Dark Matter Search with High-resolution X-ray Spectroscopy

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Outline

- **Why DM search with X-ray observations**
- **Previous results on an unidentified emission line at E=3.5 keV by X-ray CCD**
- **New results with the Hitomi satellite**

  Hitomi collaboration (2016a) Nature, 535, 117

  Hitomi collaboration (2016b) arXiV: 1607.07420

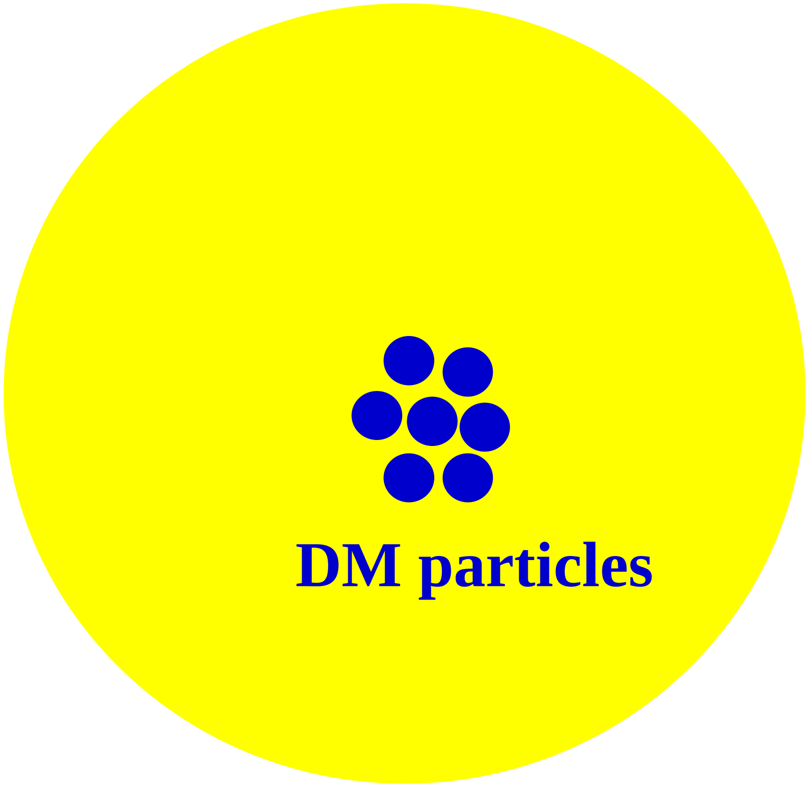
Motivation

- DM makes up >80% of total matter in the Universe.

- No firm detection in laboratory experiments or in γ-rays, so far.

- There are robust (nearly model-independent) bounds for the mass of dark matter particles in the keV range.

(1) Mass bound for "fermion DM"



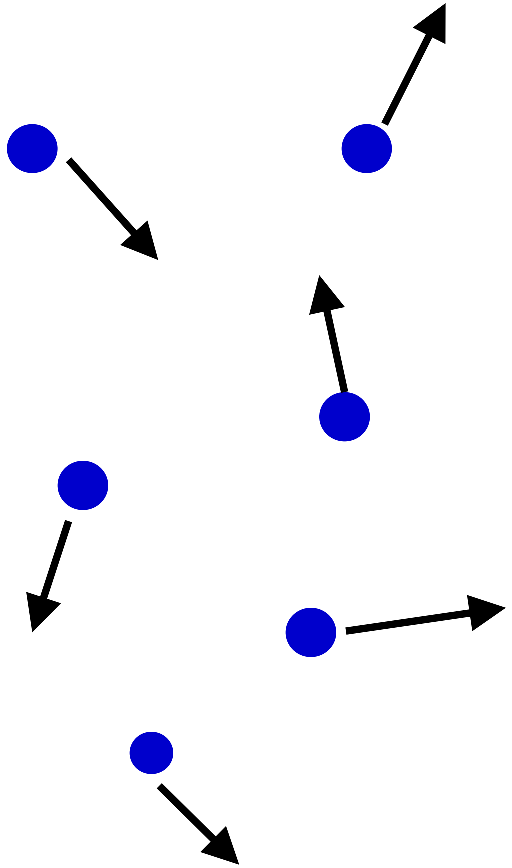
If DM is a fermion, there exits a robust lower bound of the DM mass, below which the Fermi velocity $(2\varepsilon_F/m)^{1/2}$ exceeds the escape velocity $(2GM/R)^{1/2}$.

$$m_{\rm Fermi}^4 > \frac{9\pi\hbar^3}{4\sqrt{2}G^{3/2}M^{1/2}R^{3/2}}$$
$$\sim \underline{(0.3{\rm keV})^4}$$

e.g, dwarf spheroidal galaxies (DM dominated objects)

Boyarsky et al. (2009)
cf. Tremaine and Gunn (1979)

(2) Mass bound for "nearly thermal DM"



If DM particles were moving at nearly (not necessarily exactly) thermal velocity, they were relativistic when

$$kT > mc^2$$

and smoothed density perturbations up to the free-streaming scale (comoving)

$$l_{\rm FS} \sim 1\ {\rm Mpc} \left(\frac{mc^2}{\rm keV}\right)^{-1}$$

Thus, galaxy formation is possible only if $mc^2 >$ keV.

※ Mpc=3.1 × 10^{24} cm

Why is keV DM interesting?

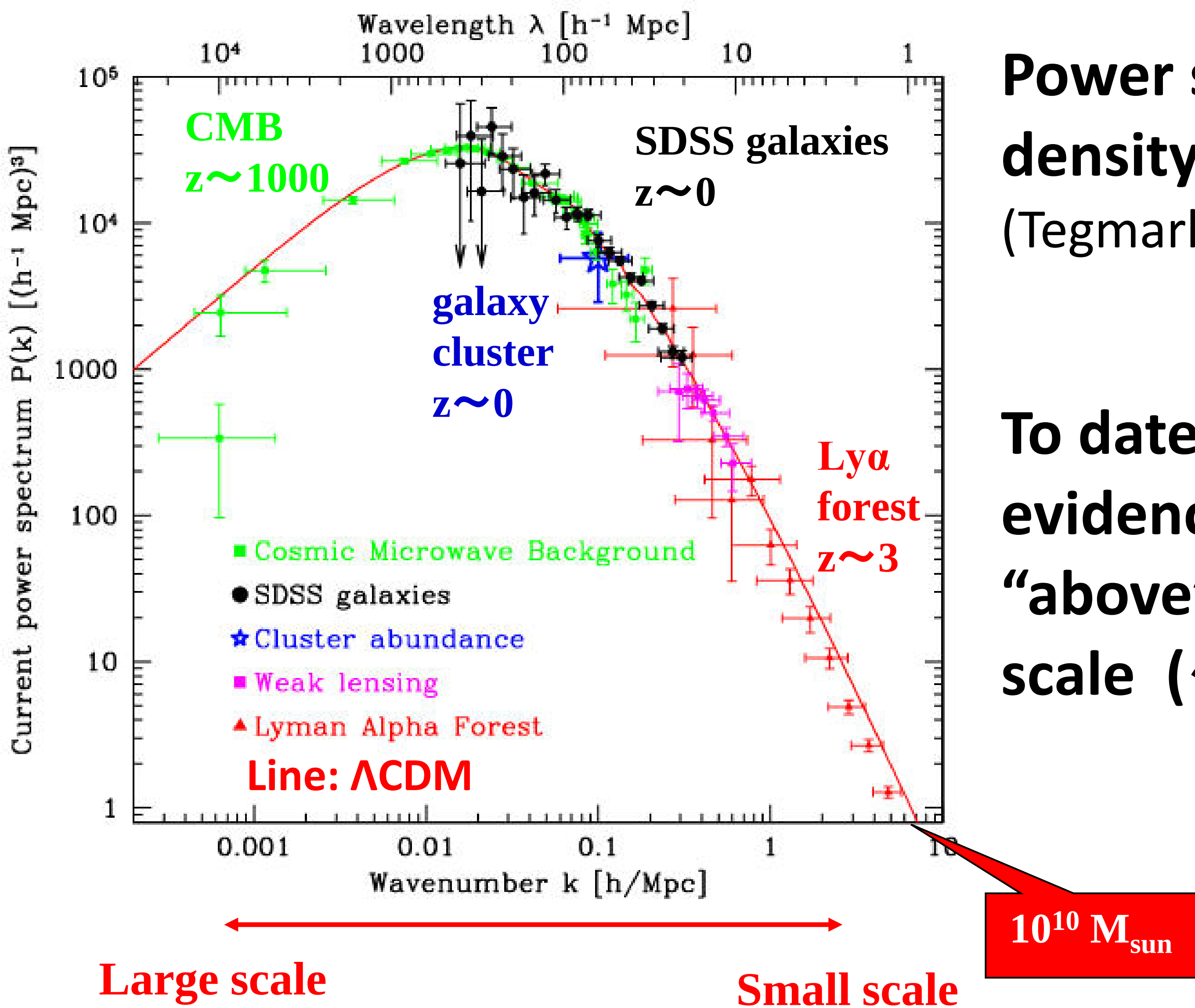
Plausible candidate of the lightest fermion DM and/or Warm DM (free-streaming ～ galaxy scale) that may resolve several shortcomings of the Cold Dark Matter Model at sub-galactic scales:

e.g.,
- **Substructure problem**
- **Angular momentum problem**
- **Flat density profile of dwarf galaxies**

(Weinberg et al. 2015, arXiv:1306.0913)

i.e., CDM tends to over-predict mass concentration at sub-galactic scales, while the roles of baryonic processes are also uncertain.

To what extent is CDM tested?



Power spectrum of density fluctuations
(Tegmark et al. 2004)

To date, observational evidences for CDM are "above" the galaxy scale（〜Mpc）.

Can we “see” DM in X-rays?

DM particles must be stable for >10^{10} yr, but they are detectable if they decay to X-ray photons in ∼10^{20} yr

$$F \sim \frac{3\times10^{-14}\mathrm{erg/s/cm^2}}{(1+z)^4}\left(\frac{\Gamma}{(10^{20}\mathrm{yr})^{-1}}\right)\left(\frac{E_\gamma}{mc^2/2}\right)\left(\frac{M_{\mathrm{DM}}^{\mathrm{FOV}}}{10^{10}M_\odot}\right)\left(\frac{D_A}{\mathrm{Mpc}}\right)^{-2}$$

Decay rate

Surface mass density within the FOV

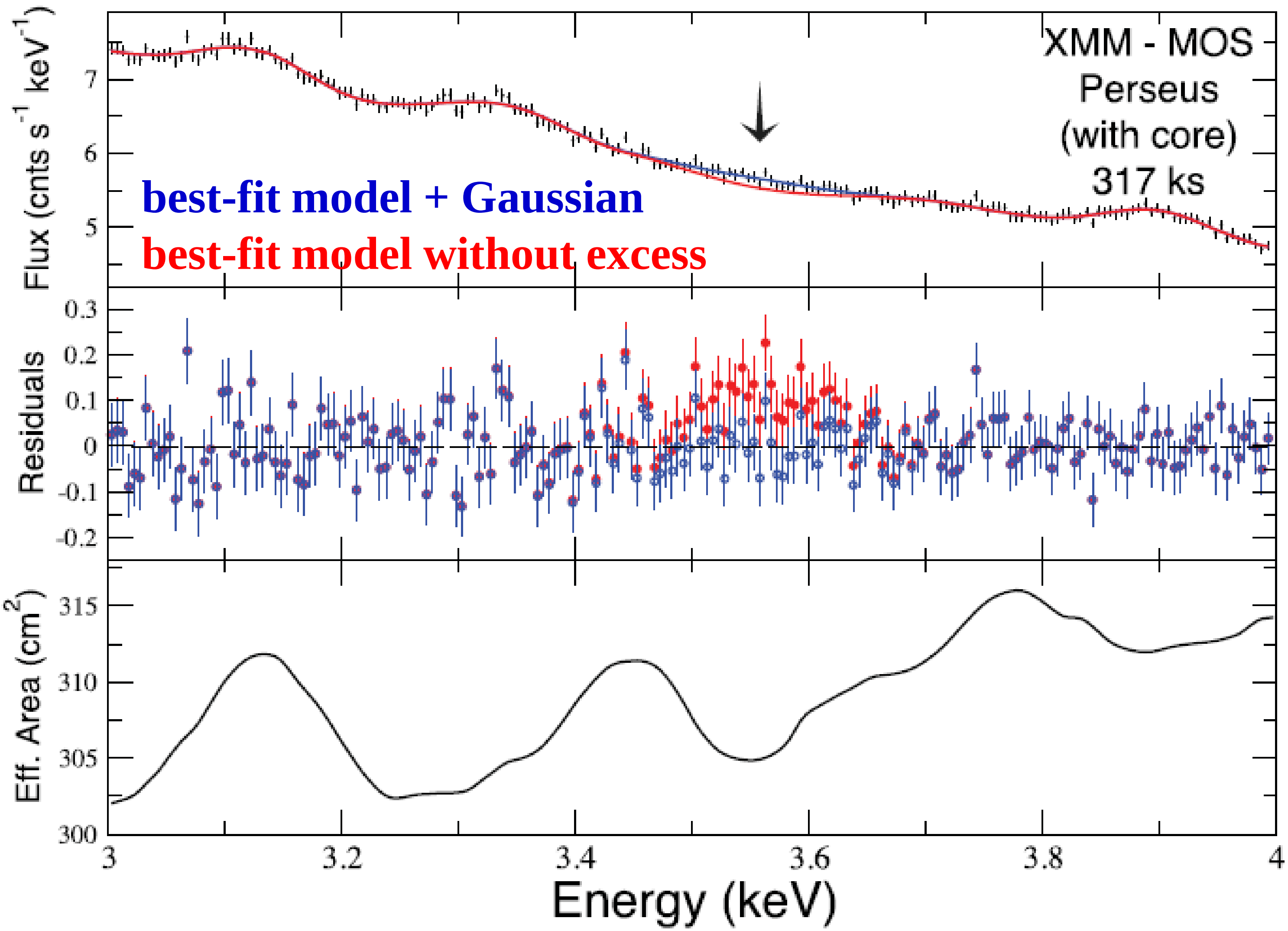
Candidate: right-handed (sterile) neutrino

$$\Gamma \simeq 1.4\times10^{-28}\mathrm{s}^{-1}\left(\frac{\sin^2 2\theta}{10^{-6}}\right)\left(\frac{m}{\mathrm{keV}}\right)^5$$

Pal and Wolfenstein (1982)

The mass can also be measured from the line energy.

Unidentified emission line at 3.5 keV?



Bulbul et al. (2014)

Perseus center (< 12')

$5.2^{+2.6}_{-1.6} \times 10^{-5}$ ph/cm^2/s

cf.

73 clusters stacked

$0.40 \pm 0.08 \times 10^{-5}$ ph/cm^2/s

Ref.	Object	Redshift	Instrument	Exposure, Msec	Line position, keV	Line flux, 10^{-6} ph/sec/cm^2
[33]	Full stacked sample	0.009-0.354	MOS	6	3.57 ± 0.02	4.0 ± 0.8
[33]	Full stacked sample	0.009-0.354	PN	2	3.51 ± 0.03	$3.9^{+0.6}_{-1.0}$
[33]	Coma+Centaurus+Ophiuchus	0.009-0.028	MOS	0.5	3.57^a	$15.9^{+3.4}_{-3.8}$
[33]	Coma+Centaurus+Ophiuchus	0.009-0.028	PN	0.2	3.57^a	< 9.5 (90%)
[33]	Perseus (< 12')	0.016	MOS	0.3	3.57^a	$52.0^{+24.1}_{-15.2}$
[33]	Perseus (< 12')	0.016	PN	0.05	3.57^a	< 17.7 (90%)
[33]	Perseus (1-12')	0.016	MOS	0.3	3.57^a	$21.4^{+7.0}_{-6.3}$
[33]	Perseus (1-12')	0.016	PN	0.05	3.57^a	< 16.1 (90%)
[33]	Rest of the clusters	0.012-0.354	MOS	4.9	3.57^a	$2.1^{+0.4}_{-0.5}$
[33]	Rest of the clusters	0.012-0.354	PN	1.8	3.57^a	$2.0^{+0.3}_{-0.5}$
[33]	Perseus (> 1')	0.016	ACIS-S	0.9	3.56 ± 0.02	$10.2^{+3.7}_{-3.5}$
[33]	Perseus (< 9')	0.016	ACIS-I	0.5	3.56^a	$18.6^{+7.8}_{-8.0}$
[33]	Virgo (< 500")	0.003-0.004	ACIS-I	0.5	3.56^a	< 9.1 (90%)
[34]	M31 (< 14')	-0.001^b	MOS	0.5	3.53 ± 0.03	$4.9^{+1.6}_{-1.3}$
[34]	M31 (10-80')	-0.001^b	MOS	0.7	3.50-3.56	< 1.8 (2σ)
[34]	Perseus (23-102')	0.0179^b	MOS	0.3	3.50 ± 0.04	7.0 ± 2.6
[34]	Perseus (23-102')	0.0179^b	PN	0.2	3.46 ± 0.04	9.2 ± 3.1
[34]	Perseus, 1st bin (23-37')	0.0179^b	MOS	0.2	3.50^a	13.8 ± 3.3
[34]	Perseus, 2nd bin (42-54')	0.0179^b	MOS	0.1	3.50^a	8.3 ± 3.4
[34]	Perseus, 3rd bin (68-102')	0.0179^b	MOS	0.03	3.50^a	4.6 ± 4.6
[34]	Blank-sky	—	MOS	7.8	3.45-3.58	< 0.7 (2σ)

Table 2: Properties of ~3.5 keV line searched in February 2014 using different X-ray datasets observed by MOS and PN cameras on-board *XMM-Newton* observatory and ACIS instrument on-board *Chandra* observatory. All error bars are at 1σ (68%) level.

[a] Line position was fixed at given value.

[b] Redshift was fixed at NASA Extragalactic Database (NED) value.

Ref.	Object	Redshift	Instrument	Exposure, Msec	Line position, keV	Line flux, 10^{-6} ph/sec/cm^2
[75]	Galactic center (2.5-12')	0.0	ACIS-I	0.8	$\simeq 3.5$	$\lesssim 25$ (2σ)
[76]	Galactic center (0.3-15')	0.0	MOS	0.7	$\simeq 3.5$	< 41
[76]	Galactic center (0.3-15')	0.0	PN	0.5	$\simeq 3.5$	< 32
[76]	M31	0.0	MOS	0.5	3.53 ± 0.07	2.1 ± 1.5^c
[77]	Galactic center (< 14')	0.0	MOS	0.7	3.539 ± 0.011	29 ± 5
[80]	Perseus core (< 6')	0.0179^b	XIS	0.74	$3.510^{+0.023}_{-0.008}$	$32.5^{+3.7}_{-4.3}$
[80]	Perseus confined (6-12.7')	0.0179^b	XIS	0.74	$3.510^{+0.023}_{-0.008}$	$32.5^{+3.7}_{-4.3}$
[80]	Coma (< 12.7')	0.0231^b	XIS	0.164	$\simeq 3.45^d$	$\simeq 30^d$
[80]	Ophiuchus (< 12.7')	0.0280^b	XIS	0.083	$\simeq 3.45^d$	$\simeq 40^d$
[80]	Virgo (< 12.7')	0.0036^b	XIS	0.09	3.55^a	< 6.5 (2σ)
[82]	Abell 85 (< 14')	0.0551^b	MOS	0.20	$3.44^{+0.06}_{-0.05}$	$6.3^{+3.9}_{-3.6}$
[82]	Abell 2199 (< 14')	0.0302^b	MOS	0.13	$3.41^{+0.04}_{-0.04}$	$10.1^{+5.1}_{-4.8}$
[82]	Abell 496 (< 14')	0.0329^b	MOS	0.13	$3.55^{+0.06}_{-0.09}$	$7.5^{+6.1}_{-4.4}$
[82]	Abell 496 (< 14')	0.0329^b	PN	0.08	$3.45^{+0.04}_{-0.03}$	$16.8^{+5.9}_{-6.4}$
[82]	Abell 3266 (< 14')	0.0589^b	PN	0.06	$3.53^{+0.04}_{-0.06}$	$8.7^{+5.1}_{-4.5}$
[82]	Abell S805 (< 14')	0.0139^b	PN	0.01	$3.63^{+0.05}_{-0.06}$	$17.1^{+9.3}_{-7.4}$
[82]	Coma (< 14')	0.0231^b	MOS	0.17	$3.49^{+0.04}_{-0.05}$	$23.7^{+10.7}_{-9.0}$
[82]	Abell 2319 (< 14')	0.0557^b	MOS	0.08	$3.59^{+0.05}_{-0.06}$	$18.6^{+10.7}_{-7.4}$
[82]	Perseus (< 14')	0.0179^b	MOS	0.16	$3.58^{+0.05}_{-0.08}$	$25.2^{+12.5}_{-12.6}$
[82]	Virgo[e] (< 14')	0.0036^b	PN	0.06	—	< 9.3

Table 3: Properties of ~3.5 keV line searched after February 2014 in different X-ray datasets observed by MOS and PN cameras on-board *XMM-Newton* observatory, ACIS-I instrument on-board *Chandra* observatory and XIS instrument on-board *Suzaku* observatory. All error bars are at 1σ (68%) level.

[a] Line position was fixed at given value.

[b] Redshift was fixed at NASA Extragalactic Database (NED) value.

[c] The line was detected at < 90% confidence level. Such a low flux (compared with [34]) was due to unphysically enhanced level of continuum at 3-4 keV band used in [76], see [85] for details.

[d] Parameters estimated from Fig. 3 of [80].

[e] Given an example of the new line non-detection, see Table II of [82] for more details.

Compiled by Iakubovskyi arXiv:1510.00358

[33] Bulbul et al. (2014)
[34] Boyarsky et al. (2014)
[64] Tamura et al. (2014)
[75] Riemer-Sorensen (2014)
[76] Jeltema, Profumo (2015)
[77] Boyarsky et al. (2015)
[80] Urban et al. (2015)
[82] Iakubovskyi et al. (2015)

X-ray CCD results (ΔE～100 eV)

1. **>3σ signatures are reported from the Perseus galaxy cluster, M31 galaxy, and a stacked sample of 73 galaxy clusters. Other individual systems have < 3σ significance.** (e.g., Bulbul et al. 2014; Boyarsky et al. 2014)

2. **The signal towards the Perseus center is >10 times brighter than the average of the other massive clusters.** (Bulbul et al. 2014)

3. **The results are sensitive to how continuum and neighboring lines are modeled. Non-detections or controversial results are also reported.** (e.g., Tamura et al. 2014; Urban et al. 2014)

Note: 3.5 keV line is NOT resolved by X-ray CCDs with ΔE～100eV. Systematics effects are not fully excluded.

How can we reduce systematics?

1. Excluding plasma origins

   Line width

   DM: velocity dispersion of collisionless particles
   (>1000 km/s for massive galaxy clusters)

   plasma ions: thermal + turbulent motion (～200 km/s)

2. Excluding instrumental effects

   Line centroid energy

   should vary with redshifts (distances) of the target objects, if the line originates from them.

Both require spectral resolution of $\Delta E < 10$eV.

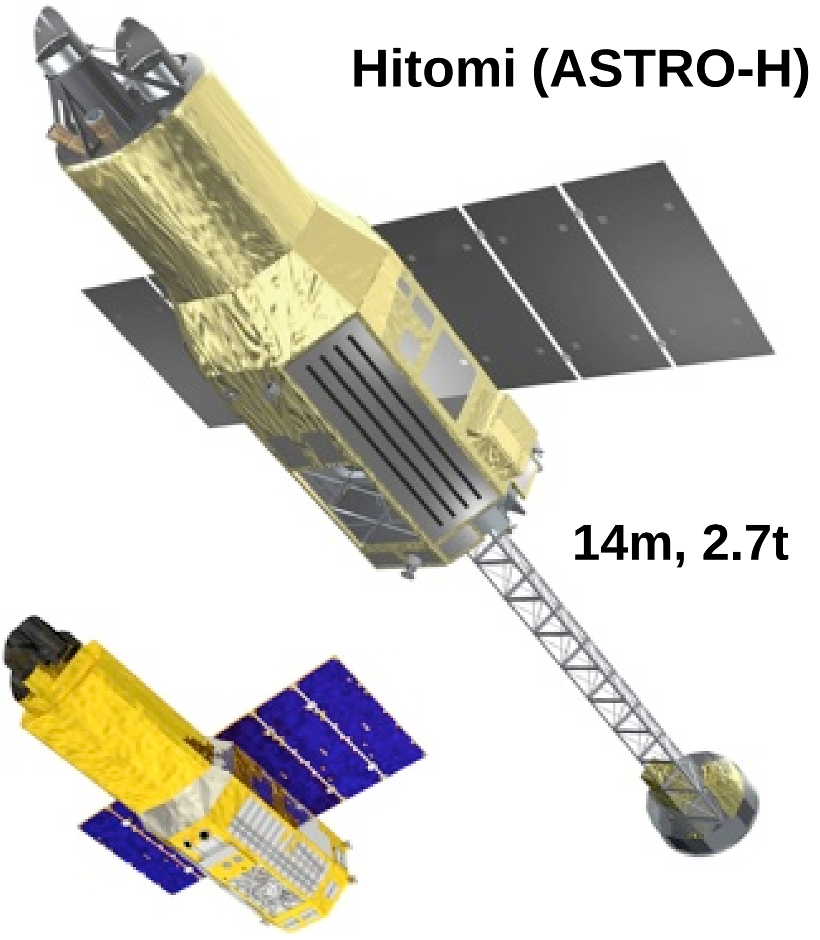
Hitomi satellite

First X-ray satellite to have achieved
ΔE=5 eV (x20 better than CCD)
for extended sources.

cf. Expected FWHM of a DM line

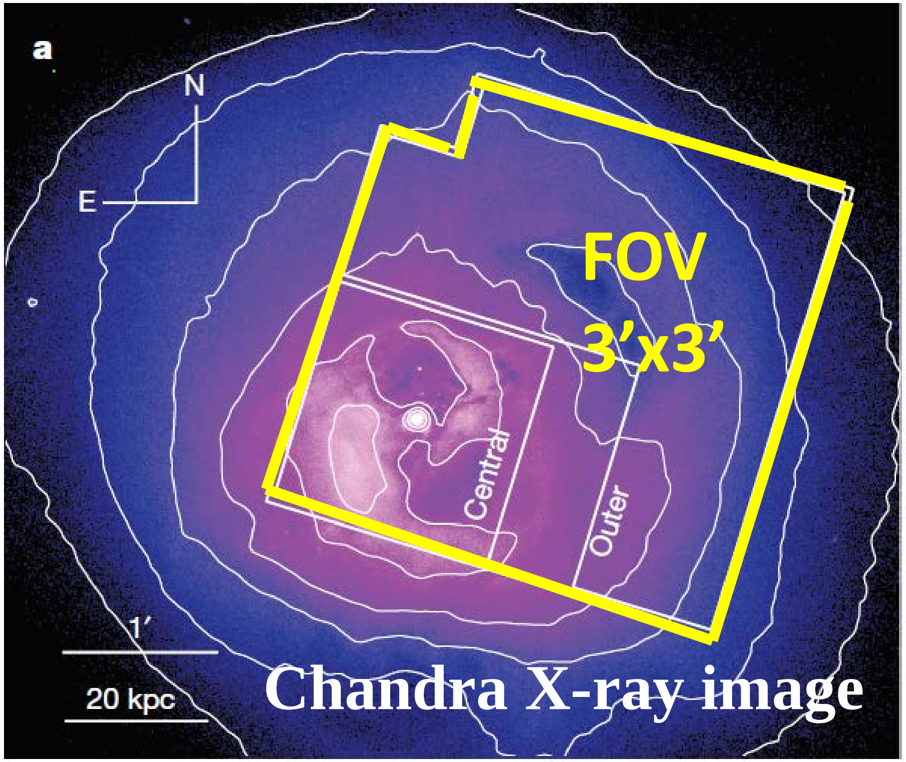
$$W_{\rm dm} \simeq 7.9\ {\rm eV} \left(\frac{\sigma_{\rm dm}}{1000\ {\rm km/s}} \right) \left(\frac{E_{\rm obs}}{\rm keV} \right).$$

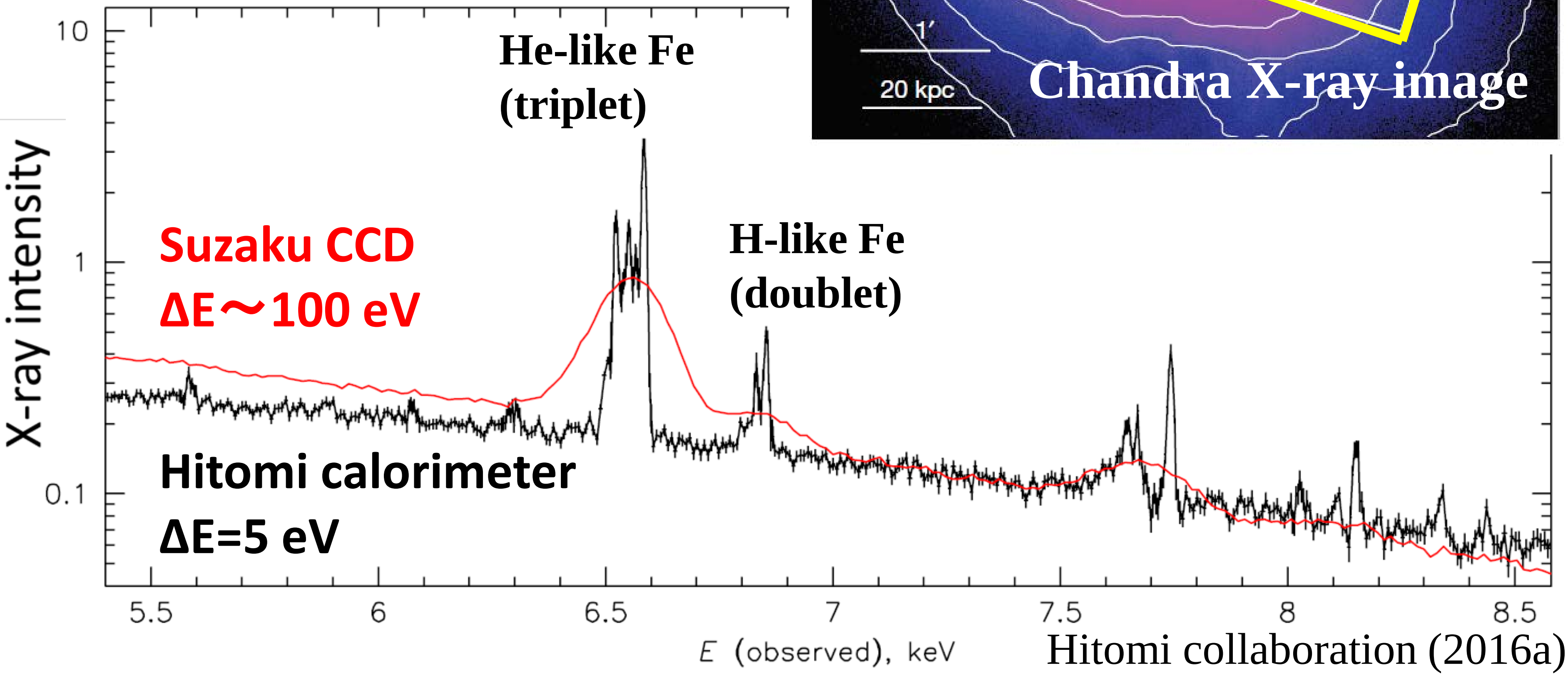
Launched in February, 2016,
observed a few targets,
and lost control in March, 2016.



Hitomi observed the Perseus cluster at z=0.0179

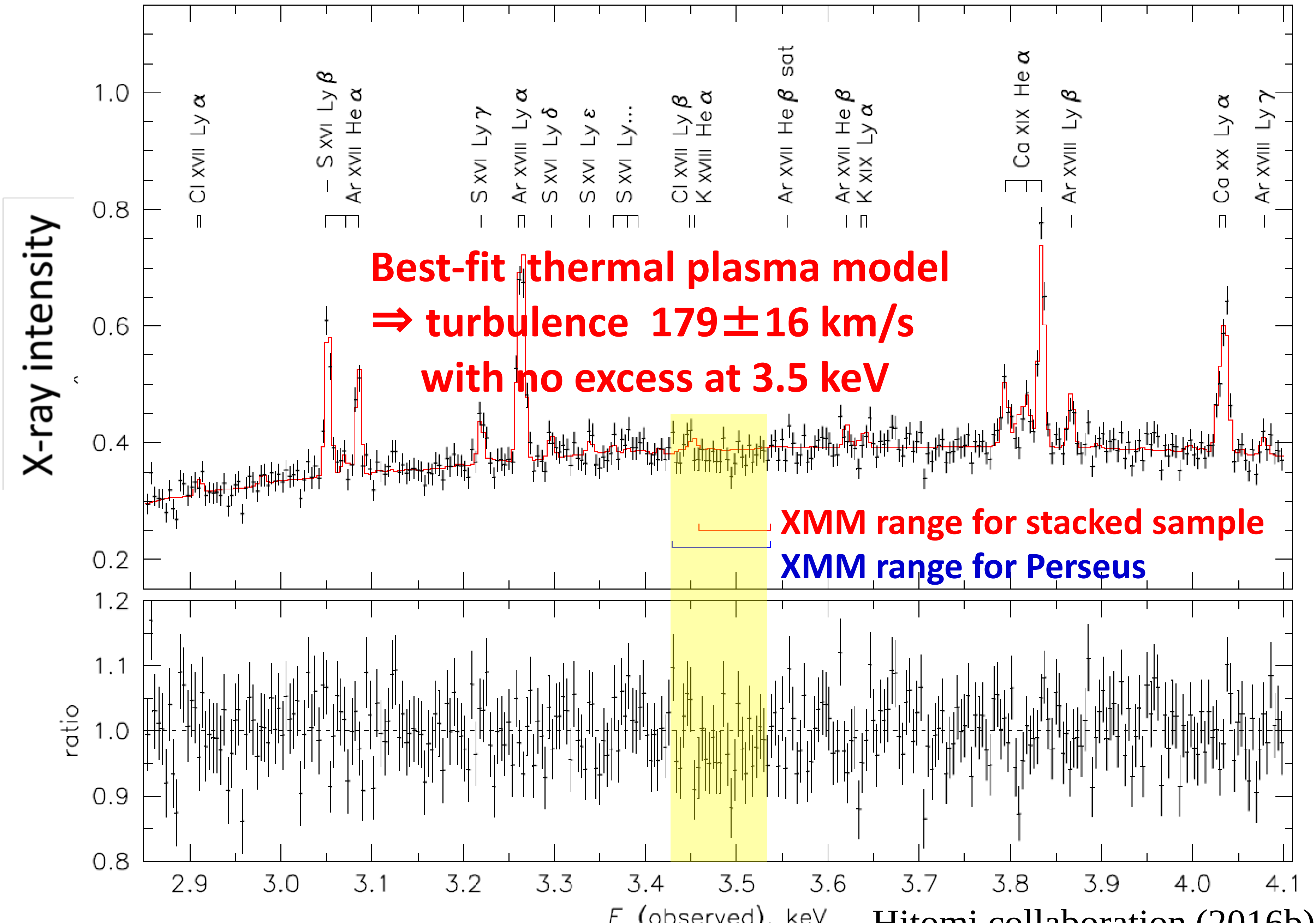
(Ohashi's talk tomorrow)



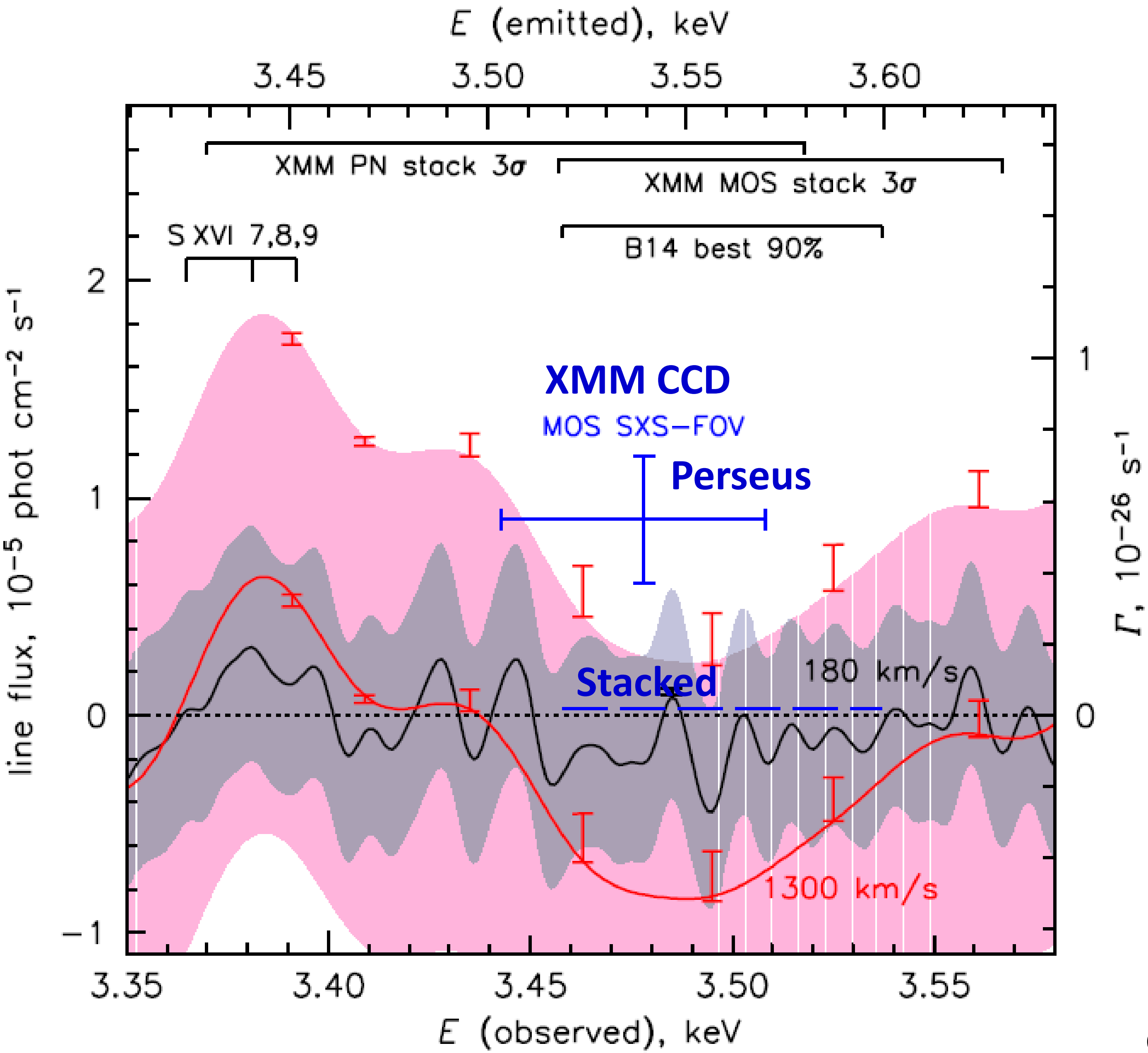


Hitomi collaboration (2016a)

Hitomi spectrum of the Perseus center around 3.5 keV



Hitomi collaboration (2016b)

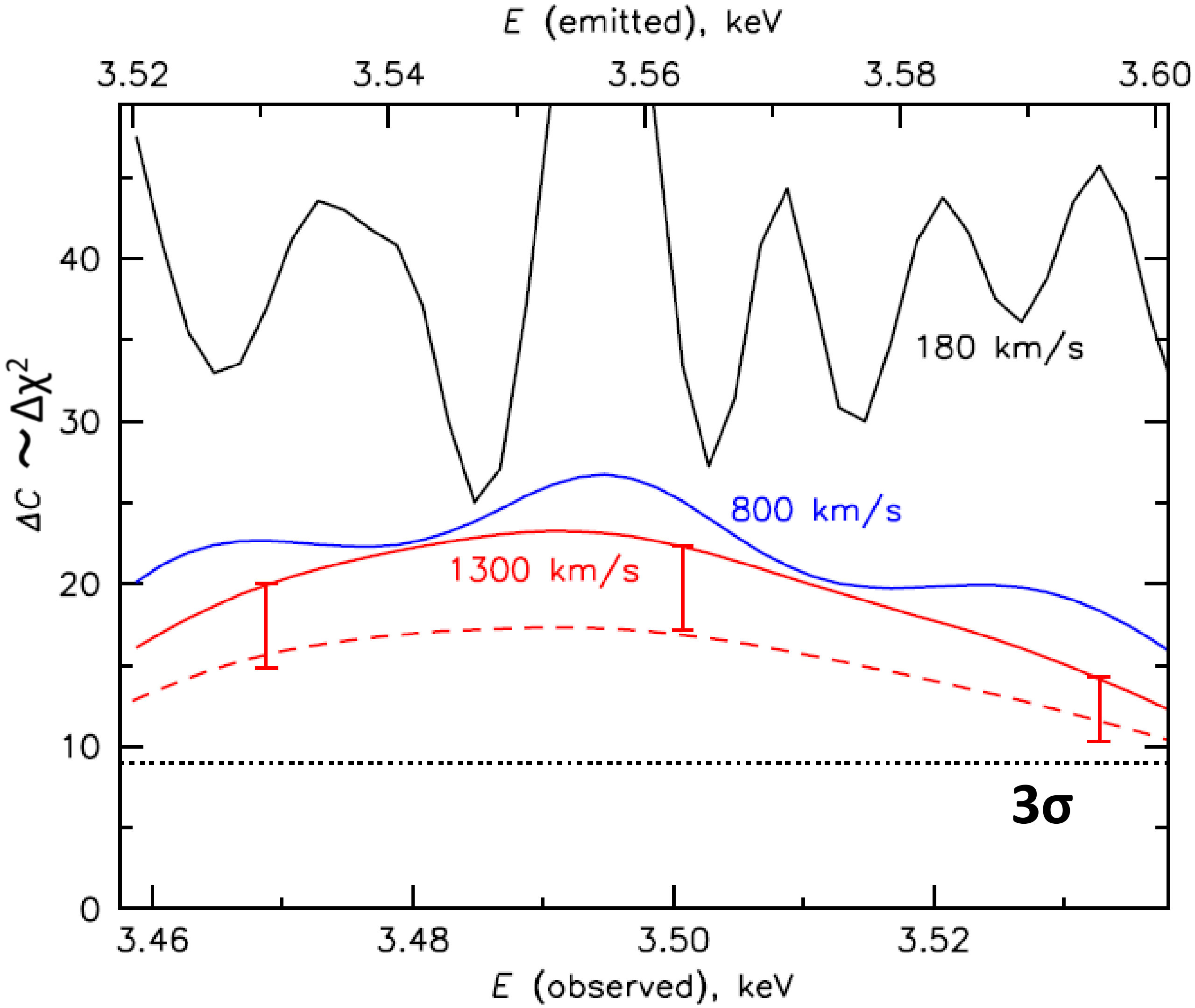


Hitomi collaboration (2016b)

Best-fit (solid) ±3σ (shaded) fluxes for an additional Gaussian line broadened by

1) **plasma turbulence (180 km/s)**
2) **DM velocity dispersion (1300 km/s)**

Red and black error bars show systematic uncertainty of the effective area of the telescope.



Hitomi collaboration (2016b)

Significance of the difference between the best-fit XMM and Hitomi results for a Gaussian line with varying widths (not including the errors of the XMM result).

Red error bars show systematic uncertainty of the effective area of the telescope. Red dashed line shows the difference from the zero flux.

Summary

1. An unidentified line at 3.5 keV was inferred in a number of systems based on unresolved spectra taken by X-ray CCD.

2. Hitomi obtained the first and only resolved spectrum toward the center of the Perseus galaxy cluster and excluded the previous CCD result (the brightest signal) for this system at >99% confidence level, taking account of uncertainty of the previous result.

3. An order of magnitude improvement in sensitivity is required to test the previous result for the fainter average signal from a sample of galaxy clusters.