Physics of the Cosmos Program
X-ray Science Interest Group

Response to Hitomi

Mark Bautz

Massachusetts Institute of Technology

Chair of the X-ray Science Interest Group

Vice-Chair of the Physics of the Cosmos Program Analysis Group

Thanks to:

Rich Kelley

Jon Miller

Niel Brandt

Jack Hughes

Ralph Kraft

Knox Long

Maxim Markevitch

Richard Mushotzky

Rob Petre

Chris Reynolds

Randall Smith

Overview

- **Hitomi Chronology and the Soft X-ray Spectrometer (SXS)**
- **Results from Hitomi SXS observation of Perseus**
- **X-ray Science Interest Group Response**
  - Community discussion with Paul Hertz
  - White Paper on importance & timeliness of calorimeter science

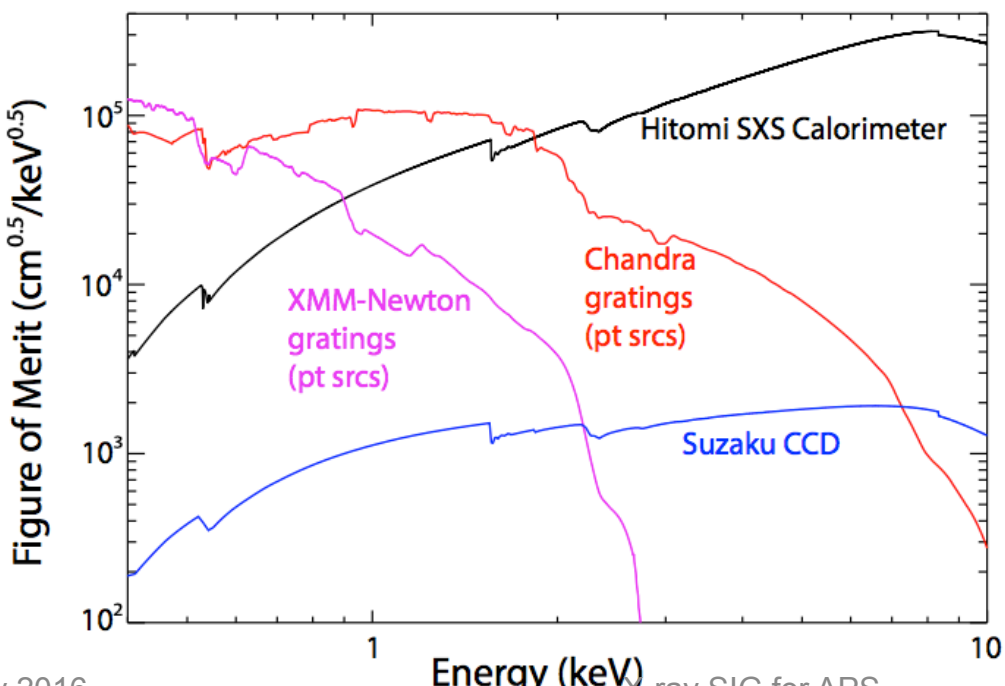
Hitomi Mission & Chronology

- **Major (2.7 T) JAXA/NASA high-energy astrophysics mission**
  - Prime instrument: X-ray micro-calorimeter 'integral field' (non-dispersive) spect rometer (SXS)
  - Also: Hard X-ray Imager (10-80 kev), Soft X-ray Imager (0.3-15 keV), Soft Gamma Compton Camera (40 – 600 keV)
  - Broad international collaboration: ~60 institutions in Japan, N. America, Europe
- **NASA provided SXS detectors & cooling chains, plus mirrors for SXS and SXI, all via Explorer Mission of Opportunity ($75M h/w)**
  - US observers would have received 40% of observing time after PV phase
  - 10% additional time available to joint US/Japan proposals
  - NASA GO program was funded at $5M/yr (total SEO ~$46M)
- **Successful Launch February 17, 2016**
- **First SXS observation began February 24**
  - Performance (e.g. FWHM = 4.9 eV) exceeded goal (5 eV) & req't (7 eV)
- **Contact with spacecraft lost March 26**
- **End of Mission declared April 28**
  - JAXA: Loss due to S/C faults & operational error unrelated to instruments

Hitomi Soft X-ray Spectrometer (SXS)

Astro 2010: "Truly revolutionary technology"; provides

- First high-resolution Xray spectroscopy of extended sources → plasma velocities, precise abundances in clusters, galaxies & SNR
- Unprecedented spectral sensitivity, esp. at Fe K lines (~ 6 keV) → e.g., outflow velocities, mass/energy feedback from SM black holes

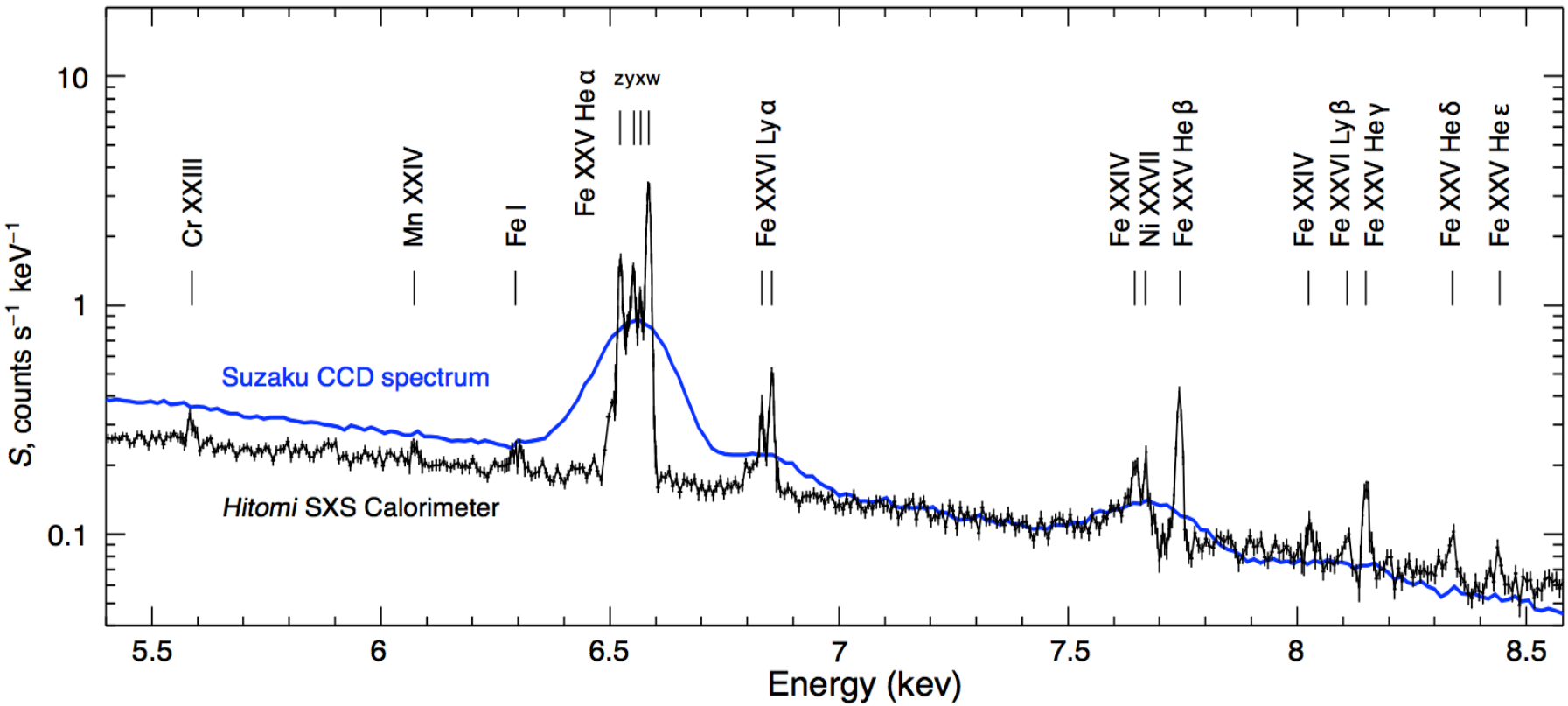


~100x better velocities in clusters, SNR, starburst galaxy flows

~50x better velocities in AGN, stars via K shell transitions of S, Ar, Ca, Fe and Ni

FoM for weak-line velocity $M \equiv (E/\Delta E)(A_{eff}/\Delta E)^{1/2}$

Hitomi SXS spectrum of Perseus cluster

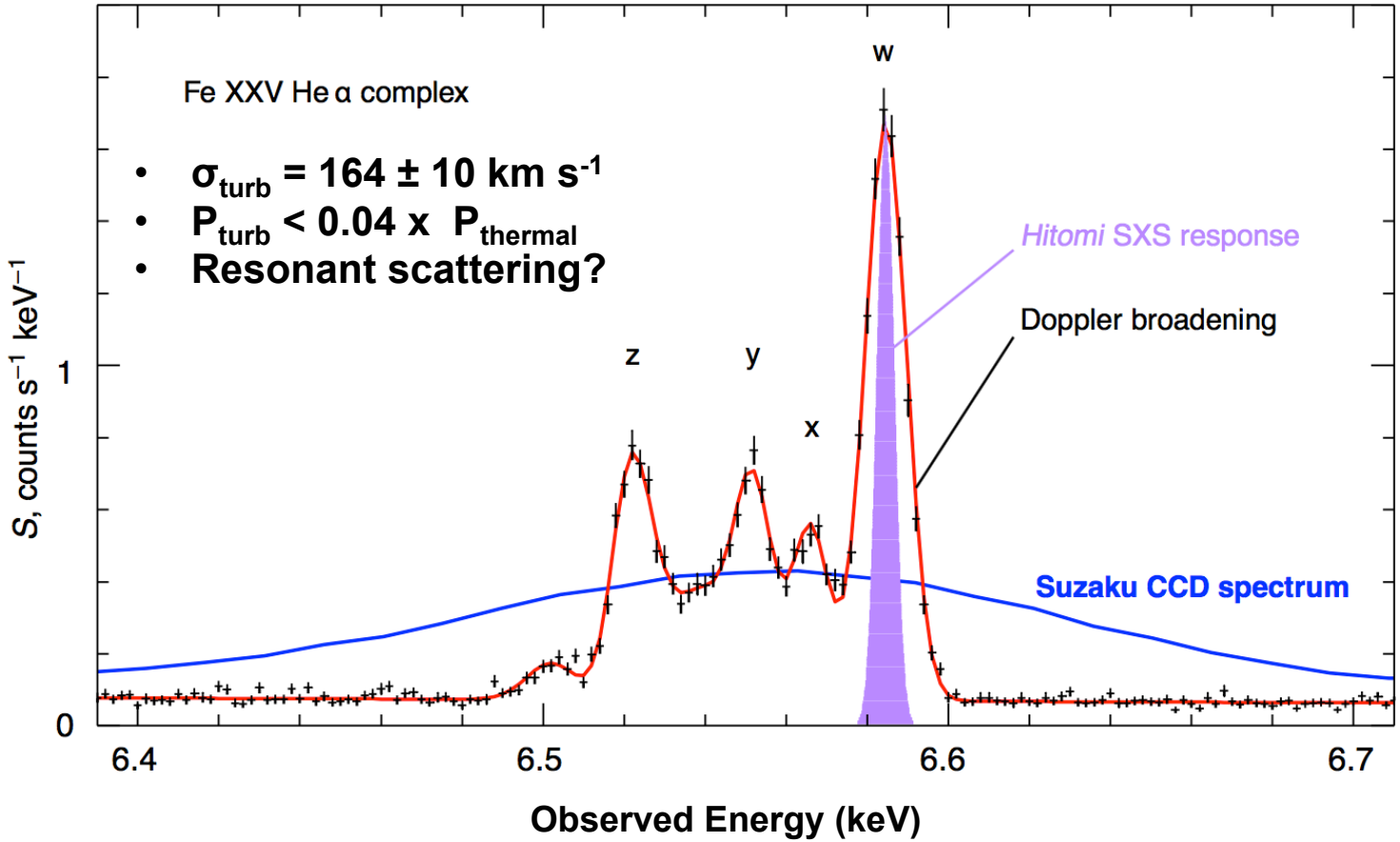


BLACK: Hitomi SXS (FWHM 4.9 eV)

BLUE: Best previous spectrum (Suzaku CCD; FWHM 140 eV)

Hitomi Collaboration, Nature 2016

Hitomi SXS spectrum of Perseus: FeXXV Heα



BLACK: Hitomi SXS data

PURPLE: Hitomi SXS line response function

BLUE: Best previous spectrum (Suzaku CCD)

Hitomi Collaboration, Nature 2016

X-ray Science Interest Group Activity

- **June 8: Telecon to discuss response to loss of Hitomi**
  - Paul Hertz, Rich Kelley (SXS PI), >75 participants
  - Consensus was reached on several issues (see next chart)
  - Paul Hertz requested community input on "timeliness and importance of microcalorimeter science"
- **July 5: A white paper, "The Scientific Significance of the Soft X-ray Spectrometer" was released in response to Paul's request**
  - Prepared by a group of X-ray SIG volunteers
  - Broadly endorsed by X-ray SIG upon release

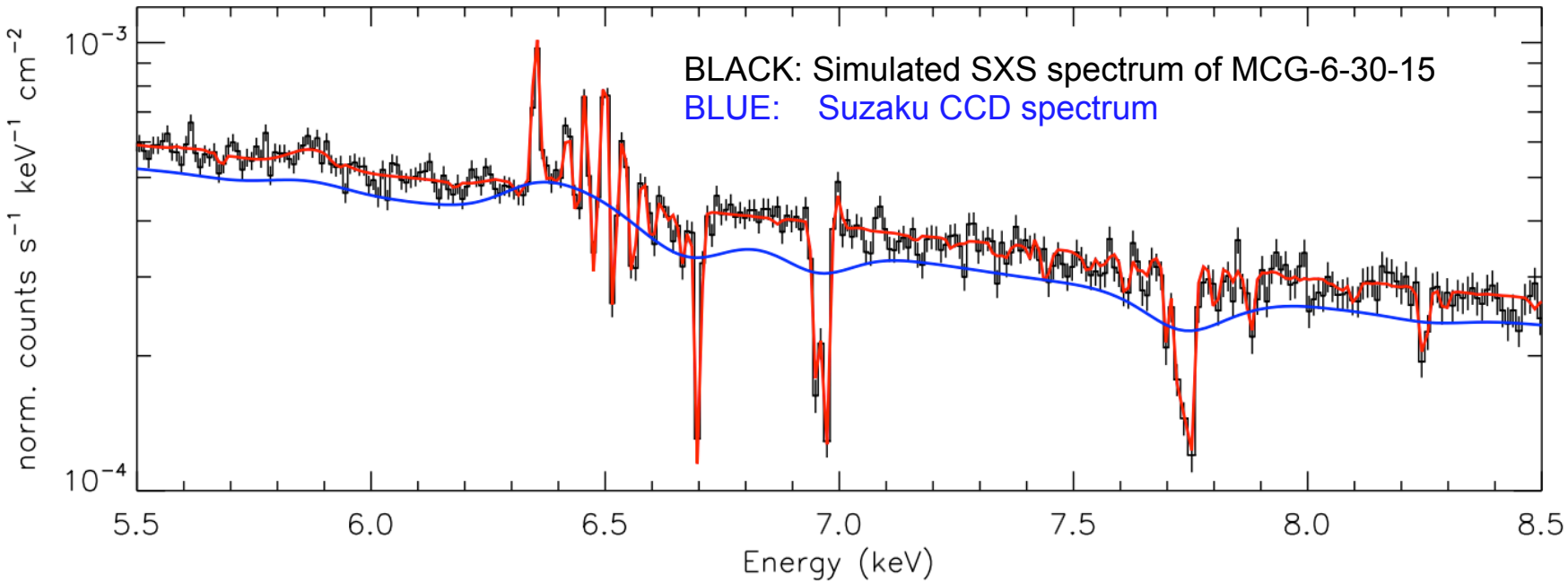
Summary of X-ray SIG Discussion June 8

- **Meeting occurred before either JAXA or NASA had made any public comment on a response to the loss of Hitomi**
  - Focus was on scientific value of re-flight, not on implementation issues
- **There is XRSIG consensus that the scientific case for a recovery mission is as strong or stronger than it was for Astro-H/Hitomi**
  - The XRSIG was invited to respond to Paul Hertz's request for a white paper on this subject.
- **There is XRSIG consensus that any recovery mission should launch well in advance of Athena (~5 years, i.e. by 2023) to be sensible.**
- **There is a great deal of community interest in understanding the viability, opportunity costs and scientific tradeoffs of a recovery mission. *Lacking information, we could not adddress these topics.***
- **There is particular concern about the impact of a recovery mission on the Astrophysics Explorer program.**

Overview of White Paper

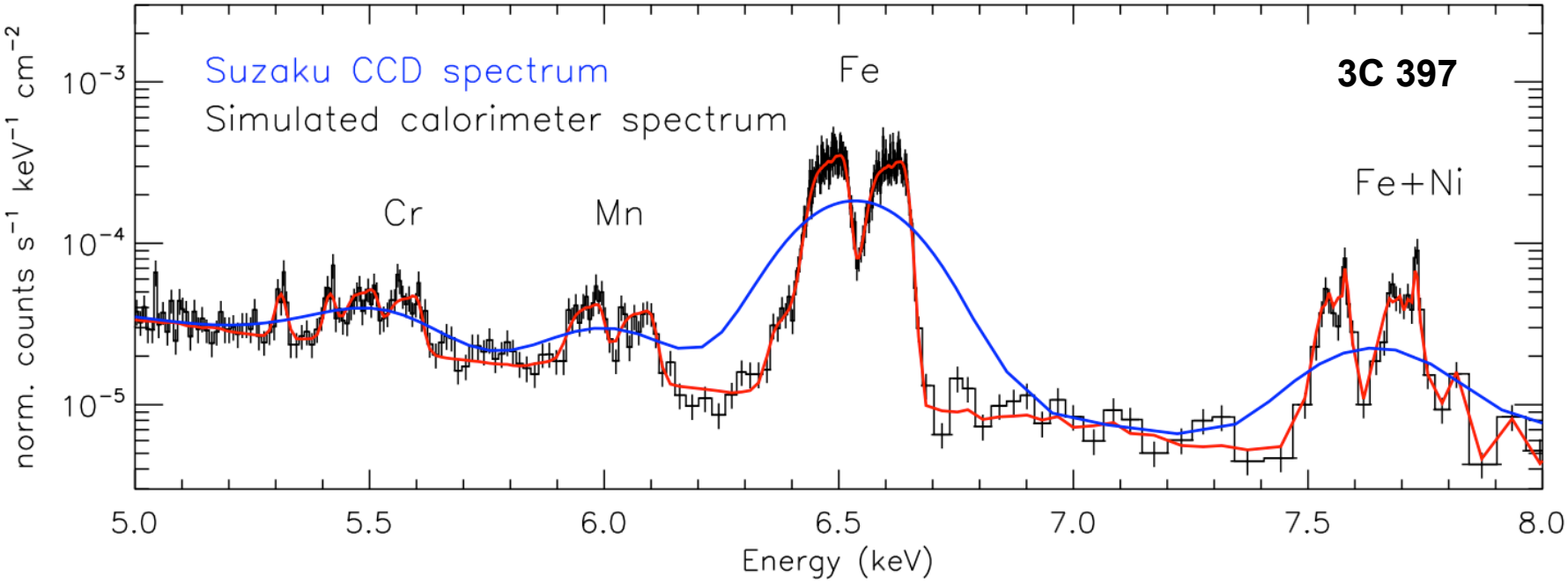
- **Deals only with the scientific importance and timeliness of a potential re-flight of the SXS instrument (& suitable mirror)**
- **Argues that "... an array of frontier scientific fields at the heart of the 2010 Decadal Survey, the NASA Physics of the Cosmos program, and the 2013 NASA Astrophysics Road map would have been transformed had the Hitomi spacecraft not been lost."**
- **Finds that re-flight [of the SXS] with a launch no later than 2023 would "fulfill much of the immense scientific promise of the Hitomi SXS."**
- **Finds that a re-flight would be timely as it would:**
  - Overlap and create synergies with JWST, HST, NuSTAR, Chandra; Athena (to launch end of 2028) would likely not do so
  - Serve as a pathfinder for more complex instruments planned for Athena & X-ray Surveyor

Simulated SXS AGN spectrum: High-ionization wind driving molecular outflow



- Fast, highly ionized winds may drive molecular outflows in quasar-mode feedback (Tombesi+ 2015)
- SXS resolves multiple absorption features, diagnosing mass outflow, kinetic power, and SMBH role in quenching star formation

Simulated SXS spectrum of SNR 3C 397: Abundance ratios and Type Ia SN channels



- Ratios of certain low-abundance elements (e.g. ^{58}Ni and ^{55}Mn) in remnants are sensitive to Type Ia explosion channel (Yamaguchi+ 2015)
- SXS detects weak lines *and* constrains complex, non-equilibrium physics & velocity structure to determine accurate abundances

Synergies & Timeliness

- **Prompt SXS re-flight would overlap HST and JWST**
  - Athena (launch no earlier than late 2028) likely will not
- **UV + X-ray spectroscopy jointly probe black hole accretion & feedback physics in quasar and Seyfert phases**
  - SMBH accretion disk structure revealed in UV and X-ray
  - UV/X-ray together constrain winds and outflows (Kaastra+ '14)
  - SXS is first X-ray spectrometer with resolving power (E/dE ~1400 @ 6.7 keV) approaching that of HST/STIS
- **JWST + SXS would pair two extraordinary new capabilities**
  - Majority of cosmic ionizing radiation is produced in obscured environments accessible only to IR & X-ray (e.g. Tombesi+, 2015)
  - SXS would thus support JWST goal of understanding role of SMBH in galaxy evolution
  - Precise SXS cluster/SNR abundances would complement JWST measurements of abundances over cosmic time
  - SXS would trace kinematics of hot ISM in star-forming galaxies, supporting JWST goal of understanding how chemical elements are distributed in galaxies
- **SXS would serve as scientific & technical pathfinder for more complex instruments on Athena and X-ray Surveyor**

Summary: SXS science is important & timely

- **The first-light Hitomi SXS observation of Perseus, when fully interpreted, will dramatically deepen our knowledge of clusters**
  - Likely implications for cosmic structure formation, cluster masses, plasma excitation, elemental abundaces, and atomic physics
- **SXS could address a broad range of other high-priority issuesid entified by Astro2010 & NASA Astrophysics Roadmap, e.g.:**
  - Formation & growth of SMBH & their impact on galaxy evolution
  - Flows of matter & energy in the circumgalactic medium
  - Mass-energy-chemical cycles in galaxies
  - Sub-populations of Type Ia supernovae
  - Star formation and evolution of circumstellar disks
- **A prompt SXS re-flight is timely:**
  - Would increase the power of HST and JWST as Athena cannot
  - Would serve as important pathfinder for Athena & X-ray Surveyor

Additional Information

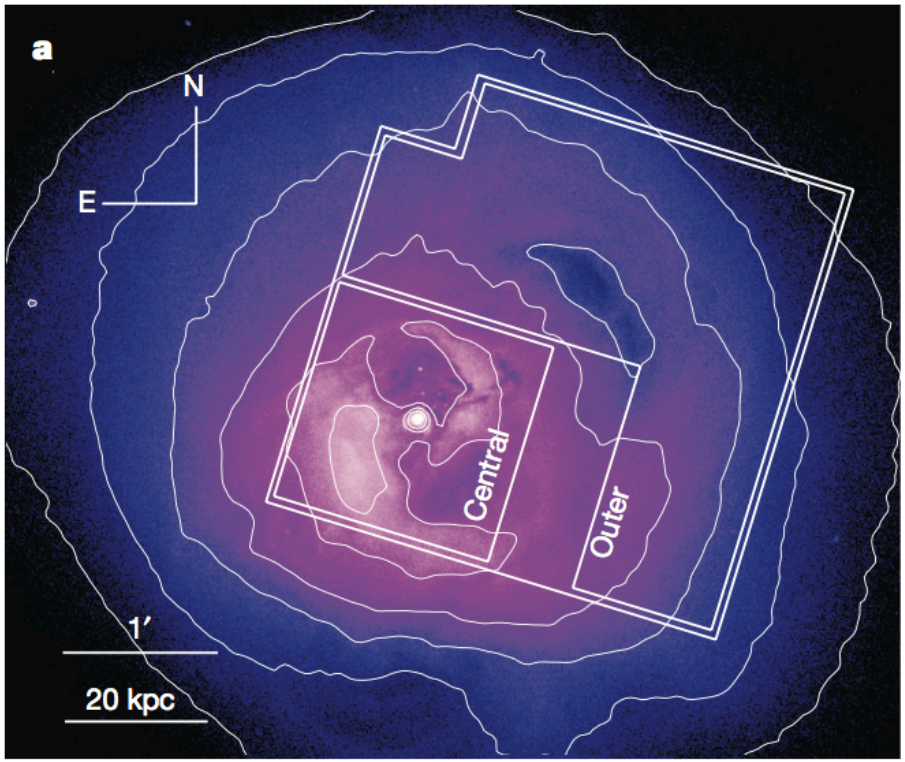
White Paper Endorsers

Table 1: Endorsements*

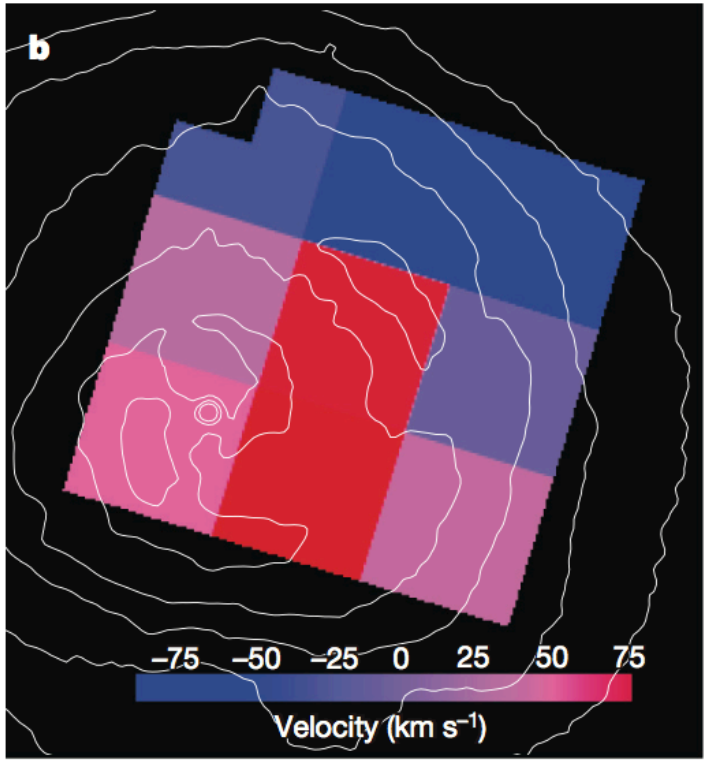
Name	Institution
Kevork Abazajian	University of California, Irvine
Steve Allen	Stanford University
Marshall Bautz	Massachusetts Institute of Technology
Roger Blandford	Stanford University
Niel Brandt	The Pennsylvania State University
Laura Brenneman	Smithsonian Astrophysical Observatory
Esra Bulbul	Massachusetts Institute of Technology
Paolo Coppi	Yale University
Abe Falcone	Pennsylvania State University
Keigo Fukumura	James Madison University
George Fuller	University of California, San Diego
Jessica Gaskin	NASA's Marshall Space Flight Center
Catherine Grant	Massachusetts Institute of Technology
Richard Griffiths	University of Hawaii at Hilo
Craig Heinke	University of Alberta (Canada)
John Hughes	Rutgers University
Michael Juda	Smithsonian Astrophysical Observatory
Margarita Karovska	Smithsonian Astrophysical Observatory
Caroline Kilbourne	NASA's Goddard Space Flight Center
Dong-Woo Kim	Smithsonian Astrophysical Observatory
Ralph Kraft	Smithsonian Astrophysical Observatory
Alexander Kusenko	University of California, Los Angeles
Maurice Leutenegger	NASA's Goddard Space Flight Center
Knox Long	Space Telescope Science Institute
Dan McCammon	University of Wisconsin
Barry McKernan	CUNY/AMNH
Greg Madejski	Stanford University
Maxim Markevitch	NASA's Goddard Space Flight Center
Eric Miller	Massachusetts Institute of Technology
Jon Miller	University of Michigan
Richard Mushotzky	University of Maryland
Paul Nulsen	Smithsonian Astrophysical Observatory
Frits Paerels	Columbia University
Thomas Pannuti	Morehead State University
Sangwook Park	University of Texas at Arlington
Christopher Reynolds	University of Maryland
Richard Rothschild	University of California, San Diego
Gregory Sivakoff	University of Alberta (Canada)
Randall Smith	Smithsonian Astrophysical Observatory
Francesco Tombesi	University of Maryland
Alexey Vikhlinin	Smithsonian Astrophysical Observatory
Martin Weisskopf	NASA's Marshall Space Flight Center
William W. Zhang	NASA's Goddard Space Flight Center

*Complete as of July 11, 2016

Hitomi SXS observation of Perseus



SXS FOV on *Chandra* image



LOS velocity variation from SXS

- Low ICM velocity dispersion despite AGN heating, bubbles etc.
- Modest but detectable large scale motions

Hitomi Collaboration, Nature 2016

Interpretation of SXS Perseus observation
(Hitomi Collaboration, 2016 Nature)

- **The intracluster medium (ICM) in the center of Perseus is remarkably placid**
  - Line broadening→ RMS ICM velocity σ_{los} = 187 ± 13 km s^{-1} despite AGN-inflated bubbles & merger-induced cold fronts
  - $P_{turb} < 0.04\ P_{thermal}$ → Systematic errors in "hydrostatic" mass due to ICM turbulence may be modest and can be constrained
  - Resonant-to-forbidden line ratio in FeXXV Heα complex is low for optically thin ICM, consistent with resonant scattering, low σ_{los}
  - If turbulence is heating the ICM, it must be replenished on short timescales (4% of t_{cool}), so it can't spread from the core to heat the rest of the cluster.
- **~150 km s^{-1} bulk velocity shear across 60 kpc observed region**
  - Comparable to shear in molecular gas in core
  - Possibly a result of residual 'sloshing' from past merger, as expected from observed cold front
- **Atomic physics (line energies & strengths) needs work**