Od supermasívnych čiernych dier po veľkoškálovú štruktúru vesmíru

Prečo viditeľný vesmír vyzerá tak ako vyzerá?

Norbert Werner

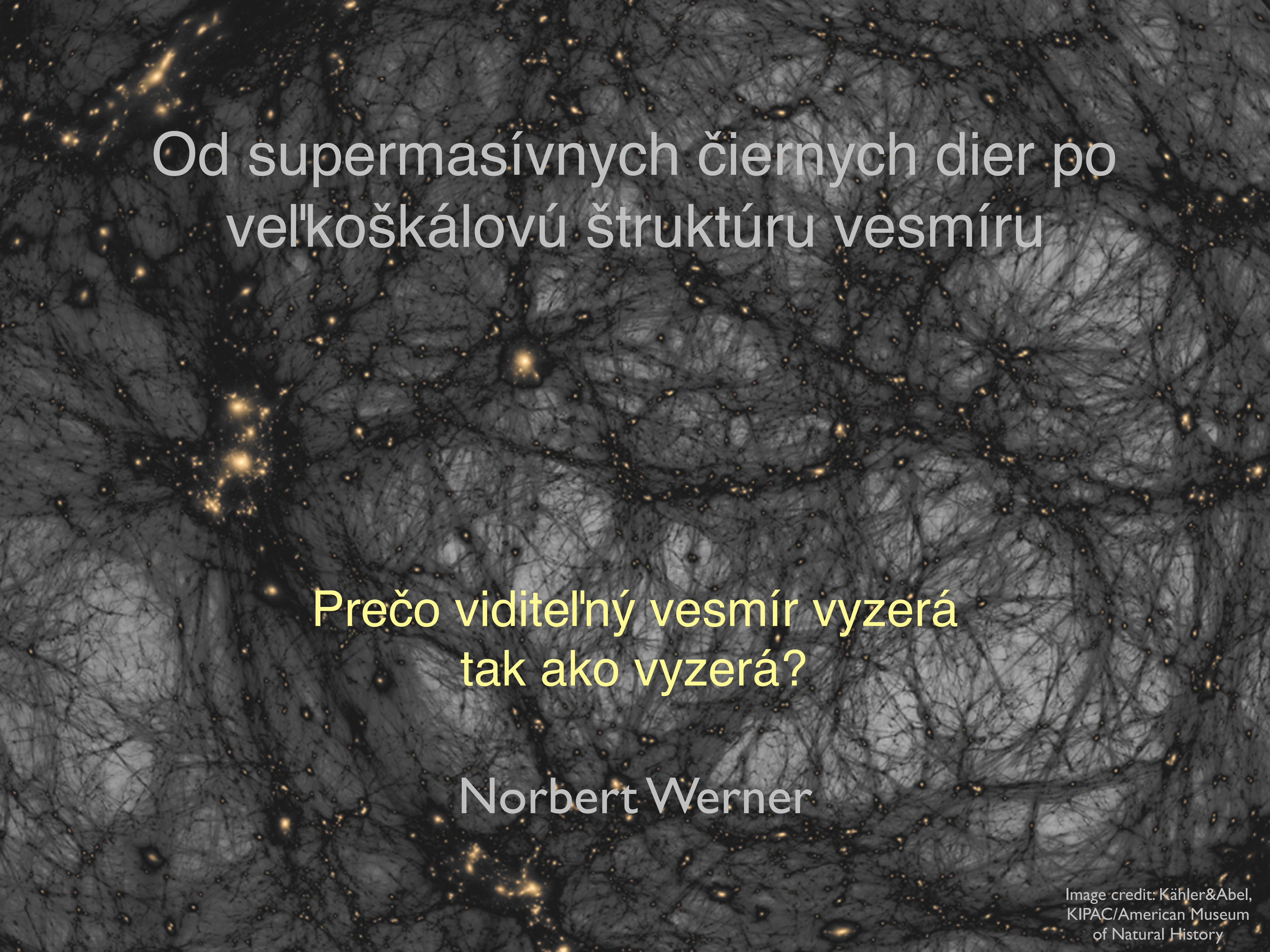


Image credit: Kähler&Abel, KIPAC/American Museum of Natural History

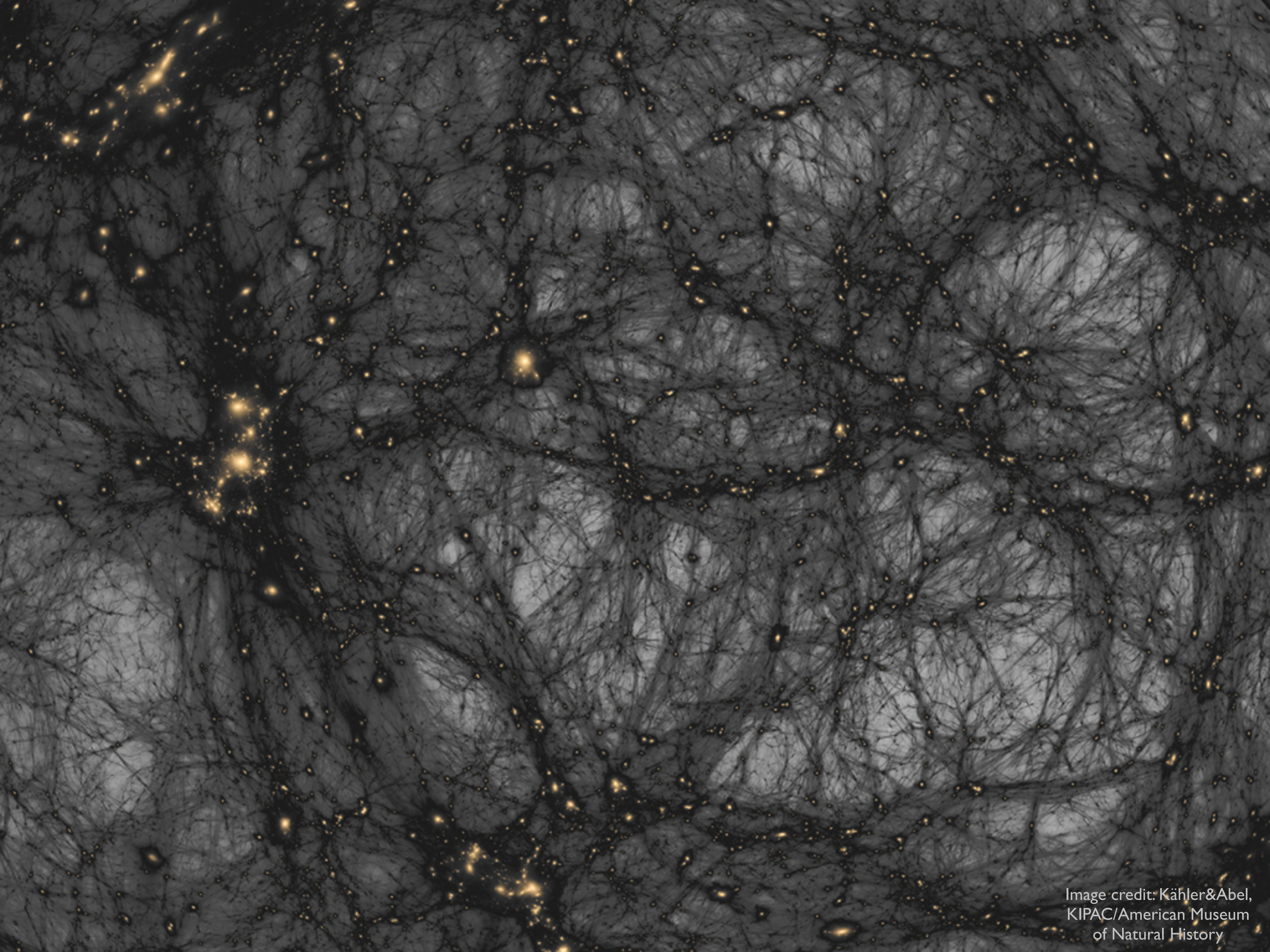


Image credit: Kähler&Abel,
KIPAC/American Museum
of Natural History

How did ordinary matter assemble into the largest structures in the Universe?

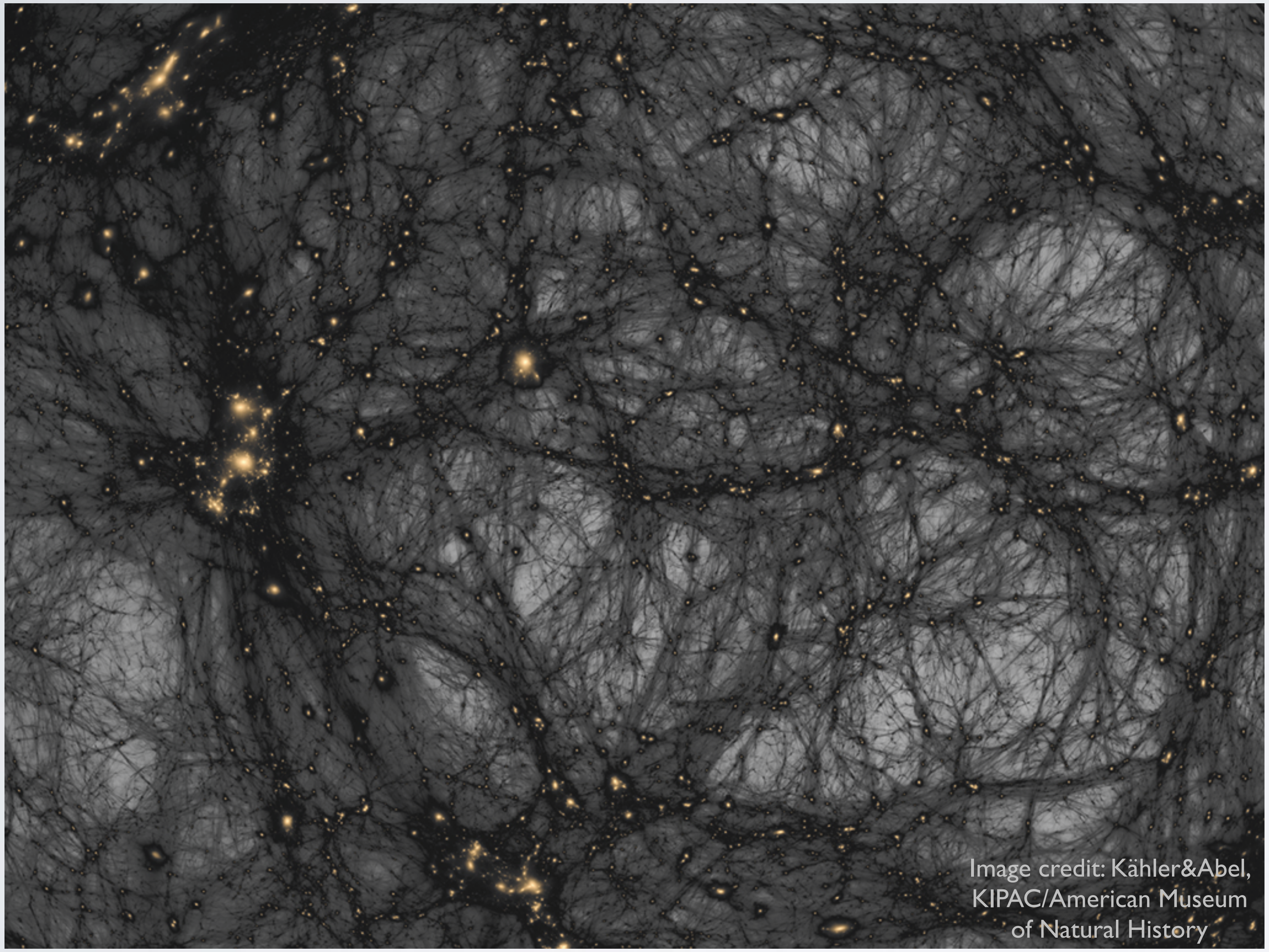
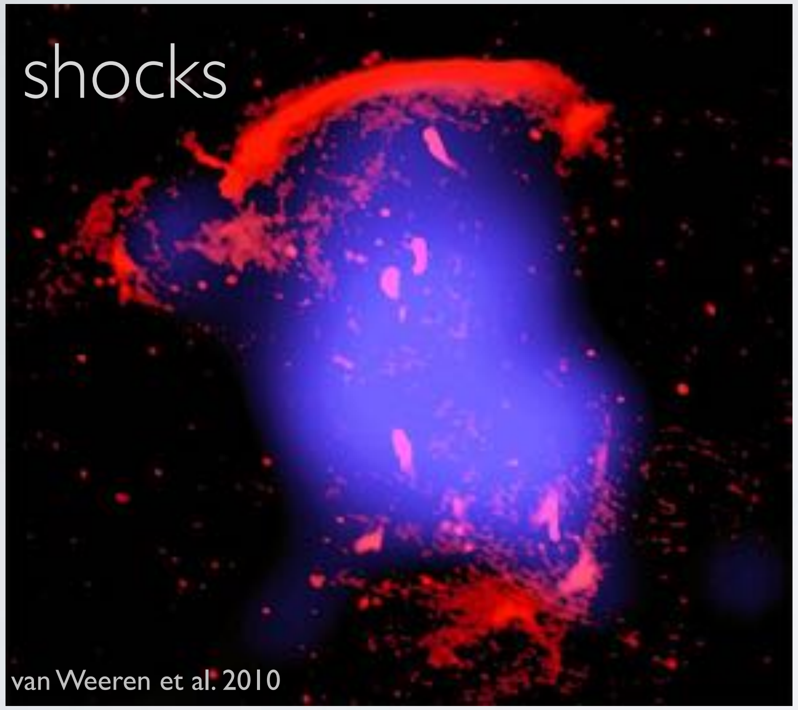


Image credit: Kähler&Abel, KIPAC/American Museum of Natural History

- tremendous success of the ΛCDM model in describing the dark matter distribution in the Universe
- **the evolution of baryonic matter is not well understood**
- most baryons are in diffuse gas

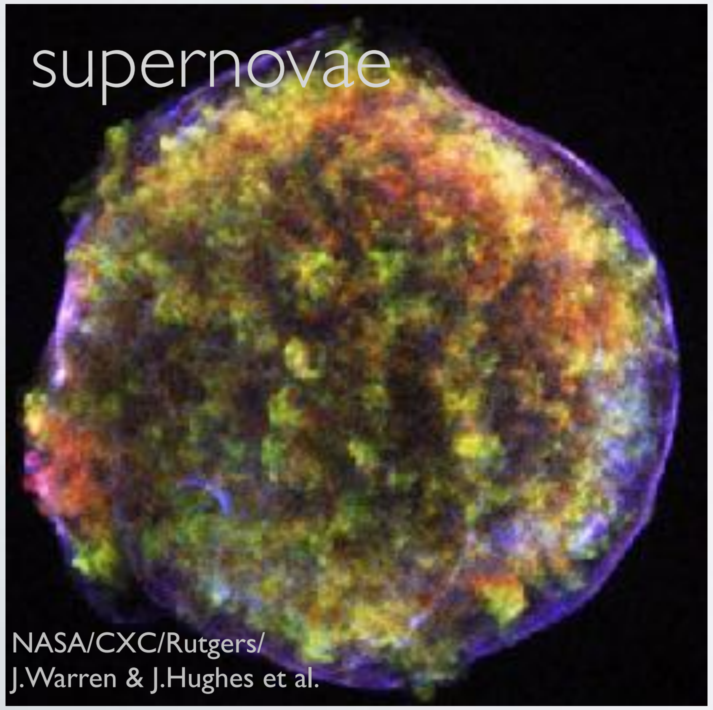
Dynamics, thermodynamics, and chemical composition of the diffuse gas


shocks

van Weeren et al. 2010


jets

NASA, ESA, Baum & O'Dea (RIT), Perley & Cotton (NRAO/AUI/NSF), STScI/AURA


supernovae

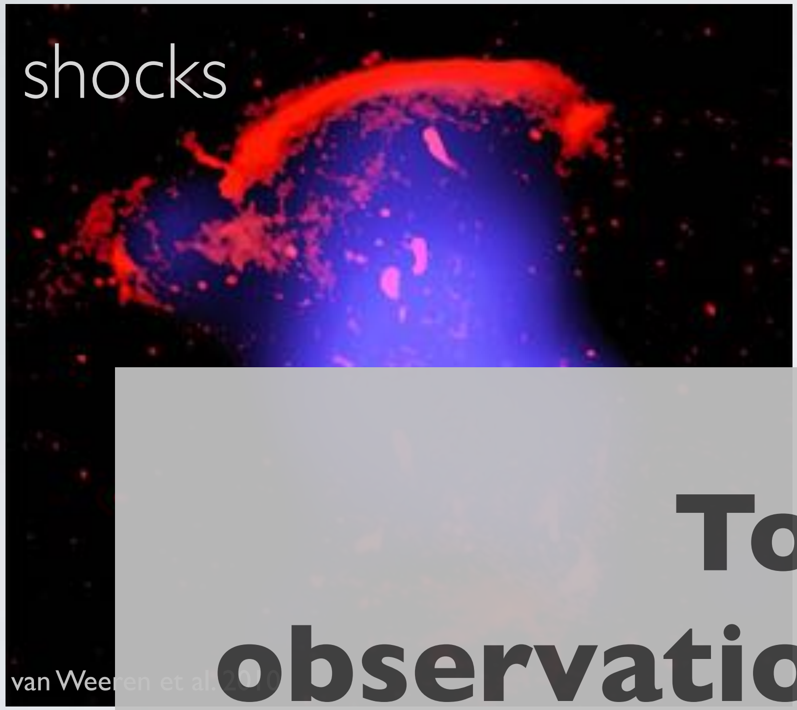
NASA/CXC/Rutgers/
J.Warren & J.Hughes et al.


galactic winds

NASA/JPL-Caltech/STScI/
CXC/UofA/ESA/AURA/JHU

- energy dissipation from **shocks**, large scale **gas flows**, and **turbulence**
- energy and momentum input from **supernovae** and **jets** of accreting supermassive **black holes**
- **how does the energy from these processes couple with the diffuse gas?**

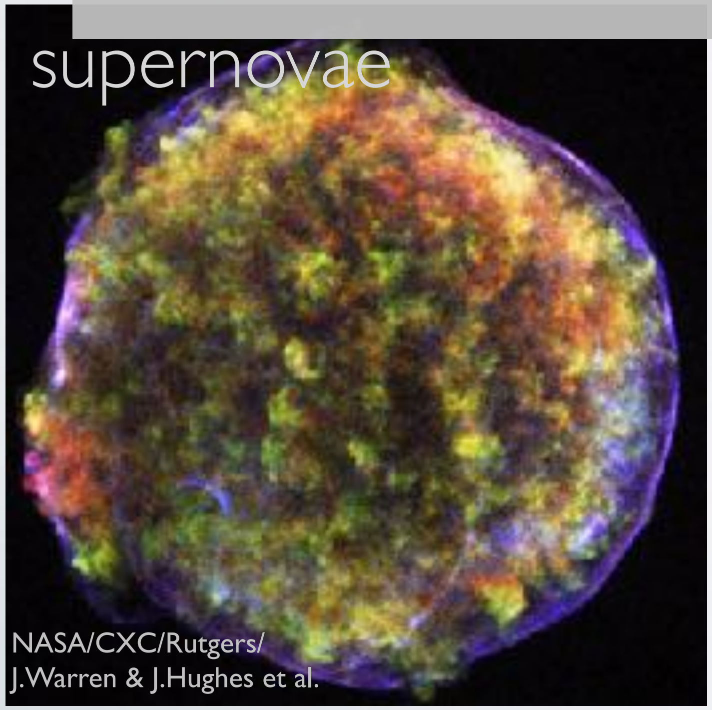
Dynamics, thermodynamics, and chemical composition of the diffuse gas


shocks

van Weeren et al. 2010


jets

NASA, ESA, Baum & O'Dea (RIT), Perley & Cotton (NRAO/AUI/NSF), STScI/AURA


supernovae

NASA/CXC/Rutgers/J.Warren & J.Hughes et al.


galactic winds

NASA/JPL-Caltech/STScI/CXC/UofA/ESA/AURA/JHU

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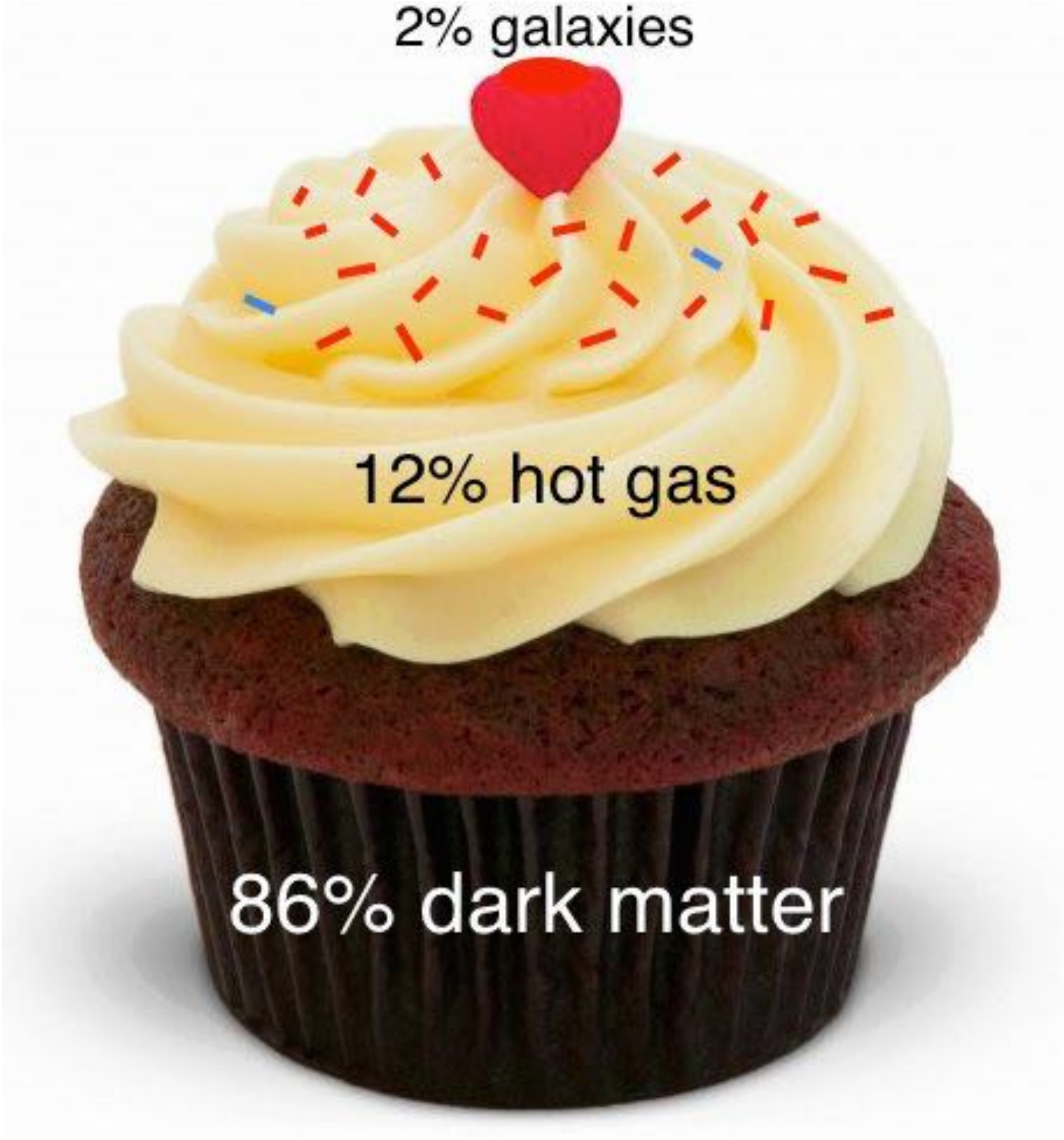
To make progress, new observational constraints are essential.

Clusters of galaxies as cupcakes



A. Mantz

low densities n=10^{-1}-10^{-5} cm^{-3}, high temperatures T=5x10^{6}-10^{8} K

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

collisional ionization equilibrium

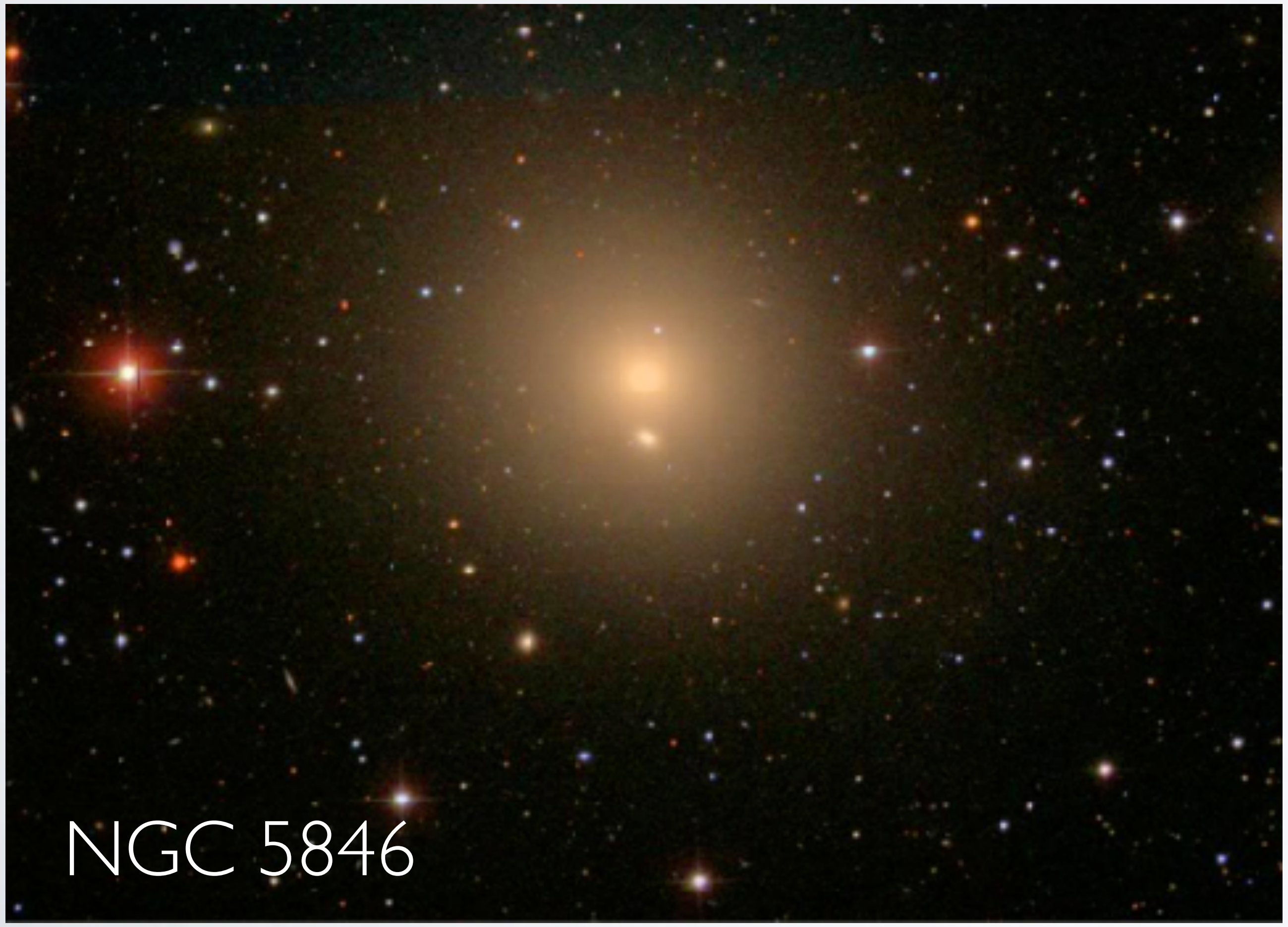
electron and ion temperatures in equilibrium

shape of spectrum entirely determined by kT and chemical abundances

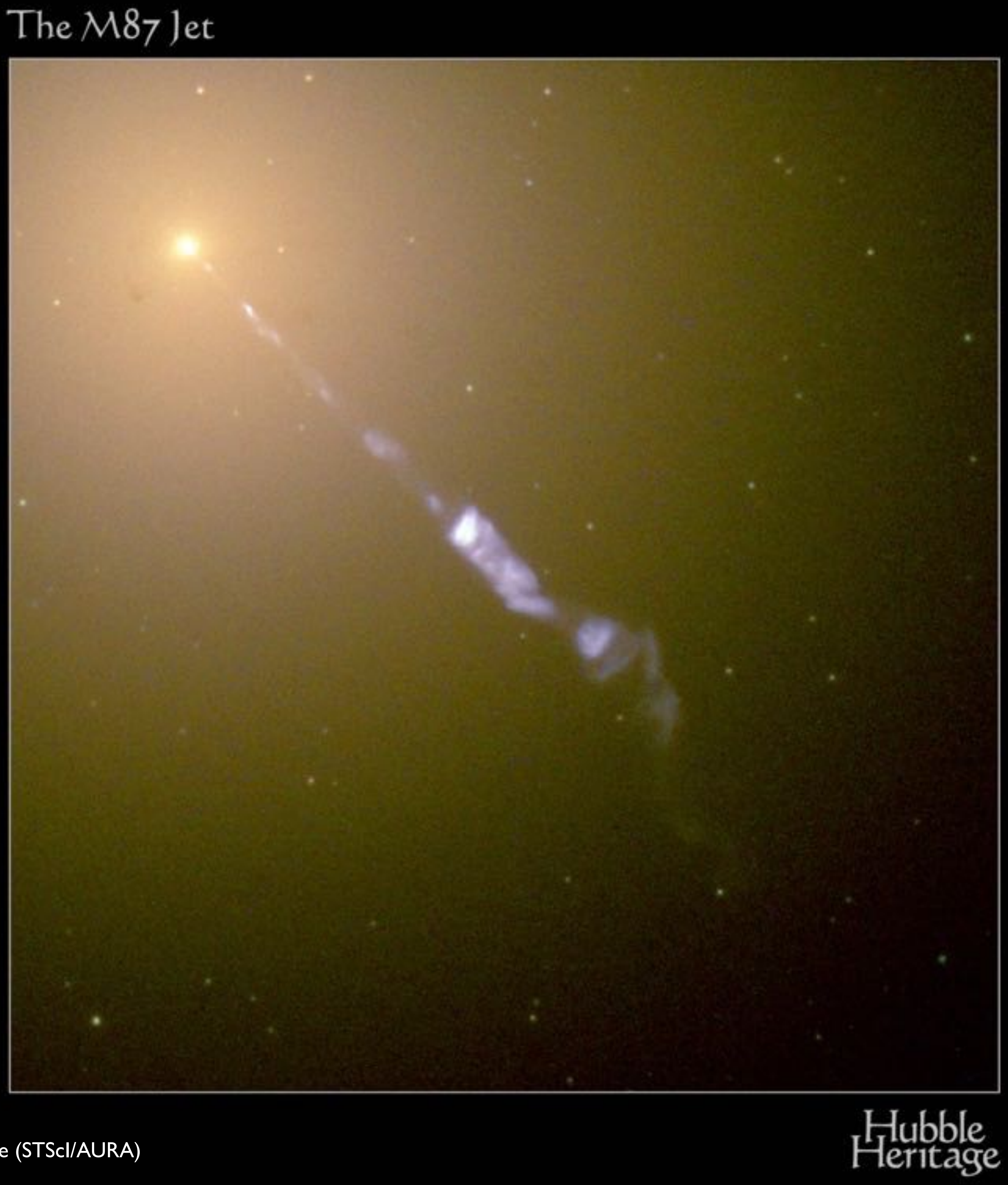
RED AND DEAD GIANT ELLIPTICAL GALAXIES


NGC 5813

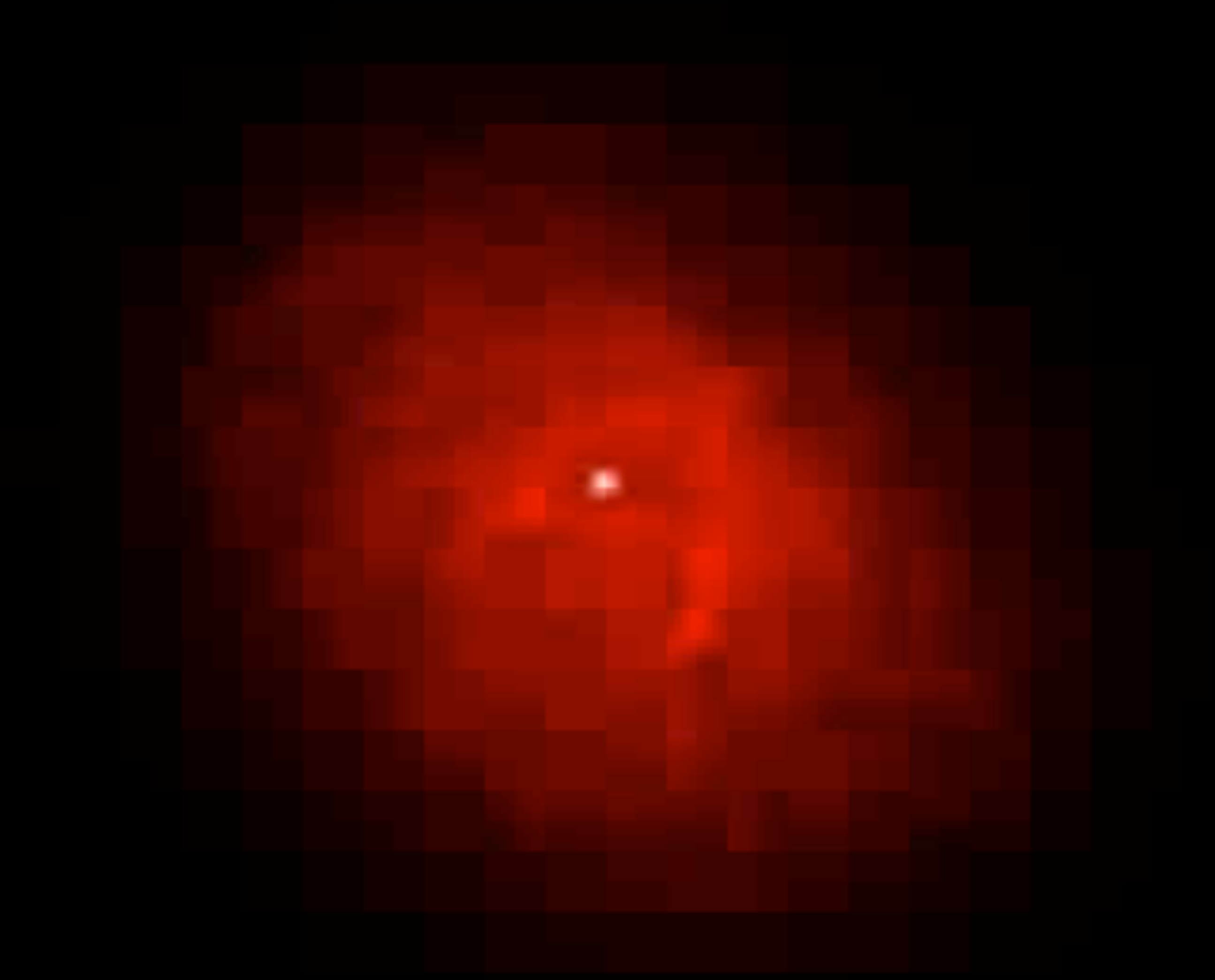

NGC 4472


NGC 5846

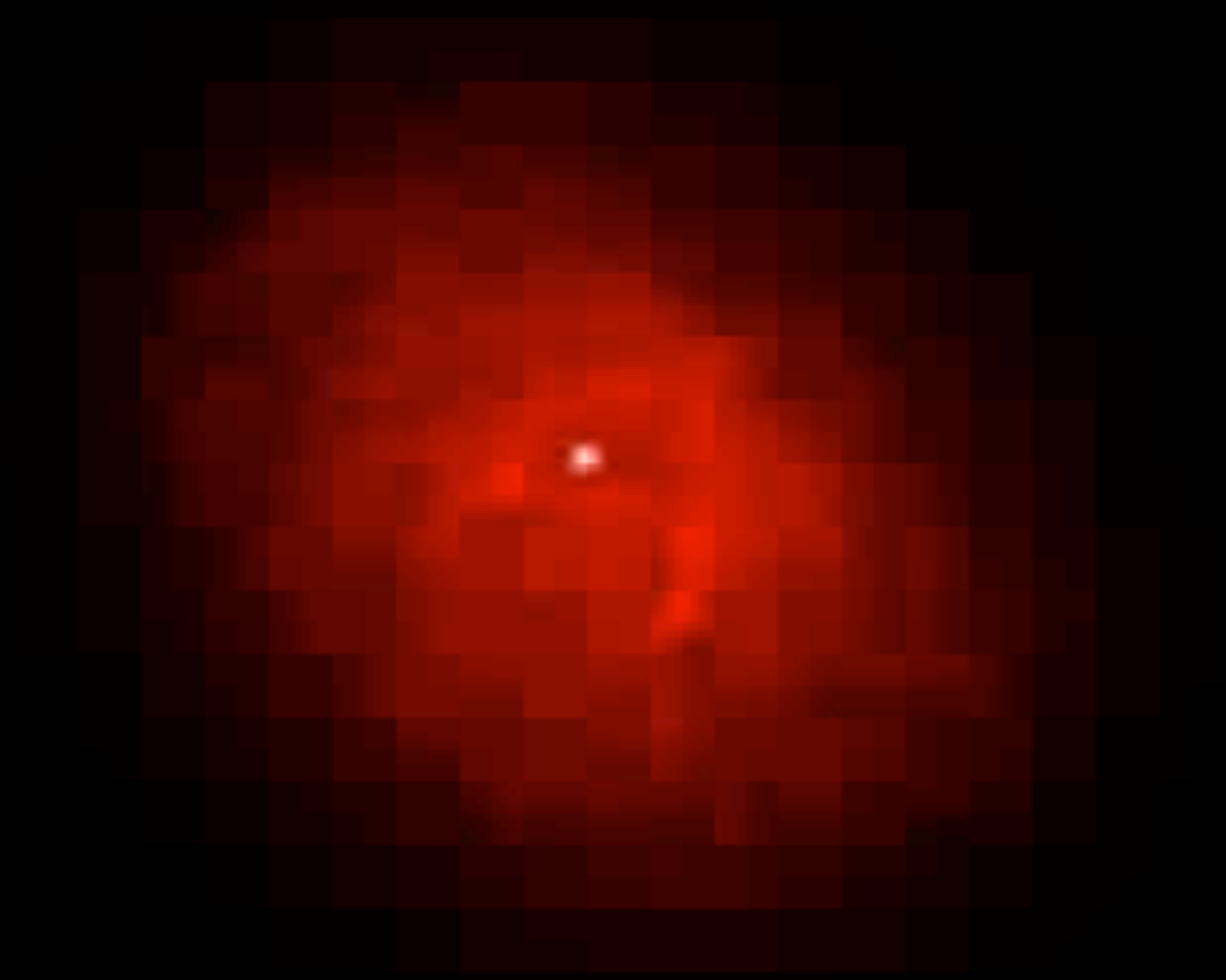

M87



NASA, ESA, Hubble Heritage (STScI/AURA)

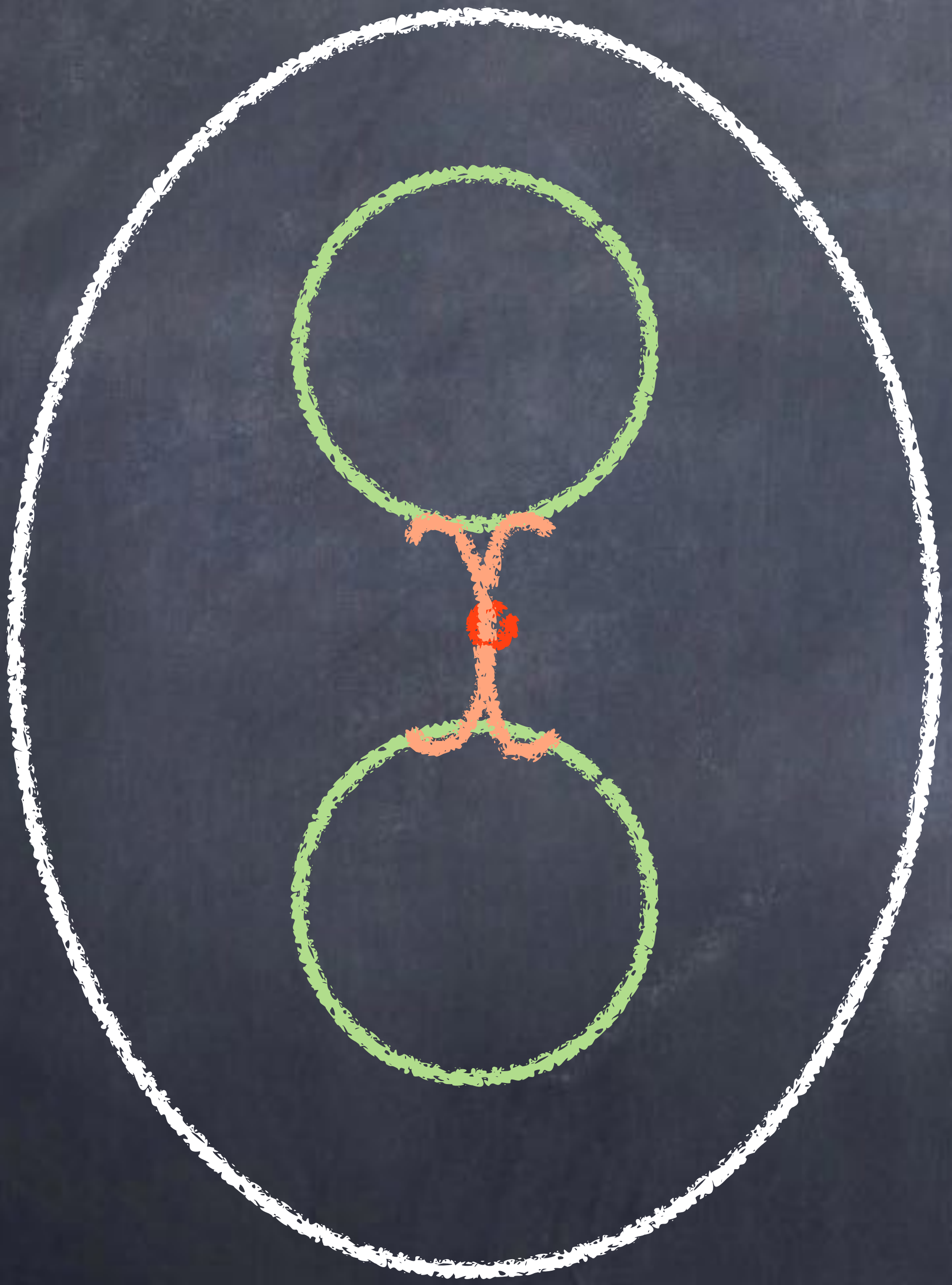


NASA/CXC/A.Hobart



NASA/CXC/A.Hobart

AGN feedback

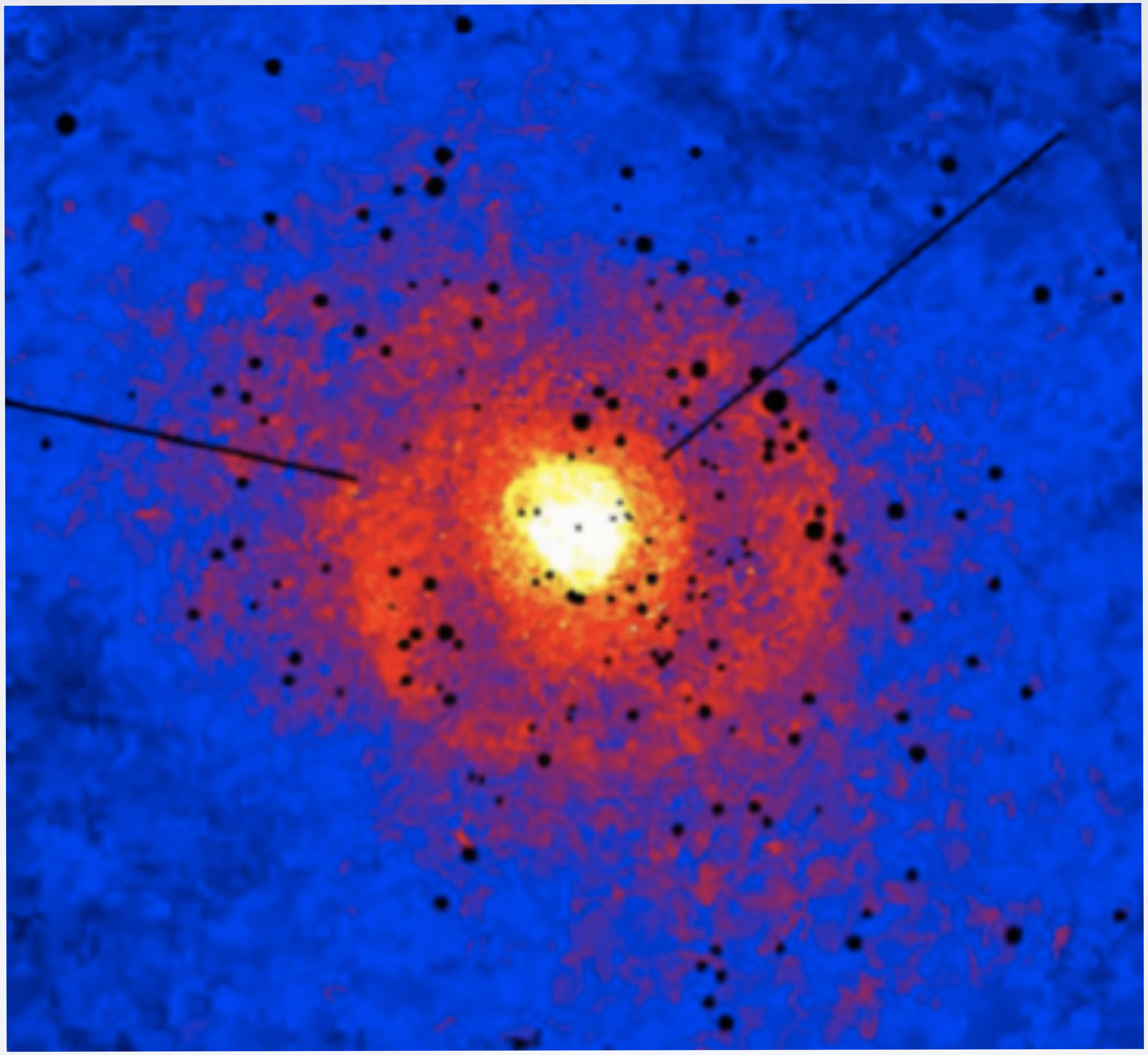


shocks: high temperature; high pressure

cavities: radio bright; X-ray faint

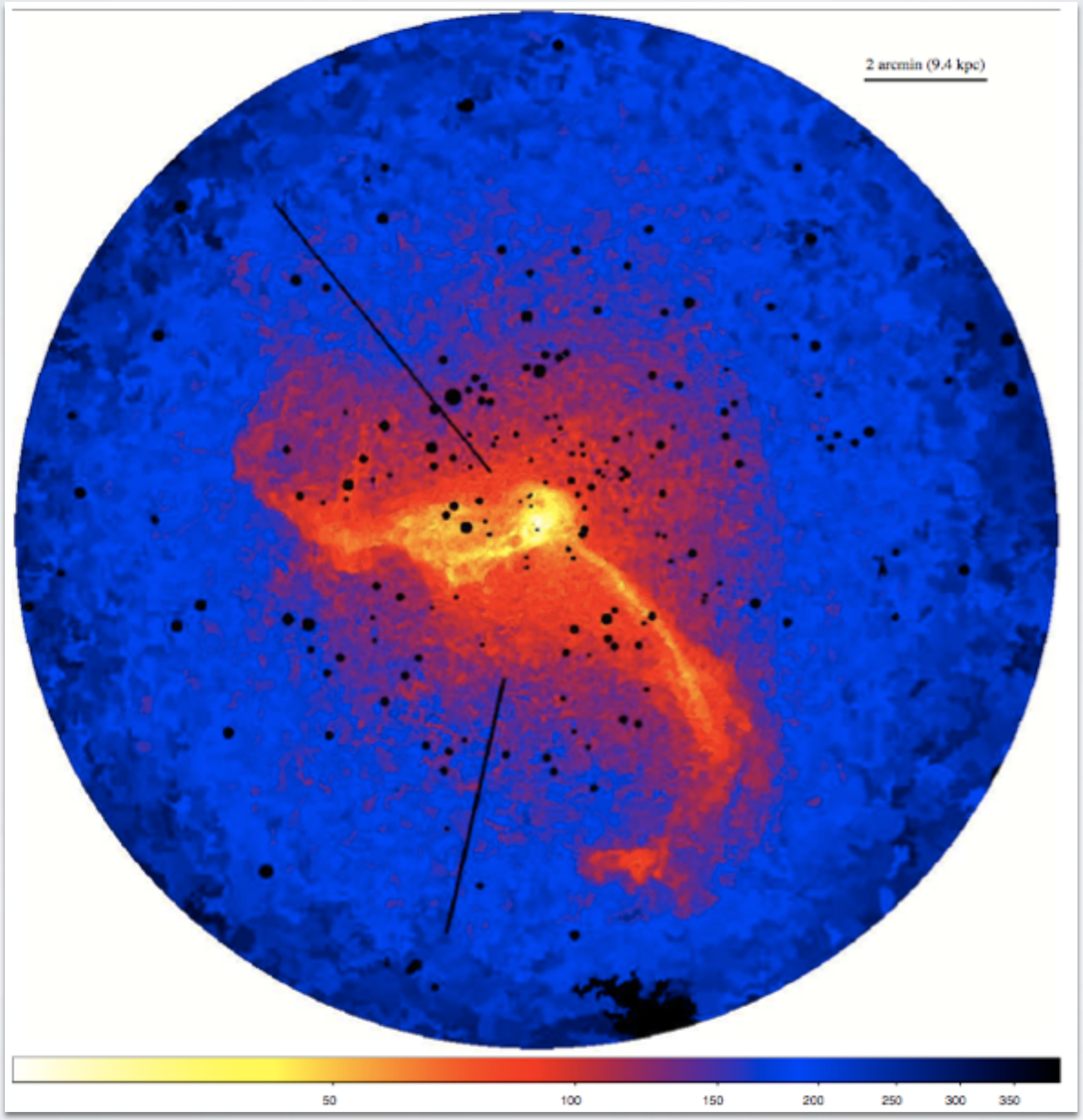
filaments: X-ray bright; low temperature; metal rich

PRESSURE (*nkT*) MAP



Millon et al. 2010

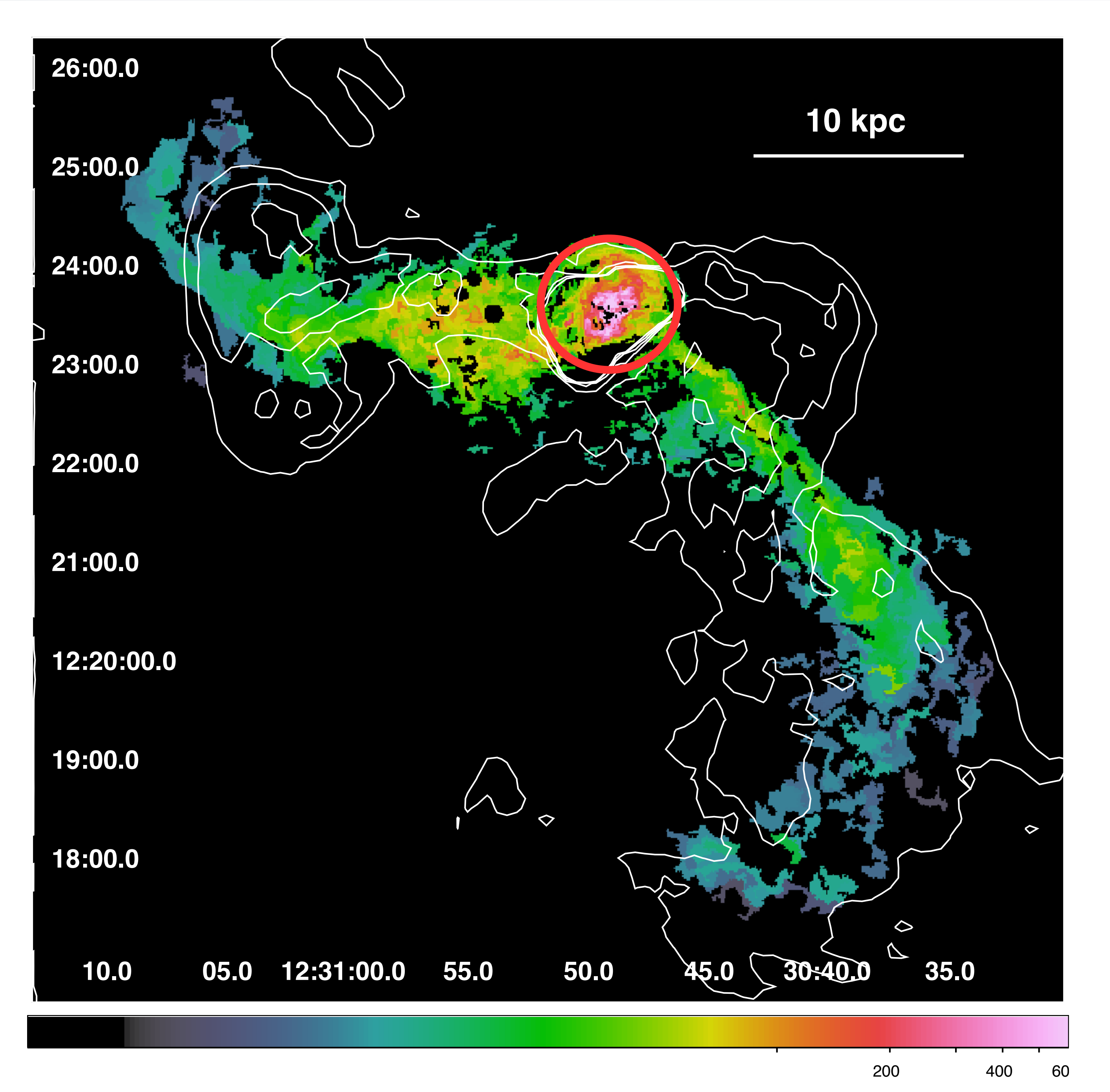
ENTROPY ($kT/n_e^{2/3}$) MAP



50 100 150 200 250 350

Million et al. 2010

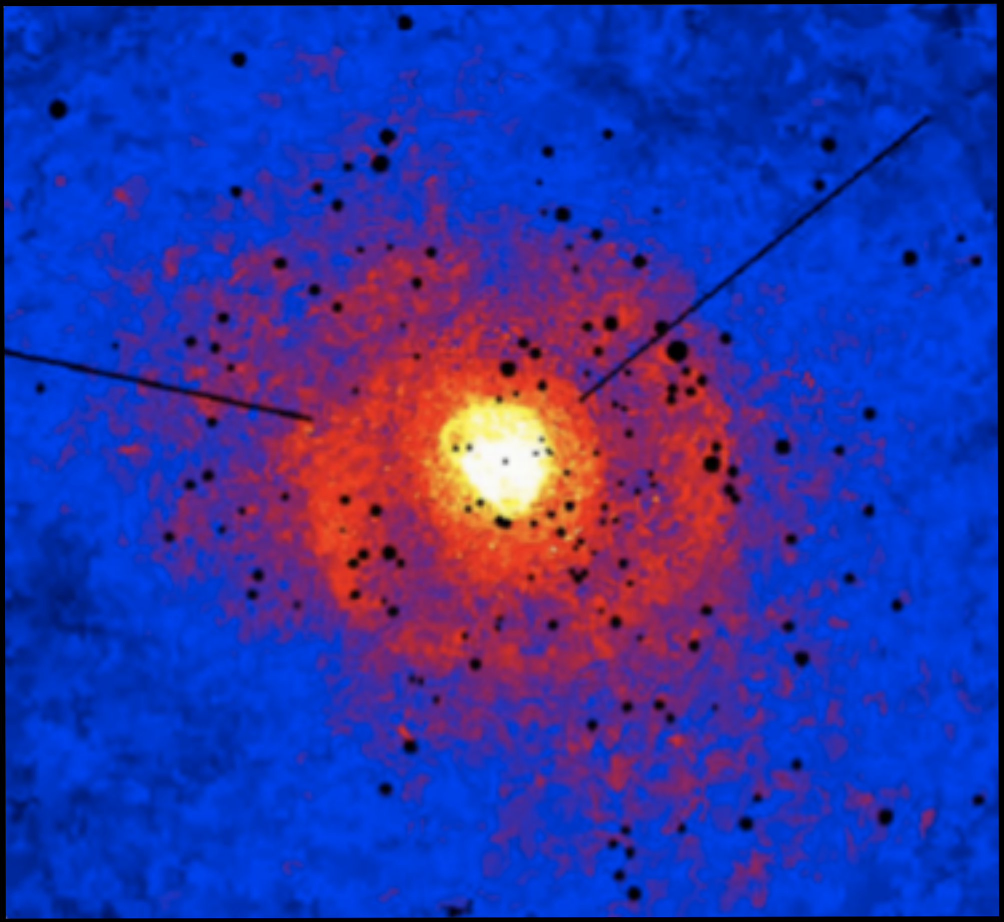
GAS UPLIFT



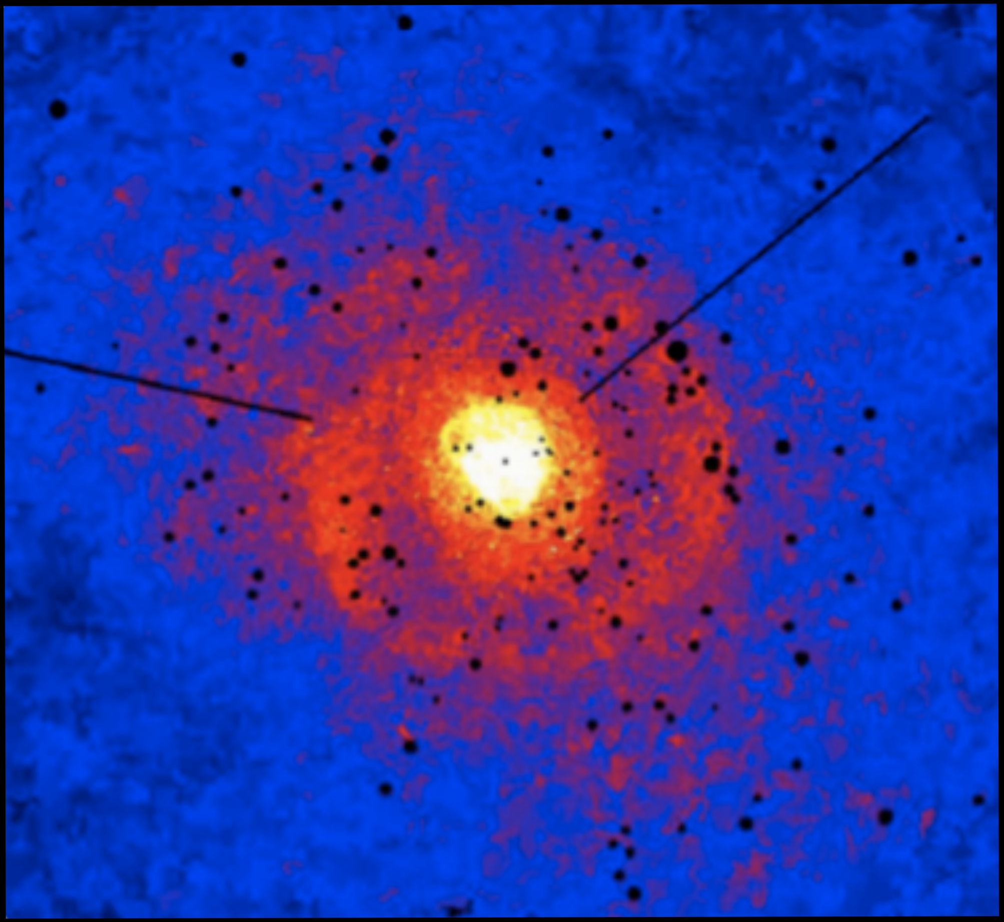
- 6-9x10^8 M_{Sun} of gas in arms
- similar to total gas mass within 3.8 kpc radius
- galaxy stripped of its lowest entropy gas
- AGN feedback in action, preventing star formation

Werner et al. 2010

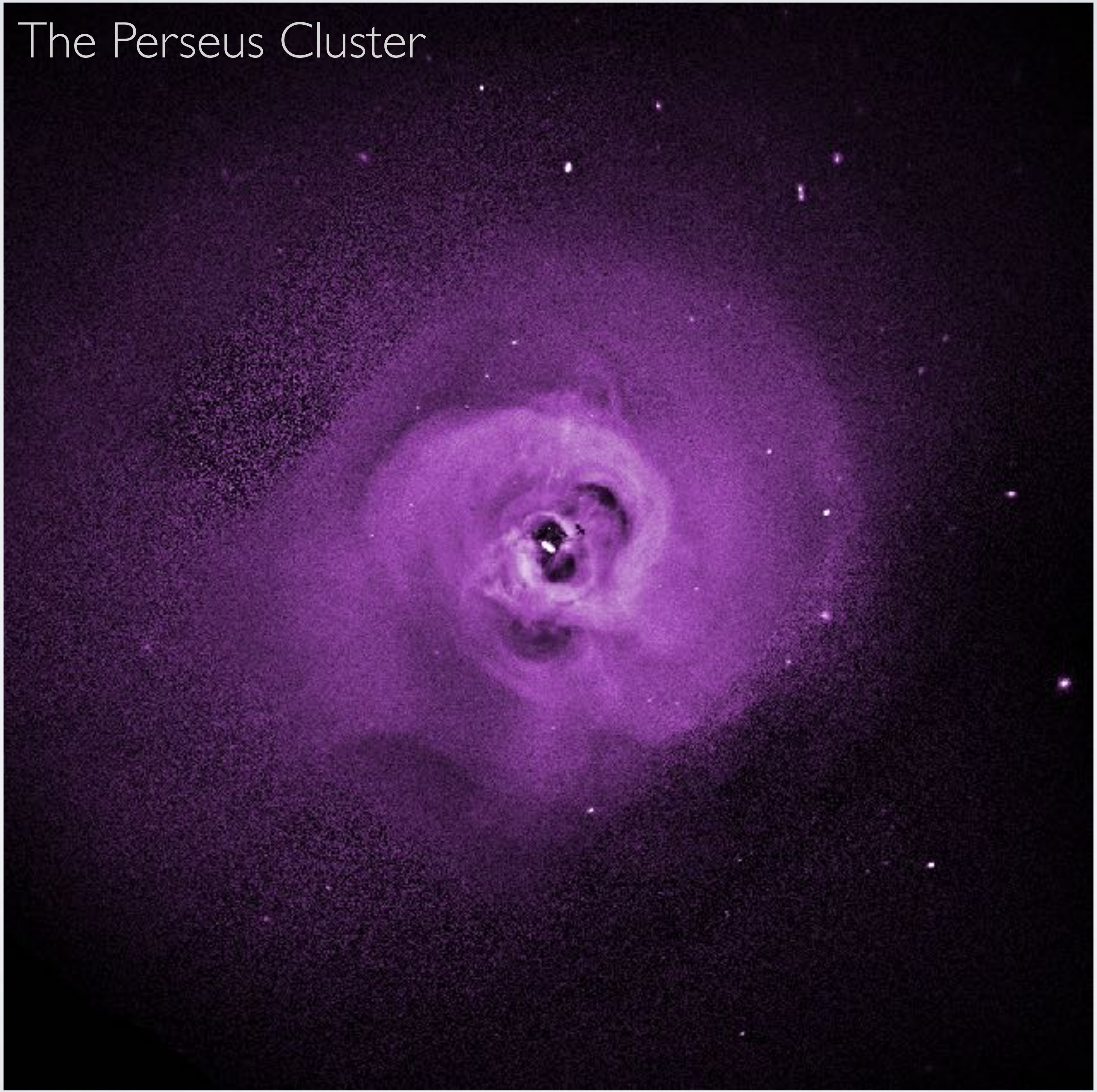
OUTBURSTS NEAR AND FAR



OUTBURSTS NEAR AND FAR



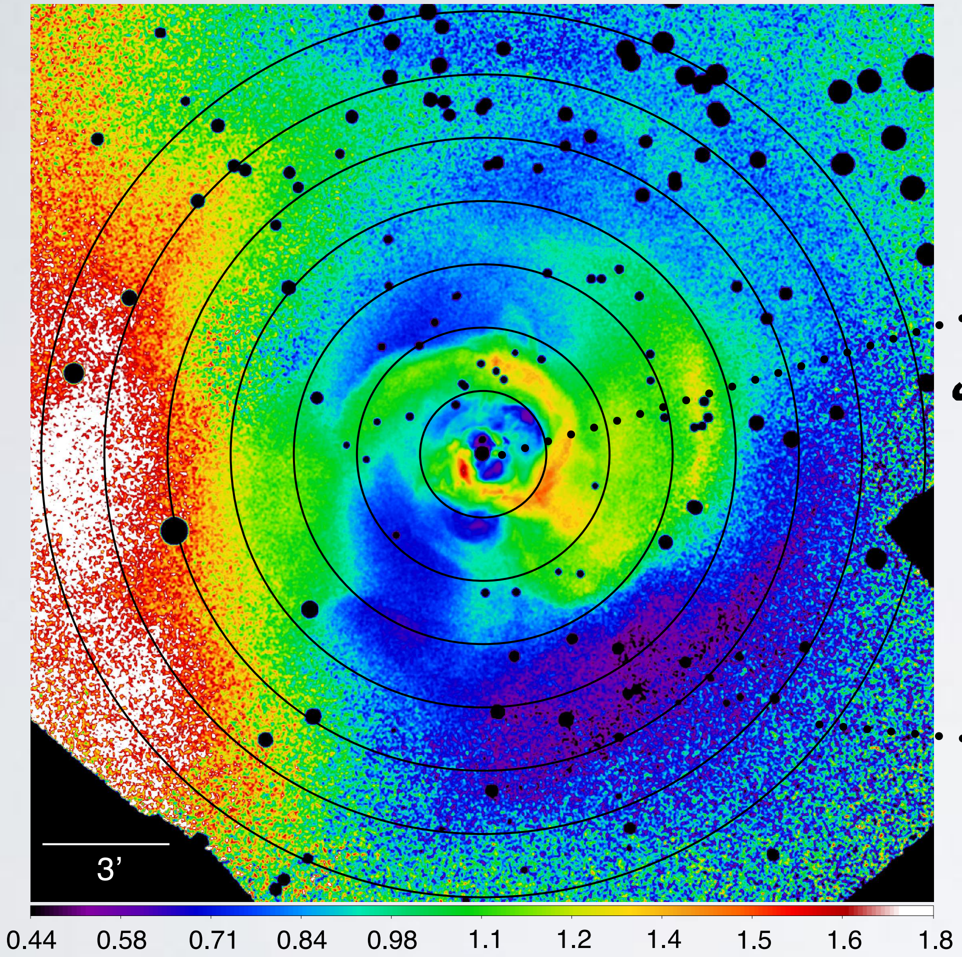
How is the energy transferred from the AGN to the diffuse gas?

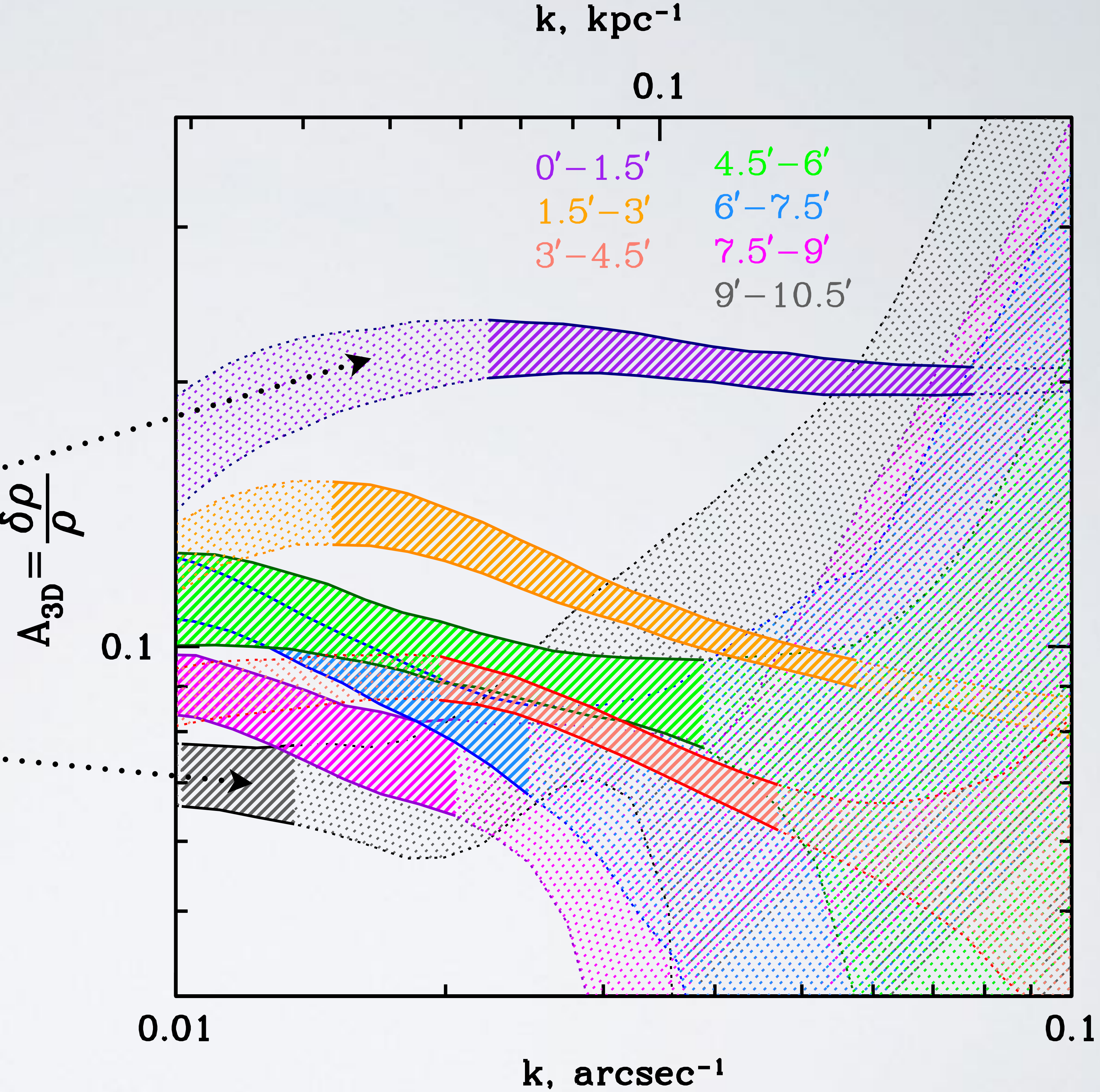


The Perseus Cluster

Amplitude of density fluctuations in Perseus

$$\frac{\delta\rho_k}{\rho} = \eta \frac{V_k}{c_s}$$



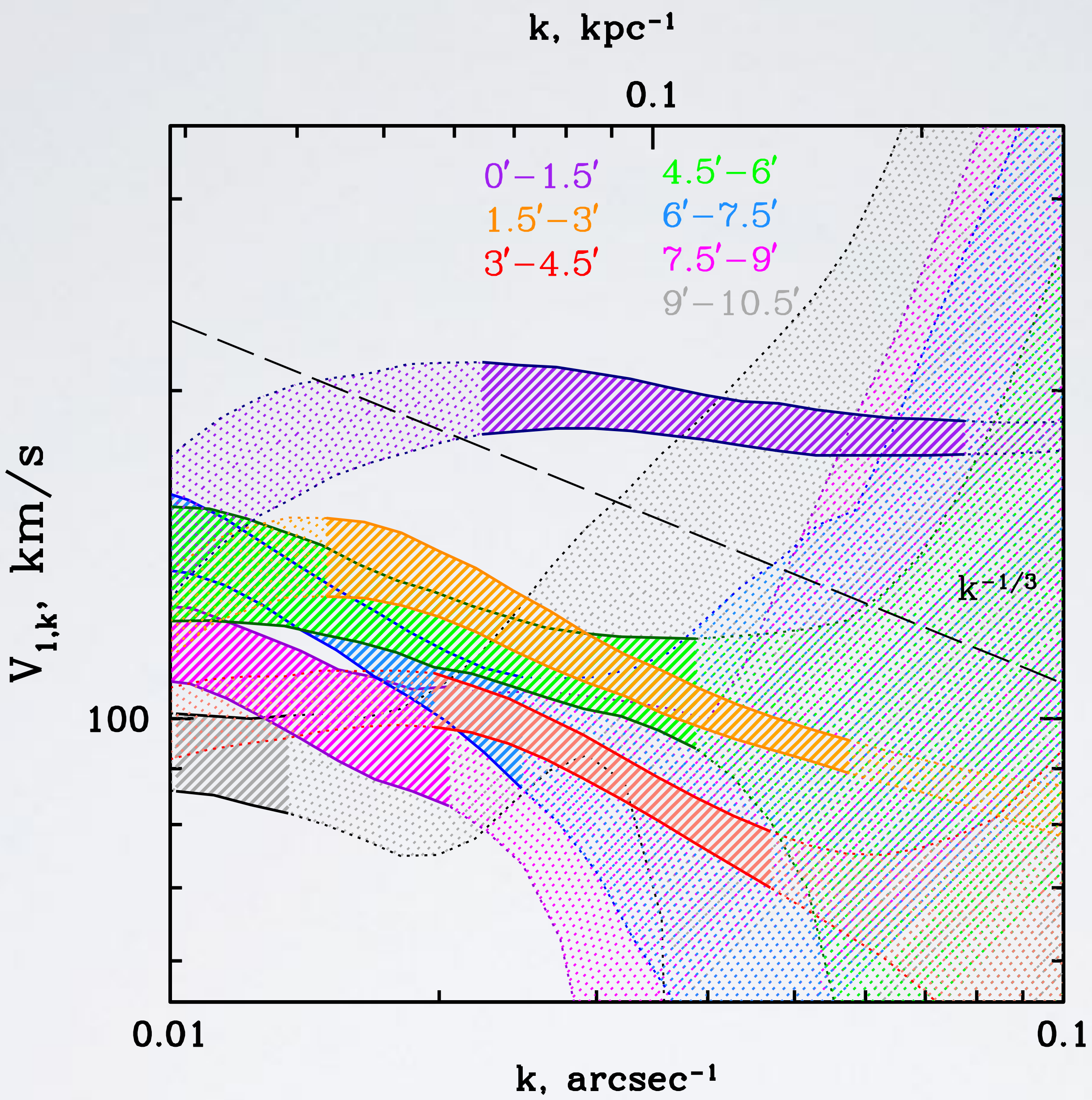


outside central 30 kpc:

$$\frac{\delta\rho_k}{\rho} \sim 7 - 15\%$$ on scales 6-30 kpc

Zhuravleva et al. 2014

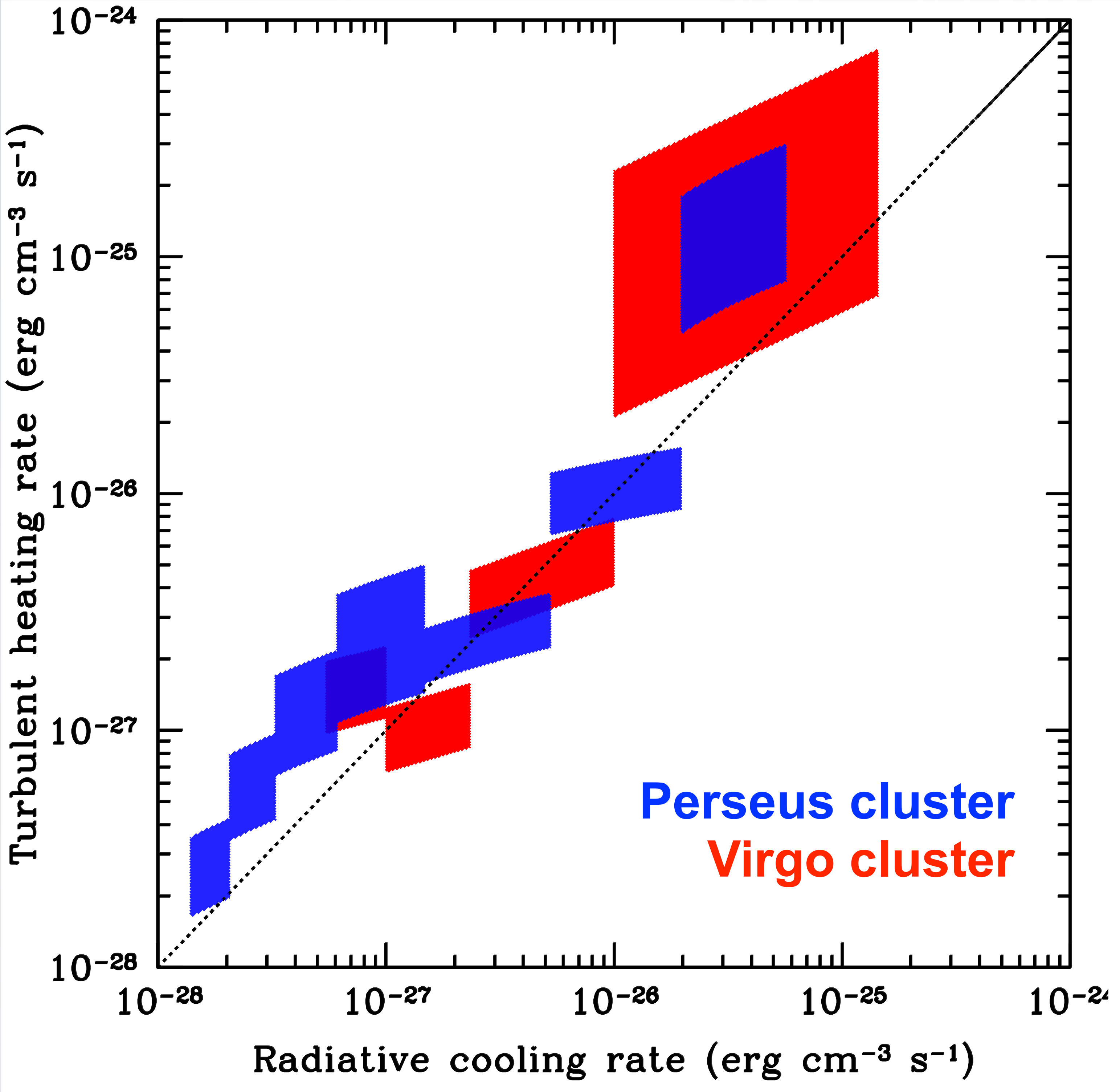
Velocity power spectrum in Perseus



- V higher towards the center —> power injection from the center
- larger V on smaller k —> consistent with cascade turbulence
- 70 km/s < $V_{1,k}$ < 200 km/s on scales 6-30 kpc (within central 200 kpc)

Zhuravleva et al., 2015

Turbulent dissipation in AGN feedback

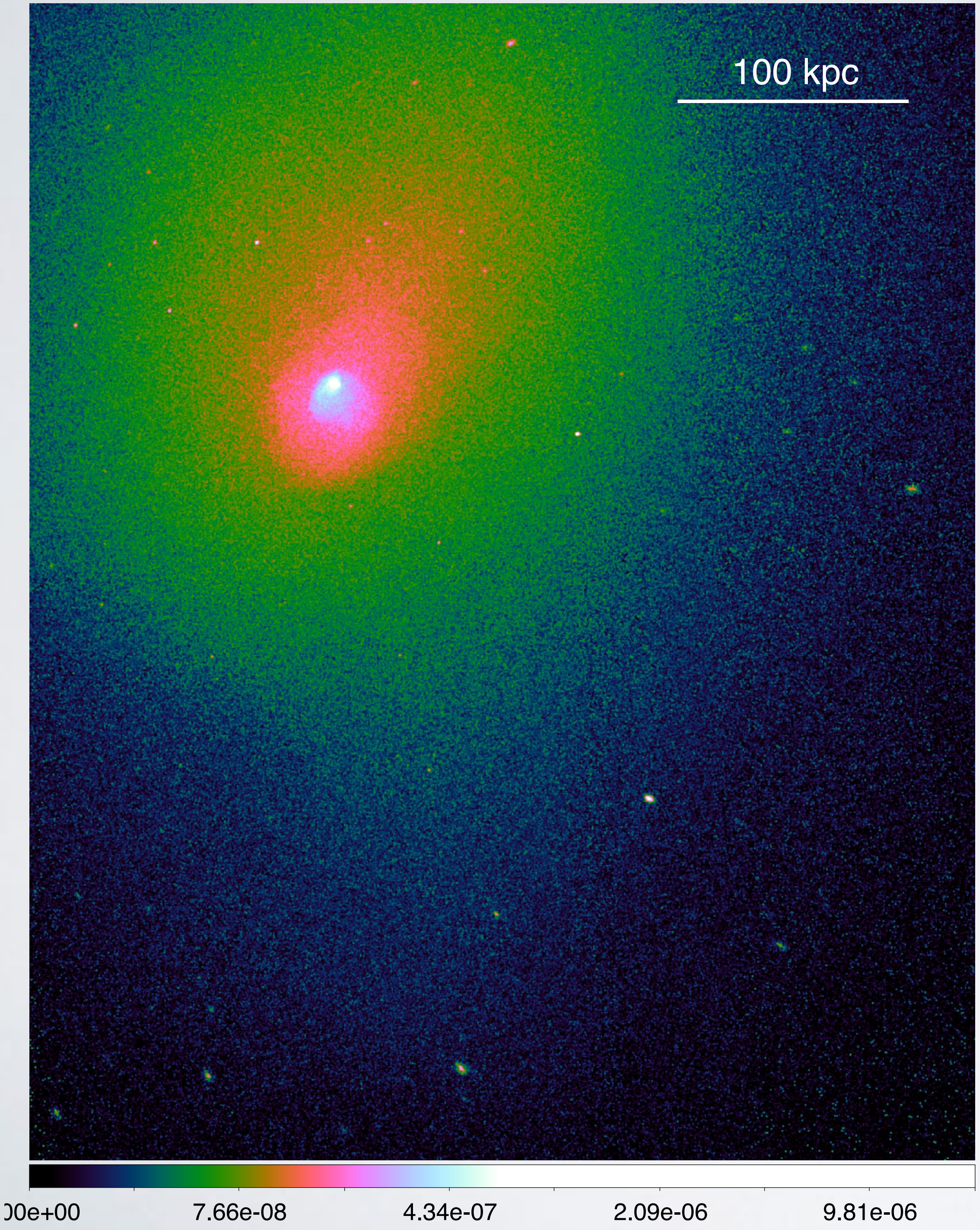


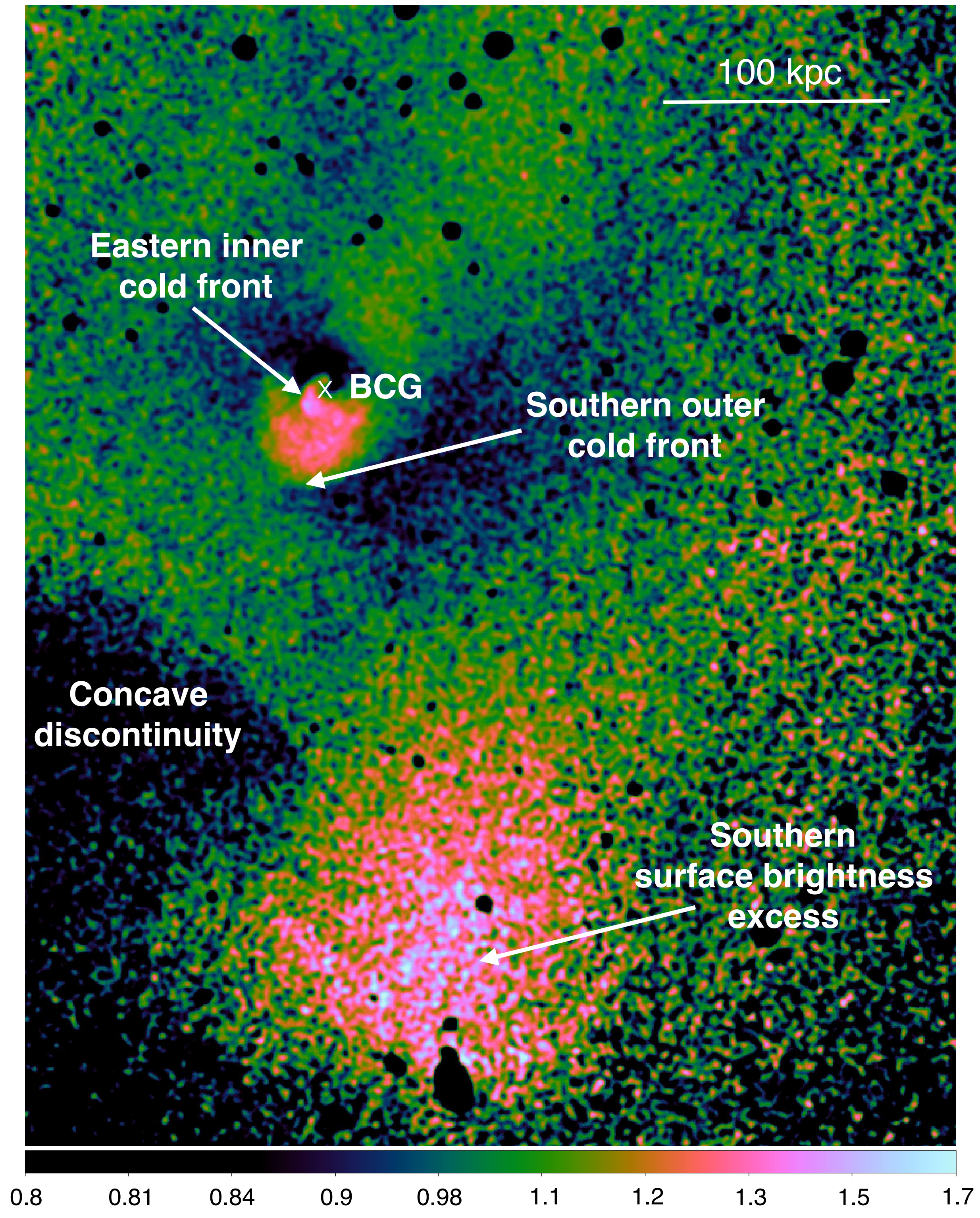
locally: cooling ~ heating

AGN —> Bubbles —> Turbulent dissipation —> Heat

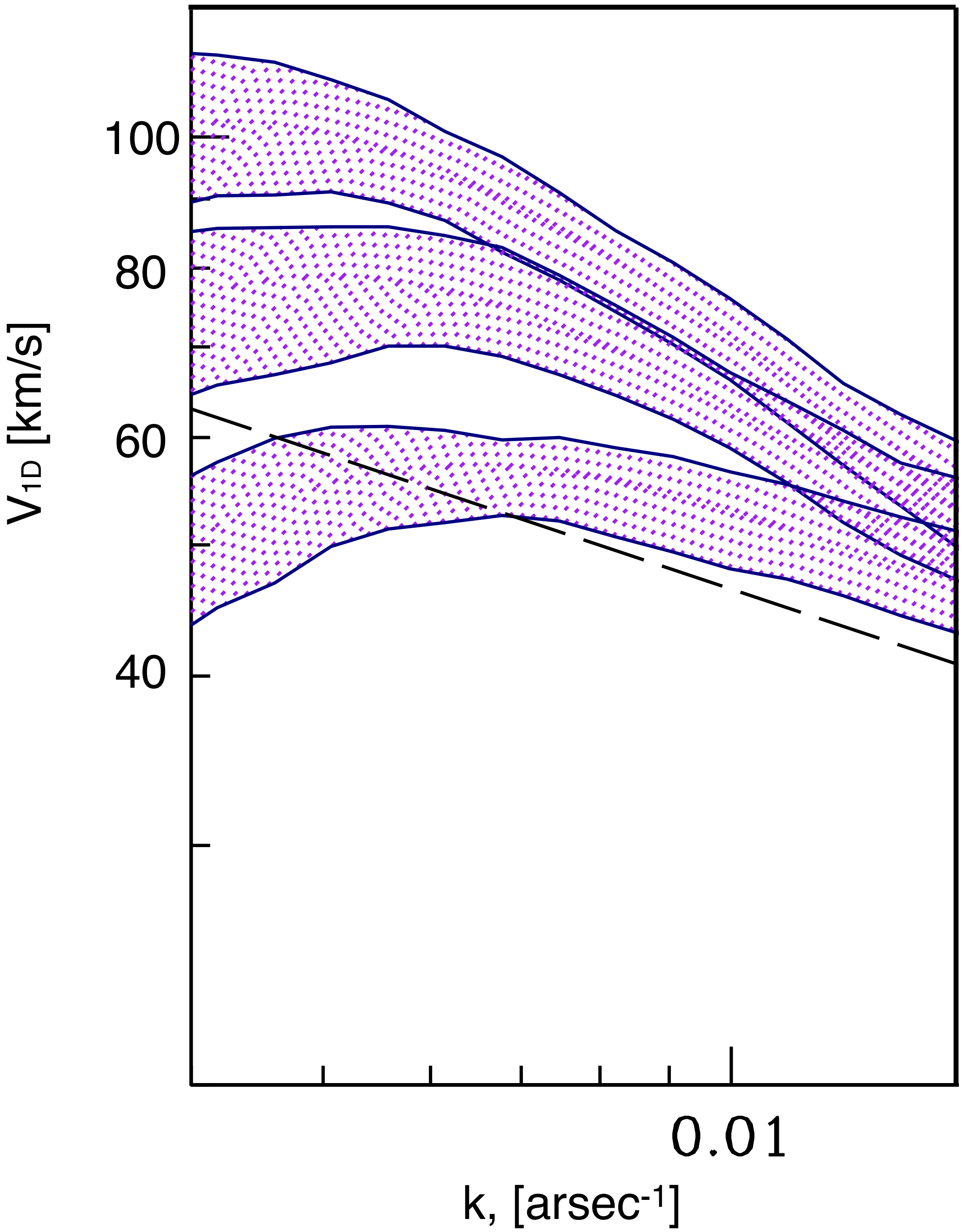
Zhuravleva et al. 2014b

Extreme clusters as probes of the ICM physics



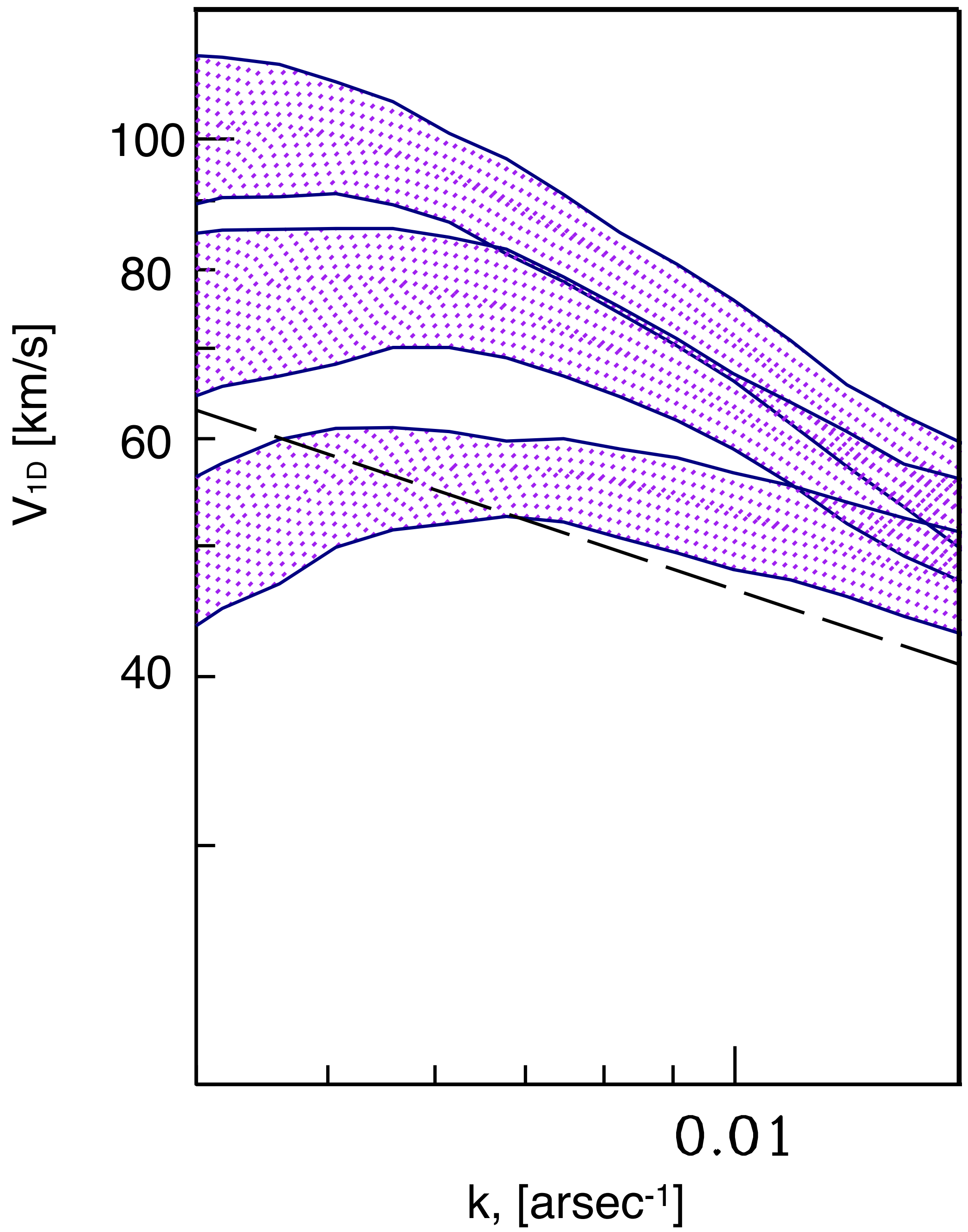


Velocities in the Ophiuchus cluster



Werner et al. 2016

Velocities in the Ophiuchus cluster

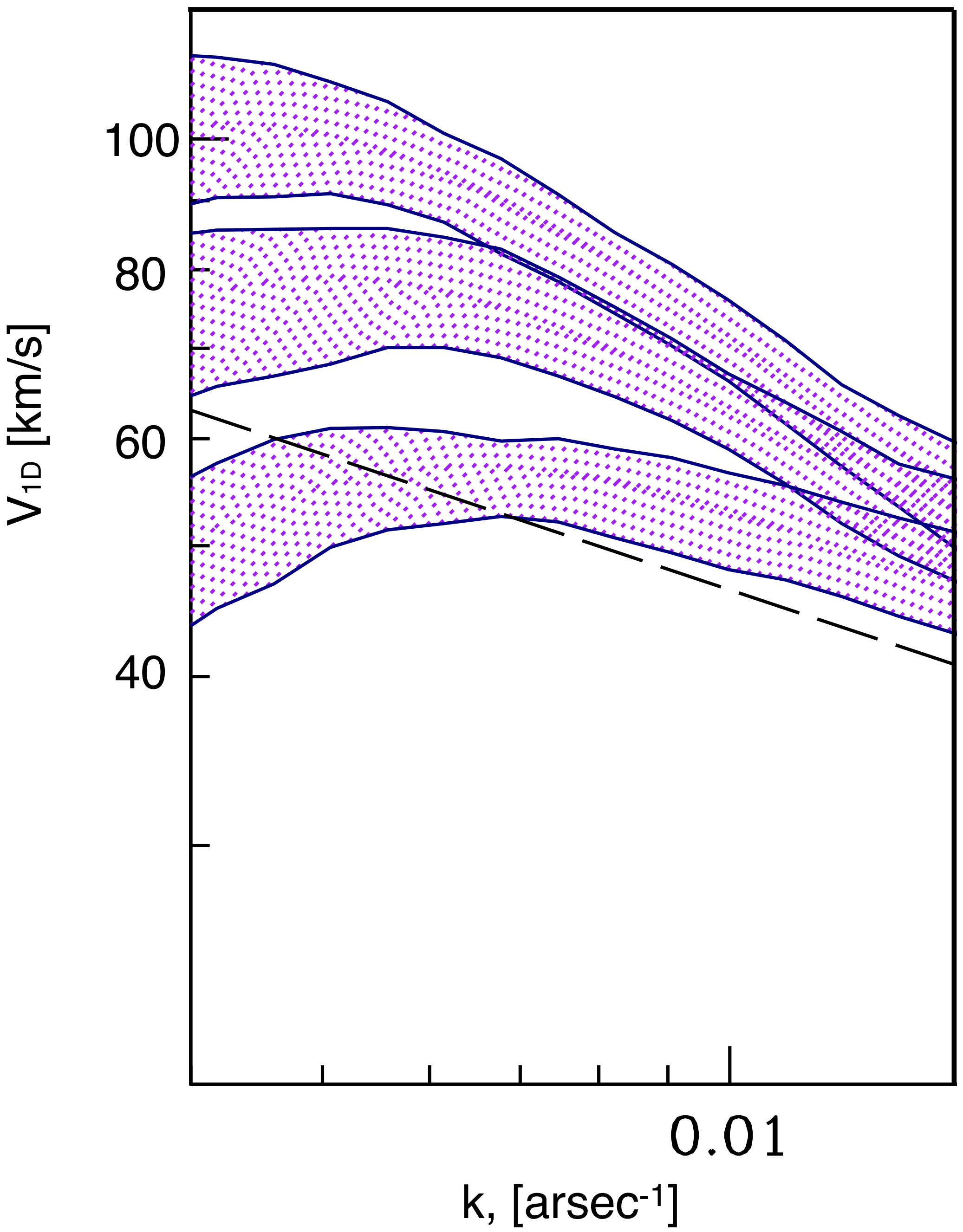


$V_{1,k}$ < 100 km/s on scales < 100 kpc

Measured velocities seem too low for a disturbed system

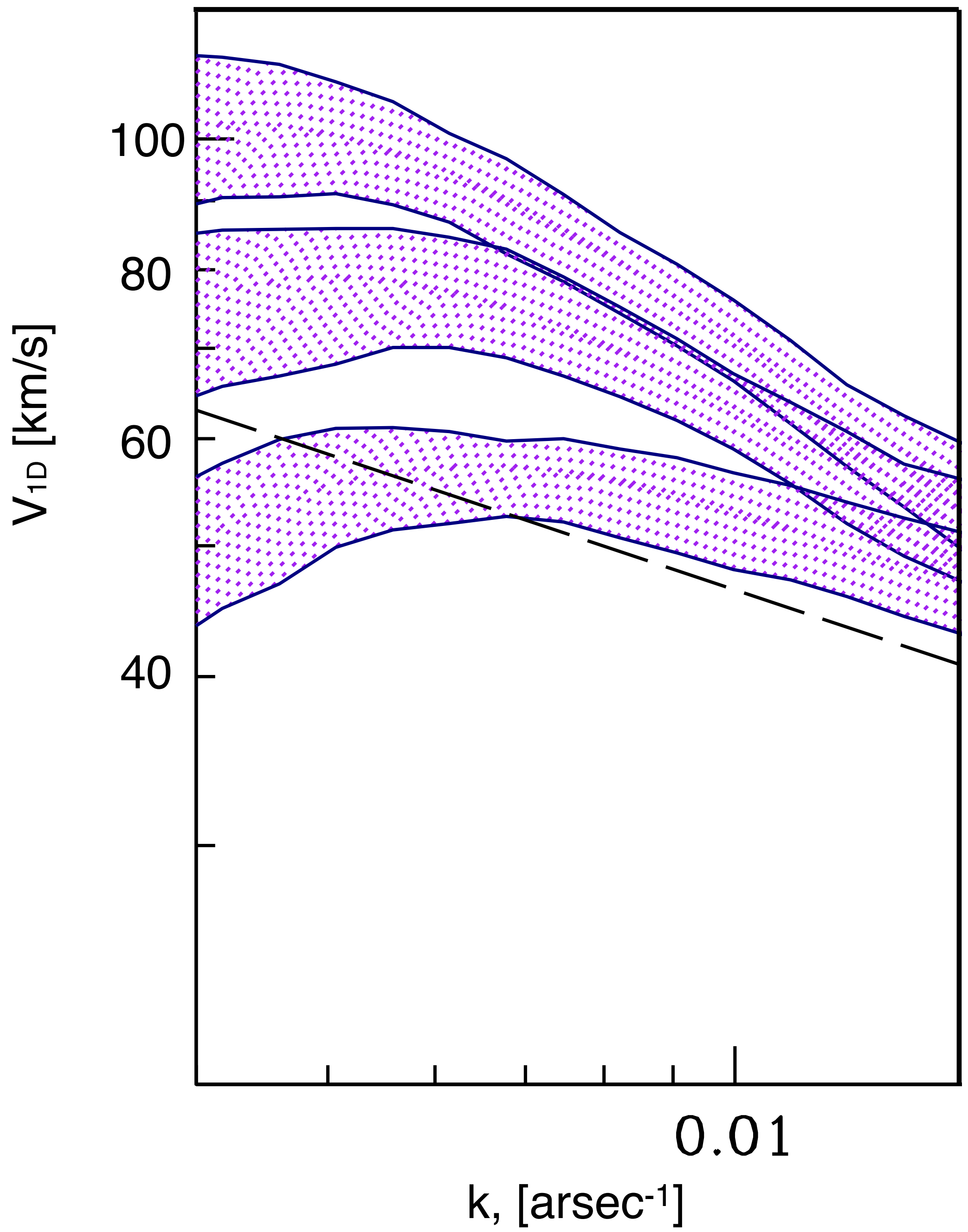
Werner et al. 2016

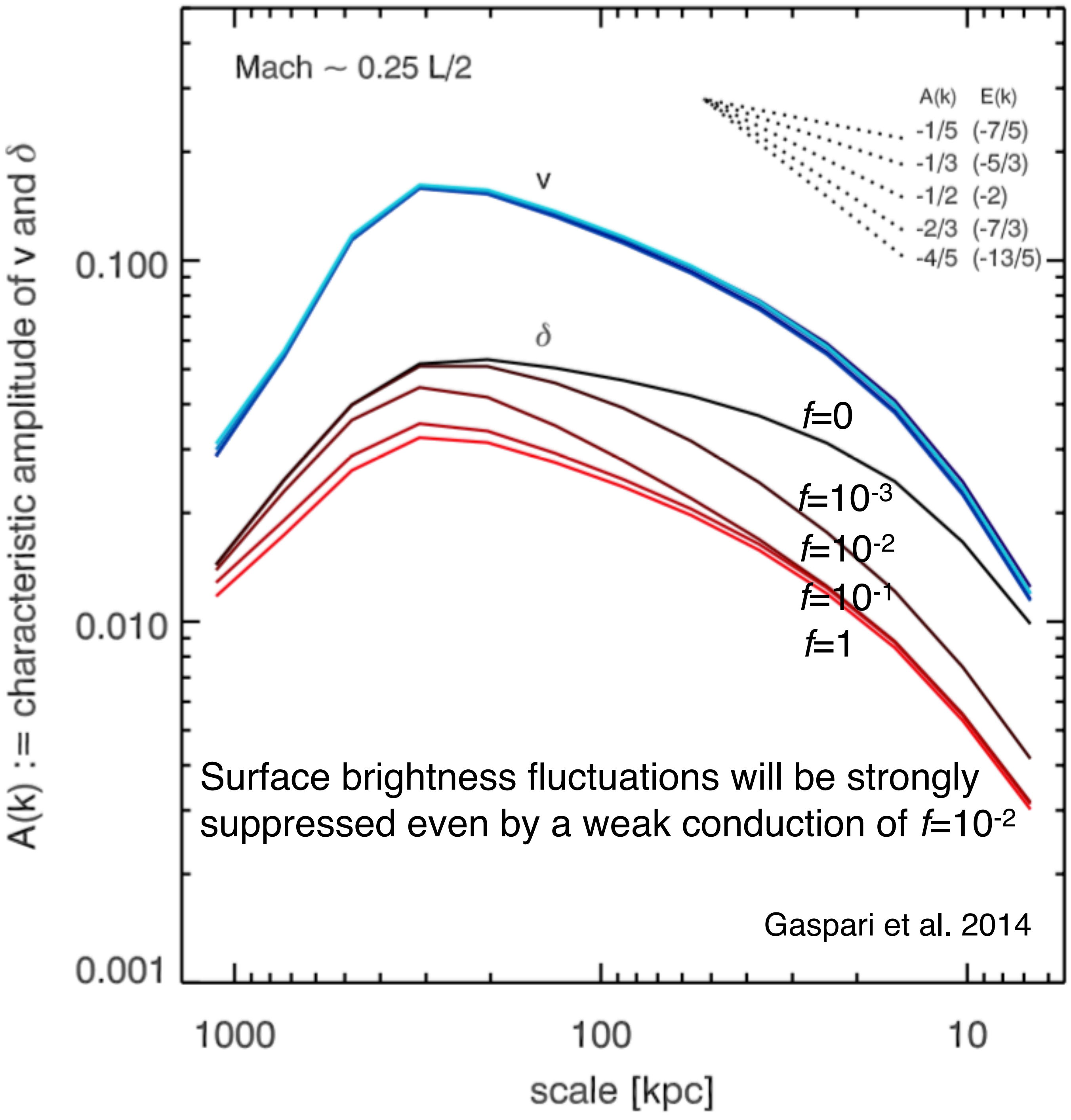
Velocities in the Ophiuchus cluster



Werner et al. 2016

Velocities in the Ophiuchus cluster



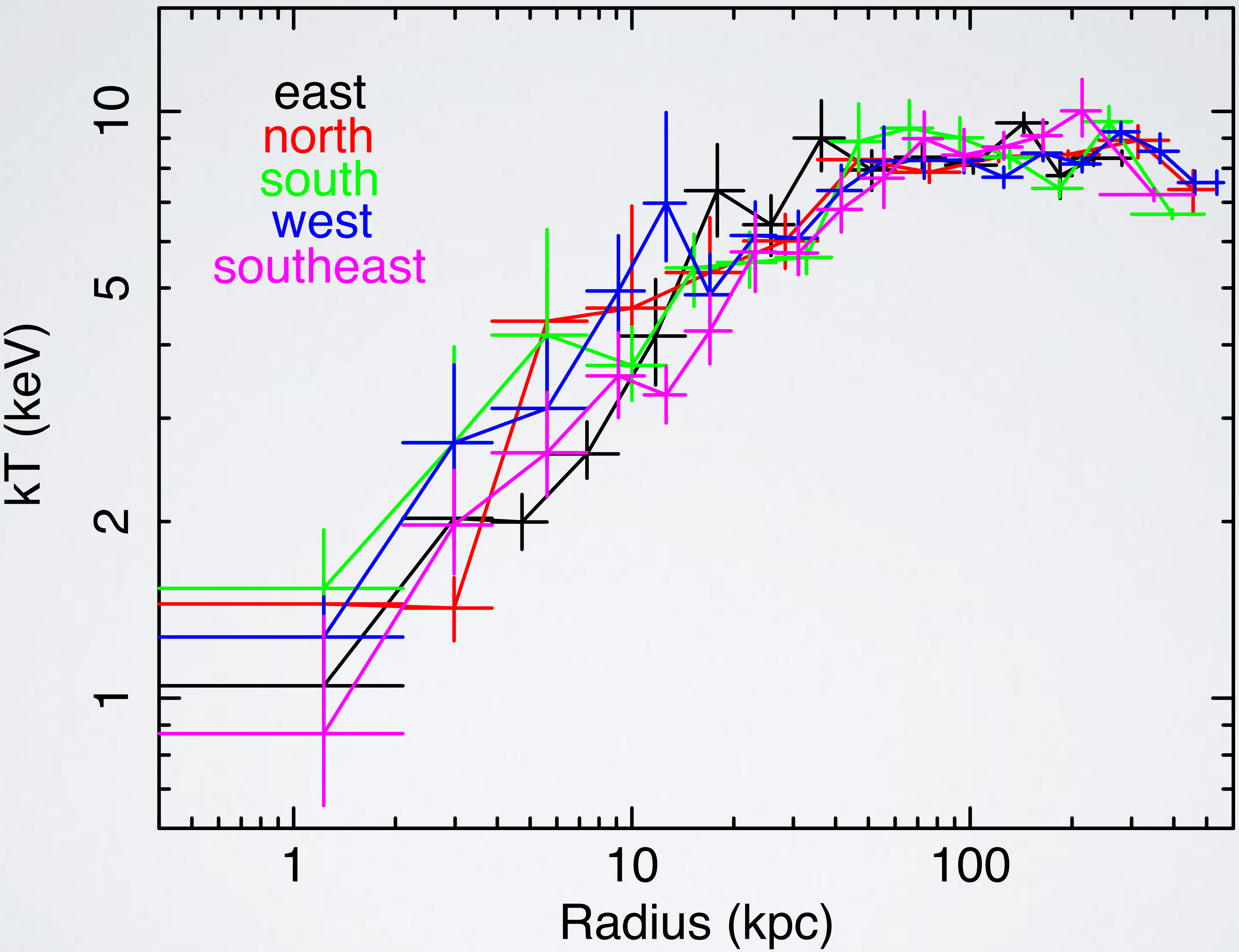


Surface brightness fluctuations will be strongly suppressed even by a weak conduction of $f=10^{-2}$

Gaspari et al. 2014

Werner et al. 2016

Thermal conduction and its suppression

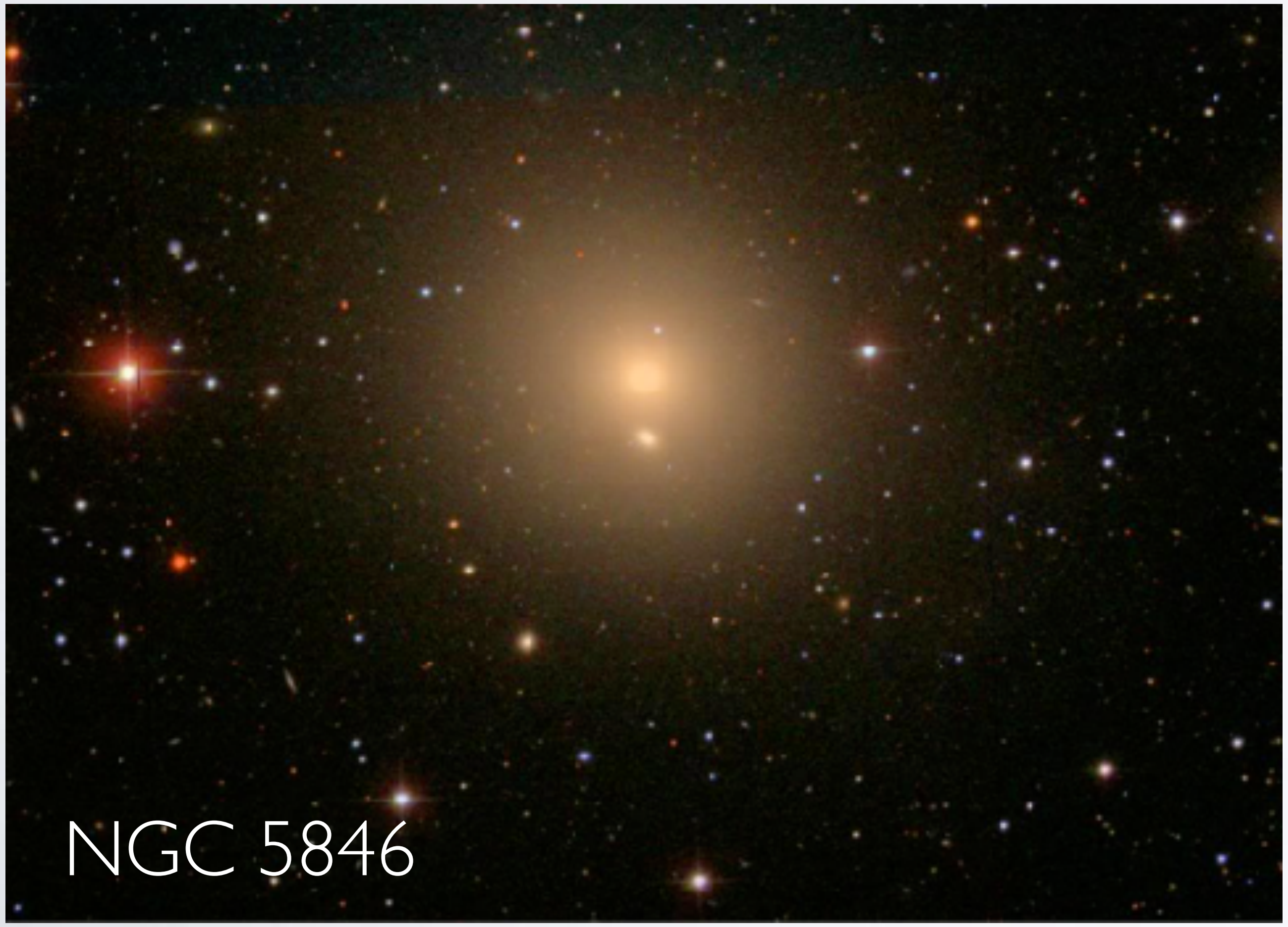


Werner et al. 2016

RED AND DEAD GIANT ELLIPTICAL GALAXIES

NGC 5813

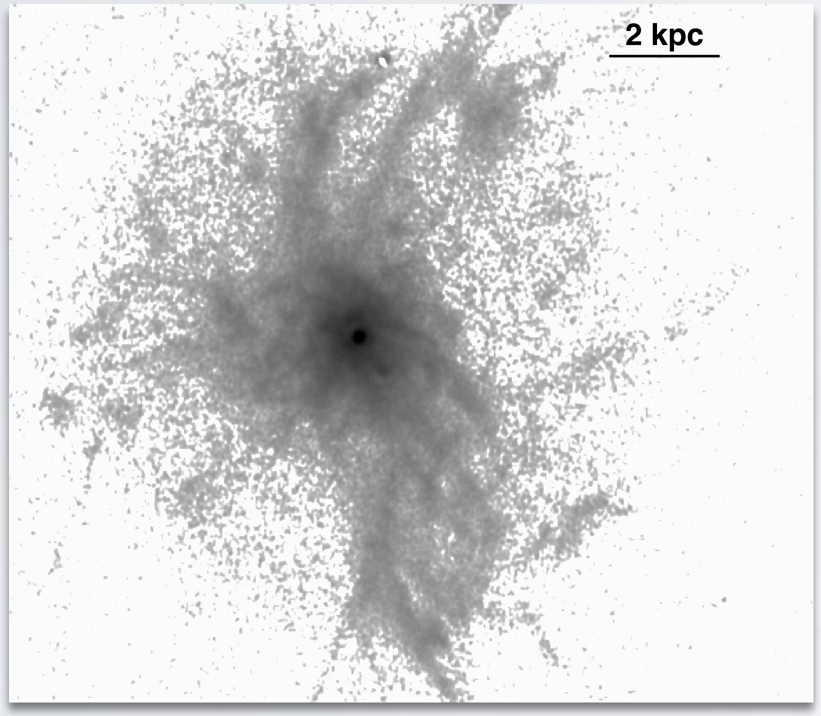
NGC 4472

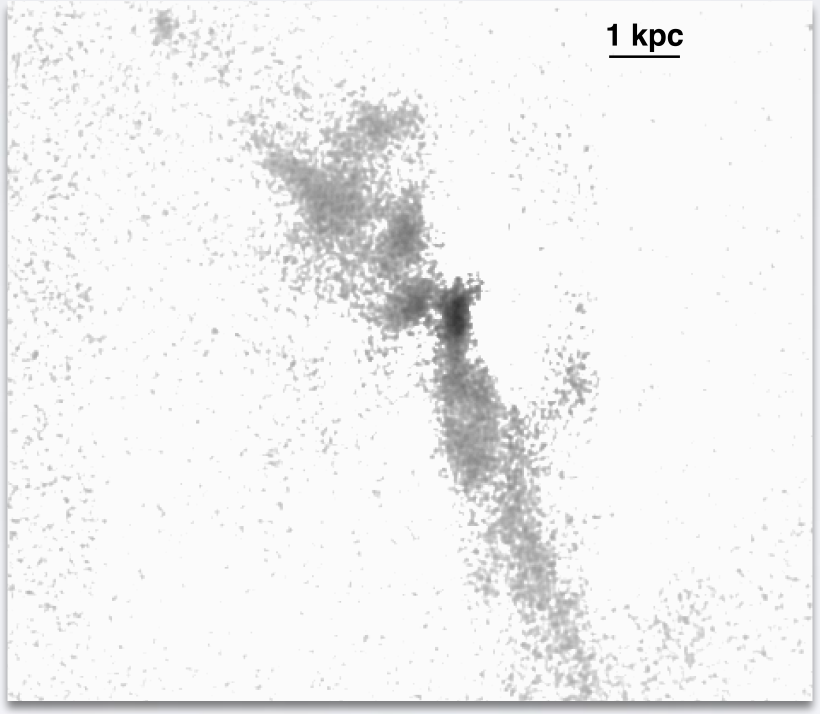


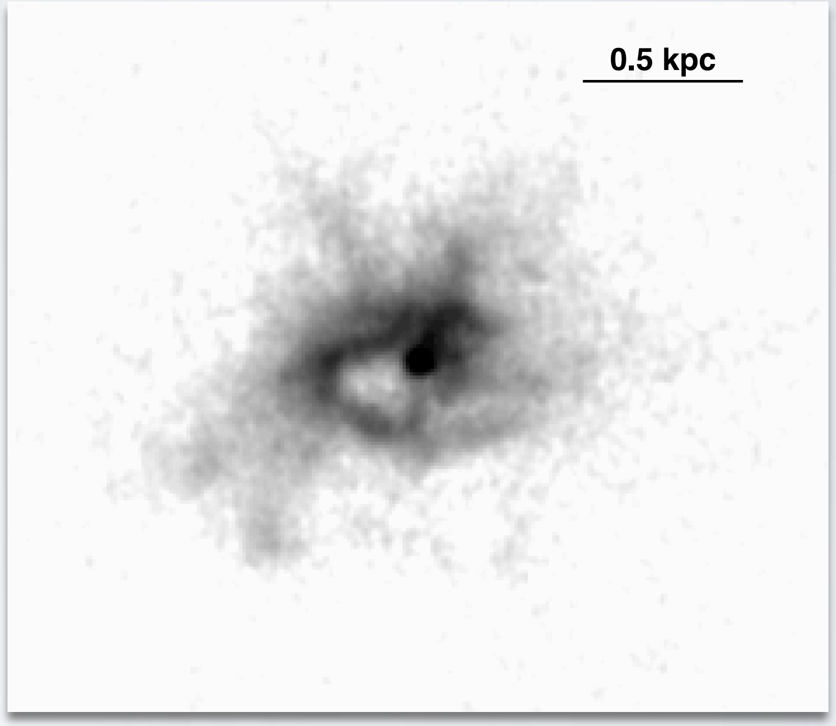
NGC 5846

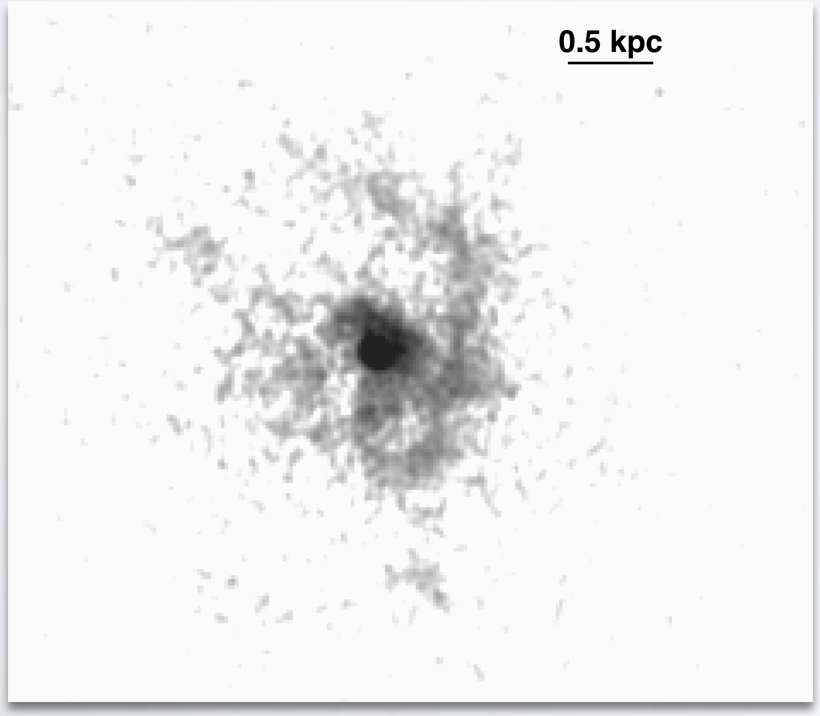
M87

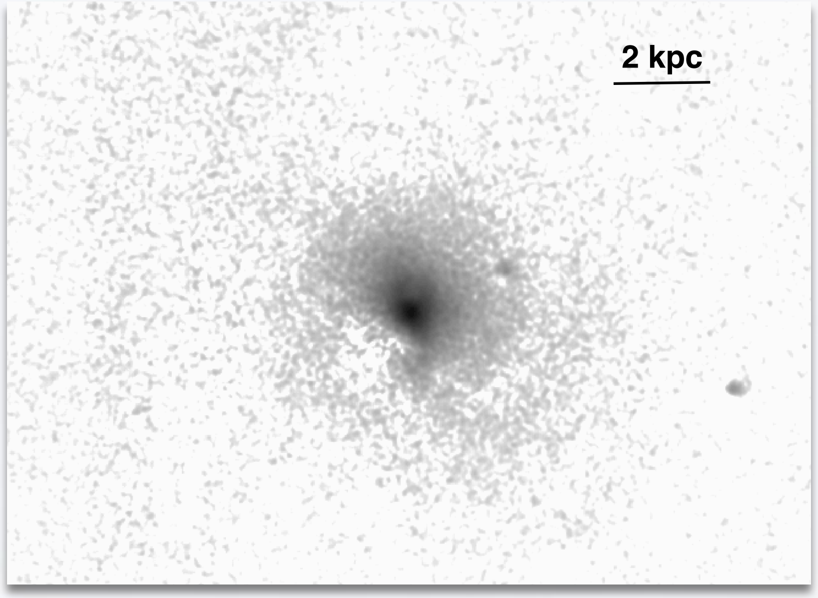
Hα+[NII] IMAGING WITH THE SOAR TELESCOPE

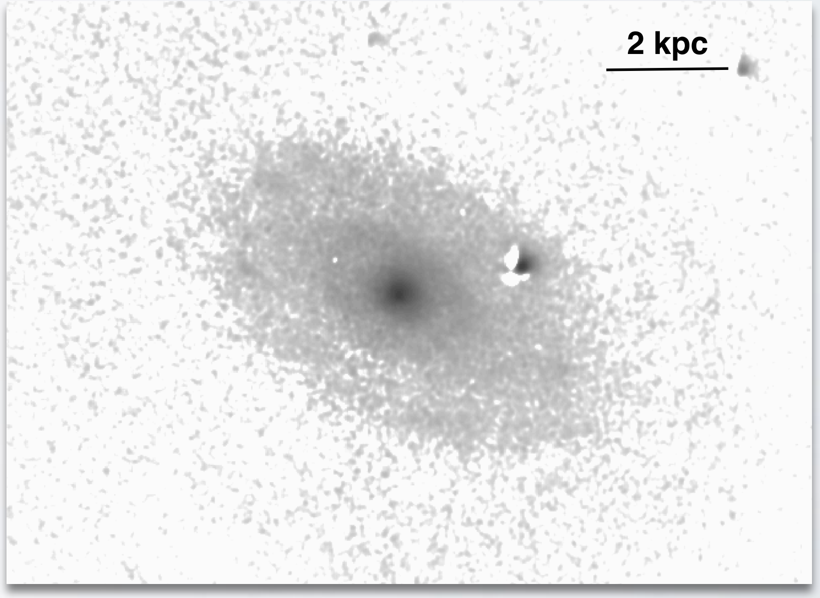












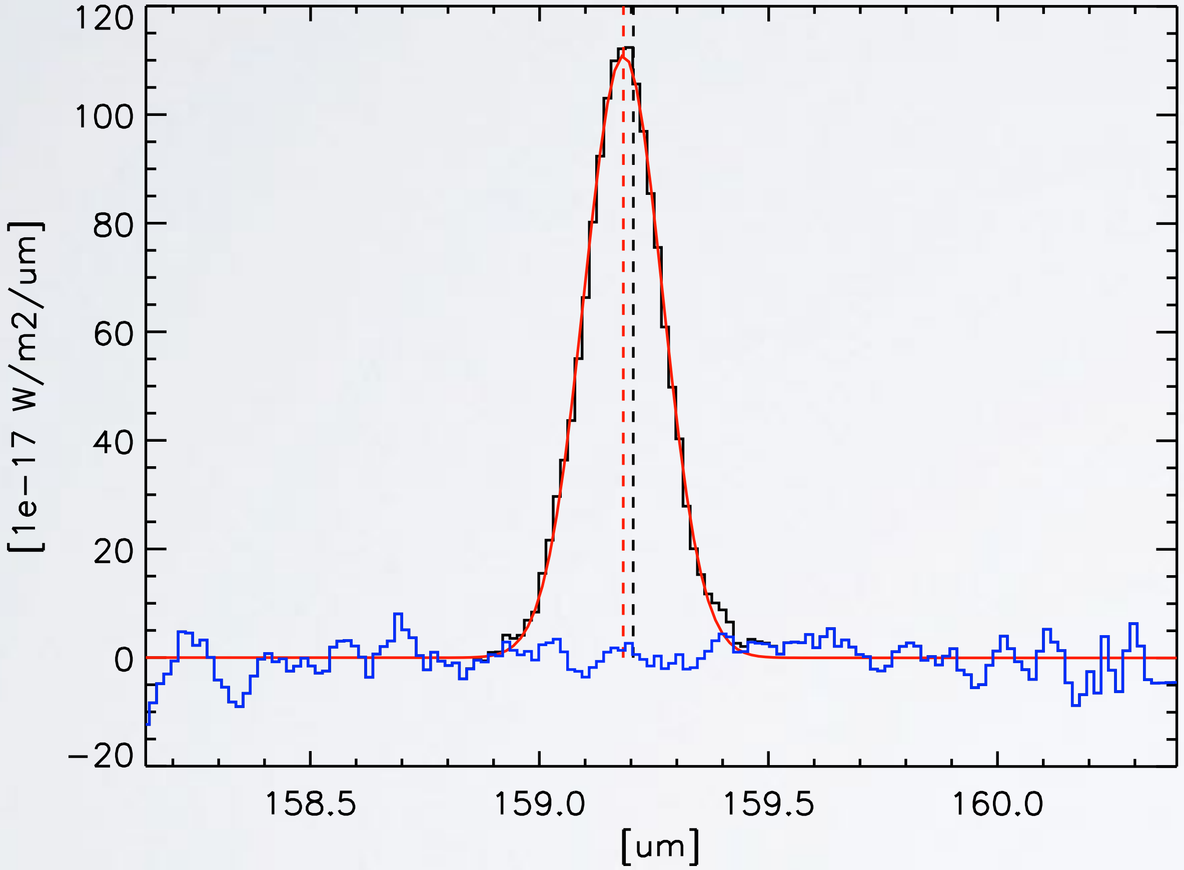
Werner et al. 2014

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

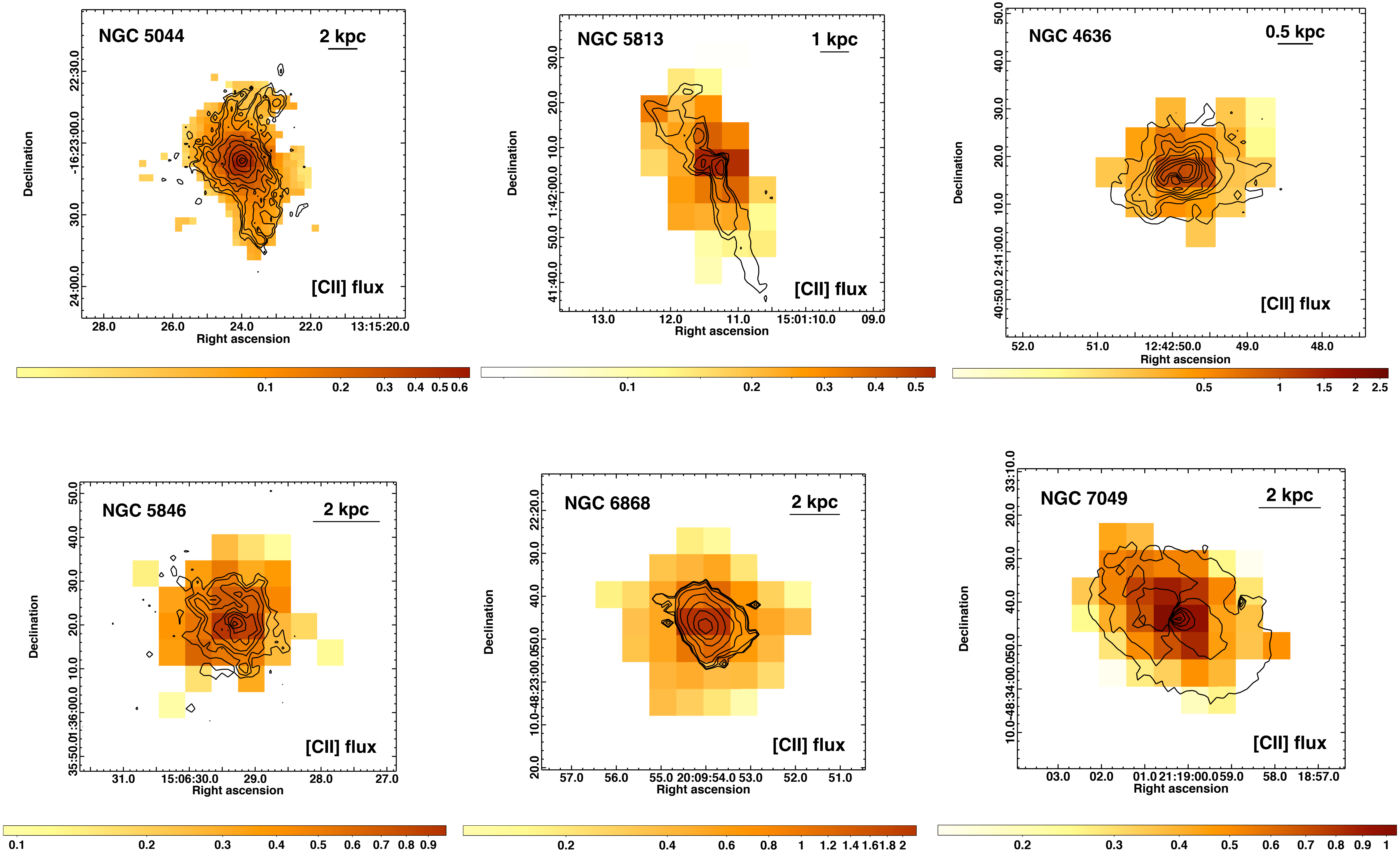
FAR-INFRARED LINE DETECTIONS IN GIANT ELLIPTICALS



- [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

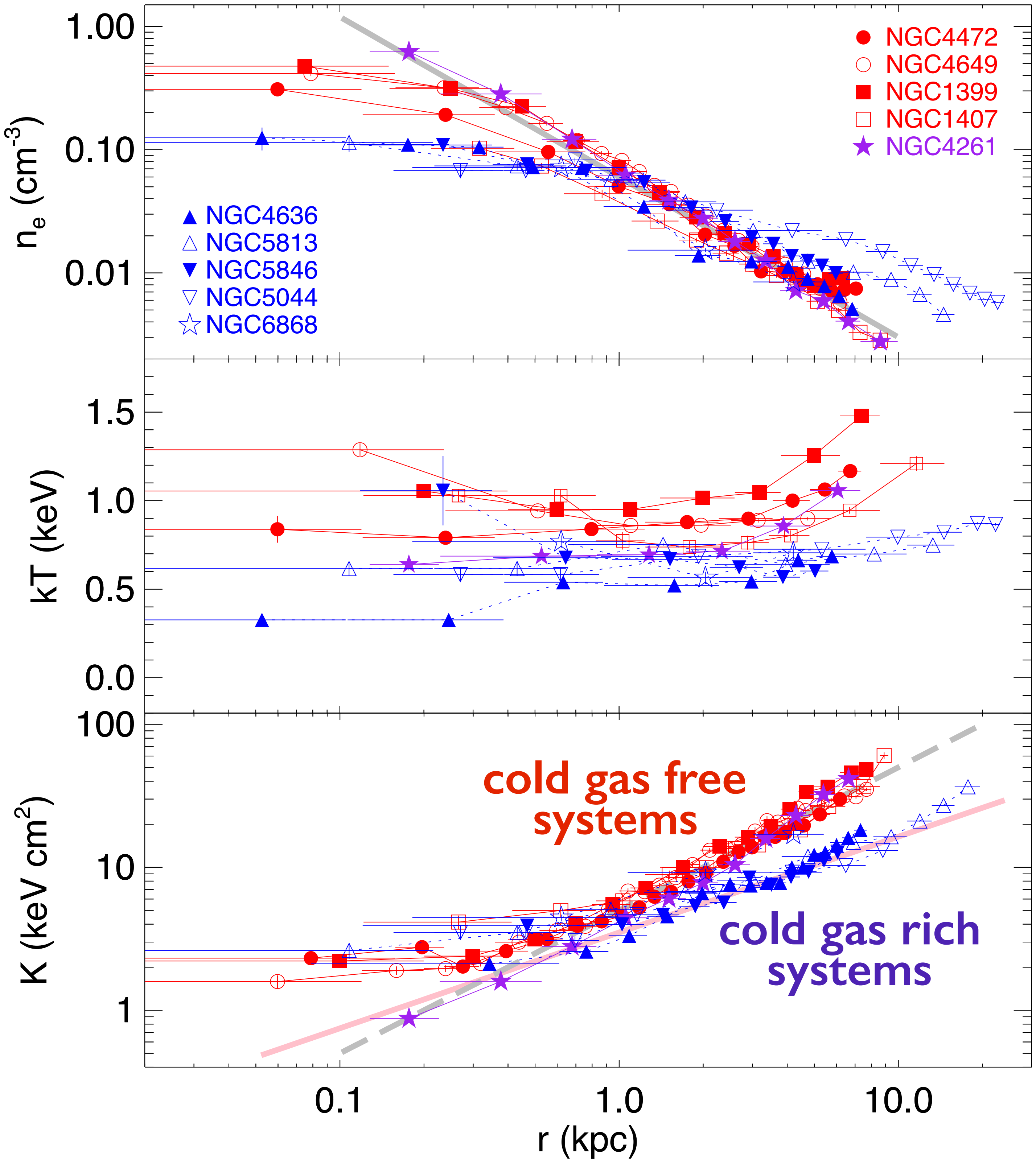
Werner et al. 2014

[CII] EMISSION FOLLOWING Hα



Werner et al. 2014

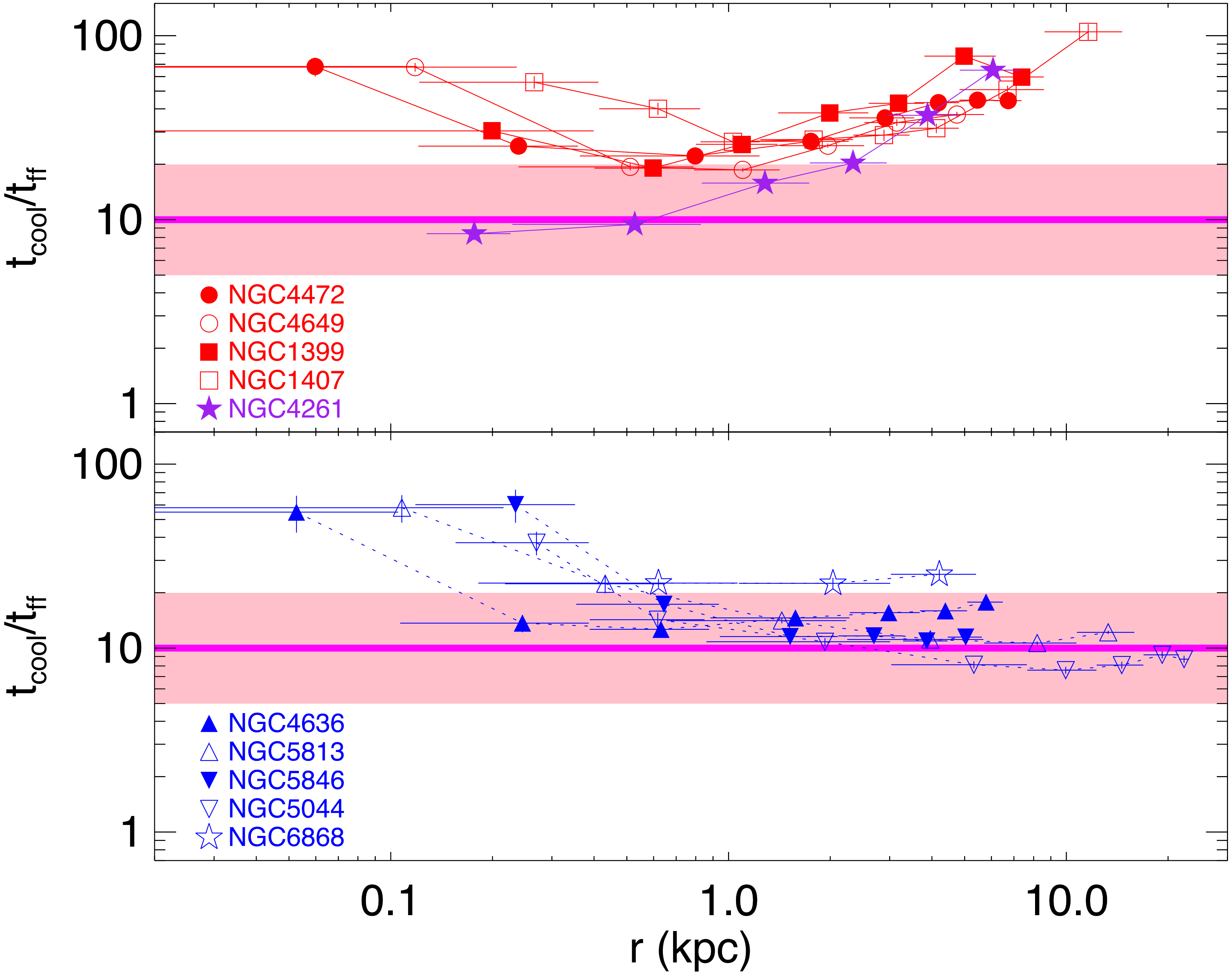
PROPERTIES OF THE HOT ISM



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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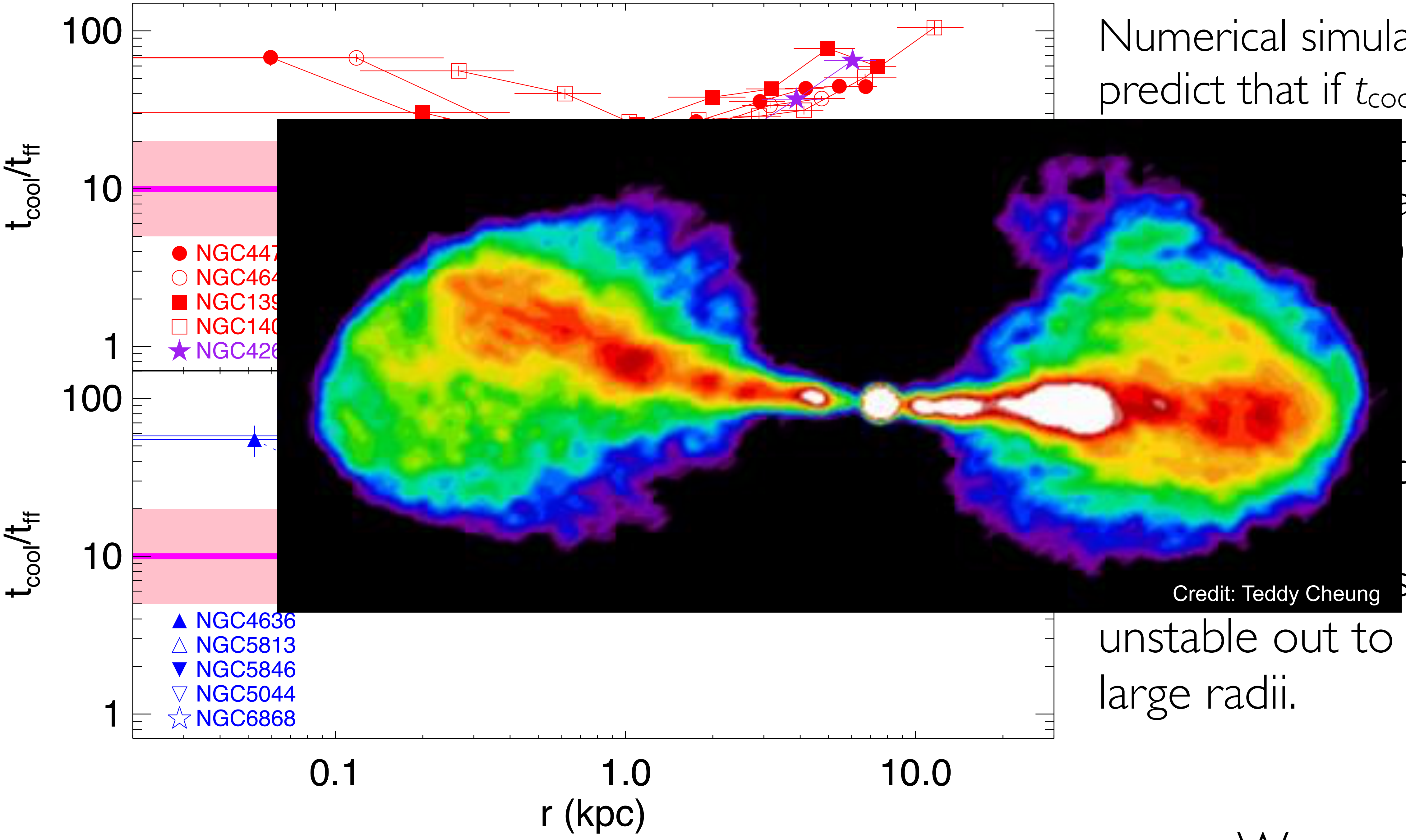

Credit: Teddy Cheung

Numerical simulations
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12, Gaspari
McCourt

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Werner et al. 2014
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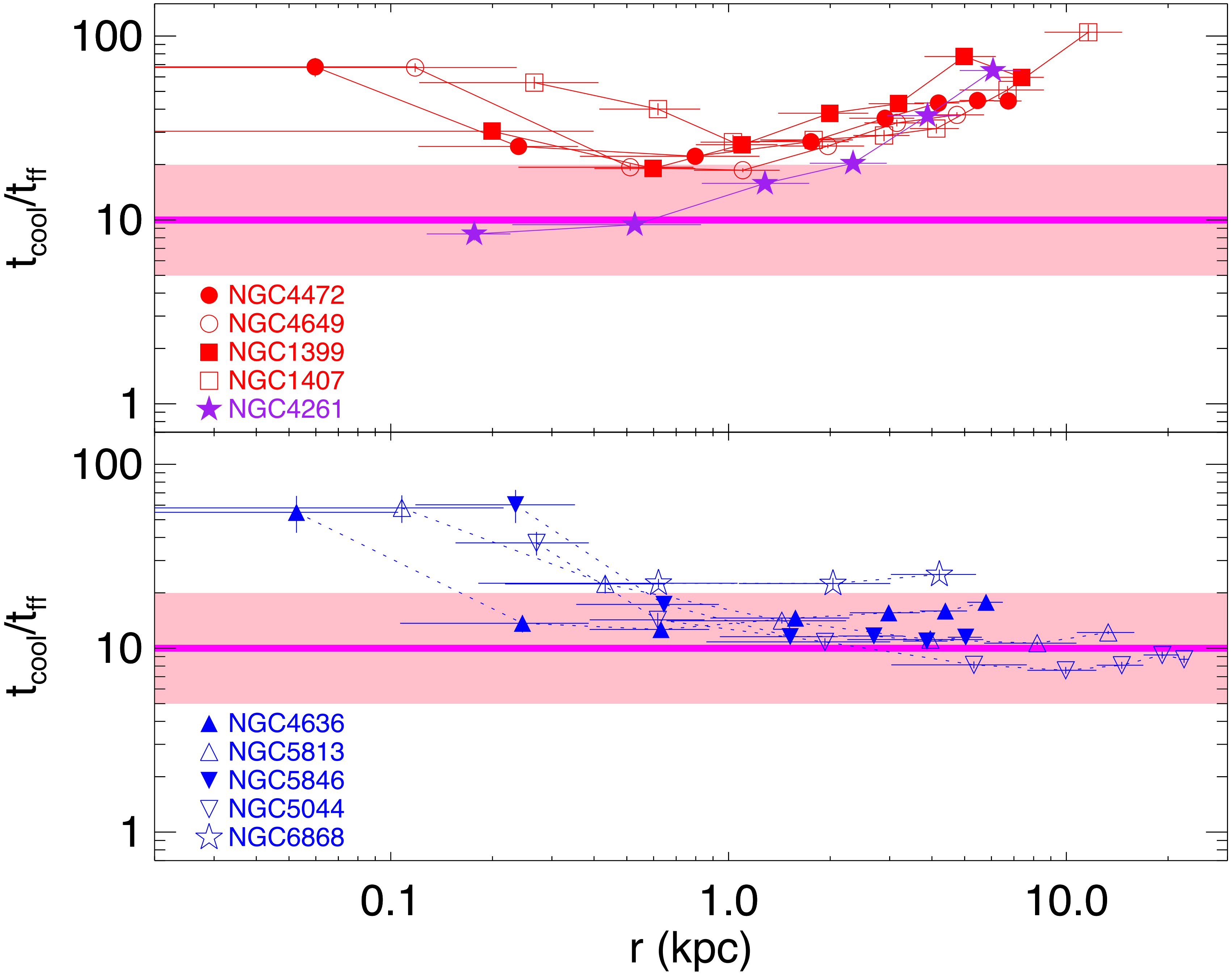

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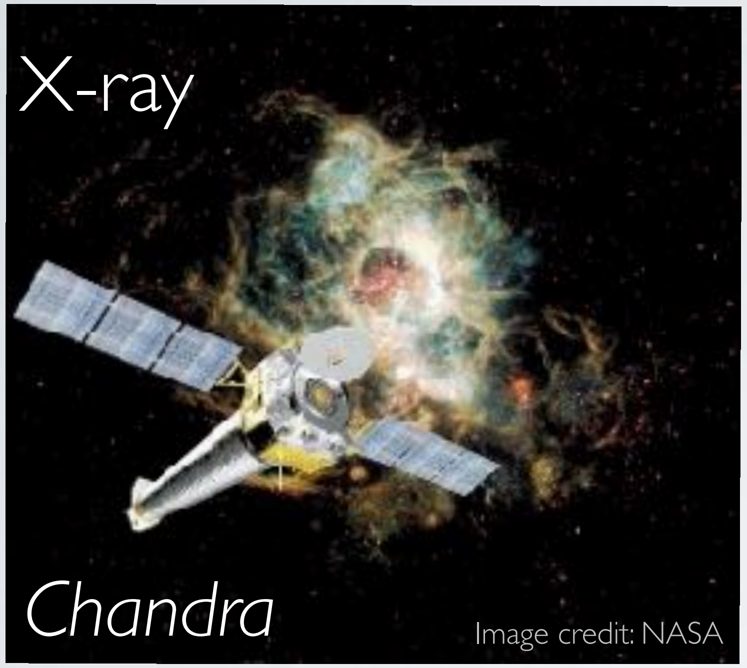
Werner et al. 2014
Voit et al. 2015

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


X-ray

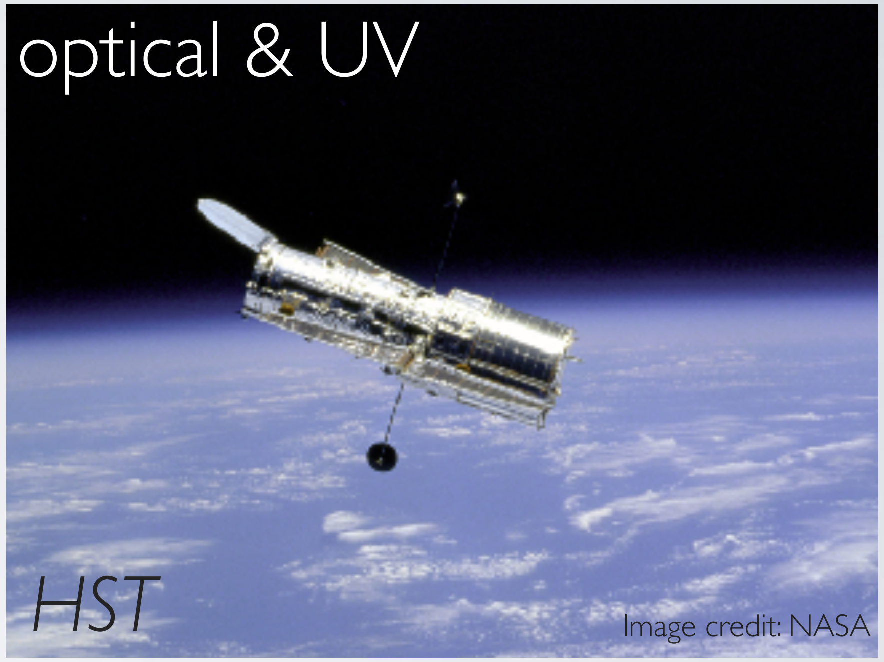
Chandra

Image credit: NASA


radio

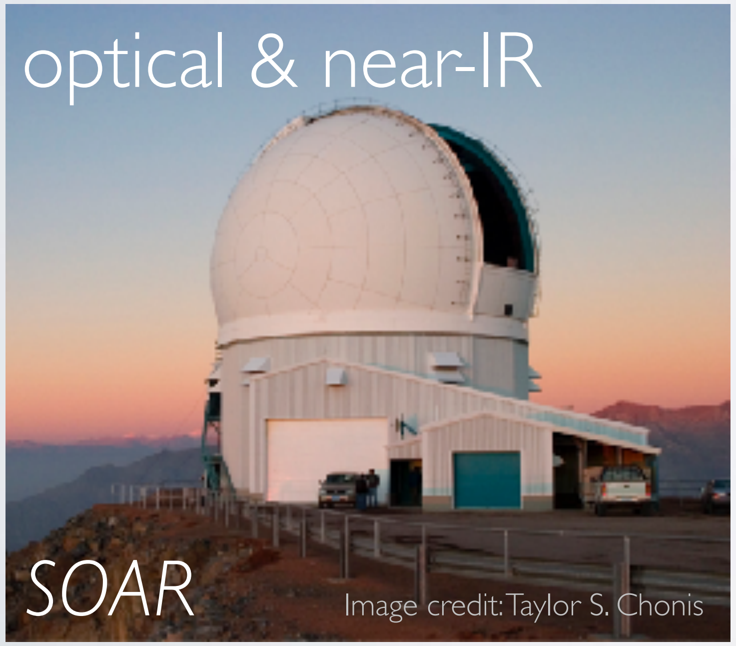
JVLA

Image credit: VLA/NRAO


optical & UV

HST

Image credit: NASA


optical & near-IR

SOAR

Image credit: Taylor S. Chonis


far infrared

SOFIA

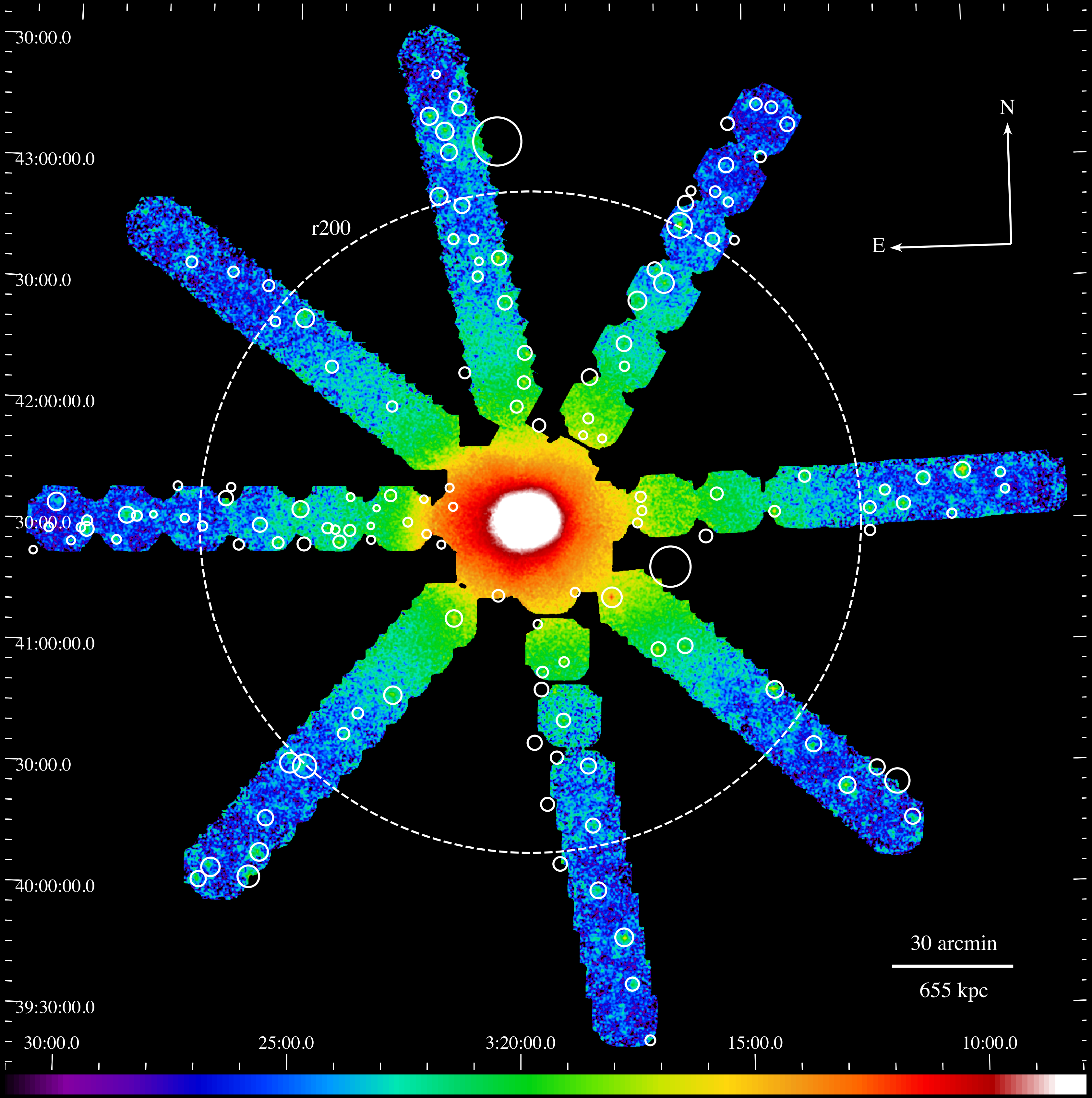
Image credit: NASA / Jim Ross


sub-mm

ALMA

Image credit: ESO/José Francisco Salgado

THE PERSEUS KEY PROJECT



85 Suzaku pointings

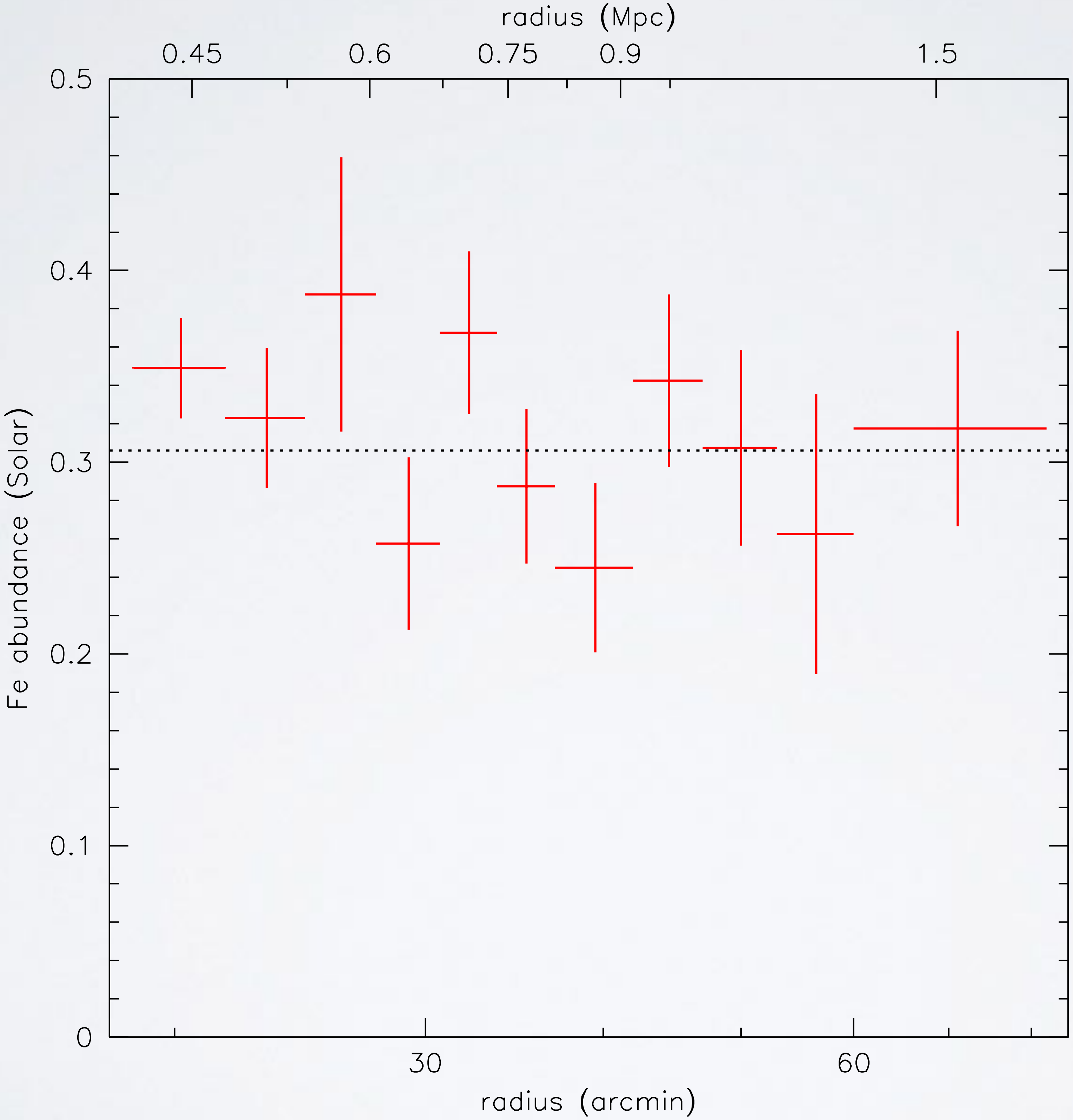
8 different directions

1Ms total exposure

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

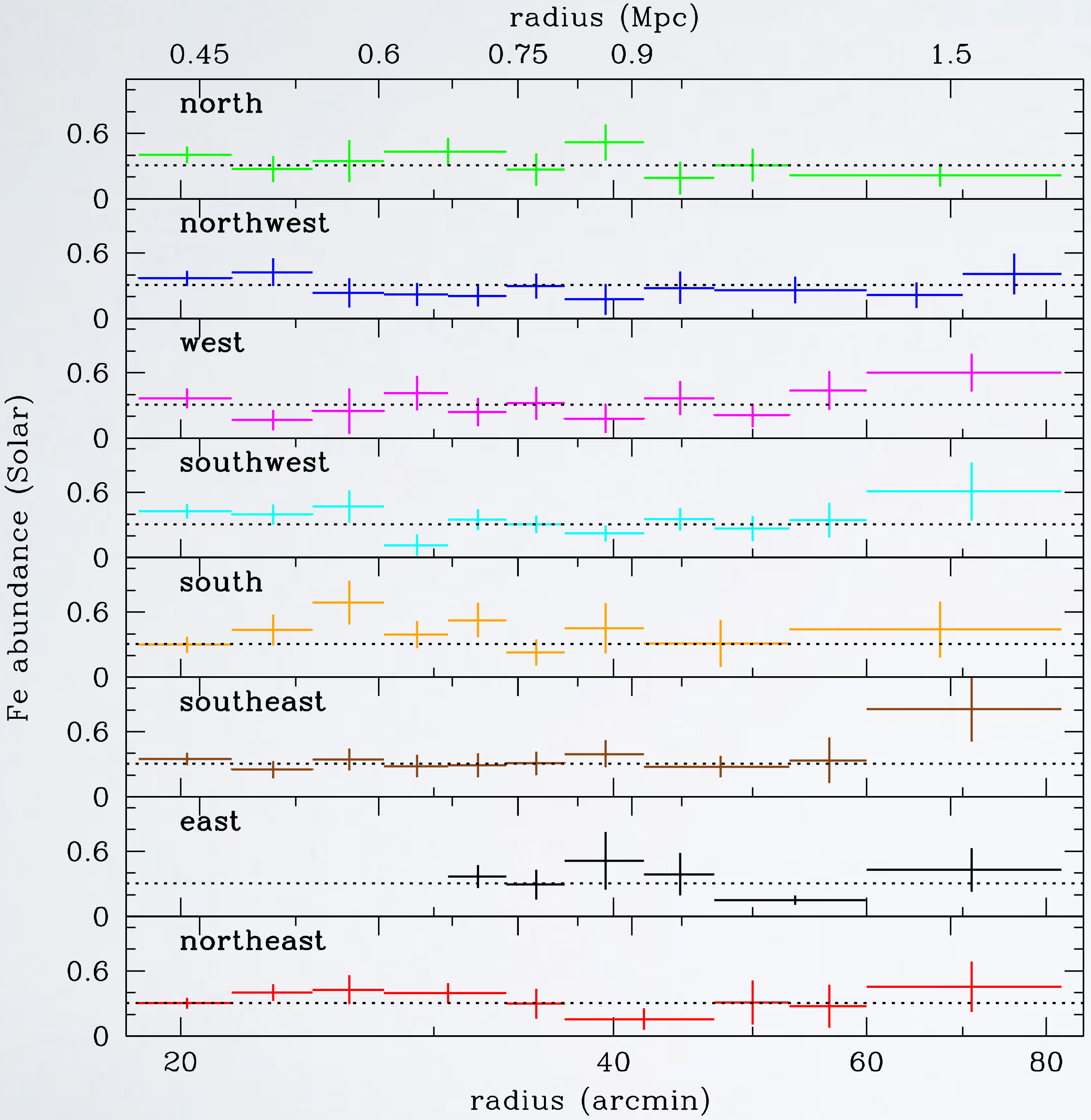
- **late enrichment:** decreasing metallicity as a function of radius
- **early enrichment**: constant metallicity as a function of radius and azimuth

METALLICITY PROFILE OF THE PERSEUS CLUSTER



Werner et al. 2013, *Nature*

IRON SPREAD SMOOTHLY THROUGHOUT THE PERSEUS CLUSTER

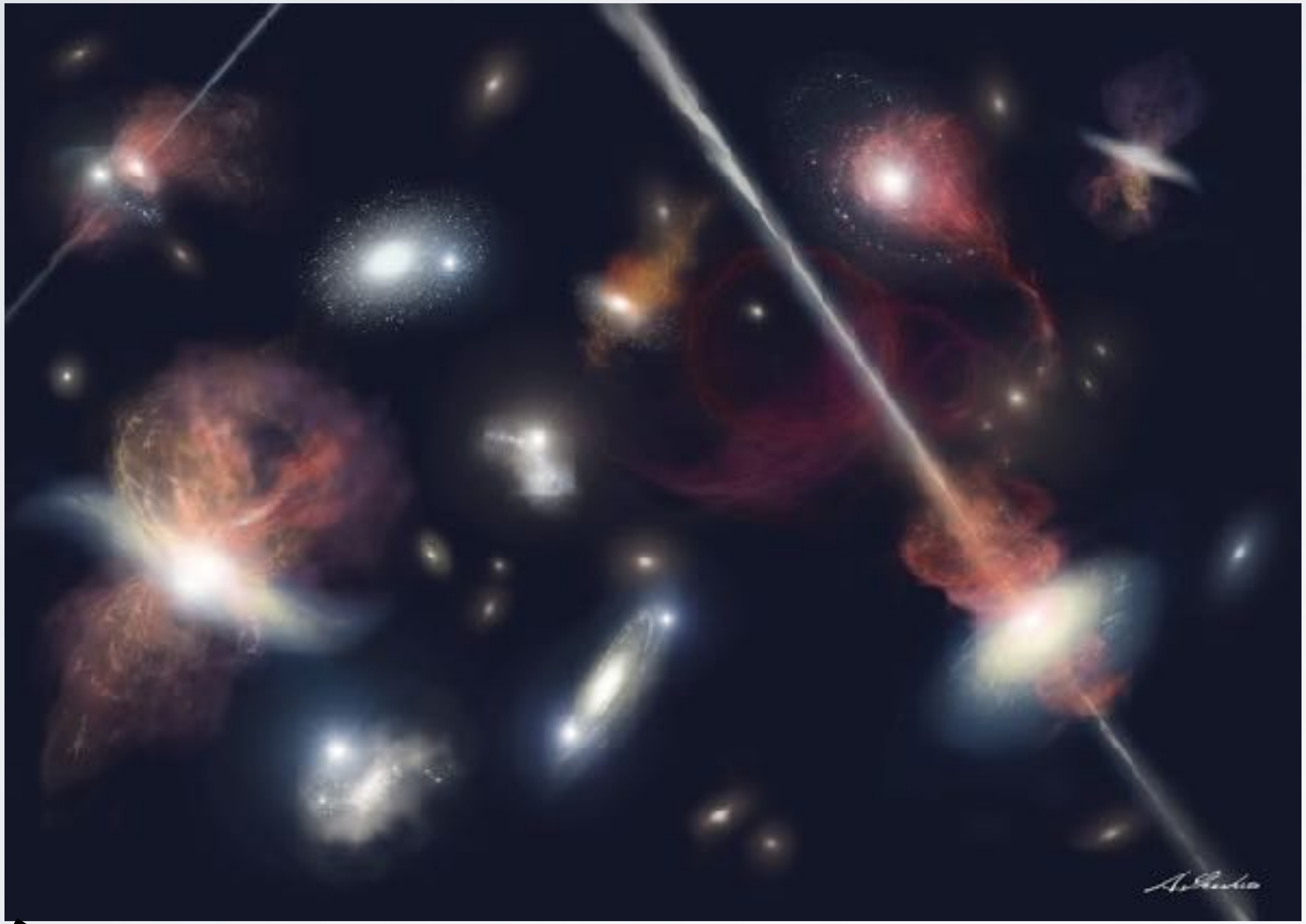


- 78 Fe abundance measurements across the cluster at different radii *and azimuths* show strikingly uniform distribution

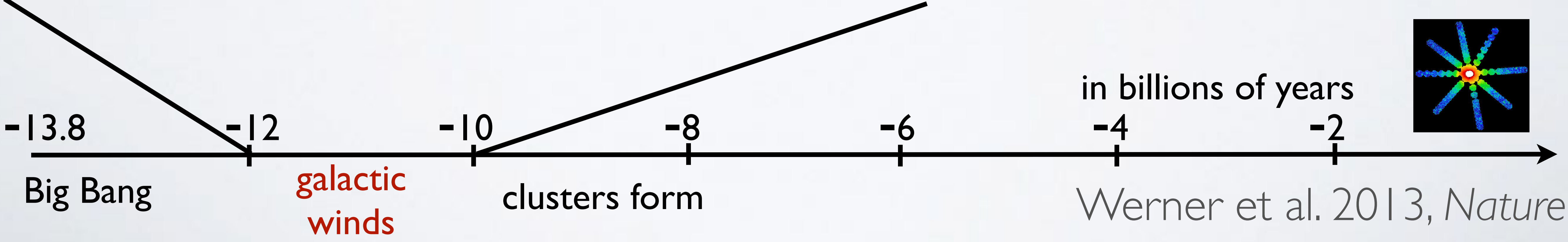
- the iron had to escape from the galaxies and get mixed into the intergalactic gas before the entropy profile became very steep, preventing efficient mixing

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*

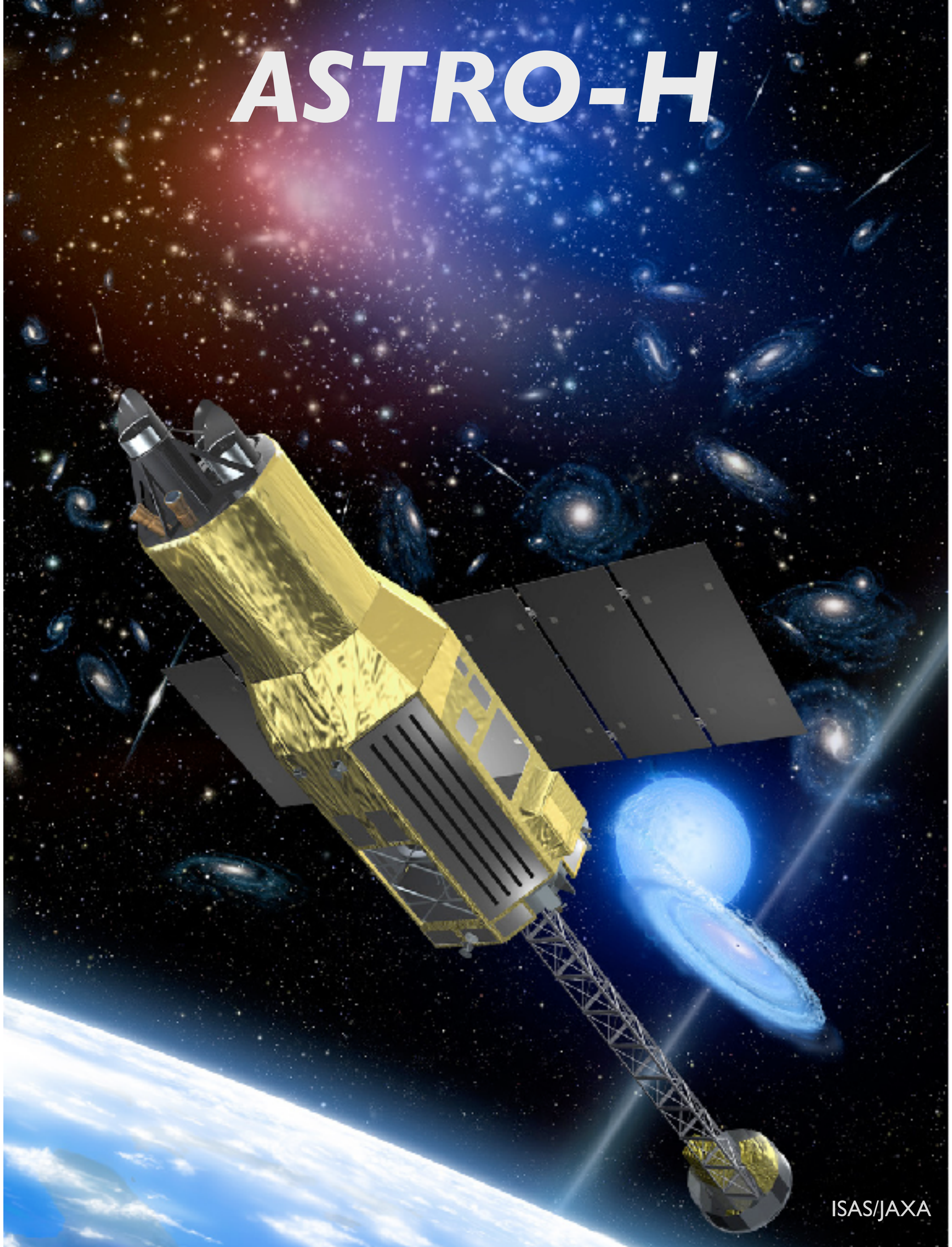
THE UNIVERSE IN A CUP

THE UNIVERSE IN A CUP

ASTRO-H

JAXA
Japan Aerospace Exploration Agency

with a contribution of other Japanese universities and institutes



ISAS/JAXA

NASA

esa

SRON

KIPAC

CSA ASC

with a contribution of other US/EU universities and institutes

JAXA
Japan Aerospace
Exploration Agency

with a
contribution of
other Japanese
universities and
institutes

NASA

esa

SRON

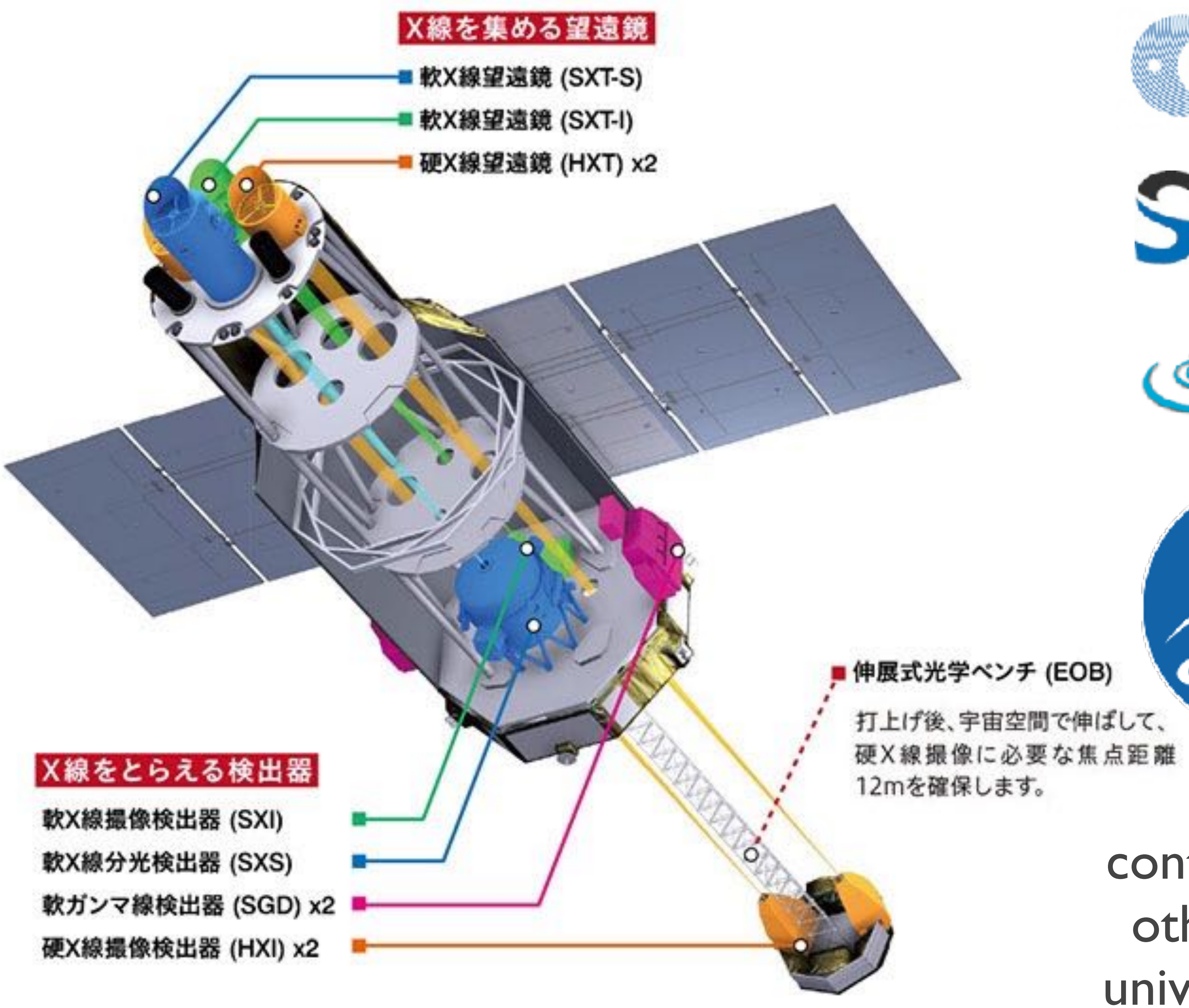
KIPAC

CSA ASC

with a
contribution of
other US/EU
universities and
institutes

ASTRO-H

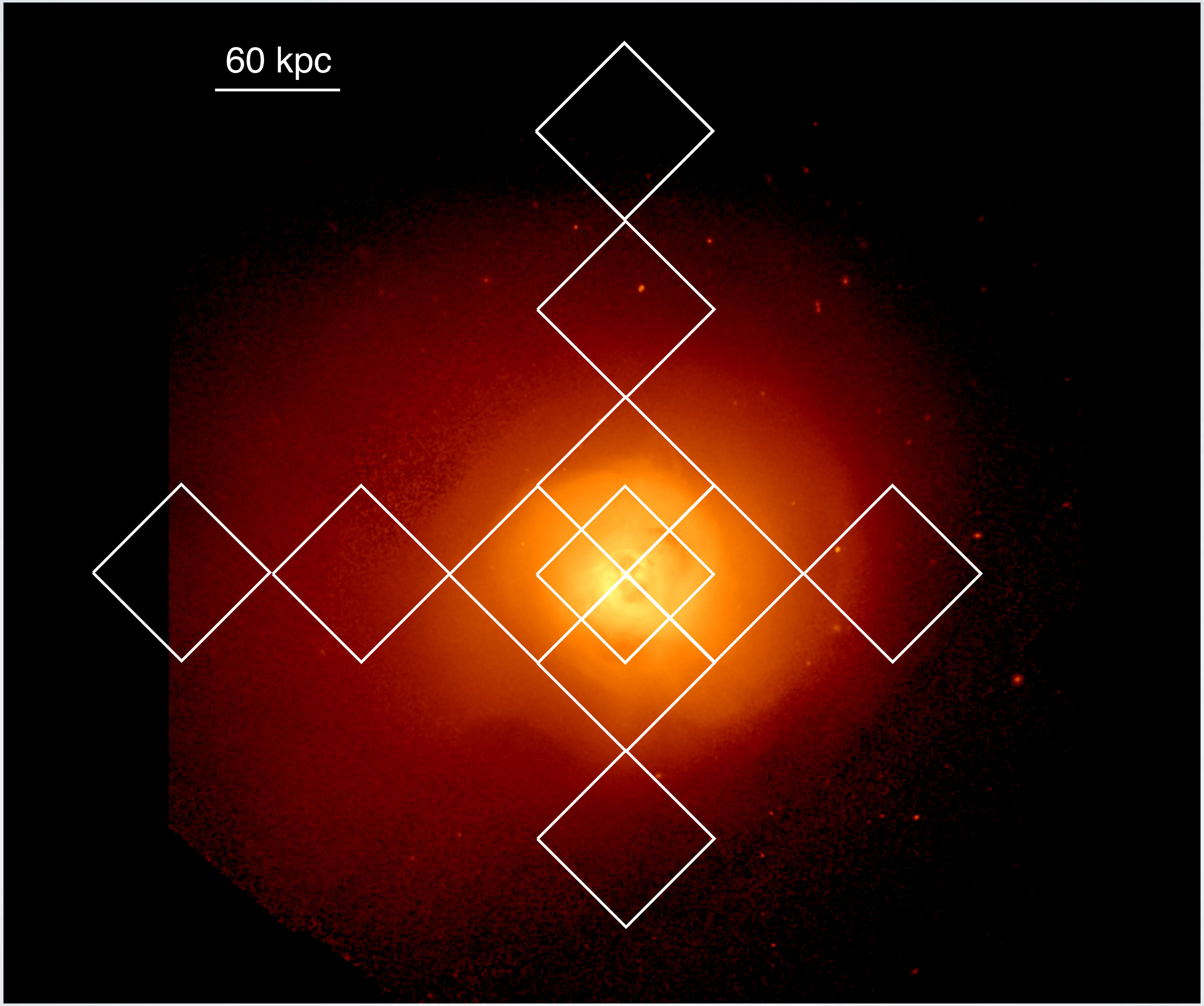
with a contribution of other Japanese universities and institutes



ISAS/JAXA

with a contribution of other US/EU universities and institutes

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



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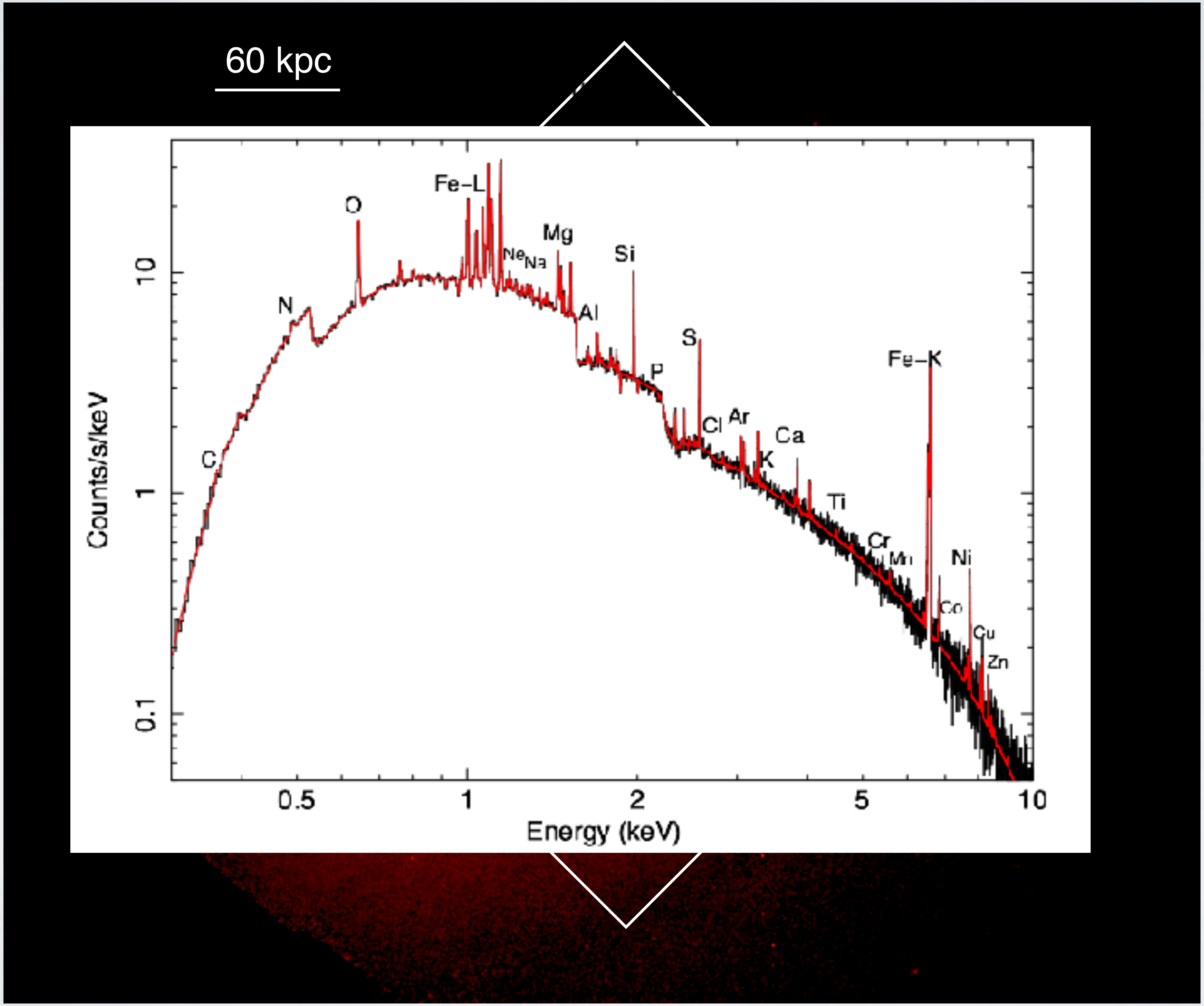

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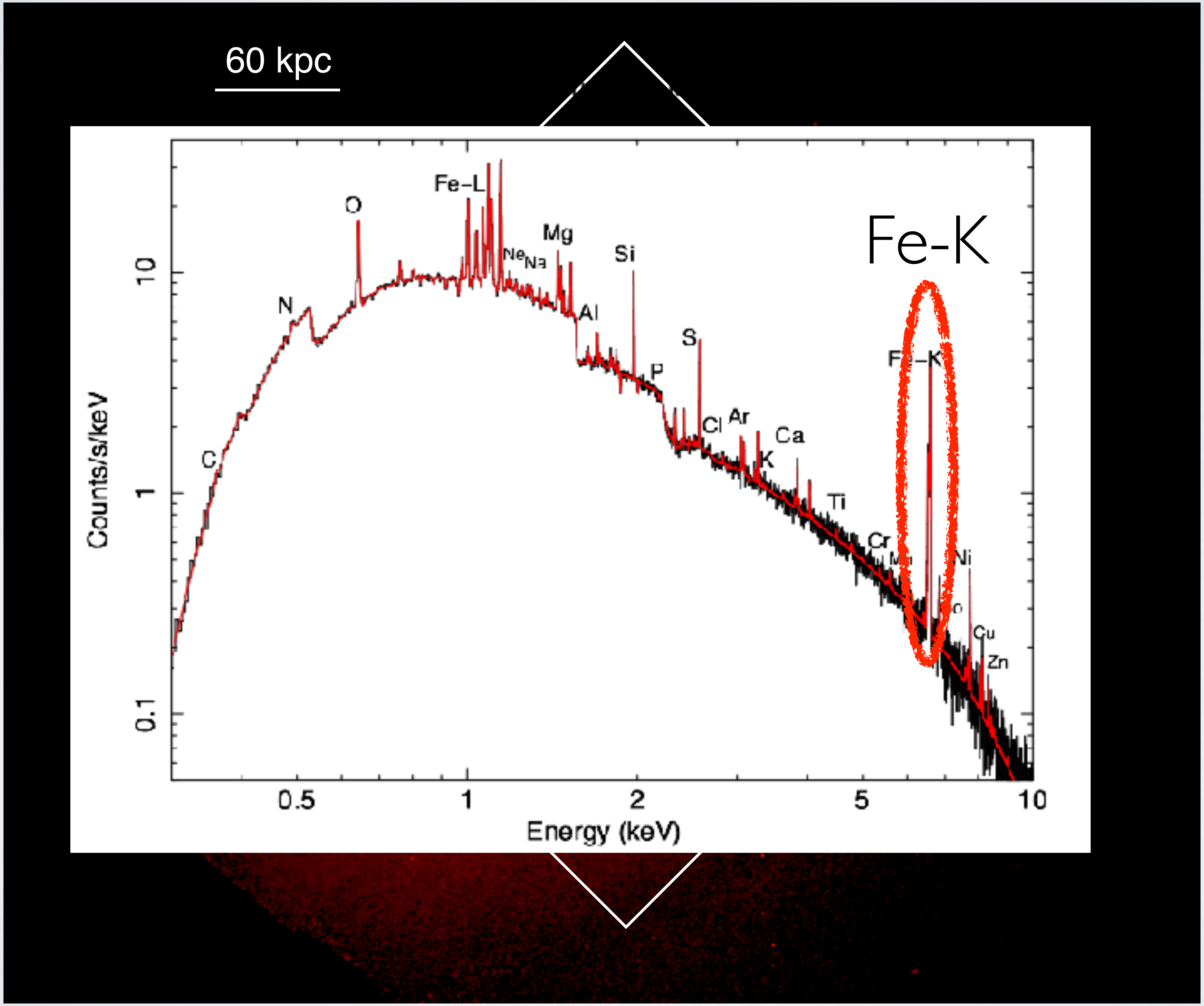
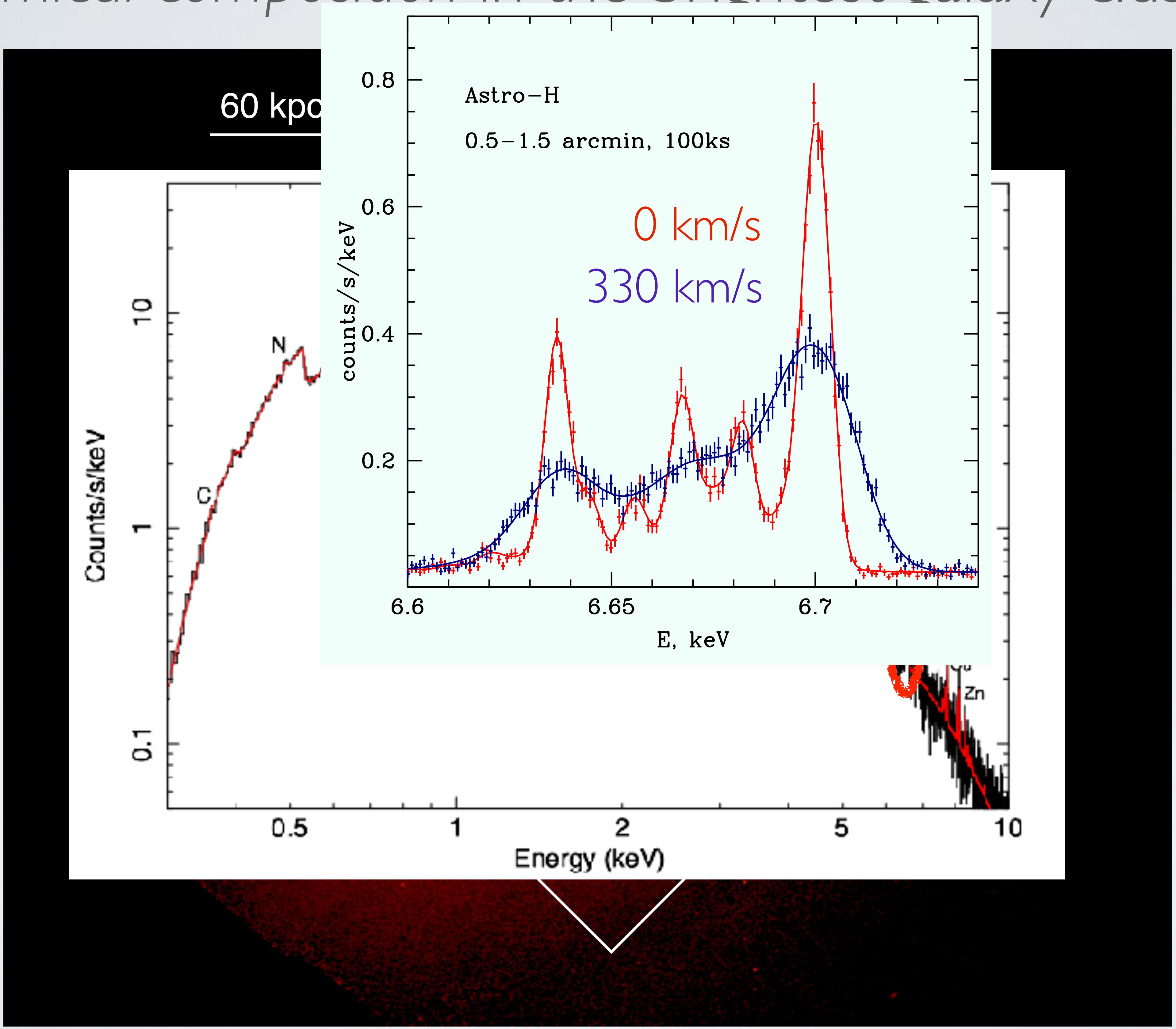
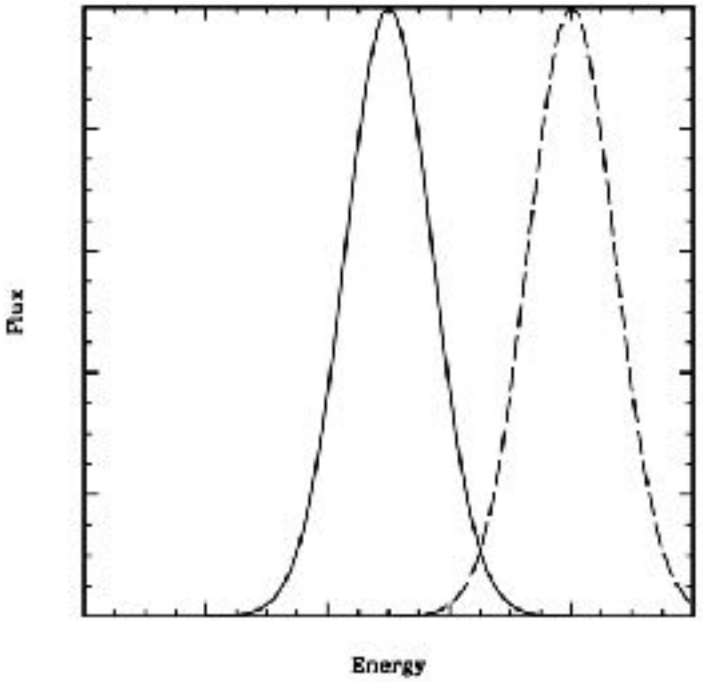


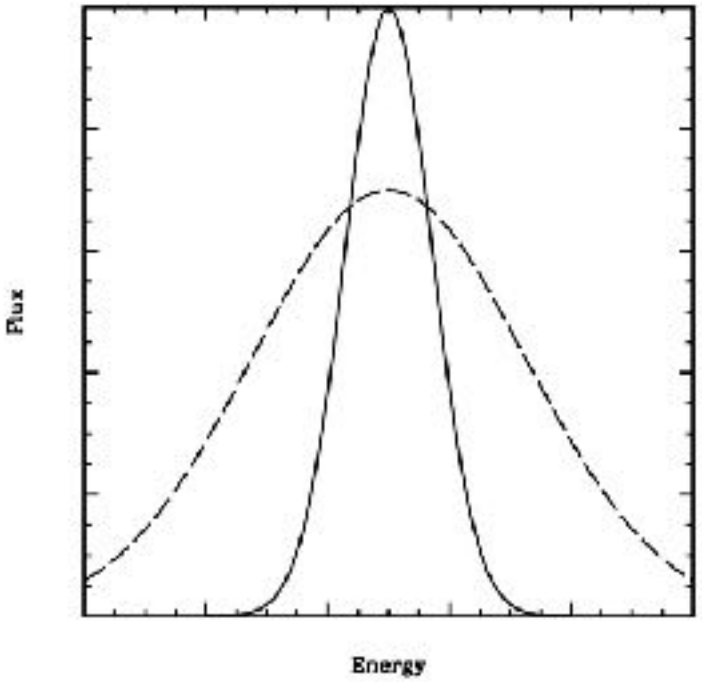
Determining gas *dynamics*, *thermodynamics* and *chemical composition* in the brightest galaxy cluster



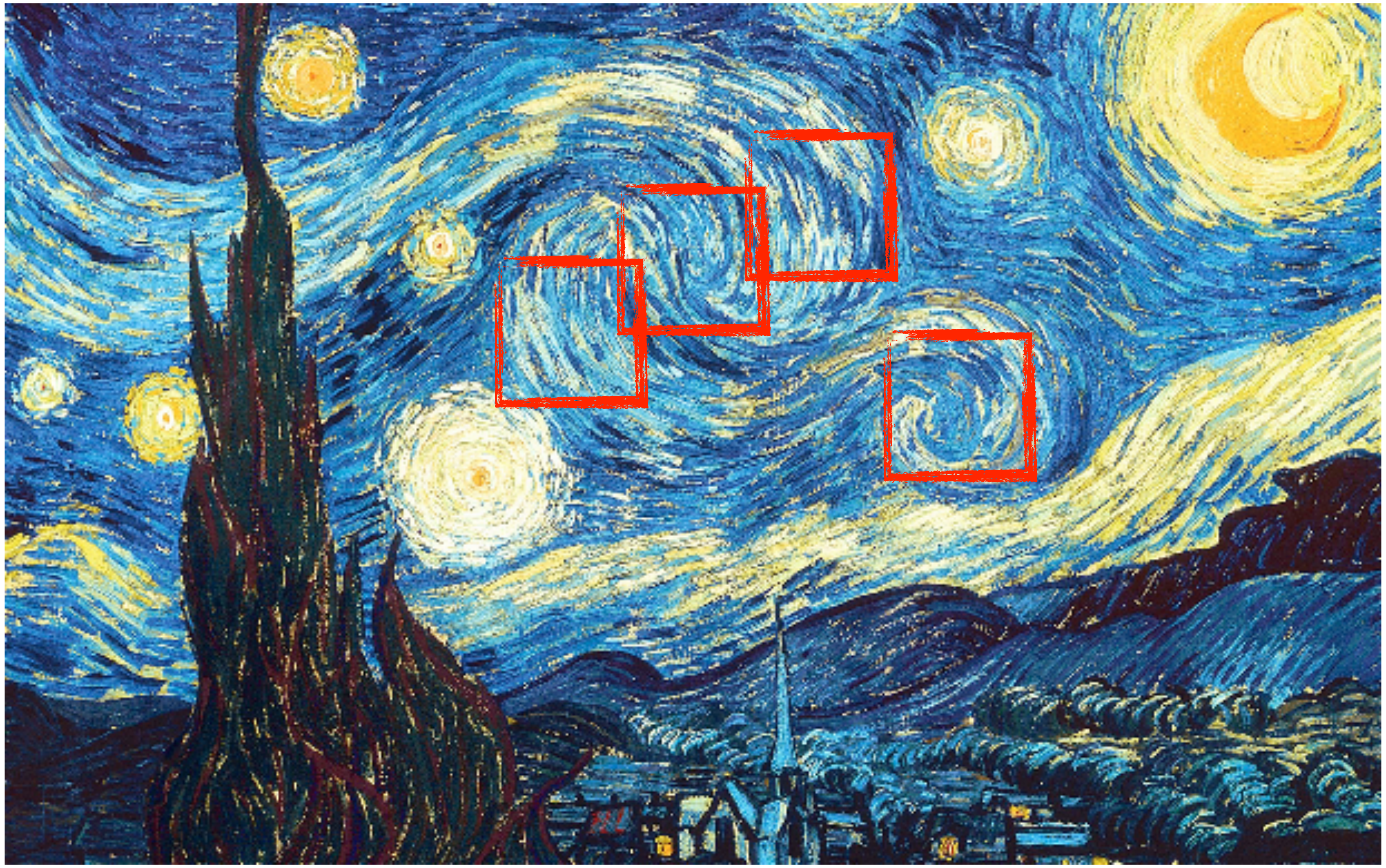
Turbulent and bulk motions



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



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



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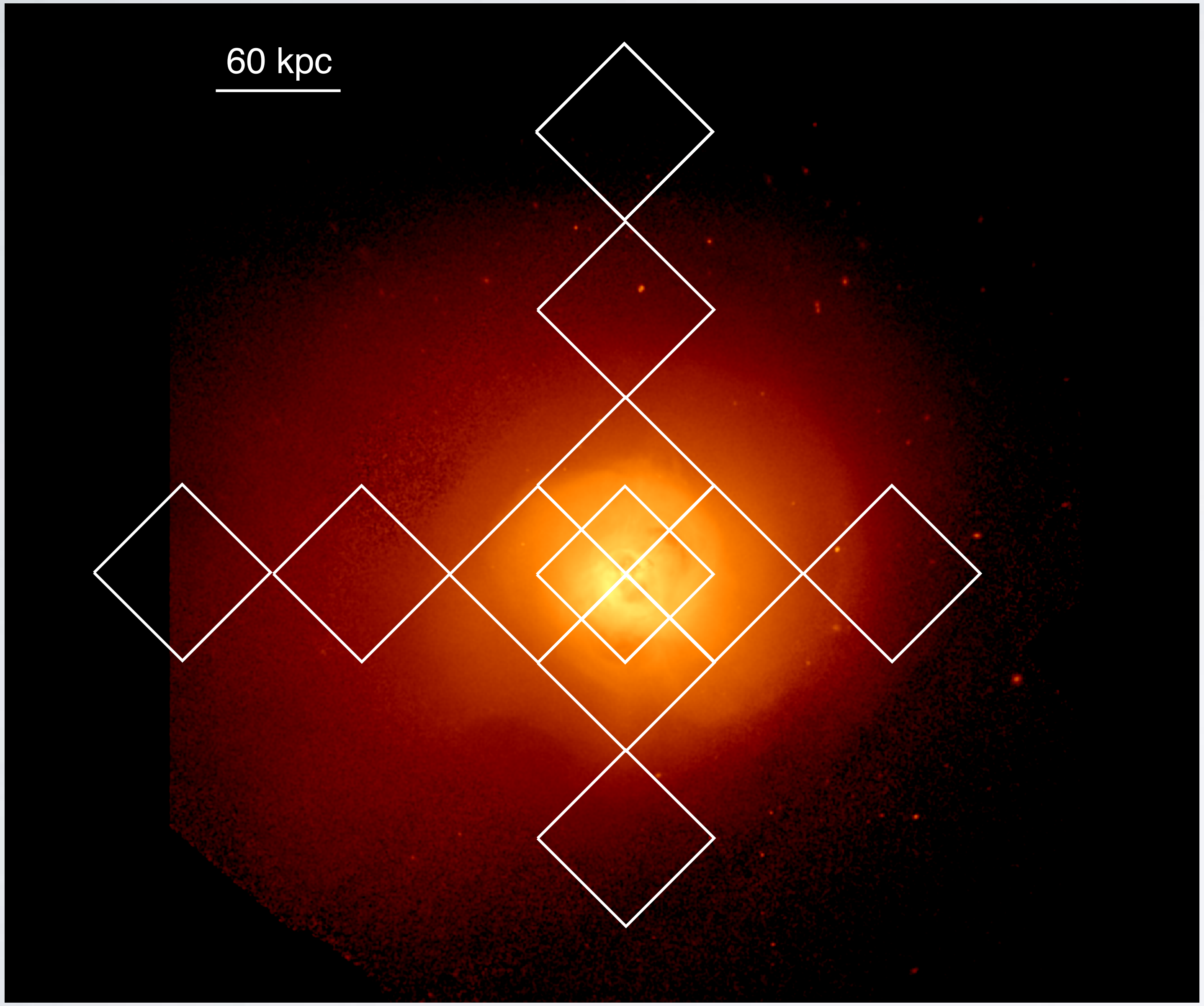
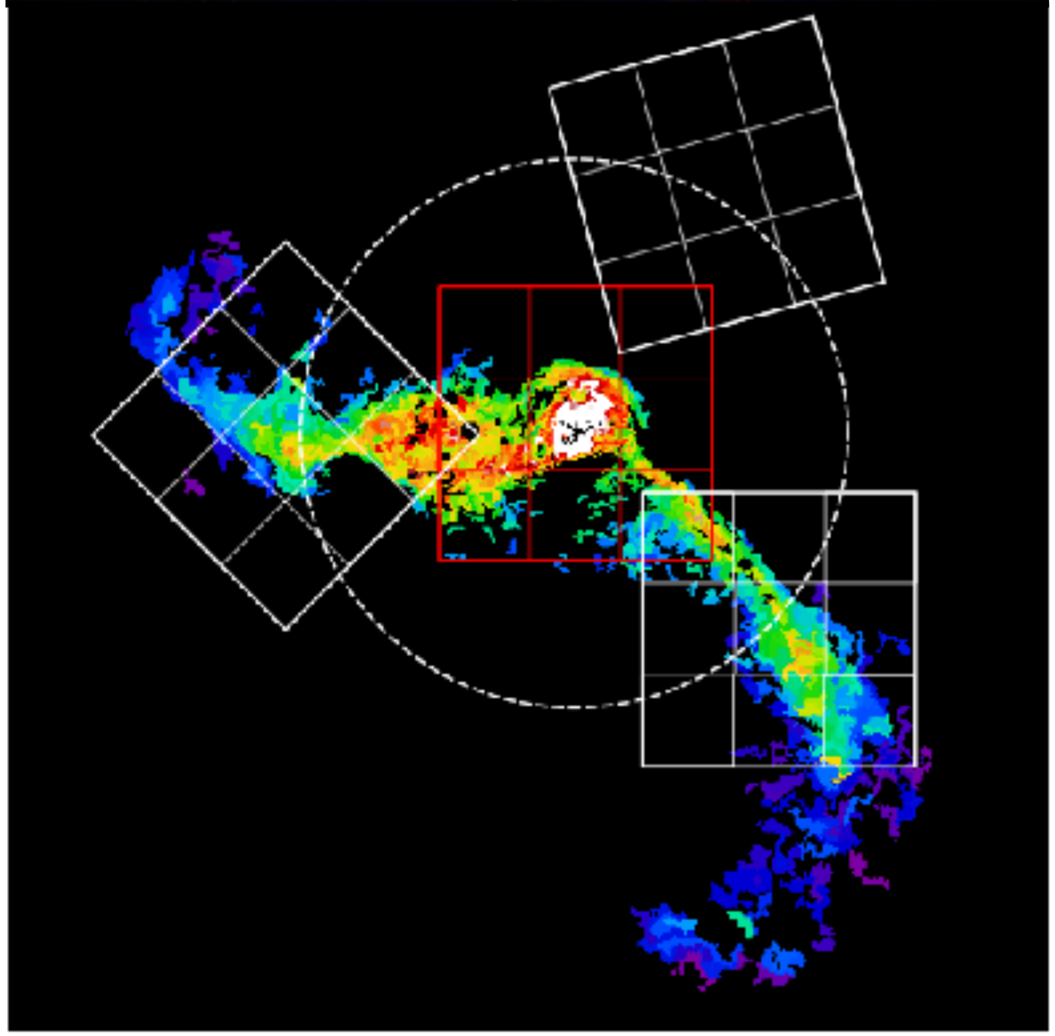
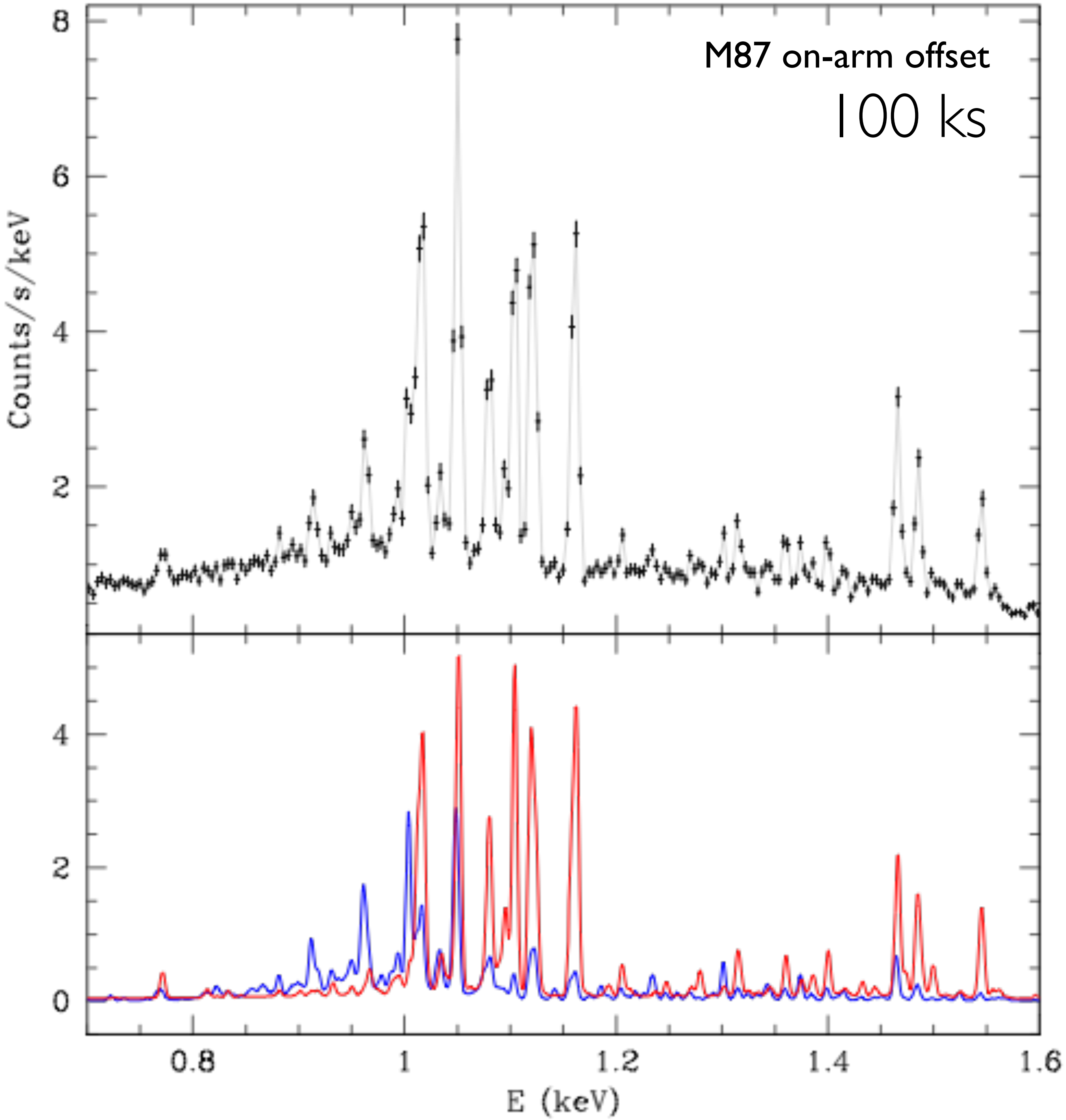


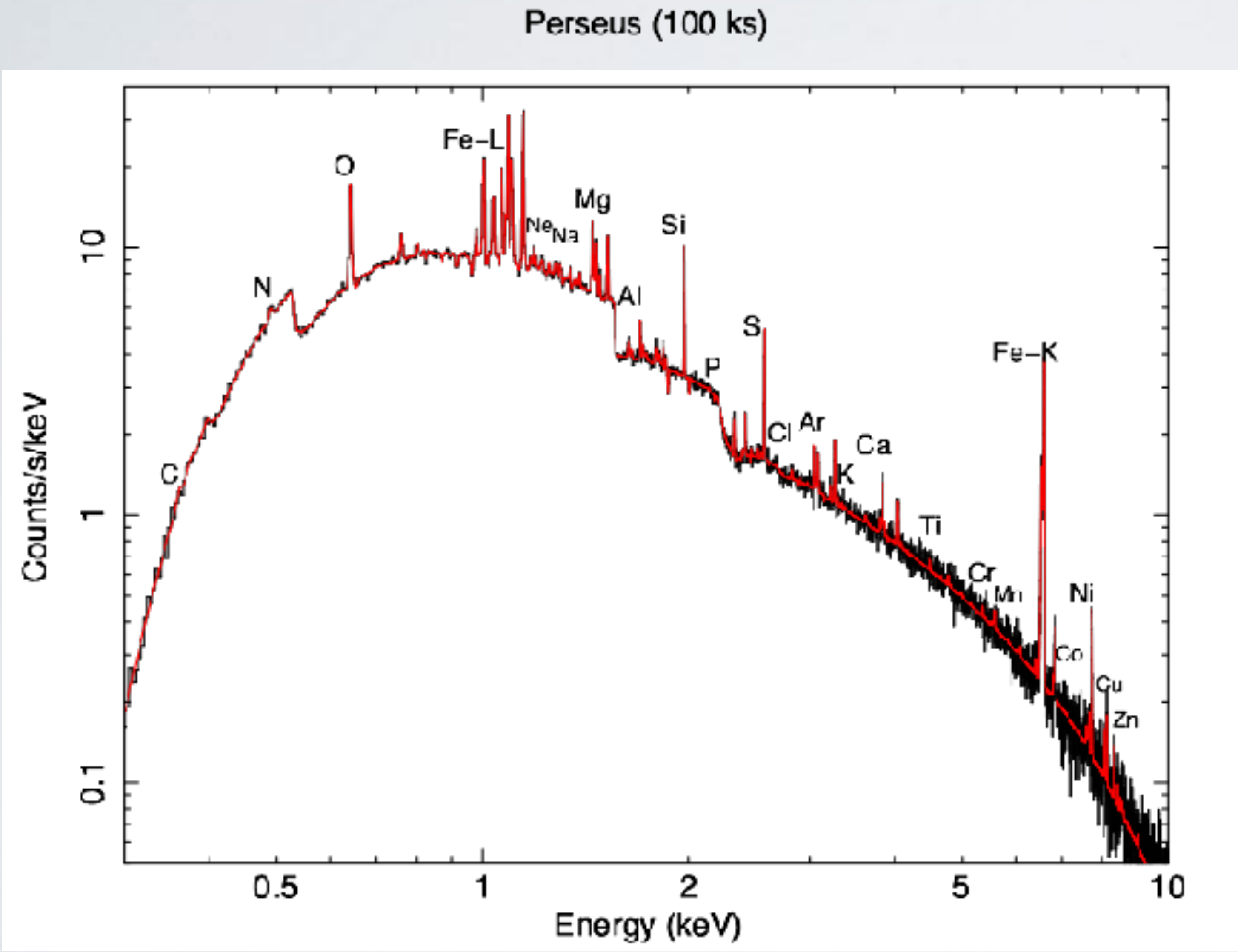
- measure the black hole driven gas motions
- characterize gas motions, including
  - how is turbulence driven?
  - how does it dissipate?
- measure the multi-temperature structure of the diffuse gas
- early focus on the brightest clusters, including Virgo, Coma
- 5 year program, guaranteed discovery with every observation



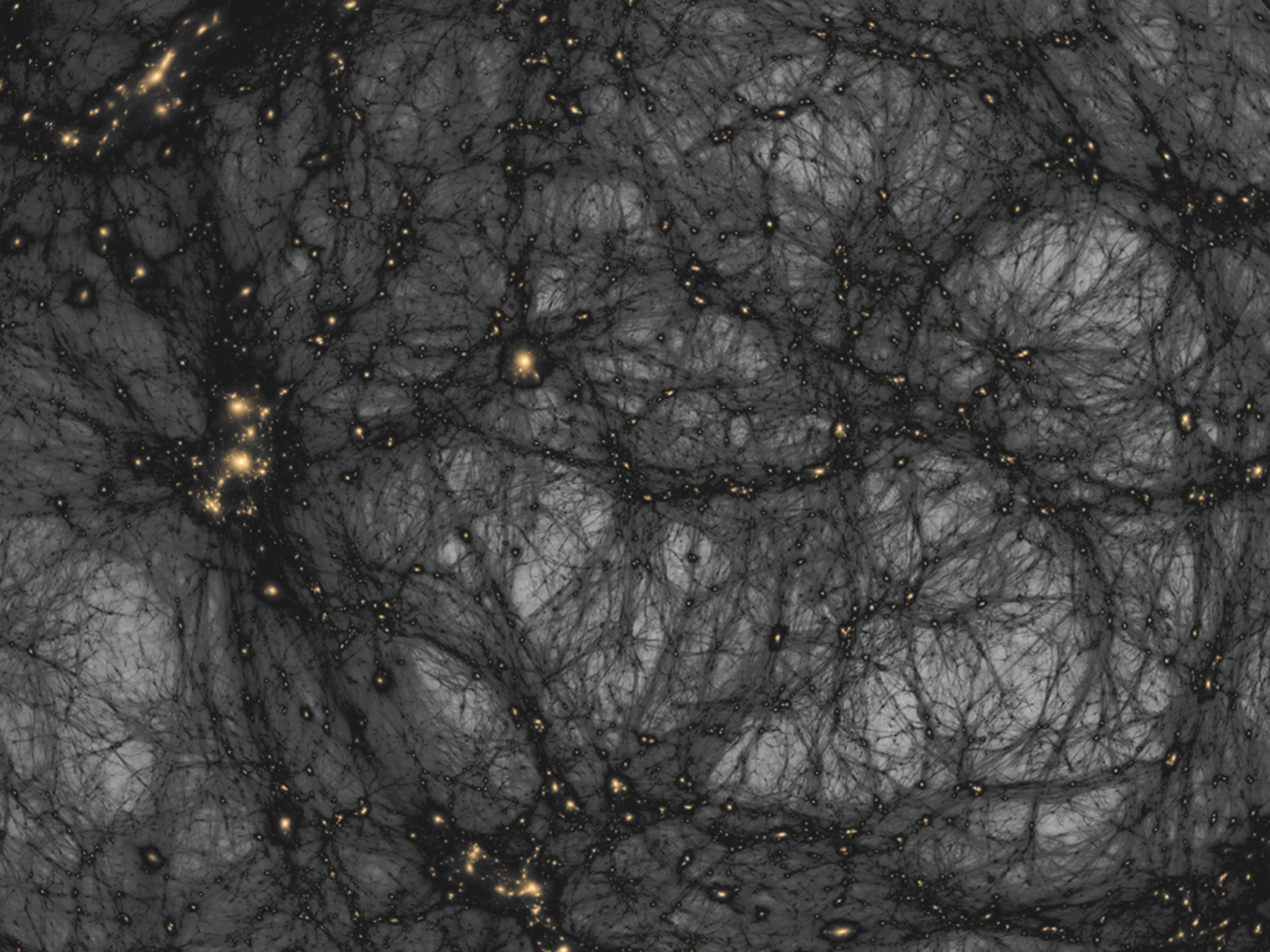
Astro-H SXS will be able to resolve line emission from the cool, uplifted gas (blue) and separate it from lines emitted by the surrounding ICM (red). We can spatially resolve the arms into several spaxels.



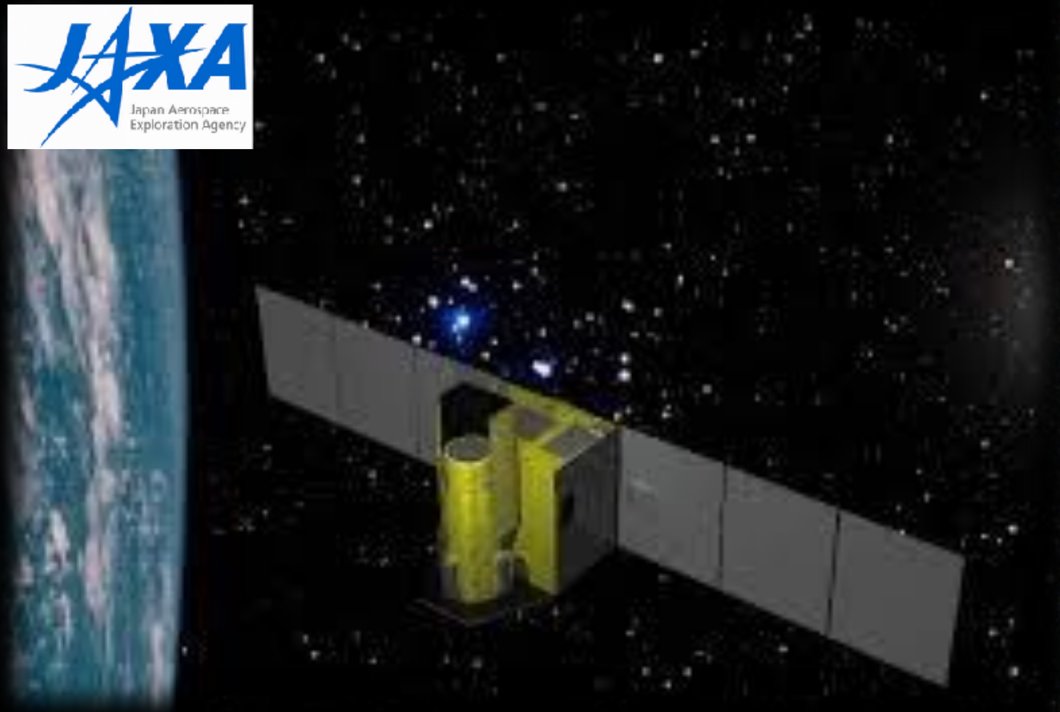
How did the star formation and chemical enrichment history of the Universe proceed?

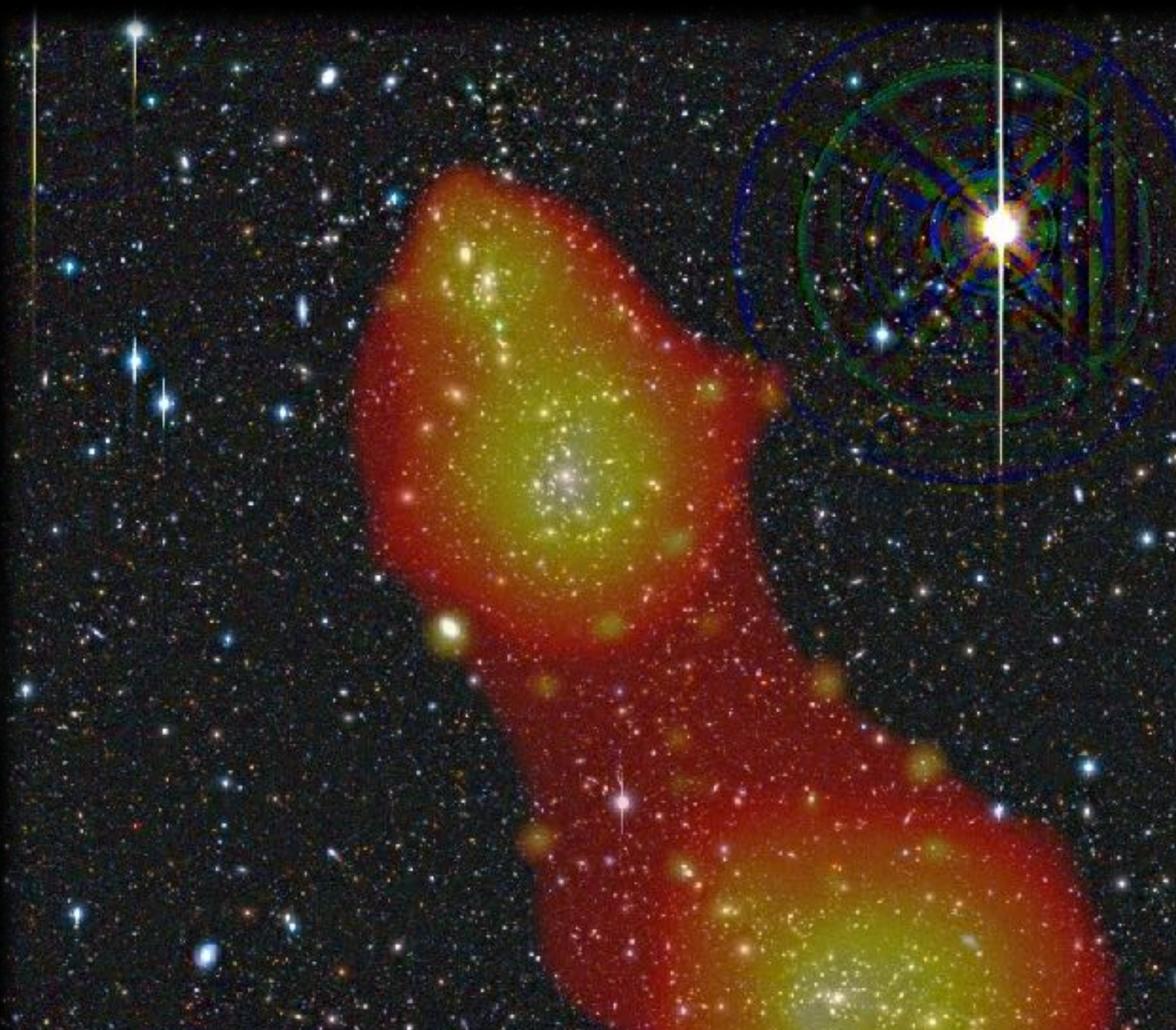


- galaxy clusters retain all the metals synthesized in constituent stars
- most metals reside in the diffuse gas
- X-ray spectroscopy of clusters - one of best tools for studying the chemical evolution of the Universe
- will constrain Type Ia supernova explosion models and the integrated stellar initial mass-function



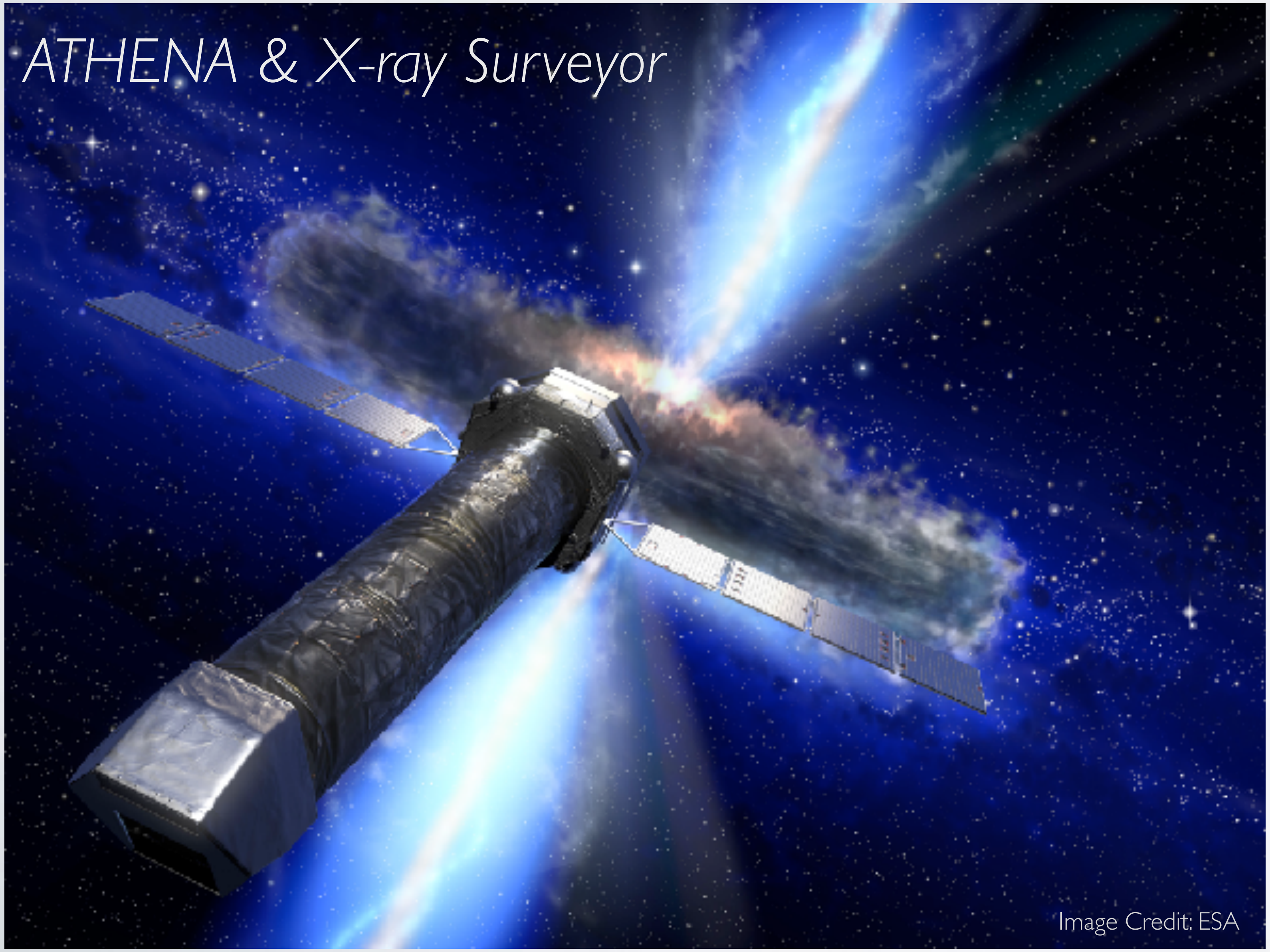
Extension to the unvirialized warm-hot intergalactic medium





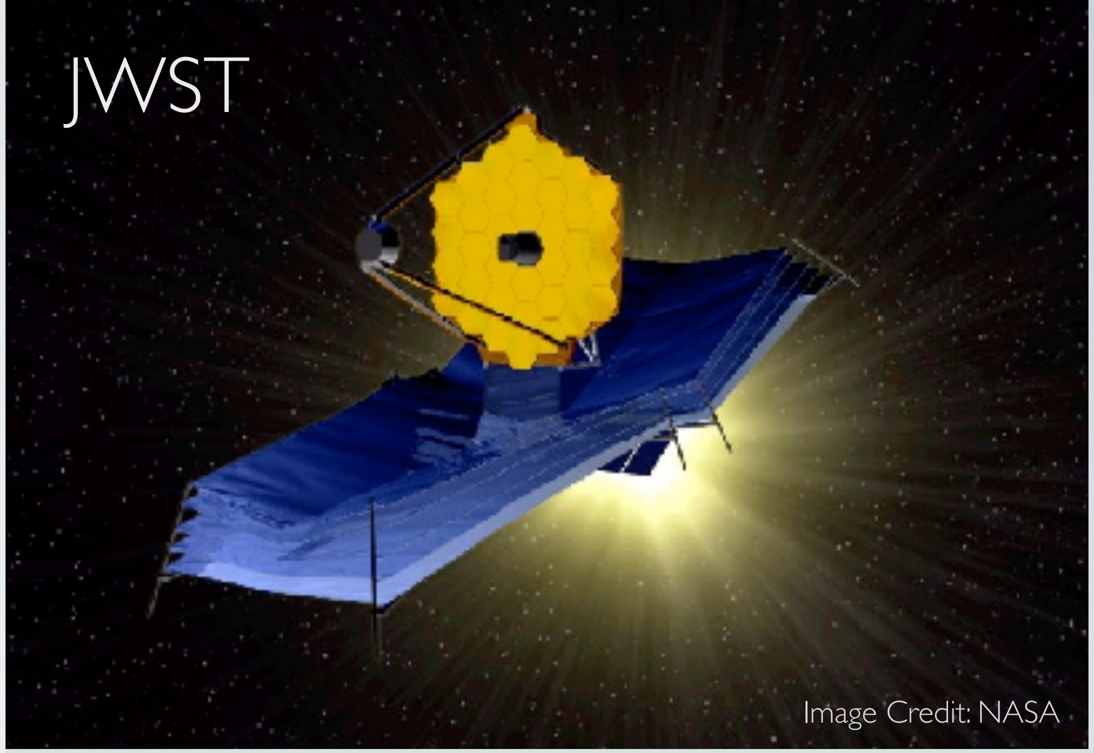
Ground-breaking science in the next decade

Extension into the high-redshift Universe



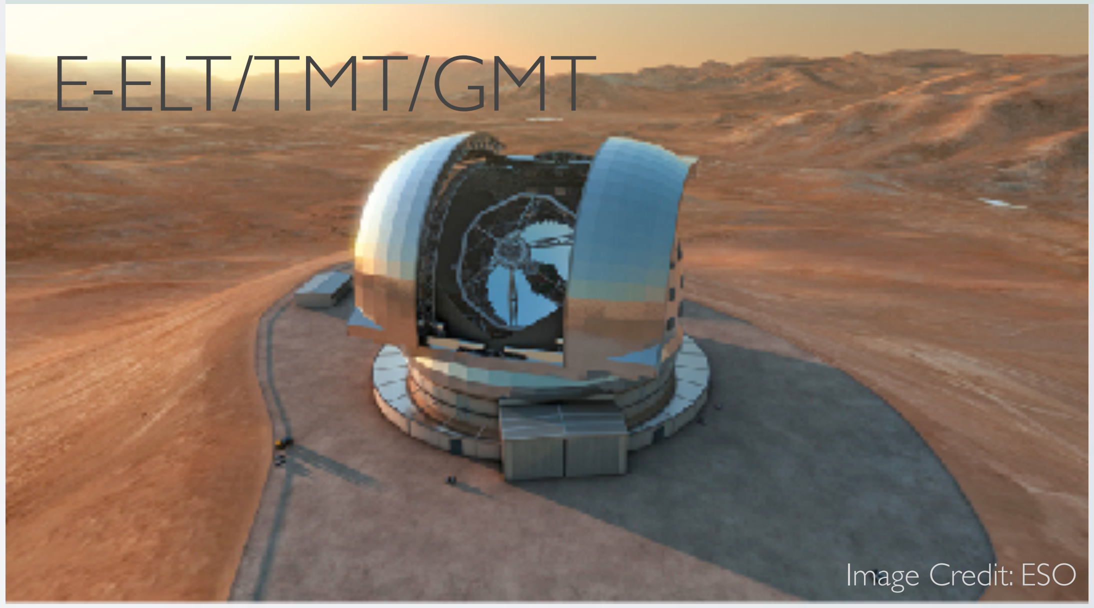
ATHENA & X-ray Surveyor

Image Credit: ESA



JWST

Image Credit: NASA



E-ELT/TMT/GMT

Image Credit: ESO

ALMA

Image Credit: ESO/C. Malin

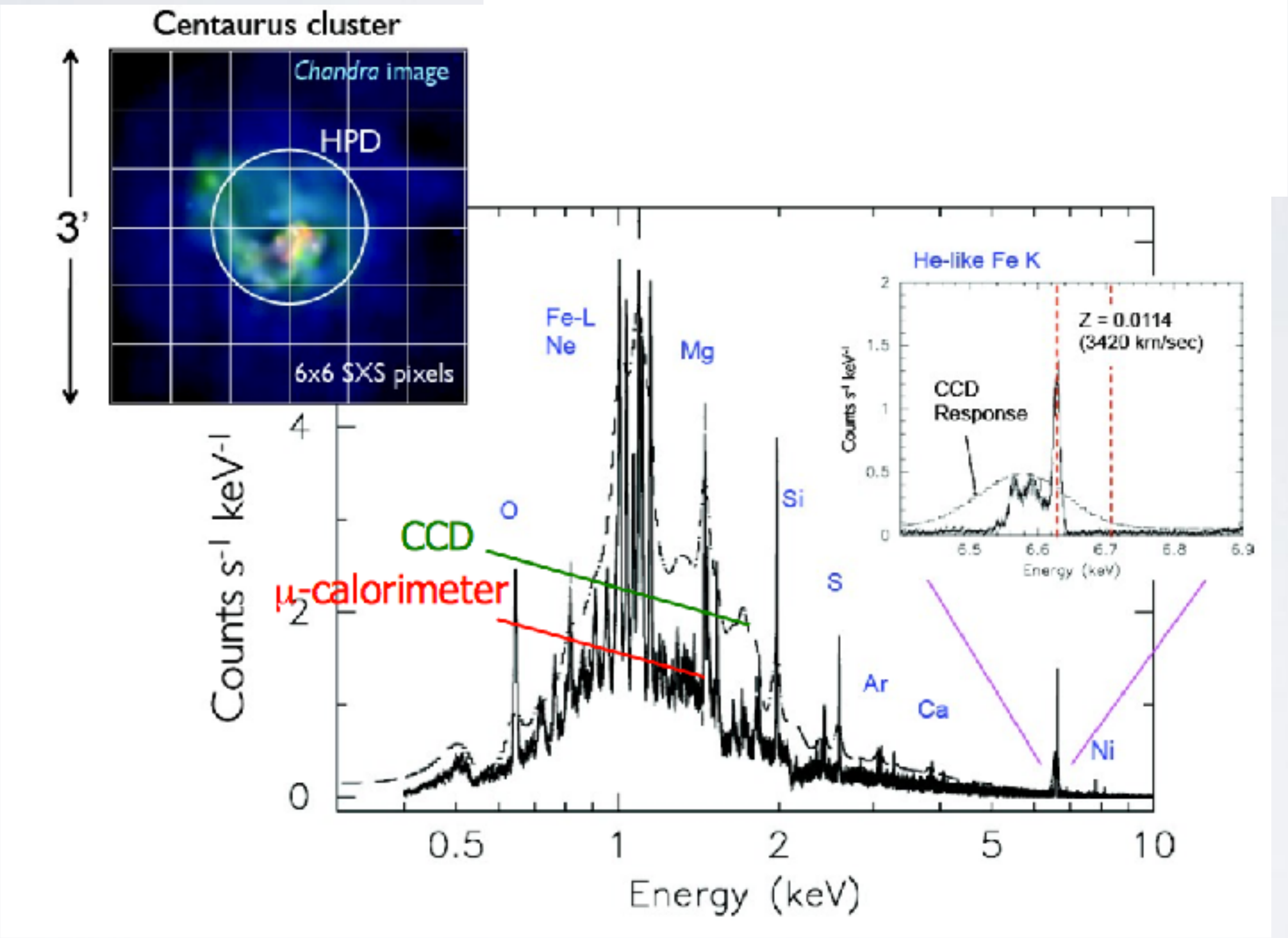
Relation of the entropy density $s = S/V$ to the entropy index K_e used by X-ray astrophysicists

$$K_e = k_B T n_e^{-2/3}$$

$$s = nk\,(3/2 \ln[\mu K_e] + 73.6)$$

$$K_e = \mu^{-1}\,\mathrm{Exp}[2/3\; s/nk - 49.1]$$

$P = K$ \rho$^{5/3}$


Centaurus cluster
Chandra image
HPD
3'
6x6 SXS pixels
Counts s⁻¹ keV⁻¹
4
2
0
0.5
1
2
5
10
Energy (keV)
O
Fe-L
Ne
Mg
Si
S
Ar
Ca
Ni
CCD
μ-calorimeter
He-like Fe K
Z = 0.0114
(3420 km/sec)
CCD
Response
Counts s⁻¹ keV⁻¹
0
0.5
1
1.5
2
6.5
6.6
6.7
6.8
6.9
Energy (keV)

Turbulent dissipation in AGN feedback

Possible channeling mechanisms:

shocks, sound waves (Randall et al. 11; Fabian et al. 06)
turbulent dissipation (Fukita et al. 04; Banerjee et al 14)
turbulent mixing (Kim & Narayan 03)
cosmic rays (Chandran & Dennis 06; Pfrommer et al. 13)
radiative heating (Ciotti & Ostriker 01; Nulsen & Fabian 00)
etc.

Turbulent dissipation in AGN feedback

rms velocity

Kolmogorov
constant

$$Q_{turb} = C_K \rho \frac{V^3}{l}$$

on outer scale

gas mass
density

dominant
length scale

Dennis & Chandran 2005

l is difficult to determine or even define:

several characteristic scales are present

Turbulent dissipation in AGN feedback

$$Q_{turb} = C_K \rho \frac{V^3}{l}$$

on outer scale

Dennis et al. 2005

For Kolmogorov turbulence:

$$E(k) = K_0 \left(\frac{Q_{turb}}{\rho} \right)^{2/3} k^{-5/3}$$

energy spectrum of turbulence

Kolmogorov constant

e.g. Sreenivasan et al. 95, Kaneda et al. 03

we measure E(k) ⇒ can find Q_{turb}

cooling rate:

$$C = n_e n_i \Lambda_n(T)$$

heating rate:

$$H(k) = C_H \rho V_{1,k}^3 k$$