X-ray Surveyor
Feedback Science Working Group

Co-chairs:
Chris Reynolds & Megan Donahue

SWG membership

Megan Donahue (MSU)	Cluster-scale feedback
Chris Reynolds (UMd)	ICM-Jet interaction / AGN winds
Nahum Arav (VT)	AGN winds / BALQSOs
Elizabeth Blanton (Boston U)	Cluster Feedback
Laura Brenneman (CfA)	Accretion and BH spin
Askbiz Danehkar (CfA)	Planetary Nebulae
Larry David (CfA)	Cluster feedback
Oleg Gnedin (U.Mich)	Cosmological Simulations / Feedback
Sebastian Heinz (U.Wisc)	Cluster and micro-quasar feedback
Julie Hlavacek-Larrondo (Montreal)	Cluster scale feedback over cosmic time
Edmund Hodges-Kluck (U.Mich)	CGM, ICM and radio-galaxies
Christine Jones (CfA)	Elliptical galaxy and cluster feedback
Peter Maksym (CfA)	Tidal disruption events
Alex Markowitz (UCSD)	AGN winds
Herman Marshall (MIT)	High-resolution spectroscopy
Brian McNamara (Waterloo)	Cluster feedback
Jon Miller (U.Mich)	Disk winds across BH mass scale
Brian Monsony (UMd)	Cluster feedback and GRBs

SWG membership (cont)

• Joey Neilsen (MIT)	AGN and GBHB winds/jets
• Paul Nulsen (CfA)	Cluster feedback
• Scott Randall (CfA)	AGN-ICM feedback
• Mateusz Ruszkowski (U.Michigan)	Galaxy and cluster AGN feedback
• Eric Schlegel (UT)	Feedback across scales
• Norbert Schulz (MIT)	Micro-quasars
• Dan Schwarz (CfA)	AGN Jets
• Paul Sell (U. Crete)	Micro-quasar feedback
• Aneta Siemiginowska (CfA)	Jet-ISM interactions
• Gregory Sivakoff (Alberta)	Accretion-jet connection in XRBs
• Makoto Tashiro (Saiama Univ)	GRB and high-z enrichment
• Francesco Tombesi (UMd)	AGN winds
• Grant Tremblay (Yale)	Galactic-scale feedback/multiwaveband
• Norbert Werner (Stanford)	Cluster Feedback
• Dan Wilkins (Stanford)	Accretion and BH spin
• Mihoko Yukita (JHU)	Stellar feedback
• Shuo Zhang (MKI)	BH jets and Sgr A*
• Irene Zhuravleva (Stanford)	Cluster feedback

How is the evolution of structure regulated by stellar processes and supermassive black hole accretion?

Subgroups

- AGN feedback in clusters (S.Randall / J.Hlavecek-Larrondo)
  - Co-chairs responsible for low-z and high-z cluster physics
- AGN feedback on group/galaxy scales (EHodges-Kluck)
  - Co-chair interfaced with Baryon-Cycling SWG
- AGN winds and quasar feedback (A.Markowitz / F.Tombesi)
  - Co-chairs interfaced with Extreme Physics SWG
- Jet physics and related feedback physics (A.Siemiginowska)
- Stellar feedback (M.Yukita)

Top level questions

- How does AGN feedback evolve as a function of cosmic time, system mass, and AGN power?
- How does stellar feedback evolve as a function of cosmic time, system mass, and star formation rate?
- What are the physical processes by which the AGN influences the ICM/ISM?
- How, and when, do SMBH accretion disks produce winds and/or jets capable of exercising feedback?
- How is AGN fueling related to, and regulated by, the environment?
- What is the role of AGN/stellar feedback processes in dispersing metals into the CGM/ICM/IGM?

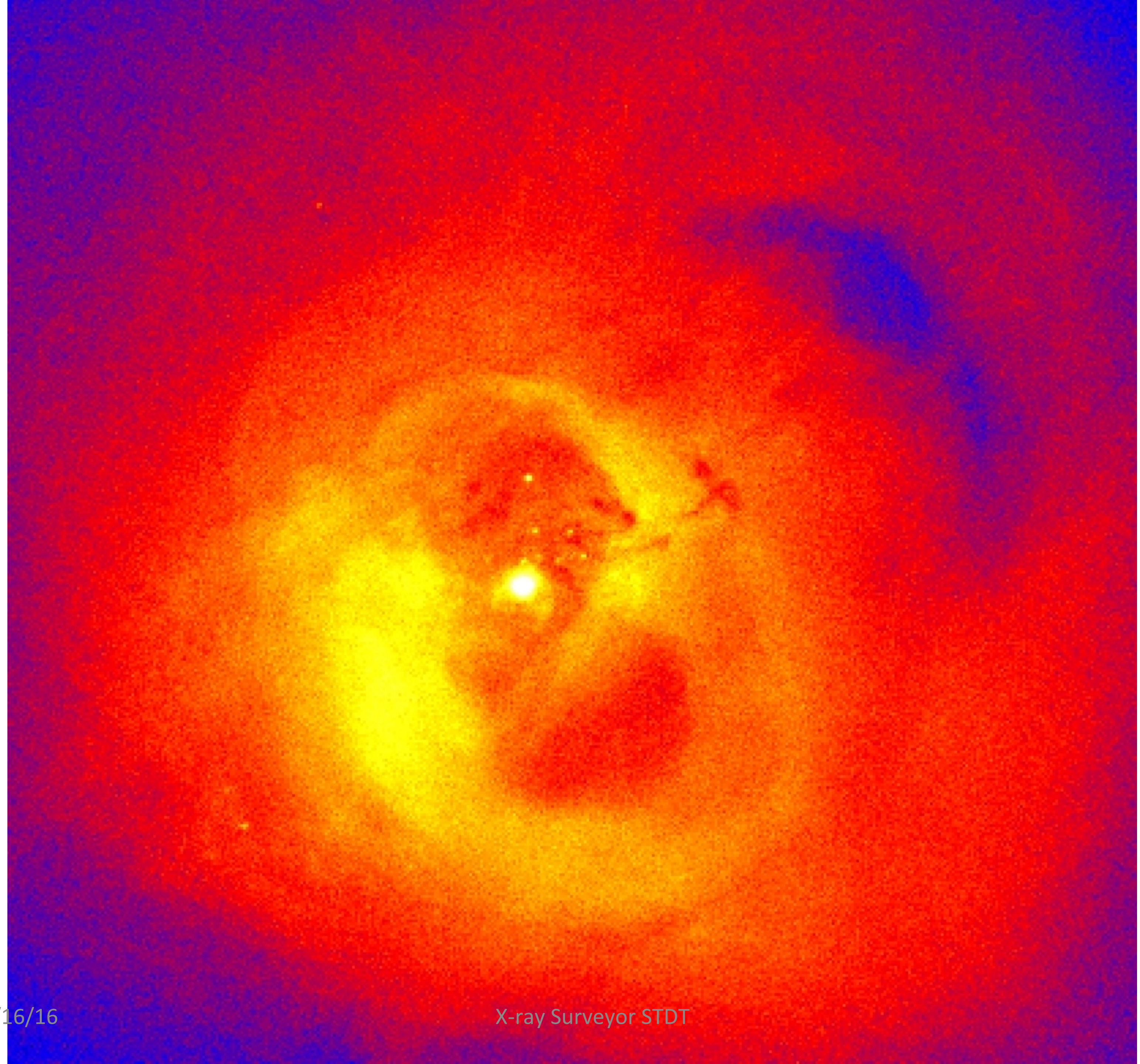
Key observations

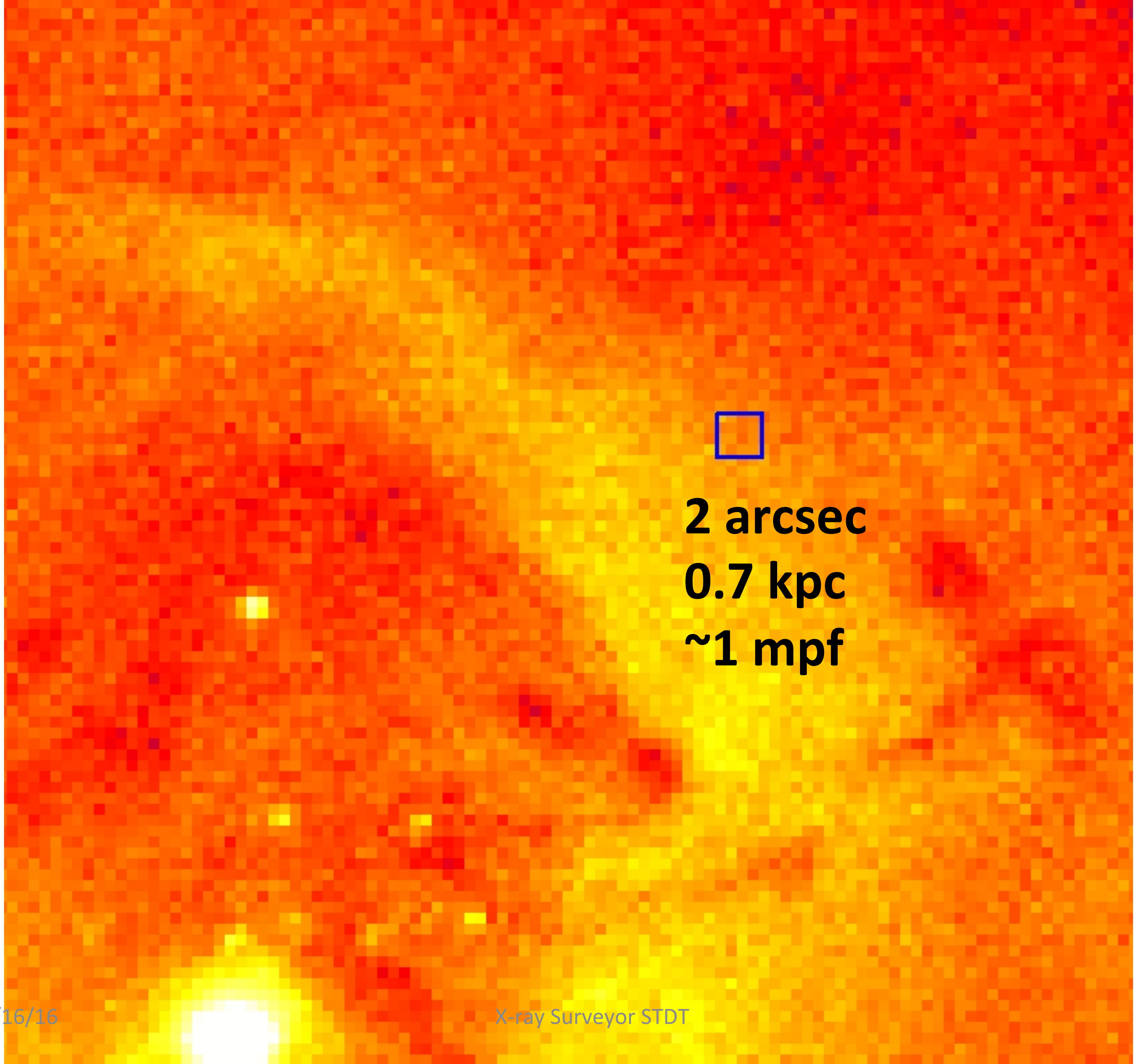
- High-spatial and high-spectral resolution maps of temperature, density, metallicity, dynamics of…
  - ICM in galaxy clusters (low-z and high-z)
  - Hot ISM of elliptical galaxies and massive spirals
  - CGM of isolated galaxies across the mass scale (low-z and high-z)
  - Internal structure of hot ISM across the mass scale (low-z and high-z)
- High-resolution spectroscopy of AGN outflows
- High-resolution, high-dynamic range imaging of core regions of luminous AGN.
- High-spatial resolution maps of AGN jets

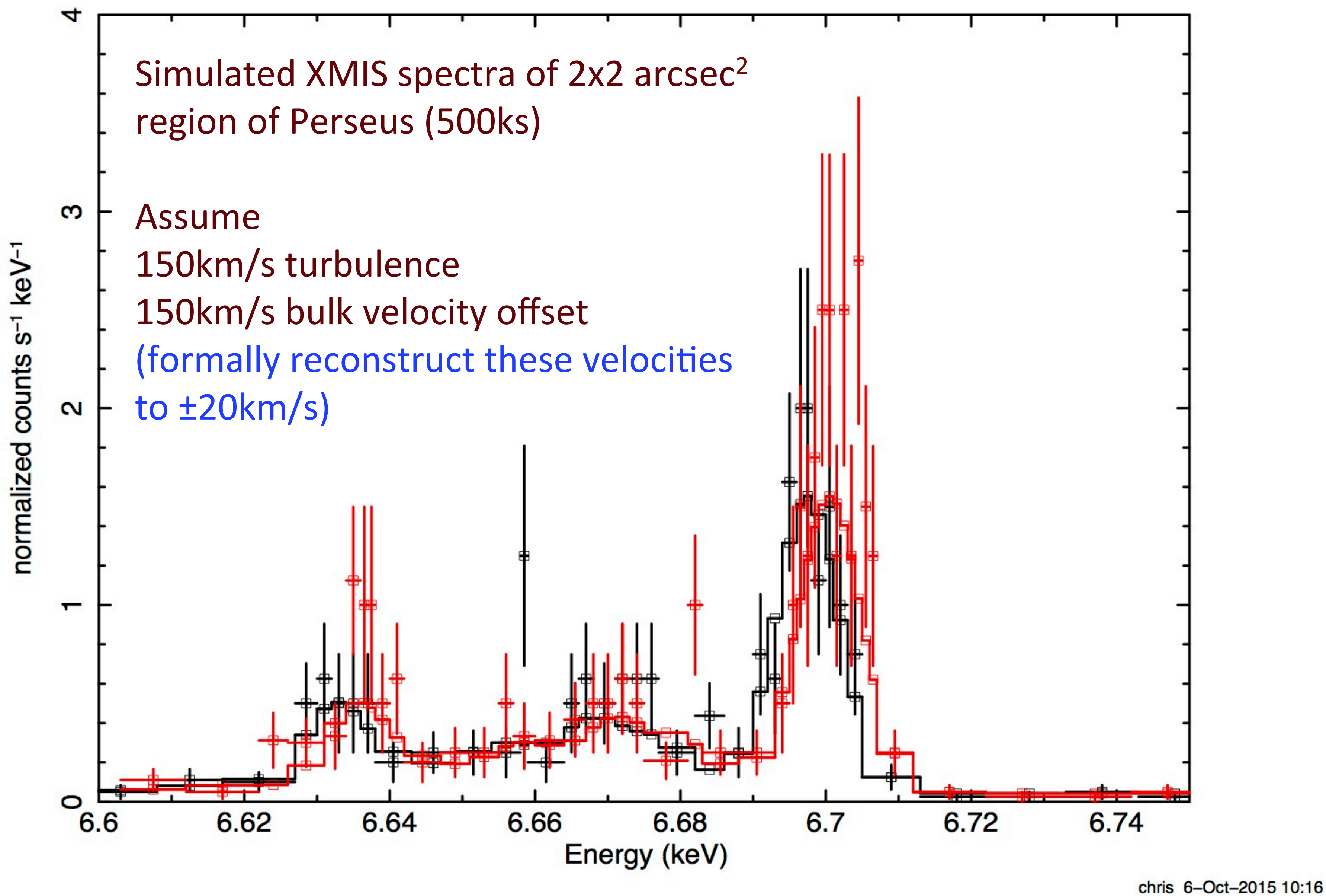
- Exploit synergies with JWST, WFIRST, LSST, ALMA, ELTs
- **Most of these key observation types have bearings on multiple science questions!**

	Low-z cluster imaging spectroscopy	High-z cluster imaging spectroscopy	Elliptical Galaxy imaging spectroscopy	Field galaxy CGM imaging spectroscopy	Intra-galaxy hot-ISM imaging spectroscopy	AGN winds (point source) spectroscopy	AGN high dynamic-range imaging	AGN jets high-spatial resolution imaging
Evolution of AGN feedback across cosmic time and system mass								
Evolution of stellar feedback across cosmic time and system mass								
Physical processes by which AGN influence ICM/ISM								
Physics of wind/jet production by accreting supermassive black holes								
The fueling and regulatory processes in AGN								
Role of feedback in dispersing metals into the CGM/ICM/IGM								

Feedback in clusters of galaxies




2 arcsec
0.7 kpc
~1 mpf



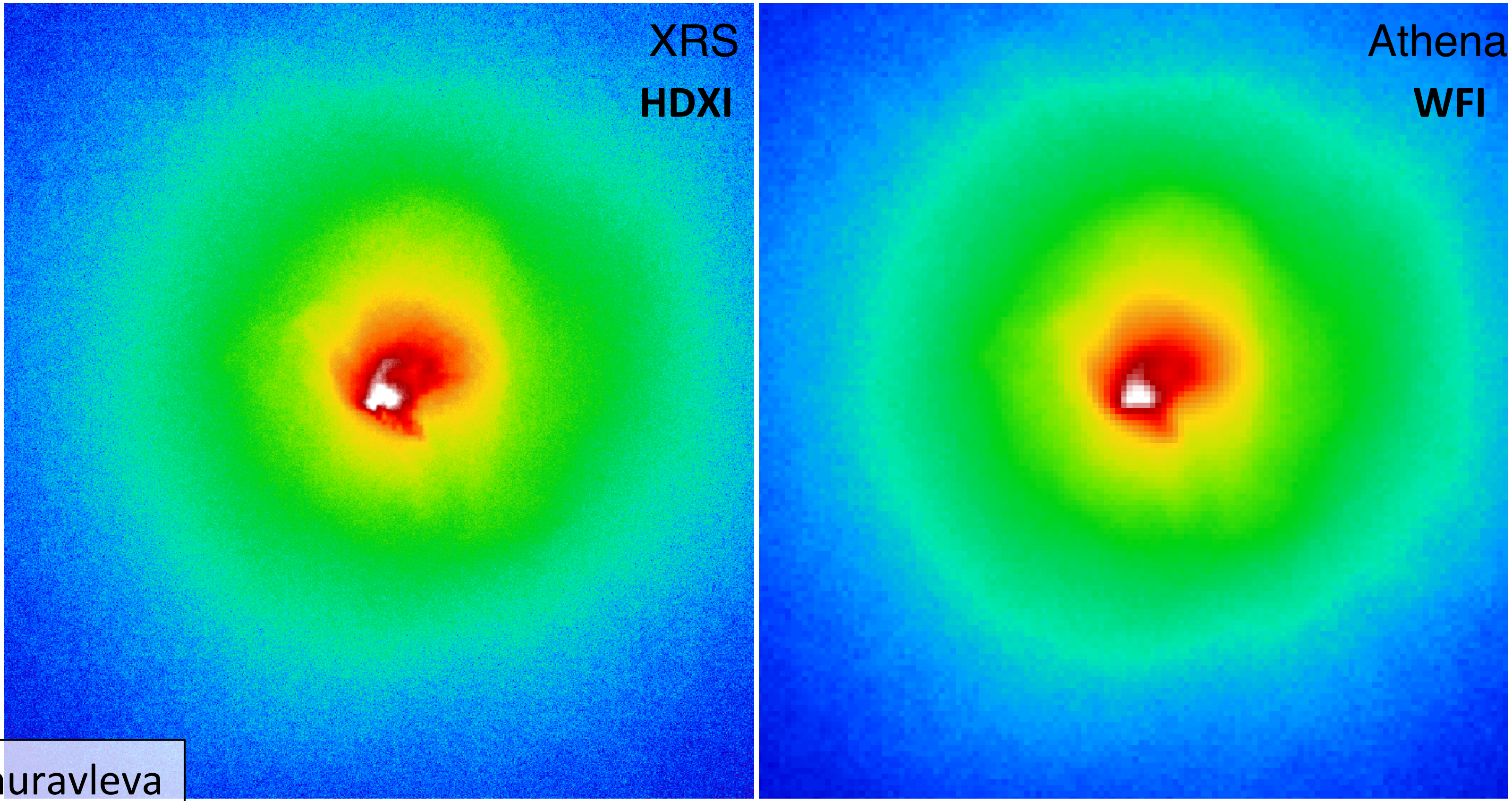
Simulated XMIS spectra of 2x2 arcsec²
region of Perseus (500ks)
Assume
150km/s turbulence
150km/s bulk velocity offset
(formally reconstruct these velocities
to ±20km/s)
normalized counts s⁻¹ keV⁻¹
Energy (keV)
0
1
2
3
4
6.6
6.62
6.64
6.66
6.68
6.7
6.72
6.74
chris 6–Oct–2015 10:16

Measuring gas fluctuations on small scales: XRS vs Athena

window for probing microphysics, including shocks, turbulence, transport processes, which are important for understanding, e.g., gas heating mechanisms

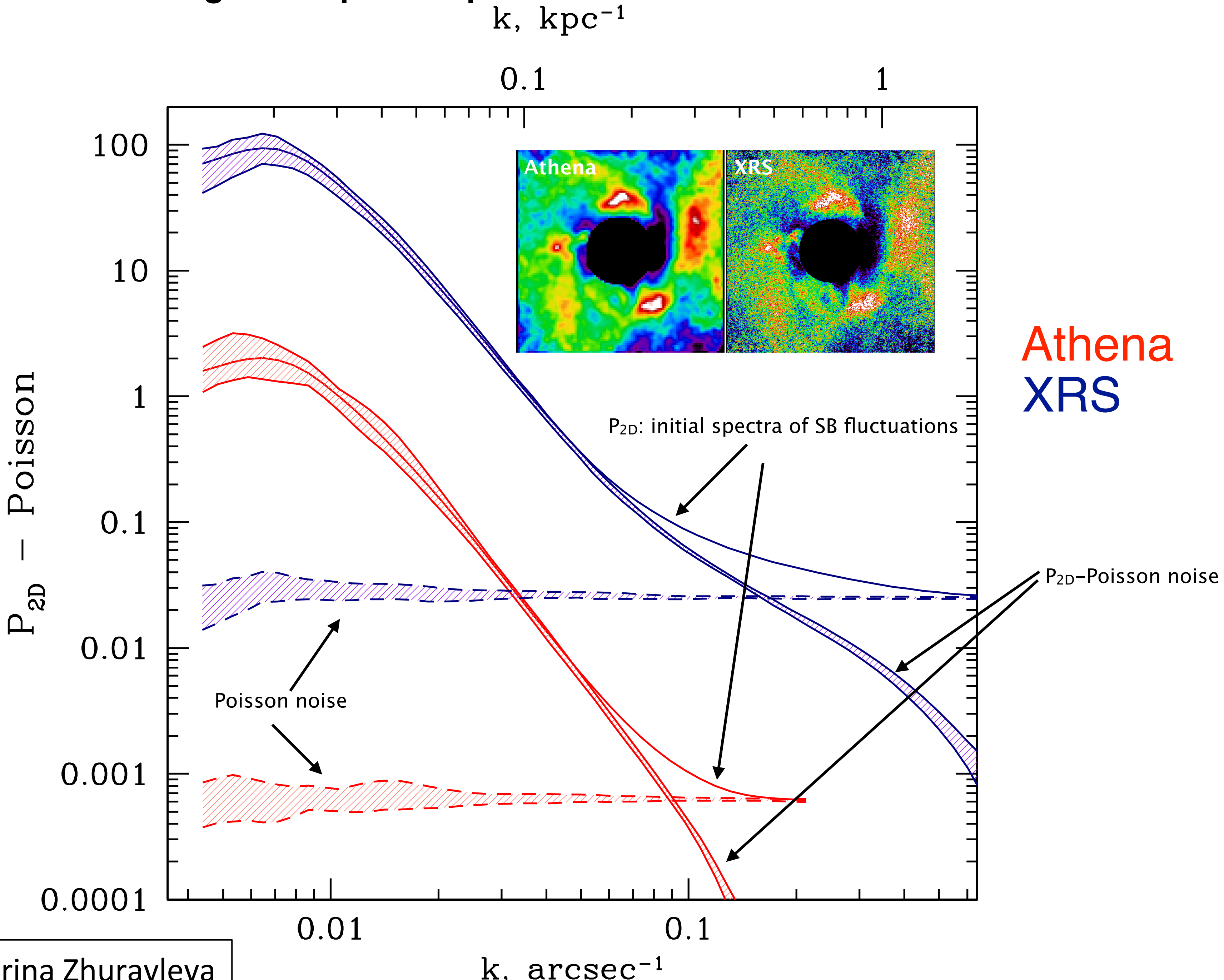
contact: Irina Zhuravleva [zhur@stanford.edu]

- simulations: #0148, z=0.05 (50ks observation)
- inner 2'=120 kpc
- use soft-band images: 0.5-3.5 keV



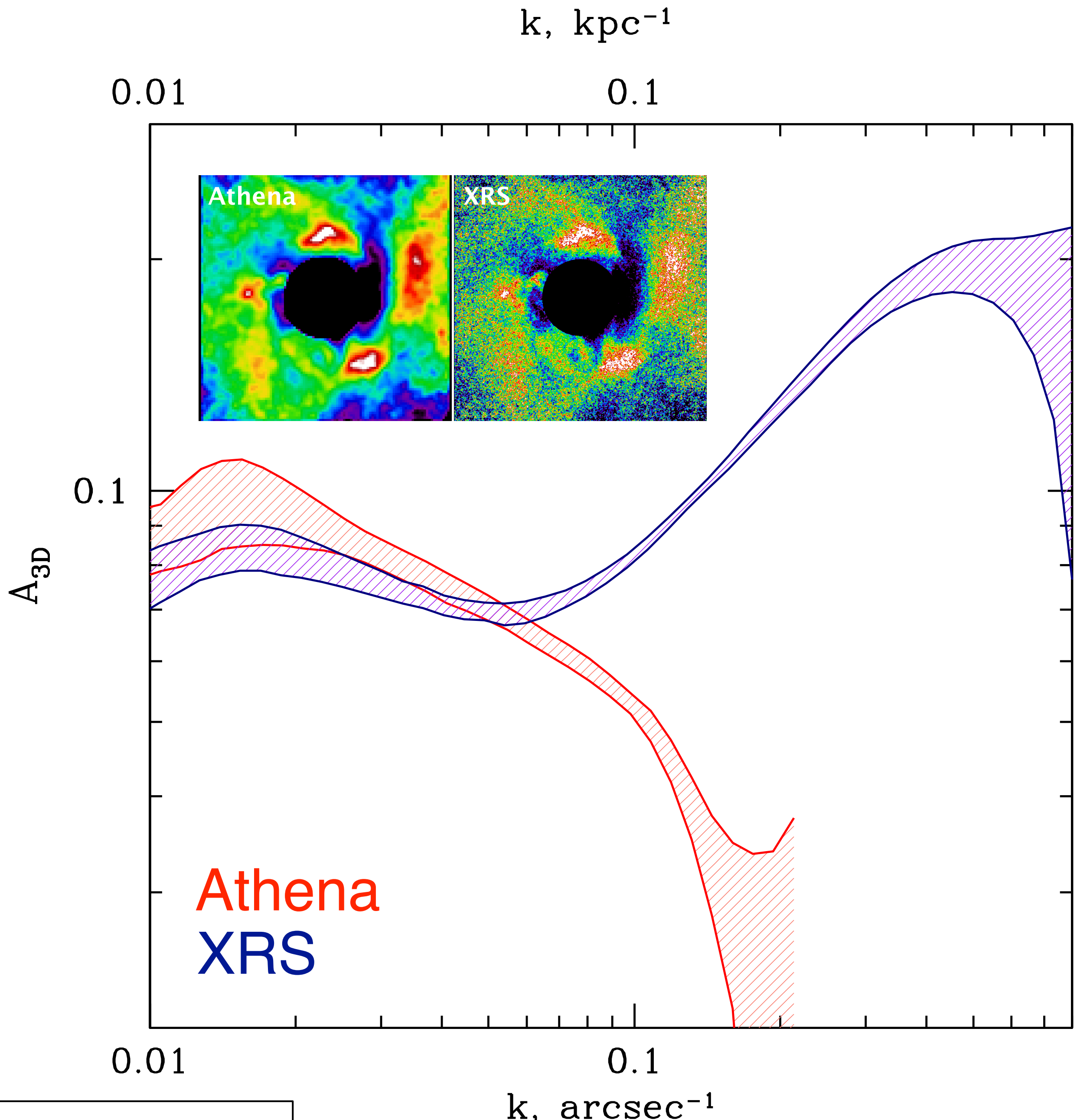
Irina Zhuravleva

Residual images and power spectra



Irina Zhuravleva

Amplitude of fluctuations



Conclusions:

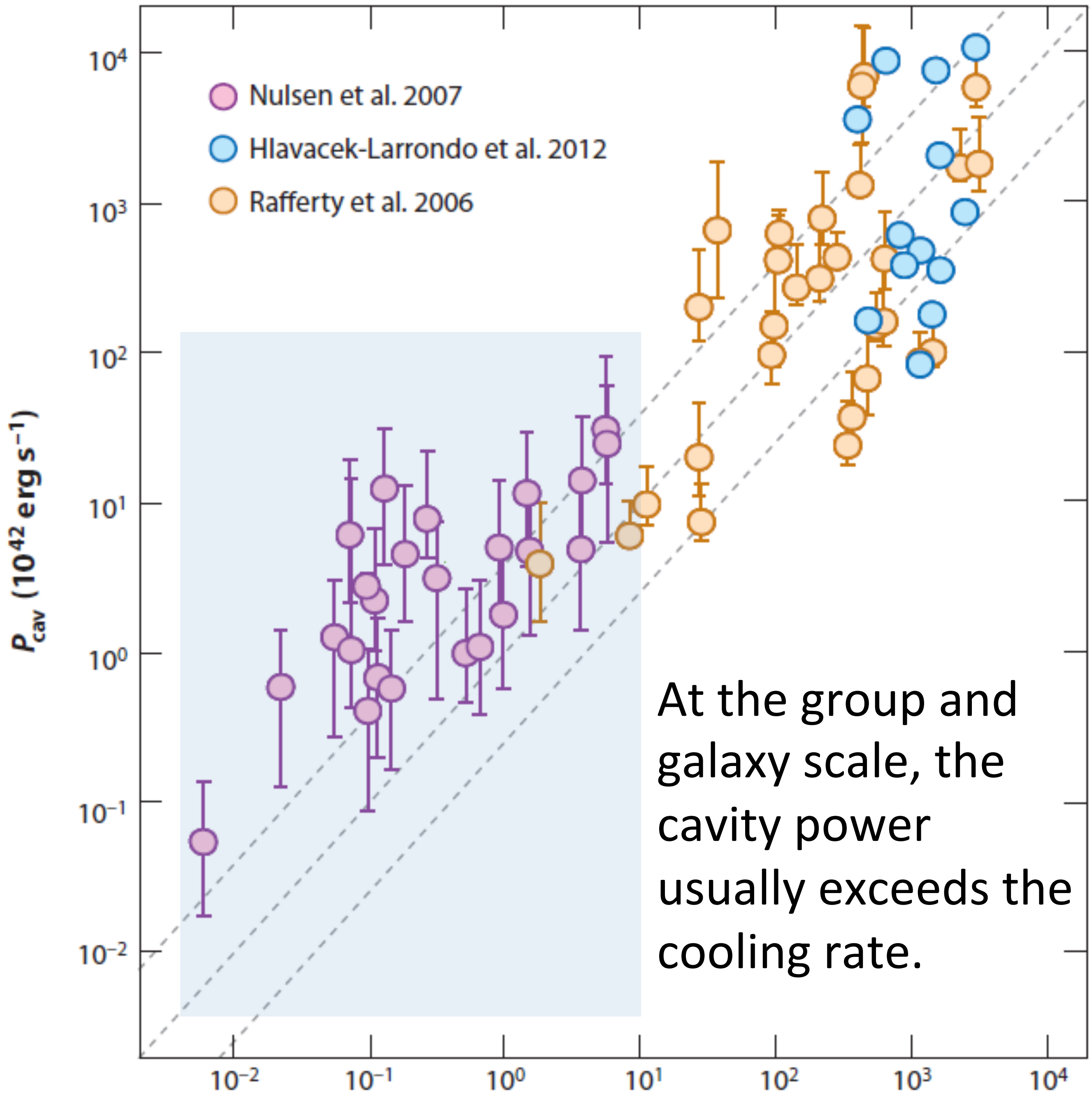
- Limited resolution of simulations produces high-k tail in case of XRS (the peak is at ~ pixel size, the peak distorts spectrum down to smaller k - this is artifact of the Mexican-hat filter used for calculations of the power spectrum).
- Resolution effect is less prominent in the case of Athena, since Athena resolution partially smears grid effects.
- Athena PSF affects scales ~ 10 kpc (comparable or even larger than the width of ripples in the Perseus cluster). With 50 ks exposure scales > 5 kpc are dominated by Poisson noise
- XRS can in principle measure fluctuations ~ 1 kpc size, but it is difficult to show with current situations. With 50 ks exposure scales > 2 kpc are dominated by noise.
- XRS will probe microphysics on scales that Athena cannot reach (or even current numerical simulations).

Irina Zhuravleva

Feedback in groups and elliptical galaxies

Feedback Energy Partitioning

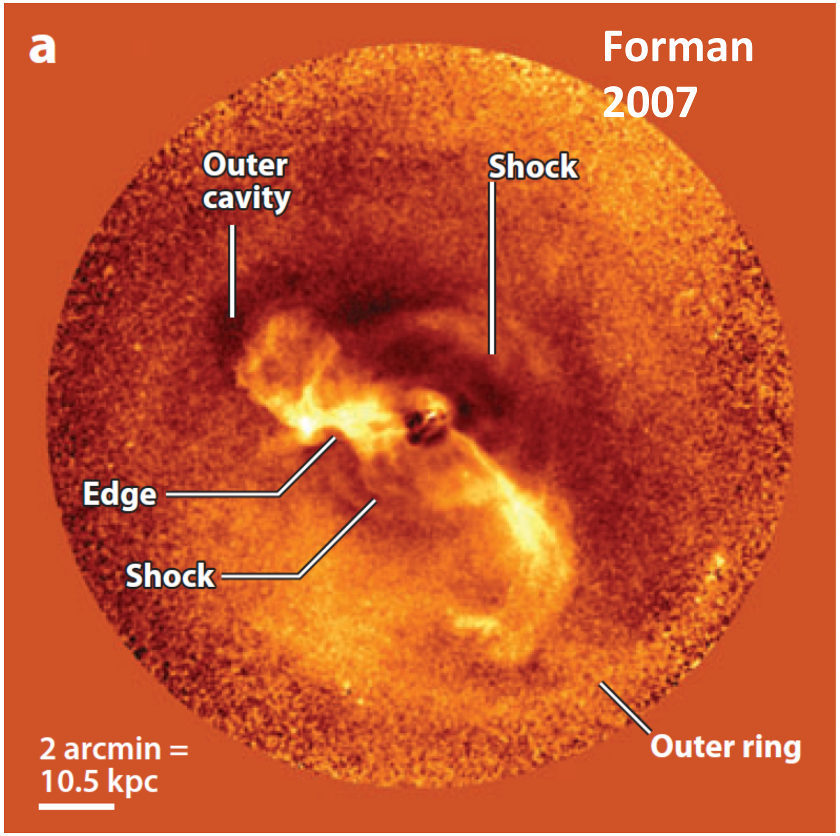
- Why don't AGN overheat groups/galaxies?
- The dominant heating mechanism or duty cycle may be different than in clusters.
- Required measurements:
  - Active outbursts: shock strength, thermal/nonthermal content of bubbles, cavity enthalpy
  - Relic outbursts: frequency, structure, surrounding kT differential
- Lower surface brightness, X-ray binaries, and other atmospheric disturbances require XRS.

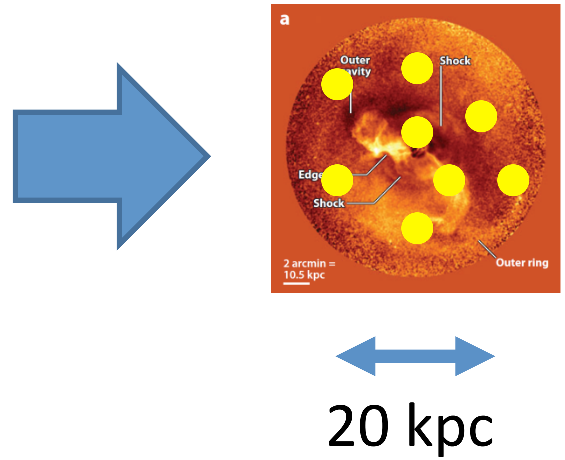


At the group and galaxy scale, the cavity power usually exceeds the cooling rate.

Fabian 2012

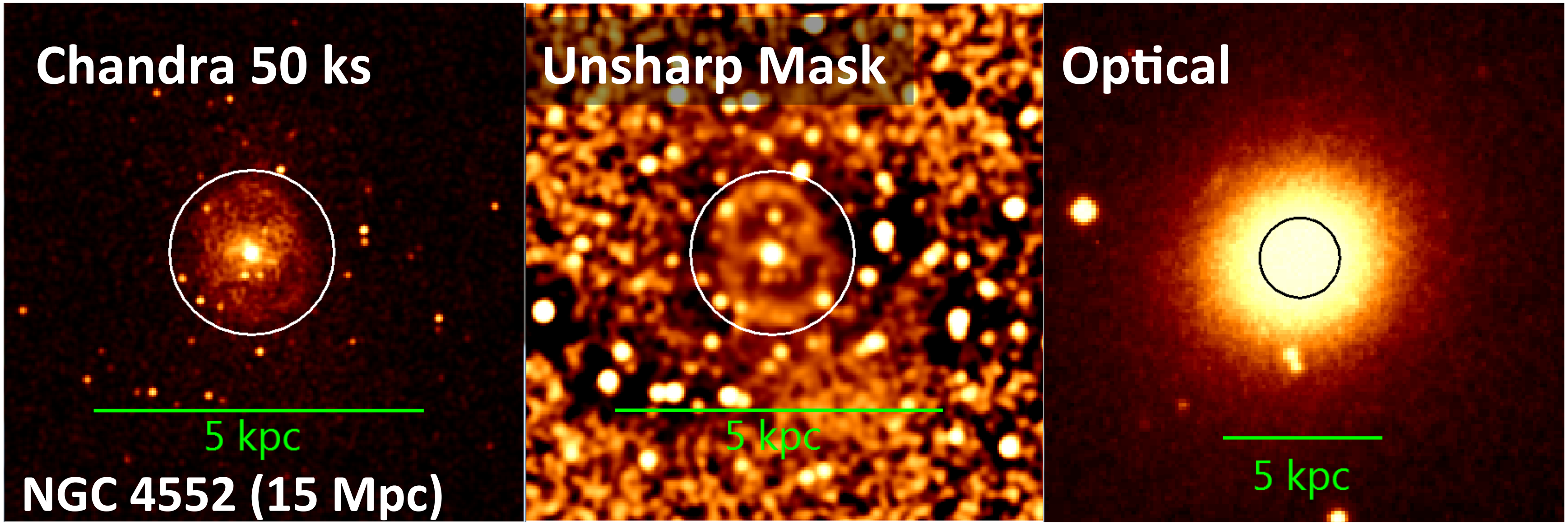
Edmund Hodges-Kluck





Observational Goal: We need Virgo or Perseus-like maps within r<10 kpc to isolate different AGN components from other disturbances. This problem is compounded by XRBs.

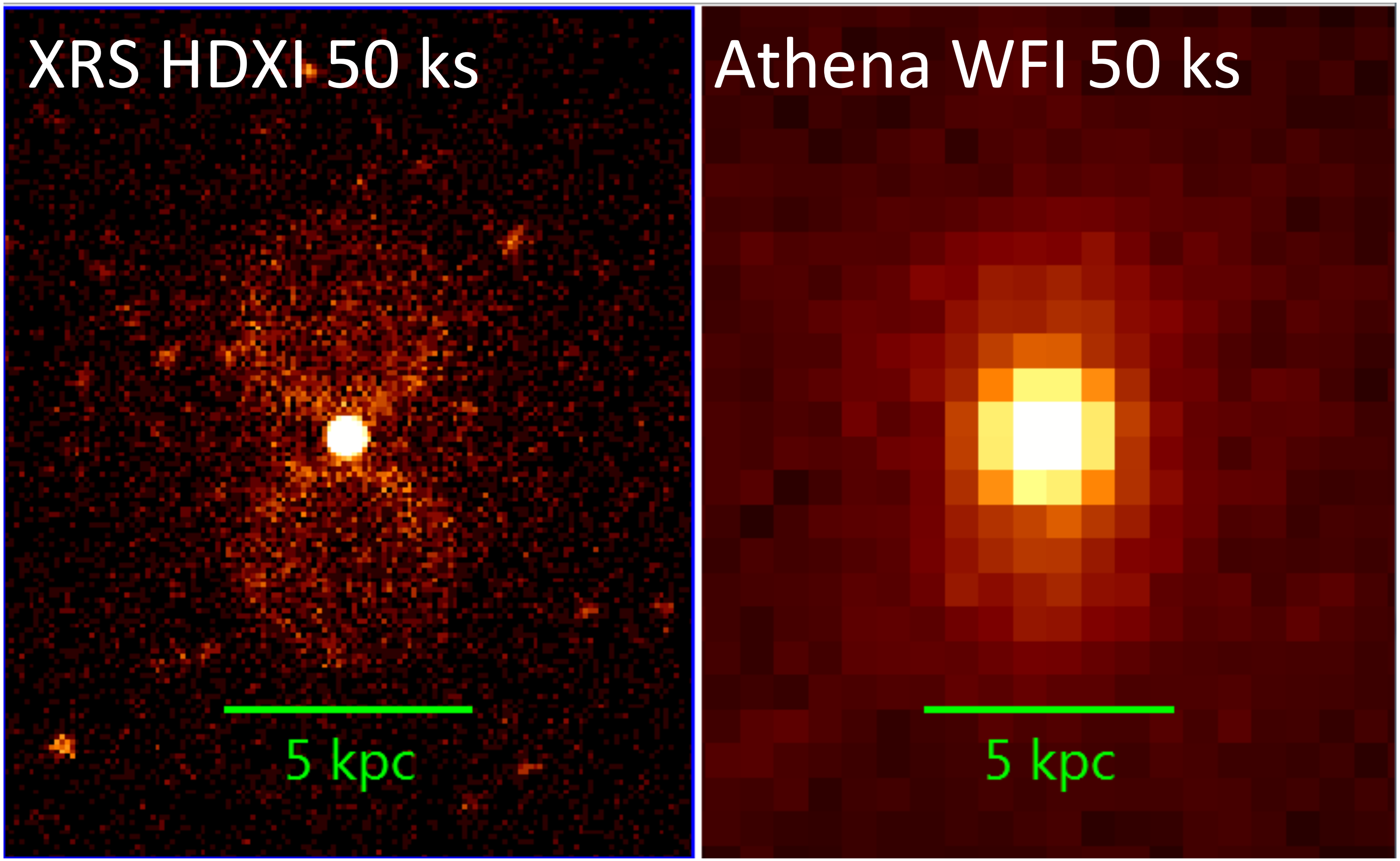
Edmund Hodges-Kluck



There are ~100 galaxies within 100 Mpc with σ > 150 km/s. Observations of nearby, low-mass halos show what to expect for more distant systems.

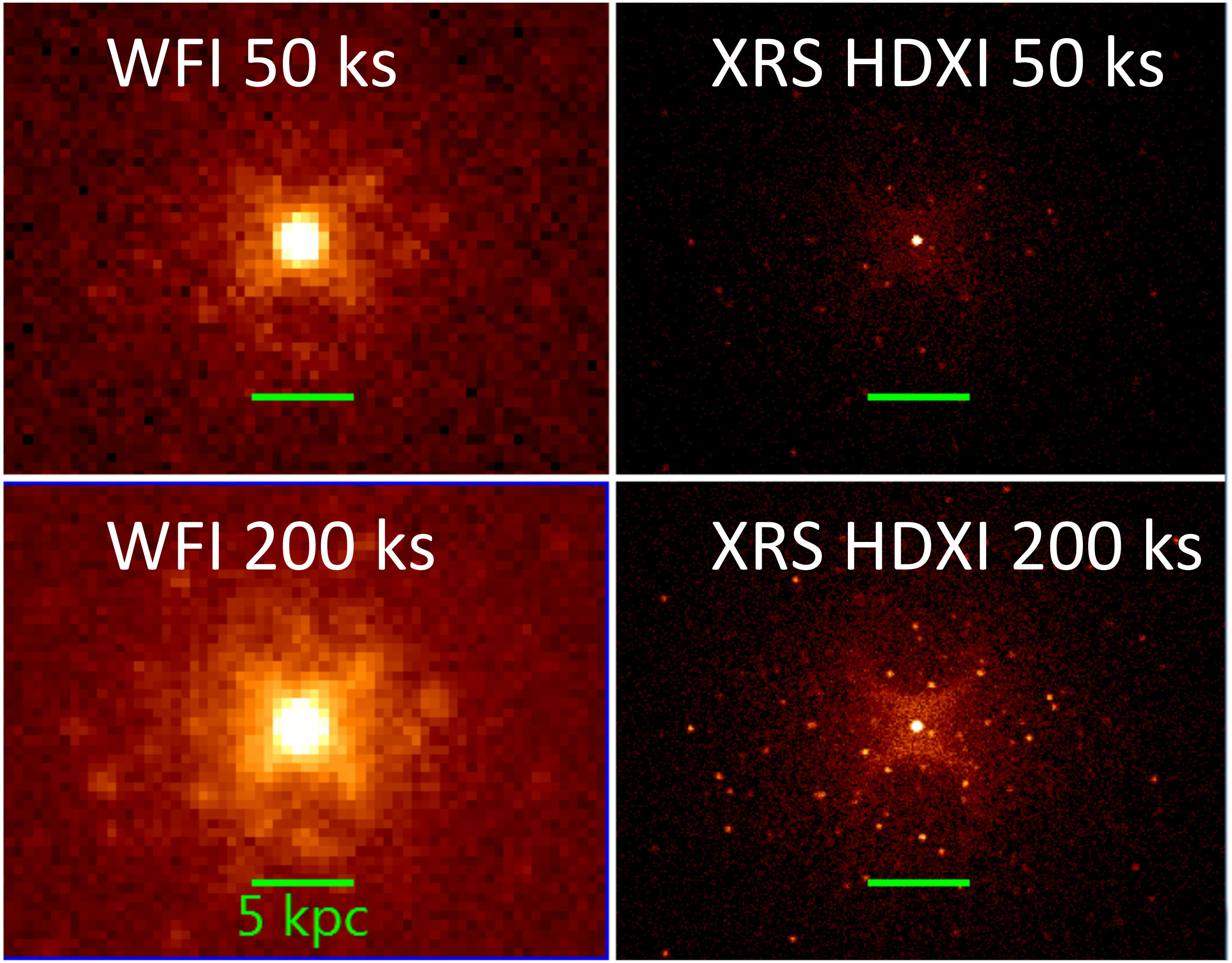
Resolving different AGN heating mechanisms requires: high S/N, resolution of a few hundred pc or better for imaging and the calorimeter IFU (≤1 arcsec).

Edmund Hodges-Kluck



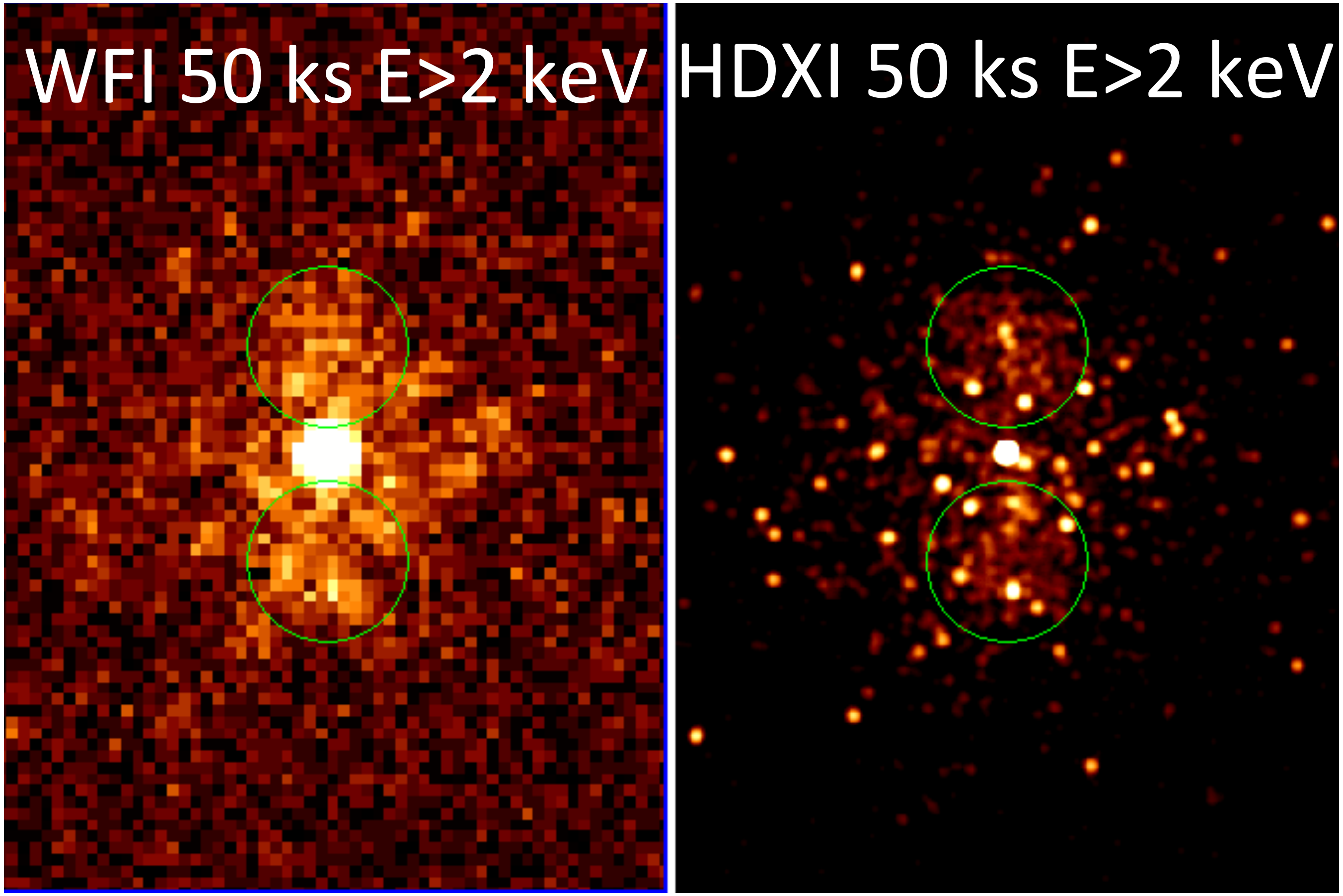
Cavity size increases with radius, but within 10 kpc Athena will be unable to reliably measure shock strengths, bubble volume, etc., even locally.

Edmund Hodges-Kluck



XRBs also limit the value of deeper Athena observations. XRS can remove them even with a steep luminosity function.

Edmund Hodges-Kluck



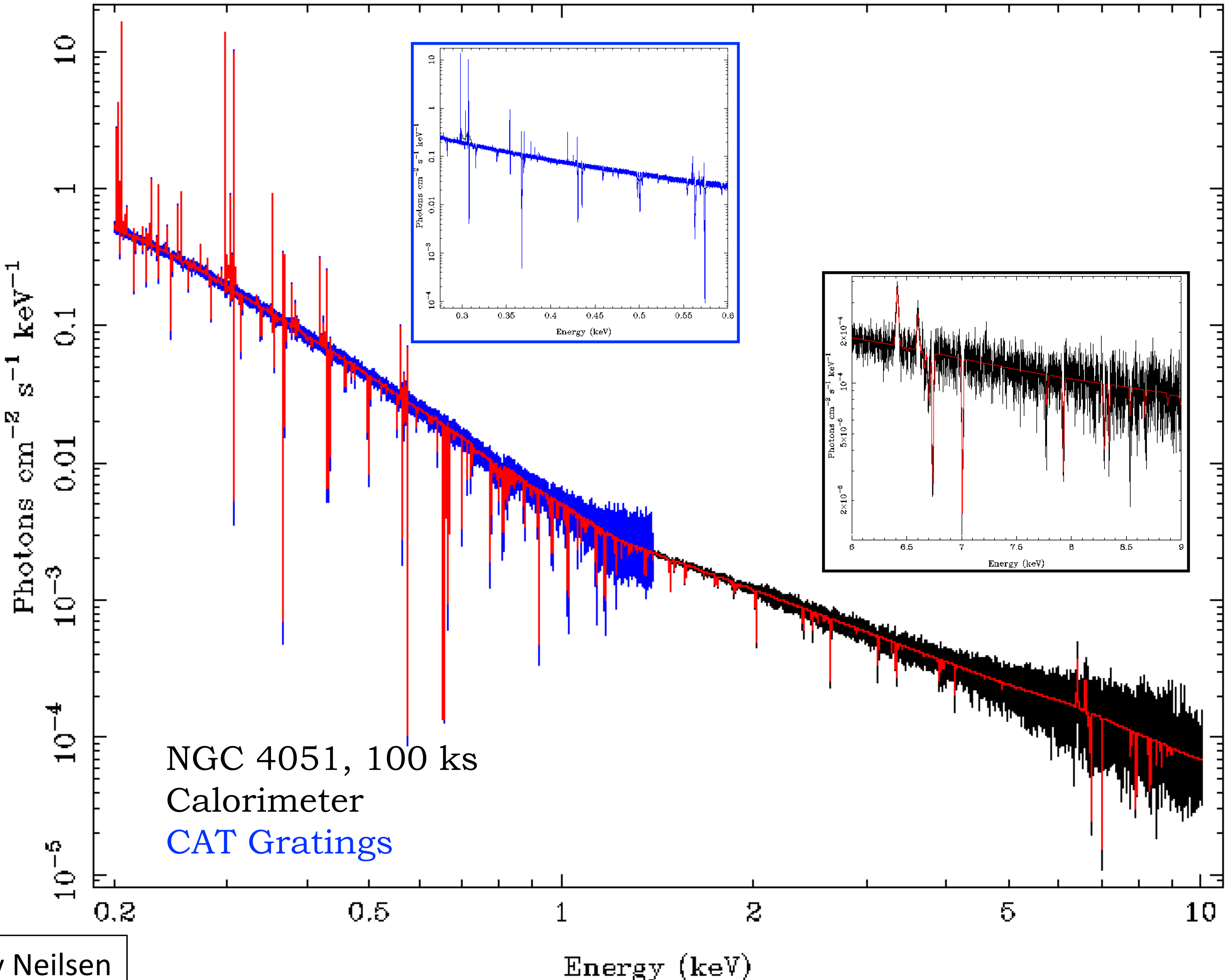
XRB contamination is a serious obstacle for detecting relic lobes, and especially for measuring their structure (which tells us how they fall apart and mix).

Exposure Times

- Active outbursts:
  - *Chandra* found cavities; XRS (+LOFAR/SKA/ALMA/optical IFUs) will show how they distribute energy.
  - A deep, high-resolution survey of 10-20 galaxies/groups (not cDs) within 100 Mpc where temperature, metallicity, and line centroids can be measured to accuracies of better than 10% across a few hundred pc (a few arcsec).
  - Exposure time per system: **100-300 ks per group, 50-300 ks per galaxy** (depends strongly on distance). *Chandra* has put ~13 Ms total into these systems (>5 Ms is dedicated to bright cluster galaxies). A transformative view of a **representative sample with XRS would require about 10 Ms** (overlapping with other major scientific goals).
- Relic radio lobes:
  - Hard X-rays trace relic lobes. The combination of hard X-rays and low-frequency radio provides the B-field, and the structure shows how the bubbles break up.
  - A deep search in tens of galaxies and groups (with and without active cavities) is necessary. For approximate equipartition between the cavity enthalpy and nonthermal radio population, 100-300 ks per target is necessary to identify and measure relic lobes through hard X-rays. Targets can be selected from LOFAR or SKA catalogs. **This involves ~10-15 Ms total, but piggy-backs on any deep observation.**

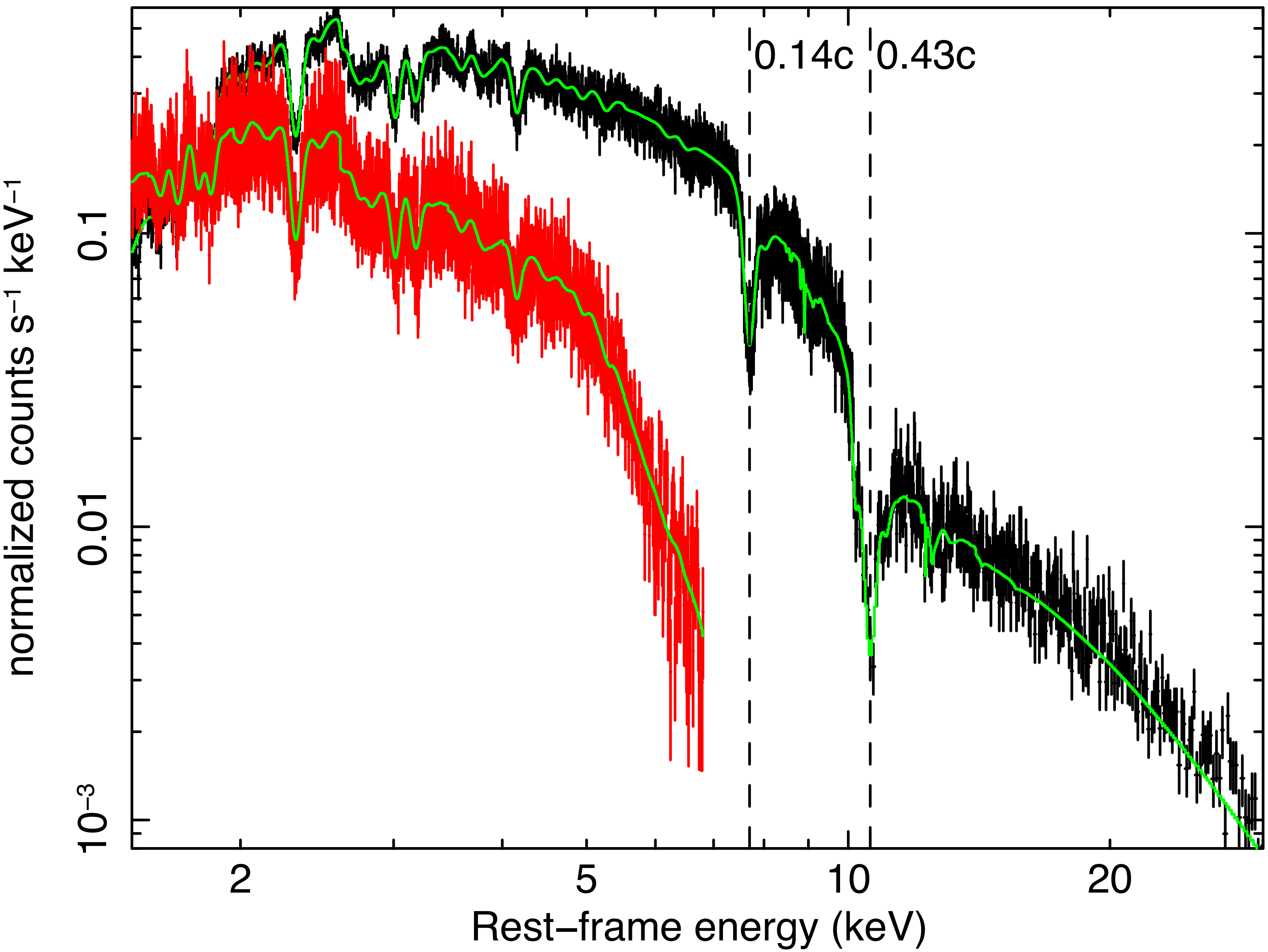
Edmund Hodges-Kluck

Physics of AGN winds and jets

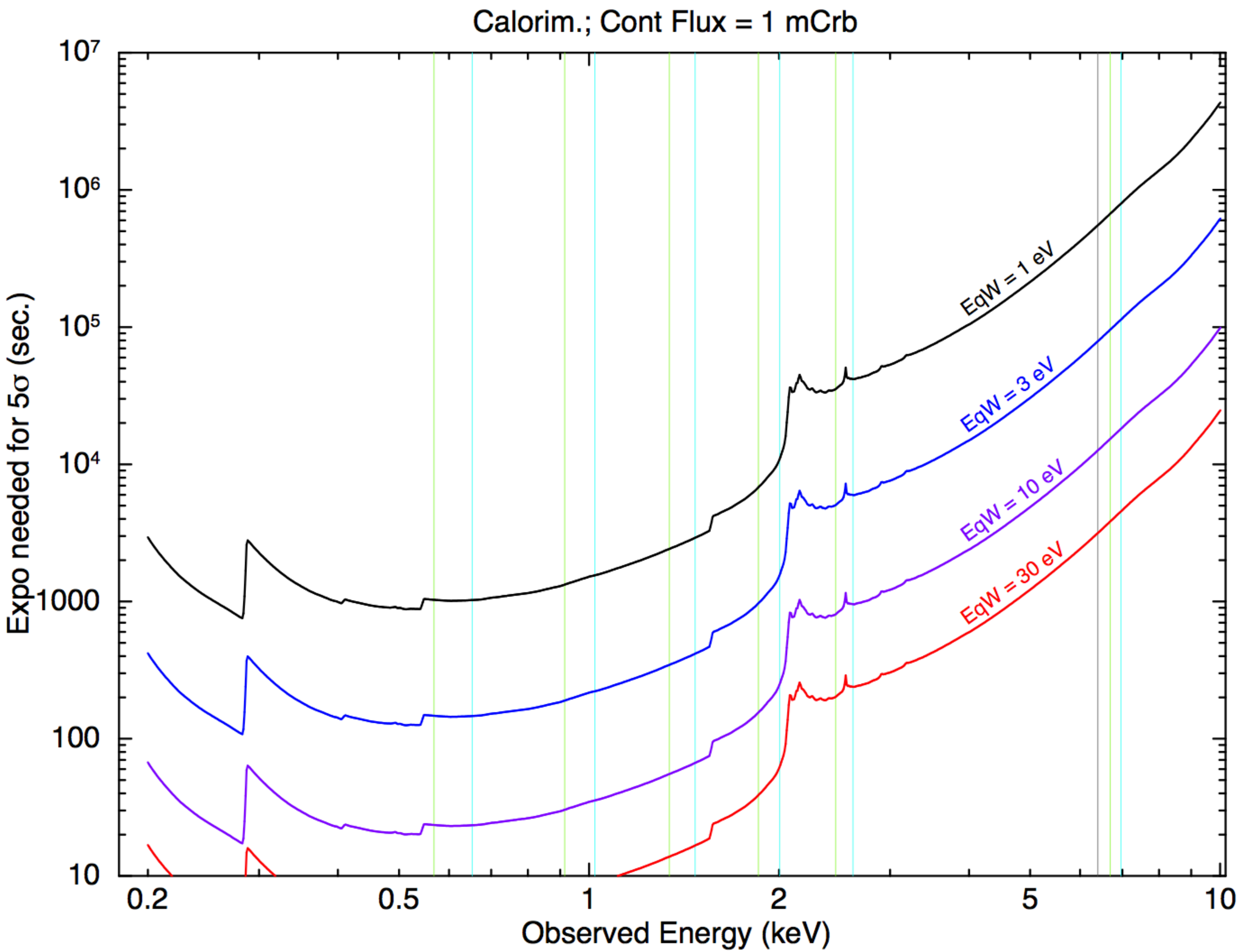


Joey Neilsen

APM 08279+5255 (z=3.9) 100ks CAL (black) CAT (red)



Alex Markowitz & Francesco Tombesi



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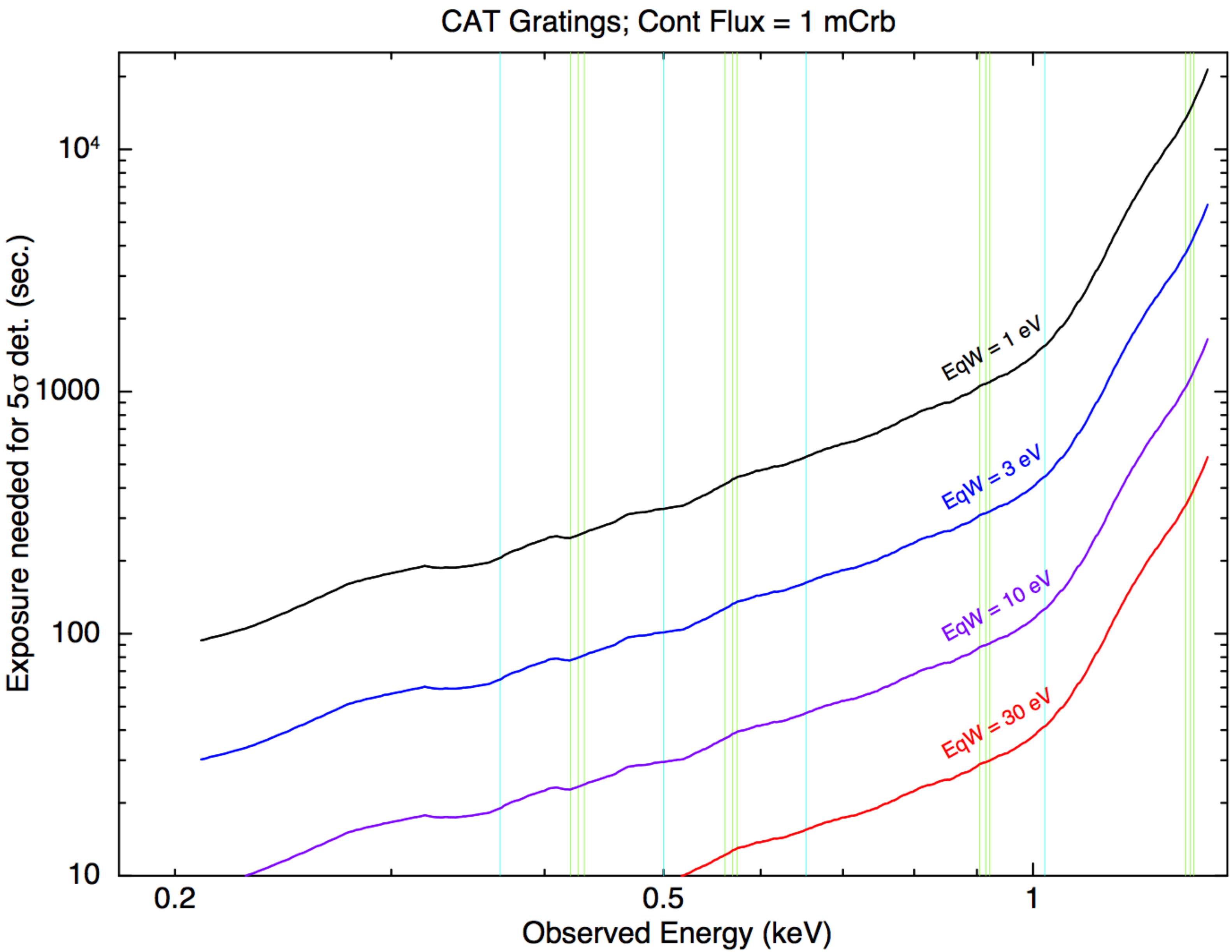
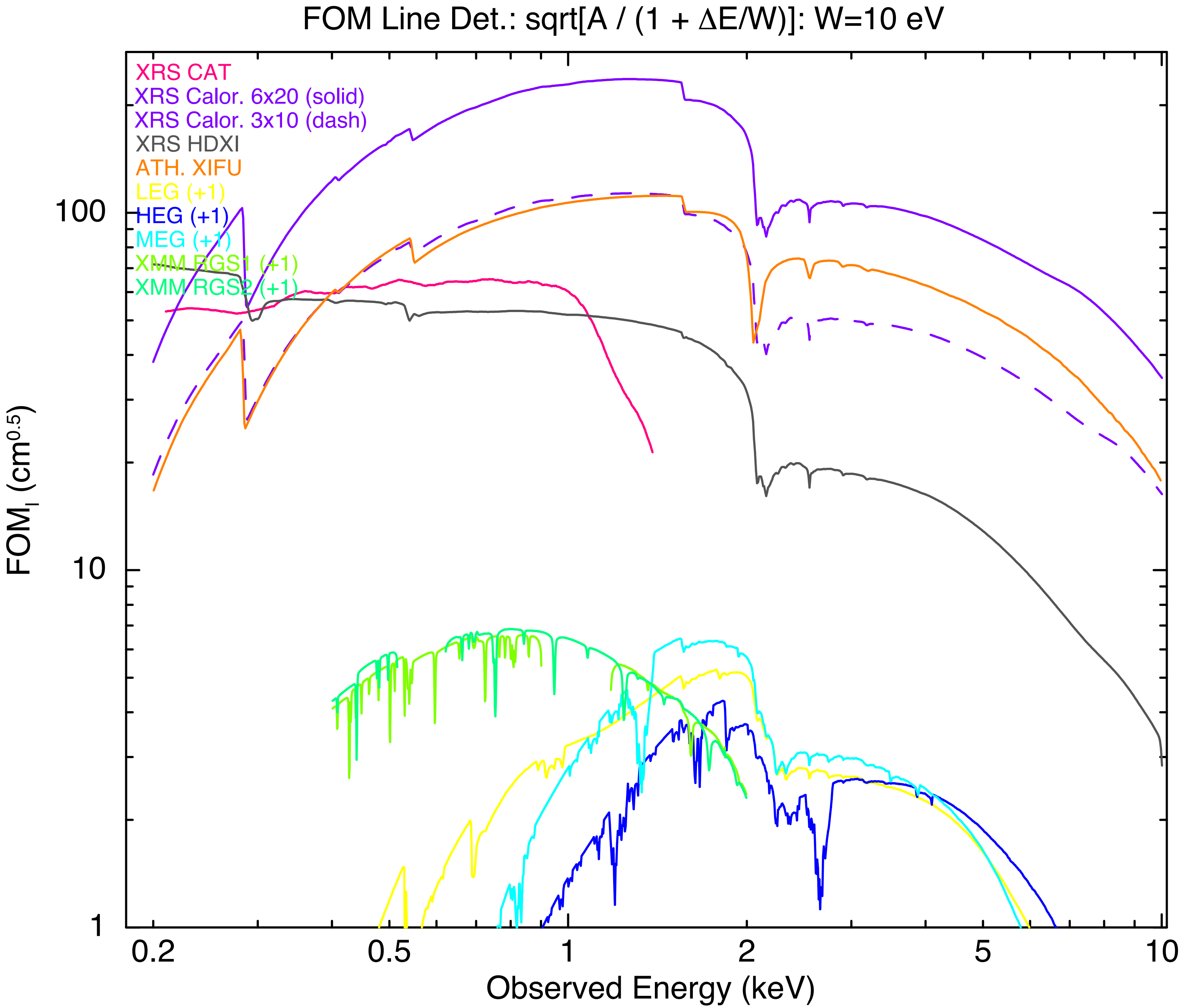


Alex Markowitz & Francesco Tombesi



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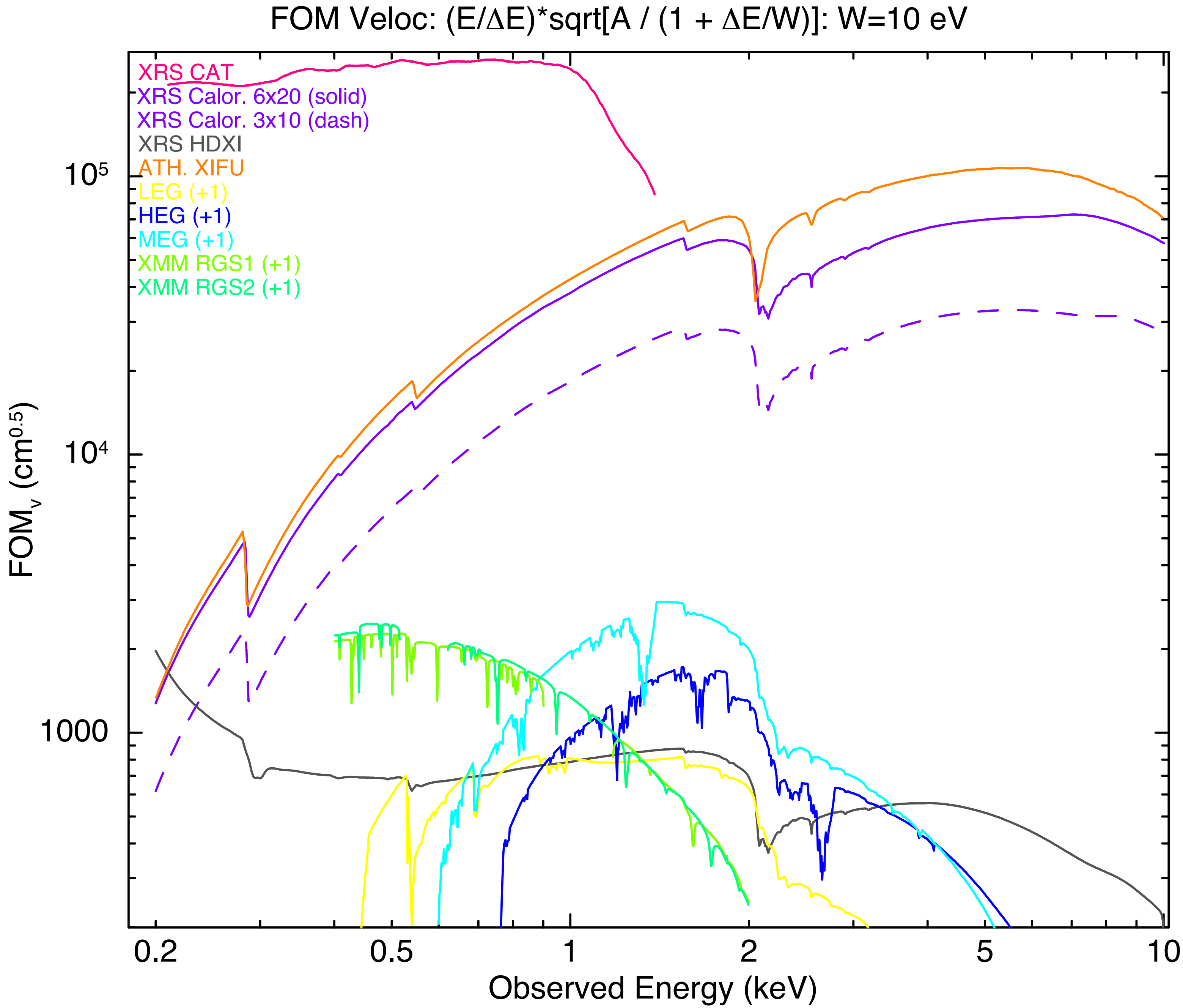


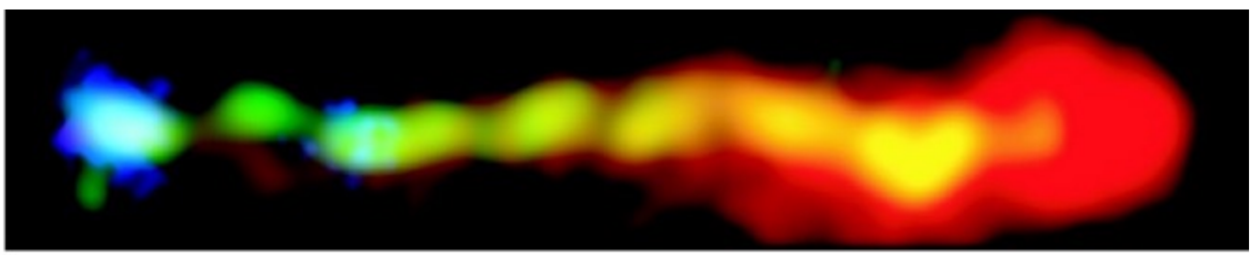
Alex Markowitz & Francesco Tombesi

Sub-arcsec Angular Resolution

Required to resolve jet structure

3C273 jet from Jester et al (2006)
Broad-band combined image:
Blue: X-rays, Green: Optical, Red: Radio

Complex emission on sub-arcsec scales:



A B1 B2 B3 C1 C2 D1 D2H3 H2

	A	B1	B2	B3 – D2H3	H2
Dominant... ...Band:	X-ray	X-ray	X-ray	——— radio/optical ———	radio
	2-zone inverse-Compton (IC) Model				
...Zone:	Spine	Spine	Spine	——— Sheath ———	Hot spot shock
...Process:	IC	IC	IC	——— Synch. ———	Synch.
	2-zone Synchroton Model				
...Zone:	Sheath	Sheath	Sheath	——— Spine ———	Hot spot shock
...Process:	Synch.	Synch.	Synch.	——— Synch. ———	Synch.

Aneta Siemiginowska

Sub-arcsec Angular Resolution

Quasar Jets and Radio galaxies at High Redshift:

Detecting faint emission close to a bright point source;
a 'peaky' narrow PSF for high dynamic range observations at high-z.

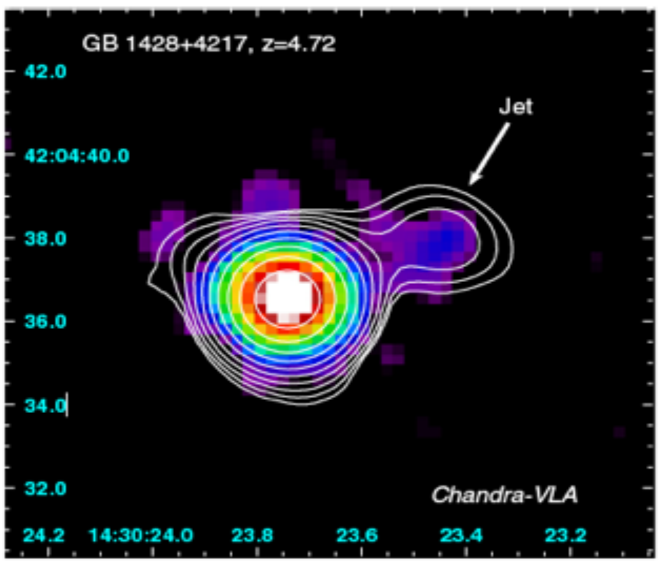


Figure 1. *Chandra* 0.3–7 keV (color) and VLA 1.4 GHz (contours) images of GB 1428+4217 showing the bright core and faint $\sim 3''.6$ distant jet knot at P.A. $\sim 295°$. Coordinates are in J2000.0 equinox. The X-ray data are binned by 1/2 of the native $0''.492$ pixels and Gaussian smoothed with kernel radius of 3 pixels. The 10 radio contours start at 0.17 mJy bm^{-1} (four times the off-source rms) increasing by factors of two up to 87 mJy bm^{-1} (peak is 155.4 mJy bm^{-1}) with circular beam size $= 1''.5$.

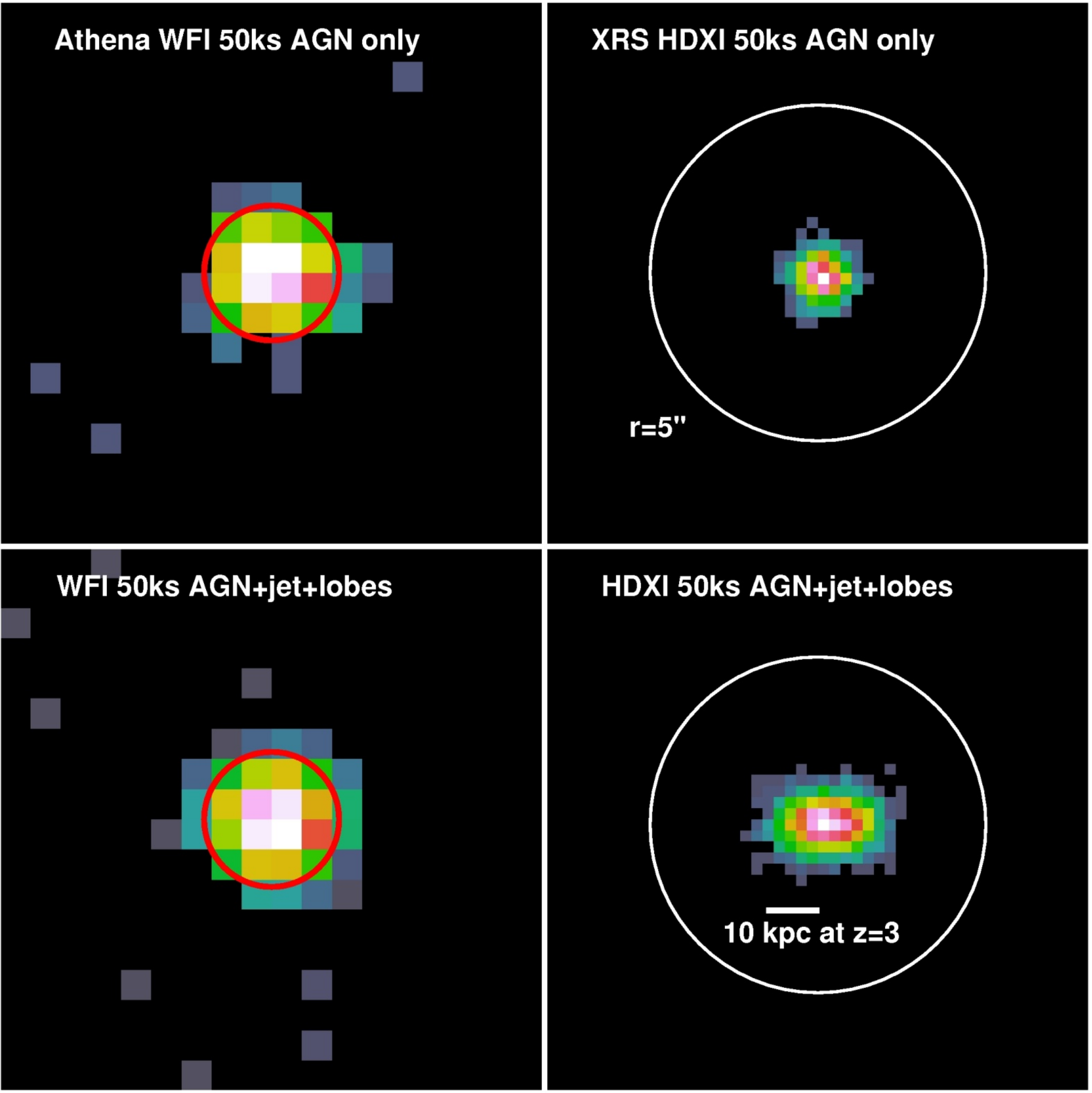
(A color version of this figure is available in the online journal.)

Example: The most distant quasar jet detected in X-rays at z=4.72. The jet knot located at 3.6 arcsec from the core

Aneta Siemiginowska

High-z Quasars

- The number of radio-loud quasars at z>3 is smaller than expected from the number of blazars
- This could result from a difference in jets, higher density surroundings, or CMB "quenching" ($u_{rad} = u_{z=0}\,(1+z)^4$). The former two could transform our understanding of feedback at high z (both in the galaxy and IGM).
- CMB quenching turns radio emission into X-ray emission. Counting jetted quasars at z>3 requires ~1 arcsec resolution and 10-50 ks per field
- SDSS quasar density for $z_{spec} > 3$ (4) is 1.2 (0.07) deg^{-2}. 500 HDXI pointings are needed to rule out CMB quenching in a blind survey (5-7 Ms). This can piggy-back on other surveys.
- If X-ray lobes are detected in a targeted search, the project is cheaper: deep observations of these sources can rule out CMB quenching (~1-1.5 Ms assuming a 10^{45} erg/s quasar).



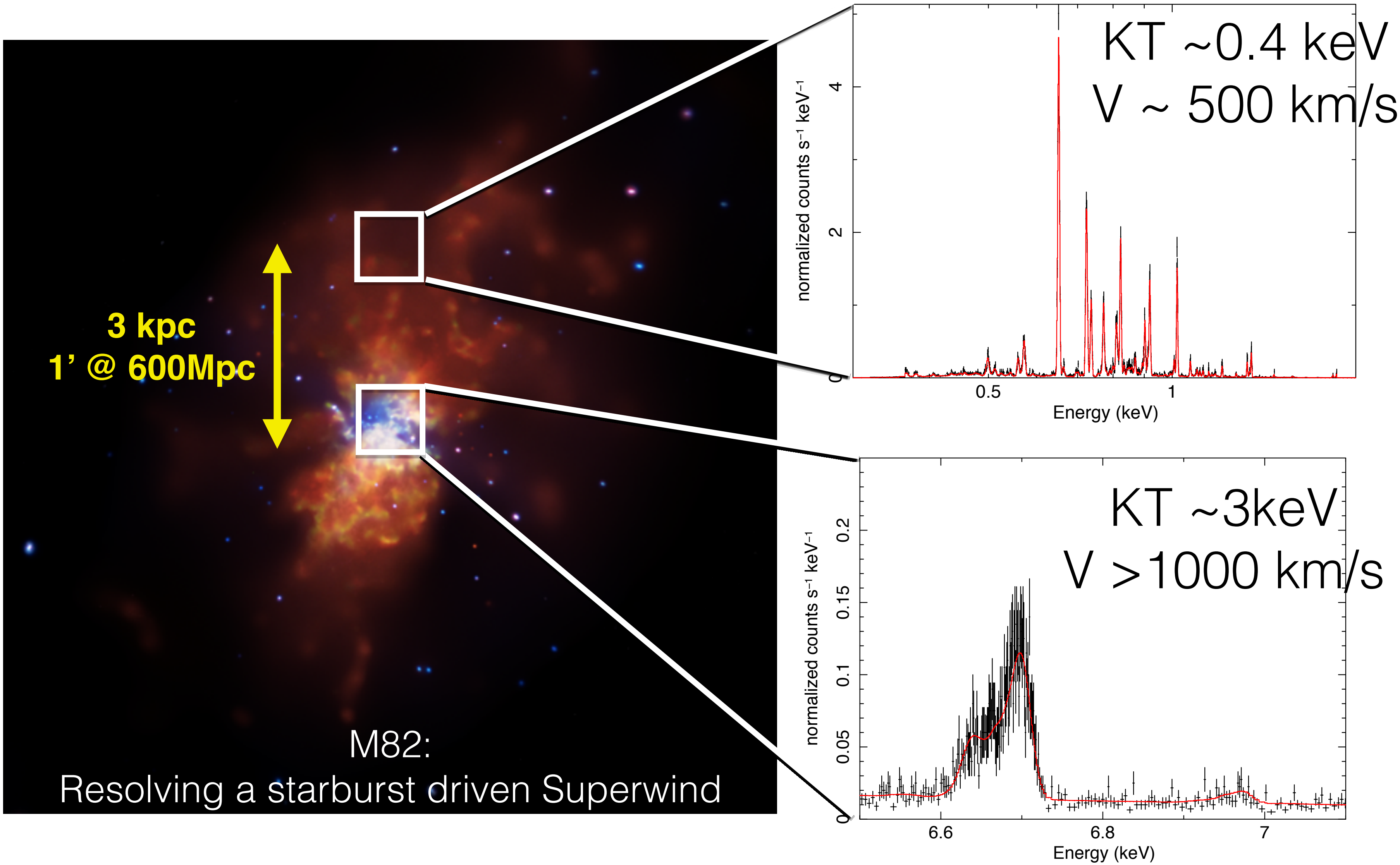
At z=3, a lobe with an extent of 10 kpc is indistinguishable from a point source in Athena but is clearly elongated in XRS HDXI.

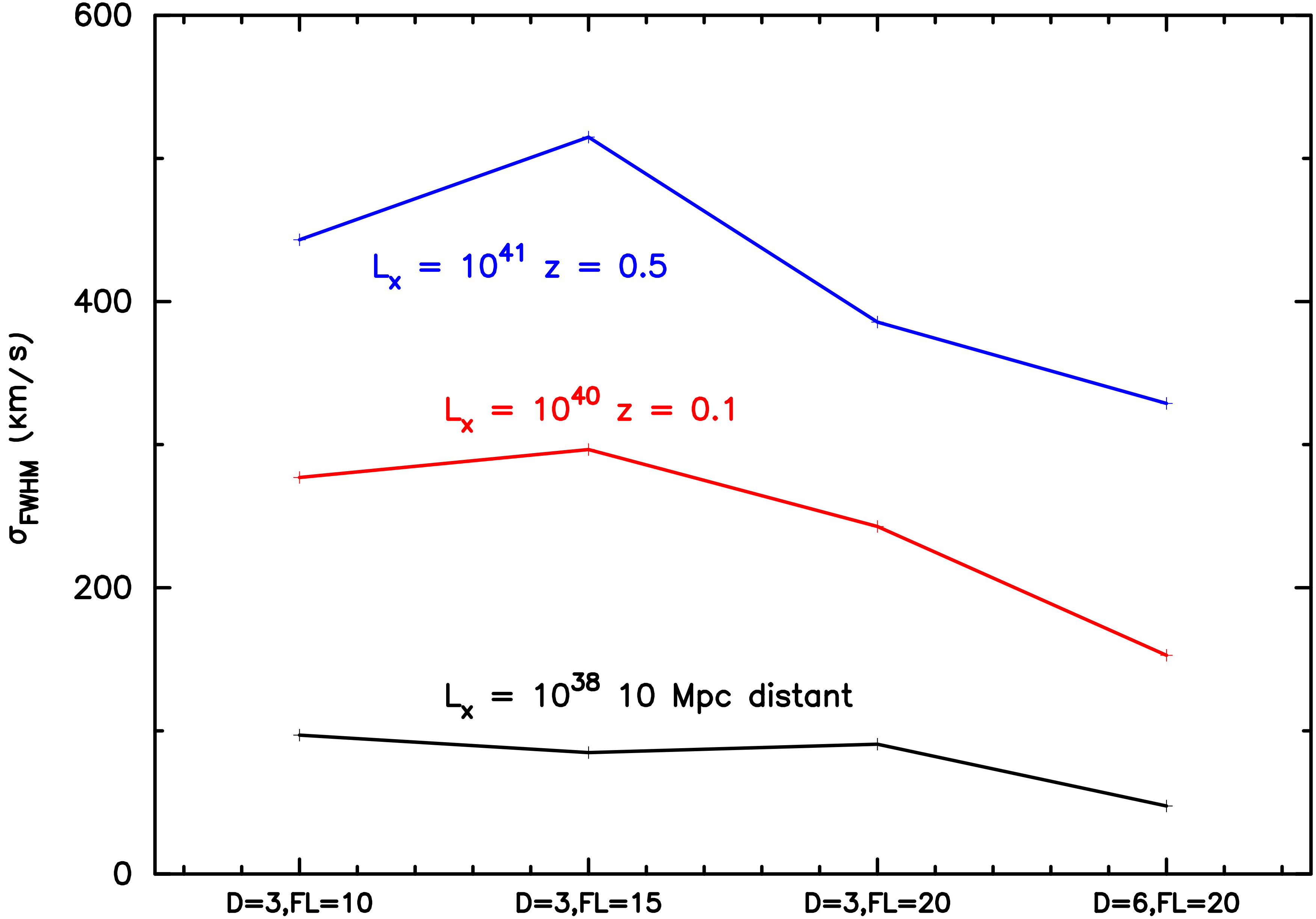
For a typical quasar luminosity of 10^{45} erg/s and a typical radio loudness, 10-50 ks is needed to find "quenched" quasars through elongated X-ray morphology.

Edmund Hodges-Kluck

Stellar-driven feedback

Stellar Feedback: XRS Spectra





600
400
200
0
σ_FWHM (km/s)
L_x = 10^41 z = 0.5
L_x = 10^40 z = 0.1
L_x = 10^38 10 Mpc distant
D=3,FL=10
D=3,FL=15
D=3,FL=20
D=6,FL=20

	Low-z cluster imaging spectroscopy	High-z cluster imaging spectroscopy	Elliptical Galaxy imaging spectroscopy	Field galaxy CGM imaging spectroscopy	Intra-galaxy hot-ISM imaging spectroscopy	AGN winds (point source) spectroscopy	AGN high dynamic-range imaging	AGN jets high-spatial resolution imaging
Evolution of AGN feedback across cosmic time and system mass								
Evolution of stellar feedback across cosmic time and system mass								
Physical processes by which AGN influence ICM/ISM								
Physics of wind/jet production by accreting supermassive black holes								
The fueling and regulatory processes in AGN								
Role of feedback in dispersing metals into the CGM/ICM/IGM								

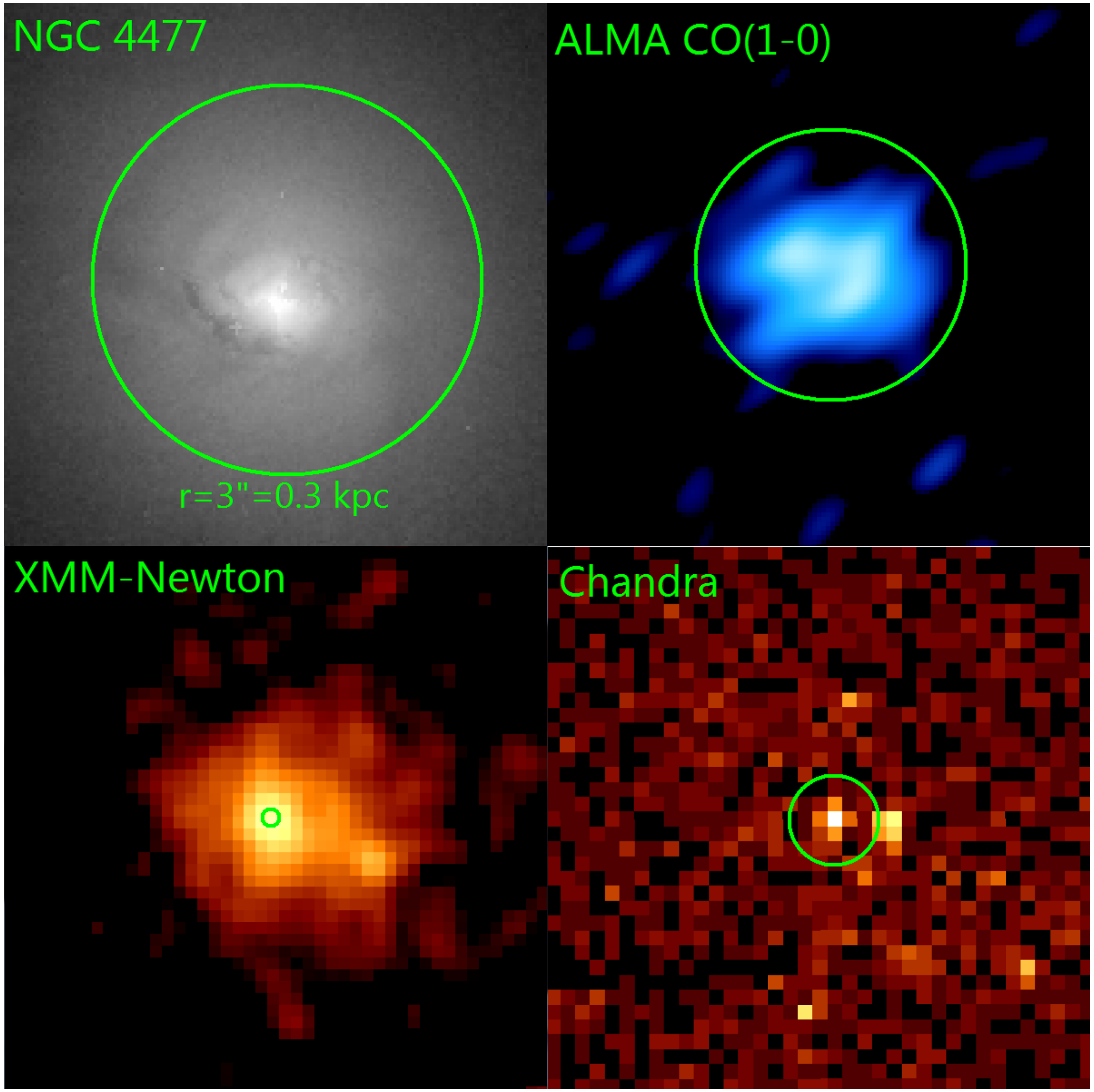
Mission drivers

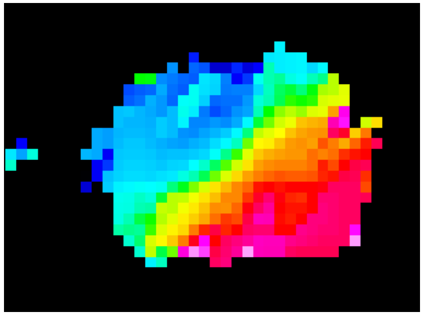
- Critical :
  - Calorimeter pixels ≤1 arcsec
    - (detailed studies of galactic nuclei / ISM)
- Desirable :
  - Calorimeter resolution ≤ 3eV
    - (detectability and characterization of abs lines)
  - Simultaneous Calorimeter and grating ability
    - (characterization of variable multi-zone winds)

Backup slides

Fueling and Feedback in the Inner kpc

- How do "maintenance-mode" AGN regulate their fuel supply?
- Episodic vs. continuous feeding
- Required measurements:
  - 2D Temperature, entropy, density, and bulk velocity maps within 1 kpc at comparable resolution (50-100 pc) to state-of-the-art IFU and ALMA/SKA.
- The kinematic measurements require the IFU calorimeter to have pixels of ≤1 arcsec.
- Athena measurements provide an important pathfinder, but are not a substitute.



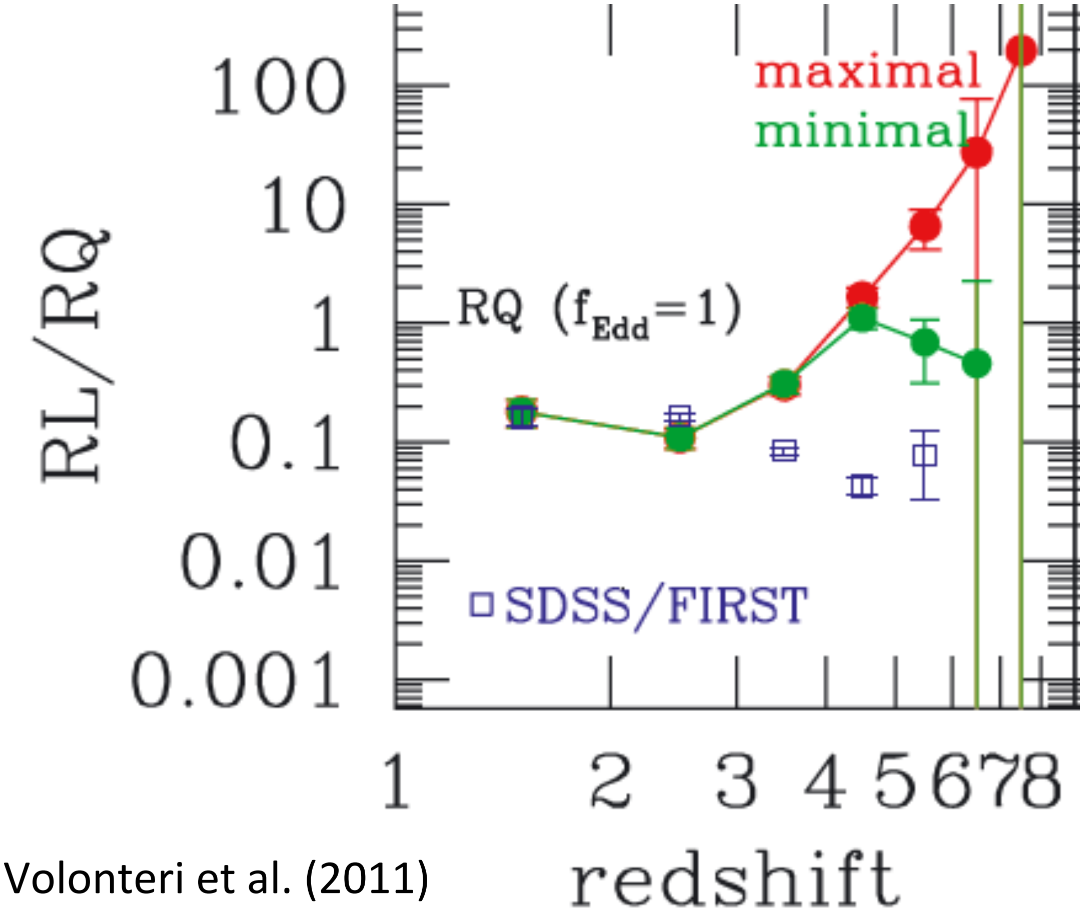


150-200 km/s rotation
(σ=175 km/s)

Even nearly-quiescent BHs often have central dust or CO disks. Is this disk built up from condensation? Or, is the hot gas outflowing?

Exposure Times

- Targets:
  - Lower activity levels preferred (no bright central AGN), and a range of atmosphere brightnesses
  - Several large central galaxies within 50-100 Mpc (deep existing *Chandra*, *XMM-Newton* data)
- Ultra-deep study with HDXI+MIS
  - Determine inflow/outflow rates, kinetic energy carried, etc. down to near the Bondi radius
  - ~500 ks – 1 Ms per target (several targets=4-6 Ms)
  - Spectroscopic simulations pending…



Volonteri et al. (2011)

Fraction of radio-loud quasars expected from blazar counts for a minimal (green) and maximal (red) model of blazar evolution. The observed fraction is shown as blue points. This model assumes quasars accrete at the Eddington ratio and that jets have a Doppler factor Γ=15.

Precipitation-Limited Luminosity

Voit+ 16, in preparation

$$\frac{t_{\rm cool}}{t_{\rm ff}} \gtrsim 10$$

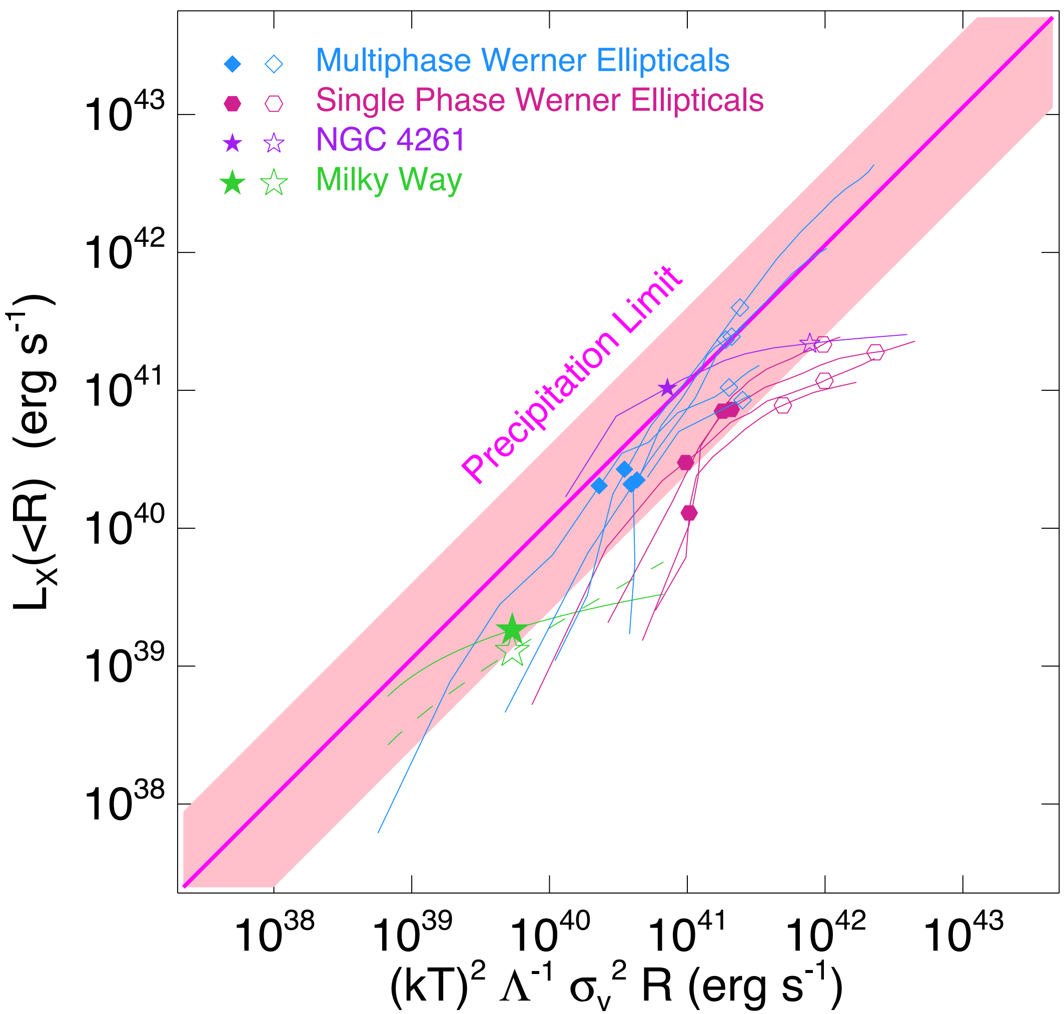
$$n_e \lesssim \frac{3kT}{10\, t_{\rm ff} \Lambda(T)}$$

$$L_X(< R) \lesssim \int_0^R 4\pi r^2 \Lambda \left(\frac{3kT}{10 t_{\rm ff} \Lambda} \right)^2 dr$$

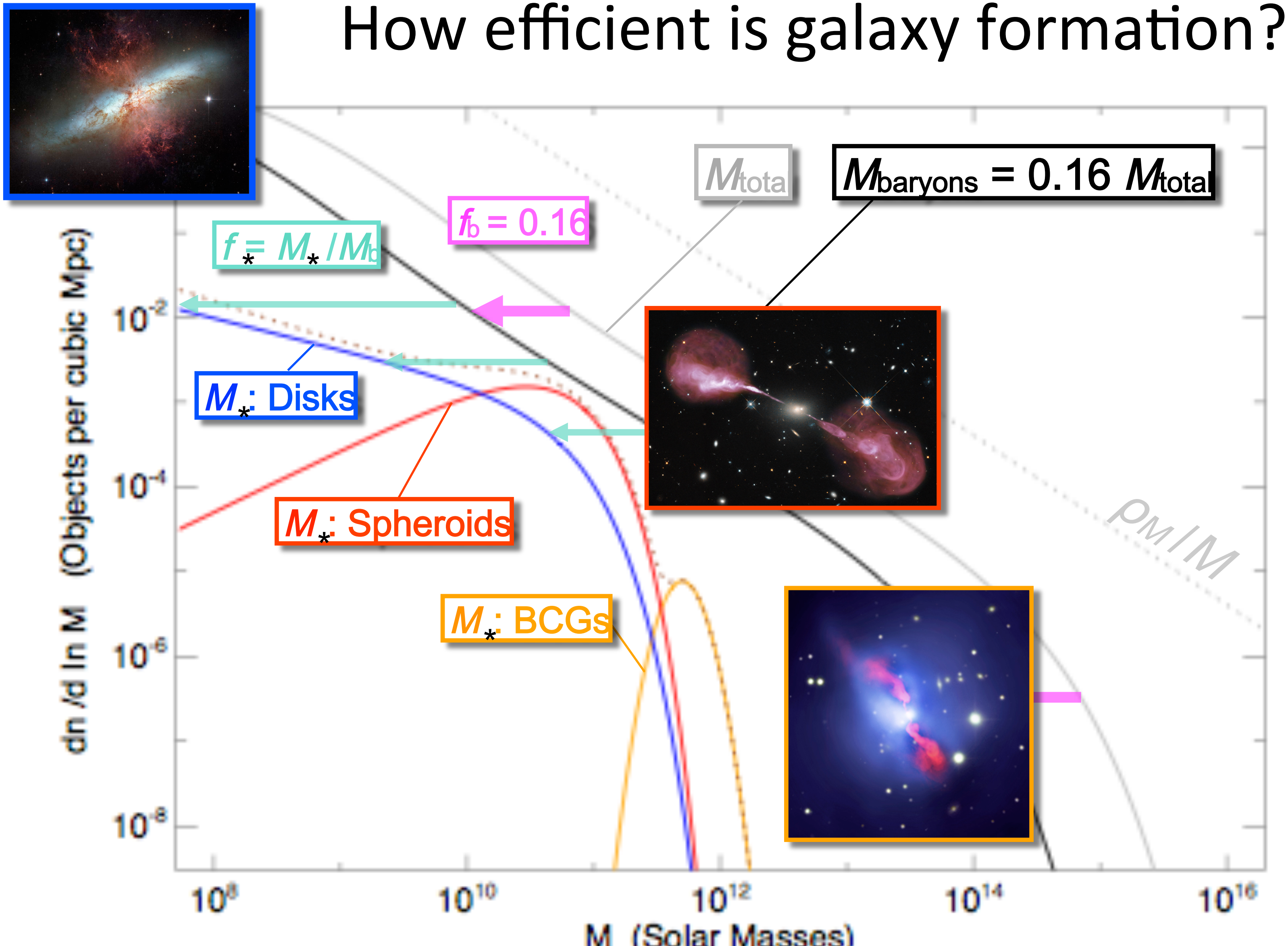
$$L_X(< R) \; \lesssim \; \frac{9\pi}{25} (kT)^2 \Lambda^{-1} \sigma_v^2 R$$

Precipitation-Limited Luminosity

Voit+ 16, in preparation



How efficient is galaxy formation?



Courtesy of Mark Voit