3.5 keV line observation and its DM interpretation

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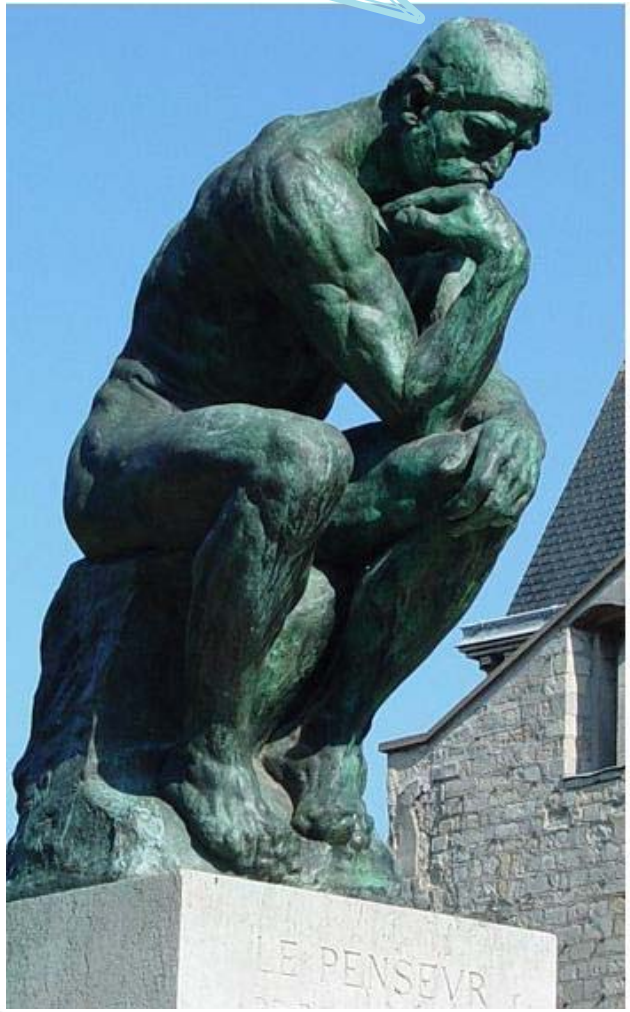
New Perspectives on Dark Matter at Fermilab

Photons from DM ?

Um… Well…



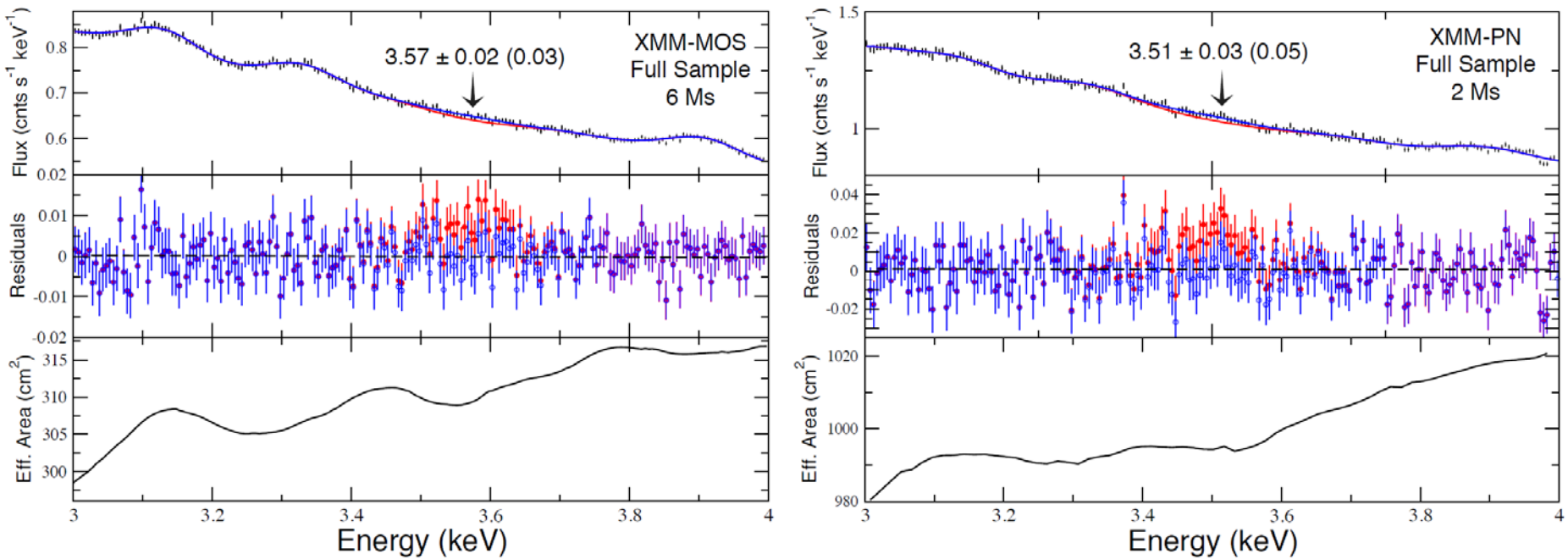
- 130 GeV
- O(GeV)
- 511 keV
- 3.5 keV
- …

Outline

- 3.5 keV line observation
- CDM vs WDM
- DM interpretations:
  - ✓ Sterile neutrino
  - ✓ Axion
  - ✓ Axino
- Conclusion

Unidentified line in X-ray I

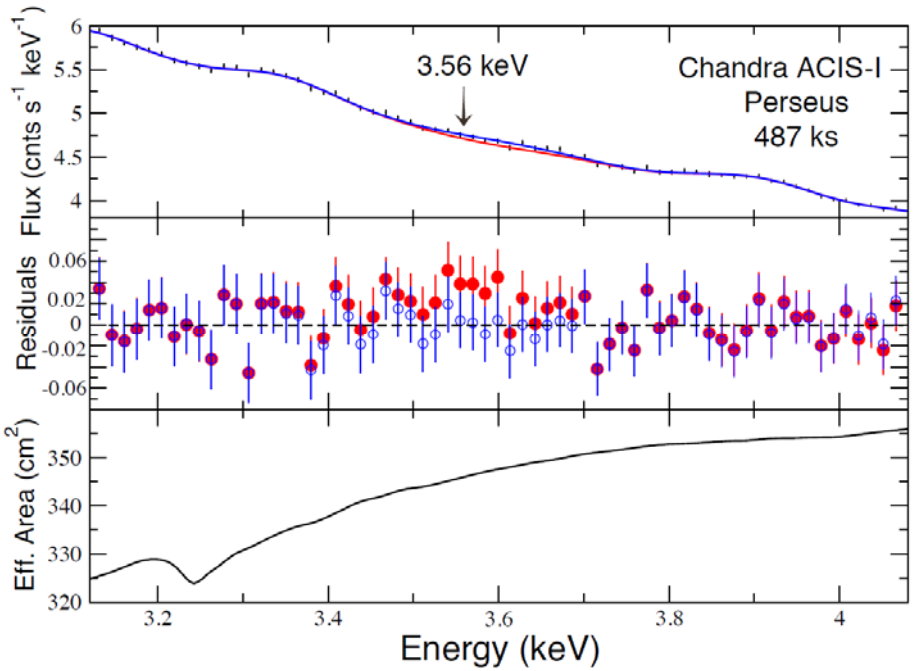
Bulbul et al. arXiv:1402.2301

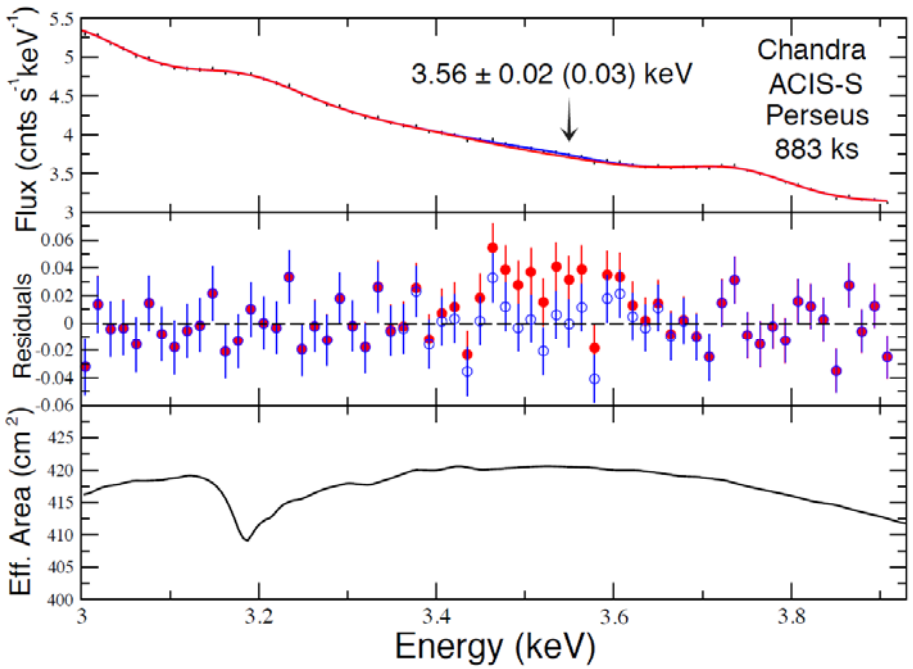


- (3.55 - 3.57)±0.03 keV emission line at 4 - 5σ
- Stacked XMM-Newton (MOS & PN CCDs) spectrum of 73 galaxy clusters in z ~ 0.01 - 0.35

Unidentified line in X-ray II

Bulbul et al. arXiv:1402.2301

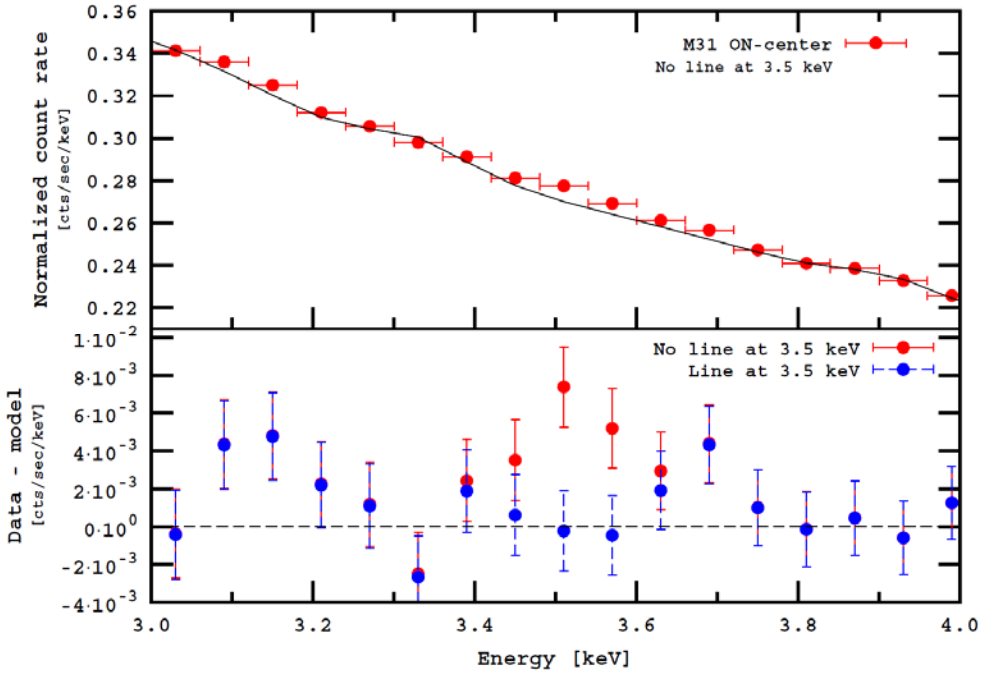




- 2 - 3σ detection in the Chandra ACIS-I & ACIS-S spectra of the Perseus
- Not seen in the ACIS-I spectrum of Virgo, but consistent upper limit

Unidentified line in X-ray III

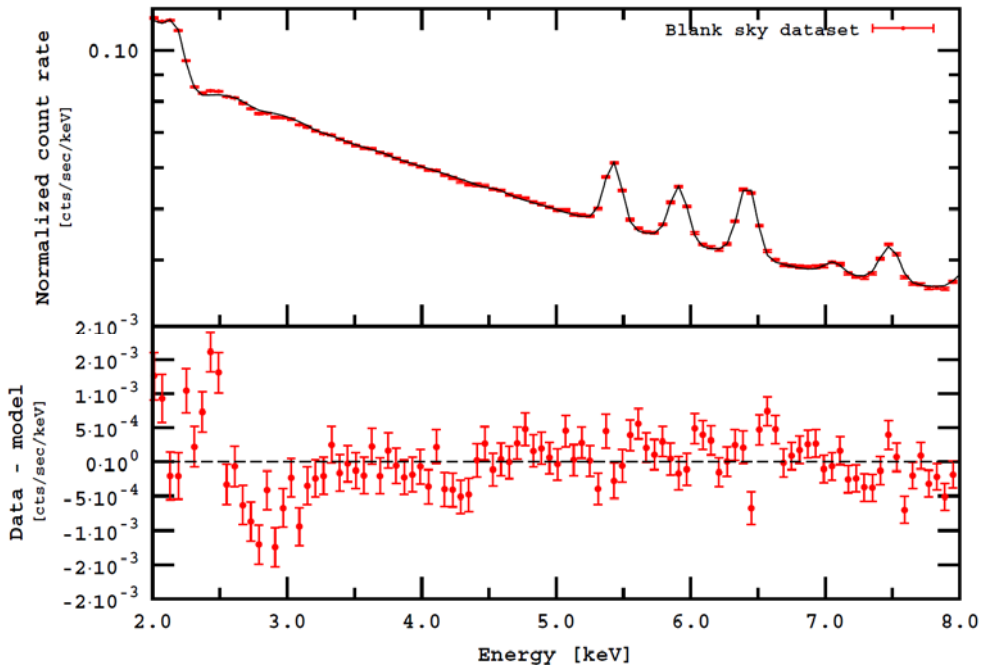
Boyarsky et al. arXiv:1402.4119



- Indications at 3.2σ (Andromeda = M31, z=-0.001) and 2.3σ (Perseus, z=0.0179) from XMM-Newton
- 3.52±0.02 keV line at 4.4σ in the combined dataset

Blank-sky

Boyarsky et al. arXiv:1402.4119

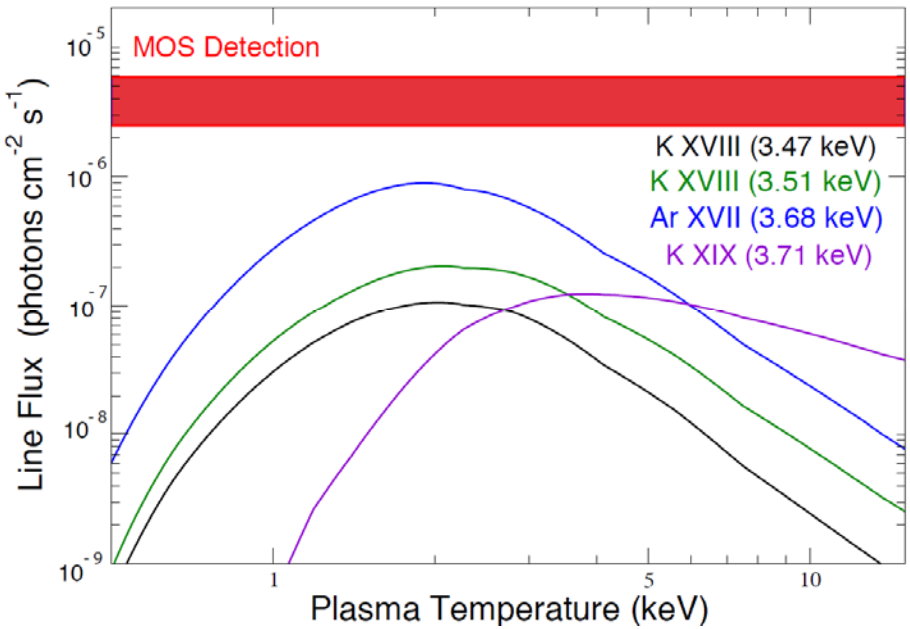


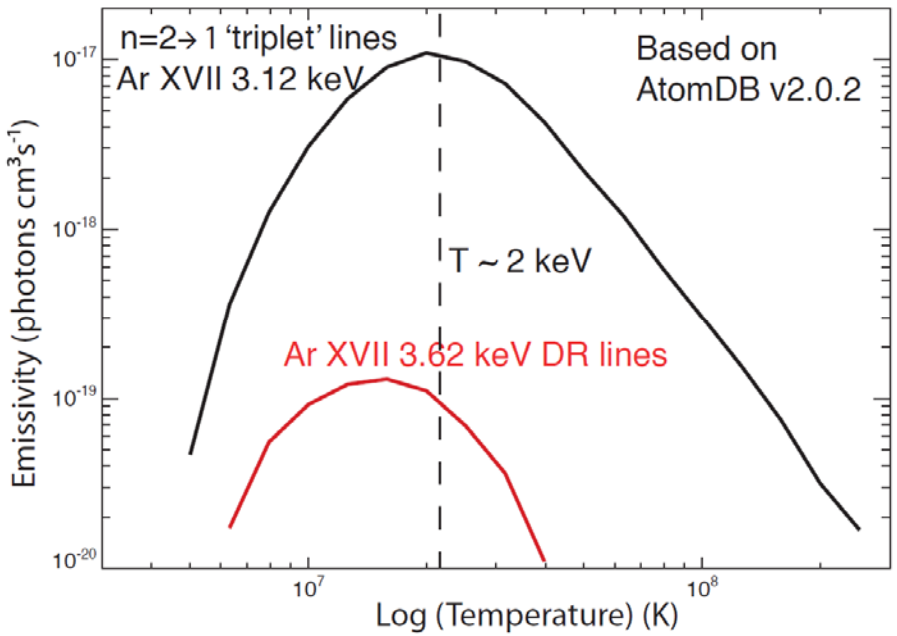
- No line-like residuals in 3.45 - 3. 58 keV

→ 2σ upper bound $7 \cdot 10^{-7}$ phs/cm²/s (cf. signals: ~$4 \cdot 10^{-6}$ phs/cm²/s)

Atomic transitions?

Bulbul et al. arXiv:1402.2301





- Estimated line fluxes at this E range are too low (using Atomic DB)
- Ar XVII DR is accompanying ~100 times larger line at 3.12 keV
- No likely candidate from atomic transitions

Data analysis & summary

- Shifting each spectrum to z=0 to improve the sensitivity to weak spectral lines & reduce systematic effects

→ BG lines or instrumental response artifacts are smeared out

- (3.55 - 3.57)±0.03 keV emission at 4 - 5σ by XMM-Newton

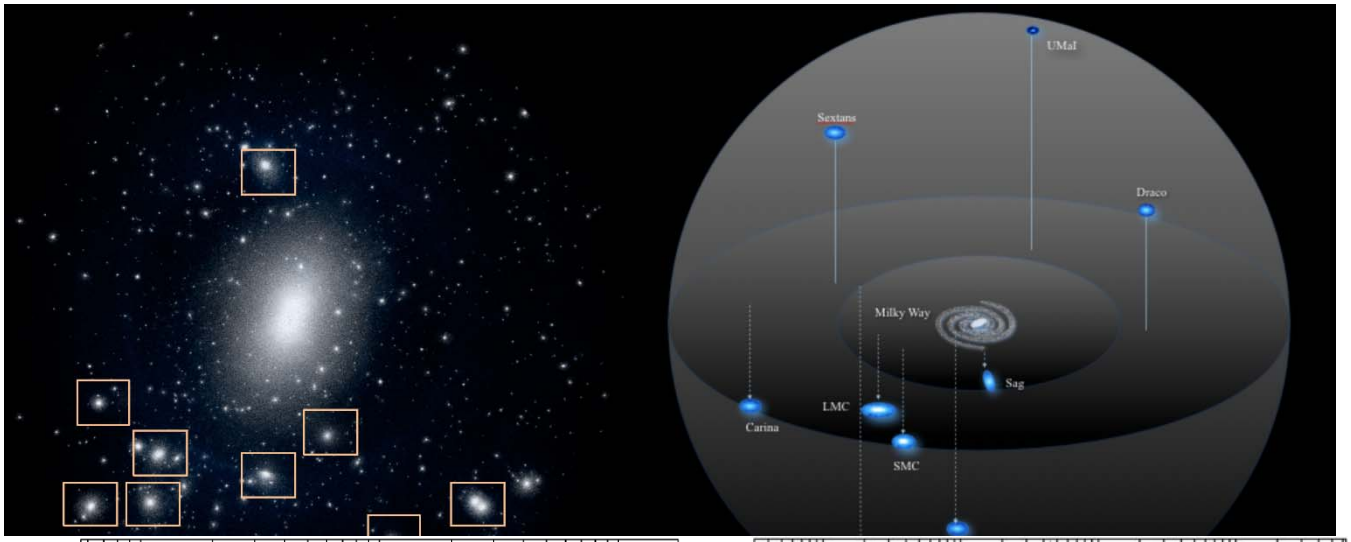
  2 - 3σ emission from Perseus by Chandra

- 3.52±0.02 keV line at 4.4σ by XMM-Newton
- Neither instrumental nor atomic transitions

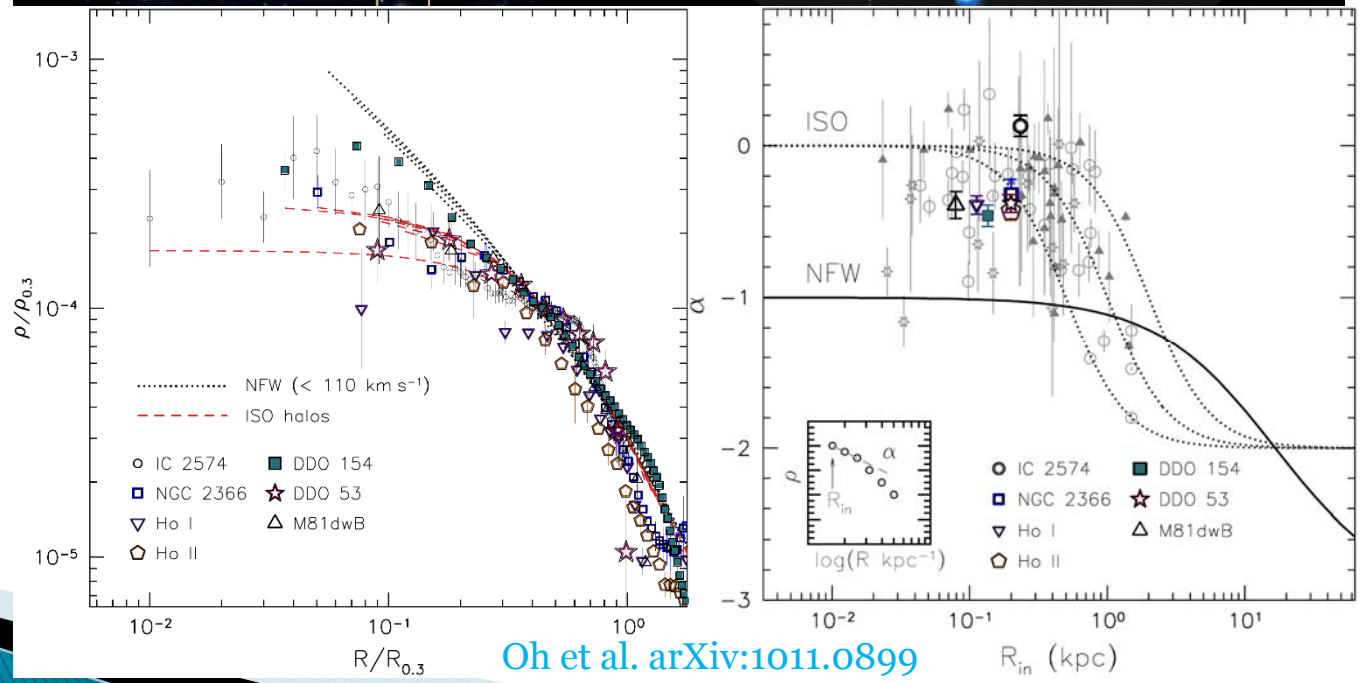
- Is DM responsible for this signal? **CDM** vs **WDM** ??

Challenges of CDM I

- Missing satellites



- Core vs Cusp

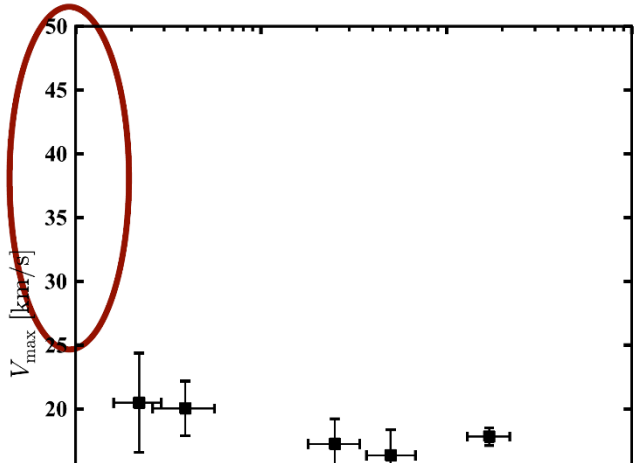


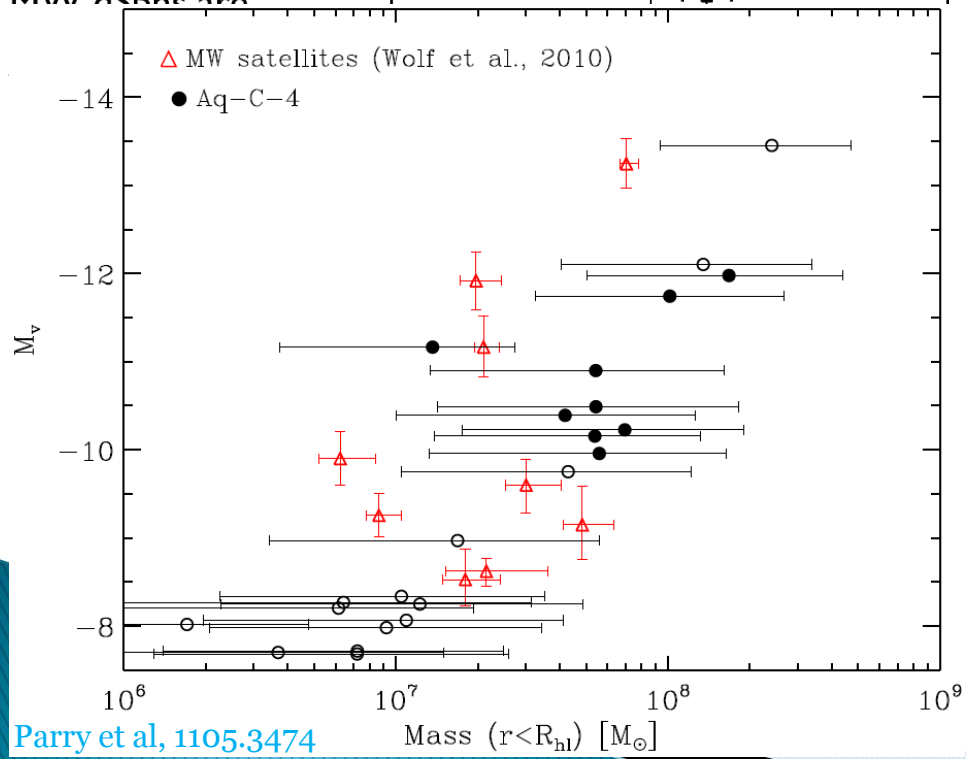
Oh et al. arXiv:1011.0899

Challenges of CDM II

"massive failures": highest resolution LCDM simulations predict ~10 subhalos in this range in the MW, but we don't see ***any*** such galaxies [except Sagittarius (?)]

All of the bright MW dSphs are



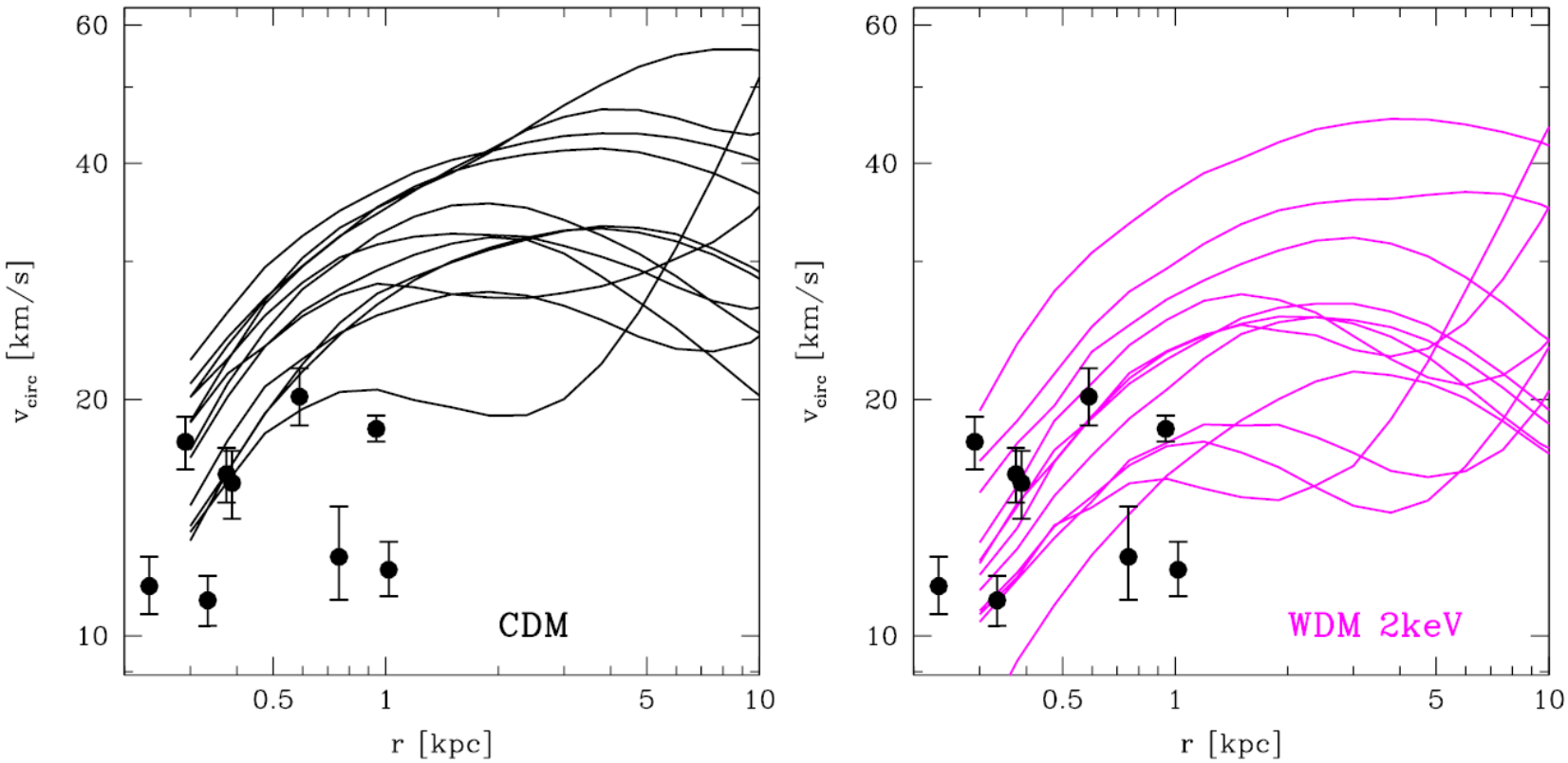


Parry et al, 1105.3474

- Massive subhalos are too dense to host MW's bright dwarf spheroidals, not massive enough to host the Magellanic Clouds
- Low mass-to-light ratios of subhalos

Warm DM

: A probable solution to the small scale puzzles!

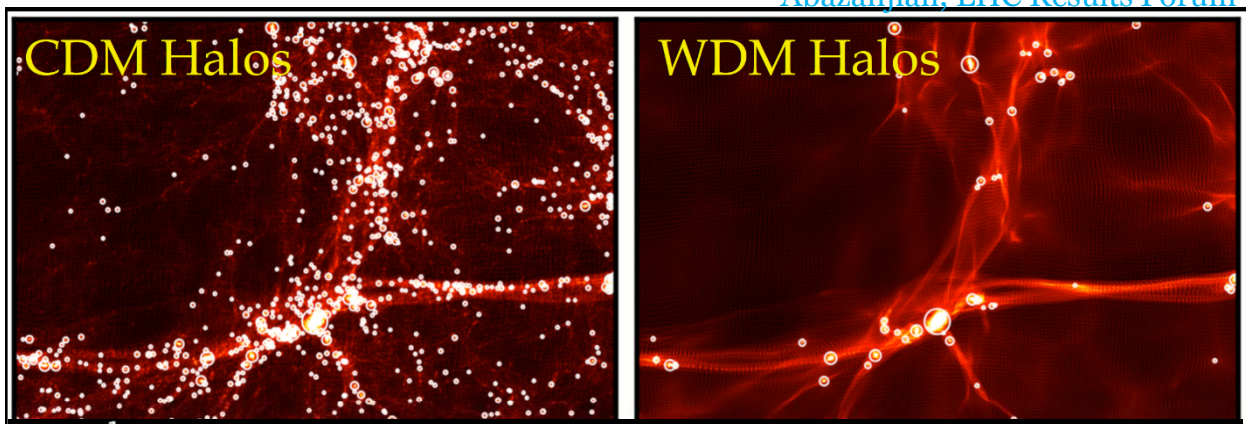


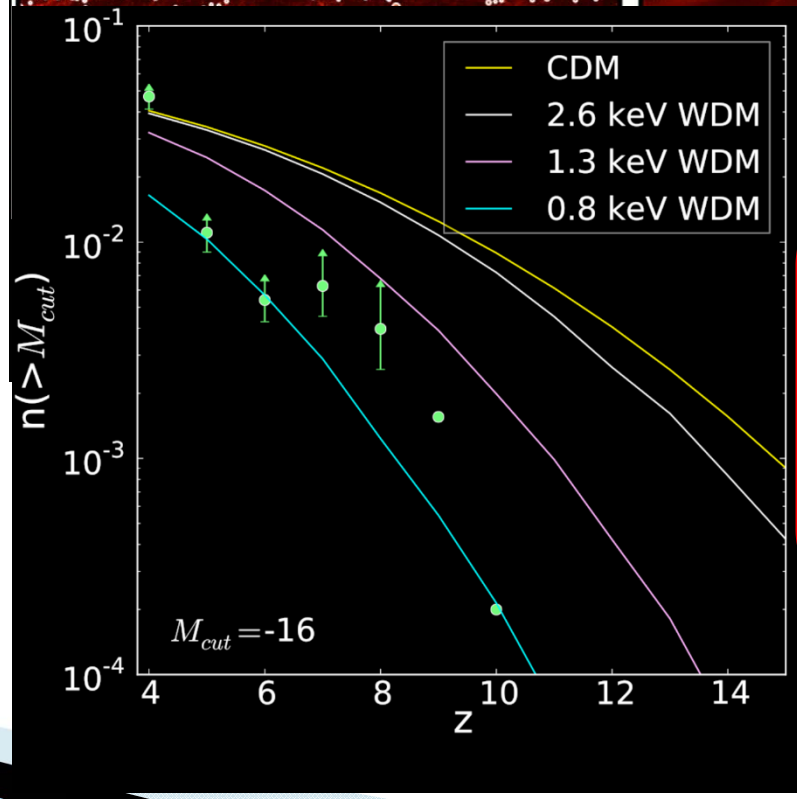
Anderhalden et al. 1212.2967

Limits on WDM I

Abazanjian, LHC Results Forum

- Early structure formation: CDM vs WDM
- Lack of structures via high-z galaxy counts





Using the observed number density at high-z (z = 4 to 8):

2.6 keV: *okay!*

1.3 keV: disfavored at 98.6% C.L. (2.2σ)

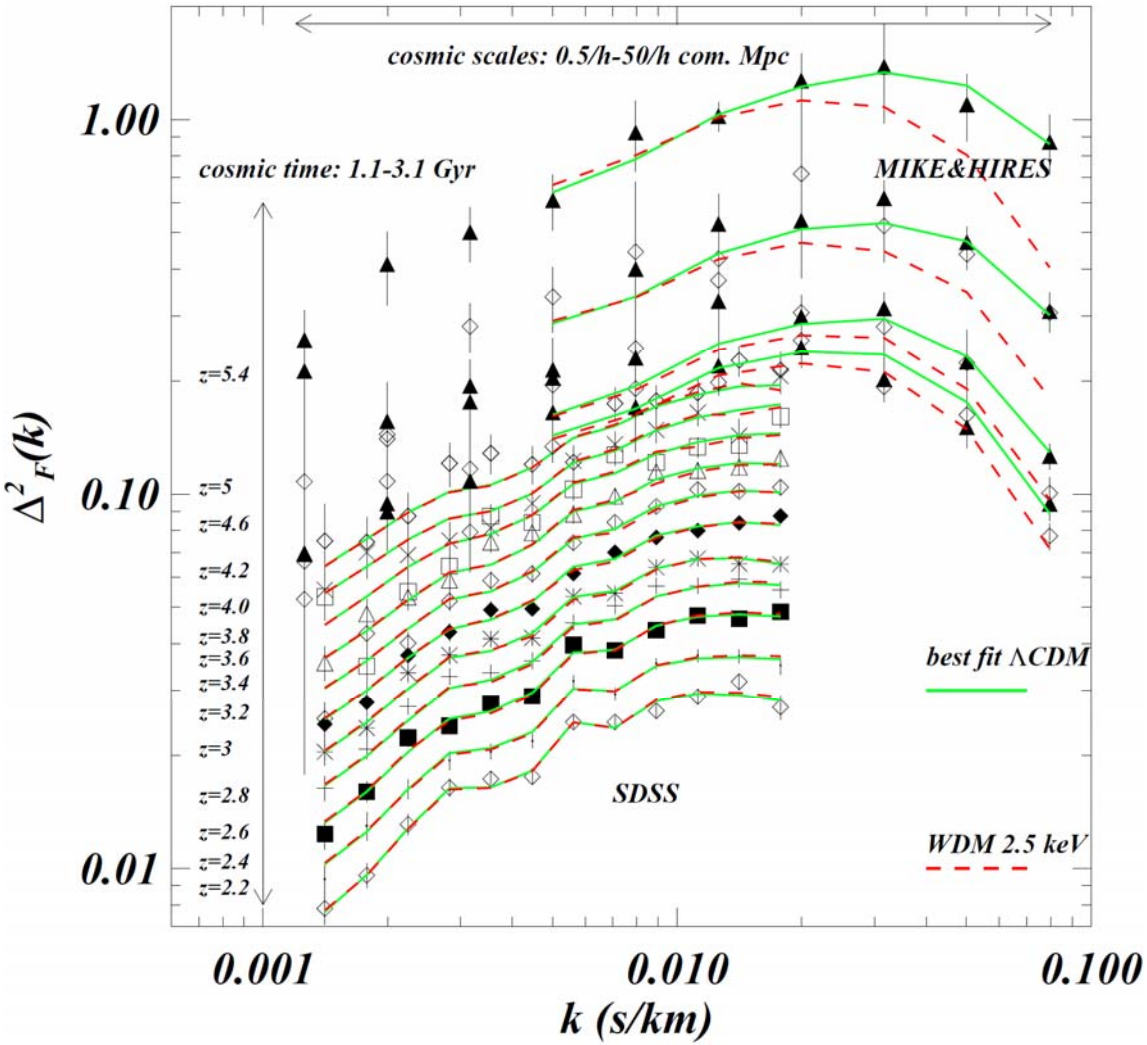
0.8 keV: ruled out at > 10σ

Schulz, Oñorbe, Abazajian & Bullock arXiv:1401.3769

Limits on WDM II

- Lyman-α forest flux power spectrum

→ $m_{WDM} > 3.3$ keV (2σ)



Viel et al. 1306.2314

CDM vs WDM

- CDM: challenges on small scales

→ WDM may cure the puzzles

- WDM: limits (m > 3keV) from larger scale

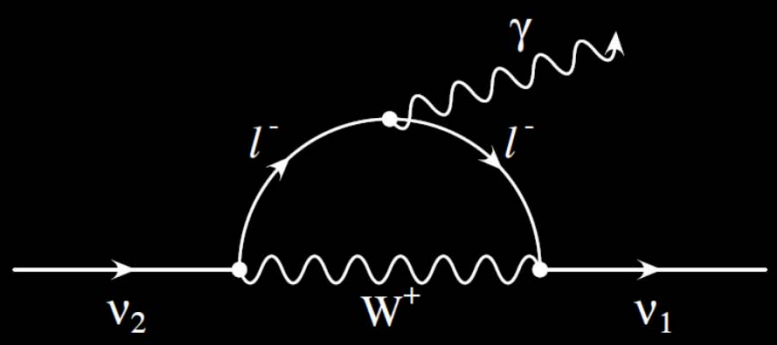
- Combination ??

- 7 keV WDM is OK & can be a solution to ~3.5 keV emission

Sterile Neutrinos
Beyond the Standard Model

- ν_s Phenomenological Insertion of Majorana & Dirac Mass Terms of Comparable Magnitude (e.g. νMSM)
- ν_s Left-Right Symmetric Models (Pati & Salam 1974; Mohapatra & Pati 1975)
- ν_s Higher Dimensional Operators in String-Inspired models (Langacker 1998)
- ν_s Bulk Fermions in Large Extra Dimensions (ADD; Dvali & Smirnov 2000)
- ν_s Axino in R-parity Violating Minimal Supersymmetric Models (Chun & Kim 1999)

Sterile ν WDM Radiative Decay in the X-ray



Decay: Pal & Wolfenstein 1981
X-ray: Abazajian, Fuller & Tucker 2001

$$\text{“}\nu_s\text{”} \rightarrow \text{“}\nu_\alpha\text{”} + \gamma$$

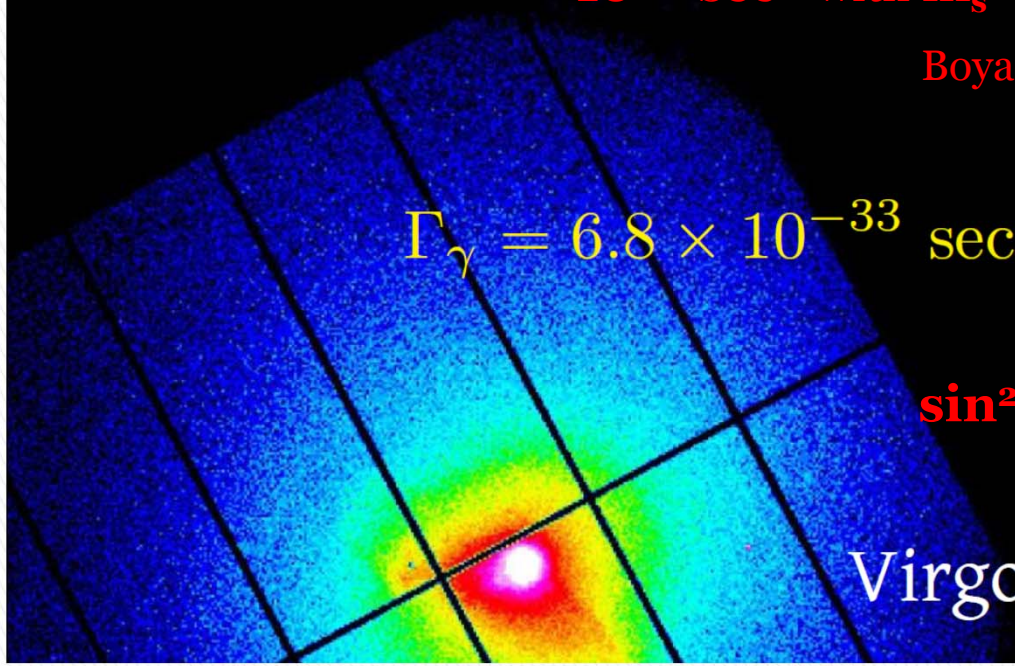
$$E_\gamma = \frac{m_s}{2} \sim 1 \text{ keV}$$

~10^{-28} sec^{-1} with **m$_s$~7 keV** for **3.5 keV** line

Boyarsky et al. arXiv:1402.4119

$$\Gamma_\gamma = 6.8 \times 10^{-33} \text{ sec}^{-1} \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_s}{1 \text{ keV}}\right)^5$$

sin^2 2θ ~ 10^{-10}

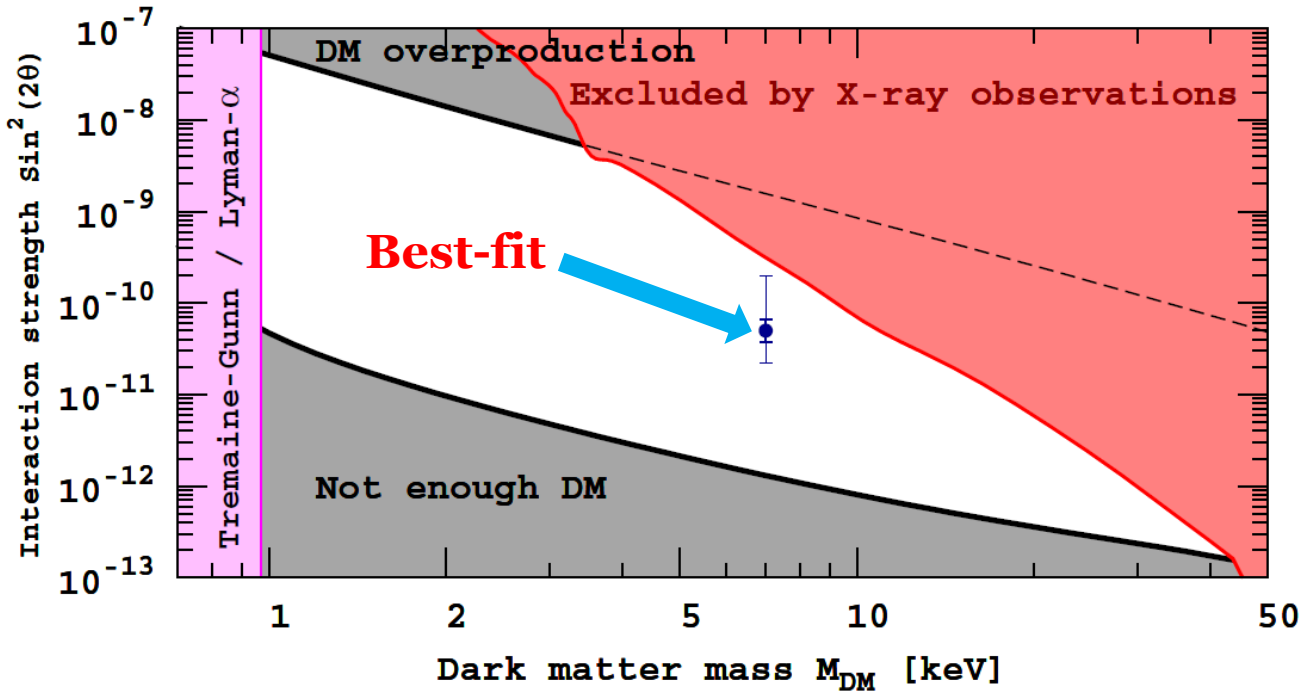


Virgo Cluster: 10^{70} DM particles

Abazanjian, LHC Results Forum

Bounds on sterile ν DM

Boyarsky et al. arXiv:1402.4119



- Sterile neutrino DM within νMSM
- Comparable with $\sin^2 2\theta \sim 7\cdot10^{-11}$ & m_s=7.1 keV from Bulbul et al. arXiv:1402.2301
- Ishida, Jeong & Takahashi (1402.5837); Abazajian (1403.0954); Robinson & Tsai (1404.7118); …

Strong CP problem & Axion

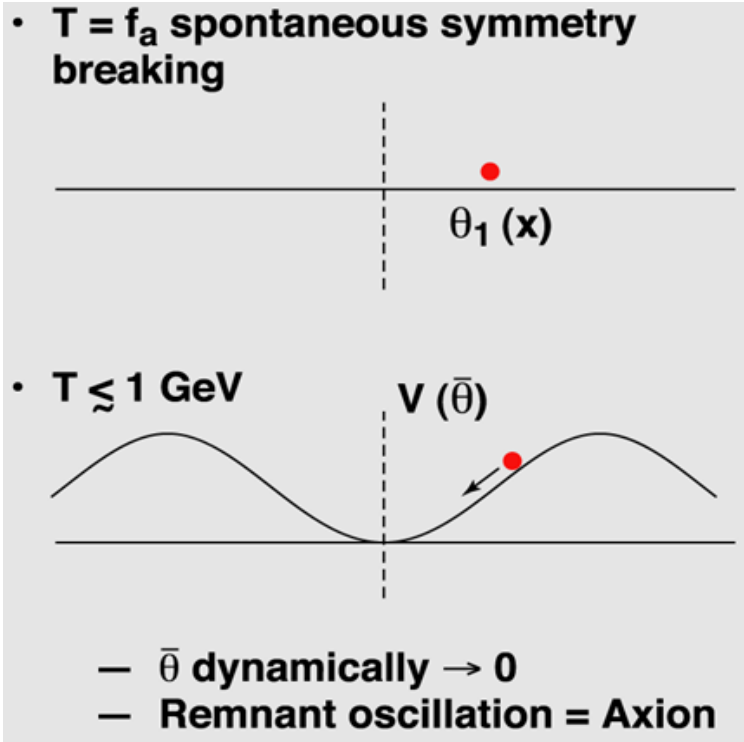
$$L_{QCD} = \ldots + \theta \frac{g^2}{32\pi^2} G^a{}_{\mu\nu} \tilde{G}^{a\mu\nu}$$

See talks of Grin, Rajendran & Rybka

- θ-term → violation of CP → EDMs of strongly interacting particles
- C & CP is conserved in QCD
- Neutron EDM: $|d_n| < 10^{-25}$ e·cm → $\theta < 10^{-10}$

Why θ is so small?

- Introducing $U(1)_{PQ}$ broken at a scale f_a
- $\theta = \varphi / f_a$: a dynamical variable
- Non-perturbative quantum effects: $\theta \to 0$
- Light pseudo-scalar is predicted: Axion



Bibber, ASK 2011

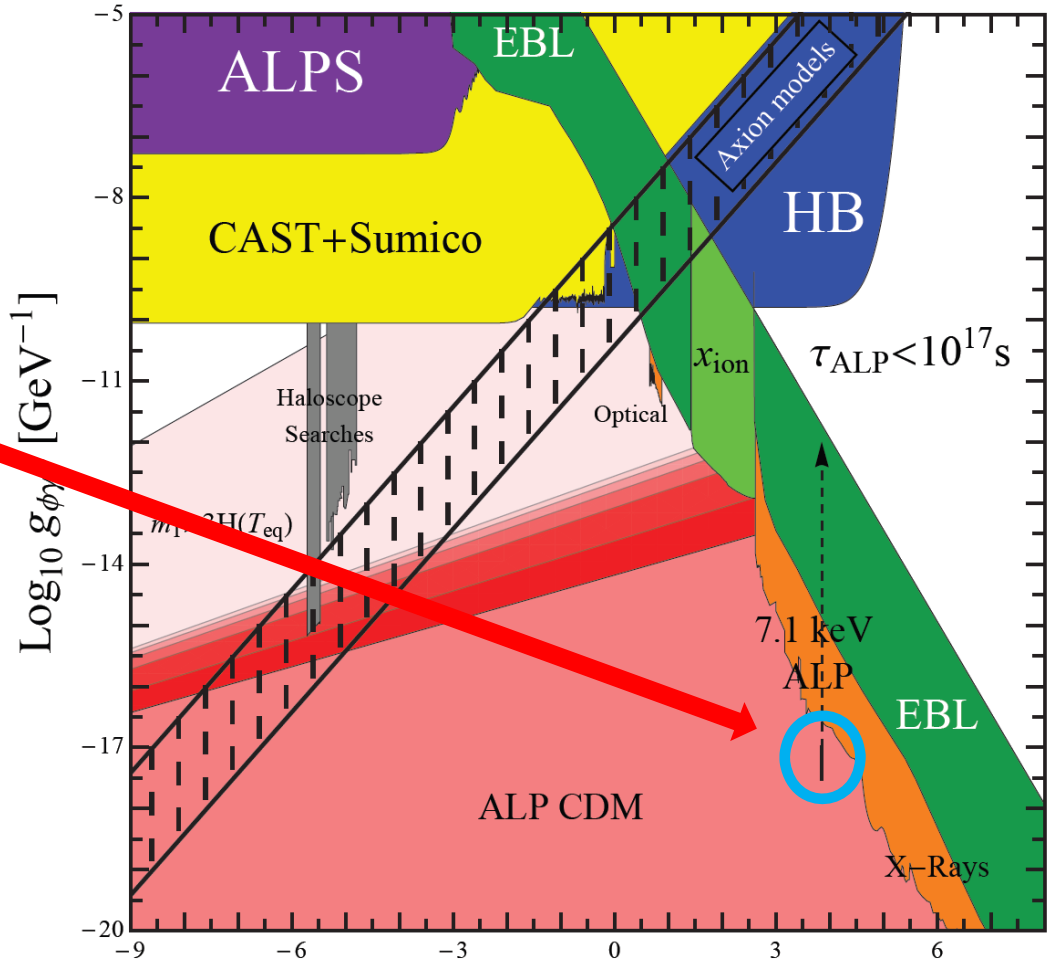
Axion(-like) particle

$$\mathcal{L}_{\rm int} = \frac{1}{4} g_{\phi\gamma\gamma} \phi F^{\mu\nu} \tilde{F}_{\mu\nu} \qquad \tau_\phi = \frac{1}{\Gamma_{\gamma\gamma}} = \frac{64\pi}{g^2_{\phi\gamma\gamma} m^3_\phi}$$

- Axion(-like) particle (ALP) can decay into two photons
- $\tau_\varphi \sim 10^{28}$ sec & m_φ=7.1 keV

→ $g_{\varphi\gamma\gamma} \sim 6\cdot10^{-18}$ GeV^{-1}

- Higaki, Jeong & Takahashi; Jaeckel, Redondo & Ringwald; Lee, SC Park & WI Park; …



Jaeckel et al. arXiv:1402.7335

Axino

- Superpartner of axion
- Decay: strongly suppressed by f_a even with R-parity violation
- $m_{\tilde{a}} \sim \frac{M_{SUSY}^2}{f_a} \sim 7\ \mathrm{keV}$ can be a good WDM Covi & Kim, arXiv:0902.0769
- Relic density: thermal production via thermal scattering and/or non-thermal production via out-of-equilibrium decays

Axino with R-parity violation

KC Kong, J-CP & SC Park
arXiv:1403.1536

- Bilinear type of R-parity violation: $W_{\not{R}} = \mu_i L_i H_u$

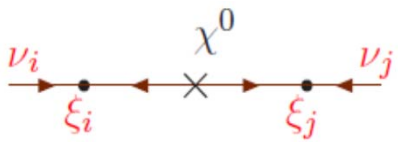
- Decay into a photon and a neutrino

$$\tau_{\tilde{a}\to\gamma\nu} \simeq 10^{28}\text{sec} \left(\frac{C_{\text{eff}}}{10^{-6}}\right)^{-2} \left(\frac{m_{\tilde{a}}}{7\ \text{keV}}\right)^{-3} \left(\frac{f_a}{3\times 10^8\ \text{GeV}}\right)^{2}$$

$$C_{\text{eff}} \equiv C_{a\gamma\gamma} \sum_i |U_{\nu_i\tilde{\gamma}}| \simeq C_{a\gamma\gamma}\, \xi\, \frac{\sqrt{2} s_W M_Z}{M_1} \qquad \mathcal{L} = \frac{\alpha_{em}}{8\pi f_a} C_{a\gamma\gamma}\, a F_{\mu\nu} \widetilde{F}^{\mu\nu} \qquad \xi_i = \langle \tilde{\nu}_i \rangle / v$$

- ~7 keV axino DM can be a good source for ~3.5 keV X-ray line

- Sneutrino VEVs generate ν masses



(Chun & Park, ph/0410242)

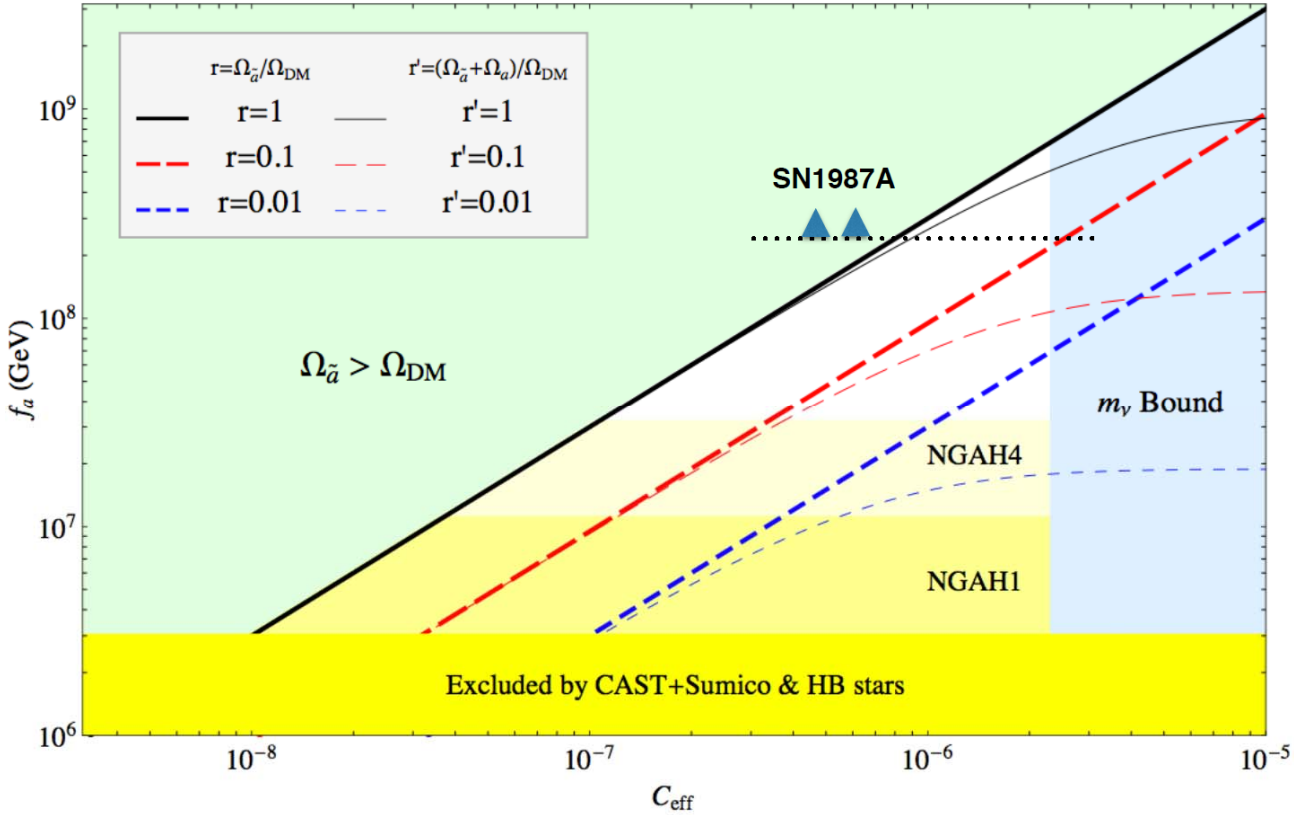
- From $m_\nu = \sum_i m_{\nu i} < 0.23$ eV (Planck, 1303.5076)

$$\xi \lesssim \frac{1.1}{\cos\beta} \times 10^{-6} \left(\frac{M_N}{M_Z}\right)^{1/2} \left(\frac{m_\nu}{0.23\ \text{eV}}\right)^{1/2}$$

$$M_N = M_1 M_2 / (c_W^2 M_1 + s_W^2 M_2) + M_Z^2 s_{2\beta}/\mu$$

Parameter space

KC Kong, J-CP & SC Park
arXiv:1403.1536



- BICEP2 result favors $f_a < H_I/2\pi$ → $\Omega_a h^2 = 2.07 \times 10^{-14} \left(\alpha^{\rm dec} + 1\right) \left(f_a/{\rm GeV}\right)^{7/6}$

See D. Grin's talk

Visinelli & Gondolo, arXiv:1403.4594

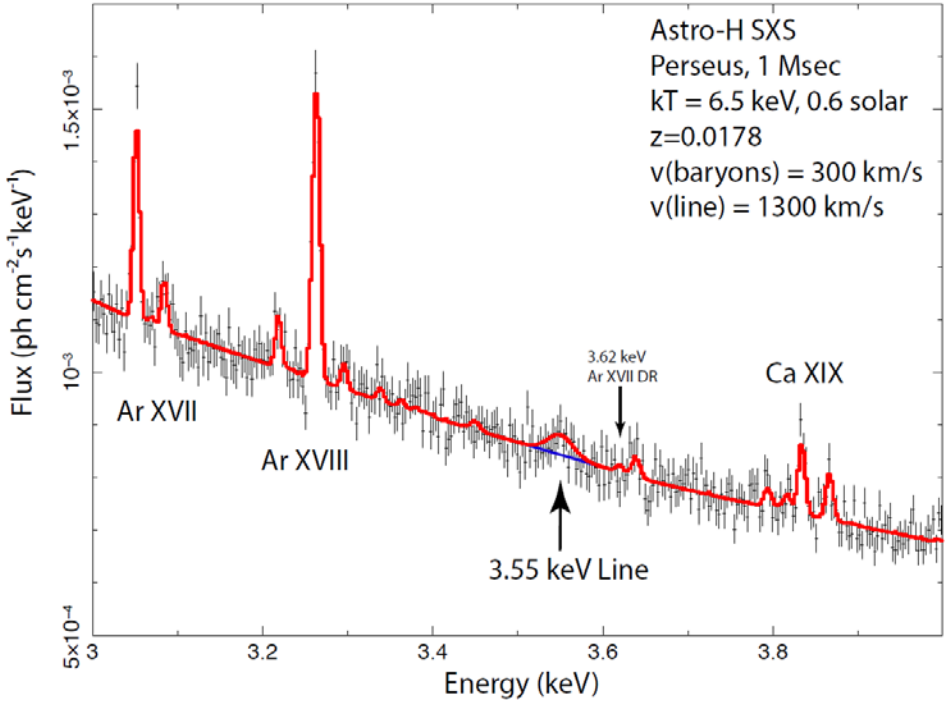
Other suggestions

- Excited DM Finkbeiner & Weiner (1402.6671), Okada & Toma (1404.4795)
- Gravitino Kolda & Unwin (1403.5580), Bomark & Roszkowski (1403.6503)
- (Hidden) bino Kolda & Unwin (1403.5580)
- Dark atom Cline et al. (1404.3729)
- Scalar DM Babu & Mohapatra (1404.2220)
- Effective Ops Frall, Reece & Roxlo (1403.1240)
- More ...

Really from DM?

Future Astro-H observations

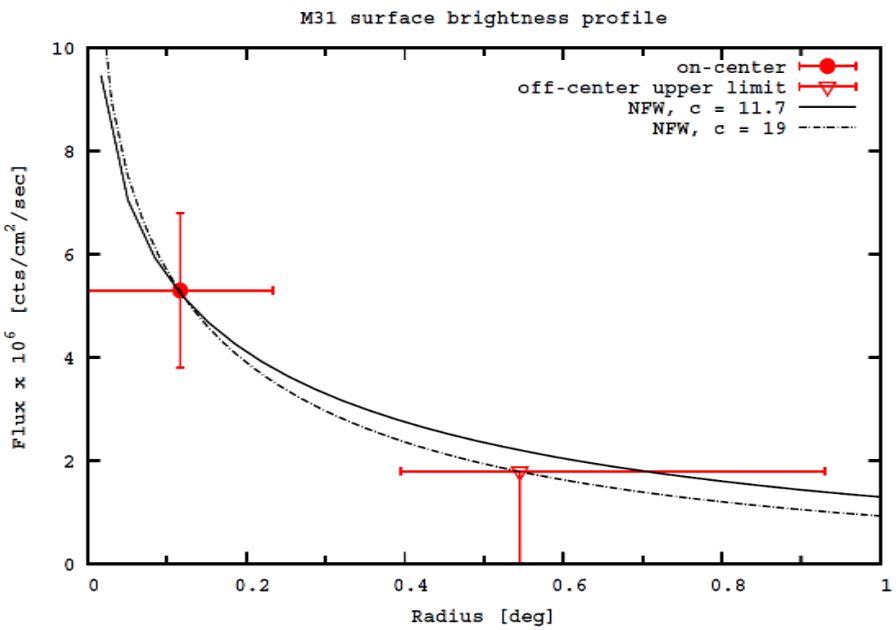
Bulbul et al. arXiv:1402.2301

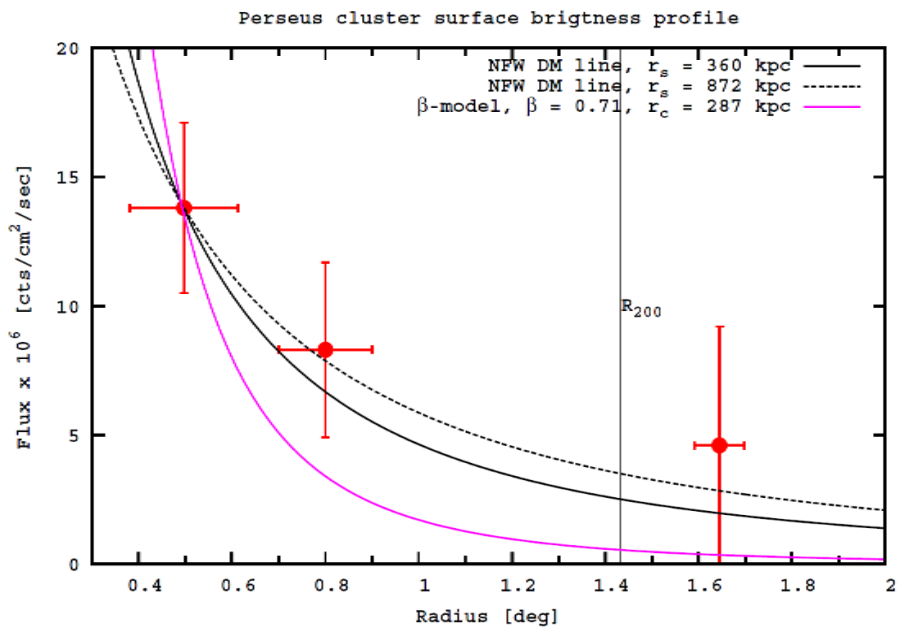


- Measurement of the broadening of the line → its velocity dispersion
- Plasma emission line: only broadened by the turbulence in the X-ray emitting gas

Line flux profile

Boyarsky et al. arXiv:1402.4119





- Better angular resolution → Spatial distribution of emissions

Conclusion

- ~3.5 keV emission (4 - 5σ) in galaxy clusters & Andromeda

  : XMM-Newton & Chandra

  Probably, neither instrumental nor atomic transitions

- Is it real ?

- DM interpretations: sterile ν, axion, excited DM, …

- ~7 keV axino DM can be a good source for ~3.5 keV line

  consistent with axion searches, m_ν, relic density, BICEP2,…

Thank you