A 3.5 keV Photon Line from a 3.5 keV ALP Line

Markus Rummel, University of Oxford

Seminar, University of Bologna 13/11/2014

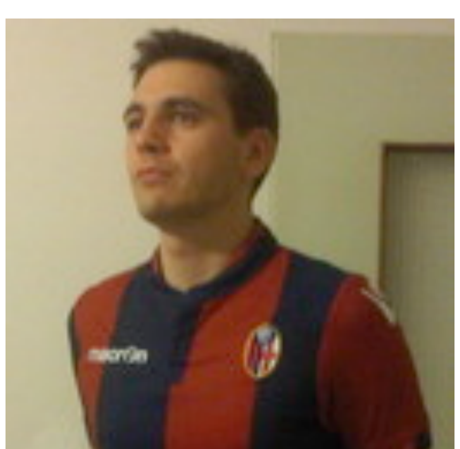
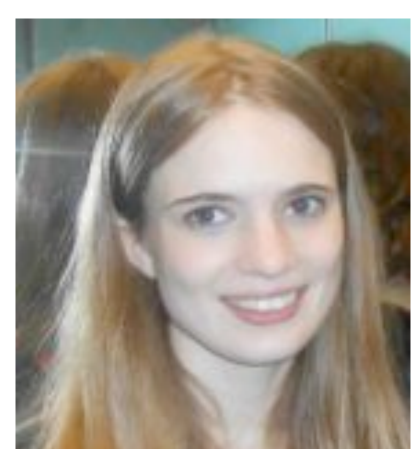
UNIVERSITY OF OXFORD

- "A 3.55 keV Photon Line and its Morphology from a 3.55 keV ALP Line", Michele Cicoli, Joseph Conlon and David Marsh, MR arXiv:1403.2370, Phys.Rev. D90 023540

- "3.55 keV photon lines from axion to photon conversion in the Milky Way and M31", Francesca Day and Joseph Conlon, arXiv:1404.7741

- "A 3.55 keV line from $\mathrm{DM} \to a \to \gamma$: predictions for cool-core and non-cool-core clusters", Andrew Powell and Joseph Conlon, arXiv:1406.5518

- "Observational consistency and future predictions for a 3.5 keV ALP to photon line", Pedro Alvarez, Joseph Conlon, Francesca Day and David Marsh, MR, arXiv:1410.1867

Outline

1. Summary of 3.5 keV observations
2. The model: $\mathrm{DM} \to a \to \gamma$
3. $\mathrm{DM} \to a \to \gamma$ vs $\mathrm{DM} \to \gamma$ morphology
4. A Cosmic Axion Background

Timeline of observational evidence

2014

Feb
- Bulbul et al.: Det. in stacked cluster (XMM, Chandra)
- Boyarsky et al.: Det. in Perseus & M31 (XMM)

May
- Riemer-Sørensen: No Det. in MW (Chandra)

Aug
- Jeltema et al.: Det. in GC, no det. in M31 (XMM)
  - Boyarsky et al.: Comment on M31
  - Bulbul et al.: Comment on atomic lines
- Boyarsky et al.: Det. in GC (XMM)
- Malyshev et al.: No det. in dwarfs (XMM)
- Anderson et al.: No det. in spirals (XMM, Chandra)

Timeline of observational evidence

2014

Nov

- Urban et al.: Det. in Perseus (Suzaku)
- Carlson, Jeltema, Profumo: Morphology of signal in Perseus and GC (XMM)
- Jeltema Profumo: Reply to comments of Bulbul et al. and Boyarsky et al.
- ...

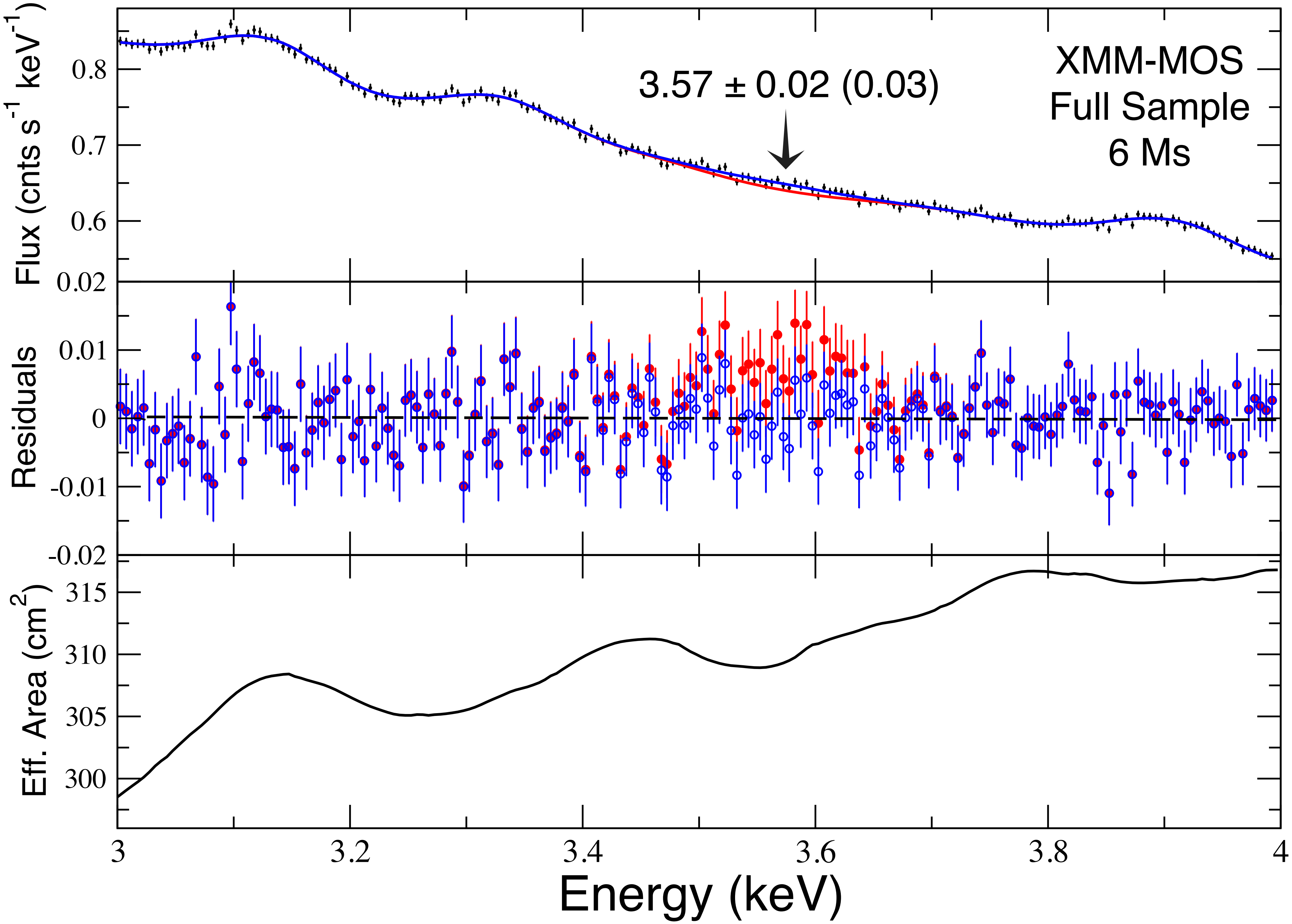
The stacked cluster analysis

[Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall '14(Feb)]

- Stacked data of 73 galaxy clusters ($0.01 < z < 0.4$) yielding ~ 8 Ms of XMM observation time
- Blue-shifted to cluster rest frame
- Detected independently in XMM-Newton PN and MOS instruments at 4-5 sigma
- Detected in all three subsamples (Perseus - also with Chandra, Coma+Ophiuchus+Centaurus, all others)

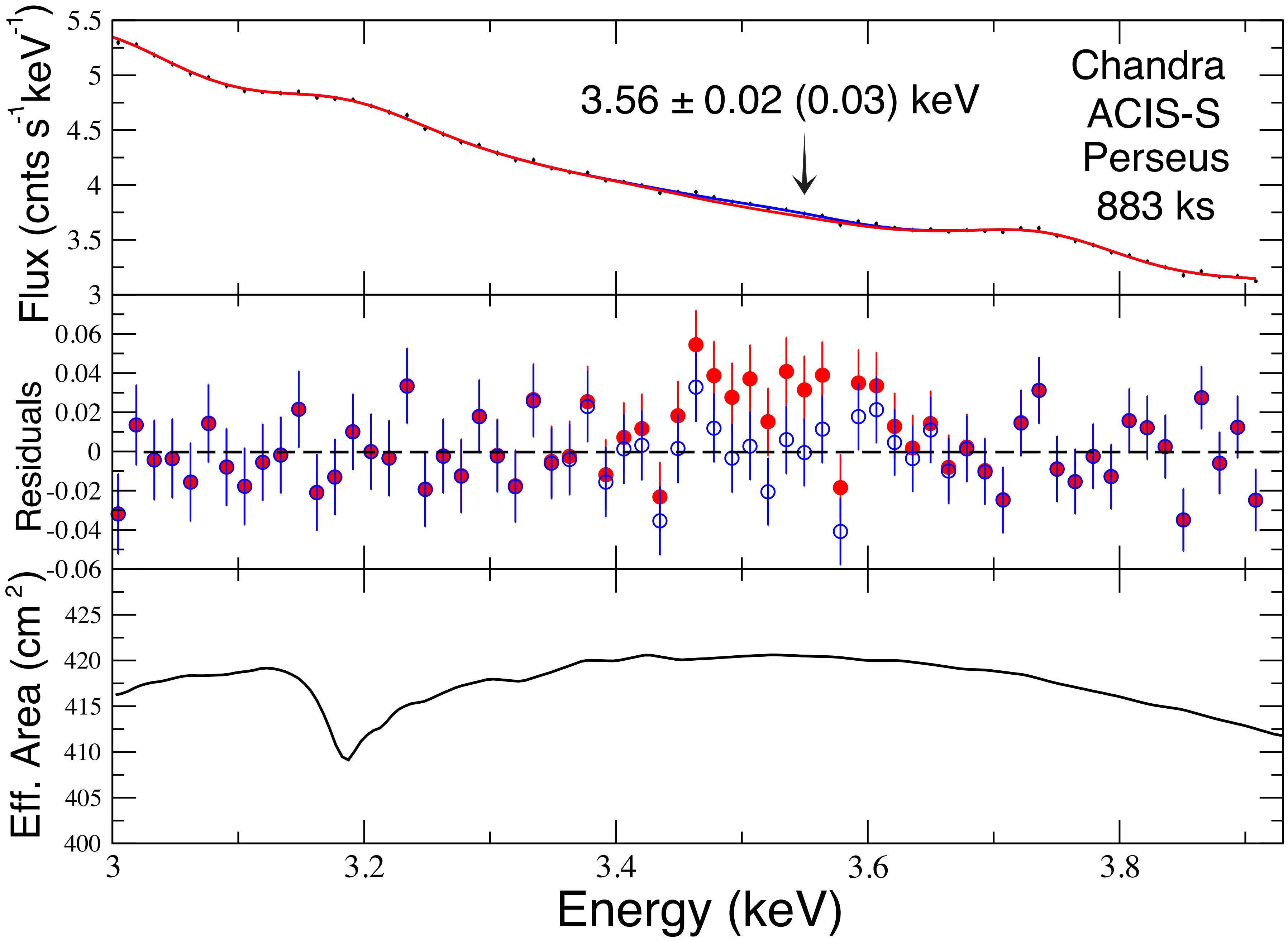
The observed line

[Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall '14(Feb)]



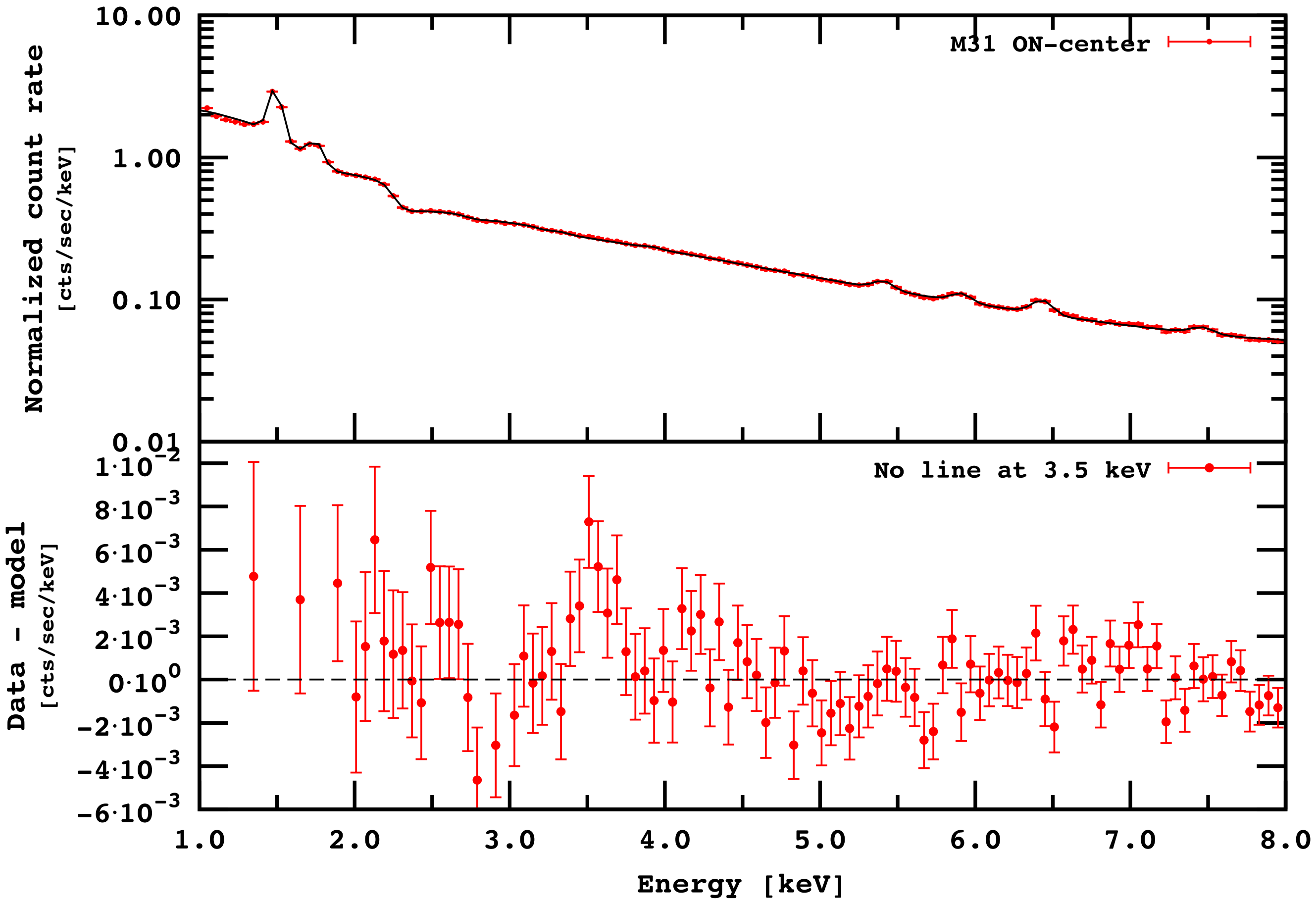
The observed line

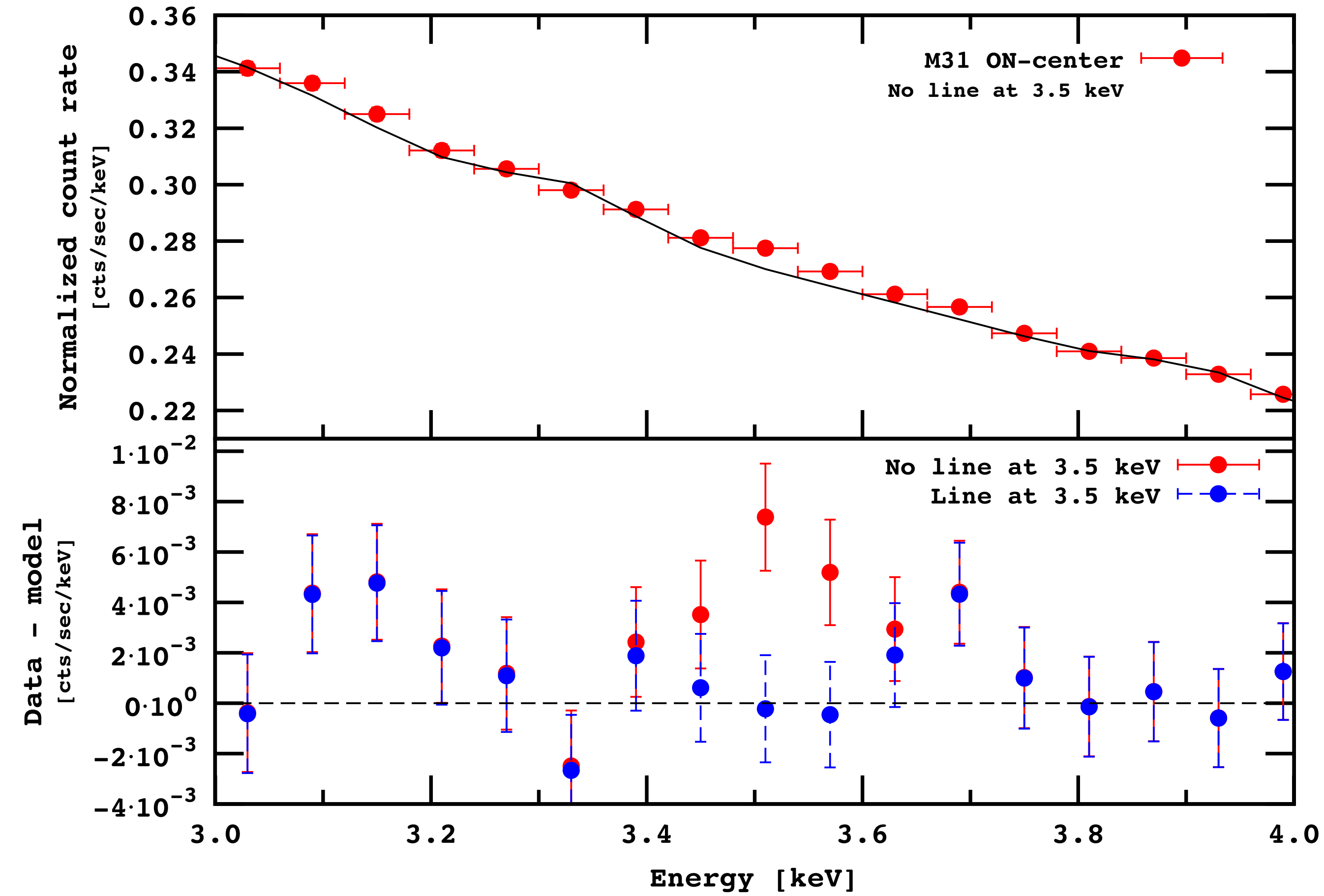
[Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall '14(Feb)]



The Boyarsky et al. analysis

[Boyarsky, Ruchayskiy, Iakubovskyi, Franse ’14(Feb)]





Detected in Perseus Cluster (0.7 Ms) and Andromeda (M31) galaxy (2.5 Ms) with XMM-Newton MOS data

The galactic center

No detection with Chandra (750 ks): [Riemer-Sørensen '14 (Aug)]

Element	Energy (keV)	Strength ($\mathrm{ph\,cm^{-2}\,s^{-1}}$)	Strength per arcmin^2 ($\mathrm{ph\,arcmin^{-2}\,cm^{-2}\,s^{-1}}$)
95 % Upper bound	3.55 keV	$\lesssim 5 \times 10^{-6}$	$\lesssim 2.1 \times 10^{-8}$
K XVIII	3.48	2.2×10^{-6}	9.2×10^{-9}
K XVIII	3.52	4.2×10^{-6}	1.8×10^{-8}
Ar XVII	3.62	4.2×10^{-6}	1.8×10^{-8}

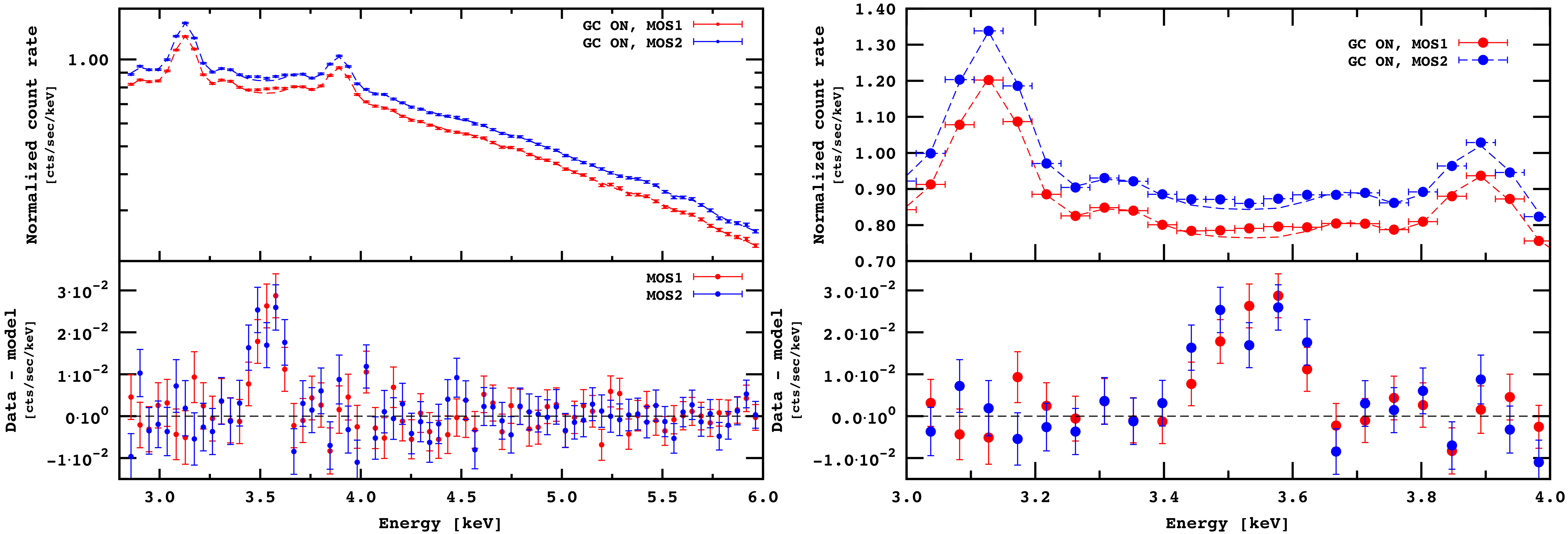
But detection with XMM (~2 Ms):

Detector	Energy (keV)	Strength ($\mathrm{ph\,cm^{-2}\,s^{-1}}$)	Strength per arcmin^2 ($\mathrm{ph\,arcmin^{-2}\,cm^{-2}\,s^{-1}}$)
XMM MOS [4]	3.5	4.1×10^{-5}	7.7×10^{-8}
XMM PN [4]	3.5	2.8×10^{-5}	5.3×10^{-8}
XMM [5]	3.53	$(2.9 \pm 0.5) \times 10^{-5}$	$(5.5 \pm 0.9) \times 10^{-8}$

[4] Jeltema, Profumo '14 (Aug), [5] Boyarsky, Ruchayskiy, Iakubovskyi, Franse '14 (Aug)

The galactic center

[Boyarsky, Ruchayskiy, Iakubovskyi, Franse '14(Aug)]



- Atomic composition of GC more complicated (multi-phase and multi temperature)
- Potassium line cannot be excluded

Dwarf spheroidal galaxies

[Malyshev, Neronov, Eckert '14(Aug)]

- Stacked XMM data of 8 dwarfs analyzed (~ 0.6 Ms)
- high mass to light ratio
- not a source of thermal X-ray emission

$\Rightarrow$ **No detection:** Exclusion of Dark matter origin of 3.5 keV line at only ~ 2 sigma

Stacked galaxy spectra

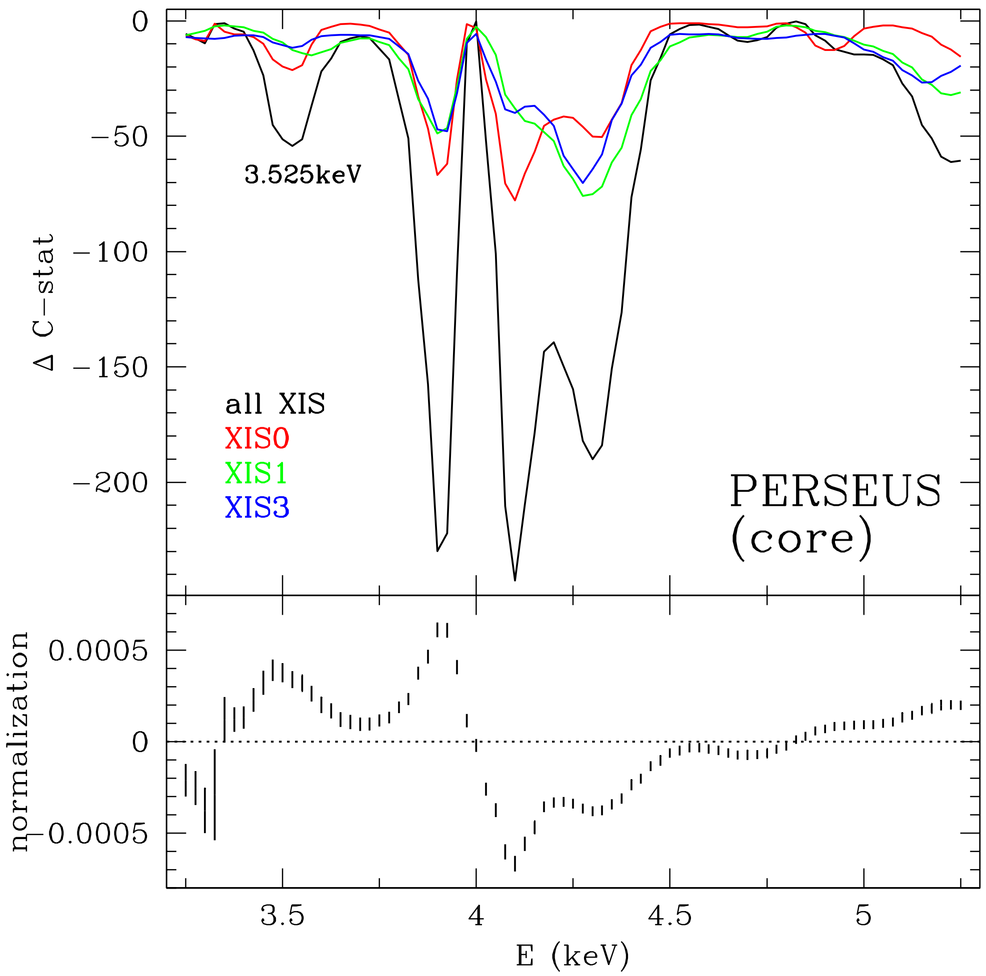
[Anderson, Churazov, Bregman '14(Aug)]

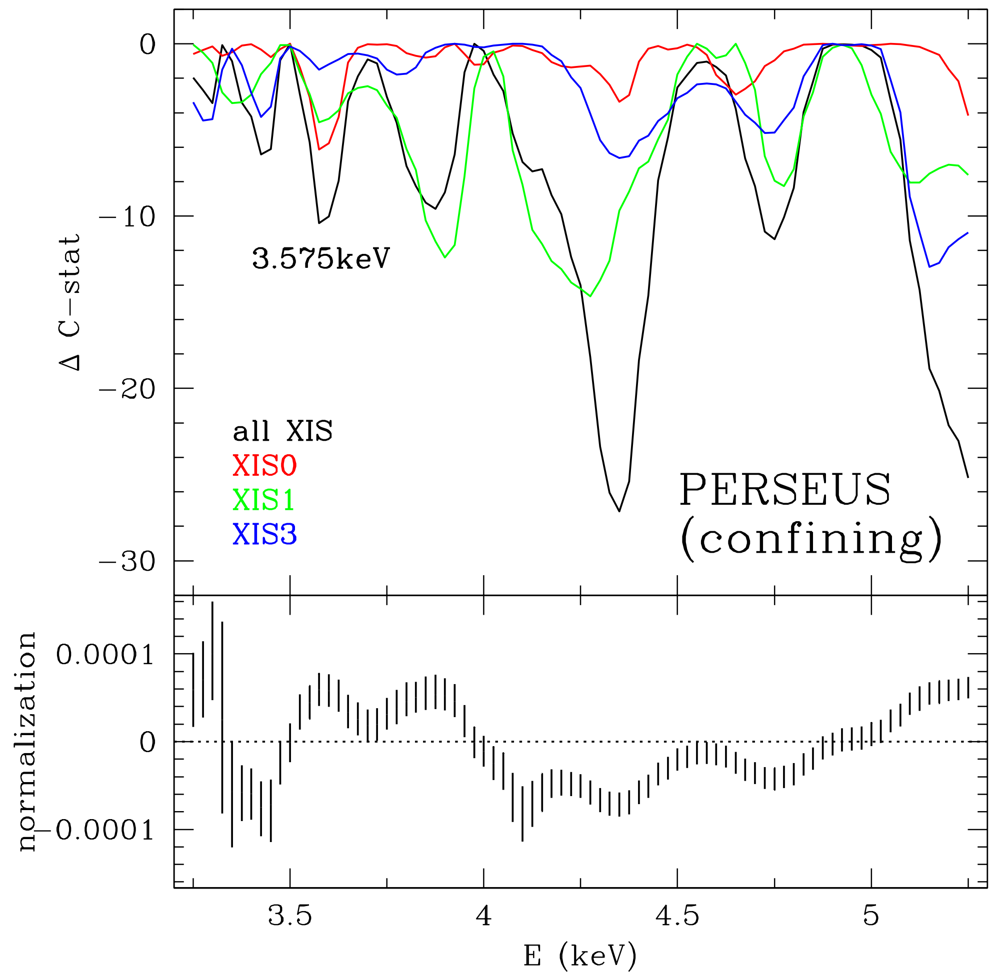
- 89 galaxies (XMM, 14.6 Ms) and 81 galaxies (Chandra, 15 Ms) with $kT \lesssim 1\ \mathrm{keV}$
- dark matter masses via virial radius
- instrumental background is not modeled and substracted but fitted with smoothing spline

$\Rightarrow$ **No detection**: Exclusion of dark matter origin at 4.4 sigma (Chandra), 11.8**(!)** sigma (XMM)

Suzaku: Perseus and nearby cluster

[Urban, Werner, Allen, Simionescu, Kaastra, Strigari '14(Nov)]





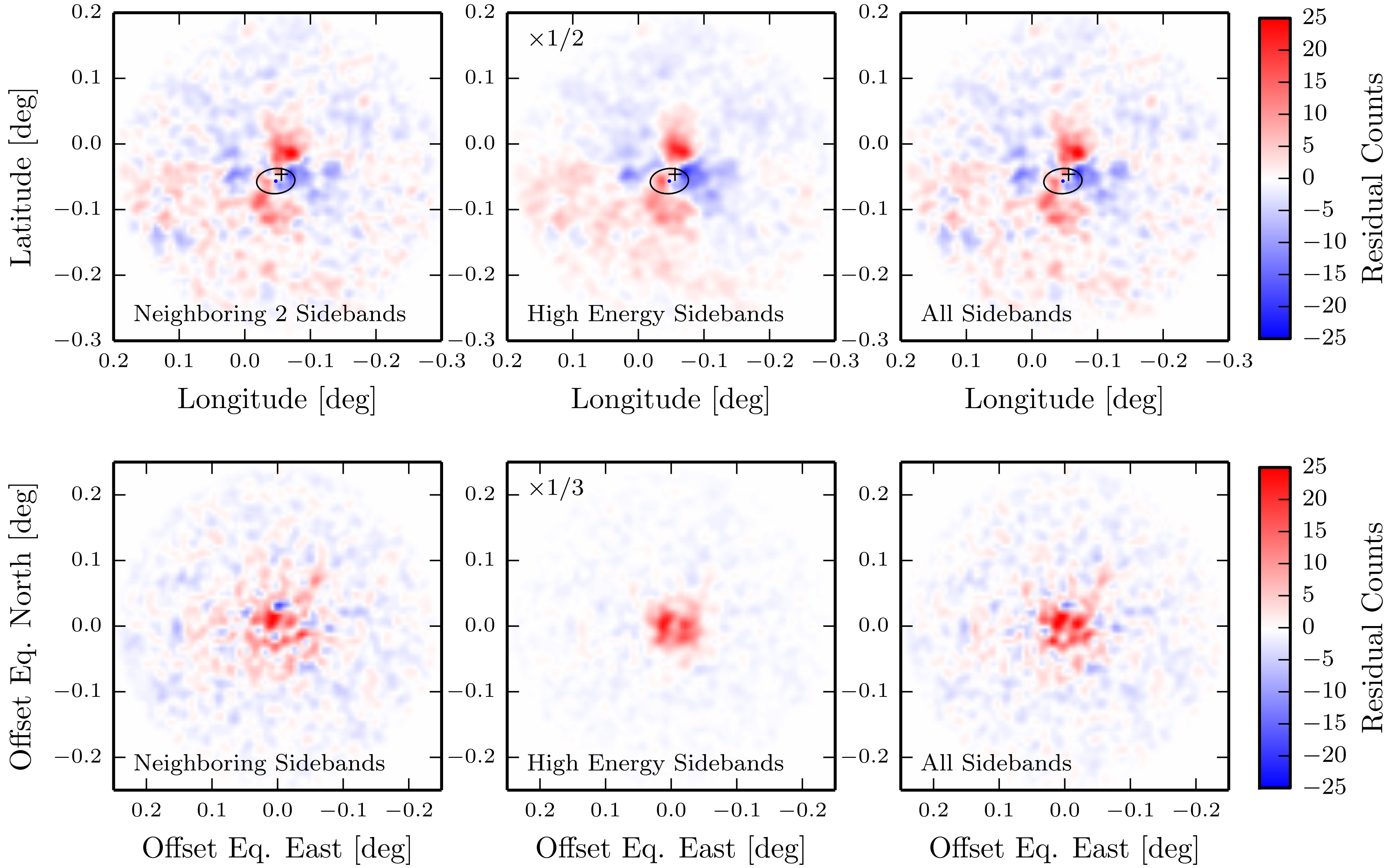
- Detected in Perseus (740 ks): Flux & Energy broadly consistent with Bulbul et al. and Boyarsky et al.

- Not detected in Coma (164 ks), Virgo (90 ks) and Ophiuchus (83 ks)

Morphology in Perseus and GC

GC

Perseus



- Both morphologies seem inconsistent with dark matter decay to photons
- Caution: Low count rates [Carlson, Jeltema, Profumo '14(Nov)]

Possible origins of the line

Instrumental effect?

- ☒ Seen by 5 different detectors (2 XMM, 2 Chandra, Suzaku)
- ☒ De-redshifting of clusters leaves line at 3.55 keV
- ☒ Not seen in blanck sky survey (16 Ms)

Possible origins of the line

Instrumental effect?

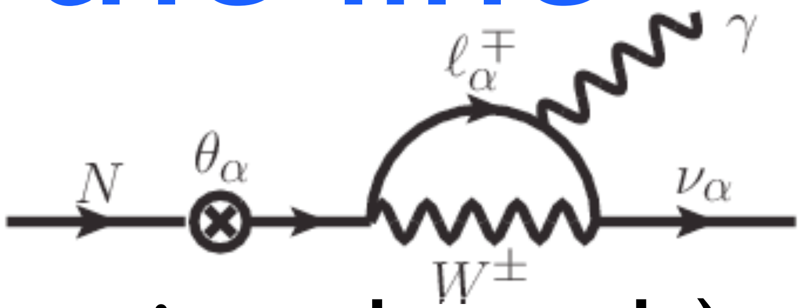
- ☒ Seen by 5 different detectors (2 XMM, 2 Chandra, Suzaku)
- ☒ De-redshifting of clusters leaves line at 3.55 keV
- ☒ Not seen in blanck sky survey (16 Ms)

Atomic line?

- ☒ No known atomic line at this energy. Apart from known lines exceeding expectation by factor ~20
- ☒ Line also detected in Andromeda (no hot gas!)

Possible origins of the line

Dark matter decay/annihilation?



- Sterile neutrinos (compatible with previous bounds)

$$\Gamma_\gamma(m_s,\theta) = 1.38 \times 10^{-29}\ \mathrm{s}^{-1}\ \left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

- ALP (Axion Like Particle) DM, Axinos, excited states of DM, Gravitinos, ...

[Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall;
Czerny, Hamaguchi, Higaki, Ibe, Ishida, Jeong, Nakayama, Takahashi, Yanagida, Yokozaki;
Jaeckel, Redondo, Ringwald; El Asiati, Hambye, Scarna;
Dudas, Heurtier, Mambrini; Bomark, Roszkowski; Frandsen, Sannino, Shoemaker, Svendsen;
Kolda, Unwin; Finkbeiner, Weiler; Kubo, Lim, Lindner; Choi, Seta; Baek, Okada, Toma;
Lee, Park, Park; Chen, Liu, Nath; Ishida, Okada; Geng, Huang, Tsai; Chiang, Yamada;
Dutta, Gogoladze, Khalid, Shafi; Rodejohann, Zhang; Cline, Frey;
Henning, Kehayias, Murayama, Pinner, Yanagida; Boddy, Feng, Kaplinghat, Shadmi, Tait;
Falkowski, Hochberg, Ruderman; Schutz, Slatyer; Cheung, Huang, Tsai]

Problems of DM to photons

- 11.8 sigma inconsistency from stacked galaxy spectra [Anderson, Churazov, Bregman '14(Aug)]

- Non-detection in dwarf spheroidals [Malyshev, Neronov, Eckert '14(Aug)]

- Galactic center: Non-detection with Chandra but detection with XMM, (morphology does not fit) [Riemer-Sørensen '14 (Aug)], [Jeltema, Profumo '14 (Aug)], [Boyarsky, Ruchayskiy, Iakubovskyi, Franse '14 (Aug)], [Carlson, Jeltema, Profumo '14 (Nov)]

Problems of DM to photons

XMM-Newton MOS: [Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall '14]

	Full Sample (73 cluster)	Coma +Centaurus +Ophiuchus	Perseus (without core)	Perseus (with core)
$\sin^2(2\theta)$ (10^{-11})	$6.8^{+1.4}_{-1.4}$	$18.2^{+4.4}_{-3.9}$	$23.3^{+7.6}_{-6.9}$	$55.3^{+25.5}_{-15.9}$

Problems of DM to photons

XMM-Newton MOS: [Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall '14]

	Full Sample (73 cluster)	Coma +Centaurus +Ophiuchus	Perseus (without core)	Perseus (with core)
$\sin^2(2\theta)$ (10^{-11})	$6.8^{+1.4}_{-1.4}$	$18.2^{+4.4}_{-3.9}$	$23.3^{+7.6}_{-6.9}$	$55.3^{+25.5}_{-15.9}$

- Signal in Perseus ~8 times stronger than in full sample
- Half of the Perseus Signal is within the central 20 kpc but $R_{DM} \simeq 360$ kpc

$\Rightarrow$ Dark matter to photon may not fit the morphology

Problems of DM to photons

XMM-Newton MOS: [Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall '14]

	Full Sample (73 cluster)	Coma +Centaurus +Ophiuchus	Perseus (without core)	Perseus (with core)
$\sin^2(2\theta)$ (10^{-11})	$6.8^{+1.4}_{-1.4}$	$18.2^{+4.4}_{-3.9}$	$23.3^{+7.6}_{-6.9}$	$55.3^{+25.5}_{-15.9}$

- Signal in Perseus ~8 times stronger than in full sample
- Half of the Perseus Signal is within the central 20 kpc but $R_{DM} \simeq 360$ kpc

$\Rightarrow$ Dark matter to photon may not fit the morphology

Problems of DM to photons

XMM-Newton MOS: [Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall '14]

	Full Sample (73 cluster)	Coma +Centaurus +Ophiuchus	Perseus (without core)	Perseus (with core)
$\sin^2(2\theta)$ (10^{-11})	$6.8^{+1.4}_{-1.4}$	$18.2^{+4.4}_{-3.9}$	$23.3^{+7.6}_{-6.9}$	$55.3^{+25.5}_{-15.9}$

- Signal in Perseus ~8 times stronger than in full sample
- Half of the Perseus Signal is within the central 20 kpc but $R_{DM} \simeq 360 \text{ kpc}$

$\Rightarrow$ Dark matter to photon may not fit the morphology

Problems of DM to photons

XMM-Newton MOS: [Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall '14]

	Full Sample (73 cluster)	Coma +Centaurus +Ophiuchus	Perseus (without core)	Perseus (with core)
$\sin^2(2\theta)$ (10^{-11})	$6.8^{+1.4}_{-1.4}$	$18.2^{+4.4}_{-3.9}$	$23.3^{+7.6}_{-6.9}$	$55.3^{+25.5}_{-15.9}$

- Signal in Perseus ~8 times stronger than in full sample
- Half of the Perseus Signal is within the central 20 kpc but $R_{DM} \simeq 360$ kpc

$\Rightarrow$ Dark matter to photon may not fit the morphology

Problems of DM to photons

XMM-Newton MOS: [Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall '14]

	Full Sample (73 cluster)	Coma +Centaurus +Ophiuchus	Perseus (without core)	Perseus (with core)
$\sin^2(2\theta)$ (10^{-11})	$6.8^{+1.4}_{-1.4}$	$18.2^{+4.4}_{-3.9}$	$23.3^{+7.6}_{-6.9}$	$55.3^{+25.5}_{-15.9}$

- Signal in Perseus ~8 times stronger than in full sample
- Half of the Perseus Signal is within the central 20 kpc but $R_{DM} \simeq 360$ kpc

$\Rightarrow$ Dark matter to photon may not fit the morphology

Problems of DM to photons

XMM-Newton MOS: [Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall '14]

	Full Sample (73 cluster)	Coma +Centaurus +Ophiuchus	Perseus (without core)	Perseus (with core)
$\sin^2(2\theta)$ (10^{-11})	$6.8^{+1.4}_{-1.4}$	$18.2^{+4.4}_{-3.9}$	$23.3^{+7.6}_{-6.9}$	$55.3^{+25.5}_{-15.9}$

- Signal in Perseus ~8 times stronger than in full sample
- Similar with Suzaku: 85% of signal is within central 130 kpc (66% expected from DM to photons) [Urban, Werner, Allen, Simionescu, Kaastra, Strigari '14(Nov)]

$\Rightarrow$ Dark matter to photon may not fit the morphology

Problems of DM to photons

XMM-Newton MOS: [Bulbul, Markevitch, Foster, Smith, Loewenstein, Randall '14]

	Full Sample (73 cluster)	Coma +Centaurus +Ophiuchus	Perseus (without core)	Perseus (with core)
$\sin^2(2\theta)$ (10^{-11})	$6.8^{+1.4}_{-1.4}$	$18.2^{+4.4}_{-3.9}$	$23.3^{+7.6}_{-6.9}$	$55.3^{+25.5}_{-15.9}$

- Signal in Perseus ~8 times stronger than in full sample
- XMM morphology: Signal is concentrated in cool core
  [Carlson, Jeltema, Profumo '14 (Nov)]

$\Rightarrow$ Dark matter to photon may not fit the morphology

Outline

1. Summary of 3.5 keV observations
2. The model: $\mathrm{DM} \to a \to \gamma$
3. $\mathrm{DM} \to a \to \gamma$ vs $\mathrm{DM} \to \gamma$ morphology
4. A Cosmic Axion Background

Dark matter to axion to photon

$$\mathrm{DM} \to a \to \gamma$$

- Axions transform to photons in cluster/galactic magnetic fields
- Theoretically equally well motivated as $\mathrm{DM} \to \gamma$ (axions are typically associated to a high scale, nothing is known about the particle nature of DM)
- Signal strength follows DM density **and** strength of the magnetic field

$\Rightarrow$ Signal peaks on scales of the cluster magnetic field! (Perseus)

Dark matter to axion decays

DM is a scalar

Decay via $\frac{\Phi}{\Lambda}\partial_\mu a \partial^\mu a$ with lifetime

$$\tau_\Phi = \left(\frac{7.1\ \mathrm{keV}}{m_\Phi}\right)^3 \left(\frac{\Lambda}{10^{17}\ \mathrm{GeV}}\right)^2 1.85 \times 10^{27}\ \mathrm{s}$$

(cosmological moduli problem, unless [Linde '96, Takahashi, Yanagida '11])

or DM is a fermion

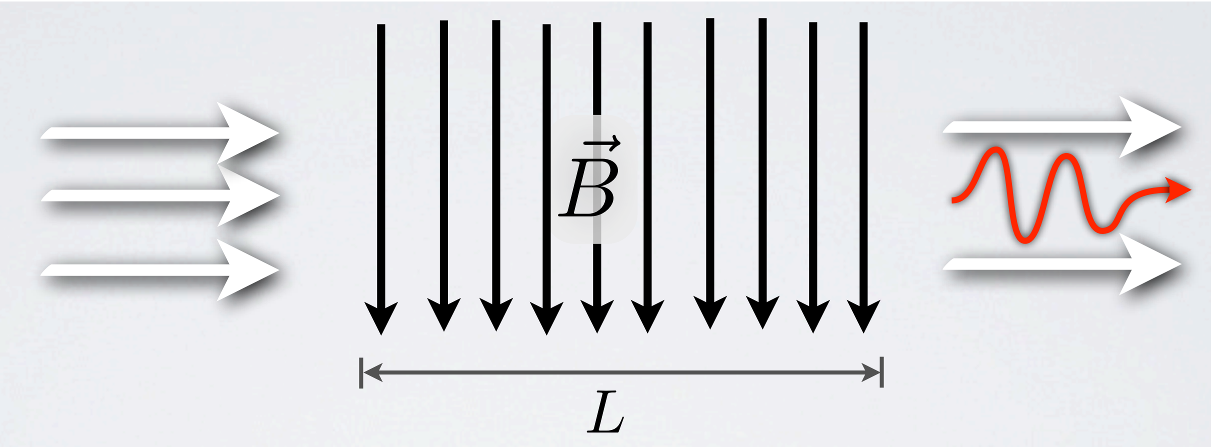
Decay via $\frac{\partial_\mu a}{\Lambda}\bar{\psi}\gamma^\mu\gamma^5\chi$ with lifetime

$$\tau_\psi = \left(\frac{7.1\ \mathrm{keV}}{m_\psi}\right)^3 \left(\frac{\Lambda}{10^{17}\ \mathrm{GeV}}\right)^2 0.92 \times 10^{27}\ \mathrm{s}$$

Axion-photon conversion

Axion-photon coupling in

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + \frac{a}{M} \mathbf{E} \cdot \mathbf{B}$$



induces [Raffelt, Stodolsky '87]

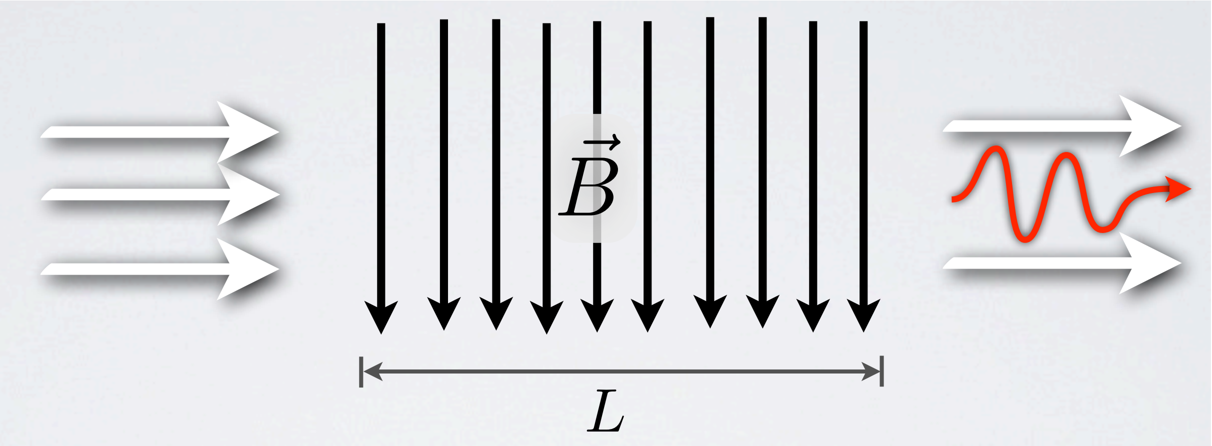
$$P(a \to \gamma) = \sin^2(2\theta) \sin^2\left(\frac{\Delta}{\cos 2\theta}\right)$$

with $\theta \sim \frac{B_\perp E_a}{M\, n_e}$, $\Delta \sim \frac{n_e L}{E_a}$ (for $m_a < 10^{-11}$ eV)

Axion-photon conversion

Axion-photon coupling in

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 + \frac{a}{M}\mathbf{E}\cdot\mathbf{B}$$



induces [Raffelt, Stodolsky '87]

$$P(a \to \gamma) = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos 2\theta}\right)$$

with $\theta \sim \frac{B_\perp E_a}{M\, n_e}$, $\Delta \sim \frac{n_e L}{E_a}$ (for $m_a < 10^{-11}$ eV)

$$P_{a\to\gamma}^{\text{cluster}} \sim \frac{B^2\, L\, R_{\text{cluster}}}{M^2}$$

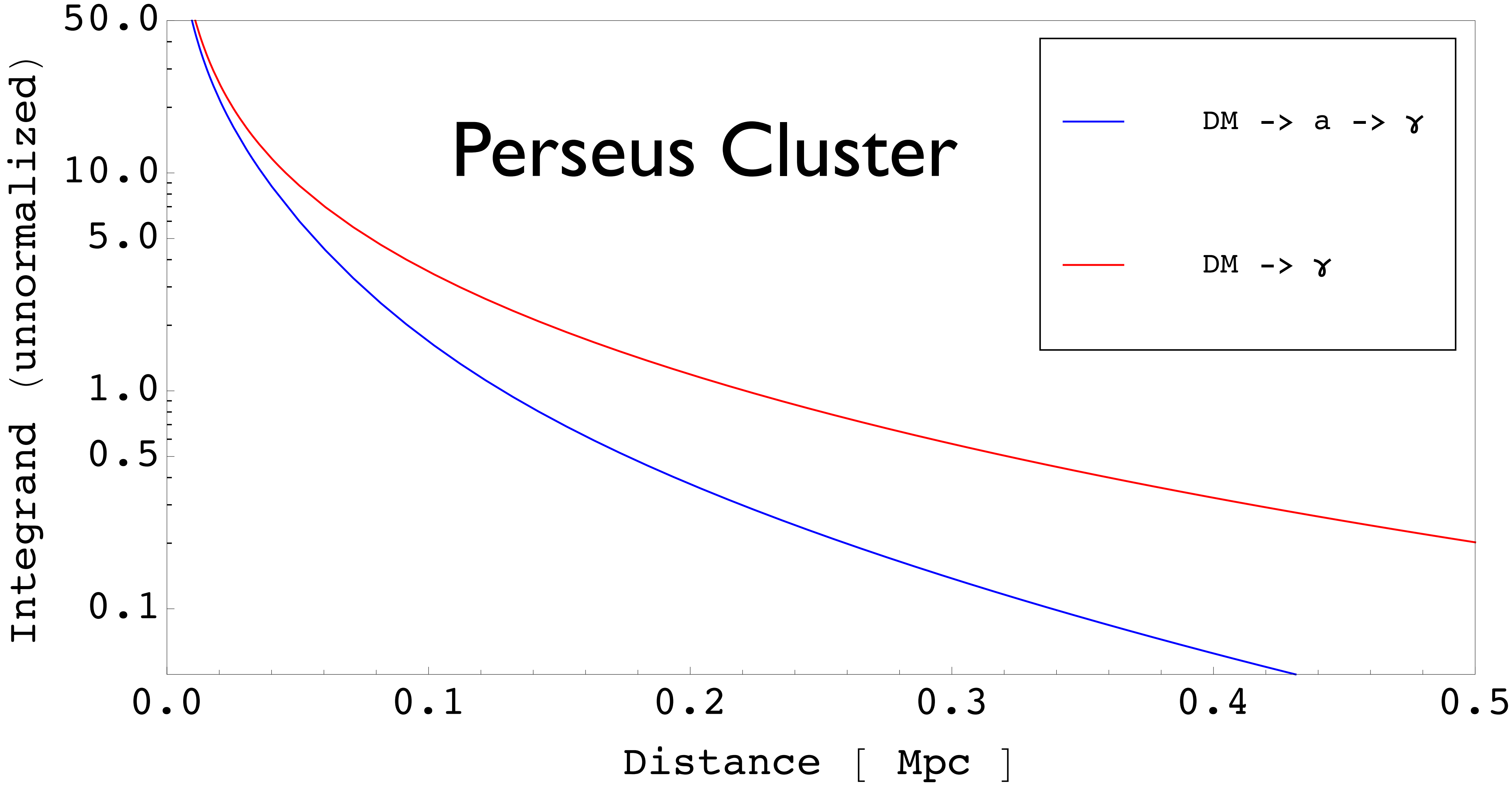
Outline

1. Summary of 3.5 keV observations
2. The model: $\mathrm{DM} \to a \to \gamma$
3. **$\mathrm{DM} \to a \to \gamma$ vs $\mathrm{DM} \to \gamma$ morphology**
4. A Cosmic Axion Background

Predictions: Cluster morphology

$$F_{DM\to a} = \frac{\Gamma_{DM\to a}}{4\pi d(z)^2}(1+z)\int_V \frac{\rho_{DM}}{m_{DM}} P_{a\to\gamma}\, dV$$

$$F_{DM\to\gamma} = \frac{\Gamma_{DM\to\gamma}}{4\pi d(z)^2}(1+z)\int_V \frac{\rho_{DM}}{m_{DM}}\, dV$$

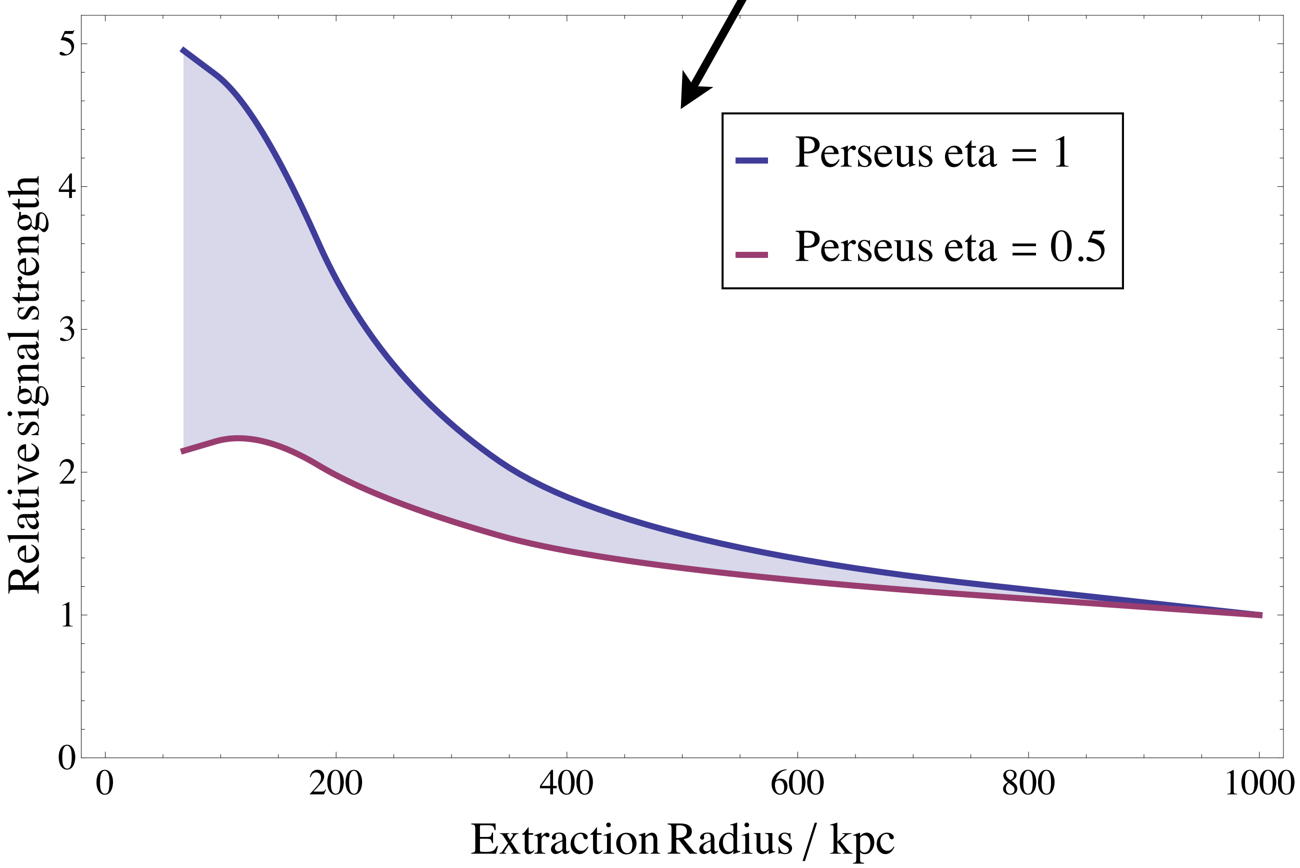


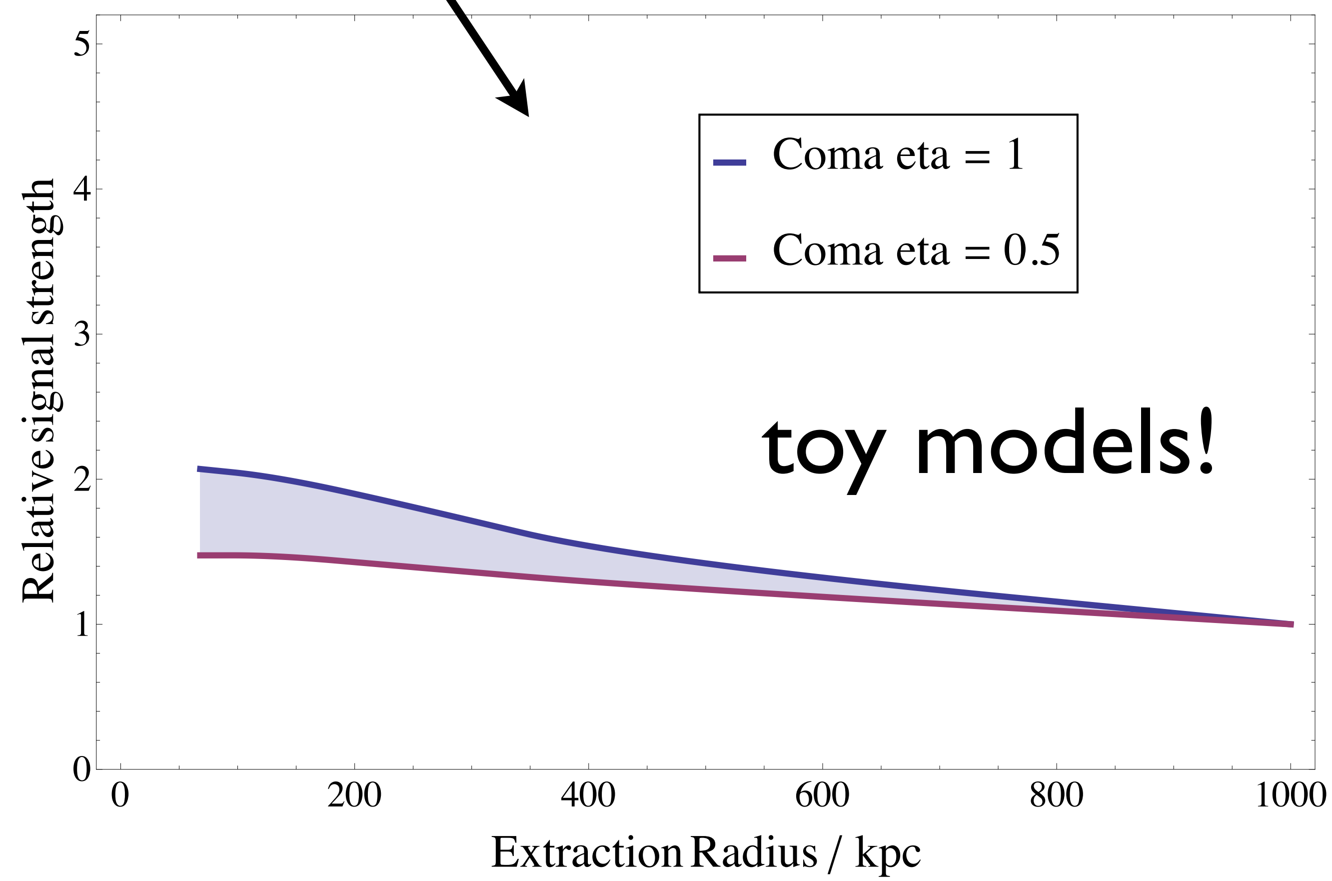
Predictions: Cluster morphology

$B(r) \sim B_0 \left(\frac{n_e(r)}{n_e(0)} \right)^\eta$ (Gaussian random field with Kolmogorov power spectrum)

$\Rightarrow$ Cool-core vs non-cool-core

[Conlon, Powell '14(June)]



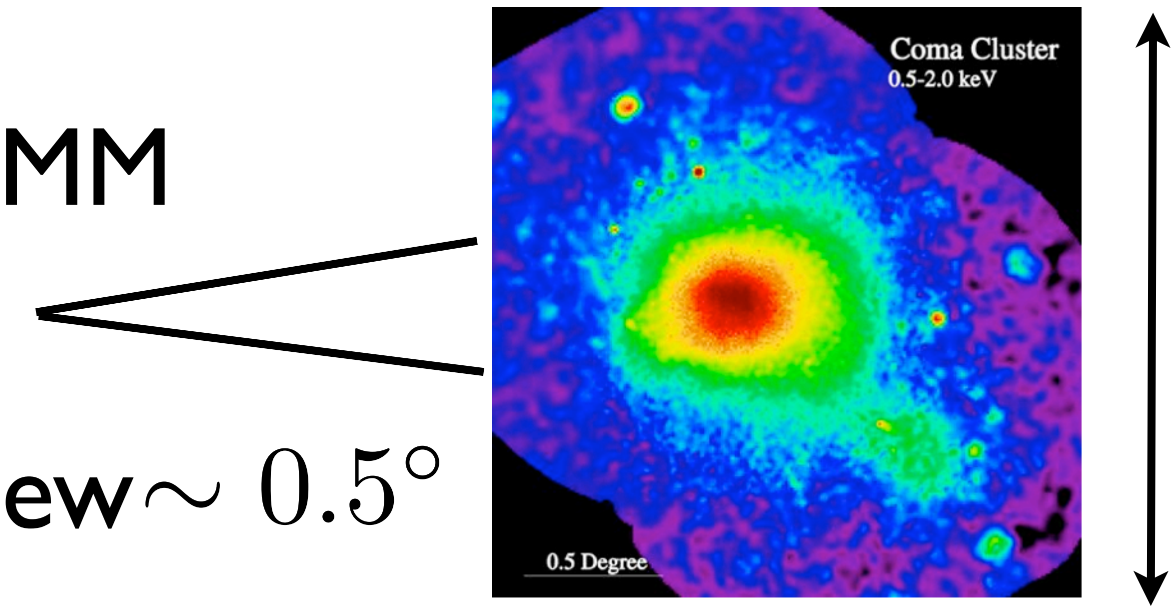


eta =0.5 (Coma): [Bonafede, Feretti, Murgia, Govoni, Giovannini, Dallacasa, Dolag, Taylor '10]
eta = 1 (Hydra A): [Kuchar, Enßlin '11]

Predictions: Clusters

- Nearby cluster do not fit in Field of view of XMM (2-3 sigma excess of nearby clusters over full sample)

XMM



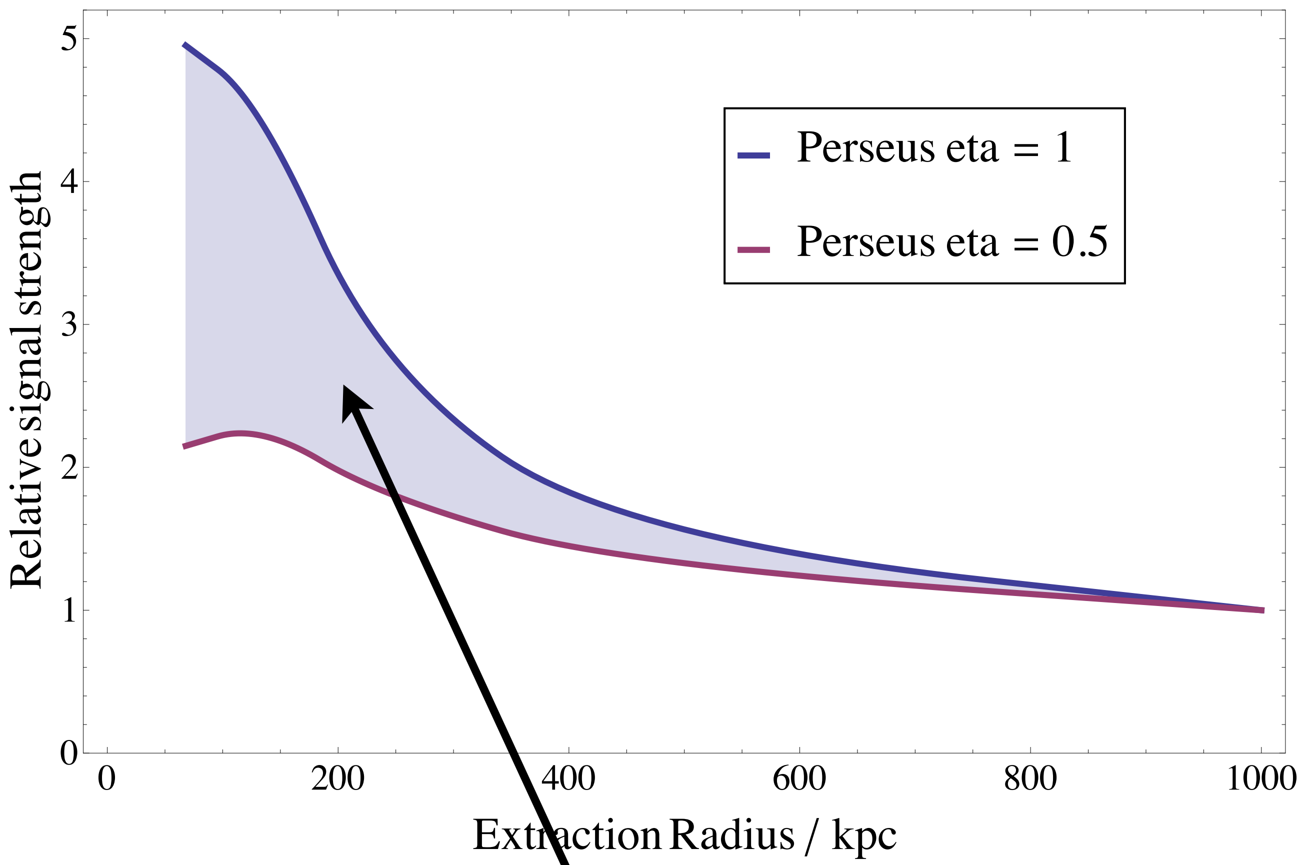
Field of view $\sim 0.5^\circ$

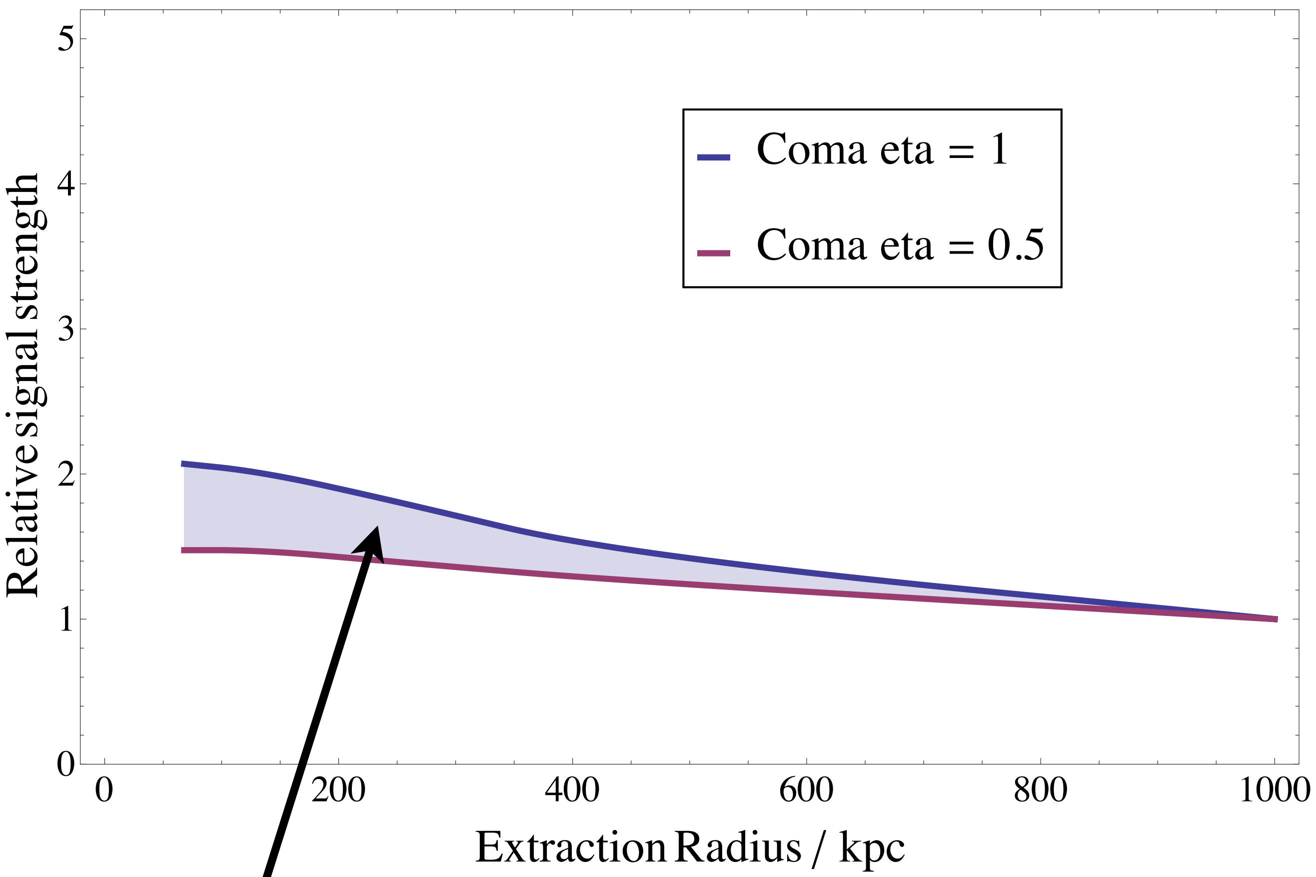
$\mathcal{O}(1^\circ)$

	Full Sample (73 cluster)	Coma +Centaurus +Ophiuchus	Perseus (without core)	Perseus (with core)
$\sin^2(2\theta)$ (10^{-11})	$6.8^{+1.4}_{-1.4}$	$18.2^{+4.4}_{-3.9}$	$23.3^{+7.6}_{-6.9}$	$55.3^{+25.5}_{-15.9}$

Predictions: Clusters

[Conlon, Powell '14 (June)]





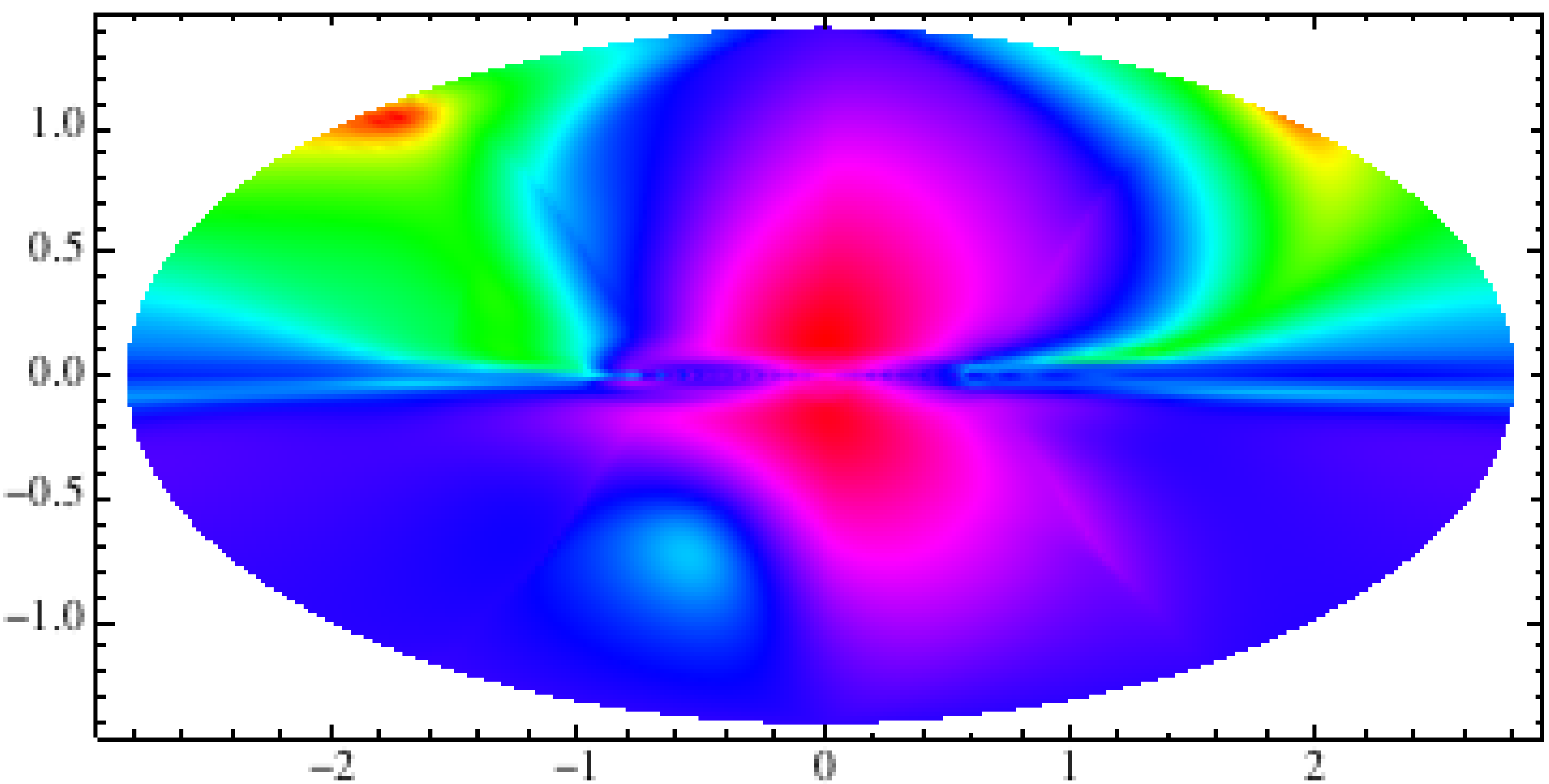
Seems to be already in the data!

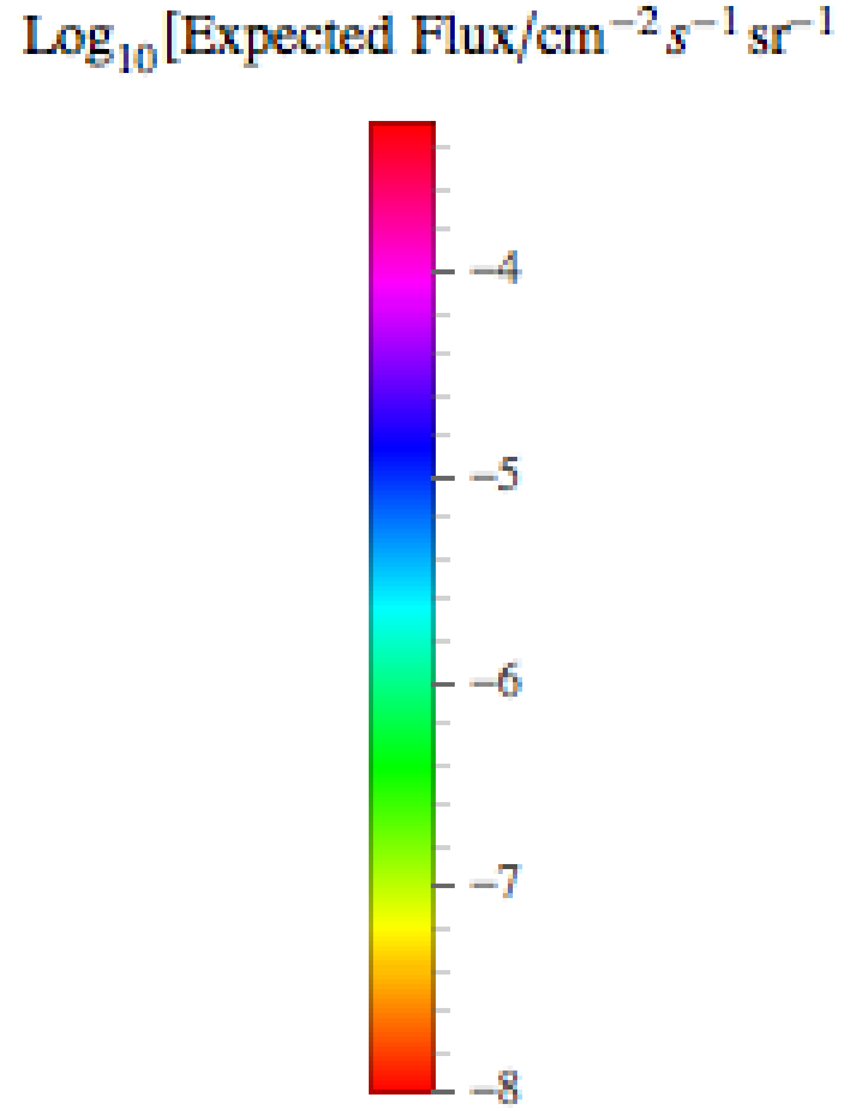
$\Rightarrow$ Stack cool-core vs non-cool-core!

Predictions: Milky Way

(excluding galactic center)

$\mathrm{DM} \to a \to \gamma$ [Conlon, Day '14(April)]



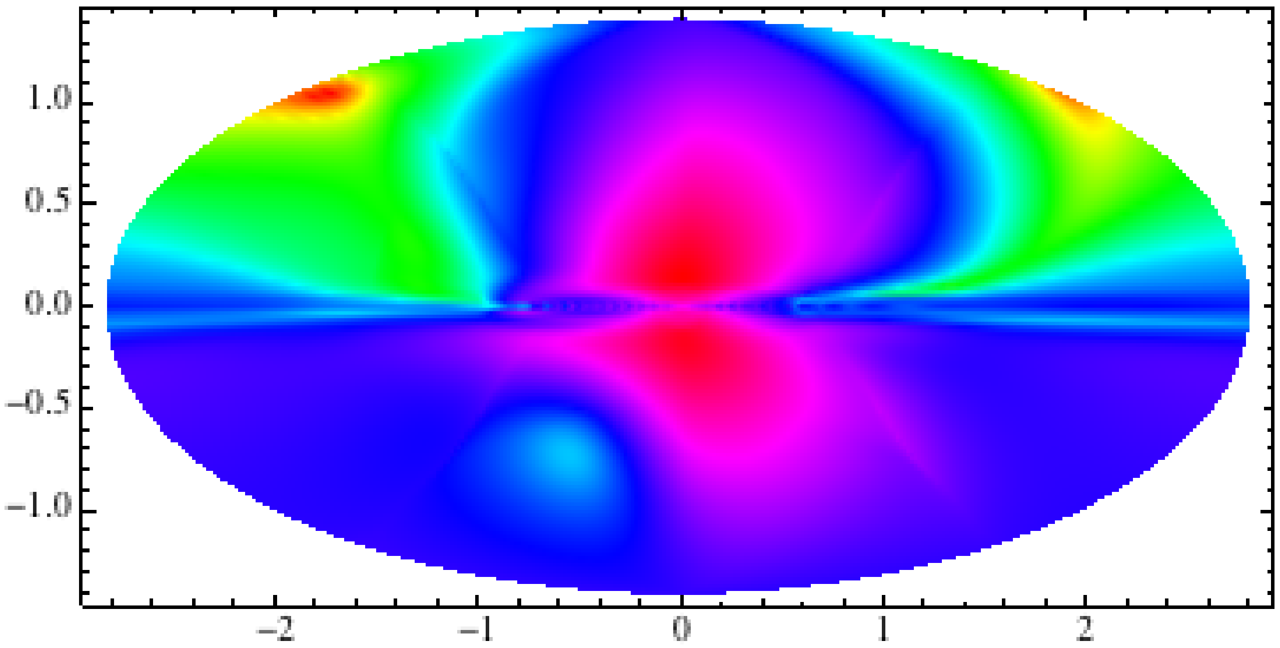


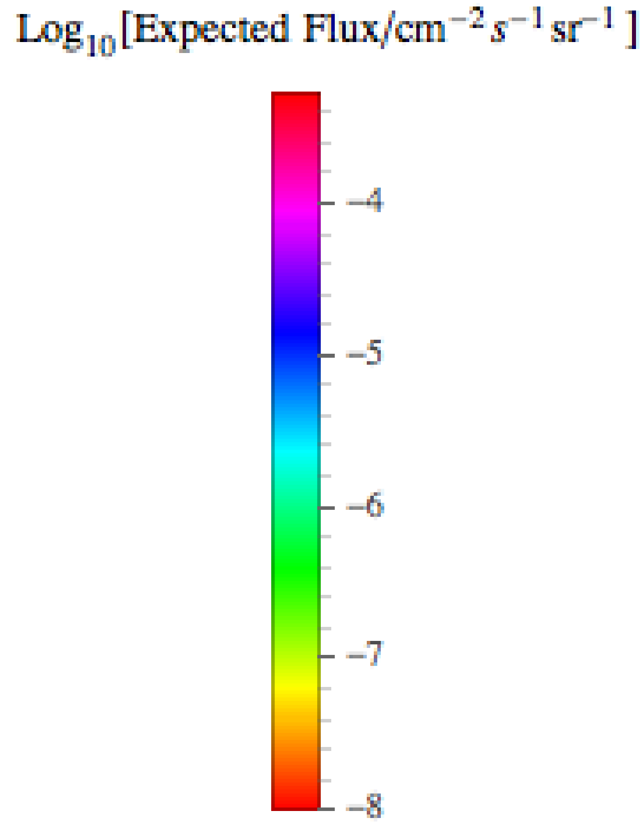
Electron density: [Gomez, Benjamin, Cox '01]

Magnetic field: [Janson, Farrar '12]

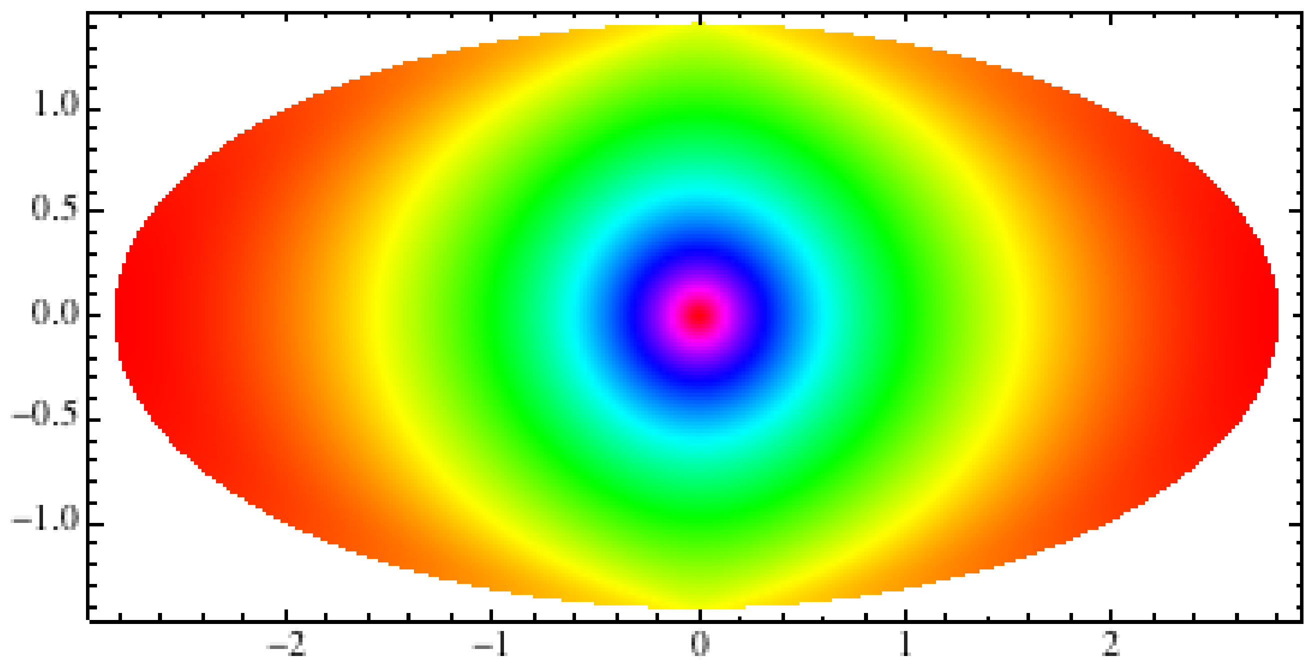
Predictions: Milky Way

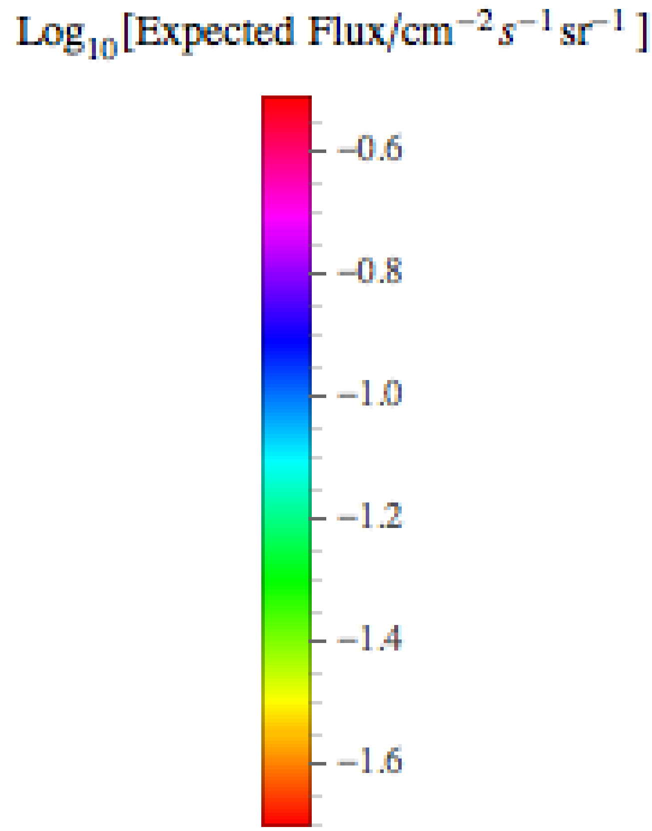
$\mathrm{DM} \rightarrow a \rightarrow \gamma$





$\mathrm{DM} \rightarrow \gamma$





[Conlon, Day ’14(April)]

M31

[Conlon, Day '14(April)]

- In many ways similar to MW but twice as big
- Regular magnetic field is significantly bigger and significantly more coherent than in MW
- $B_{reg} \sim B_{random} \sim 5\mu\text{G}$ between 6 - 14 kpc vs generally $B_{reg} \sim \frac{B_{random}}{3}$ [Han, Beck, Berkhuijsen '98], [Flechter, Berkhuijsen, Beck, Shukurov '03]
- No sign of large scale field reversal as in MW
- Close to edge on (77.5 degrees inclination)

M31

[Conlon, Day '14(April)]

- In many ways similar to MW but twice as big
- Regular magnetic field is significantly bigger and significantly more coherent than in MW
- $B_{reg} \sim B_{random} \sim 5\mu\mathrm{G}$ between 6 - 14 kpc vs generally $B_{reg} \sim \frac{B_{random}}{3}$ [Han, Beck, Berkhuijsen '98], [Flechter, Berkhuijsen, Beck, Shukurov '03]
- No sign of large scale field reversal as in MW
- Close to edge on (77.5 degrees inclination)

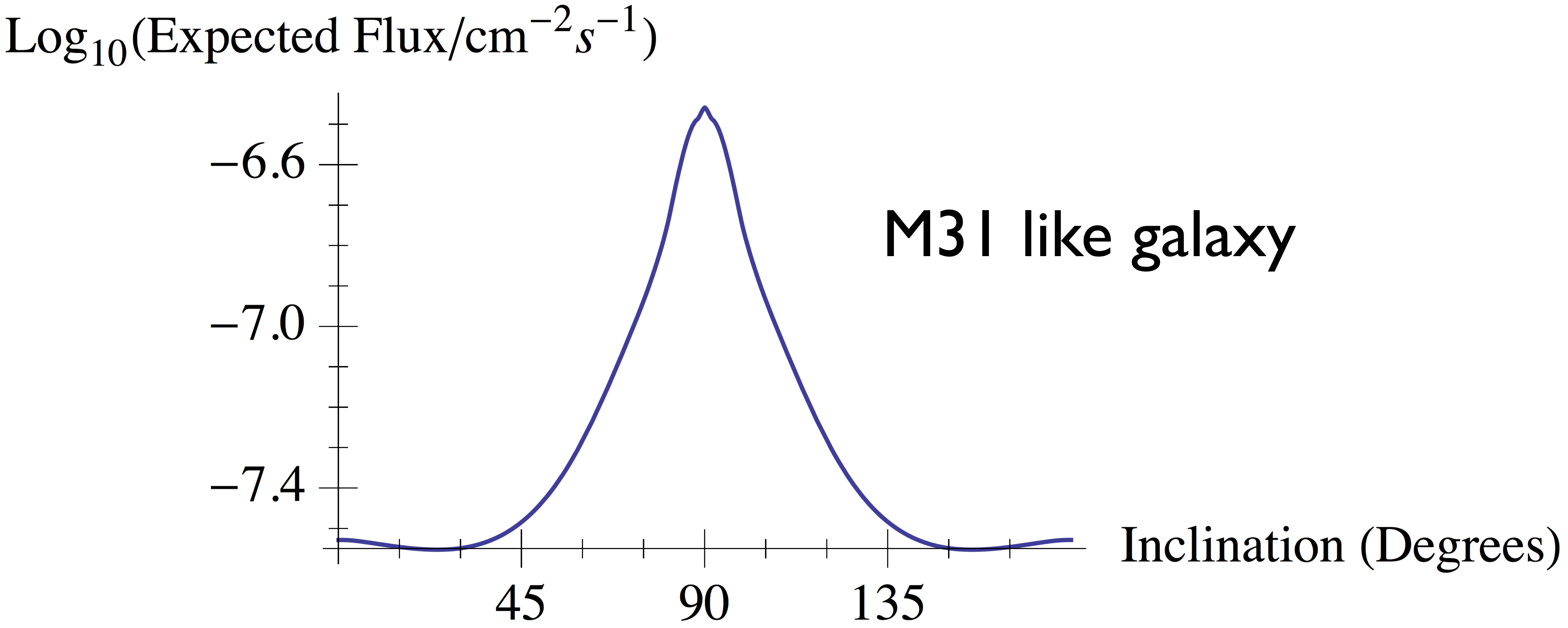
$\Rightarrow$ For $B_\perp \sim 5\,\mu\mathrm{G}$, $L \sim 20\,\mathrm{kpc}$: $P_{a\to\gamma,M31} \sim 10^2\, P_{a\to\gamma,MW}$

Predictions: Galaxies

- Signals from **edge on** galaxies should be stronger than from **face on**
- Consistent with Anderson et al. non-detection!

Stacked galaxy spectra

[Alvarez, Conlon, Day, Marsh, MR '14(Oct)]



(List of nearby edge-on spiral galaxies in paper)

Galactic center

[Alvarez, Conlon, Day, Marsh, MR '14(Oct)]

- Electron density

$$n_{e,\mathrm{GC}}(x,y,z) = 10\,\mathrm{cm}^{-3}\exp\left[-\frac{x^2+(y-y_{\mathrm{GC}})^2}{L_{\mathrm{GC}}^2}\right]\exp\left[-\frac{(z-z_{\mathrm{GC}})^2}{H_{\mathrm{GC}}^2}\right]$$

$L_{\mathrm{GC}} = 145\,\mathrm{pc}$ and $H_{\mathrm{GC}} = 26\,\mathrm{pc}$.

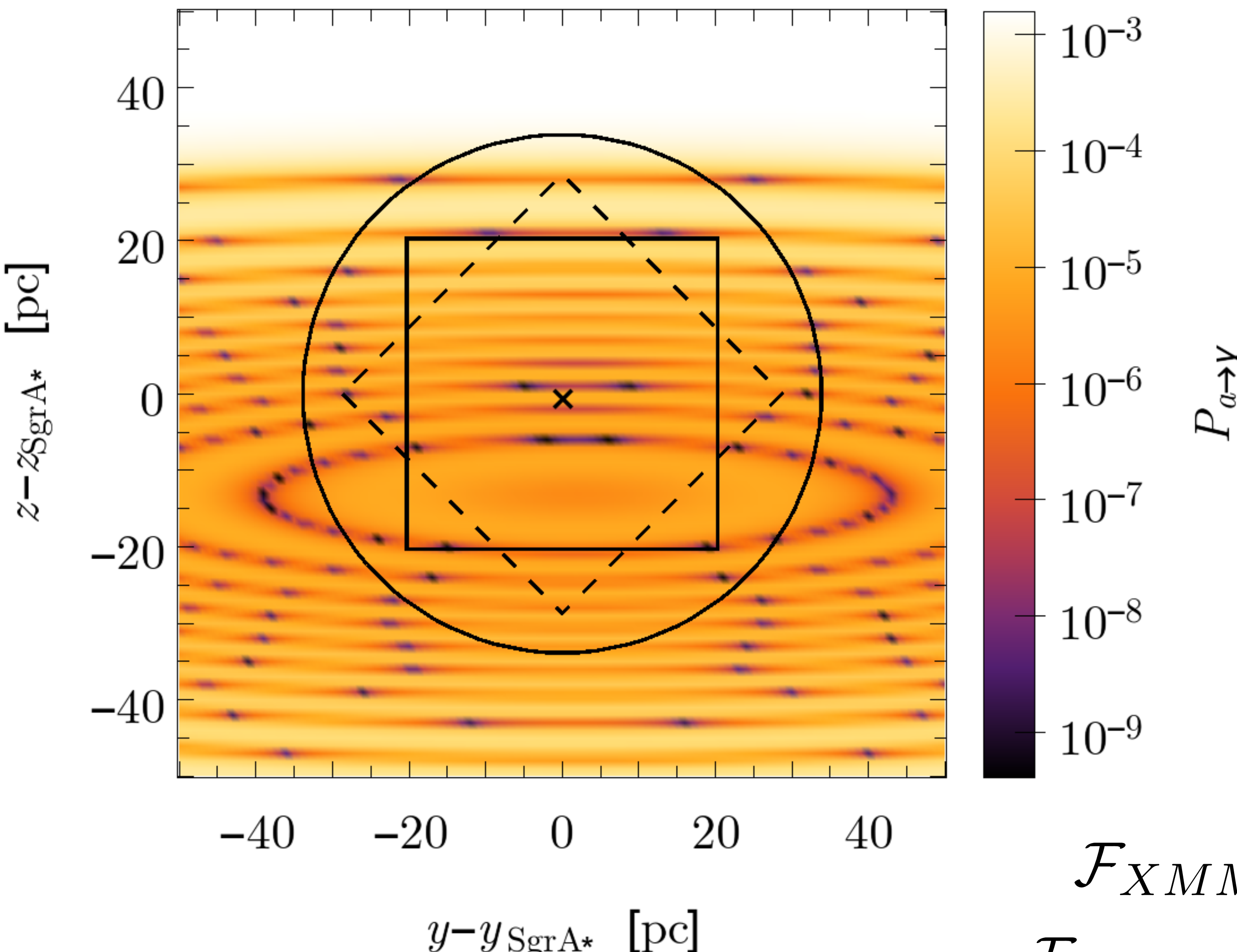
$y_{\mathrm{GC}} = 10\,\mathrm{pc}$ and $z_{\mathrm{GC}} = -20\,\mathrm{pc}$ [Cordes, Lazio '02]

- Magnetic field in central 100-200 pc highly unknown: $0.01 - 1\ \mathrm{m}G$ [Davidson '96], [Morris '07, '14], [Ferrière '09, '10]

- FOV: $r = 15'$ (XMM), $16.8' \times 16.8'$ (Chandra)

Galactic center

[Alvarez, Conlon, Day, Marsh, MR '14(Oct)]



$$\frac{\langle P_{a\to\gamma}\rangle_{XMM}}{\langle P_{a\to\gamma}\rangle_{Chandra}} = \begin{cases} \frac{3.0\times10^{-5}}{1.4\times10^{-5}} = 2.1 \\ \frac{3.0\times10^{-5}}{1.5\times10^{-5}} = 2.0 \end{cases}$$

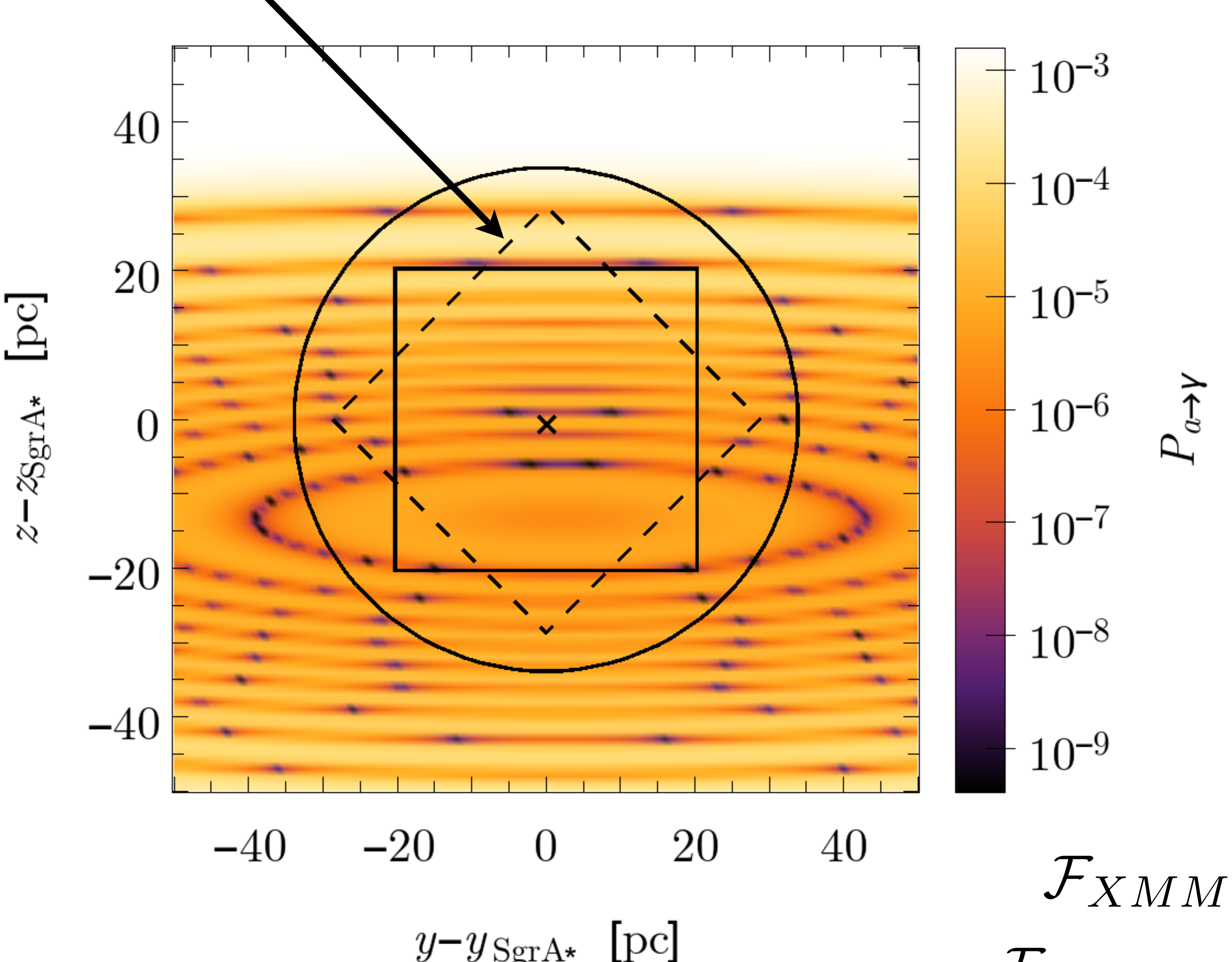
$$\frac{\mathcal{F}_{XMM}}{\mathcal{F}_{Chandra}} = \begin{cases} 4.6 & \text{for } \alpha_r = 0^\circ \\ 4.4 & \text{for } \alpha_r = 45^\circ \end{cases}$$

for $B = 1$ mG over 150 pc

$$\mathcal{F}_{XMM} = 2.9\times10^{-5} \ \text{photons s}^{-1}\text{cm}^{-2}$$
$$\mathcal{F}_{Chandra} = 6.7\times10^{-6} \ \text{photons s}^{-1}\text{cm}^{-2}$$

Galactic center

$$\mathcal{F}_{XMM}^{z>20\text{pc}} = 2.1 \times 10^{-5} \quad \text{photons s}^{-1}\text{cm}^{-2}$$ [Alvarez, Conlon, Day, Marsh, MR '14(Oct)]



$$\frac{\langle P_{a\to\gamma}\rangle_{XMM}}{\langle P_{a\to\gamma}\rangle_{Chandra}} = \begin{cases} \frac{3.0\times10^{-5}}{1.4\times10^{-5}} = 2.1 \\ \frac{3.0\times10^{-5}}{1.5\times10^{-5}} = 2.0 \end{cases}$$

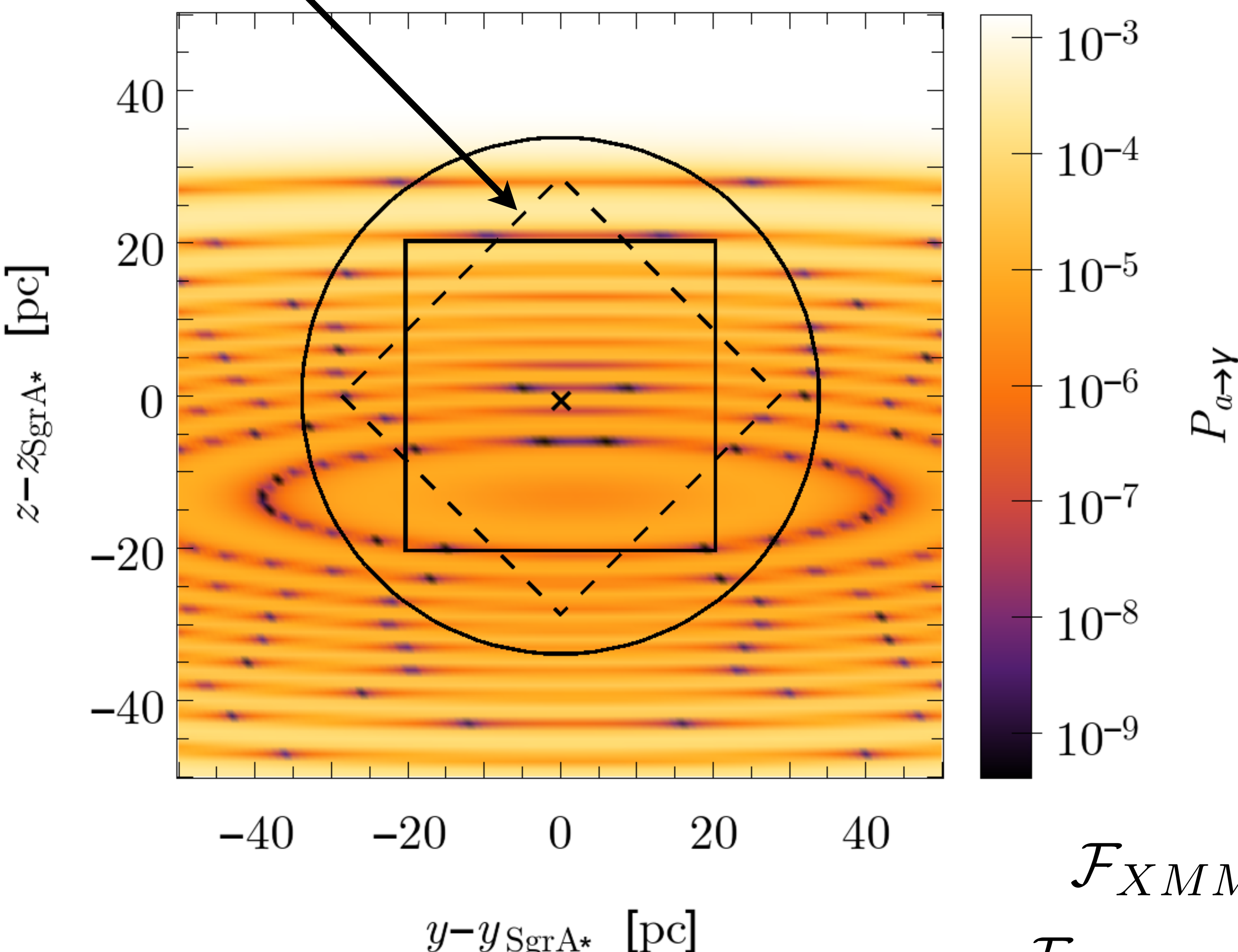
$$\frac{\mathcal{F}_{XMM}}{\mathcal{F}_{Chandra}} = \begin{cases} 4.6 & \text{for } \alpha_r = 0^\circ \\ 4.4 & \text{for } \alpha_r = 45^\circ \end{cases}$$

for $B = 1$ mG over 150 pc

$$\mathcal{F}_{XMM} = 2.9 \times 10^{-5} \quad \text{photons s}^{-1}\text{cm}^{-2}$$
$$\mathcal{F}_{Chandra} = 6.7 \times 10^{-6} \quad \text{photons s}^{-1}\text{cm}^{-2}$$

Galactic center

$\mathcal{F}_{XMM}^{z>20\text{pc}} = 2.1 \times 10^{-5}$ photons $\text{s}^{-1}\text{cm}^{-2}$ [Alvarez, Conlon, Day, Marsh, MR '14(Oct)]



$$\frac{\langle P_{a\to\gamma}\rangle_{XMM}}{\langle P_{a\to\gamma}\rangle_{Chandra}} = \begin{cases} \frac{3.0\times10^{-5}}{1.4\times10^{-5}} = 2.1 \\ \frac{3.0\times10^{-5}}{1.5\times10^{-5}} = 2.0 \end{cases}$$

$$\frac{\mathcal{F}_{XMM}}{\mathcal{F}_{Chandra}} = \begin{cases} 4.6 & \text{for } \alpha_r = 0^\circ \\ 4.4 & \text{for } \alpha_r = 45^\circ \end{cases}$$

for $B = 1$ mG over 150 pc

$$\mathcal{F}_{XMM} = 2.9 \times 10^{-5} \text{ photons s}^{-1}\text{cm}^{-2}$$
$$\mathcal{F}_{Chandra} = 6.7 \times 10^{-6} \text{ photons s}^{-1}\text{cm}^{-2}$$

$\Rightarrow$ XMM detection and Chandra non-detection reconciled

Conclusions

- For $\mathrm{DM} \to a \to \gamma$ photon signal is convolution of DM density and magnetic field along l.o.s.
- Different morphology of cluster and galaxy signals than $DM \to \gamma$: (non-)cool core, edge/face on
- Observable flux effectively depends on one free parameter $F_{DM \to a \to \gamma} \propto 1/\tau_{DM \to a} M^2$ (as $DM \to \gamma$)

Conclusions

Observational consistency of $\mathrm{DM} \to a \to \gamma$:

- Signal is produced in galaxy clusters but absent in dwarf spheroidals and stacked galaxies
- A signal is observed in M31 but not in other galaxies
- Perseus signal follows the cool-core feature

More observations will follow in the near future (particularly Astro-H), hopefully the line remains a signal of new physics!

Outline

1. Summary of 3.5 keV observations
2. The model: $\mathrm{DM} \to a \to \gamma$
3. $\mathrm{DM} \to a \to \gamma$ vs $\mathrm{DM} \to \gamma$ morphology
4. A Cosmic Axion Background

Moduli Cosmology

- String Theory compactifications come with $\mathcal{O}(100)$ moduli ϕ

[Cicoli,Conlon,Quevedo '12], [Higaki,Takahashi '12]

Moduli Cosmology

- String Theory compactifications come with $\mathcal{O}(100)$ moduli ϕ

[Cicoli,Conlon,Quevedo '12], [Higaki, Takahashi '12]

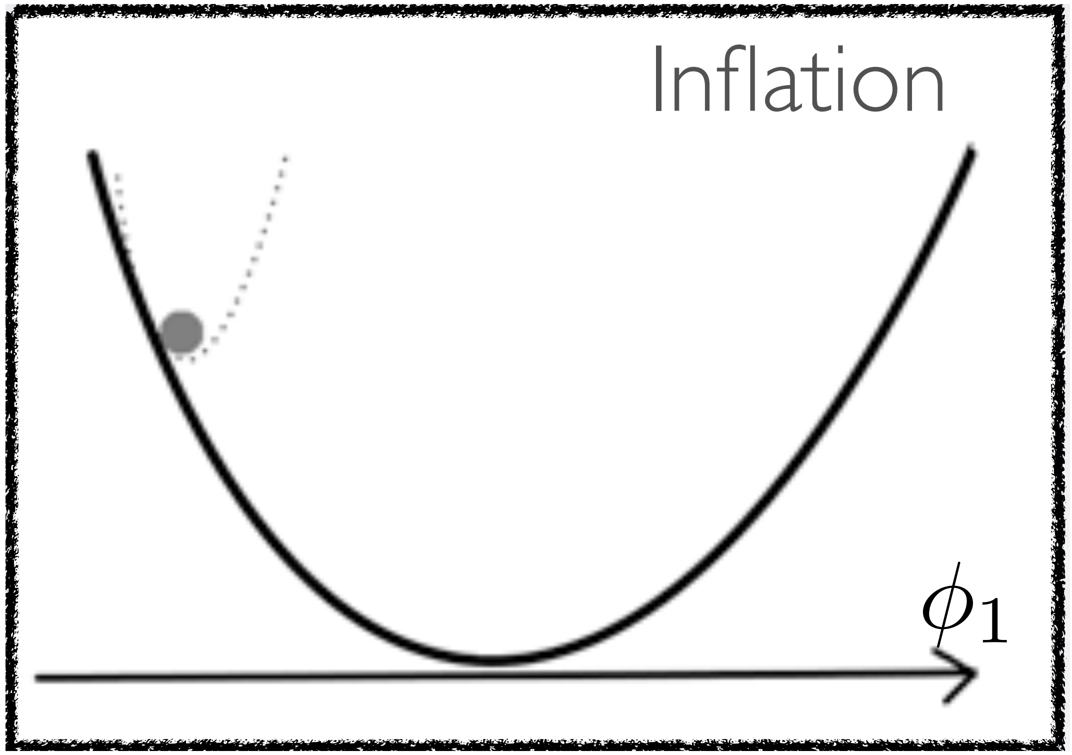
- Get displaced from minimum during inflation

Moduli Cosmology

- String Theory compactifications come with $\mathcal{O}(100)$ moduli ϕ

[Cicoli,Conlon,Quevedo '12], [Higaki,Takahashi '12]

- Get displaced from minimum during inflation

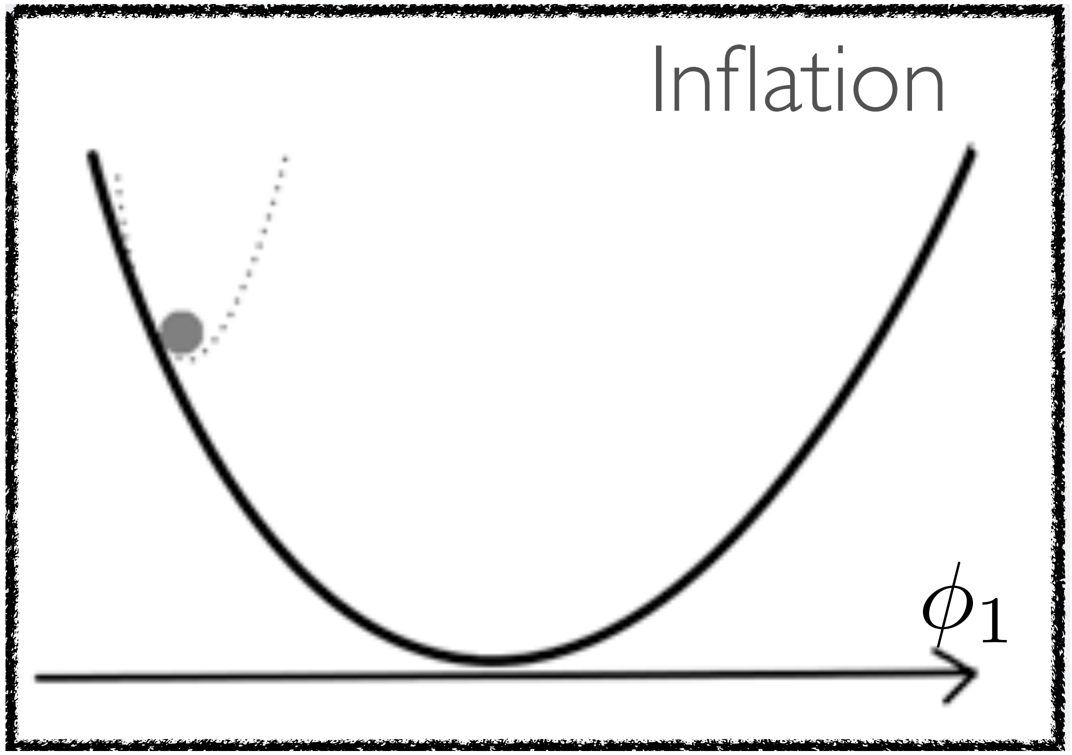


Moduli Cosmology

- String Theory compactifications come with $\mathcal{O}(100)$ moduli ϕ

[Cicoli,Conlon,Quevedo '12], [Higaki, Takahashi '12]

- Get displaced from minimum during inflation
- Lightest modulus comes to dominate energy of the universe since $\Gamma_\phi \sim m_\phi^3/M_{\rm Pl}^2$

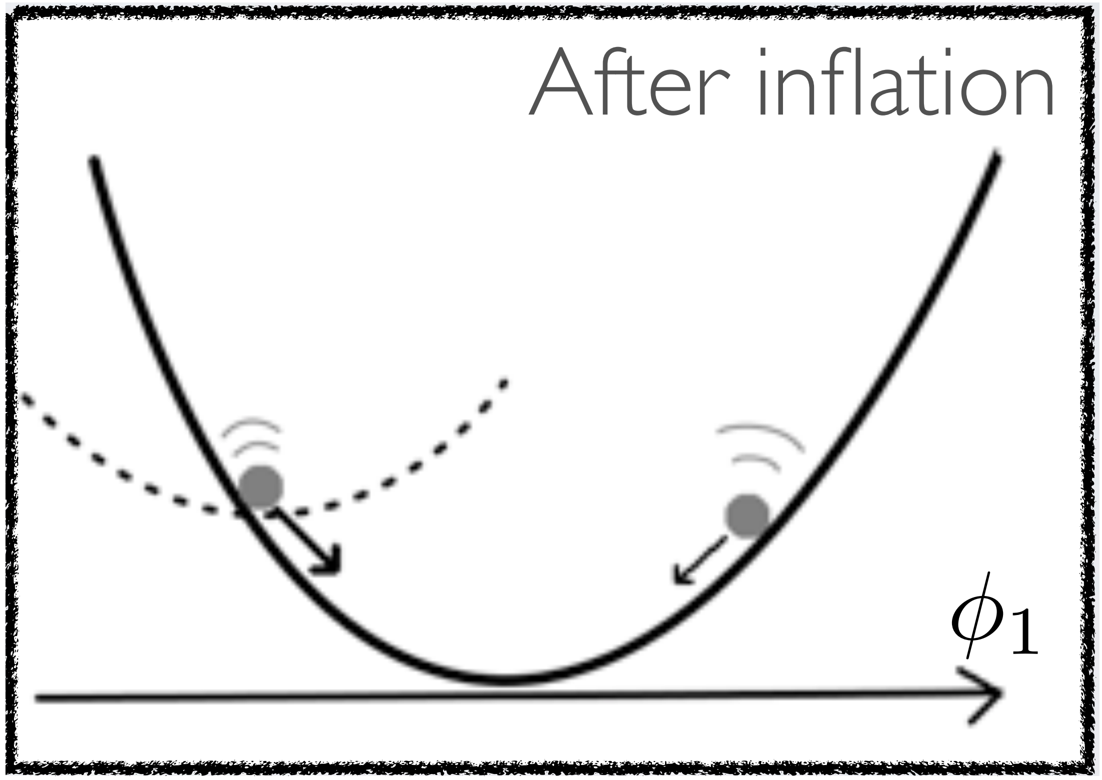


Moduli Cosmology

- String Theory compactifications come with $\mathcal{O}(100)$ moduli ϕ

[Cicoli,Conlon,Quevedo '12], [Higaki,Takahashi '12]

- Get displaced from minimum during inflation
- Lightest modulus comes to dominate energy of the universe since $\Gamma_\phi \sim m_\phi^3/M_{\rm Pl}^2$



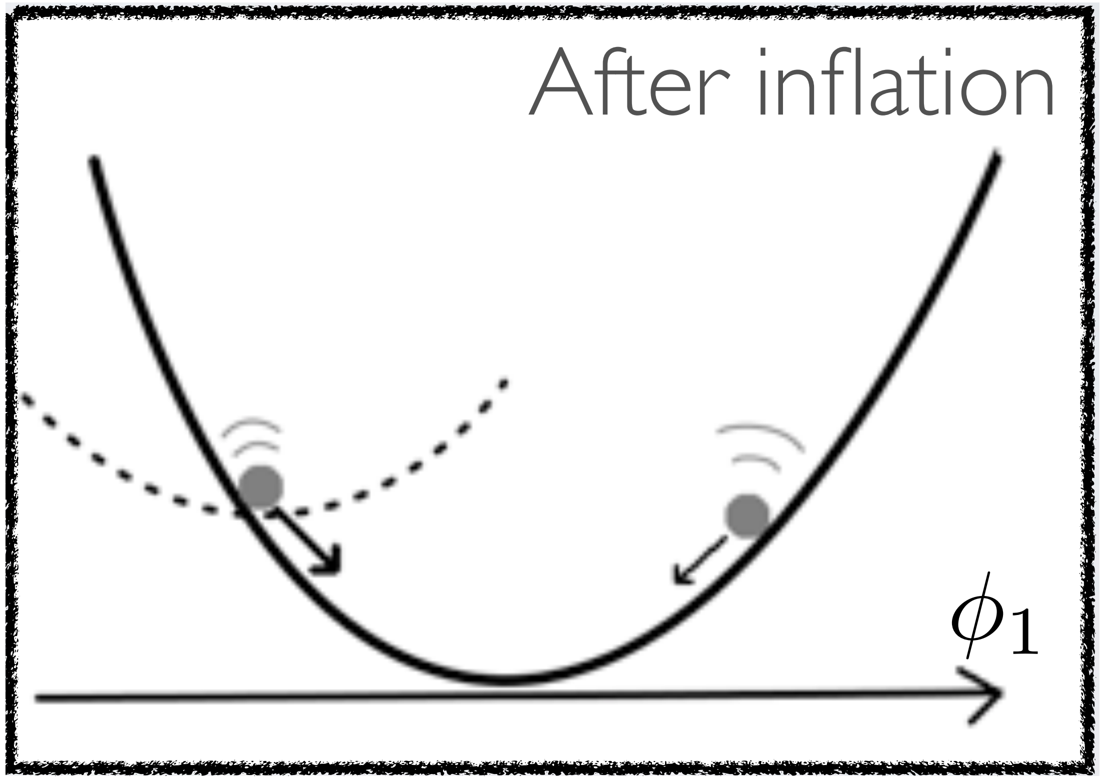
$$\rho_{\rm matter} \sim a^{-3}(t)$$
$$\rho_{\rm radiation} \sim a^{-4}(t)$$

Moduli Cosmology

- String Theory compactifications come with $\mathcal{O}(100)$ moduli ϕ

[Cicoli,Conlon,Quevedo '12], [Higaki,Takahashi '12]

- Get displaced from minimum during inflation



- Lightest modulus comes to dominate energy of the universe since $\Gamma_\phi \sim m_\phi^3/M_{\rm Pl}^2$

- Decay of lightest modulus starts big bang cosmology

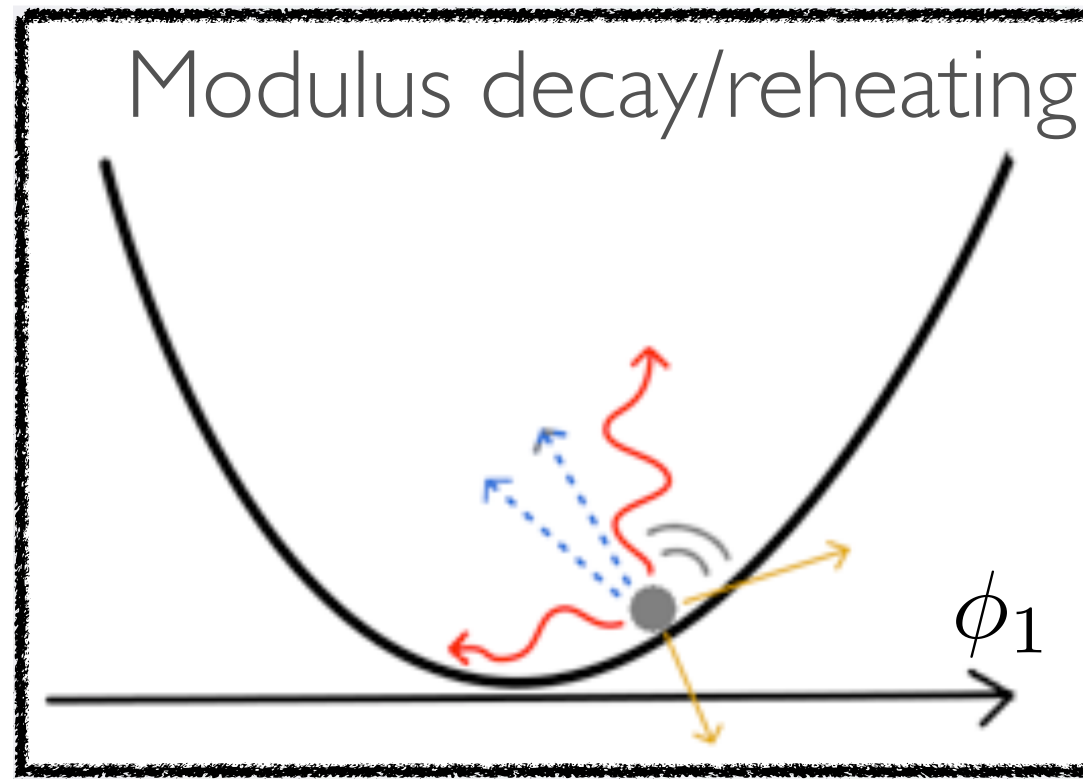
$$\rho_{\rm matter} \sim a^{-3}(t)$$
$$\rho_{\rm radiation} \sim a^{-4}(t)$$

Moduli Cosmology

- String Theory compactifications come with $\mathcal{O}(100)$ moduli ϕ

[Cicoli,Conlon,Quevedo '12], [Higaki,Takahashi '12]

- Get displaced from minimum during inflation



- Lightest modulus comes to dominate energy of the universe since $\Gamma_\phi \sim m_\phi^3/M_{\rm Pl}^2$
- Decay of lightest modulus starts big bang cosmology

A Cosmic Axion Background

[Conlon, Marsh '13]

- $\mathrm{Br}(\phi \to \mathrm{visibles})$ vs $\mathrm{Br}(\phi \to \mathrm{hidden})$ decides population of different sectors
- String compactifications typically come with light hidden sectors (e.g. hidden gauge groups, *ALPs*)
- Hidden light fields contribute as *Dark Radiation* (experimental hints: $\begin{array}{l}\text{Planck: } N_{\text{eff}} = 3.30 \pm 0.27 \\ \text{Planck} + H_0\text{: } N_{\text{eff}} = 3.62 \pm 0.25\end{array}$)
- $\phi \to \mathrm{ALPs}$ generally not suppressed (e.g. via kinetic coupling to volume modulus in type IIB)

A Cosmic Axion Background

[Conlon, Marsh '13]

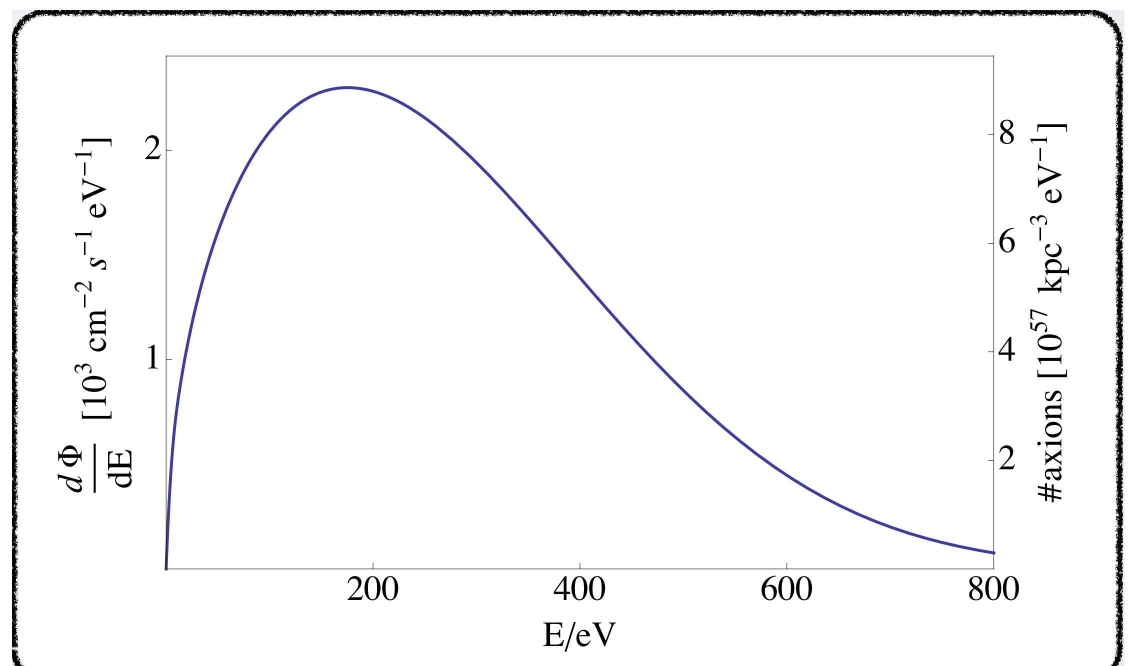
- $\mathrm{Br}(\phi \to \mathrm{visibles})$ vs $\mathrm{Br}(\phi \to \mathrm{hidden})$ decides population of different sectors
- String compactifications typically come with light hidden sectors (e.g. hidden gauge groups, *ALPs*)
- Hidden light fields contribute as *Dark Radiation* (experimental hints: $\begin{array}{l} \text{Planck: } N_{\text{eff}} = 3.30 \pm 0.27 \\ \text{Planck} + H_0\text{: } N_{\text{eff}} = 3.62 \pm 0.25 \end{array}$)
- $\phi \to \mathrm{ALPs}$ generally not suppressed (e.g. via kinetic coupling to volume modulus in type IIB)

$\Rightarrow$ ***Dark Radiation/a CAB is a rather generic prediction of String Theory Cosmology***

Properties of the CAB

- Modulus decay produces relativistic non-thermal ALPs a with $E_a = m_\phi/2$
- Energy density: $\rho_{CAB} = \Delta N_{eff} \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} \rho_{CMB}$
- CAB energy: $\frac{E_{a,\mathrm{now}}}{T_{\gamma,\mathrm{now}}} \simeq \frac{E_{a,\mathrm{init}}}{T_{\gamma,\mathrm{init}}} \sim \left(\frac{M_\mathrm{P}}{m_\Phi}\right)^{1/2}$
- For $m_\phi \sim 10^6\ \mathrm{GeV}$ ($\gtrsim 10^4\ \mathrm{GeV}$ to avoid CMP)

$\langle E_{CAB} \rangle \sim 200\ \mathrm{eV}\ (\mathrm{X\text{-}ray})$



- Couples to photons via

$$\mathcal{L} \supset \frac{1}{M} a\, \boldsymbol{E} \cdot \boldsymbol{B}$$

Galaxy Clusters and ALPs

- Galaxy Clusters are the largest gravitationally bound objects in the universe
- Typically kpc scale coherent magnetic fields $B \sim \mathcal{O}(1)\mu\mathrm{G}$

Galaxy Clusters and ALPs

- Galaxy Clusters are the largest gravitationally bound objects in the universe
- Typically kpc scale coherent magnetic fields $B \sim \mathcal{O}(1)\mu\mathrm{G}$

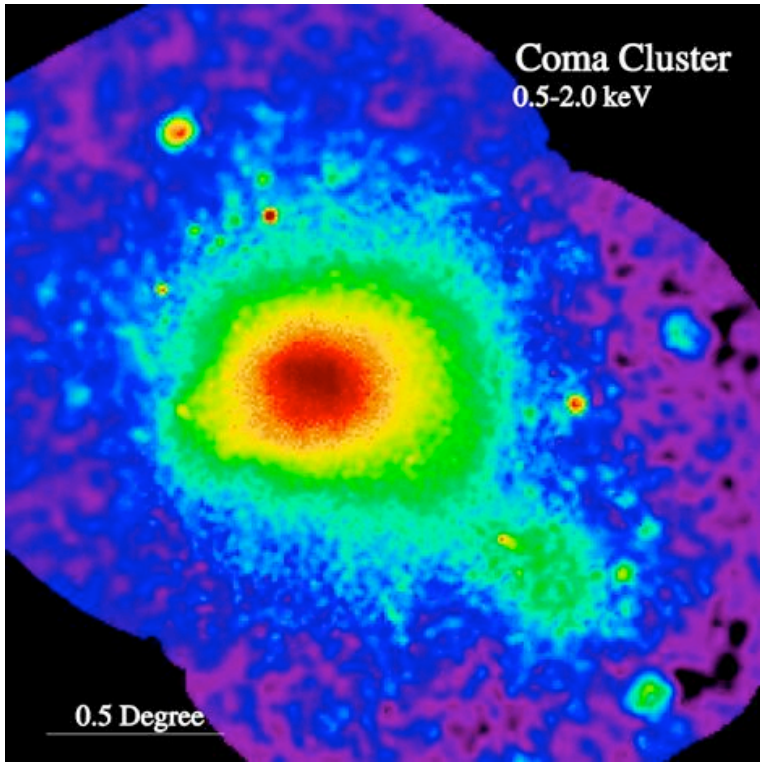
$\Rightarrow$ *Interesting "Labs" to study the CAB via ALP to photon conversion!*

[Conlon, Marsh '13]

Soft X-ray Excess in Coma

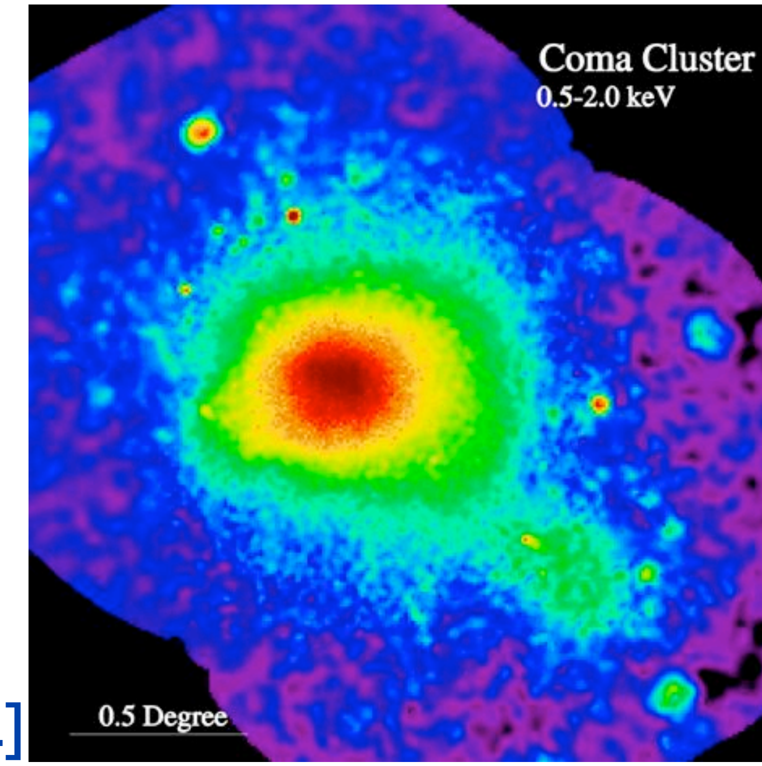
- Clusters are filled by hot gas which emits in X-rays via thermal bremsstrahlung
- Soft Excess is observed by EUVE and ROSAT in ~30% of 38 clusters

[Bonamente, Lieu, Joy, Nevalainen'02]

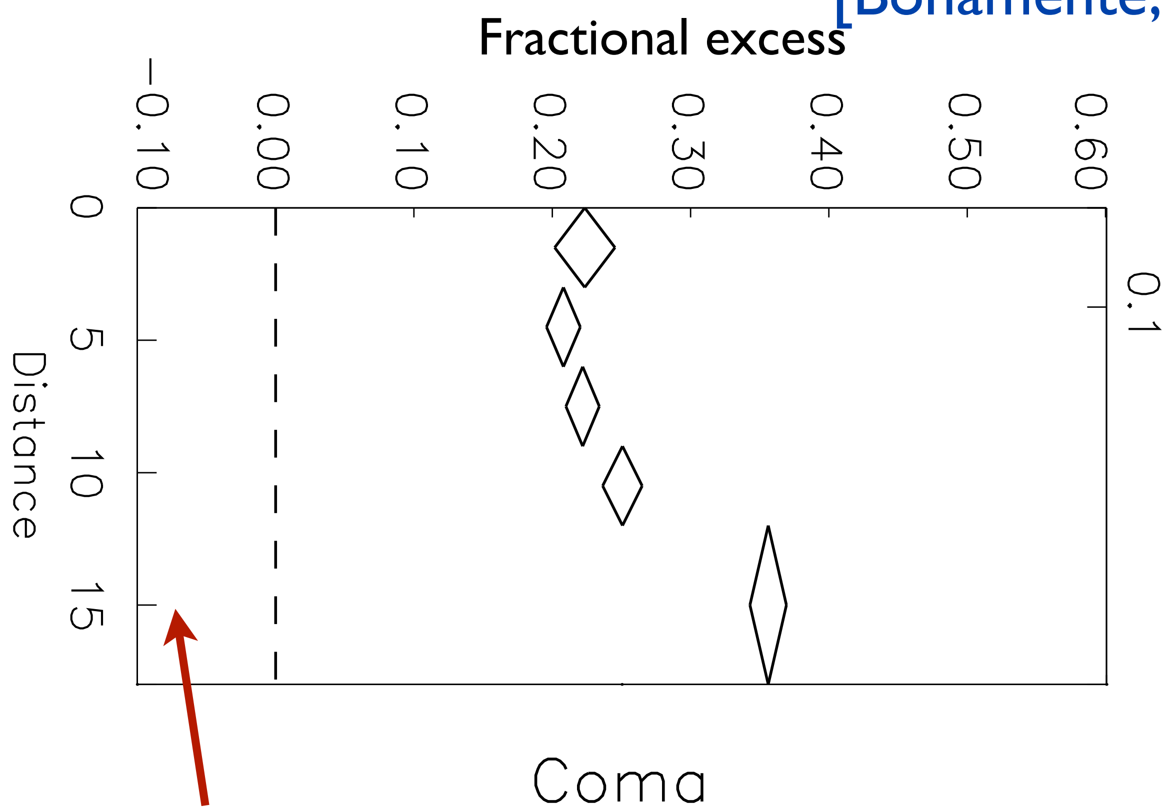


Soft X-ray Excess in Coma

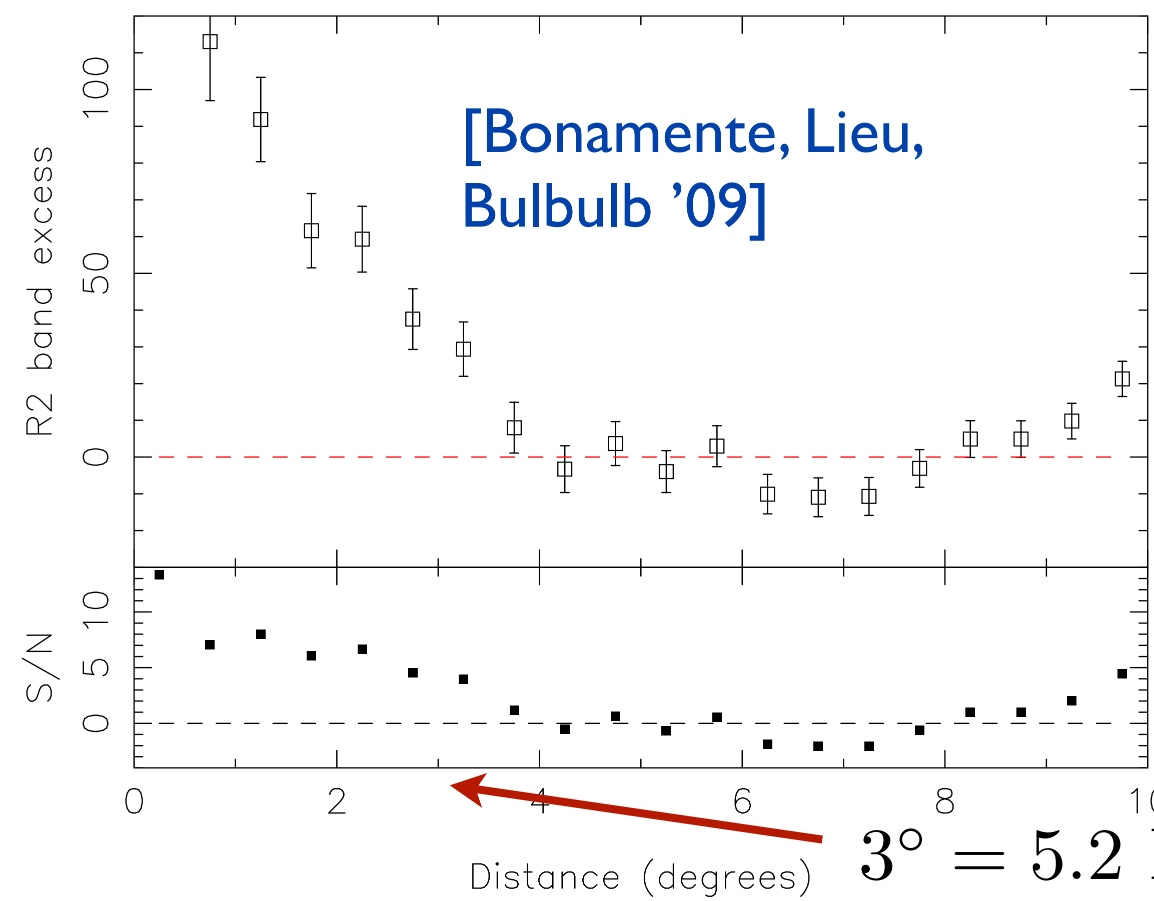
- Clusters are filled by hot gas which emits in X-rays via thermal bremsstrahlung
- Soft Excess is observed by EUVE and ROSAT in ~30% of 38 clusters



[Bonamente, Lieu, Joy, Nevalainen'02]



$15\ \mathrm{arcmin} = 0.4\ \mathrm{Mpc}$



[Bonamente, Lieu, Bulbulb '09]

$3^\circ = 5.2\ \mathrm{Mpc}$

Proposed astrophysical explanations

- *Thermal Bremsstrahlung* from a ‘colder’ (T ~ 200 eV) gas: But associated emission lines not seen
- *Inverse-Compton* scattering of the CMB by relativistic cosmic ray electrons: But no associated gamma ray bremsstrahlung flux

Proposed astrophysical explanations

- *Thermal Bremsstrahlung* from a 'colder' (T ~ 200 eV) gas: But associated emission lines not seen
- *Inverse-Compton* scattering of the CMB by relativistic cosmic ray electrons: But no associated gamma ray bremsstrahlung flux

$\Rightarrow$ *Known astrophysical explanations not compelling*

$\Rightarrow$ *Explore cosmological CAB explanation of the soft X-ray excess!*

Conversion parameters

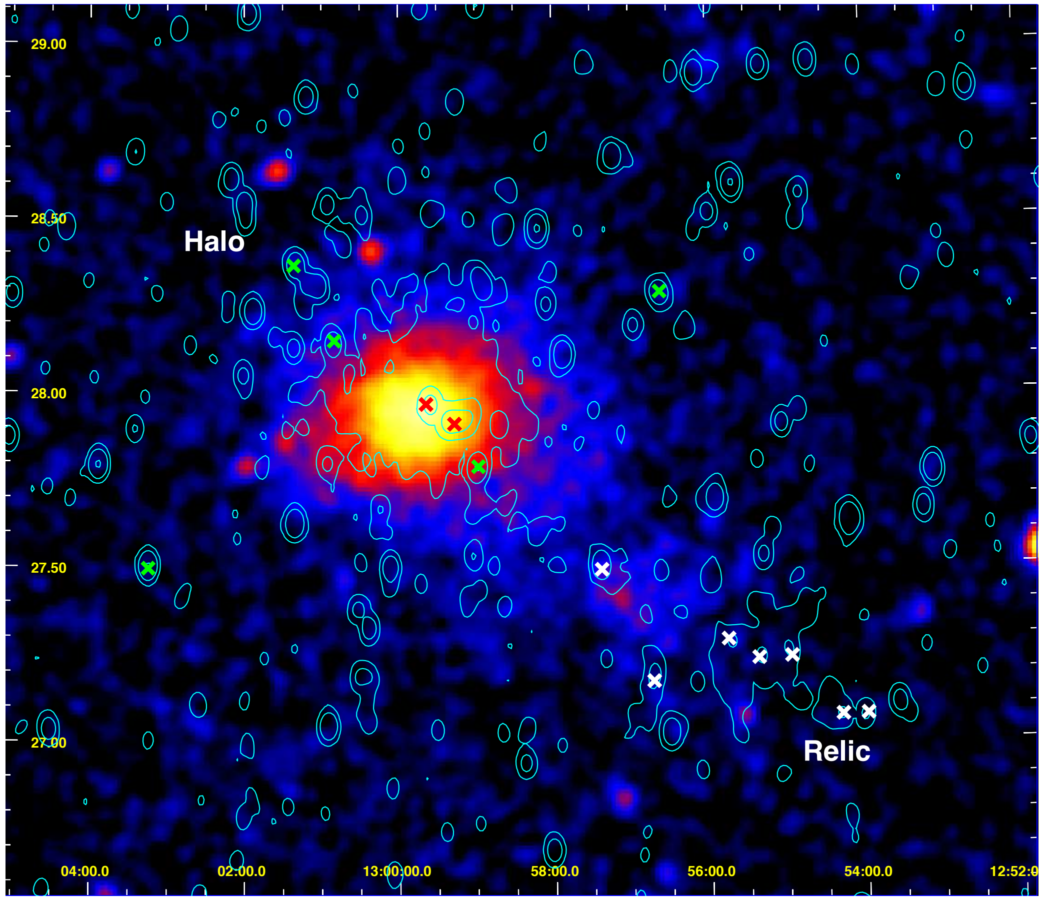
- Electron density via X-ray brightness profile

$$n_e(r) = n_0 \left(1 + \frac{r^2}{r_c^2}\right)^{-\frac{3}{2}\beta}$$

- Magnetic field via Faraday rotation $RM = \frac{e^3}{2\pi m_e^2} \int_{l.o.s} n_e(l) B_{||}(l) \mathrm{d}l$

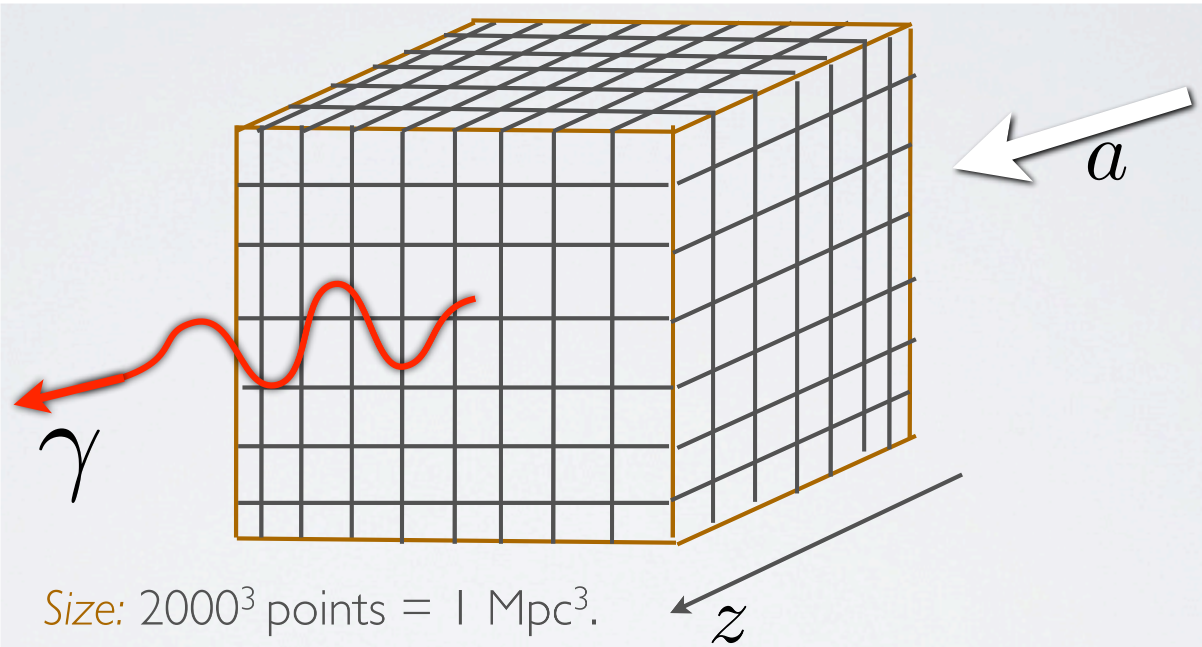
$$\Rightarrow B(r) = C \cdot B_0 \left(\frac{n_e(r)}{n_0}\right)^{\eta}$$ (via simulation vs RM)

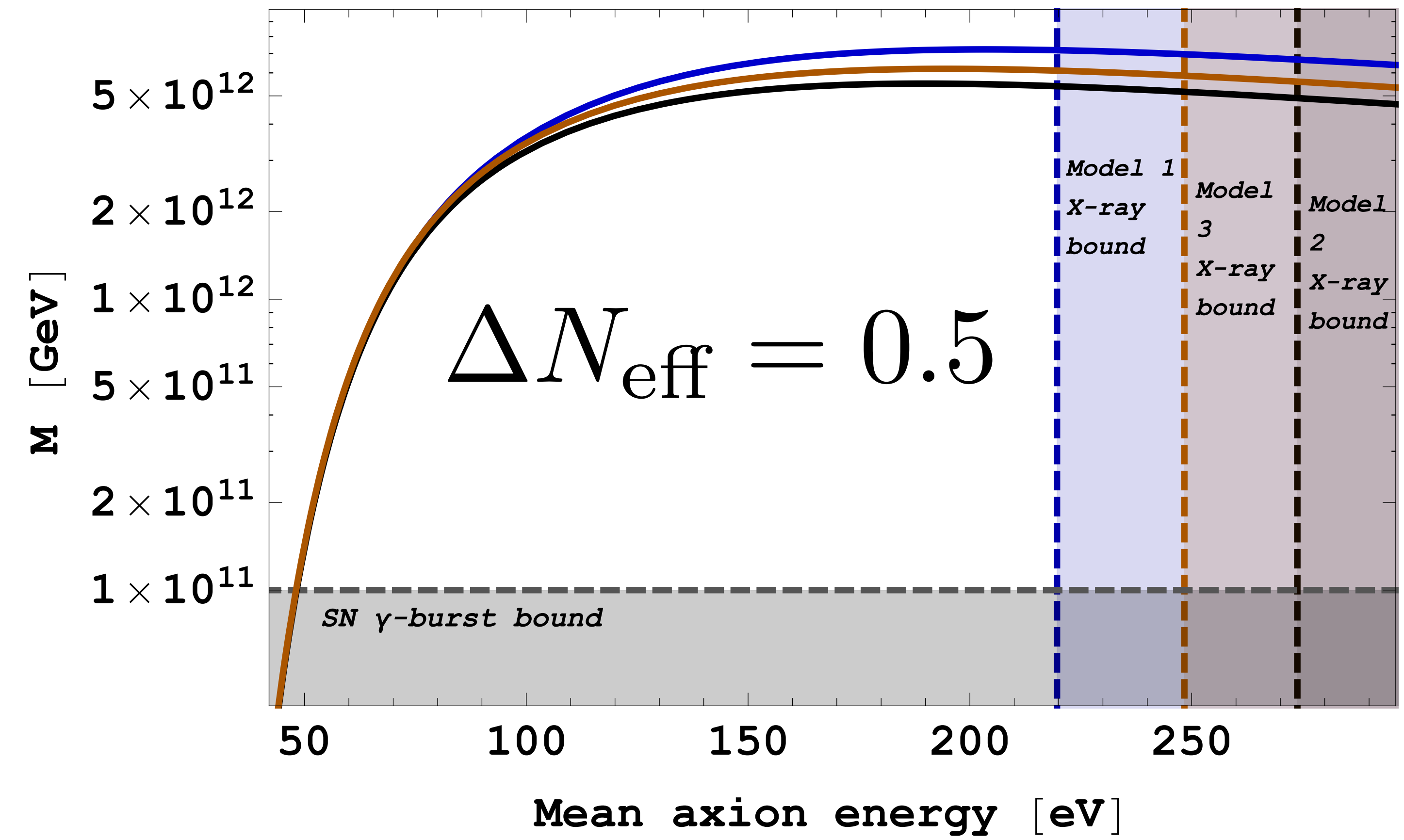
- Coherence Length $p(L, \boldsymbol{x}) \sim L^{n-6}$ or $\sim n_e^{-1} L^{n-6}$



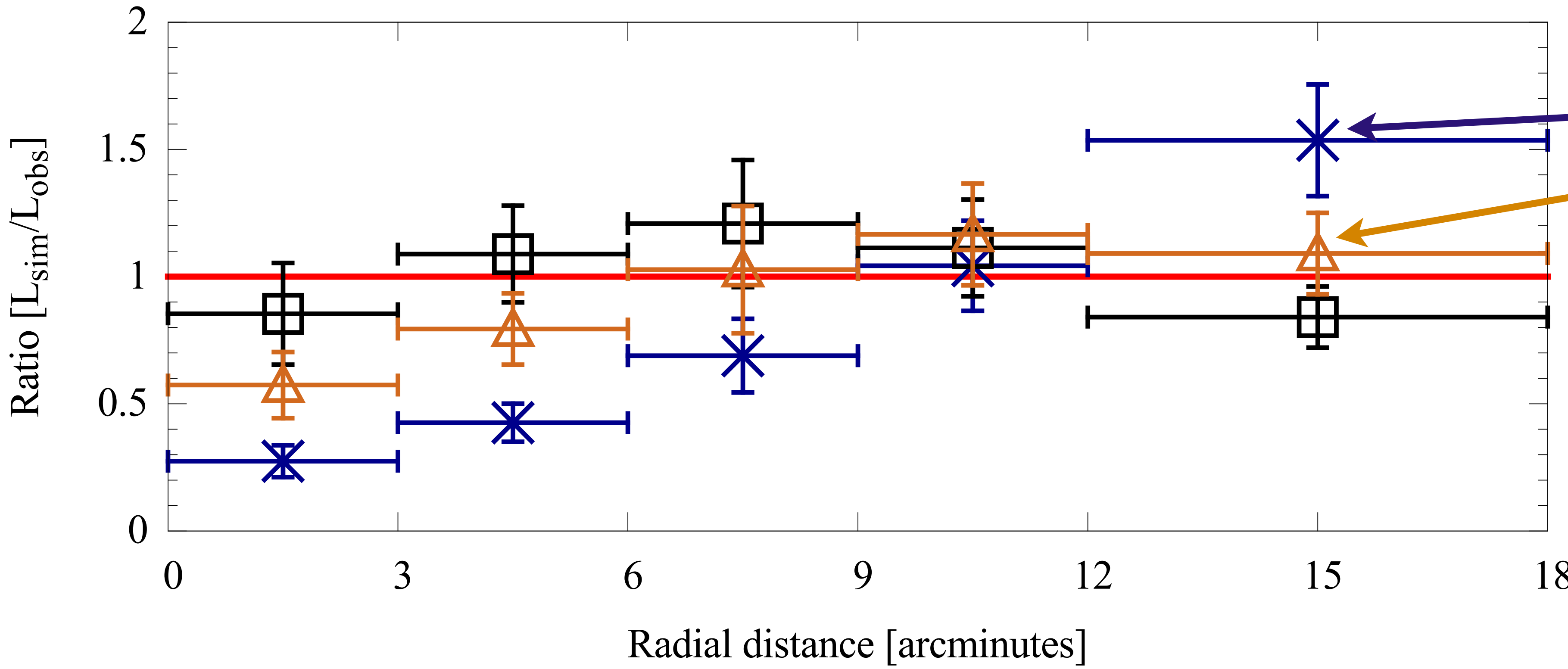
[Bonafede,Vazza,Bruggen,Murgia, Govoni,Feretti,Giovannini,Ogrean'13]

Coma center results





[Angus, Conlon, Marsh, Powell, Witkowski '13]



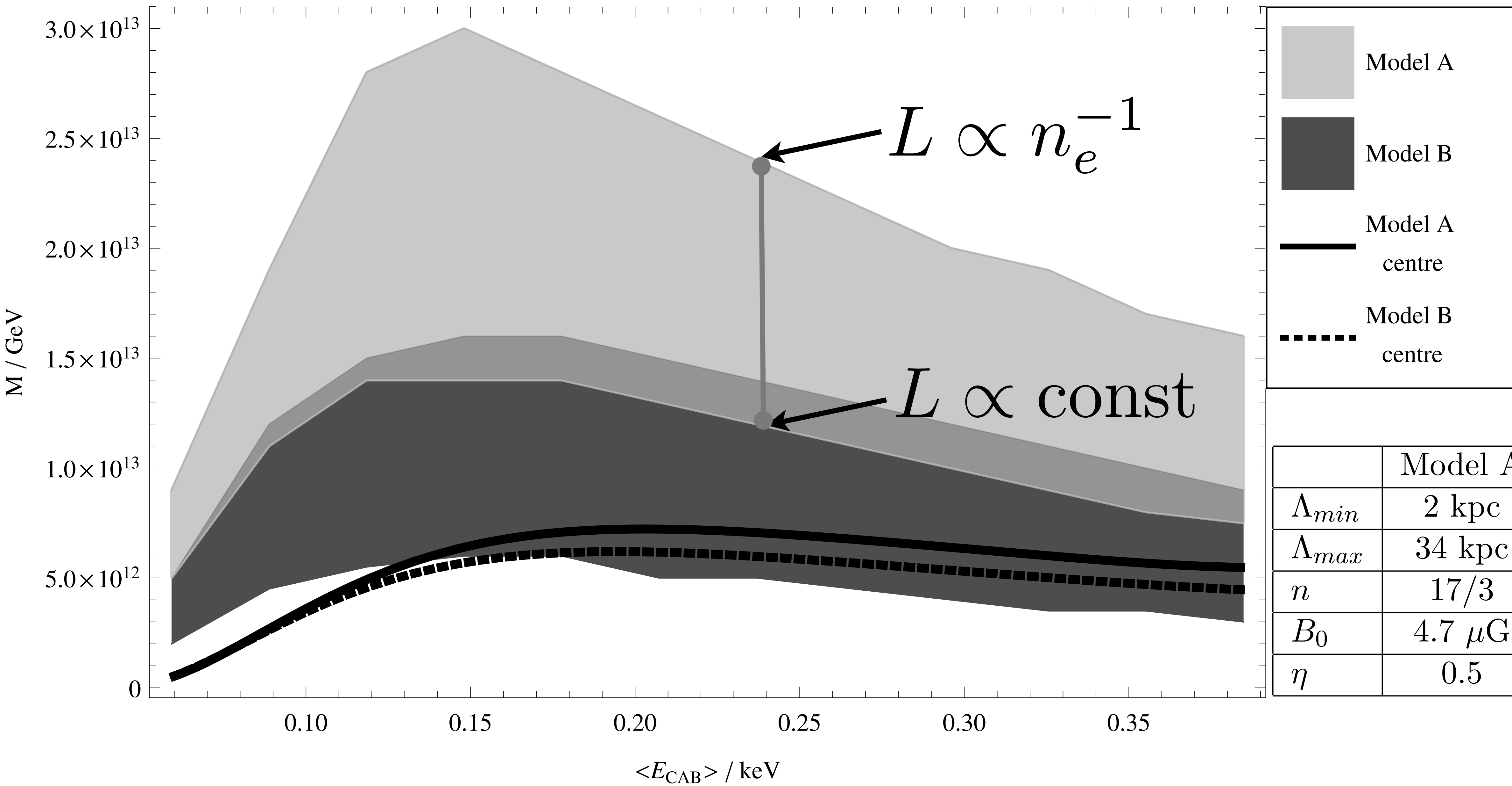
	Model A	Model B
Λ_{min}	2 kpc	2 kpc
Λ_{max}	34 kpc	100 kpc
n	17/3	4
B_0	4.7 μG	5.4 μG
η	0.5	0.7

Coma outskirts results

Semi-analytical approach:

[Conlon, Kraljic, MR '14]

$$\mathcal{L} = \int_V \int_{\Lambda_{min}(\mathbf{x})/2}^{\Lambda_{max}(\mathbf{x})/2} \int_{E_{min}}^{E_{max}} \frac{c}{L} P(a \to \gamma; L, E, \mathbf{x}) \; p(L, \mathbf{x}) \; C_{CAB} \; E \; X_{CAB}(E) \; \mathrm{d}E \; \mathrm{d}L \; \mathrm{d}\mathbf{x}^3$$



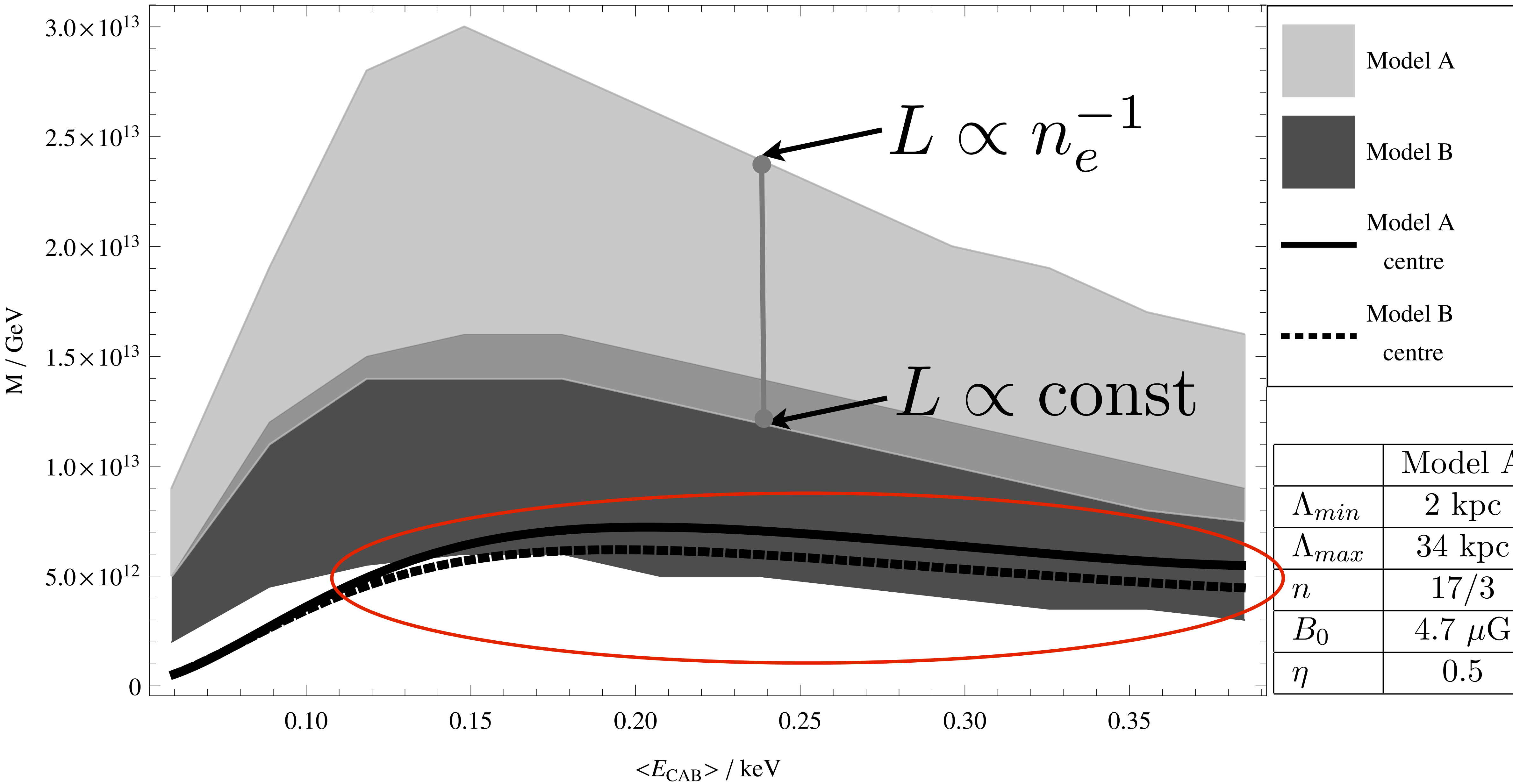
	Model A	Model B
Λ_{min}	2 kpc	2 kpc
Λ_{max}	34 kpc	100 kpc
n	17/3	4
B_0	4.7 μG	5.4 μG
η	0.5	0.7

Coma outskirts results

Semi-analytical approach:

[Conlon, Kraljic, MR '14]

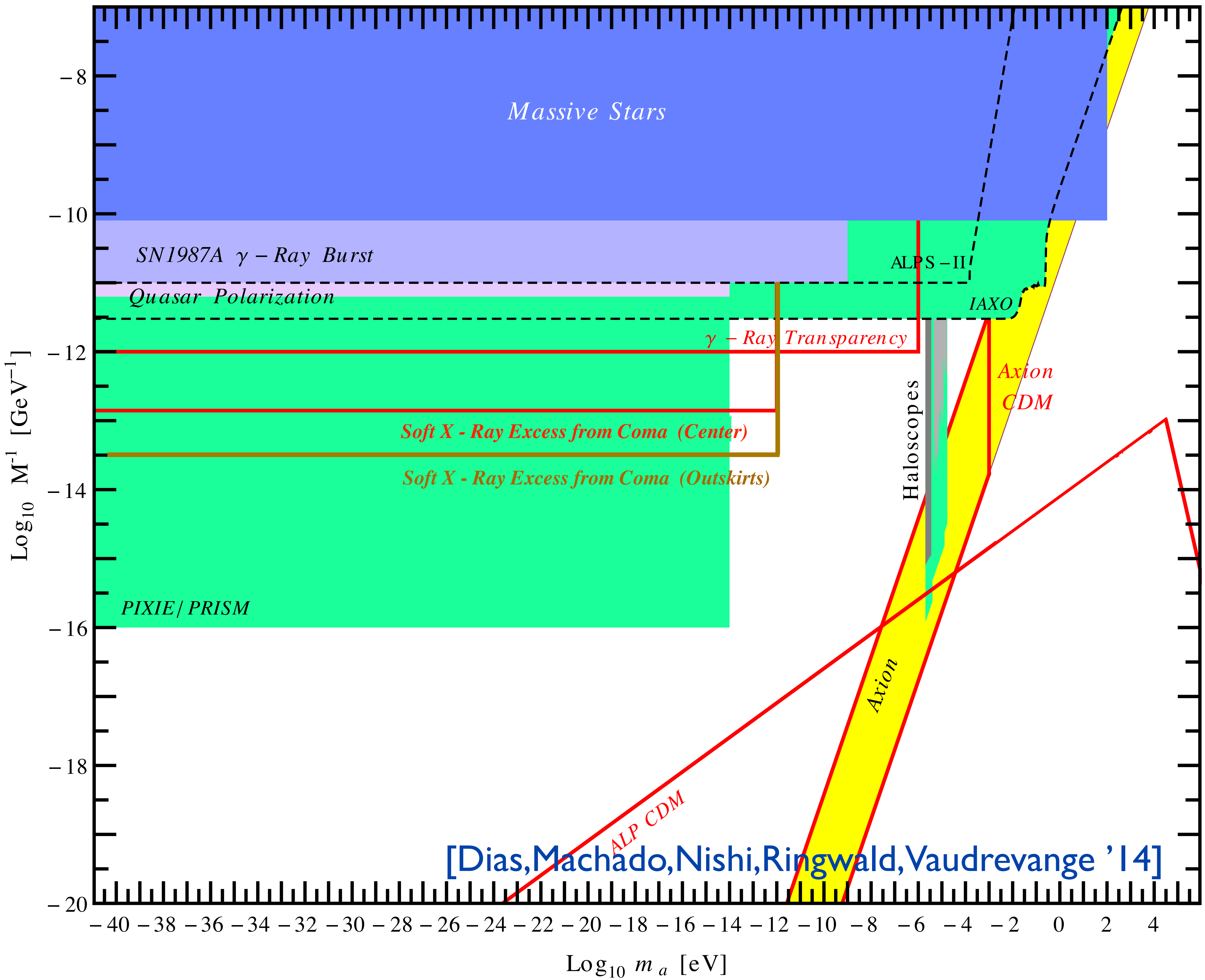
$$\mathcal{L} = \int_V \int_{\Lambda_{min}(\mathbf{x})/2}^{\Lambda_{max}(\mathbf{x})/2} \int_{E_{min}}^{E_{max}} \frac{c}{L} P(a \to \gamma; L, E, \mathbf{x})\ p(L, \mathbf{x})\ C_{CAB}\ E\ X_{CAB}(E)\ \mathrm{d}E\ \mathrm{d}L\ \mathrm{d}\mathbf{x}^3$$



	Model A	Model B
Λ_{min}	2 kpc	2 kpc
Λ_{max}	34 kpc	100 kpc
n	17/3	4
B_0	4.7 μG	5.4 μG
η	0.5	0.7

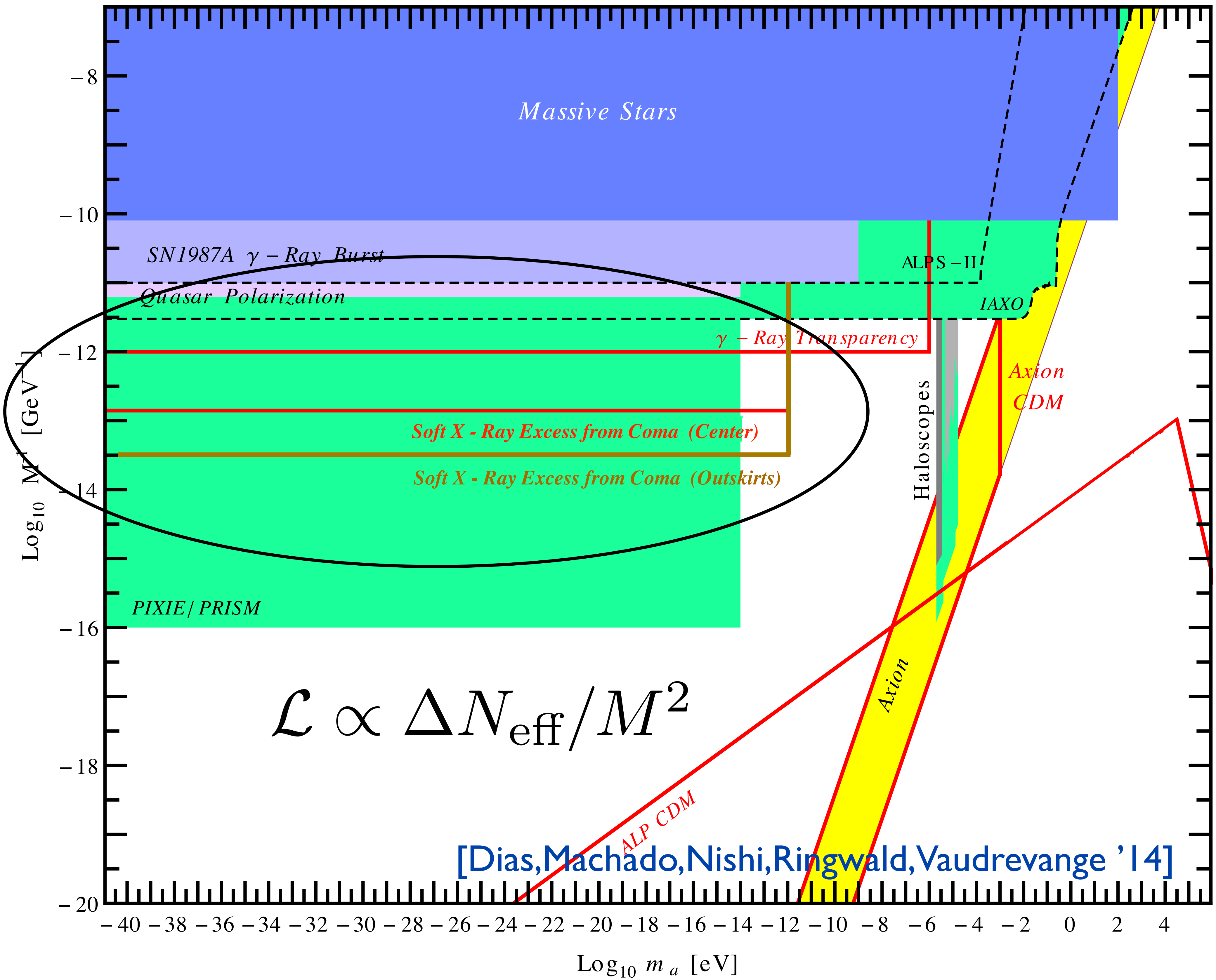
ALP parameter space

[Conlon, Kraljic, MR ’14]



ALP parameter space

[Conlon, Kraljic, MR '14]



Conclusions

- Dark Radiation/a CAB is a generic prediction of String Cosmology
- Soft X-ray excess is present in many clusters
- Cosmological vs astrophysical explanation: One CAB to fit them all $(M, \langle E_{CAB} \rangle)$

- Has to match both morphology and magnitude of soft excess
- Coma Center ☑, Coma Outskirts ☑, Other clusters (?)

Thank you for your attention!