X-ray emissions from clusters of galaxies

CRAIG L. SARAZIN

Cambridge Astrophysics Series

1. ***Hitomi*** **results on Perseus**

2. **Latest *Chandra* results on mergers, shocks and relics**

Maxim Markevitch (NASA Goddard)

Leiden, October 25, 2017

First high-resolution X-ray spectra of a galaxy cluster

Hitomi Collaboration*: F. A. Aharonian[1,2], H. Akamatsu[3], F. Akimoto[4], S. W. Allen[5,6,7], L. Angelini[8], K. A. Arnaud[8,9], M. Audard[10], H. Awaki[11], M. Axelsson[12], A. Bamba[13], M. W. Bautz[14], R. D. Blandford[5,6,7], E. Bulbul[14], L. W. Brenneman[15], G. V. Brown[16], E. M. Cackett[17], M. Chernyakova[1], M. P. Chiao[8], P. Coppi[18], E. Costantini[3], J. de Plaa[3], J.-W. den Herder[3], C. Done[19], T. Dotani[20], K. Ebisawa[20], M. E. Eckart[8], T. Enoto[21,22], Y. Ezoe[12], A. C. Fabian[17], C. Ferrigno[10], A. R. Foster[15], R. Fujimoto[23], Y. Fukazawa[24], A. Furuzawa[25], M. Galeazzi[26], L. C. Gallo[27], P. Gandhi[28], M. Giustini[3], A. Goldwurm[29], L. Gu[3], M. Guainazzi[20,30], Y. Haba[31], K. Hagino[20], K. Hamaguchi[8,32], I. Harrus[8,32], I. Hatsukade[33], K. Hayashi[20], T. Hayashi[4], K. Hayashida[34], J. Hiraga[35], A. E. Hornschemeier[8], A. Hoshino[36], J. P. Hughes[37], Y. Ichinohe[12], R. Iizuka[20], H. Inoue[20], S. Inoue[34], Y. Inoue[20], K. Ishibashi[4], M. Ishida[20], K. Ishikawa[20], Y. Ishisaki[12], M. Itoh[38], N. Iyomoto[39], J. S. Kaastra[3], T. Kallman[8], T. Kamae[5], E. Kara[9], J. Kataoka[40], S. Katsuda[41], J. Katsuta[24], M. Kawaharada[42], N. Kawai[43], R. L. Kelley[8], D. Khangulyan[36], C. A. Kilbourne[8], A. L. King[5,6], T. Kitaguchi[24], S. Kitamoto[36], T. Kitayama[44], T. Kohmura[45], M. Kokubun[20], S. Koyama[20], K. Koyama[46], P. Kretschmar[30], H. A. Krimm[8,47], A. Kubota[48], H. Kunieda[4], P. Laurent[29], F. Lebrun[29], S.-H. Lee[20], M. A. Leutenegger[8], O. Limousin[29], M. Loewenstein[8,9], K. S. Long[49], D. H. Lumb[50], G. M. Madejski[5,7], Y. Maeda[20], D. Maier[29], K. Makishima[51], M. Markevitch[8], H. Matsumoto[52], K. Matsushita[53], D. McCammon[54], B. R. McNamara[55], M. Mehdipour[3], E. D. Miller[14], J. M. Miller[56], S. Mineshige[21], K. Mitsuda[20], I. Mitsuishi[4], T. Miyazawa[57], T. Mizuno[24], H. Mori[8], K. Mori[33], H. Moseley[8], K. Mukai[8,32], H. Murakami[58], T. Murakami[23], R. F. Mushotzky[9], T. Nakagawa[20], H. Nakajima[34], T. Nakamori[59], T. Nakano[60], S. Nakashima[20], K. Nakazawa[13], K. Nobukawa[61], M. Nobukawa[62], H. Noda[63], M. Nomachi[64], S. L. O' Dell[65], H. Odaka[20], T. Ohashi[12], M. Ohno[24], T. Okajima[8], N. Ota[61], M. Ozaki[20], F. Paerels[66], S. Paltani[10], A. Parmar[50], R. Petre[8], C. Pinto[17], M. Pohl[10], F. S. Porter[8], K. Pottschmidt[8,32], B. D. Ramsey[65], C. S. Reynolds[9], H. R. Russell[17], S. Safi-Harb[67], S. Saito[36], K. Sakai[8], H. Sameshima[20], T. Sasaki[53], G. Sato[20], K. Sato[53], R. Sato[20], M. Sawada[68], N. Schartel[30], P. J. Serlemitsos[8], H. Seta[12], M. Shidatsu[51], A. Simionescu[20], R. K. Smith[15], Y. Soong[8], Ł. Stawarz[69], Y. Sugawara[20], S. Sugita[43], A. E. Szymkowiak[18], H. Tajima[70], H. Takahashi[24], T. Takahashi[20], S. Takeda[71], Y. Takei[20], T. Tamagawa[60], K. Tamura[4], T. Tamura[20], T. Tanaka[46], Yasuo Tanaka[20], Yasuyuki Tanaka[24], M. Tashiro[72], Y. Tawara[4], Y. Terada[72], Y. Terashima[11], F. Tombesi[8], H. Tomida[20], Y. Tsuboi[41], M. Tsujimoto[20], H. Tsunemi[34], T. Tsuru[46], H. Uchida[46], H. Uchiyama[73], Y. Uchiyama[36], S. Ueda[20], Y. Ueda[21], S. Ueno[20], S. Uno[74], C. M. Urry[18], E. Ursino[26], C. P. de Vries[3], S. Watanabe[20], N. Werner[5,6], D. R. Wik[8,75], D. R. Wilkins[27], B. J. Williams[8], S. Yamada[12], H. Yamaguchi[8], K. Yamaoka[4], N. Y. Yamasaki[20], M. Yamauchi[33], S. Yamauchi[61], T. Yaqoob[32,8], Y. Yatsu[43], D. Yonetoku[23], A. Yoshida[67], I. Zhuravleva[5,6], and A. Zoghbi[56]

To measure gas velocities, need a microcalorimeter

v = 100 km/s → Doppler shift 2 eV at E = 6.5 keV

- X-ray microcalorimeter first proposed 30 years ago: *AXAF-S*
descoped

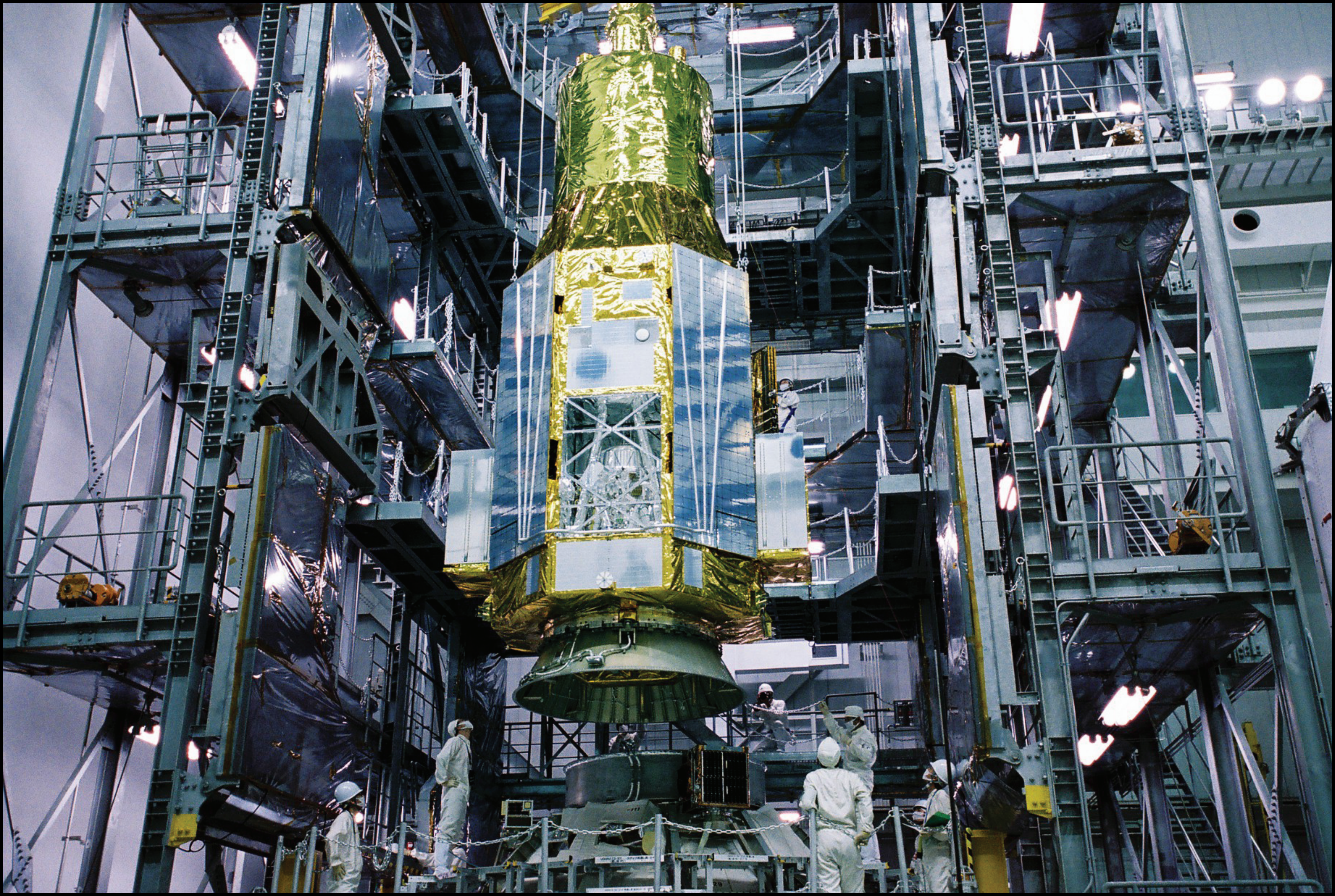
- 1st attempt: 2000, *Astro-E*
rocket exploded

- 2nd attempt: 2005, *Astro-E2* (*Suzaku*) — obtained spectrum of internal background,
"cooling short", calorimeter broke down

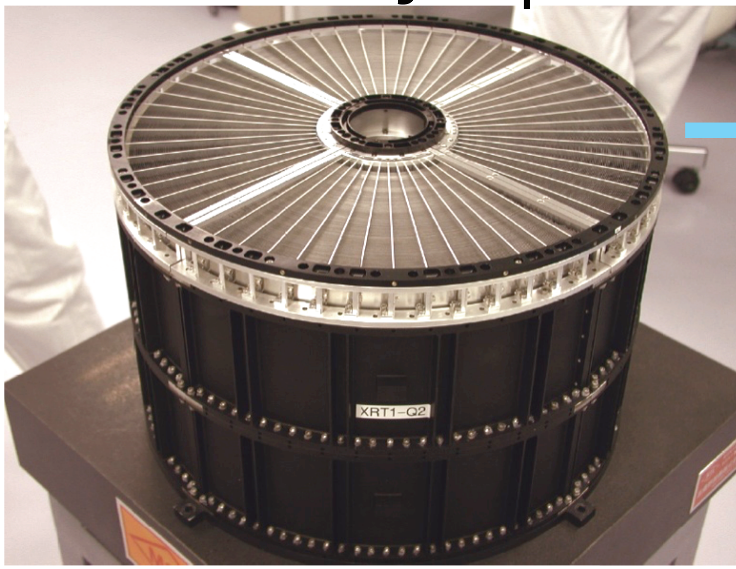
- 3rd attempt: 2016, *Astro-H* (*Hitomi*) — obtained spectra of Perseus cluster and a couple of cal. sources
attitude control failure, spacecraft broke down

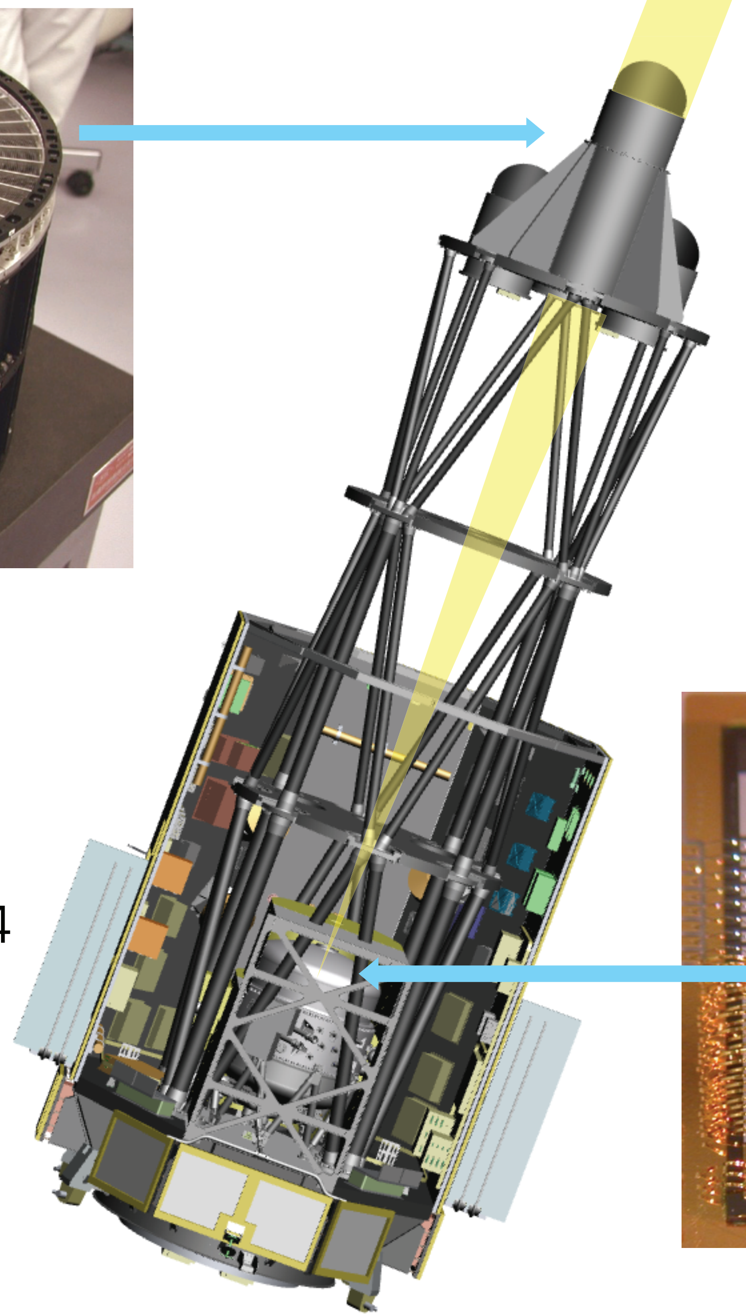
- planned 4th attempt: 2021, *XARM* — *Hitomi* without the hard X-ray instruments

Hitomi (Astro-H)



Soft X-Ray Spectrometer (SXS)





Soft X-Ray Telescope

5.6 m focal length – *fixed optical bench*

203 concentric shells (1624 individual reflectors)

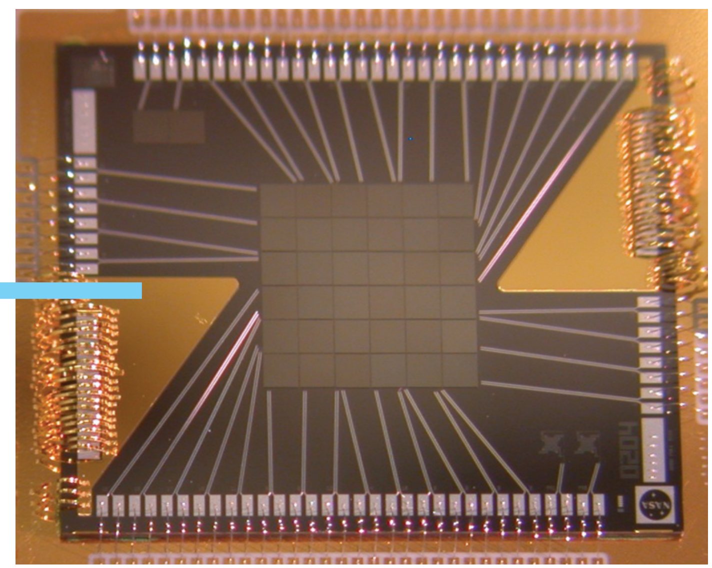
Outer Diameter: 45 cm
Mass: CBE = 46 kg.

Half-Power Diameter of better than 1.7 arcmin

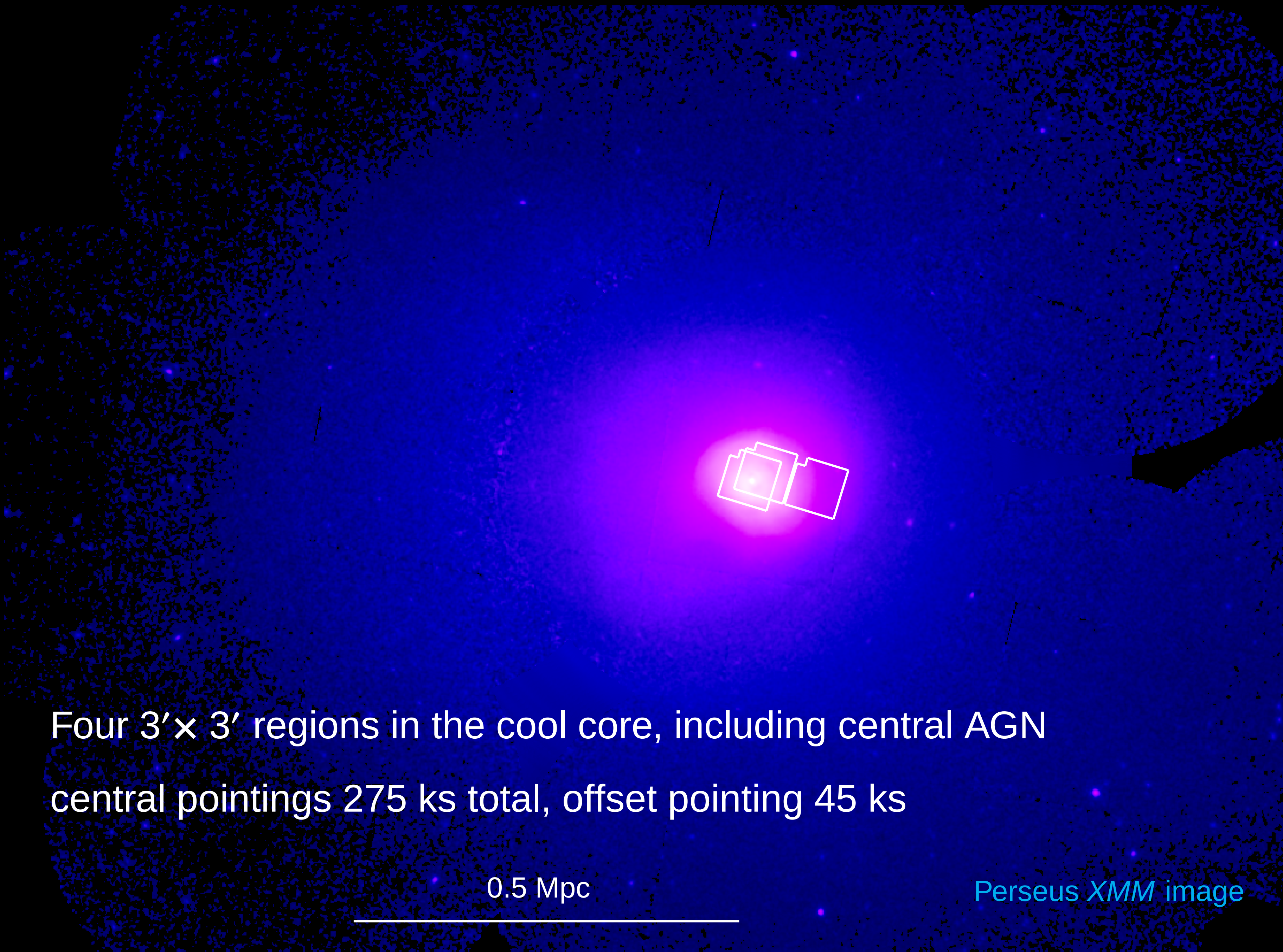
X-ray Calorimeter Spectrometer

SXS – energy resolution better than 7 eV at system level

6 x 6 array of 30″ x 30″ pixels (3 arcmin FOV)



Hitomi SXS Perseus pointings

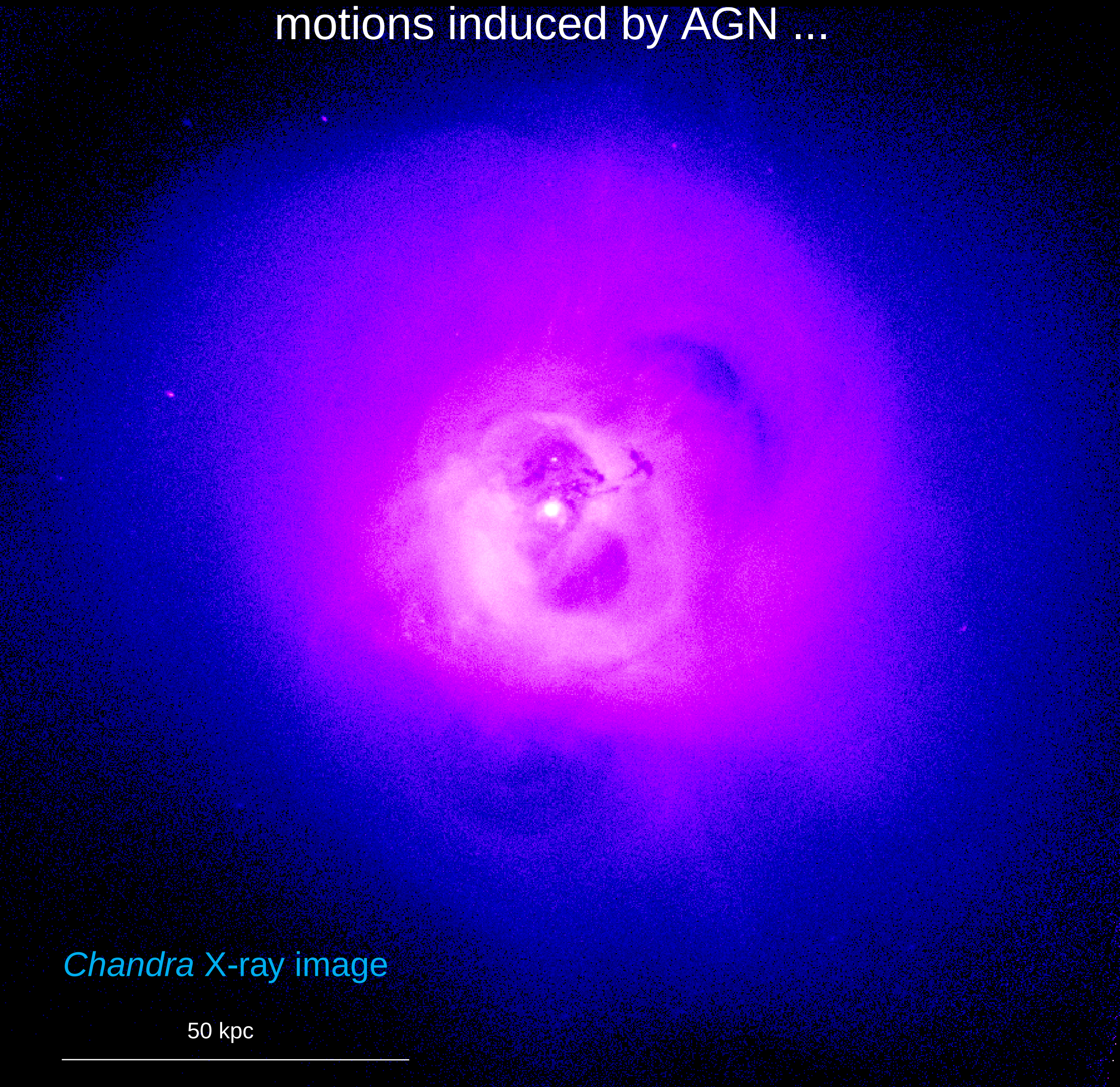


Four 3′× 3′ regions in the cool core, including central AGN

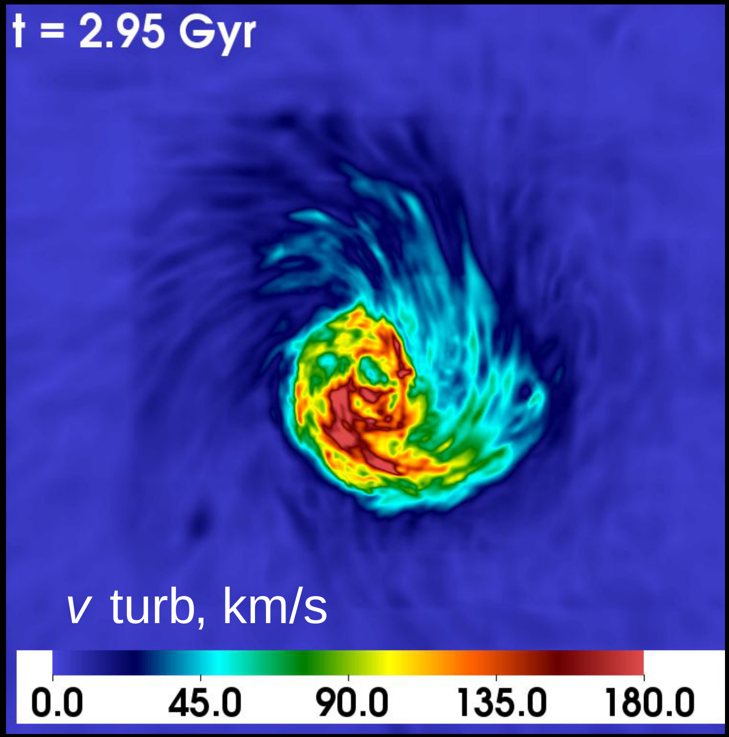
central pointings 275 ks total, offset pointing 45 ks

What do we expect to see?

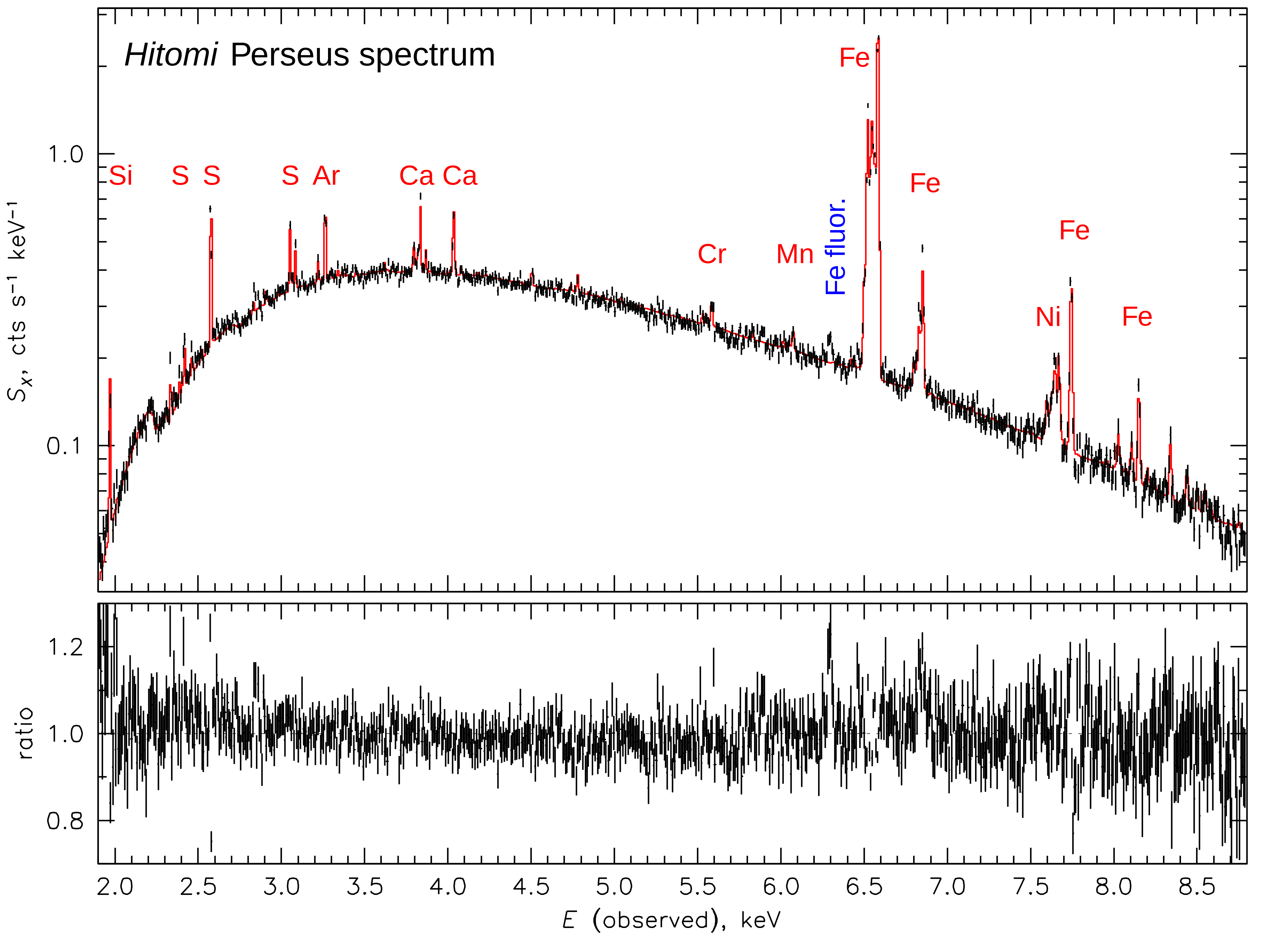
motions induced by AGN ...



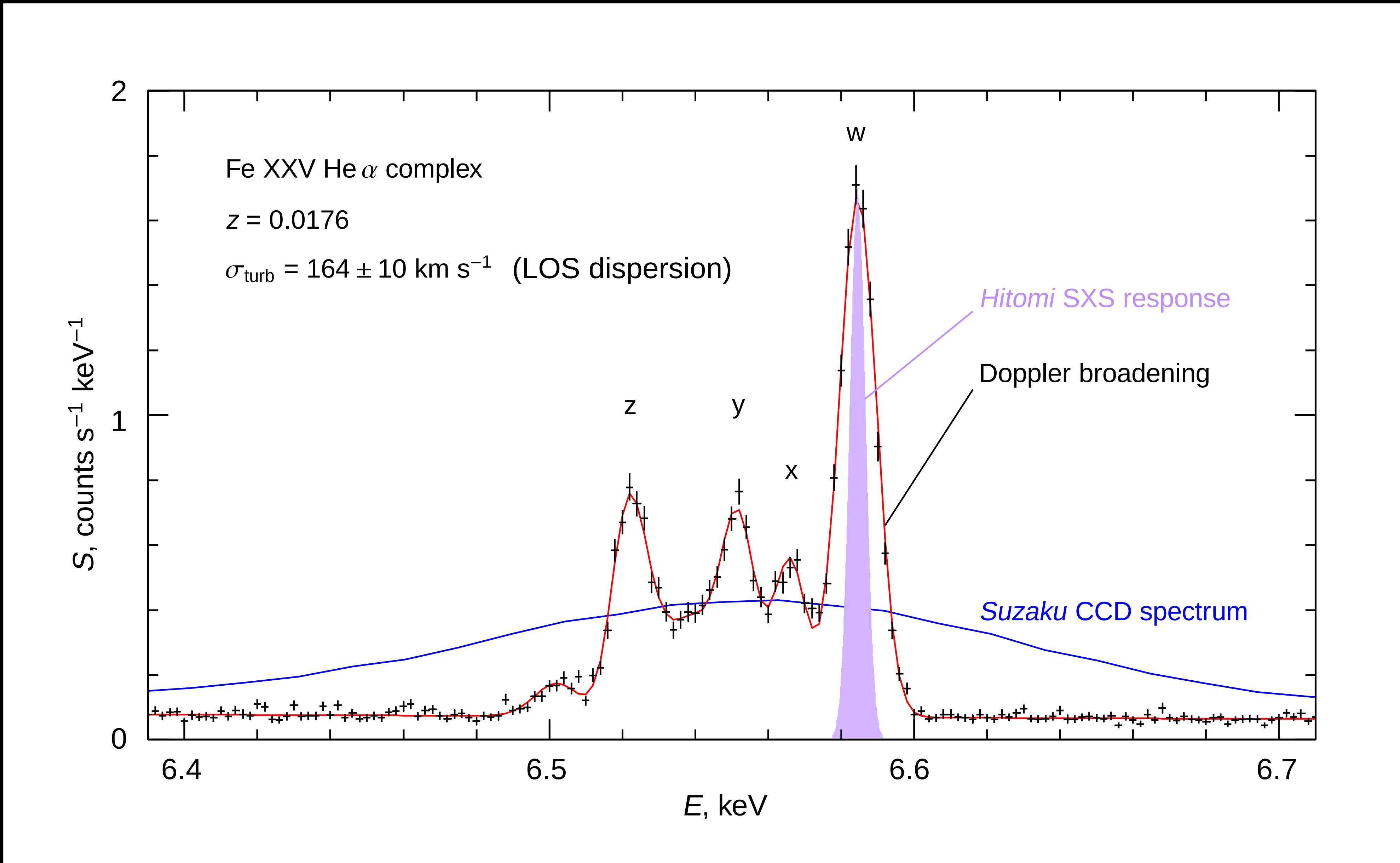
... and core sloshing



simulations (ZuHone 11, 13)


Hitomi Perseus spectrum
Si
S
S
S
Ar
Ca
Ca
Cr
Mn
Fe fluor.
Fe
Fe
Fe
Ni
Fe
1.0
0.1
S_X, cts s^{-1} keV^{-1}
1.2
1.0
0.8
ratio
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
E (observed), keV

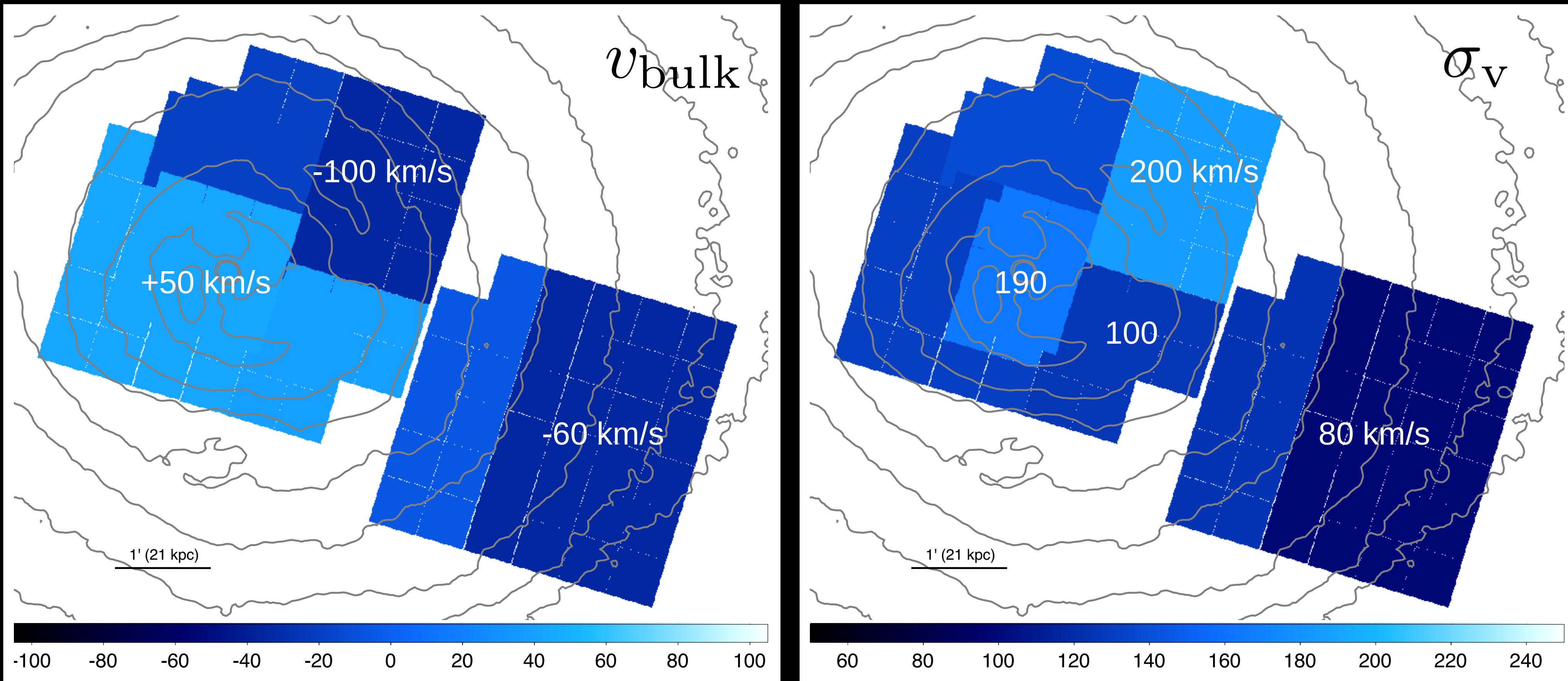
Turbulence from the width of the Fe line



Region excluding main bubbles

Hitomi collab. (2016a)

Velocity and velocity dispersion maps



compare to v_s ~ 1000 km/s

- the gas is surprisingly quiescent! E_{kin} / E_{therm} ~ 5%

  — turbulence difficult to generate and / or easy to damp?

- velocity dispersion is relatively uniform

Hitomi collab. 2017, submitted

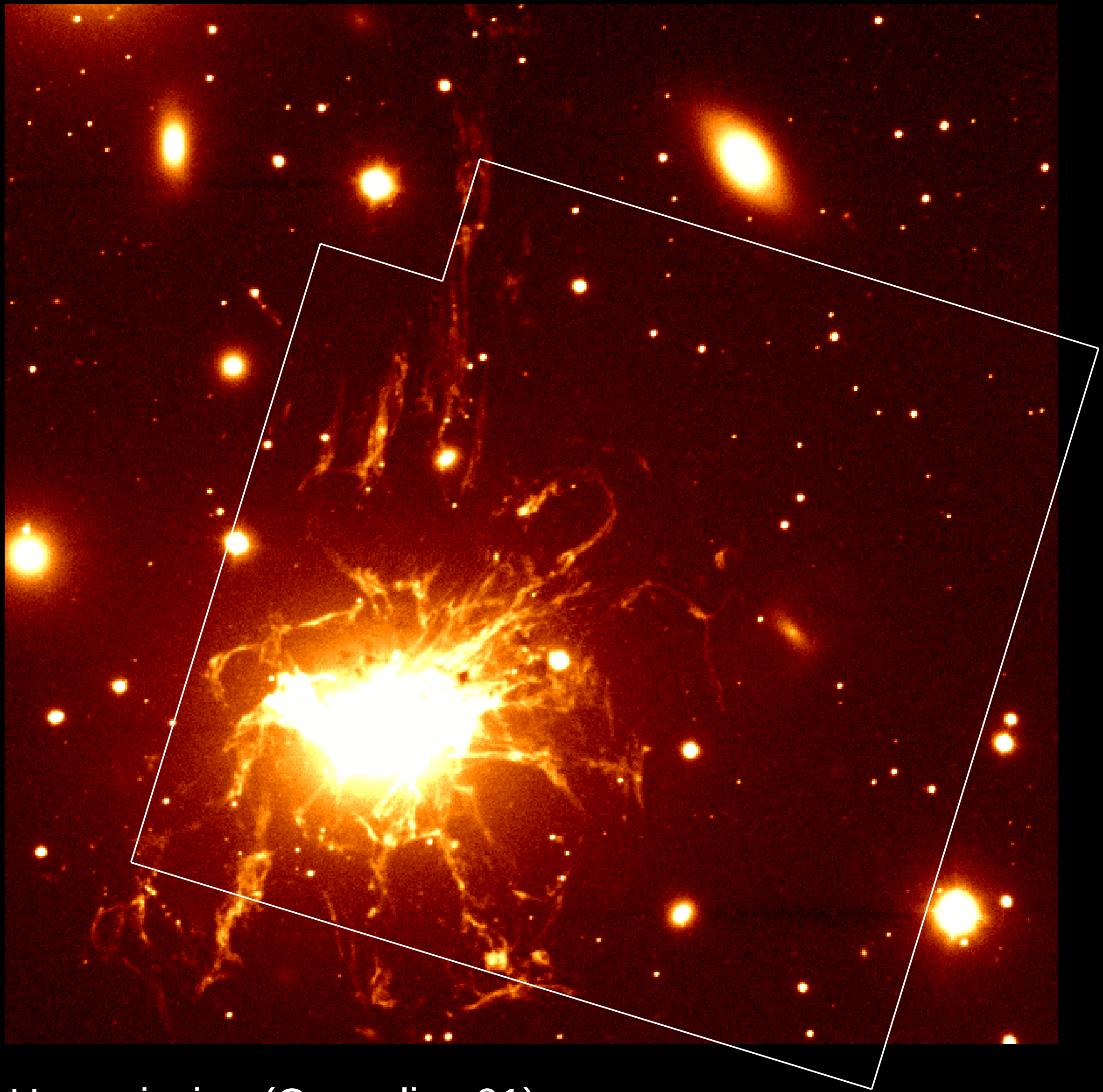
Unexpected ICM physics from *Hitomi*

Charge exchange with neutral gas?

- when a highly-ionized ion collides with an atom or a molecule, it can capture an electron on a high-*n* level
- emits a very high-*n* transition line (and forbidden lines)

- X-ray emission mechanism of comets
- soft variable X-ray background from the heliosphere

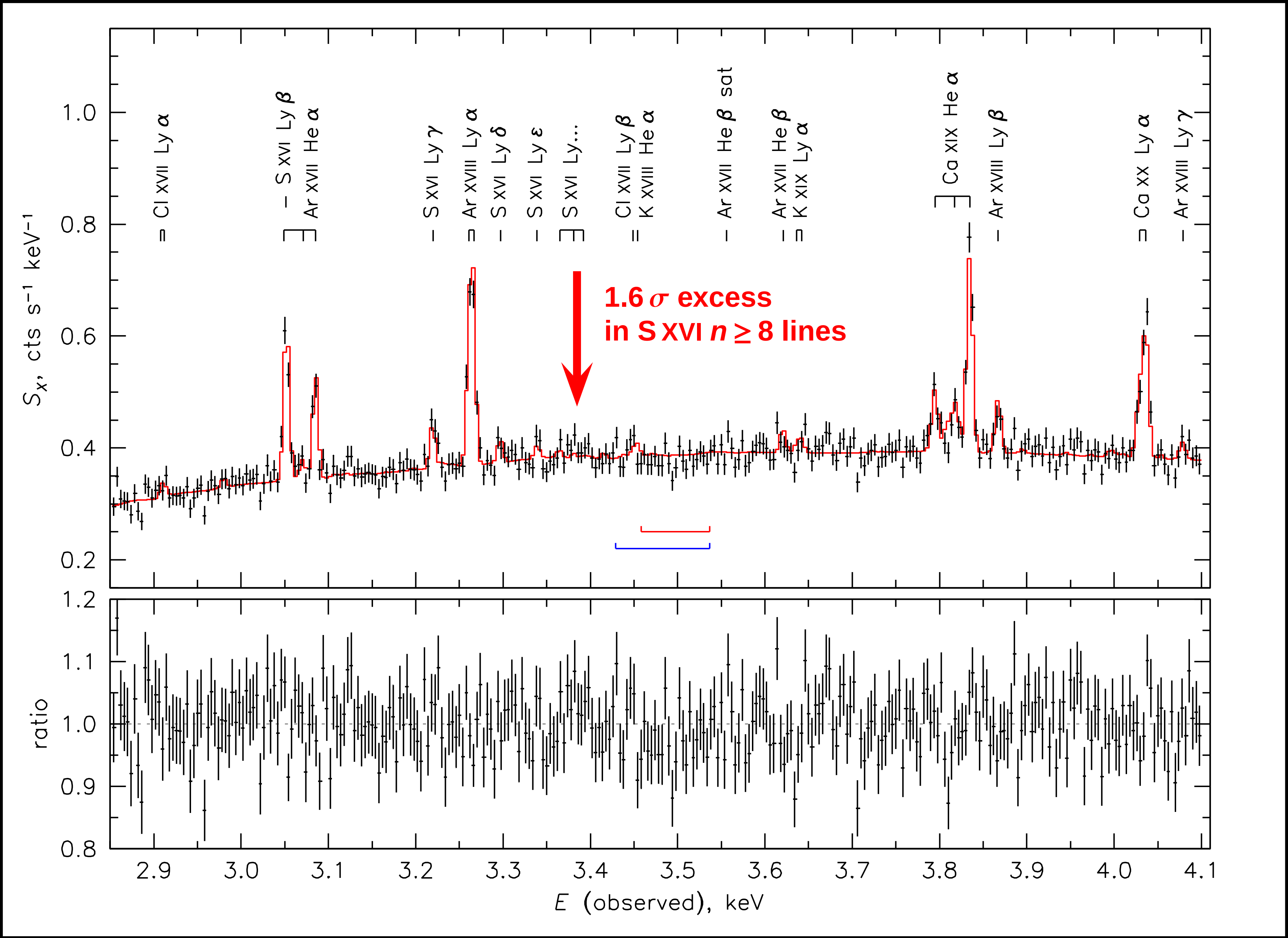
Charge exchange with neutral gas?



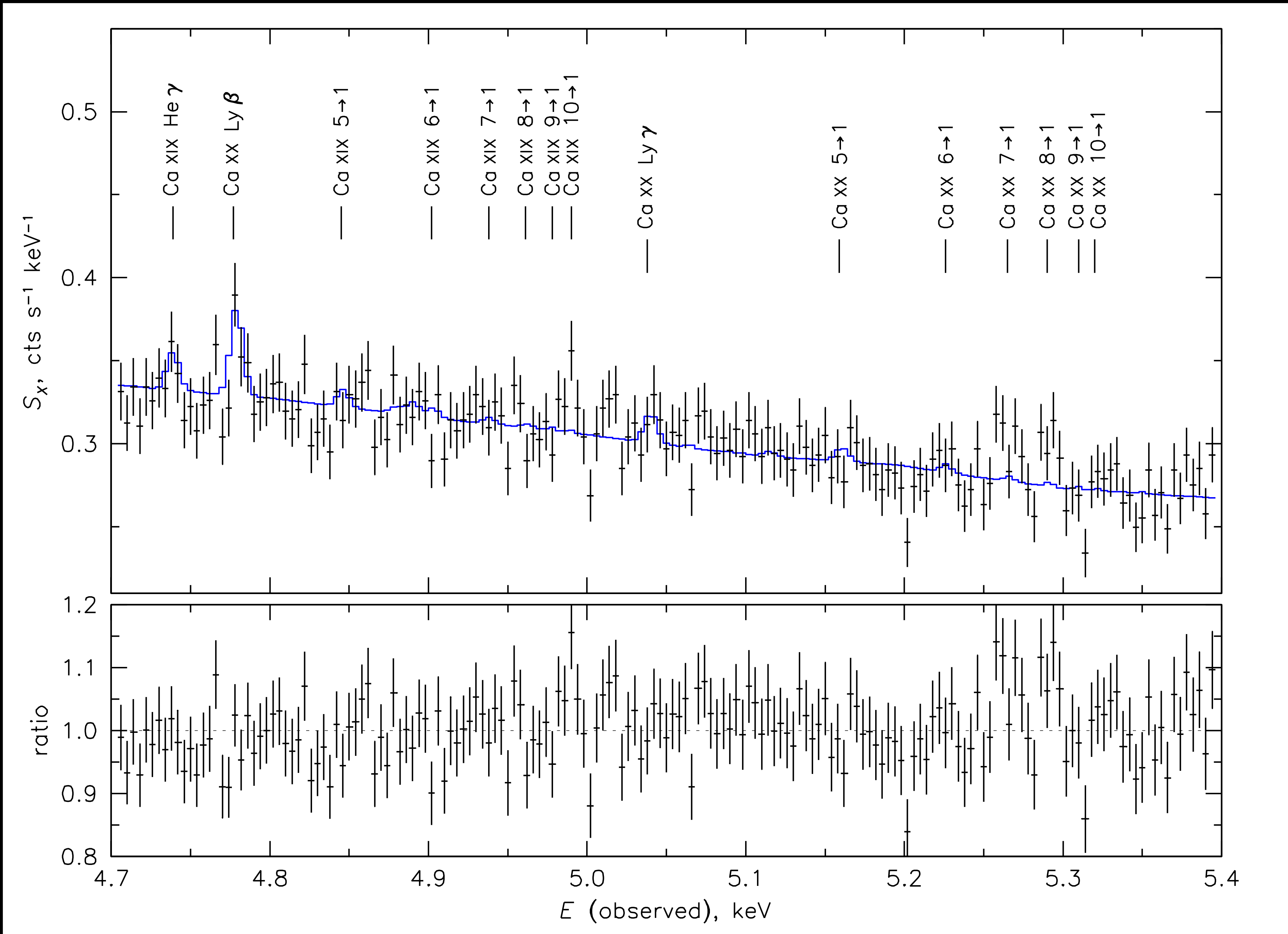
Hα emission (Concelise 01)

- molecular gas dominates total gas mass within central *r*=15 kpc

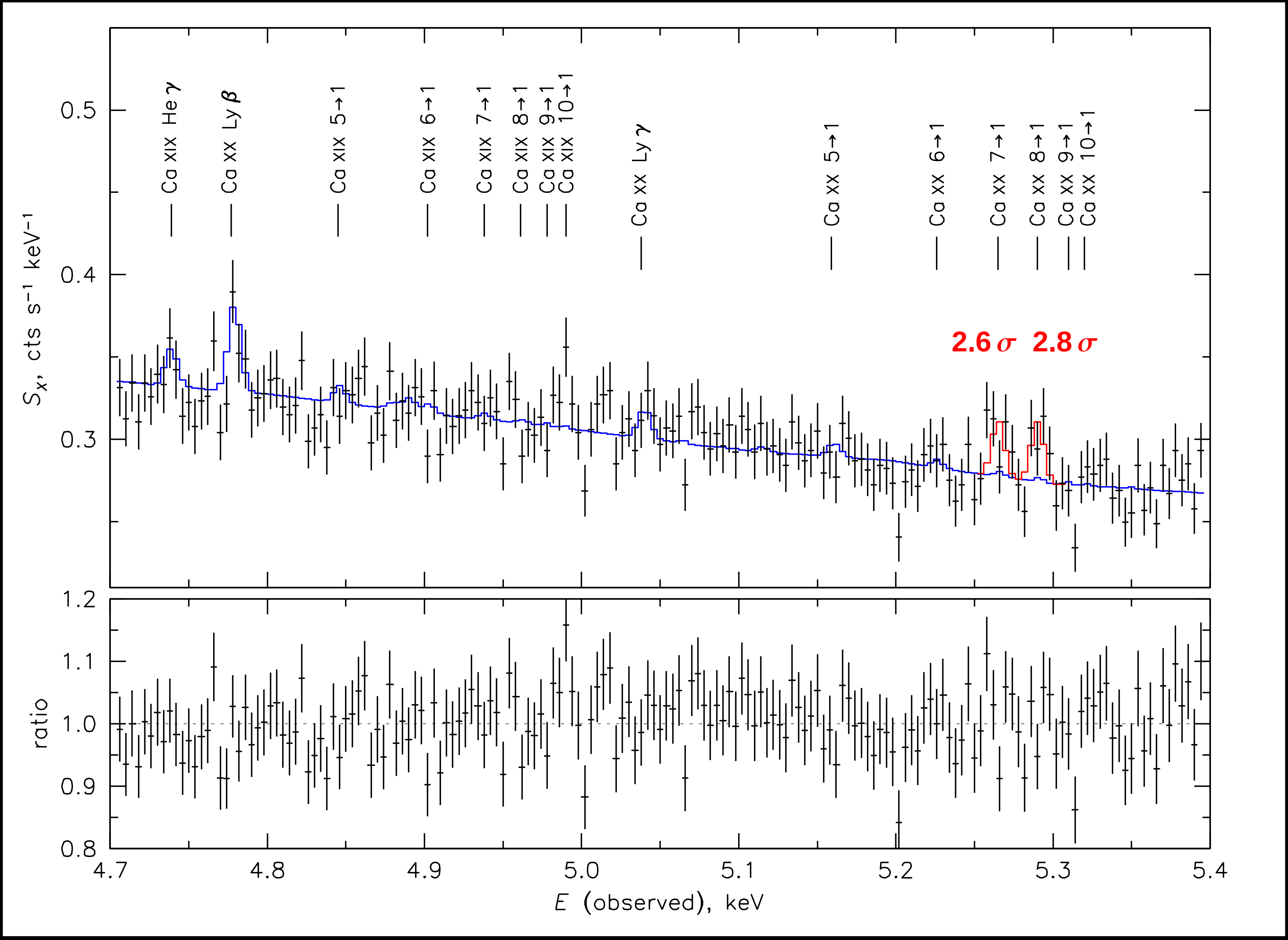
Hitomi spectrum of the Perseus core, 3–4 keV interval



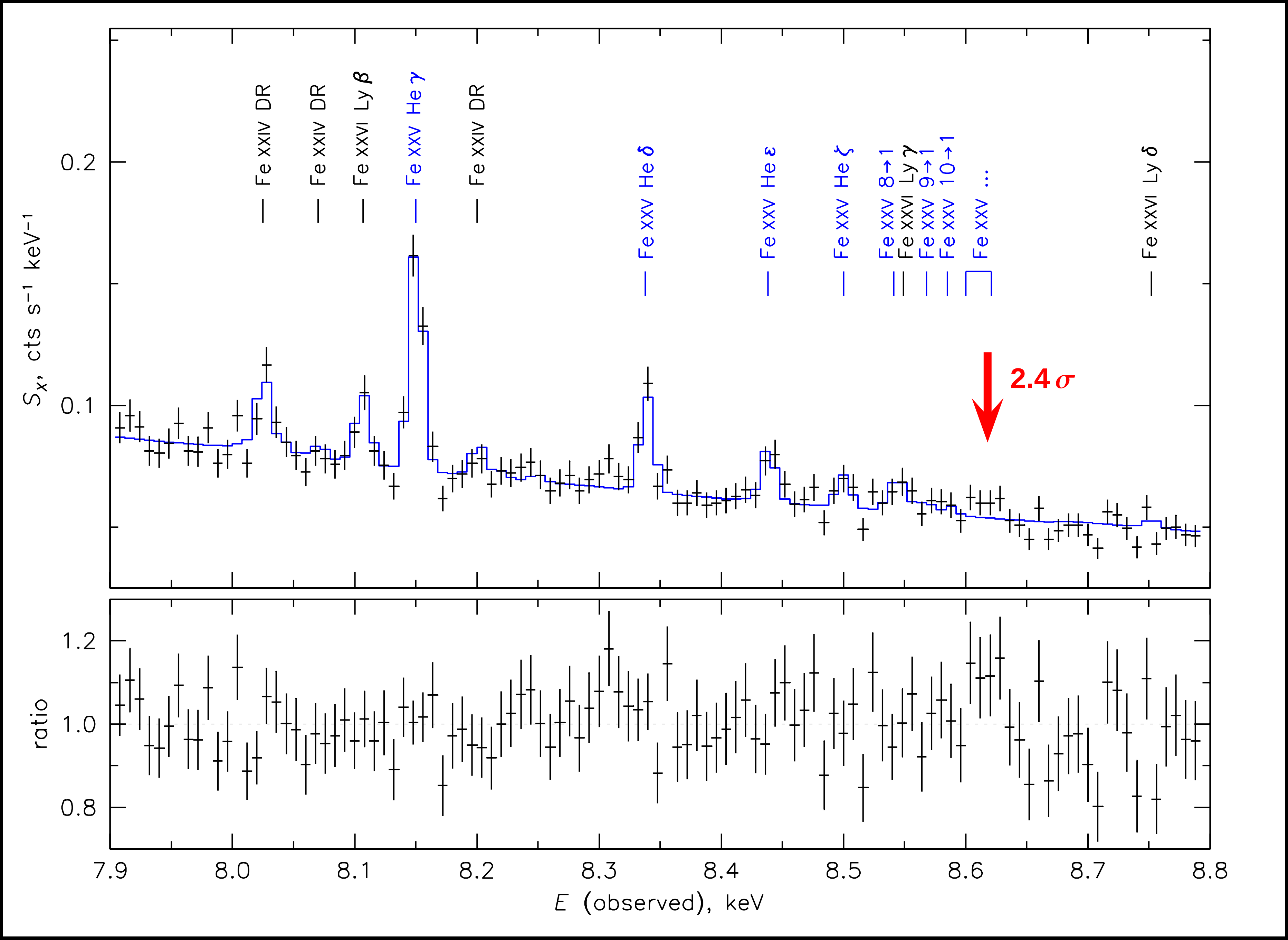
Excess Ca XX emission



Excess Ca XX emission



Excess Fe XXV emission



- Anomalously high flux in high-*n* transitions, as expected for charge exchange *

- Individual features have low stat. significance, but seen for several elements (S, Ca, Fe), so probably real

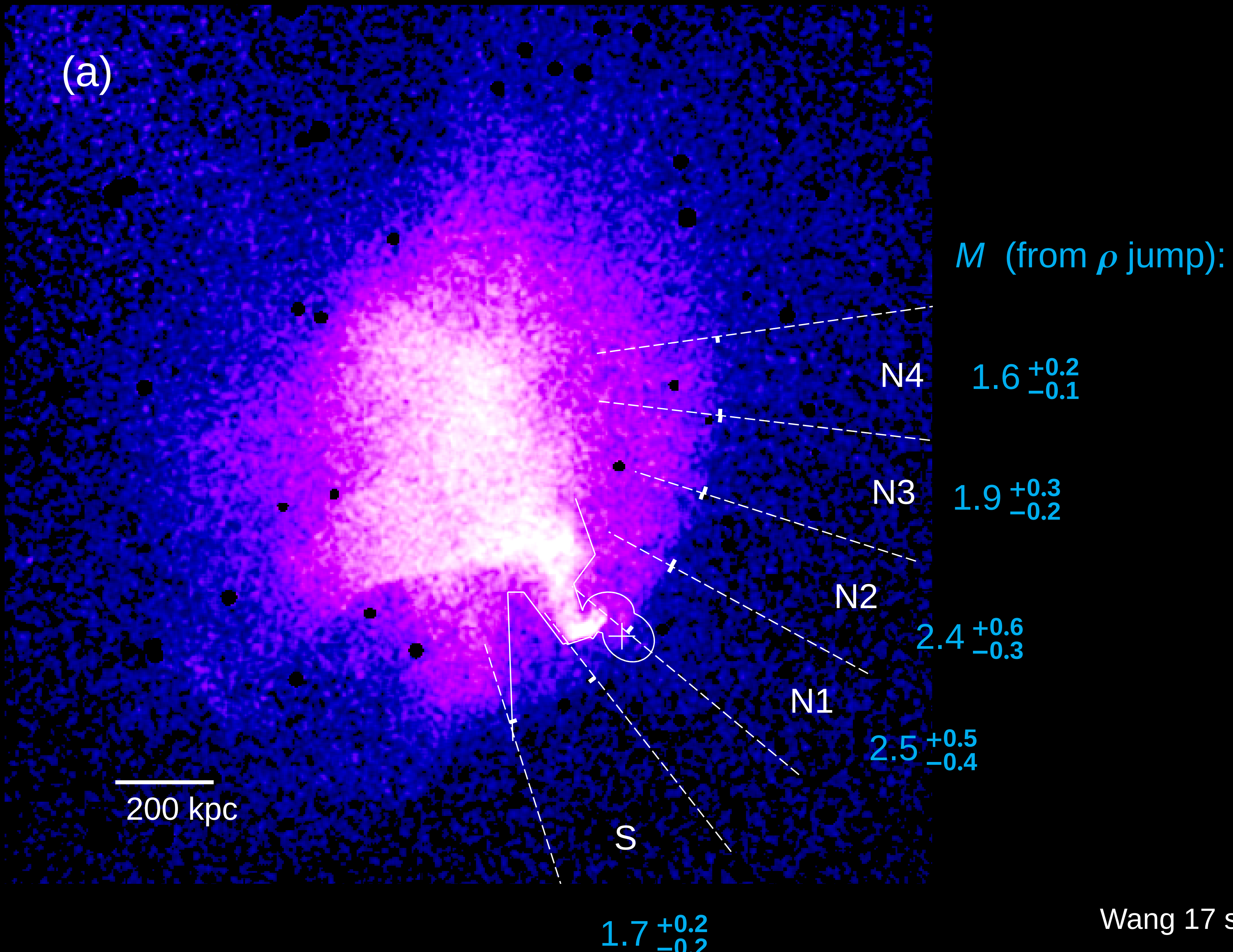
- a future tool to study the interface between hot and cold gas in cores

* Ca excess doesn't fit current CX models

Mergers, shocks and relics with *Chandra* (the latest)


A 520
Chandra X-ray image
See Wang et al. 16, 17 for details
500 kpc
z=0.2

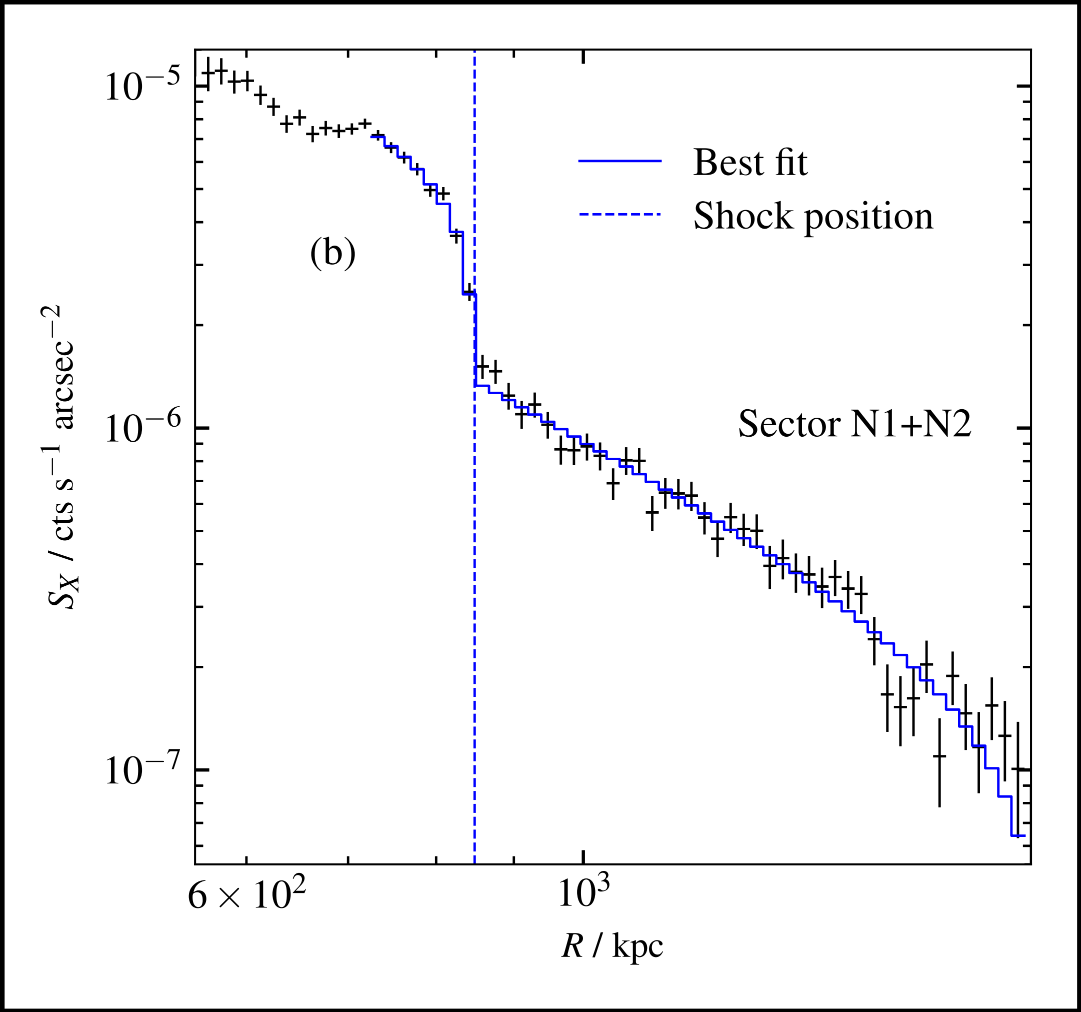
A520 shock front



Wang 17 subm.

A520 shock front

brightness profile in sector N1 + N2



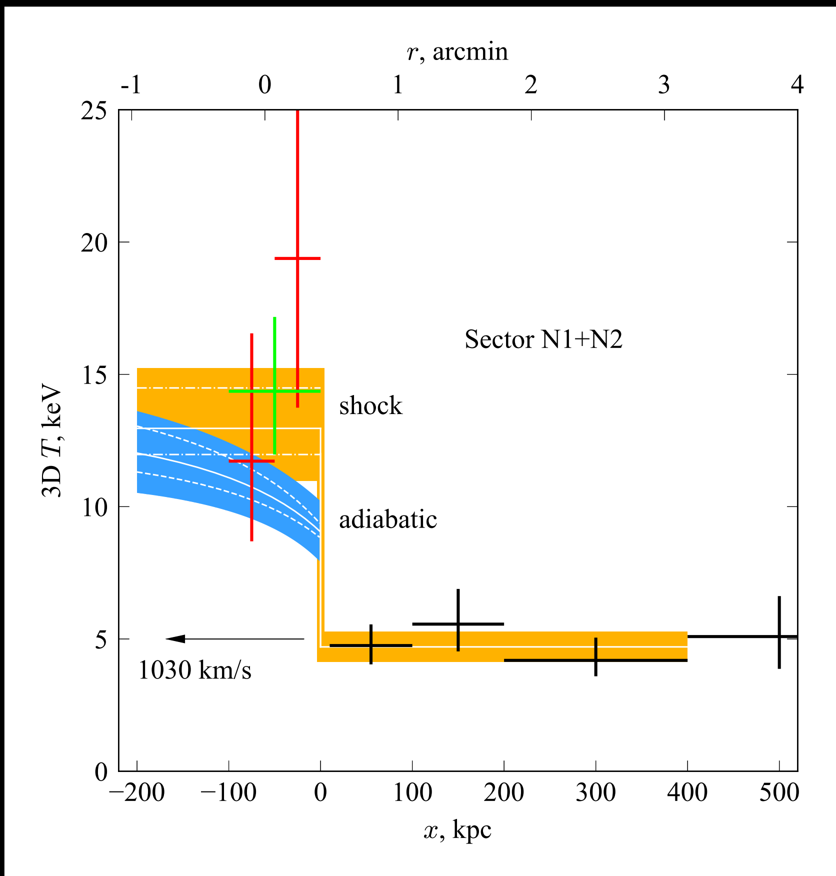
$M = 2.4^{+0.4}_{-0.2}$

Can test electron-proton equilibration timescale in cluster plasma (as in MM 05):

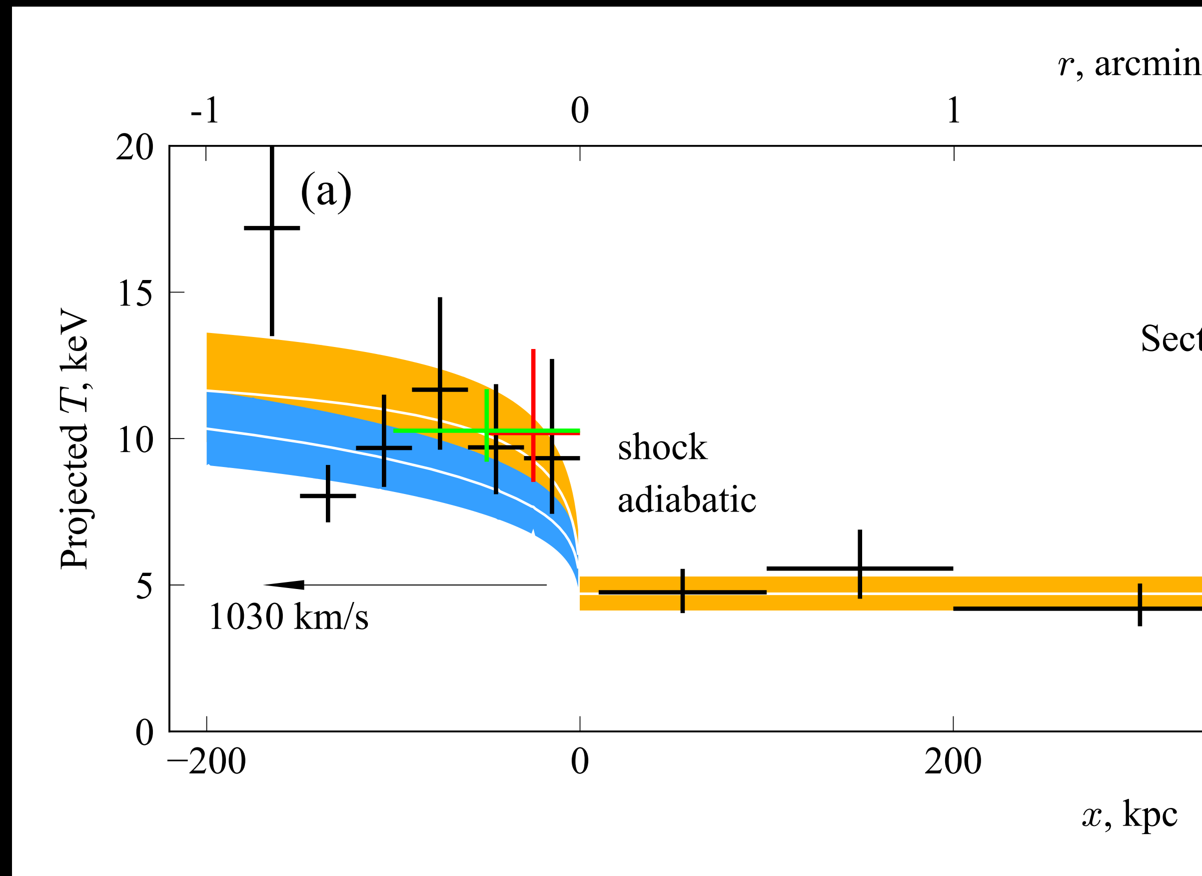
- predict temperature jump from density jump for (a) adiabatic compression and Coulomb equilibration or (b) instant equilibration

A520 shock front: electron-proton equilibration

deprojected T profile



projected T profile



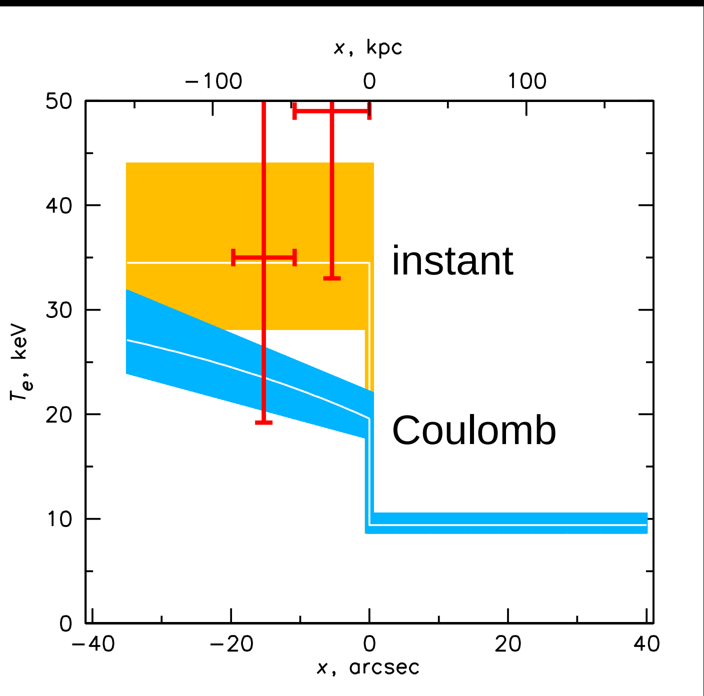
- instant equilibration preferred at 95% confidence (Wang 17 subm.)

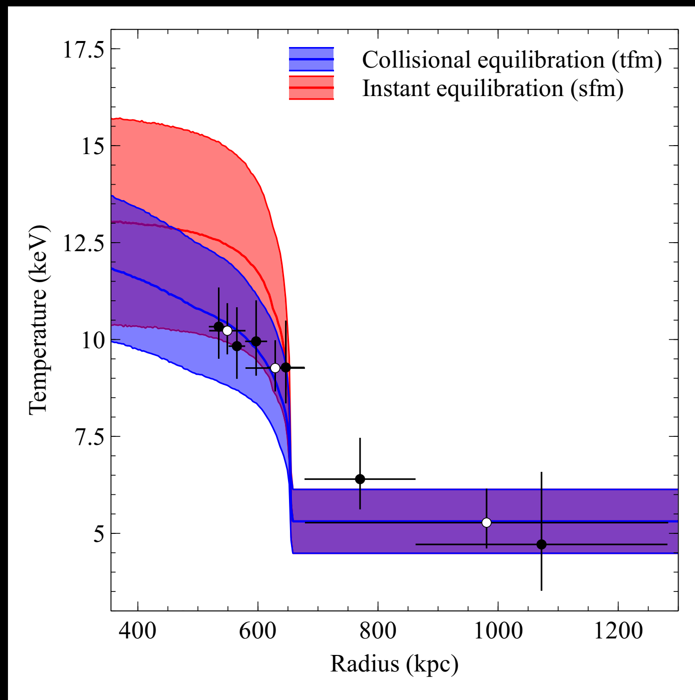
Similar test on other shocks

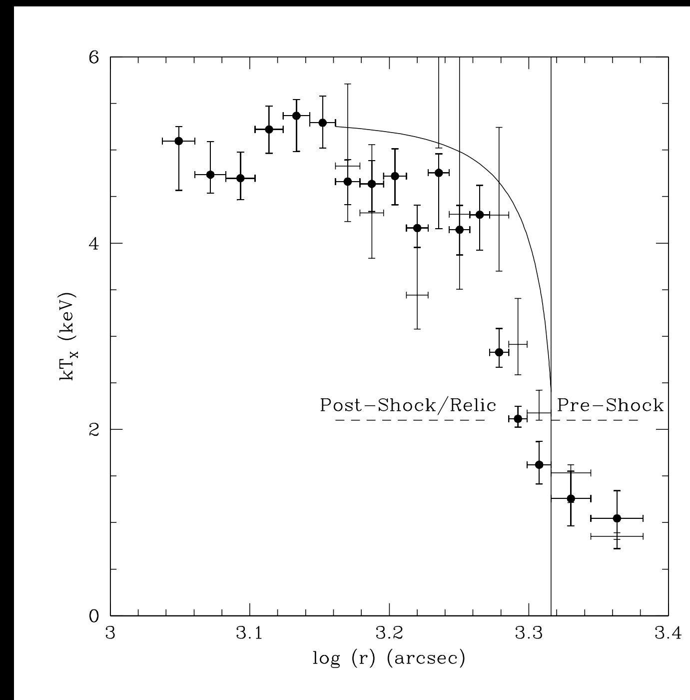
Bullet main shock
(Markevitch 05)

A2146 bow shock
(Russell 12)

A3667 relic shock
(Sarazin 16)







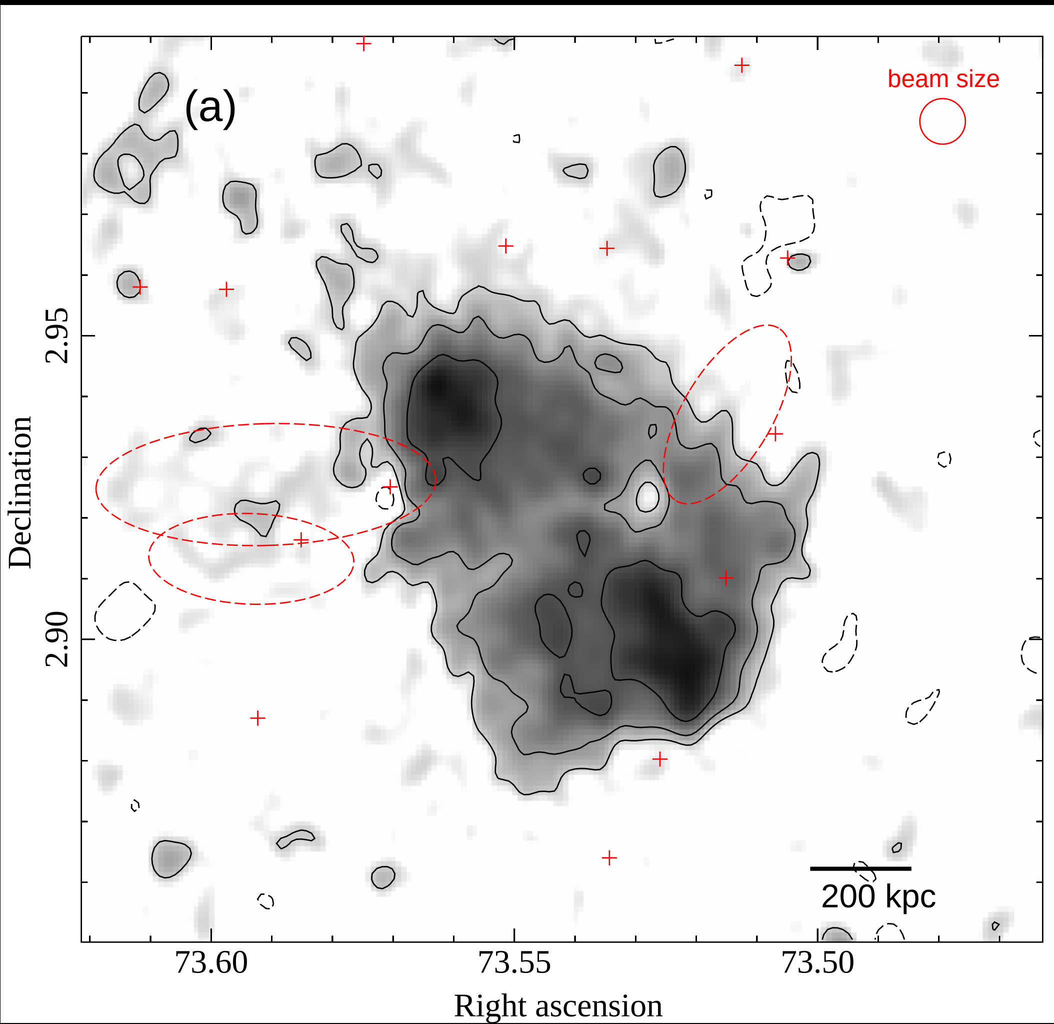
M = 3.0
instant equilibration (95%)

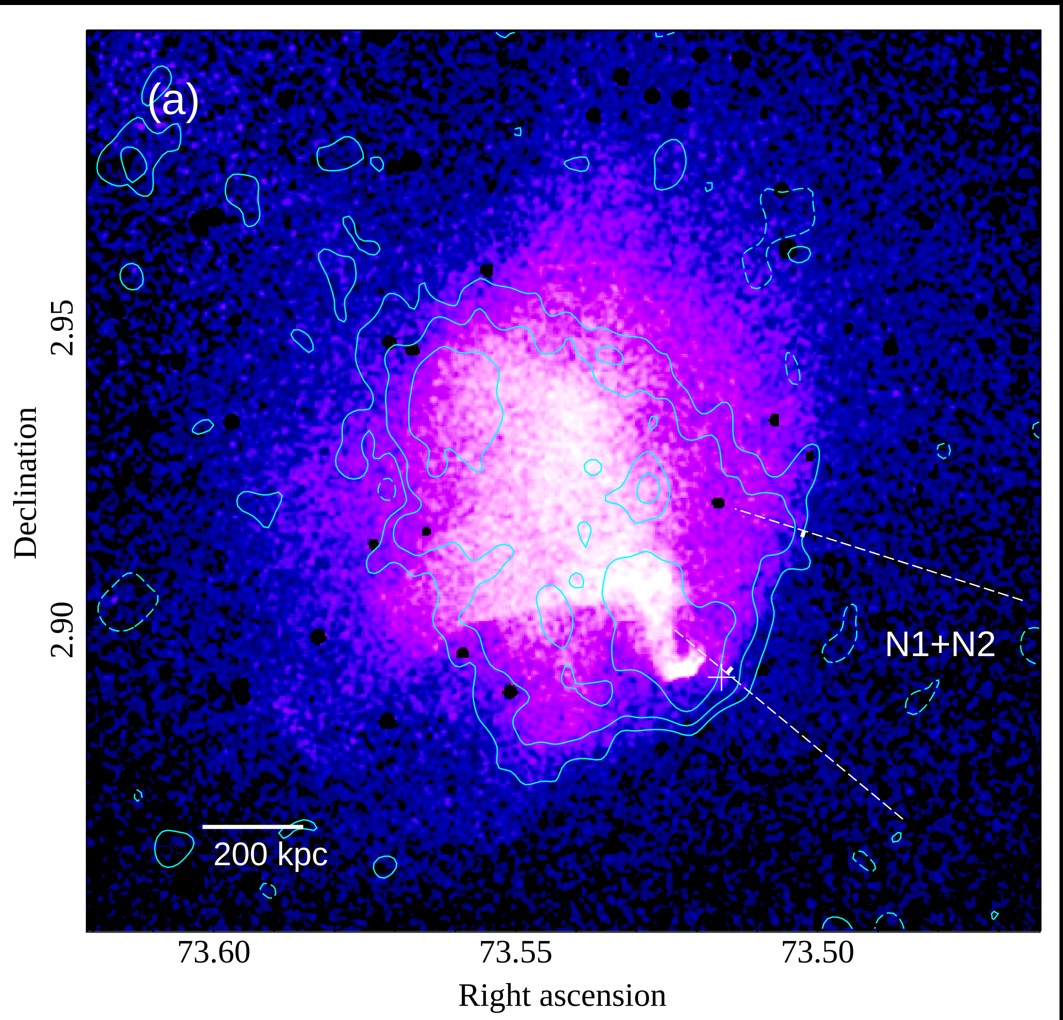
M = 2.3
Coulomb equilibration (68%)

M = 2.5
neither model fits

- systematic uncertainties: 3D geometry and projection — need a sample of simple shocks. For now, 2:1 for instant equilibration

A520 shock and radio halo





All archival *VLA* 1.4 GHz C, D datasets (Govoni 01, Vacca 14) combined (by Simona)

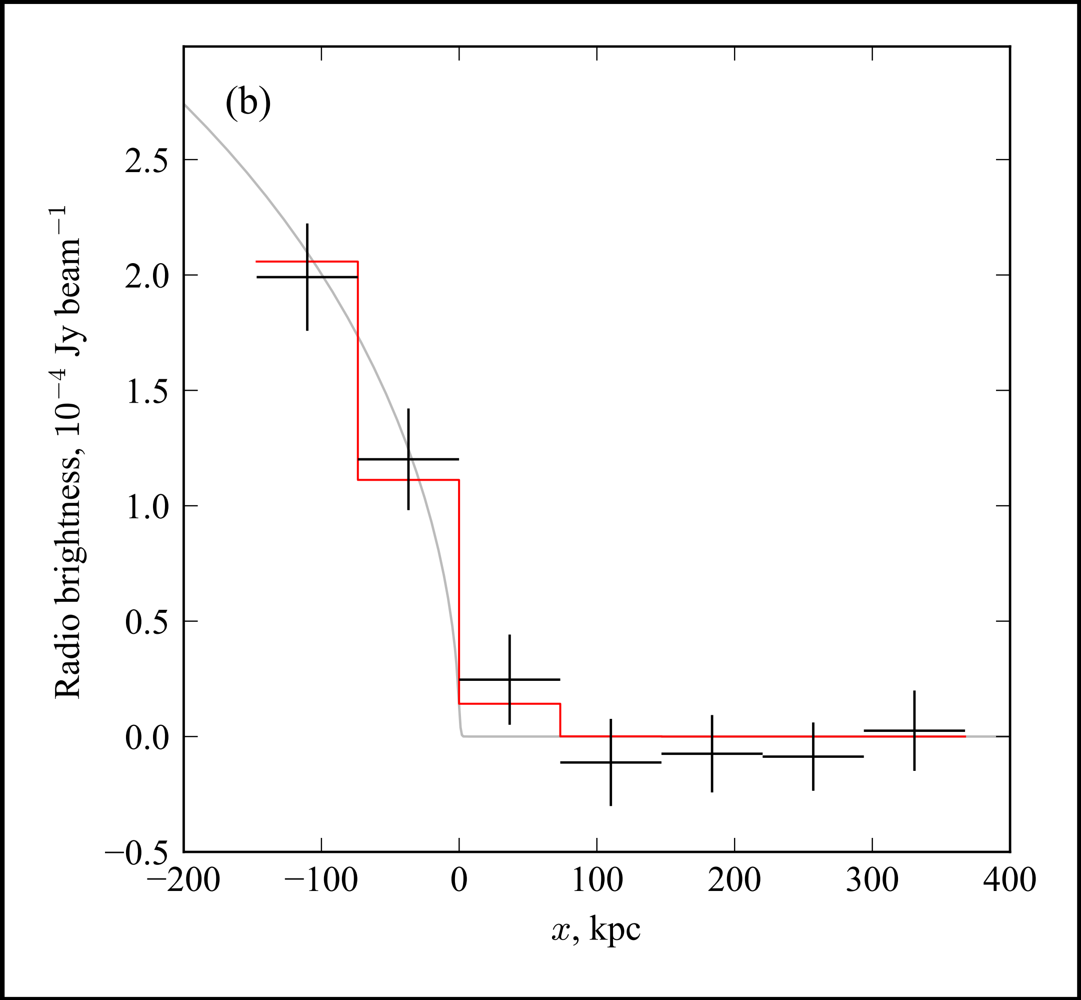
X-ray / radio

- edge of radio halo traces shock front

Wang 17 subm.

A520 radio halo edge

radio brightness profile across the shock

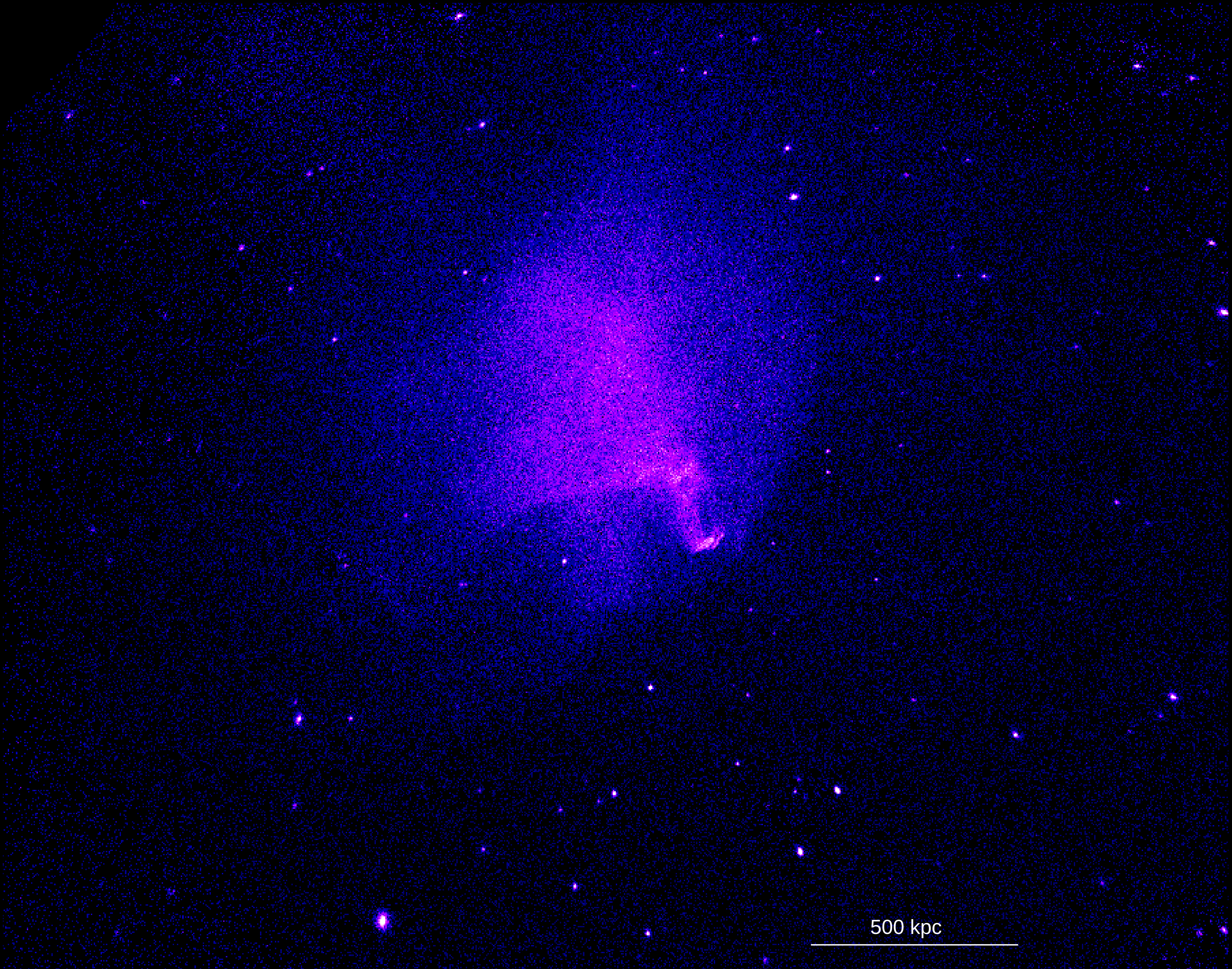


Can the radio edge be due to adiabatic compression by the shock? (MM 05)

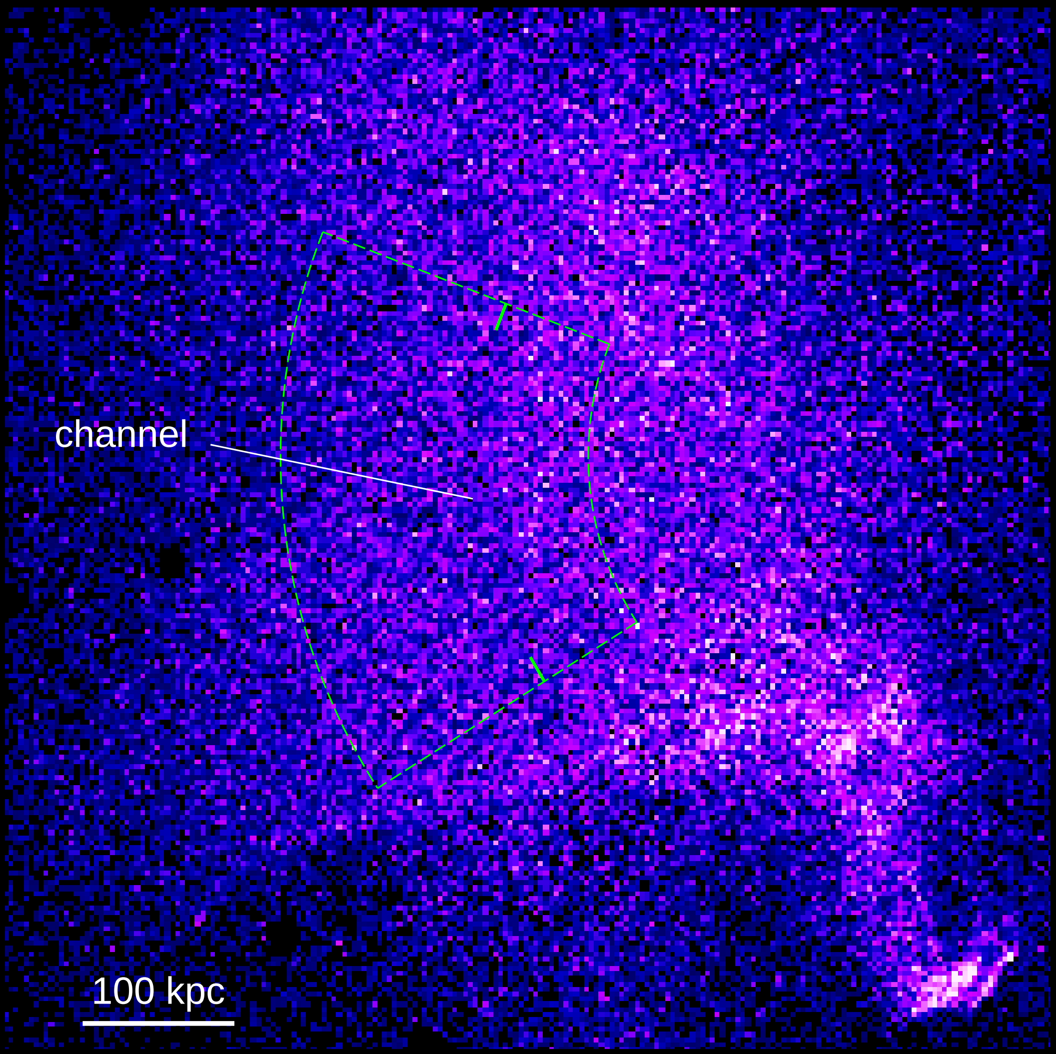
- For observed radio spectrum and shock density jump, the radio emissivity jump (in 3D) for compression model is factor ~ 26. Can't rule it out yet

A curious new phenomenon in ICM

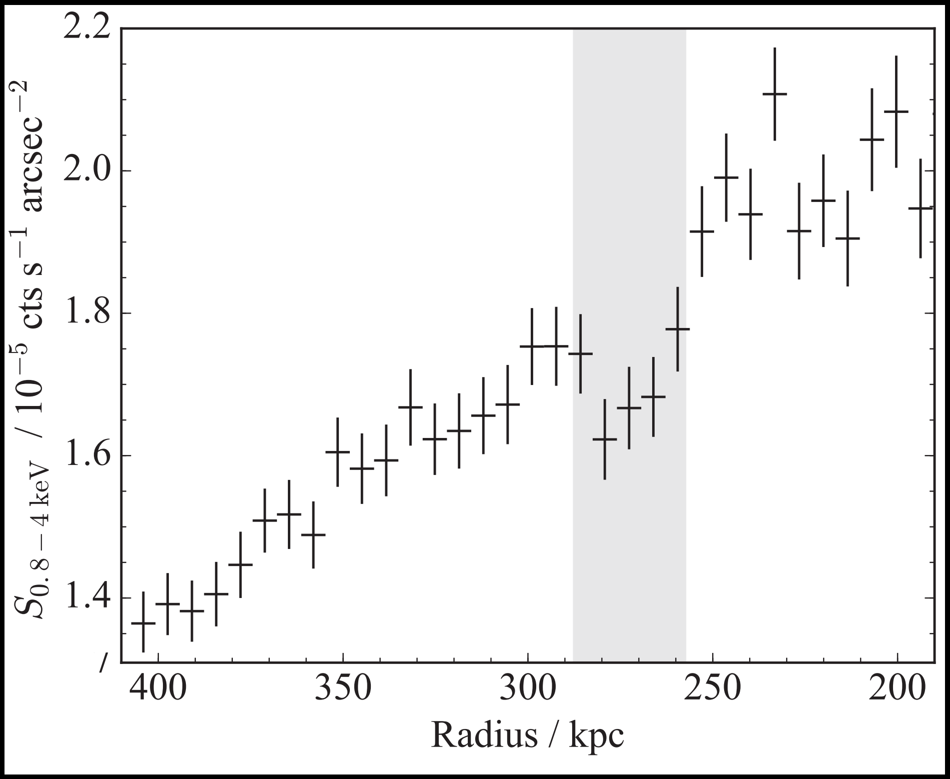
X-ray “channel” in A520



X-ray "channel" in A520



X-ray brightness profile across channel

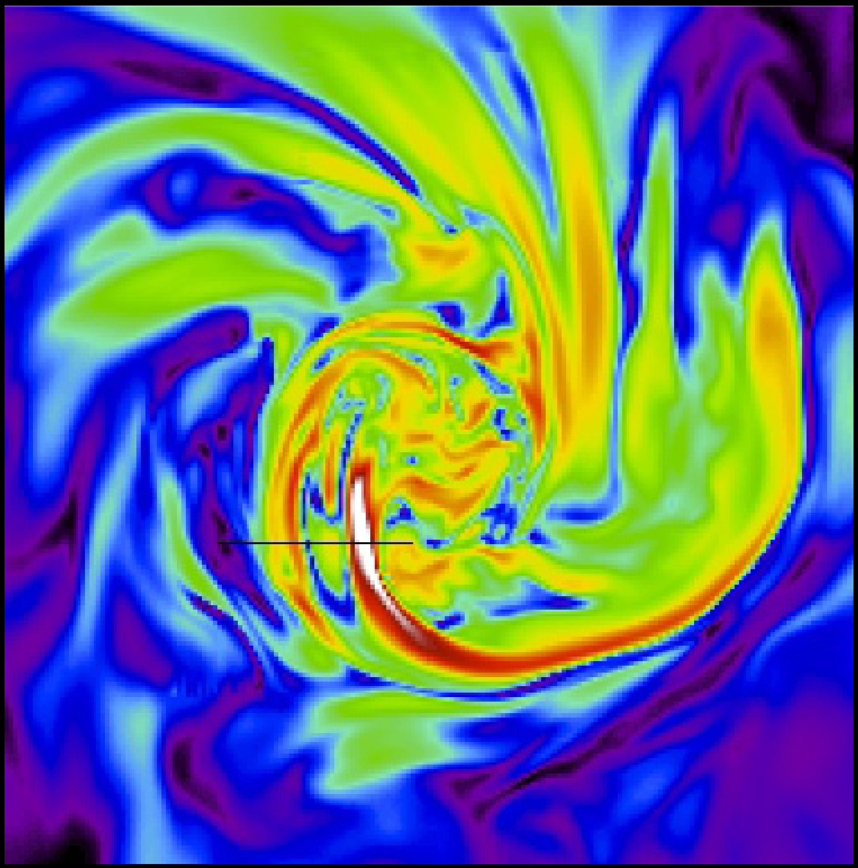


Wang et al 16

- likely a sheet in projection

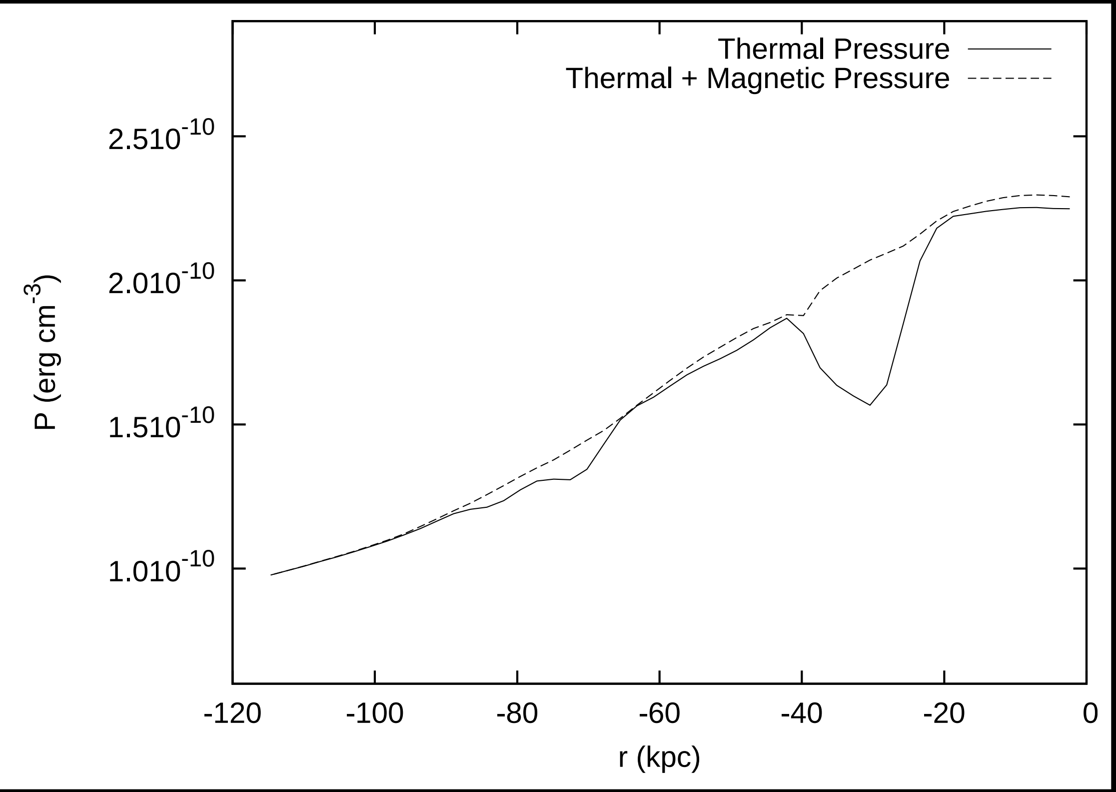
X-ray “channel” in A520

Magnetic field strength in sloshing core



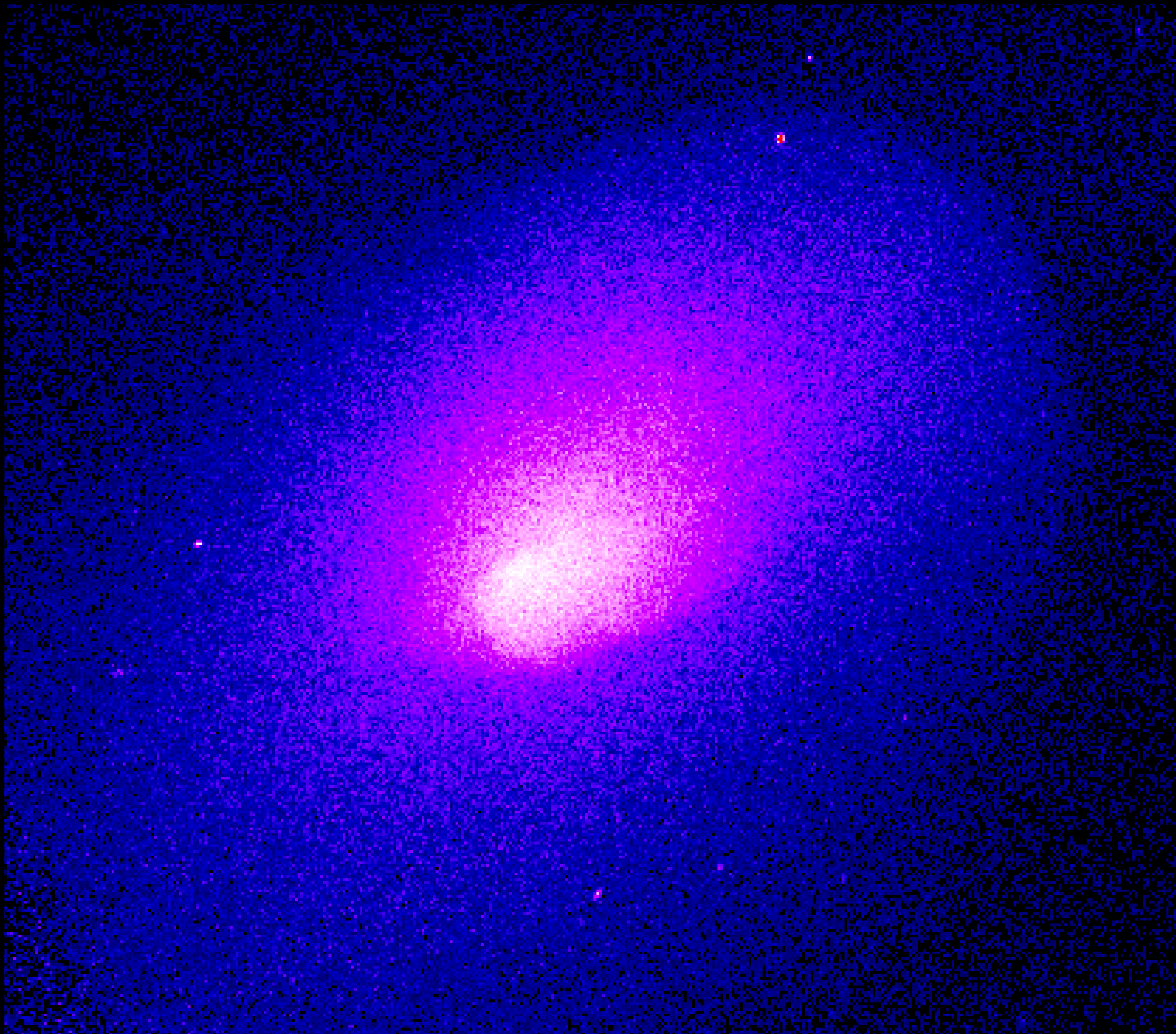
simulations ZuHone 11

Pressure profile across high-*B* filament

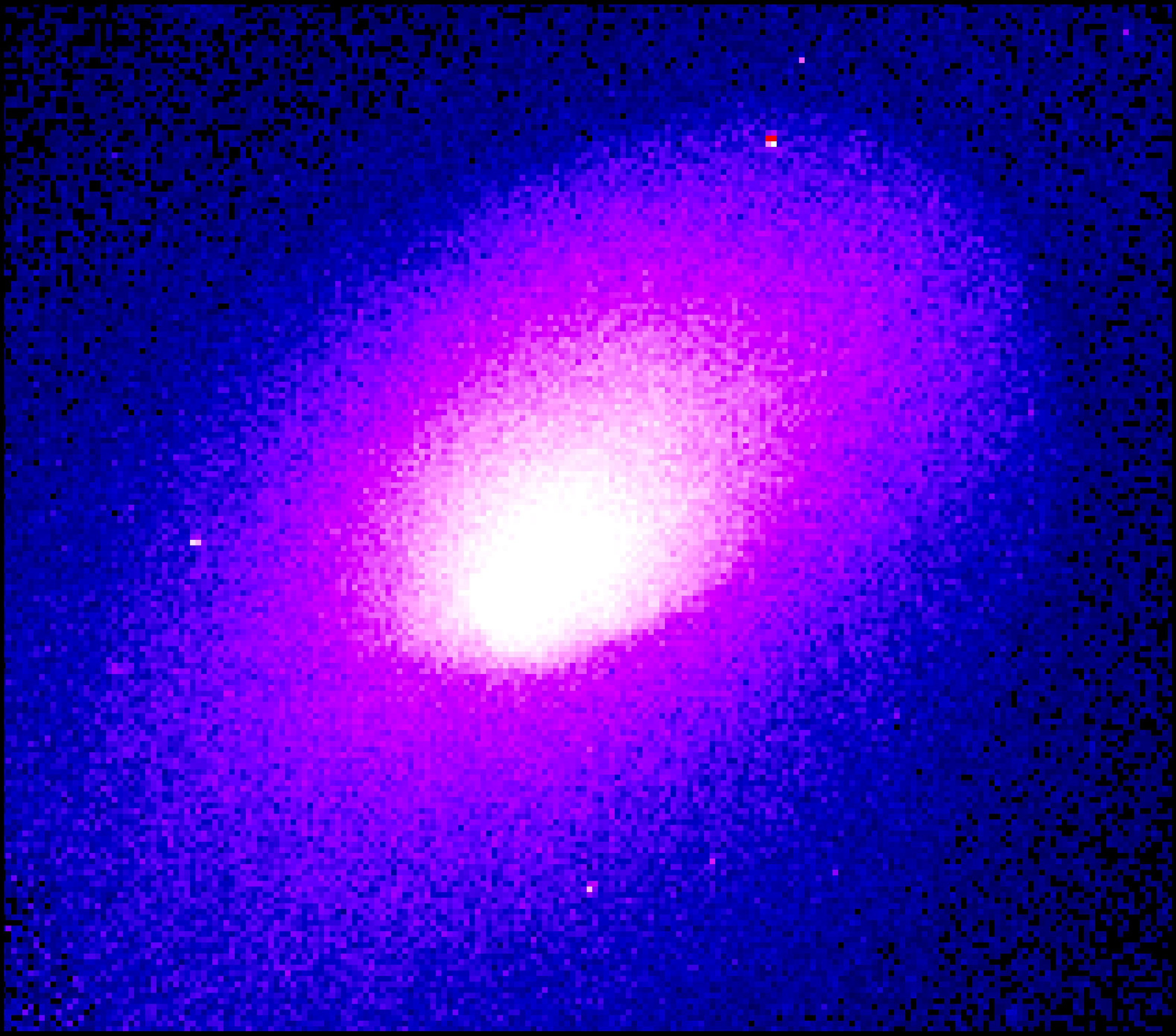


- channel is a “plasma depletion layer” with high *B* (β <10)?

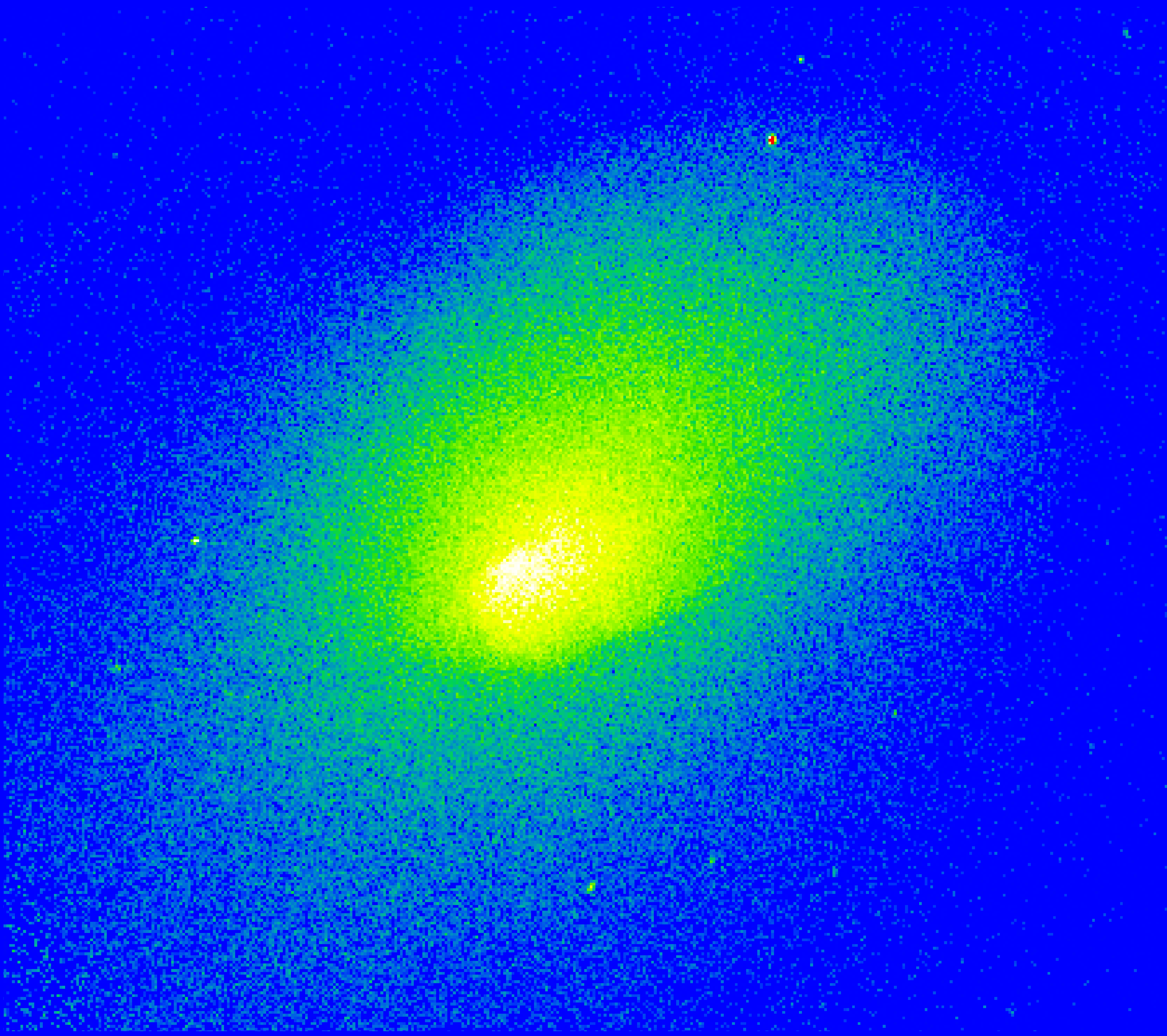
X-ray channel in A2142



X-ray channel in A2142

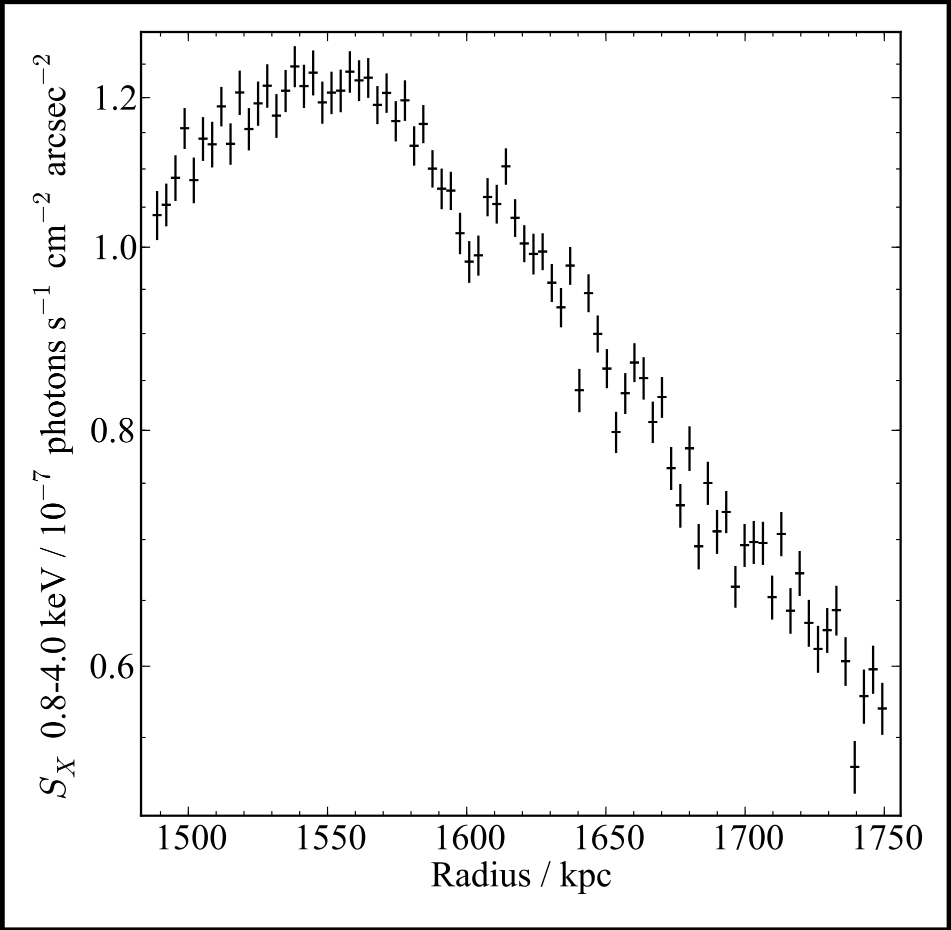


X-ray channel in A2142



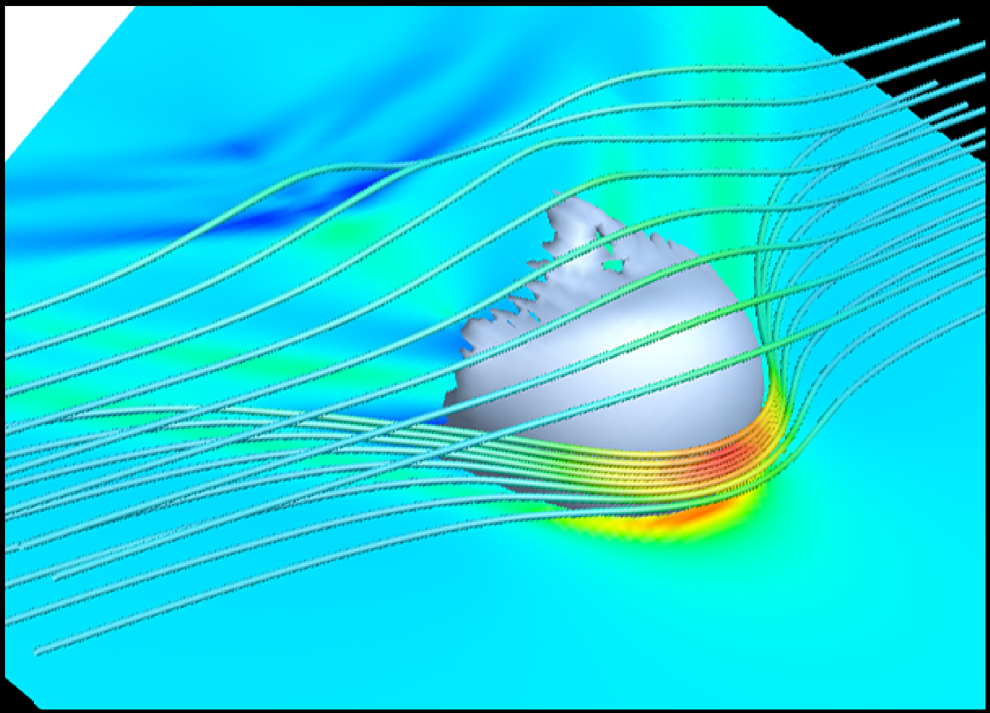
X-ray channel in A2142

X-ray brightness profile across channel



Wang 17 in prep.

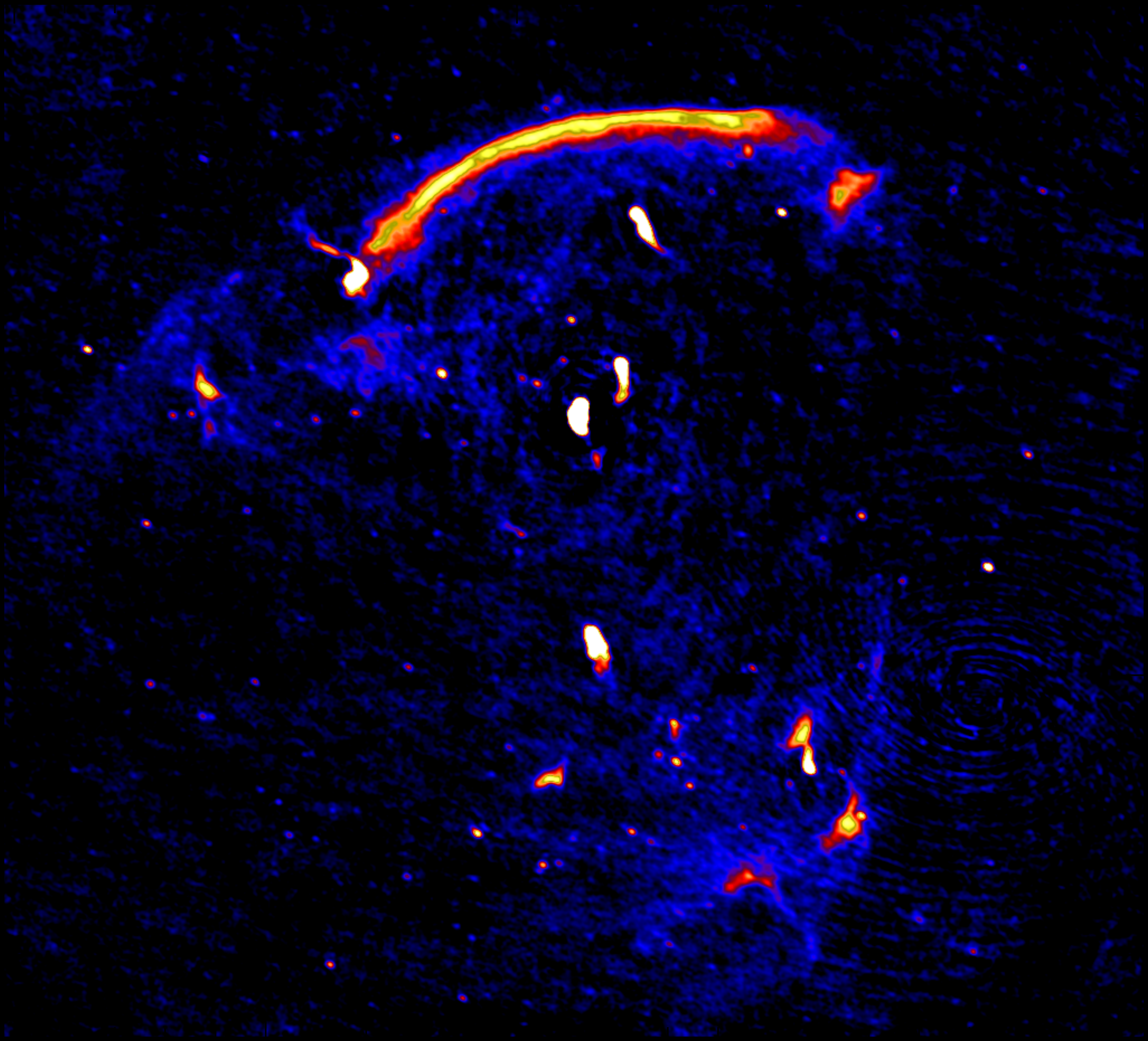
Magnetic field draping around a subcluster



simulations Dursi & Pfrommer 08

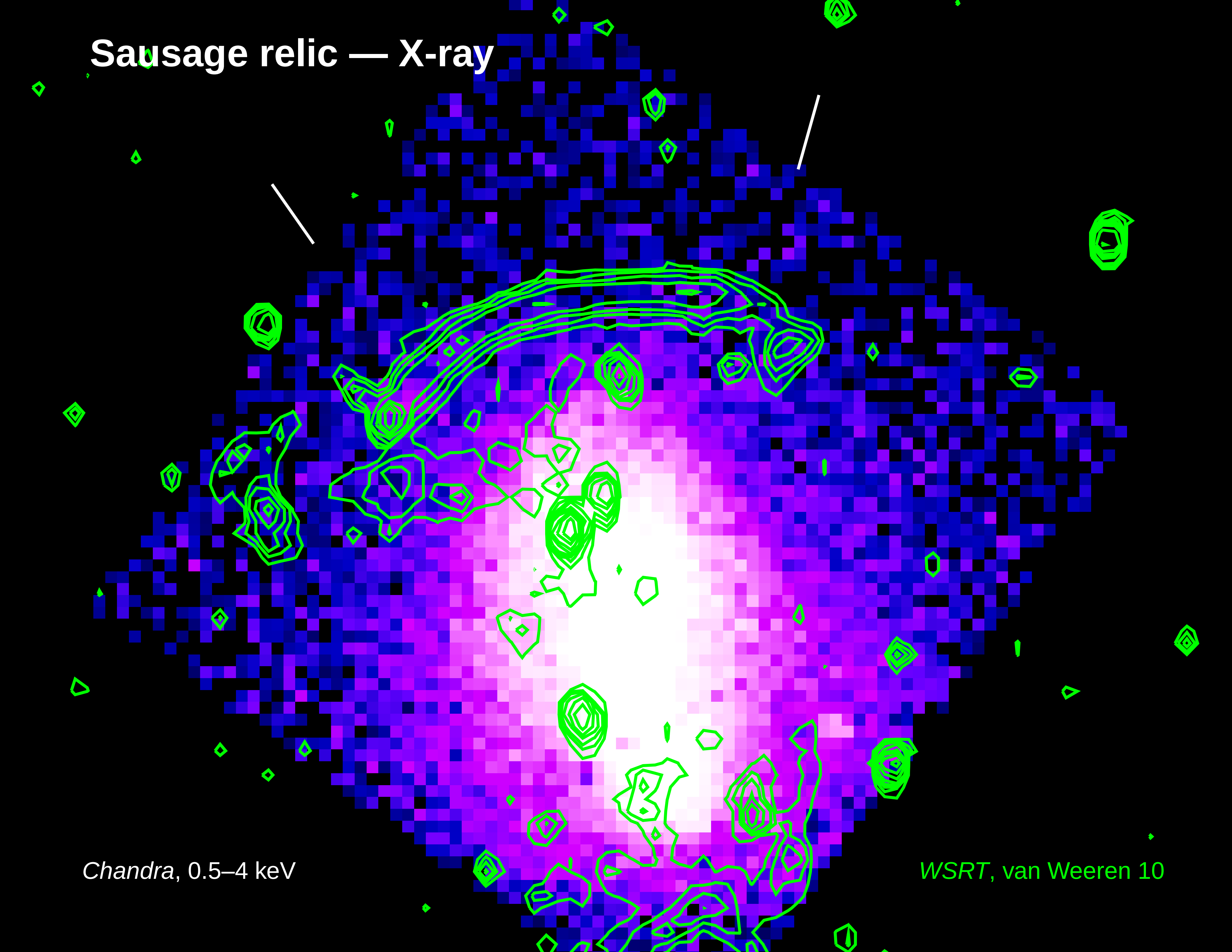
- another plasma depletion layer?
- How do they look in the radio?

Is there a shock at the Sausage relic?

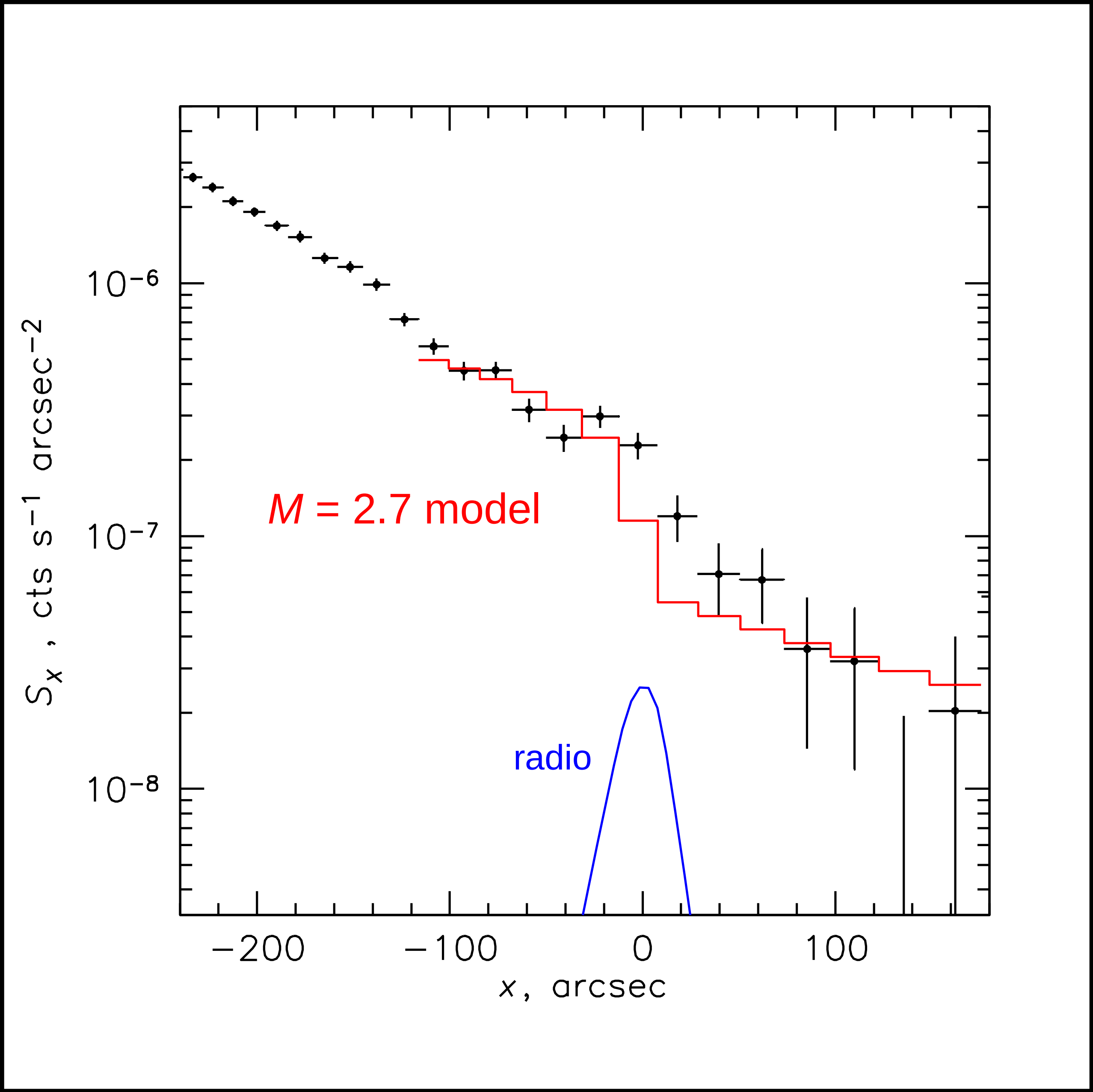


GMRT 610 MHz, van Weeren et al. (2010)

Sausage relic — X-ray

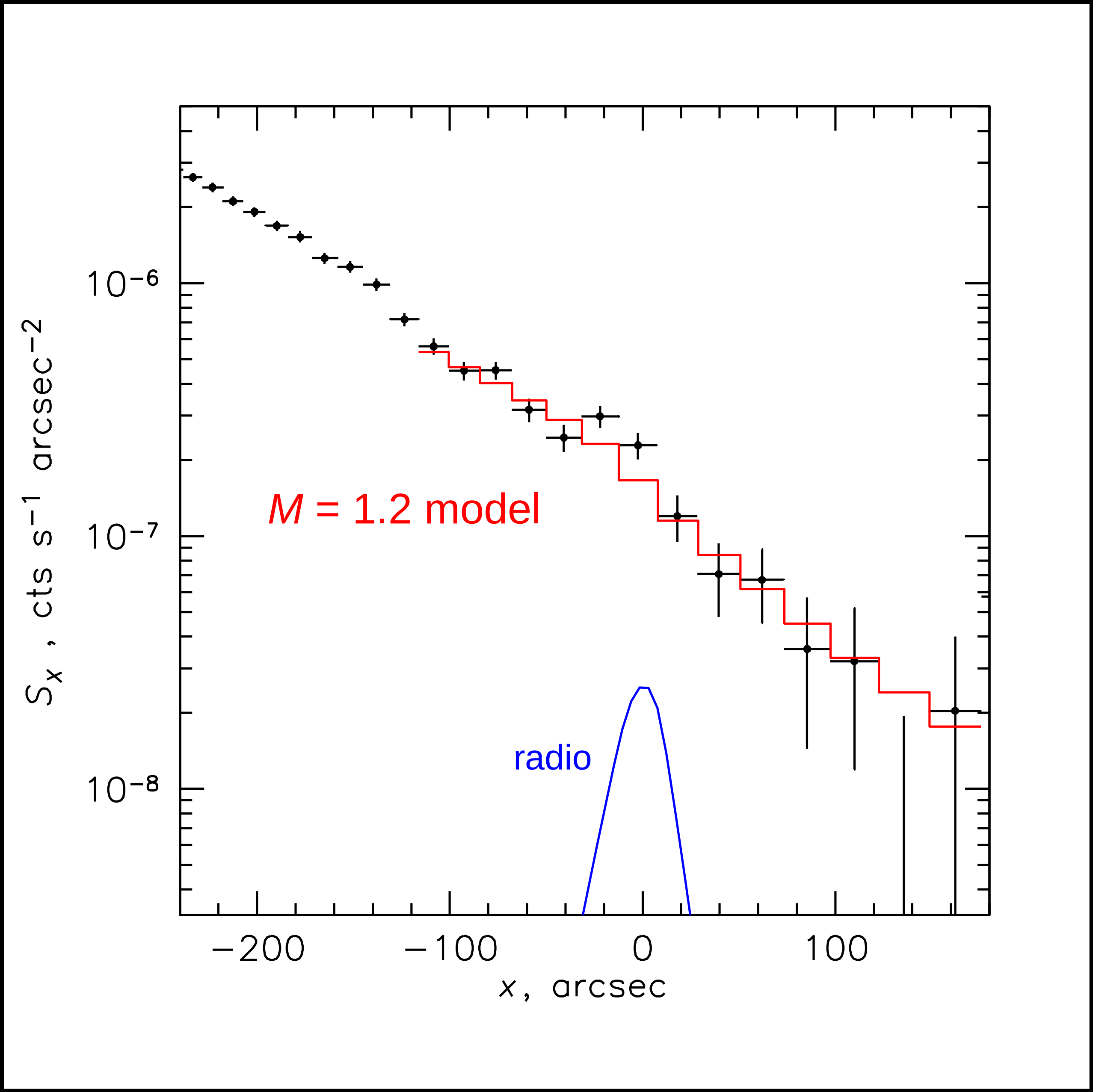


Sausage: X-ray profile across relic



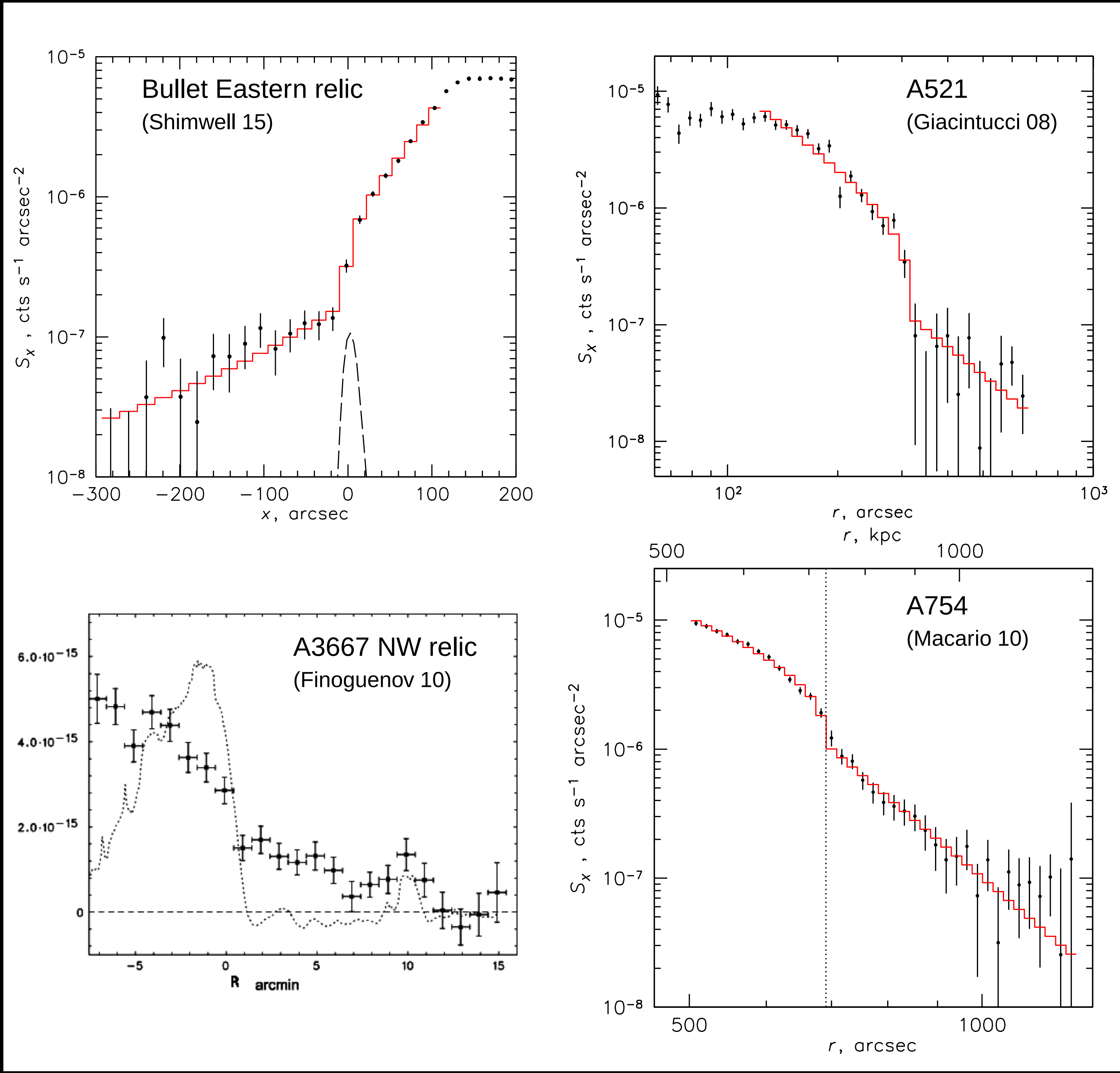
- shock at the relic position with *M* implied by *Suzaku T* jump is excluded by *Chandra*

Sausage: X-ray profile across relic

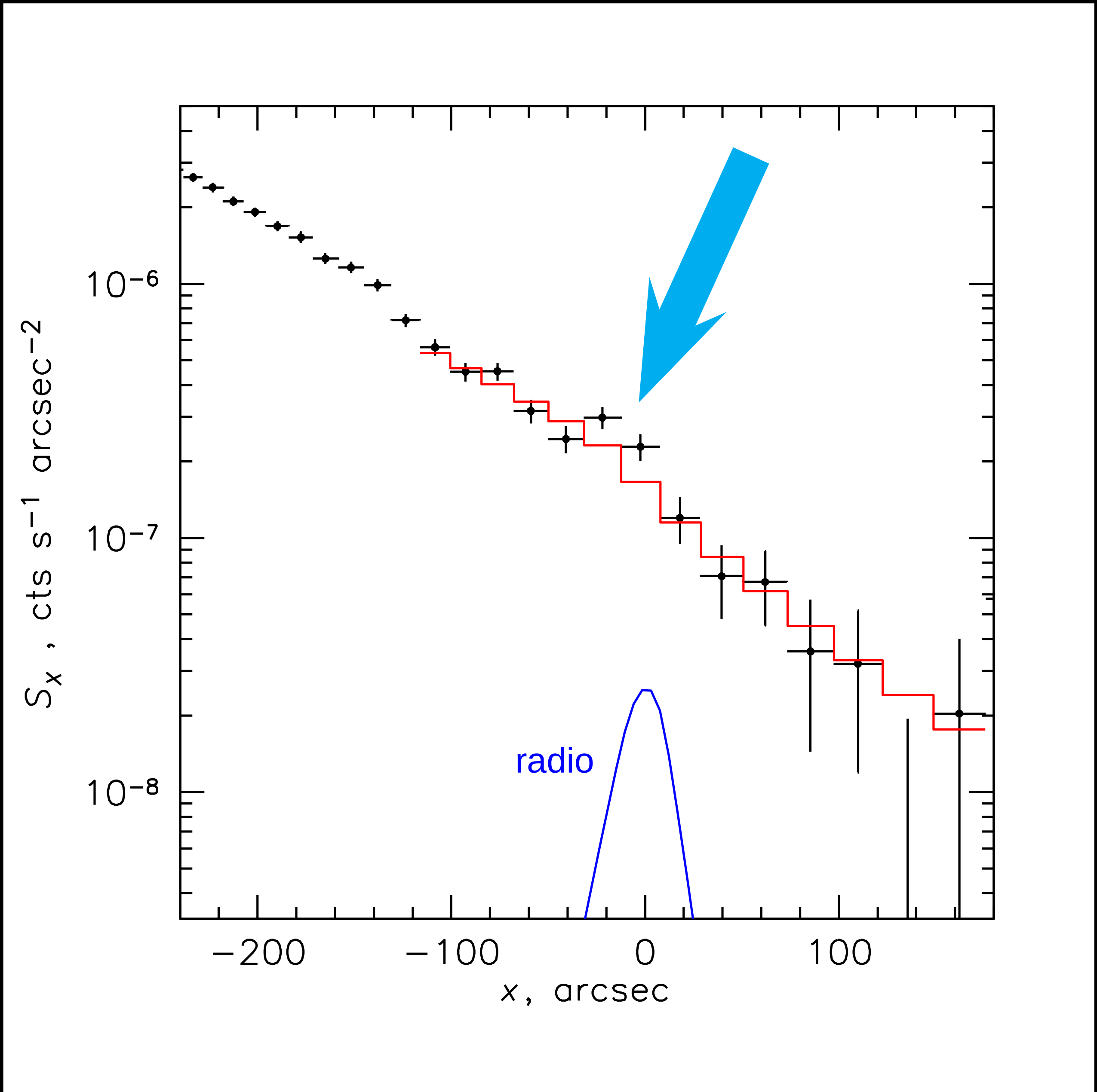


- a much weaker shock is preferred (with $\Delta\chi^2 = 23$) ... but fit is poor

Shocks at peripheral relics

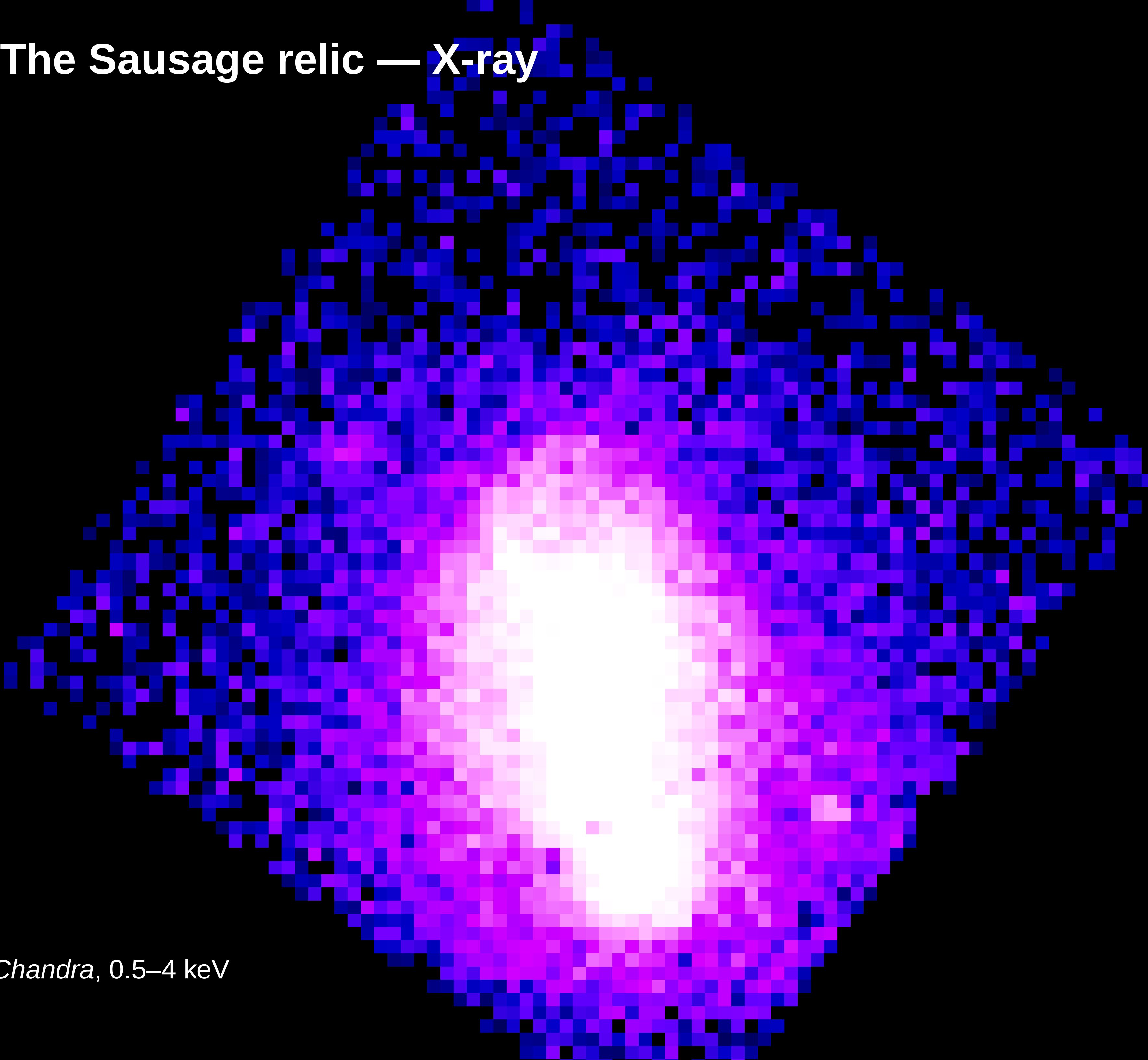


Sausage: X-ray profile across relic



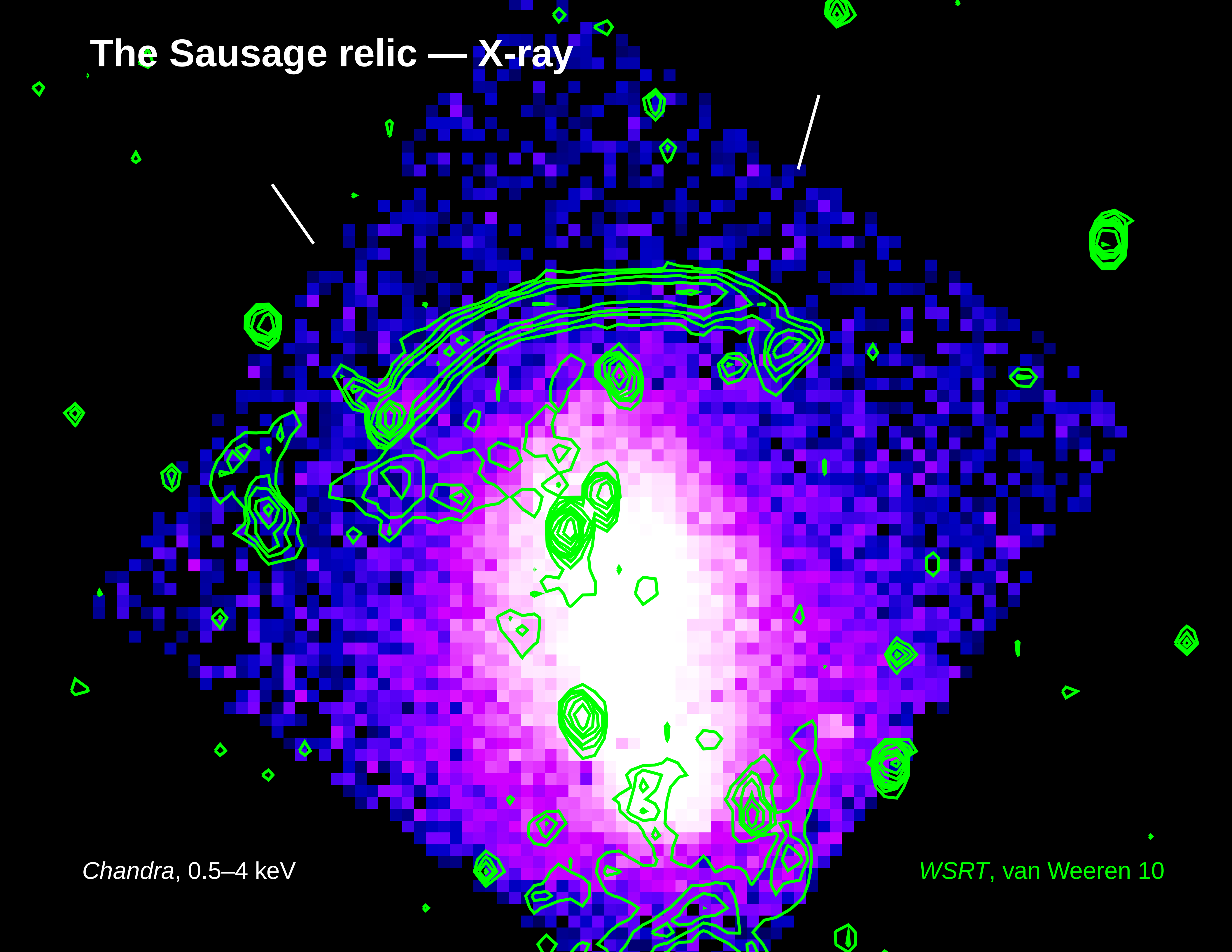
- **IC signal?** $B = 1.4\,\mu$G — compare to 1.2 or 5 μG from radio width (van Weeren 10)

The Sausage relic — X-ray



Chandra, 0.5–4 keV

The Sausage relic — X-ray



Detect inverse Compton emission using X-ray imaging?

Cosmic ray electrons with $\gamma \sim 10^{3-4}$ emit synchrotron at $\nu \sim 0.1$–1 GHz (radio halos and relics):

$$S_{\mathrm{syn}} \sim N_{\mathrm{CRe}} \; B^2$$

Same electrons should produce inverse Compton (IC) at $E \sim$ 1–20 keV:

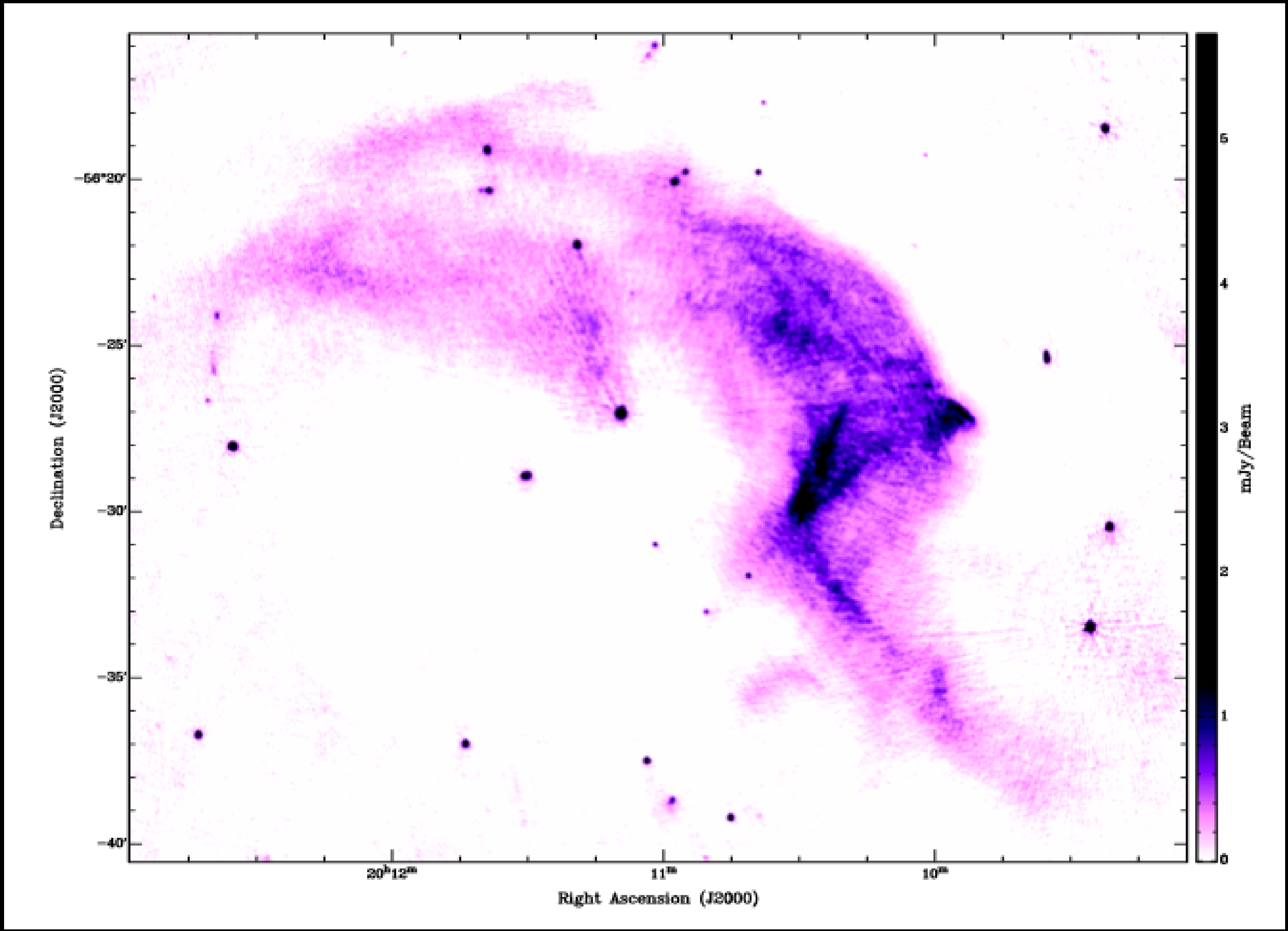
$$S_{\mathrm{IC}} \sim N_{\mathrm{CRe}} \, E_{\mathrm{CMB}}$$

• detecting "hard tails" in X-ray spectra probably hopeless (talk by Dan Wik) — difficult to distinguish power law from a combination of temperatures

Cross-correlate fine structure in relics with high-resolution X-ray images?

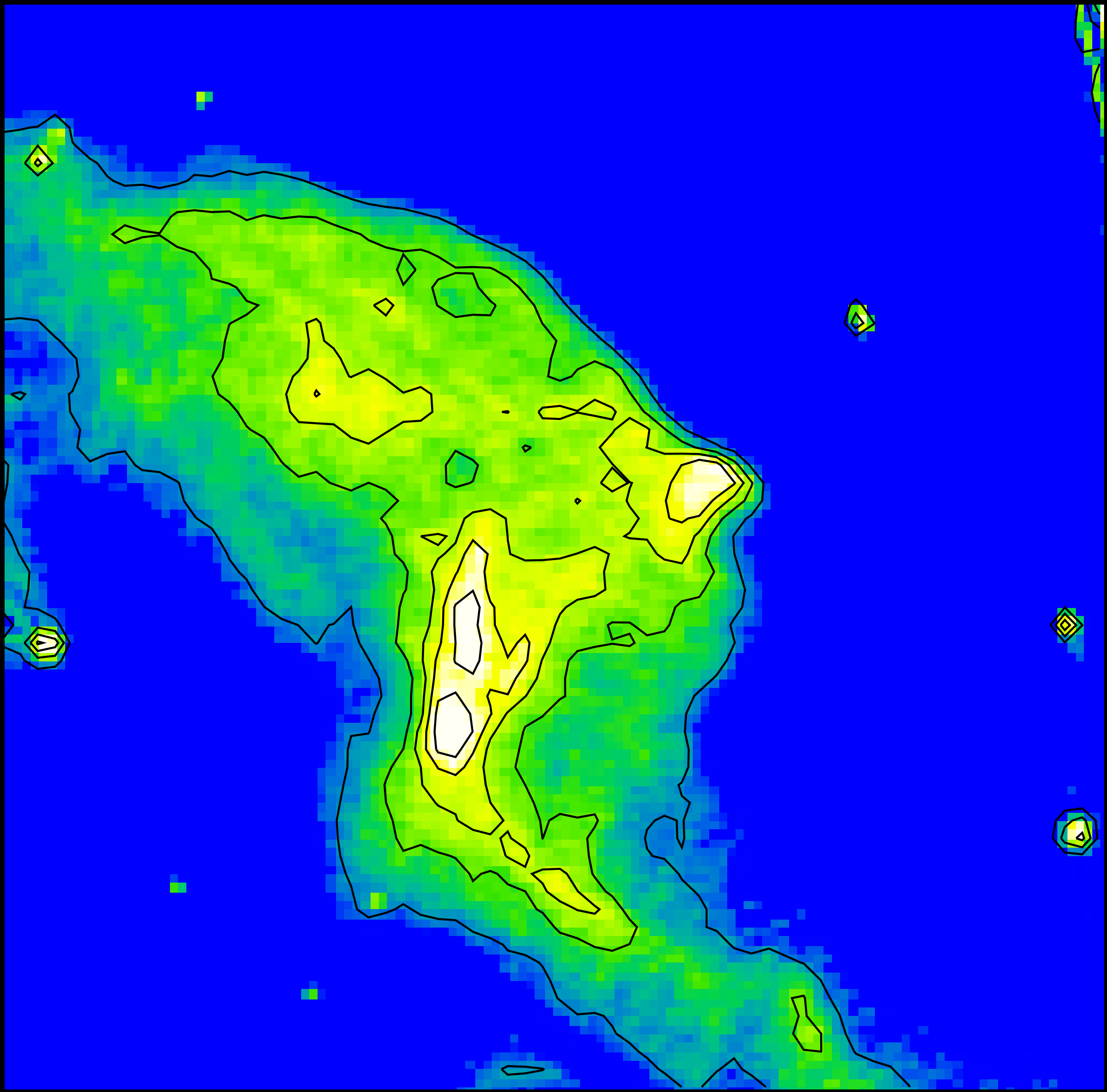
- If bright radio spots due to N_{CRe} then positive correlation — IC detection!
- If due to B^2 then anticorrelation (plasma depletion)

A3667 NW relic



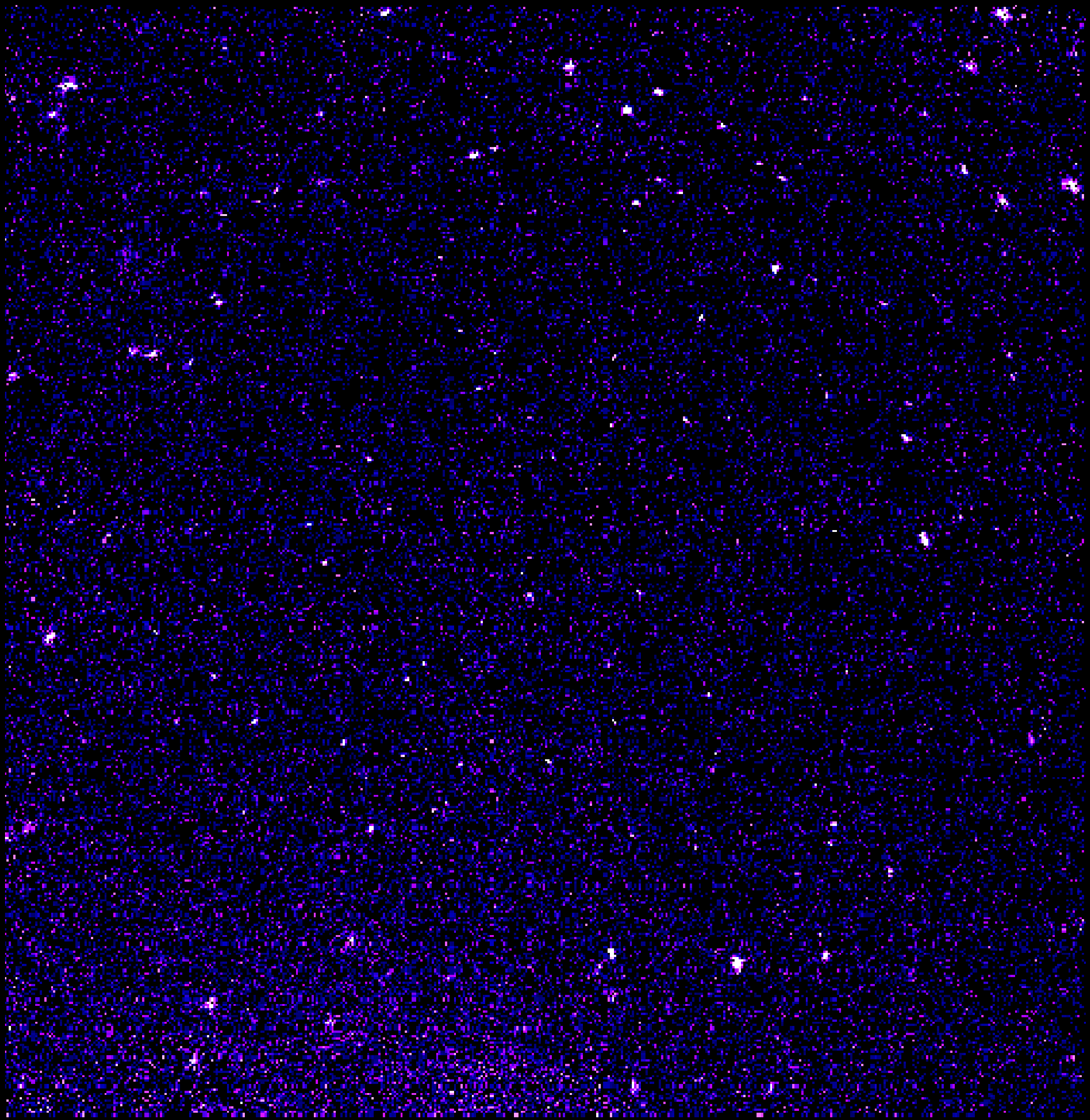
ATCA 1.4 GHz,   Johnston-Hollitt 2004

A3667 NW relic



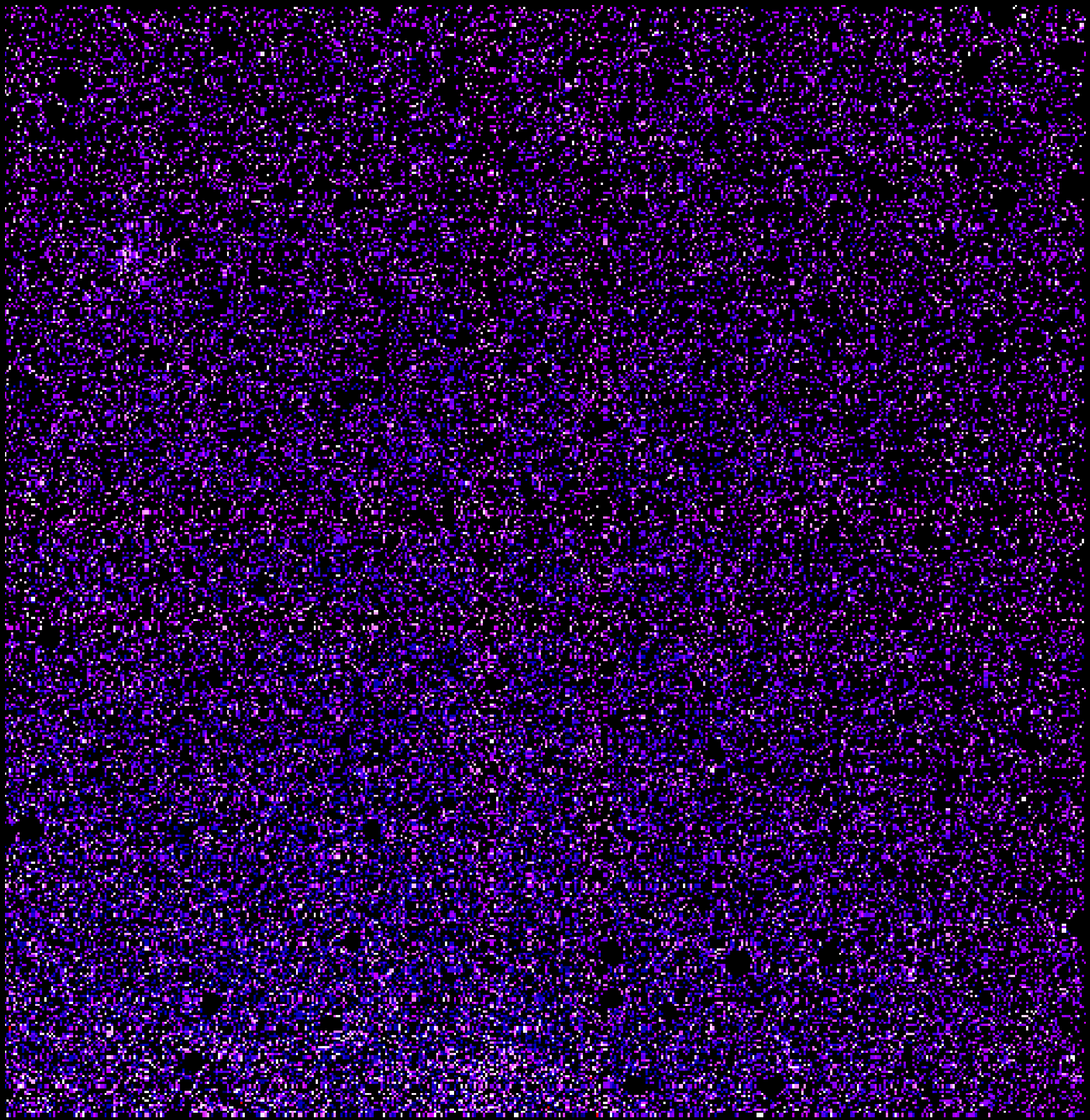
ATCA 1.4 GHz, Johnston-Hollitt 2004

A3667 NW relic



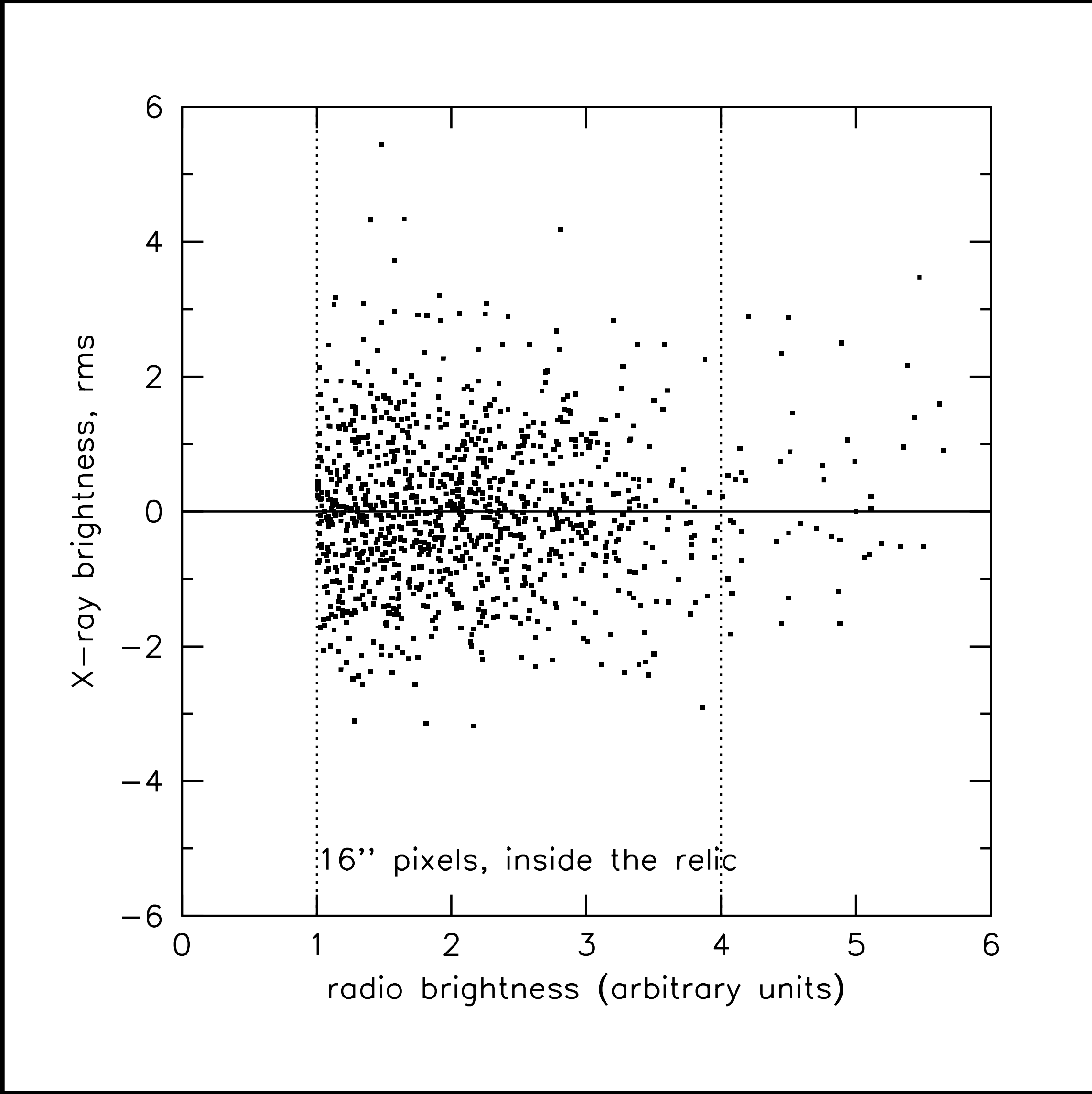
Chandra 0.5 – 4 keV, 200 ks

A3667 NW relic



Chandra 0.5 – 4 keV, 200 ks, point sources and large-scale emission removed

A3667 NW relic: radio / X-ray correlation



Positive cross-correlation, significant at 90% for whole relic, 97% for brightest spots

- nondetection, but an interesting hint of IC signal

(Markevitch 17 in prep.)