Precipitation-Regulated Galaxies

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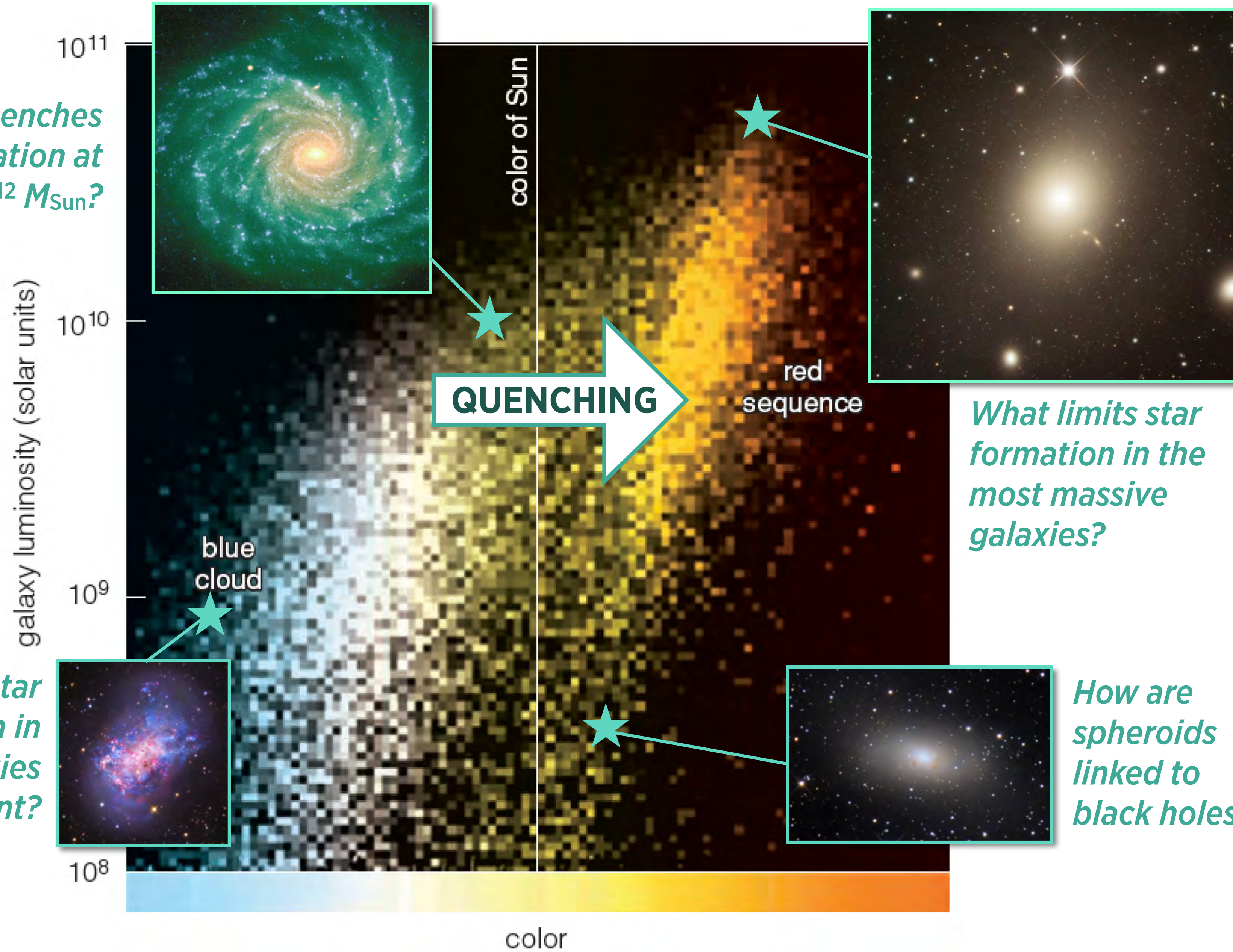
1 Fundamental Questions

What turns galaxies on and off?

What quenches star formation at $M_{halo} > 10^{12}\ M_{Sun}$?

What limits star formation in the most massive galaxies?

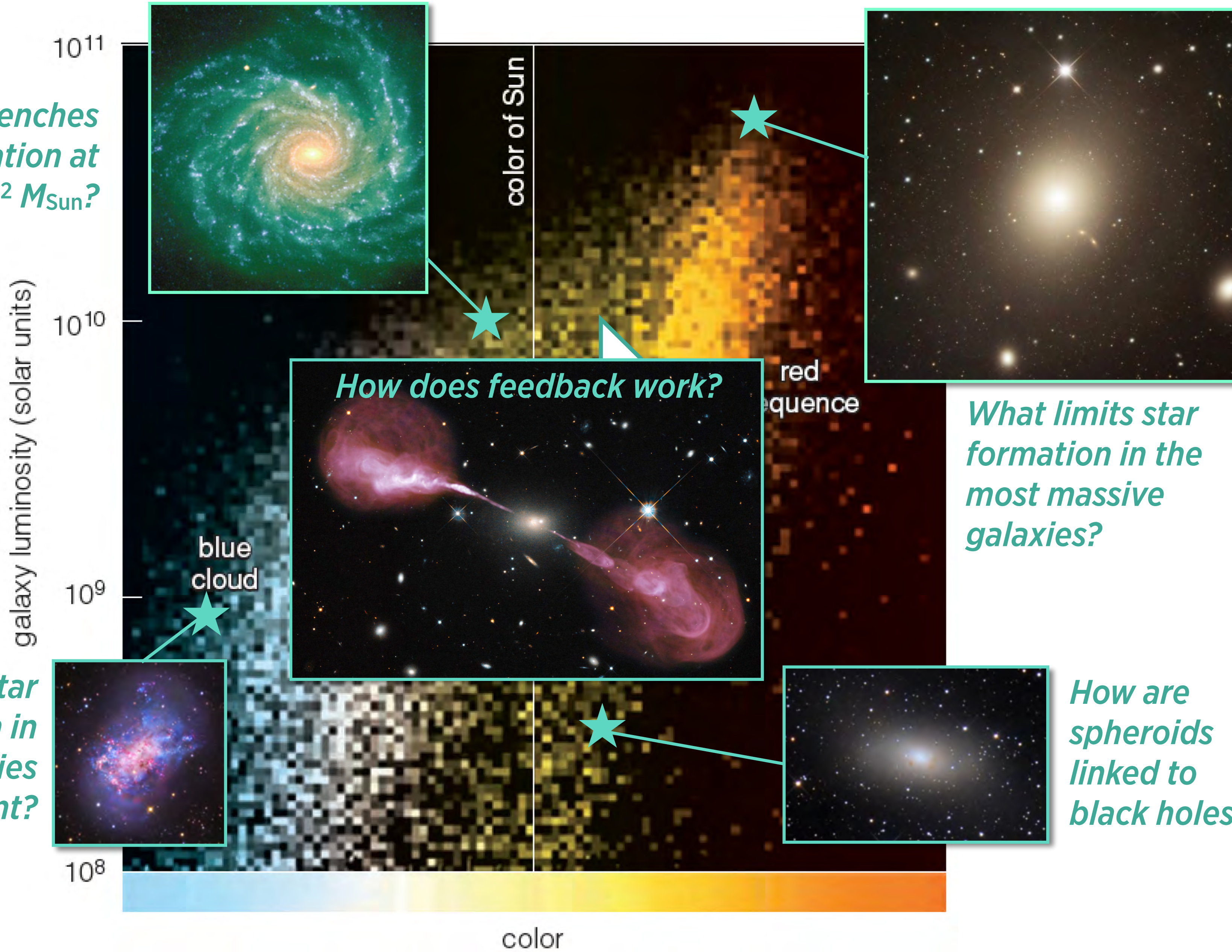


Why is star formation in small galaxies so inefficient?

How are spheroids linked to black holes?

What turns galaxies on and off?

What quenches star formation at $M_{halo} > 10^{12}$ M_{Sun}?



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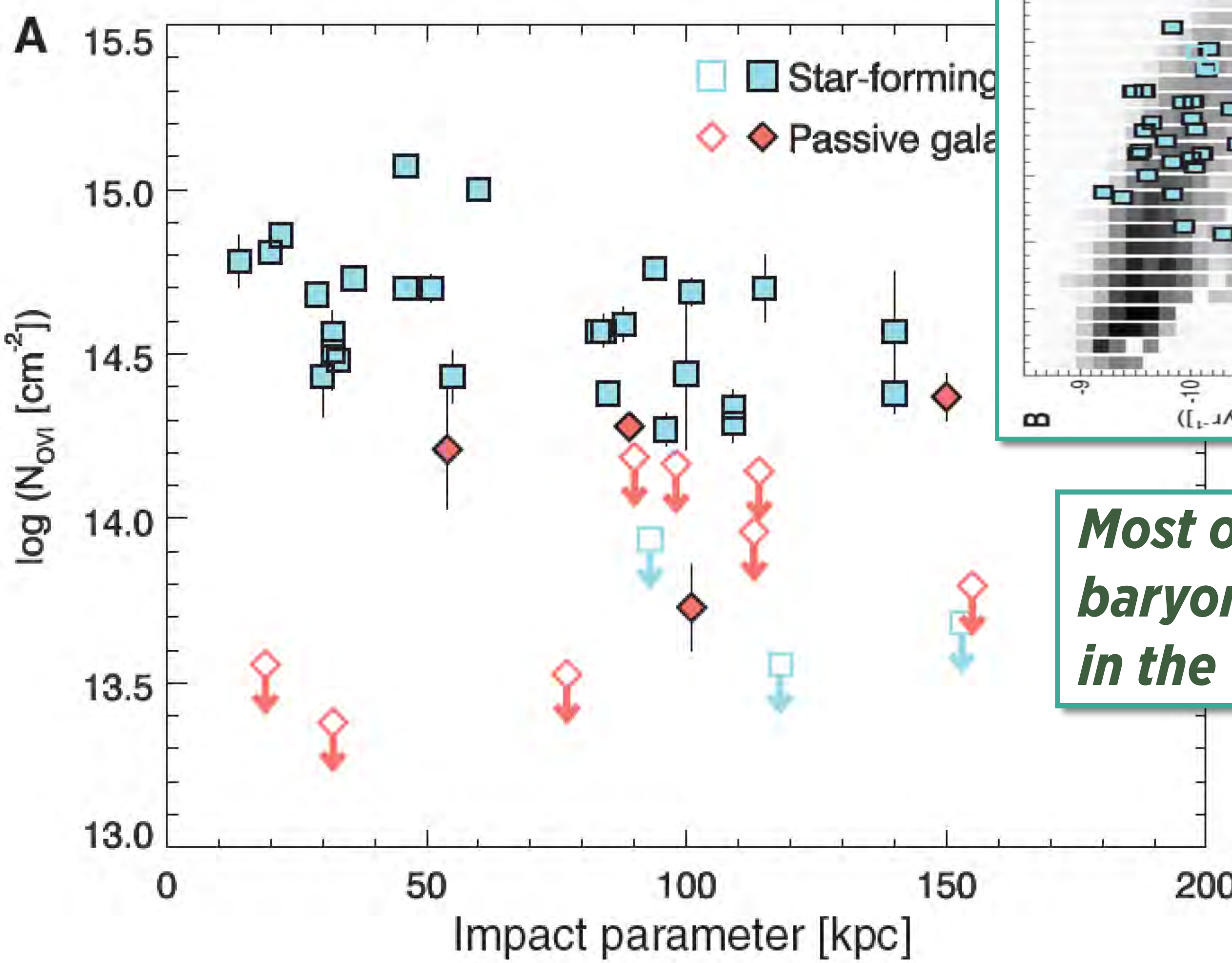
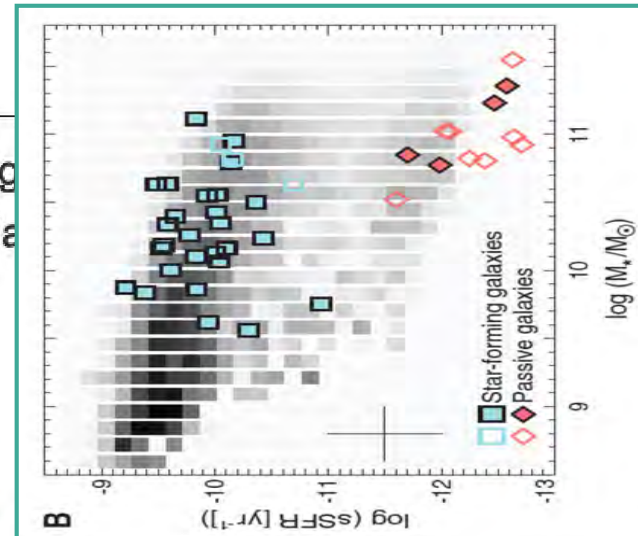
Circumgalactic Conditions

Tumlinson+ 11 (COS-Halos)





Most of a galaxy's baryons & metals are in the CGM

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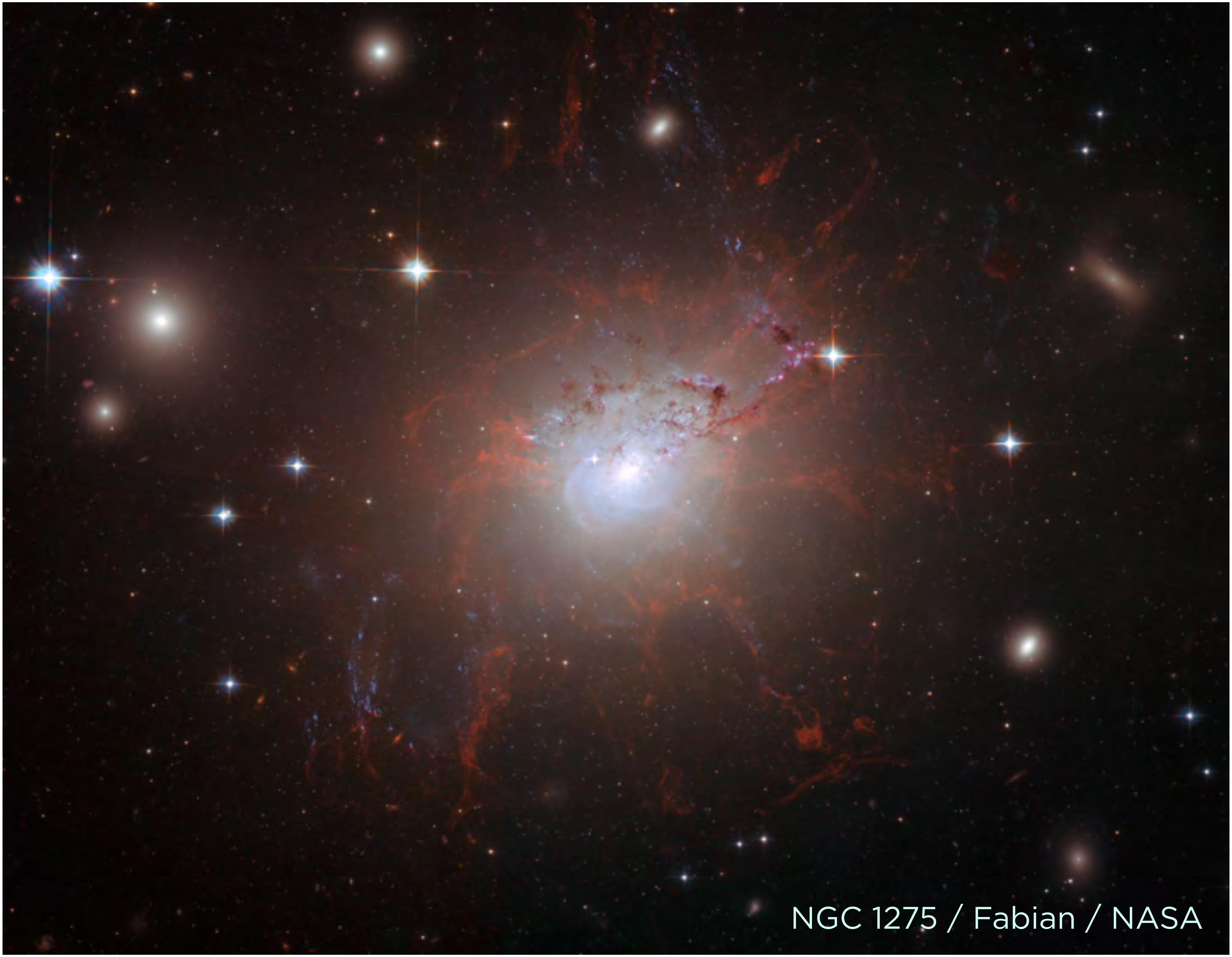
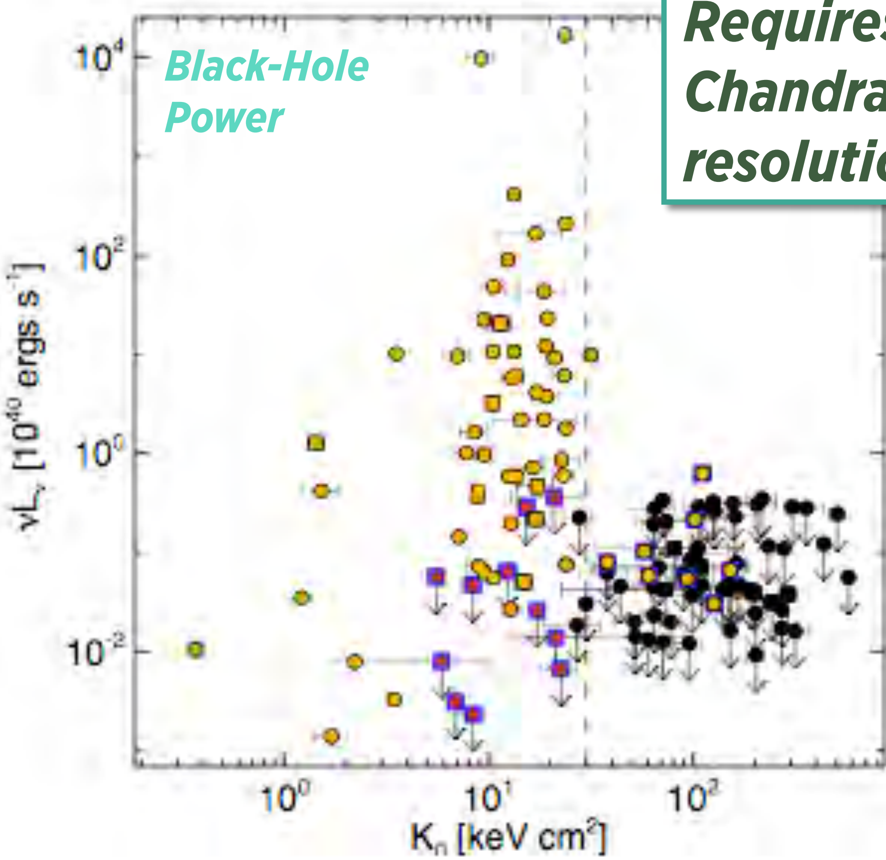
Precipitation & Cluster Cores

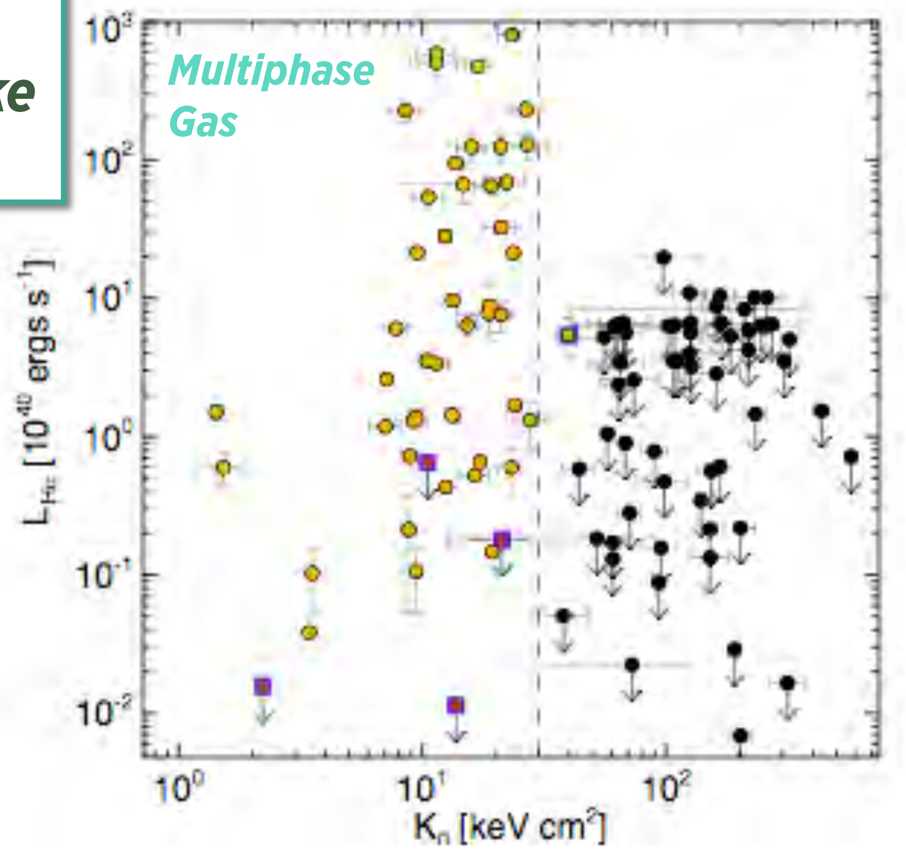

NGC 1275 / Fabian / NASA

Cold Triggering of AGN Feedback

Cavagnolo+ 08

Requires Chandra-like resolution

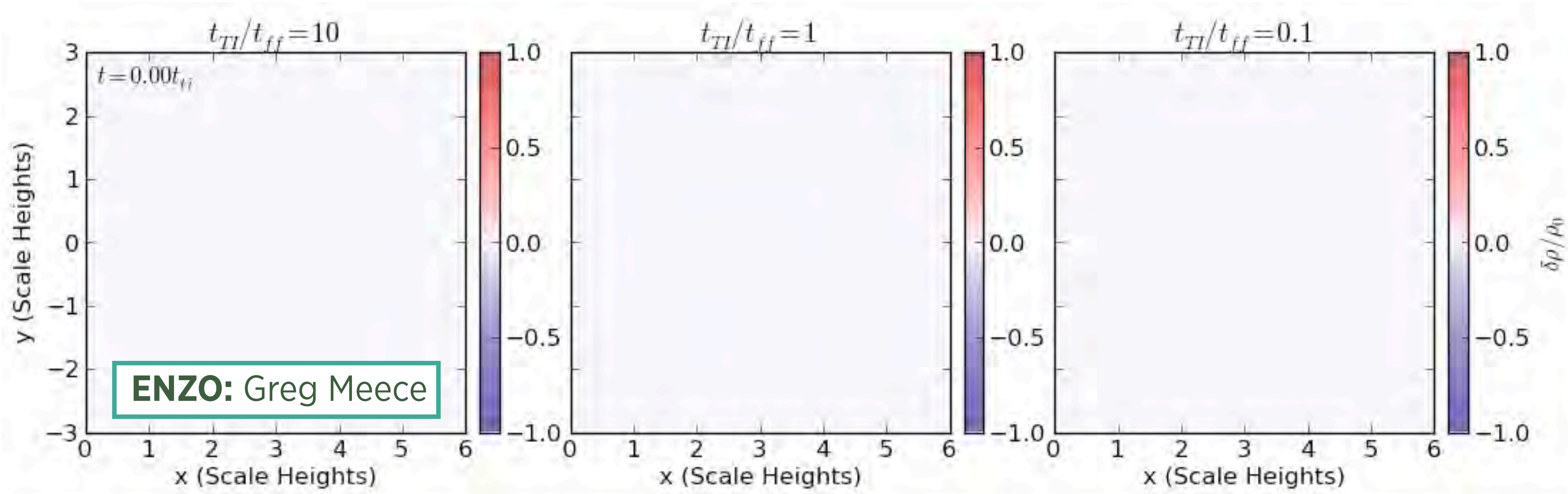




Core Entropy Index = $K_0 = kTn_e^{-2/3}$

Instability in a Thermally Balanced Medium

McCourt+ 2012, Sharma+ 2012



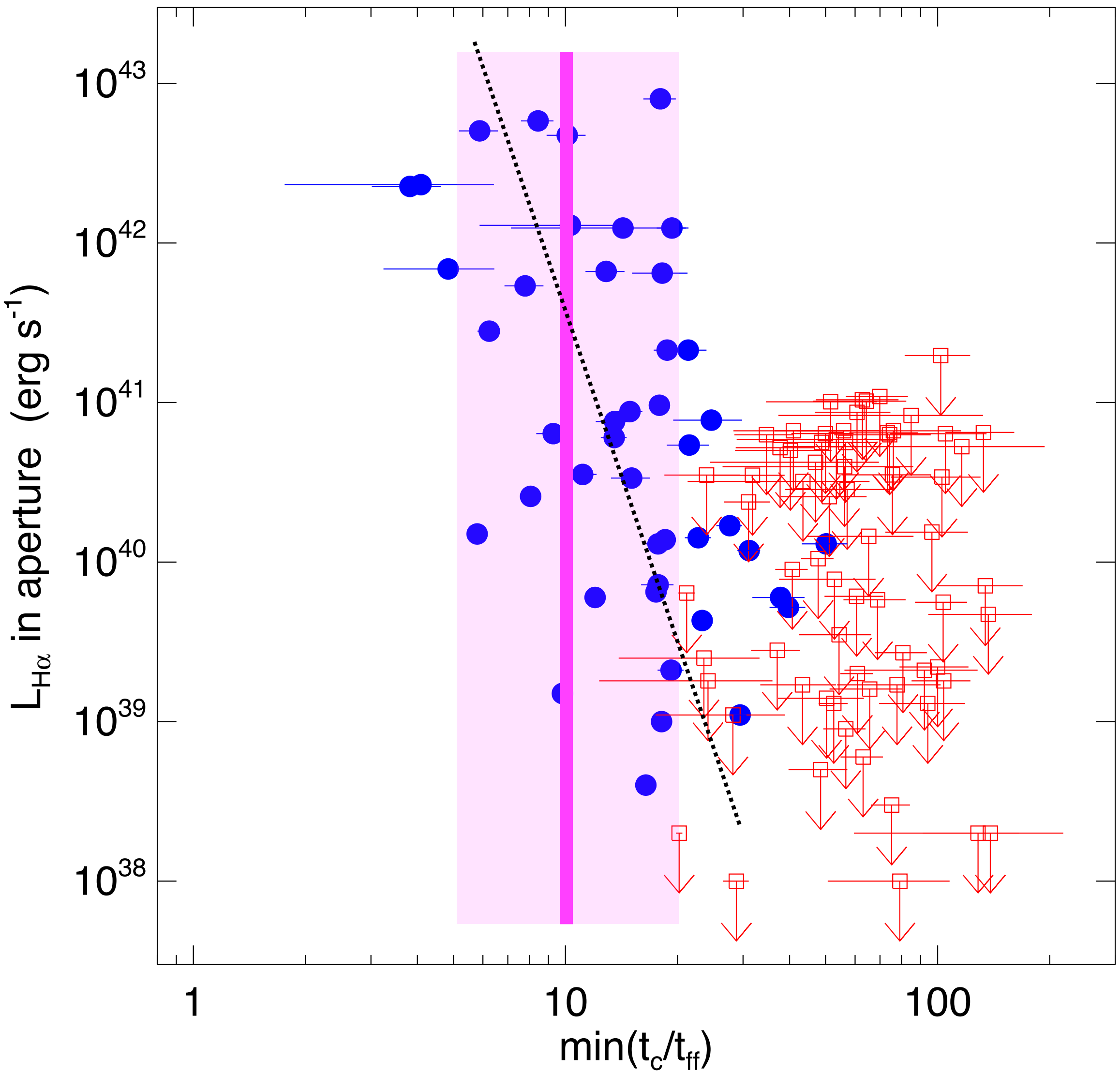
If the medium is kept in global thermal balance by feedback, then the threshold for formation of multiphase gas is:

$t_{cool}/t_{ff} \sim 1$ in a box $t_{cool}/t_{ff} \sim 10$ in a spherical potential

... but see Meece, O'Shea, & Voit 2015

Evidence for Precipitation

Voit & Donahue 2015; data: Cavagnolo thesis



Dependence of $L_{H\alpha}$ on **$\min(t_c/t_{ff})$** looks more like a steep ramp than a threshold.

Implies a very stiff black-hole feedback response that maintains **$t_c/t_{ff} \sim 10$** for most systems.

But there are outliers extending to **$t_c/t_{ff} \sim 50$**.

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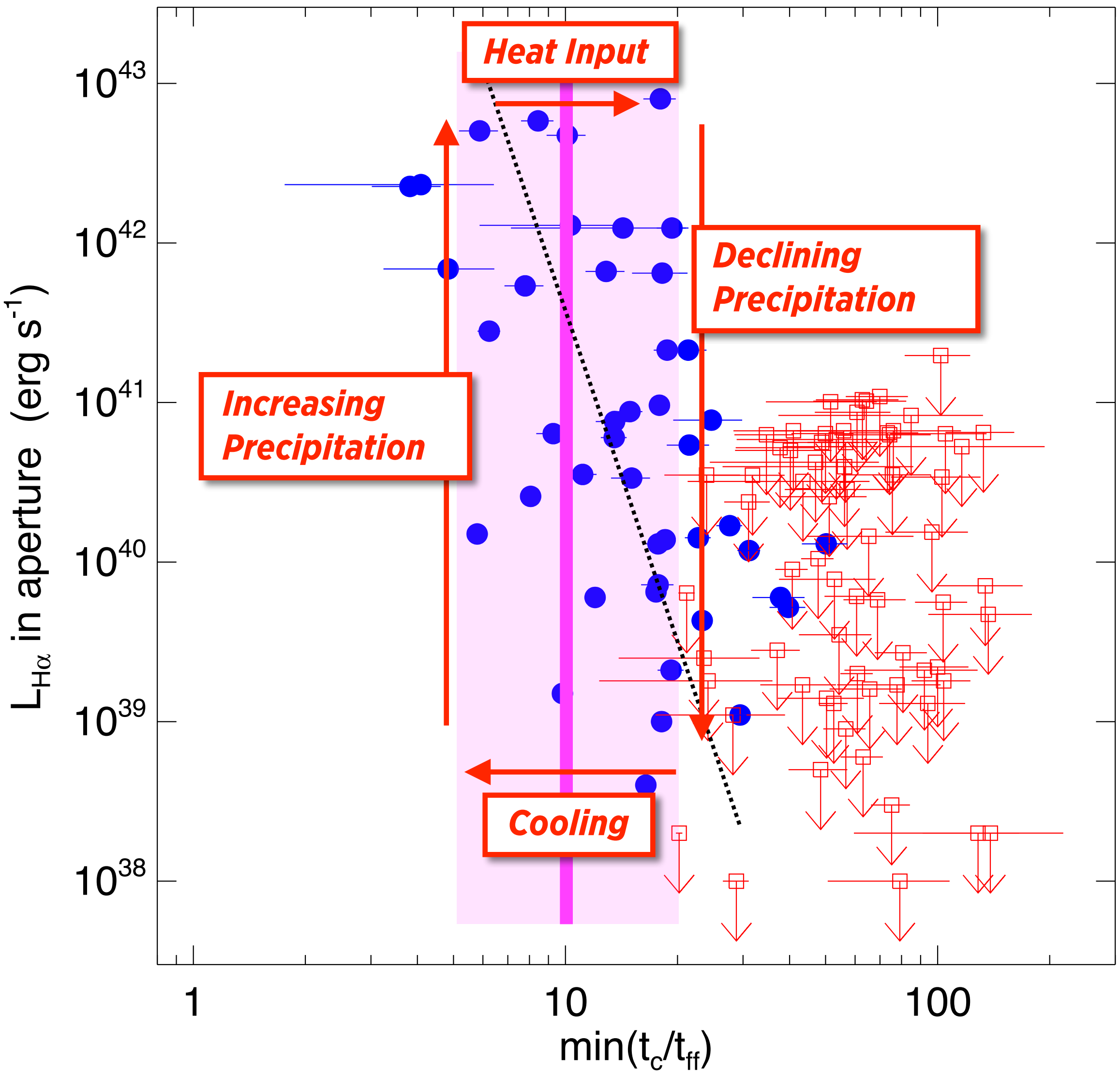

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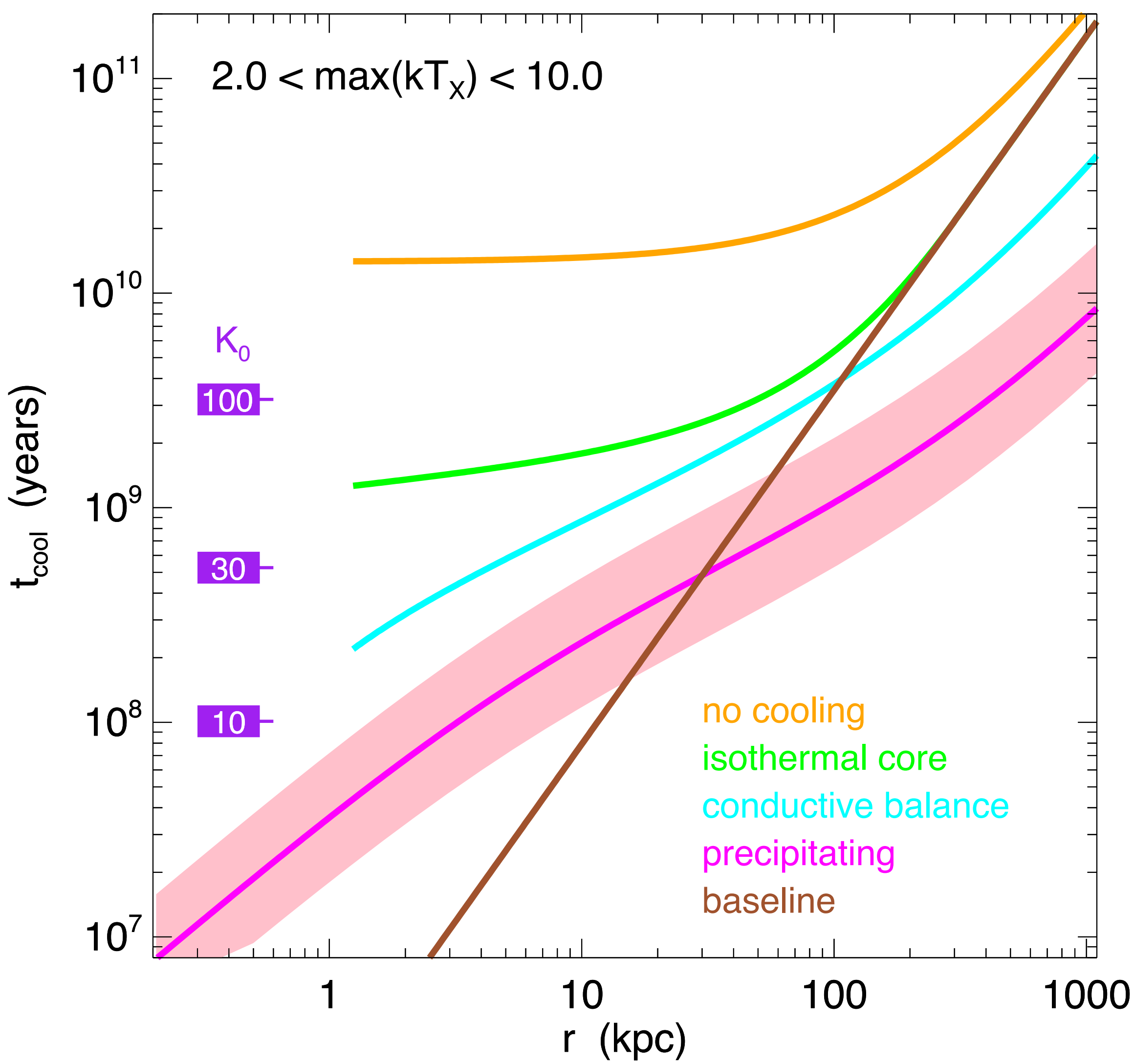
Cooling-Time Profiles

Voit+ 2015, Nature



Precipitation Threshold:

1. Use 250 km/s singular isothermal sphere for the stars.
2. Use NFW halo with $c_{500} = 3$ for the dark matter.
3. Calculate $t_{ff}(r)$.
4. Multiply by 10.

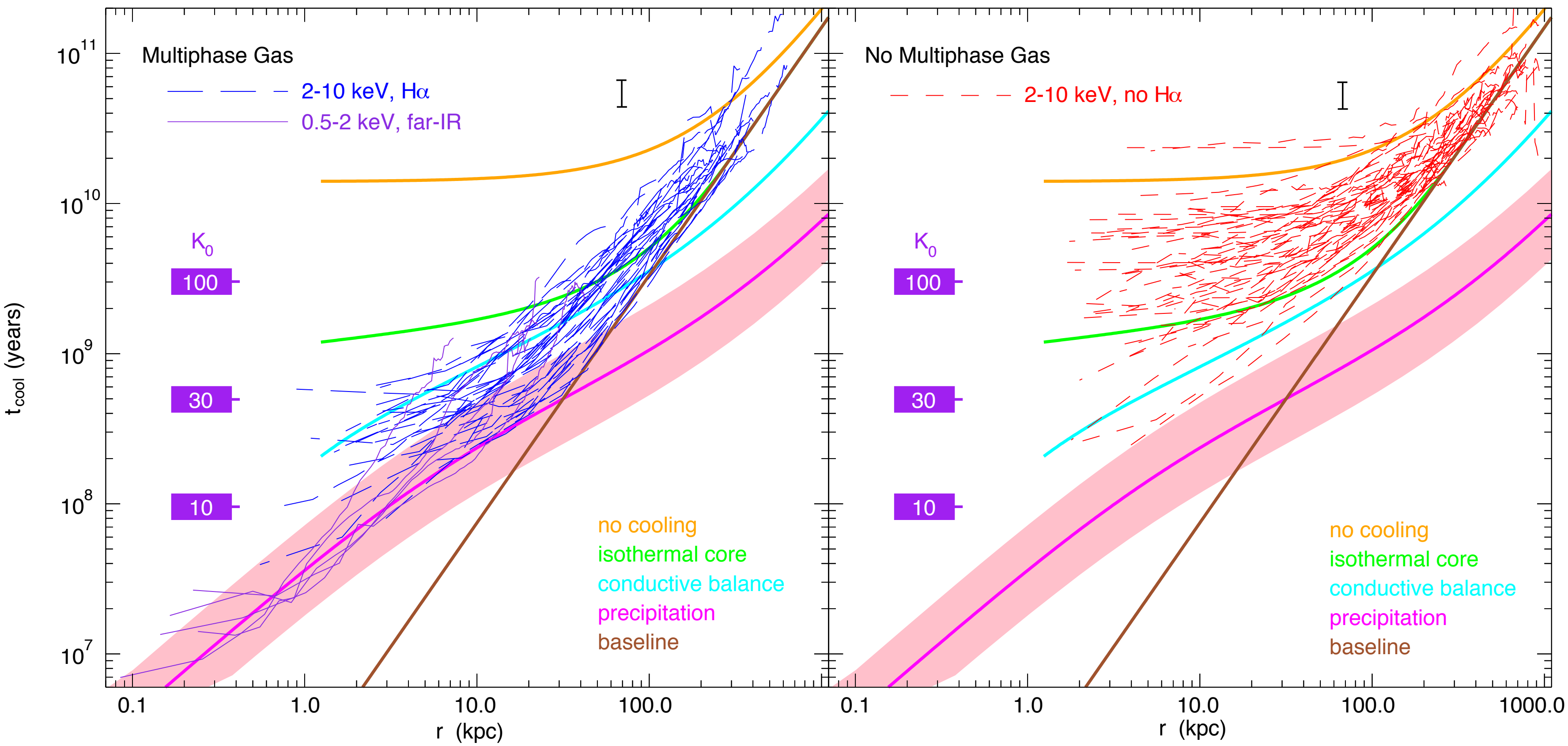
Baseline: Voit+ 2005

No Cooling: Voit+ 2002

Conduction: Voit 2011

Cooling-Time Profiles

Voit+ 2015, Nature



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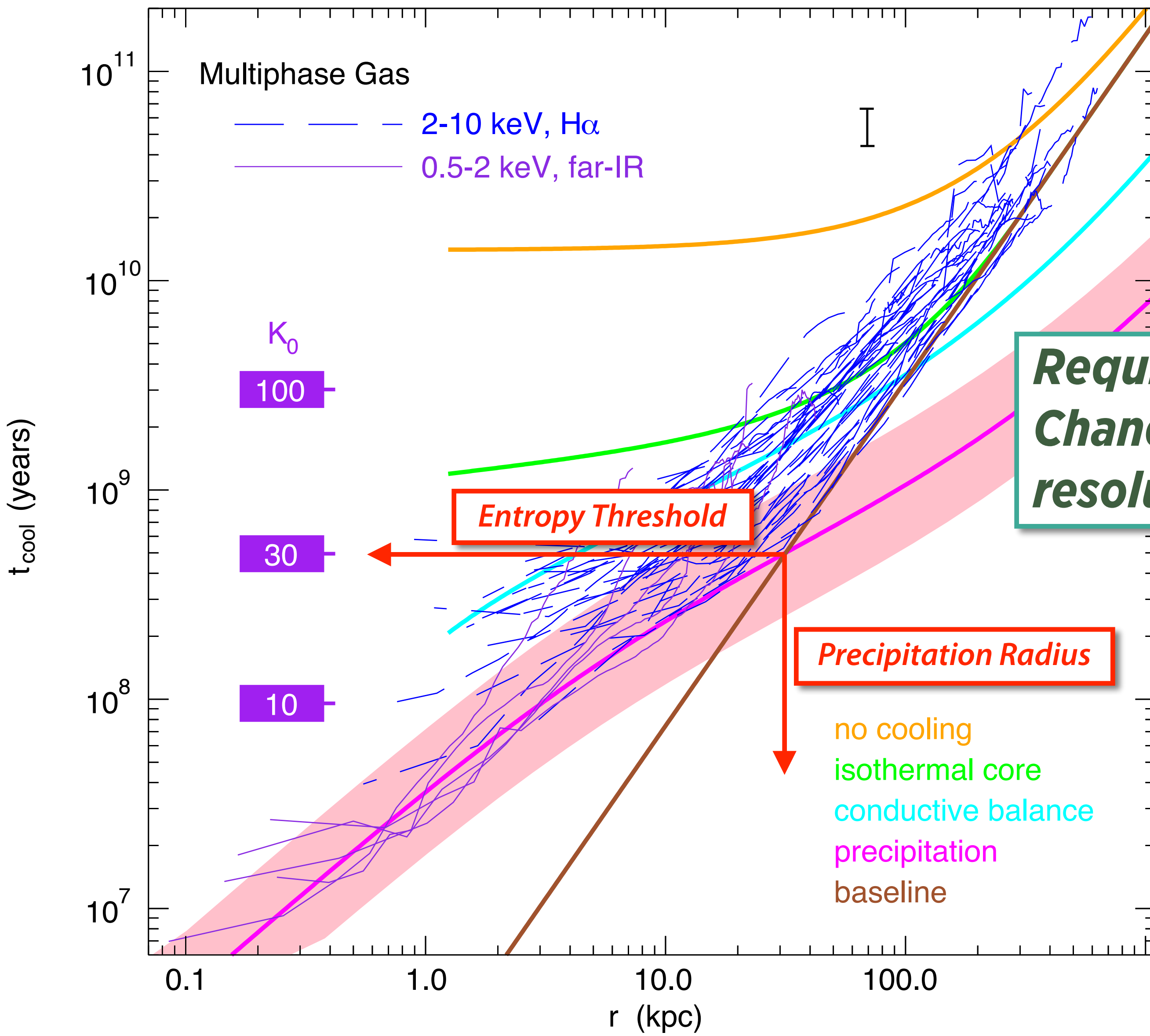
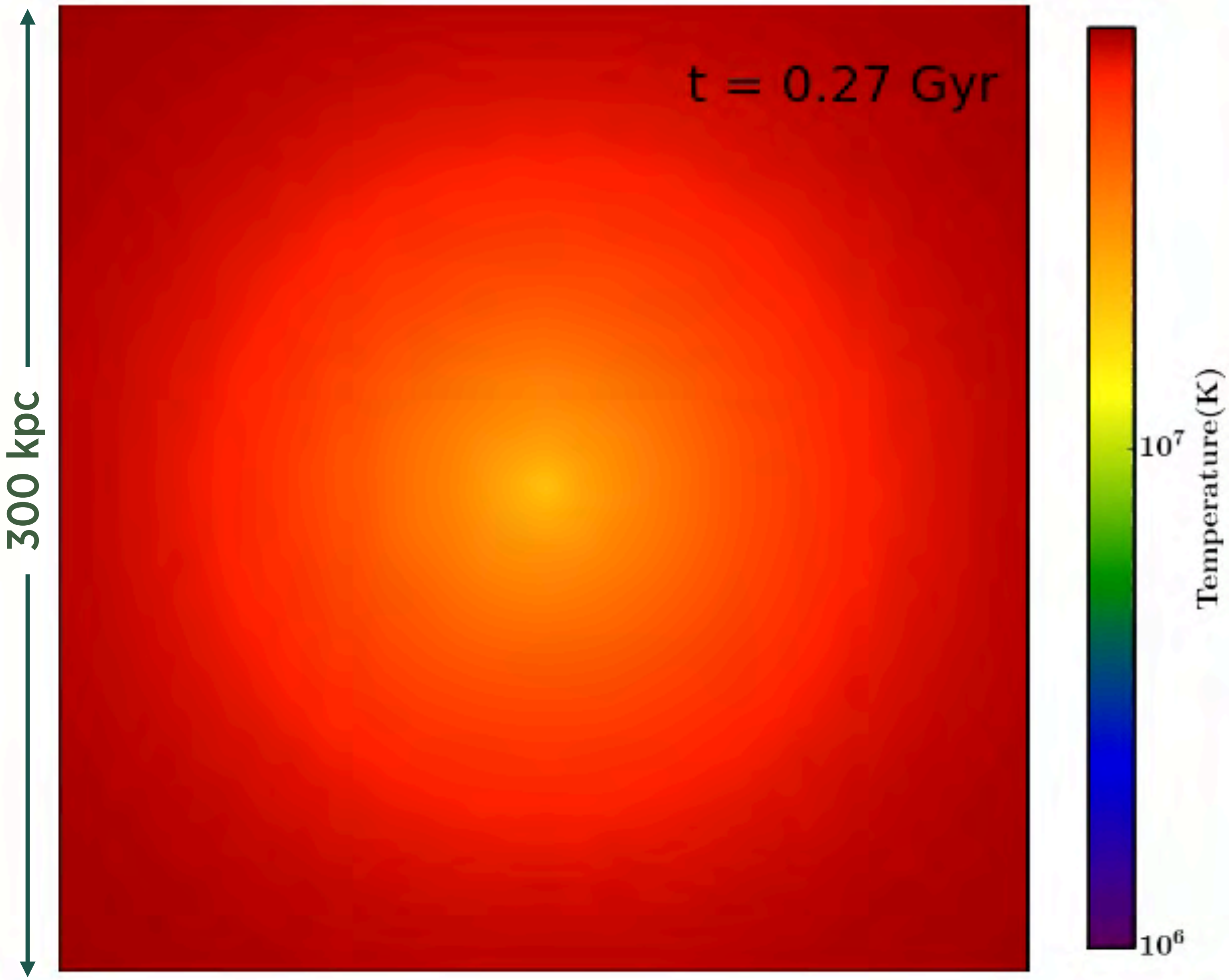


Requires Chandra-like resolution

Precipitation-Regulated Feedback

Gaspari+ 2012,2013,2014; Li & Bryan 2014a,b; Li+ 2015



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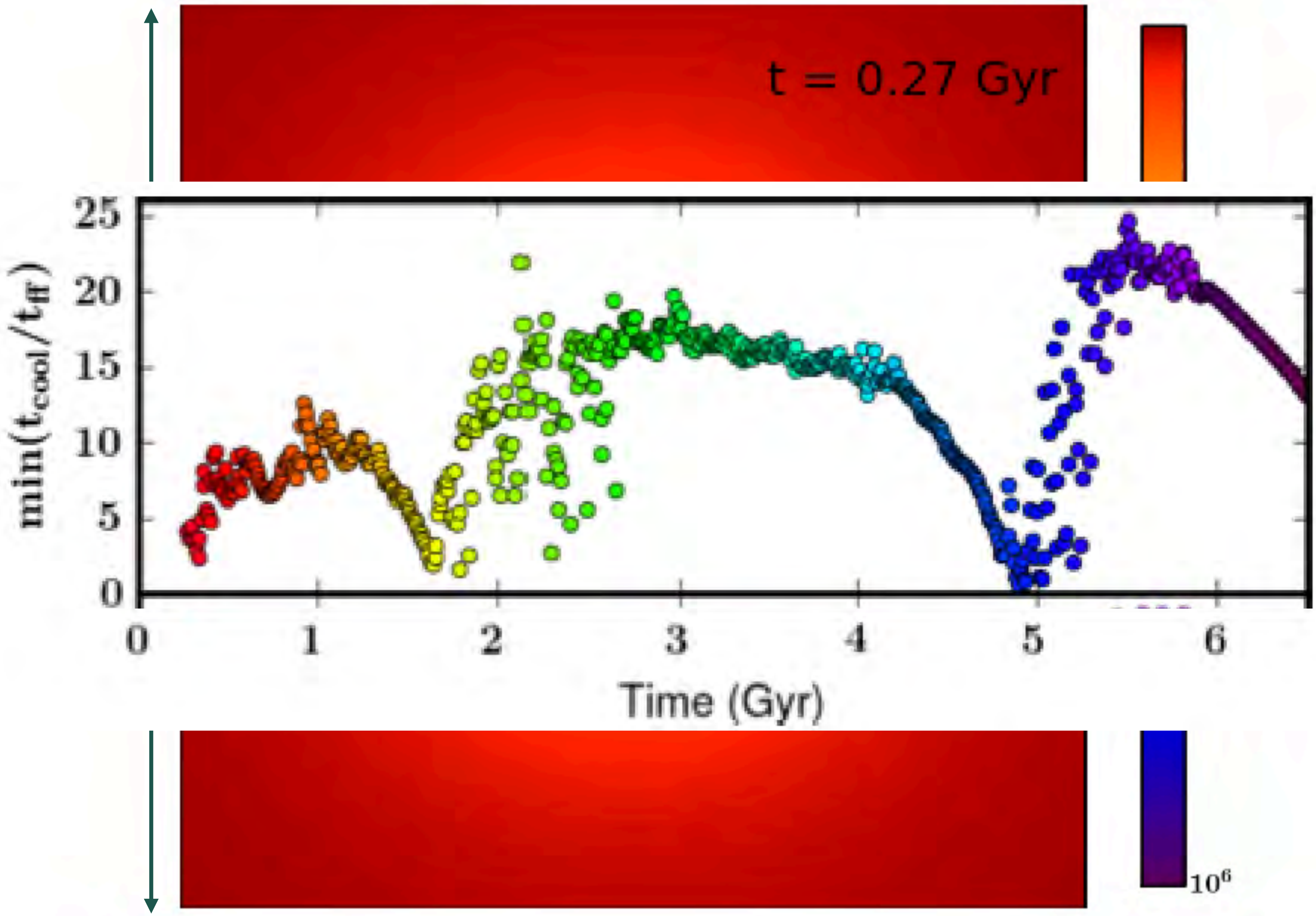
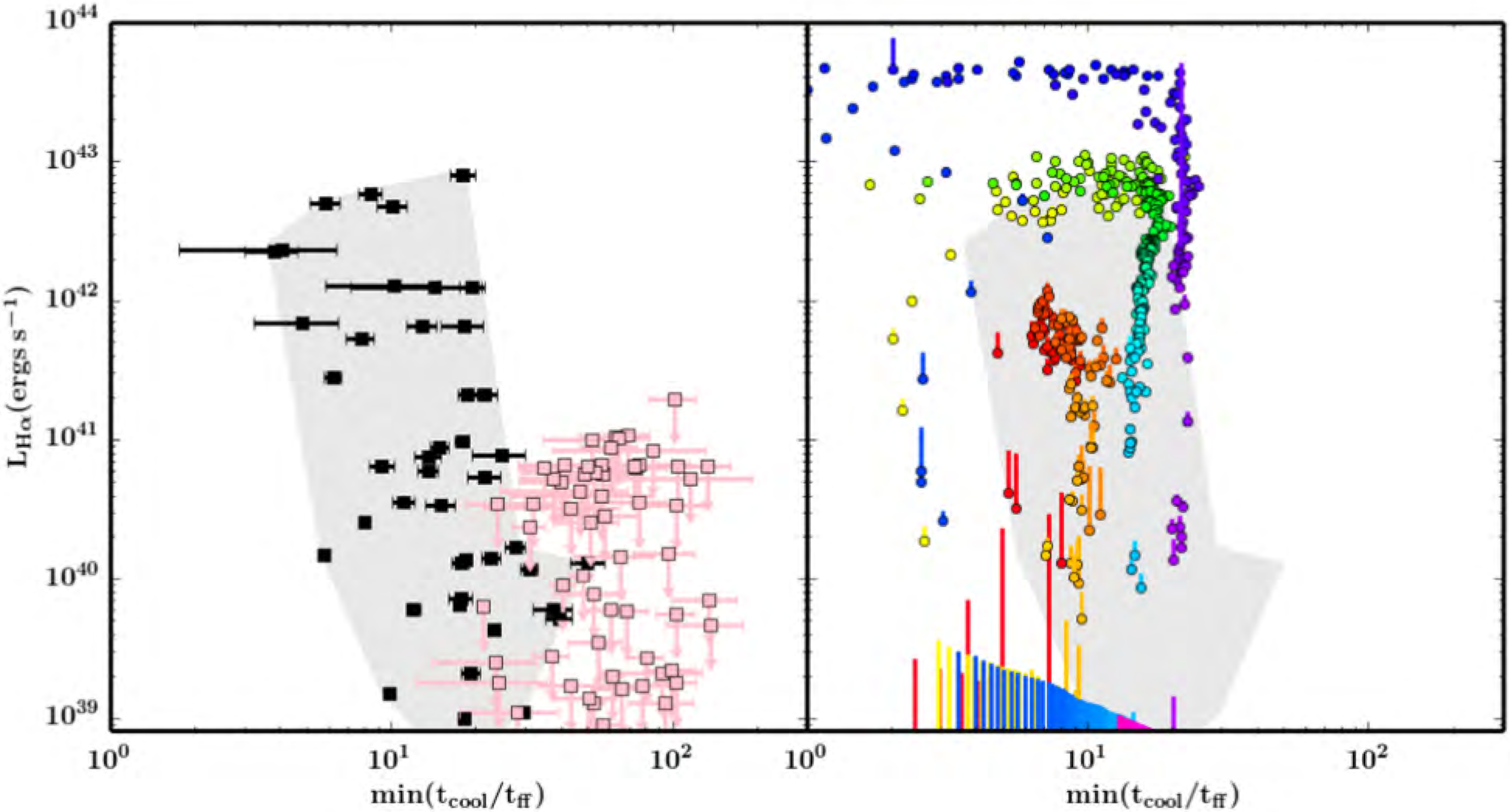


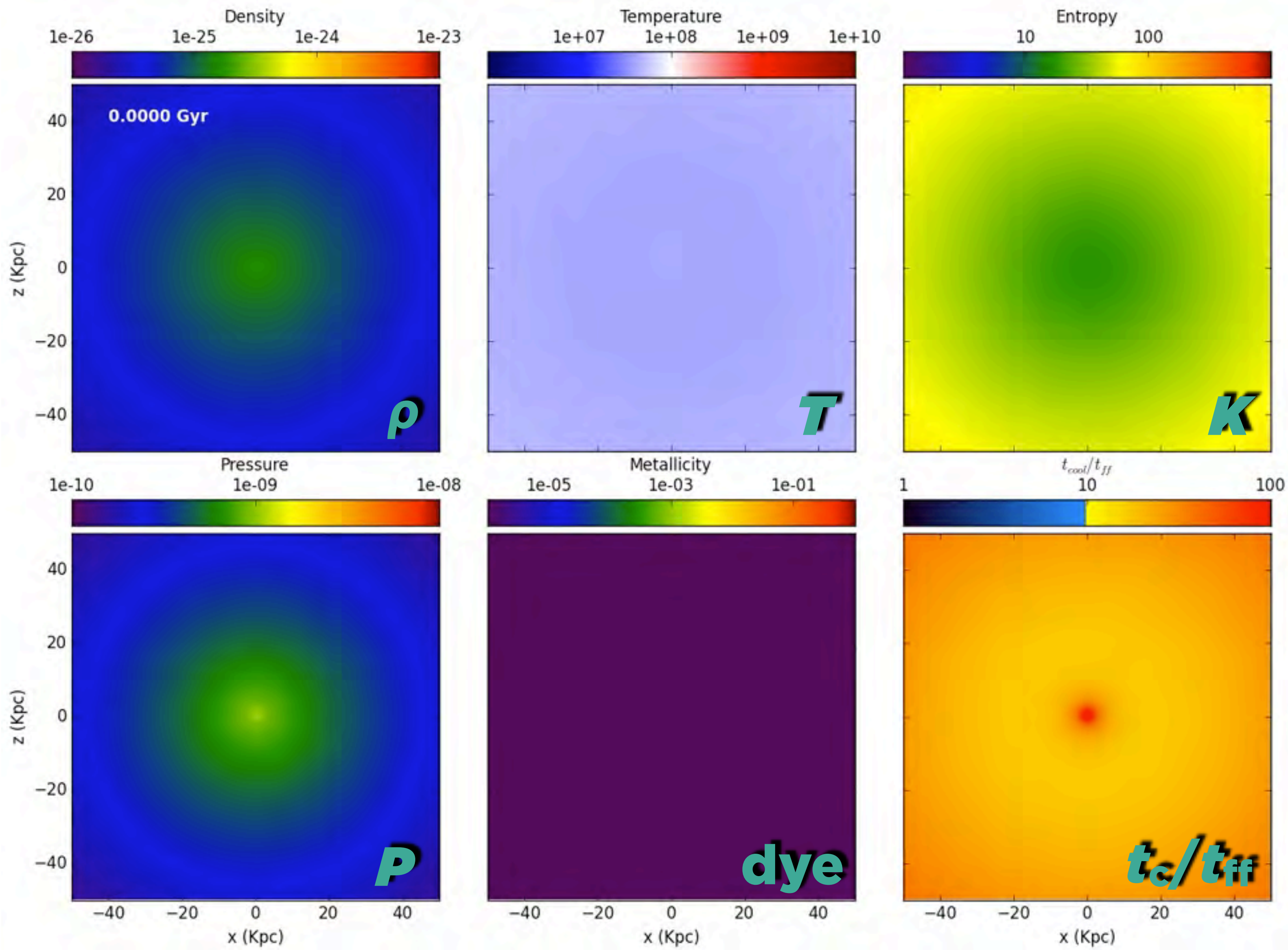
Precipitation Cycles

Li+ 2015 (in press, ApJ, arXiv:1503.02660)



Toward Cosmological Implementation

Meece Ph.D. Thesis



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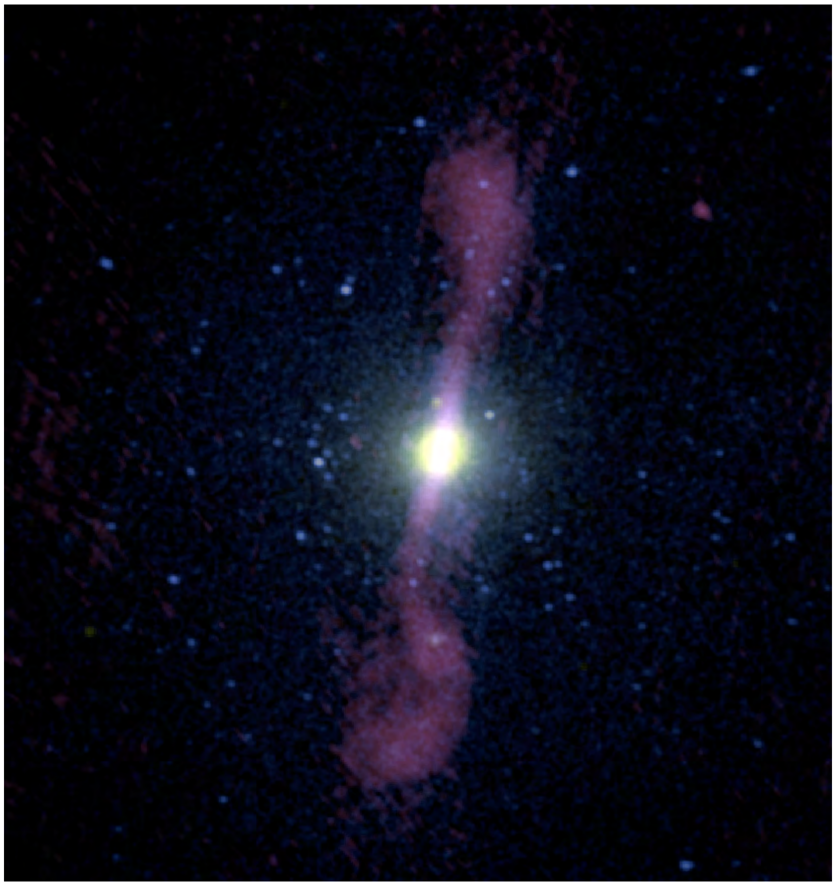
Precipitation & Quenching

Two Kinds of Massive Ellipticals

Werner+ 12, Werner+ 14

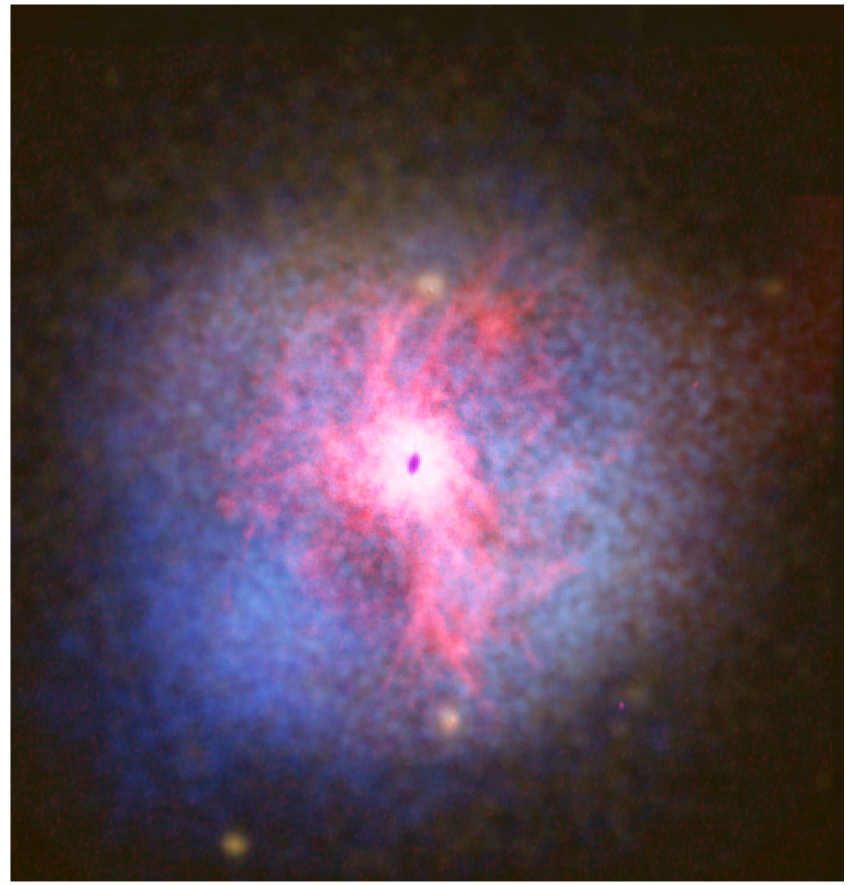
Single-Phase



NCG 1399

30 kpc

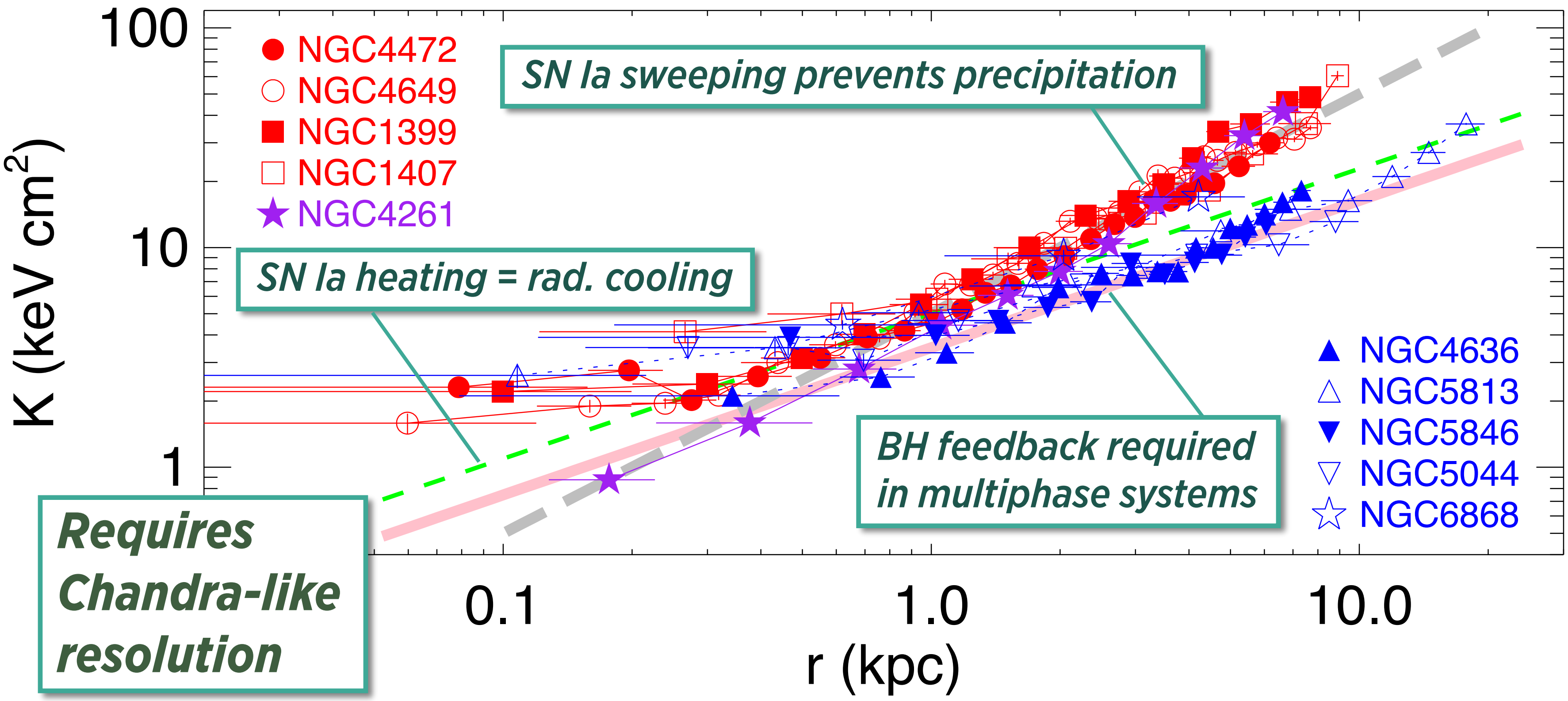
Multiphase



NGC 5044

Entropy Profiles of Ellipticals

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

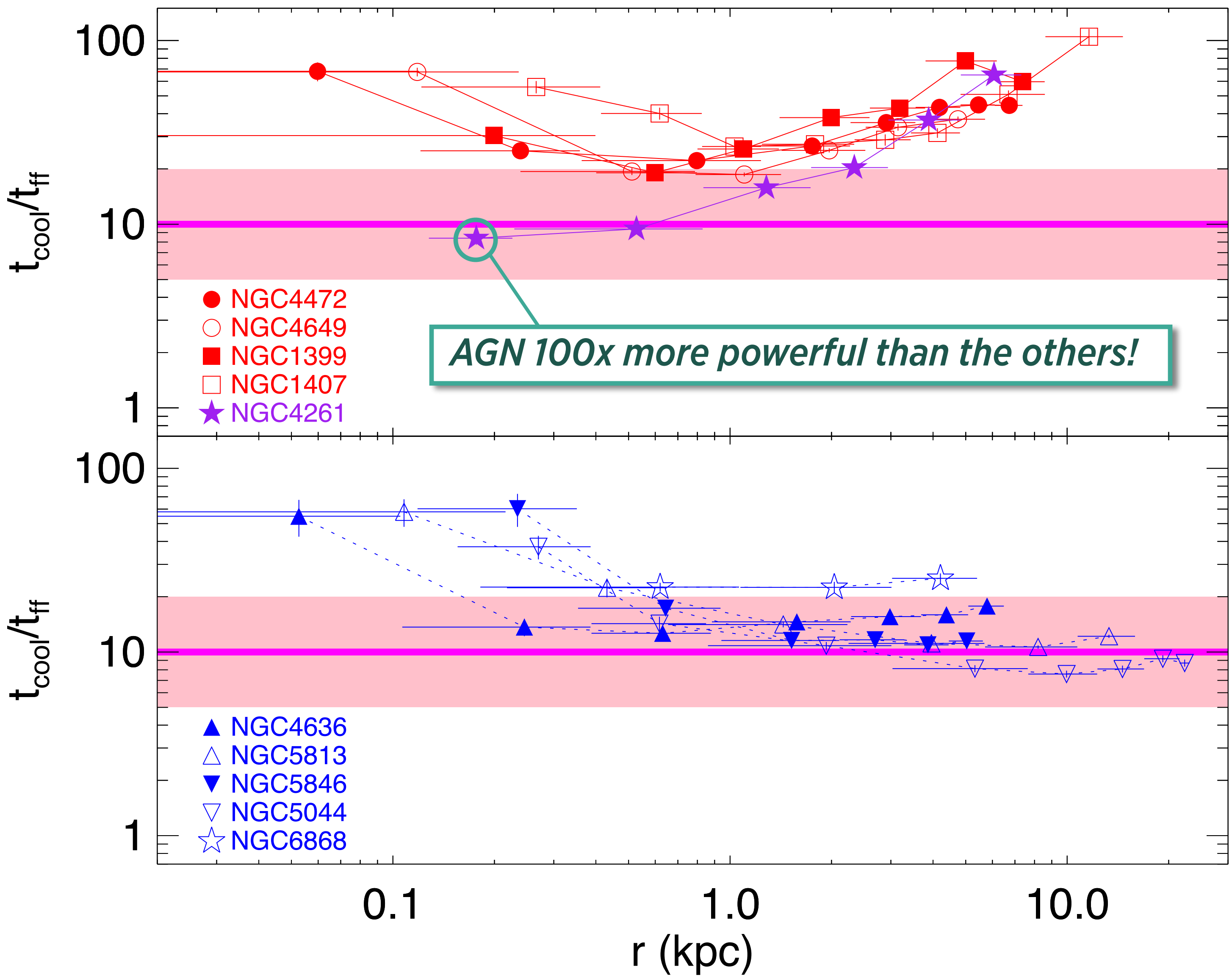


Single-phase ellipticals: $K \approx (5 \text{ keV cm}^2)\, r_{kpc}$

Multiphase ellipticals: $K \approx (3.5 \text{ keV cm}^2)\, r_{kpc}^{2/3}$

Precipitation Threshold

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



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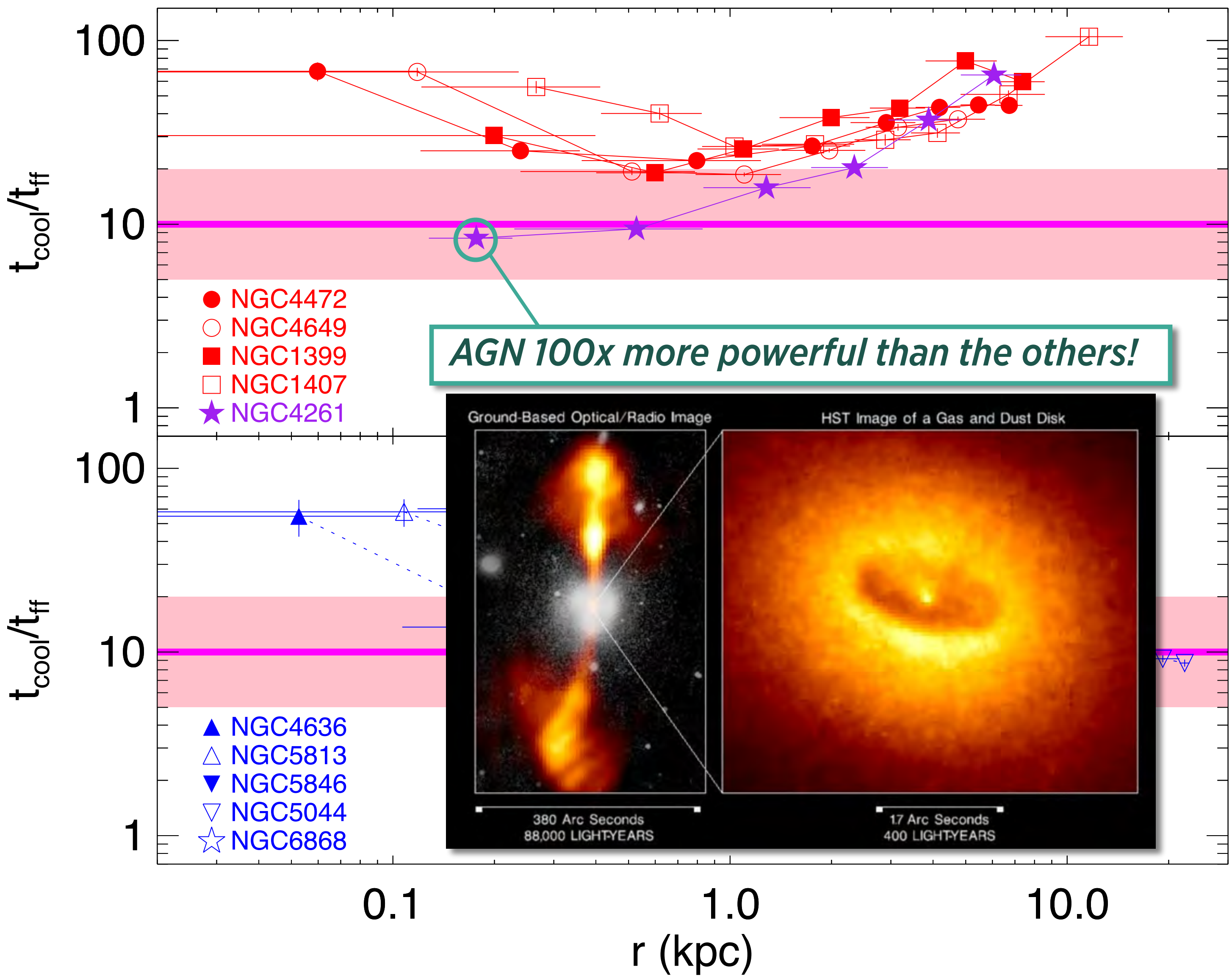

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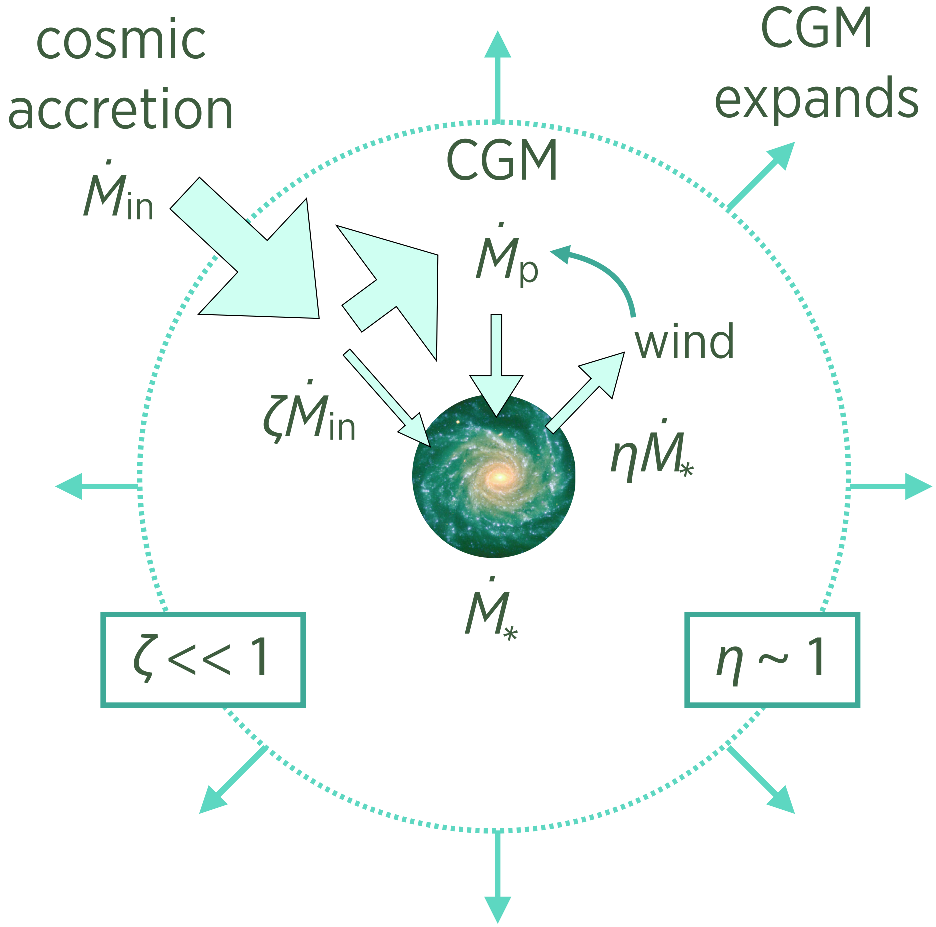
Precipitation & Regulation

Regulation via Precipitation

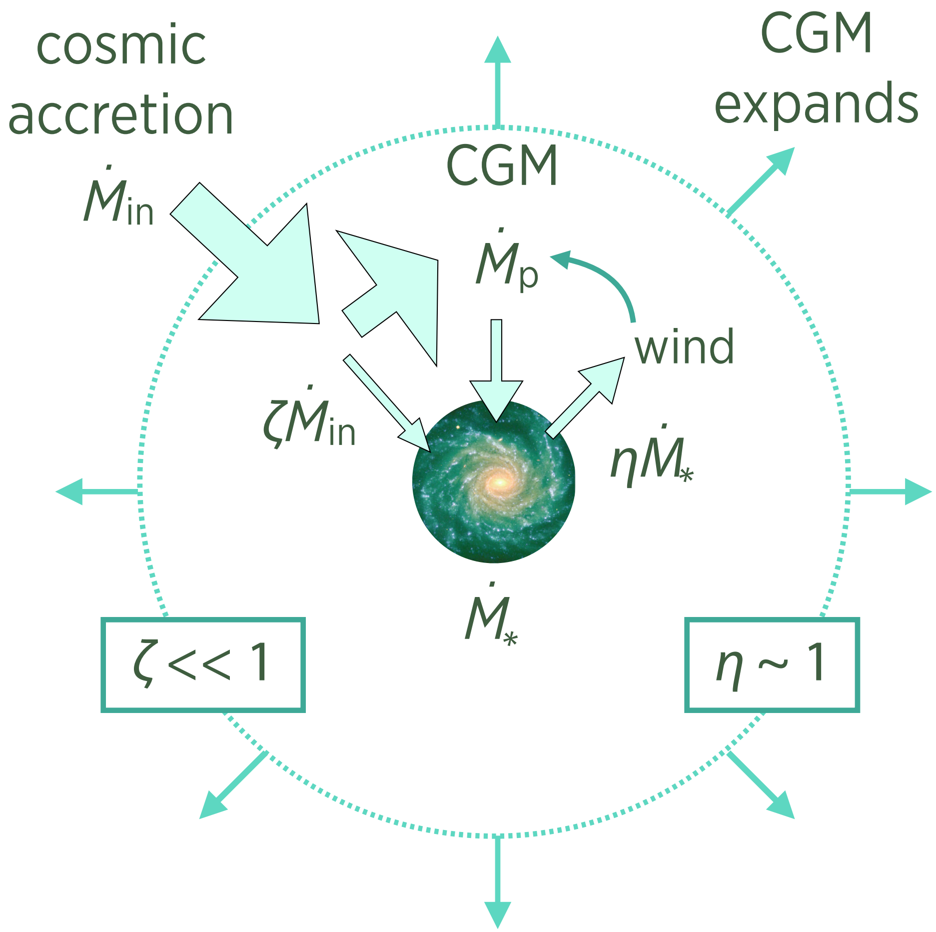


Precipitation Threshold

$$n_e(r) \approx \frac{3kT}{10\, t_{ff}(r)\, \underline{\Lambda(T,Z)}}$$

Enrichment increases cooling and triggers feedback that lowers CGM density

Regulation via Precipitation



Precipitation Threshold

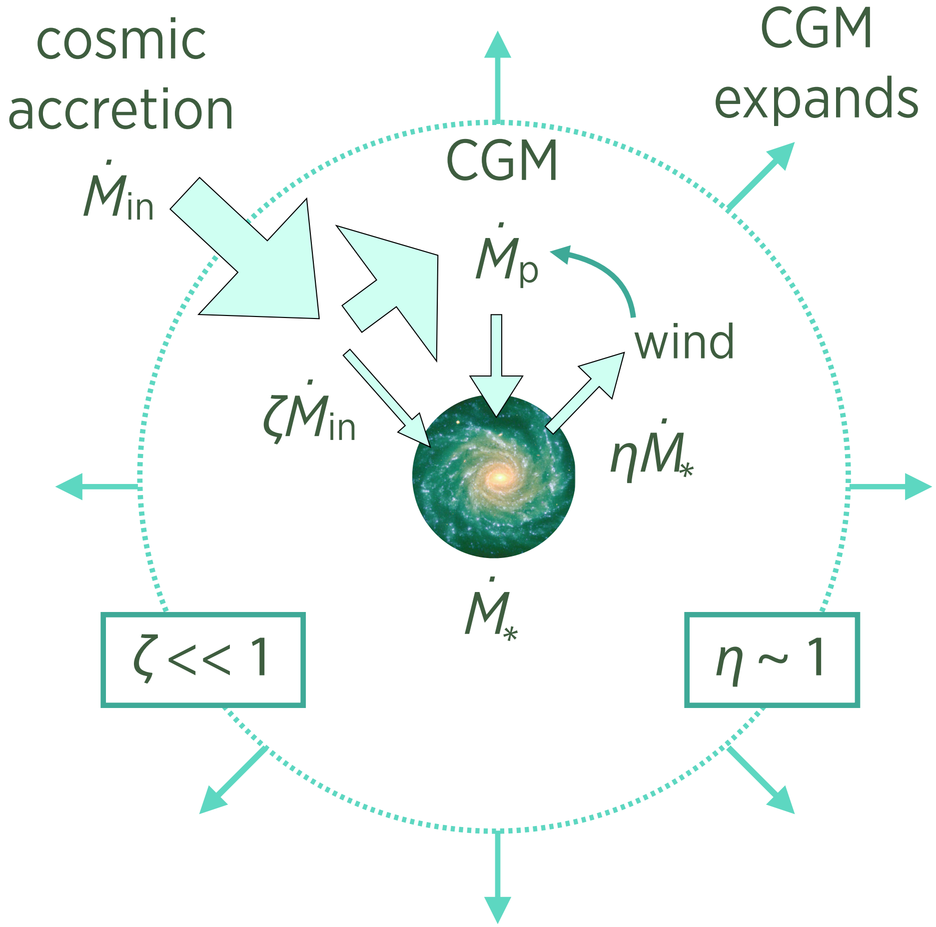
$$n_e(r) \approx \frac{3kT}{10\, t_{\rm ff}(r)\, \Lambda(T,Z)}$$

Precipitation Rate

$$\dot{M}_{\rm p} \sim \frac{\rho_{\rm CGM}\, r_{\rm c}^3}{10\, t_{\rm ff}(r_{\rm c})}$$

Reducing CGM density reduces gas supply for star formation

Regulation via Precipitation



Saturation determines $Z_{gas}(M)$ and $f_*(M)$

Precipitation Threshold

$$n_e(r) \approx \frac{3kT}{10\, t_{ff}(r)\, \Lambda(T,Z)}$$

Precipitation Rate

$$\dot{M}_p \sim \frac{\rho_{CGM}\, r_c^3}{10\, t_{ff}(r_c)}$$

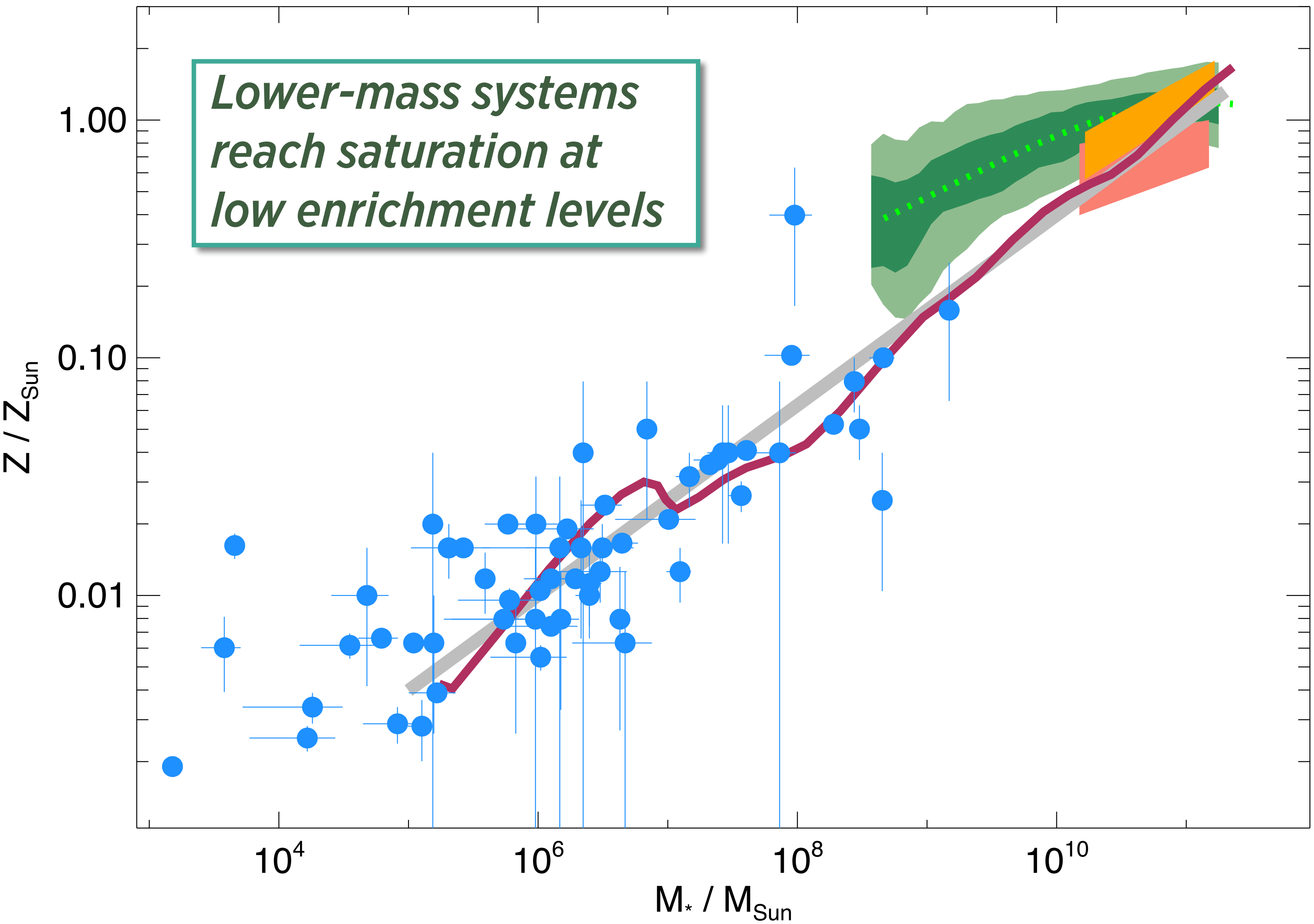
Abundance Saturation

$$\dot{Z}_{gas} \approx \frac{Y\dot{M}_* - Z_{gas}\dot{M}_{in}}{M_{gas}}$$

Enrichment $\approx$ ***Dilution***

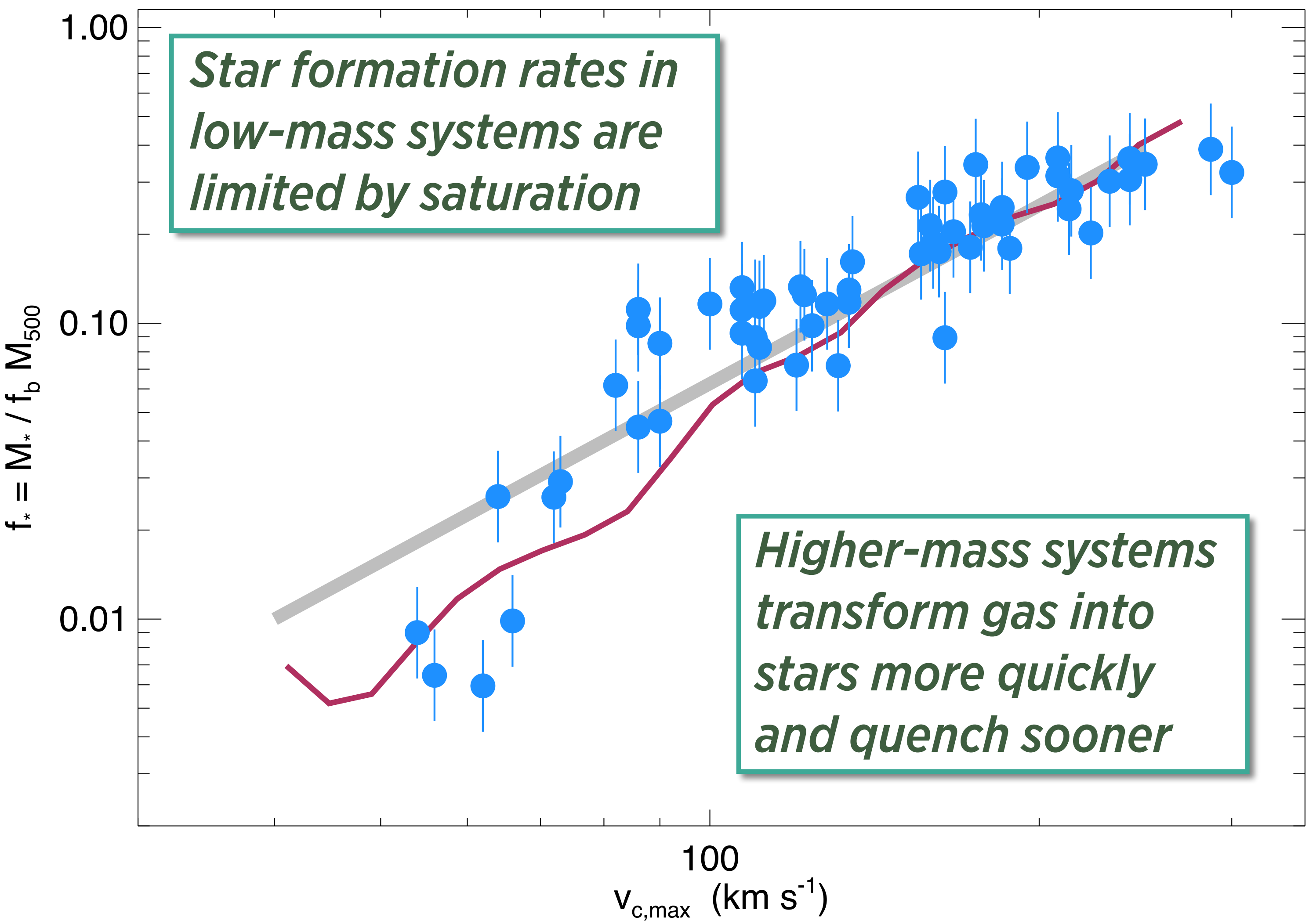
Mass-Metallicity Relation

Voit+ 15 (July 2015, ApJL)



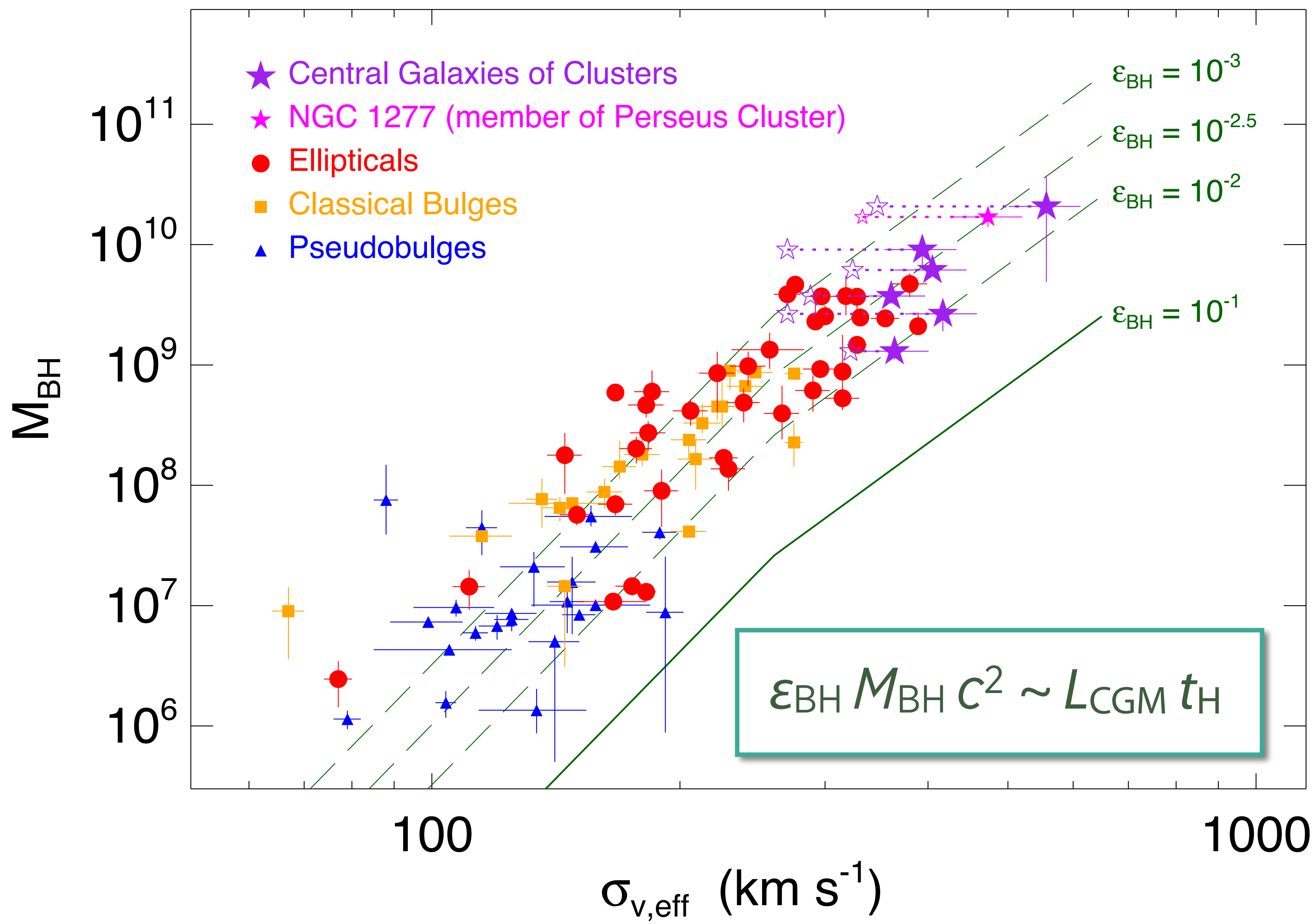
Stellar Baryon Fraction

Voit+ 15 (July 2015, ApJL)



M_{BH}–σ_v Relation

Voit+ 15 (July 2015, ApJL)



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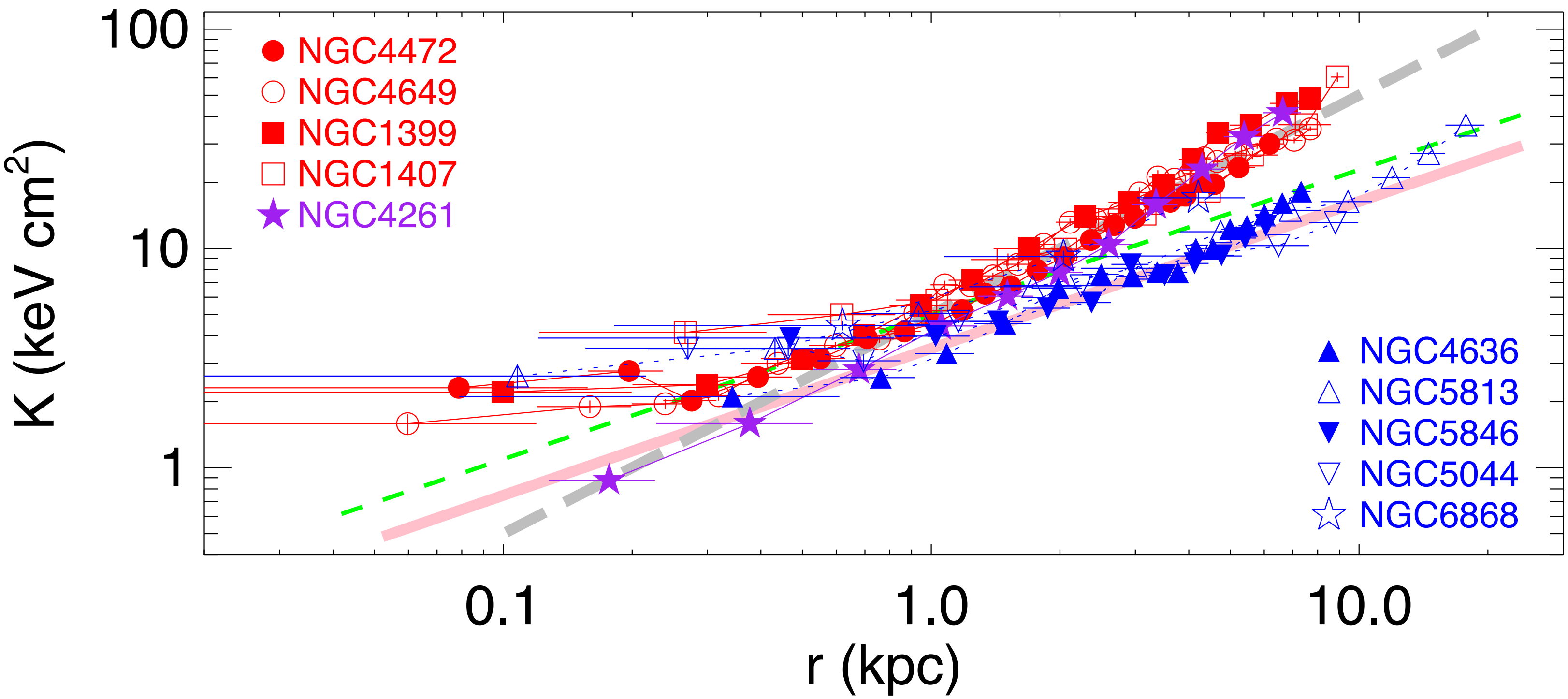
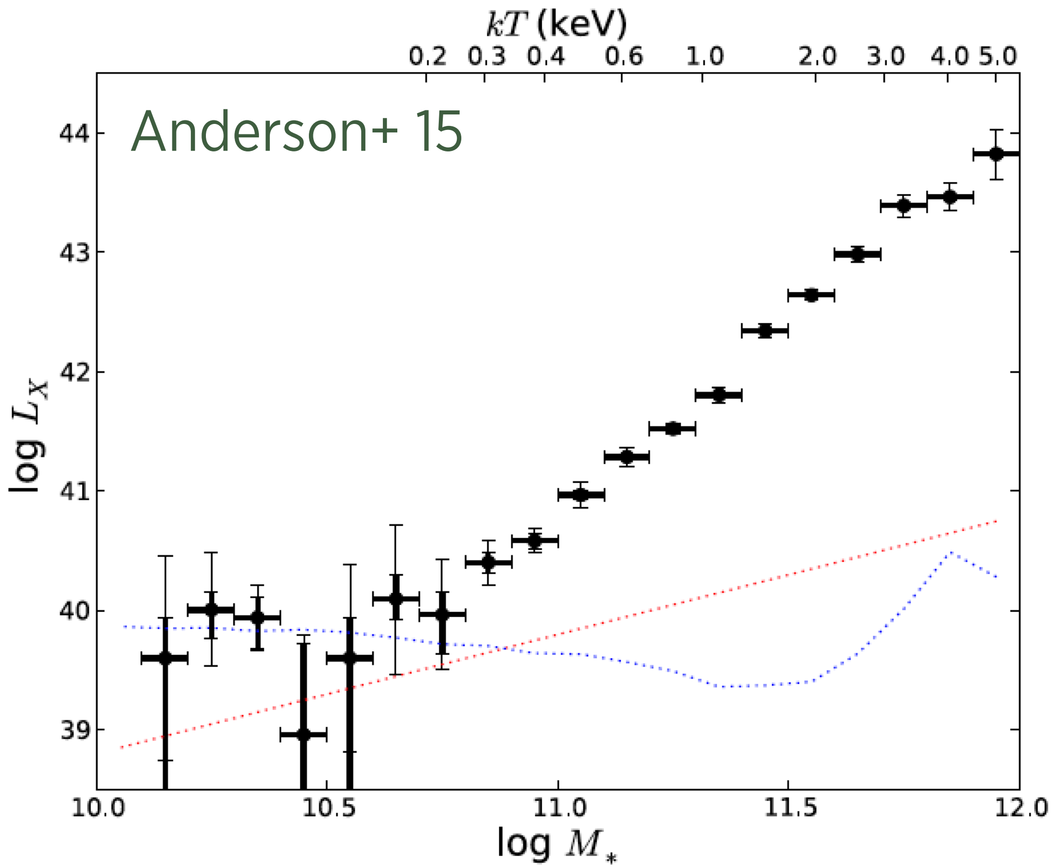
Precipitation & X-Ray Surveyor

Driver 1: *Hot Gas at ~100 pc Resolution*



Resolving the Bondi radius in early-type galaxies requires Chandra-like optical quality and many photons.

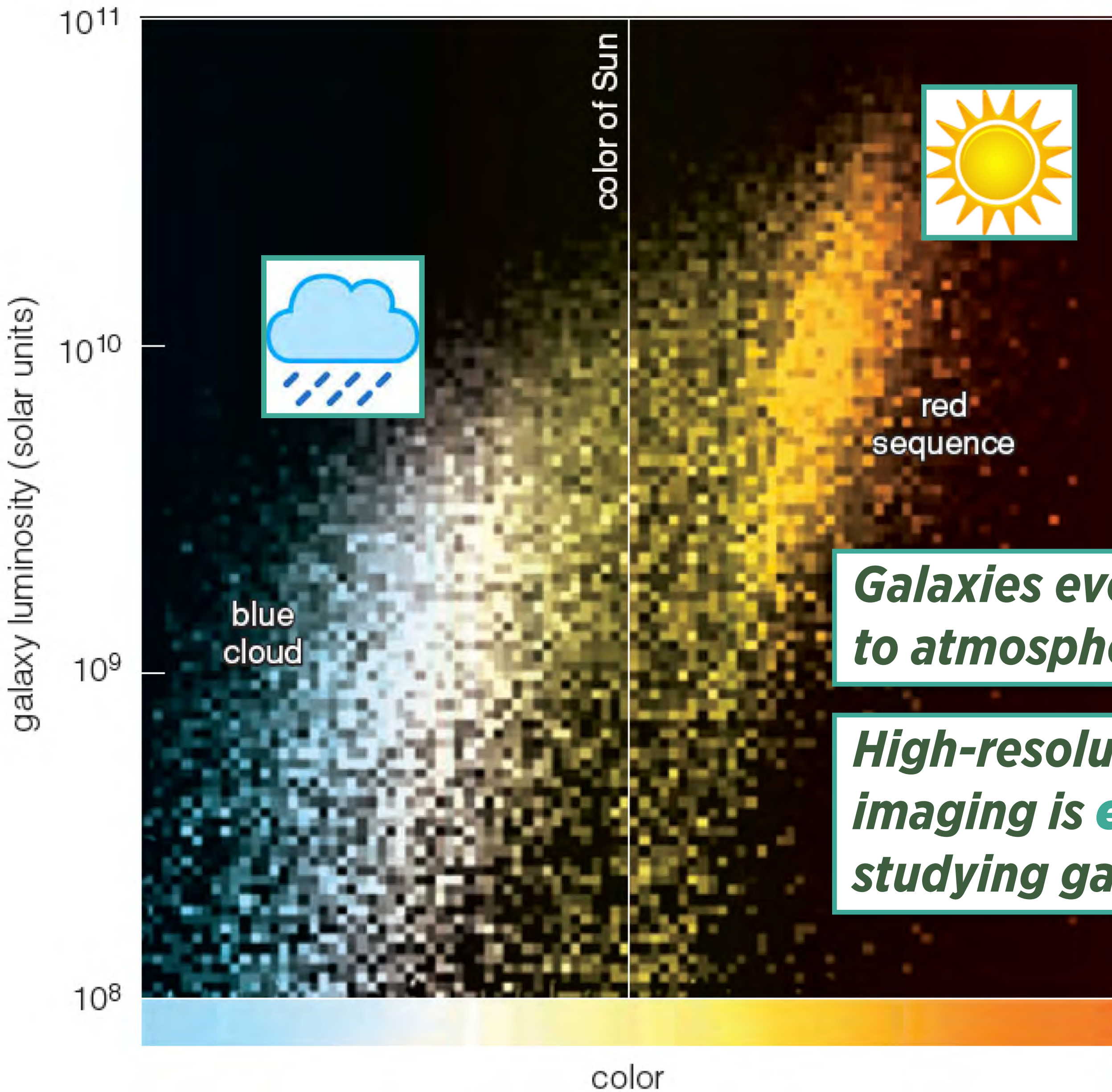
Driver 2: *CGM Imaging at < 0.5 keV*



ROSAT stacks of SDSS LRGs indicate that L_X-M_{halo} relation extends from cluster scales down to Milky Way scales

Requires Chandra-like resolution, large effective area, low background, soft X-ray sensitivity.

What turns galaxies on and off?



Galaxies evolve in response to atmospheric conditions

High-resolution X-ray imaging is essential for studying galaxy evolution