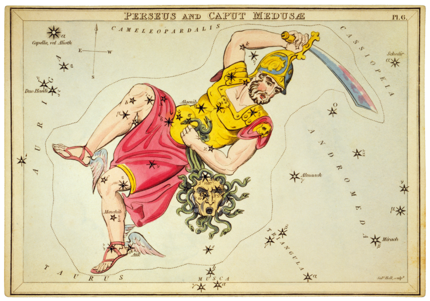
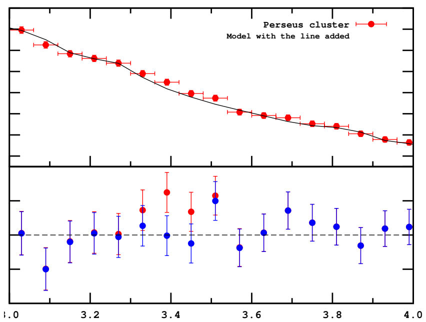
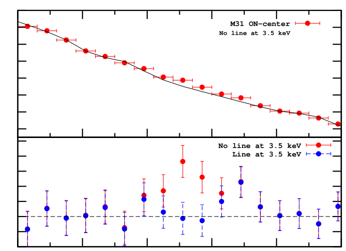
DECAYING DARK MATTER IN X-RAYS ?





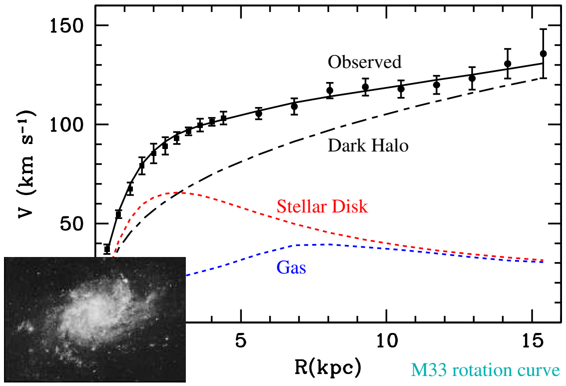
Oleg RUCHAYSKIY

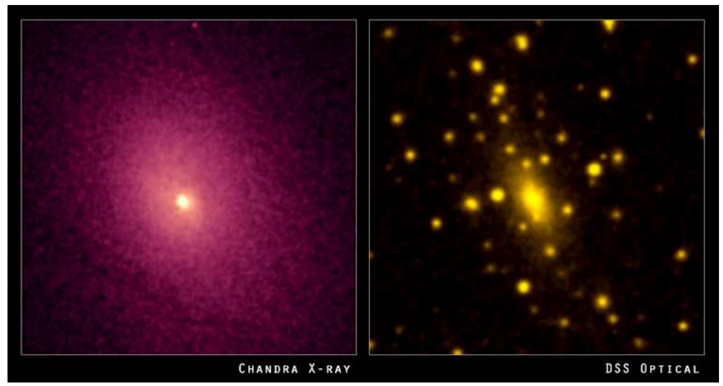
MPIK Heidelberg

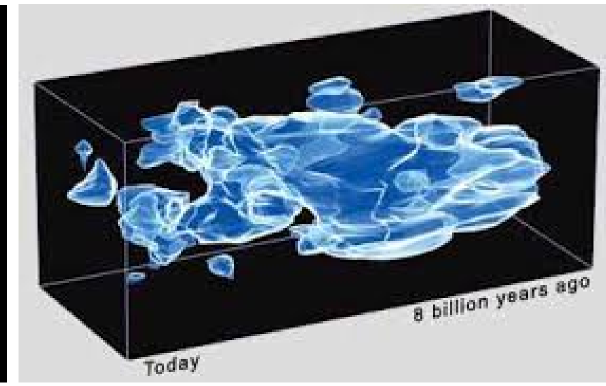


January 26, 2015

More gravitating mass than eyes see!



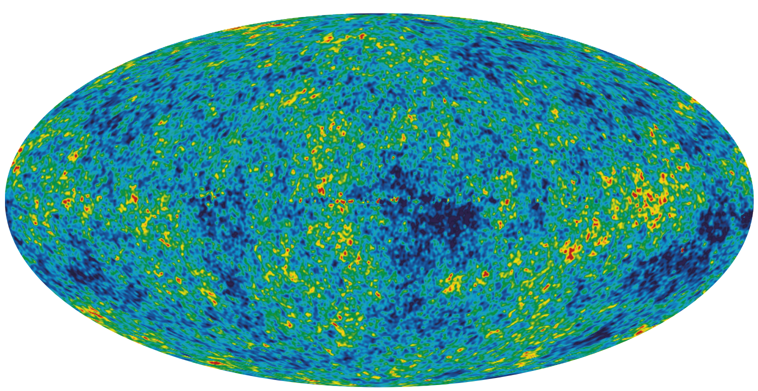




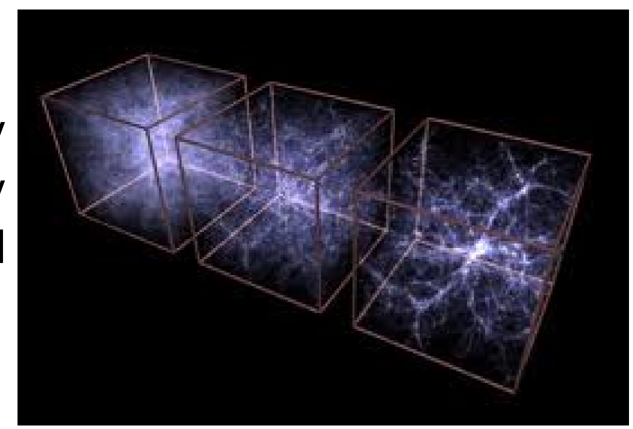
Expected: $v(R) \propto \frac{1}{\sqrt{R}}$
Observed: $v(R) \approx \text{const}$

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

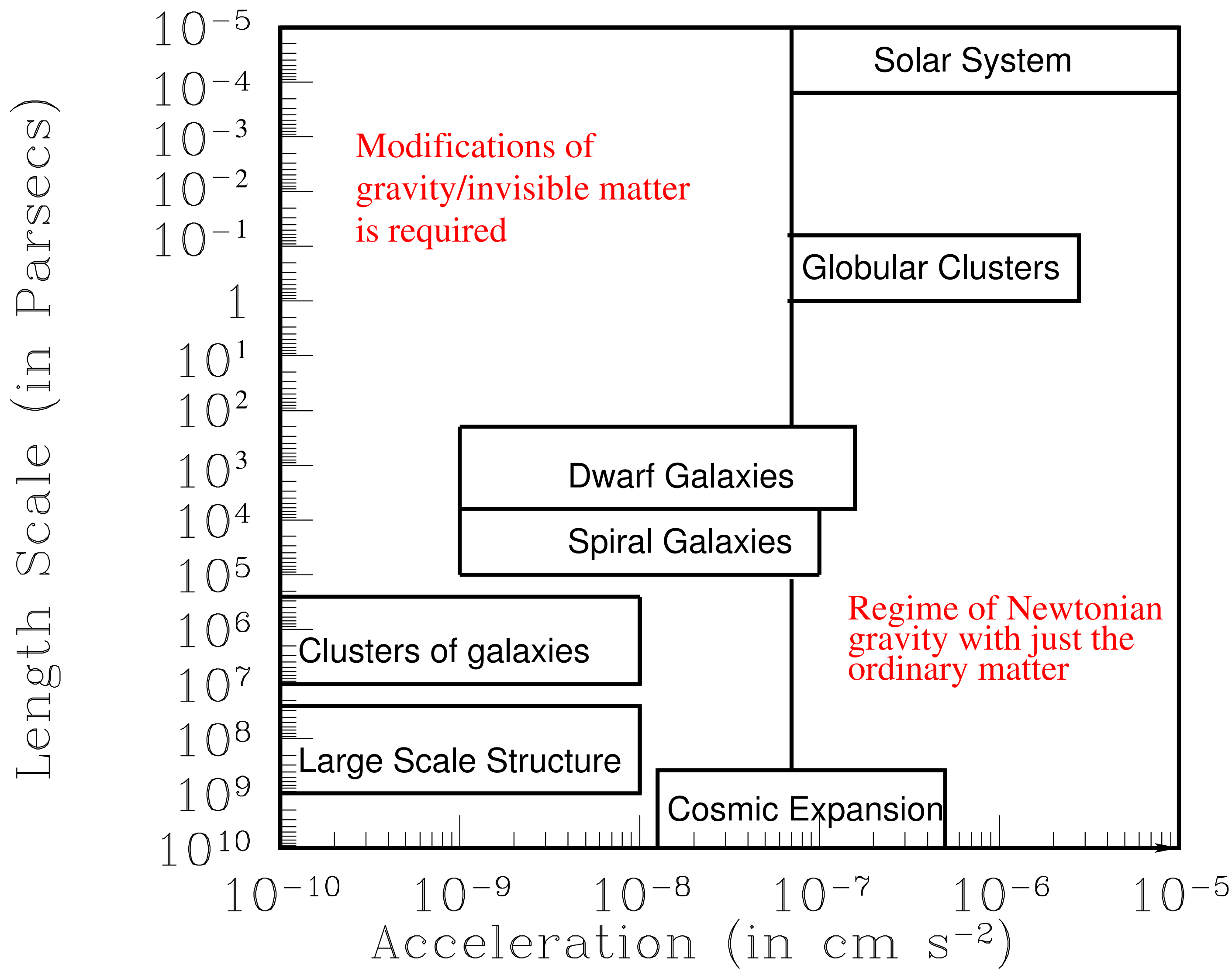
Lensing signal (direct mass measurement) **confirms** other observations



Jeans instability turned tiny density fluctuations into all visible structures



Change of fundamental laws?



From Ferreira & Starkman 0911.1212

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

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

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

Neutrino Dark Matter?

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

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

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

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

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

Hot dark matter

- 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:

Dark matter cannot be both **light** and **weakly interacting** at the same time

Two generalizations

$\swarrow$ $\searrow$

light and **super**-weakly interacting
"super" WIMP

heavy and weakly interacting
WIMP

– **Can be light** (all the way to Tremaine-Gunn bound)
particles never enter thermal equilibrium, their number density is highly sub-equilibrium

– **Can be warm** (born relativistic and cool down later)

– **Can be decaying** (stability is not required)
massive particles will decay unless we impose a new symmetry to keep it stable

Searching for decaying dark matter

Decaying dark matter signal

- Two-body decay into two massless particles (DM $\to \gamma + \gamma$ or DM $\to \gamma + \nu$) $\Rightarrow$ narrow decay line
$$E_\gamma = \frac{1}{2} m_{\mathsf{DM}} c^2$$
- 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 $\dfrac{\Delta E}{E_\gamma} \sim \dfrac{v_{\mathsf{vir}}}{c} \sim 10^{-4} \div 10^{-2}$

Dark matter decay flux

- Flux from dark matter decay is

$$\text{Decay flux} = \frac{1}{4\pi\tau_{\text{DM}} M_{\text{DM}}} \frac{M_{\text{fov}}}{D_L^2}$$

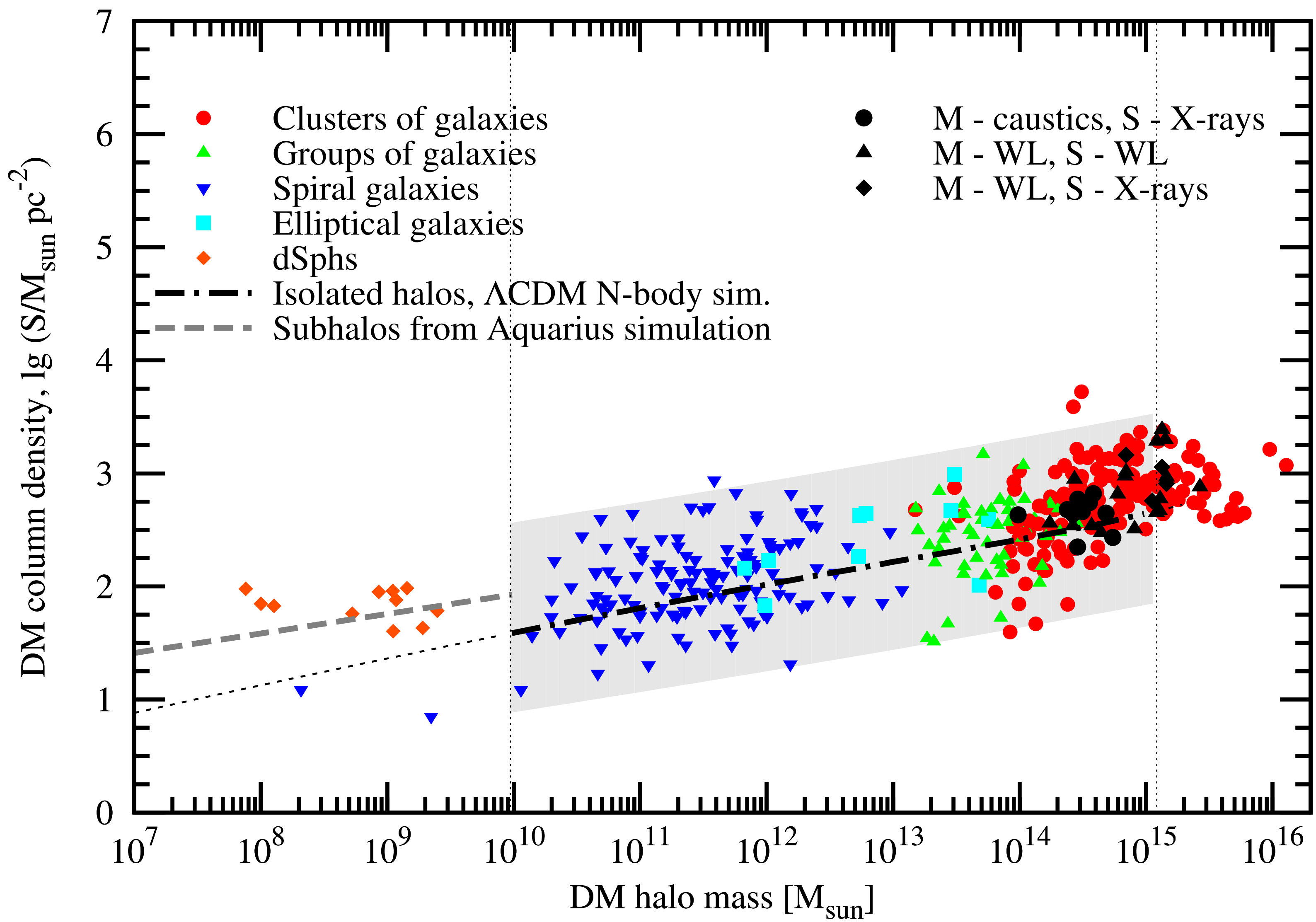
- For objects that *cover the whole FoV of the instrument*

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

— does not depend on the distance to the object!

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

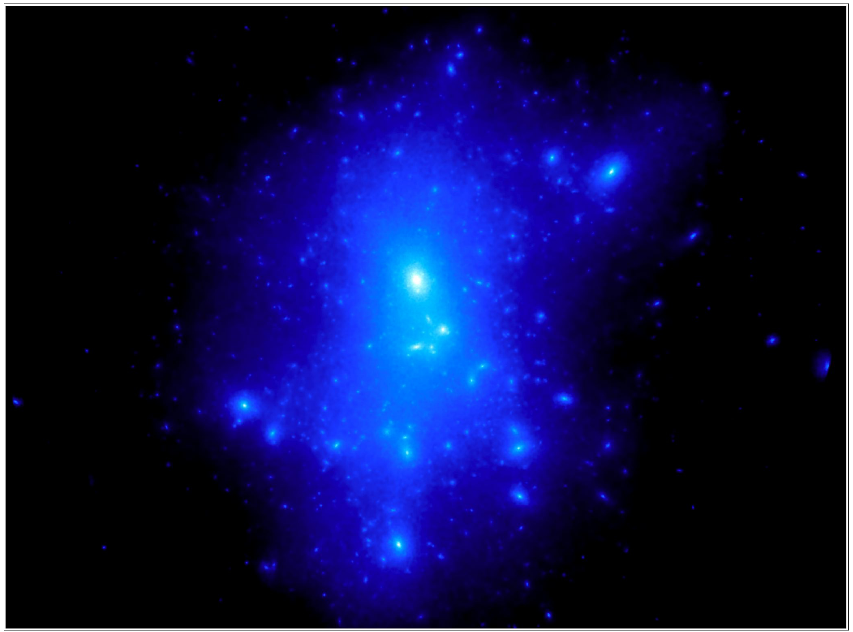
Signal from different DM-dominated objects



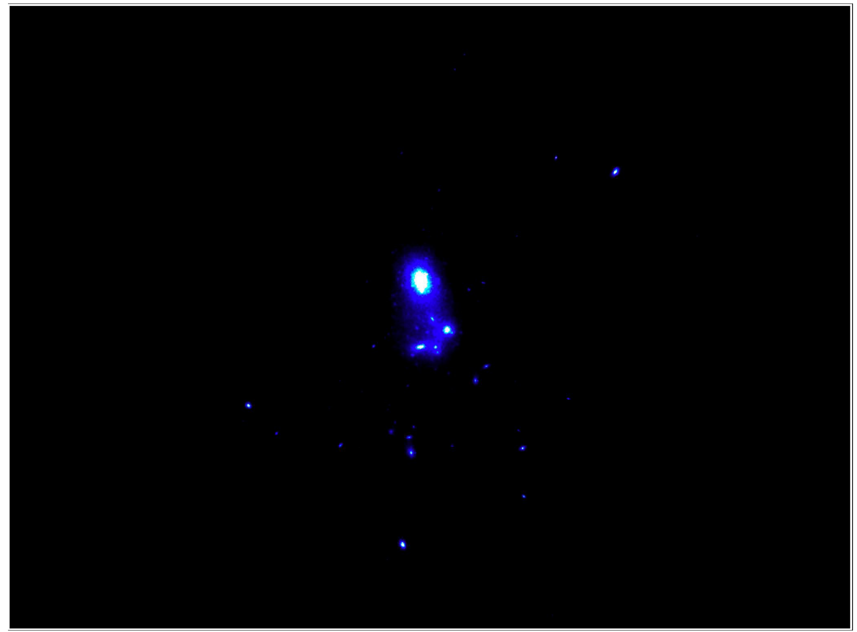
Boyarsky, Neronov, **O.R.** Shaposhnikov, Tkachev PRL'06

Boyarsky, Neronov, **O.R.** Tkachev PRL'09

Search for decaying dark matter



DM **decay** signal from a galaxy

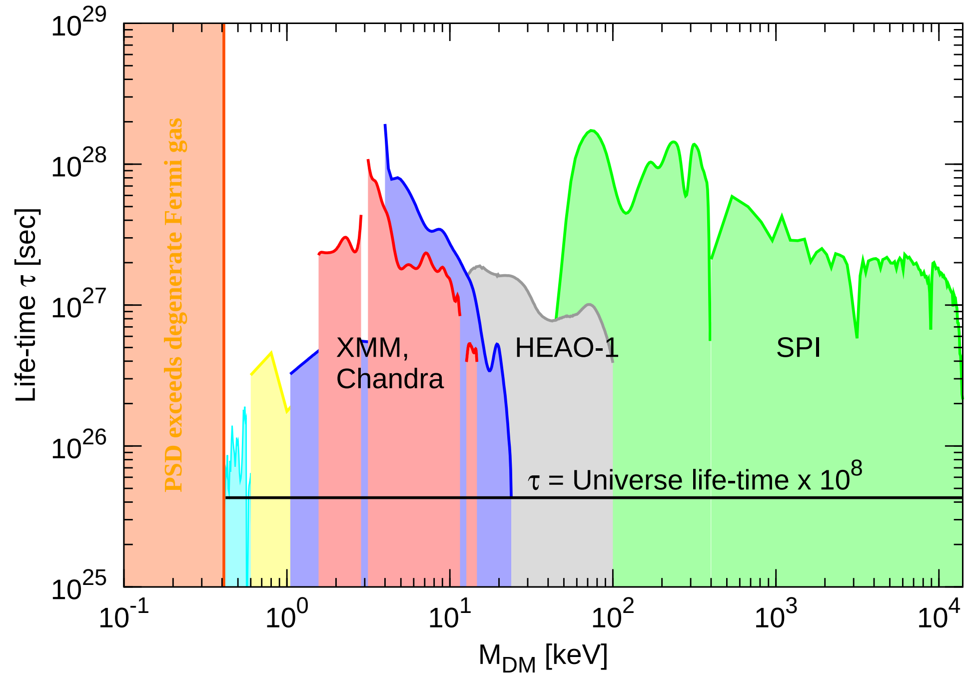


DM **annihilation** signal from a galaxy

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

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

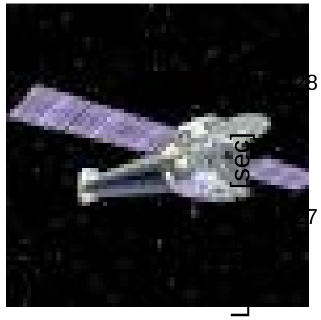
MW (XMM) 2006–2007

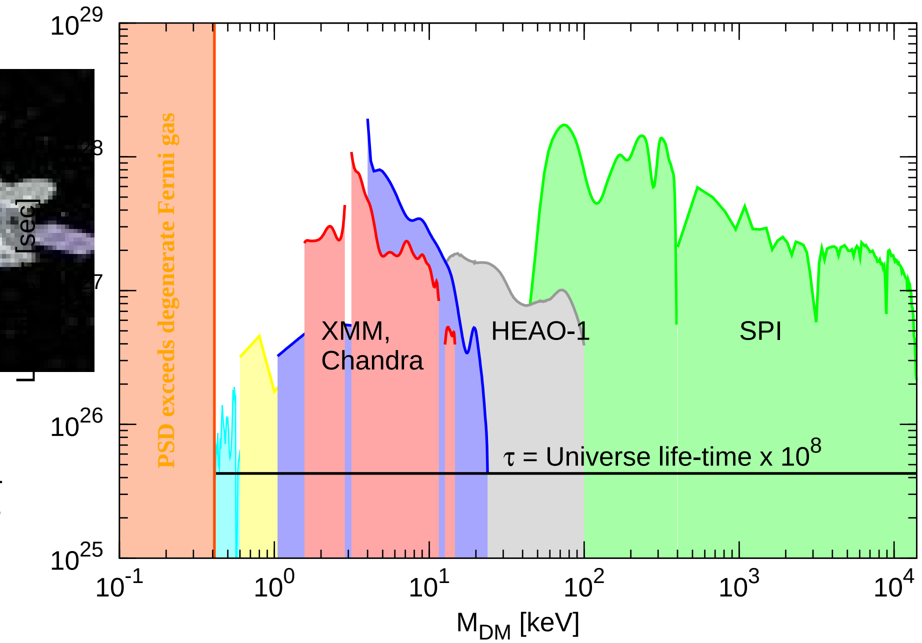
M31 (XMM) 2007, 2010

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

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

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

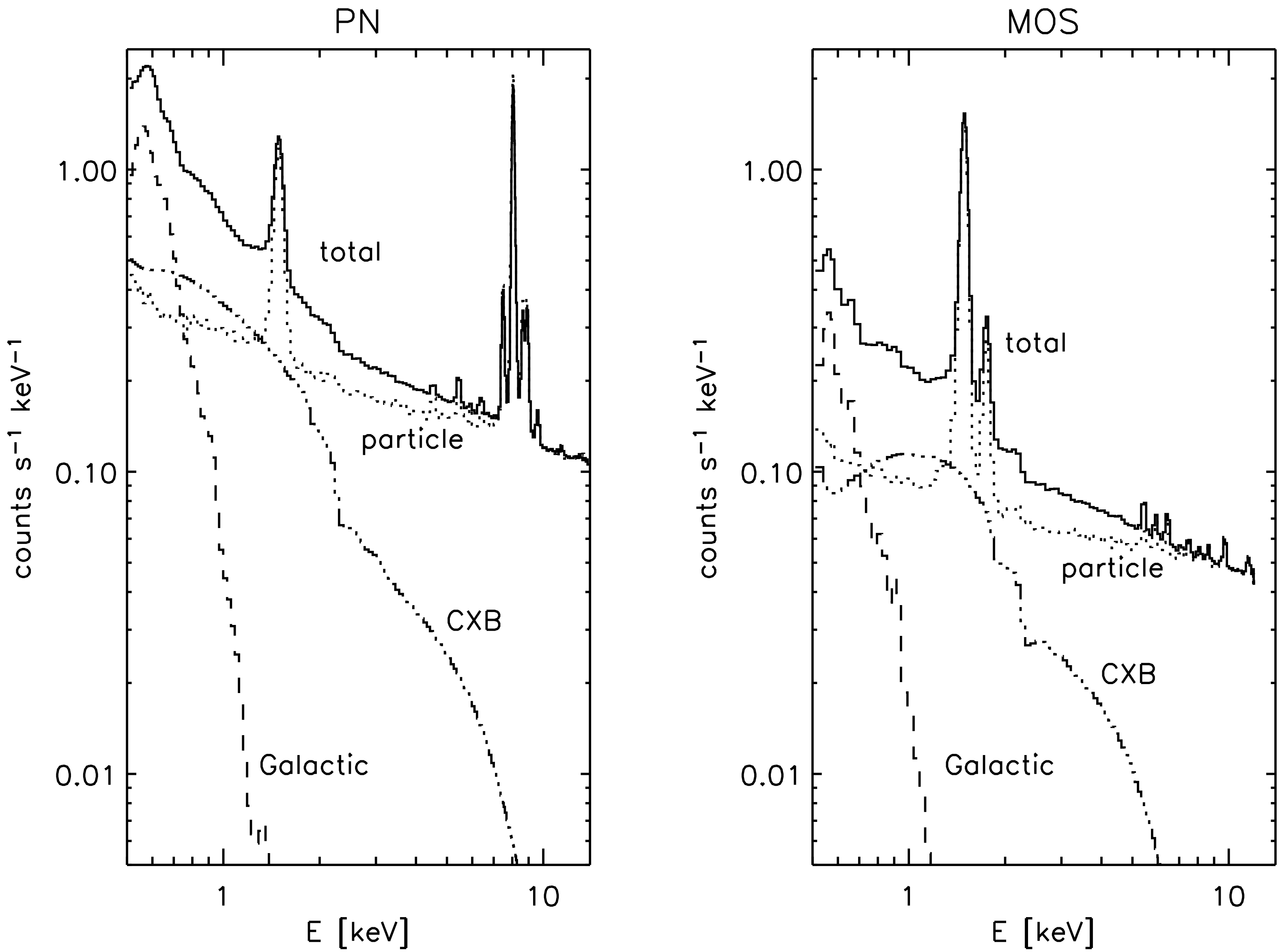
– Only 60-70% of exposure is used (cosmic flares contamination)

Can we **stack** many different observations (correcting for redshift) in a hope of seeing a weak decay line?

First results: [1306.4954]

Components that are ALWAYS present

Lumb et al.'05



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

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]
[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

ApJ (2014) [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

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[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

PRL (2014) [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…

…followed by **100+** of papers

Our Data

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

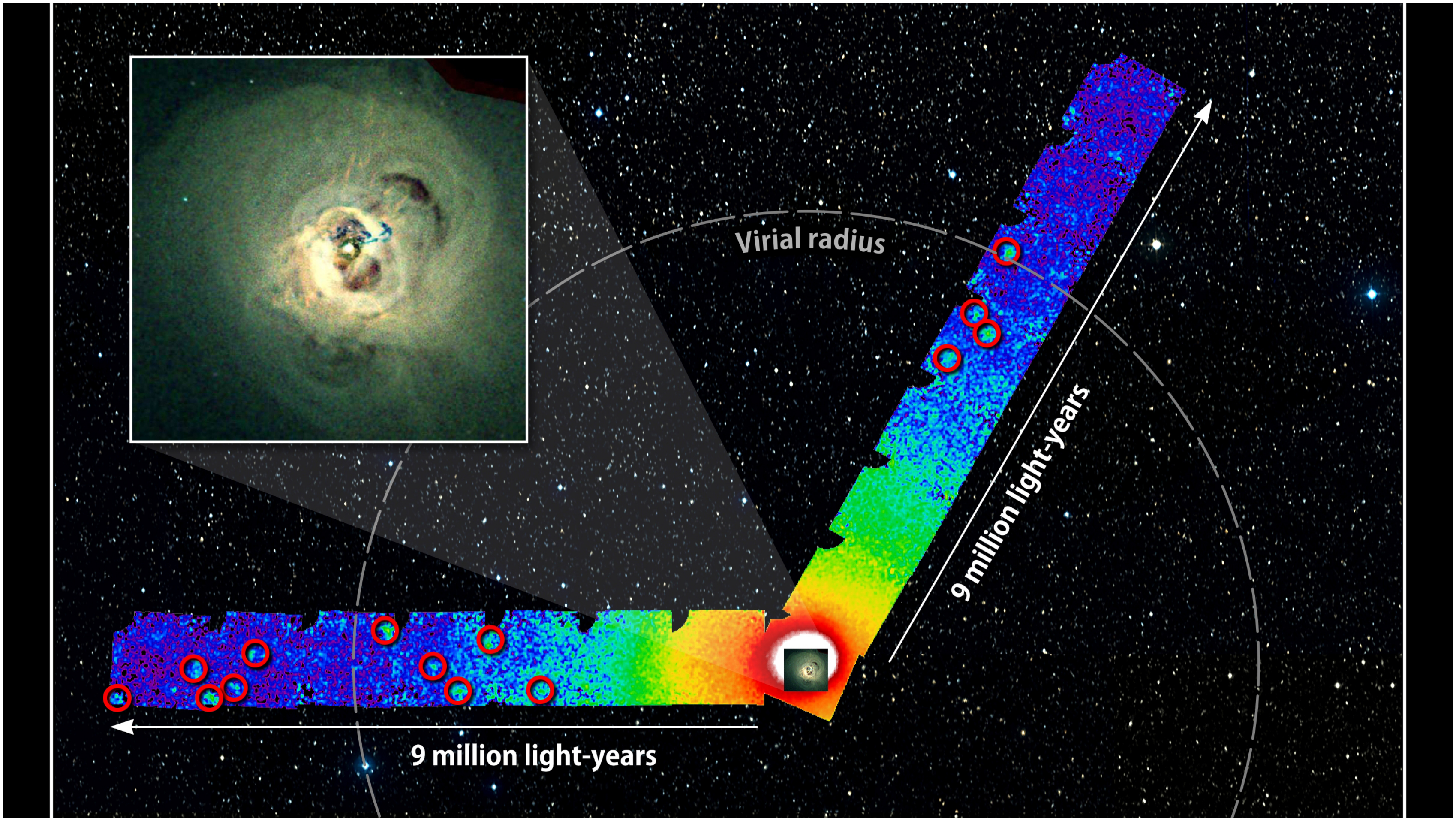
Bulbul et al. 2014

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 ~ 30 eV. Systematics (~ 50 eV – between cameras, determination of known instrumental lines)

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

Perseus galaxy cluster (0.5/0.2 Msec)



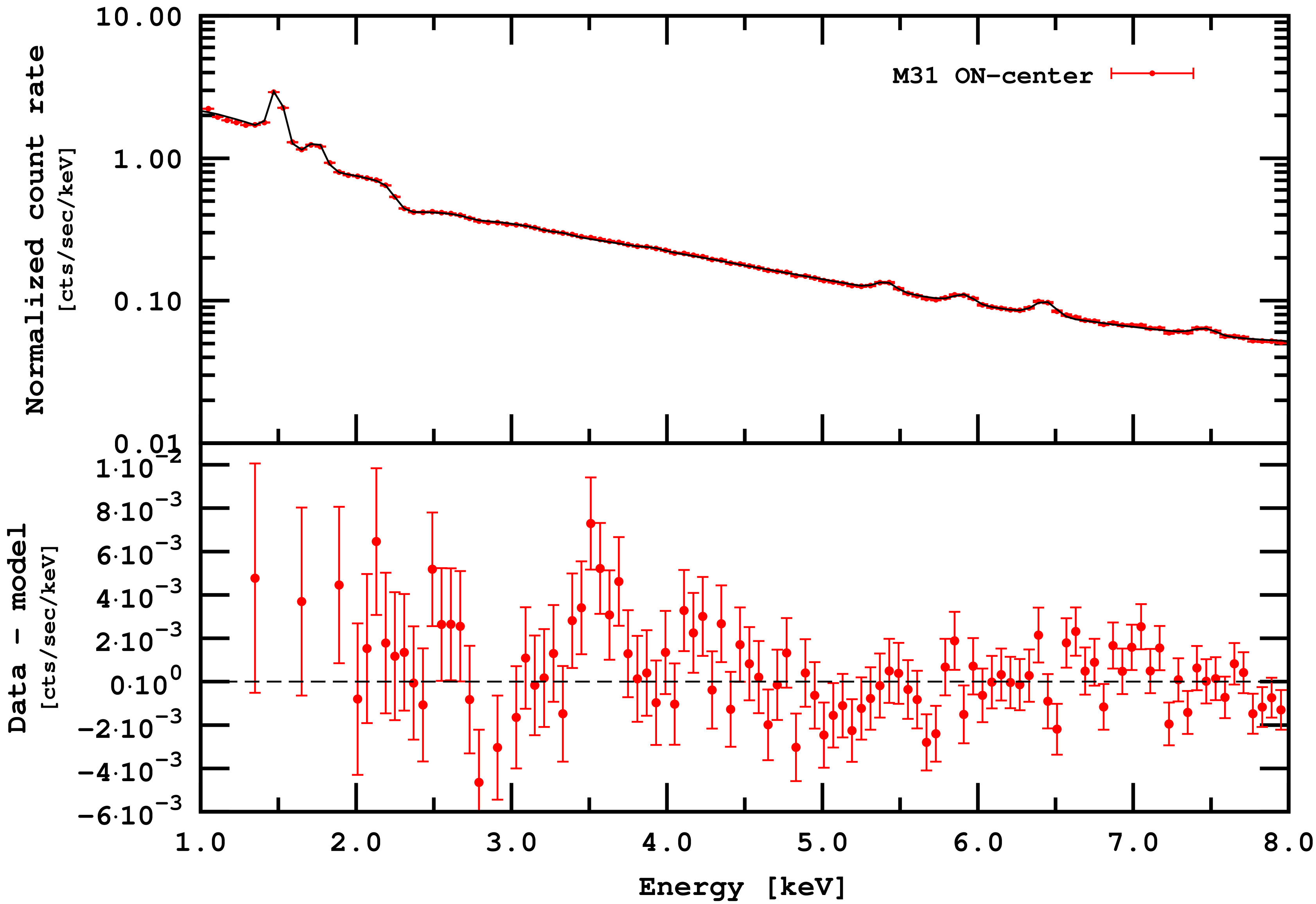
Bulbul et al. took only 2 central XMM observation – $14'$ around the cluster's center.

Also Carlson et al.; Urban et al.

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

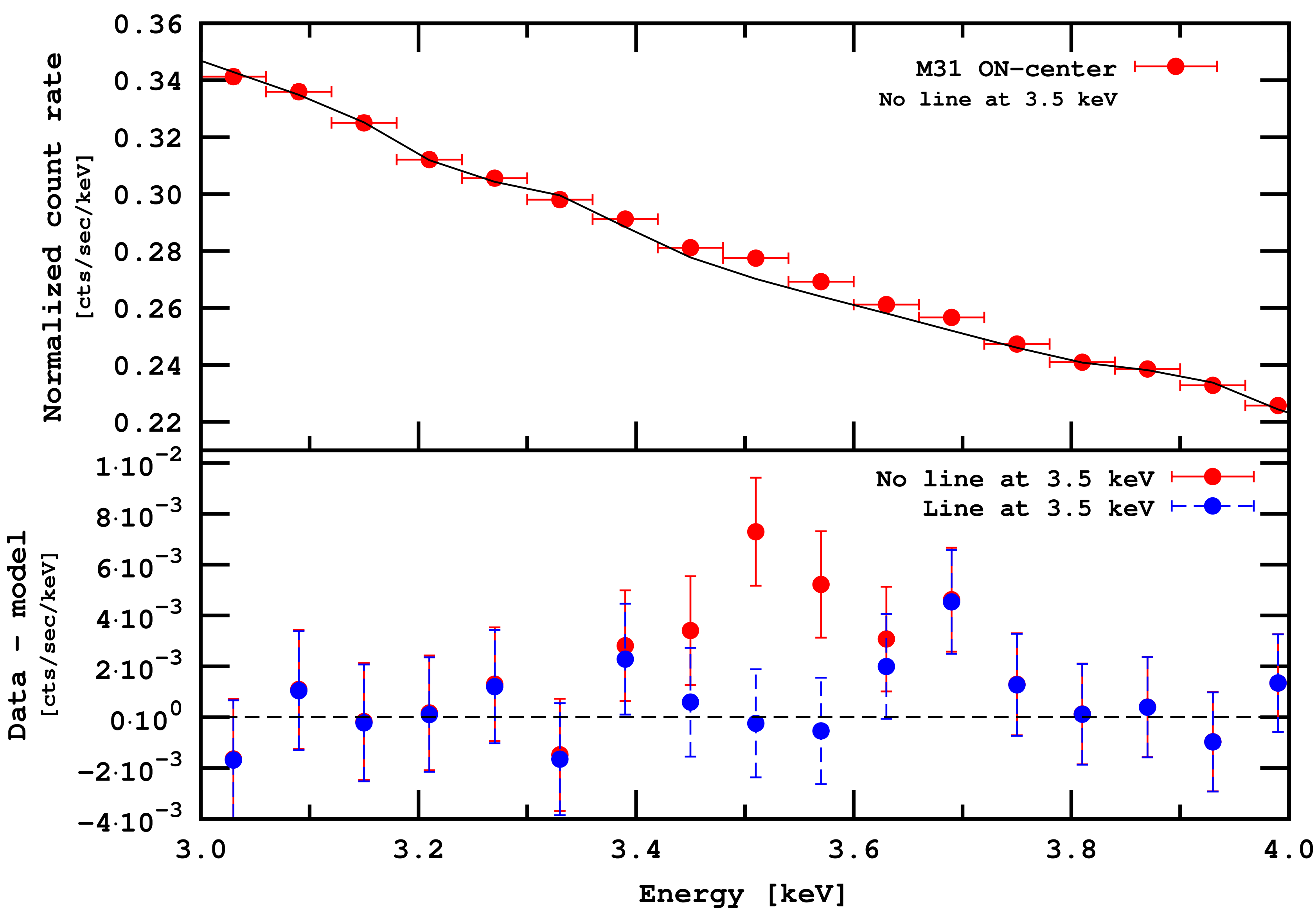
Andromeda galaxy

PRL (2014) [1402.4119]

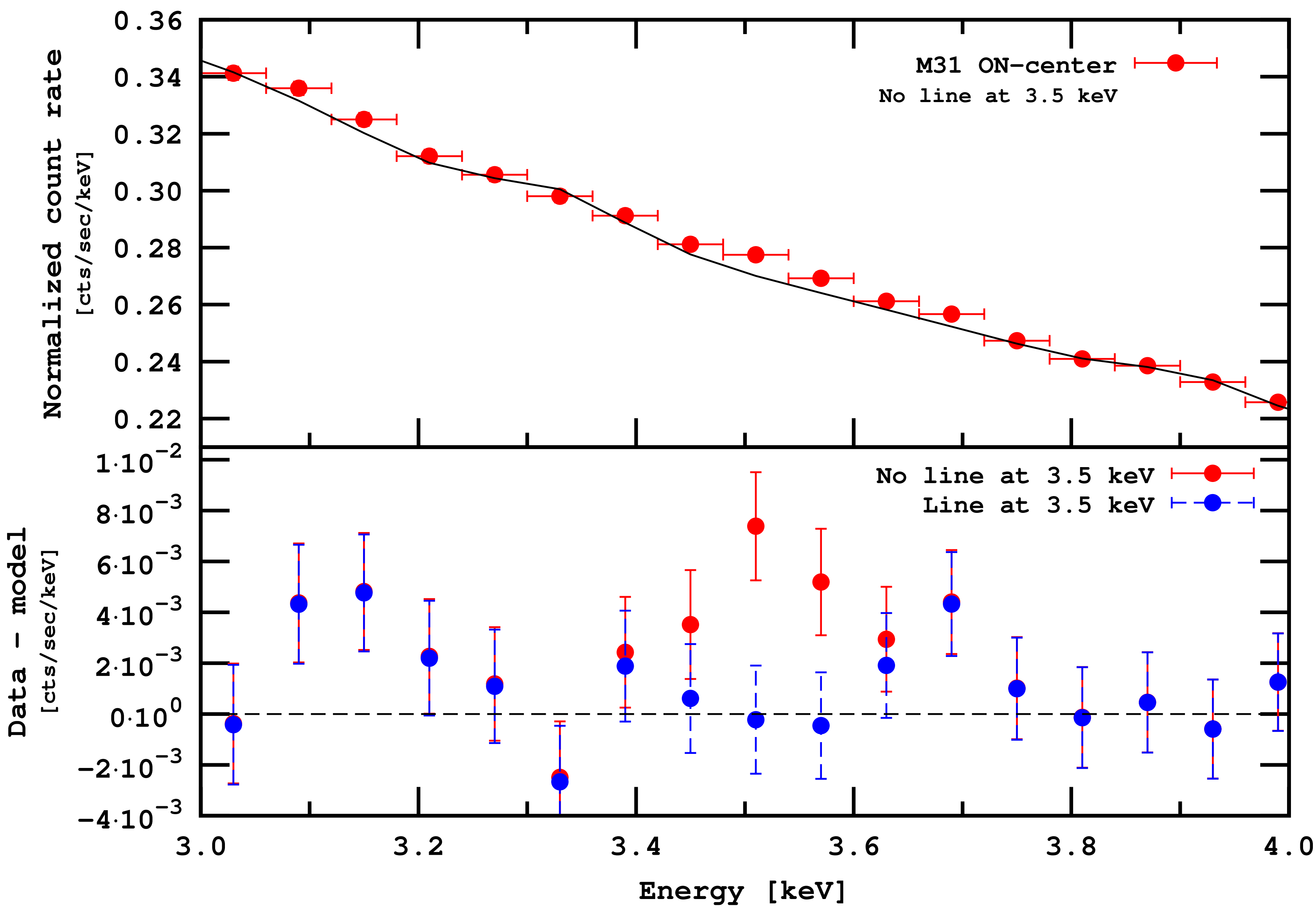


Andromeda galaxy (1 Msec) (zoom 3–4 keV)

PRL (2014)
[1402.4119]



Andromeda galaxy (zoom 3–4 keV)



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.

Global significance of detecting the same signal in 3 datasets: 4.8σ

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 (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.
...		

Consistent with decaying DM interpretation?

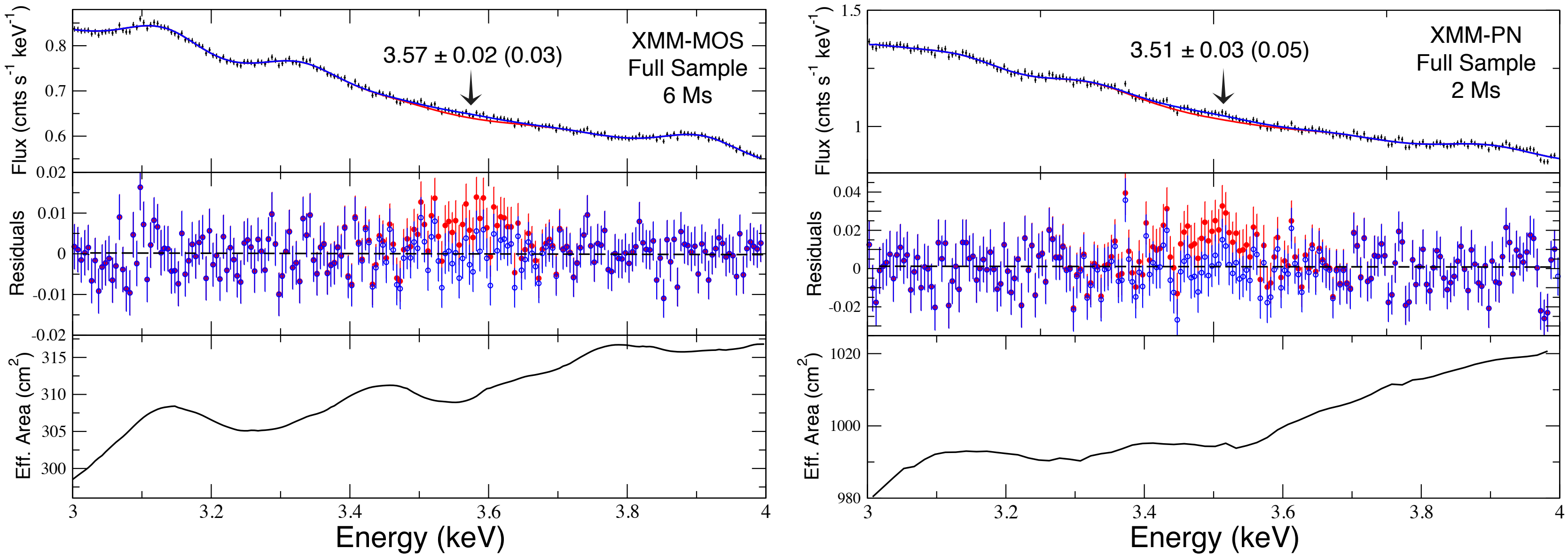
- It is challenging to exclude all possible sources of systematics
- Alternative is to check that the signal

  … Correctly scales with redshift?

  … Intensity of the line correctly changes within the object?

  … Correlates with (expected!) dark matter density in different objects?

Redshift scaling



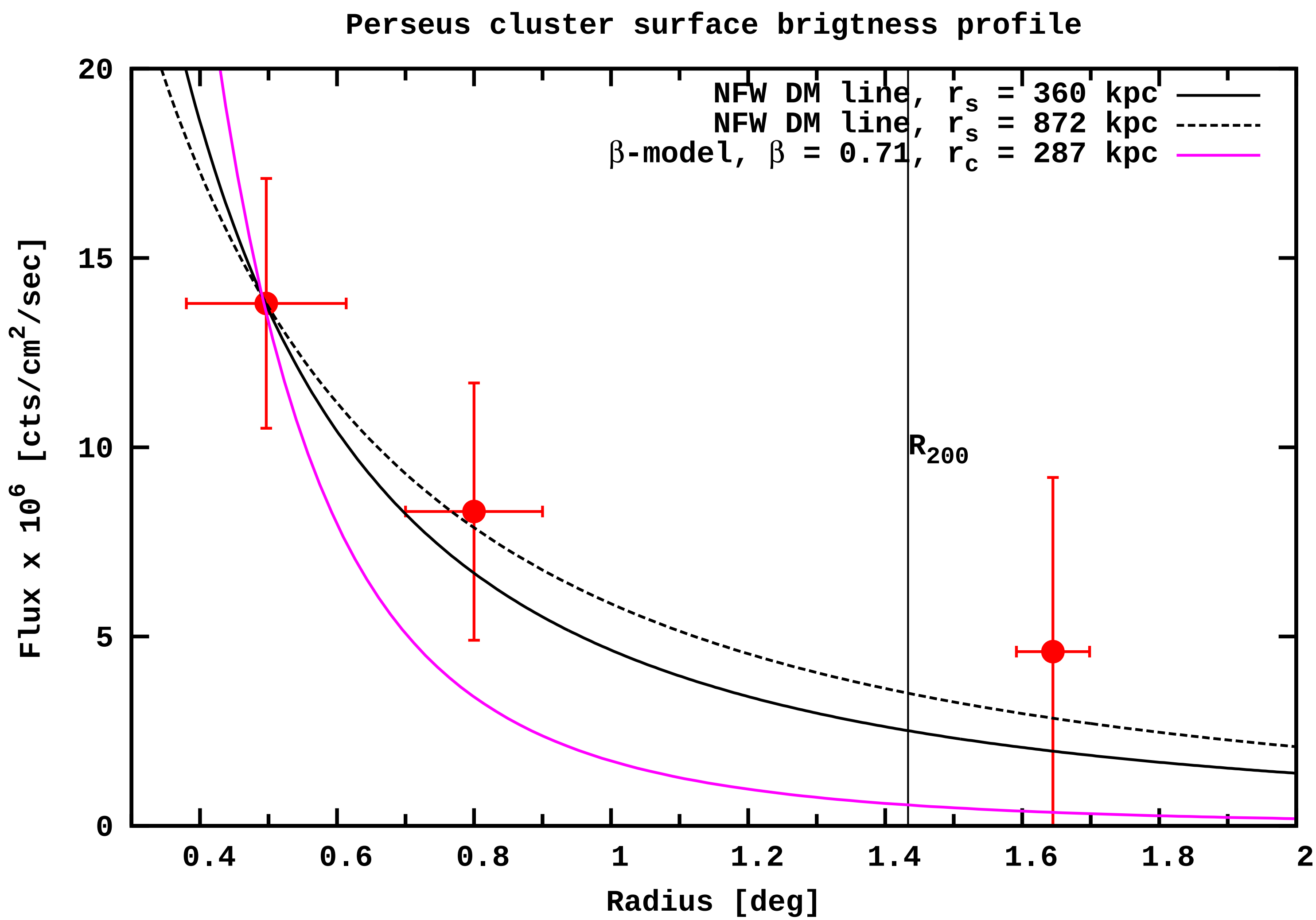
Bulbul et al. ApJ (2014) [1402.2301]

- All spectra blue-shifted in the reference frame of clusters (Bulbul et al.)
- For Perseus we detect its redshift ($z \approx 0.018$) at $\sim 2\sigma$ (Boyarsky et al.)

  position of the line has about 30 eV uncertainty

Surface brightness profile (Perseus)

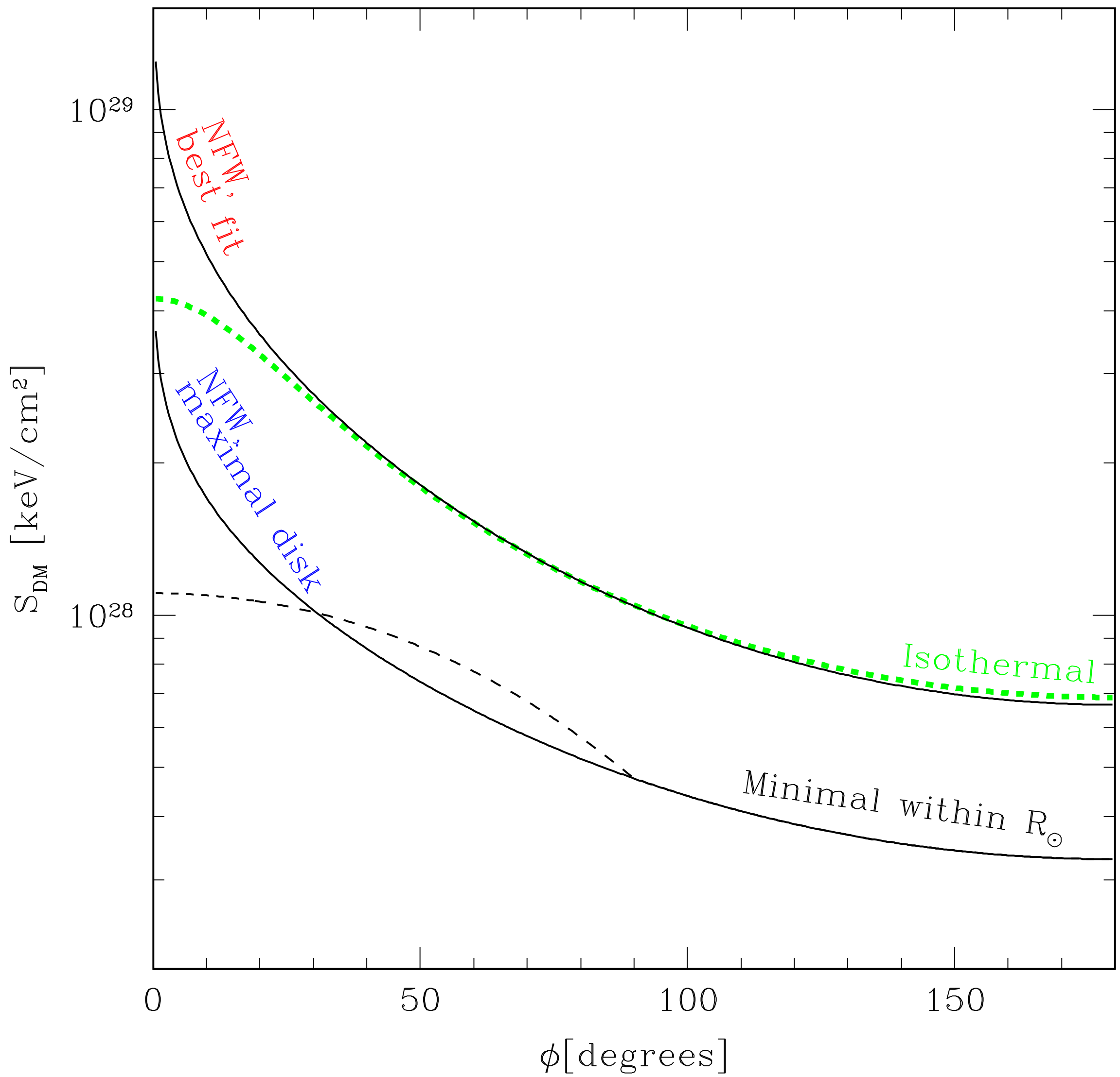
PRL (2014) [1402.4119]



This is not a fit!

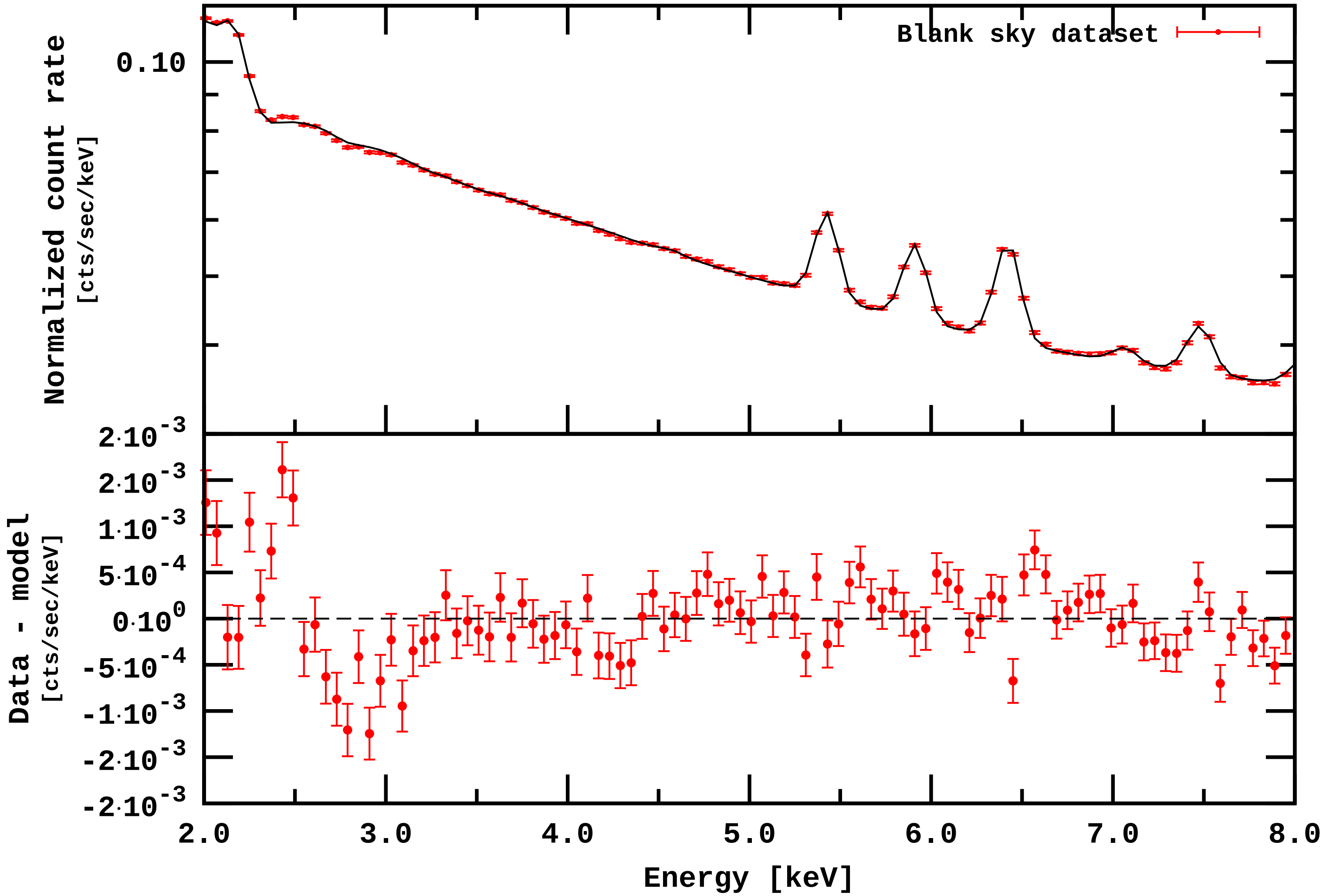
Surface brightness profile (Milky Way)?

O.R. et al (2006,2007)



Surface brightness profile (Milky Way)?

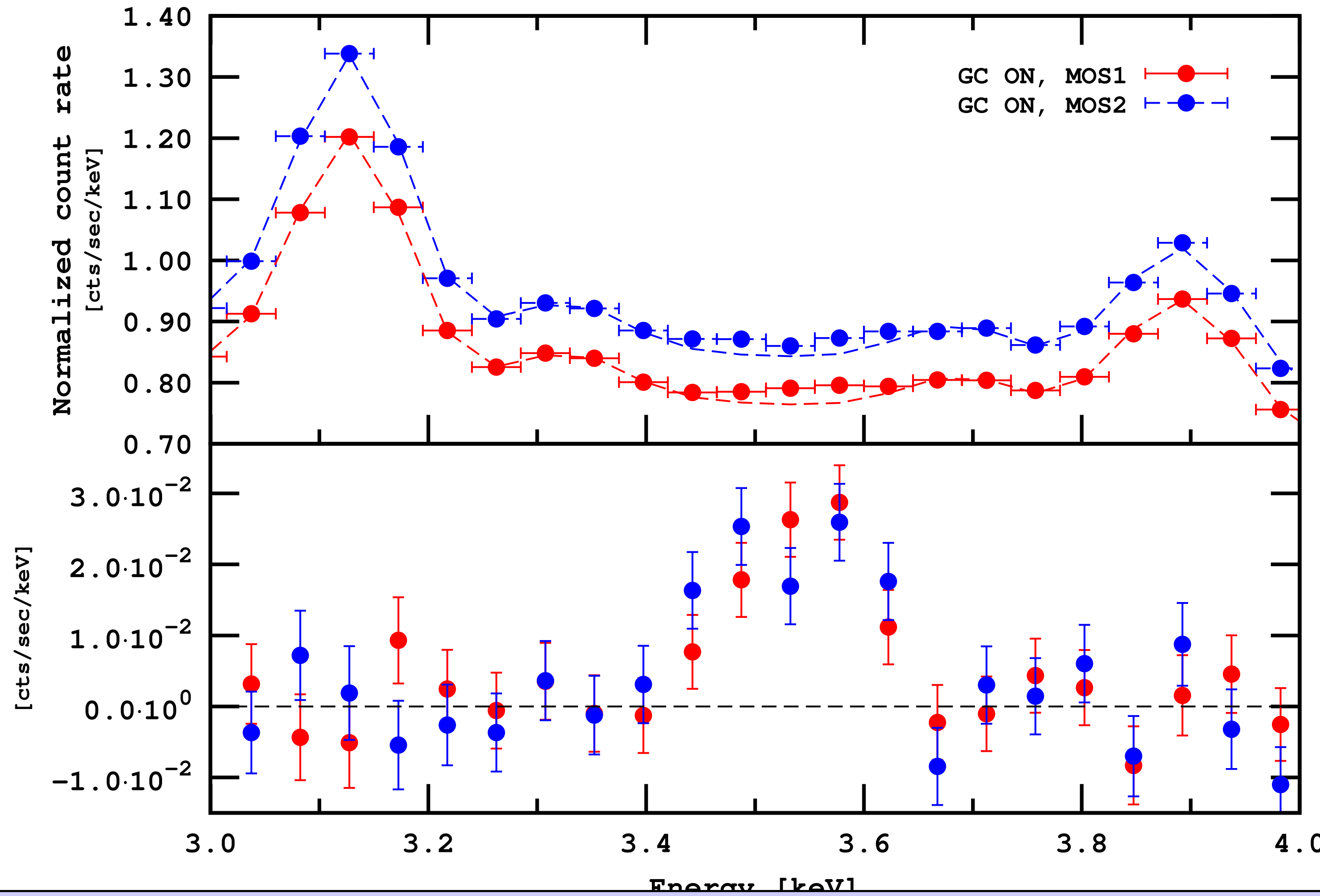
PRL (2014) [1402.4119]



No line is seen in 16 Msec observations of off-center Milky Way

Checking the dark matter origin of the line

Galactic center

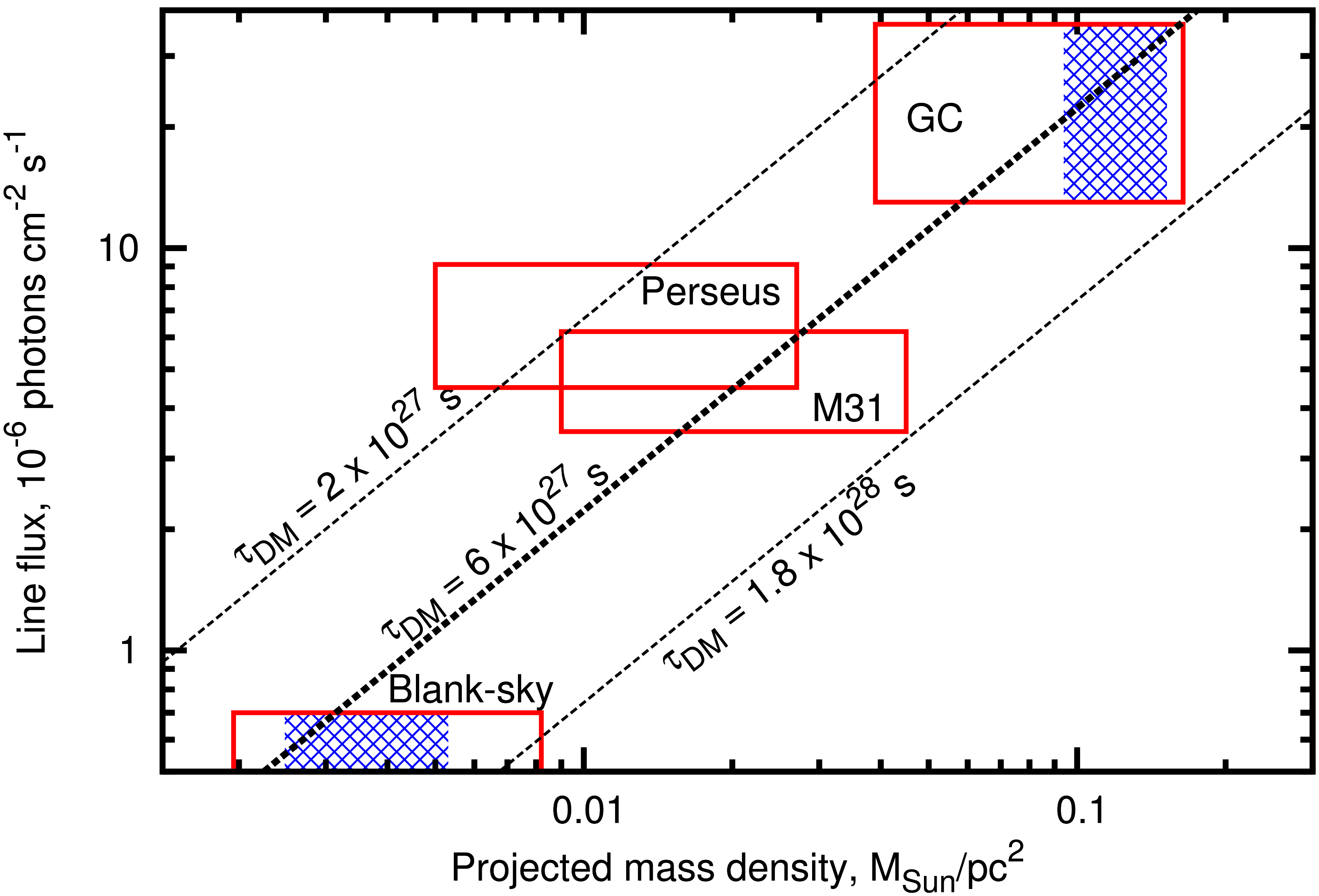


Boyarsky, **O.R** et al. [1408.2503]

The line in the center of Andromeda means we should see it in the **Milky Way center**. Yes, we see it there!

More than 4σ statistical significance. Seen also by S. Riemer-Sorensen [1405.7943]; T. Jeltema & S. Profumo [1408.1699]

Non-trivial consistency check



Milky Way profiles (data)

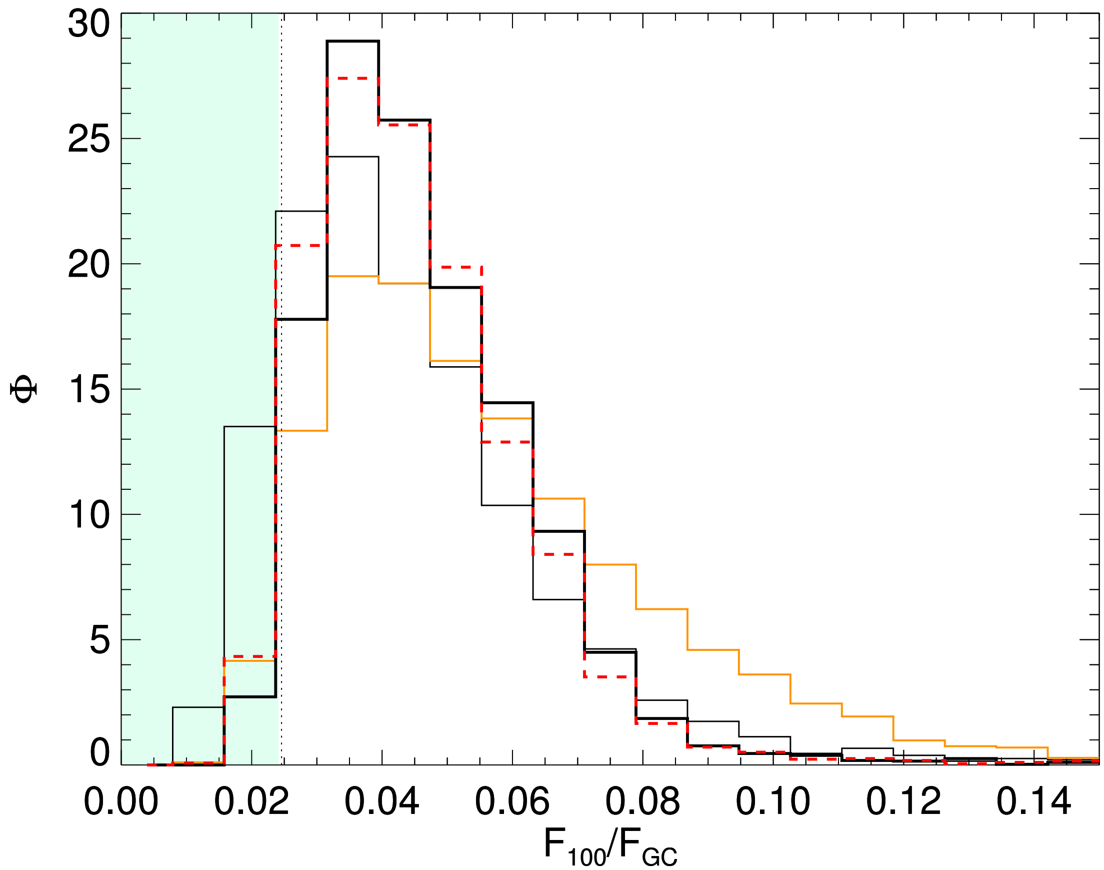
[1408.1699]

Reference	Type	ρ_*, $10^6 M_\odot$/ kpc^3	r_*, kpc	$r_\odot$, kpc	$\mathcal{S}_{\rm GC}$ M$_\odot$/pc^2	$\mathcal{S}_{\rm BS}$ M$_\odot$/pc^2	$\mathcal{S}_{\rm GC}/\mathcal{S}_{\rm BS}$ ratio
[124]	NFW	27.2 ± 15.0	10.2 ± 6.1	8.5	3402^{+2376}_{-755}	102^{+105}_{-66}	33.4 (27.9-73.5)
[129]	NFW	28.0	10.4	8.5	3579	109	32.8
[100]	NFW	20.4 ± 2.6	10.8 ± 3.4	8.33 ± 0.35	2727^{+691}_{-726}	87^{+36}_{-30}	31.3 (27.7-35.1)
[128]	EIN	10.4	20	8.3	2574	95	27.1
[123]	NFW	13.3	14.7 ± 0.7	8.0	2501^{+126}_{-127}	101^{+7}_{-8}	24.8 (24.3-25.5)
[127]	NFW	12.5 ± 6.0	17.0 ± 3.9	8.33 ± 0.35	2721^{+1057}_{-904}	112^{+53}_{-42}	24.2 (22.9-26.0)
[130]	NFW	$14.0^{+29}_{-9.3}$	$16.1^{+17.0}_{-7.8}$	8.08 ± 0.2	2893^{+6040}_{-1460}	120^{+302}_{-69}	24.1 (21.2-28.1)
[125][a]	NFW	4.74 ± 0.57	21.0 ± 3.2	8.0	1282^{+165}_{-167}	59 ± 9	21.7 (21.3-22.3)
[130]	BURK	41.3^{+62}_{-16}	$9.26^{+2.9}_{-0.93}$	$7.94^{+0.36}_{-0.24}$	481^{+429}_{-104}	144^{+173}_{-39}	3.3 (2.9-3.6)
[126]	ISO	24.5 ± 2.5	5.5 ± 0.6	8.0	326^{+30}_{-28}	104 ± 14	3.1 (3.0-3.3)

The flux ratio between Galactic Center and off-center (blank sky) observations is **consistent** for some dark matter density profiles of the Milky Way

Milky Way profiles (simulations)

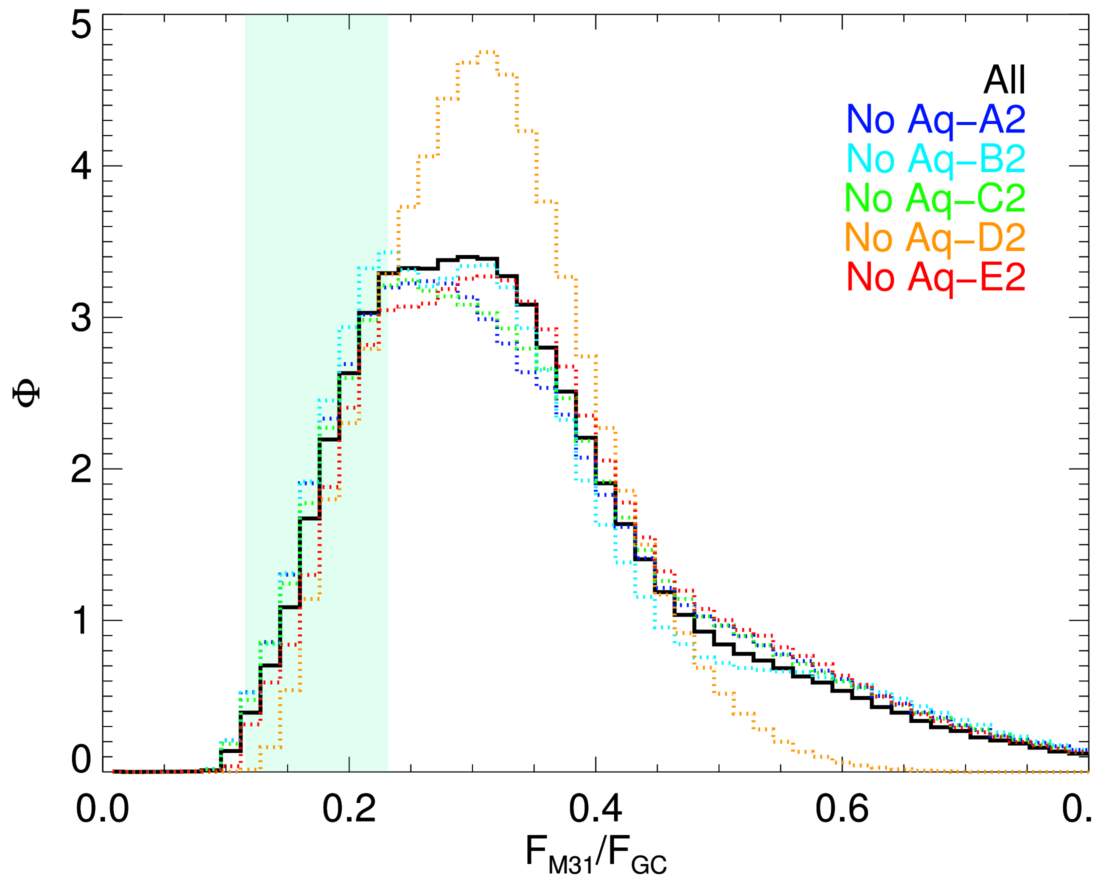
1411.0311
O.R. with Lovell, Bertone, et al.



- **Black lines**: Aq-A1 thick, Aq-A2 thin).
- Aq-B2: lightest of the Aquarius halos
- Aq-A1: observers are constrained to the plane normal to the minor axis vector

Ratio between the expected decay flux from the GC and 2σ upper bound from the Milky Way off-center based on the Aquarius halos

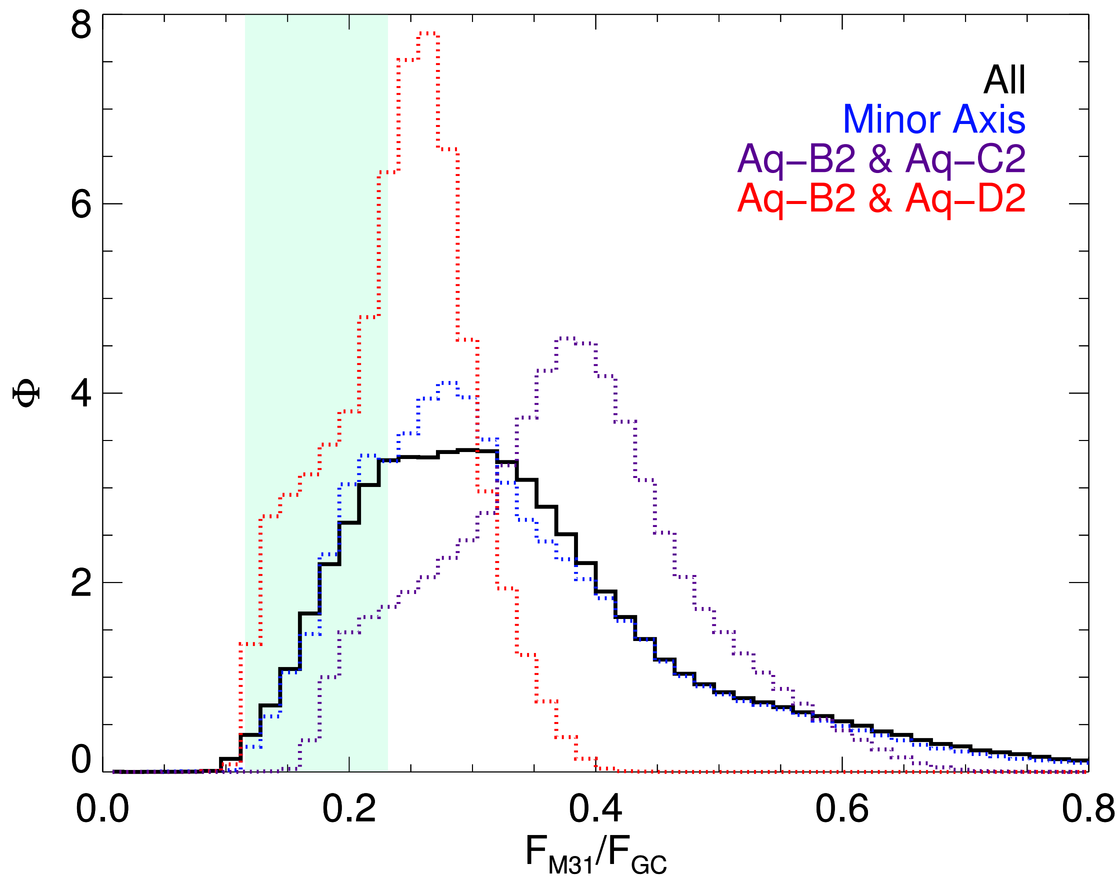
Milky Way vs. Andromeda



The probability distribution function for the M31/GC flux ratio.

Averaged over different choices of halo pairs and sightlines

Milky Way vs. Andromeda

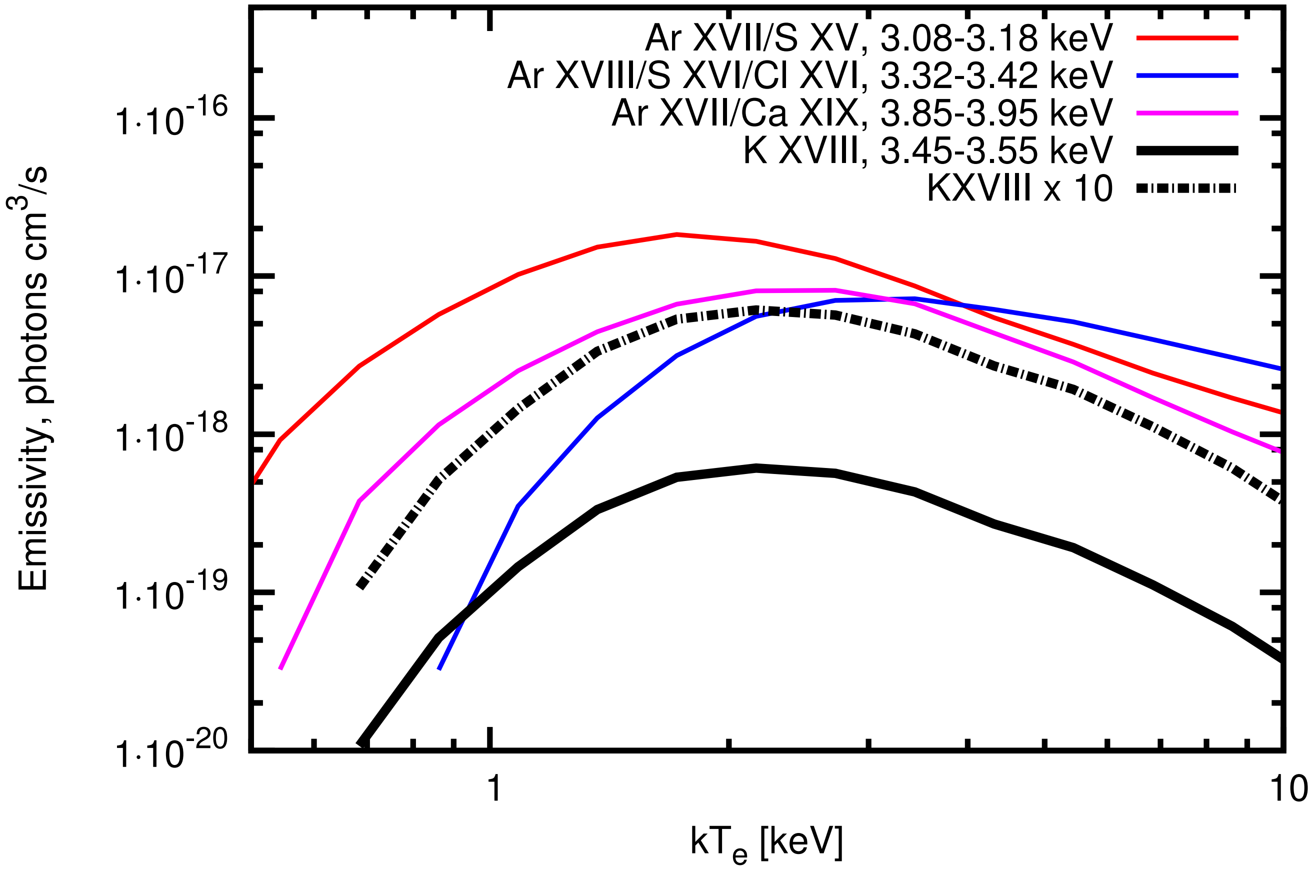


The probability distribution function for the M31/GC flux ratio

Averaged over different choices of sightlines

Line due to Potassium?

See "Comments" [1408.4388] [1409.4143]



- Interpretation of the GC line as **potassium** line (argued by S. Riemer-Sorensen [1405.7943]; T. Jeltema & S. Profumo [1408.1699])

Line due to Potassium?

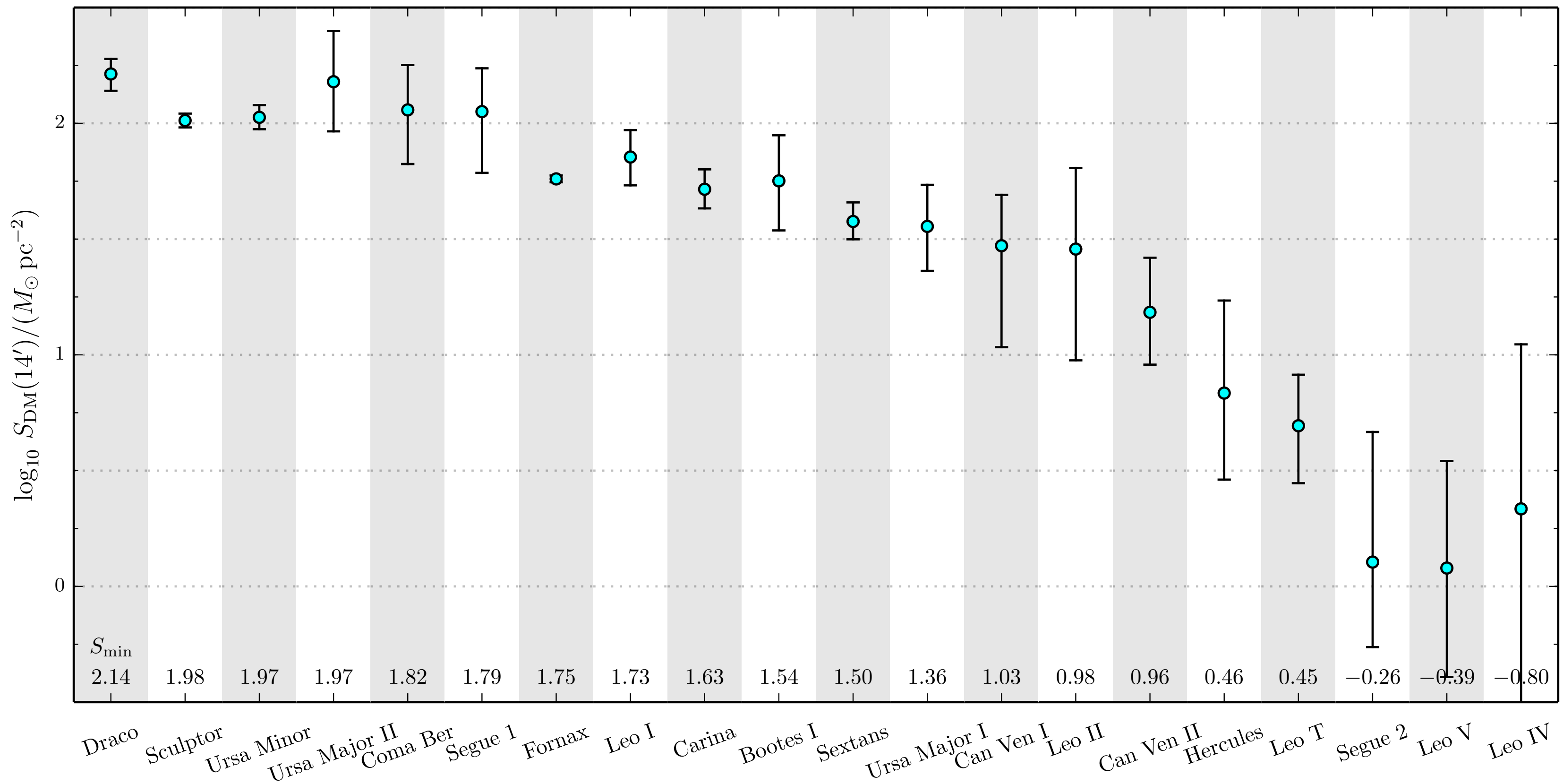
- Require some strongly supersolar abundance of potassium in the GC and strongly supersolar ratio of abundances of K to Ar, S, Ca

- Does not work as M31 explanation

- Does not work in the galaxy clusters (where potassium *is* taken into account in the `apec` plasma model)

- Dwarf spheroidal satellites of the Milky Way – best observational targets: nearby, dark, DM content most certain (PRL (2006))

Courtesy of M. Walker



Based on [1408.0002]

Stacked analysis of dwarf galaxies

Malyshev, Neronov, Eckert [1408.3531]

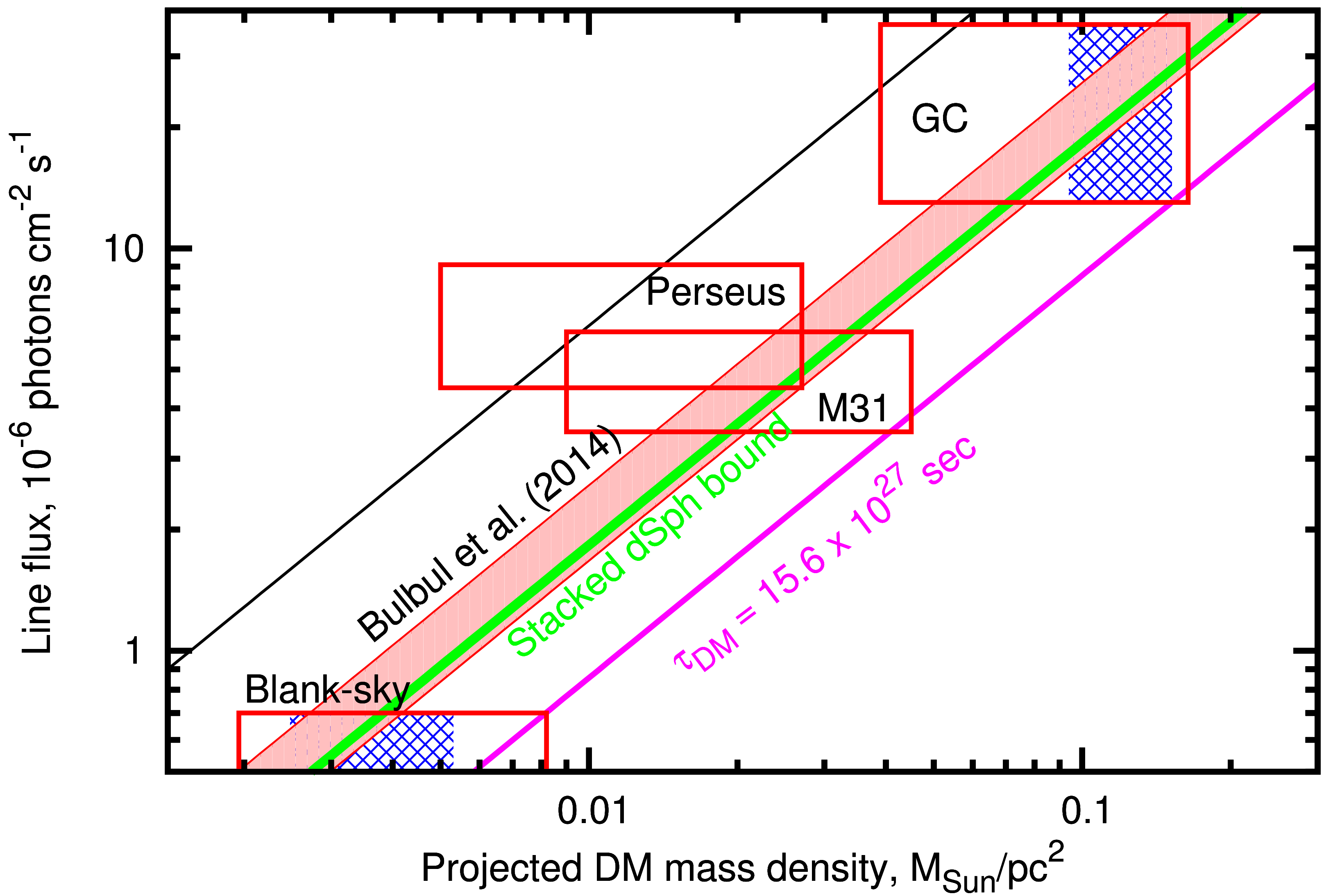
Obs Id	Name	Duration, ksec	Clean exposure, ksec
0200500201	Carina	41.9	19.2+16.7+8.4
0603190101	Draco	19.0	17.5+17.9+14.3
0603190201	Draco	19.9	18.5+18.2+14.7
0603190301	Draco	17.7	12.2+12.6+6.3
0603190501	Draco	19.9	18.6+18.5+14.9
0302500101	Fornax	103.9	65.1+65.9+53.0
0555870201	Leo	94.0	75.4+77.1+0
0652210101	NGC 185	123.5	91.4+96.2+66.7
0650180201	UMa II	34.3	11.7+12.5+7.4
0301690401	UMi	11.8	10.8+10.9+7.9
0652810101	Willman	29.3	15.0+19.0+9.5
0652810301	Willman	36.0	21.9+23.2+15.5
0652810401	Willman	36.2	27.5+28.5+16.2
TOTAL		602.3	404.8+417.2+232.8

TABLE III: XMM-Newton observations of dwarf spheroidals considered in this analysis. The total exposure time is given as the sum of effective exposures for the MOS1, MOS2 and pn cameras individually. The total clean exposure is ~ 0.6 Msec

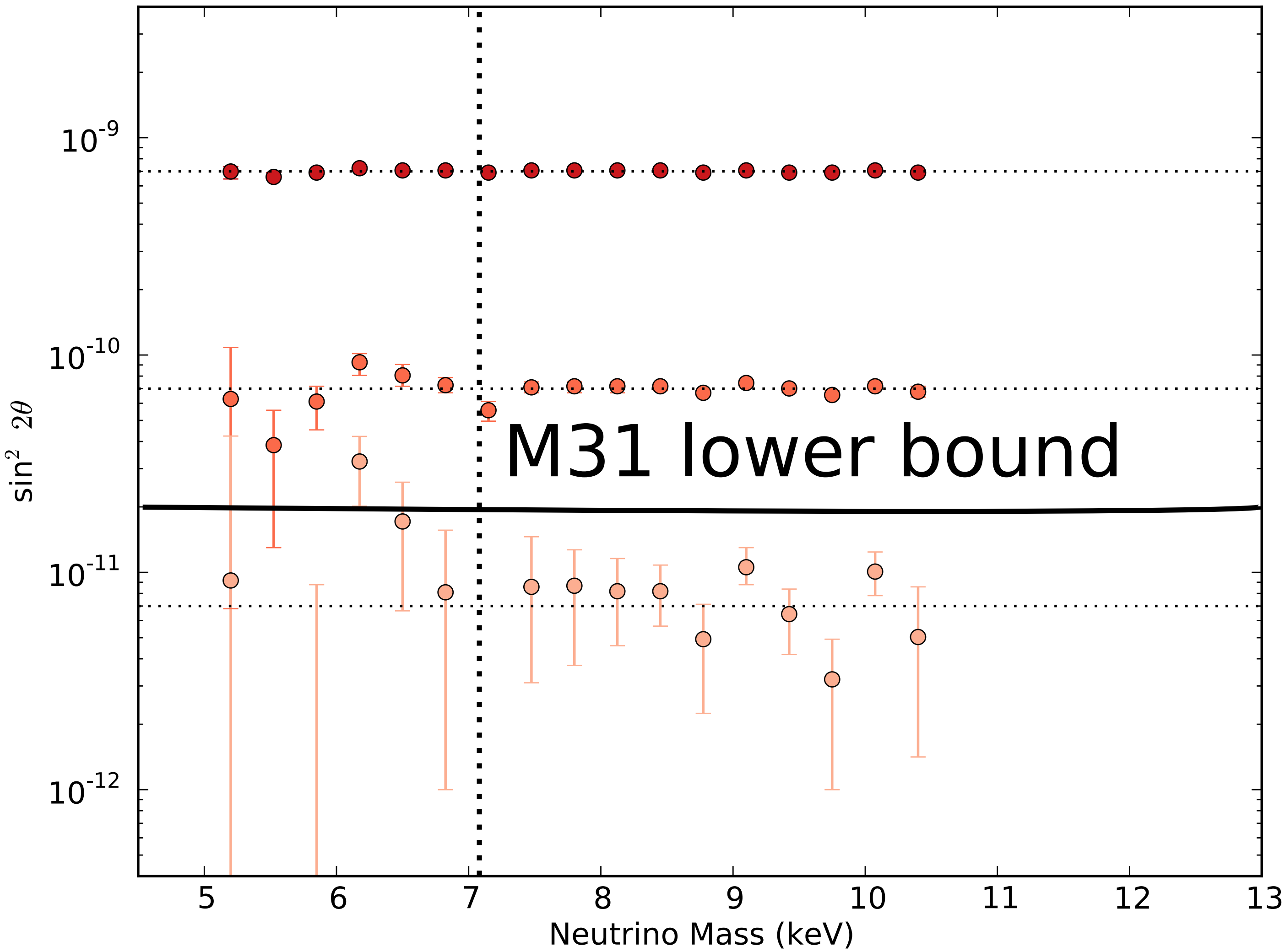
lifetime $> 7 \times 10^{27}$ seconds

Is there a contradiction between non-observation of a signal from the stacked dwarves and observation form galaxy/galaxy cluster?

Dwarfs vs. spiral galaxies



Outskirts of stacked galaxies



From Anderson et al. [1408.4115]

Other telescopes

- Perseus cluster has been extensively studied with *Suzaku*
- Two recent paper tried to check the claim with *Suzaku*
- **[1411.0050]** (Urban et al) – We detect the line from the center of Perseus cluster in Suzaku data. It is **too strong** to be consistent with non-observation from other clusters (e.g. Coma)
- **[1412.1869]** (Tamura et al.) – We **do not detect** the line from the center of Perseus cluster in Suzaku data. Second paper does not cite or comment on the first one

$\Rightarrow$ *Suzaku* – work in progress

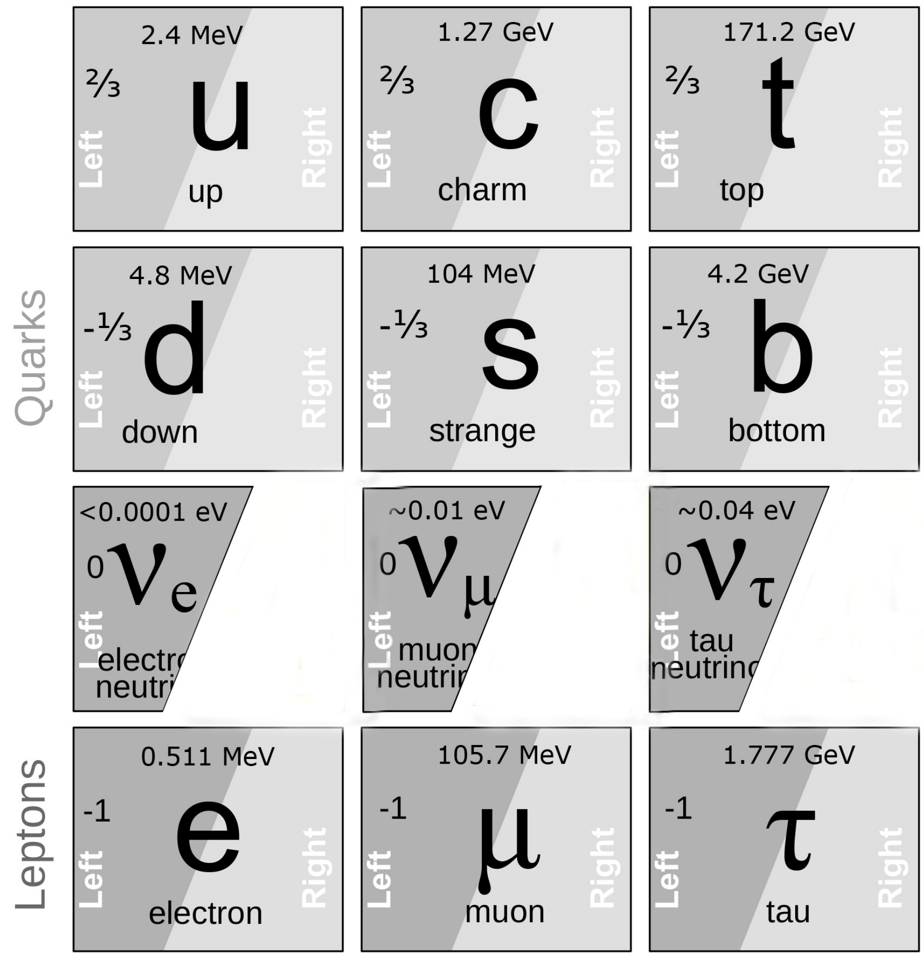
Implications if this is
“decaying dark matter line”

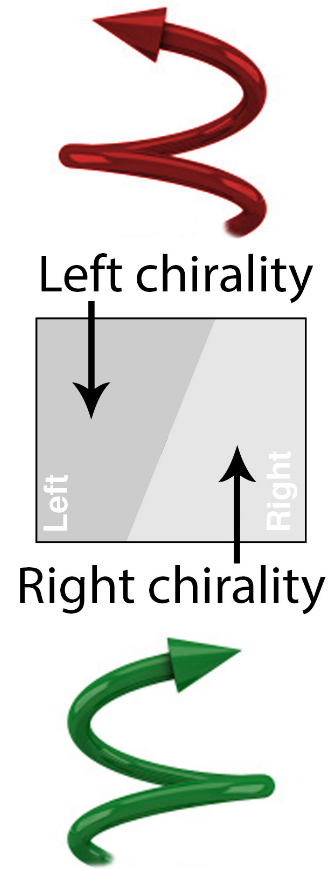
This can be anything

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. **FImP** Miracle of Sterile Neutrino Dark Matter by Scale Invariance. **Non-abelian Dark Matter** Solutions for Galactic Gamma-ray Excess and Perseus 3.5 keV X-ray Line. 3.5 keV X-ray Line Signal from Dark Matter Decay in **Local** $U(1)_{B-L}$ **Extension of Zee-Babu Model**. **SIMPle** Dark Matter: Self-Interactions and keV Lines. Exploring X-Ray Lines as **Scotogenic** Signals. **Hidden axion dark matter** decaying through mixing with QCD axion . . .

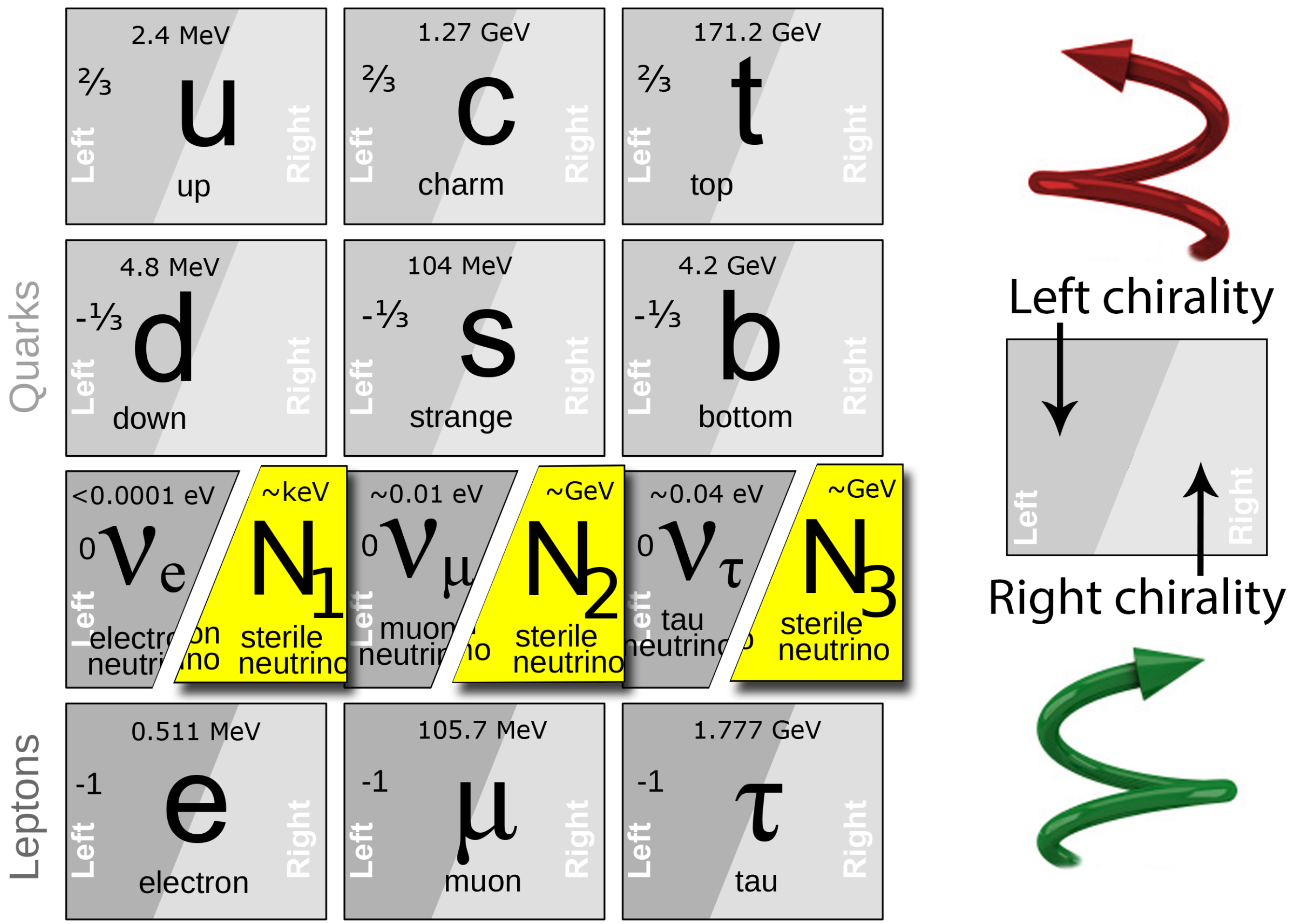
Sterile neutrino dark matter

Oscillations ⇒ new particles!

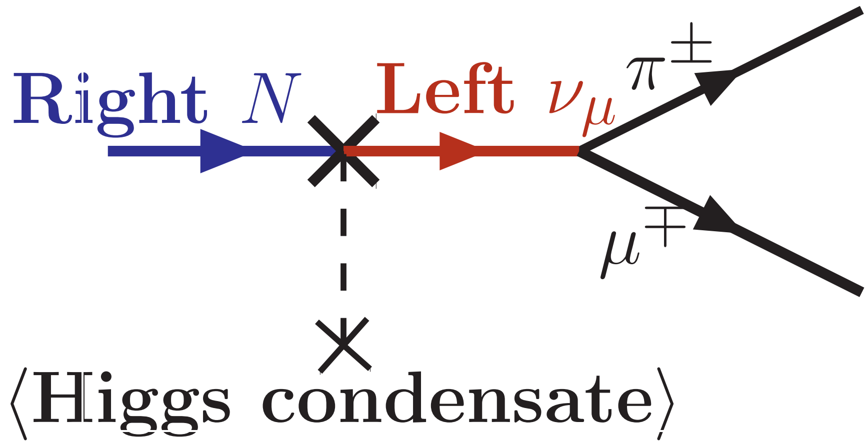


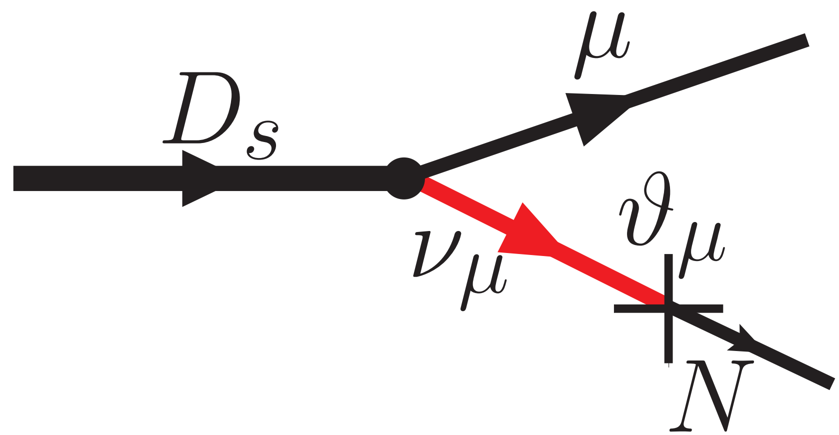


Oscillations ⇒ new particles!



Right components of neutrinos?!



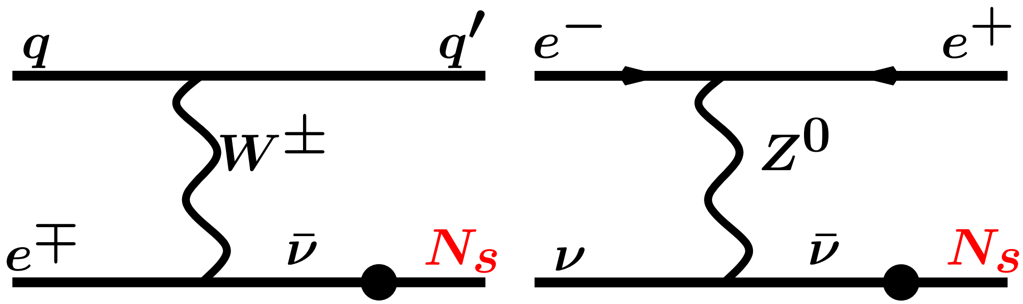


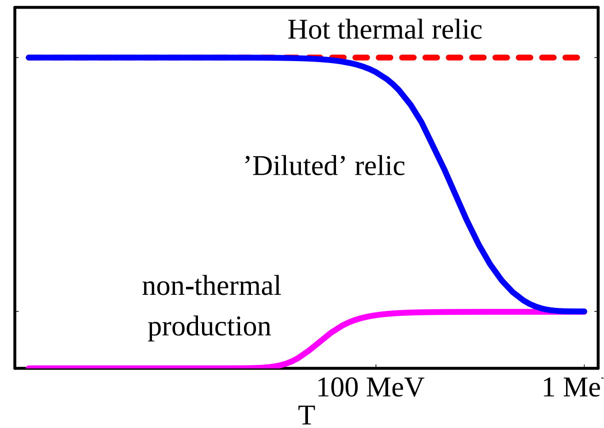
Sterile neutrinos behave as **superweakly interacting** massive neutrinos with a smaller Fermi constant $\boxed{\vartheta \times G_F}$

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

$$\vartheta^2_{e,\mu,\tau} \equiv \frac{|M_{\text{Dirac}}|^2}{M^2_{\text{Majorana}}} = \frac{\mathcal{M}_{\text{active}}}{M_{\text{sterile}}} \approx 5 \times 10^{-11} \left(\frac{1\text{ GeV}}{M_{\text{sterile}}}\right)$$

Production through mixing with neutrinos

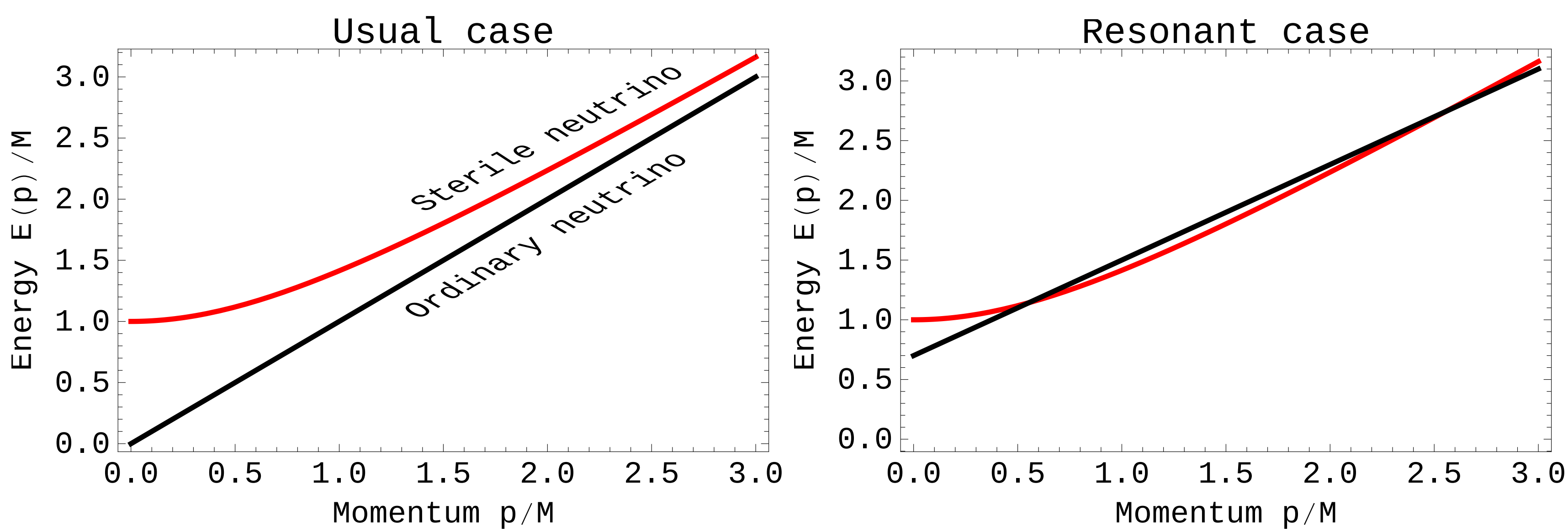


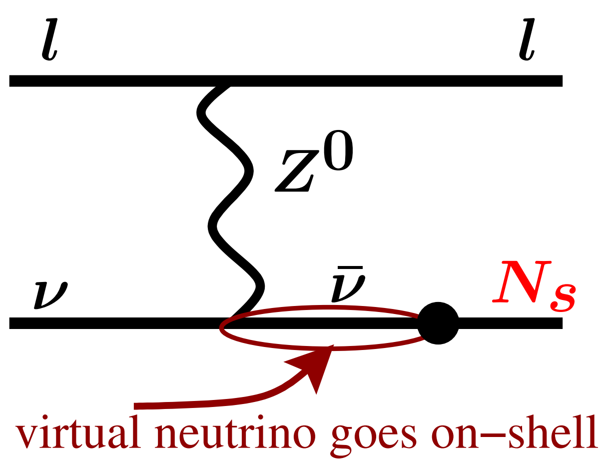


- Once every $\sim 10^8 \div 10^{10}$ scatterings a sterile neutrino is created instead of the active one
- Its abundance **slowly builds up** but **never reaches the equilibrium** value
- The distribution of sterile neutrinos $f(p) \approx \frac{\theta^2}{e^{p/T_\nu}+1}$

Dodelson & Widrow'93; Dolgov & Hansen'00

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)

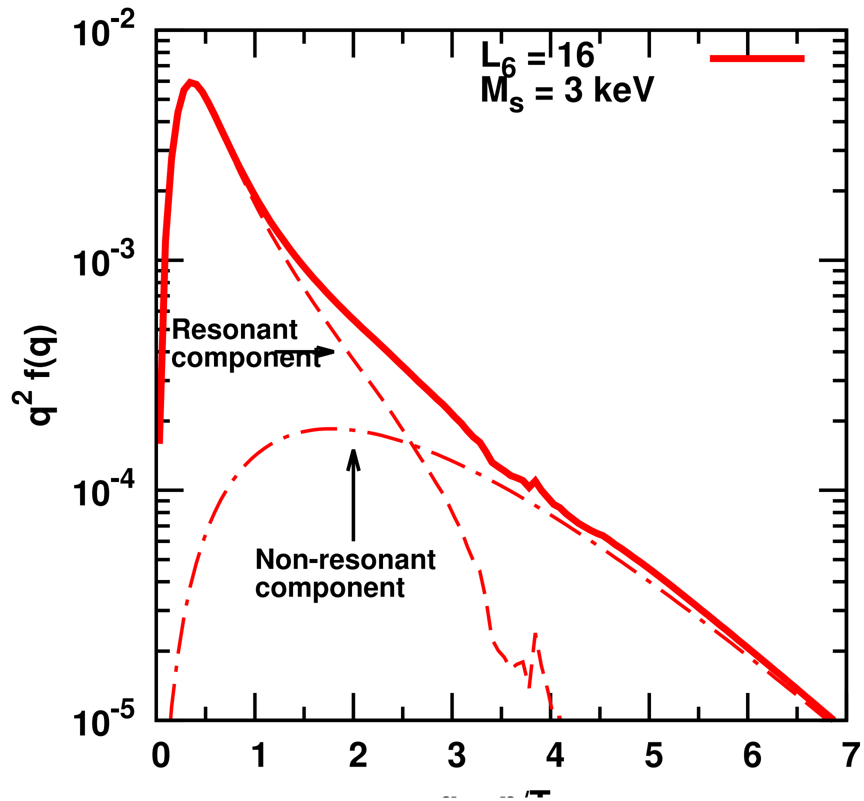
Shi & Fuller [astro-ph/9810076]

Laine & Shaposhnikov [0804.4543]

Resonant enhancement

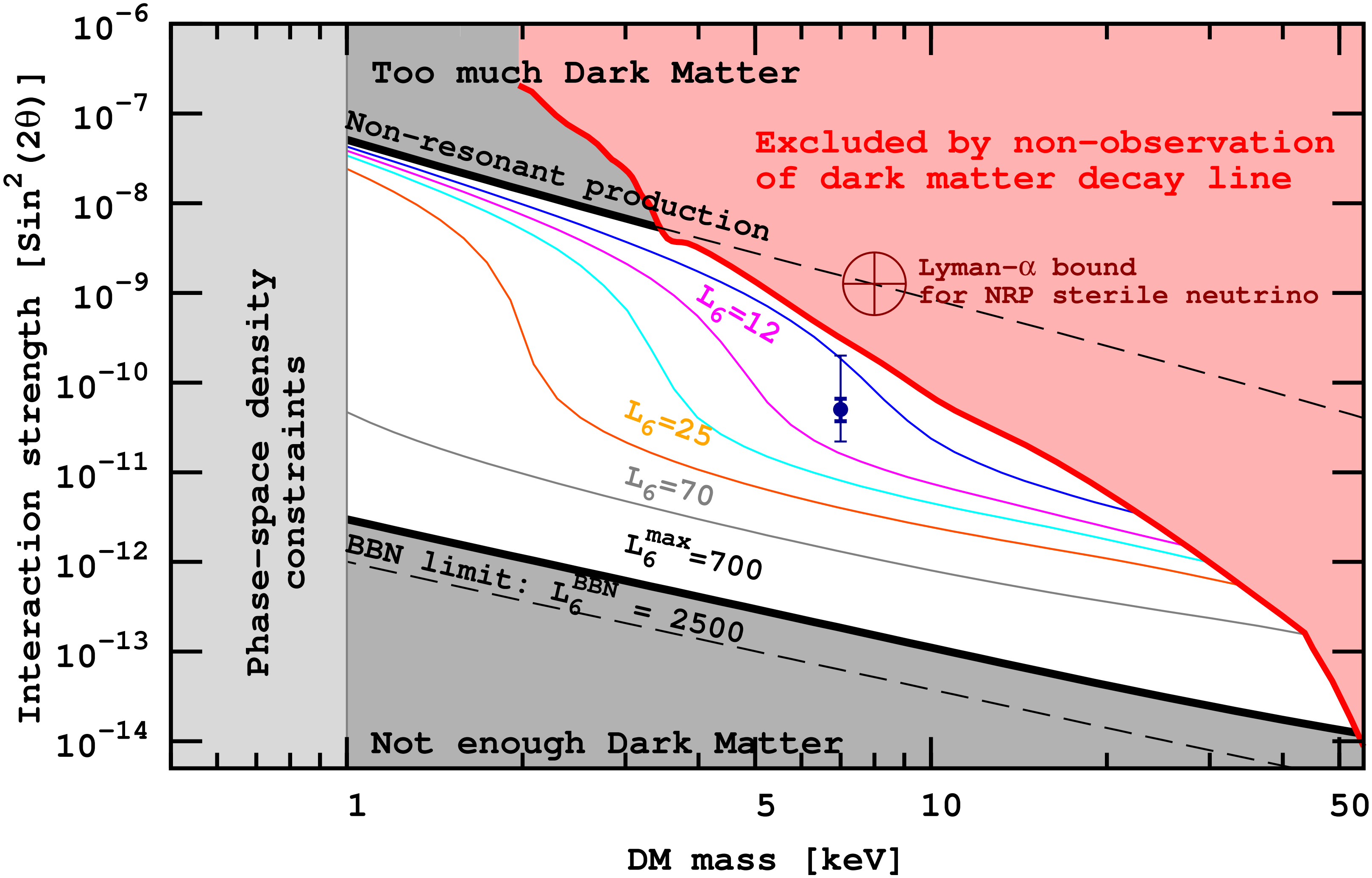
- In the presence of **large lepton asymmetry** the **MSW resonance** can take place and production of sterile neutrinos becomes much more effective

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

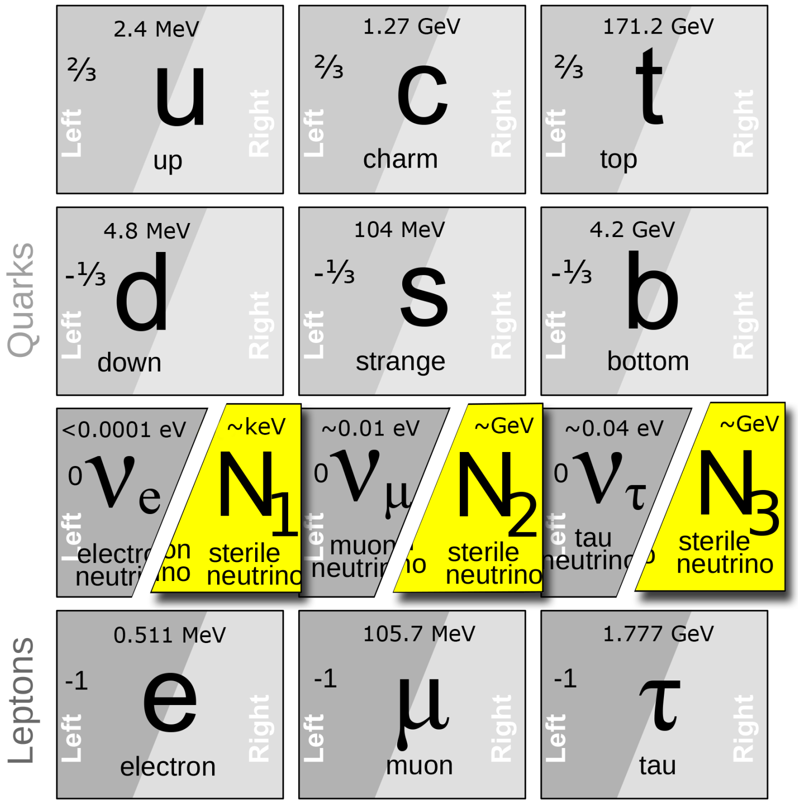


- For sterile neutrinos $p \gg M$ at production

Sterile neutrino and 3.5 keV line



Dark matter and neutrino oscillations



– **Atmospheric** and **Solar** neutrino mass splitting ⇒ need (at least) two sterile neutrino

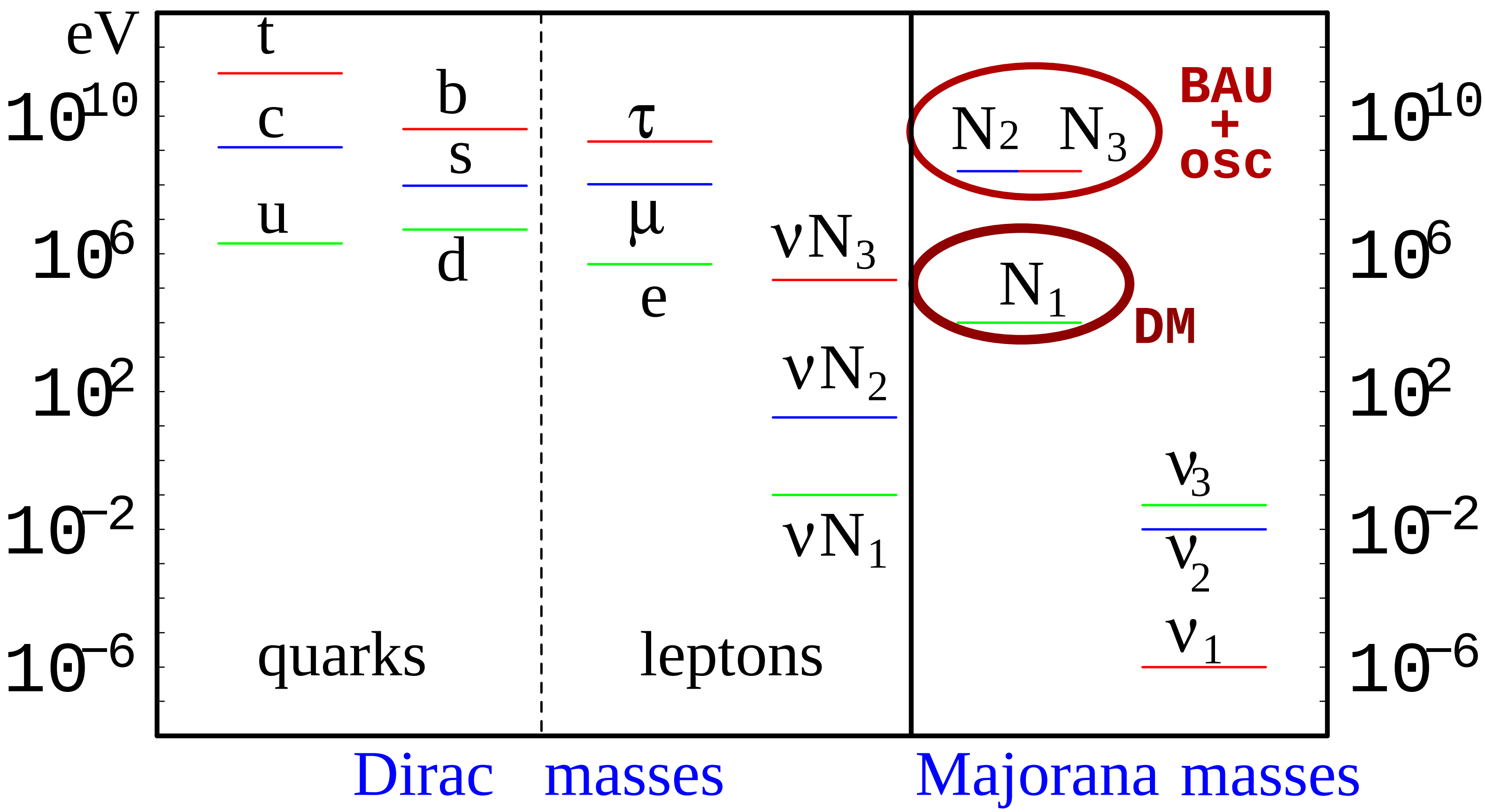
– Are they Dark matter? ⇒ No way! Very short lifetime

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

Shaposhnikov'08
Laine & Shaposhnikov'08
Canetti et al.'10–'12

Sterile neutrino is a viable dark matter candidate in a model with **at least** two other sterile neutrinos

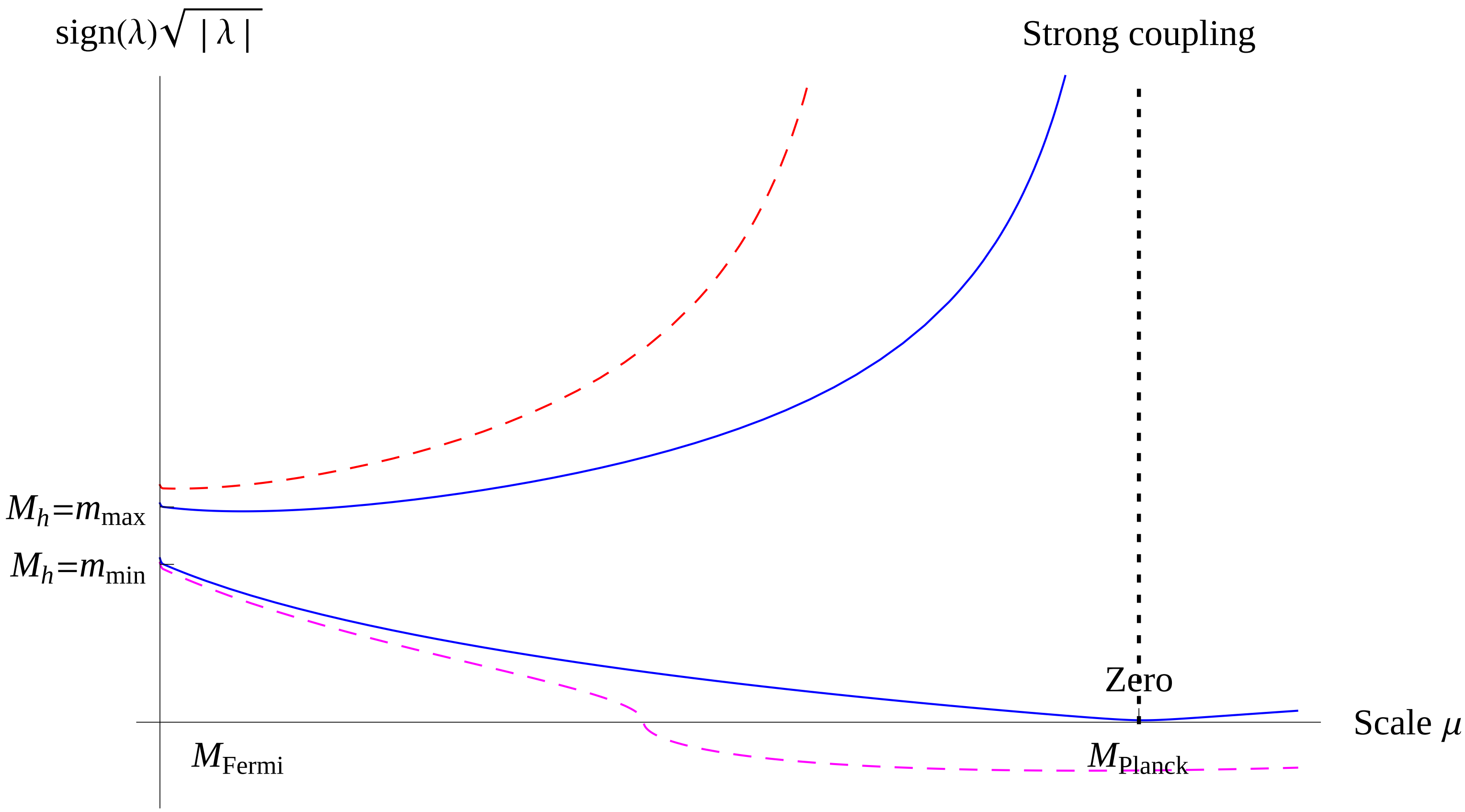
Neutrino Minimal Standard Model (νMSM)



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]

Complete. Closed. Self-consistent theory



Bezrukov et al
[1205.2893]

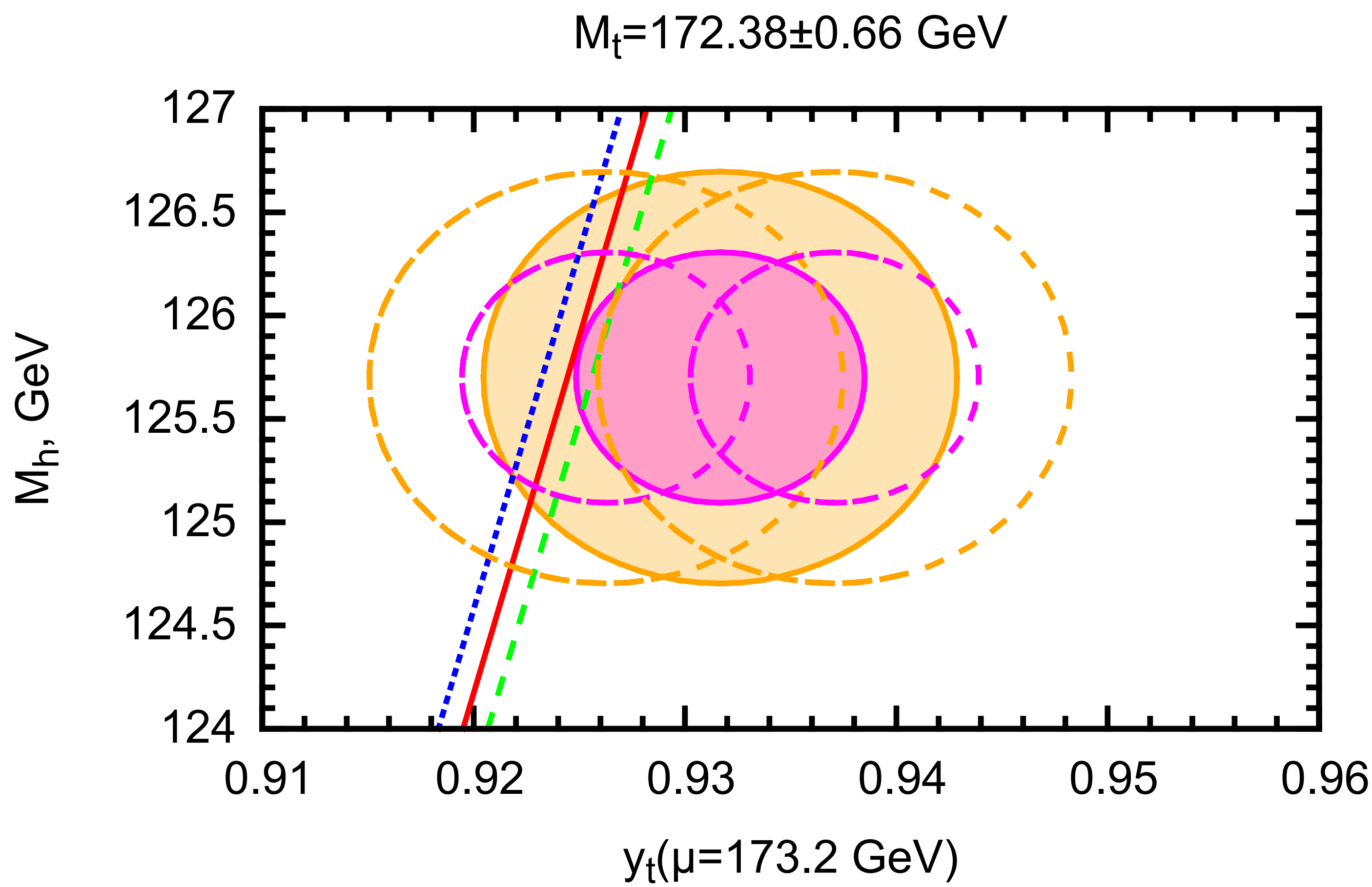
Degrassi et al.
[1205.6497]

Buttazzo et al.
[1307.3536]

Mass of the Higgs boson ~ 126 GeV means that the νMSM is a consistent weakly-coupled theory up to very high scales (probably to the Planck scale)

SM valid up to the Planck scale?

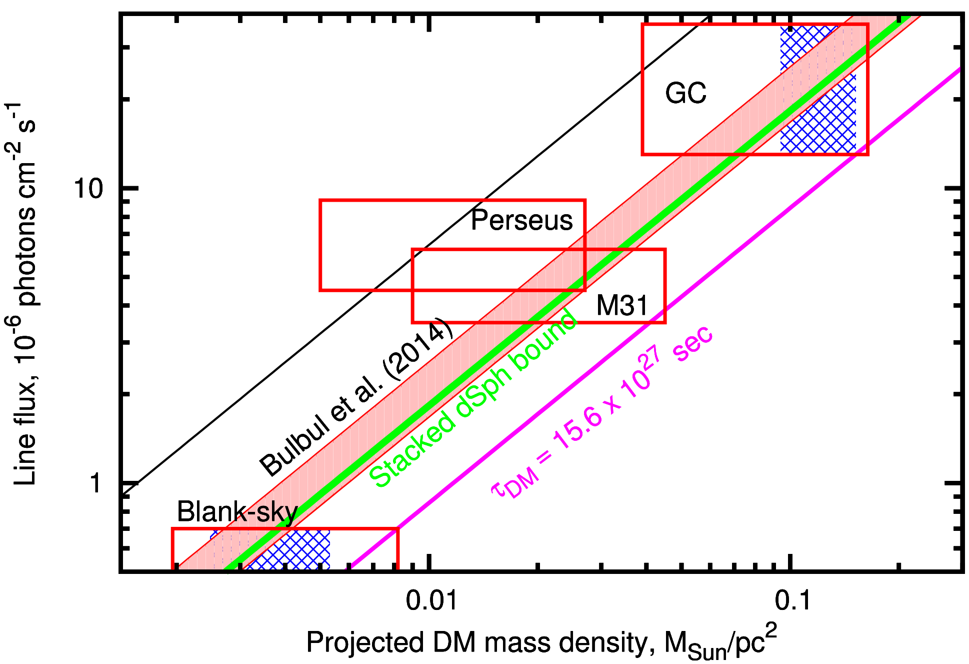
Bezrukov & Shaposnikov [1411.1923]



”It is expected that the difference between the MC mass definition and the formal pole mass of the top quark is up to the order of 1 GeV” **[1403.4427]**

What's next?

Dedicated observation of Draco dwarf

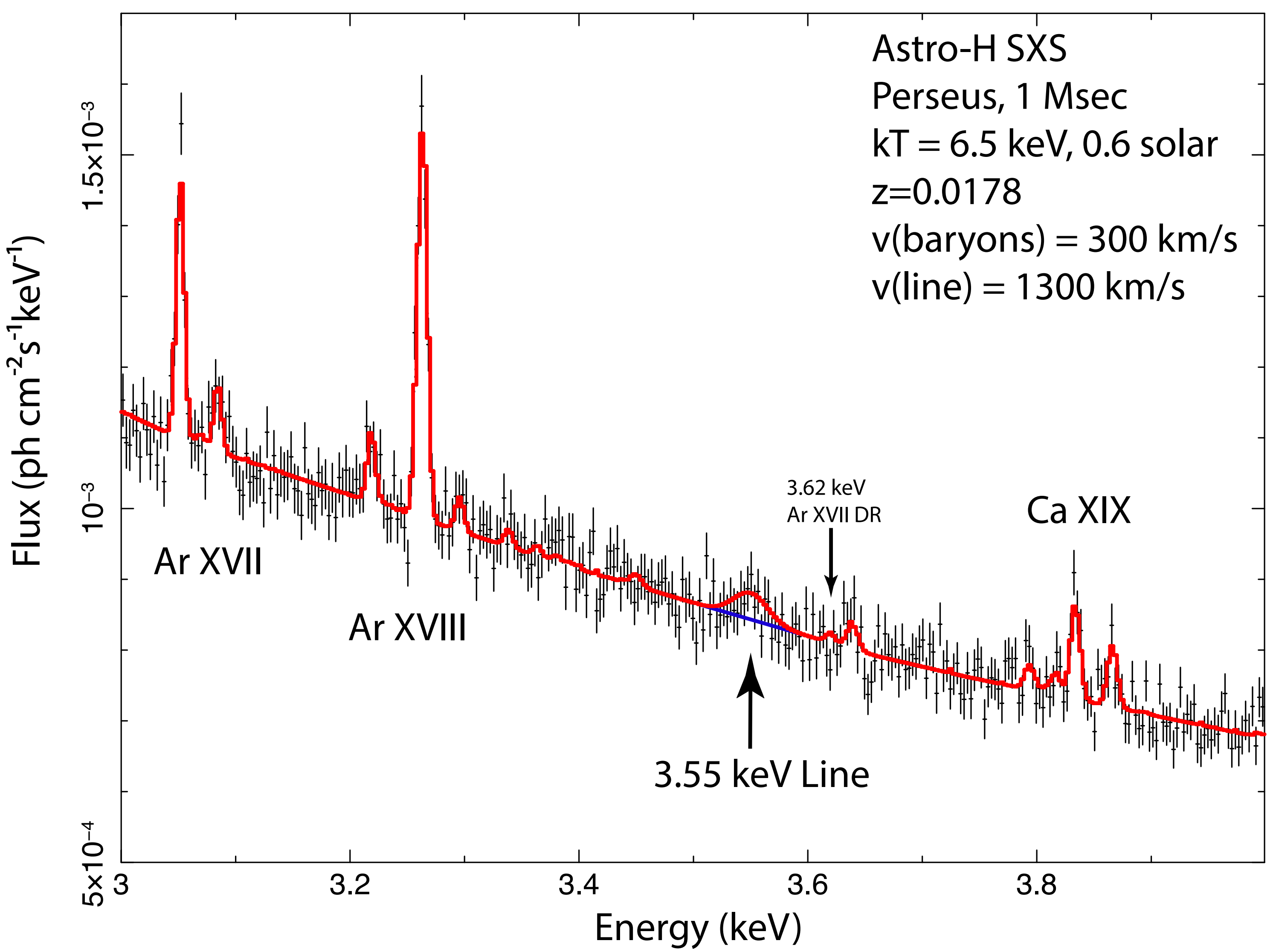


- XMM-Newton's time allocation committee has just granted us 1.4 Mega-seconds (PI: A. Boyarsky)
- This is 10% of the XMM's annual observational budget!

. . . the panel recognised that a detection of the 3.5 keV line in Draco would be a spectacular discovery. Even the non-detection represents an important result since it will rule out the dark matter origin of the 3.5 keV line detected by several teams earlier this year. Overall, the panel felt that this observation can and will trigger a lot of discussion on this topic. . .

Astro-H: better spectral resolution

ApJ (2014) [1402.2301]



Decaying dark matter with Astro-H

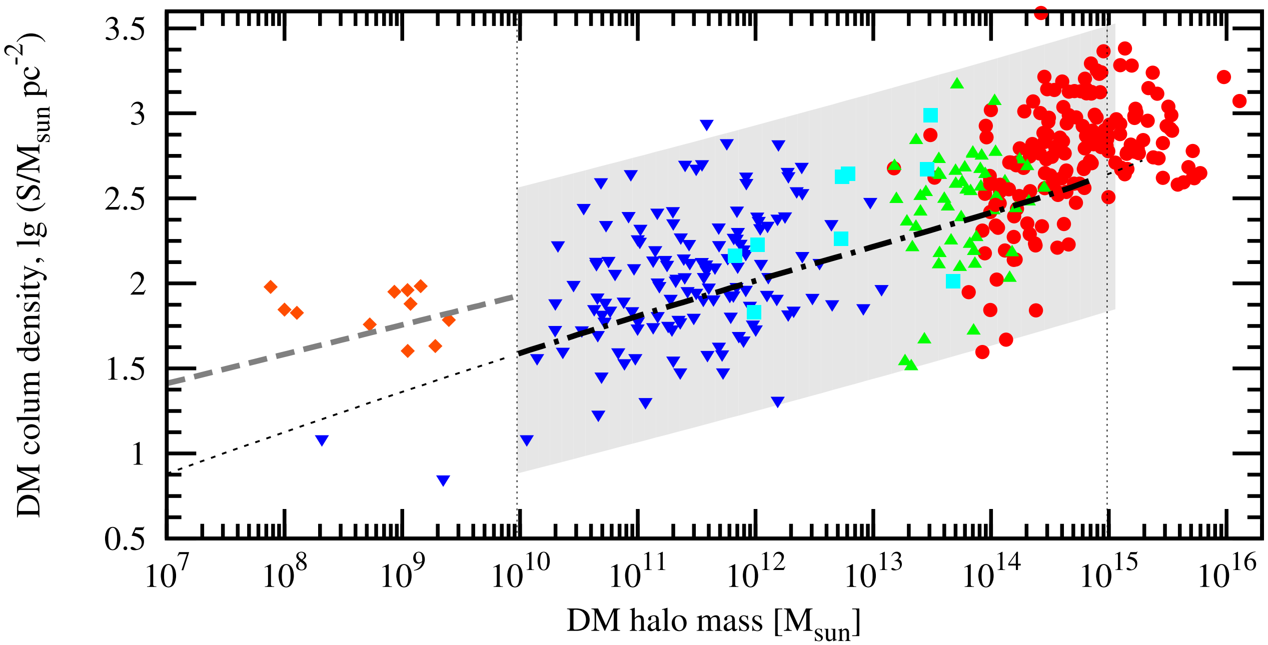
9 A Spectroscopic Search for Dark Matter

Overview

X-ray spectroscopic observations provide a unique probe of direct signatures of dark matter, such as a decay line of a hypothetical sterile neutrino in the $\sim$ keV mass range. In the event that any candidate emission line is detected in the $1-10$ keV energy band, *ASTRO-H* SXS will offer the first opportunity to resolve its shape and distinguish it from plasma lines and instrumental effects. The significance of dark matter identification will be improved crucially if the line is detected from multiple sources with distinguishable differences in redshifts and velocity dispersions. Plausible targets include nearby galaxy clusters, the Milky Way Galaxy, and dwarf spheroidal galaxies, many of which will be observed by SXS for other purposes. [16]

Clusters of Galaxies and Related Science **[1412.1176]**

More objects



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

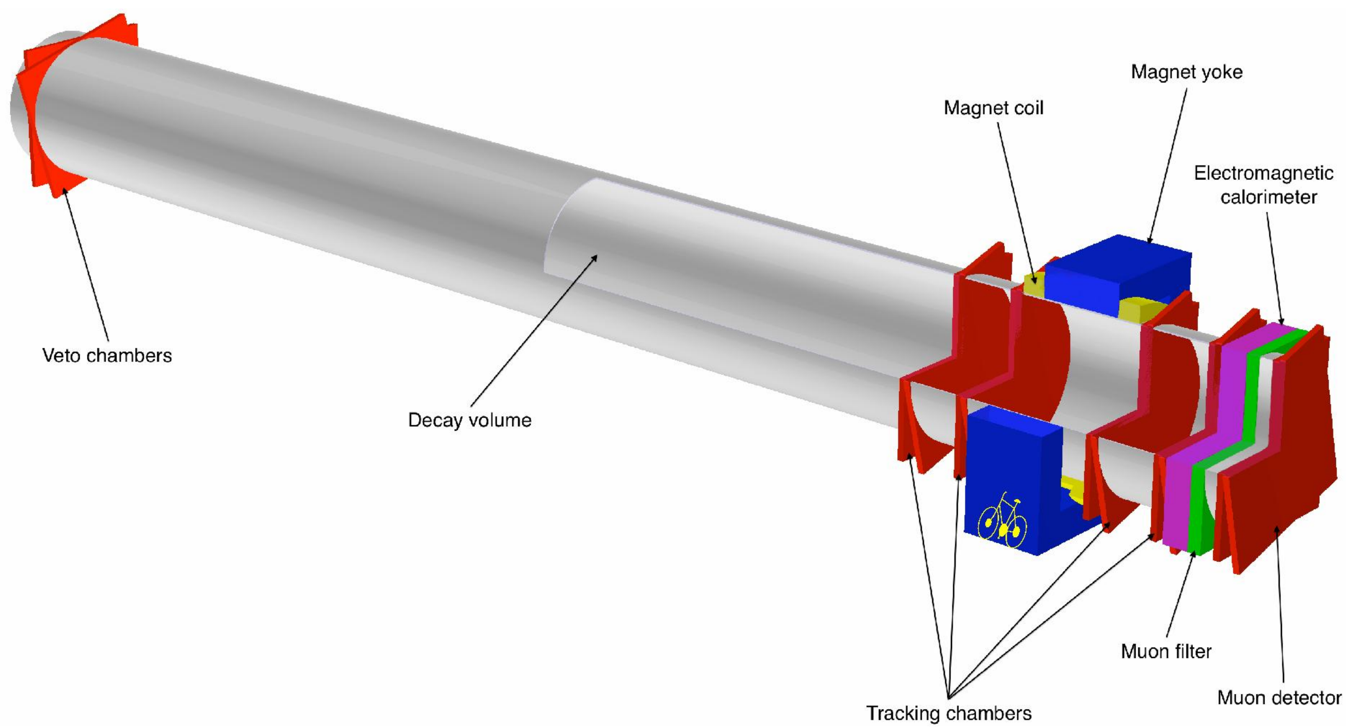
A dedicated experiment

[1310.176]

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



SHiP
Search for HIdden Particles

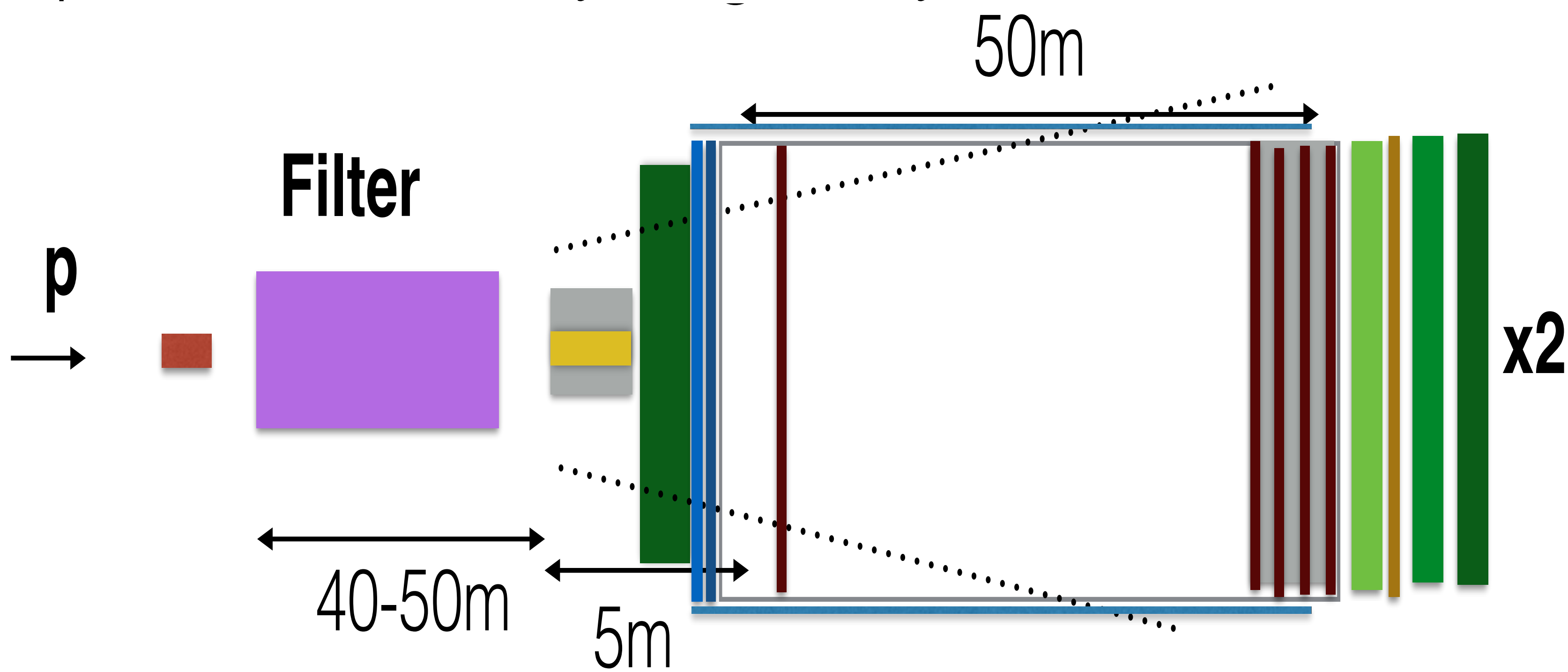
Beam dump experiment at CERN SPS

[1310.176]

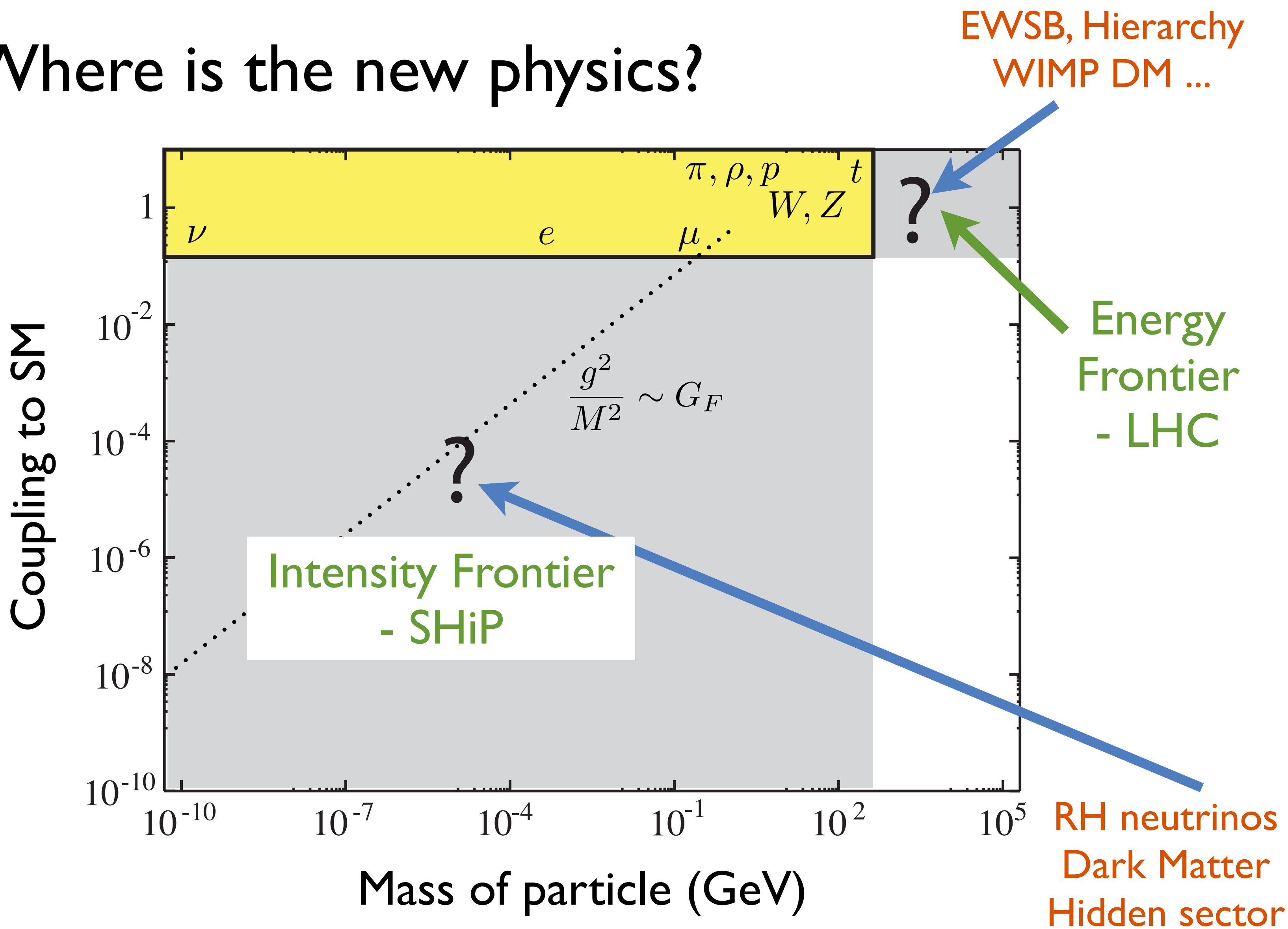
– Take the highest Energy/Intensity proton beam of the world . . .

– . . . dump it into a target . . .

– . . . followed by the closest, longest and widest possible and technically feasible decay tunnel!



Where is the new physics?



Conclusion

- An unidentified spectral line was detected in the spectra of galaxies and galaxy clusters

- Can be astrophysical: impossible to exclude with the spectral resolution of XMM or Chandra. Although would require some anomalously high abundances of elements, different for the Milky Way and Andromeda

- Possesses spatial profile **consistent** with dark matter hypothesis

- Not seen in the outskirts of spiral galaxies (M31, Milky Way, stacks of galaxies) or in the stack of dwarf galaxies $\Rightarrow$ this creates tension for DM interpretation but not exclusion yet

- A dedicated deep observation of a dwarf galaxy (Draco!) should settle the interpretation of the signal as monochromatically decaying DM line

Thank you for your attention!