The status of the 3.5 keV line

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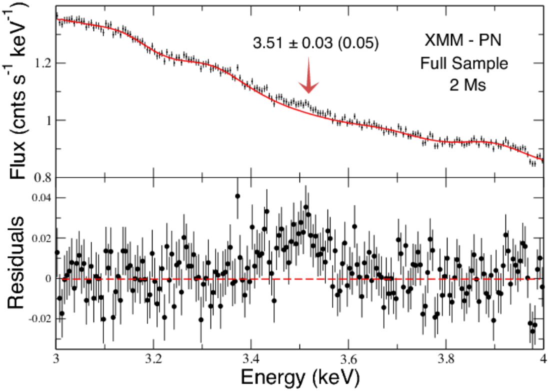
The X-Ray Universe 2017

1605.01043: M Berg, J P Conlon, FD, N Jennings, S Krippendorf, A J Powell & M Rummel

1608.01684: J P Conlon, FD, N Jennings, S Krippendorf & M Rummel

The 3.5 keV Line

3.5 keV photon line originally observed in several galaxy clusters and Andromeda (M31) at $4 - 5\sigma$ (Bulbul *et al* 1402.2301, Boyarsky *et al* 1402.4119).

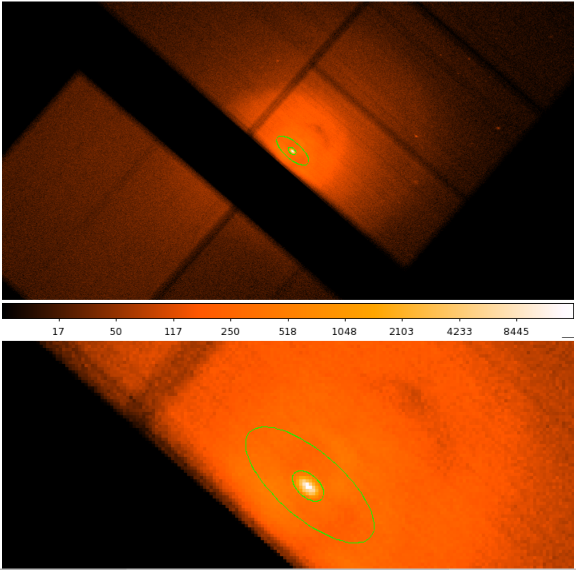


Outline

1. The 3.5 keV Dip
2. Hitomi Observations
3. Fluorescent Dark Matter
4. Conclusions

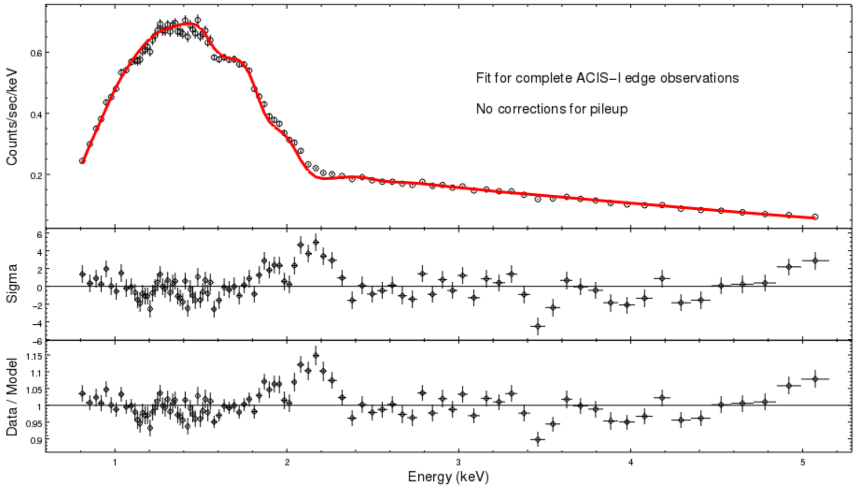
NGC1275

NGC1275



Results

Model: $F = AE^{-\gamma} \times e^{-n_H \sigma(E)}$ (*xswabs* $\times$ *powlaw1d*)

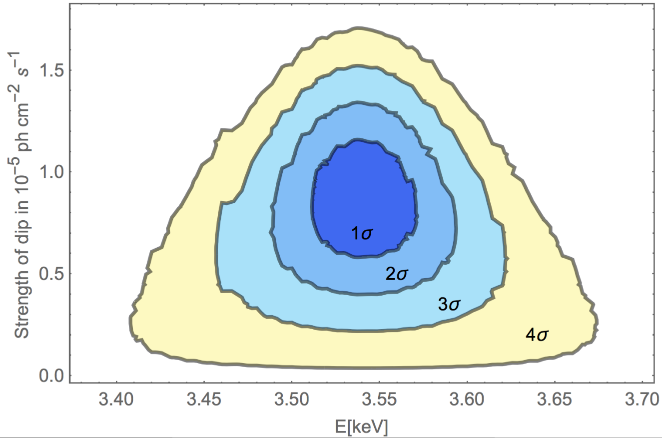


3.5 keV Dip

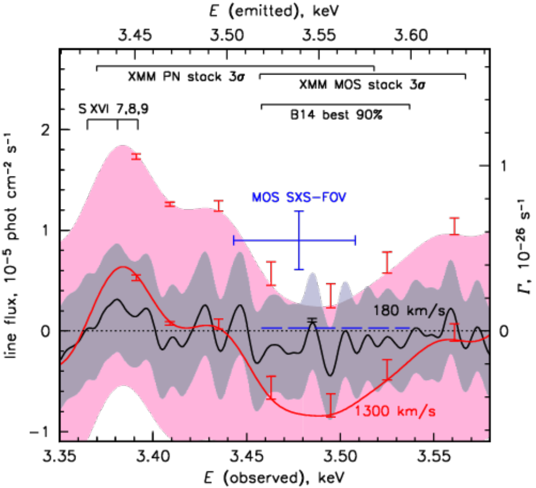
- Remains whether we subtract or model the cluster background
- Not present in the cluster background spectrum from the same observations
- Remains when we exlude the 1.8 - 2.3 keV region from the fit
- The dip's equivalent width is $\sim$ 15 eV

3.5 keV Dip

Model: *xswabs* $\times$ *(powlaw1d - xsgauss)*
Best fit energy in cluster frame $= 3.54 \pm 0.02$ keV
Best fit line strength $= (-8.7 \pm 1.9) \times 10^{-6}\,\mathrm{ph\,s^{-1}\,cm^{-2}}$
$\Delta\chi^2 = 21.1$ for best fit dip



Hitomi



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Consistency of Observations

- The AGN contributes 15% of the total counts to the 3-4 keV Hitomi spectrum
- Poor angular resolution makes removing this contribution impossible, unlike for Chandra and XMM-Newton
- Therefore Hitomi measures the sum of the diffuse and AGN emission at 3.5 keV
- What do we predict at 3.5 keV including the dip in the AGN and the line in the surrounding gas?

Consistency of Observations

AGN contribution:

- The 2009 *Chandra* data shows an AGN luminosity of $4.7 \times 10^{-3}\,\mathrm{ph\,s^{-1}\,cm^{-2}\,keV^{-1}}$ at 1 keV.
- *Hitomi* report an AGN luminosity of $9 \times 10^{-3}\,\mathrm{ph\,s^{-1}\,cm^{-2}\,keV^{-1}}$ at 1 keV - about twice as bright.
- We rescale our measured dip strength $(-8.7 \pm 1.9) \times 10^{-6}\,\mathrm{ph\,s^{-1}\,cm^{-2}}$ to $(-16.7 \pm 3.6) \times 10^{-6}\,\mathrm{ph\,s^{-1}\,cm^{-2}}$

Consistency of Observations

- *Hitomi* report that their expected diffuse 3.5 keV line strength is $(9.0 \pm 2.9) \times 10^{-6}\,\mathrm{ph\,s^{-1}\,cm^{-2}}$
- Predicted line strength $=$ 0.85 $\times$ diffuse line strength - 0.15 $\times$ dip strength $= (-7.7 \pm 4.6) \times 10^{-6}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$
- Summing the predicted diffuse and AGN spectra, we predict a small dip in the 2016 Hitomi data at 3.54 keV of $(-7.7 \pm 4.6) \times 10^{-6}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$.

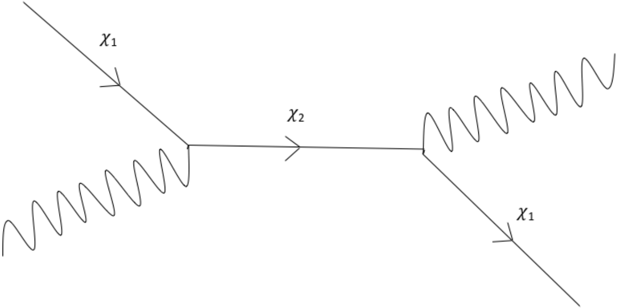
All observations of Perseus at 3.5 keV are consistent.

Dark Matter?

Could the 3.5 keV dip and 3.5 keV line be signals from dark matter?

Fluorescent Dark Matter

$$\mathcal{L} \supset \frac{c_M}{M}\bar{\chi}_2\sigma_{\mu\nu}\chi_1 F^{\mu\nu} - m_1\bar{\chi}_1\chi_1 - m_2\bar{\chi}_2\chi_2$$

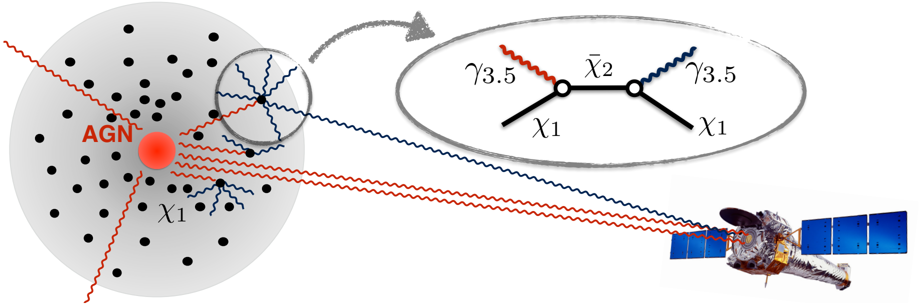


Breit-Wigner resonance at photon energy $E_0 = \frac{m_2^2 - m_1^2}{2m_1} \stackrel{!}{=} 3.54\,\mathrm{keV}$ in the rest frame of the dark matter.

Fluorescent Dark Matter

- Fluorescent Dark Matter resonantly scatters 3.5 keV photons
- The 3.5 keV dip in the AGN spectrum is a dark sector absorption line
- The diffuse 3.5 keV line arises from fluorescent re-emission

Fluorescent Dark Matter



Consistency of 3.5 keV line in Fluorescent Dark Matter

- Are the observed dip and line strengths consistent?
- Assume all 3.5 keV emission from $\chi_2 \rightarrow \chi_1 \gamma$ arises after initial absorption of a real 3.5 keV photon
- Total number of 3.5 keV photons is conserved
- In Perseus, we require the time-averaged deficit in 3.5 keV photons from the central AGN to equal the time-averaged excess in 3.5 keV photons in the diffuse cluster emission.

Consistency of 3.5 keV line in Fluorescent Dark Matter

- Dip strength in NGC1275 is $(-8.7 \pm 1.9) \times 10^{-6}\,\mathrm{ph\,s^{-1}\,cm^{-2}}$.
- The line strength integrated across the XMM Newton field of view in Perseus is $52^{+24}_{-15} \times 10^{-6}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$.
- The diffuse line strength depends on the AGN luminosity averaged over $10^4 - 10^6$ years. These values are consistent within our knowledge of this.
- The AGN luminosity is highly variable. NGC1275 was 5 - 8 times brighter in 1970 - 1988 than in 2009.

Fluorescent Dark Matter: Predictions

- 3.5 keV dip in the spectrum of point sources in or behind galaxy clusters
- Strength of dip proportional on dark matter column density up to point of complete absorption
- Strength of dip proportional to dark matter velocity dispersion
- 3.5 keV line in the diffuse emission of galaxy clusters
- 3.5 keV line strength is more sharply peaked than for decaying or annihilating dark matter when dominated by a central point source

Conclusions

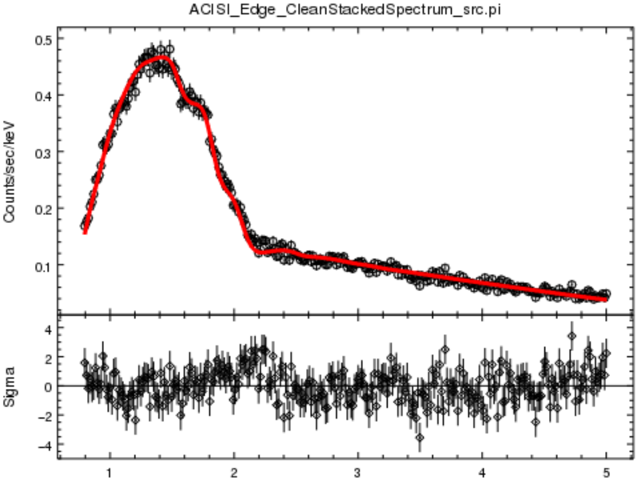
- We find a $4-5\sigma$ dip at 3.54 keV in the AGN at the centre of Perseus.
- This dip is explained by a Fluorescent Dark Matter model for the 3.5 keV line.
- Hitomi observations at 3.5 keV are consistent with a dip in the AGN and a line in the continuum.
- Further observations of the AGN with *XMM-Newton* or *Chandra* could confirm or refute this scenario.

Analysis Details

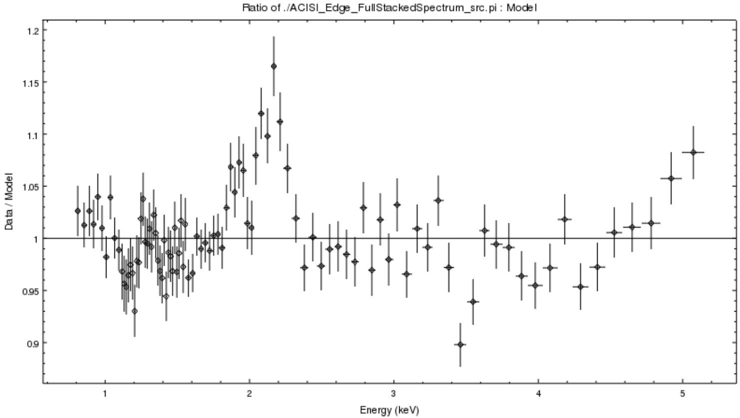
- Stack observations 11713, 12025, 12033 and 12036 ($\sim$ 200 ks)
- Extraction region: ellipse of radii 11.6" and 7.2"
- Background region: circular annulus with inner radius 12.4" and outer radius 29"
- For the two short observations 12025 and 12033 this region goes outside the chip, and a rectangular box was used instead for the background
- 266000 counts, reducing to 229000 after background subtraction
- 1.3 % of counts in the 7 - 10 keV band
- 0.09 % of counts in the 10 - 15 keV bands
- Minimum 2000 counts per bin
- Fit an absorbed power law from 0.8 - 5 keV
- Best fit $\gamma = 1.83$, $n_H = 2.3 \times 10^{21}\,\mathrm{cm}^{-2}$

Results

Model: $F = AE^{-\gamma} \times e^{-n_H \sigma(E)}$ ($xswabs \times powlaw1d$)



Results



Ratio of ./ACISI_Edge_FullStackedSpectrum_src.pi : Model
Data / Model
1.2
1.15
1.1
1.05
1
0.95
0.9
1
2
3
4
5
Energy (keV)

Resonant Interaction

We assume a Breit-Wigner resonance with a 100% branching ratio for $\chi_2 \to \chi_1\gamma$:

$$\sigma_{\rm BW}(E) = \frac{2\pi}{p_{CM}^2}\frac{\Gamma_{\chi_2\to\chi_1\gamma}}{\Gamma_{\chi_2}}\frac{(m_2\Gamma_{\chi_2})^2}{(s-m_2^2)^2+(m_2\Gamma_{\chi_2})^2}\ ,$$

where $p_{CM}^2 = \frac{m_1^2 E^2}{m_1^2+2m_1E}$ is the squared magnitude of the momentum in the centre of mass frame
$\Gamma_{\chi_2\to\chi_1\gamma}$ is the decay rate of χ_2 to $\chi_1\gamma$
Γ_{χ_2} is the total decay rate of χ_2
$\sqrt{s}$ is the centre of mass energy.

Resonant Interaction

- The equivalent with of the dip is 15 eV - approximately equal to the dark matter velocity broadening along the line of sight to NGC1275.
- It is therefore possible that all photons in the range $\sim 3.54\,\mathrm{kev} \pm 7.5\,\mathrm{eV}$ are scattered by the dark matter.
- The line is then further broadened by the energy resolution of *Chandra* ($\sim$ 100 eV).

Resonant Interaction

- We use the observed dip strength to place a lower bound on the width Γ of the resonant interaction.
- For the dark matter column density, we integrate an NFW profile:

$$\rho_{DM}(r) = \frac{\rho_0}{\frac{r}{r_s}\left(1 + \left(\frac{r}{r_s}\right)^2\right)} \, ,$$

with $r_s = 0.477$ Mpc and $\rho_0 = 7.35 \times 10^{14} M_{\odot}\,\mathrm{Mpc}^{-3}$ (Sachez-Conde *et al*, 1104.3530). We cut off the integral at 0.01 Mpc.

Resonant Interaction

- Assuming $m_{DM} \gg 3.5\mathrm{keV}$ we find:

$$\Gamma \geq \left(\frac{m_{DM}}{\mathrm{GeV}}\right) \times 5.8 \times 10^{-10}\,\mathrm{keV} \; .$$

$$M \lesssim 10\,\mathrm{GeV}$$

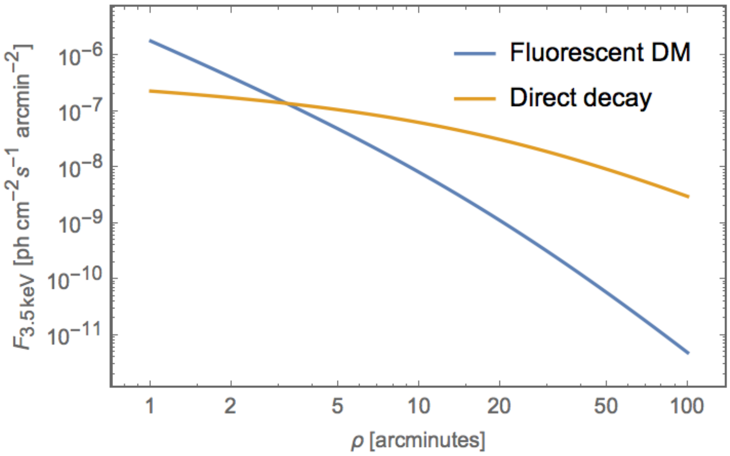
- We have only a lower bound as once 100% of photons are absorbed, an increase in Γ will not significantly increase the equivalent width of the dip.

Morphology of 3.5 keV line in Fluorescent Dark Matter

- What radial distribution does Fluorescent Dark Matter predict for the 3.5 keV line?
- The radial distribution of the 3.5 keV line strength depends on the (unknown) time variation of the AGN over the past $10^4 - 10^6$ years.
- If we neglect this effect and assume the AGN is spherically symmetric we find:

$$\mathcal{L}_{3.5\mathrm{keV}} \propto \rho_{DM}(r)\rho_{\gamma_{3.5\,\mathrm{keV}}}(r) \propto \frac{\rho_0}{r^3\left(1+\left(\frac{r}{r_s}\right)^2\right)}.$$

Morphology of 3.5 keV line in Fluorescent Dark Matter



Morphology of 3.5 keV line in Fluorescent Dark Matter

$$\mathcal{L}_{3.5\mathrm{keV}} \propto \rho_{DM}(r)\rho_{\gamma_{3.5\,\mathrm{keV}}}(r) \propto \frac{\rho_0}{r^3\left(1+\left(\frac{r}{r_s}\right)^2\right)} .$$

- Much sharper central peaking than decaying or annihilating dark matter when dominated by a central point source
- This fits the observed morphology of the 3.5 keV line in Perseus