Steep Circumgalactic Entropy Profiles around Powerful Radio Sources

6th ICM Theory and Computation Workshop
Copenhagen

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My Michigan State University Collaborators

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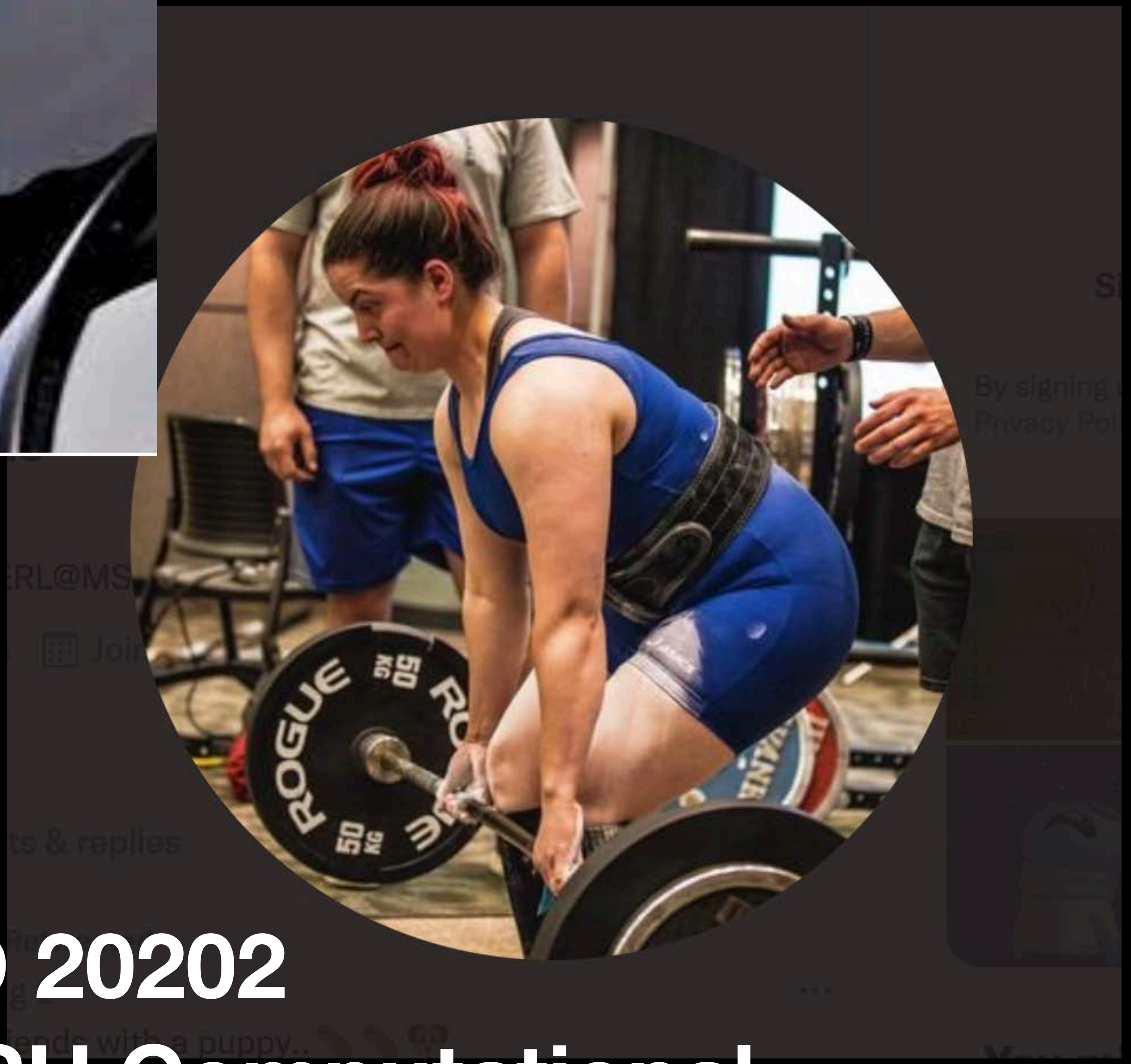

MSU Astro PhD 20202
Professor in MSU Computational Science Education Research

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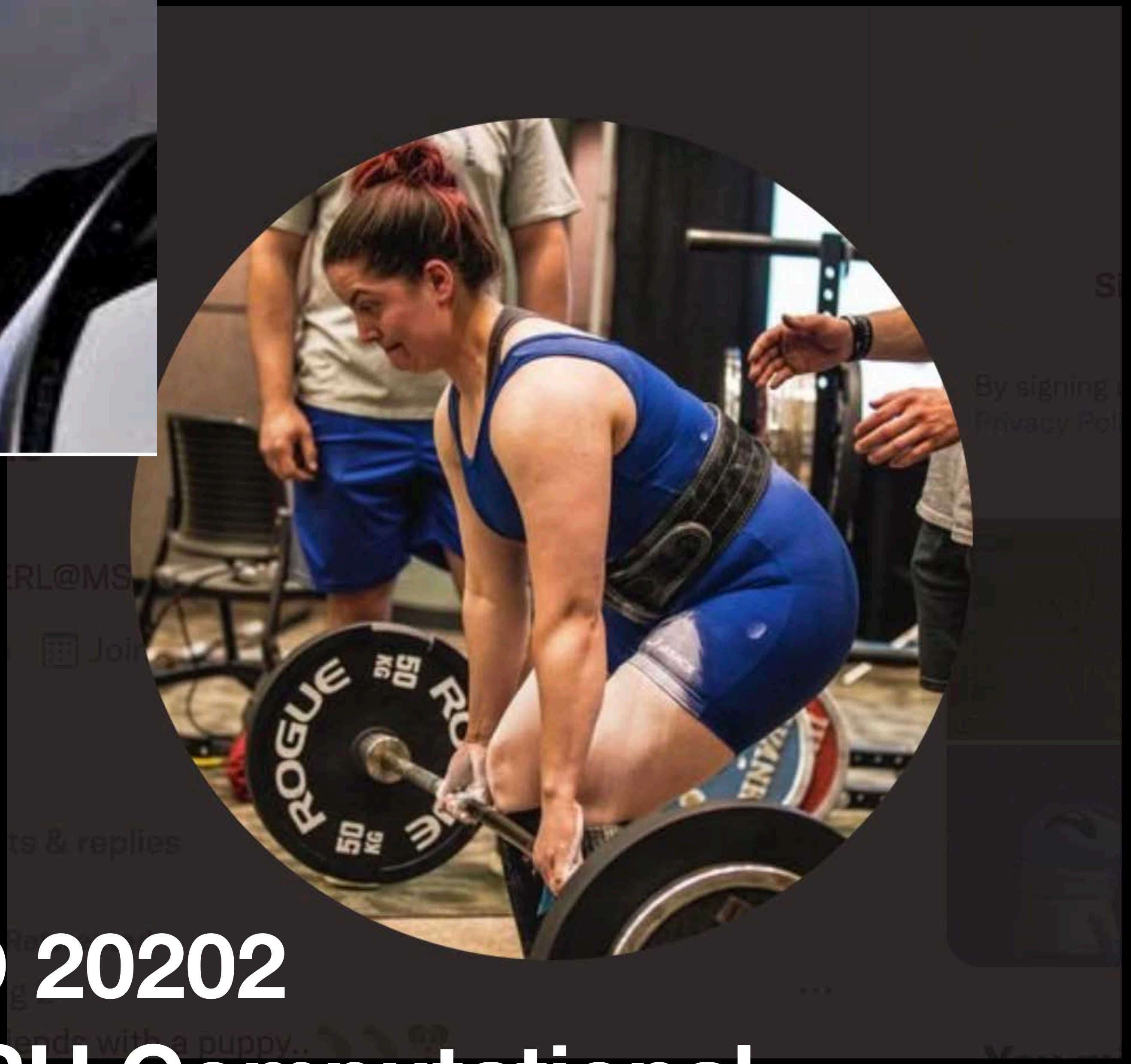

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Mark Voit

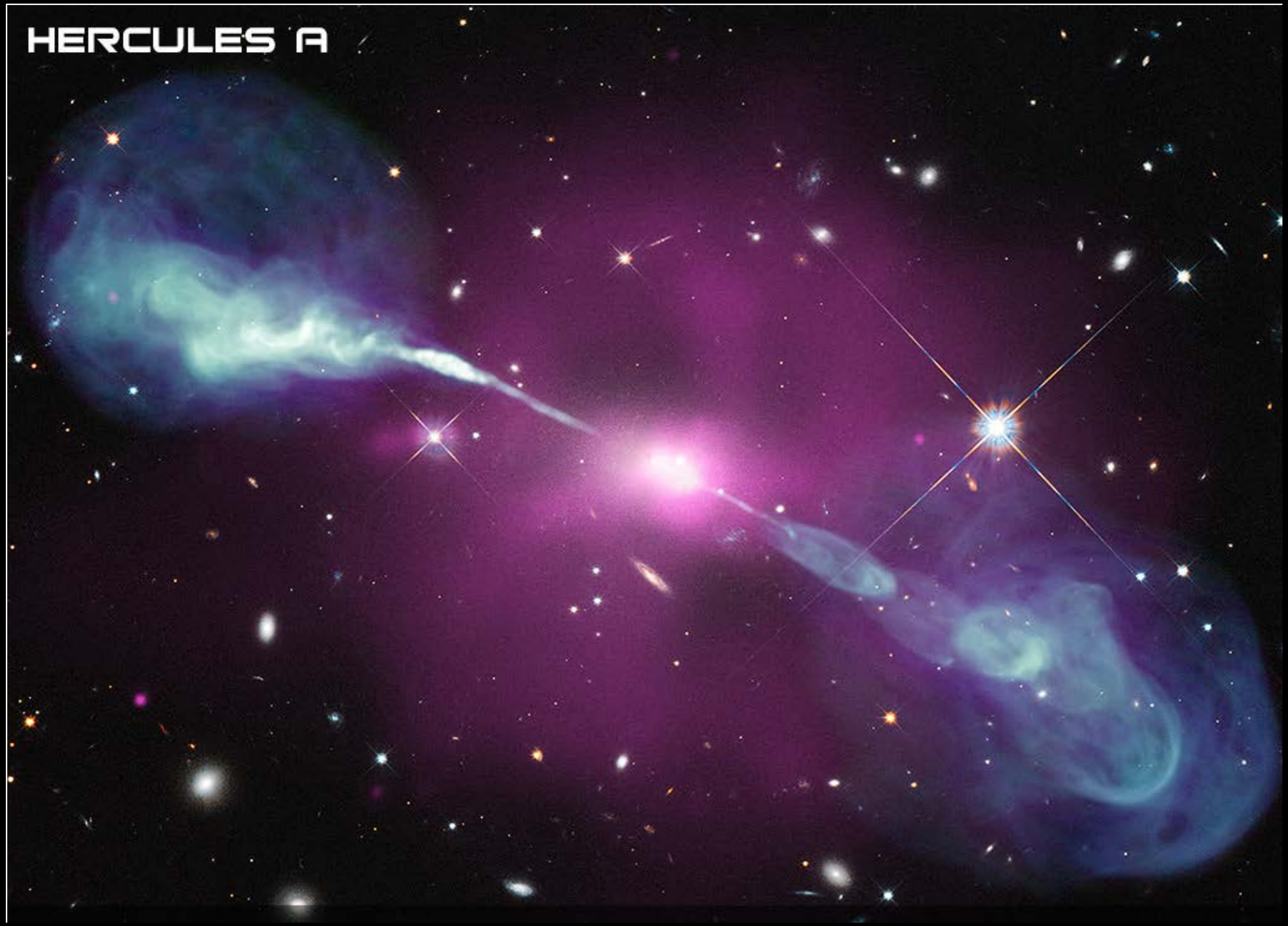
Entropy of an ideal gas

First Law of Thermodynamics:

$$ds = \frac{3}{2}\, d\ln T - \; d\ln n = \frac{3}{2}\, d\ln K$$

$$K \propto \frac{T}{n^{2/3}}$$

$$K_{x-ray} = \frac{kT}{n_e^{2/3}}\ (\text{keV cm}^2)$$



Gravity and entropy determine where the circumgalactic medium (CGM) is, in near hydrostatic equilibrium:

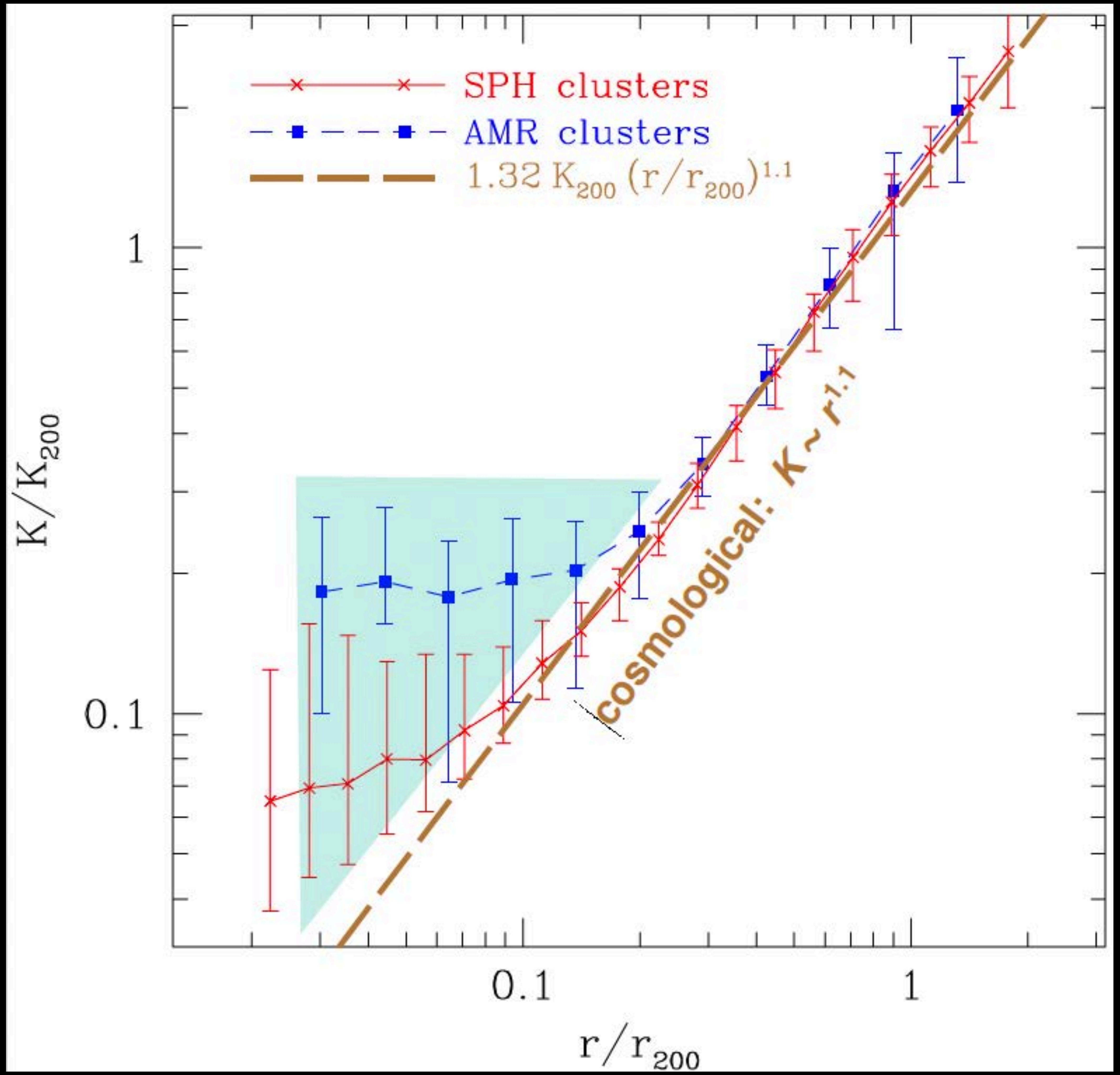
1. Shape (gradients) of the gravitational potential determines pressure gradient
2. The distribution of specific entropy in the cluster atmosphere determines the equilibrium density of the gas (and therefore the X-ray luminosity of the CGM)

Entropy profiles in gravitational potentials

Buoyancy in a gravitational potential causes low entropy gas to sink and high entropy gas to rise

Gas entropy increases inside out

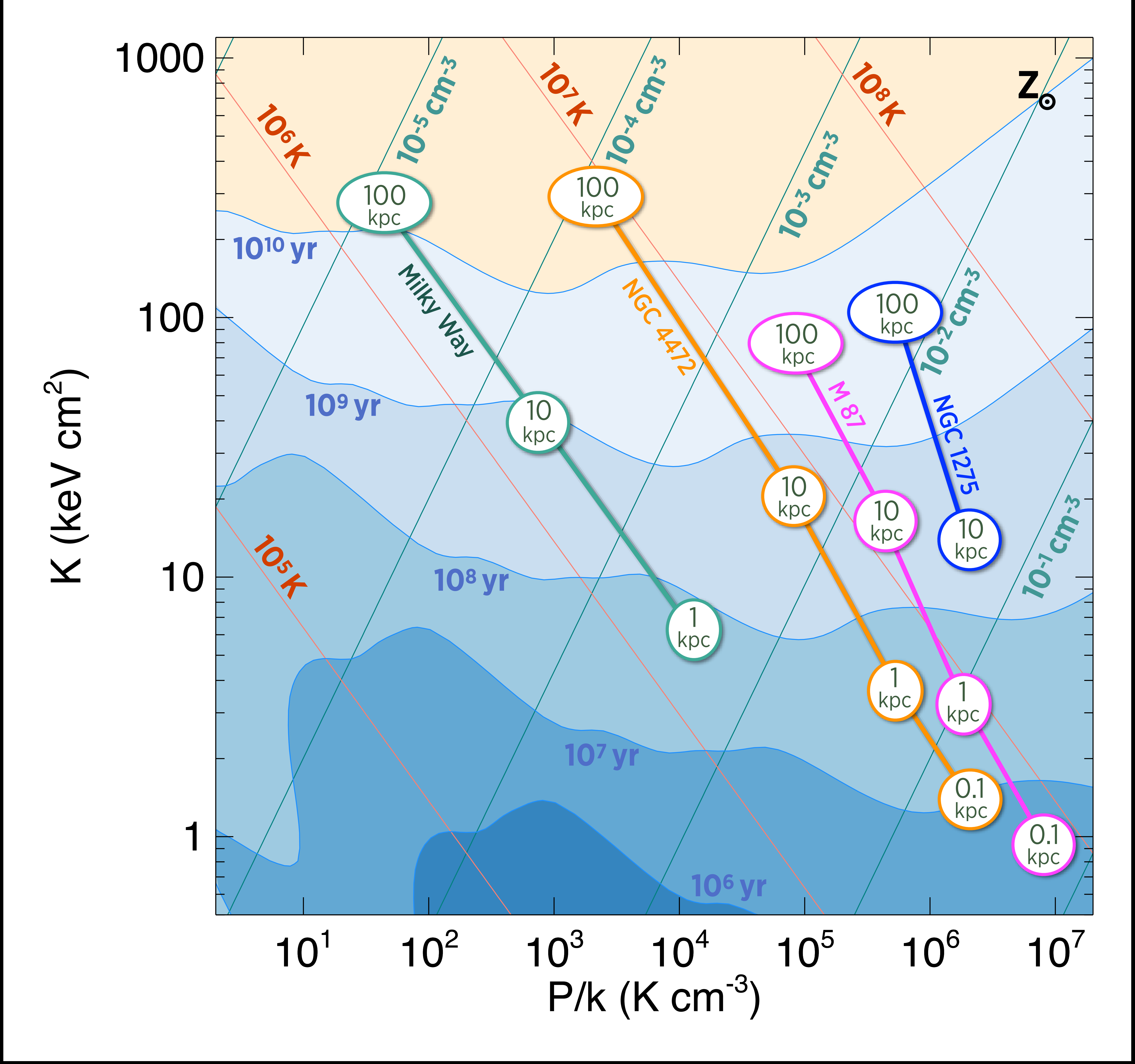
“Cosmological accretion” establishes a characteristic entropy slope in an NFW gravitational potential (Voit+2005)



Entropy and Radiative Cooling

Entropy and radiative cooling time scales are related

Within 100 kpc, entropy and corresponding cooling times as a function of physical radius in groups, clusters and galaxies not so different, while gas pressures and halo masses differ by orders of magnitude



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What determines CGM gas entropy?

Heating and Cooling of the CGM

- Cosmological accretion or shocks set the entropy to a long-lived (high) value if resulting t_{cool} is long compared to the age of the universe.
- Radiative cooling can lower hot gas entropy.
- Radiative cooling can change hot gas into non-X-ray emitting forms (cold gas, stars, planets…)
- Moving gas around (adiabatic expansion or compression) does not change gas entropy.

What determines gas entropy gradients in cluster cores and in galaxies?

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Similar slopes can arise from very different processes

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Coronae sources	NGC 4874 in Coma	central entropy "deficit" at r<4 kpc	Sun, M+2005, 2007, 2009

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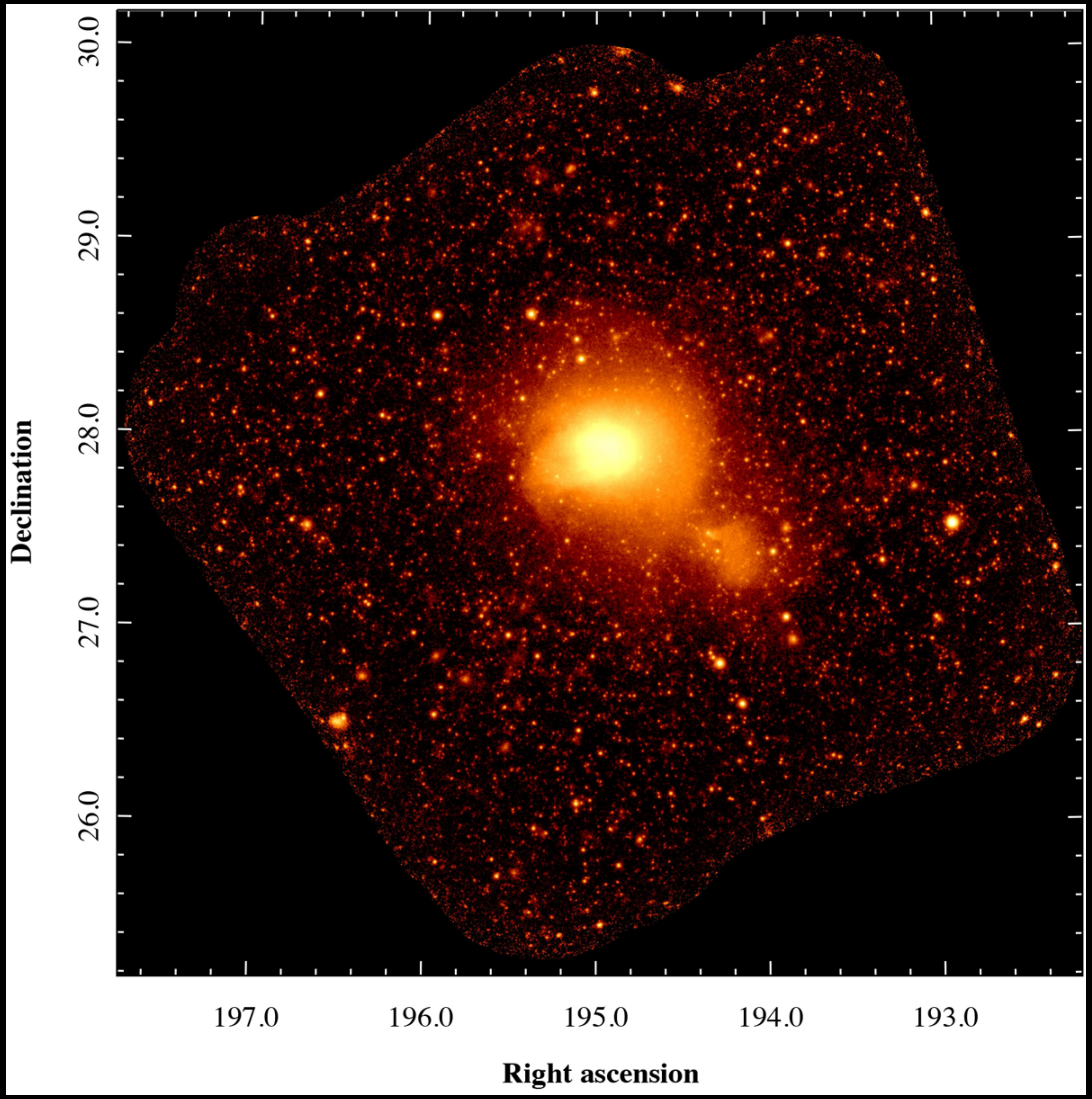
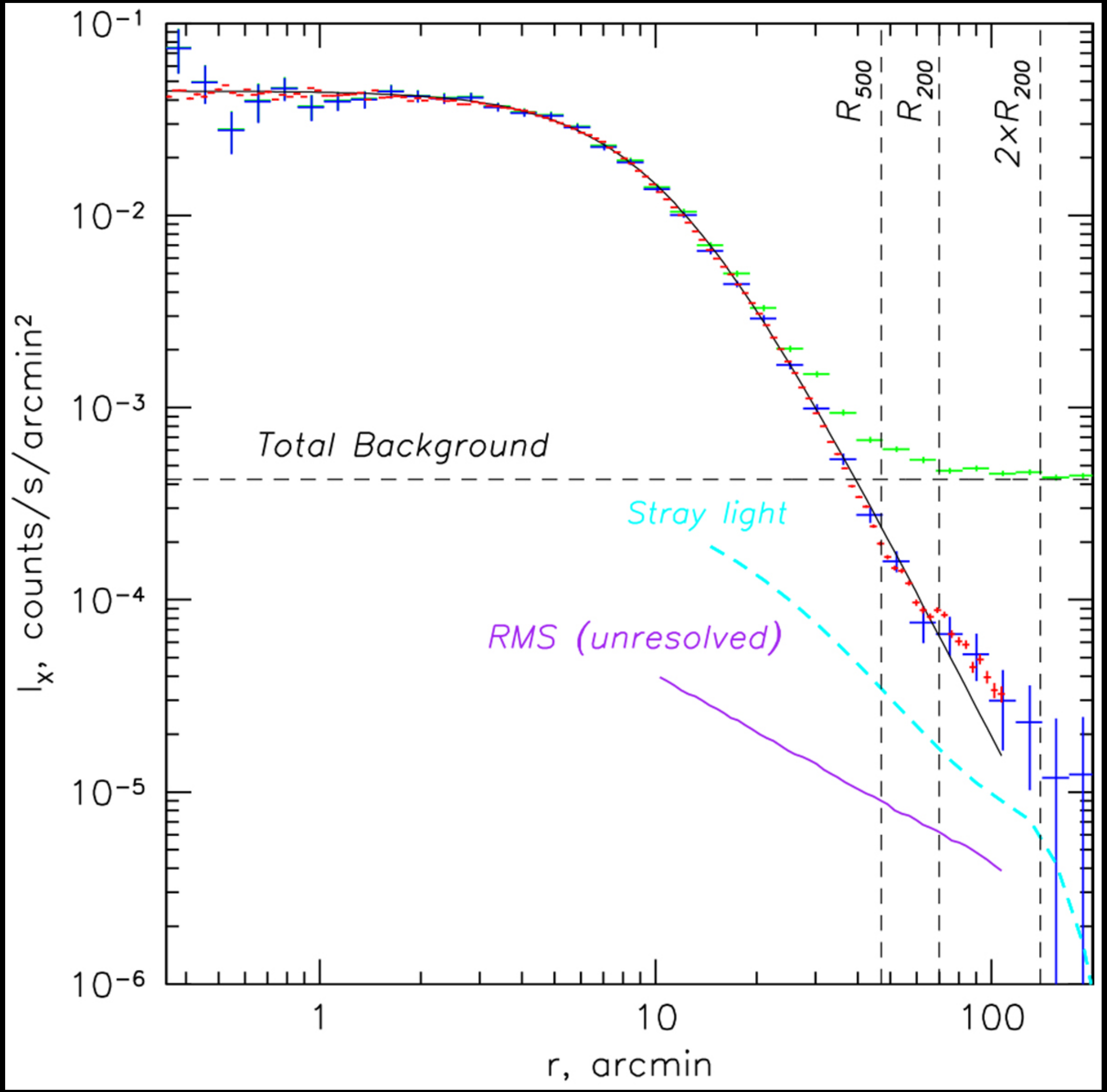


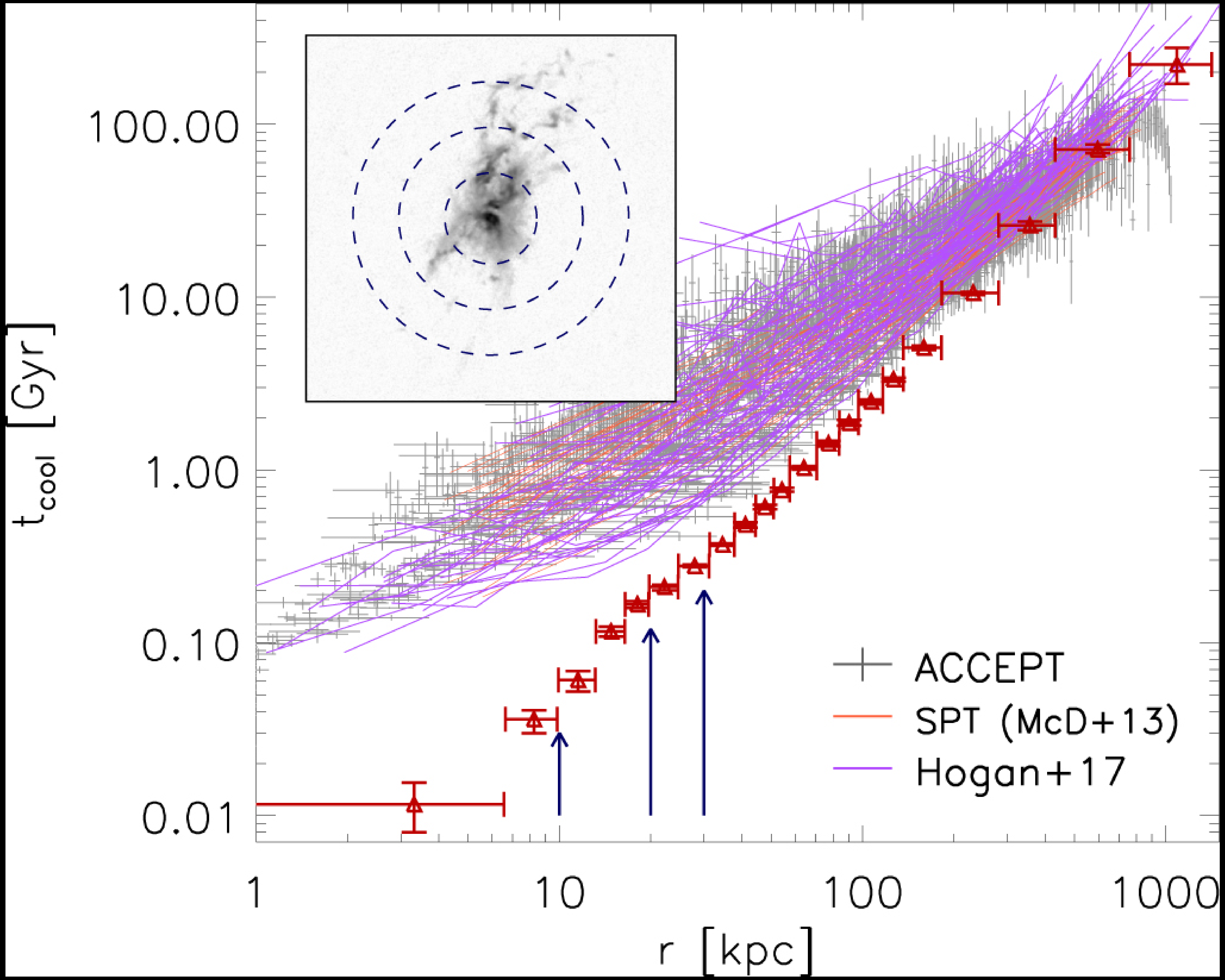
Figure 1

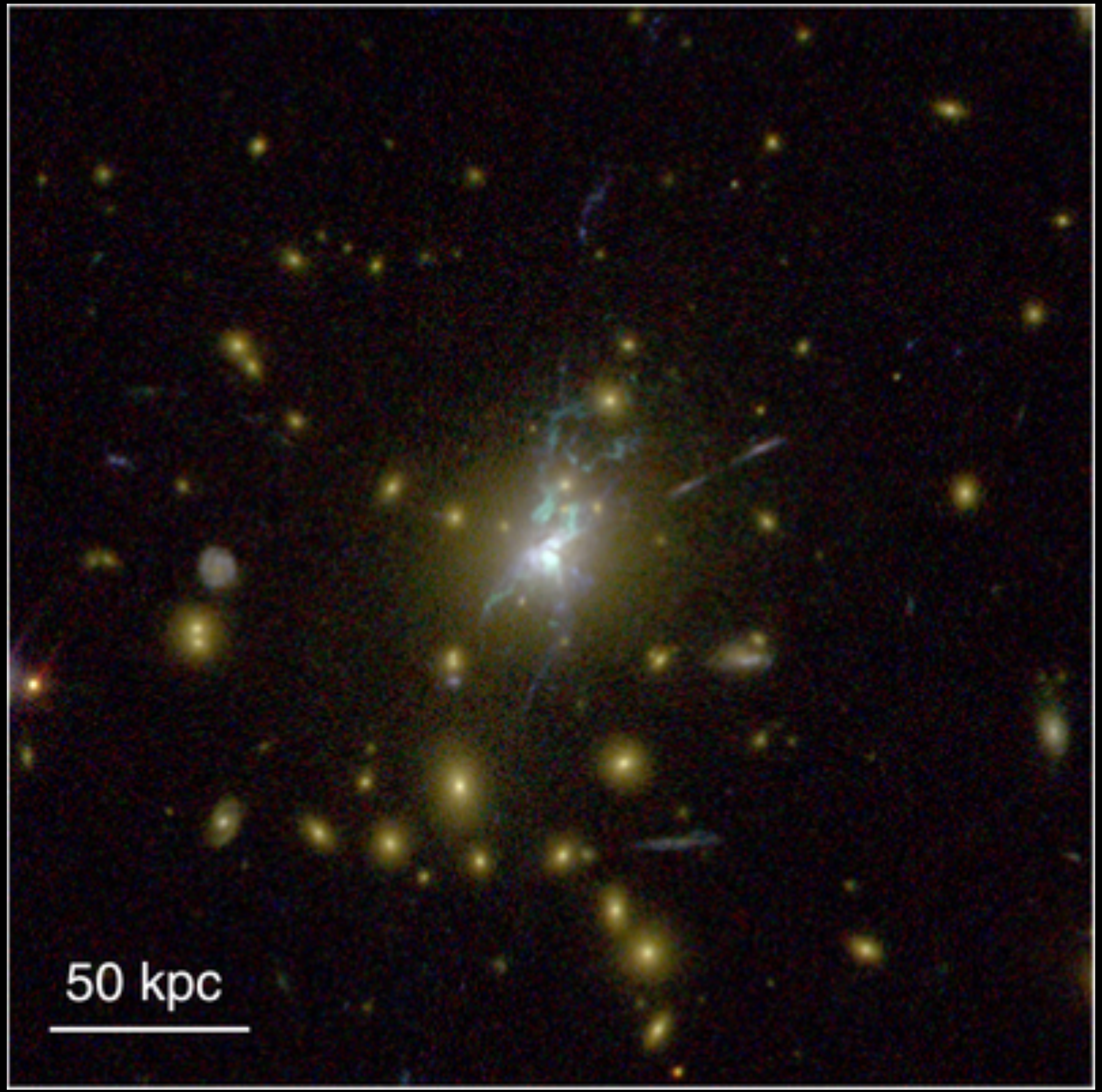


eRosita view of Coma (Churazov+2021)

Cluster Entropy Profiles of Cool Core Clusters

McDonald+2019





(The [O II]-emitting gas in Phoenix sits where t_{cool} < 100 million years)

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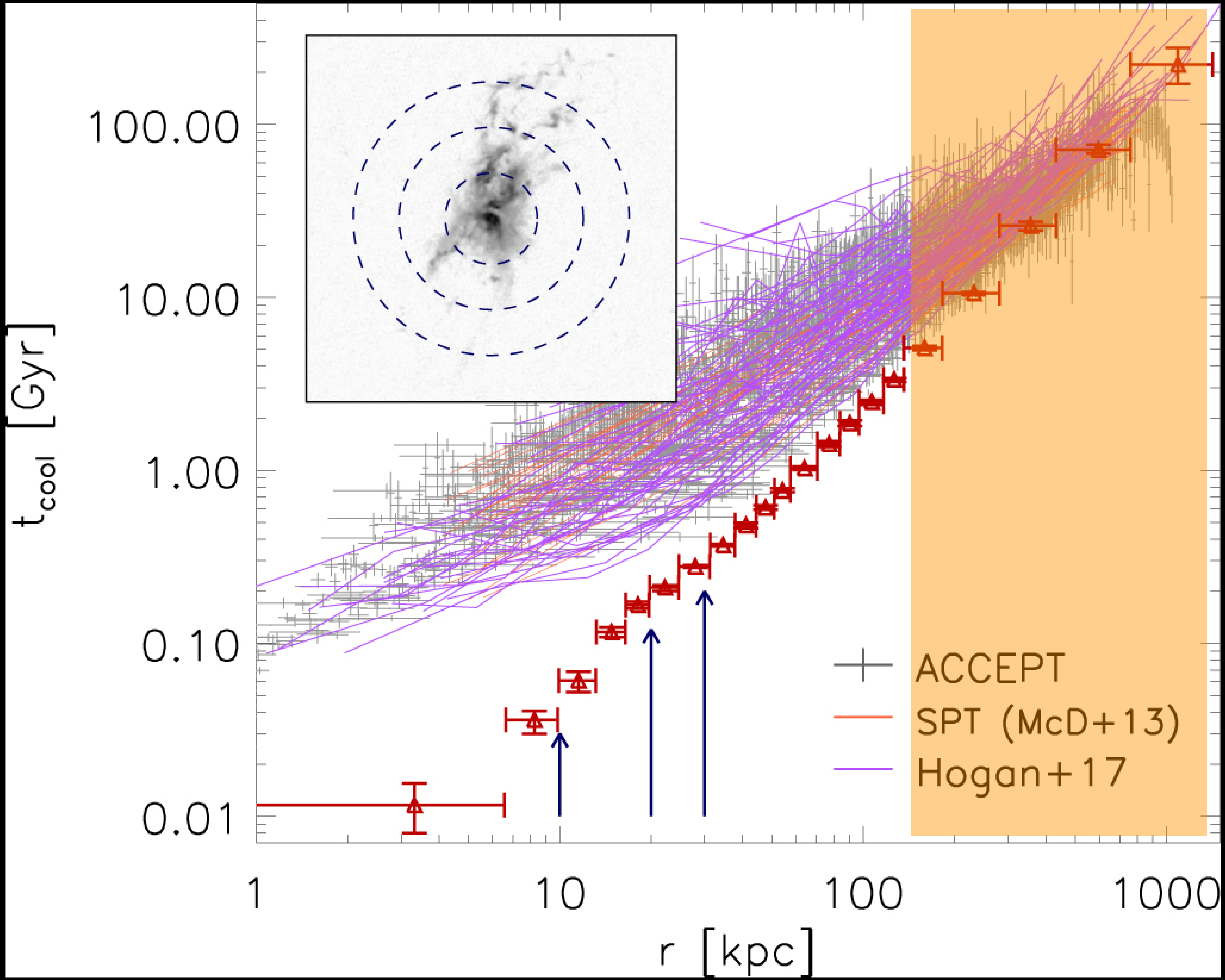

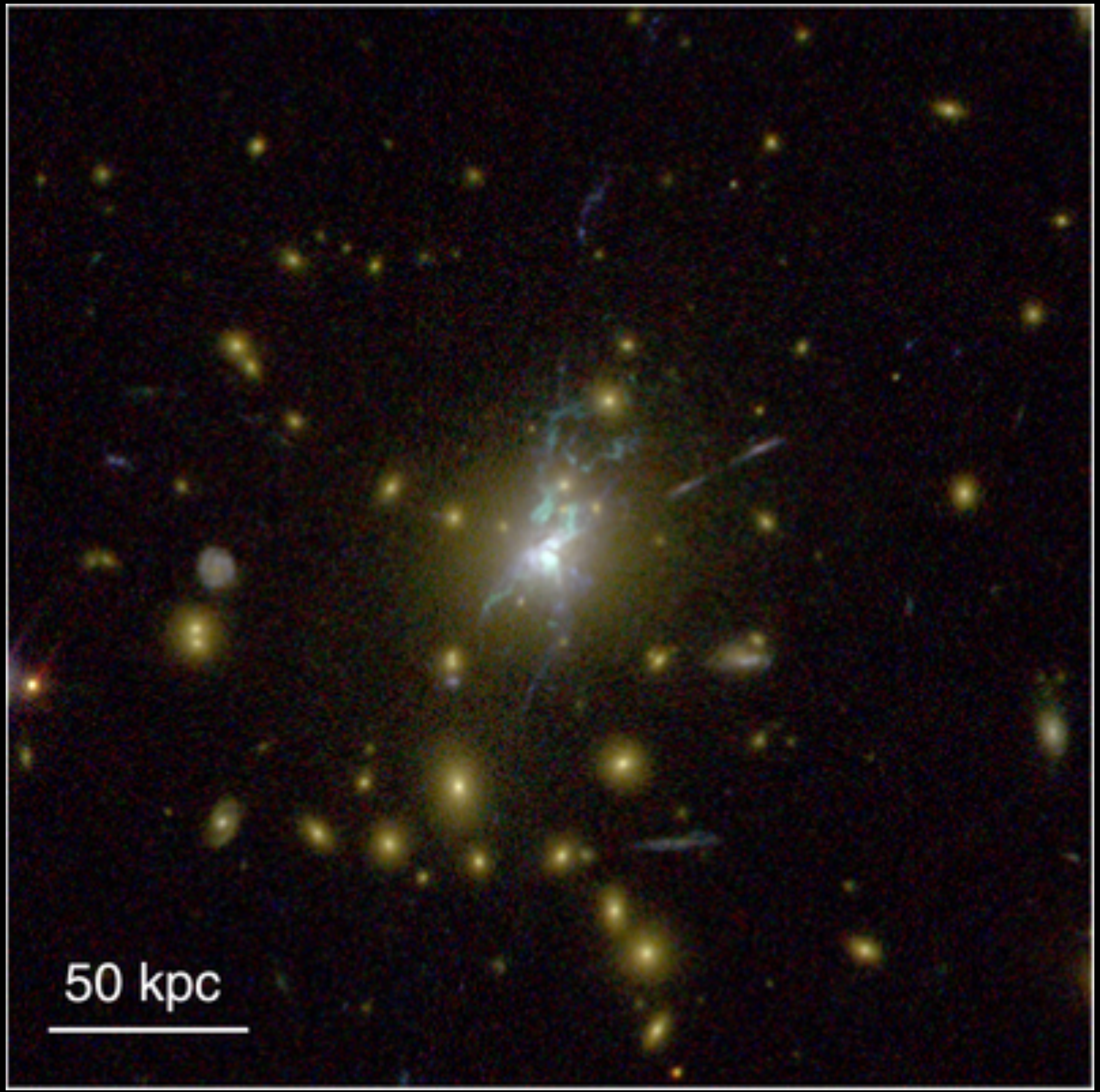

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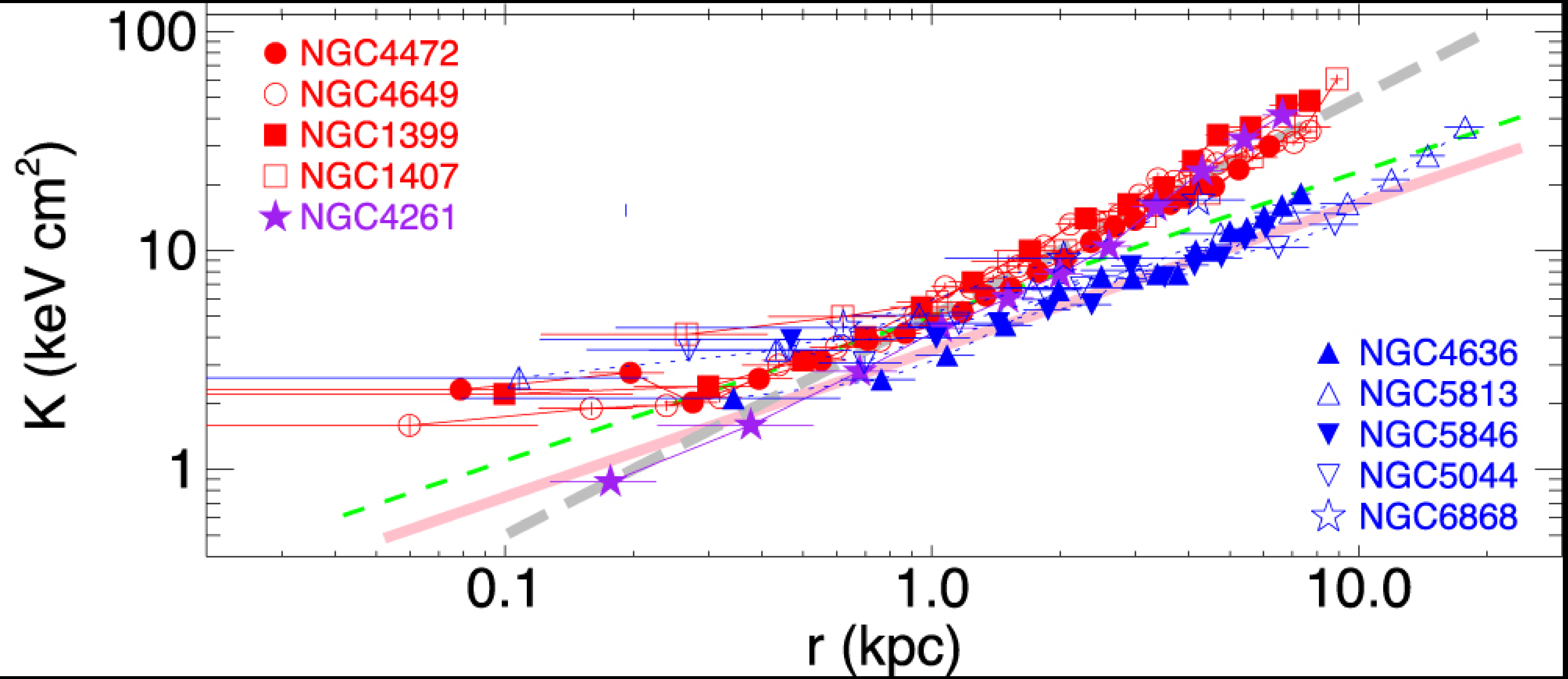
Entropy profiles around early-type galaxies

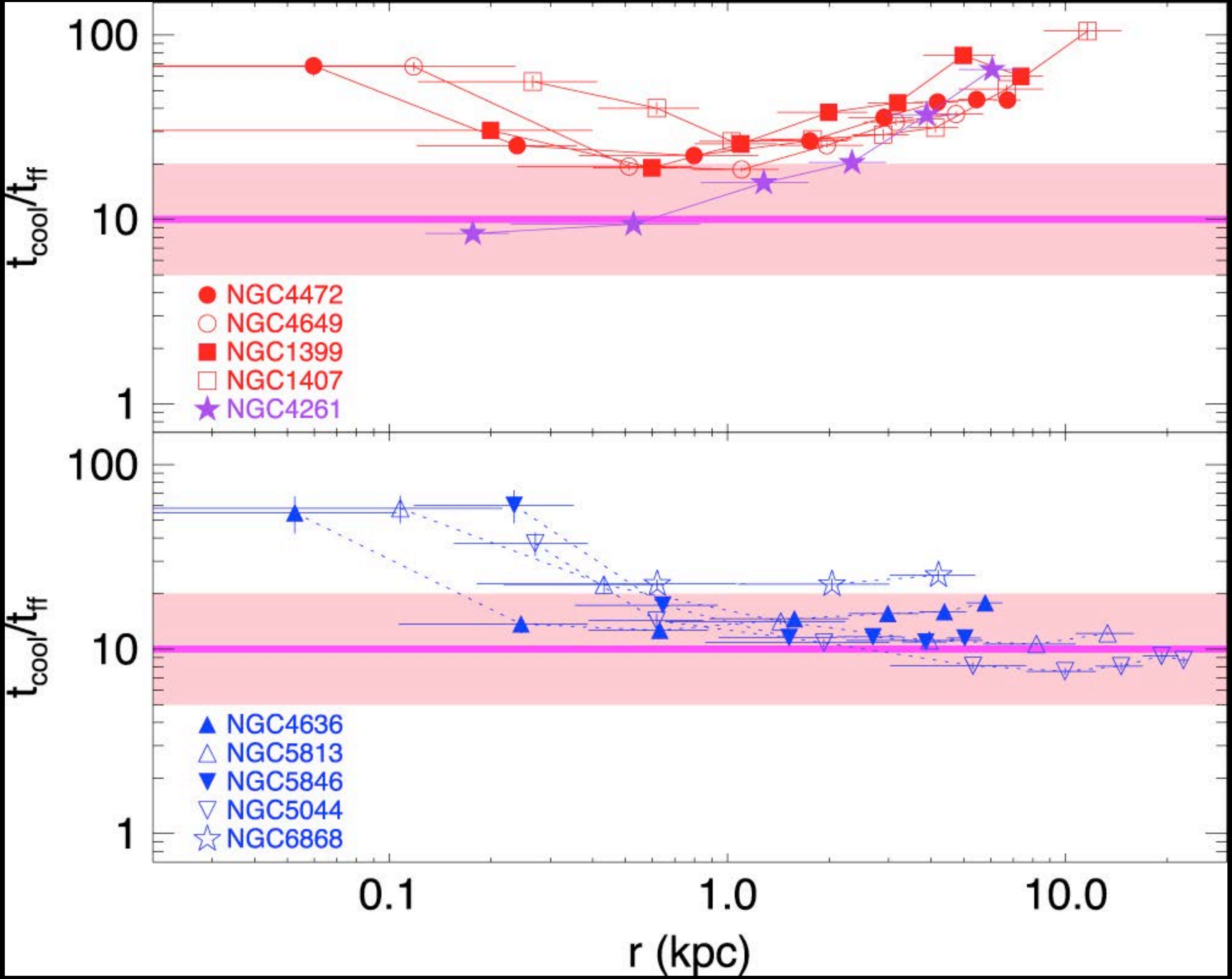
wind model $K \propto r^1$



precipitation-limited
$K \propto r^{2/3}$

Voit+2015

NGC4261: A steep entropy gradient around a powerful radio source



Jet power is 100x that of the others.

NGC4261's radio source is too powerful to be explained by Bondi accretion

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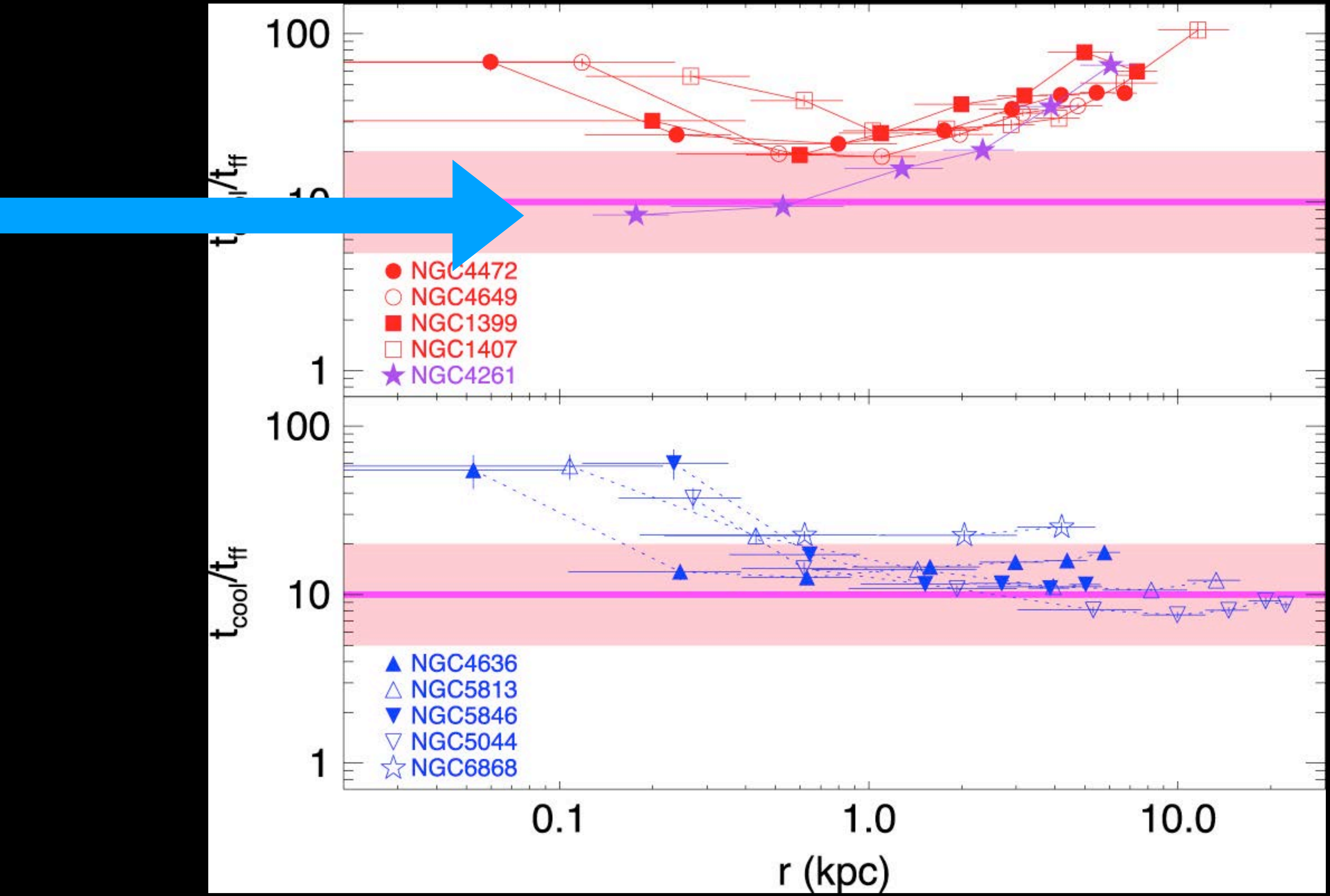

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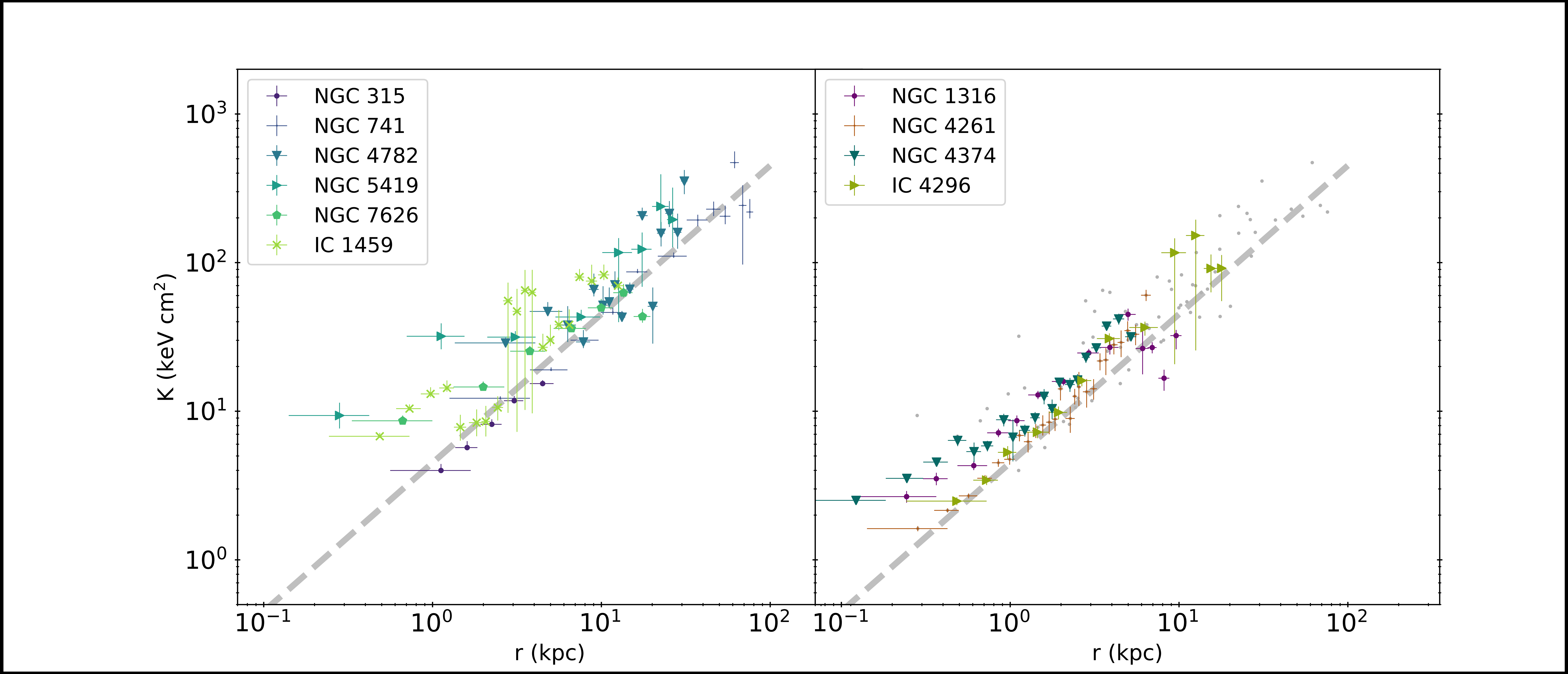
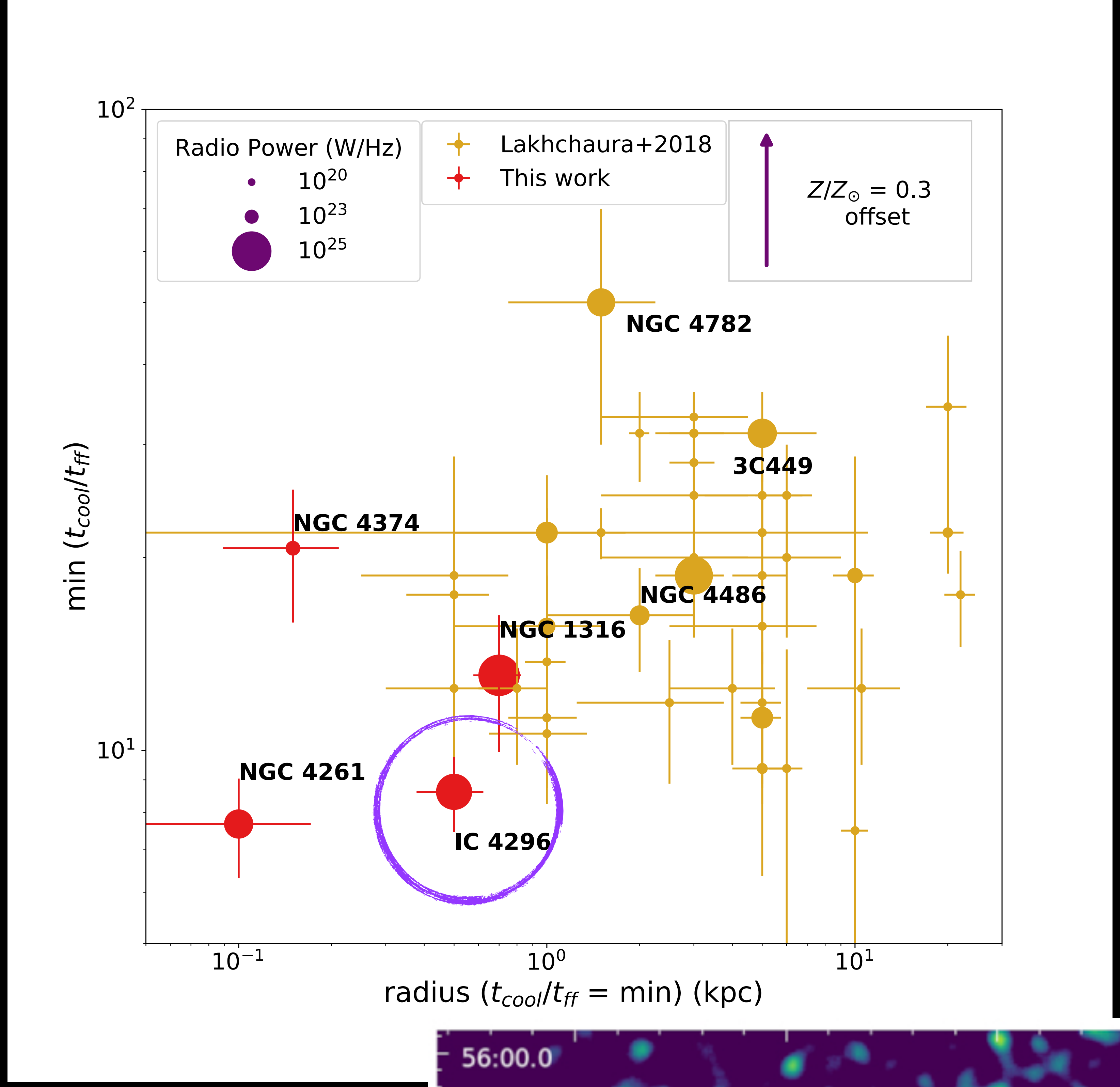
Frisbie, Donahue et al. 2020

Goal: seeking other NGC4261-type galaxies in the Chandra archive





Found at least one more like NGC4261: IC 4296!

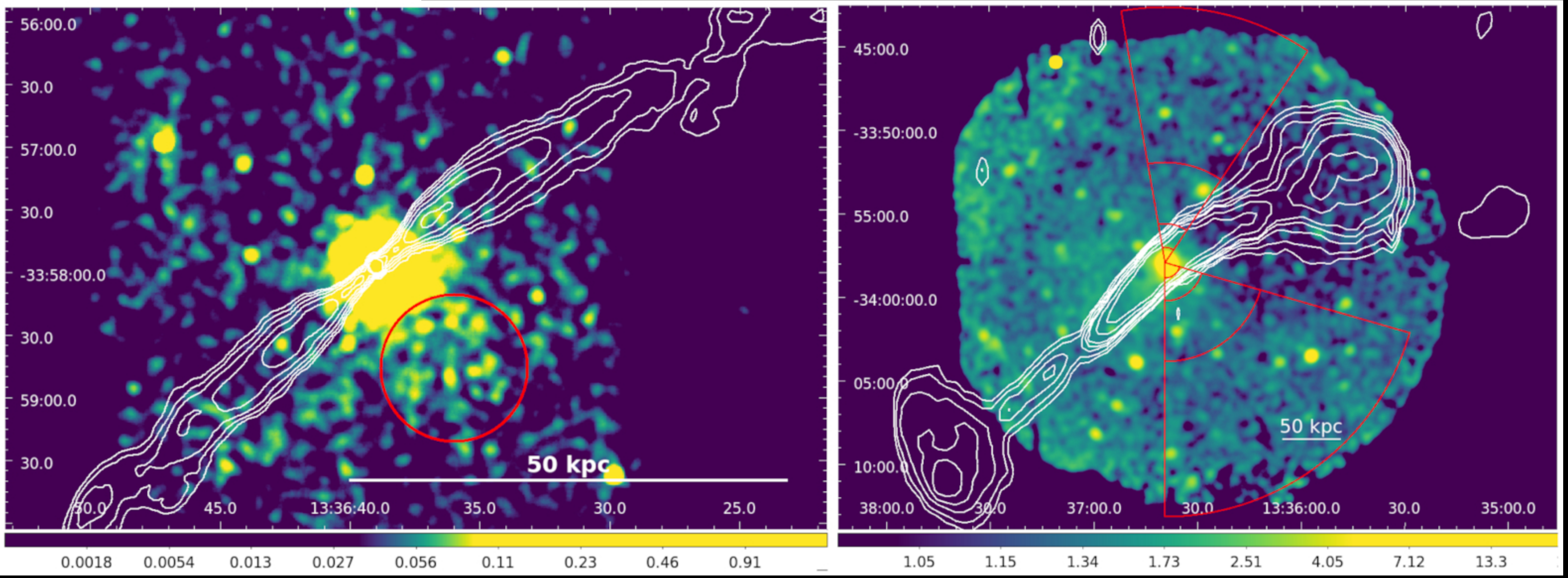
(BCG of Abell 3565)

It also is a very powerful radio source and has at least one very large X-ray cavity (Grossova+2019)

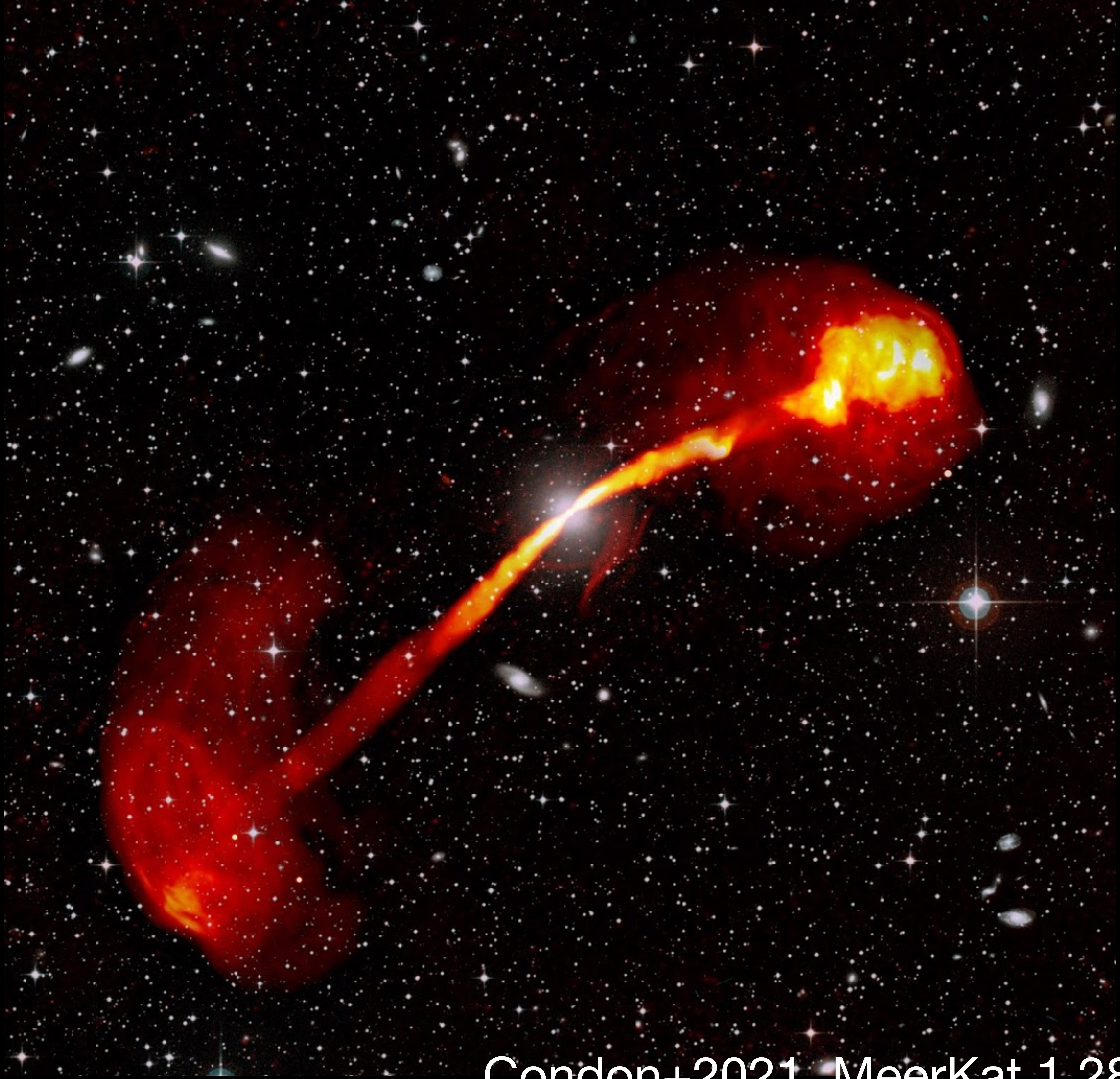
$$P_{mech} \sim 10^{44} \text{ erg s}^{-1}$$

Frisbie +2020

Grossova+2019



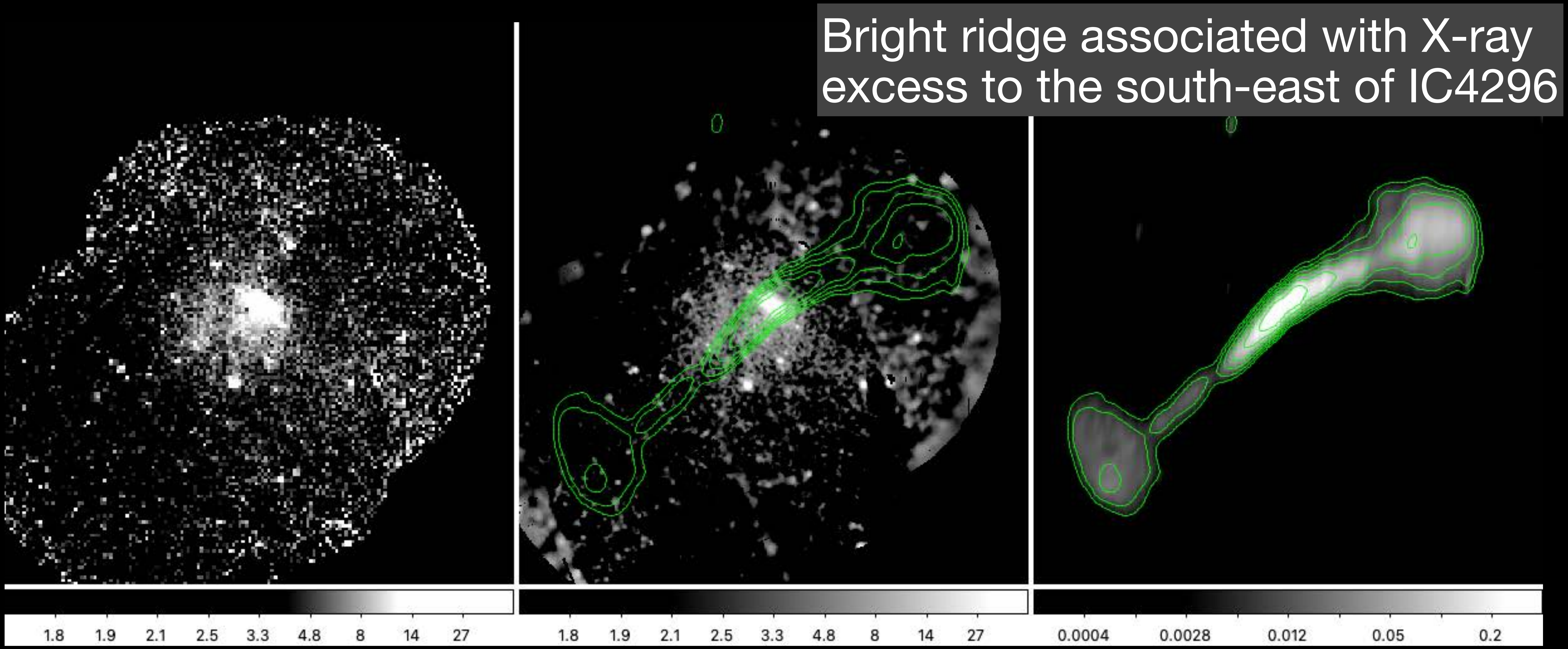
IC4296



~25’

Condon+2021, MeerKat 1.28 GHz radio image

IC4296 XMM + VLA-D



Donahue, Grossova, Frisbie, Voit, Werner, in prep

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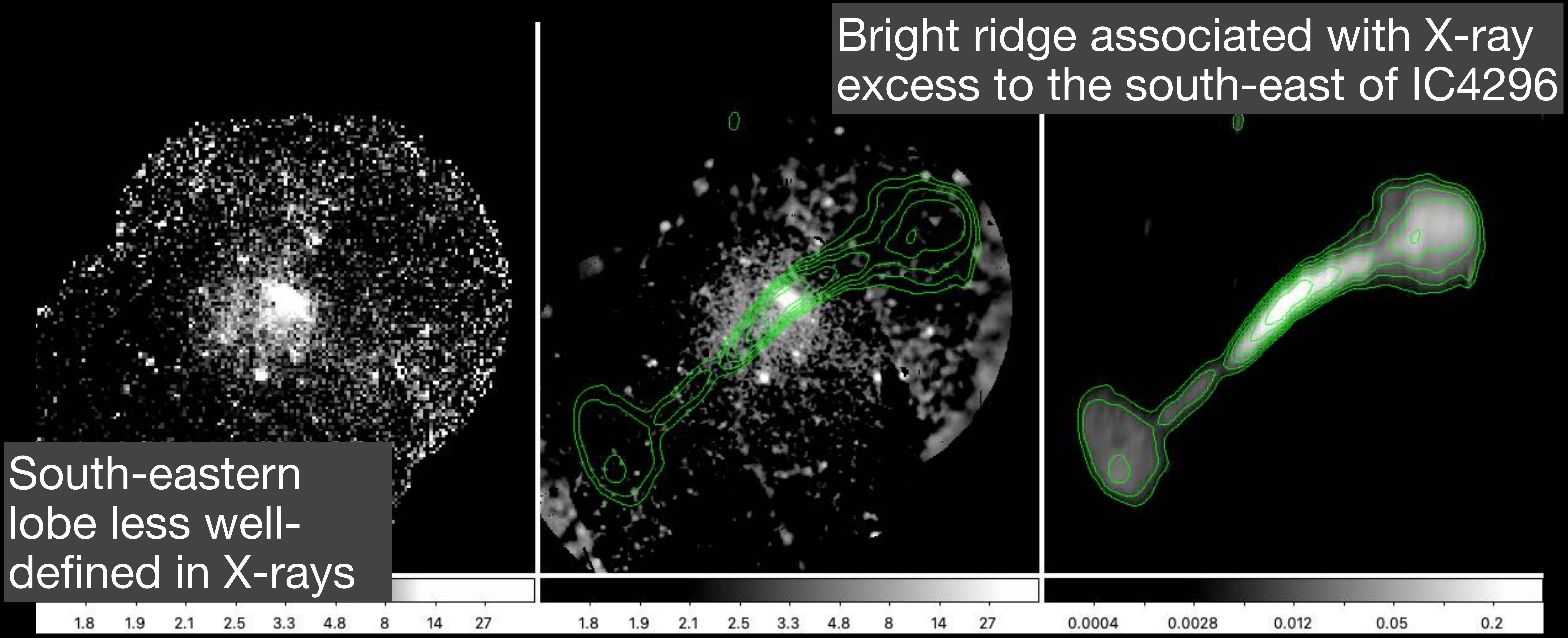

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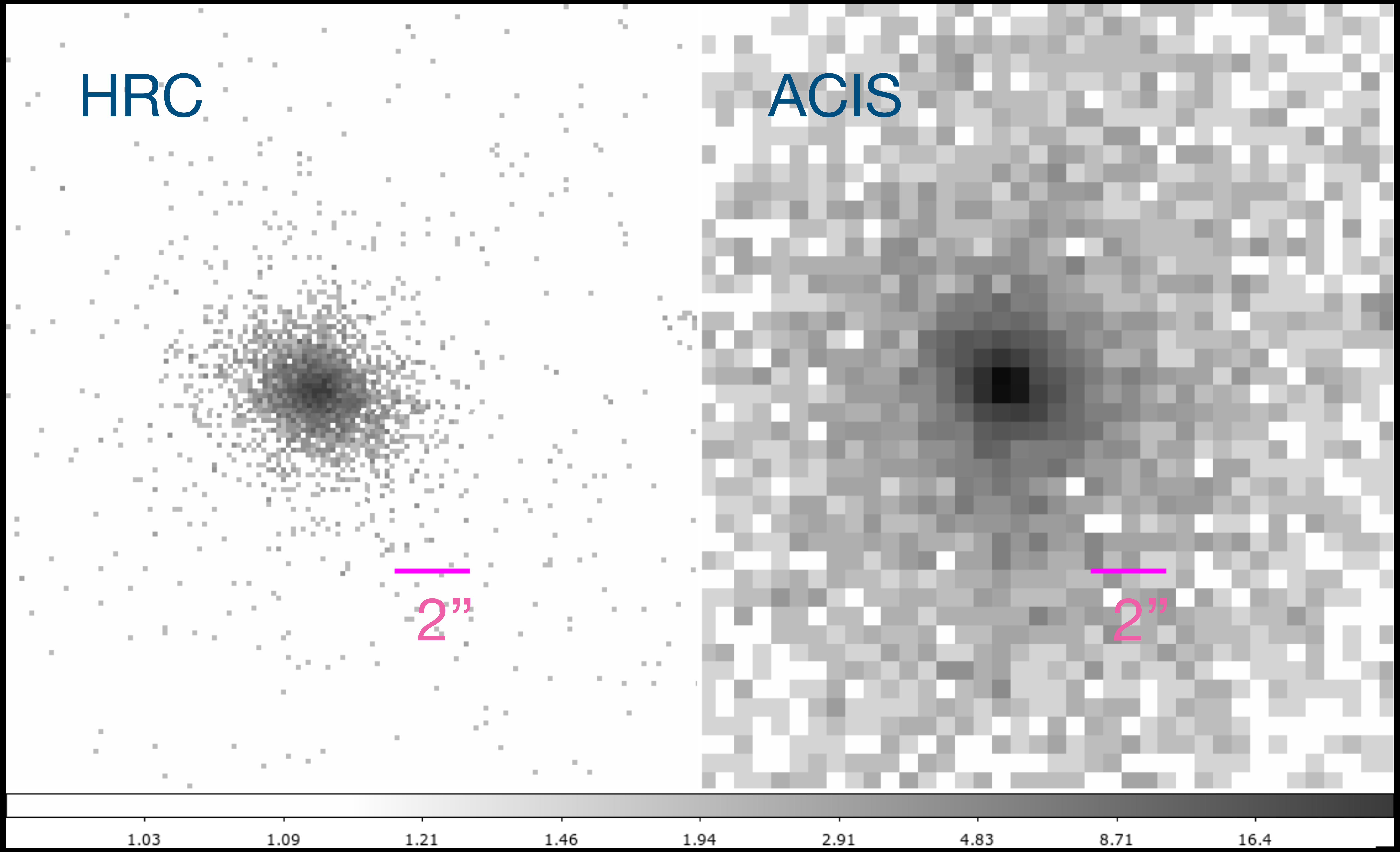
Chandra HRC and archival ACIS observations of center of IC4296

The Chandra HRC has (?) the best soft X-ray sensitivity and angular resolution (<0.5”) than any other X-ray instrument

The center of IC4296 is not dominated by a point source



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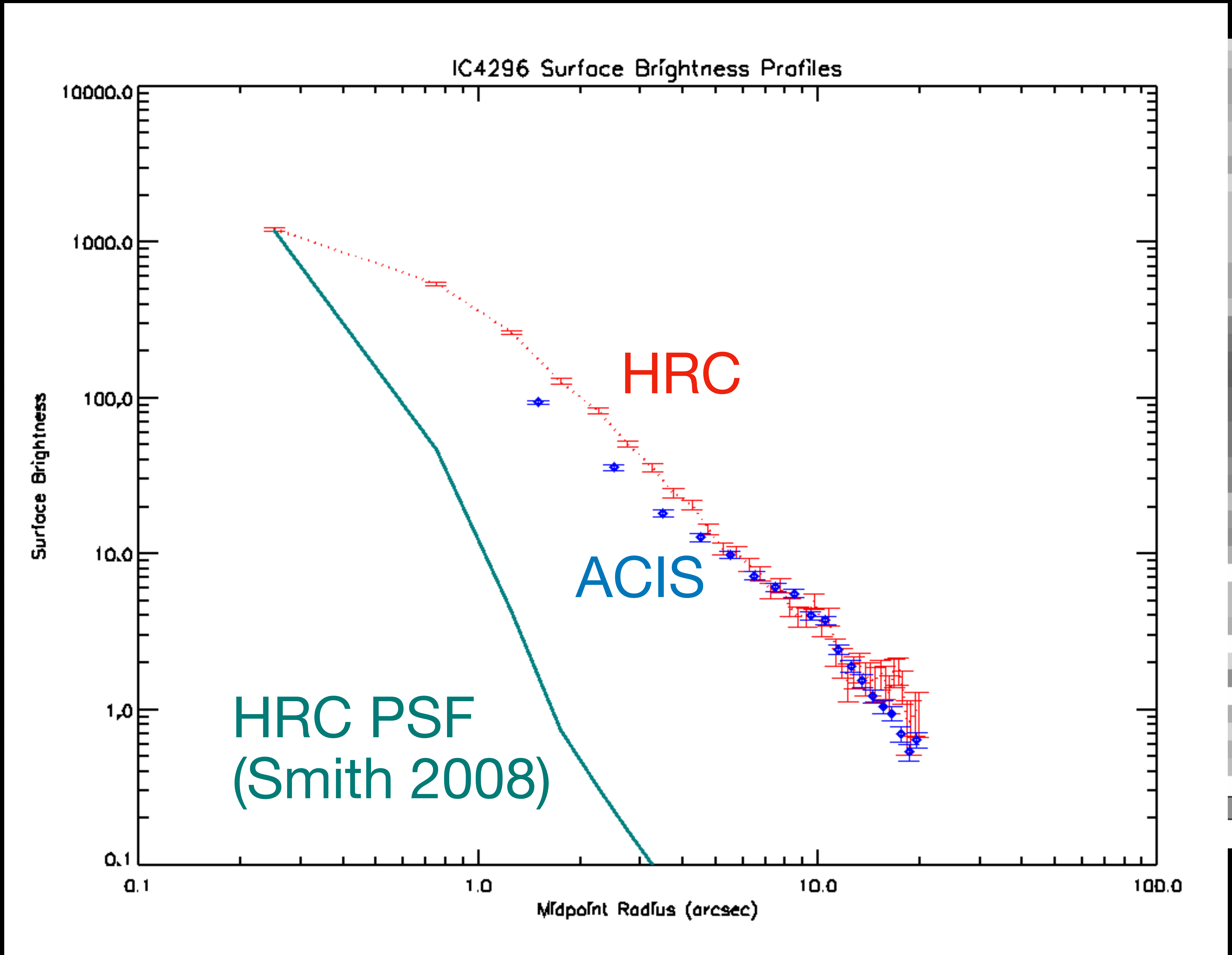
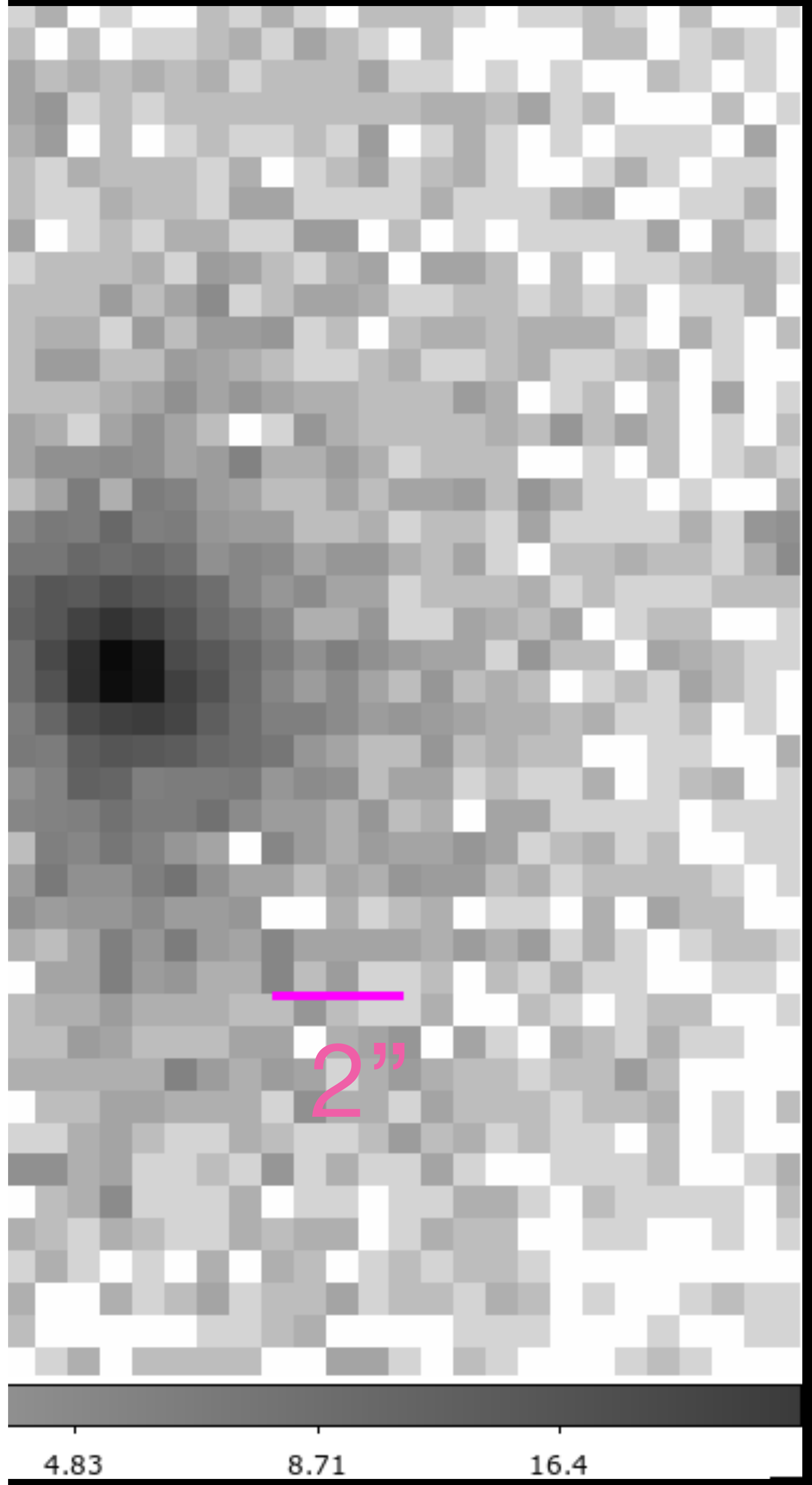
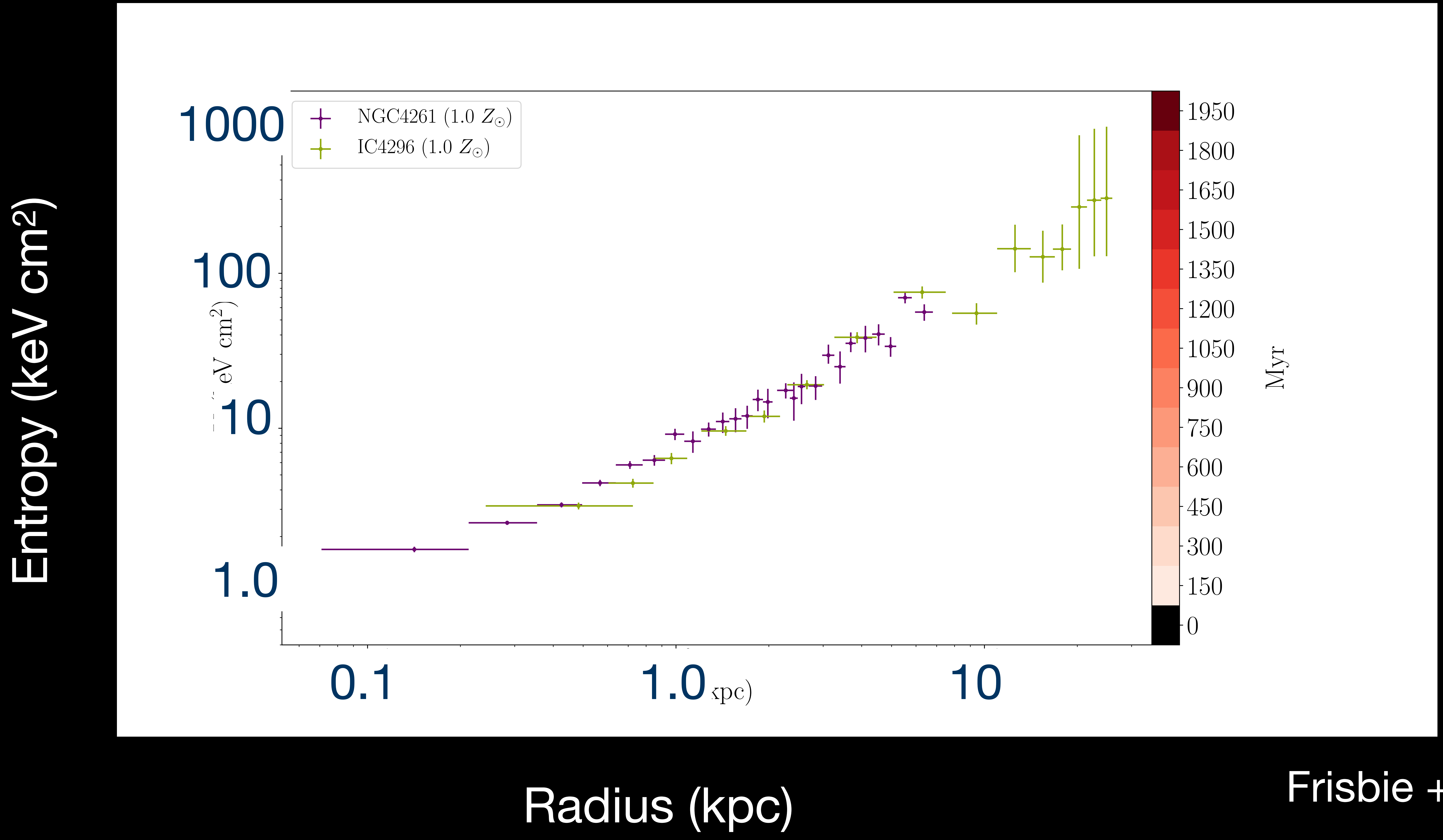




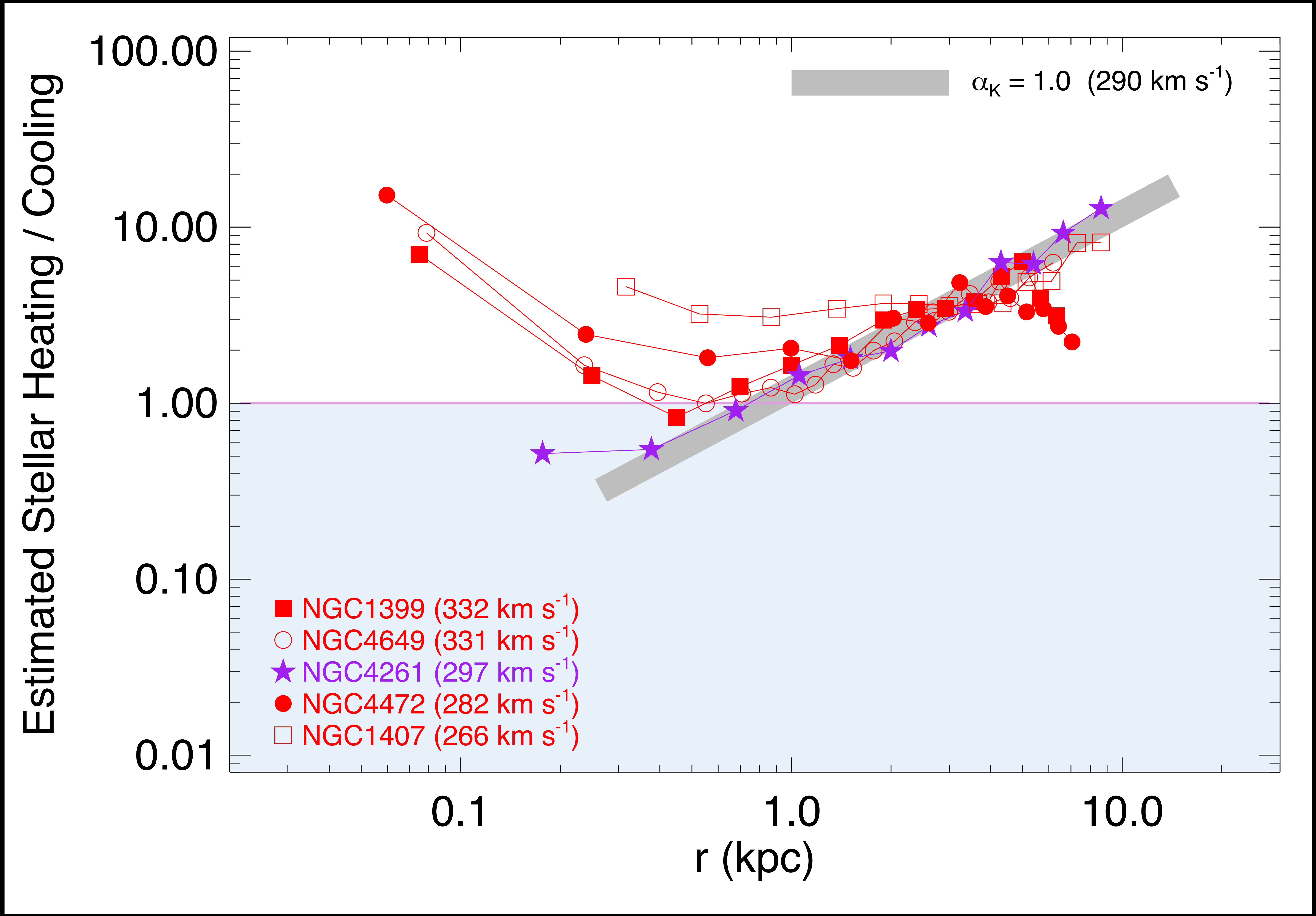


Frisbie +2020

IC4296 Entropy profile as steep or steeper than that of NGC4261

But NGC4261 and IC4296 are not "broken"

They may be in a temporary phase, though.



Cooling > Heating only in the very center of NGC4261

Voit+2020

(and also IC4296)
Donahue+ in prep

Summary

- Steep entropy gradients around powerful radio sources indicate the radio source is dumping energy at large radii (not much locally)
- The AGN increase the entropy, decrease the pressure and the density of the CGM and change the outer pressure of the CGM atmosphere.
- The steepest entropy profiles around galaxies are associated with powerful radio sources depositing most of their energy at large radii, adjusting the outer boundary condition of the "black hole valve" (see Mark Voit's talk)
- Galaxy atmosphere with steep entropy gradients are regulated by black hole feedback and stellar winds: NGC4261 and IC 4296 are not examples of "runaway cooling"