The 3.5 keV dark matter candidate line in the Milky Way

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in collaboration with
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based on arXiv:1812.10488

New Trends in High Energy Physics
Odesa, 2019

Decaying dark matter and X-rays

- While DM particles should live much more than our Universe, they should not be completely stable
- WIMPs (with GeV mass) should be stable – otherwise their large cross section implies very small lifetime (shorter than for neutron)
- For keV mass this is not true $\rightarrow$ dark matter can decay
- The corresponding decay signal should be proportional to DM column density $\mathcal{S} = \int \rho_{dm}(r) dr$

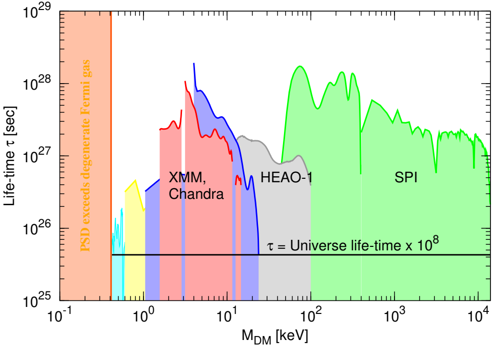
Search for Dark Matter decays in X-rays

See **"Next decade in sterile neutrino studies"** by Boyarsky et al.
Physics of the Dark Universe, **1** (2013)

Available X-ray satellites:

Suzaku, XMM-Newton,

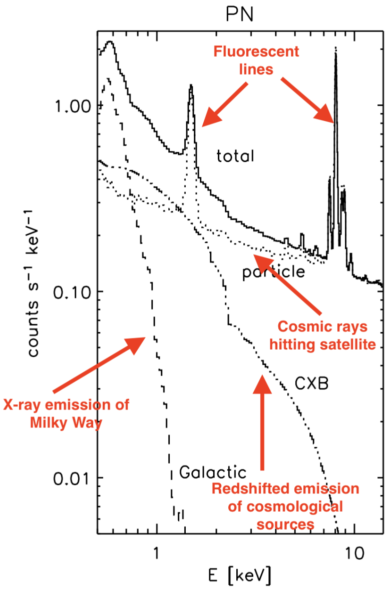
Chandra, INTEGRAL, NuStar

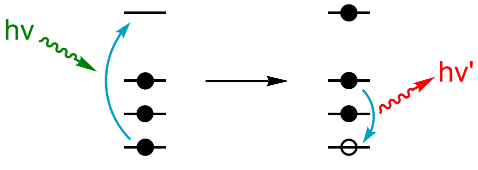


$$\text{Signal-to-noise} \propto \overbrace{\mathcal{S}_{\rm DM}}^{signal} \underbrace{\sqrt{t_{\rm exp}\cdot\Omega_{\rm fov}\cdot A_{\rm eff}\cdot\Delta E}}_{signal-over-background}$$

All types of **individual** objects/observations have been tried: galaxies (LMC, Ursa Minor, Draco, Milky Way, M31, M33,...); galaxy clusters (Bullet cluster; Coma, Virgo, ...) with all the X-ray instruments

Challenges: X-ray sky is never “empty”





- …**non-cosmic background** is due primarily to **energetic particles interacting directly with the detector**, or interacting with material around the detector and producing **fluorescent X-rays** that **then strike the detector**.
- This "particle-induced background" has **multiple components** and each component is **temporally variable**, although on **different scales**.

(Lumb et al. (2005); Kuntz & Snowden 2008)

Detection of An Unidentified Emission Line

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Submitted to ApJ, 2014 February 10

Bulbul et al. ApJ (2014) [1402.2301]

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]

[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

Boyarsky, Ruchayskiy et al. Phys. Rev. Lett. (2014) [1402.4119]

- **Energy:** 3.5 keV. Statistical error for line position $\sim 30 - 50$ eV.
- **Lifetime:** $\sim 10^{27} - 10^{28}$ sec (uncertainty: factor $\sim 3 - 5$)

Decaying dark matter?

Interpretations I

There are 4 classes of interpretations

- Statistical fluctuation *(there is nothing there at all!)*
- Unknown astrophysical emission line *(emission line of some chemical element)*
- Instrumental feature (systematics) *(We do not know our telescopes well enough)*
- Dark matter decay line

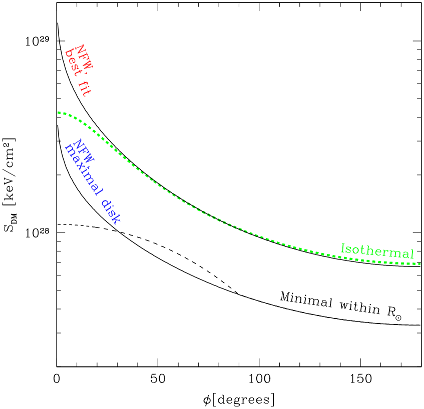
Interpretations II

One can check that the signal

- Appears in various datasets. Becomes more significant with increased statistics $\Rightarrow$ rules out **Statistical fluctuation**
- Detected with different instruments $\Rightarrow$ rules out **Systematics**
- Correctly scales with redshift? $\Rightarrow$ rules out **Systematics**
- Intensity of the line correctly changes within the object $\Rightarrow$ rules out **Systematics** and **Astrophysical explanation**
- Correlates with (expected!) dark matter density in different objects $\Rightarrow$ Confirms **dark matter origin**

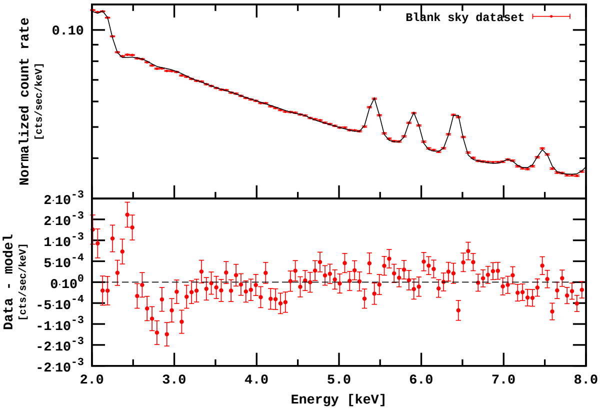
Signal from the Milky Way outskirts

- We are surrounded by the Milky Way halo on all sides
- Expect signal from any direction. Intensity drops with off-center angle
- Surface brightness profile of the Milky Way would be a “smoking gun”



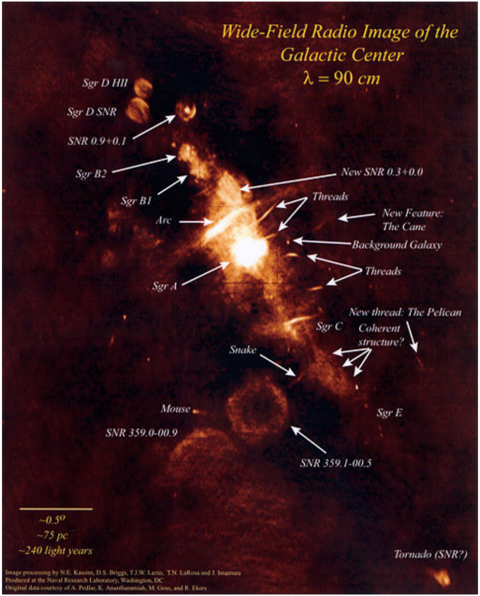
Signal from the Milky Way outskirts?

Phys. Rev. Lett. (2014) [1402.4119]



- No line is seen in 16 Msec observations of off-center Milky Way
- Confirmed by
  - (Sekiya et al. [1504.02826]) with Suzaku
  - (Figueroa-Feliciano et al. [1506.05519]) with XQC

Galactic Center is a busy place

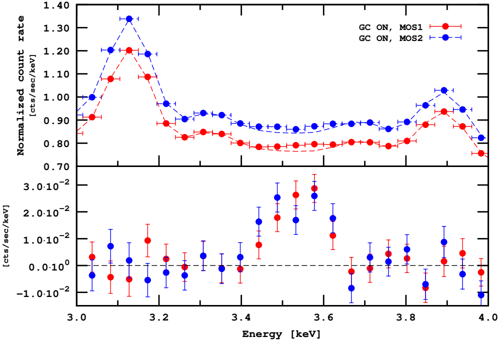


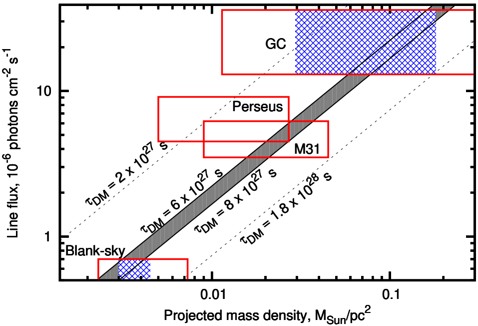
- GC is active in many wavelengths, including X-rays
- Several Ms of XMM X-ray observations
- Any detection there would be inconclusive if one cannot cross-check it

- Andromeda signal puts a **lower** bound on the expected GC flux
- Non-observations from the Milky Way outskirts puts an **upper** bound on the expected GC flux

Galactic Center – a non-trivial consistency check

Boyarsky, Ruchayskiy+ Phys. Rev. Lett. 115, (2014)



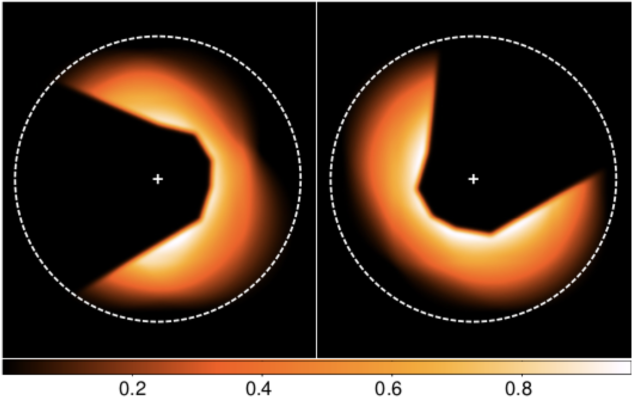


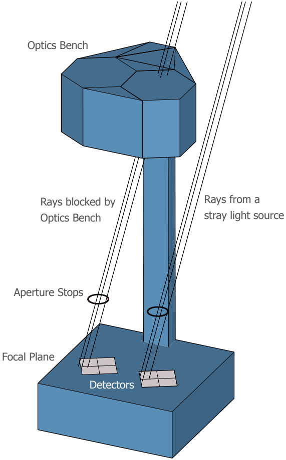
- $4\sigma+$ statistical significance
- Also in S. Riemer-Sorensen'14; Jeltema & Profumo'14

The observed signal fits into the predicted range

Another X-ray satellite: NuStar

- Has small field of view, would not be competitive with XMM, Chandra or Suzaku
- **But!** NuStar has a special **0-bounce photons** mode where FoV is 30 deg^2

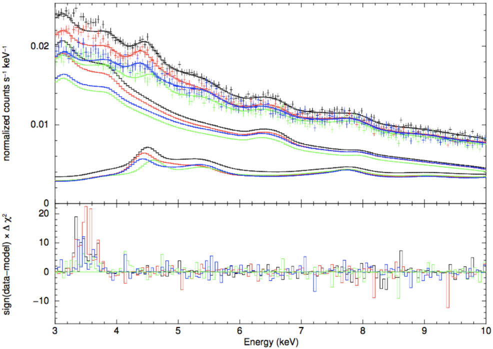




3.5 keV line in NuStar spectrum

Milky Way halo. Neronov & Malyshev [1607.07328]. Also Ng+ [1609.00667]

- The 3.5 keV is present in the **0-bounce** spectrum of the Cosmos field and CDFS (total cleaned exposure 7.5 Msec)
- Combined detection has 11σ significance
- The spectrum of NuStar ends at 3 keV, so this is a lower edge of sensitivity band

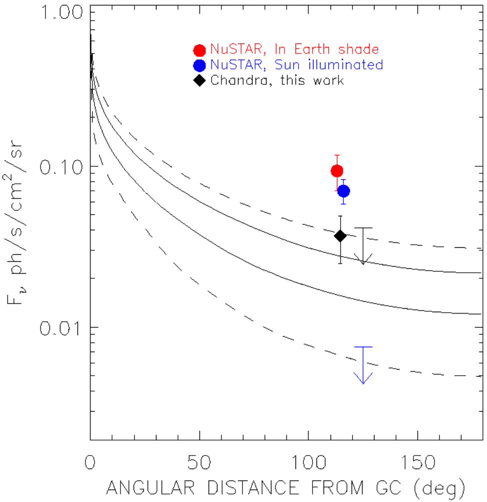


- The 3.5 keV line has been **previously attributed to reflection of the sunlight** on the telescope structure
- However, in the dataset when Earth shields satellite from the Sun **the line is present with the same flux**

Line in Chandra from the same region of the sky

Cappelluti+'17 [1701.07932]

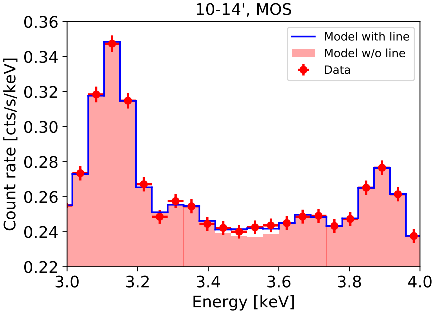
- Combined 10 Msec of Chandra observation of COSMOS and CDFS fields (same as NuStar)
- 3σ detection of a line at ~ 3.5 keV
- Flux is compatible with NuStar
- If interpreted as dark matter decay – this is a signal from Galactic halo outskirts ($\sim 115^\circ$ off center)

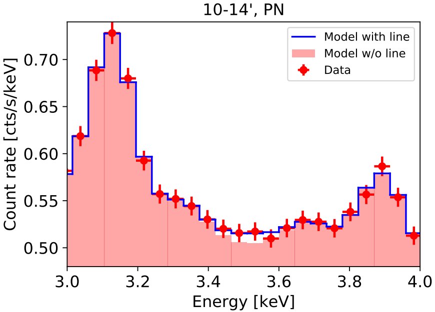


Going out of GC

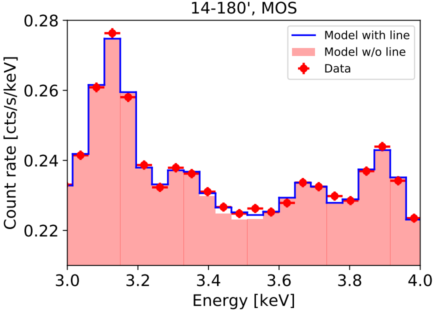
- The line is now detected **both** in Galactic Center and in outskirts;
- More detailed angular distribution will help to distinguish from astrophysical lines;
- We analyzed publicly available XMM-Newton data;
- By now, we look into an inner circle with 35° radius;
- Also, we removed the innermost circle (10') as very inhomogeneous and crowded by astrophysical sources;
- The obtained 3.5 keV lines fluxes were then compared with fluxes of bright nearby astrophysical lines at 3.1, 3.3, 3.7, 3.9 and 4.1 keV.

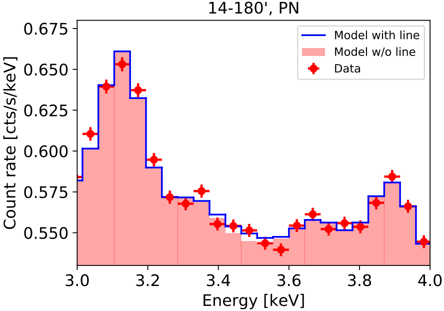
Actual spectra I



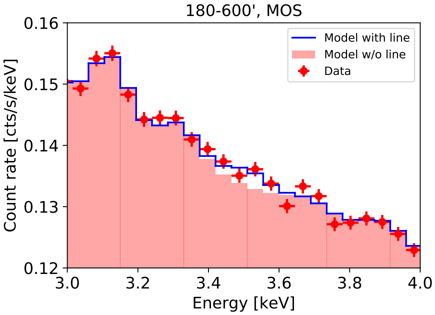


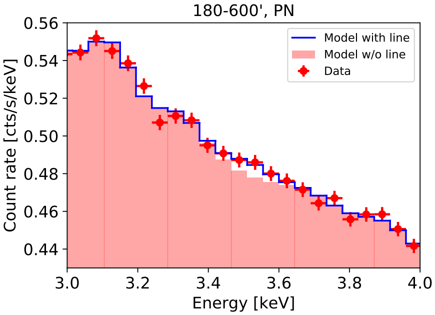
Actual spectra II



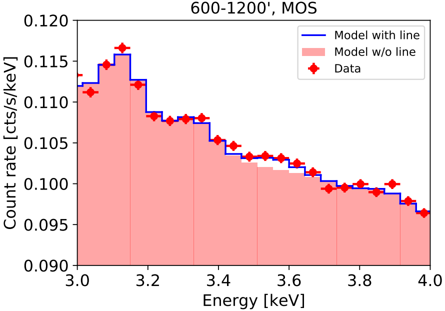


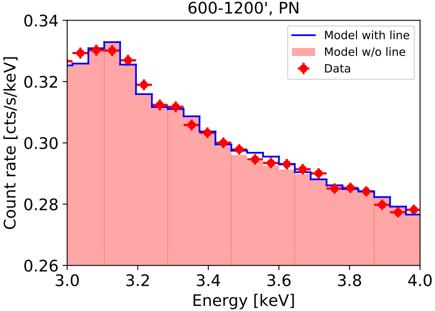
Actual spectra III



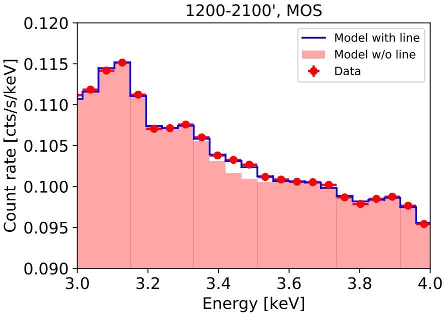


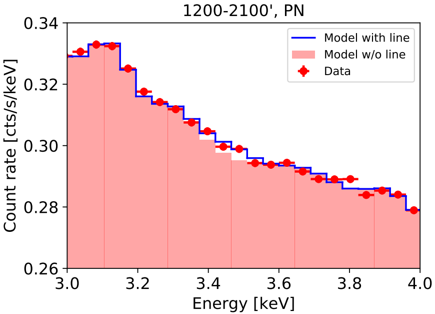
Actual spectra IV





Actual spectra V





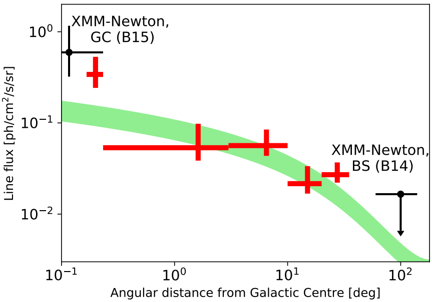
Results:

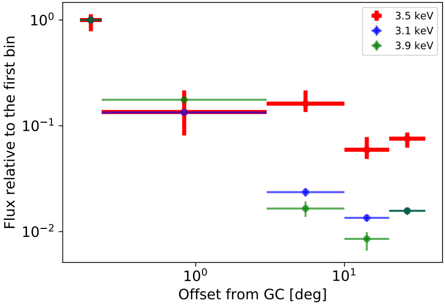
Line fluxes are in $\mathrm{cts/sec/cm^2/sr}$, positions in keV, exposures in Msec, FoVs in arcmin^2

Region	$10' - 14'$	$14' - 180'$	$3^\circ - 10^\circ$	$10^\circ - 20^\circ$	$20^\circ - 35^\circ$
MOS/PN exposure	3.1/1.1	3.0/0.8	2.2/0.7	6.2/2.3	17.0/4.1
MOS/PN clean FoV	205/197	398/421	461/518	493/533	481/542
Total χ^2	179/161	184/174	193/184	171/145	139/131
3.5 keV position	$3.52^{+0.01}_{-0.01}$	$3.48^{+0.02}_{-0.03}$	$3.51^{+0.02}_{-0.01}$	$3.56^{+0.03}_{-0.02}$	$3.46^{+0.02}_{-0.01}$
3.5 keV flux	$0.37^{+0.05}_{-0.08}$	$0.05^{+0.03}_{-0.02}$	$0.06^{+0.02}_{-0.01}$	$0.022^{+0.007}_{-0.004}$	$0.028^{+0.004}_{-0.005}$
3.5 keV $\Delta\chi^2$	**19.4**	**4.5**	**12.4**	**15.6**	**25.1**
3.1 keV flux	$8.89^{+0.09}_{-0.09}$	$1.19^{+0.04}_{-0.05}$	$0.21^{+0.02}_{-0.02}$	$0.12^{+0.01}_{-0.01}$	$0.14^{+0.01}_{-0.01}$
3.3 keV flux	$1.40^{+0.07}_{-0.08}$	$0.32^{+0.04}_{-0.04}$	$0.11^{+0.02}_{-0.01}$	$0.053^{+0.005}_{-0.007}$	$0.065^{+0.004}_{-0.004}$
3.7 keV flux	$1.30^{+0.07}_{-0.06}$	$0.30^{+0.02}_{-0.03}$	$0.033^{+0.013}_{-0.013}$	$0.026^{+0.007}_{-0.007}$	$0.050^{+0.007}_{-0.010}$
3.9 keV flux	$3.63^{+0.06}_{-0.06}$	$0.64^{+0.03}_{-0.02}$	$0.06^{+0.01}_{-0.01}$	$0.031^{+0.005}_{-0.007}$	$0.057^{+0.003}_{-0.005}$
4.1 keV flux	$0.62^{+0.06}_{-0.06}$	$0.17^{+0.02}_{-0.03}$	$0.013^{+0.013}_{-0.010}$	$0.019^{+0.007}_{-0.005}$	$0.017^{+0.003}_{-0.004}$

Results

Surface brightness profiles. Joint modelling of the halo density profile.





Profile	**Sign.** in σ	**Line position** [keV]	**Decay width** Γ $[10^{-28}\,\mathrm{sec}^{-1}]$
NFW($r_s = 20\,\mathrm{kpc}$)	7σ	$3.494^{+0.002}_{-0.010}$	0.39 ± 0.04
Burkert ($r_B = 9\,\mathrm{kpc}$)	6.4σ	$3.494^{+0.003}_{-0.014}$	$0.57^{+0.05}_{-0.08}$
Einasto ($r_s = 14.8$ kpc, $\alpha = 0.2$)	6.9σ	$3.494^{+0.002}_{-0.009}$	$0.40^{+0.04}_{-0.06}$

Results summary

- We have detected the 3.5 keV line in 5 spatial regions offset from the GC from $10'$ to 35°.
- Able to find good joint fit with relative normalization of the line in different regions fixed in accordance with a Milky Way DM density profile
- The flux in 3.5 keV line drops slower than the flux in the astrophysical lines with the distance from the Galactic center

Thank you for attention!

Backup

Not systematics!

By now the 3.5 keV line has been observed with 4 existing X-ray telescopes, making the systematic (calibration uncertainty) origin of the line highly unlikely

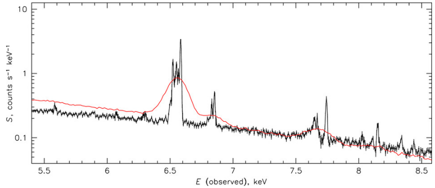
- Line is changing with redshift
- ACIS-I is a silicon CCD while the imagers of NuSTAR are two Cadmium-Zinc-Telluride detectors
- Chandra has mirrors made of Iridium (rather than Gold as XMM or Suzaku) – absorption edge origin becomes unlikely
- Different orbits of satellites – cosmic ray origin is unlikely
- Datasets accumulated over different periods (15yrs for Chandra vs. 3yrs for NuSTAR) – not related to, e.g. solar activity

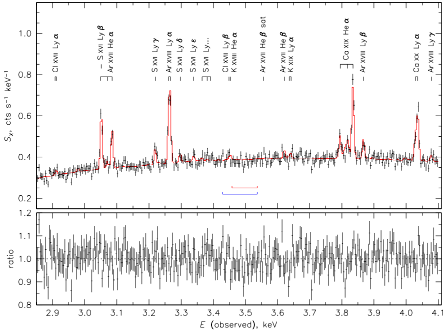
Is this a line from atomic transition(s)?

As argued by Gu+; Carlson+; Jeltema & Profumo; Riemer-Sørensen; Phillips+

Next step for 3.5 keV line: resolve the line

- A new microcalorimeter with a superb spectral resolution – Hitomi (Astro-H) was launched February 17, 2016
- During the first month of observations (calibration phase) it observed the central part of the Perseus galaxy cluster where strong line was detected by XMM & Suzaku
- Spectrometer of Hitomi is able to resolve atomic lines, measure their positions and widths (due to Doppler broadening)

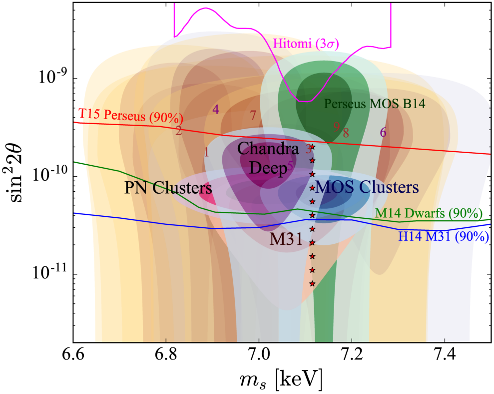




Unfortunately, the satellite was lost few weeks after the launch

What did we learn with existing Hitomi data?

- Even the short observation of Hitomi showed **no nearby astrophysical lines** in Perseus cluster $\rightarrow$ 3.5 keV line is **not astrophysical** Hitomi collaboration, 1607.04487
- Astrophysical lines in the center are Doppler broadened with velocity $v_{th} \sim 10^2\,\mathrm{km/sec}$ (as measured by Hitomi collaboration)
- Decaying dark matter line broadening is determined by the virial velocity of the Perseus galaxy cluster, $v_{vir} \sim 10^3\,\mathrm{km/sec}$
- For XMM/Chandra/Suzaku/Nustar there was no difference – they resolution did not allow to distinguish broad from narrow lines
- Hitomi sensitivity to broad line is much weaker



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Microcalorimeter on sounding rocket (2019+)

- Flying time $\sim 10^2$ sec. Pointed at GC only
- Can determine line's position and width

Another Hitomi (around 2020)

It is planned to send a replacement of the Hitomi satellite

Athena+ (around 2028)

- Large ESA X-ray mission with X-ray spectrometer (X-IFU)
- Very large collecting area ($10\times$ that of XMM)
- Super spectral resolution

"Dark matter astronomy era" begins?