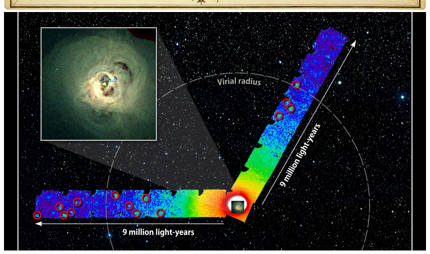
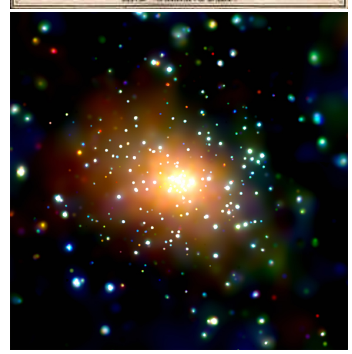
Sterile Neutrino Dark Matter



Oleg RUCHAYSKIY

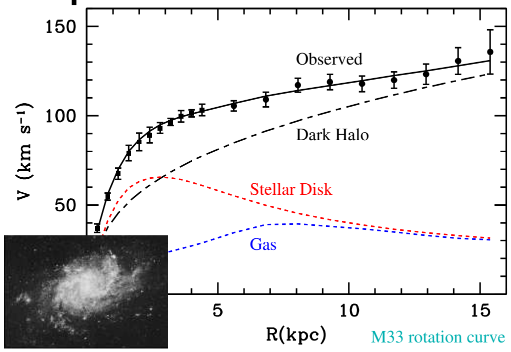
Latest Results in Dark Matter Searches

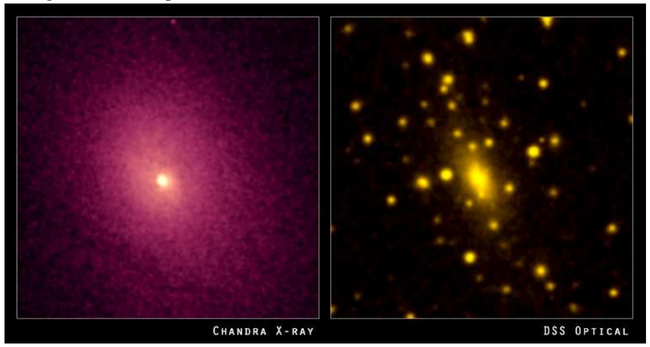


May 12, 2014

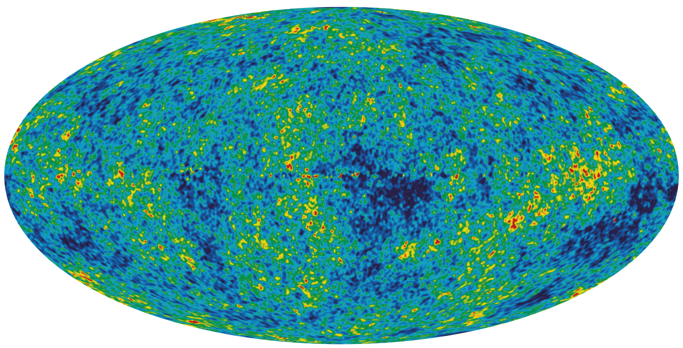
Dark matter wishlist

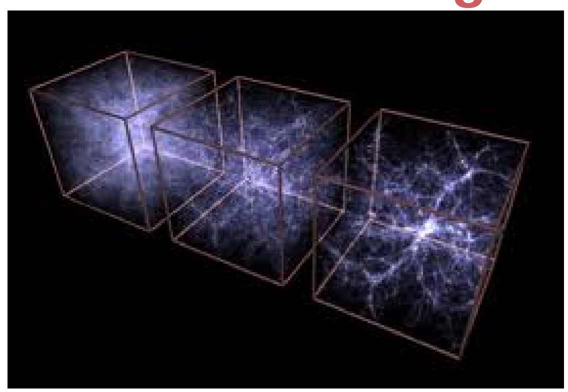
(?) Explains simultaneously **all** phenomena that we call **dark matter**





(?) Explains *both* **astrophysical** *and* **cosmological** dark matter





(?) Is **testable**

(?) Is part of the solution for other beyond-the-Standard-Model problems

Neutrino Dark Matter?

Tremaine & Gunn'79

- Any **fermionic** DM should obey Pauli exclusion principle
  $\Rightarrow$ its mass is bounded from below:

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

Macroscopic quantities   micro-physics

Boyarsky et al [0808.3902]

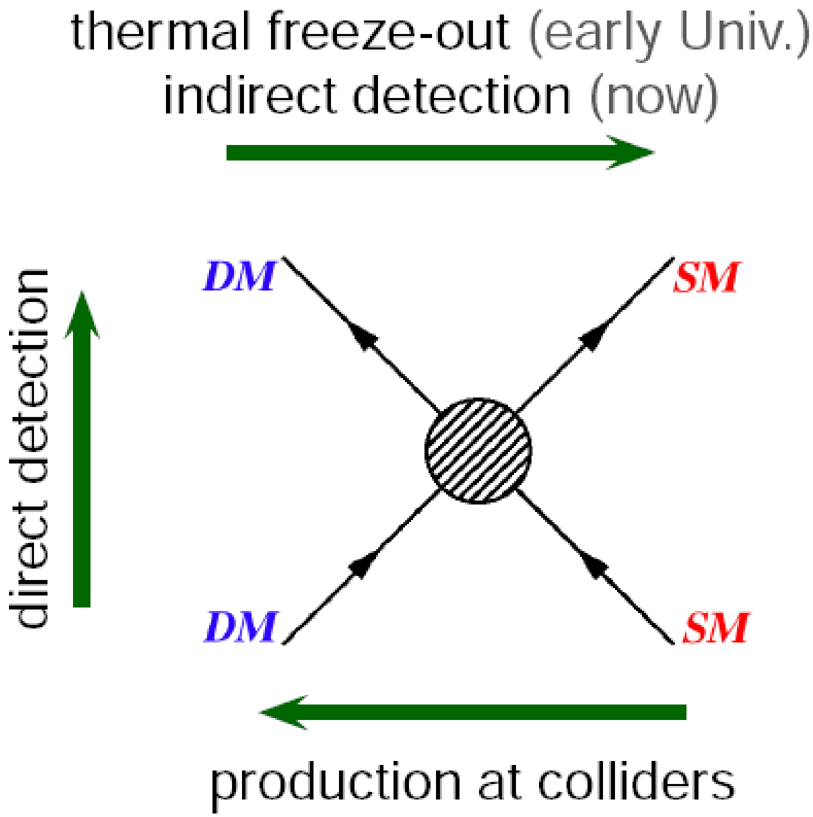
- Dwarf spheroidal galaxies lead to the lower bound on the fermionic DM mass $M_{\text{DM}} \gtrsim 300 - 400$ eV $\leftarrow$ **DM mass from astrophysics**

- Neutrino DM abundance:

$$\text{Fraction of total energy density} = m_\nu \int \frac{d^3k}{(2\pi)^3}\frac{1}{e^{\frac{k}{T}}+1} = \boxed{\frac{m_\nu[\text{eV}]}{94\ \text{eV}}}$$

- **Neutrino DM mass from cosmology:** $M_{\nu DM} \lesssim 11$ eV

Way out: WIMP



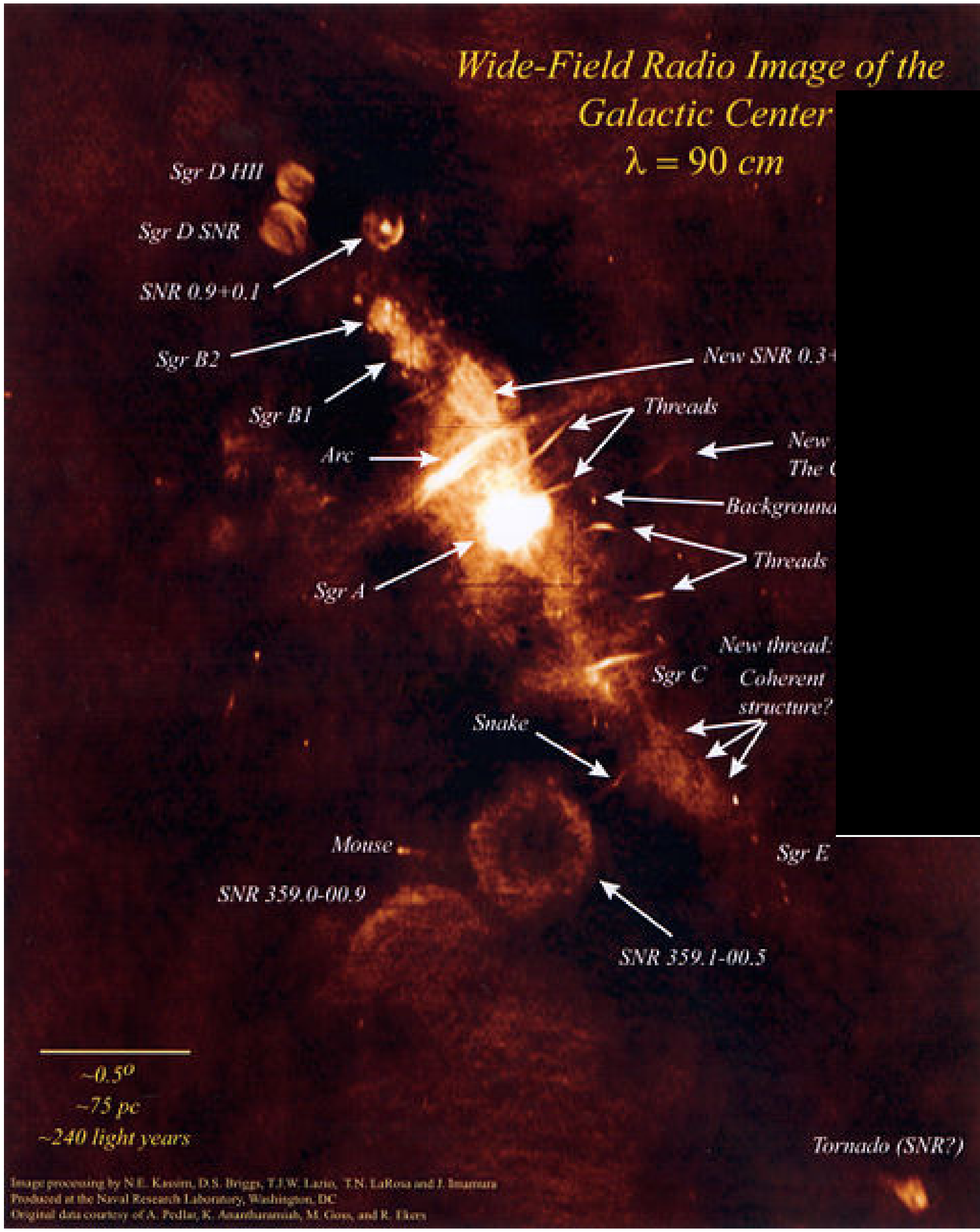
- ✓ Interacts like "neutrino" but is significantly **heavier**. Number density is Boltzmann-suppressed and Tremaine-Gunn-like contradiction is avoided

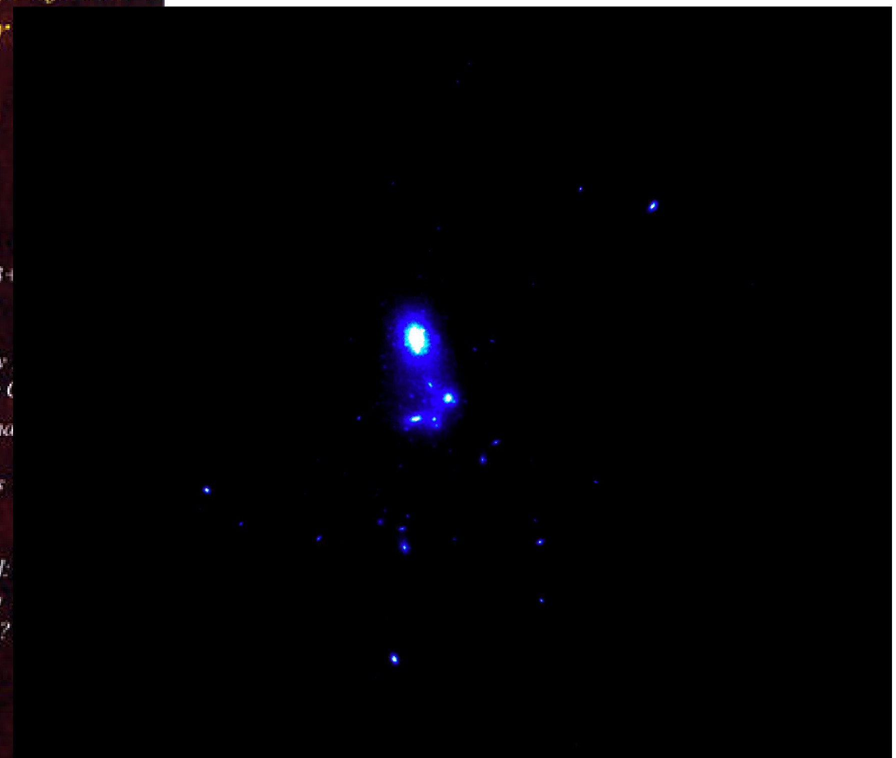
- ✓ The same interaction that is responsible for WIMP production is responsible for its detection today

- ✓ Because of the WIMP miracle is part of the overall "new physics at electroweak scale" paradigme

Very attractive idea. But no signals so far!

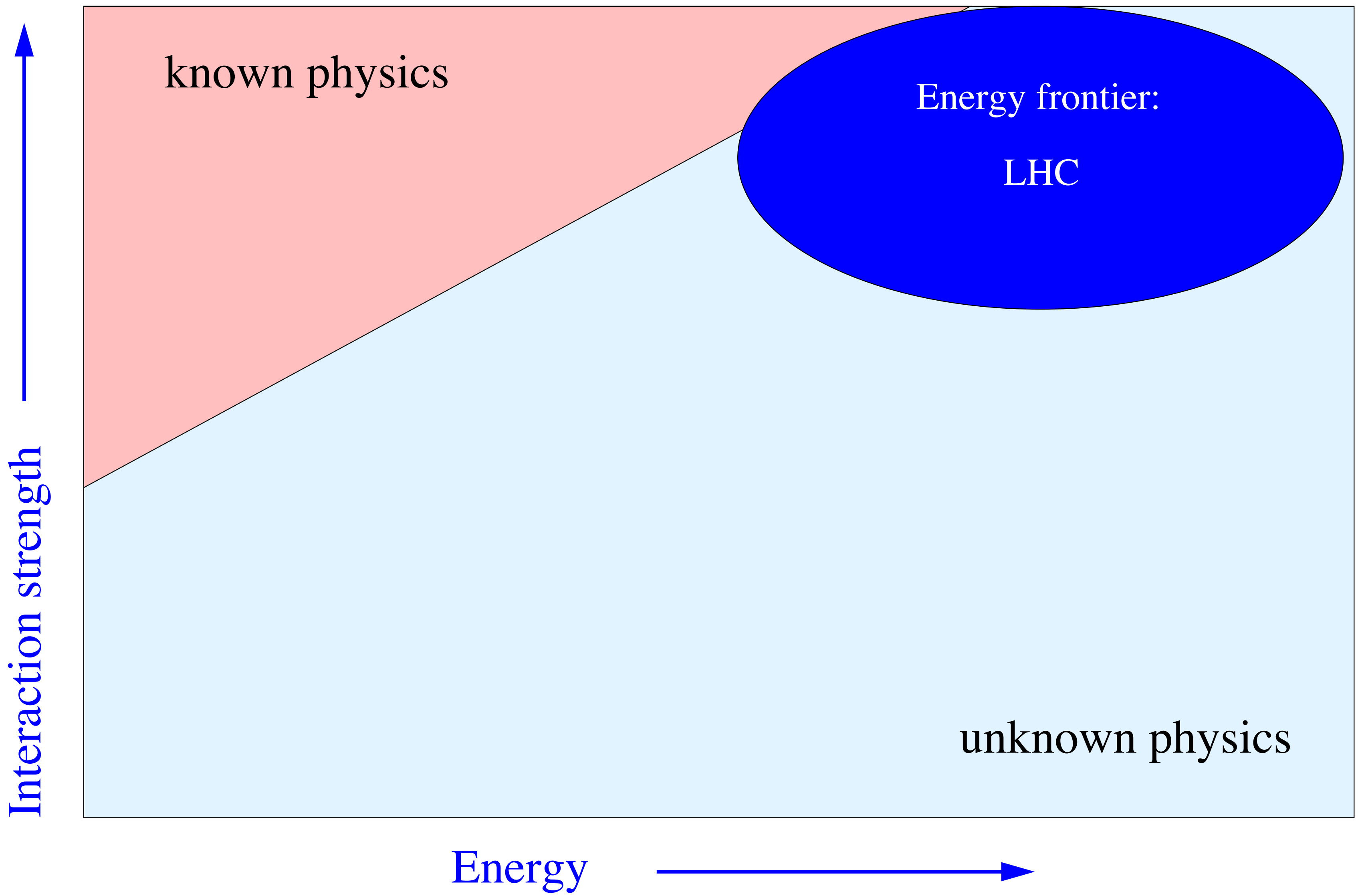
Galactic center is a busy place





Annihilation signal from the Milky way-like galaxy. If found – hard to cross-check

New physics at electroweak scale?



Alternatives?

Another way out: SUPER–weakly Interacting Particles

light and
weakly interacting
~~neutrino~~

↙ ↘

light and
super-weakly interacting
"super" WIMP

heavy and
weakly interacting
WIMP

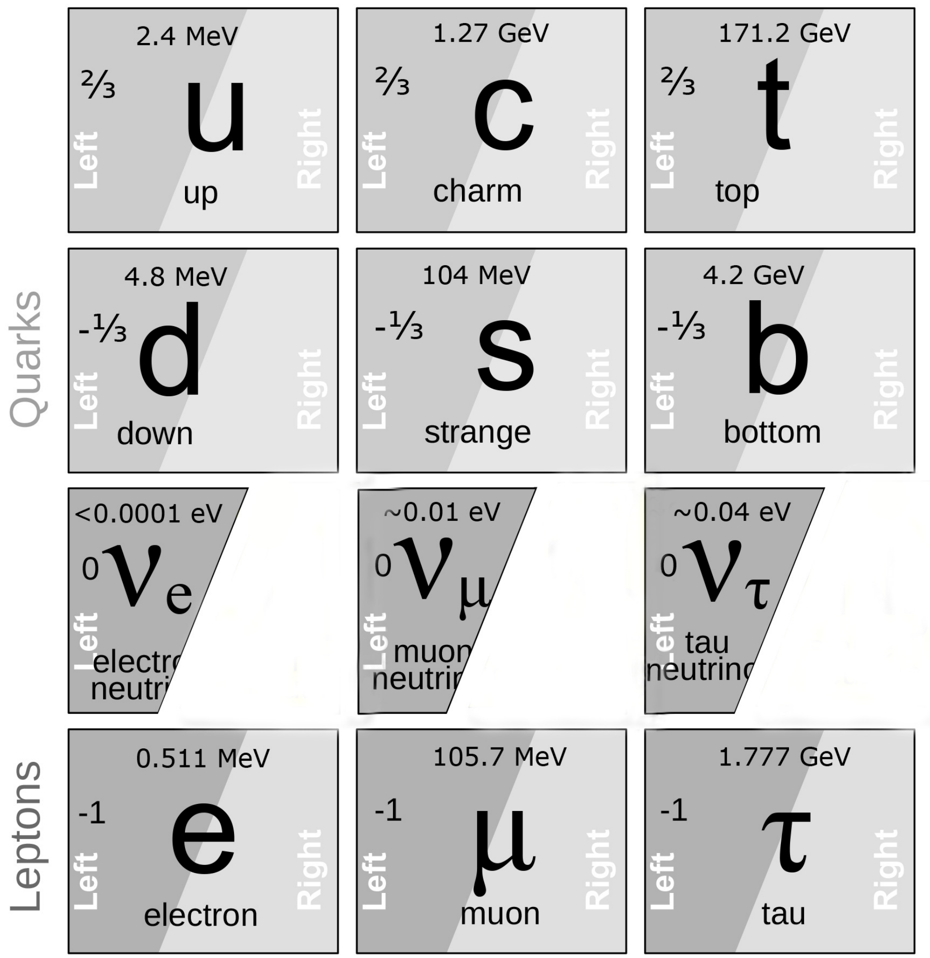
– **Can be light** (all the way to Tremaine-Gunn bound)
particles never enter thermal equilibrium, their number density is highly sub-equilibrium

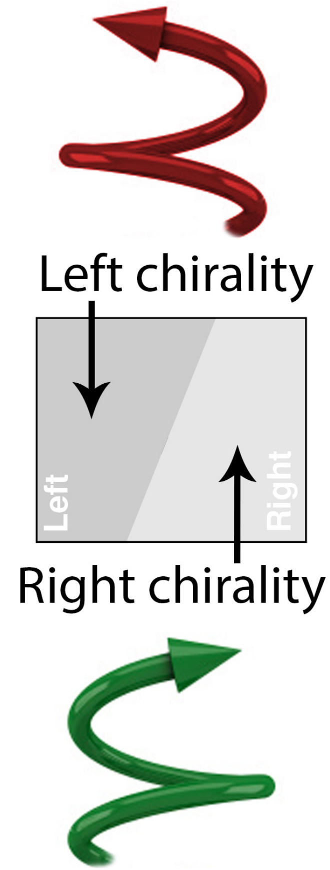
– **Can be warm** (born relativistic and cool down later)

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

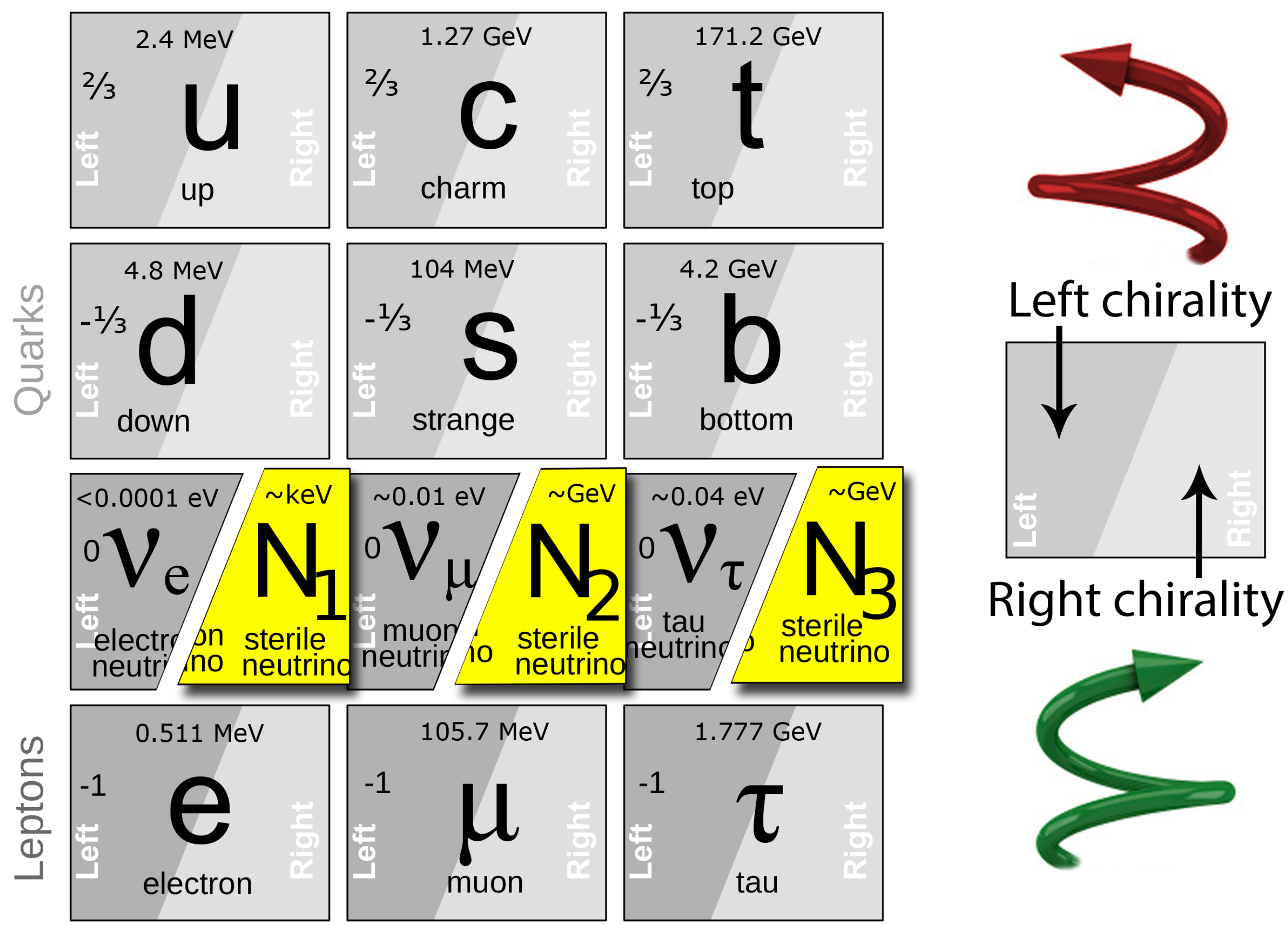
Sterile neutrino dark matter

Oscillations ⇒ new particles!



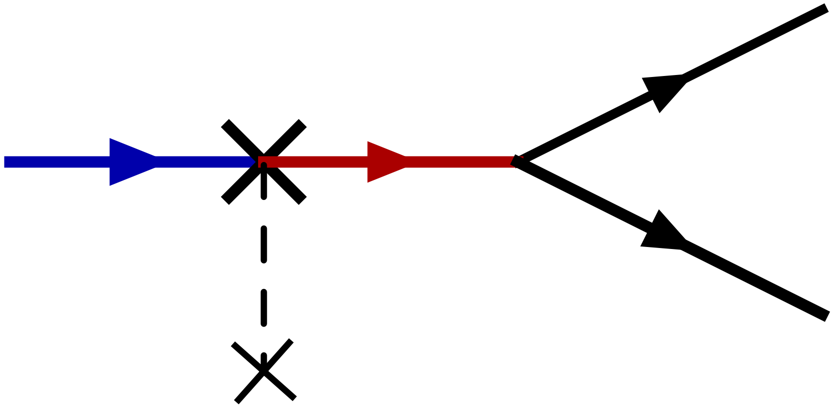


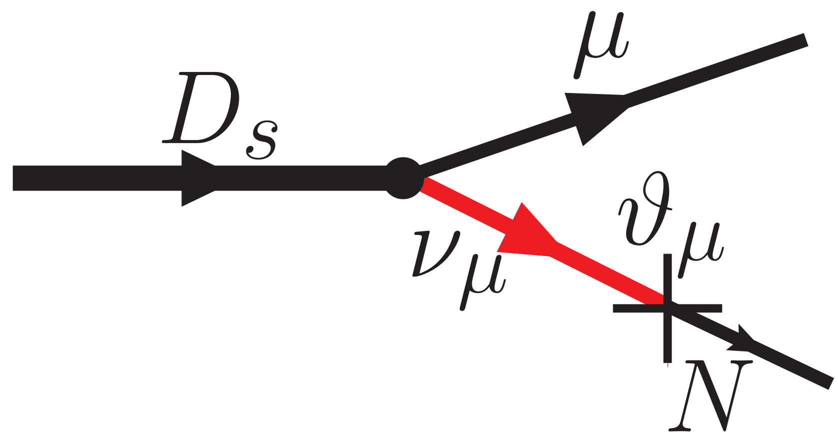
Oscillations ⇒ new particles!



Right components of neutrinos?!

Properties of sterile neutrino





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

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

Sterile neutrino dark matter

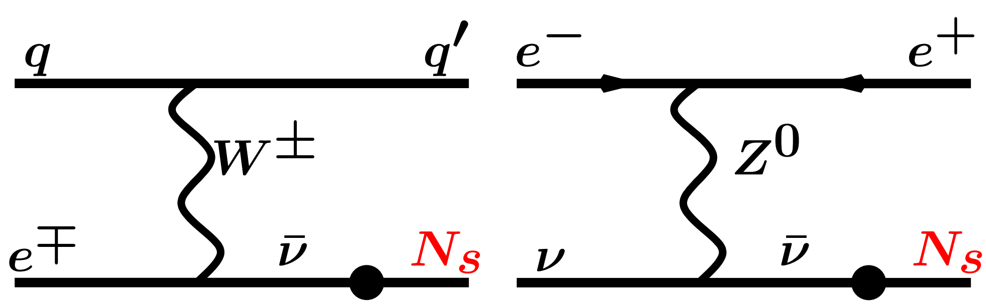
- **Sterile neutrino** is a new neutral particle, interacting **weaker-than-neutrino**

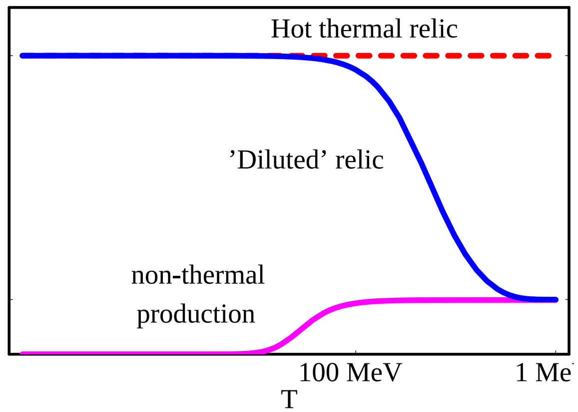
- Never was in thermal equilibrium in the early Universe $\Rightarrow$

$\Rightarrow$ Its abundance **slowly builds up** but **never reaches the equilibrium** value

Dodelson & Widrow'93; Dolgov & Hansen'00

$\Rightarrow$ avoids Tremaine-Gunn-like bound

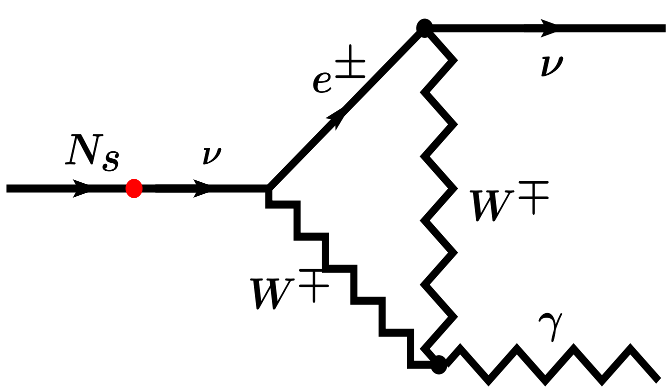




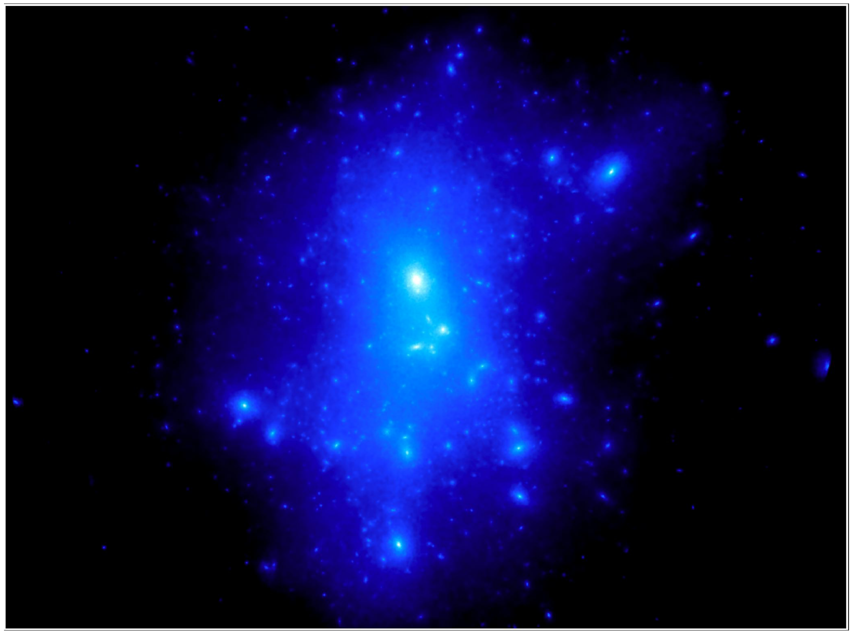
- Once every $\sim 10^8 \div 10^{10}$ scatterings a sterile neutrino is created instead of the active one

Sterile neutrino dark matter

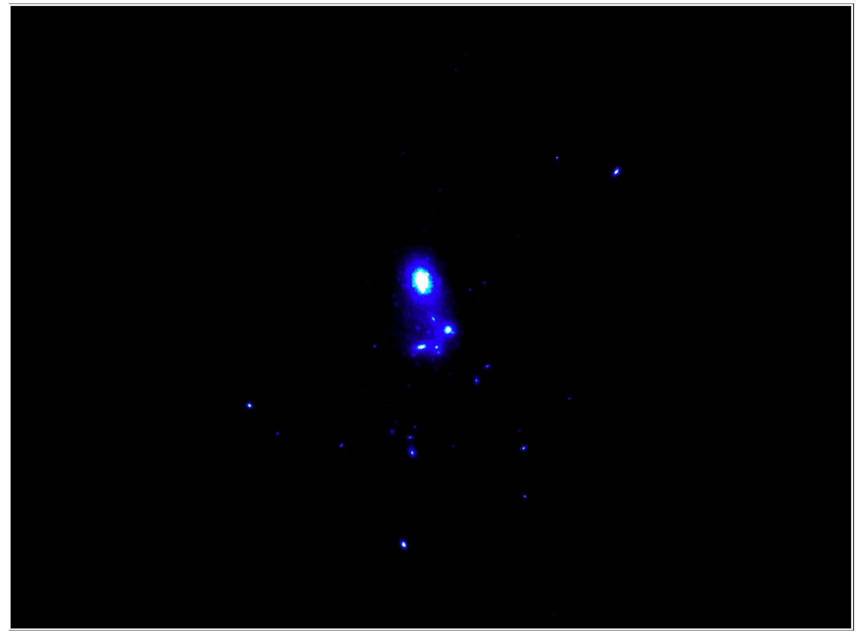
- Very hard/impossible to search at LHC
- Very hard/impossible to search in laboratory experiments
- Can be **decaying** with the lifetime exceeding the age of the Universe
- Can we detect such a rare decay?
- **Yes!** if you multiply the probability of decay by a large number – amount of DM particles in a galaxy (typical amount $\sim 10^{70}$–10^{100} particles)



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

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 $\dfrac{\Delta E}{E_\gamma} \sim \dfrac{v_{\text{vir}}}{c} \sim 10^{-4} \div 10^{-2}$

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

[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

[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…

Data

Our data

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

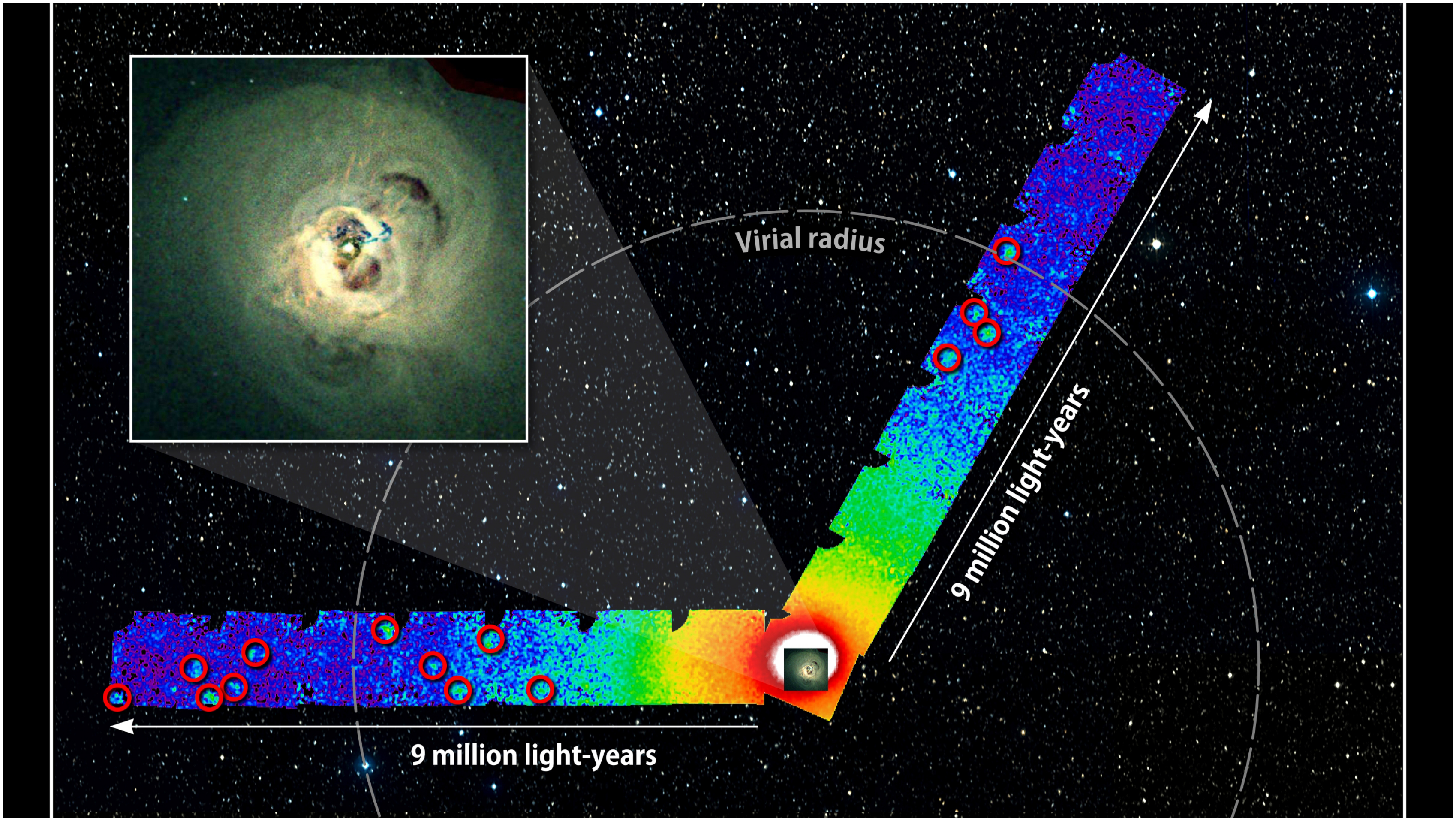
Bulbul et al. 2014

73 clusters	XMM-Newton, central regions of clusters 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

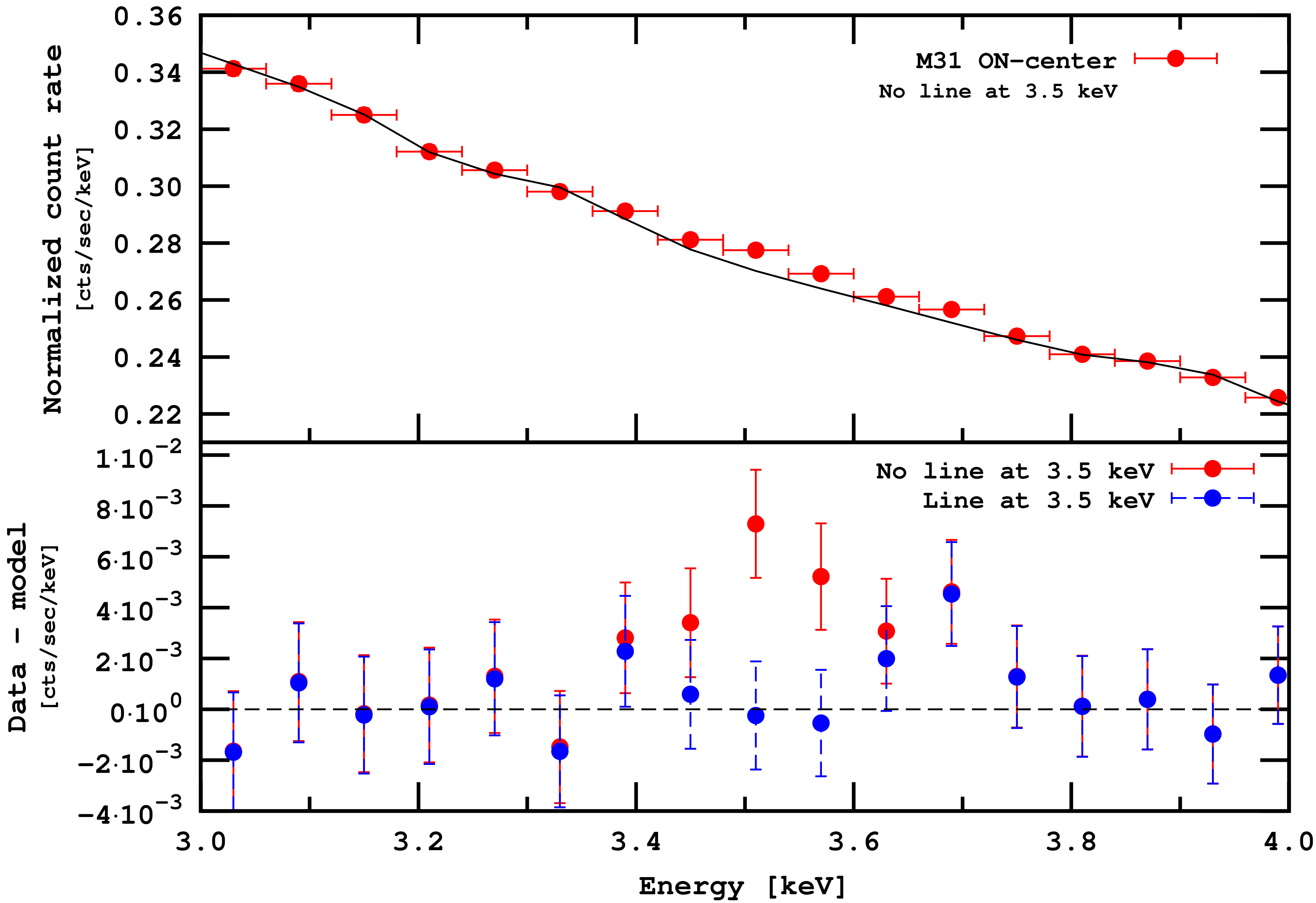


Bulbul et al. took only 2 central XMM observation – $14'$ around the cluster's center

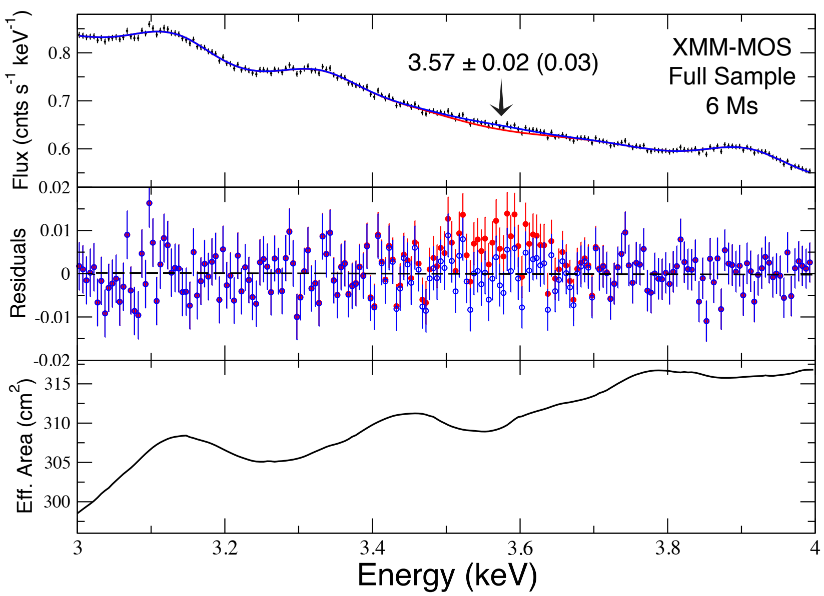
We took 16 observations **excluding** 2 central XMM observations to avoid modeling complicated central emission

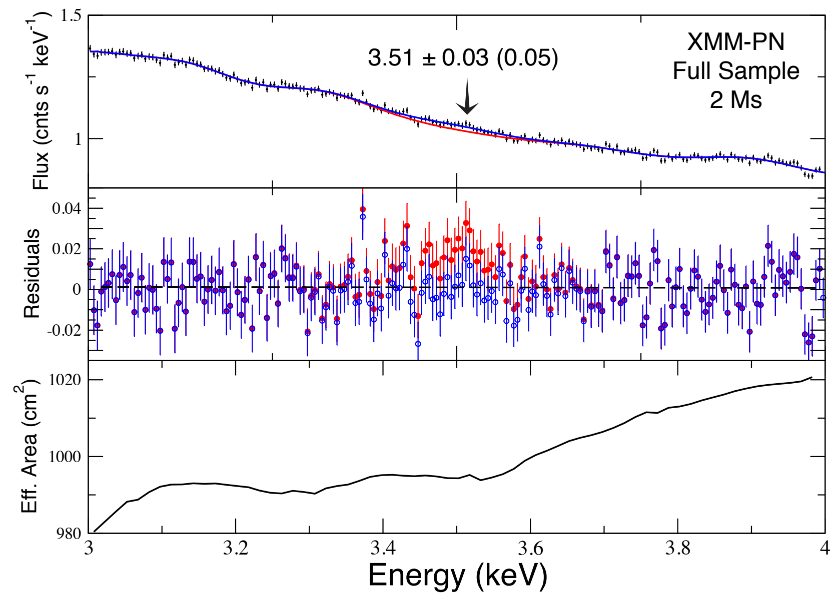
Andromeda galaxy (zoom 3–4 keV)

[1402.4119]

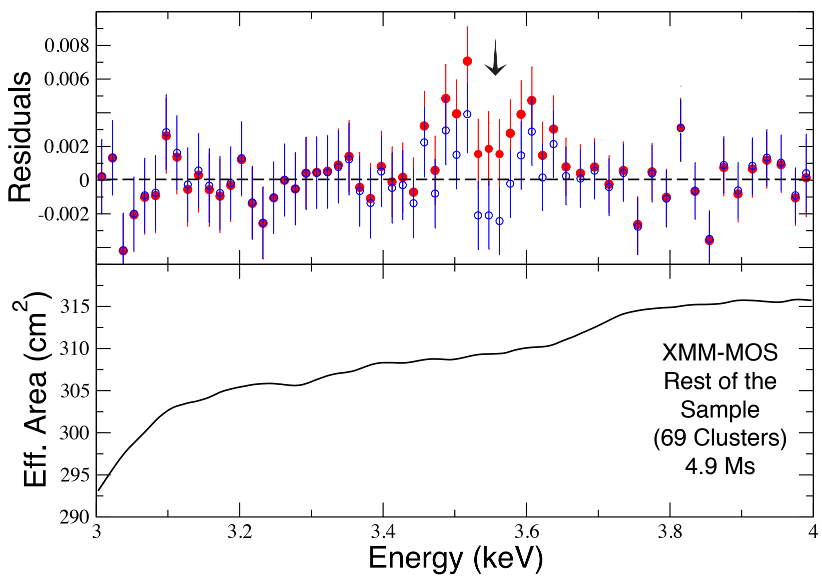


Full stacked spectra





Bulbul et al. [1402.2301]



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

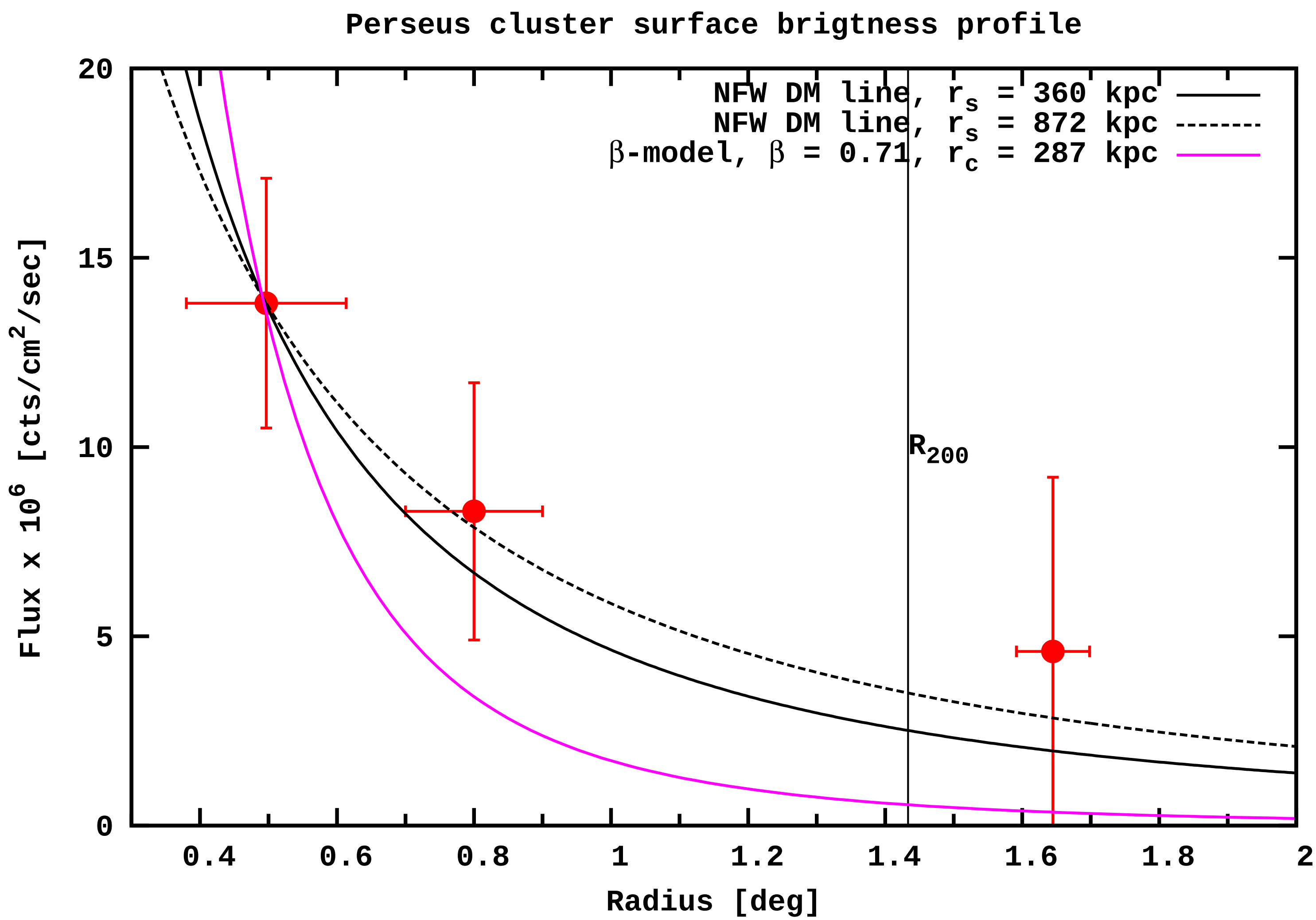
Systematics?

- 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?
- Anomalous line brightness?

Dark matter interpretation

Surface brightness profile (Perseus)

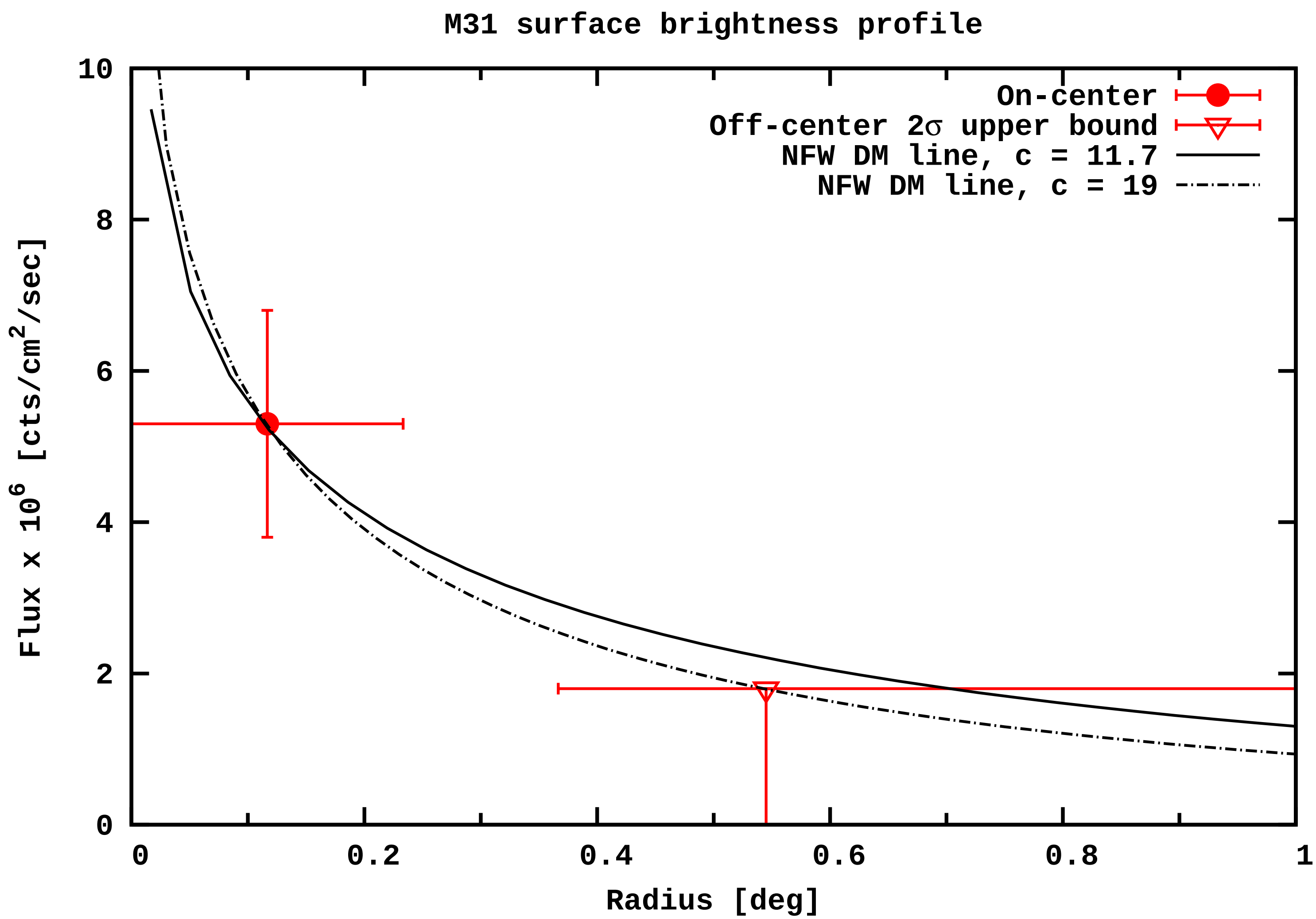
[1402.4119]



This is not a fit!

Surface brightness profile (M31)

[1402.4119]



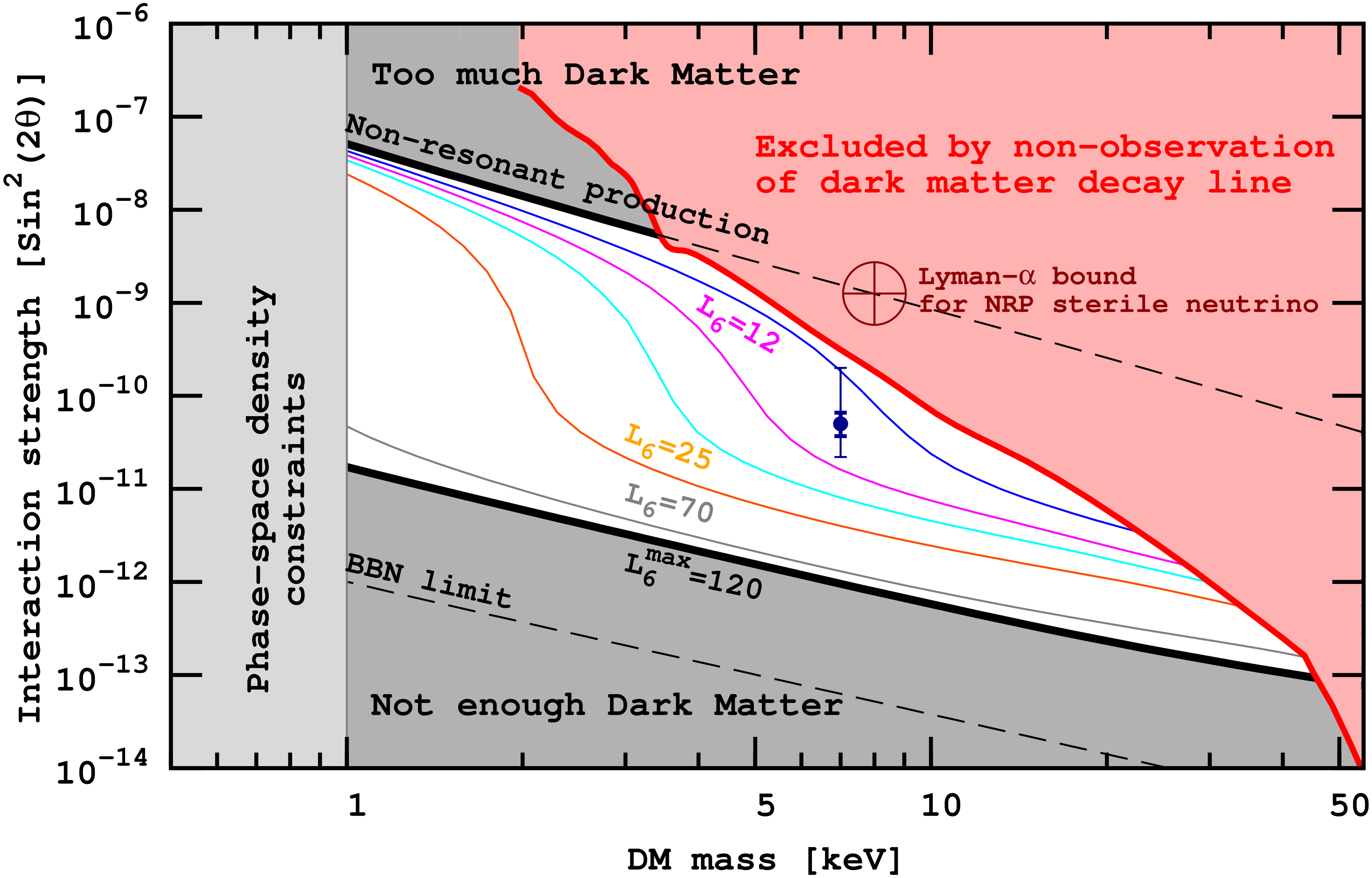
This is not a fit!

Implications if the line is “real”

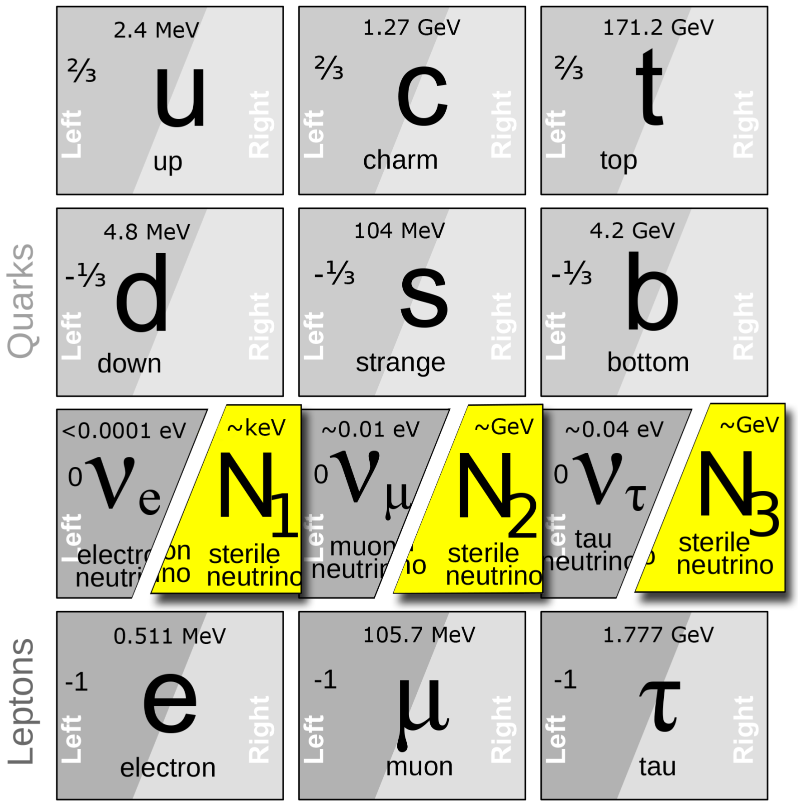
This can be anything

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 and 3.5 keV line



Dark matter and neutrino oscillations



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

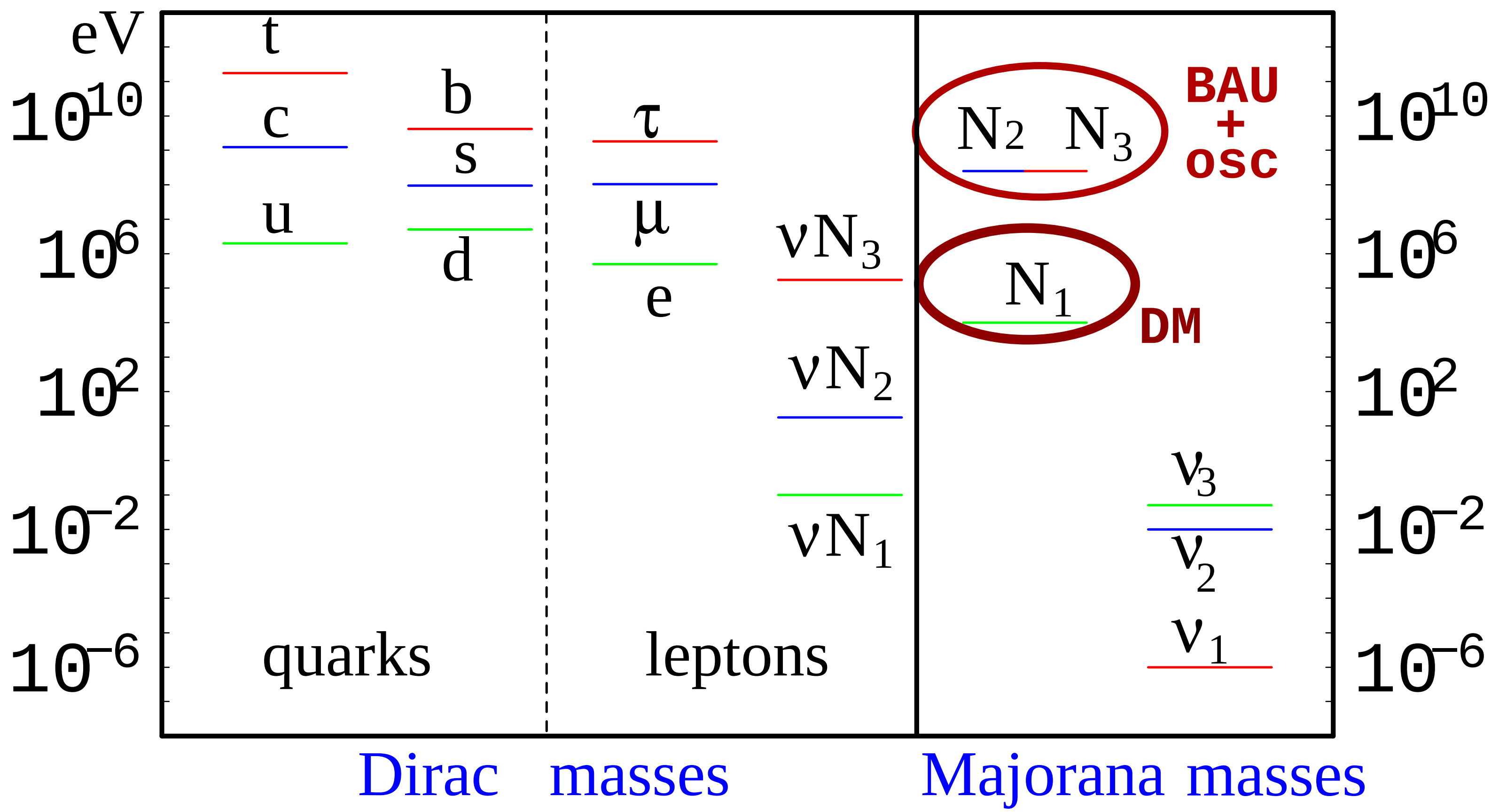
– Are they Dark matter? ⇒ No way! Very short lifetime

– 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, O.R., Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]

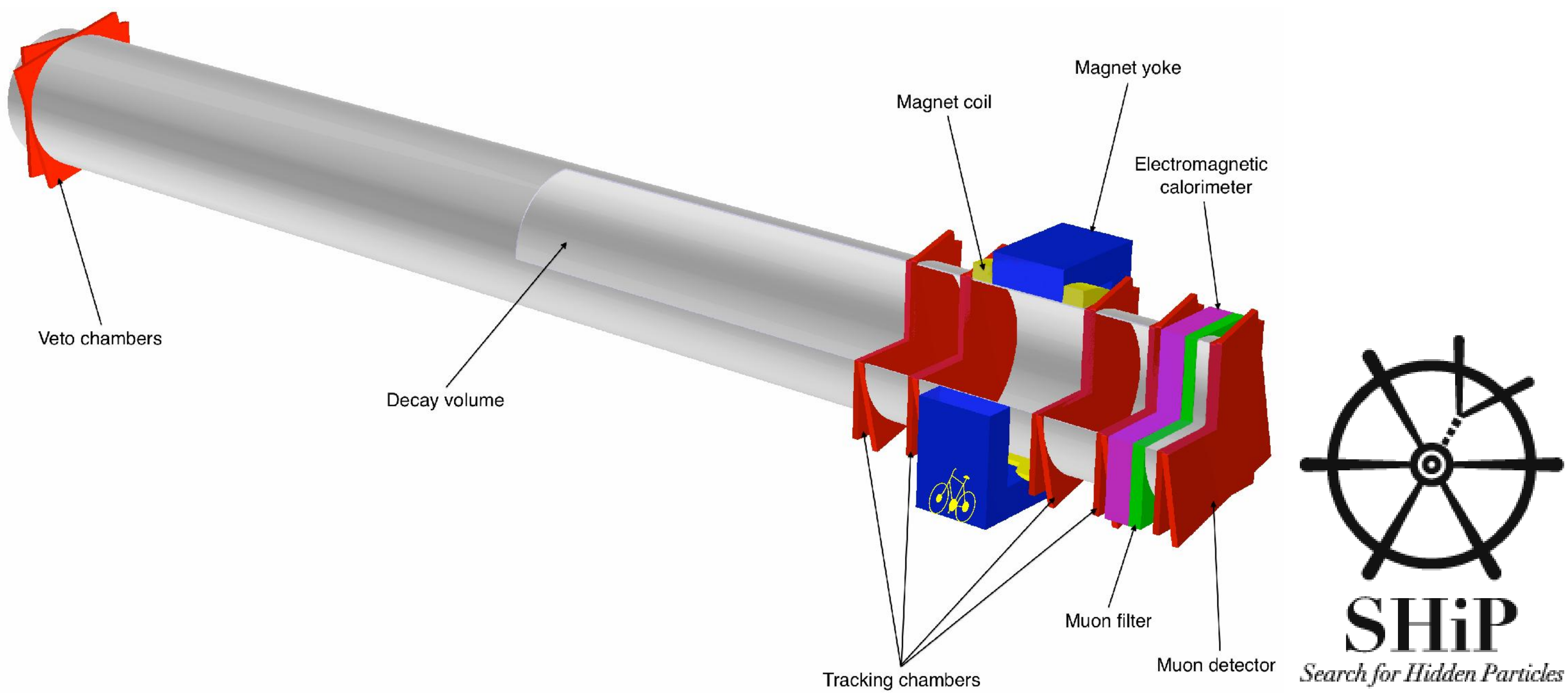
A dedicated experiment

[arXiv:1310.17

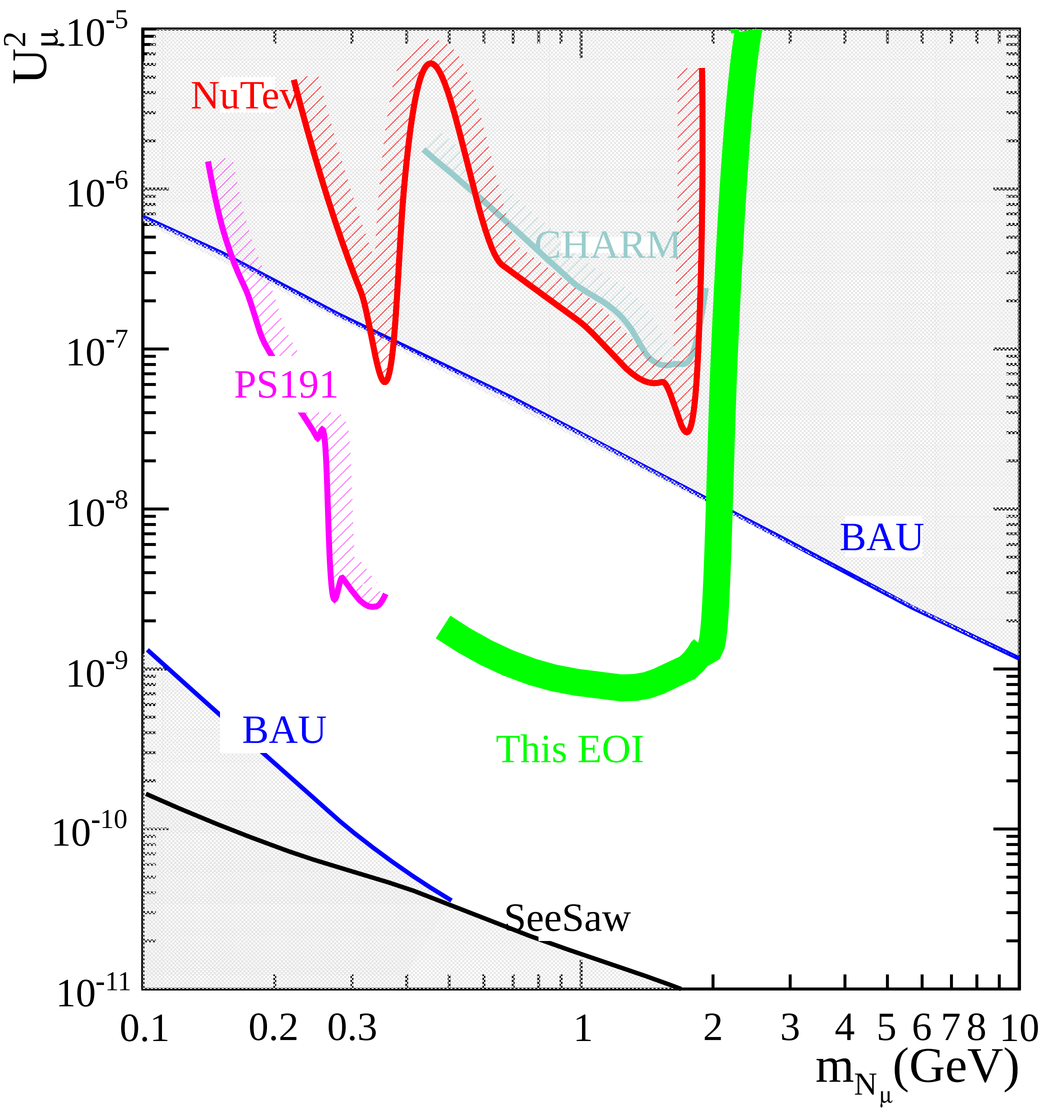
W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, **O. Ruchayskiy**, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille

Proposal to Search for Heavy Neutral Leptons at the SPS

Expression of Interest. Endorsed by the CERN SPS council



Expected sensitivity



Conclusion

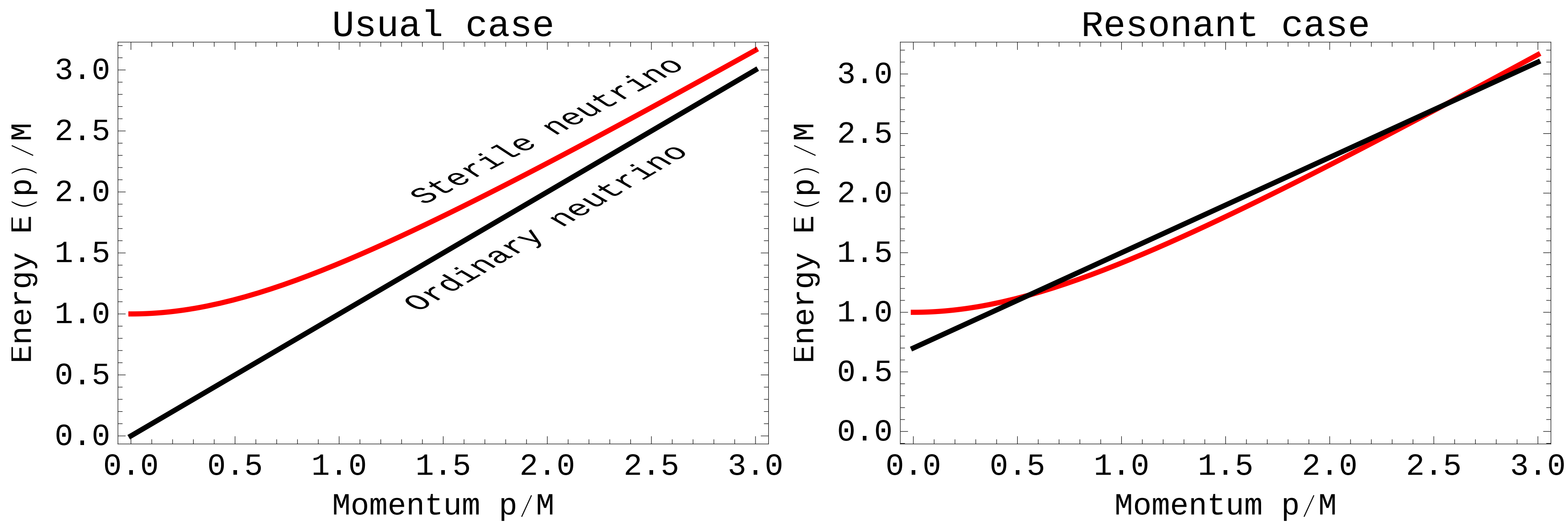
- We see a weak line in the spectra of many DM-dominated objects (clusters) and Andromeda galaxy
- Line does not have obvious systematic interpretation, observed with 4 different detectors
- If this is 7 keV sterile neutrino – its production requires significant lepton asymmetry present in the Universe below sphaleron freeze-out temperature
- 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

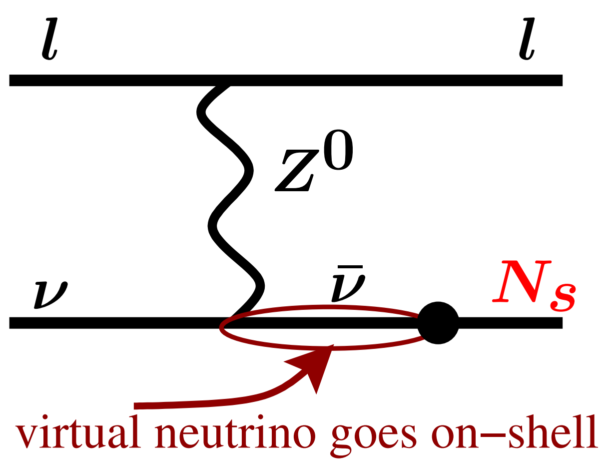
Future? Looks exciting!

Thank you for your attention!

Backup slides

Resonant enhancement





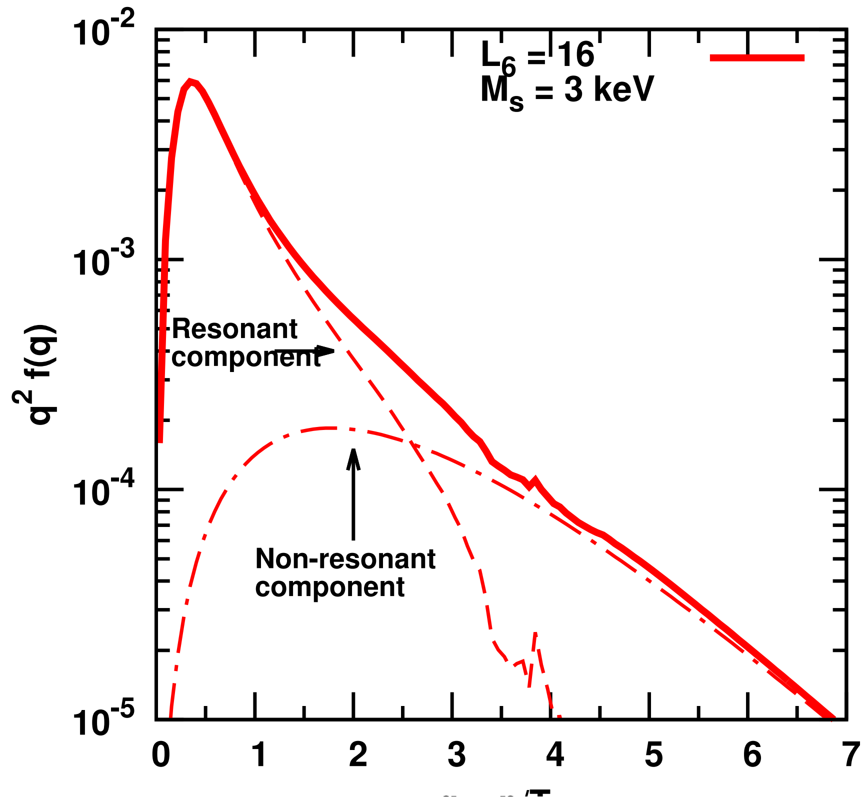
Conversion of ν to N is enhanced whenever "levels" cross and virtual neutrino goes "on-shell" (analog of MSW effect but for active-sterile mixing)

Shi & Fuller [astro-ph/9810076]

Laine & Shaposhnikov [0804.4543]

Resonant enhancement

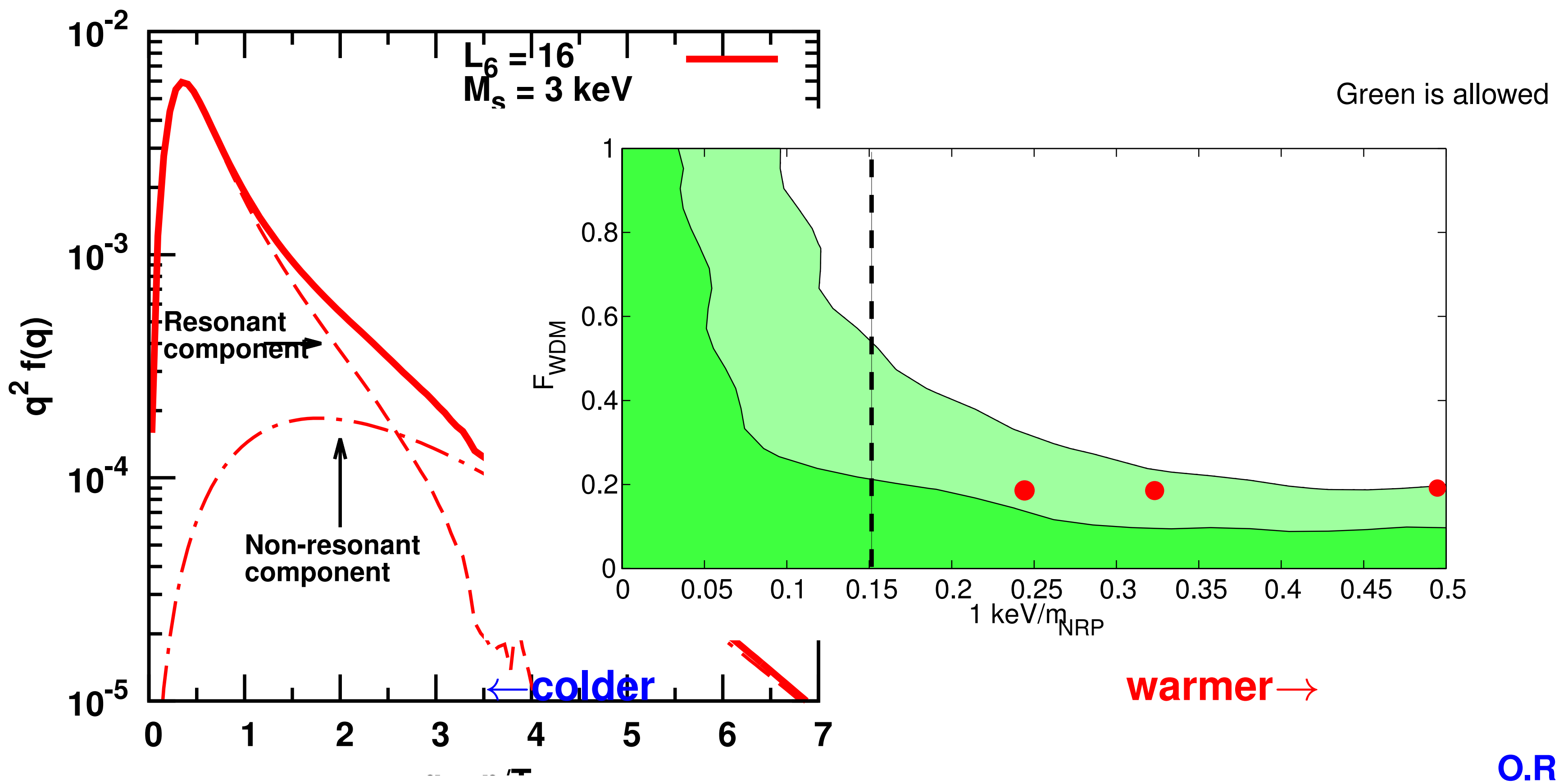
- In the presence of **large lepton asymmetry** the **MSW resonance** can take place and production of sterile neutrinos becomes much more effective



- 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

Structure formation

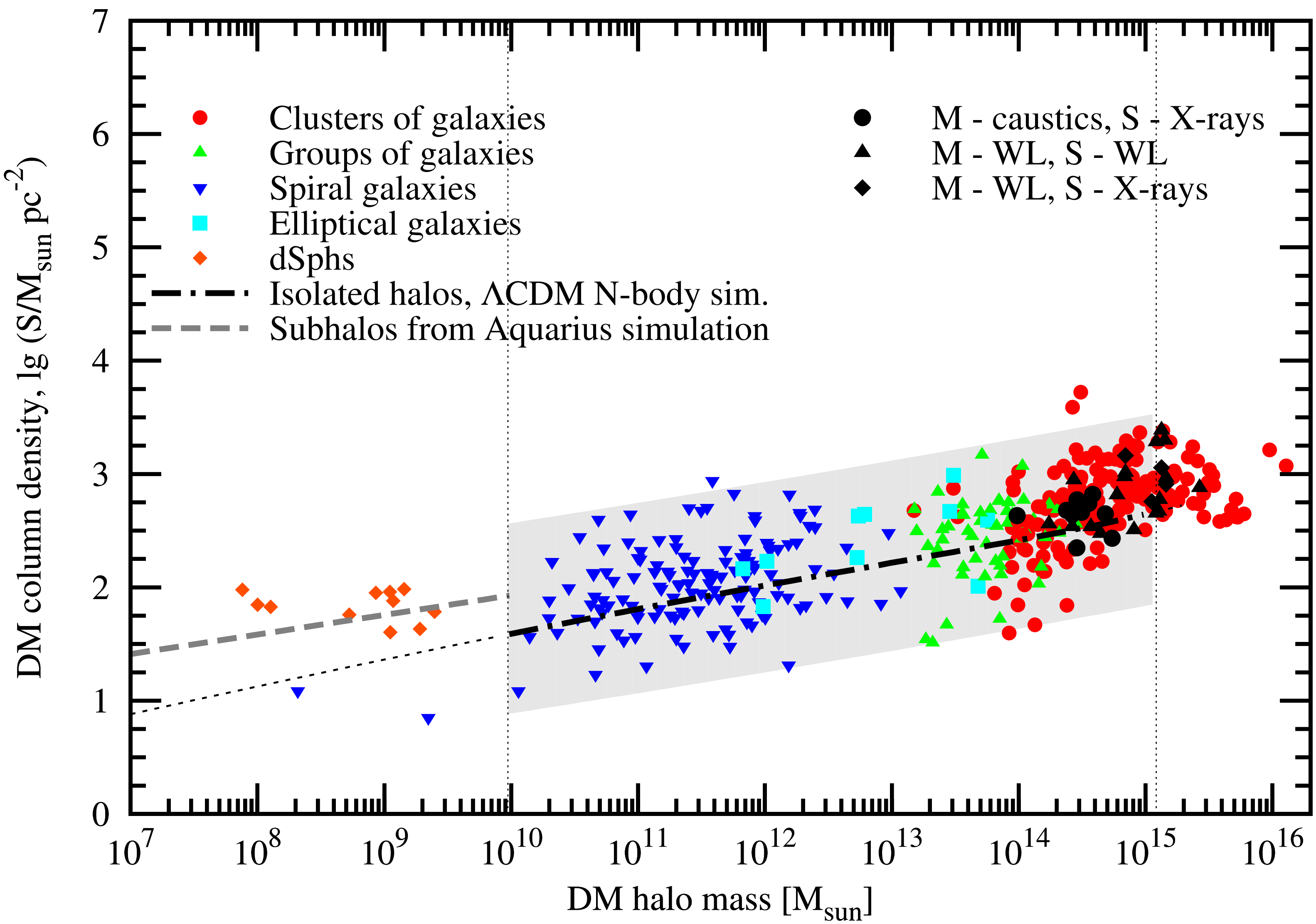


O.R. with
A. Boyarsky et
al. 2008-2009

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

Signal from different DM-dominated objects

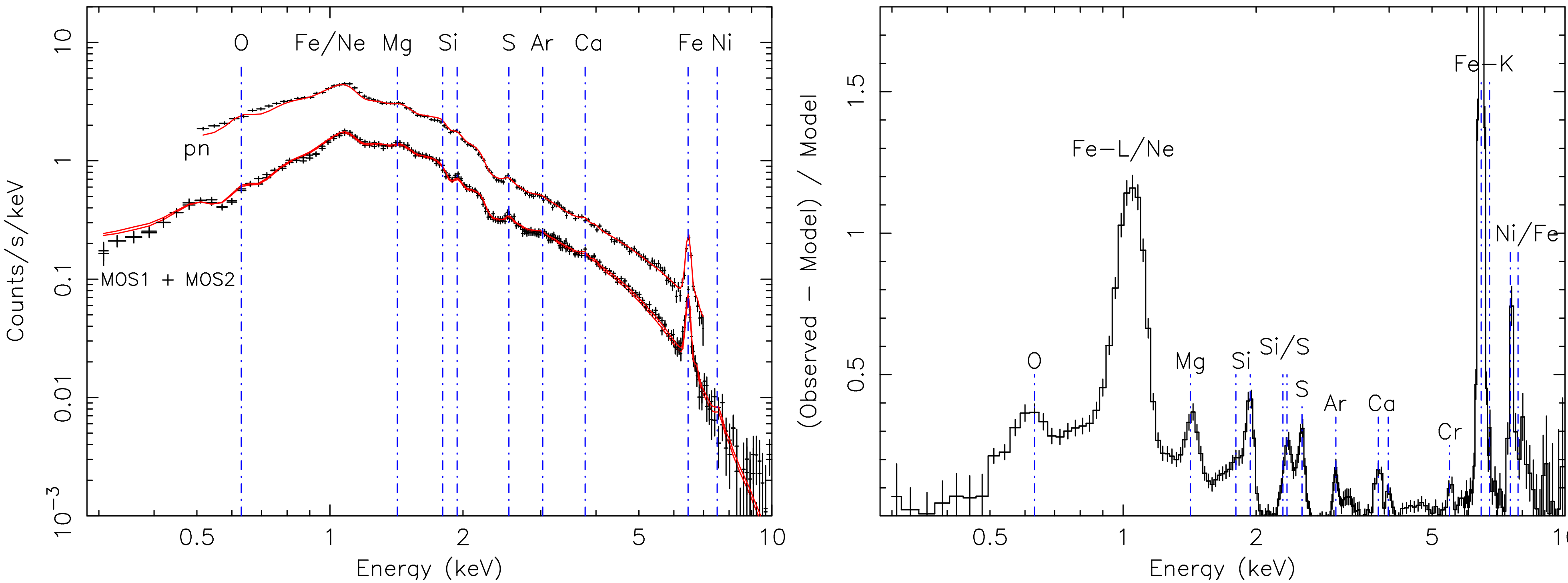
Boyarsky, **O.R** et al. PRL'09



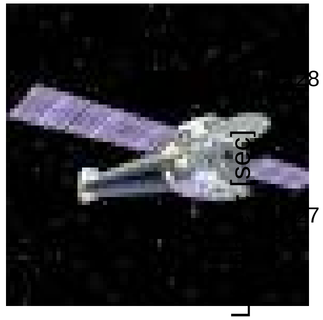
Why clusters do not obviously win?

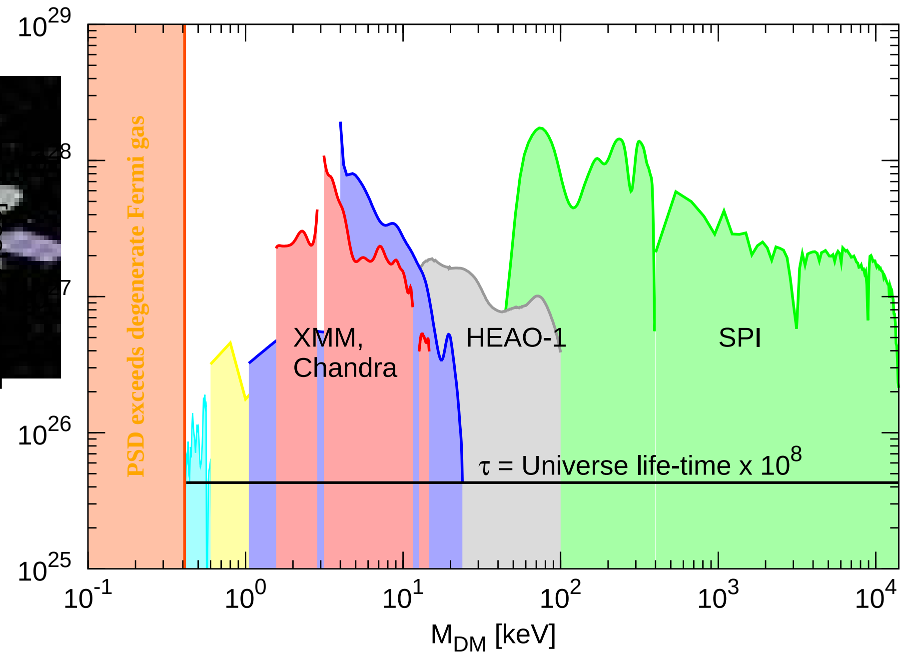
- Virial theorem: $k_B T \sim \frac{G_N M}{D}$ or $T \sim 10\,\mathrm{keV}\left(\frac{\text{Overdensity}}{10^3}\right)\left(\frac{\text{Size}}{\mathrm{Mpc}}\right)$

Werner et al.'2006



Improvements?





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

MW (HEAO-1)
2005

Coma and Virgo clusters
2006

Bullet cluster
2006

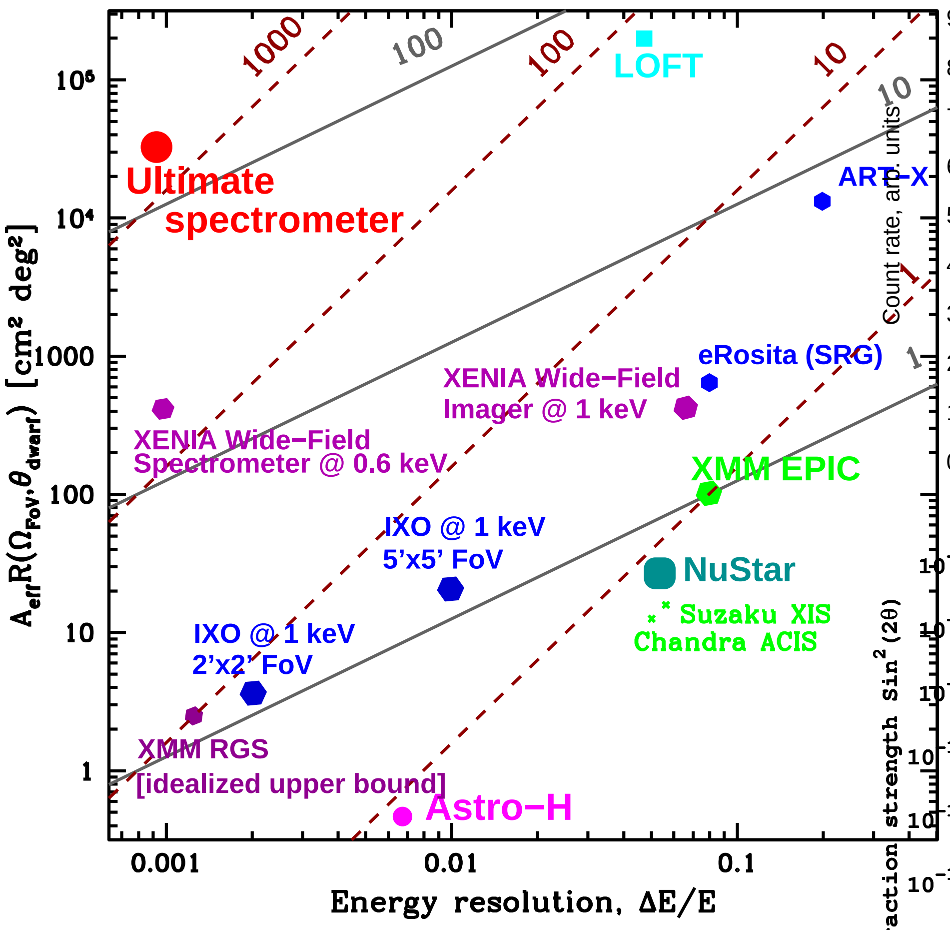
LMC (XMM)
2006

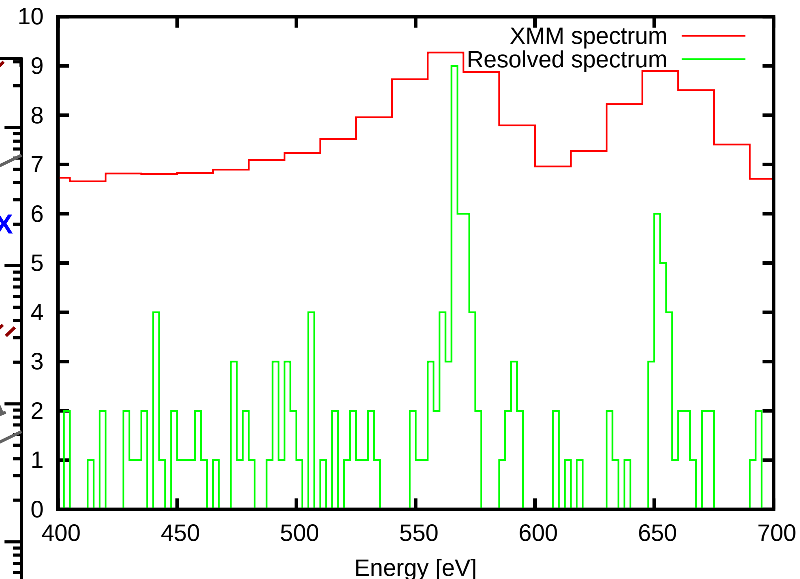
MW (XMM)
2006–2007

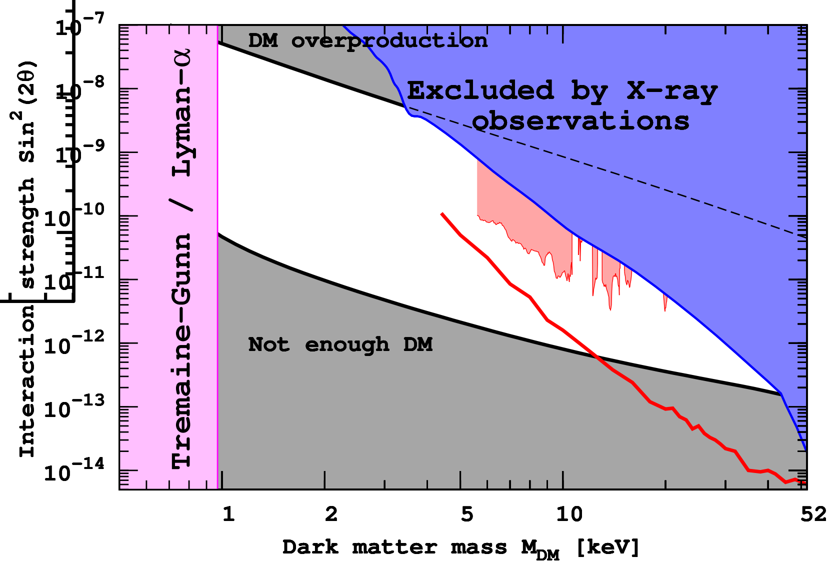
M31 (XMM)
2007, 2010

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

X-ray spectrometer to search for decaying Dark Matter





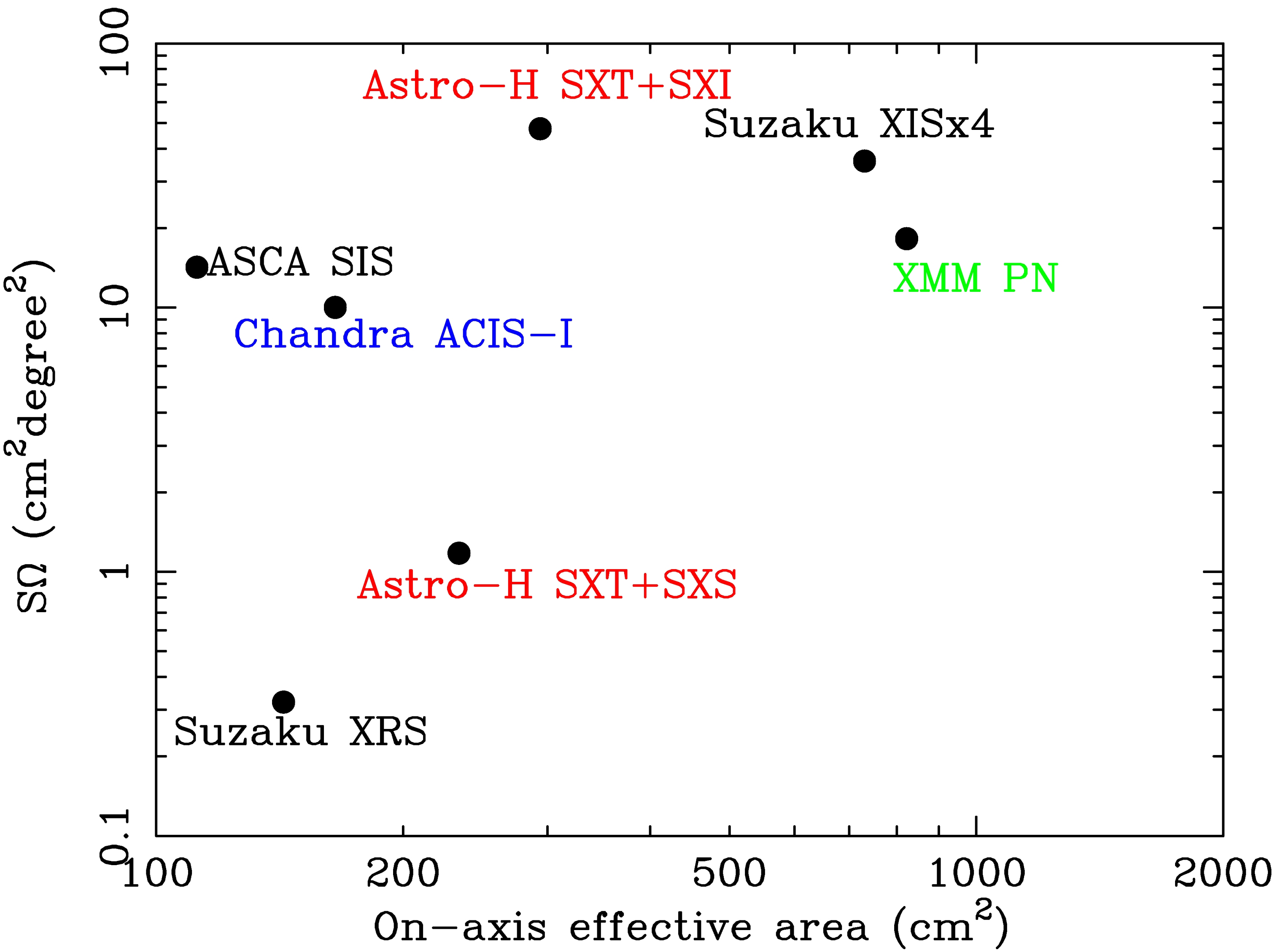


[1312.5178]
A.B. with Neronov et al.

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

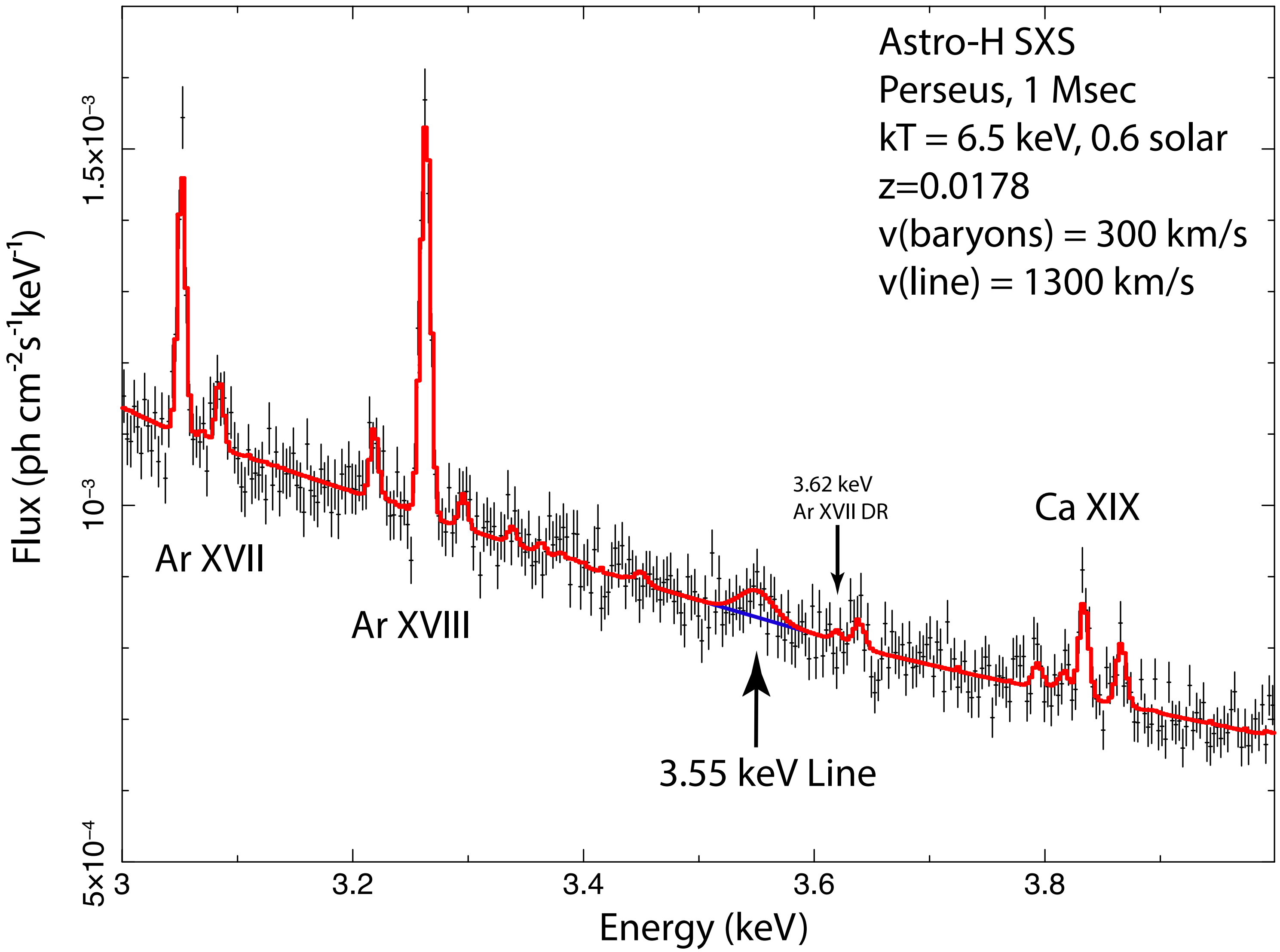
Astro-H: spectrometer

Collecting power of an instrument

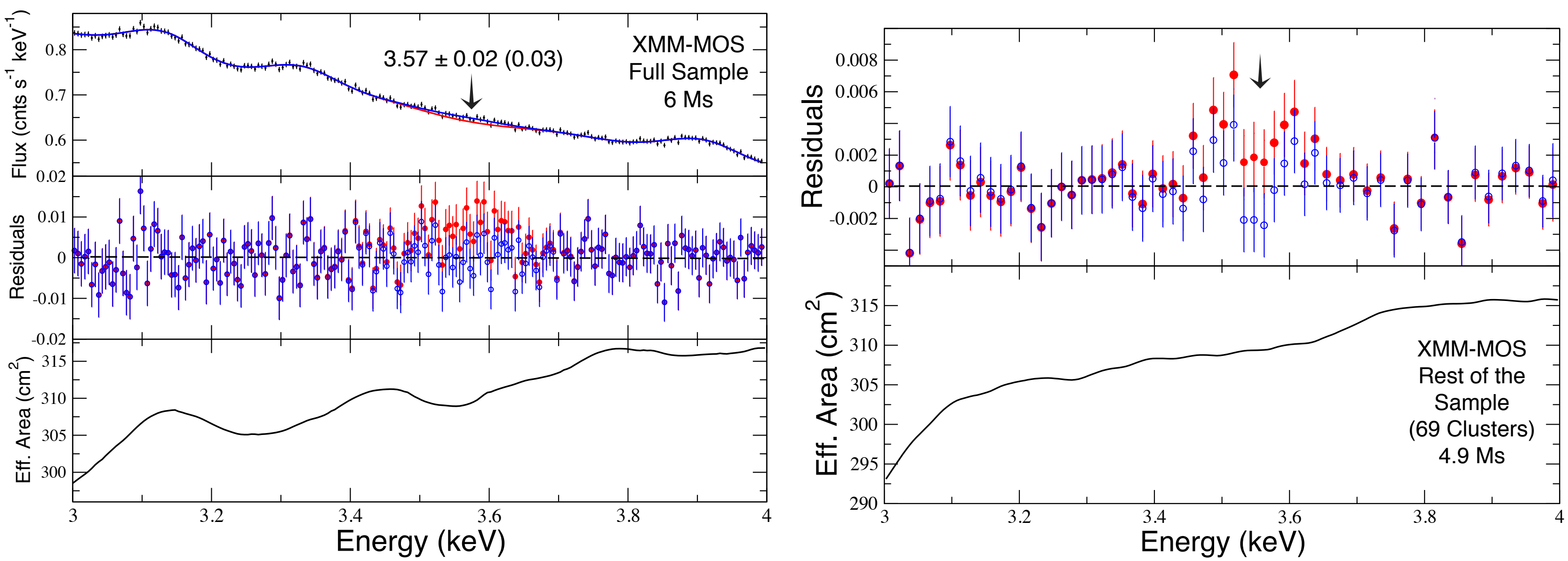


Astro-H: better spectral resolution

[1402.2301]



Wiggle in the effective area?

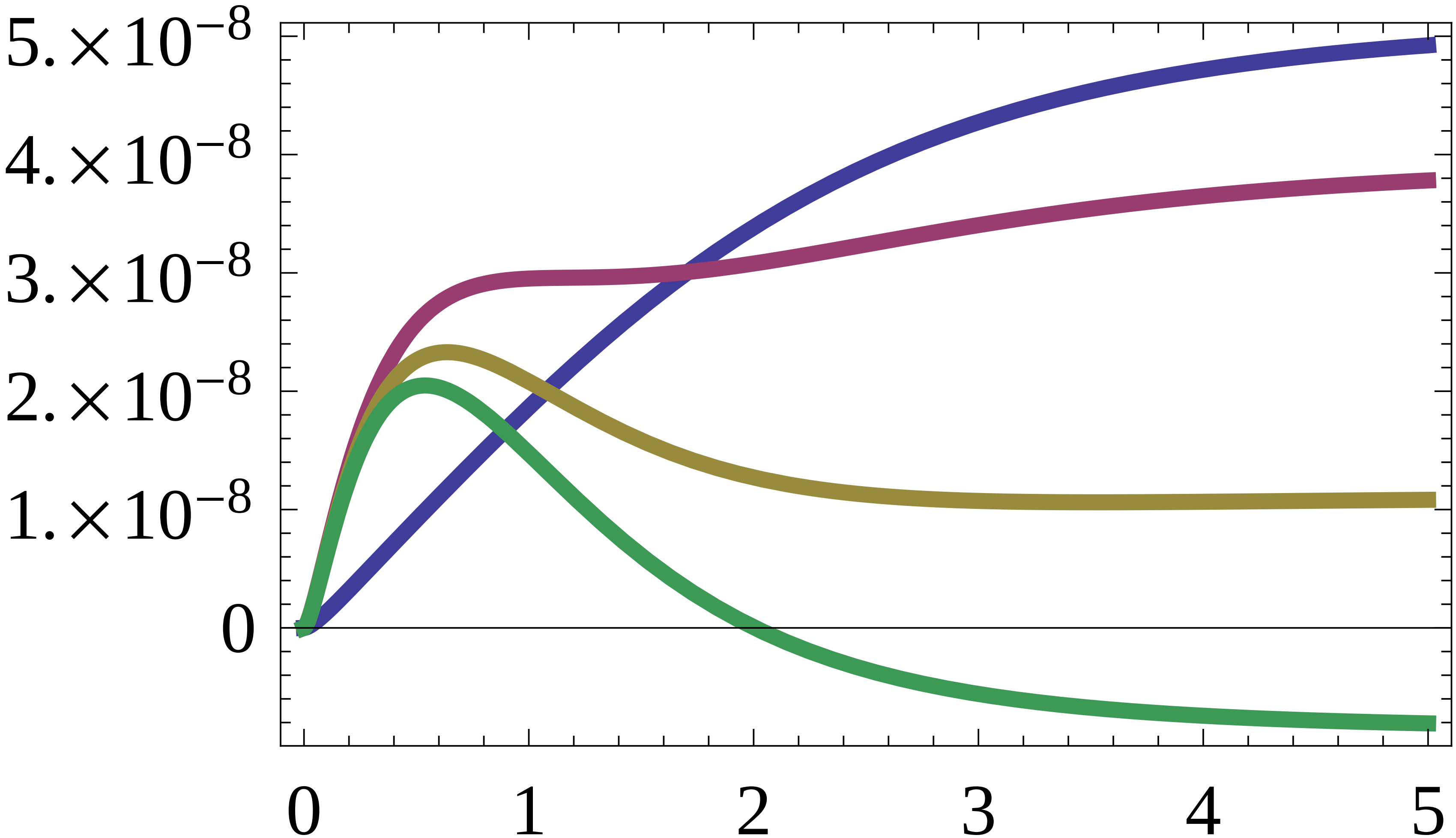


Bulbul et al. [1402.2301]

- 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, **O.R.** et al.)

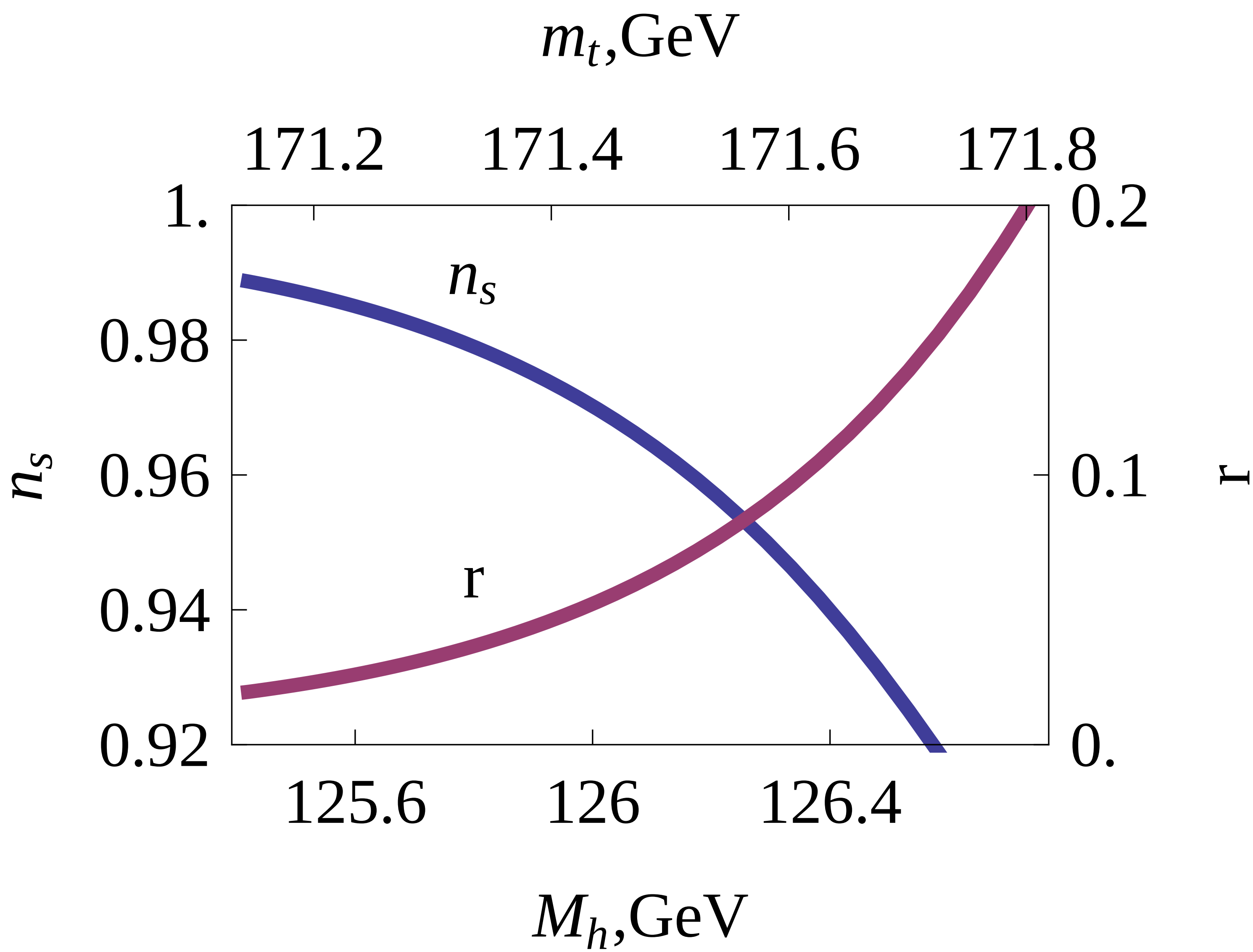
Inflation with Higgs boson

1403.5043
1403.6078



Higgs inflation and tensor modes

1403.6078

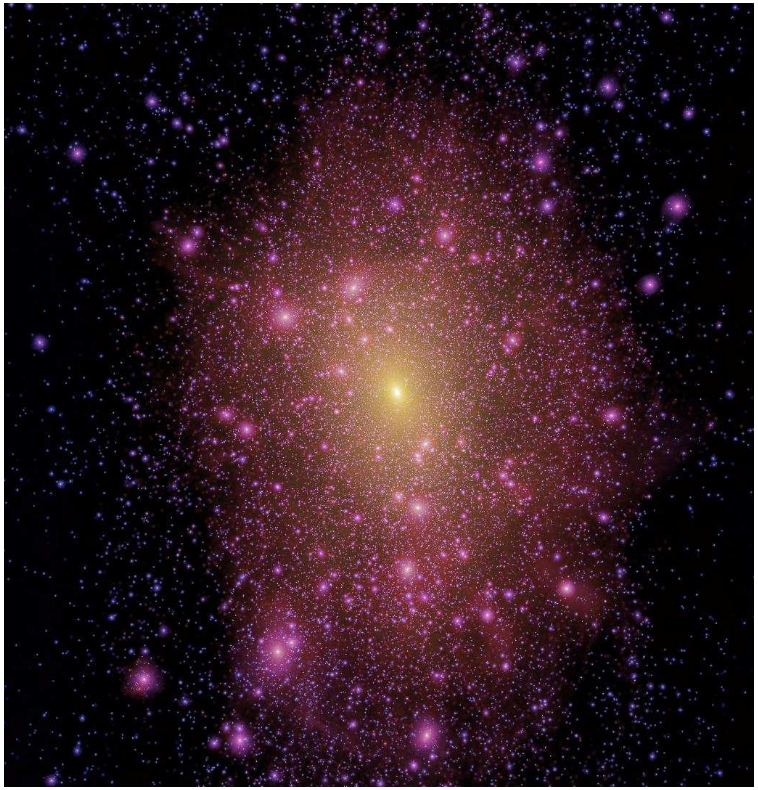


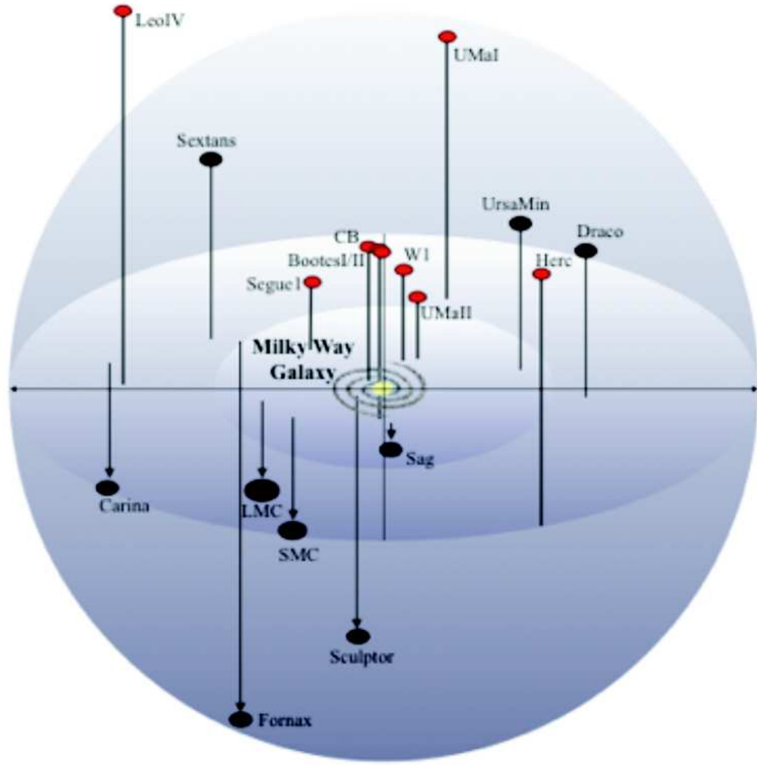
Halo (subhalo) mass function

. . . number of halos (galaxies) of different mass . . .

- Missing satellite problem
- Too big to fail problem

Halo substructure in "cold" DM universe



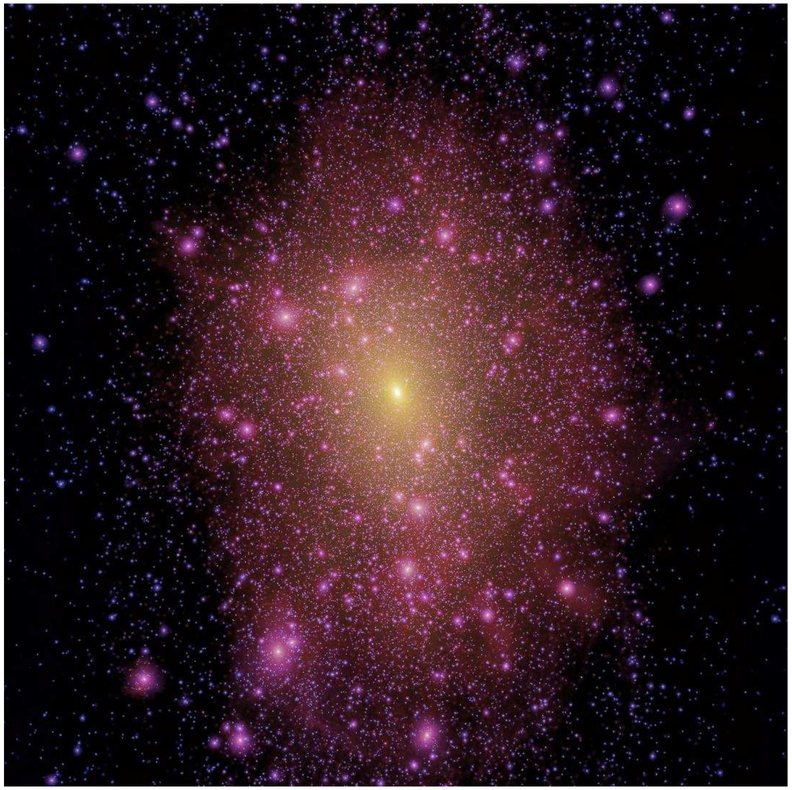


COLD DM models predict millions of substructures within a galaxy like Milky Way

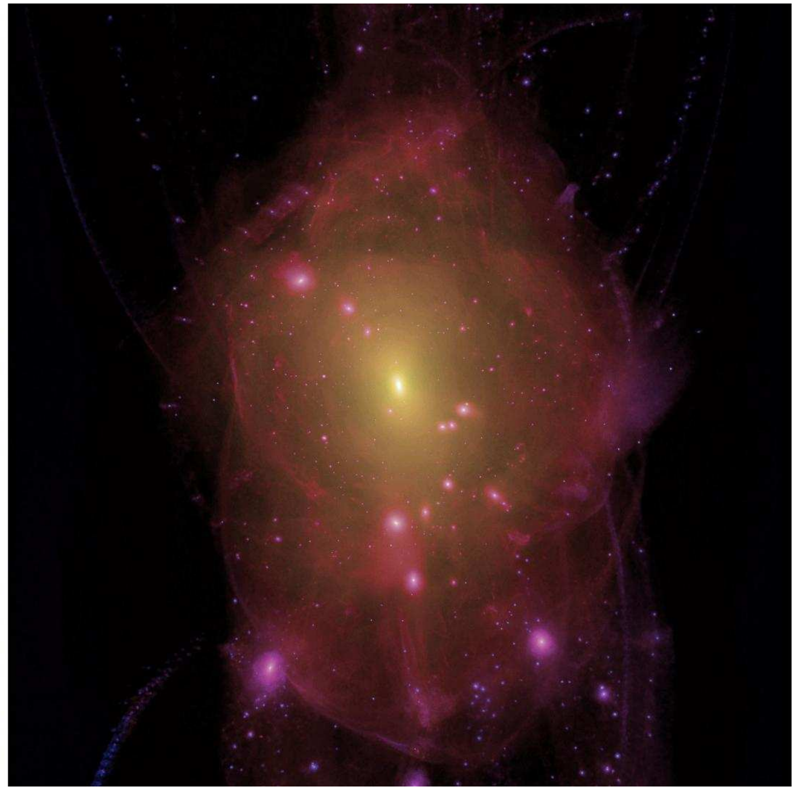
Only $\sim$ 30 are observed within our Galaxy. M. Geha 2010

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



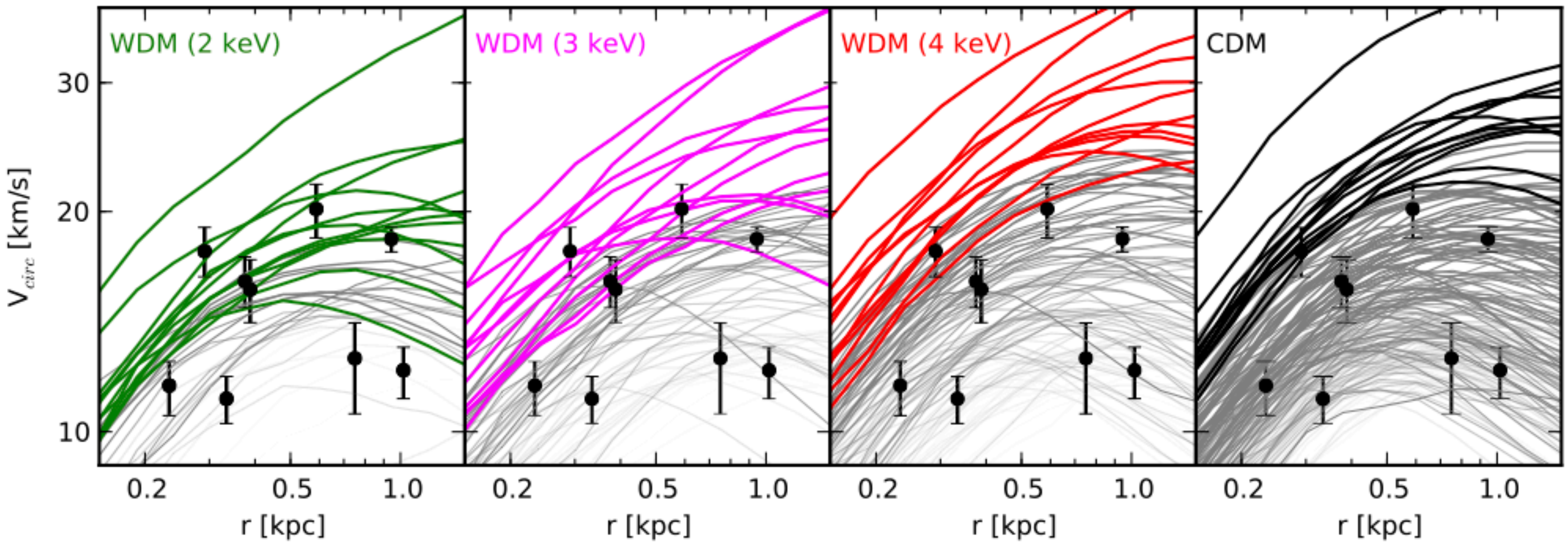
Aq-A-2 CDM halo



Aq-A-2 halo made of sterile neutrino DM (Lovell et al. 2012)

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

Too big to fail. WDM?



Boylan-Kolchin'11

Strigari, Frenk White (2011)

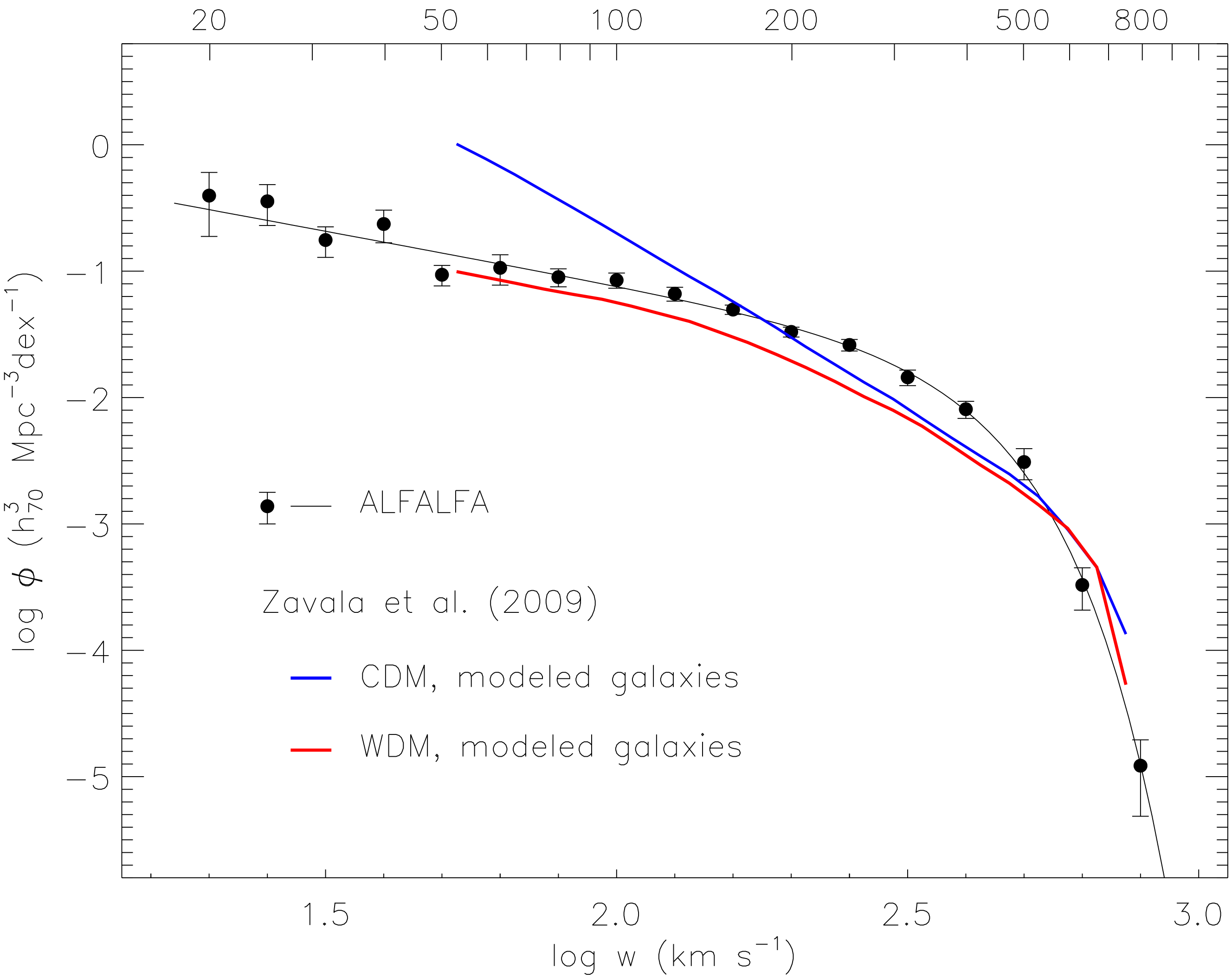
Lovell, Frenk, Eke, . . . , **O.R.** 1104.2929 [astro-ph.CO]

Schneider et al.'13

- Our galaxy contains too few small mass satellites (missing satellites problem) **and** too few large satellites (too-big-to-fail problem)
- Particles that were relativistic in the early Universe can alleviate this tension between theoretical predictions and observations

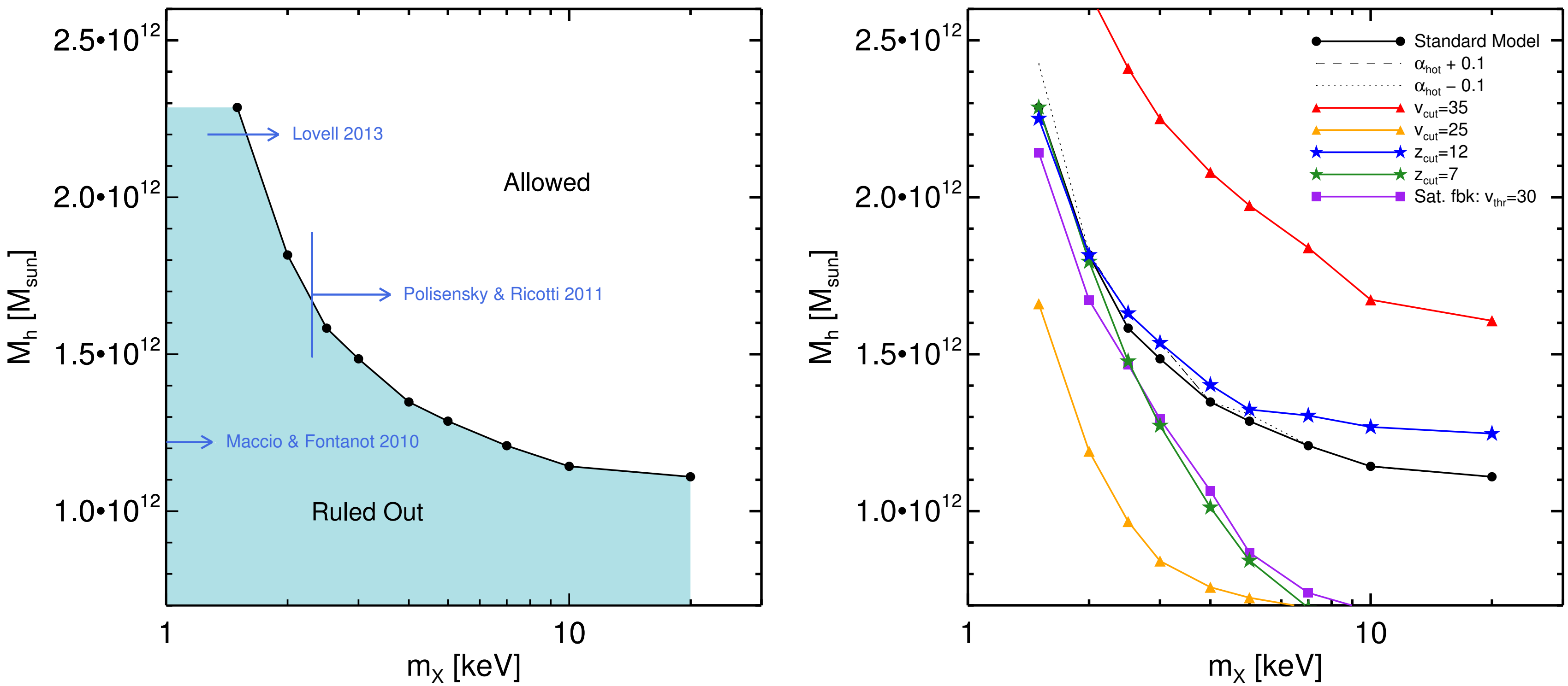
Velocity width function vs. WDM

Papastergis+ [1106.0710]



ALFALFA (HI) survey. Deviations from ΛCDM predictions for $v_{rot} \lesssim 100$ km/sec

Too big to fail. Other options?



Kennedy et al.'13

Converting dark matter only simulations into "**observable**" luminosity of satellites is subject to large uncertainties