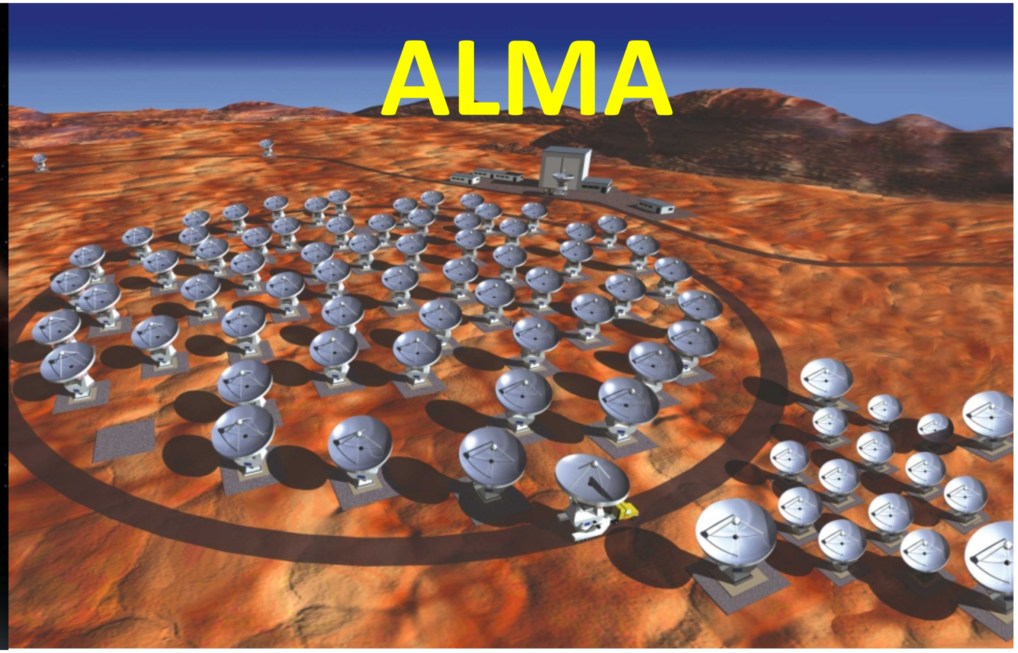
Prospects of galaxy cluster studies by ASTRO-H and ALMA

Tetsu Kitayama

Toho University, Japan



- **Probe the same intra-cluster plasma**
  - ASTRO-H: X-rays (bremsstrahlung, lines, etc.)
    - high spectral resolution (<7eV),
    - limited angular resolution (>1’)
  - ALMA: SZ effect (inverse Compton)
    - high angular resolution (5”)

- **Operate nearly at the same time**
  - ASTRO-H: 2015- (launch)
  - ALMA: 2013- (12m & 7m arrays)

~2/3 of my talk, ICM dynamics/kinematics from

ASTRO-H Space X-ray Observatory White Paper

Clusters of Galaxies and Related Science

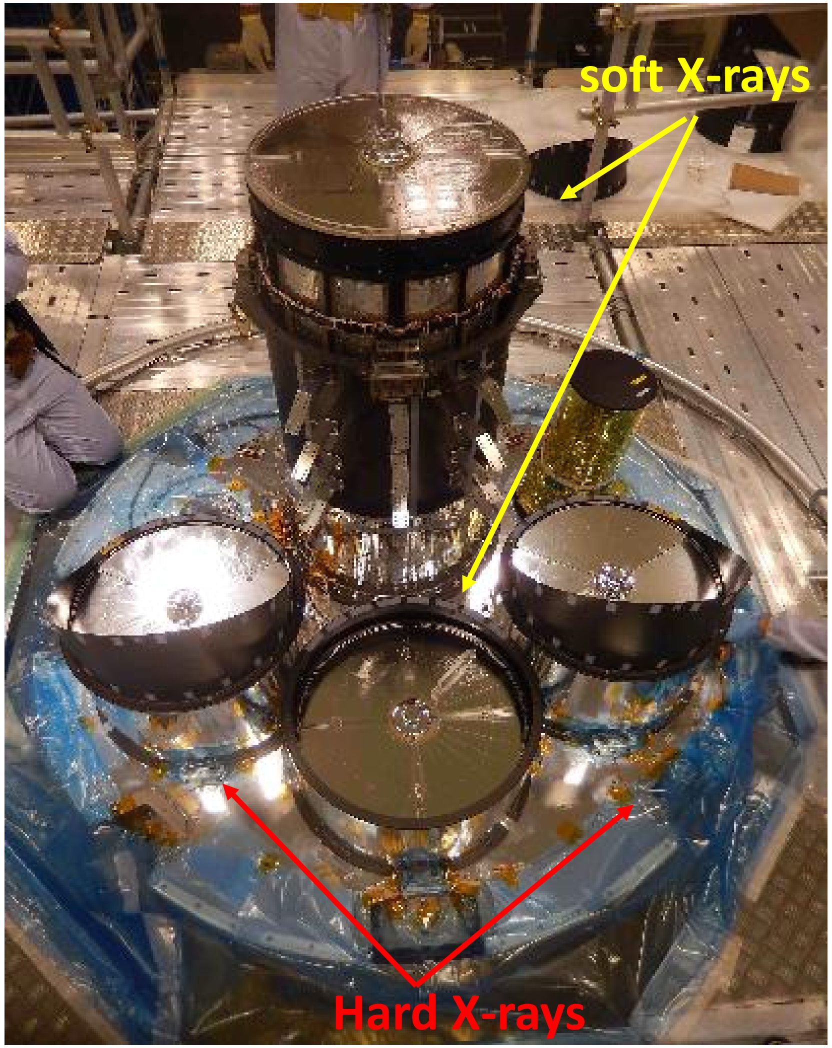
T. Kitayama (Toho University), H. Akamatsu (SRON), S. Allen (Stanford University), M. Bautz (MIT), J. de Plaa (SRON), M. Galeazzi (University of Miami), M. Kawaharada (JAXA), G. Madejski (Stanford University), M. Markevitch (NASA/GSFC), K. Matsushita (Tokyo University of Science), B. McNamara (University of Waterloo), E. Miller (MIT), K. Nakazawa (University of Tokyo), N. Ota (Nara Women's University), H. Russell (IoA, Cambridge), K. Sato (Tokyo University of Science), N. Sekiya (JAXA/University of Tokyo), A. Simionescu (JAXA), T. Tamura (JAXA), Y. Uchida (JAXA/University of Tokyo), E. Ursino (University of Miami), N. Werner (Stanford University), I. Zhuravleva (Stanford University), and J. ZuHone (NASA/GSFC) on behalf of the ASTRO-H Science Working Group

One of 16 white papers to be posted on arXiv.

What is ASTRO-H?

The 6th X-ray satellite to be launched from Japan in 2015

Body



Telescopes (viewed from the top)

ASTRO-H Team Members

The ASTRO-H X-ray Astronomy Satellite (DRAFT)

Tadayuki Takahashi[a], Kazuhisa Mitsuda[a], Richard Kelley[b], Felix Aharonian[c], Hiroki Akamatsu[d], Fumie Akimoto[e], Steve Allen[f], Naohisa Anabuki[g], Lorella Angelini[b], Keith Arnaud[h], Makoto Asai[f], Marc Audard[i], Hisamitsu Awaki[j], Philipp Azzarello[i], Chris Baluta[a], Aya Bamba[k], Nobutaka Bando[a], Mark Bautz[l], Thomas Bialas[b], Roger Blandford[f], Kevin Boyce[b], Laura Brenneman[b], Greg Brown[m], Edward Cackett[n], Edgar Canavan[b], Maria Chernyakova[c], Meng Chiao[b], Paolo Coppi[o], Elisa Costantini[d], Jelle de Plaa[d], Jan-Willem den Herder[d], Michael DiPirro[b], Chris Done[p], Tadayasu Dotani[a], John Doty[q], Ken Ebisawa[a], Megan Eckart[b], Teruaki Enoto[r], Yuichiro Ezoe[s], Andrew Fabian[n], Carlo Ferrigno[i], Adam Foster[t], Ryuichi Fujimoto[u], Yasushi Fukazawa[v], Stefan Funk[f], Akihiro Furuzawa[e], Massimiliano Galeazzi[w], Luigi Gallo[x], Poshak Gandhi[p], Kirk Gilmore[f], Matteo Guainazzi[y], Daniel Haas[d], Yoshito Haba[z], Kenji Hamaguchi[h], Atsushi Harayama[a], Isamu Hatsukade[aa], Katsuhiro Hayashi[a], Takayuki Hayashi[a], Kiyoshi Hayashida[g], Junko Hiraga[ab], Kazuyuki Hirose[a], Ann Hornschemeier[b], Akio Hoshino[ac], John Hughes[ad], Una Hwang[ae], Ryo Iizuka[a], Yoshiyuki Inoue[a], Kazunori Ishibashi[e], Manabu Ishida[a], Kumi Ishikawa[r], Kosei Ishimura[a], Yoshitaka Ishisaki[s], Masayuki Ito[af], Naoko Iwata[a], Naoko Iyomoto[ag], Chris Jewell[y], Jelle Kaastra[d], Timothy Kallman[b], Tuneyoshi Kamae[f], Jun Kataoka[ah], Satoru Katsuda[a], Junichiro Katsuta[v], Madoka Kawaharada[a], Nobuyuki Kawai[ai], Taro Kawano[a], Shigeo Kawasaki[a], Dmitry Khangaluyan[a], Caroline Kilbourne[b], Mark Kimball[b], Masashi Kimura[aj], Shunji Kitamoto[ac], Tetsu Kitayama[ak], Takayoshi Kohmura[al], Motohide Kokubun[a], Saori Konami[s], Tatsuro Kosaka[am], Alexander Koujelev[an], Katsuji Koyama[ao], Hans Krimm[b], Aya Kubota[ap], Hideyo Kunieda[e], Stephanie LaMassa[o], Casey Lambert[x], Philippe Laurent[aq], François Lebrun[aq], Maurice Leutenegger[b], Olivier Limousin[aq], Michael Loewenstein[b], Knox Long[ar], David Lumb[y], Grzegorz Madejski[f], Yoshitomo Maeda[a], Kazuo Makishima[ab], Maxim Markevitch[b], Candace Masters[b], Hironori Matsumoto[e], Kyoko Matsushita[al], Dan McCammon[as], Daniel McGuinness[b], Brian McNamara[at], Joseph Miko[b], Jon Miller[au], Eric Miller[av], Shin Mineshige[aw], Kenji Minesugi[a], Ikuyuki Mitsuishi[e], Takuya Miyazawa[e], Tsunefumi Mizuno[v], Koji Mori[aa], Hideyuki Mori[e], Franco Moroso[an], Theodore Muench[b], Koji Mukai[b], Hiroshi Murakami[ax], Toshio Murakami[u], Richard Mushotzky[ay], Housei Nagano[e], Ryo Nagino[g], Takao Nakagawa[a], Hiroshi Nakajima[g], Takeshi Nakamori[az], Shinya Nakashima[a], Kazuhiro Nakazawa[ba], Yoshiharu Namba[bb], Chikara Natsukari[a], Yusuke Nishioka[aa], Masayoshi Nobukawa[ao], Hirofumi Noda[r], Masaharu Nomachi[bc], Steve O' Dell[bd], Hirokazu Odaka[a], Hiroyuki Ogawa[a], Mina Ogawa[a], Keiji Ogi[j], Takaya Ohashi[s], Masanori Ohno[v], Masayuki Ohta[a], Takashi Okajima[b], Atsushi Okamoto[aj], Tsuyoshi Okazaki[a], Naomi Ota[be], Masanobu Ozaki[a], Frits Paerels[bf], Stèphane Paltani[i], Arvind Parmar[bg], Robert Petre[b], Ciro Pinto[n], Martin Pohl[i], James Pontius[b], F. Scott Porter[b], Katja Pottschmidt[b], Brian Ramsey[bd], Rubens Reis[au], Christopher Reynolds[ay], Claudio Ricci[aw], Helen Russell[n], Samar Safi-Harb[bh], Shinya Saito[a], Shin-ichiro Sakai[a], Hiroaki Sameshima[a], Kosuke Sato[al], Rie Sato[a], Goro Sato[ah], Yoichi Sato[aj], Makoto Sawada[k], Peter Serlemitsos[b], Hiromi Seta[bi], Yasuko Shibano[a], Maki Shida[a], Takanobu Shimada[a], Keisuke Shinozaki[aj], Peter Shirron[b], Aurora Simionescu[a], Cynthia Simmons[b], Randall Smith[t], Gary Sneiderman[b], Yang Soong[b], Lukasz Stawarz[a], Yasuharu Sugawara[bj], Satoshi Sugita[j], Hiroyuki Sugita[aj], Andrew Szymkowiak[o], Hiroyasu Tajima[e], Hiroaki Takahashi[g], Hiromitsu Takahashi[v], Shin-ichiro Takeda[a], Yoh Takei[a], Toru Tamagawa[r], Keisuke Tamura[e], Takayuki Tamura[a], Takaaki Tanaka[ao], Yasuyuki Tanaka[v], Yasuo Tanaka[a], Makoto Tashiro[bi], Yuzuru Tawara[e], Yukikatsu Terada[bi], Yuichi Terashima[j], Francesco Tombesi[b], Hiroshi Tomida[aj], Yoko Tsuboi[bj], Masahiro Tsujimoto[a], Hiroshi Tsunemi[g], Takeshi Tsuru[ao], Hiroyuki Uchida[ao], Hideki Uchiyama[bk], Yasunobu Uchiyama[ac], Yoshihiro Ueda[aw], Shutaro Ueda[g], Shiro Ueno[aj], Shinichiro Uno[bl], Meg Urry[o], Eugenio Ursino[w], Cor de Vries[d], Atsushi Wada[a], Shin Watanabe[a], Tomomi Watanabe[b], Norbert Werner[f], Nicholas White[b], Dan Wilkins[x], Shinya Yamada[s], Takahiro Yamada[a], Hiroya Yamaguchi[b], Kazutaka Yamaoka[e], Noriko Yamasaki[a], Makoto Yamauchi[aa], Shigeo Yamauchi[be], Tahir Yaqoob[b], Yoichi Yatsu[ai], Daisuke Yonetoku[u], Atsumasa Yoshida[k], Takayuki Yuasa[r], Irina Zhuravleva[f], Abdu Zoghbi[ay], John ZuHone[b],

Takahashi et al (2014) SPIE paper

More than 200 scientists
from Japan/US/Europe/Canada

ASTRO-H capabilities

Simultaneous broad-band observations of every target

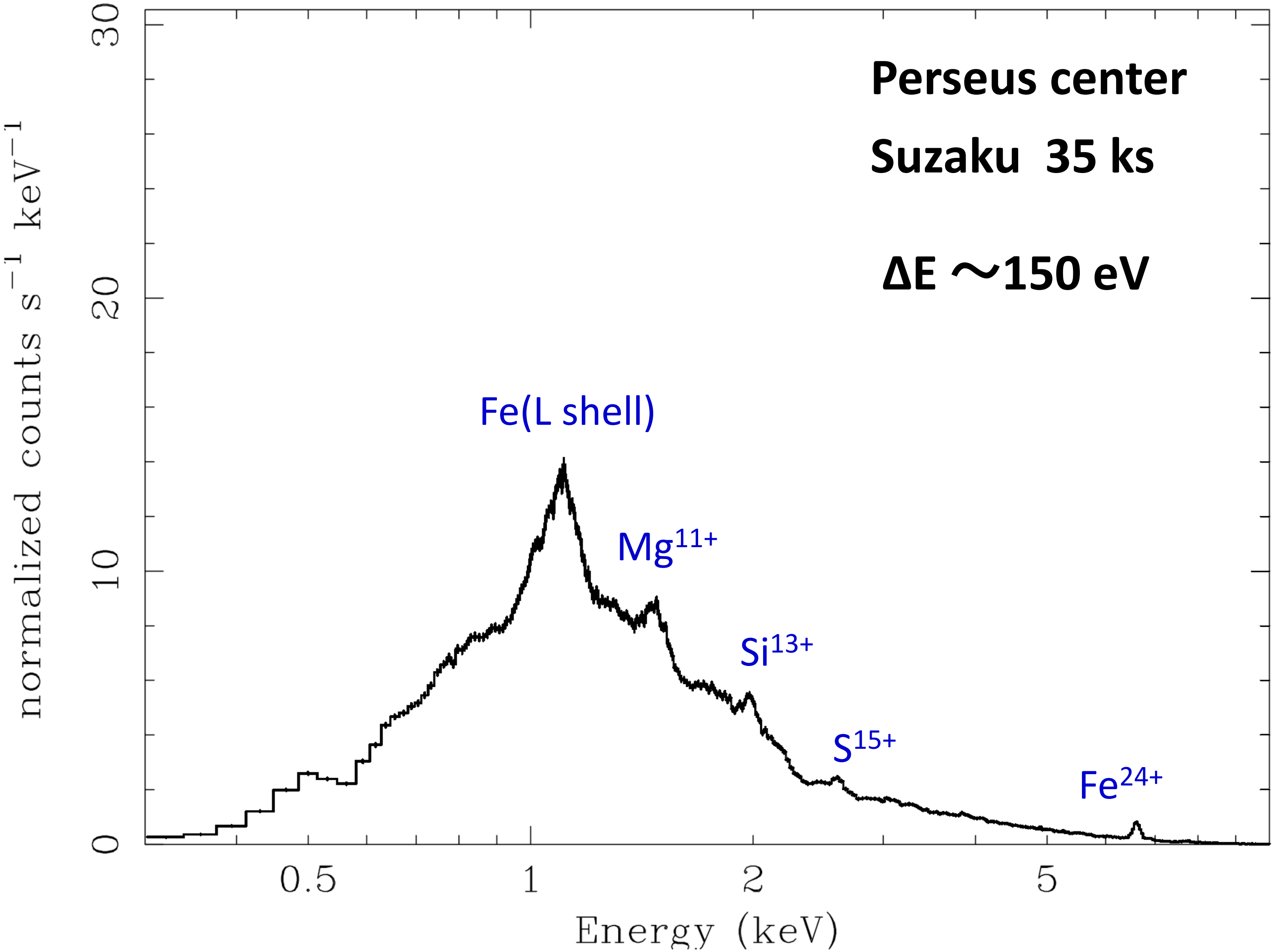
Parameter	Hard X-ray Imager (HXI)	Soft X-ray Spectrometer (SXS)	Soft X-ray Imager (SXI)	Soft γ-ray Detector (SGD)
Detector technology	Si/CdTe cross-strips	micro calorimeter	X-ray CCD	Si/CdTe Compton Camera
Focal length	12 m	5.6 m	5.6 m	–
Effective area	300 cm^2@30 keV	210 cm^2@6 keV 160 cm^2 @ 1 keV	360 cm^2@6 keV	>20 cm^2@100 keV Compton Mode
Energy range	5 –80 keV	0.3 – 12 keV	0.5 – 12 keV	40 – 600 keV
Energy resolution (FWHM)	2 keV (@60 keV)	< 7 eV	150 eV (@6 keV)	4 keV (@40 keV)
Angular resolution	<1.7 arcmin	<1.3 arcmin	<1.3 arcmin	–
Effective Field of View	$\sim 9 \times 9$ arcmin^2	$\sim 3 \times 3$ arcmin^2	$\sim 35 \times 35$ arcmin^2	0.6×0.6 deg^2 (< 150 keV)

Hard X-ray imagining (similar to NuSTAR)

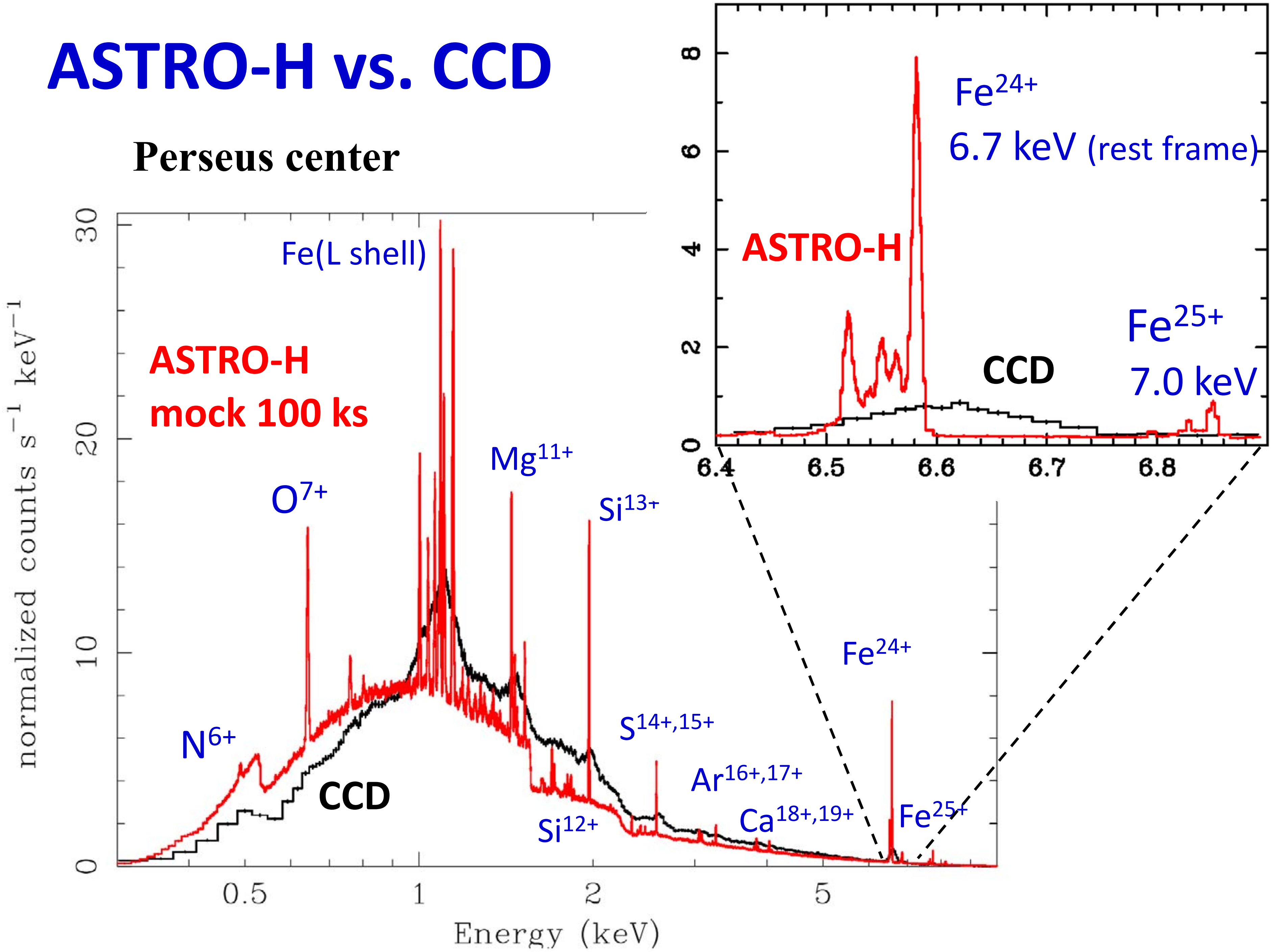
High-resolution spectroscopy: (20 -30 times better than CCD, 1st time for extended sources)

Wide-field CCD

CCD spectrum of a galaxy cluster



ASTRO-H vs. CCD



Why high spectral resolution?

1. Line shift : bulk motion

$$\Delta E = 2.2\text{eV} \left(\frac{V_{\text{bulk}}}{100\text{km/s}}\right)\left(\frac{E_{\text{obs}}}{6.7\text{keV}}\right)$$

2. Line broadening: random motion

Einstein coeff. for He-like Fe @ 6.7keV

FWHMs

natural $$W_{\text{nat}} = 0.31\ \text{eV} \left(\frac{A}{4.67\times10^{14}\ \text{s}^{-1}}\right),$$

\+

thermal $$W_{\text{therm}} = 4.9\ \text{eV} \left(\frac{kT_{\text{ion}}}{5\ \text{keV}}\right)^{1/2} \left(\frac{m_{\text{ion}}}{56\ m_{\text{p}}}\right)^{-1/2} \left(\frac{E_{\text{obs}}}{6.7\text{keV}}\right),$$

\+

turbulent $$W_{\text{turb}} = 5.3\ \text{eV} \left(\frac{V_{\text{turb}}}{100\ \text{km/s}}\right)\left(\frac{E_{\text{obs}}}{6.7\ \text{keV}}\right),$$

\+

instrumental

1D (LOS) dispersion

< 7eV spectral resolution is crucial for measuring V～100km/s & T_{ion} (apart from T_e) can be separated by multiple elements

Impact on ICM properties

Velocity of 100 km/s corresponds to

$$\frac{v_{\rm bulk}}{v_{\rm sound}} = 8.7 \times 10^{-2} \left(\frac{v_{\rm bulk}}{100\ {\rm km\ s^{-1}}}\right)\left(\frac{\mu}{0.6}\right)^{1/2}\left(\frac{kT}{5\ {\rm keV}}\right)^{-1/2},$$

for bulk motion, and

$$\frac{p_{\rm turb}}{p_{\rm therm}} \simeq 1.3 \times 10^{-2} \left(\frac{v_{\rm turb,1D}}{100\ {\rm km\ s^{-1}}}\right)^{2}\left(\frac{\mu}{0.6}\right)\left(\frac{kT}{5\ {\rm keV}}\right)^{-1}.$$

for isotropic turbulence.

Why measuring ICM motions ?

- **Strong circumstantial evidences**

  shocks, cold fronts, galaxy motions, simulation results, etc.

- **Key to understanding ICM physics**

  merger, feedback, viscosity, particle acceleration, etc.

- **Crucial for cosmological studies**

  non-thermal pressure support → total mass and its profile

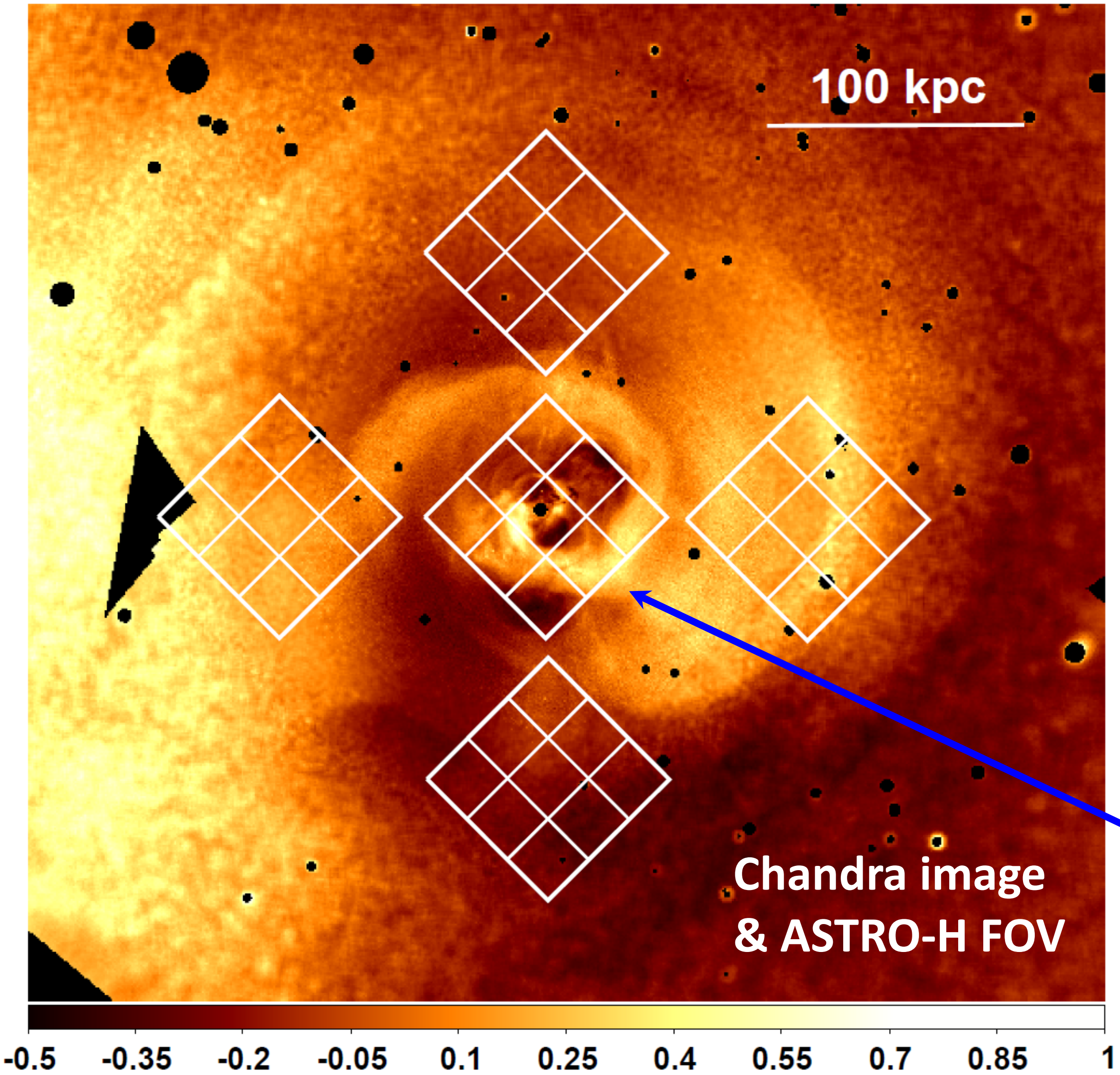
Yet, no accurate measurements so far!

e.g. bulk motion: ΔV=1500±300±300(sys) km/s toward A2256 (Tamura+2011)

turbulence : V>500 km/s from lack of scattering in Perseus (Churazov+2004)

V< 300 km/s for several cluster cores (Sanders & Fabian 2013)

Mock observations by ASTRO-H



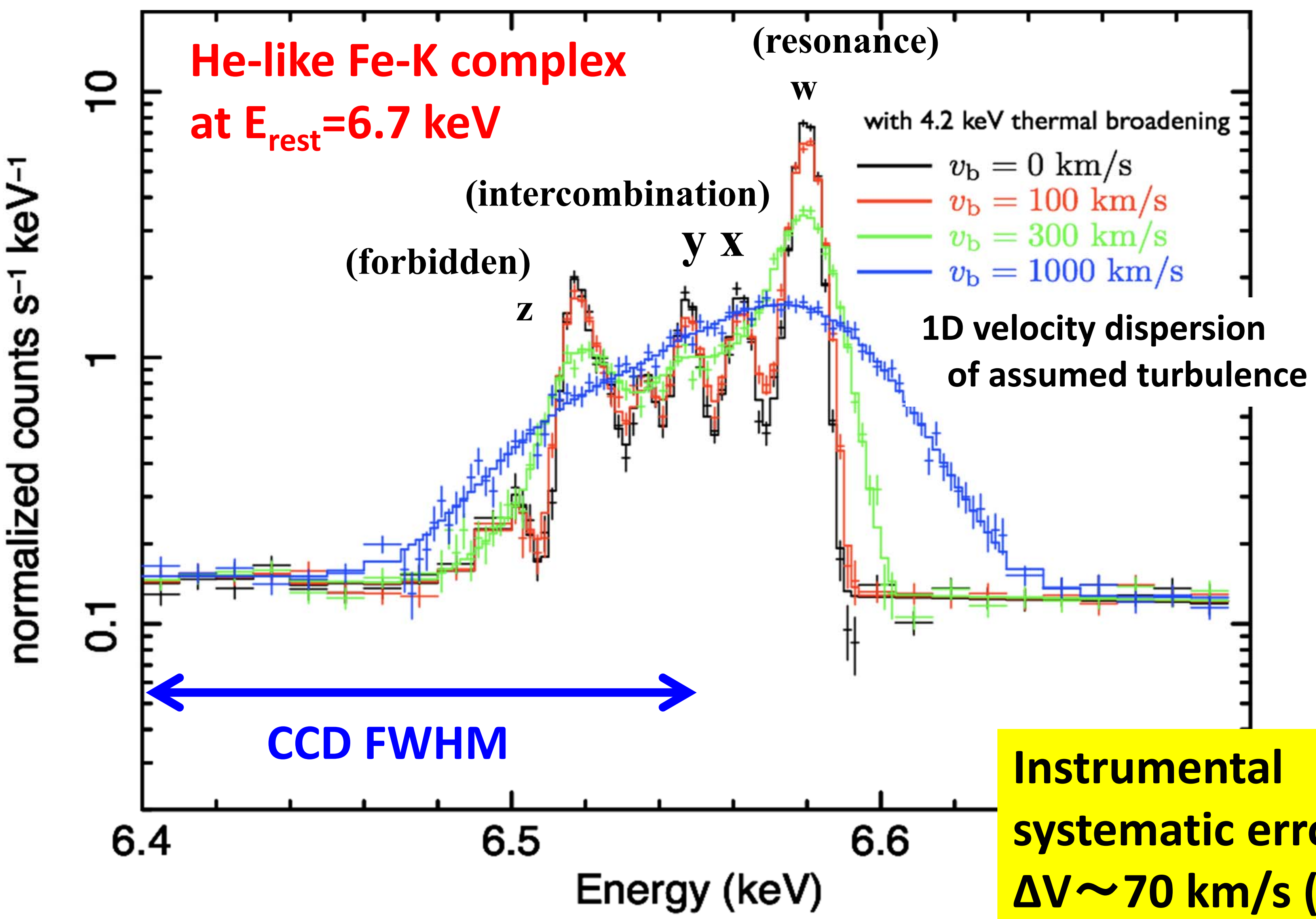
Perseus cluster
@ z=0.018

Brightest X-ray cluster
on the sky (Best target for
high-res. sepctroscopy)

Weak shocks in the center
On-going AGN feedback

3’ × 3’ FOV
1.3’HPD PSF

Mock spectra for Perseus center (100ks)



Instrumental systematic errors ΔV～70 km/s (1σ)

He-like triplet

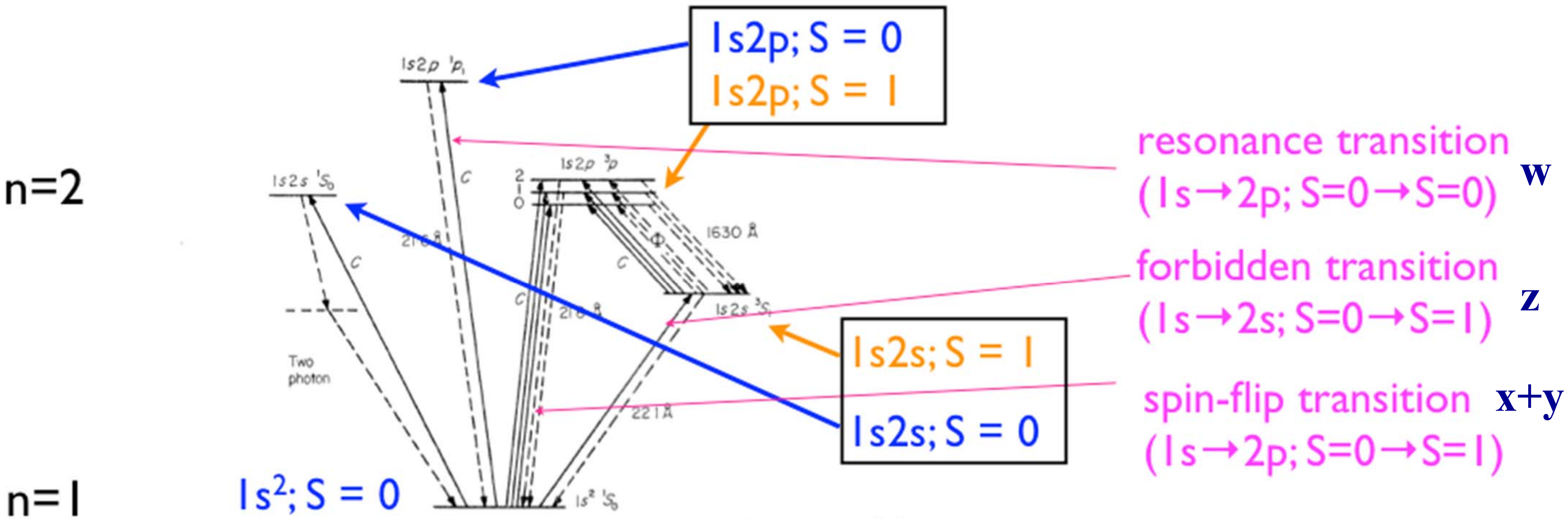
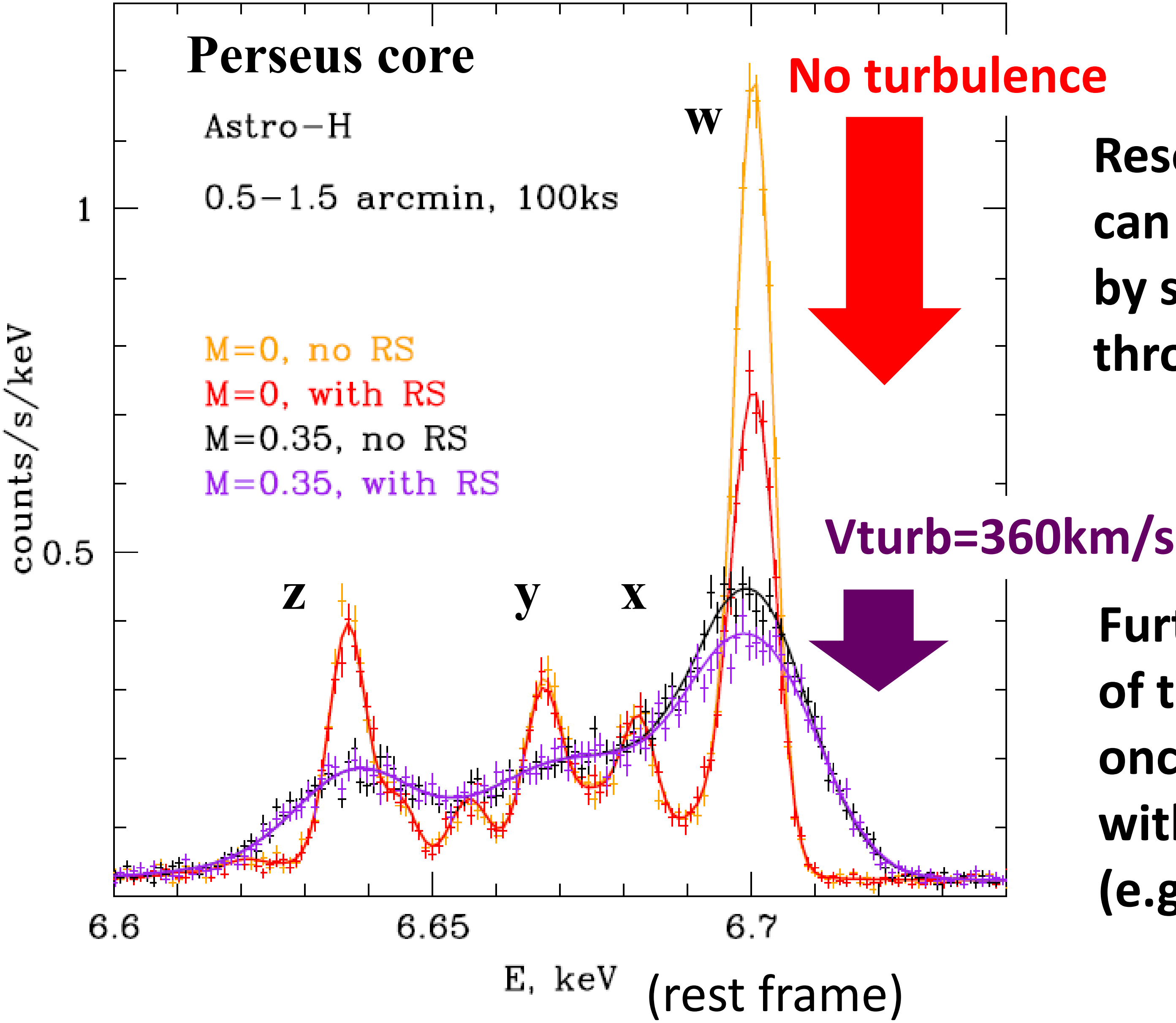


FIG. 1. *The He-like ion, showing those terms and processes involved in the present analysis. The wavelengths indicated apply to the case of oxygen VII.*

- **ASTRO-H will resolve w, x+y, z lines of He-like Fe-K at 6.7 keV**
- **G=(x+y+z)/w and R=z/(x+y) will give independent measures of T_e and n_e, respectively.**
- **Relative strength w.r.t. H-like Fe lines will provide a test of collisional ionization equilibrium.**

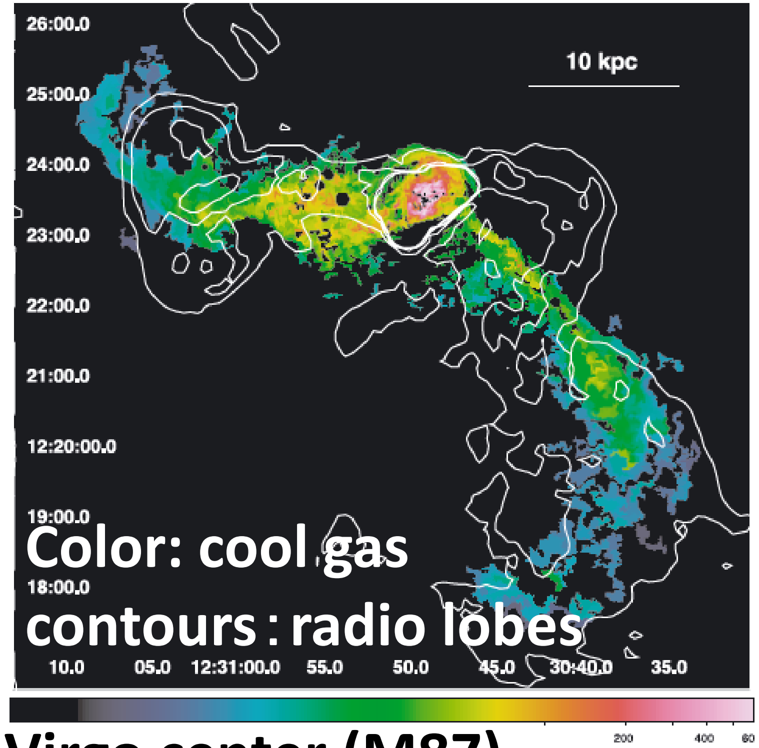
Resonance scattering



Resonance (w) lines can be suppressed by scattering through ICM.

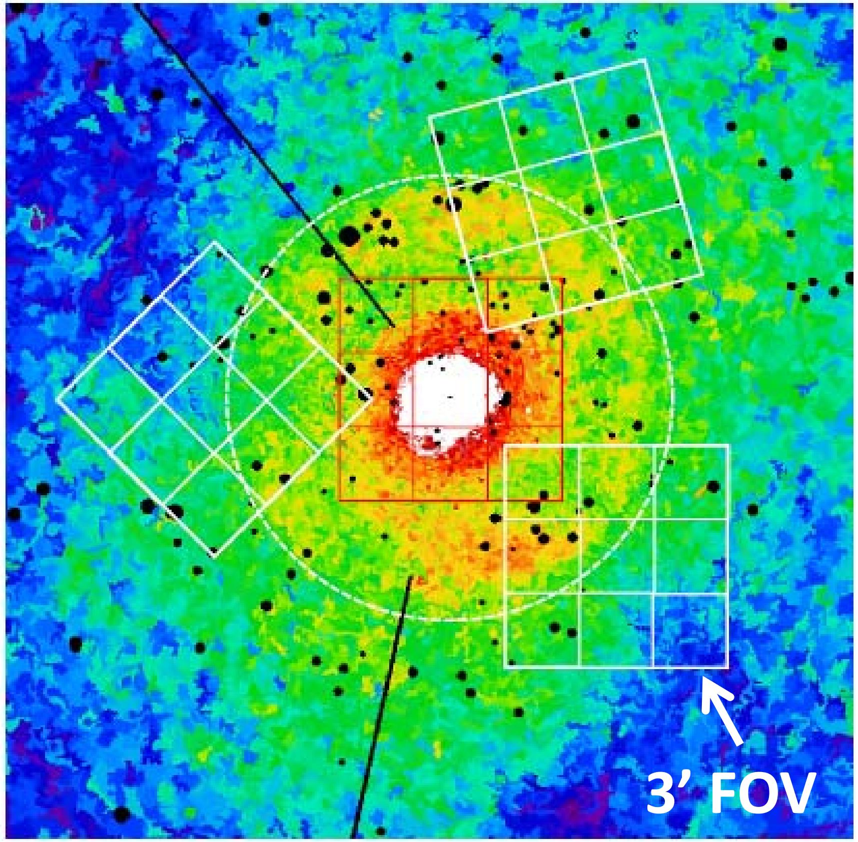
Further probe of turbulence once combined with other lines (e.g., Churazov+04)

How do AGNs heat the ICM?



Virgo center (M87)

Cool (～1 keV) gas filament embedded in 2 keV ICM correlates with radio lobes （Werner et al. 2010）



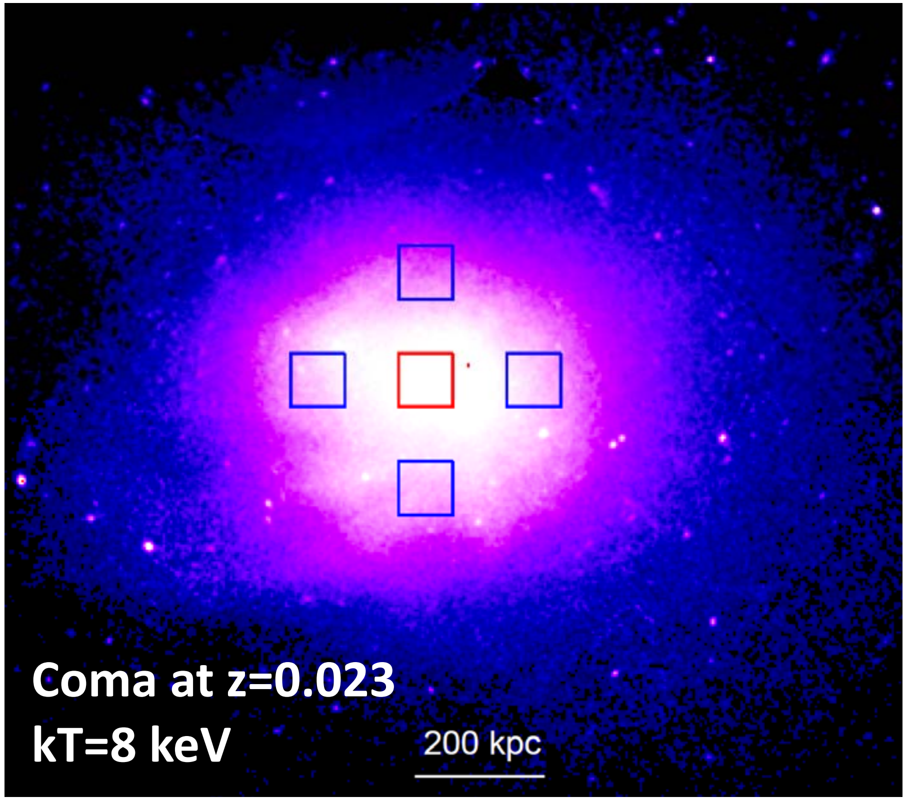
Chandra pressure map (Million+2010)

Signs of weak shocks

ASTRO-H: velocity, temperature, abundance

→ energy and metal transport to ICM

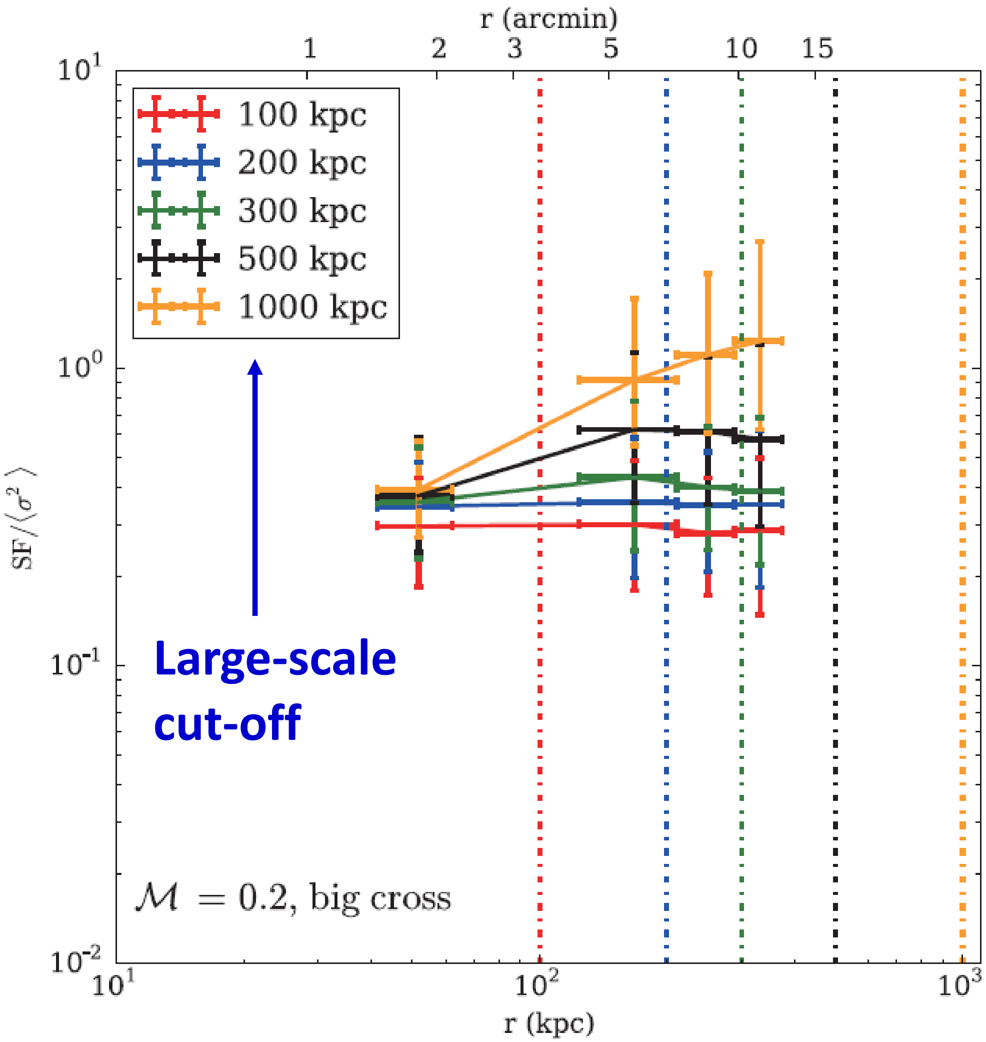
Power spectrum of turbulence



Simulations assuming **Kolmogorov spectrum with a cut-off**

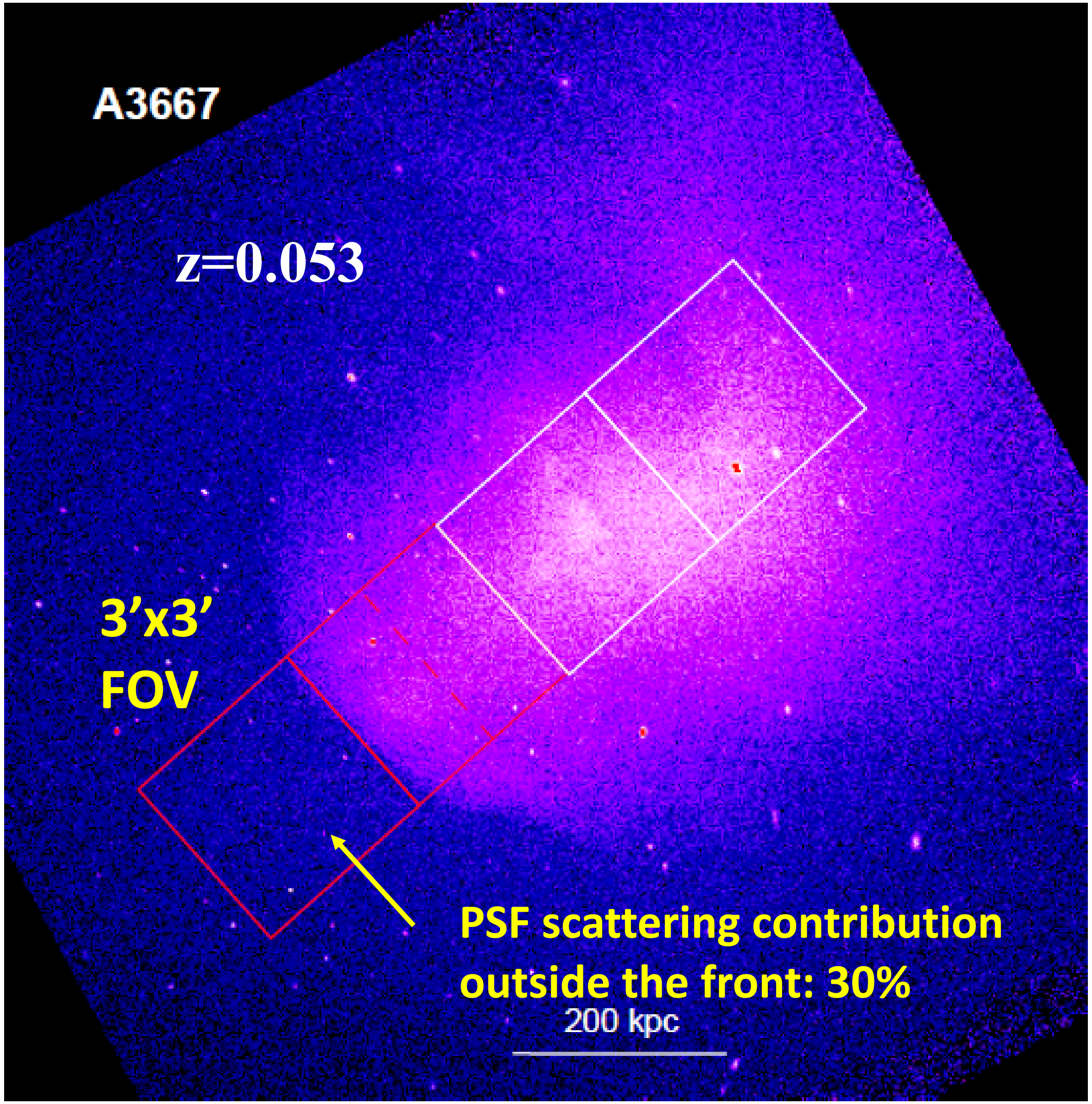
→ **$SF(r)=<[v(x+r)-v(x)]^2>$**

(ZuHone & Markevitch 2014)



Can probe **the largest scale** that drives turbulence. Insensitive to the power at small scales (<100kpc).

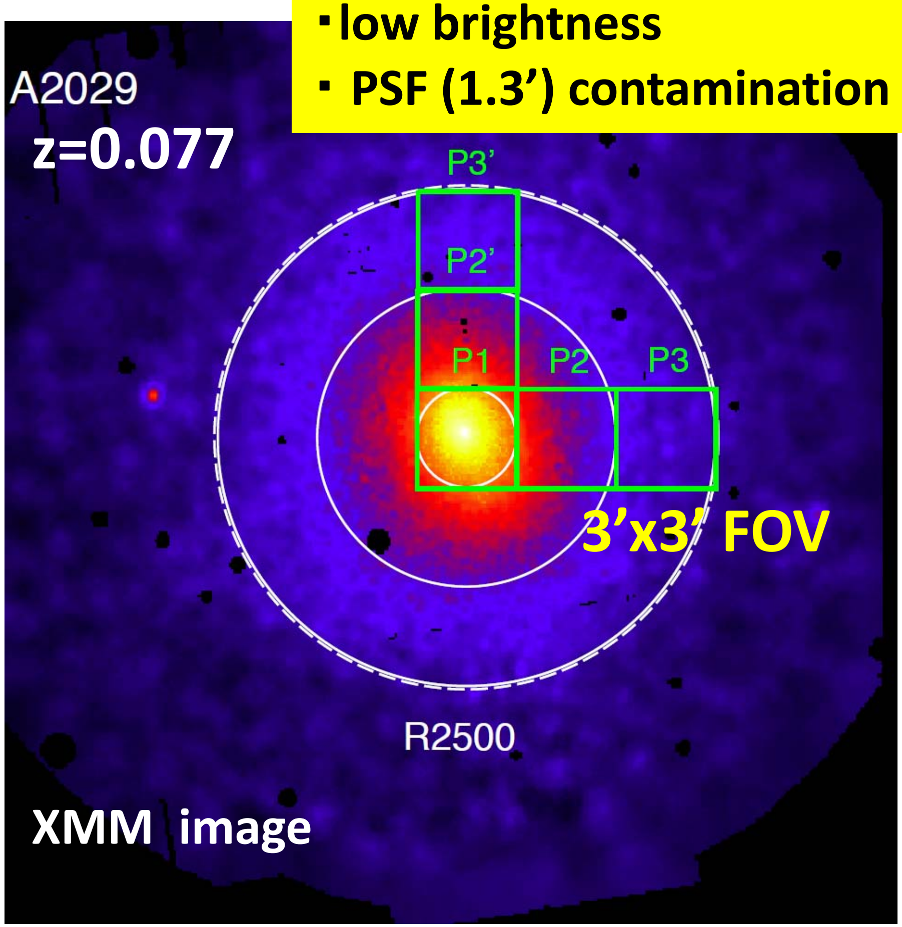
Origin of cold fronts



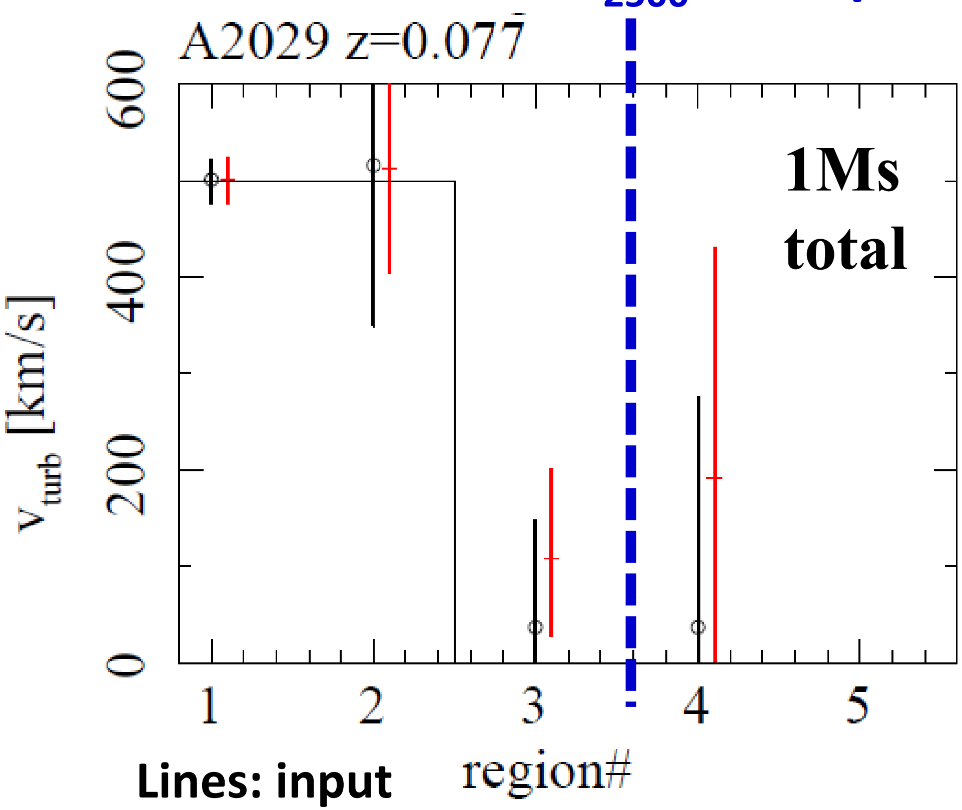
stripping ?
(broadened lines)
or
sloshing over LOS ?
(shifted lines)

How relaxed can galaxy clusters be?
How much is turbulent pressure?

Challenges:
- low brightness
- PSF (1.3') contamination



r_{2500}=660kpc



Lines: input
○ PSF corrected
+ PSF uncorrected

ΔV～100km/s will be achieved out to ～r_{2500} ～1/4 r_{200} at z<0.1

High resolution X-ray spectra will tell us

- Gas velocities：
  - Bulk motion （line shift）
  - Random motion including turbulence（line width）

New！

- Ion temperature （widths of various metal lines）
- Electron temperature & density (continuum or lines)
- Departure from ionization equilibrium (line ratios)

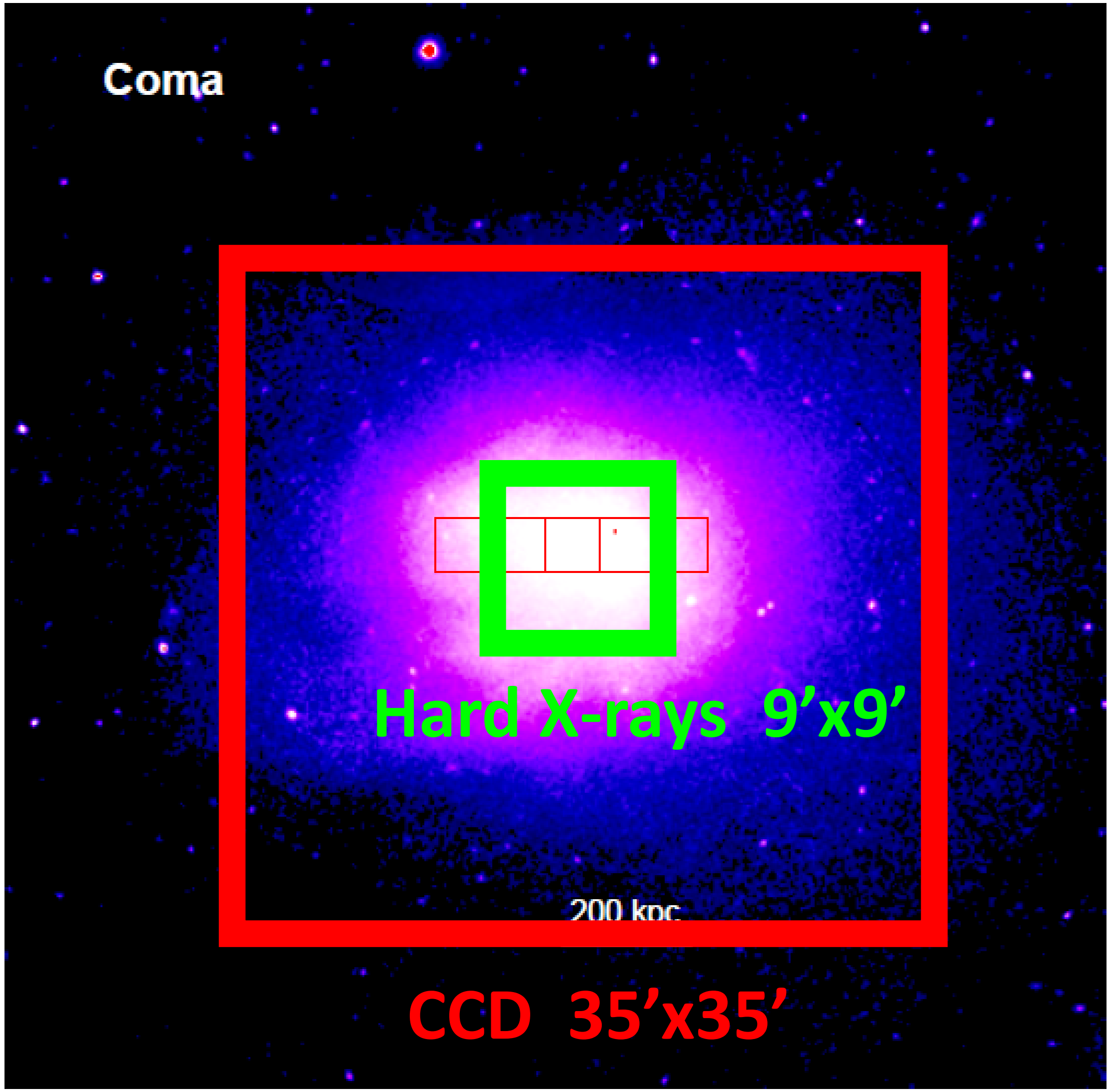
Better quality

- Metal abundances（O, Ne, Mg, Si, S, Ar, Ca, Cr, Mn,Fe, Ni,,,）

etc.

※ASTRO-H is suitable for bright nearby clusters.
Fainter or more distant regions will be studied by future missions.

Broad-band & Wide-field



ASTRO-H

1) High resolution spec
within 3'x3'

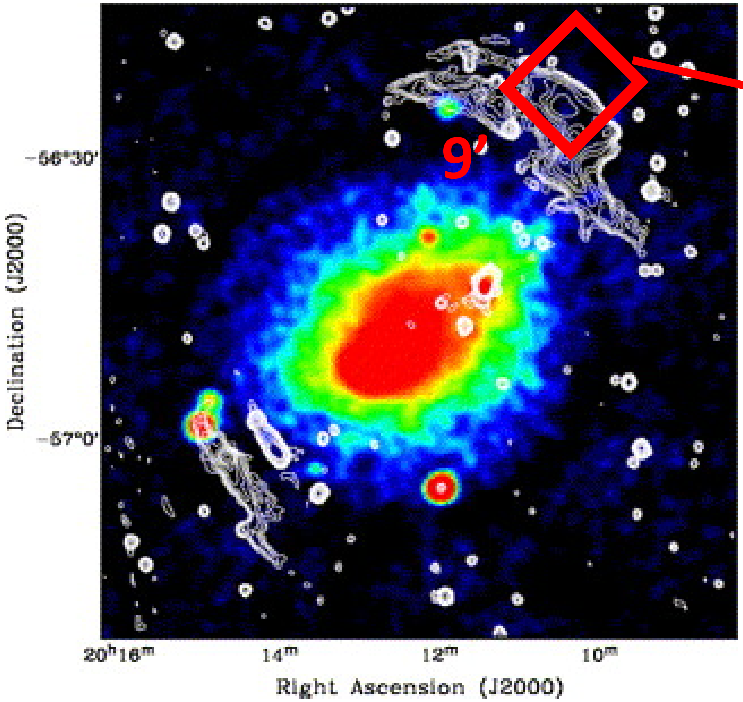
2) Hard X-rays (E>10keV)
within 9'x9'

3) Soft X-ray CCD
within 35'x35'

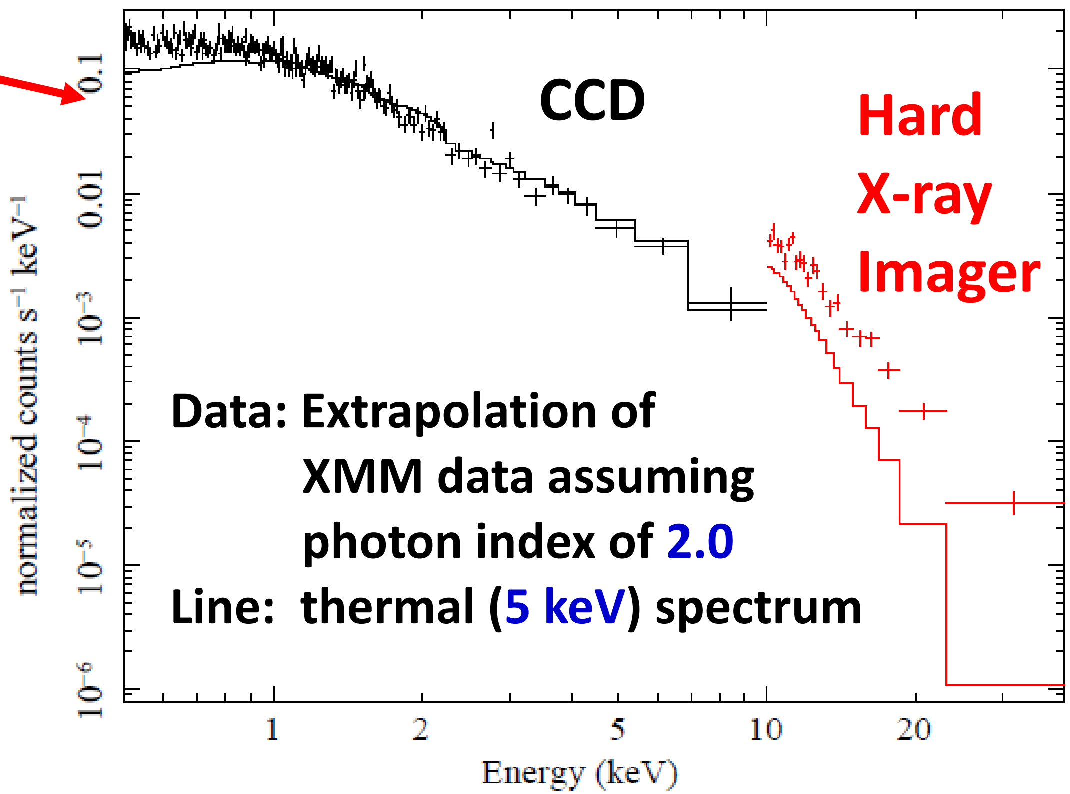
Early observations will be driven by 1) but simultaneously yield deep data by 2) and 3)

Broad-band: Non-thermal emissoin

A3667 NW relic (3.7Jy@1.4GHz, Johnston-Hollitt et al. 2008)



color: X-ray, contours: radio (Feretti et al. 2004)



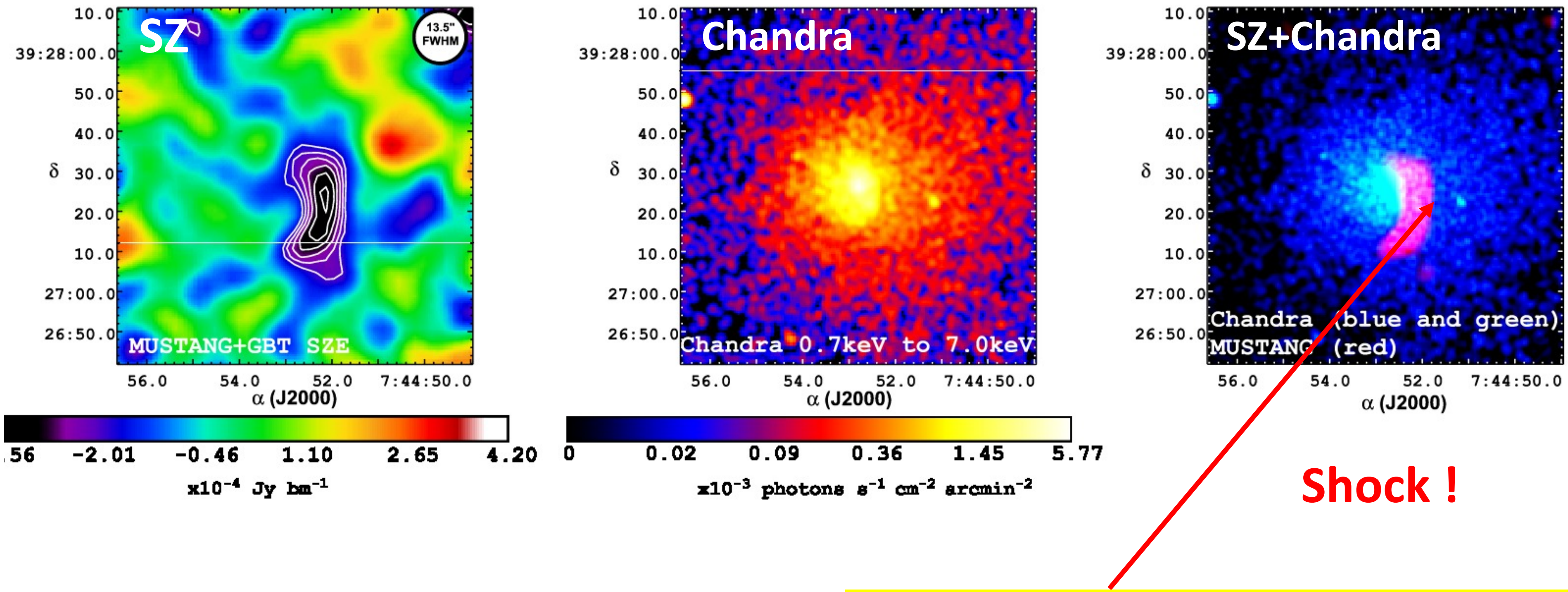
- **PSF (1.7'HPD) is larger than NuSTAR, but a pre-collimator blocks contamination from outside FOV → off-center relics**
- **6 times deeper than Suzaku → if no-detection, B>4 μG**

Prospects of high-resolution SZ effect imaging by ALMA

Collaborators:

Takuya Akahori (Kagoshima U.)
Daisuke Iono (NAOJ)
Takuma Izumi (Univ. Tokyo)
Ryohei Kawabe (NAOJ)
Kotaro Kohno (Univ. Tokyo)
Eiichiro Komatsu (MPA)
Hiroshi Matsuo (NAOJ)
Naomi Ota (Nara Women's Univ.)
Yasushi Suto (Univ. Tokyo)
Shigehisa Takakuwa (ASIAA)
Motokazu Takizawa (Yamagata U.)
Takahiro Tsutsumi (NRAO)
Kenkichi Yamada (Toho Univ.)
Kohji Yoshikawa (Univ. Tsukuba)

SZ vs. X-rays: MACS J0744 at z=0.69



SZ by MUSTANG on GBT 100m
90GHz, 13" beam
>30" is filtered out
(Korngut et al. 2010)

kTe $=19.7^{+9.7}_{-5.9}$ & $8.7^{+1.1}_{-0.8}$ keV across the front

$M=2.1^{+0.8}_{-0.5}$ from T_e
$M=1.2\pm0.2$ from n_e

※For cool cores, see Simona Giacintucci's talk

Sunyaev-Zel'dovich (SZ) effect & X-rays

For the same thermal plasma,

$I_X \propto \int n_e^2 \, T_e^{\alpha} \, dl \, / (1+z)^4$, α<0.5 depending on energy band

$I_{SZ} \propto y \propto \int n_e \, T_e \, dl$ indep. of z

SZE is suitable for

high z, high T , pressure mapping (shocks, etc.)

Caveats:

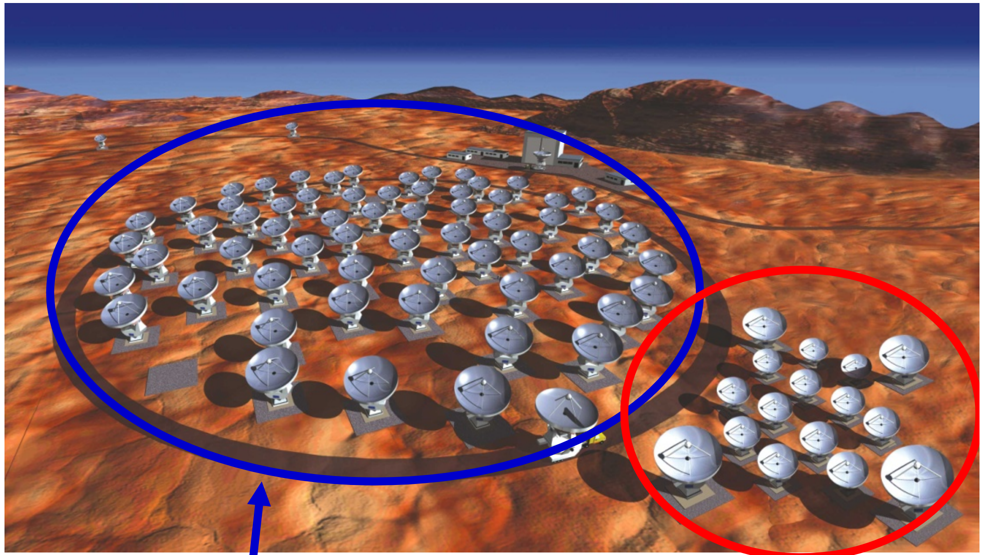
low brightness (～μJy/arcsec²)

& low angular resolution (>1') in general,

except for limited cases with ～10"

ALMA

・SZ image with ～5"
・Systematics: well-controled
※ Feasibility: non-trivial
→ imaging simulations



12m × 50
Higher resolutions

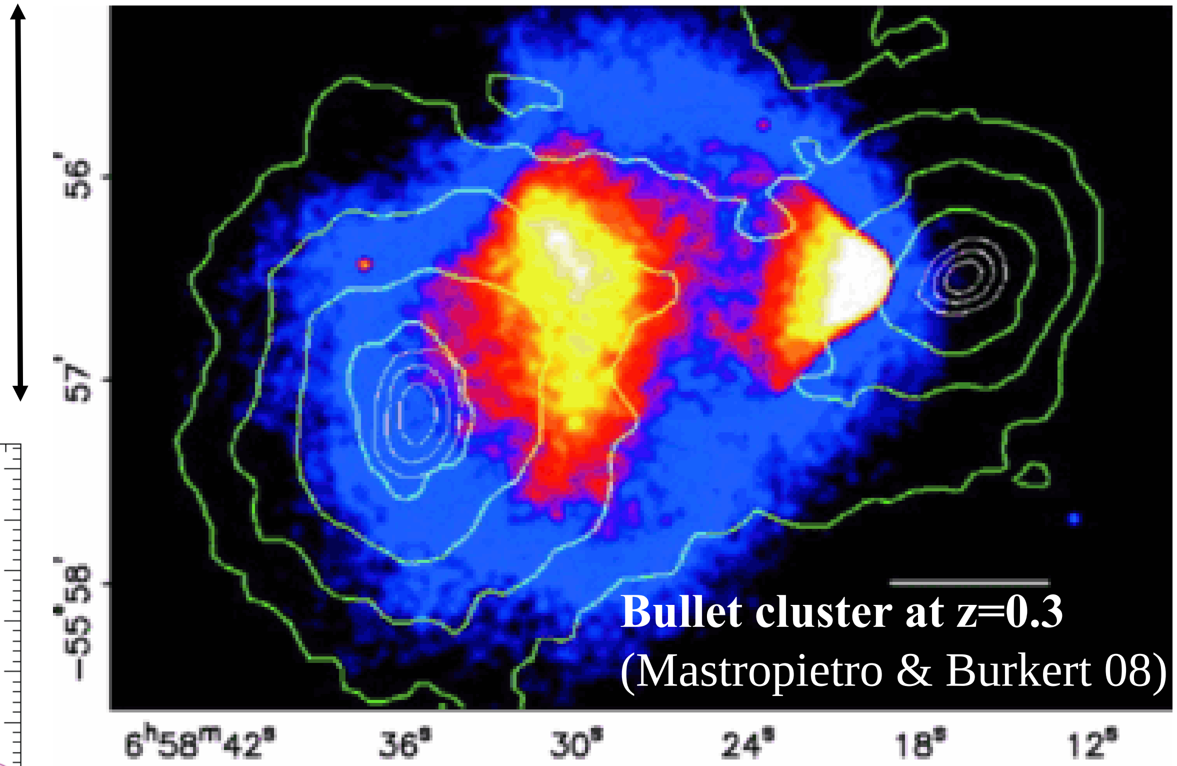
ACA
7m × 12 &
12m SD × 4
Lower resol.

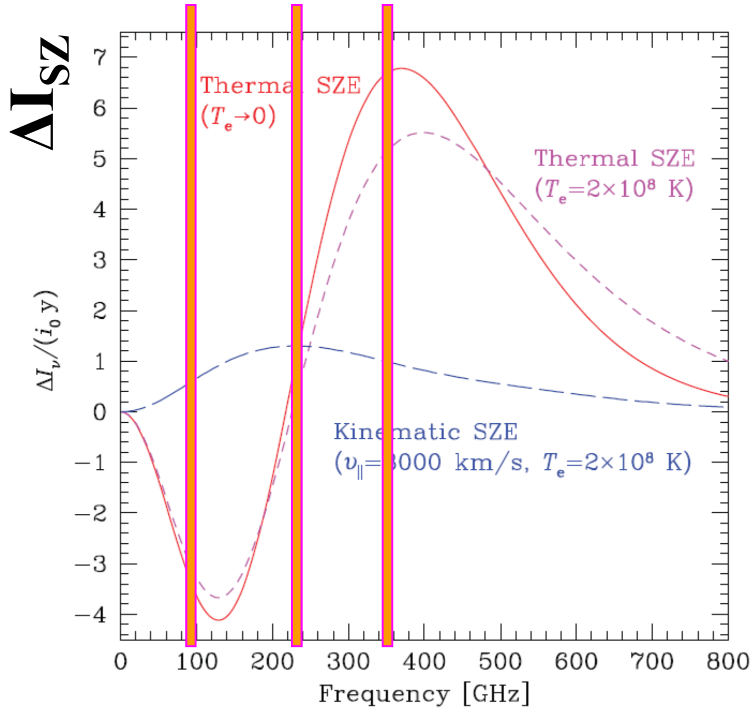
Band	ν [GHz]	resolution["]	FOV["]
(1)	31-45	13-0.1	140
(2)	67-90	6.0-0.05	80
3	84-116	4.9-0.038	62
4	125-163	3.3-0.027	43
5	163-211		33
6	211-275	2.0-0.016	27
7	275-373	1.5-0.012	19
8	385-500	1.1-0.009	14
9	602-720	0 68-0.006	9
(10)	787-950	0.52-0.005	7

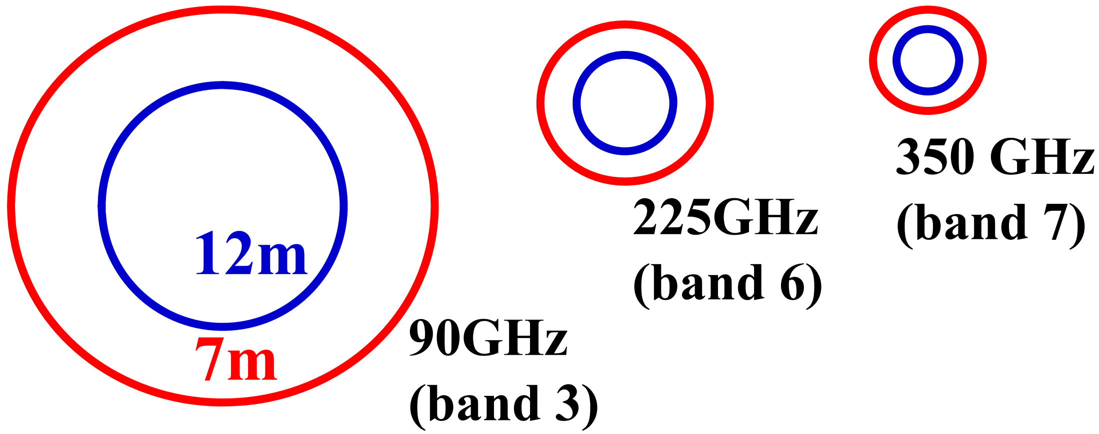
※Bands 1, 2 & 10 will be added in the future.

Fields-of-view of ALMA

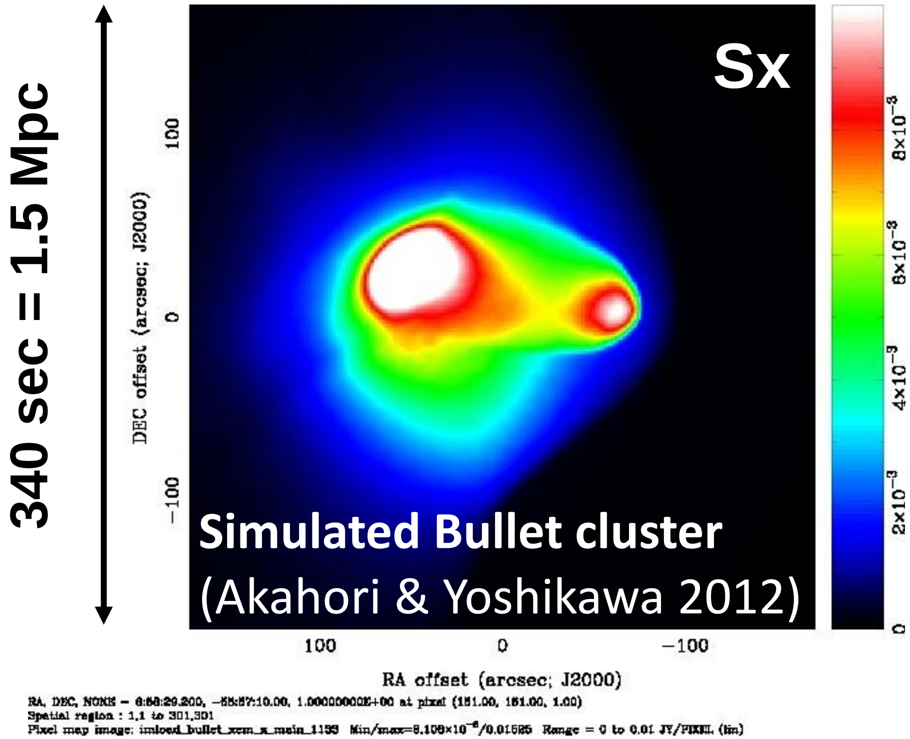
2'= 0.5 Mpc at z=0.3
= 0.7 Mpc at z=0.5
= 1 Mpc at z=1

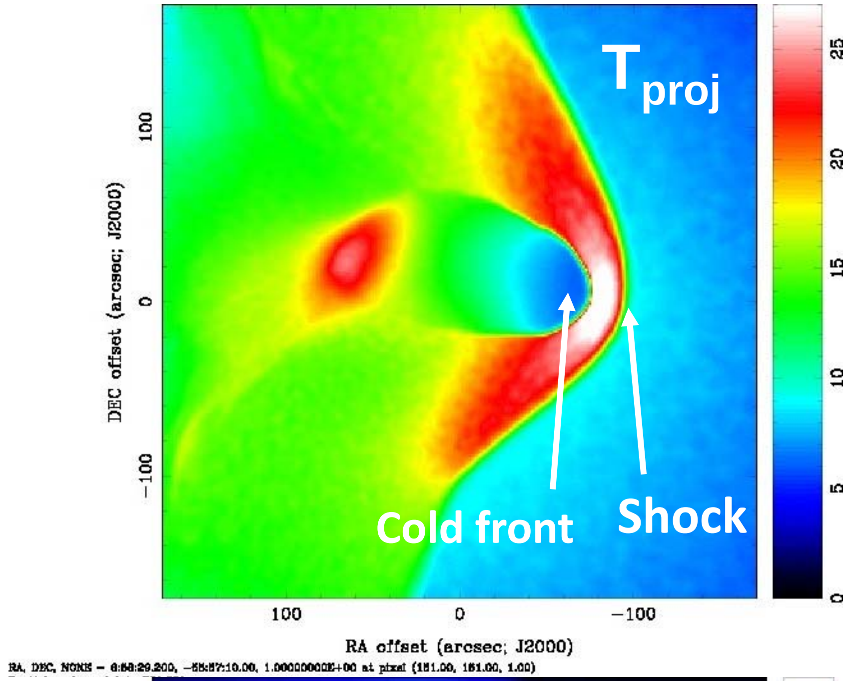


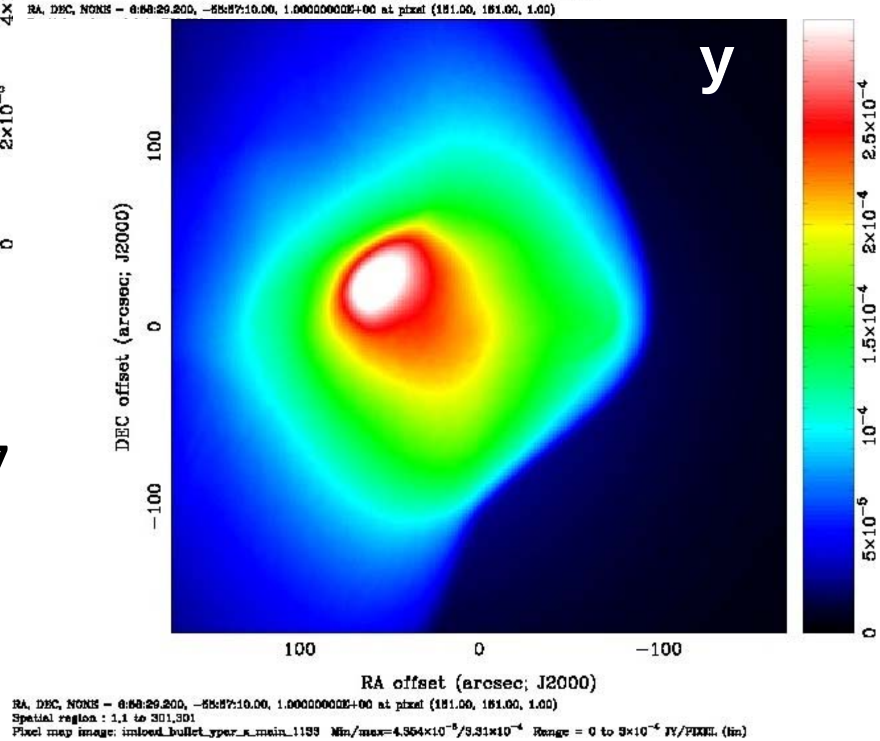


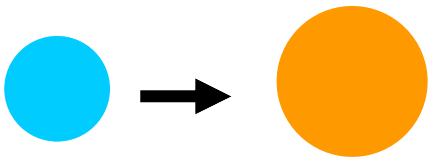


What will Bullet cluster look like via SZ ?









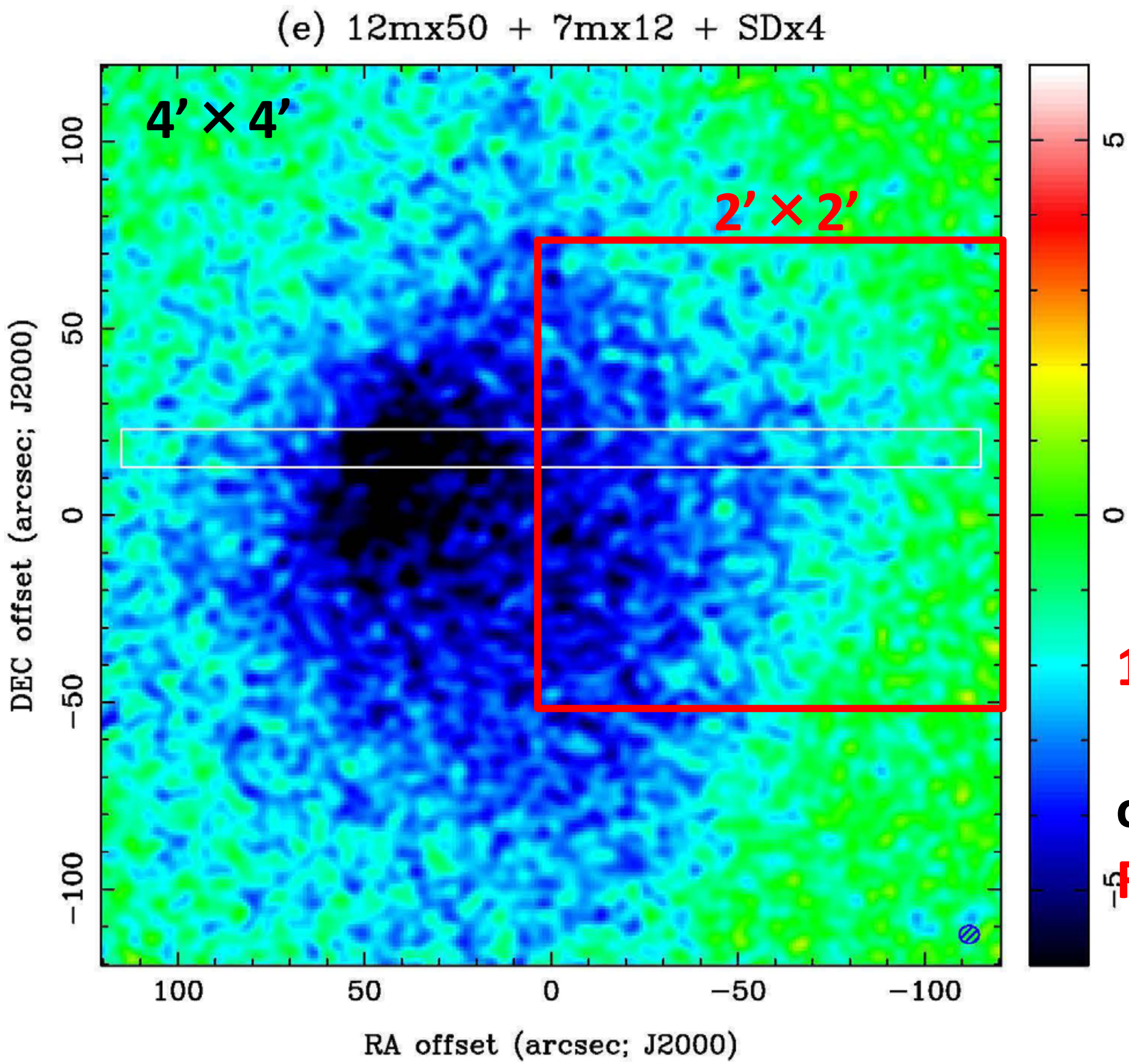
2×10^{14} M_{sun} 10^{15} M_{sun}

$N_{DM}=N_{SPH}=$ 1.2e7

V_{init}=3000km/s

at d=2Rvir

Mock Bullet at 90GHz (Yamada, TK, et al. 2012)

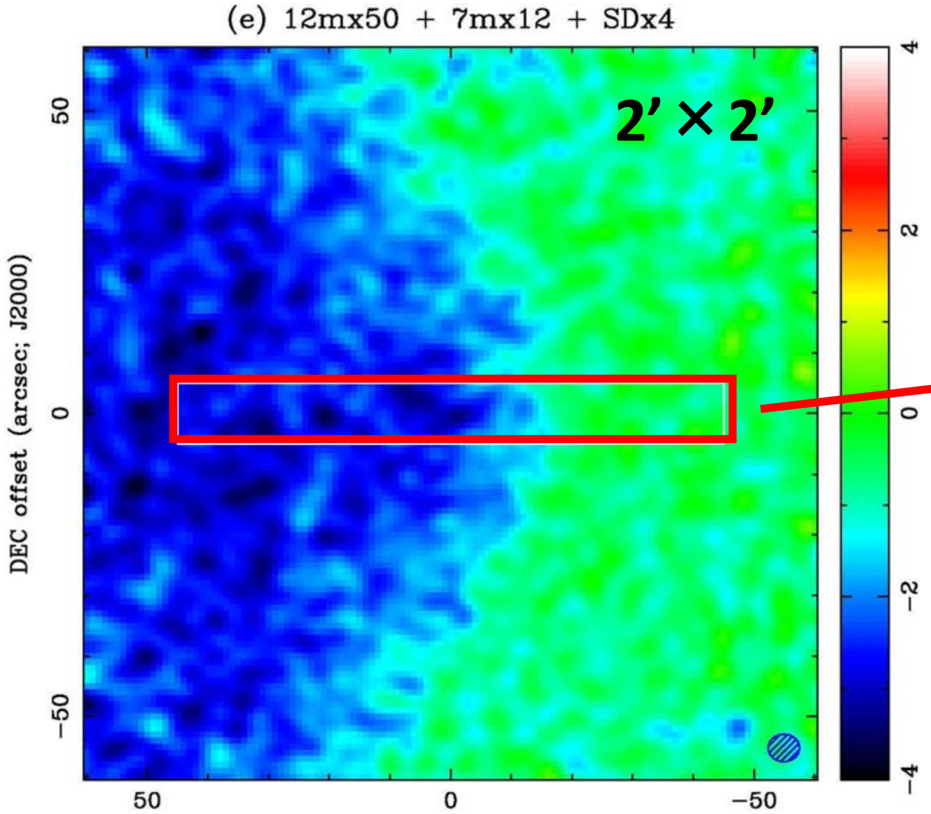


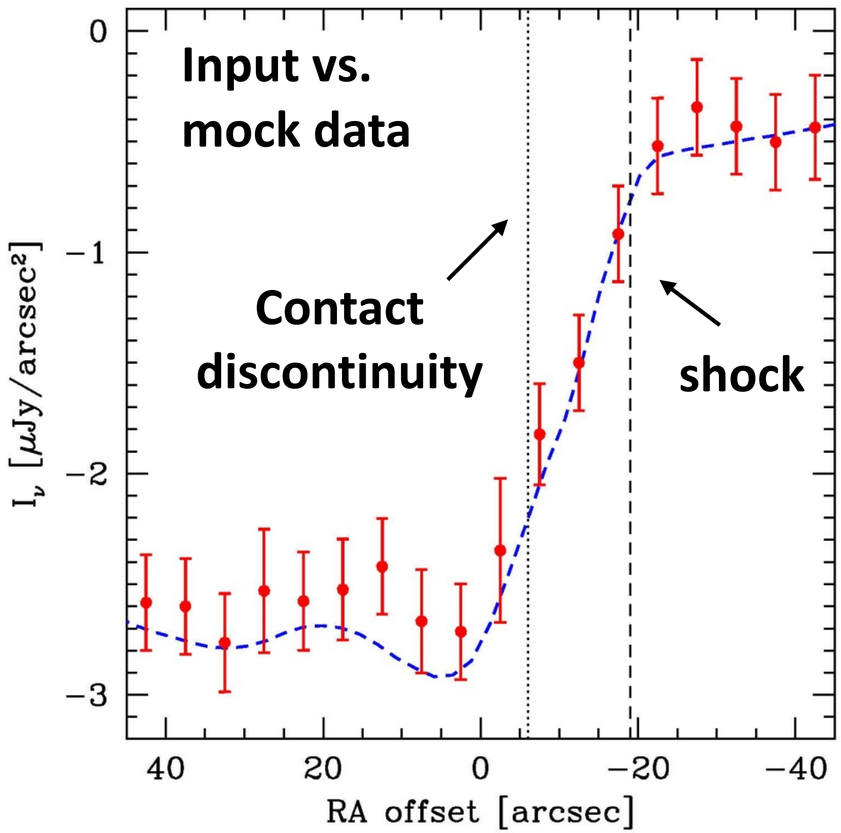
SZE + Noise
+ 12 known sources

Blindly identify & remove sources by long baseline data

12m, 10 hr, 67 mosaics
+ ACA, 40hr, 23 mosaics
σ=0.52μJy/arcsec2,
FWHM=4.9"

Resolving the shock front





90GHz (Band 3)

12m × 50, 10hr, 19 mosaics

+ACA, 40 hr, 7 mosaics

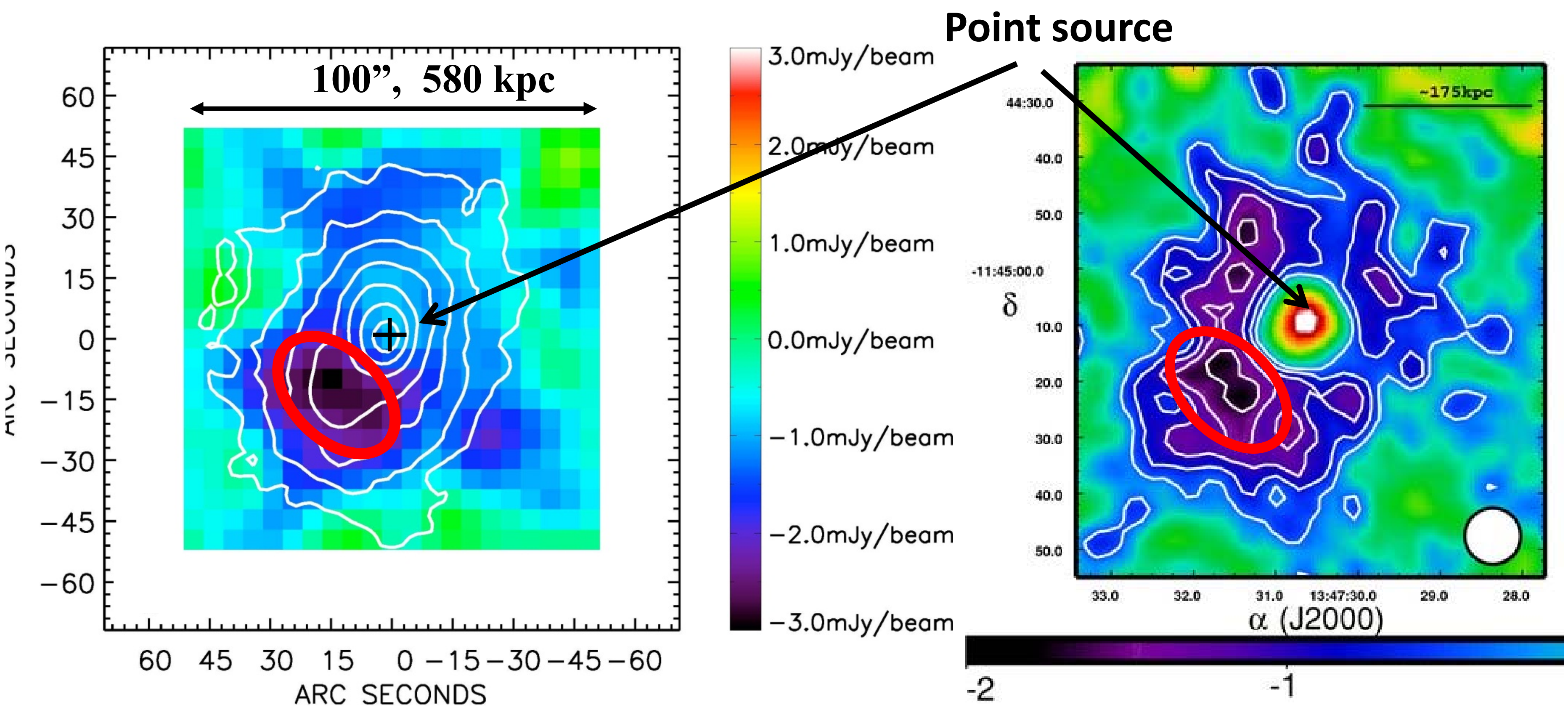
FWHM=4.8” σ= 0.3μJy/arcsec2

(Input: mesh sim. by Takizawa 2005)

15”〜60kpc @z=0.3

Resolution comparable to Coulomb m.f.p.

More compact target: RXJ 1347 at z=0.45



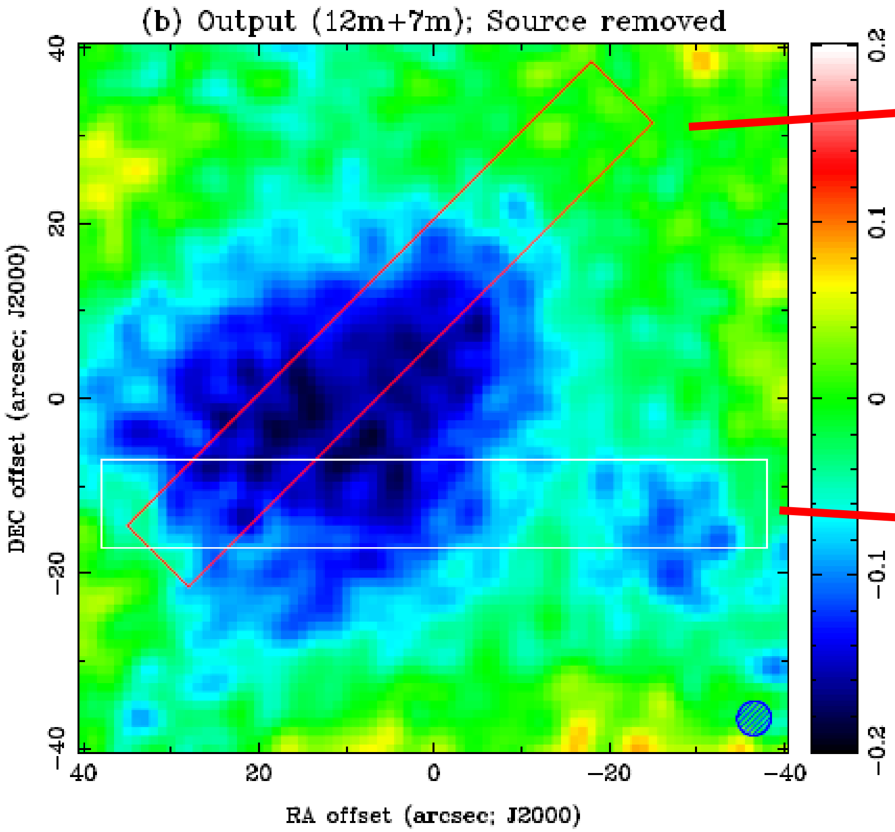
SZE at 150GHz (color) & Chandra (contours)
13” beam, NOBA (Komatsu+01; TK+04)

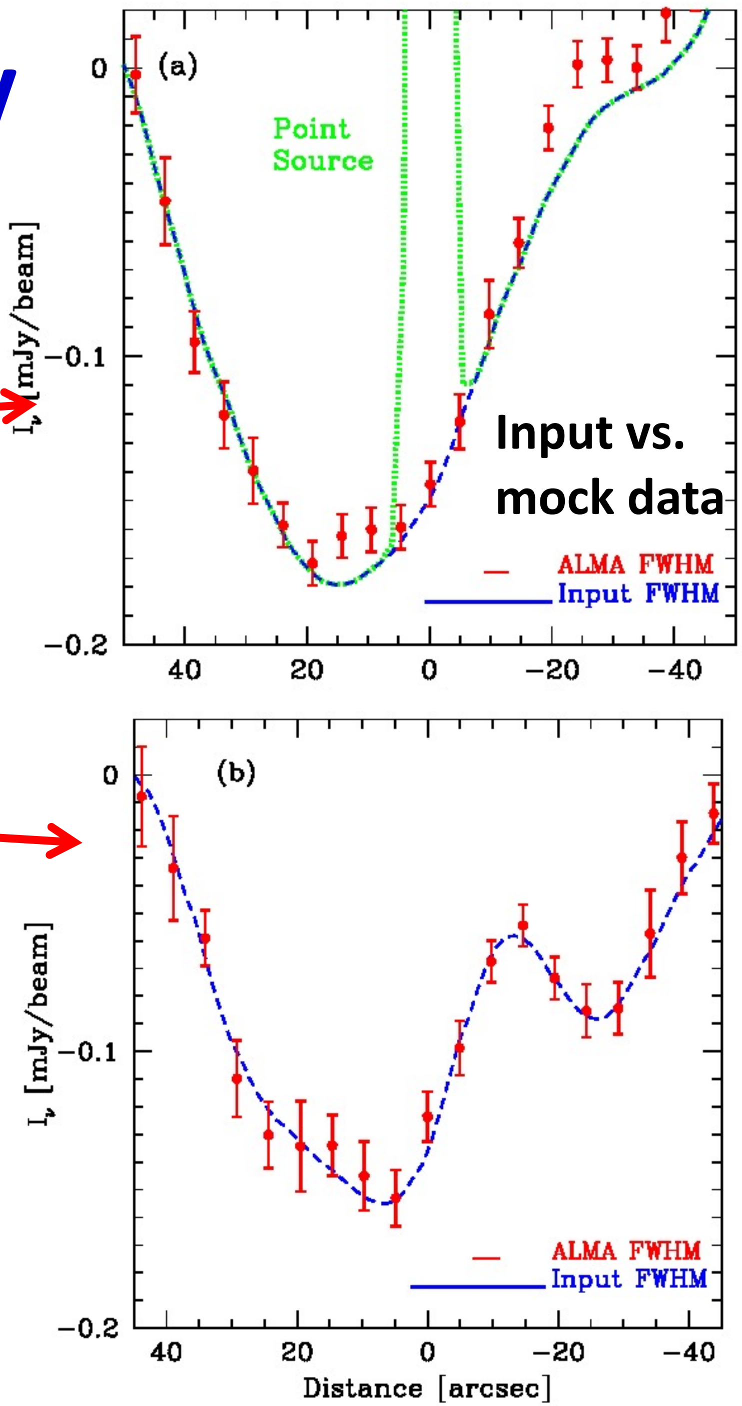
SZE at 90GHz
10” beam, MUSTANG (Mason+10)

- **Suzaku 0.4-60 keV & Chandra** (Ota+08)
  → kT_{excess}= $25.3^{+6.1}_{-4.5}$ keV

Shock front? collision geometry ?
(need to remove point sources)

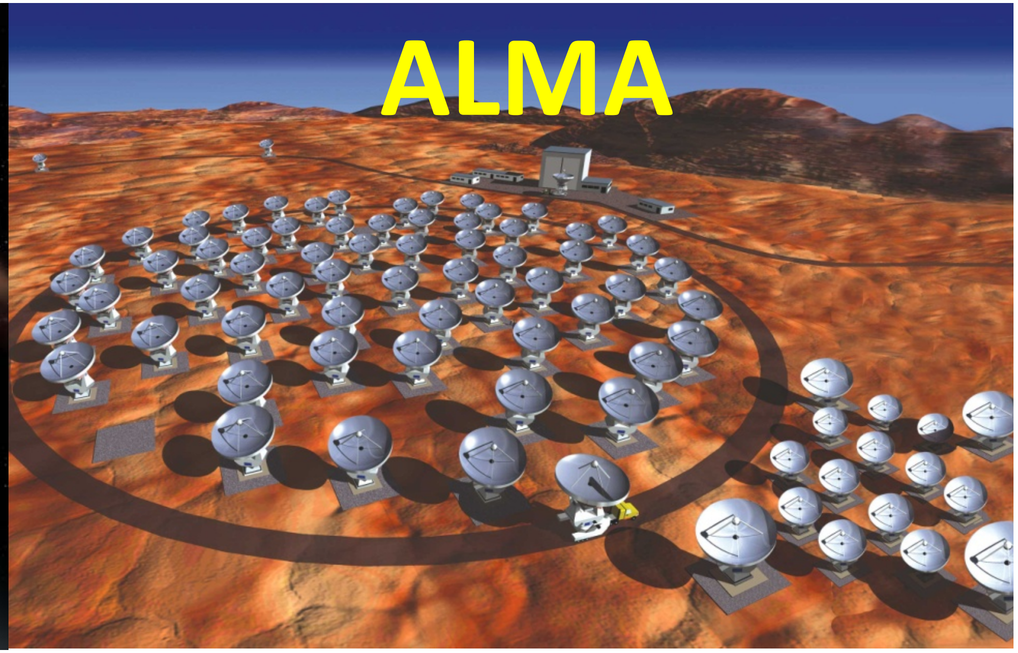
ALMA Cycle-2 underway
RXJ1347 at z=0.45





Simulated image at 90GHz

Can be mapped by current phase (～70% complete) of ALMA



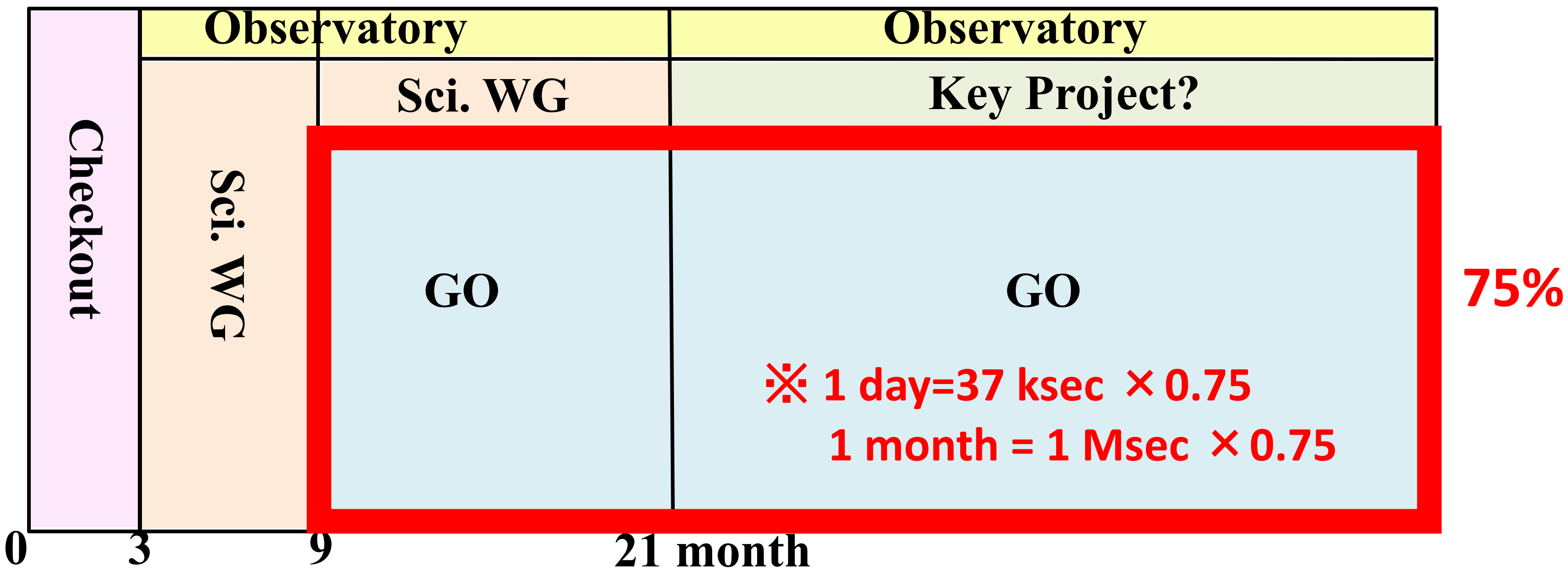
High resolution (<7eV)
X-ray spectroscopy
→ ICM velocities ～100 km/s
(～10% of the sound speed
or ～1% of thermal pressure)
& Simultaneous wide-field (35')
and broad-band (E=0.3-80 keV)
observations

High angular resolution (5")
SZE imaging
→ pressure map including shocks
up to high z
(20-30 kpc at z=0.3-0.5,
～collisional m.f.p. in ICM)

ASTRO-H Operation Schedule

Phase 0 : 3 Months : Satellite/Instruments Check out (including Calibration))
Phase 1 : 6 Months : SWG 90 % (PV Phase) Observatory 10 %
Phase 2 : 12 Months : SWG Carry Over 15 %, GO 75 %, Observatory 10 %
Phase 3 : Rest of the mission : KeyProject 15 % (TBD) , GO 75 %, Observatory 10 %

Observatory 10 % = Calibration + TOO + Director's Time



Data policy among J/Europe/US in the GO time, would be similar to the Suzaku case. But we are planning to introduce key-project type and/or early-data-released type observations from early phase of the mission.