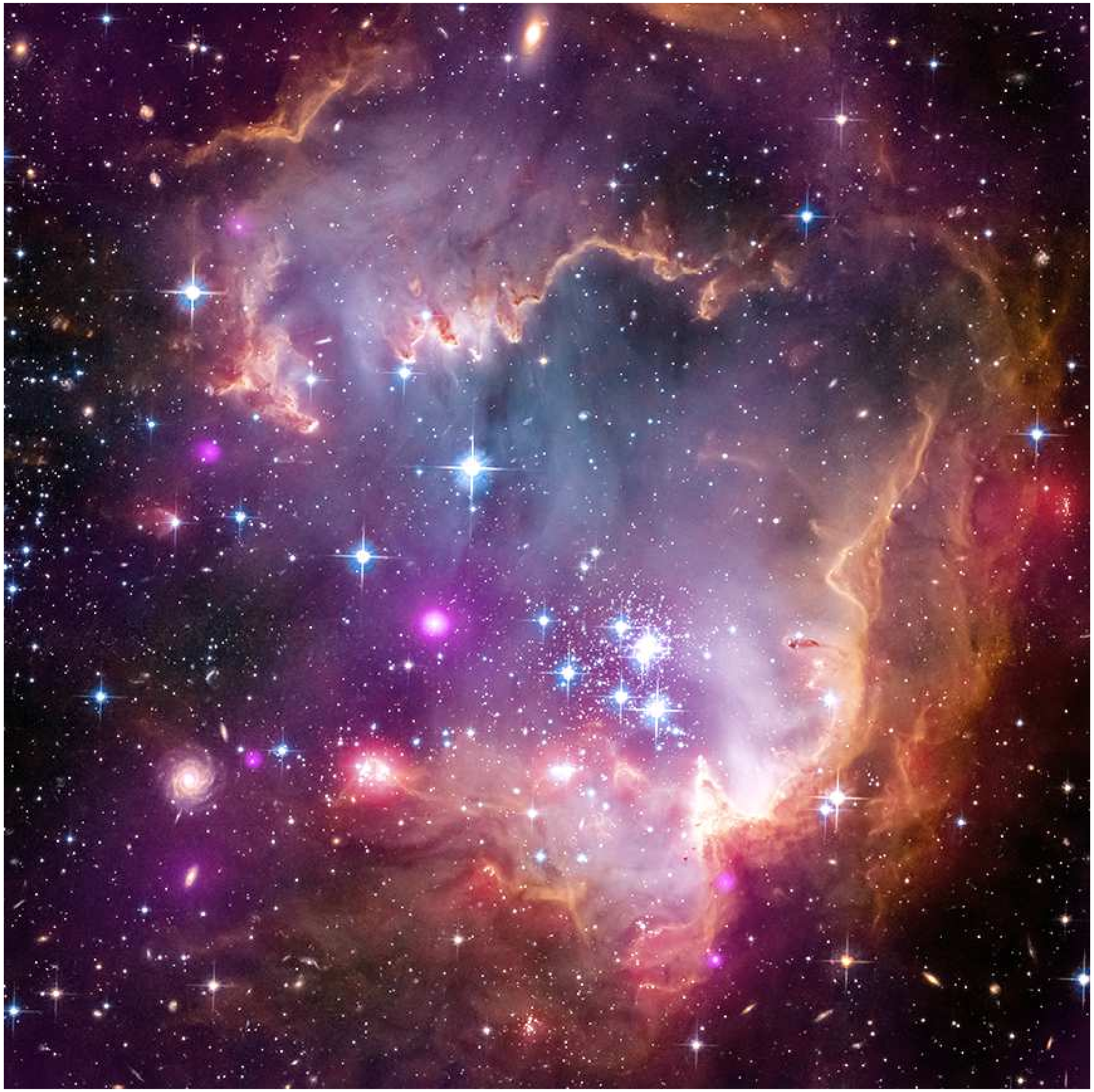
The X-Ray Universe



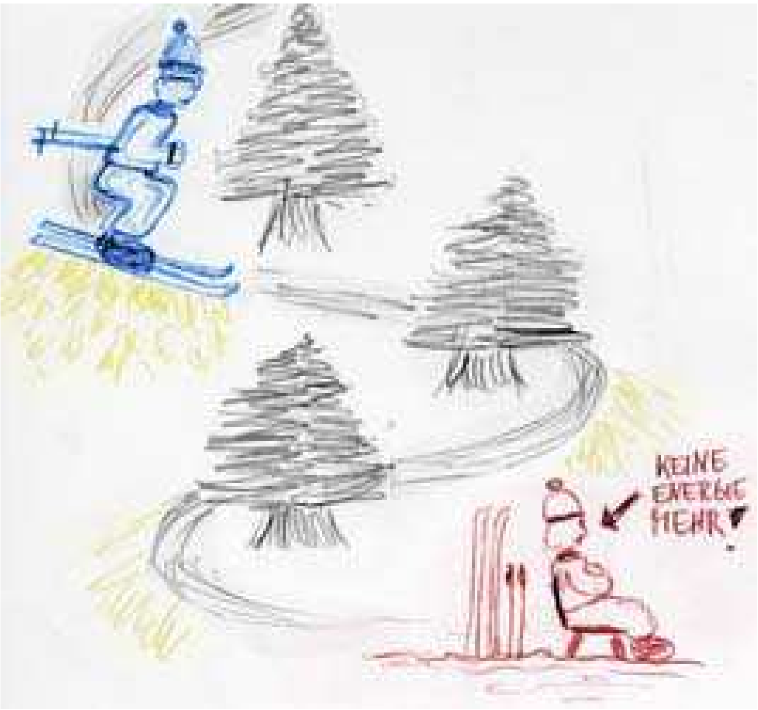
Potsdam University

Dr. Lidia Oskinova

lida@astro.physik.uni-potsdam.de
astro.physik.uni-potsdam.de
~lida/vorlesungXRAYSo17.html

Chandra X-ray, HST optical, Spitzer IR
NGC602 in the SMC
d=60pc

Thermal Bremssshtrahlung



http://www.desy.de

Bremssshtrahlung calculations

Find spectrum from single encounter of electron and ion with given impact parameter

Integrate over all possible impact paraemters

Integrate over distribution of electron velocities (in this case Maxwellian)

Important when temperatures are very high:10...100 MK

The dominant emission from cluster of galaxies

The total bremsstrahlung emission:

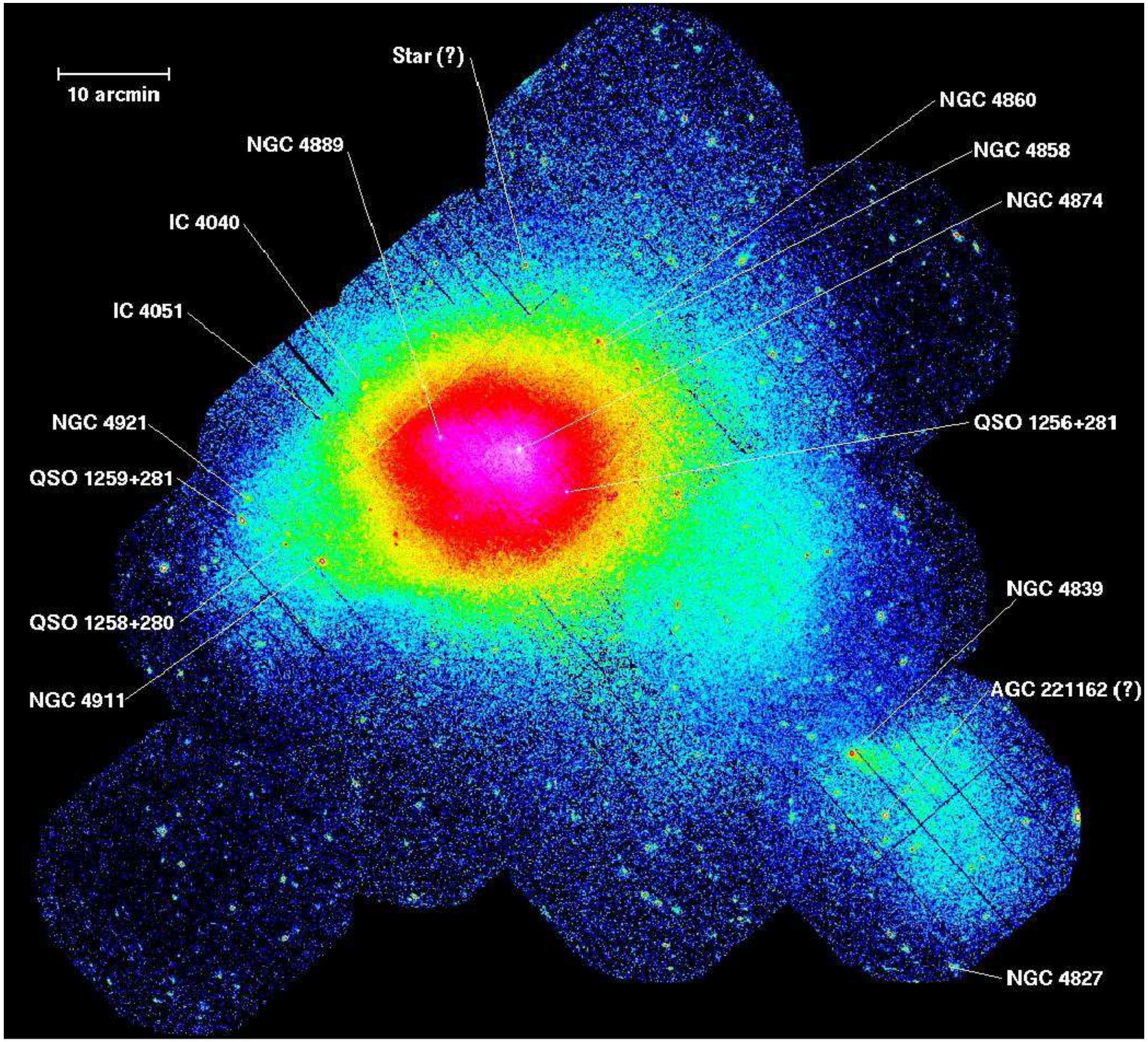
$$\frac{dP_B}{dV} = 2.4 \times 10^{-27} \sqrt{T} N_e^2 \quad [\mathrm{erg\ cm^{-3}\,s^{-1}}]$$

Note that electron distribution can be non-thermal,

$J(E)=J_0 E^{-s}$ [erg cm^{-2} s^{-1} erg^{-1}] →

spectral shape depends on the elesctron spectrum

02 X-ray measurments



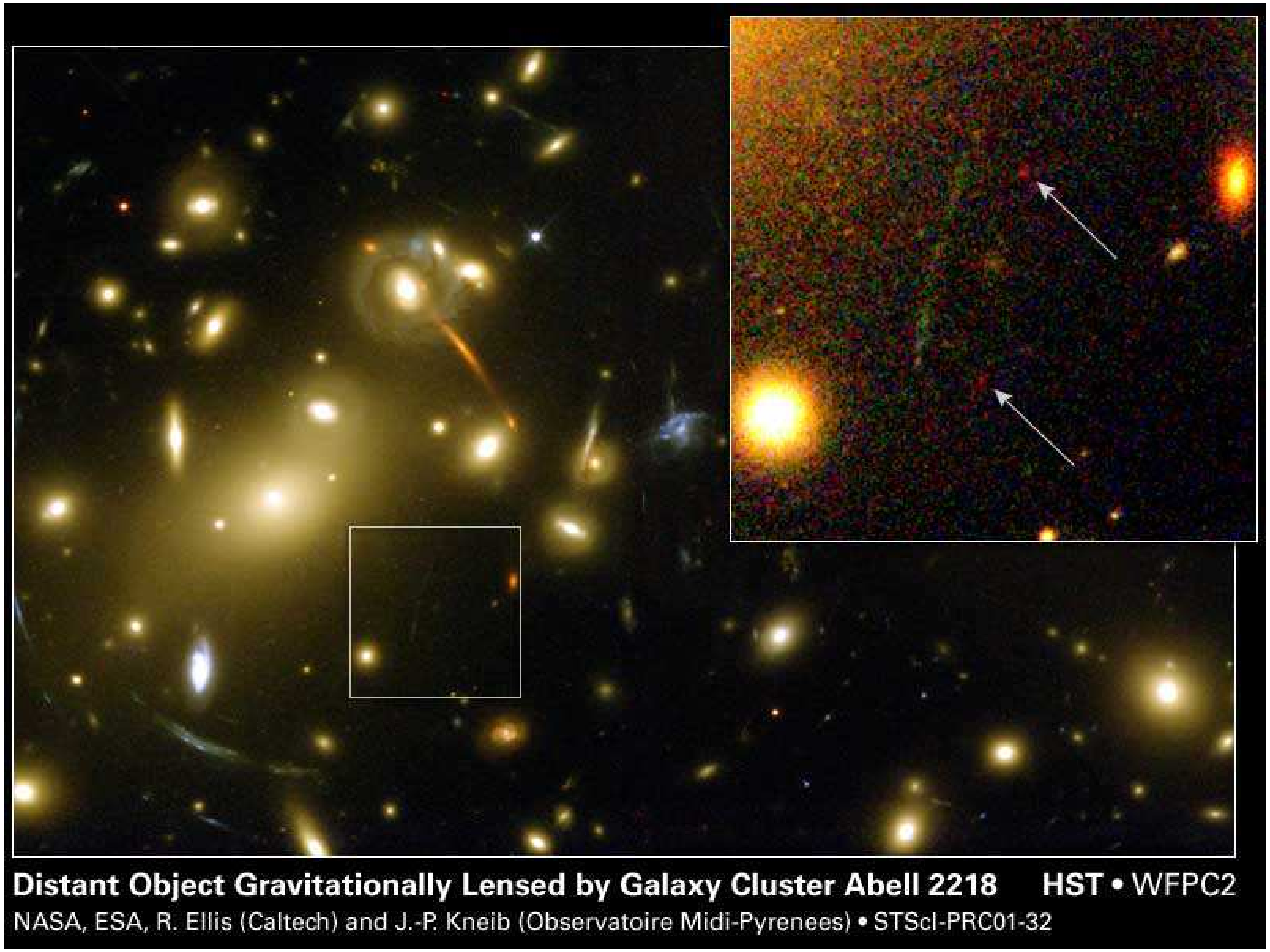
Coma Cluster of galaxies

Image courtesy of U. Briel, MPE Garching, Germany

European Space Agency

- From X-ray spectrum we measure a mean temperature (proxy for total mass), and baryon gas density.
- We can constrain the ratio of baryon to total mass → cosmology

03 Other ways to detrmine cluster mass



-- The gravitational potential acts as a lens on light from background galaxies.

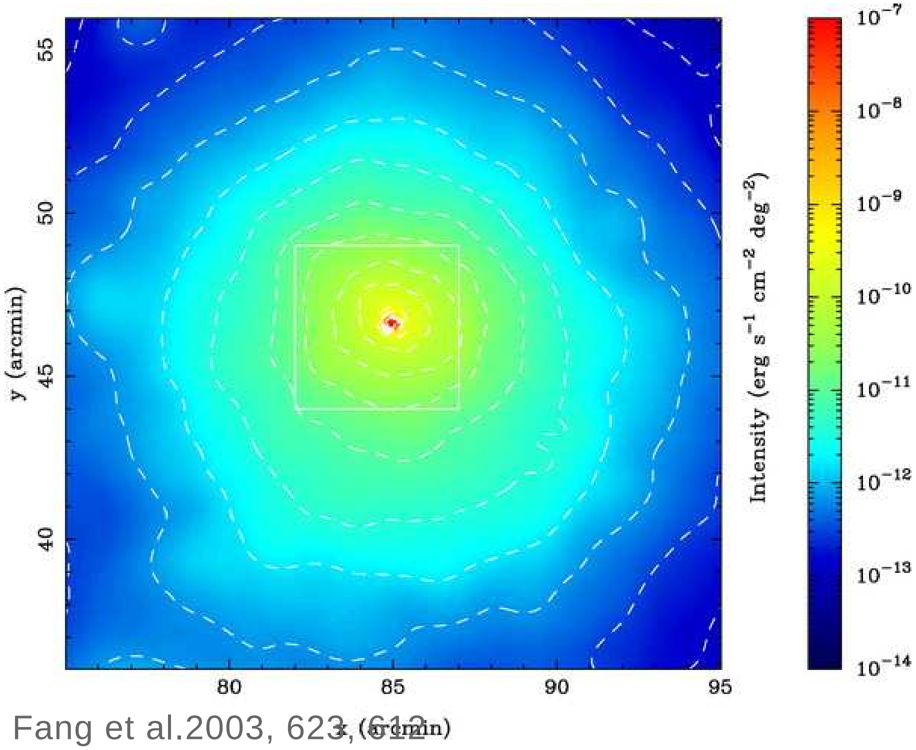
-- Solving lens equation yields the cluster mass

04 Mass determination

- X-ray observations allow **two** mass determinations for a relaxed galaxy cluster
- Mass of gas is proportional to square of X-rays emission, because the emission is thermal Bremsstrahlung.
- Total mass is proportional to the gas temperature, because this defines the cluster potential.
- Temperature profile can be used to constrain the cluster potential and find $f_{gas}=M_{gas}/M_{total}$
- Eck (1998): the mean baryonic mass fraction b within the virial radius of a cluster is similar to the universal baryon fraction. Because R_{vir} separates the region where shells of material are infalling for the first time.
- From X-ray data gas fraction is only about 82% of average barion fraction → clusters loose some gas when they form, it decreases with z.

05 Mass determination

Simulation of X-Ray Emission



Fang et al.2003, 623, (612)

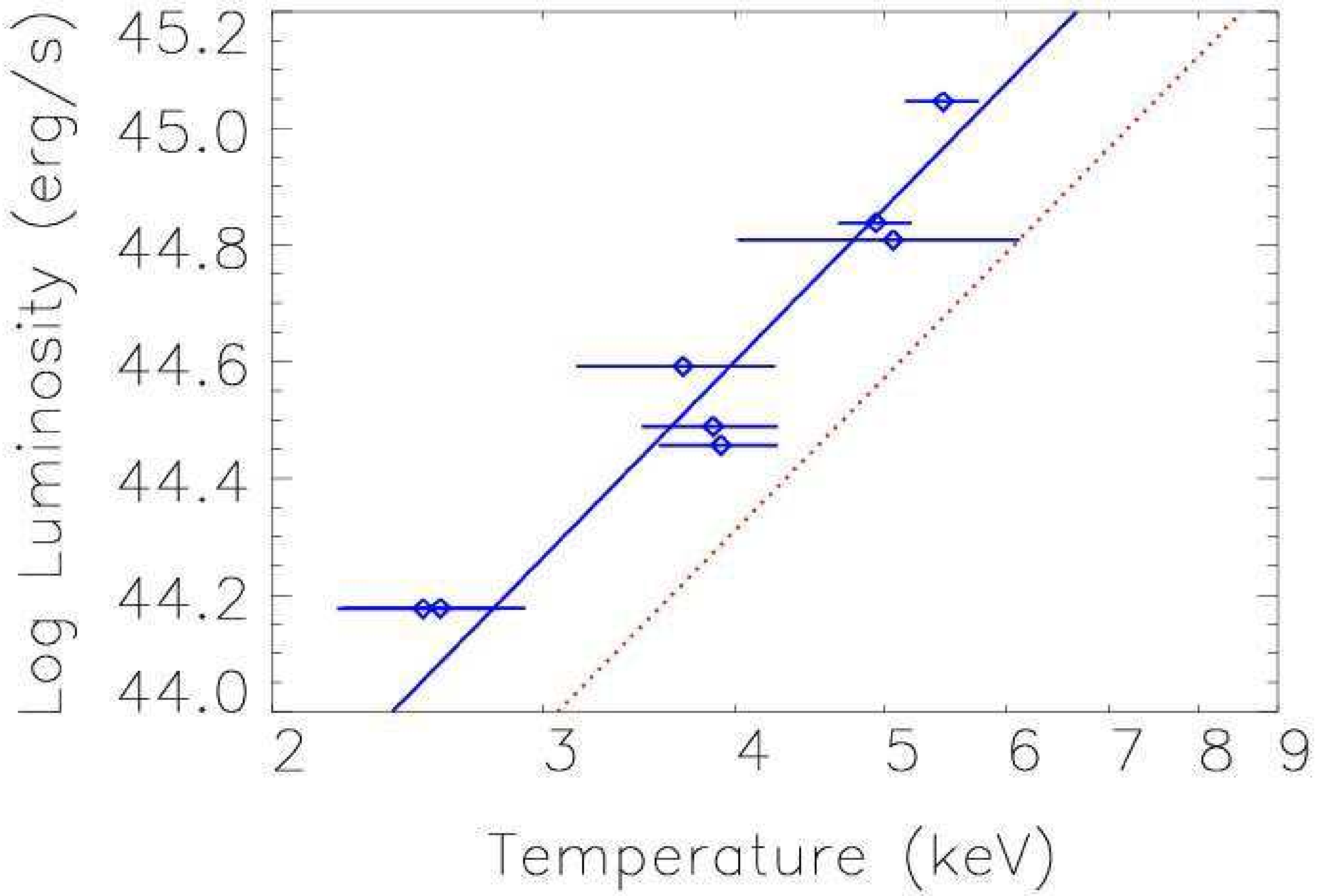
ICM: bremsstrahlung emission

$$\epsilon(E) \propto \sqrt{\left(\frac{m_e}{kT}\right)} g N^2 \exp -E/kT$$

- If we can measure the temperature and density at different positions in the cluster then assuming the plasma is in hydrostatic equilibrium we can derive the gravitational potential and hence the amount and distribution of the dark matter. (e.g. Sarazin 1998)
  - $\nabla P = -\rho_{\text{gas}} \nabla U = -\frac{GM}{r^2}\rho$, $P = \frac{\rho k T}{\mu m_{\text{H}}}$
  - $\frac{dP}{dr} = \frac{k}{\mu m_{\text{H}}}\left(T\frac{d\rho}{dr} + \rho\frac{dT}{dr}\right)$
  - $= \frac{\rho k T}{\mu m_{\text{H}}}\left(\frac{d\log\rho}{dr} + \frac{d\log T}{dr}\right)$
  - $M = -\frac{kTr^2}{G\mu m_{\text{H}}}\left(\frac{d\log\rho}{dr} + \frac{d\log T}{dr}\right)$

T, N from X-ray spectra → mass

06 Redshift evolution of the L-T relation for clusters of galaxies



Redshift evolution of the lt relation for clusters of galaxies

Image courtesy of D. H. Lumb, J.G. Bartlett et al.,

European Space Agency

- galaxy clusters for a redshift range $0.45<z<0.62$
- Low-Redshift clusters

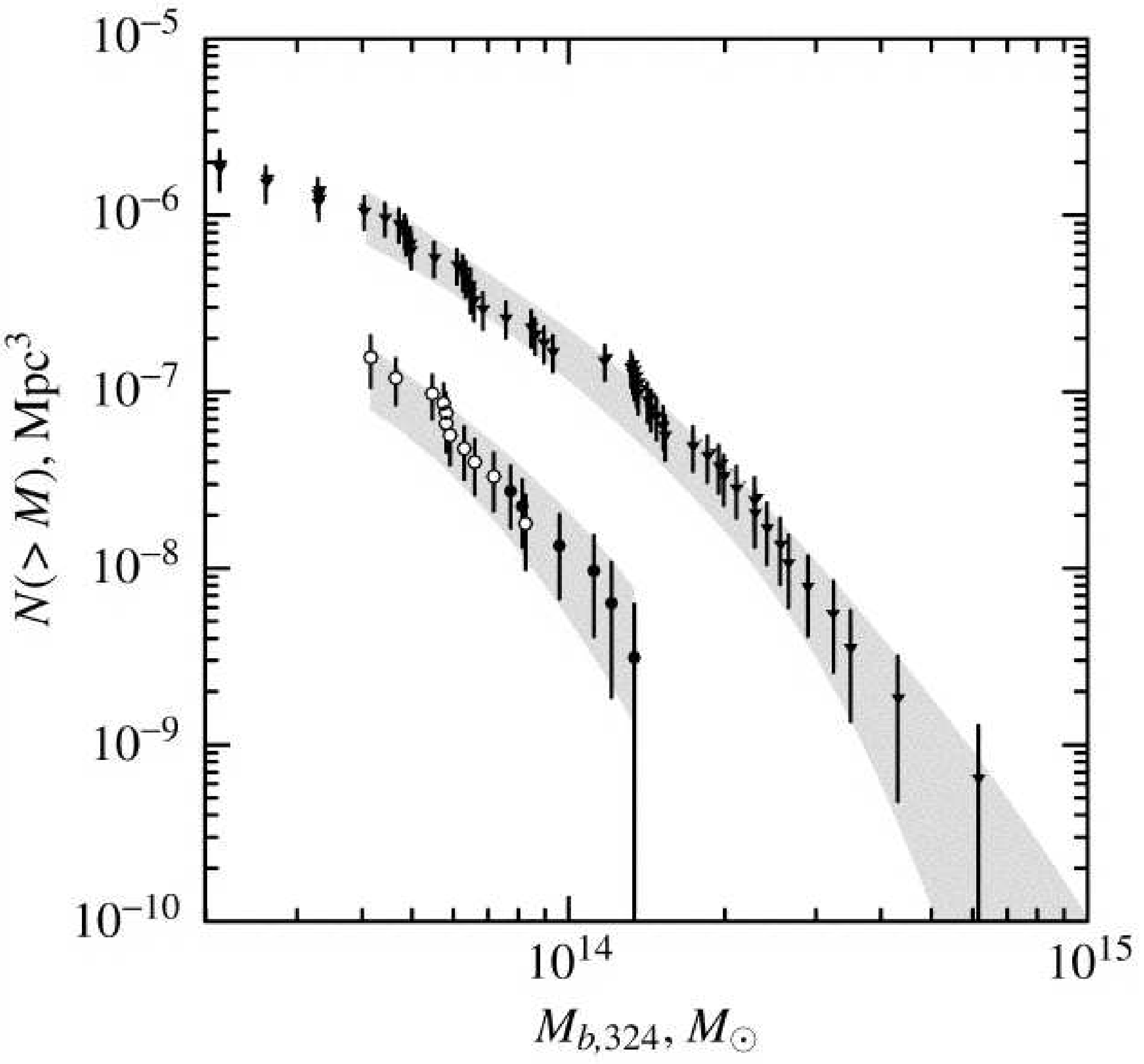
there is evolution with redshift

Cosmological simulations predict distributions of masses. If we want to use X-ray selected samples of clusters of galaxies to measure cosmological parameters then we must be able to relate the observables (X-ray luminosity and temperature) to the theoretical masses.

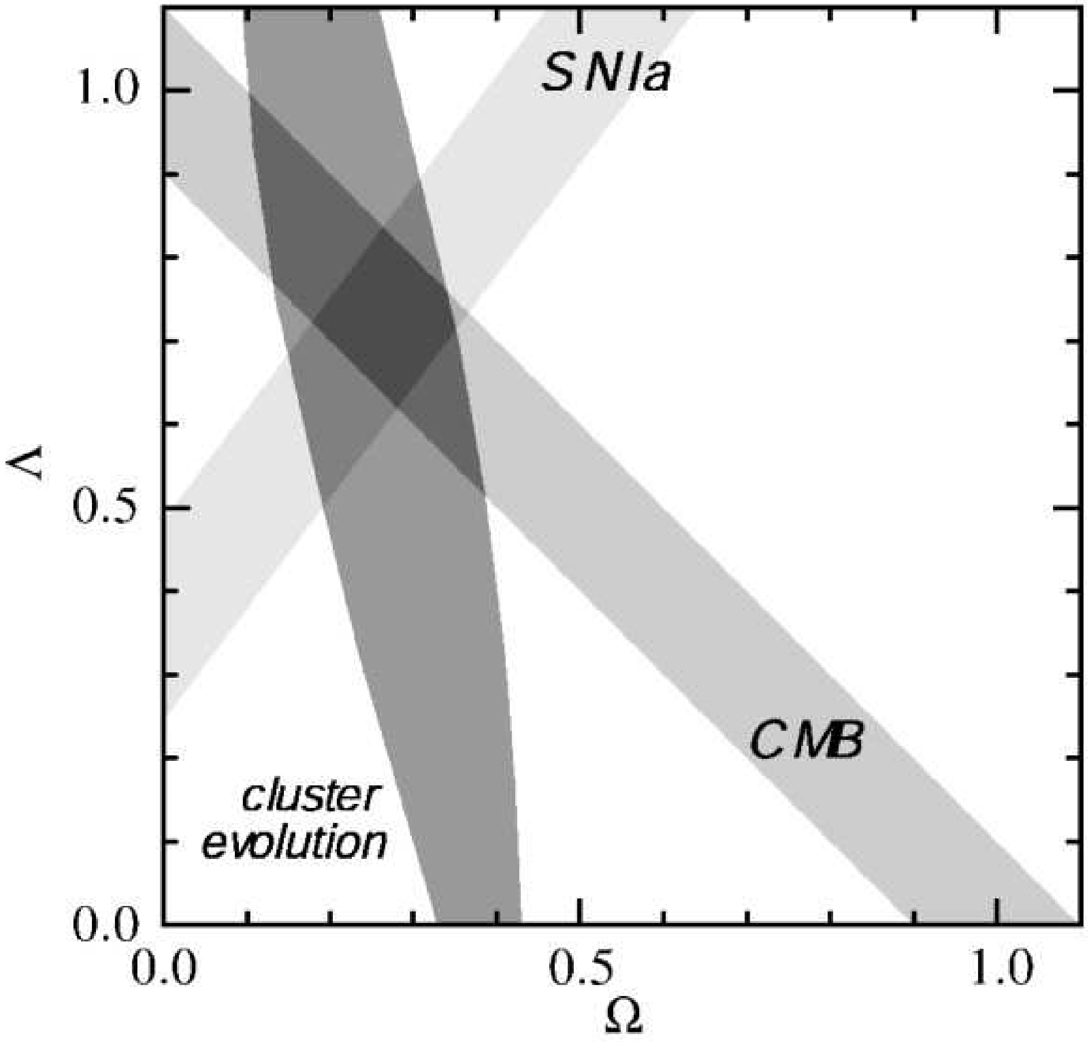
07 Cosmology from cluster evolution (Vikhlinin et al. 2003)

- Barion mass fraction from measuring T_X and L_X and used as a proxy for total M
- Cosmological simulations predict the cluster mass function at any redshift
- Constraining N of cluster of given mass with redshift constarins cosmological models.
- Most of the difficulties are on the observational side.

- Baryon mass function for the cluster survey with 0.4<z<0.8. measured by Chandra barion mass measurments: data points
- Grey: computed theoretical mass function (Ω_m=0.3, Λ=0.7) includng error bars.
- Upper curve: local Universe, cosmology independent



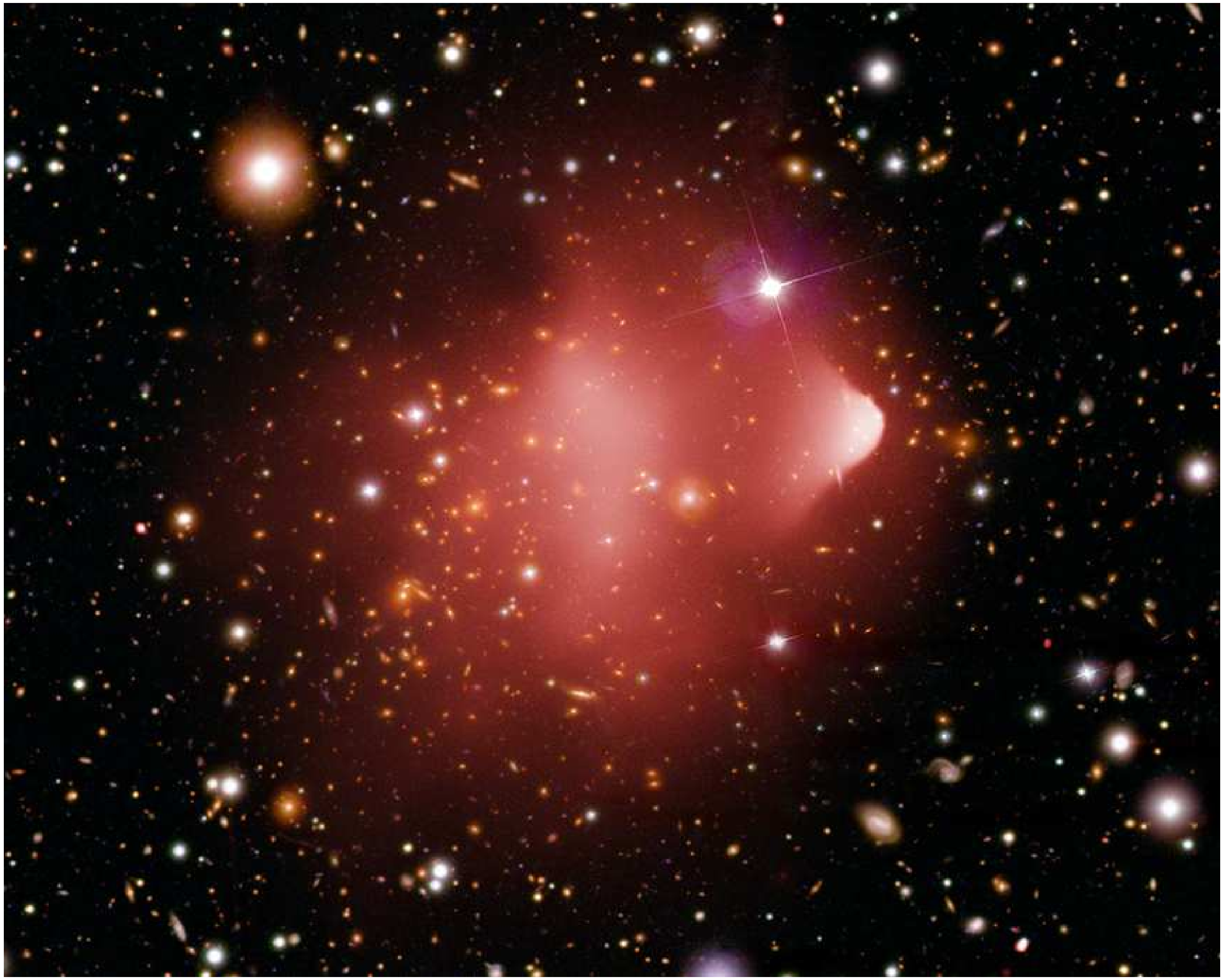
08 Cosmology from cluster evolution (Vikhlinin et al. 2003)



-- Independent on other methods

-- New surveys are underway

09 The Bullet Cluster (two interacting clusters)

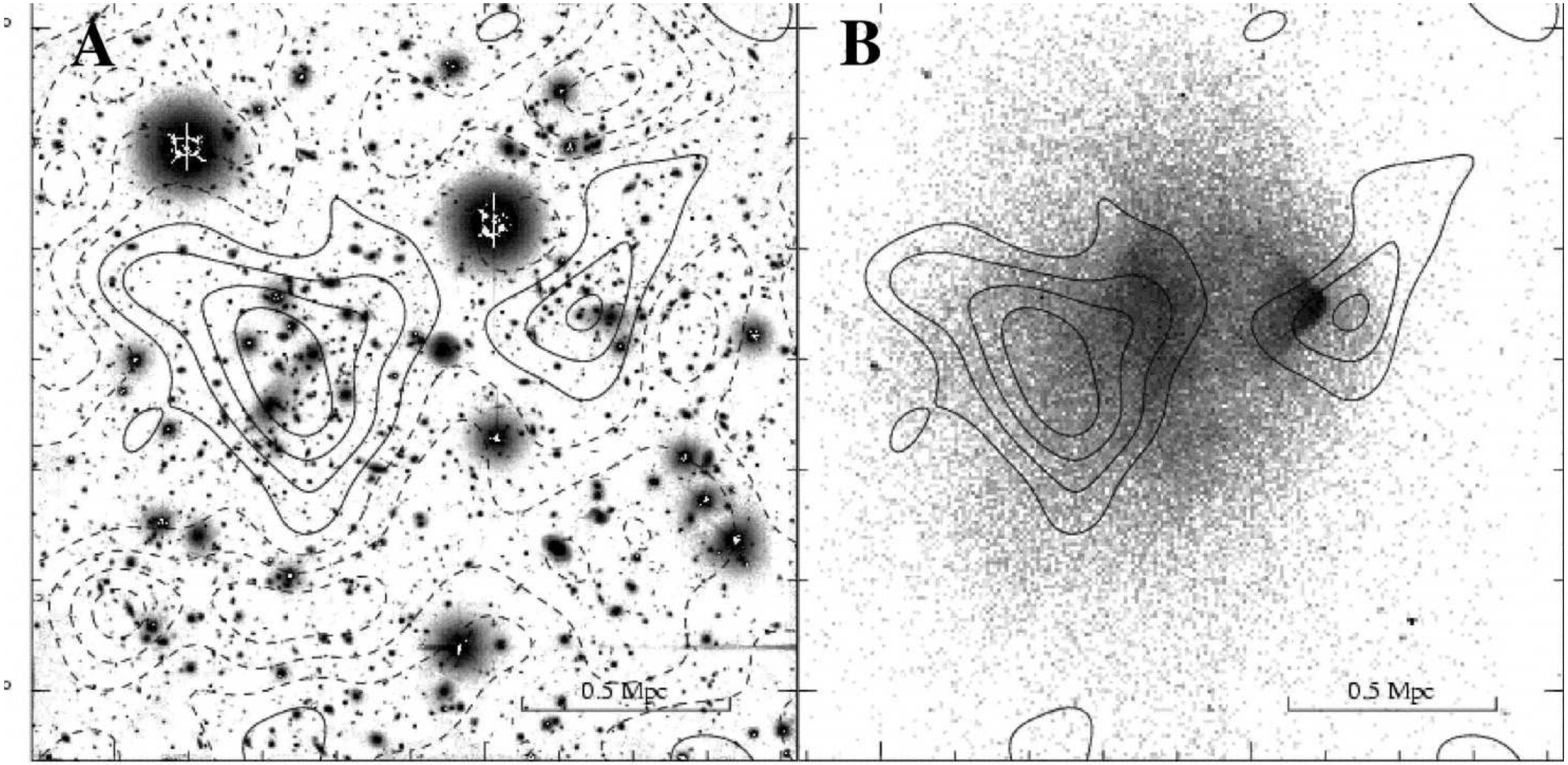


X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et

- System has just undergone pass-through: the two clusters are now moving away from one another.
- no γ-rays, no antimatter!

10 Does gravitational potential trace barions?

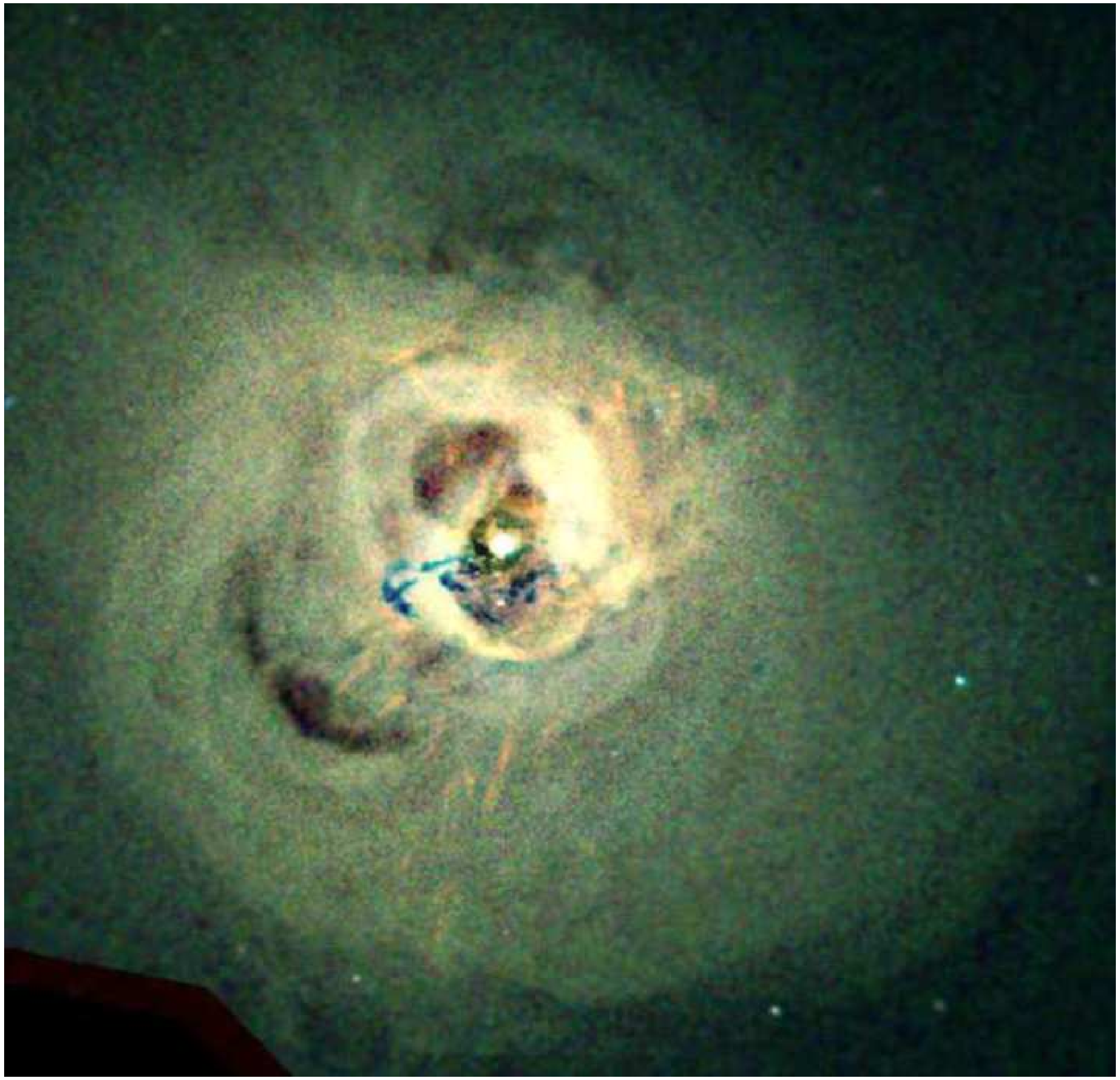
Weak-lensing maps overlayed with X-ray image



Clowe et al. 2004 ApJ 604, 596

- Galaxies are collisionless particles in the pass-through
- There is agreement in position between the mass peak and galaxy overdensity
- The X-ray gas:the ram pressure of the interacting gas halos, it is slowed down during interaction
- There is offset between barionic density (X-ray) and mass density
- Bulk of the mass is collsionless as expected for the **dark matetr**

V. Clusters of galaxies: Physics



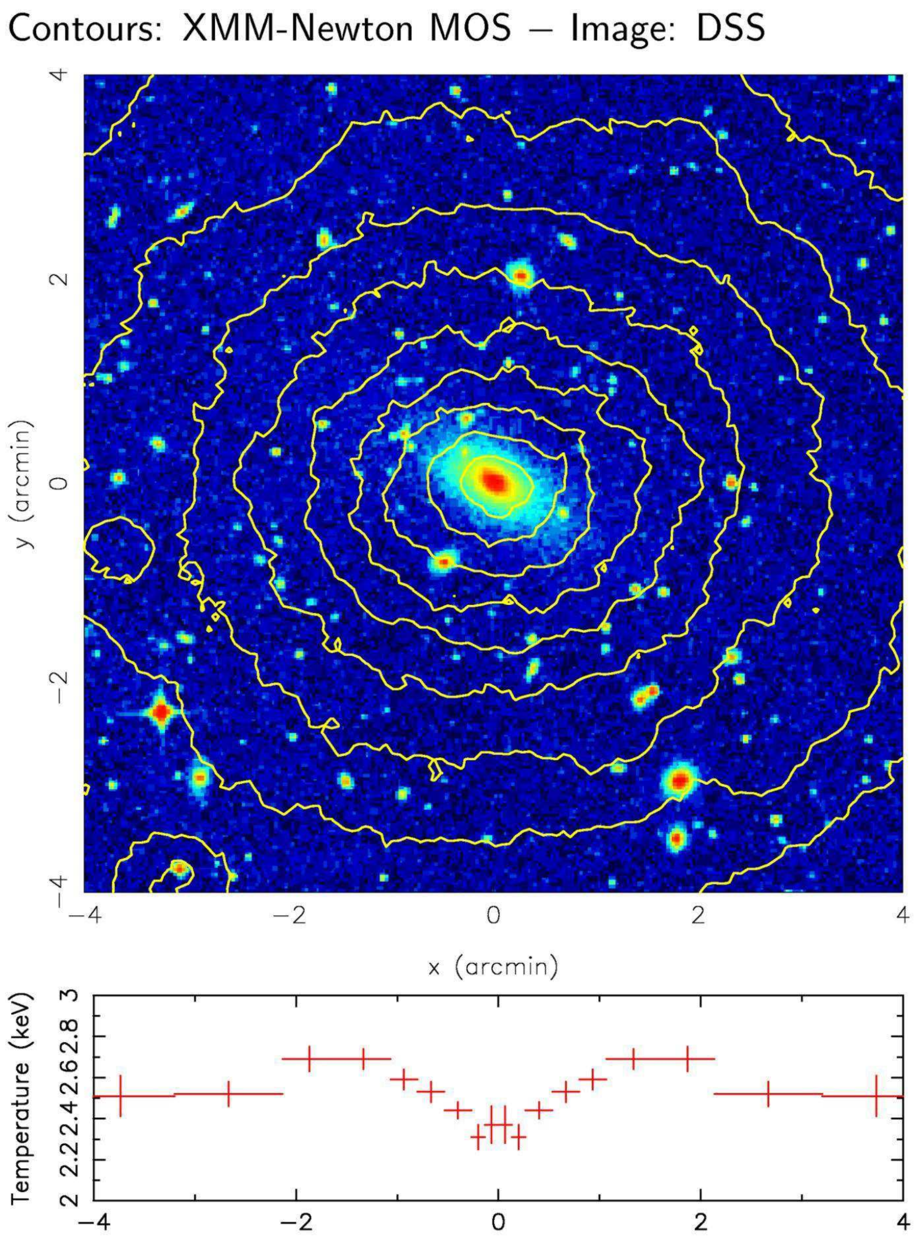
http://chandra.harvard.edu/

12 Central regions of galaxy clusters

- Basic model: Clusters are spherically symmetric balls of plasma that evolved in isolation.
- Gas density is highest at the center. $\varepsilon \sim N^2$, cooling time $t_{cool} \sim T^{0.5}/N$ is smaller than the cluster age
- Gas must lose energy by radiating X-rays
- Pressure drops, gas gets compressed by garvitational well
- Density and ε increase leading to a steady cooling inflow of plasma **cooling flow.**
- The X-ray spectra are expected to show evidence for a range of temperatures from the ambient for the cluster down to zero.
- But! They don t! little cooling gas is found **cooling flow-problem**

XMM-NEWTON SCIENCE RESULTS

Sérsic 159-03



6 December 2000

Fig. 2

Abell S1101 (=Sersic 159-03)

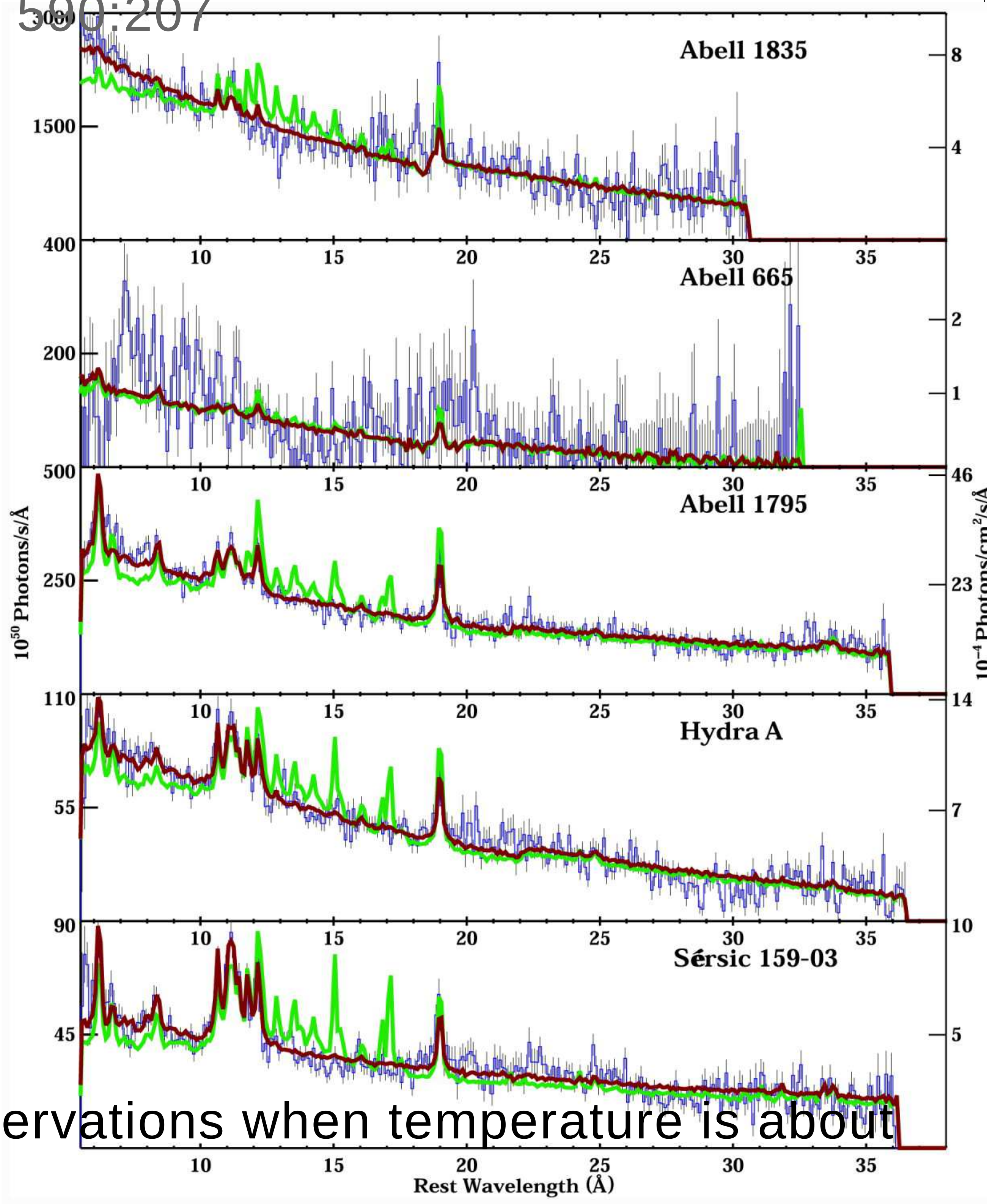
Image courtesy of J. Kaastra, SRON, Utrecht, NL

14 High-Resolution X-Ray Spectroscopy of CFs

Peterson etal. 2003

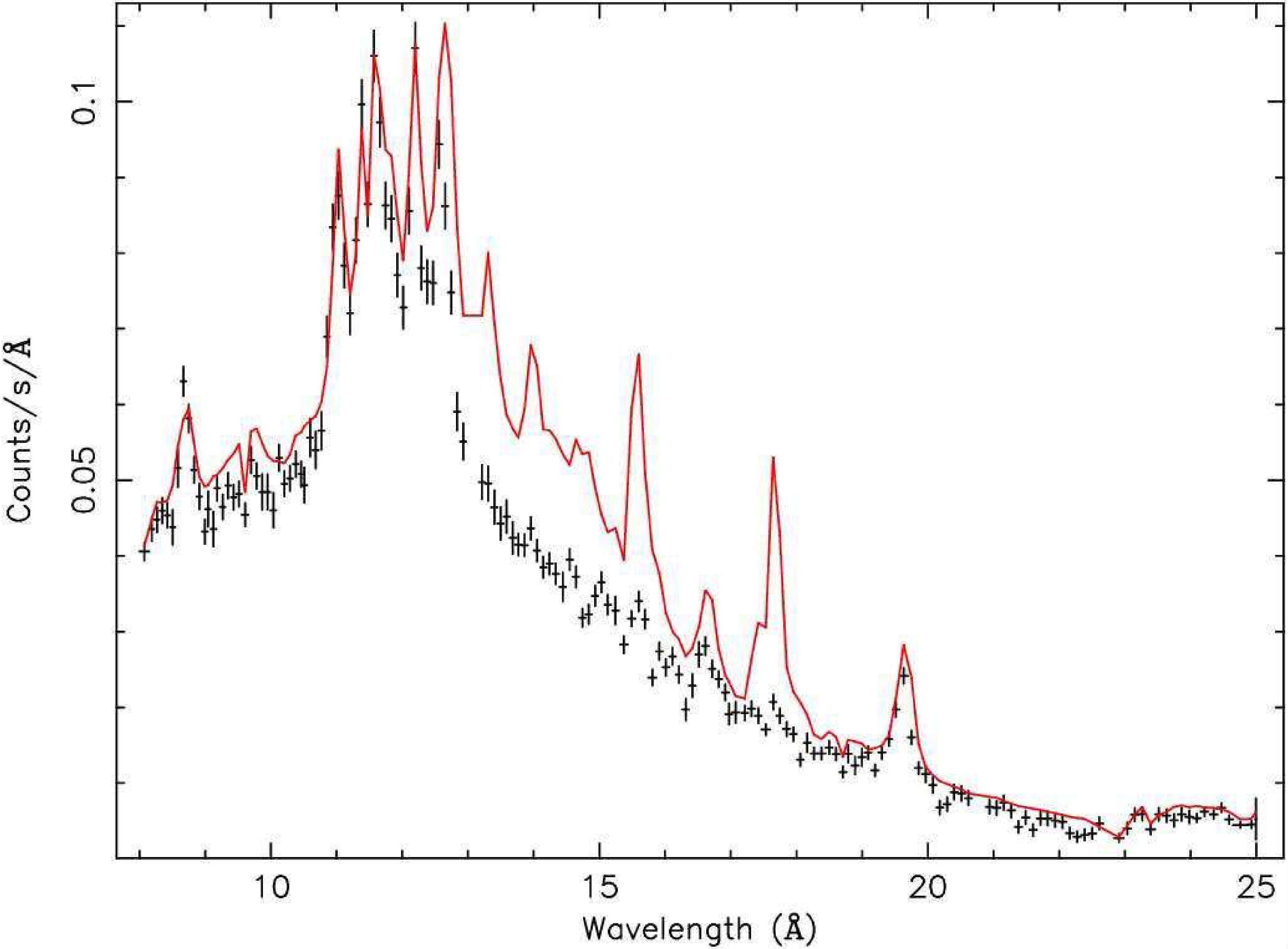
- If the blobs of plasma cool in thermal isolation at constant pressure, and the dominant energy loss mechanism is via X-radiation, then the luminosity radiated per unit temperature interval, must be proportional to the mass deposition rate
- $$\frac{\mathrm{d}L_\mathrm{X}}{\mathrm{d}T} = \frac{5}{2}\frac{\dot{M}k}{\mu m_\mathrm{p}}$$
- The only free parmeter is $\dot{M}$ - mass deposition. Can be estimated the density distribution inferred from the X-ray image.
- Then a cluster spectrum has two components: (1) the cooling-flow spectrum, as described above, and (2) an isothermal spectrum evaluated at the temperature of the background cluster gas.

From Peterson etal 2003, ApJ 590:207



observed, model, best fit

Model is inconsistent with observations when temperature is about 1/3 of the ambient value



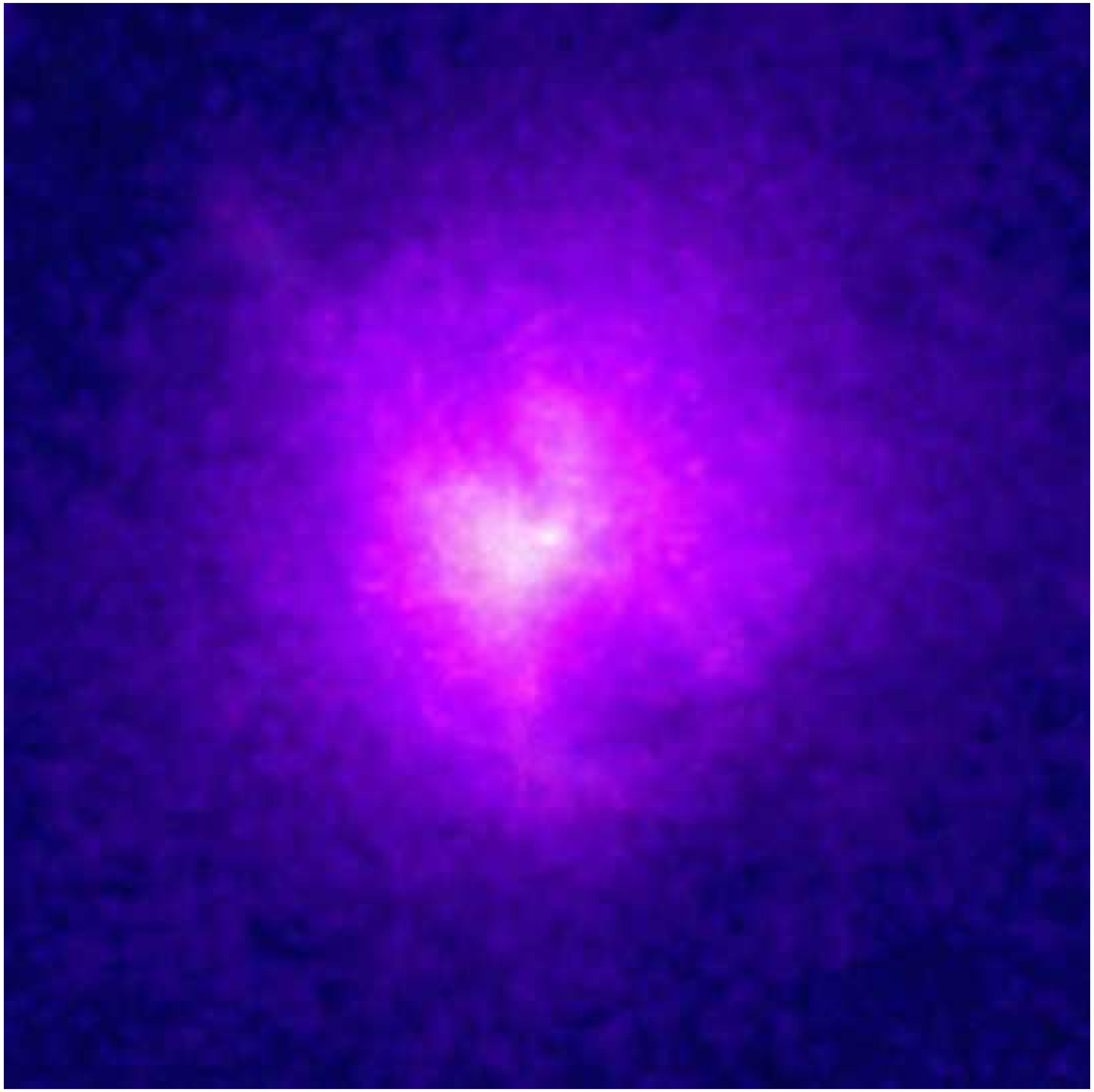
Slow cooling in the core of the galaxy cluster 2A 0335+096

Image courtesy of Jelle de Plaa, SRON, NL.

European Space Agency

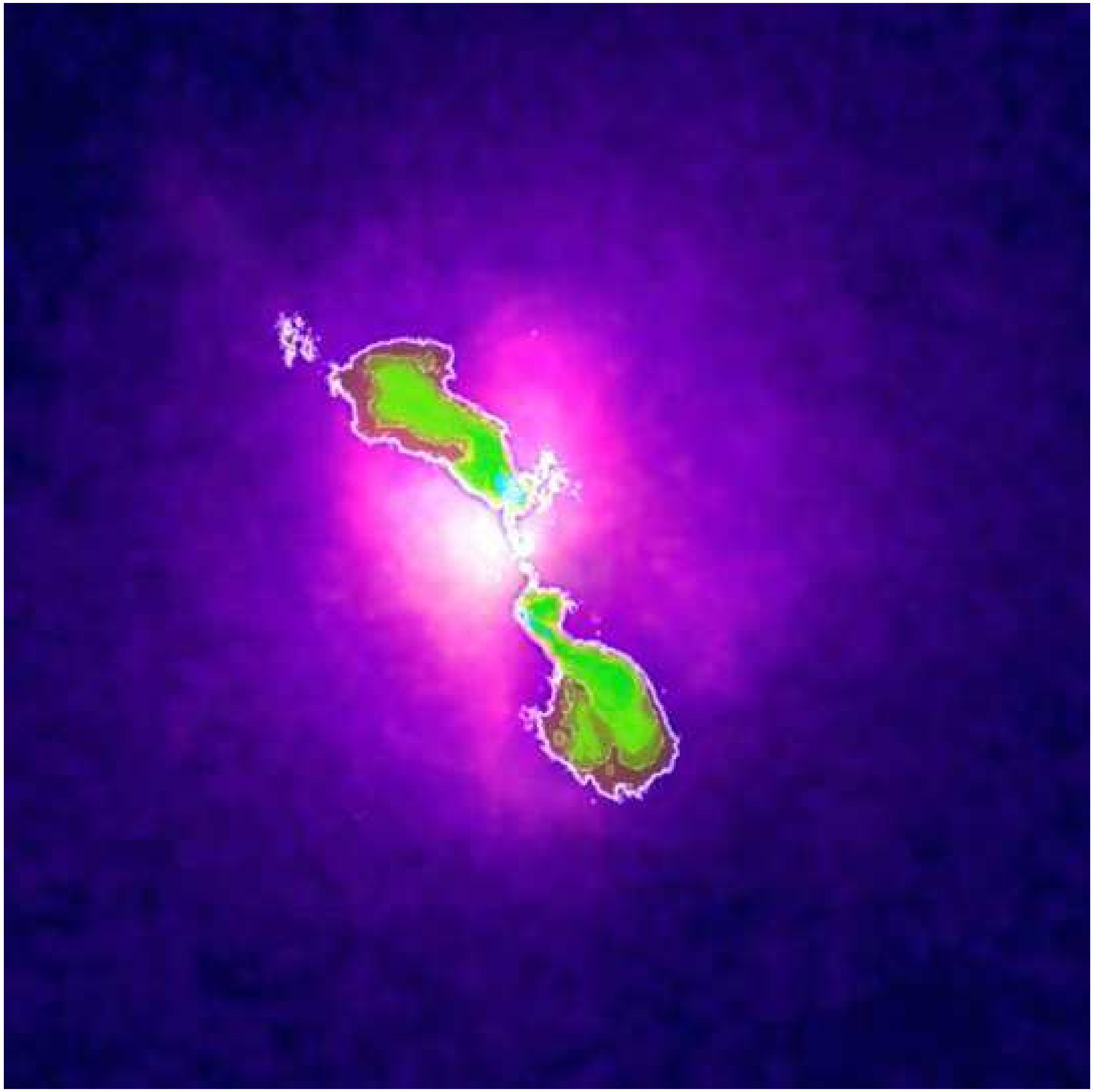
17 Hydra A: key to the CF problem?

Chandra Image



NASA/CXC/SAO

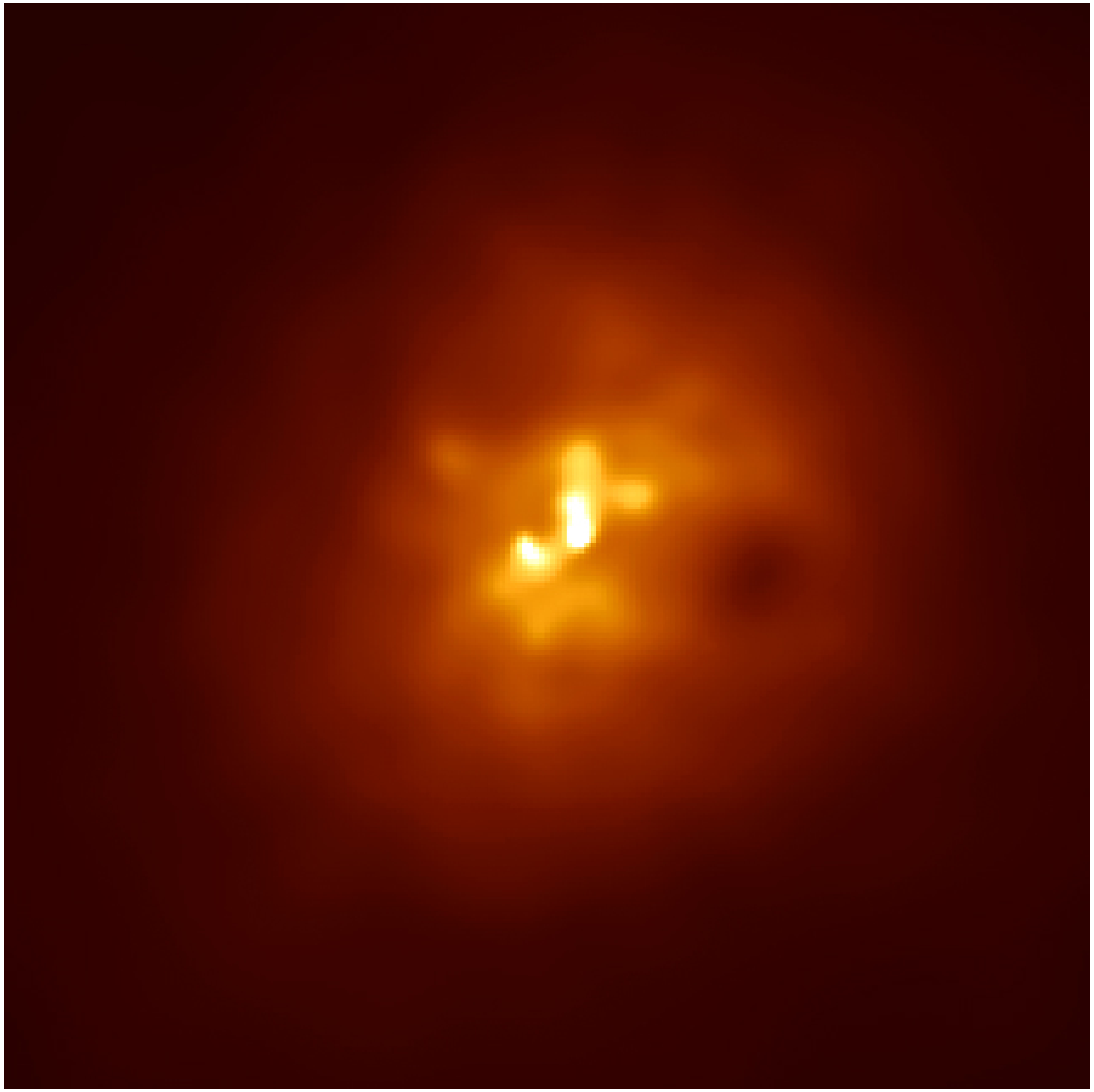
18 AGN feedback - a key to the CF problem?



NASA/CXC/SAO/NRAO Chandra + Radio Image

19 Bubbles in Abell 2597

Chandra X-ray image



NASA/CXC/SAO/NRAO

Ghost cavities are 100 million-year-old relics of an ancient eruption that originated around a massive black hole in the core of a centrally located galaxy.

Bubbles are hot gas, magnetized, high-energy particles → enough to support surrownding pressure.

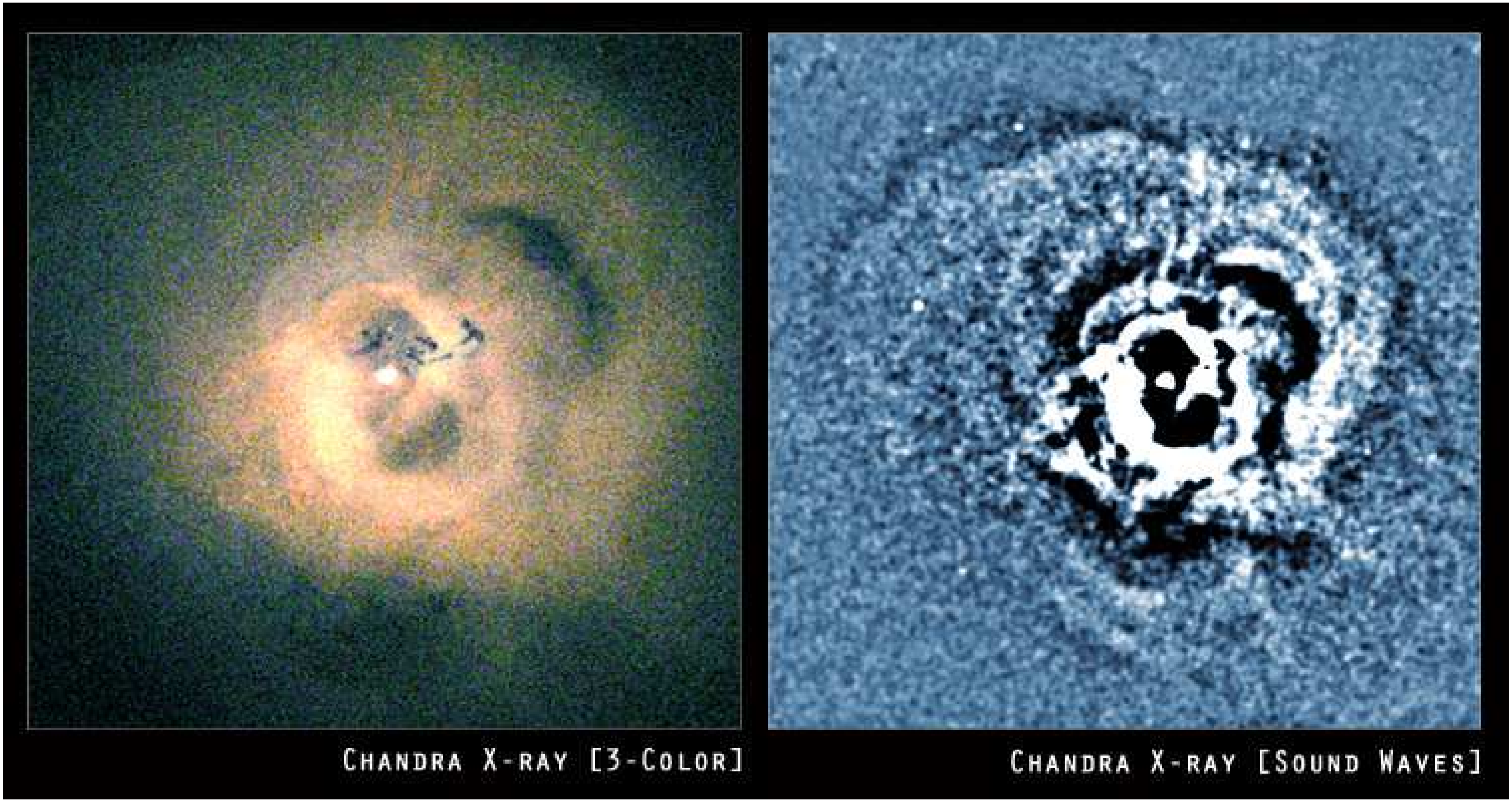
Multiple events → energy deposit into the ICM

20 Sound Waves in Perseus A

Sound waves from explosive events In the AGN in the central galaxy

Dissipation of sound waves → heating of ICM

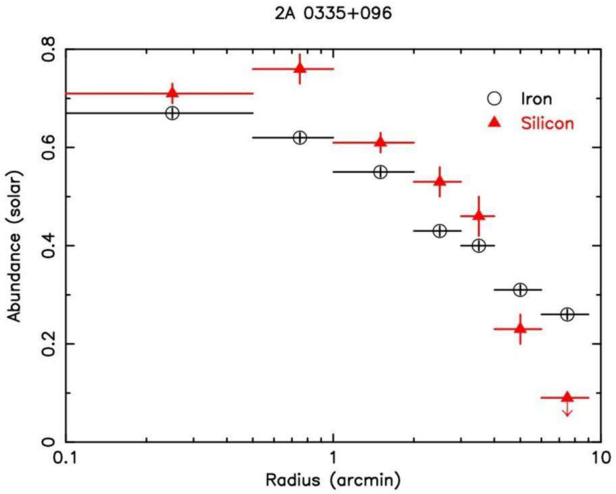
Cavities are radio sources, filled with high-energy particles and magnetic fields.

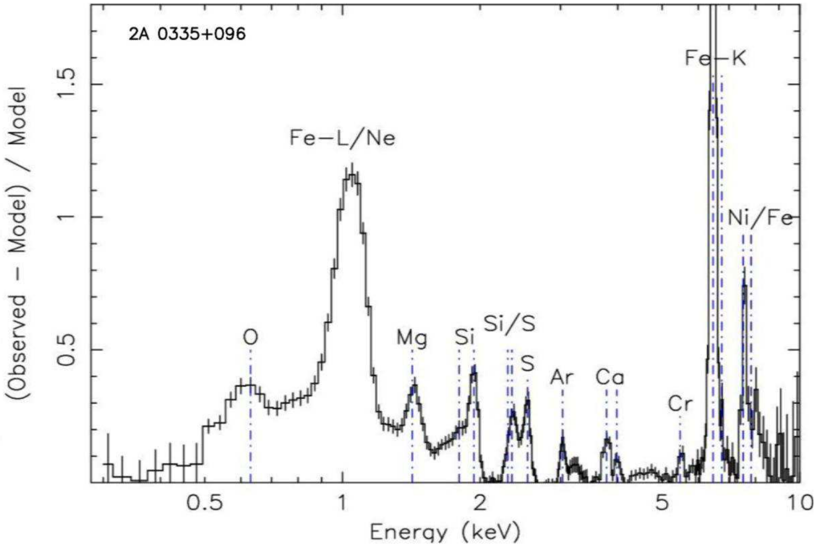


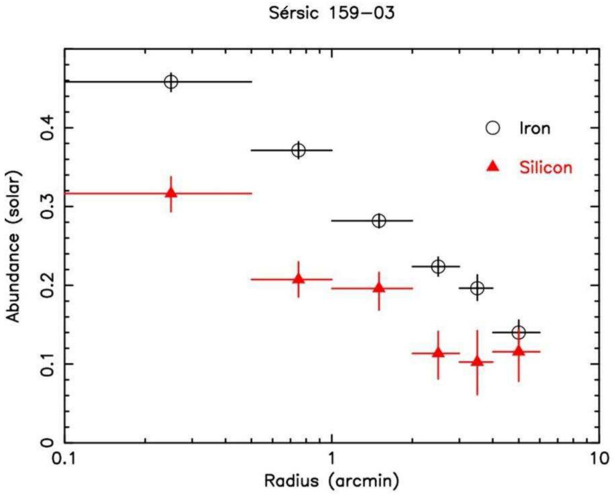
NASA/CXC/SAO/ see annimation

21 Chemical evolution of the Universe

What is the origin of the metals in the ICM and when were they injected ? What is the origin of the entropy of the ICM ?



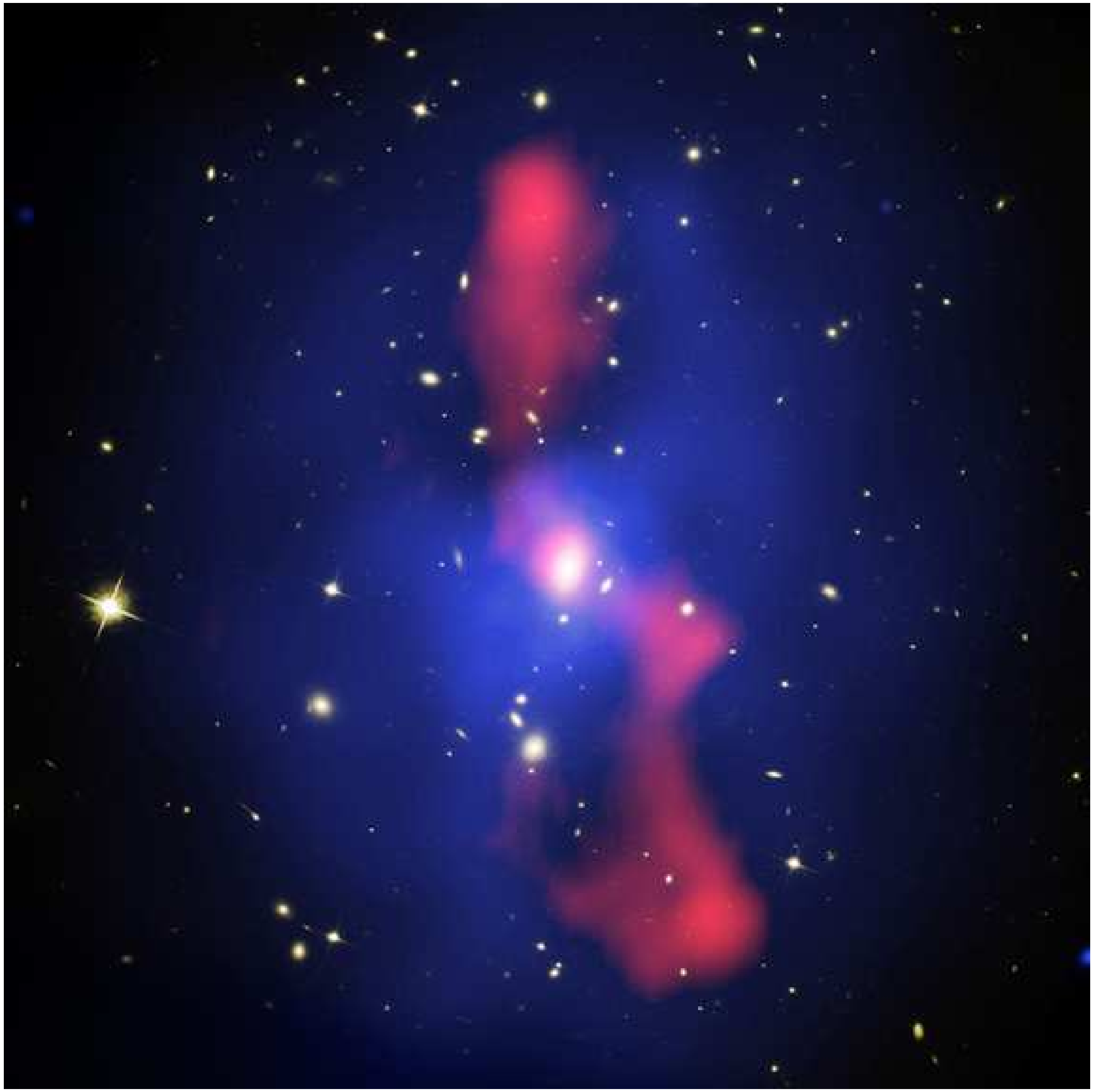




XMM-Newton reveals the origin of elements in clusters of galaxies

Image courtesy of J.S. Kaastra, J. de Plaa and N. Werner, SRON, Netherlands

23 Summary



NASA/CXC/SAO/NRAO MS 0735.6+7421:

- Hot ICM in the potential well of galaxy cluster
- Most barions in the cluster are in the hot ICM gas
- Measuring X-ray flux and temperature profiles across cluster → density and temperature distribution → barionic mass
- Clusters are weakly self-similar (z-dependence)
- Can help to contstarin cosmological models
- Gravitational potnetial traces dark matter
- AGN feedback keeps central cluster regions hot

Milky Way Center

National Geographic

Mass of the Black Hole

2.2 micron animation of the stellar orbits in the central parsec
http://www.astro.ucla.edu/~ghezgroup/gc/pictures/

- Use Kepler's III Law to determine the mass of the BH: $\mathbf{a^3 = M_{BH} P^2}$

  For this one needs to determine for many stars: a) the period P b) the size of the orbit's semimajor axis a

- Current best estimate $\mathbf{M_{BH} = 7.2}$ **millions** $\mathbf{M_{\odot}}$

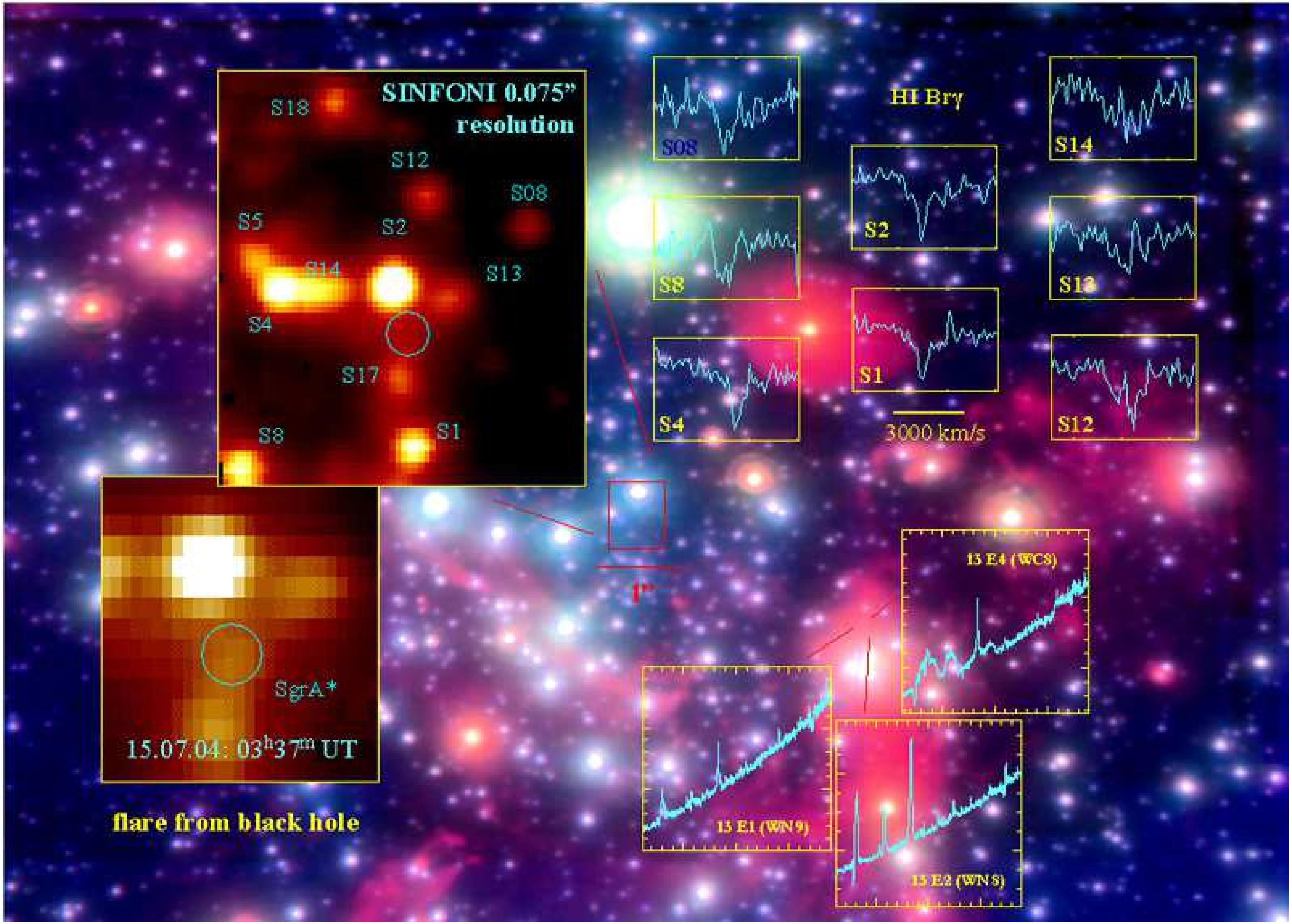
Composite image of Galactic Center in near IR (HST) and X-ray (Chandra)

X-ray luminosity of Sgr A* is ~10^{32} erg/s

Activity of our Black Hole

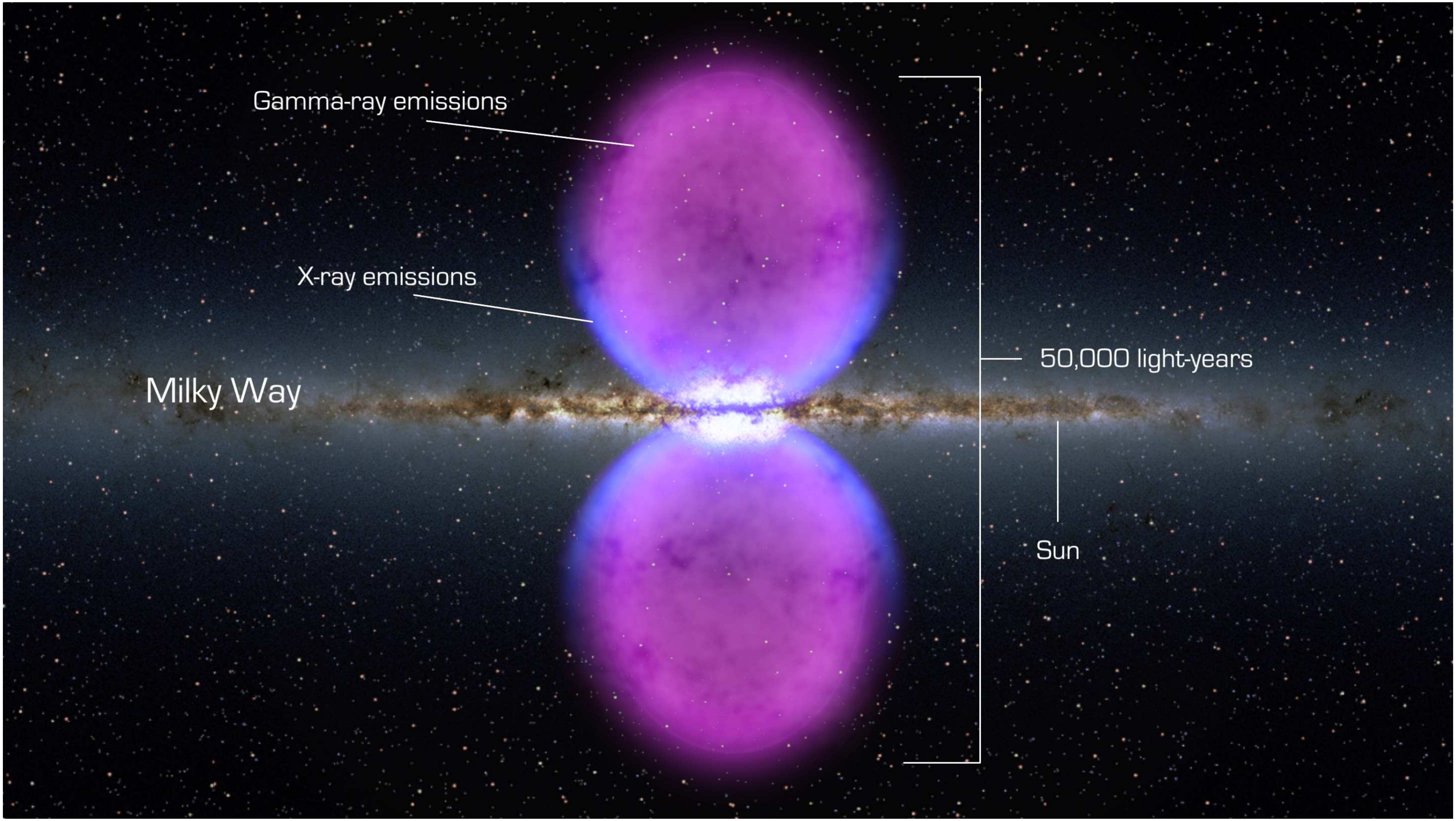
see flare at http://www.astro.ucla.edu/~ghezgroup/gc/pictures/

SINFONI VLT image

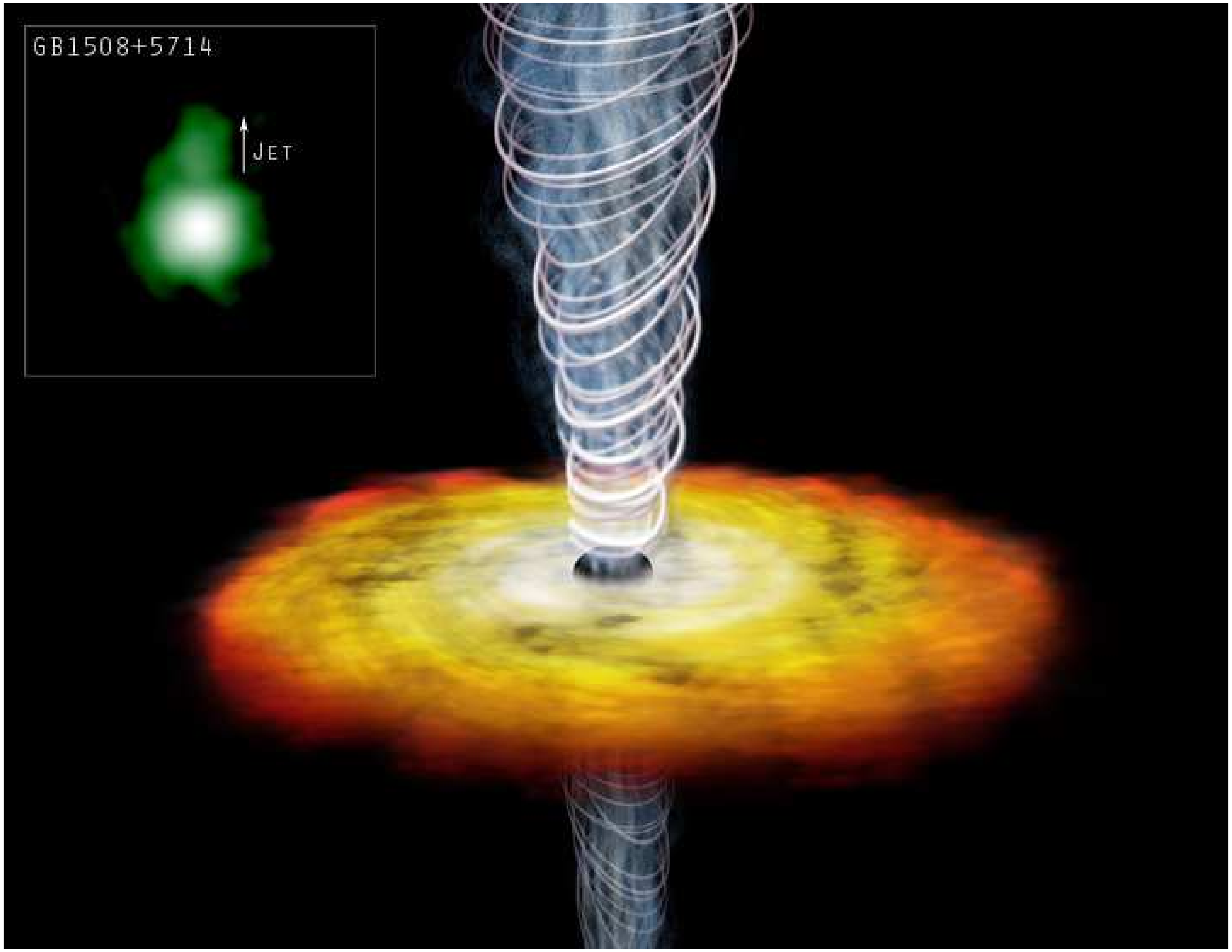


Fermi Bubbles: evidence of previous activity

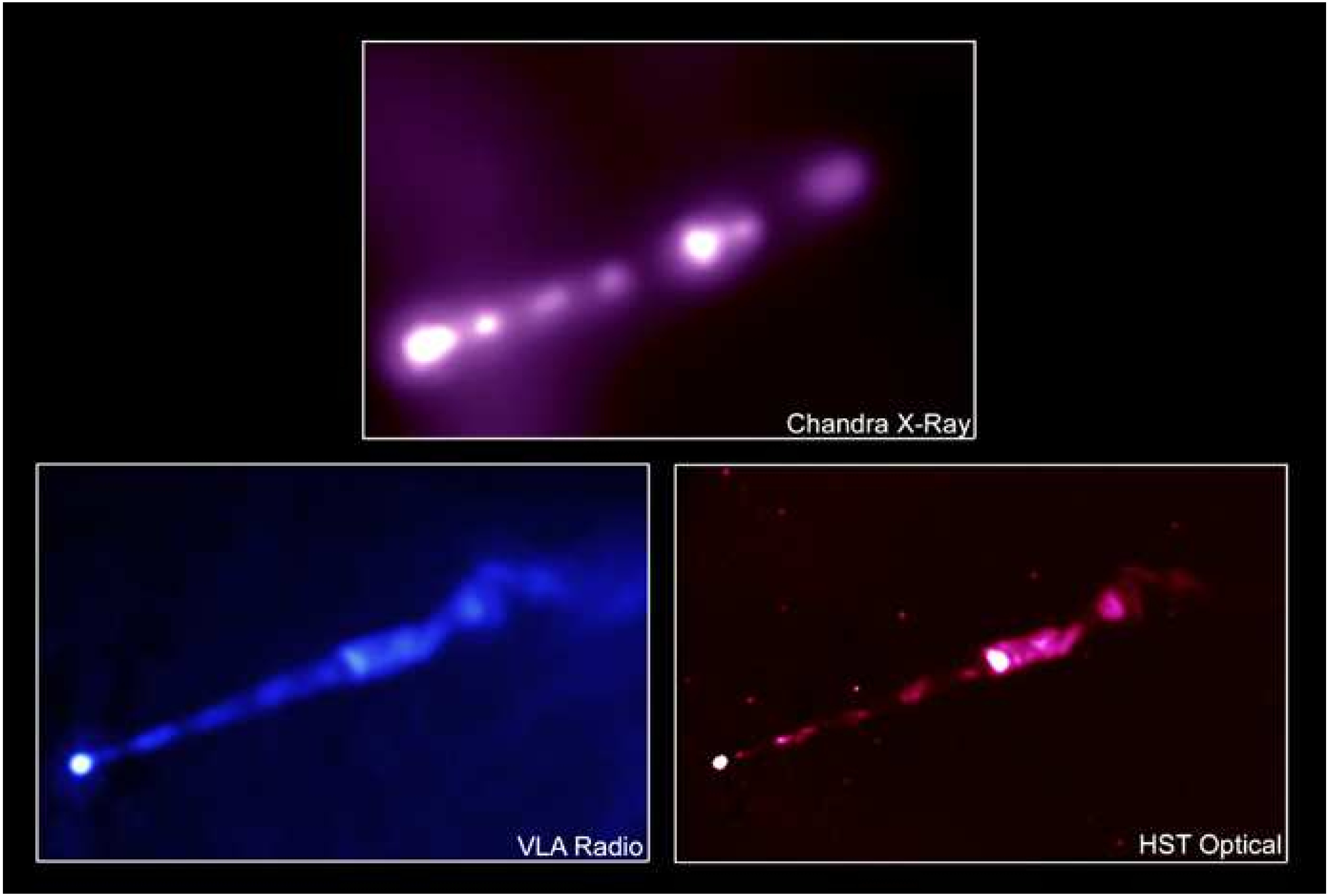
http://www.nasa.gov/mission_pages/GLAST/news/new-structure.html



Active Galactic Nuclei

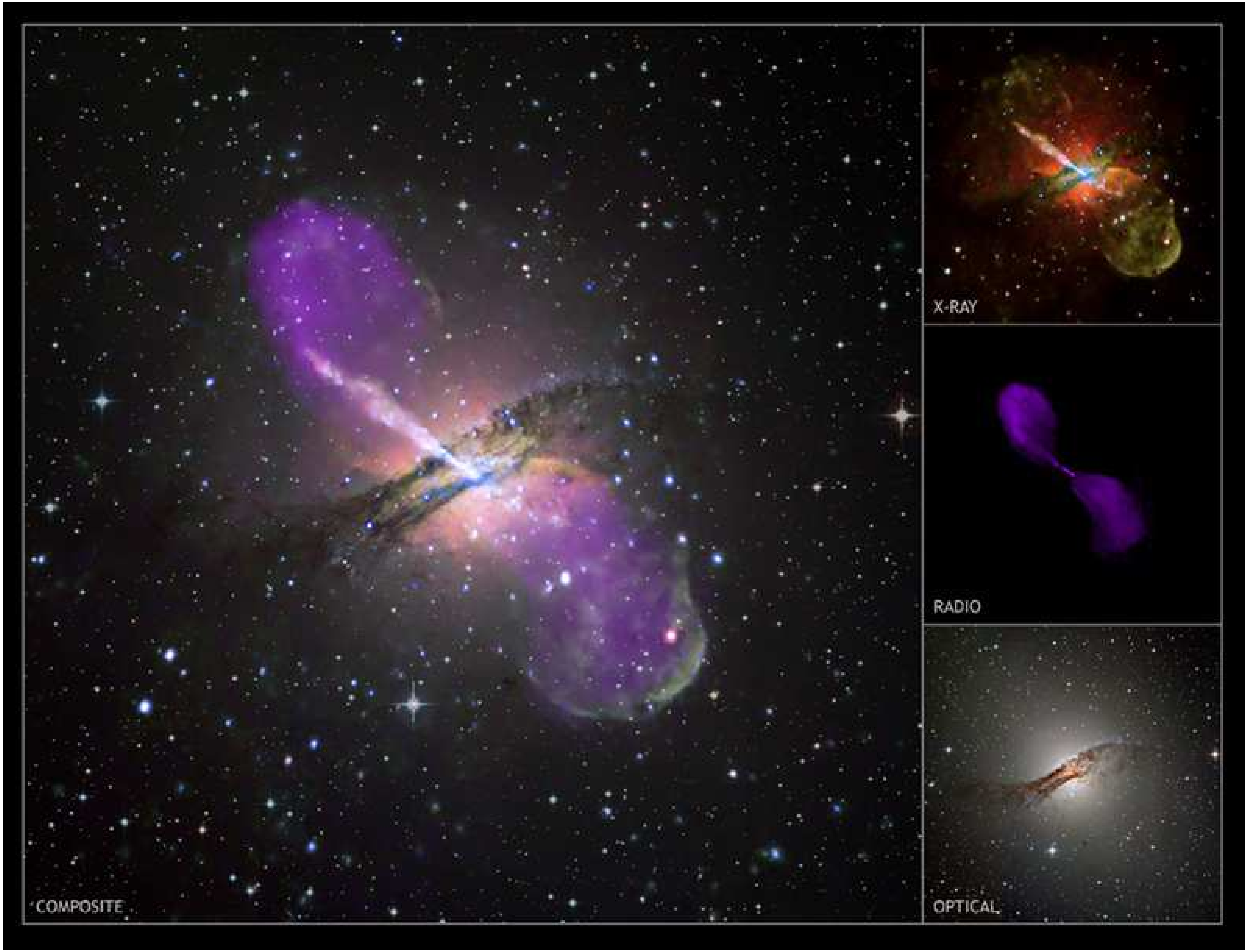


http://chandra.harvard.edu/



Credit: X-ray: NASA/CXC/MIT/H.Marshall et al. Radio: F. Zhou, F.Owen (NRAO), J.Biretta (STScI) Opt

31 The nearest active galaxy: Centaurus A



32 AGNs are scaled up XRBs

$$L_X = \eta \frac{GM\dot{M}}{R} \Rightarrow$$

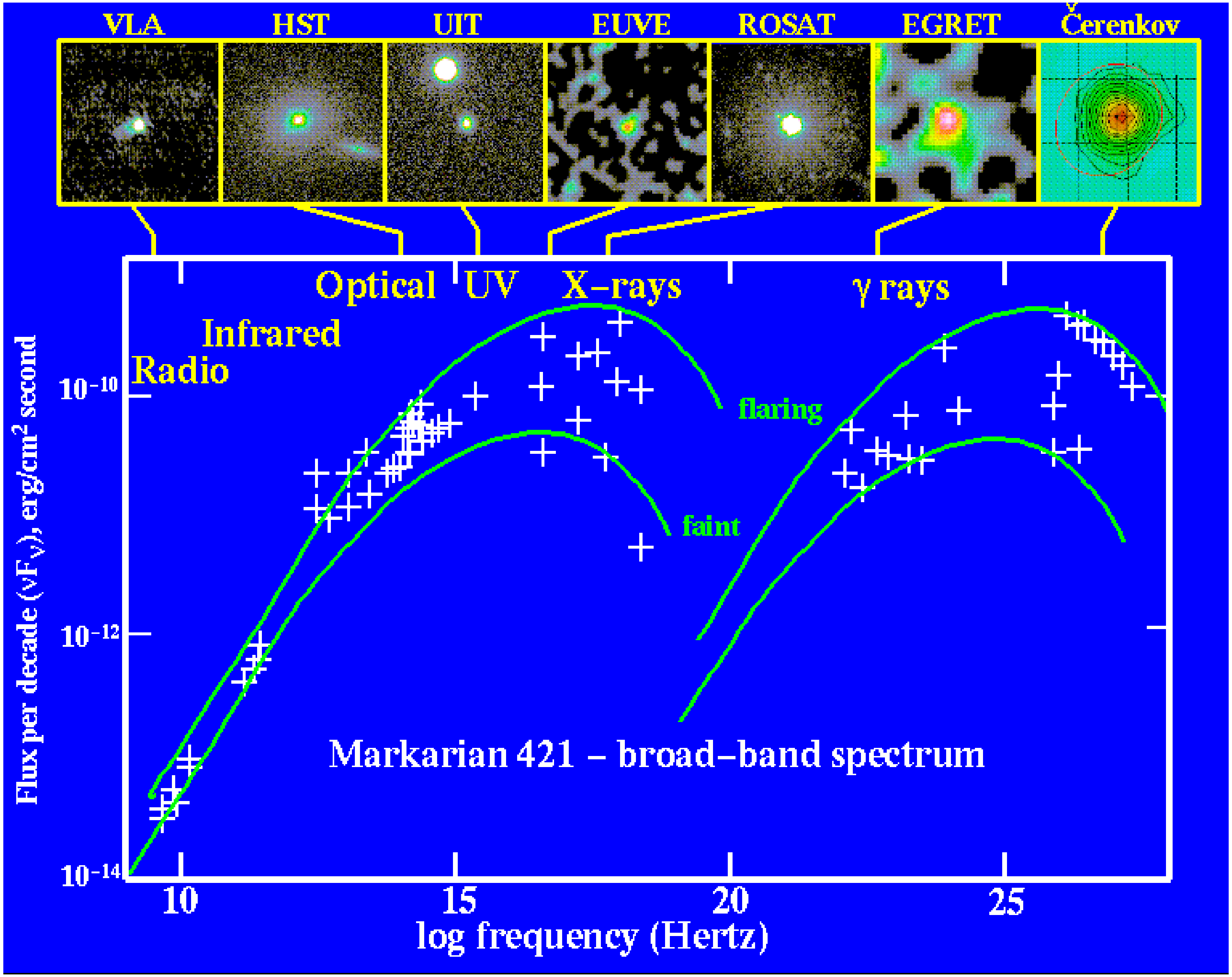
X-ray luminosity of QSO is 10 orders of magnitude higher than XRB

Eddington luminosity $L_{\mathrm{Edd}} \approx 1.3 \times 10^{38} \frac{M}{M_\odot}$ erg/s. The mass of central object should be orders of magnitude higher

XRB: M_{BH}~$10M_\odot$ → AGN: M_{BH}~$10^{6..8} M_\odot$

33 Observed properties of AGN

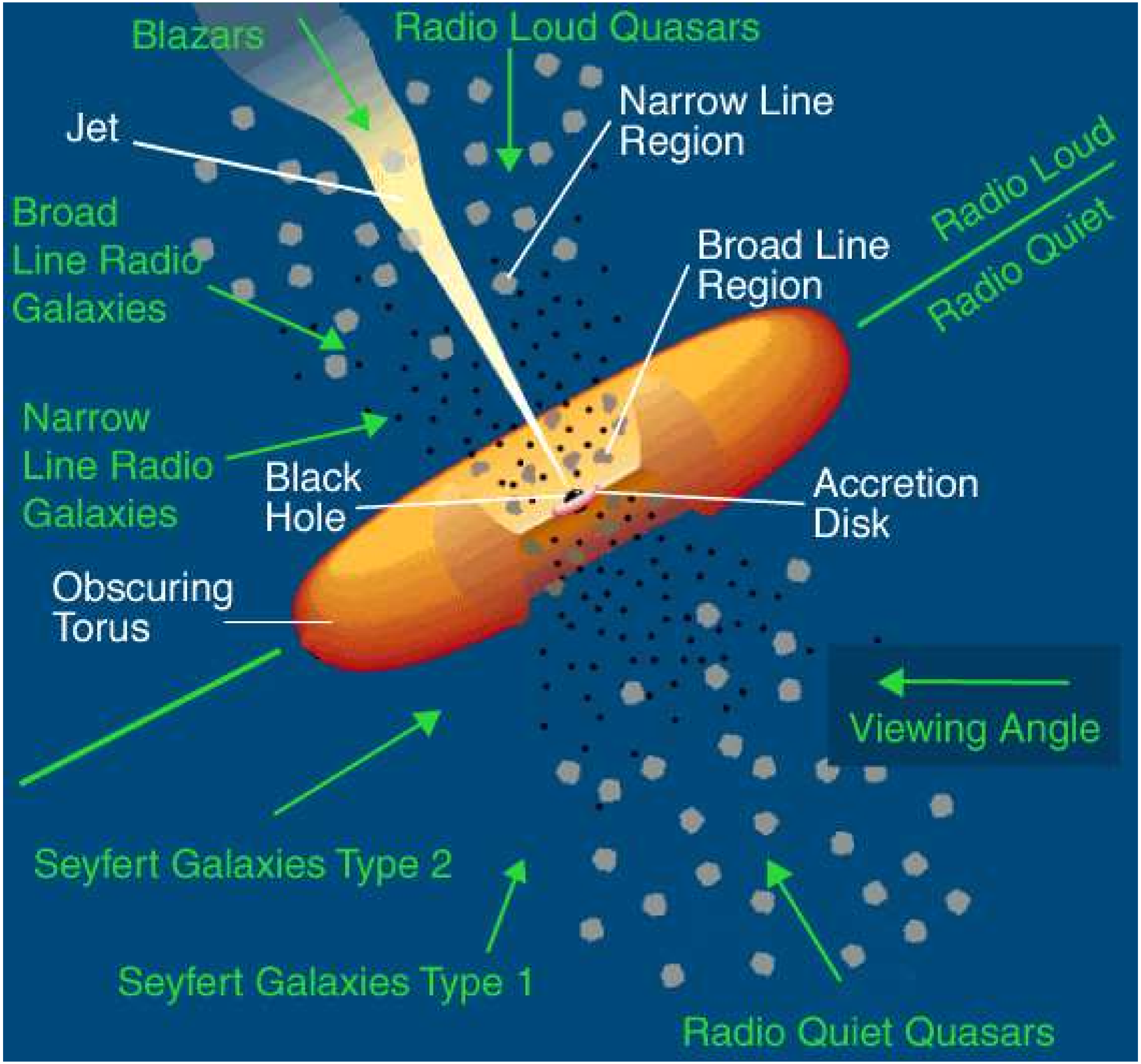
High luminosity $L_{bol}=10^{42}-10^{48}$; Size << 1pc; Variabilty; Emission & Absorption lines



http://www.astr.ua.edu/keel/agn/mkn421.html, see Dan Schwartz heasarc.gsfc.nasa.gov/docs/xrayschool/

34 AGN is common name for:

- Quasars (quasi-stars)
- QSOs (quasi-stellar objects)
- QSRSs (quasi-stellar radio sources)
- BL Lac objects
- Blazars (BL Lac type quasars)
- OVV (Optically Violent Variables)
- Seyfert Galaxies (which may be Type 1, Type 2, Type 1.x, Narrow line type 1)
- Narrow Emission Line galaxies
- LINER s (Low ionization nuclear emission region)
- LLAGN (Low Luminosity AGN)



Urry & Padovani 1995 PASP 107, 803

AGN with

$10^8 M_\odot$ BH

R_G $3\mathrm{x}10^{13}$ cm

Accretion disk

$10^{13..14}$ cm

BLR $10^{16..17}$ cm

Torus 10^{17} cm ??

NLR $10^{18..20}$ cm

Jets $10^{17..24}$ cm

36 X-ray observations

Time Variability

- Size of emitting region, and regions where radiation is reprocessed.
- QPOs → relativisitc effects

X-ray Spectra:

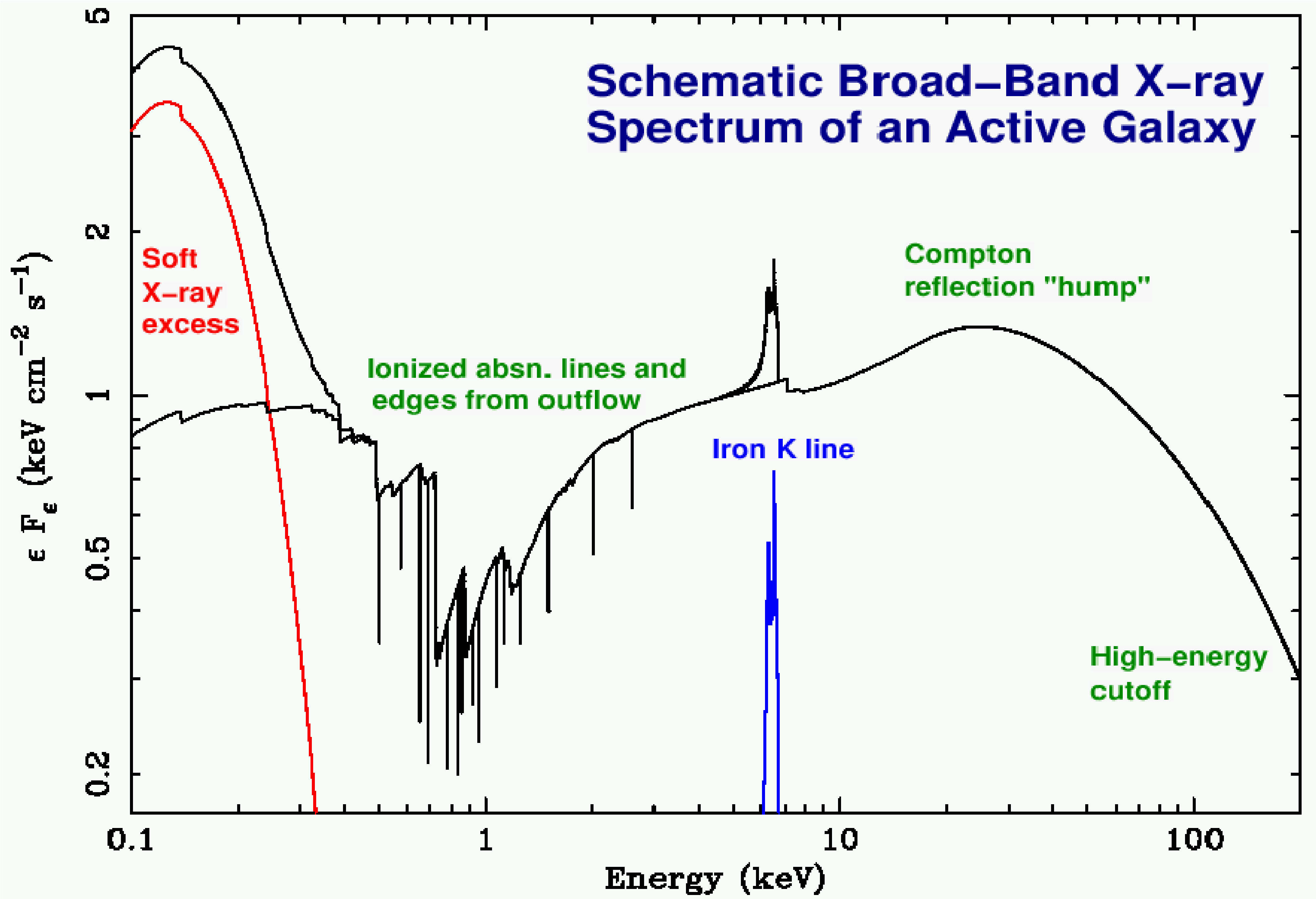
- Absorption: amount of absorbing material; velocity field (inflow/outflow); cold/warm absorbers; ionization state
- Thermal emission: from hot gas, accretion physics
- Non-thermal emission: synchrotron, Comptonisation, relativisitc effects, acceleration, magnetic fields
- Emission lines: relativistic effects

X-ray Images:

- Nucleus
- Extended emission on scale of 1 pc to 100 kpc
- Jets and radiolobes
- Correlstion between different components.

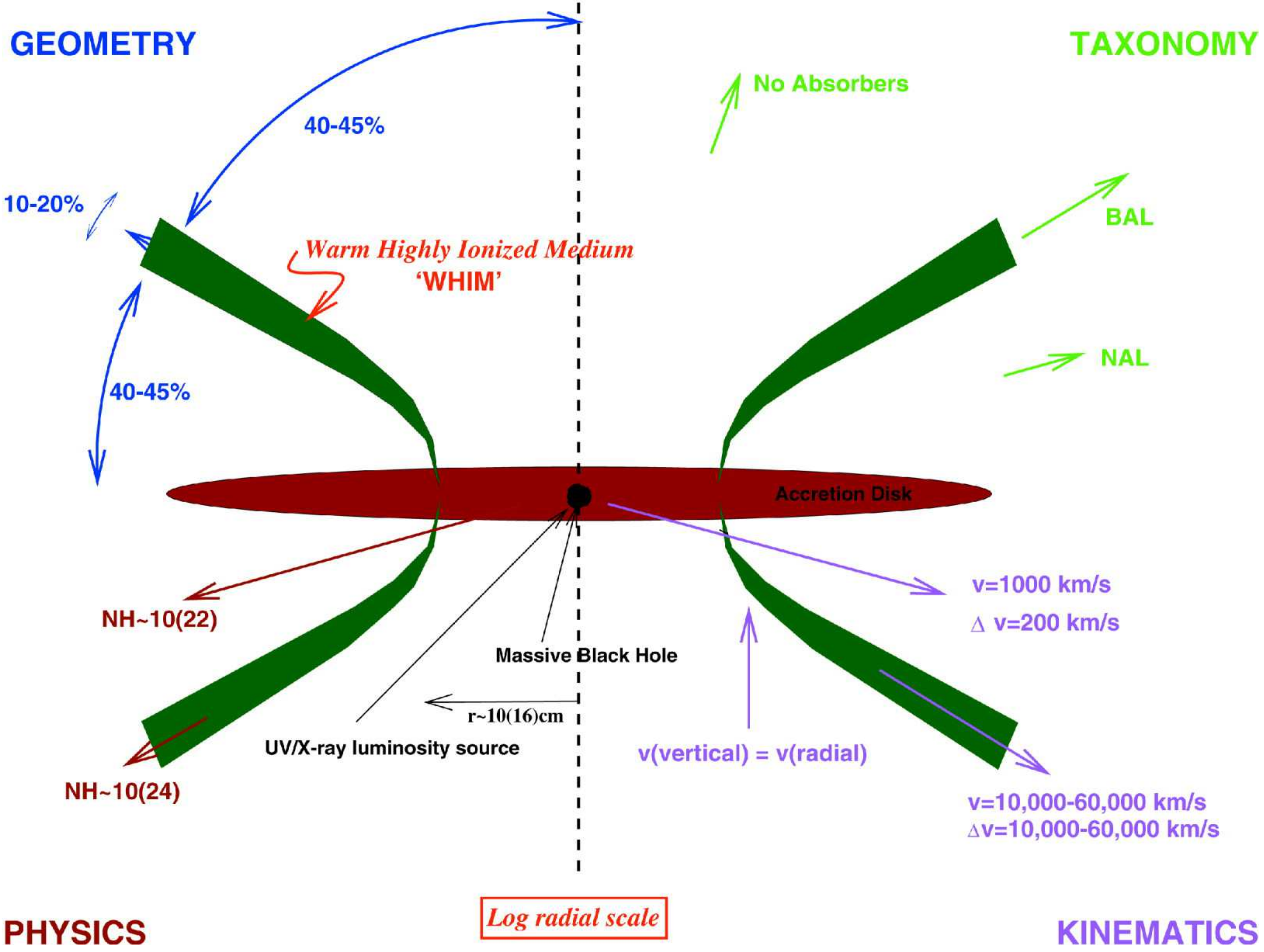
37 Schematic X-ray spectrum of AGN

From W.N.Brandt "X-raying Active Galaxies" AAS’04



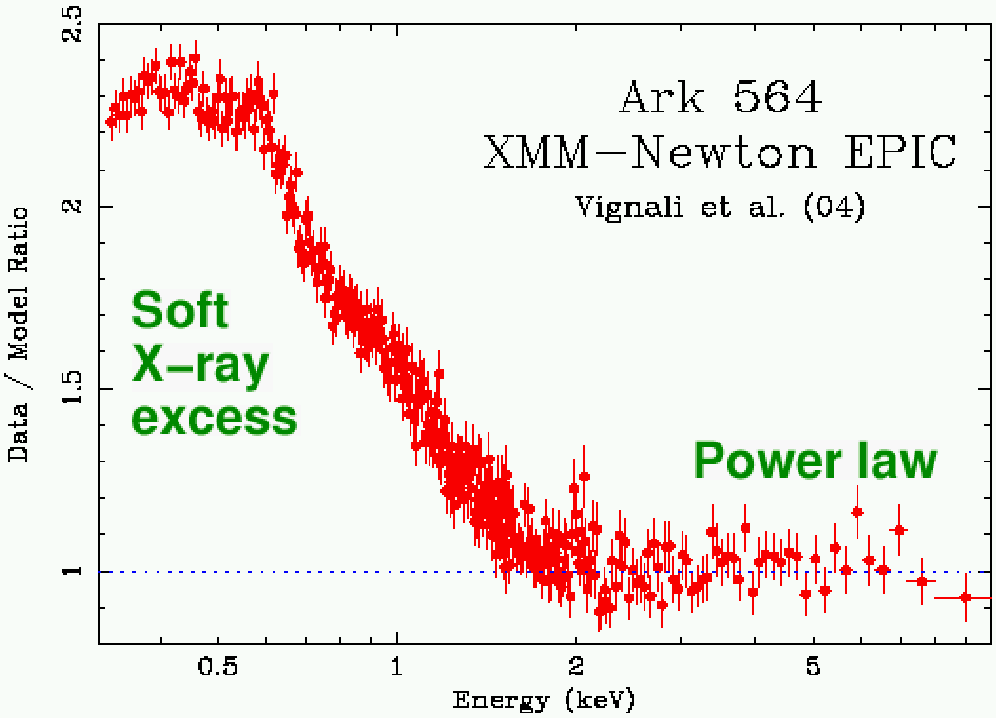
http://www.astro.psu.edu/users/niel/papers/

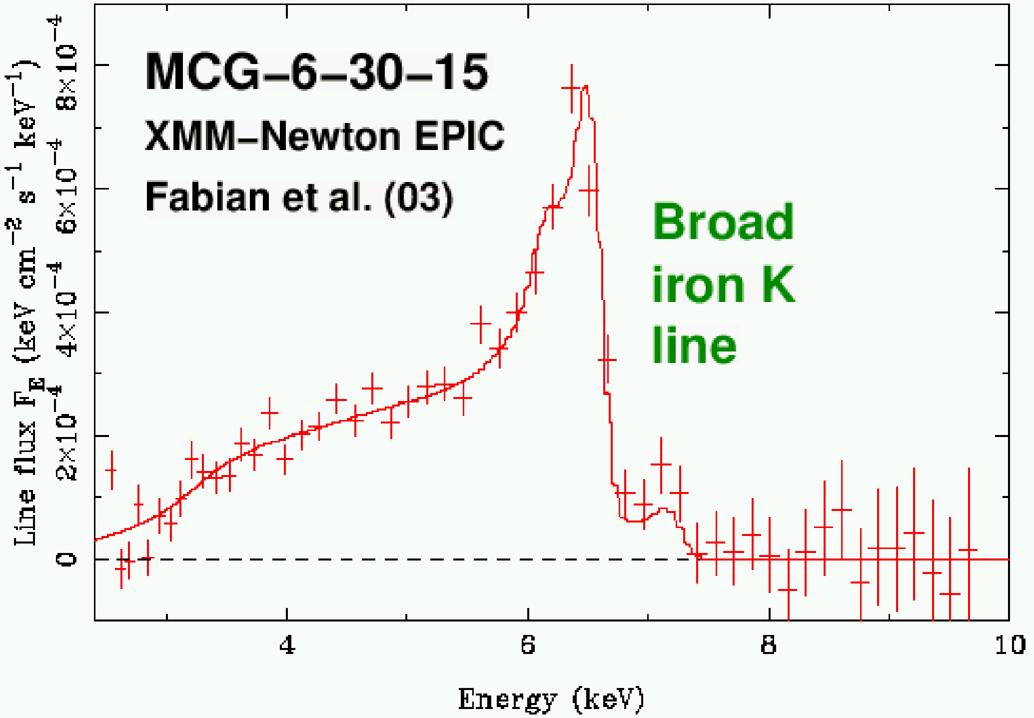
38 A Structure for Quasars

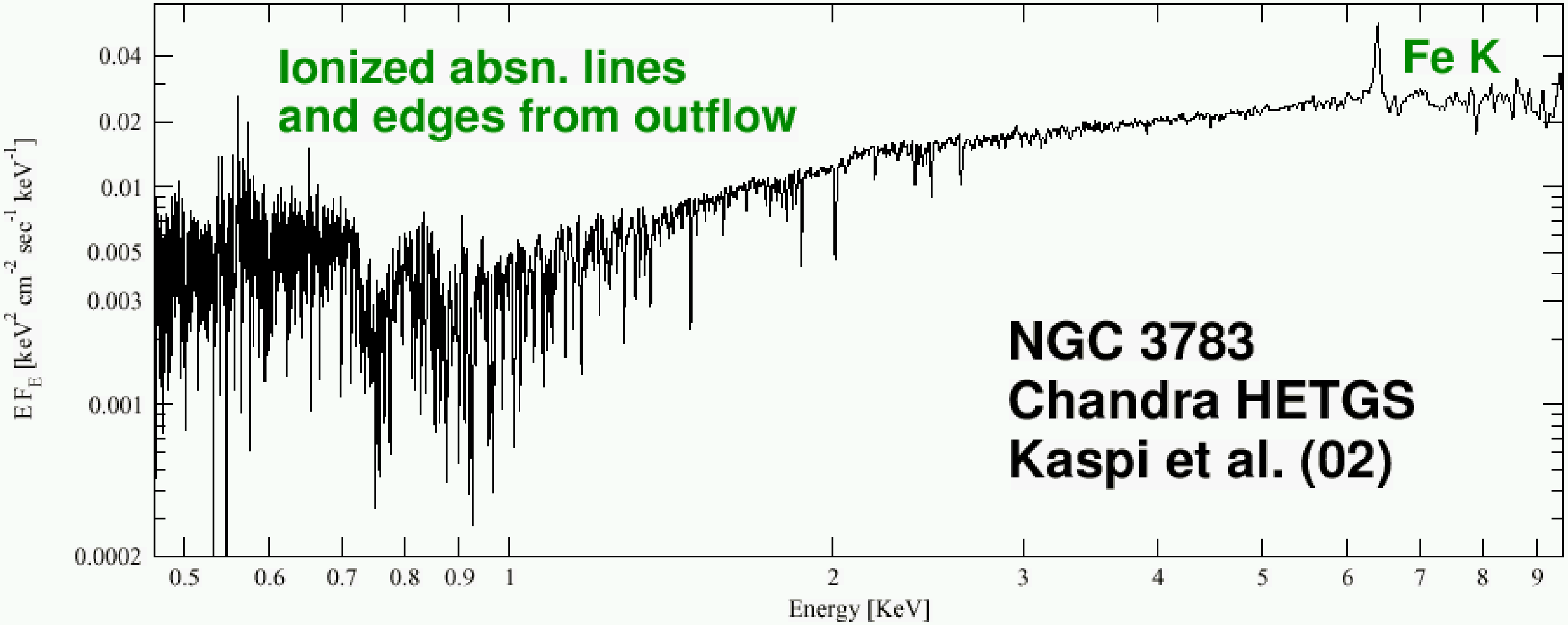


Elvis ApJ 545,63

39 Examples of obsevred AGN X-ray spectra







Also unidentified features

Also substantial jet−linked X−rays in radio−loud AGN

http://www.astro.psu.edu/users/niel/papers/ From W.N.Brandt "X-raying Active Galaxies" AAS'04