The status of the 3.5 keV line

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DESY
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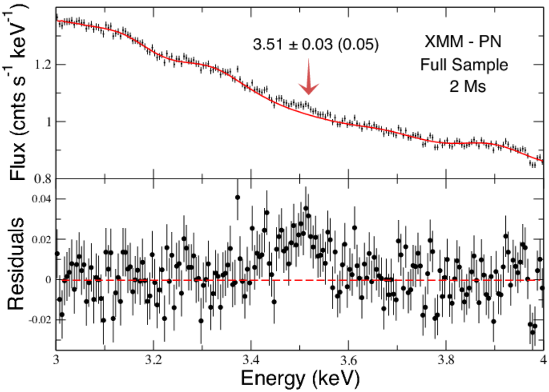
1605.01043: M Berg, J P Conlon, FD, N Jennings, S Krippendorf, A J Powell & M Rummel
1608.01684: J P Conlon, FD, N Jennings, S Krippendorf & M Rummel

Outline

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).



Observations

- NOT observed in stacked spectra of external galaxies (Malyshev *et al* 1408.3531, Anderson *et al* 1408.4155)
- Observed in the Milky Way centre with the *XMM Newton* X-Ray telescope (Boyarsky *et al* 1408.2503, Jeltema and Profumo 1408.1699)....
- ... but not with the *Chandra* X-Ray telescope (Riemer-Sorensen 1405.7943)
- Spectral modelling of the galactic centre region is highly complex - very difficult to draw definitive conclusions from observations.
- Possible weak detection in the Draco dwarf galaxy (Jeltama and Profumo 1512.01239, Ruchayskiy *et al* 1512.07217).

Morphology

- Signal from the Perseus galaxy cluster is $\sim 8\times$ stronger than for the 72 other clusters
- Half of the Perseus signal is within the central 20 kpc, whereas the dark matter density varies over $R_{DM} \simeq 360\,\mathrm{kpc}$
- Signal from Orphiuchus and Centaurus galaxy clusters is also more strongly peaked than expected from decaying dark matter

Interpretations

Instrumental Line?

- Observed at redshifts 0 - 0.35. An instrumental line would be smeared out by de-redshifting.
- Seen by four different detectors
- Not seen in blank sky data set

Interpretations

Atomic Line?

- No known line at this energy
- Nearby lines would need to exceed expected flux by a factor of ~ 20 to explain the signal
- Observed in the Andromeda galaxy - no hot gas
- Line from sulfur ion charge exchange at 3.47 keV (Shah *et al*, 1608.04751) whereas the line is at $3.55 - 3.57 \pm 0.03$ in stacked cluster sample.
- Ongoing debate

Interpretations

Dark Matter?

- Dark matter decay or annihilation to photons
- Decay scenario predicts that line flux F is proportional to dark matter density ρ_{DM}
- Annihilation predicts $F \propto \rho_{DM}^2$

Dark matter?

- Non-observation in galaxies is inconsistent with observation in galaxy clusters for dark matter decay or annihilation to photons
- Morphology of signal from clusters is inconsistent with direct decay of dark matter to photons
- All models with direct dark matter decay to photons are inconsistent with these observations
- Can we reproduced the observed morphology with Dark Matter?

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

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

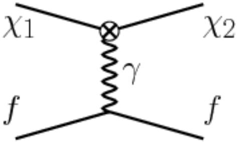
- Dark matter decays to an axion which mixes with the photon in astrophysical magnetic fields
- $F \propto \rho_{DM} P(a \to \gamma)$
- The axion to photon conversion probability is much lower in galaxies than in galaxy clusters, primarily due to size.
- See 1403.2370, 1404.7741

Exciting Dark Matter

- Inelastic $DM - DM$ scattering to an excited state DM^*
- DM^* subsequently decays to DM and a 3.5 keV photon
- $F \propto \rho_{DM}^2 < \sigma v >$
- See Cline and Frey, 1410.7766

Upscattering with Astrophysical Plasma

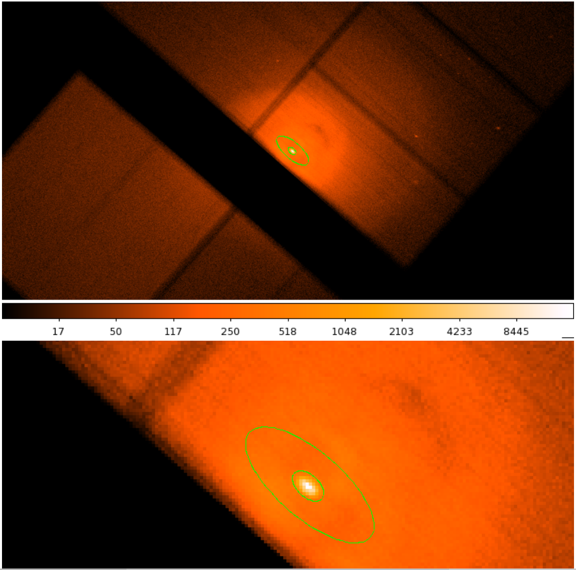
$$\mathcal{L} \supset \frac{c_M}{M}\bar{\chi}_2\sigma_{\mu\nu}\chi_1 F^{\mu\nu} + \frac{c_E}{M}\bar{\chi}_2\sigma_{\mu\nu}\gamma_5\chi_1 F^{\mu\nu} - m_1\bar{\chi}_1\chi_1 - m_2\bar{\chi}_2\chi_2$$



$m_2 \sim m_1 + 3.5\,\mathrm{keV}$
$F \propto \rho_{DM} n_e$
See D'Eramo *et al* (1603.04859)

NGC1275

Analysis



Analysis

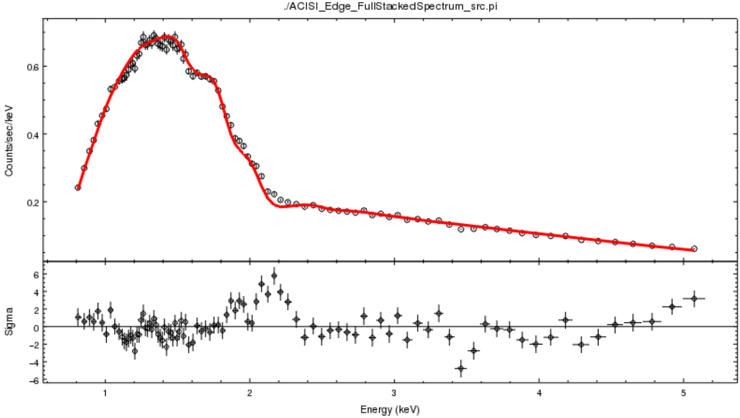
- We process the data using *Ciao*, provided by the Chandra X-ray Observatory.
- Remove time periods polluted by solar flares.
- Subtract background taken from a region near NGC1275, or model it using the temperature and abundance measured by Hitomi.
- The data is affected by pile-up - contamination of the data when the count rate is faster than the read out time.

Pile-up

- Energy of two different photon events is summed and recorded as a single photon event.
- Leads to an increased count rate at higher energies compared to the true count rate of the source
- Low levels of pile-up should not affect localised anomalies
- Fractional effect of pile-up is greatest at higher energies
- We focus on observations where NGC1275 is at the edge of the telescope's field of view.
- This means the point spread function is higher - NGC1275 is spread out over more pixels - so pile-up is reduced.

Results

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



Boring Explanations

- It is difficult to produce a dip from astrophysical or instrumental effects
- Statistical fluctuation?
- $4 - 5\sigma$ local significance in the cleanest data set.
- Exactly the same energy as the 3.5 keV line.

Boring Explanations

- Something atomic?
- We do not expect to see absorption lines at this energy
- No strong lines at this energy.
- The equivalent width of the dip is 15 eV. The velocity broadening from baryonic matter is 2.4 eV. Therefore the dip cannot arise from at atomic line.

Boring Explanations

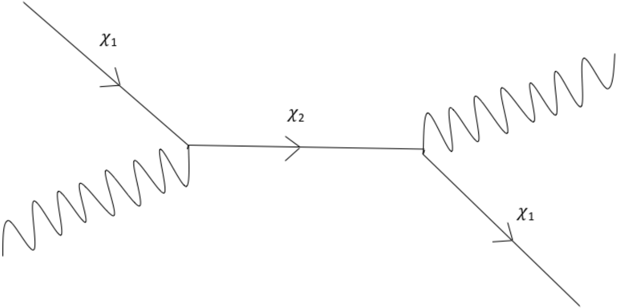
- Something instrumental?
- No effective area feature at 3.5 keV
- Remains when pileup is modeled and when high pileup regions are removed.
- Not seen in background observations in the same region of the detector.

Interesting Explanations

- Dark Matter?
- An unexplained 3.5 keV line is observed in the continuum emission of galaxy clusters
- Could the 3.5 keV dip and 3.5 keV line be signals from dark matter?
- Alternative interpretation from axion-photon mixing (1605.01043)

Fluorescent Dark Matter

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

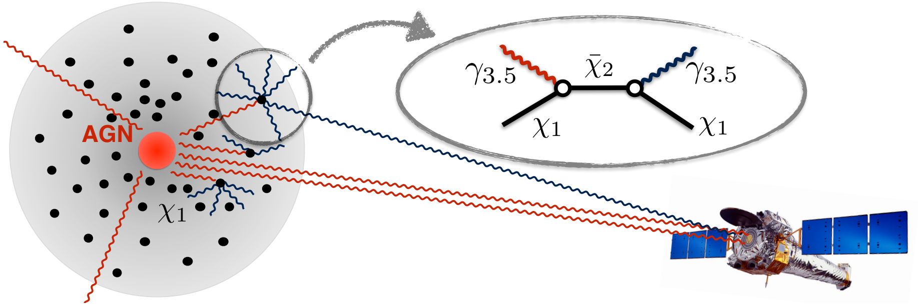


Breit-Wigner resonance at photon energy $E_0 = \frac{m_2^2 - m_1^2}{2m_1} \stackrel{!}{=} 3.54\,\mathrm{keV}$ in the rest frame of the dark matter.

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



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 $p_{CM}^2 = \frac{m_1^2 E^2}{m_1^2 + 2m_1 E}$ 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.

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 $\chi_2 \to \chi_1 \gamma$ 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.

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:

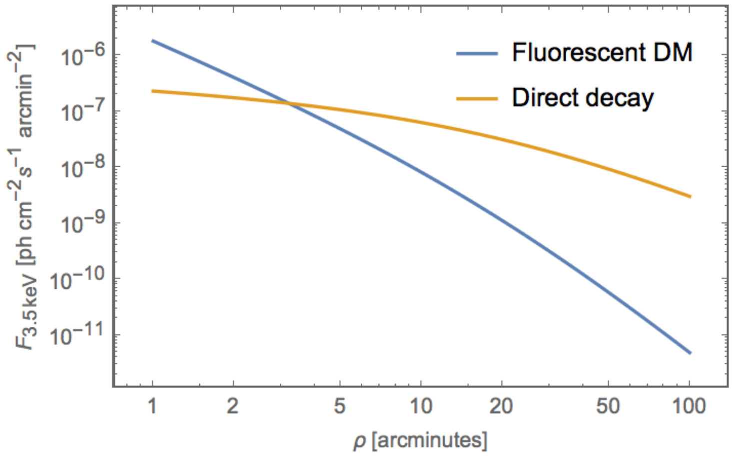
$$\mathcal{L}_{3.5\mathrm{keV}} \propto \rho_{DM}(r)\rho_{\gamma_{3.5\,\mathrm{keV}}}(r) \propto \frac{\rho_0}{r^3\left(1+\left(\frac{r}{r_s}\right)^2\right)} \, .$$

Morphology of 3.5 keV line in Fluorescent Dark Matter

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

- 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

Morphology of 3.5 keV line in Fluorescent Dark Matter



Fluorescent Dark Matter

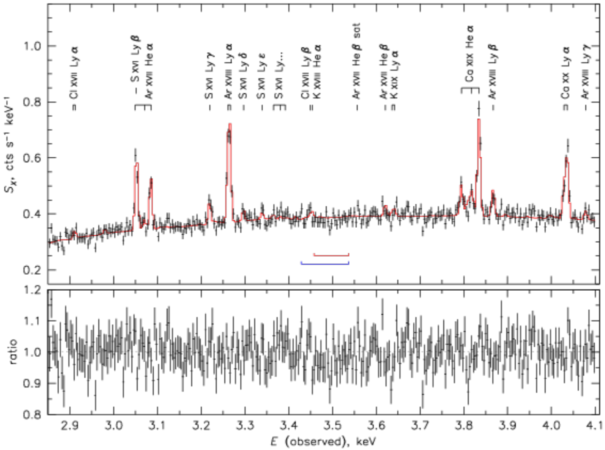
- A two state Fluorescent Dark Matter model explains both the 3.5 keV dip and the 3.5 keV line.
- The observed morphology of the 3.5 keV line is explained in this model.
- What about the non-observation of the 3.5 keV line with Hitomi?

Hitomi

Hitomi

- Launched on 17th February and lost on 26th March
- Returned spectra of the centre of Perseus
- Huge improvement in energy resolution $\Delta E \sim 5\,\mathrm{eV}$
- Poor spatial resolution compared to Chandra
- Hitomi observations exclude a 3.5 keV line from decaying dark matter at $> 3\sigma$ (*Hitomi Collaboration*, 1607.07420)

Hitomi



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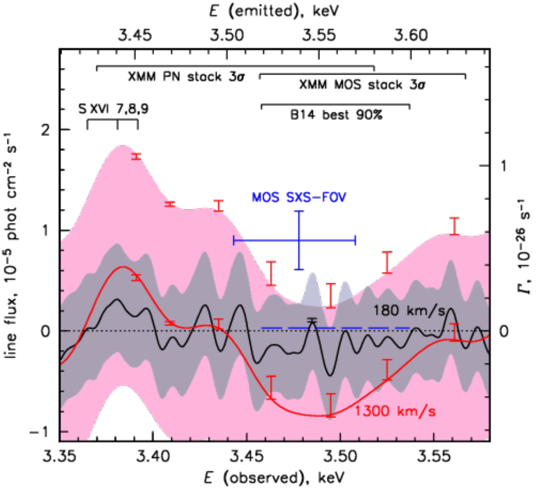
Consistency of Observations



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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

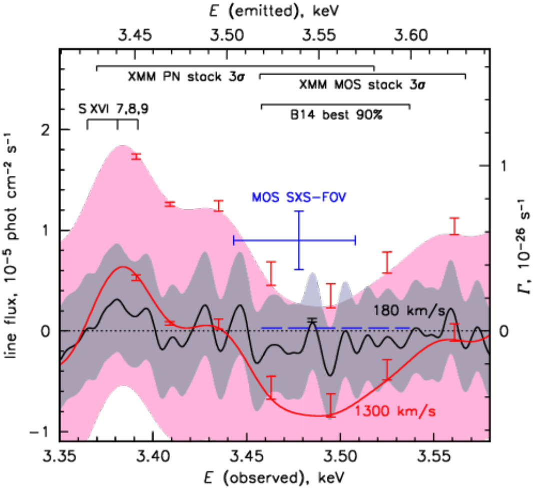
AGN contribution:

- 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, Fluorescent Dark Matter predicts a dip in the 2016 Hitomi data at 3.54 keV of $(-7.7 \pm 4.6) \times 10^{-6}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$.

Consistency of Observations



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Consistency of Observations

For a line broadened by the dark matter velocity dispersion of $1300\,\mathrm{km\,s^{-1}}$ the Hitomi data shows a best-fit dip of $(-8 \times 10^{-6})\,\mathrm{ph\,cm^{-2}\,s^{-1}}$ at $E = (3.55 \pm 0.02)$ keV at an approximate significance of 2.5σ.

All observations of Perseus at 3.5 keV are consistent in Fluorescent Dark Matter

Fluorescent Dark Matter: Predictions

- 3.5 keV dip in the spectrum of point sources in or behind galaxy clusters and (perhaps) galaxies
- 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.