# X-ray and Phase Space Density Constraints on the Properties of the Dark Matter Particle

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*Many Thanks to*
My Collaborators:
Peter Biermann (MPI, Univ. of Bonn, Univ of AL), Zhiyuan Li (CfA/UCLA) & Joe Cheeney, Chris Pelikan, Nick Polley, Leon Yu (Millikin)
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Norma and Hector for inviting me.

# OUTLINE

- **Properties of Sterile Neutrinos**
- **Models of Sterile Neutrino Interactions & Production**
- **X-ray Constraints from Previous Studies**
  - **CXB**
  - **Galaxy Clusters**
  - **Dwarf Galaxies**
- **The Advantages of Andromeda**
- **Constraints from *XMM* Observations of Andromeda**
- **Constraints from *Chandra* Observations of Andromeda**
- **The Bulbul et al. (2014) Anomaly in Context**
  - **vs. X-ray Constraints**
  - **vs. Galaxy Constraints**
- **Improved Phase Space Density Constraints via MW dSphs**
  - **Implications for DM Particle mass + Galaxy Formation/Evolution**

# The Fertile Phenomenology of Sterile Neutrinos

- **Non-zero active neutrino masses [1,2]**
- **Baryon & Lepton Asymmetries [15-20]**
- **Big Bang Nucleosynthesis [19]**
- **Evolution of the matter power spectrum [21,22]**
- **Reionization [23-31]**
- **Active Neutrino Oscillations [32-33]**
- **Pulsar Kicks [34-39]**
- **Supernovae [40-42]**
- **Excellent Dark Matter Particle Candidate [3-14, 43-57]**
- ***Most Importantly: Readily Testable***
  - ***Can decay into detectable X-ray photons***

# Detecting Sterile Neutrino Radiative Decays:

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

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


**If**

**1 keV < $m_s$ < 20 keV,**

***Chandra* & XMM**

**can detect the**

**X-ray photons**

**associated with**

**sterile neutrino**

**radiative decays.**

# Sterile Neutrino Interactions with SM Particles

(Abazajian, Fuller, Patel 2001 [5]; Abazajian, Fuller, Tucker 2001 [6])

*Very small* mixing $(\sin^2 2\theta \lesssim 10^{-7})$ between

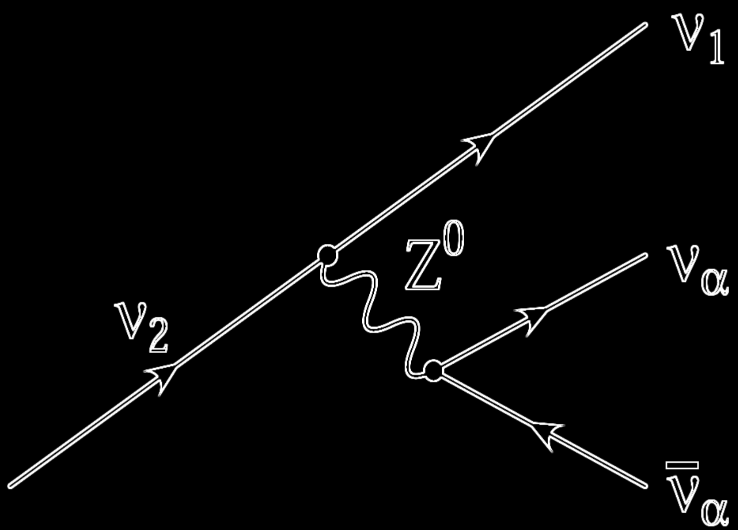
mass $|\nu_{1,2}>$ & flavor $|\nu_{\alpha,s}>$ states:

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

For $m_s < m_e$,

3ν Decay Mode Dominates:

$$\Gamma_{3\nu} \simeq 1.74\times 10^{-30}s^{-1}\left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^5$$




Radiative Decay Rate is:

$$\Gamma_s \simeq 1.36\times 10^{-32}s^{-1}\left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^5 \quad \nu_s \longrightarrow \nu_\alpha + \gamma$$

# The Sterile Neutrino Radiative Decay Signal:

- Radiative Decay Luminosity:

$$\mathrm{L}_{\mathbf{x,s}} = E_{\gamma,s} N_s^{FOV} \Gamma_s = \frac{m_s}{2}\left(\frac{M_{DM}^{FOV}}{m_s}\right)\Gamma_s$$

$$\backsimeq 1.2 \times 10^{33} \mathrm{erg}\ s^{-1} \left(\frac{M_{DM}^{FOV}}{10^{11} M_\odot}\right) * \left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^5$$

- Measured Flux: $\Phi_{x,s} = \frac{\mathrm{L}_{x,s}}{4\pi D^2}$

$$\phi_{x,s}(\sin^2 2\theta) \backsimeq 1 \times 10^{-17} \mathrm{erg\ cm}^{-2} s^{-1} \left(\frac{D}{\mathrm{Mpc}}\right)^{-2}$$

$$\times \left(\frac{M_{DM}^{FOV}}{10^{11} M_\odot}\right)\left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{\mathrm{keV}}\right)^5$$

# Sterile Neutrino Production:

- Dodelson-Widrow Model [3]
  - Density-Production Relationship [43]:

$$\mathrm{m_s} = 55.5\ \mathrm{keV}\left(\frac{\sin^2 2\theta}{10^{-10}}\right)^{-0.615}\left(\frac{\Omega_s}{0.24}\right)^{0.5}$$

**(for $T_{QCD} \sim 170$ MeV)**

  - Mixing Angle-Independent Flux:

$$\phi_{x,s}(\Omega_s) \simeq 7.0 \times 10^{-15}\mathrm{erg\ cm^{-2}}s^{-1}\left(\frac{D}{\mathrm{Mpc}}\right)^{-2} \times \left(\frac{M_{DM}^{FOV}}{10^{11}M_\odot}\right)\left(\frac{\Omega_s}{0.24}\right)^{0.813}\left(\frac{m_s}{\mathrm{keV}}\right)^{3.374}$$

  - Agrees with Asaka et al. model [48] for

$$1\ \mathrm{keV} \lesssim \mathrm{m}_s \lesssim 10\ \mathrm{keV}$$

## To maximize the sterile neutrino decay signal:

$$\Phi_{x,s}(\sin^2 2\theta) \simeq 1.0 \times 10^{-17} \mathrm{erg\ cm^{-2} s^{-1}} \left(\frac{D}{\mathrm{Mpc}}\right)^{-2} \times \left(\frac{M_{DM}^{FOV}}{10^{11} M_\odot}\right) \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_s}{\mathrm{keV}}\right)^5$$

**the ideal object to study is:**

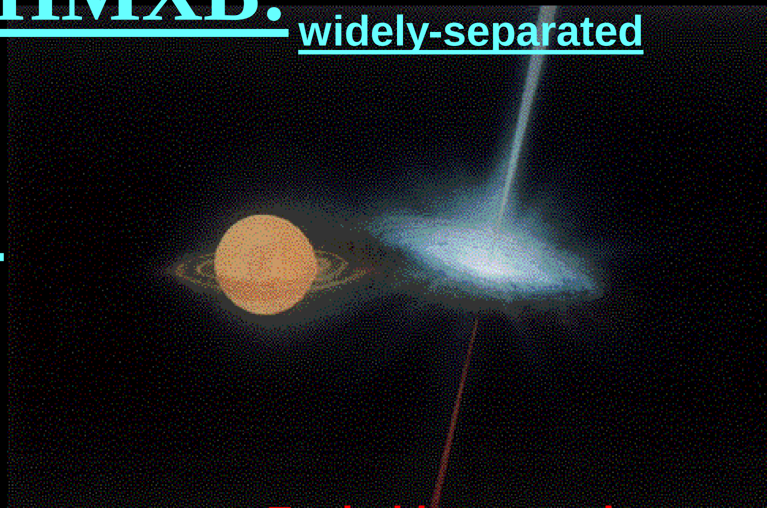
- **nearby: small Distance D,**
- **massive: large $M_{DM}$ (in FOV),**
- **quiescent: low astrophysical background.**

# Astrophysical X-ray Sources:

## Stellar Sources:

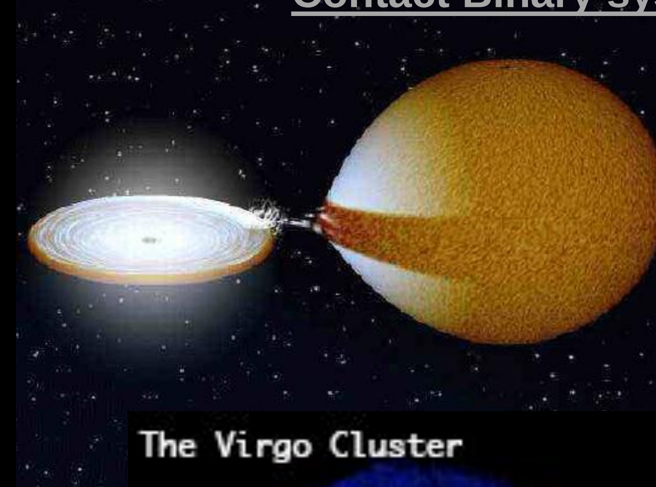
### HMXB:

Fueled by stellar wind; widely-separated



### LMXB:

Roche Lobe accretion; Contact Binary systems

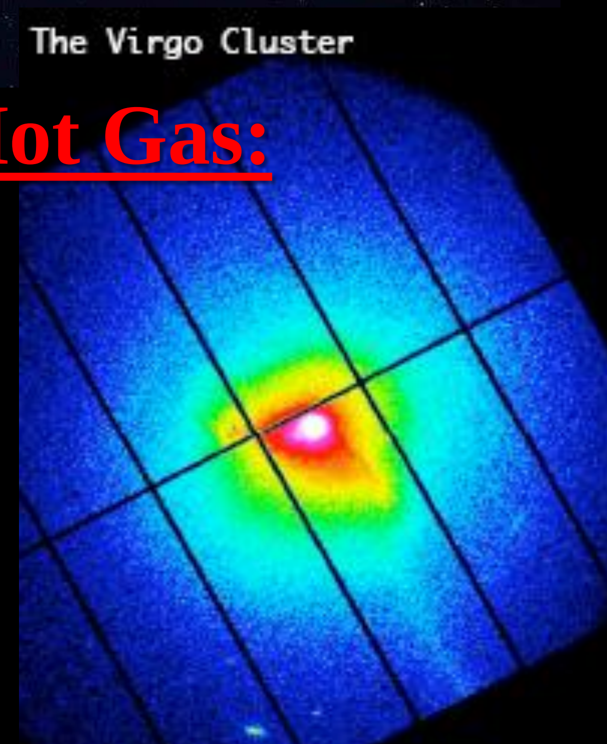


## Nuclear & Diffuse Sources:

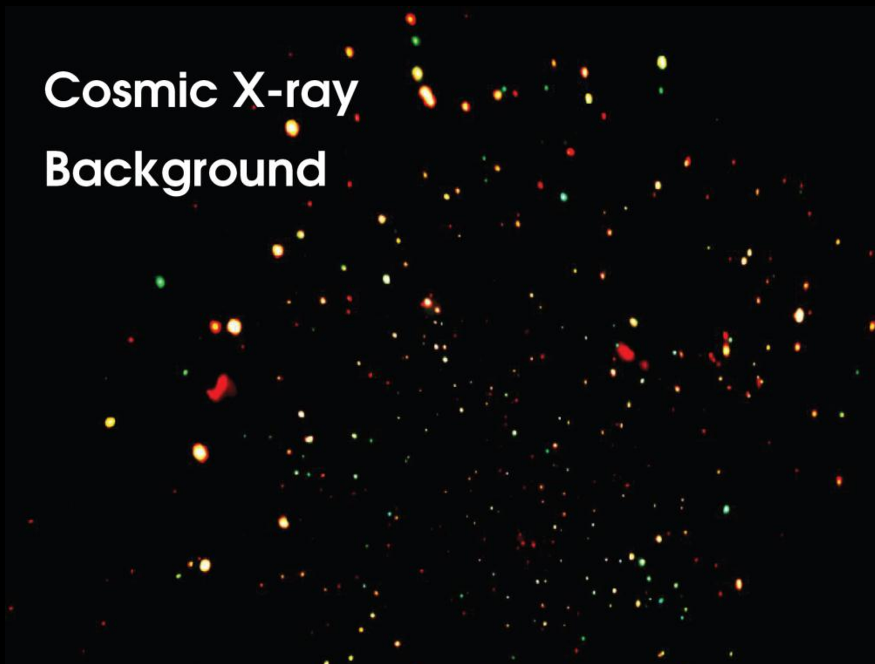
### AGN:

Fueled by accretion onto Supermassive BHs

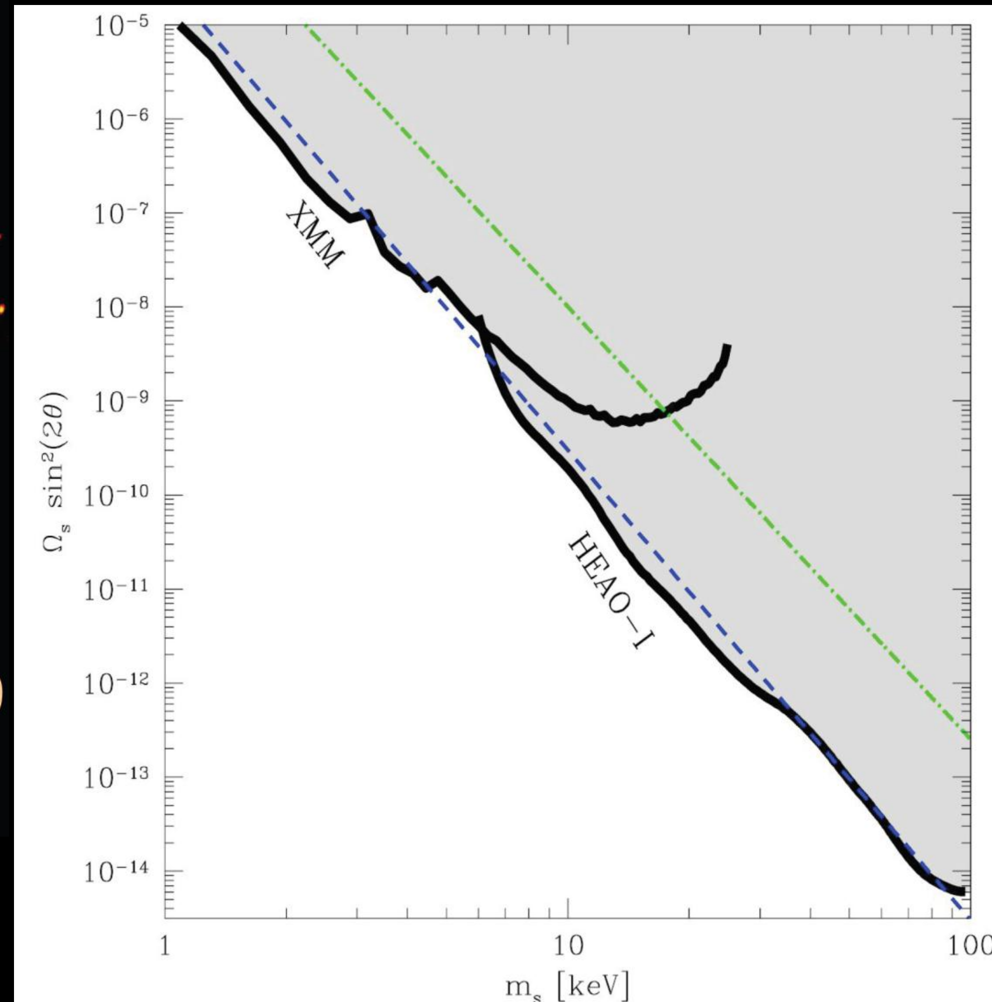
### Hot Gas:



# Previous work I: Cosmic X-ray Background




HUGE range of $m_s$ - $\sin^2 2\theta$ probed via combined XMM & HEAO-I Data [61].

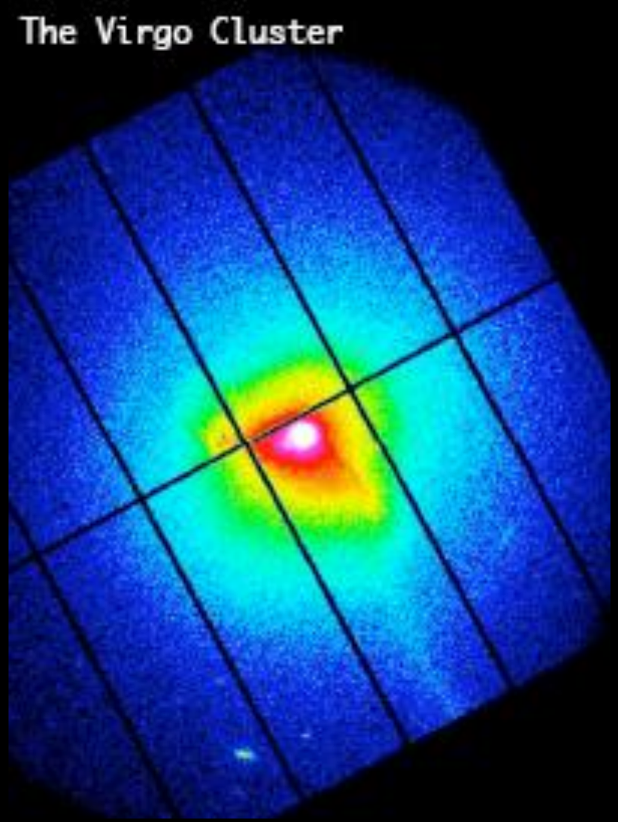


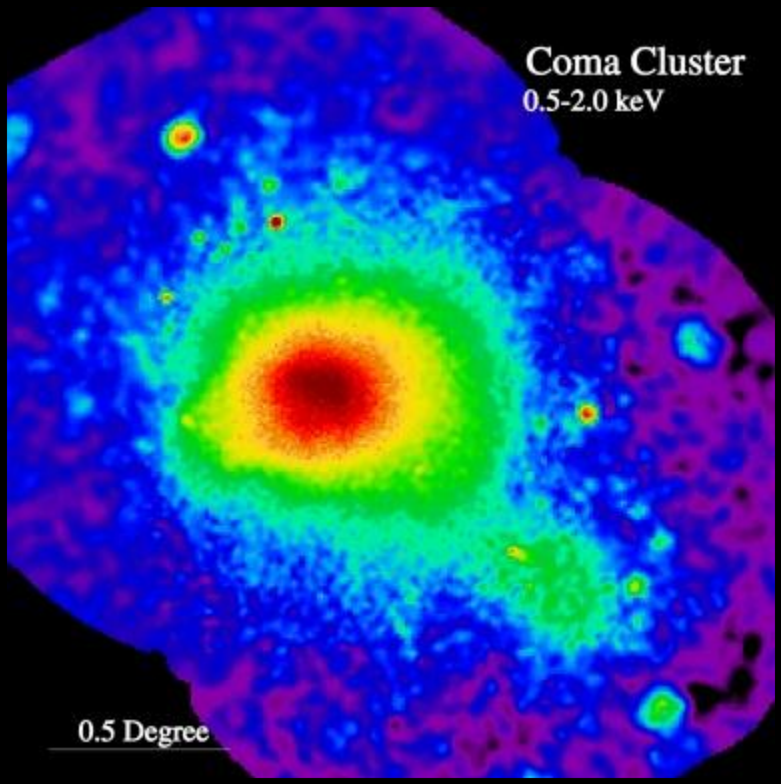

Rekindled interest in $m_s$ X-ray constraints [6].

**Constraints: $m_s$ < 9.3 keV**

**(for DW Model $\nu_s$ [3, 43]).**

# Previous work II: Galaxy Clusters




**Advantage:** HUGE $M_{DM} \sim 10^{13} M_\odot$

**PROBLEMS:** HUGE background; D > 10 Mpc

**Constraints (for DW Model $\nu_s$ [3, 43]):**

$m_s$ < 8.2 keV (Virgo [44]); $m_s$ < 6.3 keV (Virgo + Coma [13, 63]).

# Advantages of Andromeda (M31)

(Watson, Li, Polley 2012, Watson, Beacom, Yuksel, Walker 2006 [66])

**Nearby: D = 0.78 ± 0.02 Mpc [102, 103]**

**LOW astrophysical background (little hot gas & bright point sources can be excised)**

**Well-measured Dark Matter Distribution based on analyses of extensive Rotation Curve Data**

(Klypin, Zhao, Somerville 2002 [104], Seigar, Barth, & Bullock 2007 [105])

## Prospective Sterile Neutrino Signals

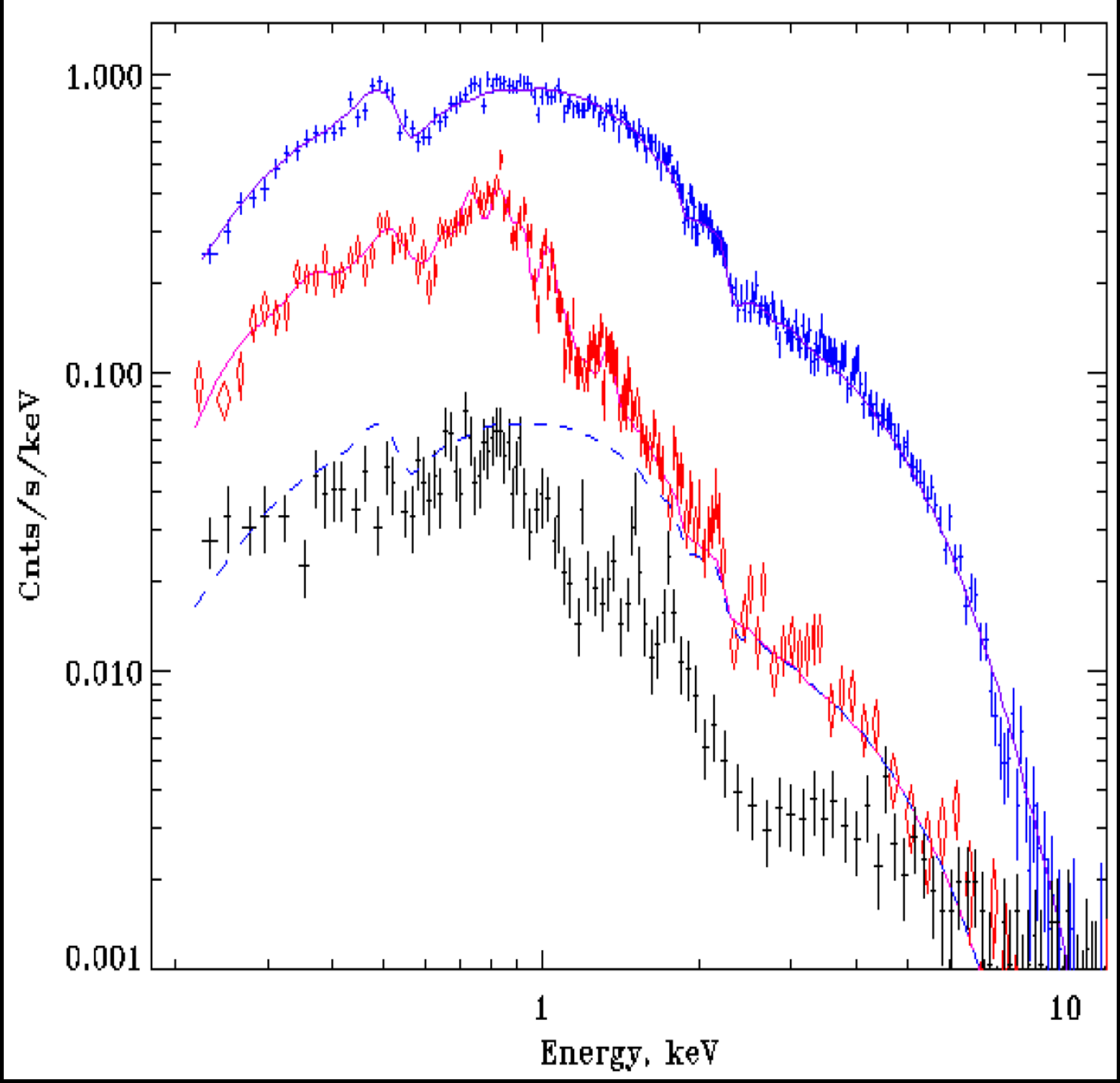
**Comparable to Massive Clusters without the background**

**Exceeding Ultra Nearby Dwarf Galaxies**

$$\frac{\Phi_{\mathrm{M31}}}{\Phi_{\mathrm{Clus}}} = \left(\frac{M_{M31}^{FOV}}{M_{\mathrm{Clus}}^{FOV}}\right)\left(\frac{D_{\mathrm{Clus}}}{D_{\mathrm{M31}}}\right)^2 \backsimeq \frac{\Phi_{\mathrm{M31}}}{\Phi_{\mathrm{Dwarf}}} = \left(\frac{M_{M31}^{FOV}}{M_{\mathrm{Dwarf}}^{FOV}}\right)\left(\frac{D_{\mathrm{Dwarf}}}{D_{\mathrm{M31}}}\right)^2 \gtrsim 1$$

# Unresolved 5' *XMM* Spectrum of Andromeda

(from Shirey et al. 2001 [96])



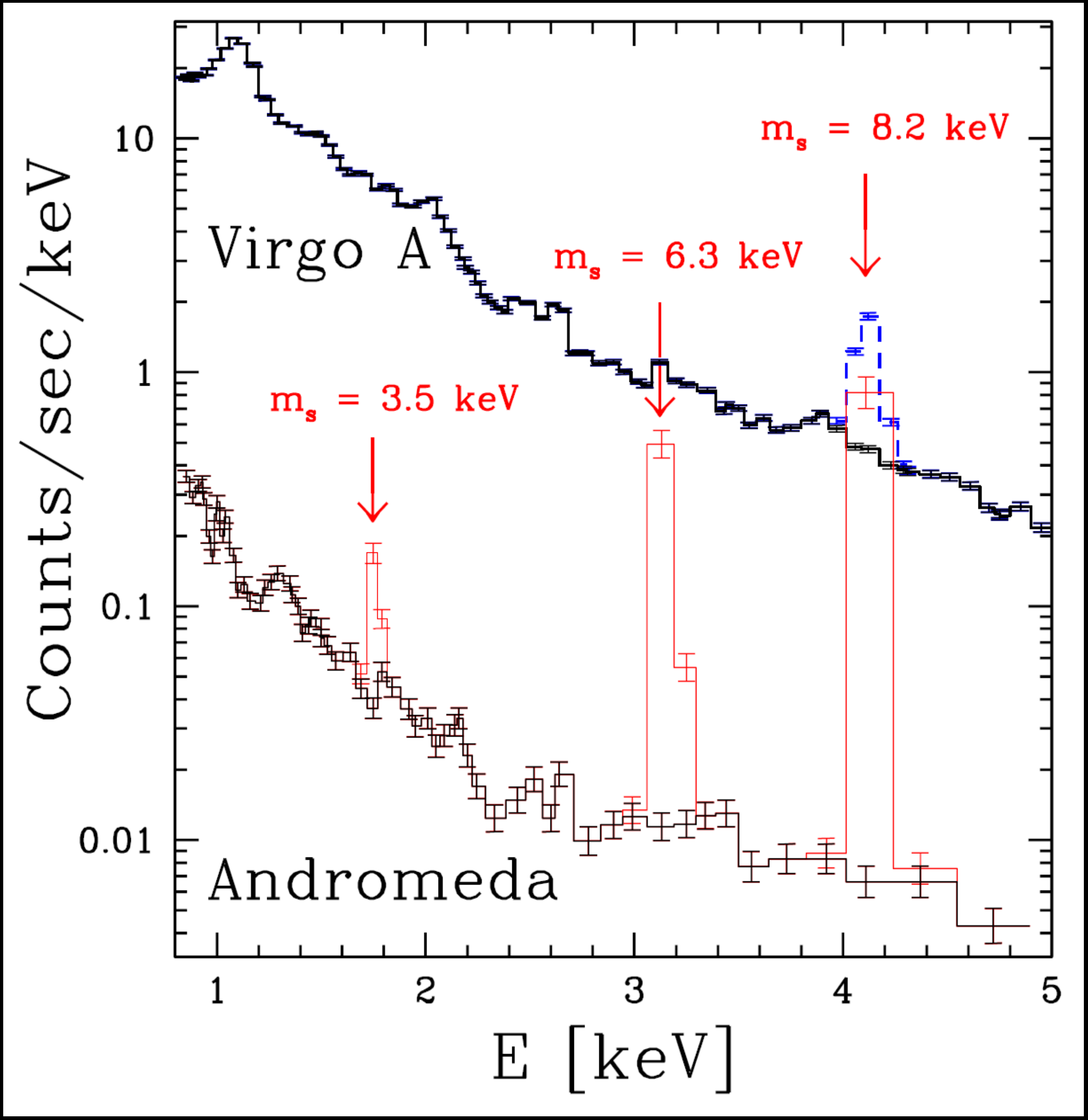

**REDUCED Astrophysical Background:**

**Bright point sources *removed*** **(in Ref. [96])**

***Intrinsically LOW*** **hot gas emission**

# RESULTS

**For $\Omega_s$ = 0.24 & L = 0 density-production relationship [43]:**




## Andromeda:

**$m_s$ < 3.5 keV**

**[66]**

## Virgo A:

**$m_s$ < 8.2 keV**

**[44]**

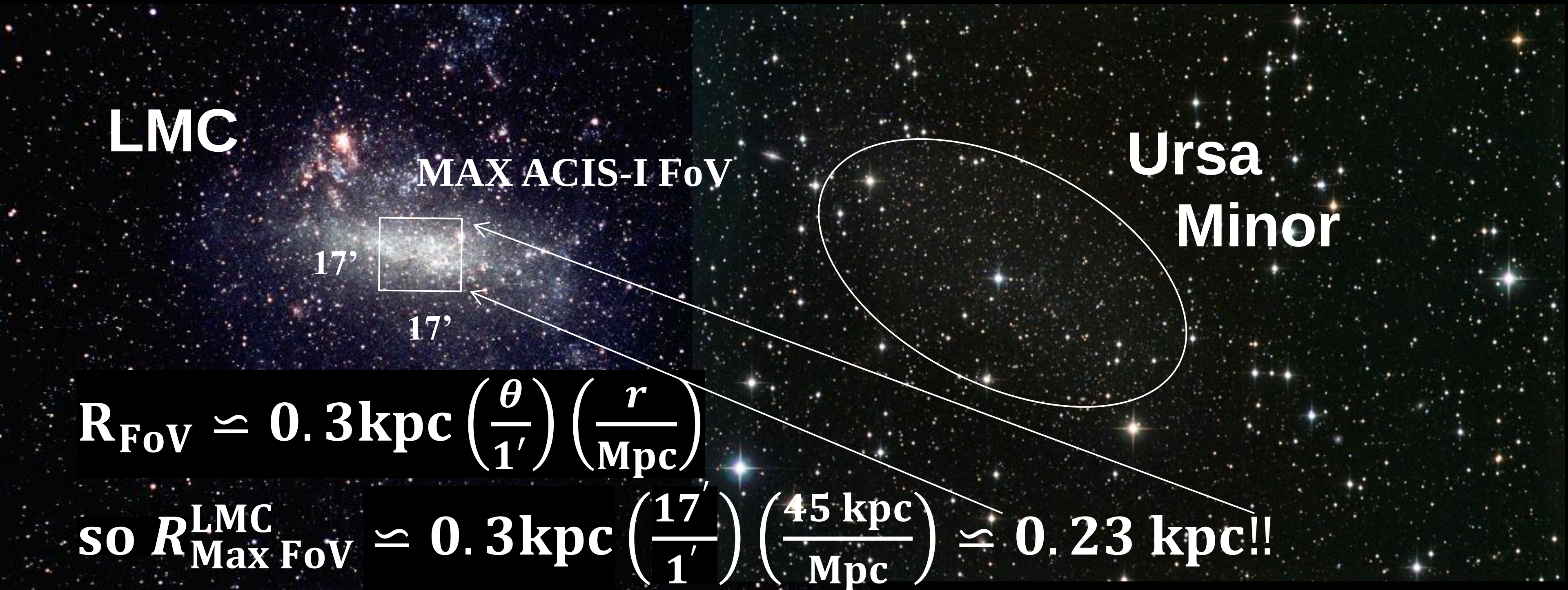
## Virgo A+Coma:

**$m_s$ < 6.3 keV**

**[13, 63]**

**$m_s$ = 6.3 keV & $m_s$ = 8.2 keV decay peaks are also shown relative to Andromeda data.**

# Previous work III: Dwarf Galaxies




$$\mathrm{R_{FoV}} \backsimeq 0.3\mathrm{kpc}\left(\frac{\theta}{1'}\right)\left(\frac{r}{\mathrm{Mpc}}\right)$$

$$\text{so } R^{\mathrm{LMC}}_{\mathrm{Max\ FoV}} \backsimeq 0.3\mathrm{kpc}\left(\frac{17'}{1'}\right)\left(\frac{45\ \mathrm{kpc}}{\mathrm{Mpc}}\right) \backsimeq 0.23\ \mathrm{kpc}!!$$

**Advantages:** Small D; Low background

**PROBLEMS:** Low & Uncertain $M_{DM}$ in FOV.

Constraints (for DW Model $\nu_s$ [3, 43]):

$m_s < 3$ keV** (LMC + MW) [69]

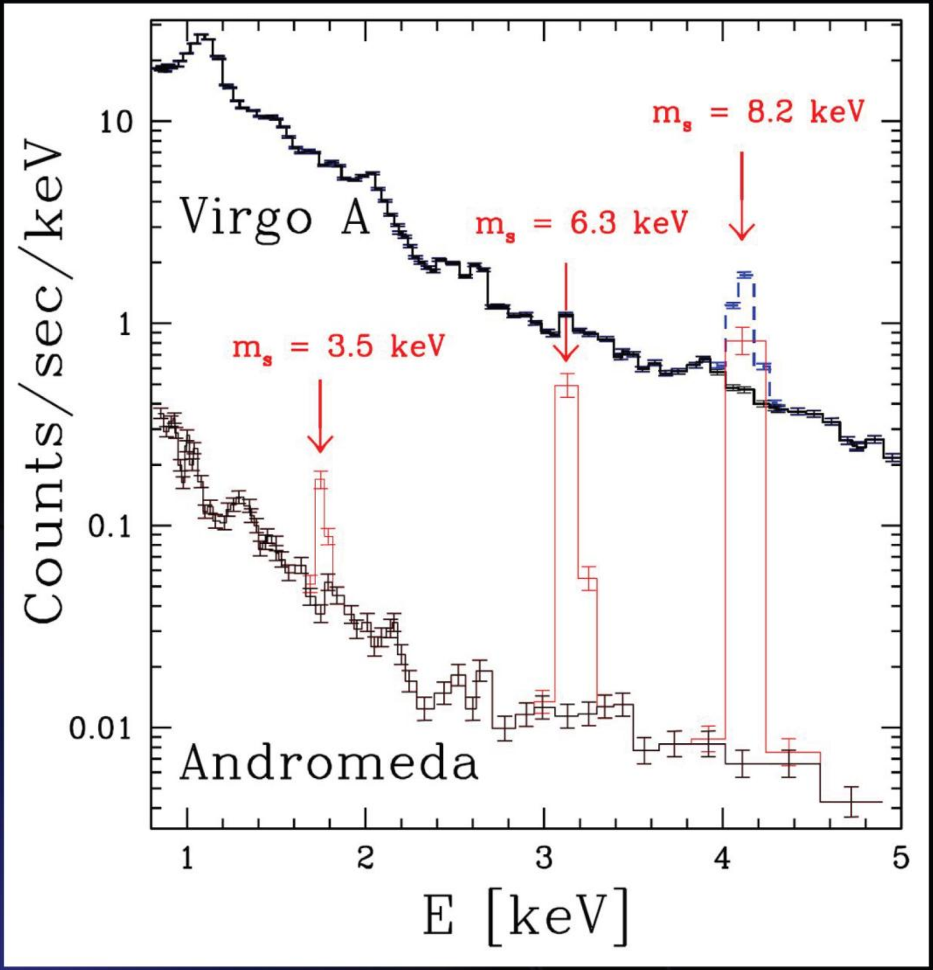
** VERY WEAK EXCLUSION CRITERION

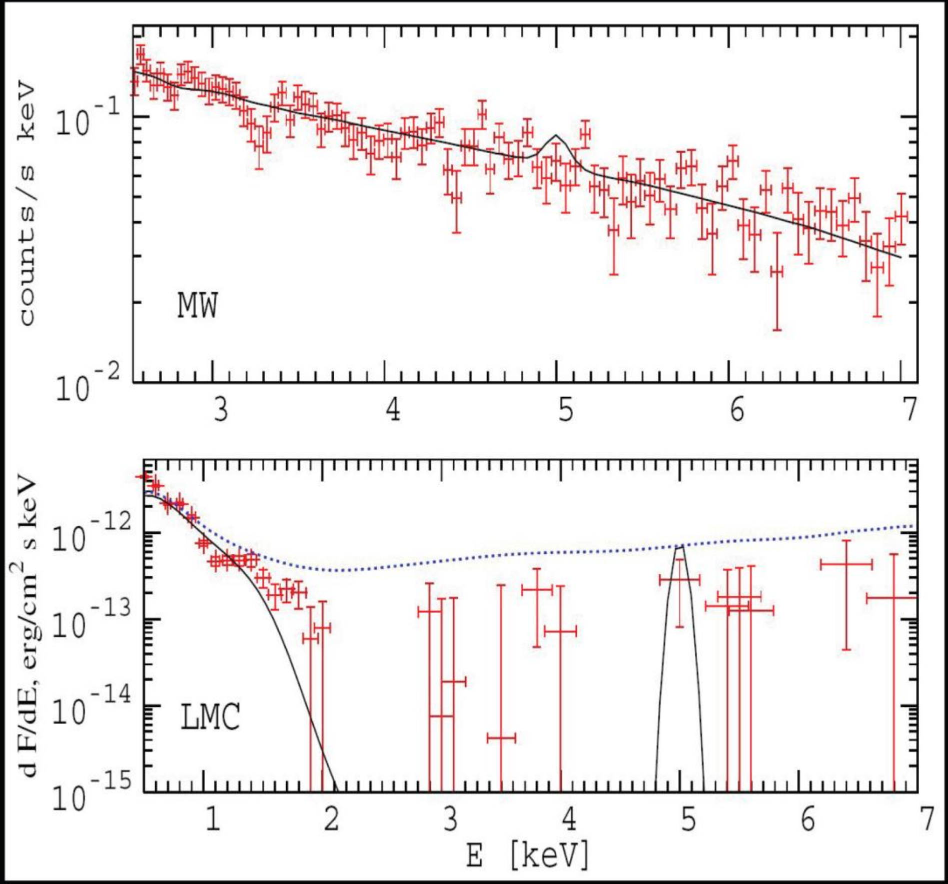
# Andromeda (*XMM*) vs. Dwarf/MW Constraints

**Andromeda** [66] & **LMC + MW** [69]

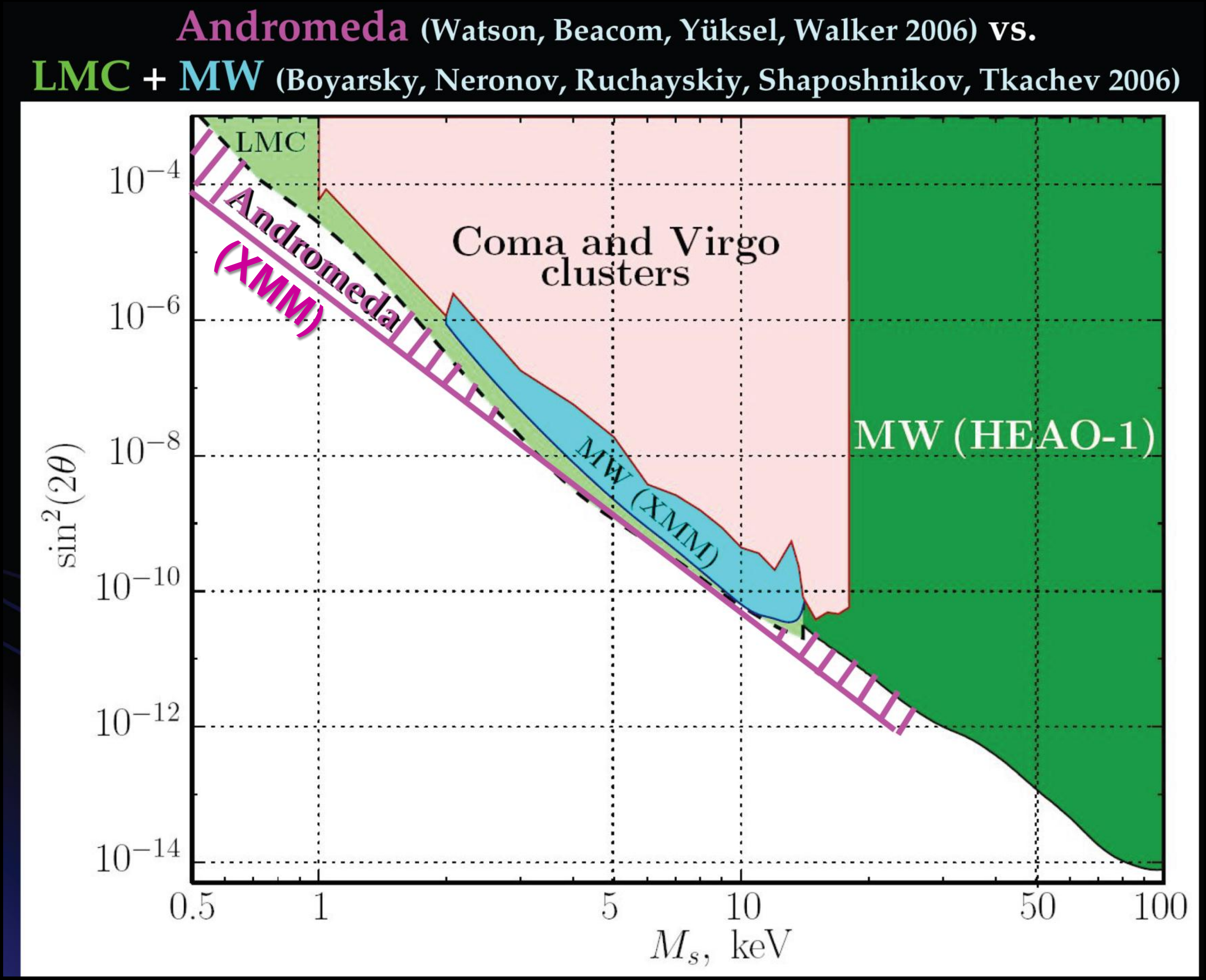
(Watson, Beacom, Yüksel, Walker 2006)

(Boyarsky, Neronov, Ruchayskiy, Shaposhnikov, Tkachev 2006)



# Andromeda (*XMM*) vs. Cluster/Dwarf/MW

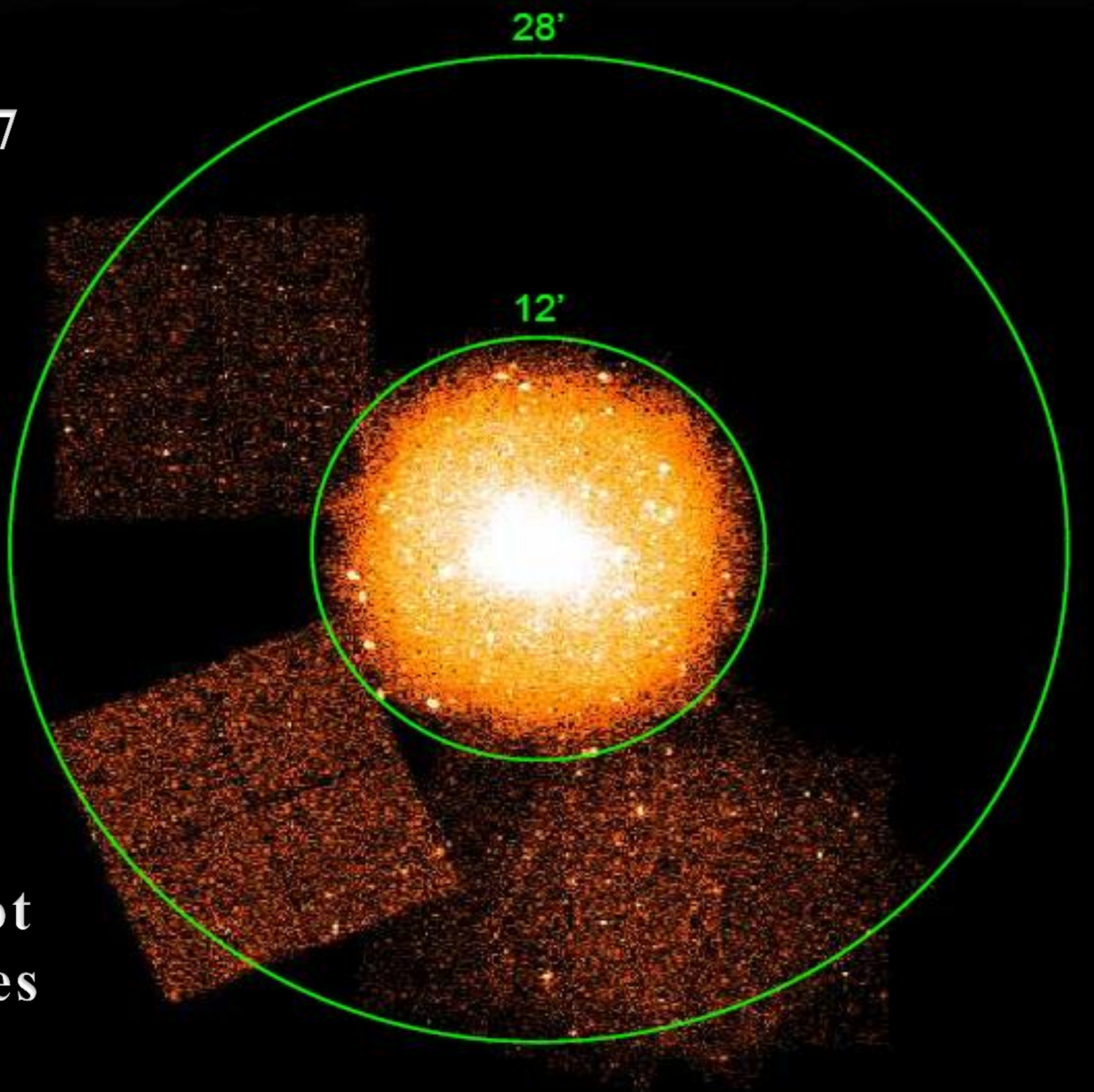


# *Chandra* FOV of M31: $\Delta\theta = 12' - 28'$

- Raw counts associated with the 7 Chandra ACIS-I exposure regions.

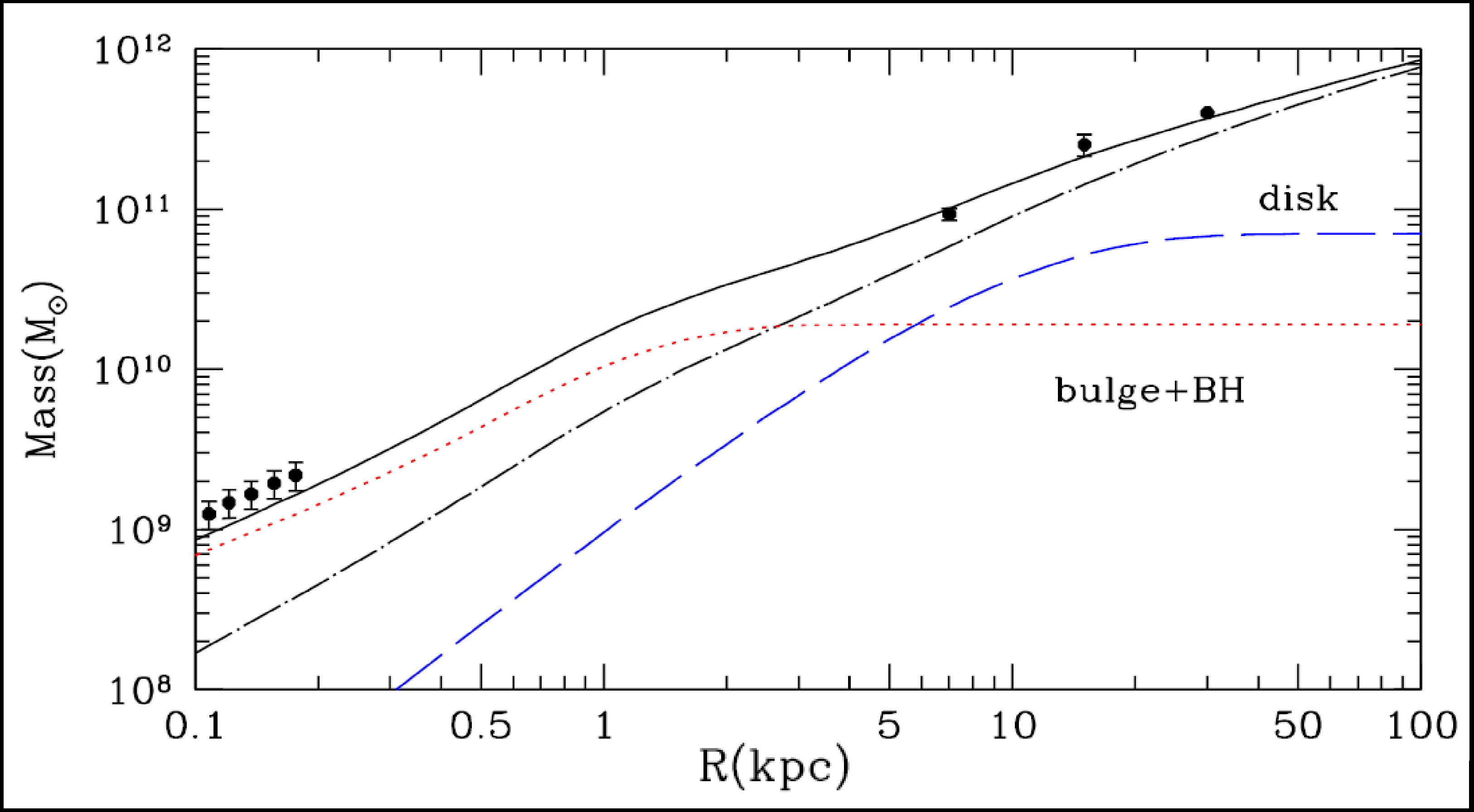
- Exposure times range from 5ks to 20ks

- Central 12' is excluded because of high astrophysical background from hot gas and point sources in that region



# Andromeda's

## Well-measured Matter Distribution:

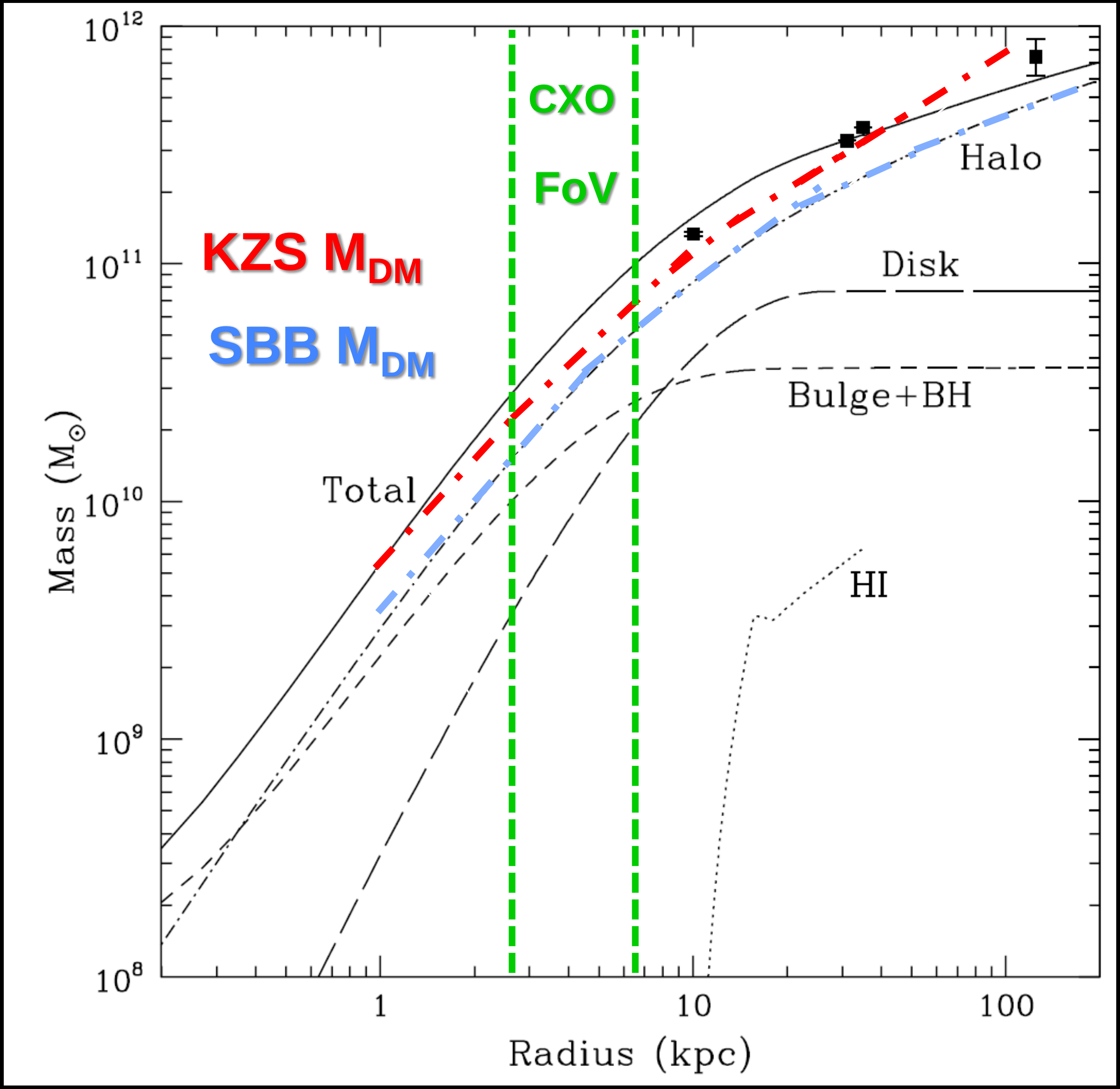



**Constraints at small radii are from Stellar Motions in the Nucleus.**
**Three points at R>5 kpc characterize the spread in $v_{rot} = 255 \pm 15$ km/s.**

**(Klypin, Zhao, Somerville 2002 [104] (KZS))**

**(Additional Data & updated analysis in Seigar, Barth, & Bullock 2007 [105] (SBB))**

# More Conservative DM Matter Distribution:




SBB $M_{DM}$

<

KZS $M_{DM}$

by a factor of

~ 1.05 – 1.2

in *Chandra* FoV

SBB $M_{DM}$

<

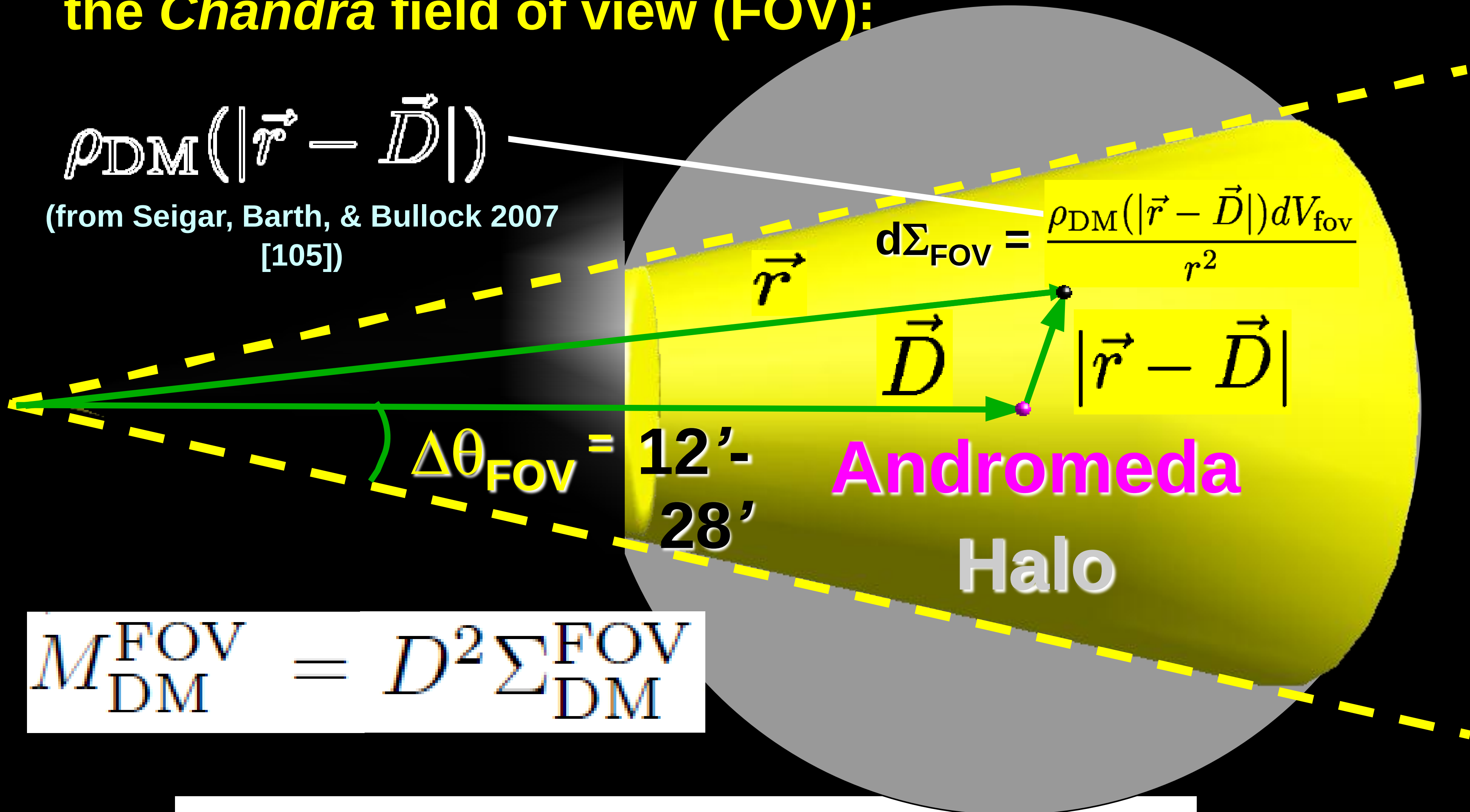
Burkert $M_{DM}$
[67, 106]

by a factor of

~ 1.2 – 1.4

in *Chandra* FoV

# The Fraction of Andromeda's Dark Matter Mass in the *Chandra* field of view (FOV):




$$M_{\mathrm{DM}}^{\mathrm{FOV}} = D^2 \Sigma_{\mathrm{DM}}^{\mathrm{FOV}}$$

$$\Sigma_{\mathrm{DM,M31}}^{\mathrm{FOV}} \simeq (0.8 \pm 0.04) \times 10^{11} M_{\odot} \mathrm{Mpc}^{-2}$$

$$M_{\mathrm{DM,M31}}^{\mathrm{FOV}} \simeq (0.49 \pm 0.05) \times 10^{11} M_{\odot}$$

# Conversion of Decay Signal to Detector Units:

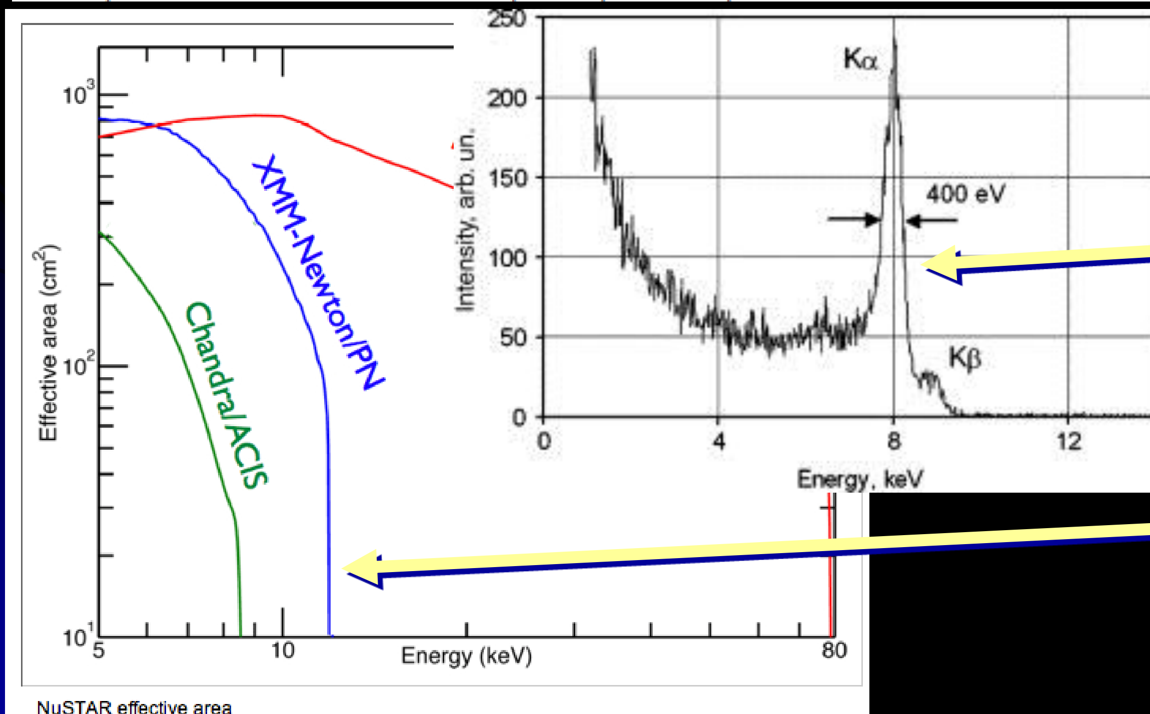
$$\frac{dN_{\gamma,\mathrm{s}}}{dE_{\gamma,\mathrm{s}}dt}(\Omega_{\mathrm{s}}) = \left(\frac{\Phi_{\mathrm{x,s}}(\Omega_{\mathrm{s}})}{E_{\gamma,\mathrm{s}}}\right)\left(\frac{A_{\mathrm{eff}}(E_{\gamma,\mathrm{s}})}{\Delta E}\right)$$

$$= 6.7\times 10^{-2}\ \mathrm{Counts/sec/keV}\left(\frac{\mathrm{A_{eff}(E_{\gamma,s})}}{100\ \mathrm{cm}^2}\right)$$

$$\times\left(\frac{\Sigma^{\mathrm{FOV}}_{\mathrm{DM}}}{10^{11}M_{\odot}\mathrm{Mpc}^{-2}}\right)\left(\frac{\Omega_{\mathrm{s}}}{0.24}\right)^{0.813}\left(\frac{m_s}{\mathrm{keV}}\right)^{1.374}$$

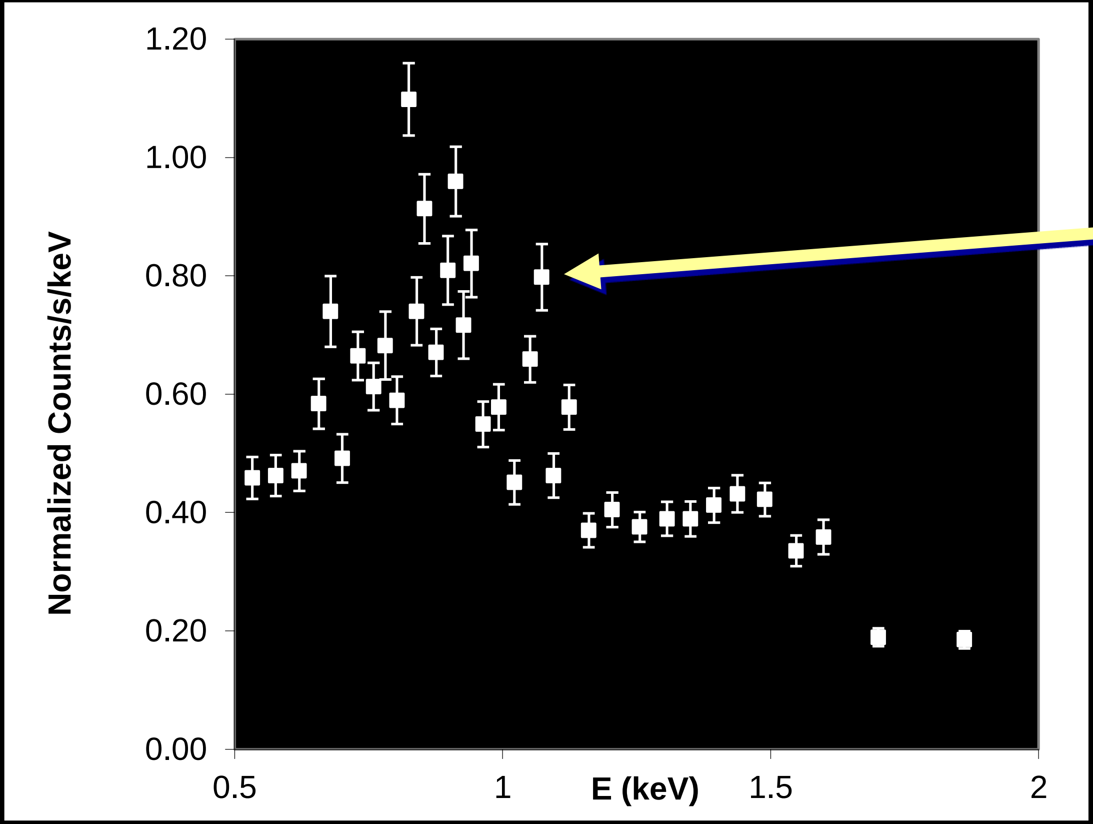
**Detection of $\nu_s$ Decays at $E_{\gamma,s}$ depends on**

- $\Phi_{x,s}$
- Spectral Energy Resolution $\Delta E \simeq E/15$
- ACIS-I Effective Area $A_{eff}(E_{\gamma,s})$



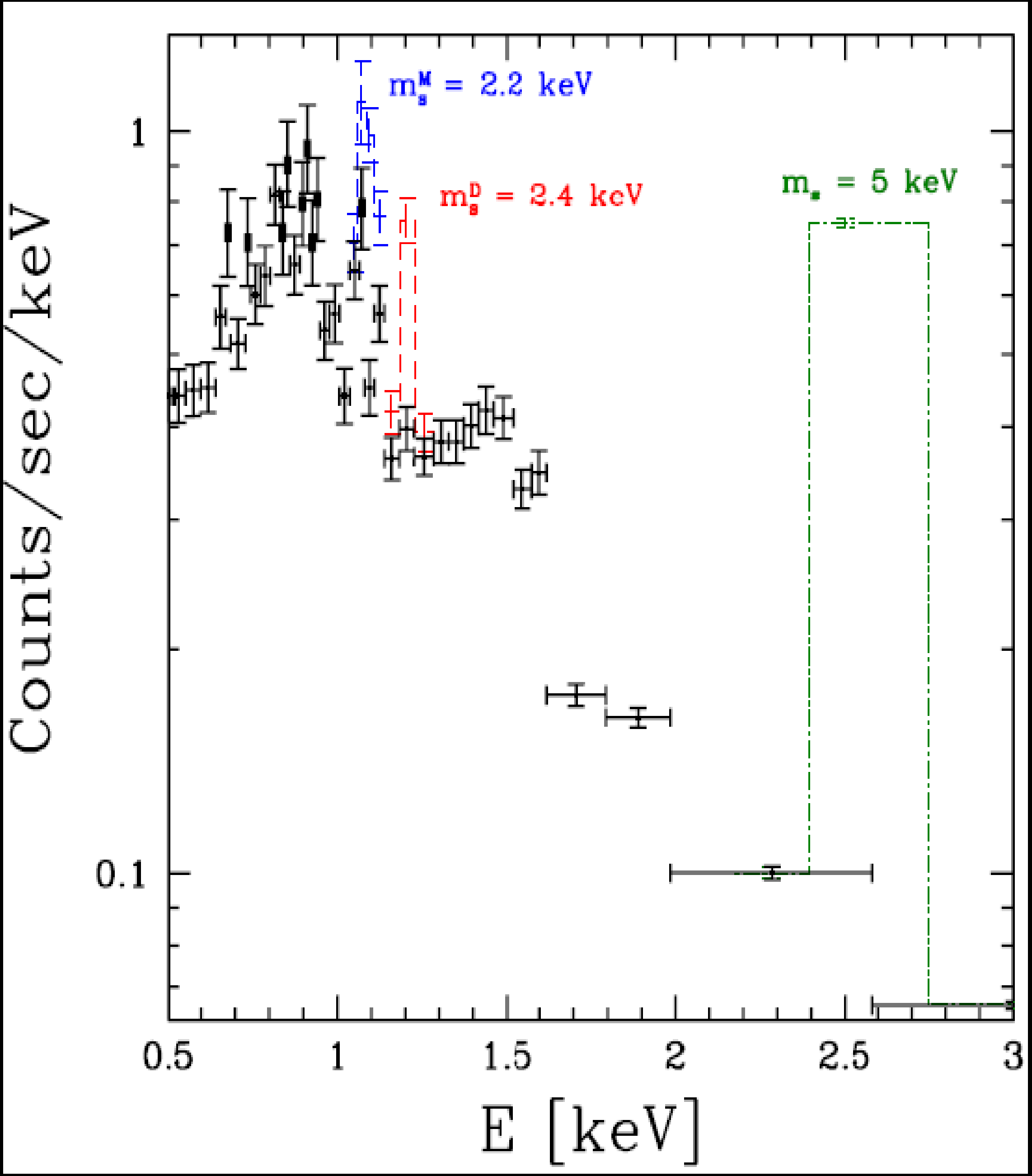
# Detection/Exclusion Criterion:

$$\frac{dN_{\gamma,\mathrm{s}}}{dE_{\gamma,\mathrm{s}}dt}(\Omega_{\mathrm{s}}) \geq \Delta\mathcal{F}$$




- Sterile Neutrino Decay Signal $dN_{\gamma,s}/dE_{\gamma,s}dt$
- $\geq$ *Chandra* Data $\Delta\mathcal{F}$
- in a given bin of energy $E_{\gamma,s}$

# Limits on $m_s$ from *Chandra* Observations of M31




***Chandra*** **unresolved X-ray spectrum emitted from 12' - 28' annular region of Andromeda (M31).**

**Majorana:**

**$m_s$ < 2.2 keV**

**Dirac:**

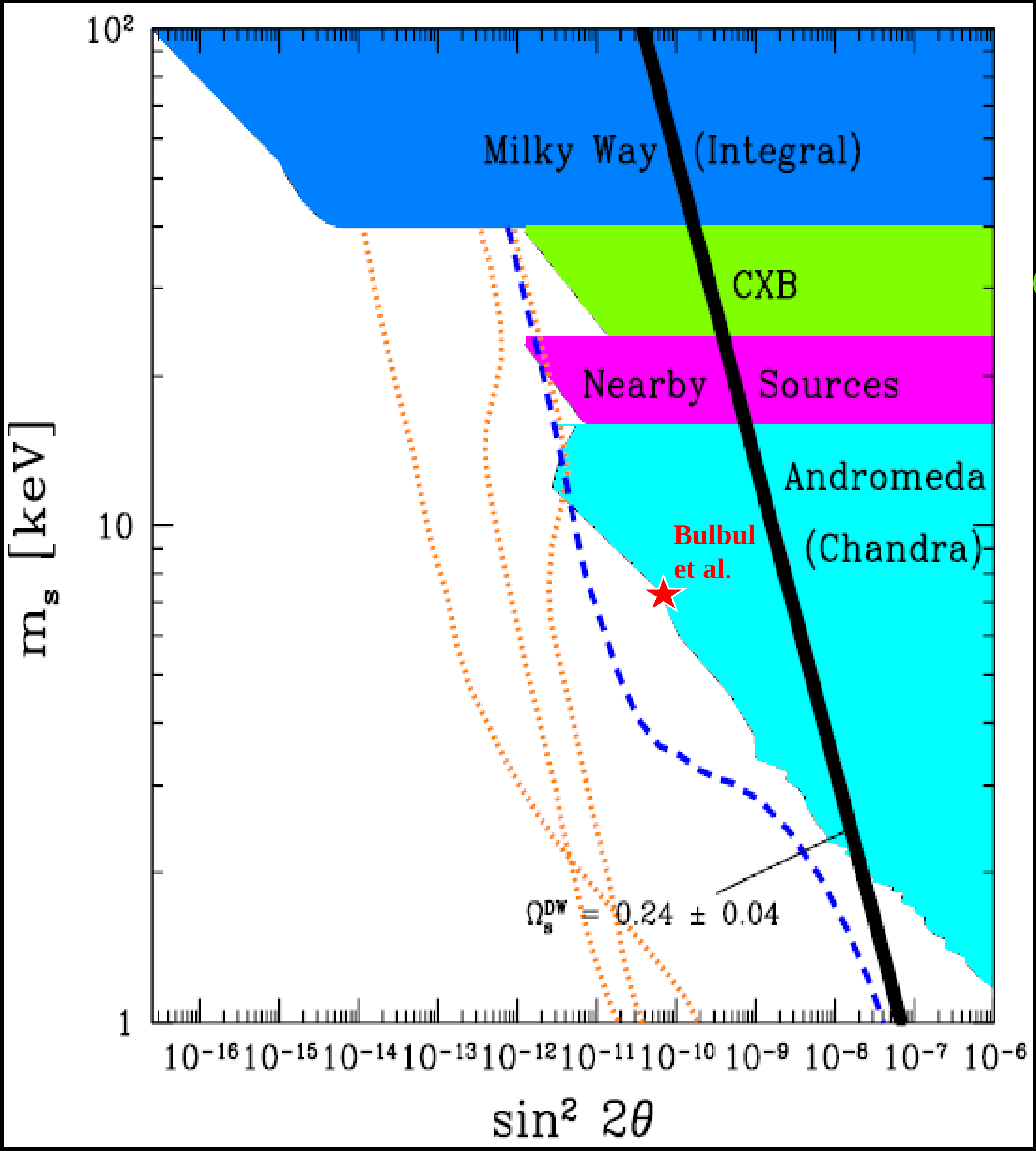
**$m_s$ < 2.4 keV**

**Claimed Detection:**

**$m_s$ = 5 keV**

**(Loewenstein & Kusenko 2010 [82]) STRONGLY excluded by our data!**

# Generalized constraints in the $m_s - \sin^2 2\theta$ plane




**Exclusion Regions:**

**Milky Way (Integral):**

[77, 78]

**Cosmic X-ray Background:**

[61,62]

**Andromeda (XMM):**

[66]

**Andromeda (CXO):**

(Watson, Li, & Polley 2012)

**Density-Production Models:**

**Dodelson-Widrow Model**

[3]

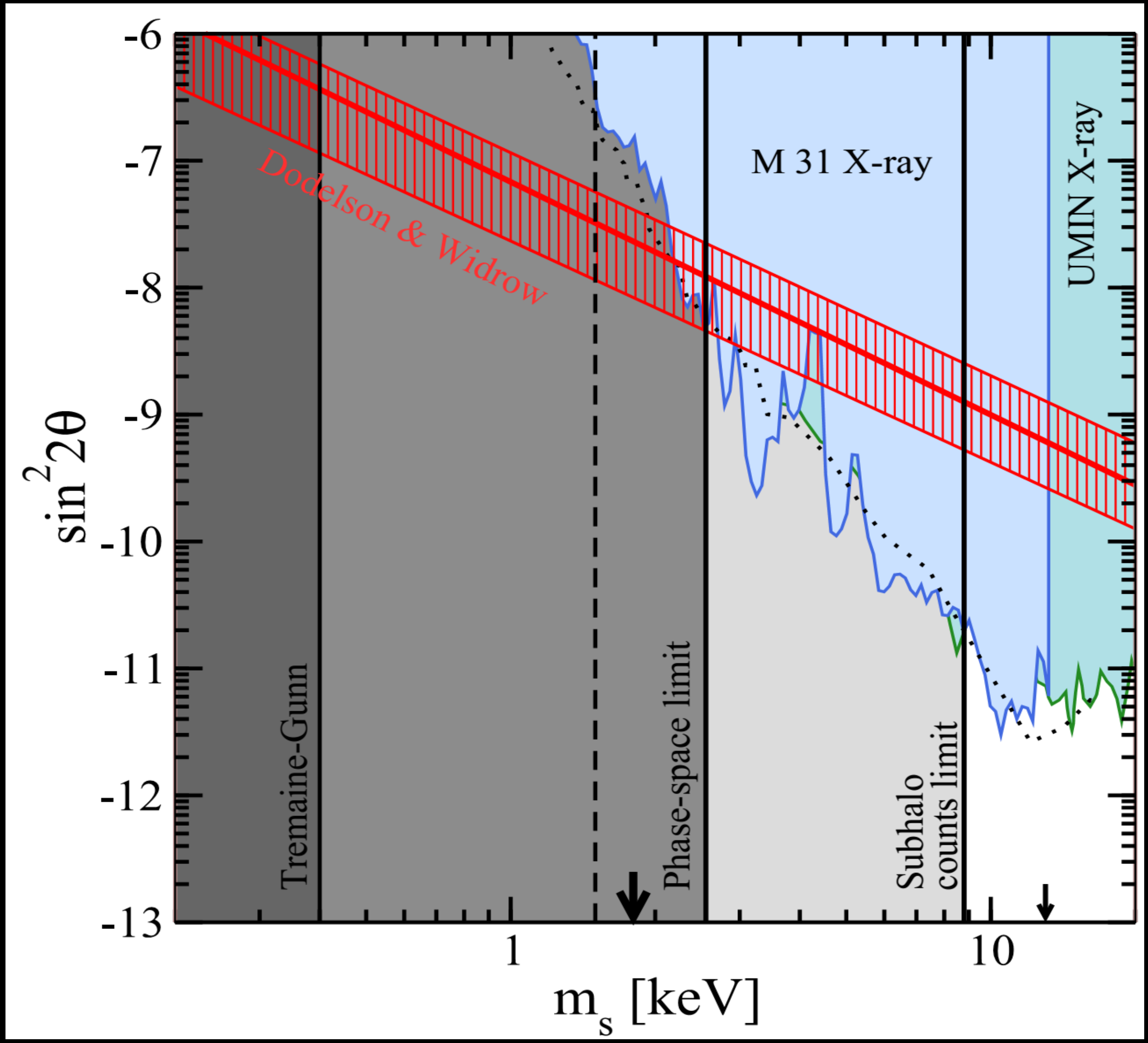
**Shi-Fuller Model**

[4, 53]

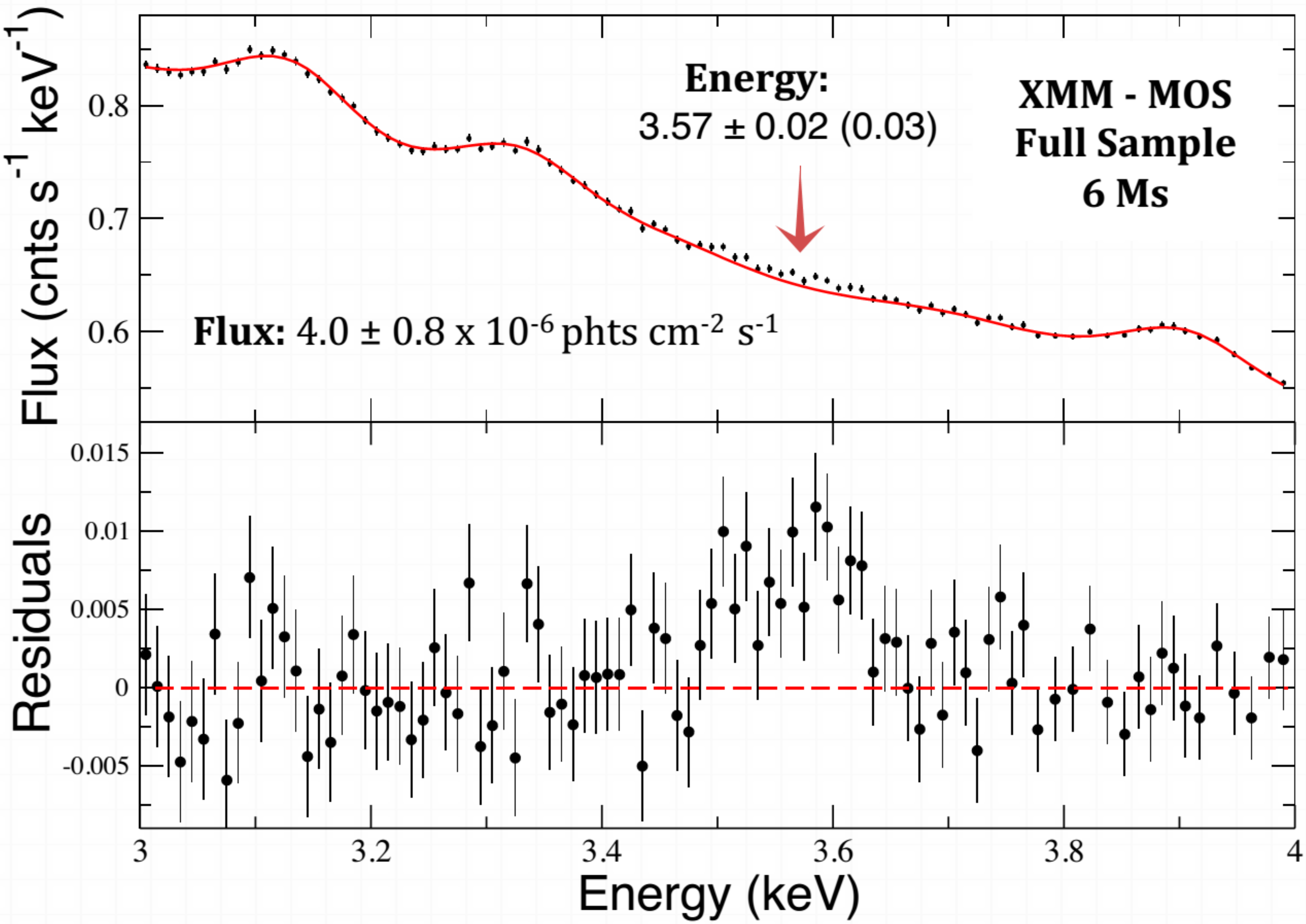
**3 L >> $10^{-10}$ Lines**

[13]

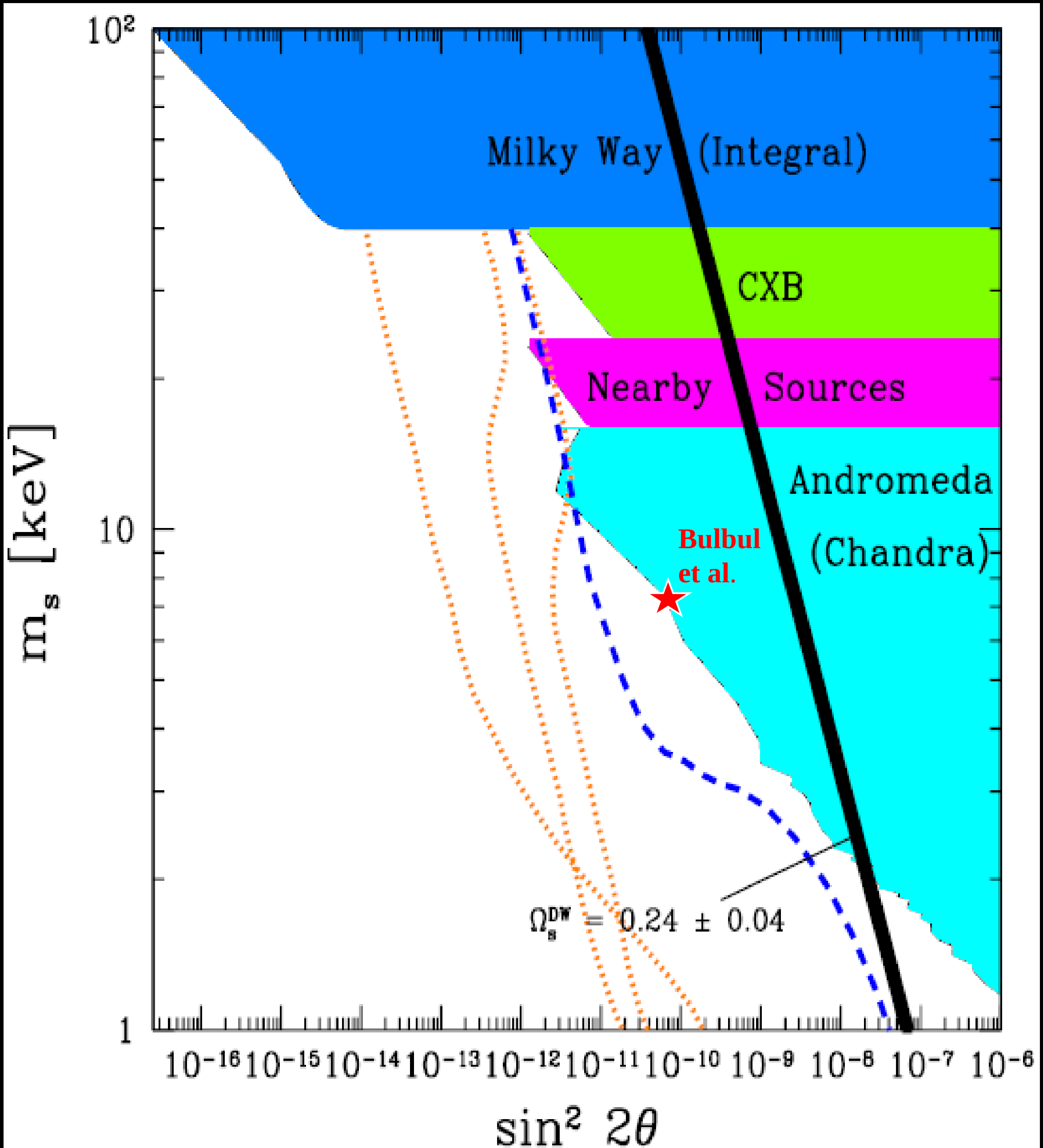
# Dodelson-Widrow Excluded according to Horiuchi et al. (2014)



# Bulbul et al. (2014):
## Detection of An Unidentified Emission Line



# Possible Detection?




**Bulbul et al. (2014):**

$m_s = 7.14 \pm 0.1$ **keV**

$\sin^2 2\theta = 6.7 \pm 2.5 \times 10^{-11}$

- Not a background feature
- Not an instrumental line
- Not a detector feature
- Not a modeling artifact
- Comes from all clusters rather than a few dominant bright clusters
- Flux is centrally concentrated

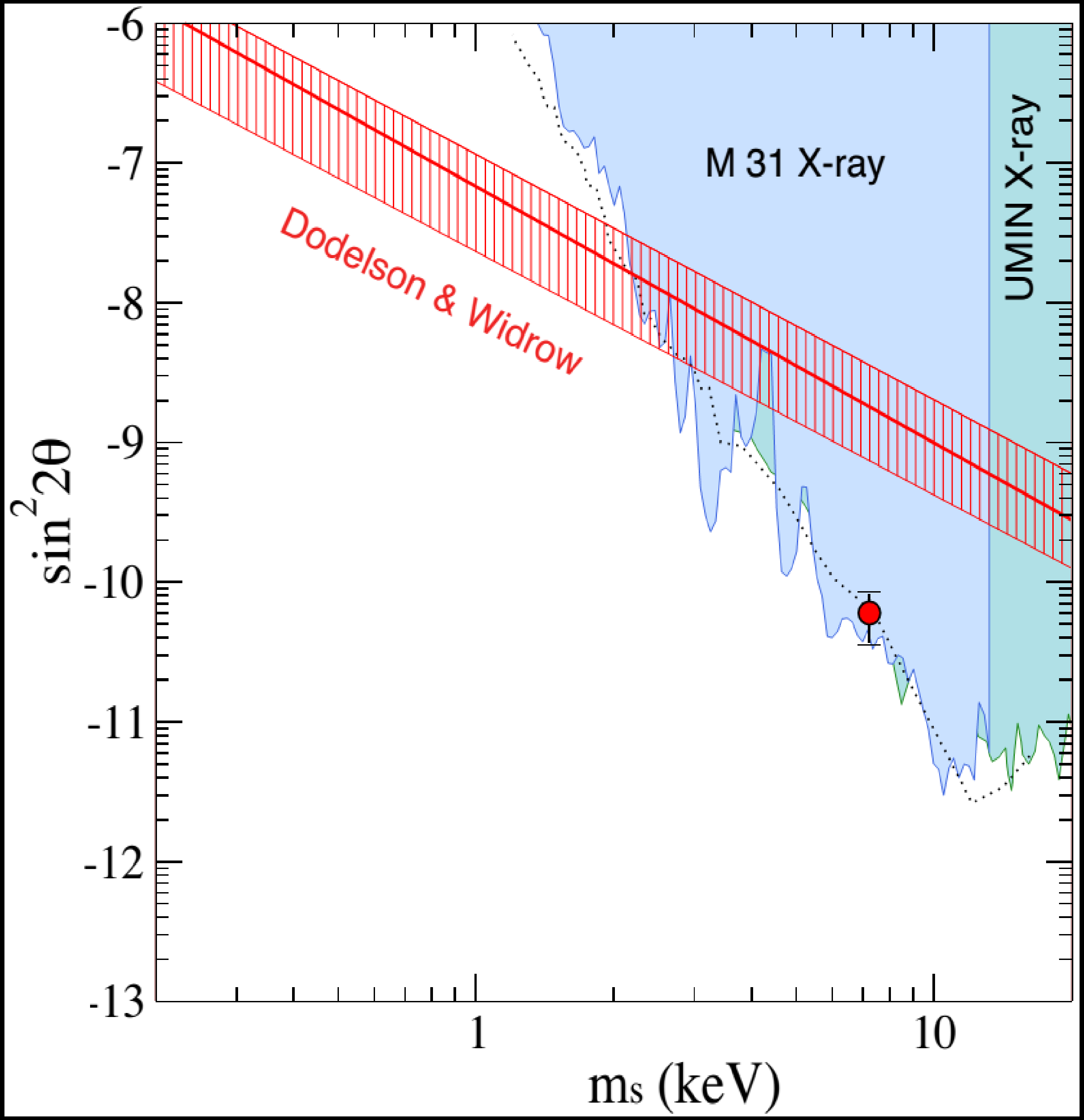
**On the cusp of exclusion:**

**Andromeda (CXO)**

(Watson, Li, & Polley 2012)

(Horiuchi et al. 2014)

# Bulbul et al. result avoids exclusion at lowest mixing




**Bulbul et al. OK if:**

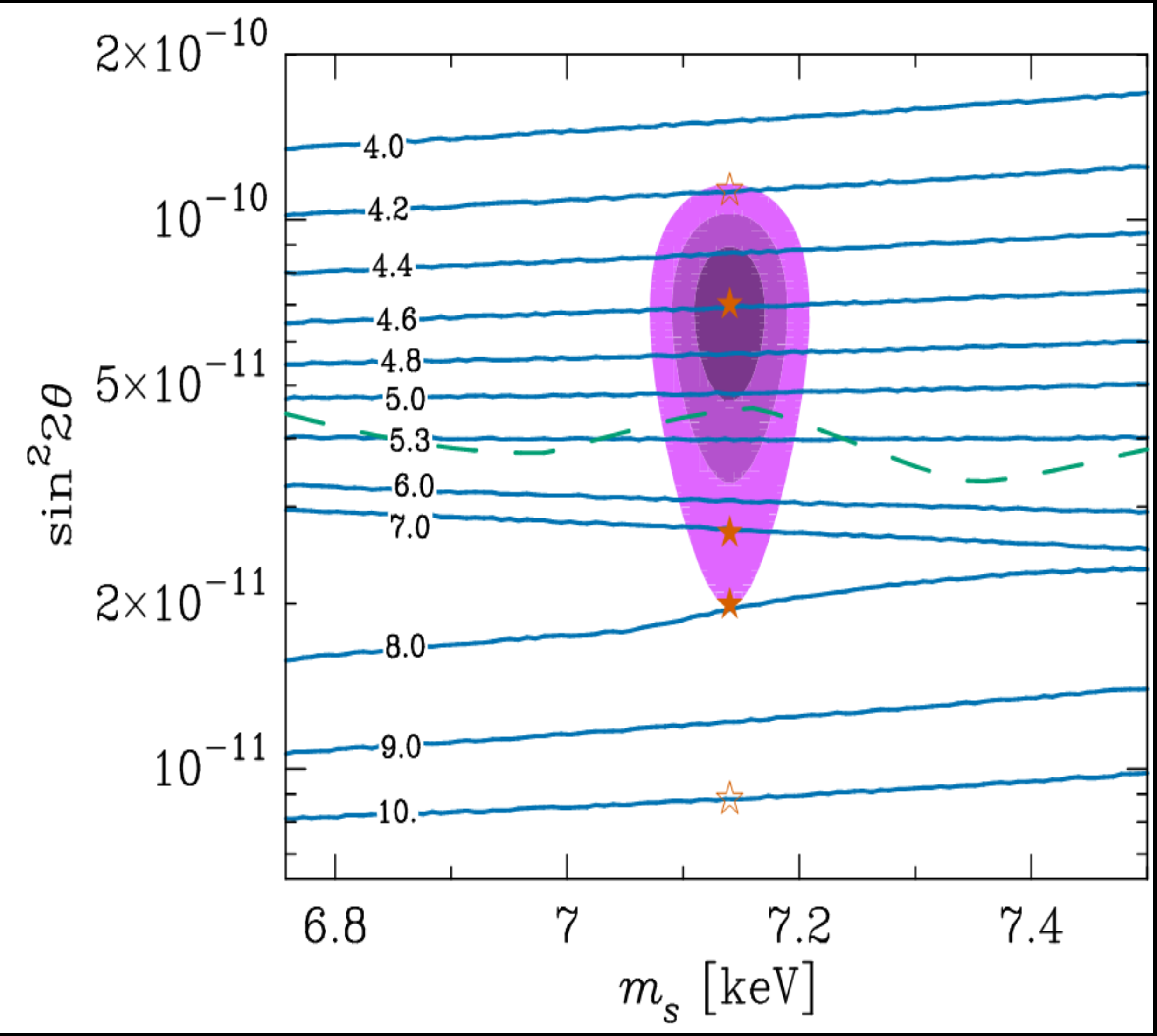
$\sin^2 2\theta \simeq$ 3-4x10$^{-11}$

**Andromeda (CXO) Exclusion Constraints:**

**Dotted** (Watson, Li, & Polley 2012)

**Solid** (Horiuchi et al. 2014)

# Shi-Fuller Models (Abazajian 2014)




**Bulbul et al.:**

**$m_s = 7.14 \pm 0.1$ keV**

**$\sin^2 2\theta \simeq 6.7\times10^{-11}$**

**corresponds to**

**$L = 4.6\times10^{-4}$,**

**i.e., $L_4 = 4.6$**

**IMPORTANT**

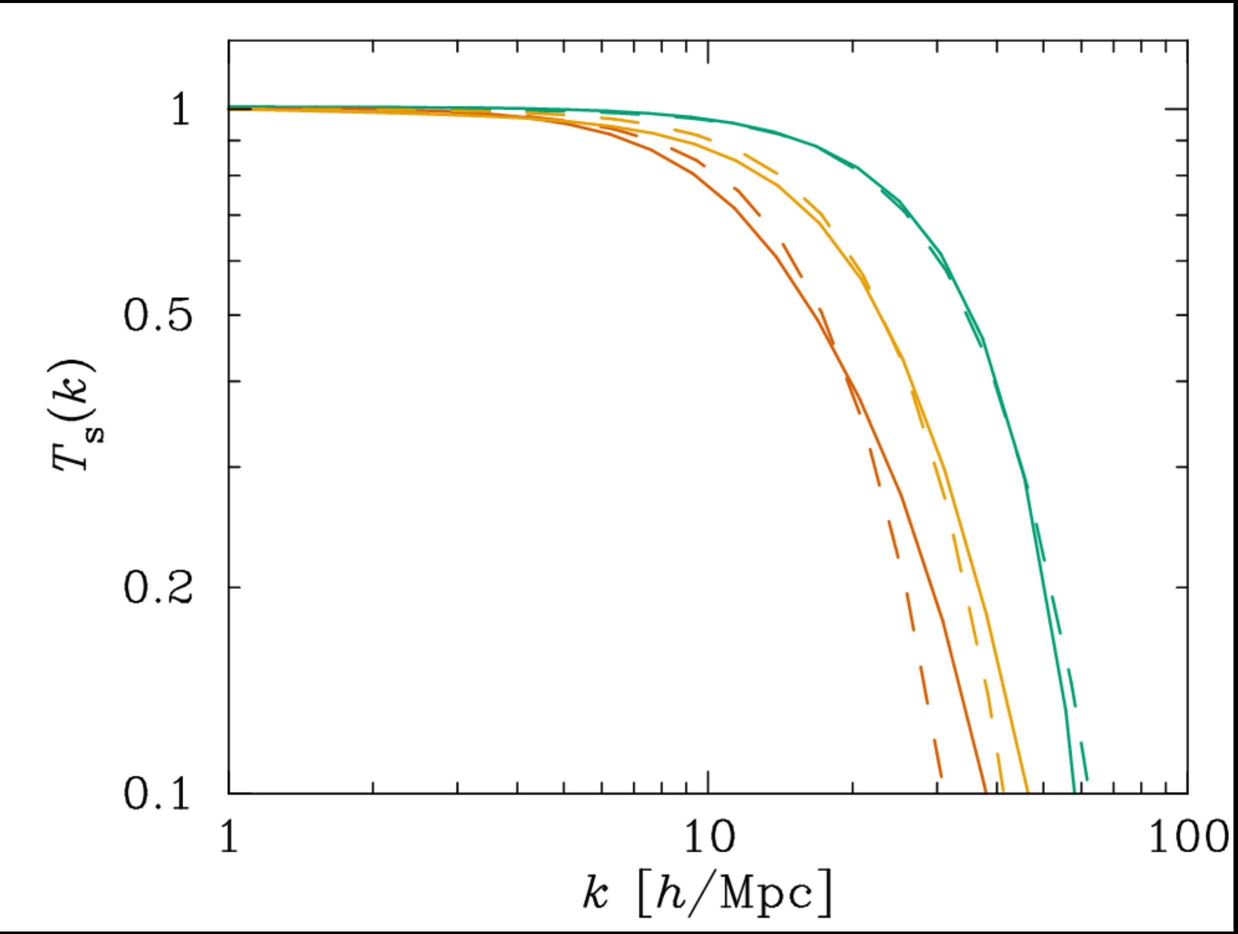
**Lower mixing:**

**$\sin^2 2\theta \simeq 3\times10^{-11}$**

**corresponds to**

**$L_4 = 7.0$**

# WDM Transfer Functions: Shi-Fuller vs. Thermal (Abazajian 2014)




**Solid**

$L_4$ = 8, 7, 4.6

**Dashed**

$m_{th}$/keV = 1.6, 2.0, 2.9

# Galaxy Constraints Satisfied by 2 keV Thermal Sterile Neutrino (Abazajian 2014)

- **Local Group Phase Space Density and Subhalo Counts:**
  **$m_{th} > 1.7$ keV** (Horiuchi et al. 2014)

- **High Redshift Galaxy Counts:**
  **$m_{th} > 1.3$ keV** (Schultz et al. 2014)

- **Abundance, Radial Distribution, and Inner Density Profile Crises of Milky Way Satellites solved if:**
  **$m_{th} \simeq 2$ keV** (e.g., Lovell et al. 2012 and Abazajian 2014 for additional references)

- **Recall that a 7.14 keV Shi-Fuller $\nu_s$ with $L_4 = 7$:**
  **BEHAVES LIKE $m_{th} \simeq 2$ keV!**

# Summary I

**DW excluded via phase space constraints**

**from MW dwarfs.**

**(Horiuchi, et al. 2014)**

**$m_s = 7.14 \pm 0.1$ keV detection still viable**

**but close to X-ray exclusion.**

**(Bulbul, et al. 2014)**

**A 7.14 keV Shi-Fuller sterile neutrino with $L_4 = 7$:**

- **Accounts for X-ray line anomaly found by Bulbul et al.**
- **Satisfies all galaxy constraints like $m_{th} \gtrsim 2$ keV**
- **Avoids exclusion by Andromeda X-ray Constraints**

**(Abazajian, et al. 2014)**

# Phase Space Density Overview I

$$Q \propto \frac{\rho}{\sigma^3}$$

- For a fermionic thermal relic, Hogan & Dalcanton (2001) find:

$$Q_{\rm HD} = \frac{\rho}{(3\sigma^2)^{3/2}} = AQ_* \left(\frac{m}{\rm keV}\right)^4$$

- where A = $5 \times 10^{-4}$ and $Q_* = \frac{M_\odot/pc^3}{({\rm km\ s}^{-1})^3}$
- adiabatic invariant
- strongly mass-dependent

# Phase Space Density Overview II

- **Hogan & Dalcanton's assume a 1-D velocity disperson.**
- **As in Horiuchi et al. (2014), we assume MB:**

$$Q = \frac{\rho}{(2\pi\sigma^2)^{3/2}} \simeq 0.33 Q_{\mathrm{HD}}$$

$$Q_P = A Q_* \left(\frac{m}{\mathrm{keV}}\right)^4$$

- **where A = 1.65 x 10$^{-4}$ and** $Q_* = \frac{M_\odot / pc^3}{(\mathrm{km\ s^{-1}})^3}$

# Connecting the Past to the Present

- **Galaxy formation processes alter Q by an unknown factor Z:**

$$Z = \frac{Q_P}{Q_0}$$

- **De Vega & Sanchez (2010) explored a number of analytical methods to find Z, concluding that**
  - **$1 \leq Z \leq 10^4$, in agreement with simulations**
  - **the mass of a thermal relic DM particle is ~ keV:**

$$\frac{m_{\rm th}}{\rm keV} = \left(\frac{Q_p}{A}\right)^{1/4} = \left(\frac{ZQ_0}{A}\right)^{1/4} \simeq 1 - 10$$

# Goals of Our Project

1. **Determine Z directly from the dwarf galaxy data to produce a model-independent mapping between $Q_p$ and $Q_0$.**
2. **Use this empirical Z factor to determine the DM particle mass – both for thermal and non-thermal relics.**
3. **Identify primordial dwarf galaxies – i.e., systems for which $Q_0 \simeq Q_P$.**
4. **Draw insights from these primordial objects about the formation and evolution of galaxies.**

# Dwarf Galaxy Data (Sample)

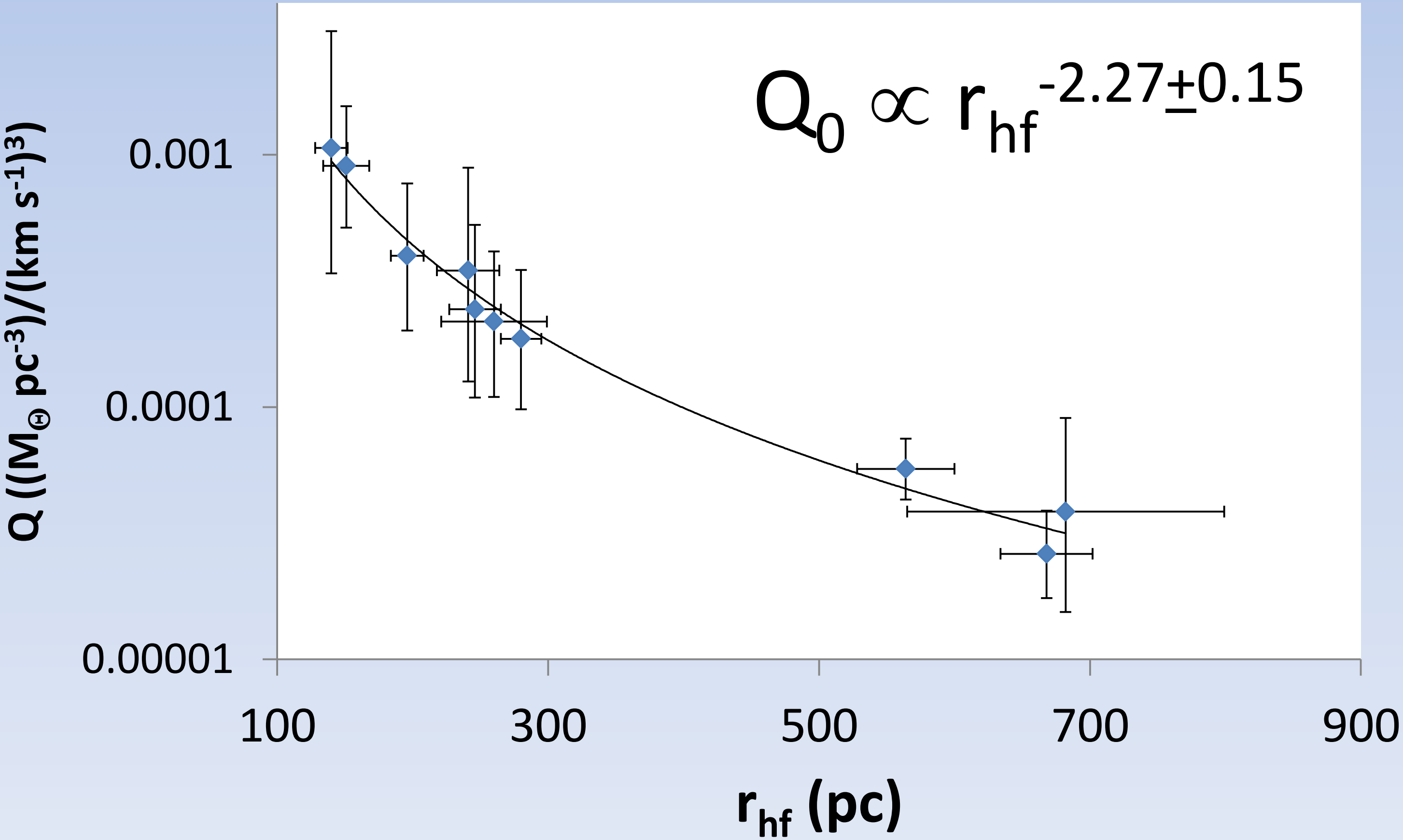
- Data for 23 dSphs from Walker et. al. (2009)

| Dwarf | $\sigma$ (km/s) | | | $\rho$ ($M_\Theta$ pc$^{-3}$) | | | $r_{hf}$ (pc) | | | $M(r_{hf})$ ($10^7$ $M_\Theta$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carina | 6.6 | $\pm$ | 1.2 | 0.1 | $\pm$ | 0.04 | 241 | $\pm$ | 23 | 0.61 | $\pm$ | 0.23 |
| Draco | 9.1 | $\pm$ | 1.2 | 0.3 | $\pm$ | 0.08 | 196 | $\pm$ | 12 | 0.94 | $\pm$ | 0.25 |
| Fornax | 11.7 | $\pm$ | 0.9 | 0.042 | $\pm$ | 0.007 | 668 | $\pm$ | 34 | 5.3 | $\pm$ | 0.9 |
| Leo I | 9.2 | $\pm$ | 1.4 | 0.19 | $\pm$ | 0.06 | 246 | $\pm$ | 19 | 1.2 | $\pm$ | 0.4 |
| Leo II | 6.6 | $\pm$ | 0.7 | 0.26 | $\pm$ | 0.06 | 151 | $\pm$ | 17 | 0.38 | $\pm$ | 0.09 |
| Sculptor | 9.2 | $\pm$ | 1.1 | 0.17 | $\pm$ | 0.05 | 260 | $\pm$ | 39 | 1.3 | $\pm$ | 0.4 |
| Sextans | 7.9 | $\pm$ | 1.3 | 0.019 | $\pm$ | 0.007 | 682 | $\pm$ | 117 | 2.5 | $\pm$ | 0.9 |
| U Minor | 9.5 | $\pm$ | 1.2 | 0.16 | $\pm$ | 0.04 | 280 | $\pm$ | 15 | 1.5 | $\pm$ | 0.4 |
| C Ven I | 7.6 | $\pm$ | 0.4 | 0.025 | $\pm$ | 0.003 | 564 | $\pm$ | 36 | 1.9 | $\pm$ | 0.2 |
| U Ma II | 6.7 | $\pm$ | 1.4 | 0.32 | $\pm$ | 0.14 | 140 | $\pm$ | 25 | 0.36 | $\pm$ | 0.16 |

# Q – $r_{hf}$ Power-Law Relation

- **The power-law relations from Walker et al. (2009):**

$$\rho \propto r_{hf}^{-1.6}; \sigma \propto r_{hf}^{0.2} \rightarrow \quad Q \propto \frac{\rho}{\sigma^3} \propto r_{hf}^{-2.2}.$$



# Phase Space Density of the DM

- **$Q_0$ shown in the previous plot is based on *stellar* velocity dispersions, $\sigma_*$.**
- **Horiuchi et al. (2014) find**

$$\eta_* = \sigma/\sigma_* = 1.5 \pm 0.2$$

- **Adopting this correction factor, we find**

$$Q_{0,\mathrm{DM}} = (1.61 \pm 0.42) Q_* \left(\frac{r_{hf}}{\mathrm{pc}}\right)^{-n}$$

- **where** $n = 2.27 \pm 0.15$ **and** $Q_* = \dfrac{M_\odot/pc^3}{(\mathrm{km\ s^{-1}})^3}$

# Using $Q(r_{hf})$ to find Z

- We can rewrite the $Q(r_{hf})$ power-law in terms of:
  - the unknown, primordial $Q_p$

  and

  - an unknown radial scale, $r_p$:

$$Q_0 = Q_P \left(\frac{r_p}{r_{hf}}\right)^n = Q_P / Z_{\rm em}$$

$$Z_{\rm em} = (r_{hf}/r_p)^n$$

- Thus, determining $r_p$ is the key to the empirical Z factor.

# Empirical Limits on $r_P$

**Q can only decrease (Liouville's Theorem), so**

$$Z = (r_{hf}/r_p)^n \geq 1$$

$$r_p \leq r_{hf,min}$$

**<u>Minimum $r_{hf}$ values:</u>**

- **Willman 1: $r_{hf} = 25 \pm 6$ pc**
- **Segue 1: $r_{hf} = 29 \pm 7$ pc**
- **Segue 2: $r_{hf} = 34 \pm 5$ pc**
- **Leo V: $r_{hf} = 42 \pm 5$ pc**

$$r_p \lesssim 19 - 47 \text{ pc}.$$

# Finding $r_p$ analytically

- **Determine when the virial mass (Boylan-Kolchin et al. 2013) of the MW halo entered the horizon:**
  - **Earliest time causal processes could affect the PSD of DM in a MW-sized overdensity and in its primordial subhalo overdensities**

$$M_{\rm MW} = \frac{4}{3}\pi\rho_{m,0}(1+z)^3\left(\frac{d_H(z)}{2}\right)^3 = 1.6^{+0.8}_{-0.6}\times 10^{12}\,M_{\odot}$$

- **This occurs when**
  - $z_{\rm MW} = 9.4^{-1.2}_{+1.6}\times 10^4$
  - $r_p = d_H(z_{\rm MW})/2 = 26.7^{+8.3}_{-7.2}\ \rm pc$

**which agrees with empirical limits.**

# $Q_p$ Values + DM Particle Mass

- **Max/Min $Q_0$ ratio is ~ $10^4$**

$$Q_P = Z_{em} Q_0$$

- **Max/Min $Q_p$ differ by ~ 4.5**

$$\frac{m_{\rm th}}{\rm keV} = \left(\frac{Z_{\rm em} Q_0}{A}\right)^{1/4} = \left(\frac{\left(\frac{r_{hf}}{r_p}\right)^n Q_0}{A}\right)^{1/4}$$

- **Max/Min $m_{th}$ values differ by ~ 1.5**

**Including all galaxy data uncertainties**

- **$1 < Z < 10^4$**
- **$0.74 < m_{th}/\text{keV} < 2.8$ (mean 1.55 keV)**

# Non-thermal DM

- **If the DM particle is a sterile neutrino, we can use the following transformation equations (e.g., Viel et al. 2005; Abazajian 2014) to find the corresponding non-thermal limits:**

$$m_{s,\mathrm{DW}} = 4.27\mathrm{keV}\left(\frac{\mathrm{m_{th}}}{\mathrm{keV}}\right)^{4/3}\left(\frac{\Omega_{\mathrm{m},0}\mathrm{h}^2}{0.1371}\right)^{-1/3} \simeq 1.5 m_{s,\mathrm{SF}}$$

- **Applying these transformations, we find:**

**2.9 < m/keV < 16.9 (Dodelson-Widrow) X (Watson et al. 2012)**

**1.9 < m/keV < 11.2 (Shi-Fuller) Bulbul et al. (2014) OK**

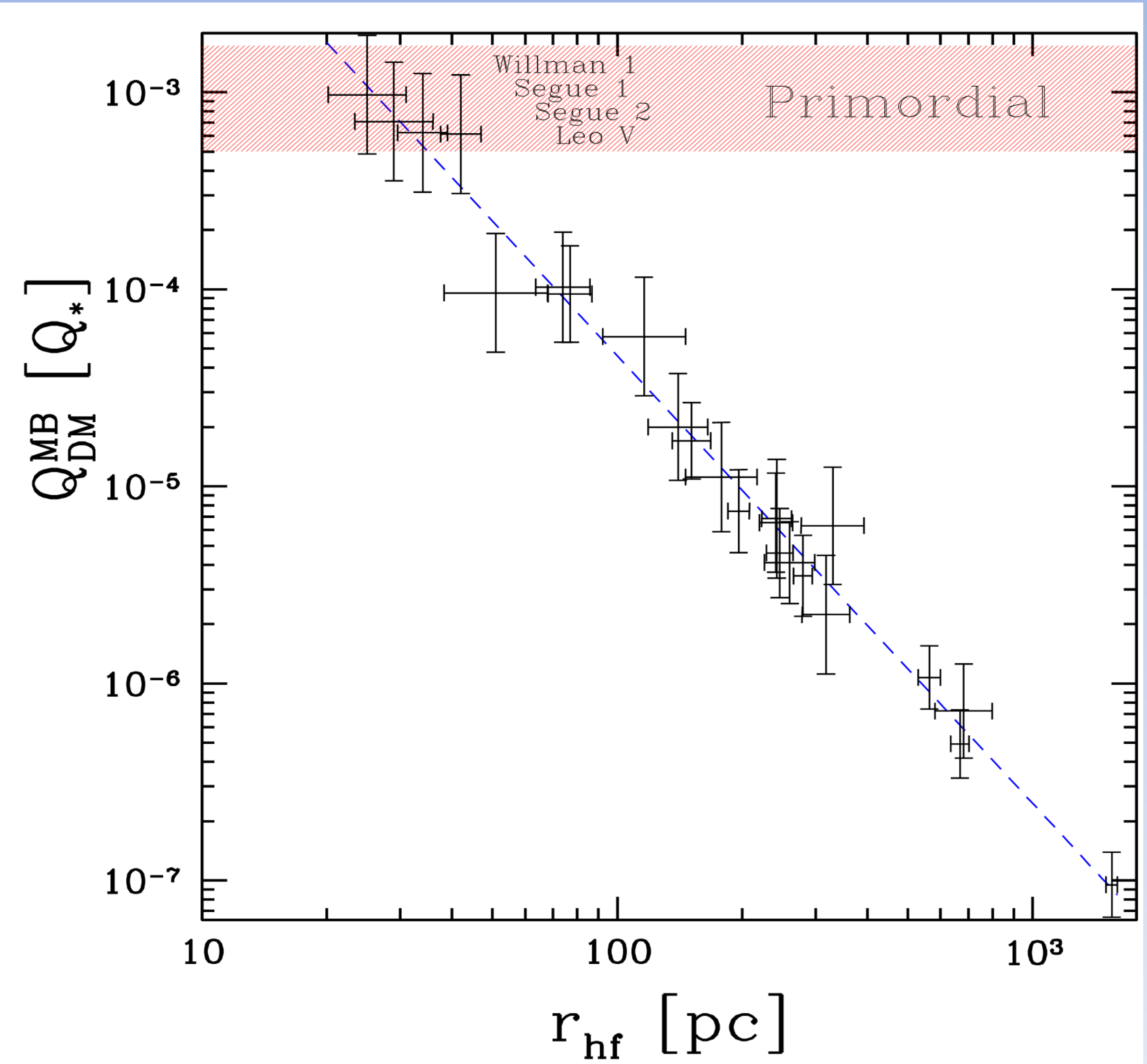
- **Alternative transformations (deVega & Sanchez 2013):**

$$m_\nu^{\mathrm{DW}} = 2.85\mathrm{keV}\left(\frac{m_{\mathrm{th}}}{\mathrm{keV}}\right)^{4/3};\, m_\nu^{\mathrm{SF}} \cong 2.55 m_{th}$$

**1.9 < m/keV < 11.3 (Dodelson-Widrow) X (Horiuchi et al. 2014)**

**1.9 < m/keV < 7.2 (Shi-Fuller) Bulbul et al. (2014) OK**

# Identification of Primordial Objects



# Implications for Galaxy Formation/Evolution

- If the 4 “primordial” dSphs have evolved undisturbed, their current densities should match virial values:

$$\rho_{\rm obs} = 358\rho_{\rm b,vir} = 358\rho_{M,0}(1+z_{\rm coll})^3$$

- Using $\rho_{obs} = \rho(r_{hf})$,
- $34 < z_{coll} < 78$ (25 Myrs – 85 Myrs)
- Nice agreement with early formation epoch of first stars in sterile neutrino cosmological models, e.g., Biermann and Kusenko (2006).

# The Universal dSph DM Halo and the Free-Streaming Scale

- **Observed properties of MW dSphs suggest that they formed from a consistent DM Halo (Wolf et al. 2013):**

$$M^{\rm Univ}_{\rm MW\ Sat} = (3.0 \pm 0.5) \times 10^9 M_\odot$$

- **Does this universality suggest a special scale, perhaps the free-streaming mass scale?**

$$M_{fs} = 4/3\pi\rho_{0,m}\left(\frac{\lambda_{fs}}{2}\right)^3 = 6.4 \times 10^{10} M_\odot \left(\frac{m_{\rm th}}{\rm keV}\right)^{-4}$$

- **Taking** $M^{\rm Univ}_{\rm MW\ Sat} = M_{fs}$ **yields**

$$m_{\rm th} = 2.15 \pm 0.1\ {\rm keV}$$

# Summary II

- Using data from Walker et. al. (2009), we found a strong correlation between Q and $r_{hf}$ for Milky Way dwarf satellite galaxies.
- Determing the primordial radial scale $r_p$, we established $Q_P$ and limits on the DM particle mass:
  - $0.74 < m_{th}/\text{keV} < 2.8$ (mean 1.55 keV)
  - DW ruled out, Shi-Fuller $1.9 < m_{SF}/\text{keV} < 11.2$
- Comparing to $Q_P$, we see 4 primordial MW dSphs: Leo V, Segue 1, Segue 2, and Willman 1.
- Implied Virialization Epochs for primordial dSphs $34 < z_{coll} < 78$ (25 Myrs – 85 Myrs)
- Interpretting Univ. dSph DM Halo as $M_{fs}$ implies $m_{th} = 2.15 \pm 0.1$ keV

# Conclusions

**DW excluded via M31 X-ray constraints and phase space density constraints from MW dSphs.**

**(Watson et al. 2012, Horiuchi, et al. 2014, This Work)**

**A 7.14 keV Shi-Fuller sterile neutrino with $L_4 = 7$:**

- **Accounts for X-ray line anomaly found by Bulbul et al.**
- **Satisfies all galaxy constraints like $m_{th} \gtrsim 2$ keV**
- **Avoids exclusion by Andromeda X-ray Constraints**

**(Abazajian, et al. 2014)**

- **Consistent with Phase Space Density Constraints on MW dSphs**
- **Consistent with Free-Streaming Mass Scale implied by MW dSphs**

**(Horiuchi et al. 2014 + This Work)**