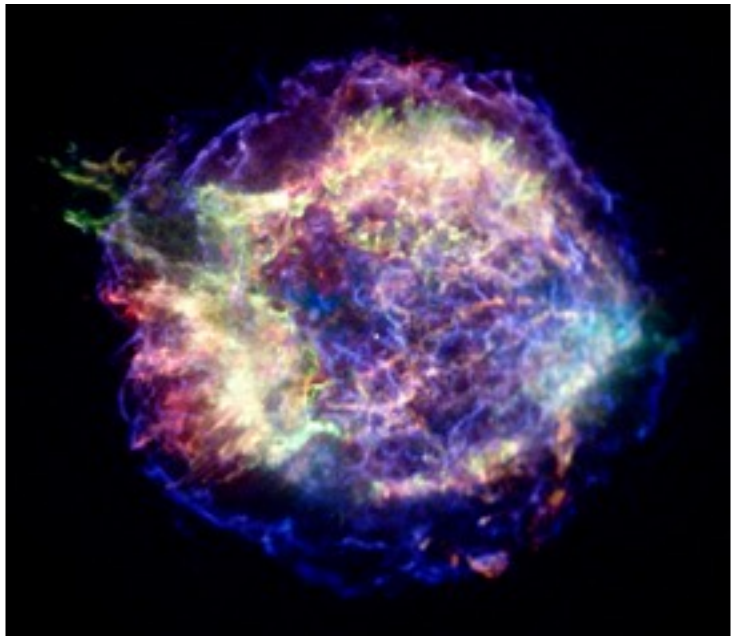
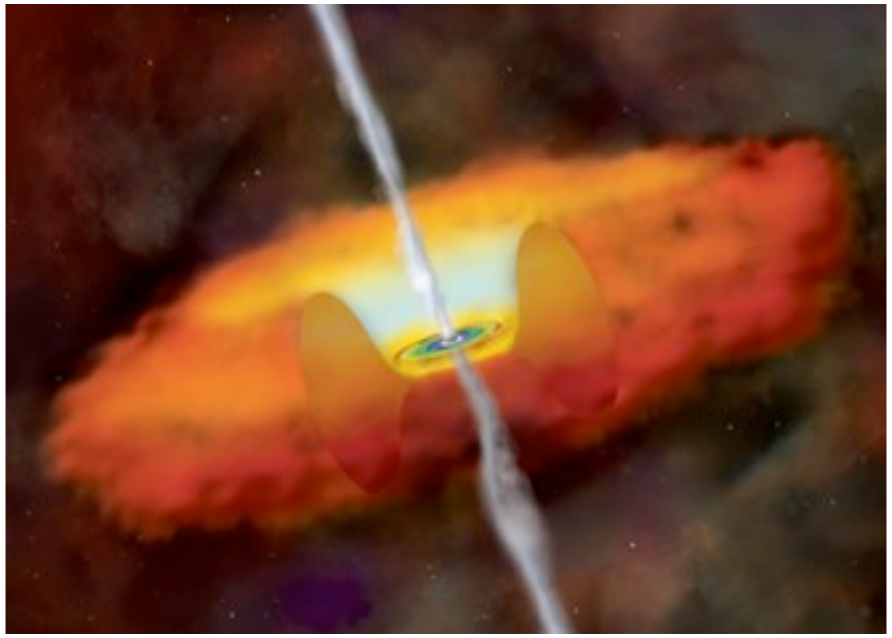
The Hot and Energetic Universe





Norbert Werner

Stanford University

Anja von der Linden

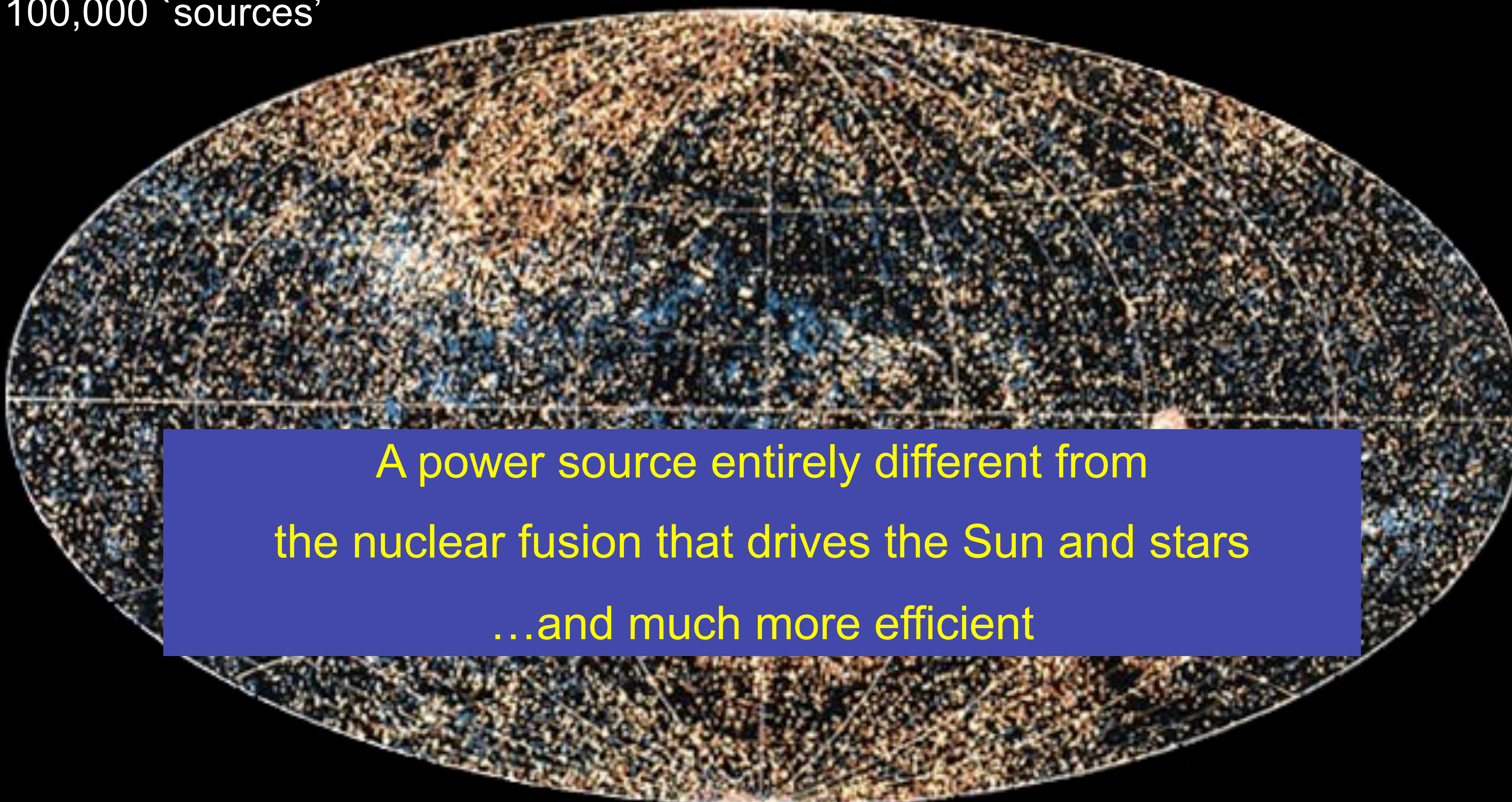

NASA, ESA, S. Beckwith (STScI) and the HUDF team

Powerful sources of X-rays

X-ray map of the whole sky:

100,000 `sources'

Rosat All Sky Survey

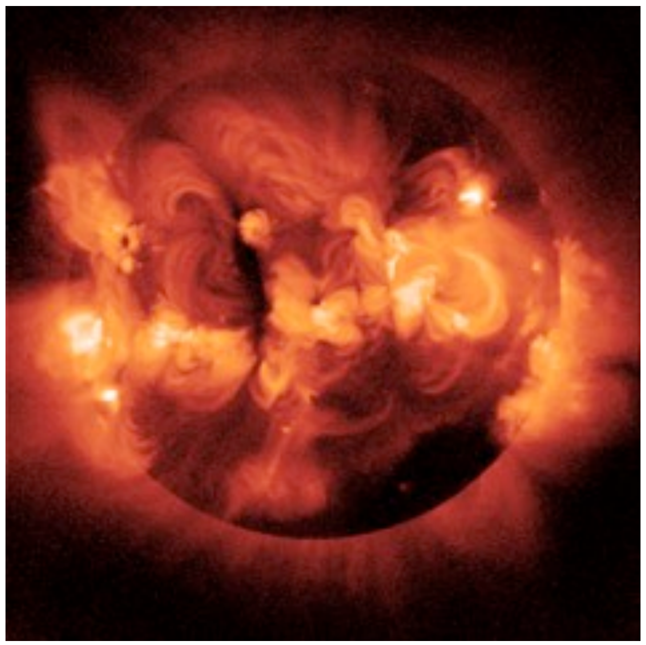


X-ray astrophysics tries to find out what could cause such extraordinary power

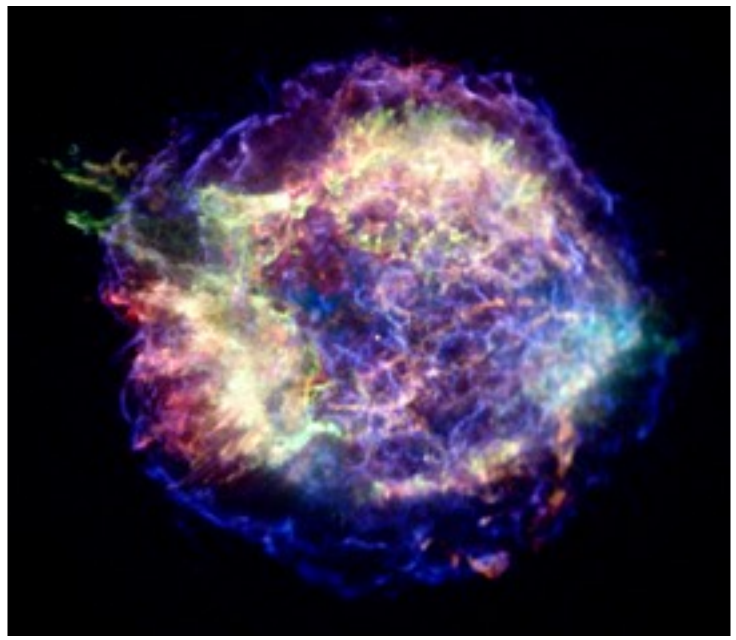
The hot and energetic Universe

What can get as hot as a million degrees?

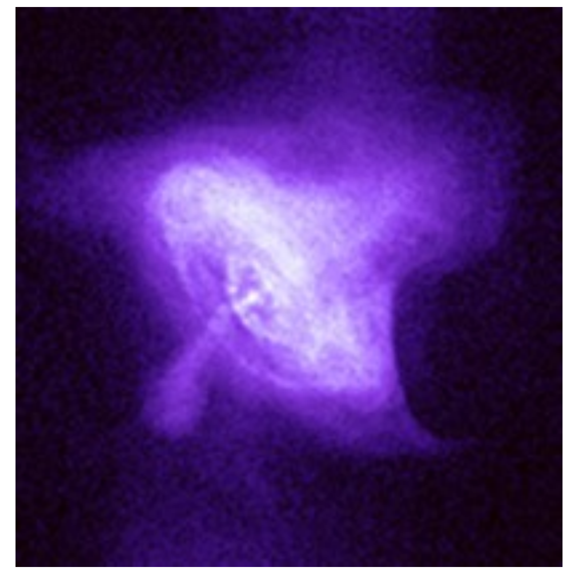
Plasma heated by magnetic reconnection



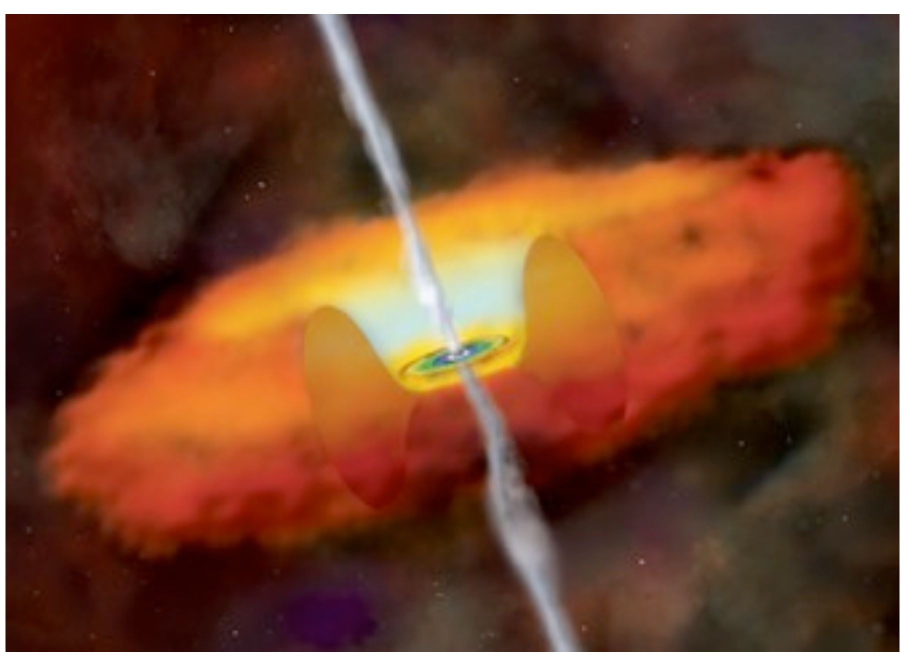
Explosions: Supernovae and their remnants

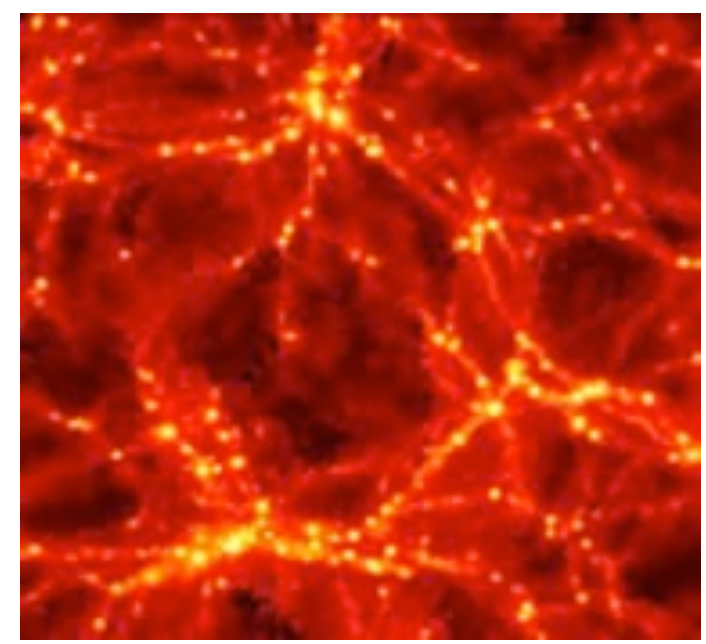


Particles moving near the **speed of light in magnetic fields**

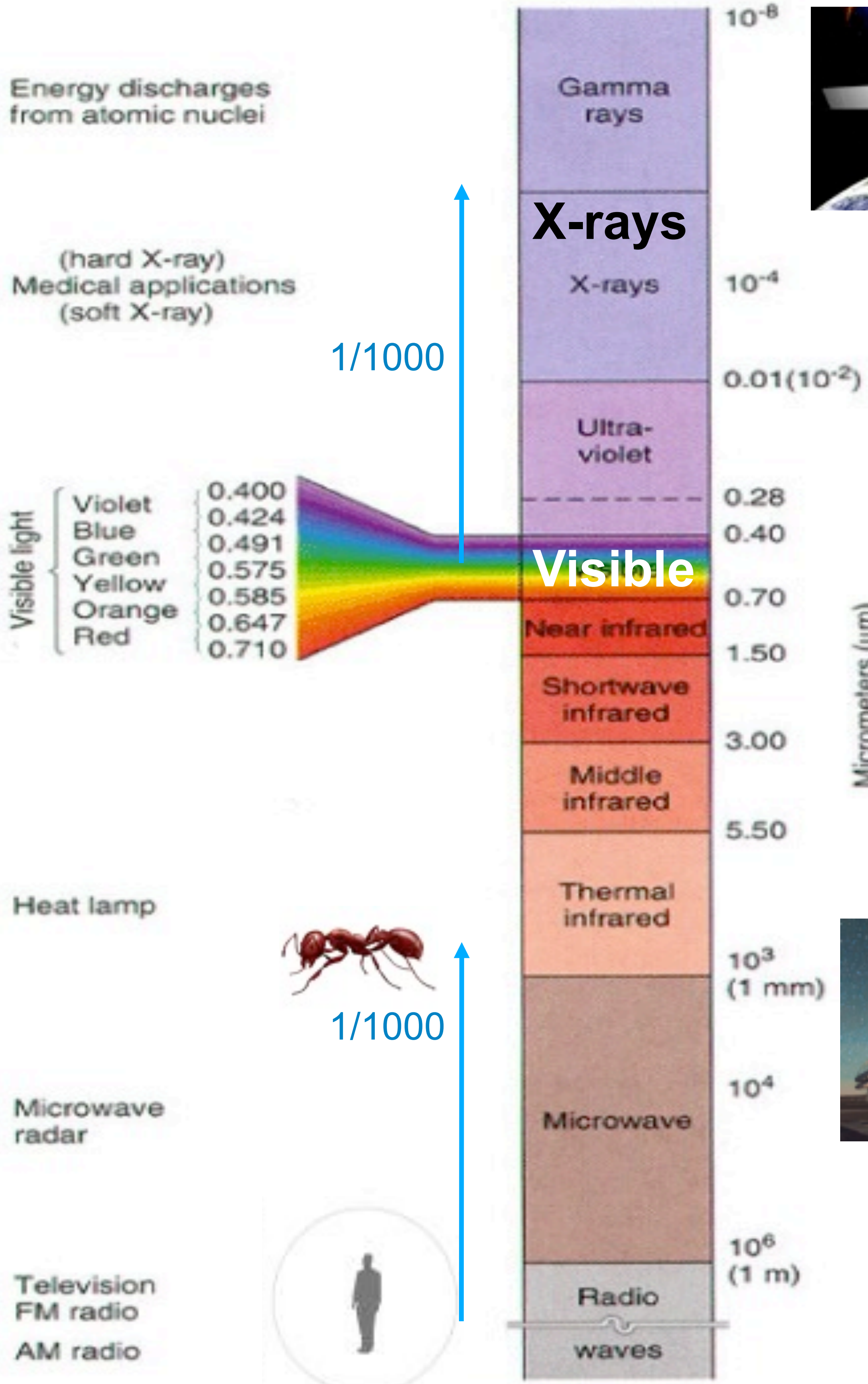


Matter falling into **deep gravitational wells** (most common source of X-rays)





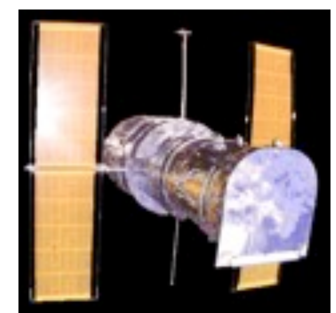
X-ray Astronomy studies the short wavelength light from the Universe



Source: Christopherson (2000) *Geosystems*

The *Fermi* Gamma-Ray Space Telescope

Chandra



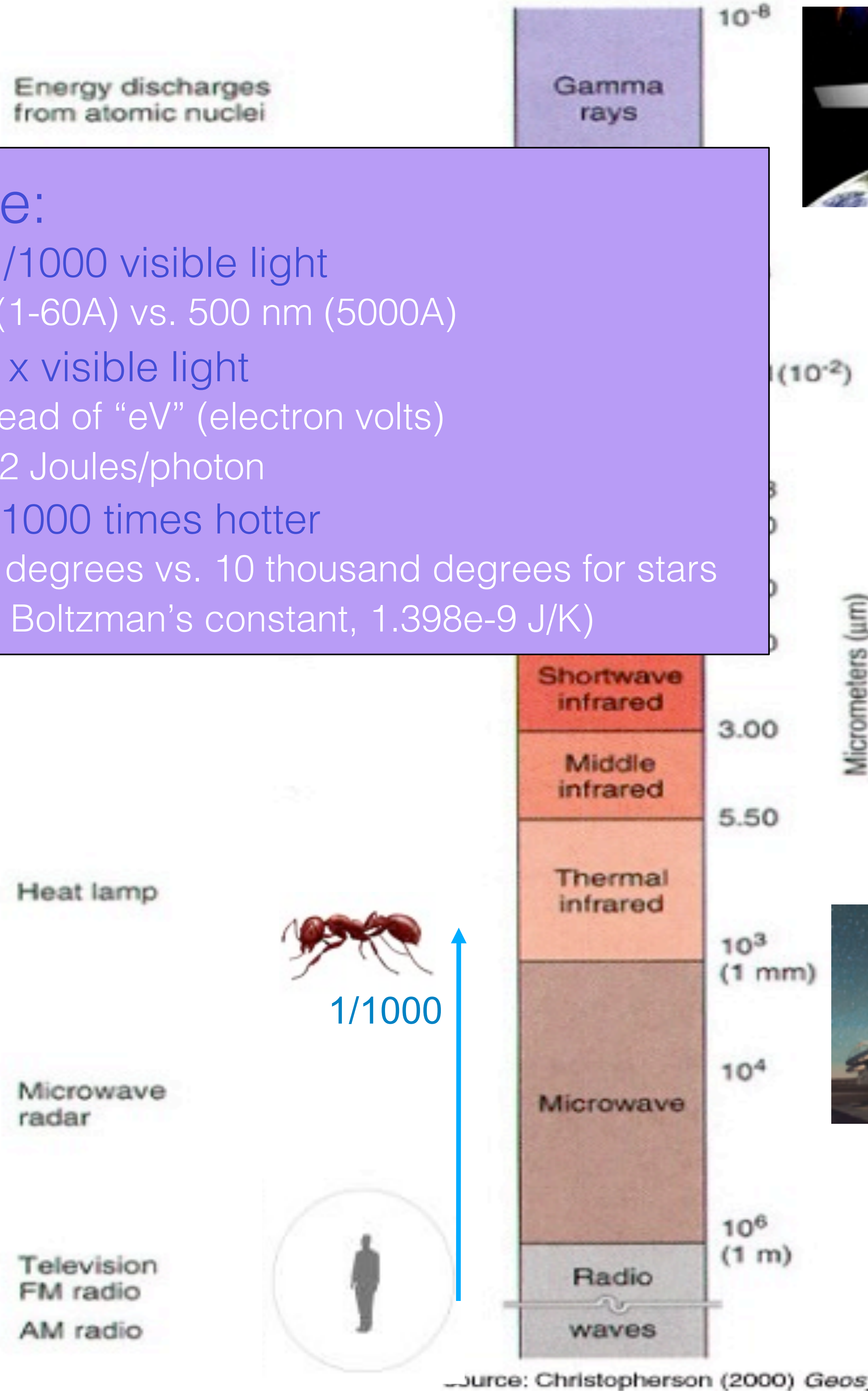
Hubble Space Telescope

SOFIA

ALMA

JVLA

X-ray Astronomy studies the short wavelength light from the Universe



X-rays have:

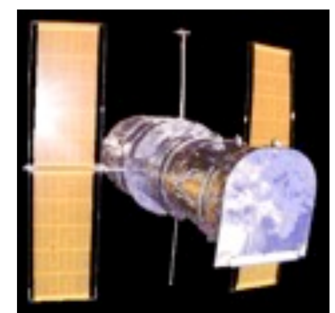
Wavelengths: 1/1000 visible light
- 0.1-6 nm (1-60A) vs. 500 nm (5000A)

Energies: 1000 x visible light
- "keV" instead of "eV" (electron volts)
- About 0.02 Joules/photon

Temperatures: 1000 times hotter
- 10 million degrees vs. 10 thousand degrees for stars
- E=kT (k= Boltzman's constant, 1.398e-9 J/K)

The *Fermi* Gamma-Ray Space Telescope

Chandra



Hubble Space Telescope

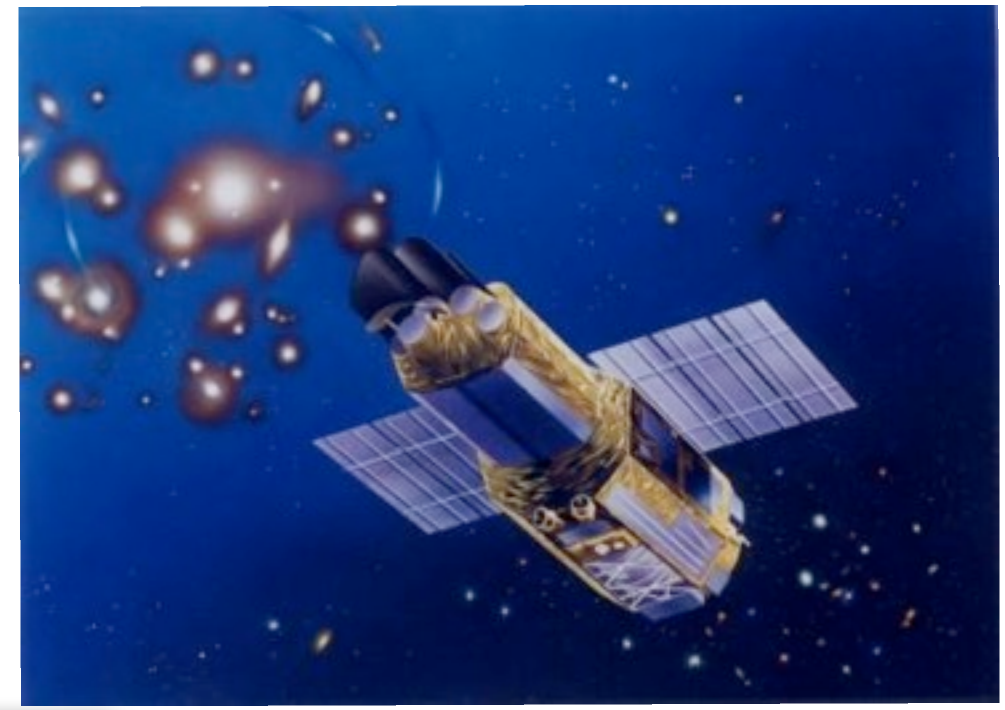
SOFIA

ALMA

JVLA

X-ray observatories

XMM-Newton

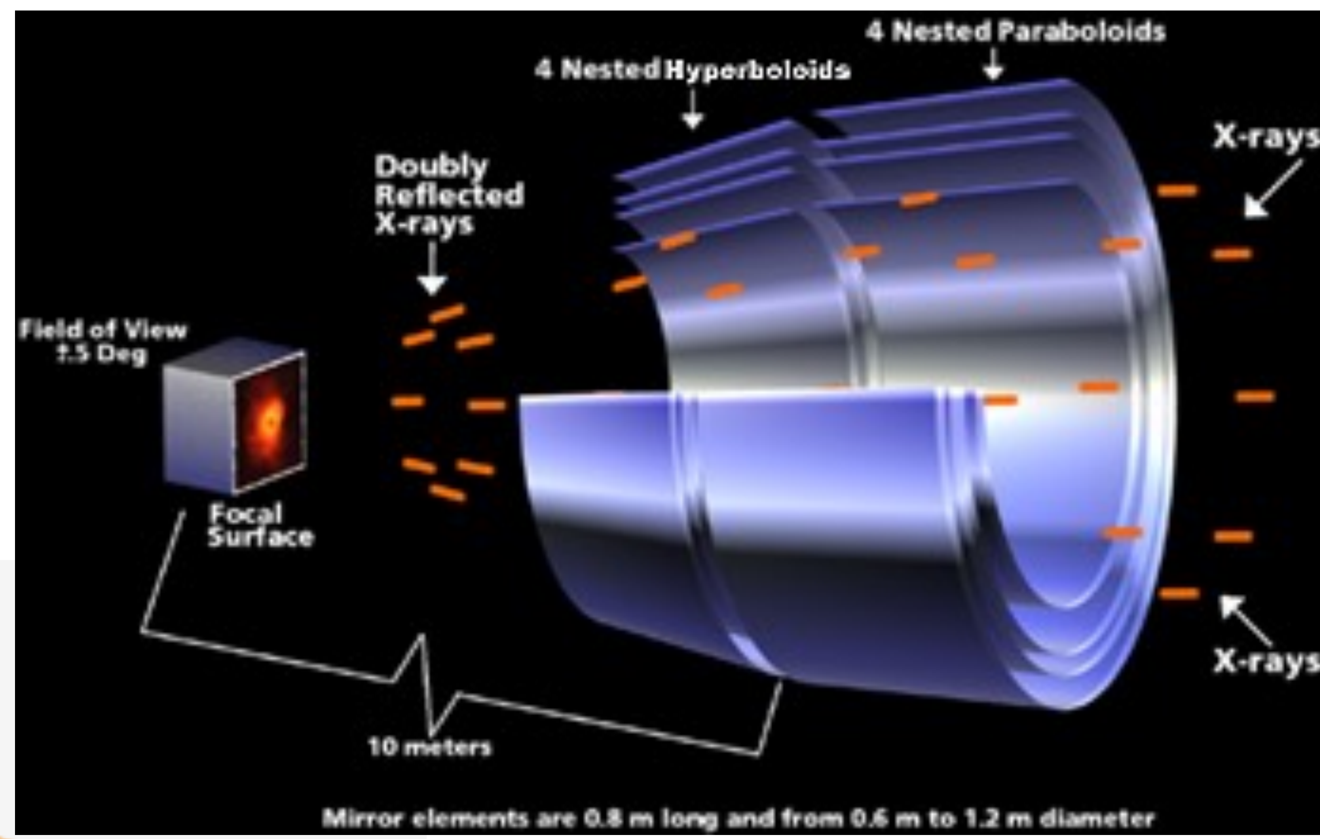


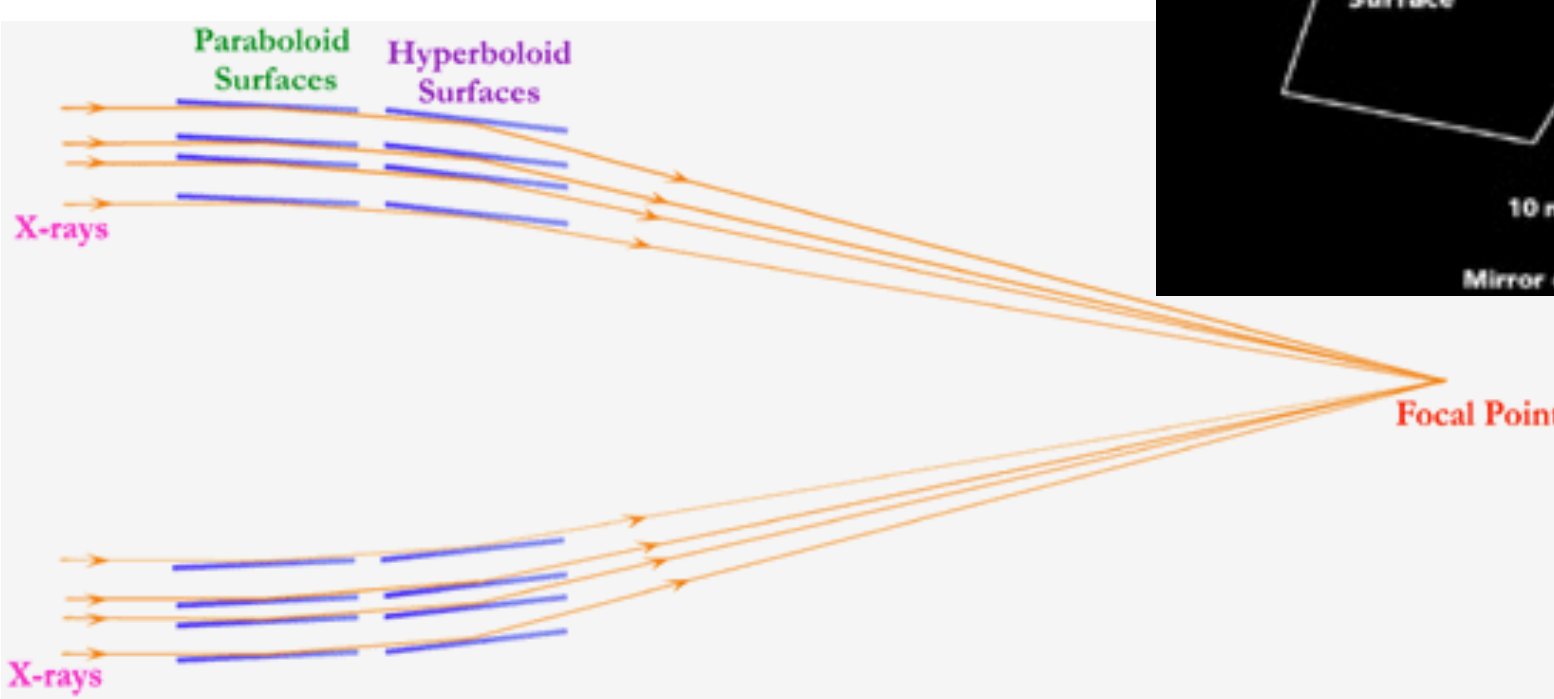
Suzaku

Chandra

X-ray telescopes are different

- X-ray mirrors are almost cylinders
- X-rays don't reflect off a normal mirror – they get absorbed
- Only by striking a mirror at a glancing angle, about 1°, do X-rays reflect
- Then they act like visible light and can be focused





low densities $n=10^{-1}$-10^{-5} cm^{-3}, high temperatures $T=5\times10^{6}$-10^{8} K

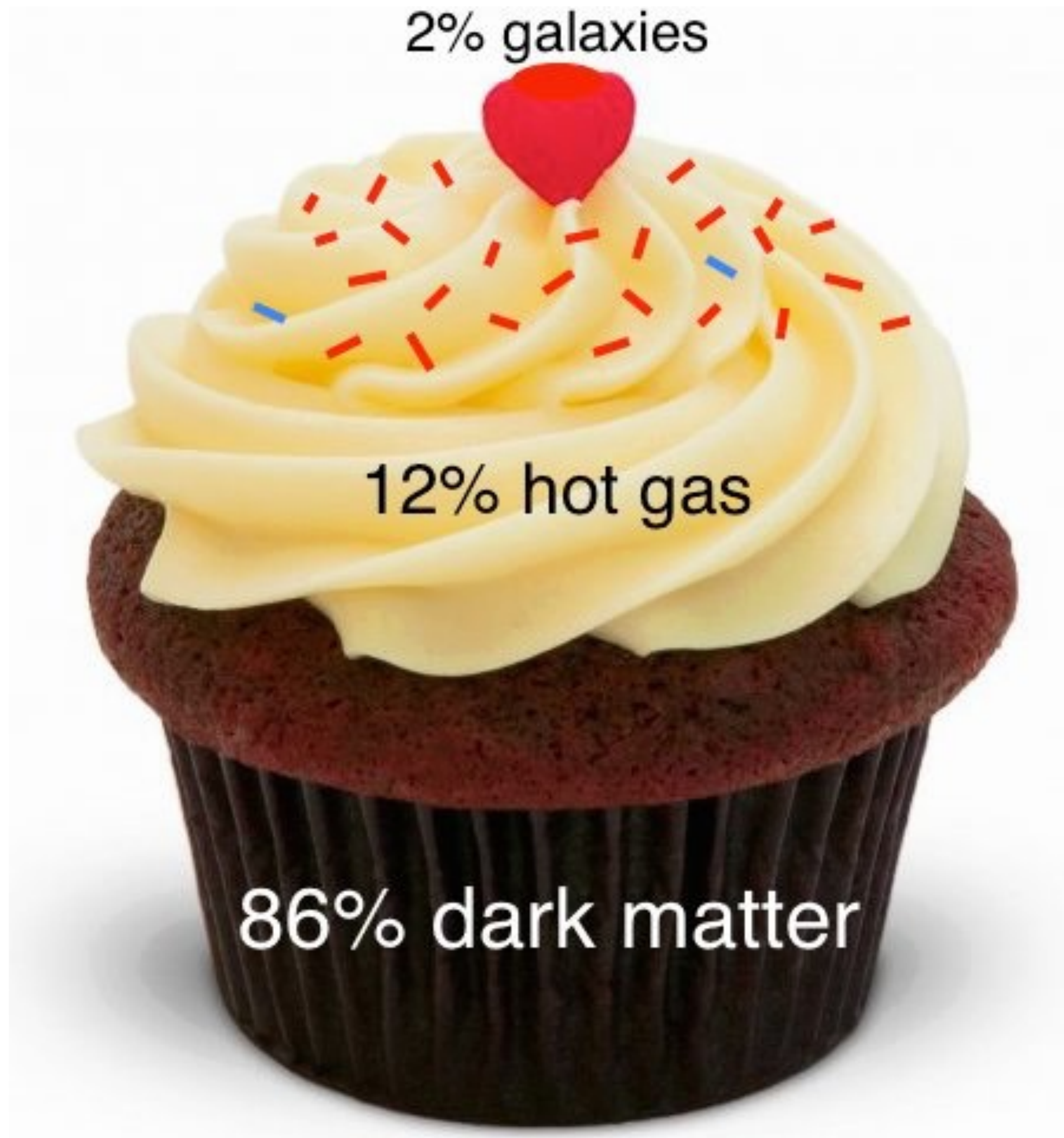
bremsstrahlung (free-free), recombination (free-bound), de-excitation (bound-bound)

collisional ionization equilibrium

electron and ion temperatures in equilibrium

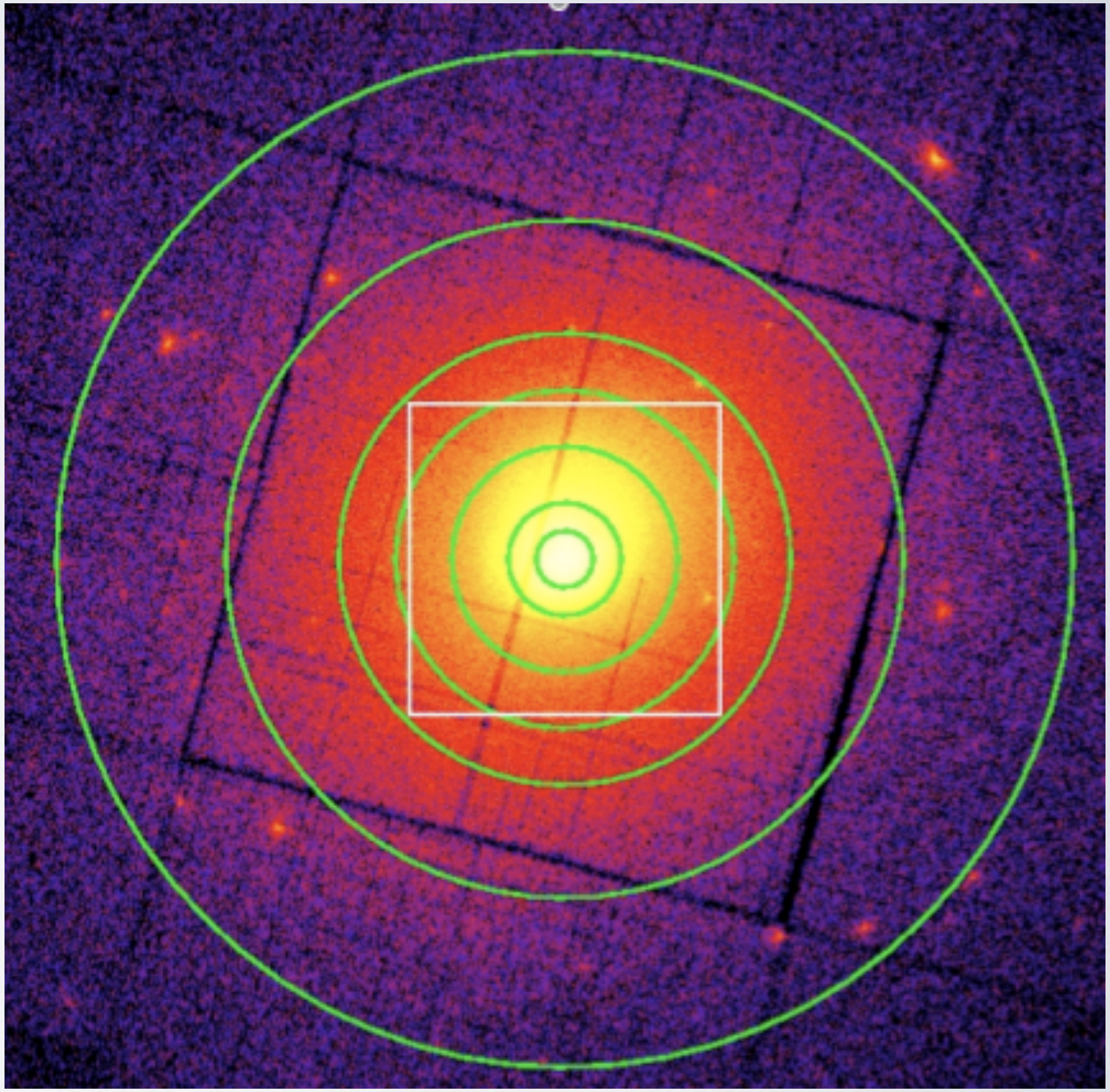
shape of spectrum entirely determined by kT and chemical abundances

CLUSTERS OF GALAXIES AS CUPCAKES

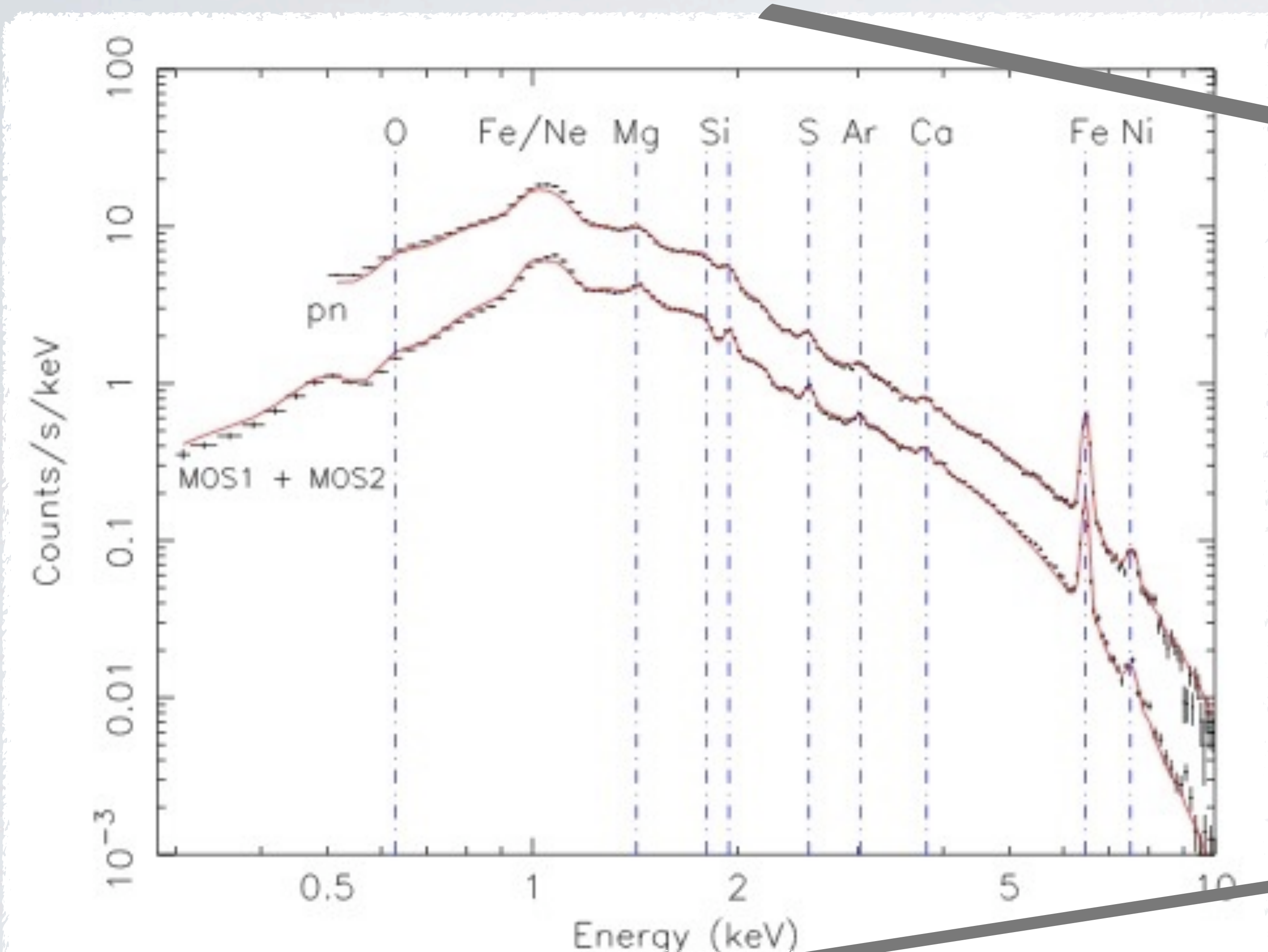


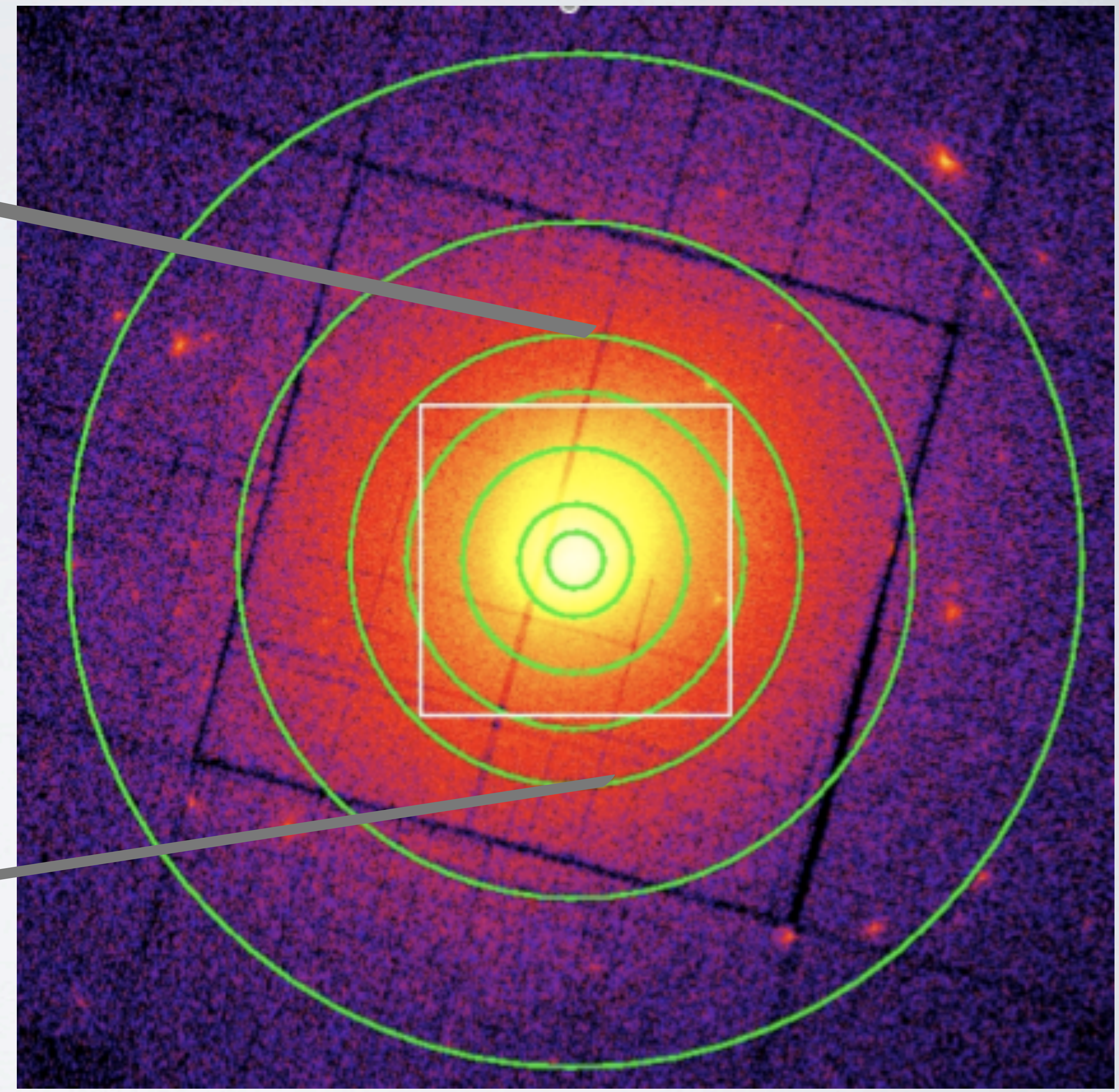
A. Mantz

X-RAY SPECTRA OF HOT DIFFUSE PLASMA



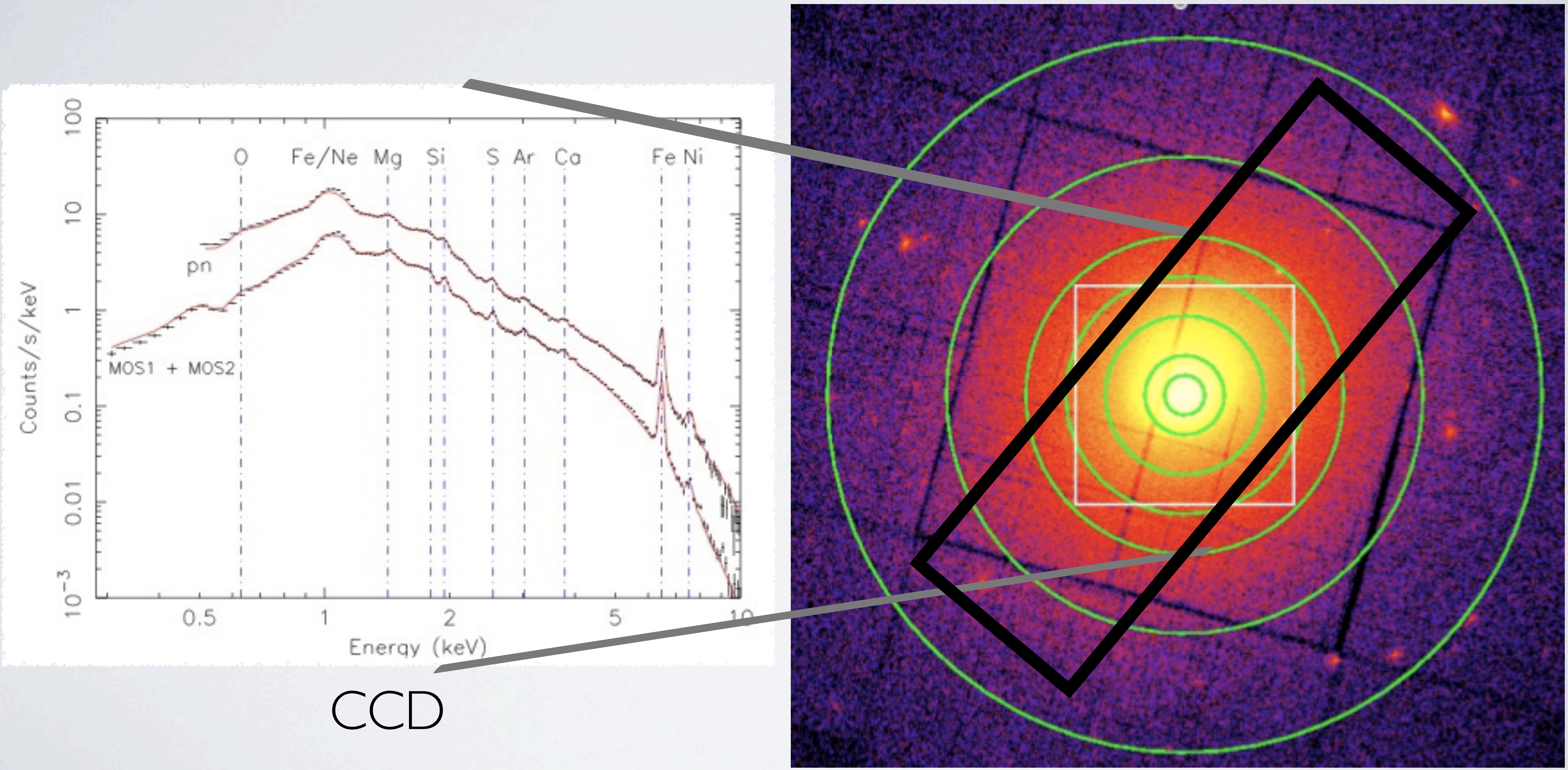
X-RAY SPECTRA OF HOT DIFFUSE PLASMA





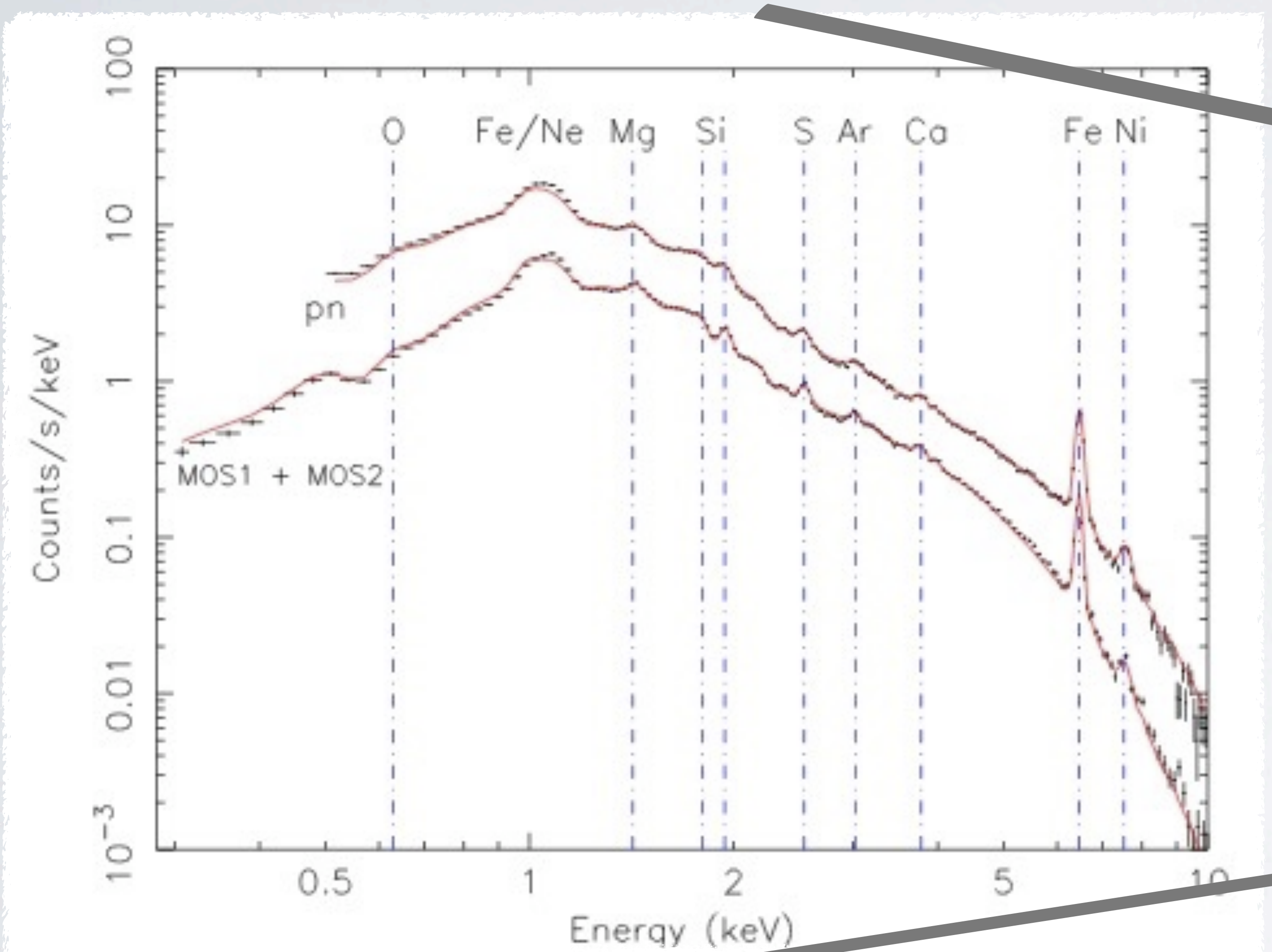
CCD

X-RAY SPECTRA OF HOT DIFFUSE PLASMA

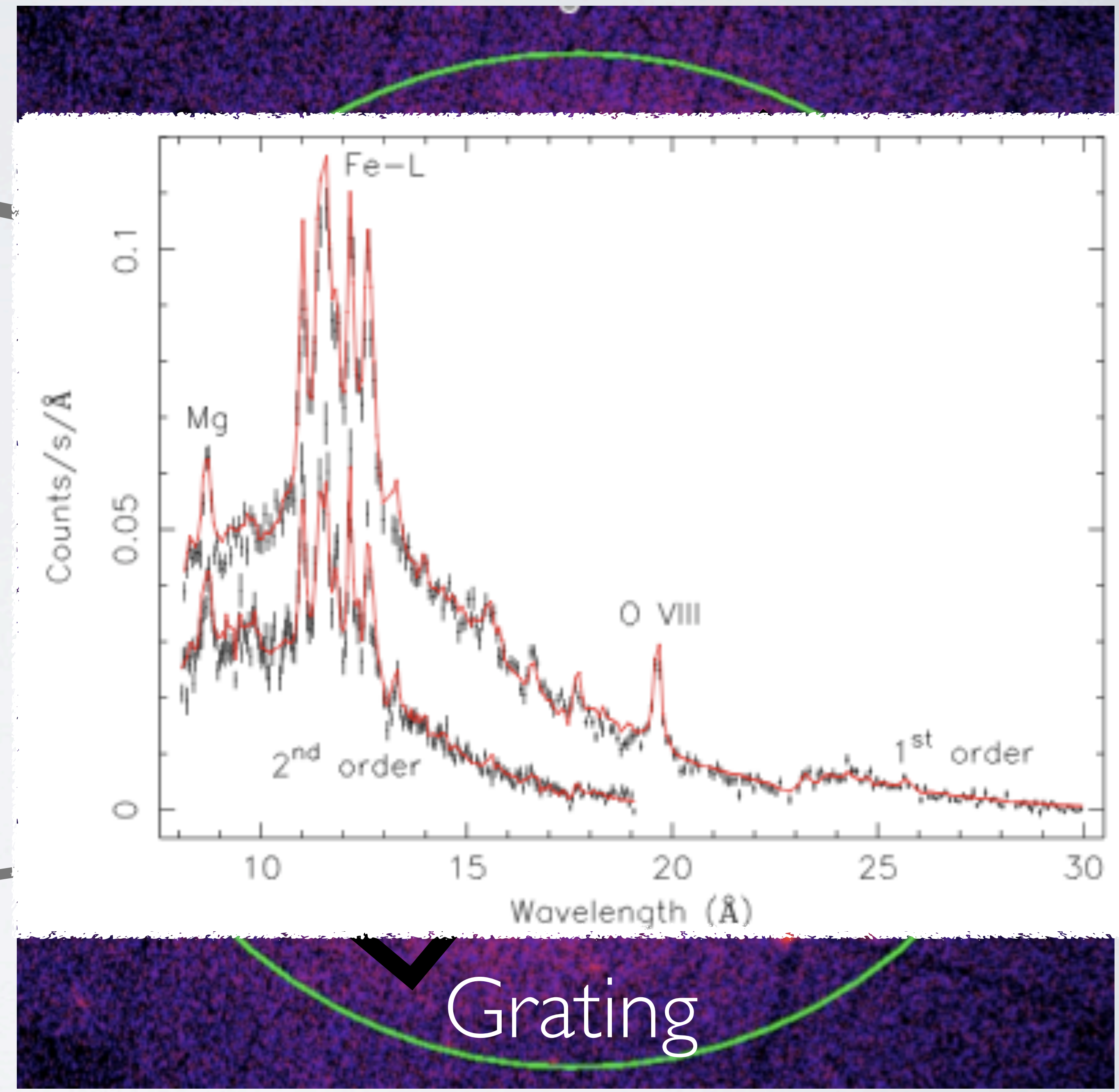


CCD

X-RAY SPECTRA OF HOT DIFFUSE PLASMA

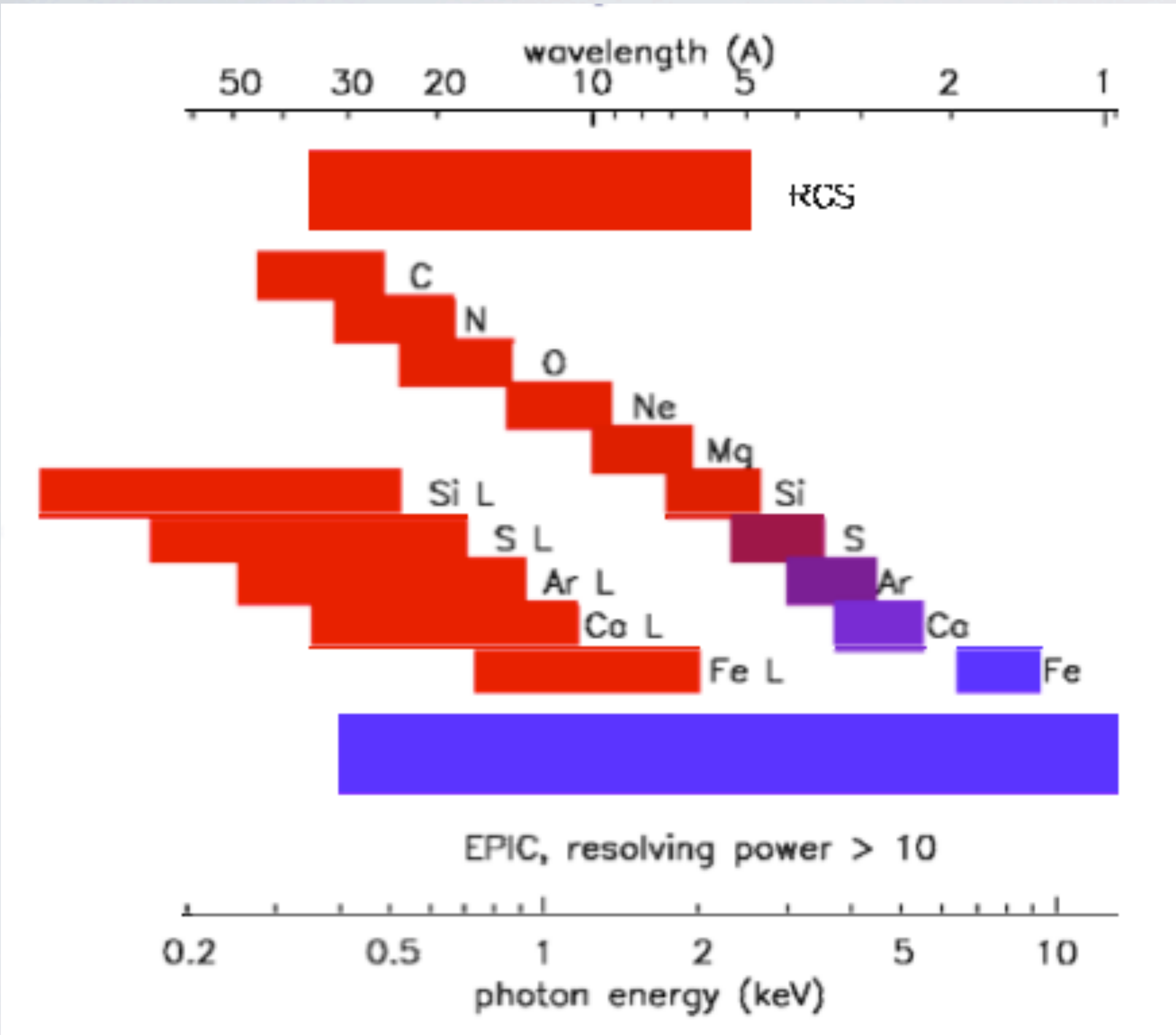


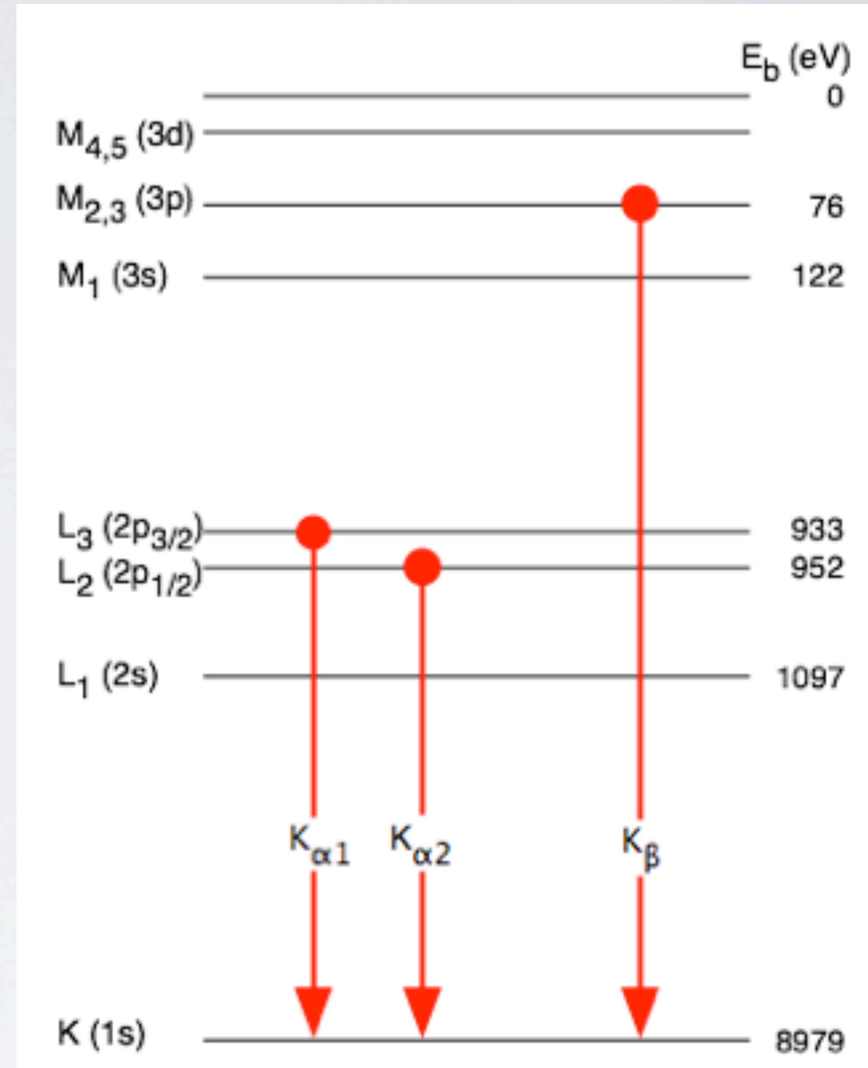
CCD



Grating

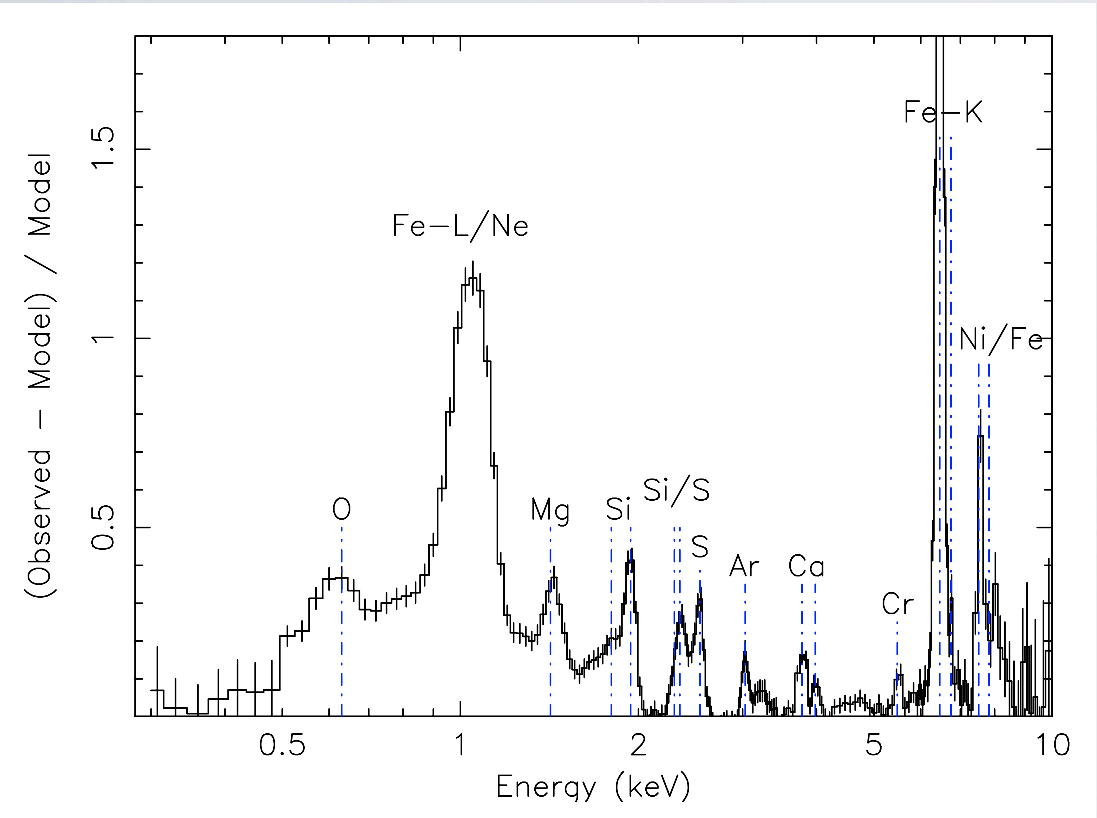
WHICH ELEMENTS, WHERE?

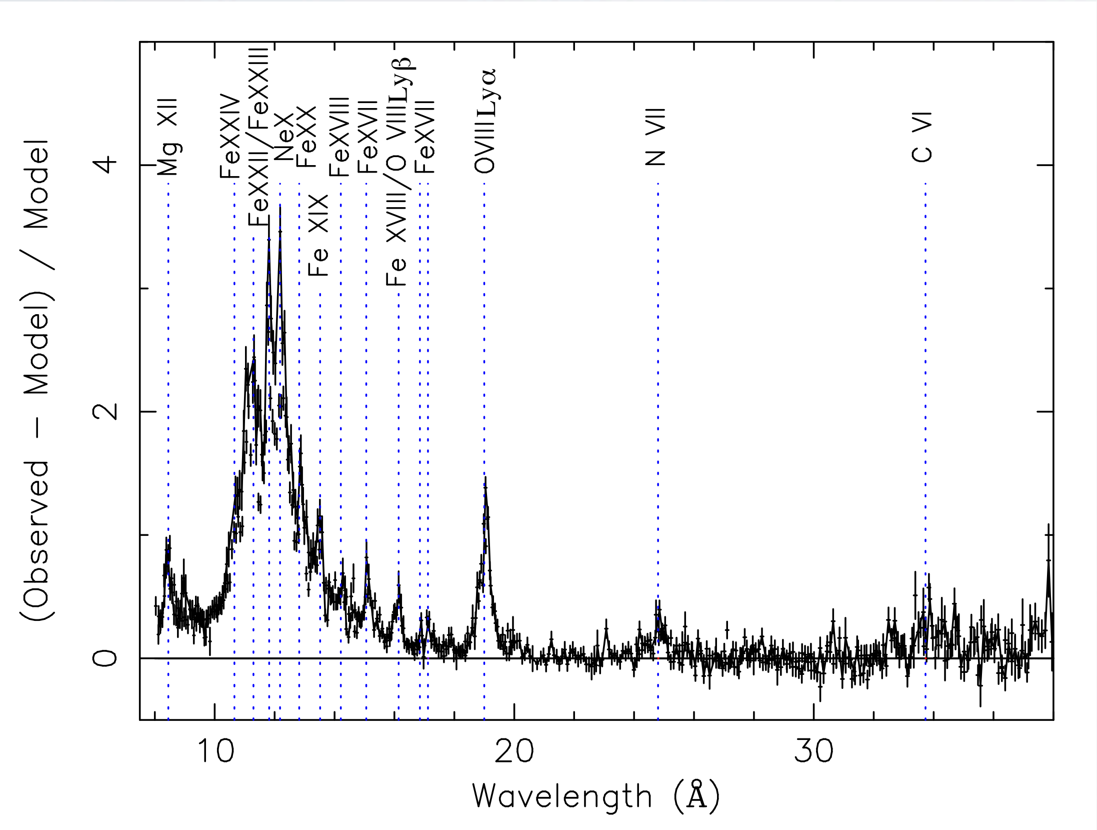




- X-ray lines between neutral fluorescent n=2-1, and H-like n=1-∞ (think of the Bohr model!)
- in ICM mostly He and H like lines

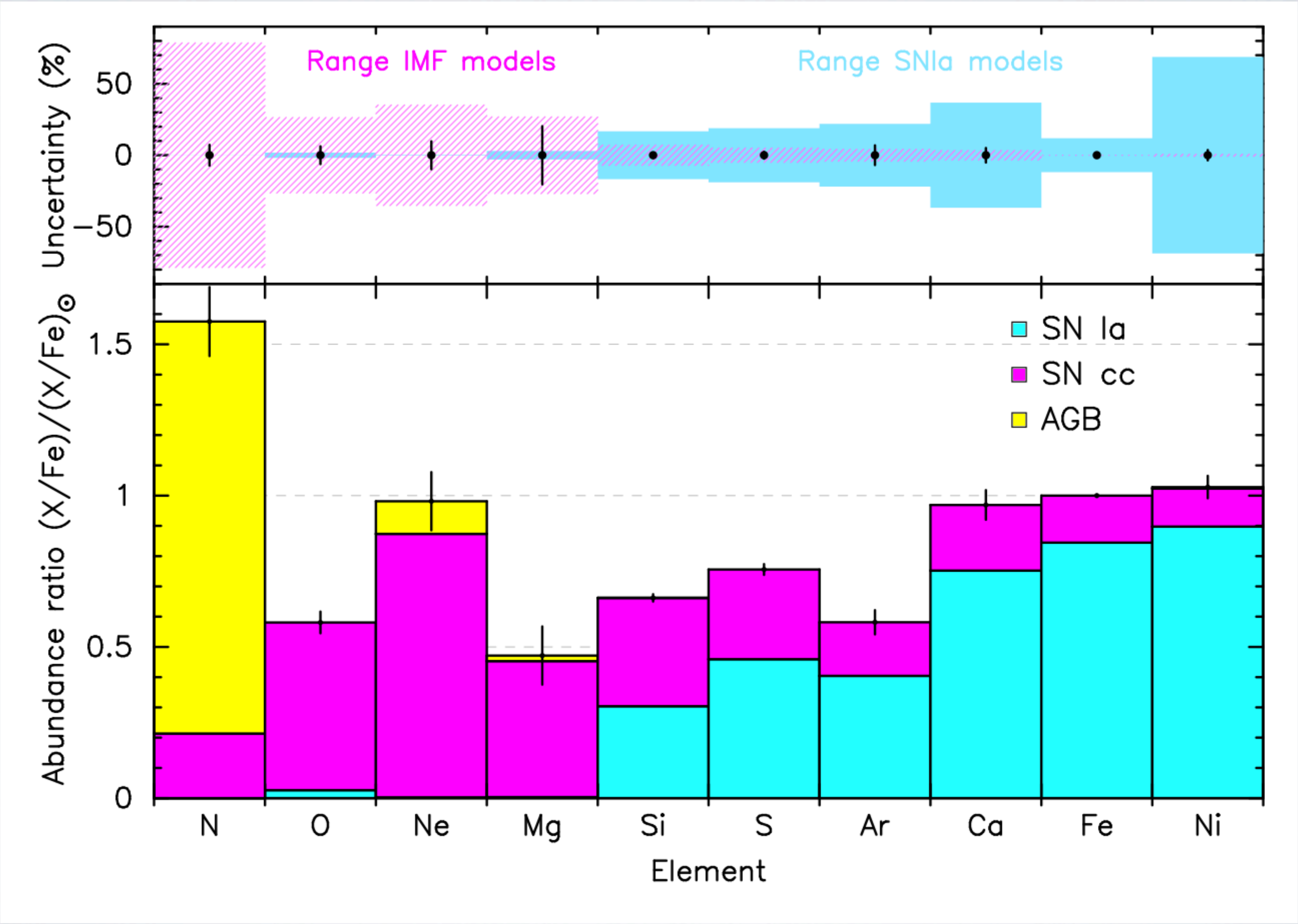
CONSTRAINING CHEMICAL ENRICHMENT



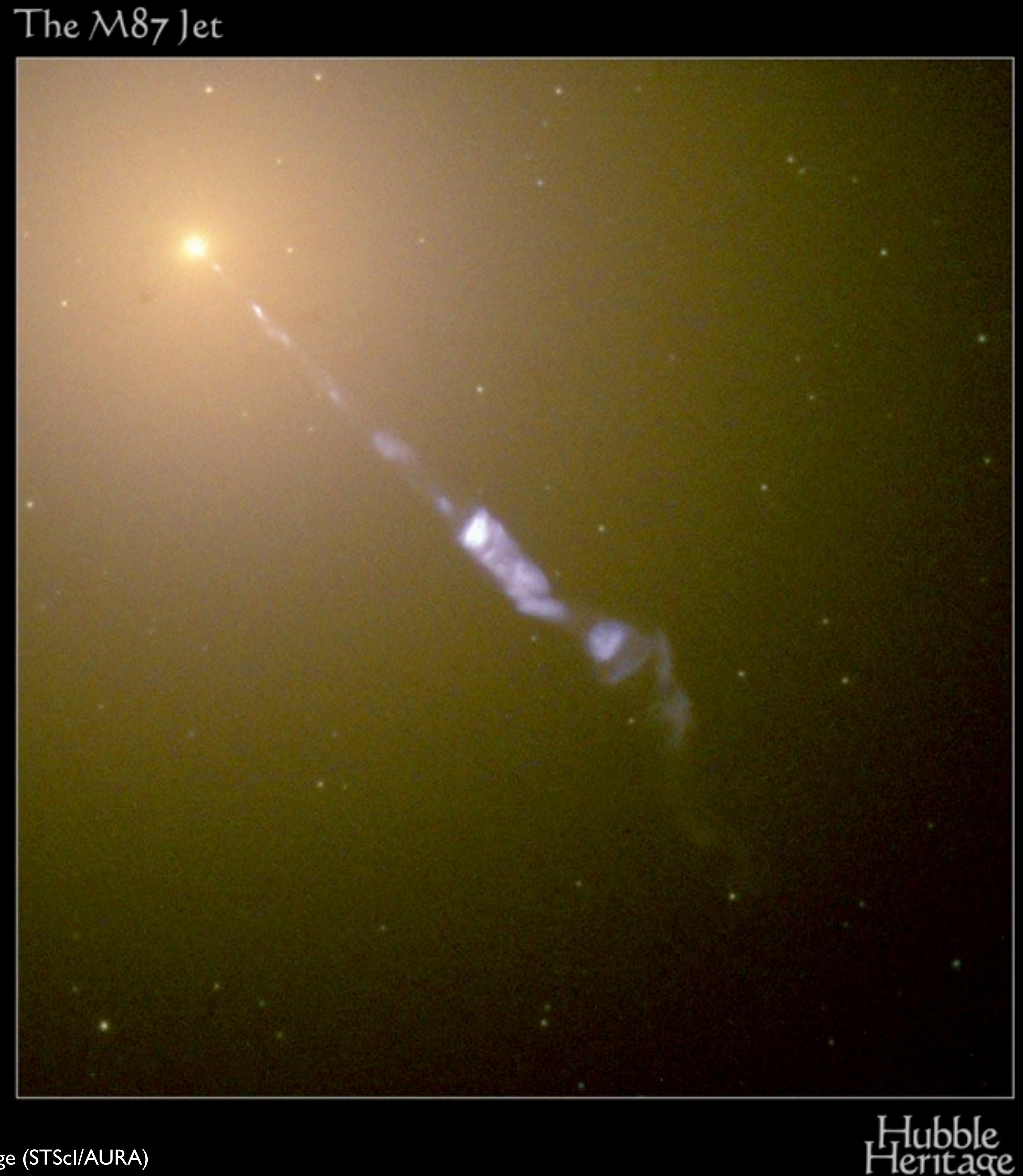


- Clusters of galaxies retain all the metals synthesized in constituent stars
- Most of baryons (also metals) reside in the diffuse gas
- X-ray spectroscopy of clusters - one of the best tools for studying the chemical evolution of the Universe
- Allows us to constrain Type Ia supernova models and the integrated stellar initial mass function

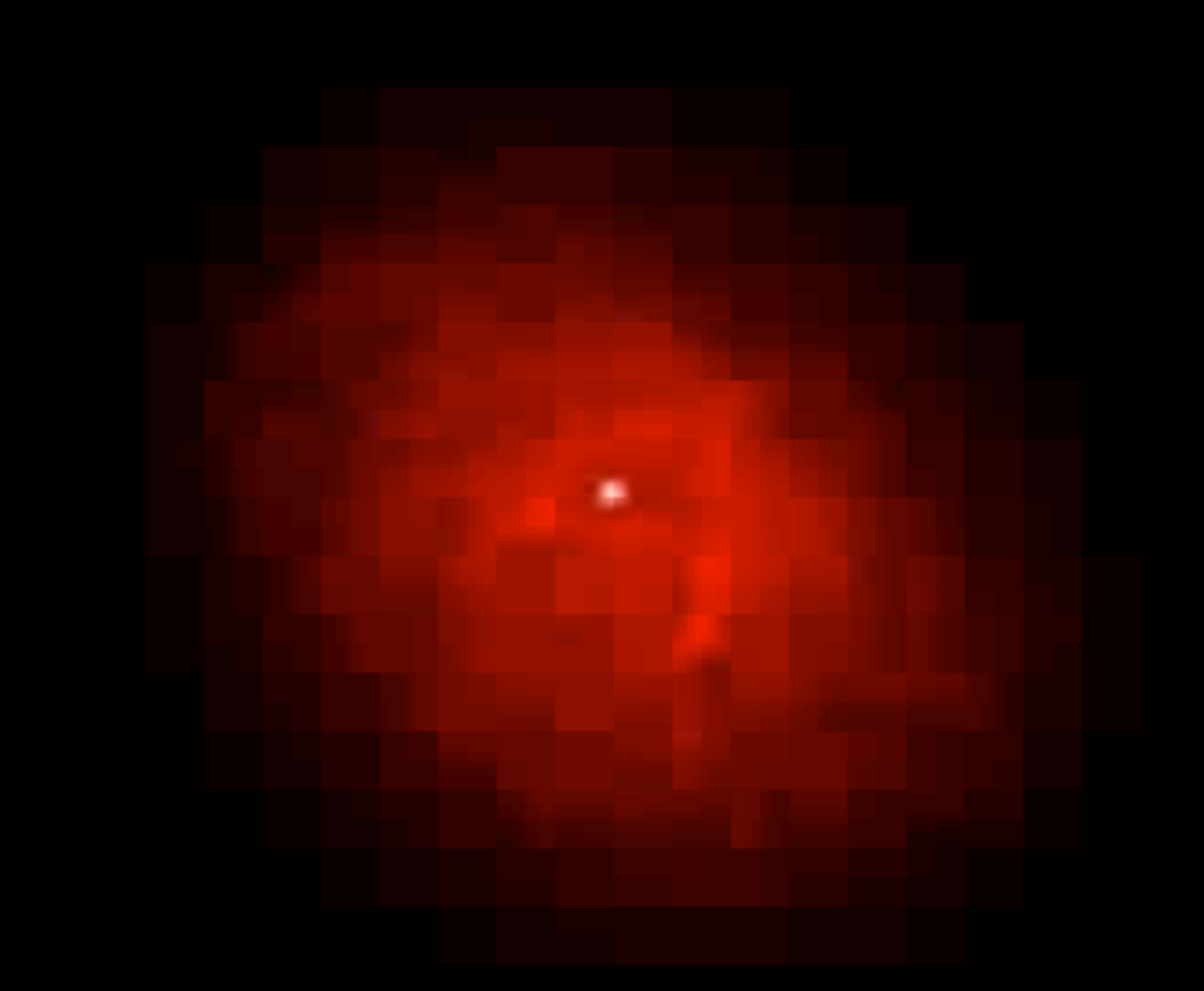
CONSTRAINING CHEMICAL ENRICHMENT




by Robert Gendler

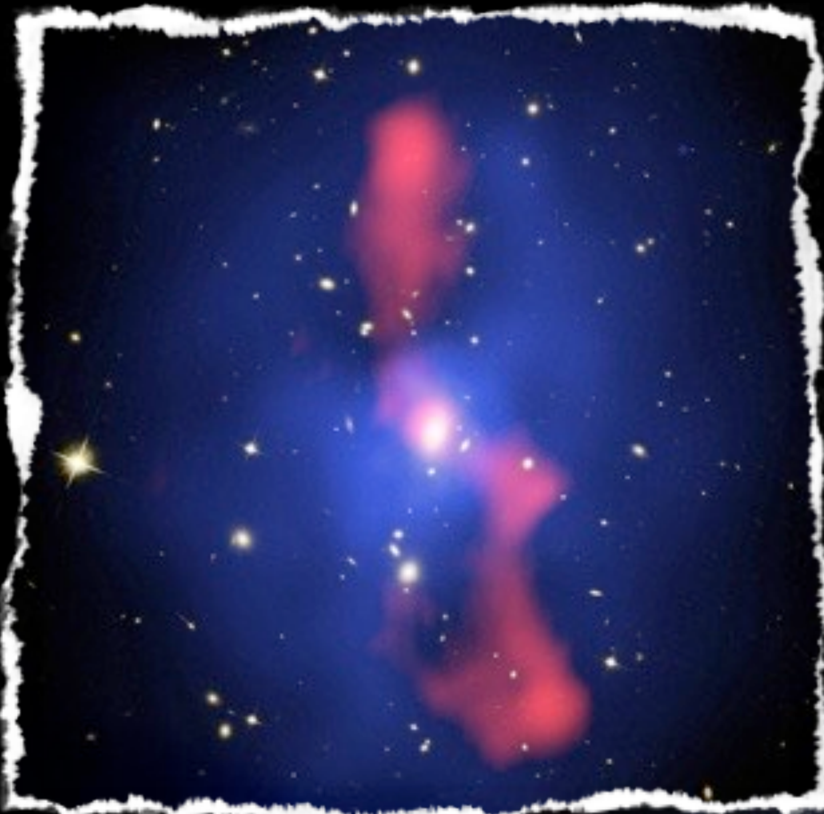


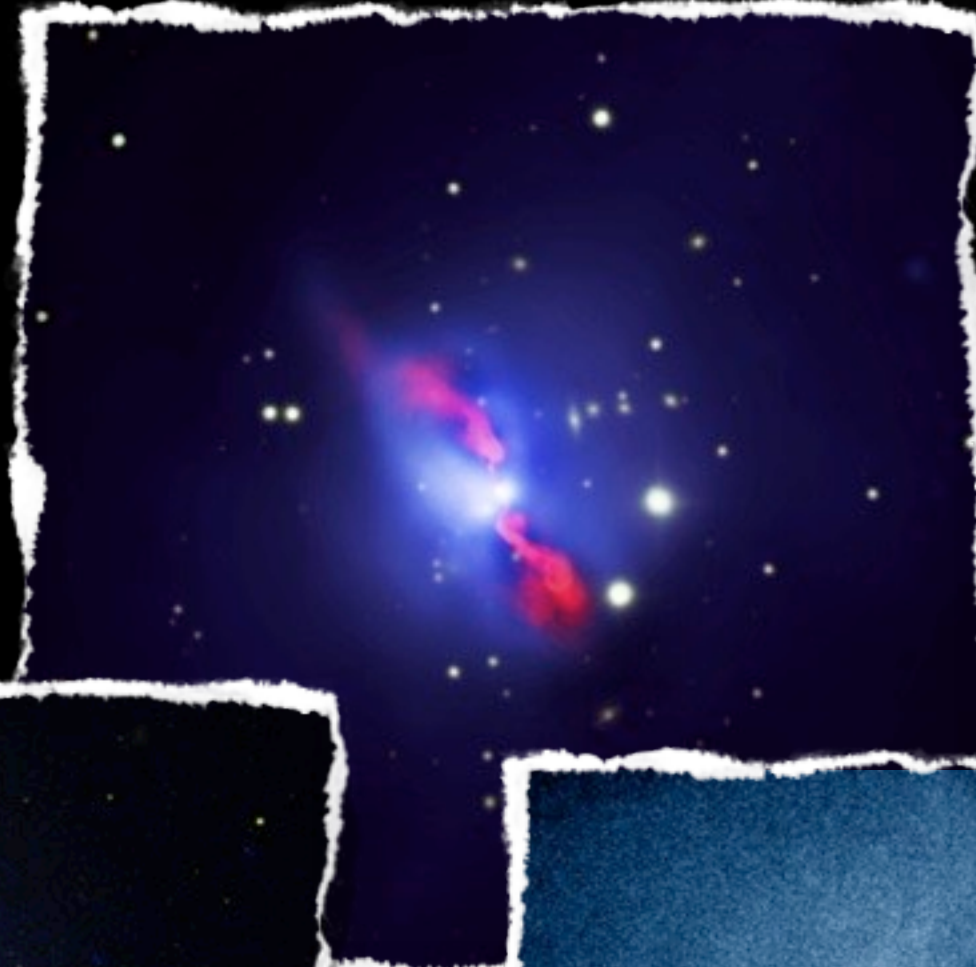
NASA, ESA, Hubble Heritage (STScI/AURA)



NASA/CXC/A.Hobart

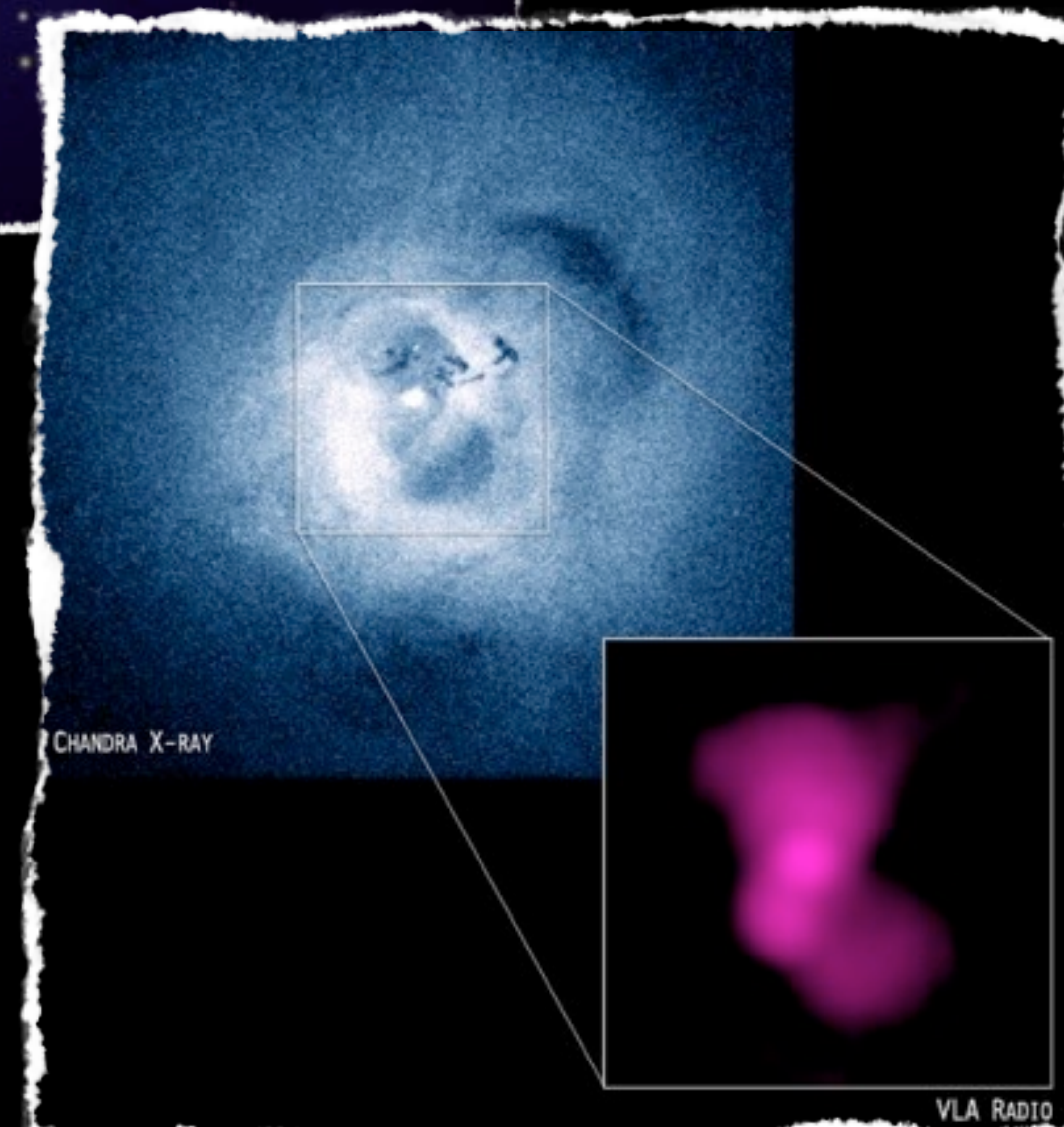
MS0735.6+7421





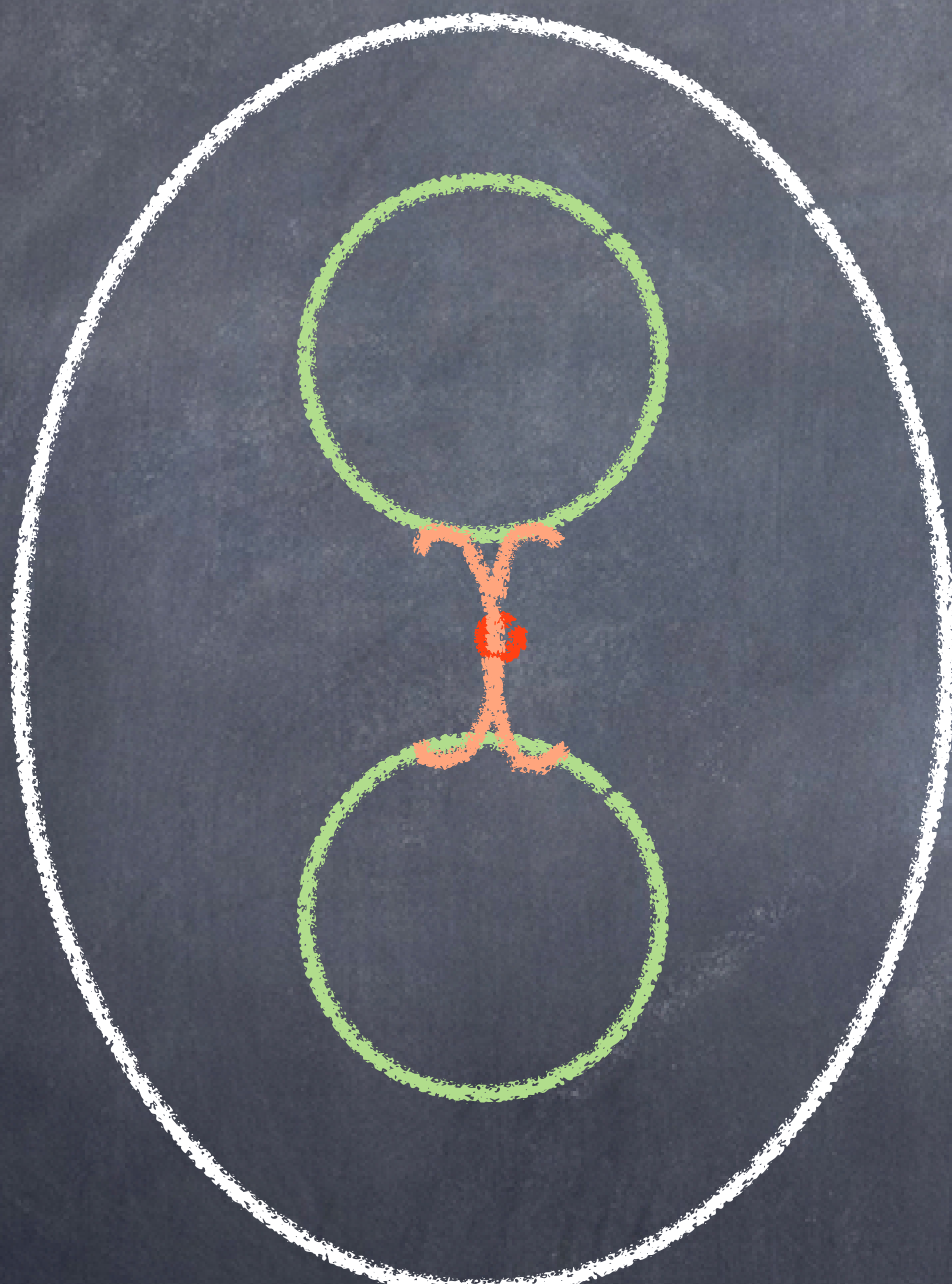
Hydra A

M87 / Virgo



NGC1275 / Perseus

AGN feedback

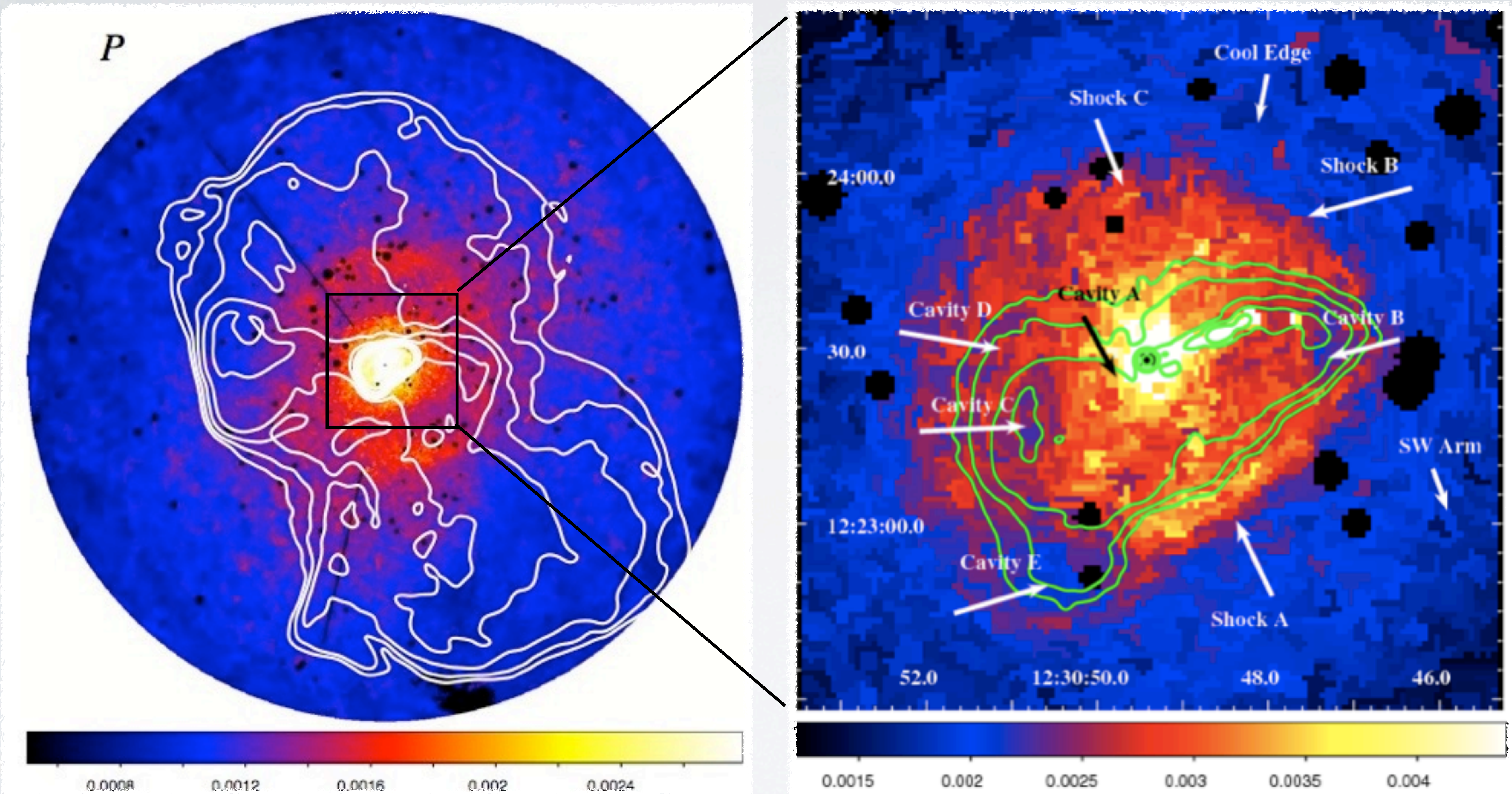


shocks: high temperature; high pressure

cavities: radio bright; X-ray faint

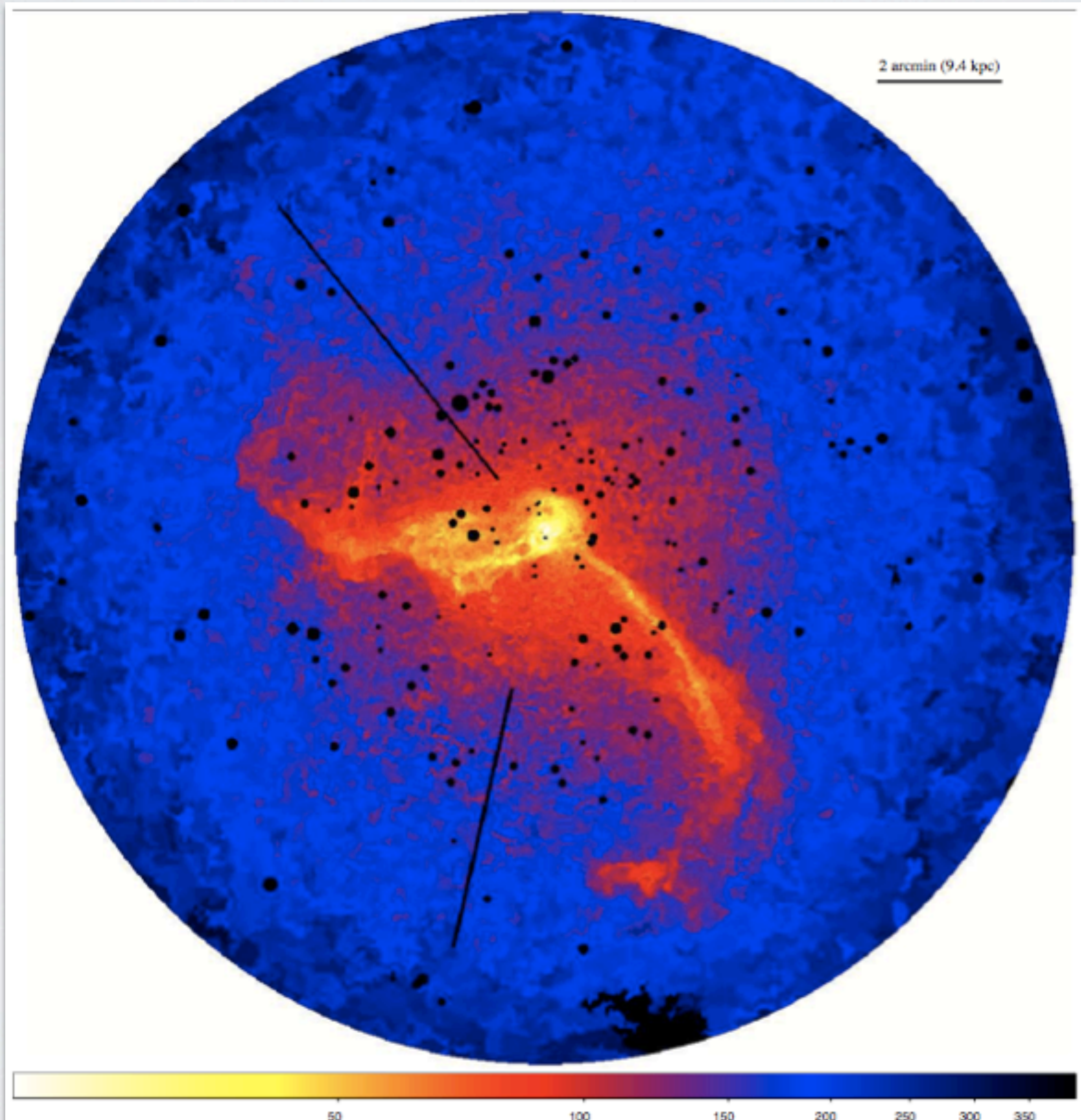
filaments: X-ray bright; low temperature; metal rich

PRESSURE MAP: SPHERICAL SHOCKS



Million et al. 2010

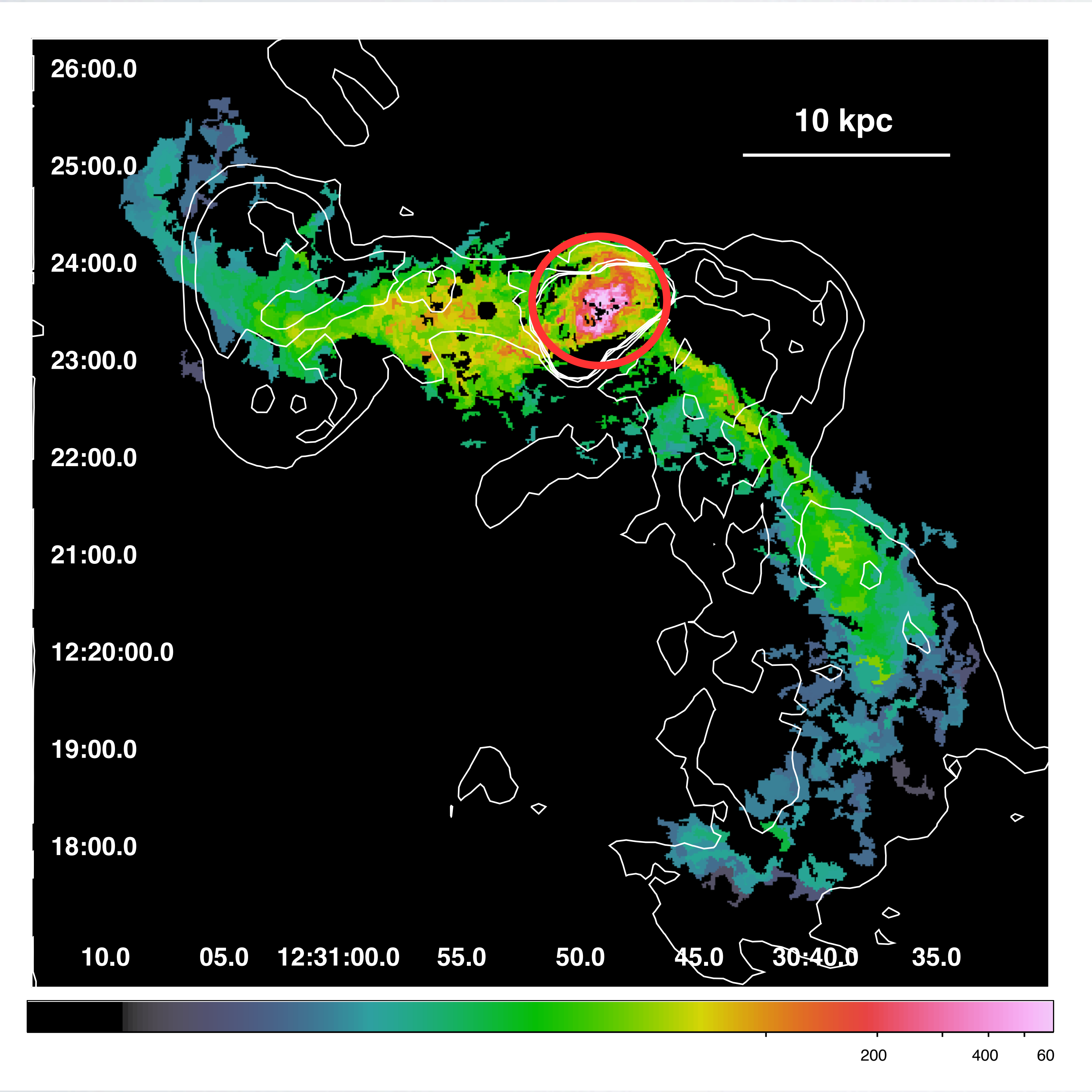
ENTROPY ($kT/n^{2/3}$) MAP



50 100 150 200 250 350

Million et al. 2010

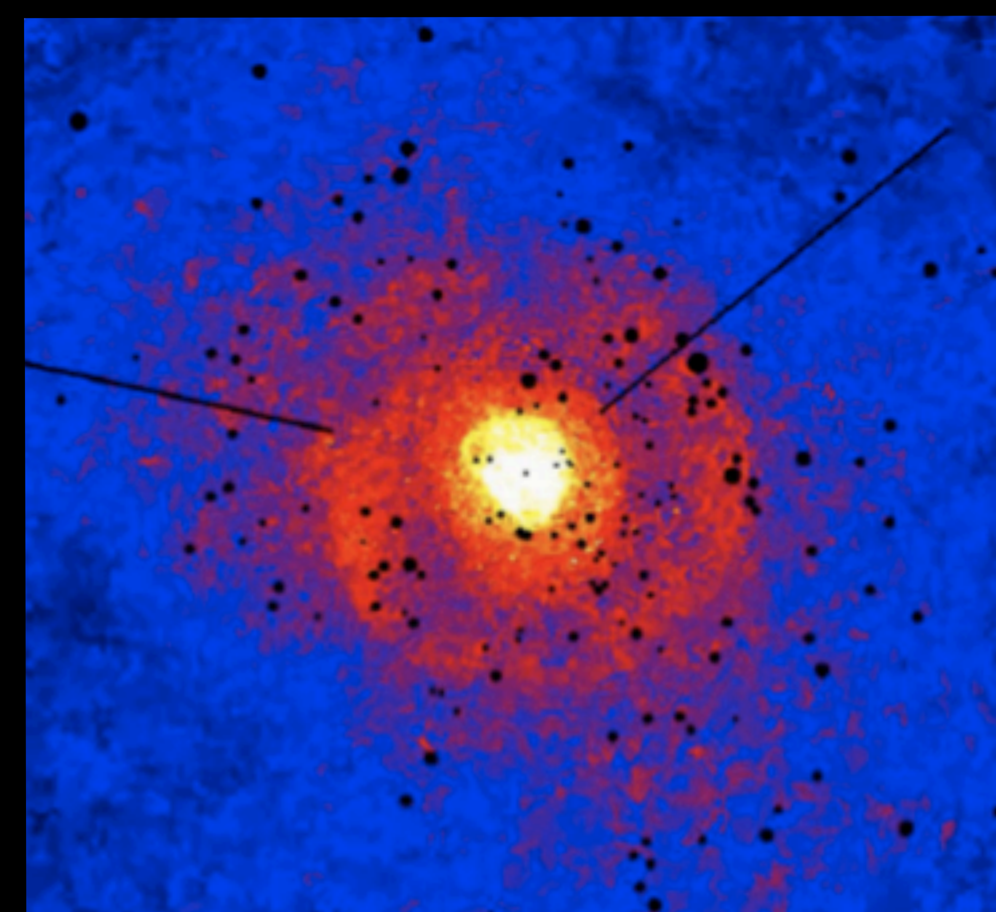
GAS UPLIFT

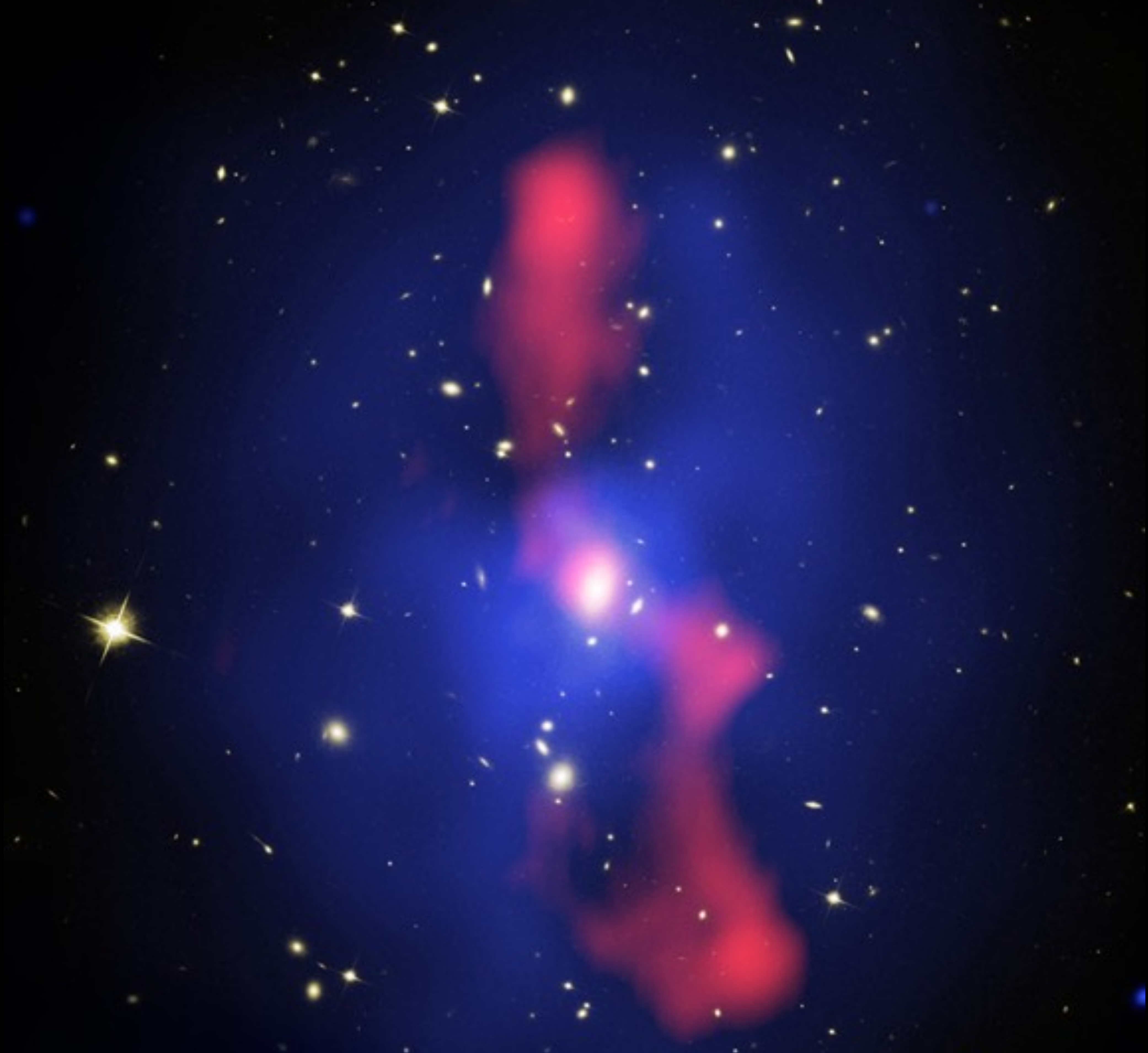


- 6-9x10^8 Msun of gas in arms
- similar to total gas mass within 3.8 kpc radius
- galaxy stripped of its lowest entropy gas
- AGN feedback in action, preventing star formation

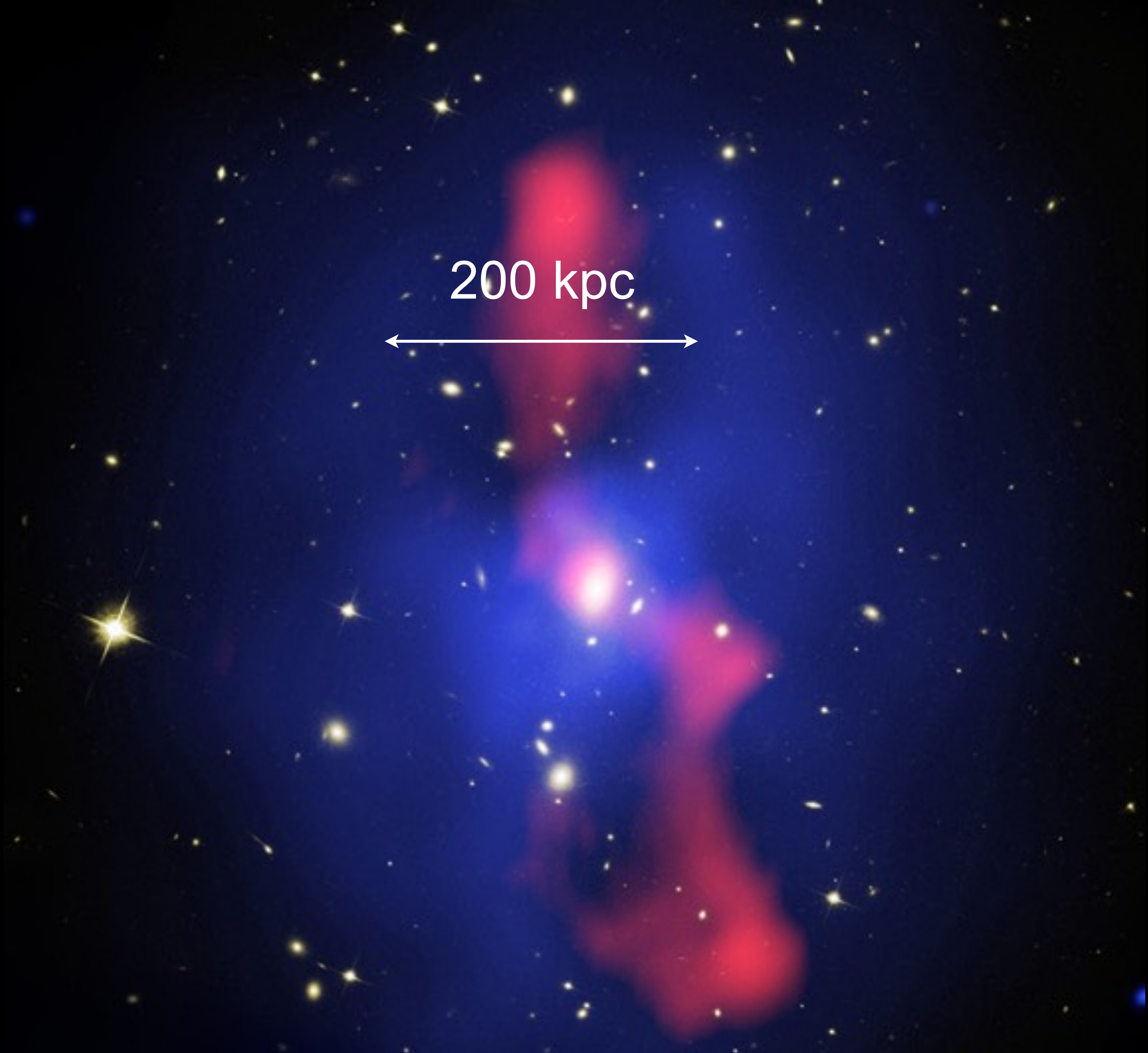
Werner et al. 2010

OUTBURSTS NEAR AND FAR



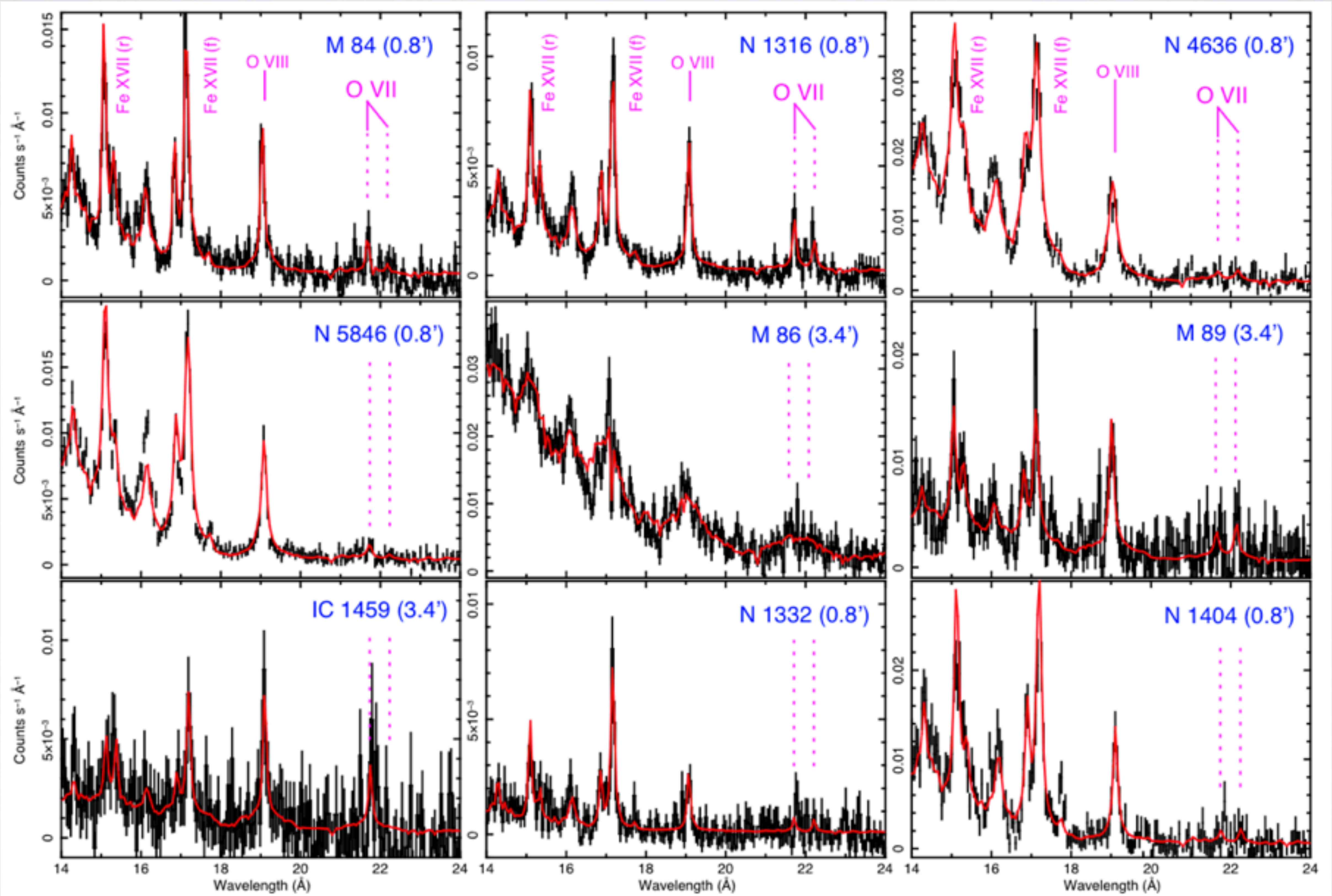


X-ray: NASA/CXC/Univ. Waterloo/B.McNamara; Optical: NASA/ESA/STScI/Univ. Waterloo/B.McNamara; Radio: NRAO/Ohio Univ./L.Birzan et al.



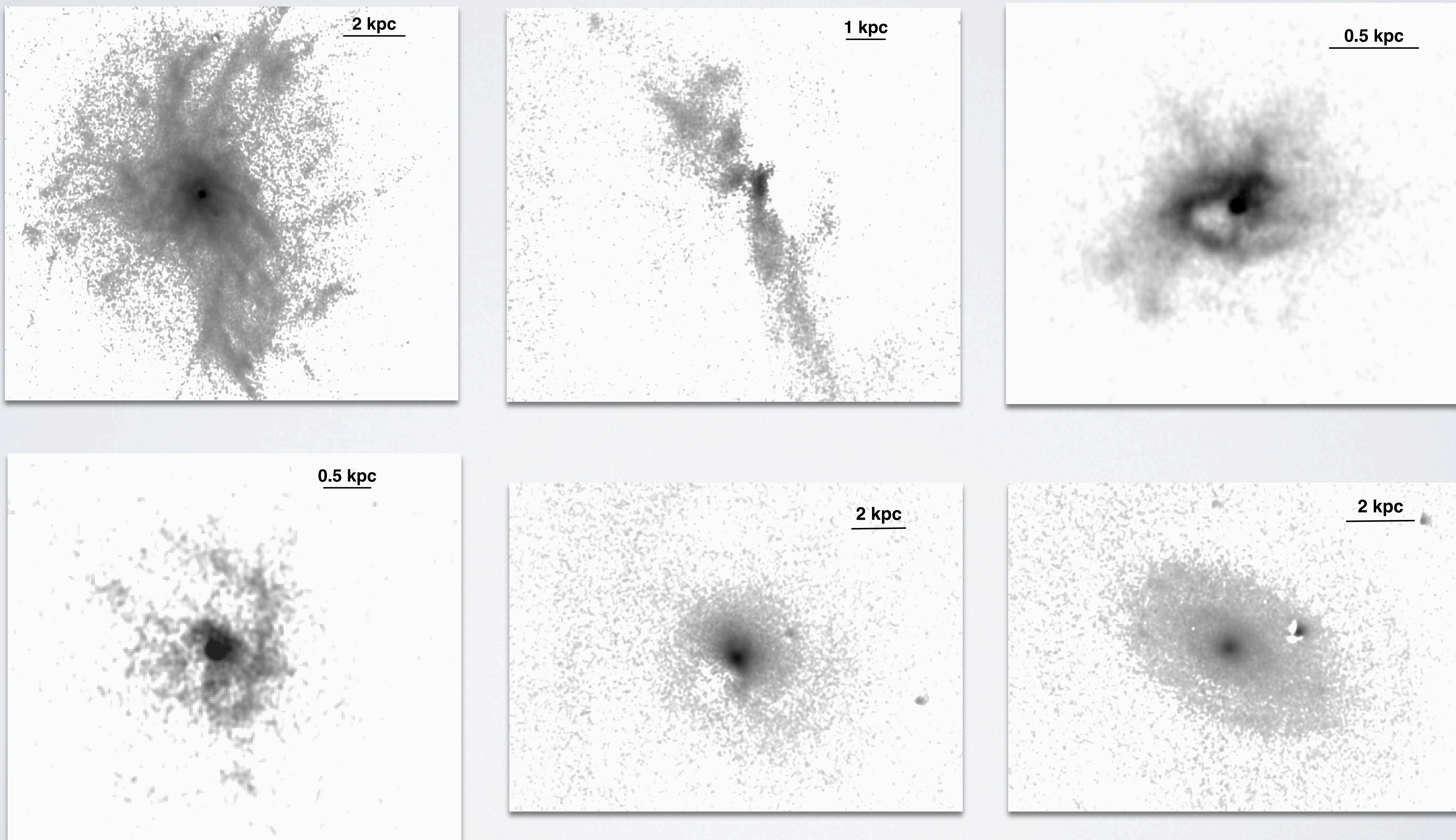
X-ray: NASA/CXC/Univ. Waterloo/B.McNamara; Optical: NASA/ESA/STScI/Univ. Waterloo/B.McNamara; Radio: NRAO/Ohio Univ./L.Birzan et al.

RESIDUAL COOLING



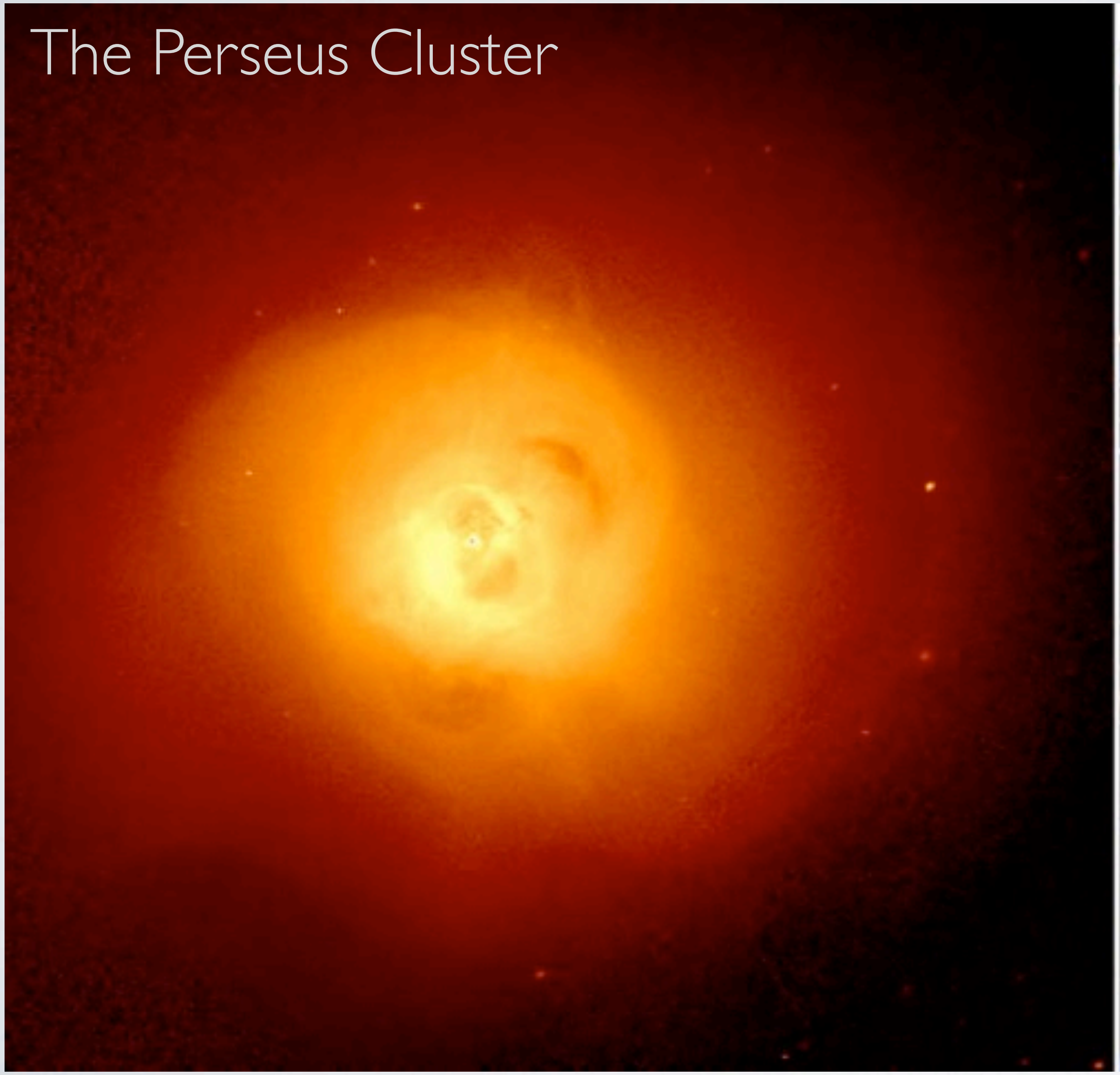
Pinto et al. 2015

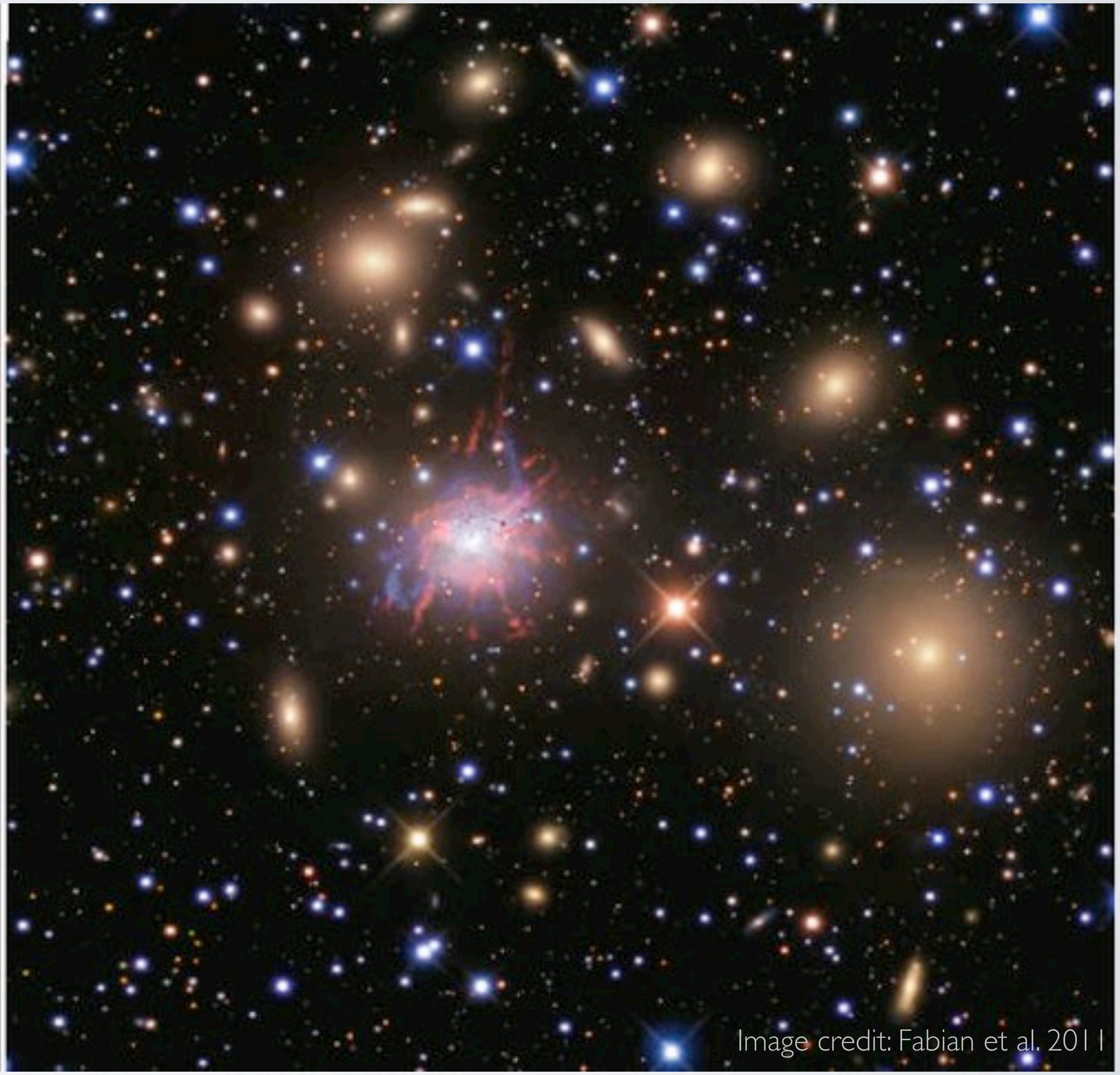
Hα+[NII] IMAGING WITH THE SOAR TELESCOPE



Werner et al. 2014

Filaments of ionized and molecular gas surrounding NGC 1275 in the centre of the Perseus Cluster



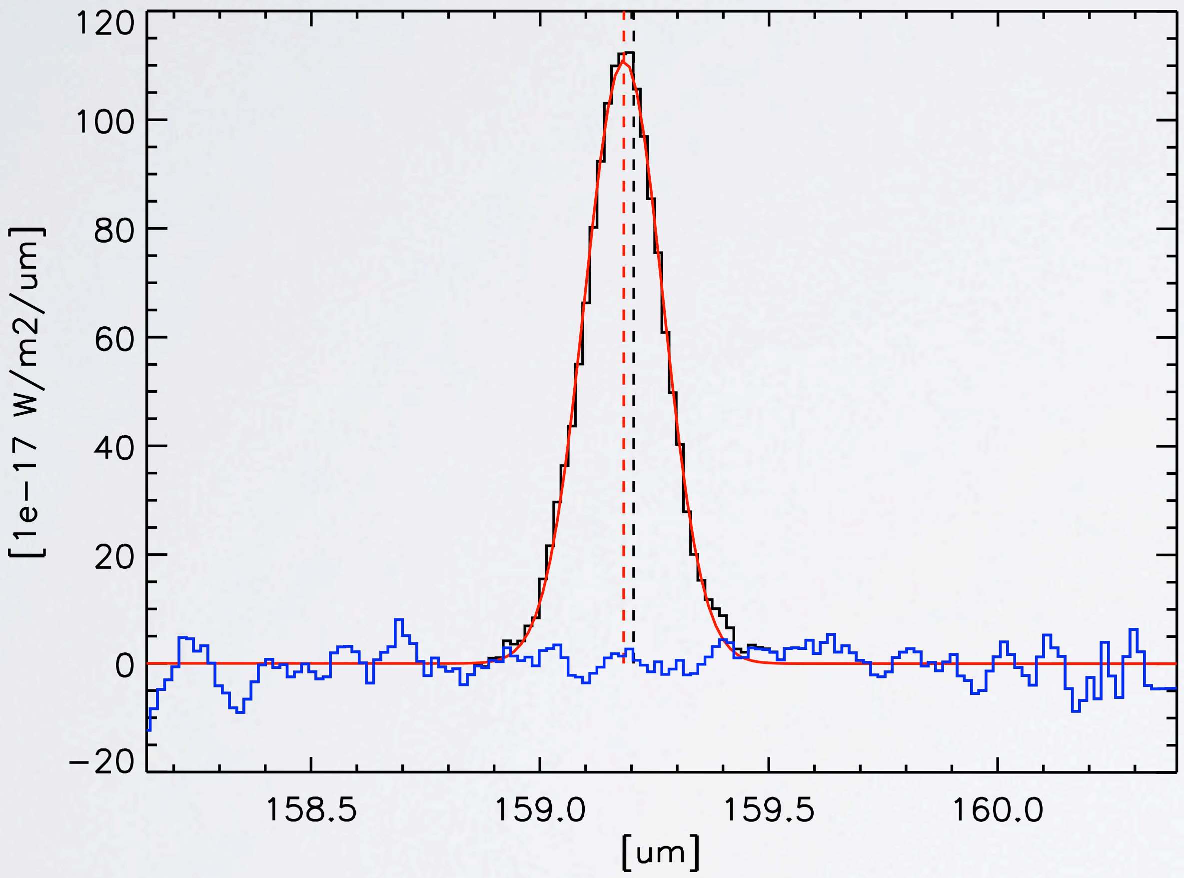


SEARCH FOR COLD GAS WITH THE *HERSCHEL* SPACE OBSERVATORY

- we observed the cooling lines of [CII], [OI] with *Herschel*
- [CII] an excellent tracer of 100 K gas, its flux is usually a few thousand times stronger than CO

Werner et al. 2013a, 2014

FAR-INFRARED LINE DETECTIONS IN GIANT ELLIPTICALS

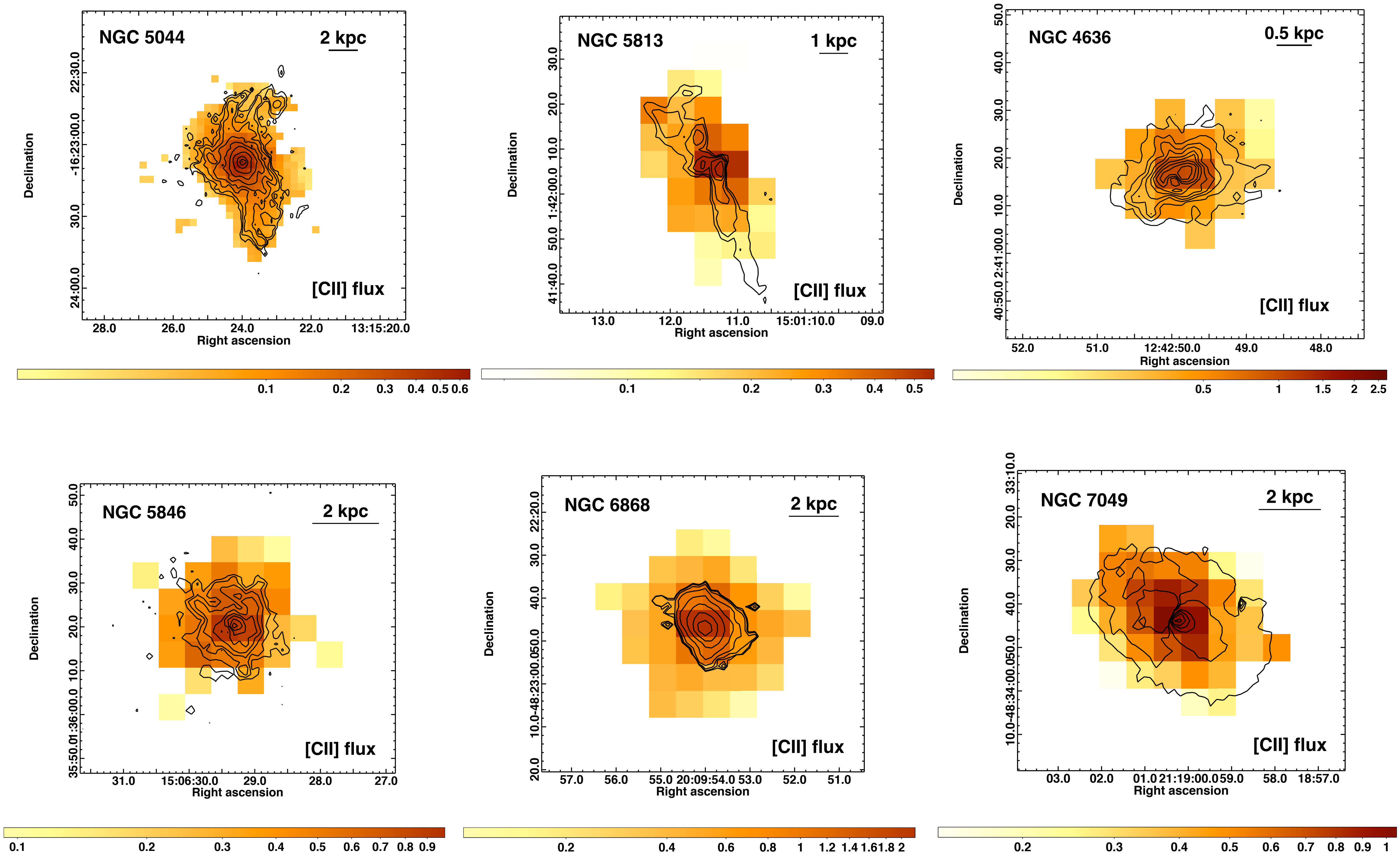


- [CII] detected in every single galaxy (6/8) with extended Hα line emitting nebulae

- in 4/8 systems also detected the [OI] line and in 3/8 the [OIb] line

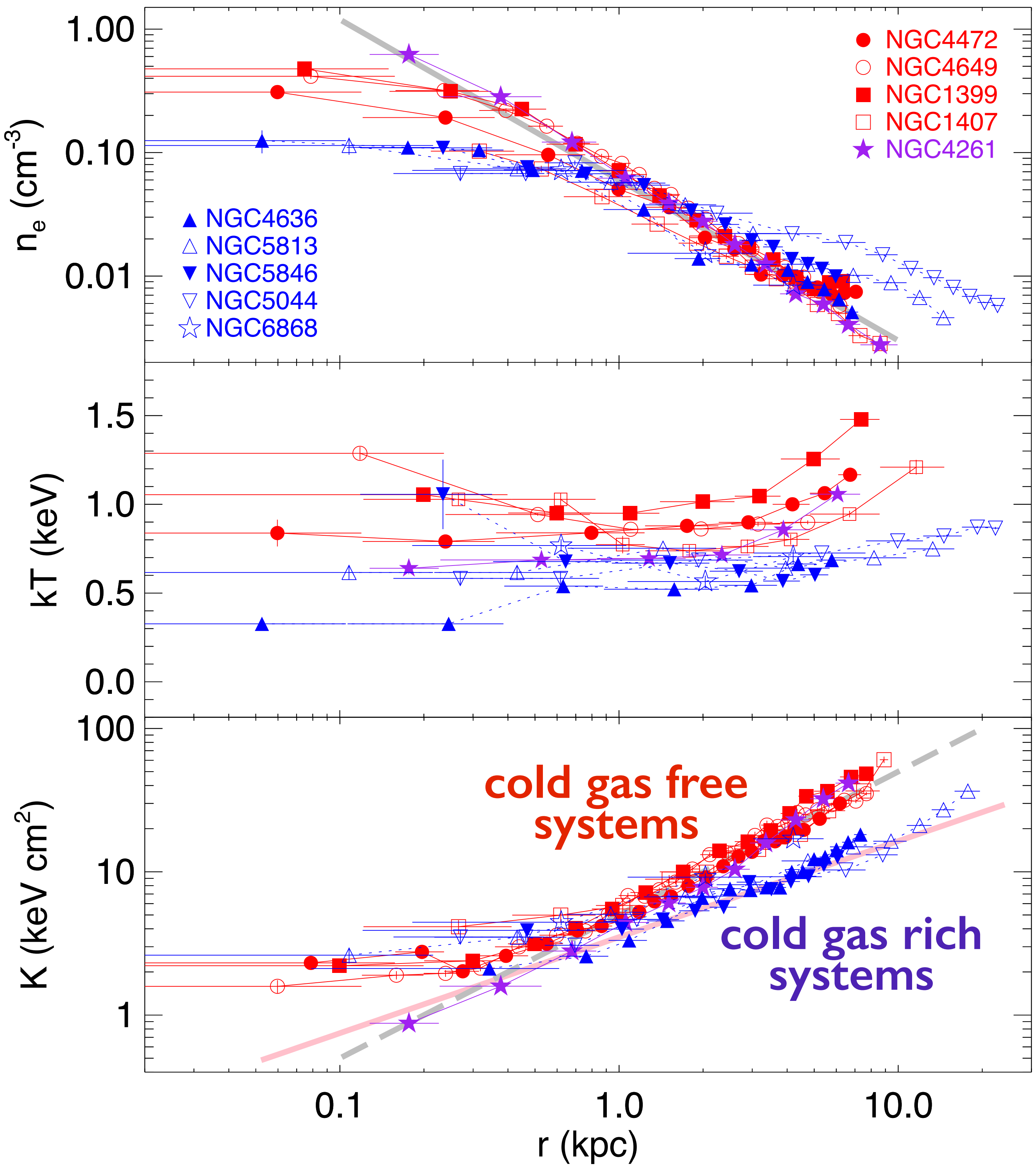
Werner et al. 2014

[CII] EMISSION FOLLOWING Hα



Werner et al. 2014

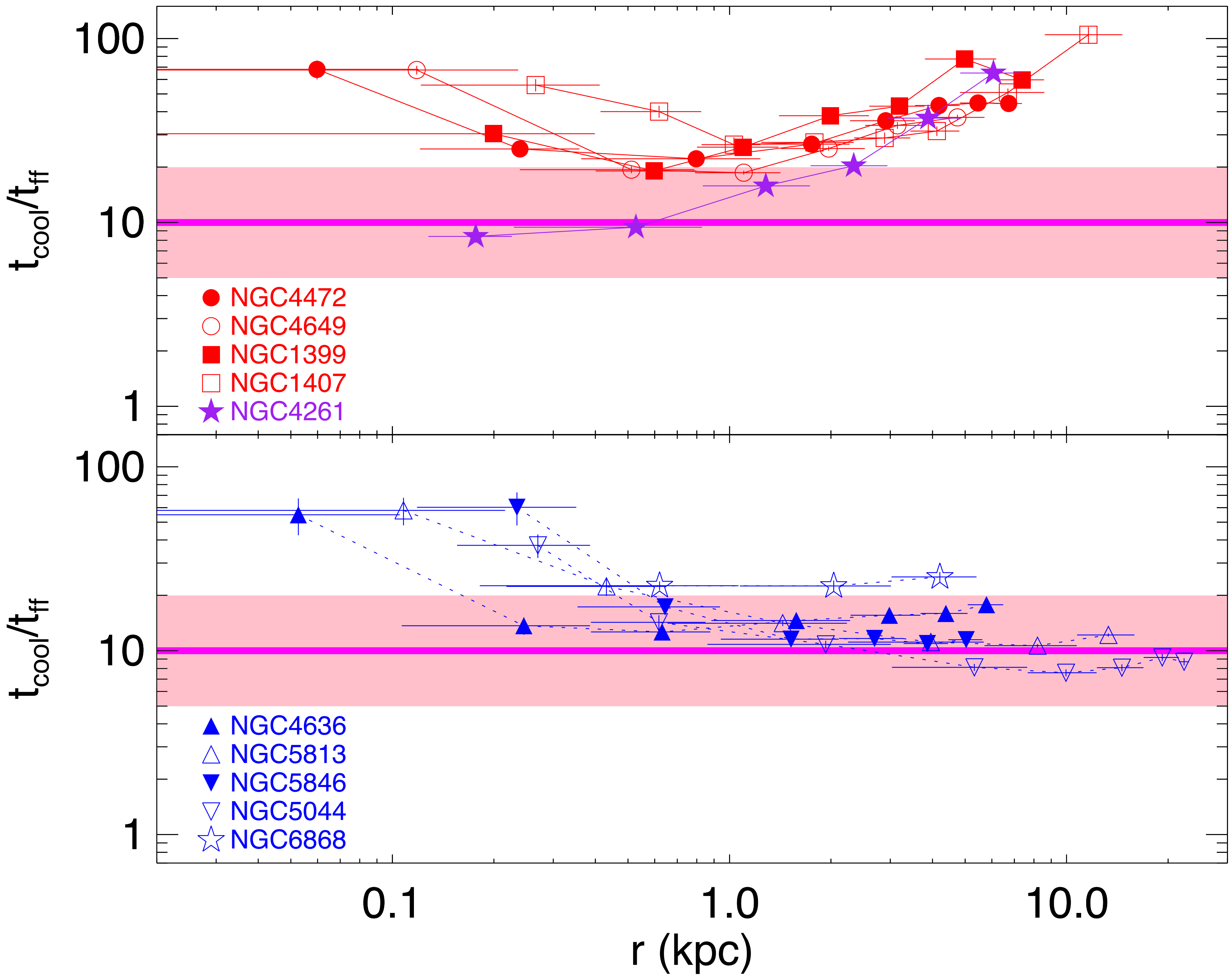
PROPERTIES OF THE HOT ISM



Outside of the innermost core, the entropy and temperature of systems containing cold gas is lower

Werner et al. 2014
Voit et al. 2015

COLD GAS RICH SYSTEMS PRONE TO COOLING INSTABILITIES



Numerical simulations predict that if $t_{cool}/t_{ff} \lesssim 10$, local thermal instabilities will create a multiphase medium (Sharma et al. 2012, Gaspari et al. 2012, 2013, McCourt et al. 2012)

We observe a clear dichotomy with the cold-gas-rich systems remaining unstable out to relatively large radii.

Werner et al. 2014
Voit et al. 2015

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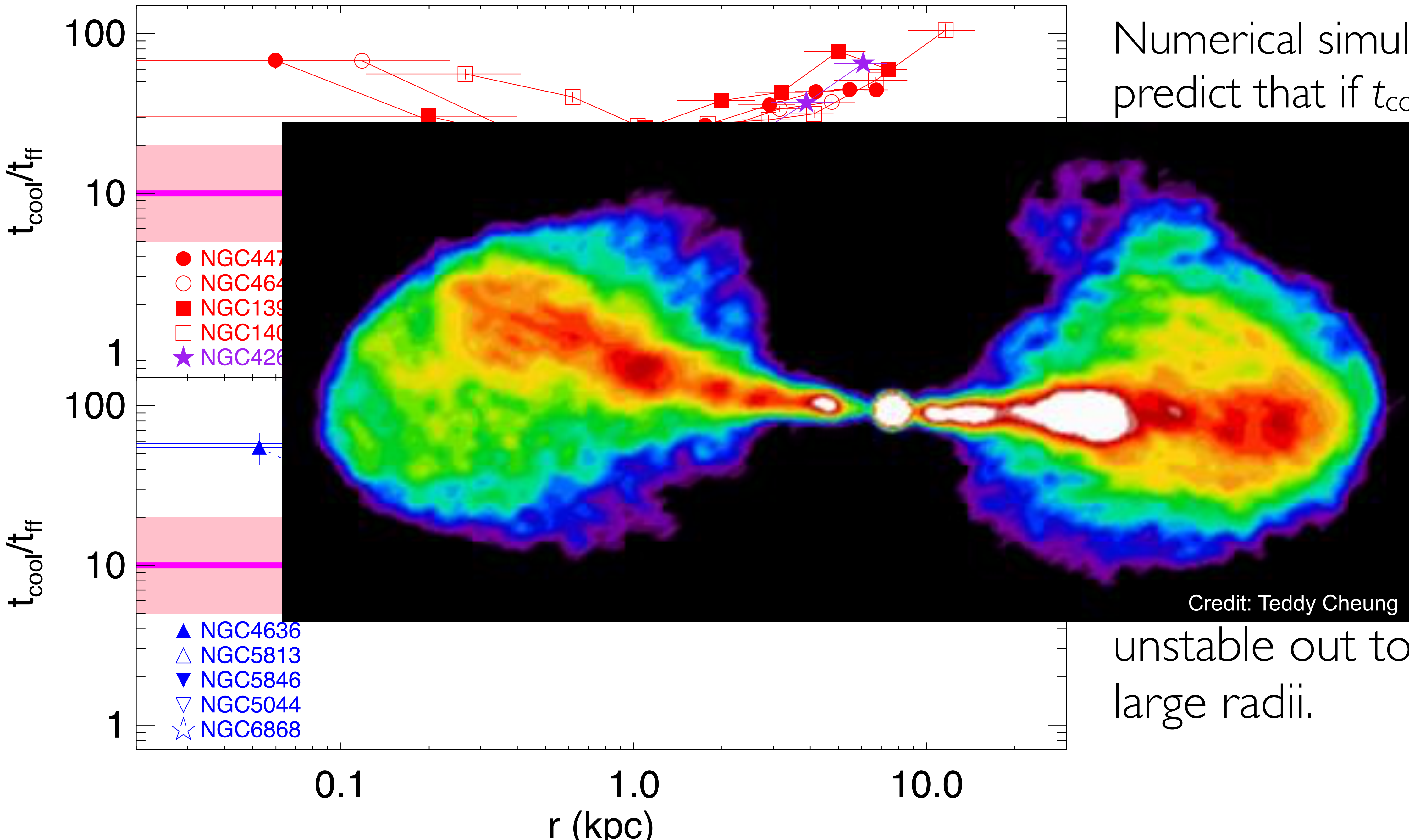

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… clear … the cold- … s remaining unstable out to relatively large radii.

Werner et al. 2014
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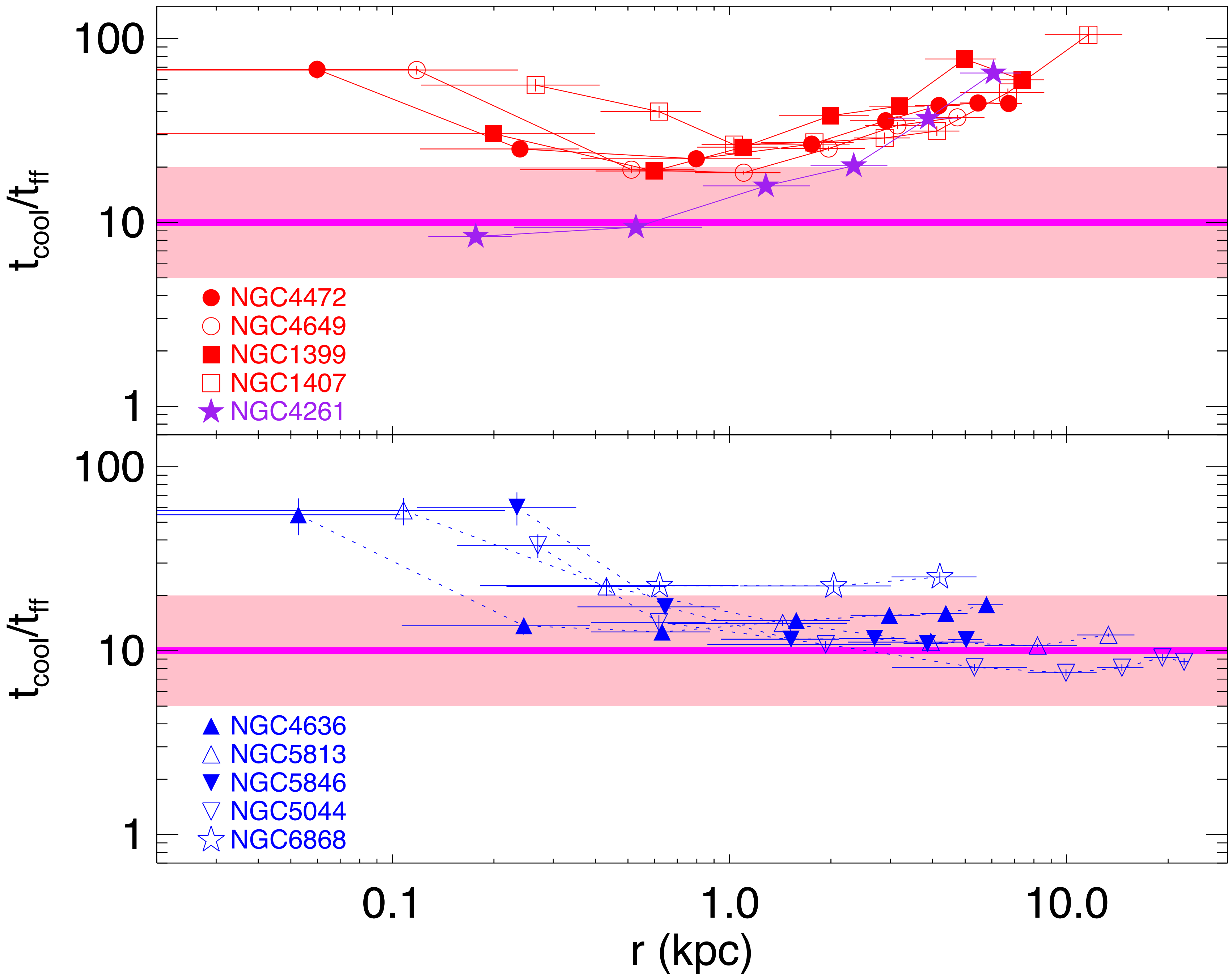
COLD GAS RICH SYSTEMS PRONE TO COOLING INSTABILITIES



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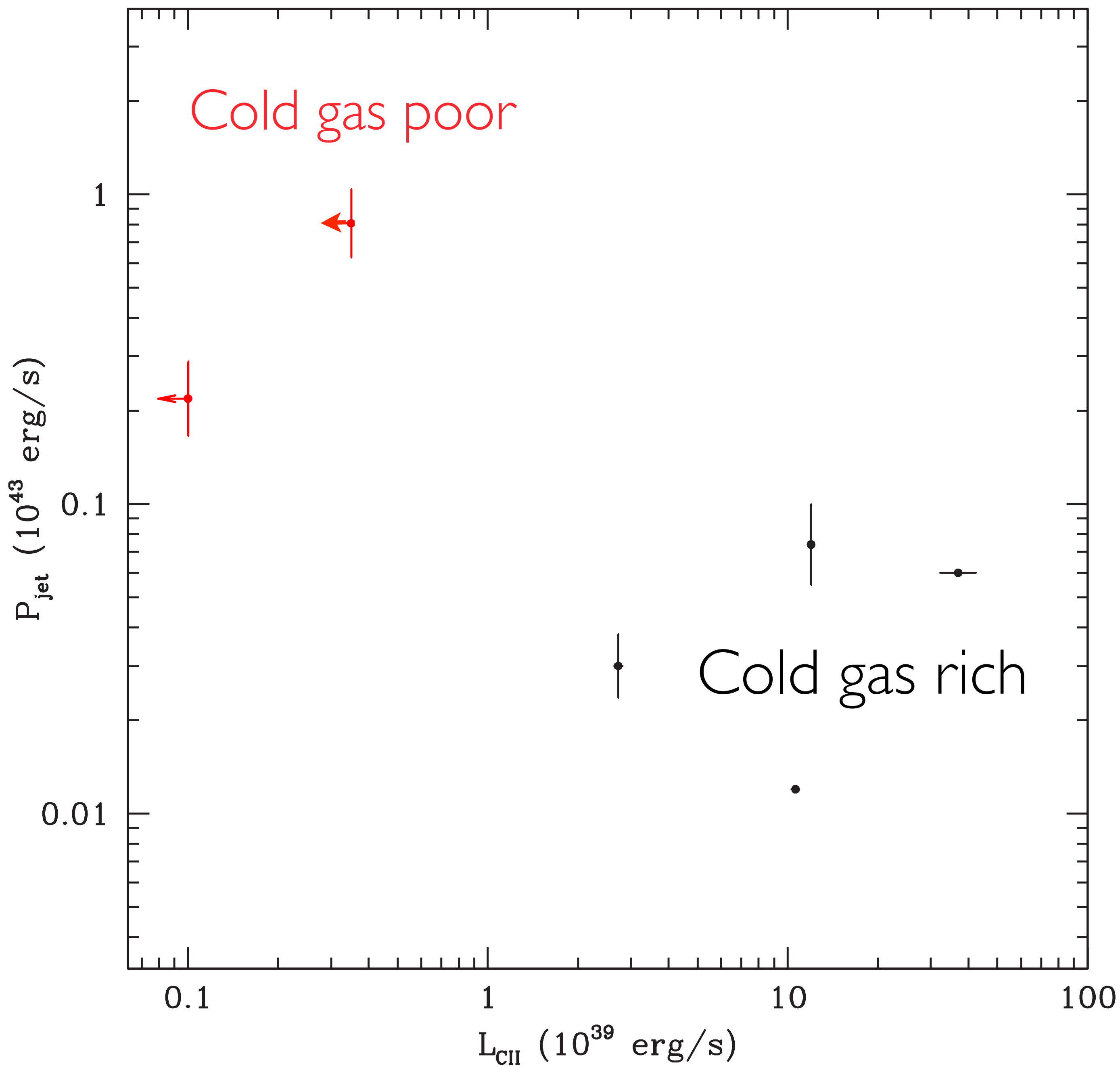
Werner et al. 2014
Voit et al. 2015

Jet powers and cold gas

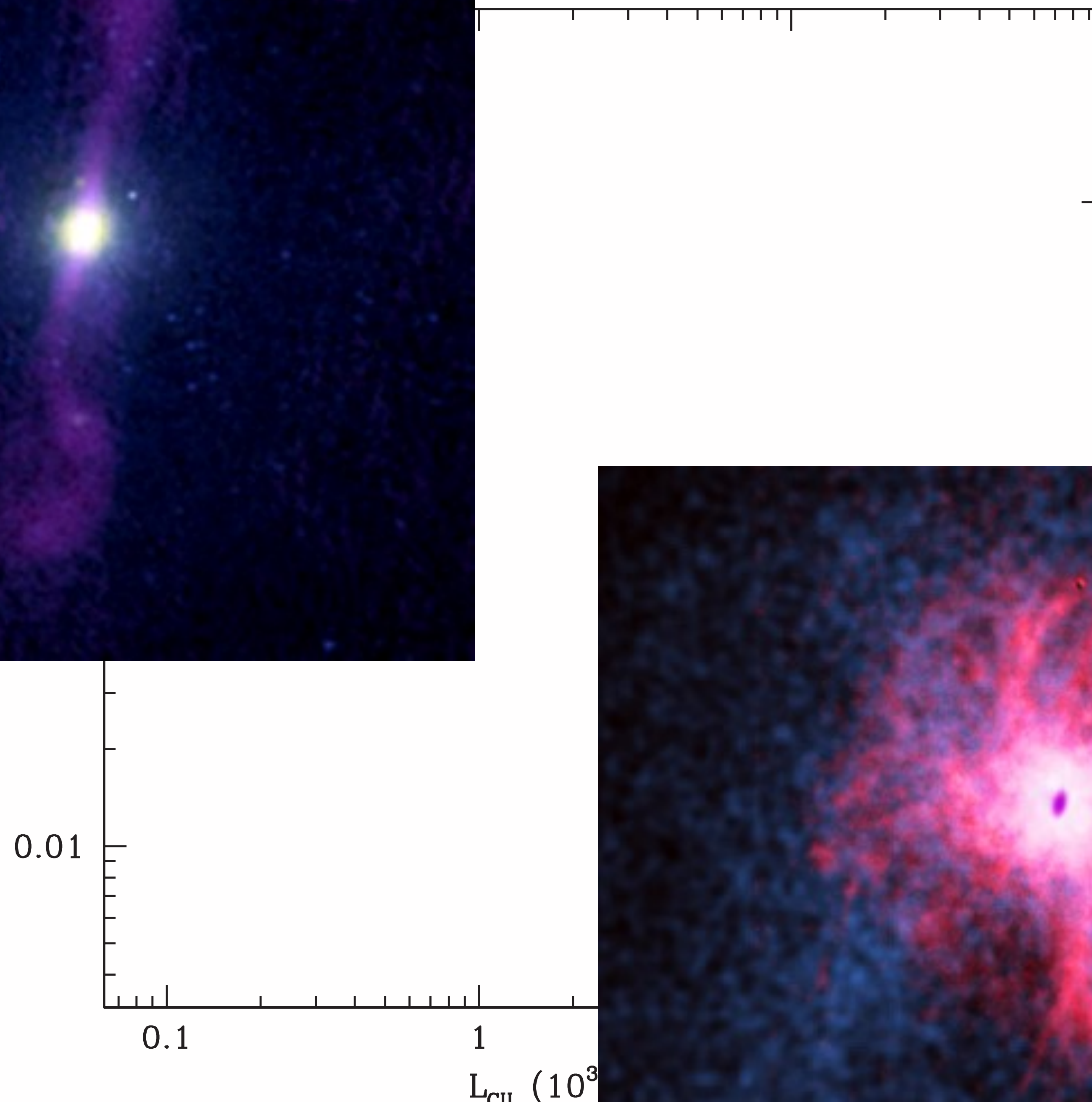


Power input (measured from X-ray cavities) into the ICM from radio mode AGN does not increase with the amount of cold gas

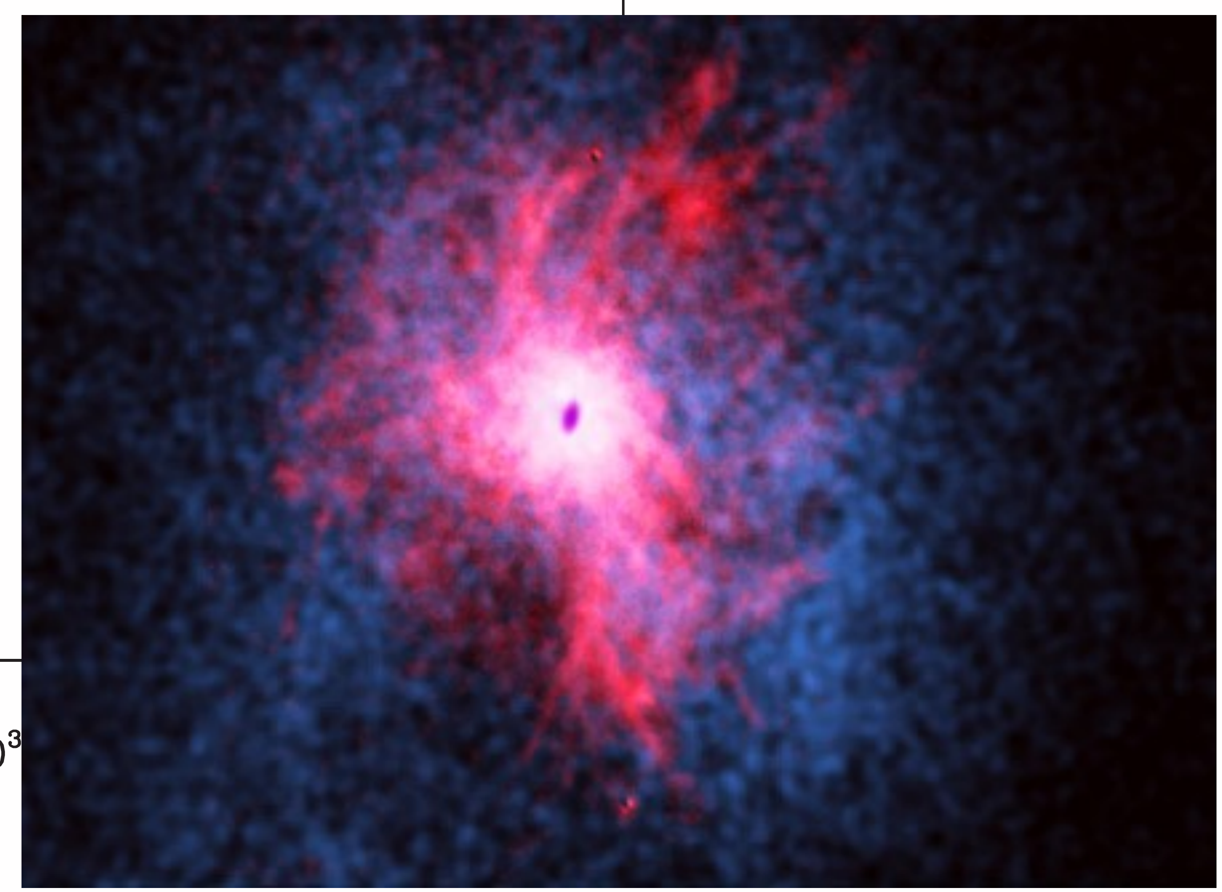
Werner et al. 2014

Jet powers and cold gas

Small jet power, many X-ray cavities and disturbed morphology, plenty of cold gas

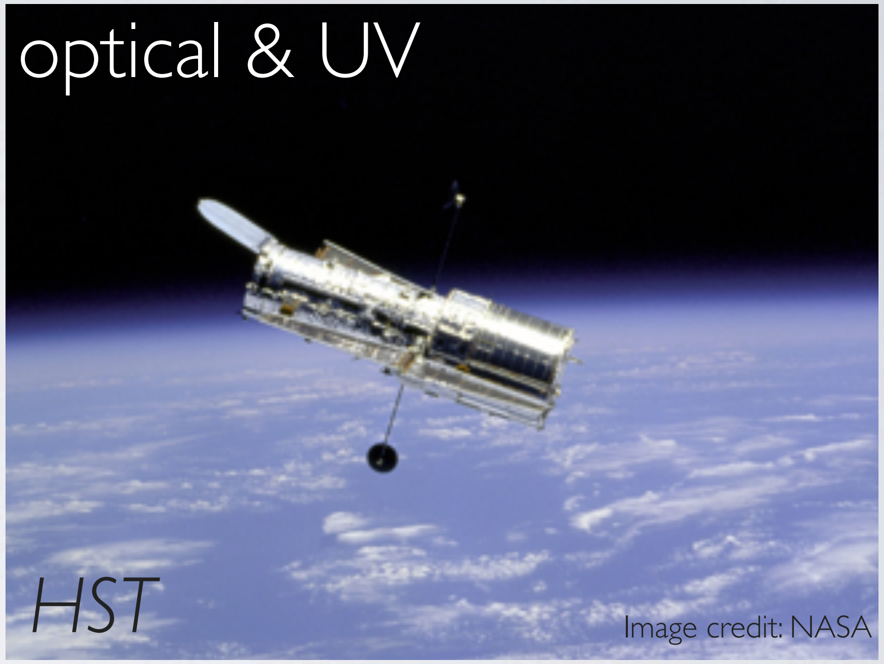


Large jet power, no cold gas, relaxed X-ray



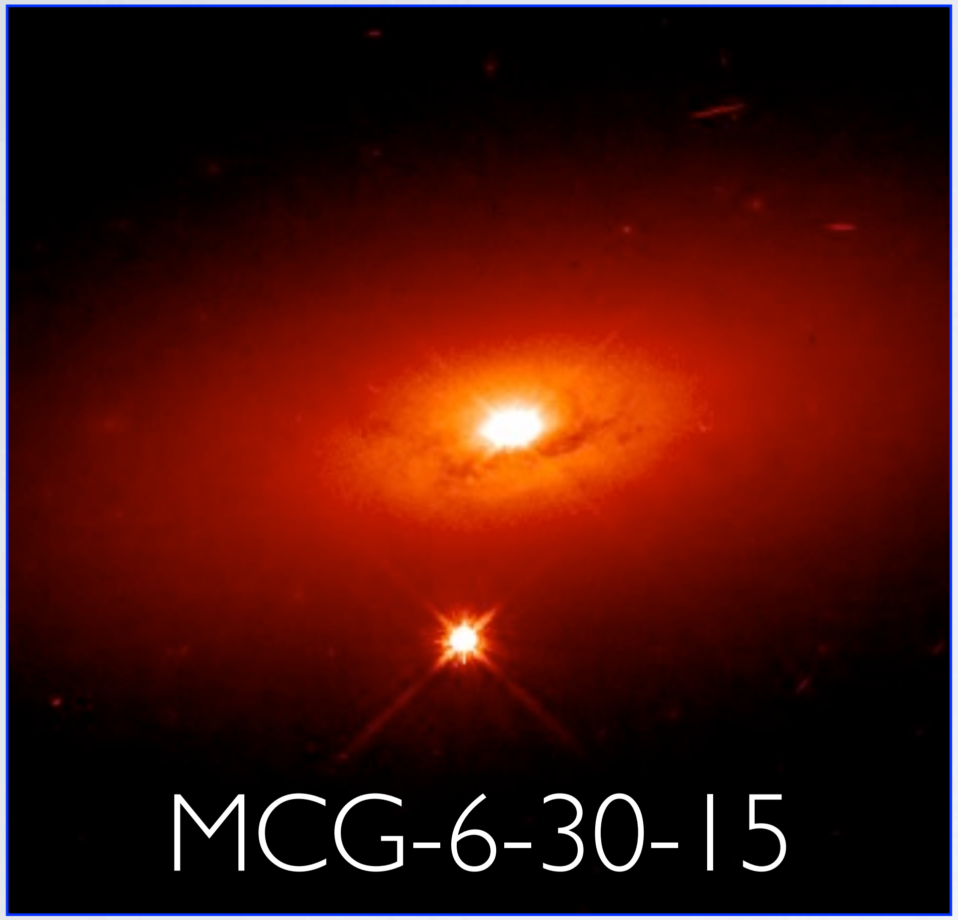
Werner et al. 2014

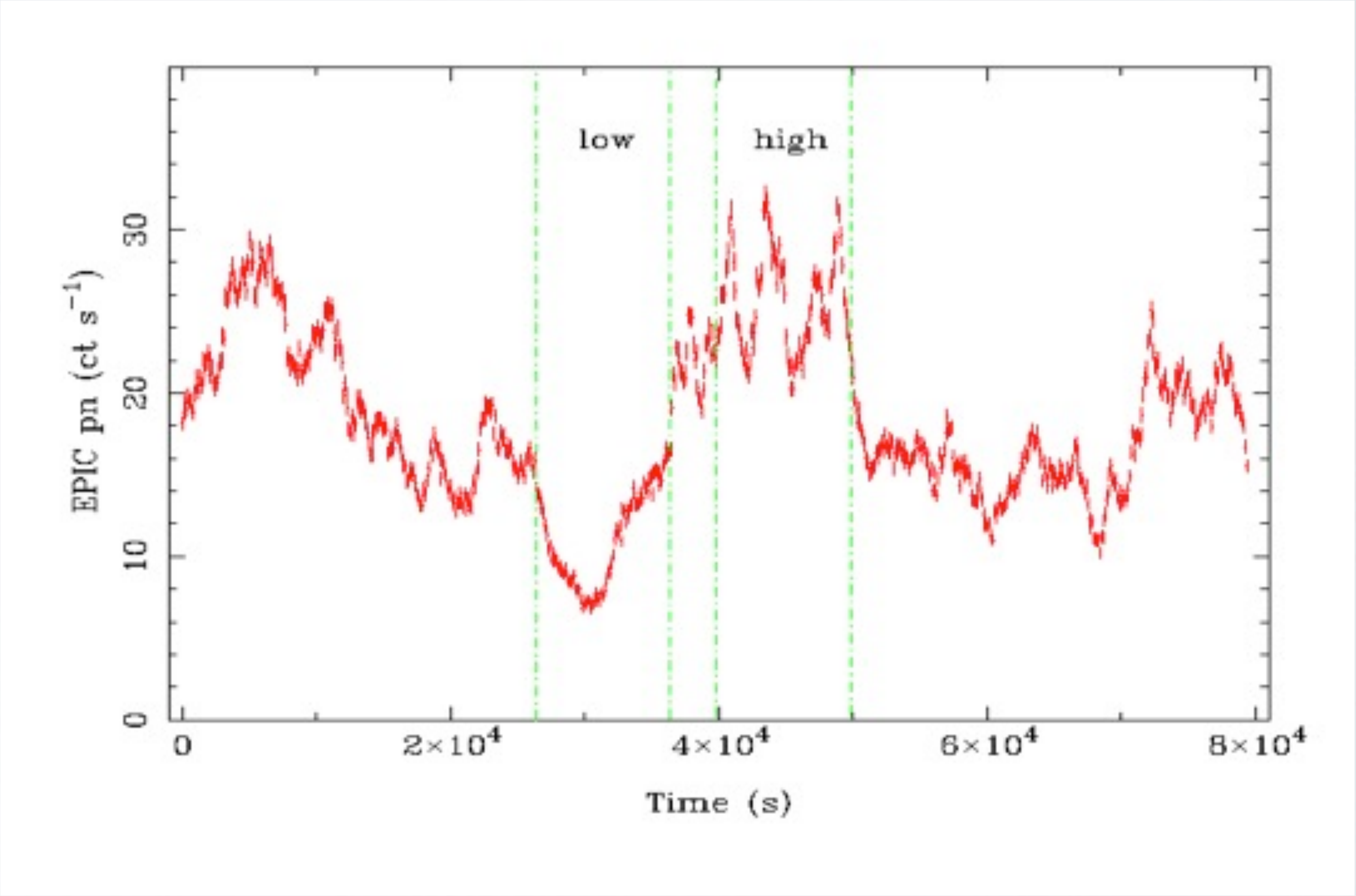
Systematic multi-wavelength study:
How do black holes regulate the growth of structure?



X-RAY BRIGHT ACCRETING SUPERMASSIVE BLACK HOLES

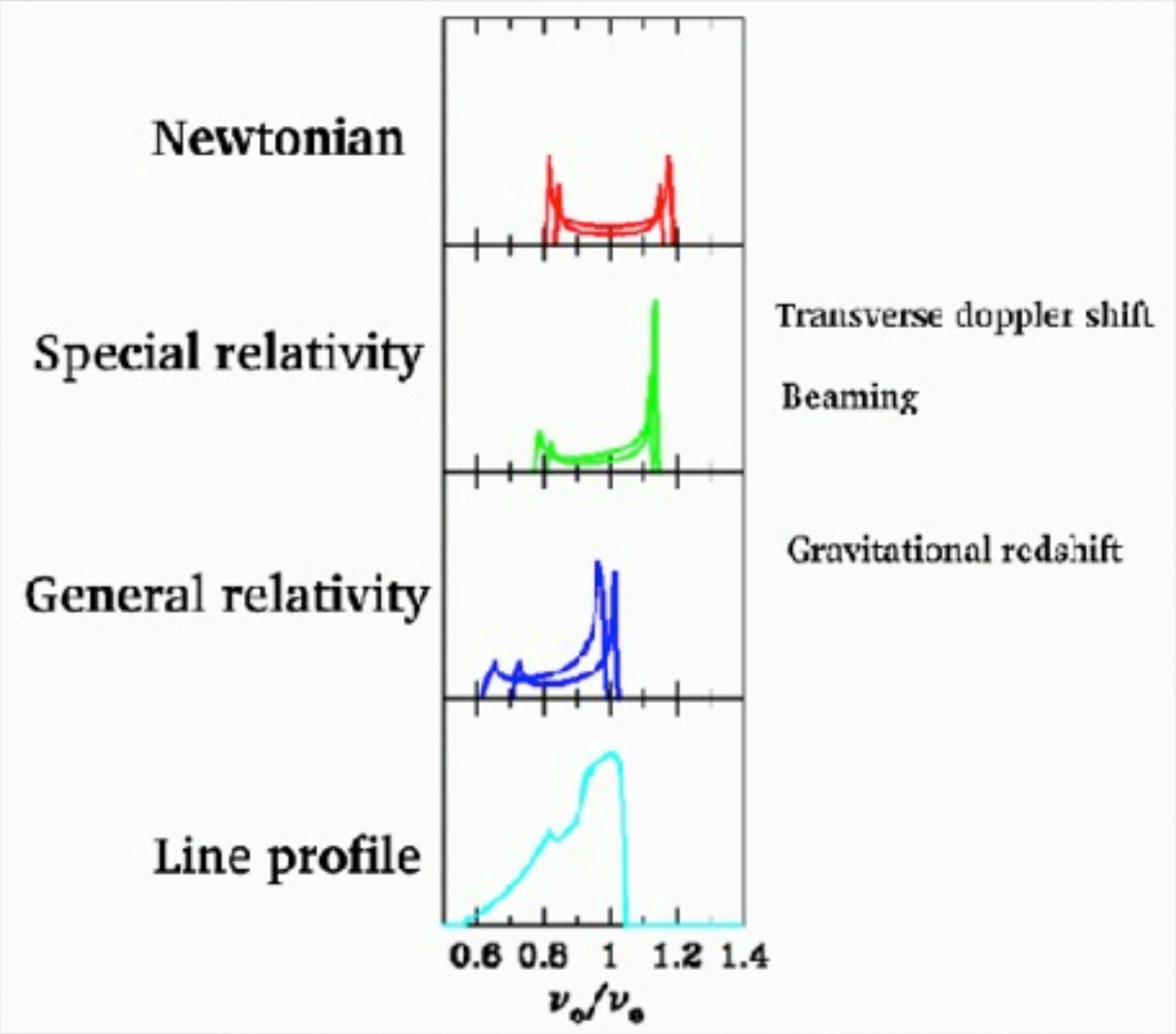
WHY DO WE USE X-RAYS

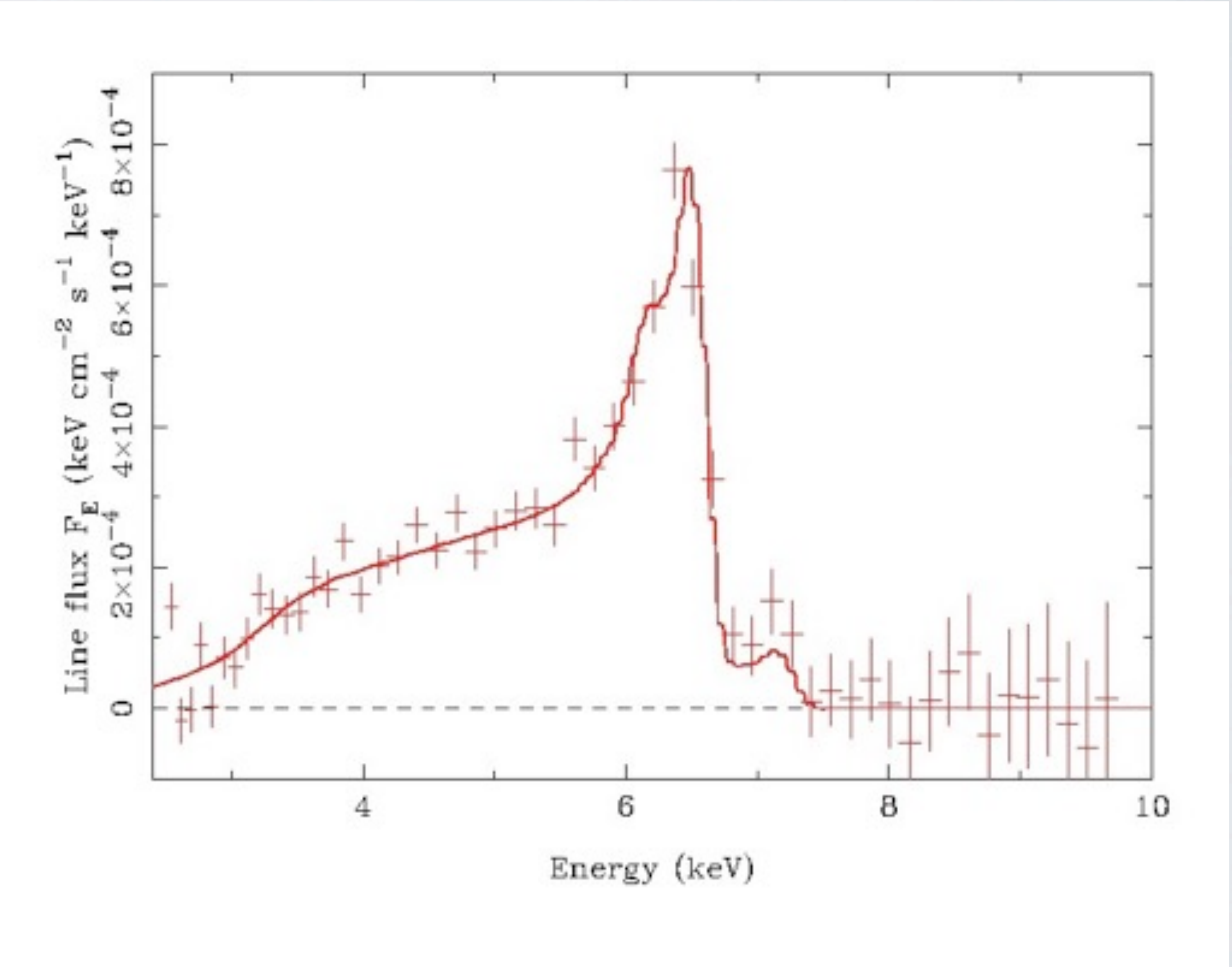




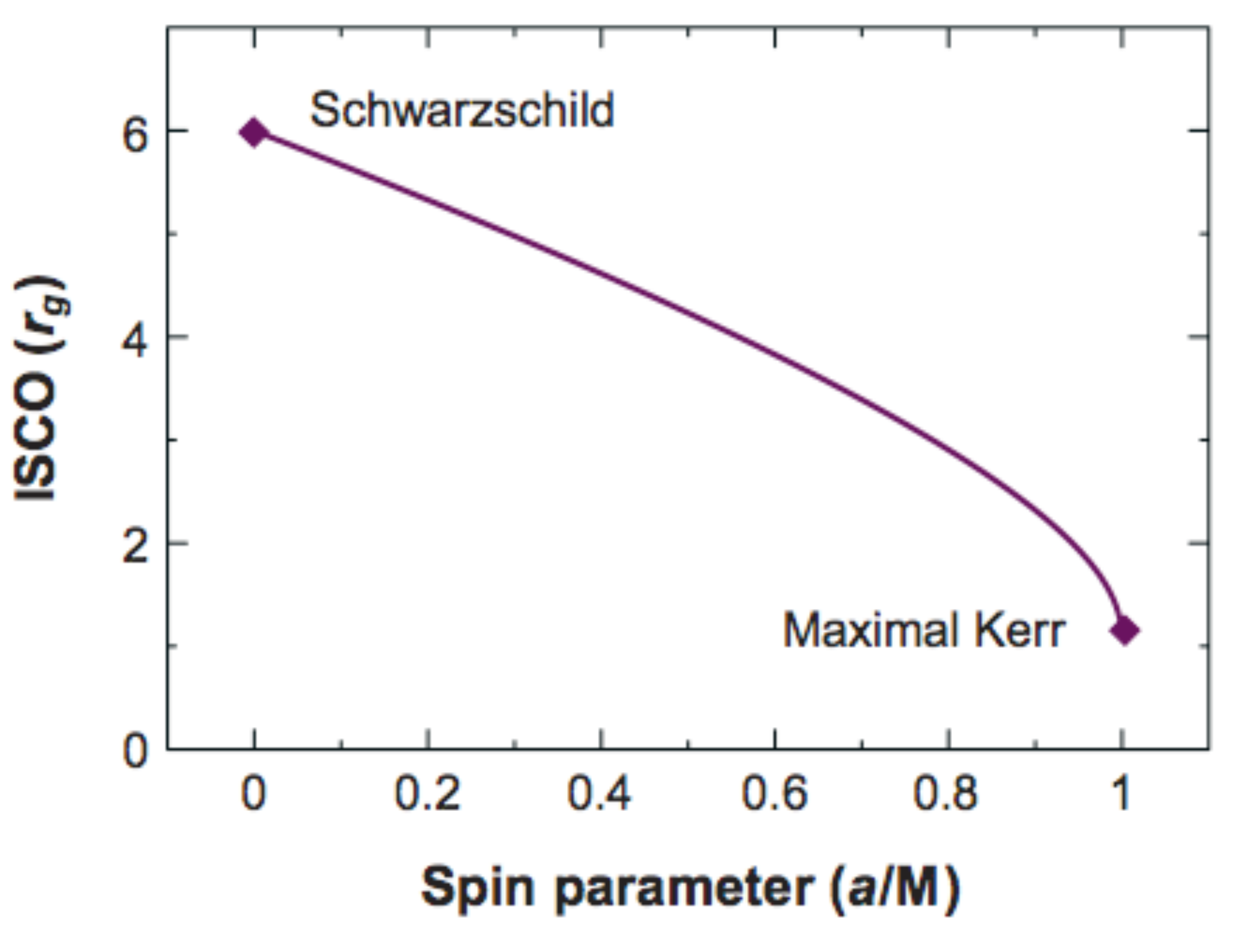
Rapid variability of AGN reveals that the X-ray photons come from the innermost accretion disk!

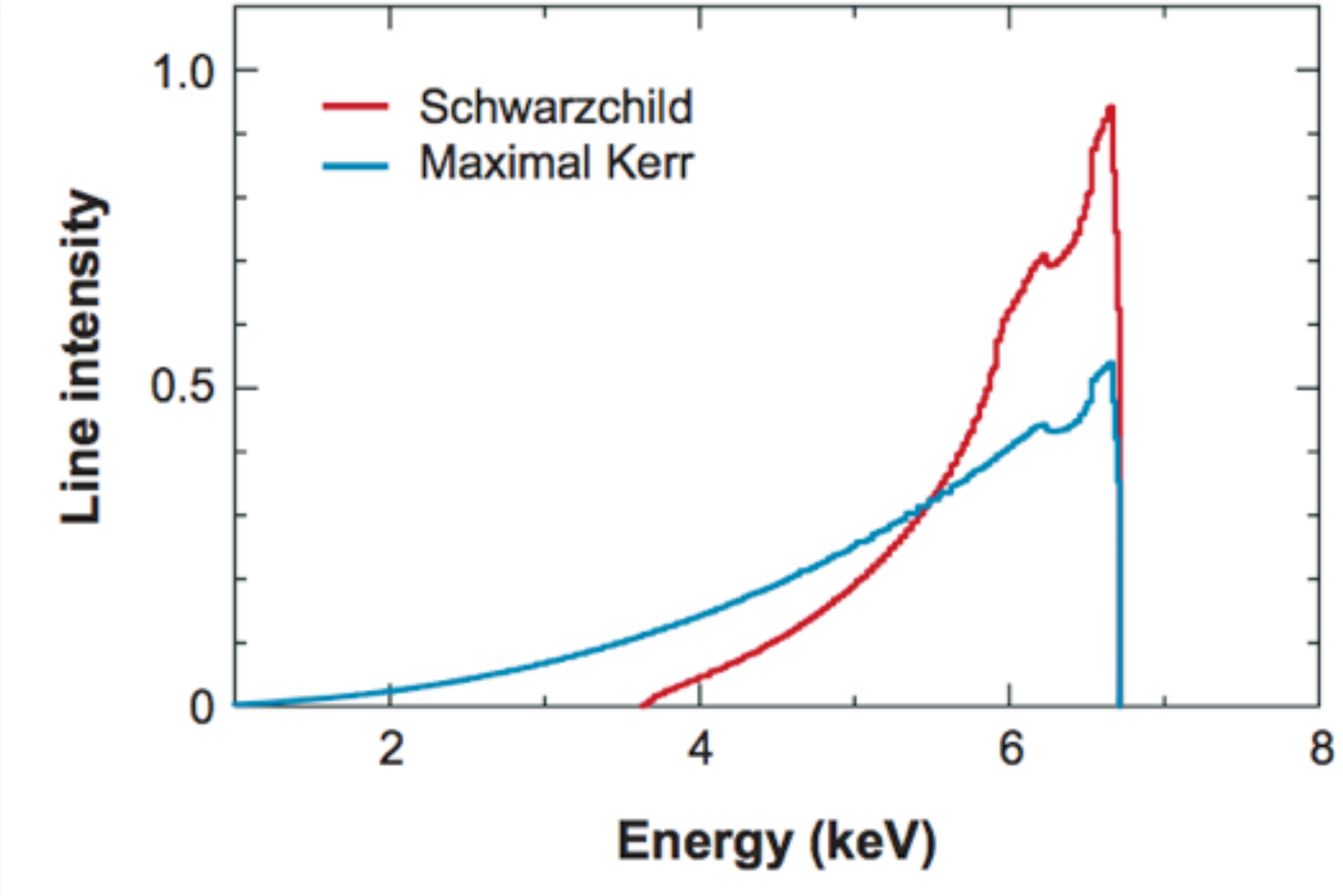
RELATIVISTICALLY BROADENED AND SKEWED EMISSION LINES





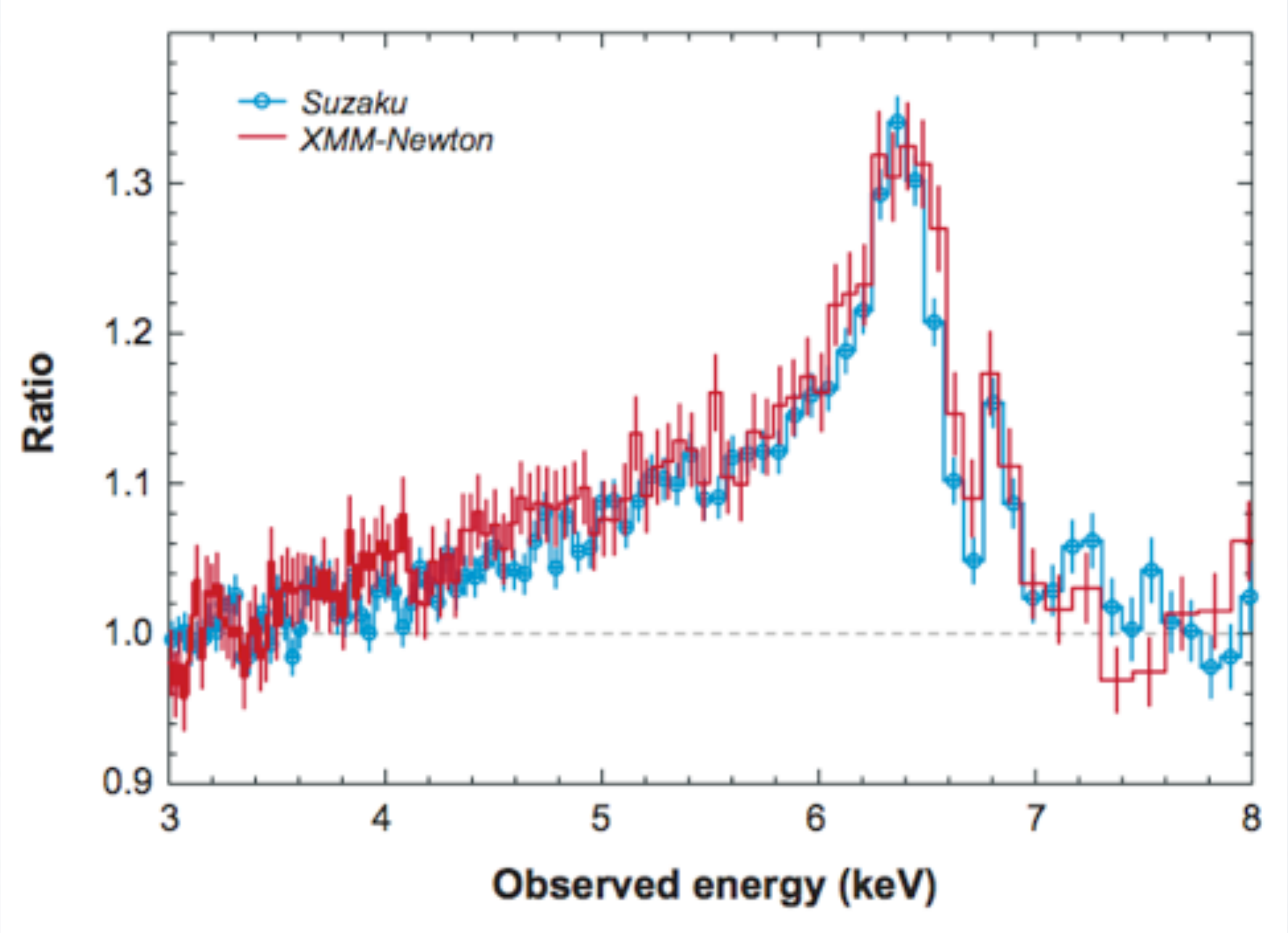
RELATIVISTICALLY BROADENED AND SKEWED EMISSION LINES





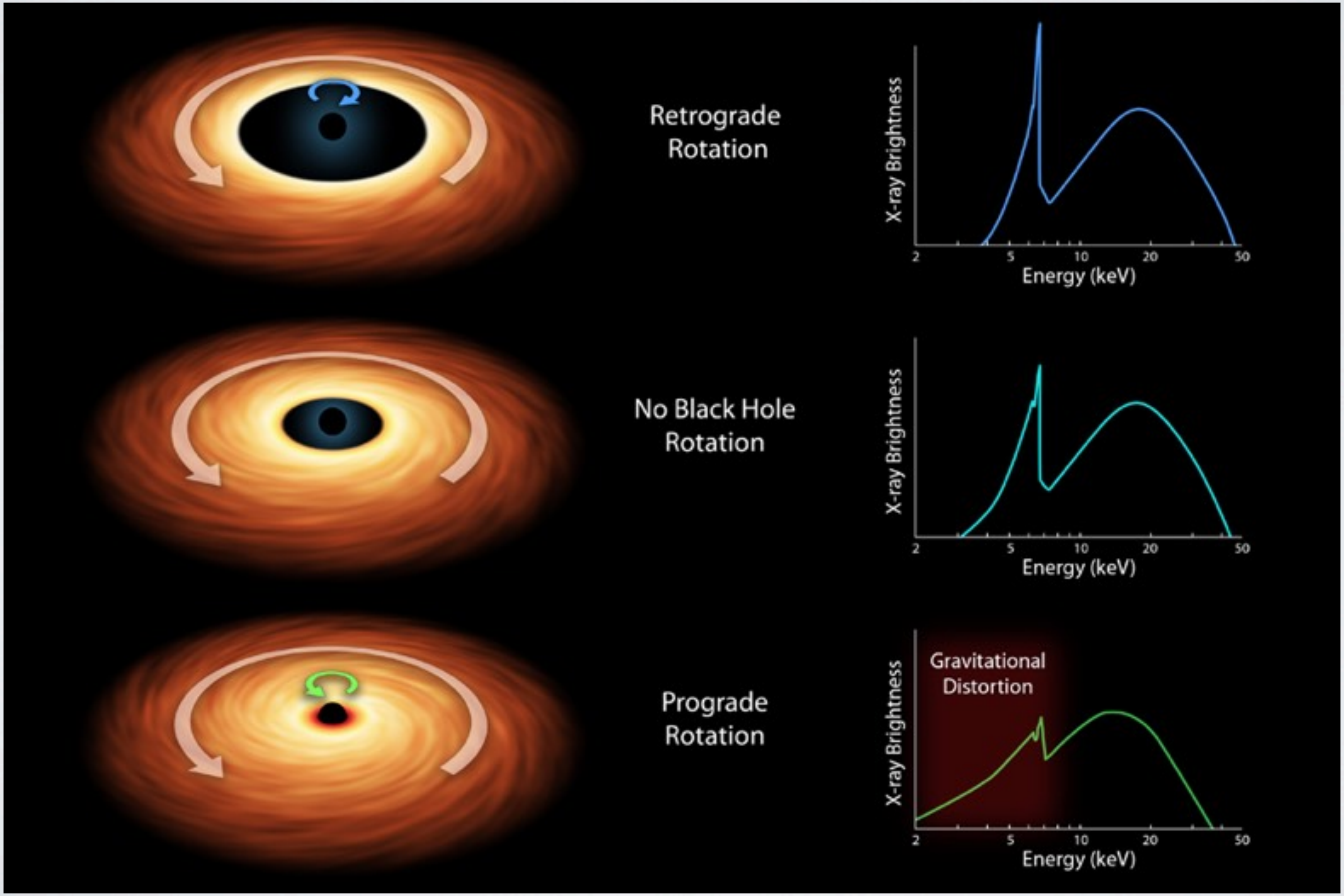
RELATIVISTIC LINE BROADENING IN MCG-6-30-15

- emission very close to black hole ISCO<2R_g
- accretion disk oriented at 30^o from our l.o.s.
- rotates at 0.989 of maximal Kerr spin



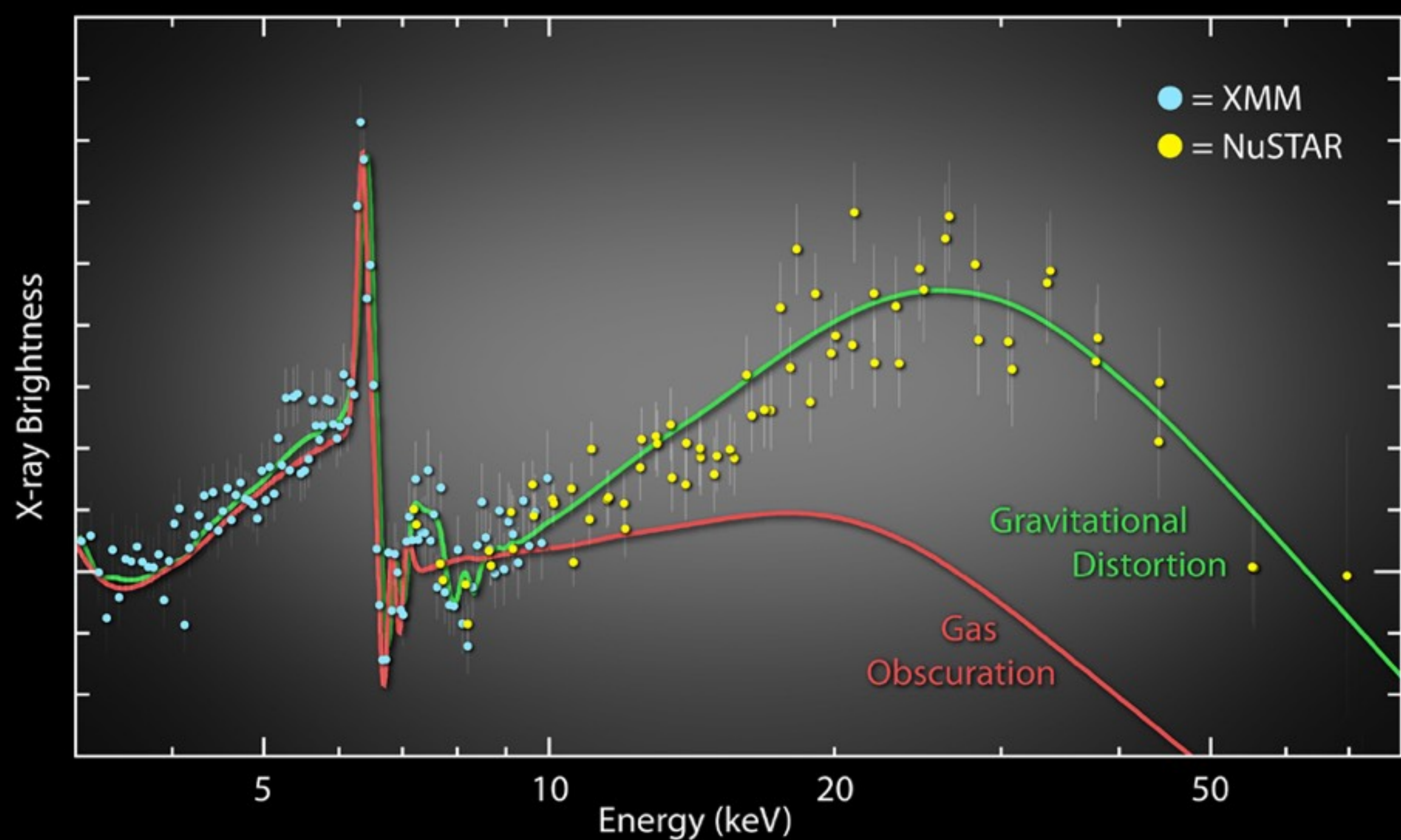
Spin of a Black Hole

Measure radius of the innermost stable circular orbit



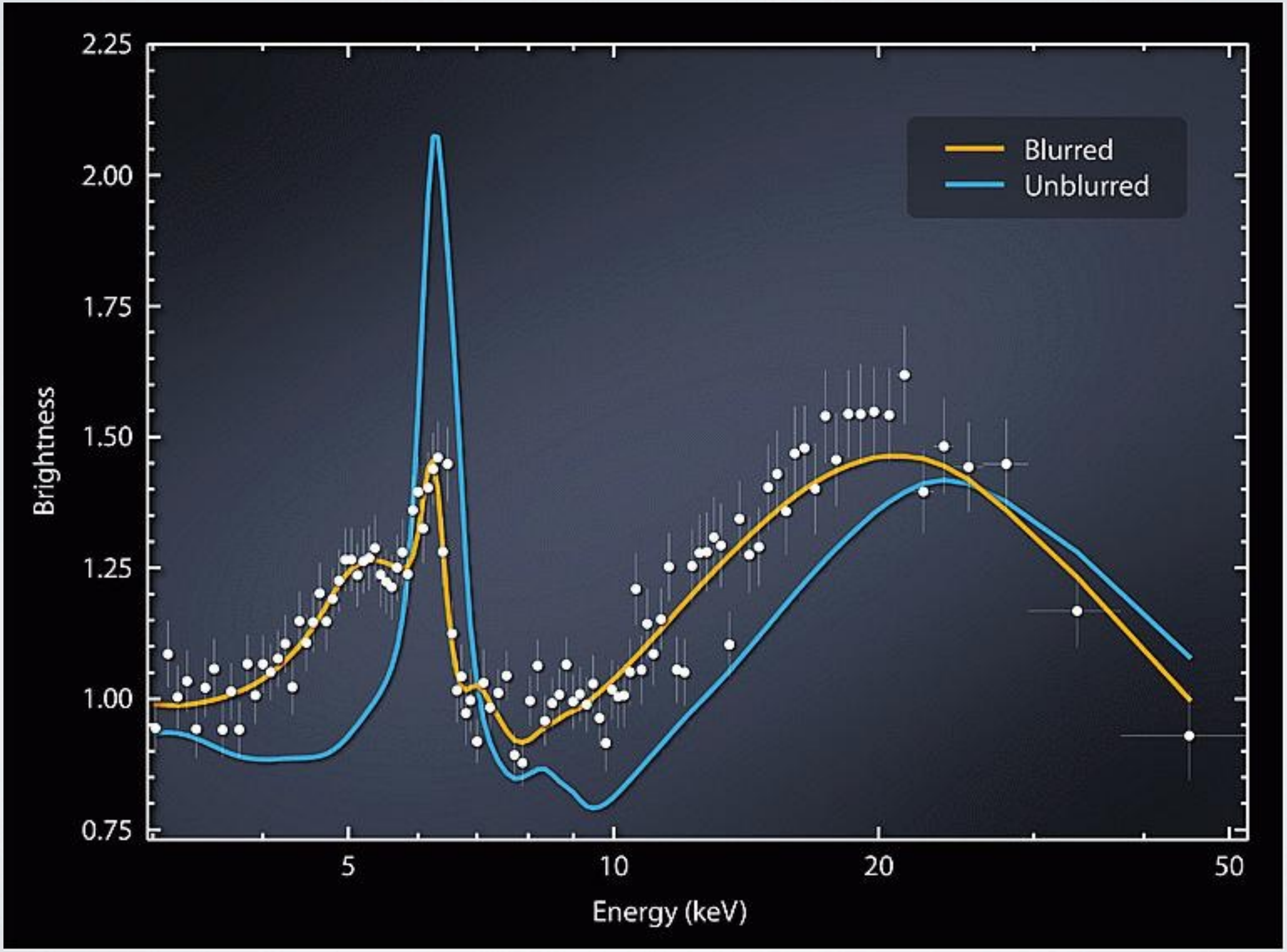
Relativistic Broaden lines

NGC 1365 - not gas obscuration



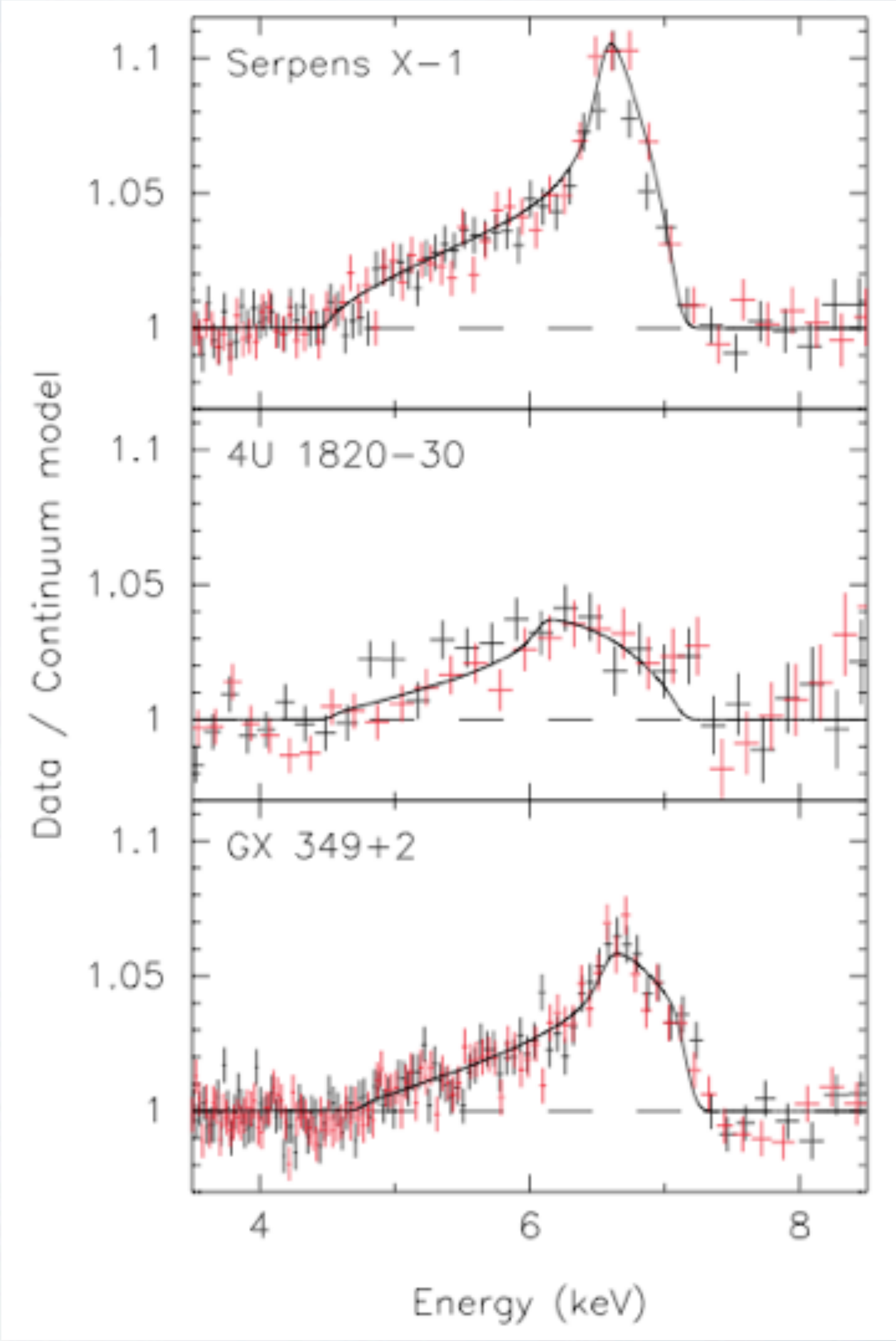
RELATIVISTIC BROAD FE LINE

- Mrk 335



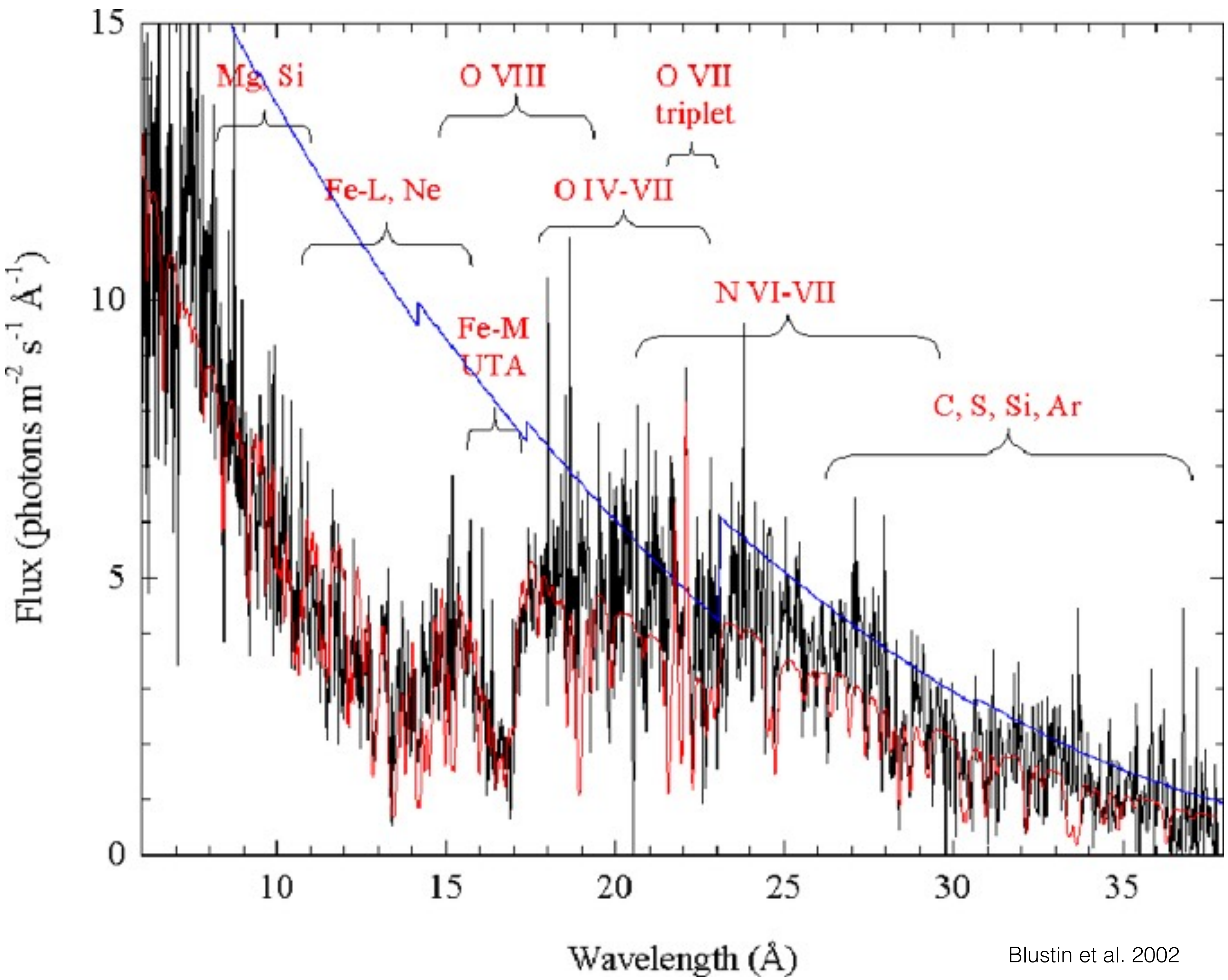
ALSO IN BINARIES WITH NEUTRON STARS

- inner disk radius upper limit on neutron star size
- upper limits of 14.5-16.5 km for 1.4 Msun neutron stars
- narrower than broad AGN lines



AGN Warm Absorbers

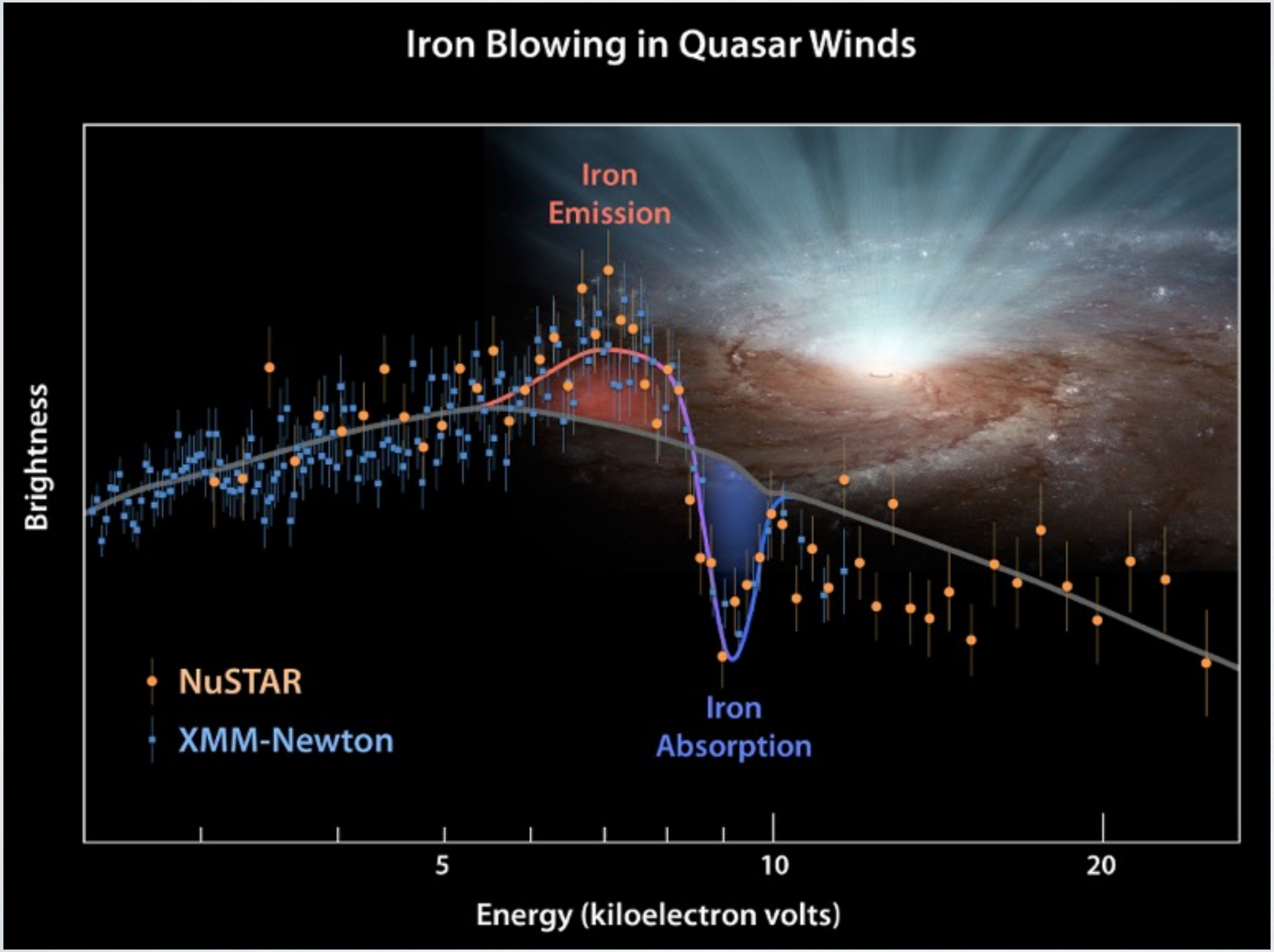
NGC 3783



Blustin et al. 2002

AGN ULTRA-FAST OUTFLOWS

PDS 456

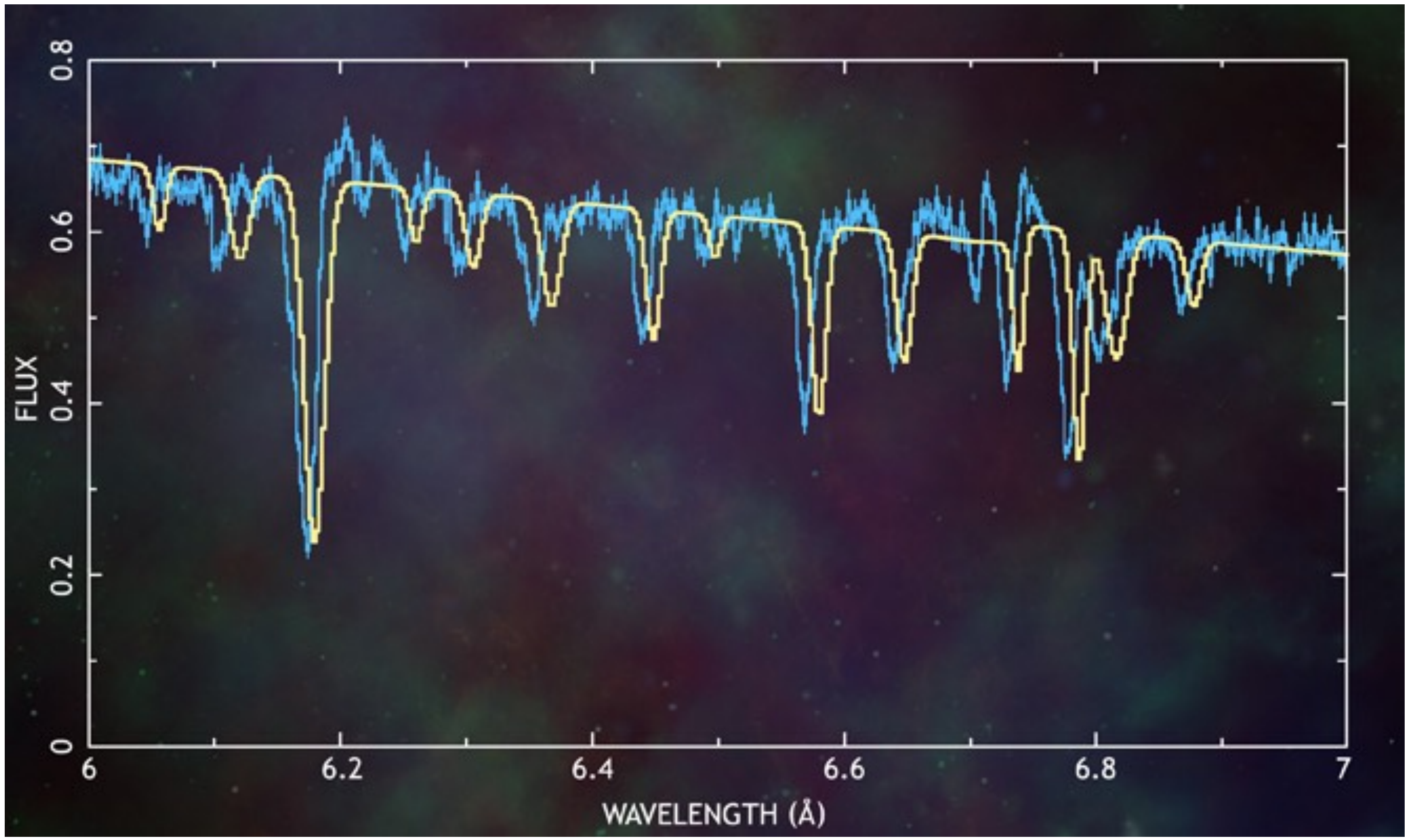


Nardini et al. 2015

X-ray Binary Winds

"High-Soft State"

Thermal Dominated State



GRO 1655-40 - yellow is at the rest wavelength

-the absorption is blue shifted, i.e. outflowing

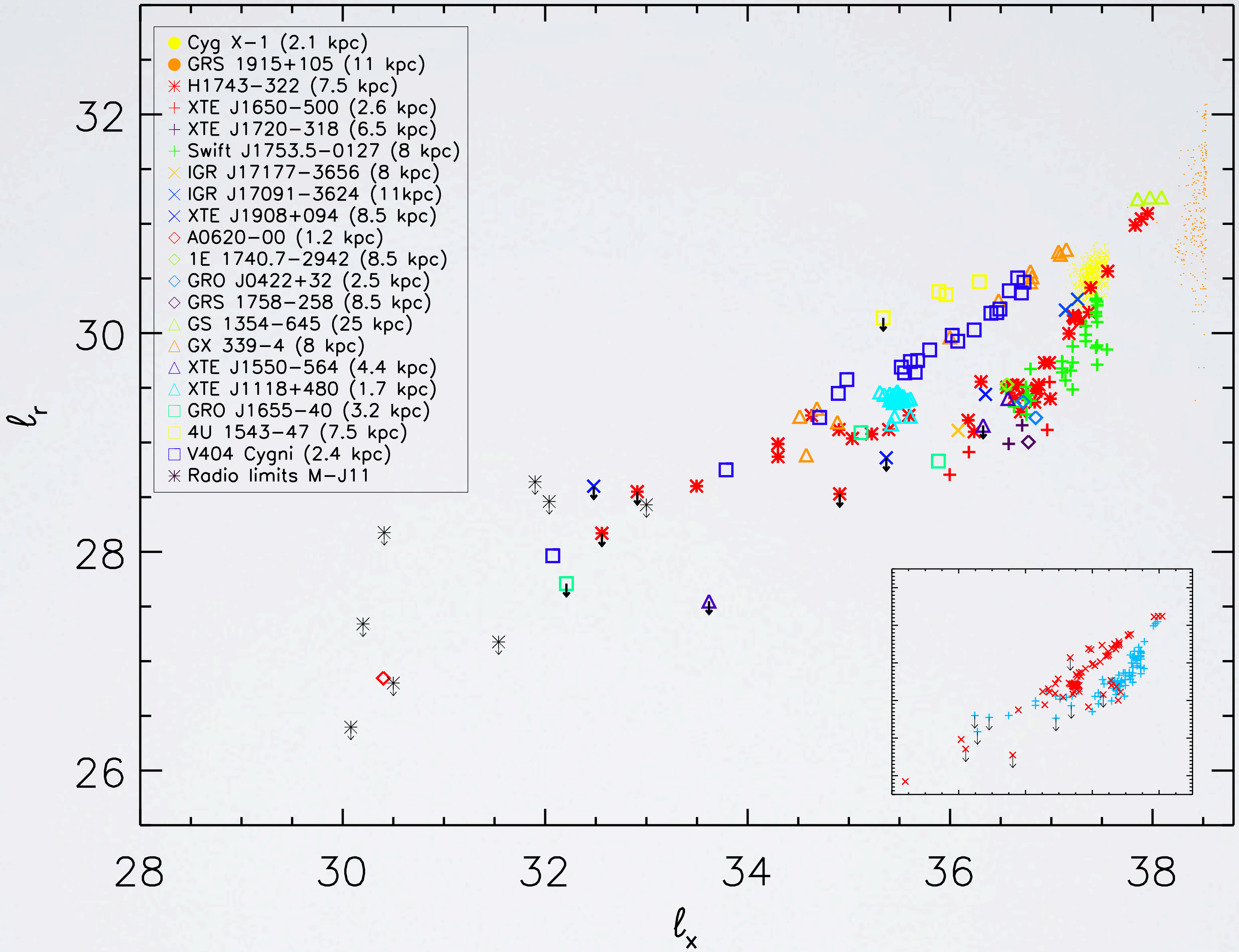
-Magnetically Driven

Miller et al. 2006

X-RAY BINARIES JETS

"LOW-HARD STATE"

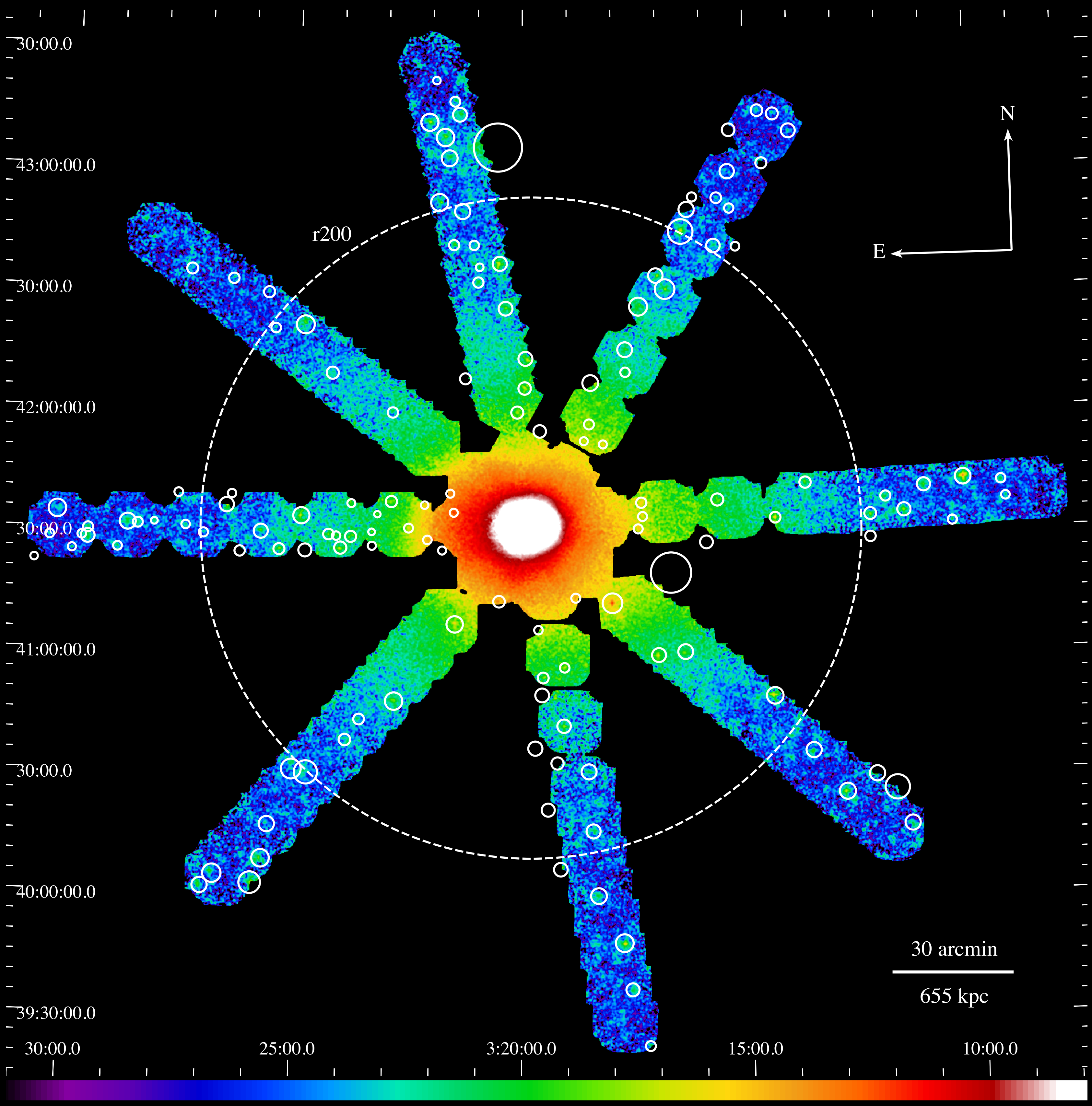
POWER-LAW DOMINATED STATE



Gallo et al. 2012

X-ray Luminosity (accretion) correlates with Radio luminosity (Jet)

THE PERSEUS KEY PROJECT



85 Suzaku pointings

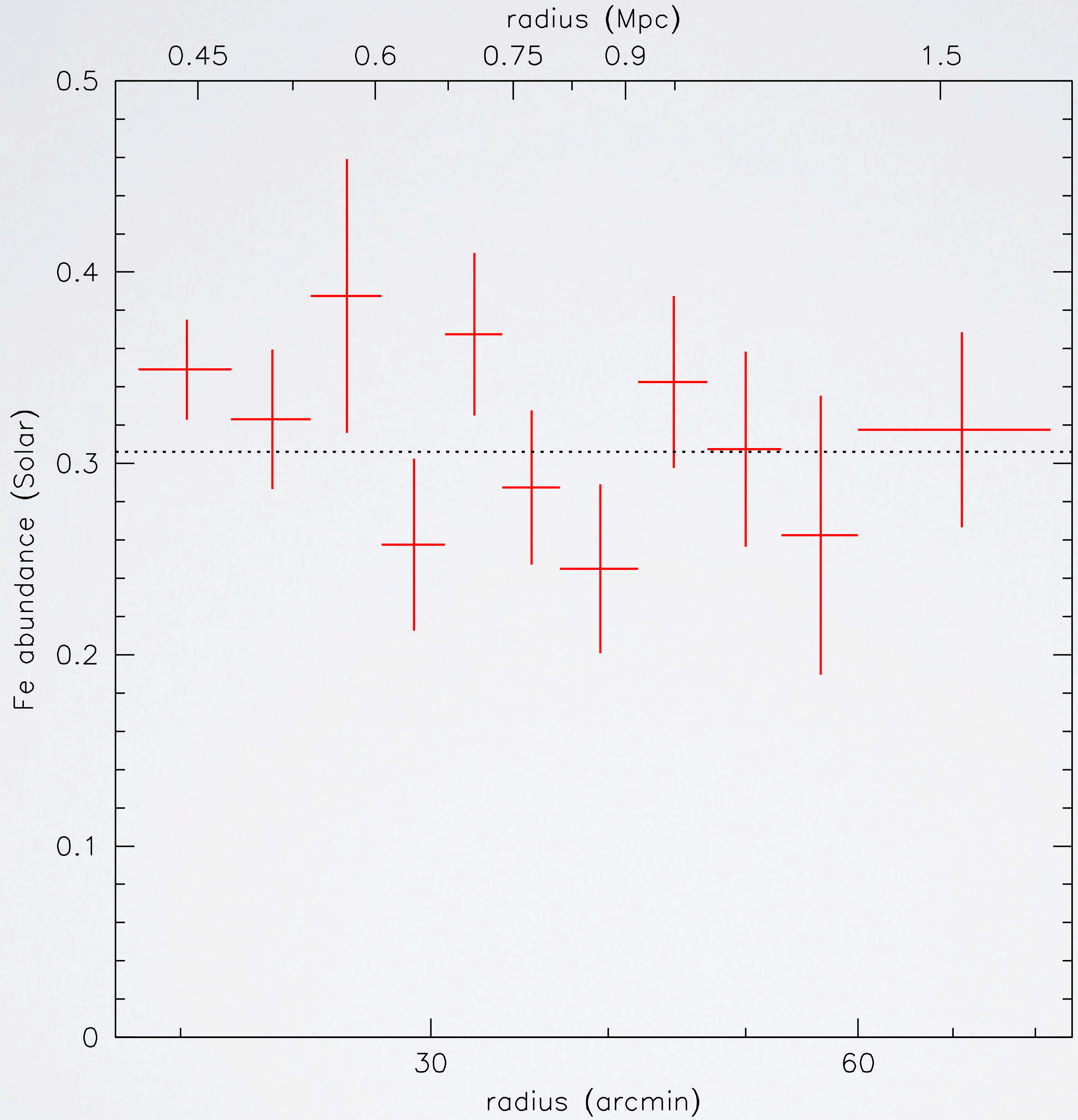
8 different directions

1Ms total exposure

AO 4-6 (July '09 - Sept '11)

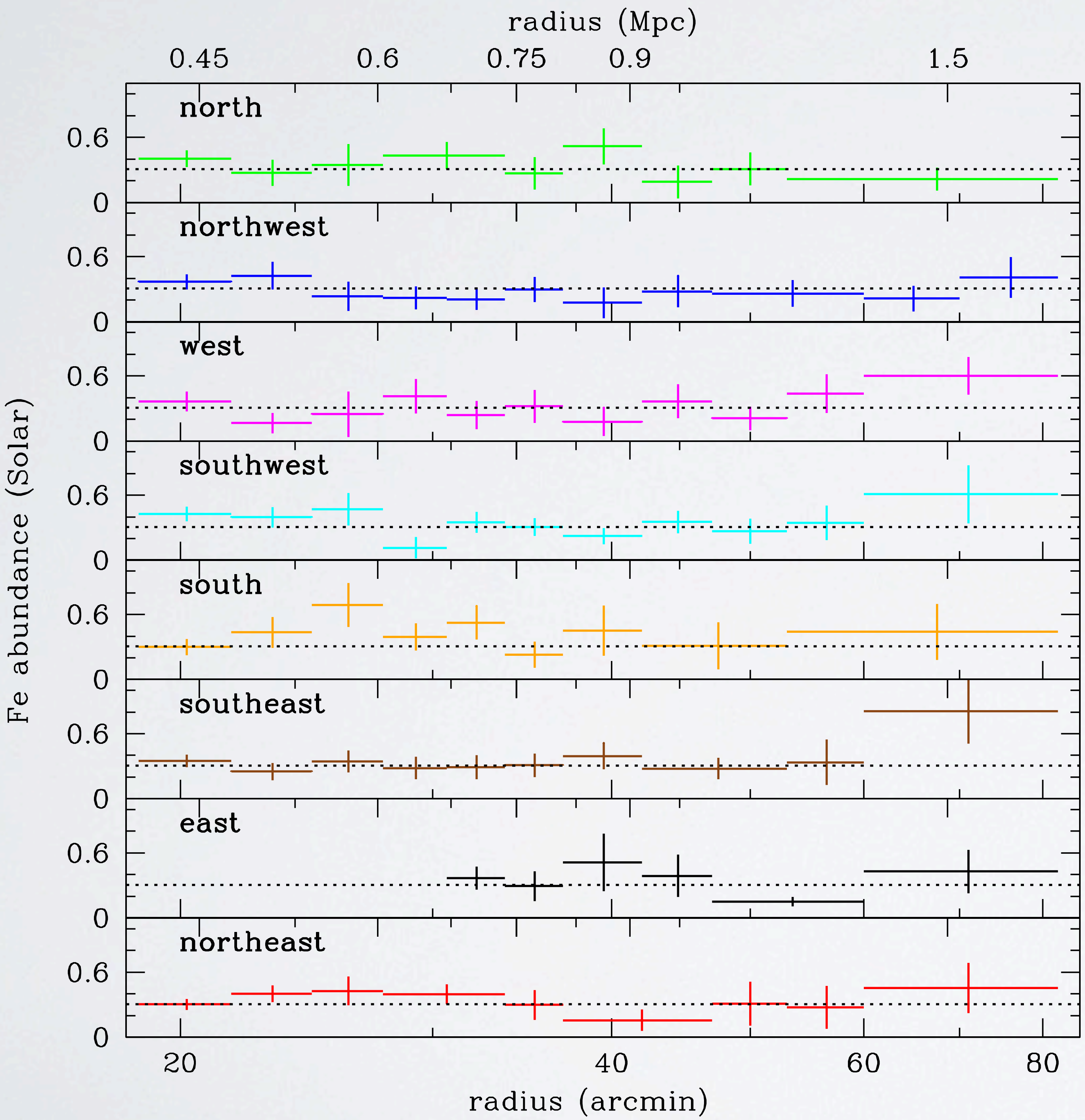
- **late enrichment:** decreasing metallicity as a function of radius
- **early enrichment**: constant metallicity as a function of radius and azimuth

METALLICITY PROFILE OF THE PERSEUS CLUSTER



Werner et al. 2013, *Nature*

IRON SPREAD SMOOTHLY THROUGHOUT THE PERSEUS CLUSTER



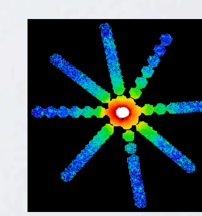
- 78 Fe abundance measurements across the cluster at different radii *and azimuths* show strikingly uniform distribution

- the iron had to escape from the galaxies and get mixed into the intergalactic gas before the entropy profile became very steep, preventing efficient mixing

Werner et al. 2013, *Nature*

THE TURBULENT YOUNG UNIVERSE

- 10-12 billion years ago galaxies formed stars at very high rates, resulting in many supernova explosions
- at the same time, black holes grew fast by accreting matter
- combined energy of these processes produced winds blowing material out of galaxies



in billions of years

-13.8 | -12 | -10 | -8 | -6 | -4 | -2

Big Bang

galactic winds

clusters form

Werner et al. 2013, *Nature*

IMPLICATIONS OF EARLY METAL ENRICHMENT

- all massive clusters should show a similar, uniform level of enrichment at 1/3 of the Solar metallicity.

- many type Ia supernovae (SNIa), which are the main sources of Fe, must have exploded shortly after the epoch of peak star-formation. This is consistent with recent findings based on SNIa delay time distributions (Maoz et al. 2012).

- this scenario predicts that the <u>warm-hot intergalactic medium</u> in large-scale structure filaments connecting to massive clusters is also metal-rich, and can be detected in line-emission with future high-spectral resolution missions.

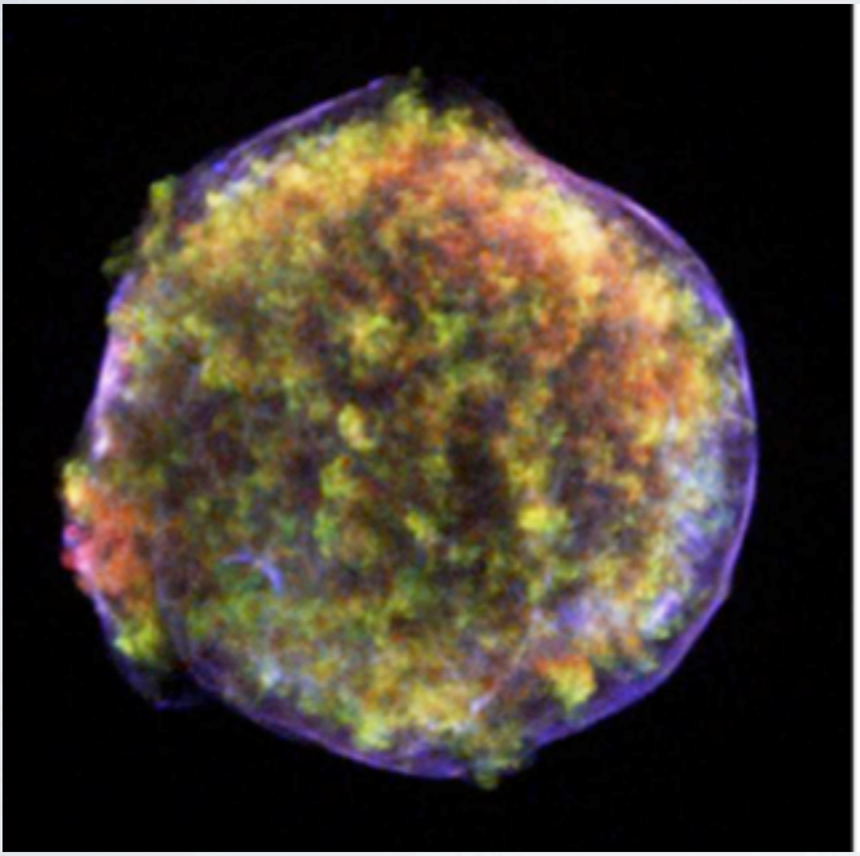
- if the material currently falling into massive clusters is iron-rich, iron nuclei are likely to be accelerated as they pass through the accretion shocks, providing an important source of the <u>highest energy cosmic rays</u>.

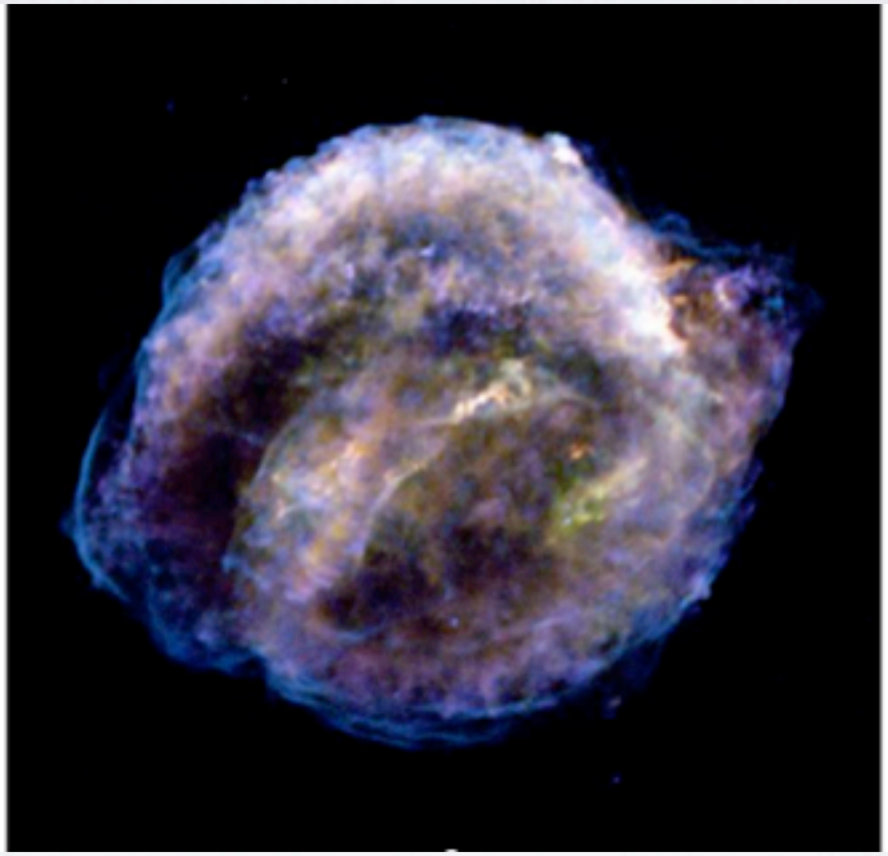
THE UNIVERSE IN A CUP

THE UNIVERSE IN A CUP

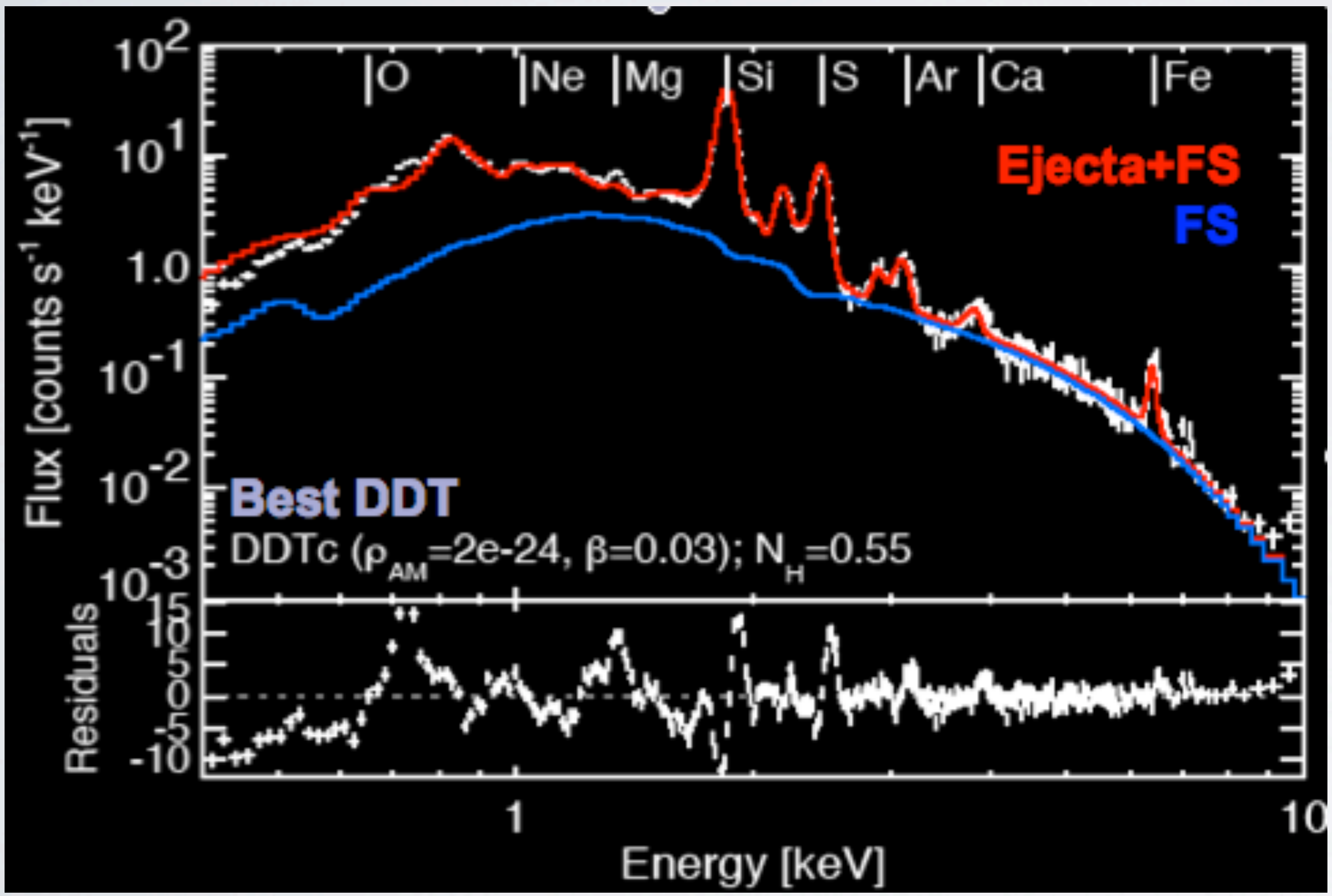
SUPERNOVA REMNANTS

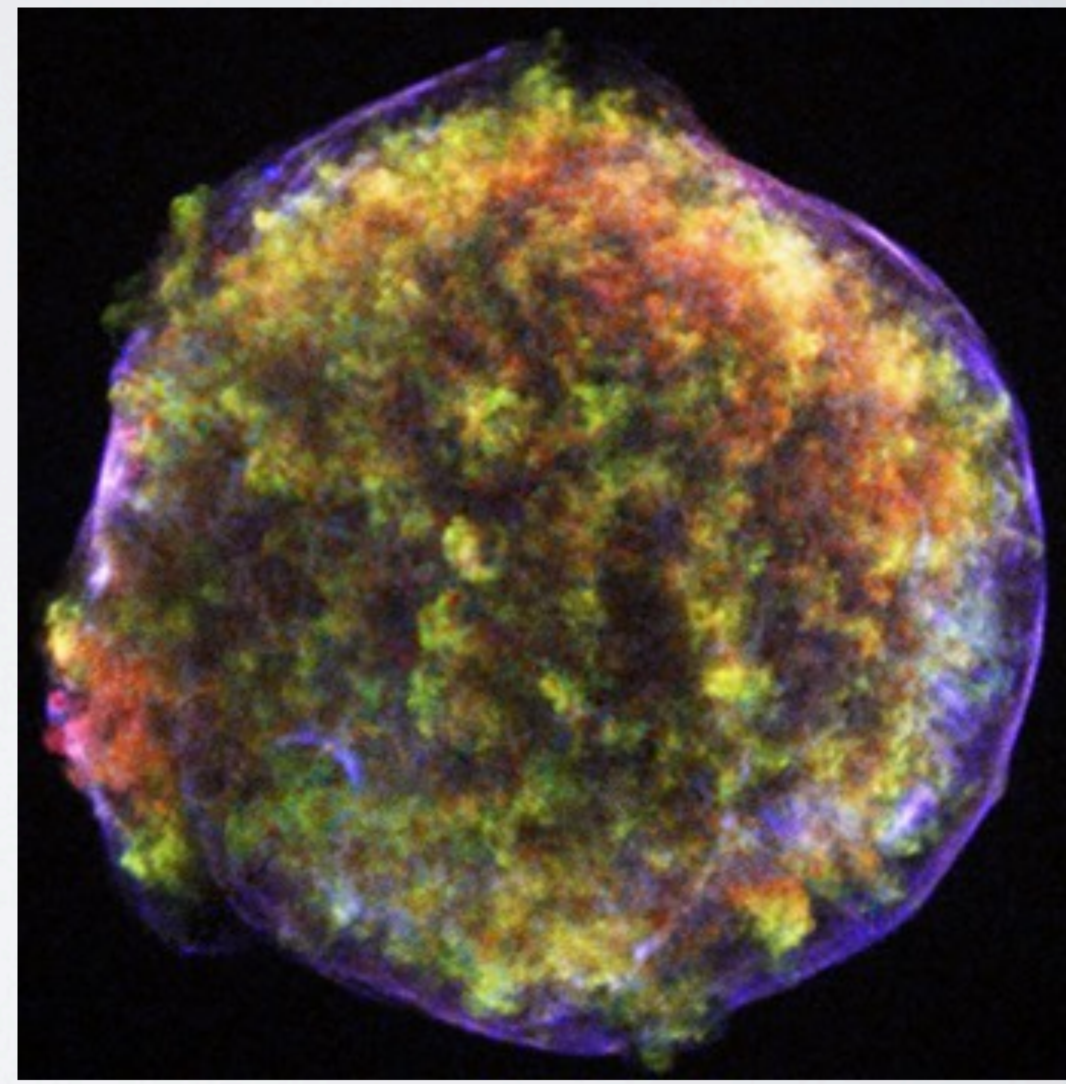
REMNANTS OF SUPERNOVA EXPLOSIONS

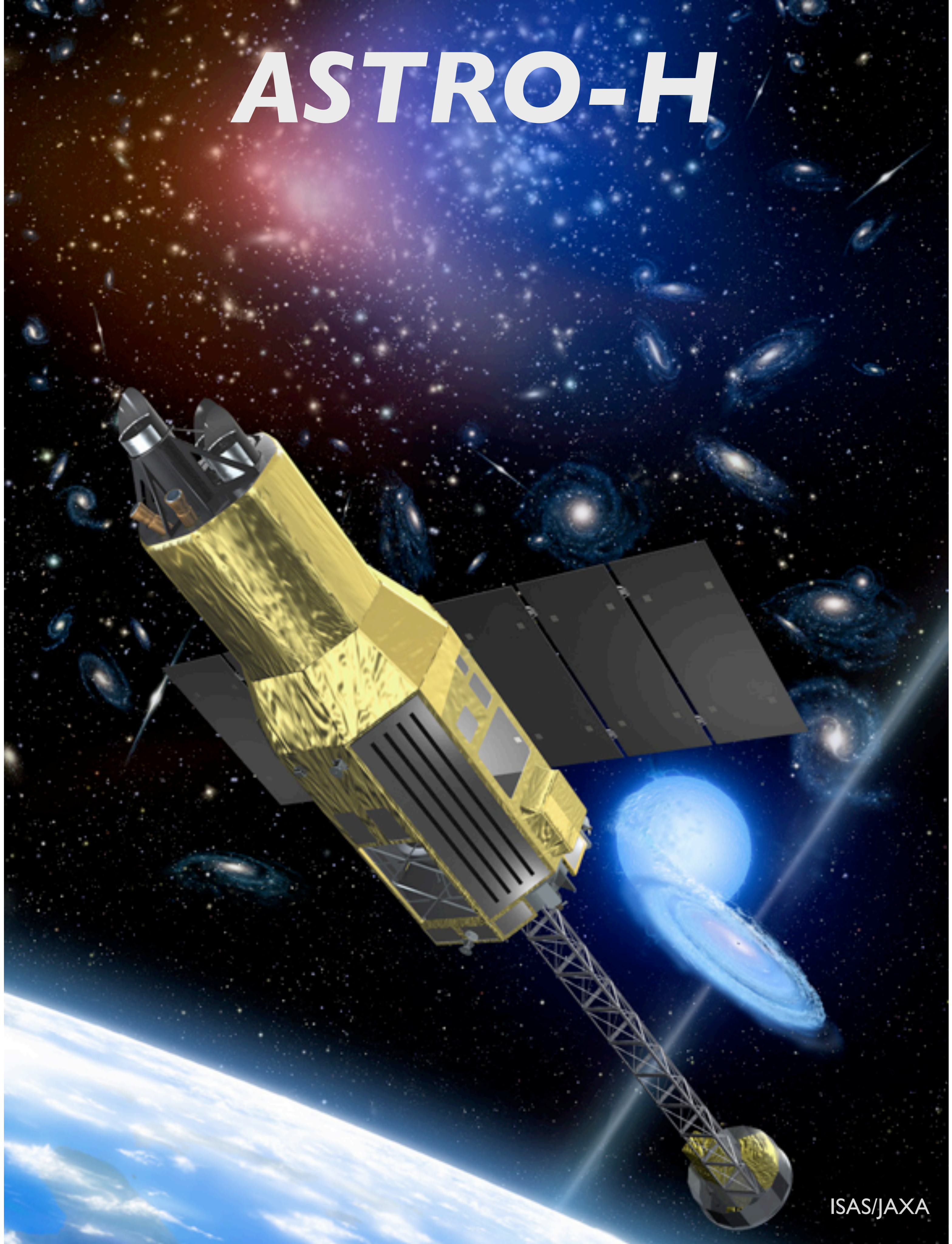




THE TYCHO SUPERNOVA REMNANT



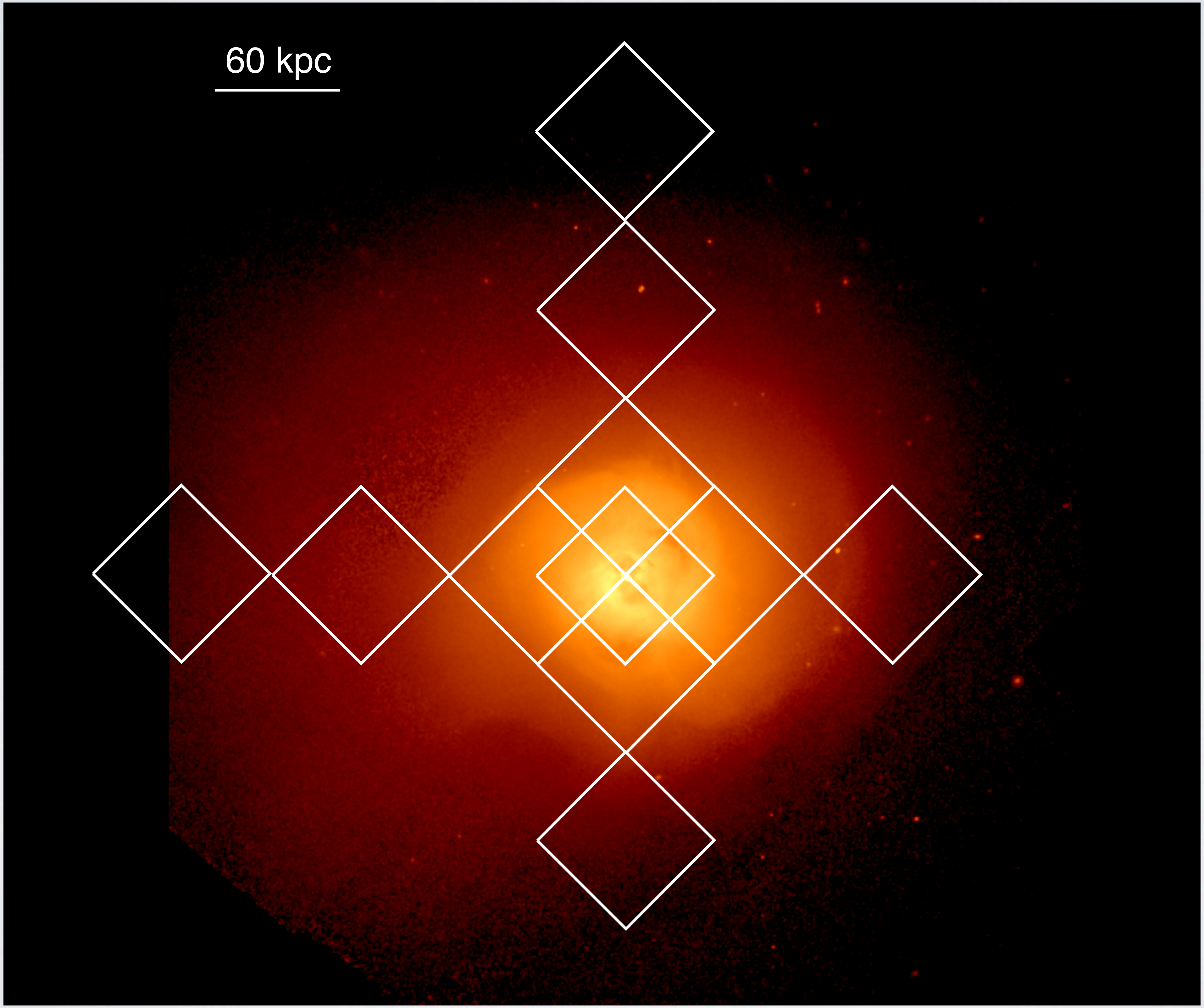




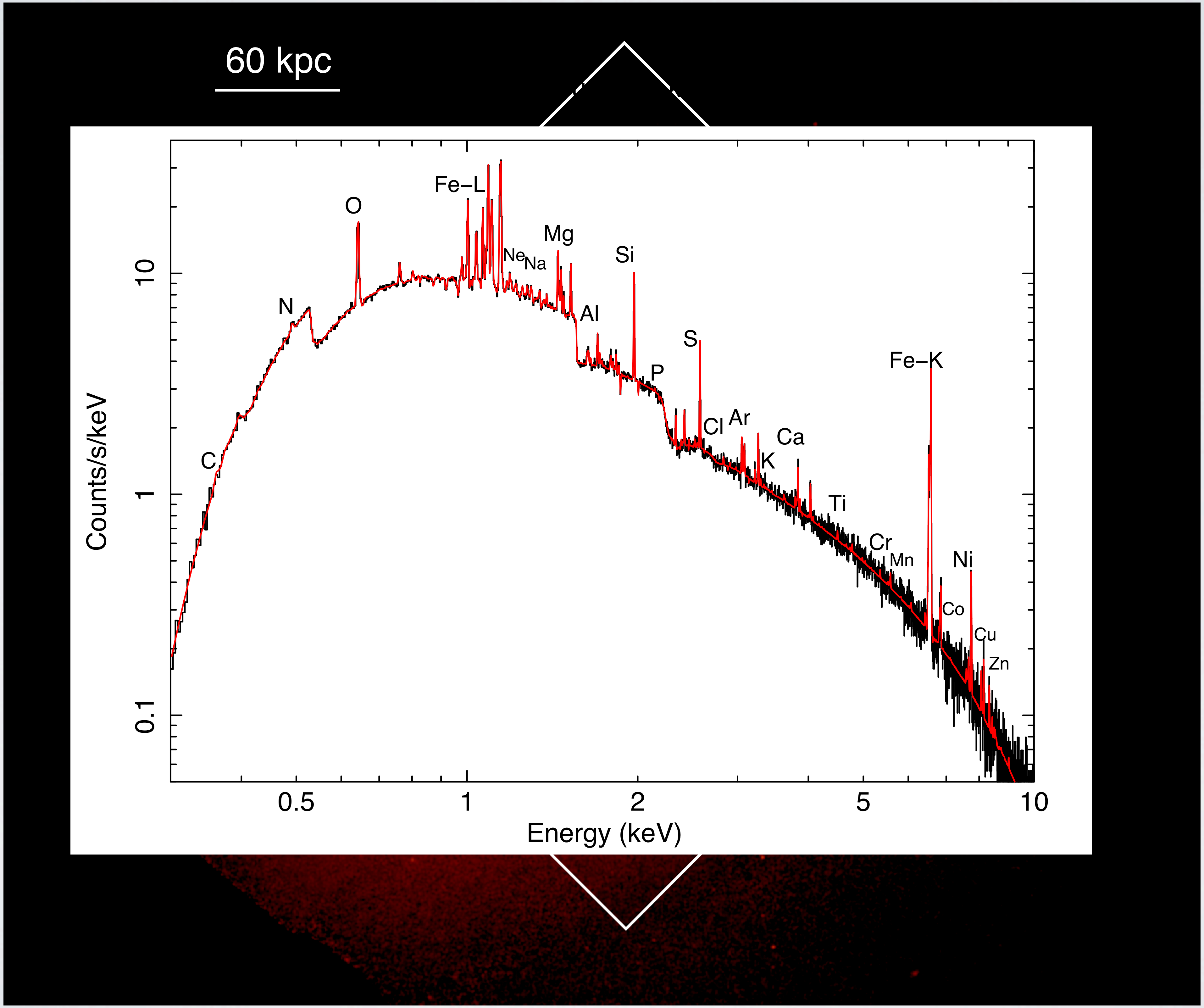
with a contribution of other Japanese universities and institutes

with a contribution of other US/EU universities and institutes

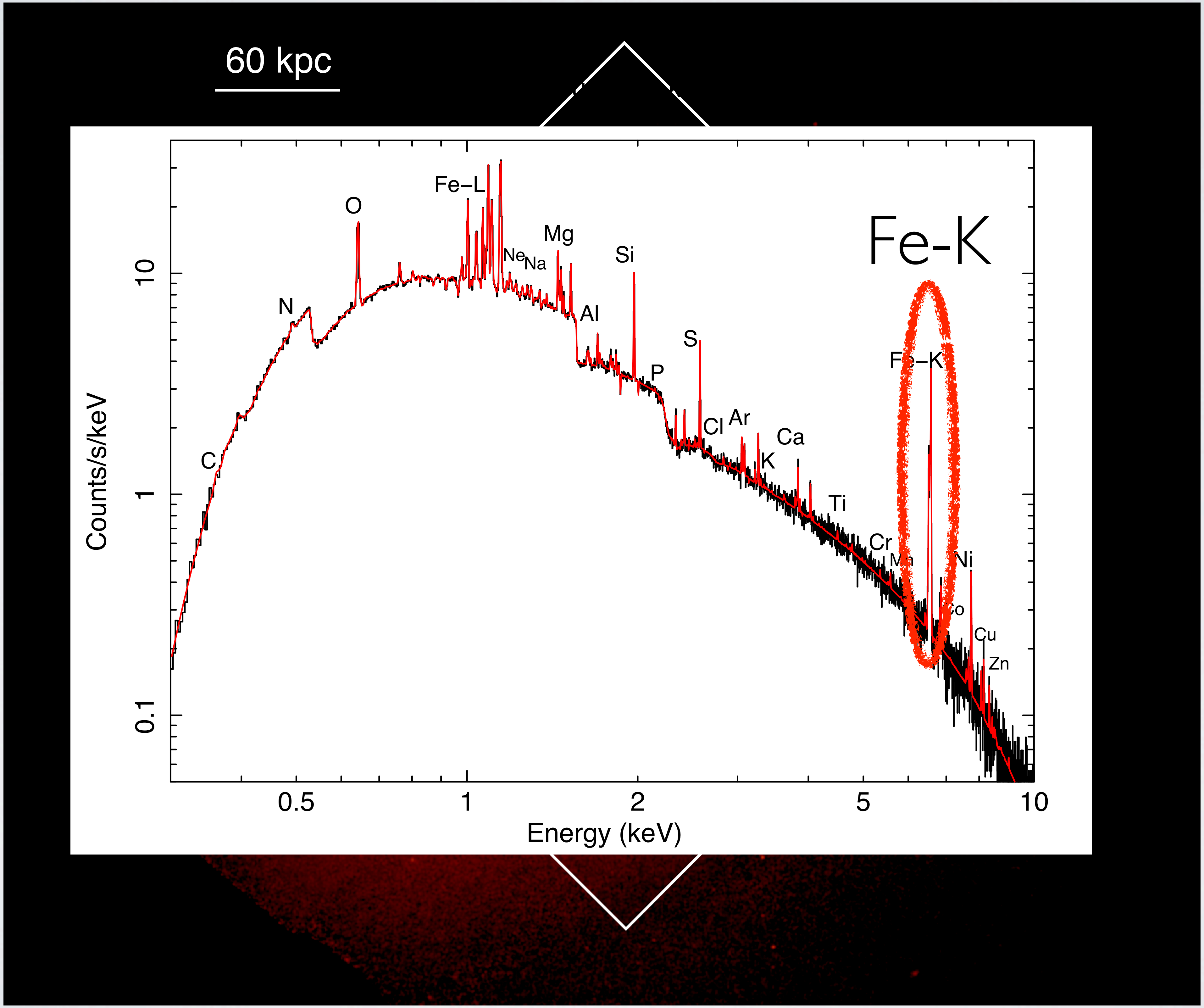
Determining gas *dynamics*, *thermodynamics* and *chemical composition* in the brightest galaxy cluster



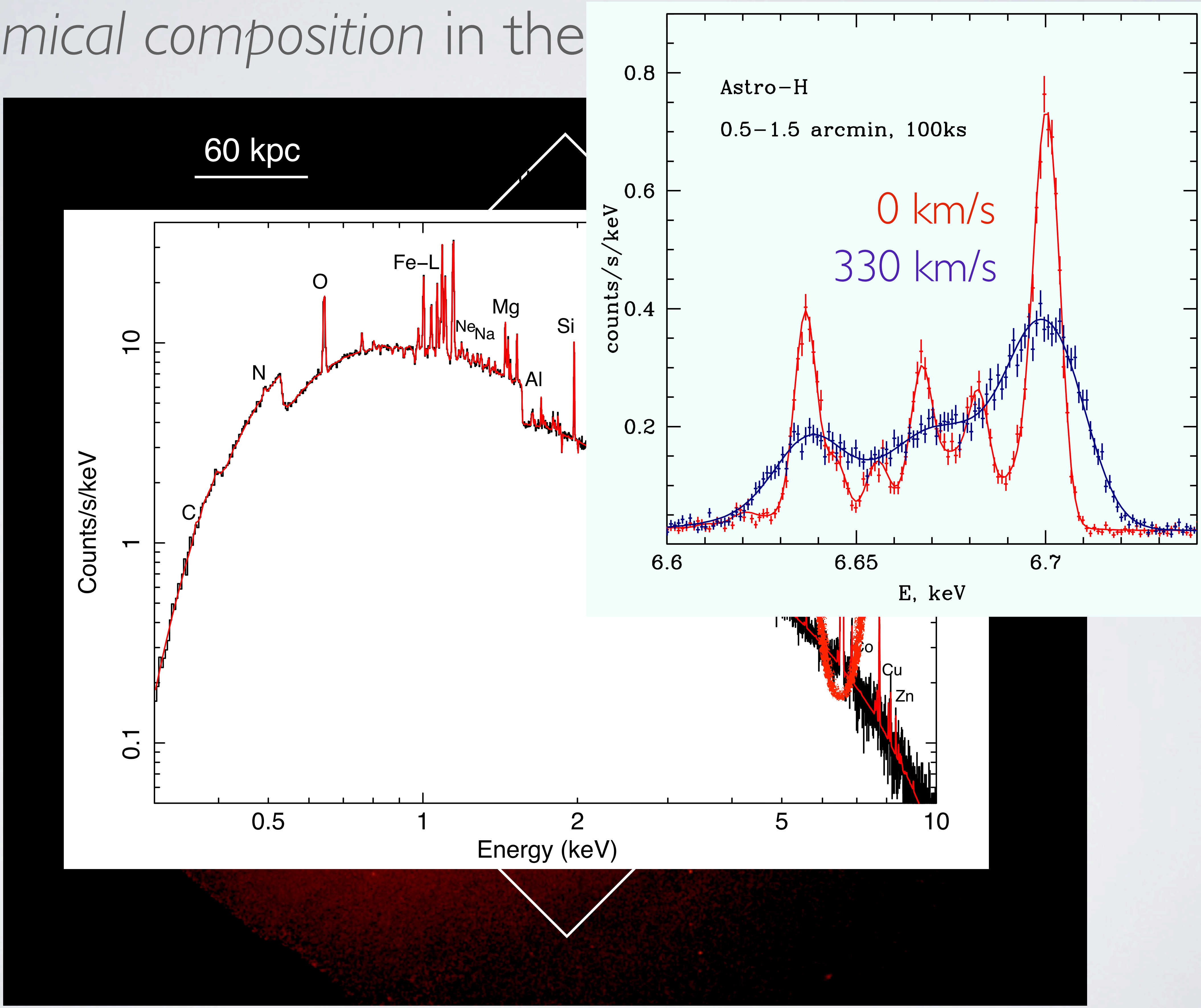
Determining gas *dynamics*, *thermodynamics* and *chemical composition* in the brightest galaxy cluster



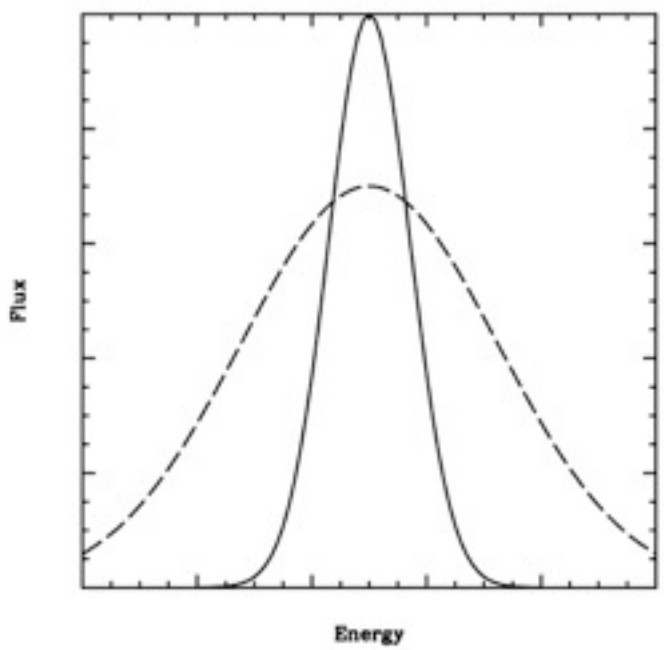
Determining gas *dynamics*, *thermodynamics* and *chemical composition* in the brightest galaxy cluster



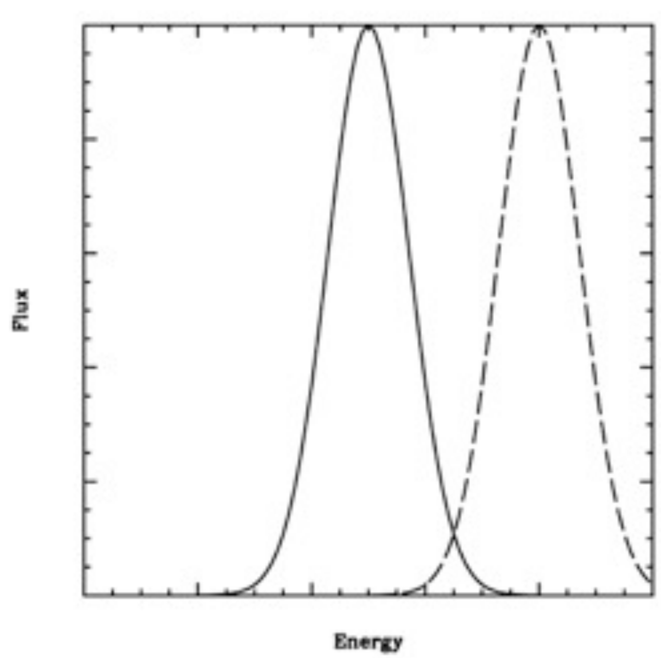
Determining gas *dynamics*, *thermodynamics* and *chemical composition* in the



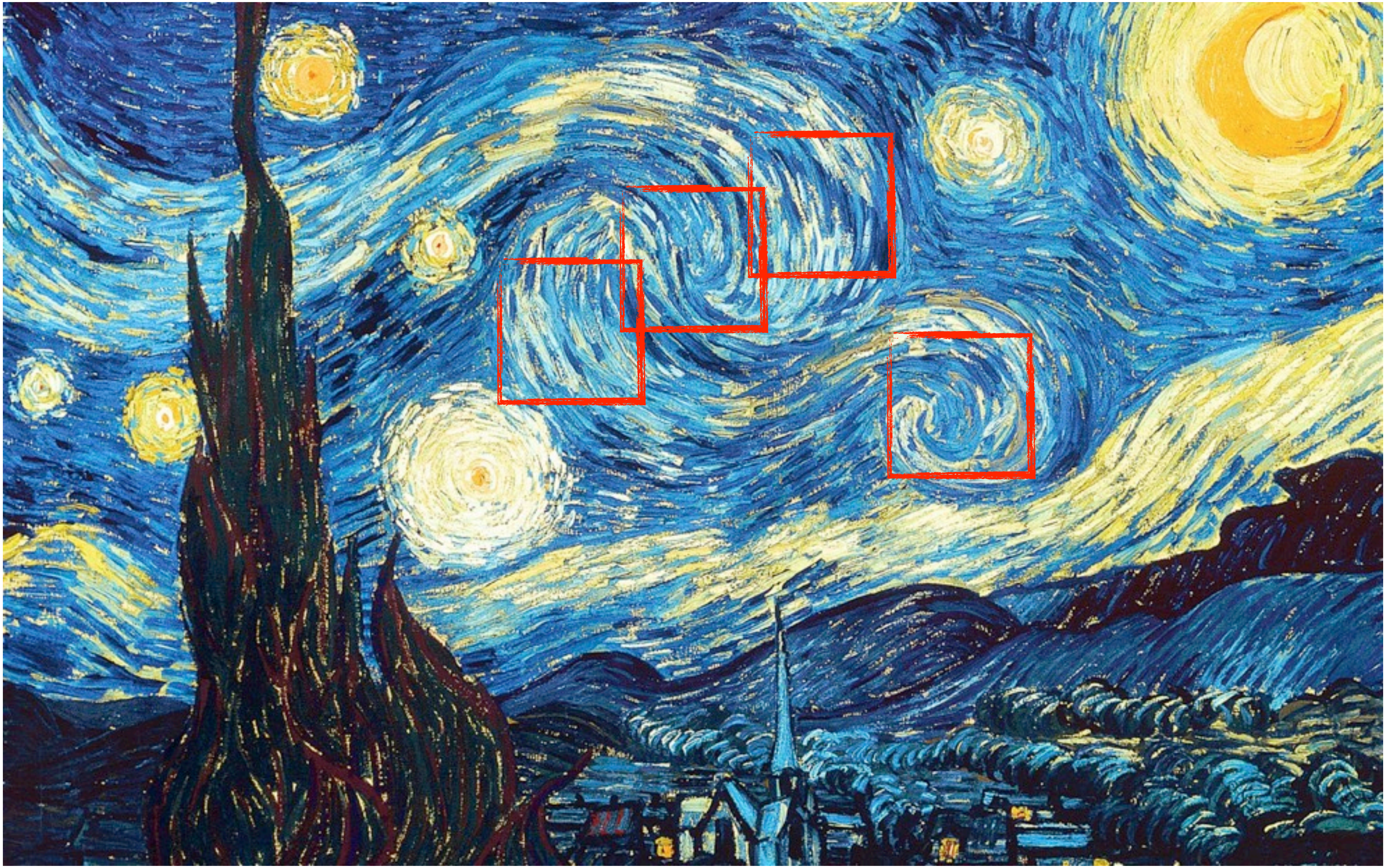
Turbulent and bulk motions

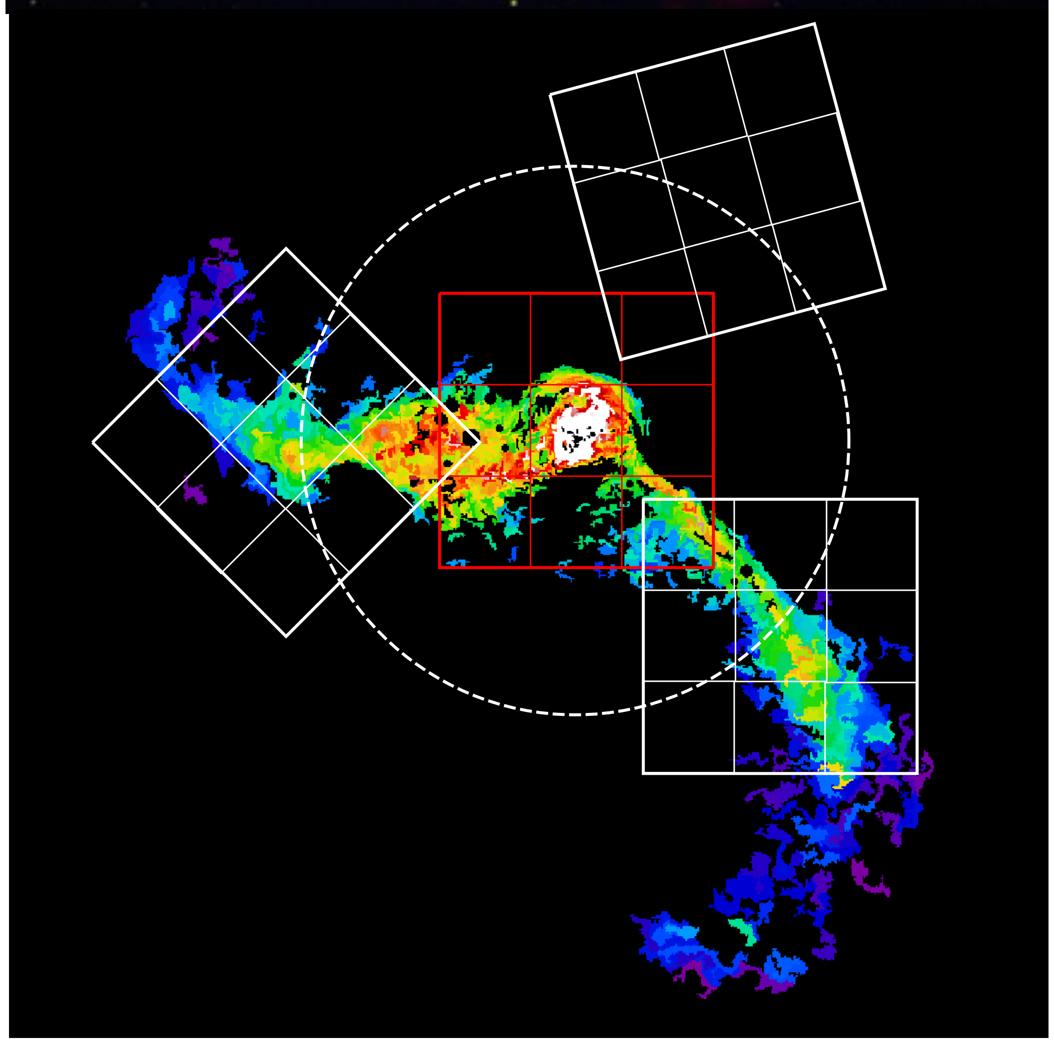


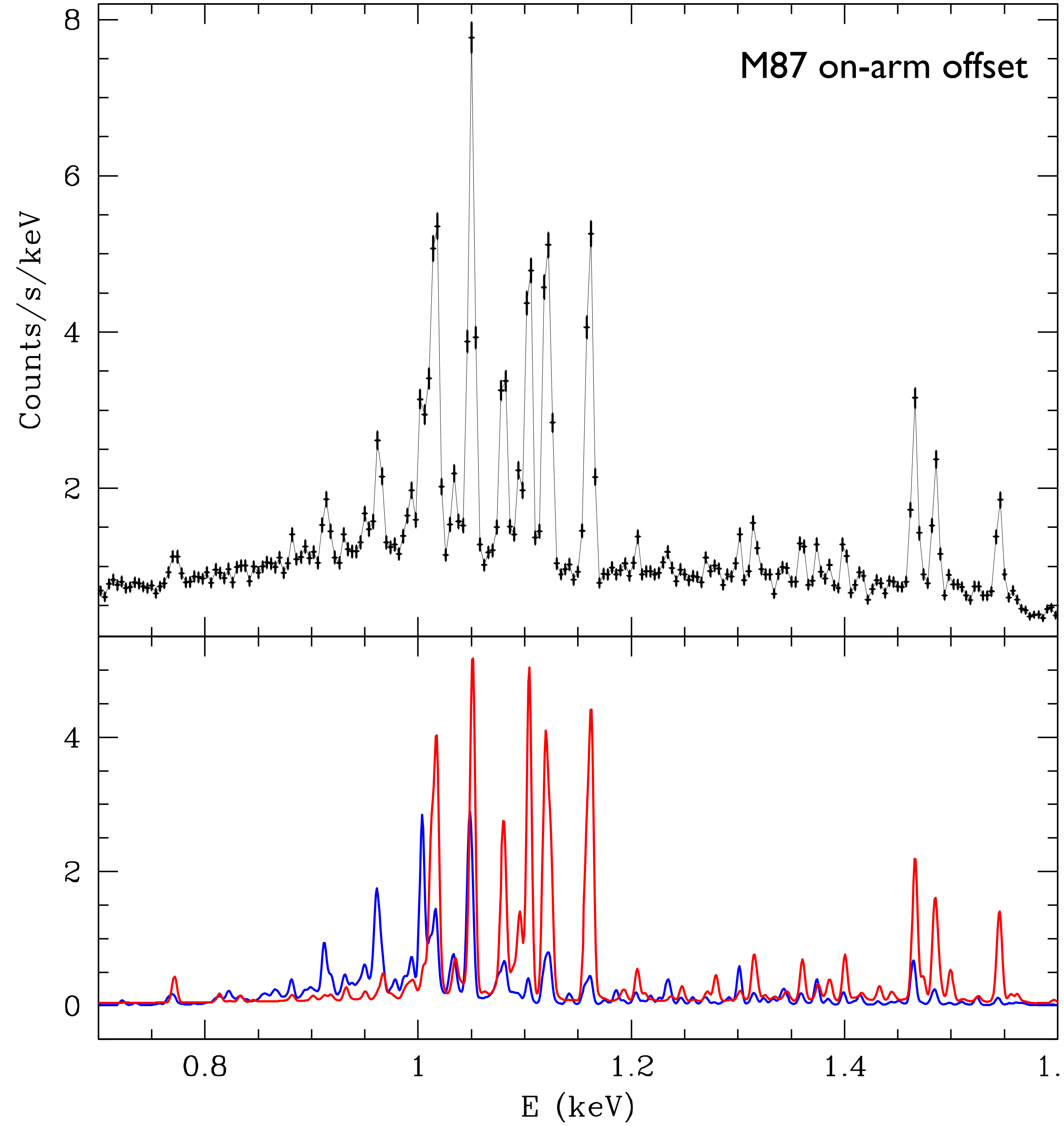
for gas motions on small spatial scales we expect significant line-of-sight velocity dispersion σ, resulting in line broadening, but no centroid shifts



if the spatial scale of motions is large, then we expect significant centroid shifts



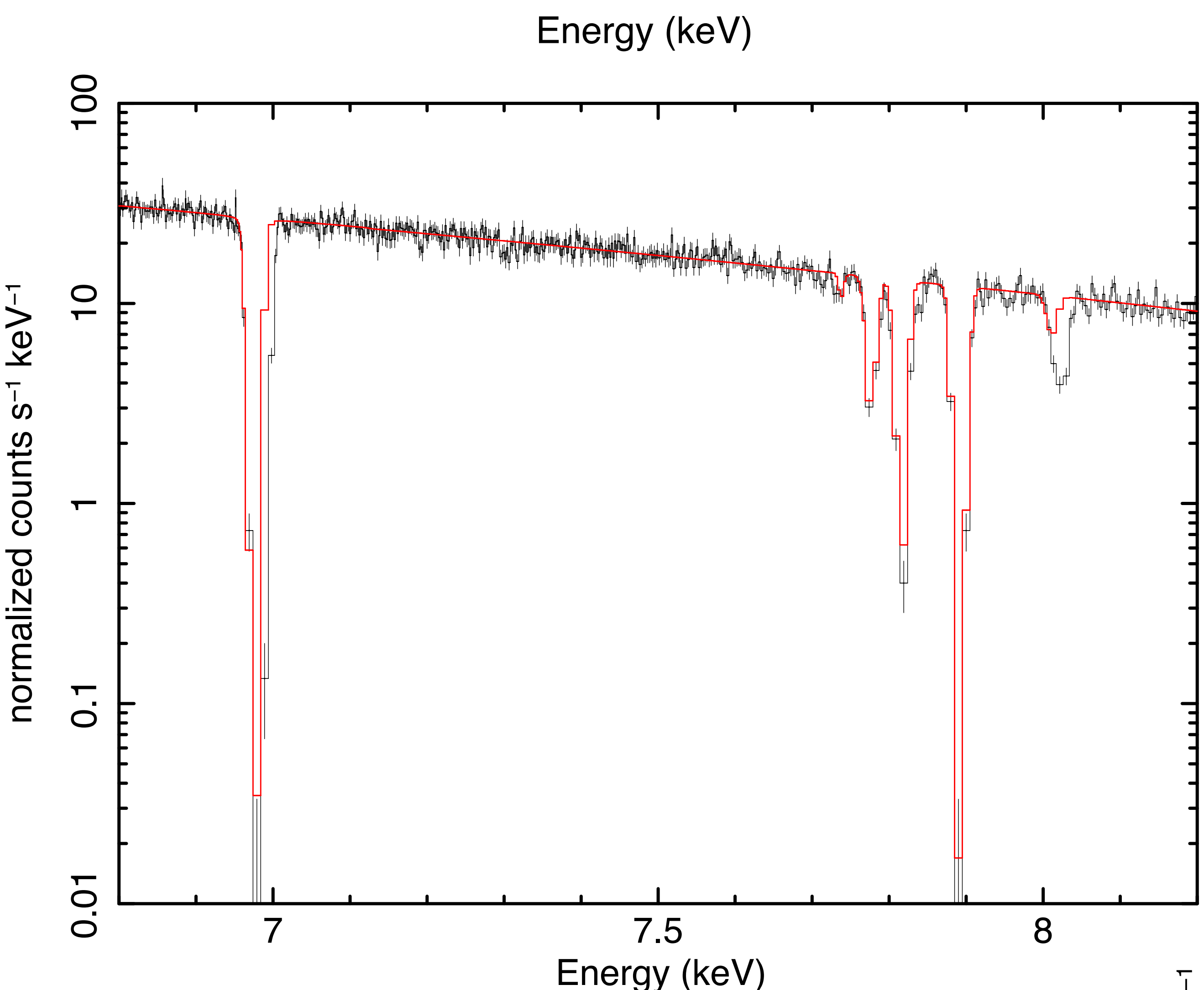




Measure velocity and metallicity of gas uplifted by AGN → understand how AGN stops star formation by removing cool material from the center; important for galaxy evolution!

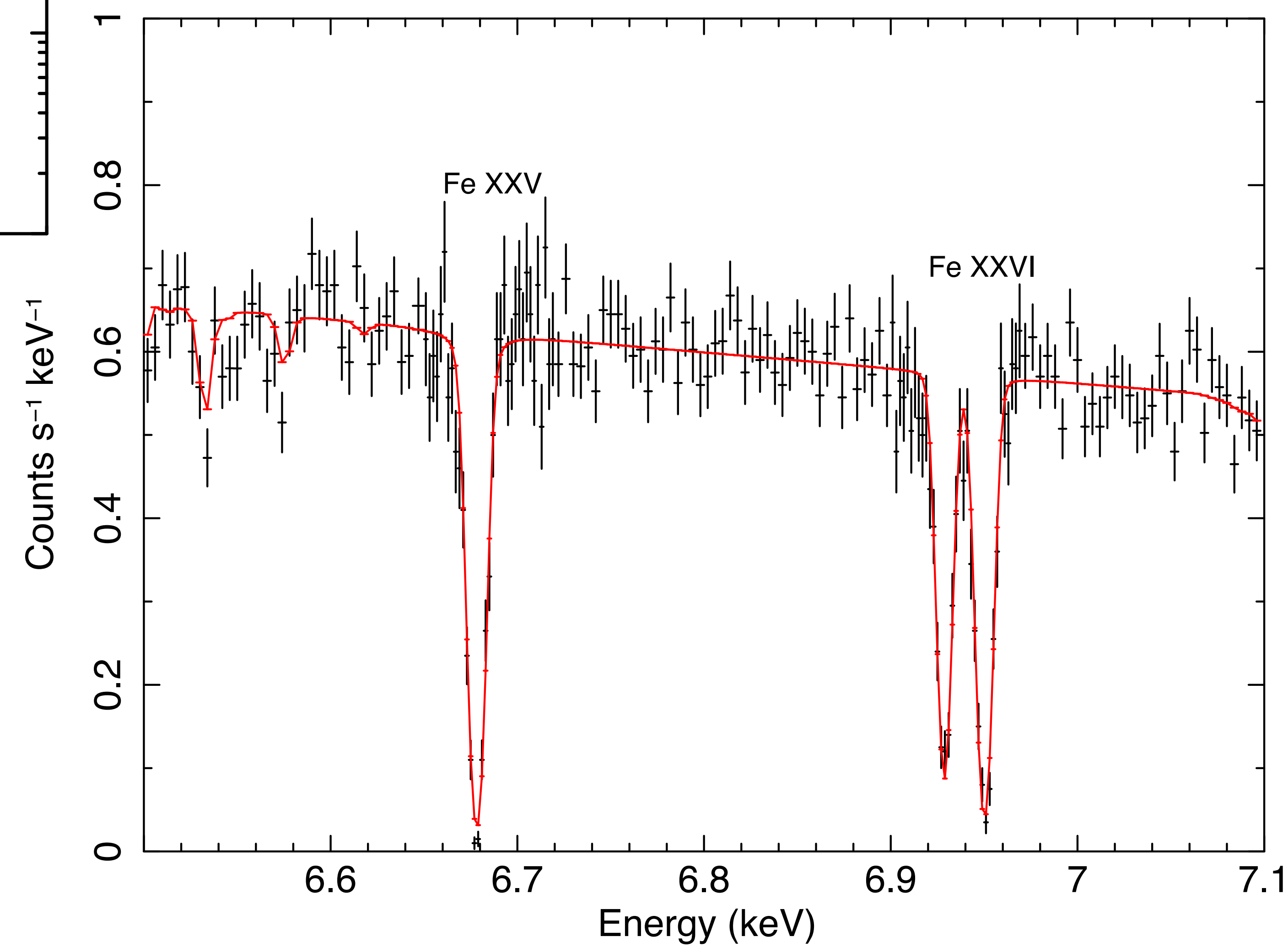
Disk winds and accretion physics across the mass scale

- improve measurements of the velocities, densities, dynamics, launching radii of disk winds, which contain significant amounts of highly ionized outflowing material → how are winds driven?
- separate discrete components with different ionizations, column densities and outflow velocities
- are winds in stellar and supermassive BH similar?



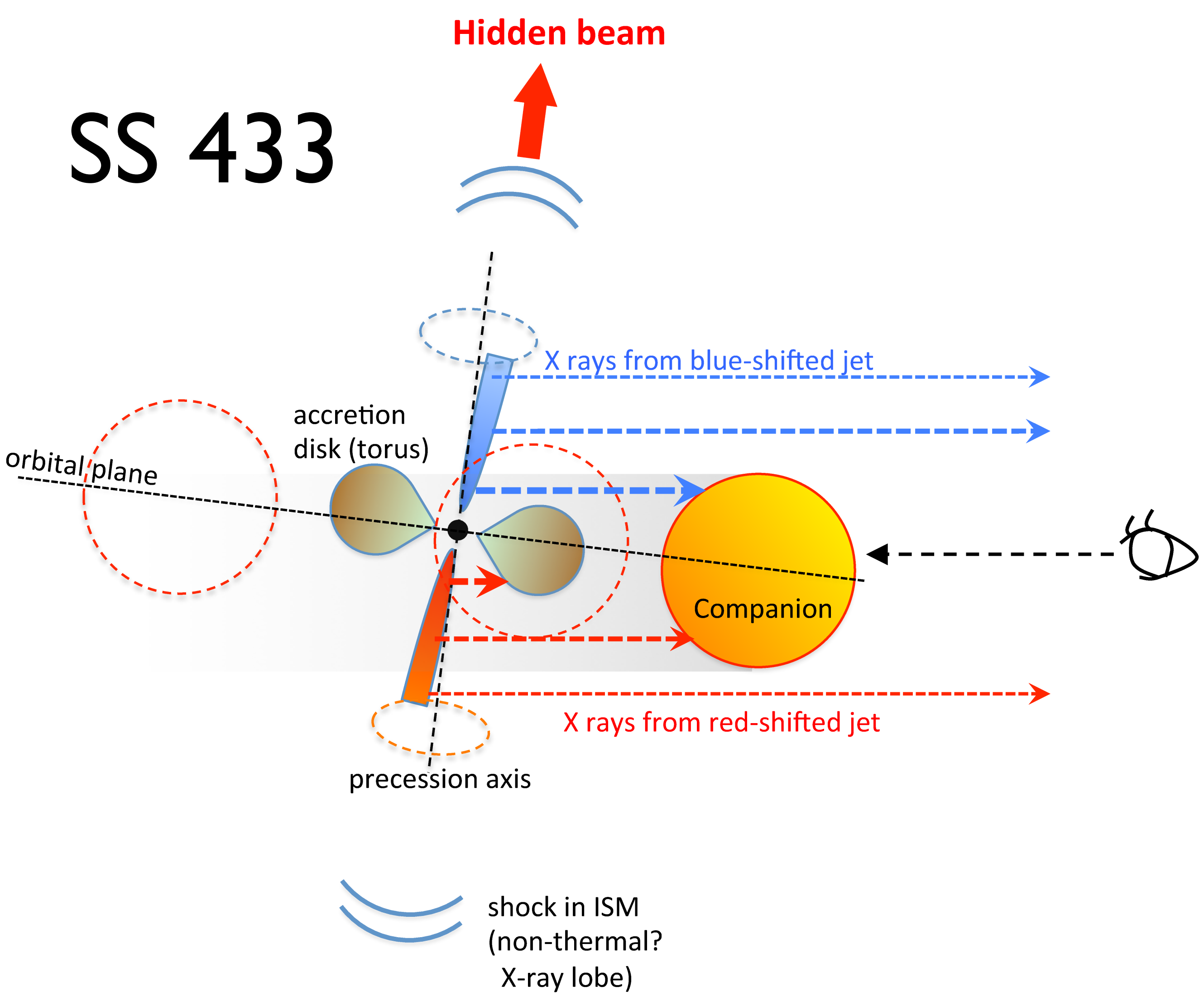
stellar:
GRO J1655-40

supermassive:
NGC 4151



Jet physics

SS 433

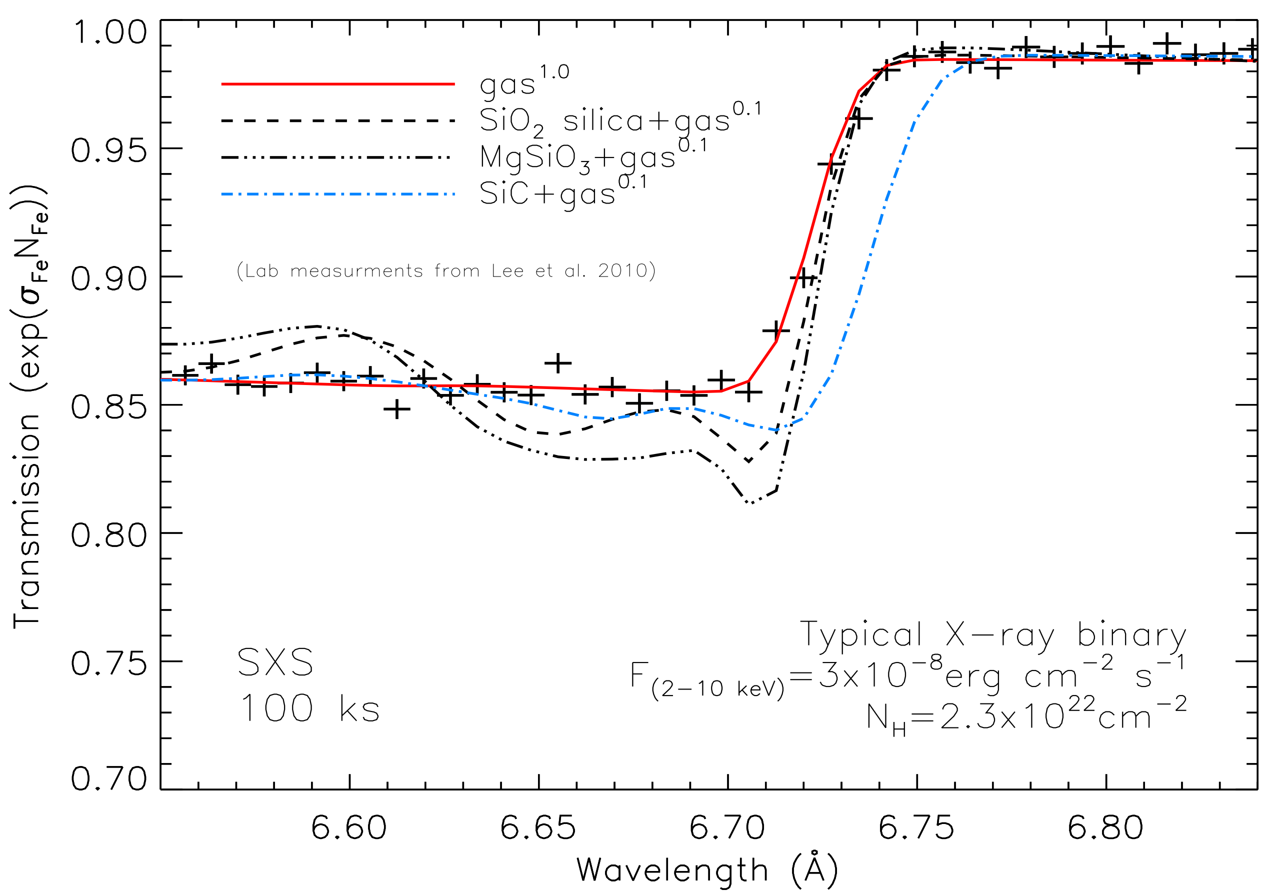


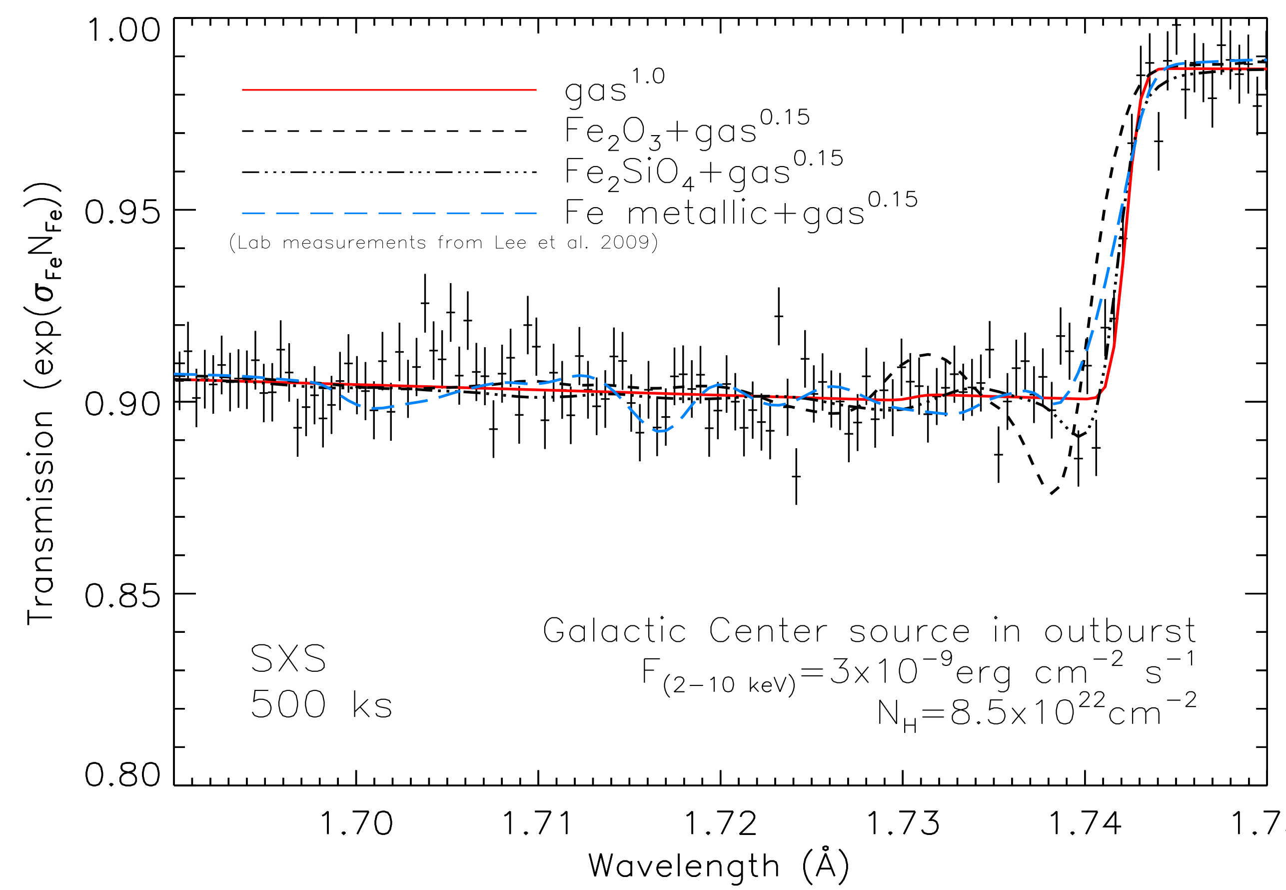
the only source with clear evidence of baryonic matter that has been launched to a fraction of the speed of light.

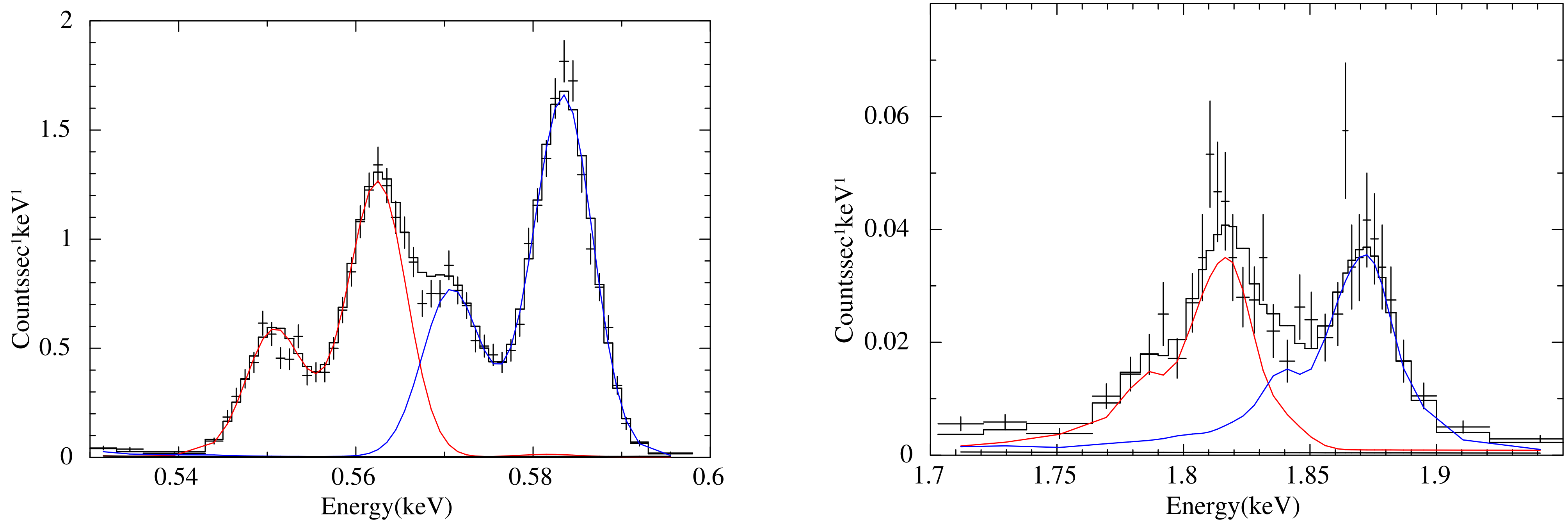
measure differences in line widths between elements and charge states, e.g. is width of Fe K line broader than for lighter elements emitted further along the jet? → collimation

Galactic Interstellar Dust Absorption

- use background light of X-ray binaries to study micro-crystalline structure and composition of dust by looking at 'X-ray Absorption Fine Structure' (XAFS) features in the spectrum near absorption edges: Mg-K, Si-K, Fe-K







(a) Oxygen (b) Silicon

Figure 10: Simulated SXS observations of a pointing near the center of SN1006 showing Oxygen (*Left*) and Silicon (*Right*) that demonstrates how cleanly we will be able to separate the emission from the approaching (blue curves) and receding (red curves) hemispheres of the expanding shell of ejecta.

Accurate measurements of ejecta dynamics - on an element by element basis!

Ground-breaking science in the next decade

Extension into the high-redshift Universe in the next decades