Using X-ray Observations to Constrain Sterile Neutrino Warm Dark Matter

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Chris Purcell (Pittsburgh)
and
Hector J. de Vega & Norma Sanchez
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 Road to Improved Constraints**
  - **Issues with Current-Generation Detectors**
  - **Expectations for Next-Generation Detectors**
  - **Targets of Opportunity while we wait**
- **Summary & Conclusion**

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 could 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

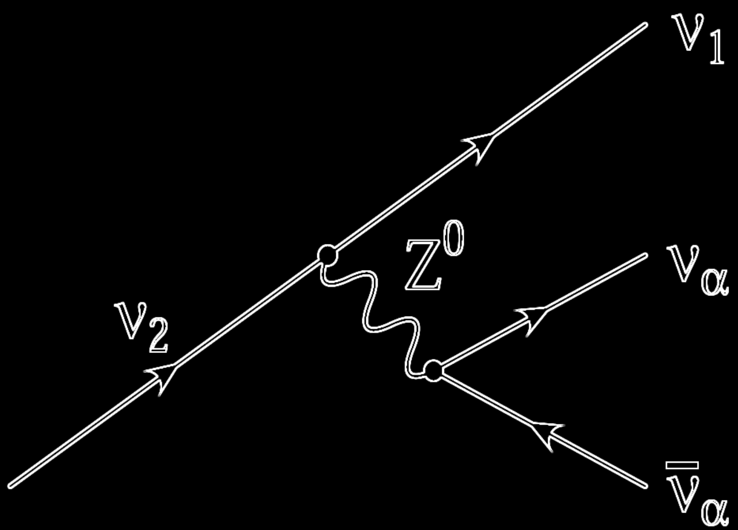
mass $|\nu_{1,2}>$ & flavor $|\nu_{\alpha,s}>$ states:

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

For $m_s < m_e$,

3ν Decay Mode Dominates:

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



Radiative Decay Rate is:

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

The Sterile Neutrino Radiative Decay Signal:

- Radiative Decay Luminosity:

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

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

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

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

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

Sterile Neutrino Production:

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

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

(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

$$\mathbf{1\ keV \lesssim m_s \lesssim 10\ keV}$$

To maximize the sterile neutrino decay signal:

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

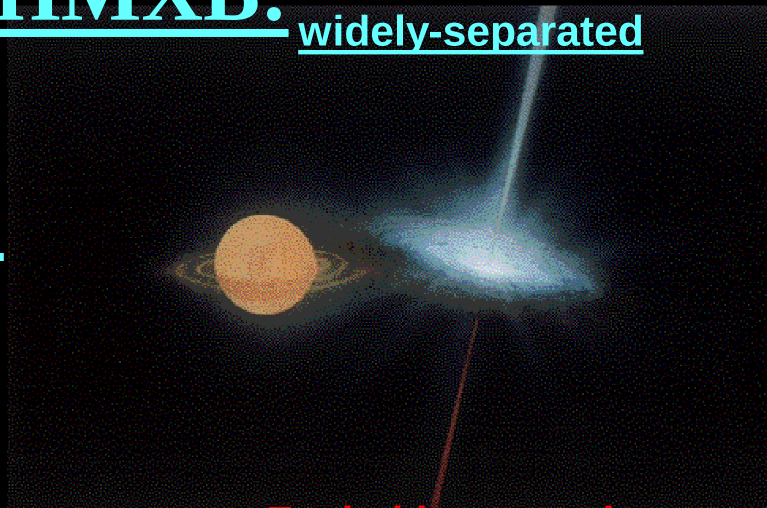
the ideal object to study is:

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

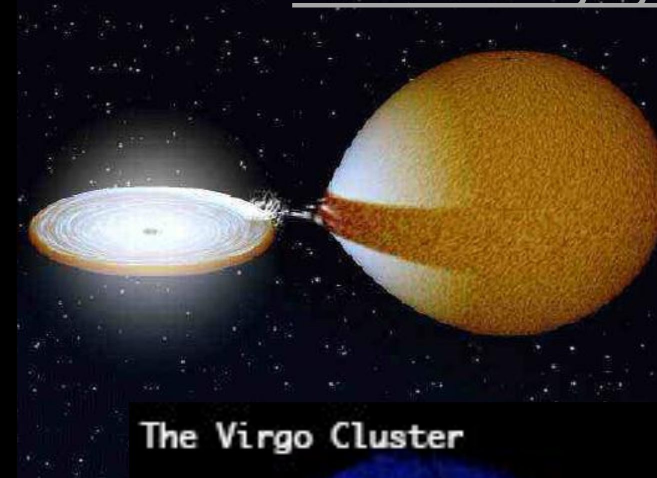
Astrophysical X-ray Sources:

Stellar Sources:

HMXB:
Fueled by stellar wind; widely-separated



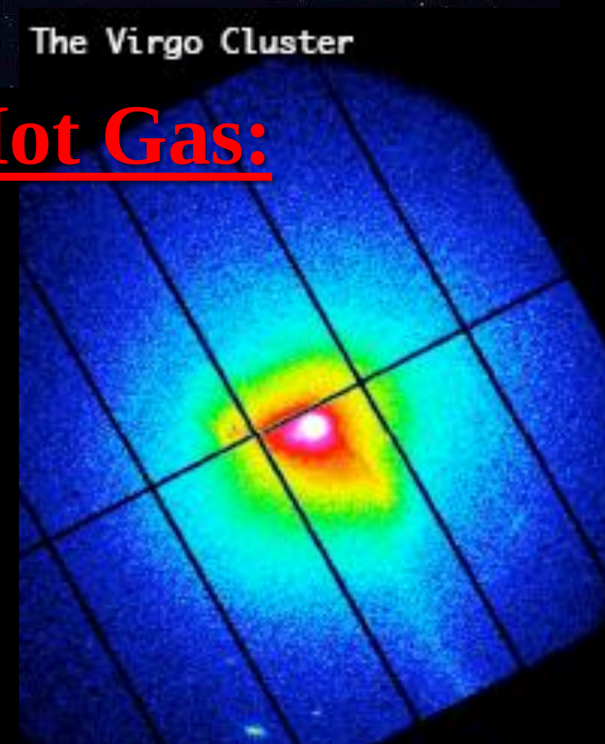
LMXB:
Roche Lobe accretion; Contact Binary systems



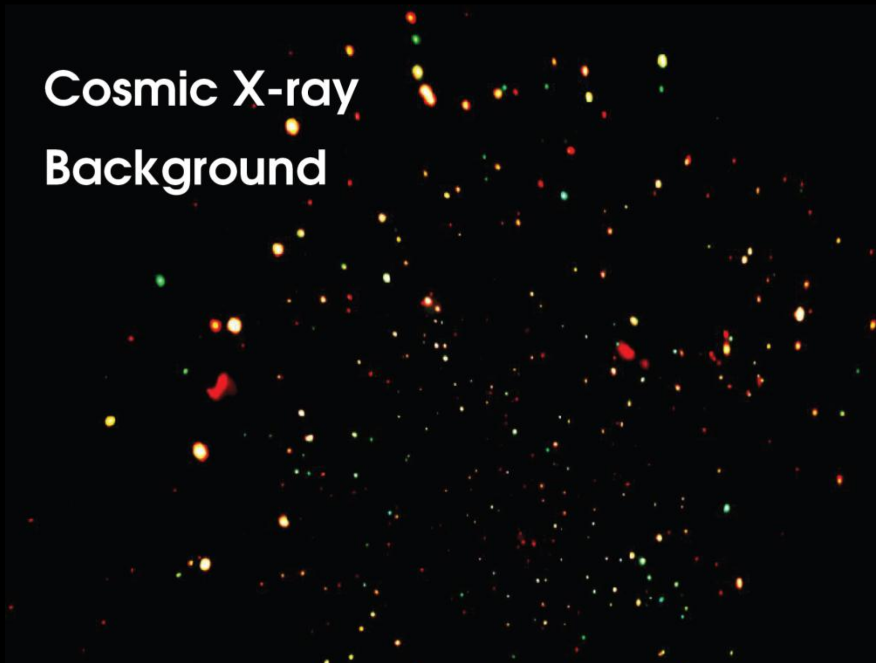
Nuclear & Diffuse Sources:

AGN:
Fueled by accretion onto Supermassive BHs

Hot Gas:

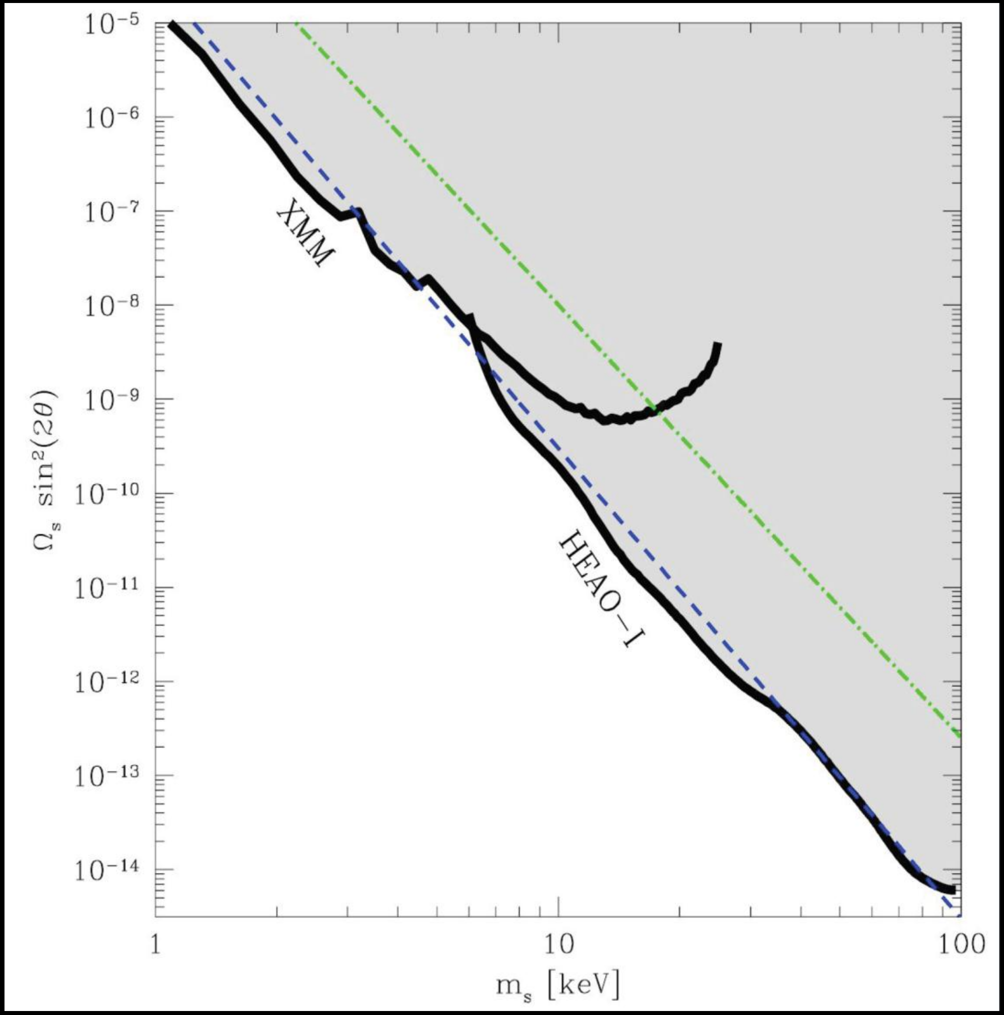


Previous work I: Cosmic X-ray Background



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

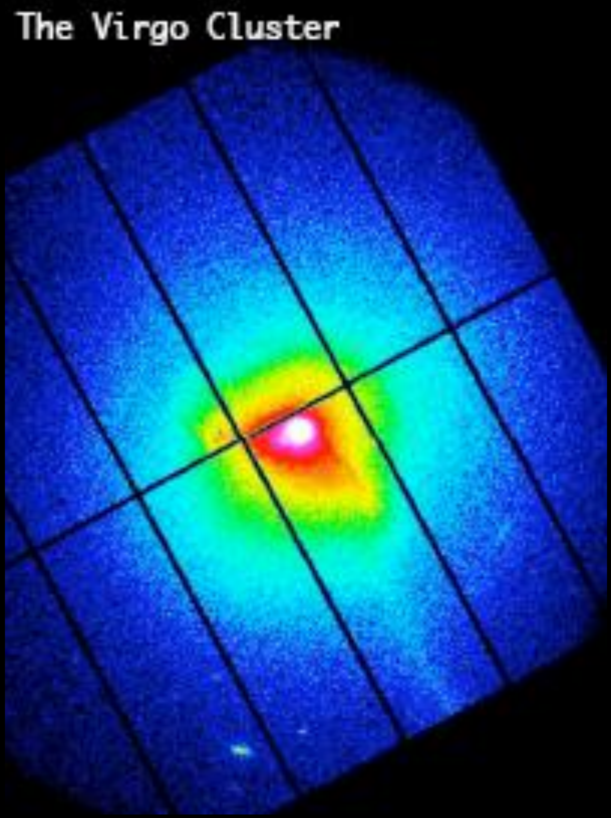
Rekindled interest in m_s X-ray constraints [6].

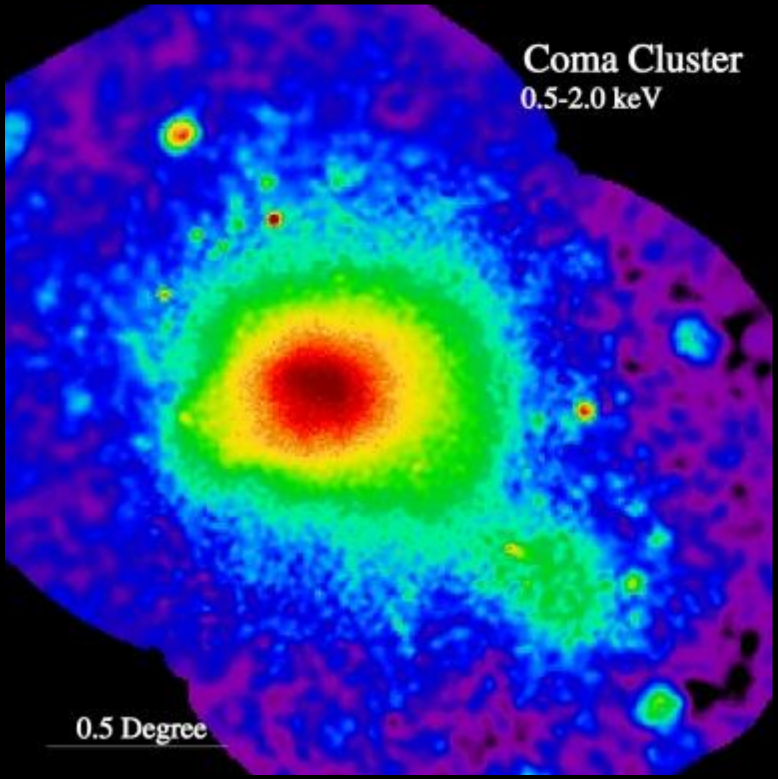


Constraints: m_s < 9.3 keV

(for DW Model ν_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 ν_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

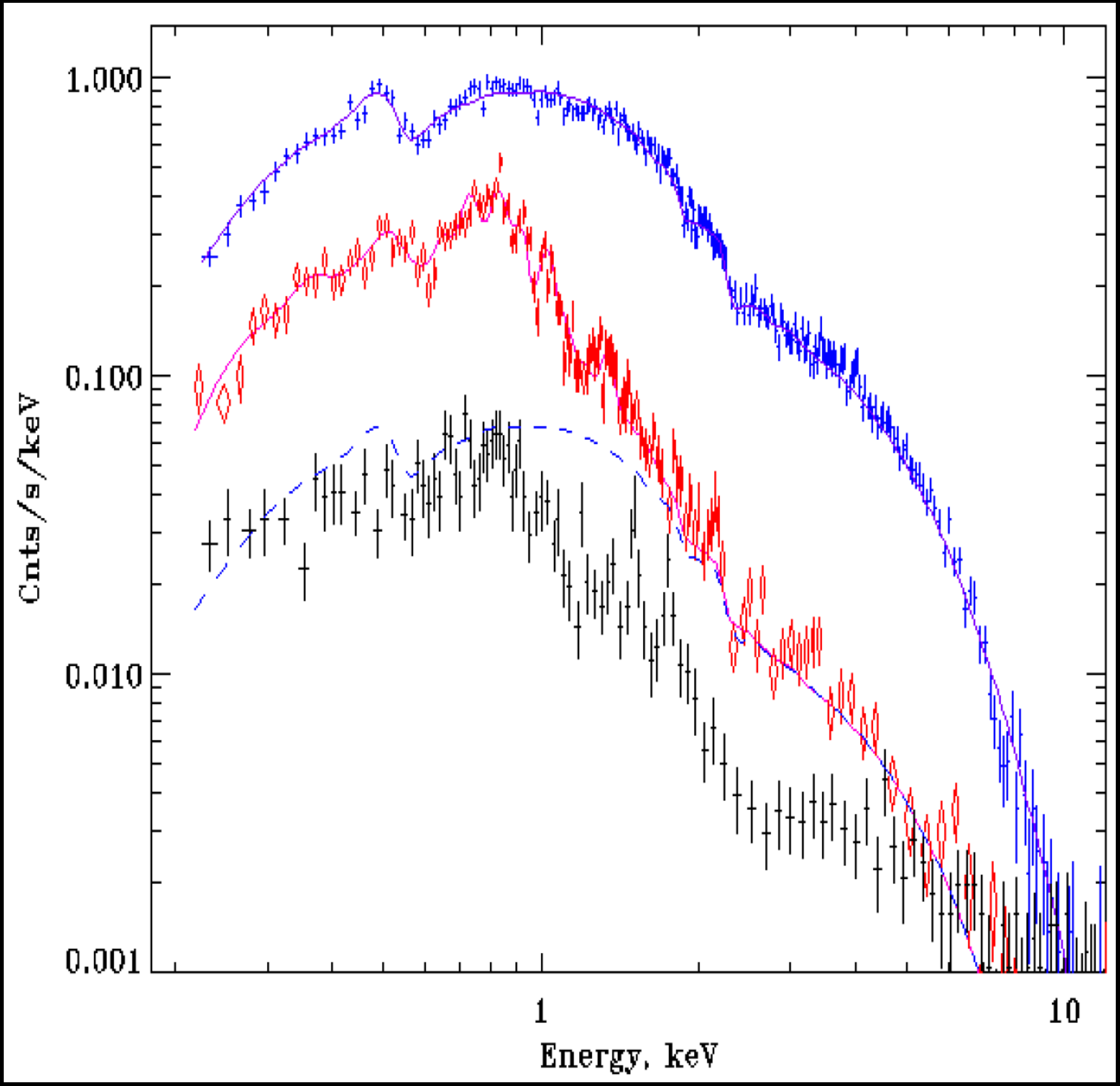
Comparable to Massive Clusters without the background

Exceeding Ultra Nearby Dwarf Galaxies

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

Unresolved 5' *XMM* Spectrum of Andromeda

(from Shirey et al. 2001 [96])



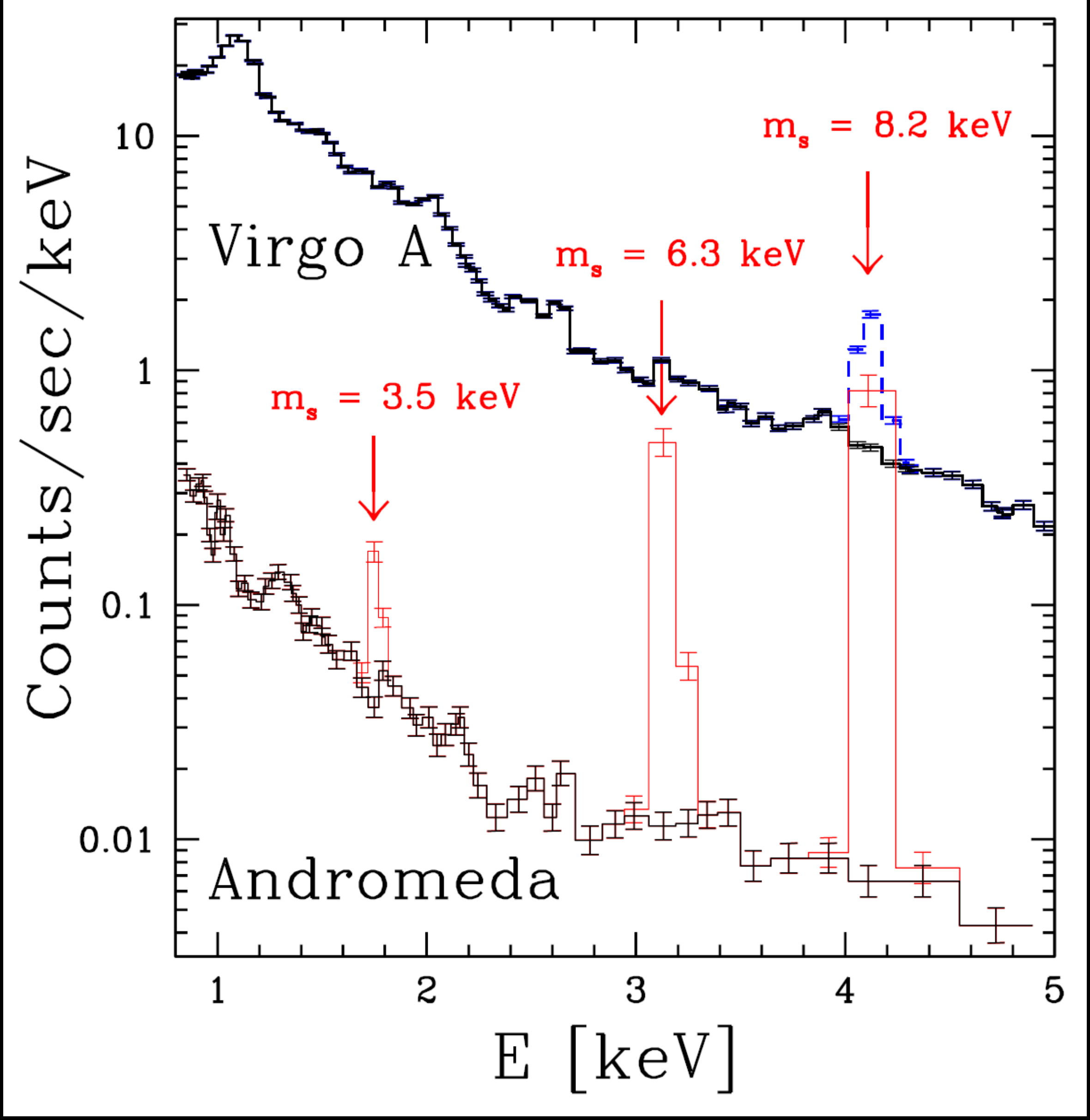
REDUCED Astrophysical Background:

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]

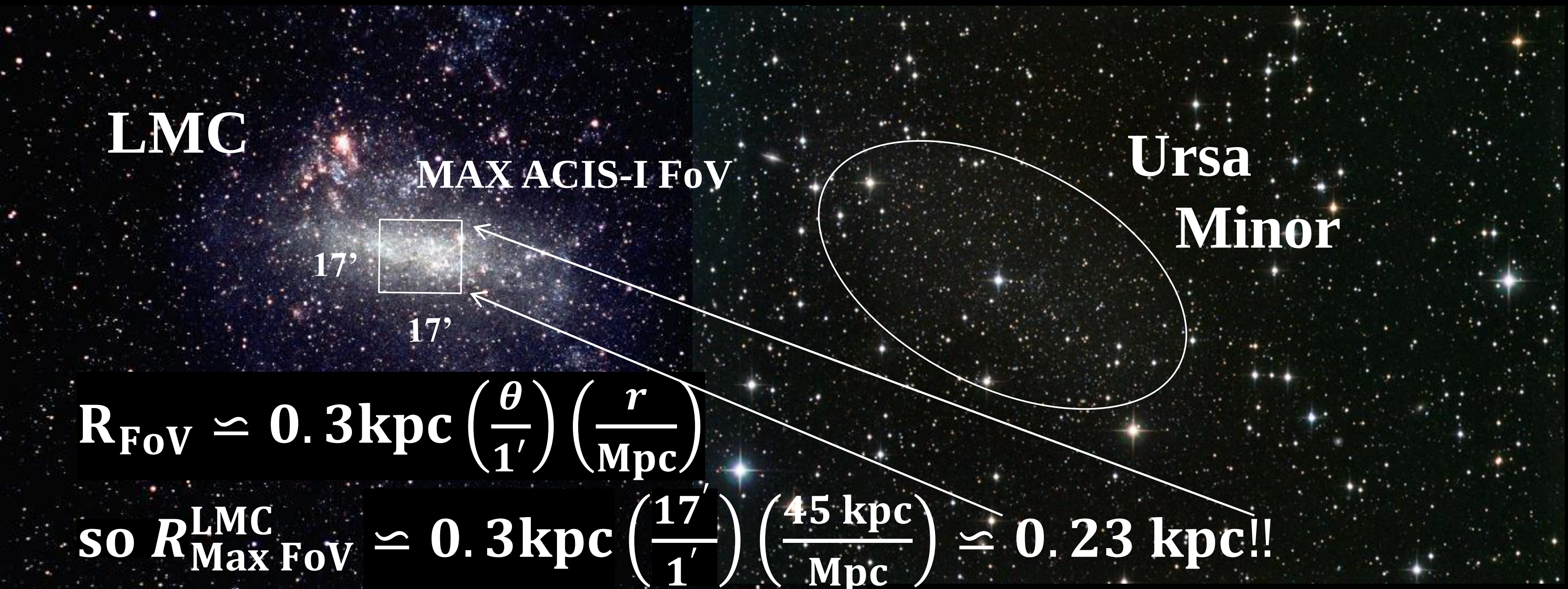
Virgo A+Coma:

$m_s < 6.3$ 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



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

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

Advantages: Small D; Low background

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

Constraints (for DW Model ν_s [3, 43]):

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

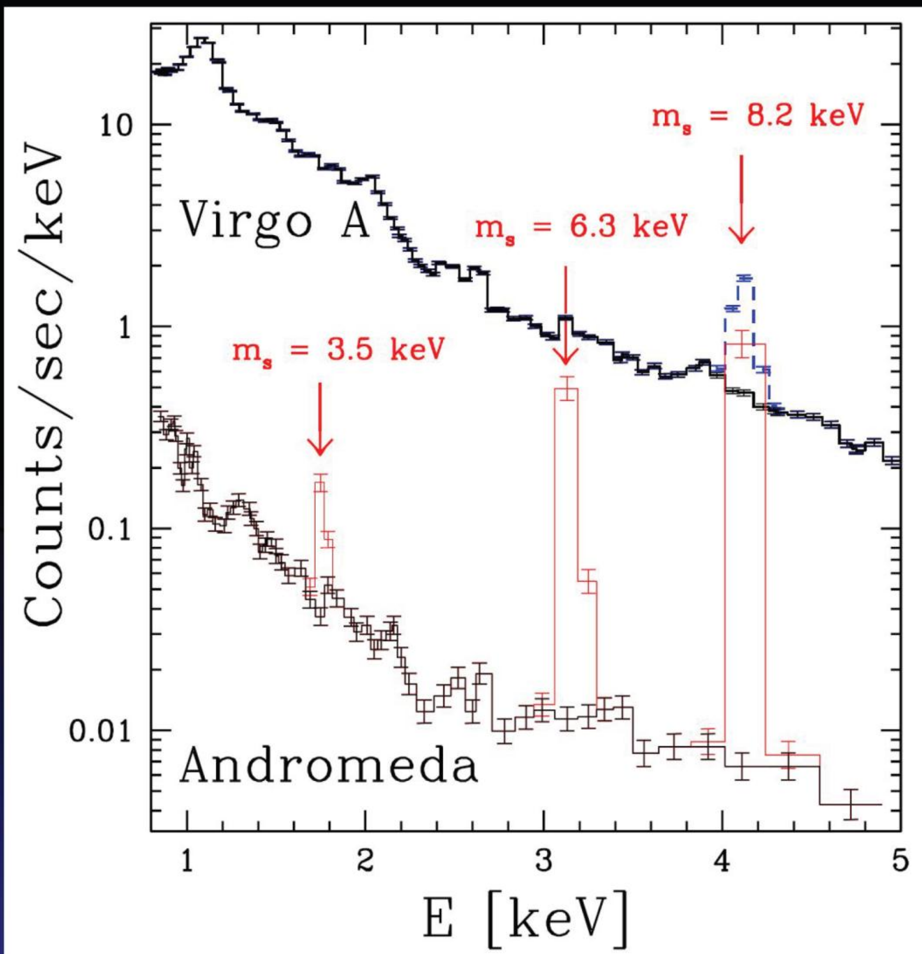
** VERY WEAK EXCLUSION CRITERION

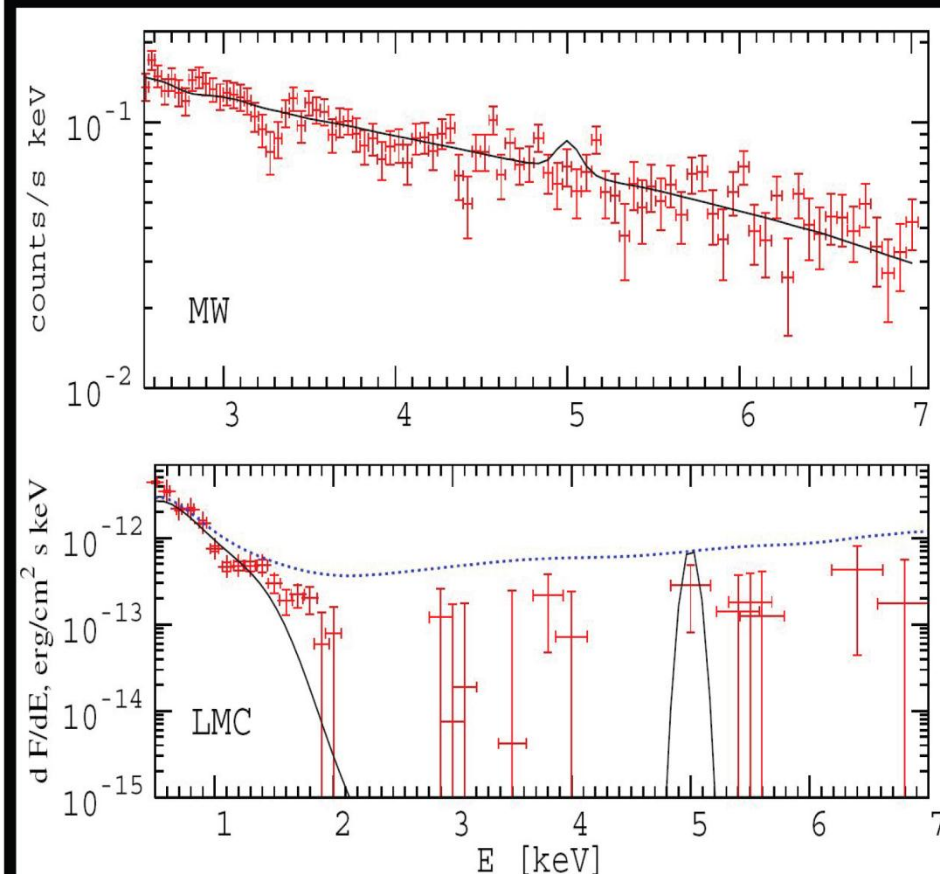
Andromeda (*XMM*) vs. Dwarf/MW Constraints

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

(Watson, Beacom, Yüksel, Walker 2006)

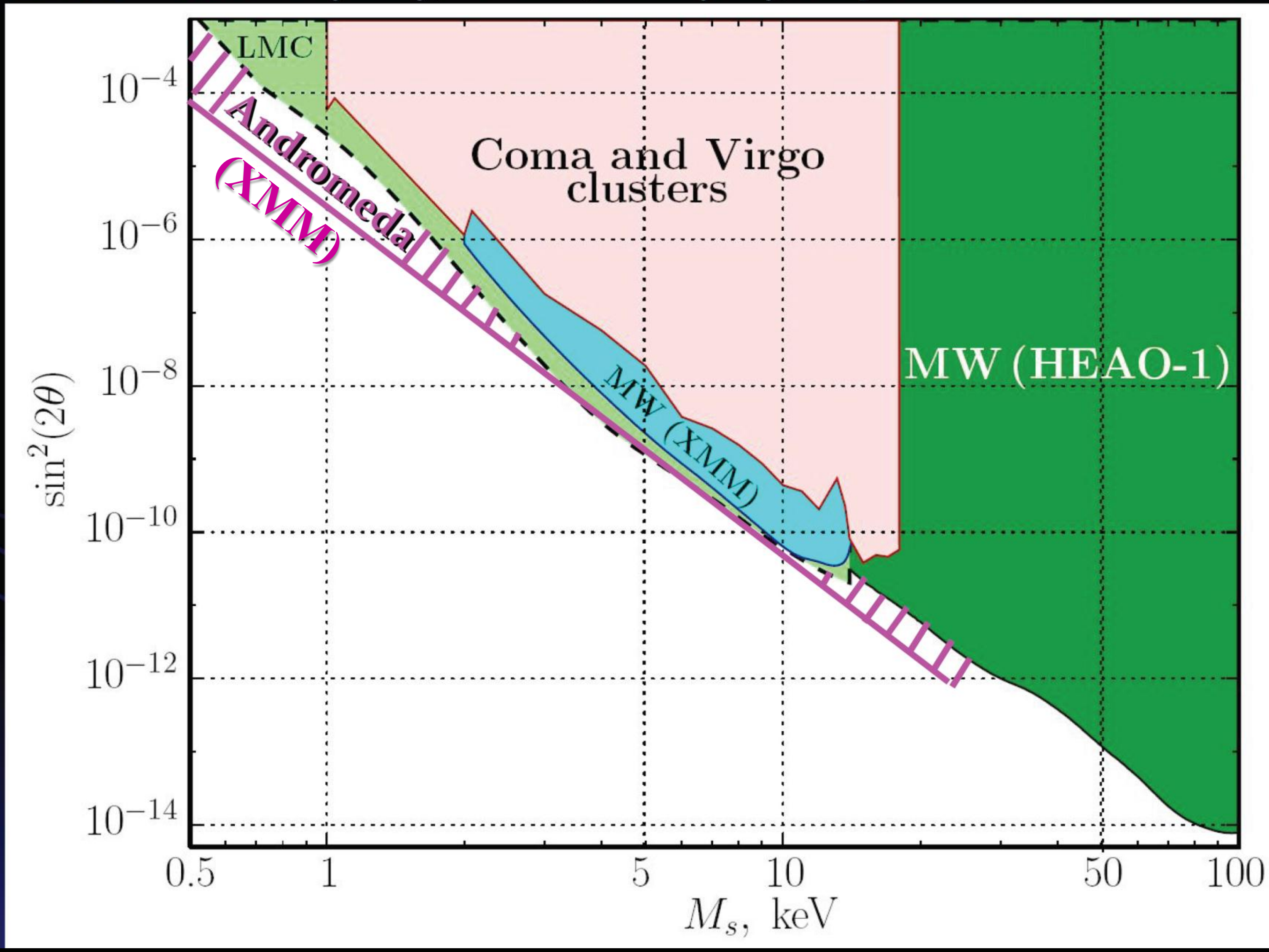
(Boyarsky, Neronov, Ruchayskiy, Shaposhnikov, Tkachev 2006)





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

Andromeda (Watson, Beacom, Yüksel, Walker 2006) vs.
LMC + MW (Boyarsky, Neronov, Ruchayskiy, Shaposhnikov, Tkachev 2006)

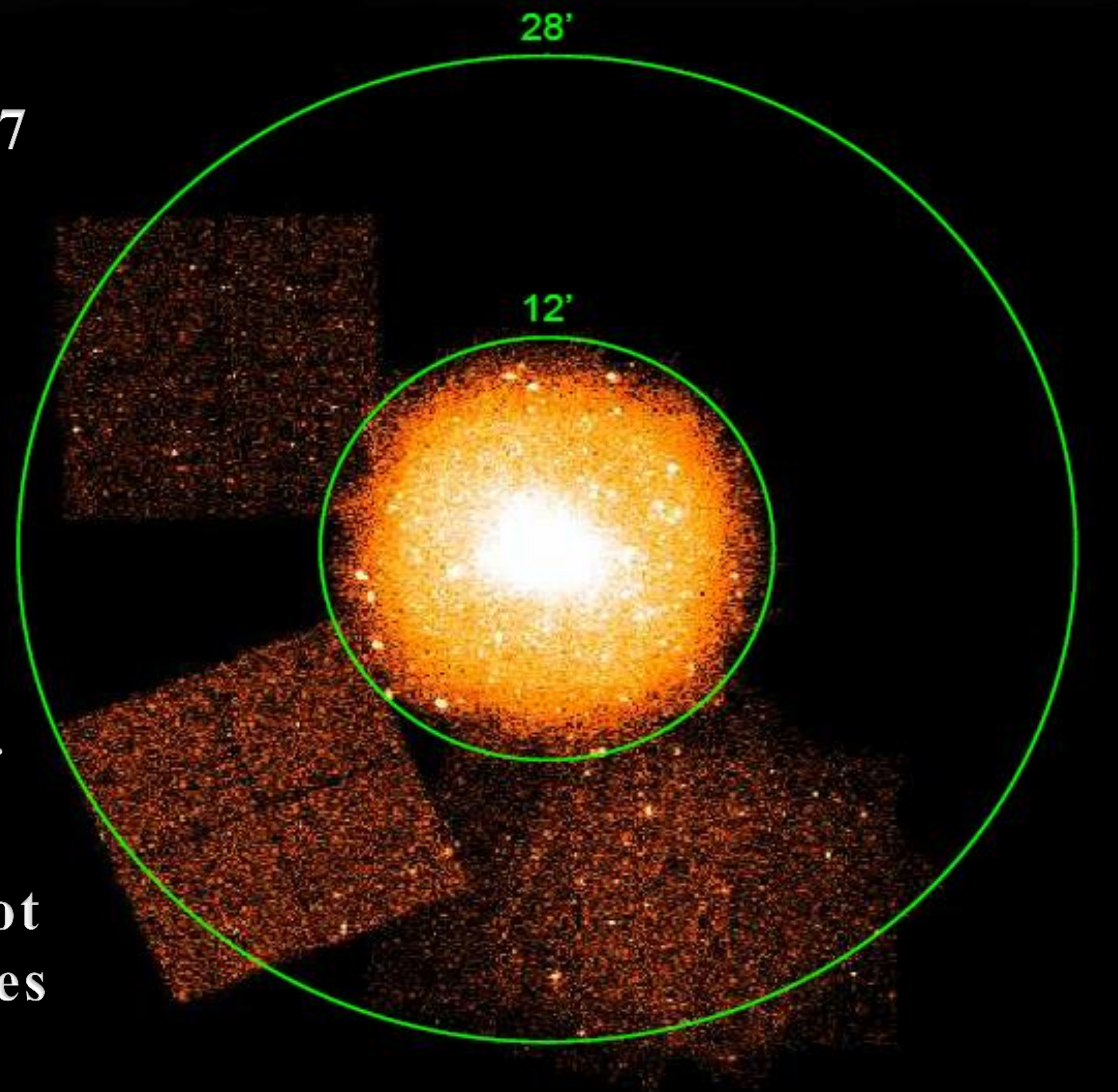


Chandra FOV of M31: $\Delta\theta$ = 12’ – 28’

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

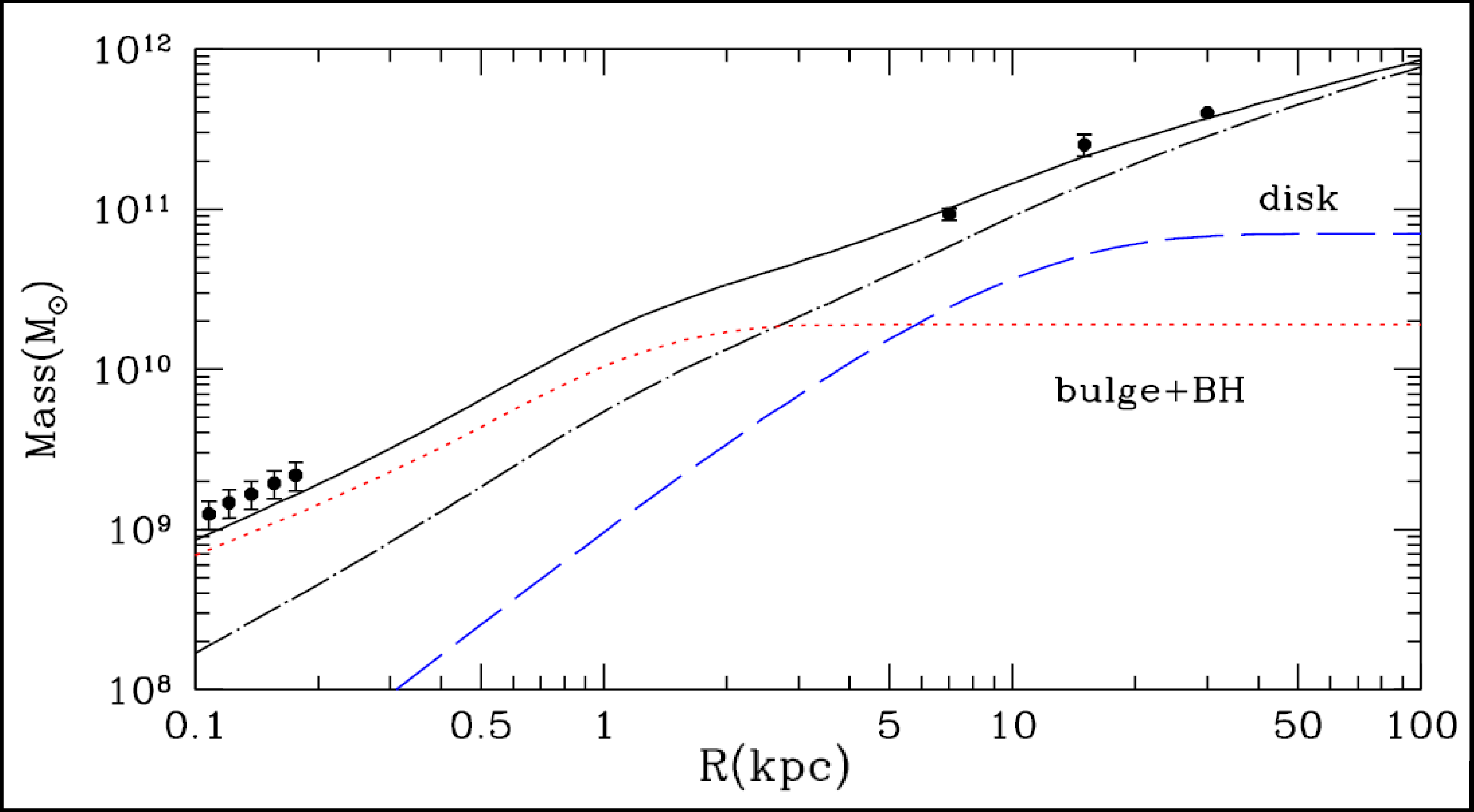
- Exposure times range from 5ks to 20ks

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



Andromeda's

Well-measured Matter Distribution:

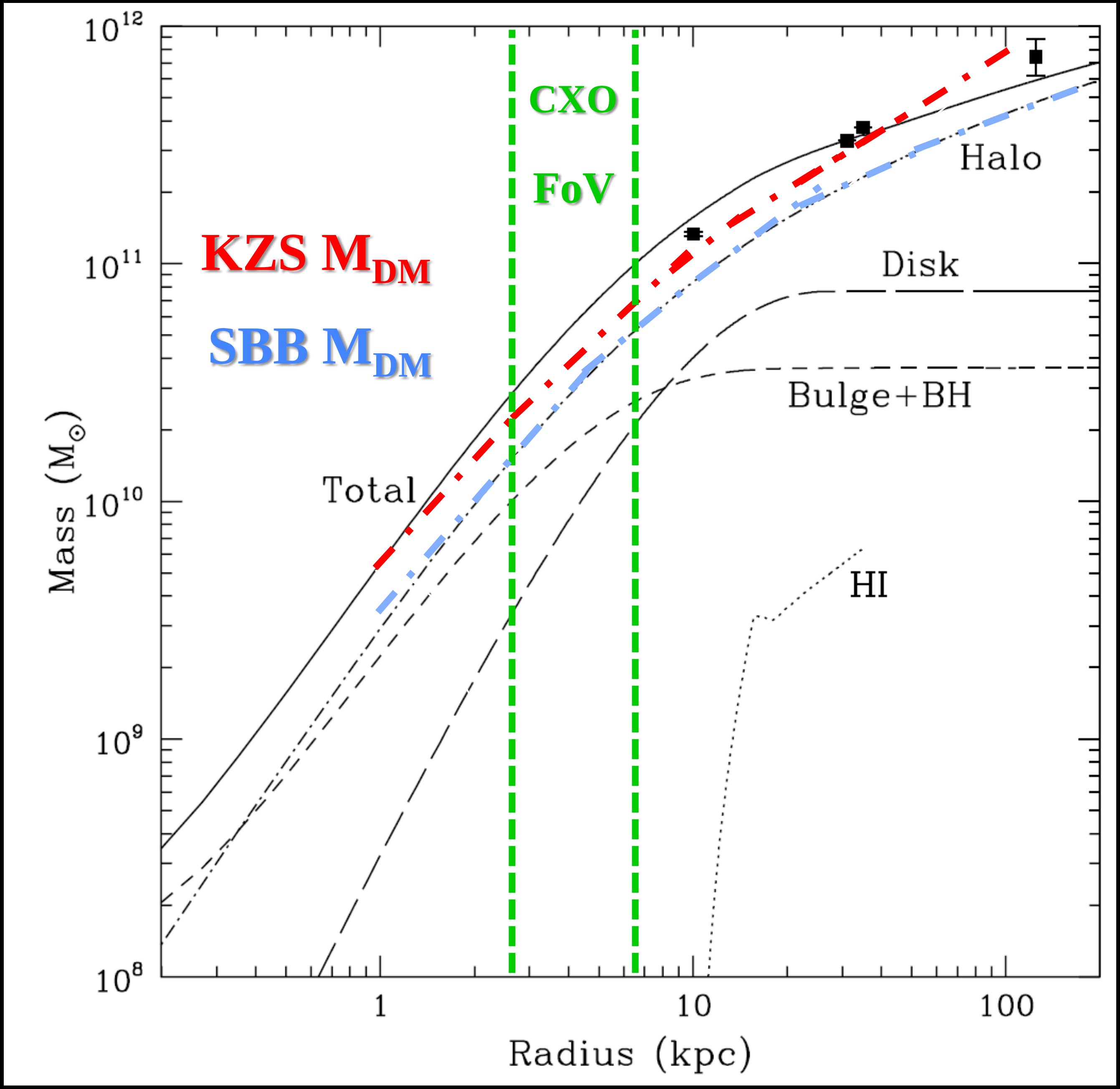


Constraints at small radii are from Stellar Motions in the Nucleus.
Three points at R>5 kpc characterize the spread in v_{rot} = 255 ± 15 km/s.

(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}

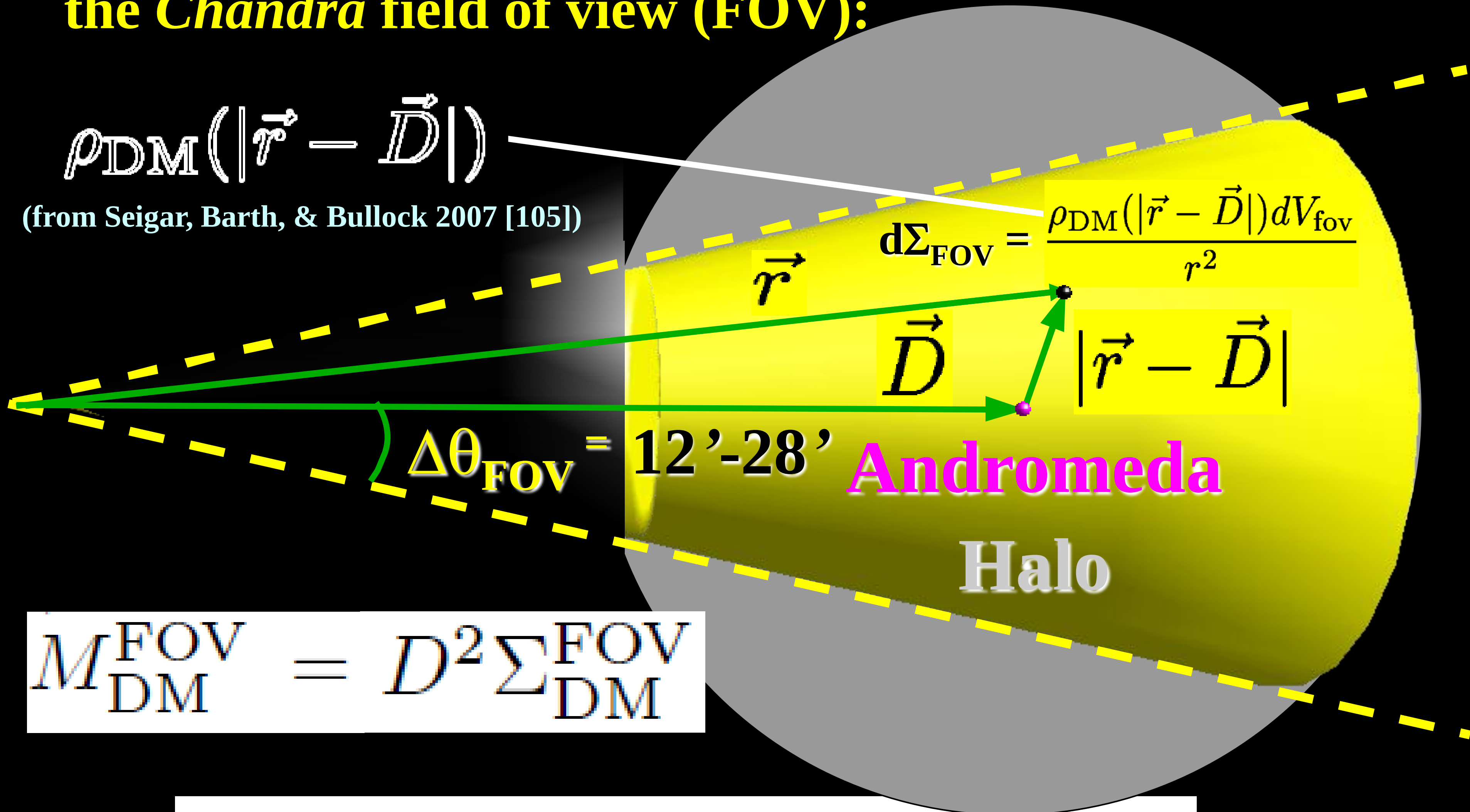
[67, 106]

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):



$$M^{\rm FOV}_{\rm DM} = D^2 \Sigma^{\rm FOV}_{\rm DM}$$

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

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

Conversion of Decay Signal to Detector Units:

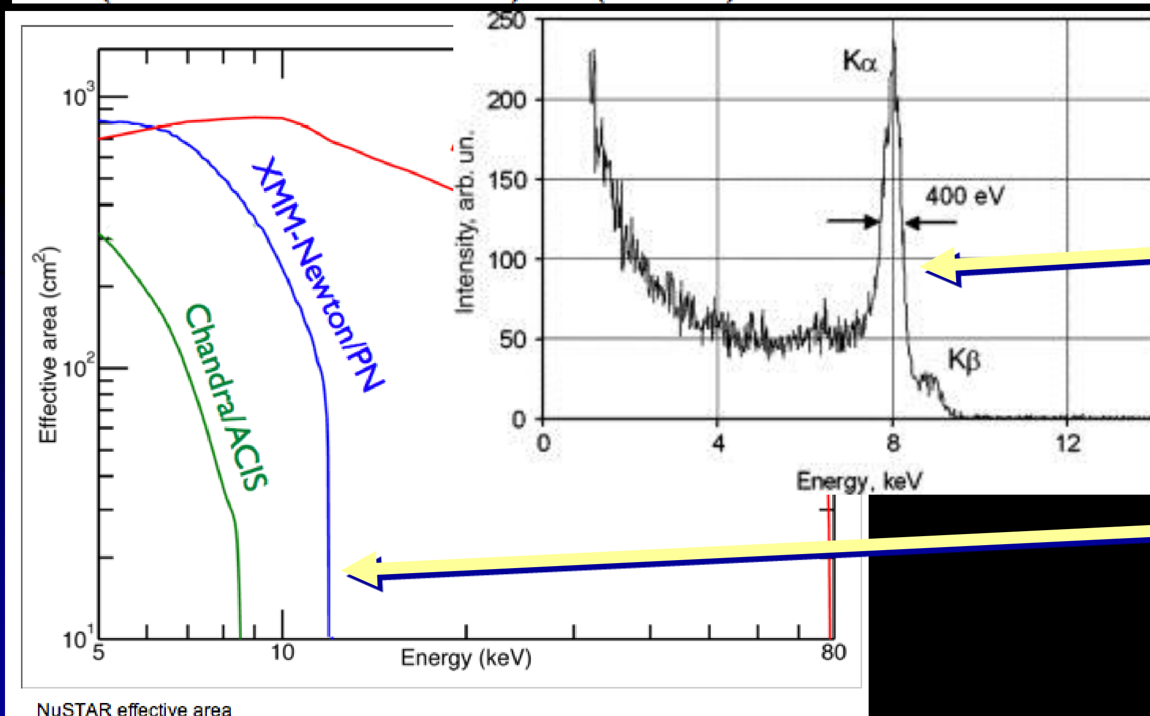
$$\frac{dN_{\gamma,\mathrm{s}}}{dE_{\gamma,\mathrm{s}}dt}(\Omega_\mathrm{s}) = \left(\frac{\Phi_{\mathrm{x,s}}(\Omega_\mathrm{s})}{E_{\gamma,\mathrm{s}}}\right)\left(\frac{A_\mathrm{eff}(E_{\gamma,\mathrm{s}})}{\Delta E}\right)$$

$$= 6.7\times10^{-2}\ \mathrm{Counts/sec/keV}\left(\frac{\mathrm{A_{eff}(E_{\gamma,s})}}{100\ \mathrm{cm}^2}\right)$$

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

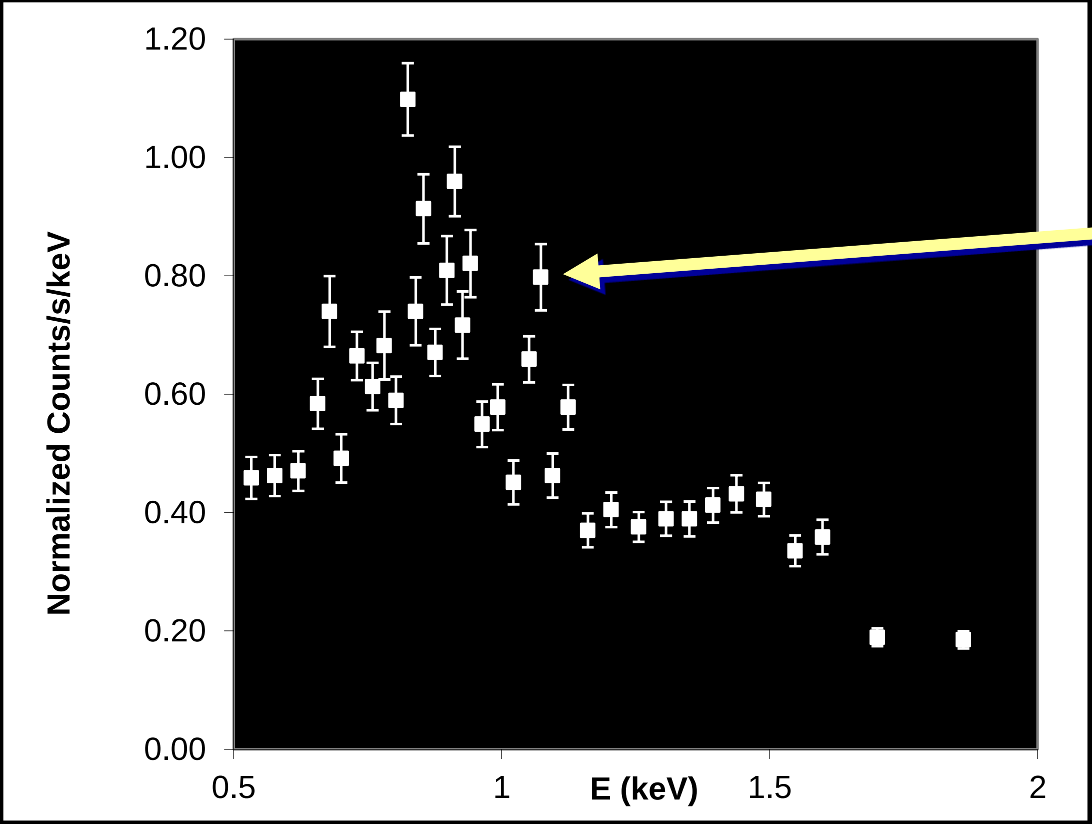
Detection of ν_s Decays at $E_{\gamma,s}$ depends on

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



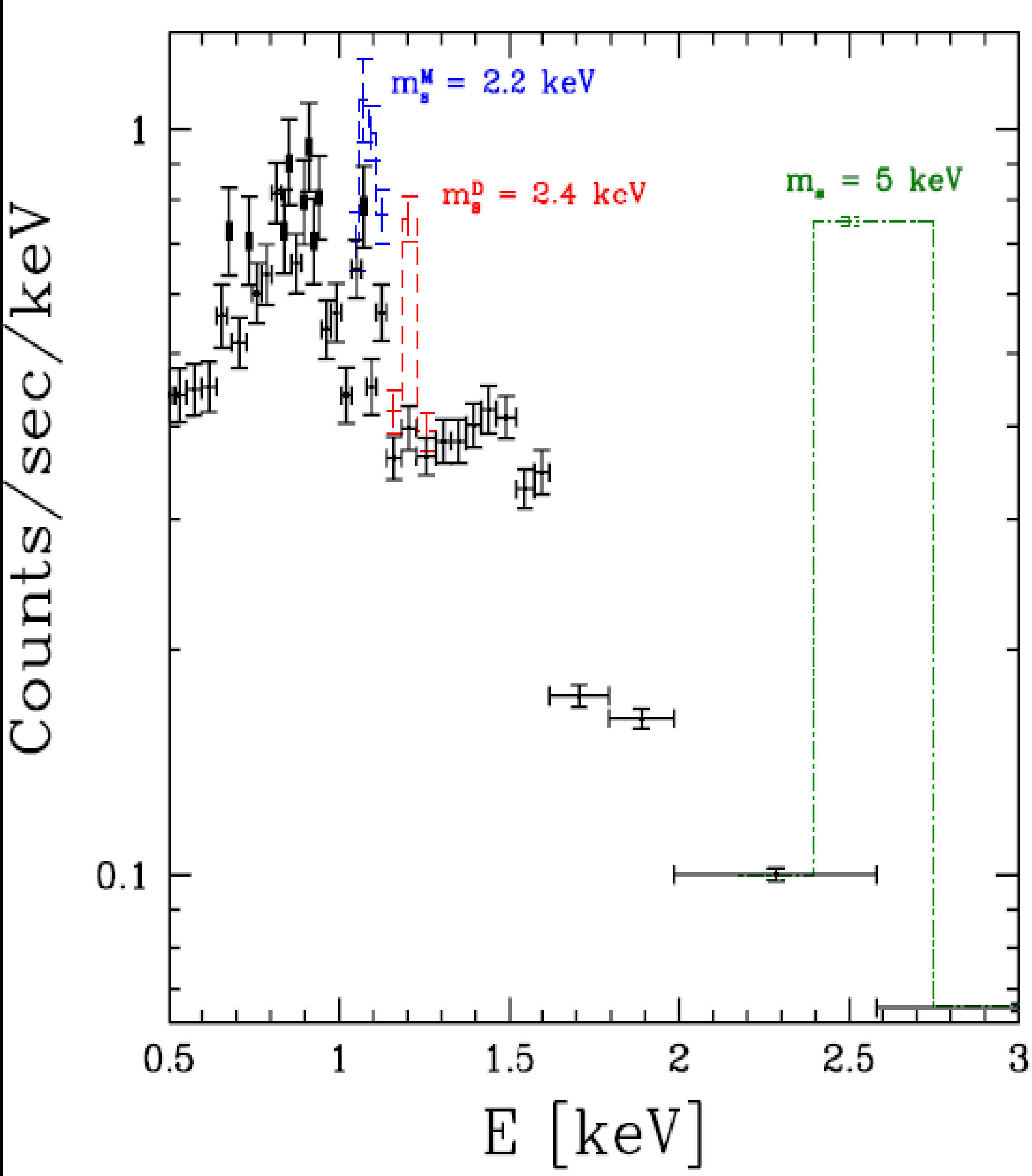
Detection/Exclusion Criterion:

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



- 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

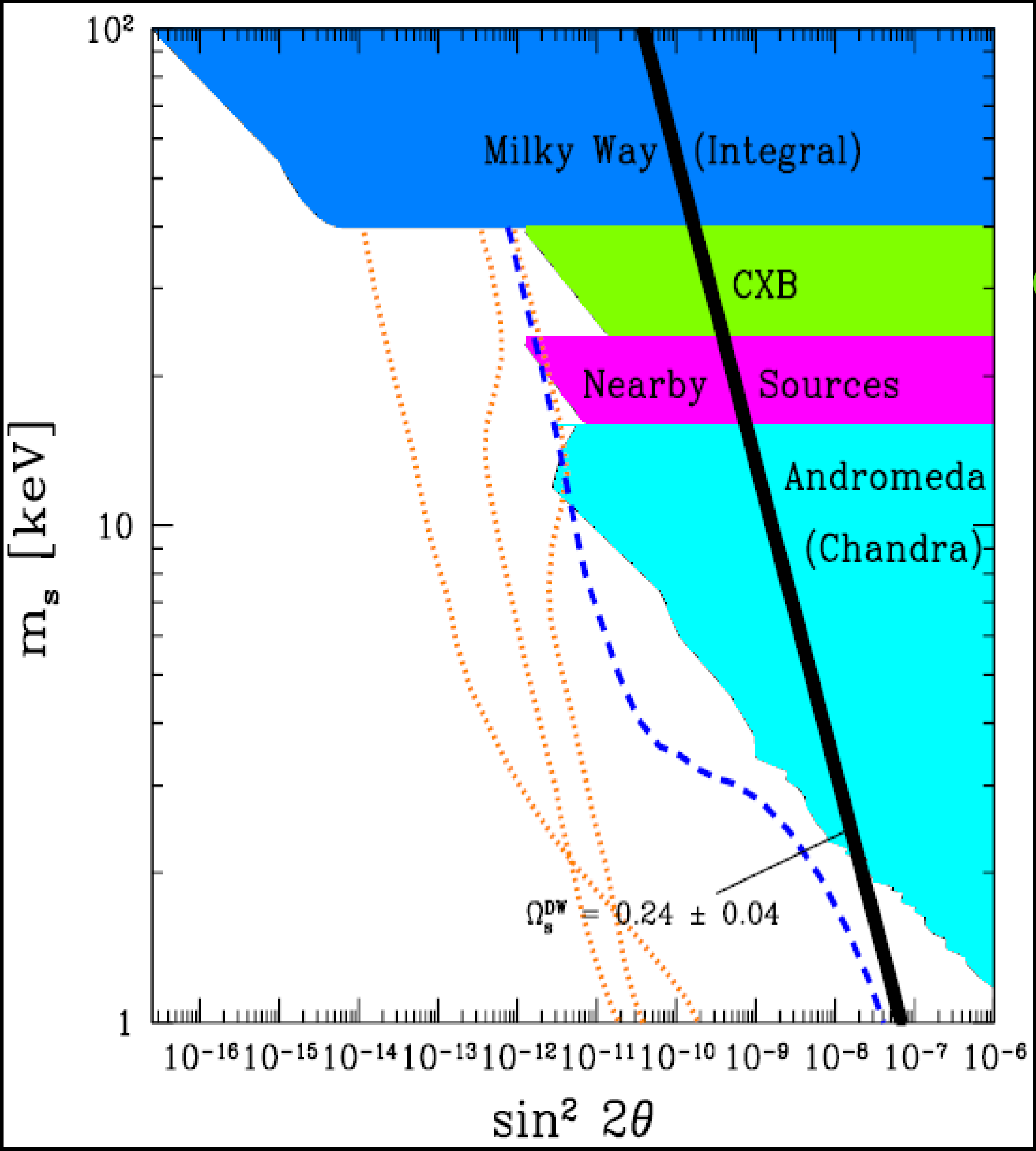
Claimed Detection:

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]

Summary I

Our *Chandra* M31 Constraint (at L=0): $m_s < 2.2$ keV

+

Tremaine-Gunn Bound: $m_s > 0.4$ keV

(Tremaine & Gunn 1979 [108])

restricts m_s to a narrow window

consistent with the range of m_s values

that best explains the core of the

Fornax Dwarf Spheroidal Galaxy.

(Strigari, et al. 2006 [109])

Higher mass ν_sWDM also remains viable if the Lepton Asymmetry is very large, i.e., $L \gg 10^{-10}$

(Abazajian & Koushiappas 2006 [13])

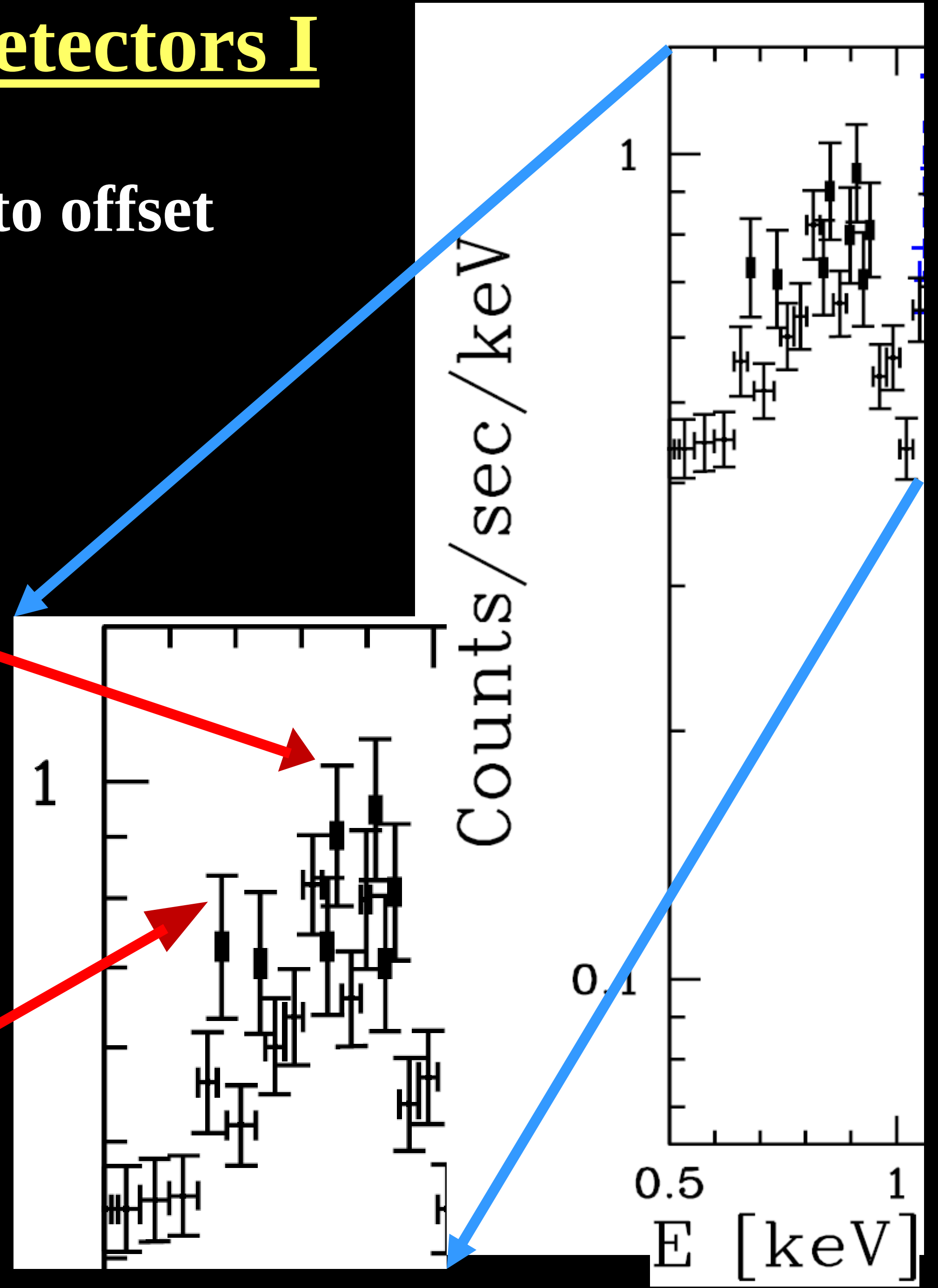
Issues with Current Detectors I

Need larger effective Area to offset diminishing decay signal

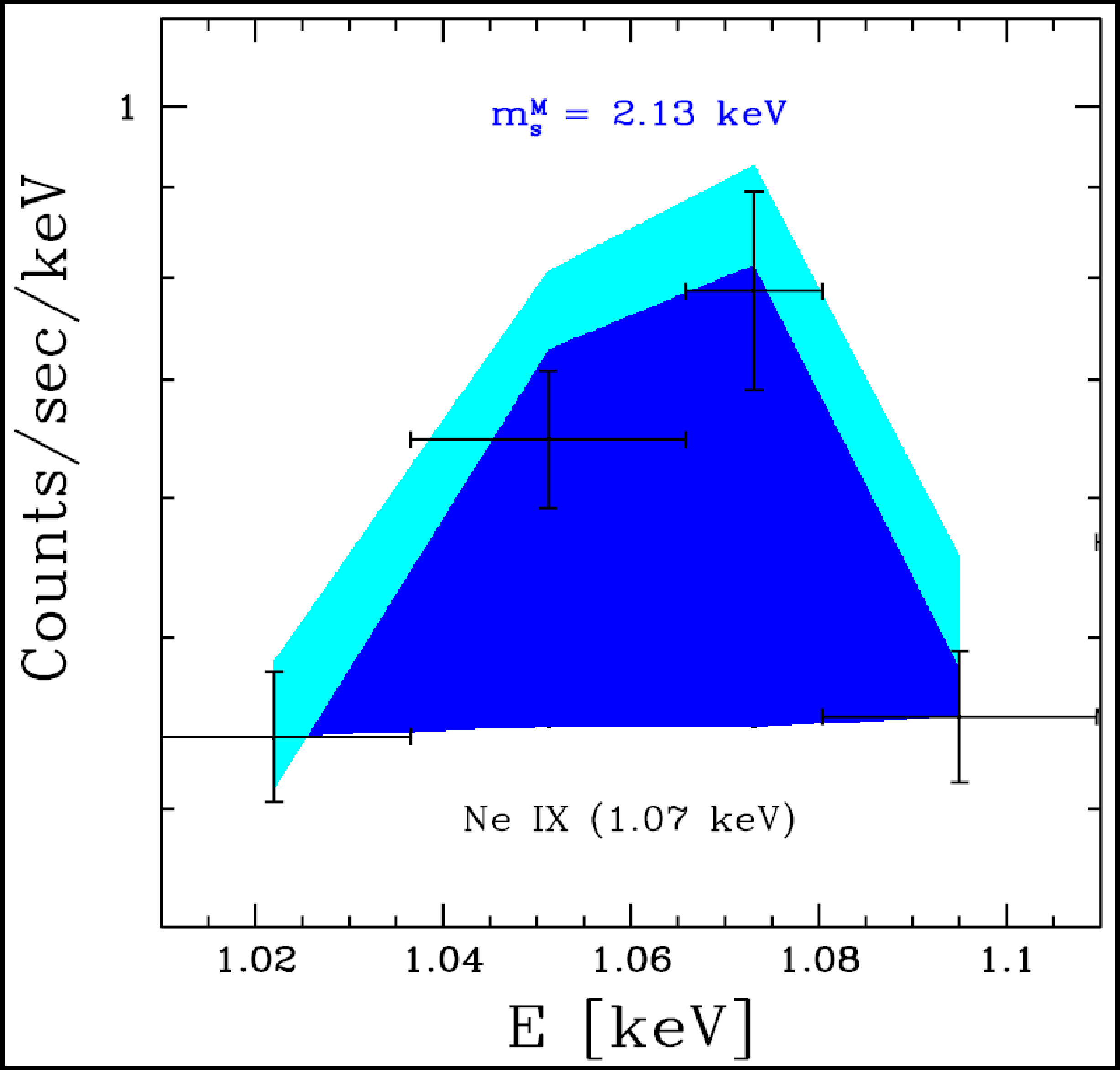
$$\frac{dN_s}{dE_\gamma dt} \propto E_\gamma^{1.374}$$

against rising backgrounds at lower Eγ.

And improved ΔE to distinguish adjacent lines.



Issues with Current Detectors II

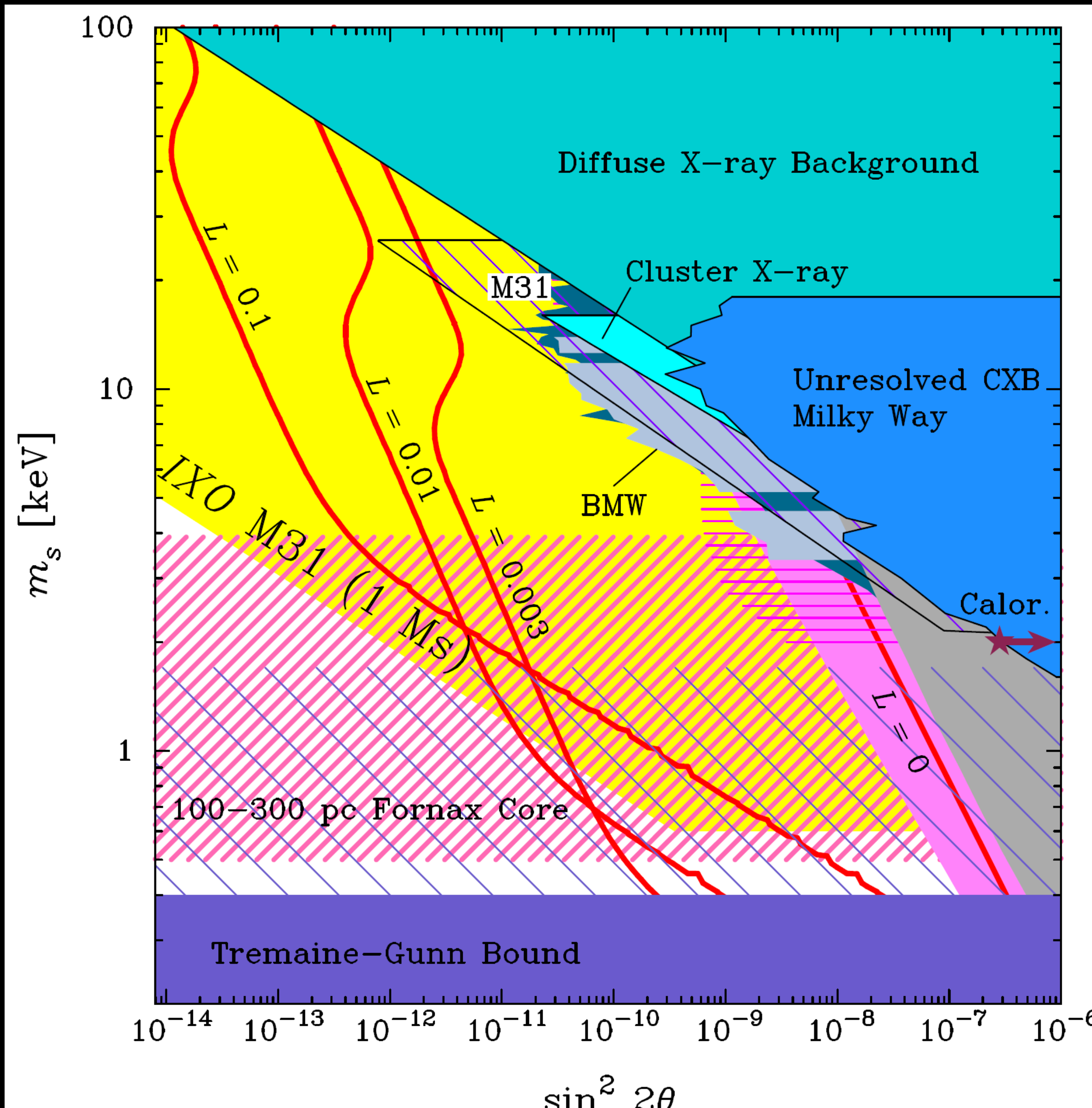


Based on Σ_{DM}^{FOV}

2.13 keV Majorana sterile neutrino decay statistically reproduces 1.07 keV Ne IX peak (Chandra Data).

Prospects for Future Constraints:

IXO Observations of Andromeda (Abazajian 2009 [111])



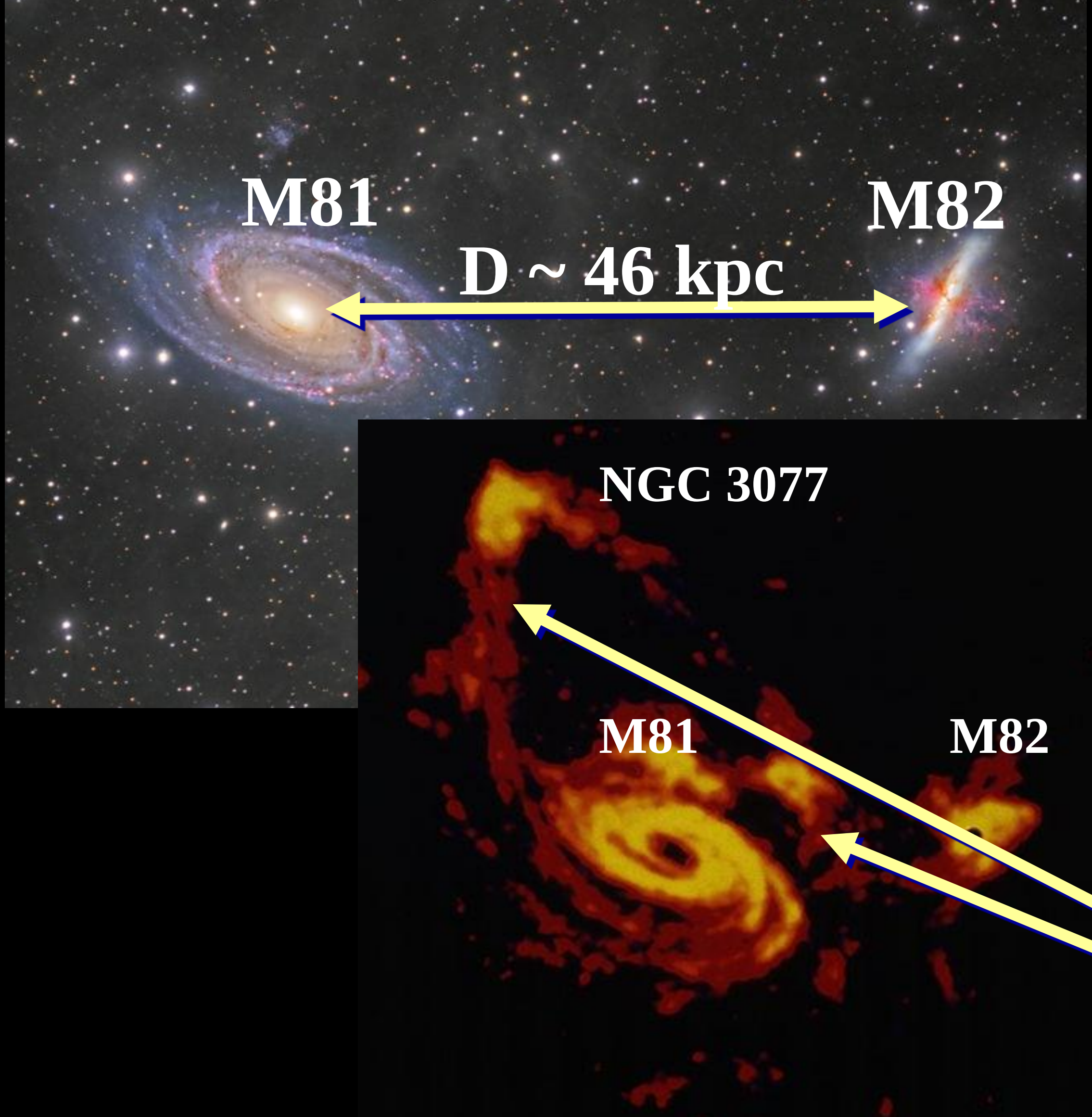
IXO vs. *Chandra*

- ~ comparable FOV
- ~ 100 X larger A_{eff}
- ~ 10 X better ΔE
- ~ 10 X lower instrumental background

~1 Ms observation of M31 can *significantly* improve sterile neutrino constraints.

Current Targets of Opportunity:

Dark Matter Filaments between Merging Galaxies

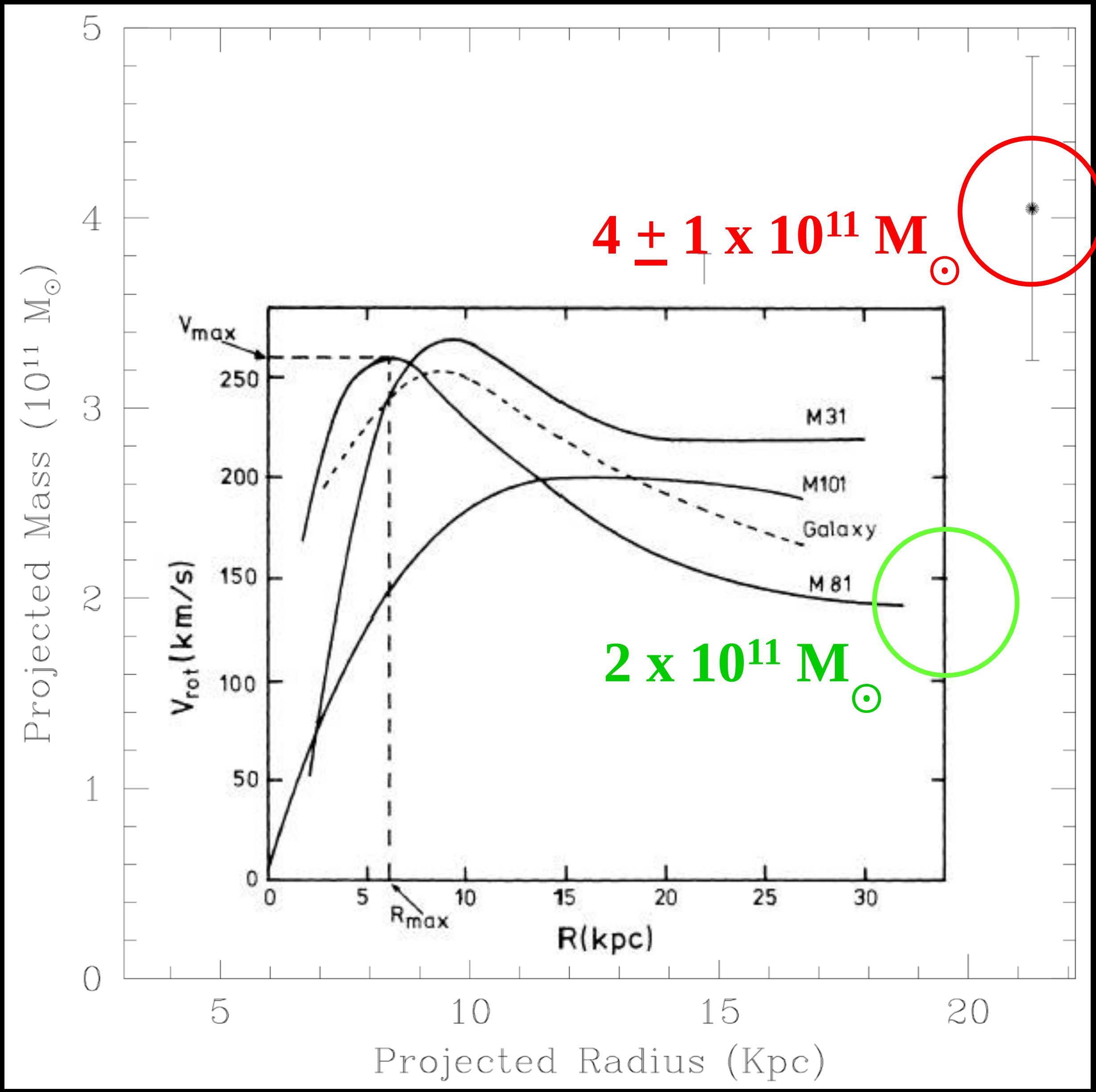


M81/M82 System

Excellent Laboratory for Examining DM Filaments

- **Nearby (3.6 Mpc)**
- **Small Separation**
- **Starburst Activity shows evidence of close pass 0.2-0.3 Gyrs**
  de Mello et al. (2007)
- **Radio Observations Reveal Extensive Network of Neutral Hydrogen Filaments**
  Chynoweth et al. (2008)

Kinematic Evidence of Tidally Stripped Mass?



M81/M82 Group Mass:

~10^{12} $M_\odot$

Karachentsev & Kashibadze (2006)

M81 Mass:

~ 2 - 5 x 10^{11} $M_\odot$

Roberts & Rots (1973)

Schroder et al. (2001)

M82 Mass:

~ 10^{10} M

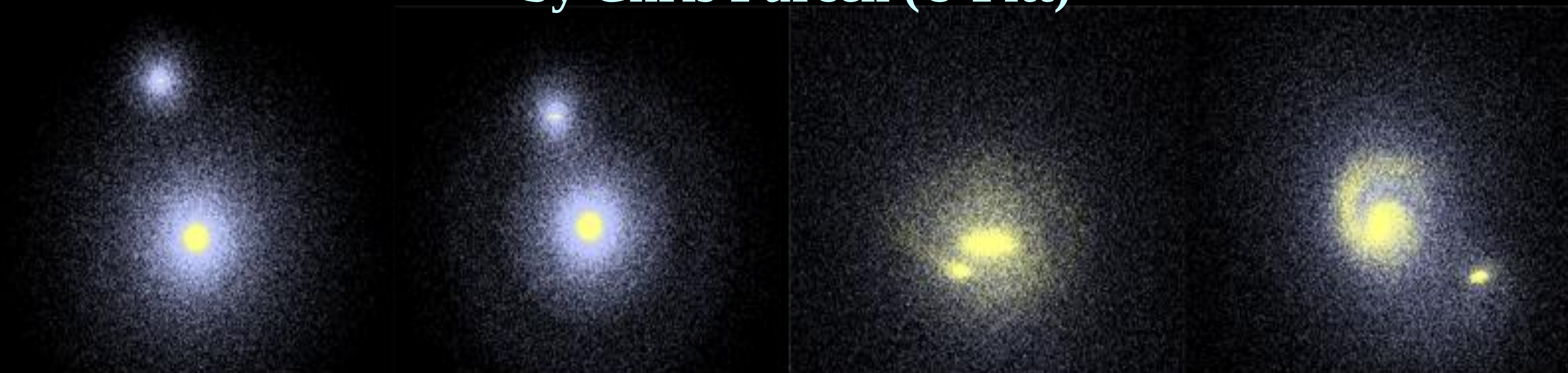
Greco et al. (2012)

Only 2 more "large" galaxies in group (both smaller than M81)

Mass Discrepancy points to possibility of significant filament(s).

Simulated Dynamics & Filament Formation I:

by Chris Purcell (U Pitt)



Initial Conditions:

$M81 = 7x10^{11}\ M_{\odot}$ (within 200 kpc)

$M82 = 1x10^{11}\ M_{\odot}$ (within 100 kpc)

$D_{separation}$ = 200 kpc

Infall vel. = 100 km/s

Sofue (2008)

Approach:

τ = 0.47 Gyrs

120 kpc

Pericenter:

τ = 0.89 Gyrs

16 kpc

Final State:

τ = 1.14 Gyrs

$\Delta\tau \sim$ 0.25 Gyr since pericenter

as in de Mello et al. (2007)

$M81 \simeq 5x10^{11}\ M_{\odot}$

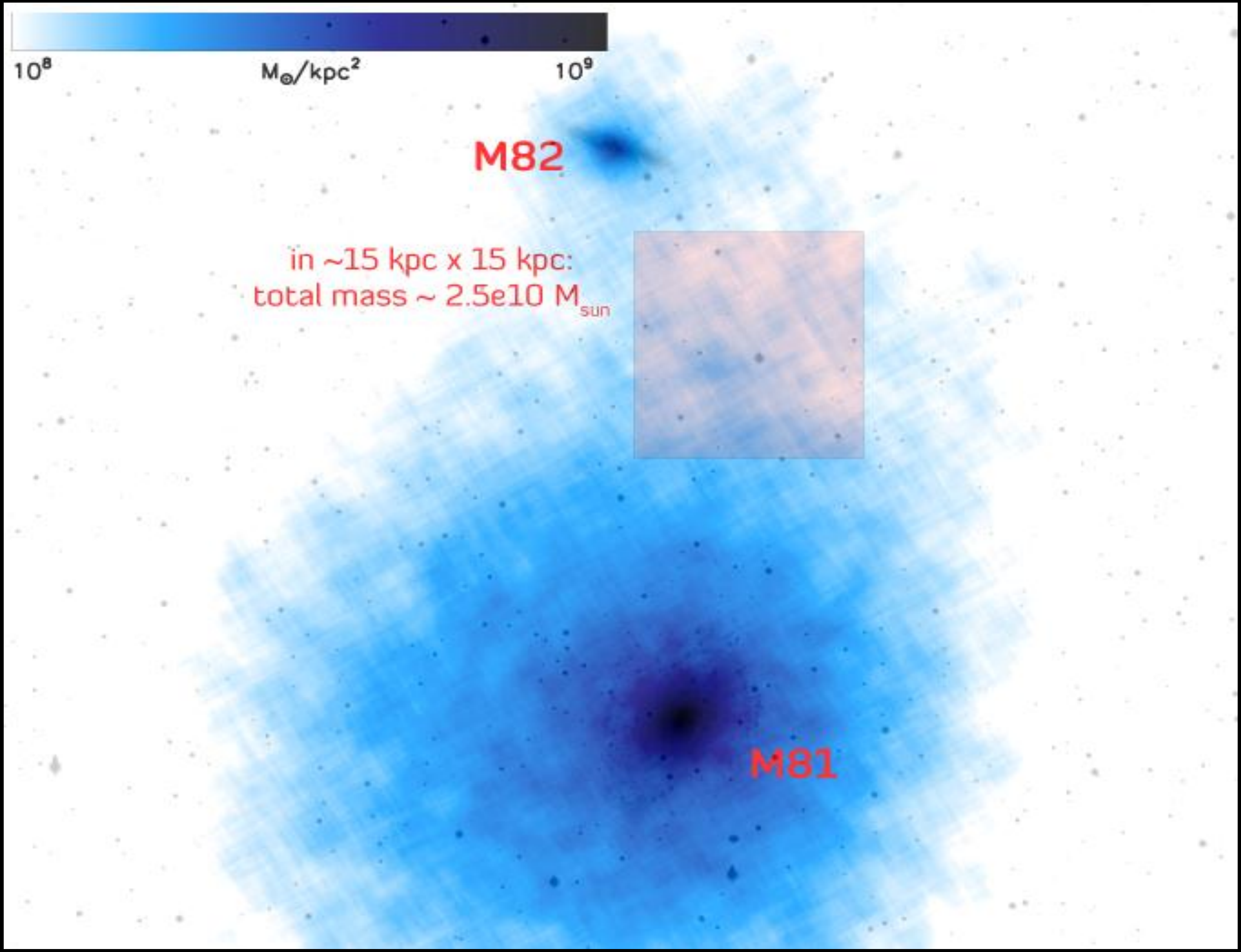
as in Schroder et al. (2001)

$M82 = 10^{10}\ M_{\odot}$

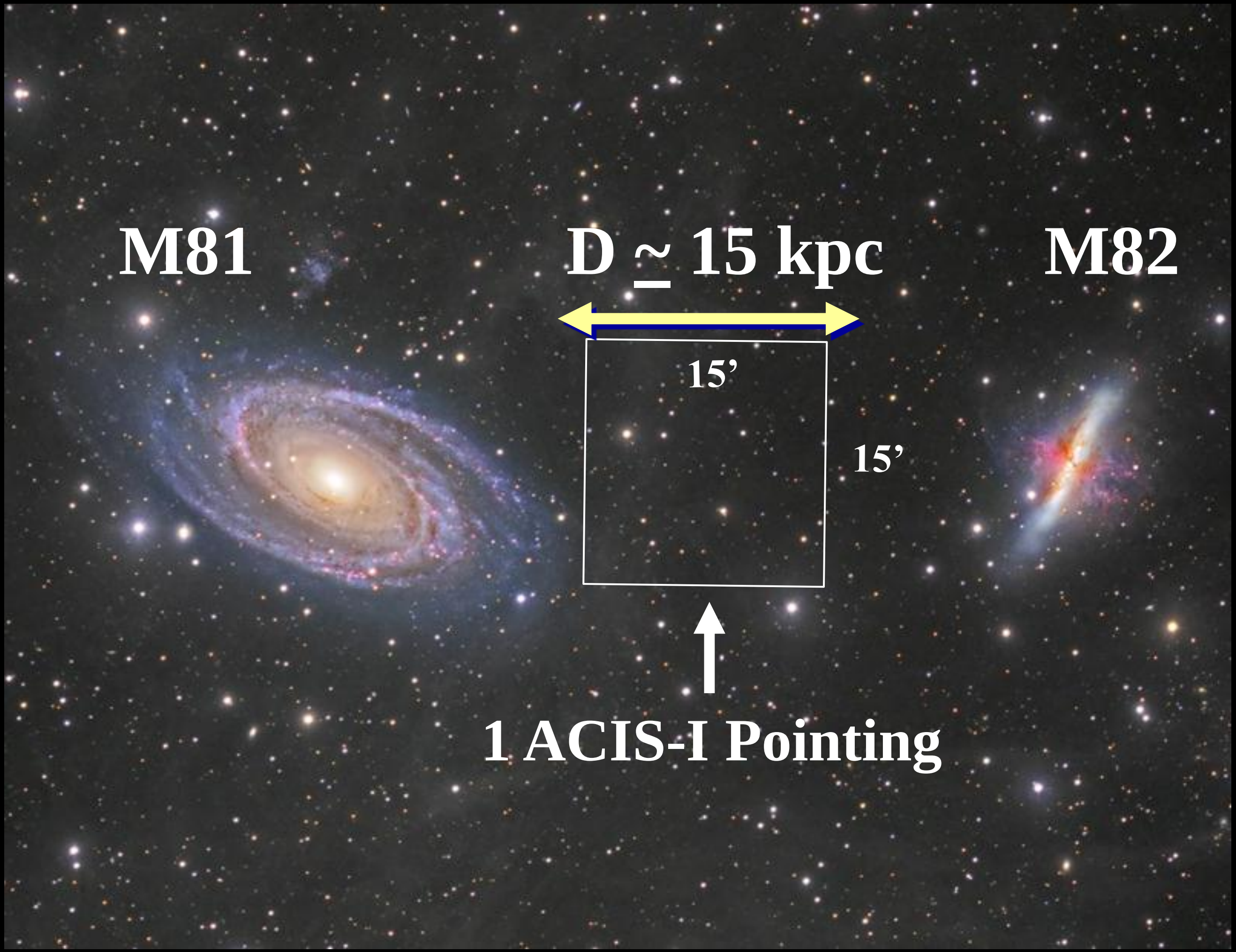
as in Greco et al. (2012)

36 kpc

Simulated Dynamics & Filament Formation II:



Proposed *Chandra* Observations:

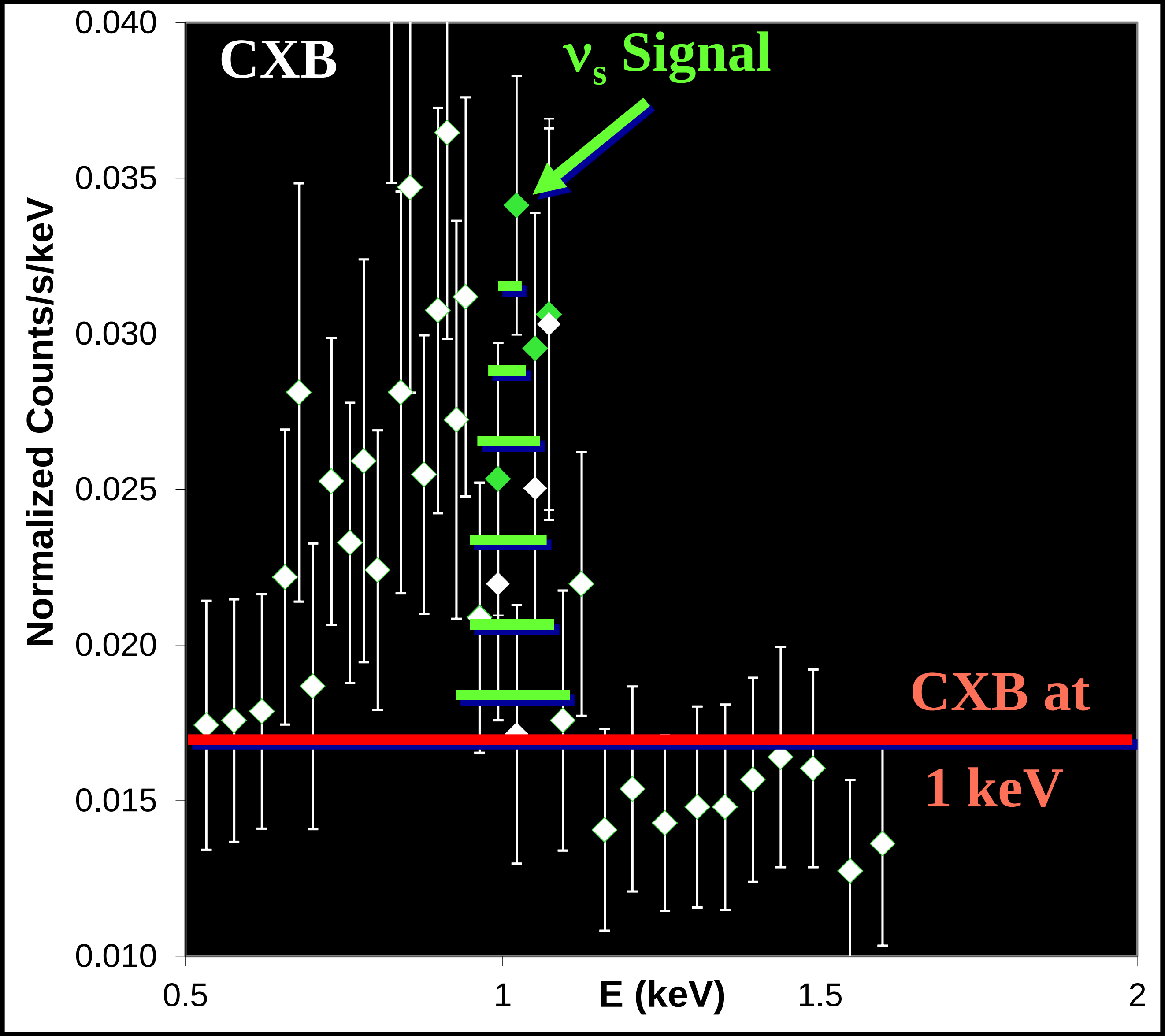


At D ~ 3.6 Mpc,
1' ~ 1 kpc

so

Only 1 *Chandra* ACIS-I Pointing needed to cover the space between M81 & M82 that should be relatively free of hot gas.

Forecast for Observations & Constraints:



Prospective Data:
Chandra **CXB in a 15' x 15' FoV**

M_{Fil} in FoV:
2.5 x 10^{10} $M_\odot$

Σ_{FoV} ($10^{11} M_\odot Mpc^{-2}$)
$\Sigma_{fil} \simeq 0.019$
$\Sigma_{MW} \simeq 0.009$
(Low mass MW [76])
$\Sigma_{tot} \simeq 0.028$

ν_s Signal:
Exclusion/Detection at m_s = 2 keV

Summary II

Current *Chandra* Constraints: m_s < 2.2 keV
are close to the limit of contemporary detectors

Long-term progress requires next generation instruments with greatly improved A_{eff} & ΔE.

To make near-term progress, examine nearby systems with the potential for large amounts of spatially separated dark matter – such as prospective DM filaments in merging galaxies, i.e., M81/M82.