Feedback and the Hot Circumgalactic Medium

Megan Donahue
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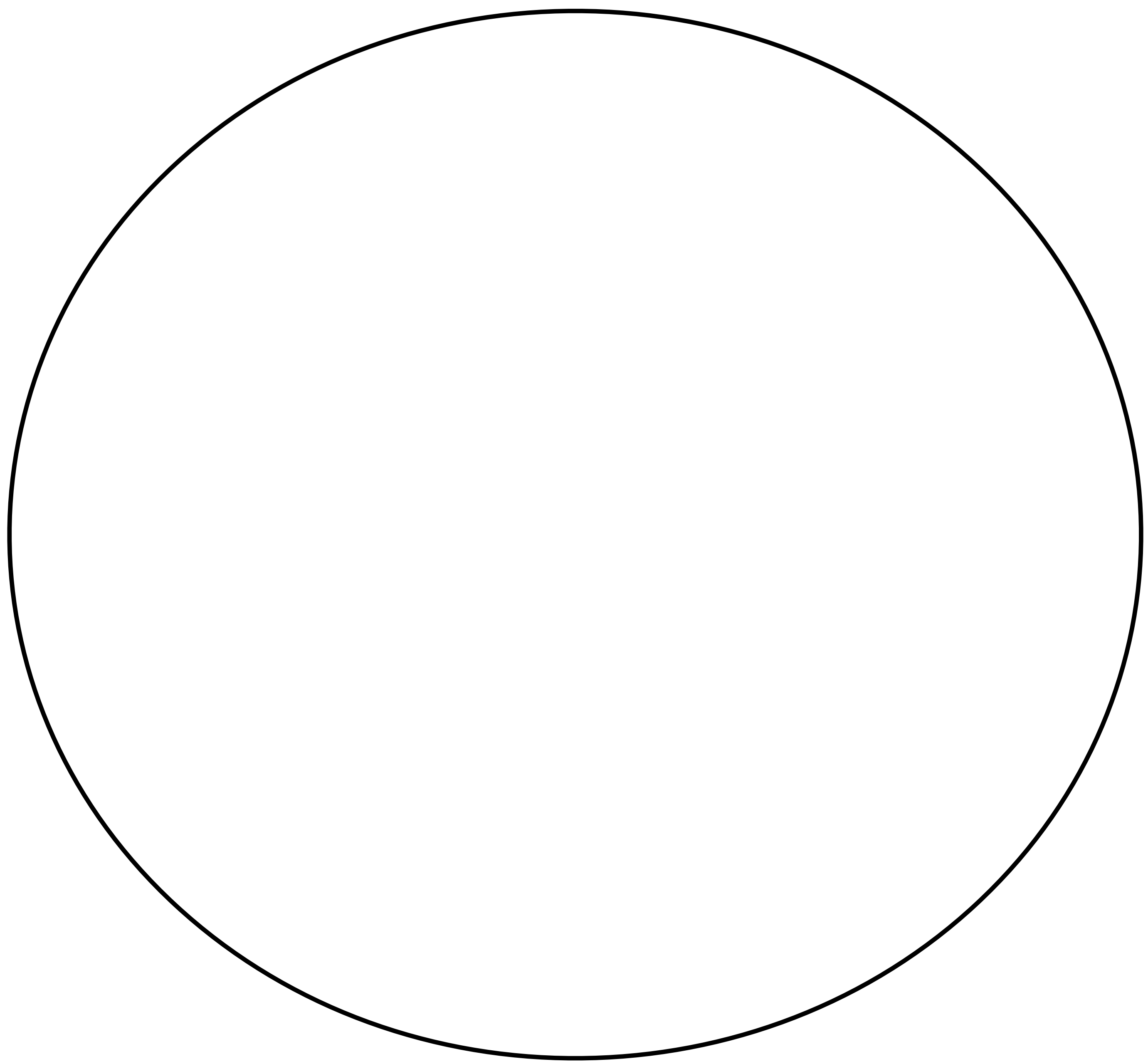
Outline

- An overview of our evolving understanding of gas in a cluster gravitational potential
- Link between hot gas and activity in the central galaxy.
- A model for feedback: Precipitation model inspired by cluster and elliptical galaxy observations by Chandra
- (Why "thermal feedback" doesn't work)
- Application of the model to lower mass galaxies
- Lynx applications

gas in a dark matter halo
a cartoon
not to scale



- dark-matter dominated (mostly)
- nearly hydrostatic
  - T ~ M/R
- X-ray luminosity is determined by ϕ_g and gas entropy ($K=kT/n_e^{2/3}$)

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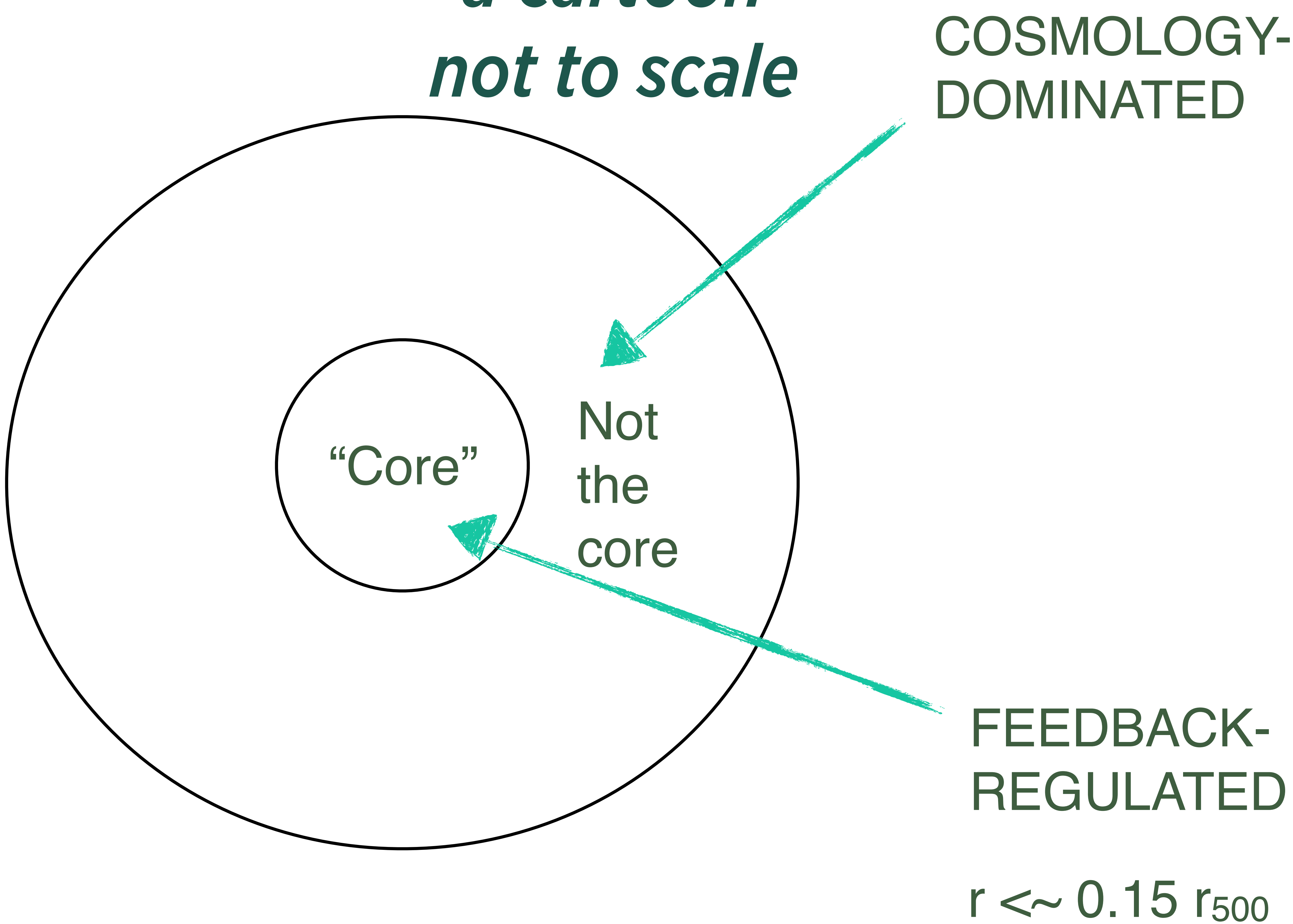
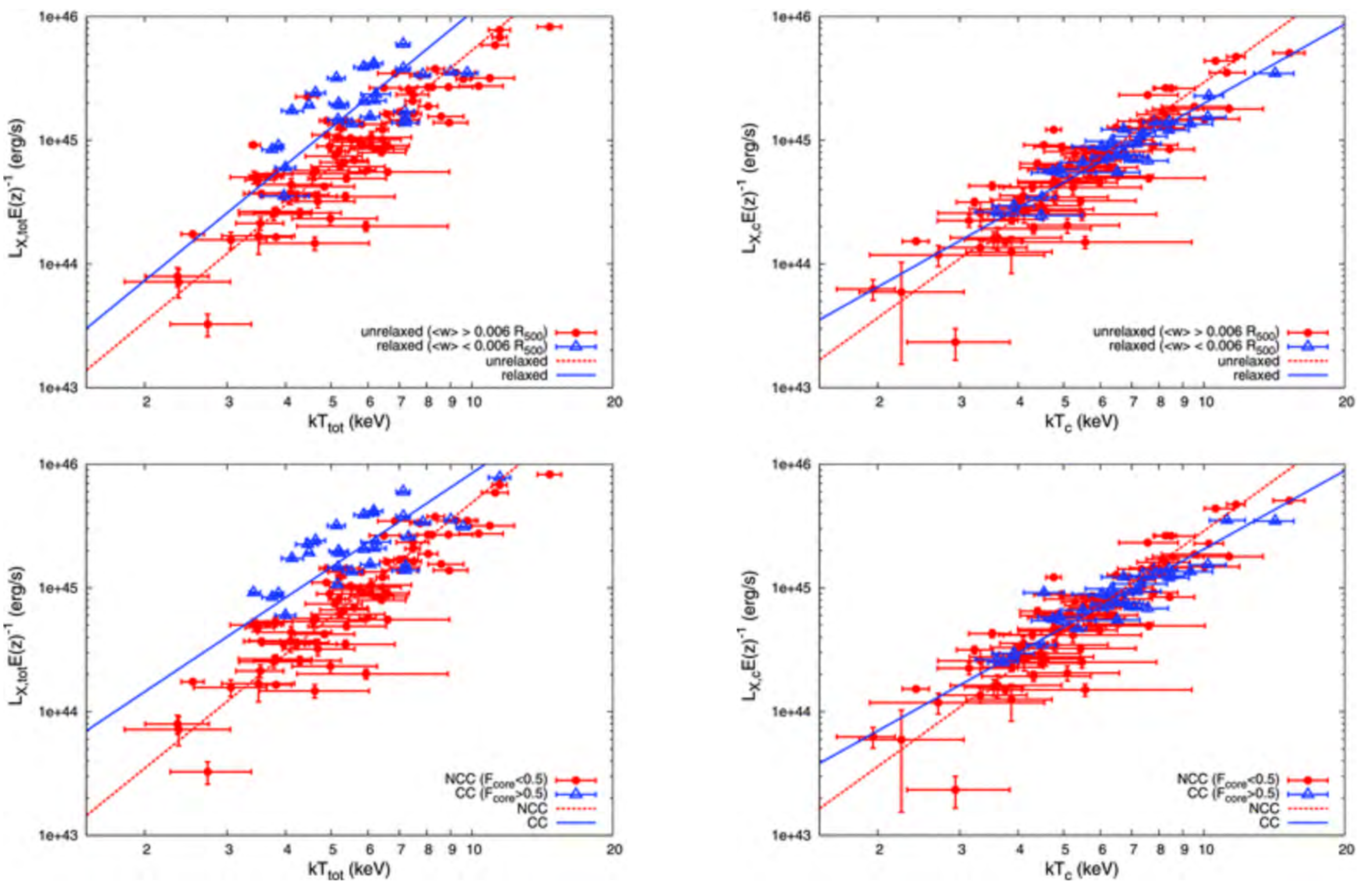


The Luminosity-Temperature Relation



Maughan+2012

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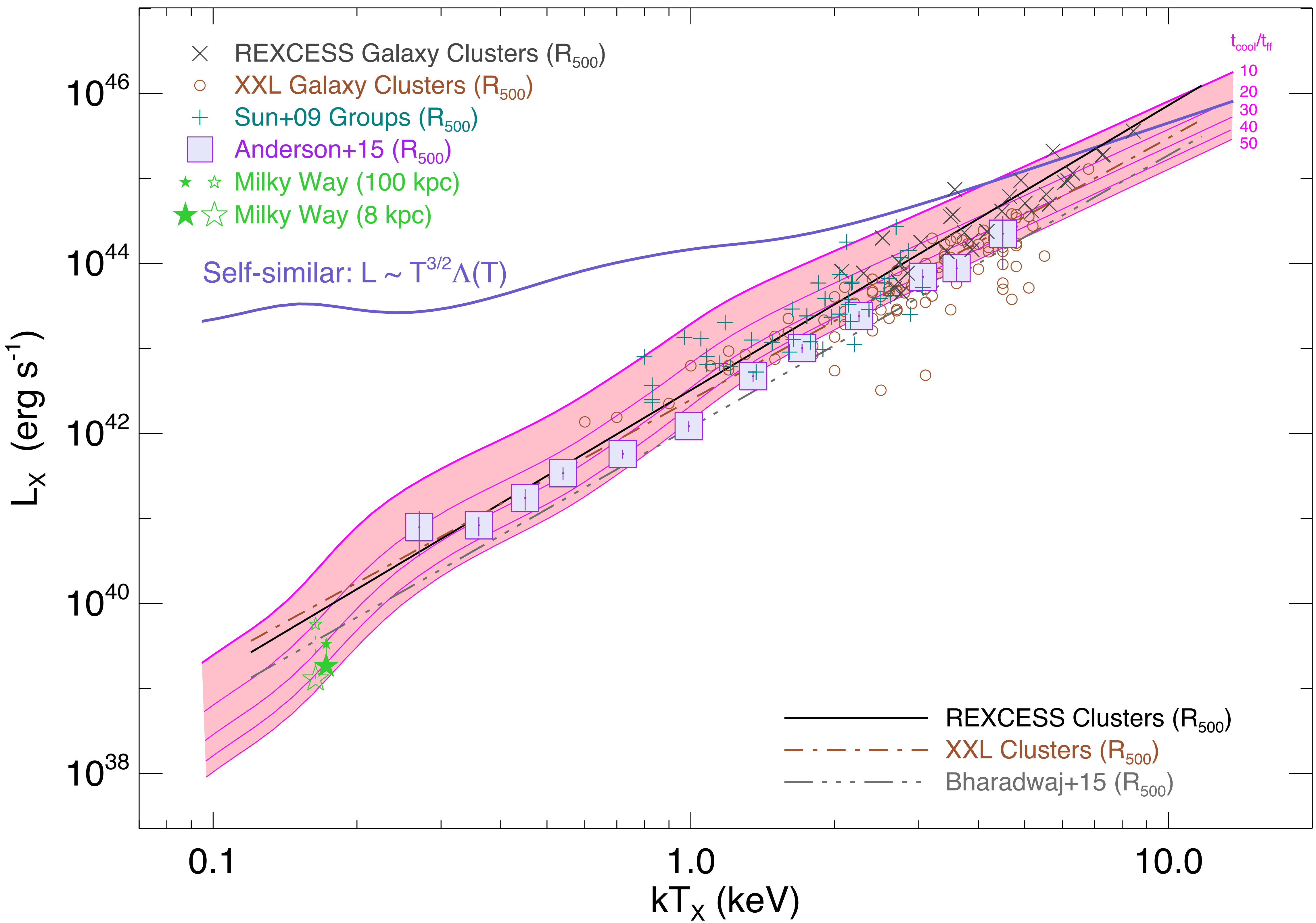
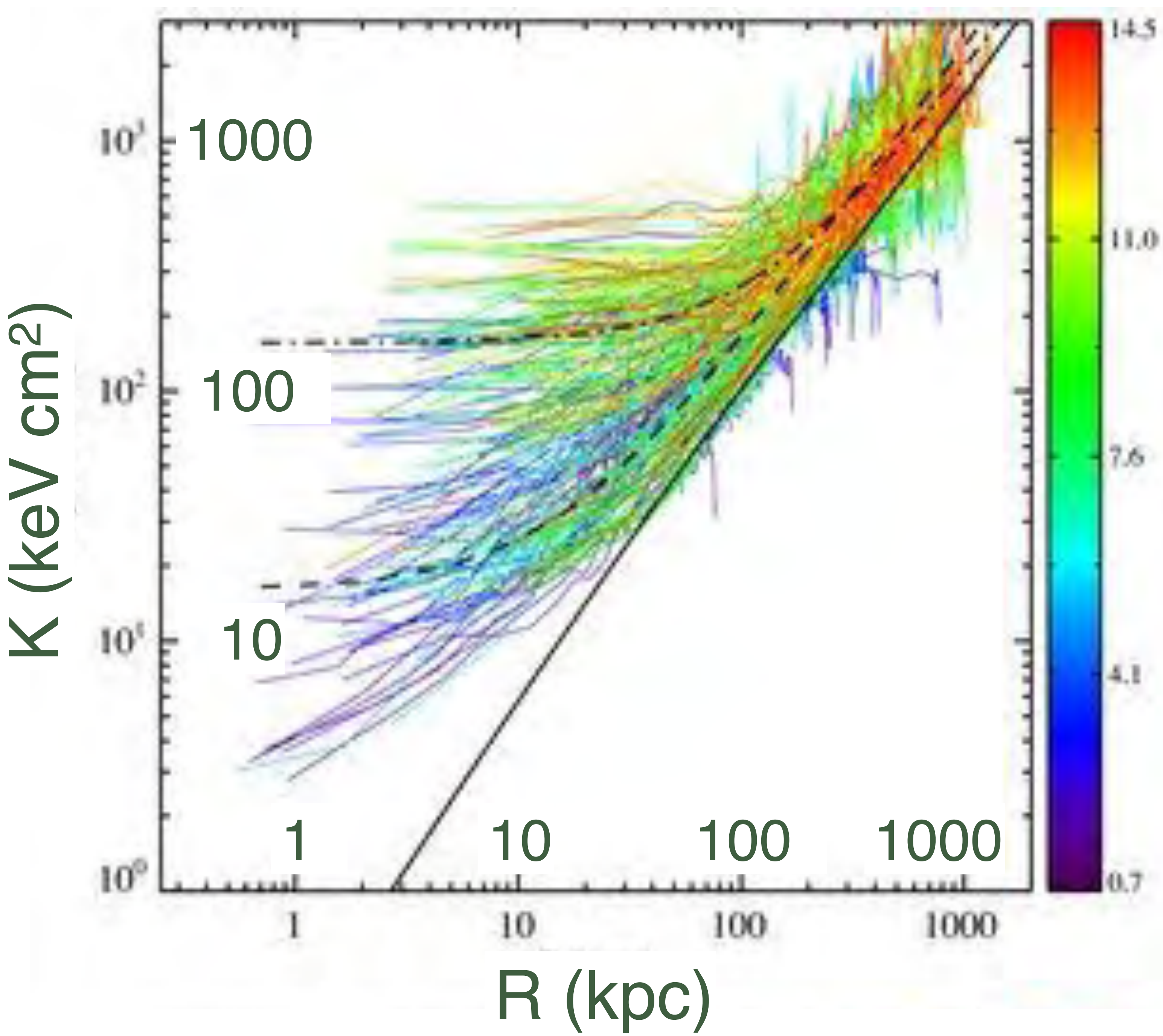


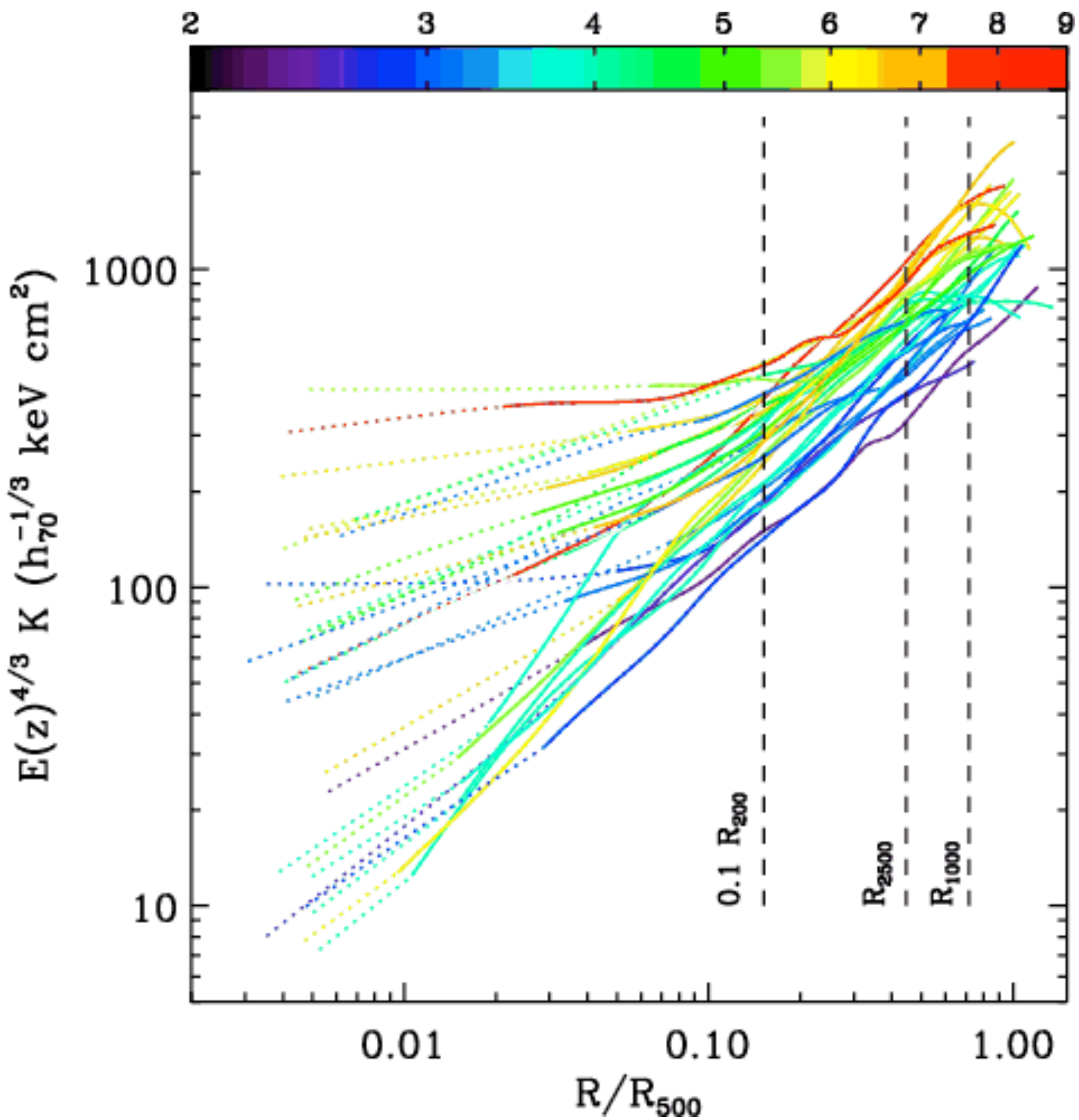
ACCEPT Entropy Profiles



$$K = kTn_e^{-2/3}$$

Cavagnolo+2009
233 Chandra clusters
z<0.2

REXCESS (XMM) Entropy Profiles



Pratt+2010

25 representative clusters, z~0.1

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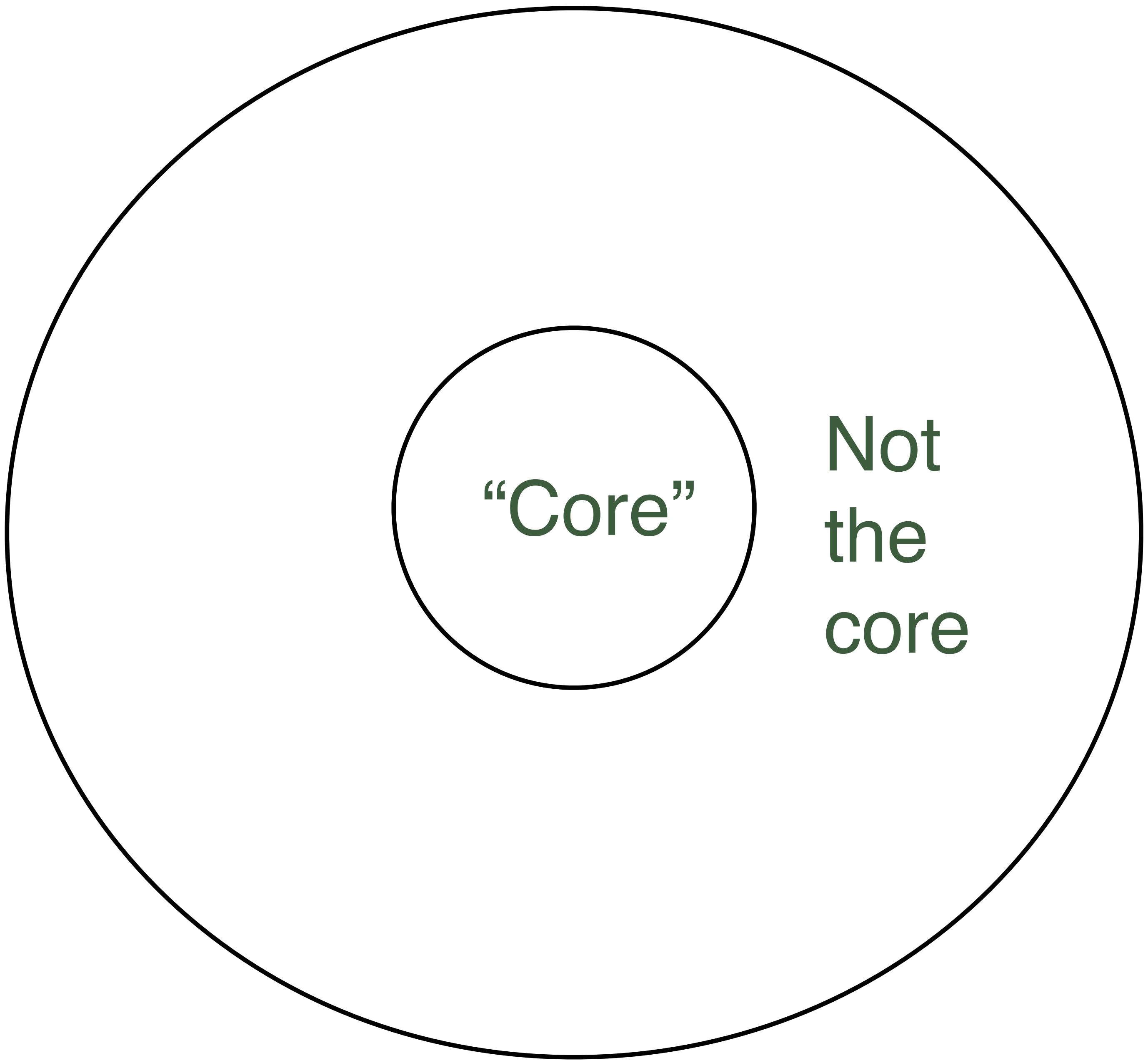


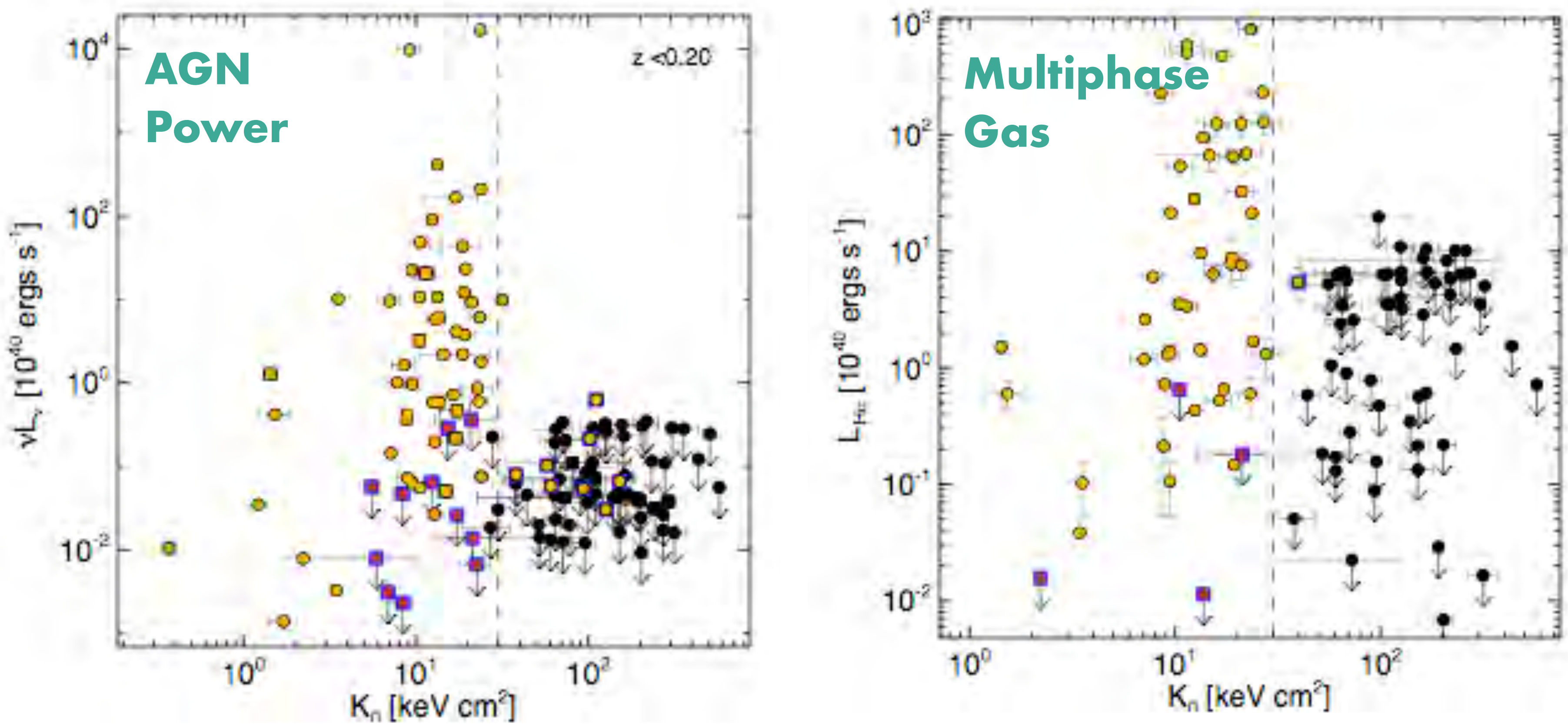
t_{cool} = (thermal energy)/(luminosity)

t_{cool} increases with gas entropy.

“core” vs. “not core” set by local thermodynamic timescale (t_{cool}) and the gravitational timescale (t_{ff})

Multiphase Threshold

Voit+ 08, Cavagnolo+ 08, Rafferty+ 08



Core Entropy Index = K_0 = $kTn_e^{-2/3}$

equivalent to t_{cool} ~ 10^9 yr

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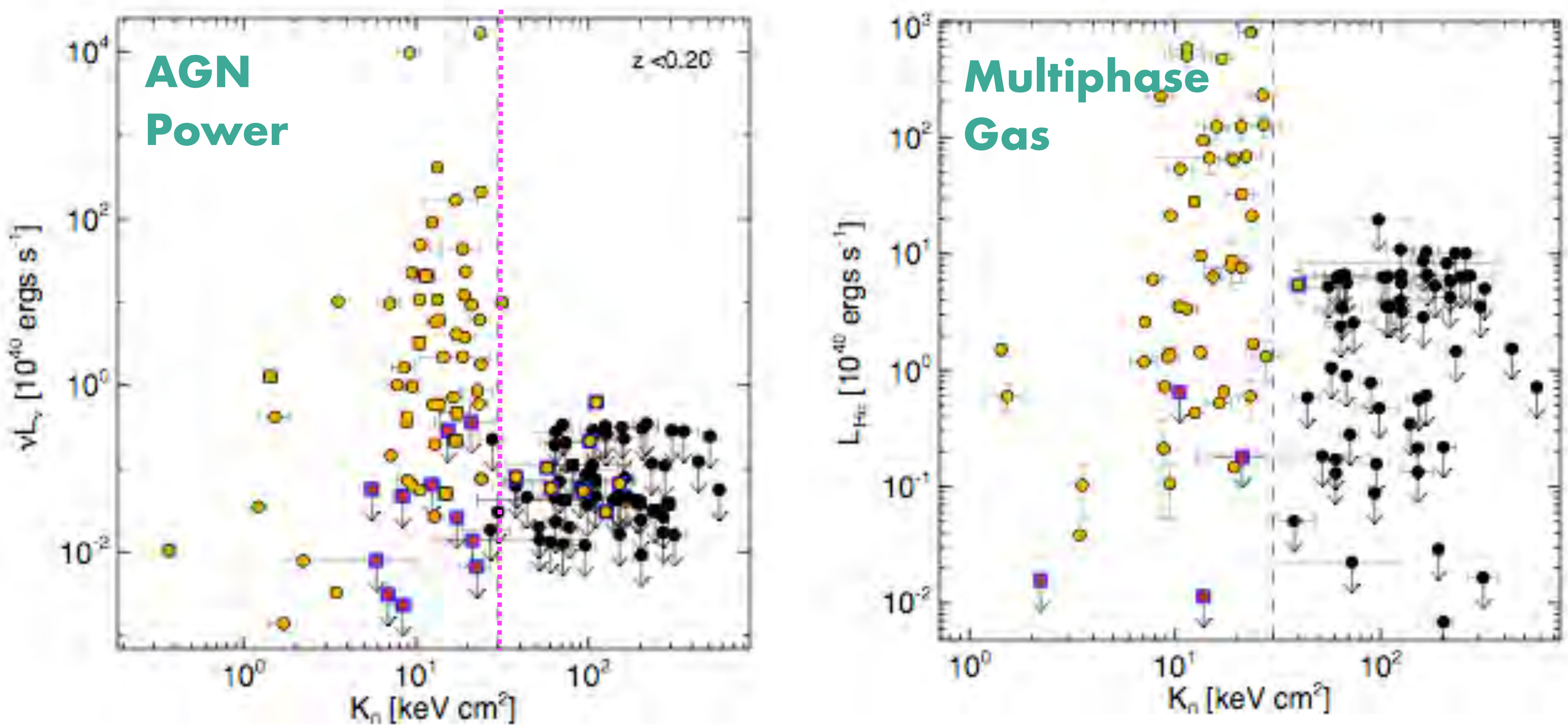

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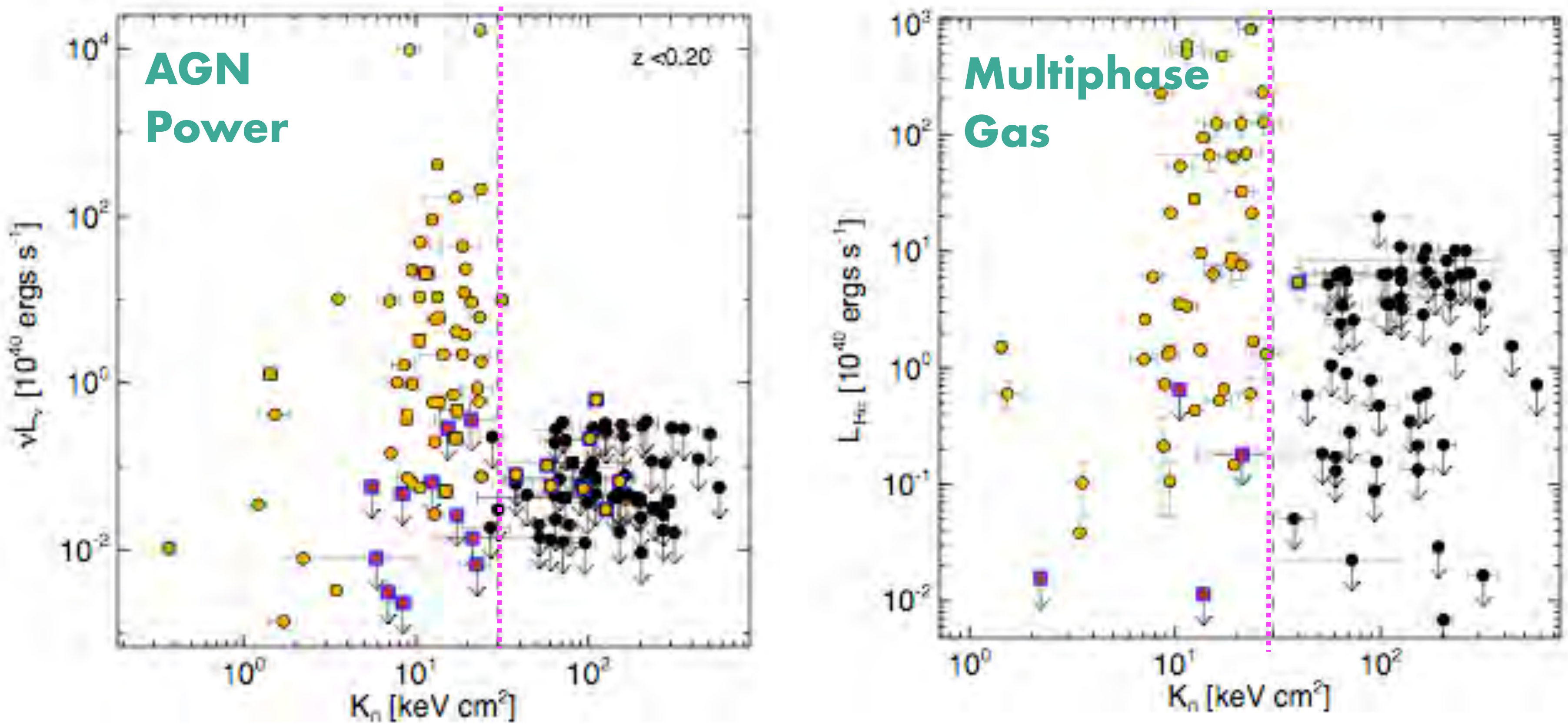
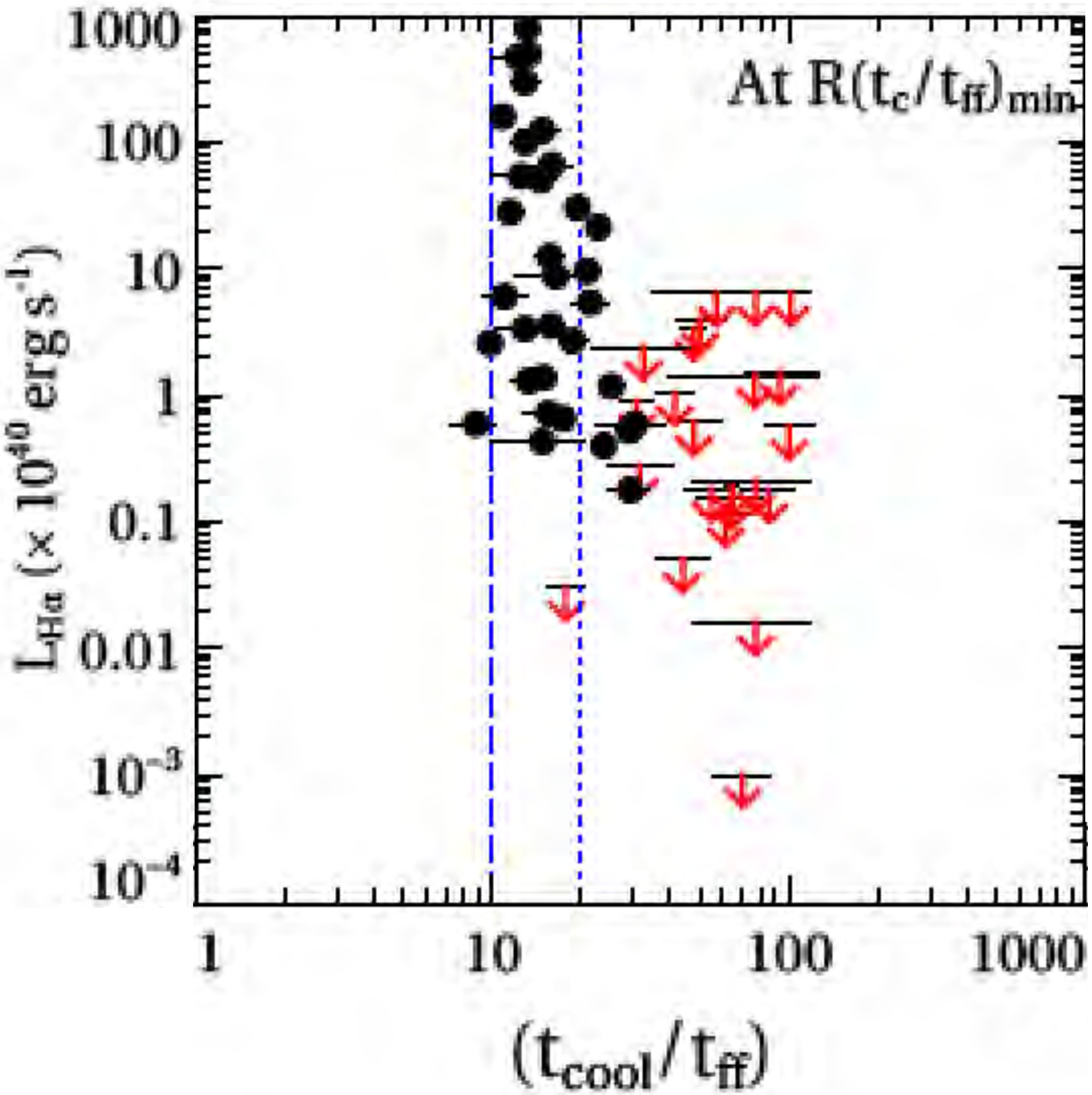


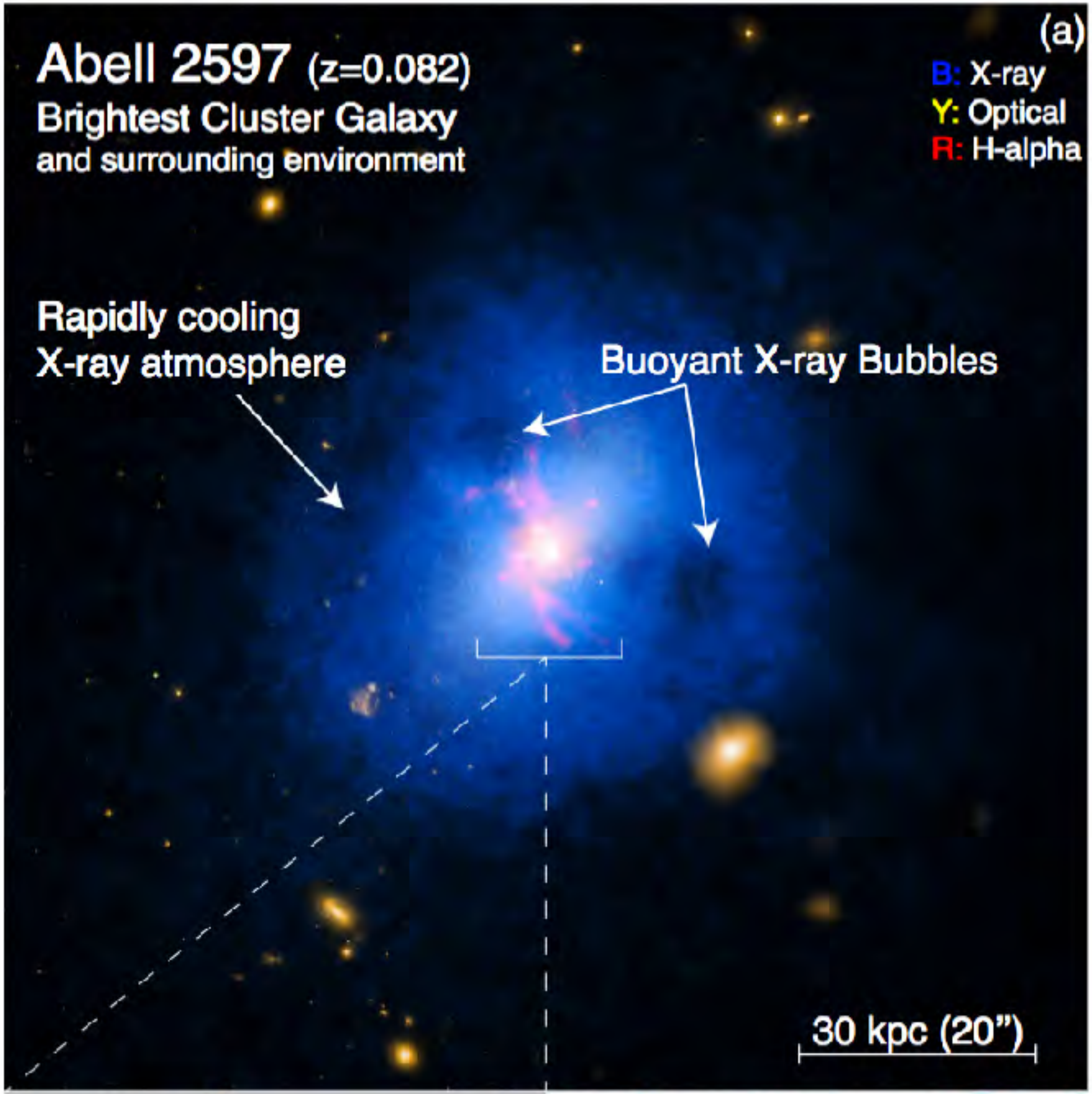
Core Entropy Index = $K_0 = kTn_e^{-2/3}$

equivalent to $t_{cool} \sim 10^9$ yr

Multiphase Core Gas and min(t_{cool}/t_{ff})

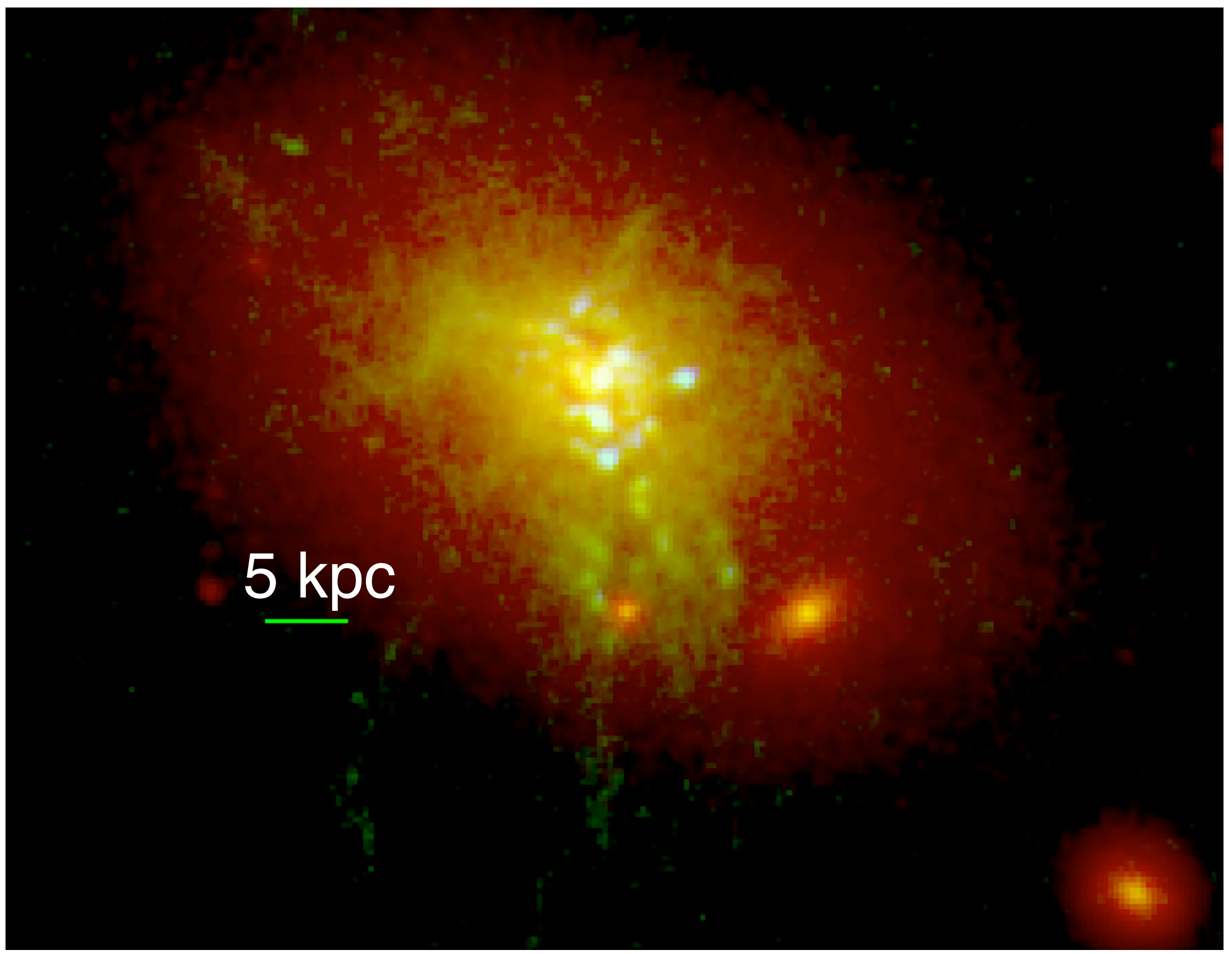


Hogan+2017



Tremblay+ 2016, Nature

Lyman α from SF-UV clumps in Brightest Cluster Galaxy MACS J1532+30

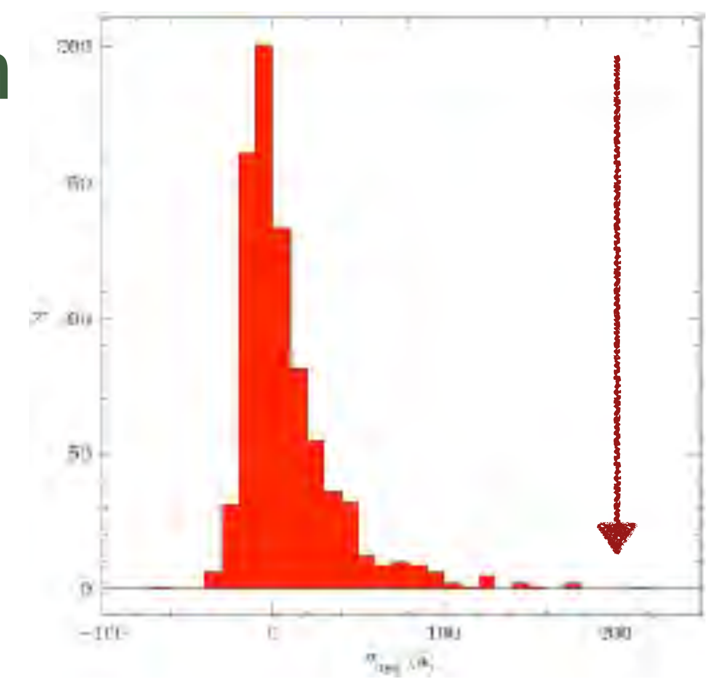


Donahue+2017

Number of Lyman Break Galaxies

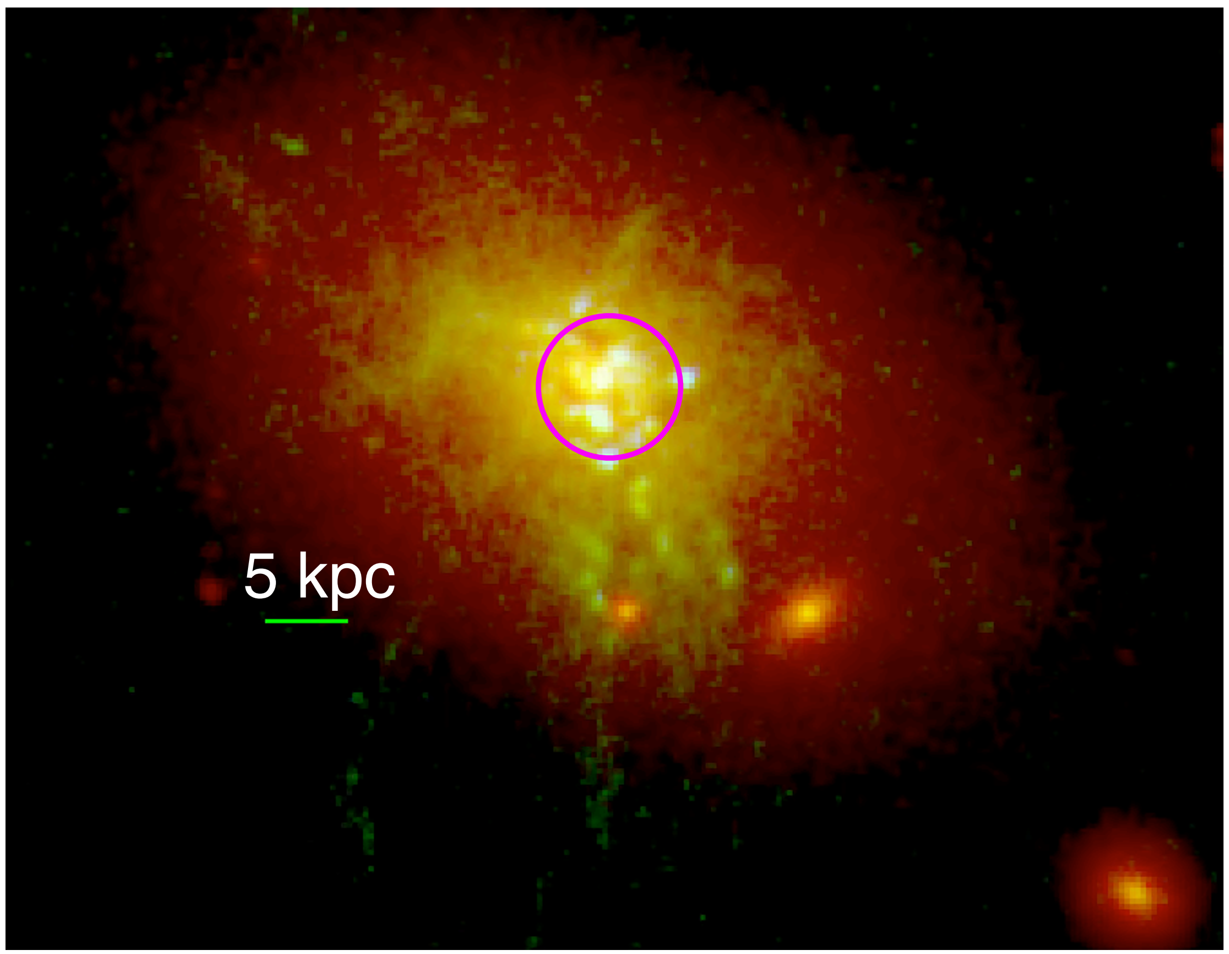
(z~3)

Shapley+2003



Equivalent Width in Angstroms

Lyman α from SF-UV clumps in Brightest Cluster Galaxy MACS J1532+30



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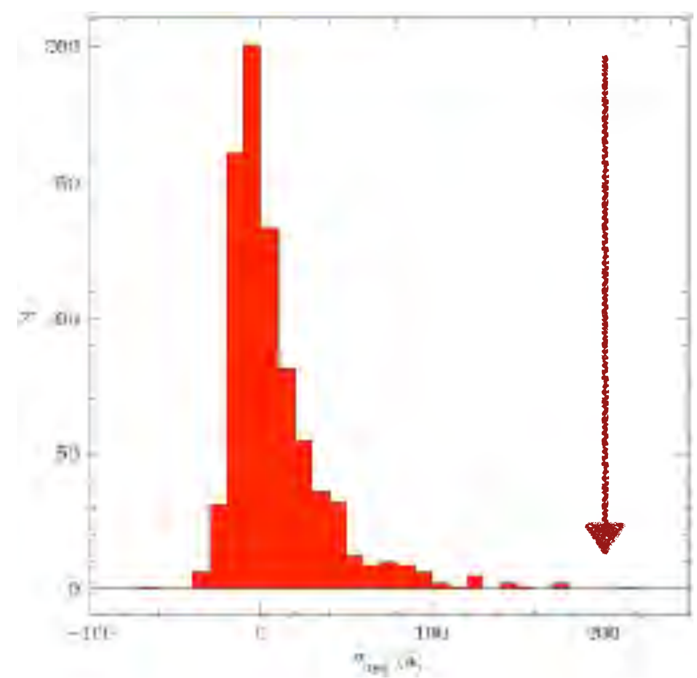

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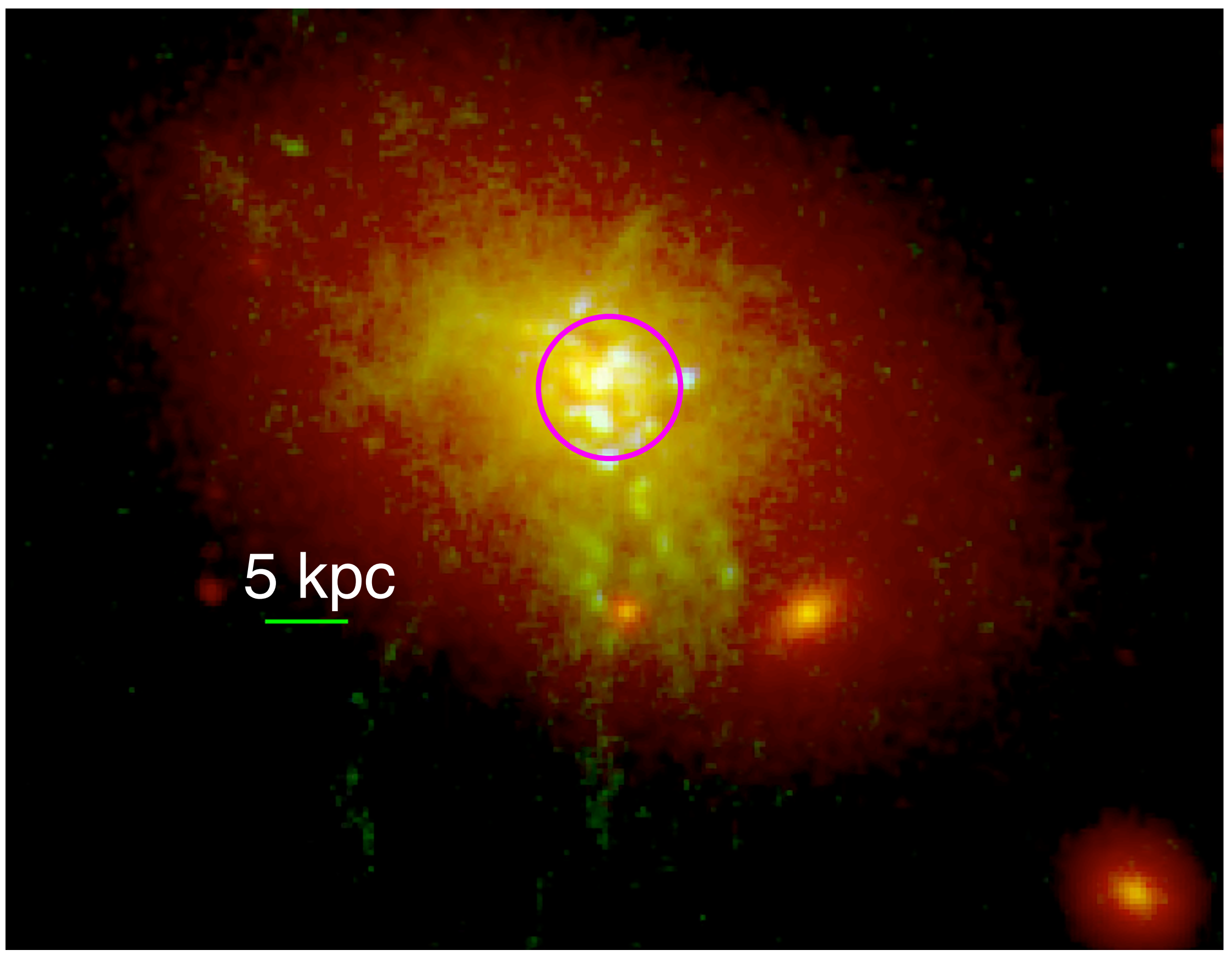
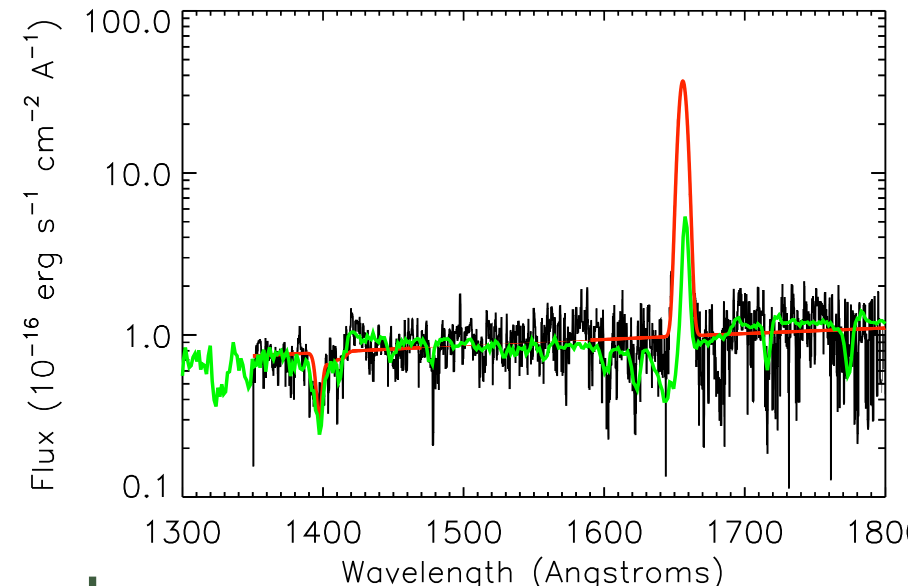


Donahue+2017



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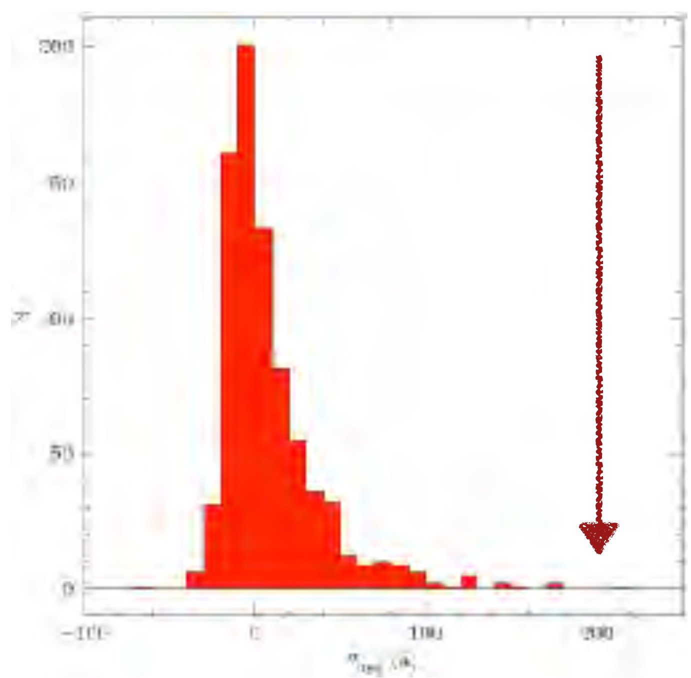

Equivalent Width in Angstroms

Feedback and the Hot CGM

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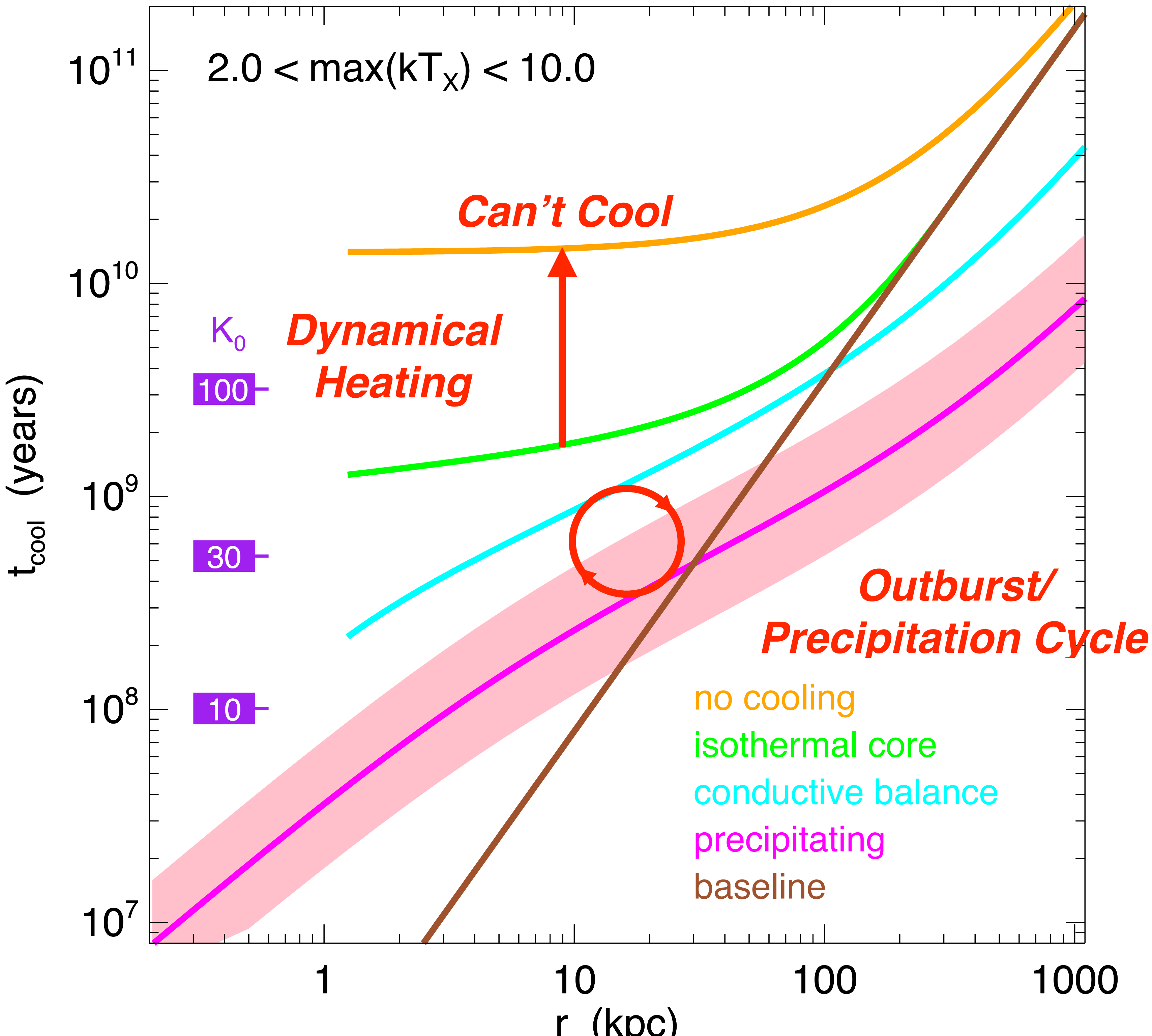
Cluster Cooling-Time Profiles

Voit+ 2015, Nature

Note: simple "thermal" AGN feedback does not work.



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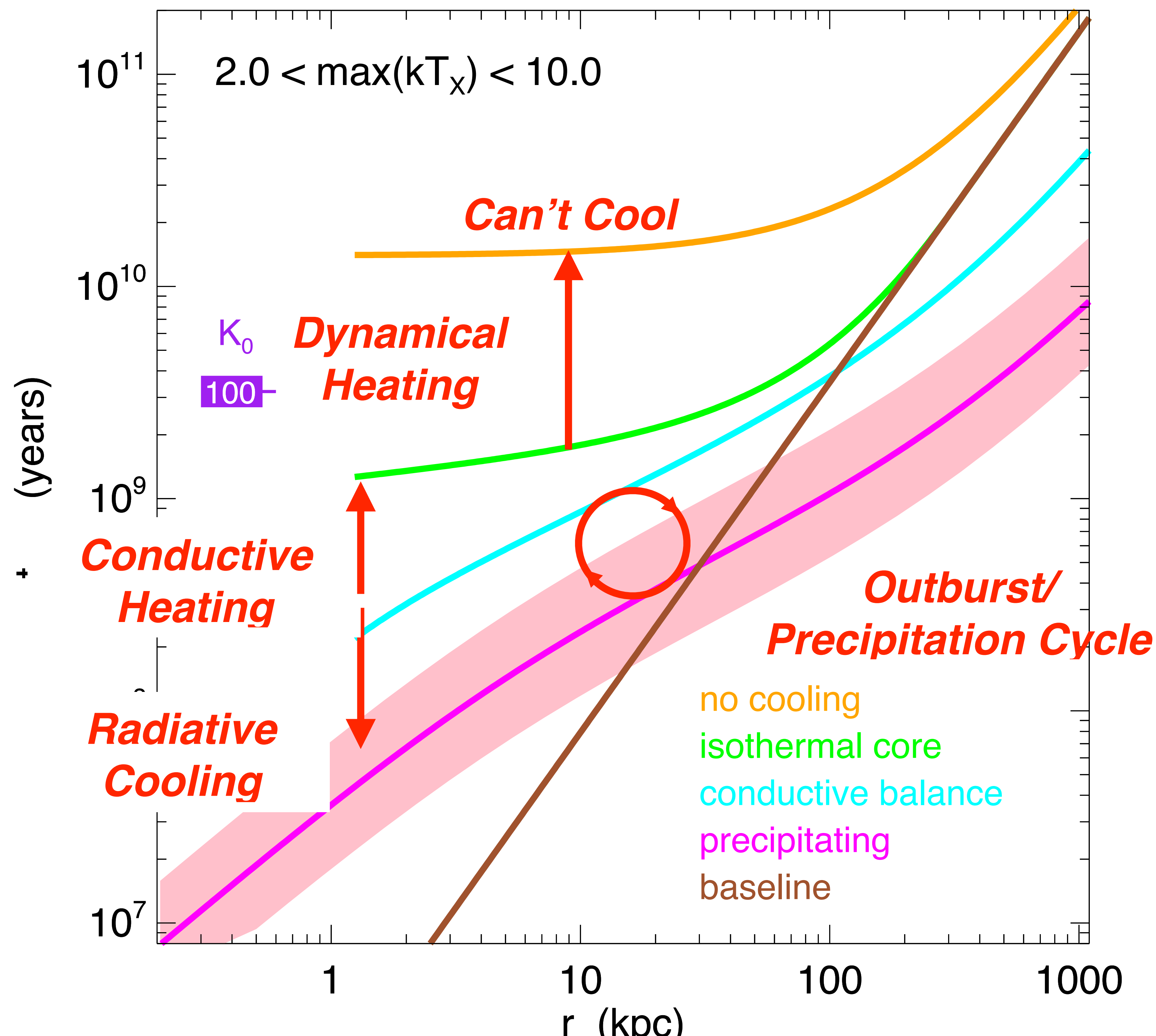

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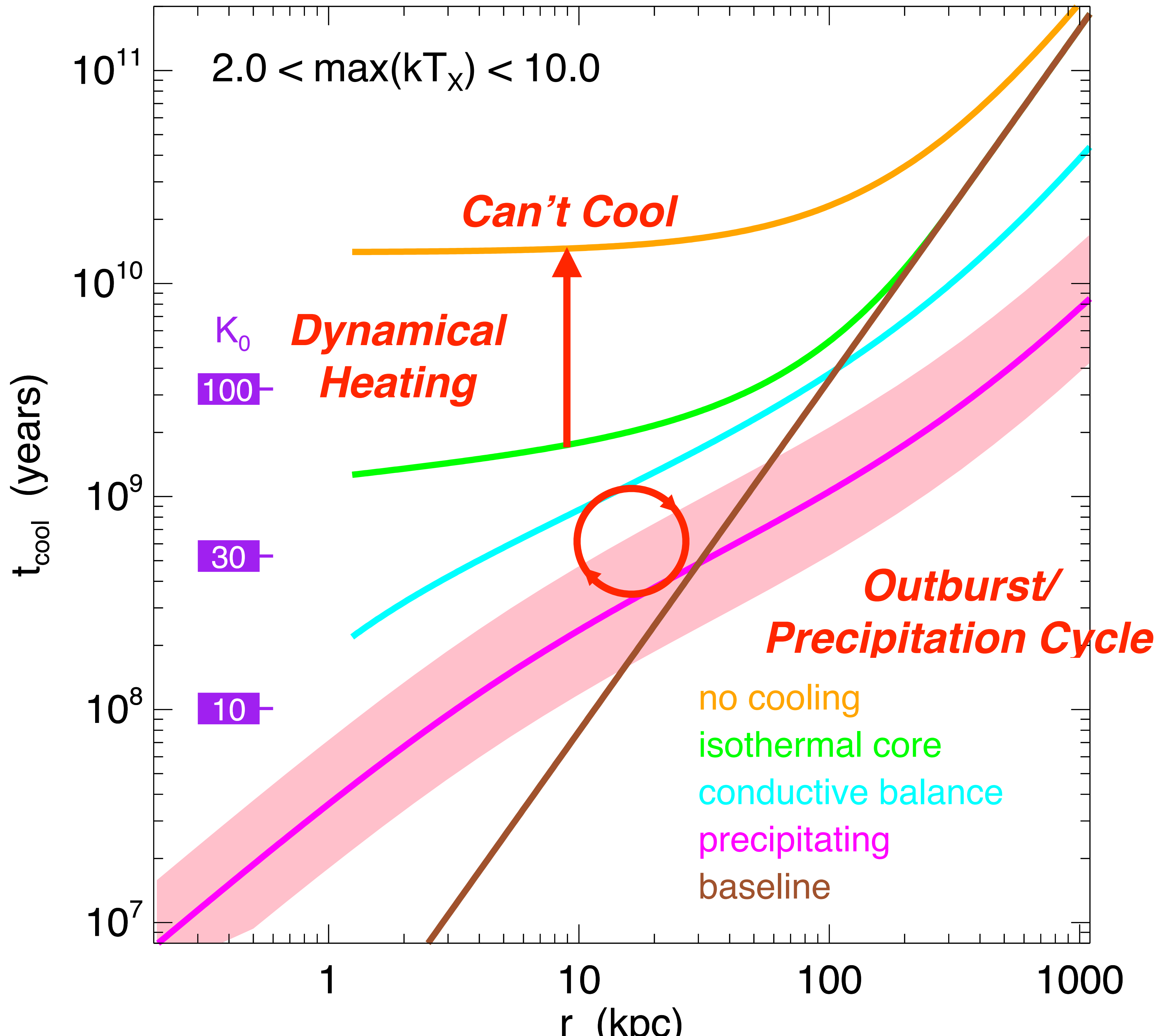

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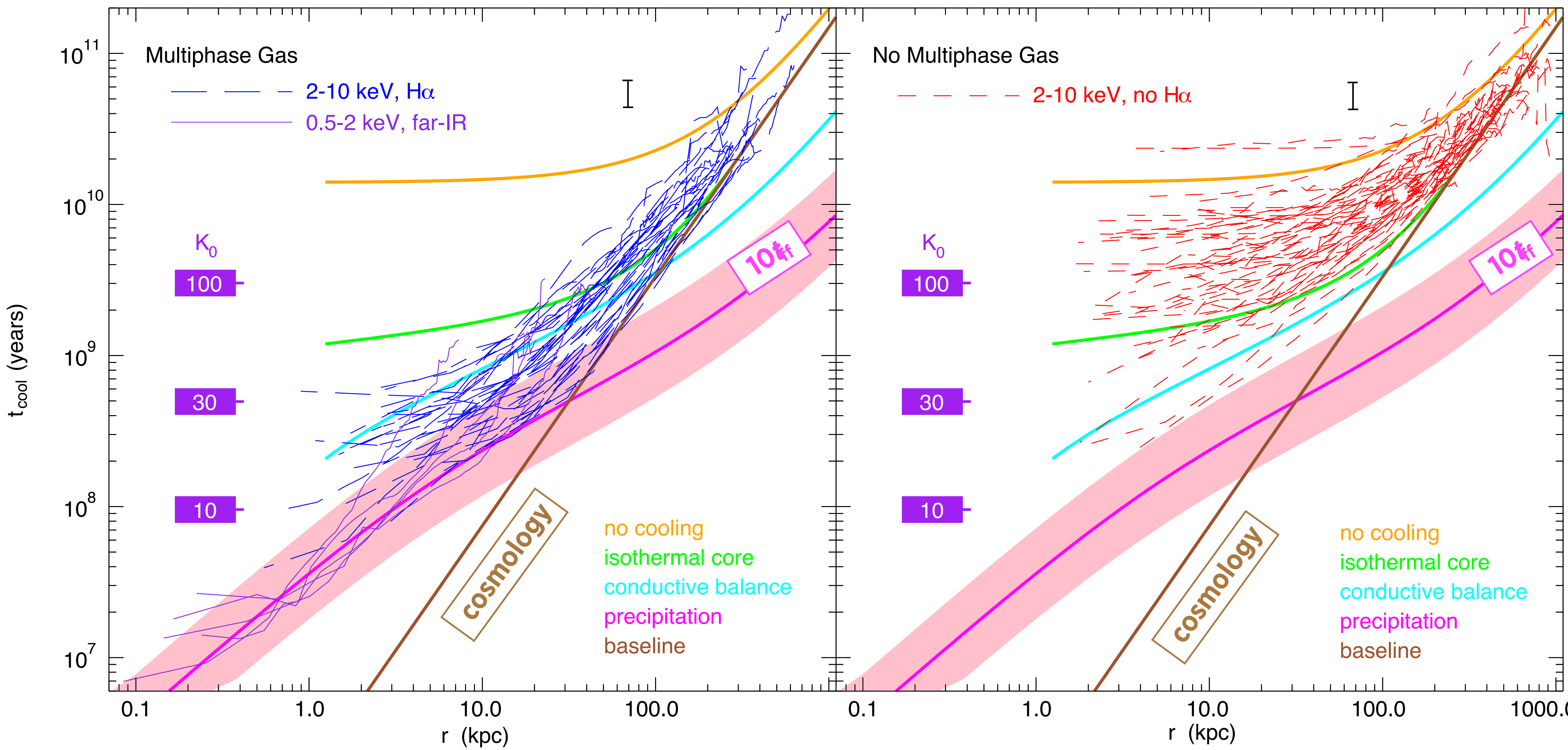

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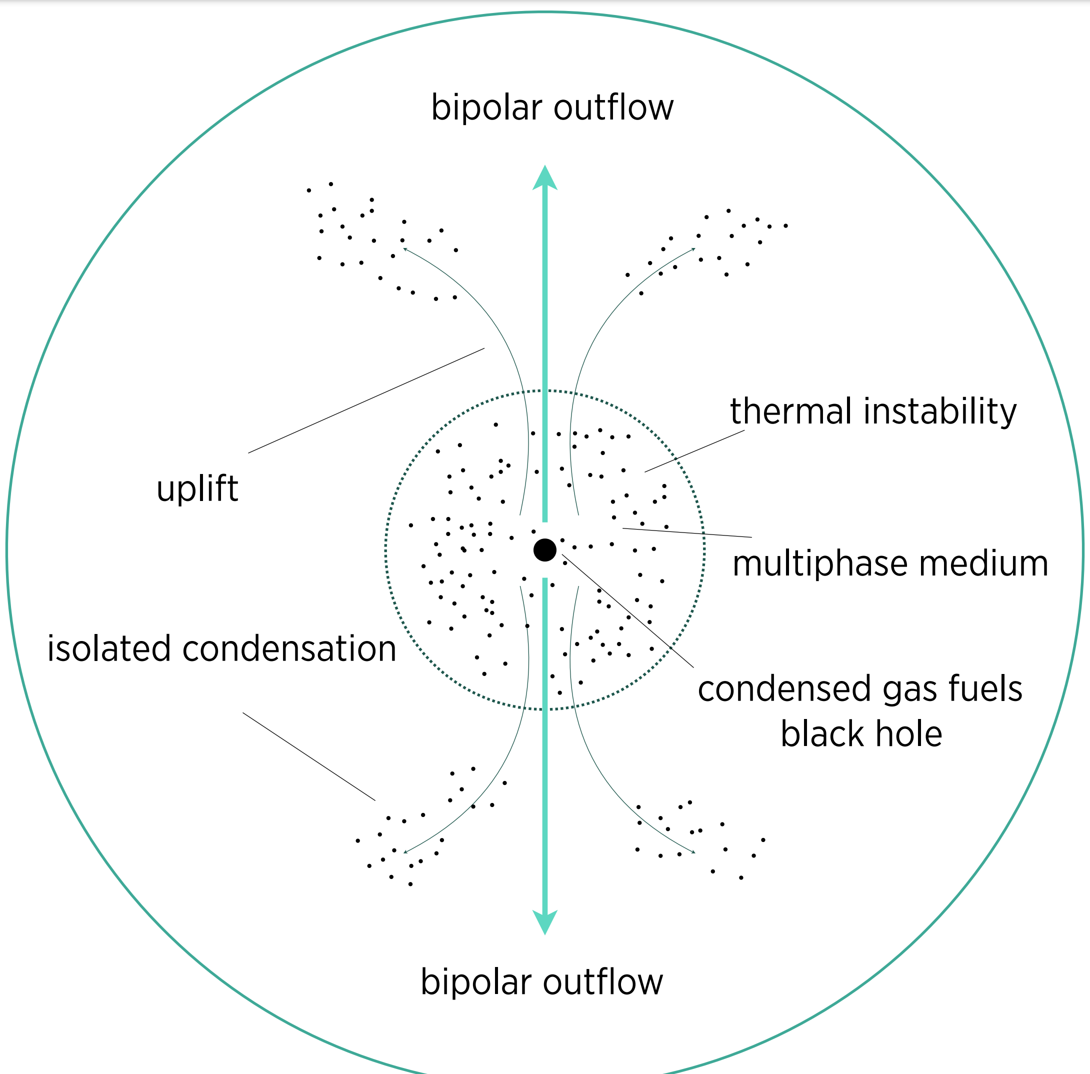
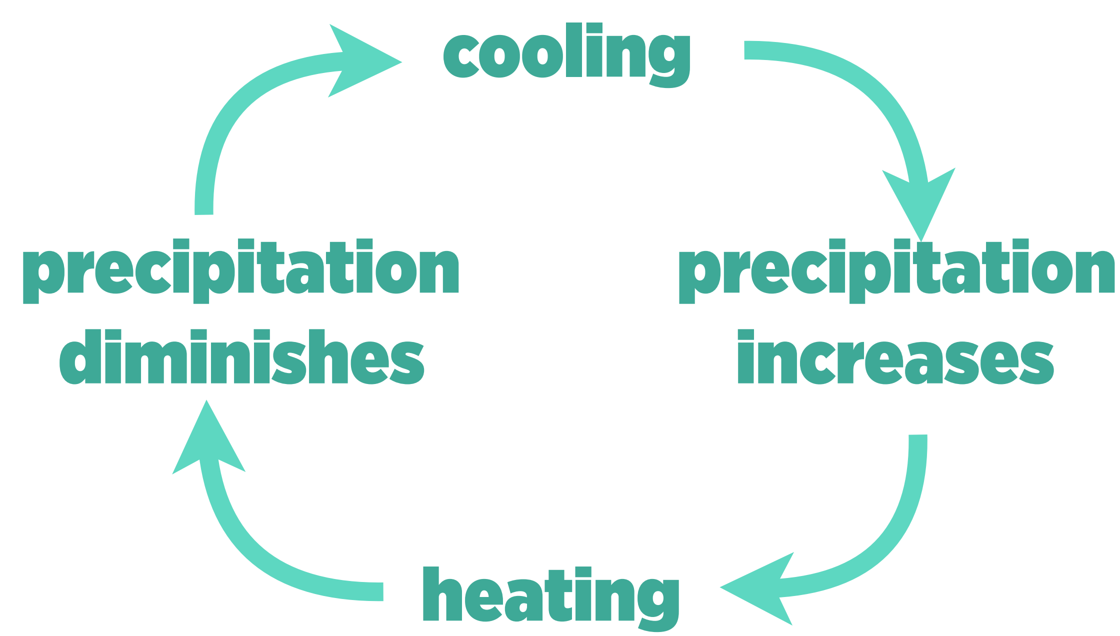
The Precipitation Hypothesis

Feedback from the central black hole maintains the CGM in a state marginally unstable to condensation

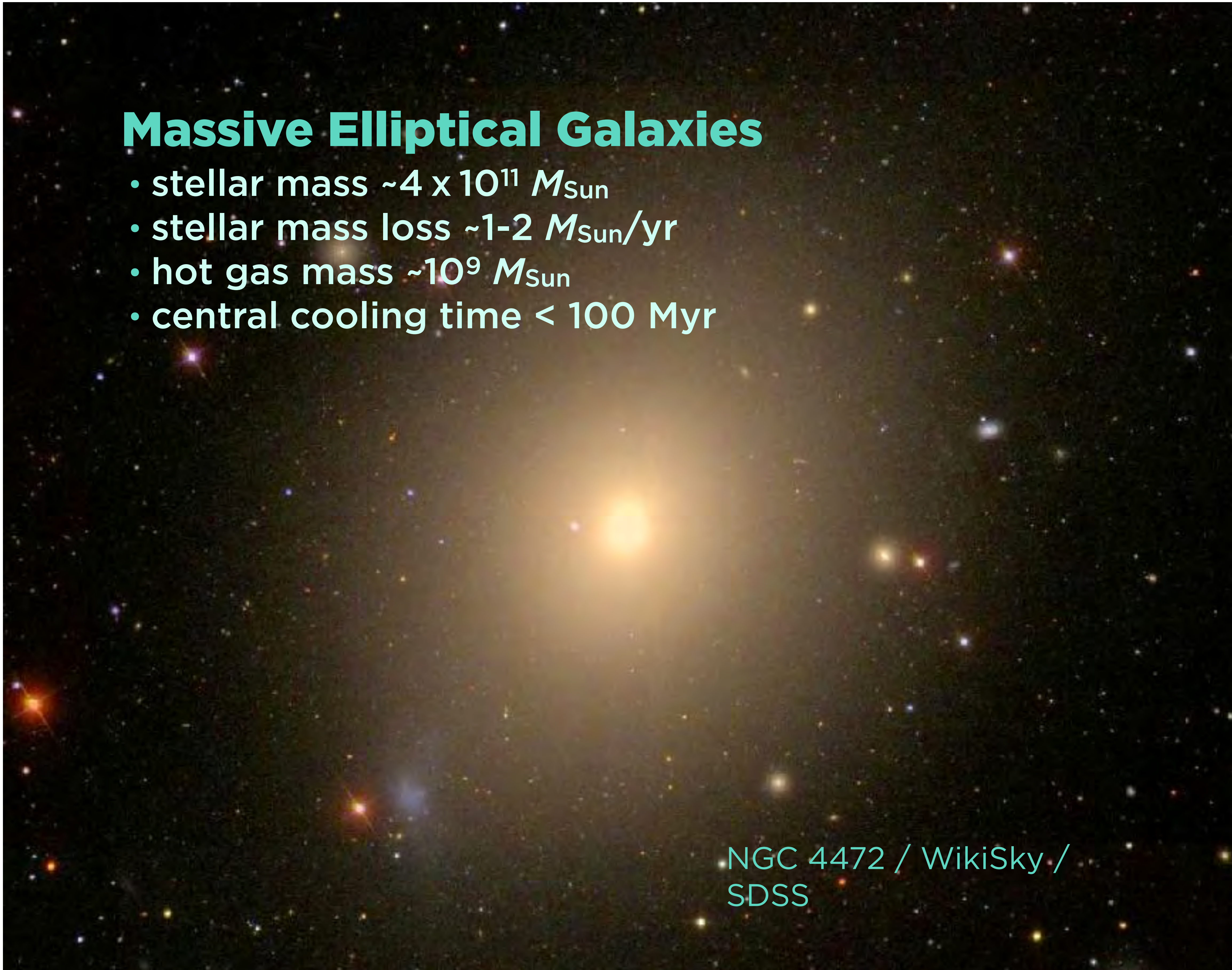




Voit+ 2015 Nature, Voit, Donahue+ ApJ Letters; Voit+2017 ApJ

Massive Elliptical Galaxies

- stellar mass ~4 x 10^{11} M_{Sun}
- stellar mass loss ~1-2 M_{Sun}/yr
- hot gas mass ~10^9 M_{Sun}
- central cooling time < 100 Myr

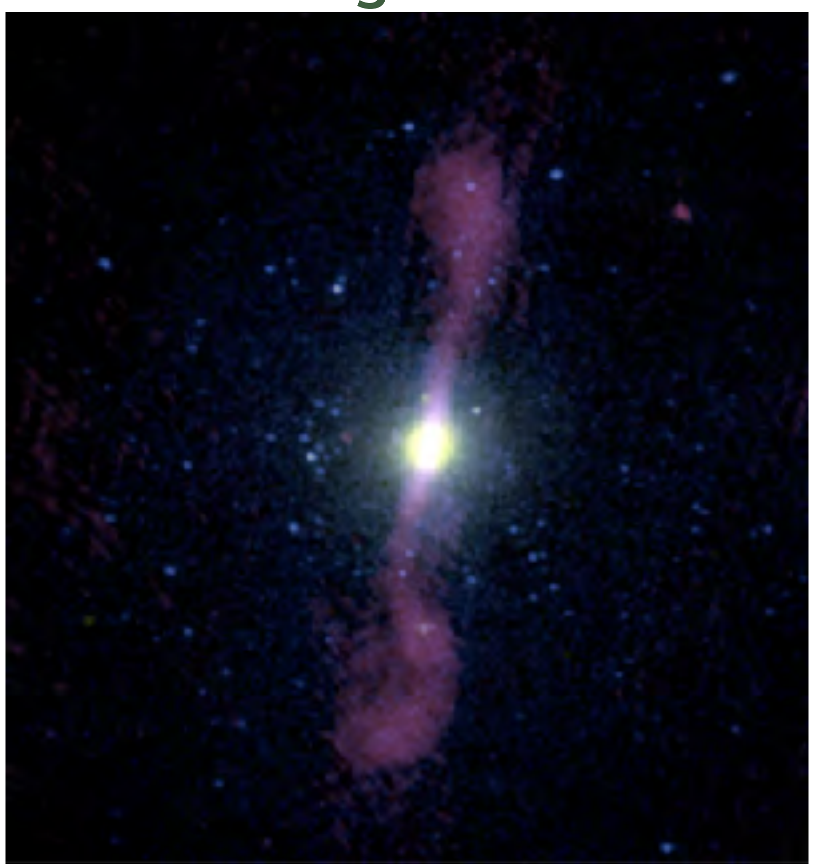


NGC 4472 / WikiSky / SDSS

Two Kinds of Massive Ellipticals

Werner+ 12, Werner+ 14

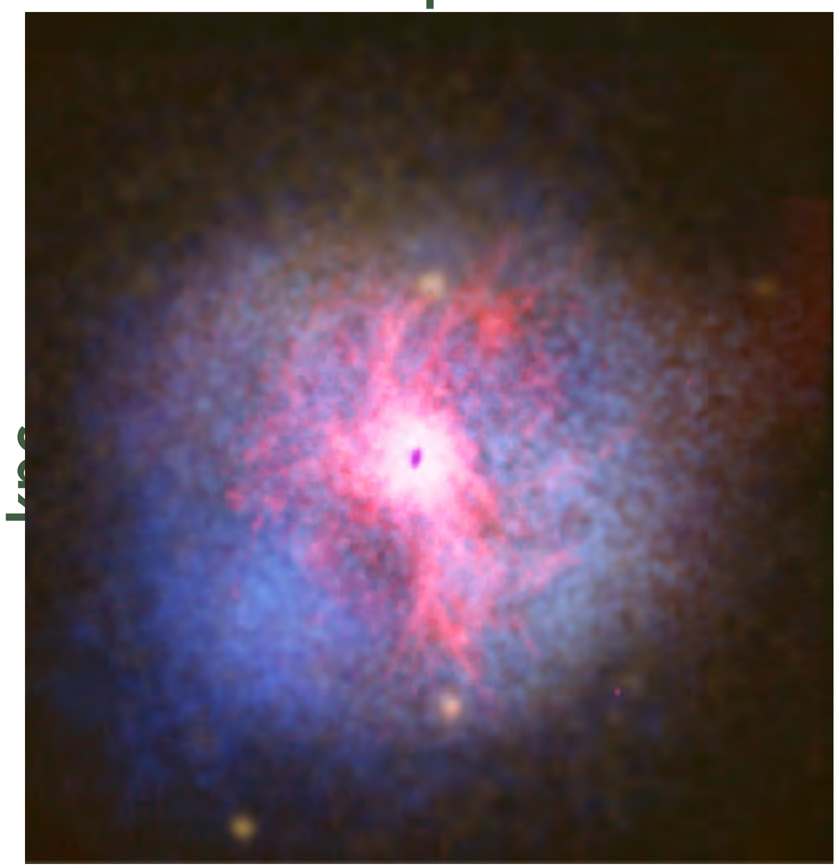
Single-



NCG 1399

30

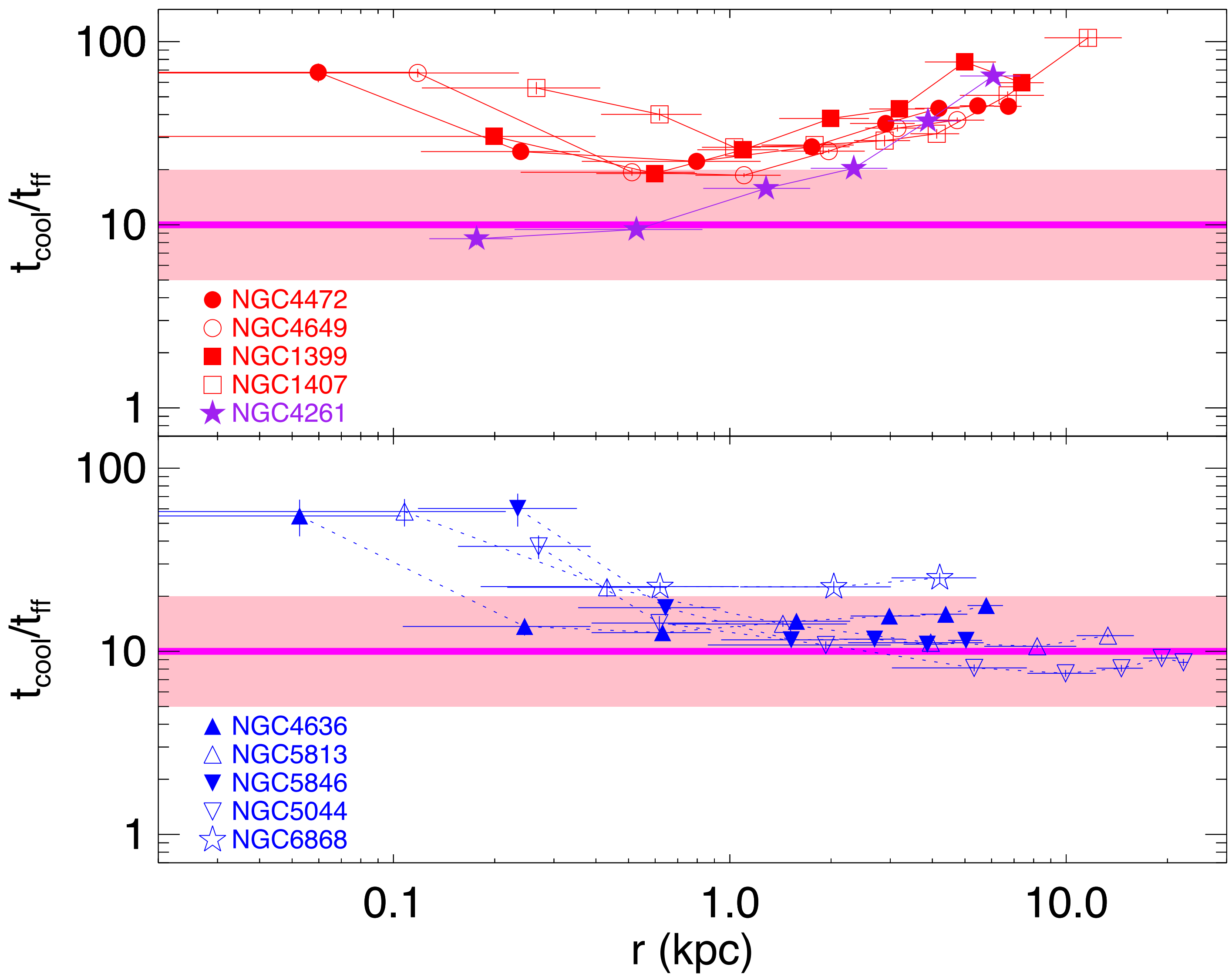
Multiphas



NGC
5044

Precipitation Threshold in Ellipticals

Voit+ 15 (Apr 2015, ApJL) , data: Werner+ 12,14



No Extended Multiphase Gas

- X-ray gas profile consistent with galaxy wind

Extended Multiphase Gas

-X-ray gas profile consistent with tcool/tff~10

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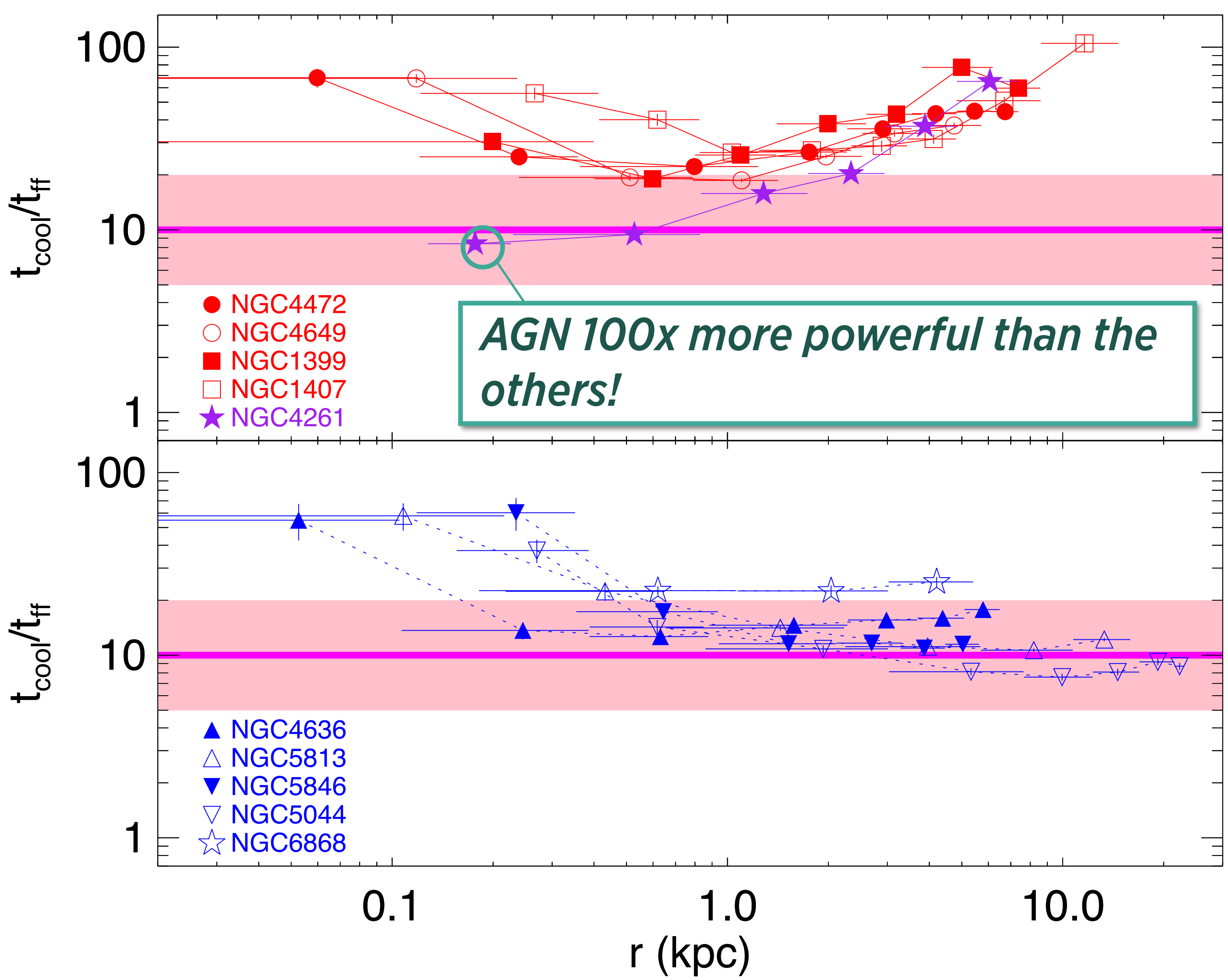

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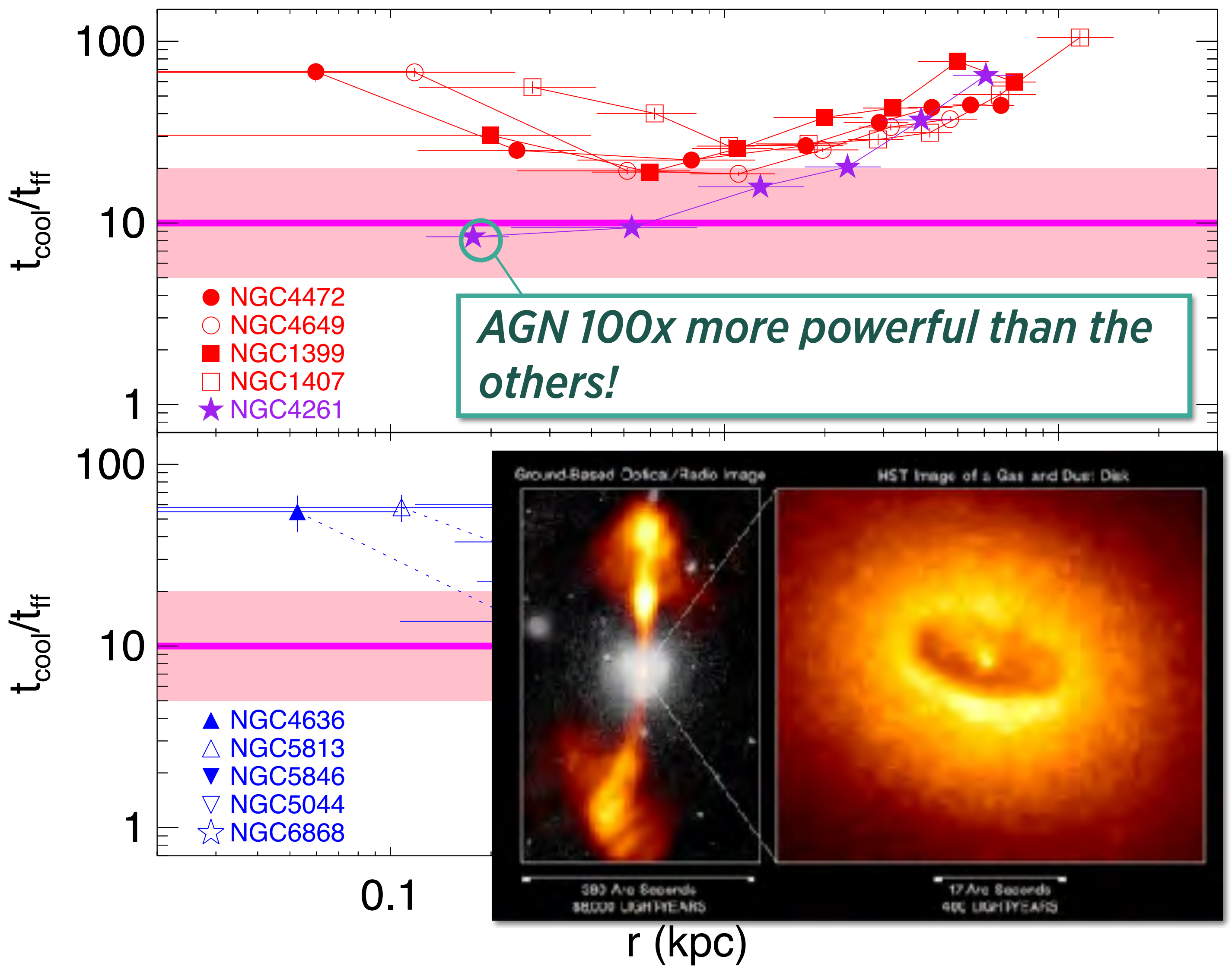

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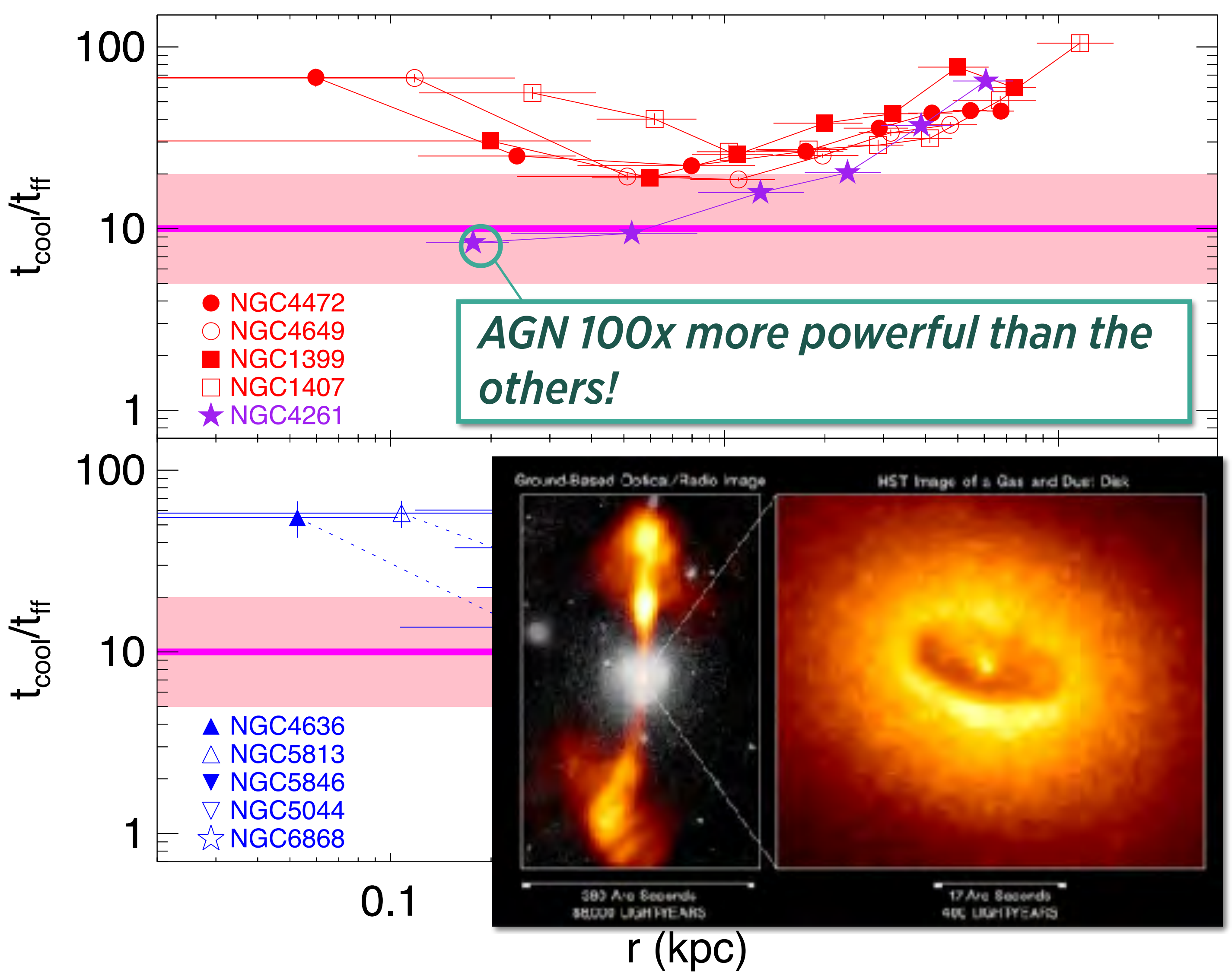

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Lynx science: probe the gas conditions in the centers of ellipticals with and without power radio sources.

Precipitation-Limited Luminosity

Voit, Ma, Greene, Goulding, Pandya, Donahue, Sun 2017,
astro-ph, (yesterday),
arxiv.org/abs/1708.02189

$$\frac{t_{\rm cool}}{t_{\rm ff}} \gtrsim 10$$

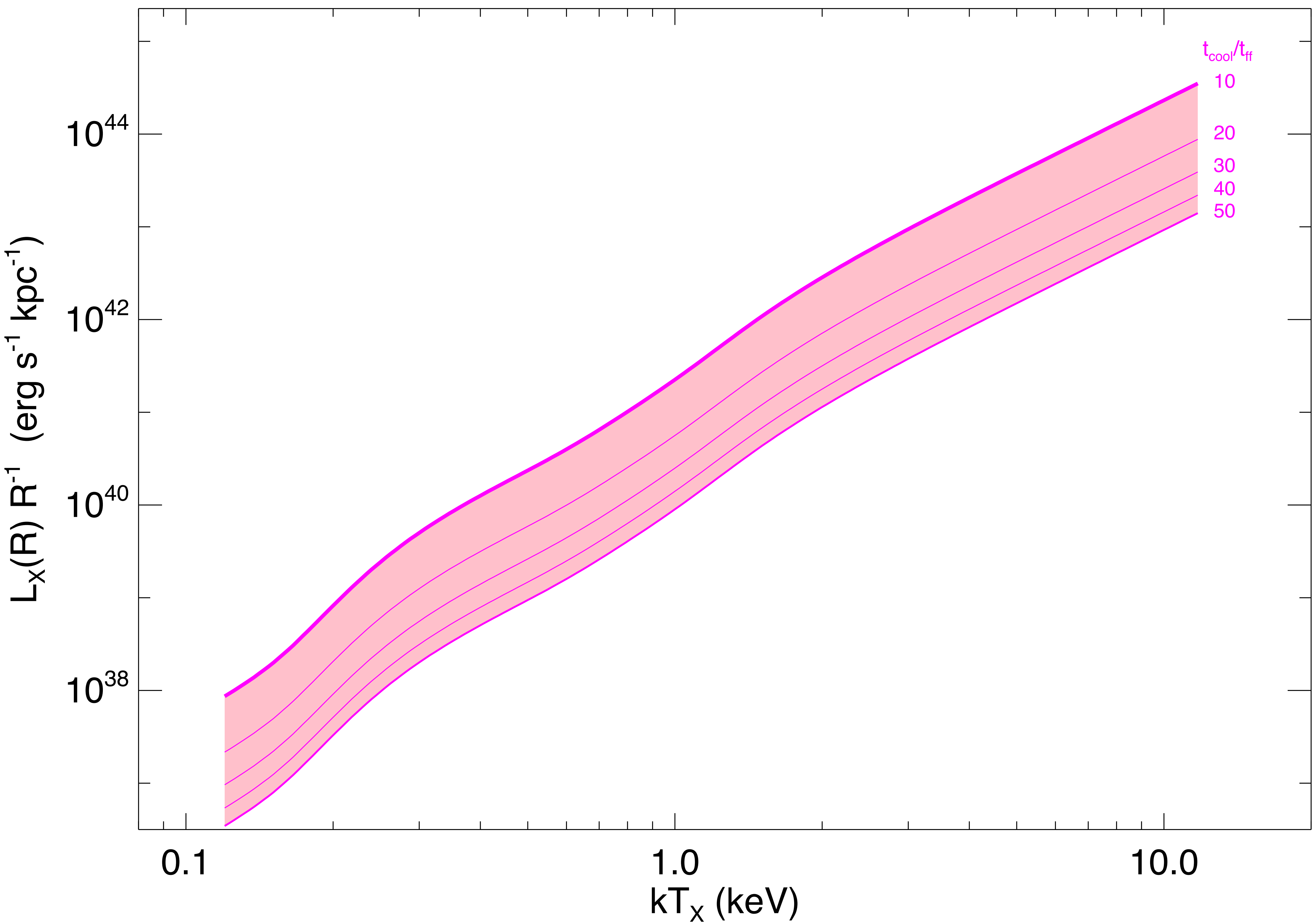
$$n_e \lesssim \frac{3kT}{10\, t_{\rm ff} \Lambda(T)}$$

$$L_X(< R) \lesssim \int_0^R 4\pi r^2 \Lambda \left(\frac{3kT}{10 t_{\rm ff} \Lambda} \right)^2 dr$$

$$L_X(< R) \lesssim \frac{9\pi}{25} (kT)^2 \Lambda^{-1} \sigma_v^2 R$$

Feedback and the Hot CGM

Precipitation-Limited Luminosity



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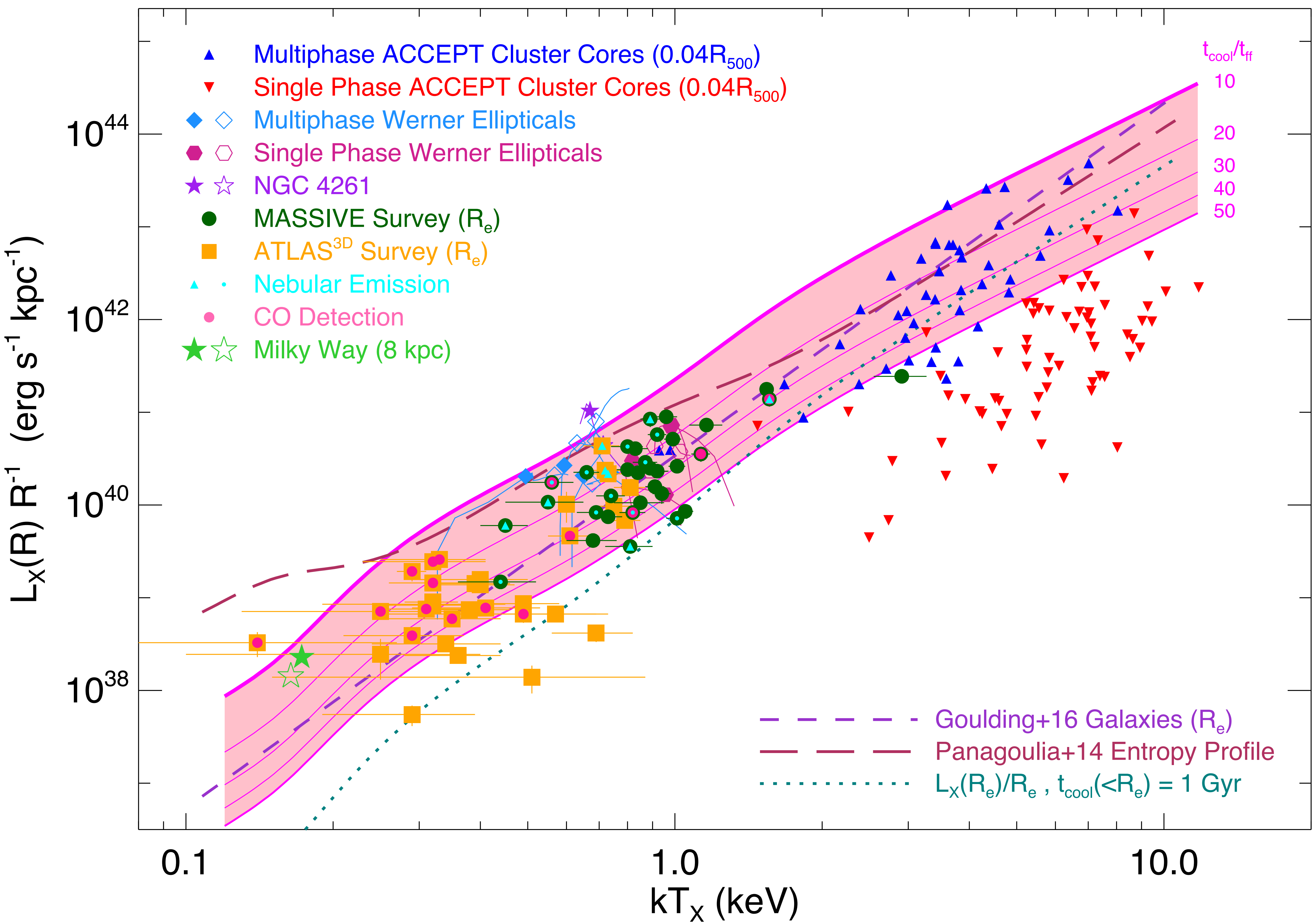

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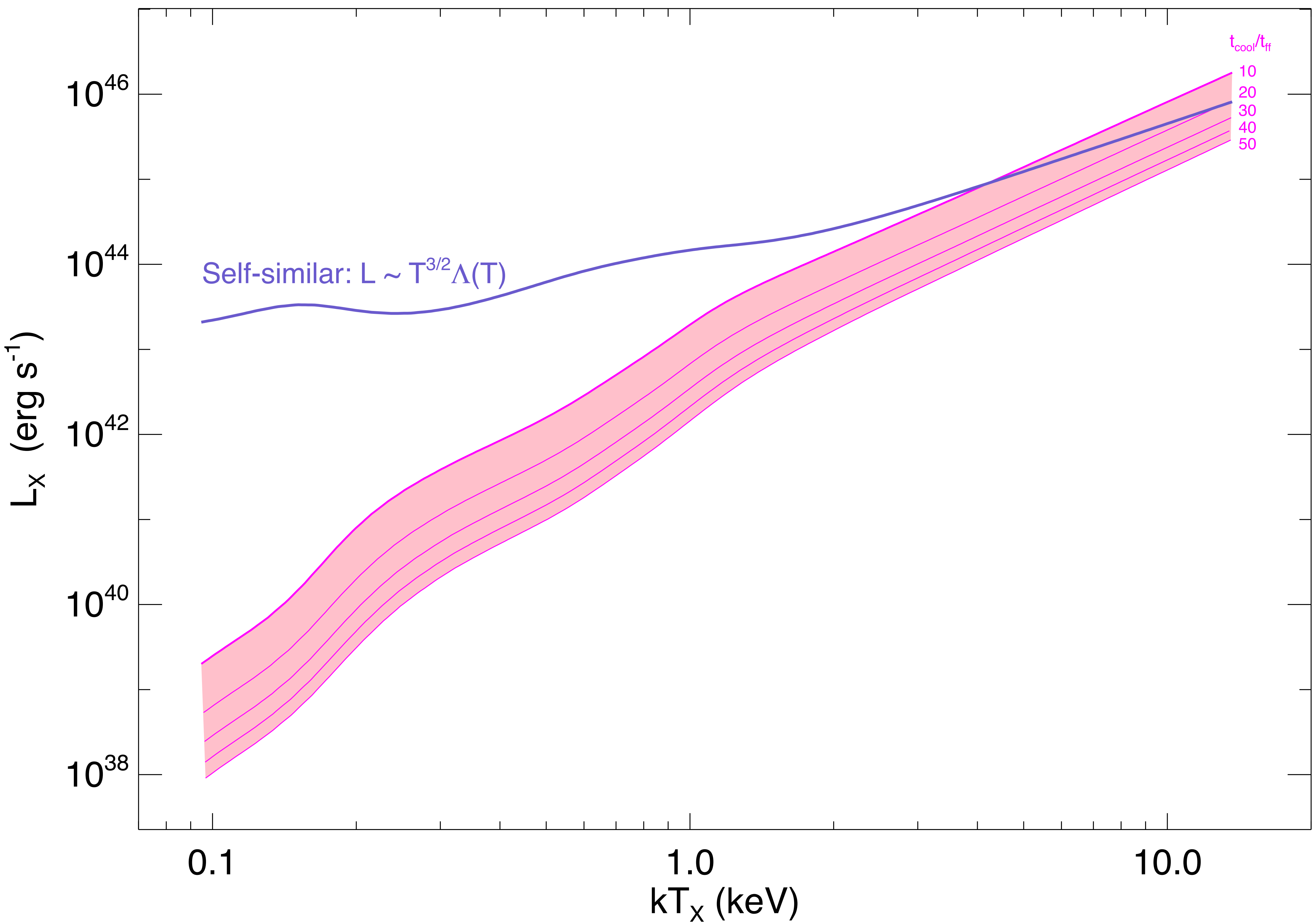

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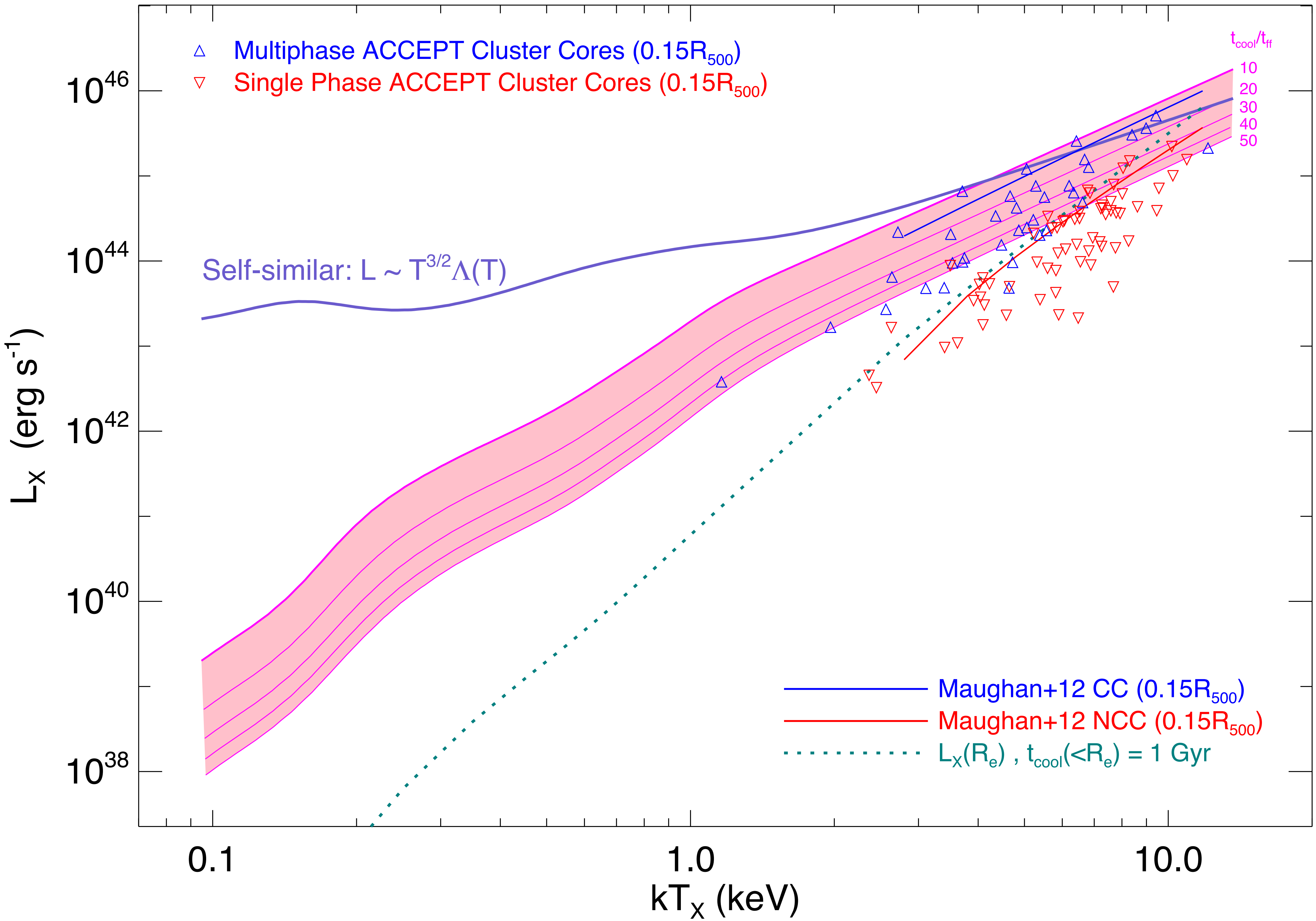

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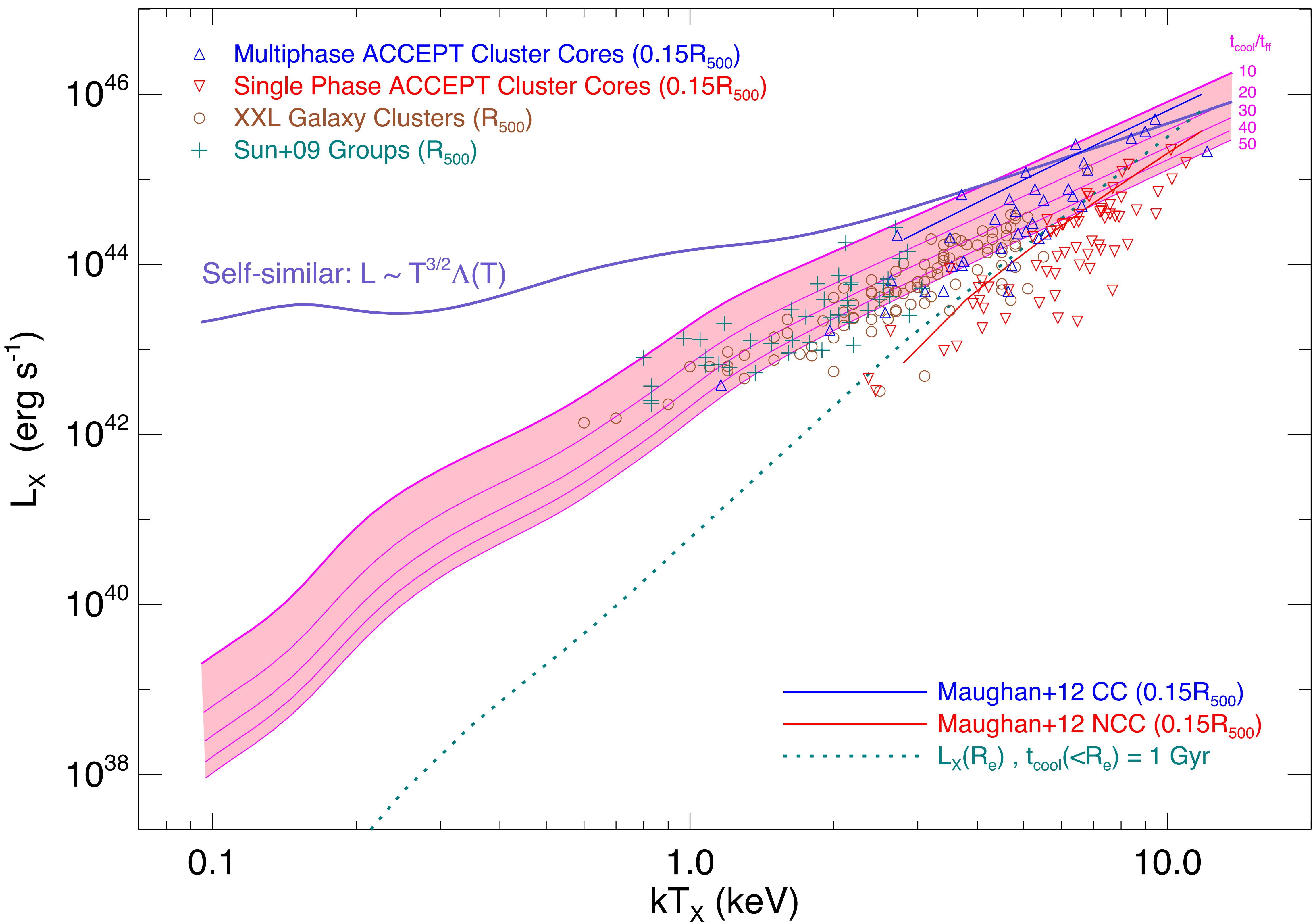

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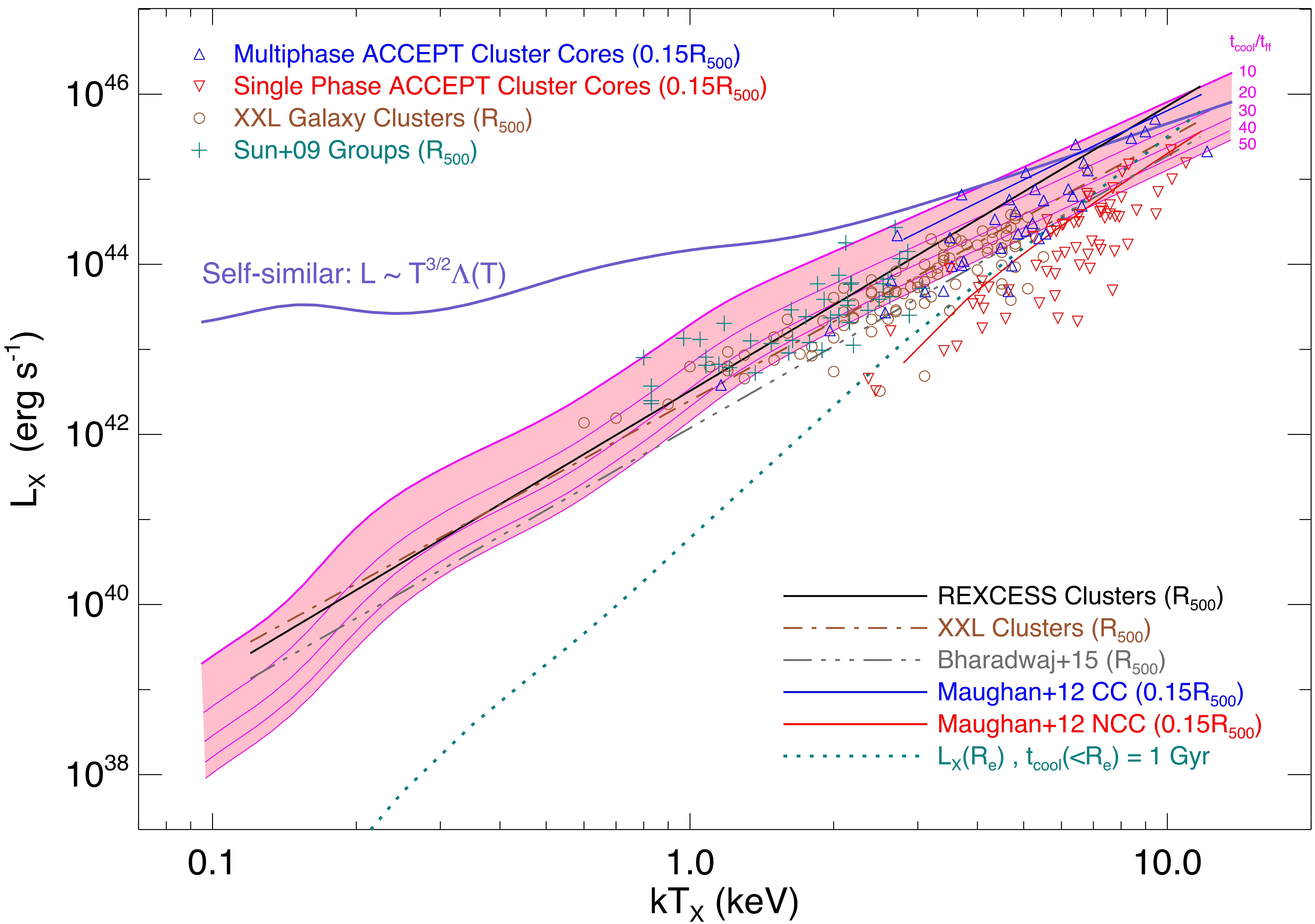

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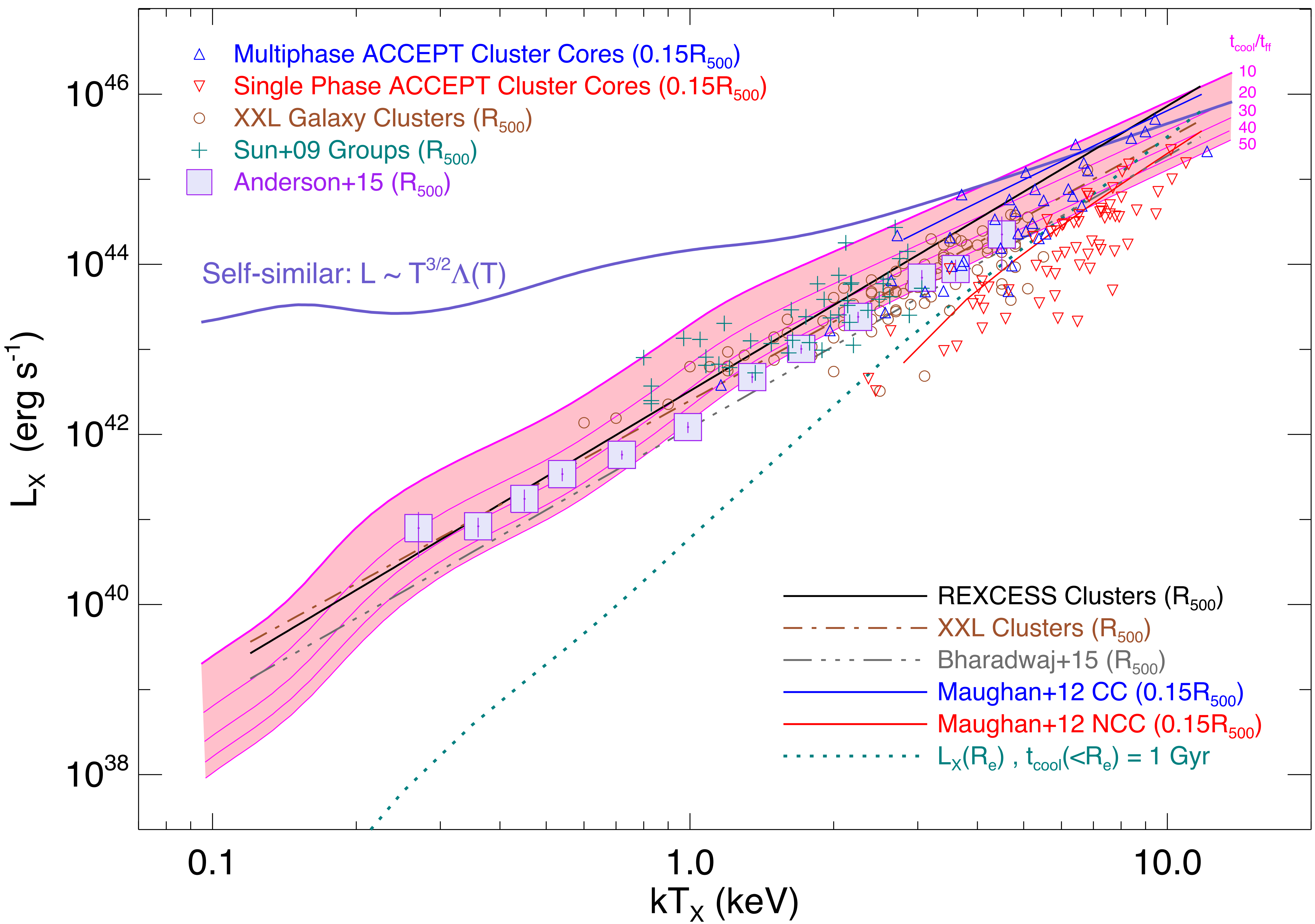

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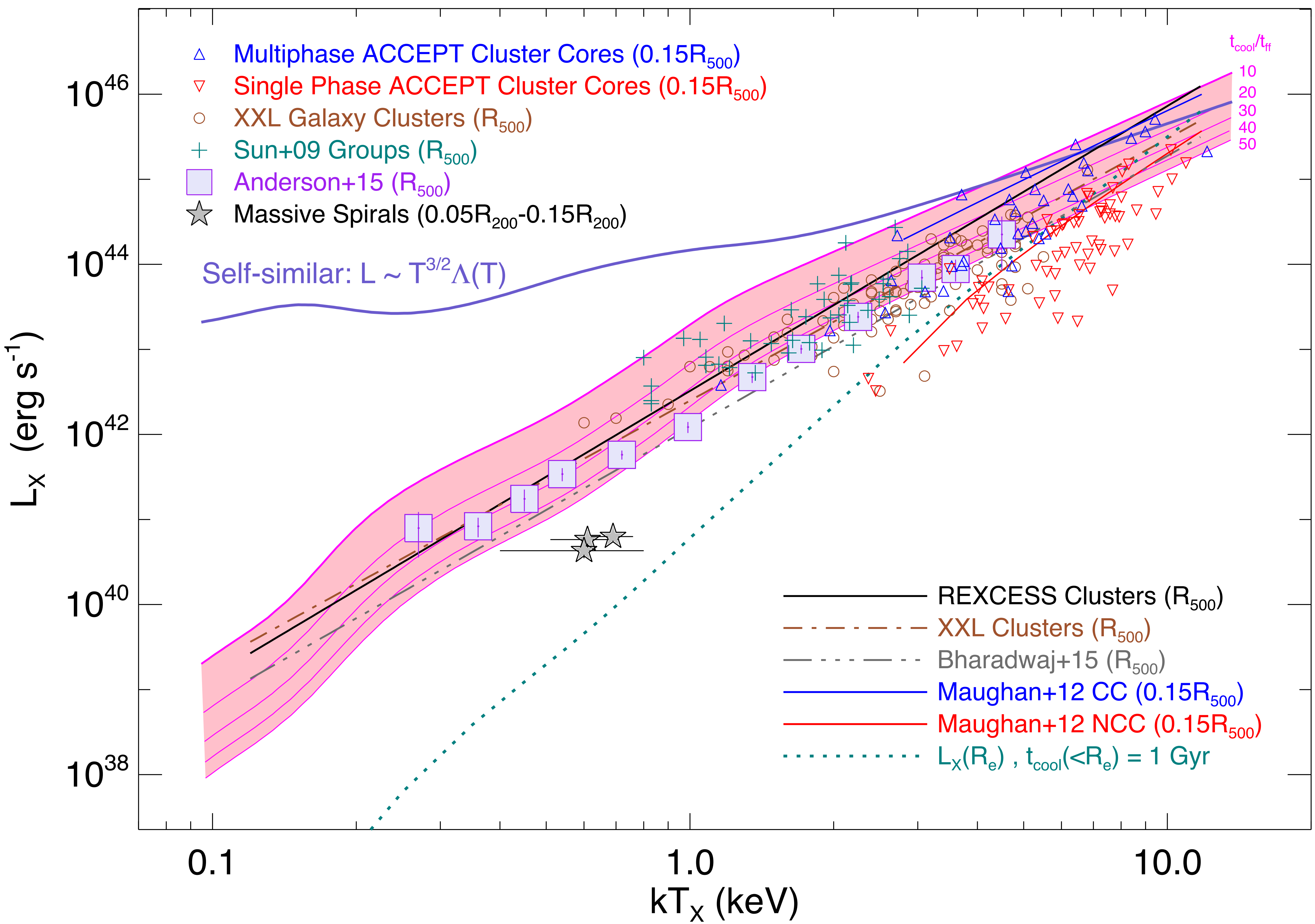

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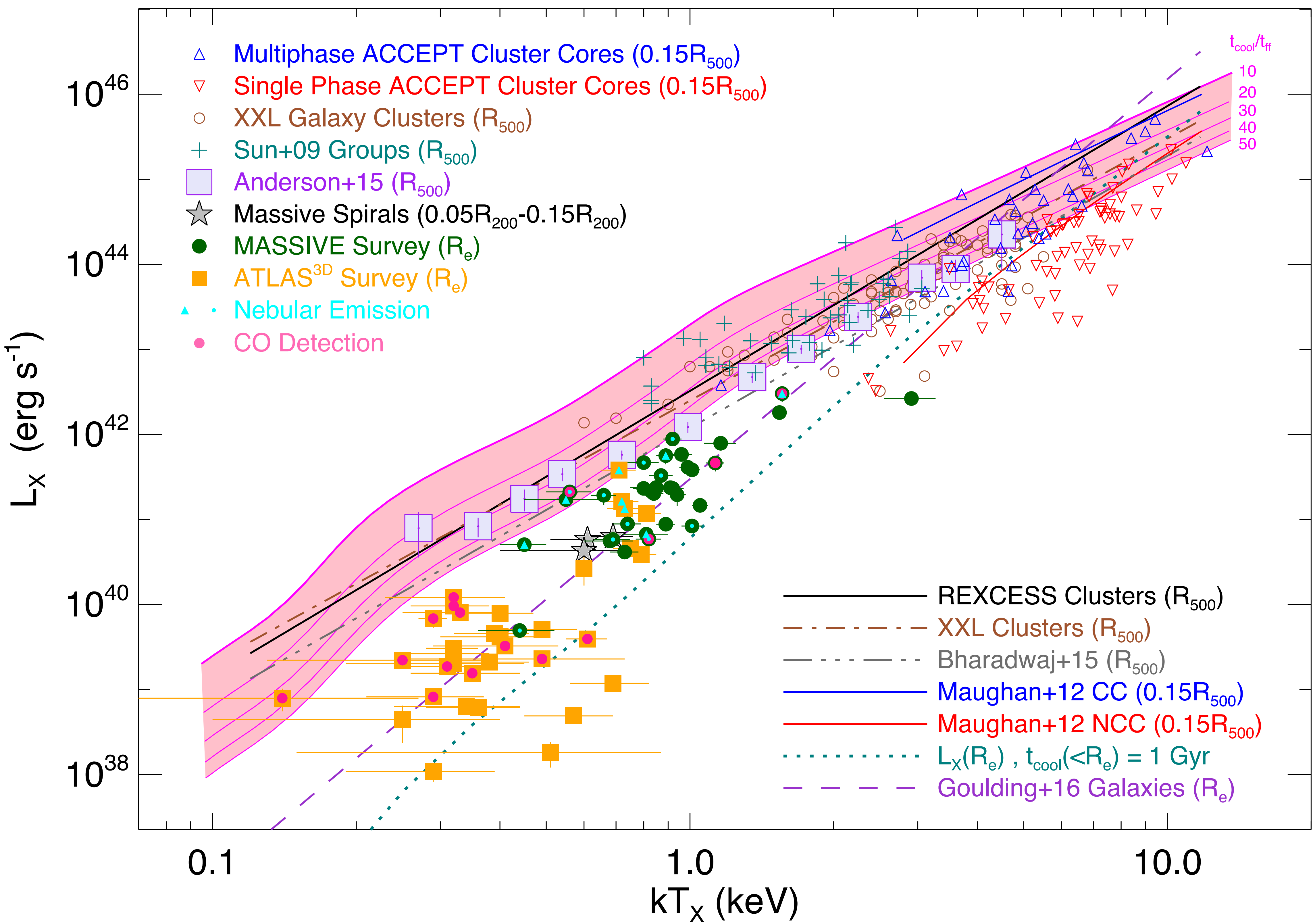

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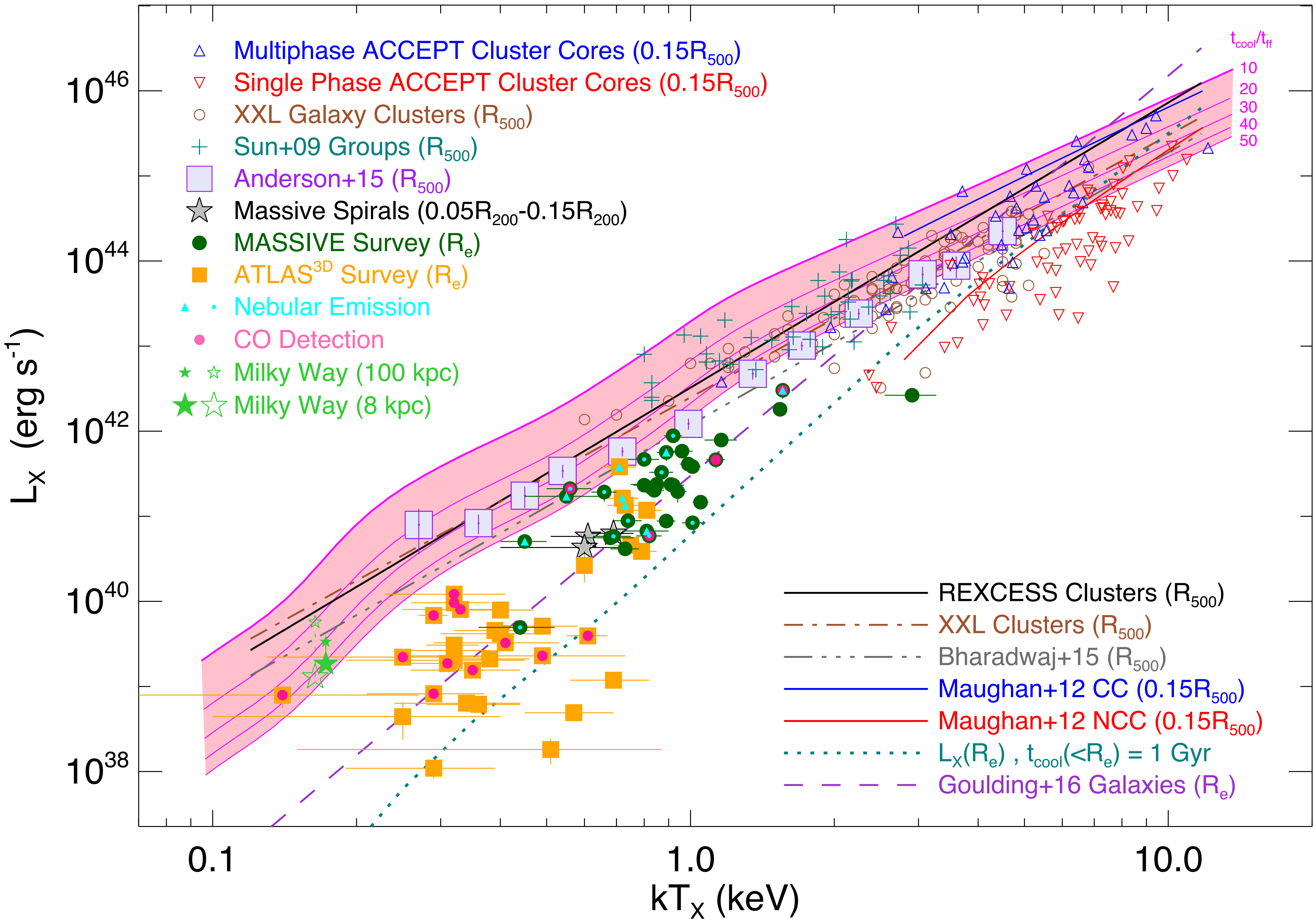

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Lynx high-resolution imaging of high S/N cluster sources

- Cavities will be detectable with 1” PSF and larger collecting area than Chandra
- Zhuraleva/Churazov fluctuation analysis (dT/T vs. dn/n) will be possible with a local sample of clusters: how is the CGM in clusters heated?
- Fluctuation analysis will probe smaller scales (more reliable quantification of turbulence)
- Velocities and velocity - widths of order 100 km/s will be of interest

Lynx high-resolution profiles for hot gas in galaxies with and without AGN and cold gas

- Resolving hot gas profiles to radii close to the AGN (<1 kpc) gives important discriminants between wind-stabilized atmospheres and marginally precipitating ones.
- May be able to detect and measure bubbles around the AGN and in the CGM
- Simulations will be important for planning and interpreting observations: backgrounds and binary/AGN contamination will be significant sources of noise.

summary

- Multiphase gas halos around BCGs are the source of fuel for AGN and SF.
- Gas halos around BCGs are regulated primarily by AGN feedback.
- AGN feedback, done right, makes the entropy profile less steep but does not flatten or invert it (except temporarily or very close in).
- Applying the precipitation scenario to lower-mass galaxies predicts the MAXIMUM X-ray luminosity of a halo over 8 orders of magnitude of X-ray luminosity.
- One testable hypothesis: Galaxies closest to this limit will be more likely to have multiphase gas.
- Simulation development at cosmological scales is required: the "recipes" for feedback even a couple of years ago are falsified by X-ray data already. But to explore effects of duty cycle, galaxy interactions, magnetic fields, environment, we will need simulations.