Sterile Dark Matter Cosmological Neutrinos

Kevork Abazajian
University of California, Irvine

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INT Program 15-2a: Neutrino Astrophysics & Fundamental Properties

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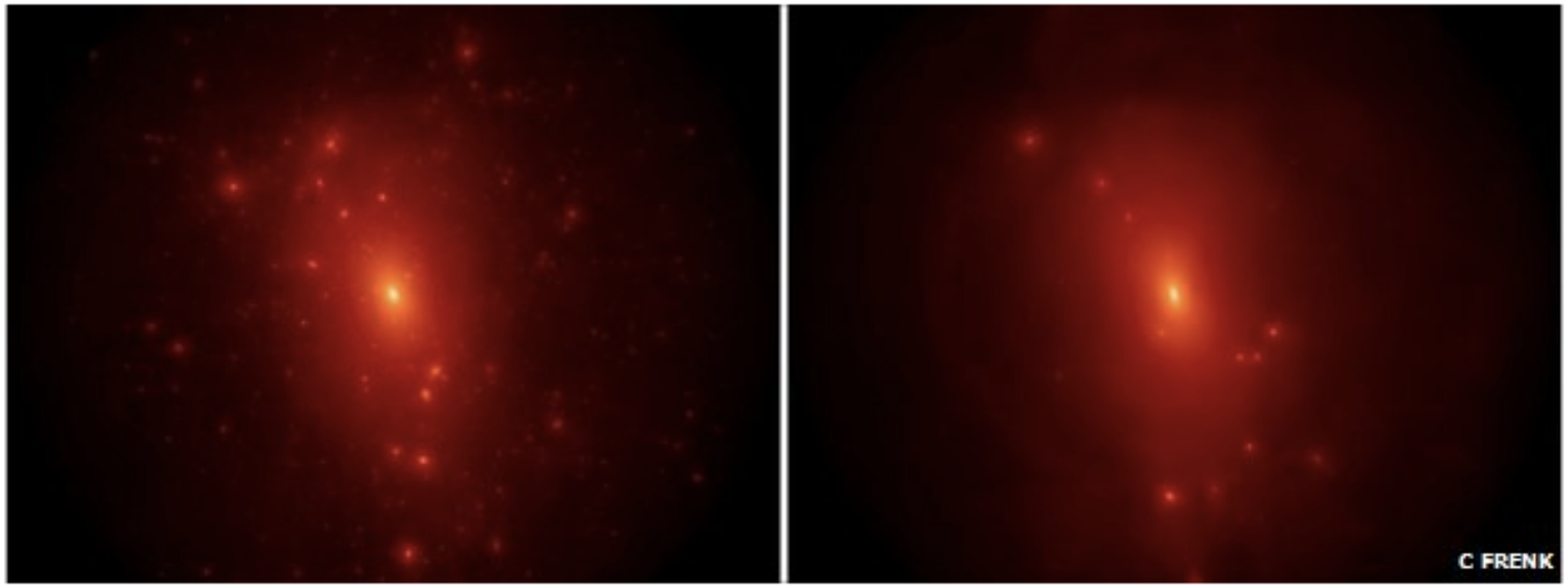
Dwarf galaxies suggest dark matter theory may be wrong

By Leila Battison
Science reporter, Bradford



Dwarf galaxies around the Milky Way are less dense than they should be if they held cold dark matter

Scientists' predictions about the mysterious dark matter purported to make up most of the mass of the Universe may have to be revised.

Research on dwarf galaxies suggests they cannot form in the way they do if dark matter exists in the form that the most common model requires it to.

That may mean that the Large Hadron Collider will not be able to spot it.

Leading cosmologist Carlos Frenk spoke of the "disturbing" developments

Related Stories

Dark matter hunters see 67 hints

Is LHC closing in on elusive Higgs particle?

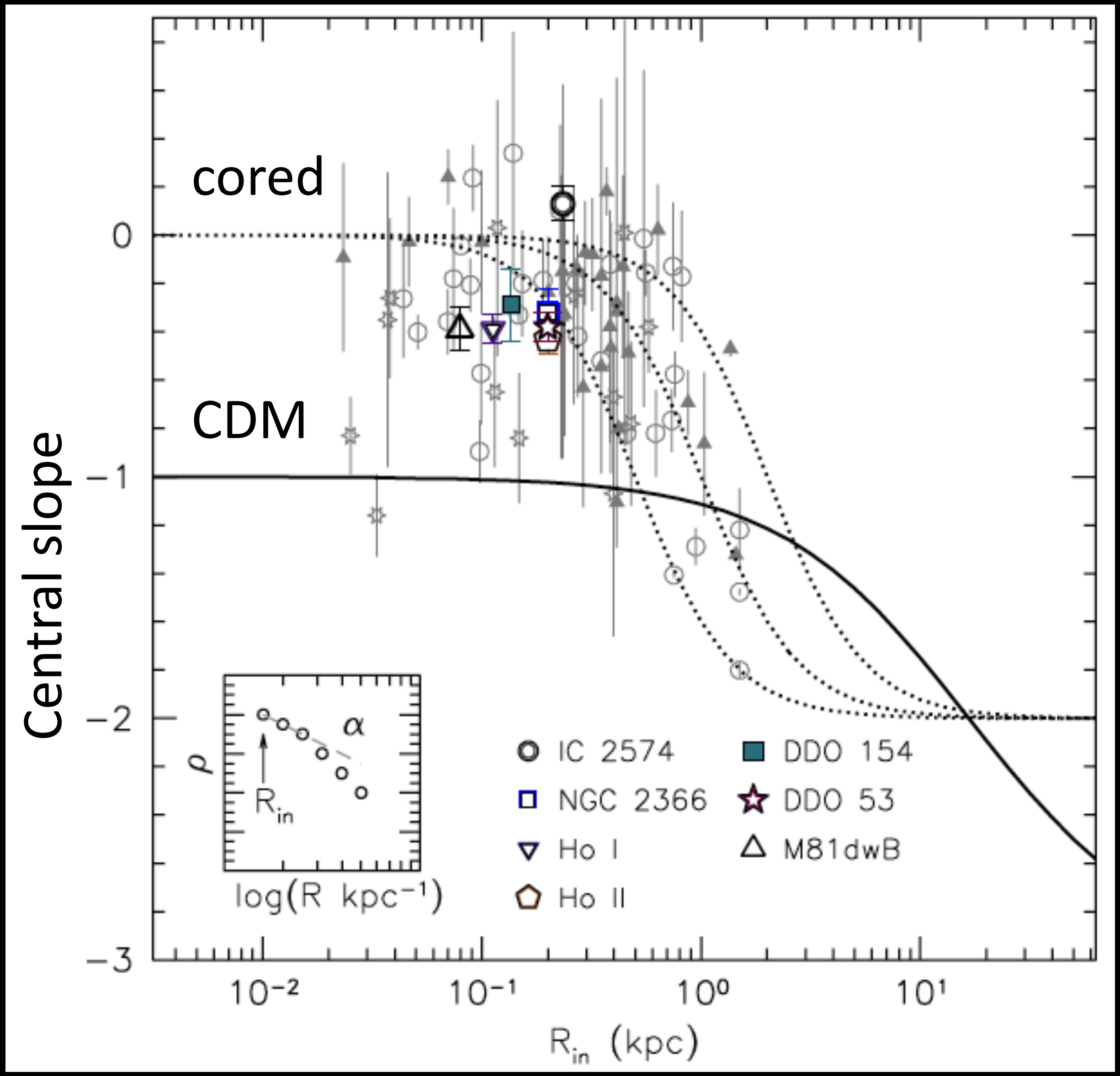
'Filaments' hold dark matter test

CDM: challenges

CDM is challenged on observations probing small scales

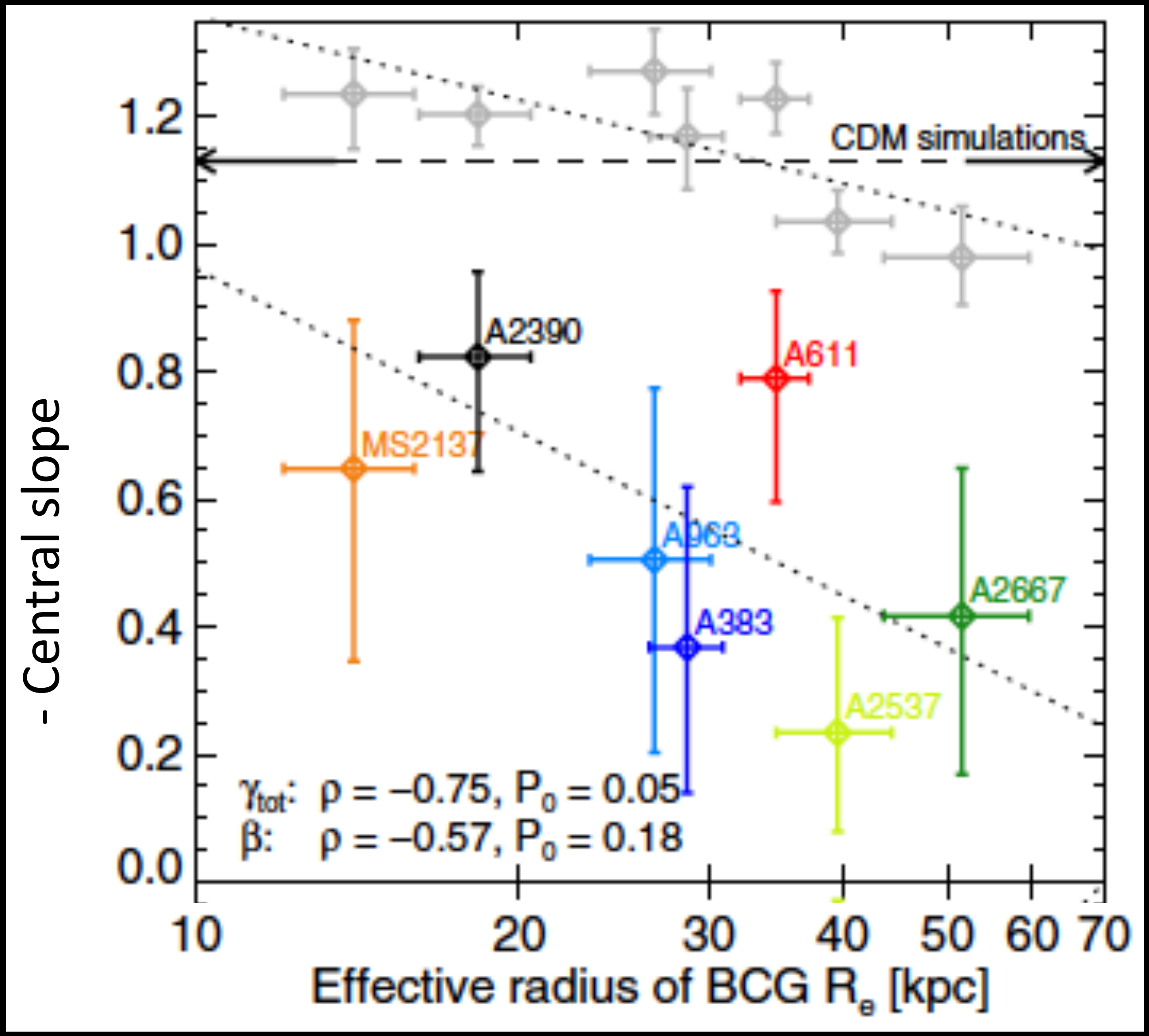
1. <u>Core/cusp problem:</u> predicted inner density profile steeper than data

Low-surface brightness dwarf galaxies



Oh et al (2011) [THINGS]

Cluster of galaxies



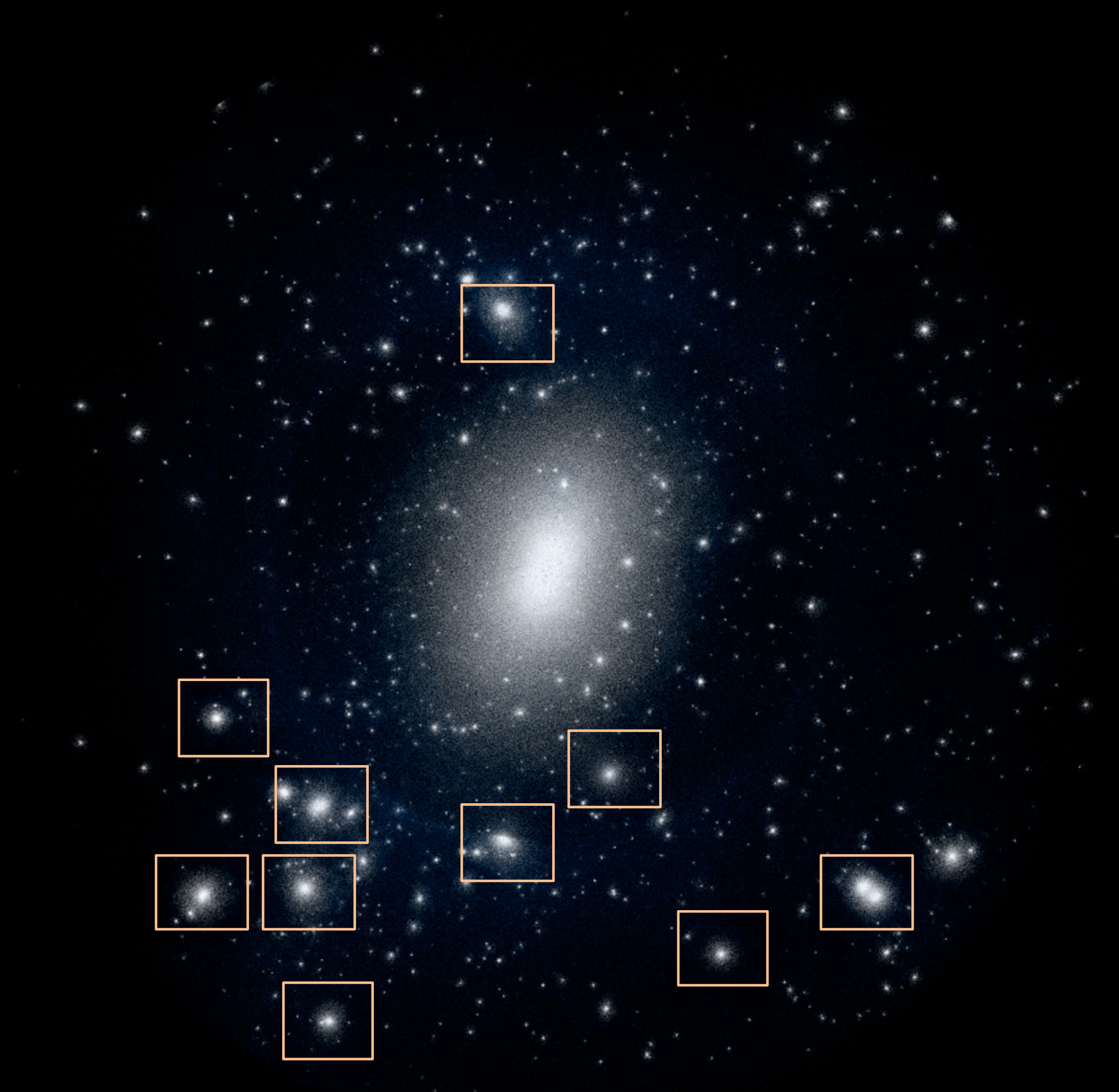
Newman et al, ApJ (2013)

Courtesy Shunsaku Horiuchi (Virginia Tech)

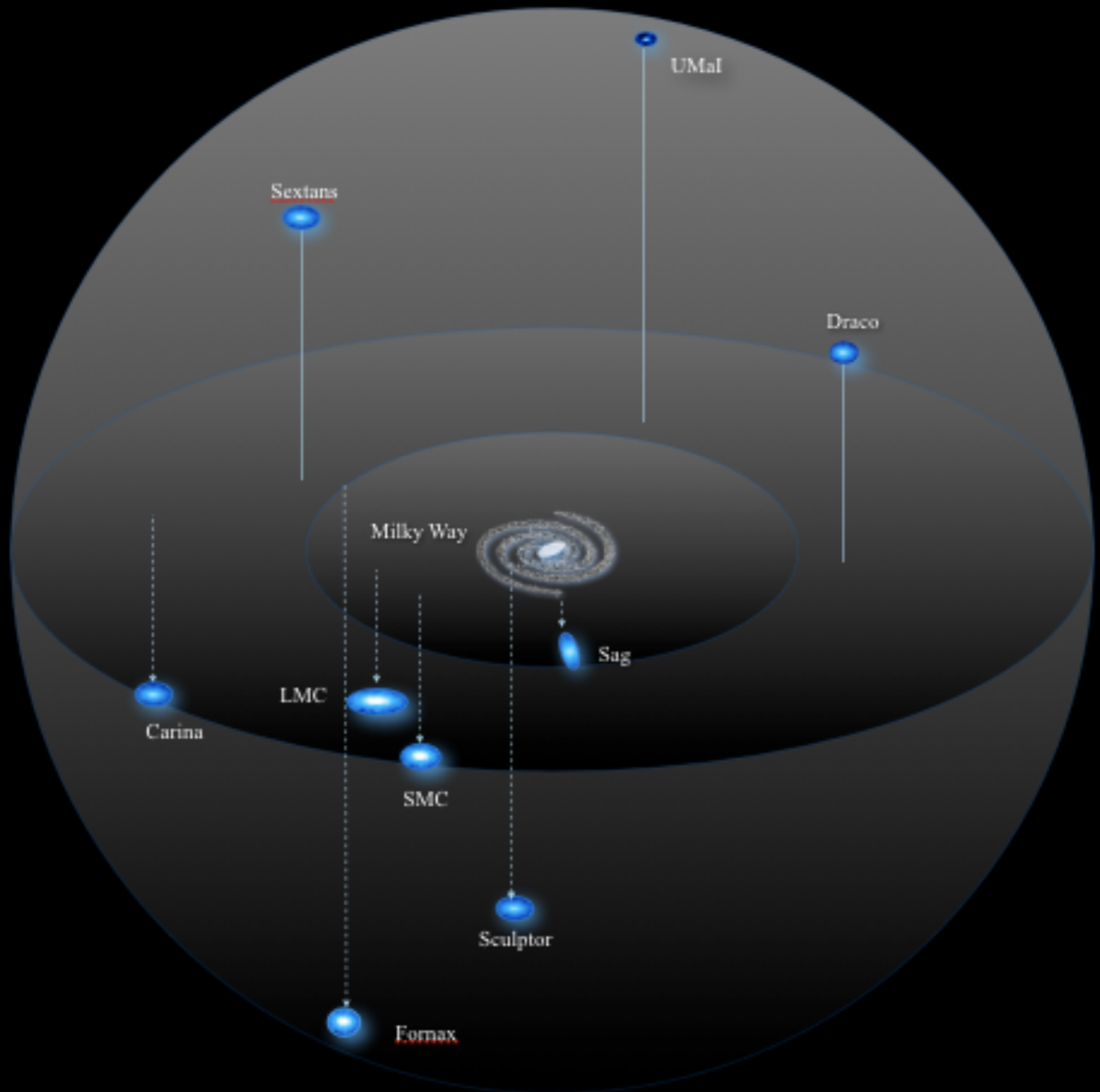
CDM: challenges

CDM is challenged on observations probing small scales

1. Core/cusp problem: inner density profile steeper than data
2. Missing satellites problem: expect $O(100)$ satellites but see $\sim$10



Theory N > 100



Observed $N_{lum} \sim 10$

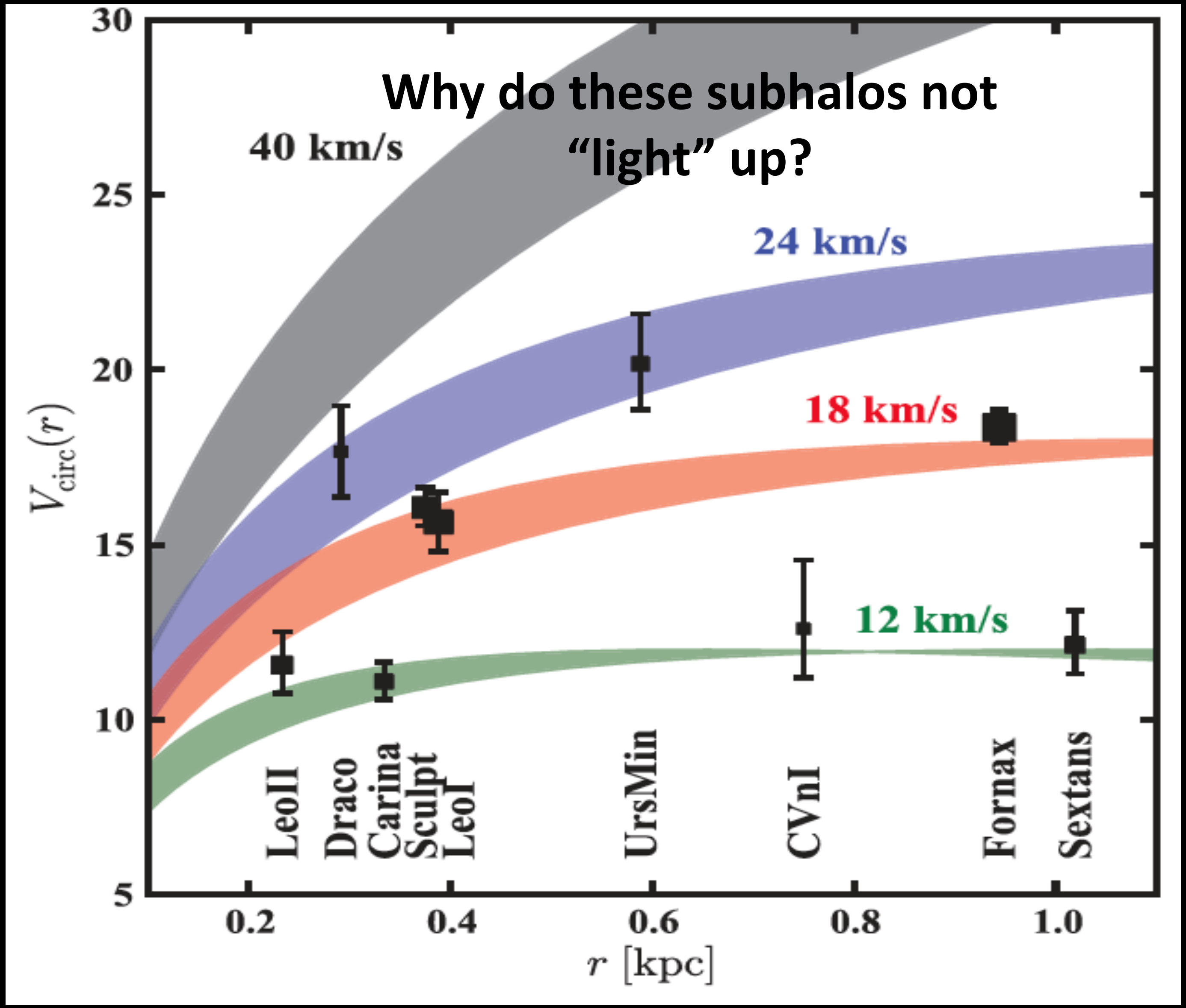
Klypin et al. (1999), Moore et al. (1999), Kauffmann et al. (1993)

Courtesy Shunsaku Horiuchi (Virginia Tech)

CDM: challenged

CDM is challenged on observations probing small scales

1. <u>Core/cusp problem:</u> inner density profile steeper than data
2. <u>Missing satellites problem:</u> expect $O(100)$ satellites but see ~20
3. <u>Too big to fail problem</u>: massive subhalos are too dense to match data



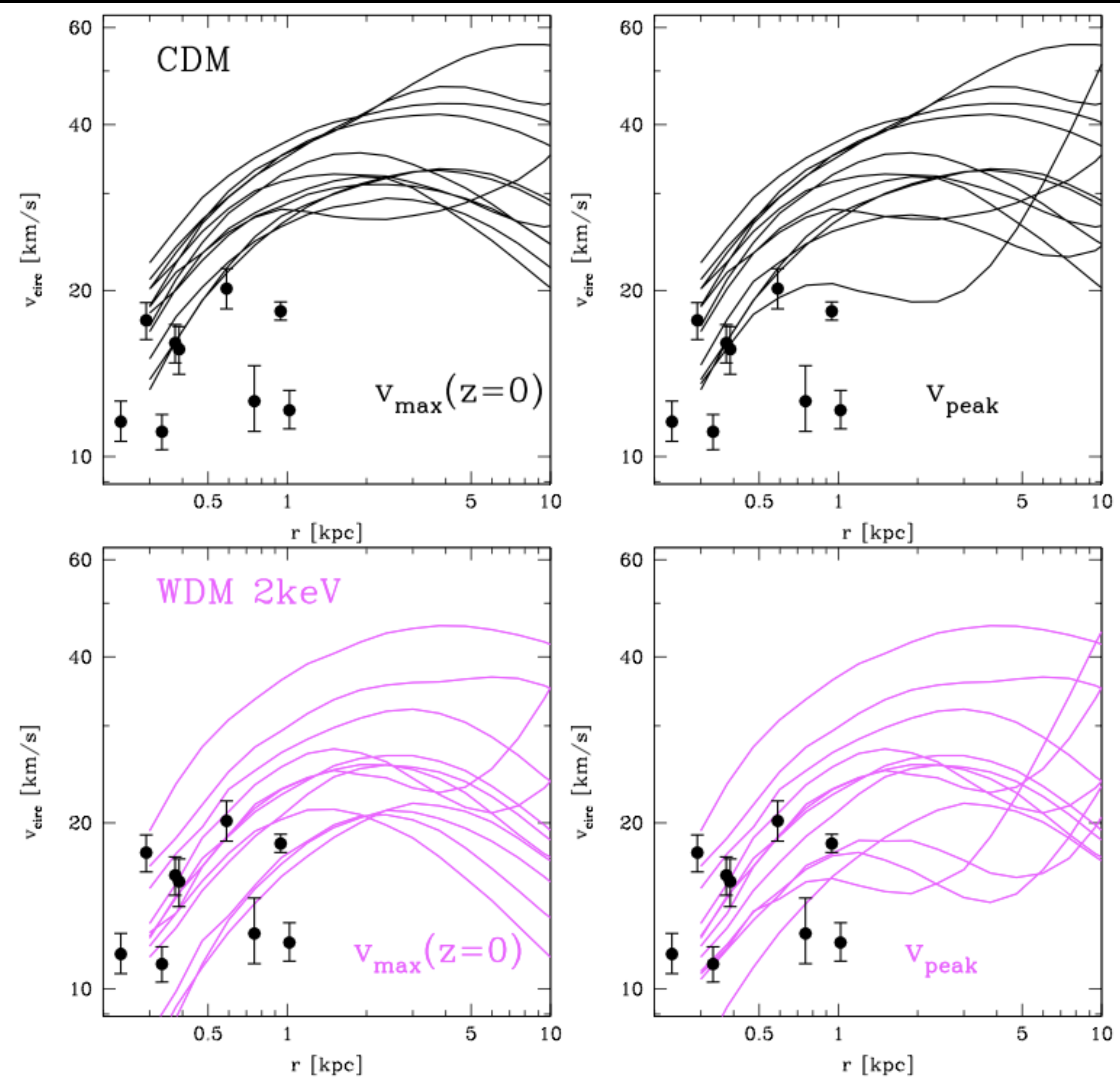
Boylan-kolchin et al, MNRAS (2011, 2012)

Expect 5 – 40 subhalos with V_{max} > 25 km/s (based on 48 realizations)

Garrison-Kimmel et al, 2014

Courtesy Shunsaku Horiuchi (Virginia Tech)

WDM Solution to All Local Group Galaxy Properties?



Anderhalden et al. arXiv:1212.2967

"It seems that only the pure WDM model with a 2 keV [thermal] particle is able to match the all observations" of the Milky Way Satellites: "the total satellite abundance, their radial distribution and their mass profile" (or TBTF)

Sterile Neutrinos as Dark Matter: History

- "Super-weak" neutrinos ($G < G_F$) [Olive & Turner, 1982]: Earlier Decoupling, abundance set by standard dark matter production mechanism of decoupling temperature and degrees of freedom disappearance

- "Sterile" neutrinos [Dodelson & Widrow, 1993]: No SM interactions beyond mass terms, inclusion of finite-temperature modifications to self-energy, lack of thermalization. WDM.

- "Resonant" sterile neutrinos [Shi & Fuller, 1999]: Finite temperature production with non-zero lepton number resonant enhanced production. WDM to CDM. "Cool" Dark Matter.

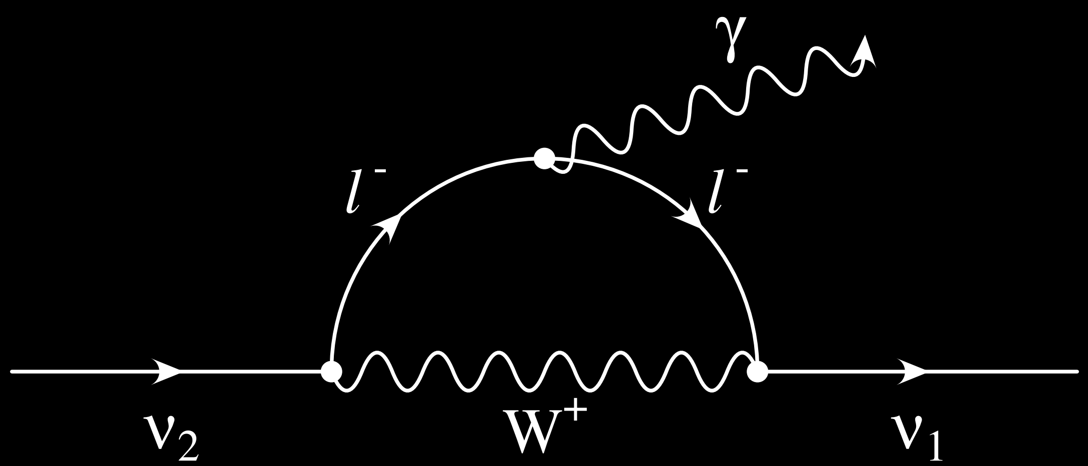
- "Precision" Sterile Neutrino Dark Matter & **Proposal for X-ray Detection** [Abazajian, Fuller & Patel 2001; KA 2005]: Full momentum-space production description with QCD transition corrections, resonant to non-resonant solutions as a continuum in lepton number.

Sterile Neutrinos

Beyond the Standard Model of Particle Physics

- ν_s Phenomenological Insertion of Majorana & Dirac Mass Terms of Comparable Magnitude (atmos. & solar) (e.g. νMSM Asaka et al 2006)
- 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

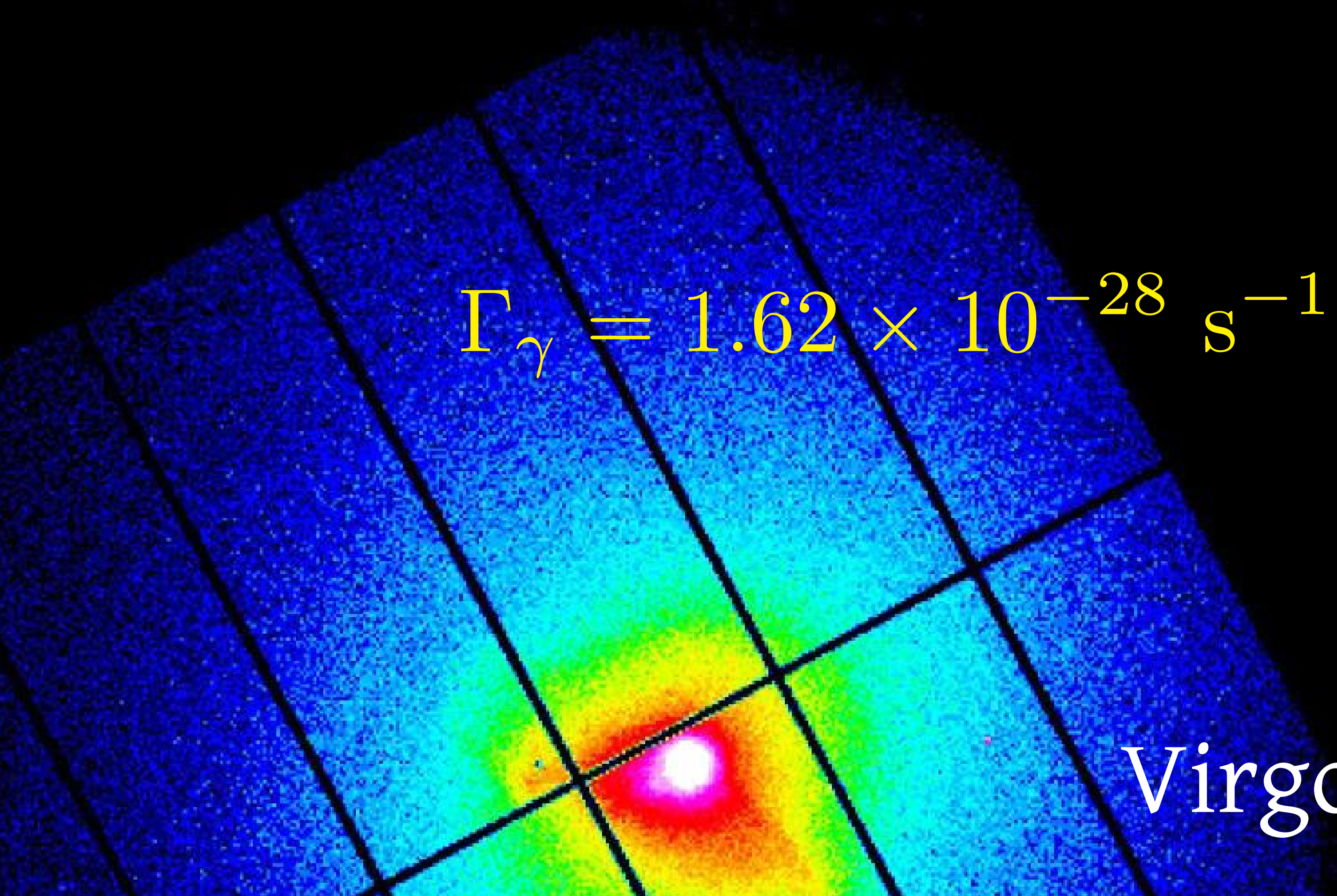


Decay: Shrock 1974; Pal & Wolfenstein 1981
X-ray: Abazajian, Fuller & Tucker 2001

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

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

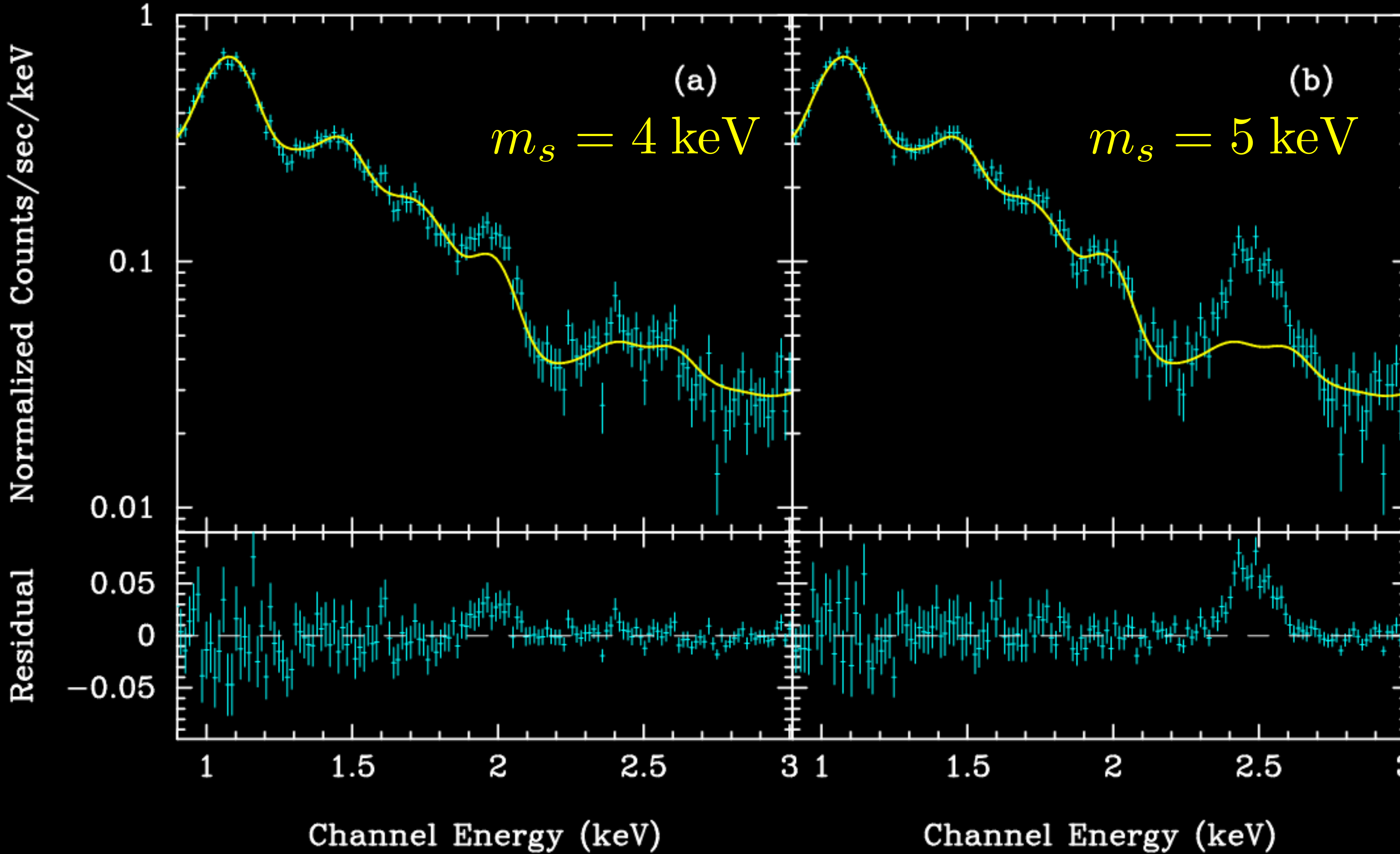
$$\Gamma_\gamma = 1.62 \times 10^{-28}\ \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{7 \times 10^{-11}}\right)\left(\frac{\mathrm{m_s}}{7\ \mathrm{keV}}\right)^5$$



Virgo Cluster: 10^{78} DM particles

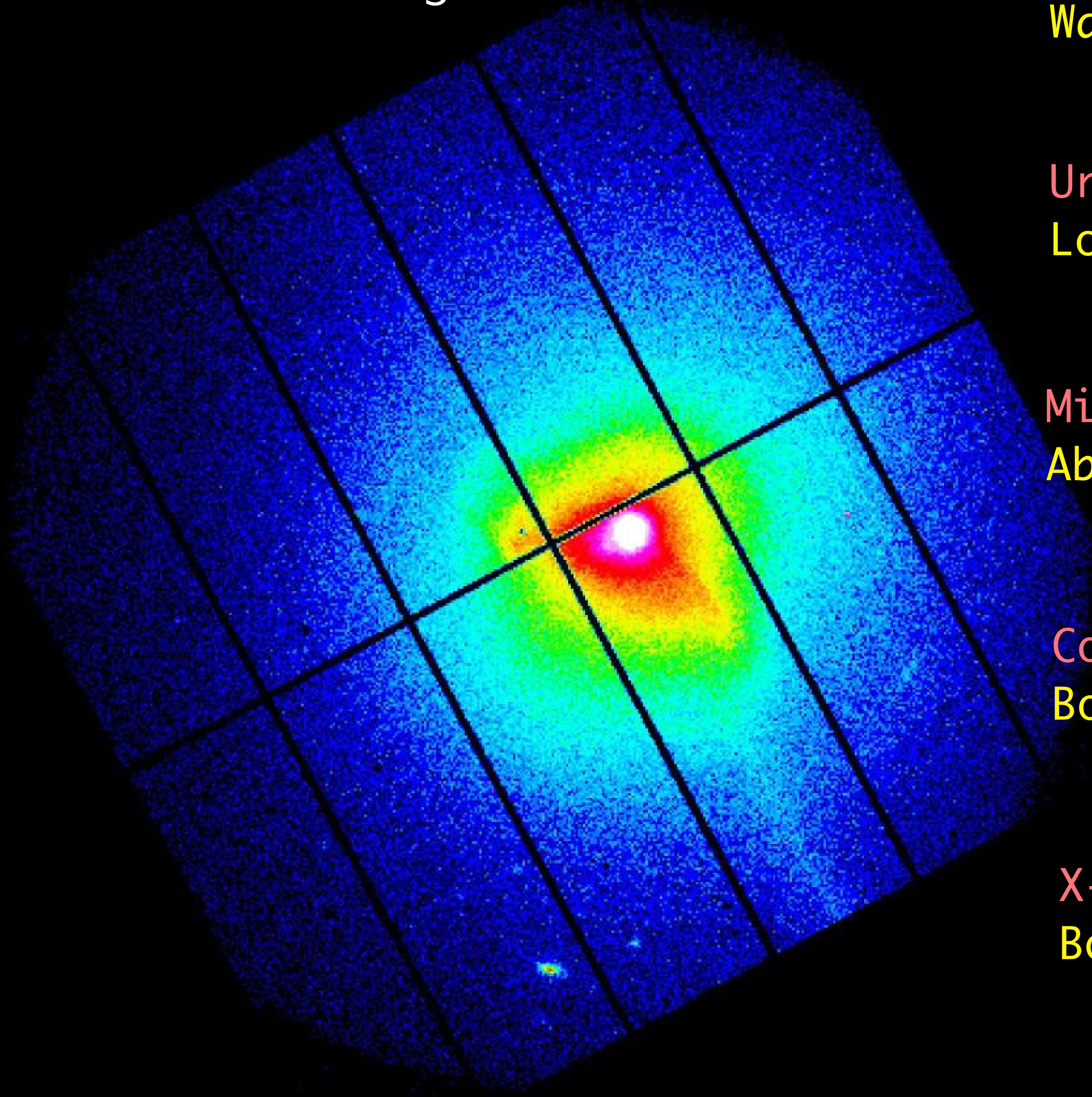
Upper Mass Limit on ν_s DM: X-ray observations of Virgo

Abazajian, Fuller & Tucker 2001



X-ray Constraint Summary

XMM Newton: The Virgo Cluster



Andromeda Galaxy:
Watson et al. 2011

$$m_s < 2.2 \text{ keV}$$

Ursa Minor:
Lowenstein et al. 2008

$$m_s < 3.1 \text{ keV}$$

Milky Way in CXB:
Abazajian et al. 2006

$$m_s < 5.7 \text{ keV}$$

Coma + Virgo Clusters:
Boyarsky et al. 2006

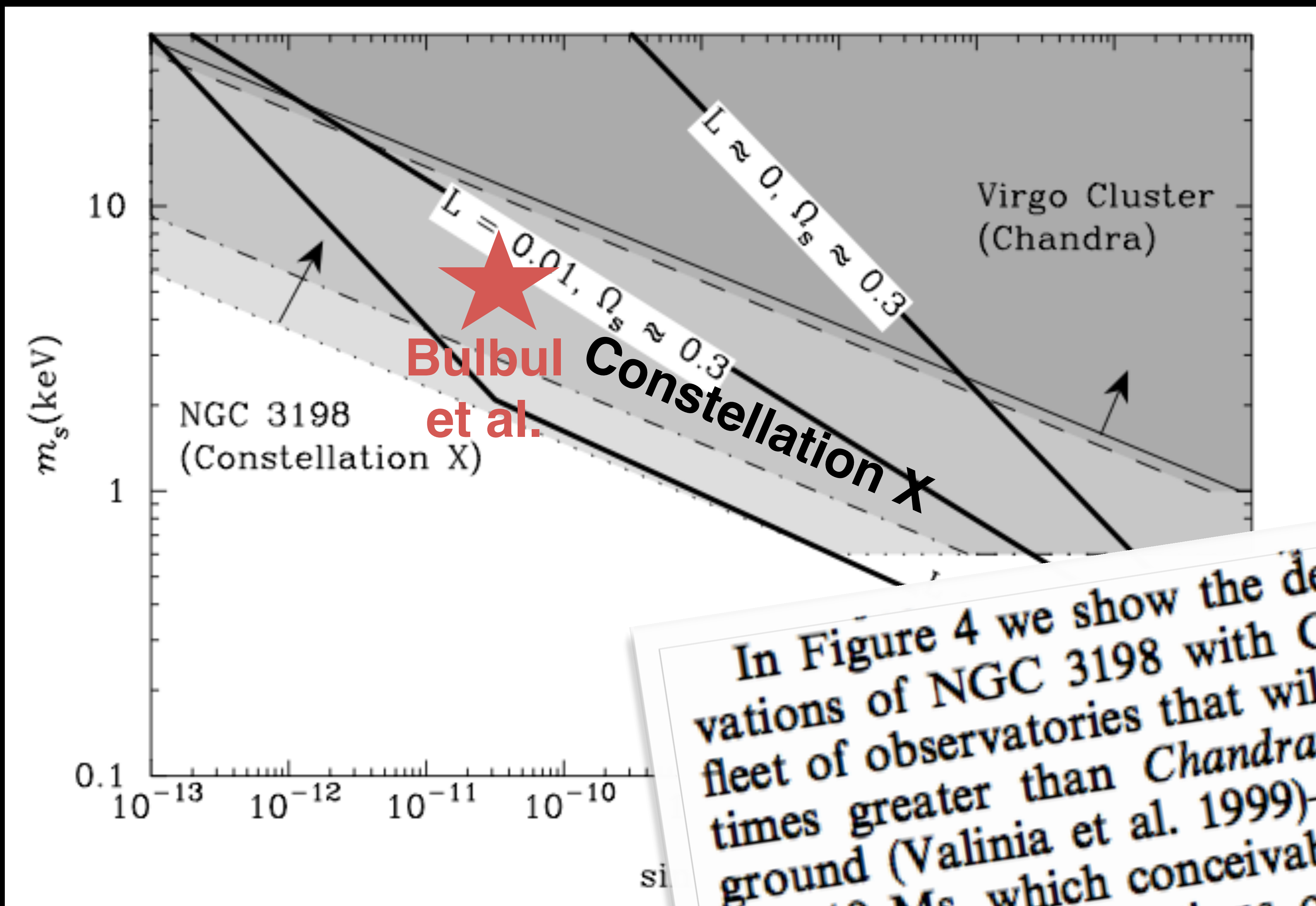
$$m_s < 6.3 \text{ keV}$$

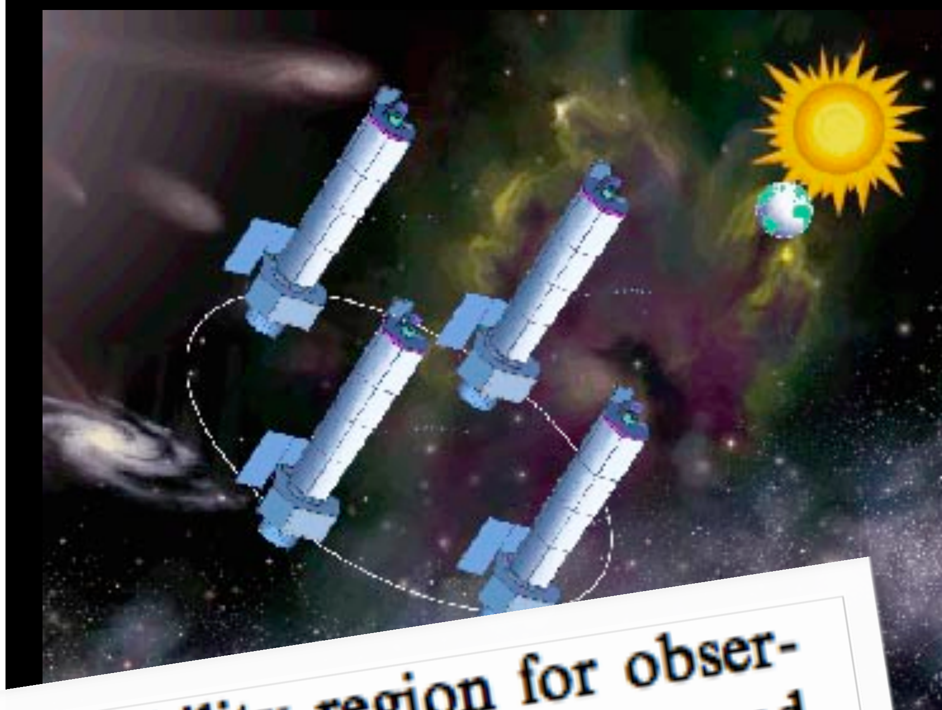
X-Ray Background:
Boyarsky et al. 2006

$$m_s < 8.9 \text{ keV}$$

Forecast X-ray Observation Sensitivity for *Constellation-X*

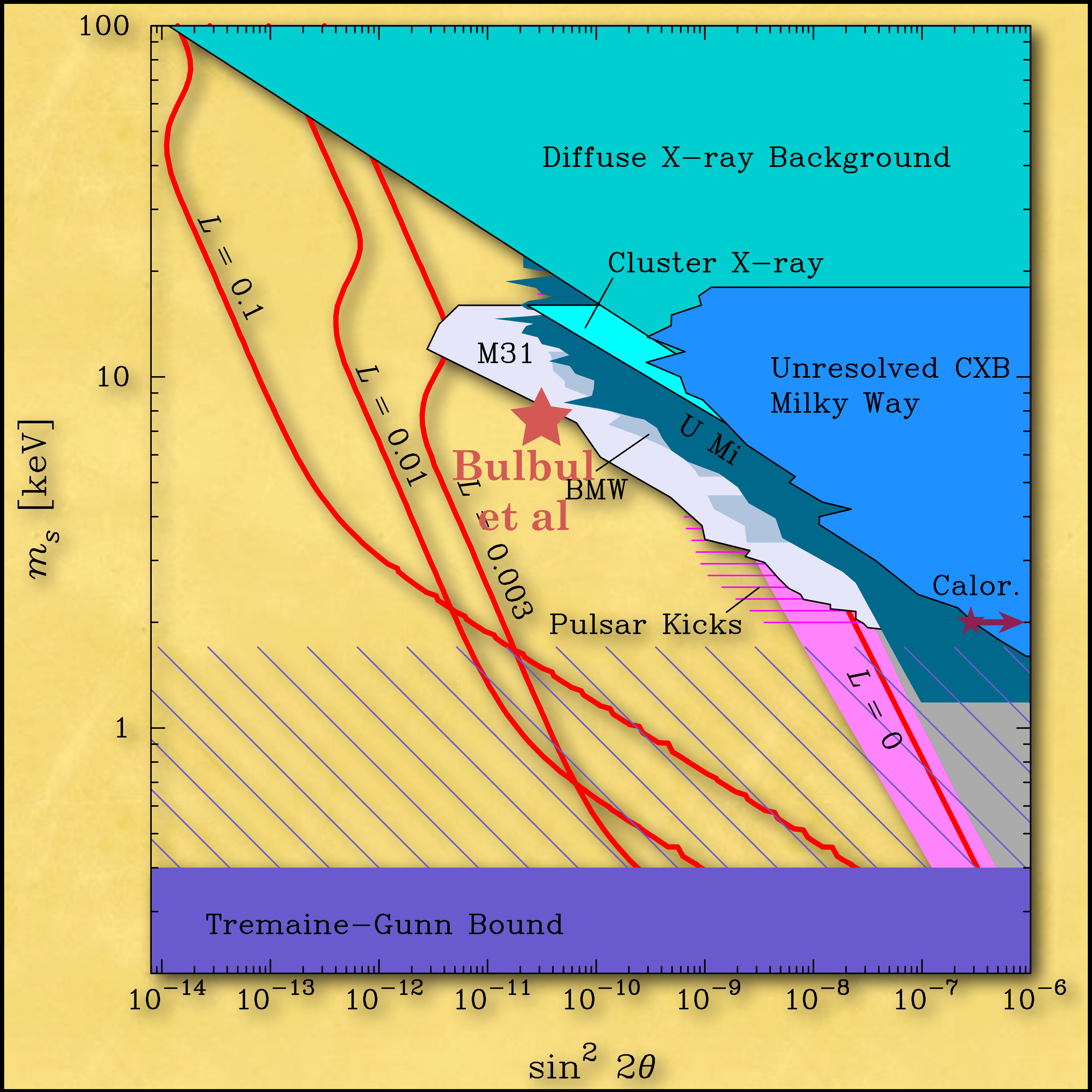
Abazajian, Fuller & Tucker 2001





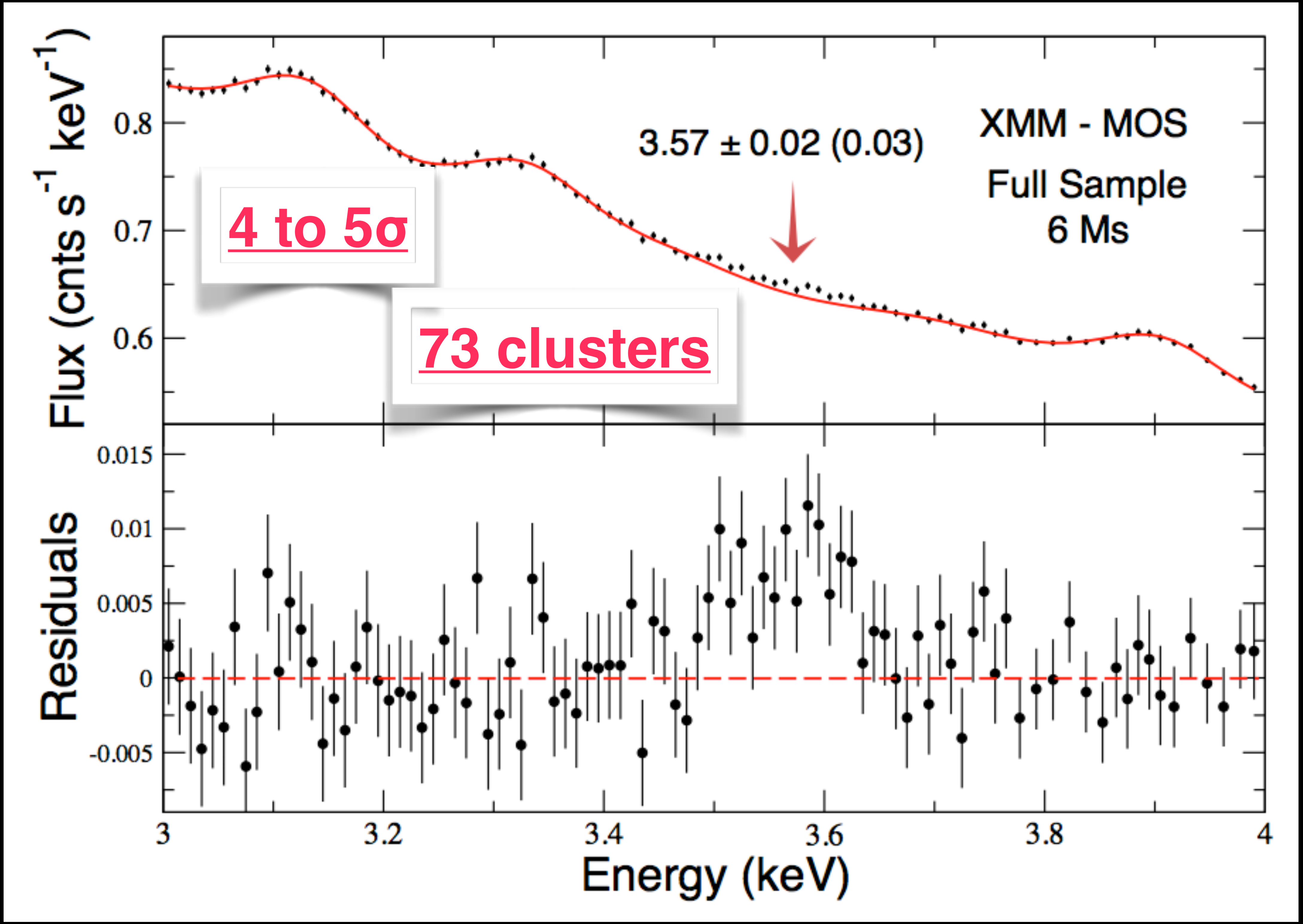
In Figure 4 we show the detectability region for observations of NGC 3198 with Constellation X—a proposed fleet of observatories that will have an effective area ~10 times greater than *Chandra* and no instrumental background (Valinia et al. 1999)—for two integration times, 1 and 10 Ms, which conceivably could be achieved through several long observations over a few years. An exposure equivalent to this could be obtained by a stacking analysis of the spectra of a number of similar clusters (see, e.g., Brandt et al. 2001; Tozzi et al. 2001). Constellation X, with very long integration times, holds out the prospect of covering nearly the entire WDM parameter space of interest for

Sterile Neutrino Dark Matter
Parameter Space Summary



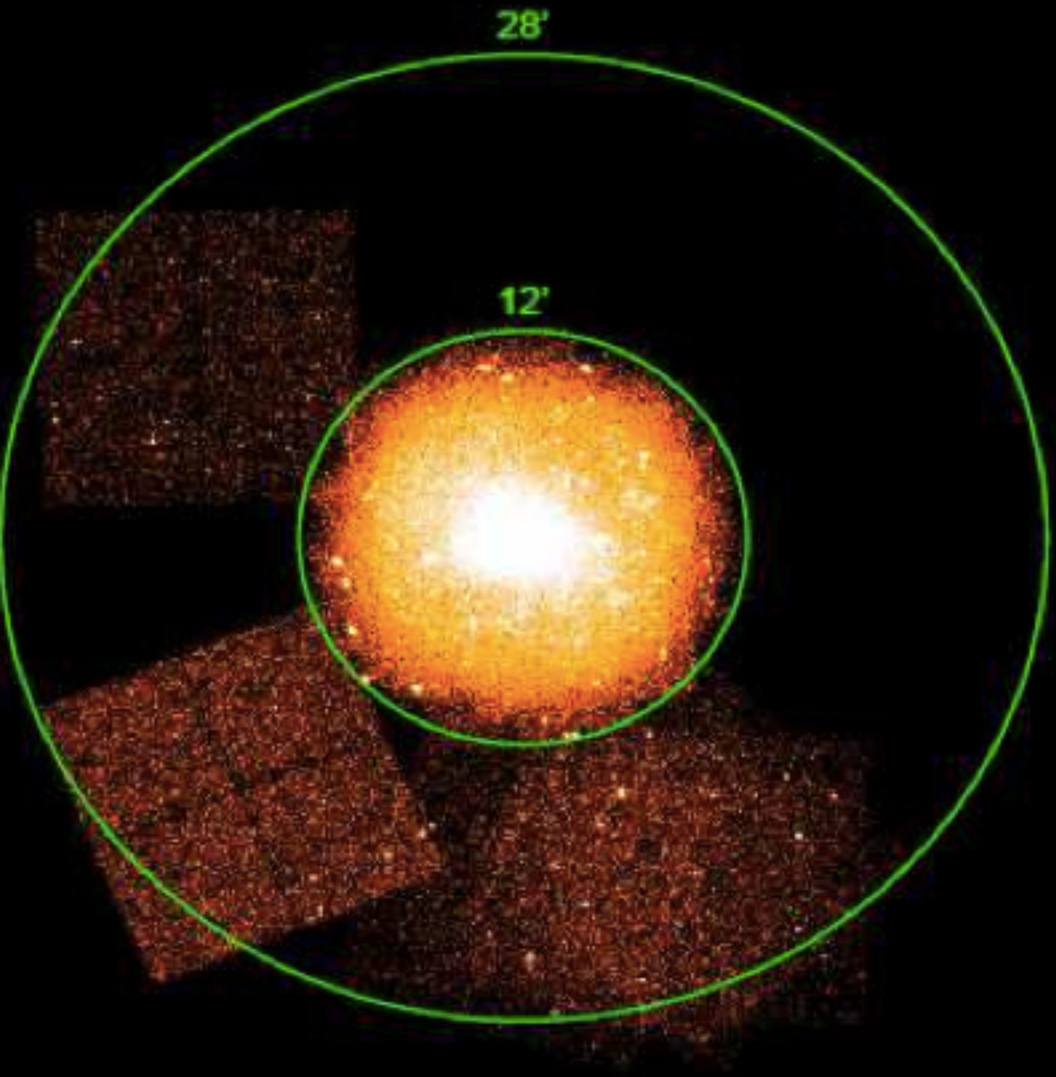
Abazajian 2011

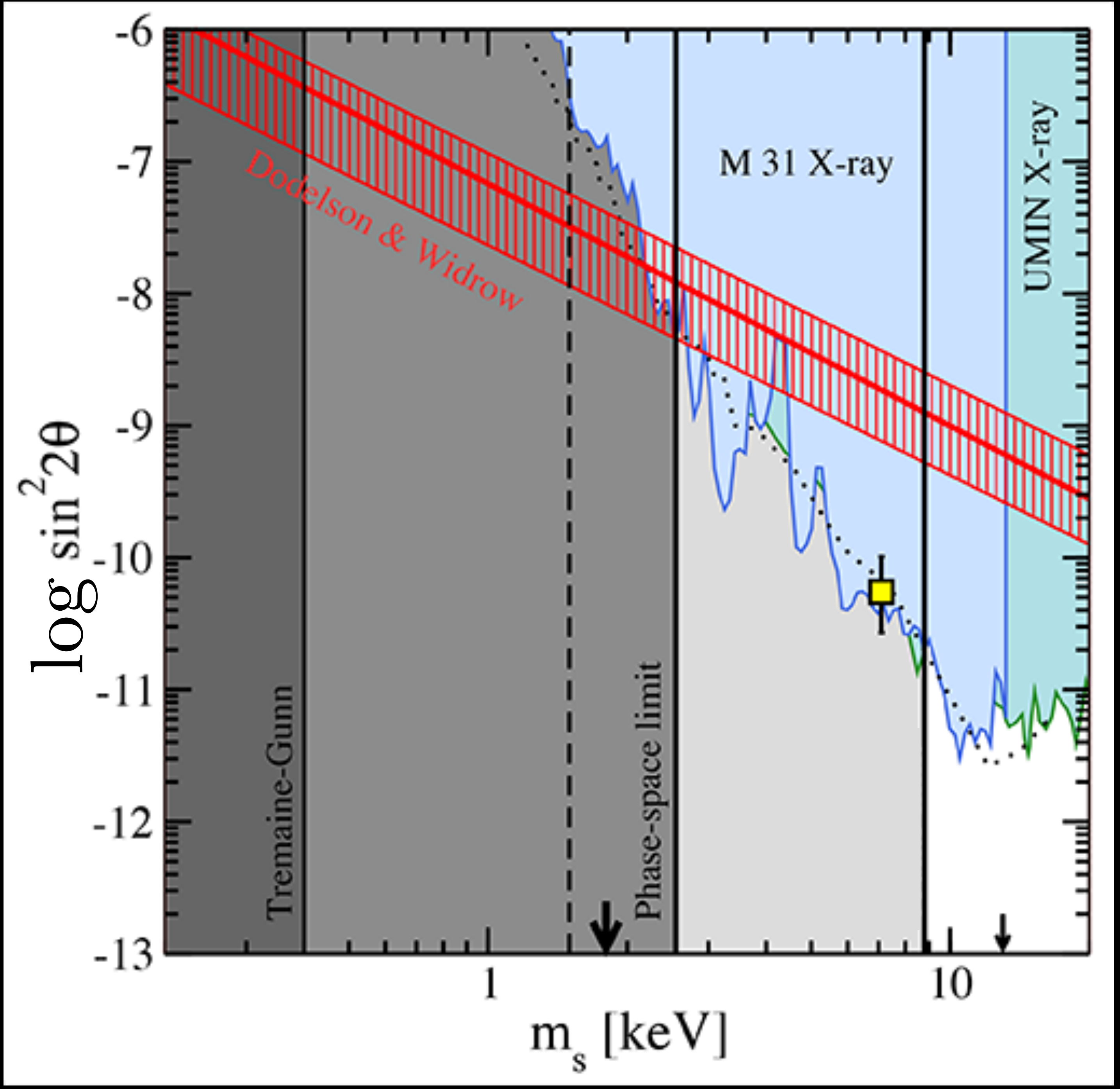
The Detection of an Unidentified Line



Bulbul et al. arXiv:1402.2301

Chandra X-ray M31 plus substructure constraints

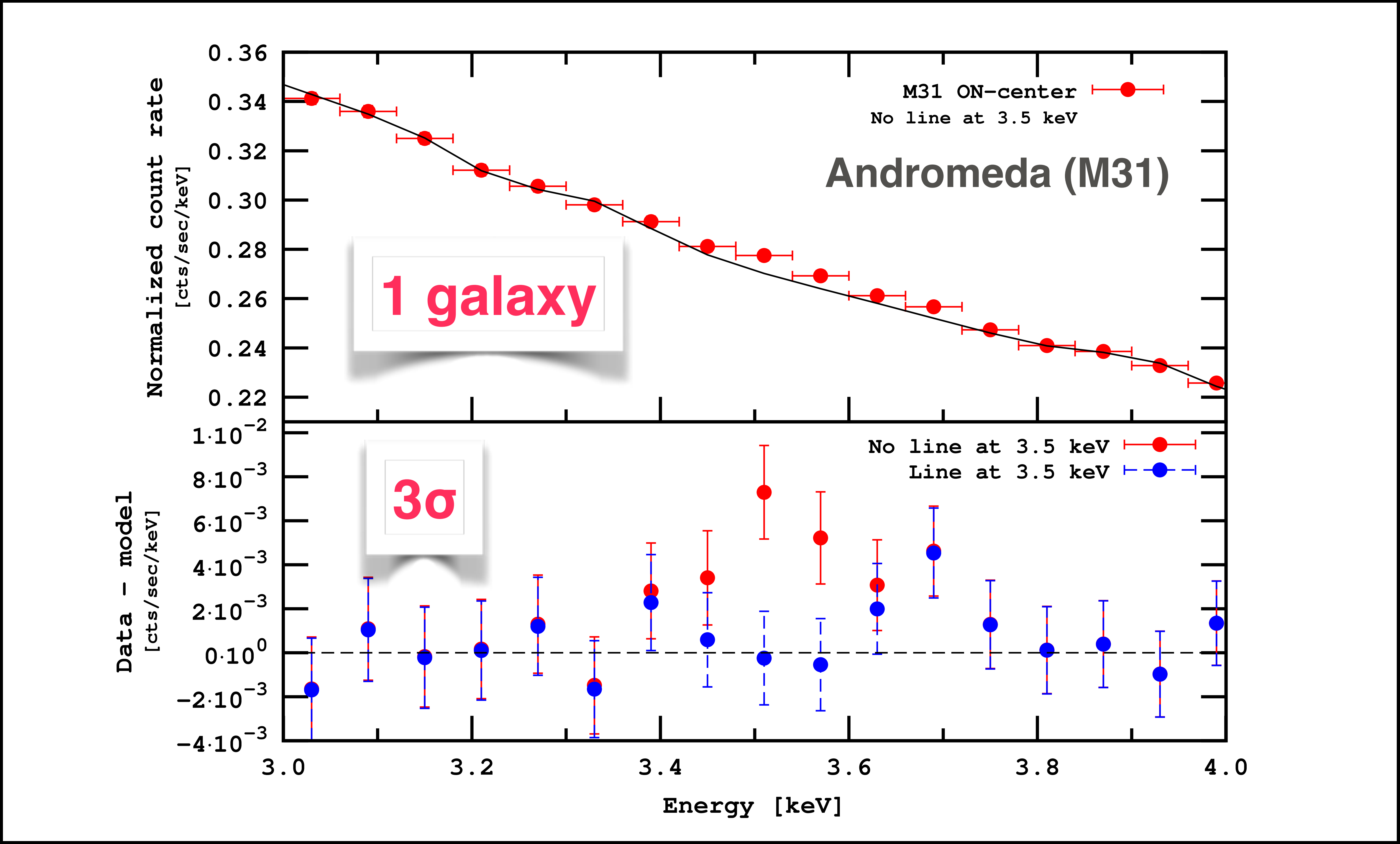




Combined subhalo and X-ray constraints: exclude standard ν_s

Horiuchi, Humphrey, Abazajian & Kaplinghat, PRD arXiv:1311.0282

The Detection of an Unidentified Line II

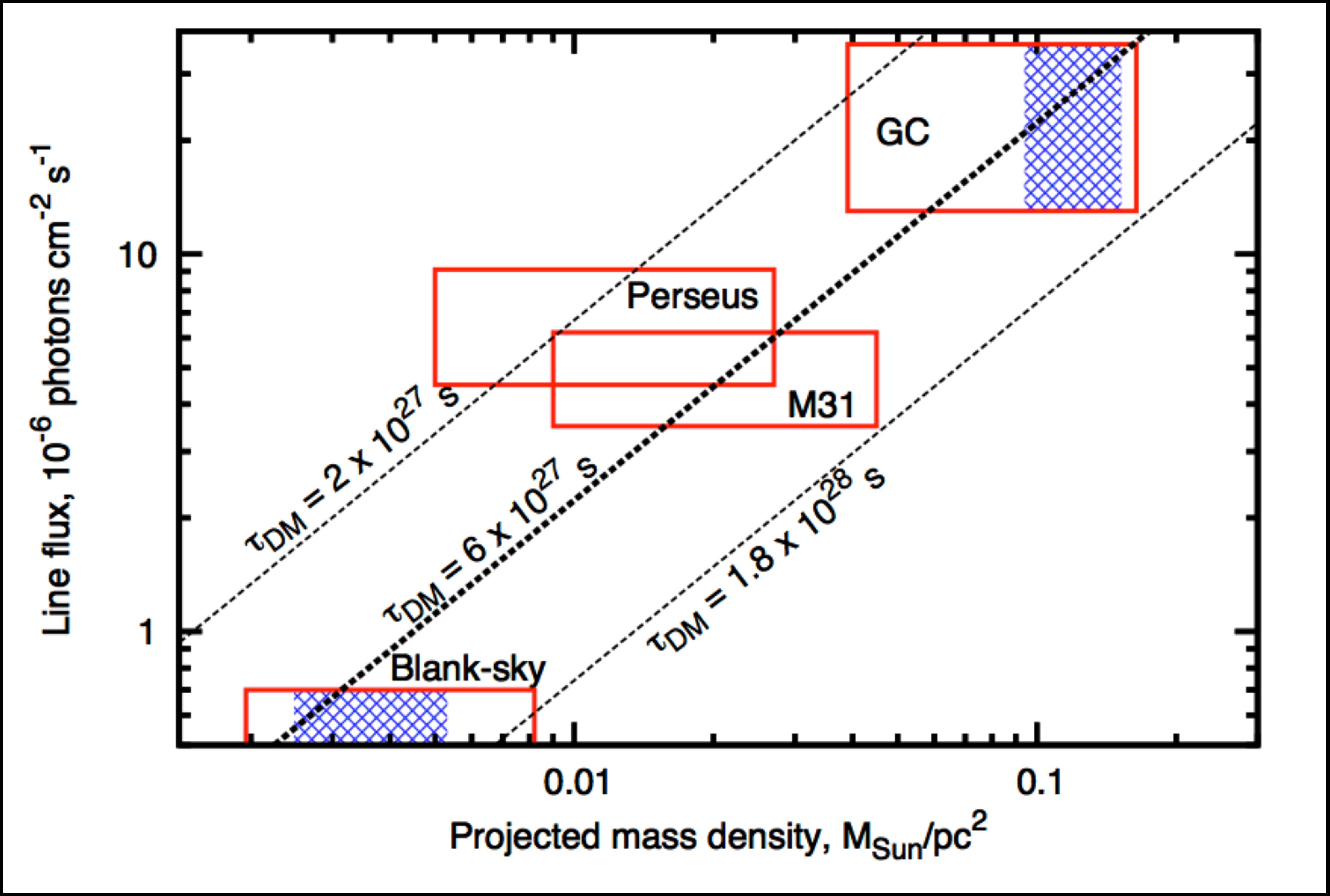


Boyarsky et al. PRL arXiv:1402.4119

X-ray Observations

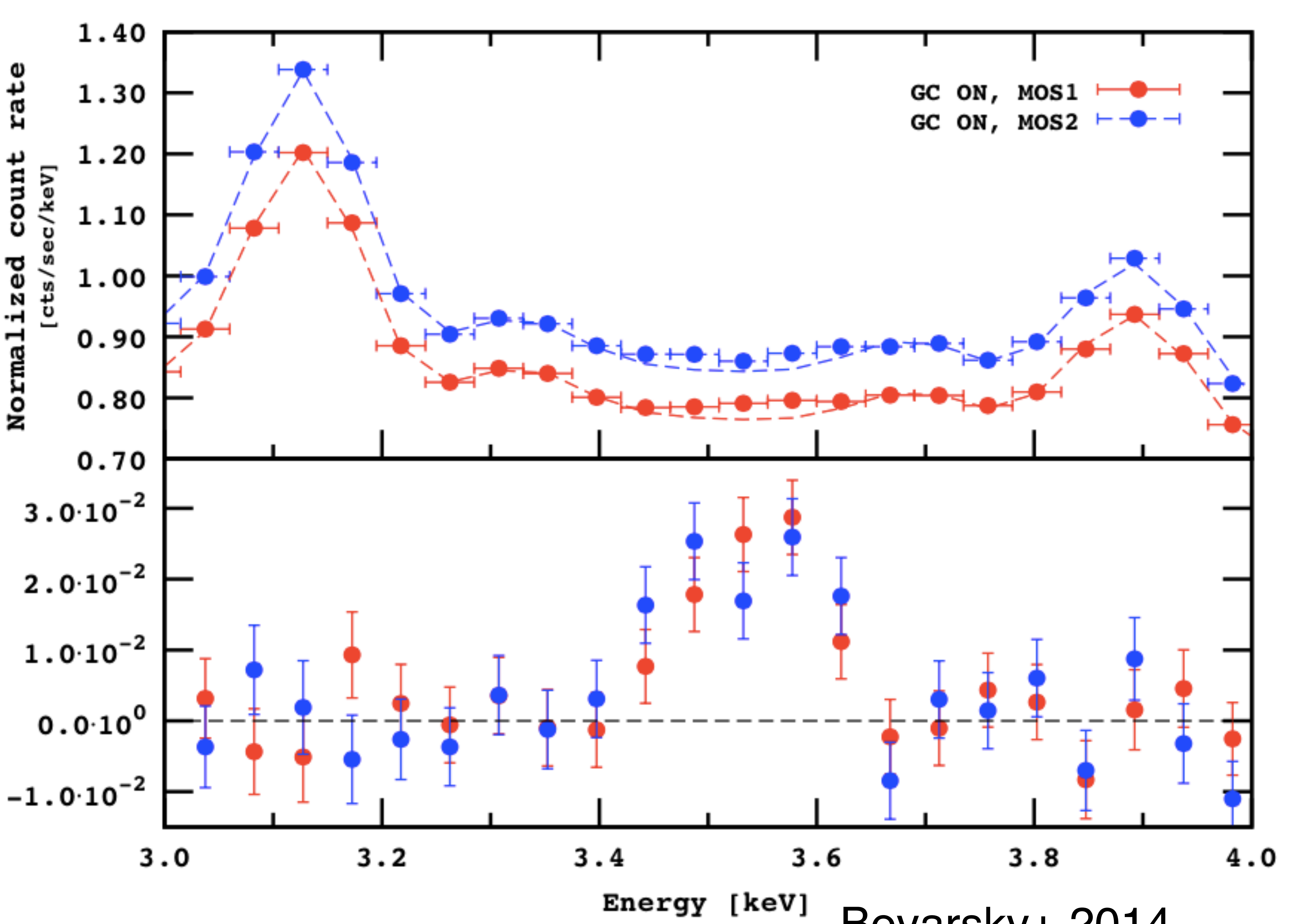
- **Bulbul et al. (ApJ arXiv:1402.2301)**
  - **73 clusters** with *XMM-Newton*, **MOS** + **PN** CCDs
    - stacking $z = 0.01$ to 0.35 clusters
      - blends features in the instrument response function
      - increases total exposure
    - **4 - 5σ in full MOS data set**
    - found in several subsets of observations
      - ***→Trials factor unnecessary***
  - **Indications at 2.2σ Perseus** with *Chandra*
  - Not seen in Virgo, but consistent upper limit
- **Boyarsky et al. (PRL arXiv:1402.4119)**
  - **Andromeda indication** at 3σ - *XMM-Newton*
  - **Perseus indication** at 2.3σ - *XMM-Newton*
  - Combined detection at **4.4σ**

Galactic Center Detection (?!)



Boyarsky+ 2014

Galactic Center Detection (?!)



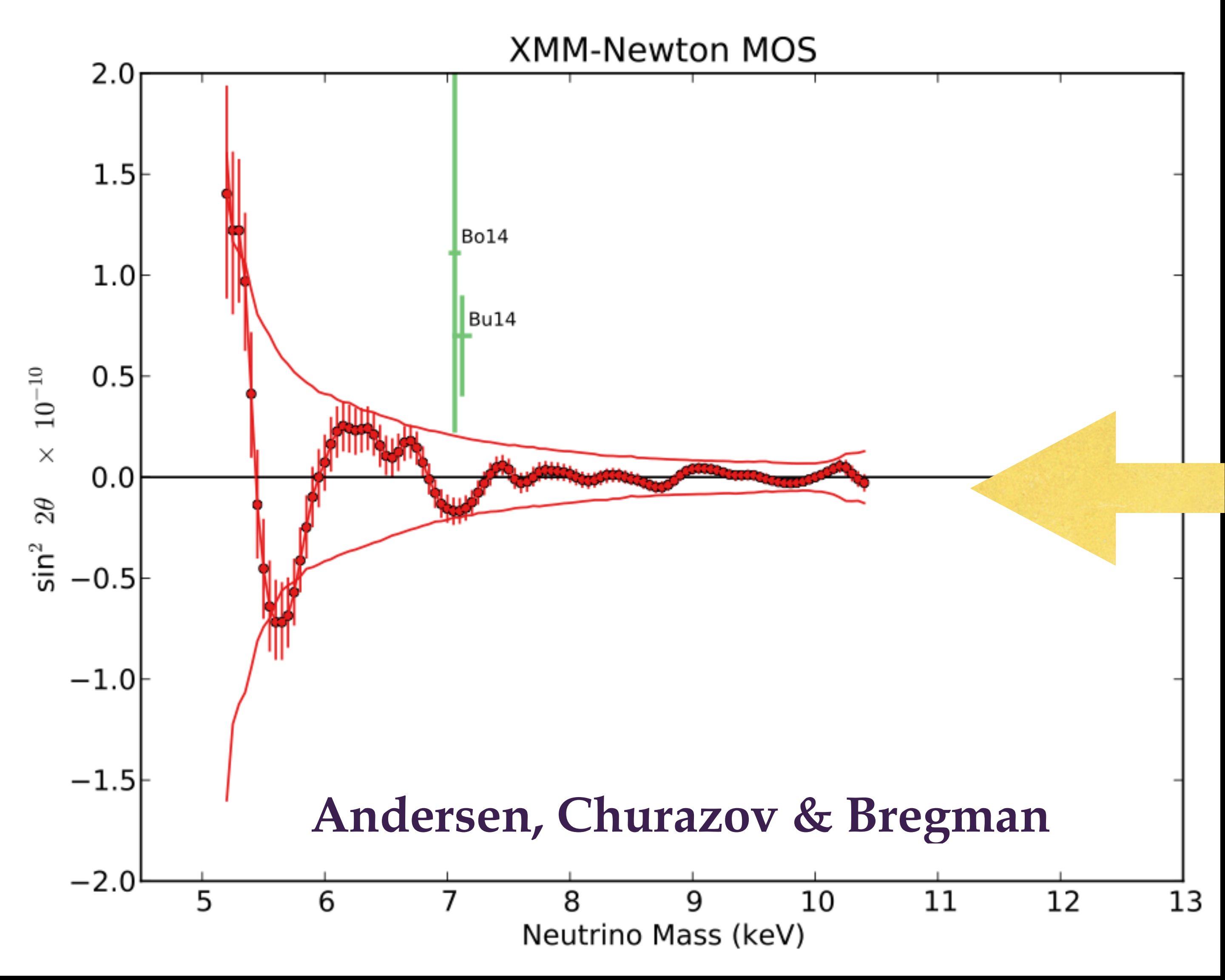
Boyarsky+ 2014

Galactic Center X-ray Constraints? Potassium Lines? M31?

"Bananas" Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

- JP claim that the Galactic Center excludes a dark matter interpretation
  - » JP makes the assumption of all of the 3.5 keV flux coming from K XVIII, and then placing constraints on dark matter decay from the Galactic Center after this assumption. The flux from the Galactic Center is in fact consistent with the dark matter mass within the region [Boyarsky+ arXiv:1408.2503].
- JP claim that there is less than 2σ evidence for the line in XMM-Newton data of M31
  - » The Boyarsky team showed how the JP M31 analysis is flawed in using much too narrow of an energy window in their line search modeling [arXiv:1408.4388].
- JP claim line ratios in the cluster data do not allow for a consistent model for the temperature of Perseus
  - » The Bulbul+ team showed that JP use over-simplified single-temperature model arguments with incorrect line ratios in their X-ray cluster modeling [arXiv:1409.0920].

Stacked Observations I: Galaxies



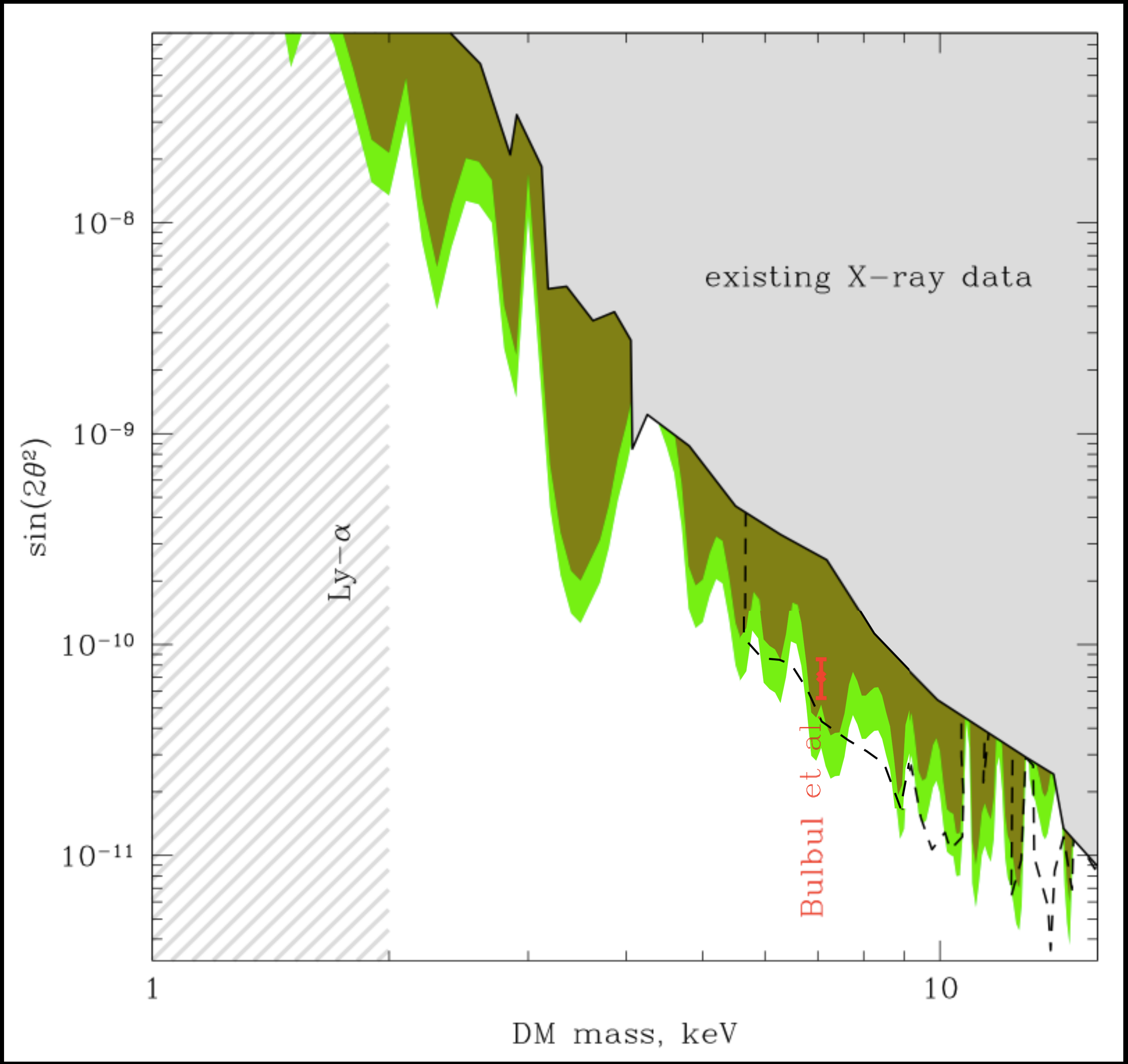
Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

Quoted exclusion of the 3.5 keV line at fixed $\sin^2 2\theta$ by 11.8σ

Systematic errors are of order the uncertainties on detected $\sin^2 2\theta$

There was no test of the line hypothesis in mutual data of clusters plus galaxies (that is: is there any mixing angle that fits all data?), *no presentation of limits in parameter space*

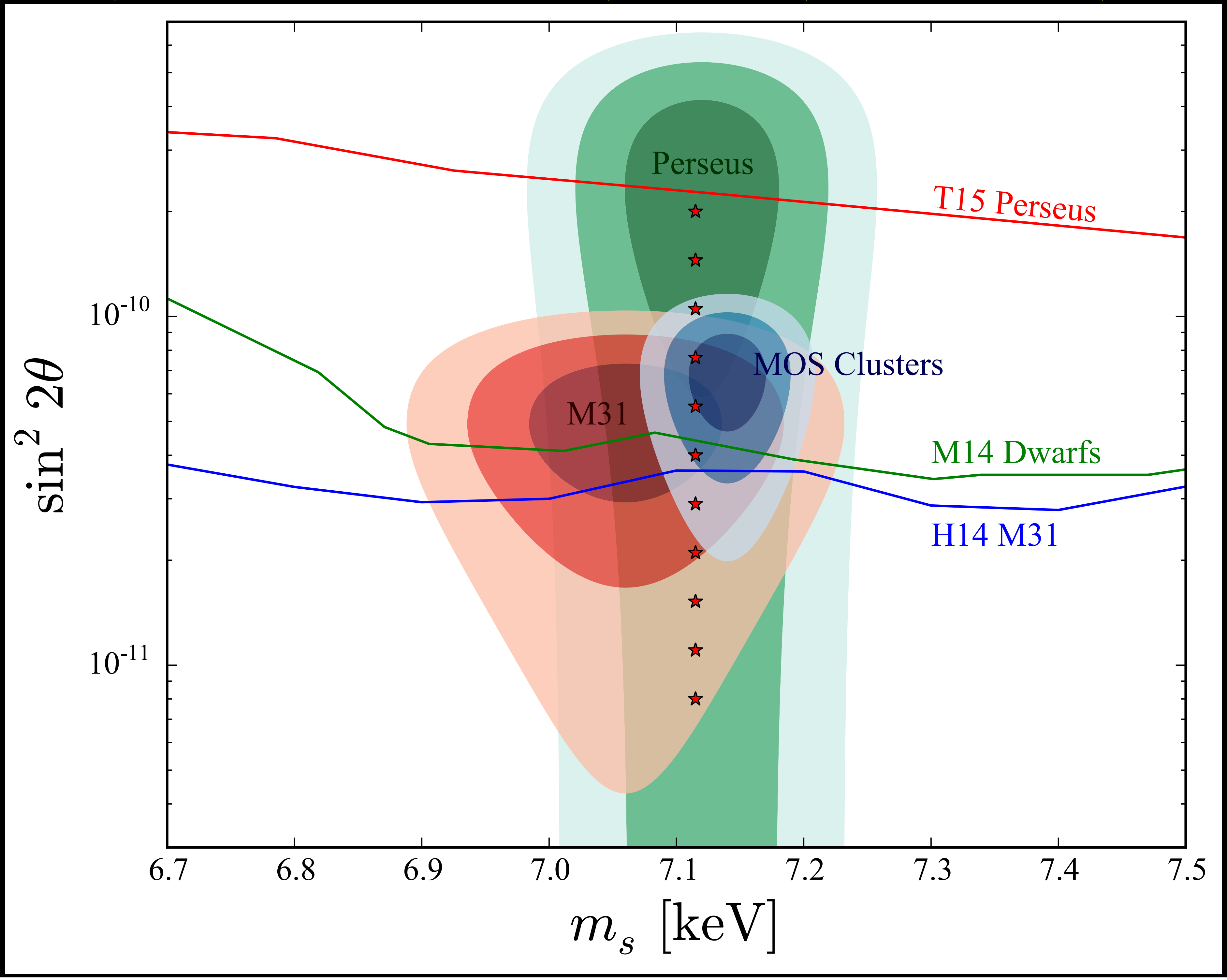
Stacked Observations II: Dwarf Galaxies



sample of 8 dwarf galaxies observed with XMM-Newton, total of ~408 ksec of observations

Malyshev, Neronov & Eckert 2014

Where X-ray signals & limits are now…

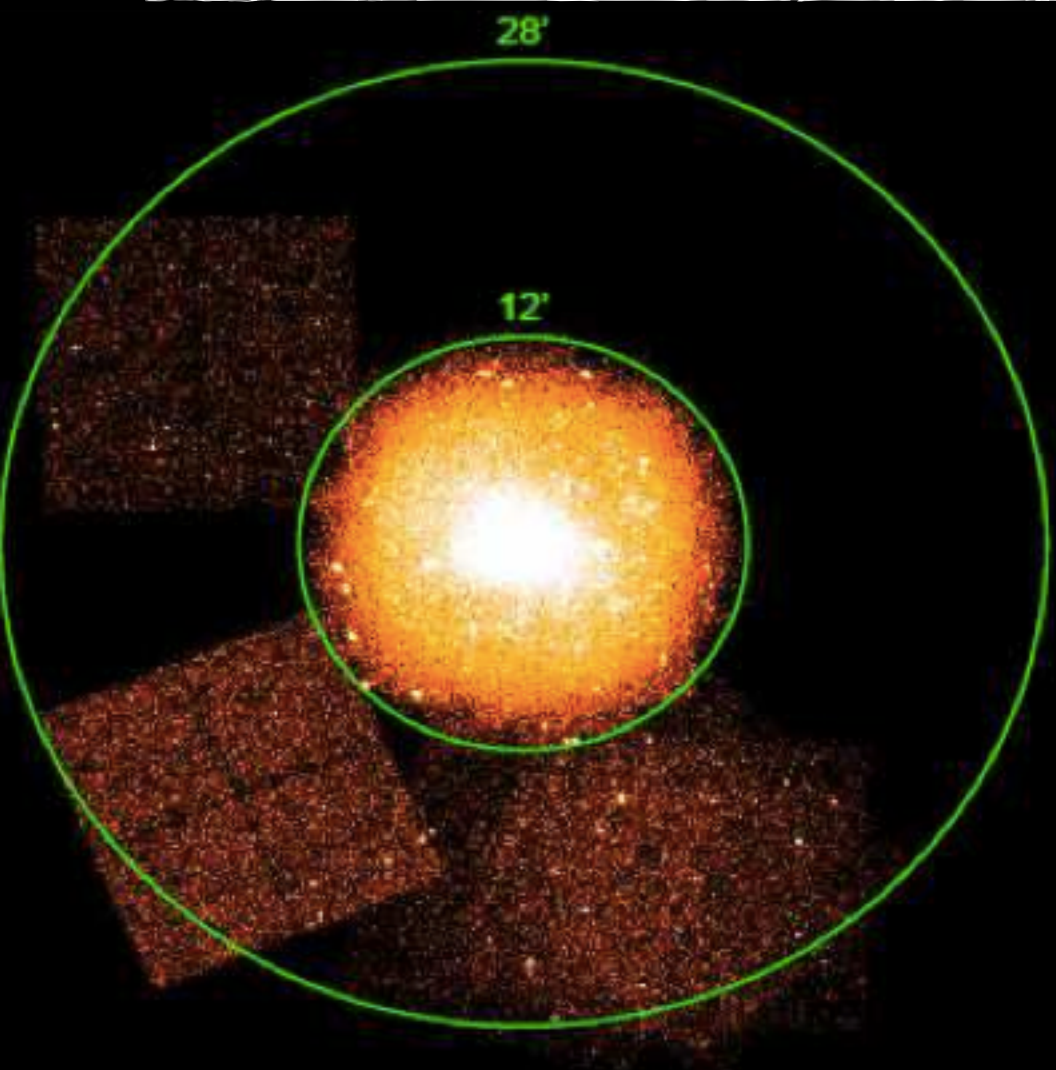


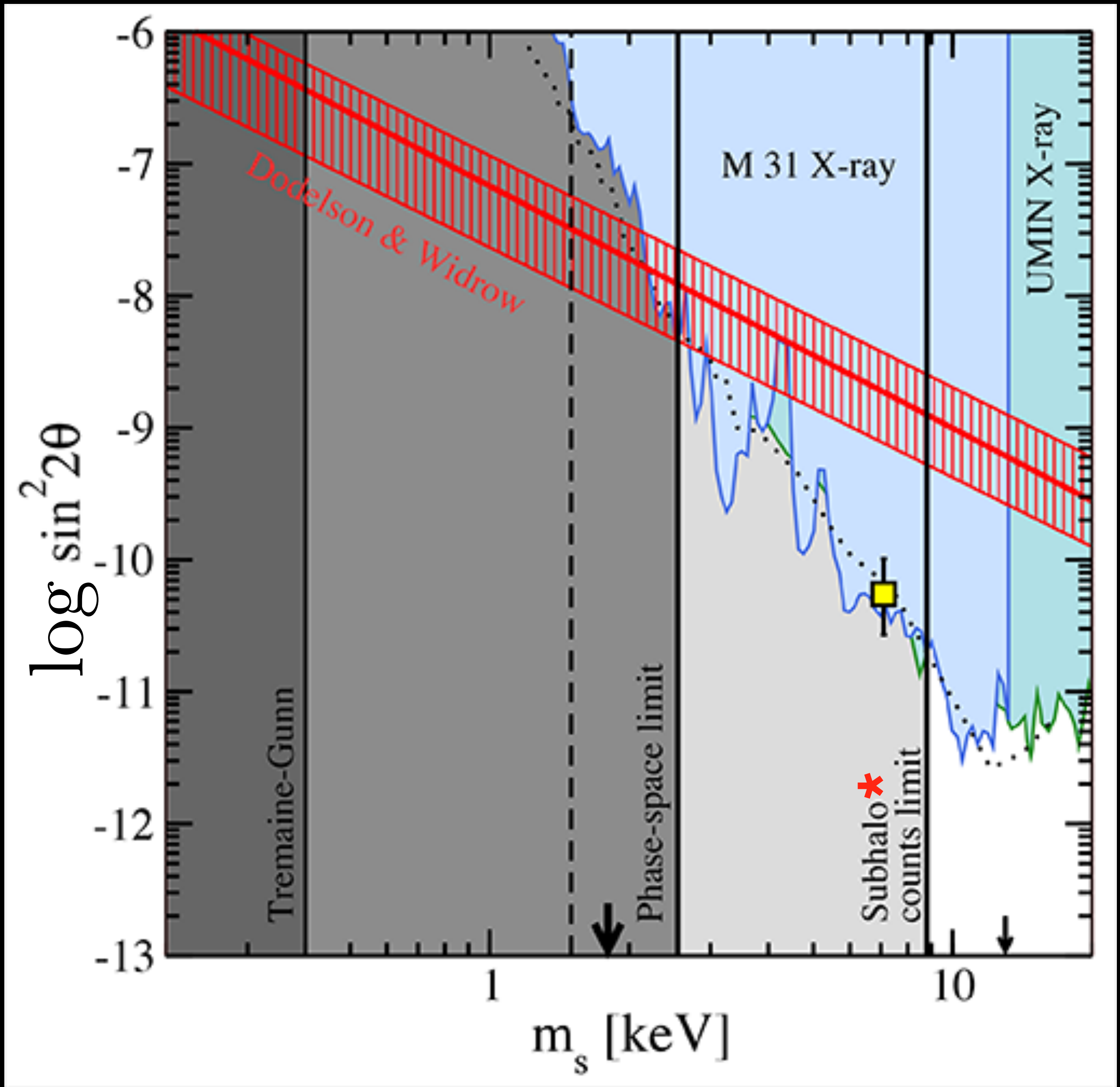
H14 M31: Horiuchi+ 2014

T15 Perseus: Tamura+ 2015

M14 Dwarfs: Malyshev+ 2014

Chandra X-ray M31 plus substructure constraints





Combined subhalo and X-ray constraints: exclude standard ν_s

Horiuchi, Humphrey, Abazajian & Kaplinghat, PRD arXiv:1311.0282

Sterile Neutrino Dark Matter Production

Quantum Field Theory + Statistical Mechanics

$$\rho(\epsilon, t) = \sum_{i,j} \rho_{i,j}(\epsilon, t)|\nu_i\rangle\langle\nu_j| \qquad \epsilon \equiv p_\nu / T$$

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_s\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

$$\dot{\rho}(\epsilon, t) = -i[H, \rho] \;\Rightarrow\; \rho(\epsilon, t) = \frac{1}{2} P_0(\epsilon, t)\left[1 + \mathbf{P}(\epsilon, t)\cdot\sigma\right]$$

$$\begin{aligned} \frac{\partial}{\partial t}\mathbf{P}(\epsilon, t) =& \mathbf{V}(\epsilon, t) \times \mathbf{P}(\epsilon, t) + \left[1 - P_z(\epsilon, t)\right] \\ & \times \left[\frac{\partial}{\partial t} \ln P_0(\epsilon, t)\right]\hat{z} \\ & - \left[D(\epsilon, t) + \frac{\partial}{\partial t}\ln P_0(\epsilon, t)\right]\left(P_x(\epsilon, t)\hat{x} + P_y(\epsilon, t)\hat{y}\right) \end{aligned}$$

Sterile Neutrino Dark Matter Production

$$\Gamma_\alpha(p) \sim G_F^2 p T^4 \sim T^5$$

$$\Delta^2 \sim p^{-2} \sim T^{-2}$$

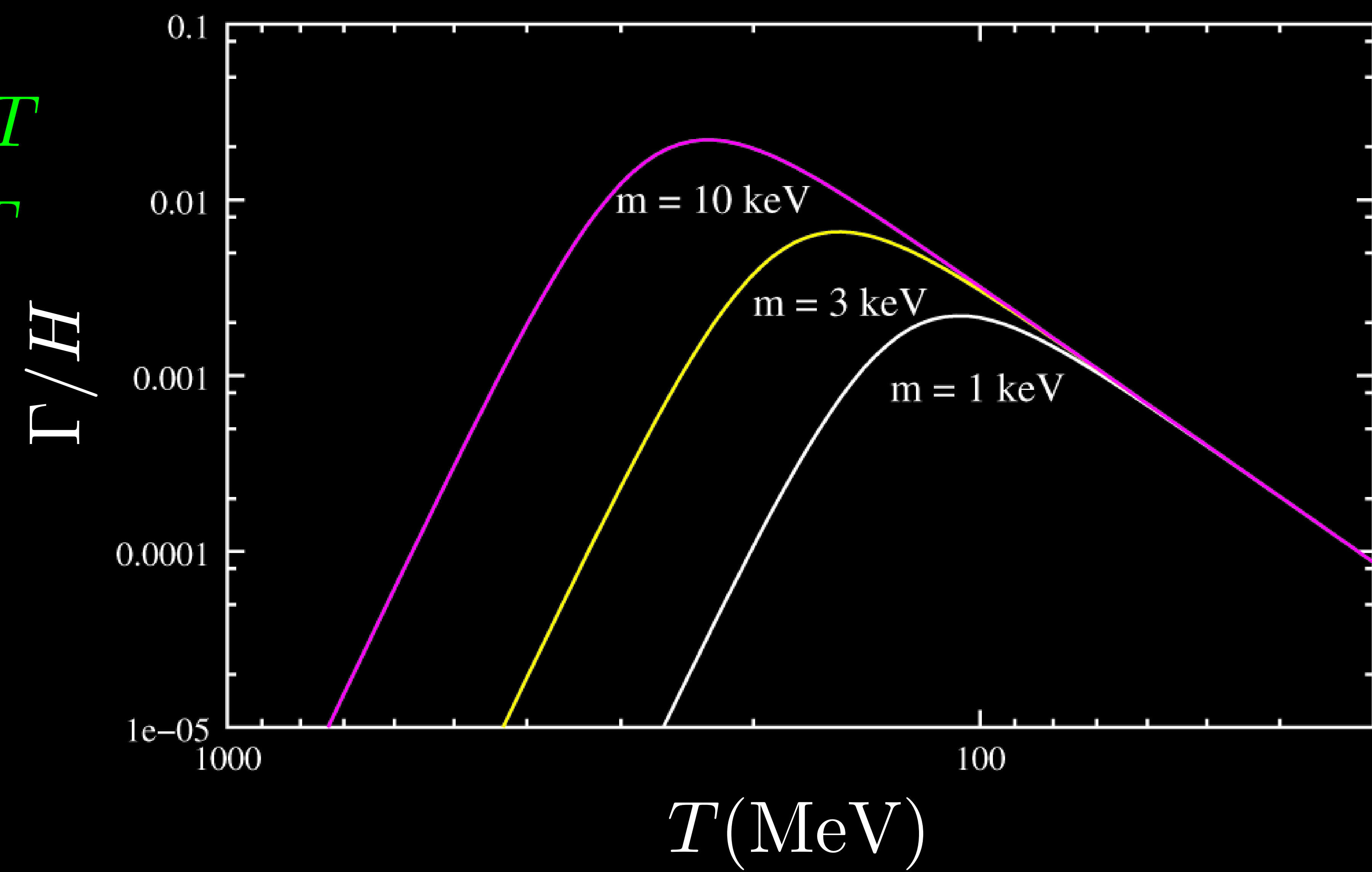
$$\Gamma(\nu_\alpha \to \nu_s) \sim \frac{\Gamma_\alpha(p)\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + D^2(p) + [\Delta(p)\cos 2\theta - V^L(p) - V^T(p)]^2}$$

$$D(p)^2 \sim T^{10}$$

$$[V^T]^2 \sim T^{10}$$

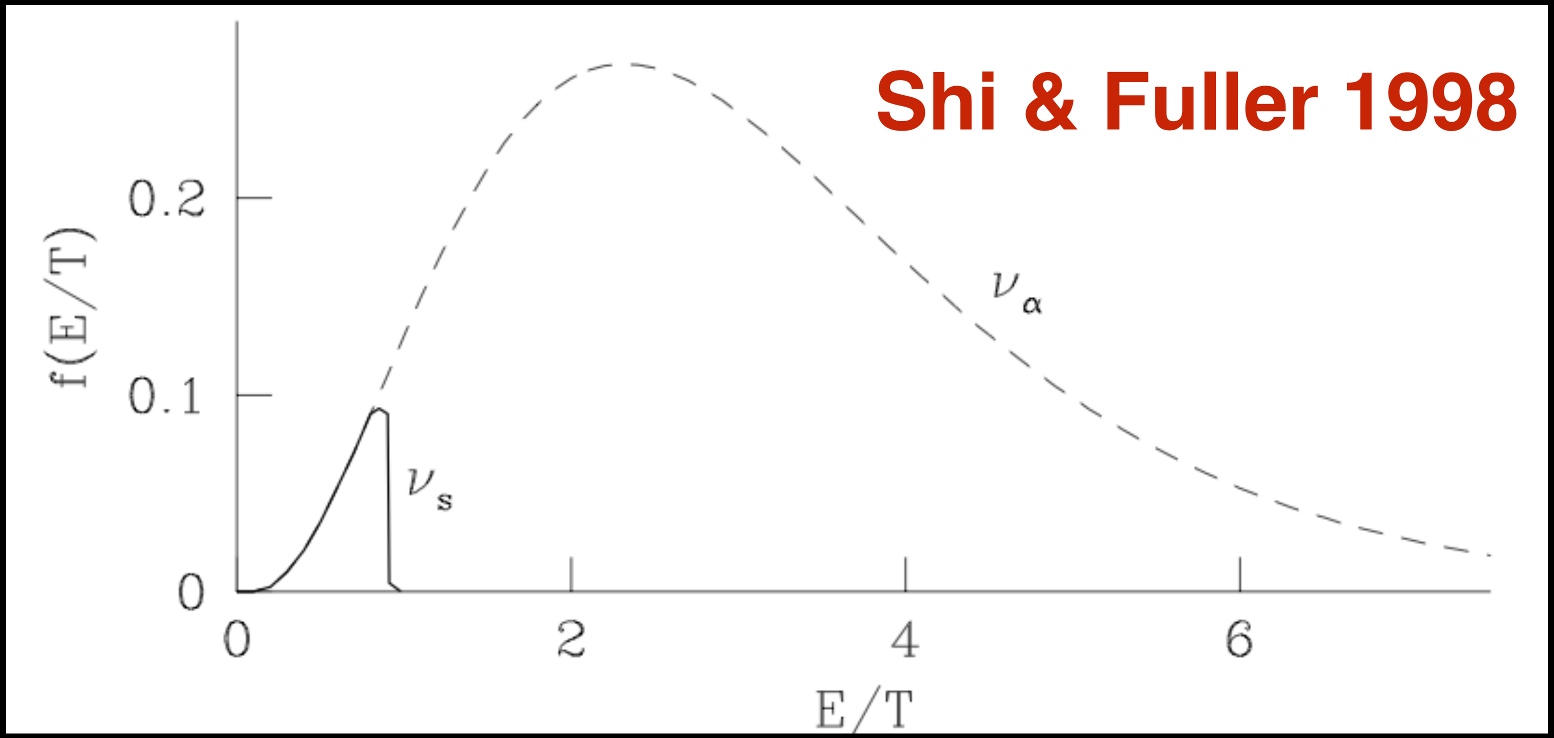
$$H^2 = \frac{8\pi}{3} G\rho \sim T^4$$

$$\frac{\Gamma}{H} \sim \begin{cases} T^{-9} & \text{High } T \\ T^3 & \text{Low } T \end{cases}$$



Never in Equilibrium!!

Resonant Production



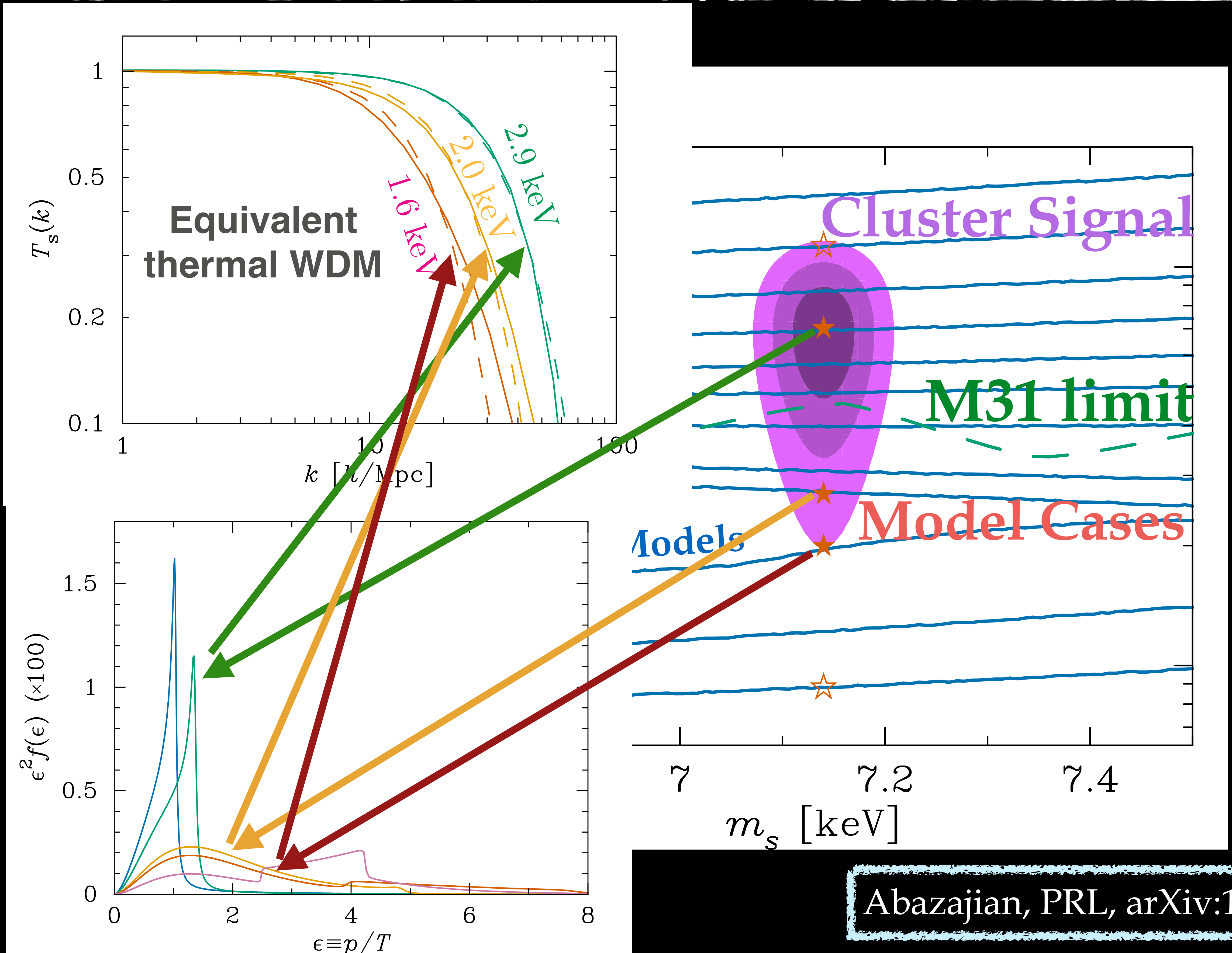
Matter (thermal) mixing angle:

$$\sin^2 2\theta_m = \frac{\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + [\Delta(p)\cos 2\theta - V^D - V^T(p)]^2}$$

$$\Rightarrow \qquad \epsilon_{\rm res} \approx \frac{\delta m^2}{(8\sqrt{2}\zeta(3)/\pi^2)G_{\rm F}T^4 L}$$

$$\approx 3.65\left(\frac{\delta m^2}{(7\,{\rm keV})^2}\right)\left(\frac{10^{-3}}{L}\right)\left(\frac{170\,{\rm MeV}}{T}\right)^4$$

Exact Shi-Fuller Parameter Space & Structure Formation



Abazajian, PRL, arXiv:1403.0954

New Physics in 2015

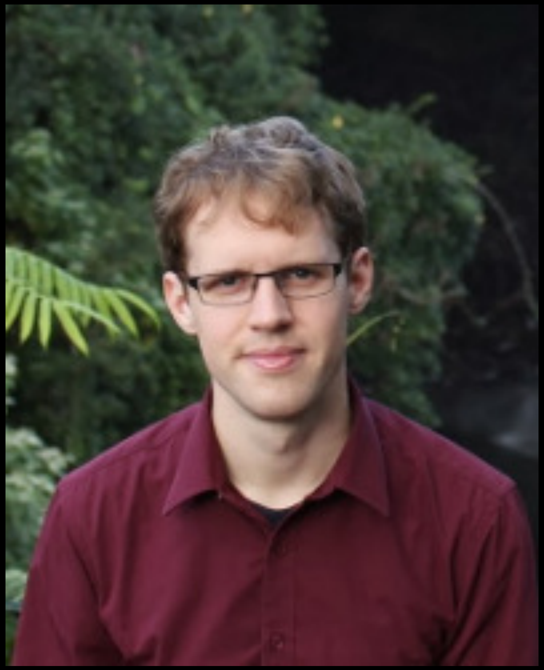
Updated physics included in the past year:

1. Redistribution of lepton asymmetry in collisional processes

2. More accurate inclusion of neutrino scattering on leptons, hadrons, quarks

Teja Venumadhav
Caltech → IAS

Chris Hirata
OSU



Francis-Yan Cyr-Racine
JPL/Caltech → Harvard

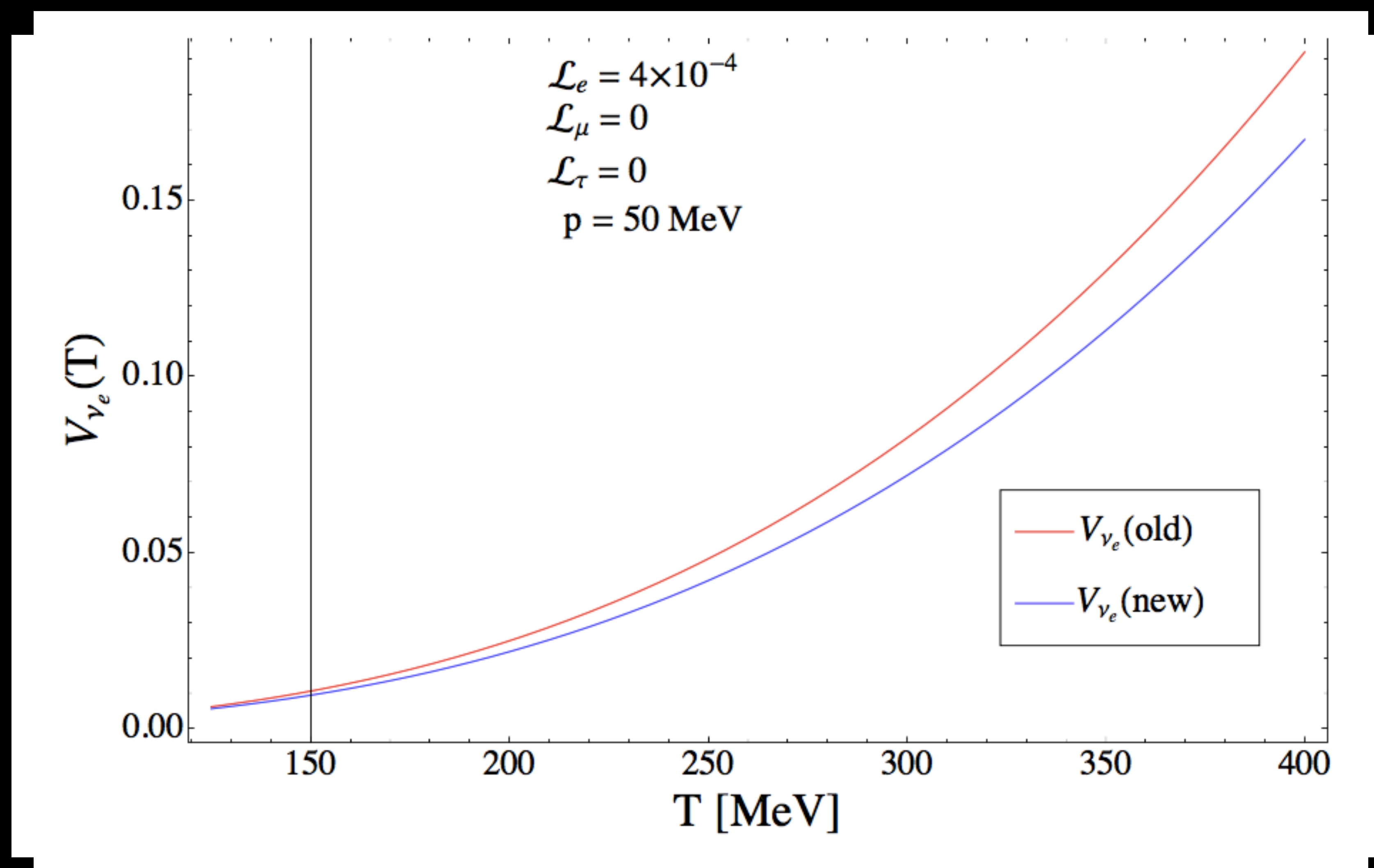
Redistribution of Lepton Asymmetries

The following reactions redistribute lepton asymmetry among the charged leptons and neutrinos:

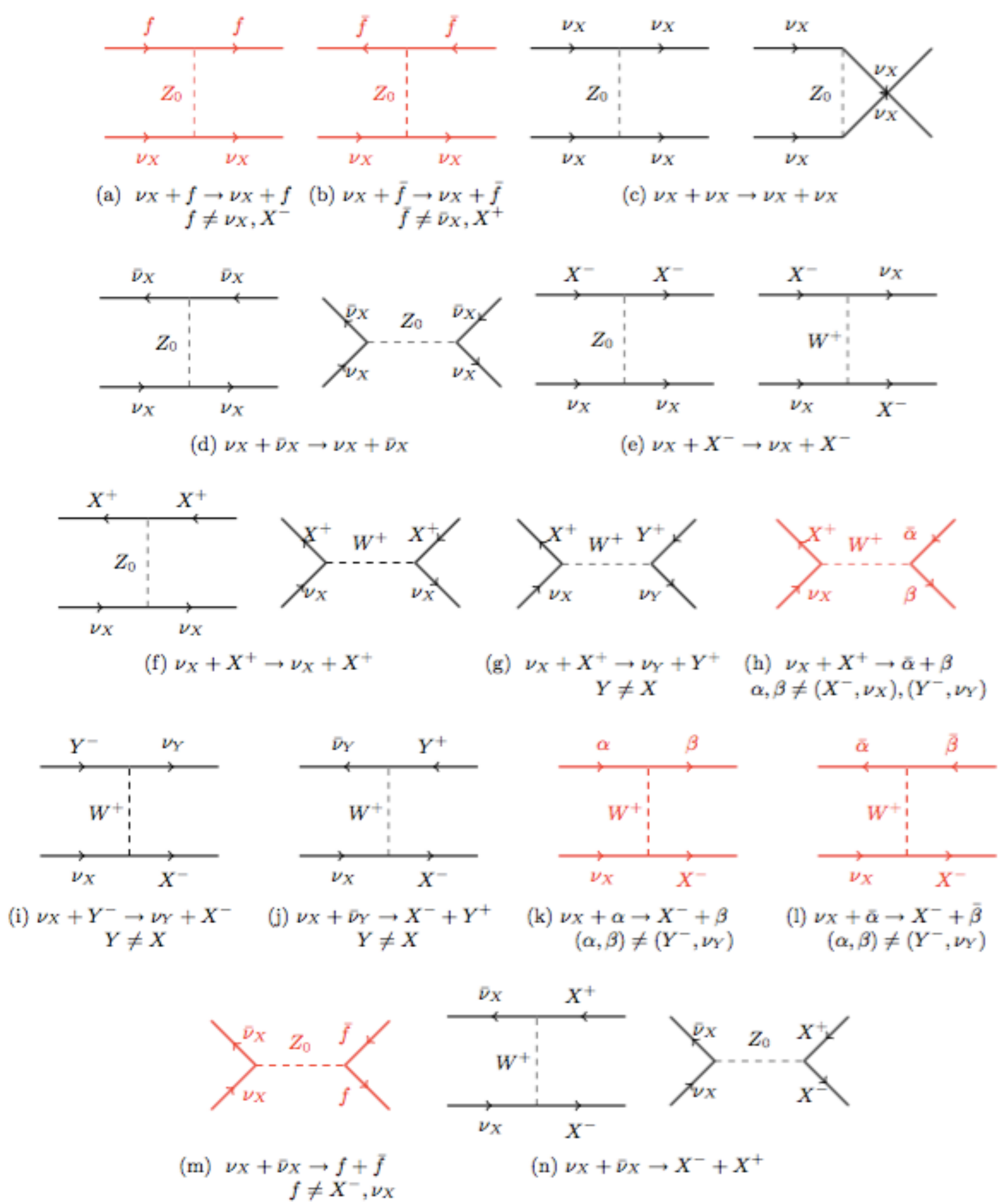
$$\nu_\mu + e^- \rightleftharpoons \nu_e + \mu^-$$
$$\nu_e + e^+ \rightleftharpoons \nu_\mu + \mu^+$$
$$\nu_e + e^+ \rightleftharpoons \underset{(u+\bar{d})}{\pi^+} + \text{stuff}$$
$$\nu_\mu + \mu^+ \rightleftharpoons \underset{(u+\bar{d})}{\pi^+} + \text{stuff}$$
$$\nu_e + e^+ \rightleftharpoons \underset{(u+\bar{s})}{K^+} + \text{stuff}$$
$$\nu_\mu + \mu^+ \rightleftharpoons \underset{(u+\bar{s})}{K^+} + \text{stuff}$$
$$\pi^+ + \pi^0 \leftrightharpoons K^+ + \text{stuff}$$

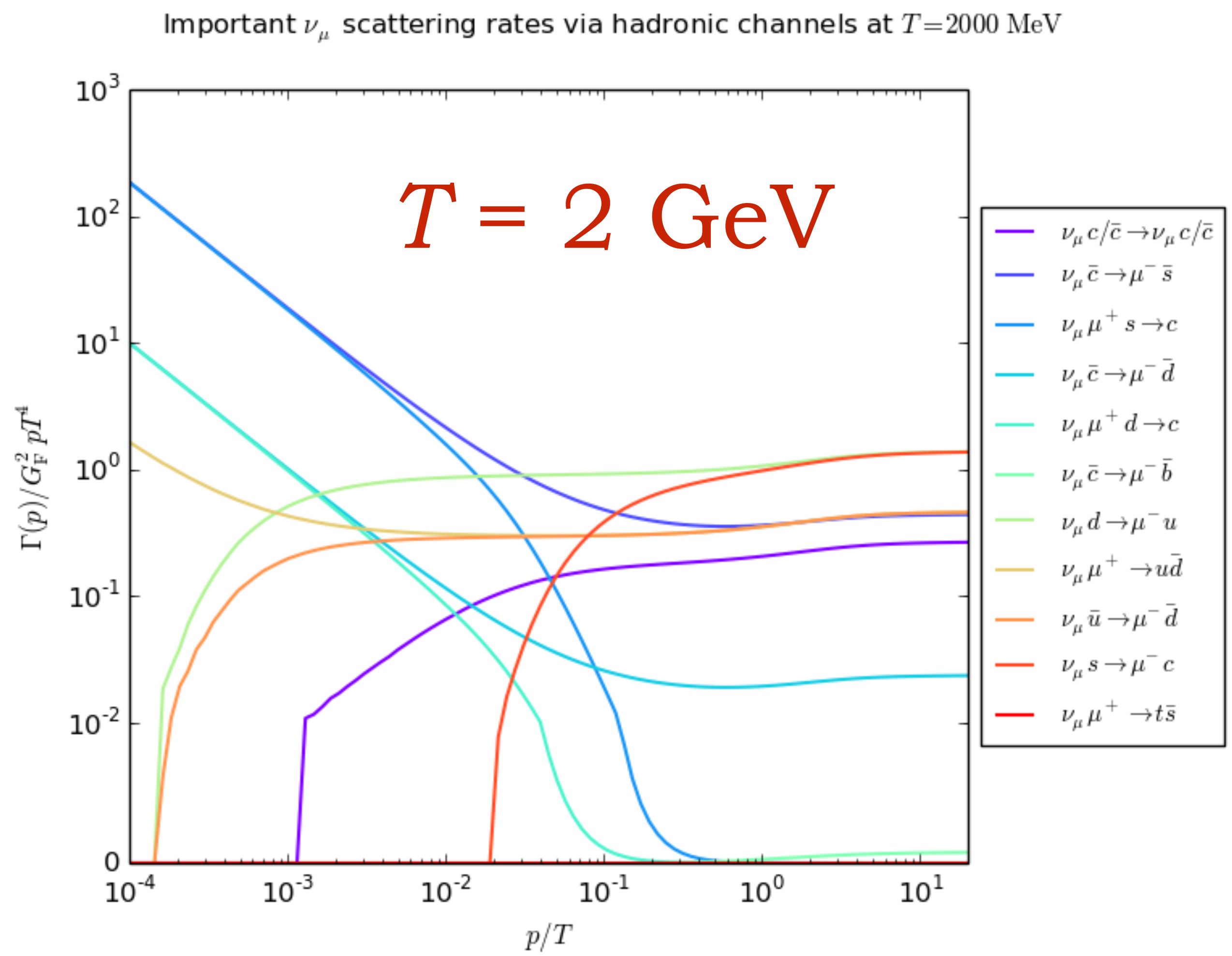
The quantum numbers are related to the chemical potentials via the susceptibility matrix

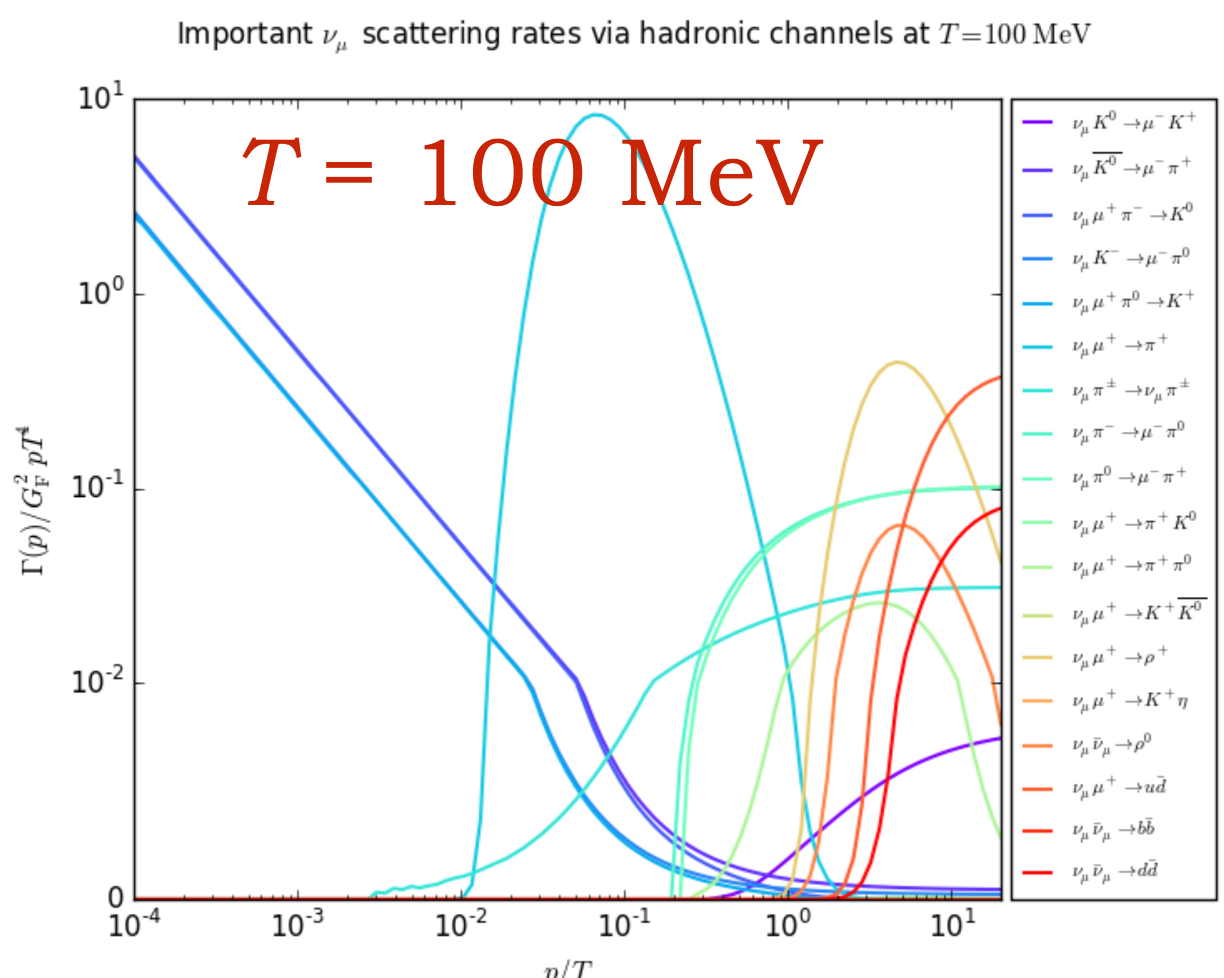
$$\begin{pmatrix} \langle Q \rangle \\ \langle B \rangle \end{pmatrix} = \begin{pmatrix} \chi_2^Q & \chi_{11}^{QB} \\ \chi_{11}^{BQ} & \chi_2^B \end{pmatrix} \begin{pmatrix} \mu_{Q,\text{sys}} \\ \mu_{B,\text{sys}} \end{pmatrix}$$



Exact neutrino scattering

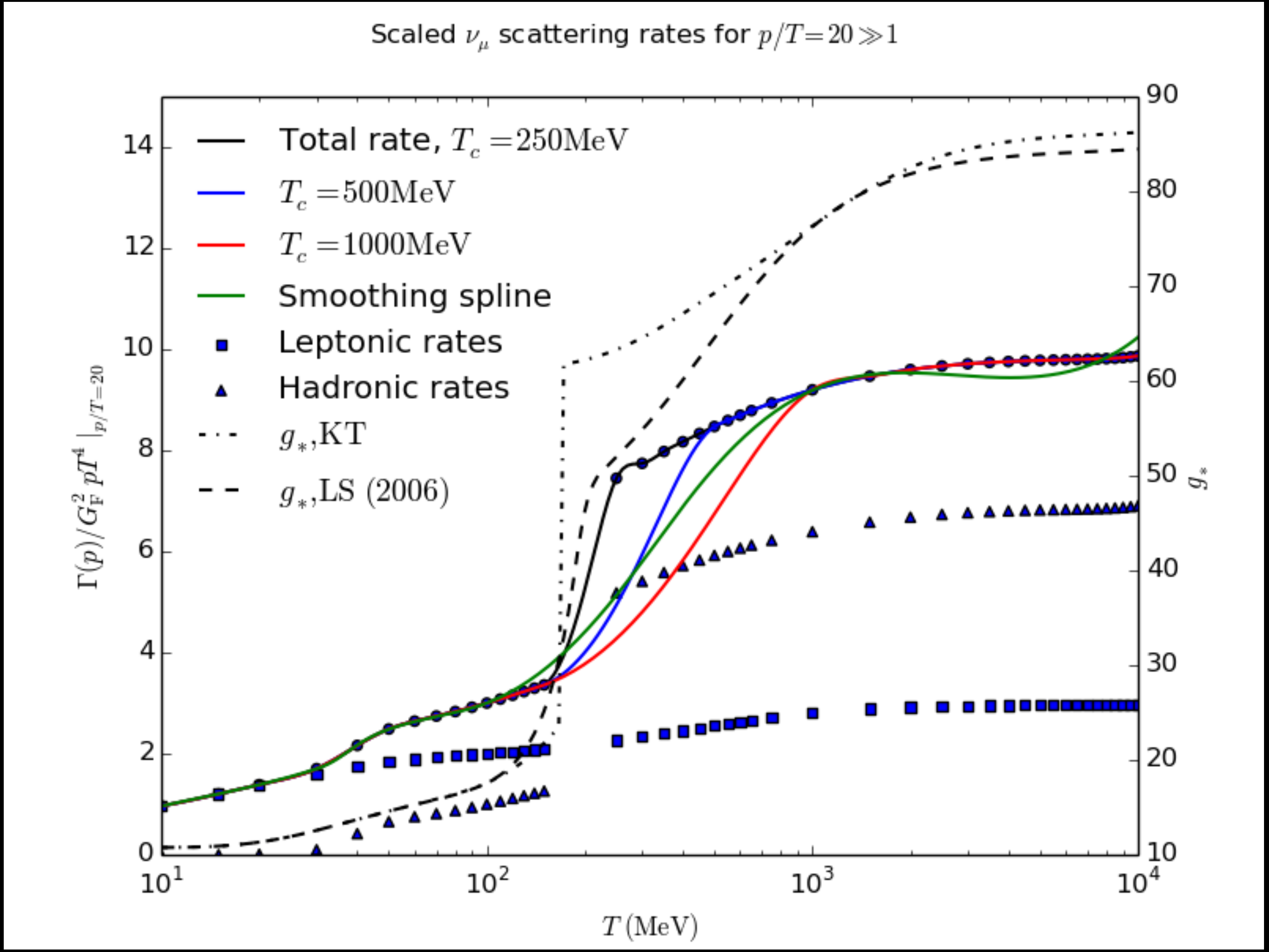




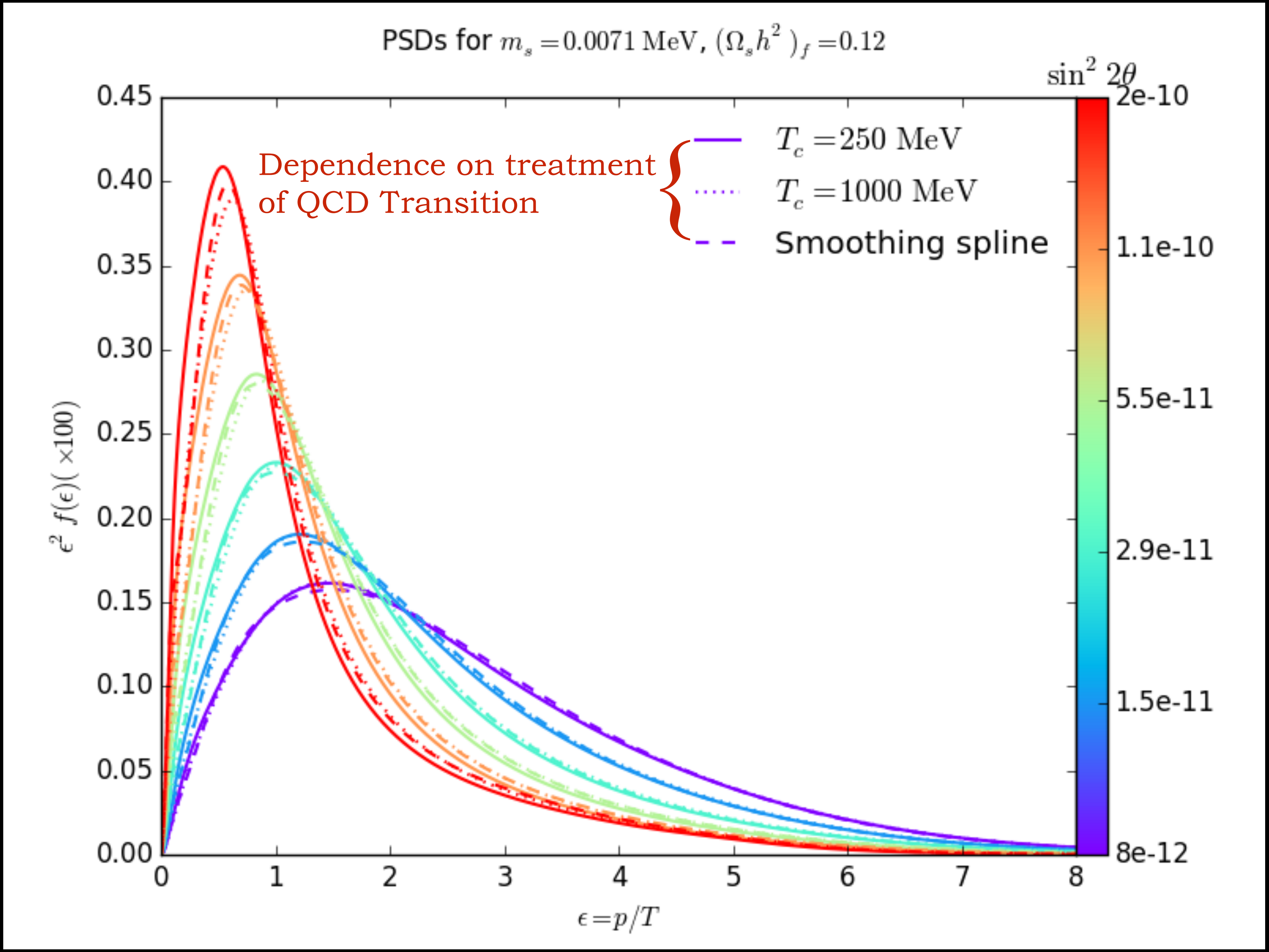


Exact neutrino scattering

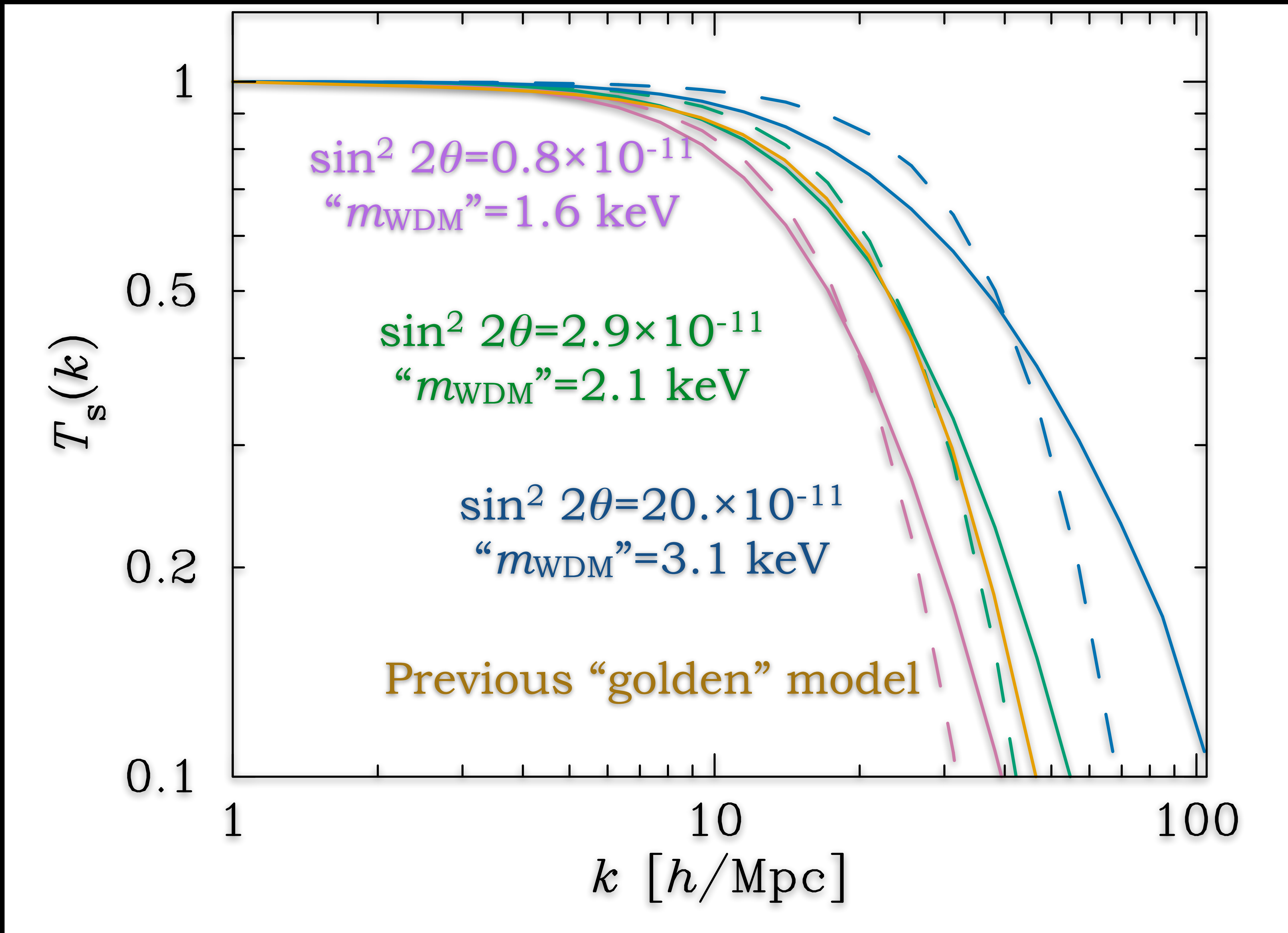
Total rates are shown here, with approximations from the quark phase to the hadron phase



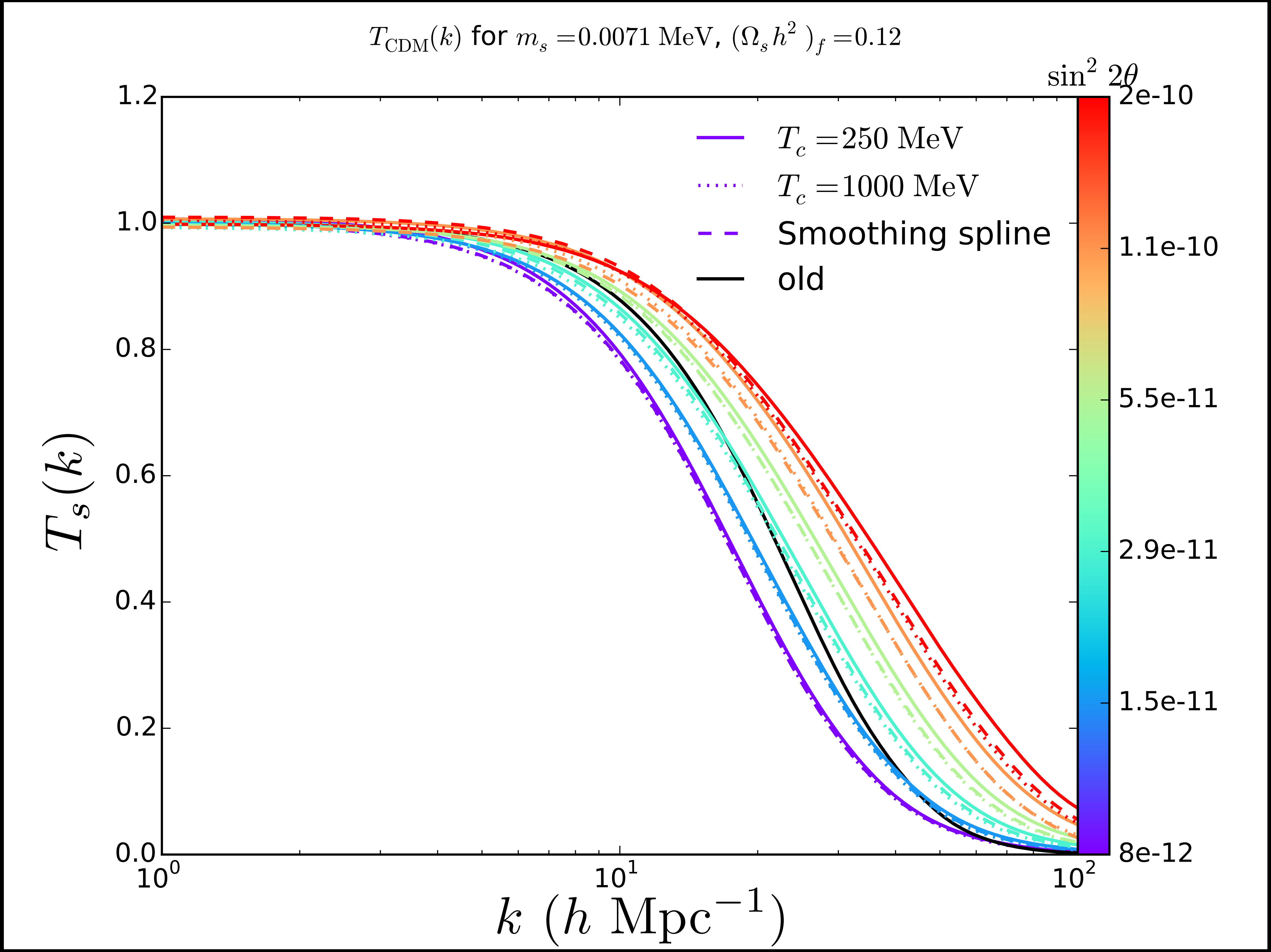
Final phase space density results



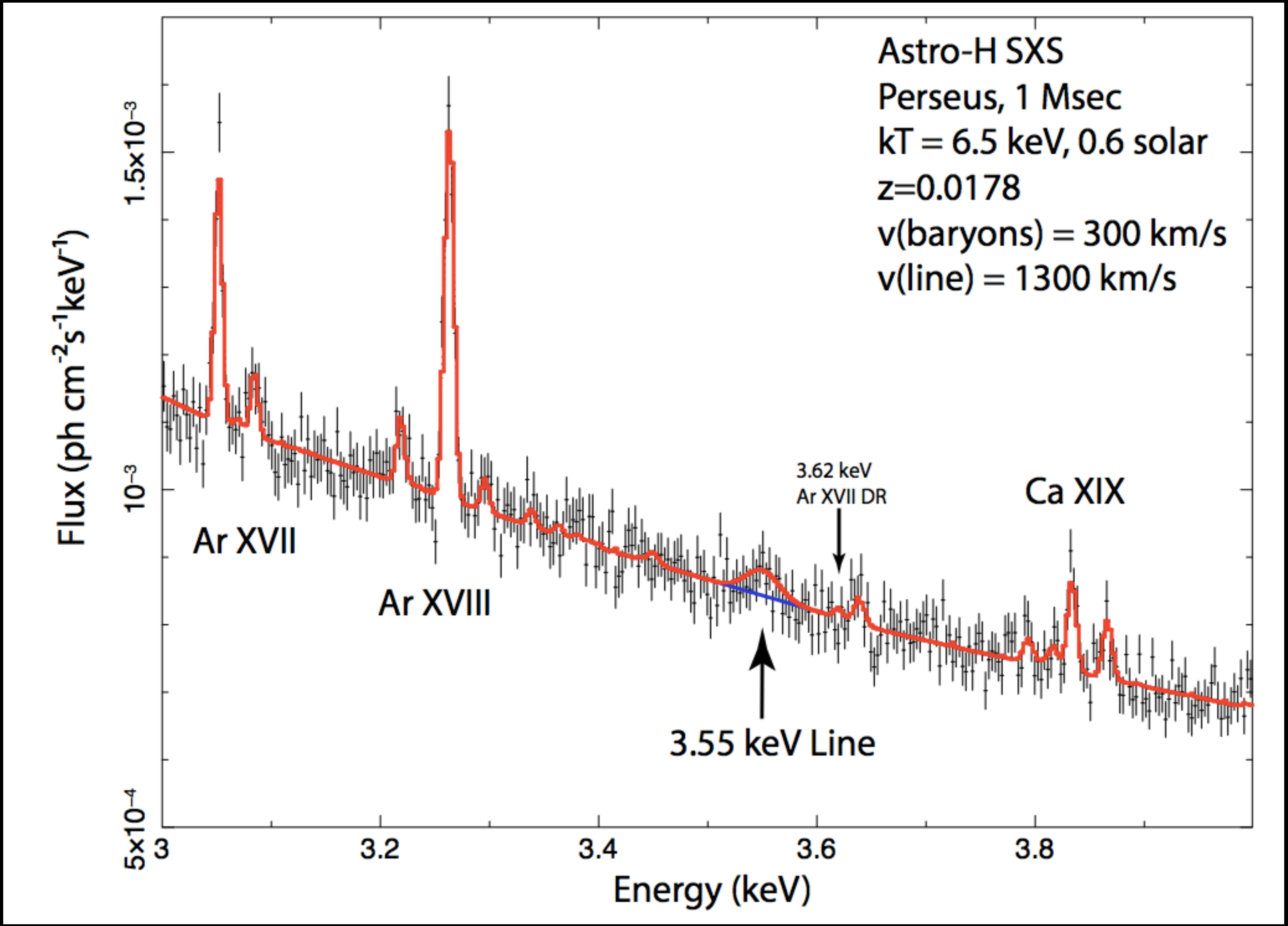
Preliminary Structure Formation Transfer Functions



Preliminary Structure Formation Transfer Functions

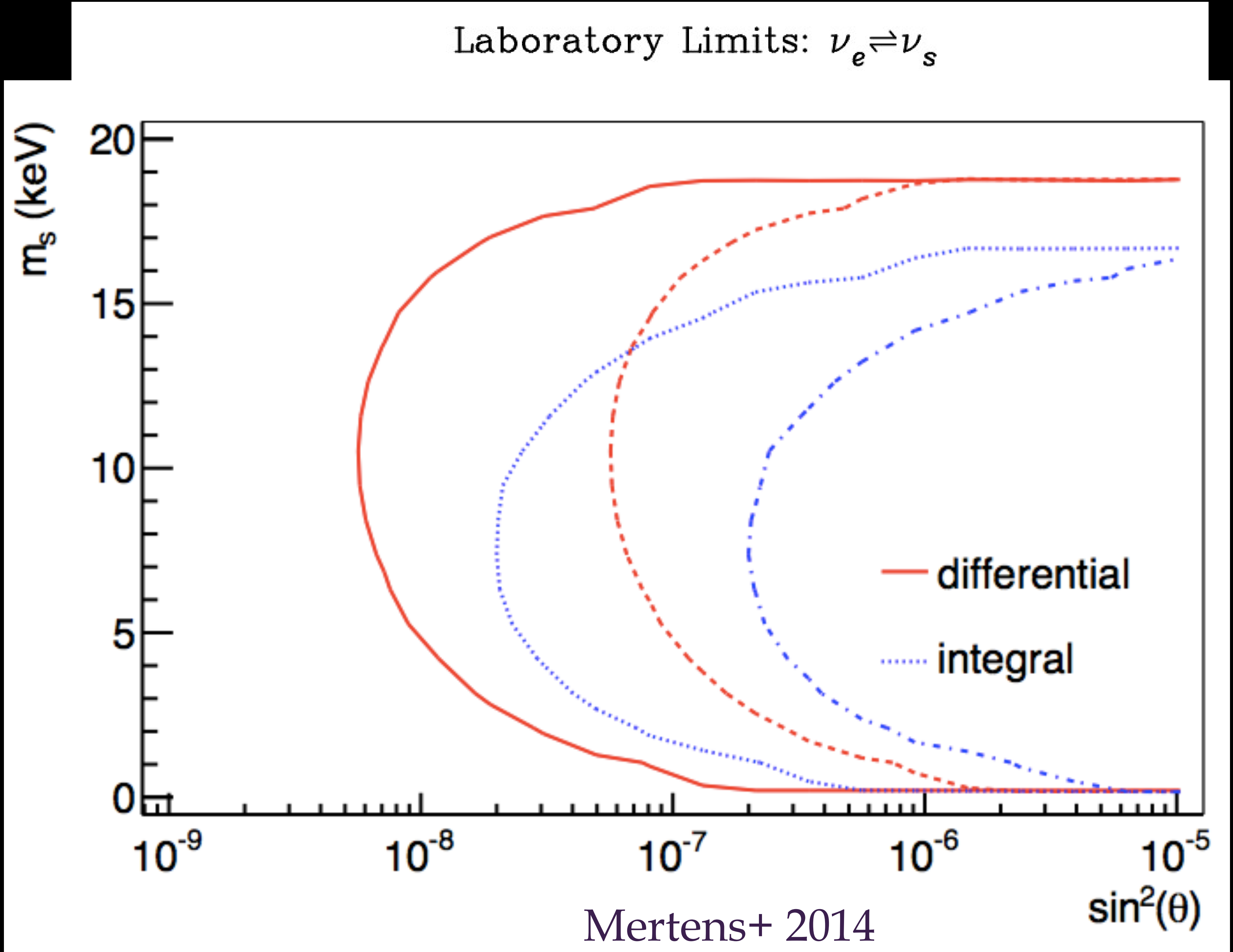


Confirmation: Astro-H launches late 2015 or 2016



Bulbul et al. arXiv:1402.2301

Confirmation Wish List: searches in nuclear β-decay & EC capture

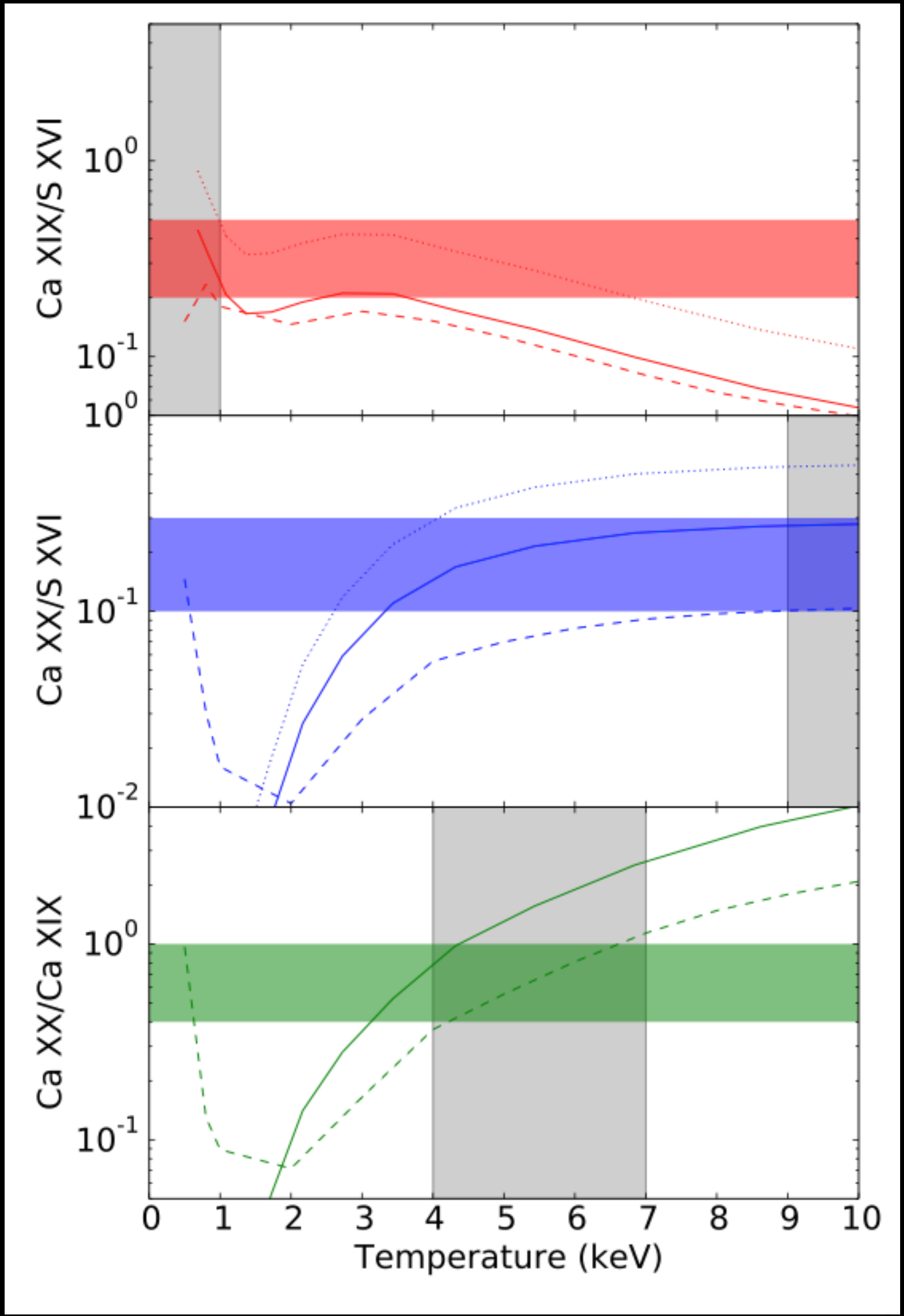


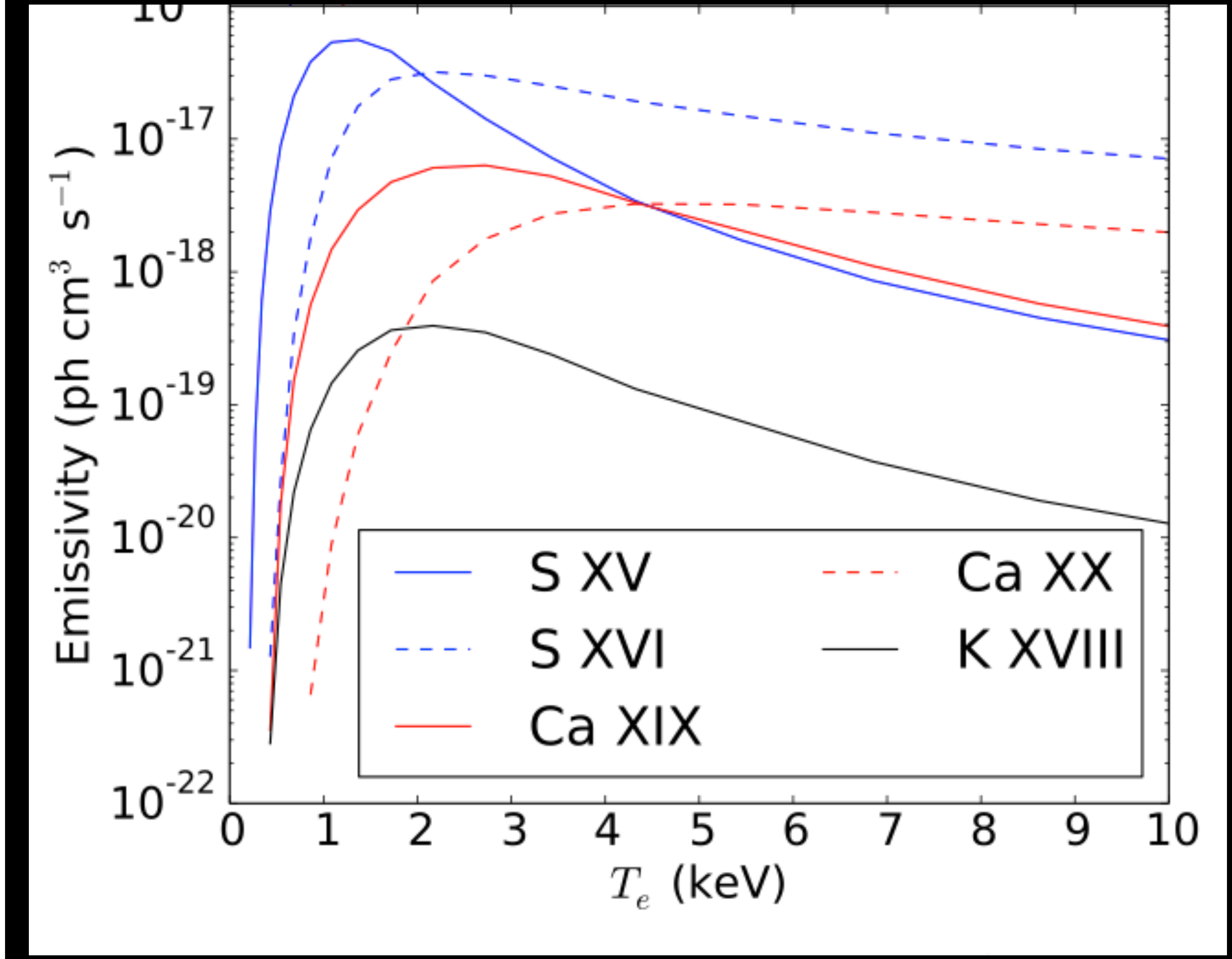
Mertens+ 2014

Summary

- An unidentified line has been detected at 4σ to 5σ in two independent samples of stacked X-ray clusters with XMM-Newton, with several subsamples showing the line. It is independently seen by the same group in the Perseus Cluster with Chandra data. (Bulbul et al. 2014)
- Within a week, an independent group found a line at the same energy toward Andromeda (M31) and Perseus with *XMM-Newton*, with combined statistical evidence of 4.4σ. (Boyarsky et al. PRL 2014)
- No astrophysical interpretation exists for the unidentified X-ray line.
- The simplest model for the signal is resonant sterile neutrino production at with $L\sim10^{-3}$. The signal crosses a transition region from “cold” dark matter to “warm” dark matter, particularly at a small-scale structure cutoff scale of great interest in galaxy formation of the local group of galaxies, ~2 keV thermal WDM.

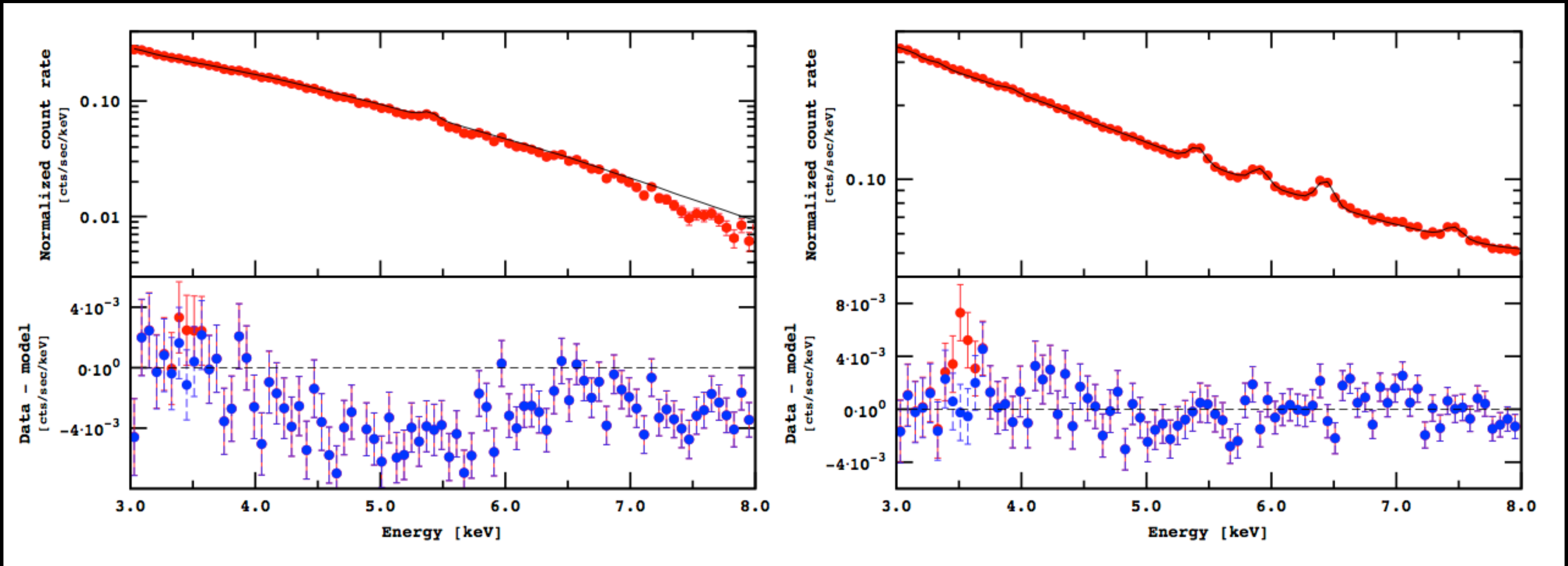
Inconsistent T? Potassium Line? (JP)





Bulbul+: "An independent consideration is the observed absolute line fluxes. Because the Ca XX, Ca XIX and S XVI emissivities drop steeply at low temperatures (lower panel in Fig. 3), any cool component would have to have a very high abundance of those elements to contribute significantly to the observed line fluxes. For example, to produce all of the observed Ca XX line in the Perseus MOS spectrum with a T = 1 keV plasma, the Ca abundance would have to be over 100 times solar (which is unlikely given the observed values of 0.3 – 2 solar in clusters, including their cool cores)."

No detection in M31? Consistent with K? (JP)



Boyarsky+ 2014: "The observation of the line at 3.53 keV in the center of M31 is in stark contradiction with its interpretation as a K XVIII atomic transition – it would require an extremely super-solar abundance of K XVIII and a super-solar ratio of abundance of K XVIII relative to AR XVII and CA XIX. The presence of this line in different types of objects – galaxy clusters, M31, and the Galactic Center – makes it challenging to explain all these signals together by emission from K XVIII, even if this interpretation is hard to exclude from the GC data only."

A Morphological Template Analysis

"Where do the 3.5 keV photons come from?" Carlson, Jeltema & Profumo claim not finding DM template morphology when including templates from continuum and line residuals [arXiv:1411.1758], and claim to"robustly exclude dark matter origin"

Comments from **Maxim Markevitch (Goddard)** ***on the Galactic Center (GC) analysis*****:**

- **Their spatial analysis of the GC signal is meaningless**, because they do not include X-ray absorption, which is very high in the GC direction, and likely patchy and irregular, because of the irregular coverage by molecular clouds. The observed variation in H column density gives a qualitative idea of the possible spatial variations of the brightness of the DM (or any other) signal. So the correct DM template will not be symmetric; The sky distribution of N_H could look just like their quadrupolar Fig. 2 since molecular clouds indeed tend to align with the Galactic plane.

- CJP make the same mistake for their mixing angle constraints, regardless of their spatial analysis — the conversion between the observed and emitted line flux is incorrect by factor up to 3.

A Morphological Template Analysis

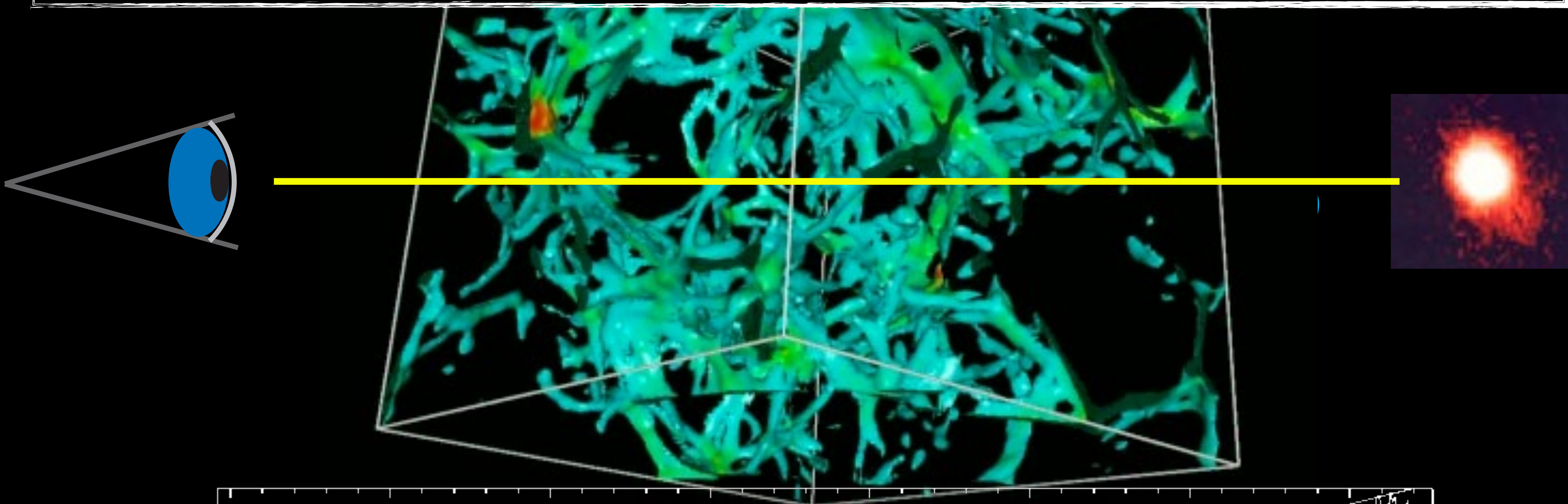
Comments from **Maxim Markevitch (Goddard)** ***regarding the CJP Perseus Cluster analysis***

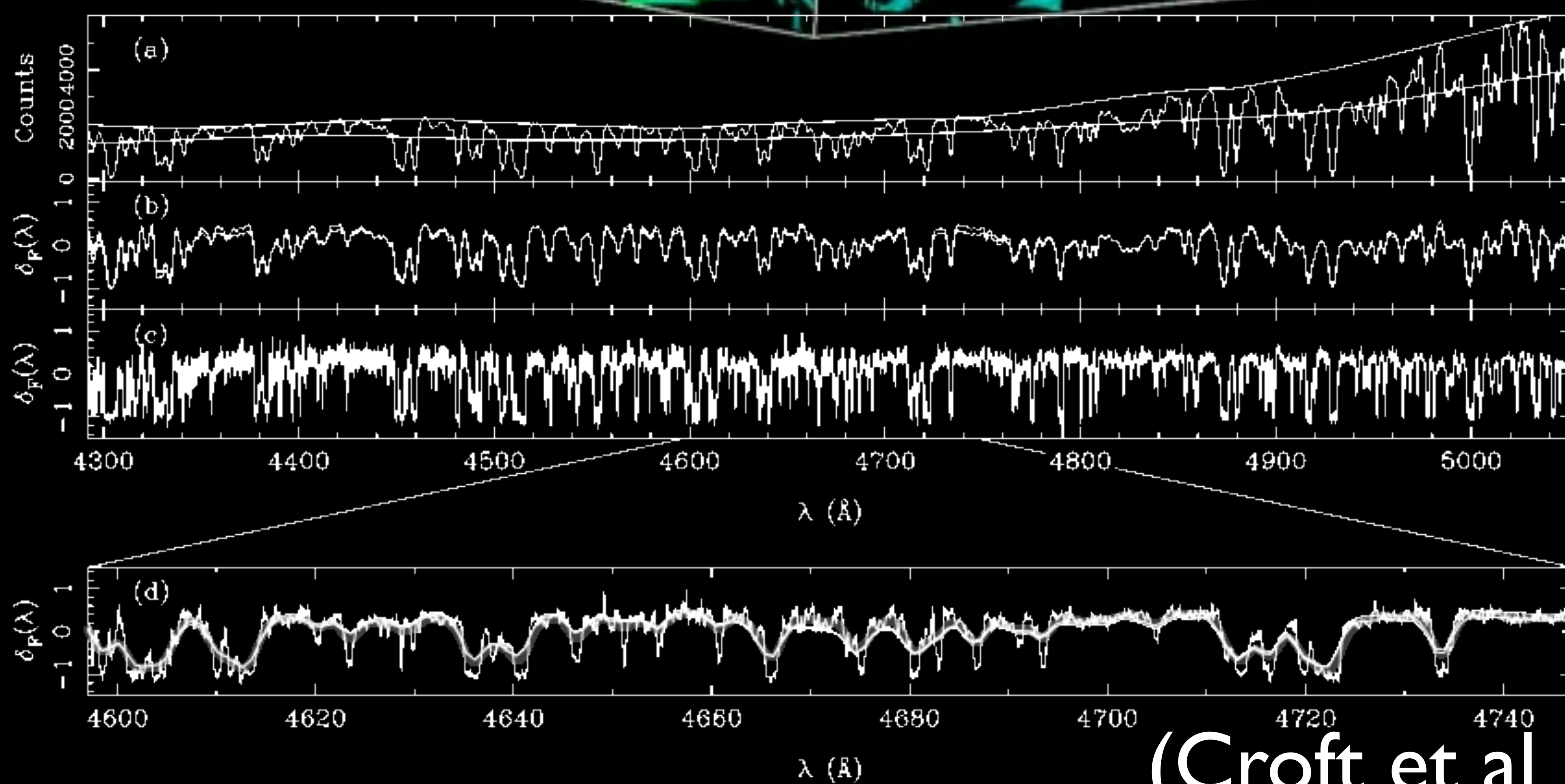
- The line flux in clusters (including Perseus) is of order 1% of the continuum flux within the 100 eV XMM energy resolution bin. Therefore, to see the line, the continuum model has to be accurate to better than a percent at 3.55 kev. It's impossible to model it to this accuracy using their method.

  Now, if the continuum model is incorrect by, say, 5% (which is very optimistic), and the line is 1% of the continuum, then their residual signal would be 5/6 continuum and only 1/6 the line. Since all their continuum templates are astrophysical, their residual map will have the astrophysical spatial distribution. Given that it's very unlikely that their continuum is <1% accurate, their signal is strongly biased against a DM-like spatial distribution. **To me this makes this whole analysis worthless.**

- [The discussion] about “clumped nature of these hot spots” in Perseus residuals that's “difficult toreconcile with the much smoother distribution” of DM, they are seriously discussing a clumped distribution of photons that are detected at 3.4 sigma from the whole cluster. **Those clumps are, of course, the direct analog of canals on Mars.**

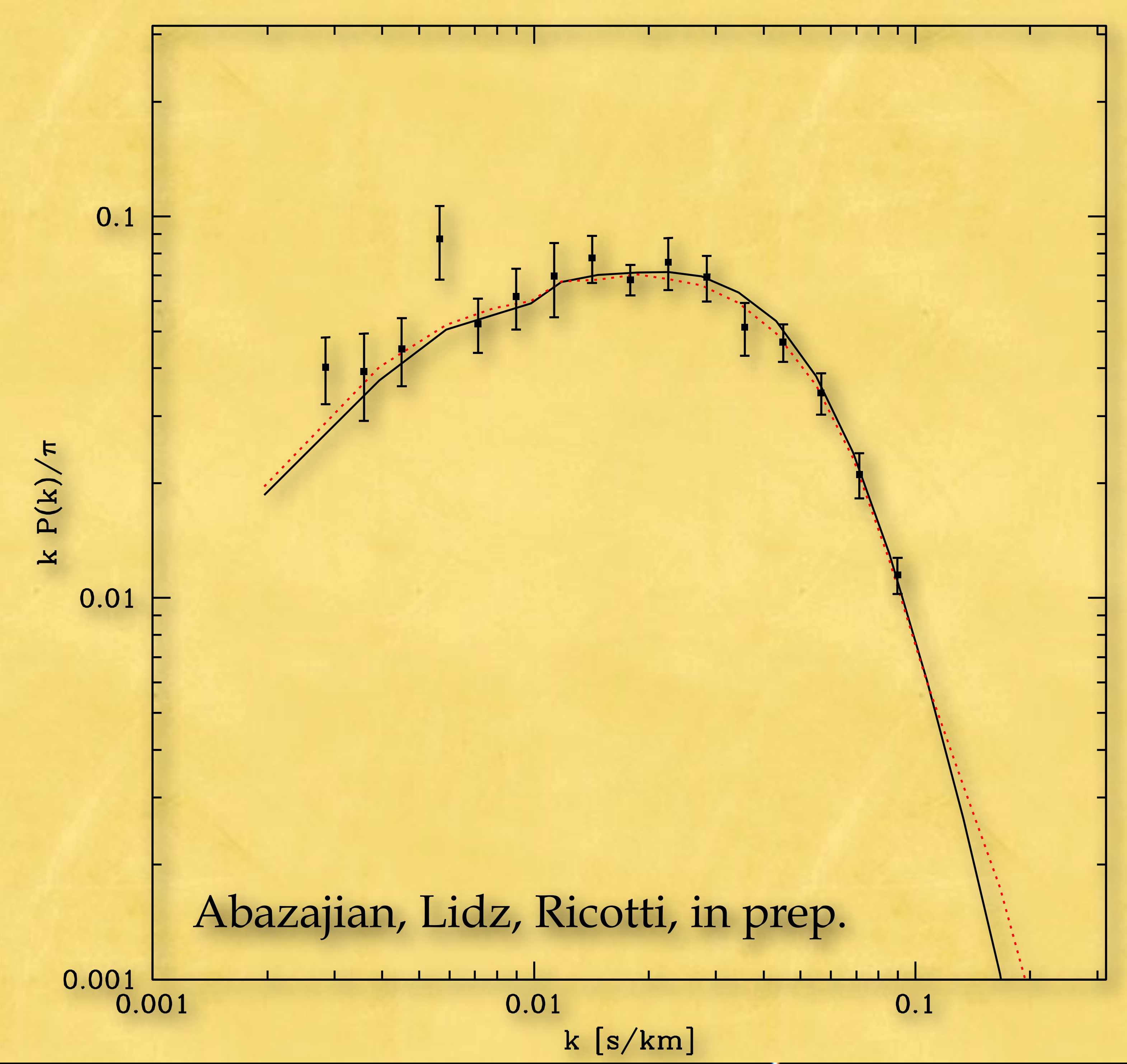
The Lyman-α Forest: Powerful & Challenging

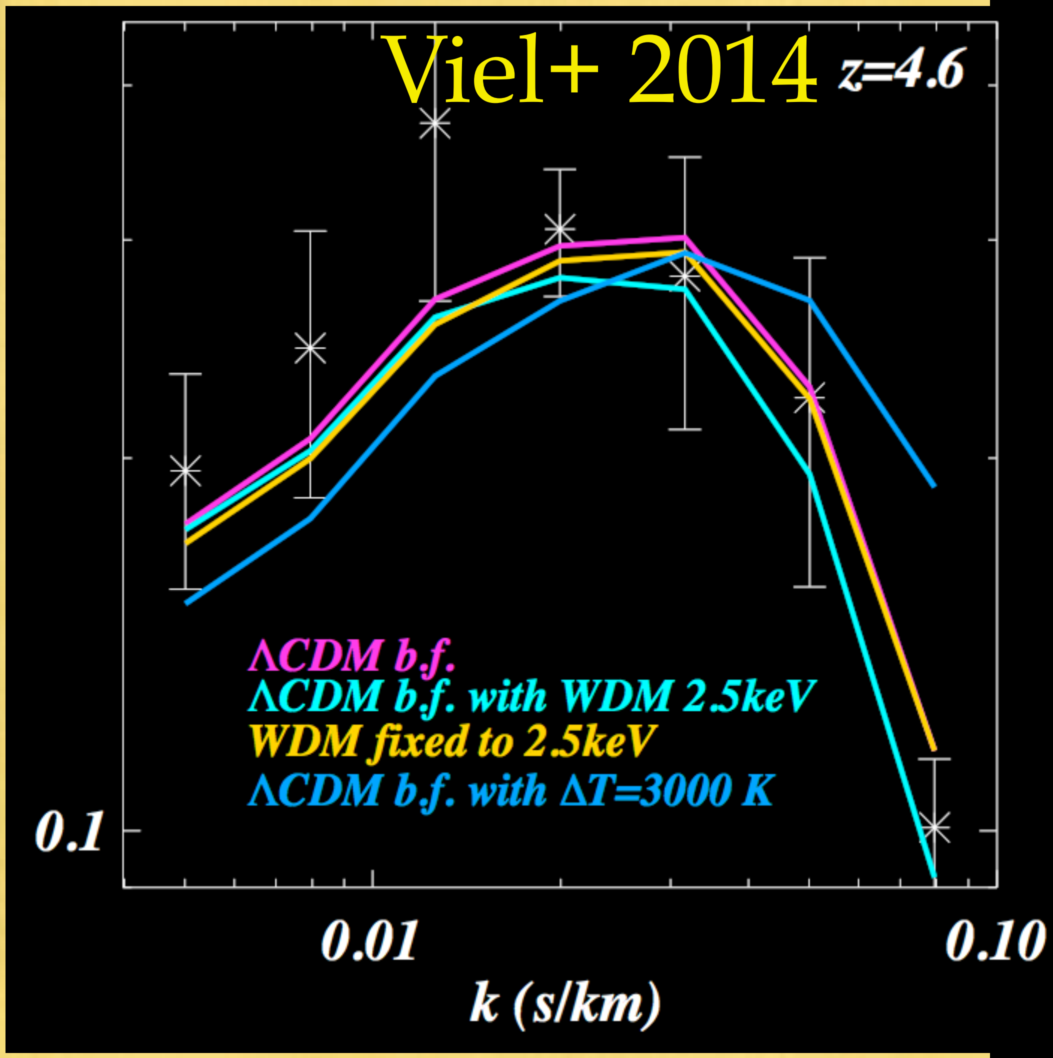




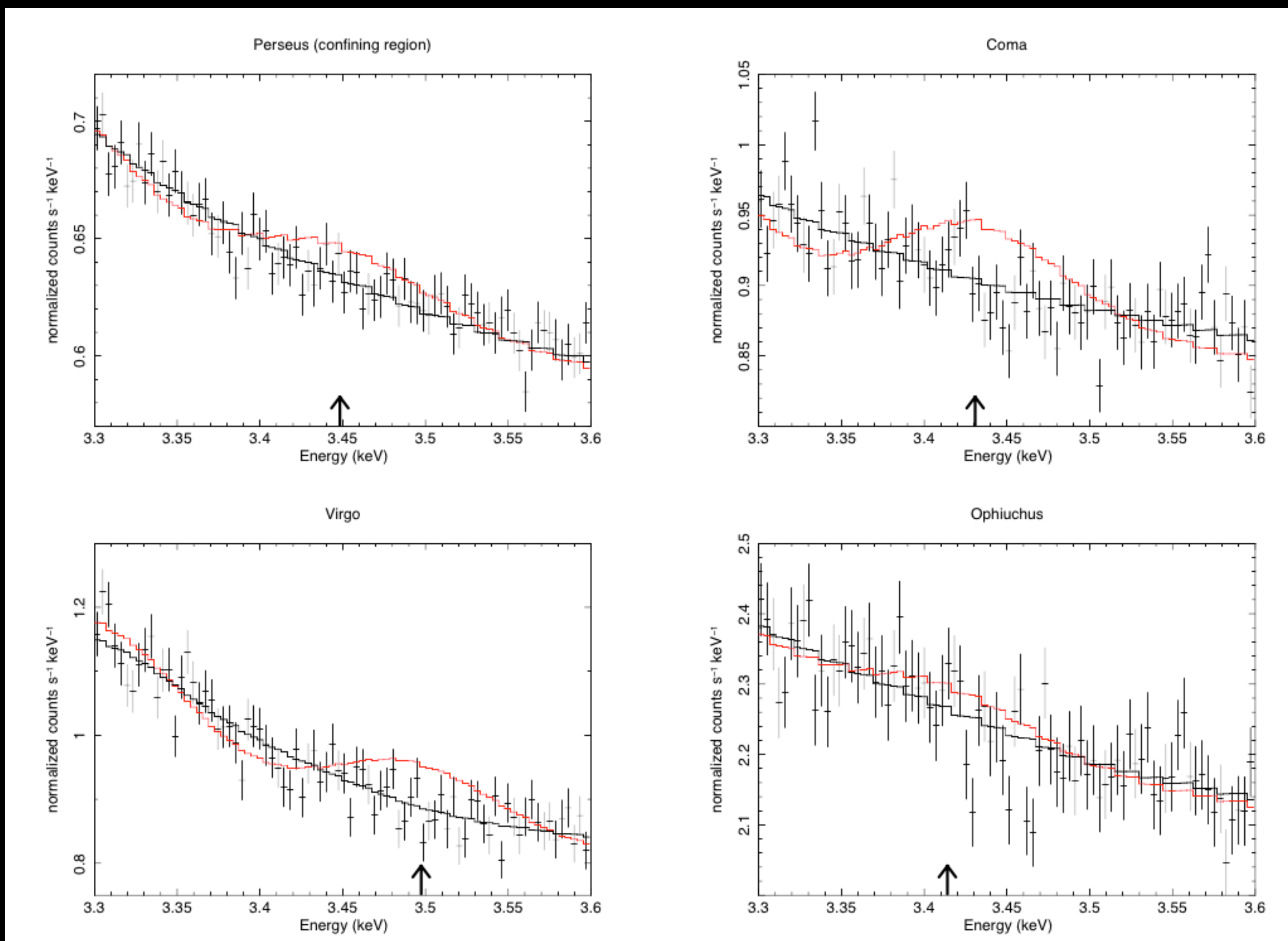
(Croft et al 1999)

T impacts structure of H I Ly-a Forest





Suzaku Observations: Galaxy Clusters



Urban+ 2014

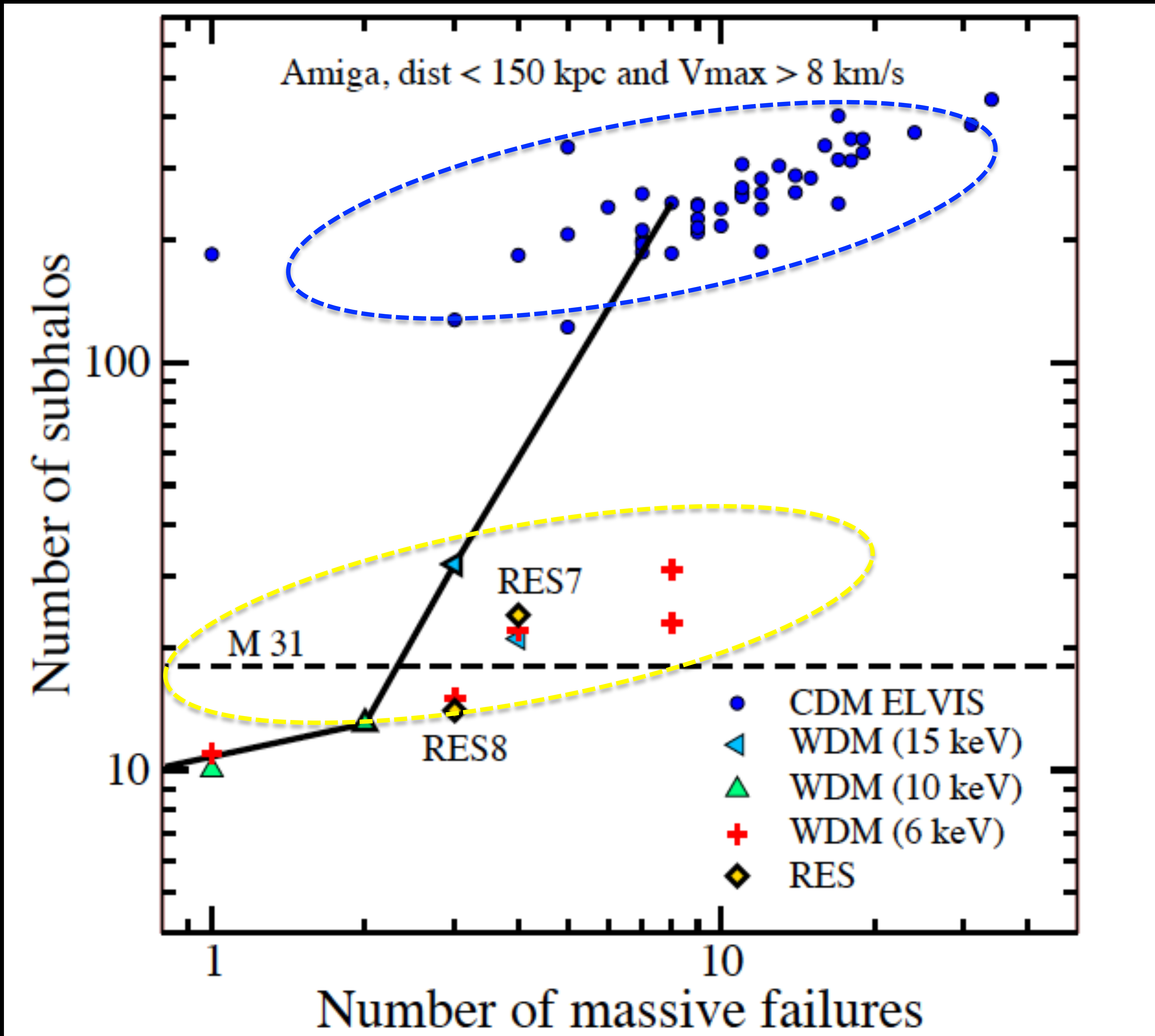
Urban+ 2014 searched for line in Perseus data taken with the Suzaku X-ray Telescope

Detected line in Perseus core and outside core

Did not detect it ***at same flux*** in Coma, Virgo, Ophiuchus

Tamura+ 2014 do not detect the line Suzaku data of Perseus, place limit on flux, weaker than other limits

Alleviation of Too Big to Fail & Satellite Number



Horiuchi+ 2015 in prep