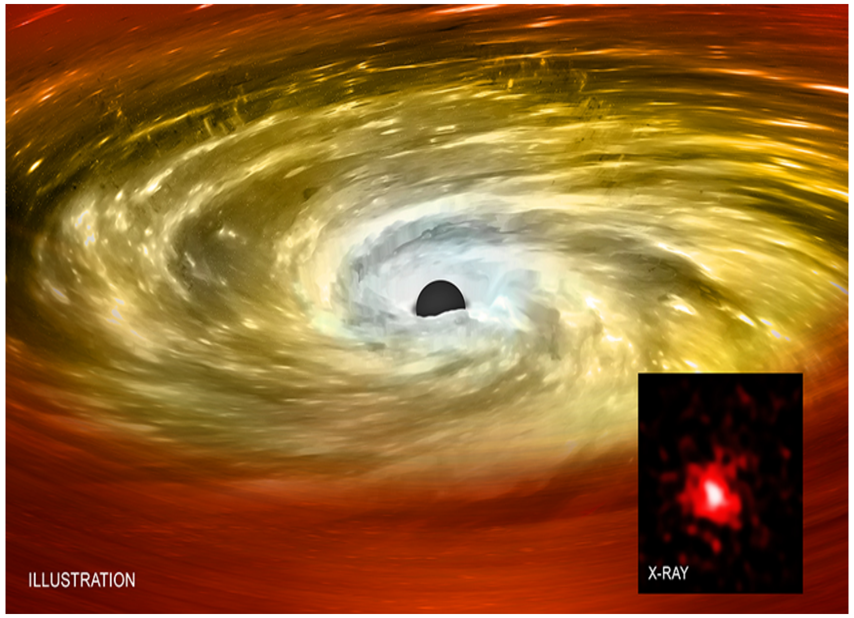
Hot Atmospheres and AGN Feedback in Early Type Galaxies




Norbert Werner
MTA-Eötvös University/Masaryk University

My team:
MTA-ELTE Lendület Hot Universe Research Group

Postdoctoral researchers:

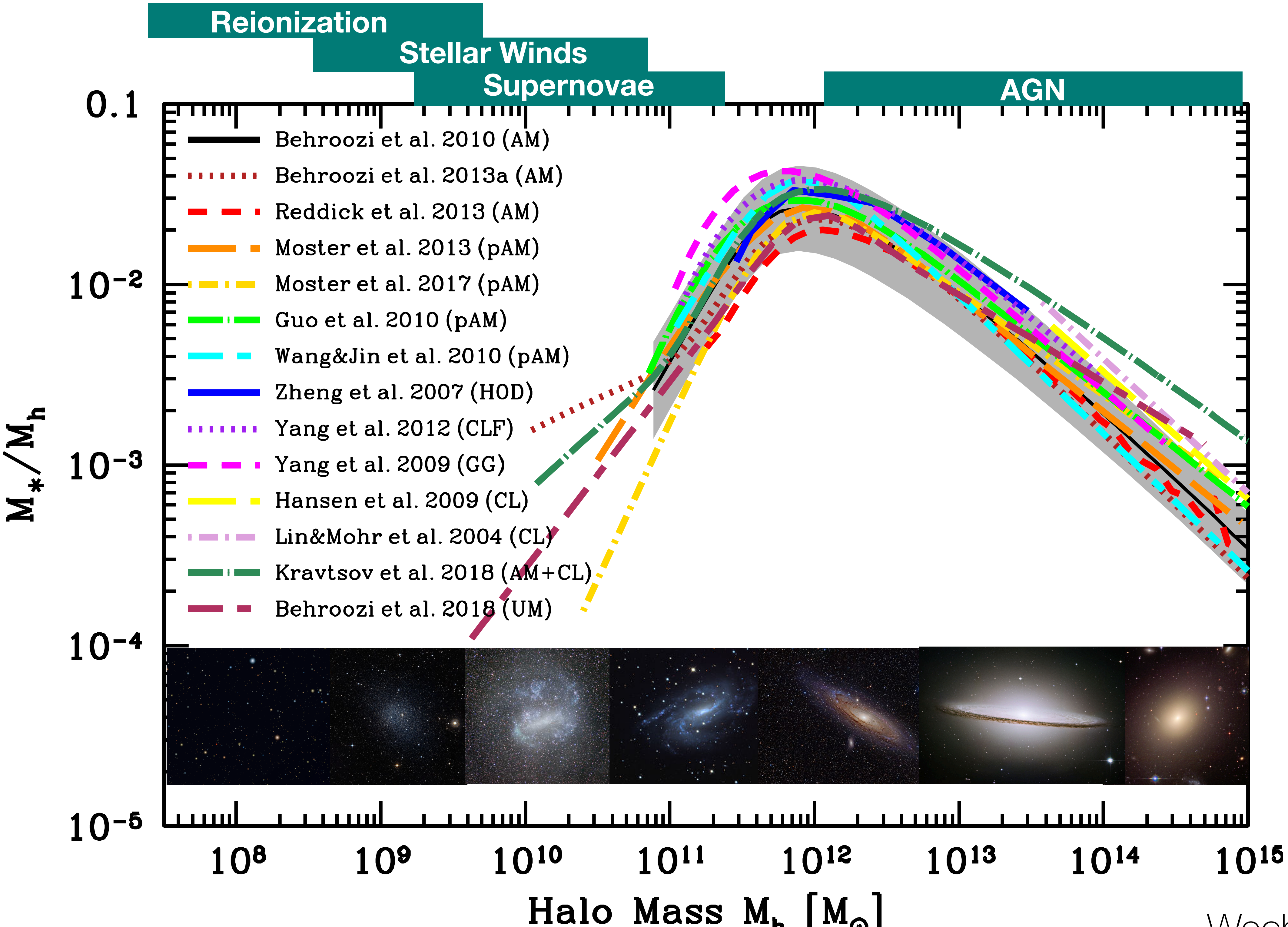
Nhut Truong
Numerical simulations

Kiran Lakhchaura
Black hole feedback

Francois Mernier
Chemical enrichment

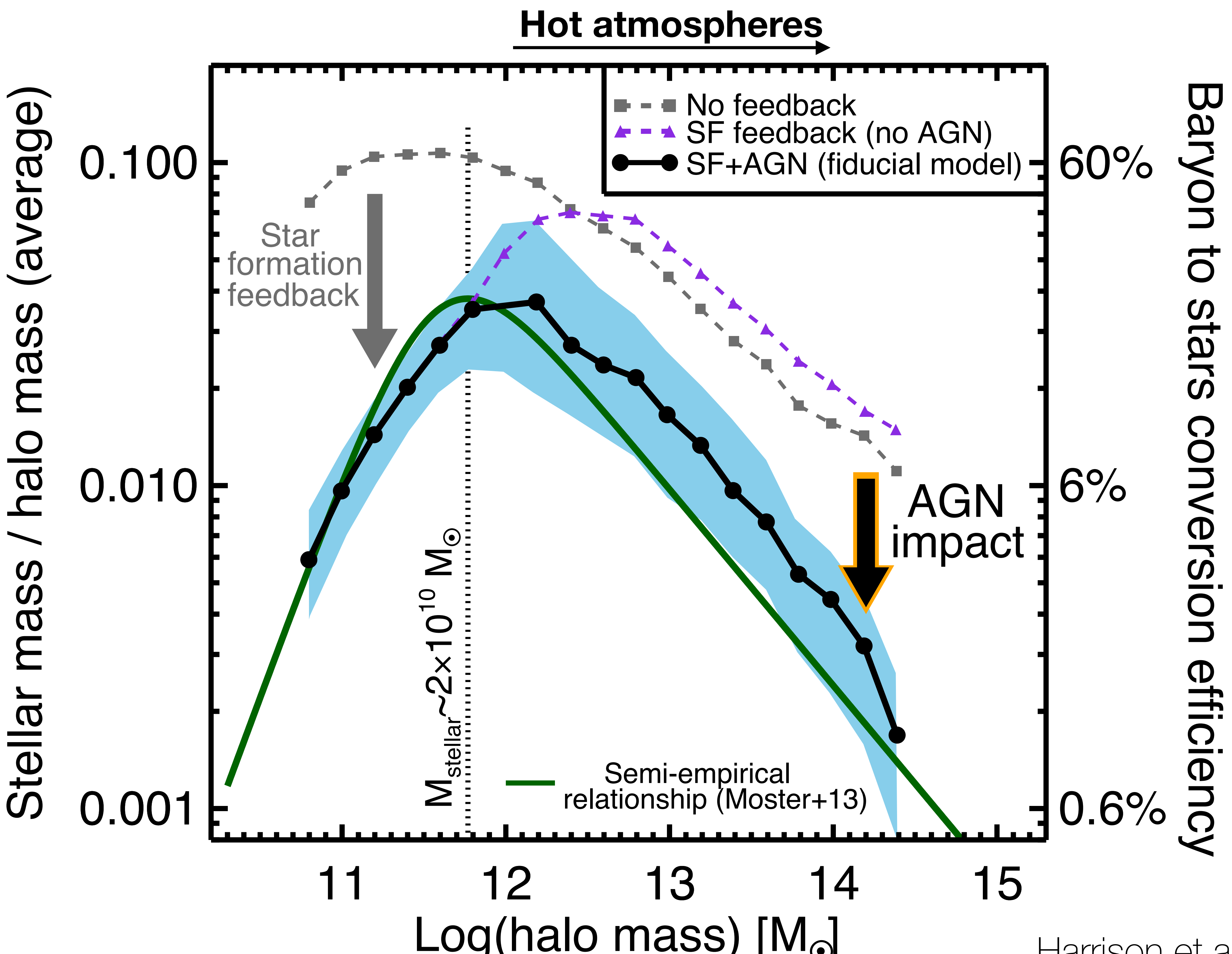
Jakub Řípa
Gamma-ray bursts

Why so Much Gas and so Few Stars?



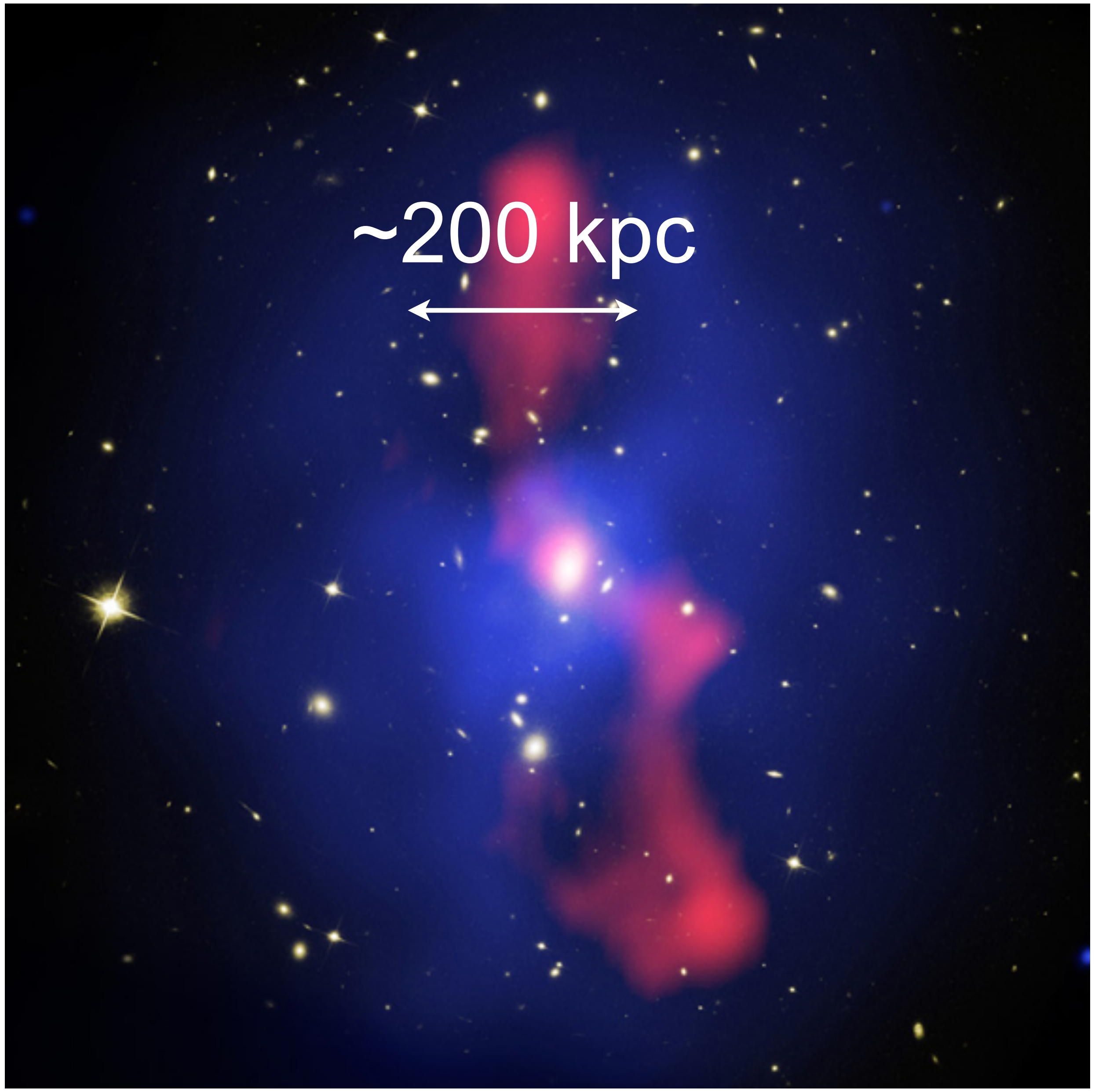
Wechsler et al. 2018

Why so Much Gas and so Few Stars?

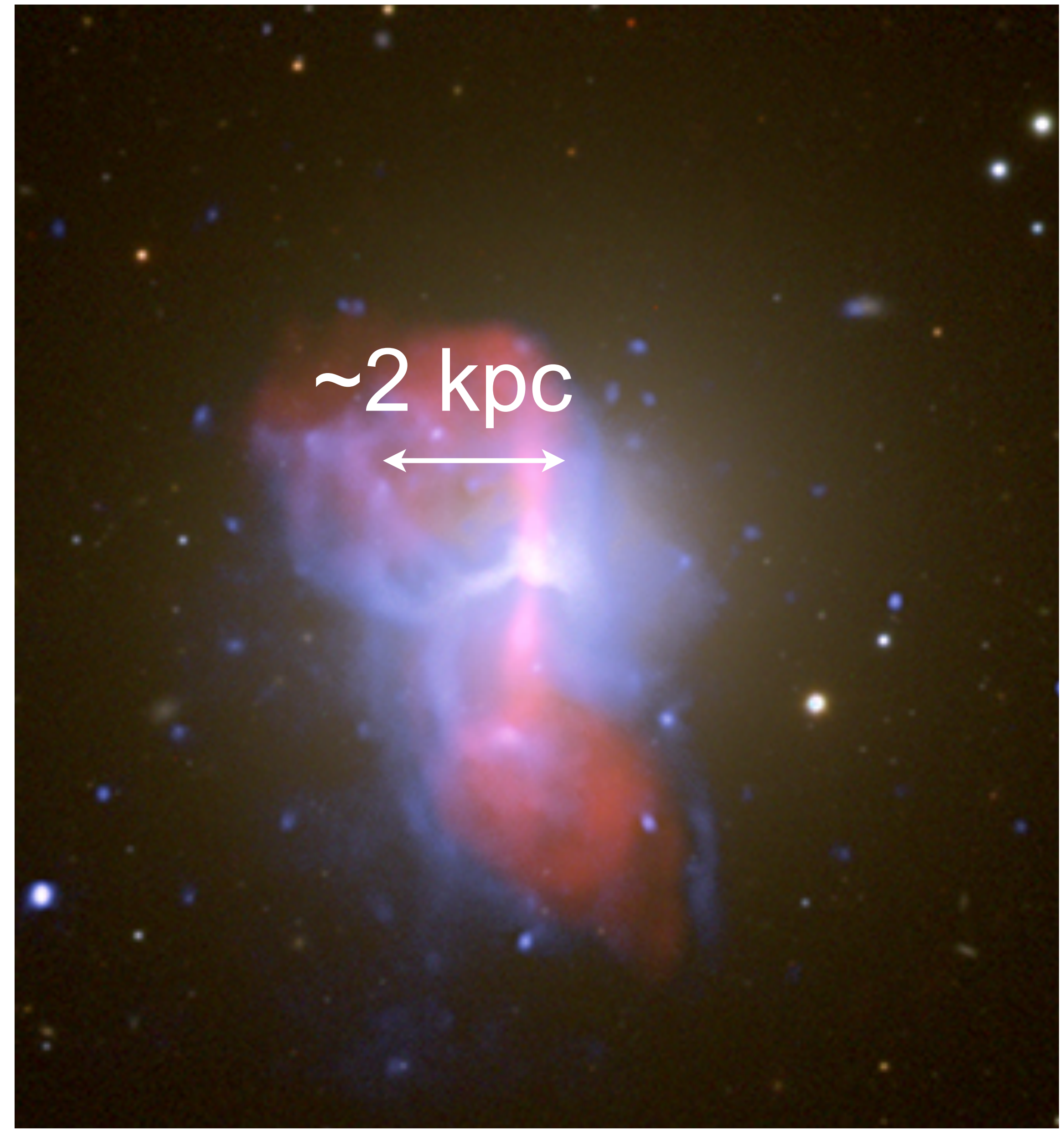


Harrison et al. 2017

Hot Atmospheres and AGN Feedback in Early Type Galaxies



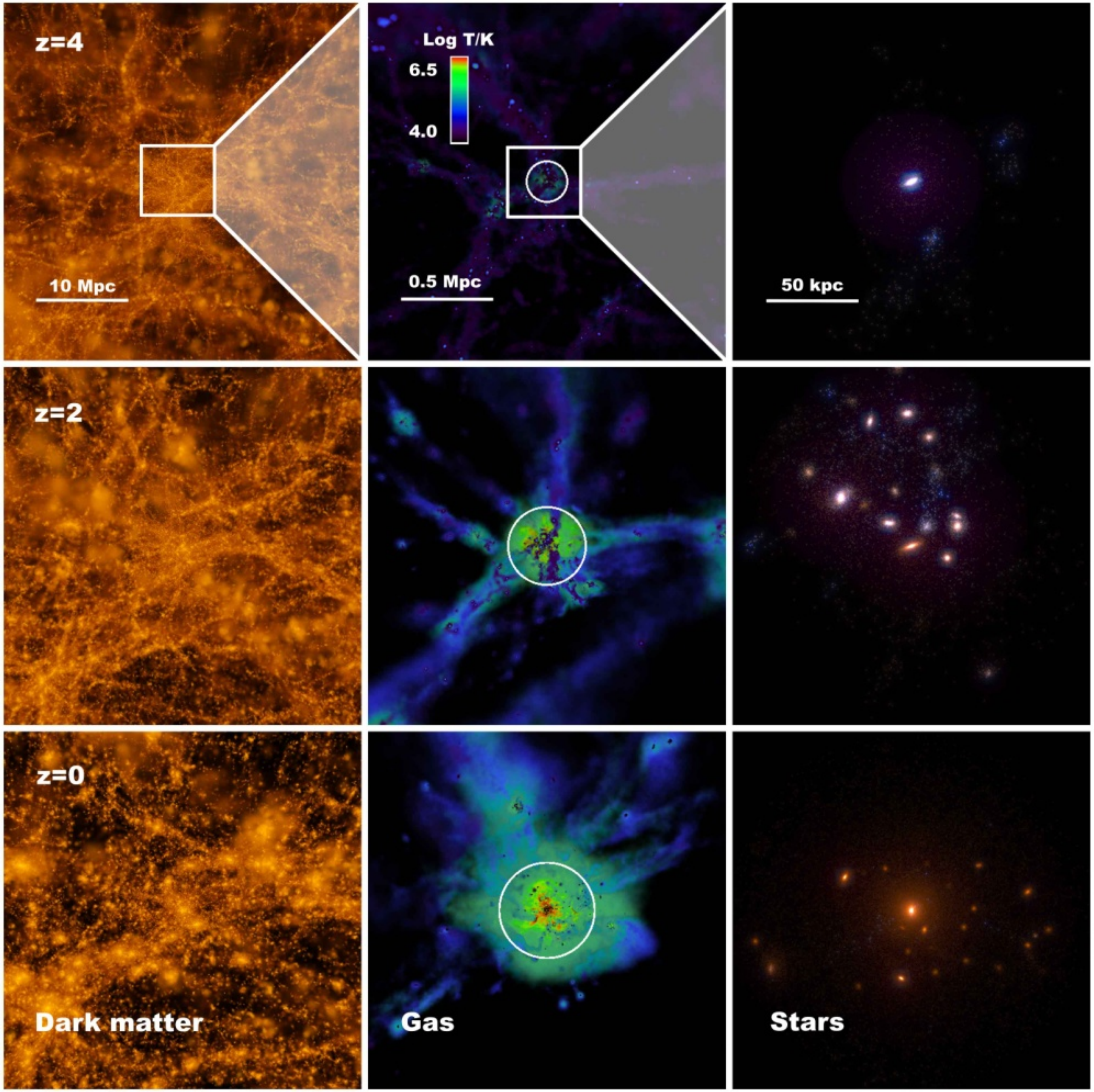
L_x ~ 10^{46} erg s^{-1}
E_{bubble} ~ 10^{62} erg



L_x ~ 10^{41} erg s^{-1}
E_{bubble} ~ 10^{56} erg

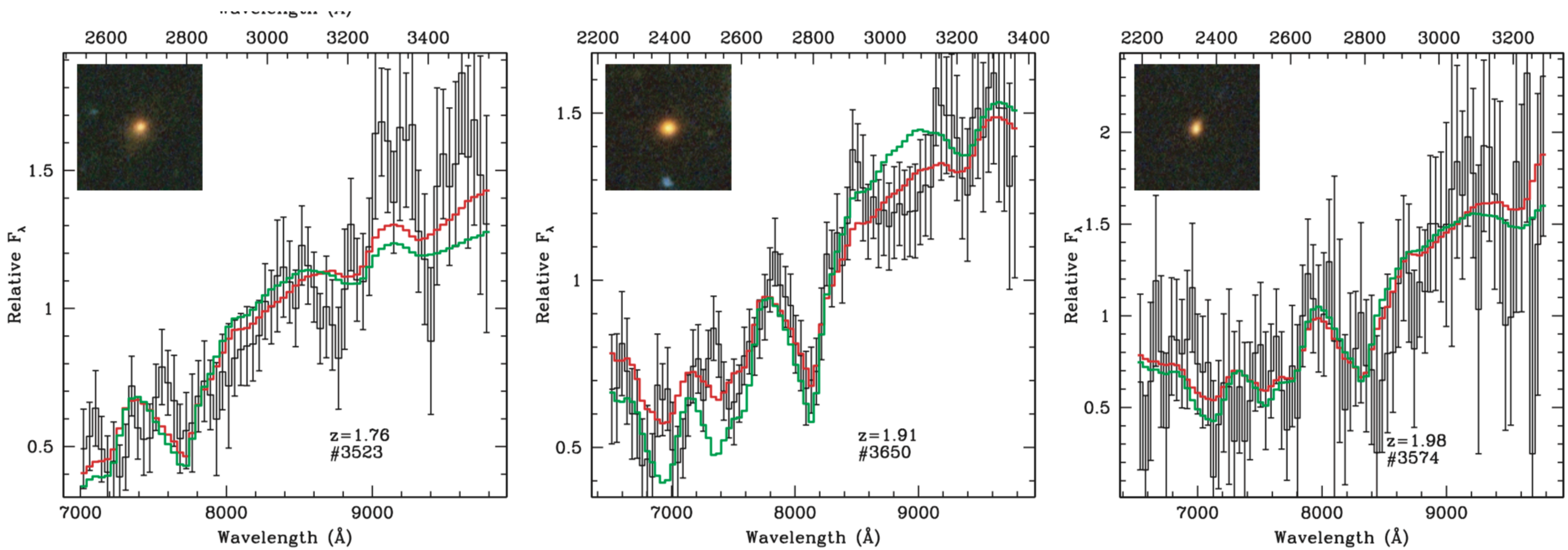
RED AND DEAD GIANT ELLIPTICAL GALAXIES

FORMATION OF AN ELLIPTICAL GALAXY



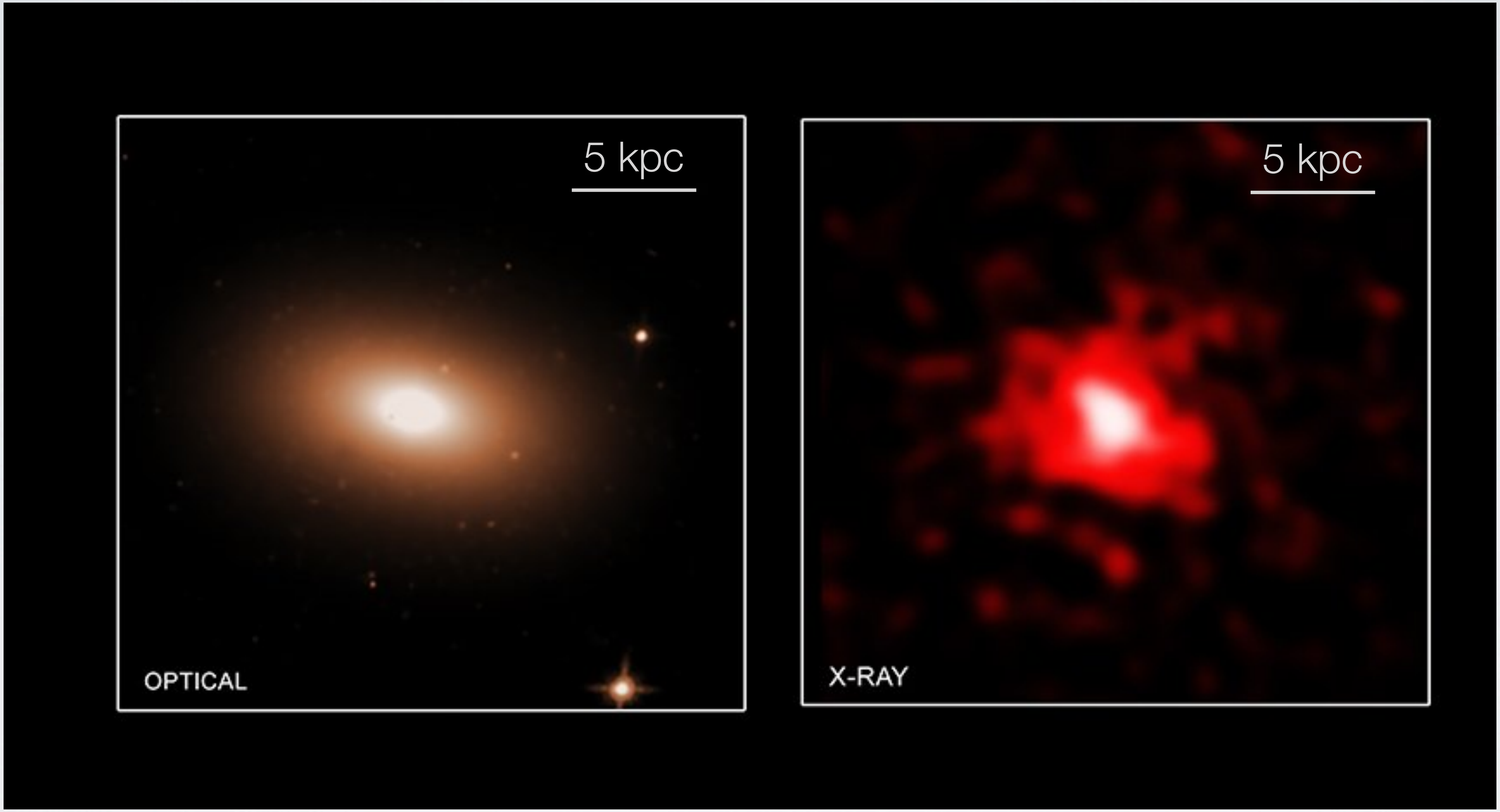
Cattaneo et al. 2009

THE DISCOVERY OF "**RED NUGGETS**"



Daddi et al. 2005

MRK 1216 A RELIC RED NUGGET



$M_{stellar} = (2.0 \pm 0.8) \times 10^{11}\ M_\odot$

$R_e = 2.3 \pm 0.1$ kpc

Age = 12.8±1.5 Gyr

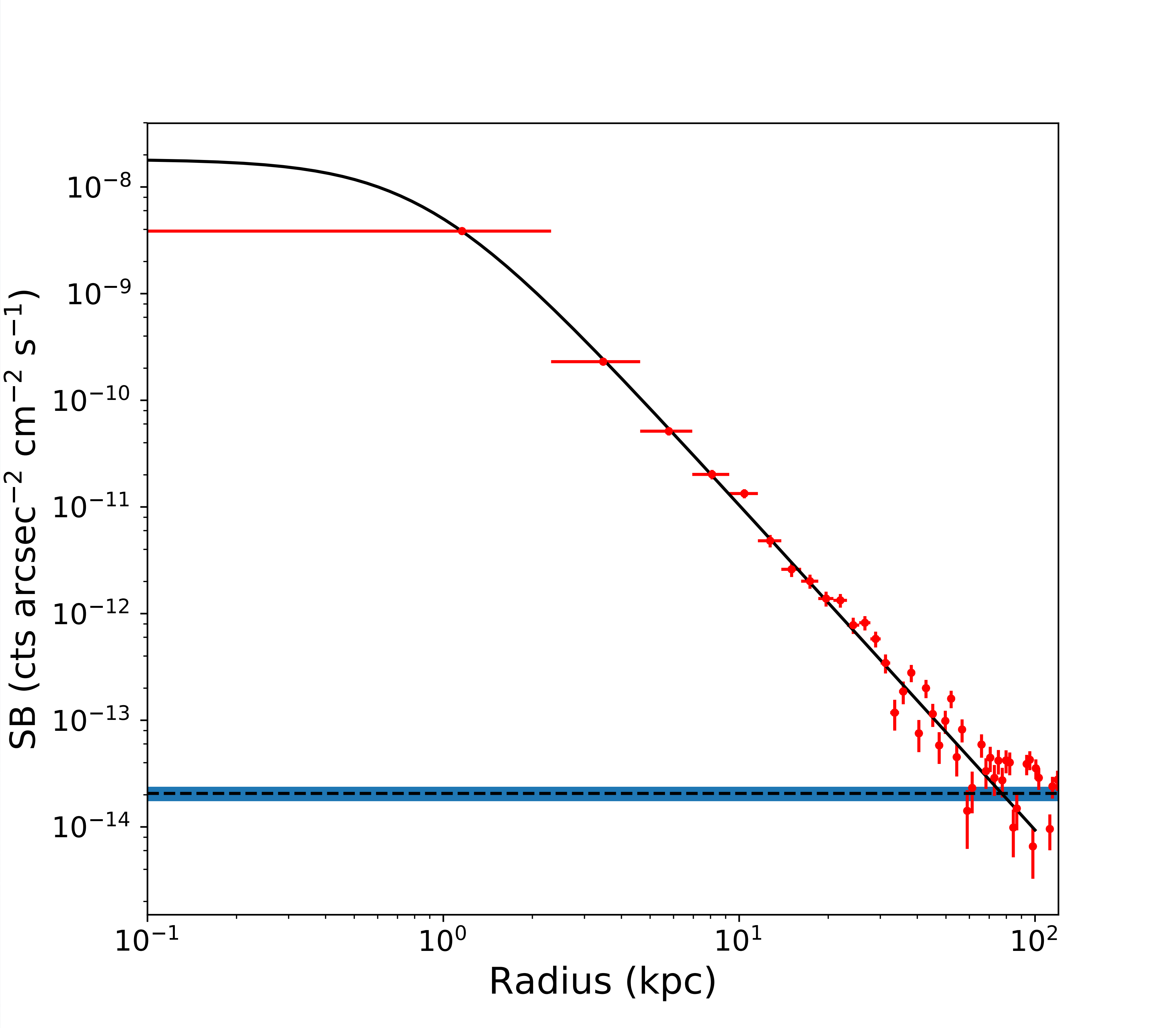
$M_{BH} = (4.9 \pm 1.7) \times 10^9\ M_\odot$

D = 97 Mpc (Ferre-Mateu et al. 2017)

$L_X = 6.9 \times 10^{41}$ erg s^{-1}
within r<10 kpc

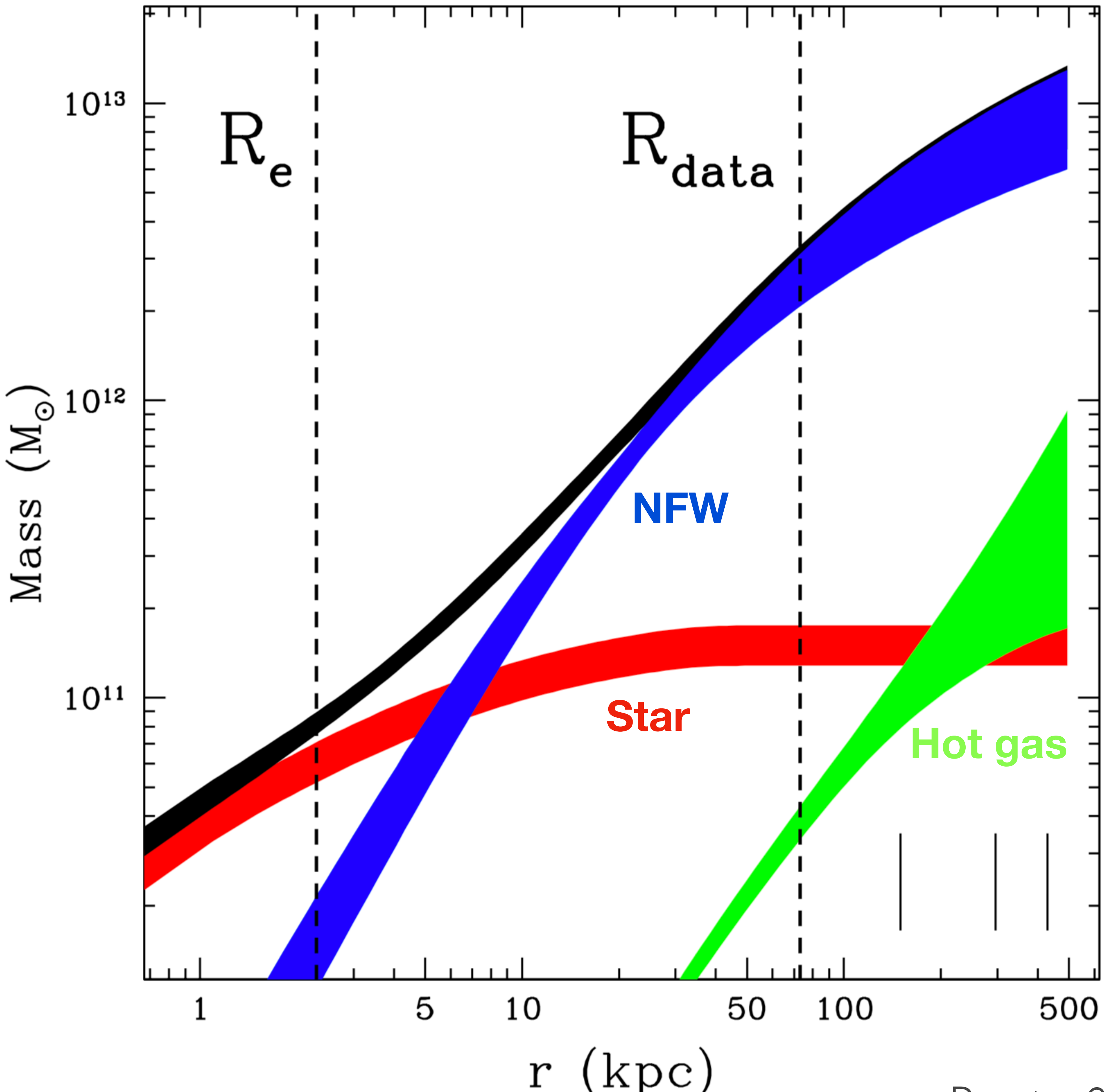
Werner et al. 2018

THE HOT ATMOSPHERE OF THE RELIC RED NUGGET MRK 1216



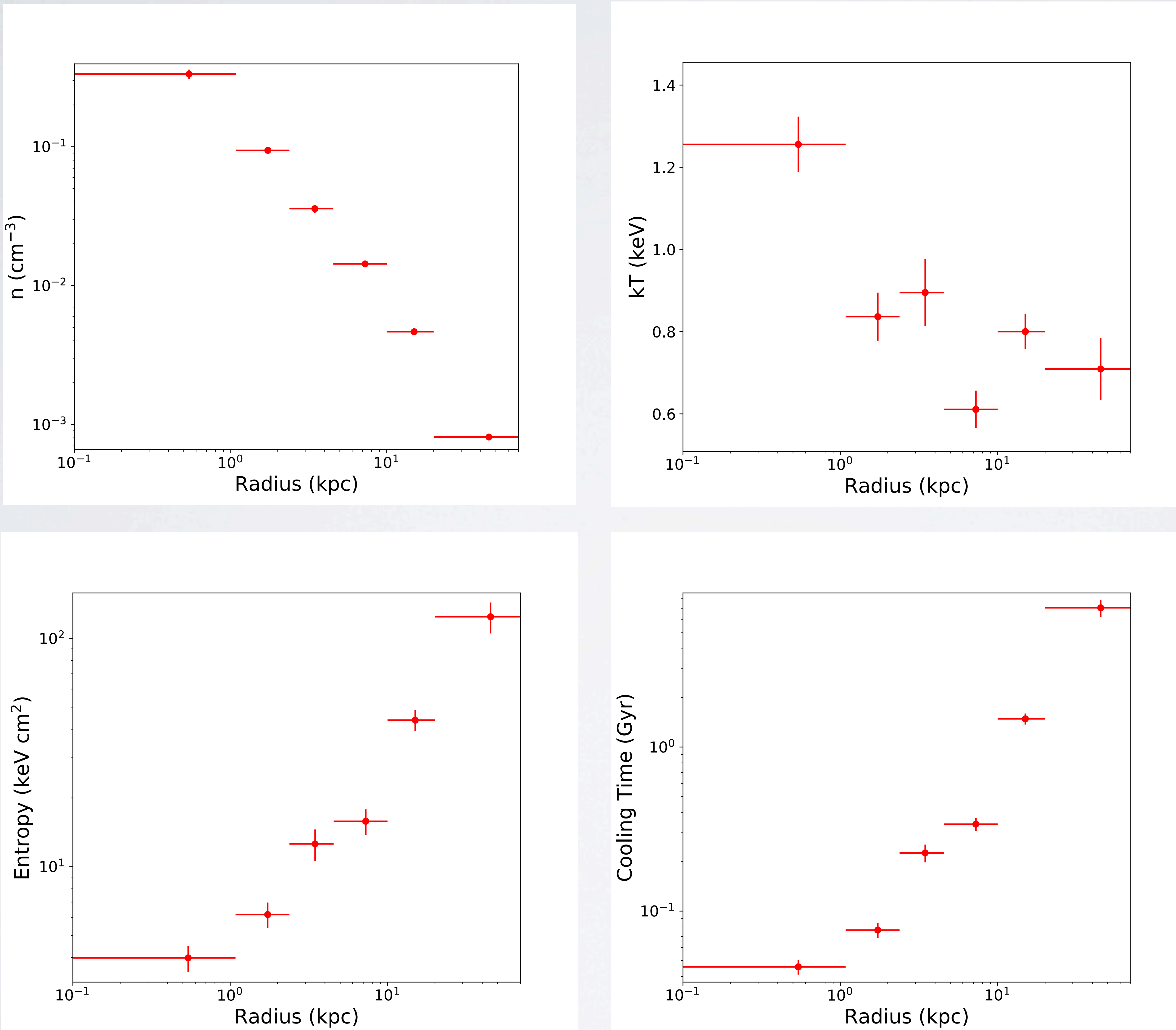
Werner et al. 2018

THE MASS OF MRK 1216



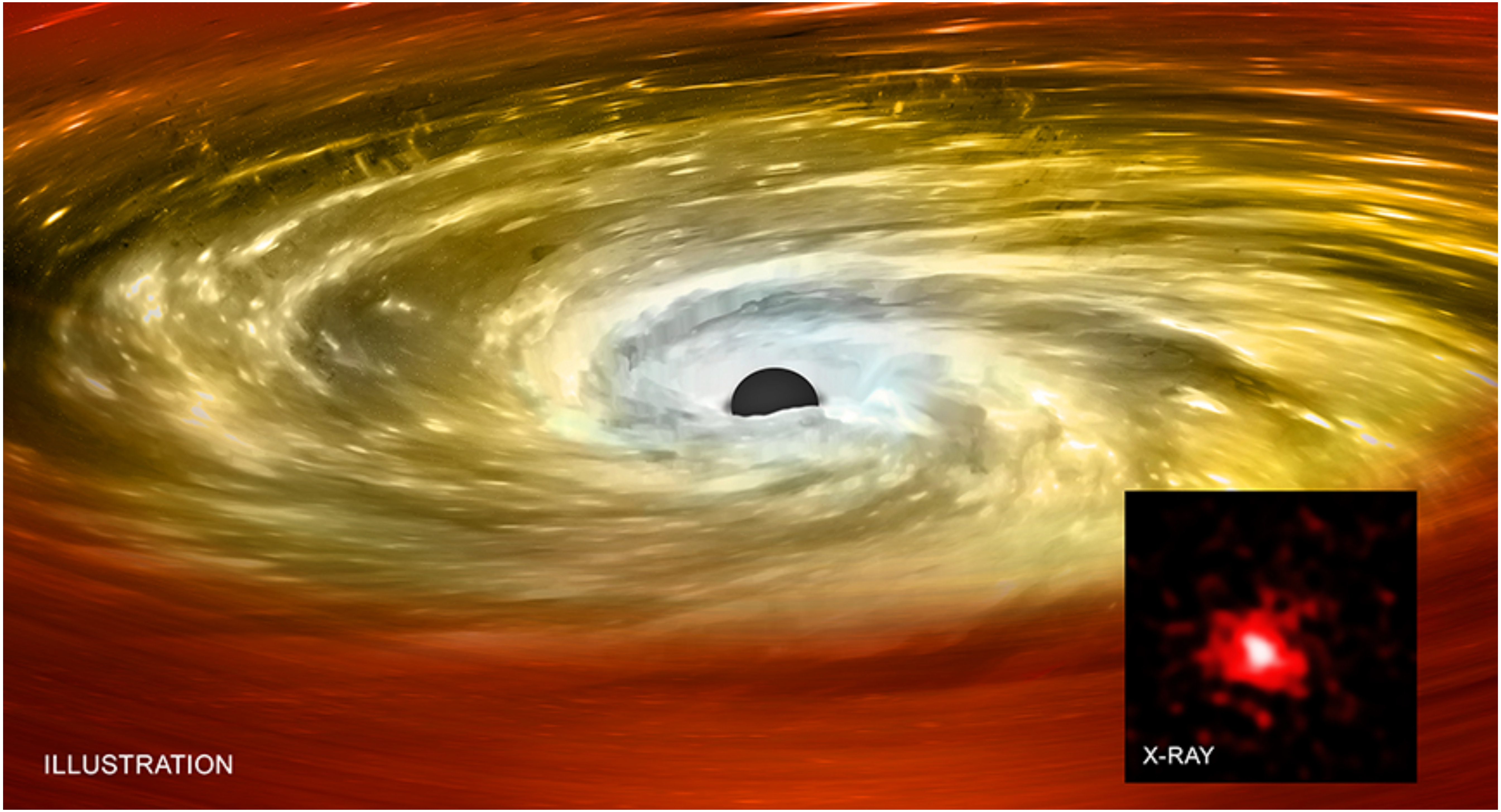
Buote & Barth et al. 2018

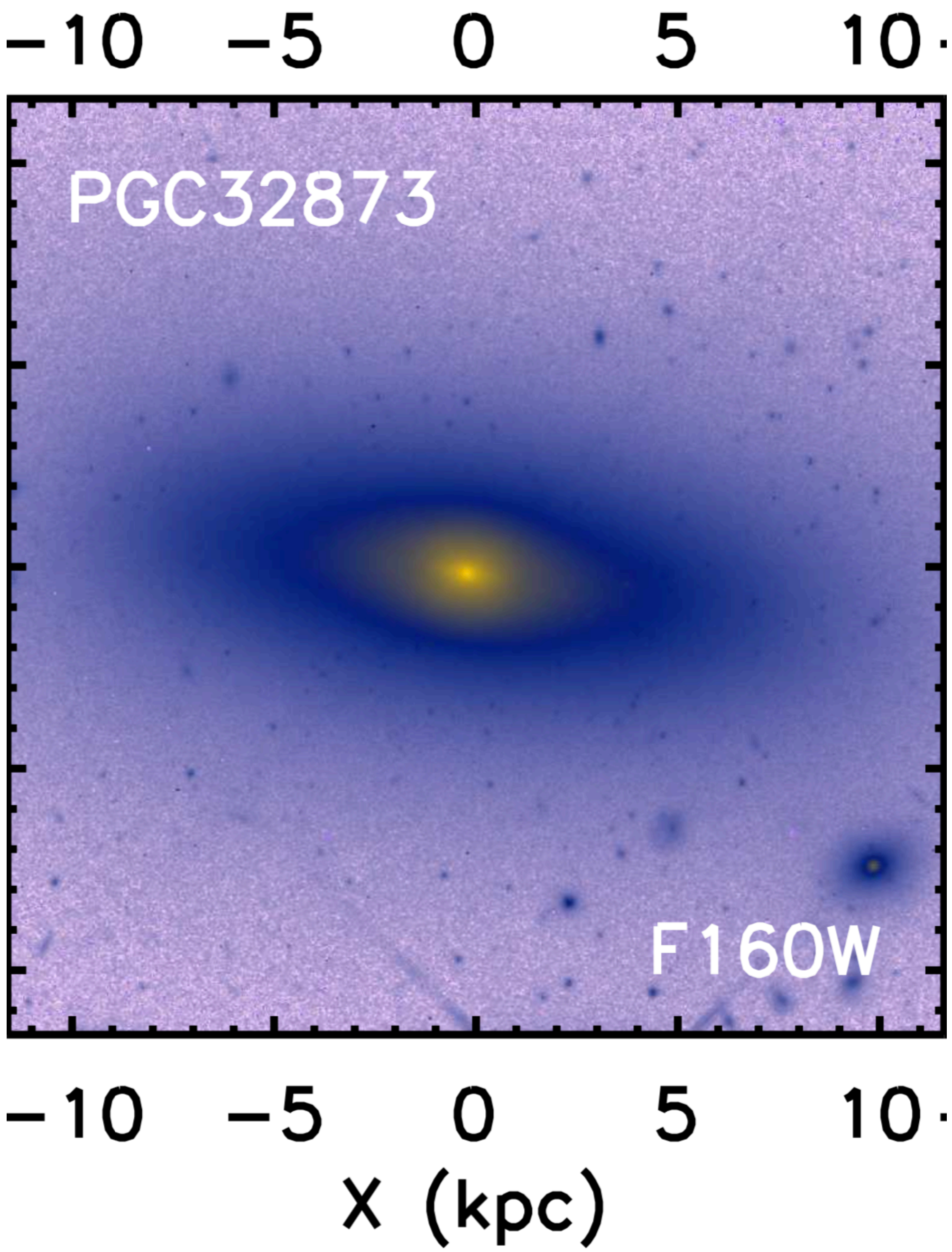
Hot atmosphere surrounding a relic red nugget

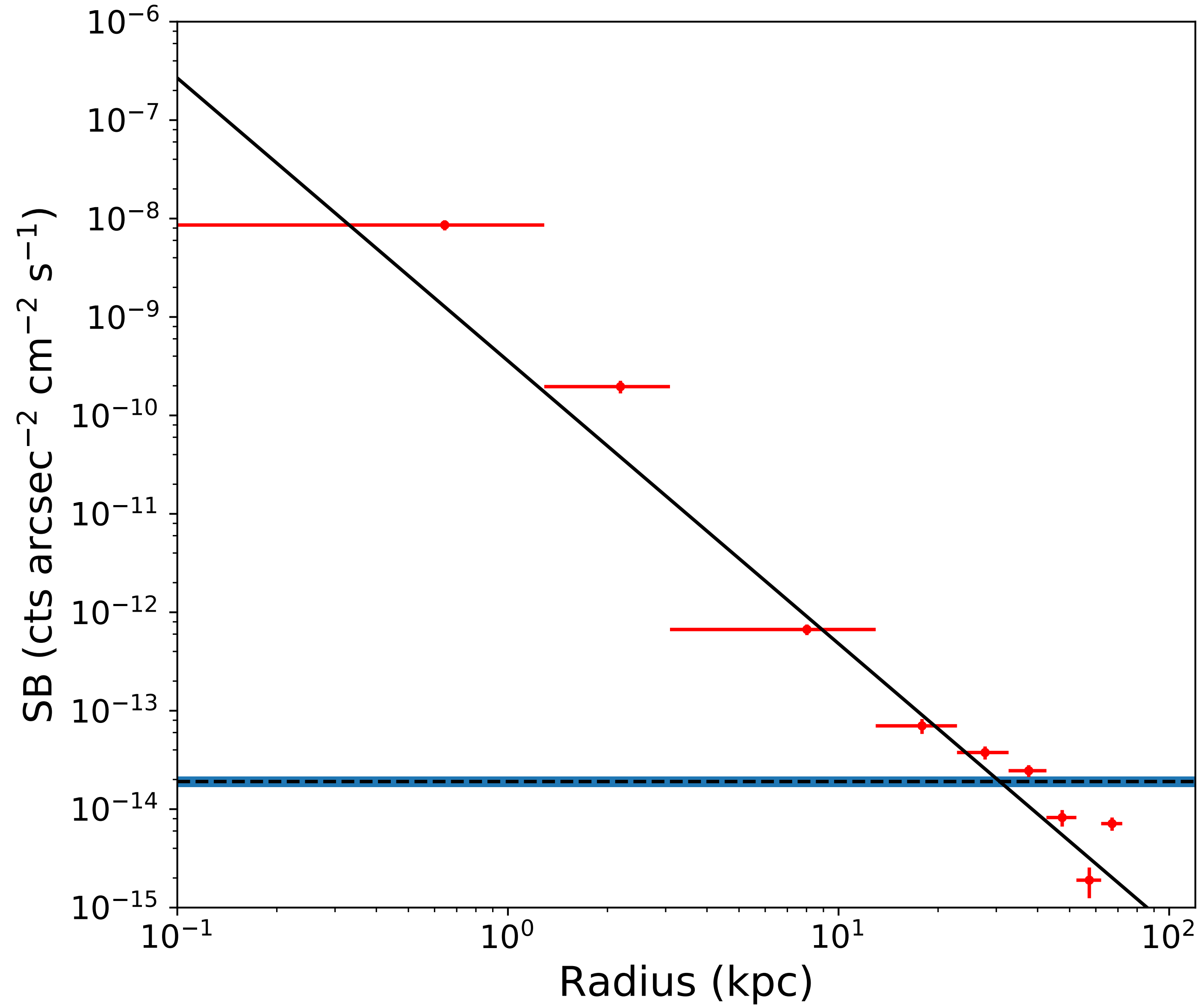


Werner et al. 2018

AGN feedback preventing star formation for ~13 billion years!







$M_{stellar}$ = (2.3 ± 0.9) × 10^{11} $M_\odot$

R_e=1.8 ± 0.2 kpc

Age = 12.7±1.6 Gyr

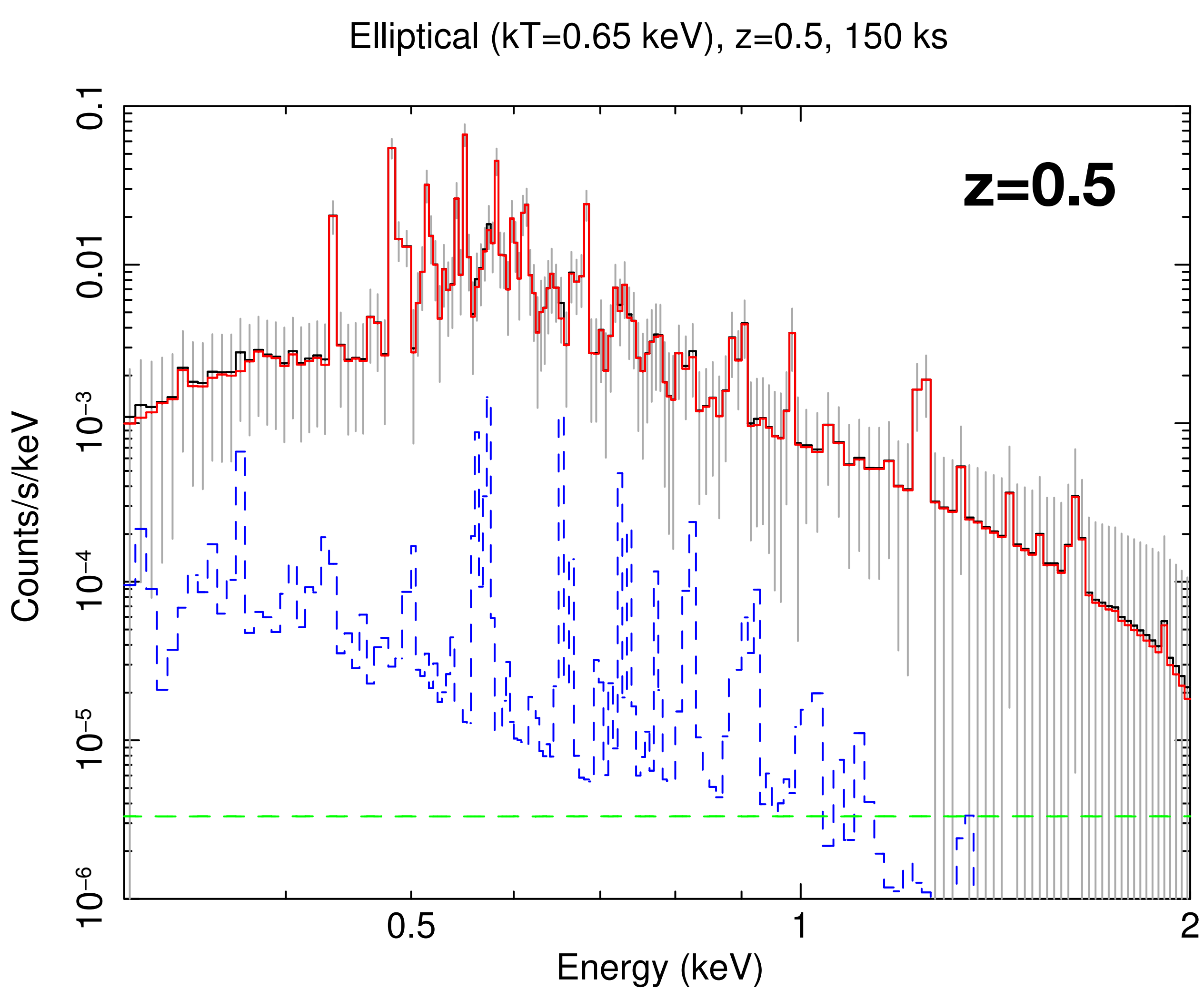
M_{BH} = (4.9 ± 1.7) × 10^9 $M_\odot$

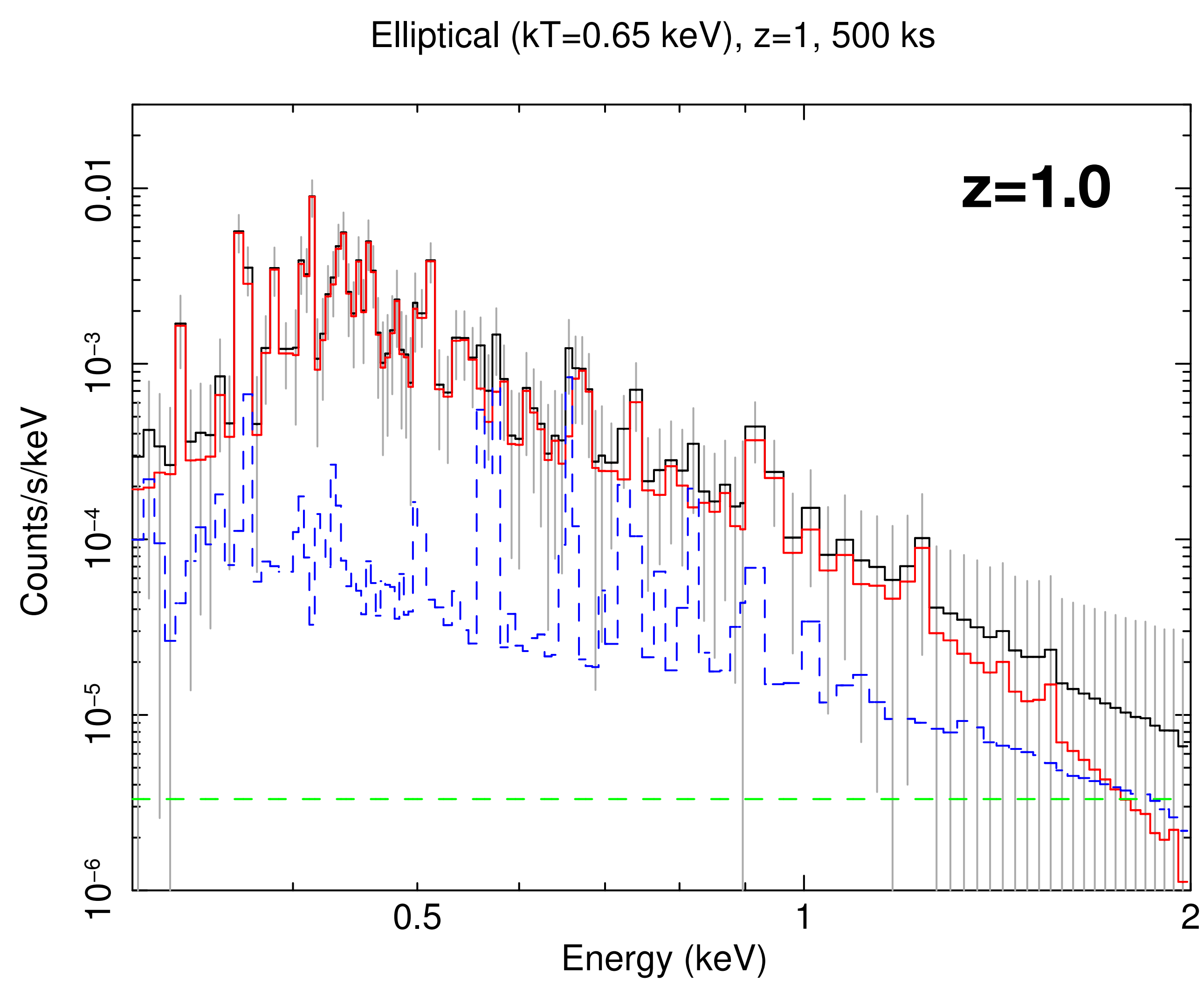
D = 108 Mpc

L_X = 5.3 × 10^{40} erg s^{-1} within r<10 kpc

Werner et al. 2018

Galactic atmospheres at high redshifts with *Athena*



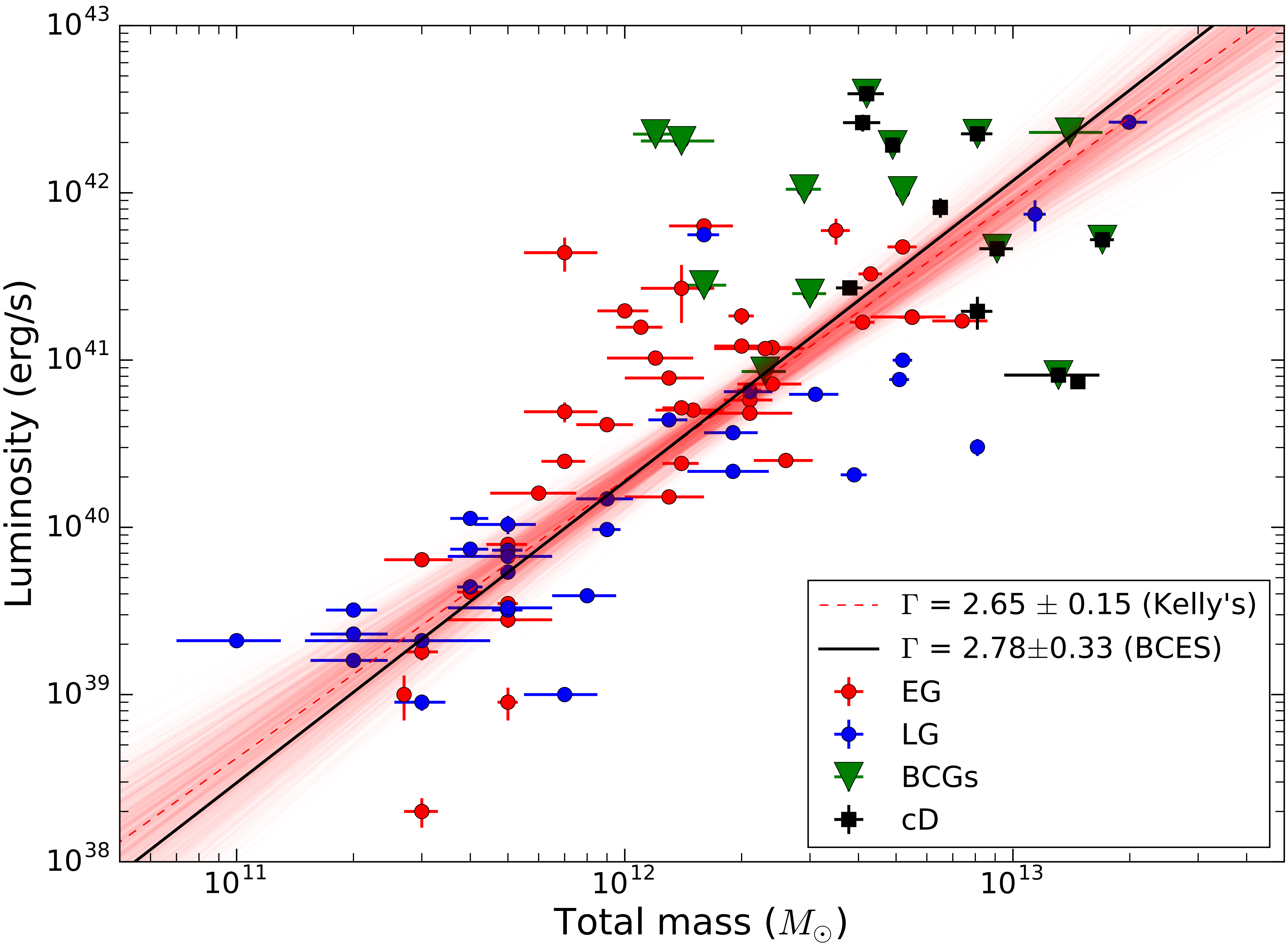


Simulations by F. Mernier

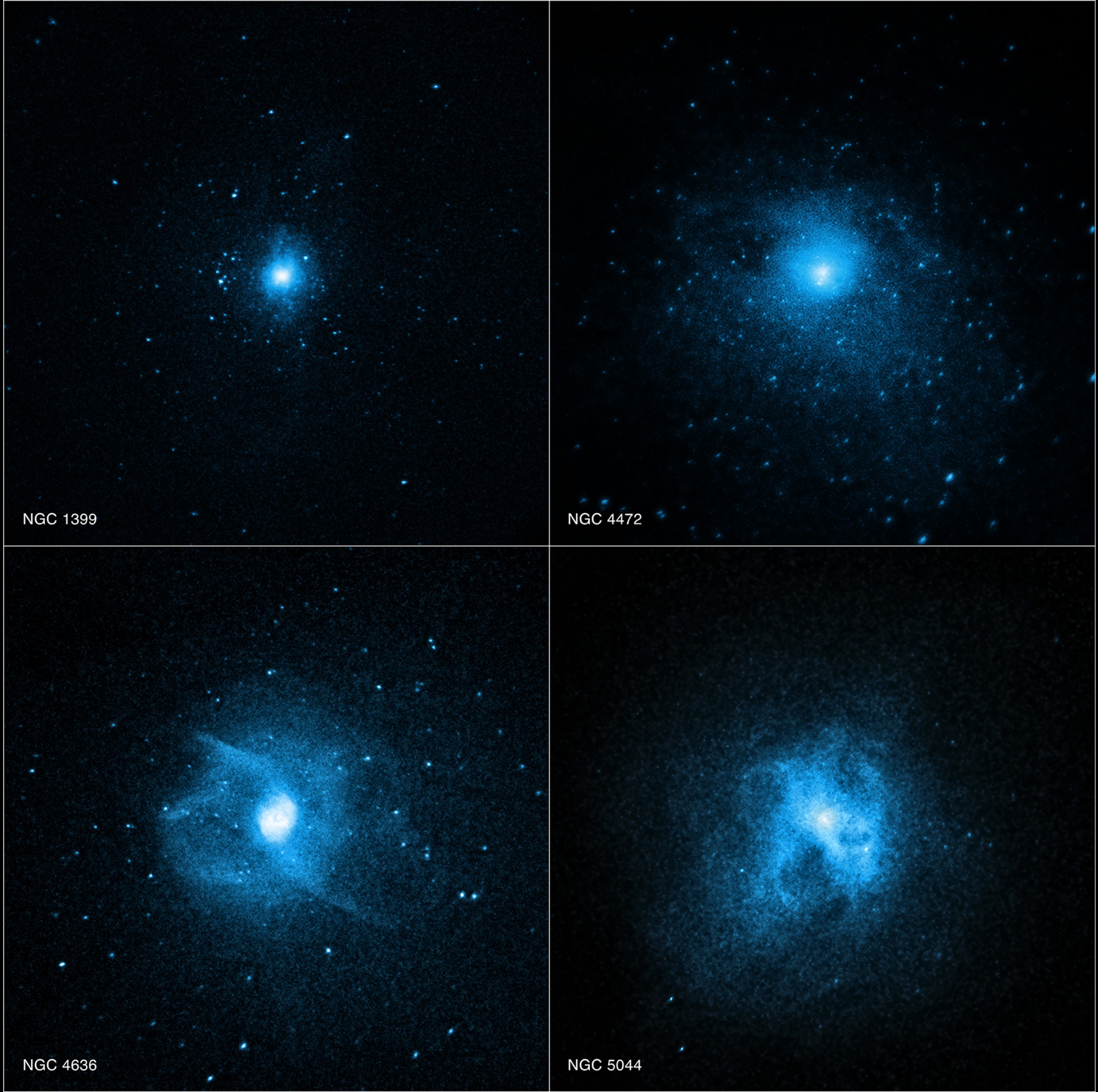
Hot atmosphere surrounding a relic red nugget

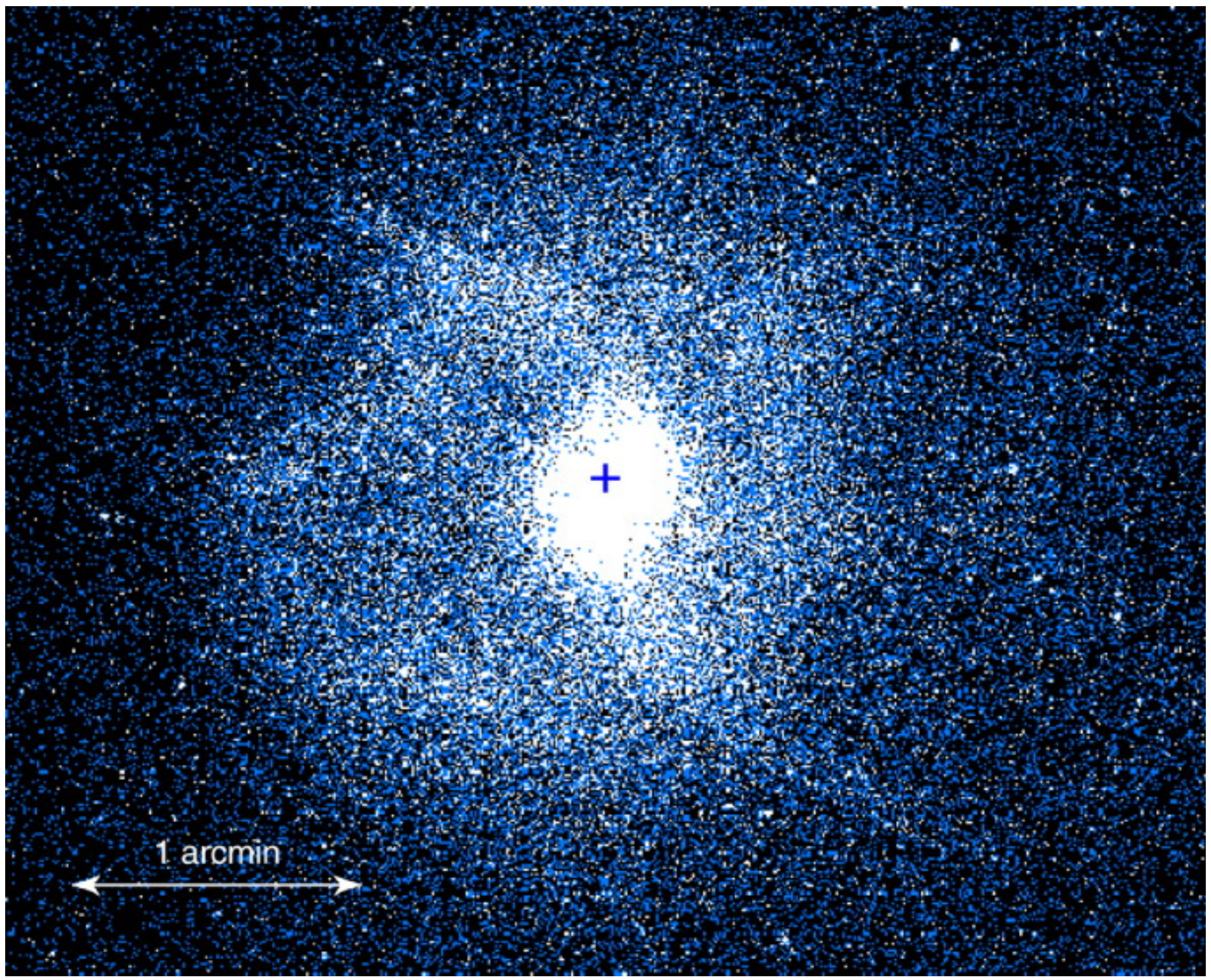
- The first detection of an X-ray emitting atmosphere surrounding such a relic galaxy
- The hot atmospheres extend far beyond the stellar populations and the luminosities and gas masses show an order of magnitude difference
- The presence of an X-ray atmosphere with a short nominal cooling time and the lack of young stars indicate the presence of a sustained heating source, which prevented star formation since the dissipative formation of the galaxy 13 Gyrs ago - **radio-mechanical AGN feedback**
- Given that over the past ~ 13 billion years both galaxies appear to have evolved passively and in isolation, the difference in their current X-ray luminosity could be traced back to a difference in the ferocity of the AGN outbursts in these systems.

Werner et al. 2018

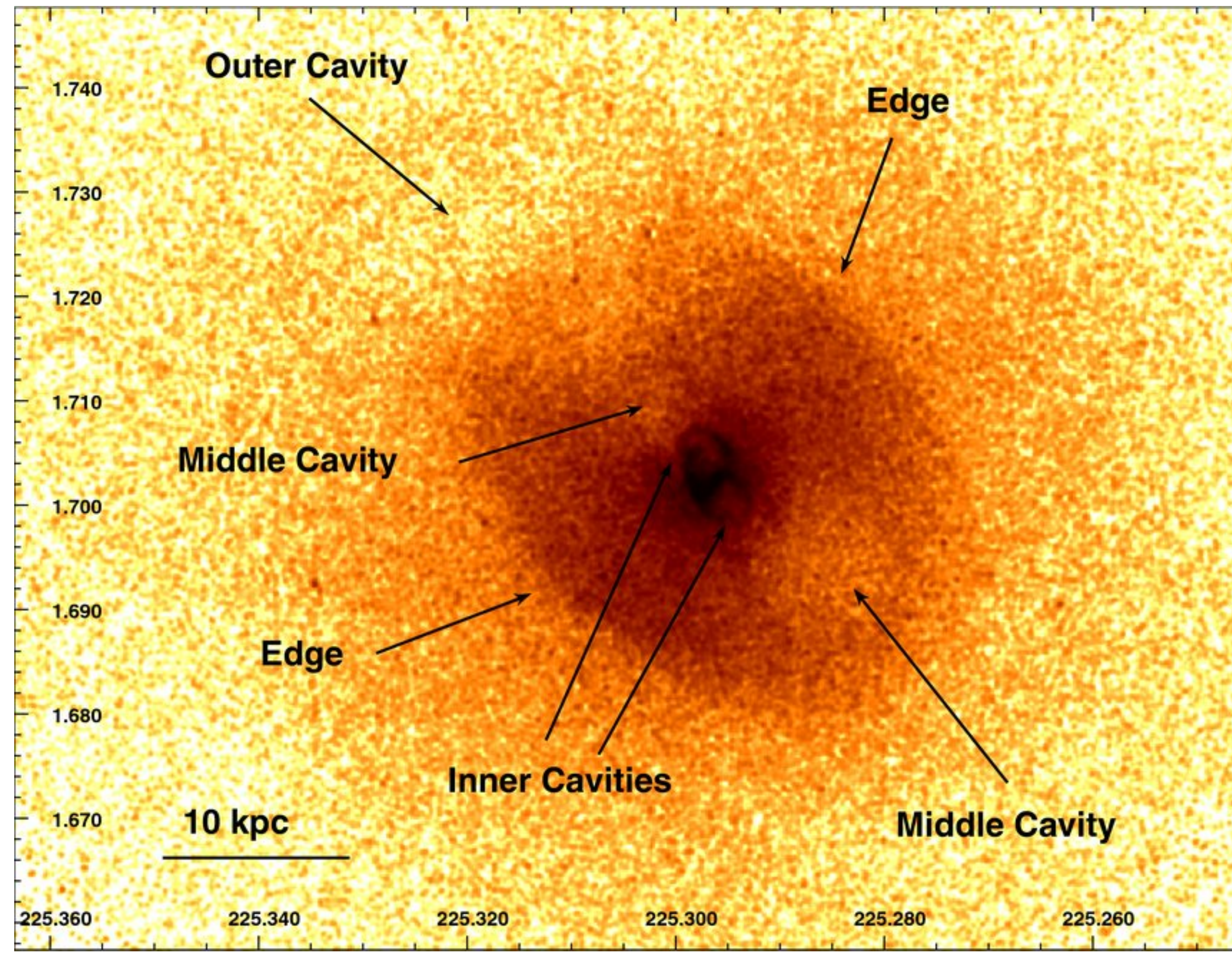


Babyk et al. 2018

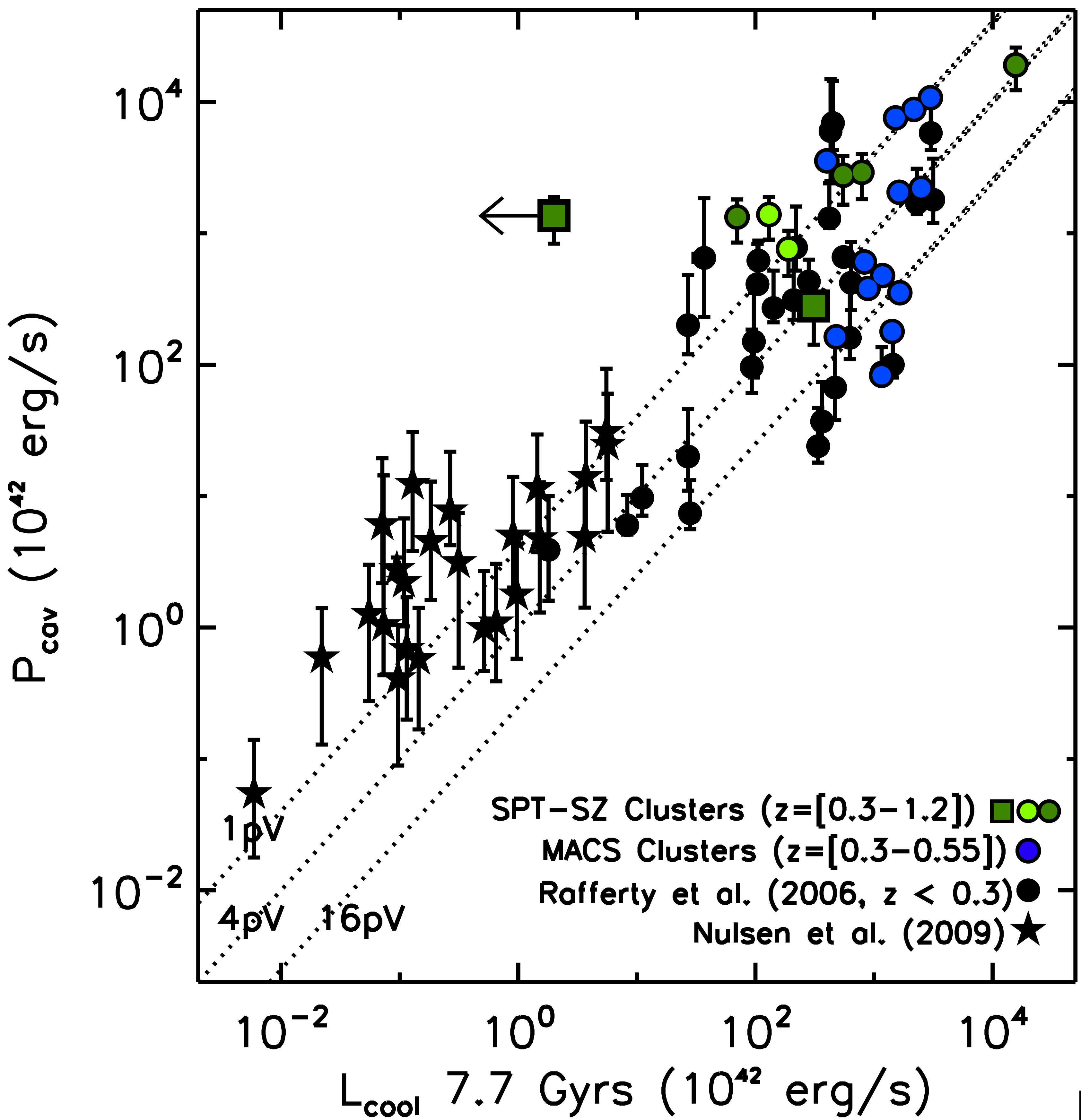

NGC 1399
NGC 4472
NGC 4636
NGC 5044



Jones et al. 2002
Baldi et al. 2009

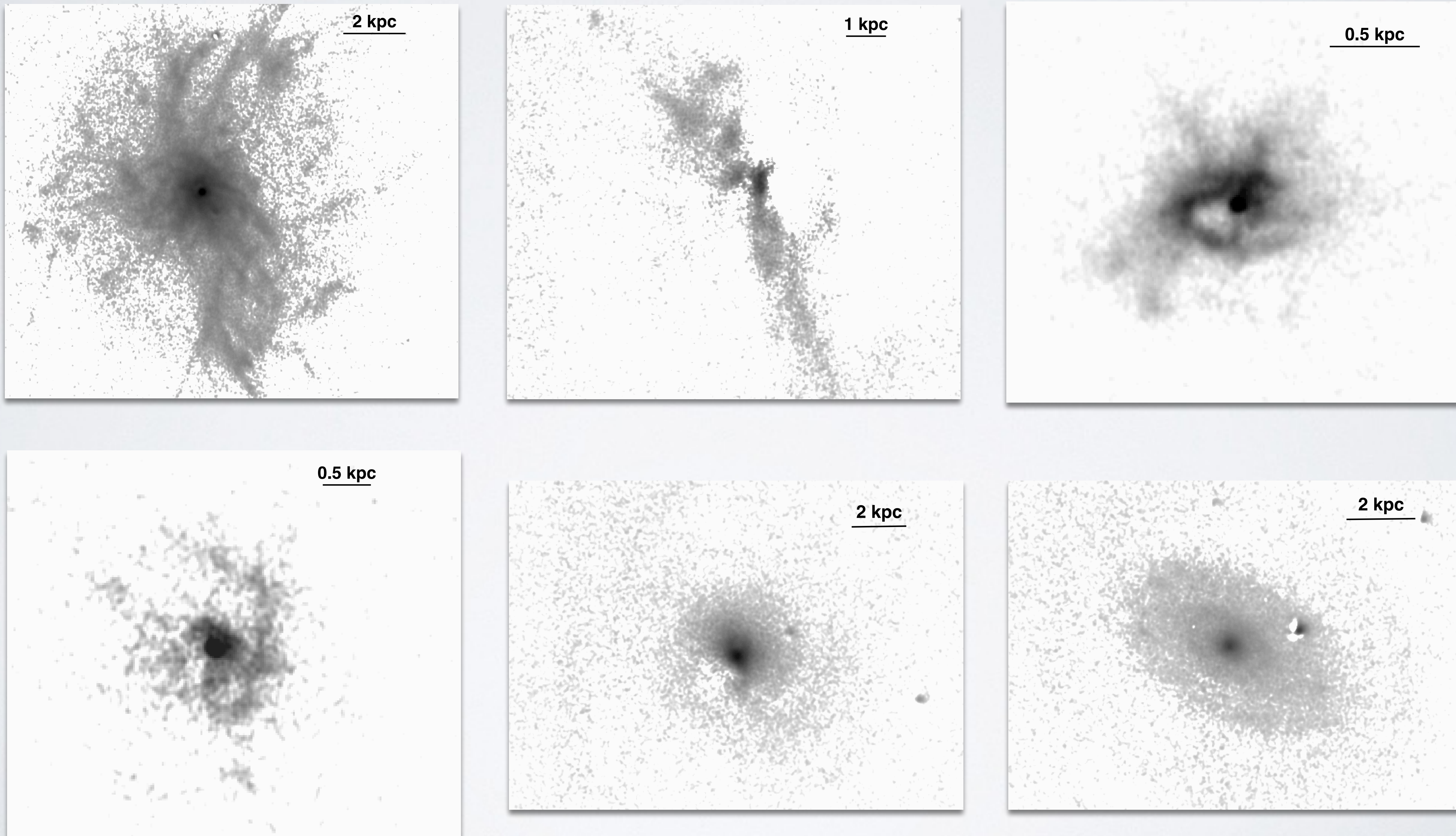


Randall et al. 2015



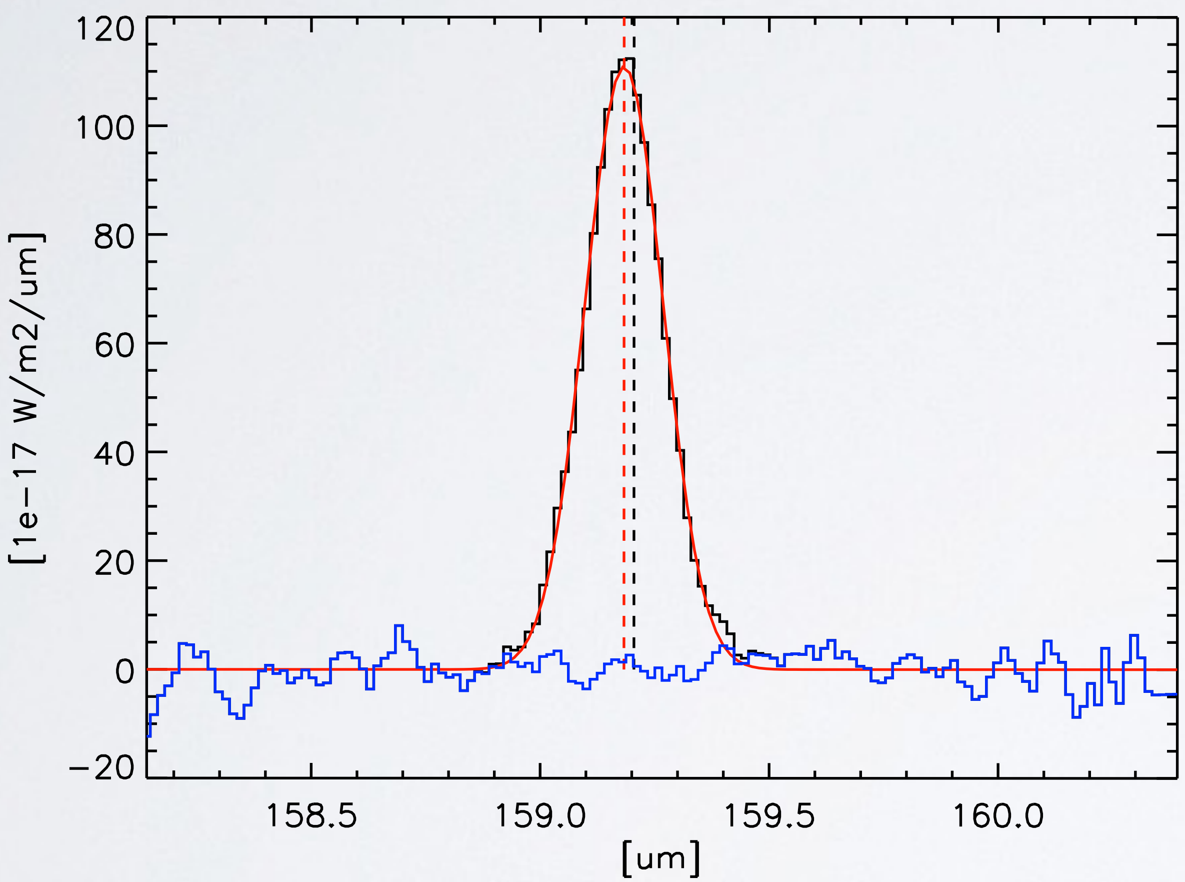
Hlavacek-Larrondo et al. 2015

Hα+[NII] IMAGING WITH THE SOAR TELESCOPE



Werner et al. 2014

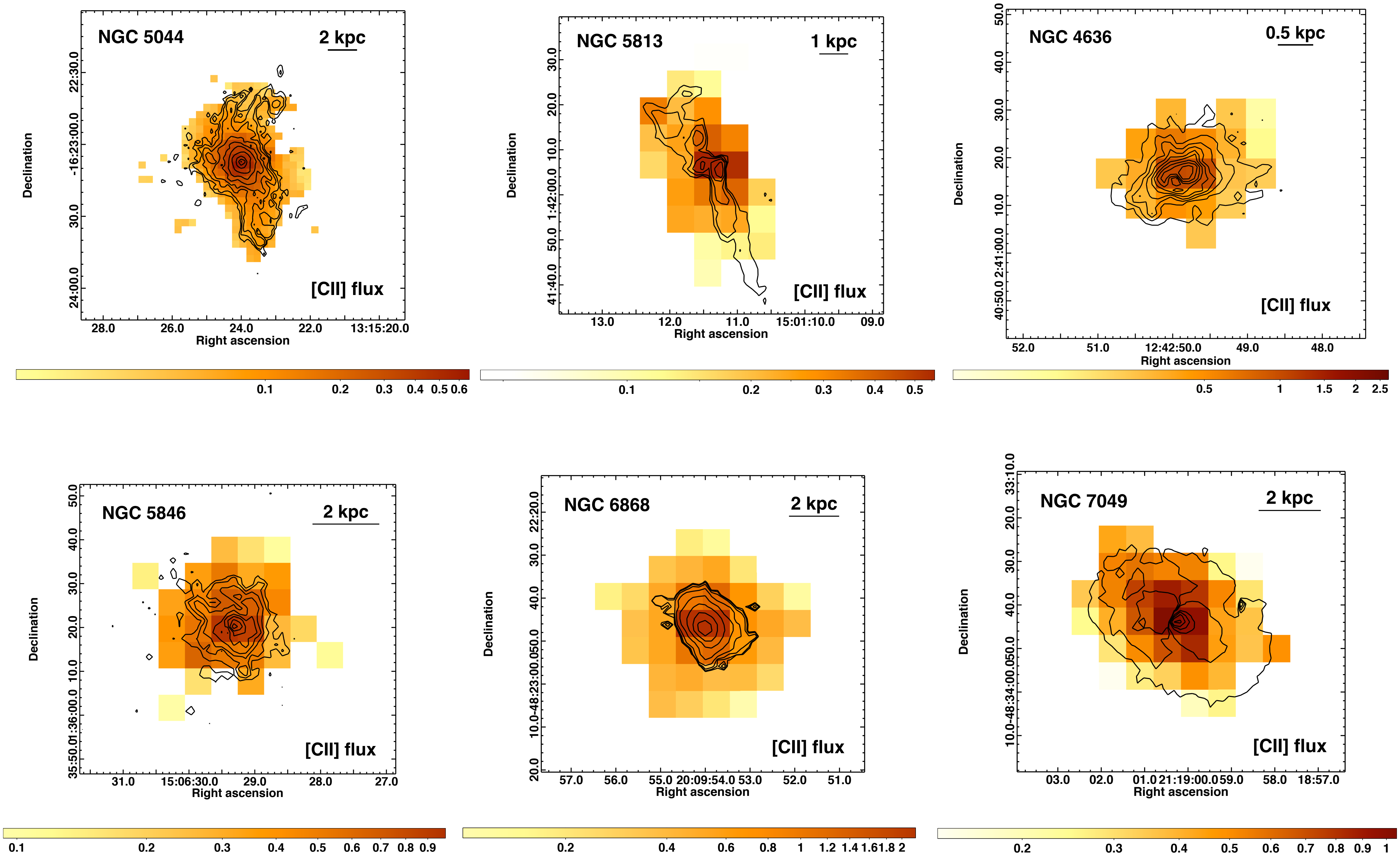
FAR-INFRARED LINE DETECTIONS IN GIANT ELLIPTICALS



- [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

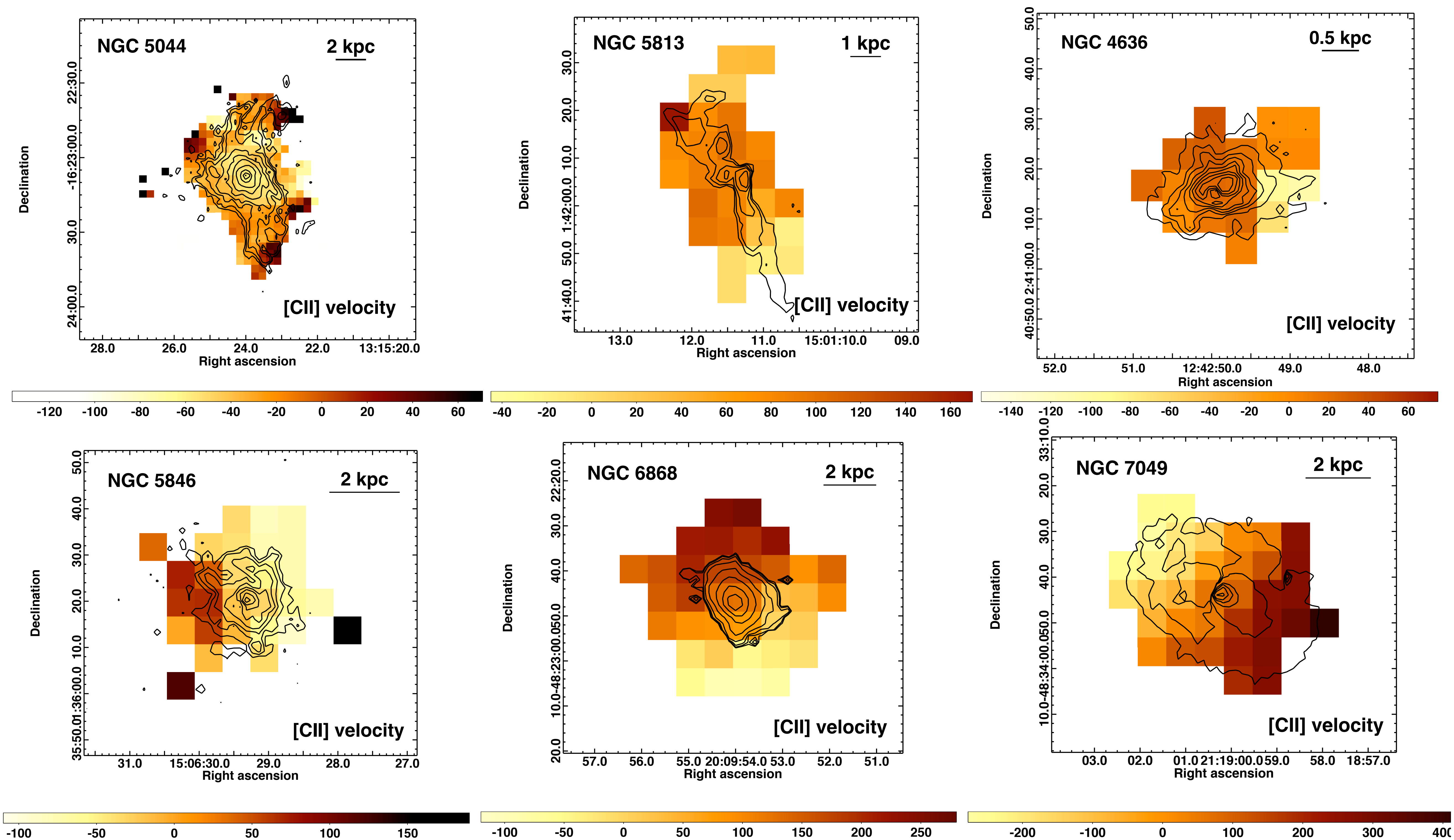
Werner et al. 2014

[CII] EMISSION FOLLOWING Hα



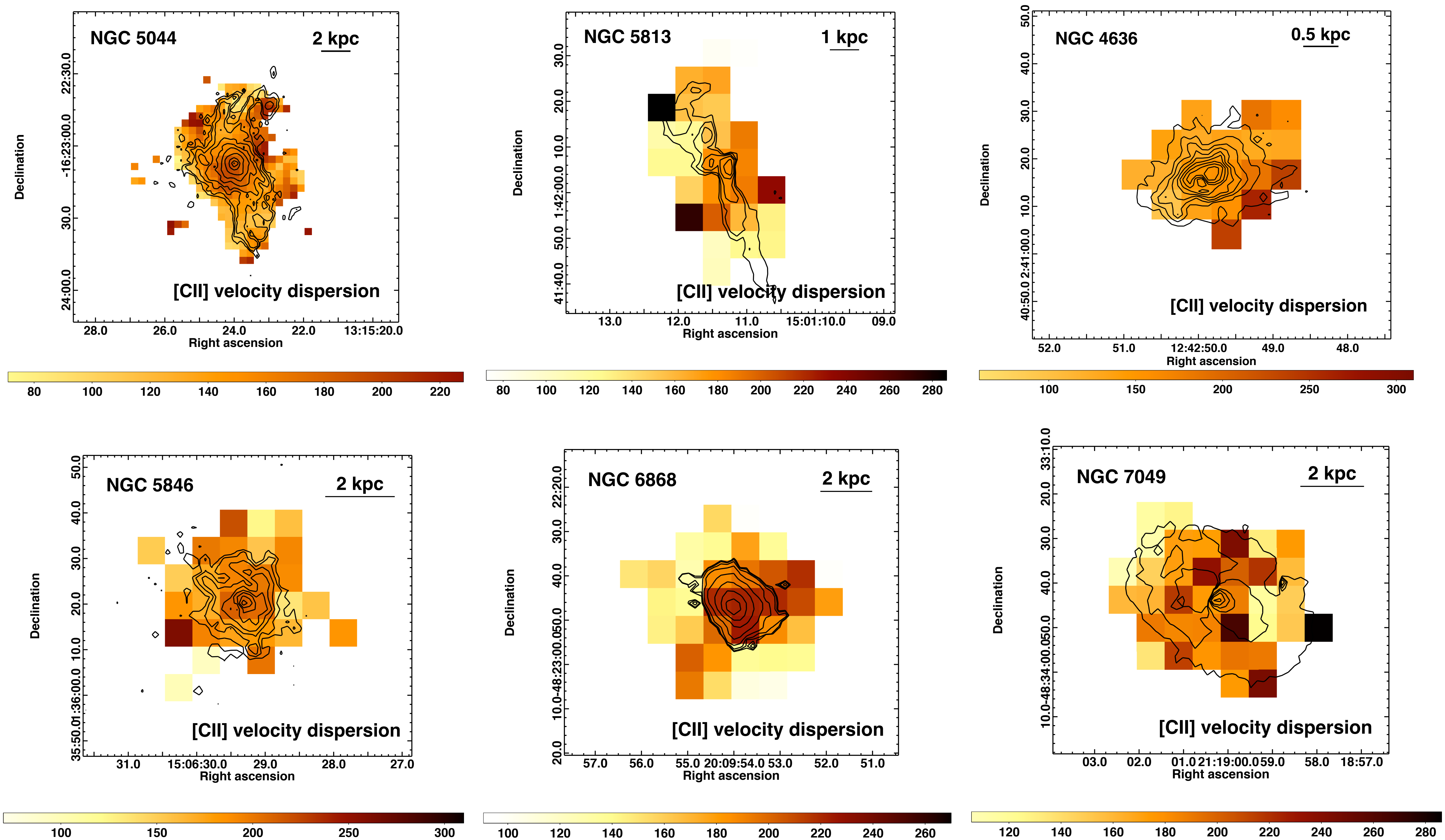
Werner et al. 2014

VELOCITIES OF THE COLD ISM

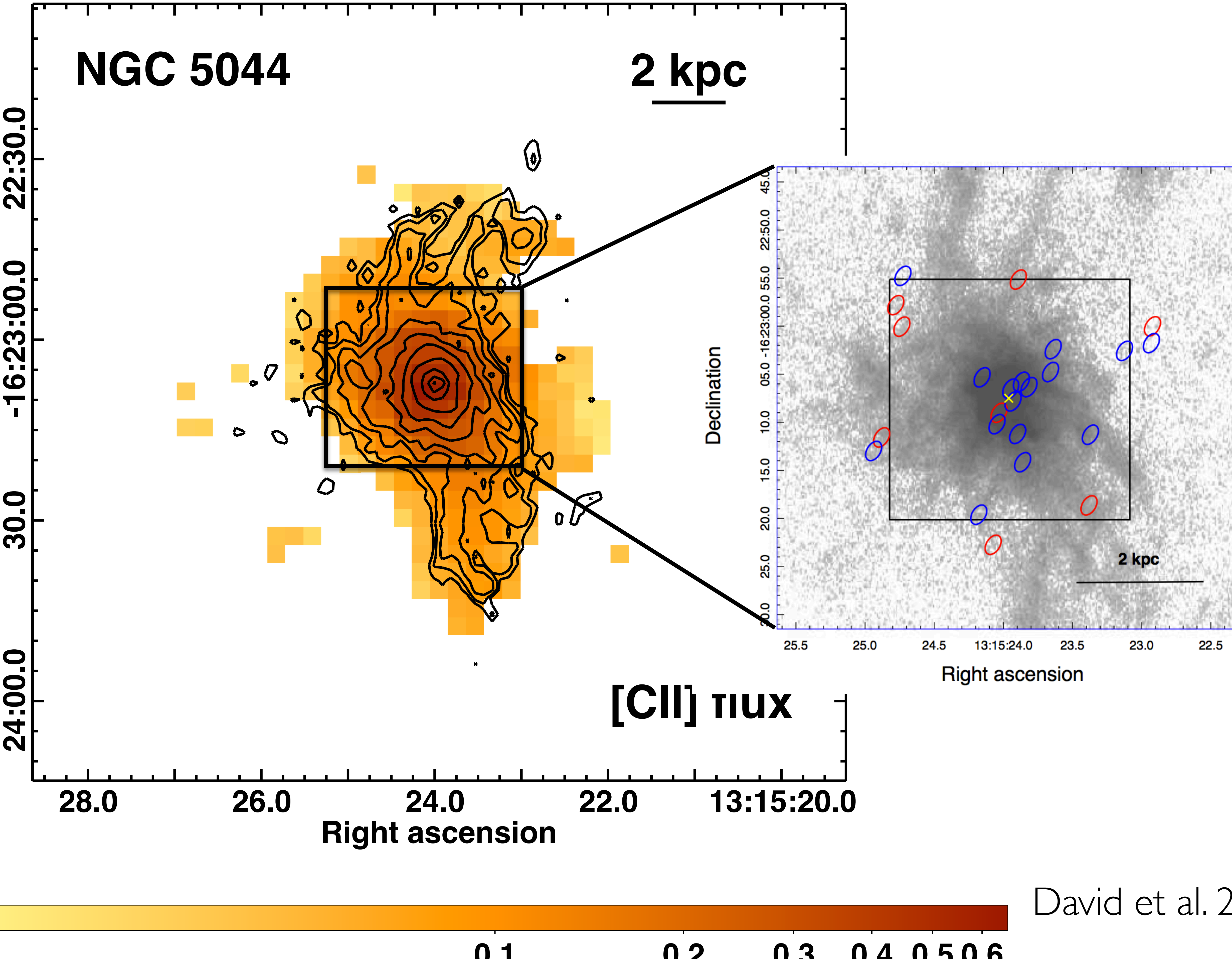


Werner et al. 2014

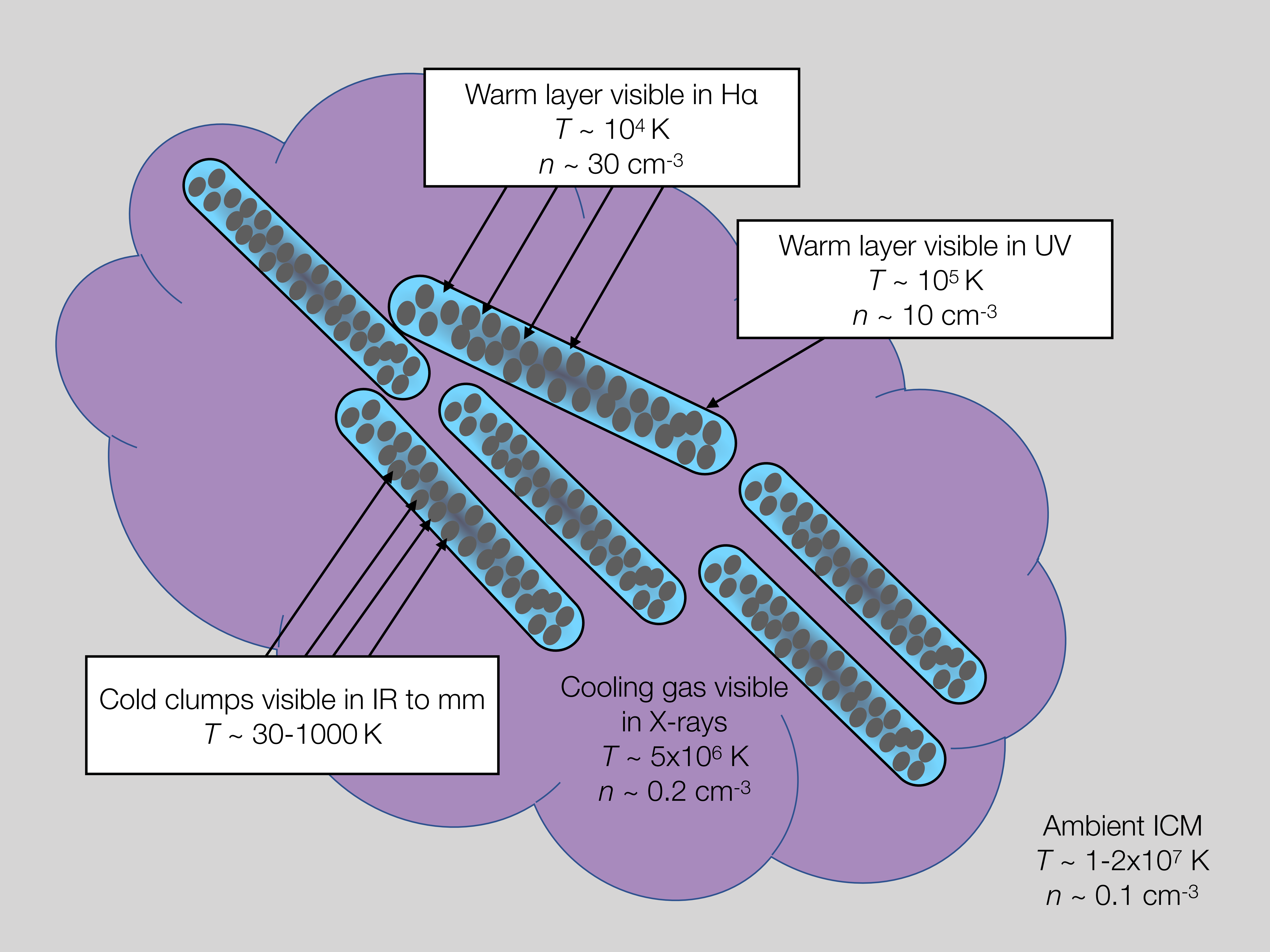
VELOCITY DISPERSIONS IN THE COLD ISM



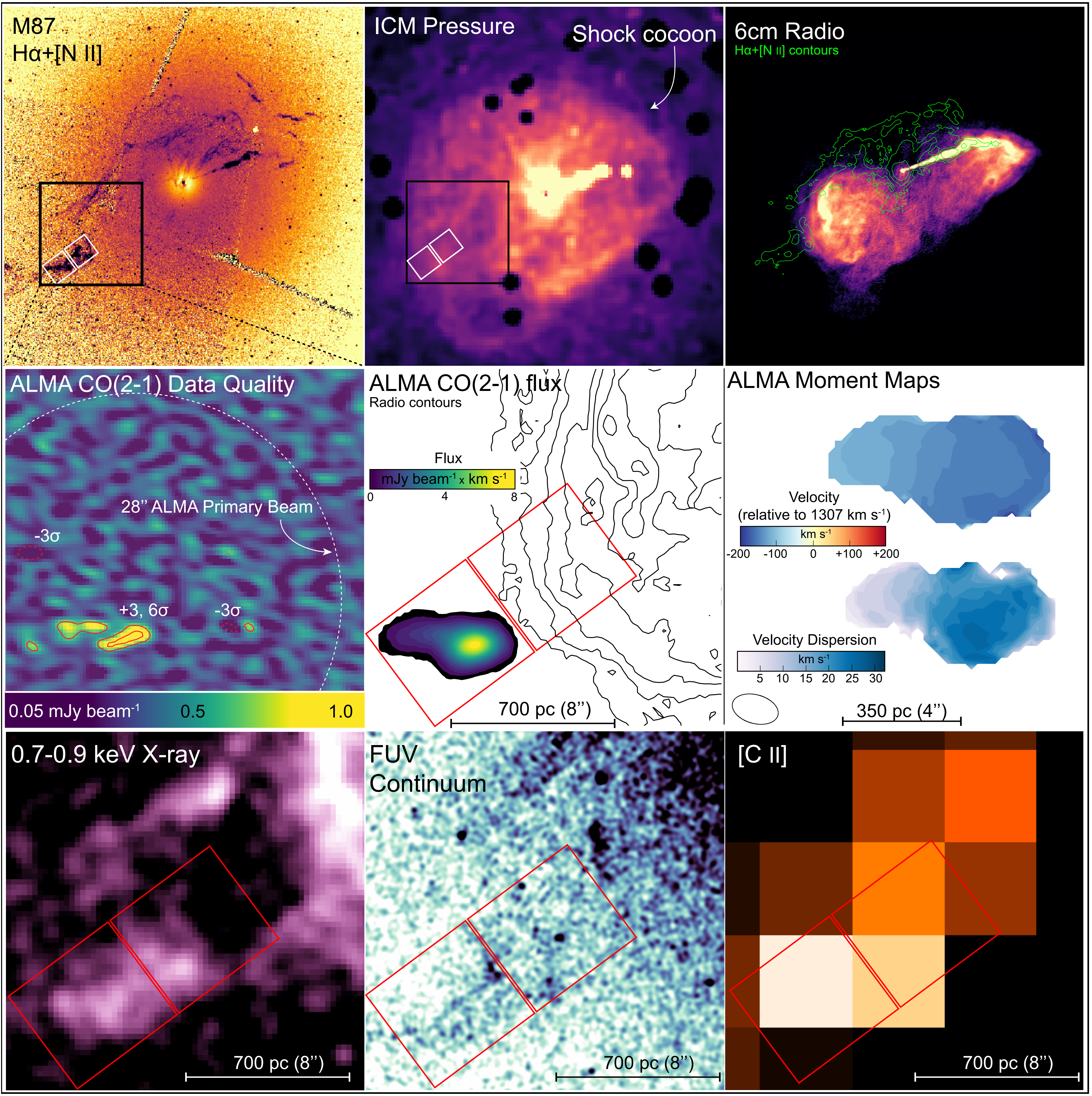
Werner et al. 2014



David et al. 2014

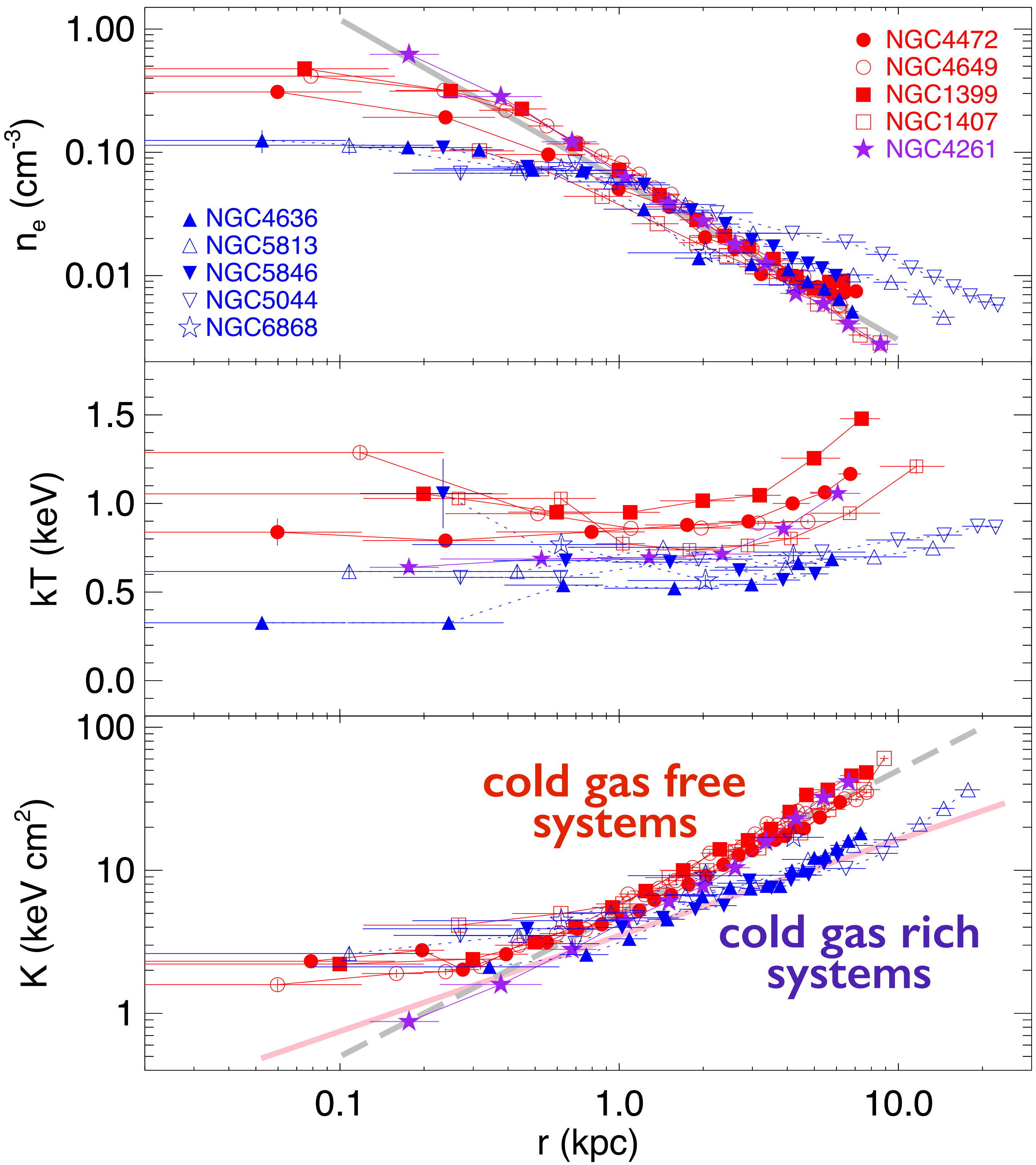

Warm layer visible in Hα
$T \sim 10^4$ K
$n \sim 30$ cm^{-3}
Warm layer visible in UV
$T \sim 10^5$ K
$n \sim 10$ cm^{-3}
Cold clumps visible in IR to mm
$T \sim 30$-1000 K
Cooling gas visible
in X-rays
$T \sim 5\text{x}10^6$ K
$n \sim 0.2$ cm^{-3}
Ambient ICM
$T \sim 1$-$2\text{x}10^7$ K
$n \sim 0.1$ cm^{-3}

DESTRUCTION OF MOLECULAR GAS BY RADIO LOBES



Simionescu et al. 2018

PROPERTIES OF THE HOT ISM

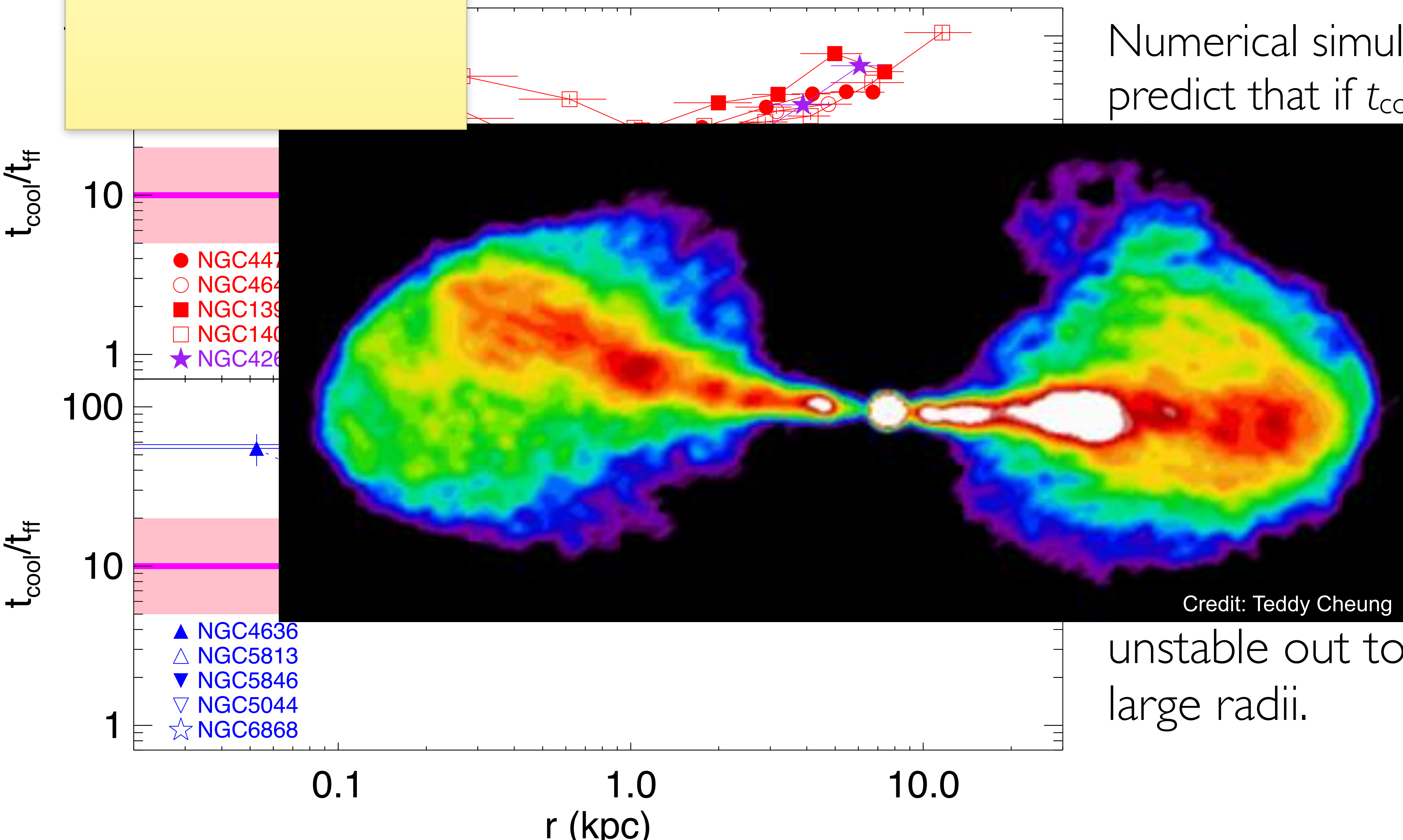


Outside of the innermost core, the entropy and temperature of systems containing cold gas is lower

Werner et al. 2014
Voit et al. 2015

COLD GAS RICH SYSTEMS PRONE TO COOLING INSTABILITIES

simulation?
Eliot student plot… ?

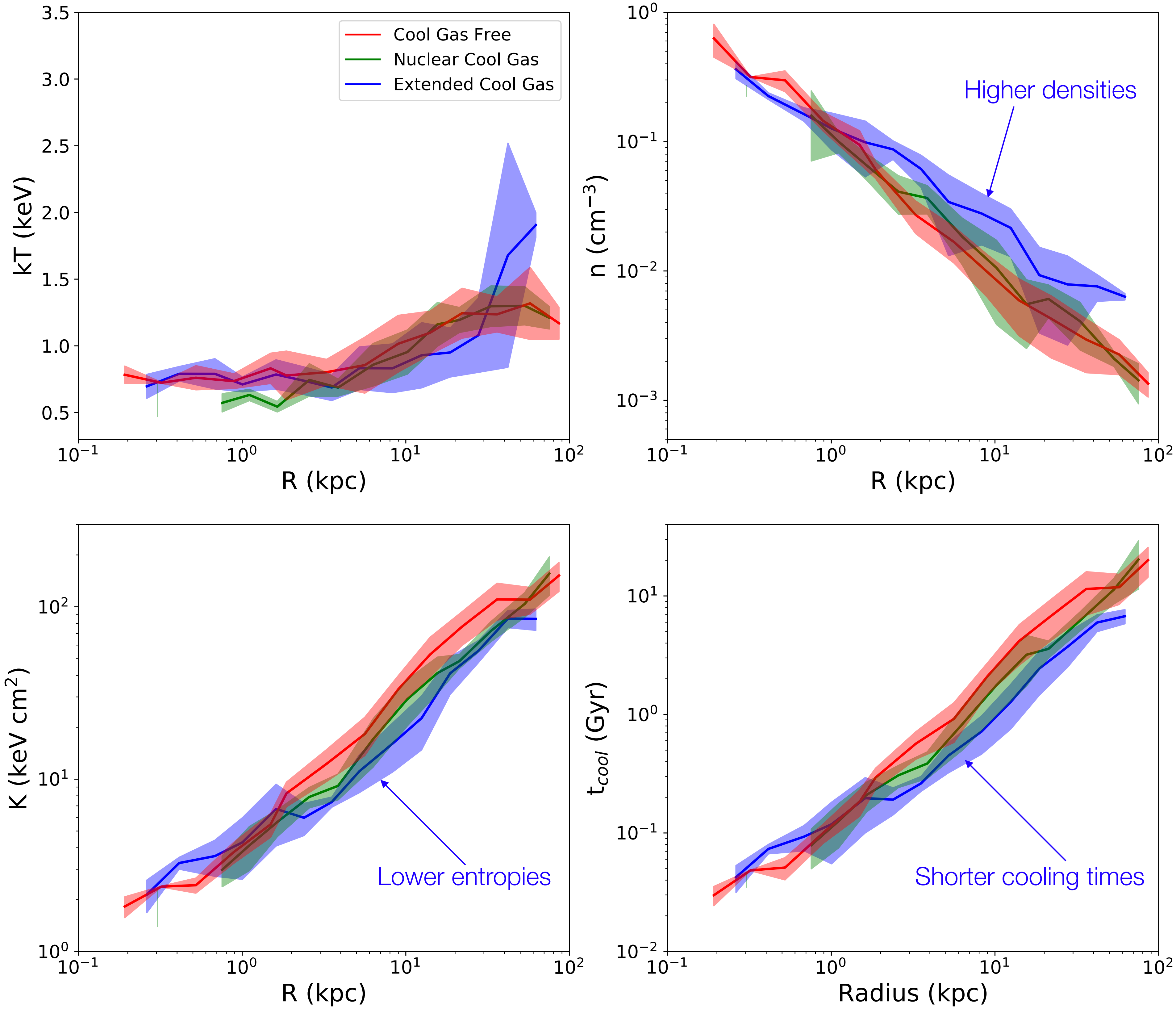


Numerical simulations predict that if $t_{cool}/t_{ff} \lesssim 10$,
tabilities will
ase medium
12, 2013,
2, McCourt

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

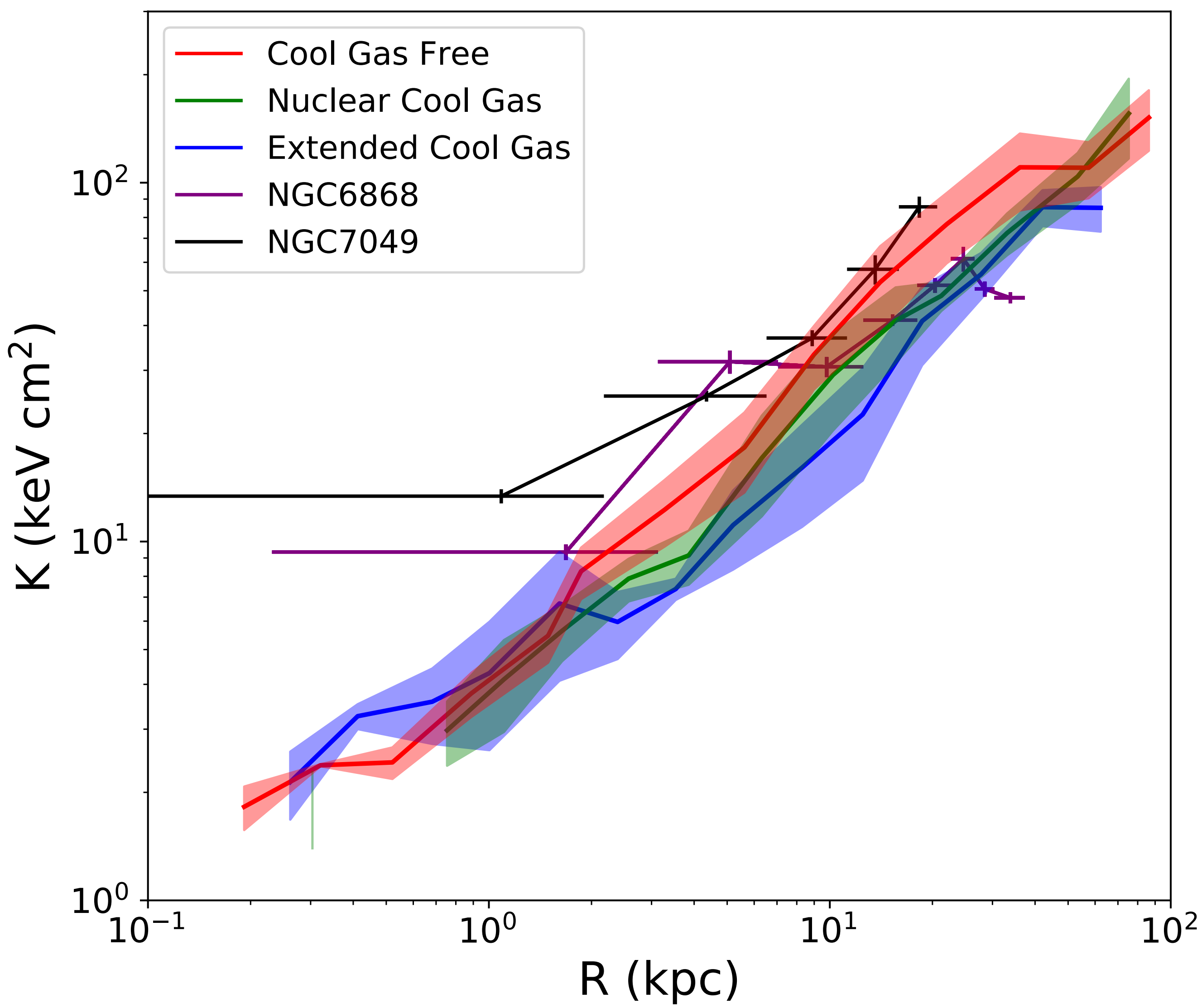
Werner et al. 2014
Voit et al. 2015

Cooling vs. Heating in galactic atmospheres



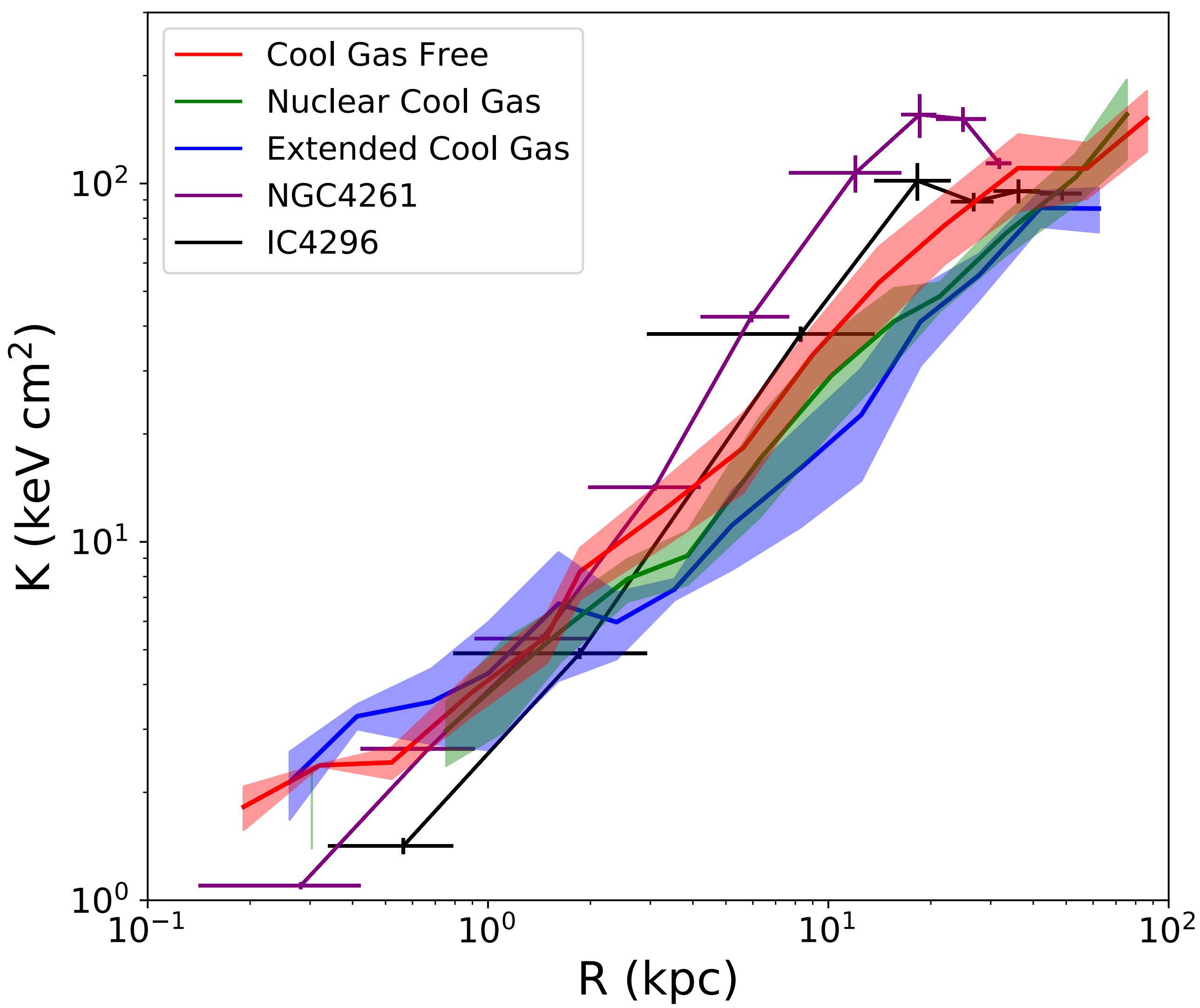
Lakhchaura et al. 2018

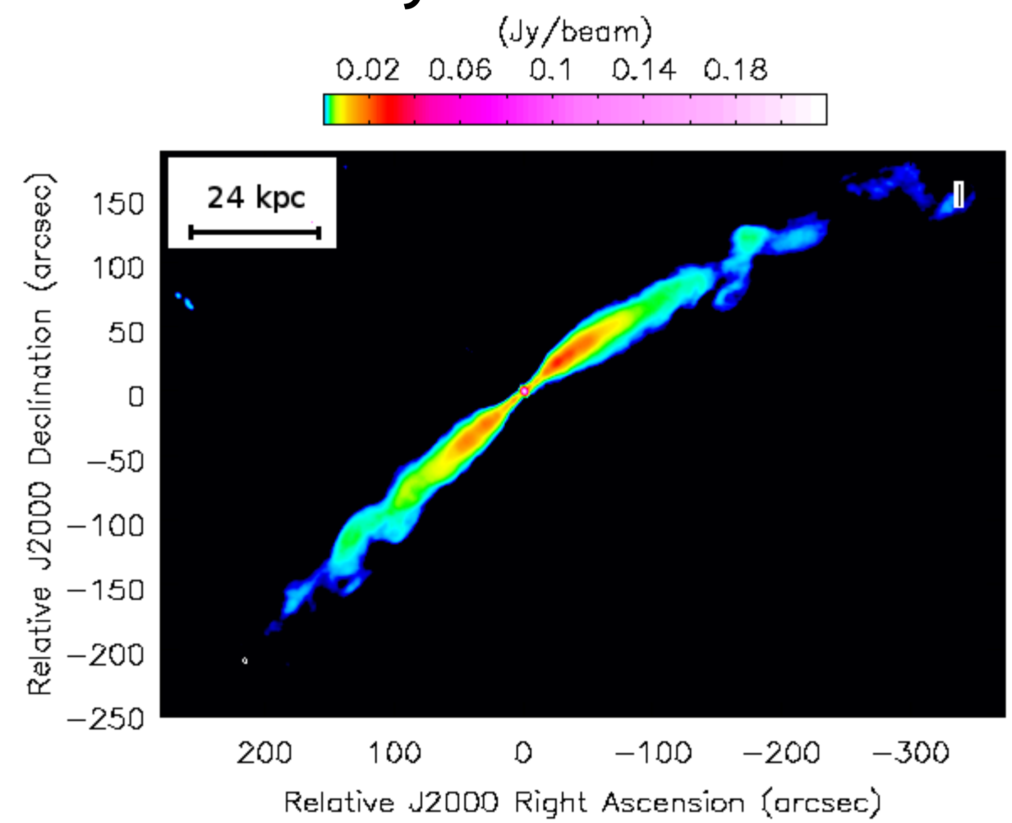
Cooling in a rotating X-ray atmosphere

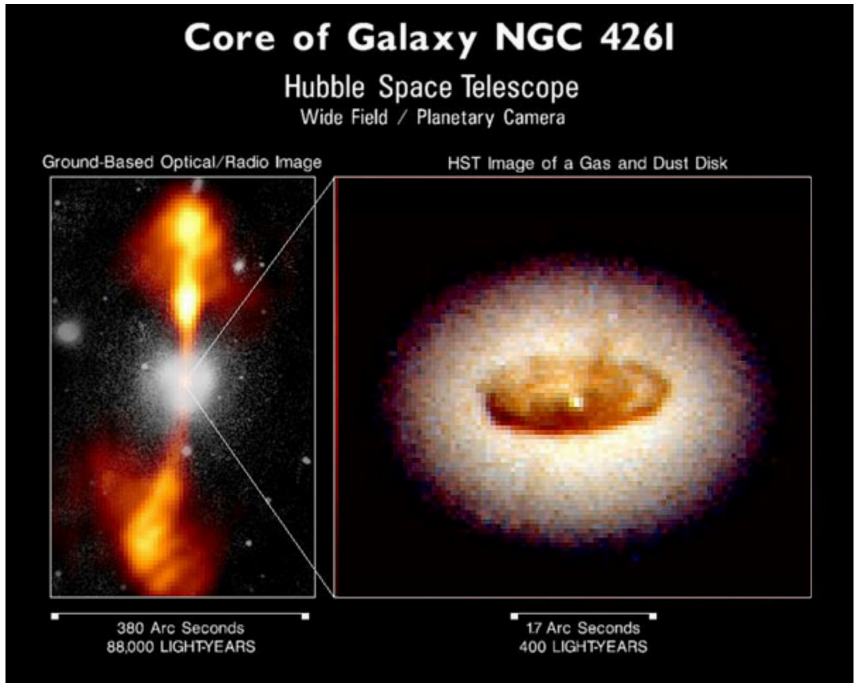


Juráňová et al. 2018.

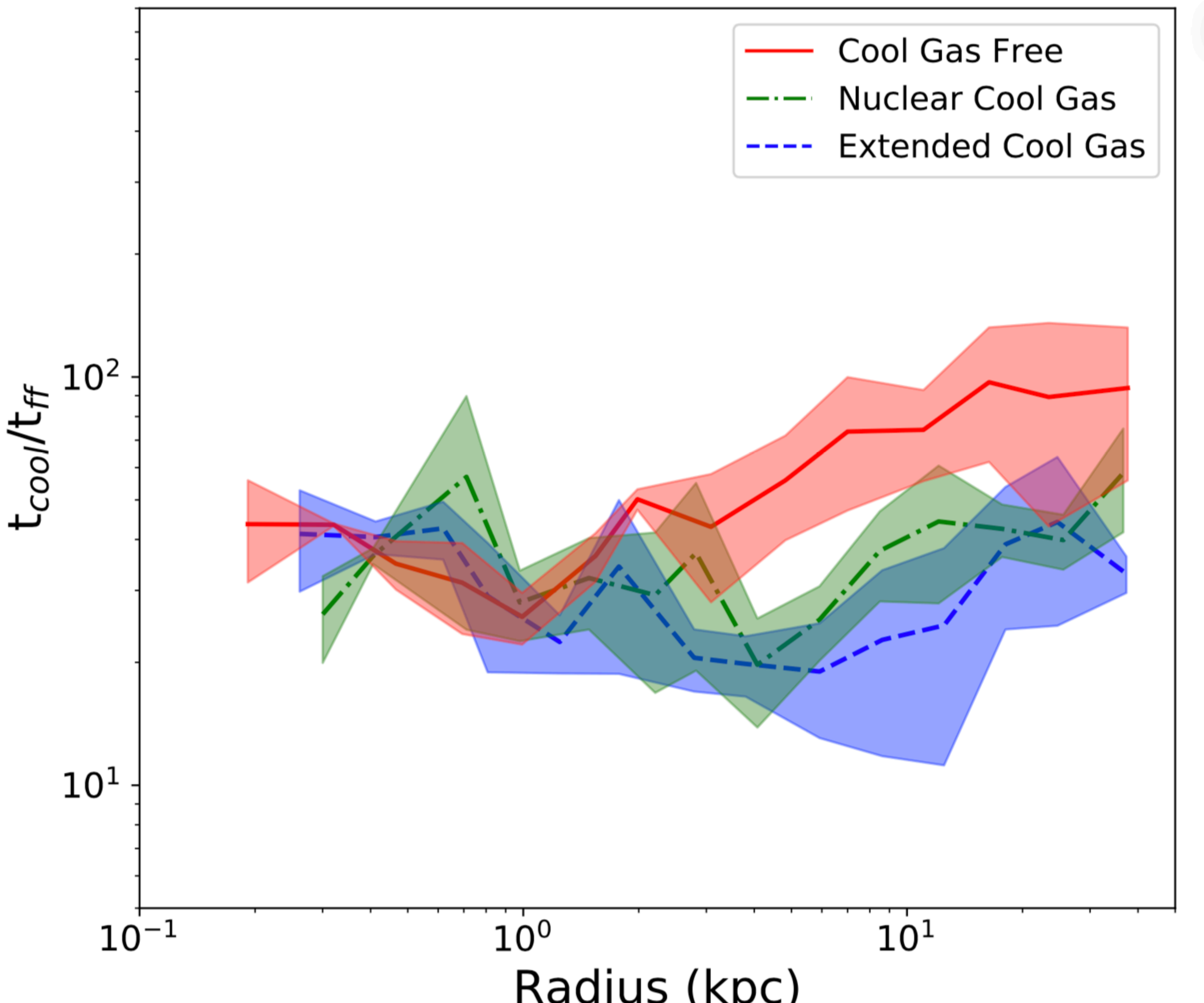
Unusually steep entropy profiles in systems with powerful jets



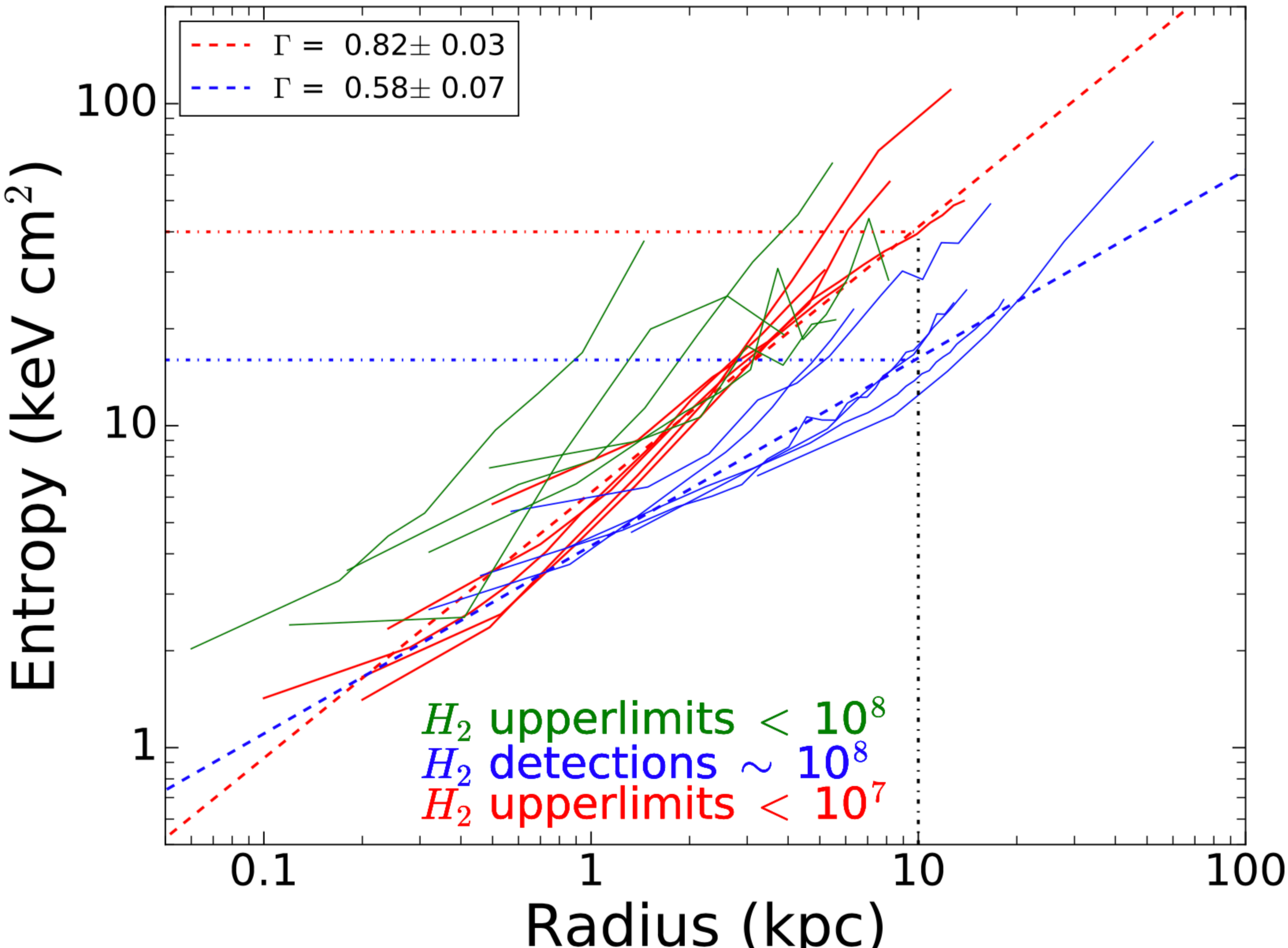




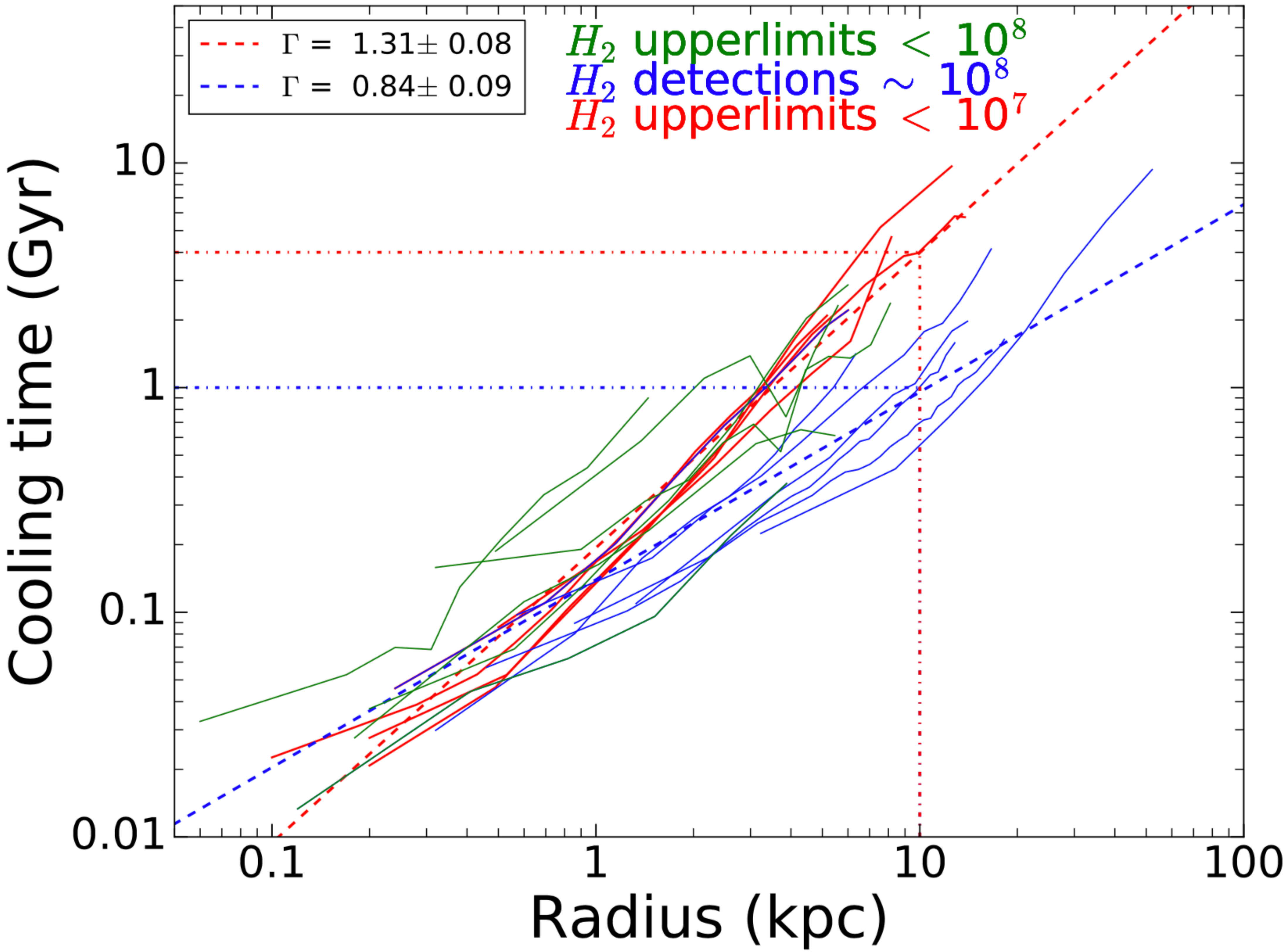
Grossova et al. 2018.



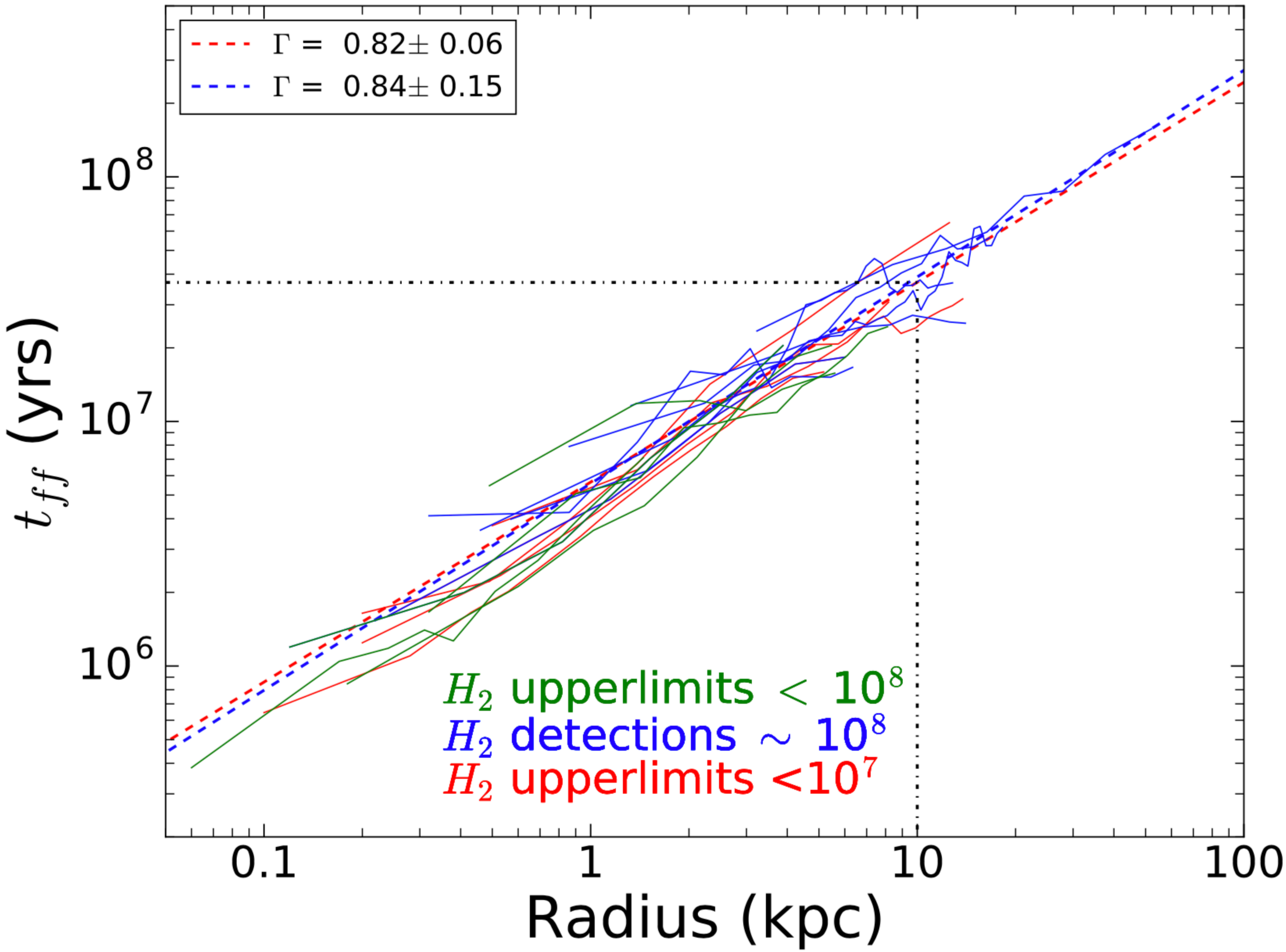
Lakhchaura et al. 2018



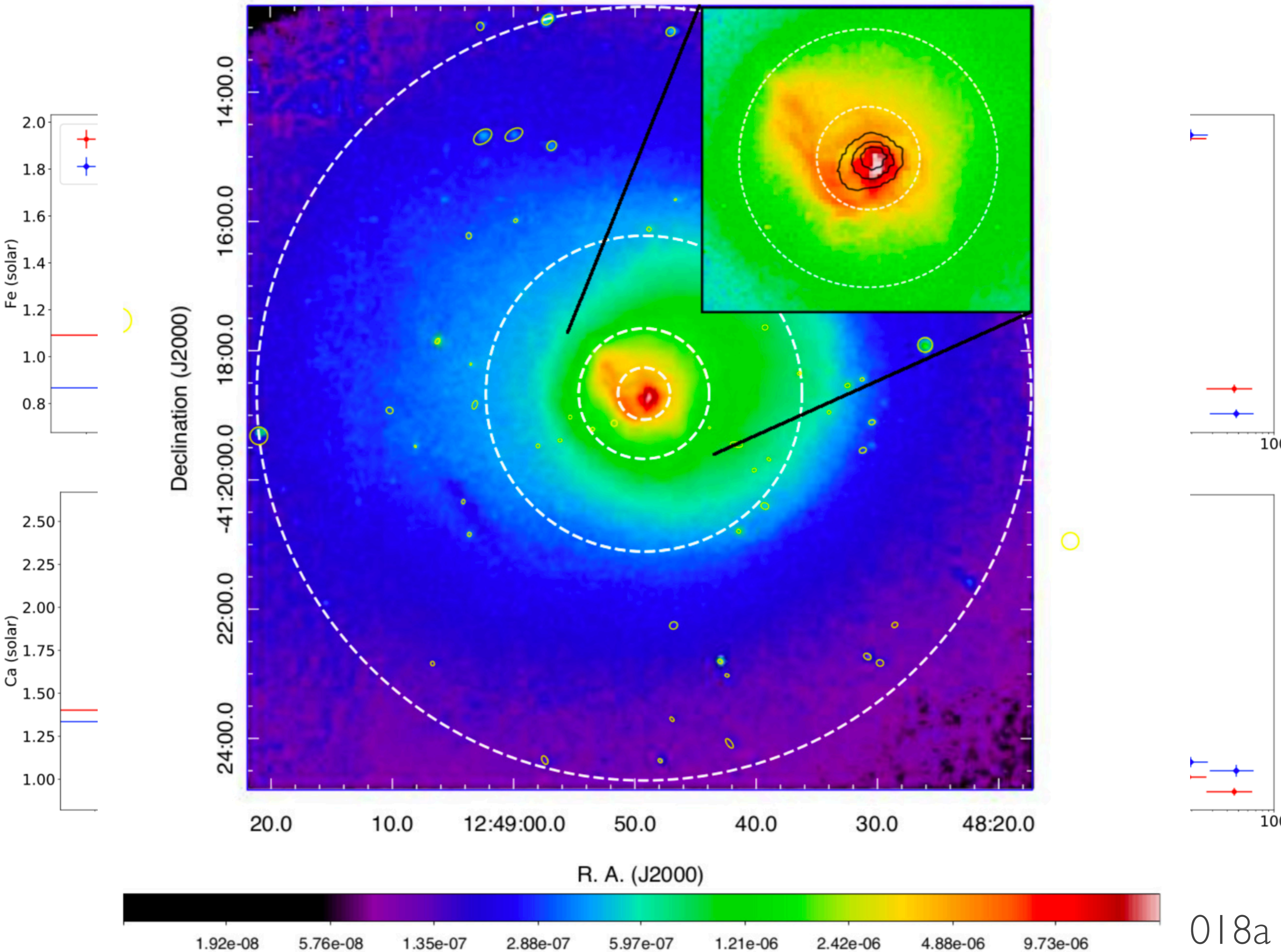
Babyk et al. 2018



Lakhchaura et al. 2018



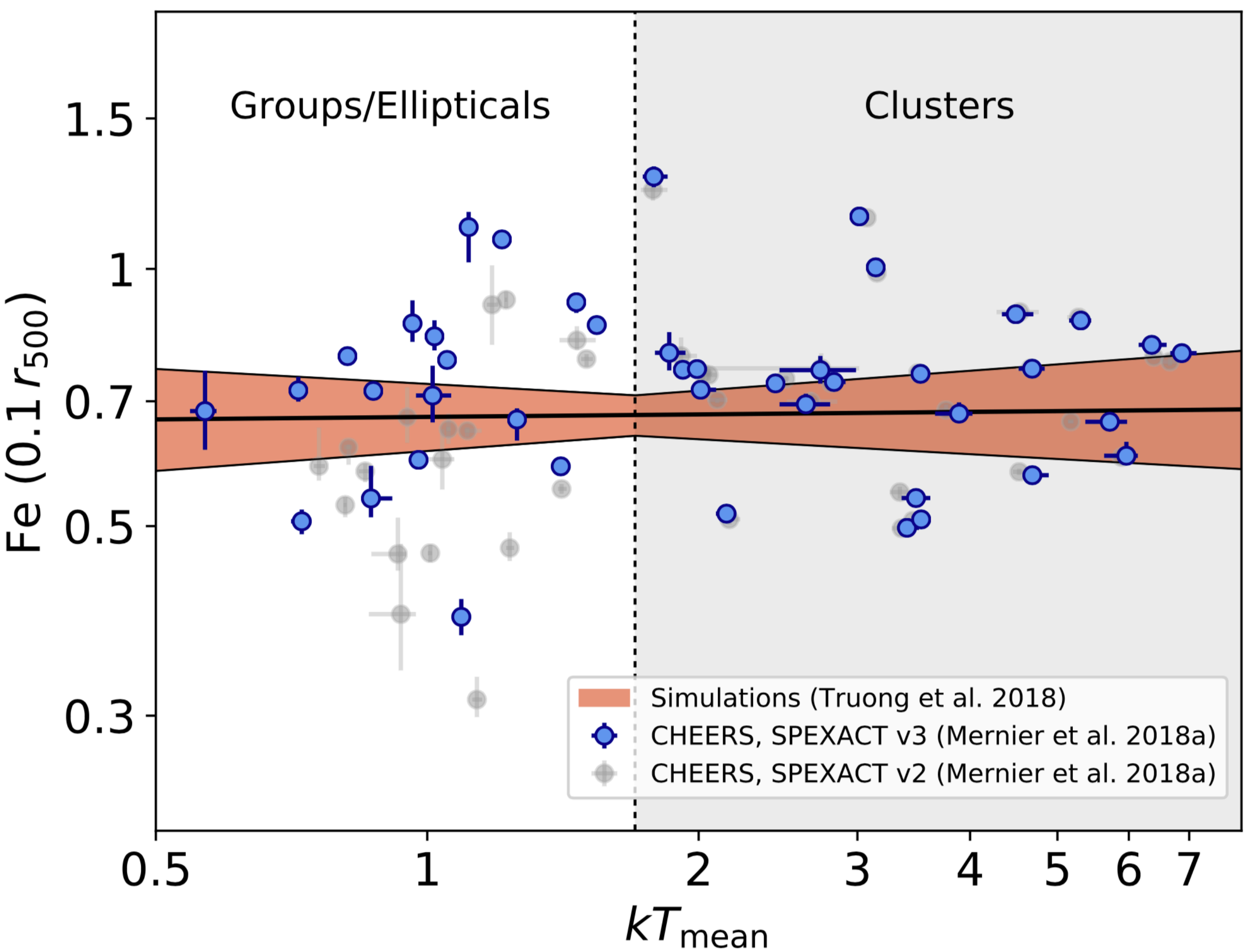
Lakhchaura et al. 2018



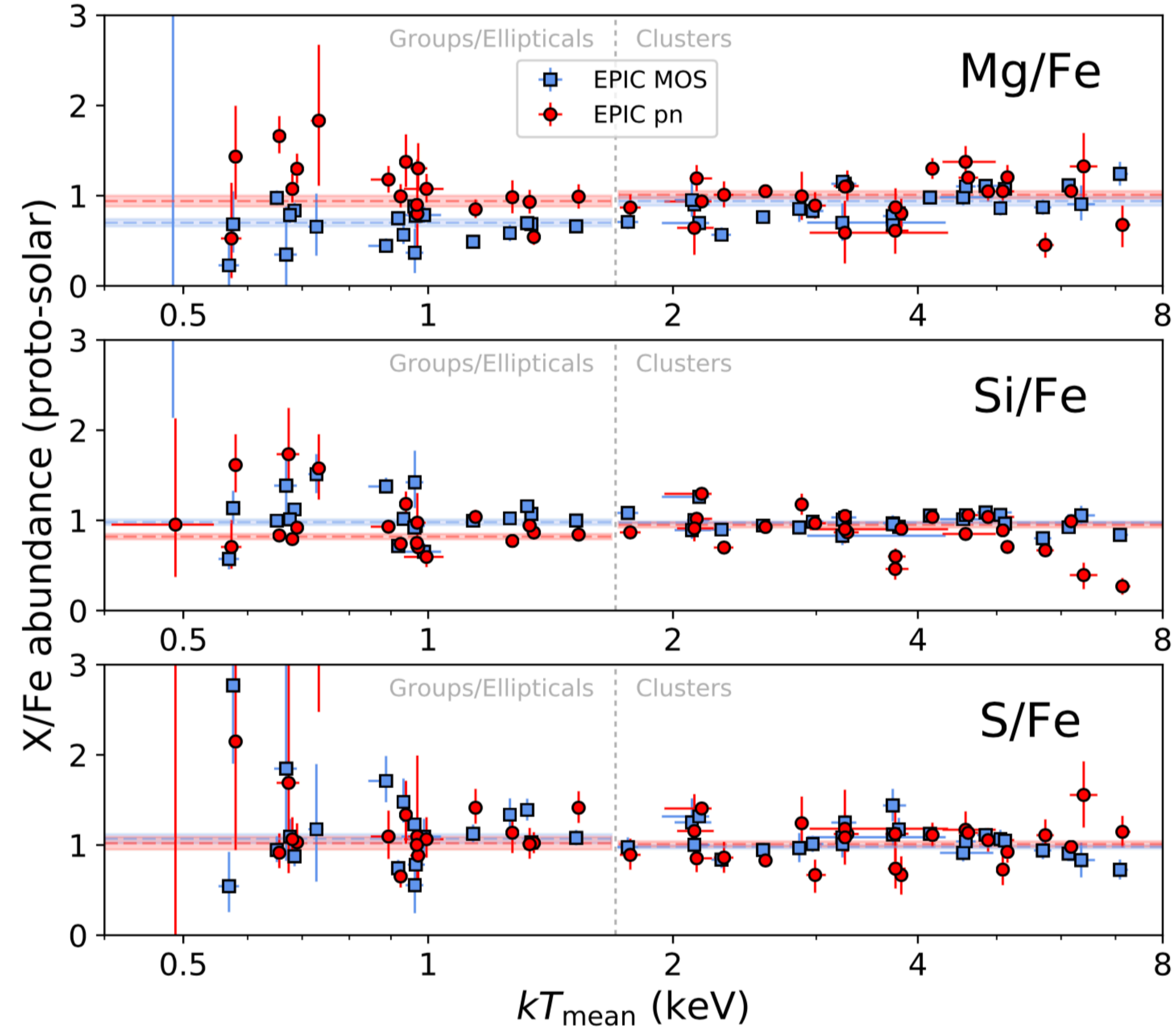
Fe (solar)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
Ca (solar)
2.50
2.25
2.00
1.75
1.50
1.25
1.00
Declination (J2000)
14:00.0
16:00.0
18:00.0
-41:20:00.0
22:00.0
24:00.0
20.0
10.0
12:49:00.0
50.0
40.0
30.0
48:20.0
R. A. (J2000)
1.92e-08
5.76e-08
1.35e-07
2.88e-07
5.97e-07
1.21e-06
2.42e-06
4.88e-06
9.73e-06
100
100

018a

Atmospheres of early type galaxies were accreted externally (and augmented by stellar mass loss)



Mernier et al. 2018a

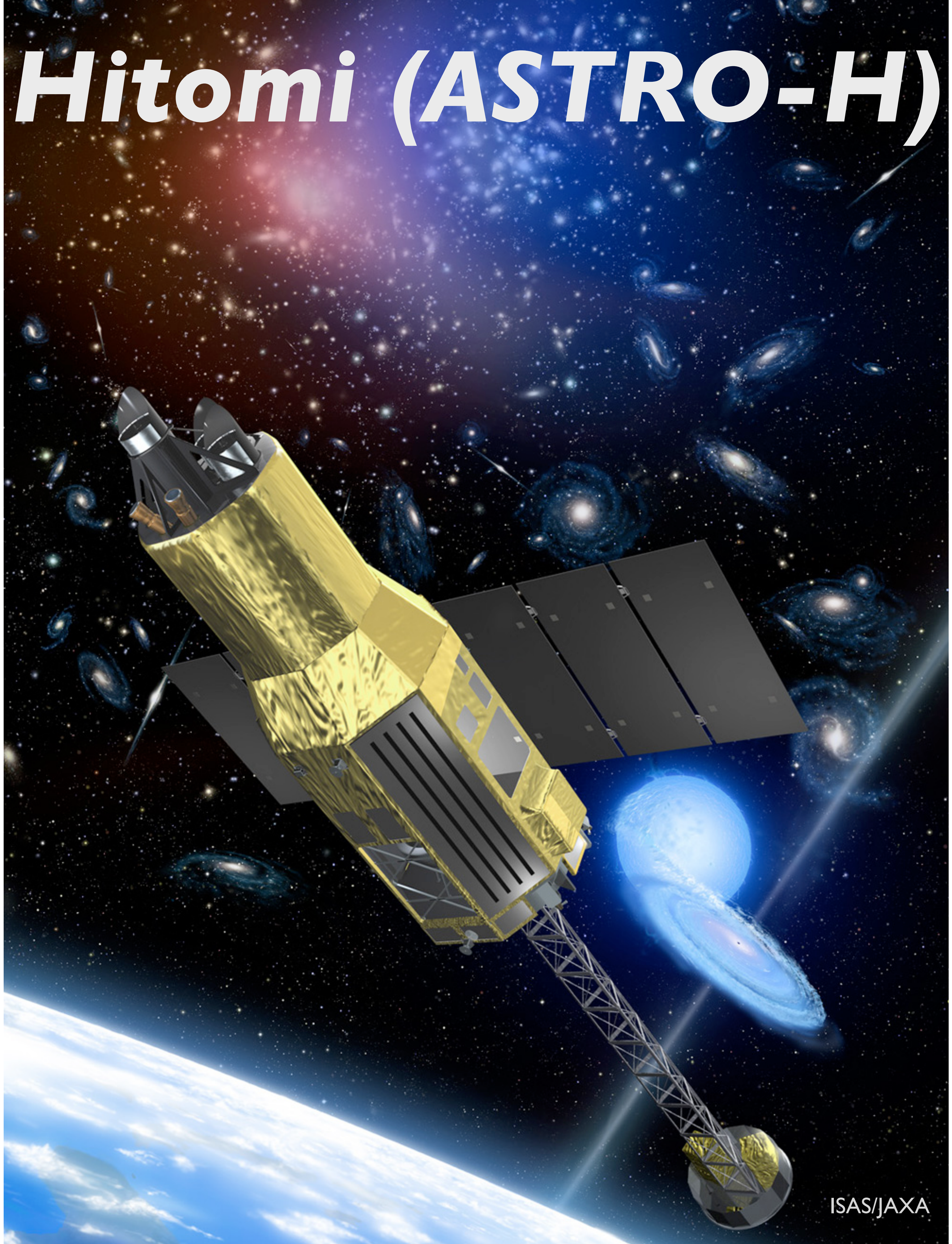


Mernier et al. 2018b
see also de Plaa et al. 2017

Hitomi (ASTRO-H)

JAXA
Japan Aerospace
Exploration Agency

with a
contribution of
other Japanese
universities and
institutes



NASA

esa

SRON

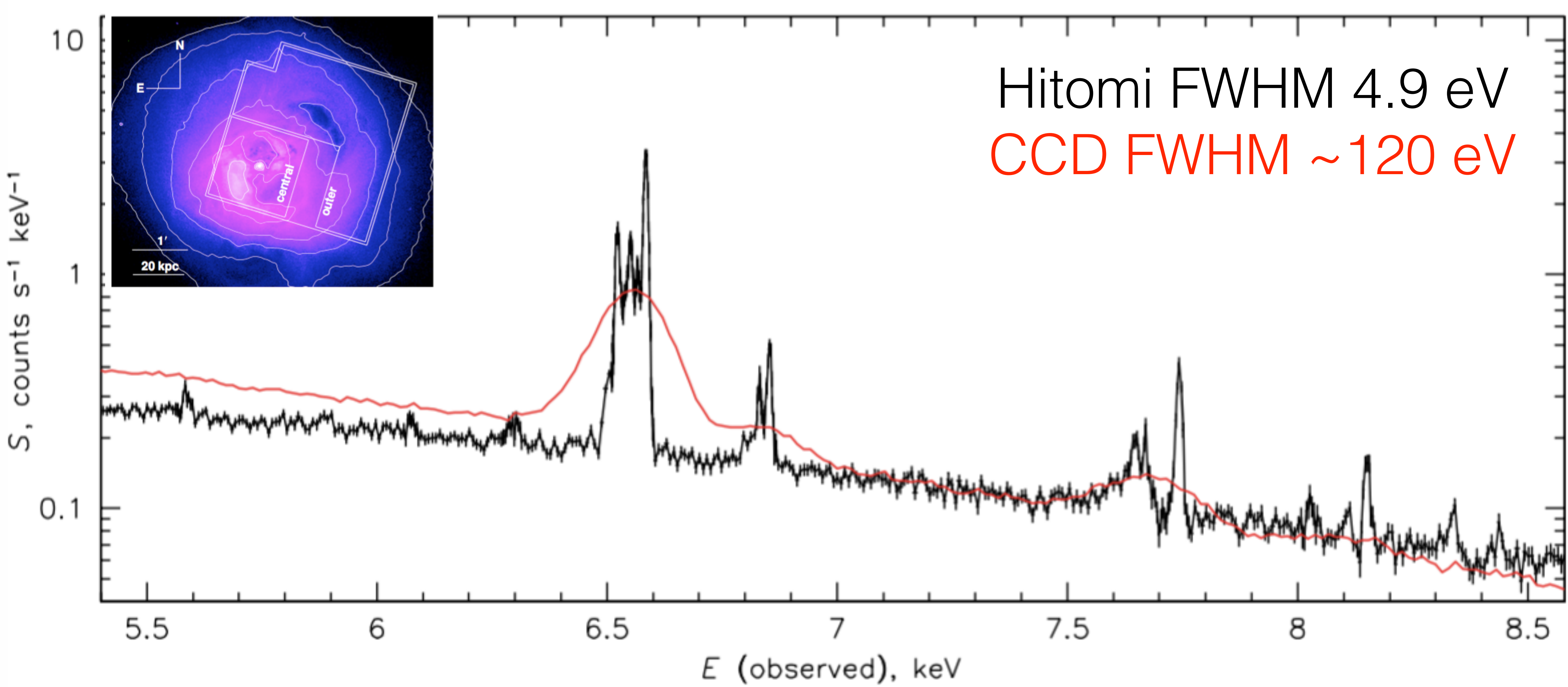
KIPAC

CSA ASC

with a
contribution of
other US/EU
universities and
institutes

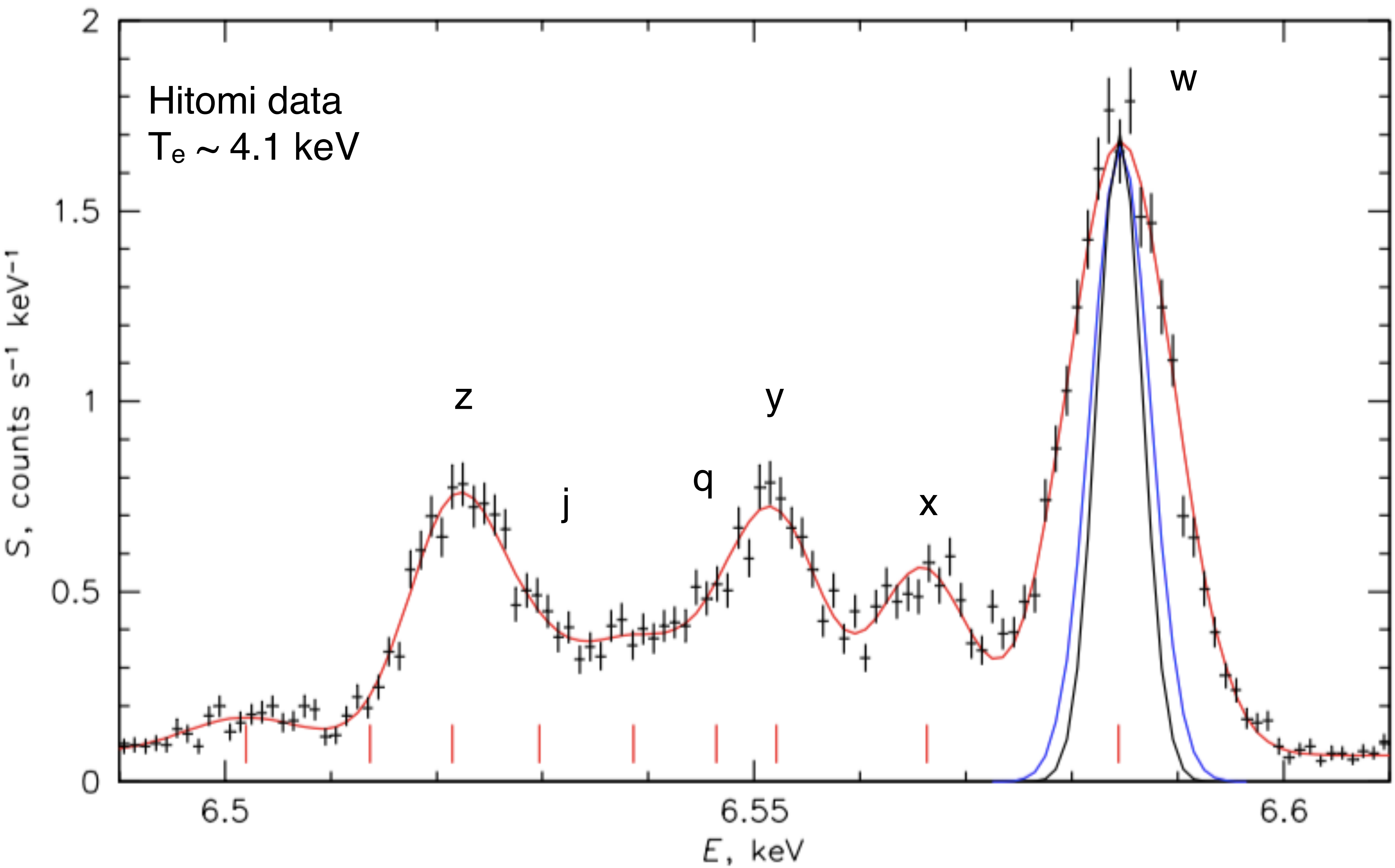
Hitomi (ASTRO-H) Observation

X-ray spectrum of the core of the Perseus cluster



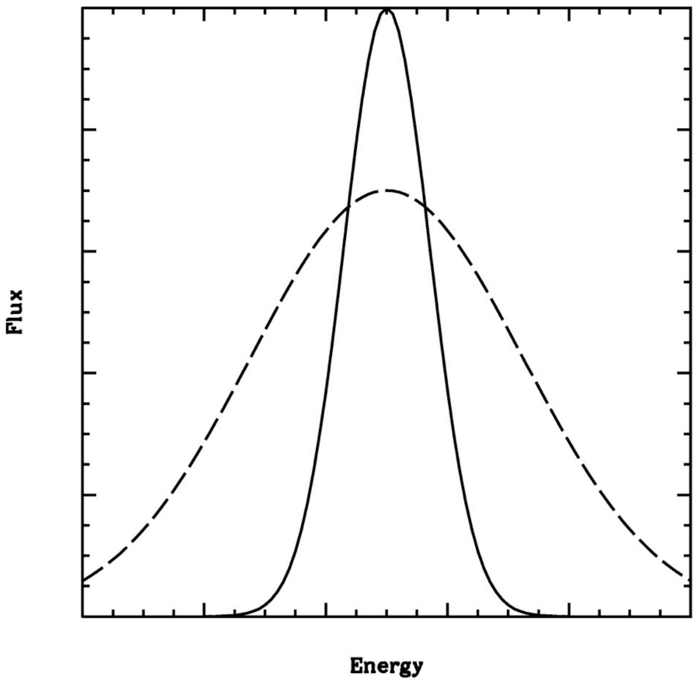
Hitomi collaboration, Nature, 2016

Fe XXV He$_\alpha$

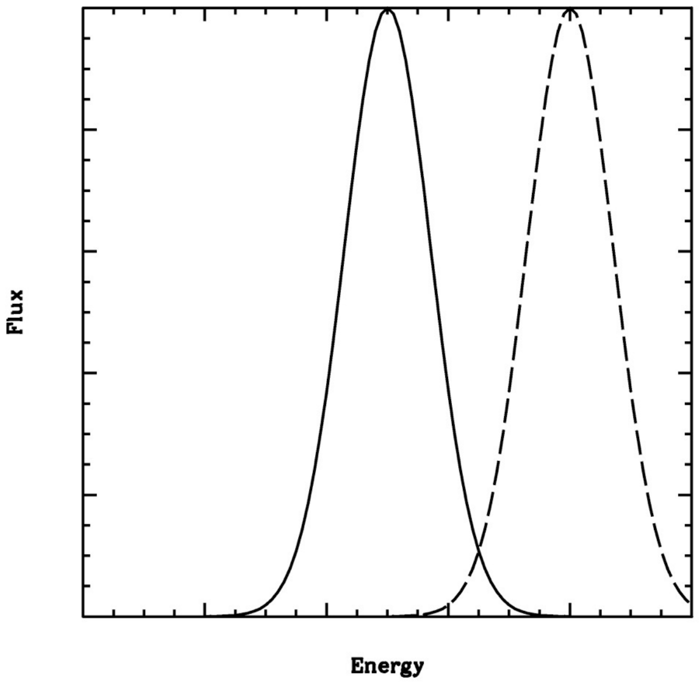


Hitomi collaboration, Nature, 2016

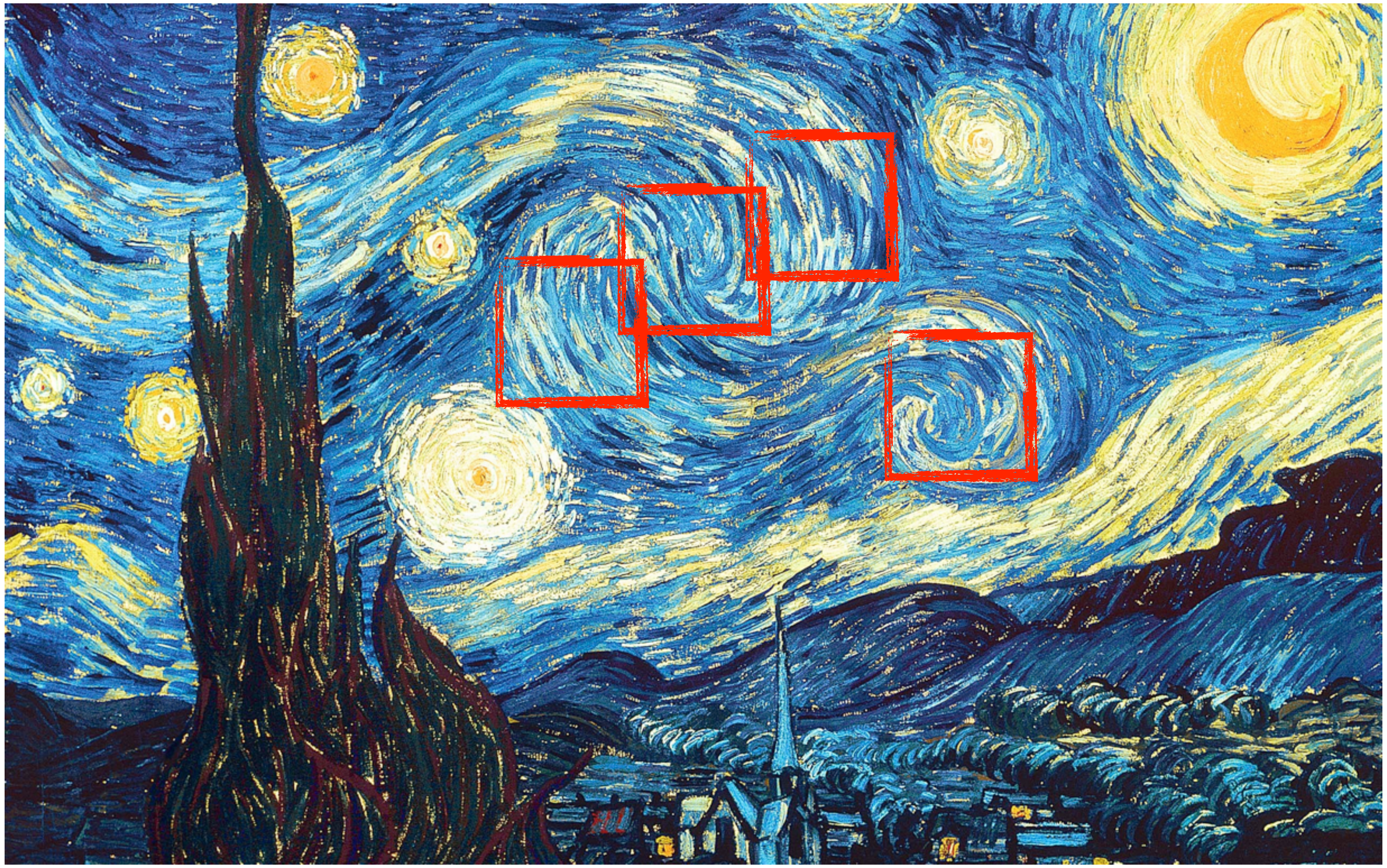
Turbulent and bulk motions



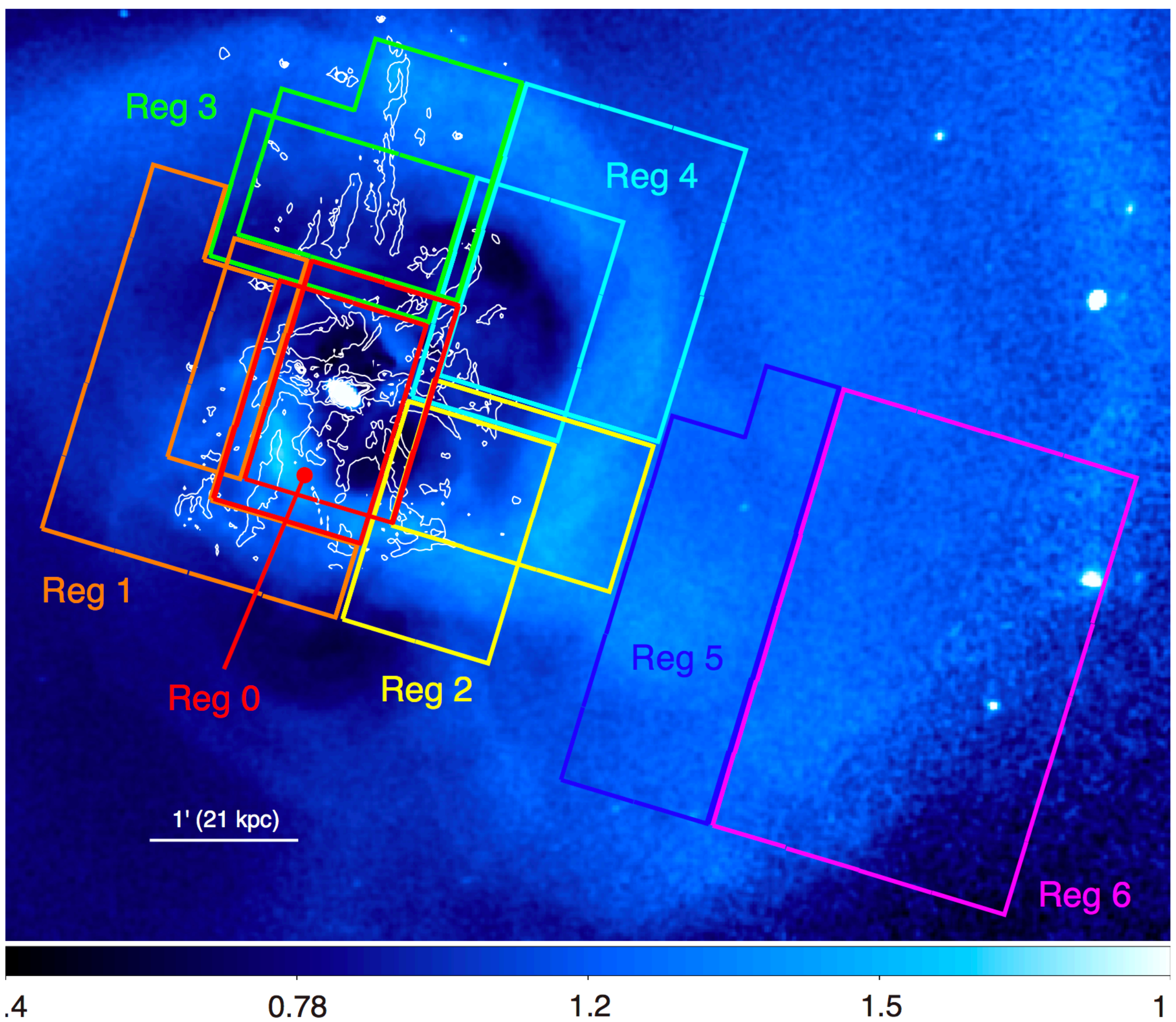
for gas motions on small spatial scales we expect significant line-of-sight velocity dispersion σ, resulting in line broadening, but no centroid shifts



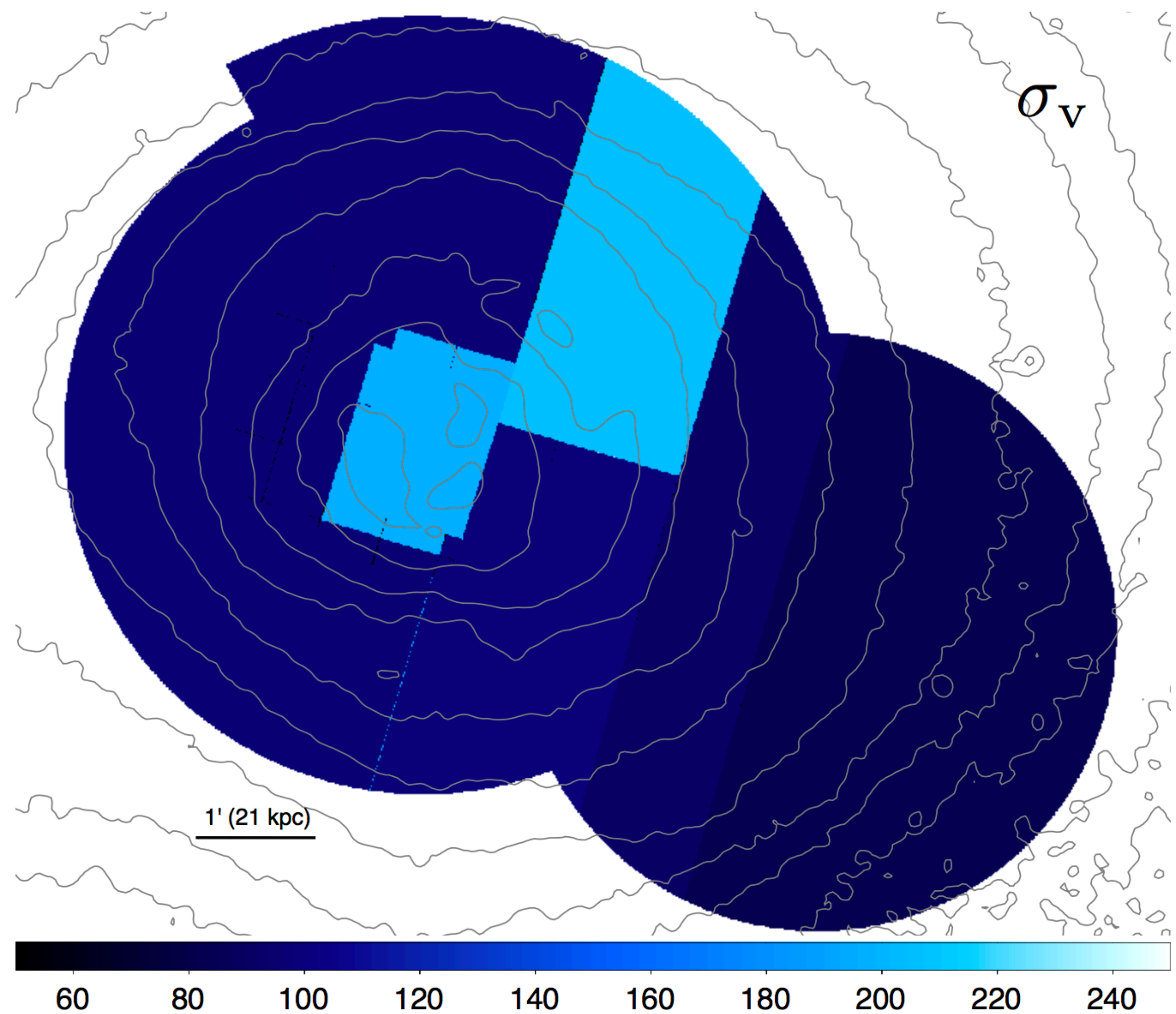
if the spatial scale of motions is large, then we expect significant centroid shifts



First Direct Velocity Measurements



line broadening

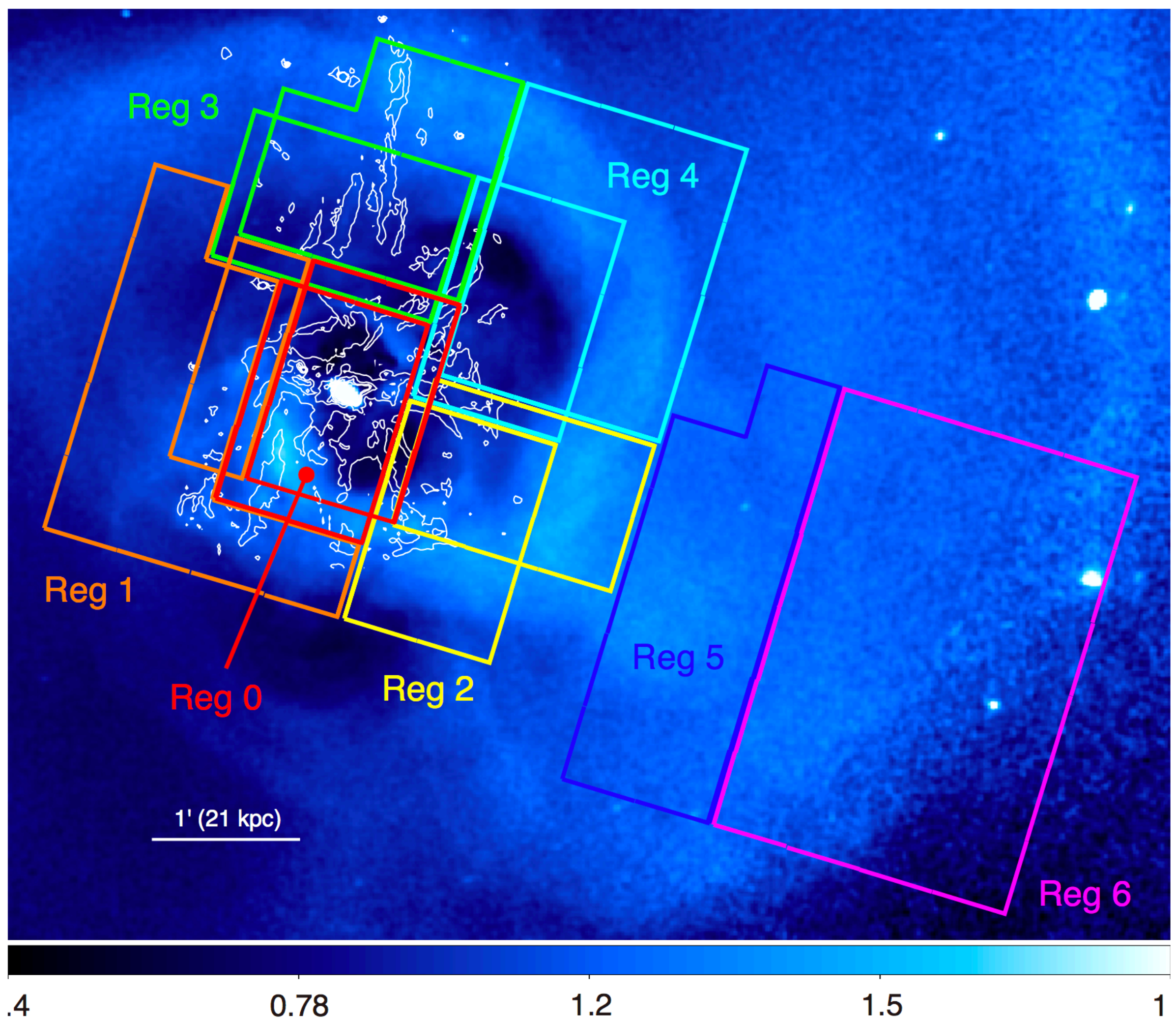


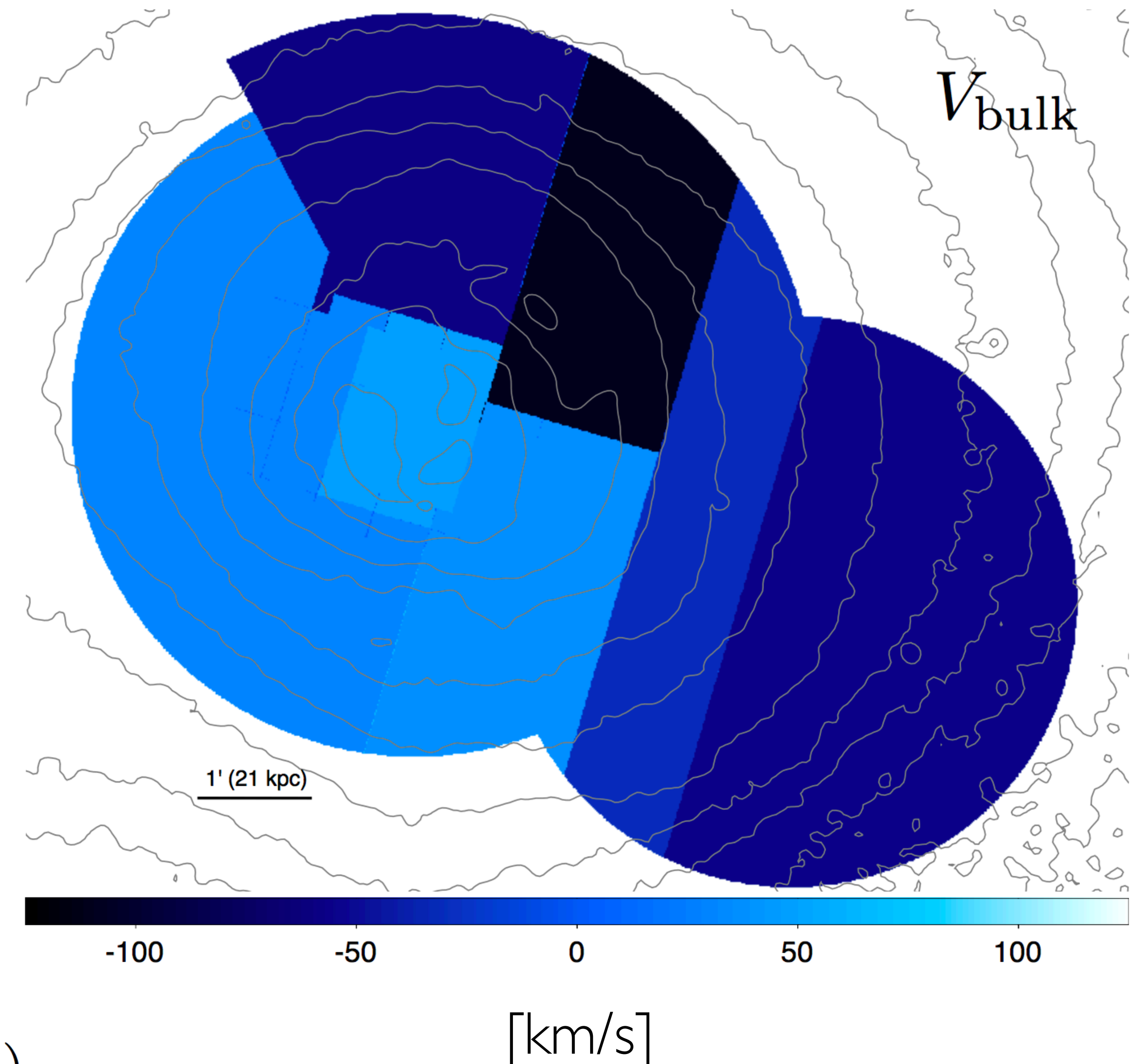
E_{turb}/E_{therm} ~ 2–6%

Hitomi collaboration, PASJ 2018

First Direct Velocity Measurements

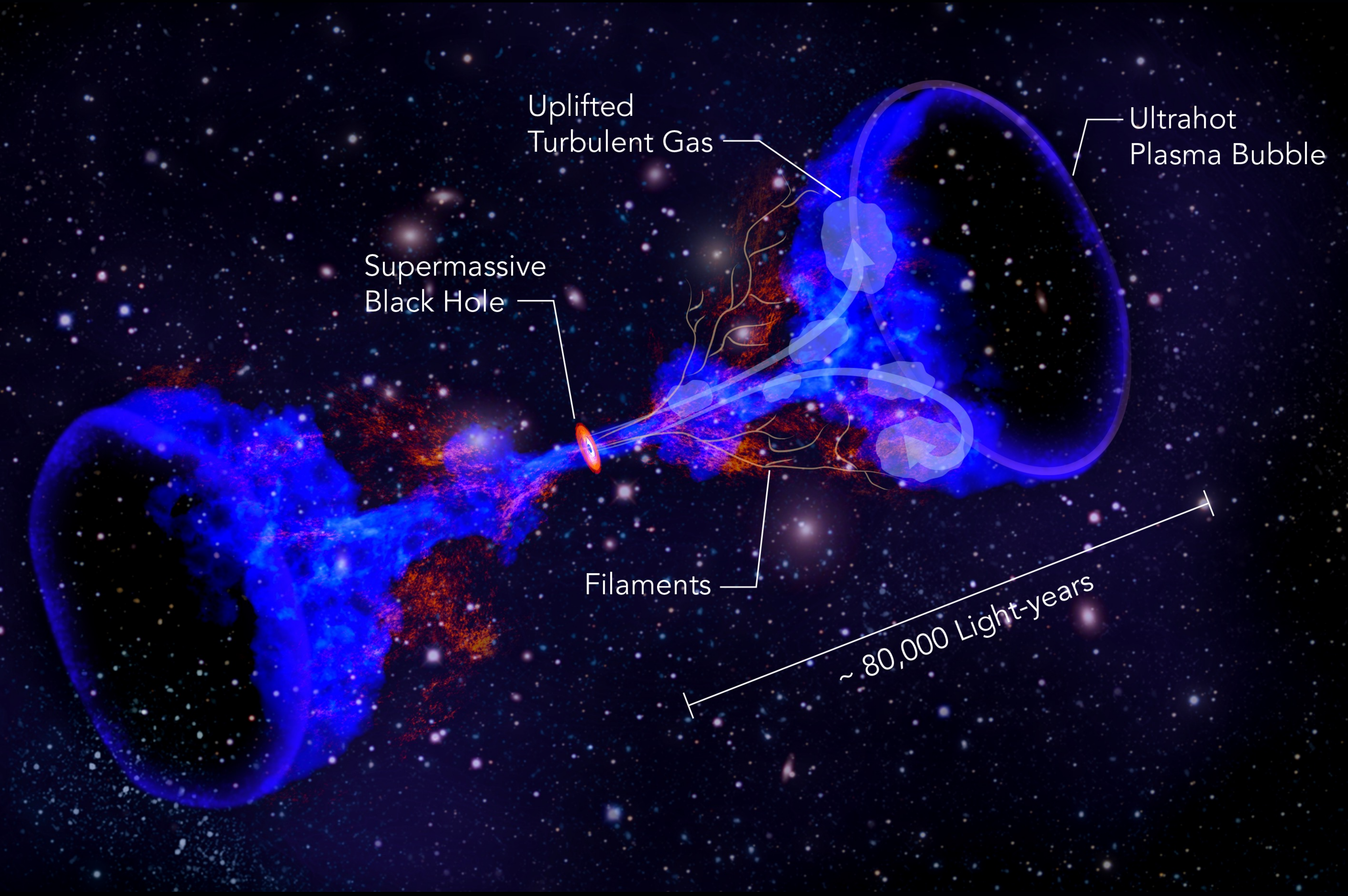
line shifts

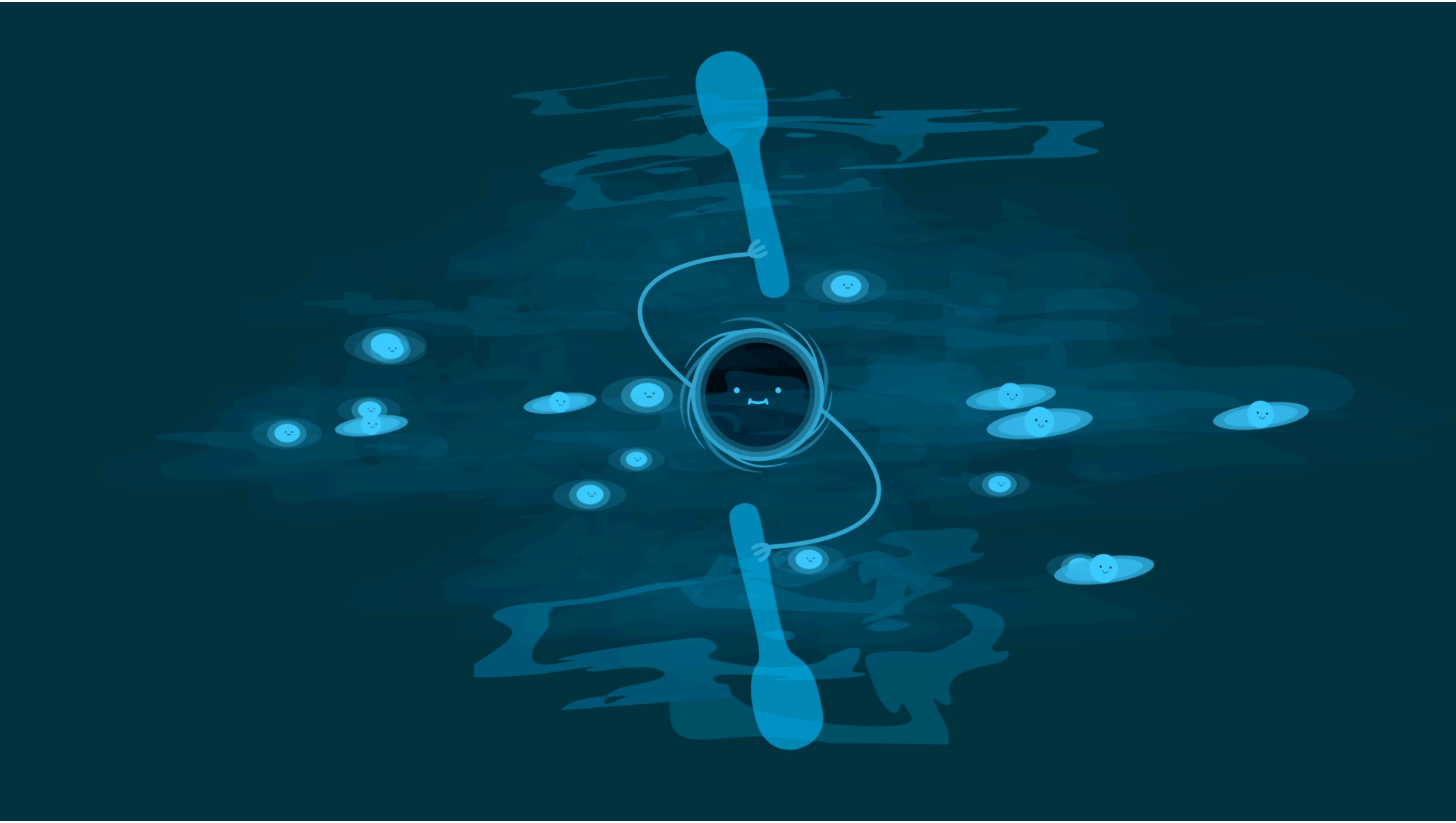




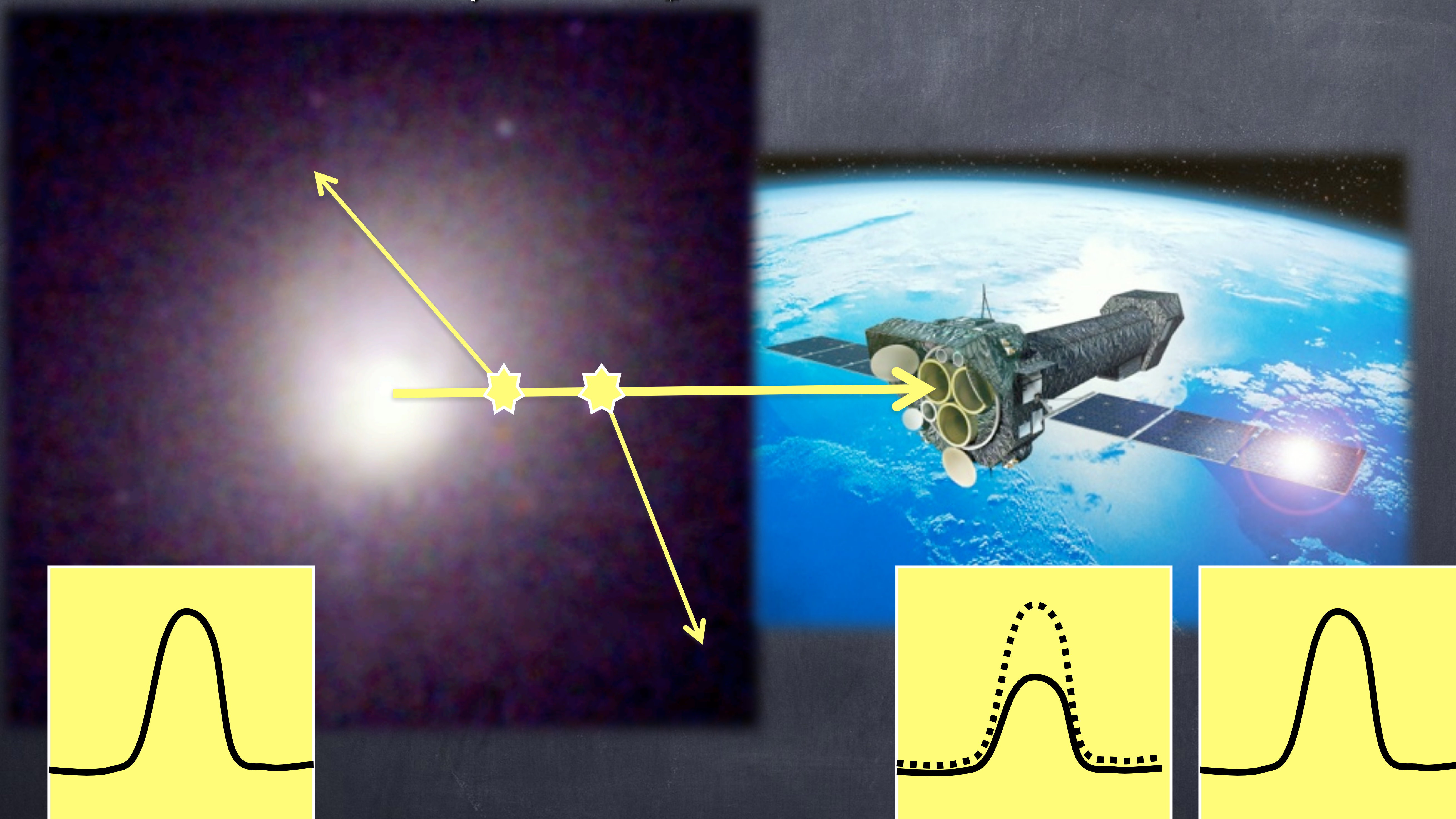
$$\frac{\epsilon_{\rm kin}}{\epsilon_{\rm therm}} = \frac{\mu m_{\rm p}(3\sigma_{\rm v}^2 + V_{\rm bulk}^2)}{3kT} \sim 0.02 - 0.07$$

Hitomi collaboration, PASJ 2018

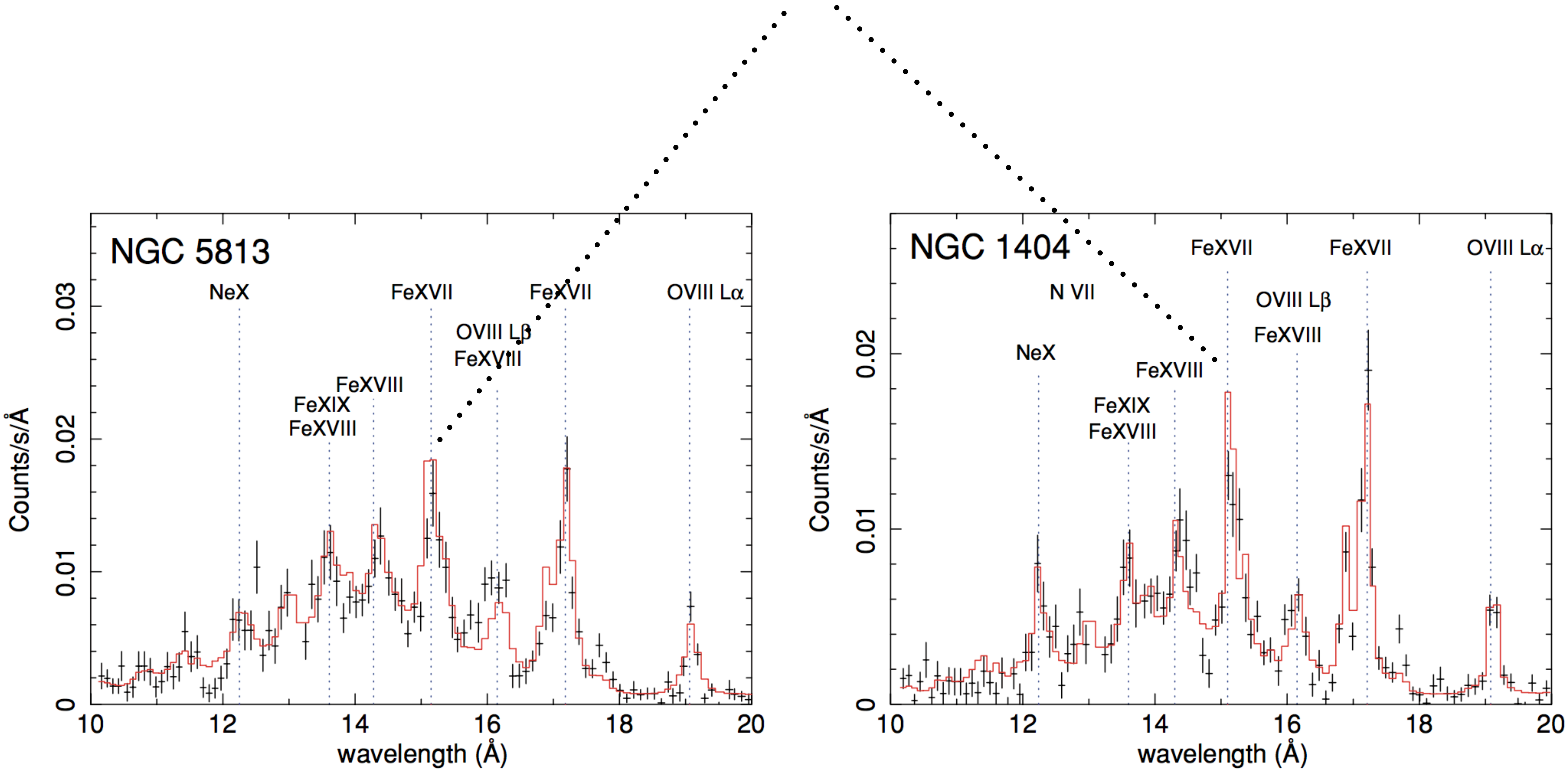

Uplifted
Turbulent Gas
Ultrahot
Plasma Bubble
Supermassive
Black Hole
Filaments
~ 80,000 Light-years

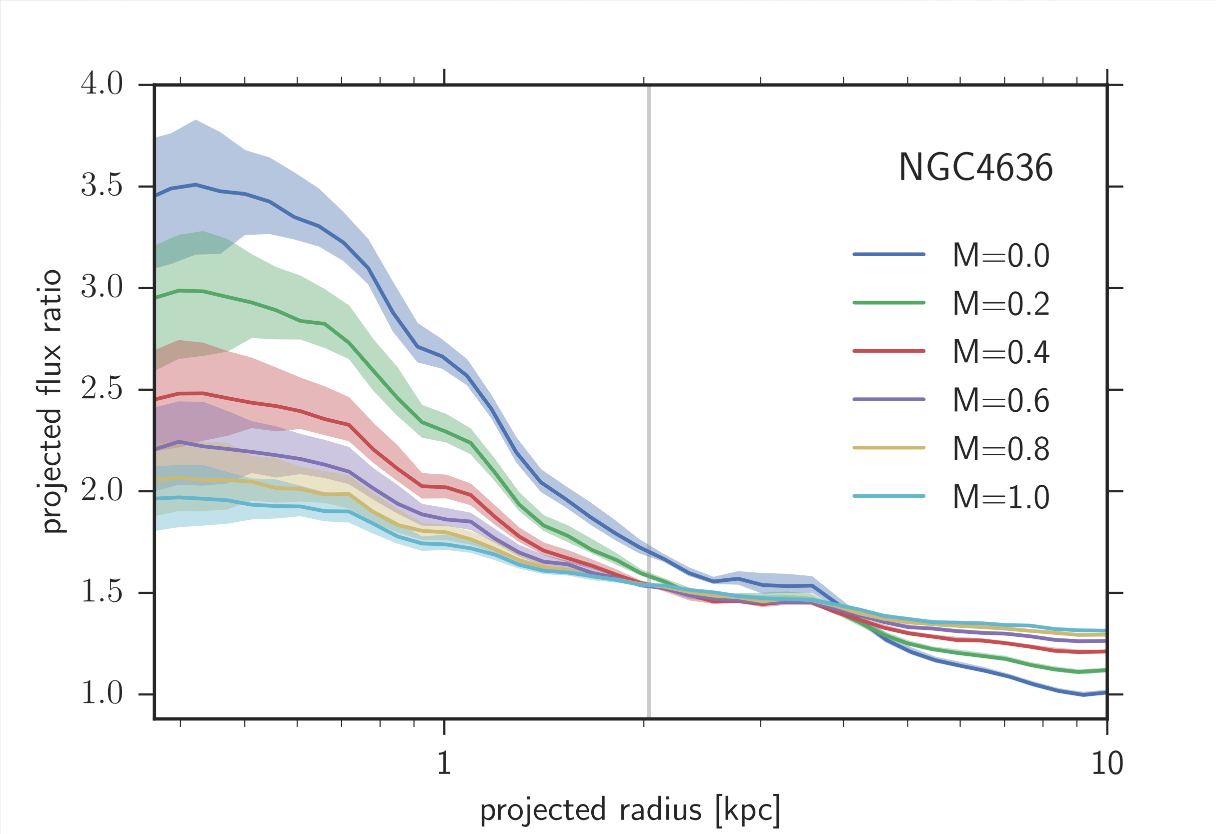


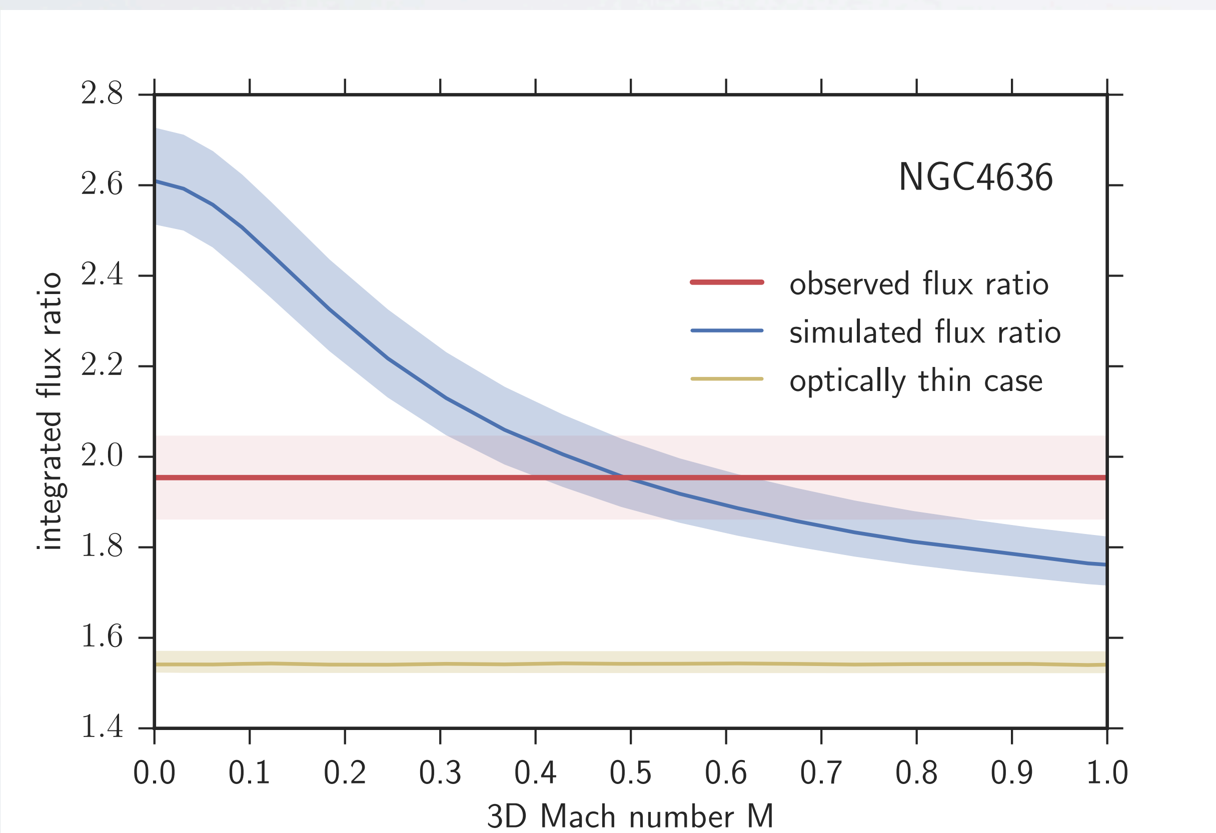
Resonance scattering in optically thick lines

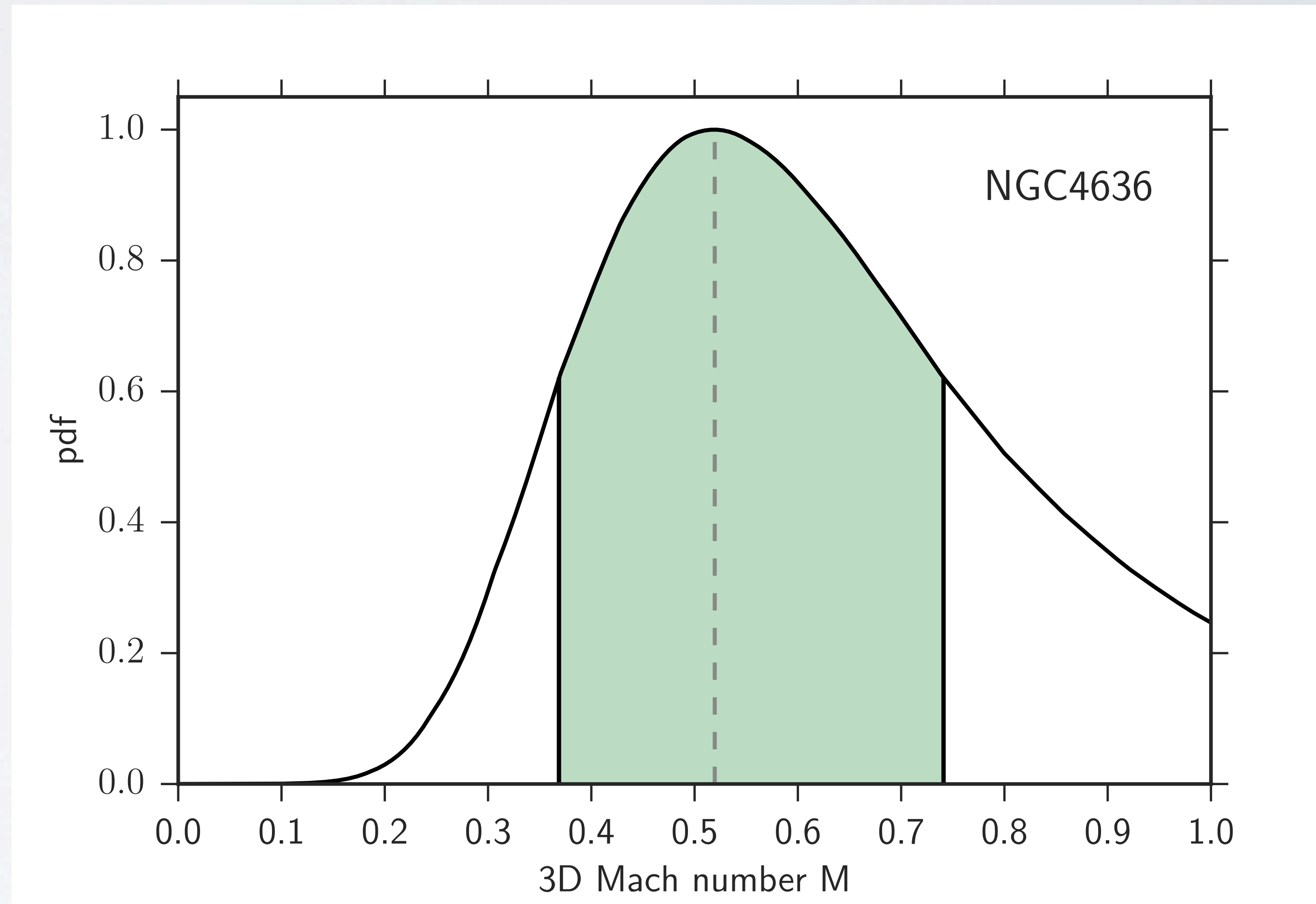


Line suppressed by resonance scattering

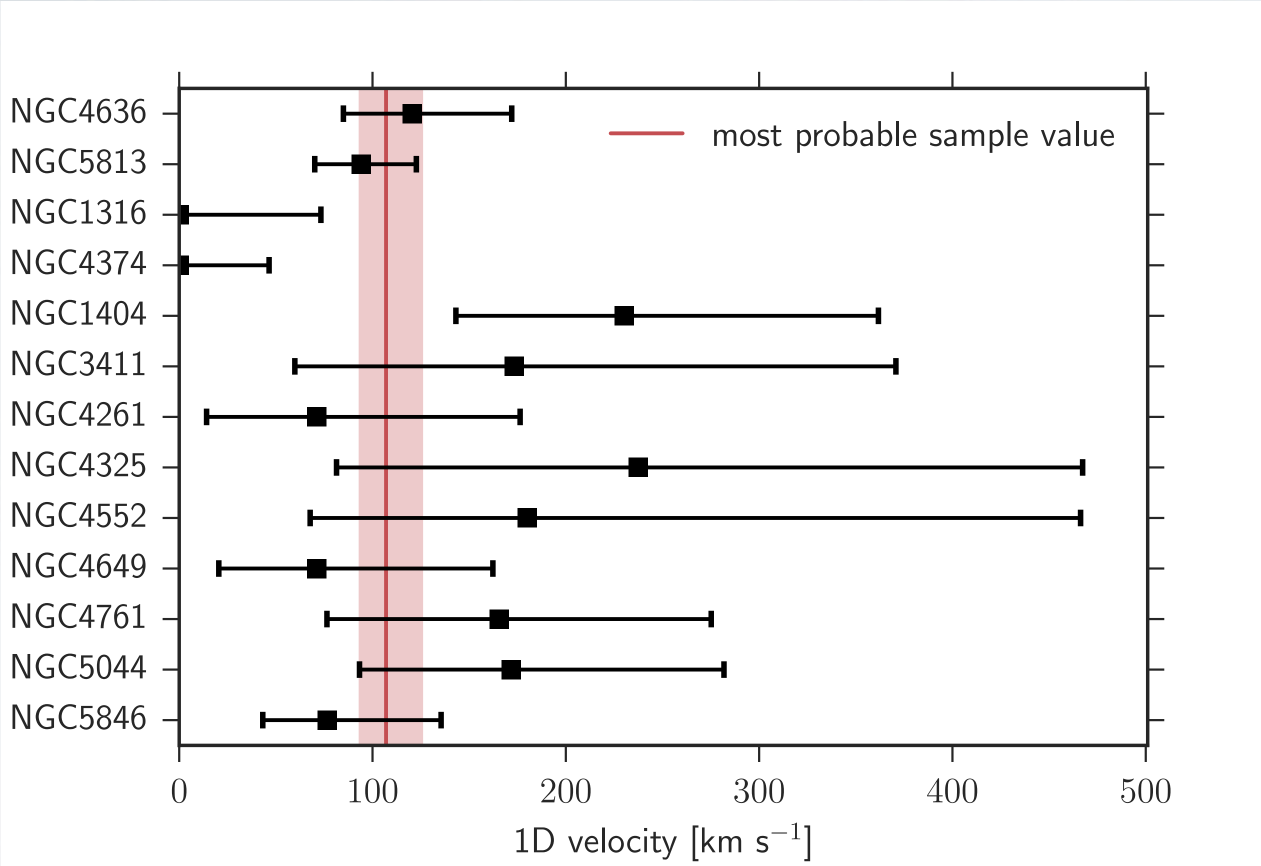


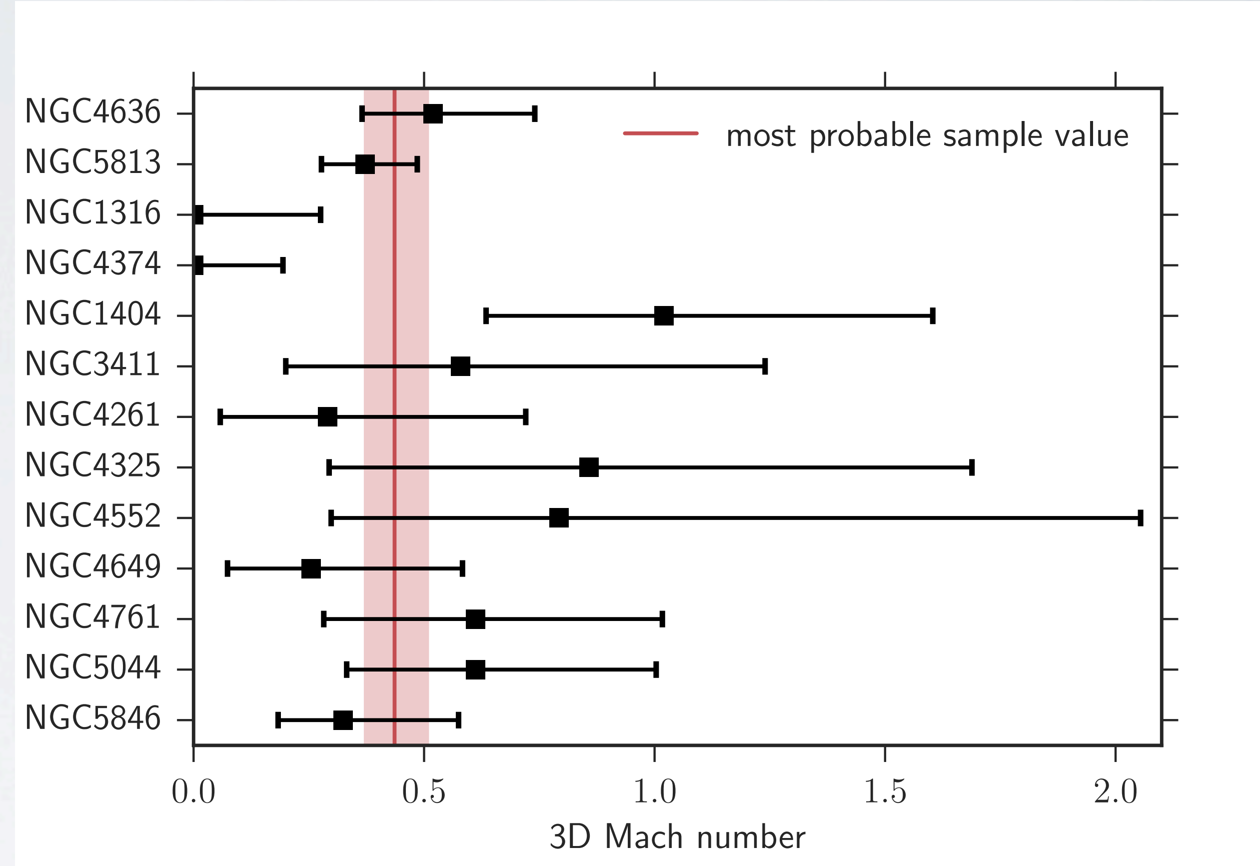


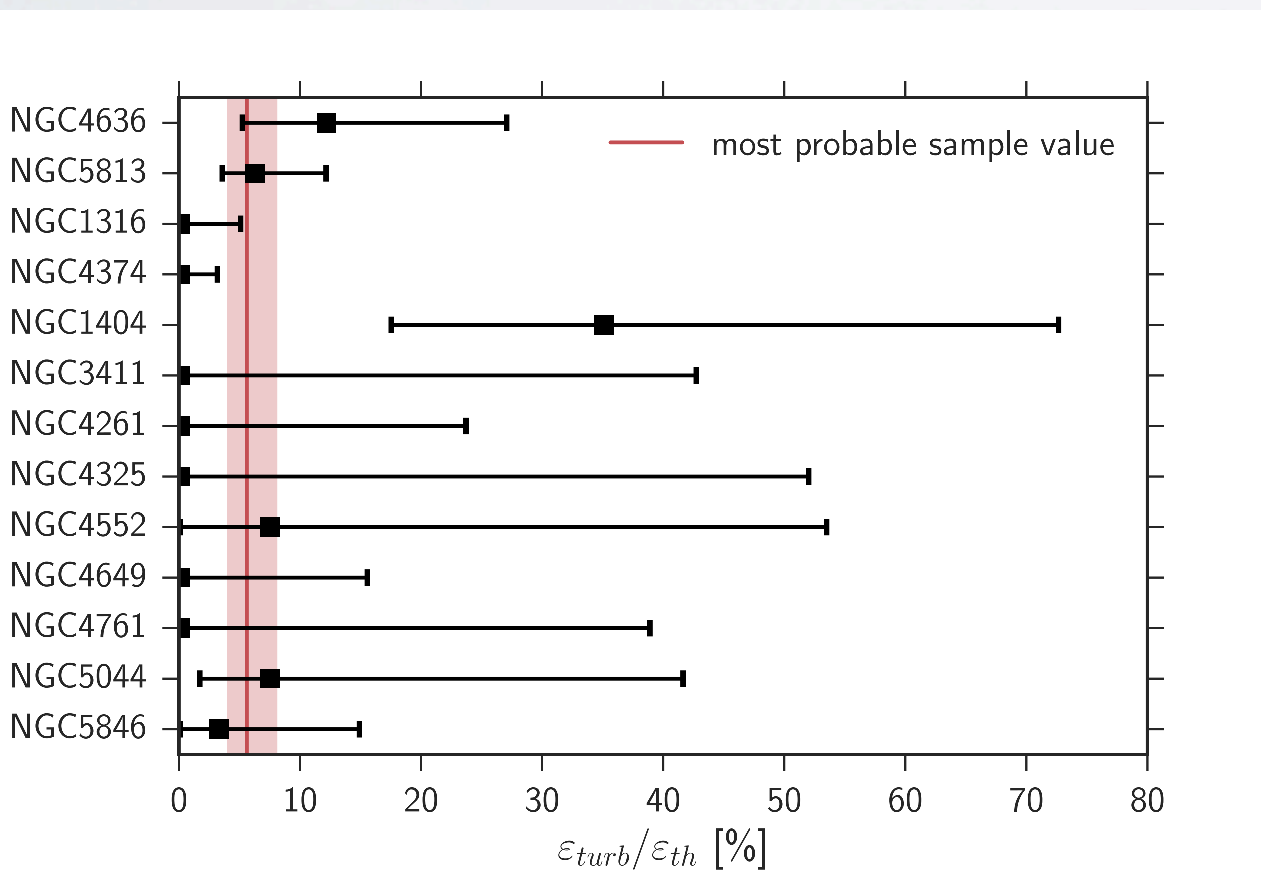




Ogorzalek et al. 2017







1D velocity 107 km/s
3D velocity of Mach 0.44
pressure support of 5.6 %

scatter consistent with zero
(but errors are large)

Summary

- Galaxies with halo mass similar to the Milky Way ($\approx 10^{12}\ M_{\odot}$) or higher host hot X-ray emitting atmospheres and central supermassive black holes.
- Jets emanating from blacks holes accreting at highly sub-Eddington rate are sufficiently powerful to balance the radiative cooling of hot atmospheres and limit further star-formation.
- The chemical composition of giant elliptical atmospheres is at variance with their stellar populations, which typically show an overabundance of α elements.
- Recent studies have shown that most molecular gas in ellipticals has likely cooled from their hot atmospheres.
- Non-thermal (kinetic) pressure support in the hot atmospheres of galaxies and clusters is less than 10%