Searching for light dark matter particles.

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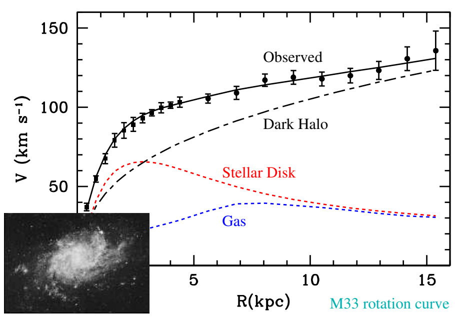
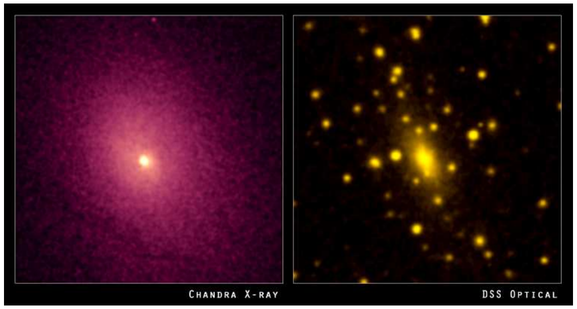
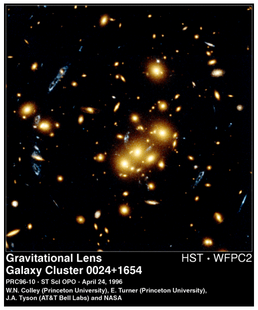
Dark Matter in the Universe

- Rotation curves of stars in galaxies and of galaxies in clusters
- Distribution of intracluster gas
- Gravitational lensing data

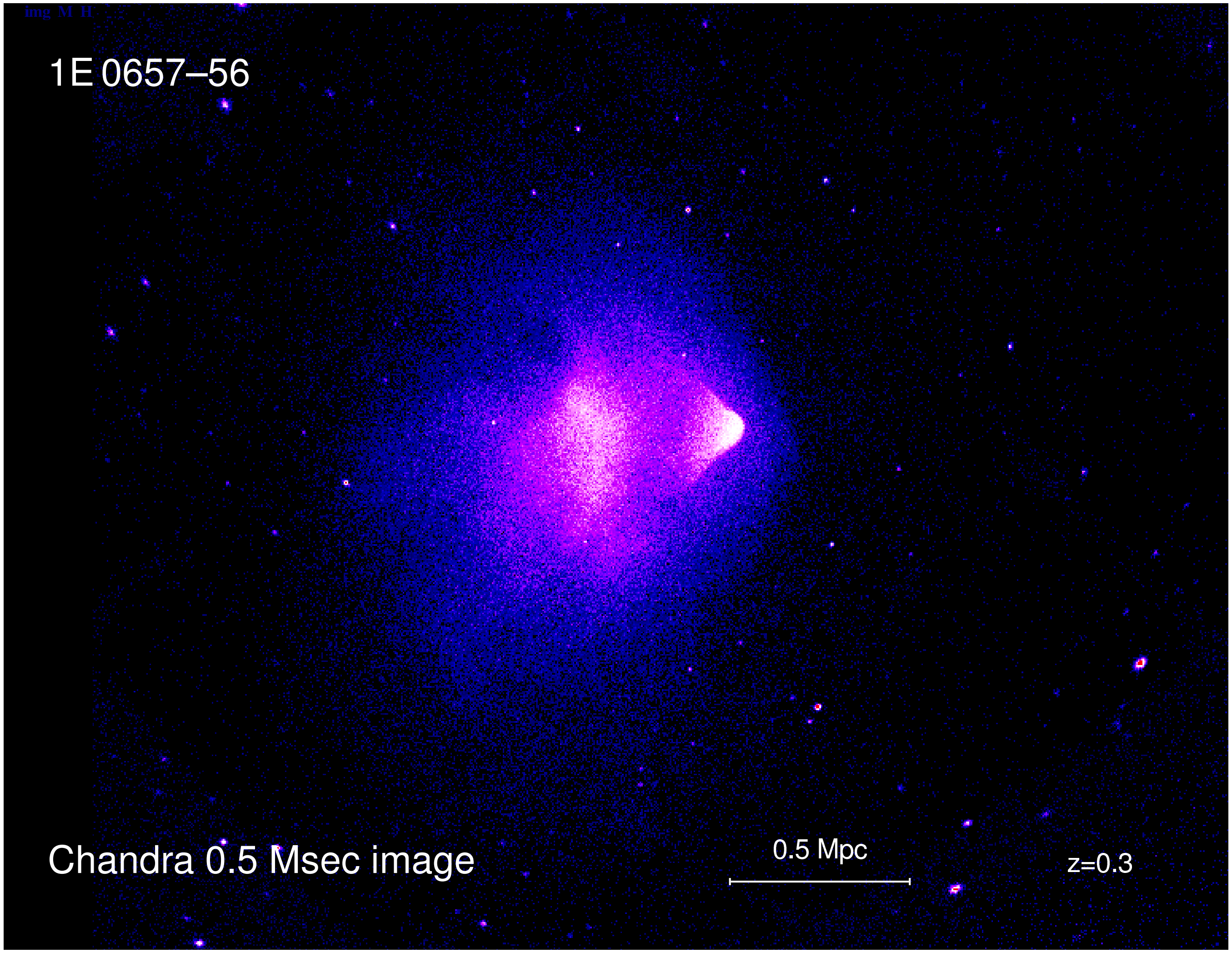
These phenomena are **independent tracers** of gravitational potentials in astrophysical systems. They all show that dynamics is dominated by a matter that is not observed in any part of electromagnetic spectrum.







"Bullet" cluster

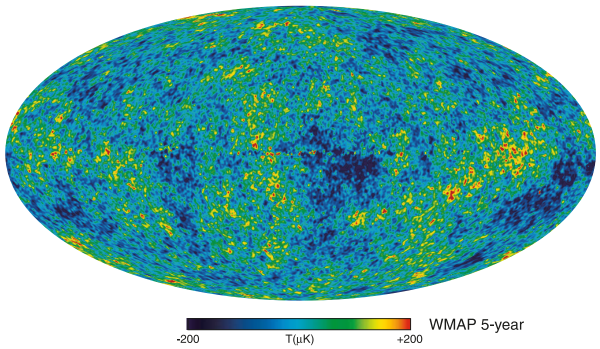


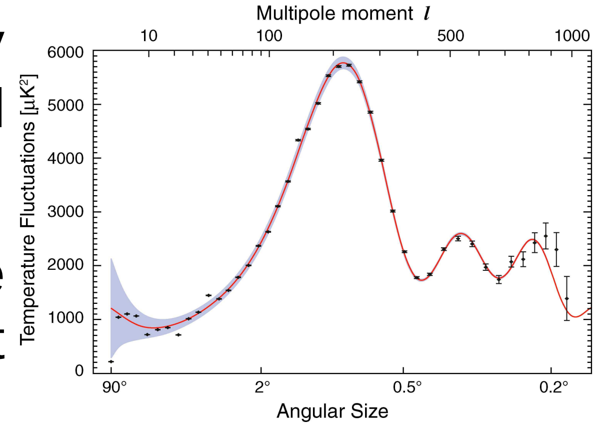
Cluster 1E 0657-56
Red shift $z = 0.296$
Distance $D_L = 1.5$ Gpc

Cosmological evidence for dark matter

- Universe at large scales is not completely homogeneous

- We see the structures today and 13.7 billions years ago, when the Universe was 380 000 years old (encoded in anisotropies of the temperature of cosmic microwave background)





- All the structure is produced from tiny density fluctuations due to gravitational Jeans instability

- In the hot early Universe before recombination photons smeared out all the fluctuations

- To explain the observed anisotropies **we need DM particles** that started to cluster *before* recombination.

A few basic questions

- Is evidence for DM convincing?
  Yes

  There are still other options nevertheless

- Is DM made up of particles?
  Plausible assumption .

  But no **hard** evidence. More exotic possibilities such as primordial black holes or MACHOs are not completely ruled out

- We will study the scenario of dark matter particle and its consequences for particle physics.

Properties of a DM candidate

- DM is **not** baryonic
- DM is **not** a SM particle (neutrinos **could be but . . .)**
- Any DM candidate must be
  - Produced in the early Universe and have correct relic abundance
  - Very weakly interacting with electromagnetic radiation ("dark")
  - Be stable or cosmologically long-lived
- There are plenty of ***non-SM candidates***

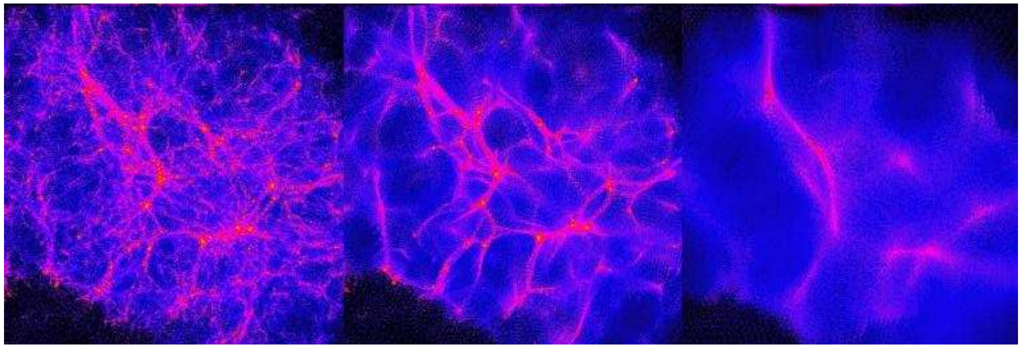
Neutrino dark matter

- 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*** is approximately equal to the horizon at the **time of non-relativistic transition** t_{nr} (when$\langle p \rangle \sim m$)

- Upper bound on neutrino masses $\sum m_\nu < 0.58$ eV (WMAP+LSS, 95% CL).



- Neutrinos are relativistic after recombination ($z_{nr} < 850$)

- Neutrino DM would homogenize the Universe at scales below $\lambda_{FS}^{\text{co}} > 1$ Gpc. This contradicts to the observed large scale structure and data on CMB anisotropies

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Interactions of a DM candidate

- DM interacts with the rest of the matter gravitationally
- Other possible interactions?
- It is possible that DM particles interact only in the early (very) hot Universe with some unknown particles
- To be produced from the SM matter the DM particles should interact
- It may be absolutely stable and interact with SM particles via annihilation only: $\boxed{\text{DM+DM}\to\text{SM}\ldots}$
- It may decay with very small rate, ensuring cosmologically long life-time: $\boxed{\text{DM}\to\text{SM}\ldots}$

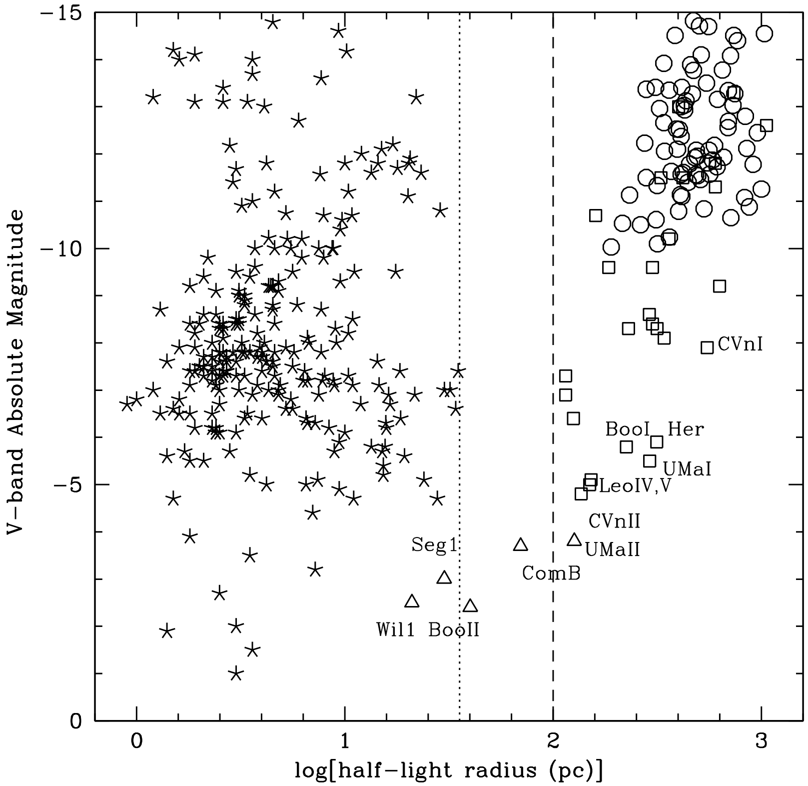
At what energies to look?

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

Universal DM bound 2008



- Since 1979 a number of known dwarf spheroidal galaxies more than doubled. Gilmore et al. 2007-2008
- New dSph's are very dense $Q_{obs} = 10^4 - 10^5\, M_\odot\,\text{kpc}^{-3}[\text{km s}^{-1}]^{-3}$.
- Bound on any fermionic DM improved to become $m_{\mathbf{DM}} > 0.41\,\mathbf{keV}$ Boyarsky, Ruchayskiy, Iakubovskyi'08

- Can this bound be further improved?

Yes!

Sterile neutrinos: a minimal unified model of all observed BSM phenomena.

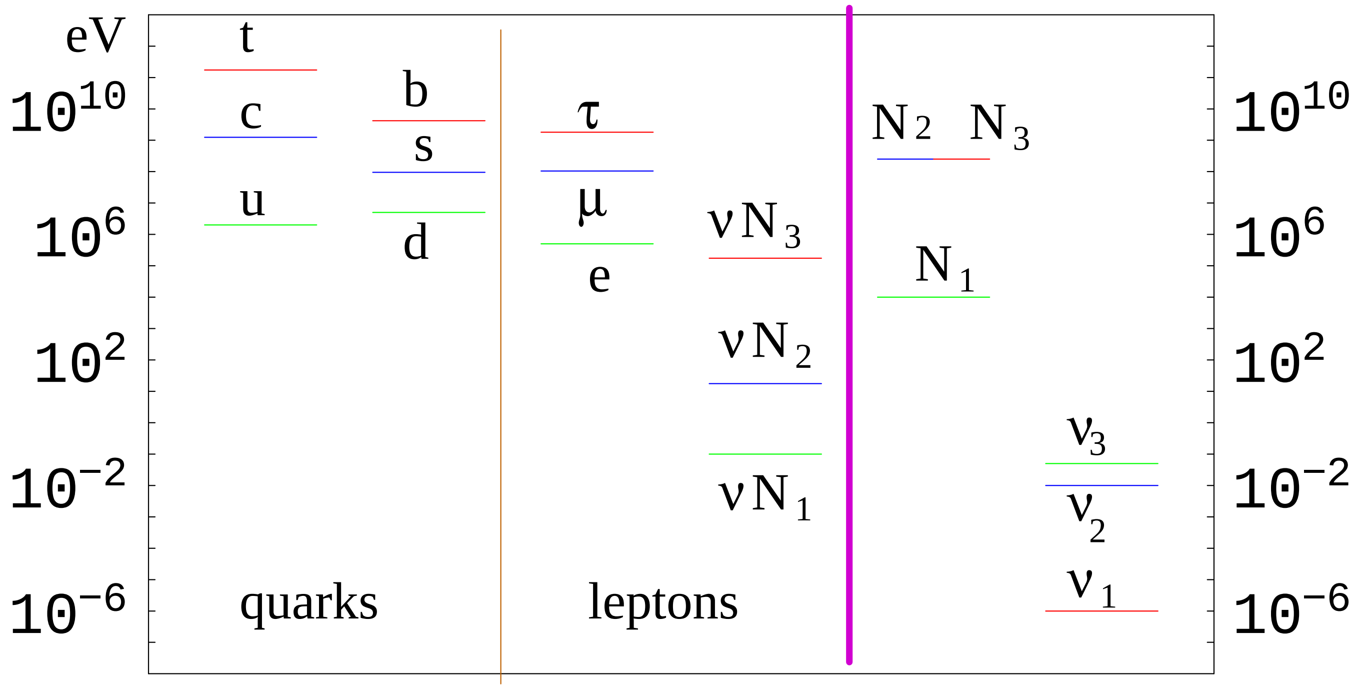
νMSM: all masses below electroweak scale

Just add 3 right-handed (sterile) neutrinos N_R^I to MSM:

$$\mathcal{L}_{\nu MSM} = \mathcal{L}_{SM} + i\bar{N}_R^I \partial\!\!\!/ N_R^I - \left(\bar{L}_\alpha M_{\alpha I}^D N_R^I + \frac{M_I}{2} (\bar{N}_R^I)^c N_R^I + h.c. \right)$$

Asaka, Shaposhnikov, PLB **620**, 17 (2005)

The spectrum of the νMSM



Dirac masses

Majorana masses

νMSM: all masses below electroweak scale

A very modest and simple modification of the SM which can explain **within one consistent framework**

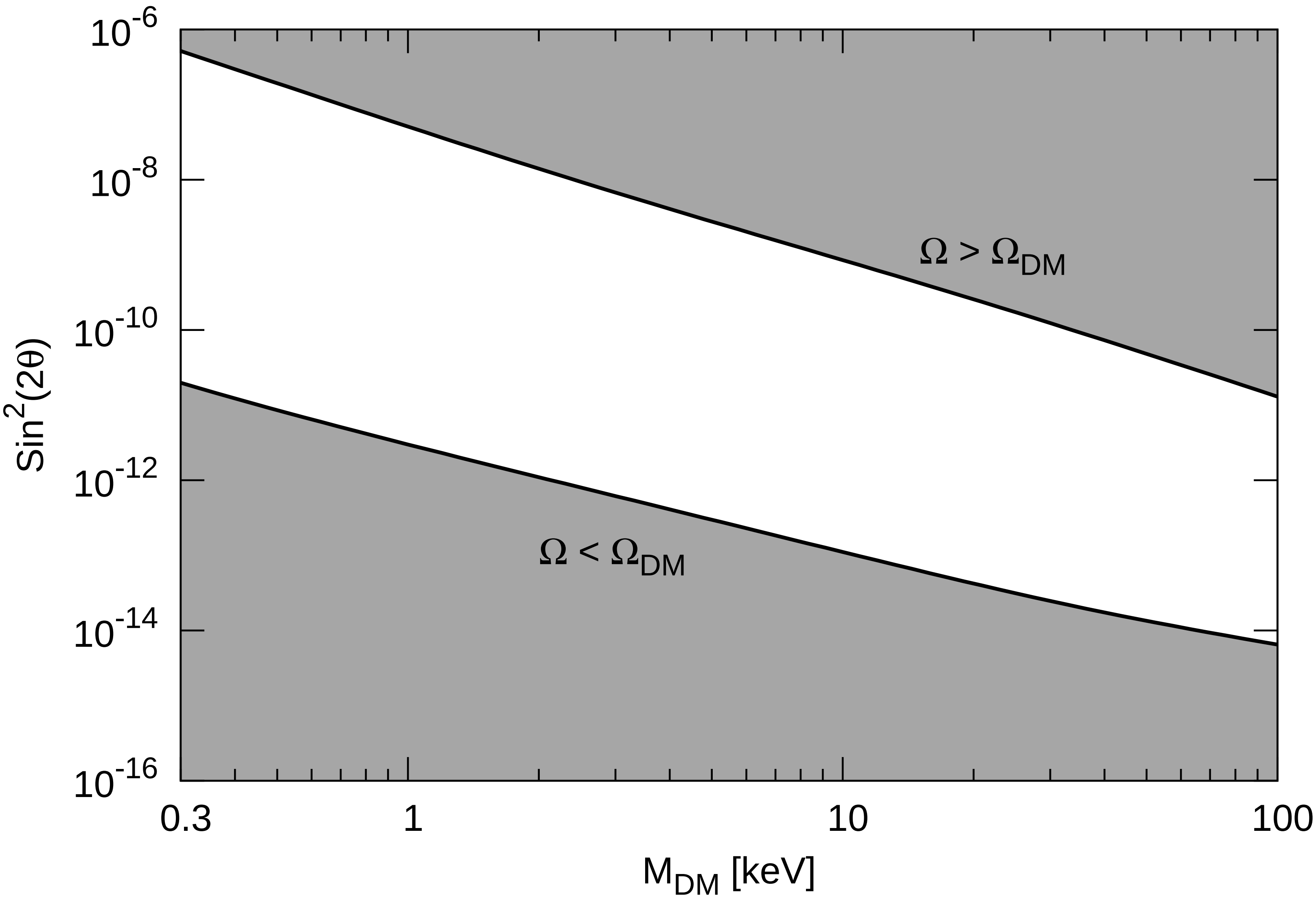
✓ ...neutrino oscillations

✓ ...baryon asymmetry of the Universe

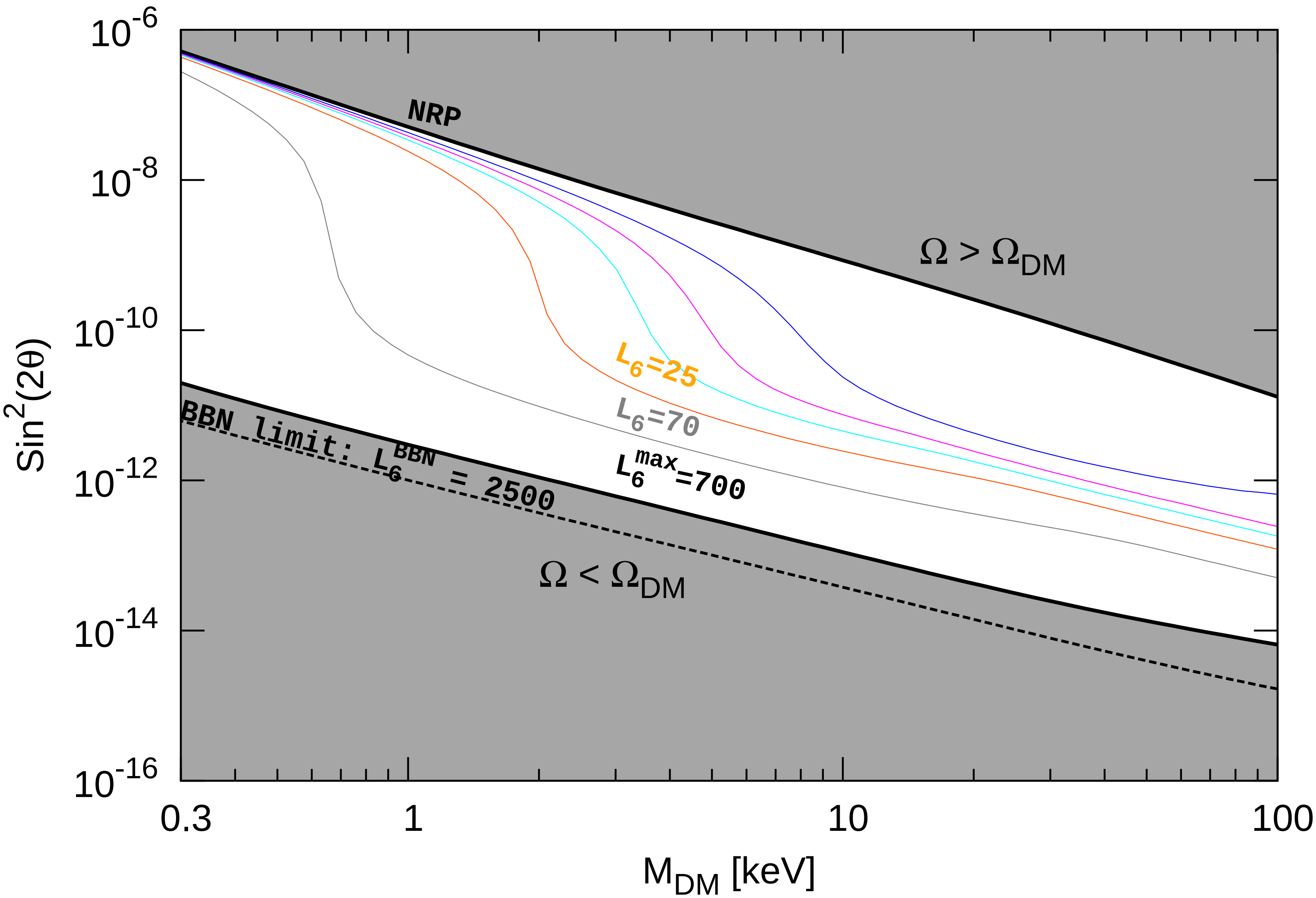
✓ ...provide a viable (warm or cold) Dark Matter candidate

This model may be verified by existing experimental technologies. It is importnat to confirm it or rule it out.

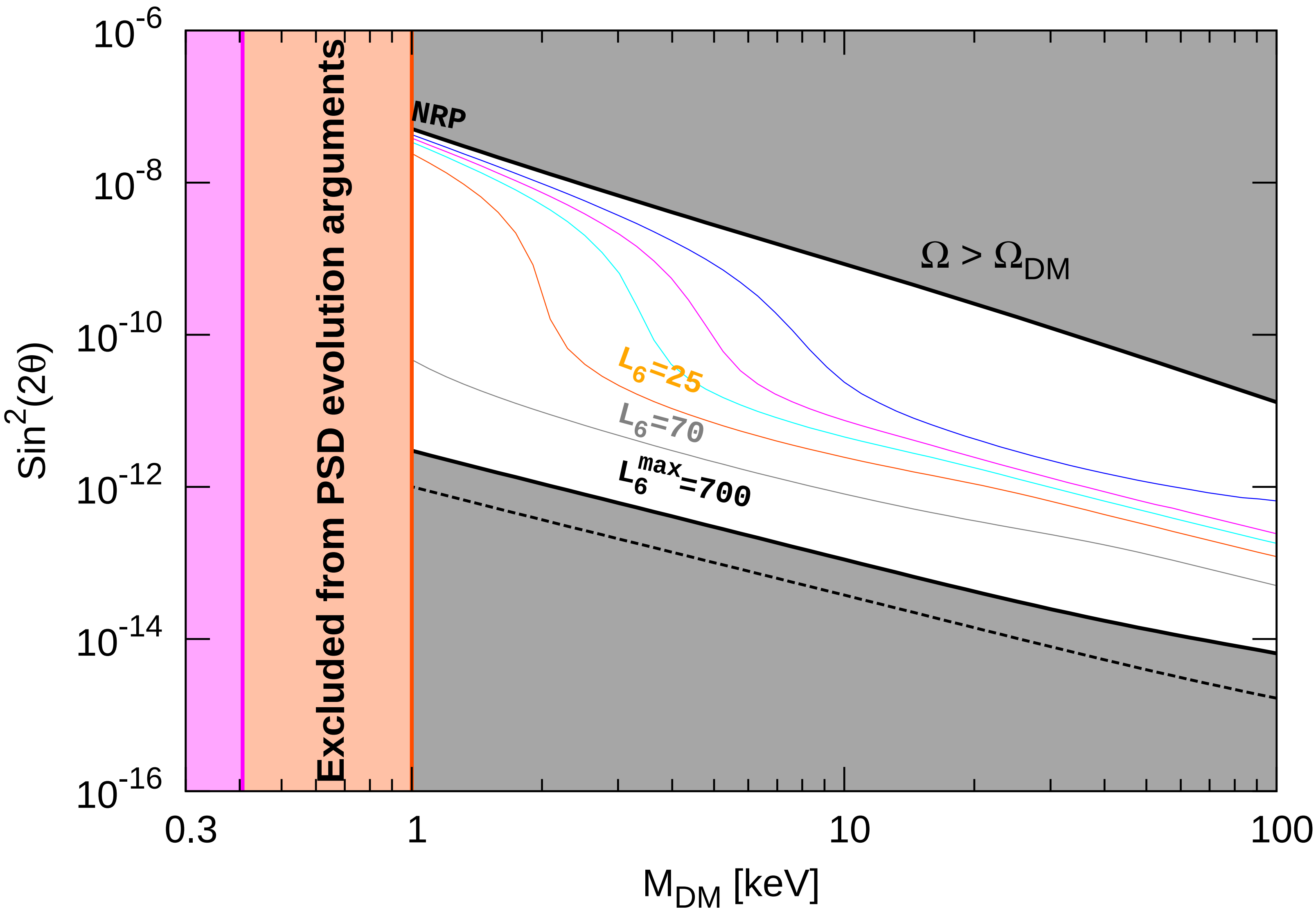
Window of parameters of sterile neutrino DM



Allowed range of parameters

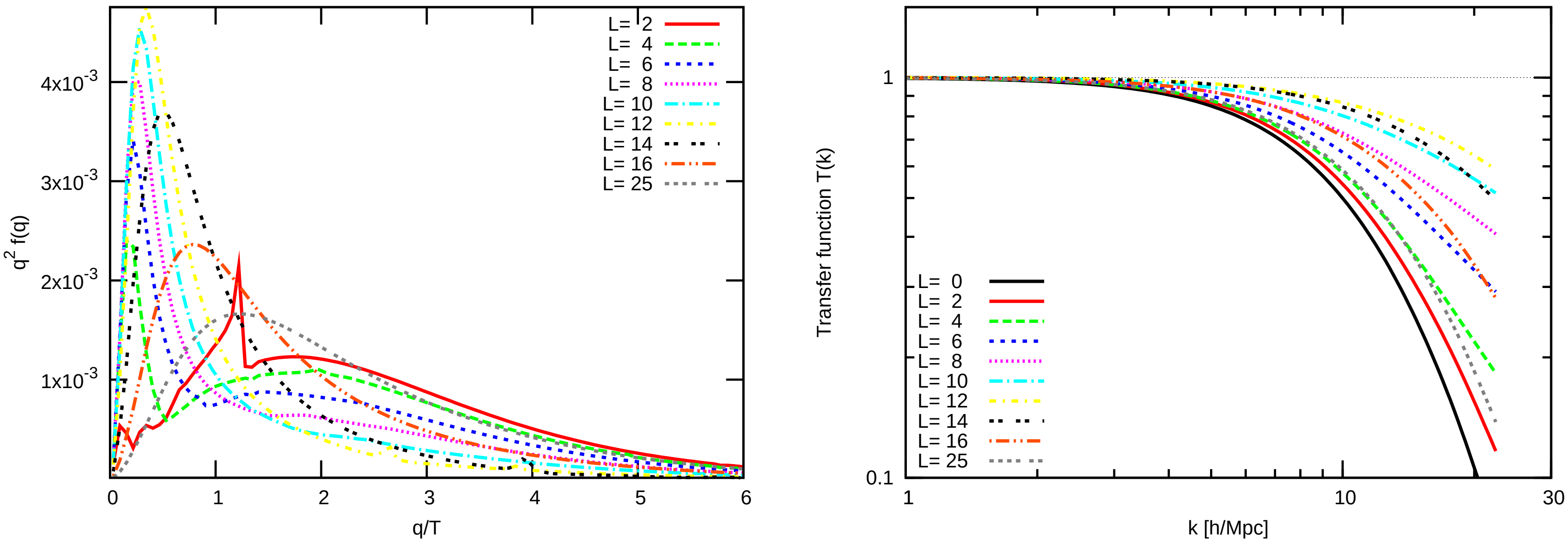


Allowed range of parameters



Primordial properties of super-WIMPs

- Feeble interaction strength of super-WIMP DM particles means that in general they have not an equilibrium primordial velocity spectrum
- For super-WIMPs primordial velocity spectrum carries the information about their production
- In case of such DM particles free-streaming **does not** describe the suppression of power spectrum



Lyman-α forest and cosmic web

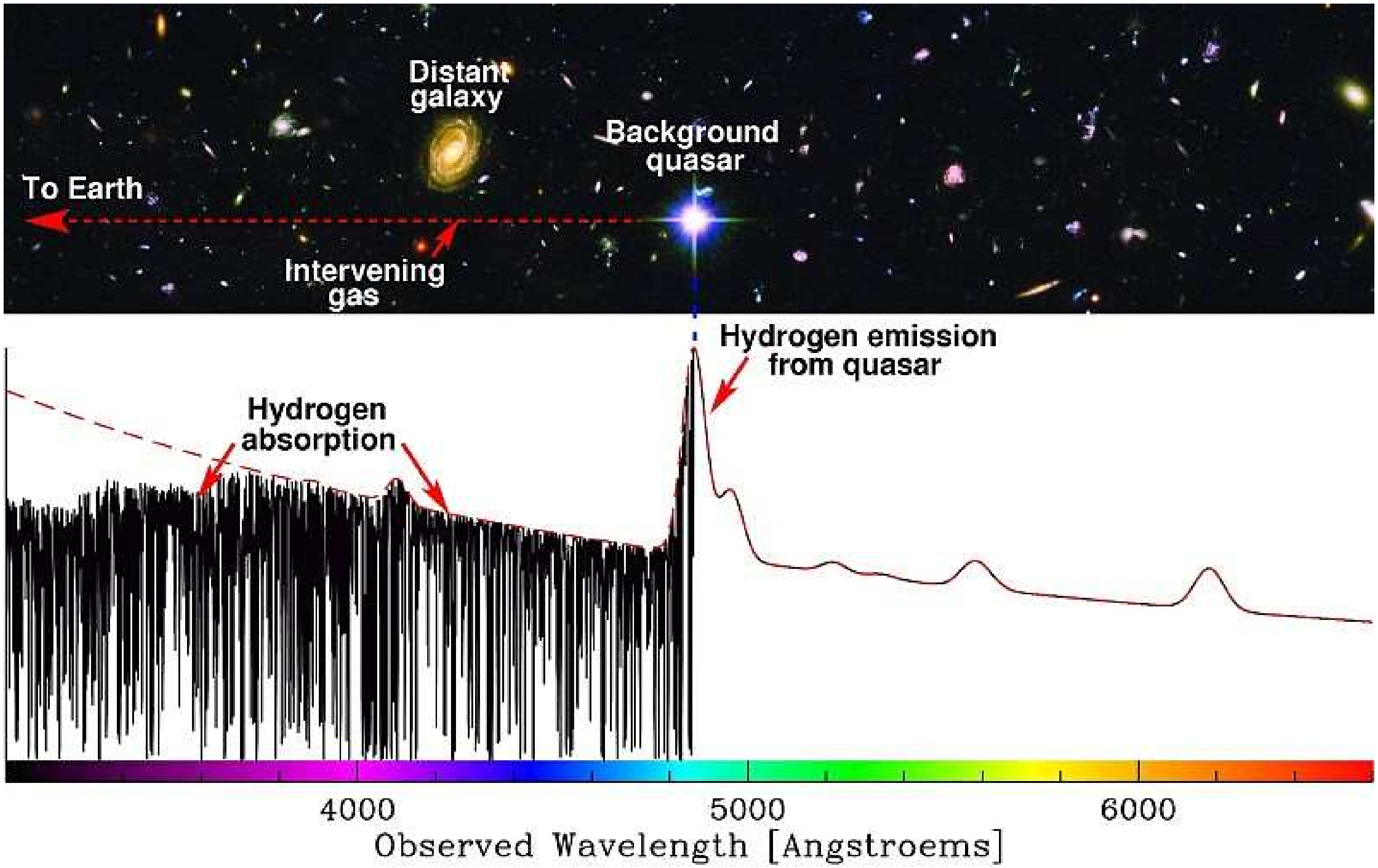


Image: Michael Murphy, Swinburne University of Technology, Melbourne, Australia

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

The Lyman-α method includes

- Astronomical data analysis of quasar spectra
- Astrophysical modeling of hydrogen clouds
- N-body simulations of DM clustering at non-linear stage
- Solving numerically Boltzmann equations for SM in the early Universe
- Finding global fit to the whole set of cosmological data (CMB, LSS, Ly-α), using Monte-Carlo Markov chains

Main challenge: reliable estimate of systematic uncertainties

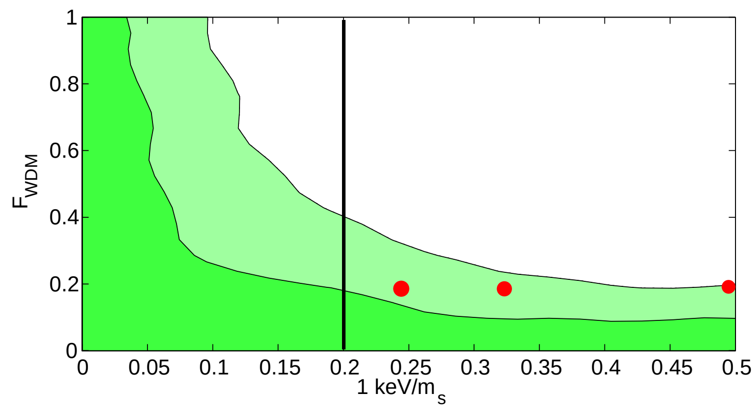
Lyman-α forest and warm DM

- Previous works (**Viel et al.'05-'06; Seljak et al.'06**) 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
- In **Boyarsky, Lesgourgues, Ruchayskiy, Viel'08** we revised these bounds and demonstrated that

Boyarsky+ JCAP'09; PRL'09

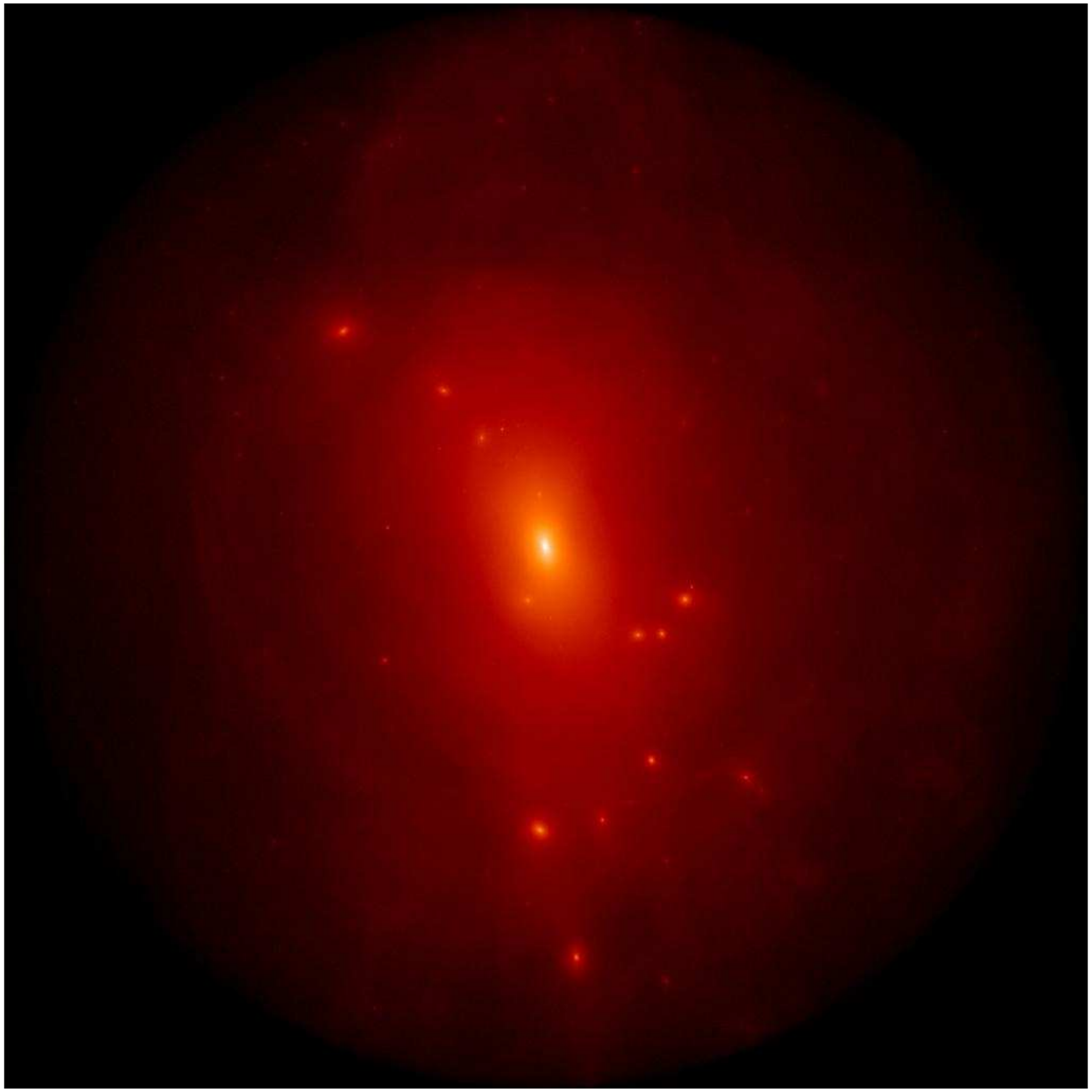
– The primordial spectra are not described by free-streaming

– There exist viable models with the mass as low as 2 keV, consistent with the Lyman-α

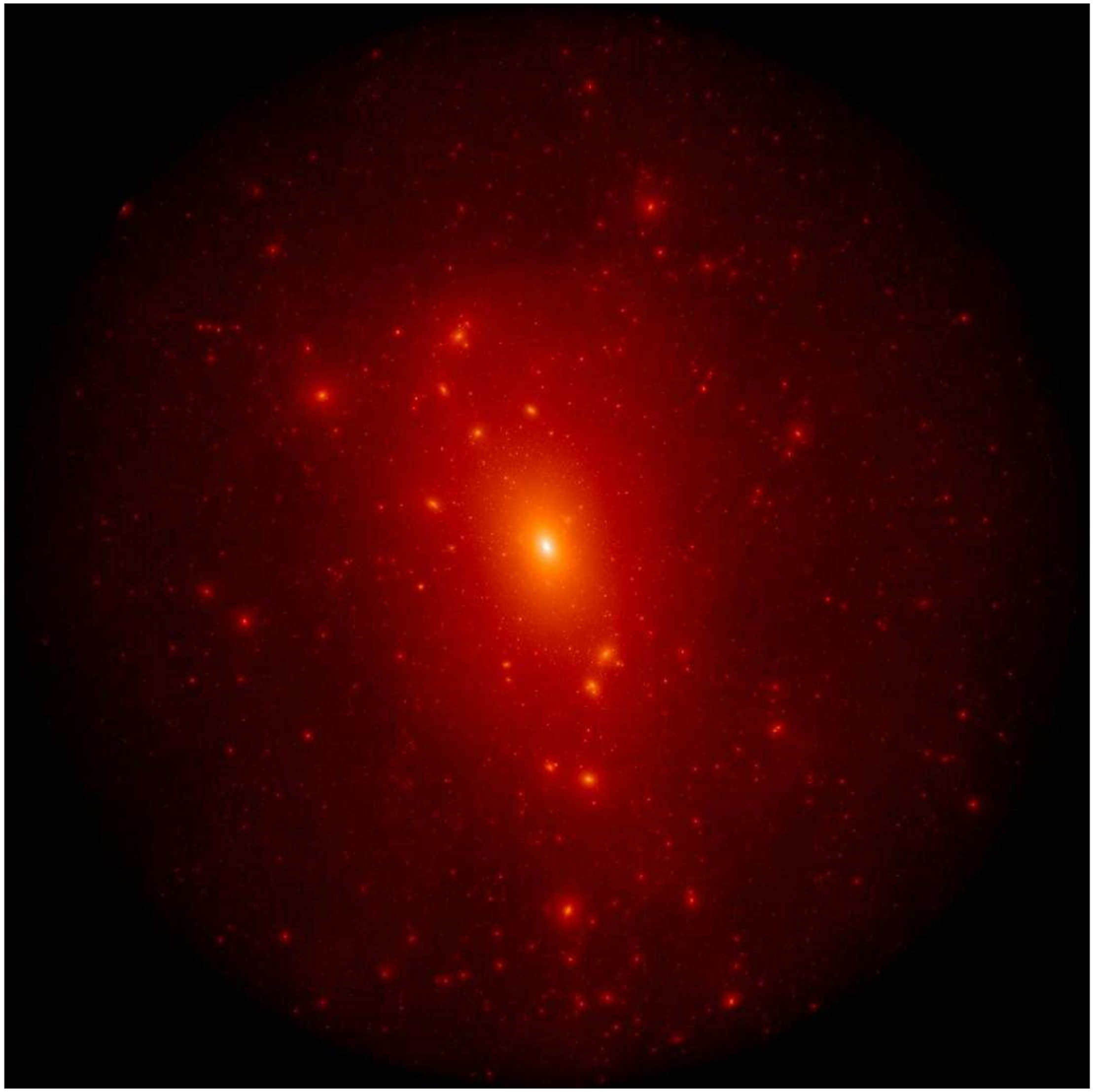


Halo (sub)structure in CDM+WDM universe

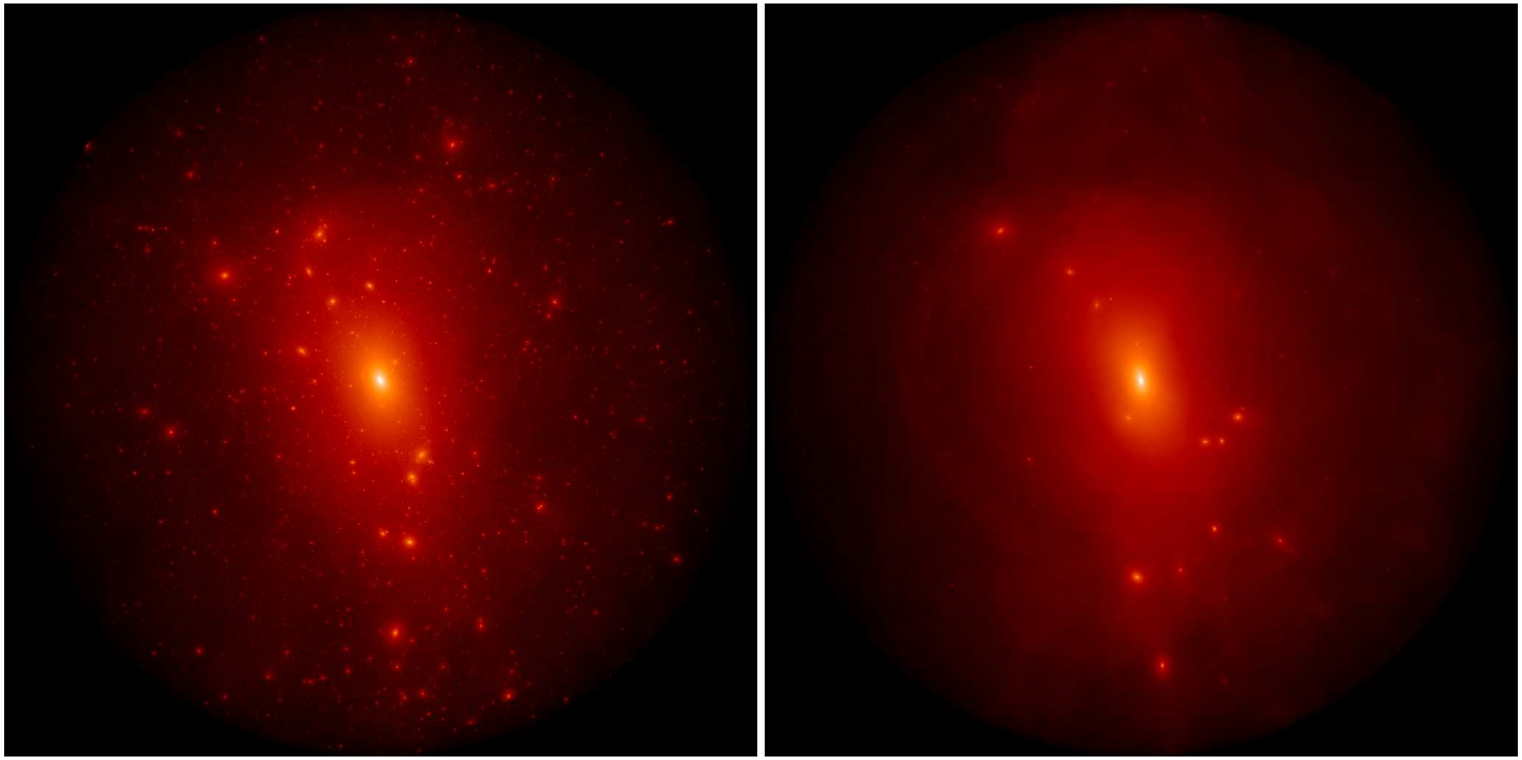
work in progress



Halo (sub)structure in CDM universe



Halo (sub)structure in CDM+WDM universe



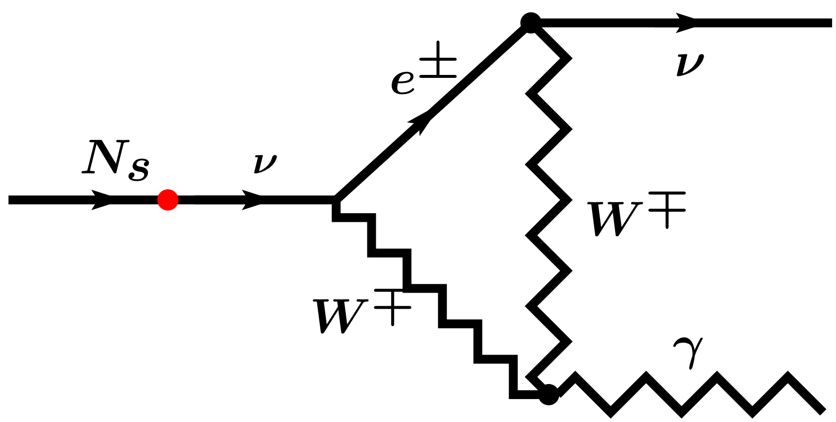
PRELIMINARY: ***Aq-A-2 halo*** in CDM and CDM+WDM simulations (Gao, Theuns, Frenk, **O.R.**, . . .)

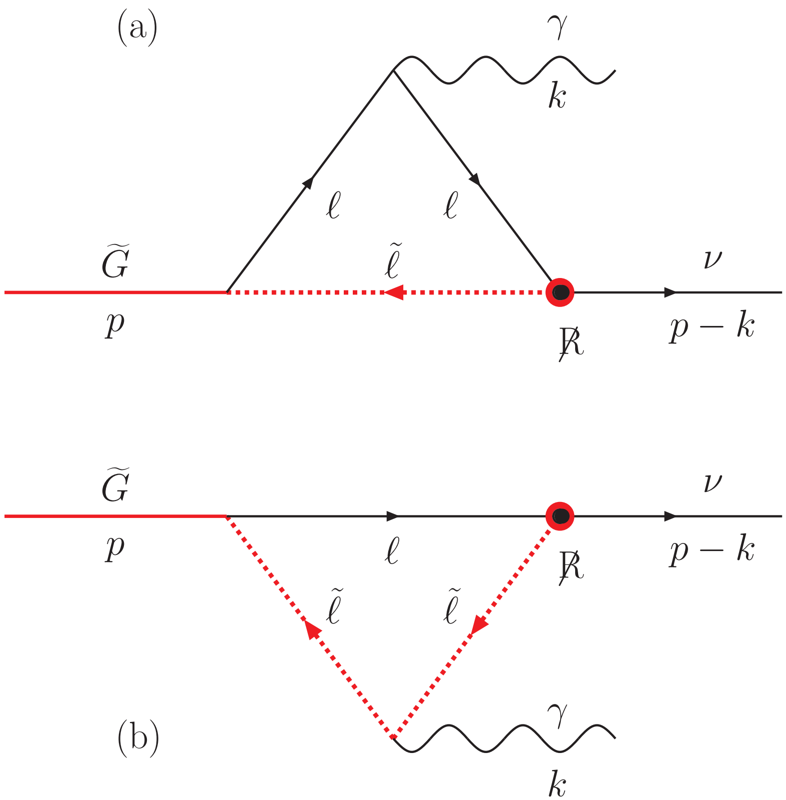
- Simulated CWDM model (right) is fully compatible with the Lyman-α forest data but provides a structure of Milky way-size halo different from CDM (left)

Searching for decaying dark matter

Decaying DM

DM with **radiative signatures:** DM $\to \gamma + \nu,\ \gamma + \gamma,\ e^+ + e^- \ldots$





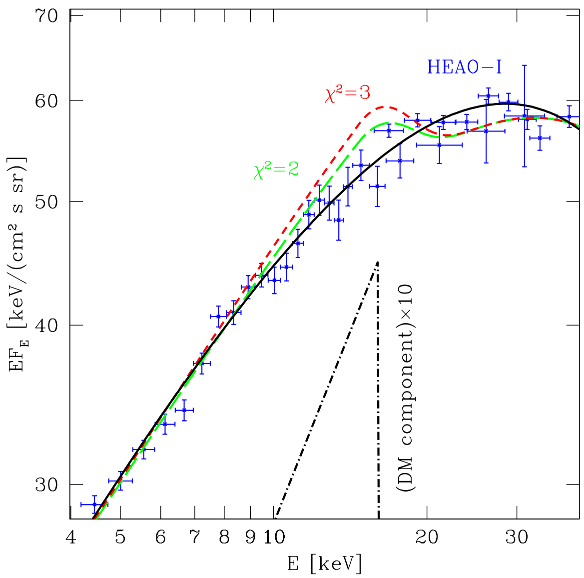
Appears in many models:

Right-handed neutrino
Dodelson & Widrow'93;
Asaka, Shaposhnikov et al.'05

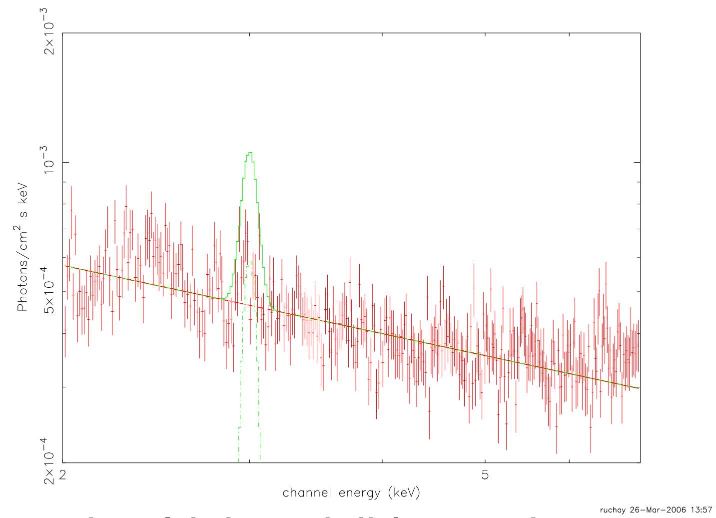
Gravitino with broken R-parity
Takayama & Yamaguchi'00
Buchmüller'07

Volume Modulus
Quevedo'07

Constraints from X-ray observations



DM decay should produce a line in X-ray spectra of various objects.



It should be visible against e.g power law spectrum of diffuse extragalactic background.

$$\frac{\Delta E}{E} \sim \begin{cases} 10^{-2} & \text{Galaxy cluster} \\ 10^{-3} & \text{Milky Way} \\ 10^{-4} & \text{dSph} \end{cases}$$

XMM/Chandra: $\Delta E/E \sim 10^{-2}$
SPI: $\Delta E/E \sim 10^{-3}$
Fermi: $\Delta E/E \sim 10^{-1}$

Properties of decaying DM

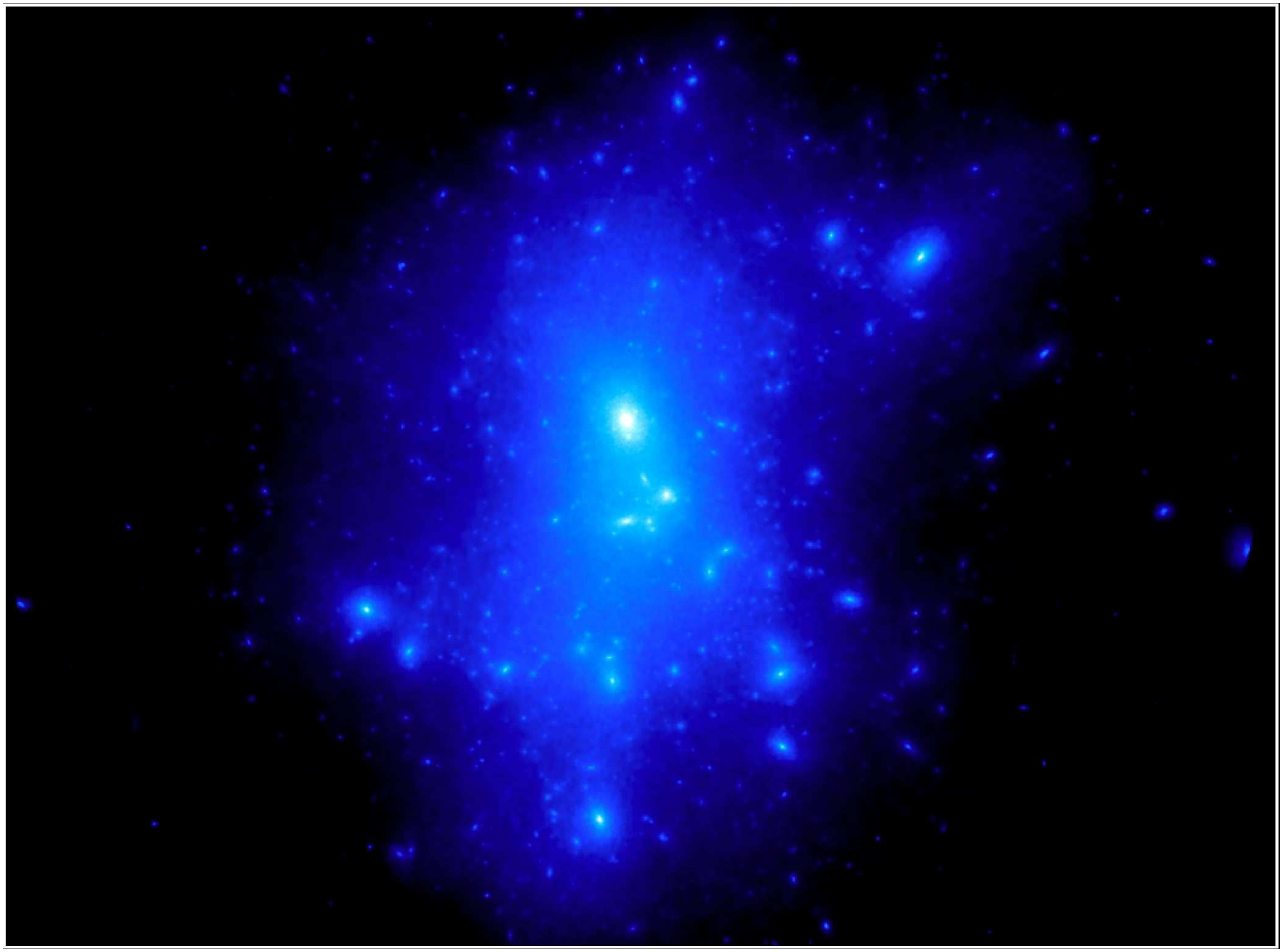
- The properties of decaying DM are much less studied.
- Crucial property: the flux from DM decay

$$F_{\rm DM} = \frac{E_\gamma}{m_{\rm DM}} \frac{\Gamma \mathcal{M}_{\rm DM}^{\rm fov}}{4\pi D_L^2} \approx \frac{\Gamma \Omega_{\rm fov}}{8\pi} \int \rho_{\rm DM}(r) dr \quad (z \ll 1, \quad \Omega_{\rm fov} \ll 1)$$

line of sight

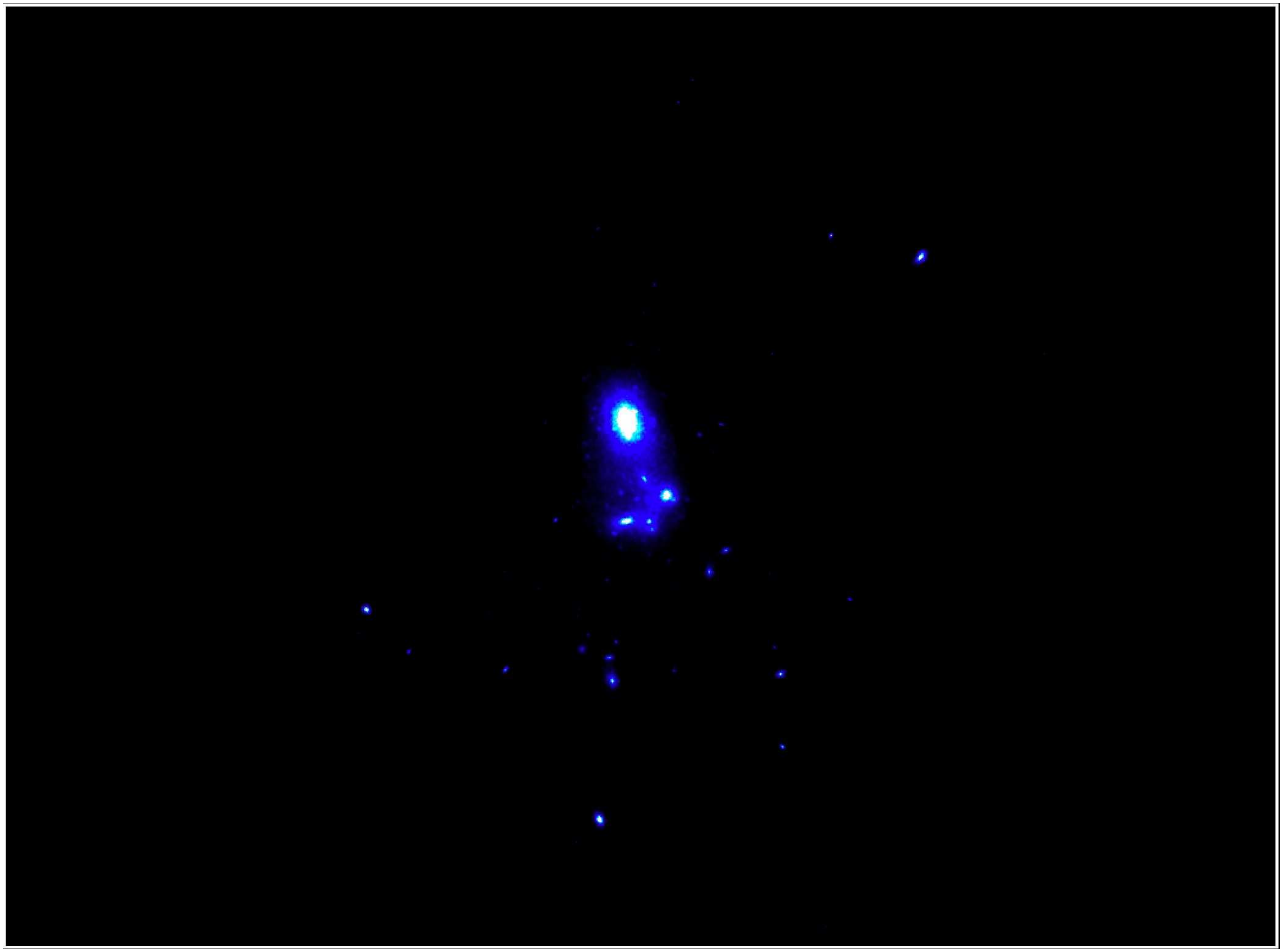
- The flux $F_{\rm DM} \sim \int \rho_{\rm DM}(r) dr$ and **NOT** to $\int \rho_{\rm DM}^2(r) dr$, as in the case of **annihilating** DM.
- The difference is **HUGE**.

Decay signal from MW-sized galaxy



Moore et al. 2005

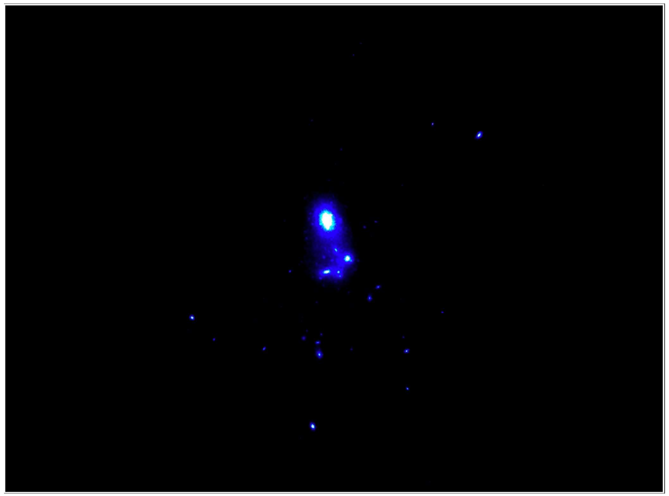
Annihilation signal from MW-sized galaxy



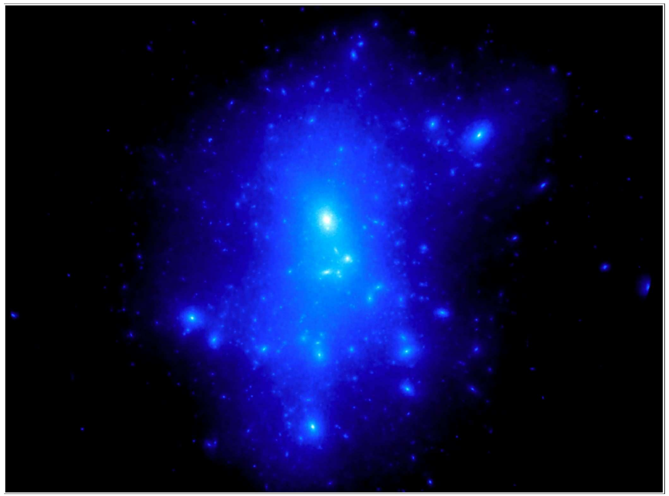
Moore et al. 2005

Decay vs. annihilation

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



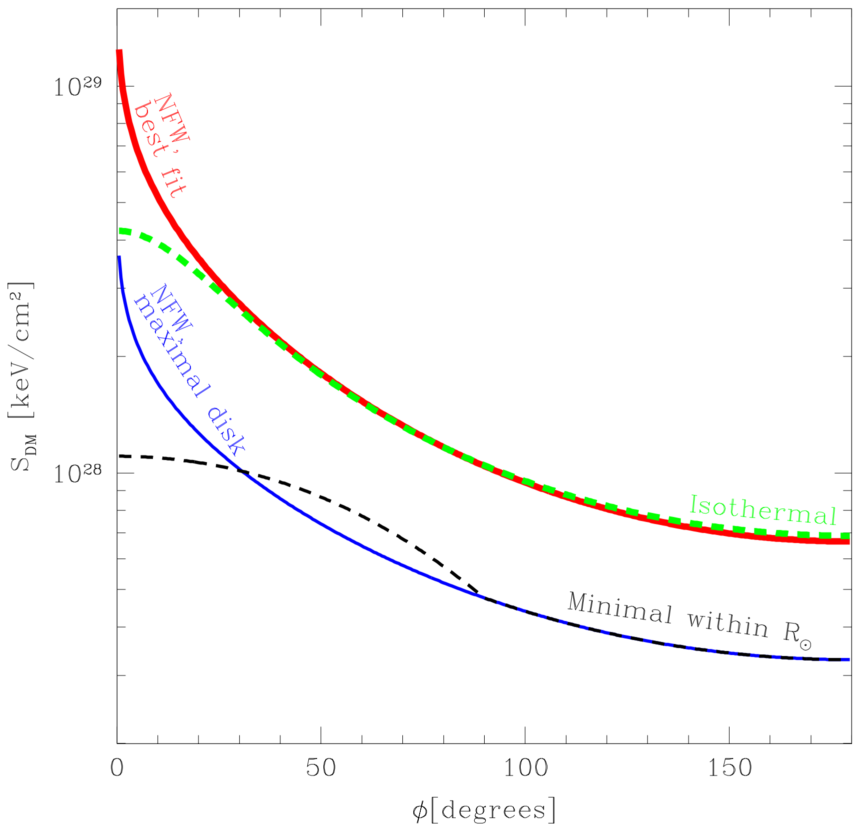
- We have a lot of freedom in choosing observation targets and, therefore, can unambiguously check DM origin of a suspicious signal.

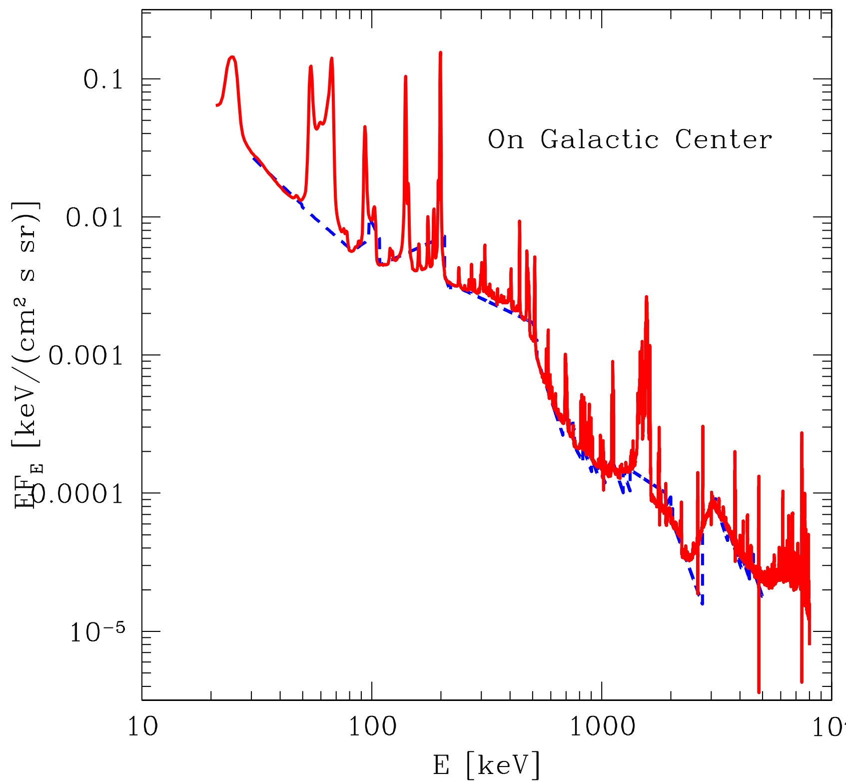


For decaying DM "indirect" search becomes very promising!

Search for decaying DM: main challenges

- Control of astrophysical and instrumental background



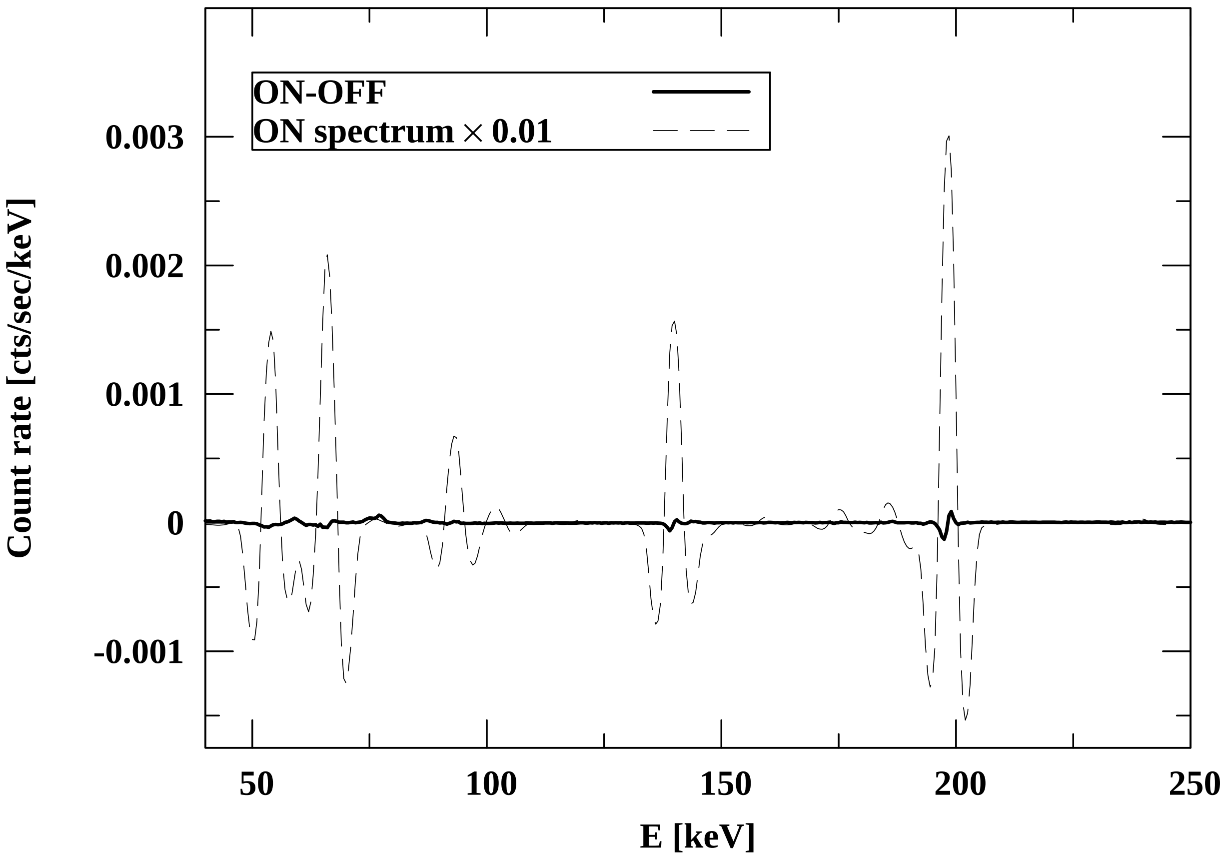


- Reliable determination of dark matter content of an object

SPI background subtraction

- Find observation off-GC "close in time"
- Normalize by count rate of 198 keV (strong instrumental line)

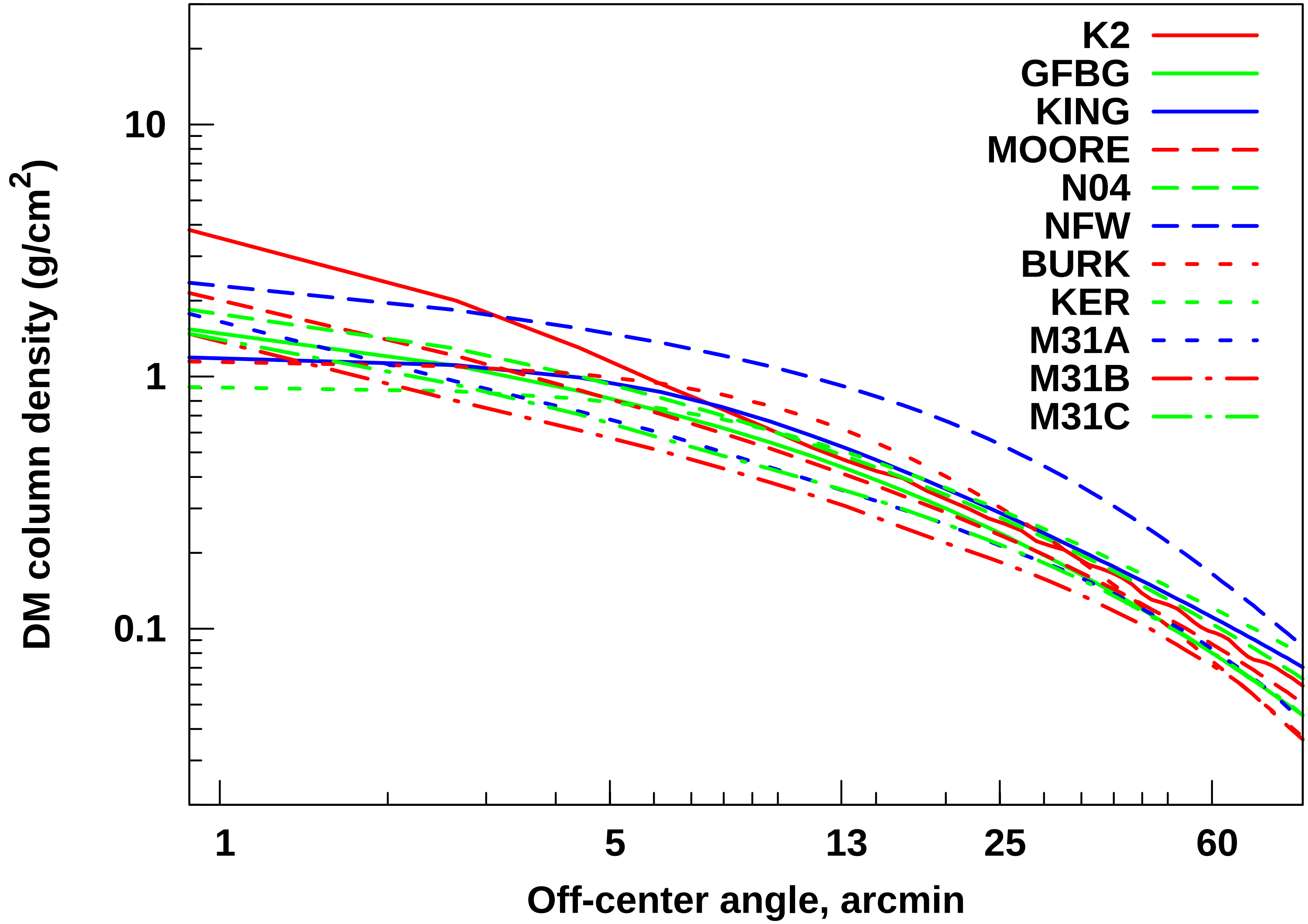
Teegarden
Watanabe
2006



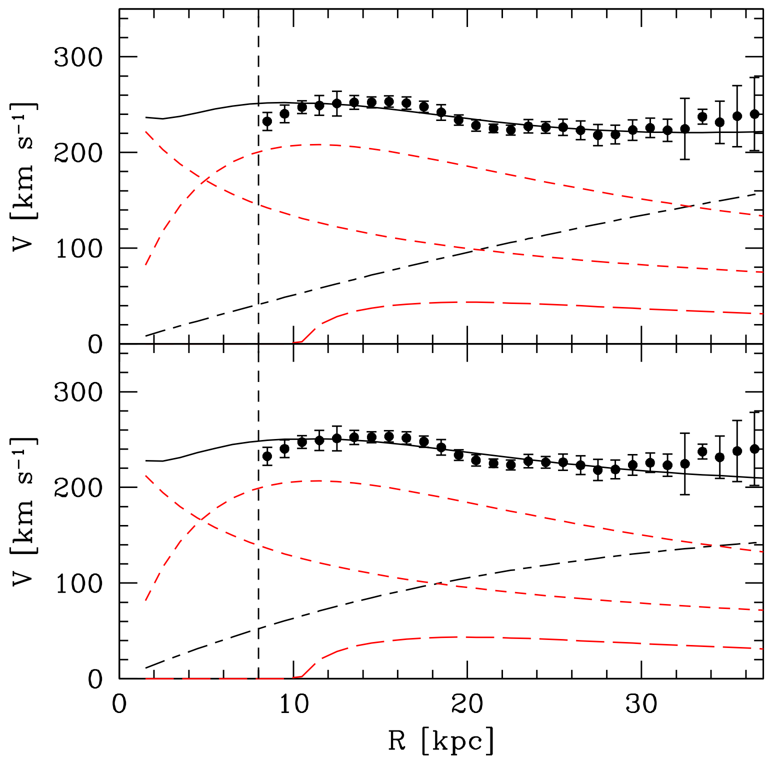
- Hundreds of lines cancel better than 1% by fixing only **one number**
- Line at 511 keV remains visible at $\sim 50\sigma$
- No other lines above $3-4\sigma$

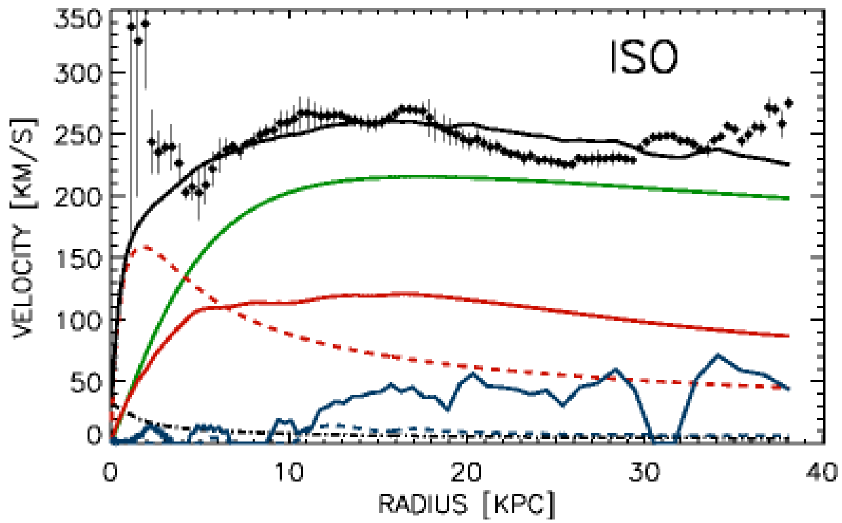
DM in Andromeda galaxy (2007)

0709.2301



Mass-to-light ratio in Andromeda galaxy?



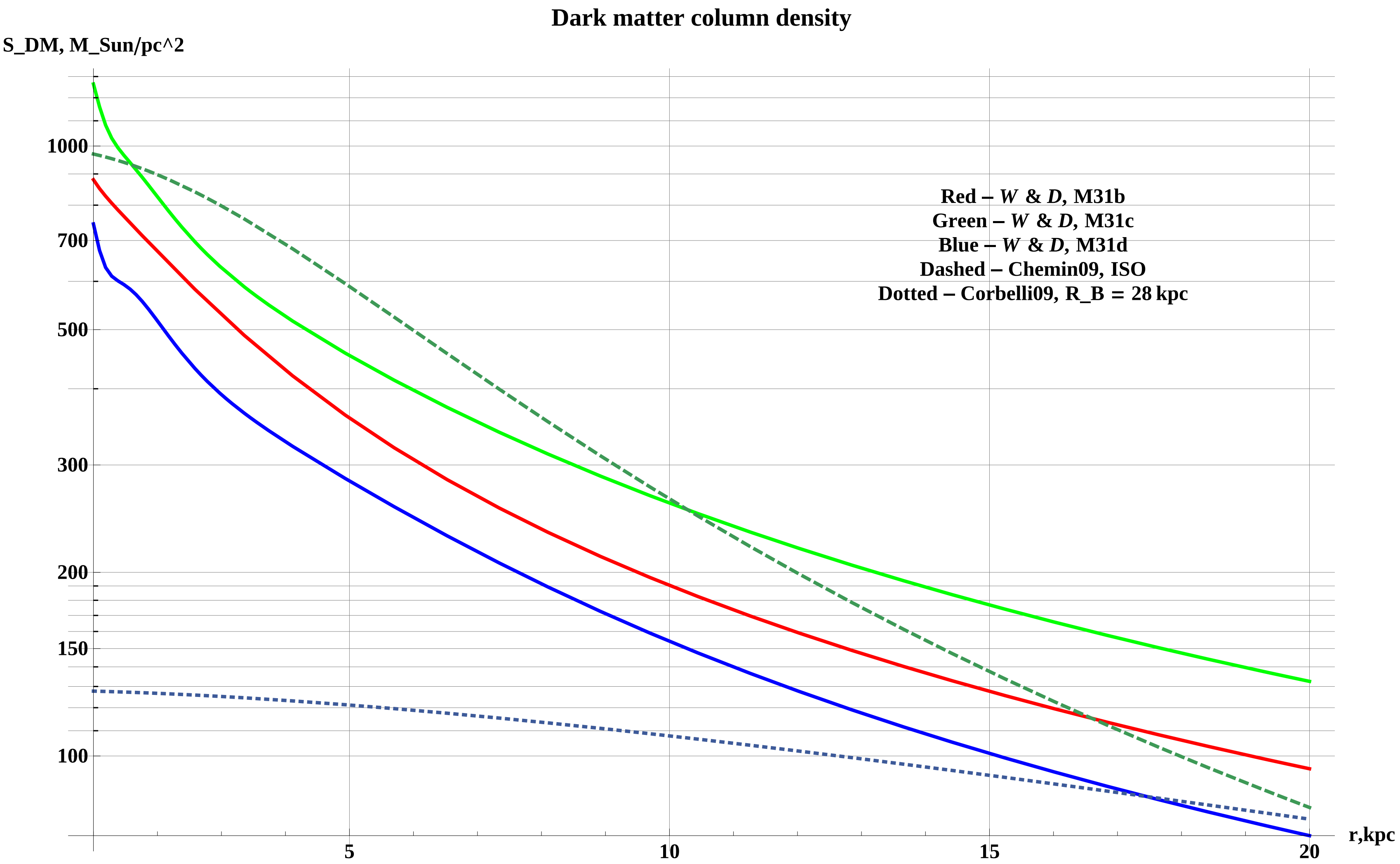


Chemin et al. ApJ 2009

Corbelli et al. A&A 2009

Mass-to-light ratio of bulge and disk components vary by a factor ~ 4

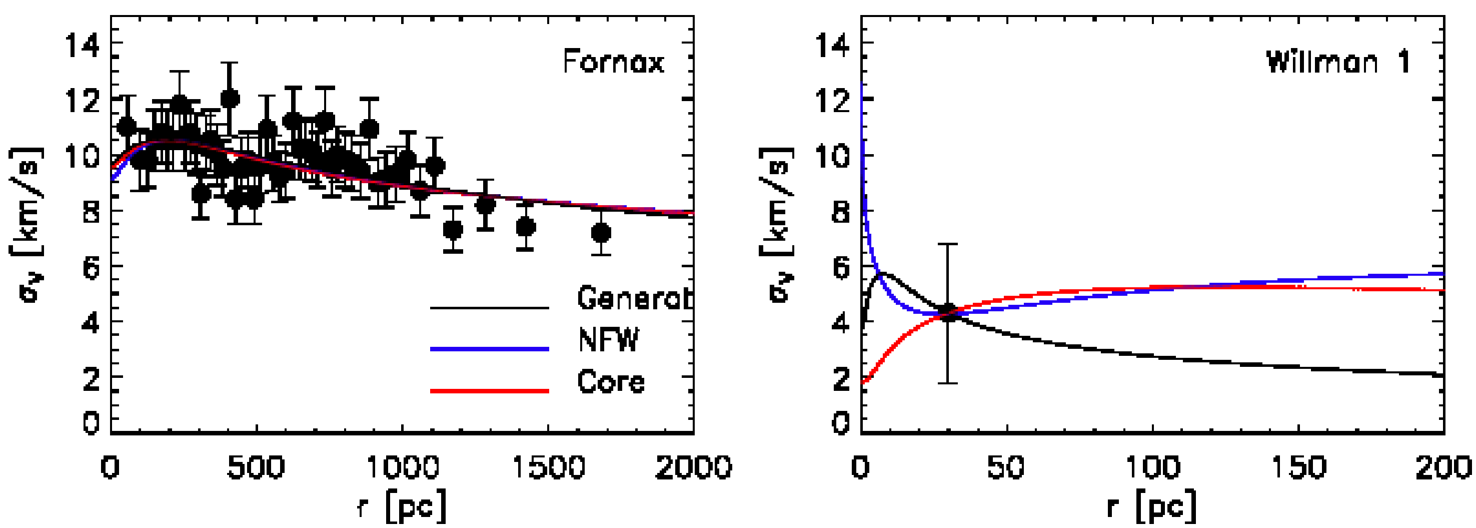
DM in Andromeda galaxy (2010)



DM distribution in individual objects

- Knowledge of dark matter distribution in individual objects is crucial for astrophysical searches of decay/annihilation signals
- Dark matter column density is uncertain within a factor of few (much more for $\int \rho^2 dl$)
- Uncertainty in modeling of the baryonic contribution
- Dwarf spheroidal galaxies

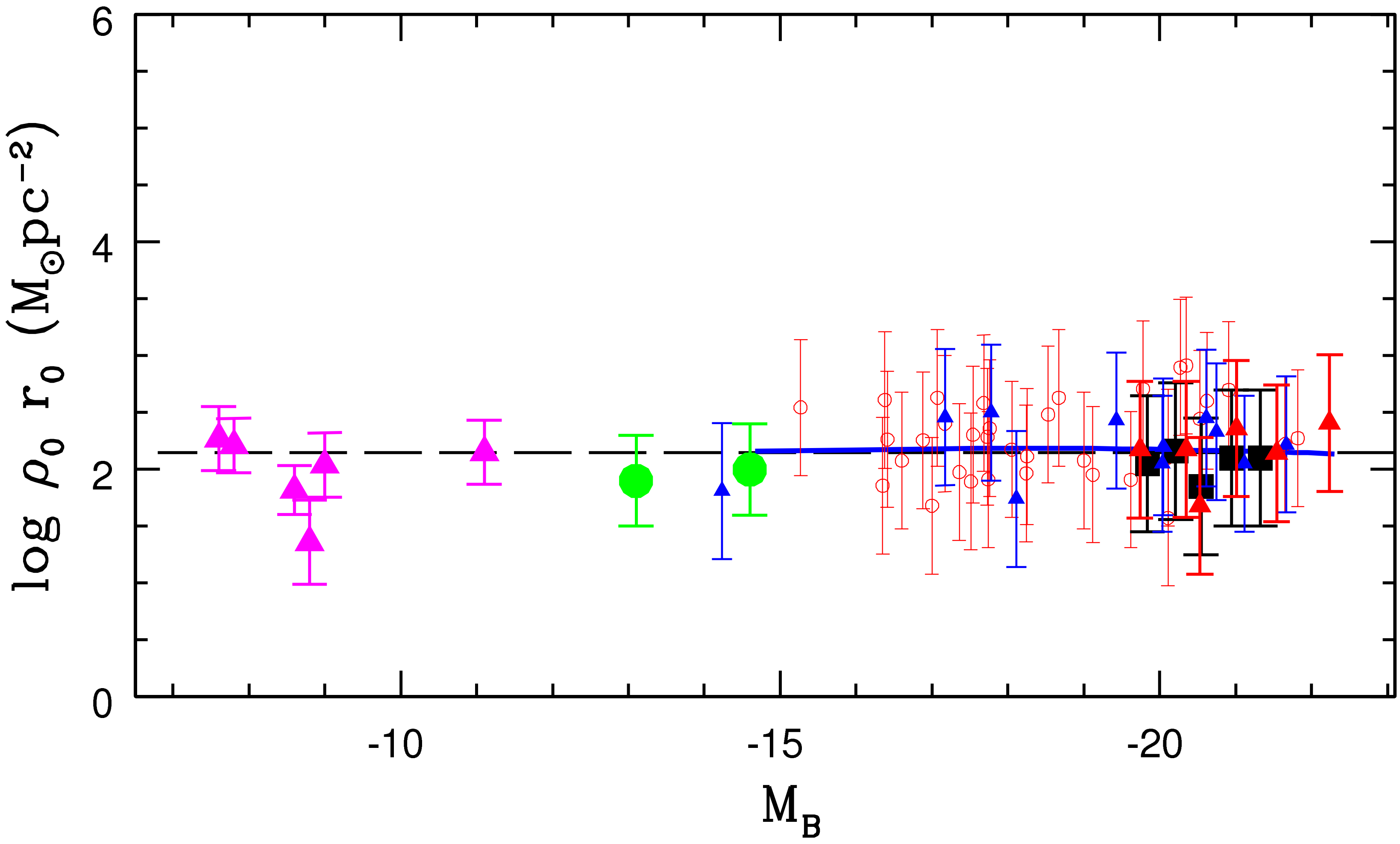
PRL'06



Universal properties of DM distribution

- Fortunately, it is possible to minimize the dependence of the results on astrophysical uncertainties related to individual objects.
- One can exploit **a universal property of DM distributions.**

Constant surface density?

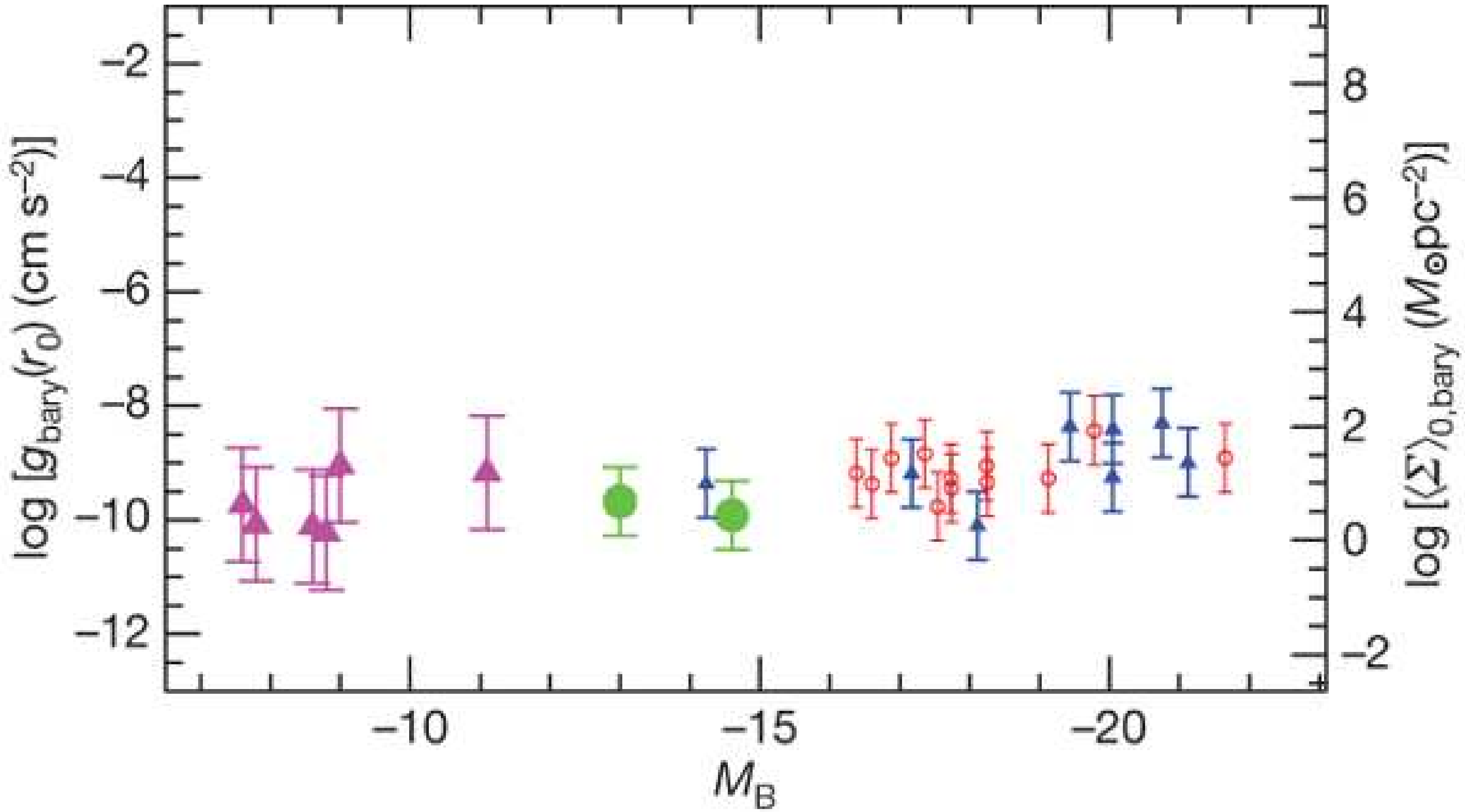


Kormendy, Freeman'94; Donato et al. 2009; **PRL'06**

Dark matter surface density remains for different types of galaxies?

An evidence in favor of MOND?

Gentile et al.
Nature'09



Baryonic surface density for different types of galaxies.

Universal properties of DM distributions?

- 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

Boyarsky et al **0911.1774**

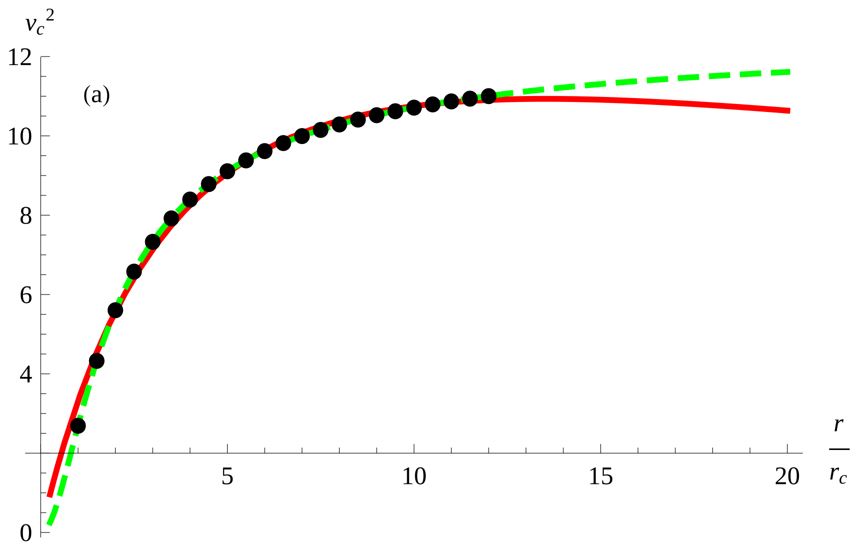
- Different methods (rotation curves, X-rays, weak lensing, . . .). Different observational groups fit the mass distribution with different velocity profiles (isothermal sphere, Navarro-Frenk-White, Burkert, . . .)

- Important questions:
  - What properties to compare?
  - Often fits to different DM density profiles exist for the same object. How to relate their parameters?
  - Any universality is observed?

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

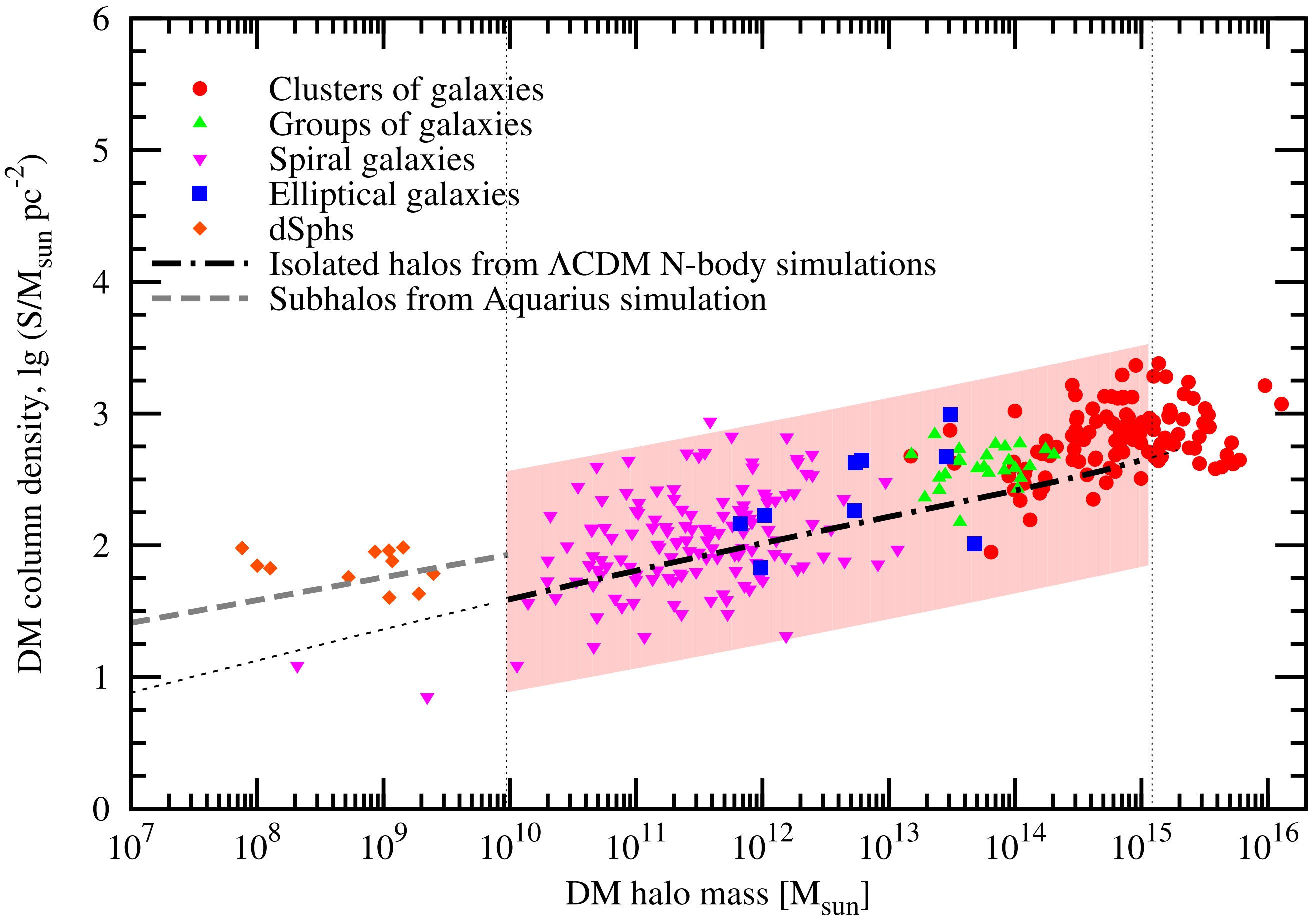


- NFW vs. ISO : $r_s \simeq 6.1\, r_c; \rho_s \simeq 0.11\, \rho_c$
- NFW vs. BURK : $r_s \simeq 1.6 r_B \quad ; \quad \rho_s \simeq 0.37 \rho_B$
- For most observed objects $\rho_\star r_\star = \text{const}$

- Observable not sensitive to the choice of dark matter density profile – **Dark matter column density**

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

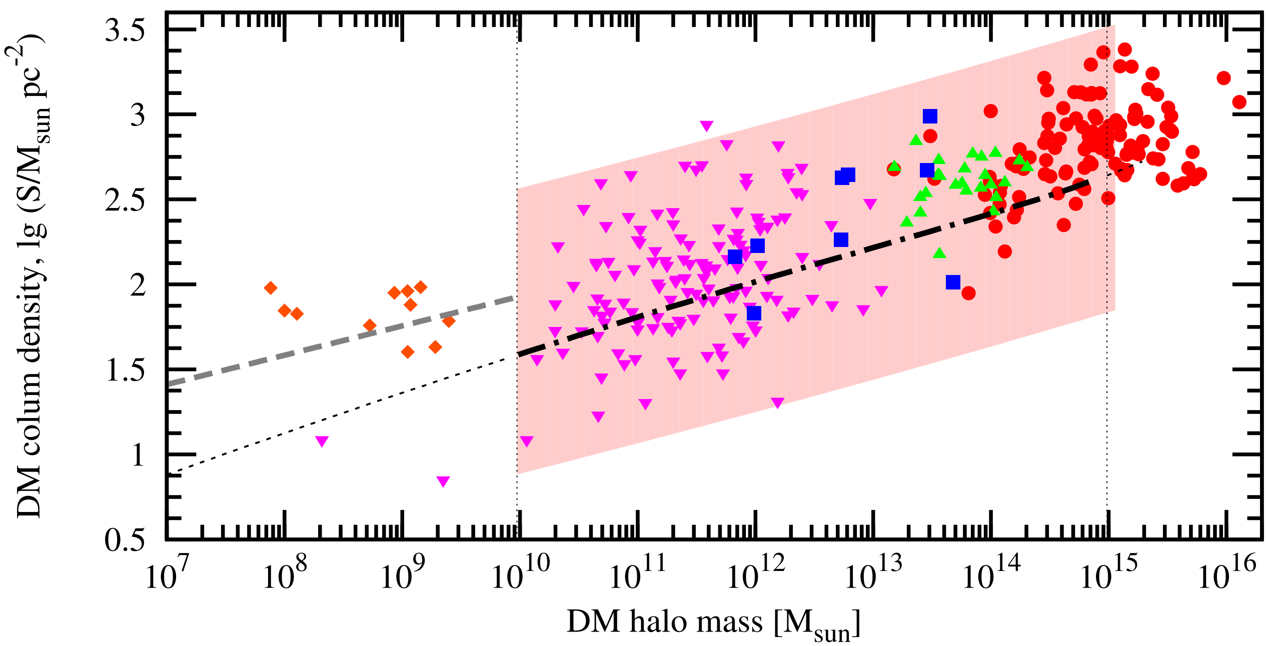
Observations vs. simulations



0911.1774
$\mathcal{S}$ changes slowly. There is a universal scaling.

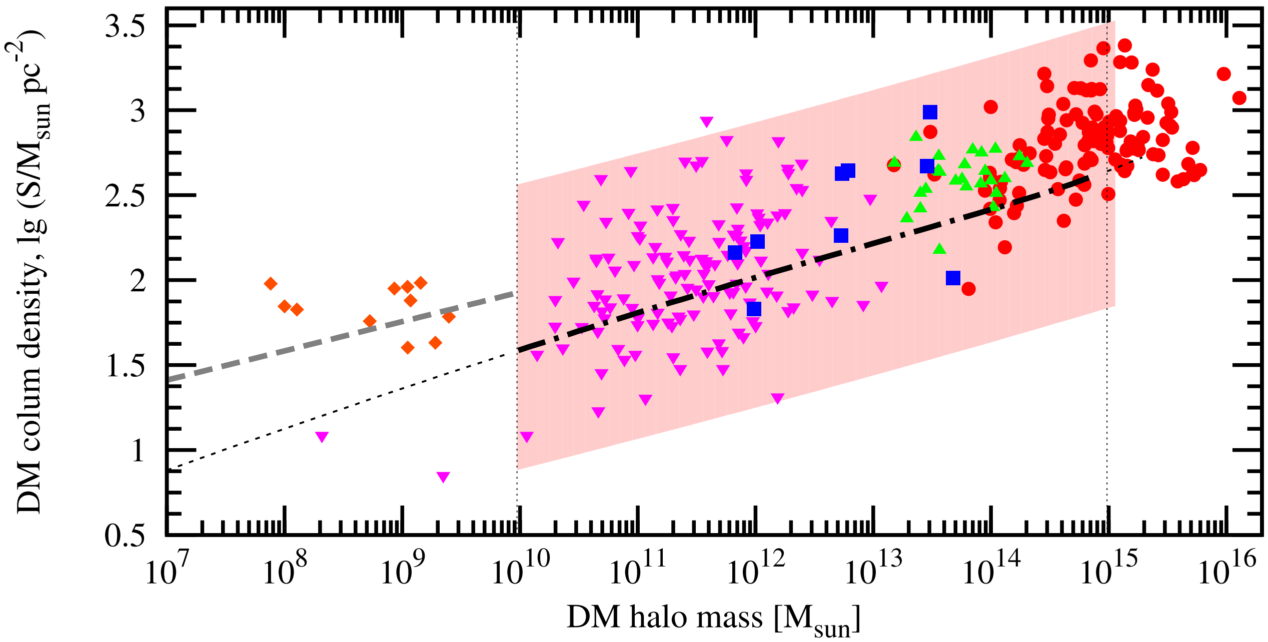
$$\mathcal{S} \sim \left(M_{\text{halo}}\right)^{\approx 0.2}$$

Universal scaling of DM column density



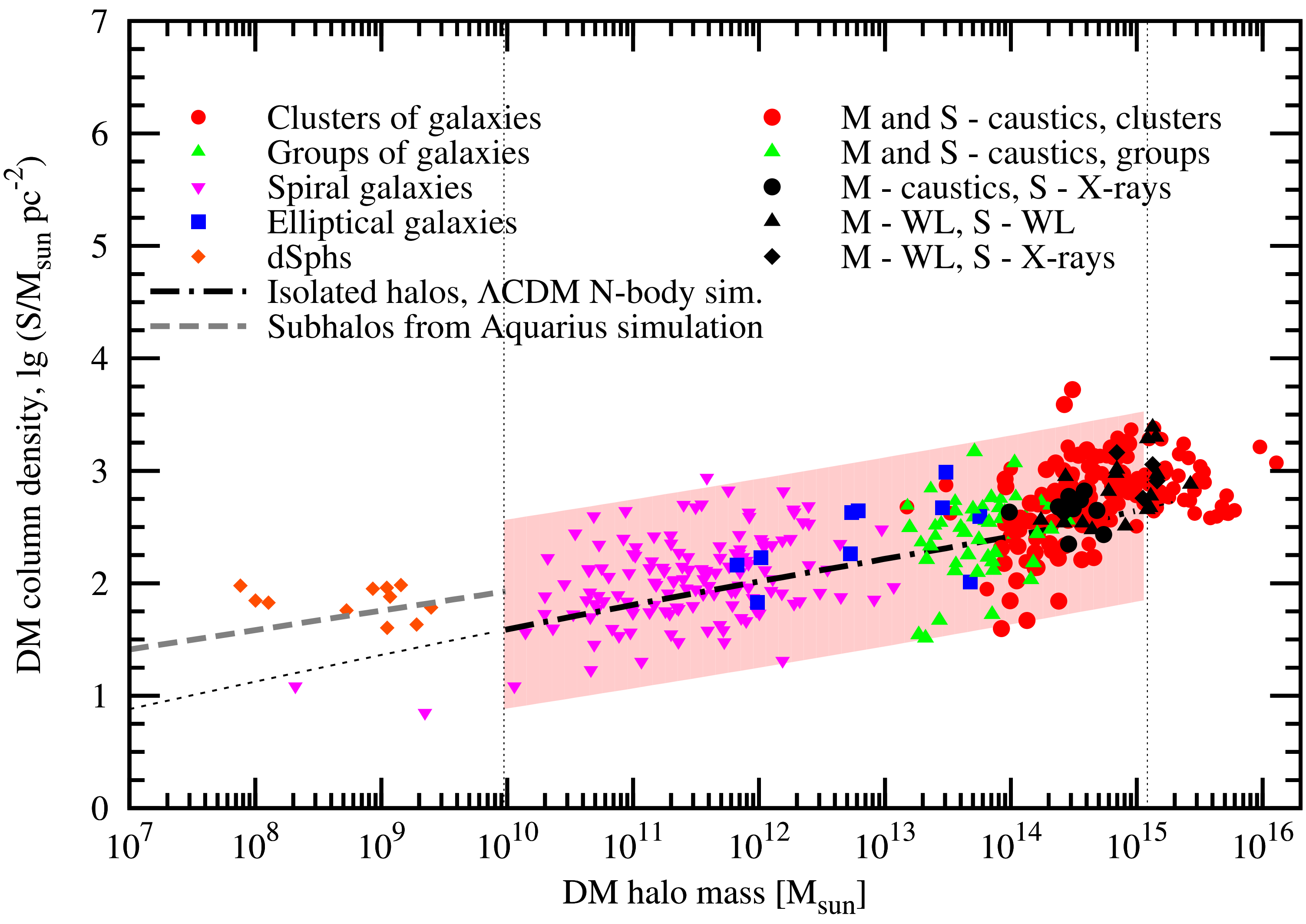
- The relation between $\mathcal{S}$ and M_{halo} is observed for isolated halos of all scales (for all observed halo masses from $10^8 M_\odot$ to $10^{15} M_\odot$). **0911.1774**
- Slope of subhalos (Aquarius simulation) is reproduced
- Median value and scatter coincide remarkably with **pure DM** simulations.

Universal scaling of DM column density



- No visible features – universal (**scale-free**) dark matter down to the lowest observed scales and masses
- No deviations from CDM down to $M_{\text{halo}} = 10^{10} M_\odot$
- **new proof that dark matter exists**!

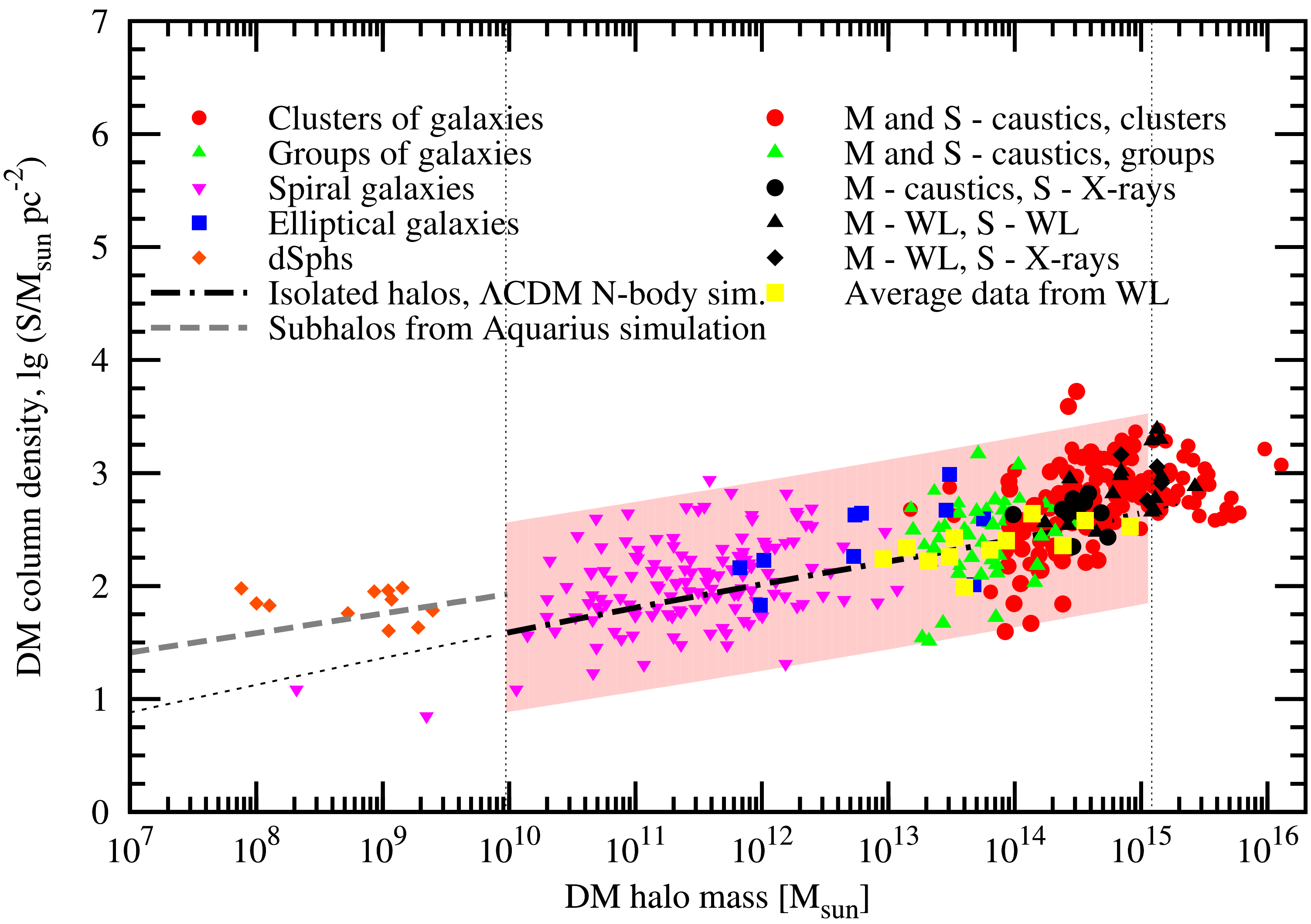
Independent determination of mass



work in progress Rines & Diaferio 2006, 2010

Independent determination of mass

Mandelbaum et al. JCAP 8 (2008) 6

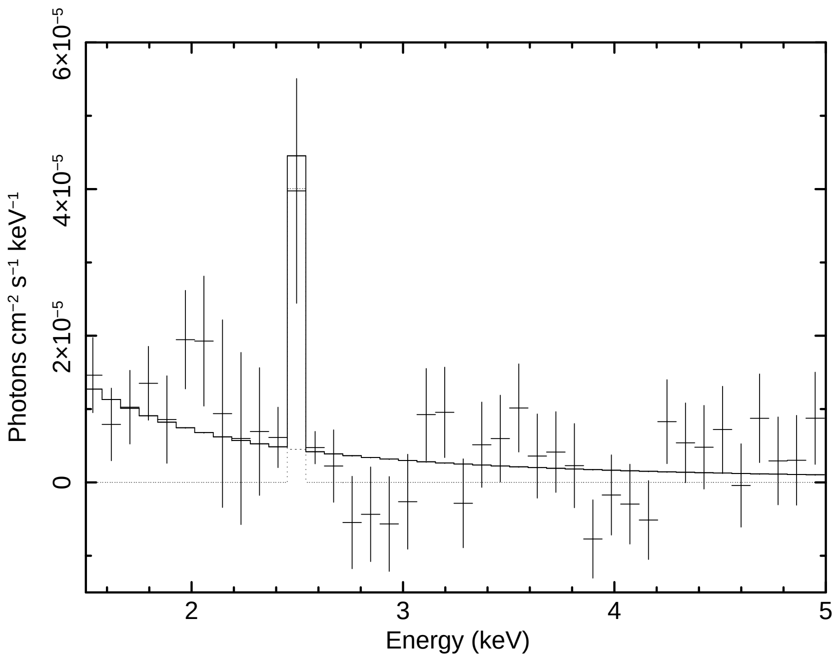


Direct astrophysical detection.

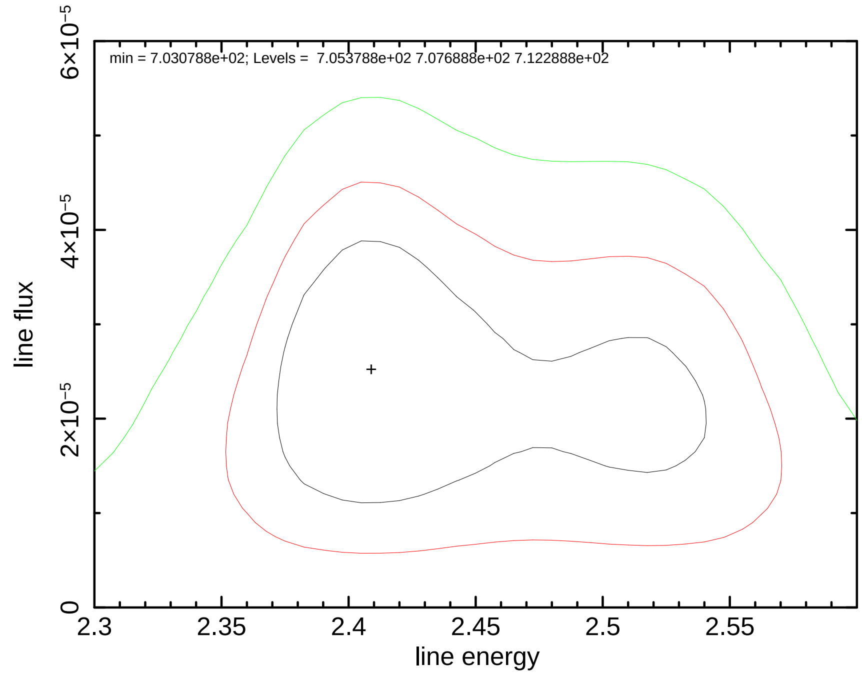
- As column density does not vary too much, decaying DM produces an all-sky signal with some hot spots.
- Objects of different scales and nature can be used to put robust bounds.
- Ones a candidate line is found, spacial distribution can be compared with DM column density map.
- DM origin can thus be unambiguously checked.

For decaying DM
"indirect" search becomes
"direct" !

Example: Spectral feature in Willman 1



[Loewenstein & Kusenko [0912.0552]]



68%, 90% and 99% confidence intervals

Dark matter decay signal

- If the signal found in Willman 1 is due to DM decay – we expect **detectable** signals from other objects.

- Decay flux is proportional to average **DM column density** within the FoV:

$$\mathcal{S} = \int_{\text{l.o.s.}} \rho_{\text{DM}}(r)dl$$

- Expected flux from another object:

$$F_X = F_{\text{Wil}\,1} \times \frac{\mathcal{S}_X}{\mathcal{S}_{\text{Wil}\,1}}$$

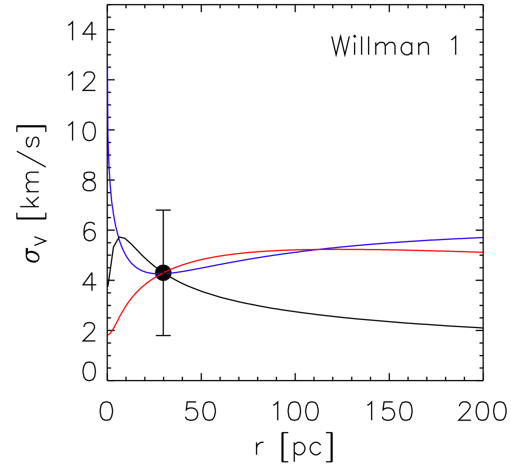
- $(\text{Signal/Noise}) \propto \mathcal{S}_X \times \sqrt{\text{Time} \cdot \text{Area} \cdot \Omega_{\text{fov}} \cdot \Delta E}$

  $\Longrightarrow$ *XMM-Newton* usually provides an improvement in (Signal/Noise)

  Collection area of EPIC cameras ~ 4 times larger; FoV $\sim 13'$

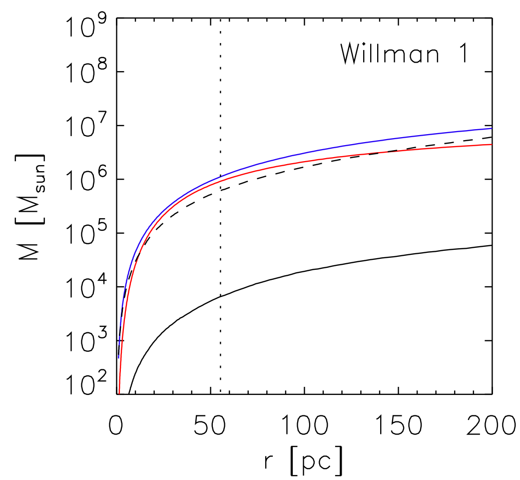
Observational targets

$$\Delta(\text{Signal/Noise}) \propto \frac{\mathcal{S}_X}{\mathcal{S}_{\text{Wil 1}}} \times \sqrt{\text{Time} \times \text{Area} \times \Omega_{\text{fov}} \times \Delta E}$$



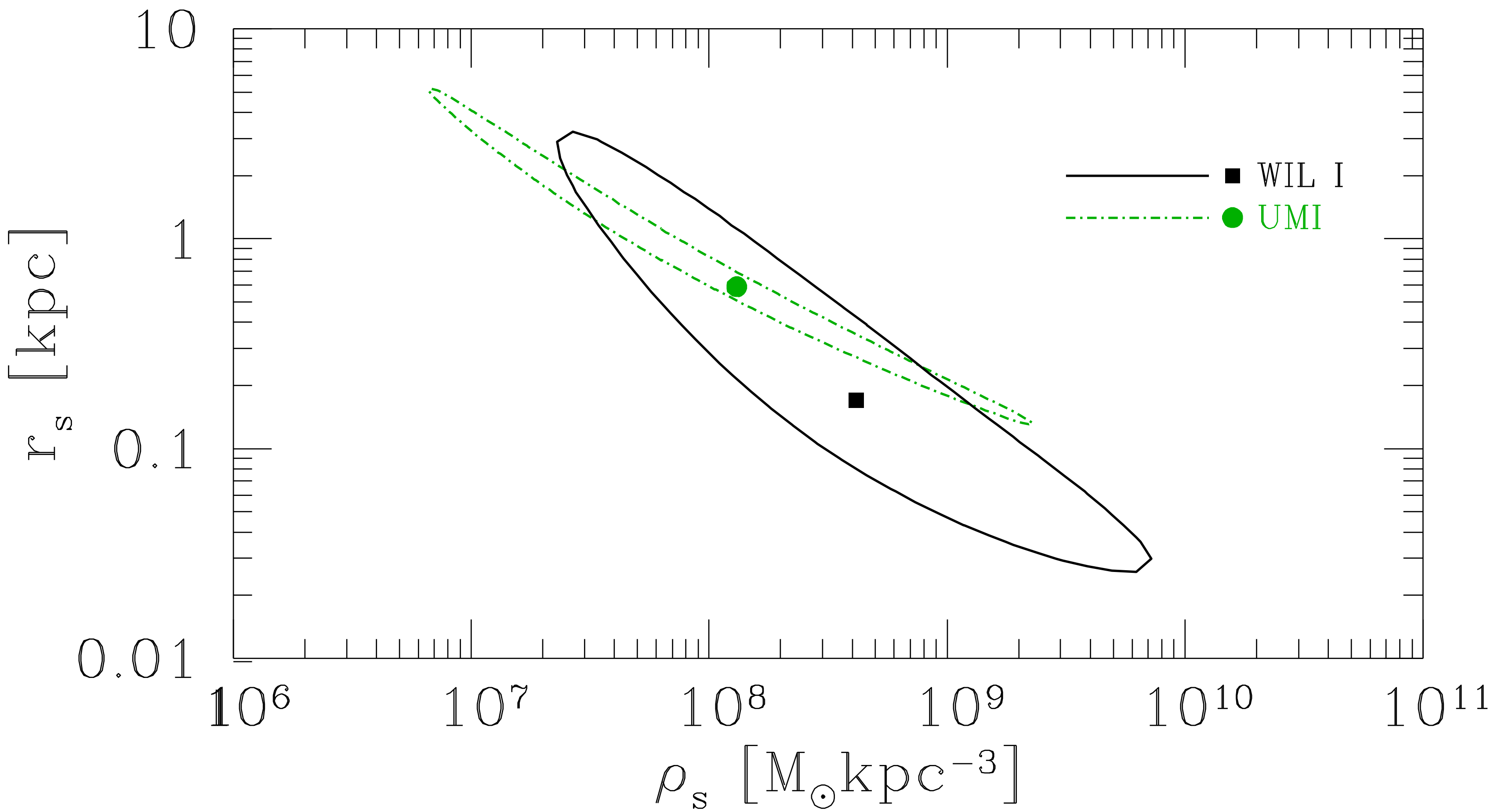
- DM content in Willman 1 (adopted in [Loewenstein & Kusenko'09])

$$\mathcal{S}_{\text{Wil 1}} \simeq 210 M_\odot\ \text{pc}^{-2}$$



- This estimate is based on [Strigari et al.'08]
- In [arXiv:1001.0644] we used this estimate to be conservative

DM in Willman 1

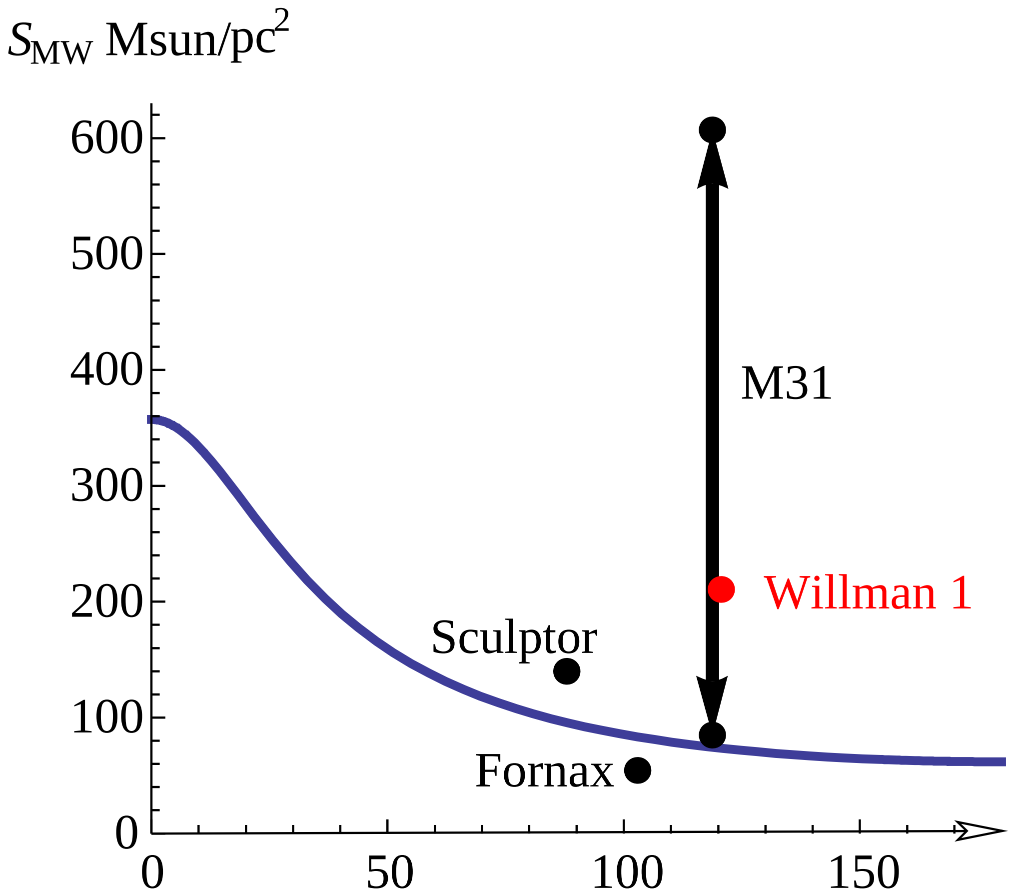


Strigari et al.'08

Uncertainty in $\mathcal{S}_{\text{Wil 1}}$ is factor 2-3; for Ursa Minor $\mathcal{S}_{UMi}$ changes by about 50% (within 90%CL).

The one-parameter fit assuming the relation between the NFW parameters predicted by the ΛCDM N-body simulations

Observational targets



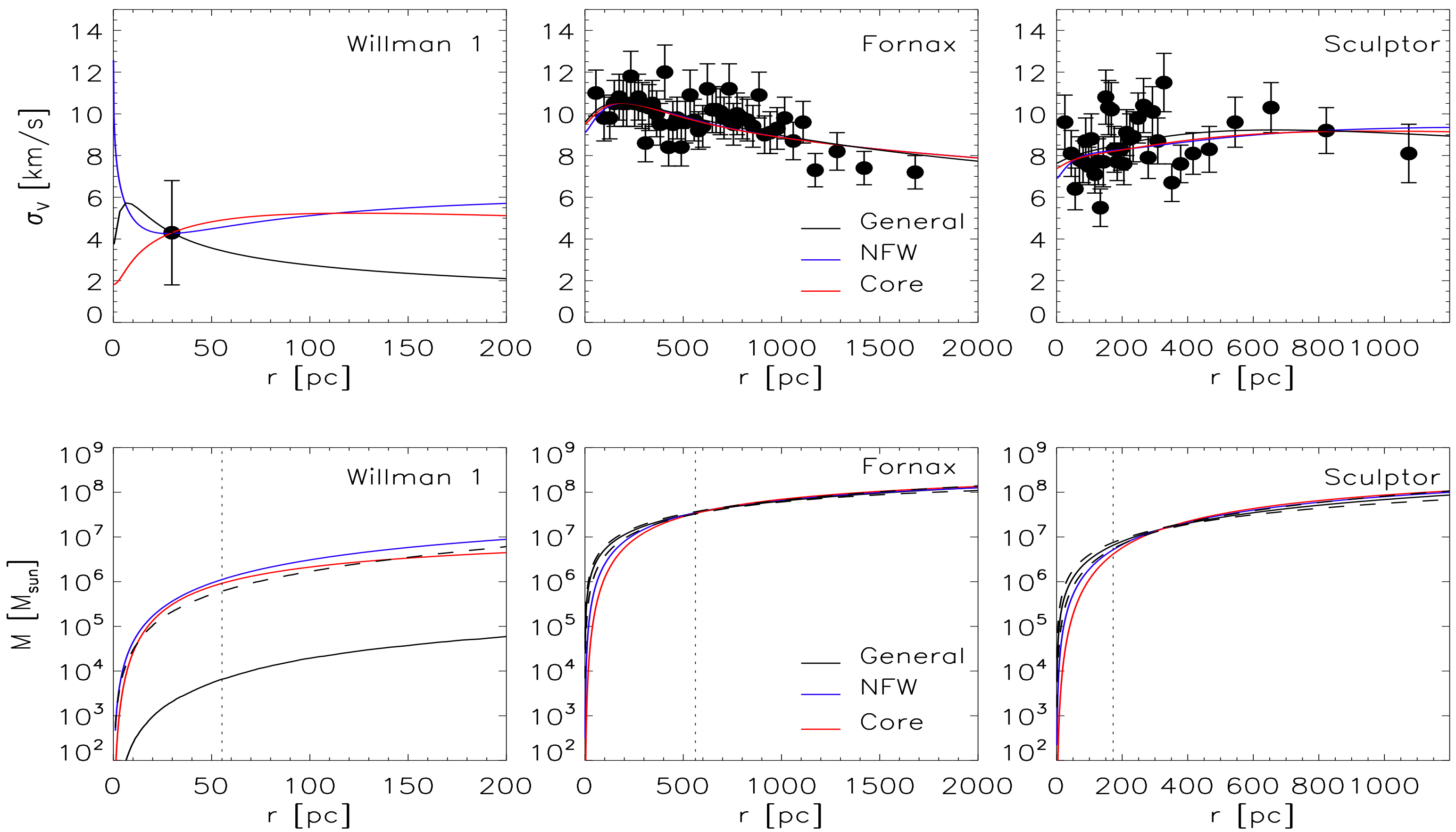
Objects for which archival data is available (used in [arXiv:1001.0644])

- **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)** : $90 M_\odot\,\mathrm{pc}^{-2} < \mathcal{S}_{M31} < 600 M_\odot\,\mathrm{pc}^{-2}$
- **Milky Way** : $70 M_\odot\,\mathrm{pc}^{-2} \lesssim \mathcal{S}_{\mathrm{MW}} \lesssim 95$

[Boyarsky et al. PRL'06; A&A'07]

DM in Dwarf Spherodiadals



DM content in "classical" dSphs is much more certain. Very low diffuse emission in X-rays. Not much baryons. Classical dSphs – preferred observational targets. **[Boyarsky et al. PRL'06]**

Checking for DM line in dSphs

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

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

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

- No significant lines were found in spectra of dSphs

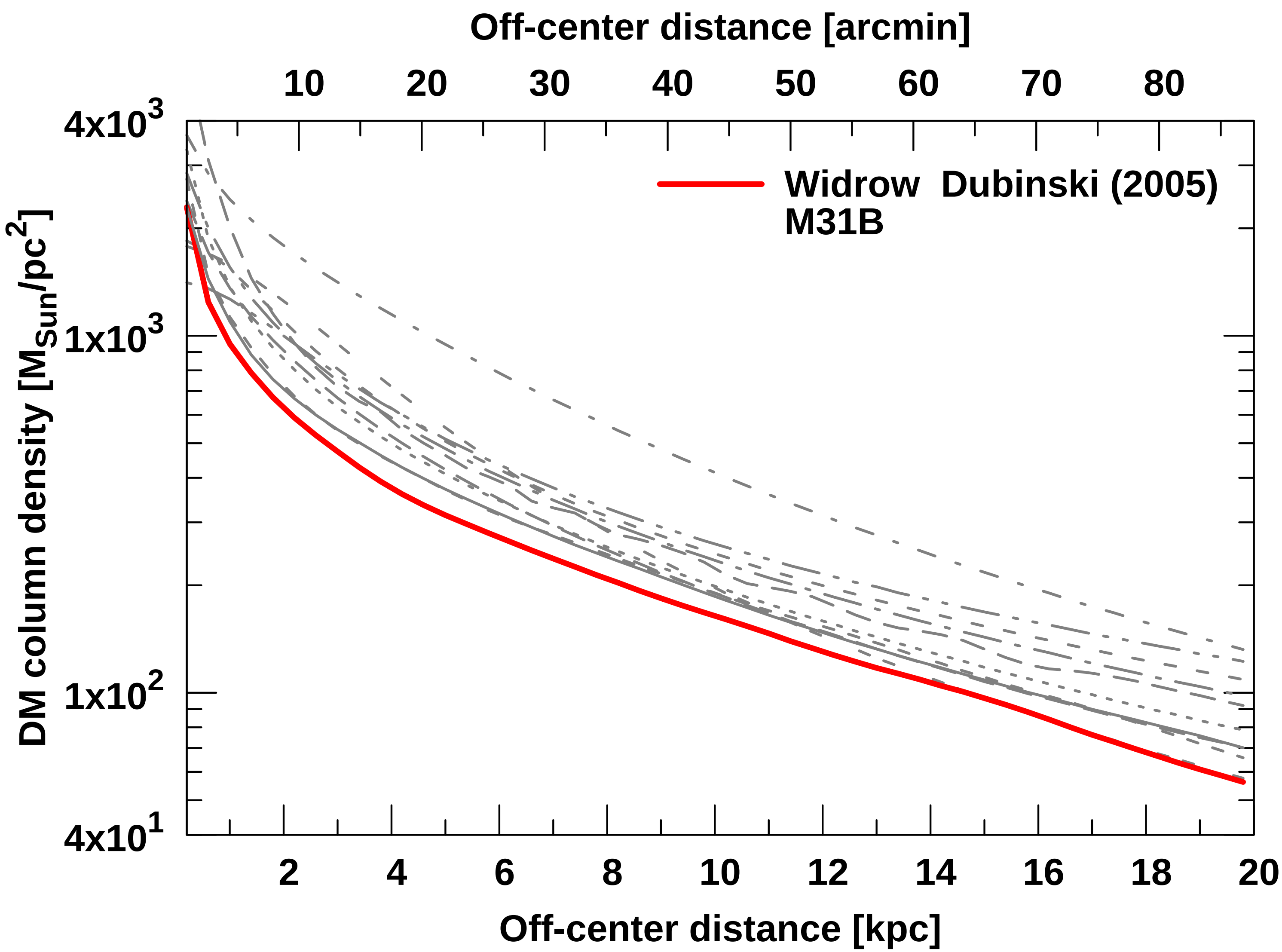
- We obtain the following exclusions

	$2.44 - 2.58$ keV	$2.30 - 2.72$ keV
Fornax dSph:	5.1σ	3.3σ
Sculptor dSph:	3.0σ	2.5σ
Fornax + Sculptor	5.9σ	4.1σ

- In case of the DM decay origin of the line we were expecting about 4σ detection from Fornax. However adding the line makes fit worse.

DM in Andromeda galaxy (2008)

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



Checking for DM line in M31

Exclusion from Fornax + Sculptor dSph:

	$2.44-2.58$ keV	$2.30-2.72$ keV
Fornax + Sculptor dSph	5.9σ	4.1σ

Andromeda galaxy

- Diffuse spectrum above 2 keV is a featureless power law

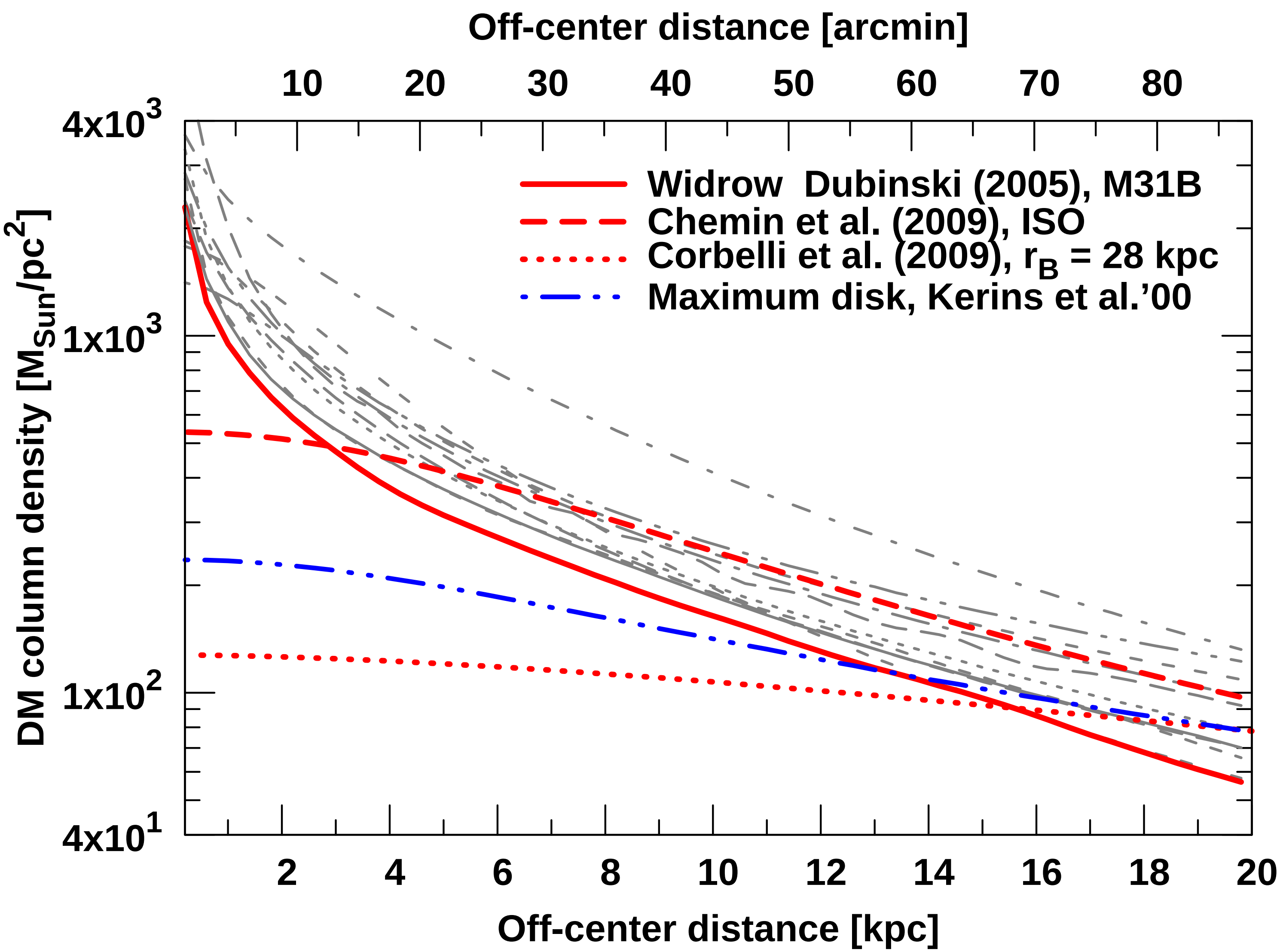
MNRAS'08 [0709.2301]

	$2.44-2.58$ keV	$2.30-2.72$ keV
M31, 1kpc $< R <$ 3kpc:	22.7σ	20.1σ
M31, 5 kpc off-center: circle radius 3 kpc	10.4σ	10.4σ
M31, both regions	24.9σ	23.3σ

1001.0644

- Extremely significant exclusion from central 8 kpc of Andromeda!
- All bounds are based on the conservative DM estimate from **[Widrow & Dubinski'05]**!

DM in Andromeda galaxy (2010)



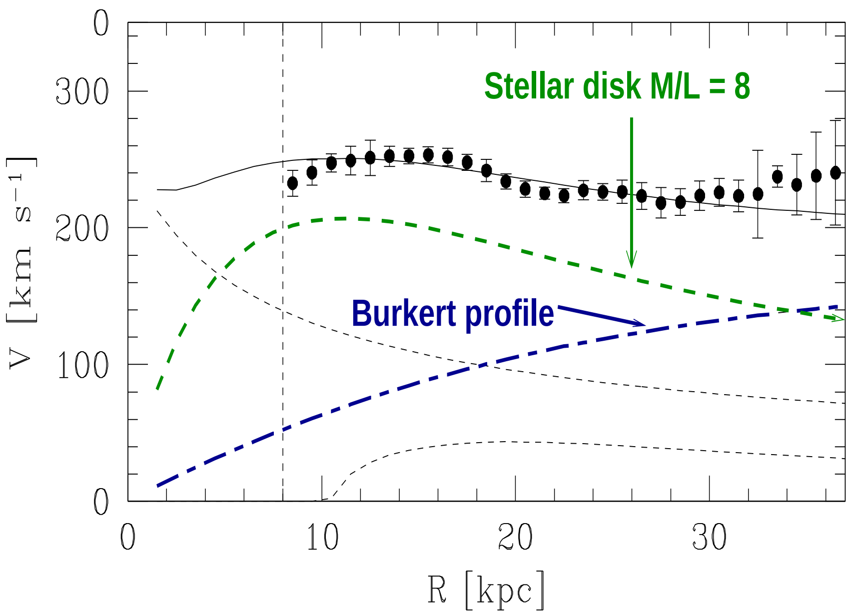
Boyarsky, O.R. et al. MNRAS'08

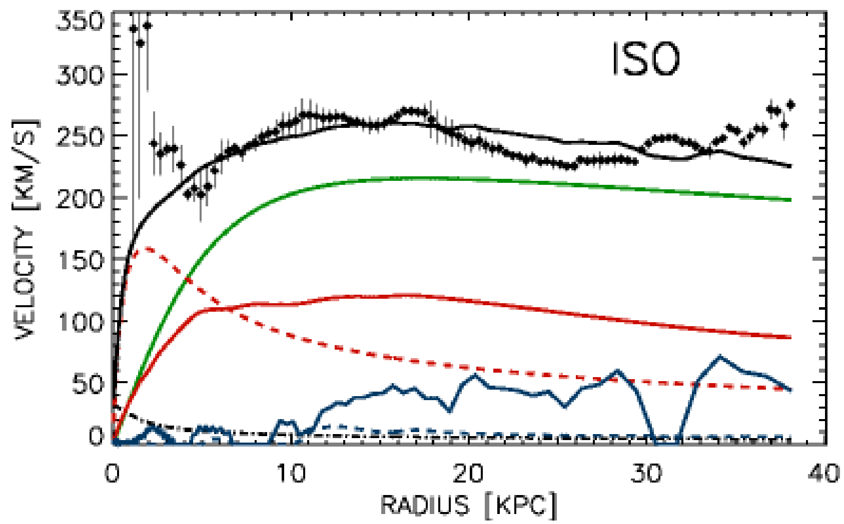
Chemin et al. 0909.3846

Corbelli et al. 0912.4133

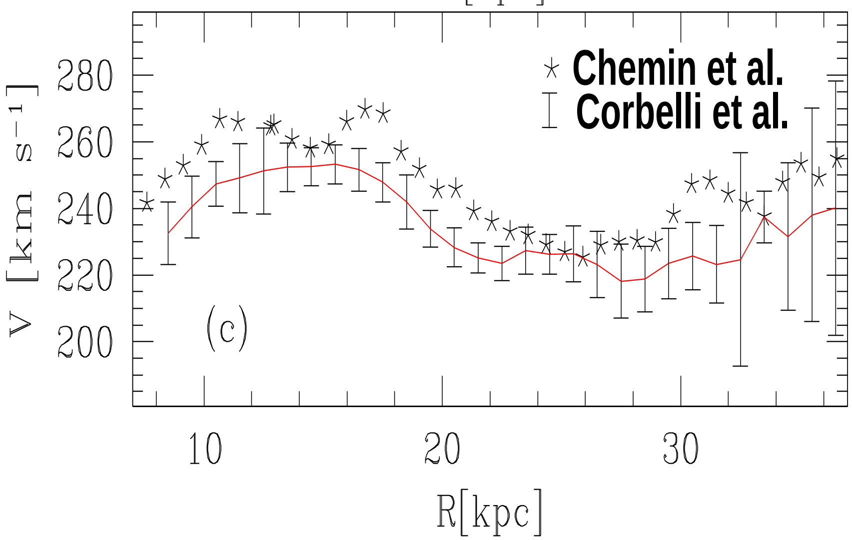
Kusenko & Loewenstein 1001.4055

New data and mass-to-light ratio in M31





Chemin et al. ApJ 2009 [0909.3846]



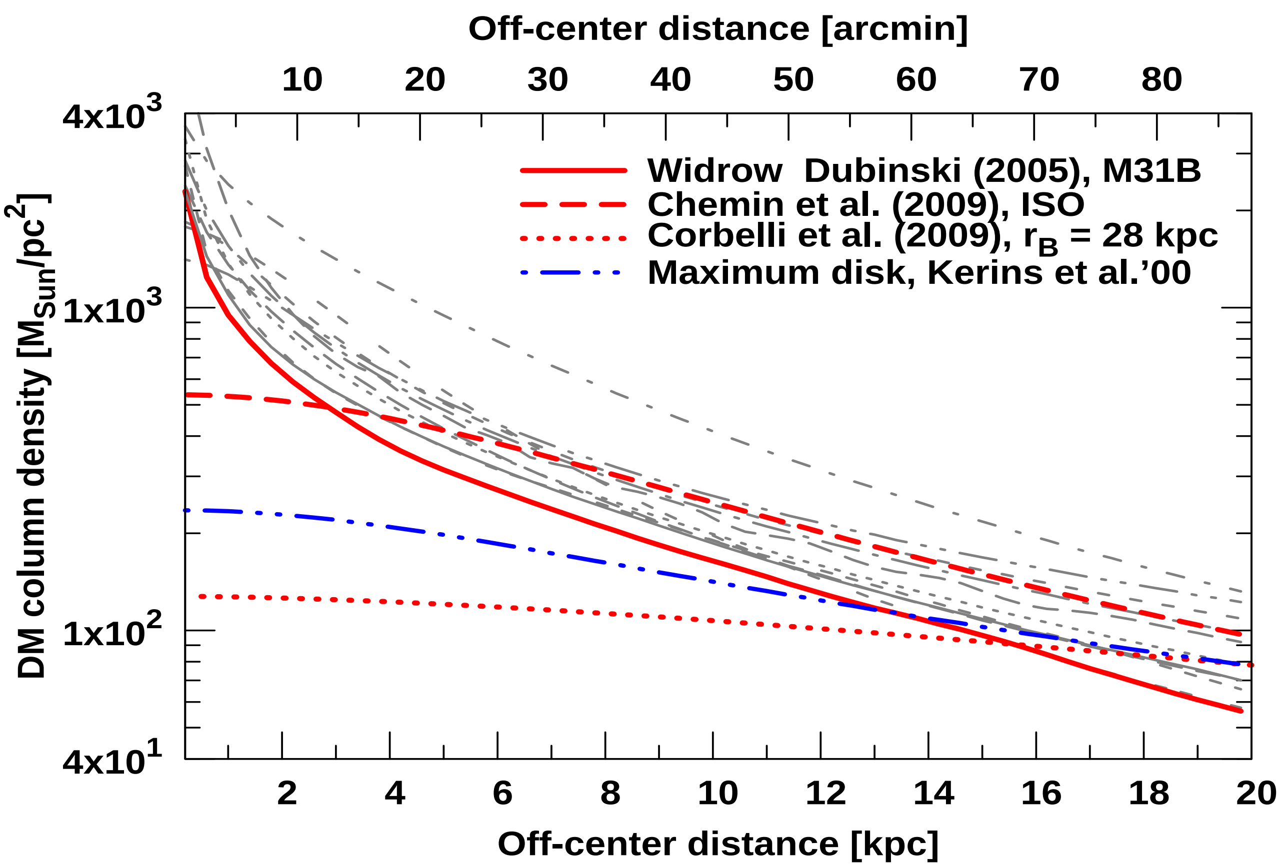
Corbelli et al. A&A 2009 [0912.4133]

– New precise HI data resolve features within inner 5–8 kps

– **Chemin et al.** model this region

– **Corbelli et al.** exclude this region from the analysis

DM in Andromeda galaxy



- Bounds in [arXiv:1001.0644v1] are from 1–3 kpc and 2–8 kpc (based on the model by [Widrow & Dubinski'05]
- To be conservative in the final version we repeat the analysis for [Corbelli et al.'09] and added data from 10-20 kpc.

Checking for DM line in M31

- Exclusion from Fornax and Sculptor dSphs:

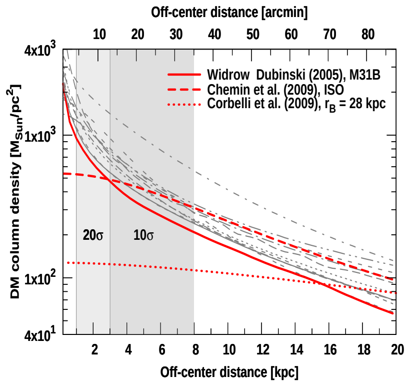
$2.44 - 2.58$ keV	$2.30 - 2.72$ keV
5.9σ	4.1σ

- Exclusion from **central 8 kpc of Andromeda**:

$2.44 - 2.58$ keV	$2.30 - 2.72$ keV	DM model
24.9σ	23.3σ	**[Widrow & Dubinski'05]**
7.9σ	6.9σ	**[Corbelli et al.'09]**

1001.0644

Summary of exclusions



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

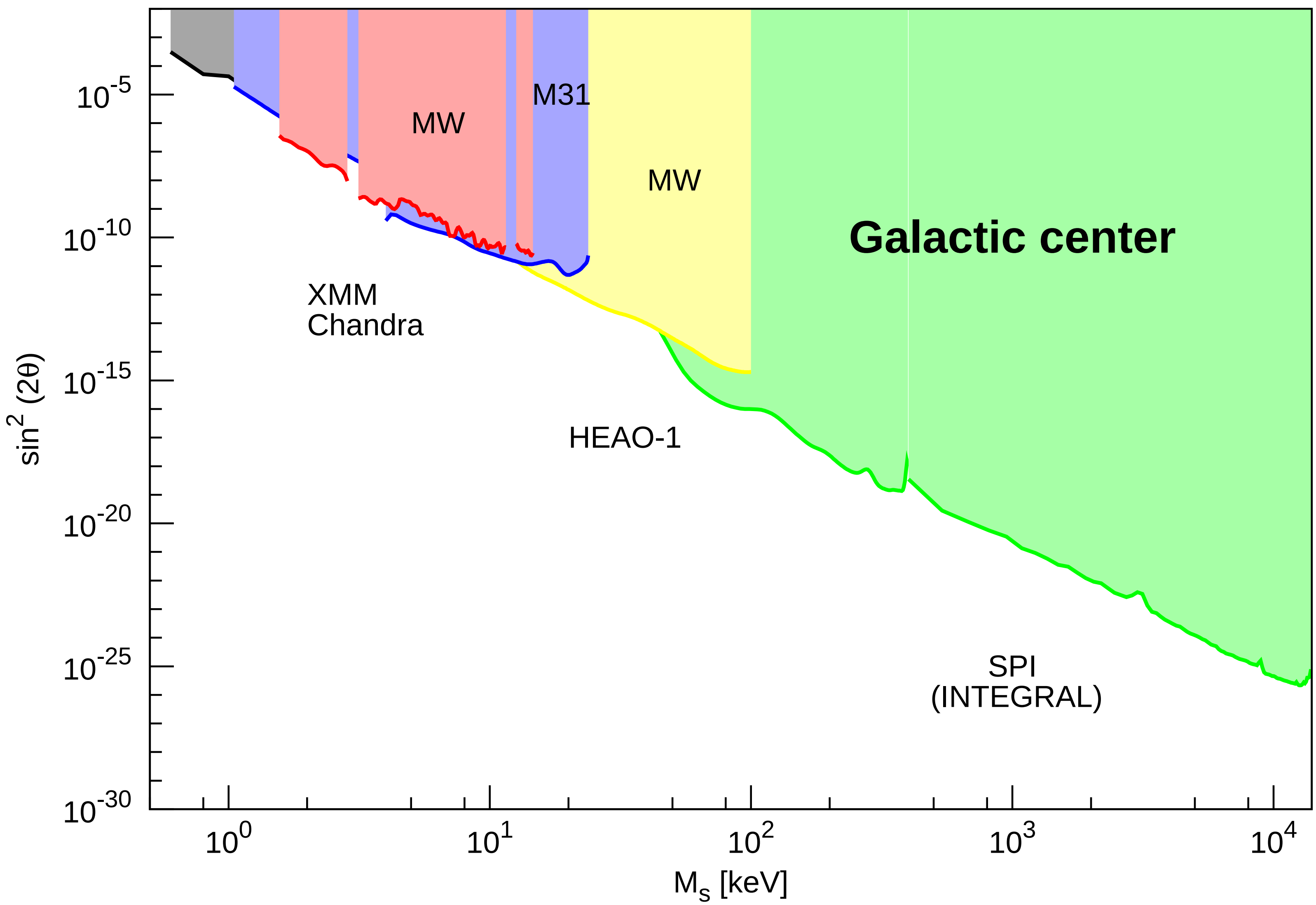
68% CL: 2.44 keV – 2.58 keV

99%CL: 2.30 keV – 2.72 keV

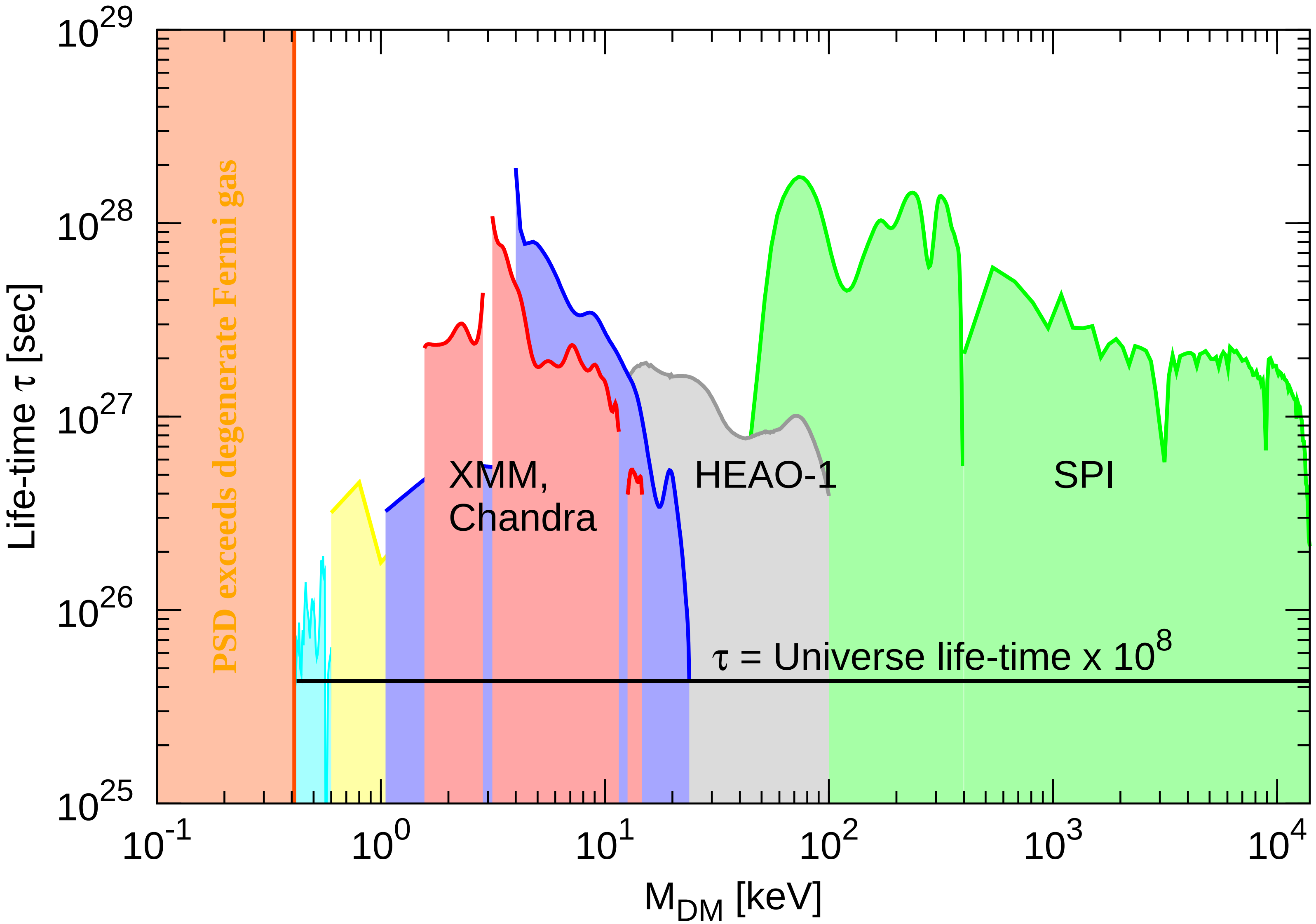
- The DM origin of the spectral feature in Willman 1 at ~ 2.5 keV is **excluded with 14σ significance**!

Restrictions on sterile neutrino DM

Boyarsky et al
MNRAS-2008



Restrictions on life-time of decaying DM



Boyarsky+ :
XRB HEAO-1
2005;

Bullet cluster
Chandra 2006;

LMC XMM

MW XMM

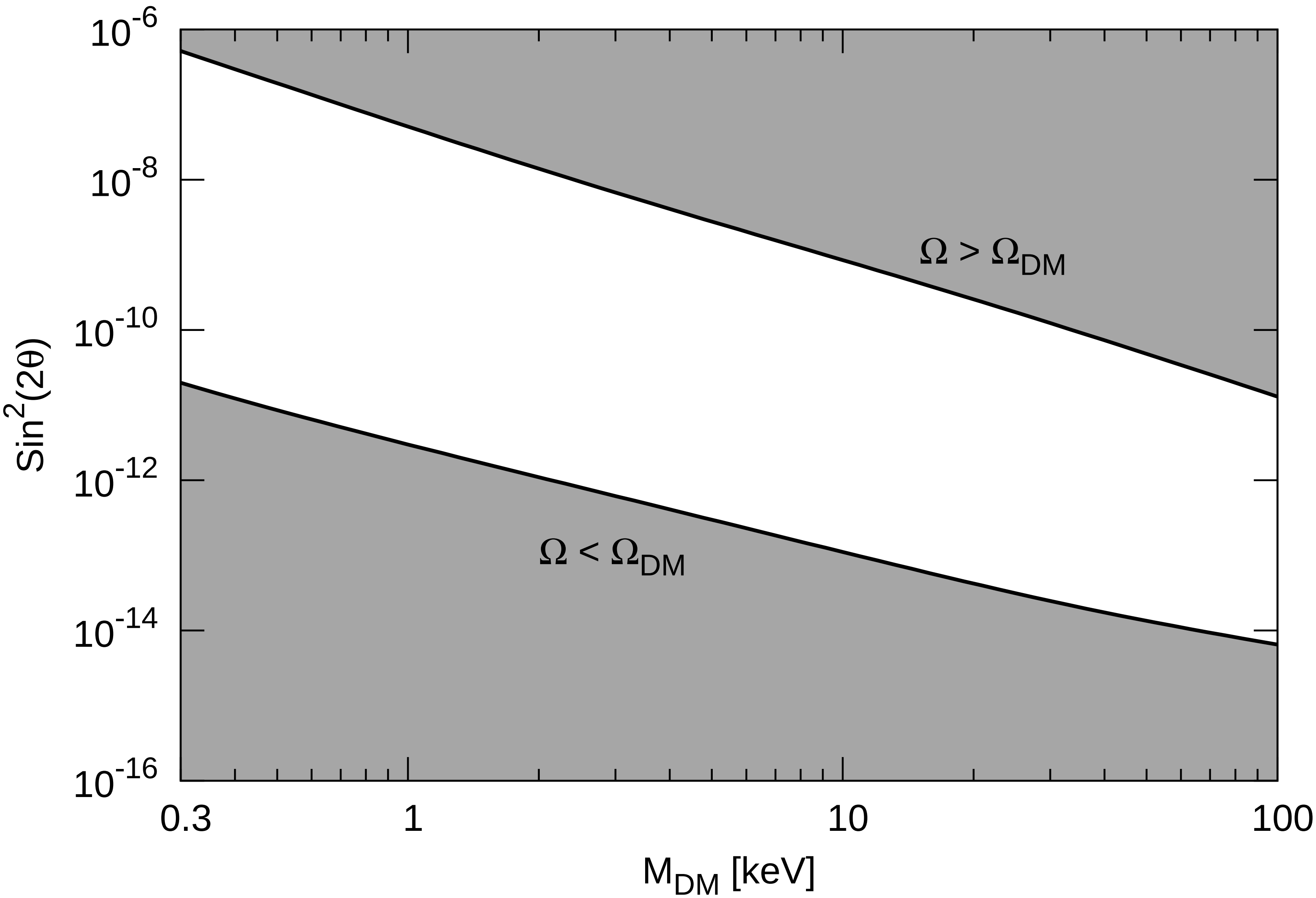
2006-2007

MW Chandra
Riemer-Sørensen+.;
Abazajian+ 2007

M31
Watson+ 2006;
Boyarsky+ 2007

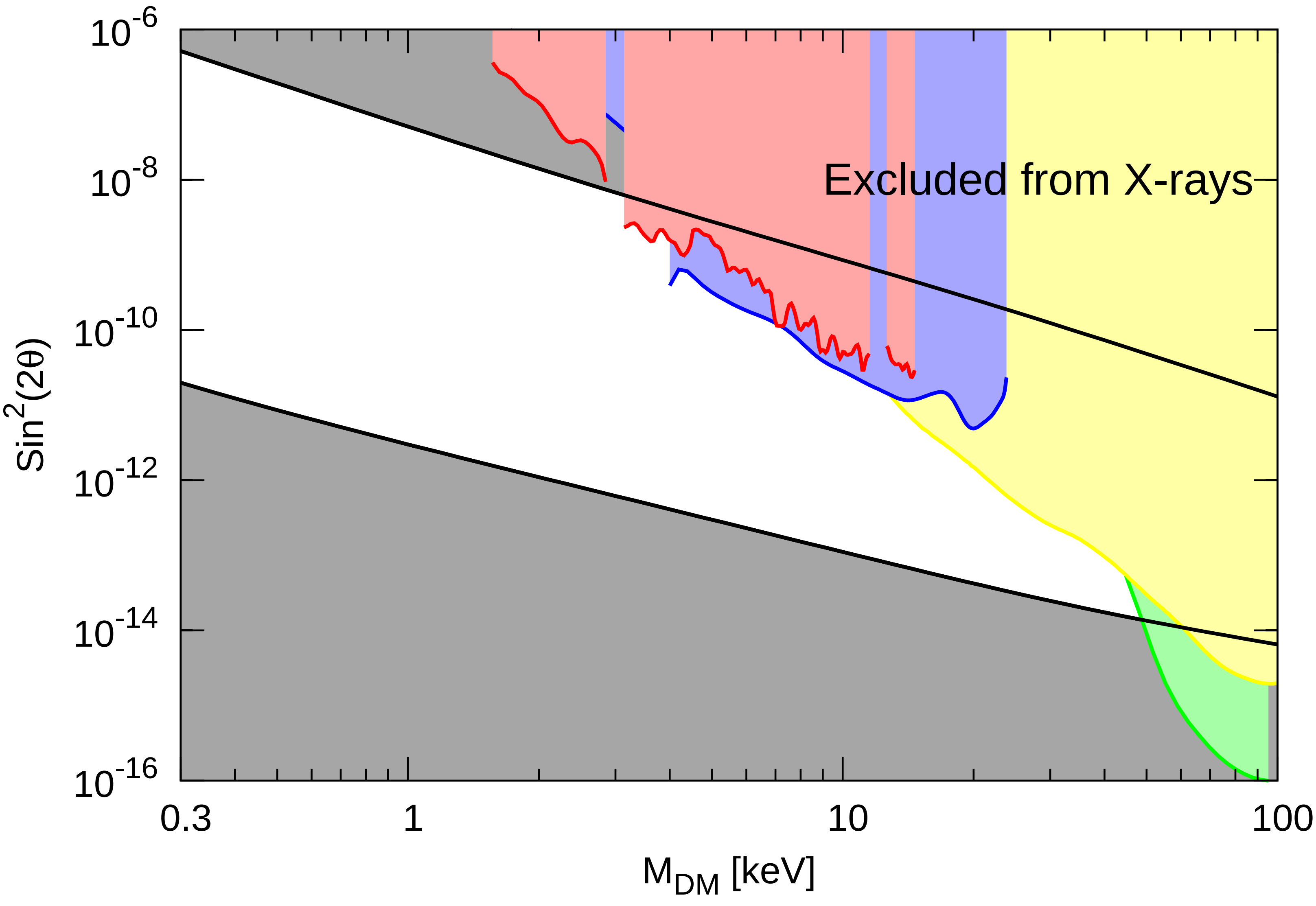
dSps(UMi, Draco,W1, Sc, Forn), Suzaku, Chandra, XMM
Boyarsky+ 2006,2010;
Loewenstein, Kusenko 2008-2009

Window of parameters of sterile neutrino DM



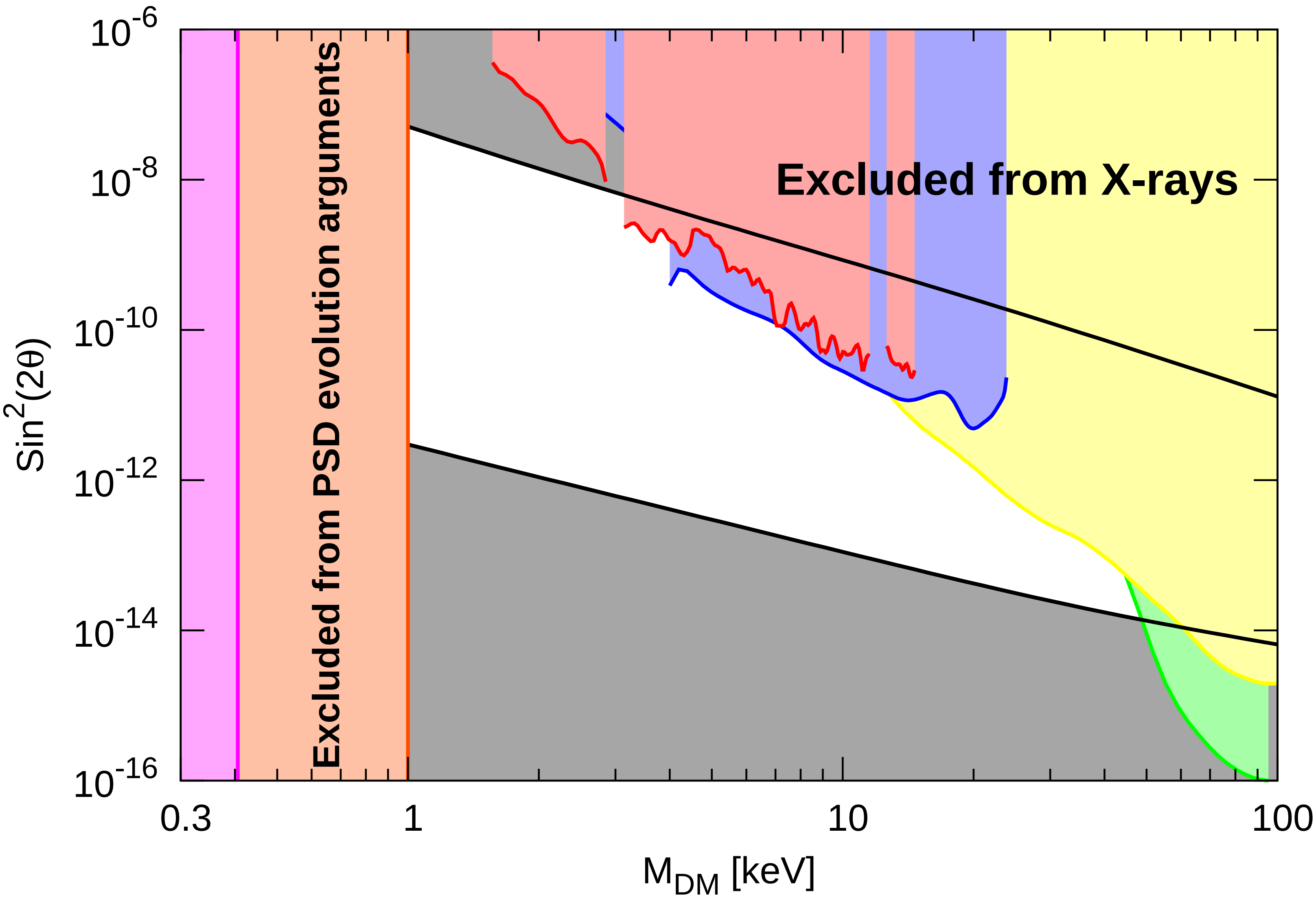
Window of parameters of sterile neutrino DM

Boyarsky, Ruchayskiy et al. 2005-2008

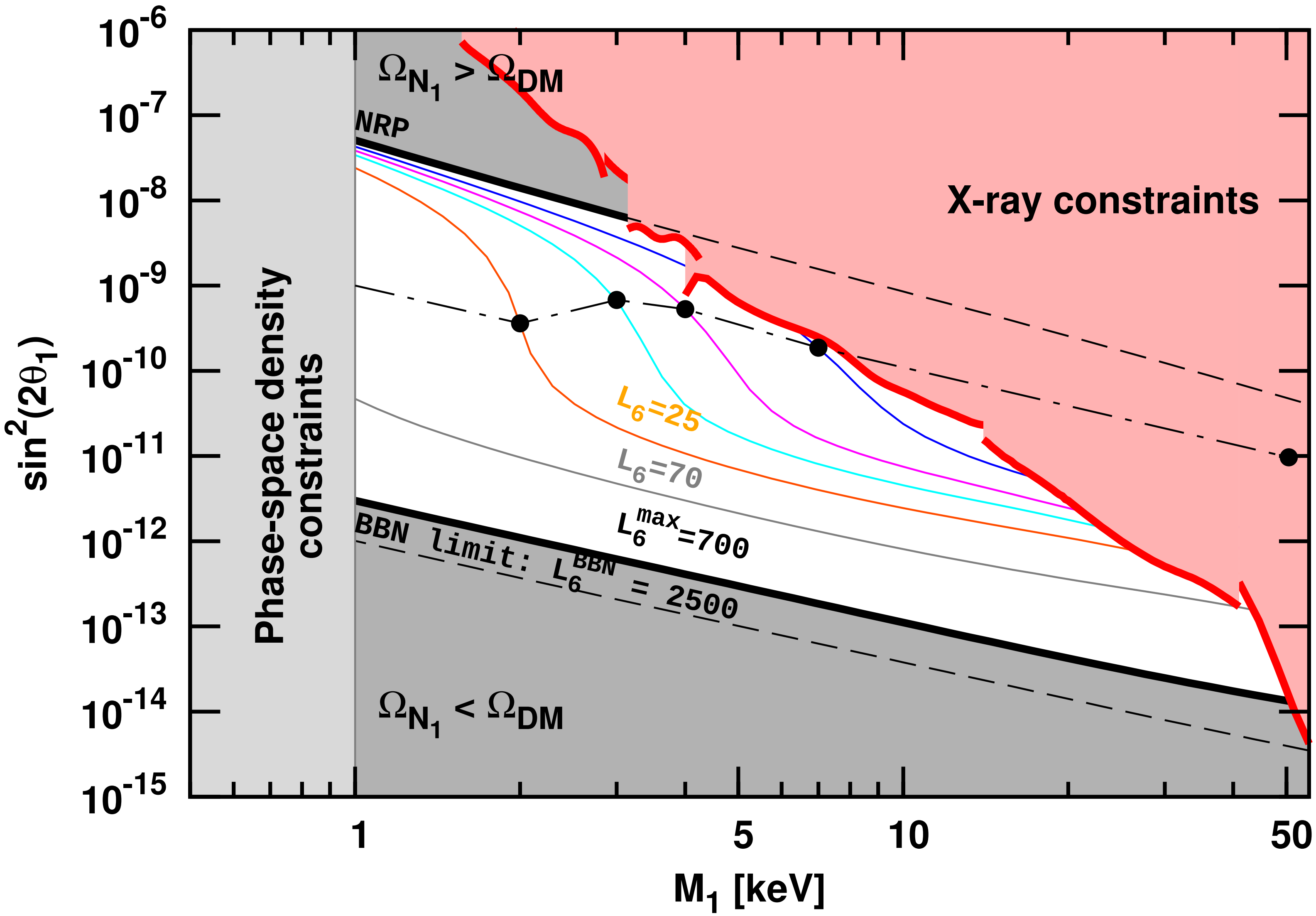


Window of parameters of sterile neutrino DM

Boyarsky, Ruchayskiy et al. 2005-2008



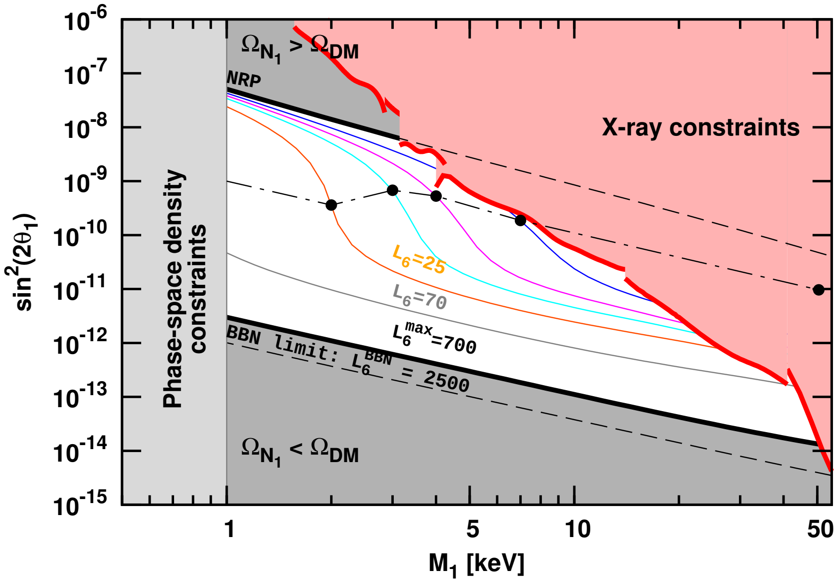
Window of parameters of sterile neutrino DM



Boyarsky, Ruchayskiy, Lesgourgues, Viel [0812.3256]

Boyarsky, Ruchayskiy, Shaposhnikov [0901.0011]

Window of parameters of sterile neutrino DM



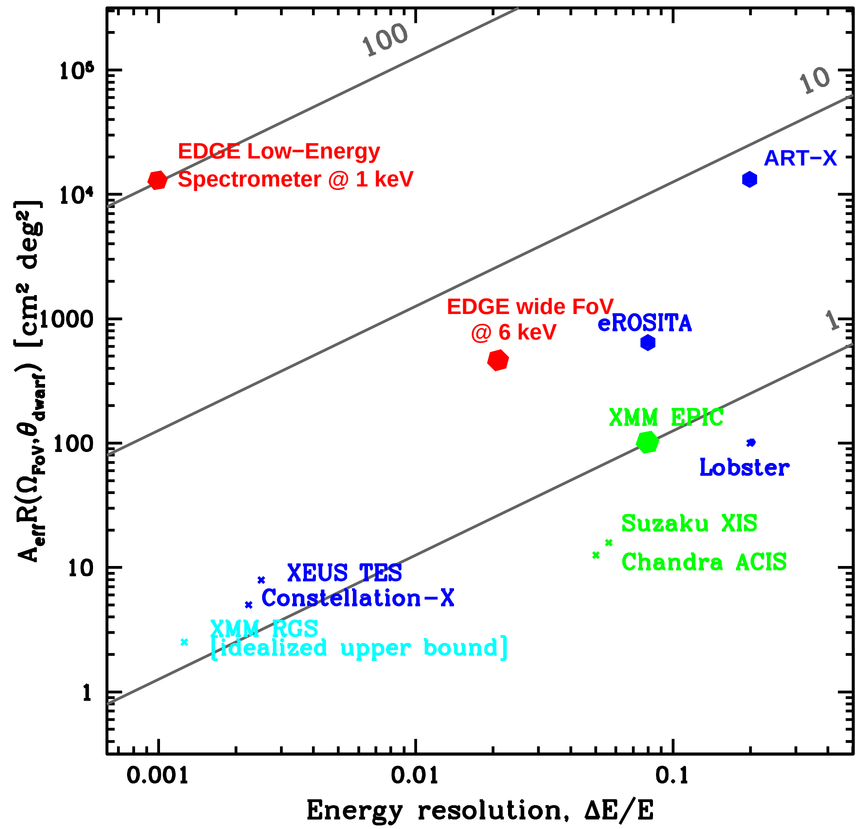
Boyarsky, Ruchayskiy, Lesgourgues, Viel [0812.3256]

Boyarsky, Ruchayskiy, Shaposhnikov [0901.0011]

- Sterile neutrino is still viable and very attractive DM candidate. The νMSM should be verified.
- To explore the allowed window, more theoretical efforts, both on **particle physics and astrophysics** sides, and new methods of analysis of the full set of the cosmological and astrophysical data is needed.

New mission: EDGE/XENIA

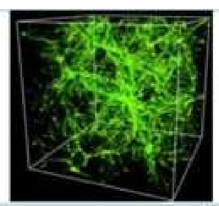
- Spectrometers with big FoV and spectral resolution better than 10^{-3} are needed
- Future missions (*XEUS* or *Constellation X*) will have better spectral resolution but very small FoV
- XENIA (former EDGE), proposed for NASA's *Cosmic Origins* by the team from NASA/MSFC, INAF, SRON + ISDC, EPFL,...).

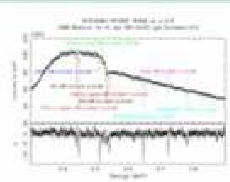


A.Boyarsky, *et al.* (2007)

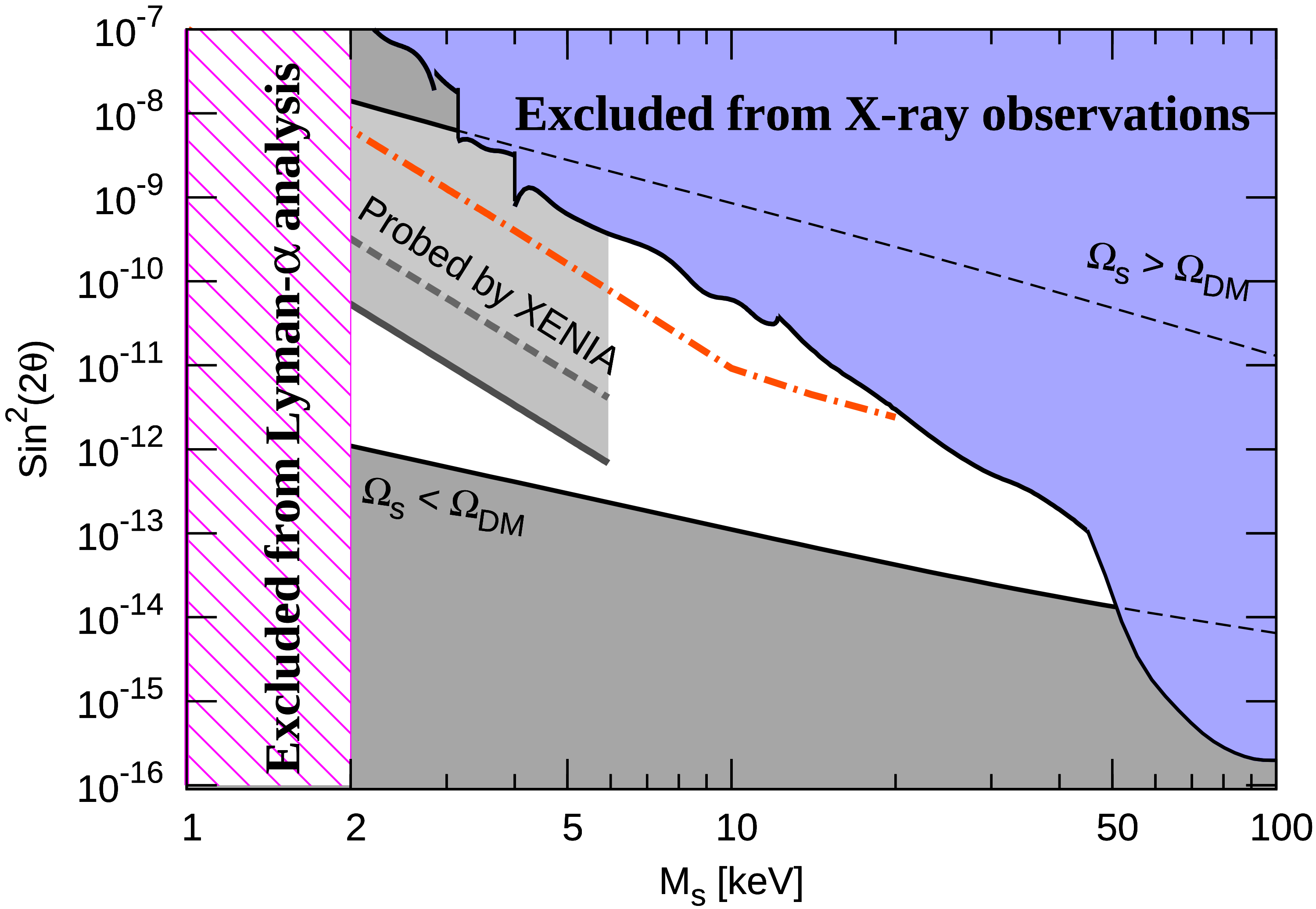
EDGE

Explorer of **D**iffuse **E**mission and **G**amma-ray burst **E**xplosions





Improved bounds on DM decay



Thank you for your attention