A DEEP VIEW ON NEUTRINOS AS DARK MATTER

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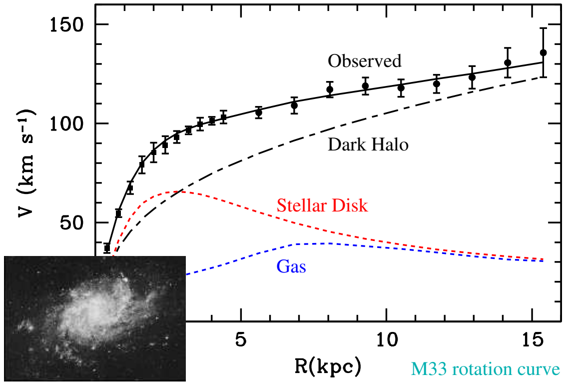
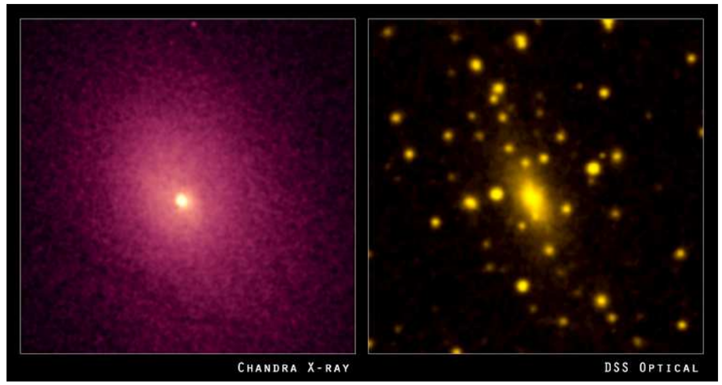
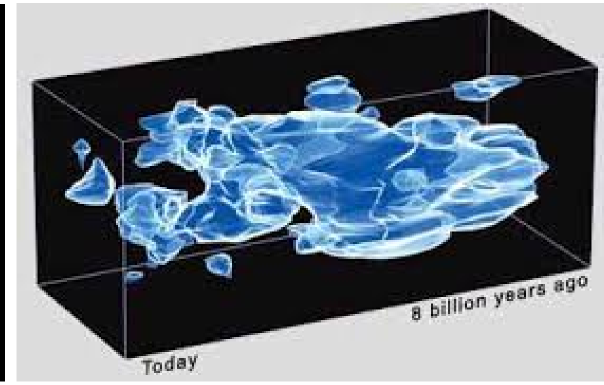
June 11, 2014

More gravitating mass than eyes see!



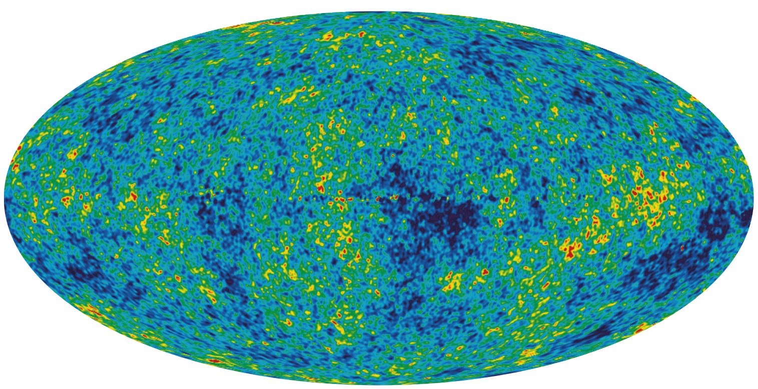




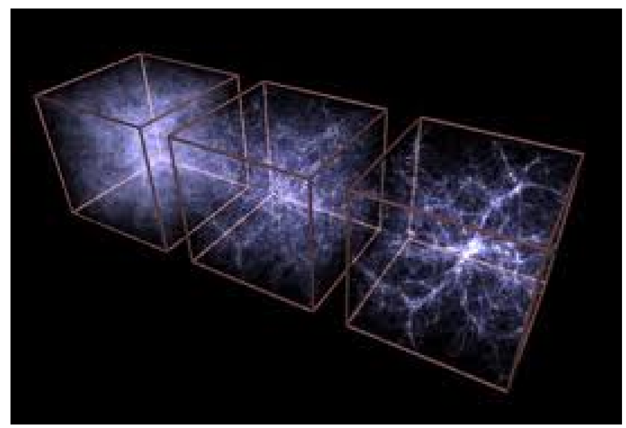
Expected: $v(R) \propto \frac{1}{\sqrt{R}}$
Observed: $v(R) \approx \text{const}$

Expected:
$\text{mass}_{\text{cluster}} = \sum \text{mass}_{\text{galaxies}}$
Observed: 10^2 times more mass confining ionized gas

Lensing signal (direct mass measurement) **confirms** other observations

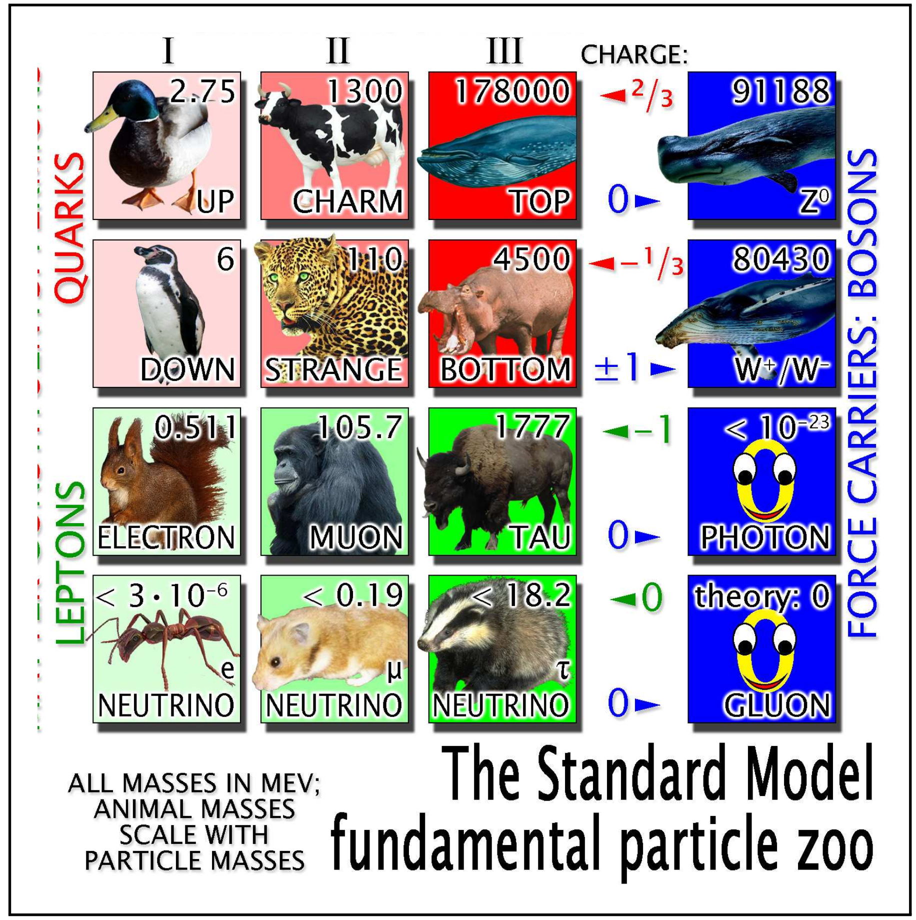


Jeans instability turned tiny density fluctuations into all visible structures



Properties of Dark Matter particles

- DM particle should be: **massive**
  (relativistic particles do not cluster)
- If DM particles ever were relativistic – they should have **slow down early** in the history of the Universe
- DM particles should be **neutral**
  (not to interact with photons)
- DM particles should be **stable** or have cosmologically **long lifetime**



Any candidates in the Standard Model?

Neutrino Dark Matter?

- In 1979 when S. Tremaine and J. Gunn published in Phys. Rev. Lett. a paper *"Dynamical Role of Light Neutral Leptons in Cosmology"*
  - The smaller is the mass of Dark matter particle, the larger is the number of particles in an object with the mass M_{gal}
  - Average phase-space density of **any fermionic** DM should be **smaller** than density of **degenerate Fermi gas**

⇒ If dark matter is made of fermions – its mass is bounded from below:

$$\frac{M_{\text{gal}}}{\frac{4\pi}{3}R_{\text{gal}}^3}\,\frac{1}{\frac{4\pi}{3}v_\infty^3} \leq \frac{2{m_{\text{DM}}}^4}{(2\pi\hbar)^3}$$

[0808.3902]

- Objects with highest phase-space density – dwarf spheroidal galaxies – lead to the **lower bound** on the fermionic DM mass

$$\boxed{M_{\text{DM}} \gtrsim 300 - 400\ \text{eV}}$$

Neutrino Dark Matter?

- **However**, if you compute contribution to DM density from massive active neutrinos ($m_\nu \lesssim$ MeV), you get

$$\Omega_{\nu\,\text{DM}} h^2 = \sum m_\nu \int \frac{d^3k}{(2\pi)^3} \frac{1}{e^{\frac{k}{T}} + 1} = \boxed{\frac{\sum m_\nu[\text{eV}]}{94\text{ eV}}}$$

- Using minimal mass of 300 eV you get $\Omega_{\text{DM}} h^2 \sim 3$ (**wrong by about a factor of 30!**)

- Sum of masses to have the correct abundance $\boxed{\sum m_\nu \approx 11\text{ eV}}$

Massive Standard Model neutrinos cannot be simultaneously "astrophysical" and "cosmological" dark matter: to account for the missing mass in galaxies **and** to contribute to the cosmological expansion

- Next blow to neutrino DM came around 1983–1985 when M. Davis, G. Efstathiou, C. Frenk, S. White, *et al.* "*Clustering in a neutrino-dominated universe*"

- They argued that structure formation in the neutrino dominated Universe (with masses around 100 eV would be incompatible with the observations)

http://www.adsabs.harvard.edu/abs/1983ApJ...274L...1W

Abstract

The nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution has been simulated . . . . **The conventional neutrino-dominated picture appears to be ruled out.**

Two obvious generalizations of neutrino DM:

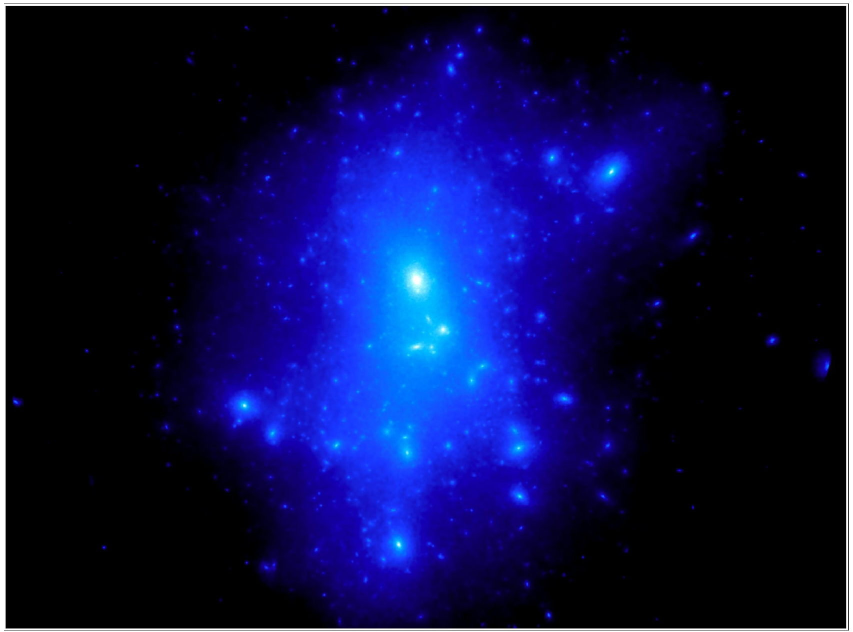
1) Make the "neutrino" **heavier** so that it decouples non-relativistic (and therefore the expression $\Omega_{\text{DM}} h^2 = \frac{\sum \mathcal{M}_\nu[\text{eV}]}{94\ \text{eV}}$ is not applicable anymore) but keep the interaction of the same order.

2) Make the "neutrino" interact **weaker-than-weak**, so that it never enters the equilibrium with the plasma in the first place (and therefore the expression $\Omega_{\text{DM}} h^2 = \frac{\sum \mathcal{M}_\nu[\text{eV}]}{94\ \text{eV}}$ is not applicable anymore)

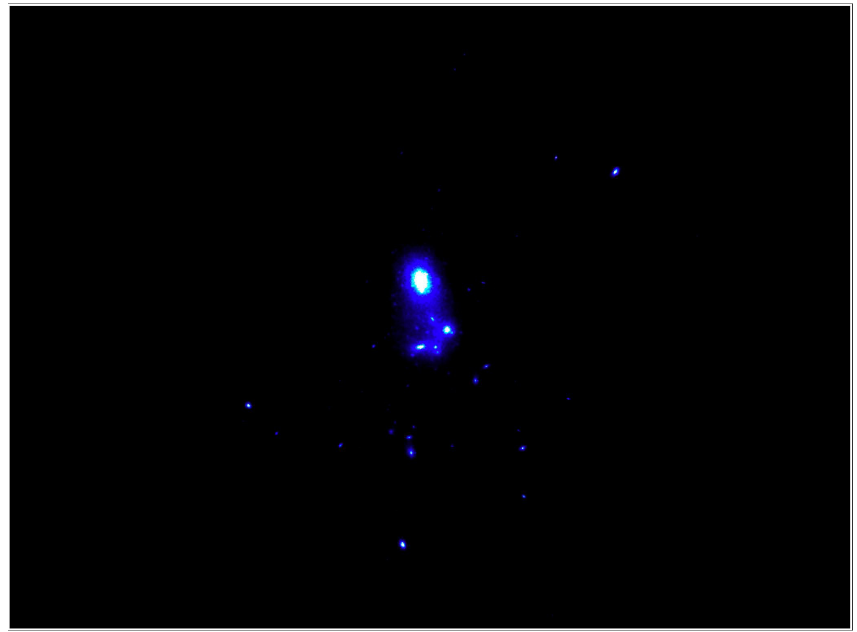
- First modification is called .... **WIMP**
  large mass and interaction strength of such a particle means that it will be unstable unless there is an exact symmetry, protecting it from decay

- Second modification is called .... **sterile neutrino**
  mass that can be rather small ($\mathcal{O}(0.5$ keV) and super-weak interaction strength of such a particle means that it **can** be unstable but still provide a correct phenomenology

Search for decaying dark matter



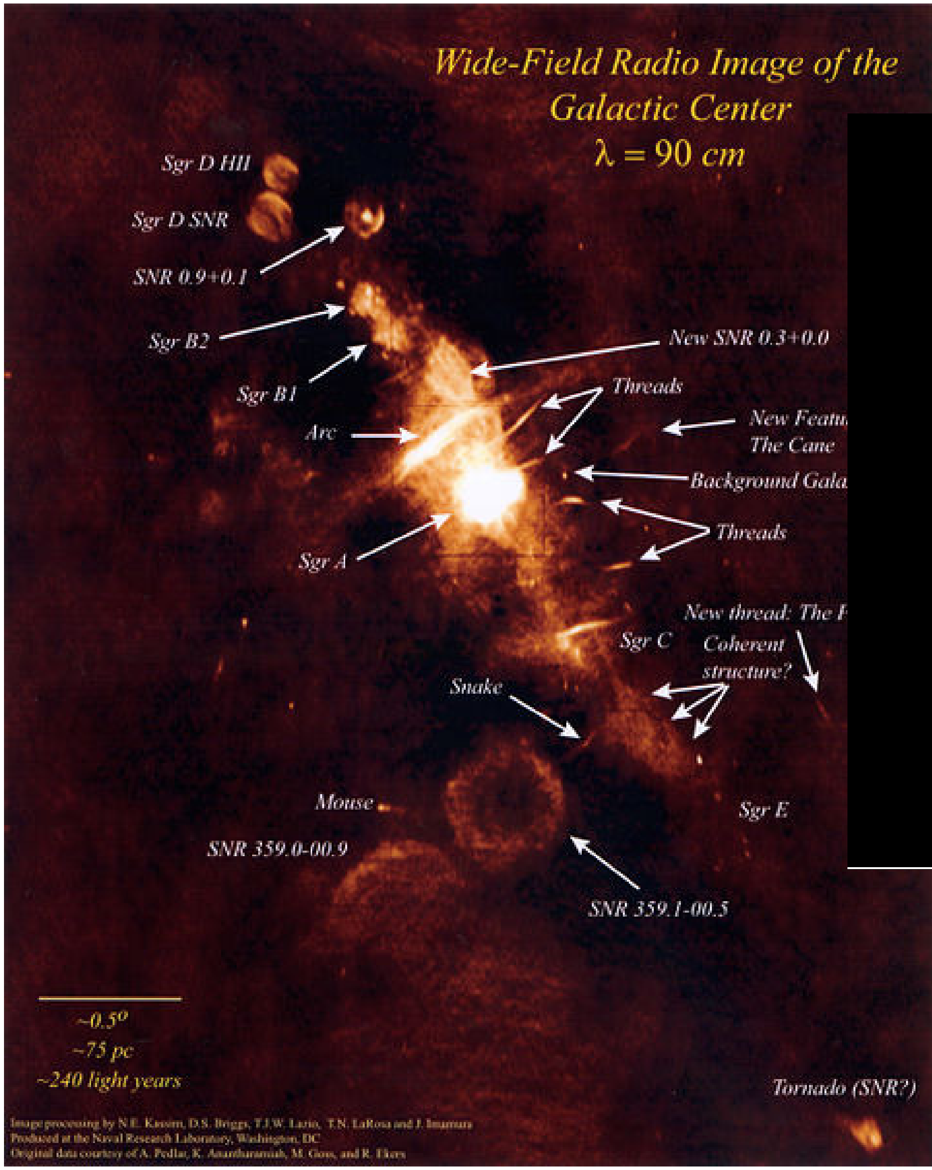
DM **decay** signal from a galaxy

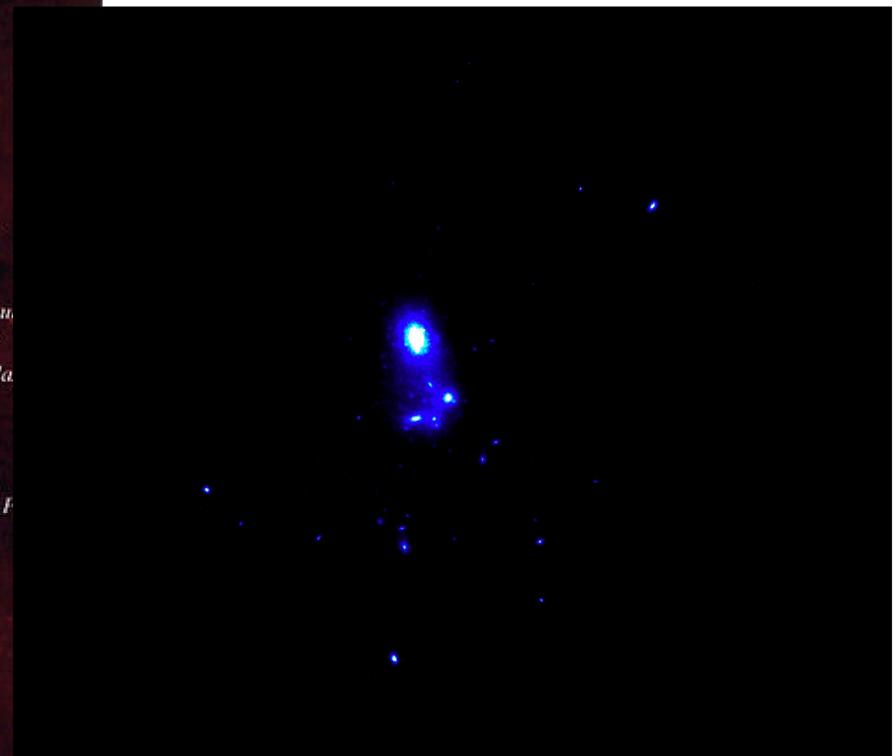


DM **annihilation** signal from a galaxy

For decaying dark matter astrophysical search is (almost) "**direct detection**" as any candidate line can be unambiguously checked (confirmed or ruled out) as DM decay line

Galactic center is a busy place





Annihilation signal from the Milky way-like galaxy

Decaying dark matter signal

- Two-body decay into two massless particles (DM $\to \gamma + \gamma$ or DM $\to \gamma + \nu$) $\Rightarrow$ narrow decay line
$$E_\gamma = \frac{1}{2} m_{\text{DM}} c^2$$
- The width of the decay line is determined by **Doppler broadening**
- Typical virial velocities:
  - A dwarf satellite galaxy: $\sim 30\,\mathrm{km/sec}$
  - Milky Way or Andromeda-like galaxy: $\sim 200\,\mathrm{km/sec}$
  - Typical velocity in the galaxy cluster $\sim 1500\,\mathrm{km/sec}$
- Very characteristic signal: narrow line in all DM-dominated objects with $\dfrac{\Delta E}{E_\gamma} \sim \dfrac{v_{\text{vir}}}{c} \sim 10^{-4} \div 10^{-2}$

Dark matter decay flux

- Flux from dark matter decay is Flux $= \frac{1}{4\pi\tau_{\rm DM}M_{\rm DM}}\frac{M_{\rm fov}}{D_L^2}$

- For objects that *cover the whole FoV of the instrument*

$$\frac{M_{\rm fov}}{D_L^2} \approx \Omega_{\rm fov} \int_{\text{line of sight}} \rho_{\rm DM}(r)dr$$

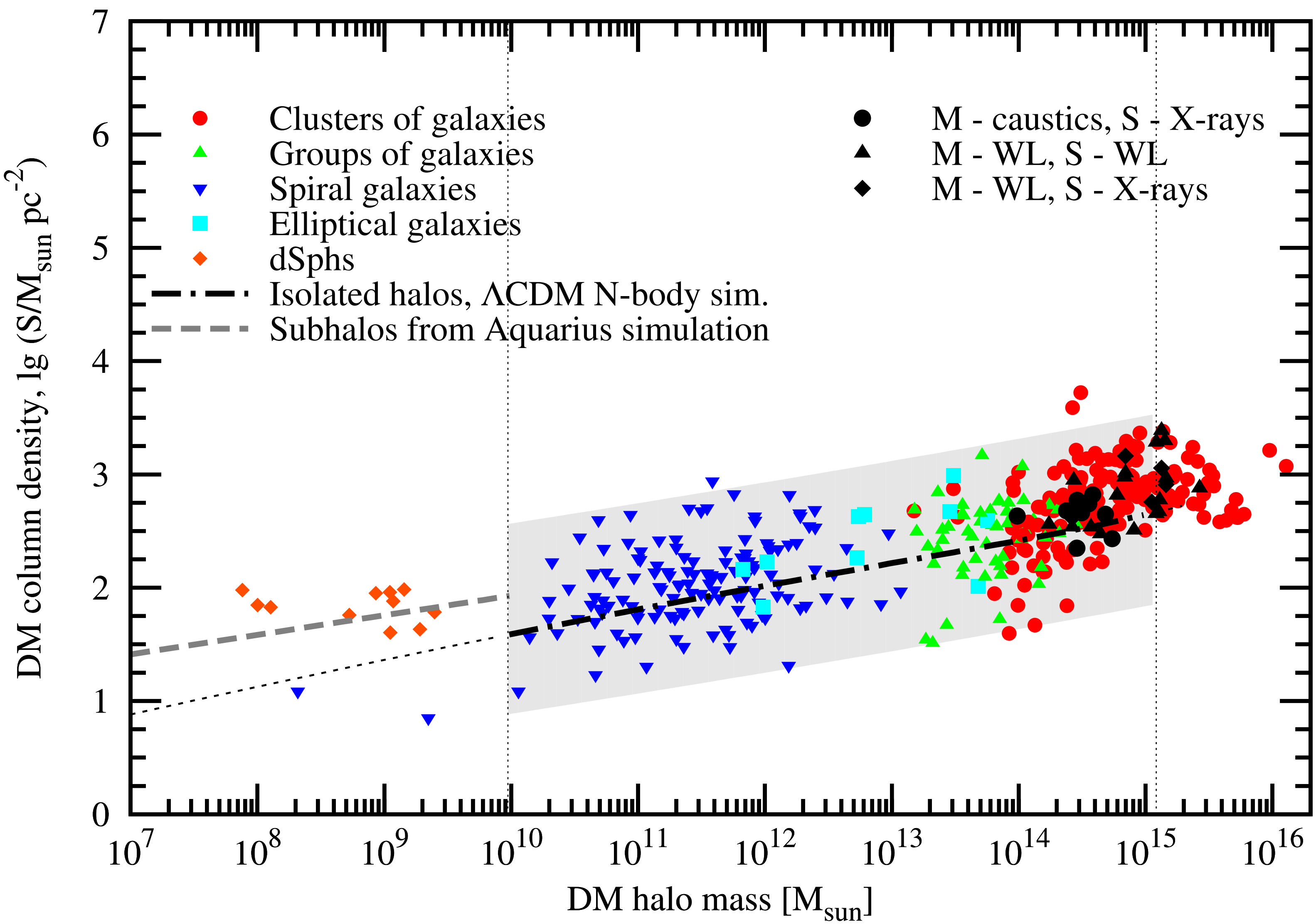
— does not depend on the distance to the object!

- **column density** $\boxed{\mathcal{S} = \int \rho_{\rm DM}(r)dr}$ remains **remarkably constant** from one object to another!

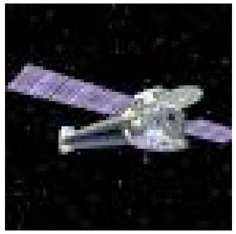
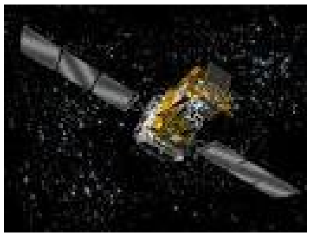
- – Distance to the Galactic Center: 8 kpc
  – Distance to the Andromeda galaxy: 780 kpc
  – Distance to the Perseus cluster: 73.6 Mpc
  – Distance to the Virgo cluster: 18 Mpc

Signal from different DM-dominated objects

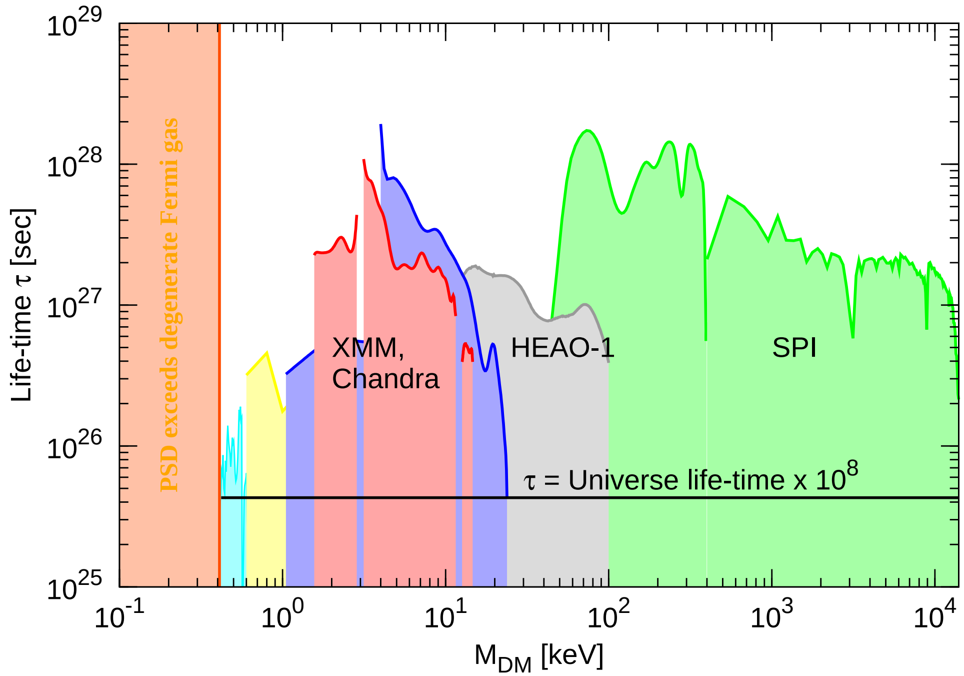
Boyarsky et al
PRL'09



Search for Dark Matter decays in X-rays


Available X-ray satellites: Suzaku, XMM-Newton, Chandra, INTEGRAL



MW (HEAO-1)
2005

Coma and Virgo clusters
2006

Bullet cluster
2006

LMC (XMM)
2006

MW (XMM)
2006–2007

M31 (XMM)
2007, 2010

$$\text{Signal-to-noise} \propto \mathcal{S}\sqrt{t_{\text{exp}} \cdot \Omega_{\text{fov}} \cdot A_{\text{EFF}} \cdot \Delta E}$$

All types of individual objects/observations have been tried: galaxies (LMC, Ursa Minor, Draco, Milky Way, M31, M33,...); galaxy clusters (Bullet cluster; Coma, Virgo, ...) with all the X-ray instruments

Detection of An Unidentified Emission Line

Detection of An Unidentified Emission Line

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

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[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Submitted to ApJ, 2014 February 10

[1402.2301]

We detect a weak unidentified emission line at E=(3.55-3.57)+/-0.03 keV in a stacked XMM spectrum of 73 galaxy clusters spanning a redshift range 0.01-0.35. MOS and PN observations independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is significantly detected in all three independent MOS spectra and the PN "all others" spectrum. It is also detected in the Chandra spectra of Perseus with the flux consistent with XMM (though it is not seen in Virgo)...

Detection of An Unidentified Emission Line

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

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[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

[1402.4119]

We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters. Although the line is weak, it has a clear tendency to become stronger towards the centers of the objects; it is stronger for the Perseus cluster than for the Andromeda galaxy and is absent in the spectrum of a very deep "blank sky" dataset…

Our Data

M31 galaxy	XMM-Newton, center & outskirts
Perseus cluster	XMM-Newton, outskirts only
Blank sky	XMM-Newton

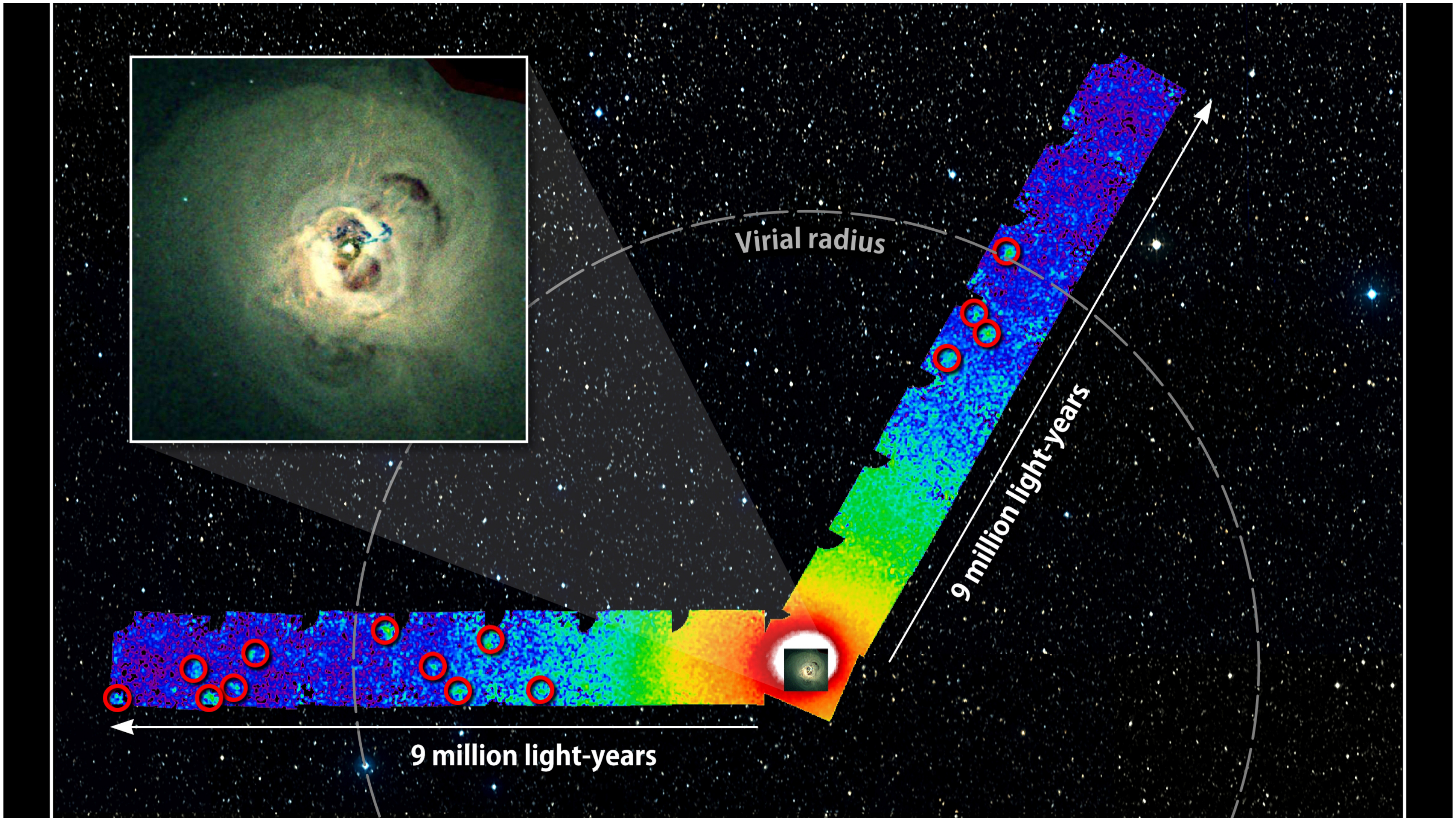
Bulbul et al. 2014

73 clusters	XMM-Newton, centers only. Up to $z = 0.35$, including Coma, Perseus
Perseus cluster	Chandra, center only
Virgo cluster	Chandra, center only

Position: 3.5 keV. Statistical error for line position $\sim$ 30 eV. Systematics (~ 50 eV – between cameras, determination of known instrumental lines)

Lifetime: $\sim 10^{28}$ sec (uncertainty $\mathcal{O}(10)$)

Perseus galaxy cluster

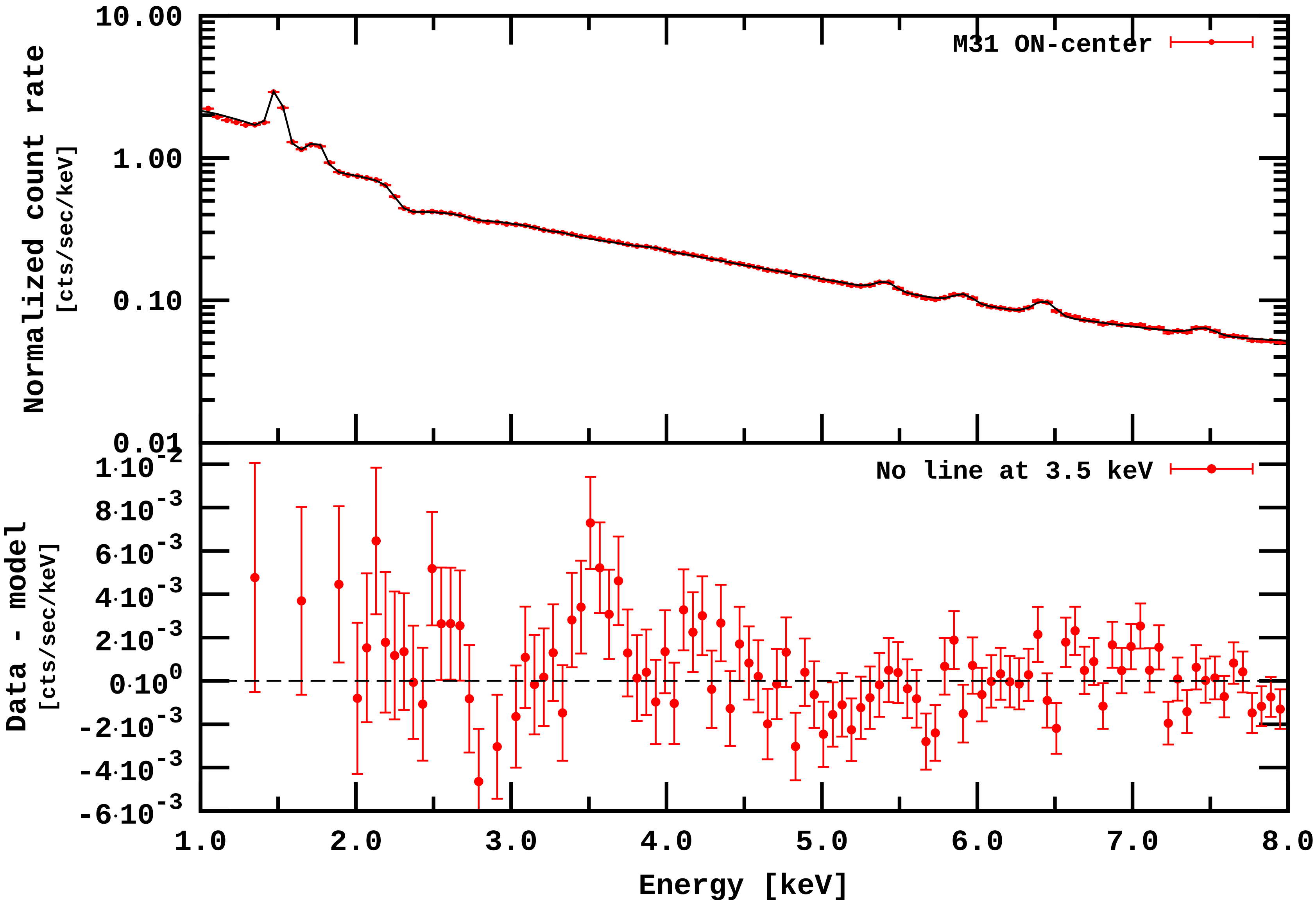


Bulbul et al. took only 2 central XMM observation – $14'$ around the cluster's center

We took 16 observations **excluding** 2 central XMM observations to avoid modeling complicated central emission

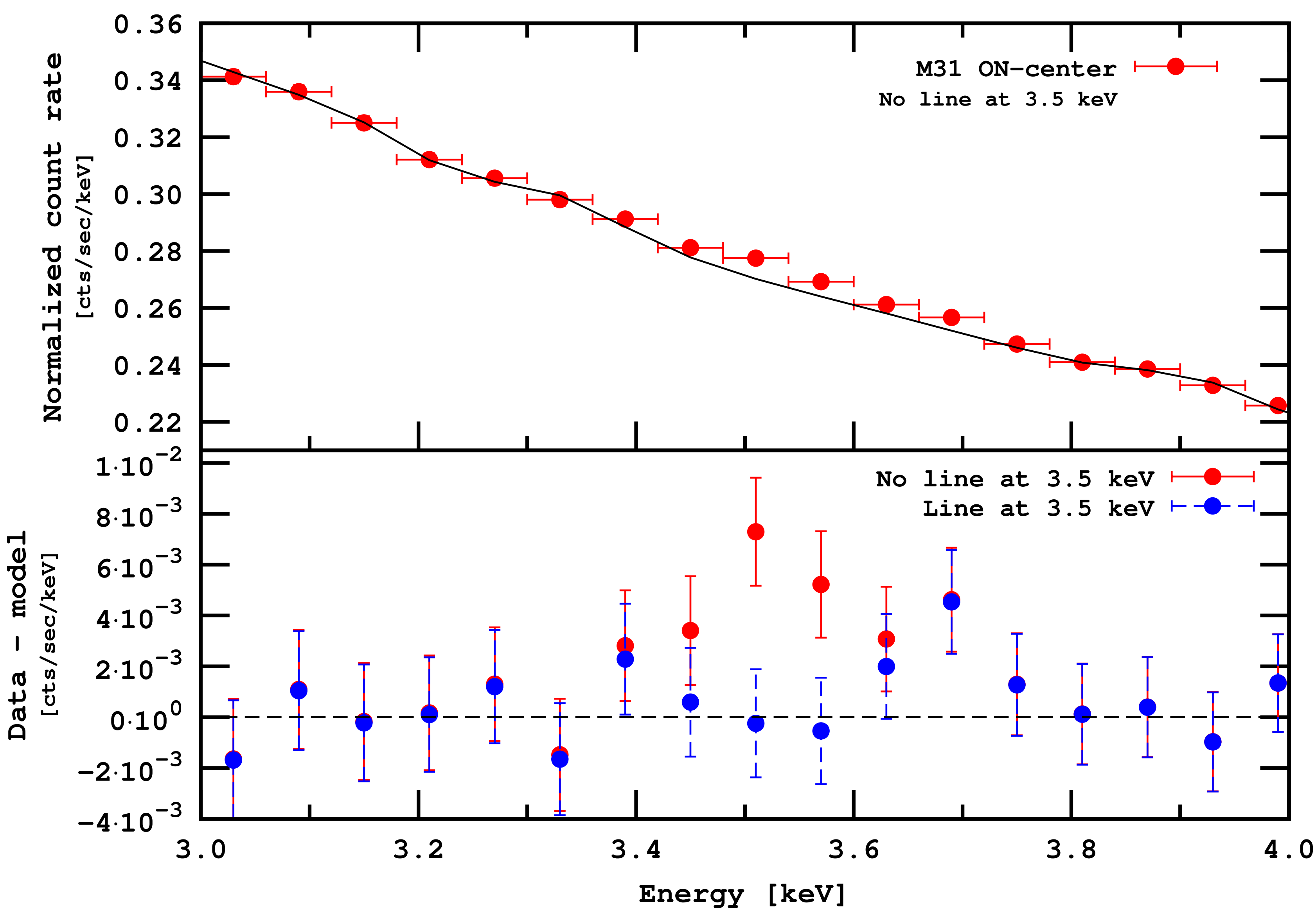
Andromeda galaxy

[1402.4119]

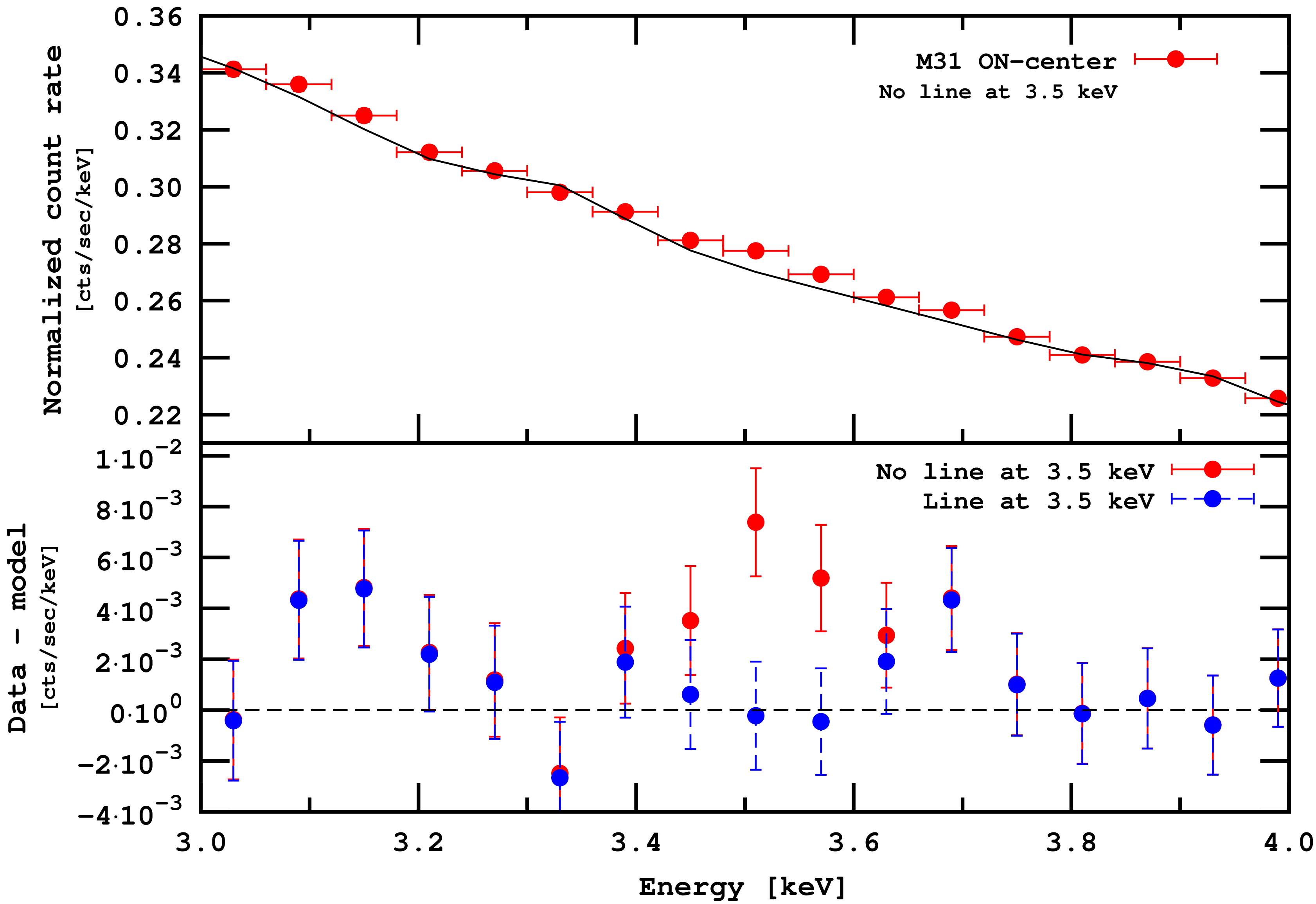


[1402.4119]

Andromeda galaxy (zoom 3–4 keV)

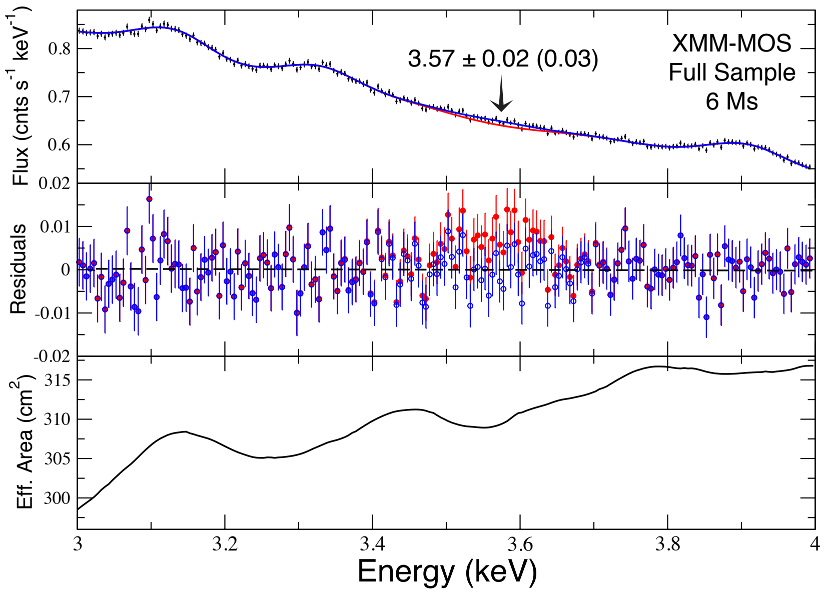


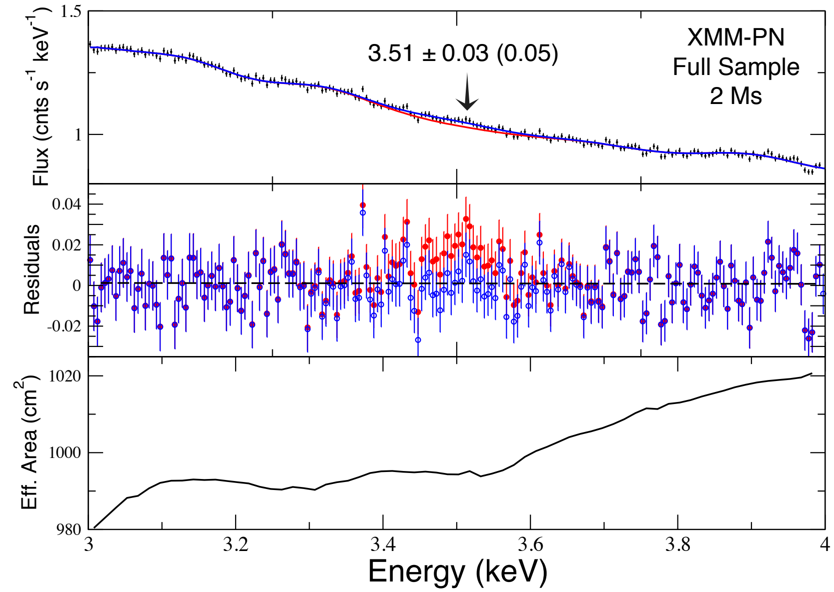
Andromeda galaxy (zoom 3–4 keV)

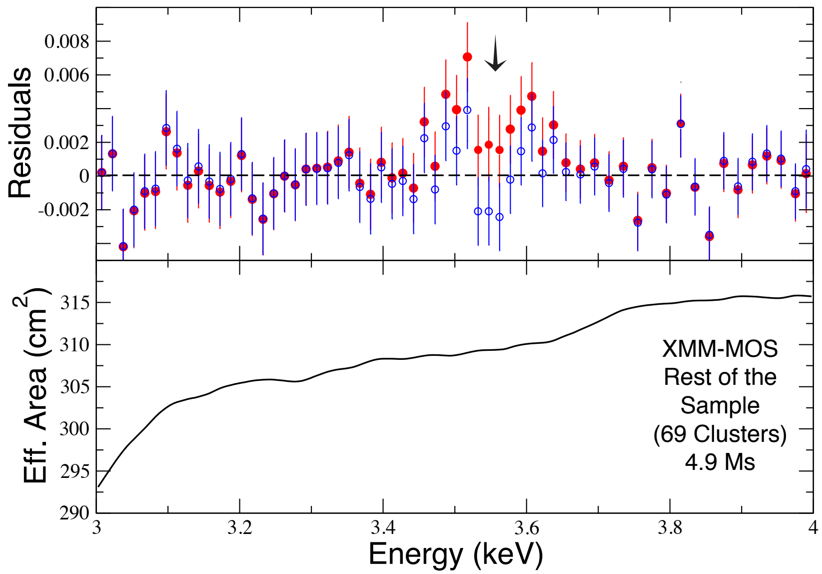


Full stacked spectra

Bulbul et al. [1402.2301]







- All spectra blue-shifted in the reference frame of clusters
- Instrumental background processed similarly and **subtracted**

Significance

Our Data

M31 galaxy	$\Delta\chi^2 = 13.0$	3.2σ for 2 d.o.f.
Perseus cluster (MOS)	$\Delta\chi^2 = 9.1$	2.5σ for 2 d.o.f.
Perseus cluster (PN)	$\Delta\chi^2 = 8.0$	2.4σ for 2 d.o.f.
Blank sky	No detection	
M31 + Perseus (MOS)	$\Delta\chi^2 = 25.9$	4.4σ for 3 d.o.f.

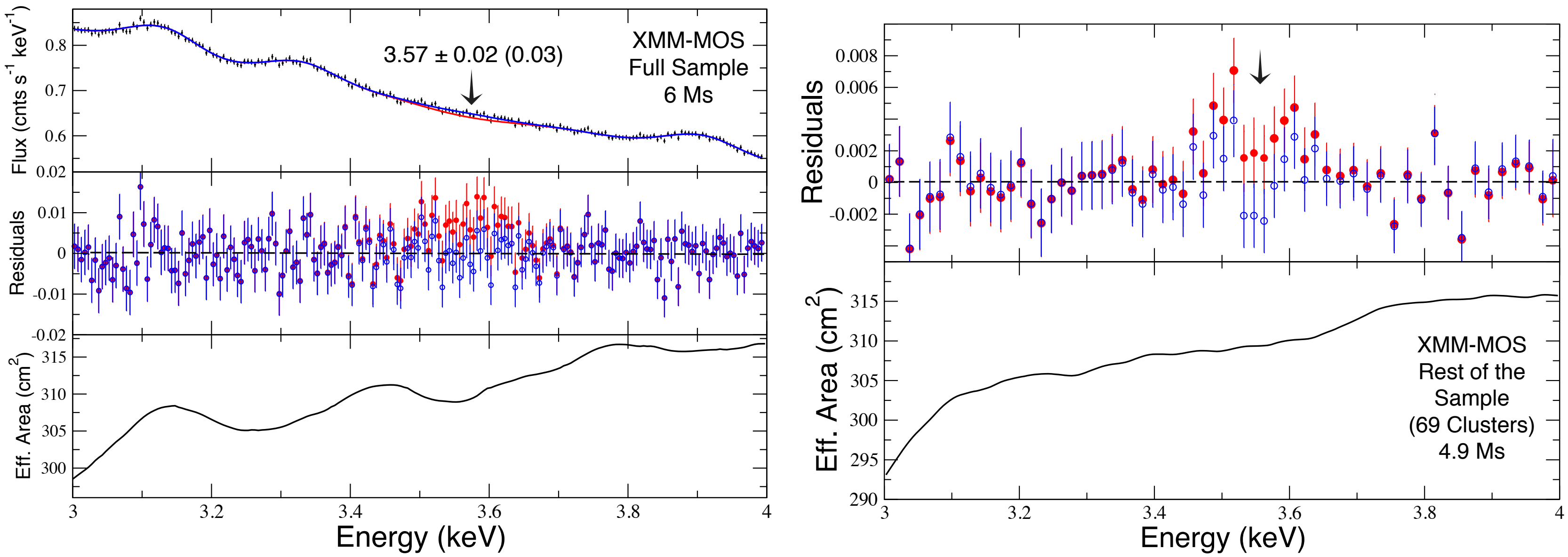
Bulbul et al. 2014

73 clusters (XMM, MOS)	$\Delta\chi^2 = 22.8$	4.3σ for 2 d.o.f
73 clusters (XMM, PN)	$\Delta\chi^2 = 13.9$	3.3σ for 2 d.o.f
Perseus center (XMM, MOS)	$\Delta\chi^2 = 12.8$	3.1σ for 2 d.o.f.
Perseus center (XMM, PN)	No detection	
Perseus center (Chandra, ACIS-S)	$\Delta\chi^2 = 11.8$	3.0σ for 2 d.o.f.
Perseus center (Chandra, ACIS-I)	$\Delta\chi^2 = 6.2$	2.5σ for 1 d.o.f.
Virgo cluster (Chandra, ACIS-I)	No detection	

Systematics?

- Detection with two instruments: XMM-Newton and Chandra
- Detection with four detectors: EPIC MOS, EPIC PN, ACIS-S and ACIS-I
- Detection in galaxy clusters (nearby and stacked) and in the Andromeda galaxy
- Correct redshift dependence: stacked clusters (Bulbul et al.) and Perseus vs. M31 (Boyarsky et al.)
- Some unknown effect related to the brightness – No! We have checked bright objects without DM and did not see there a signal
- Wiggle in the effective area?

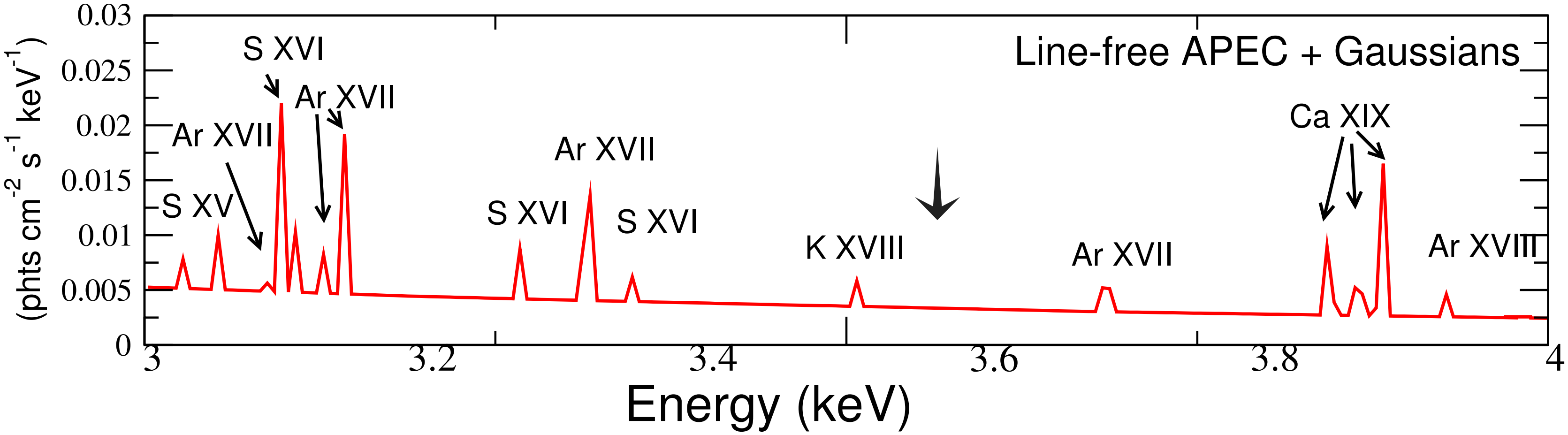
Wiggle in the effective area?



Bulbul et al. [1402.2301]

- Easiest way to get a weak line: Divide a powerlaw signal by an effective area with a dip at ~ 3.5 keV
- Wiggle is not present in the stacked redshifted dataset but the signal is (Bulbul et al.)
- Wiggle would cause a signal in the blank sky data (Boyarsky, et al.)

Atomic line?



Line-free APEC + Gaussians
S XVI
Ar XVII
Ar XVII
S XV
Ar XVII
S XVI
S XVI
K XVIII
Ar XVII
Ca XIX
Ar XVIII
(phts cm^-2 s^-1 keV^-1)
Energy (keV)
0.03
0.025
0.02
0.015
0.01
0.005
0
3
3.2
3.4
3.6
3.8
4

Atomic line?

- Not likely : need anomalous line ratios at the level 20-30

  Bulbul et al.

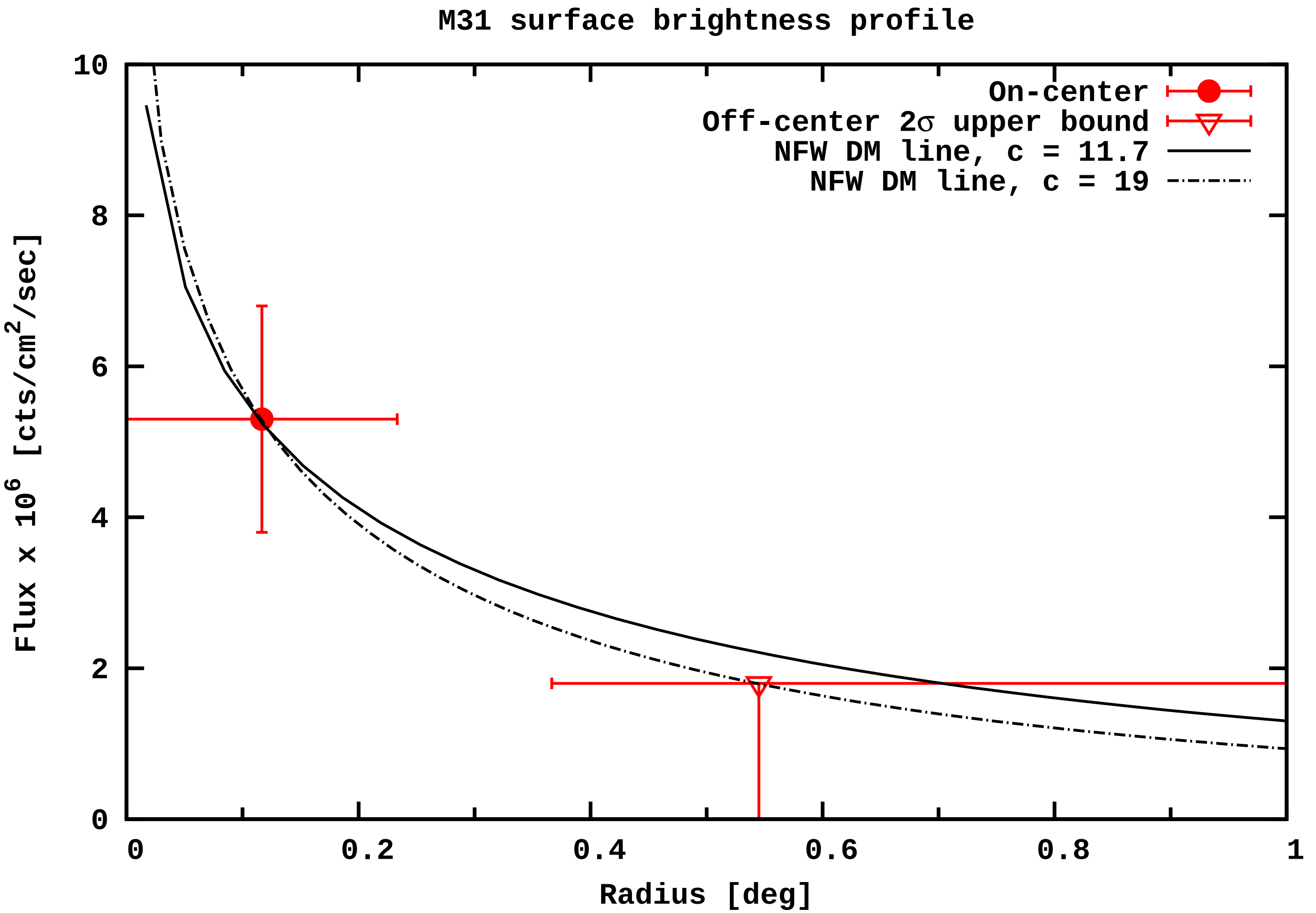
- Not likely : the line is present in the Andromeda galaxy with comparable strength (different gas temperature, different element abundance). The line is **not** detected in the Milky Way

  Boyarsky et al.

Dark matter interpretation

Surface brightness profile (M31)

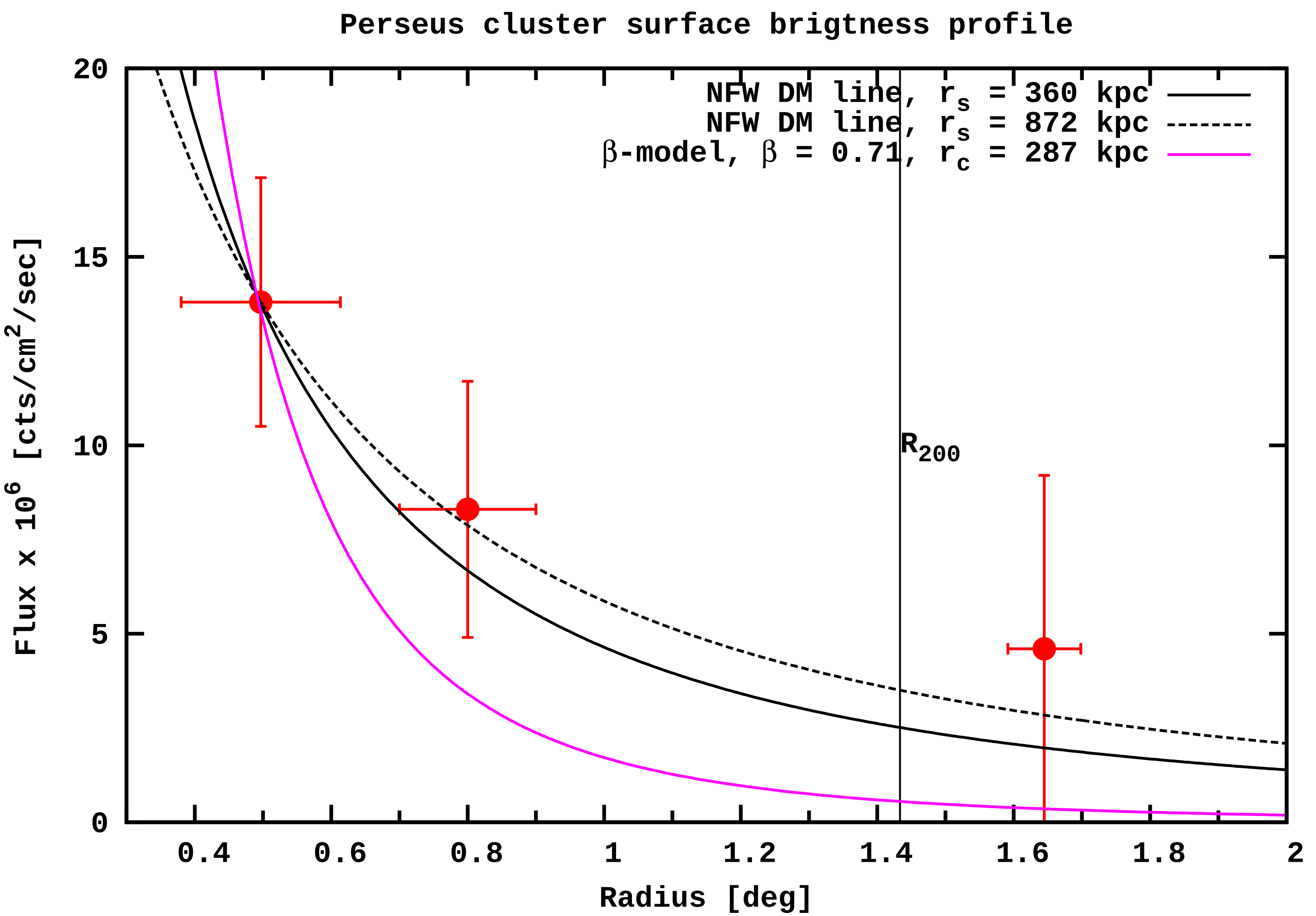
[1402.4119]



This is not a fit!

Surface brightness profile (Perseus)

[1402.4119]



This is not a fit!

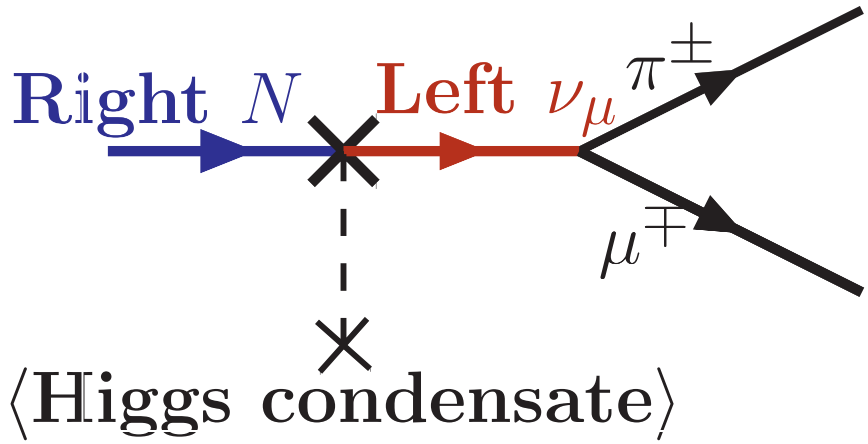
Implications if the line is “real”

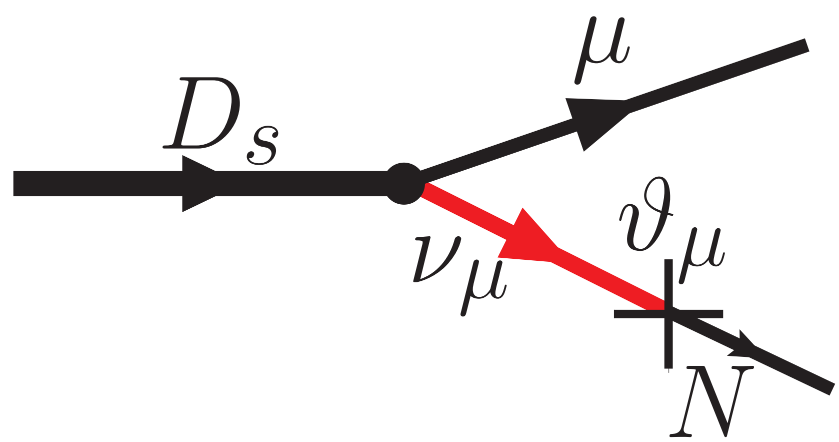
This can be anything

The 3.5 keV X-ray line from decaying **gravitino** dark matter. **Axino** dark matter in light of an anomalous X-ray line. The Quest for an Intermediate-Scale Accidental **Axion** and Further **ALPs**. keV Photon Emission from Light **Nonthermal Dark Matter**. X-ray lines from R-parity violating decays of keV **sparticles**. Neutrino masses, leptogenesis, and **sterile neutrino** dark matter. A Dark Matter Progenitor: **Light Vector Boson Decay** into (Sterile) Neutrinos. A 3.55 keV Photon Line and its Morphology from a 3.55 keV ALP Line. 7 keV Dark Matter as X-ray Line Signal in Radiative Neutrino Model. X-ray line signal from decaying **axino** warm dark matter. The 3.5 keV X-ray line signal from **decaying moduli** with low cutoff scale. X-ray line signal from 7 keV **axino** dark matter decay. Can a **millicharged dark matter** particle emit an observable gamma-ray line?. Effective field theory and keV lines from dark matter. Resonantly-Produced 7 keV **Sterile Neutrino Dark Matter** Models and the Properties of Milky Way Satellites. Cluster X-ray line at $3.5\,\mathrm{keV}$ from axion-like dark matter. Axion Hilltop Inflation in Supergravity. A 3.55 keV hint for decaying axion-like particle dark matter. The 7 keV axion dark matter and the X-ray line signal. An X-Ray Line from **eXciting Dark Matter**. 7 keV sterile neutrino dark matter from split flavor mechanism.

Sterile neutrino dark matter

(neutrino portal)



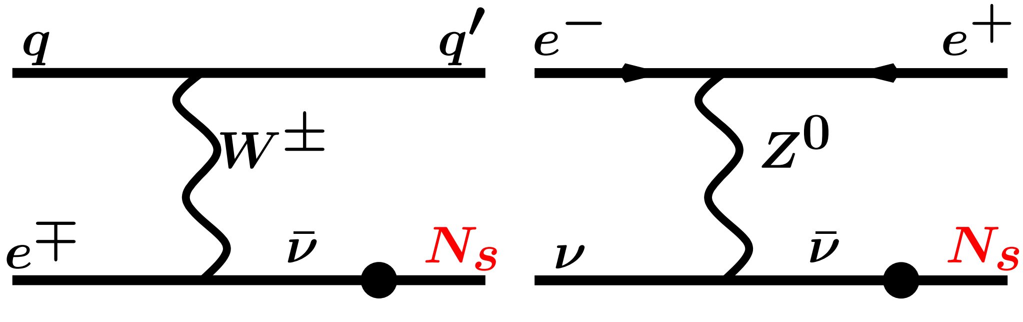


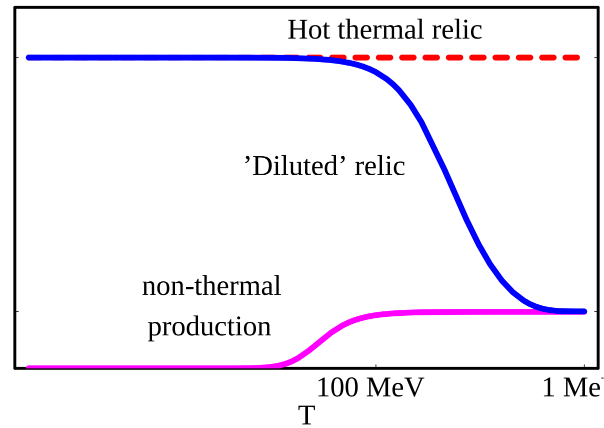
Sterile neutrinos behave as **superweakly interacting** massive neutrinos with a smaller Fermi constant $\boxed{\vartheta \times G_F}$

- This **mixing strength** or **mixing angle** is

$$\vartheta^2_{e,\mu,\tau} \equiv \frac{|M_{\text{Dirac}}|^2}{M^2_{\text{Majorana}}}$$

Production through mixing with neutrinos



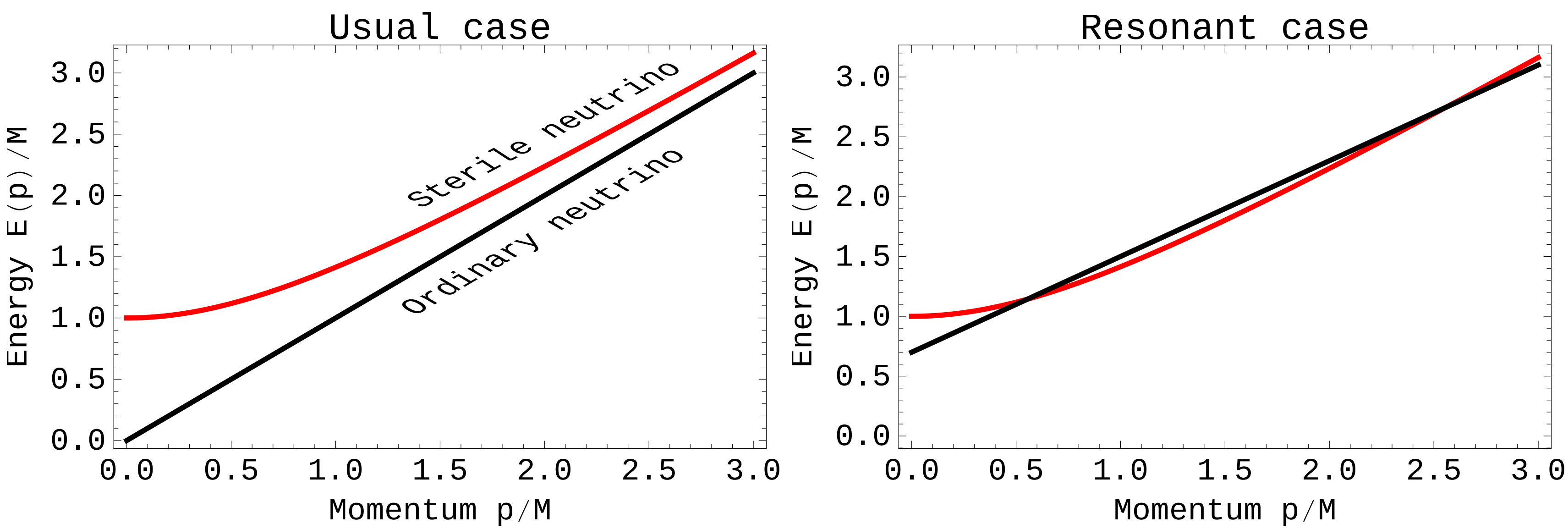


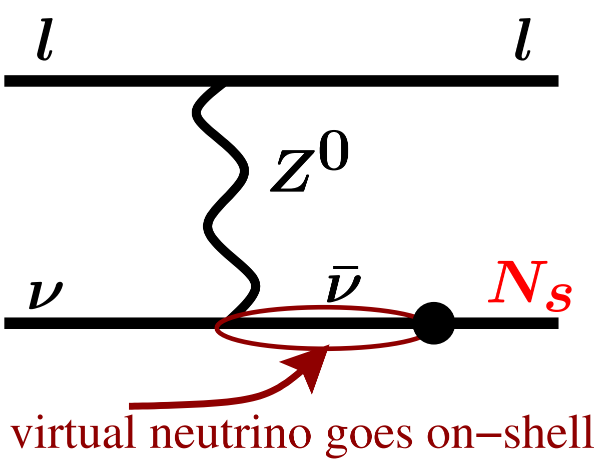
- Once every $\sim 10^8 \div 10^{10}$ scatterings a sterile neutrino is created instead of the active one
- Its abundance **slowly builds up** but **never reaches the equilibrium** value

Dodelson & Widrow'93; Dolgov & Hansen'00

- The distribution of sterile neutrinos $f(p) \approx \frac{\vartheta^2}{e^{p/T_\nu}+1}$

Resonant enhancement





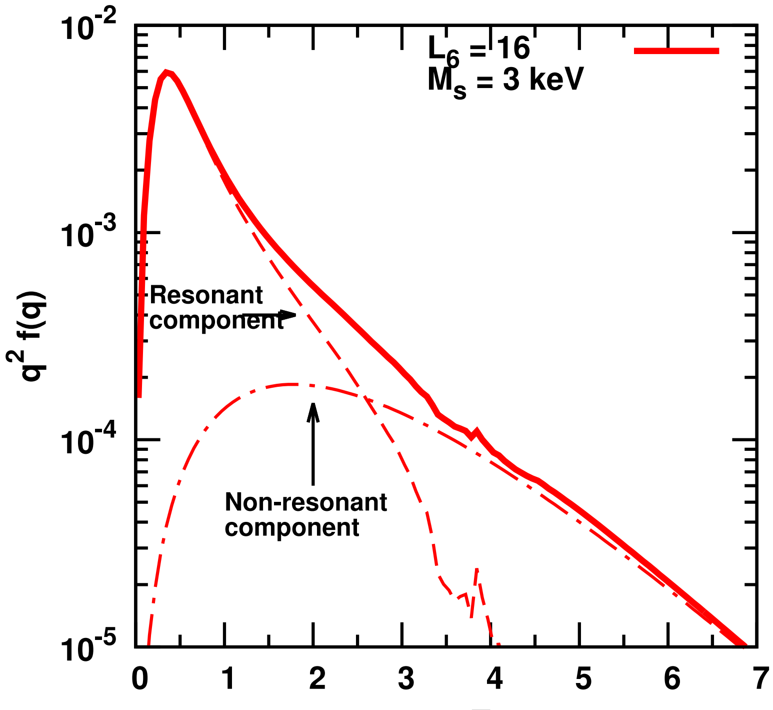
Conversion of ν to N is enhanced whenever "levels" cross and virtual neutrino goes "on-shell" (analog of MSW effect but for active-sterile mixing)

Shi & Fuller [astro-ph/9810076]

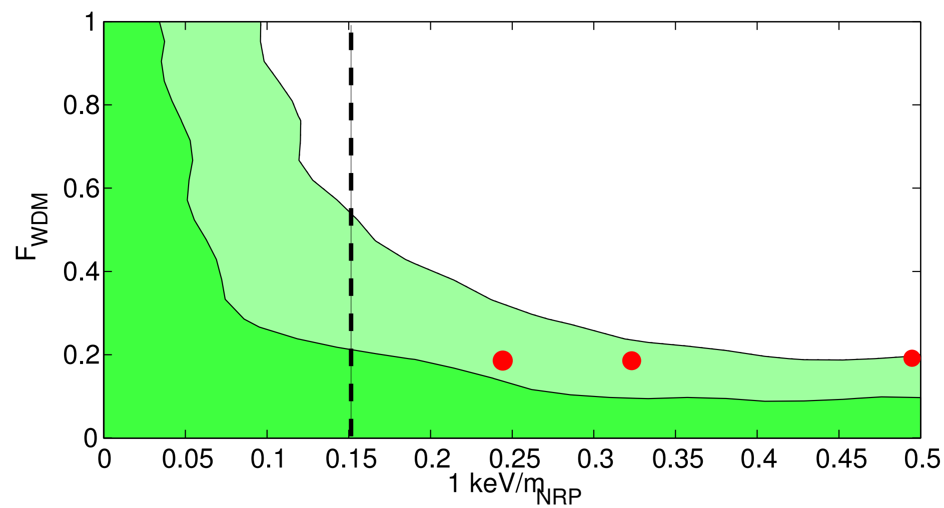
Laine & Shaposhnikov [0804.4543]

Resonant enhancement

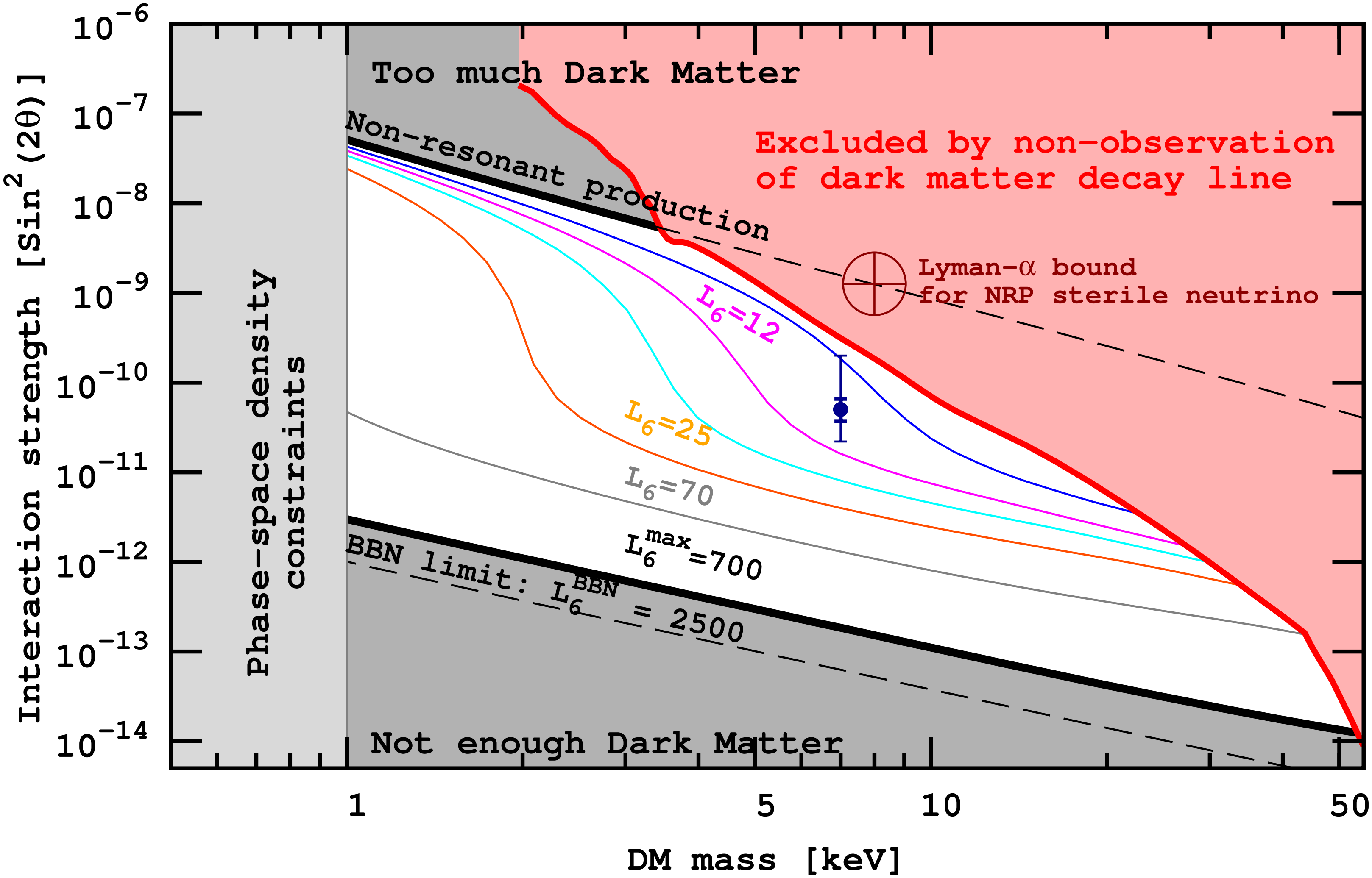
- In the presence of **large lepton asymmetry** the **MSW resonance** can take place and production of sterile neutrinos becomes much more effective



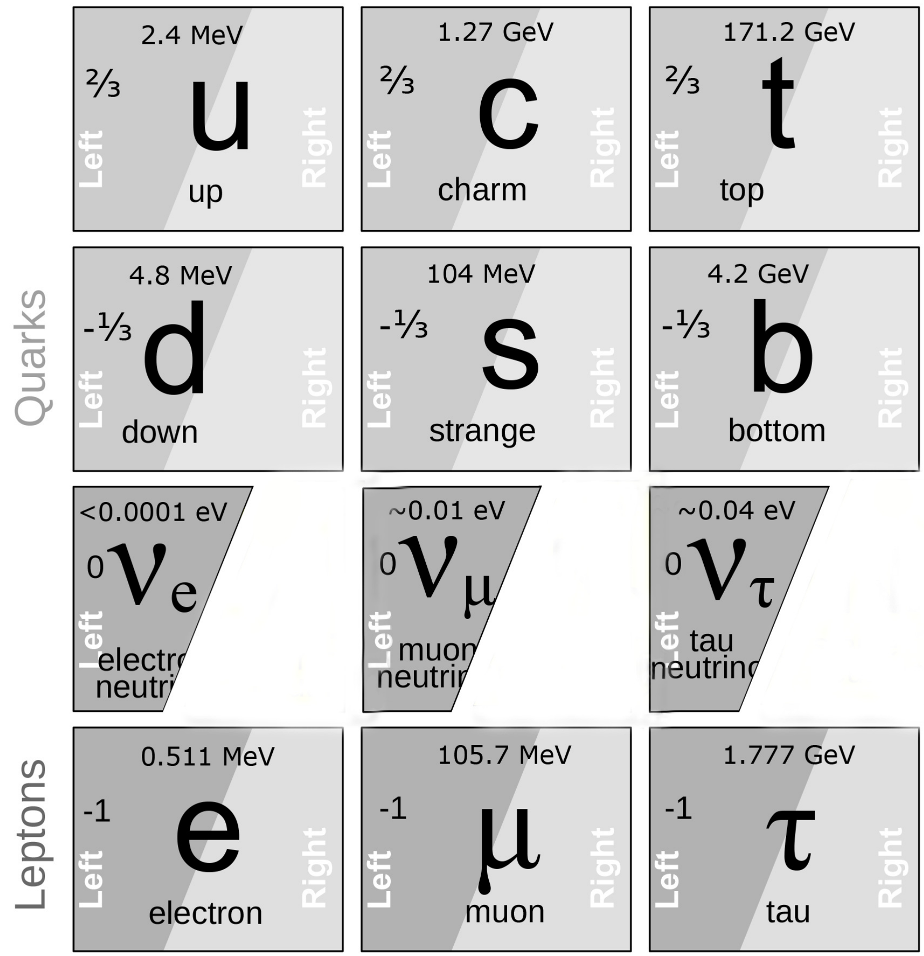
- The condition for resonance occurs only for specific values of momentum during limited time.

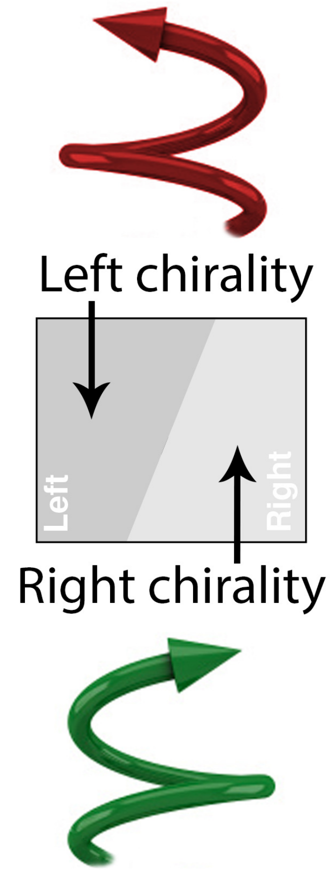


Sterile neutrino and 3.5 keV line

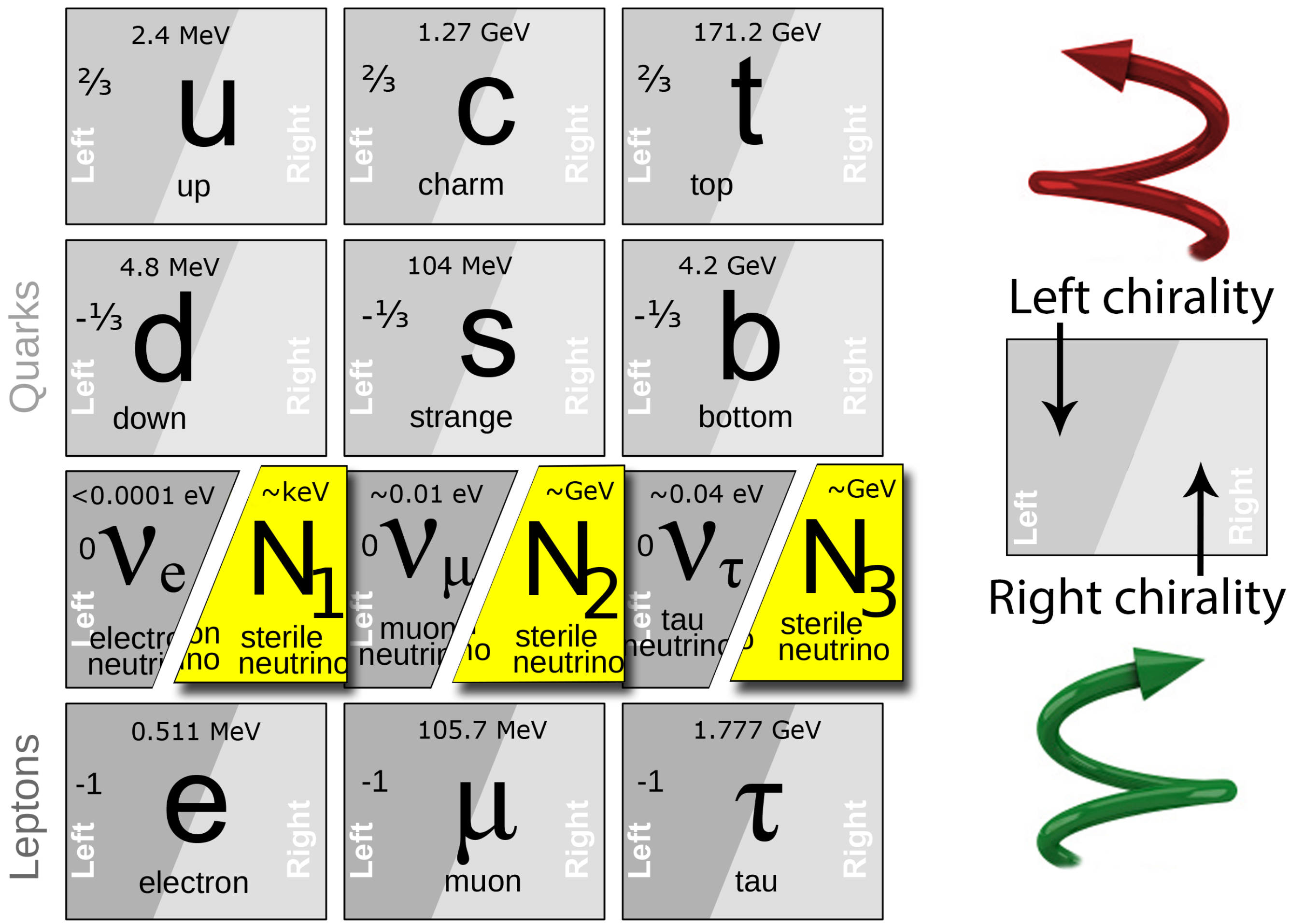


Oscillations ⇒ new particles!



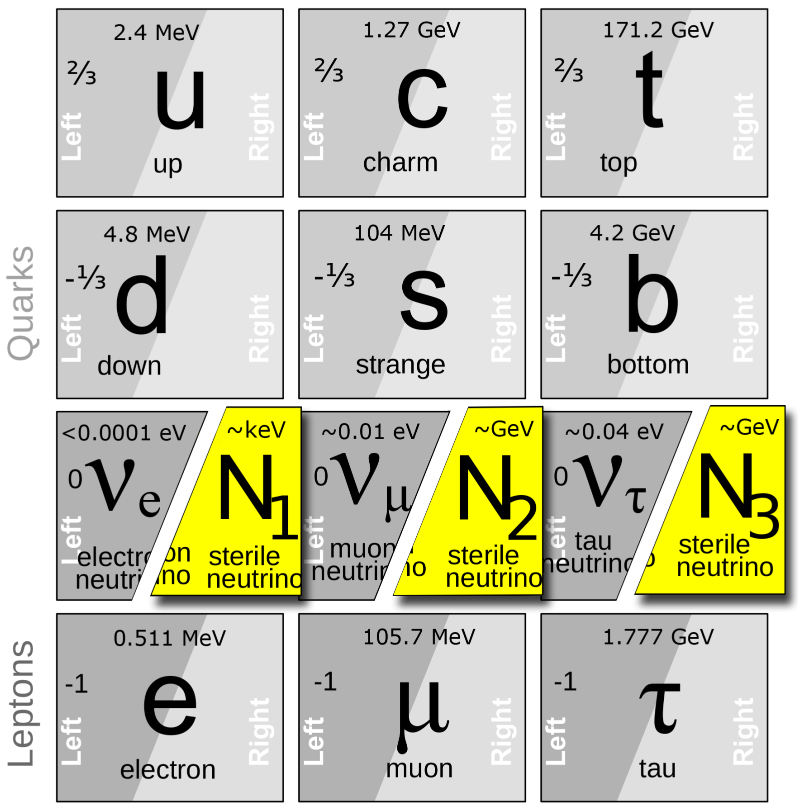


Oscillations ⇒ new particles!



Right components of neutrinos?!

Dark matter and neutrino oscillations



– Two neutrino mass splitting ⇒ need (at least) two sterile neutrino

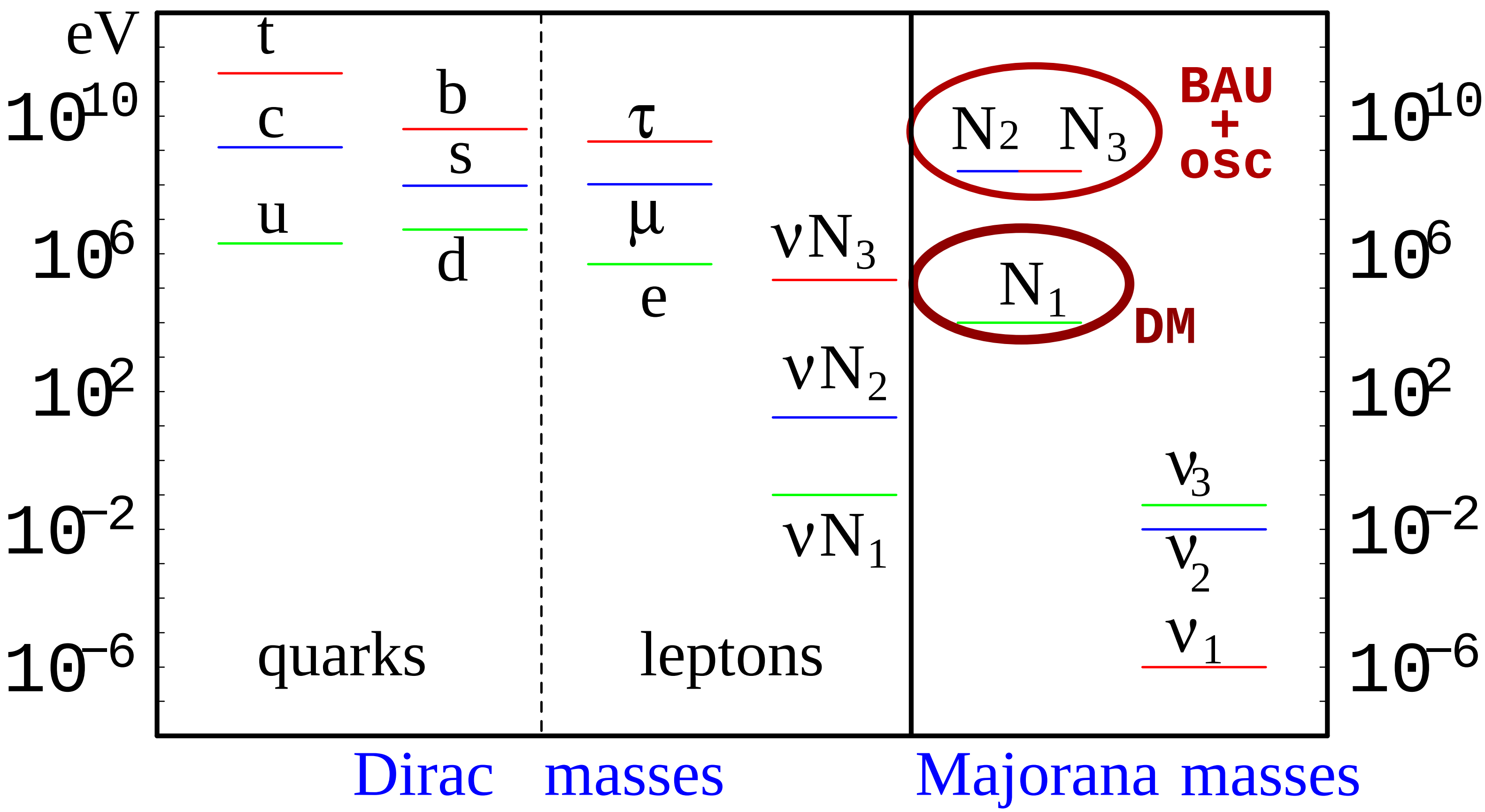
– Are they Dark matter? ⇒ No way! Very short lifetime

$$\text{Lifetime}_N = \left(\frac{\vartheta^2 G_F^2 M_N^5}{86\pi^3}\right)^{-1}$$

$$\approx 0.3\,\text{sec}\left(\frac{1\ \text{GeV}}{M_N}\right)^4$$

– Third sterile neutrino? ⇒ Yes! Great DM (its exact properties depend on two other sterile neutrinos)

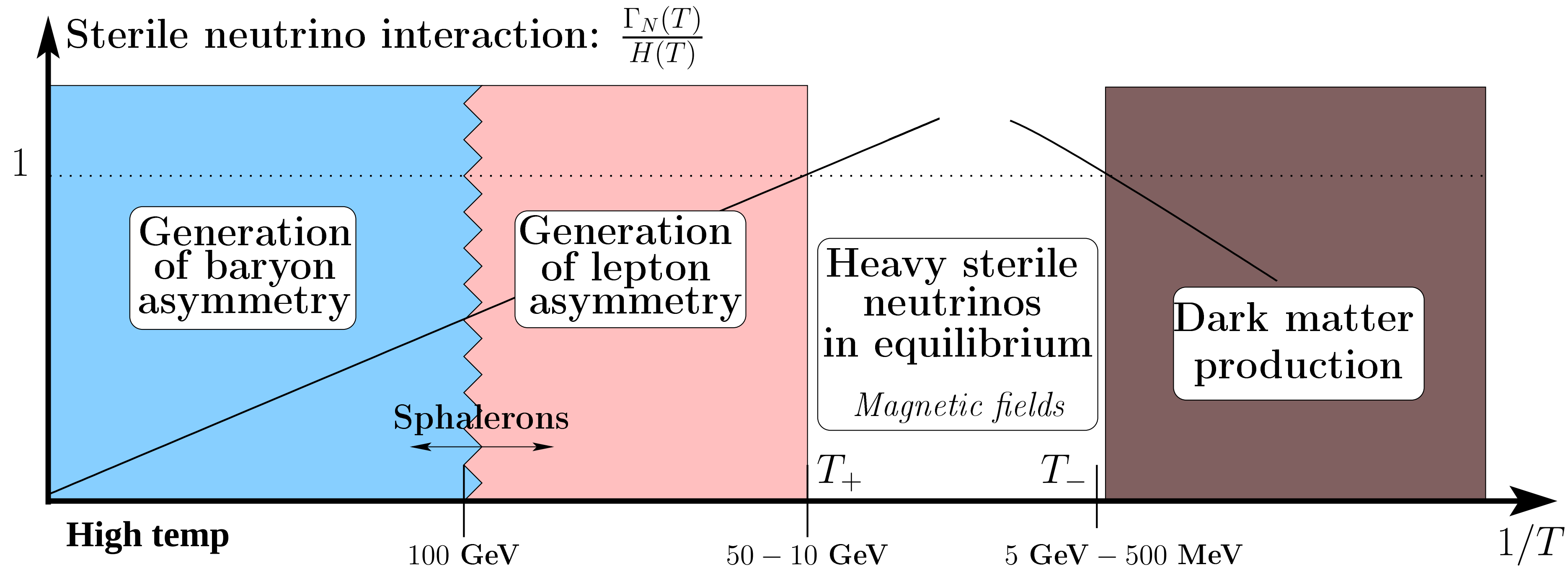
Neutrino Minimal Standard Model (νMSM)



Masses of sterile neutrinos as those of other leptons
Yukawas as those of electron or smaller

Review: Boyarsky, Ruchayskiy, Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]

Early Universe in the presence of sterile neutrinos



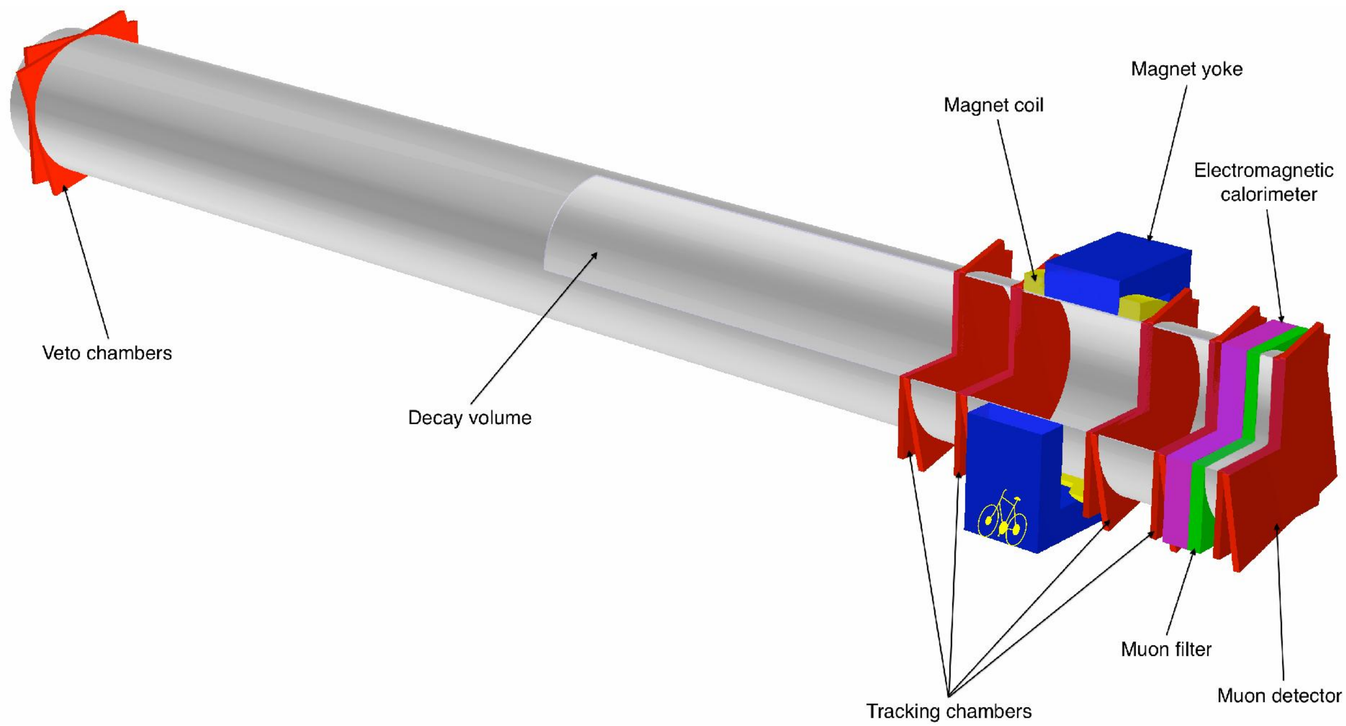
A dedicated experiment

[arXiv:1310.17

W. Bonivento, **A. Boyarsky**, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, O. Ruchayskiy, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille

Proposal to Search for Heavy Neutral Leptons at the SPS

Expression of Interest. Endorsed by the CERN SPS council



Open collaboration meeting

Conclusion

- We see a weak line in the spectra of many DM-dominated objects (clusters) and Andromeda galaxy

- Line does not have obvious systematic interpretation, observed with 4 different detectors

- If this is 7 keV sterile neutrino – its production requires significant lepton asymmetry present in the Universe below sphaleron freeze-out temperature

Talk by Misha next week

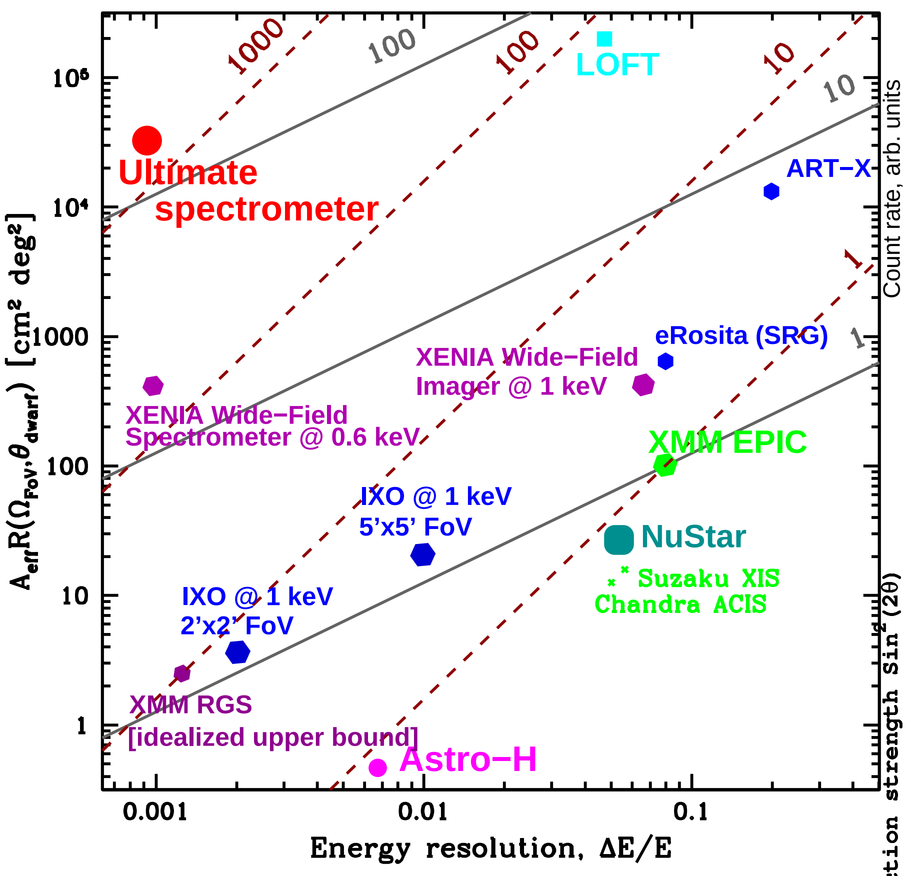
- Particles, responsible for production of such lepton asymmetry can be found at beam dump experiment (**SHiP** – **S**earch for **Hi**dden **P**articles)

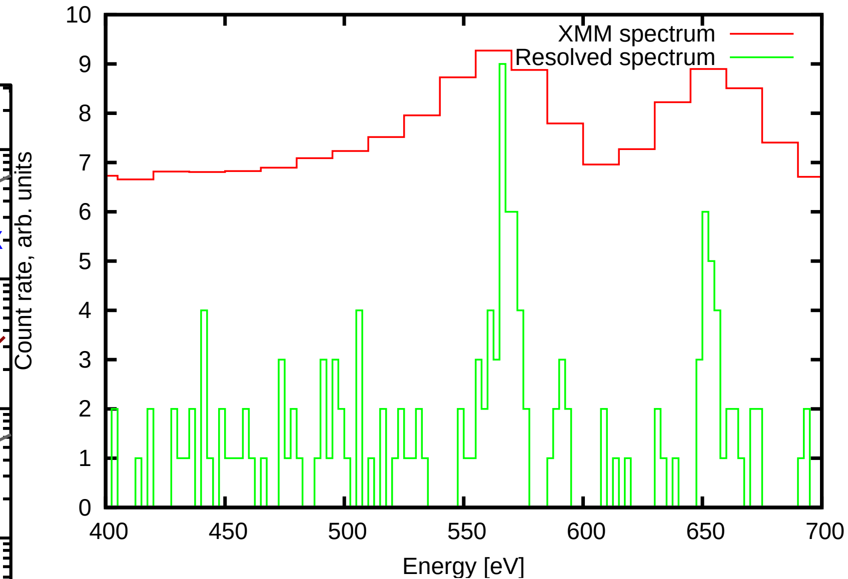
- For such a sterile neutrino we should see some imprints in the formation of the structures in the recent Universe

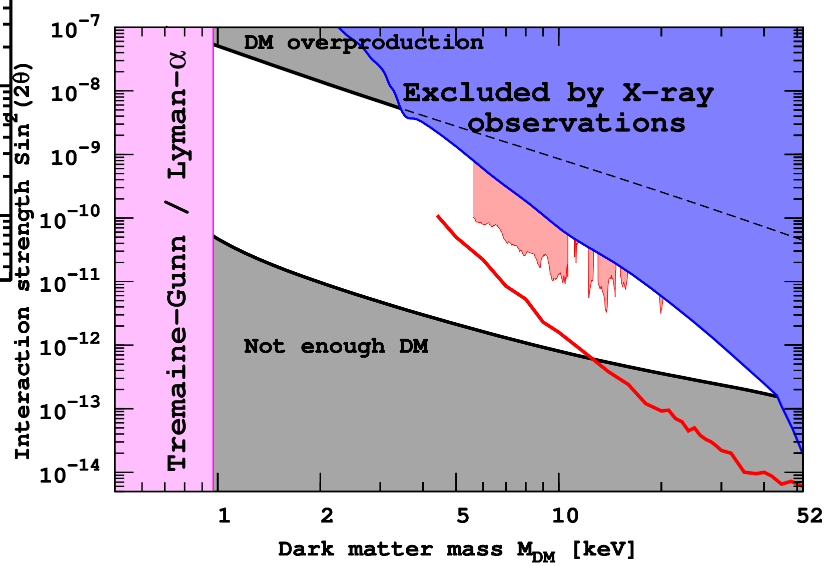
Thank you for your attention!

What's next?

X-ray spectrometer to search for decaying Dark Matter





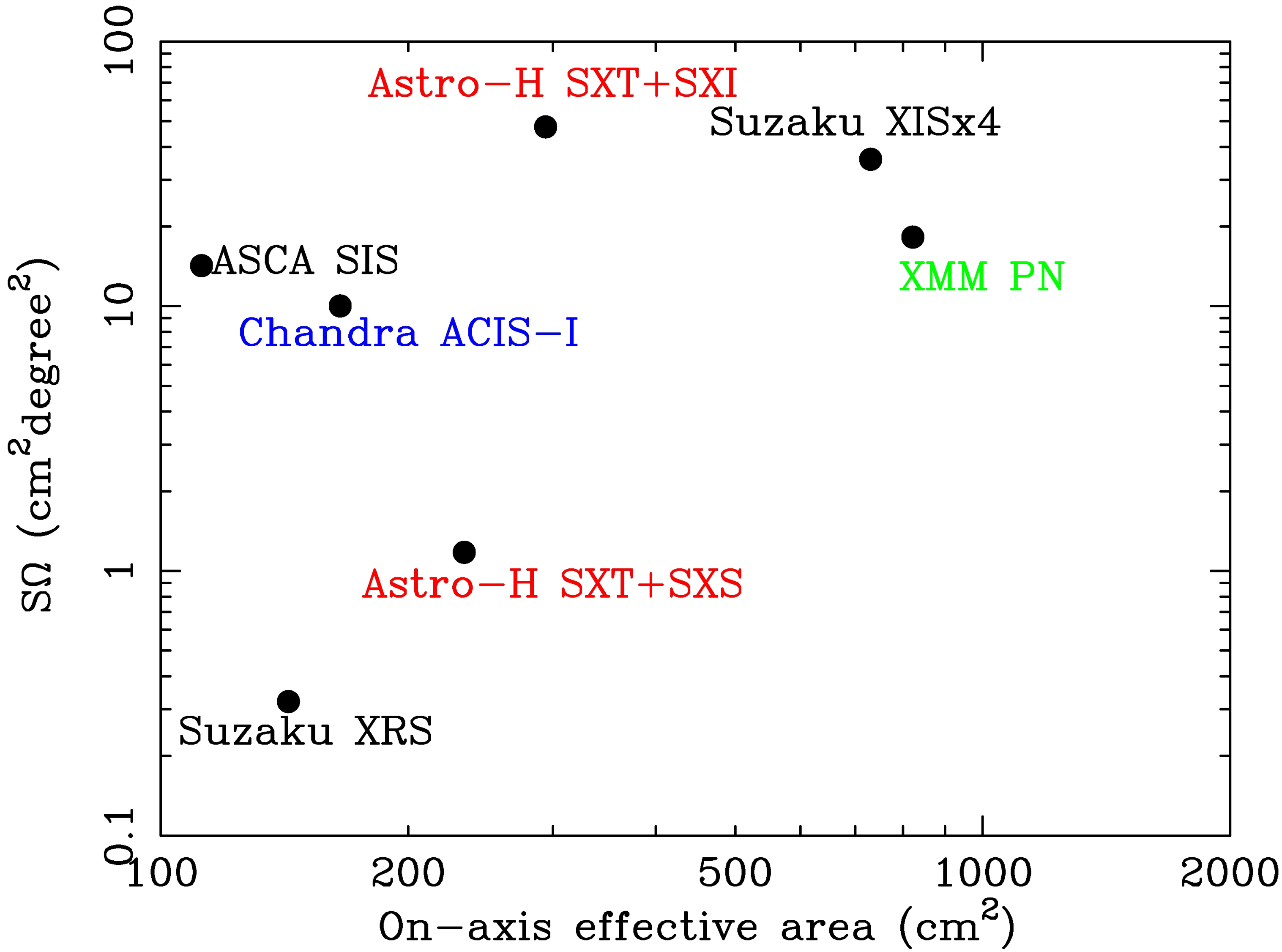


[1312.5178] Boyarsky with Neronov et al.

See our review *"Next decade in sterile neutrino studies"* [1306.4954]

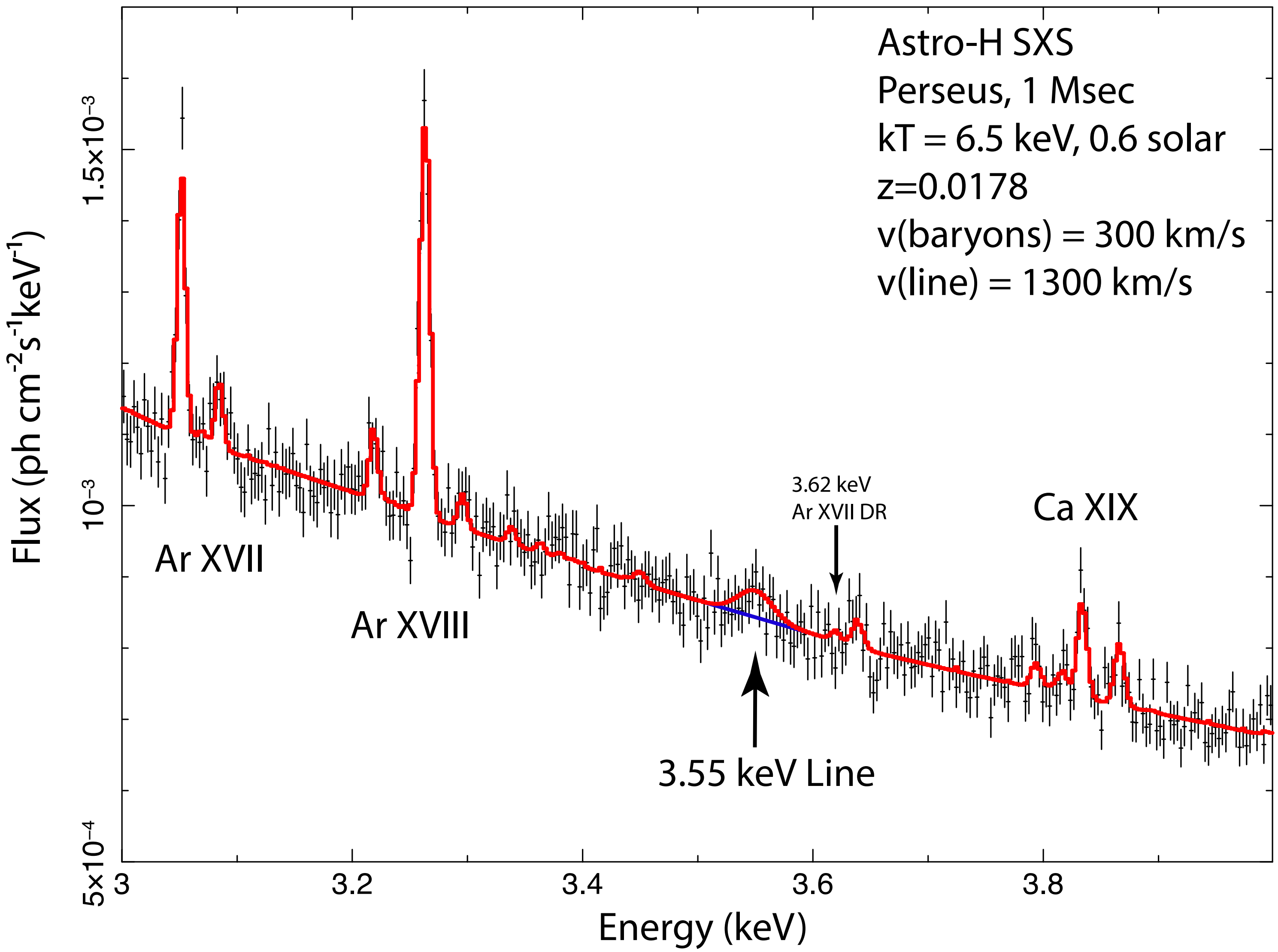
Astro-H: spectrometer

Collecting power of an instrument

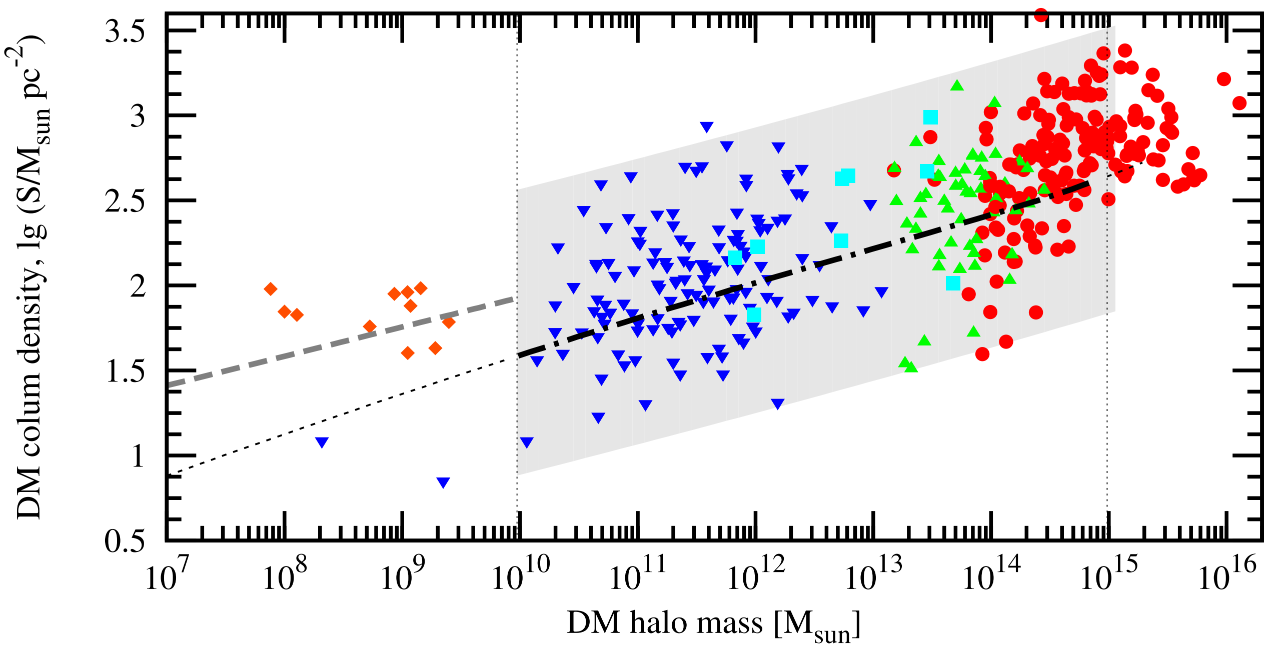


Astro-H: better spectral resolution

[1402.2301]



More objects

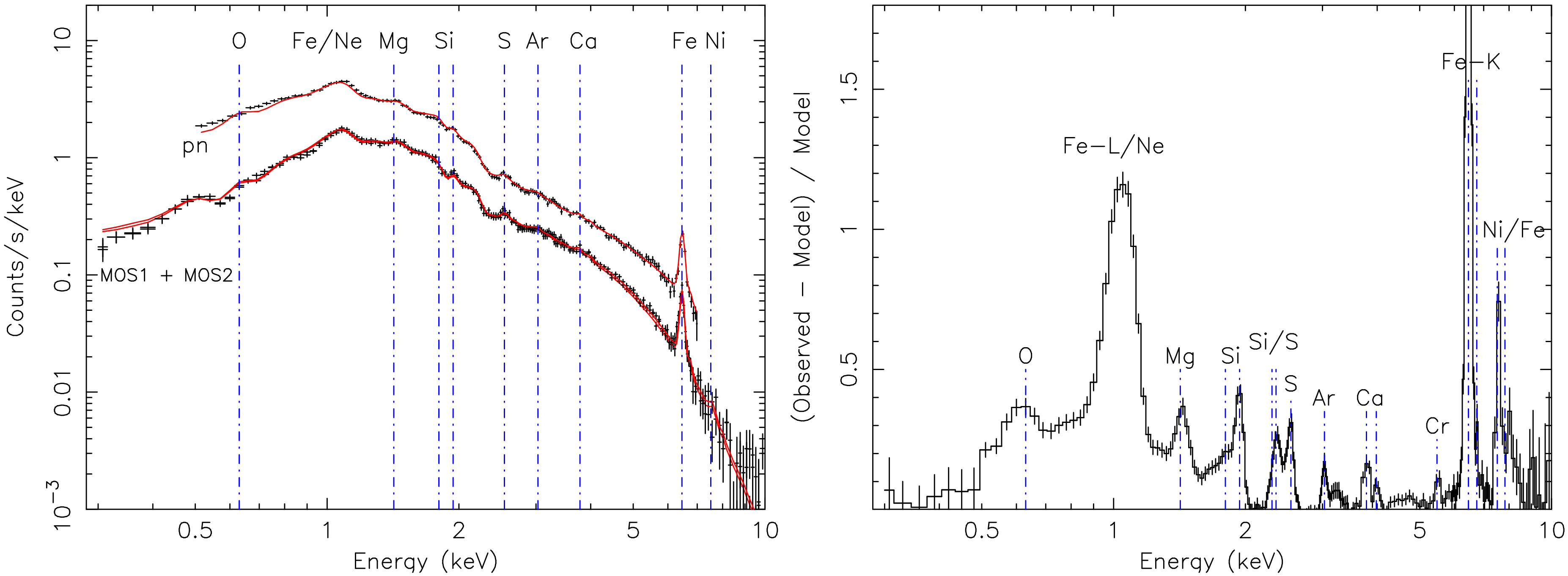


- Dark matter is everywhere – check more objects (galaxies, clusters, **dwarf spheroidals**)
- Dark matter is uncertain – determine column density better

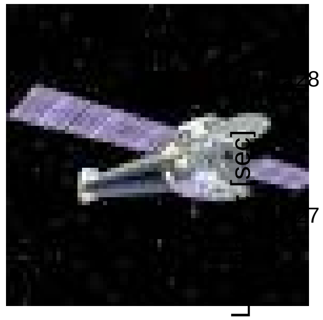
Why clusters do not obviously win?

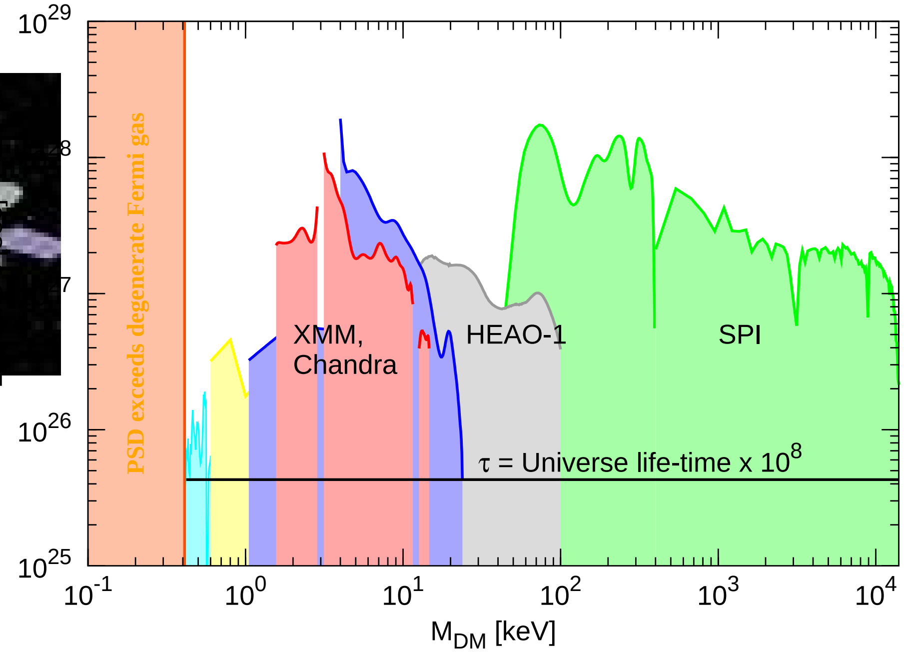
- Virial theorem: $k_B T \sim \frac{G_N M}{D}$ or $T \sim 10\,\mathrm{keV}\left(\frac{\text{Overdensity}}{10^3}\right)\left(\frac{\text{Size}}{\mathrm{Mpc}}\right)$

Werner et al.'2006



Improvements?





$$\frac{S}{N} \propto \mathcal{S}\sqrt{t_{\text{exp}} \cdot \Omega_{\text{fov}} \cdot A_{\text{EFF}} \cdot \Delta E}$$

MW (HEAO-1)
2005

Coma and Virgo clusters
2006

Bullet cluster
2006

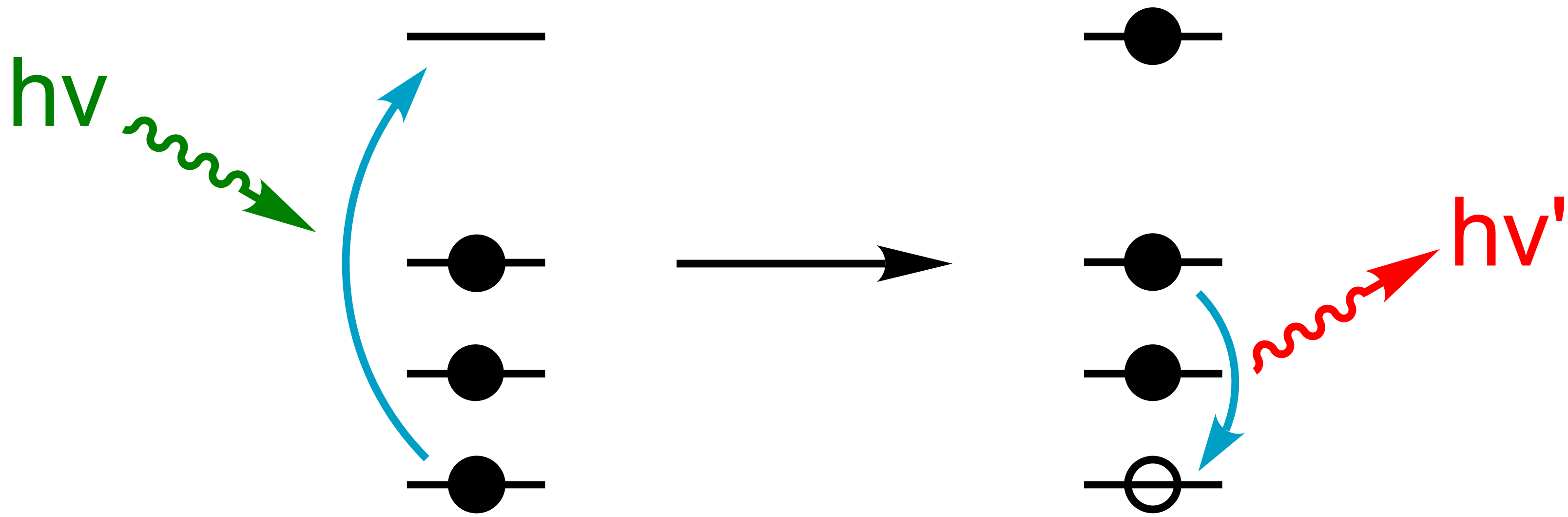
LMC (XMM)
2006

MW (XMM)
2006–2007

M31 (XMM)
2007, 2010

- Individual observation: 50-100 ksec
- One year of XMM-Newton observational programme: 14 Msec
- Only 60-70% of exposure is used (cosmic flares contamination)
- Long exposure $\mathcal{O}(10^3)$ photons/bin $\Rightarrow$ small statistical errors

Challenges

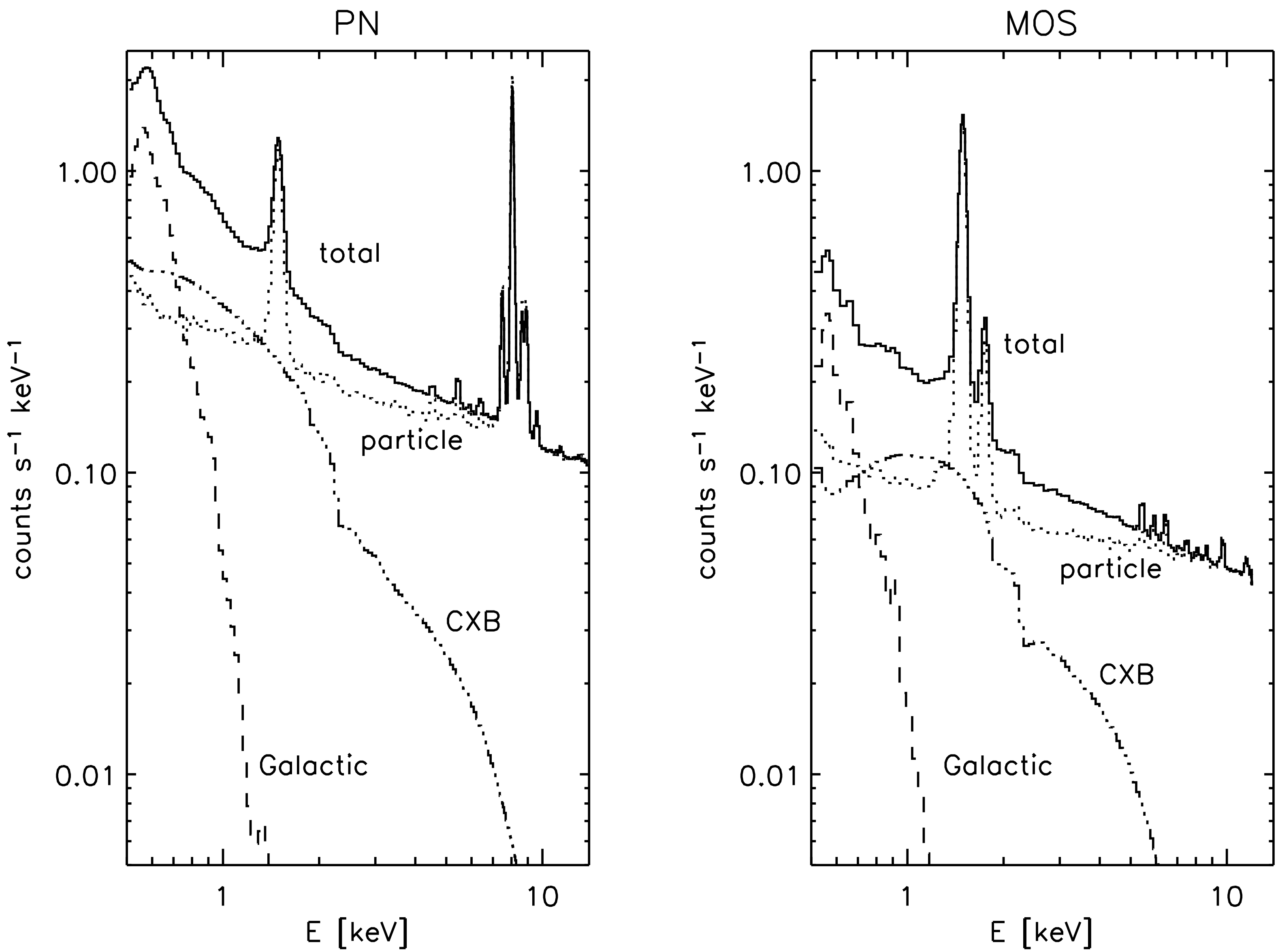


Kuntz & Snowden'08

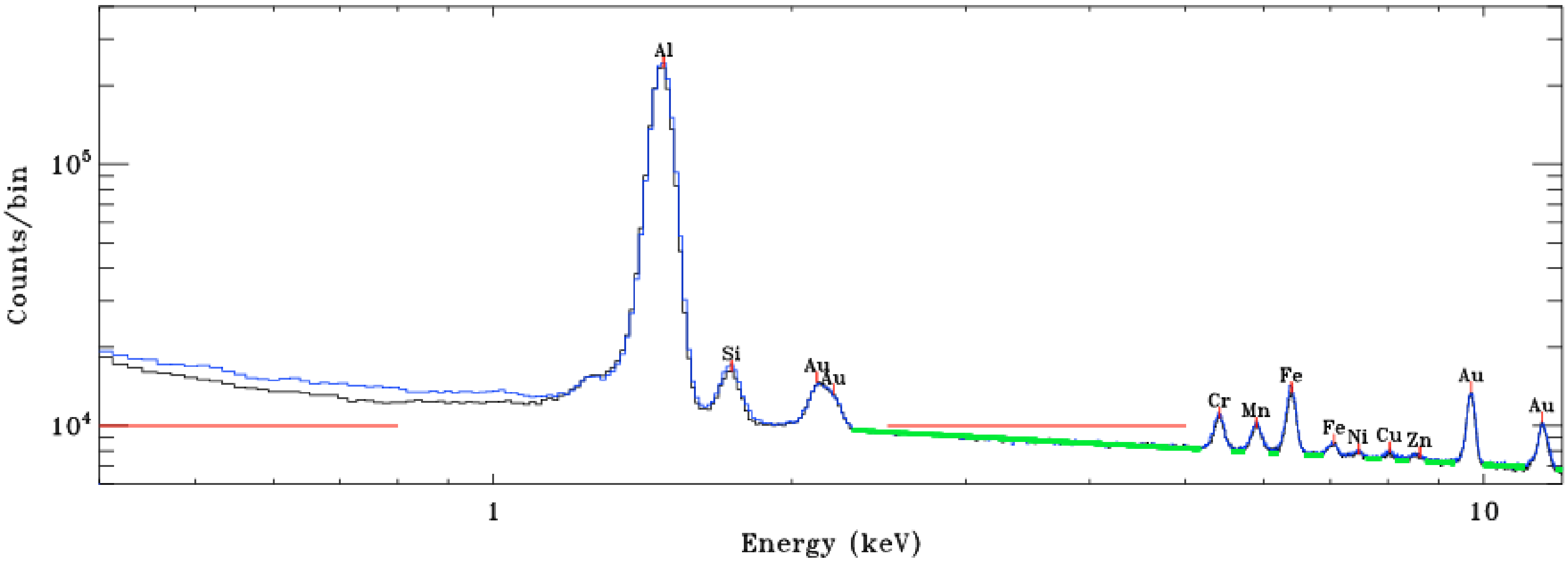
The non-cosmic background is due primarily to energetic particles interacting directly with the detector, or interacting with material around the detector and producing fluorescent X-rays that then strike the detector. This ”particle-induced background” has multiple components and each component is temporally variable, although on different scales. Since the particle background is temporally variable, using the particle background derived from another observation is likely to be unsatisfactory.

Challenges

Lumb et al.'05



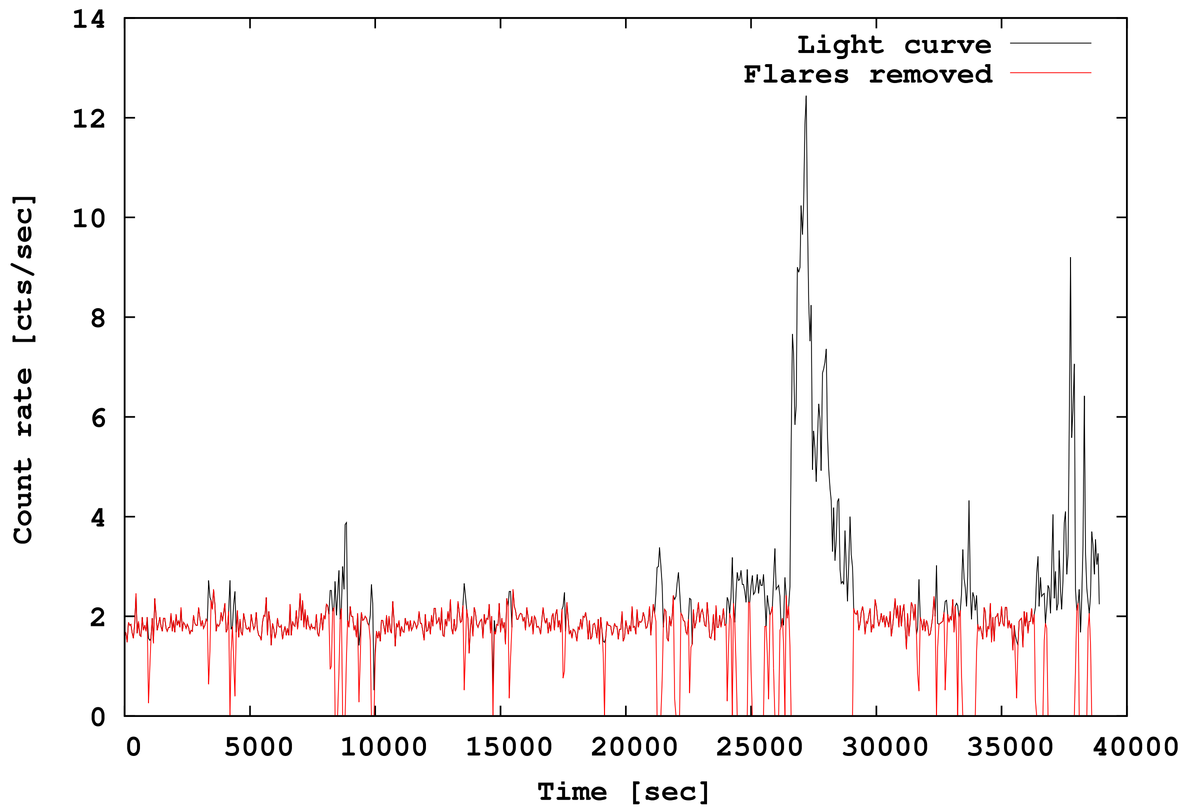
Instrumental background



Kuntz & Snowden'08

- Instrumental (particle) background can be **subtracted** or modeled
- For the dataset of the size **greater** than Msec subtraction of available backgrounds is not useful
- Model above ~ 2 keV: **unfolded** continuum plus lines

Flare removal

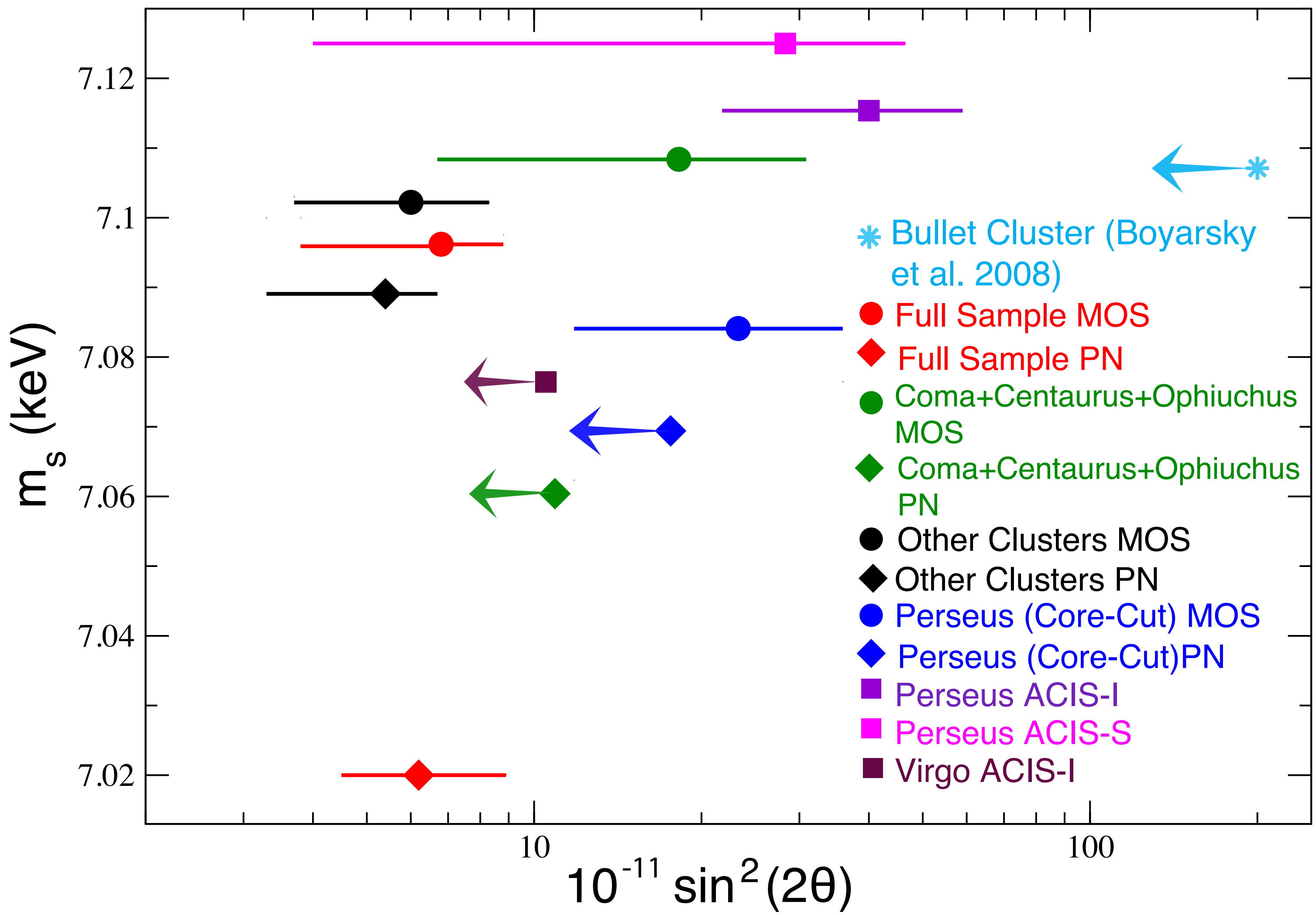


From XMM Handbook

- Few x 100 keV solar protons, accelerated by magnetospheric reconnection events. Dominate times of high-BG.
- Flares (up to 1000%). Unpredictable. Significant quiescent component (long flares) - survive GTI screening.

Comparison between the objects

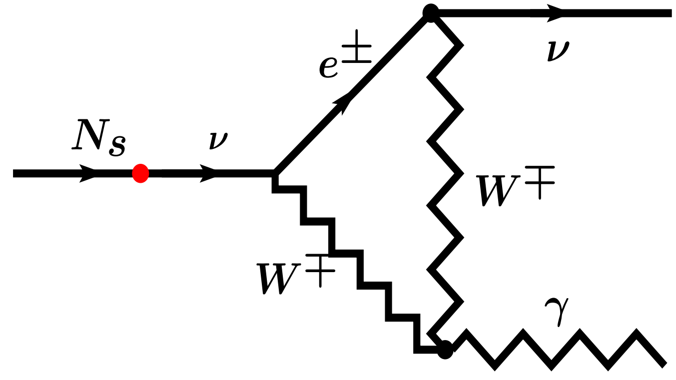
[1402.2301]



Only uncertainties in the line's flux are plotted!

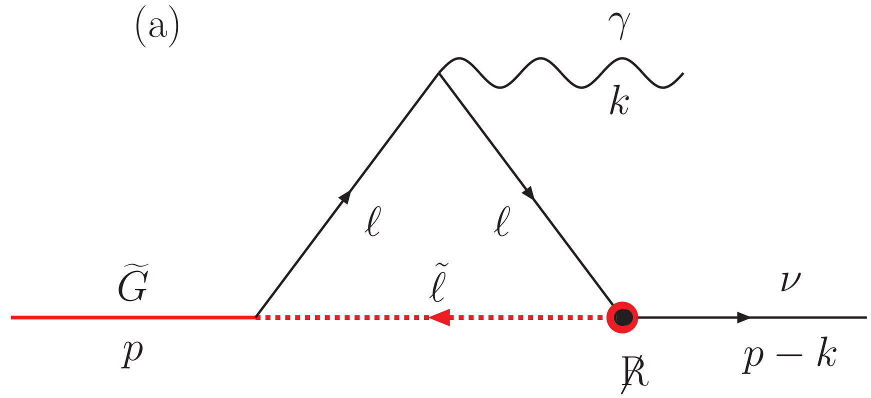
Decaying dark matter

- Sterile neutrino $N \to \nu + \gamma$



(a)

- R-parity violating gravitino
  $\tilde{g} \to \nu + \gamma$

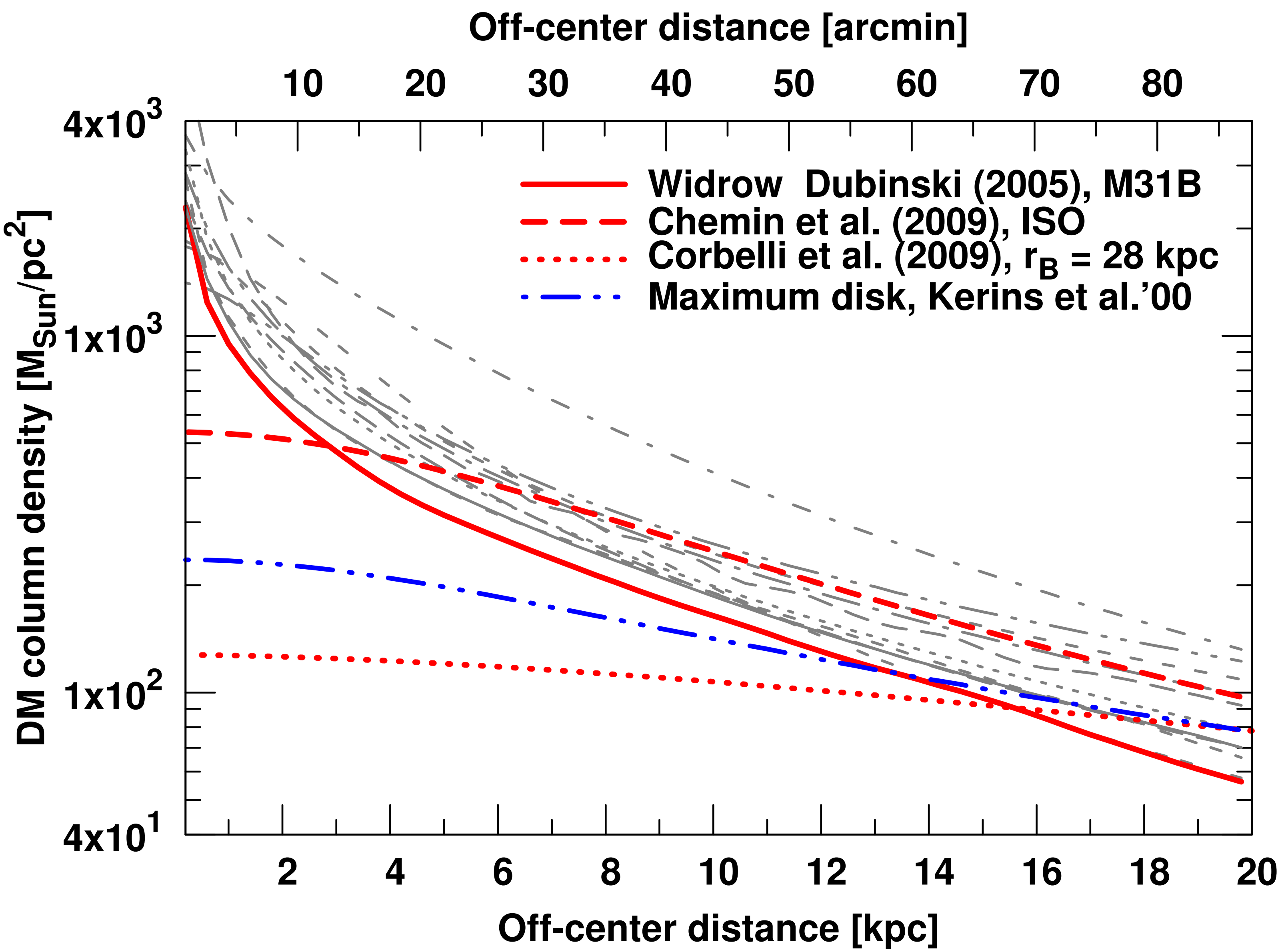


- Also R-parity violating axino, ...

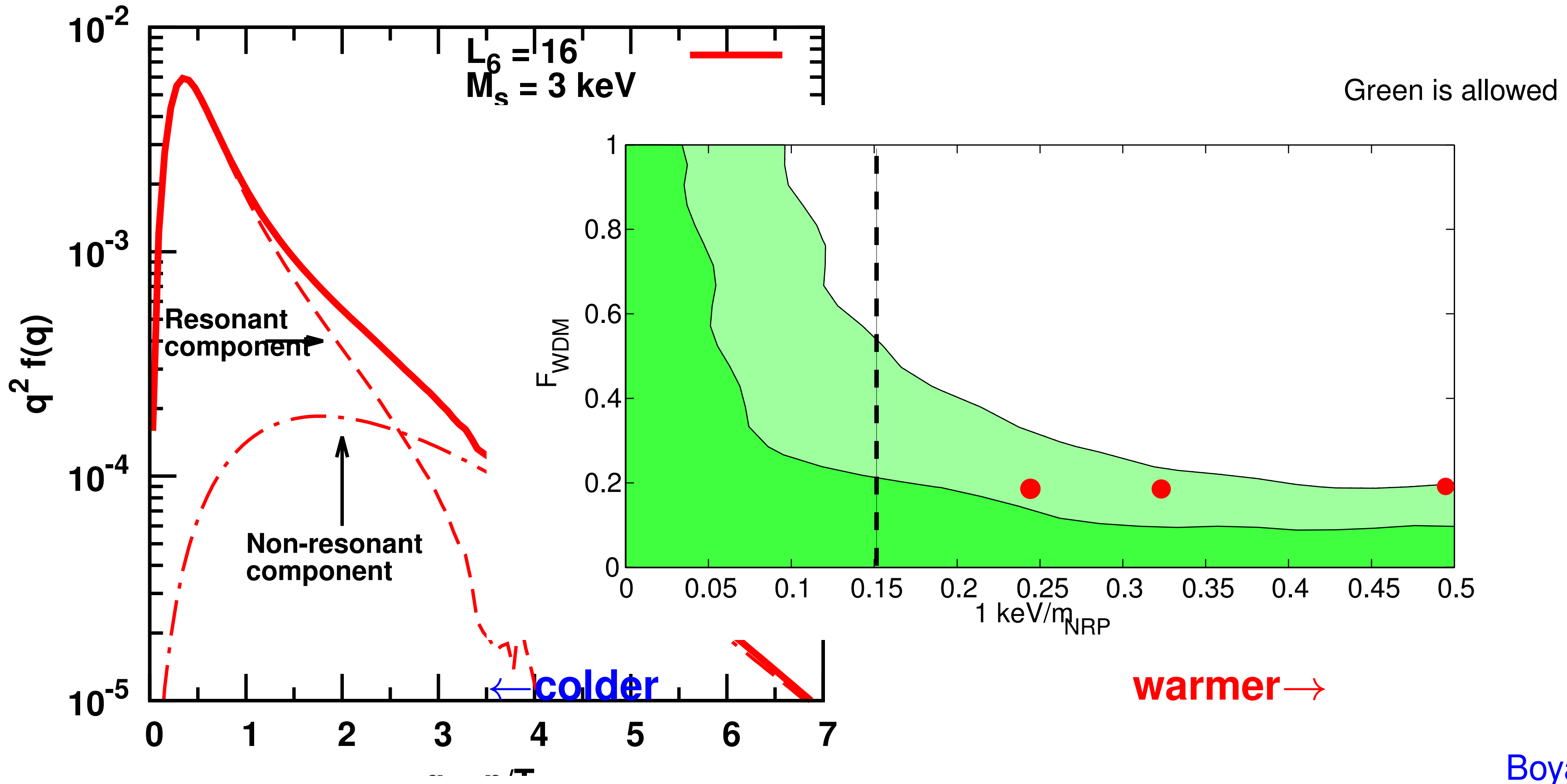
- For bosonic DM axions (or axion-like particles) would decay $a \to \gamma\gamma$

Dark matter column density M31

From [1001.0644]



Structure formation



Boyarsky, Ruchayskiy et al. 2008-2009

- About $\sim 60\%$ of 7 keV sterile neutrino can be **rather warm**
- Such sterile neutrino can leave noticeable traces on the halo structure