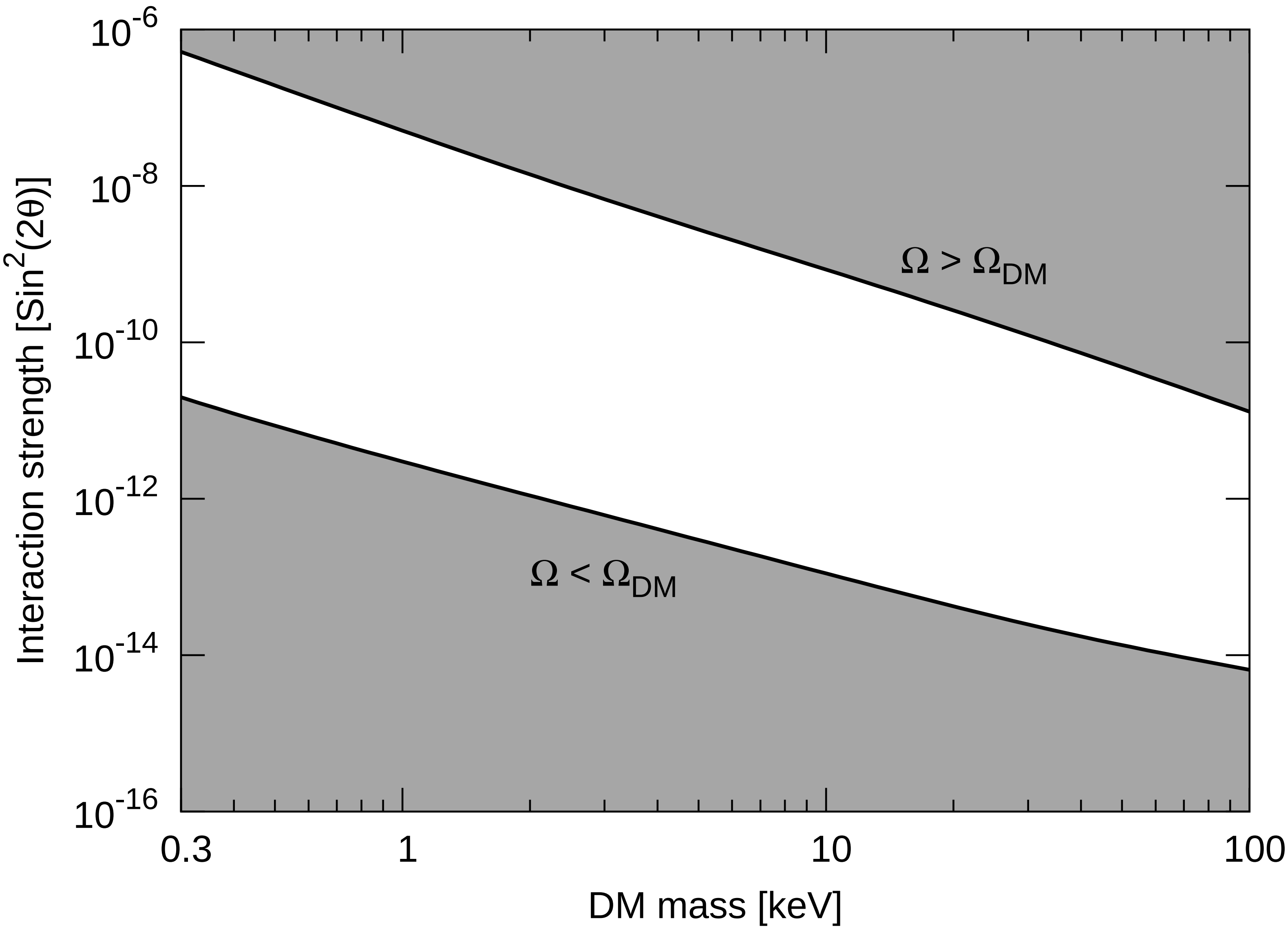
— **resonant production of sterile neutrino**

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

- In the νMSM CP-violating scatterings/decays of sterile neutrinos continue to generate lepton asymmetry **below** the sphaleron scale thus making it significantly large than η_B Shaposhnikov (2008)

Window of parameters of sterile neutrino DM

Laine, Shaposhnikov



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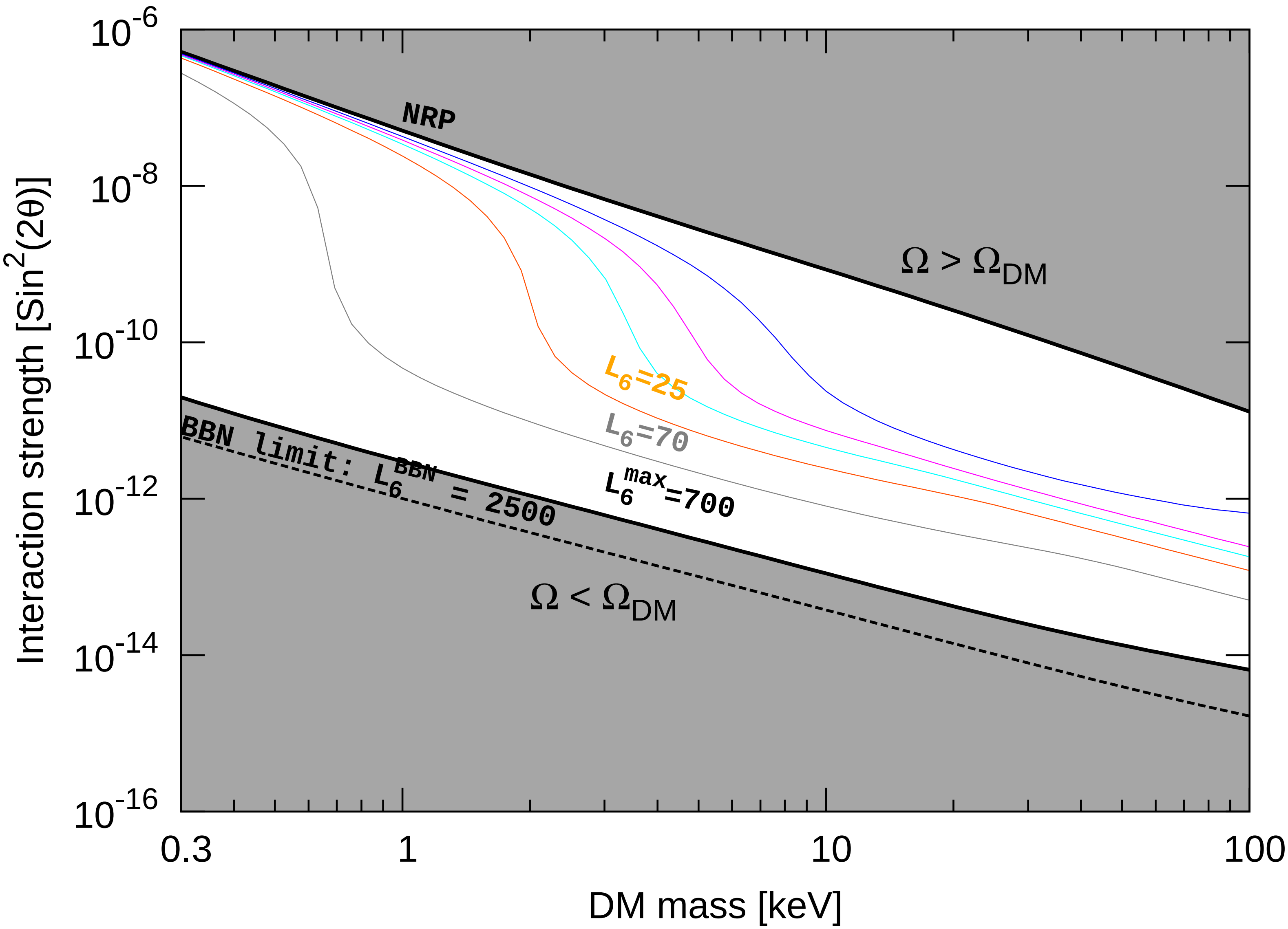
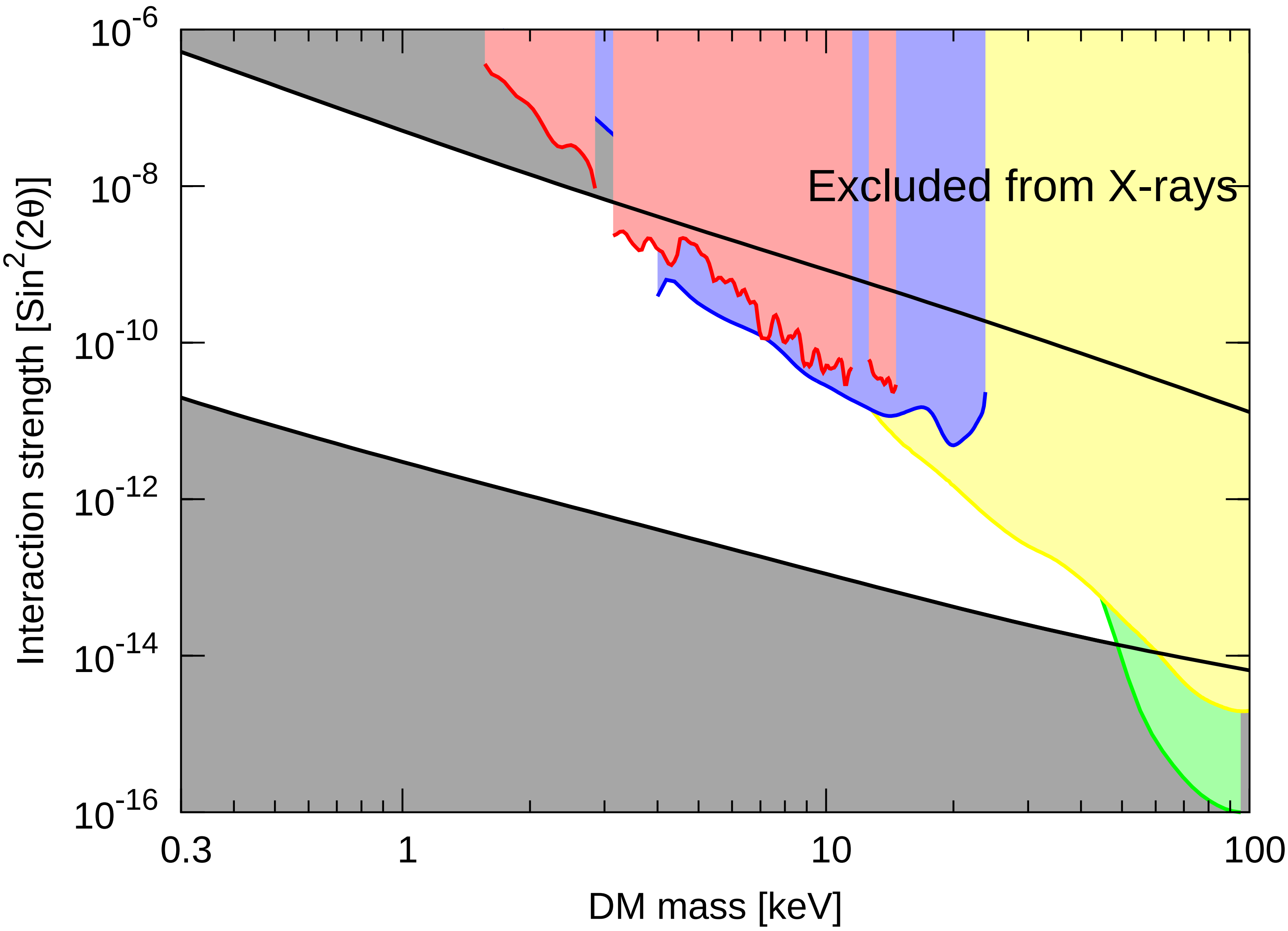


Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov

Window of parameters of sterile neutrino DM

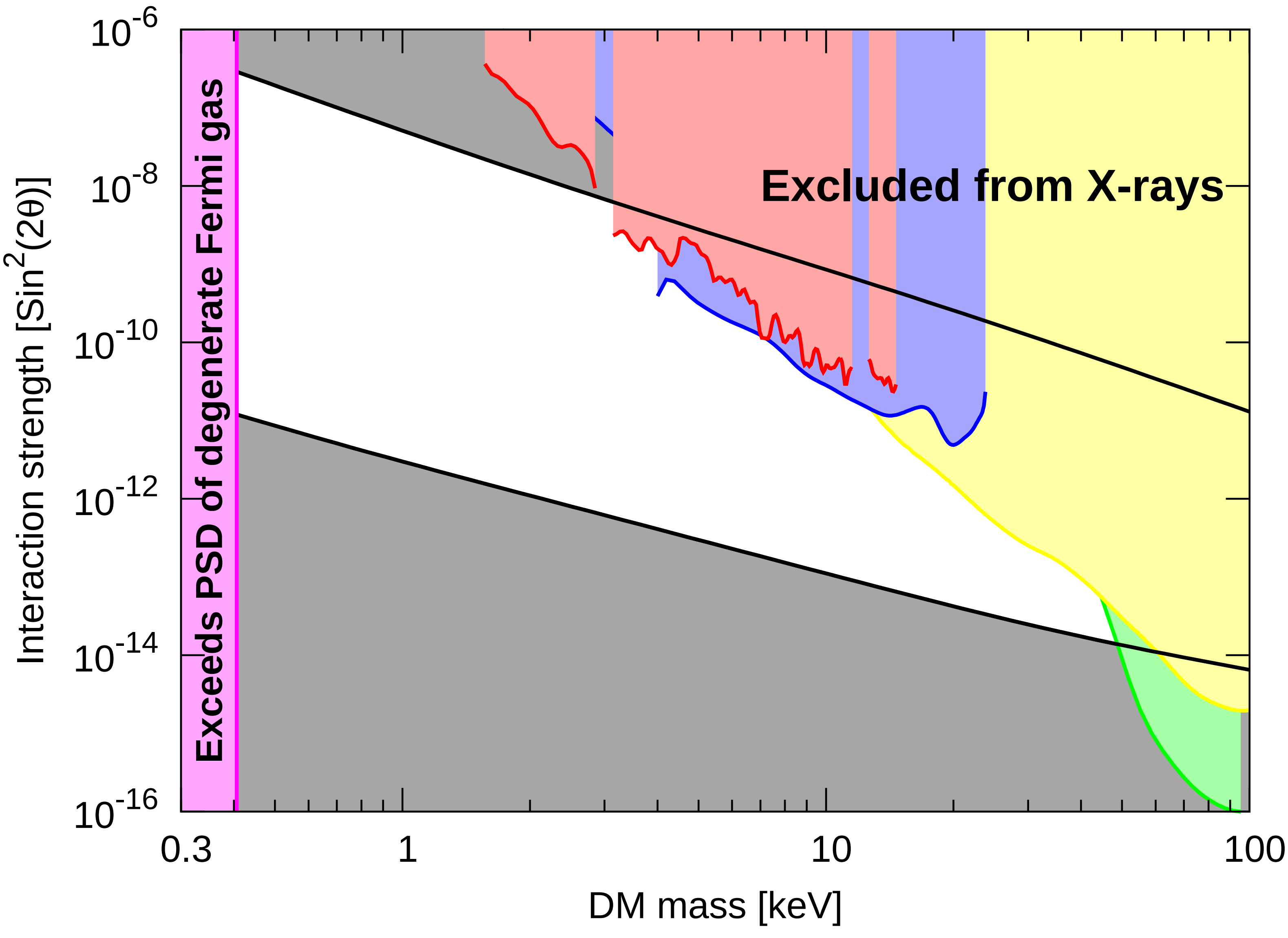


Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov

O.R. and many others 2005-2010

Window of parameters of sterile neutrino DM



Asaka, Laine, Shaposhnikov

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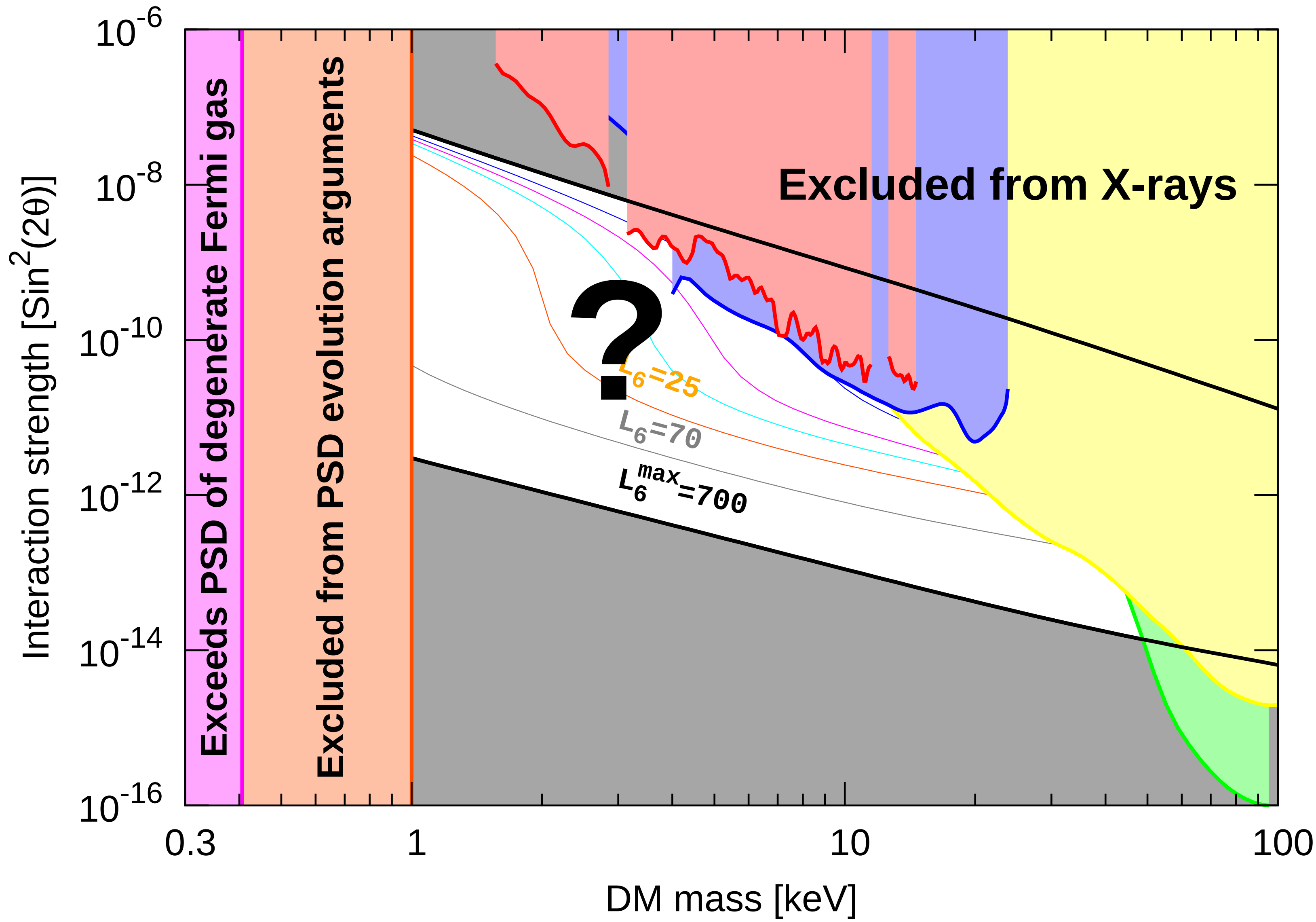
Window of parameters of sterile neutrino DM



Asaka, Laine, Shaposhnikov

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O.R. and many others 2005-2010

Restrictions on life-time of decaying DM

- *Is* $10^{25} - 10^{26}$ *sec a long lifetime? Is it something to be expected?* – Sterile neutrino DM naturally requires $\theta \ll 1$ to provide correct DM abundance for keV (MeV) masses
- *In what situations an upper bound on the lifetime of DM can exist? Should we continue to search?* – If the same interaction was responsible for production of DM particles and their decay, than search for decay signal provides us with valuable restrictions
- In the νMSM – can we push further into the interesting region of low masses (and high lepton asymmetries)?
- . . . These particles were produced relativistic (at the time of production $\langle p \rangle \sim 300 - 500$ MeV mass $\lesssim 50$ keV)

Probing primordial velocities of dark matter particles

Free-streaming and power suppression

- Free relativistic particles do not cluster

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

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

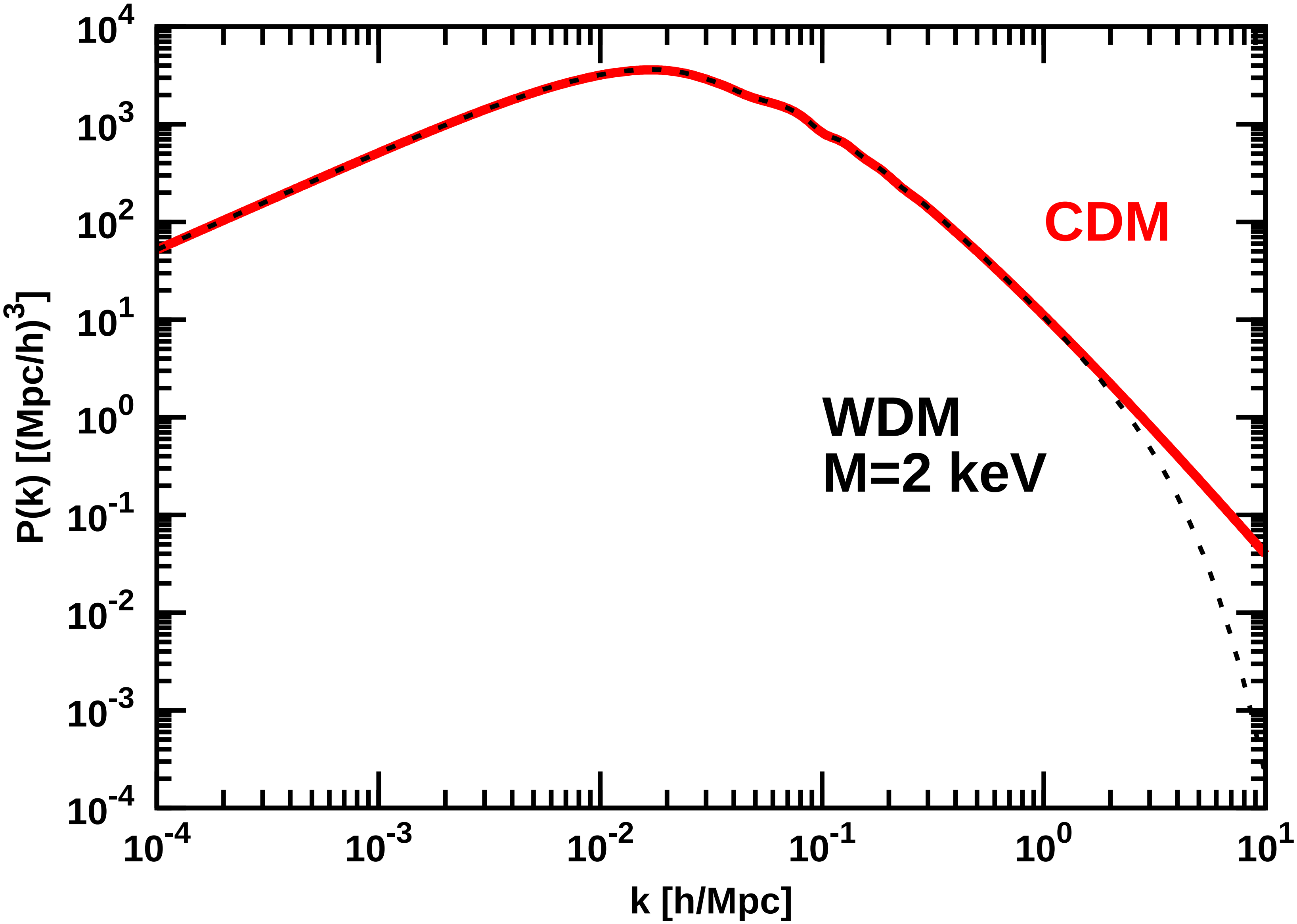
- Comoving free-streaming $\sim$ horizon at the **time of non-relativistic transition t_{nr}** (when $\langle p\rangle \sim m$)

- Free-streaming horizon determines power spectrum suppression scale.

- For particle with Fermi-Dirac spectrum (*thermal relics*) this suppression is strong:

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

Influence of primordial velocities



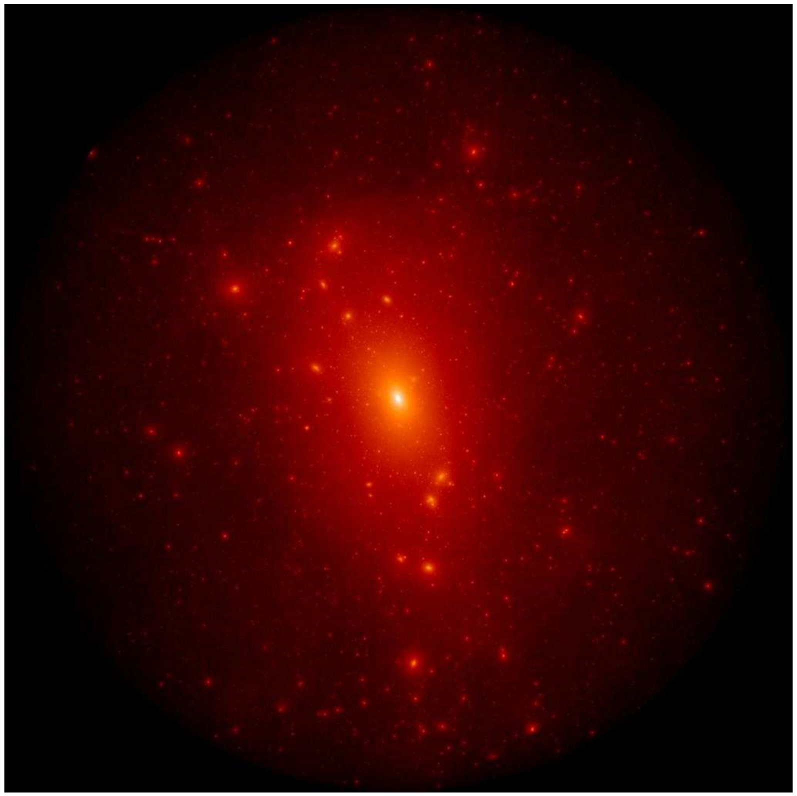
How to probe primordial velocities?

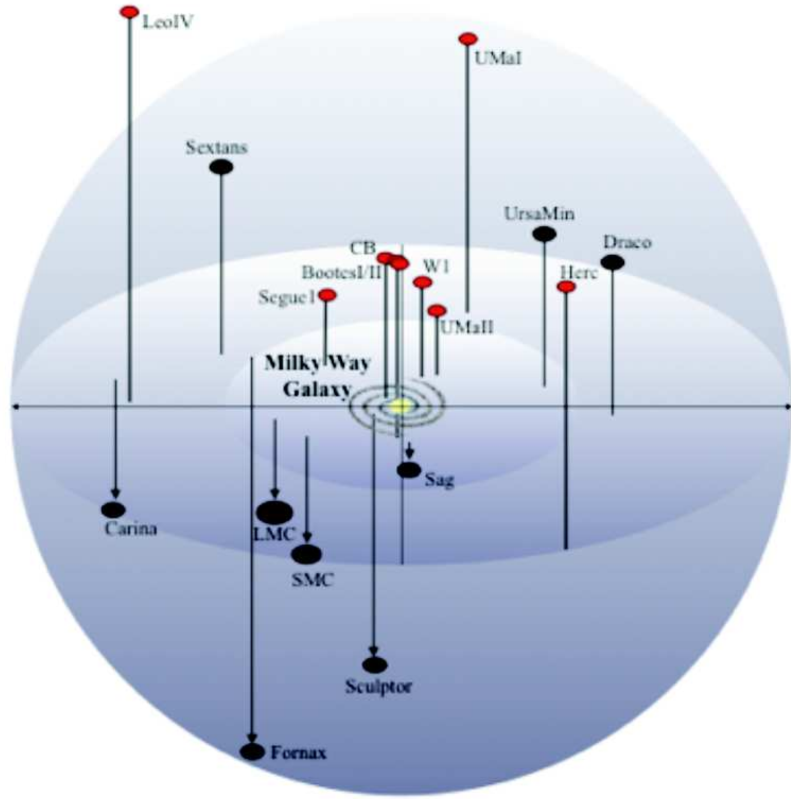
- Primordial velocities **affect**:
  - Power-spectrum of density fluctuations (suppress normalization at large scale)
  - Halo mass function (number of halos of small mass decreases)
  - Dark matter density profiles in individual objects
- Scales probed by CMB experiments (linear regime of perturbation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



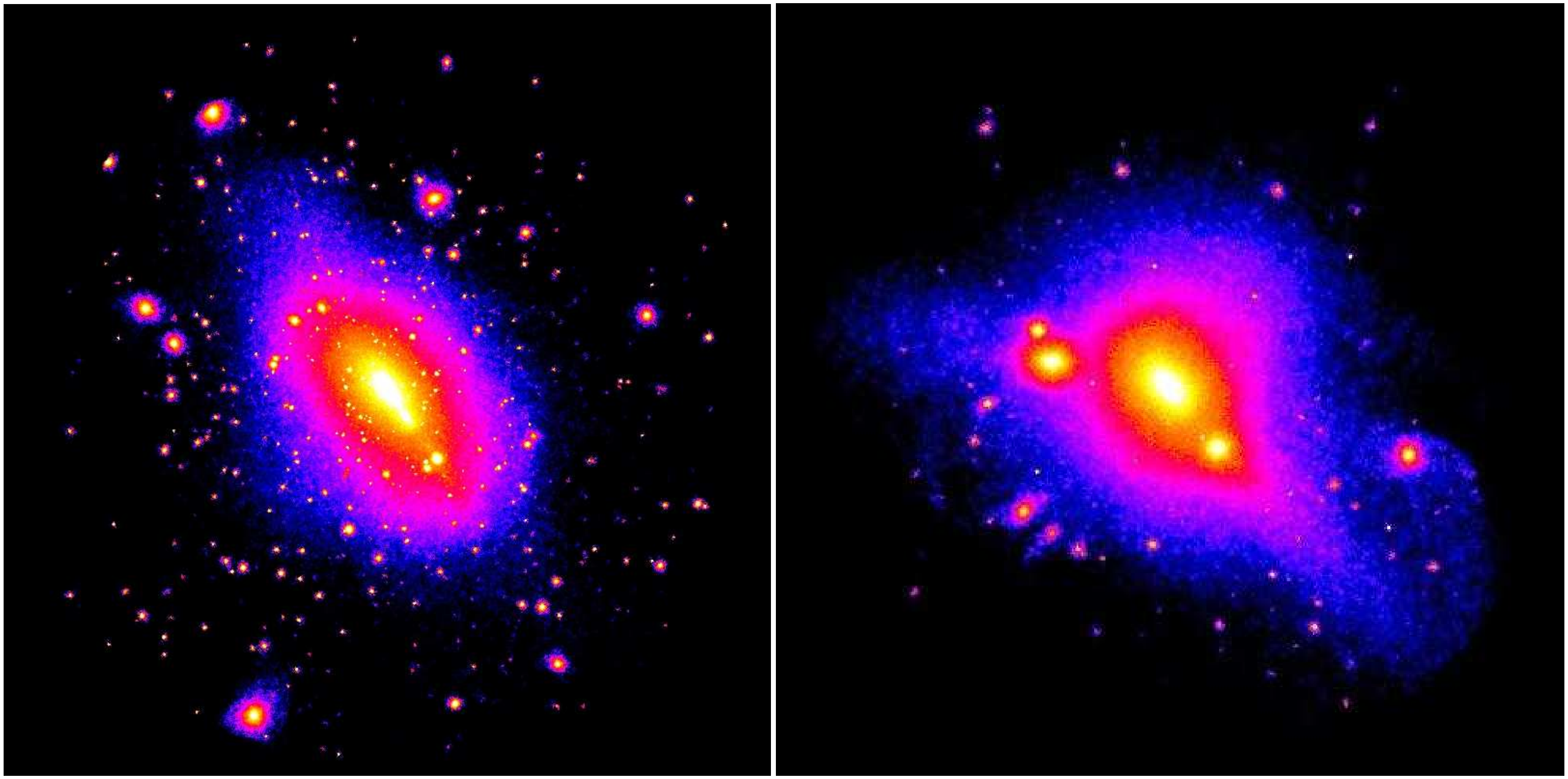


45×10^3 substructures (Aquarius simulation)

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

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

WDM substructure suppression

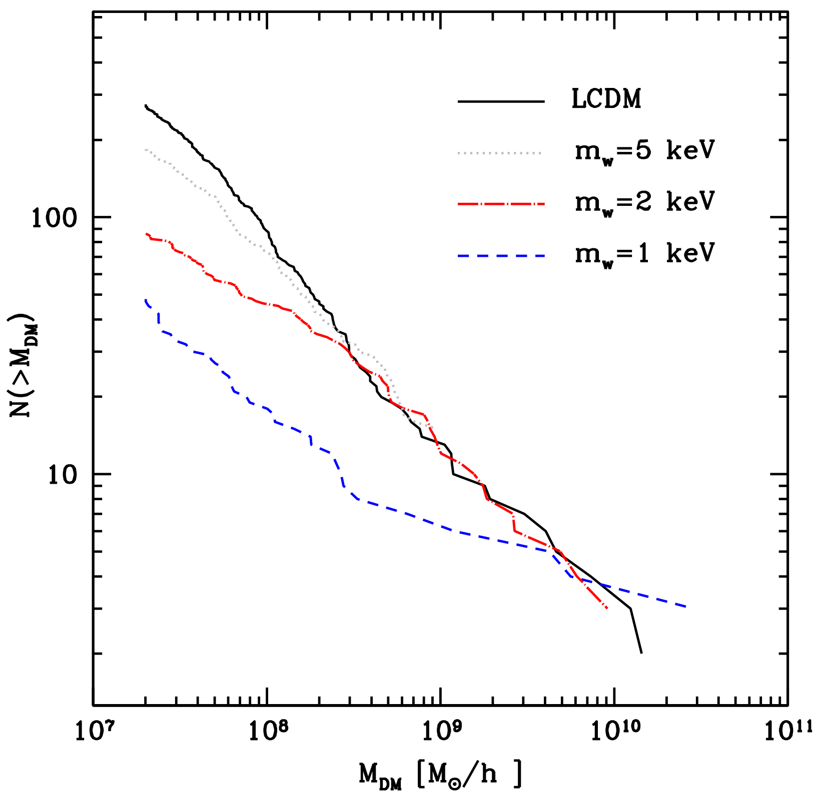


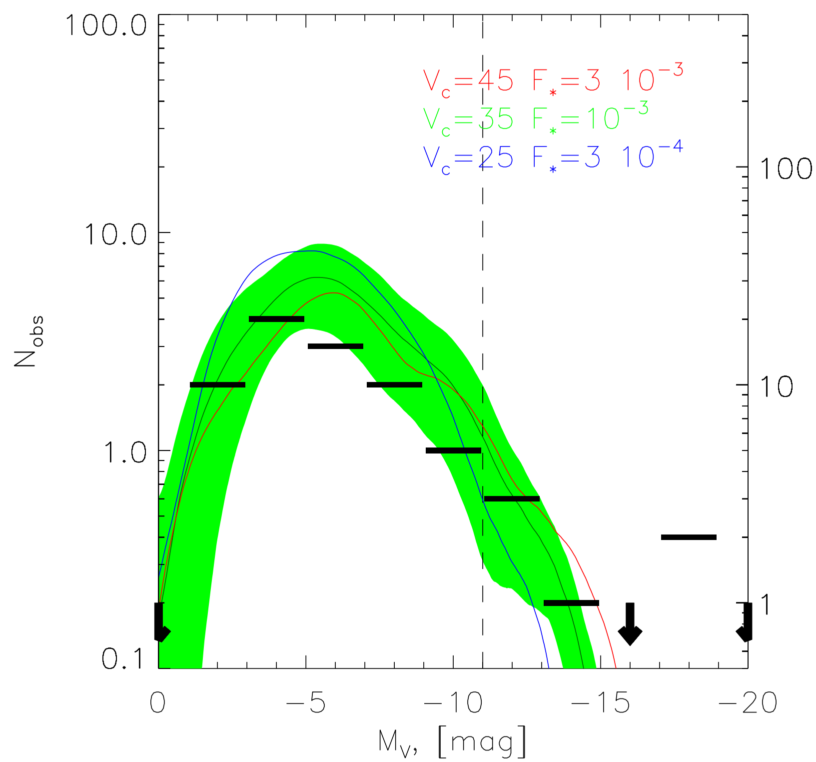
Thermal relics with mass ~ 1 keV would erase **too many substructures**. Anything "colder" would produce enough structures to explain observed Milky Way structures

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?

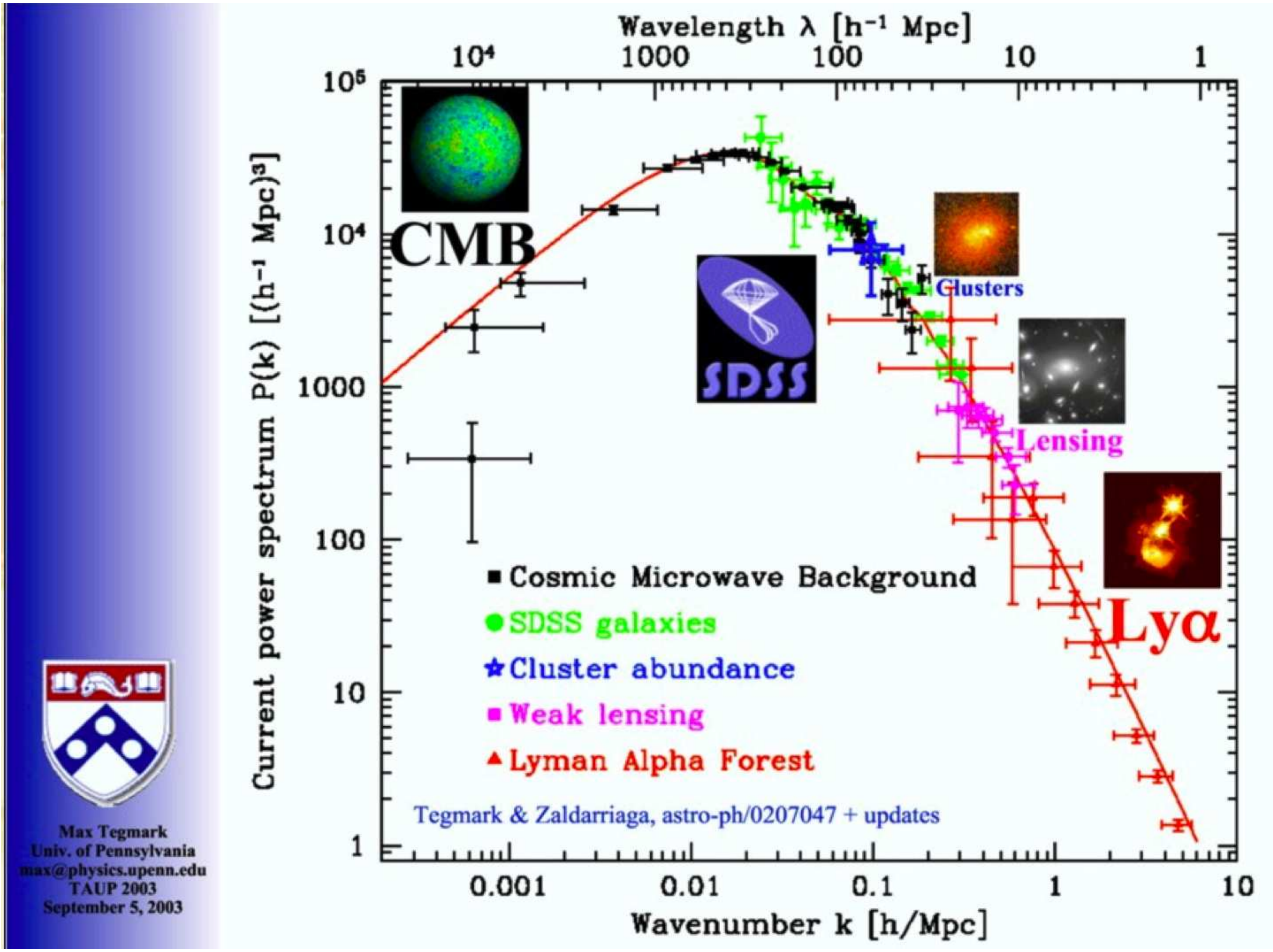
Probing primordial velocities

- Large scale cosmological observations (CMB, LSS – linear stage of structure formation) provide constraints for hot or “very warm” models (with free-streaming on super-Mpc scales)

- Observations of the low mass and low surface brightness dwarf satellites do not provide definitive conclusion about the presence/absence of primordial velocities due to the presence of strong bias between luminosity and mass functions

- The tool that probes formation of structures at Mpc and sub-Mpc scales is the data on the Lyman-α forest.

Power spectrum



Lyman-α forest and cosmic web

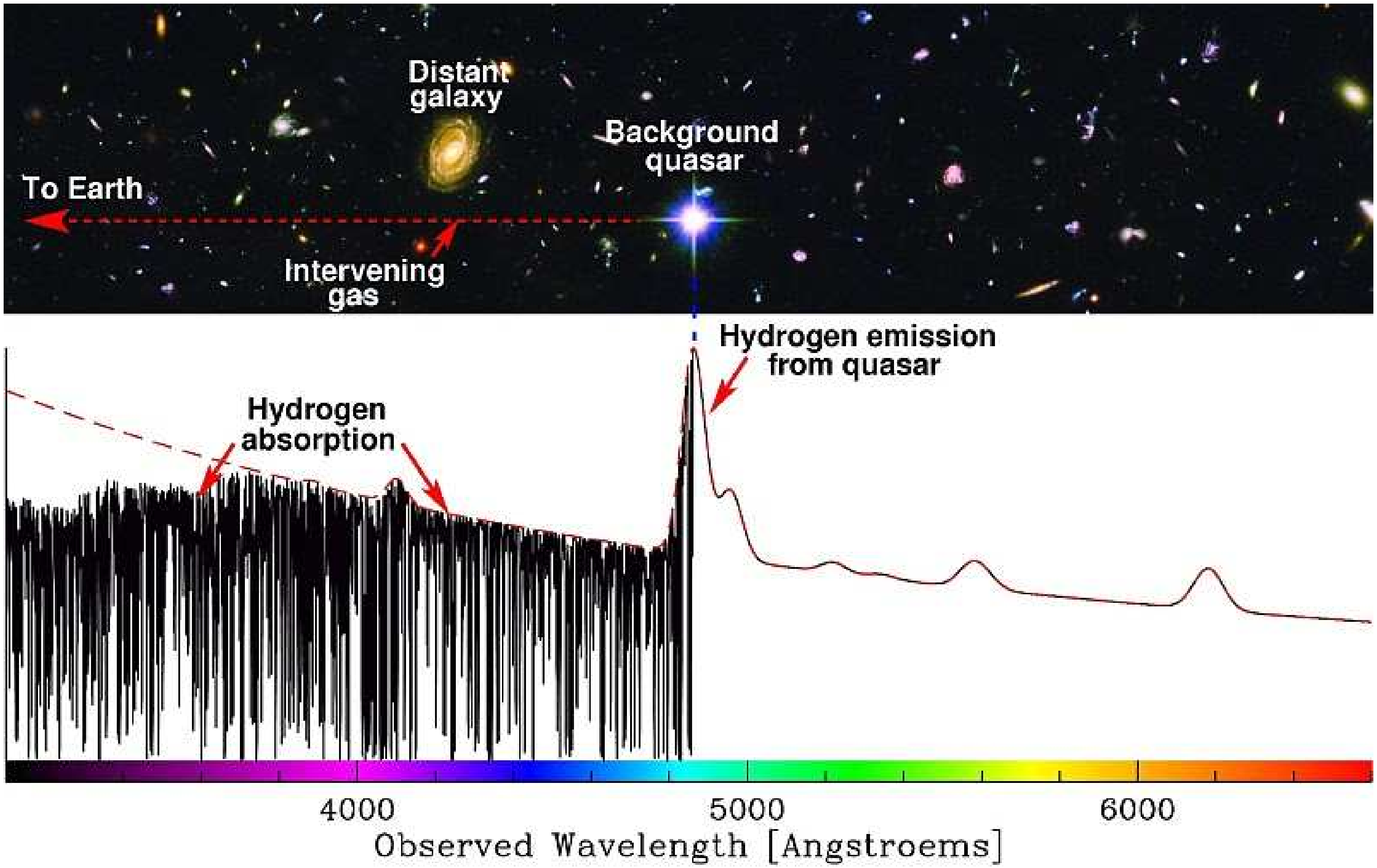


Image: Michael Murphy, Swinburne University of Technology, Melbourne, Australia

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

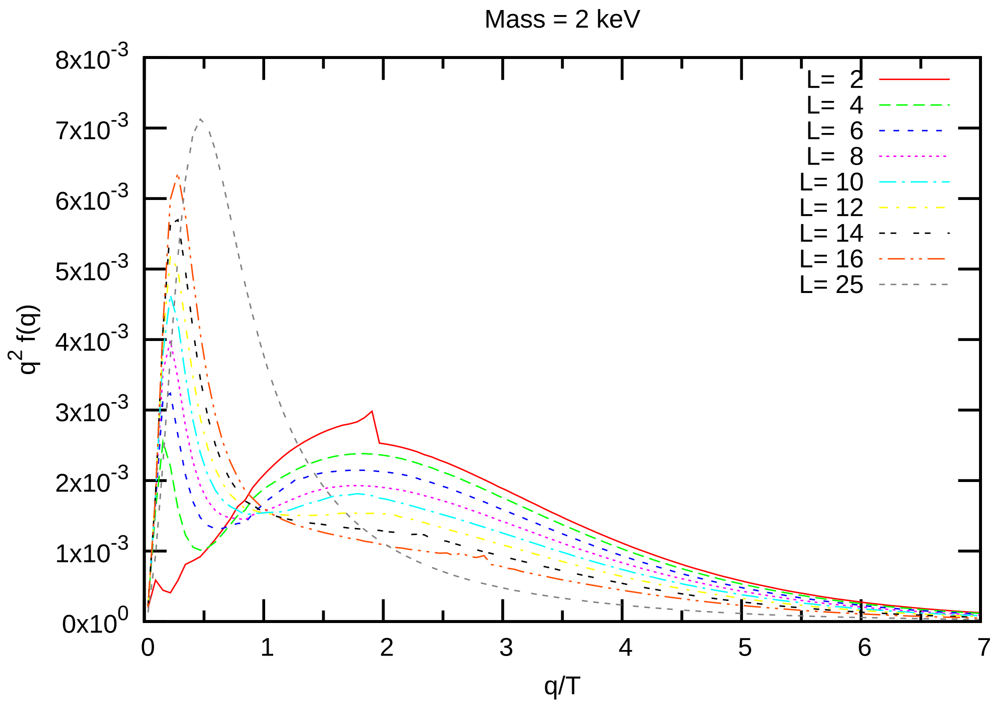
The Lyman-α method includes

- 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)

Main challenge: reliable estimate of systematic uncertainties

Free-streaming of non-CDM models

- For super-WIMPs primordial velocity spectrum carries the information about their production
- In general: not an equilibrium primordial spectrum. In many particle physics models the primordial momentum spectra can be quite complicated. . .



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

Free-streaming of non-CDM models

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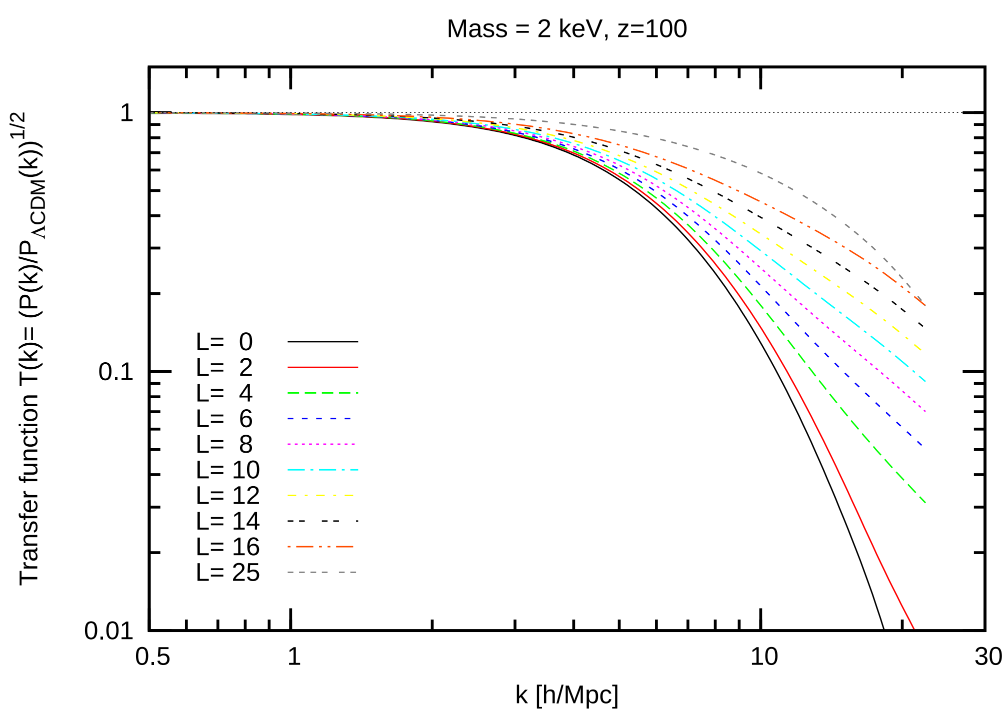

Transfer functions of resonantly produce sterile neutrinos with the mass 2 keV, produced at different lepton asymmetries

Free-streaming of non-CDM models

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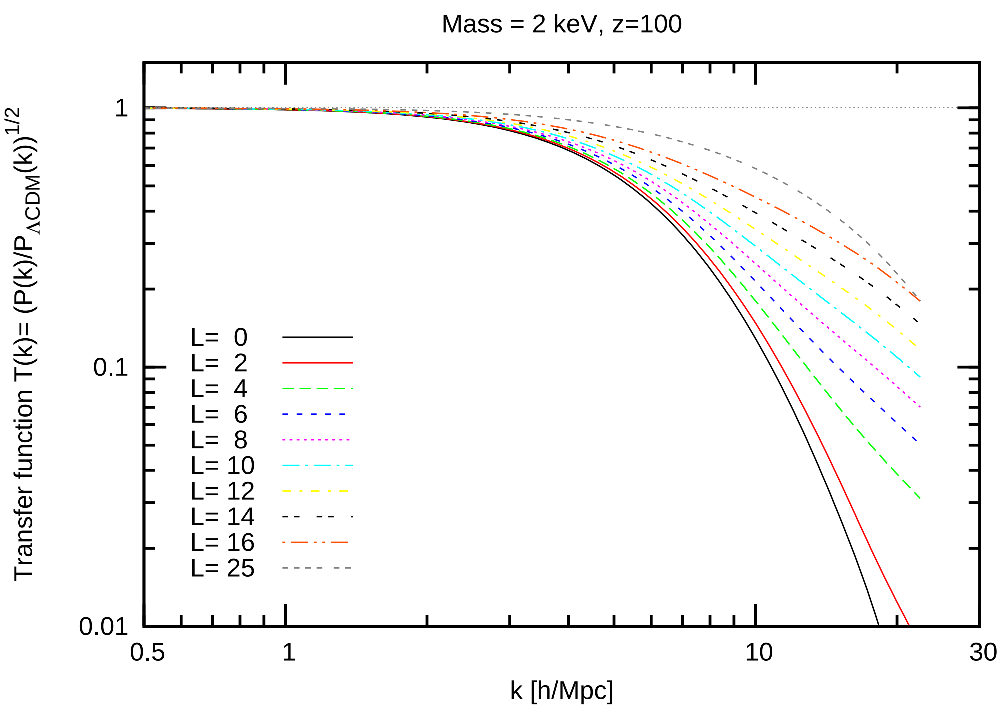
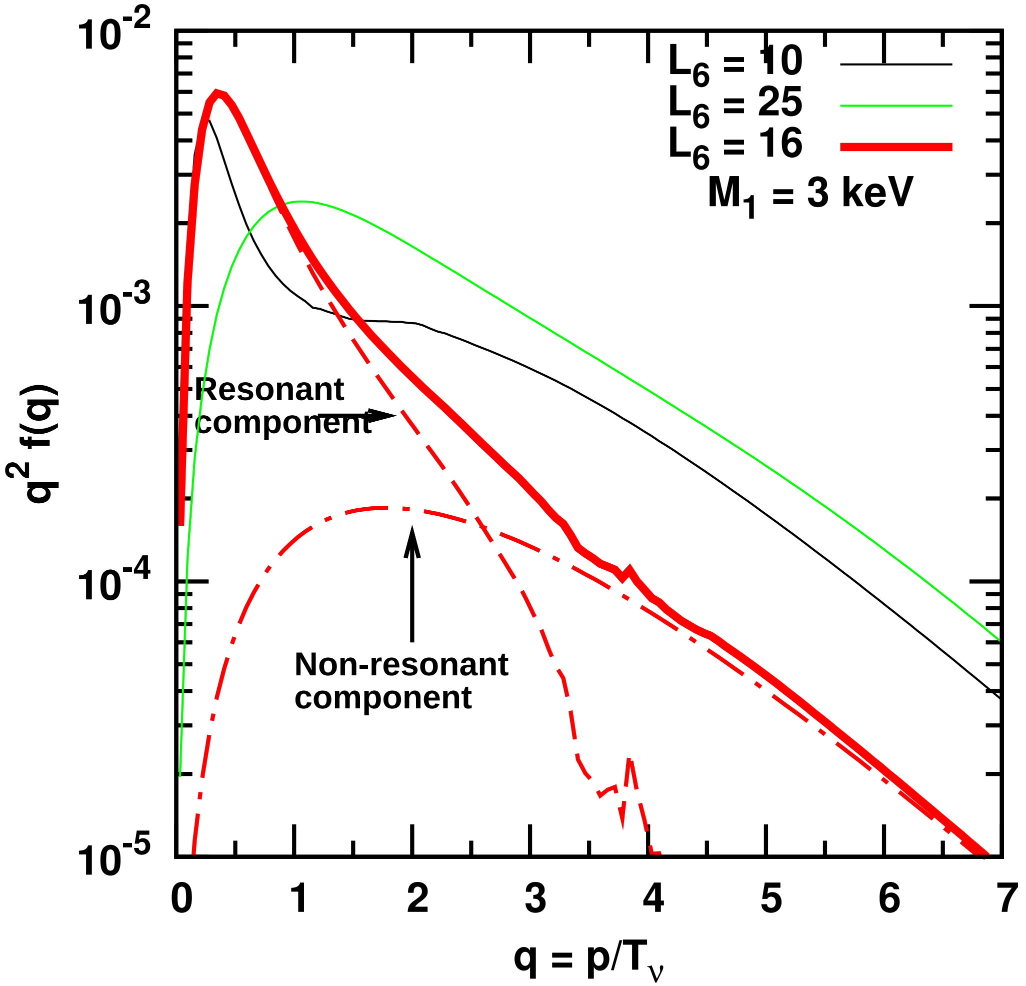


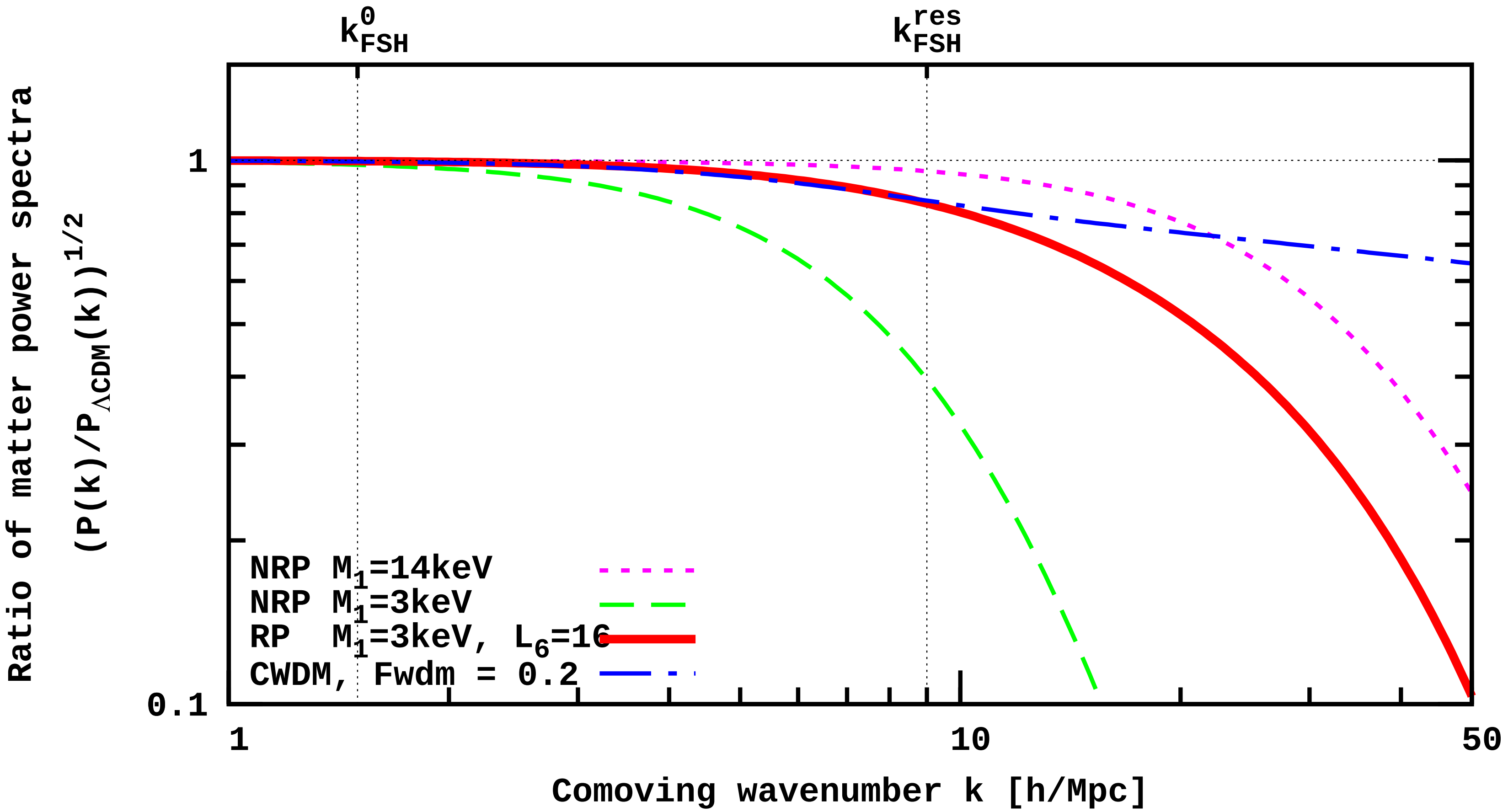
How to perform Lyman-α analysis for all these models?

RP sterile neutrino spectra



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

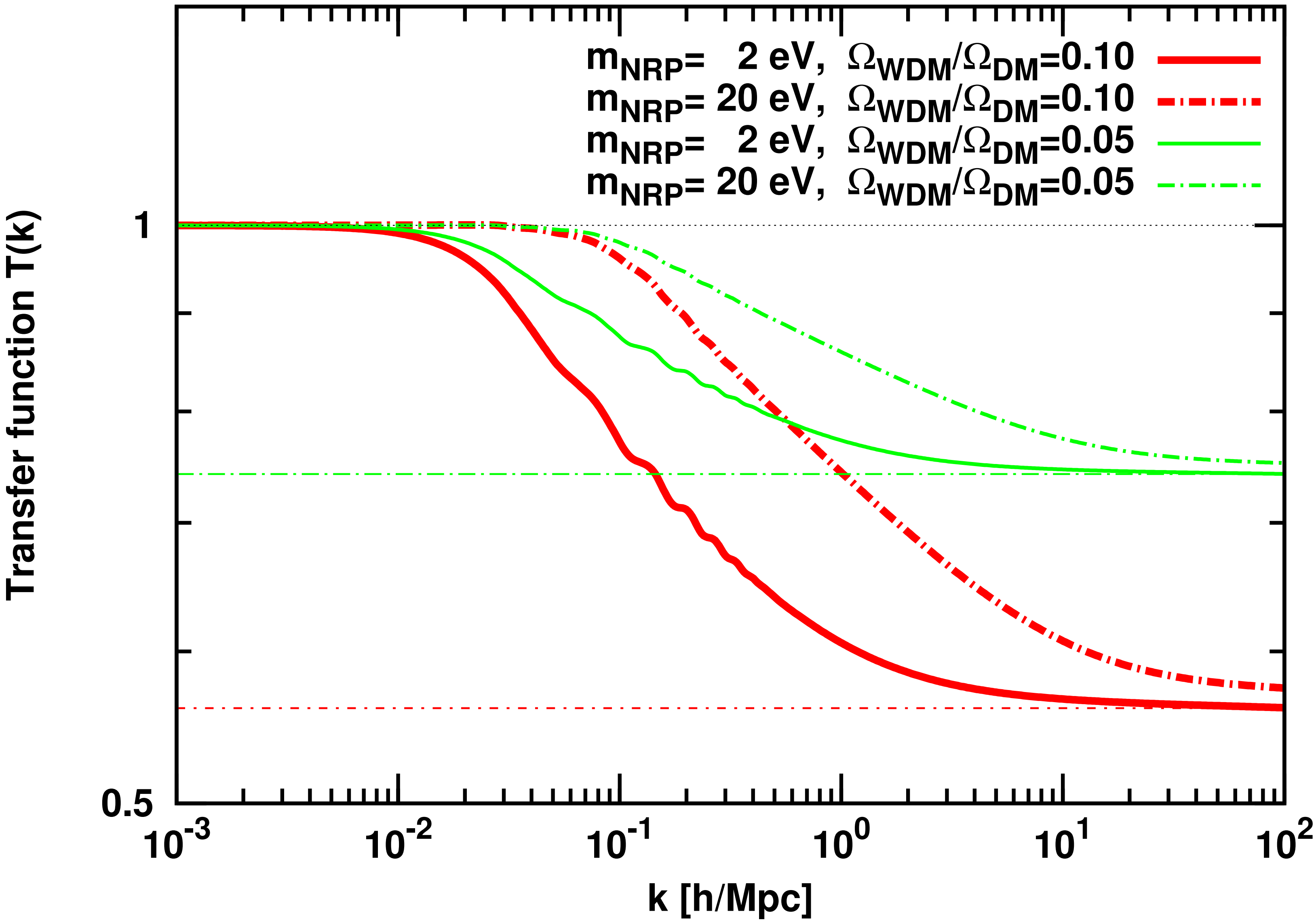
Power spectrum for sterile neutrinos



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

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

Power spectrum for CWDM models

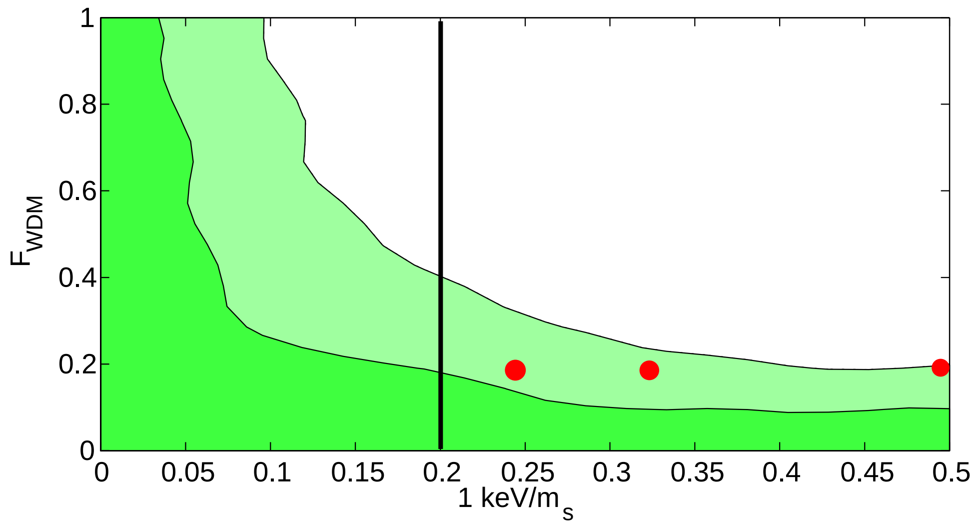


Lyman-α forest and warm DM

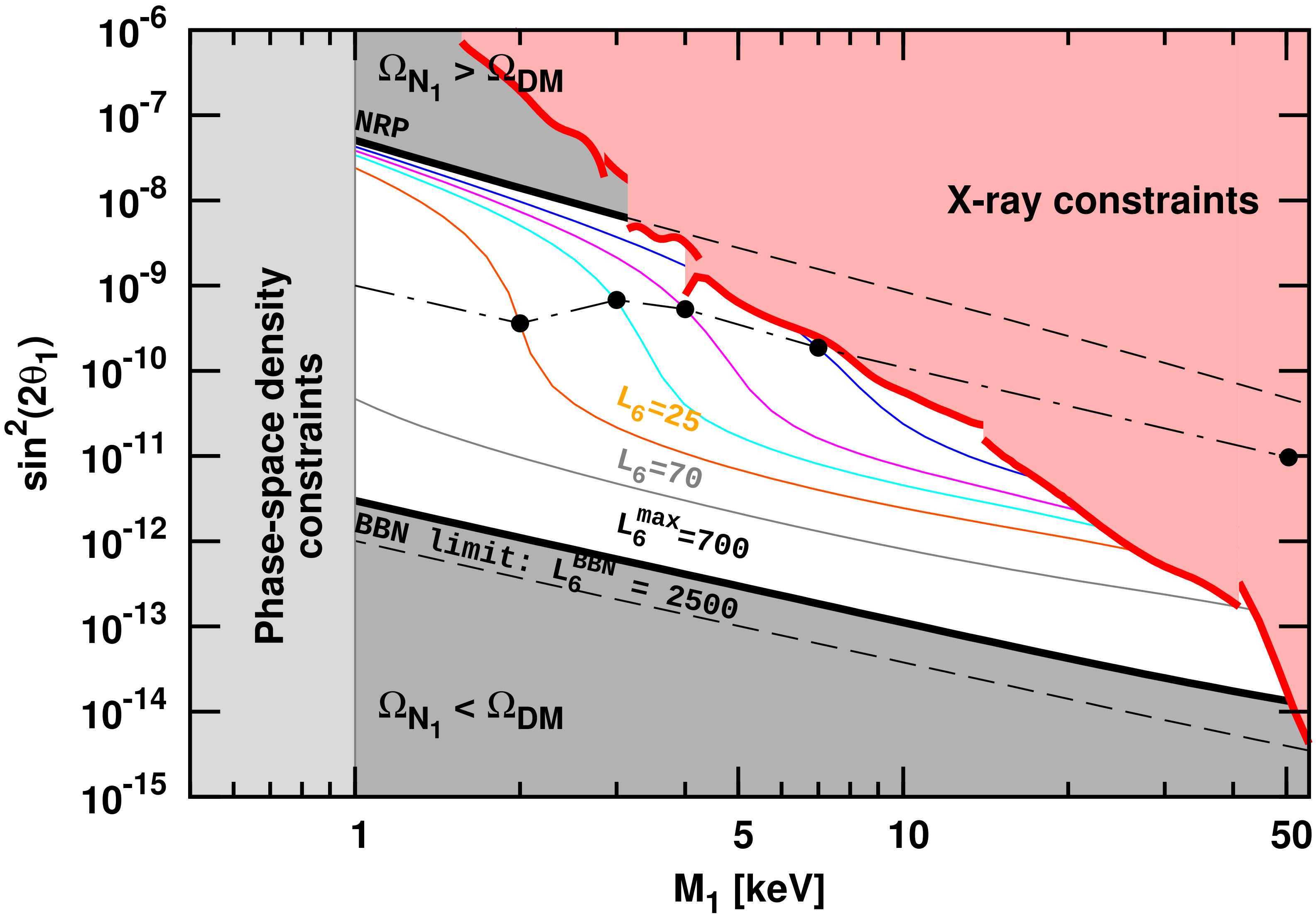
- Previous works put bounds on free-streaming $\lambda_{FS} \lesssim 100$ kpc ("WDM mass" > 10 keV)
- Pure warm DM with such free-streaming would not modify visible substructures
- Revised version of these bounds in CDM+WDM (mixed, CWDM) models demonstrates that
  – The primordial spectra are not described by free-streaming
  – There exist viable models with the masses as low as 2 keV

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

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



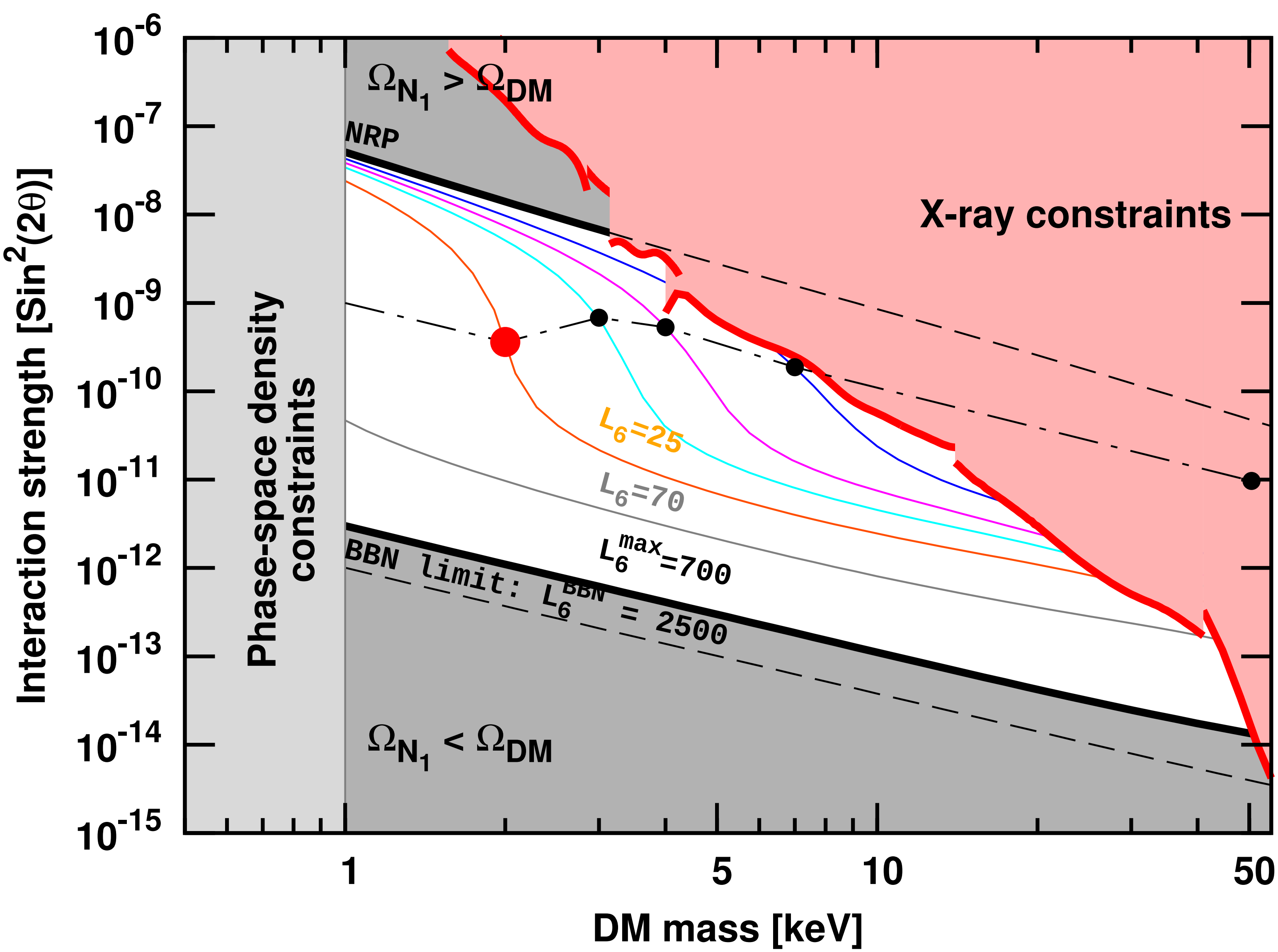
Sterile neutrino DM



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

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

Sterile neutrino DM in the νMSM

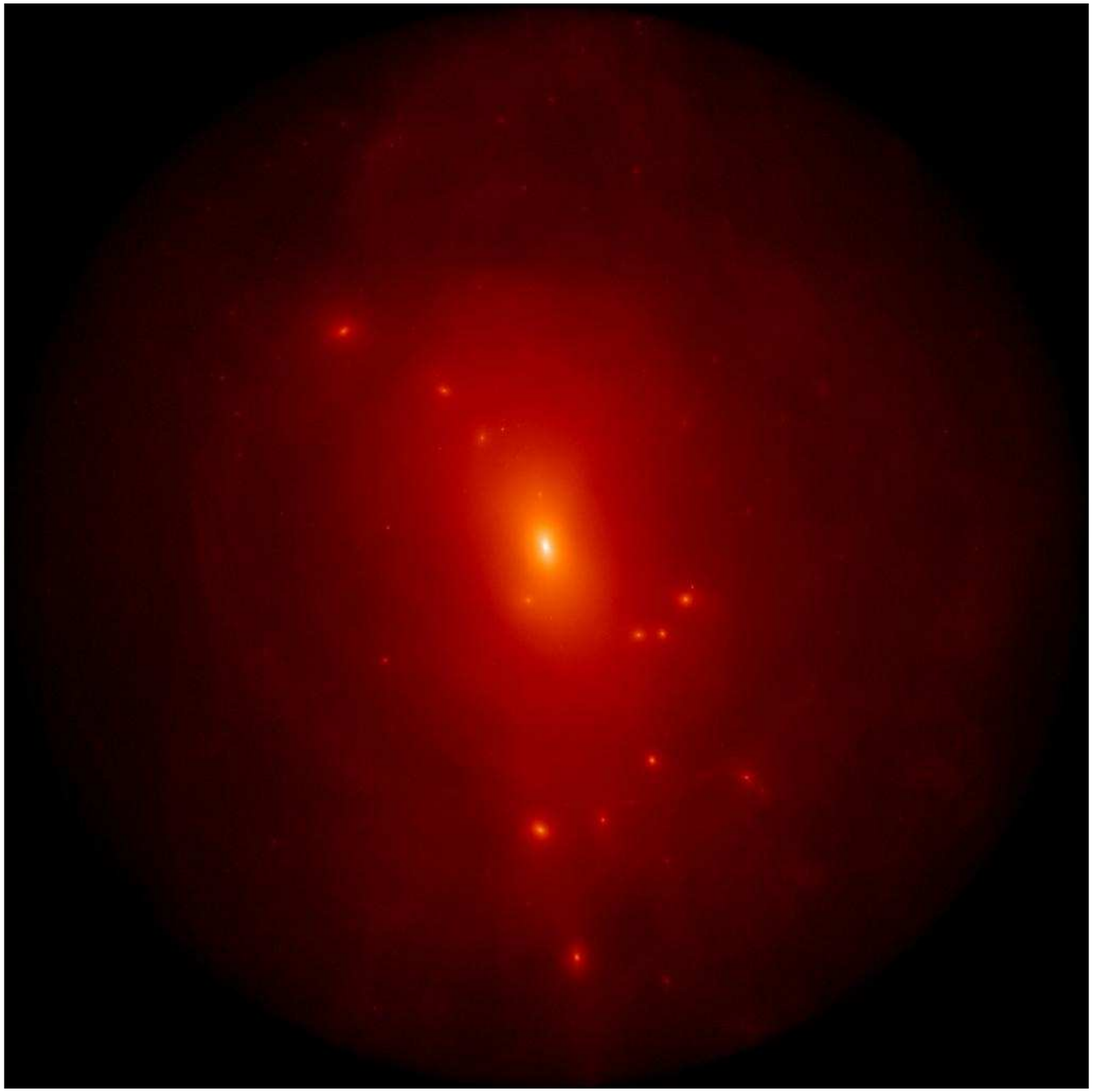


Boyarsky, **O.R.**, Lesgourgues, Viel PRL (2009)

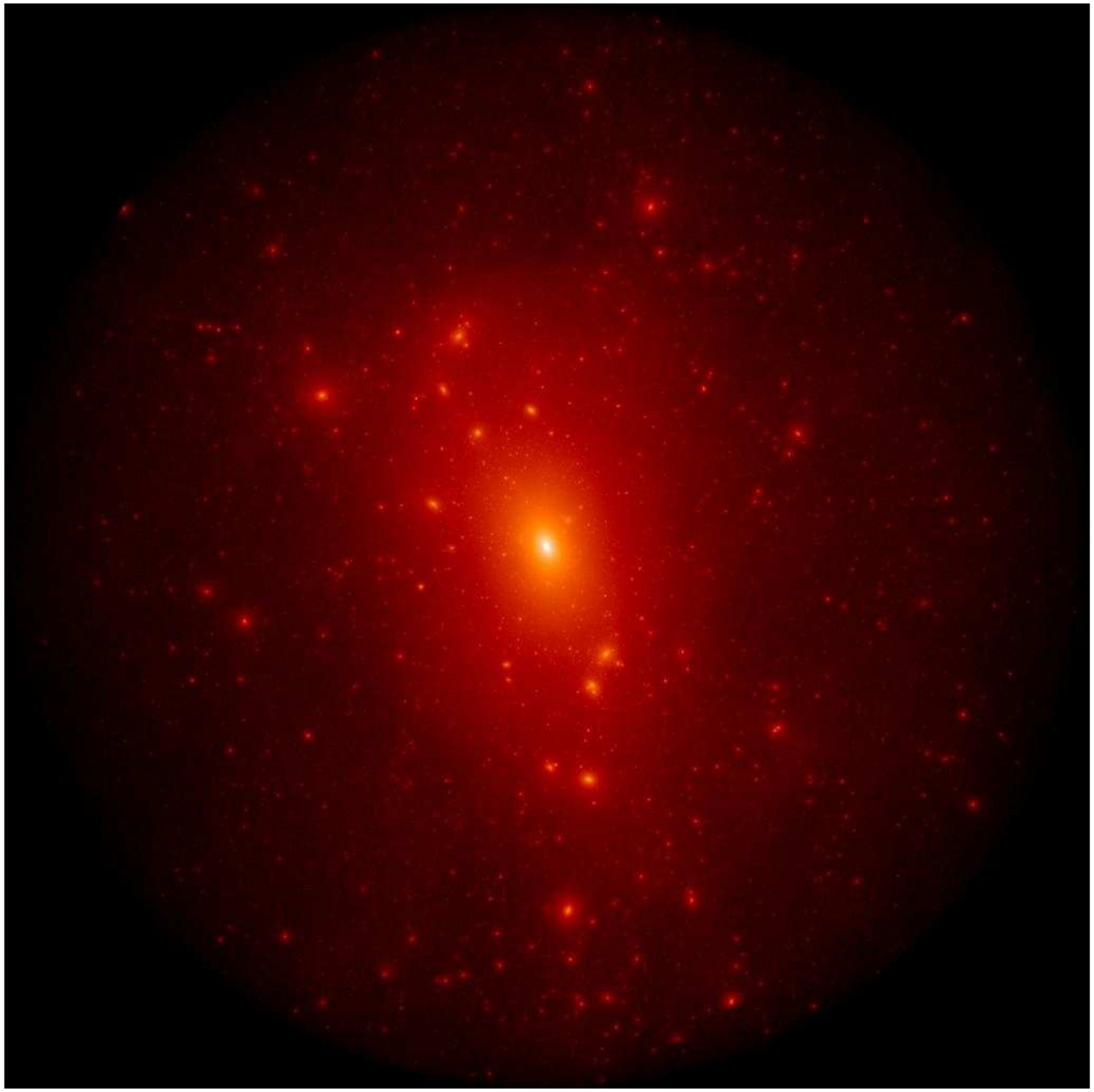
Boyarsky, **O.R.**, Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009)

Halo (sub)structure in CDM+WDM universe

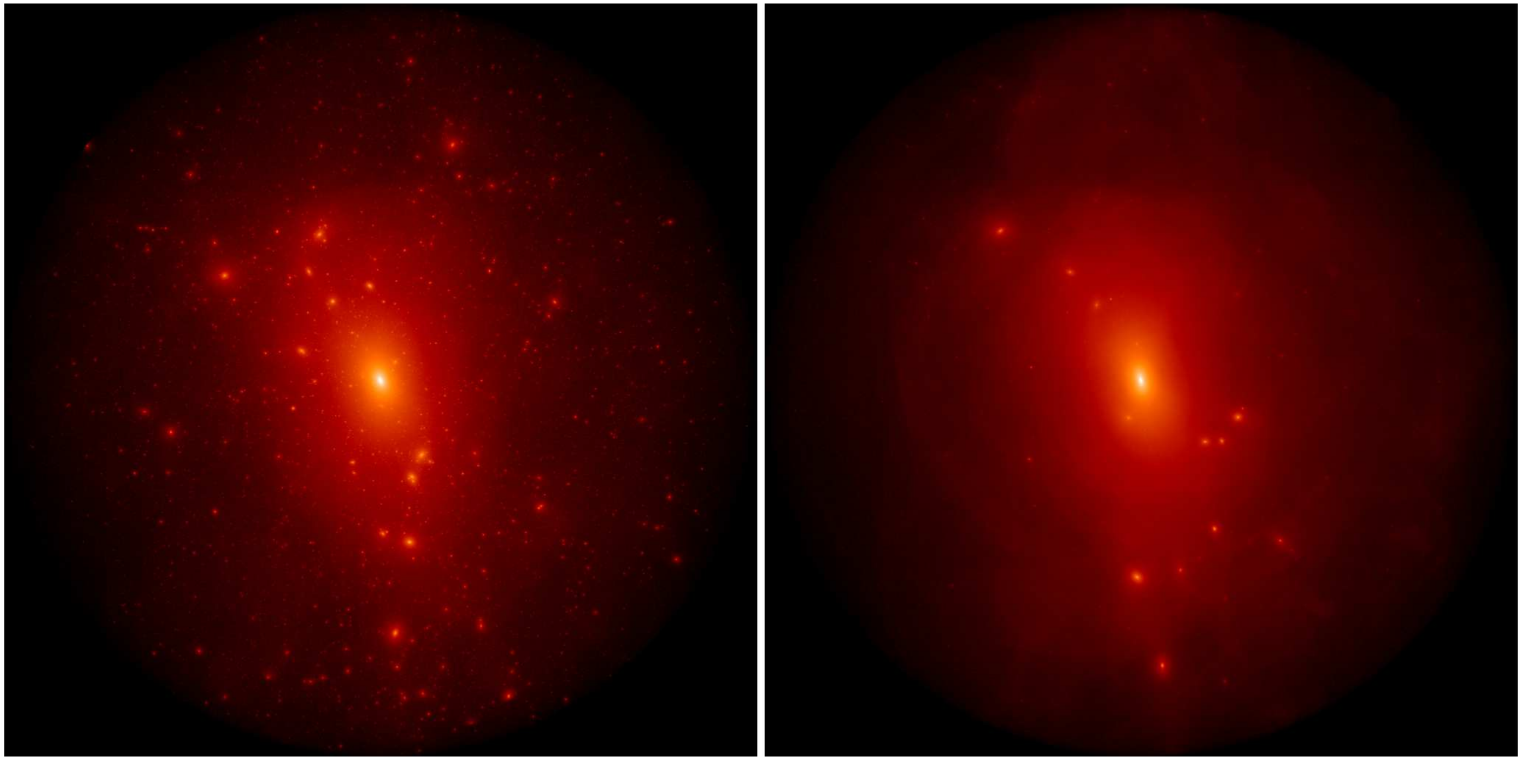
work in progress



Halo (sub)structure in CDM universe



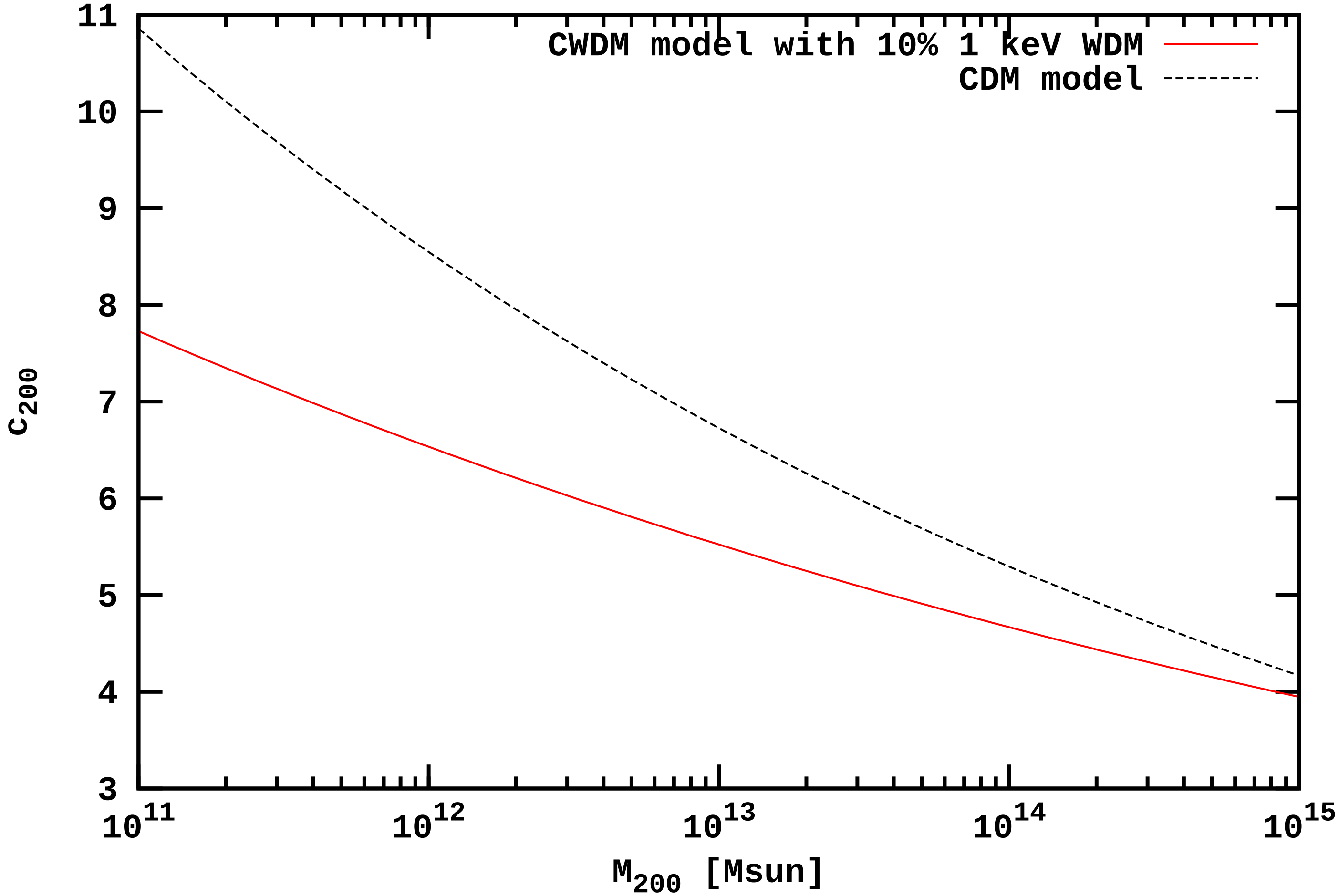
Halo (sub)structure in CDM+WDM universe



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

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

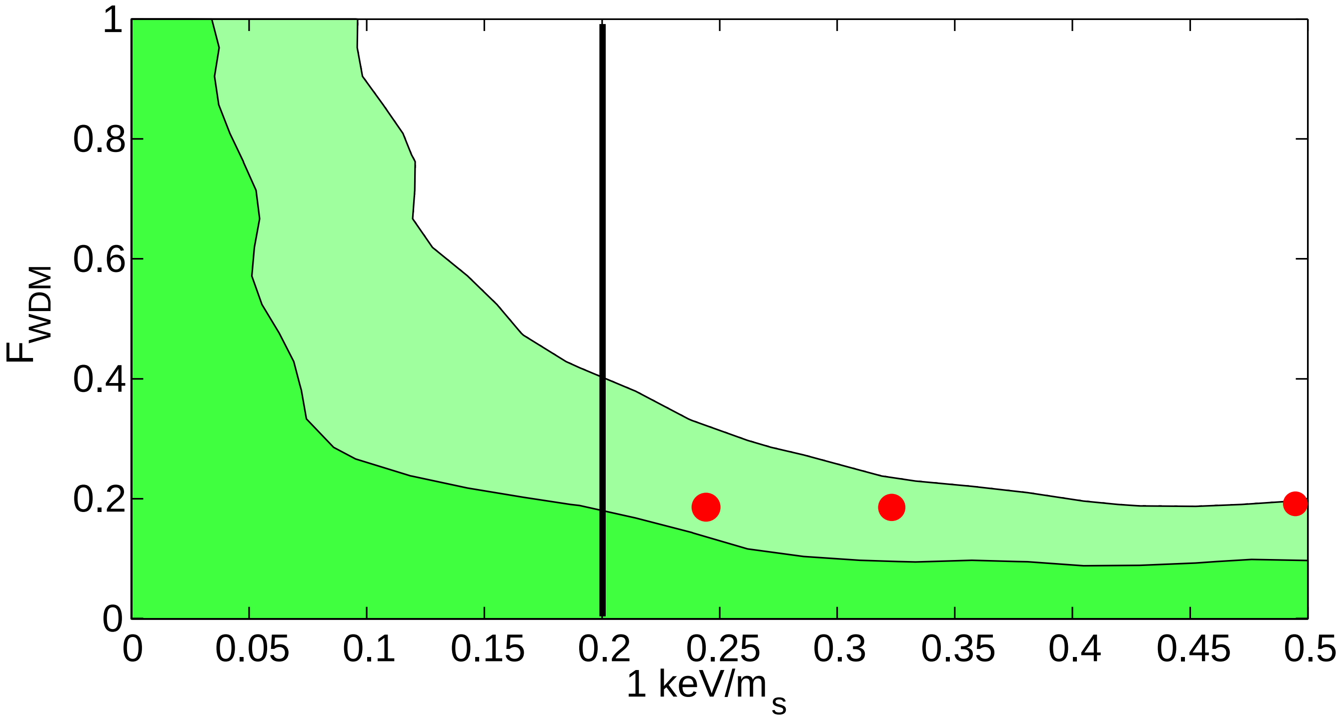
c-M relation in CWDM universe



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

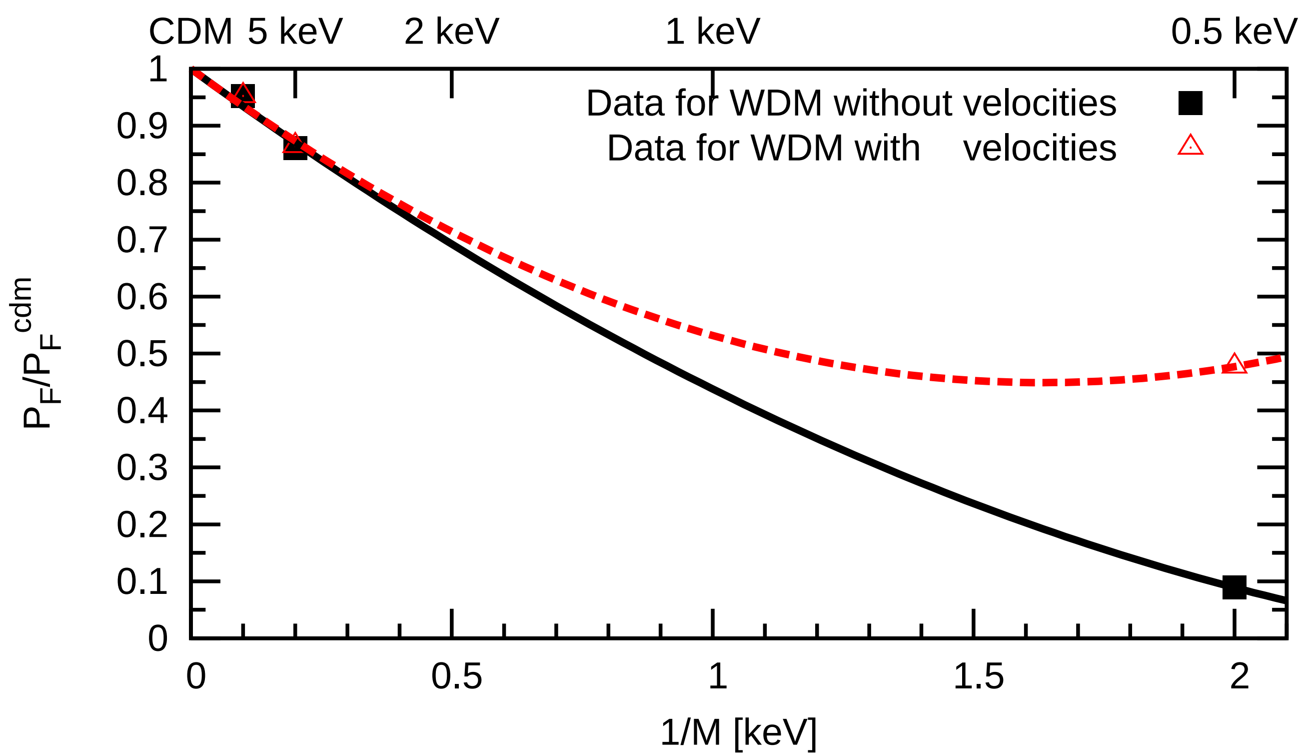
Lyman-α analysis in CWDM models

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



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

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

Cosmological magnetic fields

- At temperatures below ~ 80 TeV all left and right-chiral components have the same amount (although for leptons $m \ll T$, the chirality flipping processes are extremely fast and efficient)

- Generation of lepton asymmetry in the νMSM creates left-right asymmetry between "active" (ν) and sterile (N) neutrinos. As a result asymmetry between left and right electrons is induced

- The difference of chemical potentials leads to the instability in Maxwell equations:

$$\mathrm{curl}\,\vec{H} = \Delta\mu\vec{H} + 4\pi\sigma\vec{E} \Longrightarrow \vec{H}_+ \propto e^{\frac{\Delta\mu^2 t}{\sigma}}$$

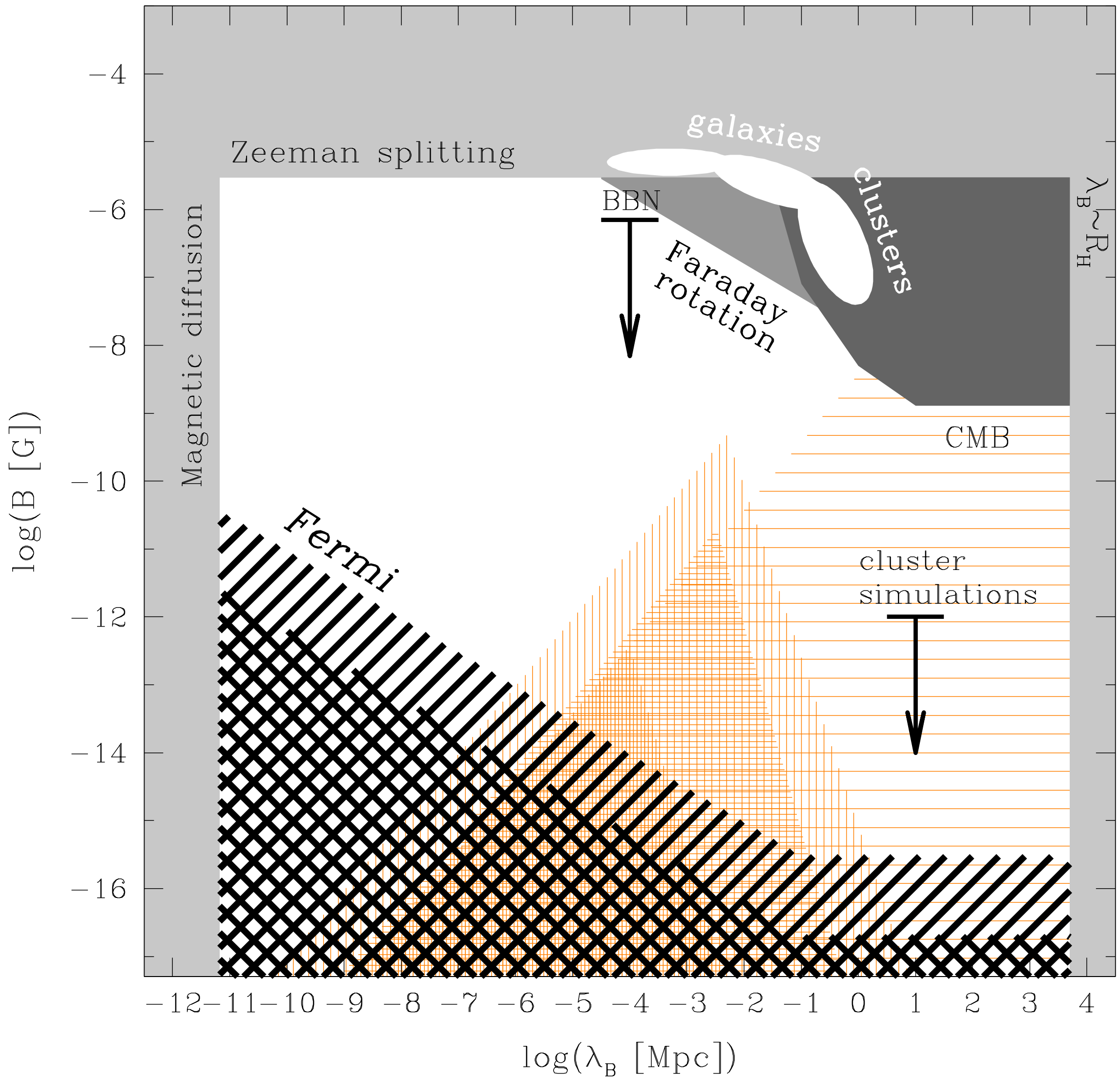
Joyce & Shaposhnikov (1998);

Fröhlich & Pedrini (2000)

- **Lepton asymmetry in the νMSM gives birth to cosmological magnetic fields**

O.R. work in progress

Evidence for magnetic fields in voids?



Neronov & Vovk, Science (2010);

Dolag et al. (2010);

Tavecchio et al. (2011)

Conclusions

- Super-WIMP DM candidates are quite attractive both from theoretical and phenomenological points of view
- Warm DM (thermal relics) with interesting astrophysical and cosmological applications are ruled out by Lyman-α
- However, more general "warm models" (e.g. CWDM) are quite possible, sharing advantages of pure WDM models while avoiding some of their drawbacks
- Sterile neutrino dark matter (as a part of the νMSM model) is a viable dark matter candidate

Thank you for your attention