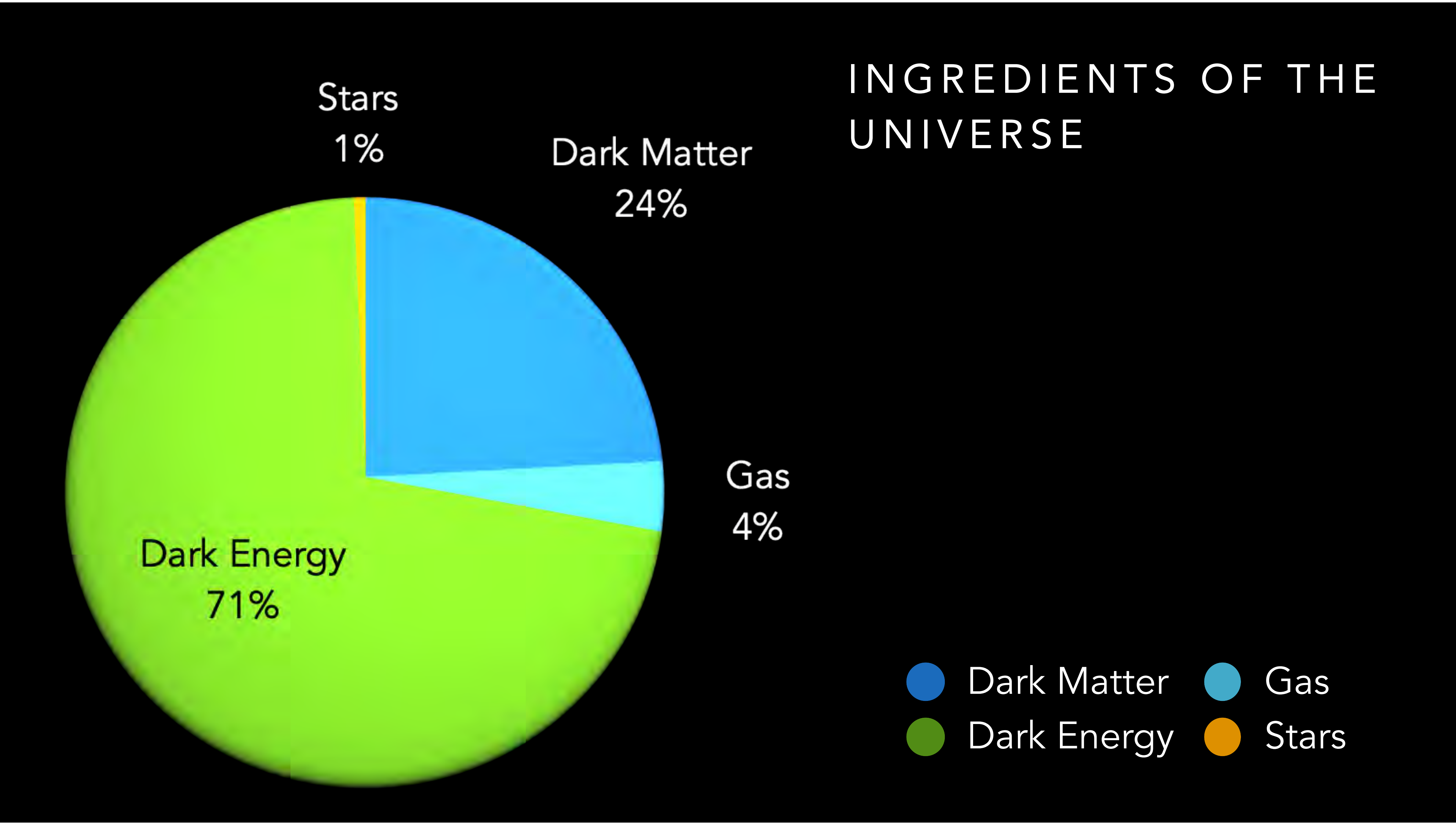
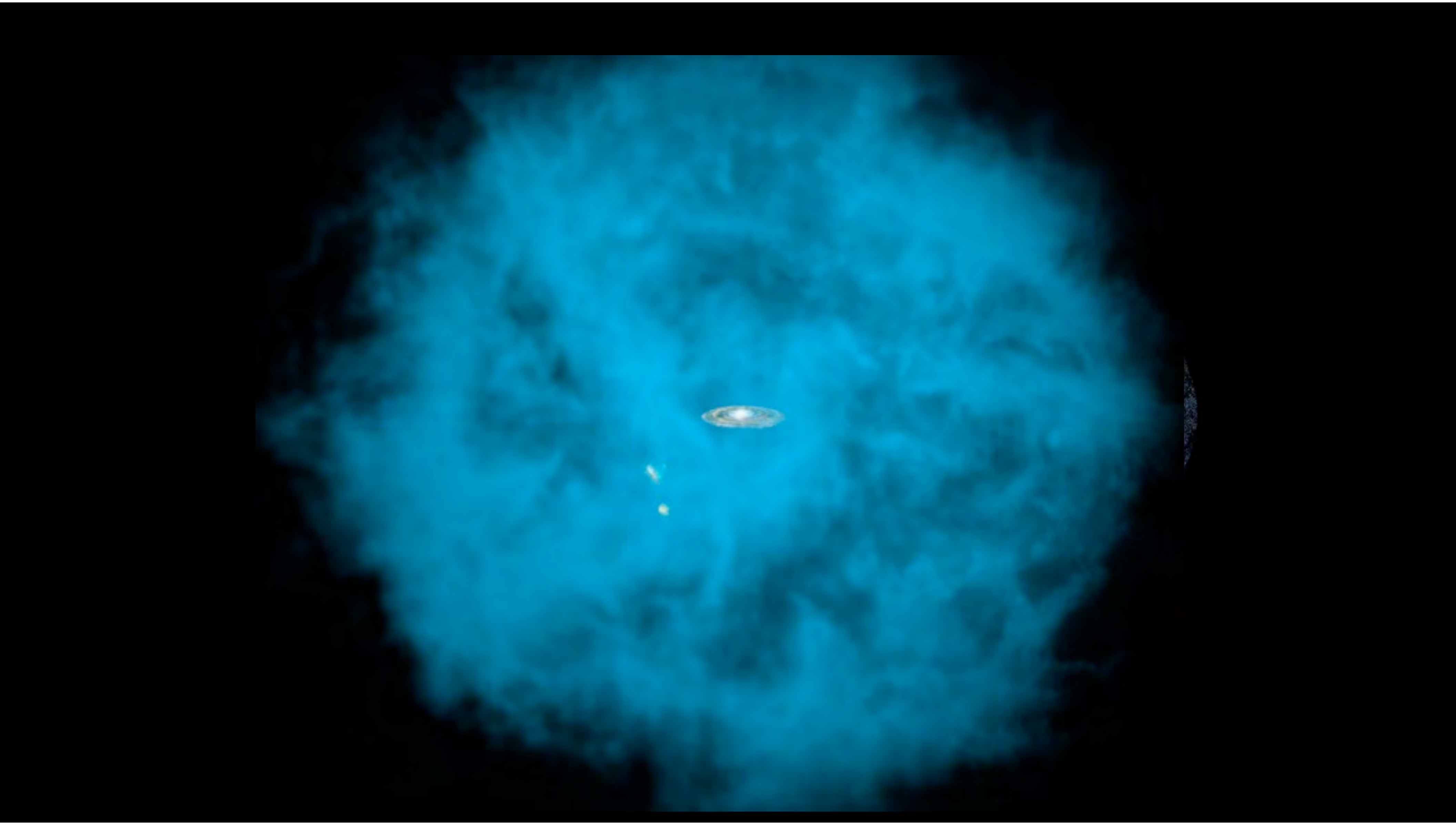
MEGAN DONAHUE
MICHIGAN STATE UNIVERSITY

HOW AGN AND GALACTIC WINDS REGULATE THE BEHAVIOR OF BARYONS


INGREDIENTS OF THE UNIVERSE
Stars
1%
Dark Matter
24%
Gas
4%
Dark Energy
71%
Dark Matter
Gas
Dark Energy
Stars

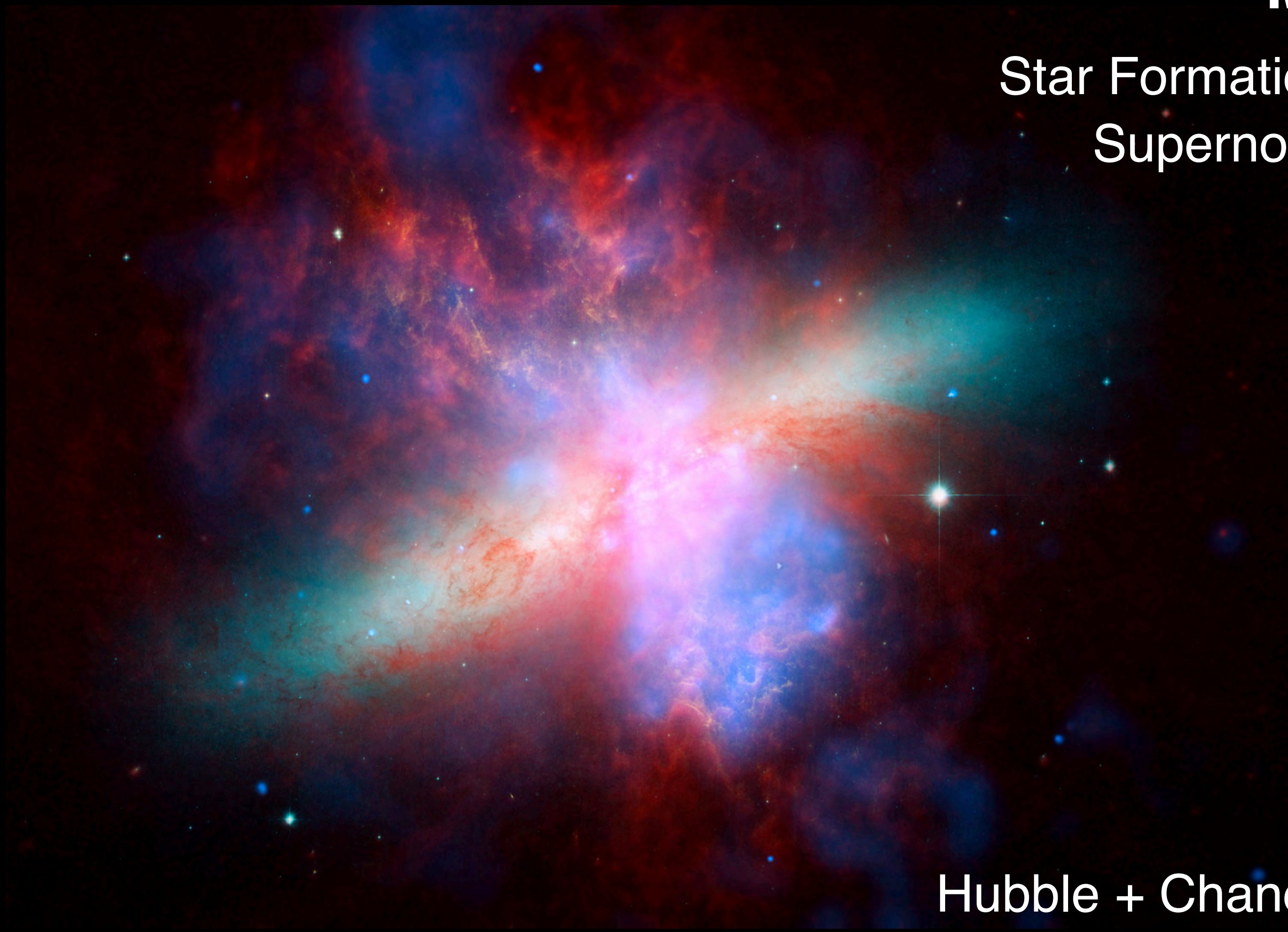


GALACTIC WINDS

M82

Star Formation Rate ~ 10 $M_{\rm Sun}$/yr

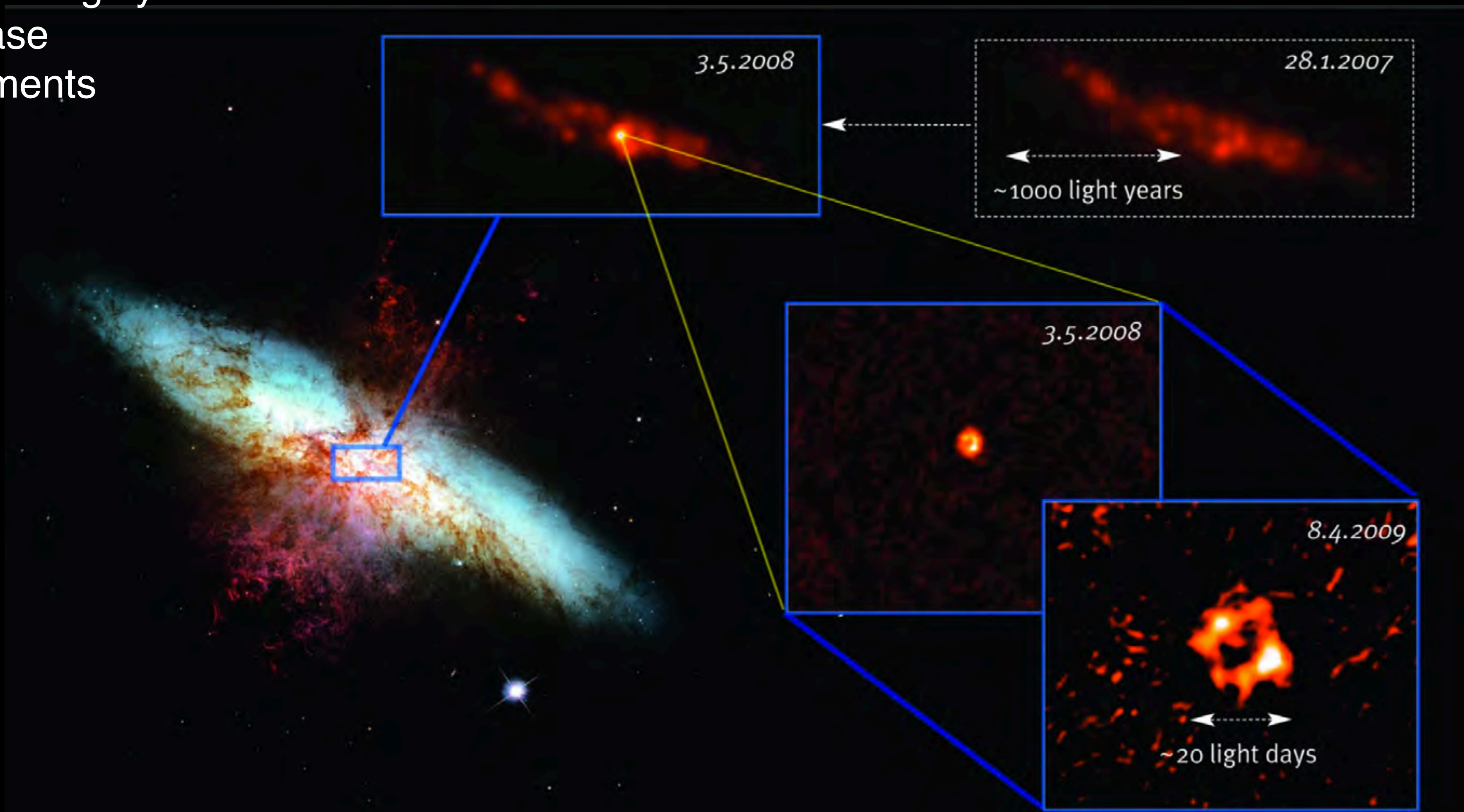
Supernova Rate ~ 0.1/yr



Hubble + Chandra(blue) + Spitzer(red)

SUPERNOVAE IN M82

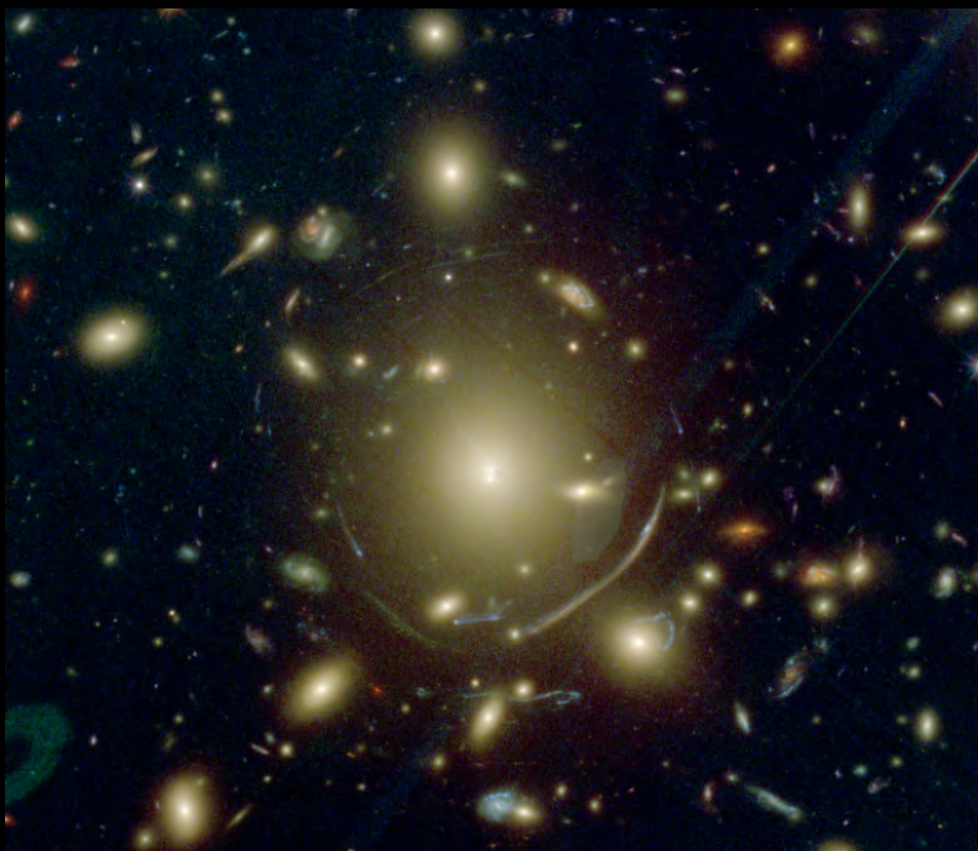
Supernovae explode in highly multiphase environments



Numerical simulations are unable to resolve all of the necessary physics —> sub-grid models

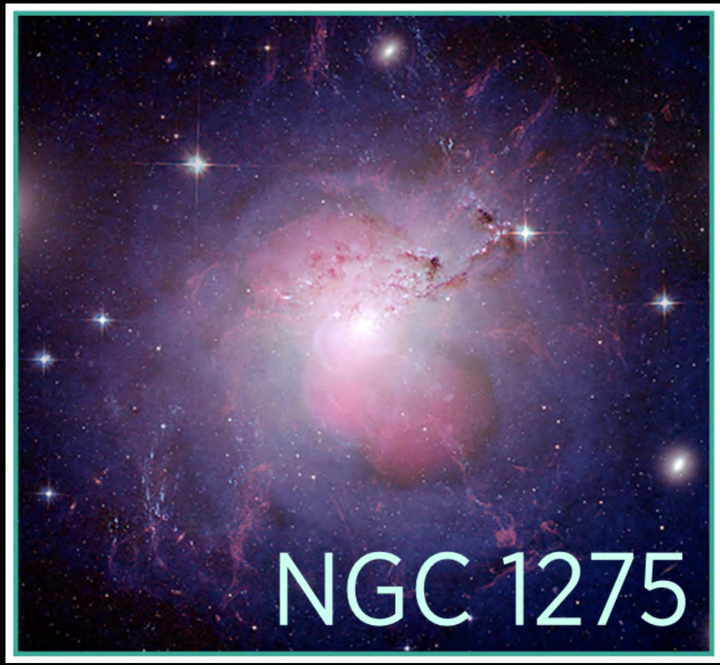
A CLUSTER OF GALAXIES: ABELL 383

Hubble Space Telescope



Chandra: X-ray
+Hot Gas (Pink)

(VERY) MASSIVE CENTRAL GALAXIES



On

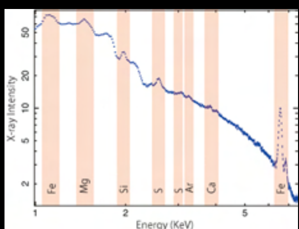
Off

BRIGHTEST CLUSTER GALAXIES IN MASSIVE CENTRAL GALAXIES

On

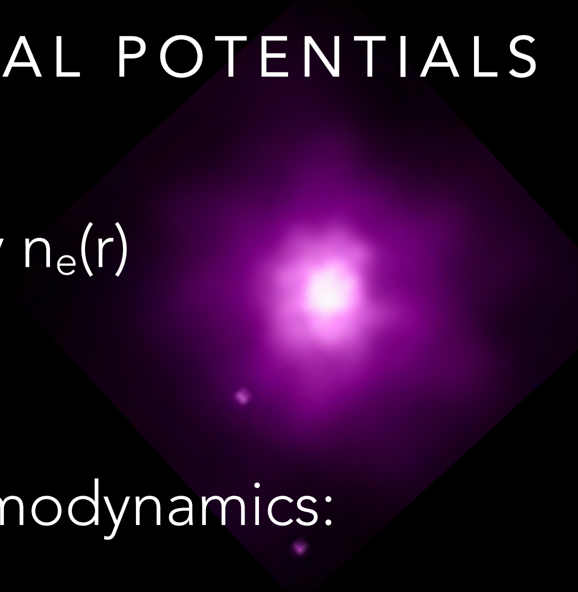
Off

X-RAY DIAGNOSTICS OF HOT BARYONS CONFINED IN DARK-MATTER DOMINATED GRAVITATIONAL POTENTIALS



X-ray Surface Brightness: Election density $n_e(r)$

X-ray spectrum: Temperature $T(r)$



but if you want to understand structure and thermodynamics:

Pressure $P(r) = n_e\, T$

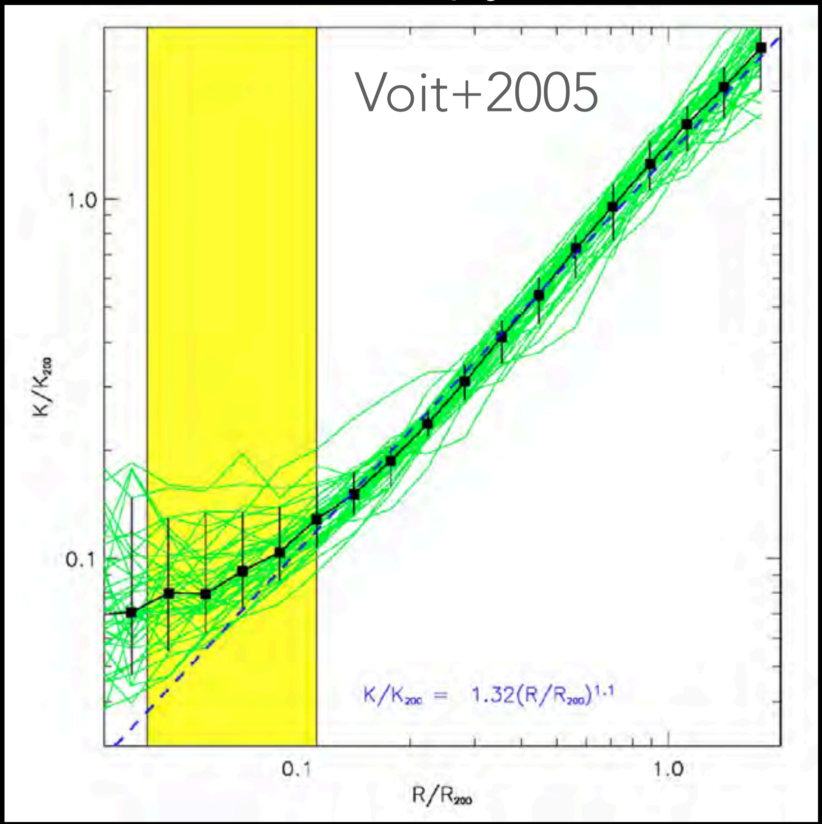
Entropy $K(r) = n_e^{-2/3}\, T$

cooling time $t_c = \dfrac{3\,P}{n_e n_i\, \Lambda(T)}$

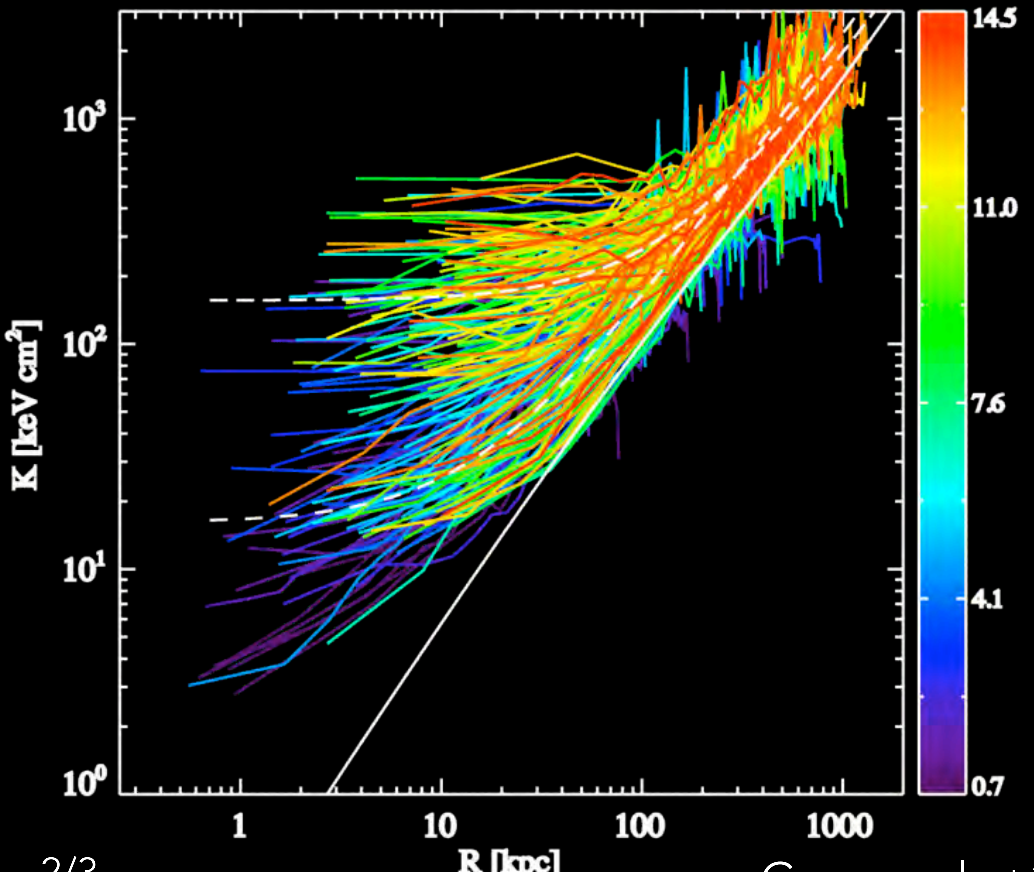
especially compared to a gravitational dynamic time

(COSMOLOGICAL) ACCRETION OF GAS

Simulated Entropy Profiles



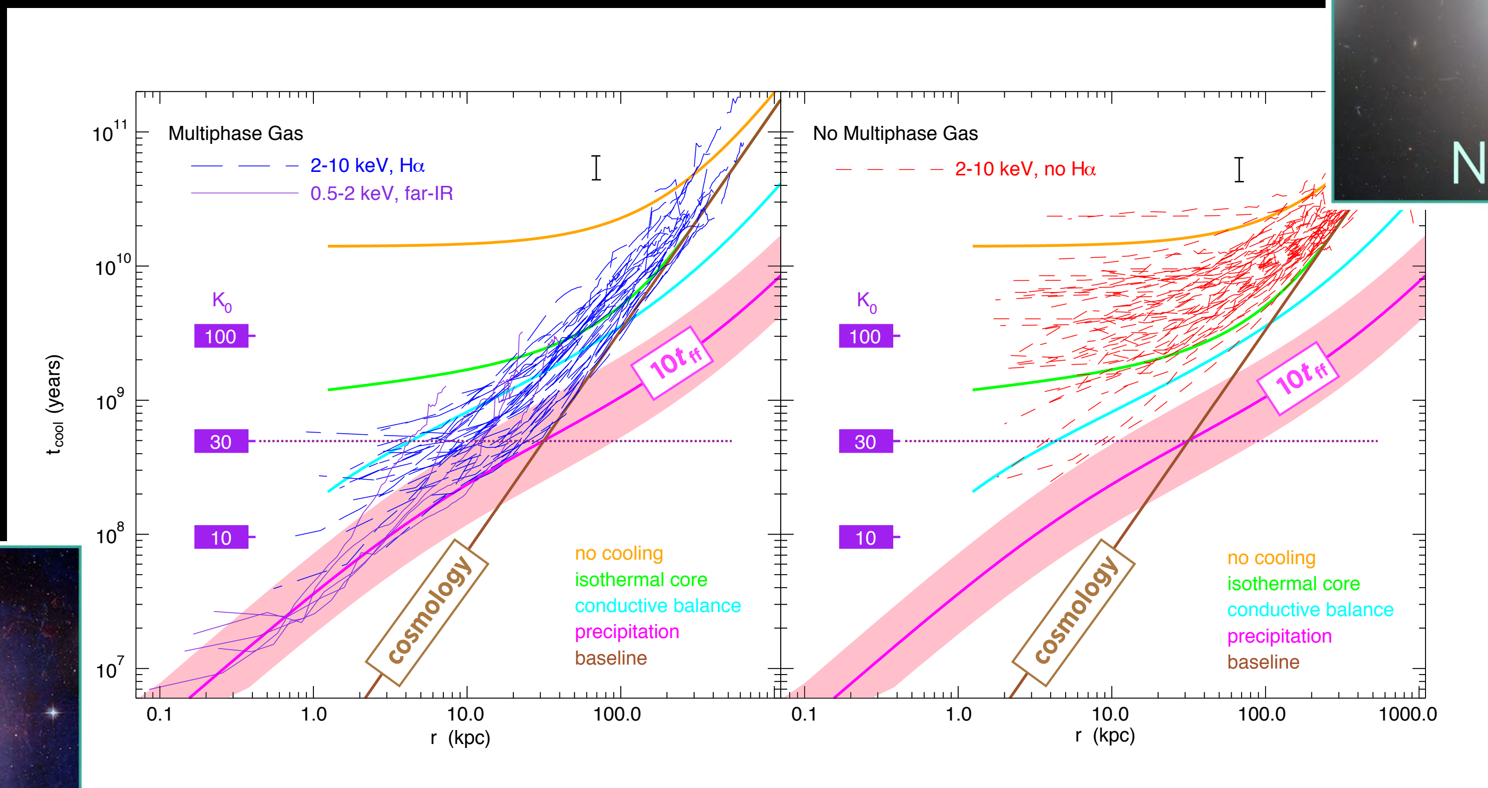
200+ Cluster Gas Profiles (ACCEPT)

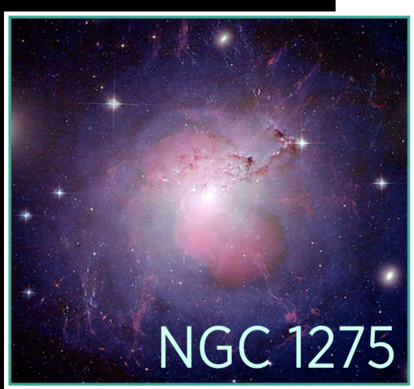


Observed gas entropy $K = kT\ n_e^{-2/3}$

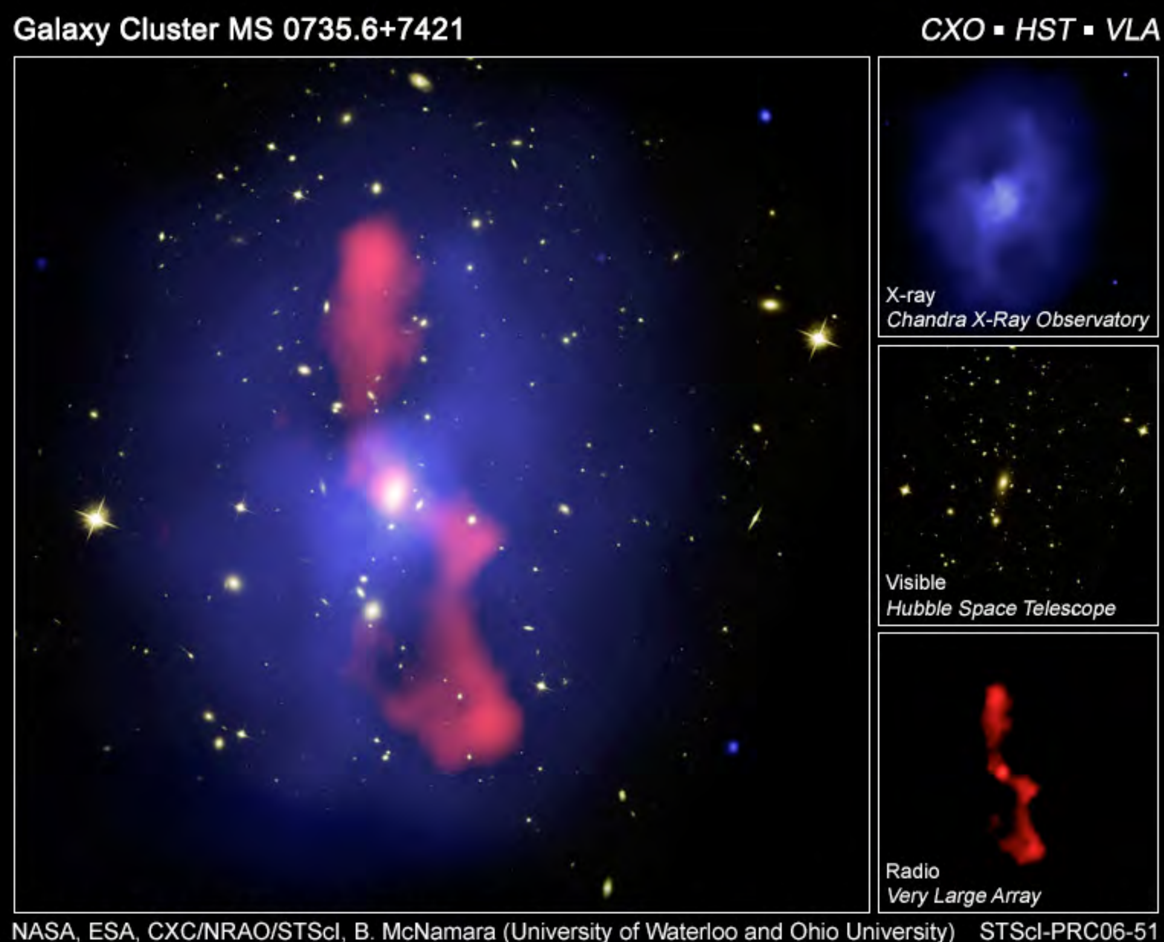
Cavagnolo+2009

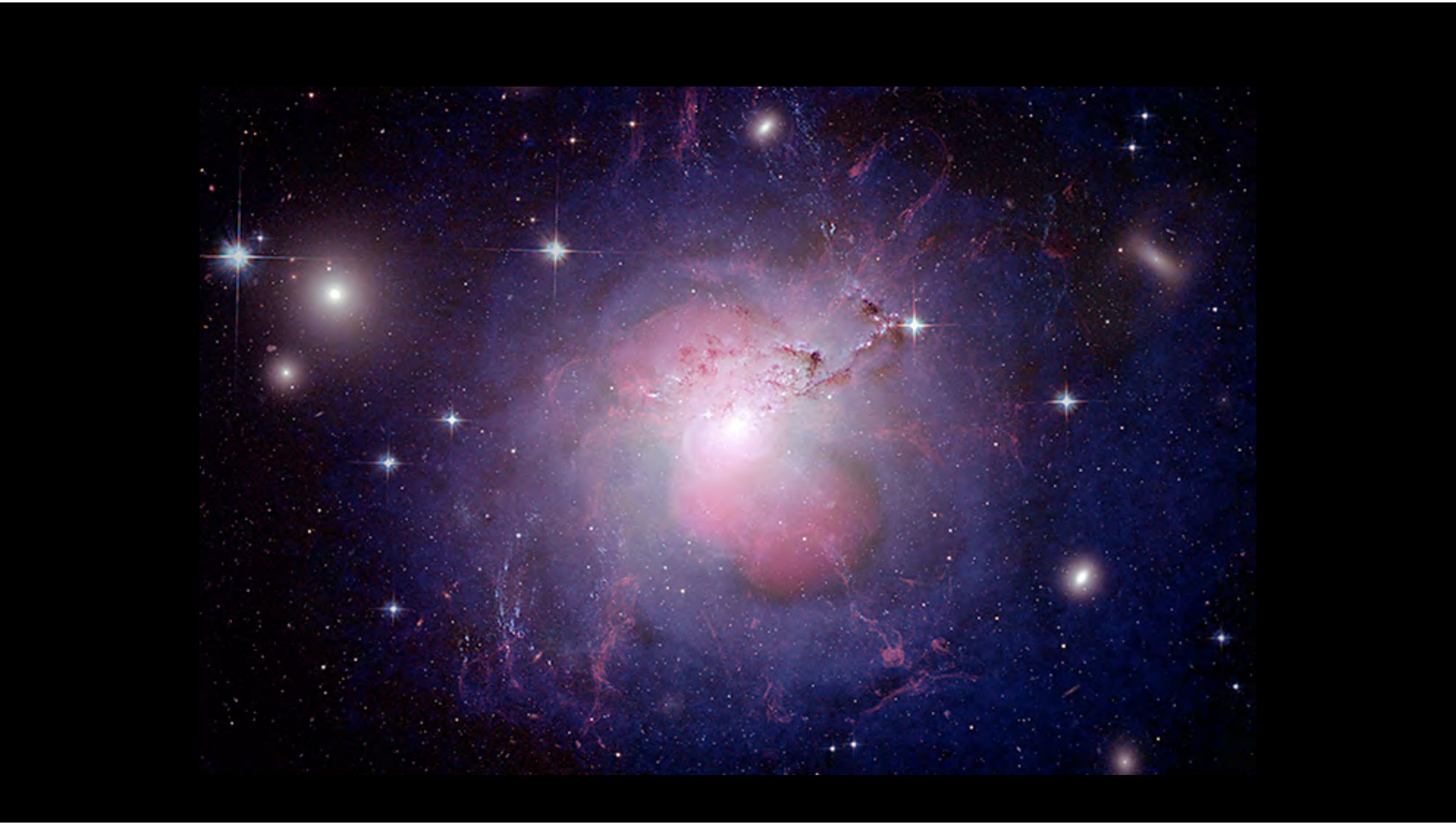
THE CIRCUMGALACTIC GAS STATE IS DIFFERENT FOR ACTIVE VS. QUIESCENT BCGS

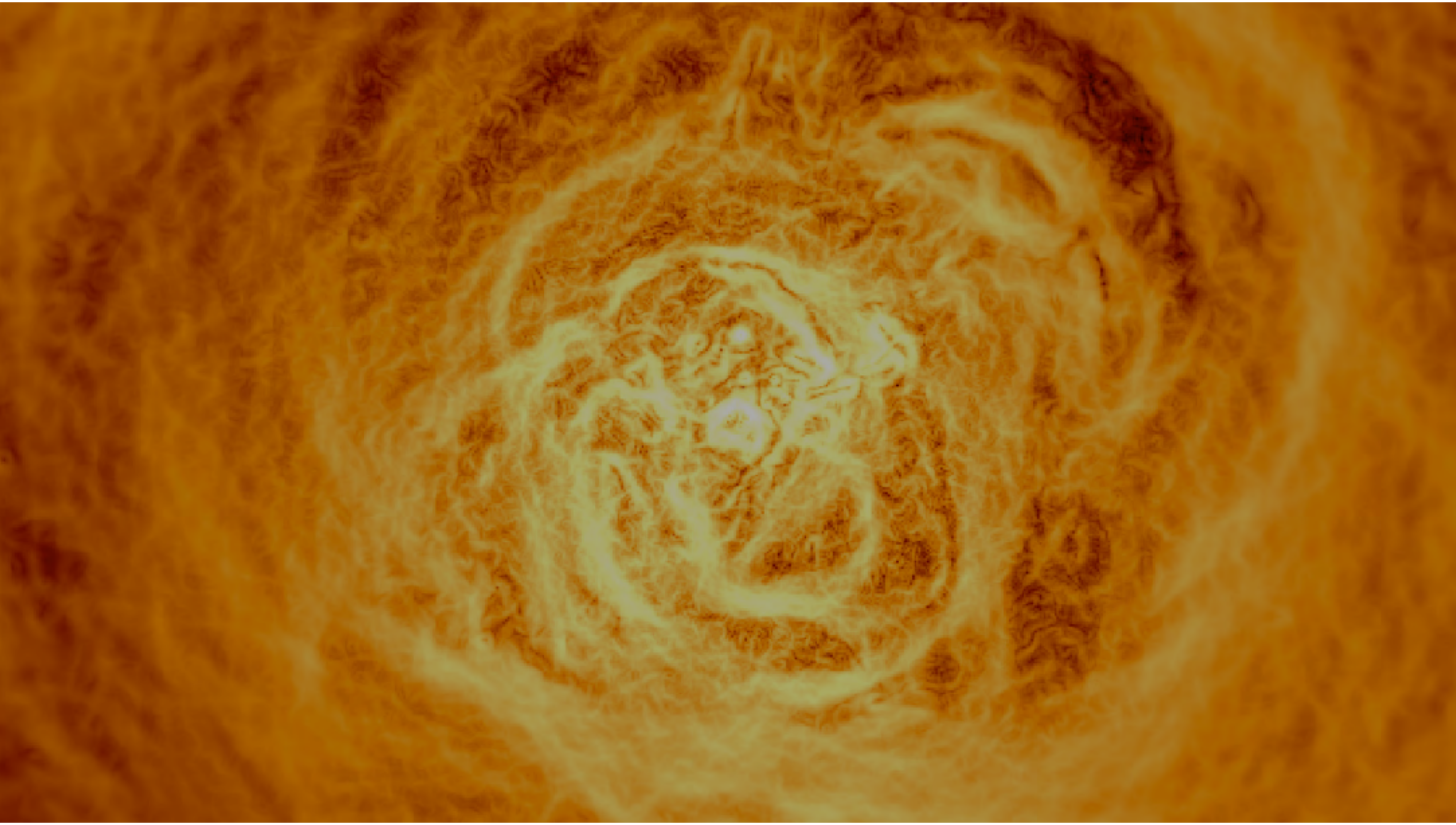




AGN FEEDBACK IN ACTION





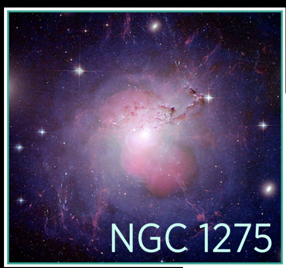


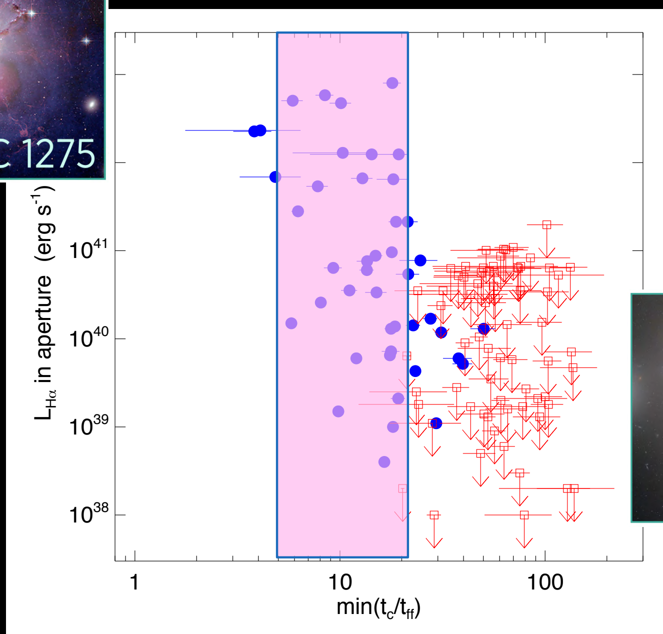
takeaway #1 & 2

All the baryons are observable in the centers of clusters.

High-resolution X-ray observations of the hot gas in clusters transformed our picture of the role of AGN

RED: QUIESCENT
BLUE: MULTI-PHASE (EXTENDED H-ALPHA)





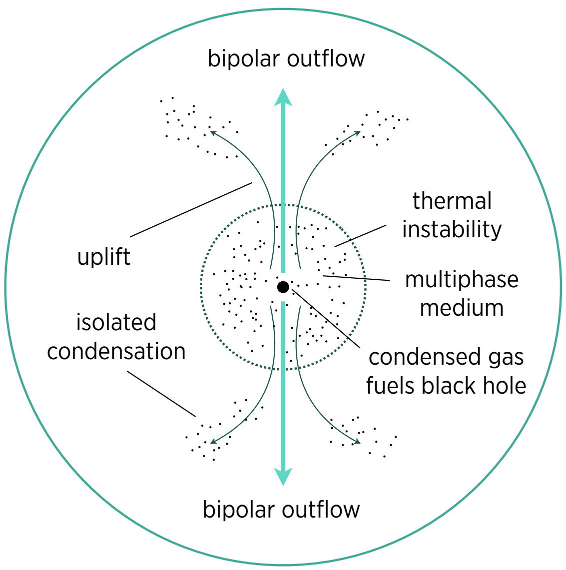
Voit & Donahue 2015

takeaway #3

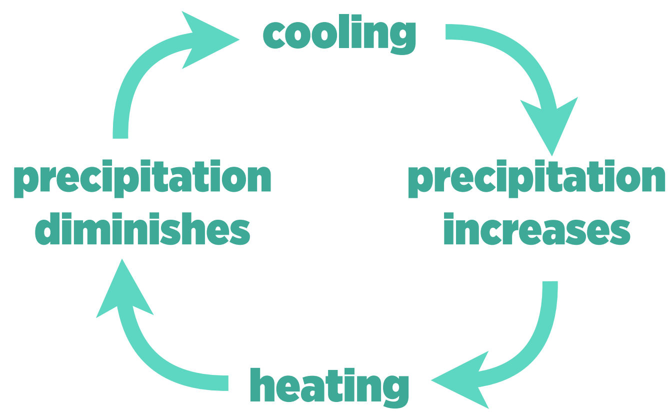
Nature says: t_{cool}/t_{ff} ~ 5-20 & condensation happens: we see “multi-phase” gas in the BCGs

The Precipitation Hypothesis

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

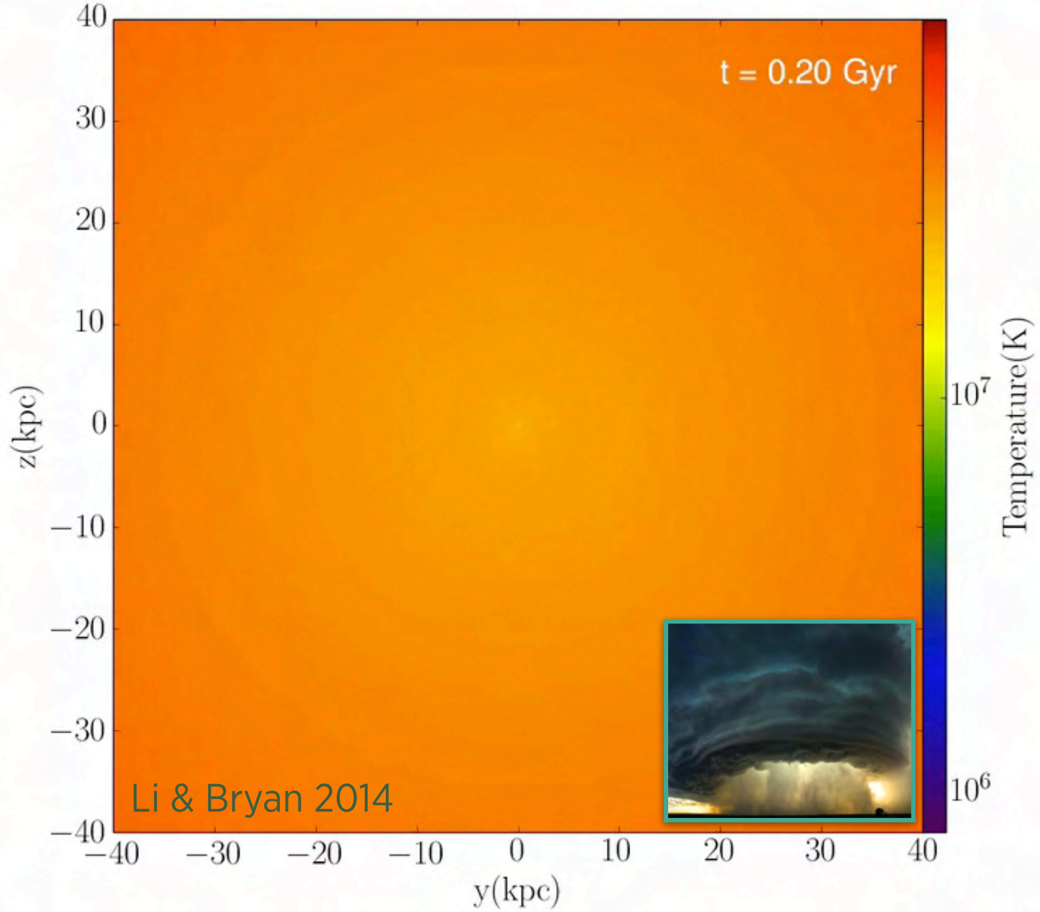


core: $t_{cool} \sim 5\text{-}20\ t_{free\text{-}fall}$



Outflow-Induced Precipitation

Gaspari+ 2012; Li & Bryan 2014a,b



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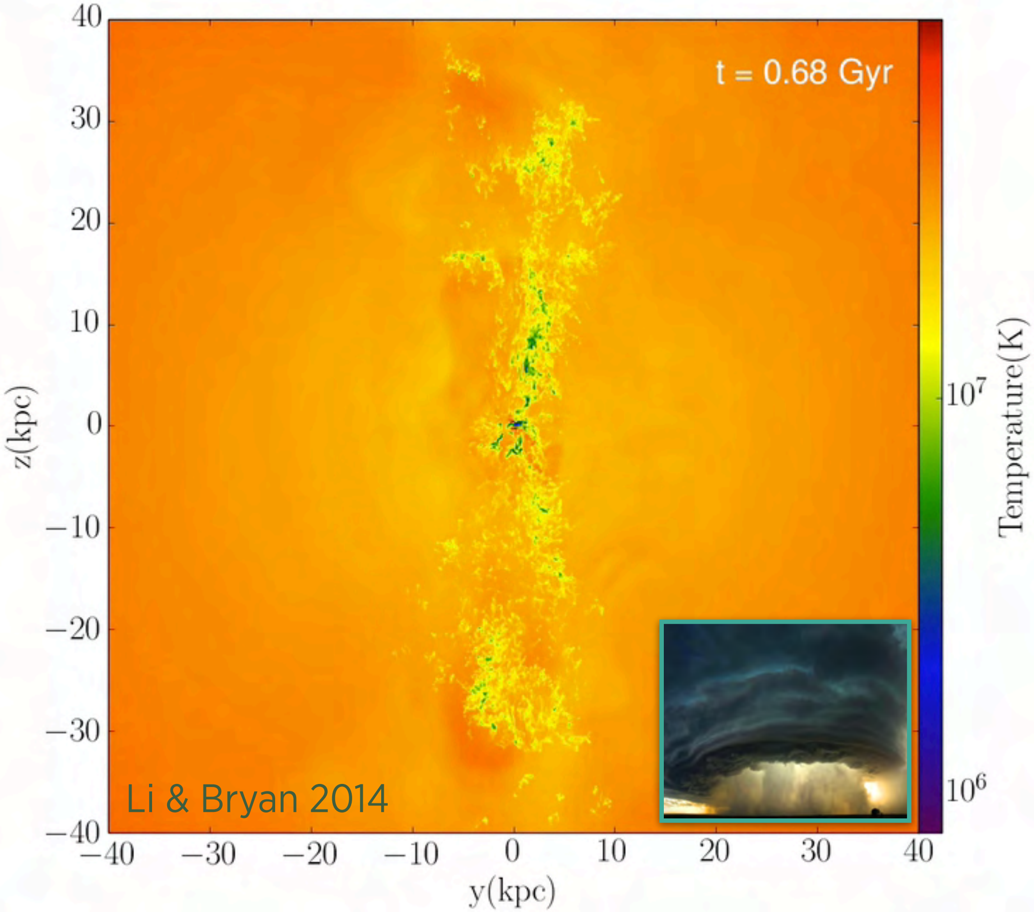
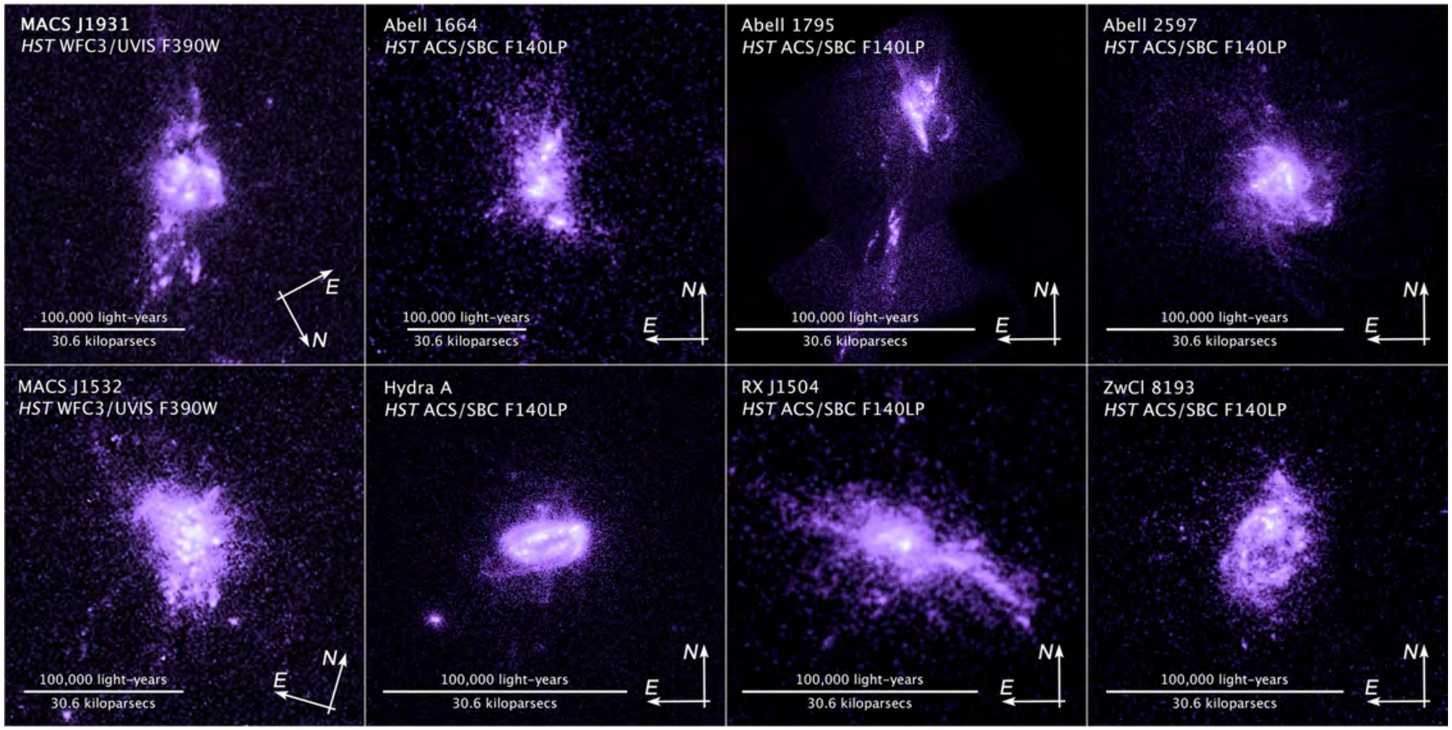
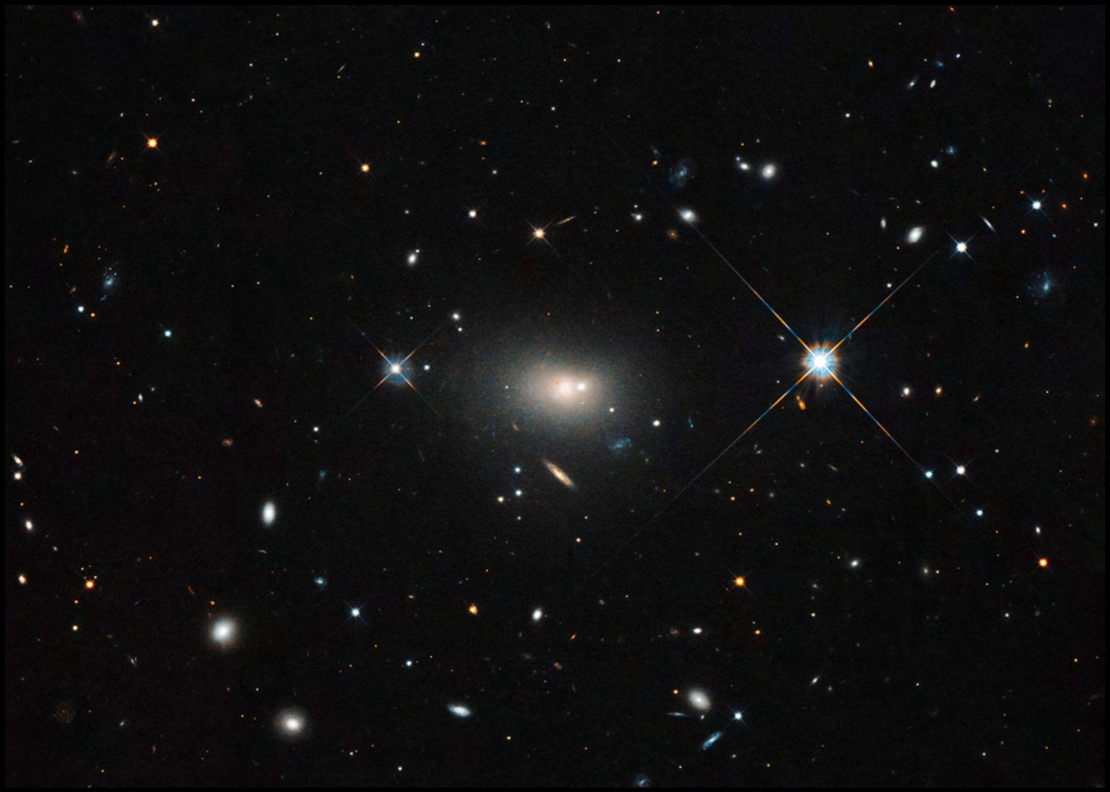


UV Images of Cluster Cores

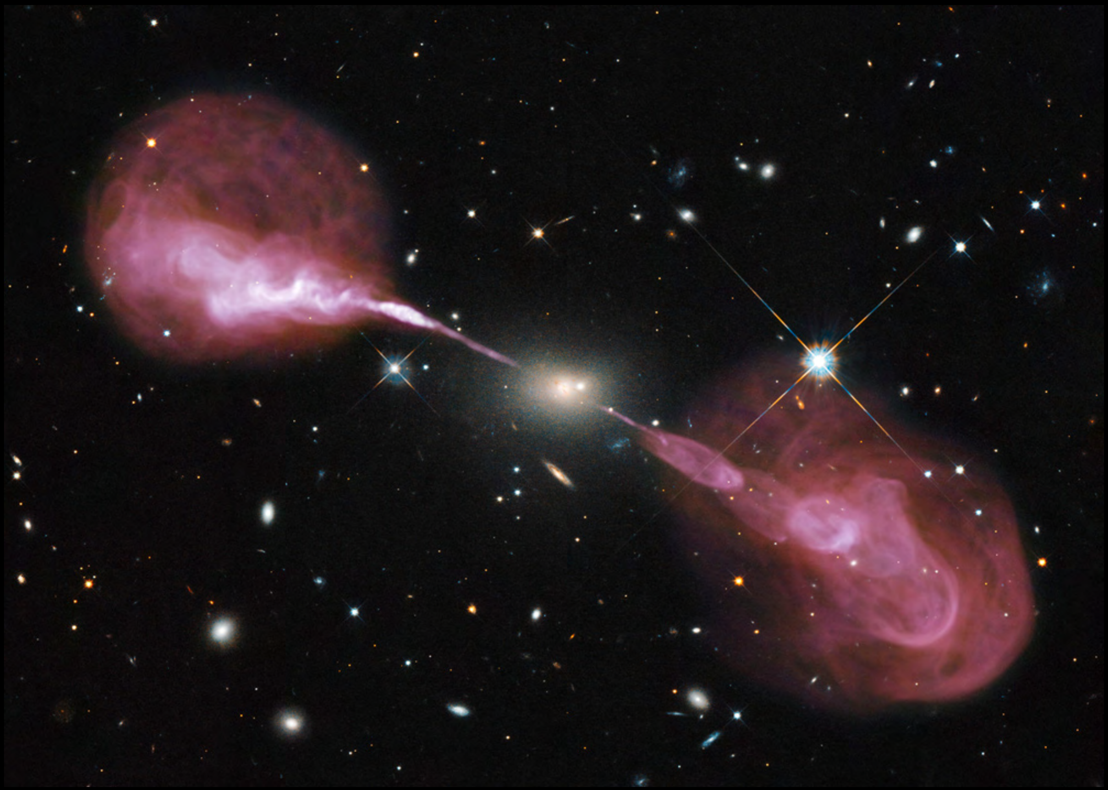
Donahue+ 15, Tremblay+ 15



What about individual galaxies?

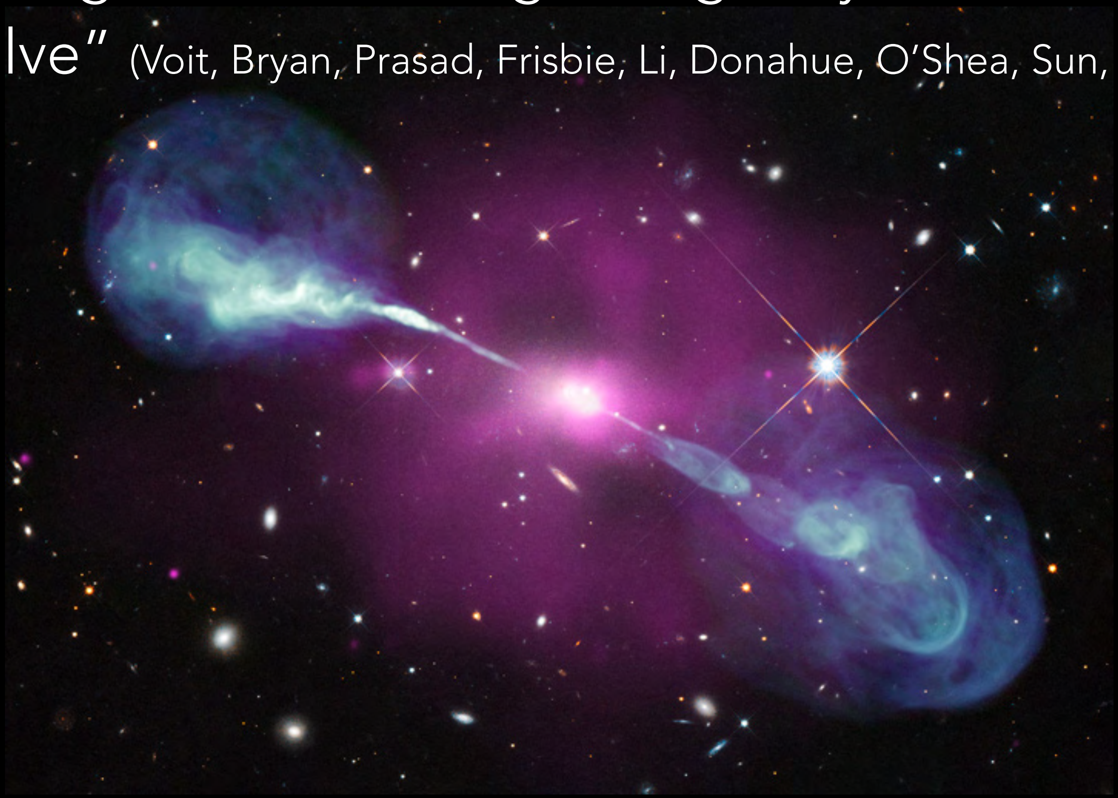


Hercules A, O’Dea/Baum/Hubble Heritage



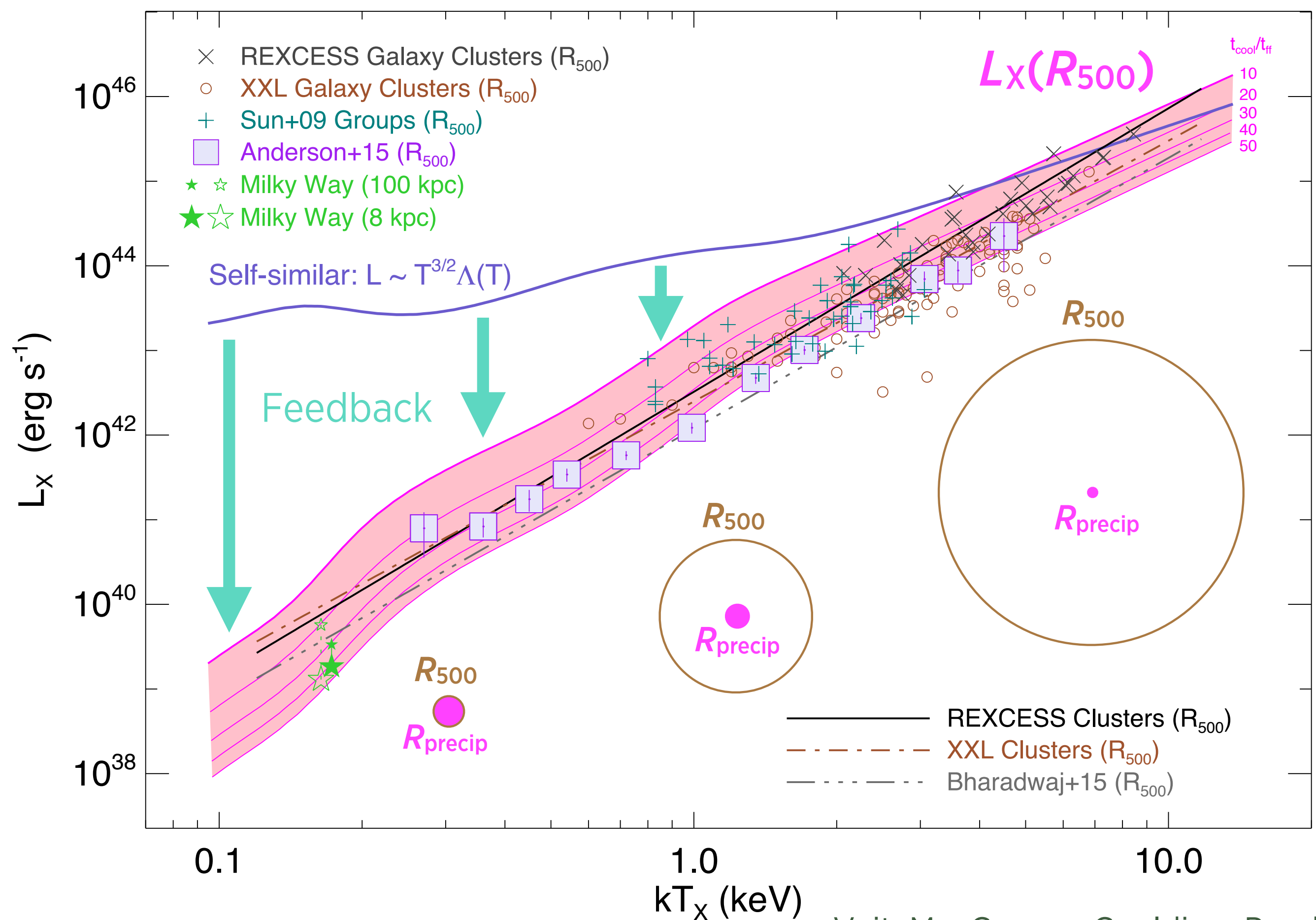
Hercules A, O’Dea/Baum/Hubble Heritage
3C 348

AGN can regulate the outer pressure boundary condition in individual galaxies, working with galaxy winds: the Black Hole "Valve" (Voit, Bryan, Prasad, Frisbie, Li, Donahue, O'Shea, Sun, Werner 2020)



X-ray: NASA/CXC/SAO, Optical: NASA/STScI, Radio: NSF/NRAO/VLA

The precipitation-model predicts the maximum luminosity as a function of halo mass



Voit, Ma, Greene, Goulding, Pandya, Donahue, Sun 2018 takeaway #4

The precipitation model provides a framework for understanding observations and simulations of feedback at galaxy and cluster scales.

Voit+2015, 2017, 2018, 2020

TO REMEMBER

- Understanding how stars and black holes interact with their environment - particularly with the hot, volume-filling CircumGalactic Medium (CGM) is crucial to understanding how galaxies evolve.
- The precipitation model provides a useful framework for understanding observations (and simulations).
- The crucial CGM entropy and pressure profiles require X-ray (and UV) observations. Testing these ideas will require new and more sensitive space telescopes.