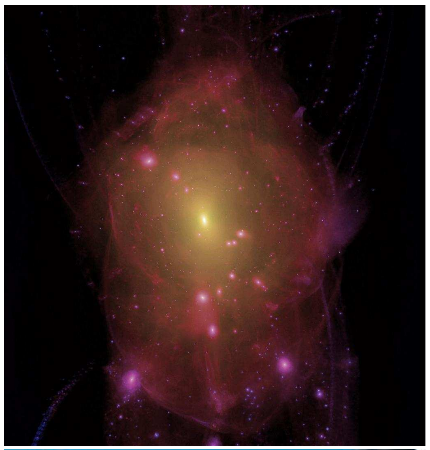
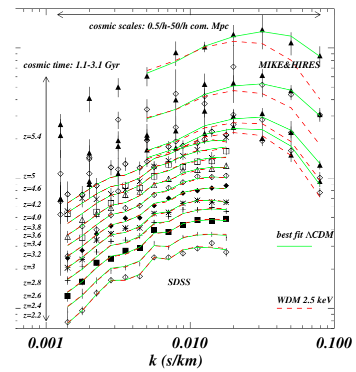
HNLs AND DARK MATTER

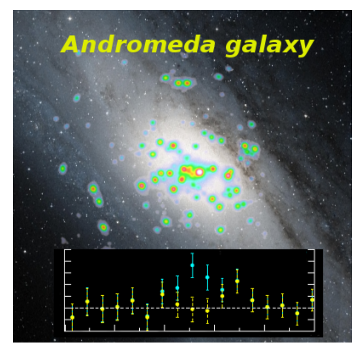
Alexey Boyarsky



Universiteit Leiden



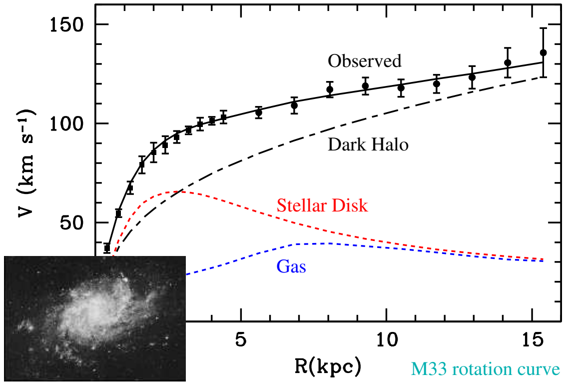
SHiP
Search for Hidden Particles

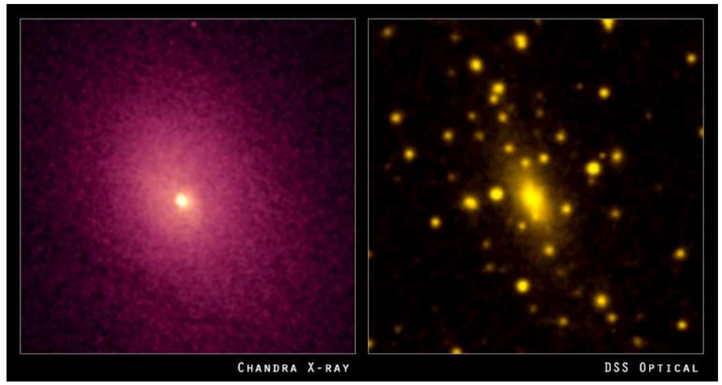


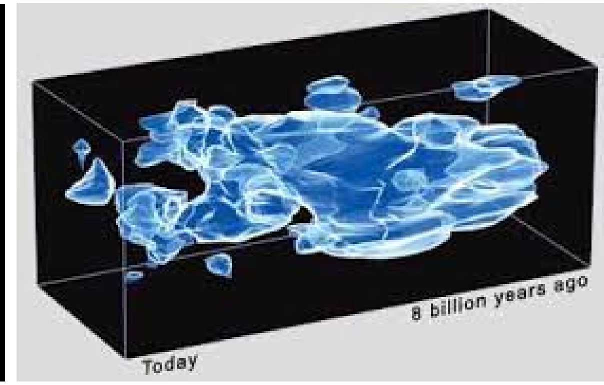
6[th] SHiP collaboration meeting

October 10, 2015

Massive neutral particles fill the Universe



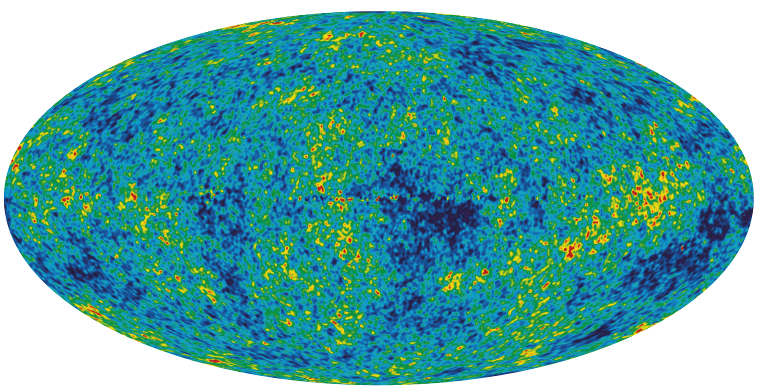




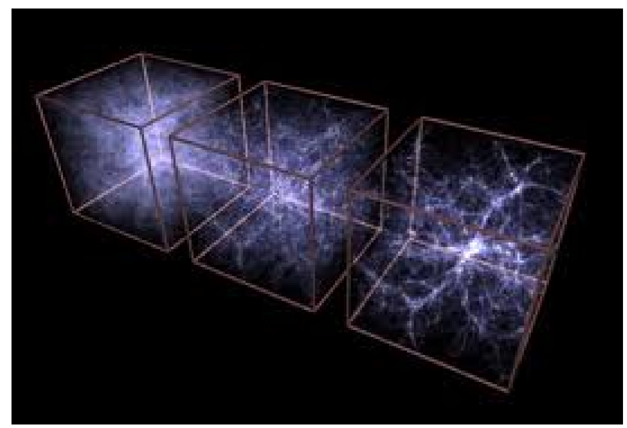
Expected: $v(R) \propto \frac{1}{\sqrt{R}}$
Observed: $v(R) \approx \text{const}$

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

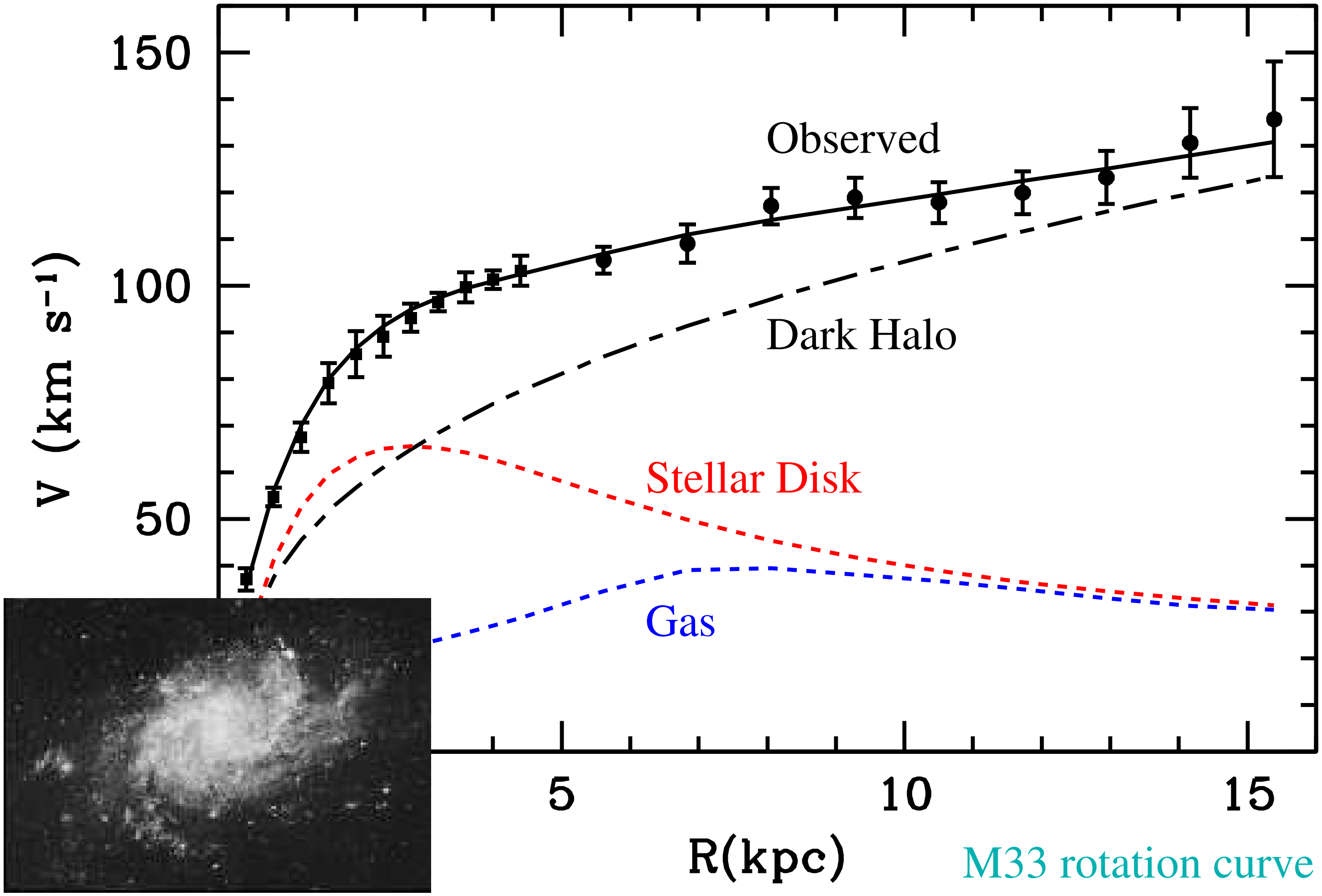
Lensing signal (direct mass measurement) **confirms** other observations



Jeans instability turned tiny density fluctuations into all visible structures



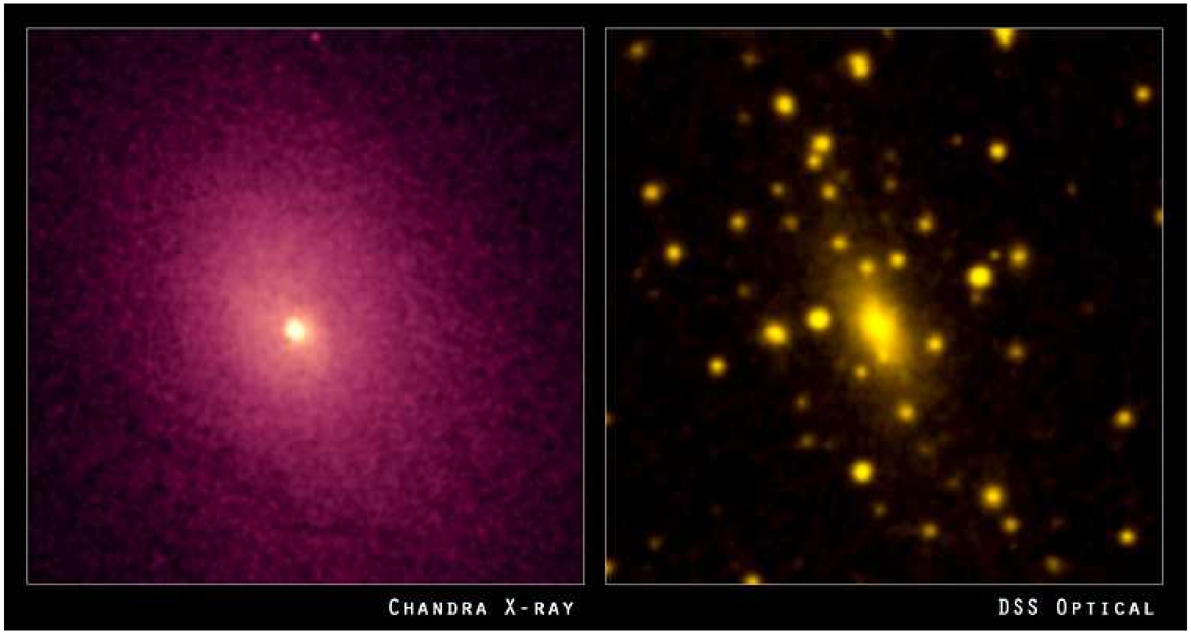
Rotation curves of spiral galaxies



[Back to DM](#)

Newton dynamics: $\mathrm{V}(R) \sim \frac{1}{\sqrt{R}}$

Intracluster gas



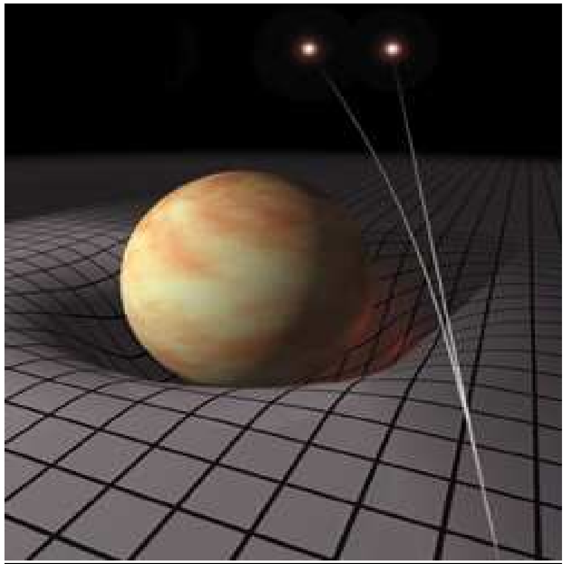
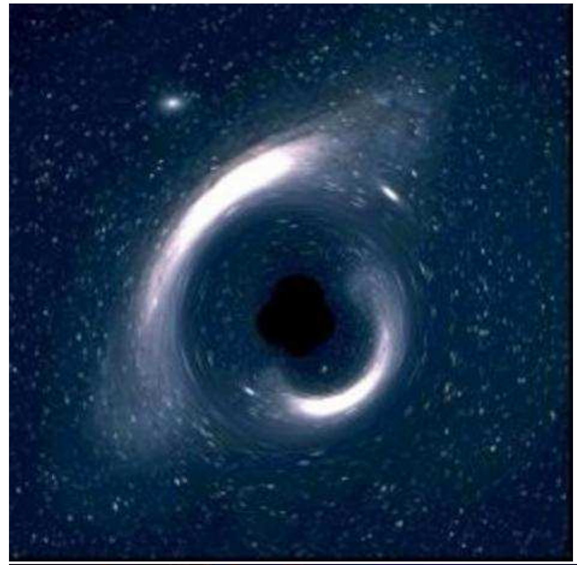
Cluster Abell 2029. **Credit: X-ray: NASA/CXC/UCI/A.Lewis et al. Optical: Pal.Obs. DSS**

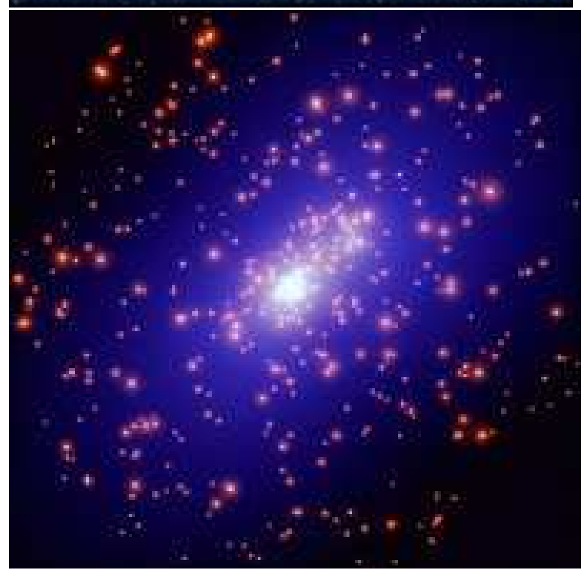
Dark Matter	$\sim 85\%$
Intracluster gas	$\sim 15\%$
Galaxies	$\sim 1\%$

$$\frac{\text{DM in cluster}}{\text{Baryons in cluster}} \approx \frac{\Omega_{\text{DM}}}{\Omega_{\text{baryons}}}$$

Temperature of the intra-cluster gas: $1 - 10$ keV $\sim 10^7 - 10^8$ K

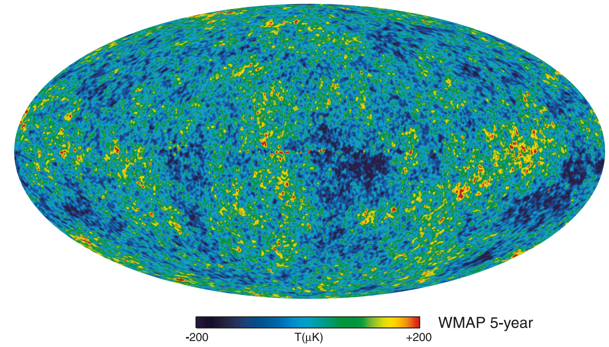
Gravitational lensing

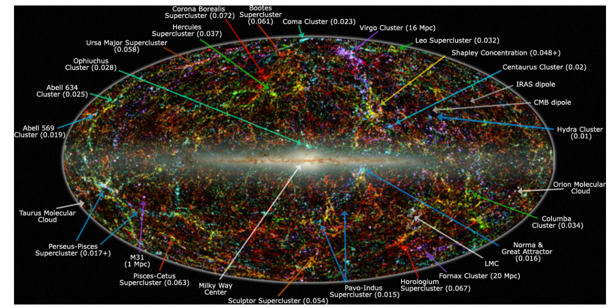



Cosmological evidence for dark matter

- We see the structures in the Universe when it was only **380 000** years old (encoded in the anisotropies of the temperature of the cosmic microwave background)



- All the today's structures are produced from tiny density fluctuations due to gravitational Jeans instability



- At CMB $\delta\rho/\rho \sim 10^{-5}$, then grow $\delta\rho/\rho \sim a$ (matter domination)
- $\frac{a_{today}}{a_{dec}} = 1 + z_{dec} \sim 10^3$ **Not enough!**

Some matter-like substance decoupled from photon gas should have been present in the Universe at the time of decoupling

Is this 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:

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

Our paper [0808.3902]

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

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

Is this 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

Today this is confirmed by CMB, LSS and neutrino experimental data

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 generalizations of neutrino DM:

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

Two classes of alternatives:

Light yet **super-weakly** interacting

– **Can be light** (down to Tremaine-Gunn bound)

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

– **Can be decaying** (stability is not required)

Heavy and therefore weakly interacting — **WIMP**

I shall not speak about it

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

$$E_\gamma = \frac{1}{2} m_{\text{DM}} c^2$$

- 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 $\sim 1500\,\mathrm{km/sec}$

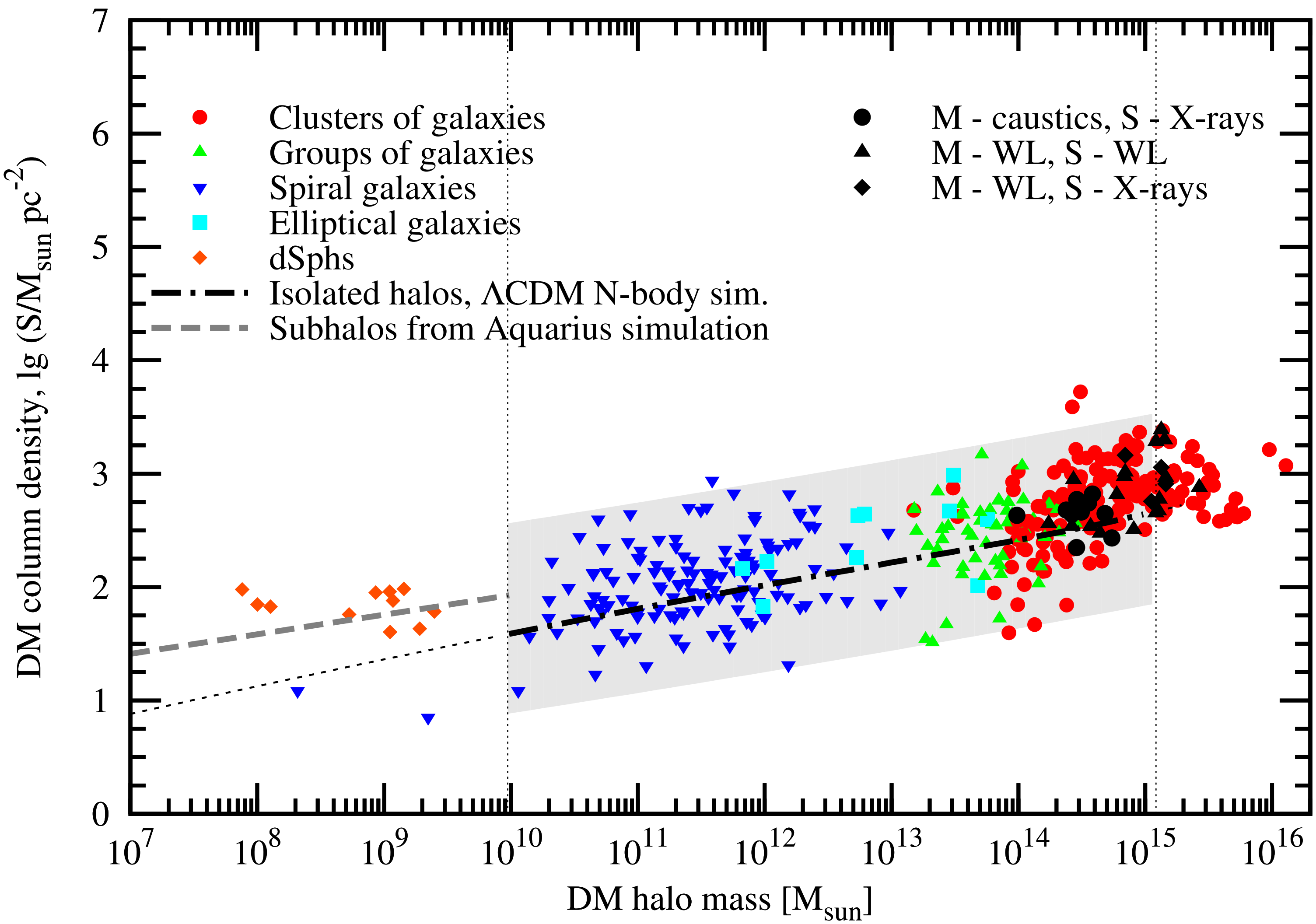
- Very characteristic signal: narrow line in all DM-dominated objects with $\dfrac{\Delta E}{E_\gamma} \sim \dfrac{v_{\text{vir}}}{c} \sim 10^{-4} \div 10^{-2}$

Signal from different DM-dominated objects

Boyarsky et al PRL'06

Boyarsky, Neronov, Ruchayskiy, Tkachev PRL'09

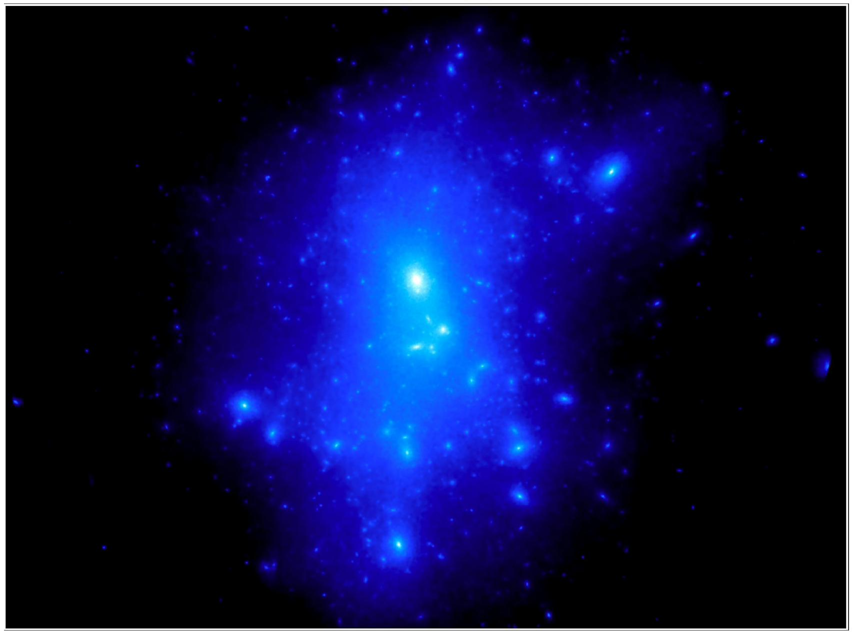
Decay signal is proportional to this

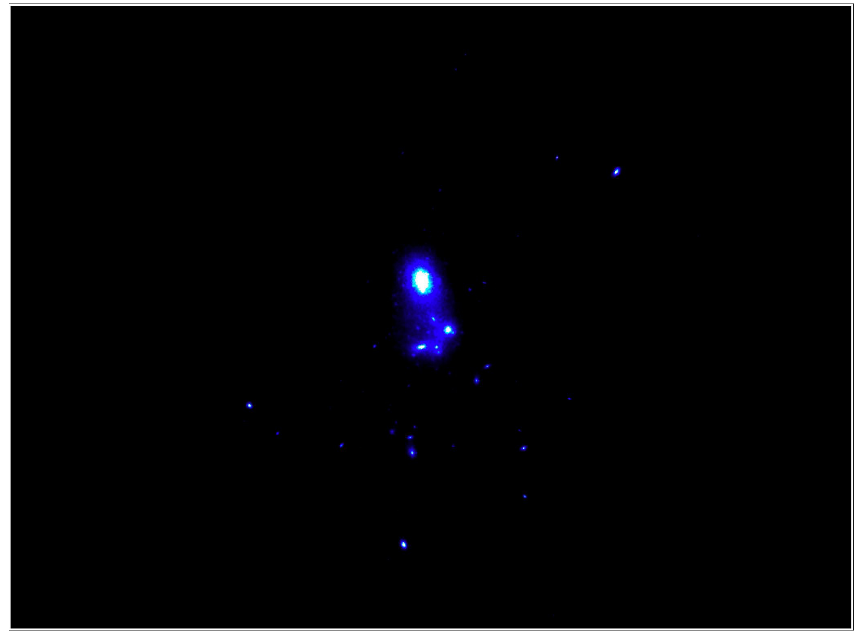


Milky Way satellites

Galaxy clusters

Why nearby objects?

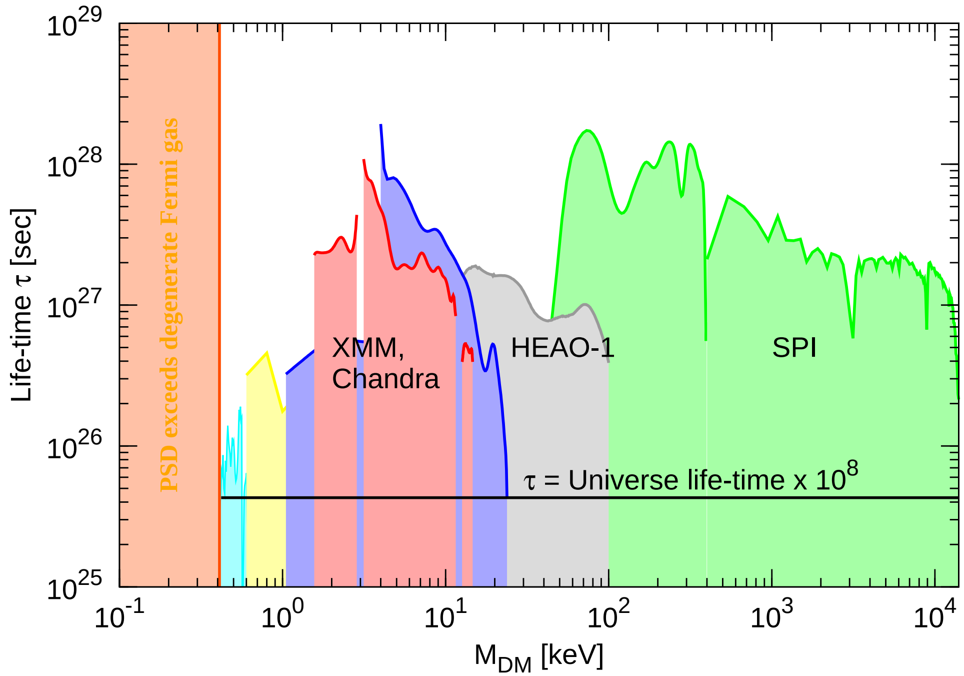

DM **decay** signal from a galaxy


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

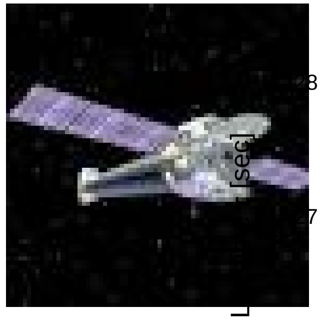
MW (XMM) 2006–2007

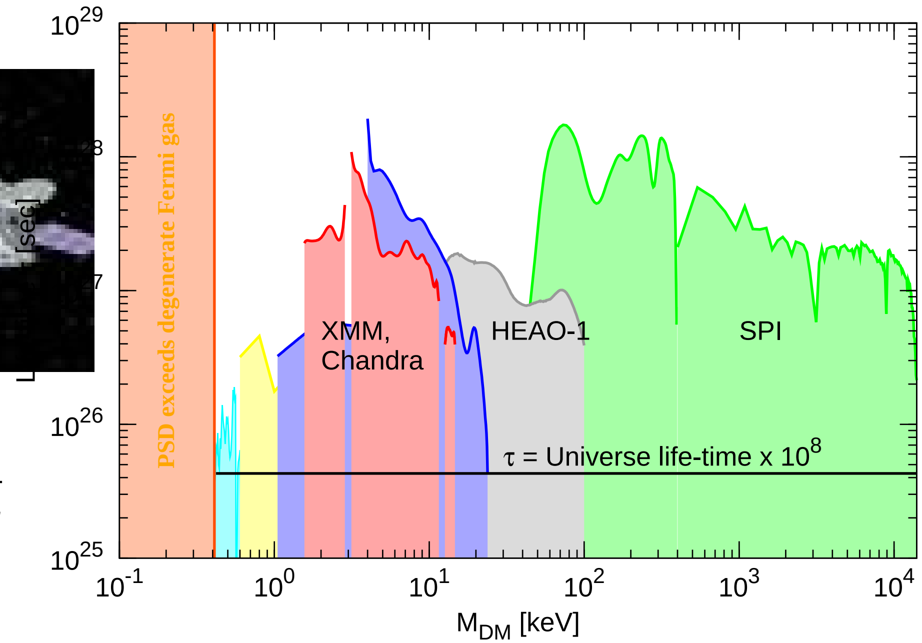
M31 (XMM) 2007, 2010

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

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?





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

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?

DECAYING DARK MATTER CANDIDATE

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]

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]

- **Energy:** 3.5 keV. Statistical error for line position $\sim 30 - 50$ eV.
- **Lifetime:** $\sim 10^{28}$ sec (uncertainty: factor ~ 3)
- **Possible origin:** decay DM $\to \gamma + \nu$ (fermion) or DM $\to \gamma + \gamma$ (boson)

Our Data

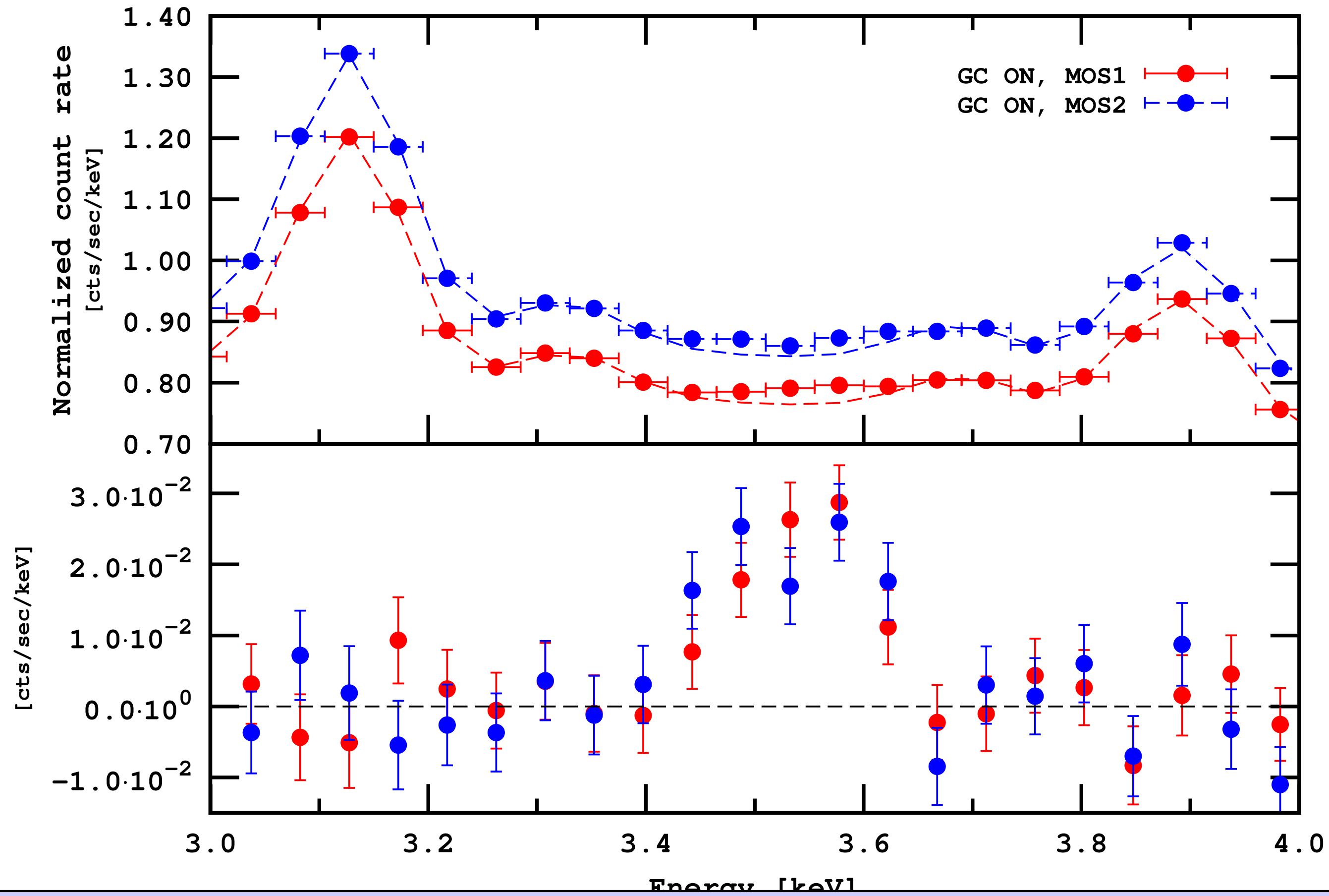
M31 galaxy	$\Delta\chi^2 = 13.0$	3.2σ for 2 d.o.f.
Perseus cluster (MOS)	$\Delta\chi^2 = 9.1$	2.5σ for 2 d.o.f.
Perseus cluster (PN)	$\Delta\chi^2 = 8.0$	2.4σ for 2 d.o.f.
Blank sky	No detection	
M31 + Perseus (MOS)	$\Delta\chi^2 = 25.9$	4.4σ for 3 d.o.f.

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.
....		

Galactic center

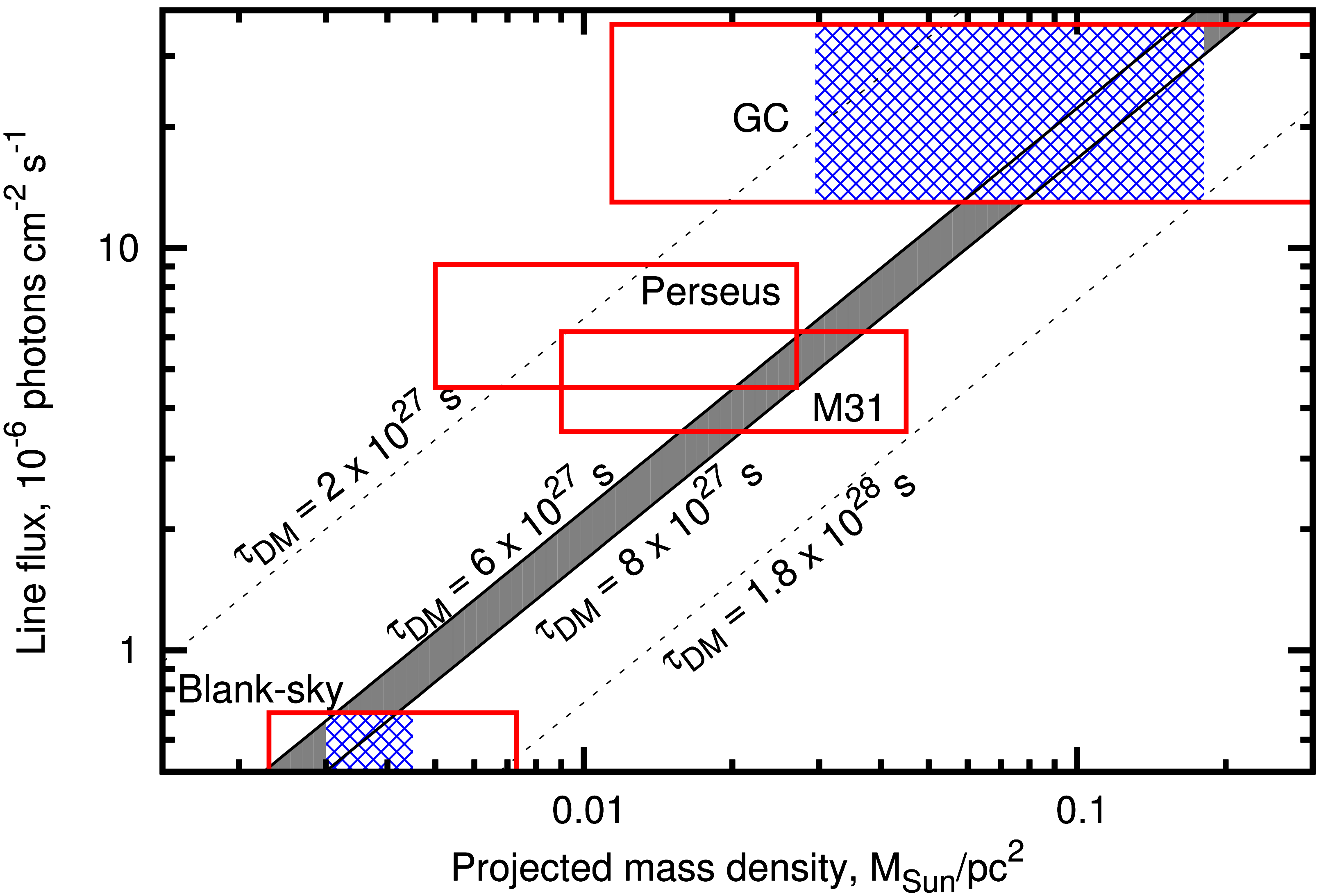


Boyarsky et al [1408.2503], PRL 2015

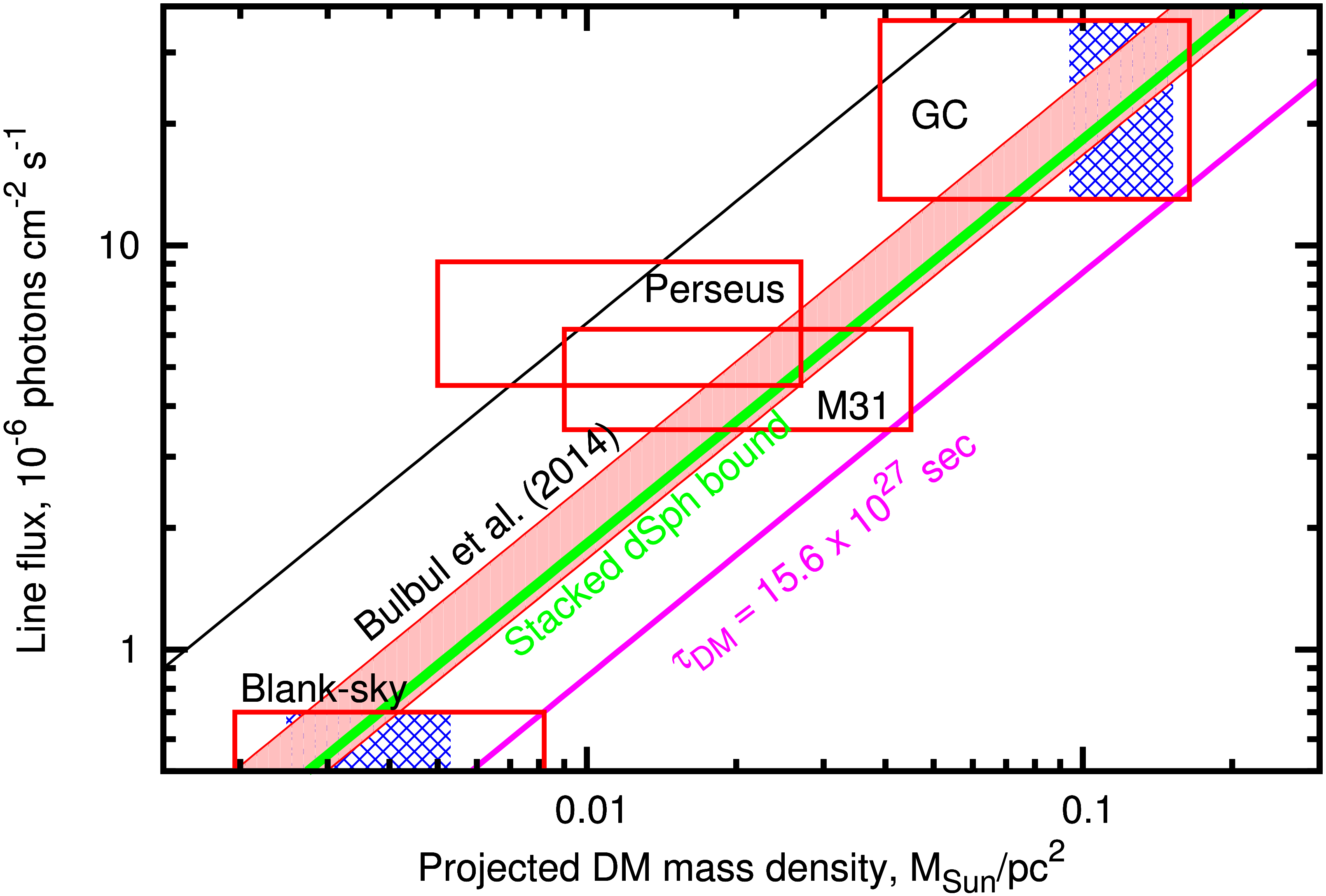
The line in the center of Andromeda means we should see it in the **Milky Way center**. Yes, we see it there!

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

Non-trivial consistency check



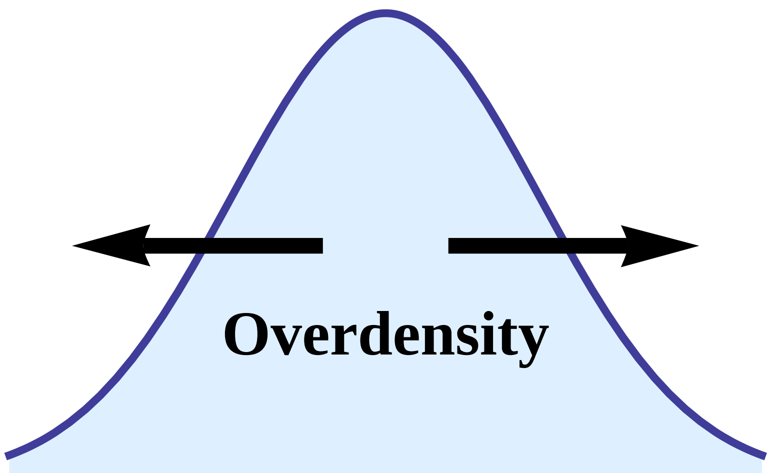
Dwarfs vs. spiral galaxies



Warm Dark Matter?

- Particles are born relativistic $\Rightarrow$ they do not cluster

- Relativistic particles **free stream** out of overdense regions and smooth primordial inhomogeneities

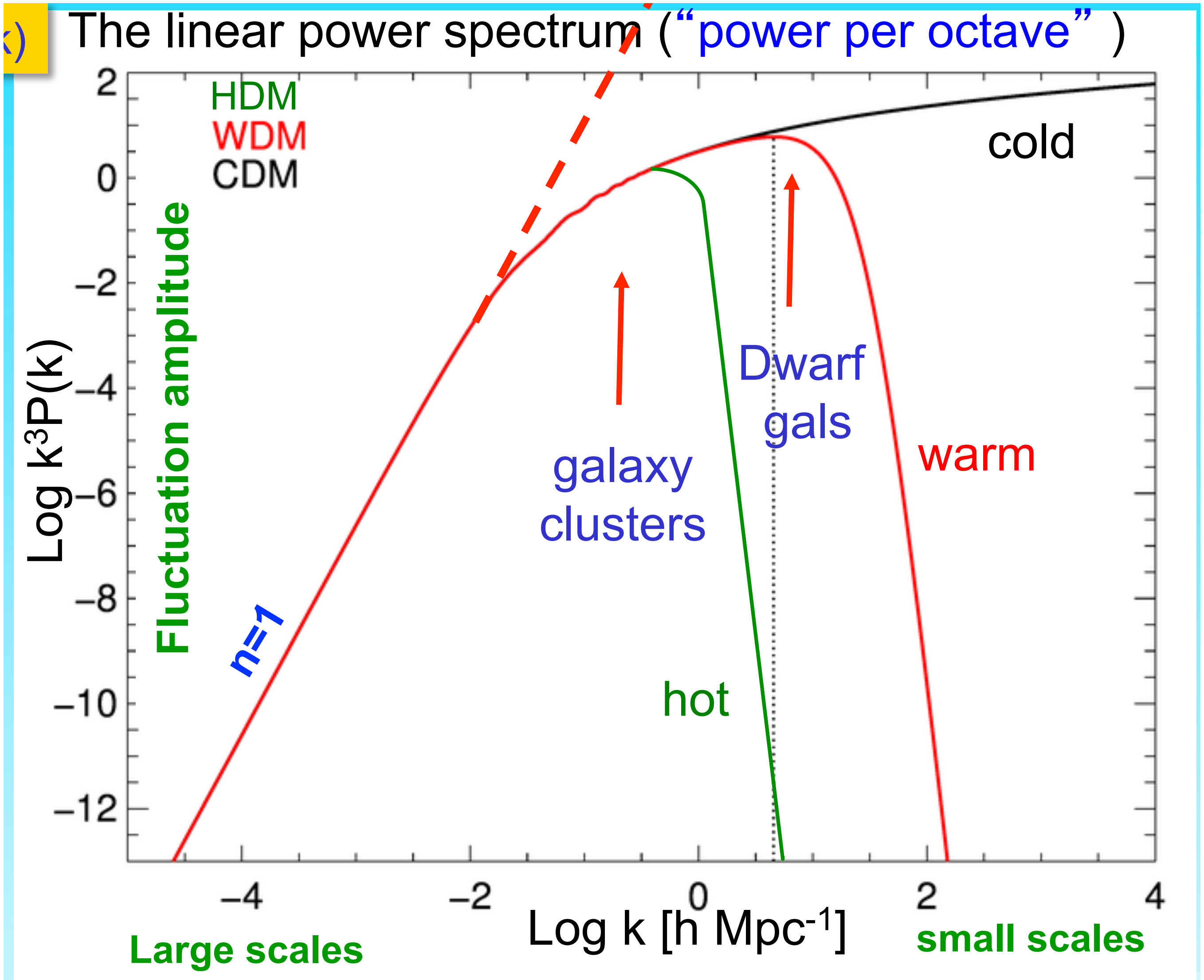


– Free-streaming scale:

$$\lambda_{FS}^{co} = \int_0^t \frac{v(t')dt'}{a(t')} = 1\ \text{Mpc} \left(\frac{\text{keV}}{M_{\text{sterile}}}\right)$$

– Particle velocities means that warm dark matter has effective **pressure** that prevents small structure from collapsing

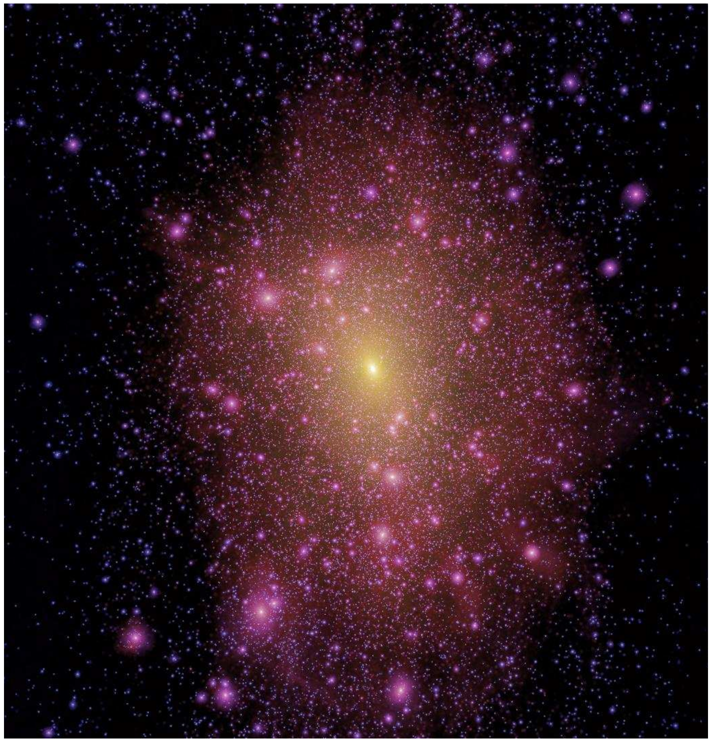
Suppression of power spectrum

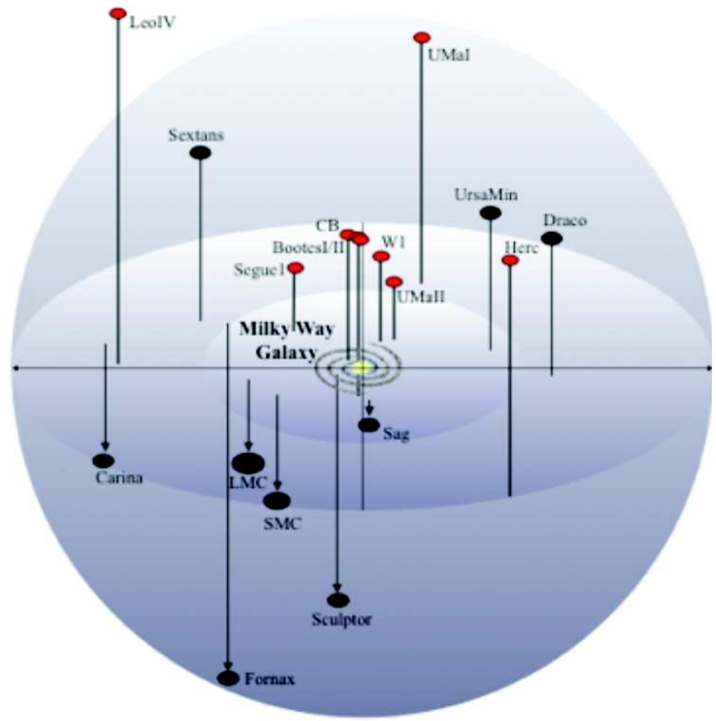


$$k^3 P(k) \sim |\delta_k|^2$$

DWARF GALAXIES (SMALL STRUCTURES INSIDE MILKY WAY)

Halo substructure in "cold" DM universe



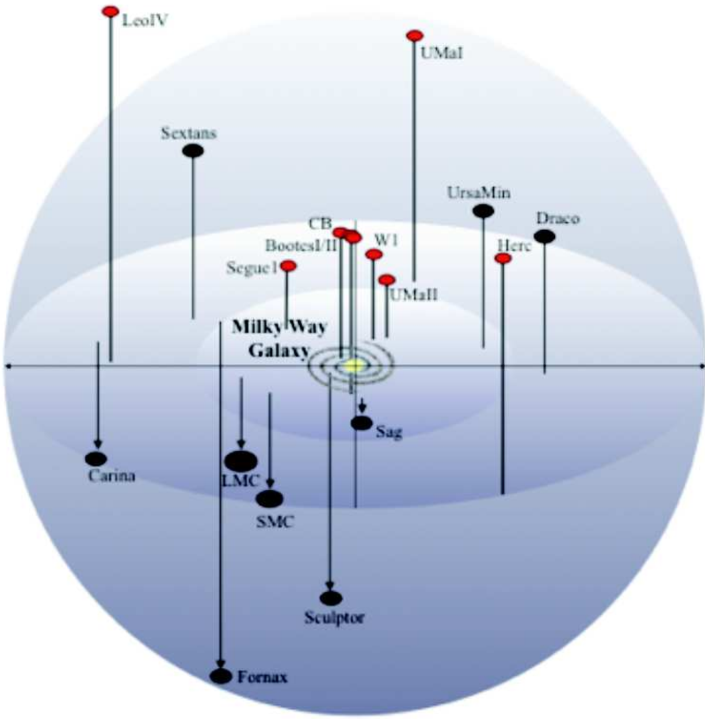


COLD DM models predict millions of substructures within a galaxy like Milky Way

Only ~ 30 are observed within our Galaxy. M. Geha 2010

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

Halo substructure in "warm" DM universe

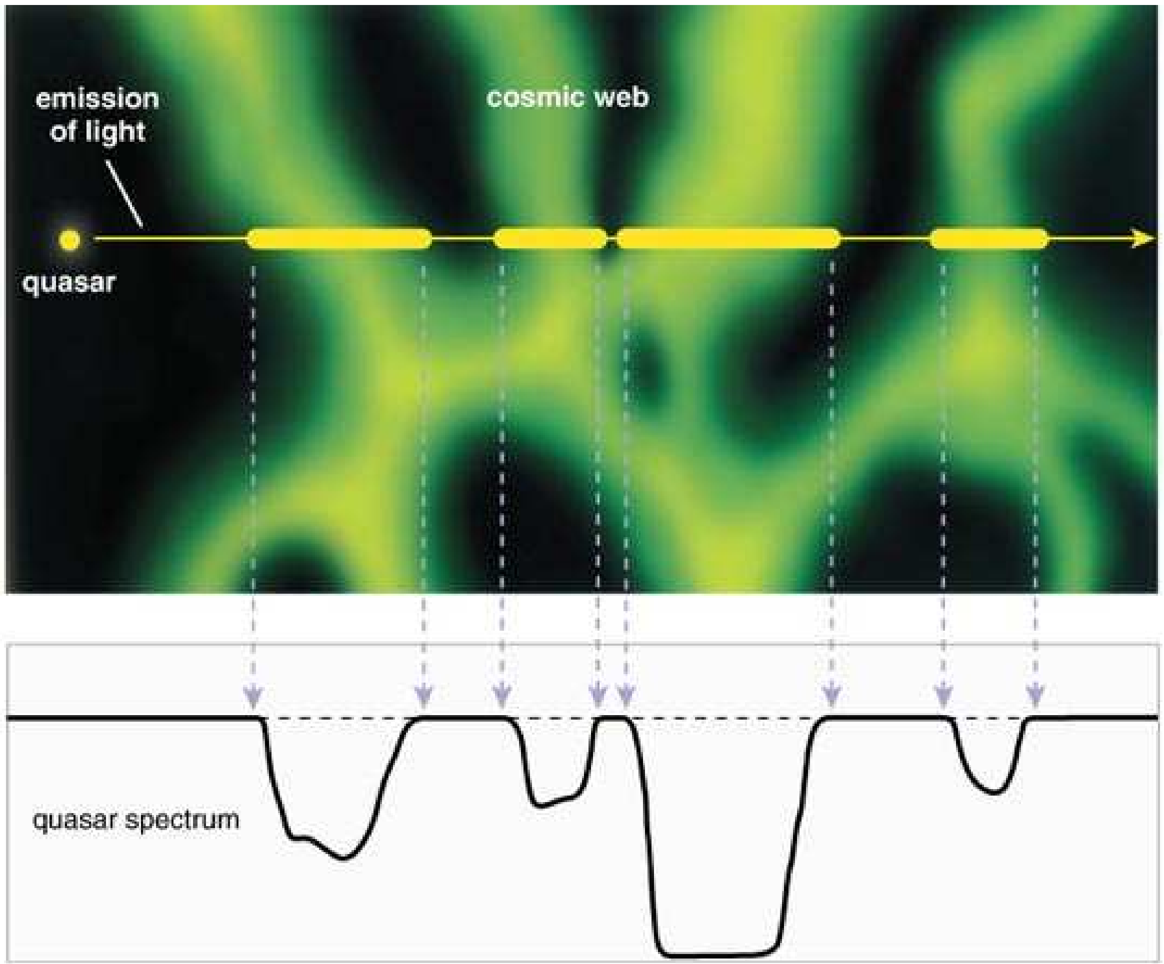


Aq-A-2 halo made of sterile neutrino DM (with C. Frenk, T. Theuns, . . .)

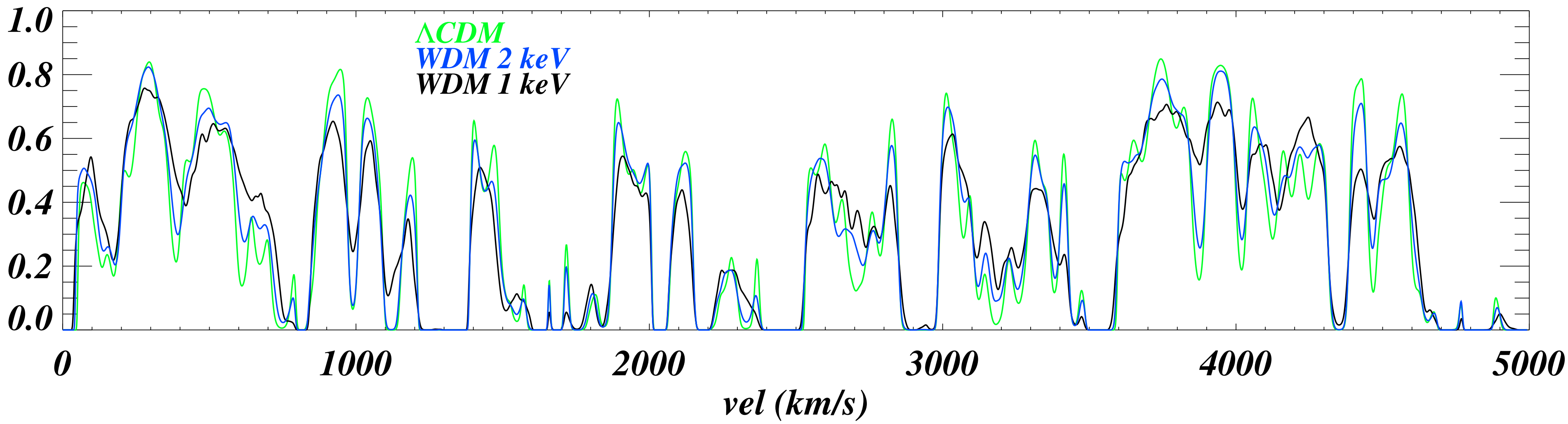
Simulated sterile neutrino DM halo is compatible with the Lyman-α forest data but provides a structure of Milky way-size halo different from CDM

LYMAN-α FOREST DATA

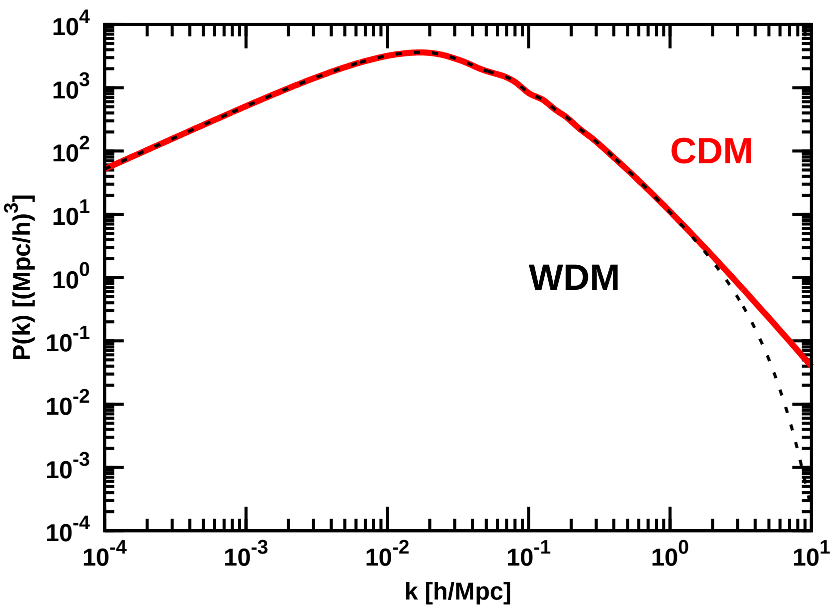
Lyman-α forest and power spectrum



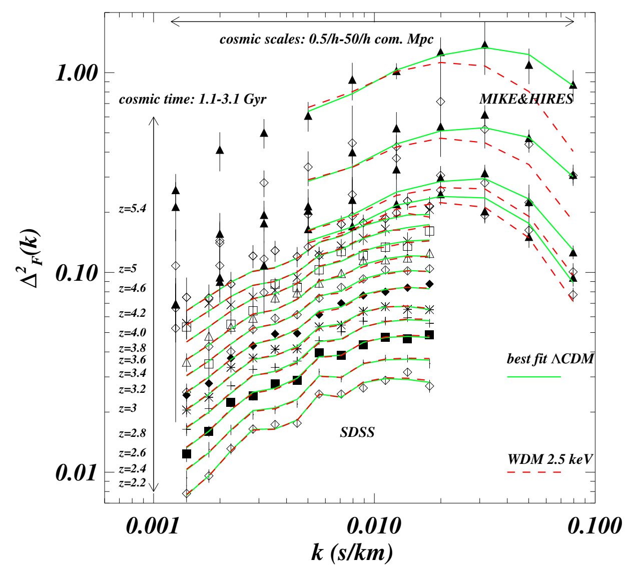
Lyman-α forest and power spectrum



Viel et al.'13

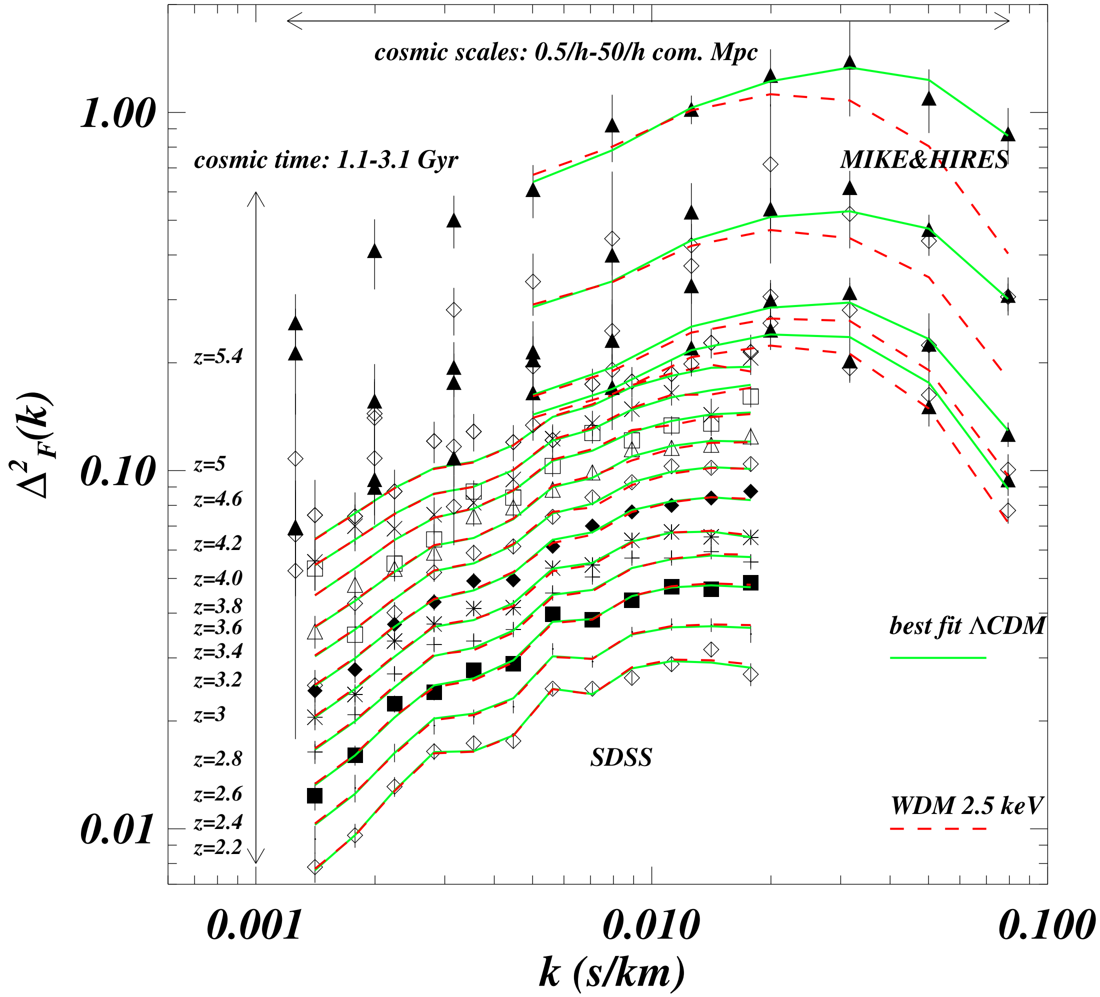


$\Longrightarrow$



Lyman-α forest data

Viel et al. [1306.2314]



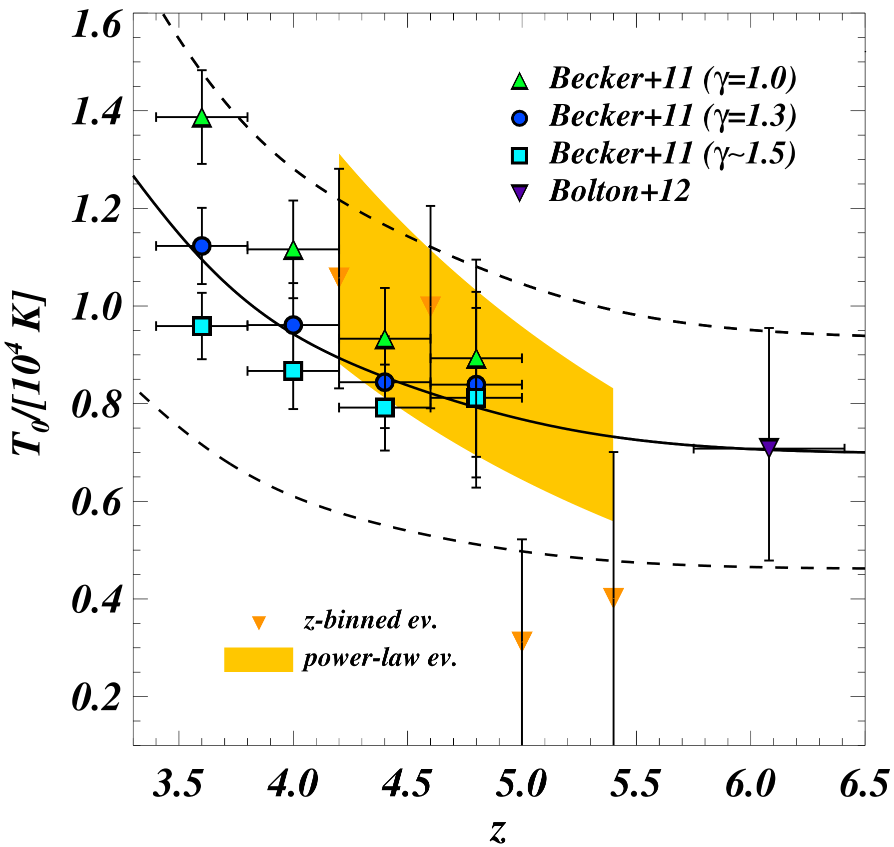
Suppression in the flux power spectrum may be due to

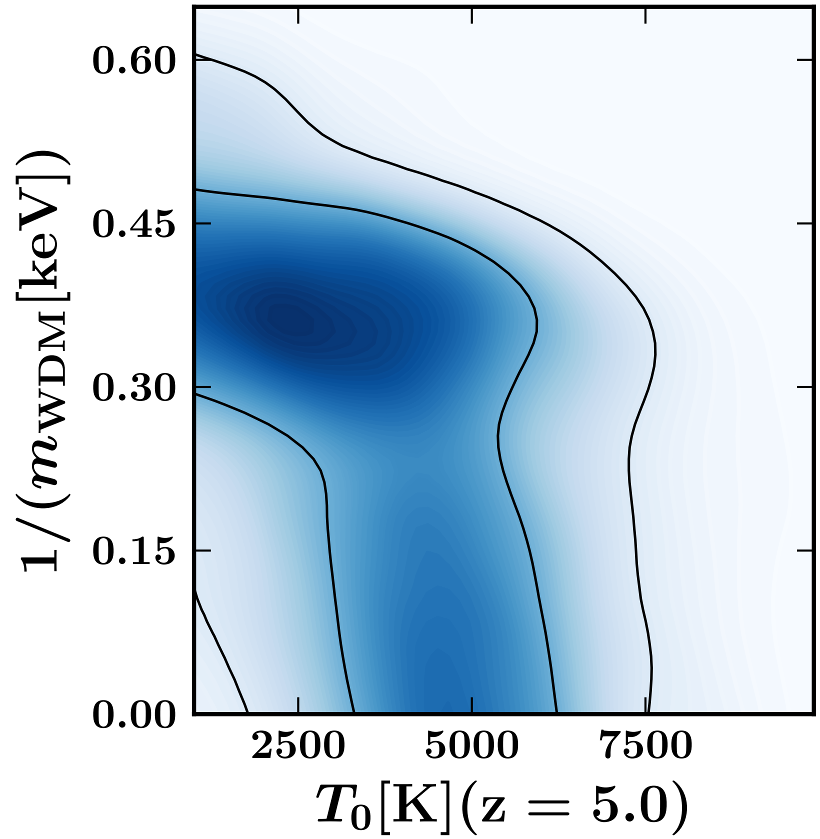
- Thermal effects (Jeans broadening)
- Doppler broadening
- WDM

Large scales: no suppression CDM-like spectrum

Small scales: suppression in the power spectrum! WDM?!

Warm dark matter + cold IGM





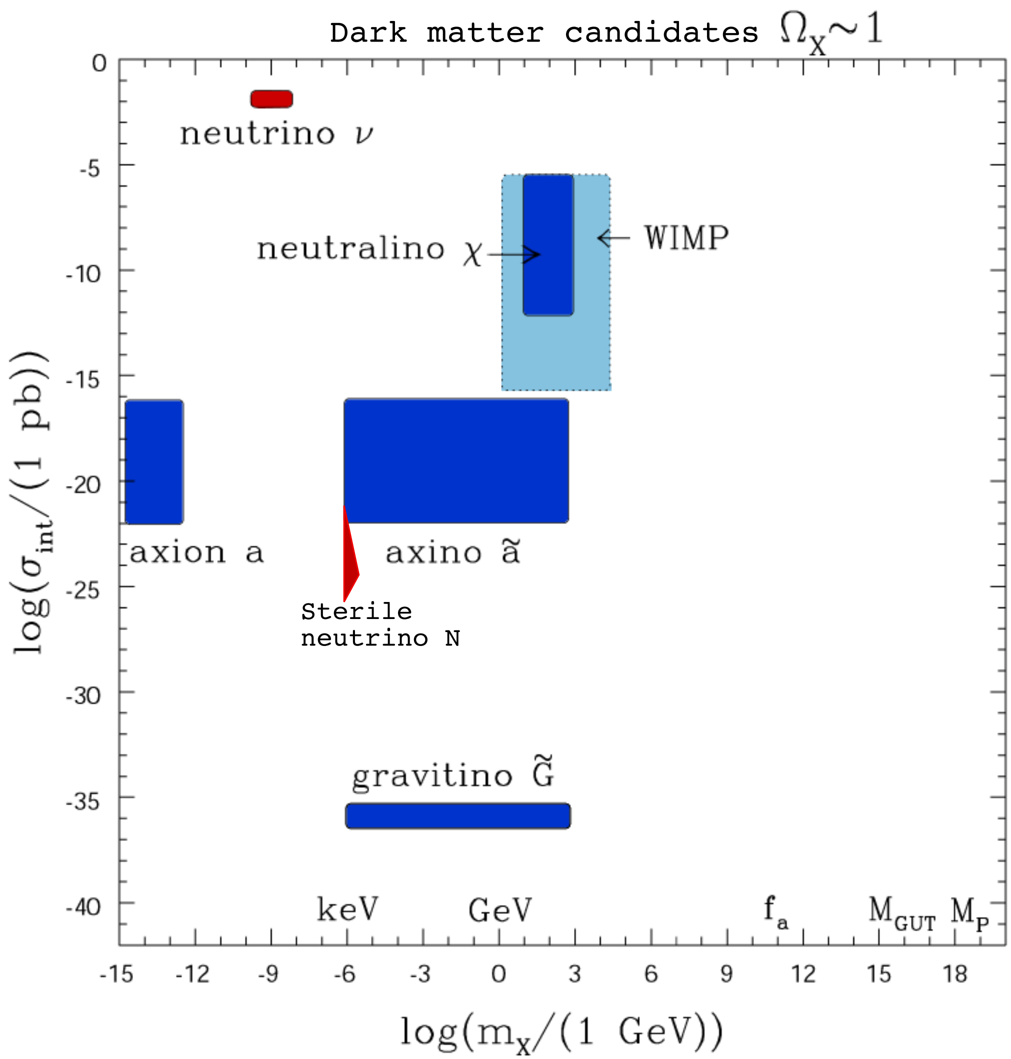
Data prefers cold IGM medium around redshift $z = 5$ $\Rightarrow$ power spectrum suppression is due to **something else**?

A. Garzilli et al. [1510.***]**

DARK MATTER AND PARTICLE PHYSICS

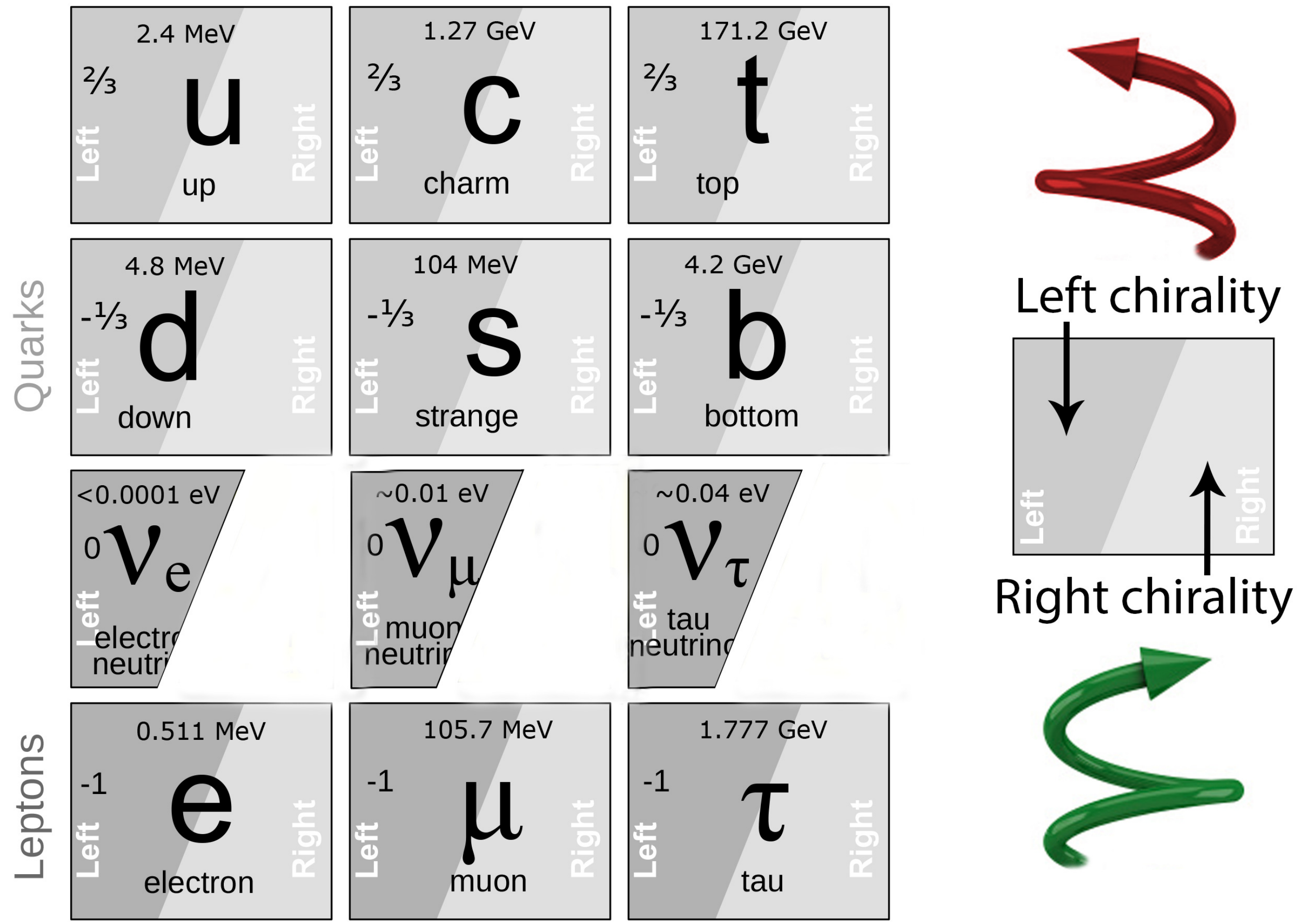
Dark matter candidates

L.Roszkowski

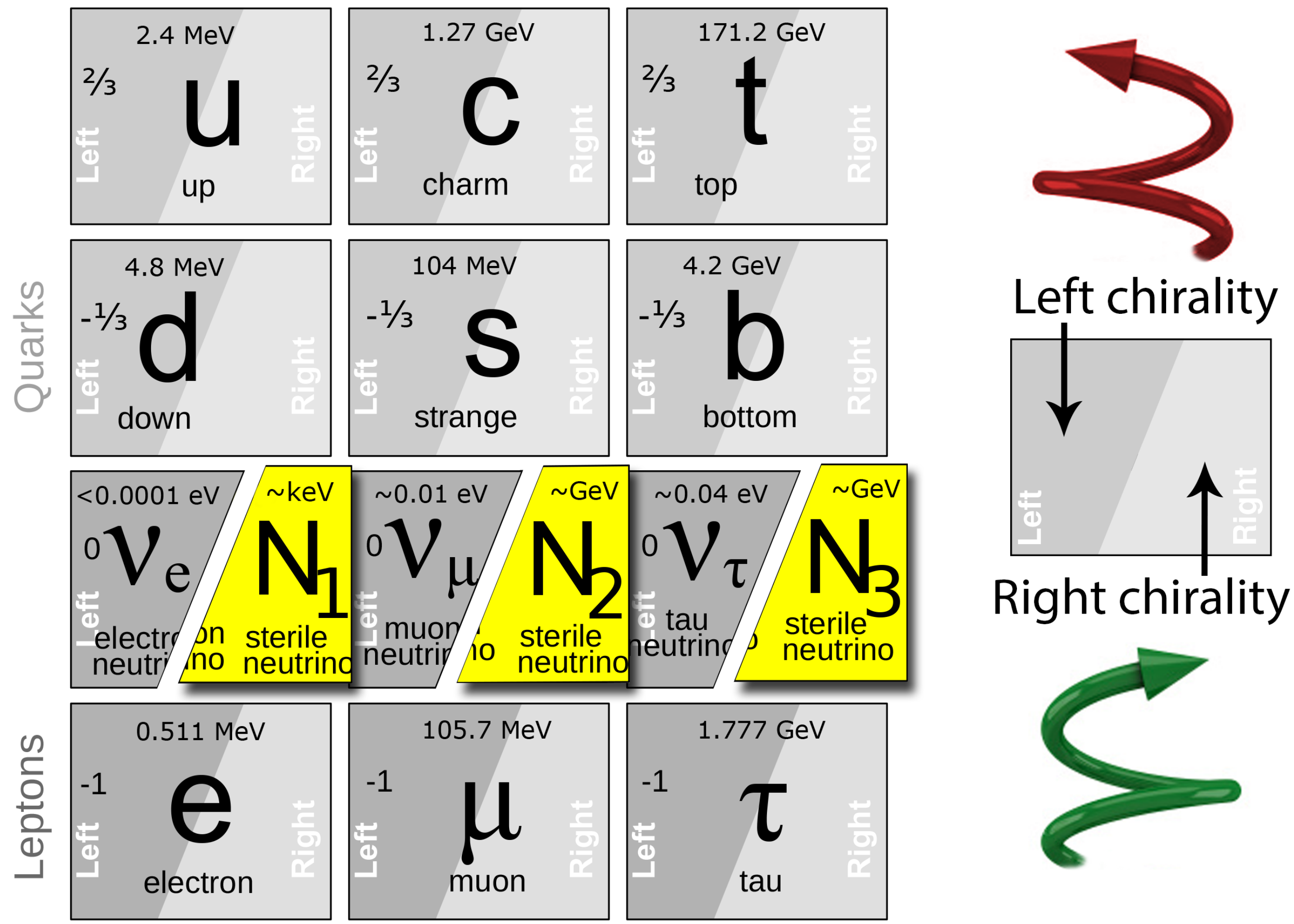


HNL DARK MATTER

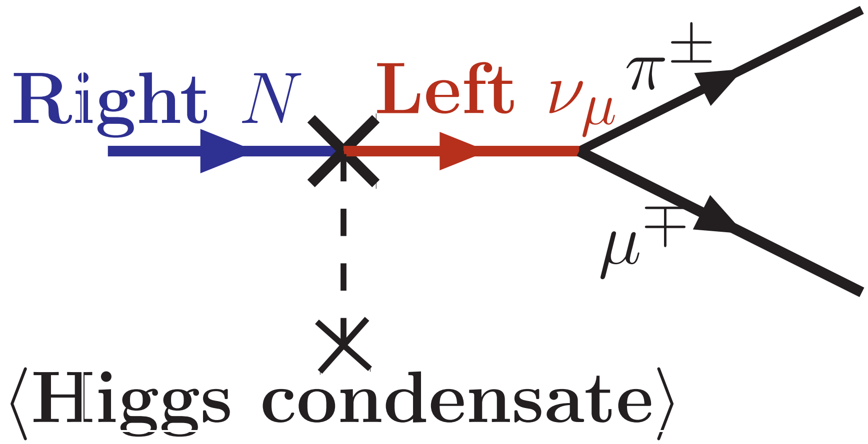
Oscillations ⇒ new particles!

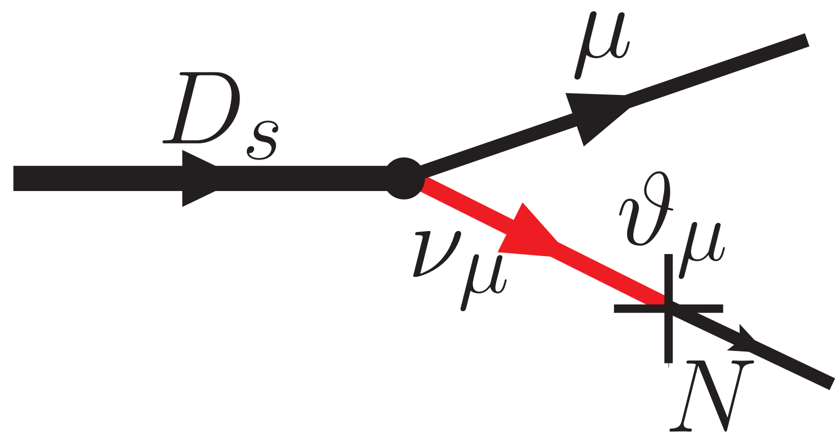


Oscillations ⇒ new particles!



Right components of neutrinos?!



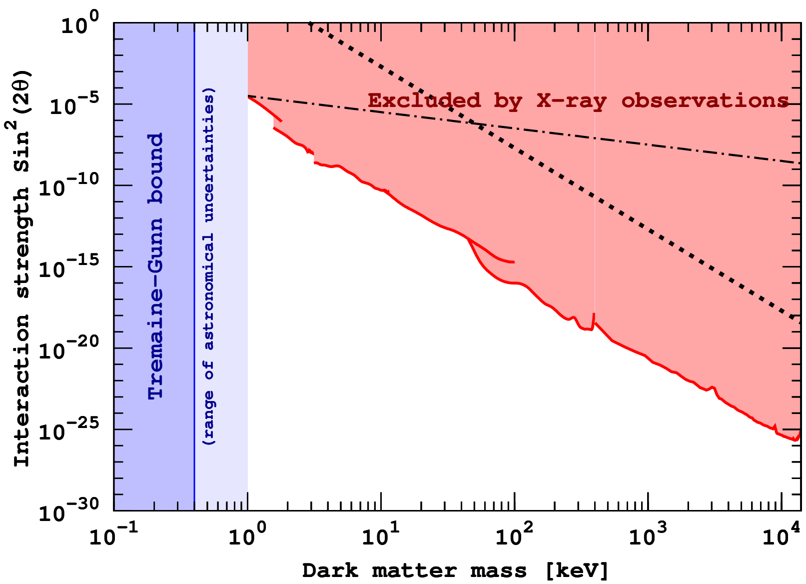


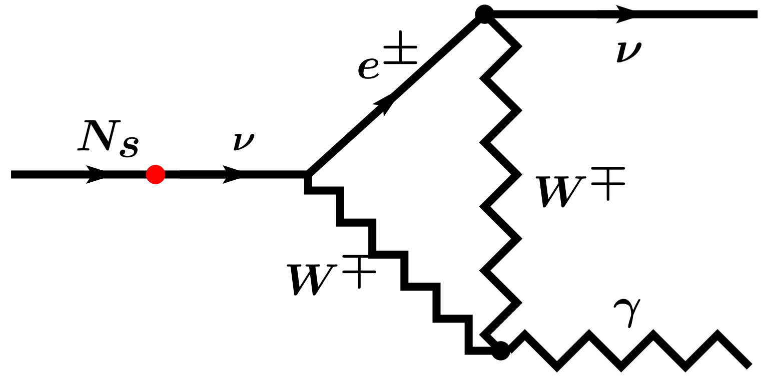
Sterile neutrinos behave as **superweakly interacting** massive neutrinos with a smaller Fermi constant $\boxed{\vartheta \times G_F}$

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

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

- HNL is **decaying dark matter candidate:** $N \to \nu + \gamma$
- Existing bounds on DM decay limit its parameter space

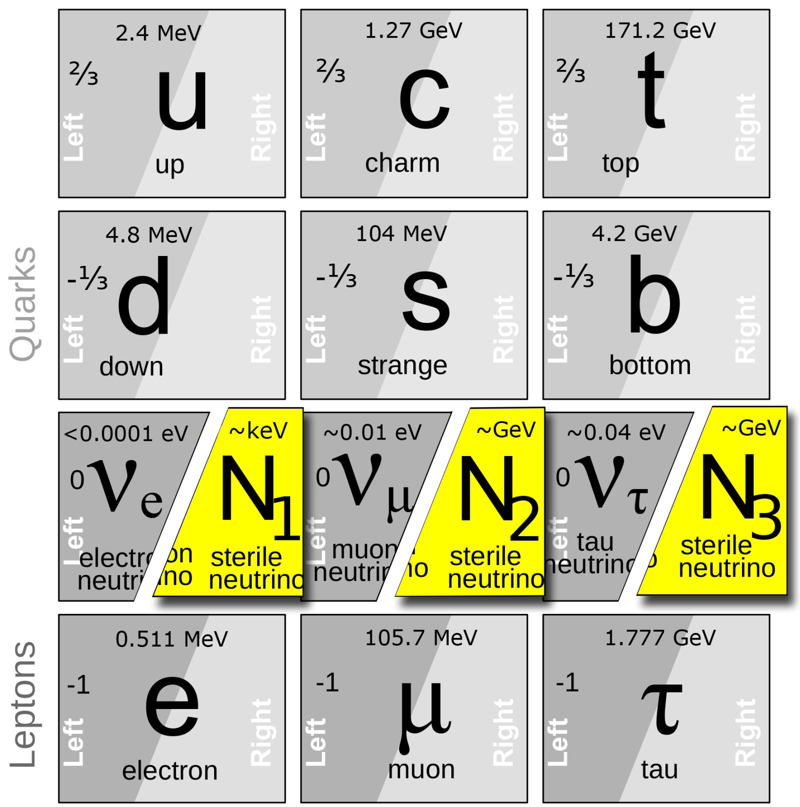




- Dotted line: lifetime equal to the lifetime of the Universe
- Dashed-dotted line: HNL contributes to neutrino mass matrix at the level $\Delta m^2_\odot$

HNL cannot be a dark matter candidate **and** contribute significantly to the neutrino masses

Dark matter and neutrino oscillations

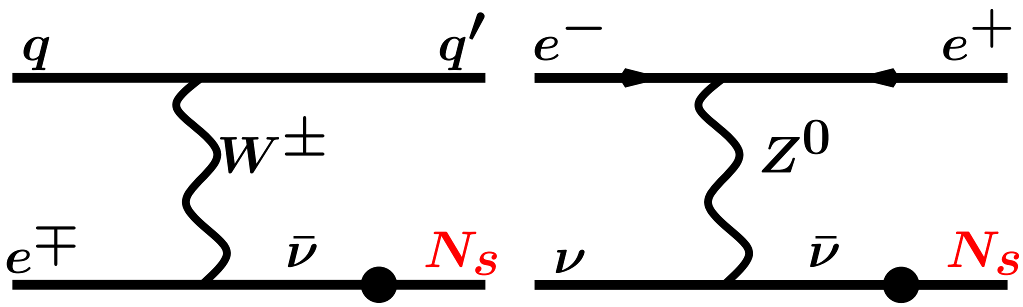


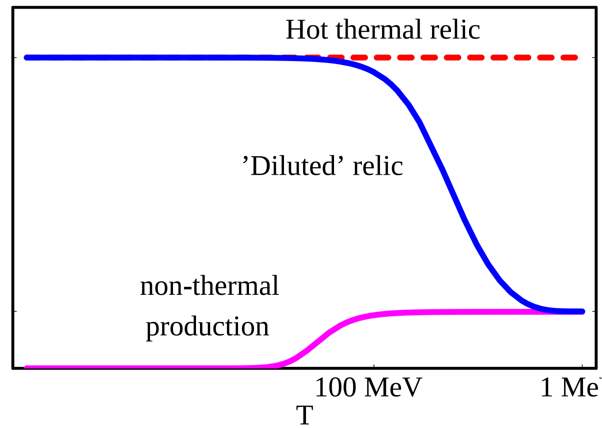
– **Atmospheric** and **Solar** neutrino mass splitting ⇒ need (at least) two sterile neutrino

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

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

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

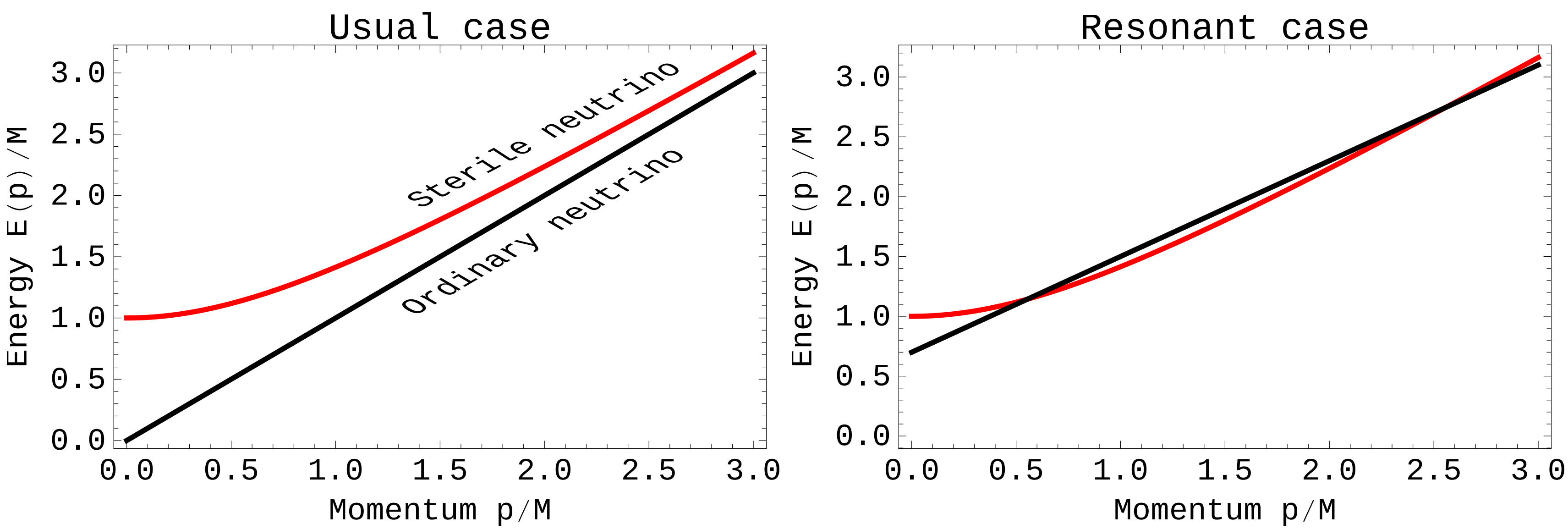


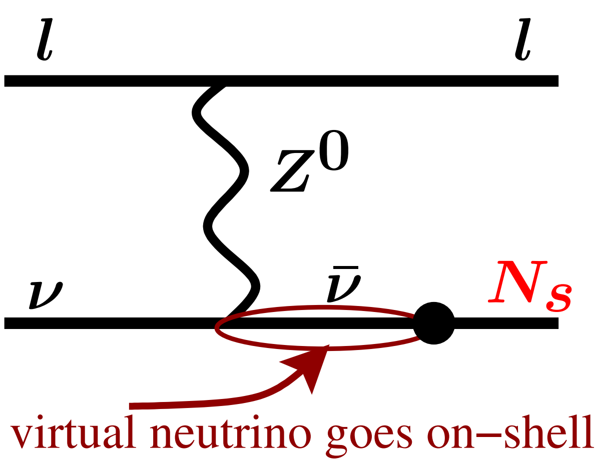


- Once every $\sim 10^8 \div 10^{10}$ scatterings a sterile neutrino is created instead of the active one
- Its abundance **slowly builds up** but **never reaches the equilibrium** value
- The distribution of sterile neutrinos $f(p) \approx \frac{\theta^2}{e^{p/T_\nu}+1}$

Dodelson & Widrow'93; Dolgov & Hansen'00

Resonant enhancement



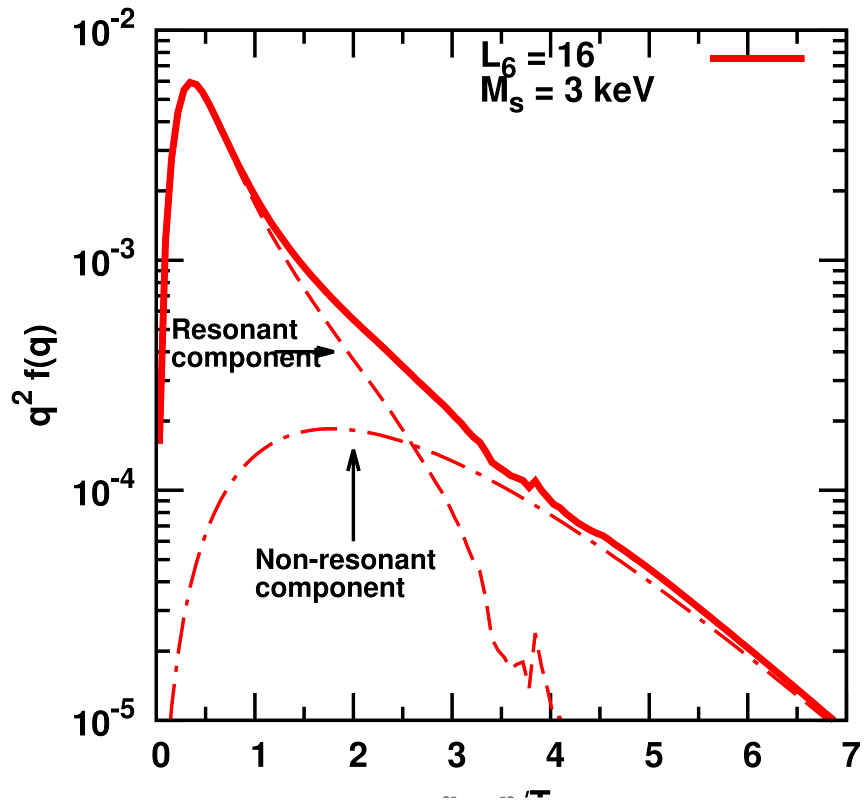


Conversion of ν to N is enhanced whenever "levels" cross and virtual neutrino goes "on-shell" (analog of MSW effect but for active-sterile mixing)

Shi & Fuller [astro-ph/9810076]

Laine & Shaposhnikov [0804.4543]

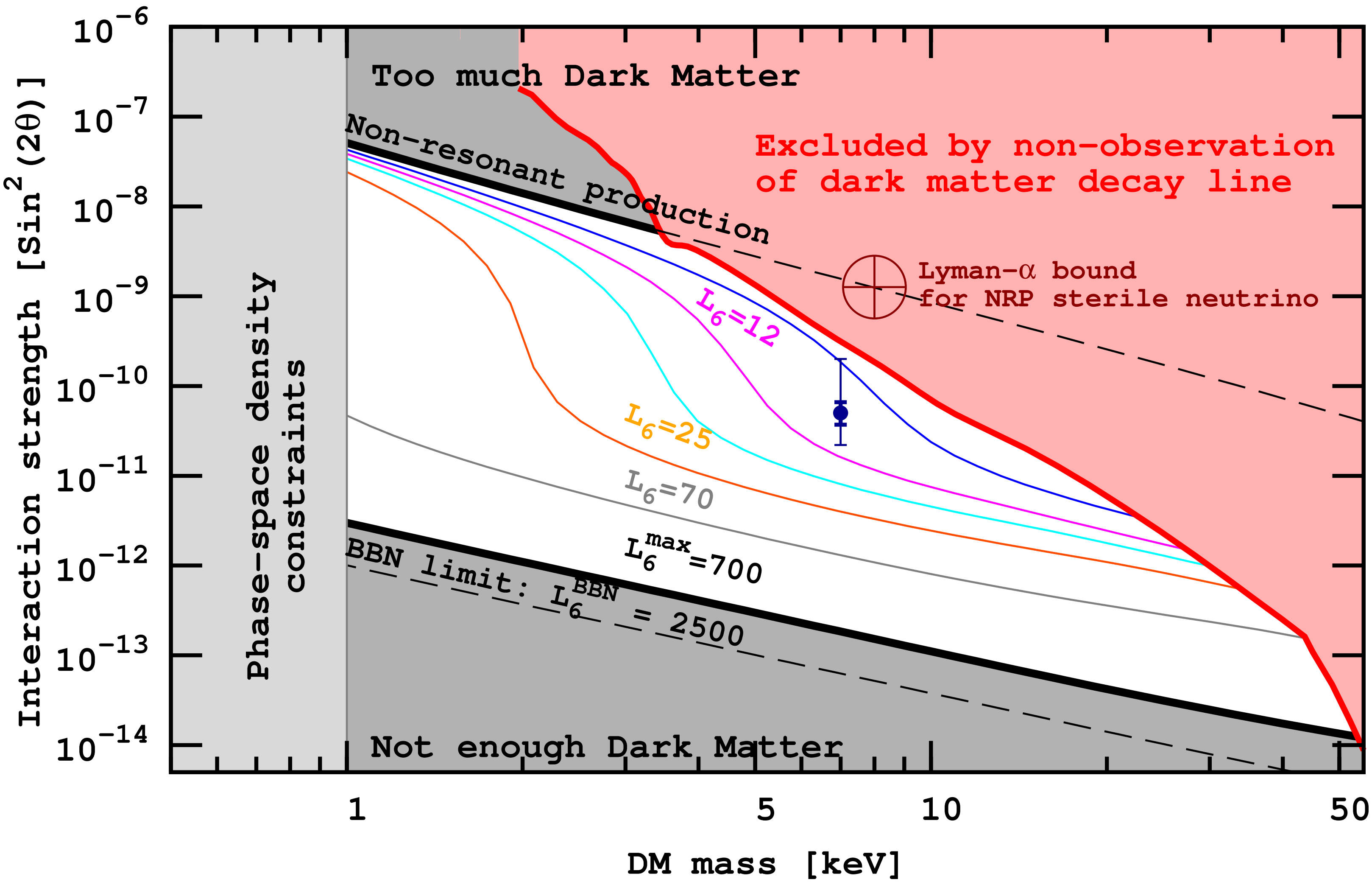
- In the presence of **large lepton asymmetry** the **MSW resonance** can take place and production of sterile neutrinos becomes much more effective



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

- For HNLs $p \gg M$ at production $\Rightarrow$ **HNL is warm dark matter**

Sterile neutrino and 3.5 keV line



Ly-α bounds: Viel, Lesgourgues et al.'05-'06

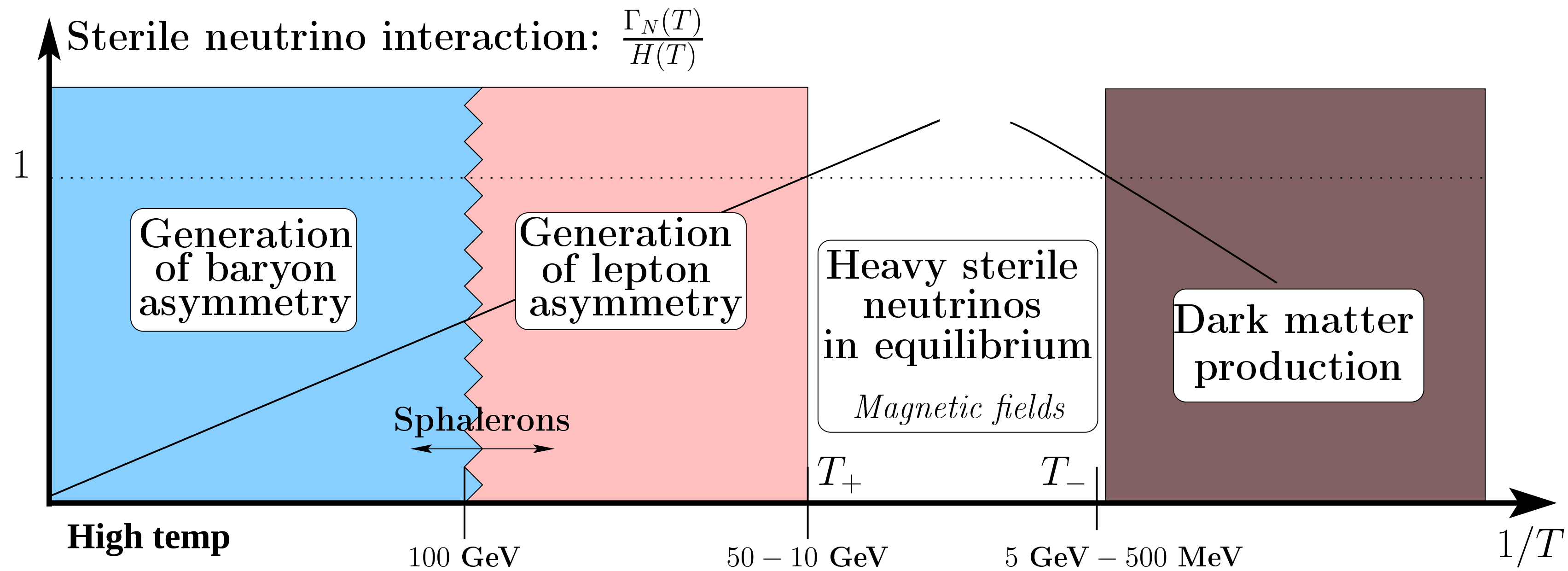
Ly-α in resonan case: Boyarsky, Lesgourgues, O.R. Viel '08

X-rays: '05-'14 Boyarsky, Ruchayskiy et al. Abazajian et al. Hansen et al. Watson et al. Kusenko, Lowenstein

Production: Laine & Shaposhnikov'08

from PRL (2014)

Thermal history of the Universe



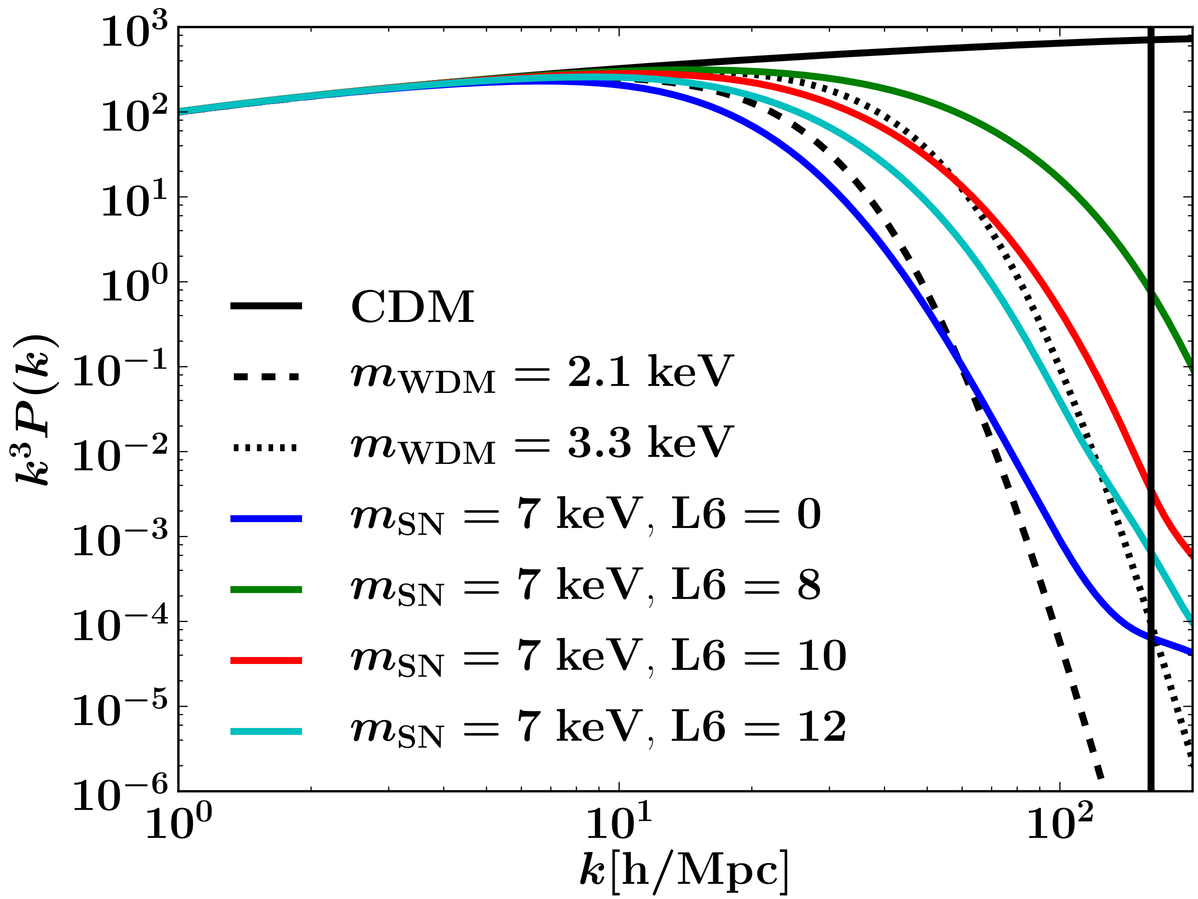
Magnetic fields make baryogenesis (around $T \sim 100$ GeV) and dark matter production (around $T \sim 100$ MeV) related and sourced by the same mechanism – generation of lepton asymmetry by out-of-equilibrium transitions of two sterile neutrinos with the masses 10 MeV $\lesssim M \lesssim 80$ GeV

Conclusion

- Super-WIMP dark matter is a part of the paradigme about **feebly interacting** (*rather than heavy*) new physics.
- Super-WIMPs can be **light** (*e.g. keV scales*); can **decay** (*rather than annihilate*) and can be **warm** (*erasing primordial density perturbations*)
- Current status of warm dark matter searches: missing information about state of IGM at $z \sim 5$ can drastically change the situation: rule out WDM as an astrophysically interesting scenario **or confirm existence of warm dark matter**
- The searches for decaying dark matter are ongoing. Stay tuned!
- All the data looks consistent with a ~ 7 keV sterile neutrino produced in the model like νMSM

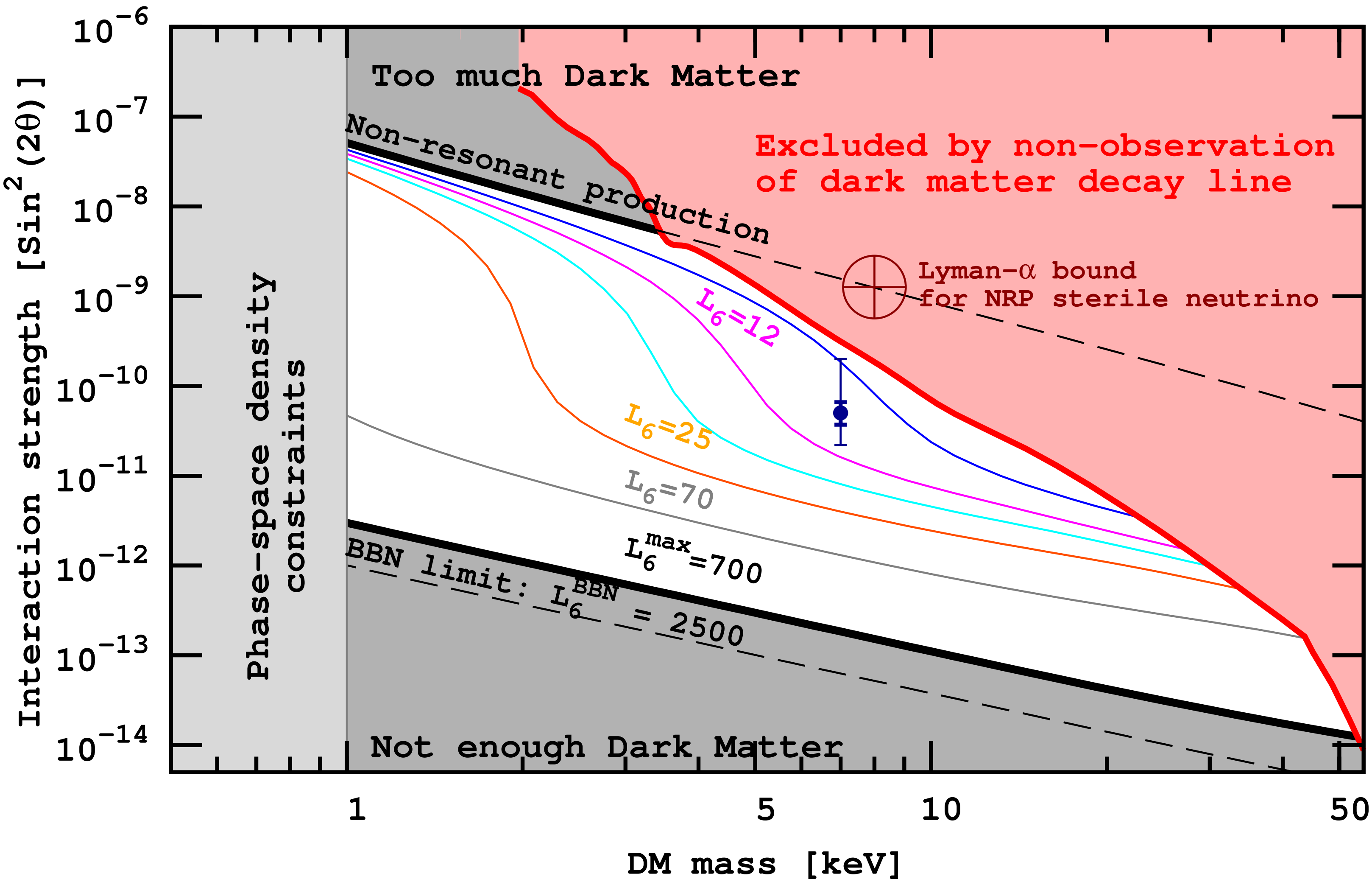
THANK YOU FOR YOUR ATTENTION!

7 keV sterile neutrino and Lyman-α forest



Constraints on HNL dark matter $\Rightarrow$ constraints on the properties of N_2, N_3 from cosmology and astrophysics.

Sterile neutrino and 3.5 keV line



Ly-α bounds: Viel, Lesgourgues et al.'05-'06

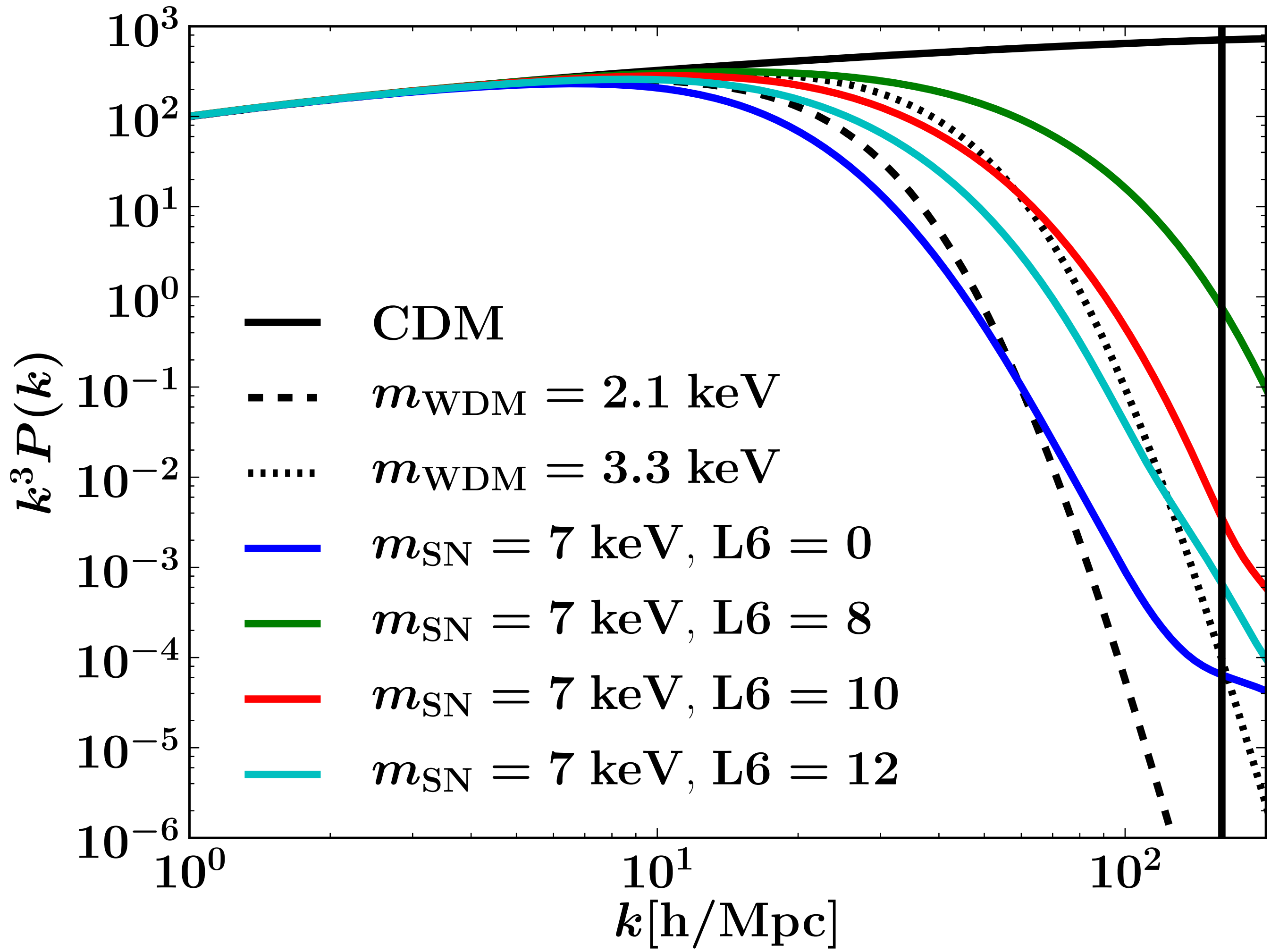
Ly-α in resonant case: Boyarsky, Lesgourgues, Ruchayskiy. Viel '08

X-rays: '05-'14 Boyarsky, Ruchayskiy et al. Abazajian et al. Hansen et al. Watson et al. Kusenko, Lowenstein

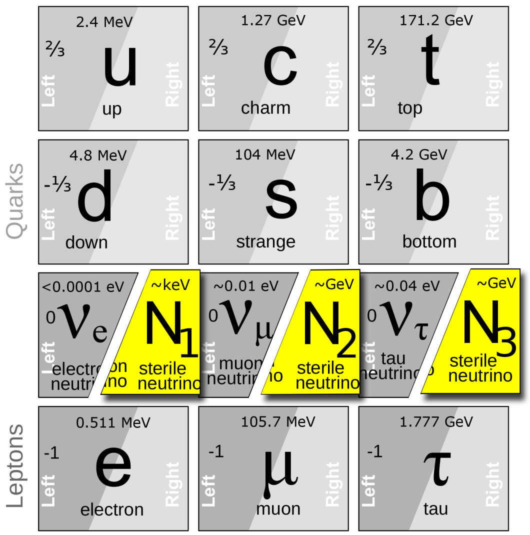
Production: Laine & Shaposhnikov'08

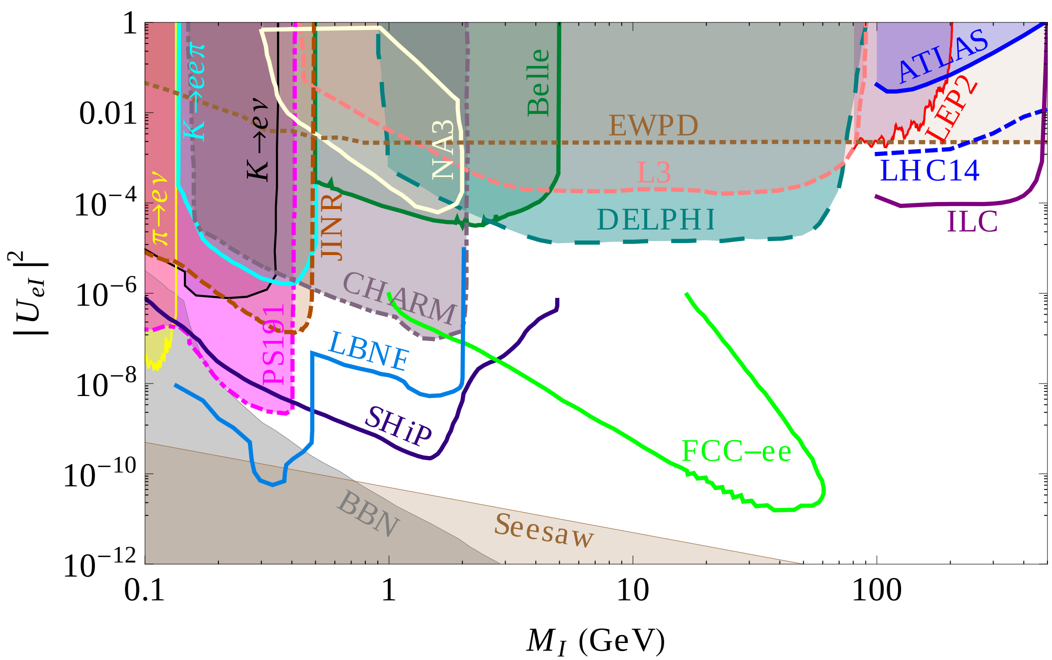
from PRL (2014)

7 keV sterile neutrino and Lyman-α forest



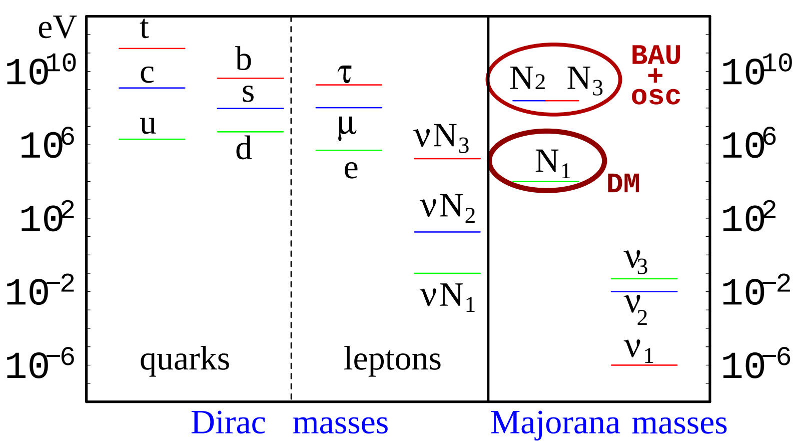
SHiP: Search for Hidden Particles





1504.04956 : Technical proposal

1504.04855 : physics case



- Particle N_1 with the mass 7 keV is the dark matter
- Particles N_2 and N_3 with $\mathcal{O}(1)$ GeV mass are discovered by SHiP
- Their properties (mass/interaction strength) are related

Our Data

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

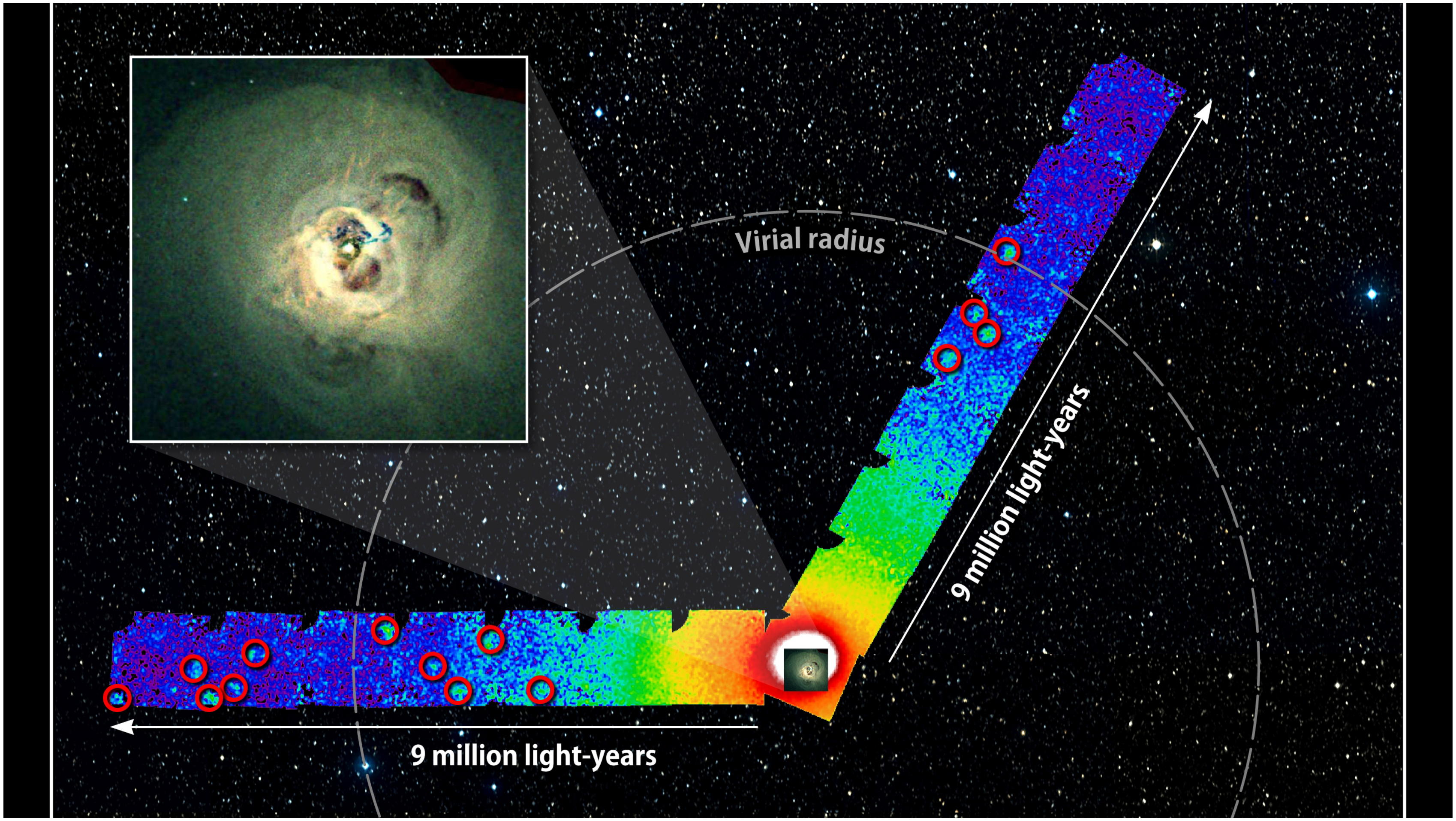
Bulbul et al. 2014

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)



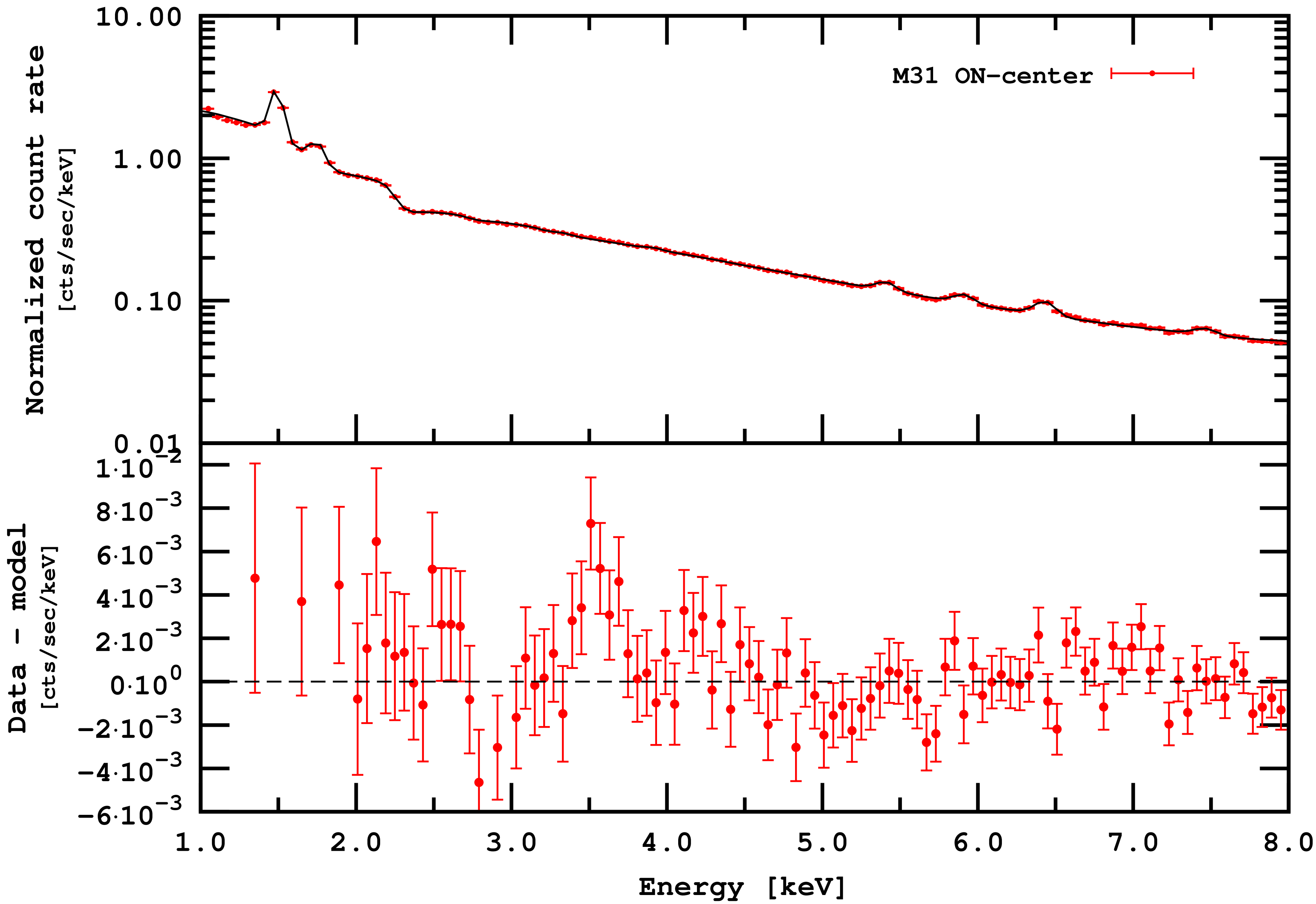
Bulbul et al. took only 2 central XMM observation – $14'$ around the cluster's center.

Also Carlson et al.; Urban et al.

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

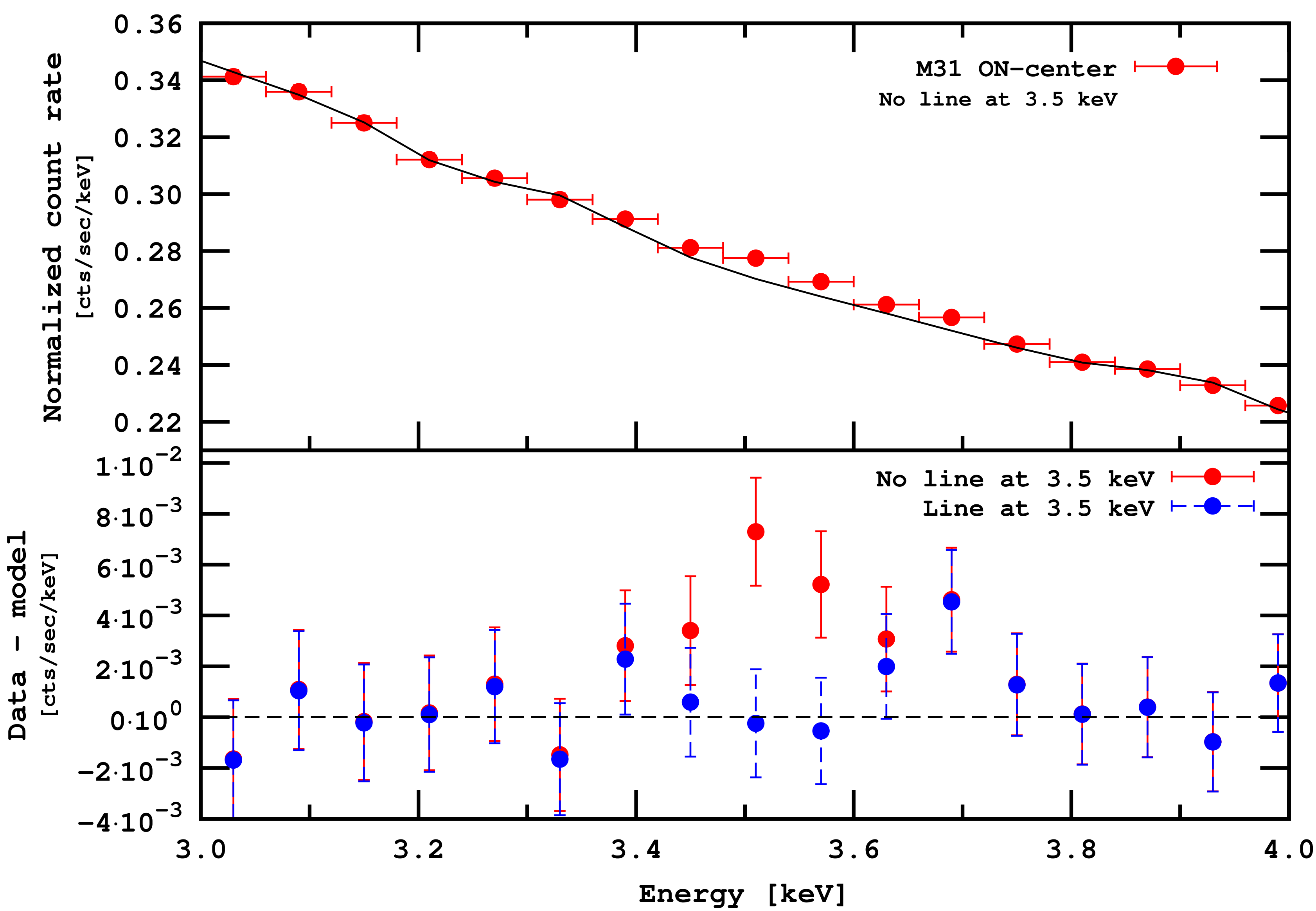
Andromeda galaxy

PRL (2014)
[1402.4119]

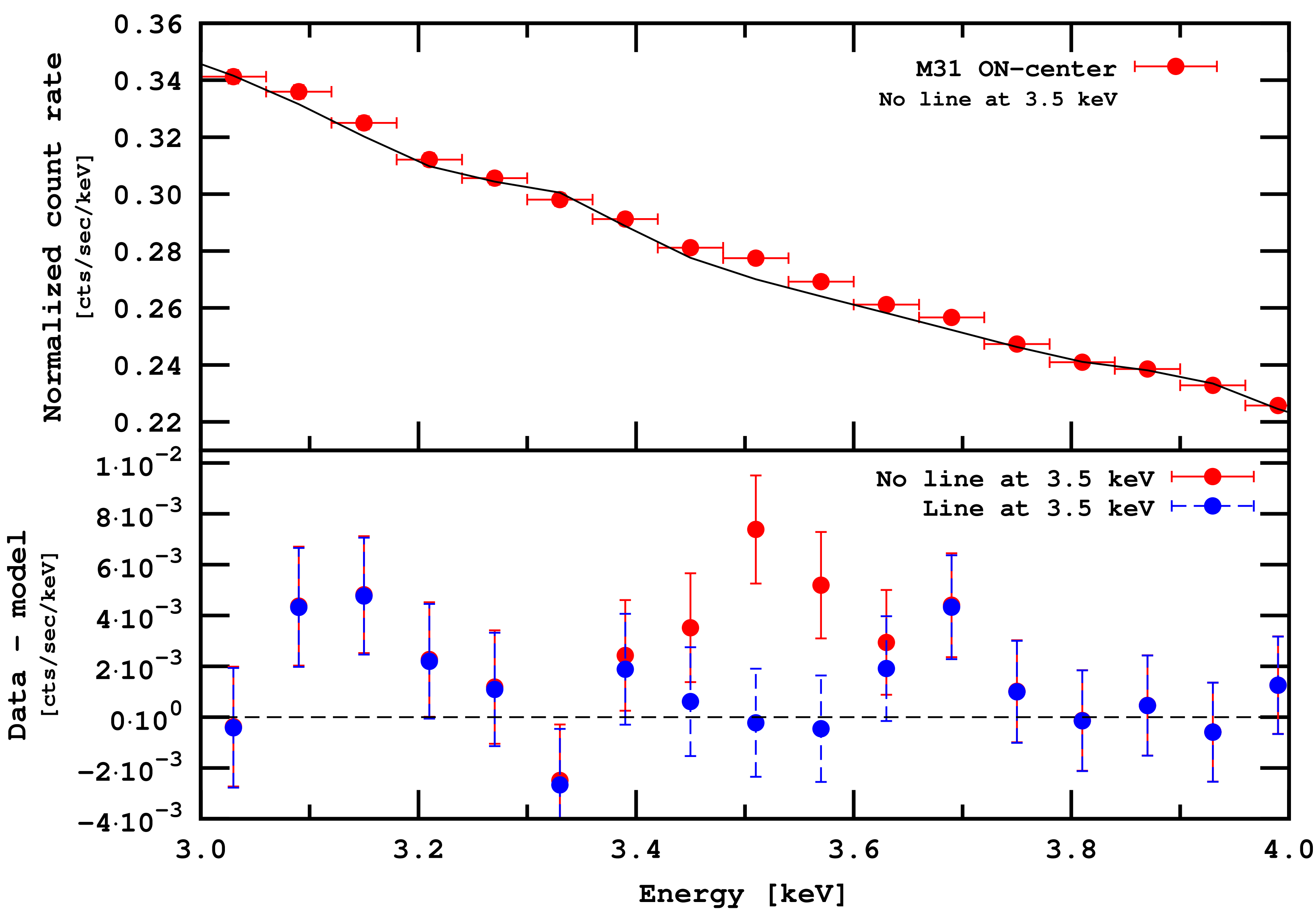


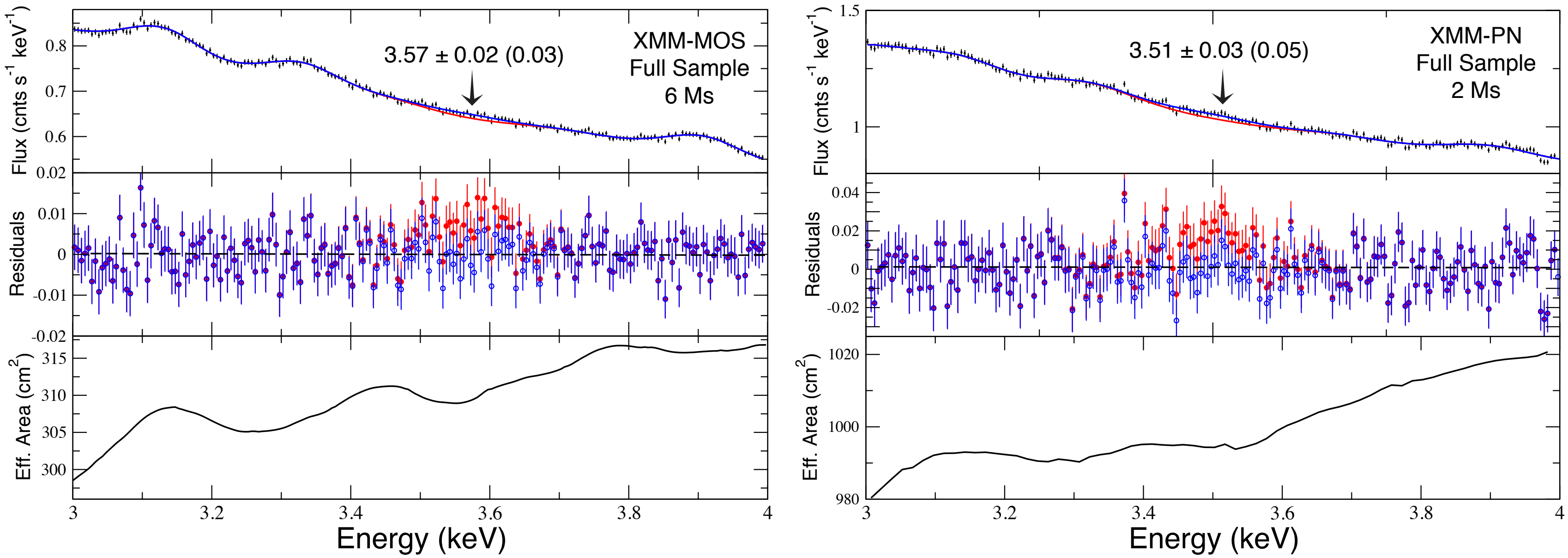
Andromeda galaxy (1 Msec) (zoom 3–4 keV)

PRL (2014)
[1402.4119]



Andromeda galaxy (zoom 3–4 keV)



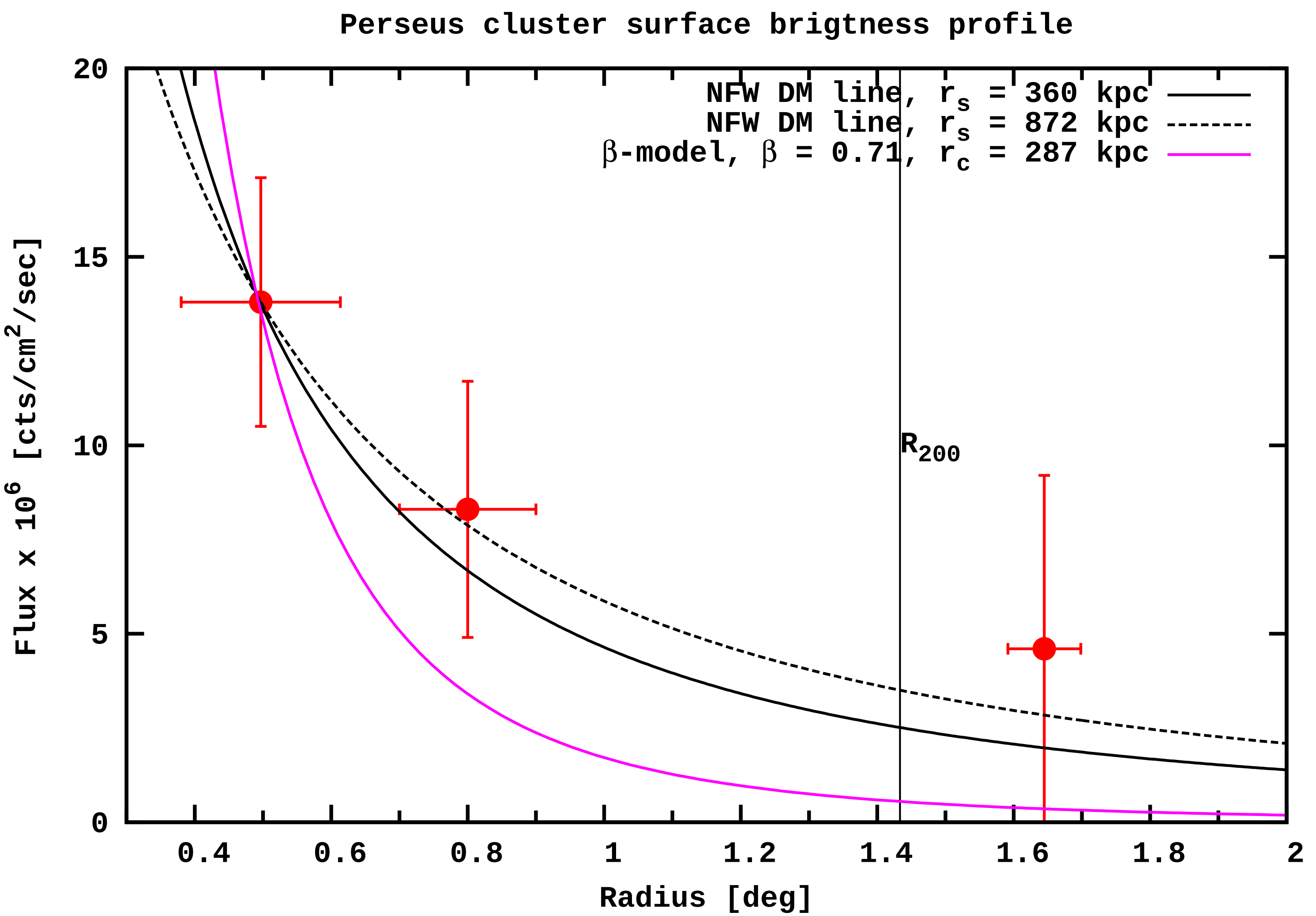


Bulbul et al. ApJ (2014) [1402.2301]

- 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)

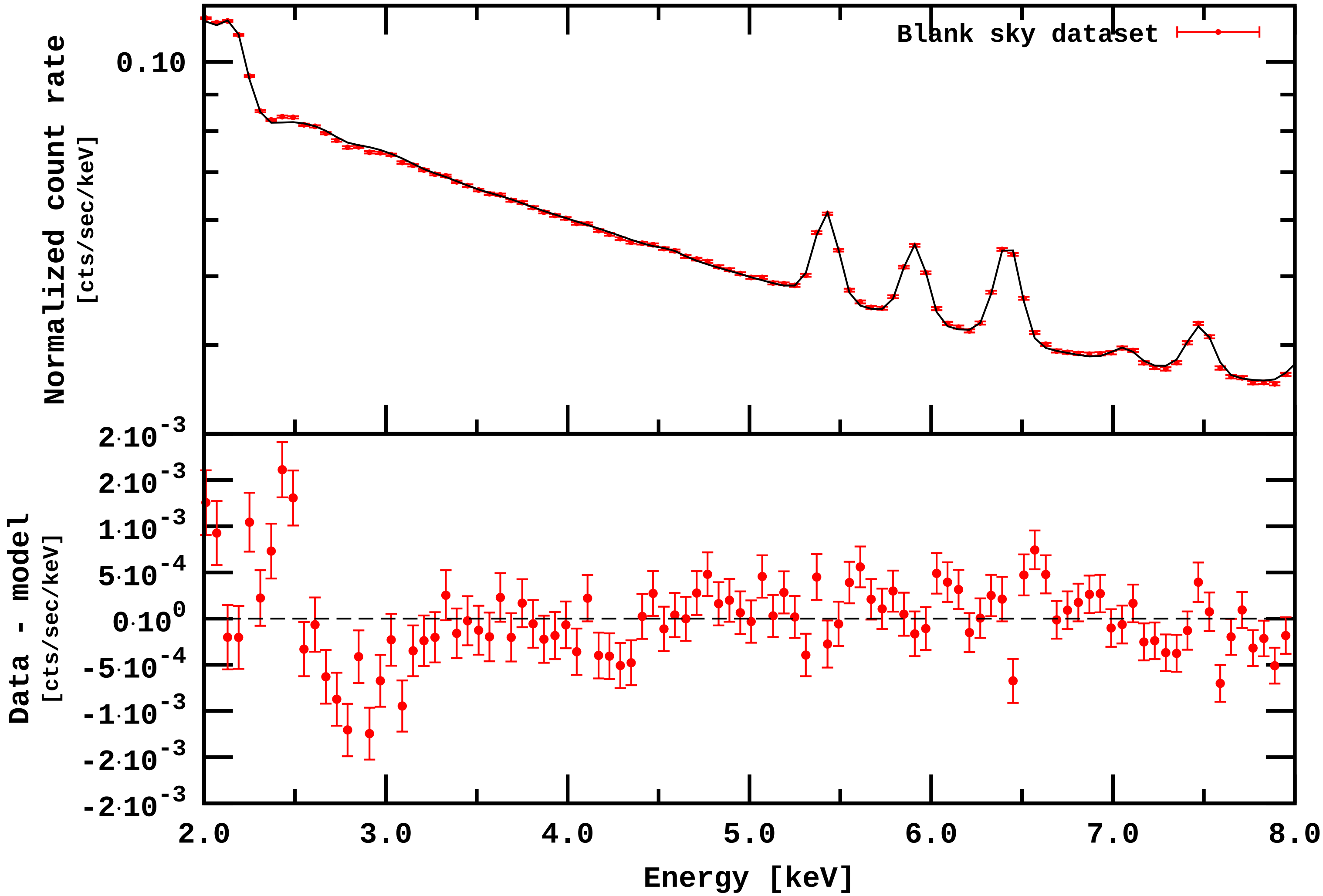
PRL (2014) [1402.4119]



This is not a fit!

Surface brightness profile (Milky Way)?

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

Expect large signal from GC → ``easy'' cross-check