# Galaxy assembly in the thermal era

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**With:**
**John Mulchaey**
**Dan Kelson**
**Alan Dressler**
**Ryan Quadri**
**Pat McCarthy**
**Marijn Franx (Leiden)**

# Smooth CMB to clumpy structure

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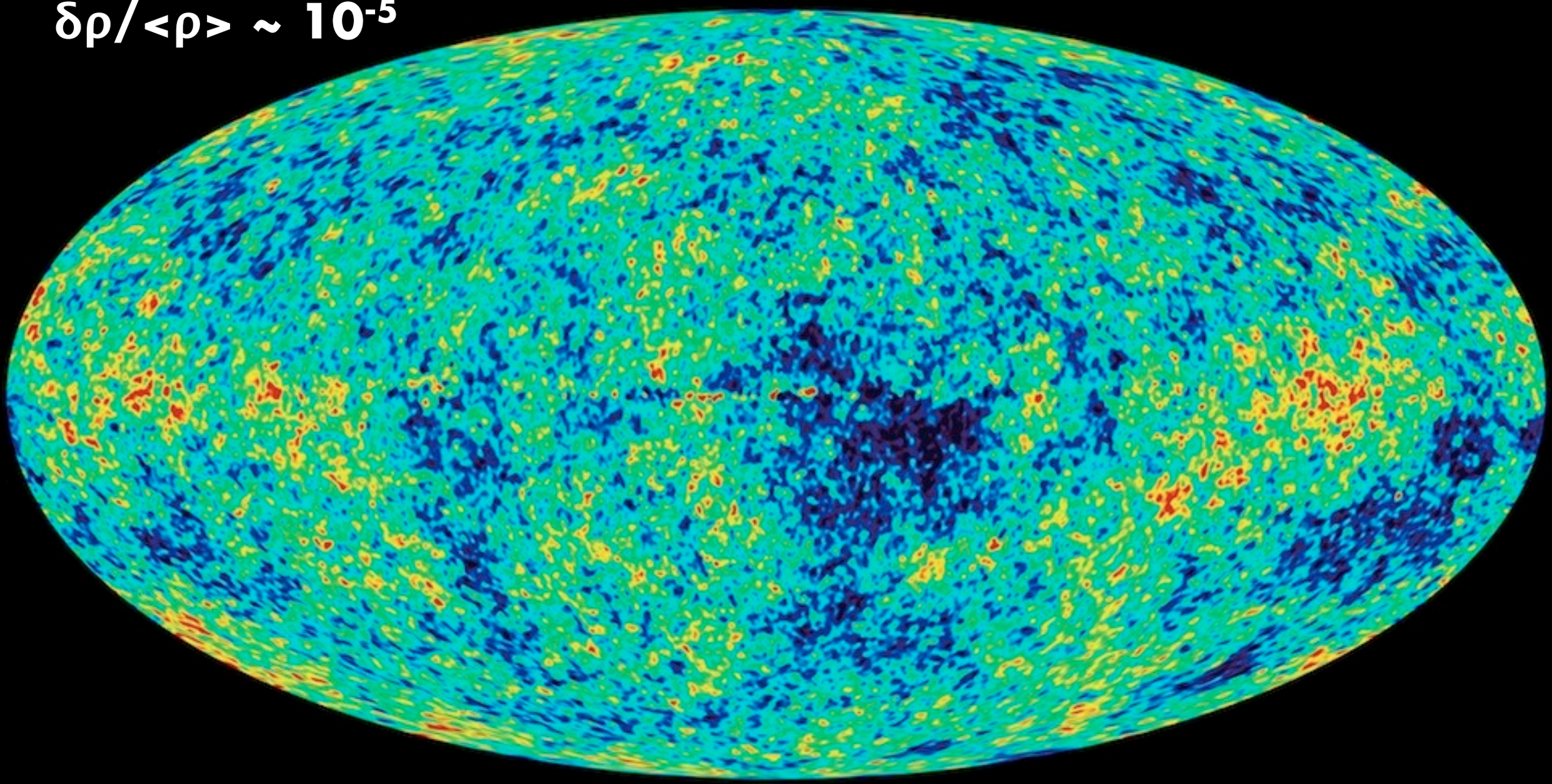
$\delta\rho/\langle\rho\rangle \sim 10^{-5}$



Wilkinson Microwave Anisotropy Probe

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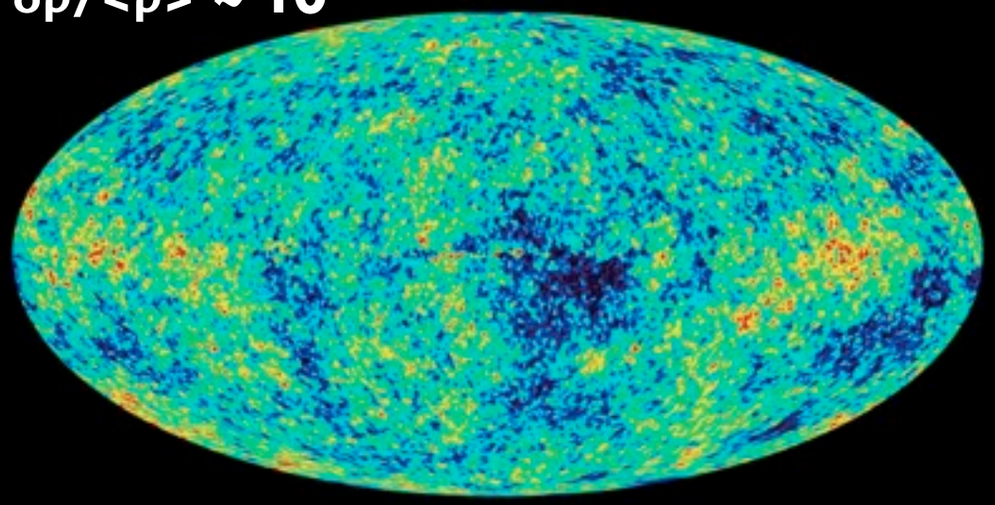
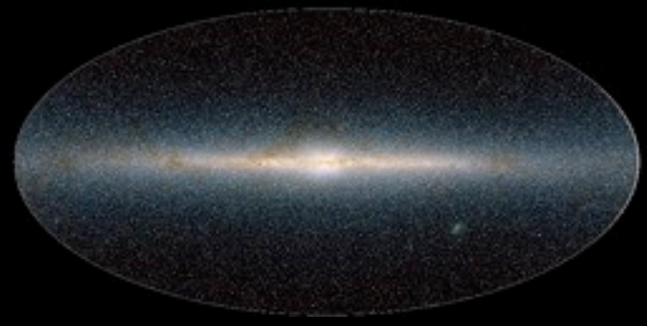


Wilkinson Microwave Anisotropy Probe

$\delta\rho/\langle\rho\rangle \sim 10^{6}$



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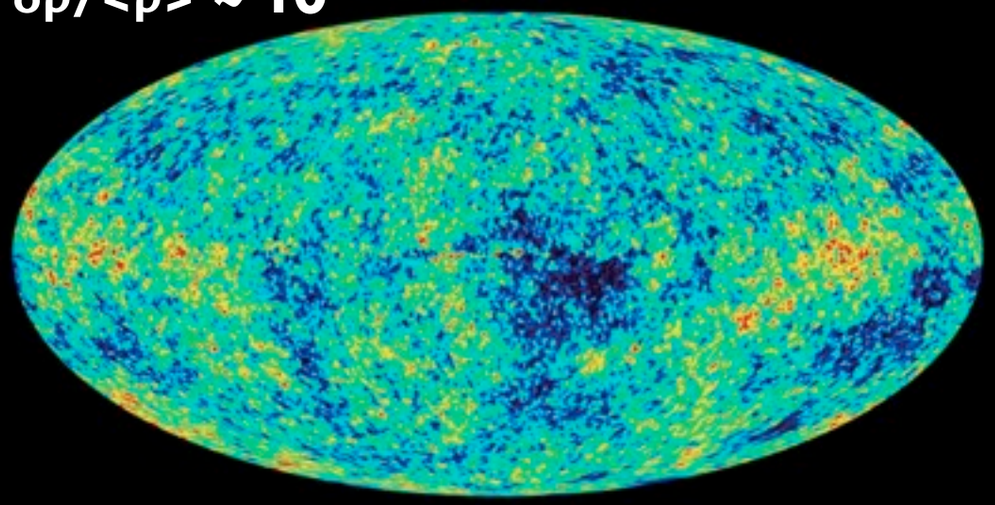

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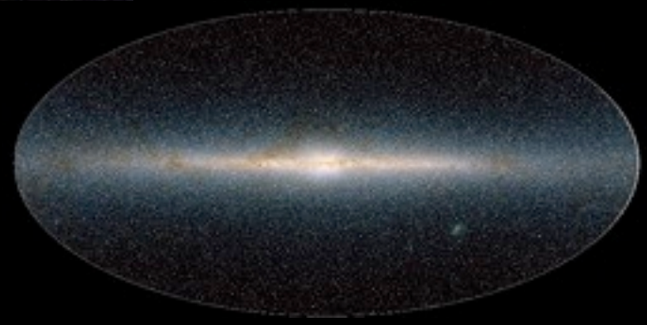

# The Cosmic Pie

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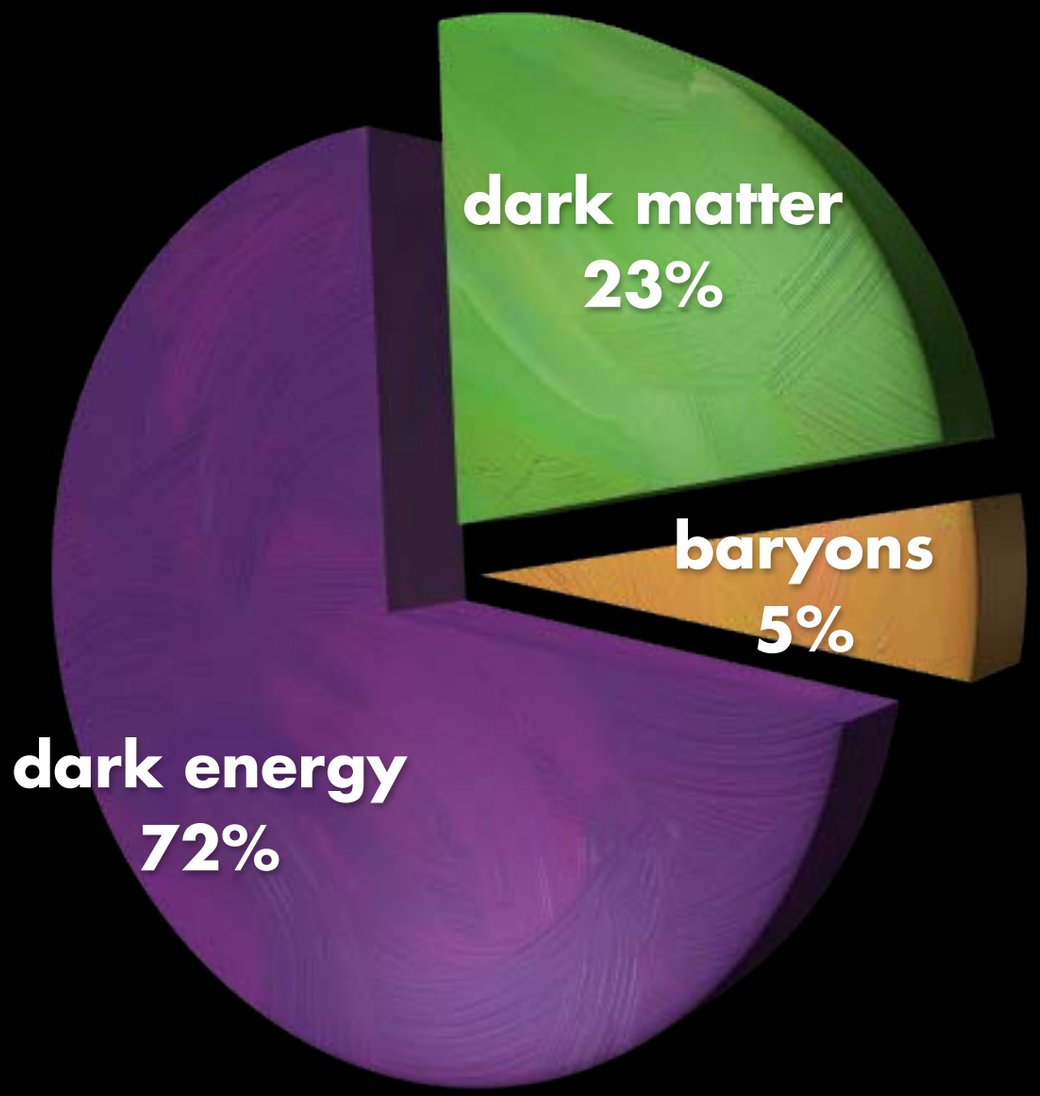

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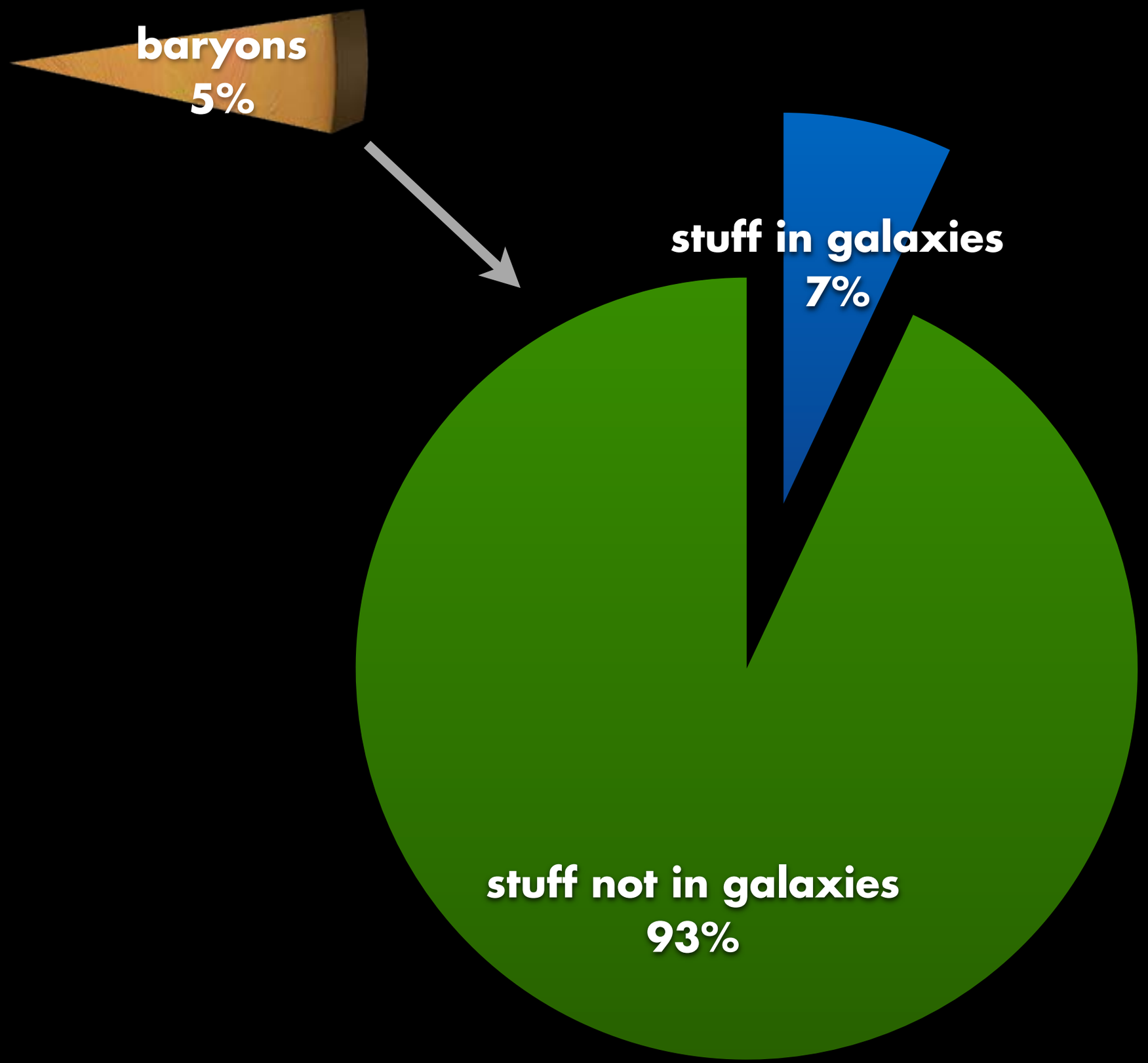


# The Cosmic Pie

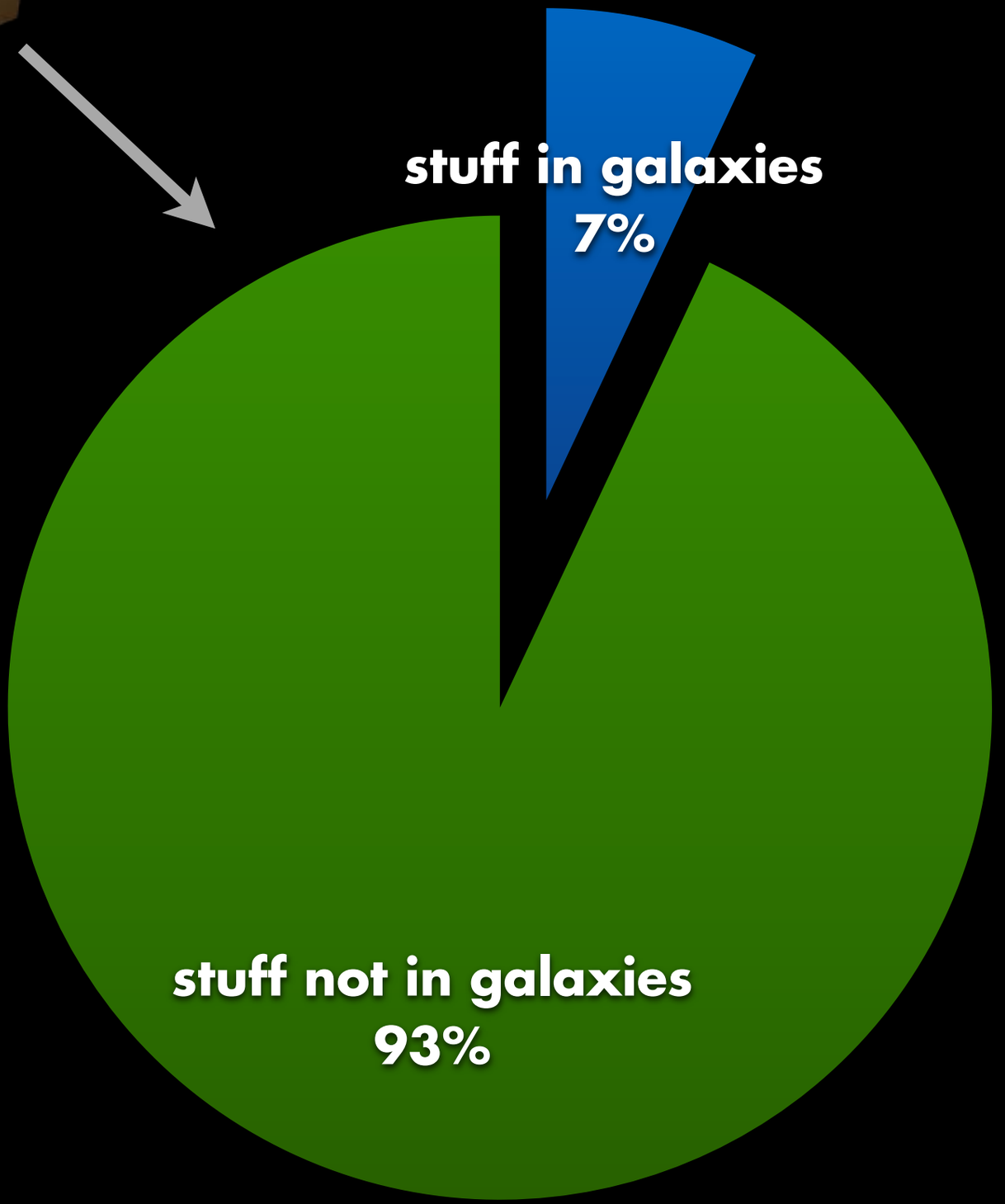
baryons
5%


stuff in galaxies
7%

stuff not in galaxies
93%

# The Cosmic Pie





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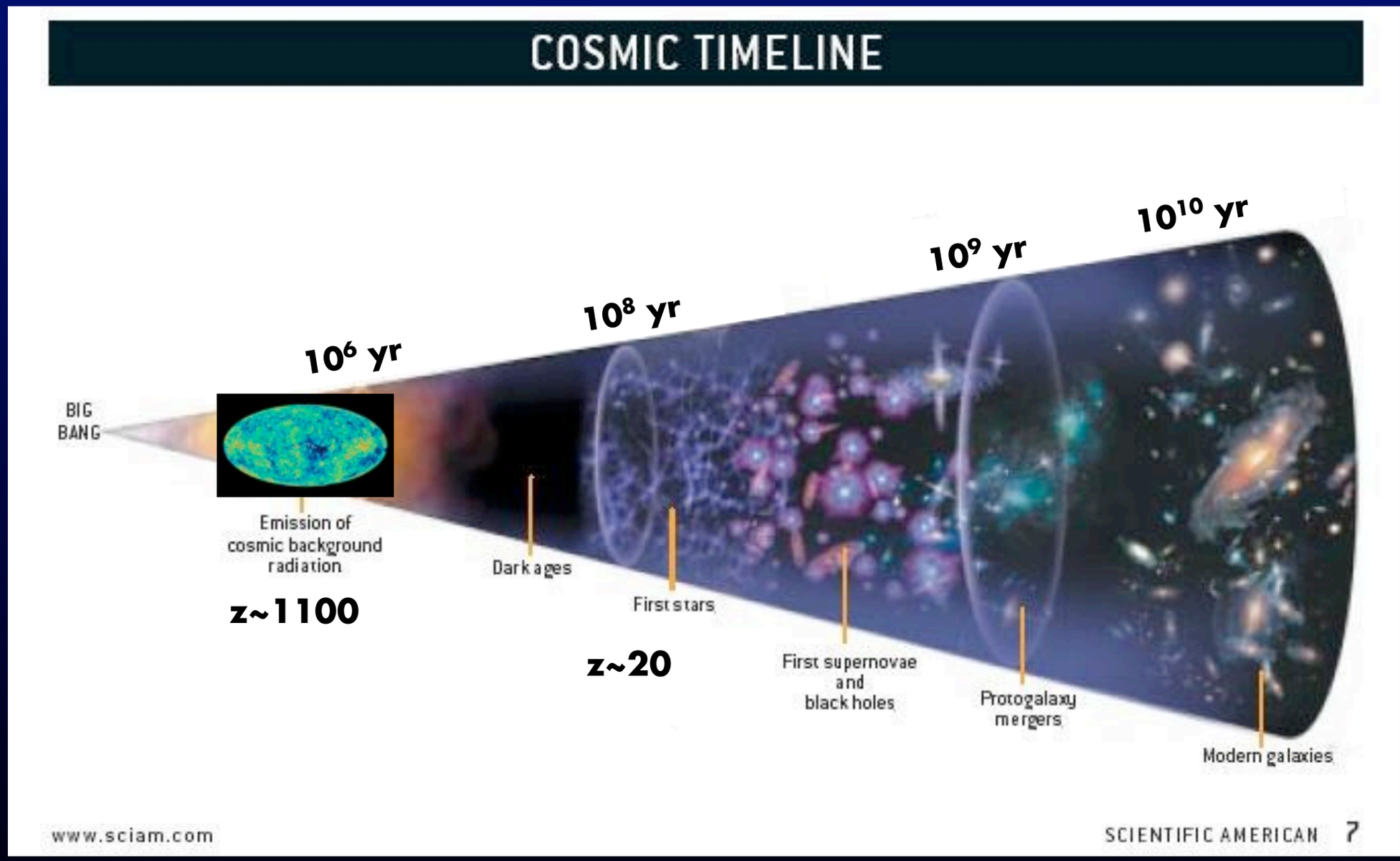

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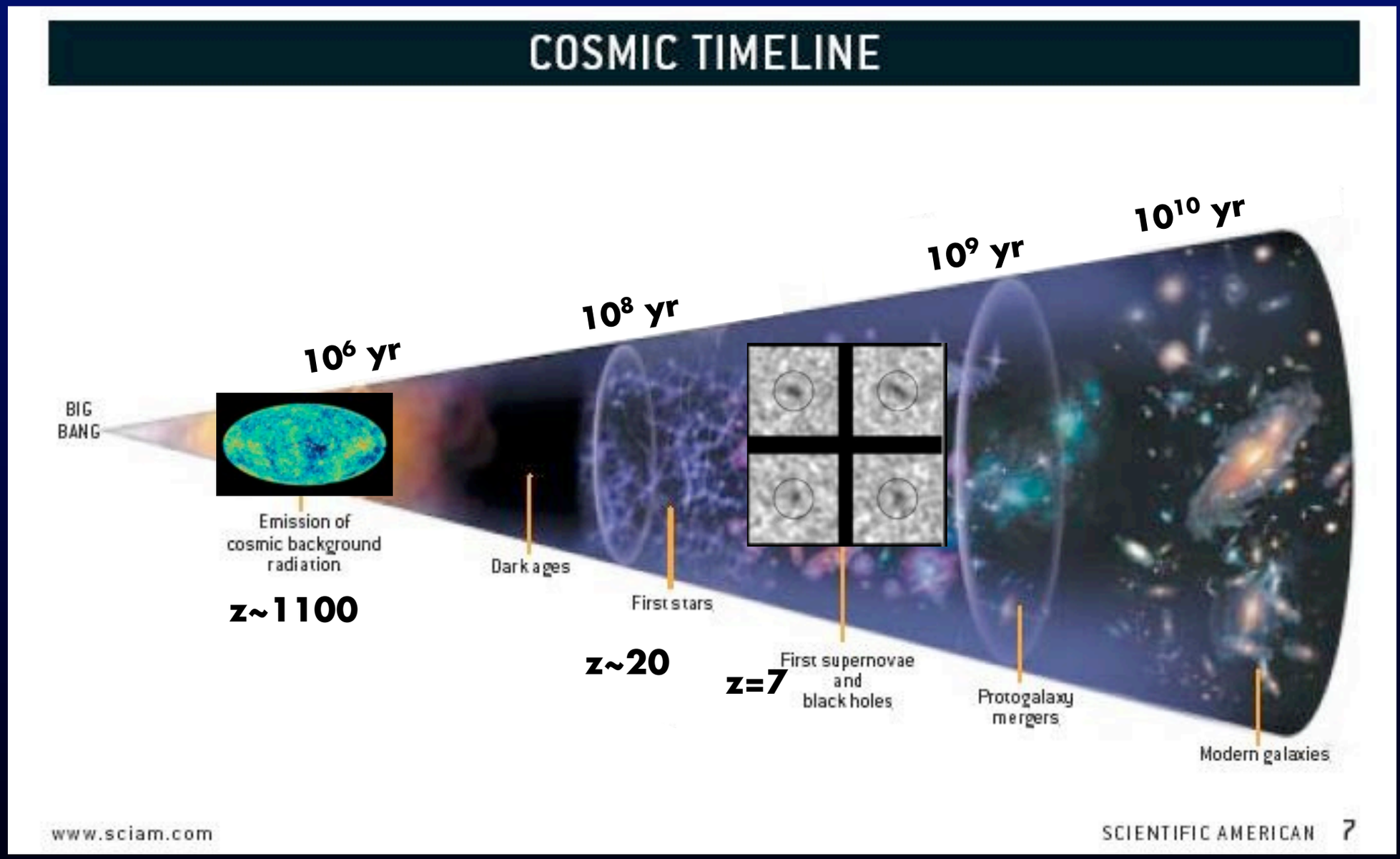

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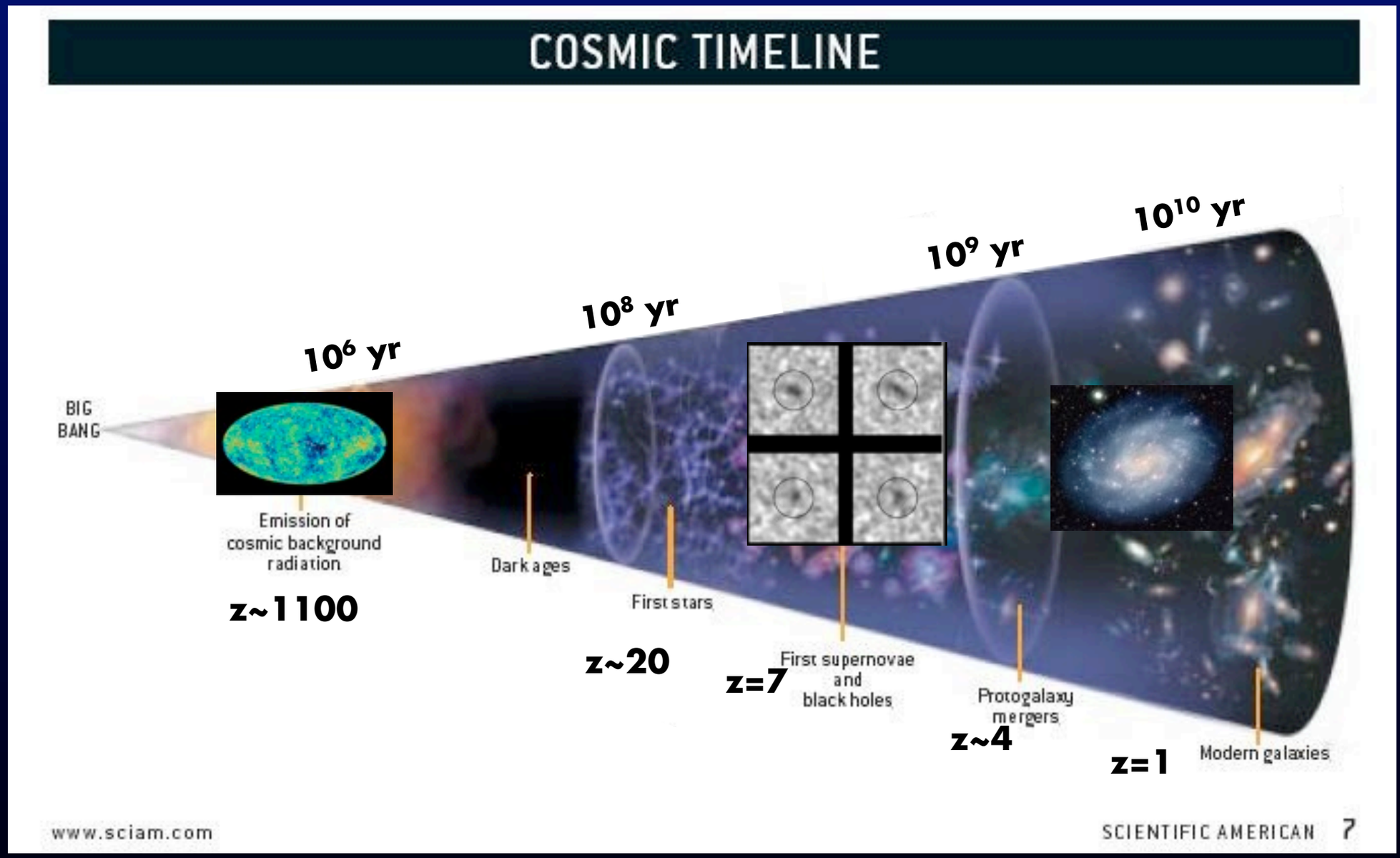

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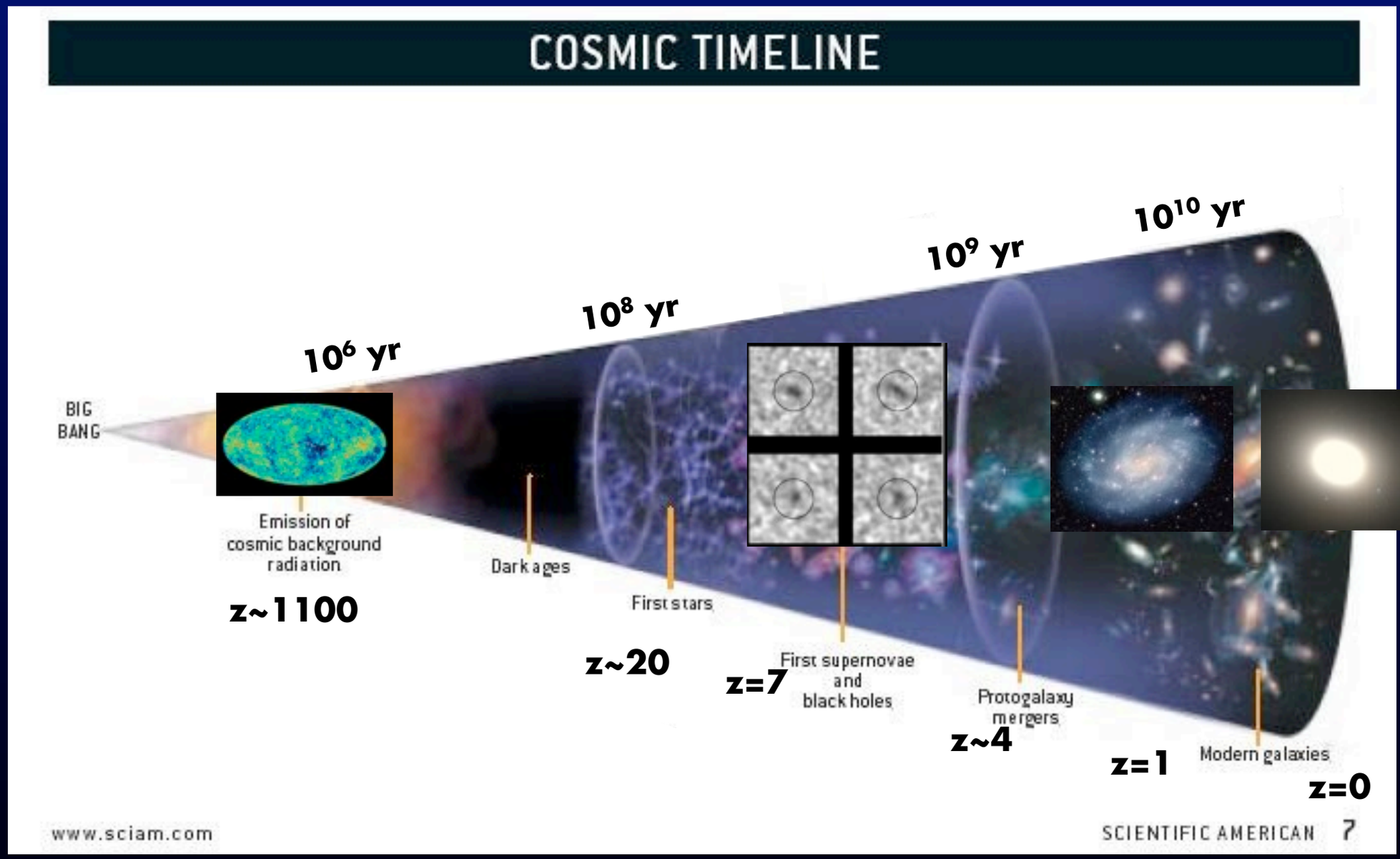

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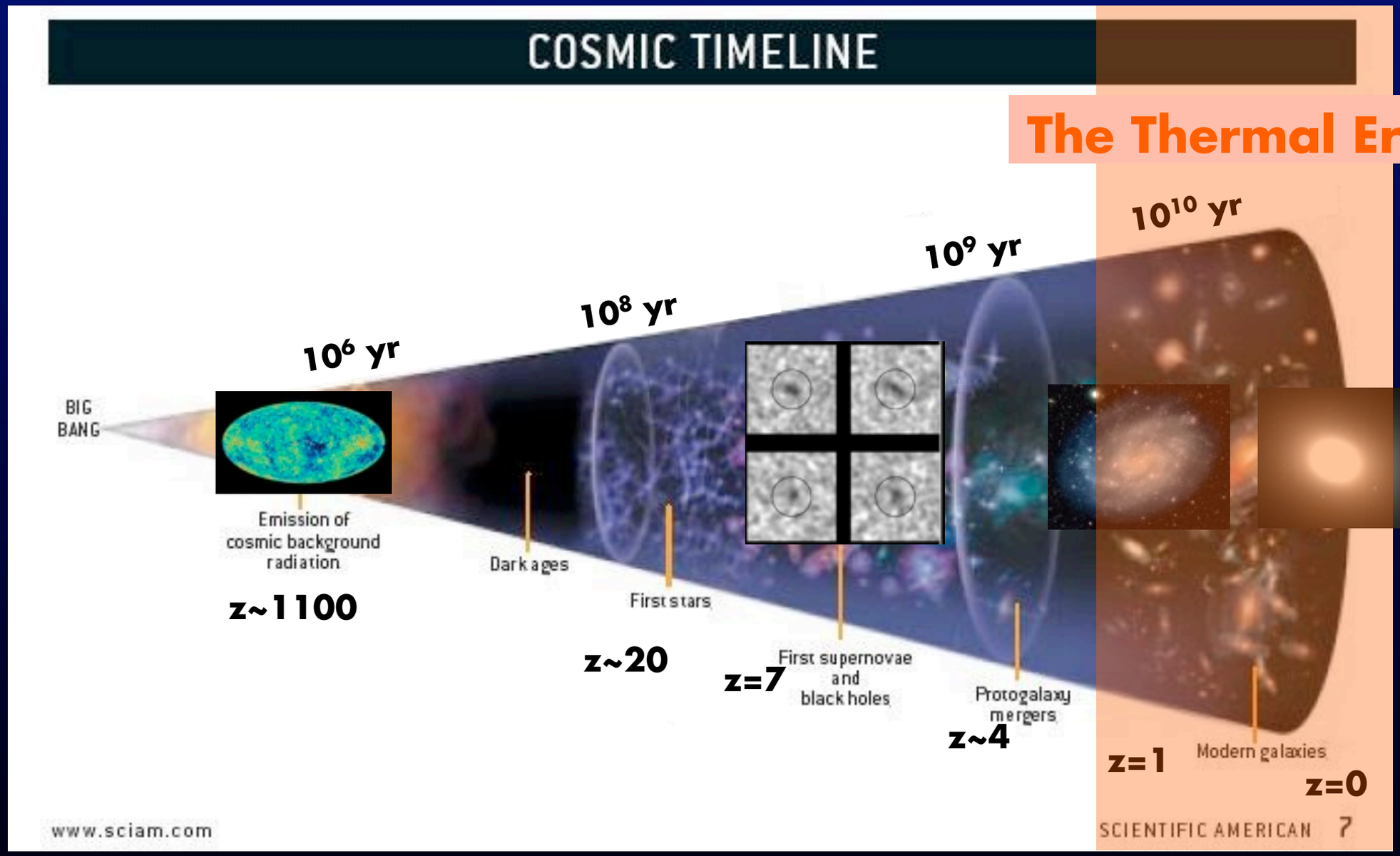
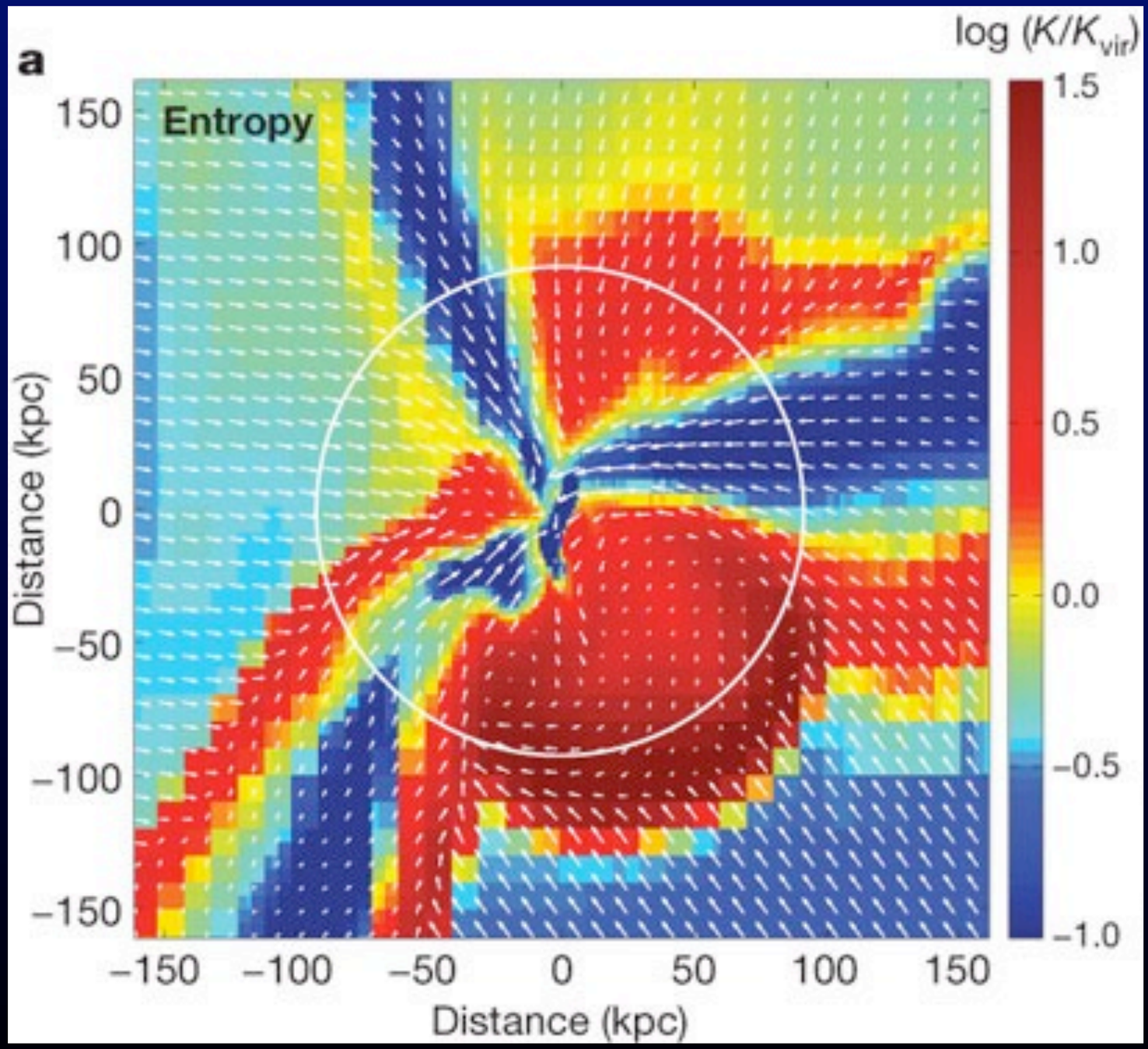


# Galaxy formation, cold era

**(~1-3 Gyr after Big Bang; z>2.5)**




Dekel et al. 2009

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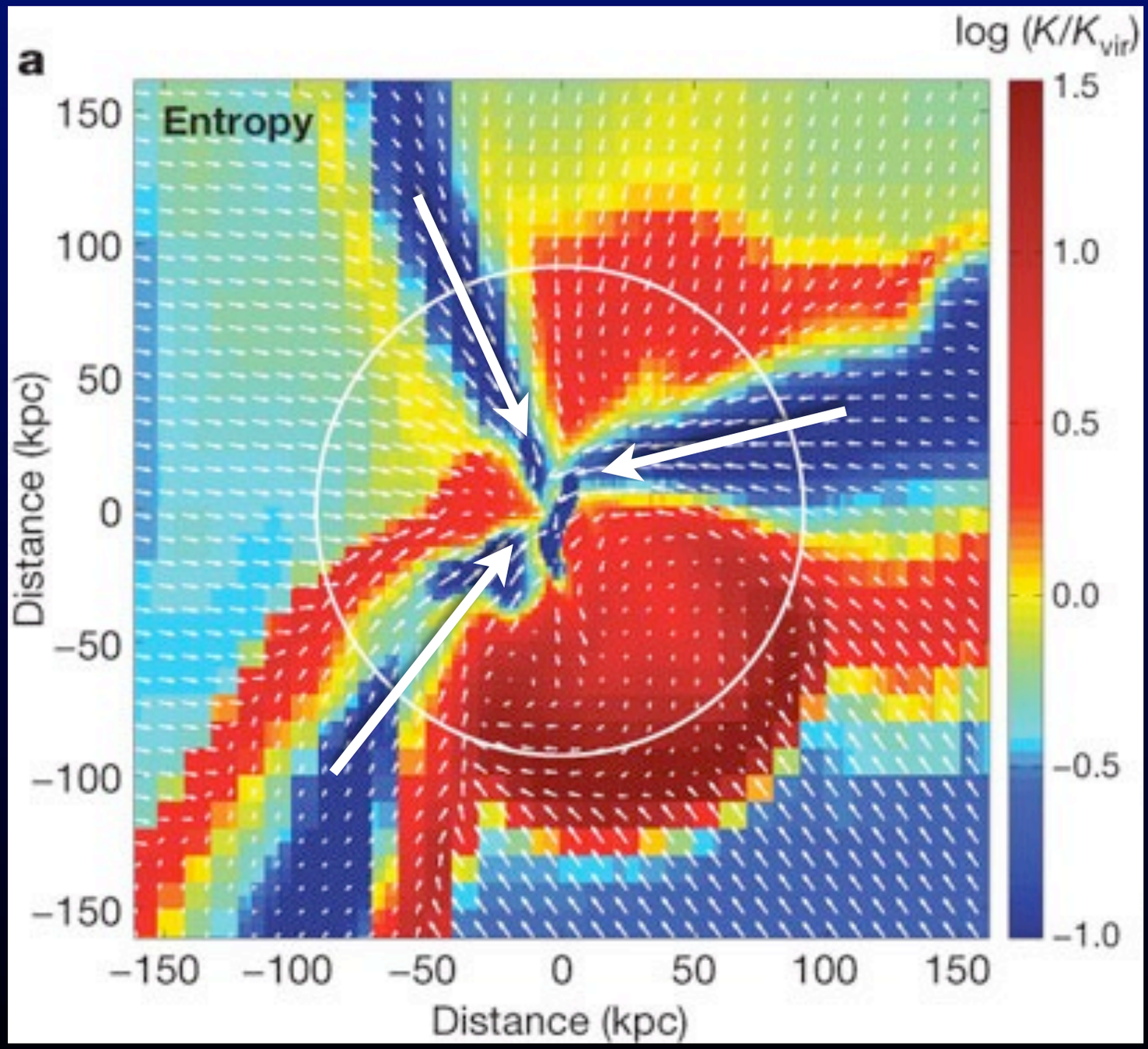
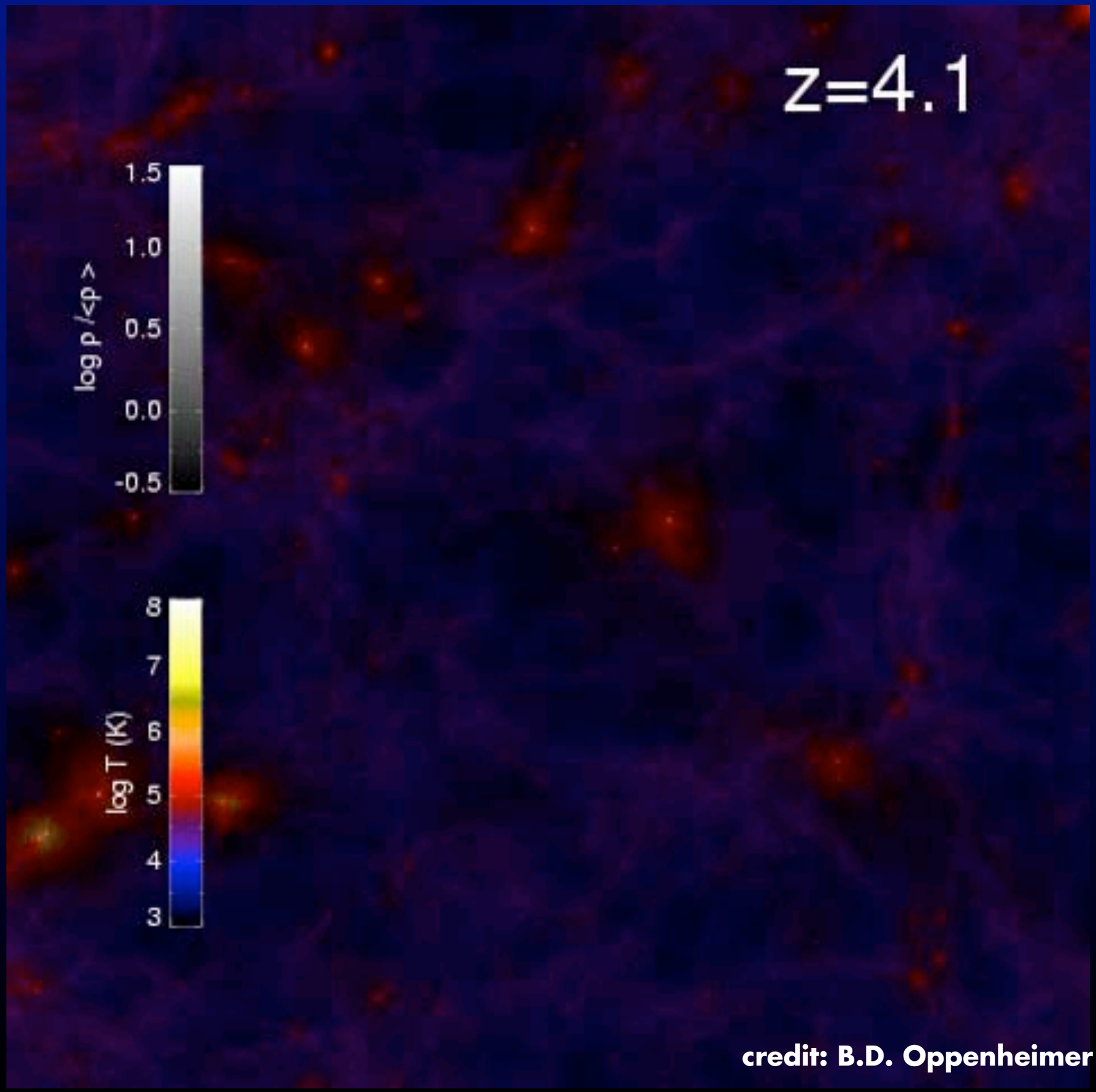



**Dekel et al. 2009**

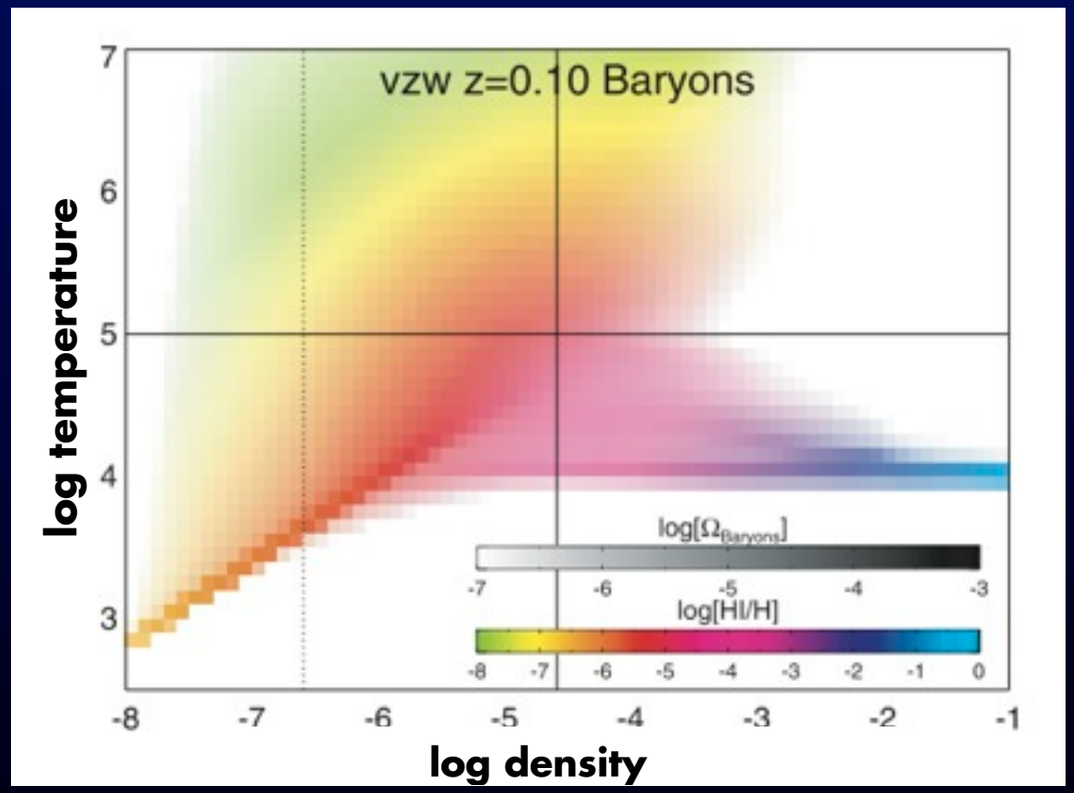
# Galaxy formation, t > 3 Gyr

credit: B.D. Oppenheimer


z=4.1
log ρ /<ρ>
1.5
1.0
0.5
0.0
-0.5
log T (K)
8
7
6
5
4
3
credit: B.D. Oppenheimer

# Galaxy assembly in the thermal era

## Gas




Davé et al. 2010

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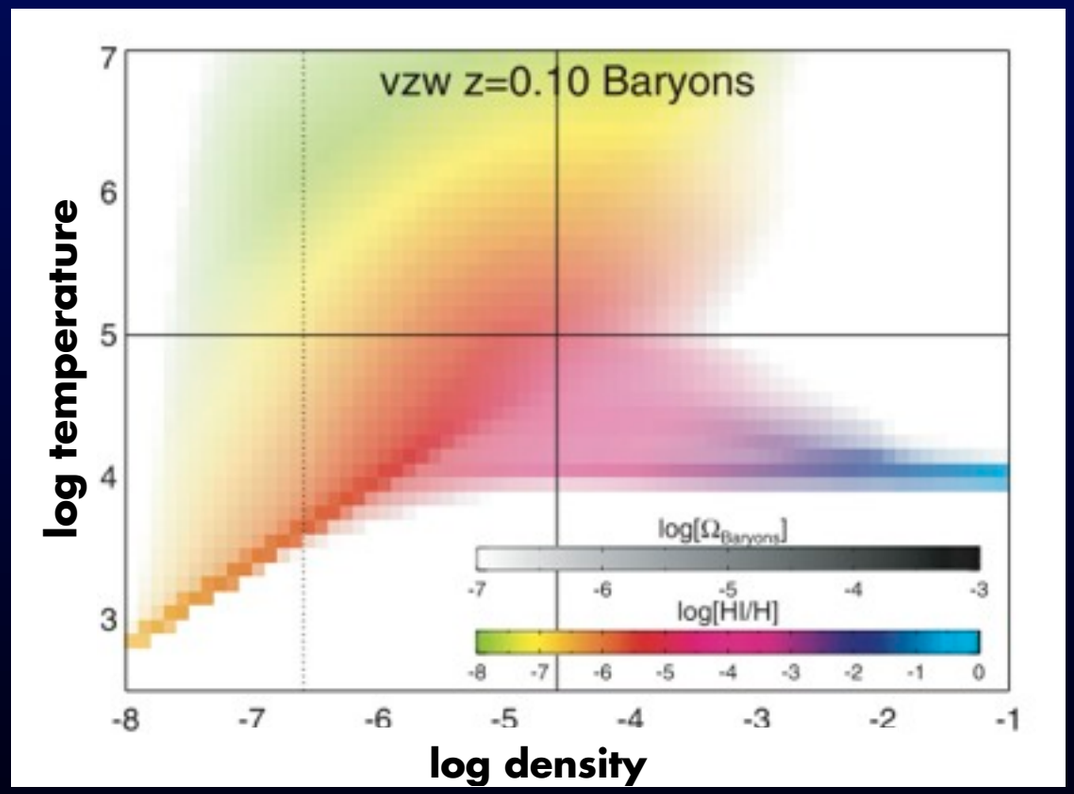
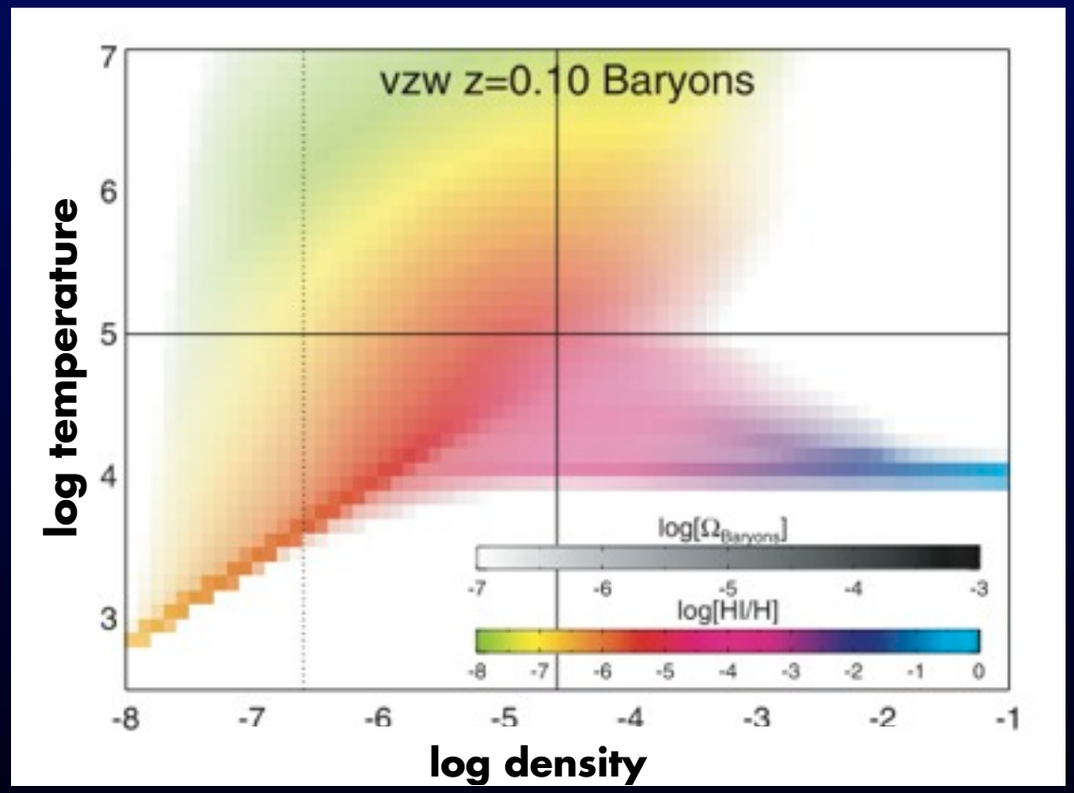



Davé et al. 2010

## Stars

# Galaxy assembly in the thermal era

## Gas



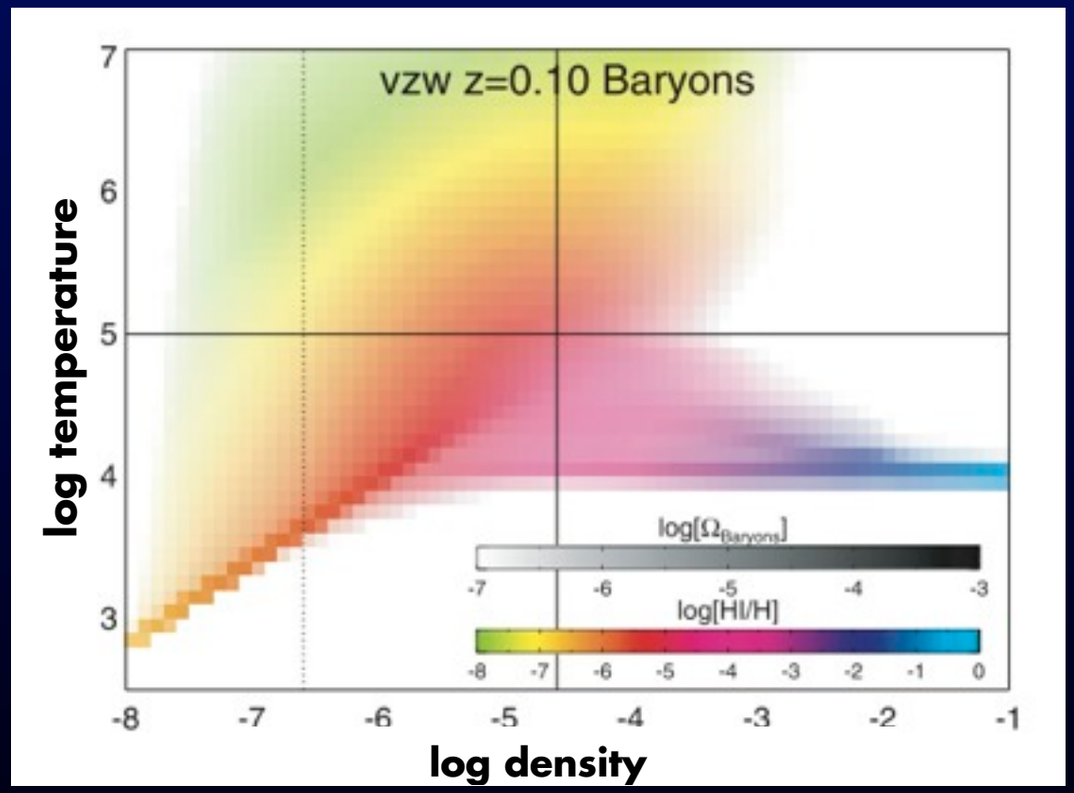

Davé et al. 2010

## Stars

# Galaxy assembly in the thermal era

## Dynamically hot structures surrounded by thermally hot gas.

**Gas**




**Stars**

Davé et al. 2010

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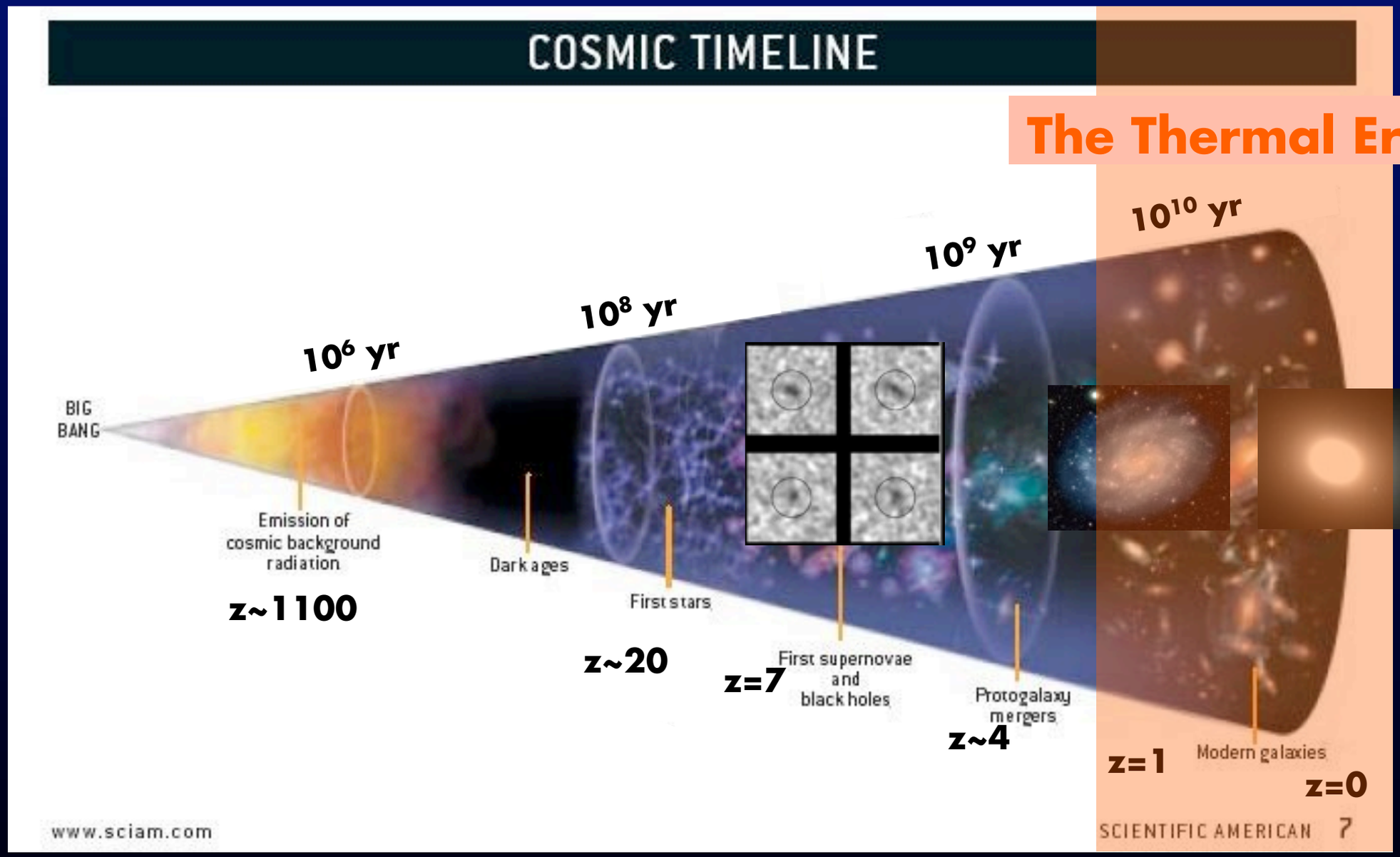
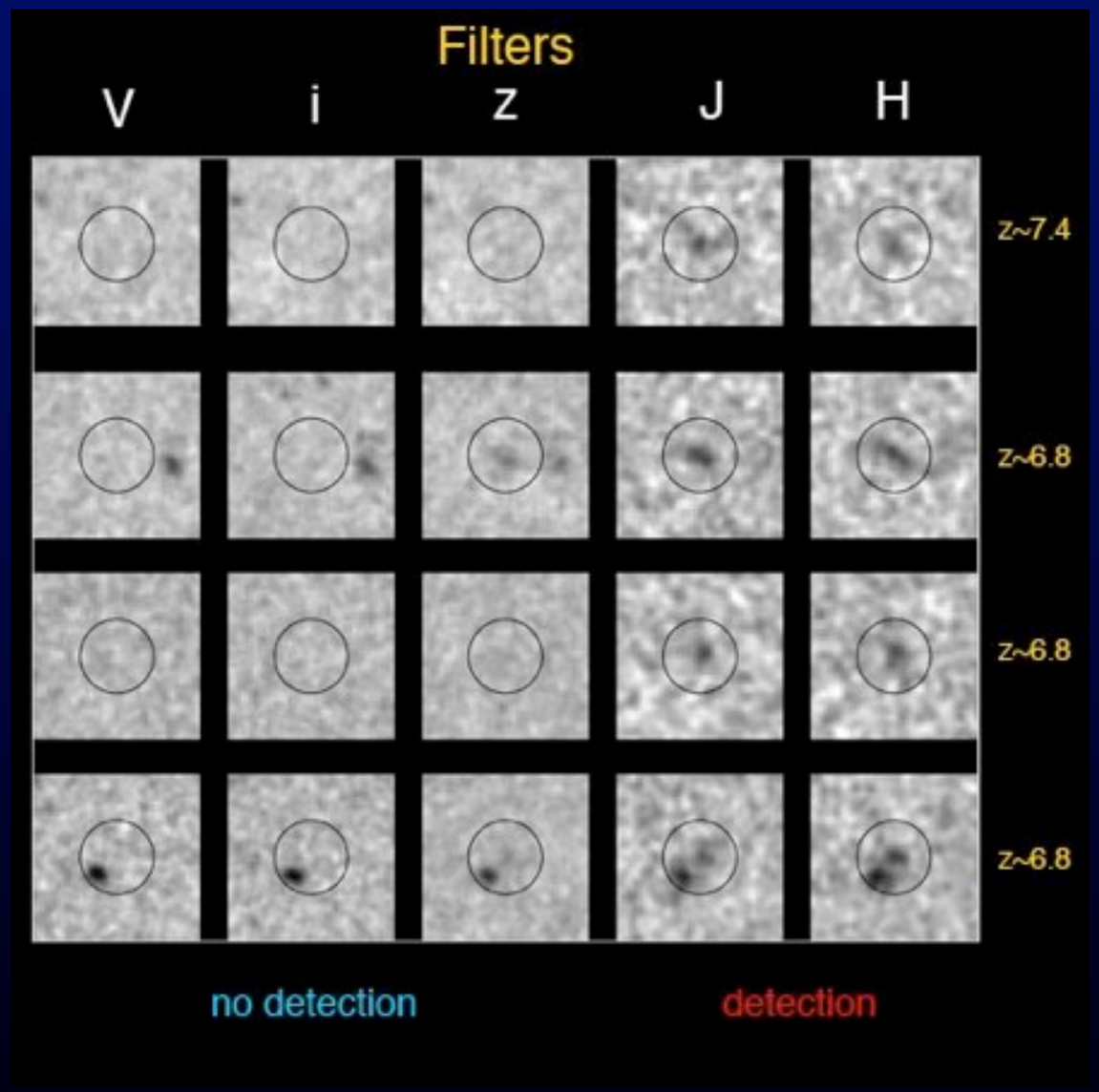
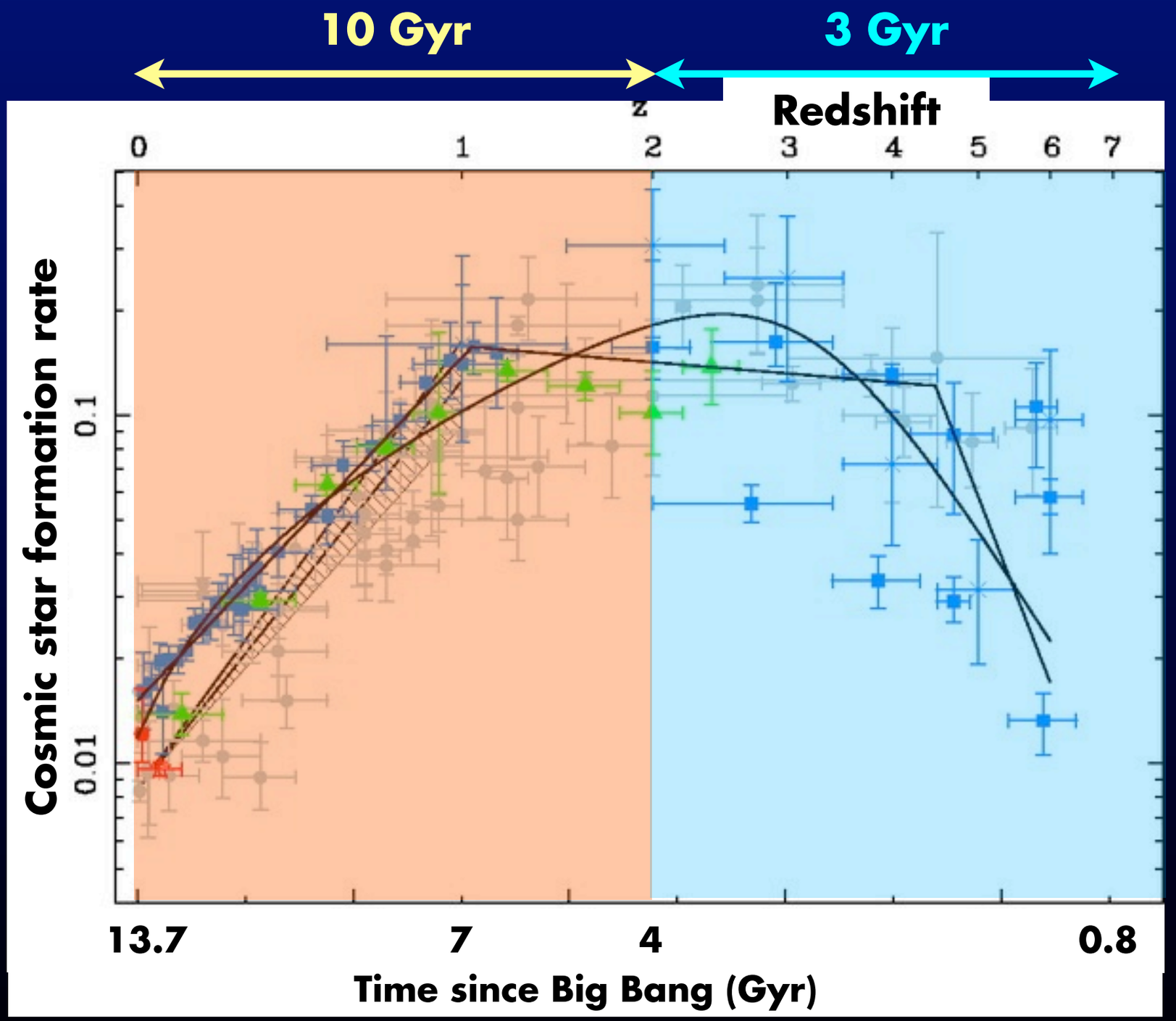


# Cold vs. Hot Universe




**z~7 galaxy candidates (R. Bouwens)**

# Cold vs. Hot Universe




Hopkins & Beacom 2006

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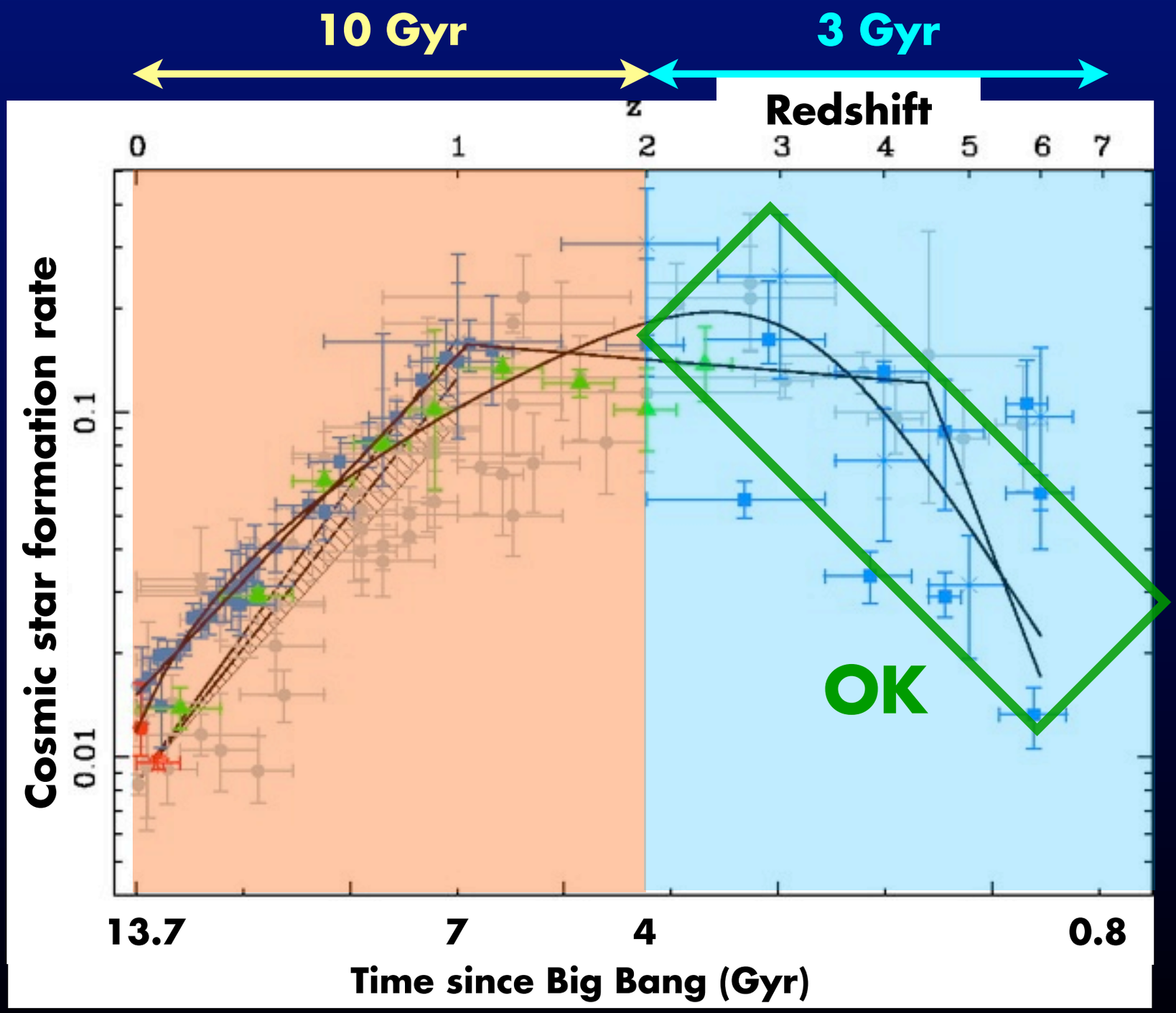


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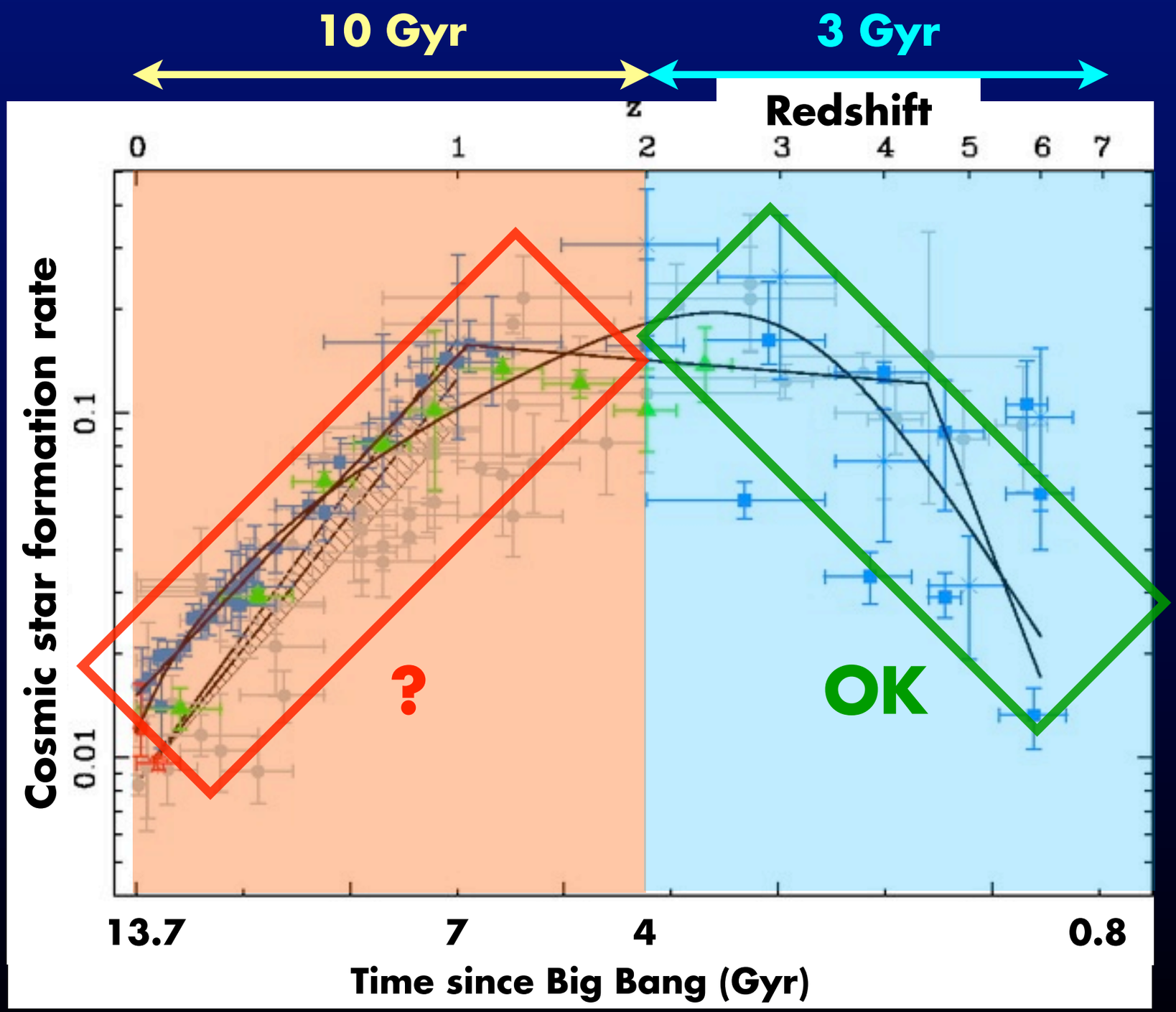


Hopkins & Beacom 2006

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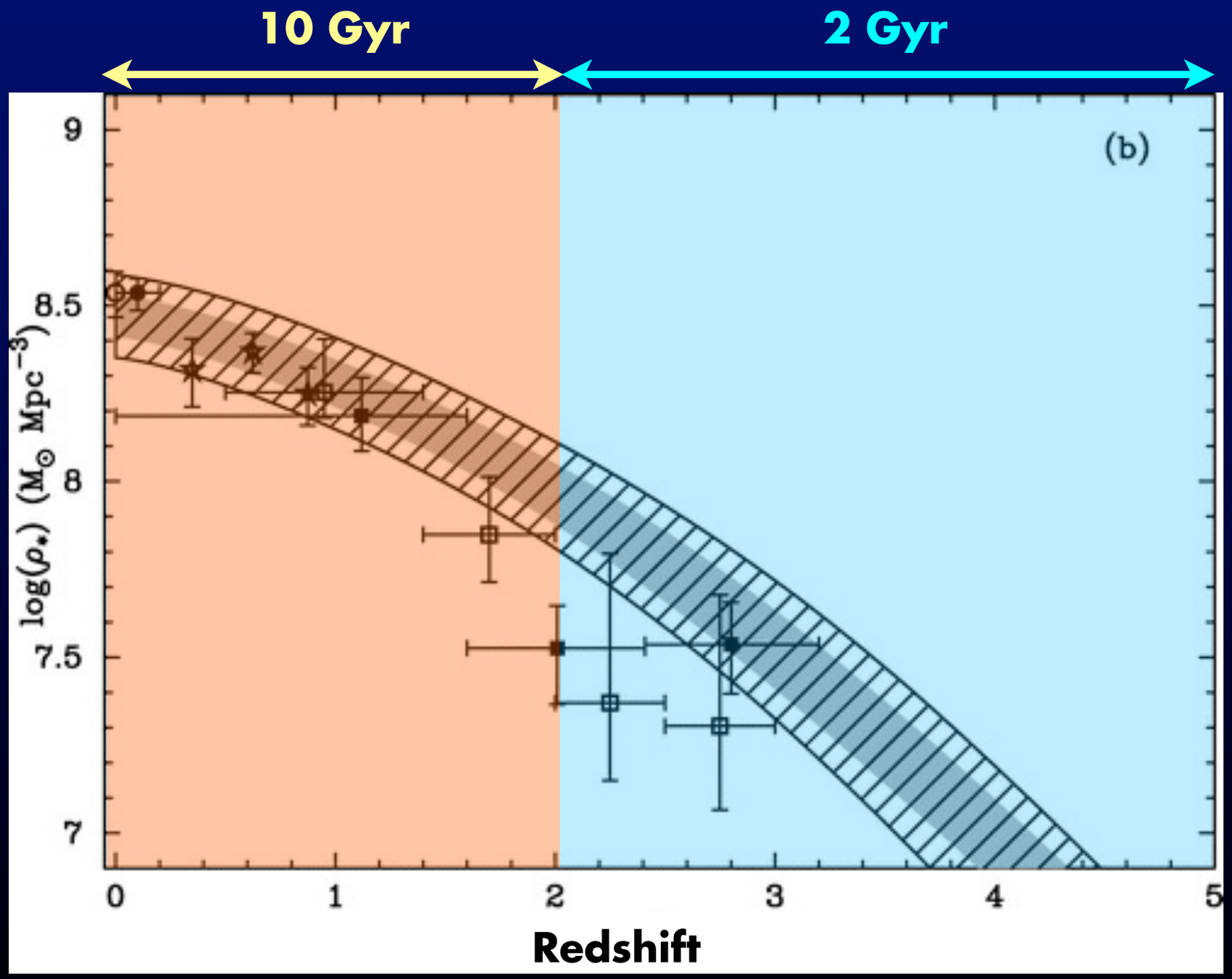


Hopkins & Beacom 2006

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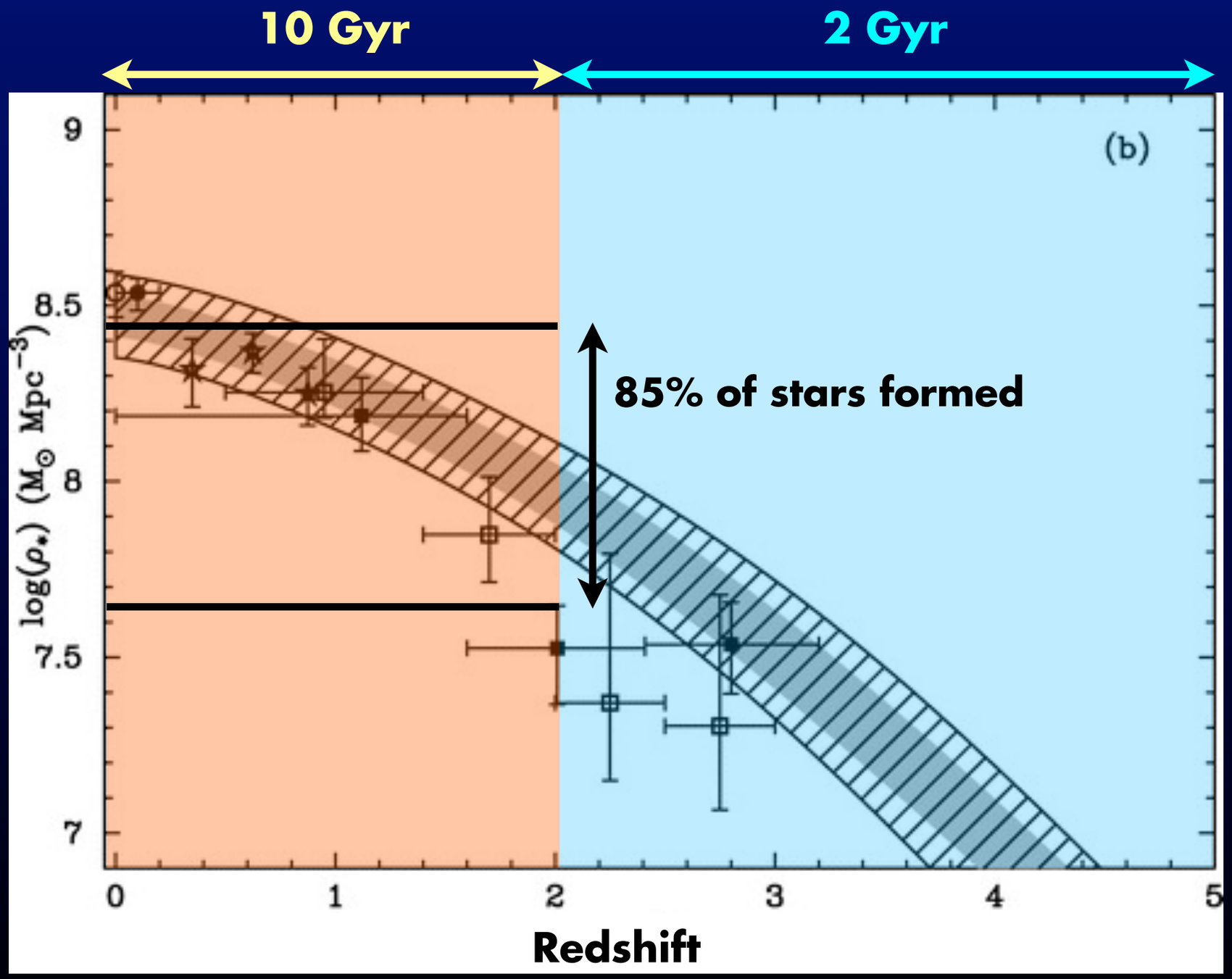
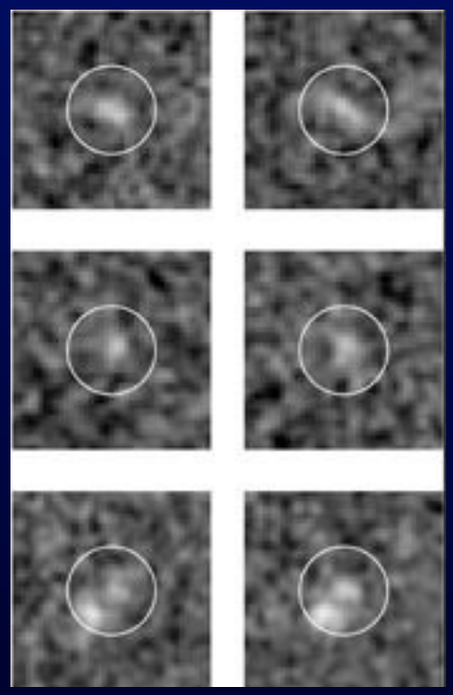
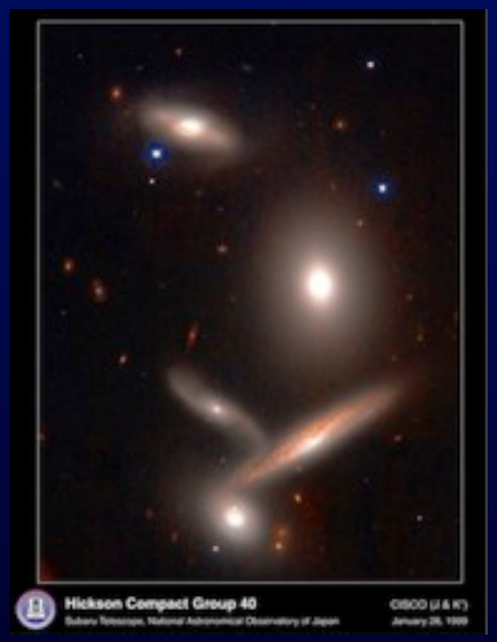



Hopkins & Beacom 2006

# Surveys and Galactic Anthropology

z3, t3 | z2, t2 | z1, t1 | now





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z3, t3 — z2, t2 — z1, t1 — now

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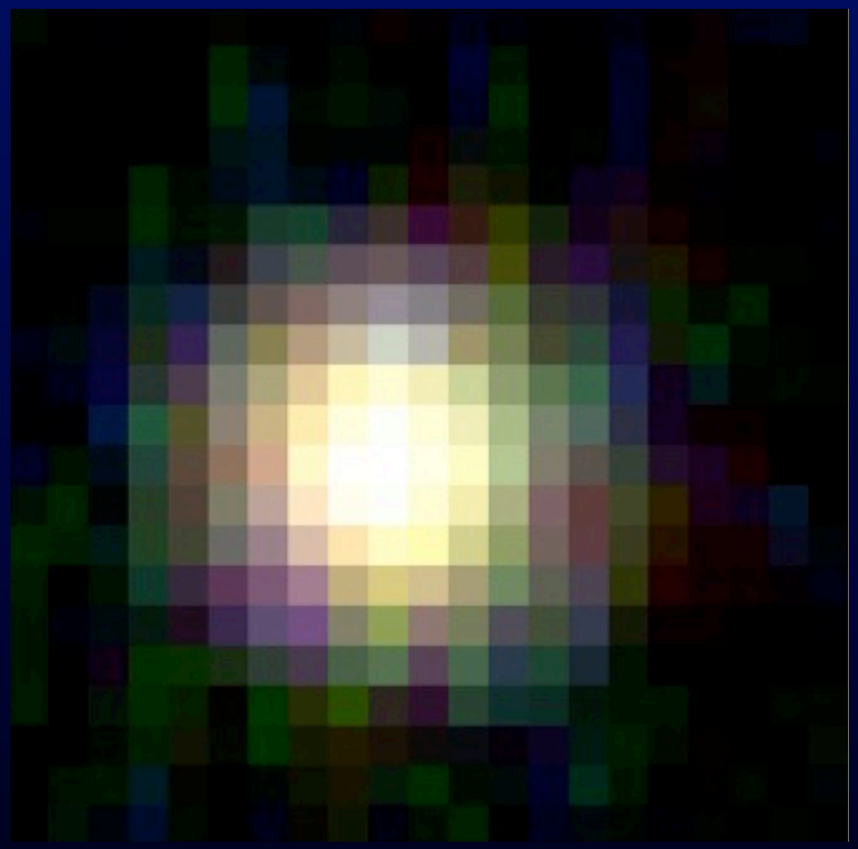

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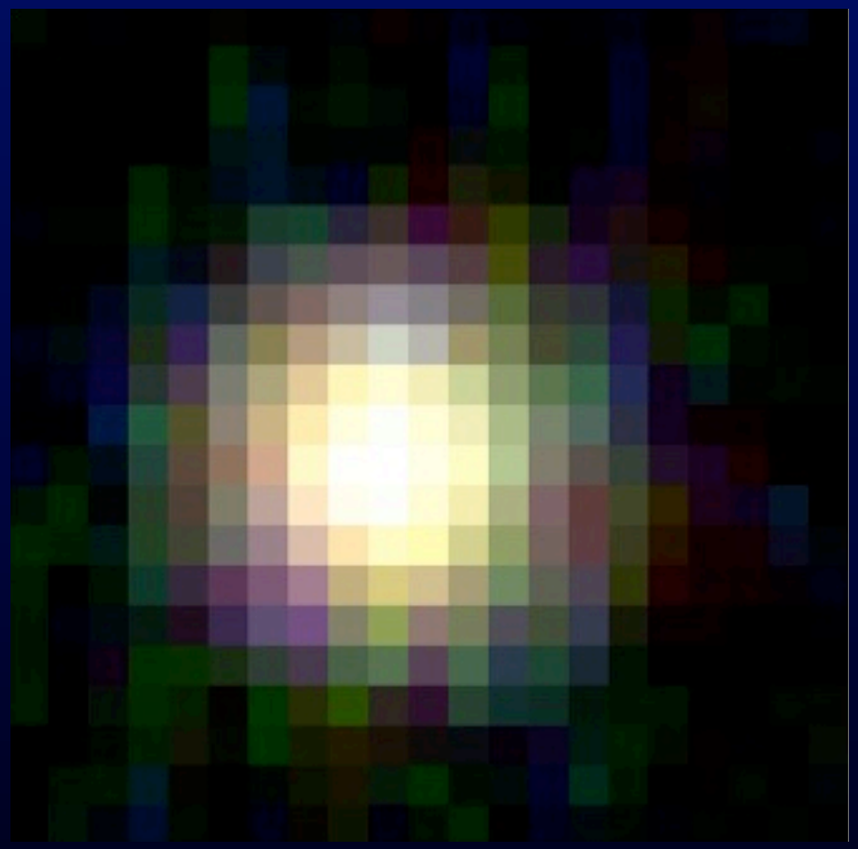

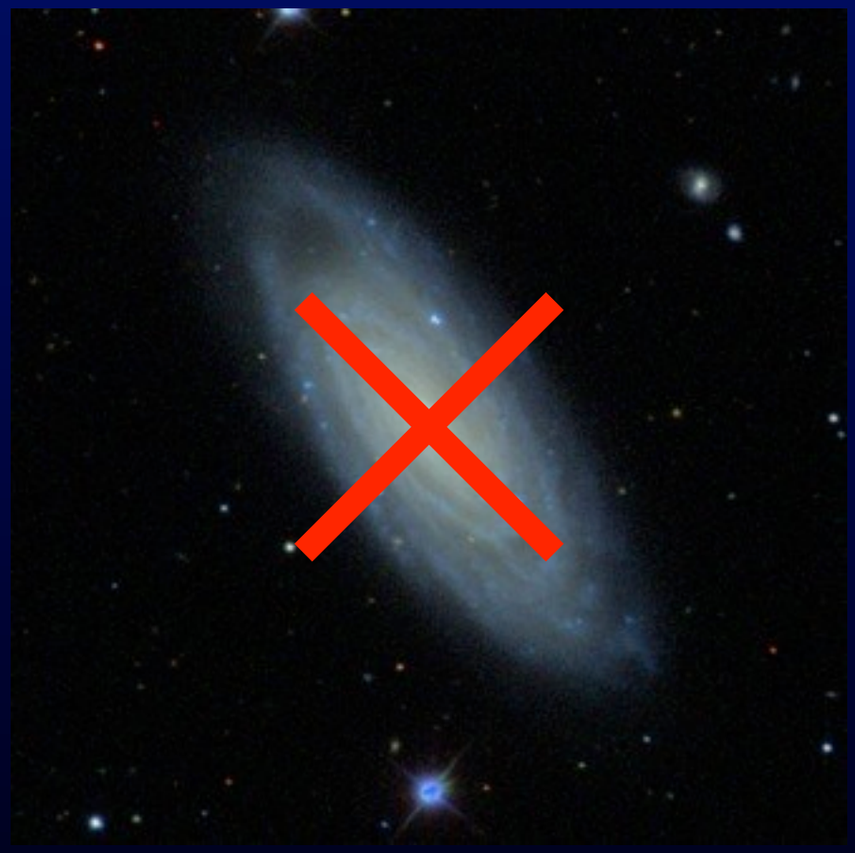

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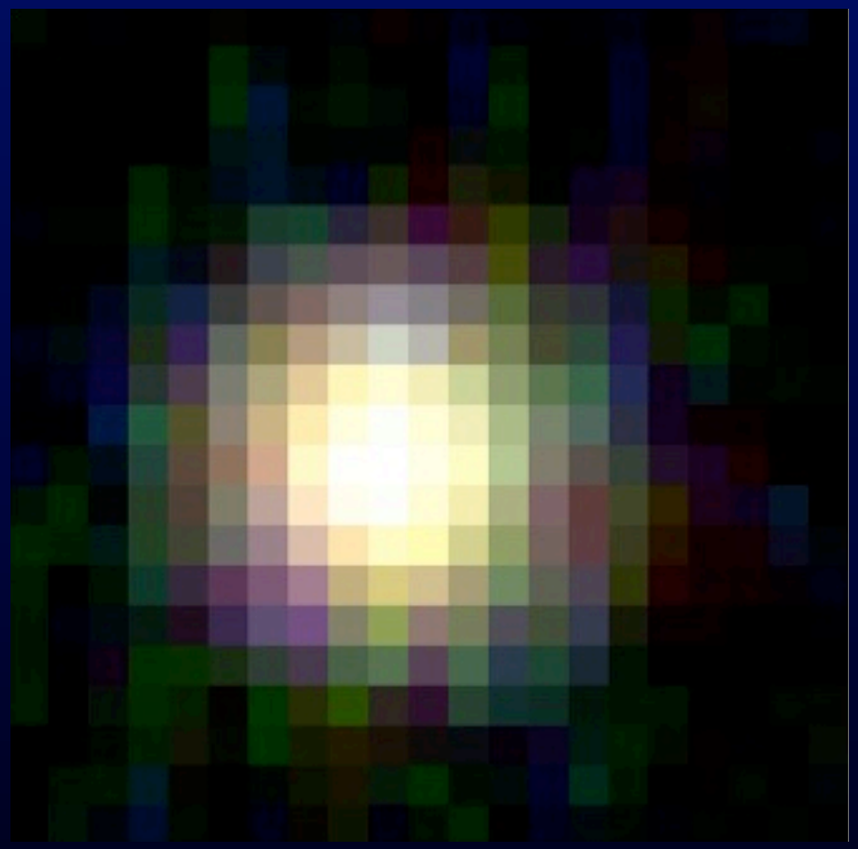

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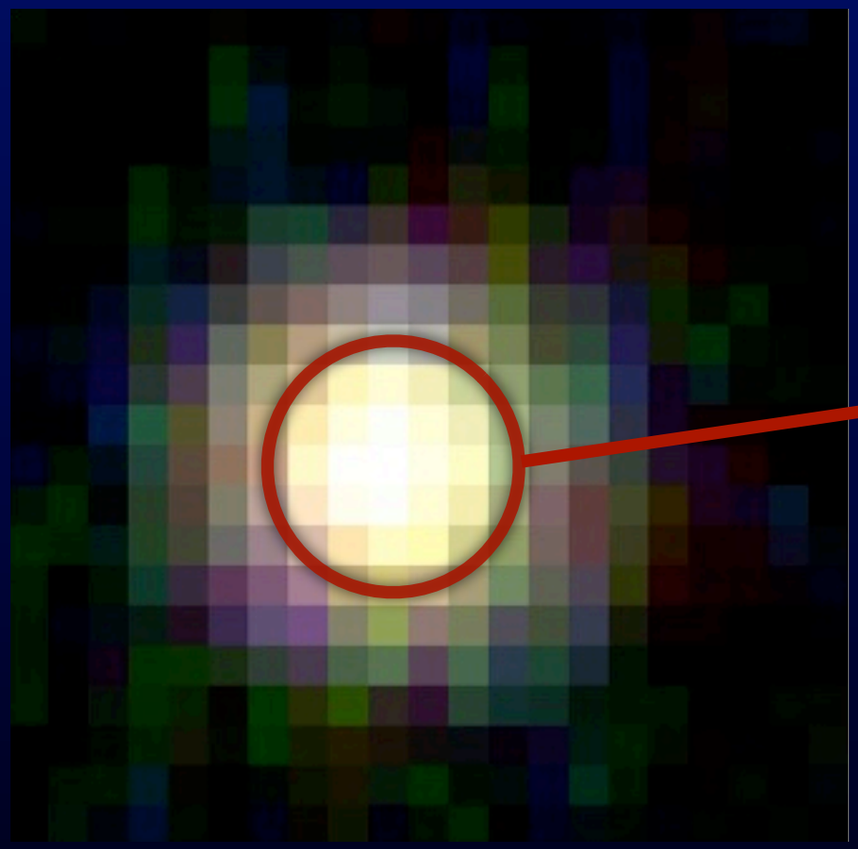
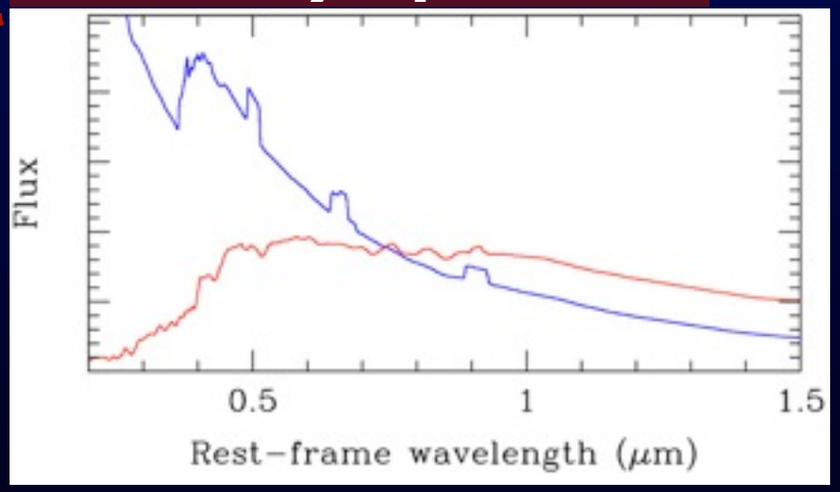


luminosity, spectrum



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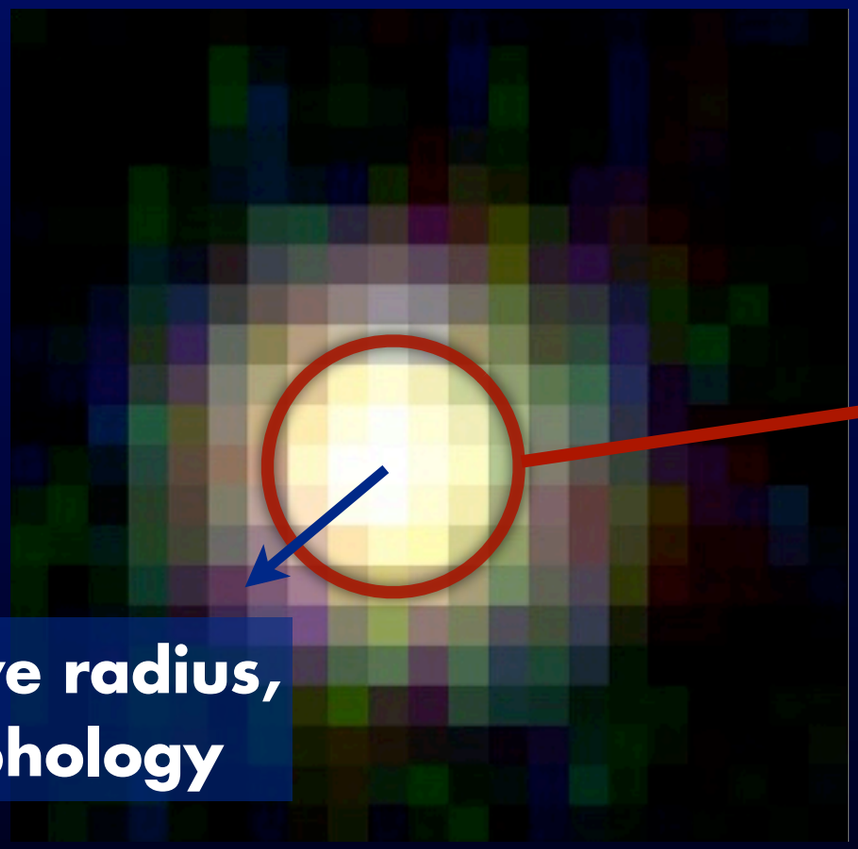
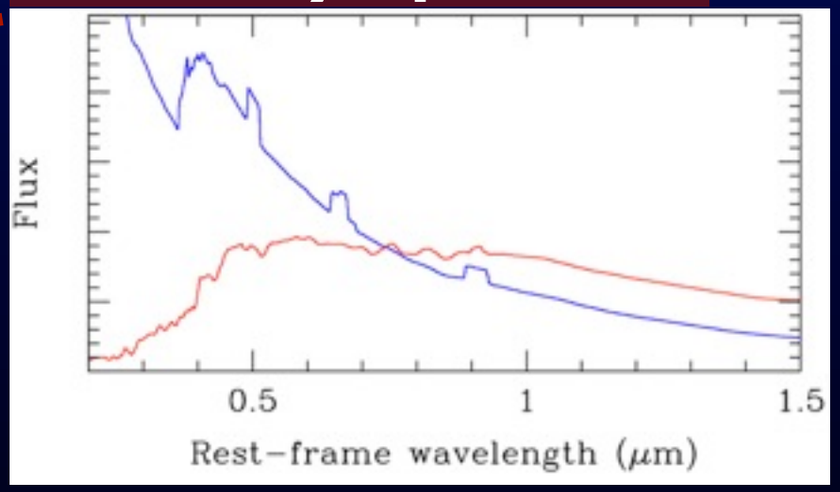
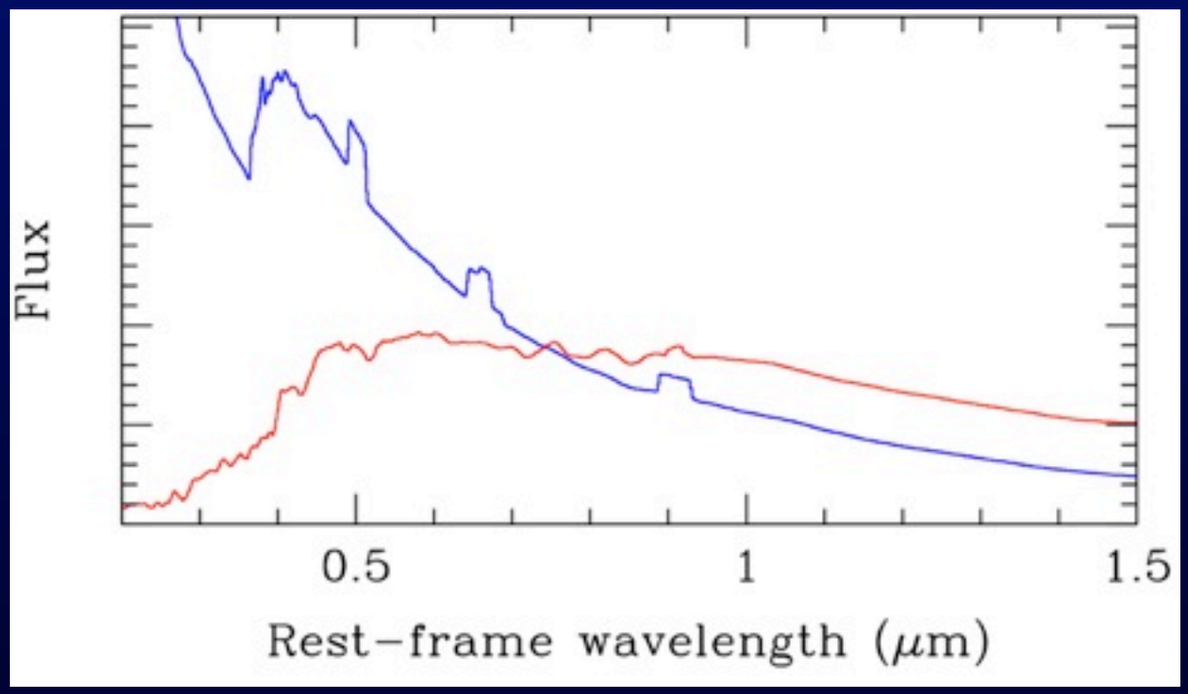


effective radius, morphology

luminosity, spectrum



# Gathering photons



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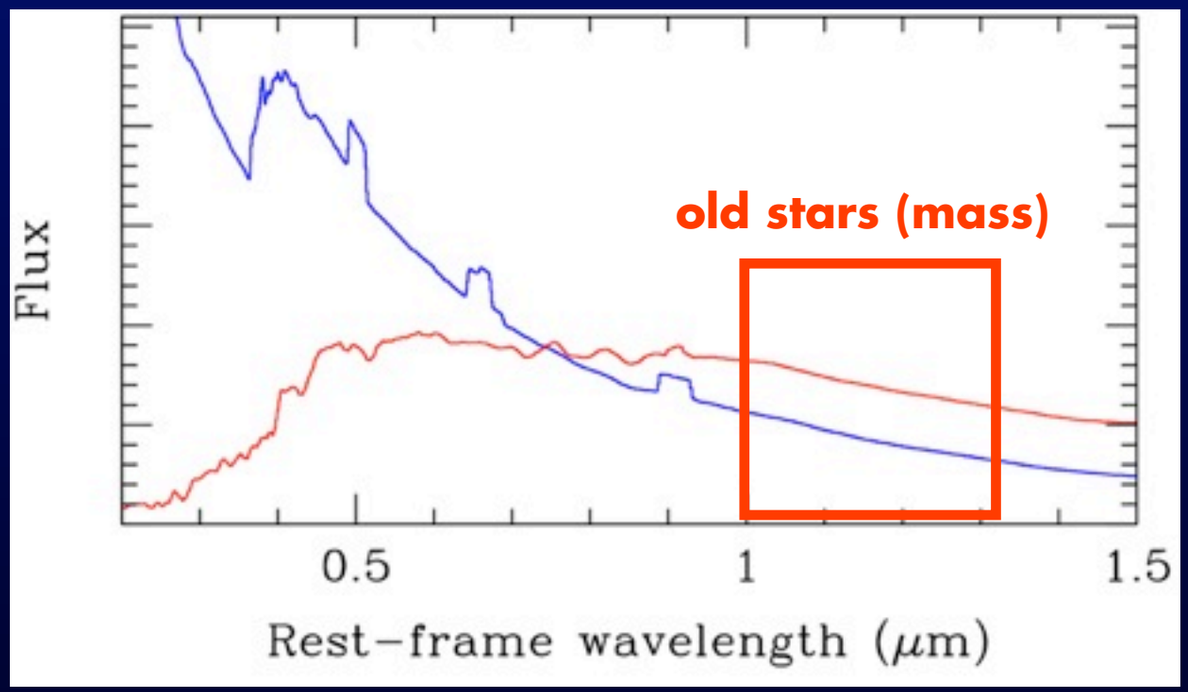
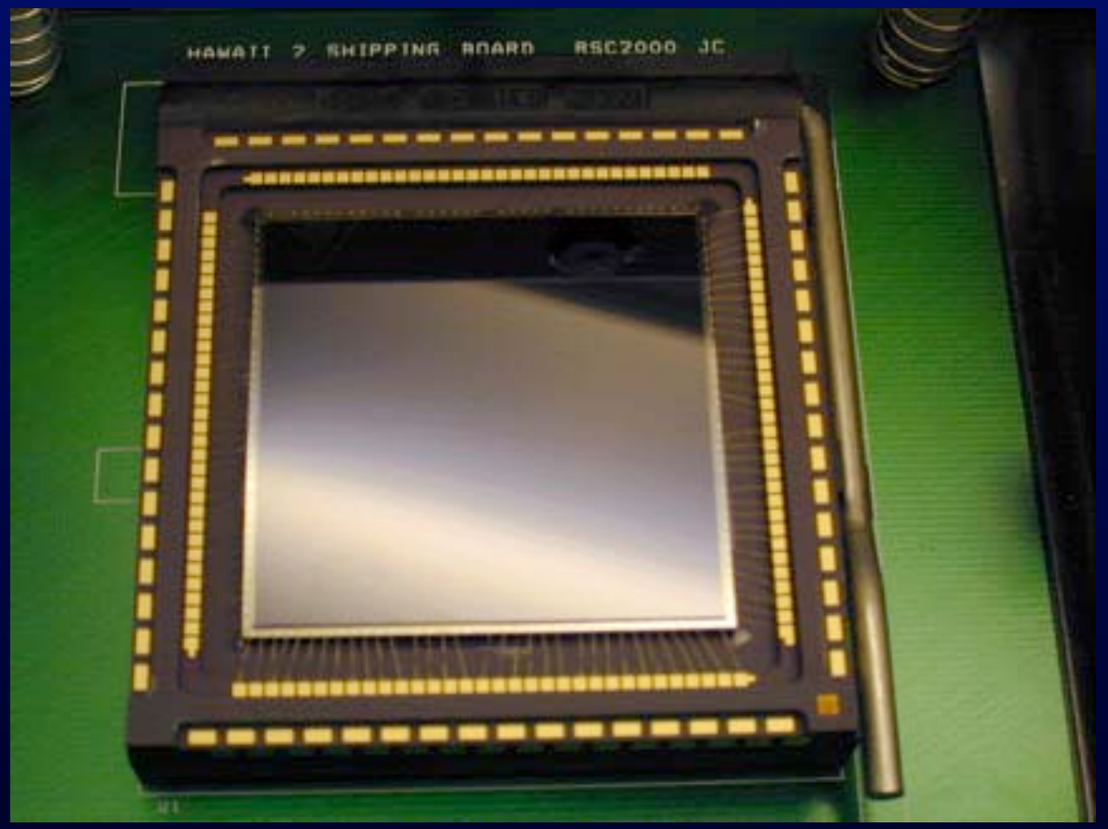
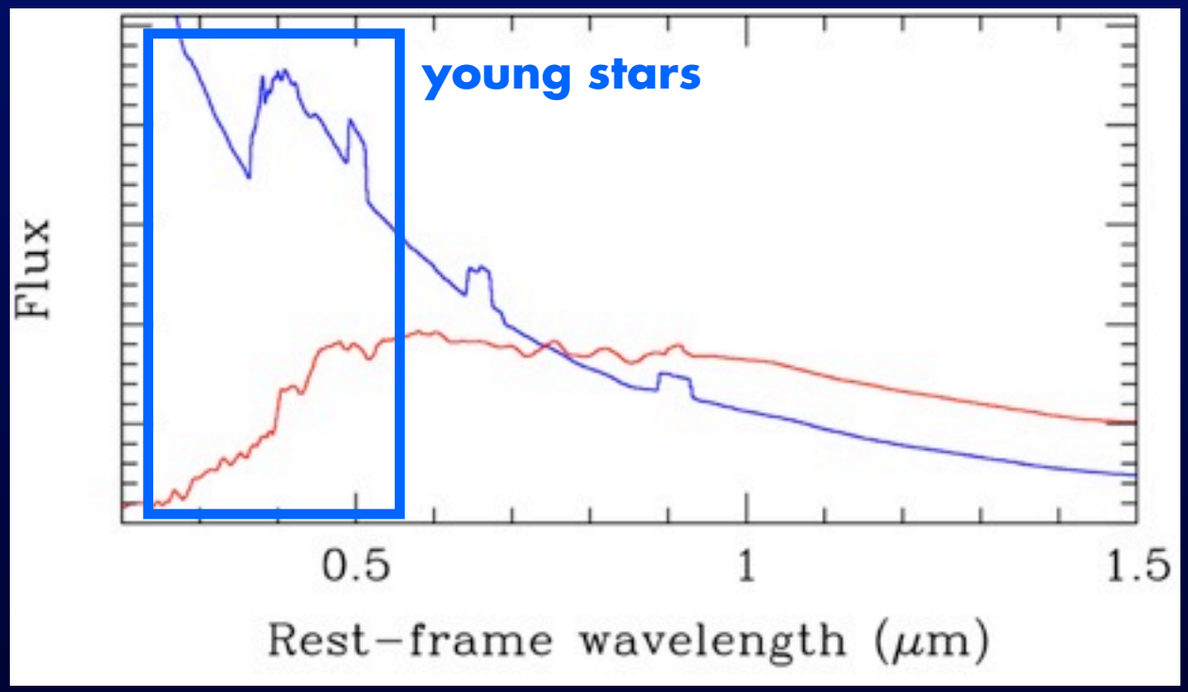


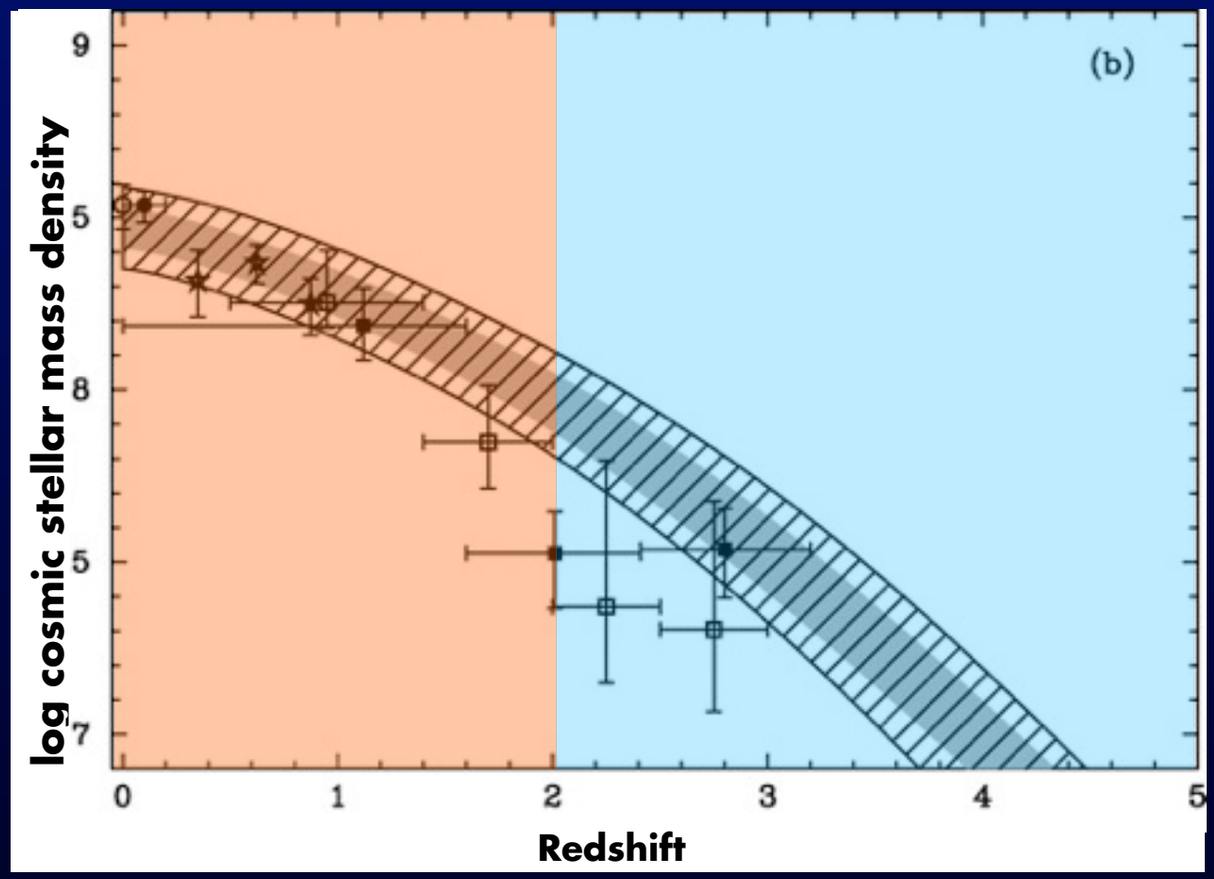

**WFCAM detector, UK Infrared Telescope**

# Gathering photons




IMACS spectrograph, Magellan

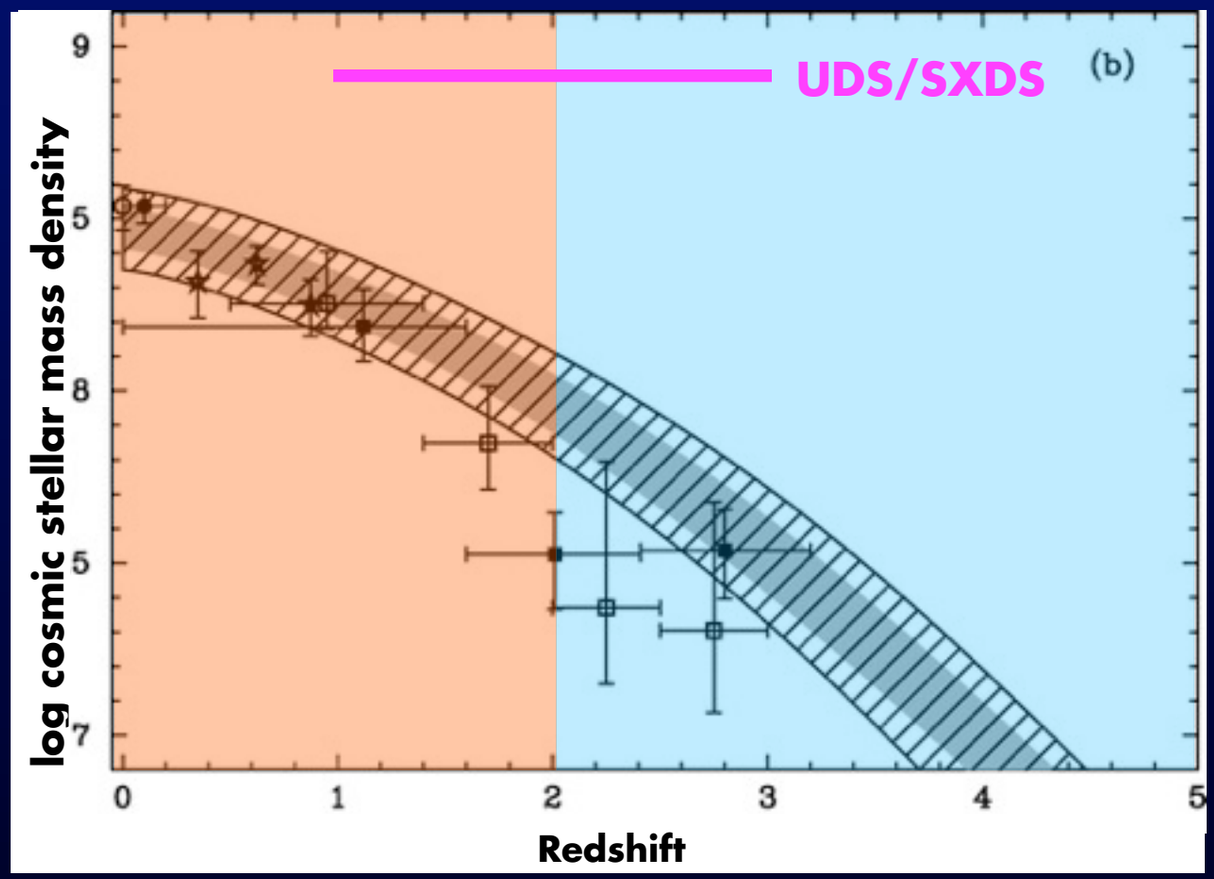
# Gathering photons




Hopkins & Beacom 2006

# Gathering photons

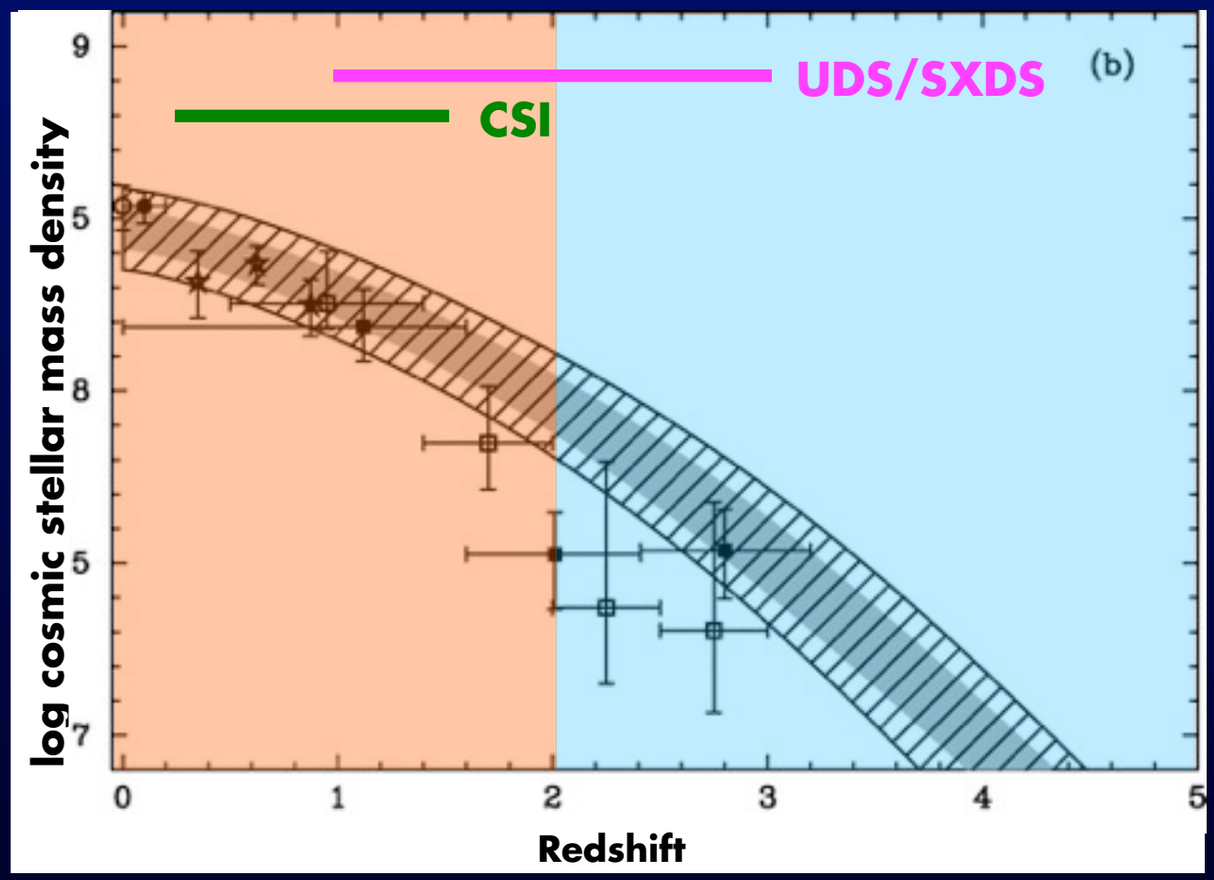
- UKIDSS UDS / Subaru-XMM Deep Survey (z=1-3)
  - 0.8 square degrees of optical-mid IR photometry, ~80,000 detected galaxies
  - K-selected
  - Photometric redshifts to ~2%




Hopkins & Beacom 2006

# Gathering photons

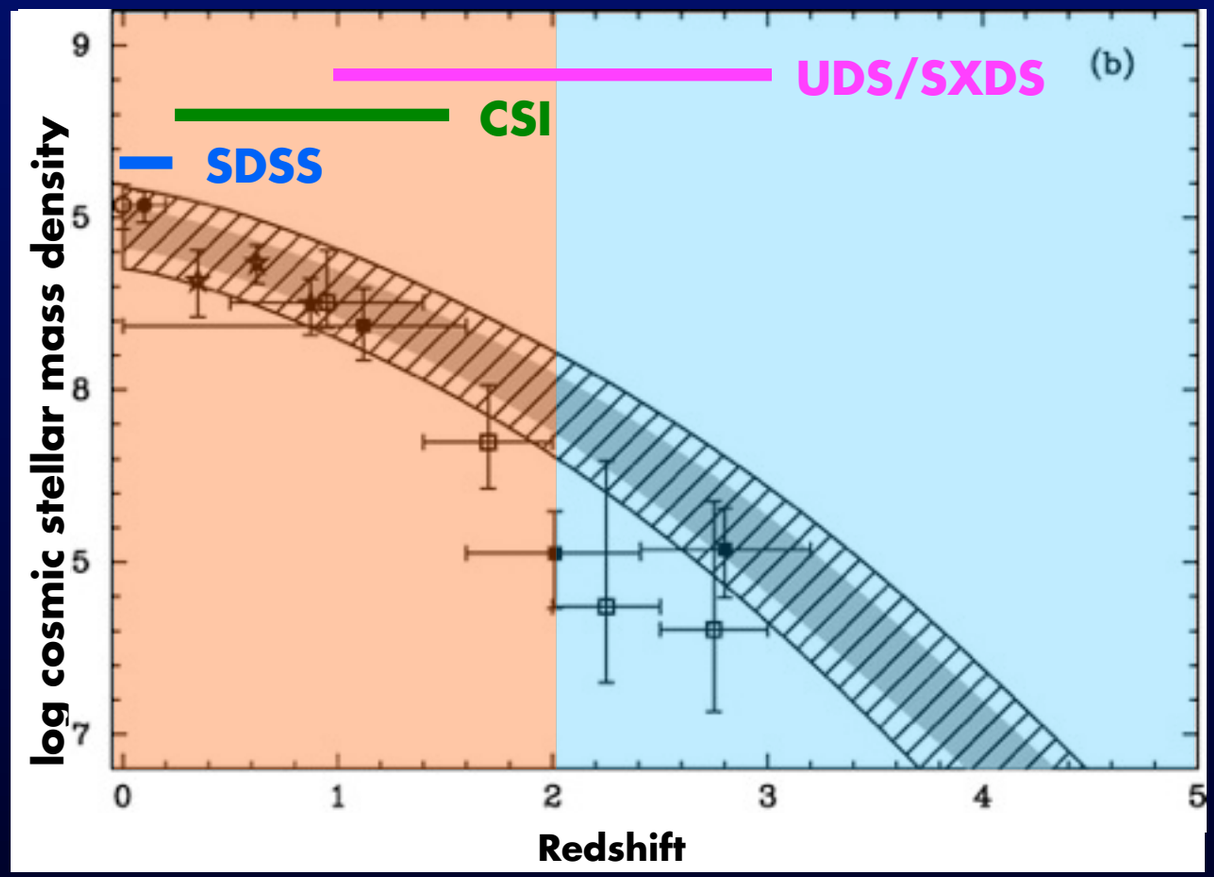
- Carnegie-Spitzer-IMACS Survey (z=0.3-1.3)
  - 5.3 square degrees, photometry and low-resolution prism spectroscopy
  - 35,000 galaxy spectra
  - Redshifts to 1%, strong emission lines
  - IRAC 3.6um selected
  - Ultimately: 15 square degrees, ~100,000 galaxies




Hopkins & Beacom 2006

# Gathering photons

- Sloan Digital Sky Survey (z<0.2)
  - Millions of spectra over 25% of the sky (but we cut it down to ~$10^4$ galaxies)



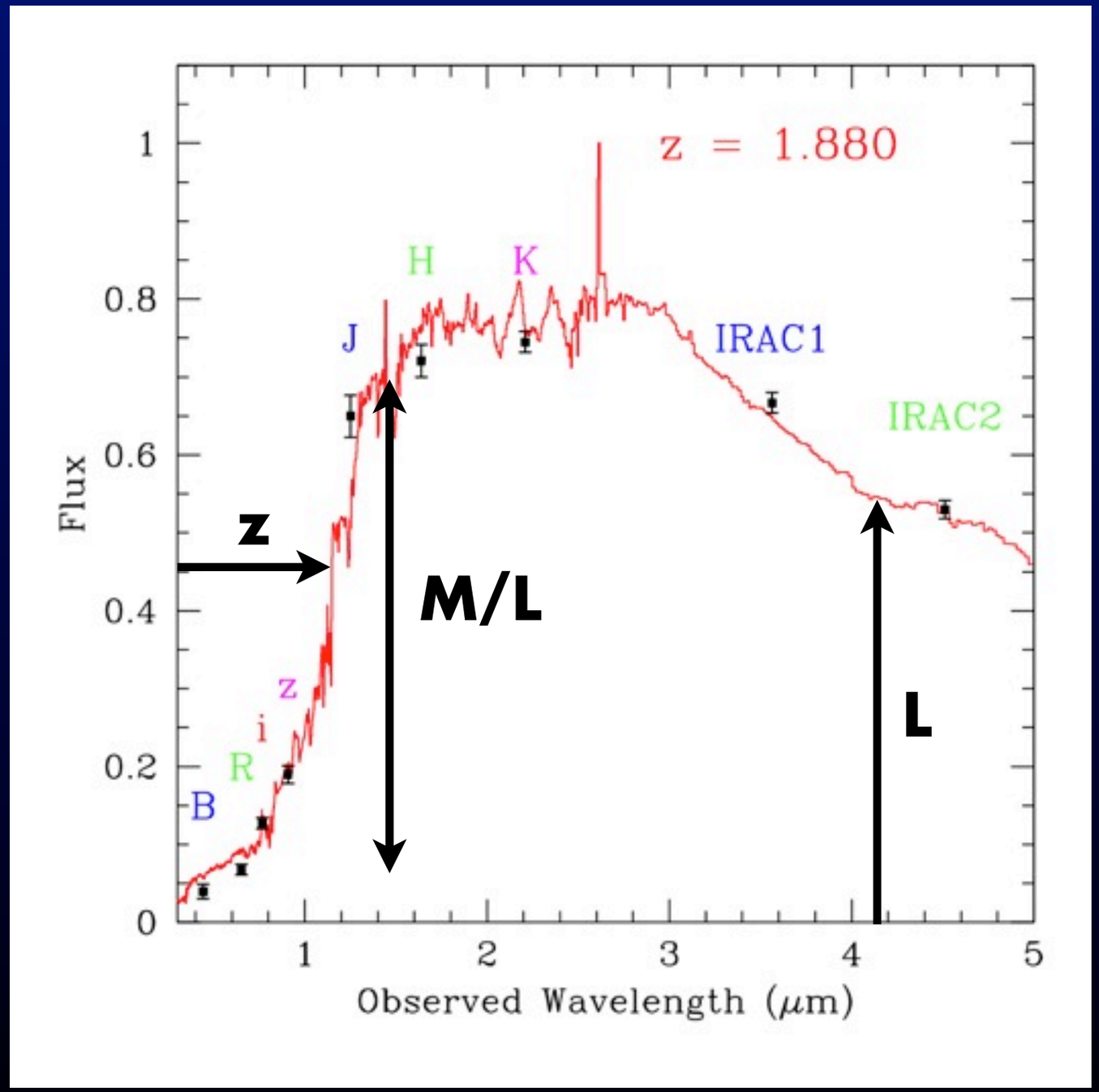

Hopkins & Beacom 2006

# From photons to physics

## ✣ SED fitting

**Maximum likelihood fit of a library of stellar population models; varying age, dust, star formation rate**

**Best-constrained parameters:**
**Redshift**
**Luminosity**
**Mass-to-light ratio**




UDS catalog, Williams et al. 2009

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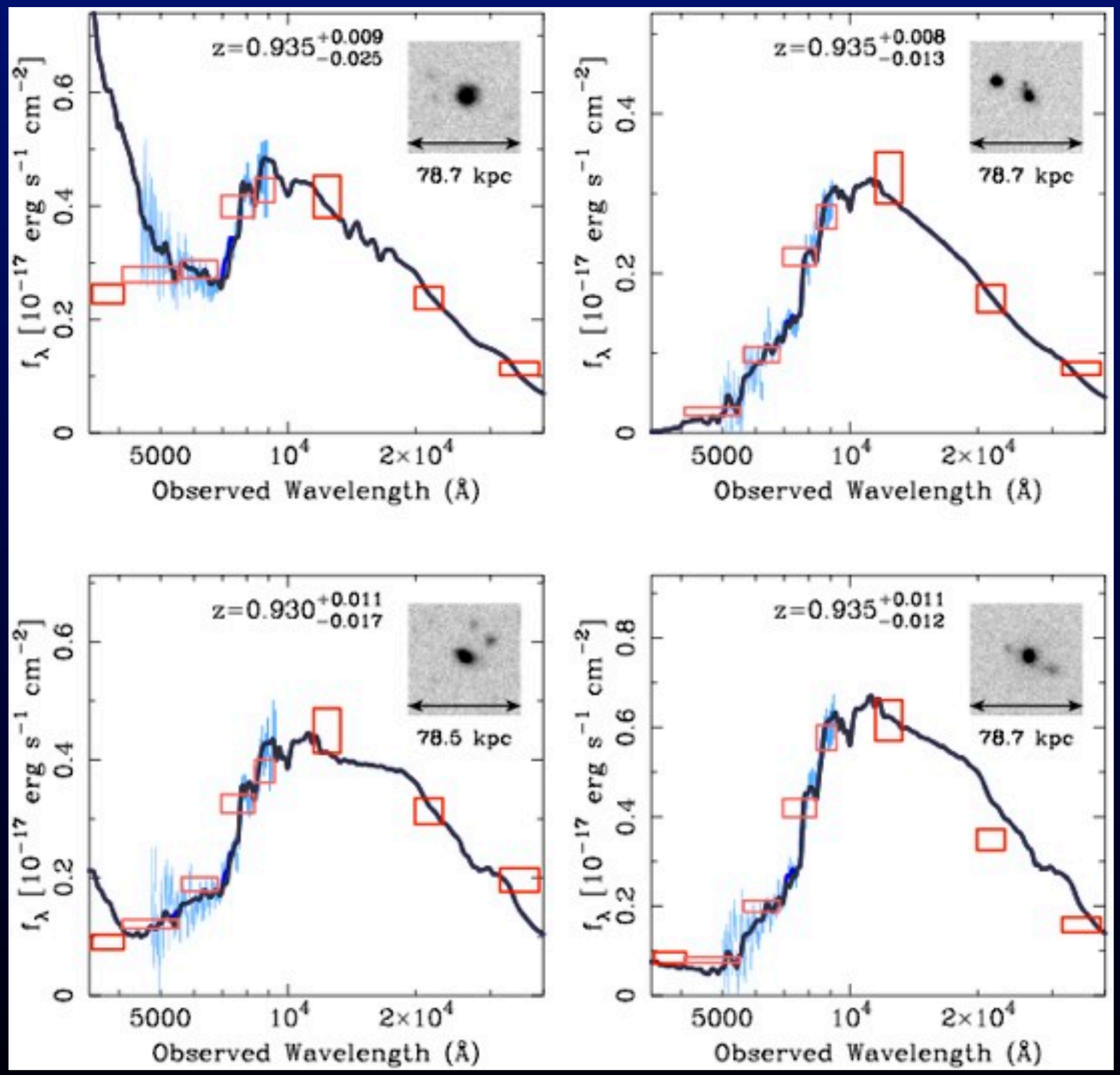


CSI, Kelson et al. (2013)

# Shutdown of star formation

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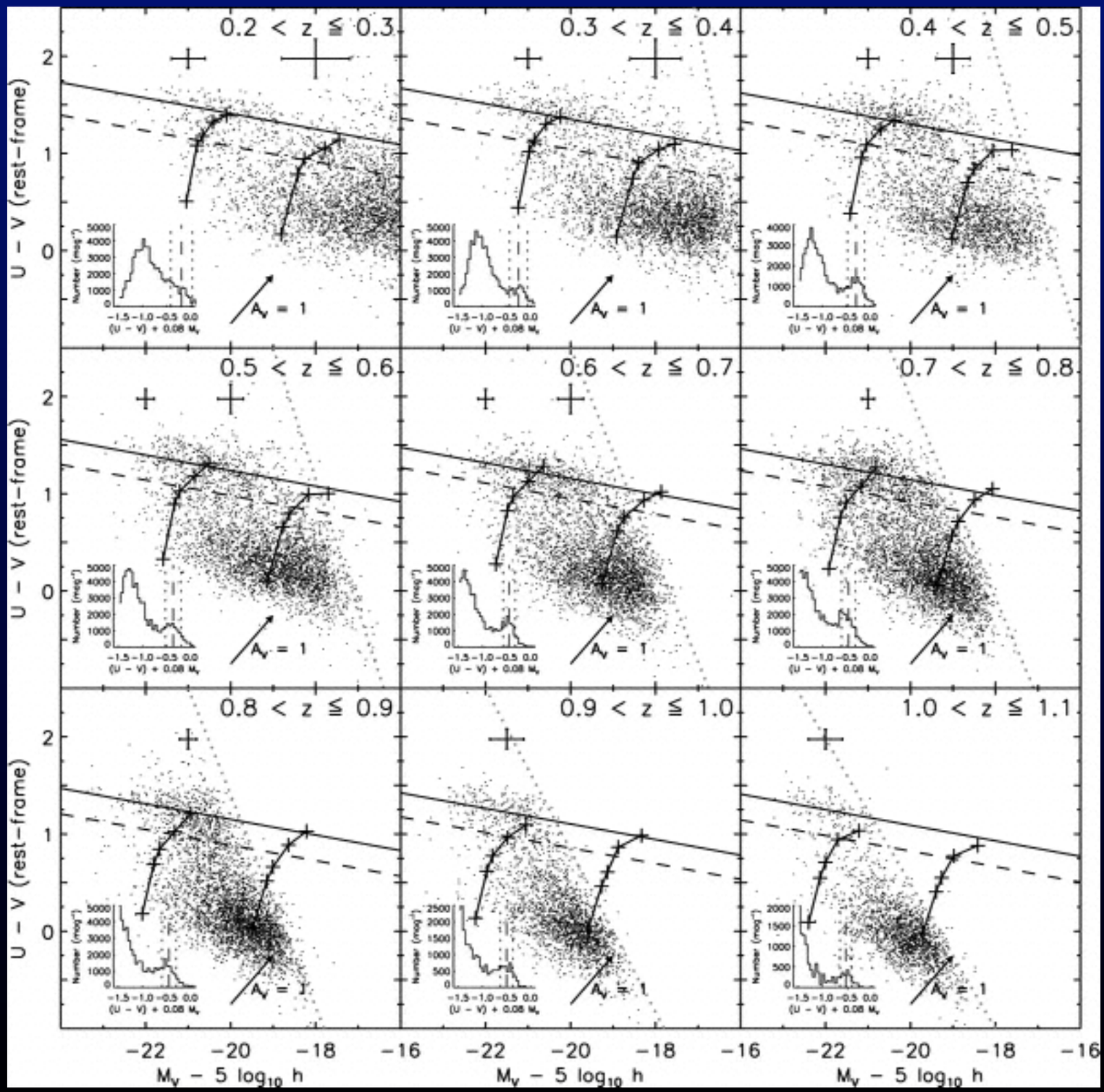
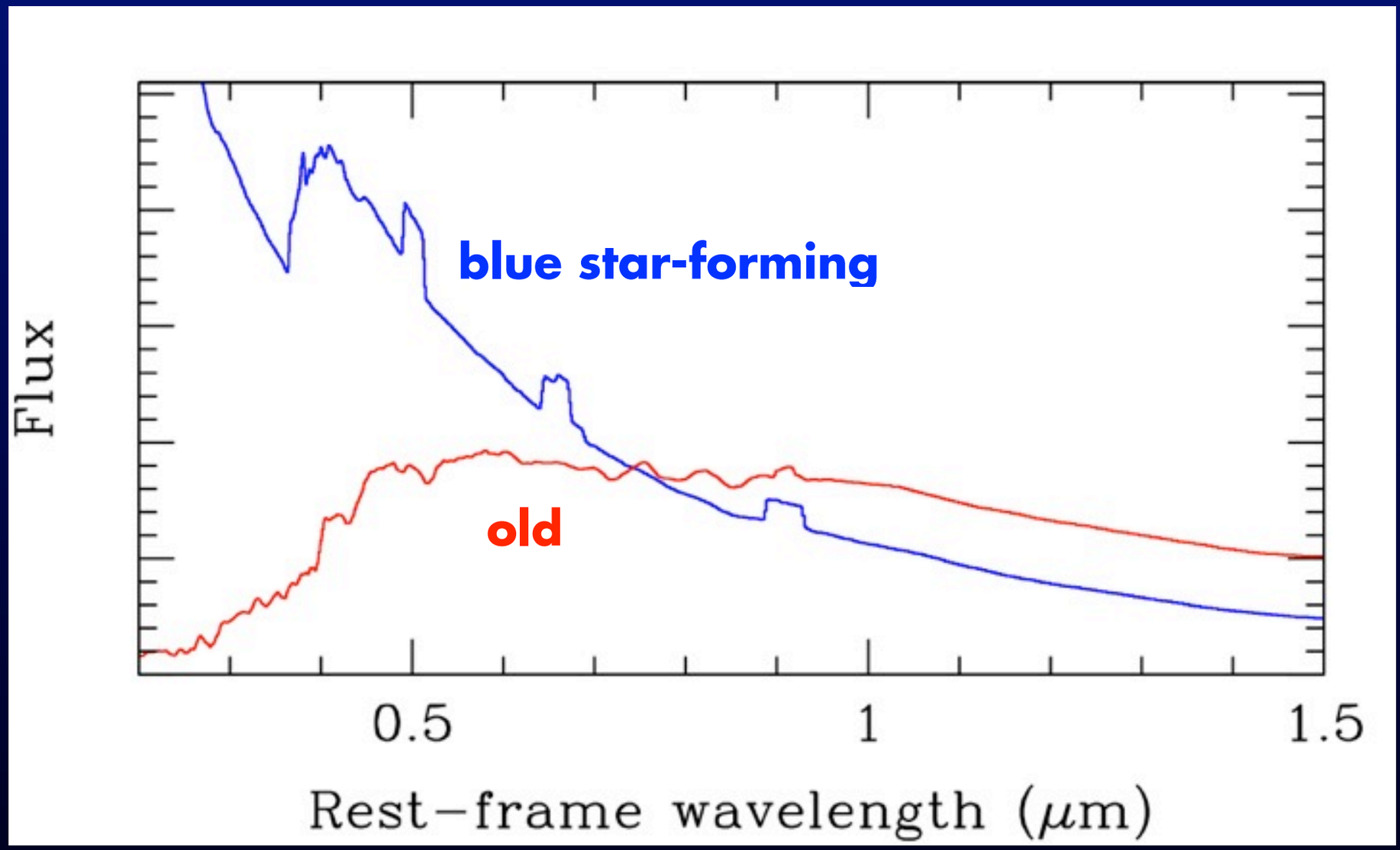



Bell et al. (2004)

# Shutdown of star formation



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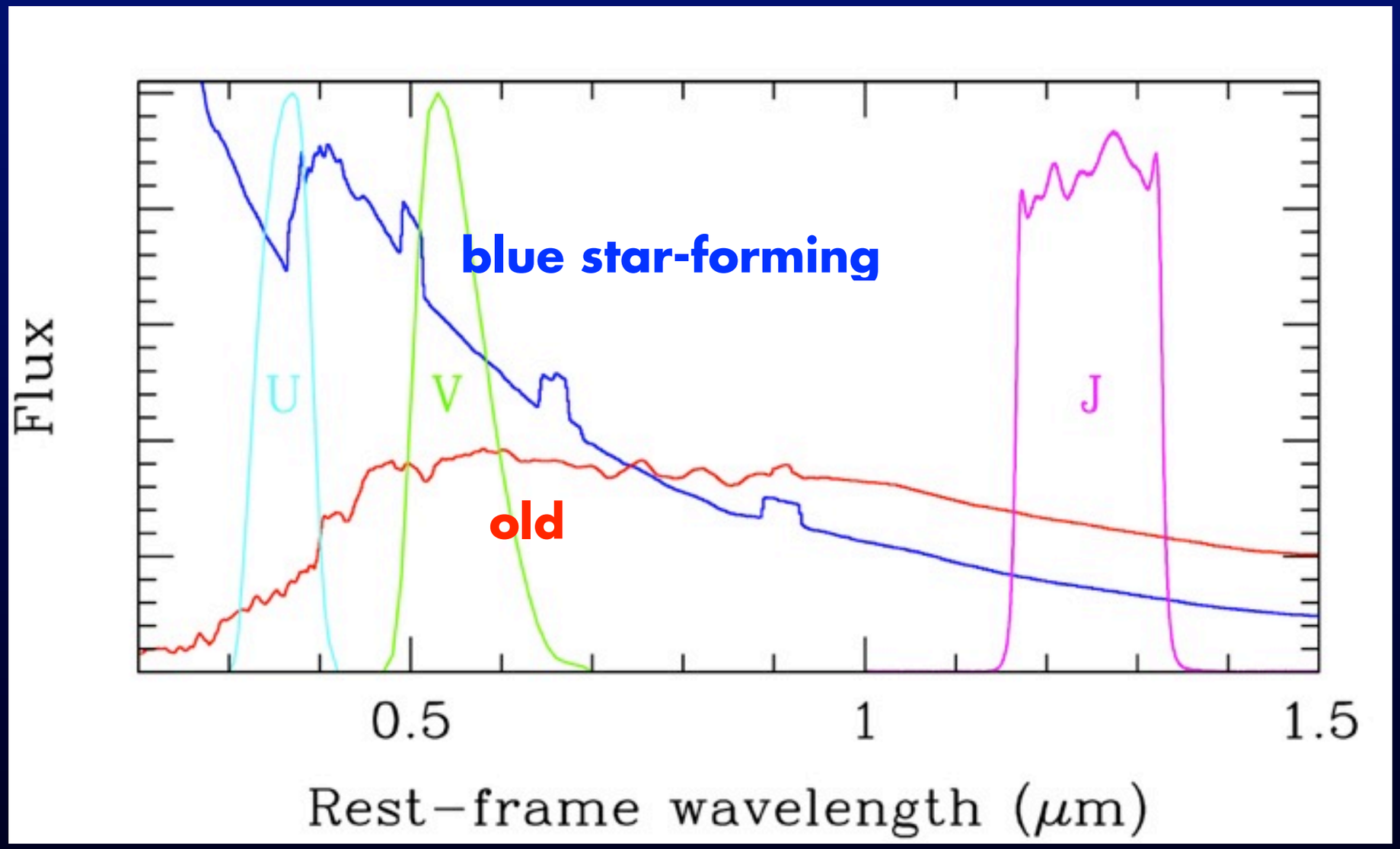

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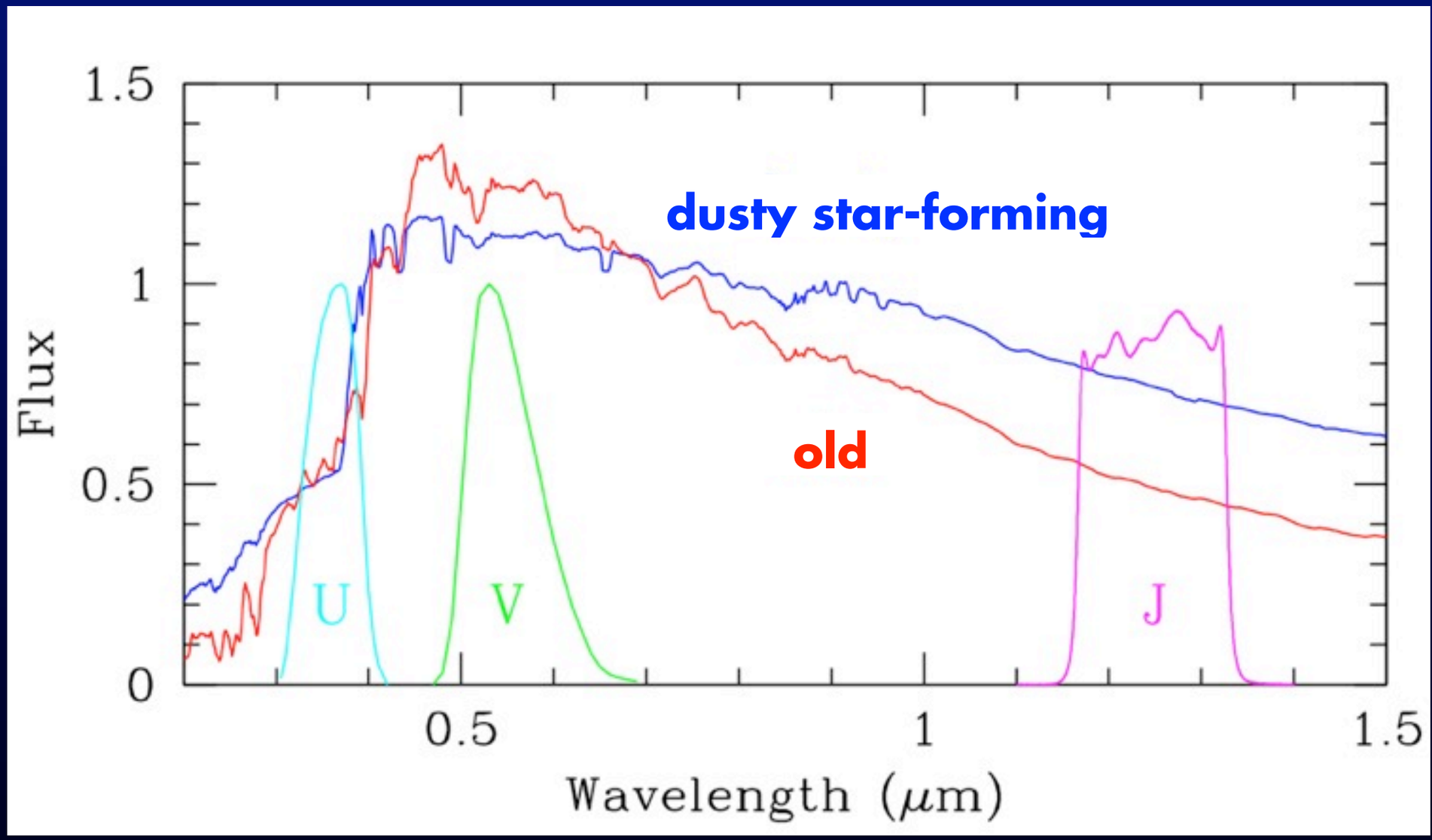
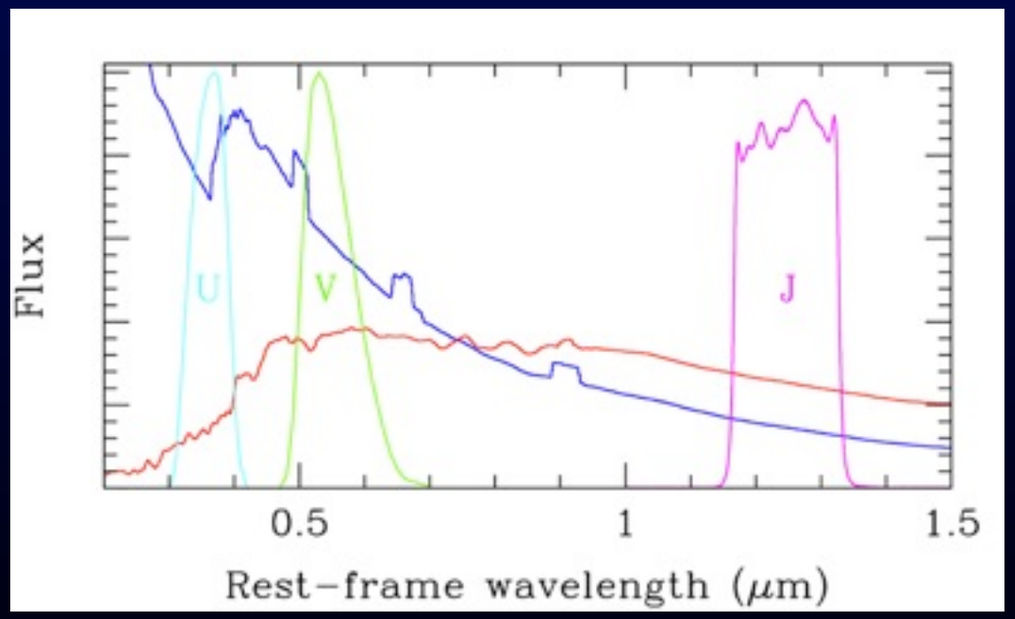
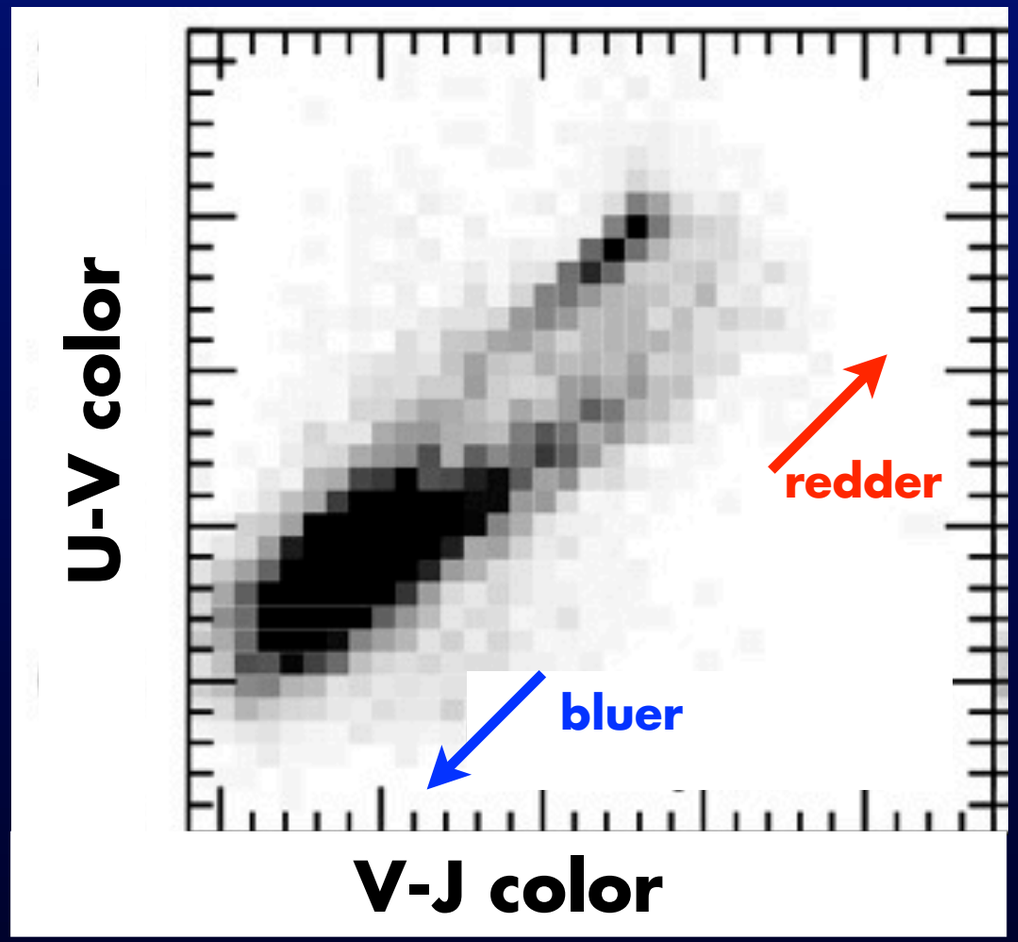


# Shutdown of star formation

## ✣ UVJ Color Cut

**Rest-frame colors cleanly separate star-forming and quiescent galaxies**




**Williams et al. 2009; 2013 in prep**

# Shutdown of star formation

## ✣ UVJ Color Cut

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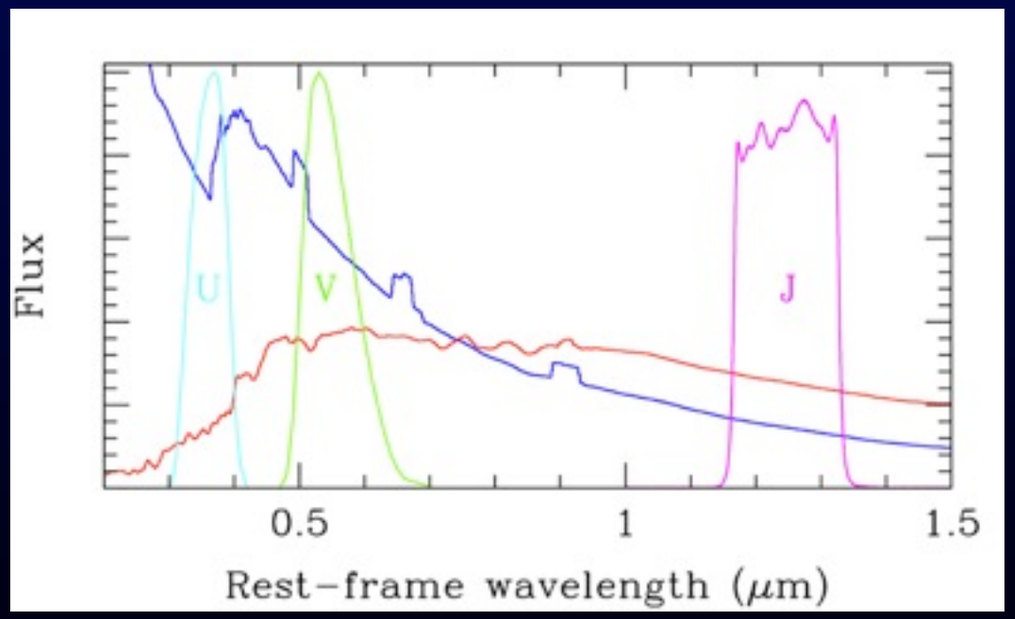


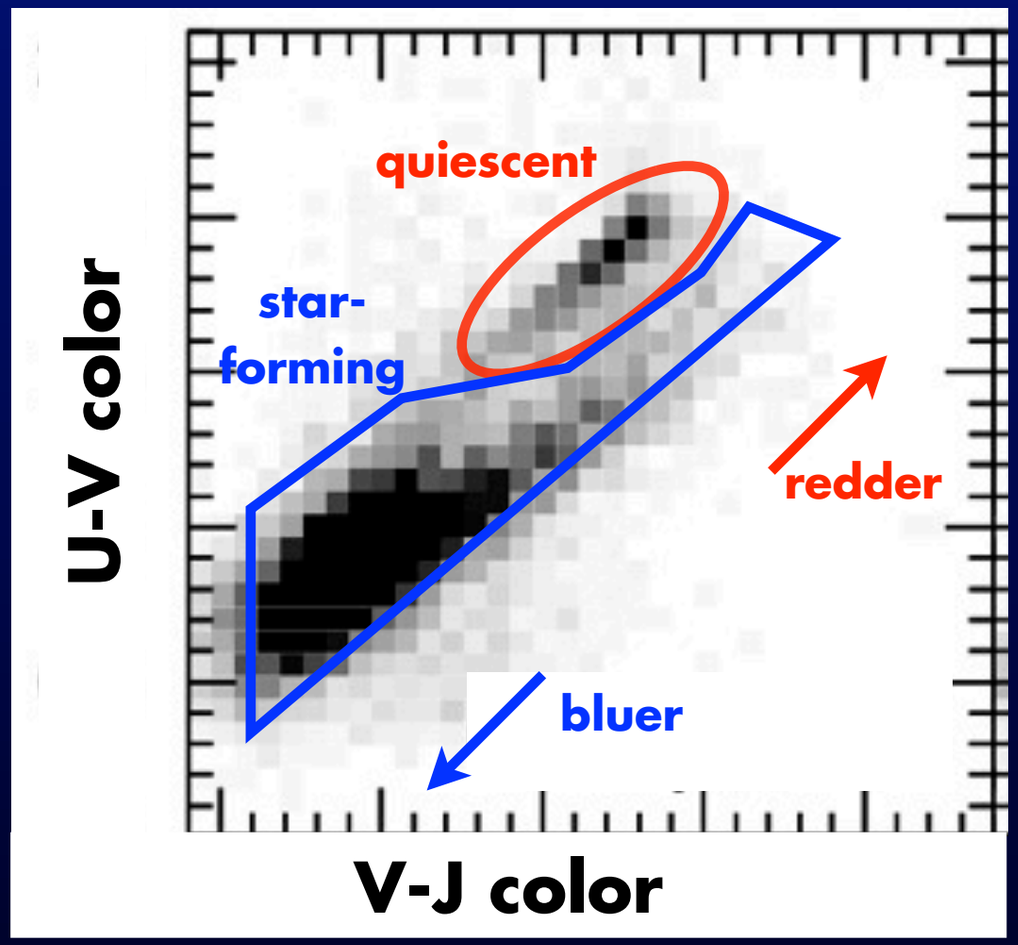


Williams et al. 2009; 2013 in prep

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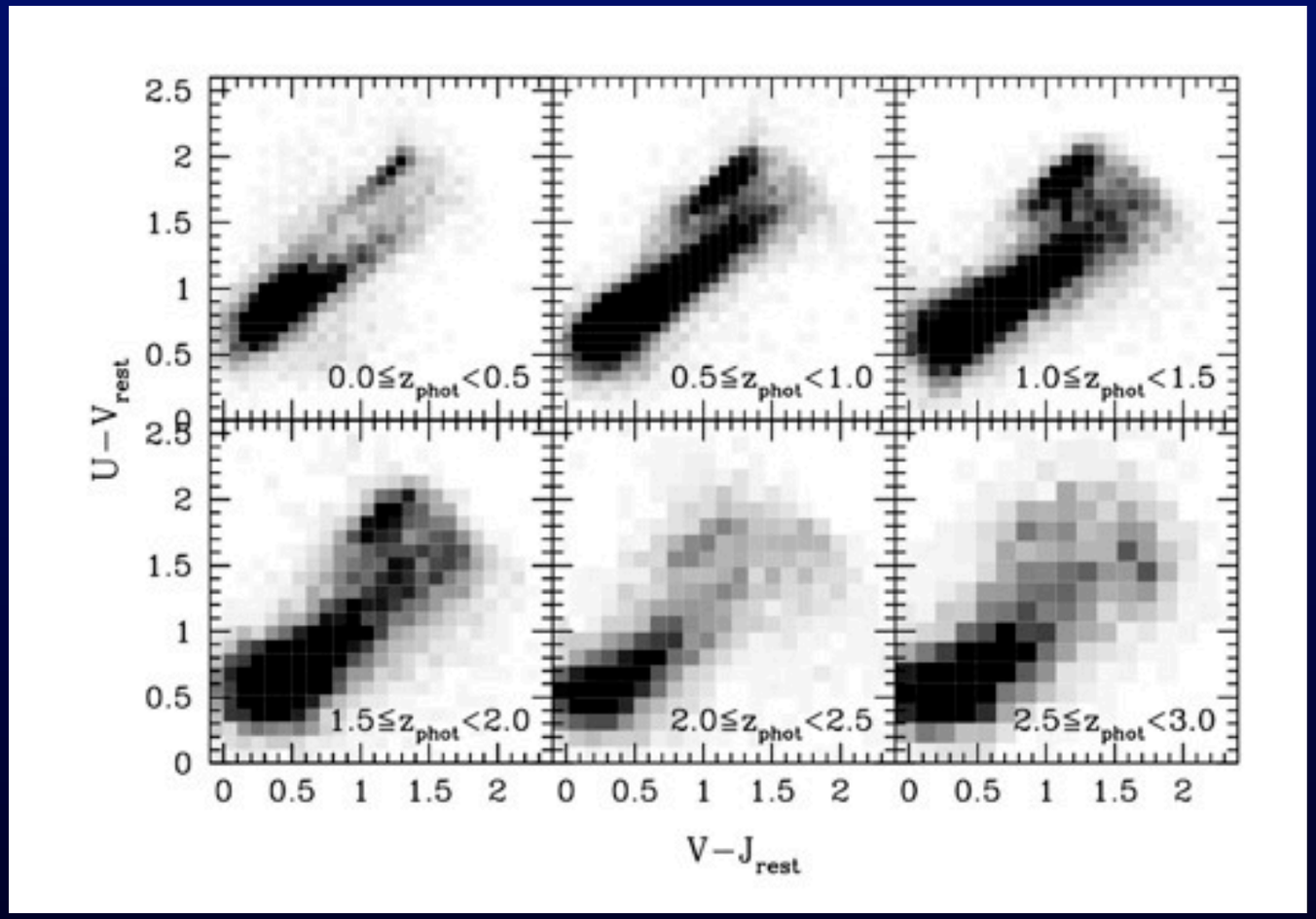
**Strong bimodality suggests rapid quenching, persists to z>2**

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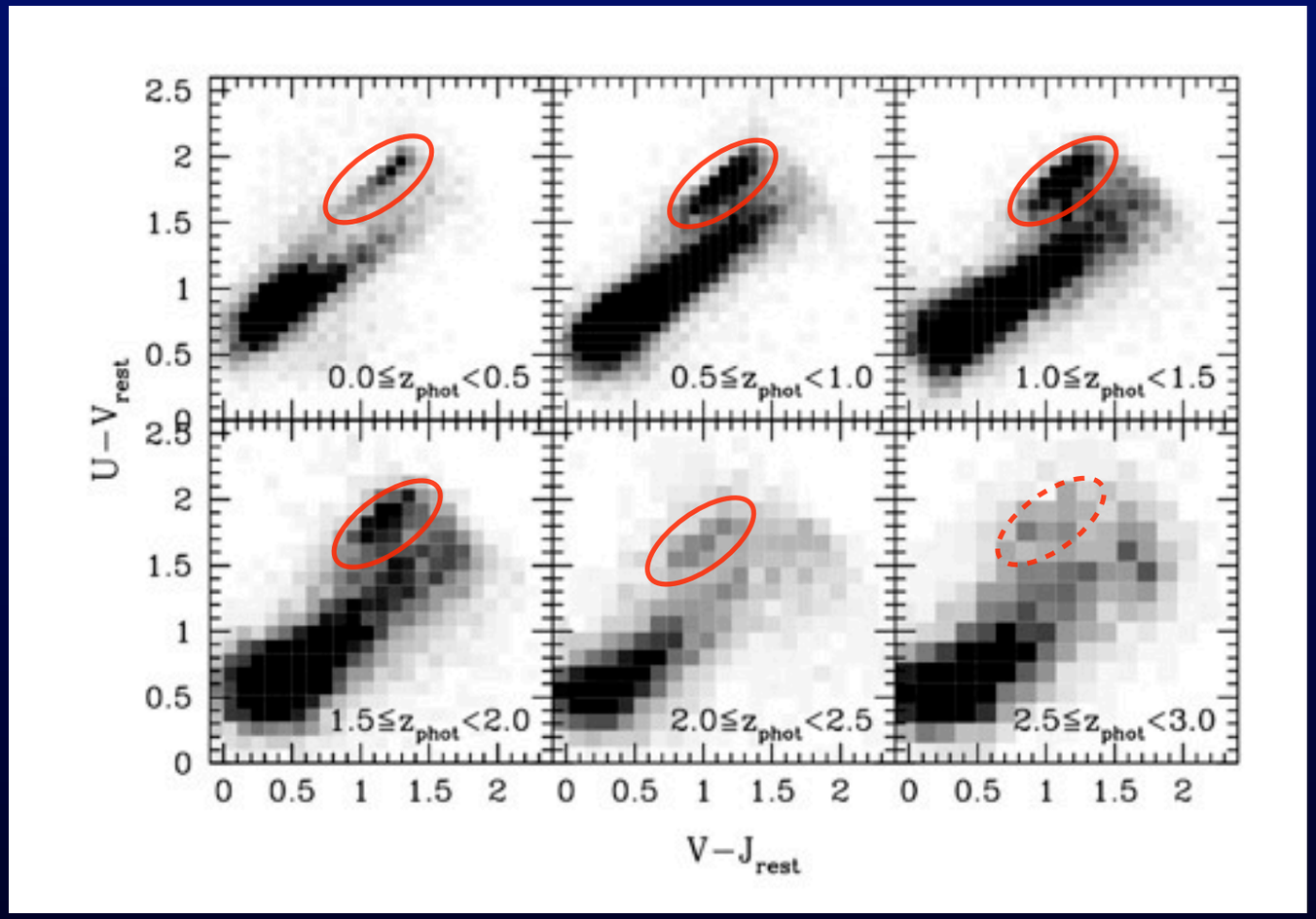


Williams et al. 2009; 2013 in prep

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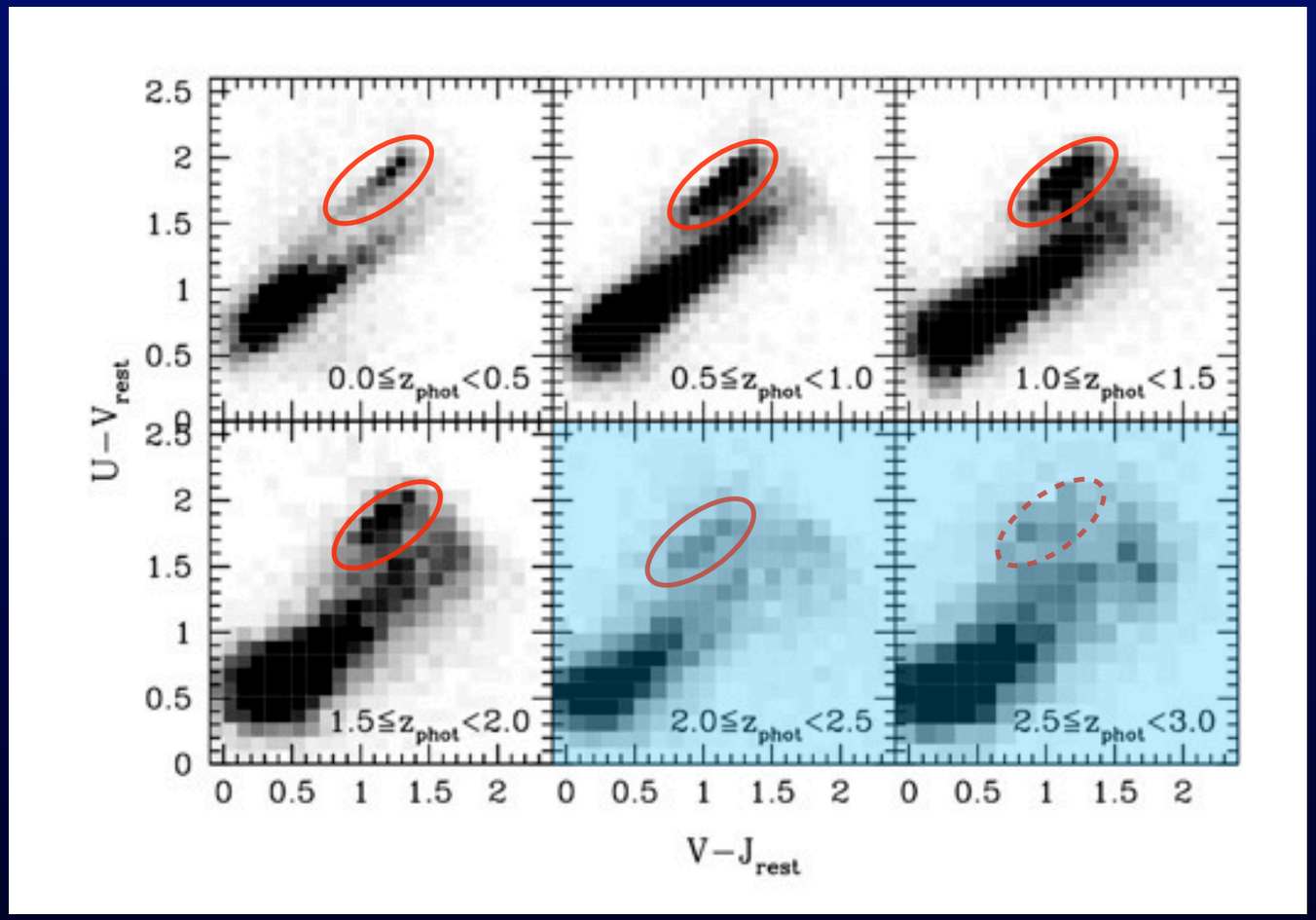


Williams et al. 2009; 2013 in prep

# What are the driving mechanisms?

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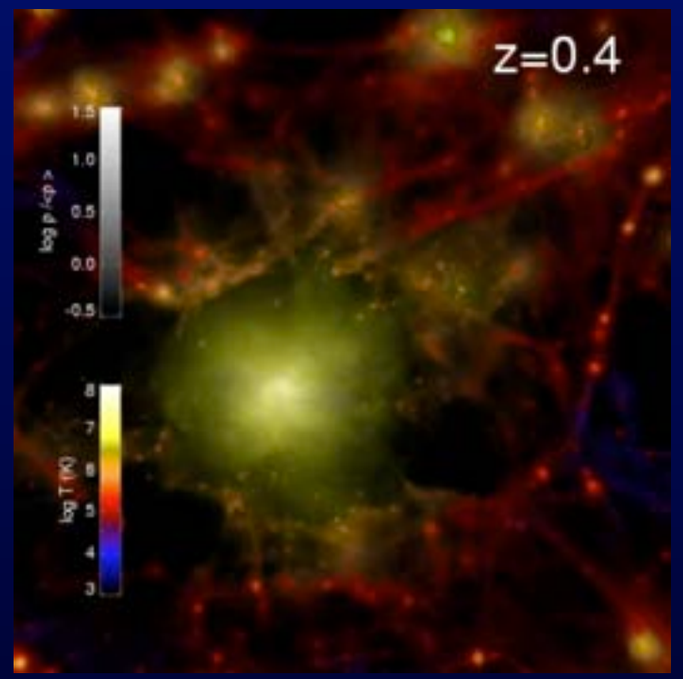

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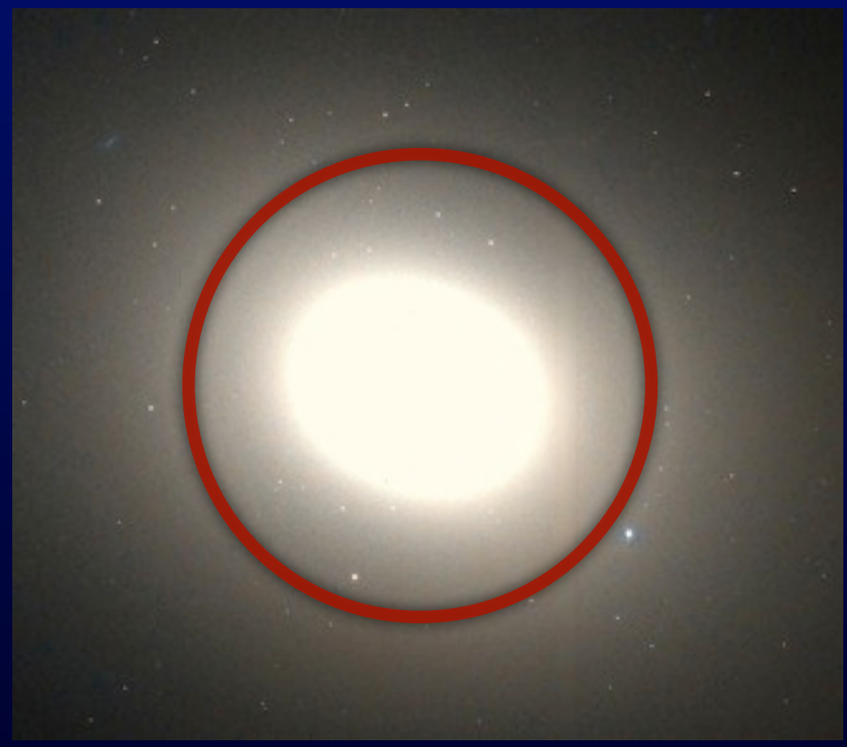

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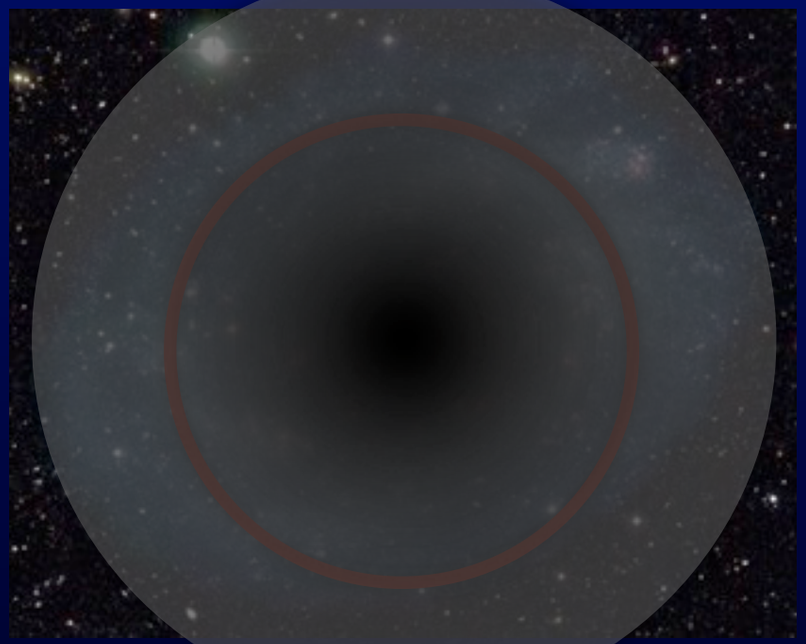

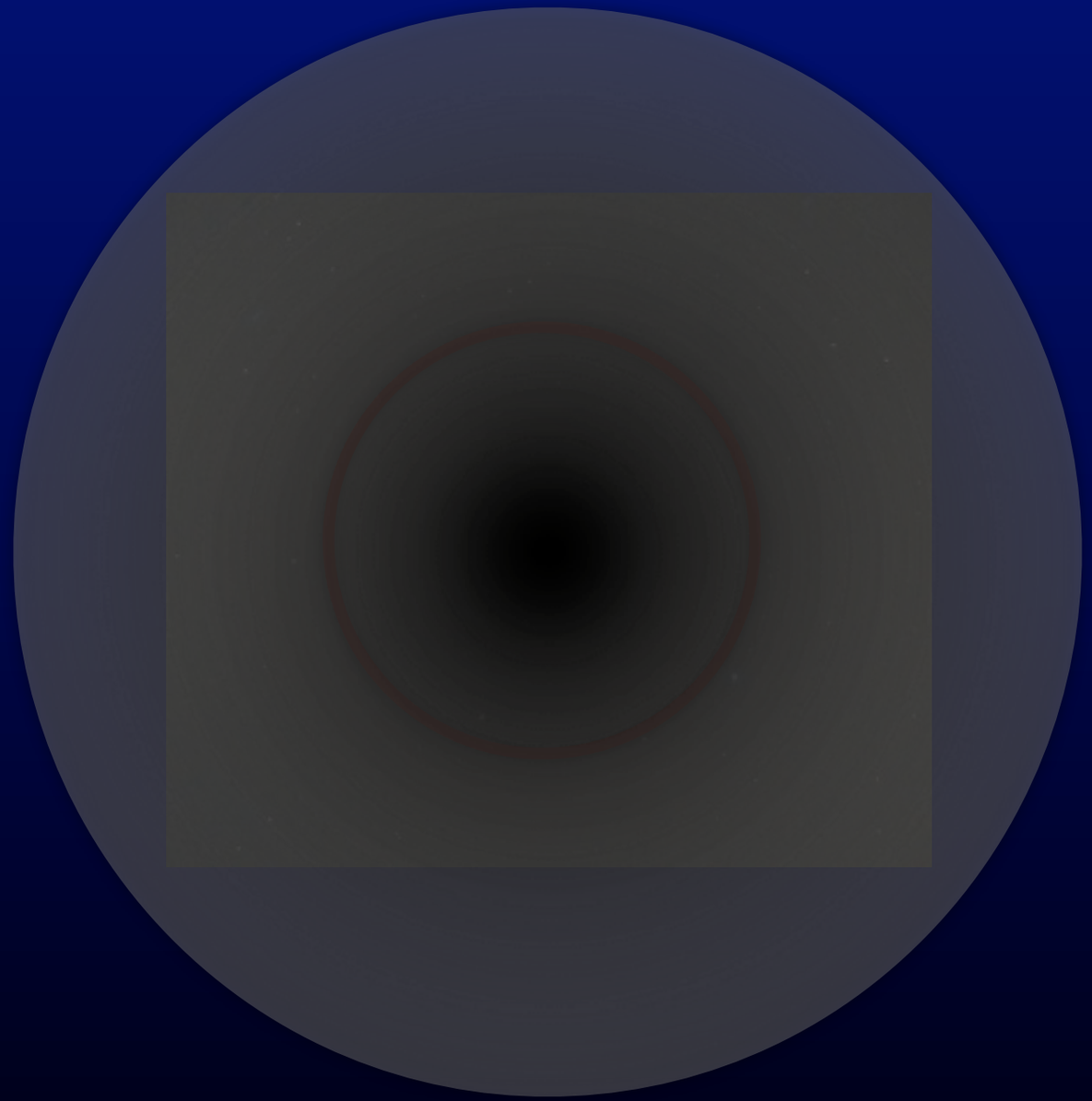

# Clustering: measuring halo masses

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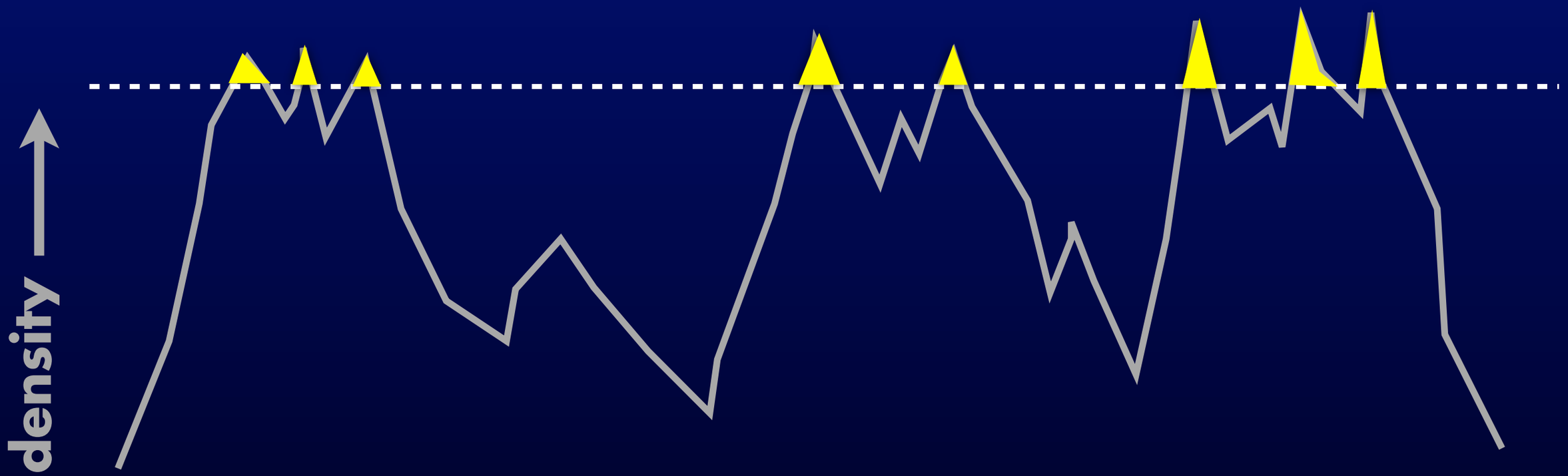

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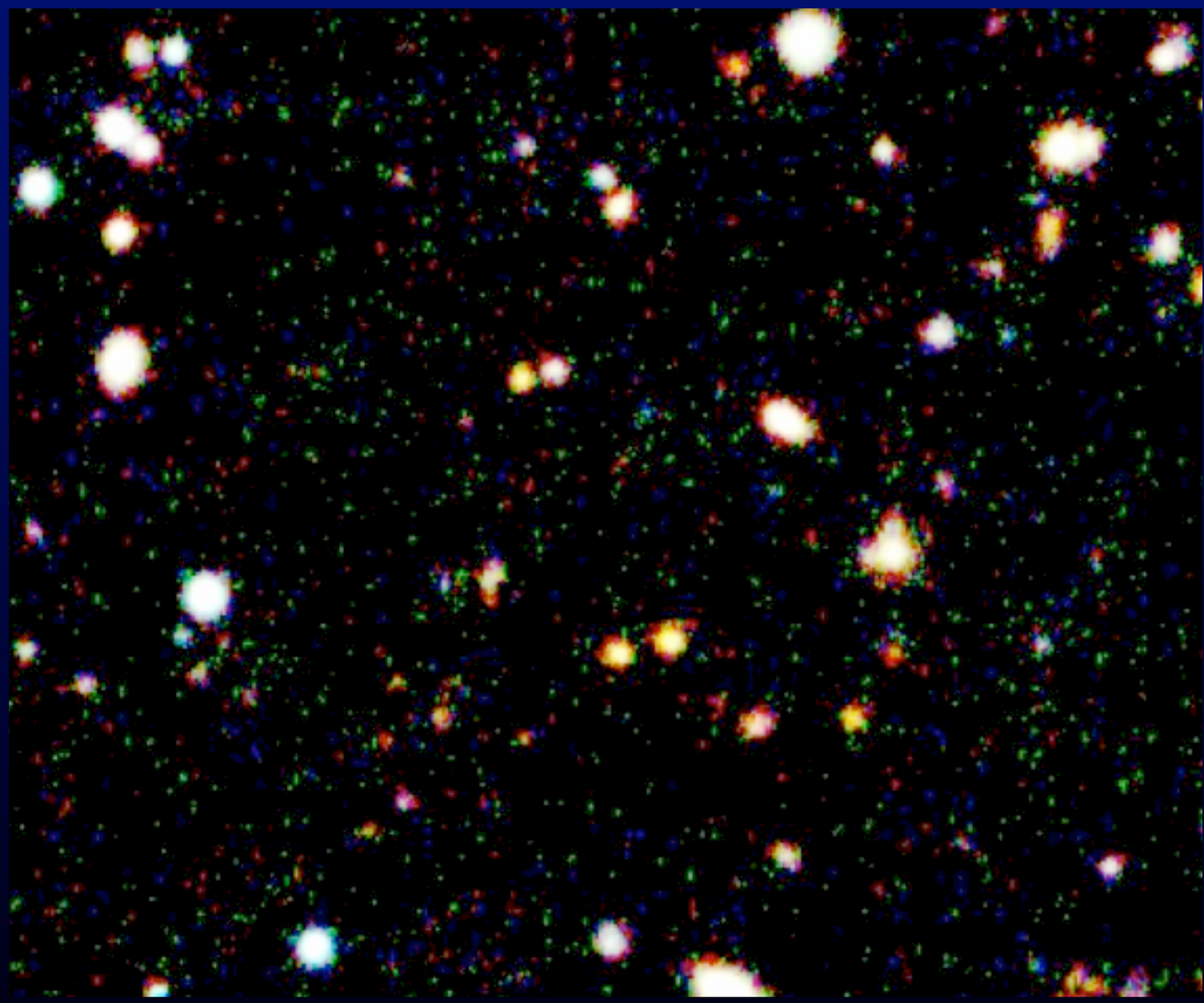


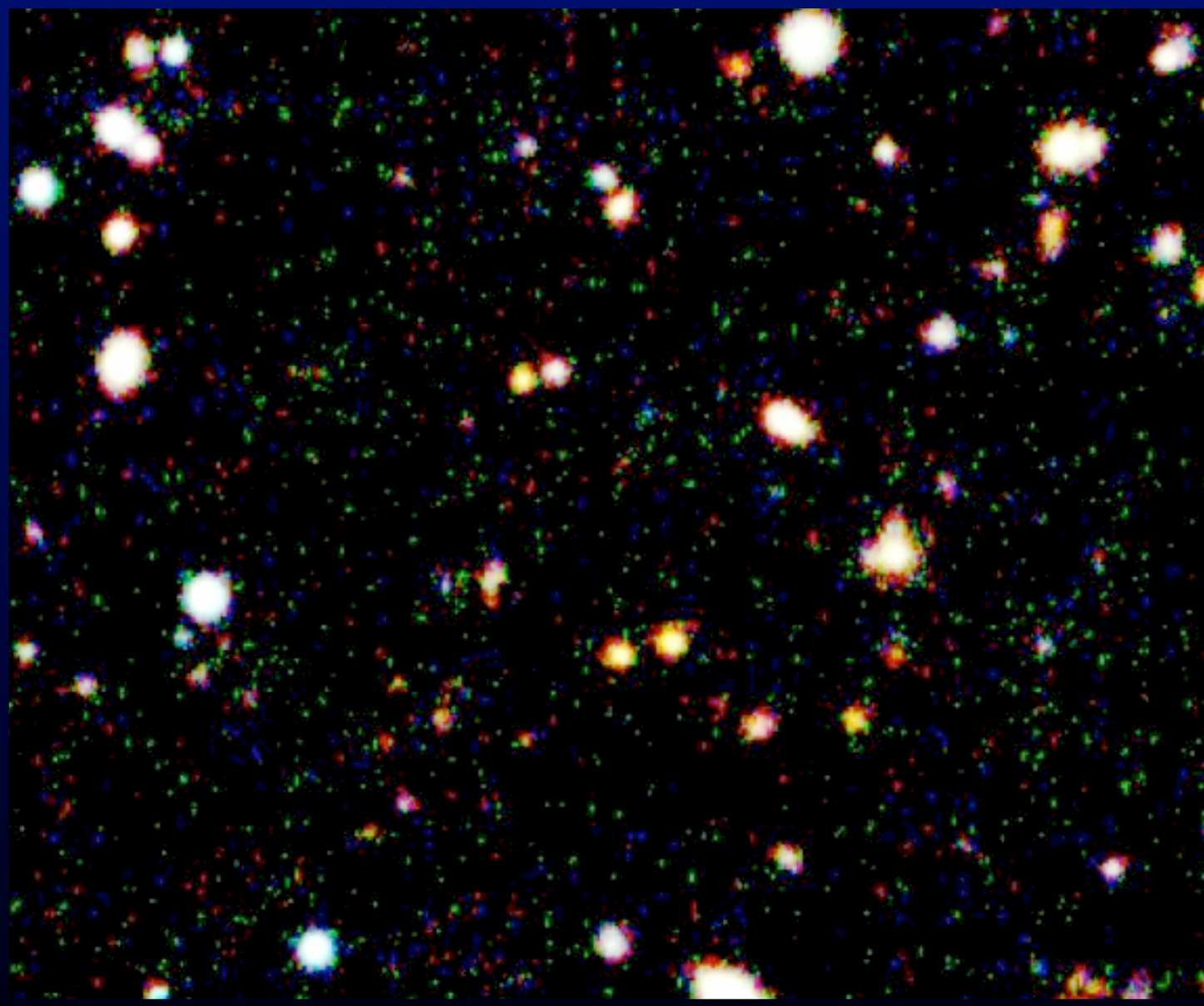
# Clustering: measuring halo masses

**Angular correlation fn**
$w(\theta) = A\ \theta^{-\delta}$

**Landy-Szalay estimator:**

$$w(\theta) \sim \frac{DD(\theta) - 2DR(\theta) + RR(\theta)}{RR(\theta)}$$

**DD = data-data pairs**
**DR = data-random**
**RR = random-random**



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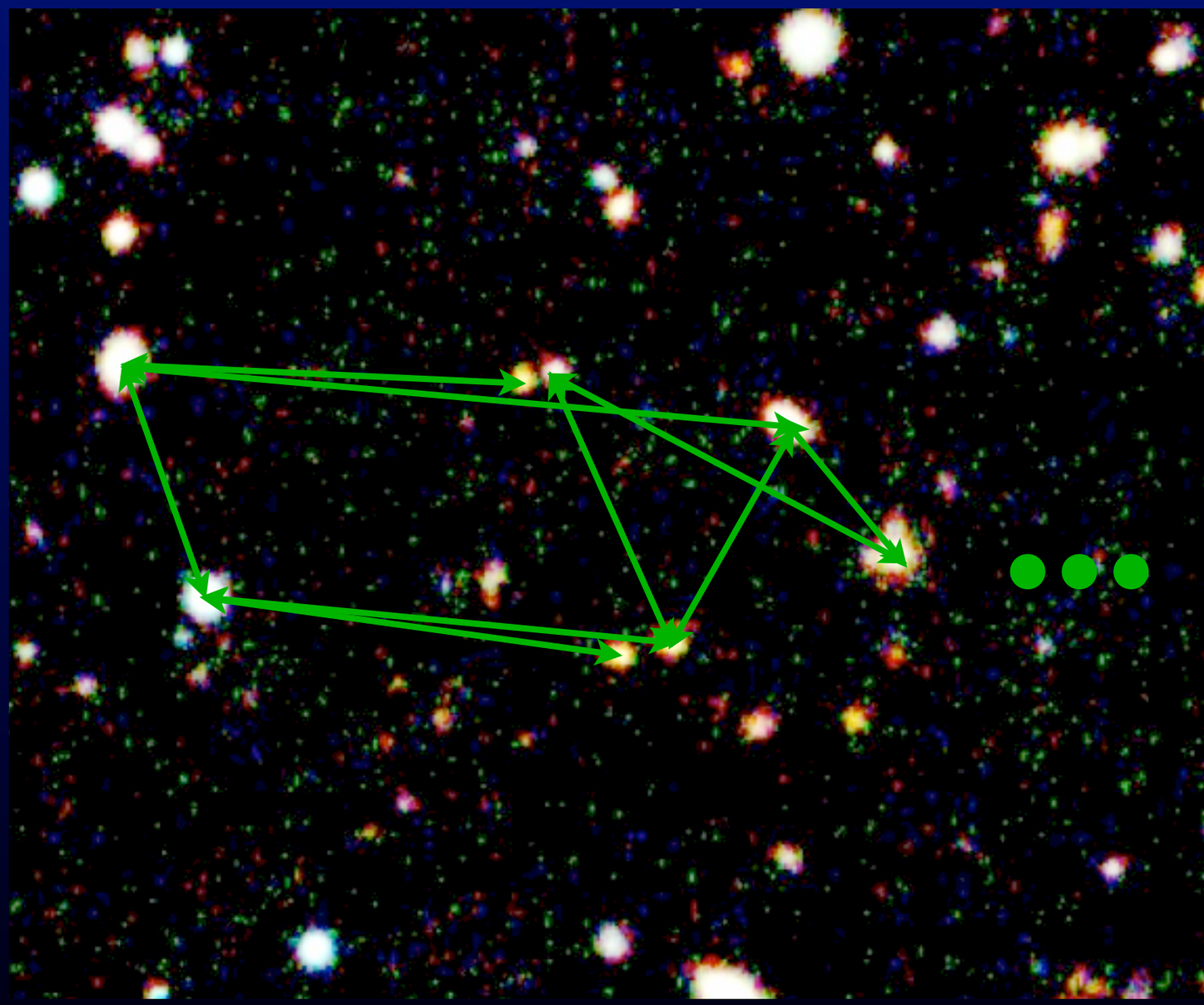
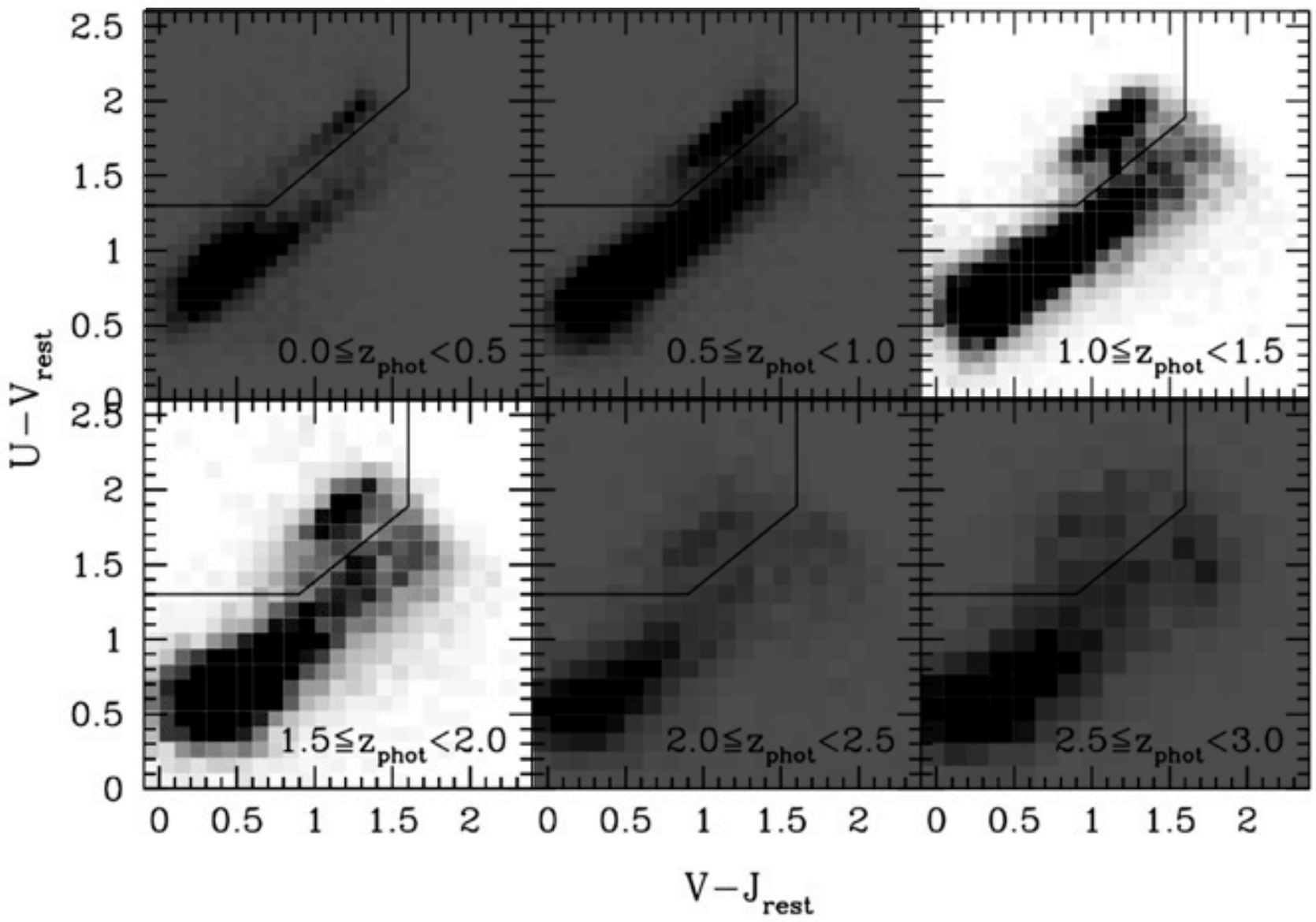


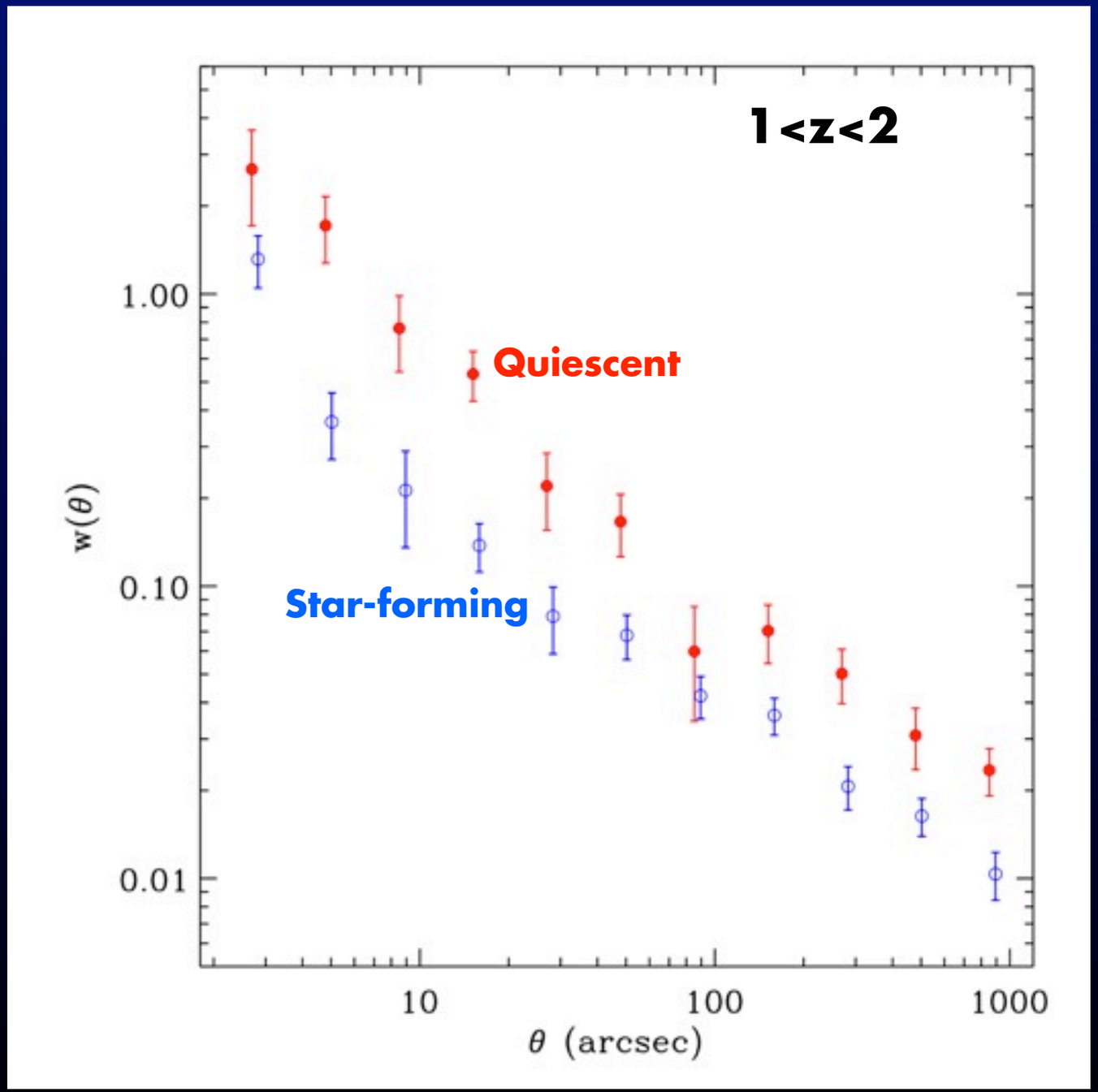
# Separating the samples




Williams et al. 2009

# Clustering: measuring halo masses

**Quiescent galaxies cluster more strongly, live in higher-mass DM halos**

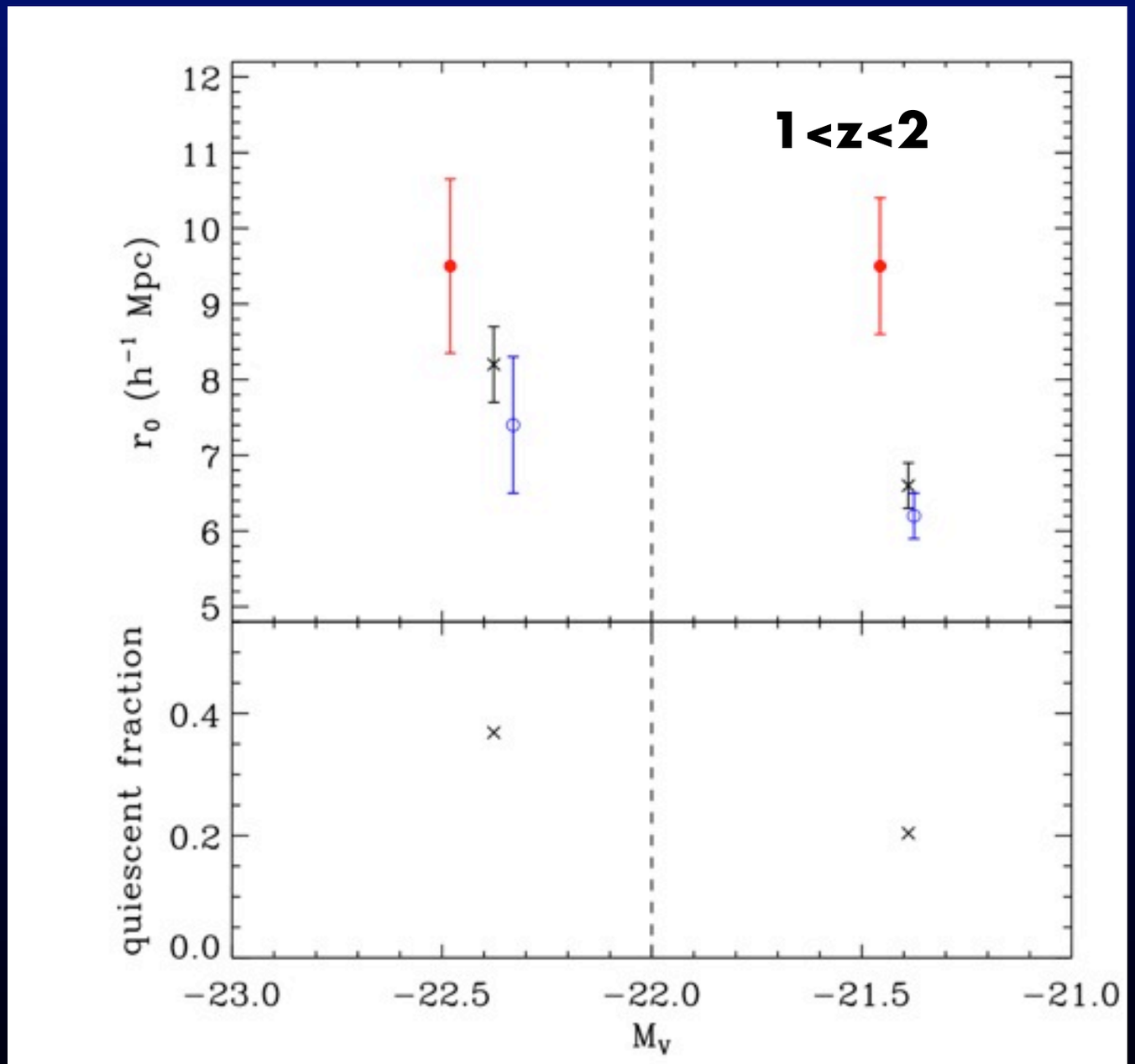



Williams et al. 2009

# Clustering: measuring halo masses

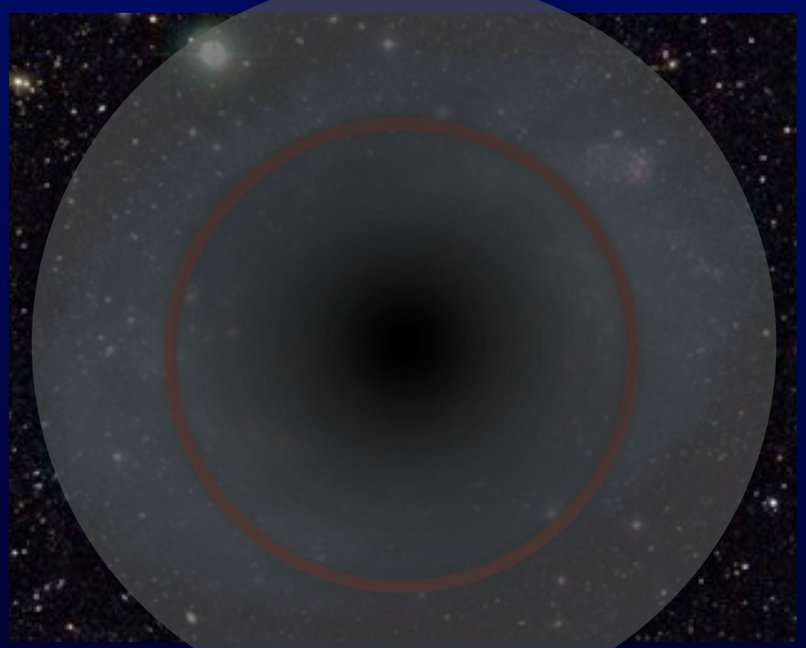
**Quiescent galaxies cluster more strongly, live in higher-mass DM halos**

**This effect is independent of stellar mass**



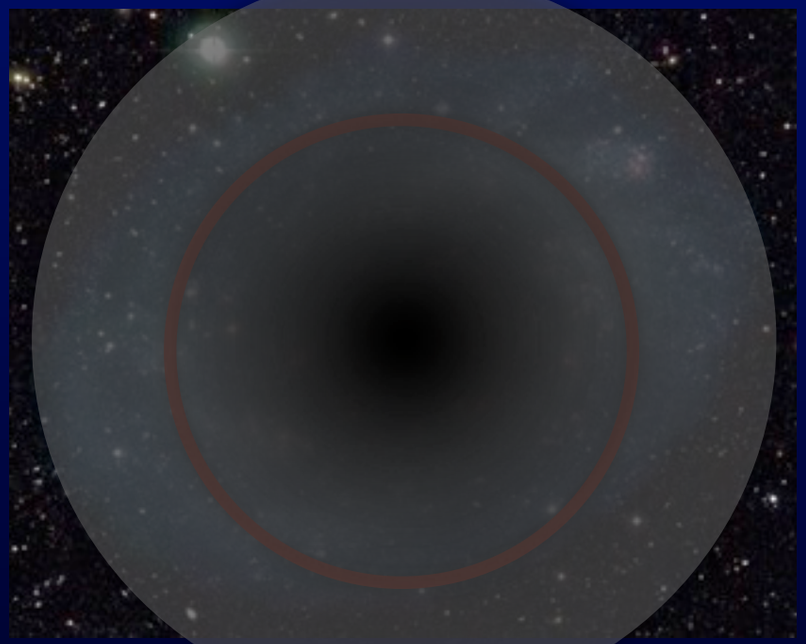

Williams et al. 2009

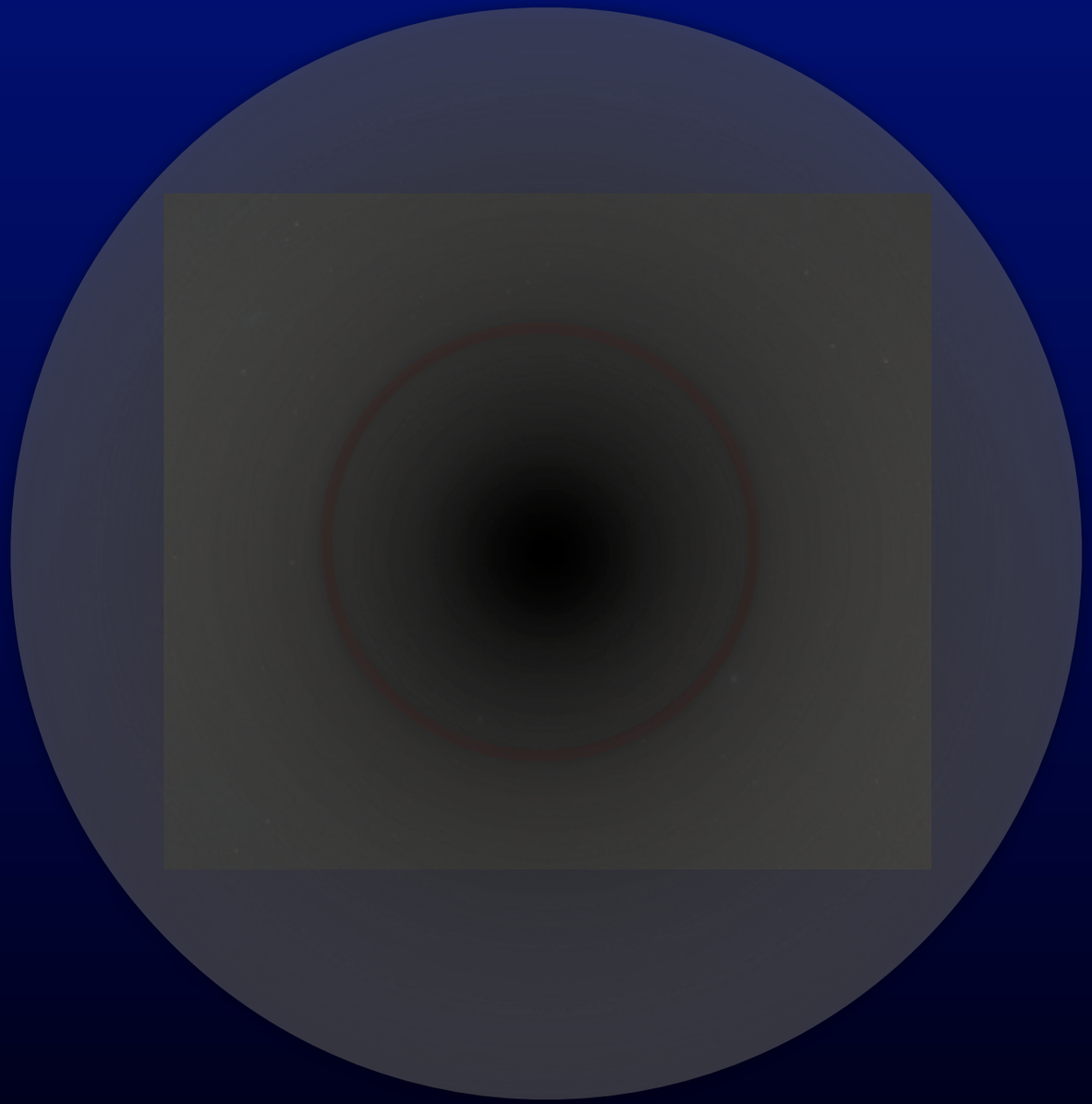
# There may be a (halo) mass threshold for quiescence.



$\sim 10^{12}\ M_{sun}$
(consistent with theory)

# Galaxy halos or something bigger?





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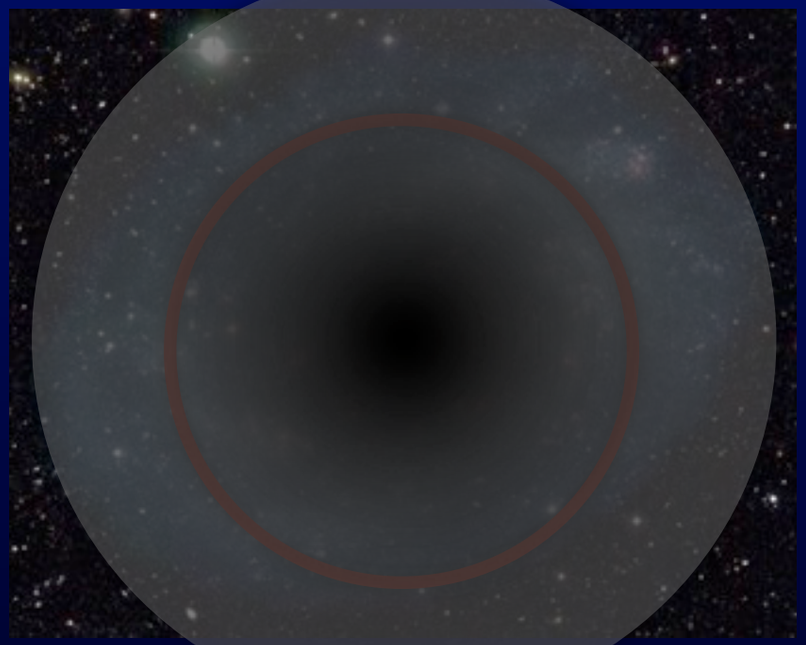

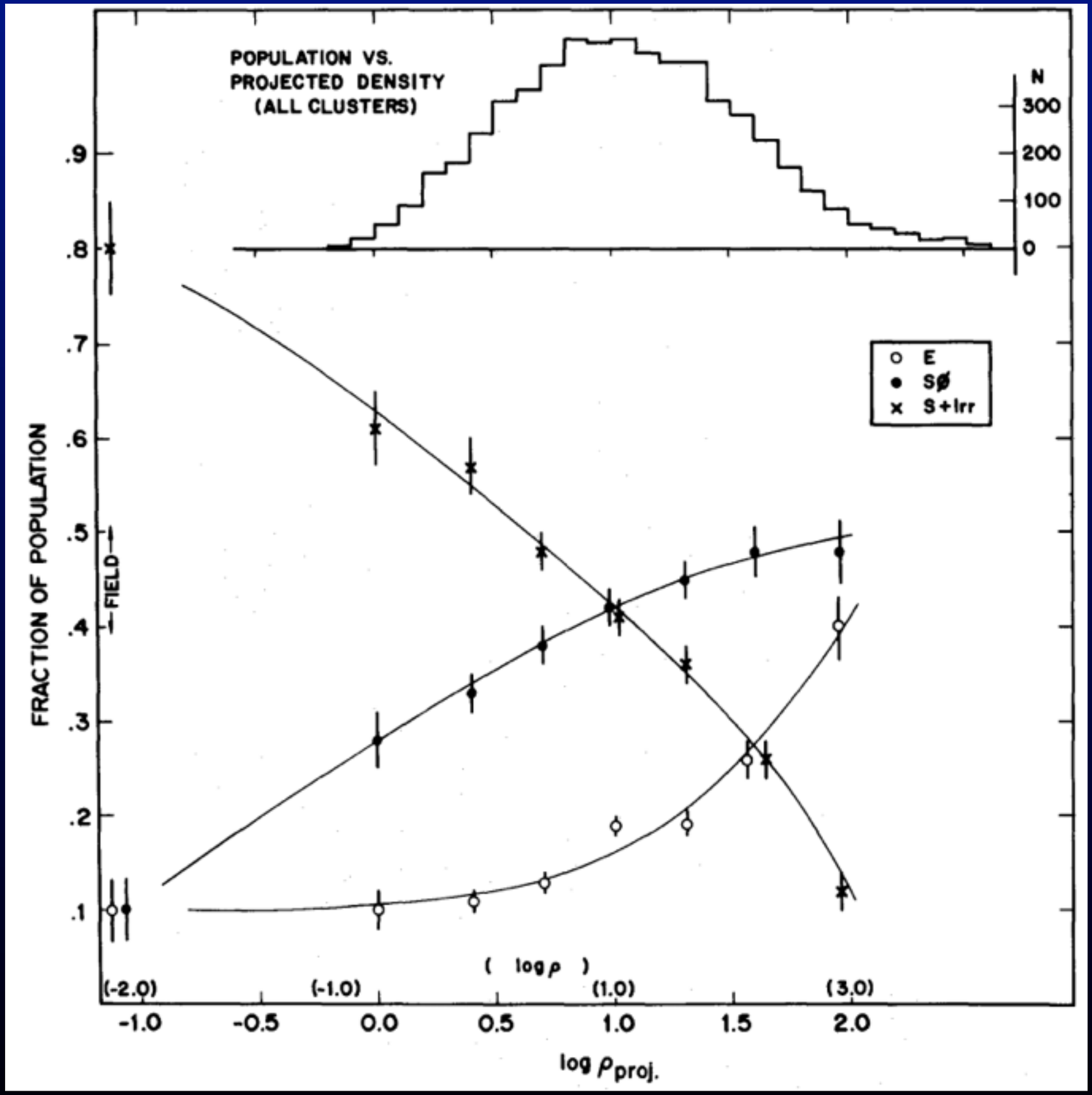


Dressler 1980

# Growth of galaxy groups

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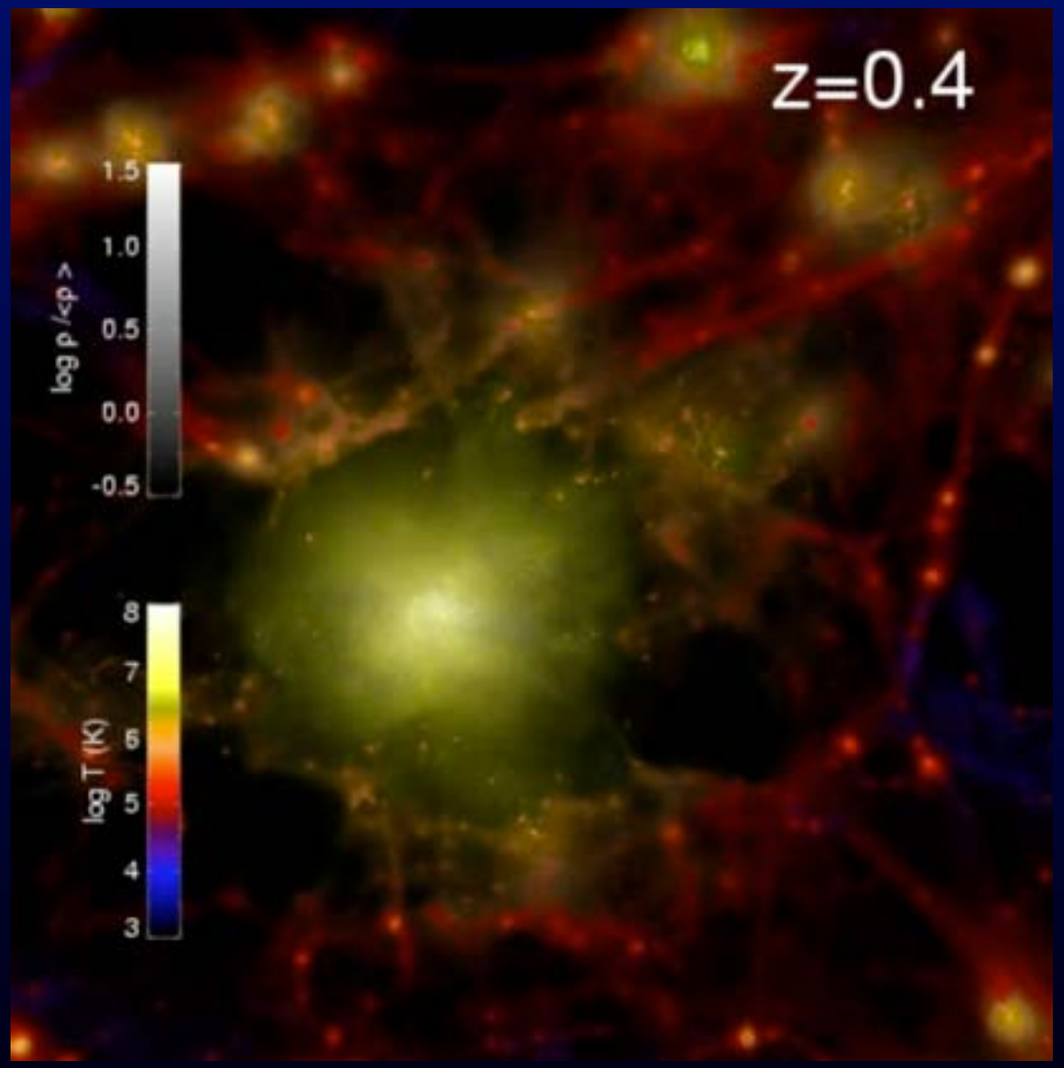

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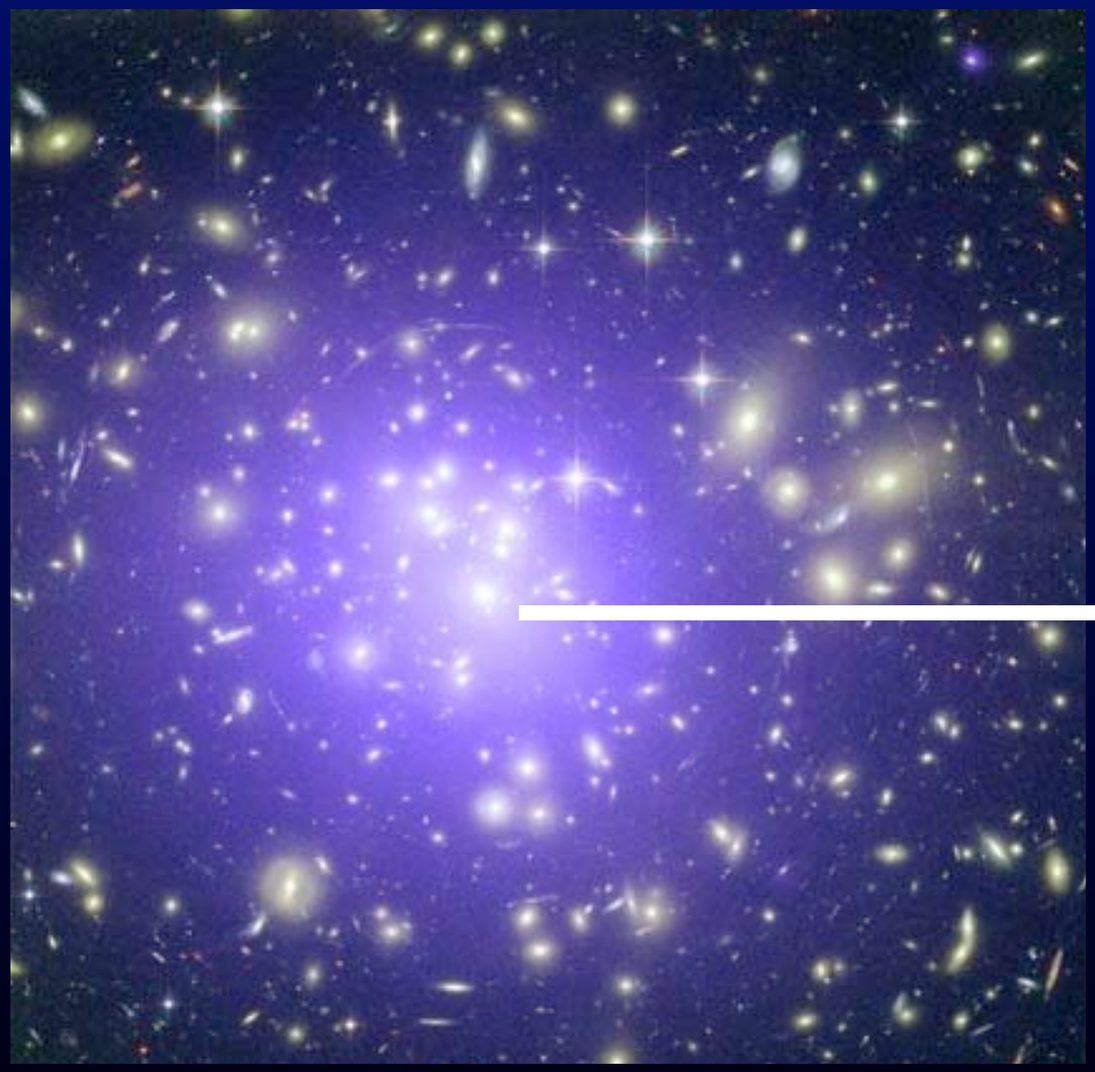

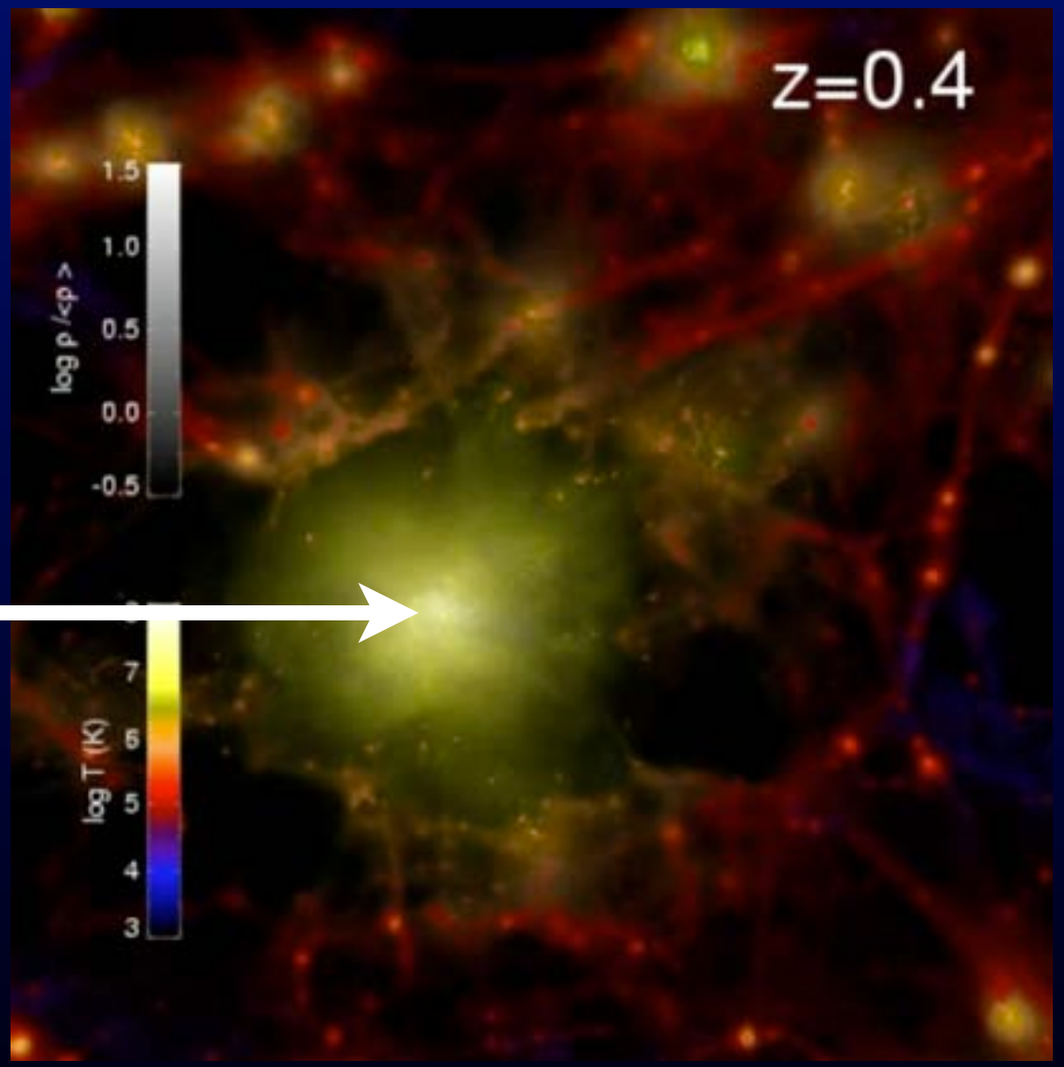

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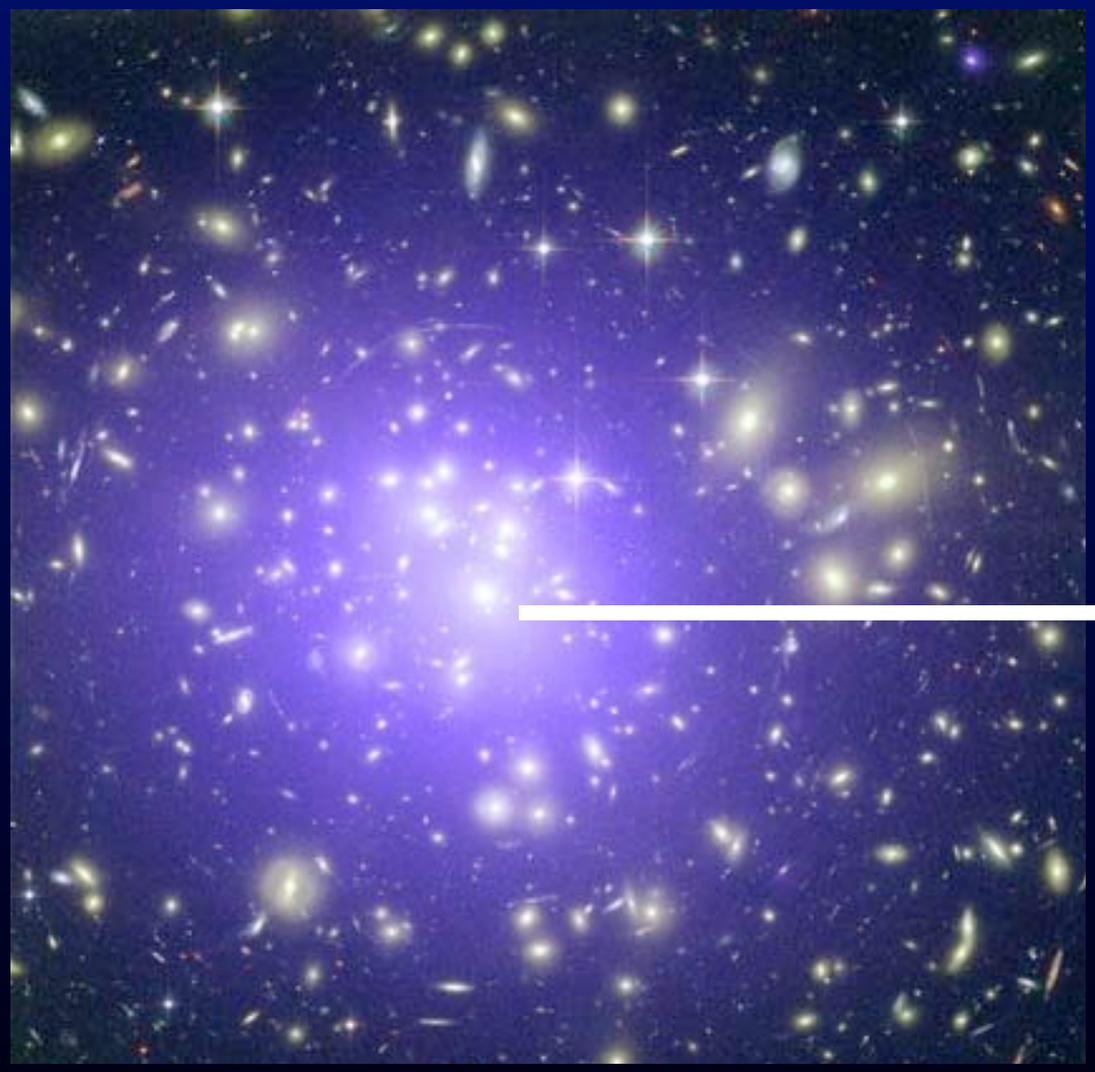

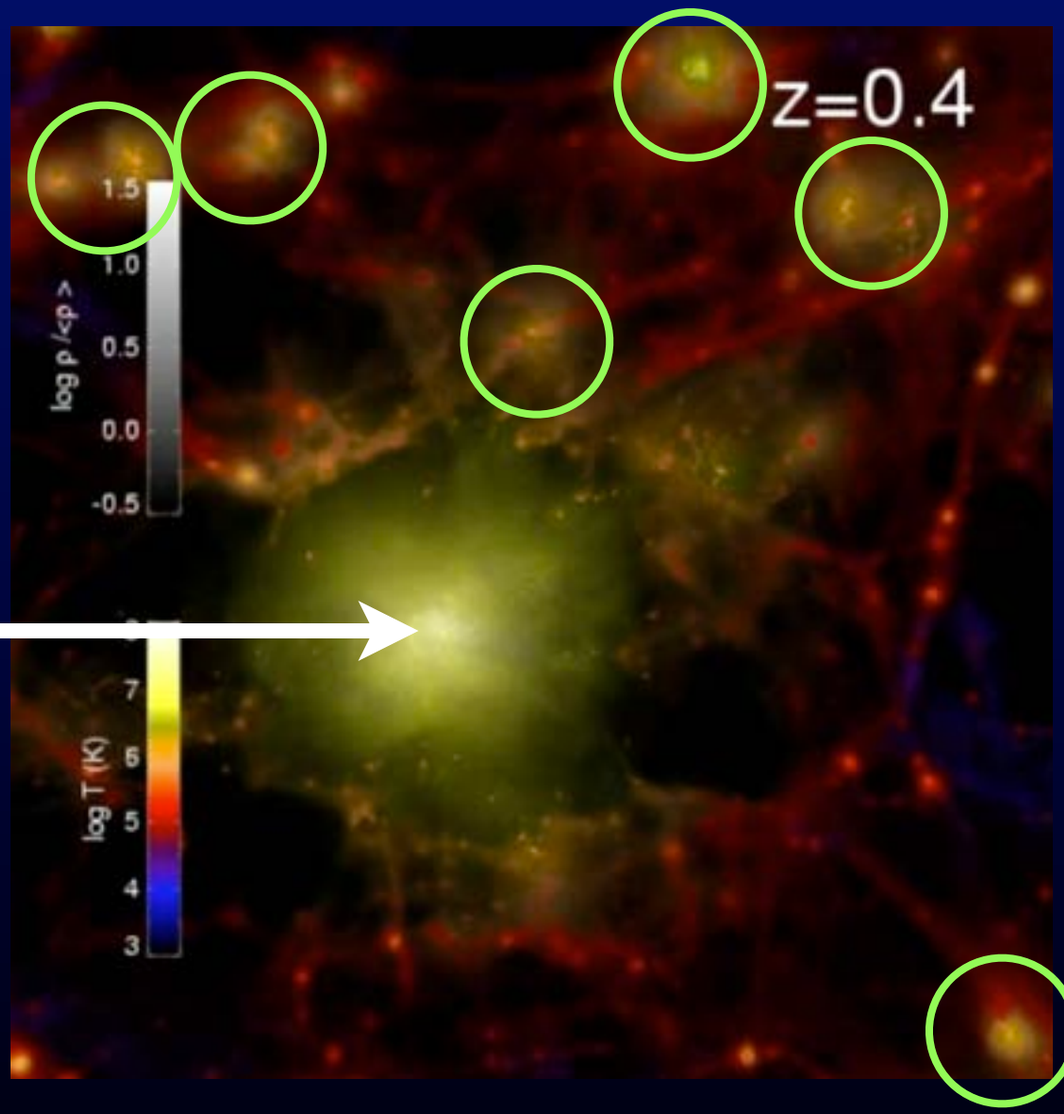

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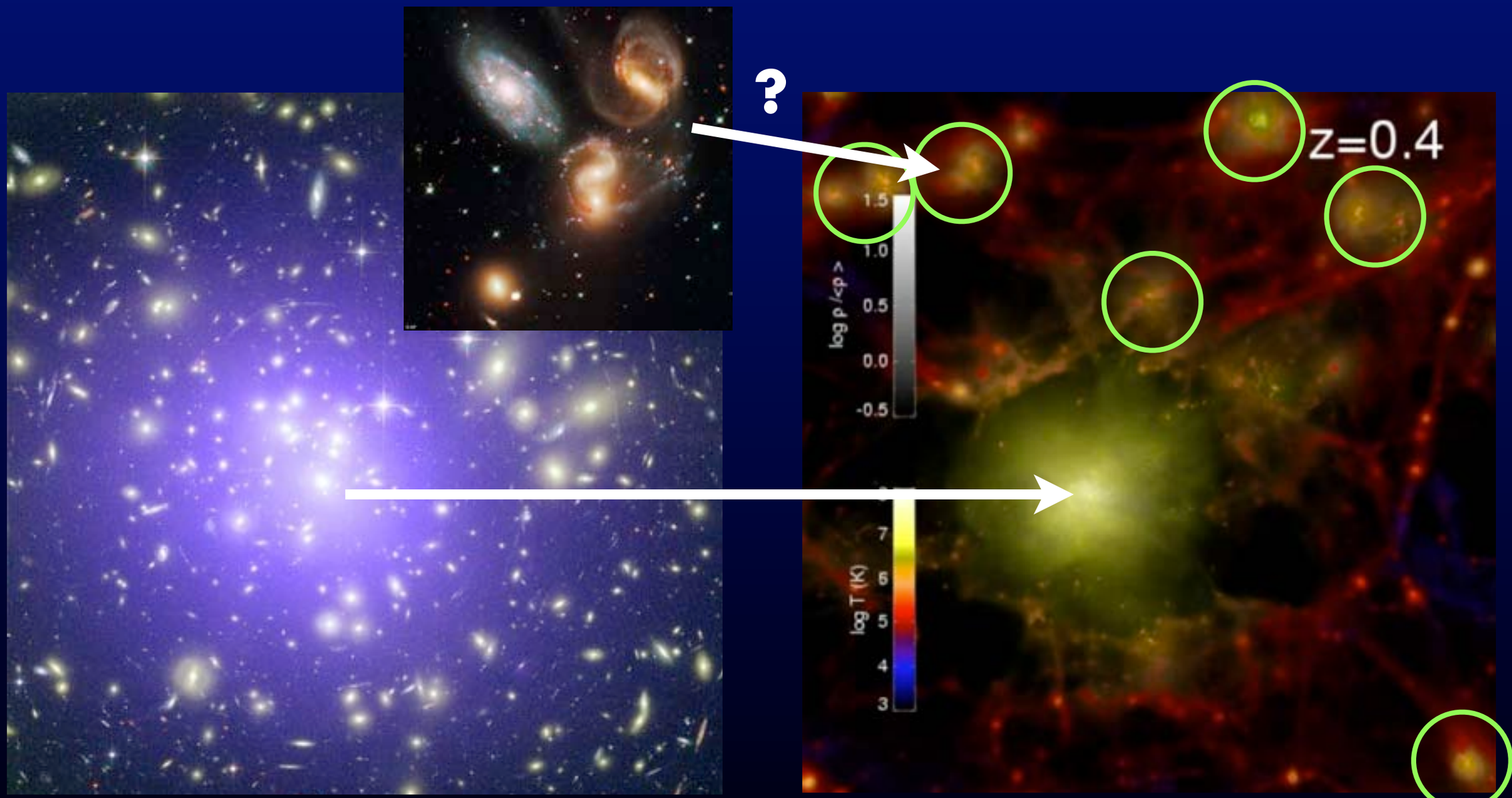

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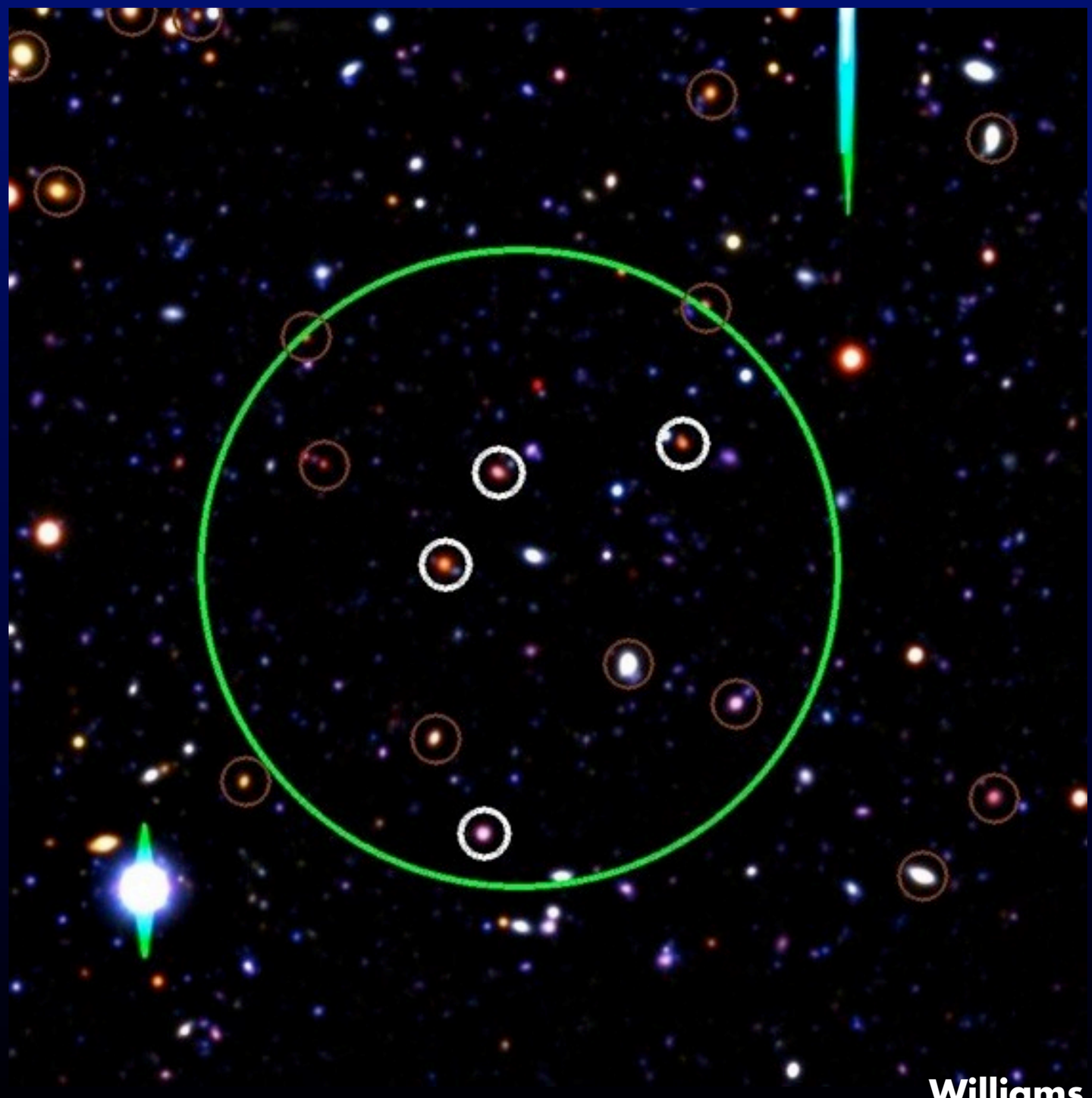

Williams et al. 2012

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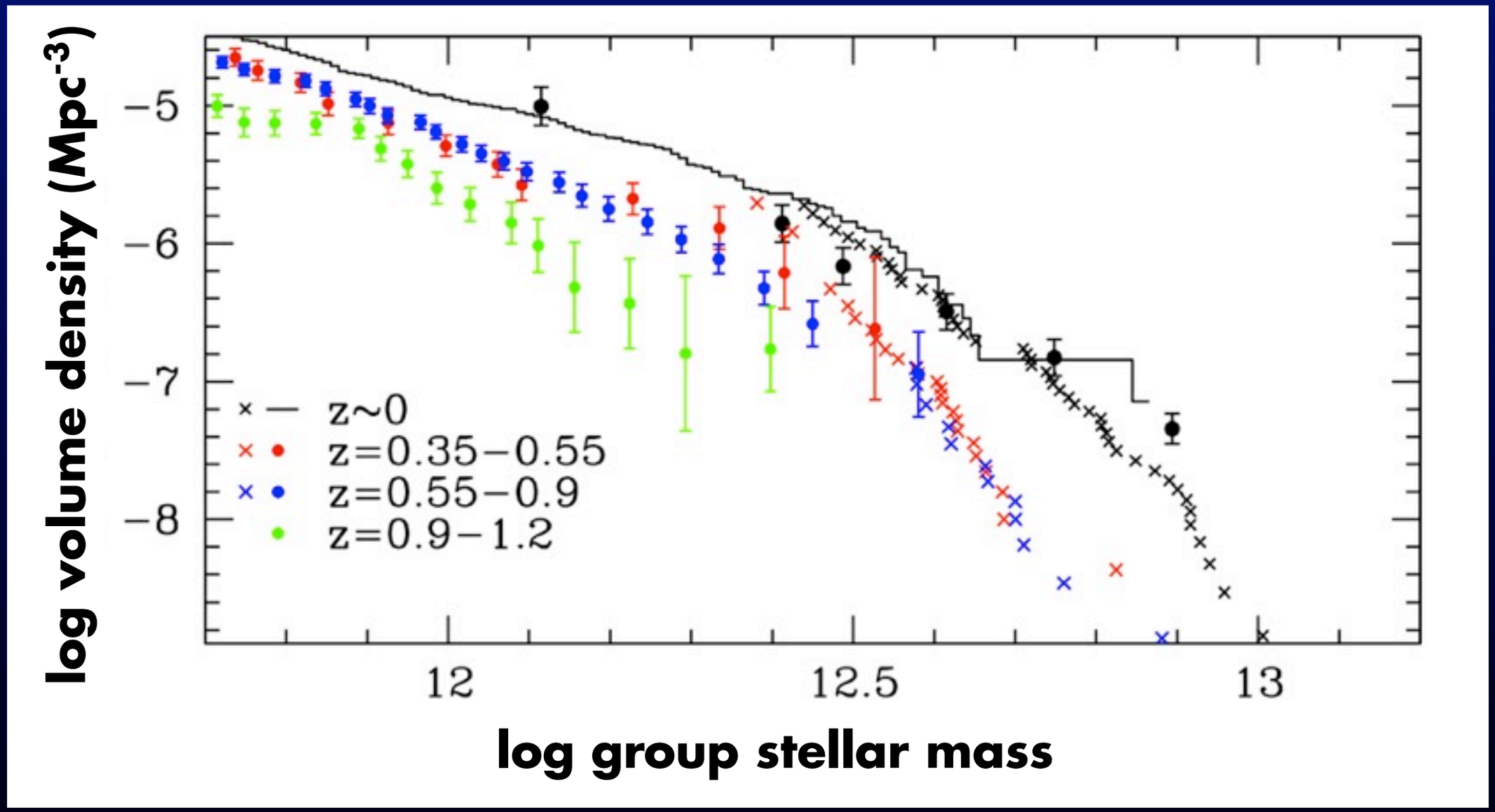


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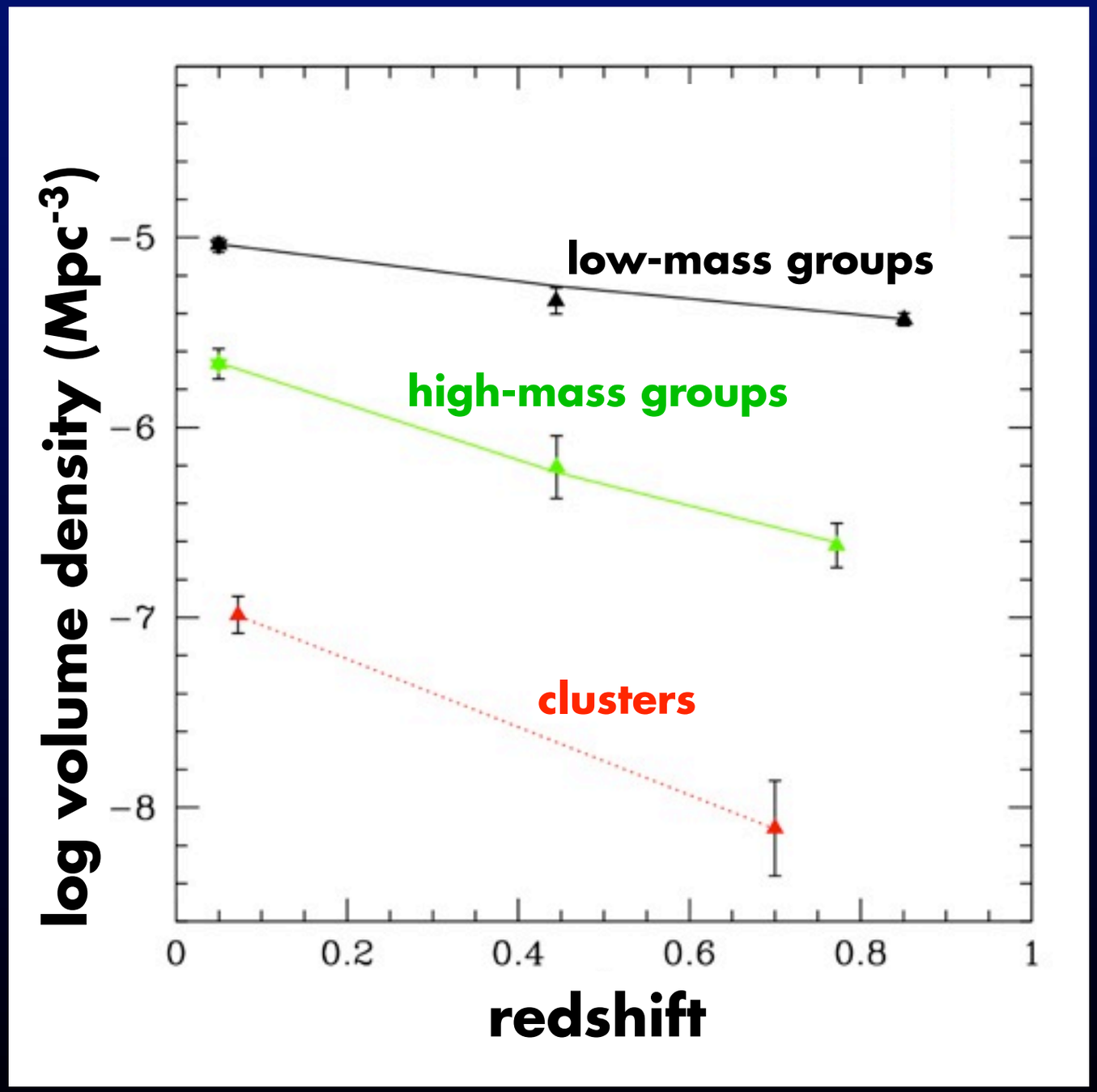


Williams et al. 2012

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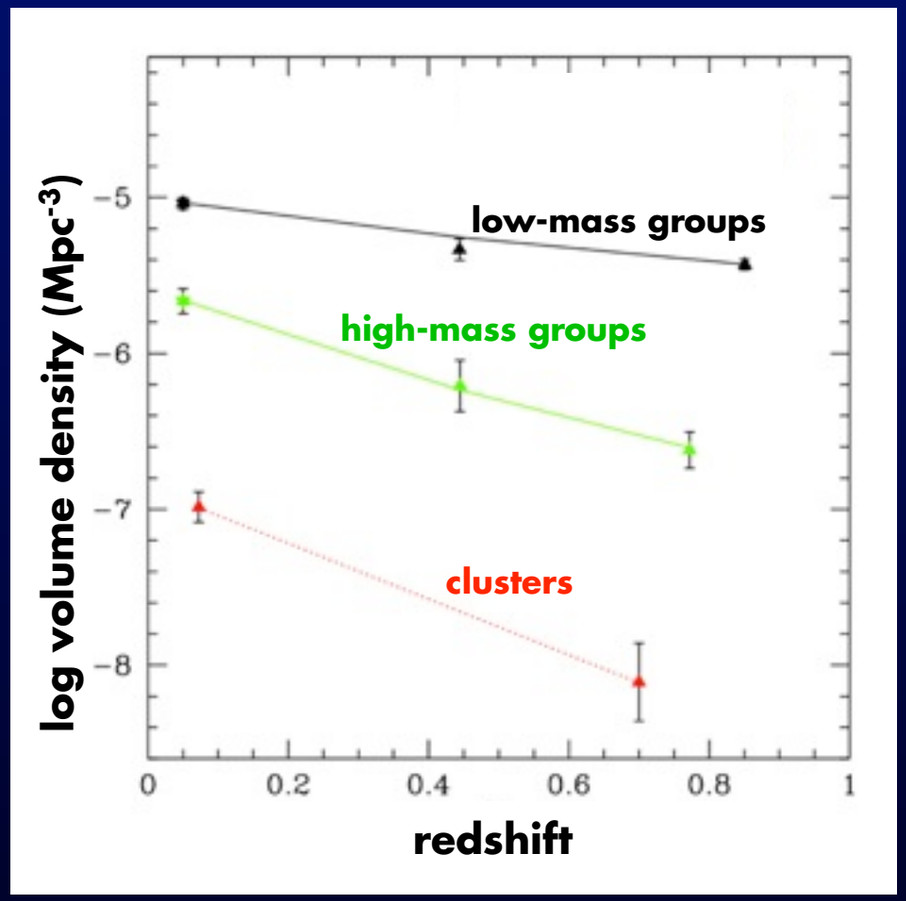
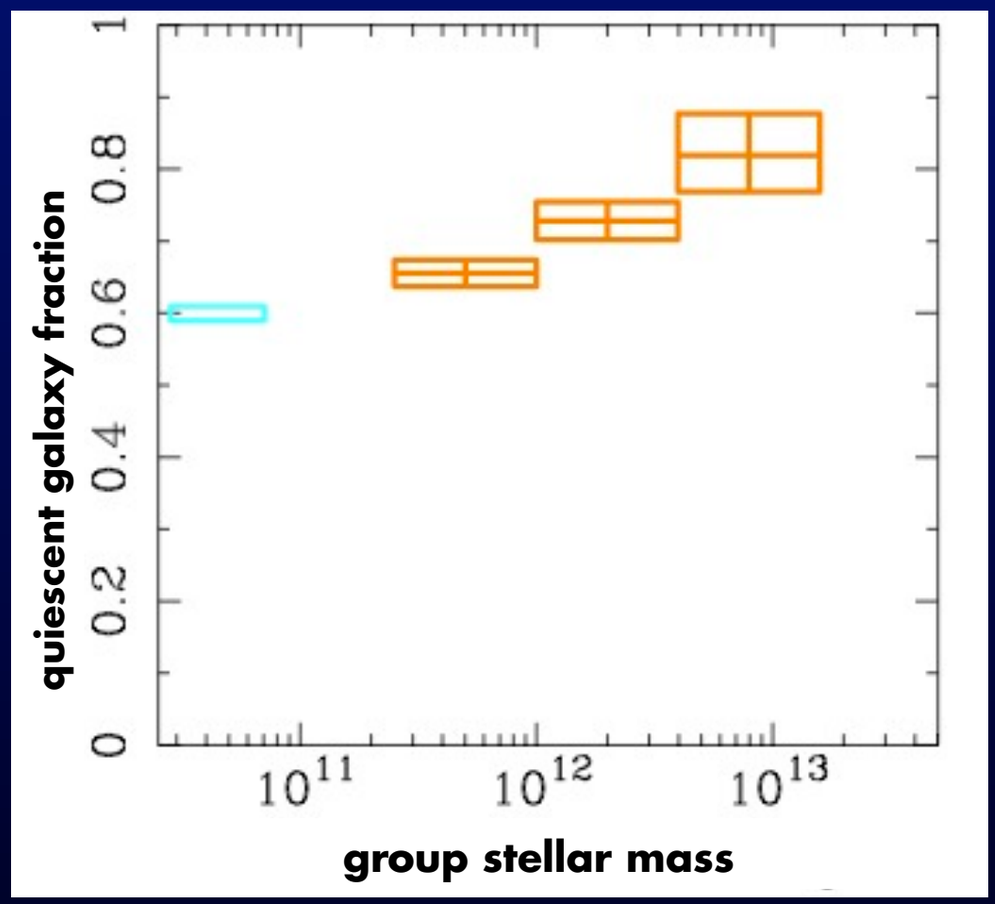
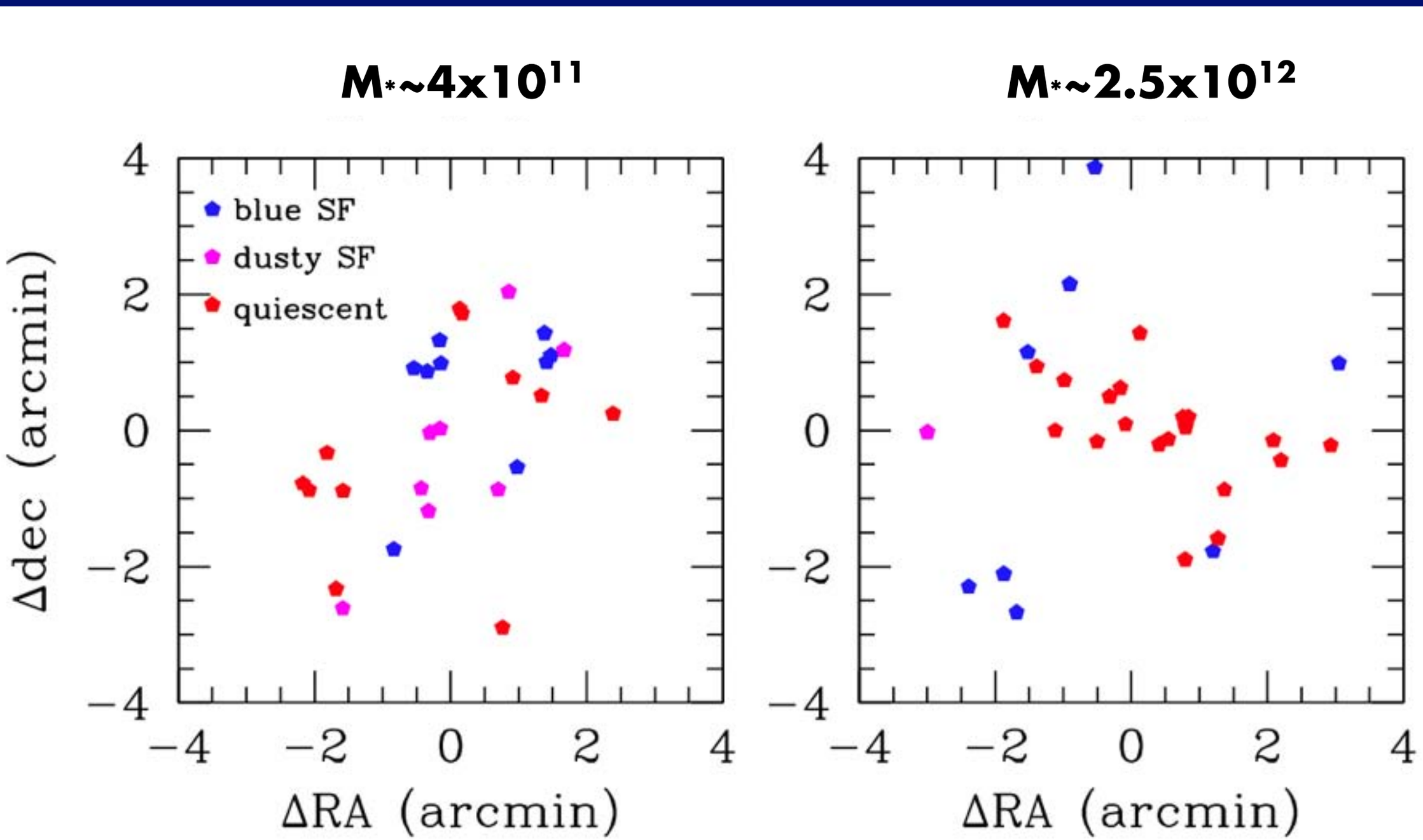



Williams et al. 2012




Williams et al., in prep

# High-resolution followup (preliminary!)



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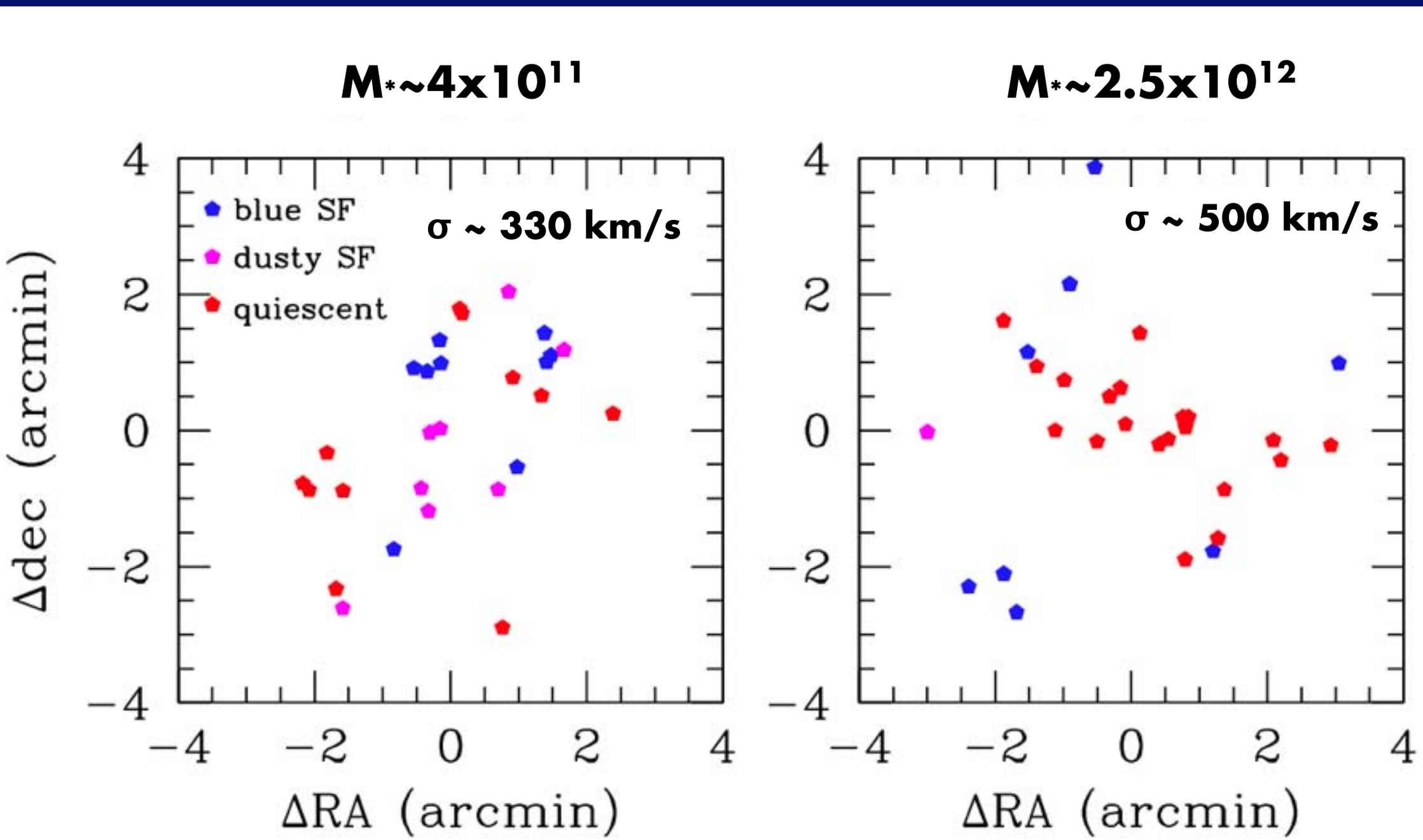
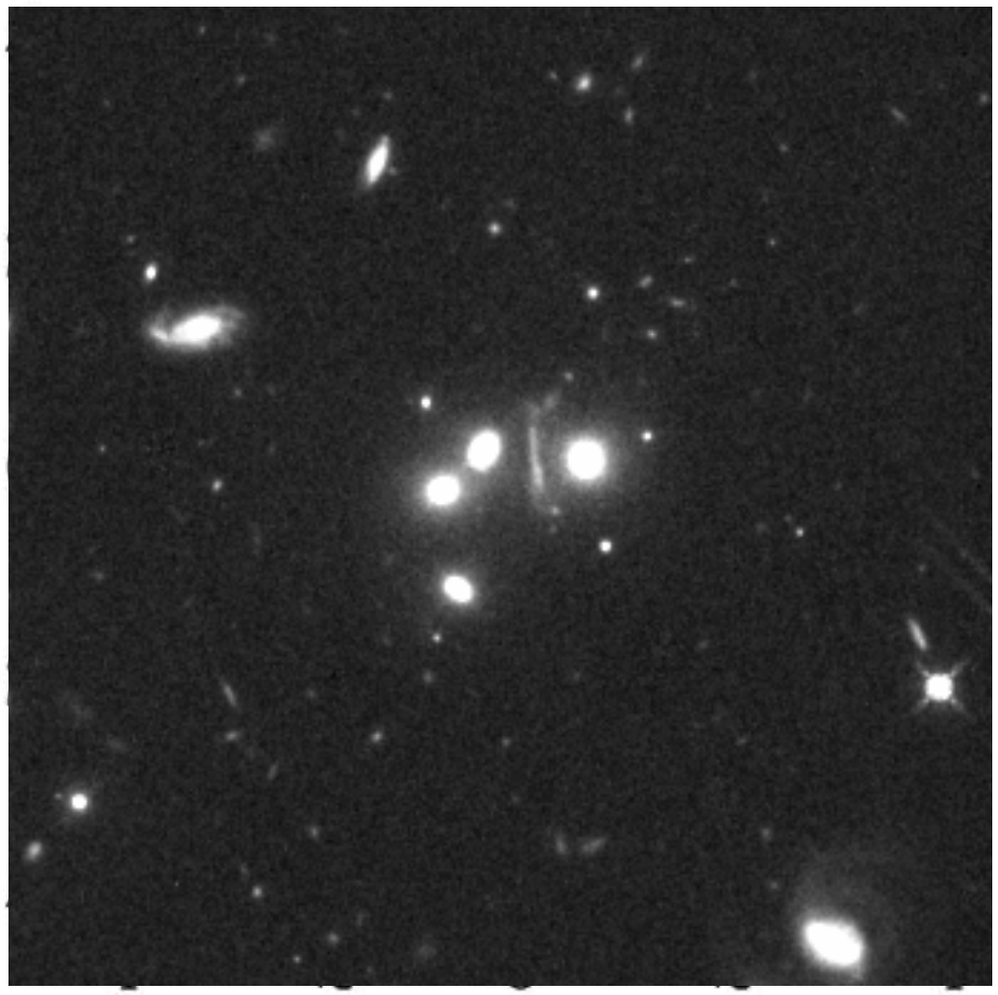
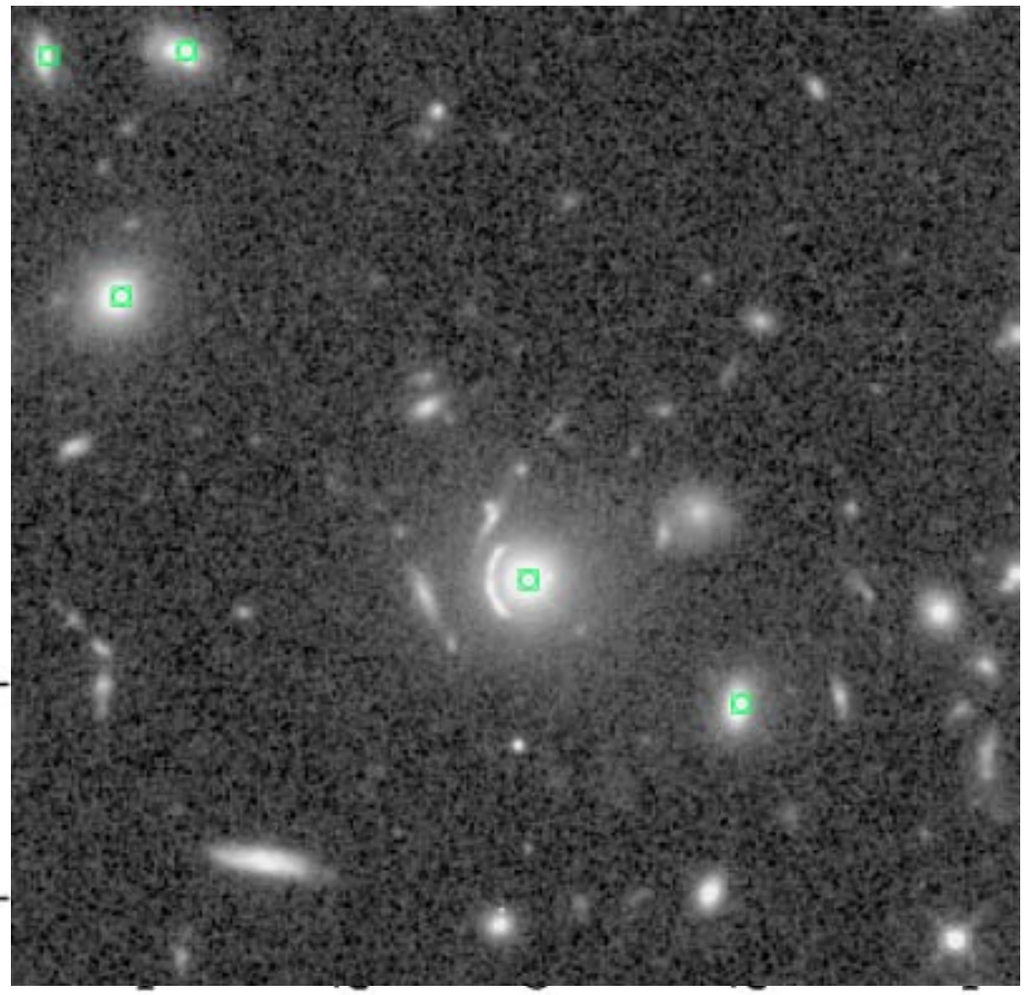


# High-resolution followup (preliminary!)

$M_* \sim 4 \times 10^{11}$




$M_* \sim 2.5 \times 10^{12}$



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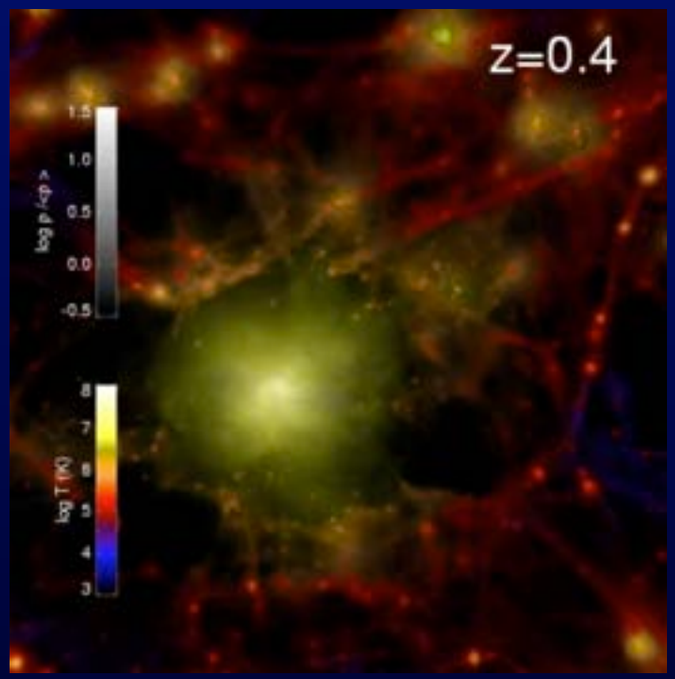

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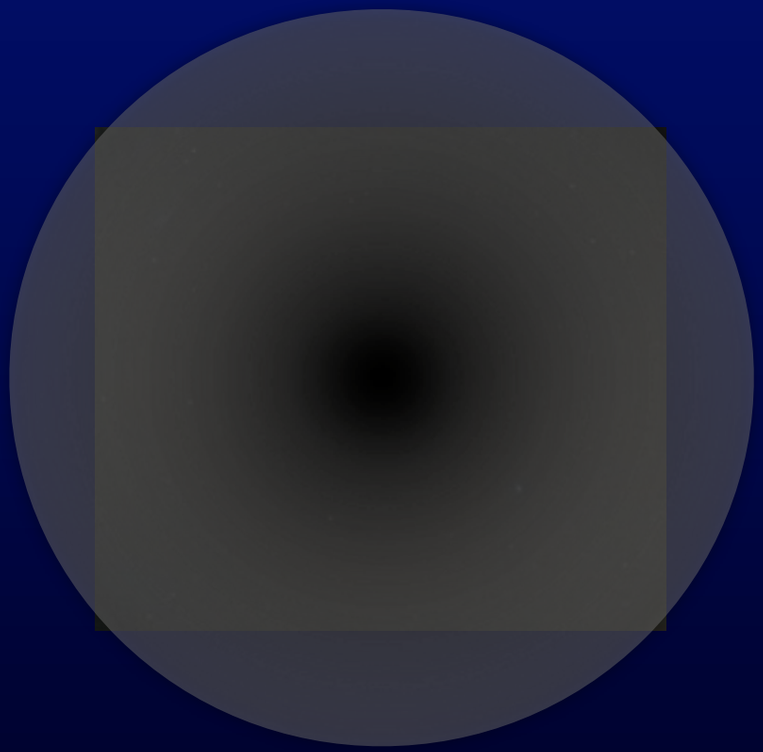

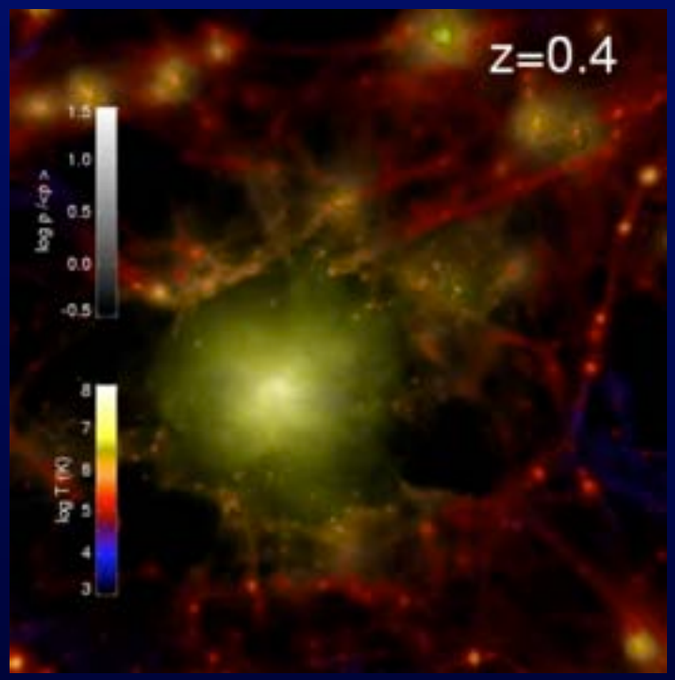

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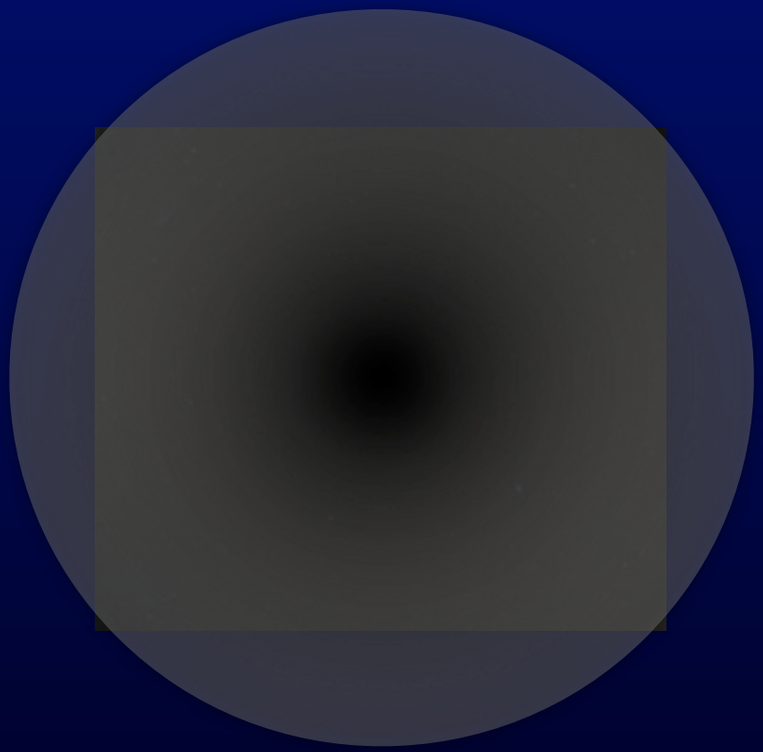

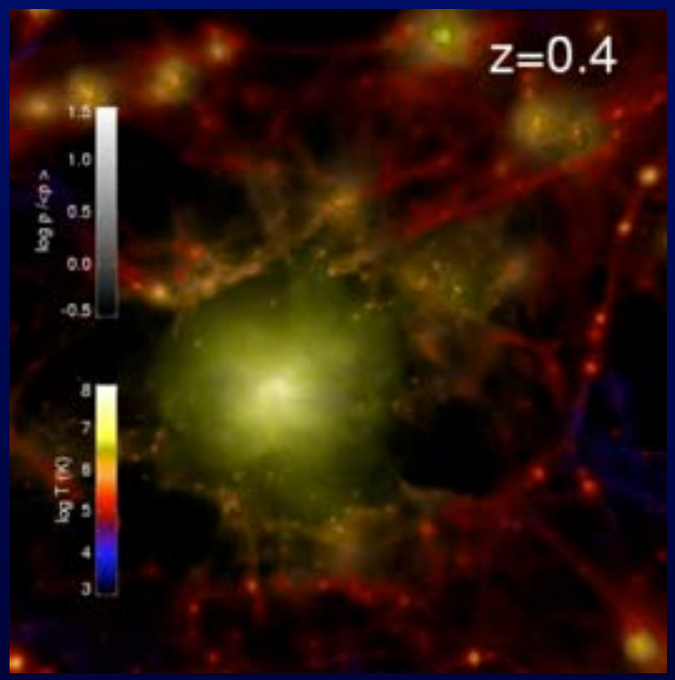

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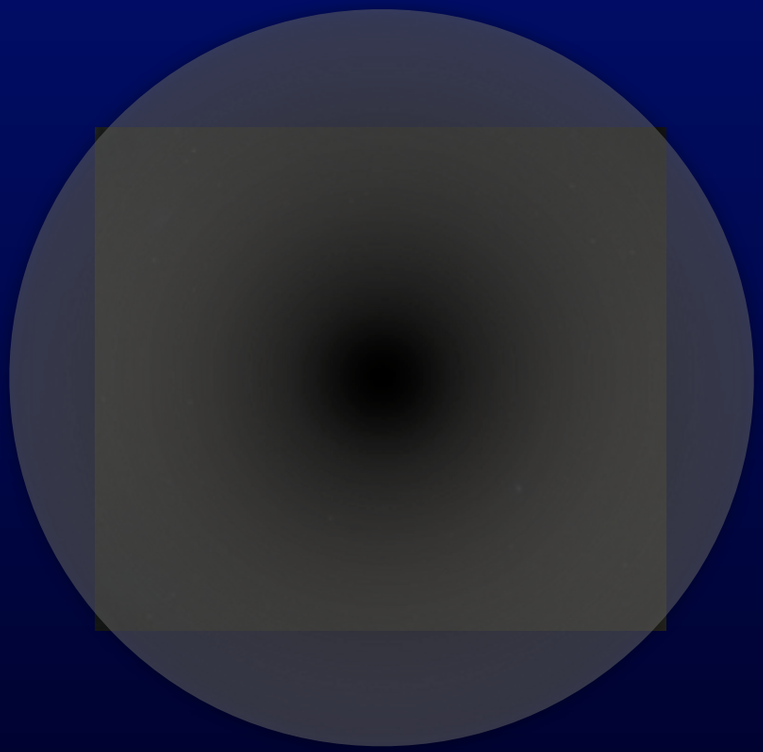

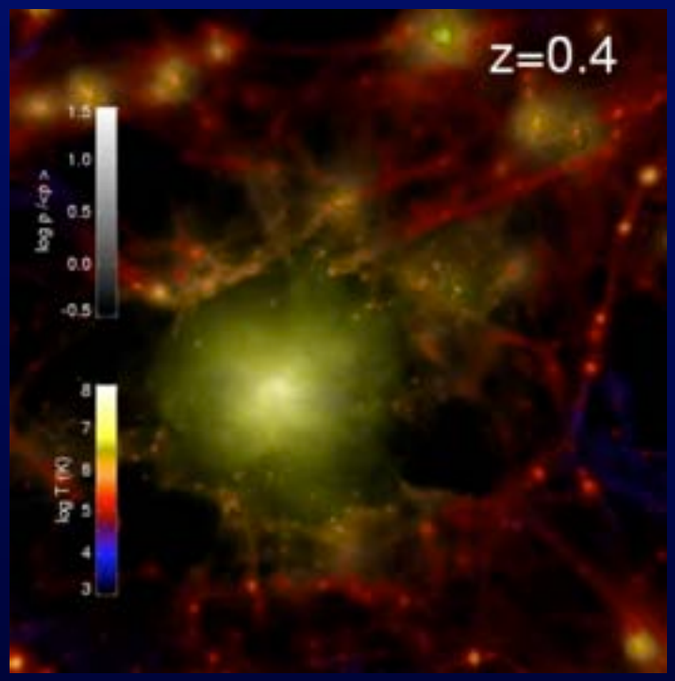


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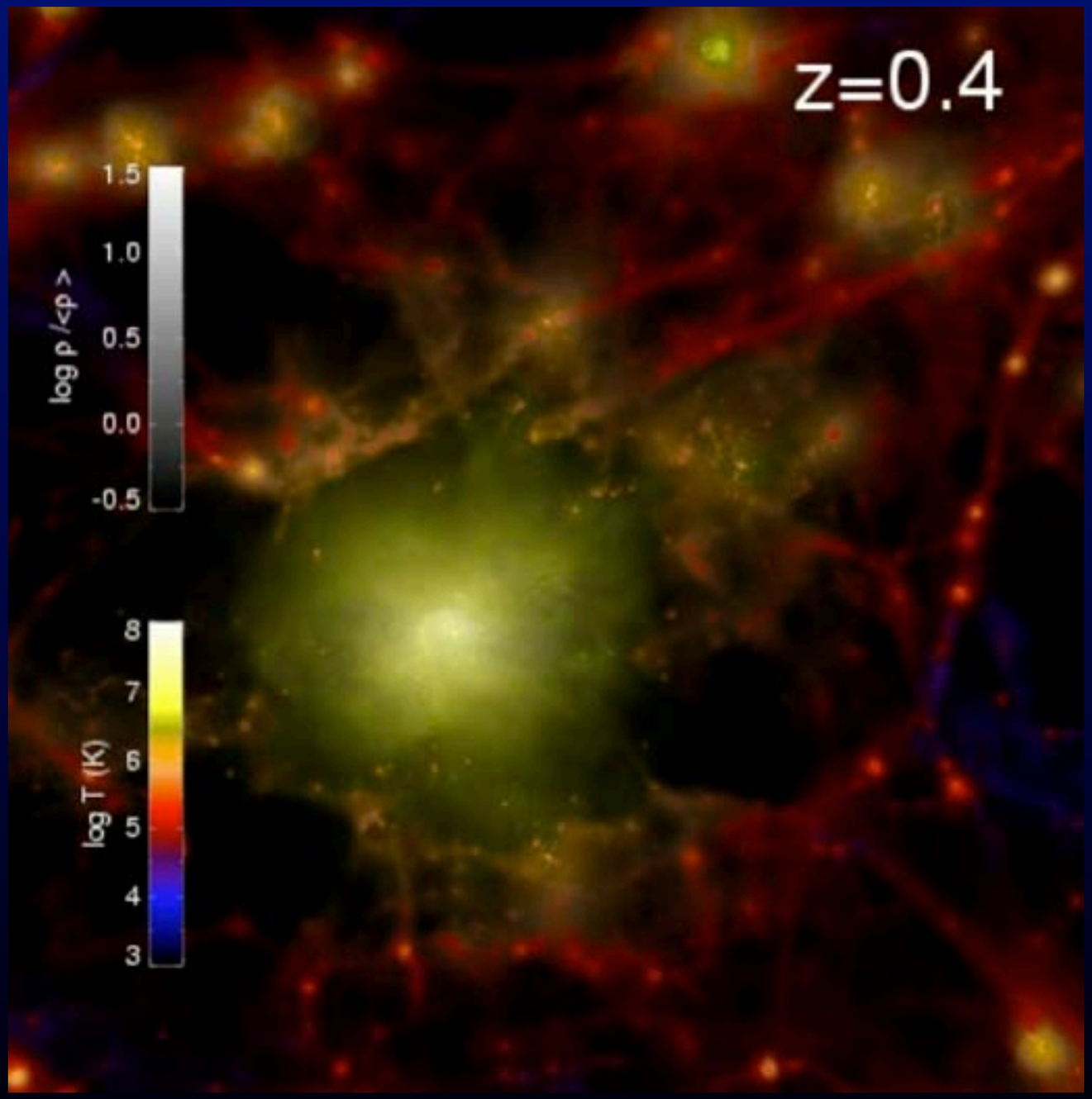
# Direct signatures of the thermal era



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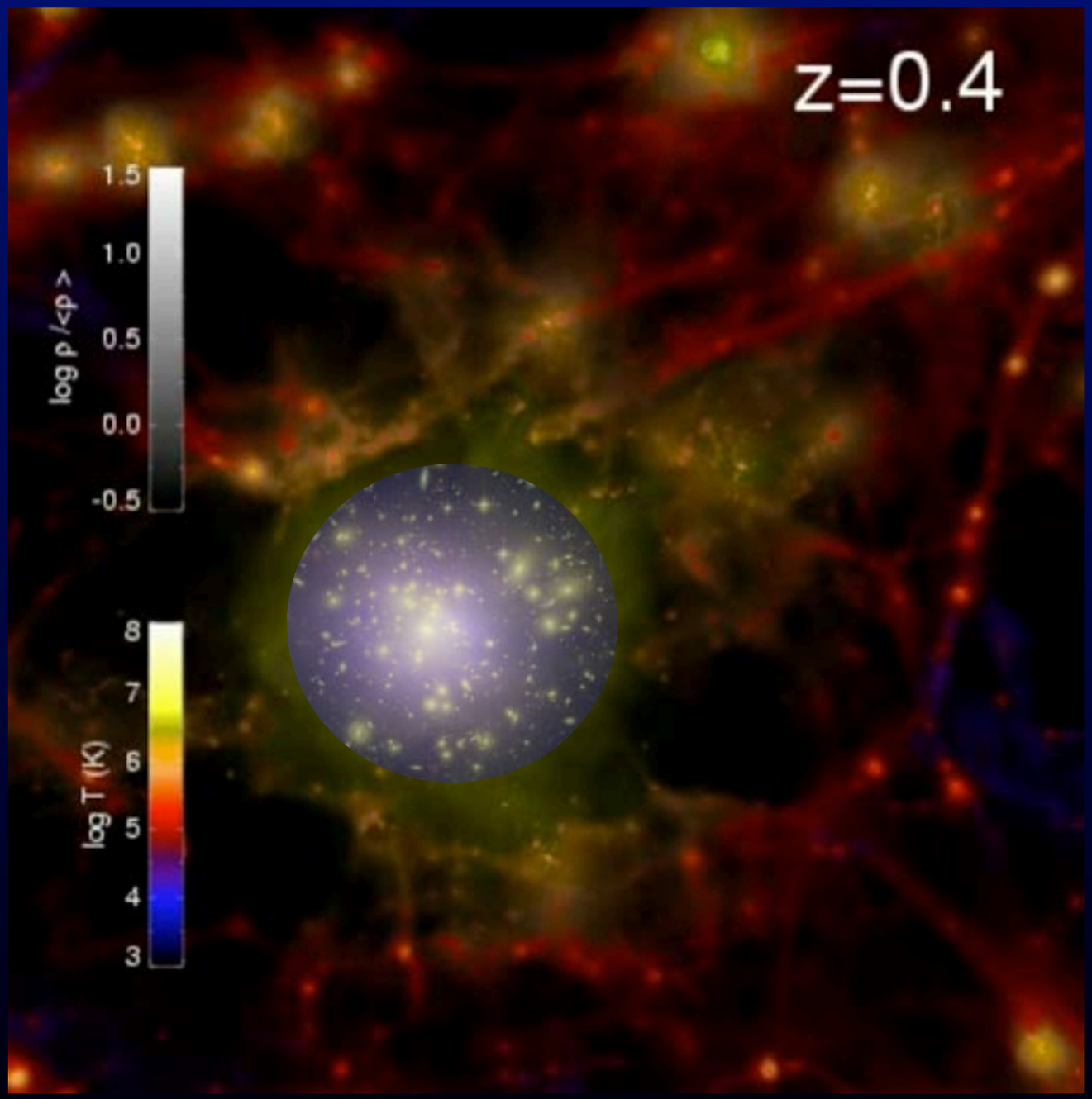

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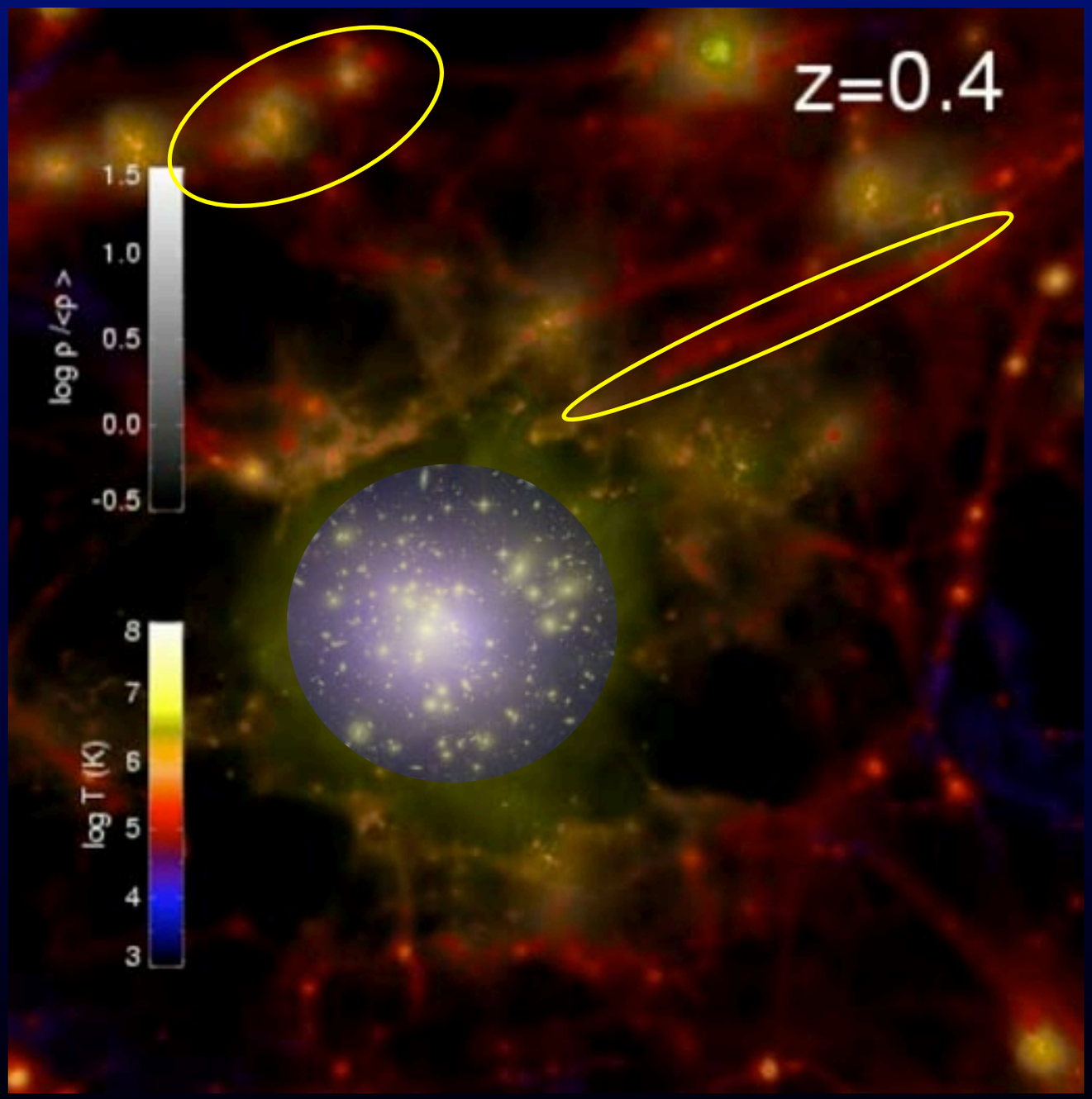

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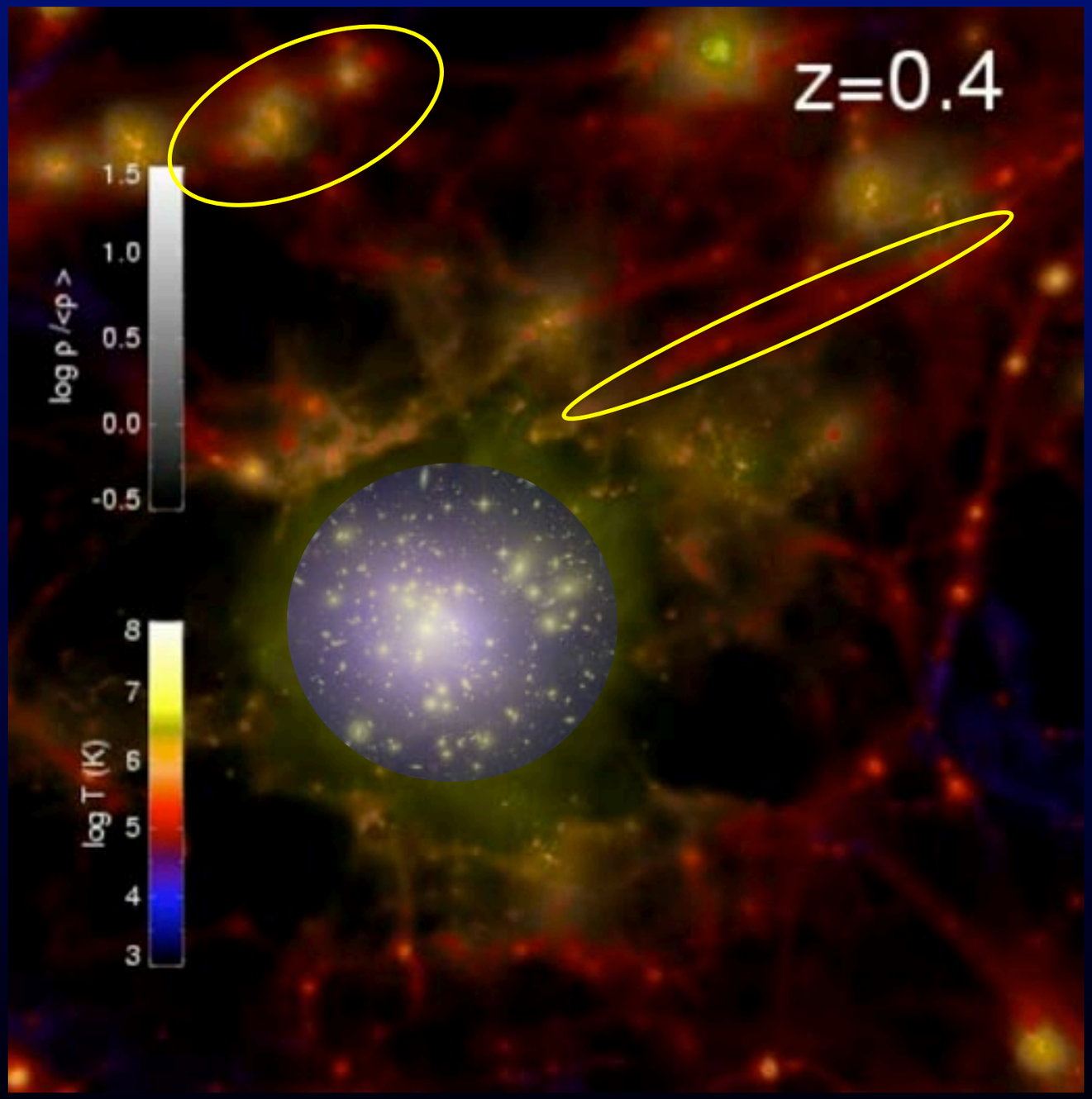


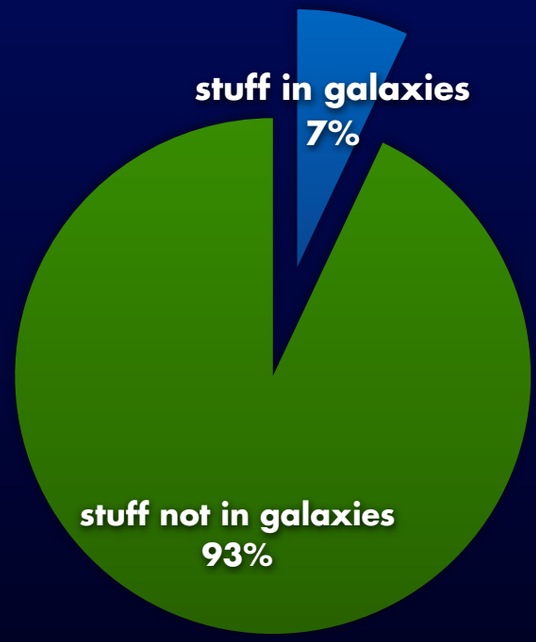

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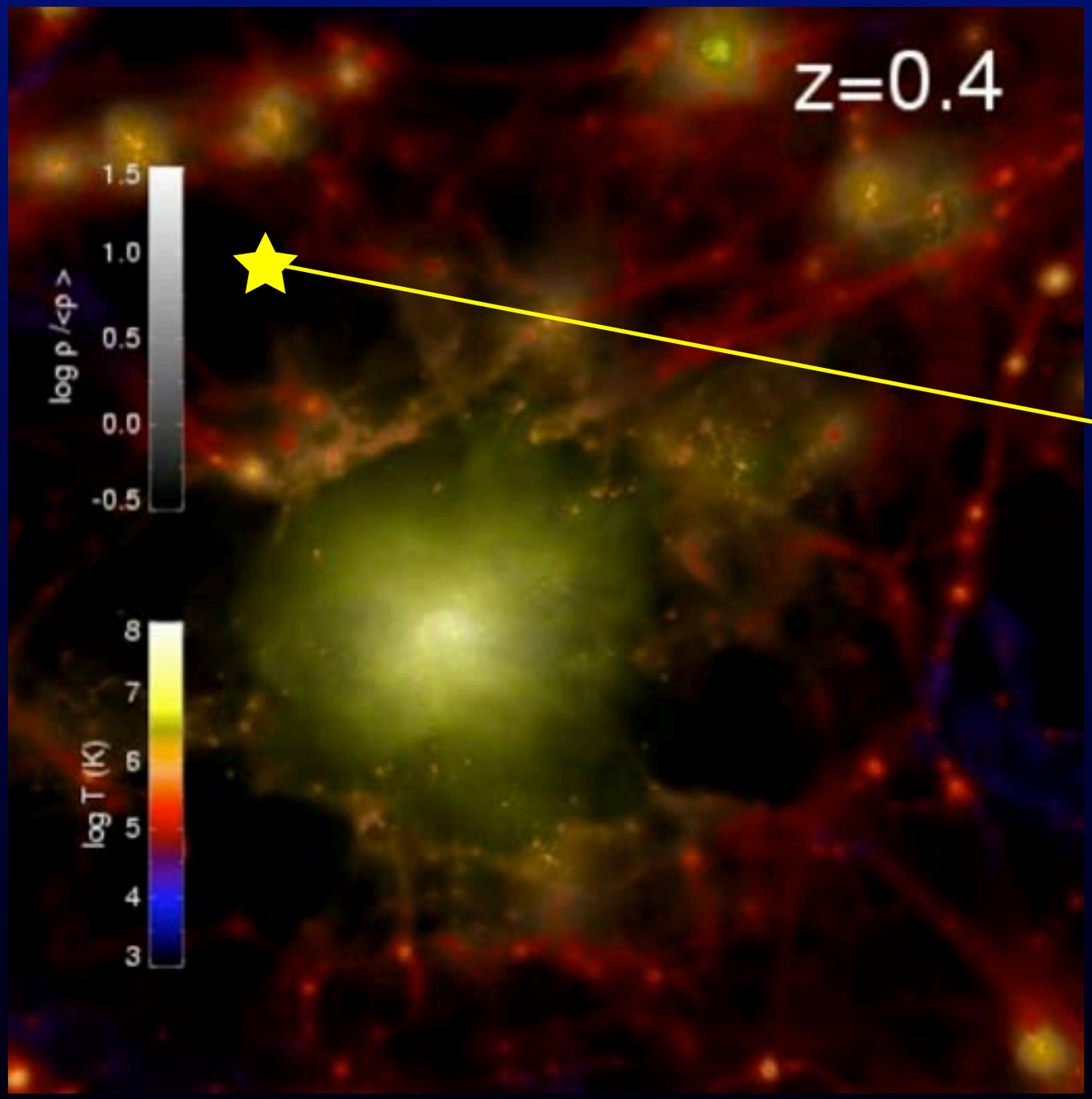


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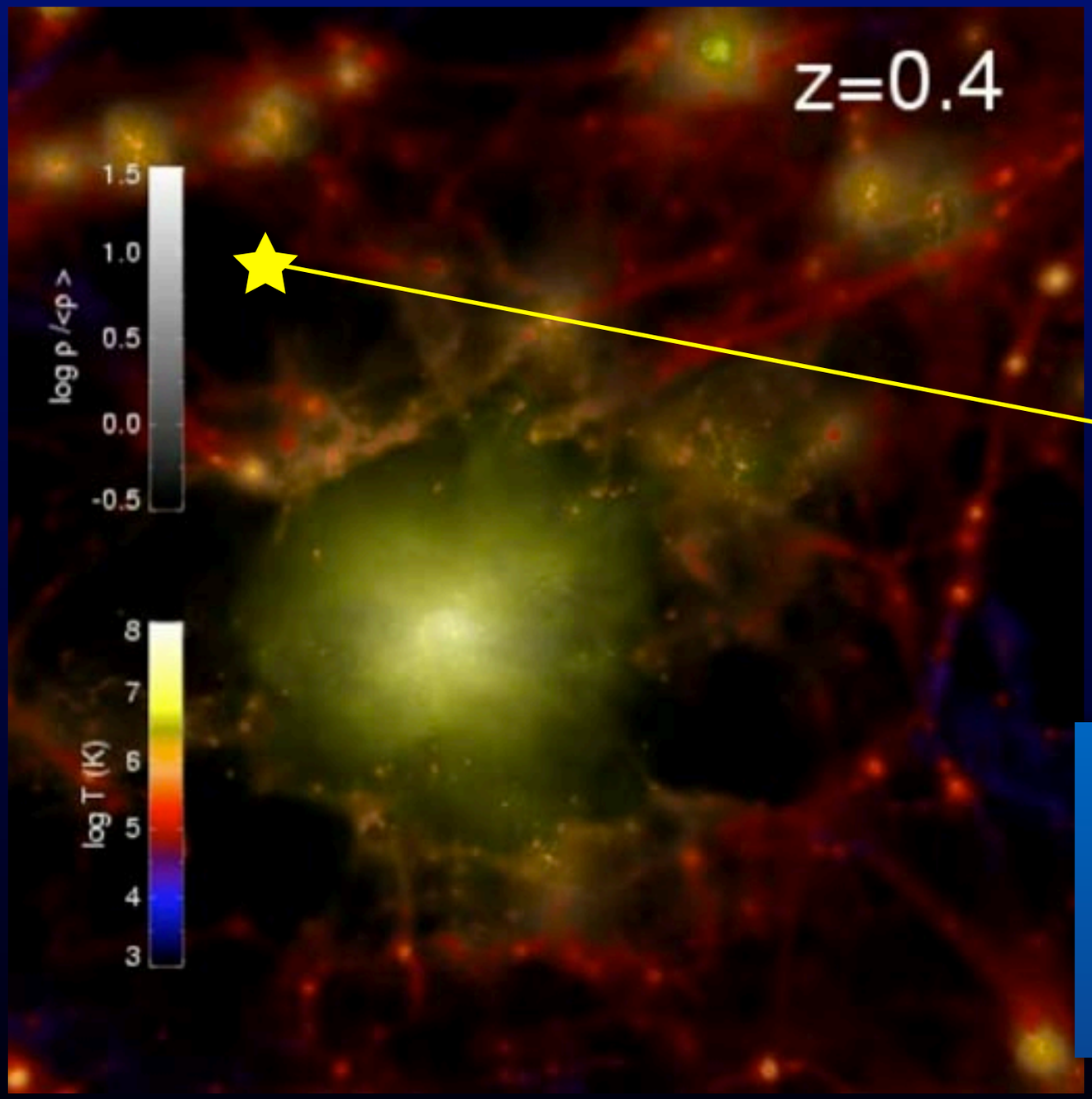


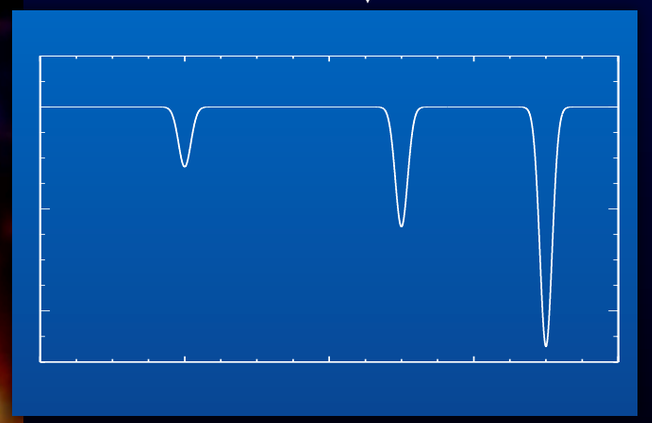

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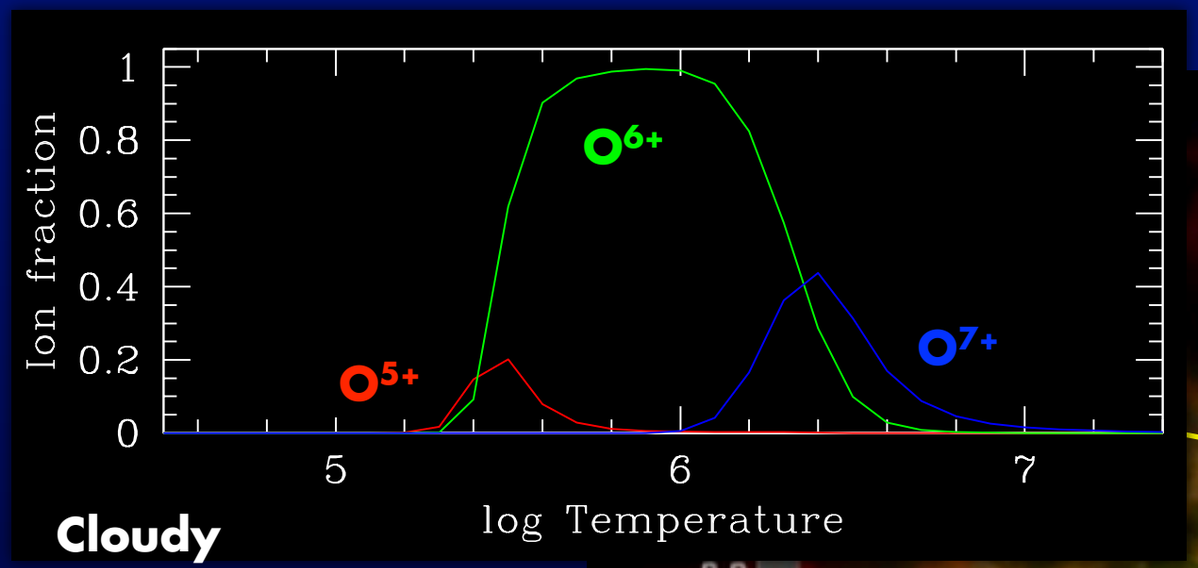
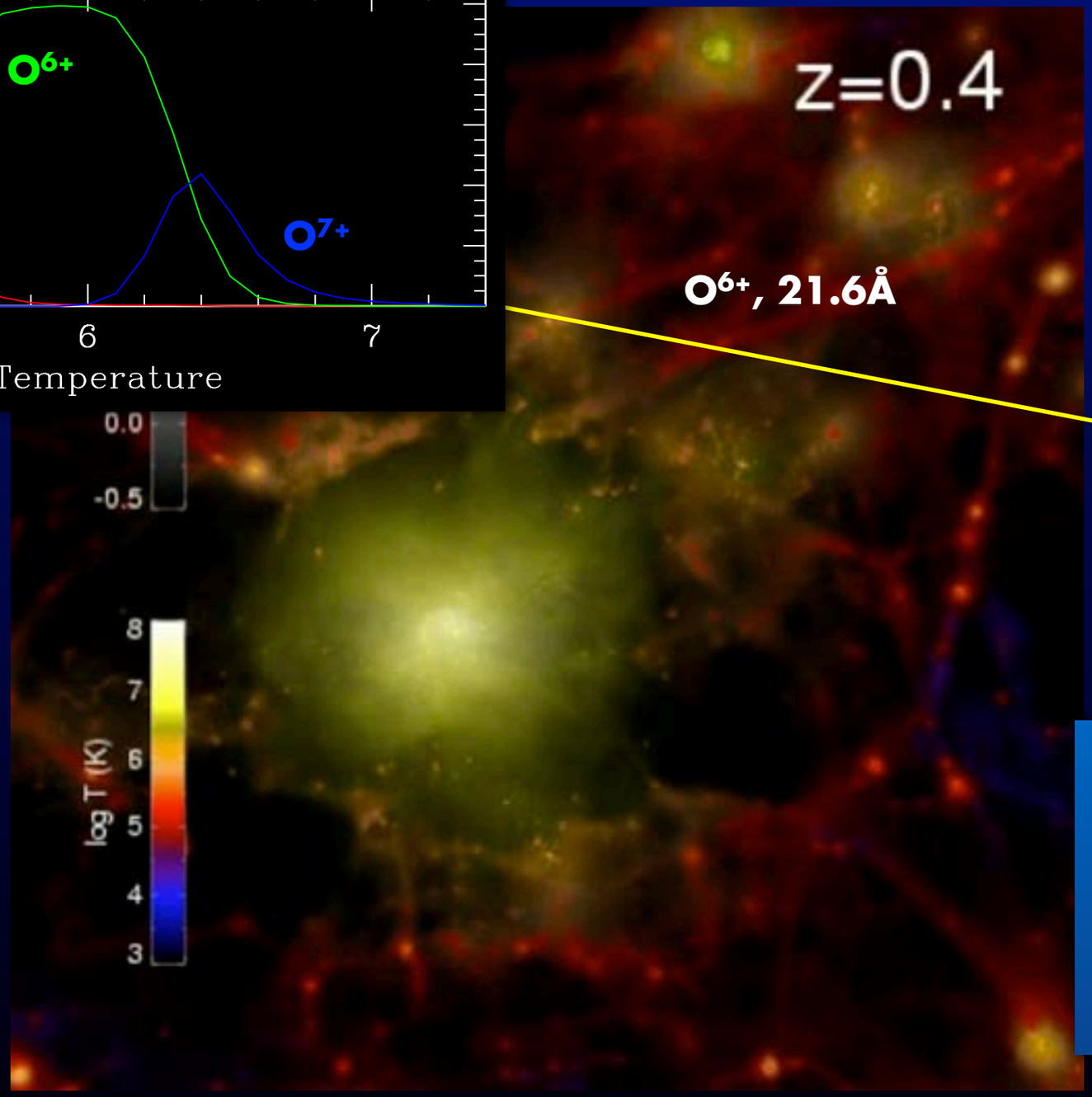
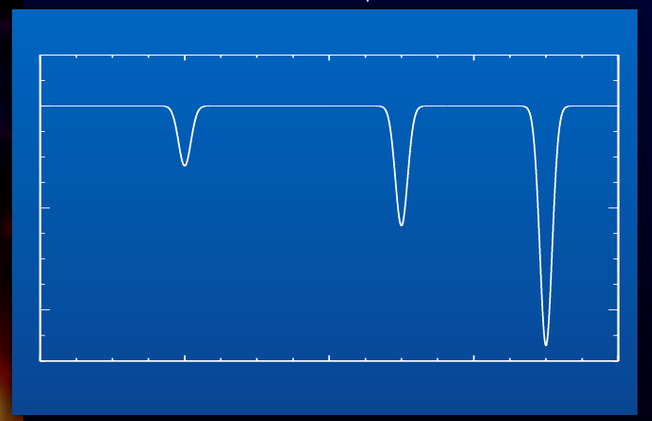
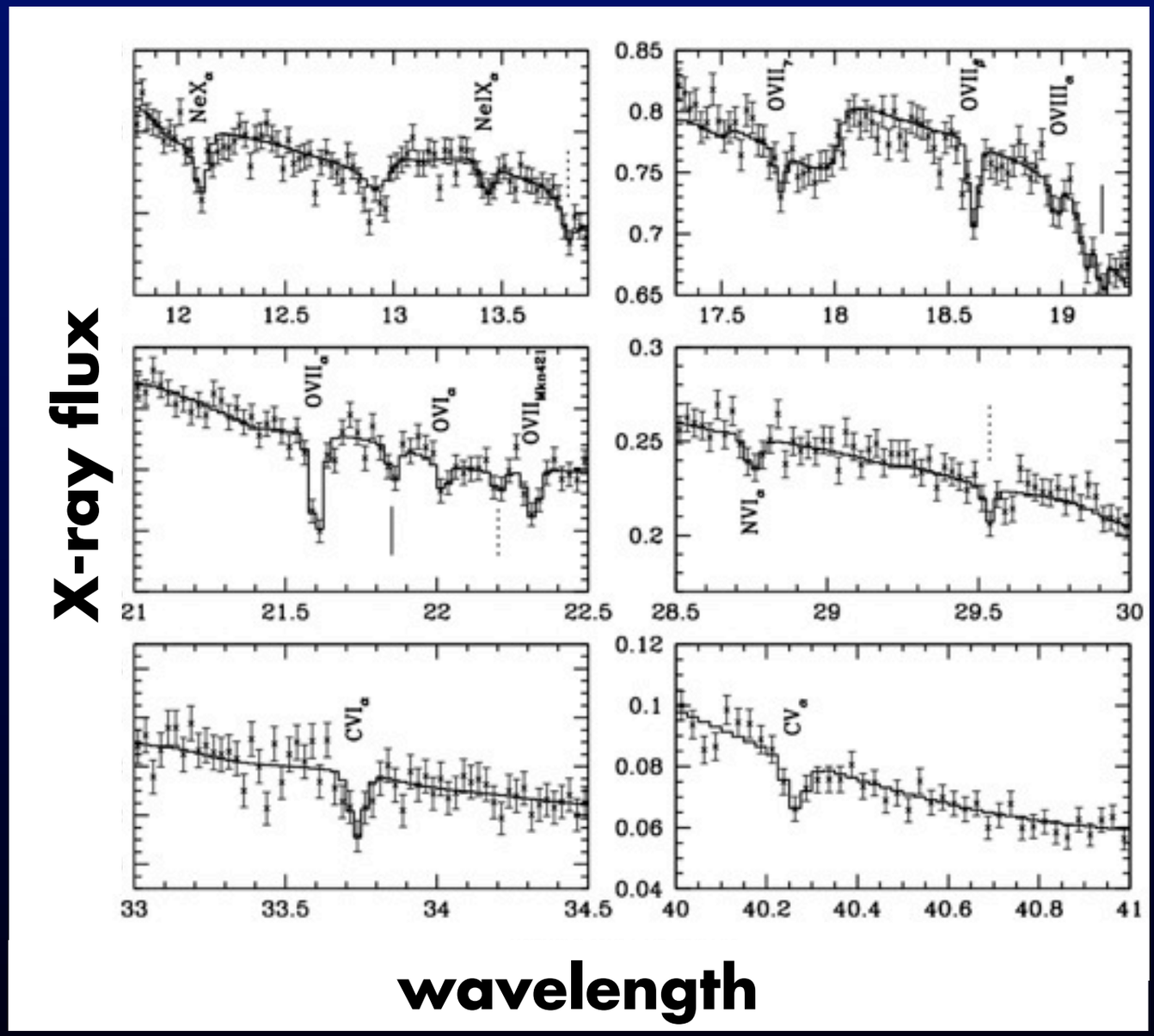


# Direct signatures of the thermal era




Williams et al. 2005

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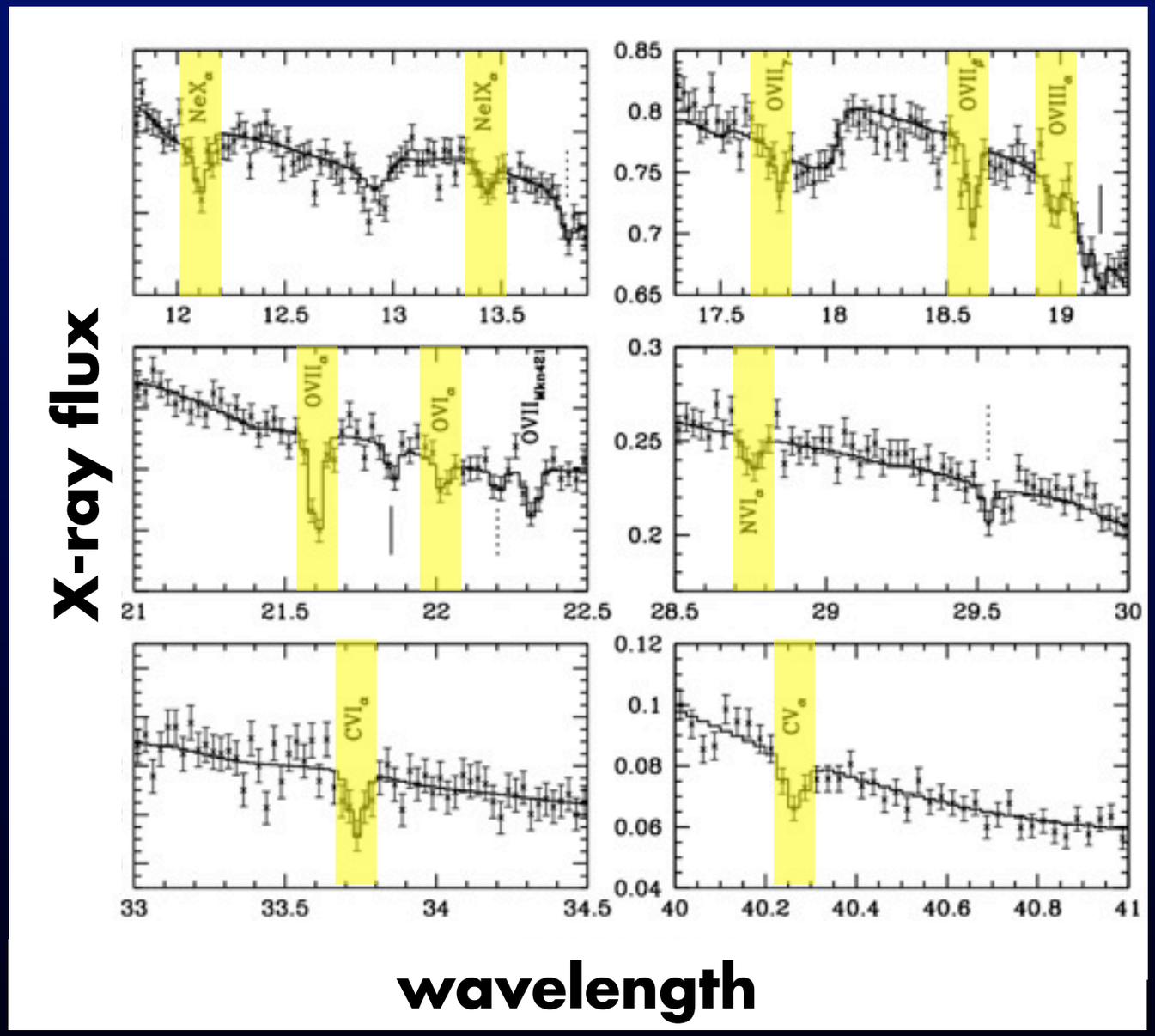


Local

Williams et al. 2005

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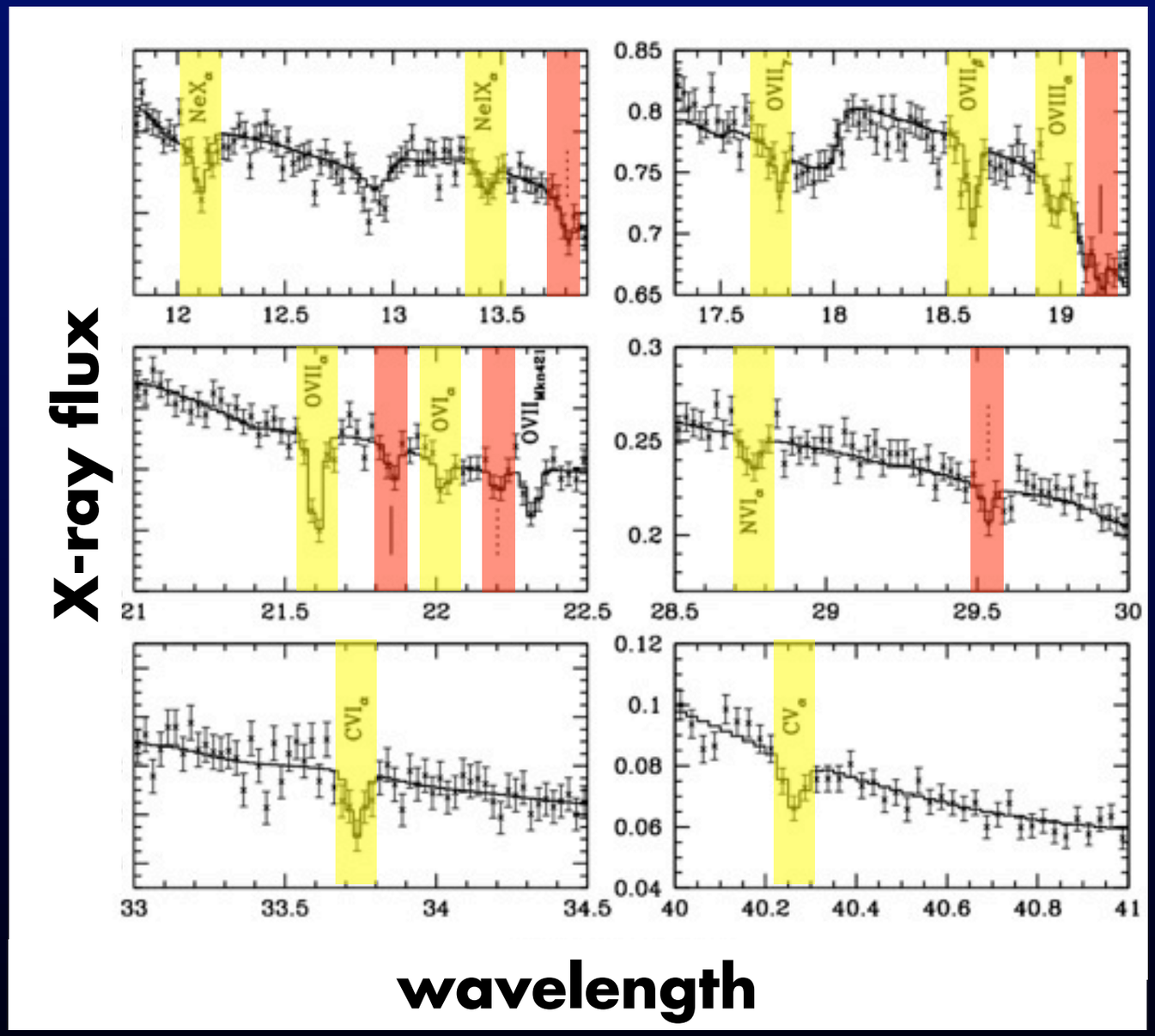


**Local**

**Groups/ Filaments?**

Williams et al. 2005

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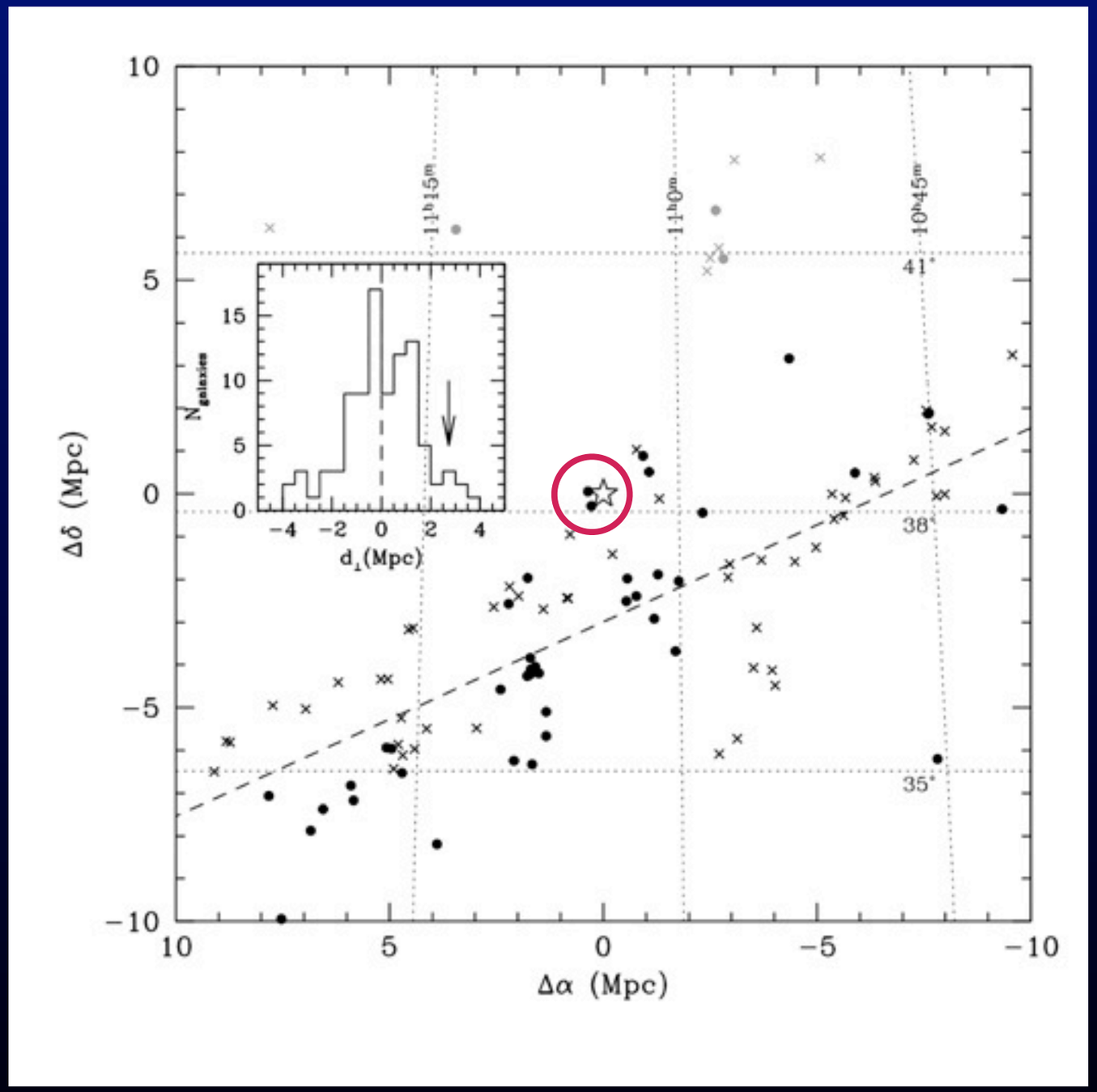


Williams et al. 2010b

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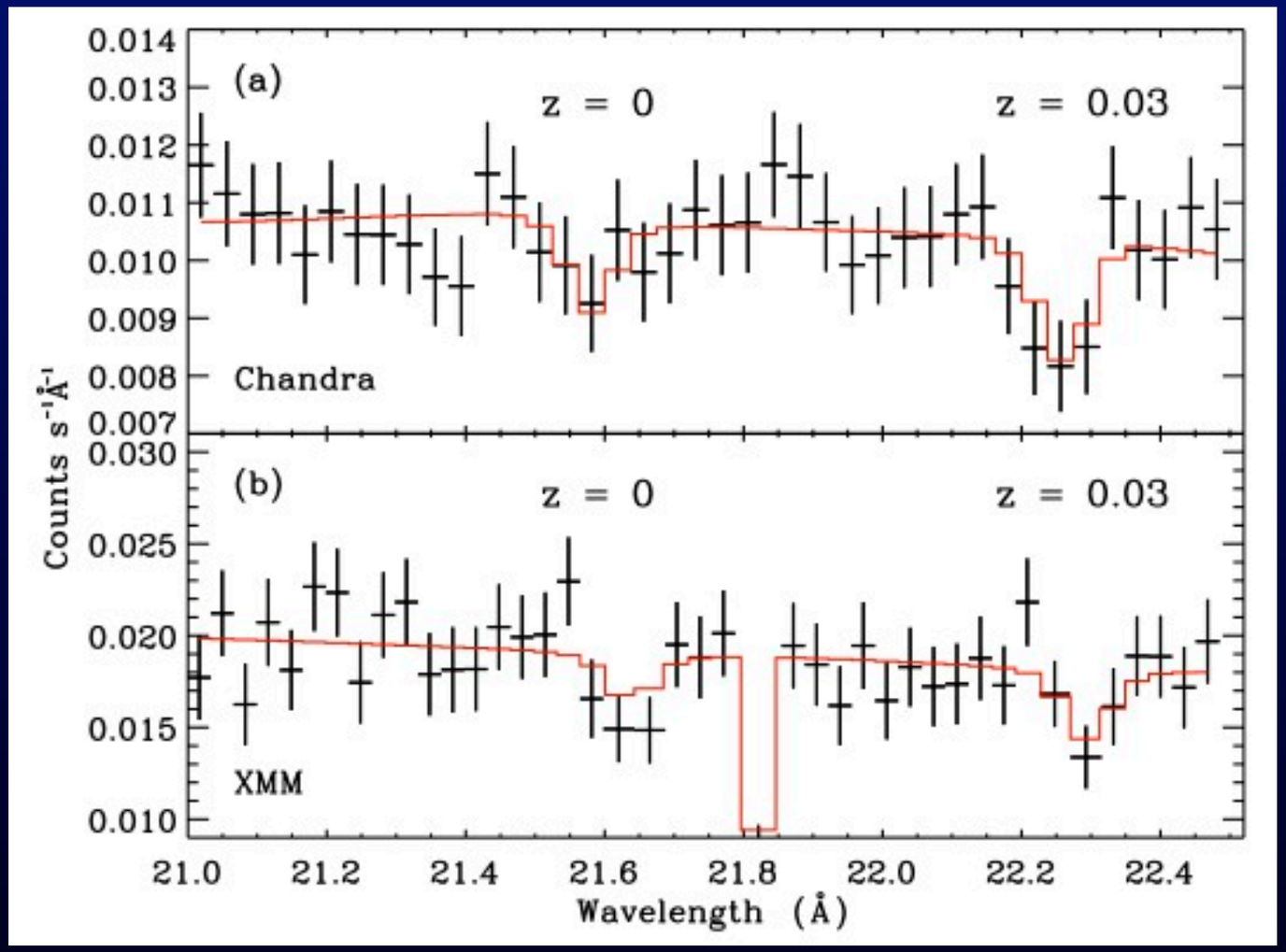


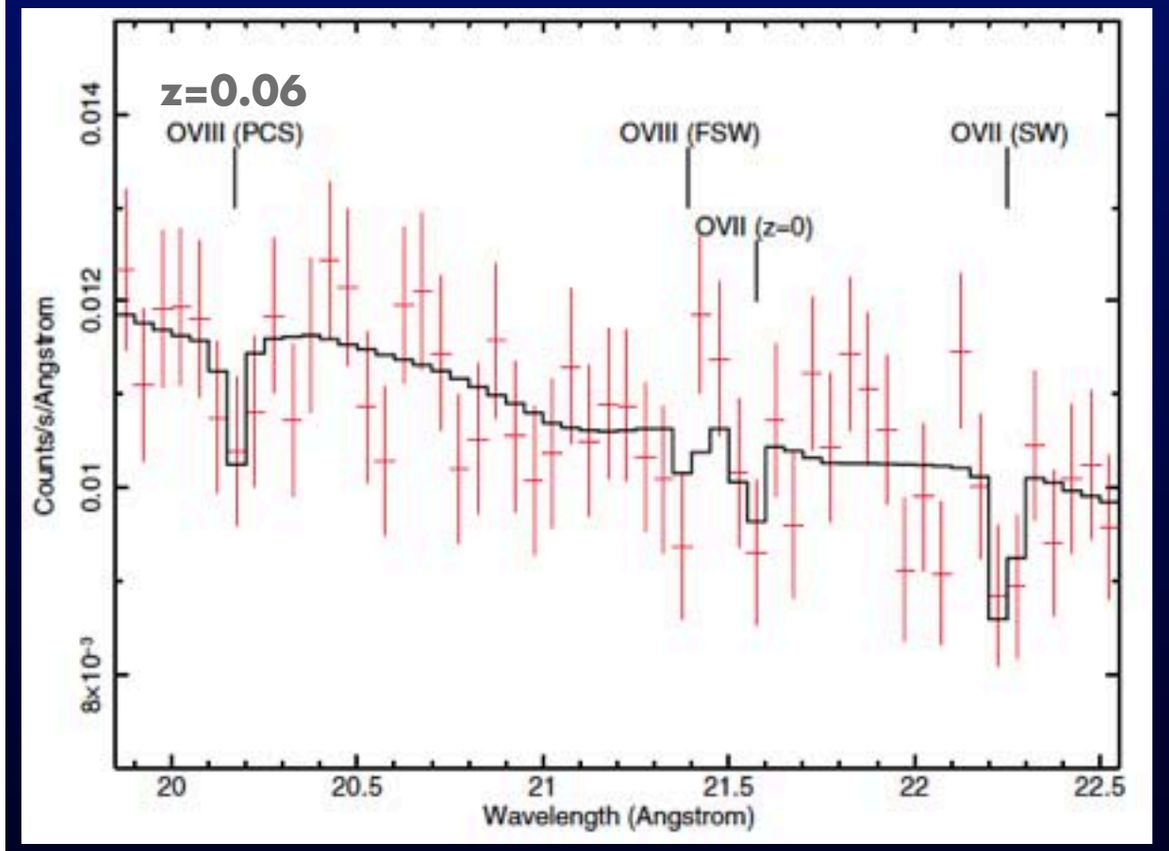


Zappacosta et al. (2010)

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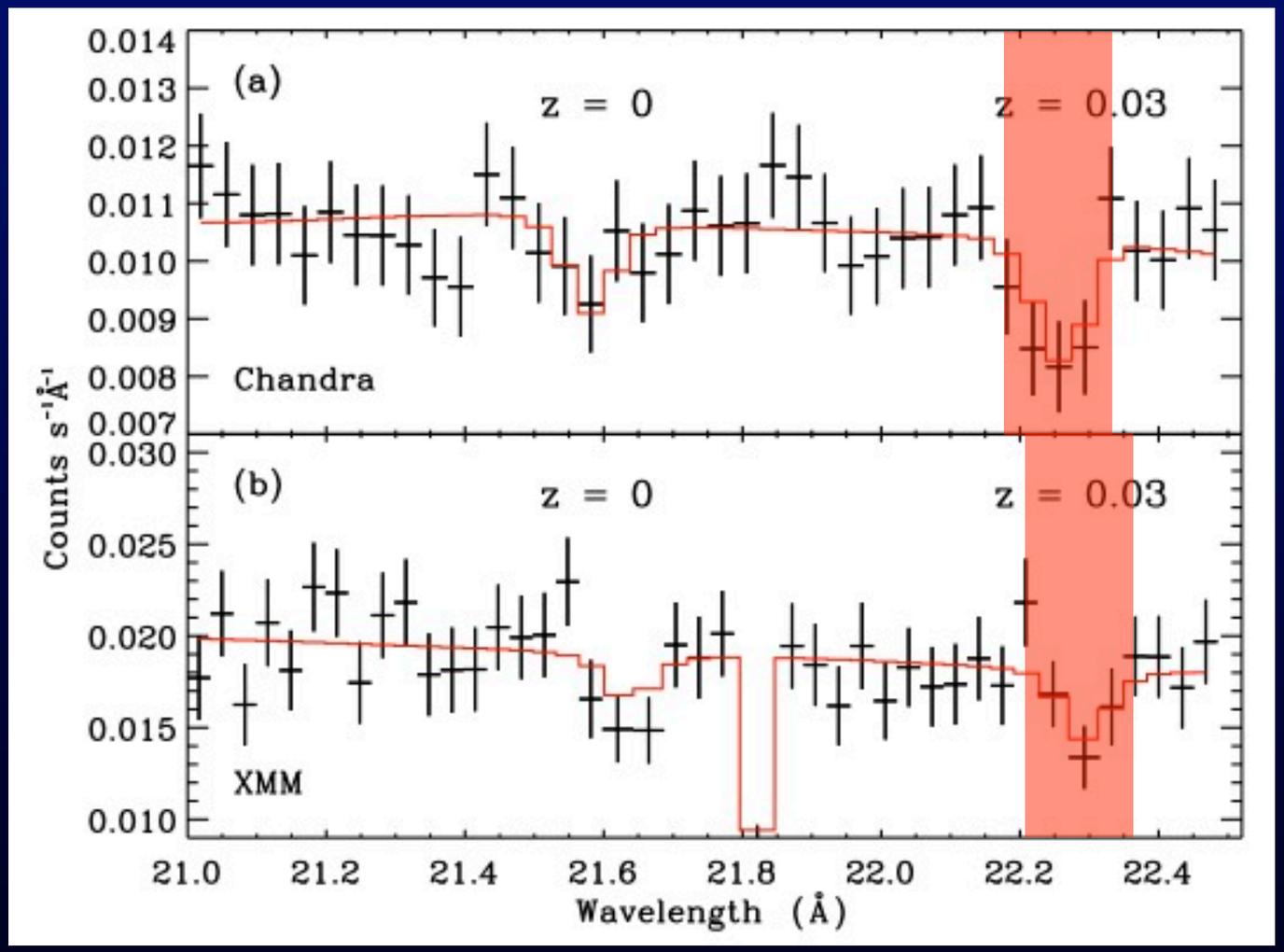


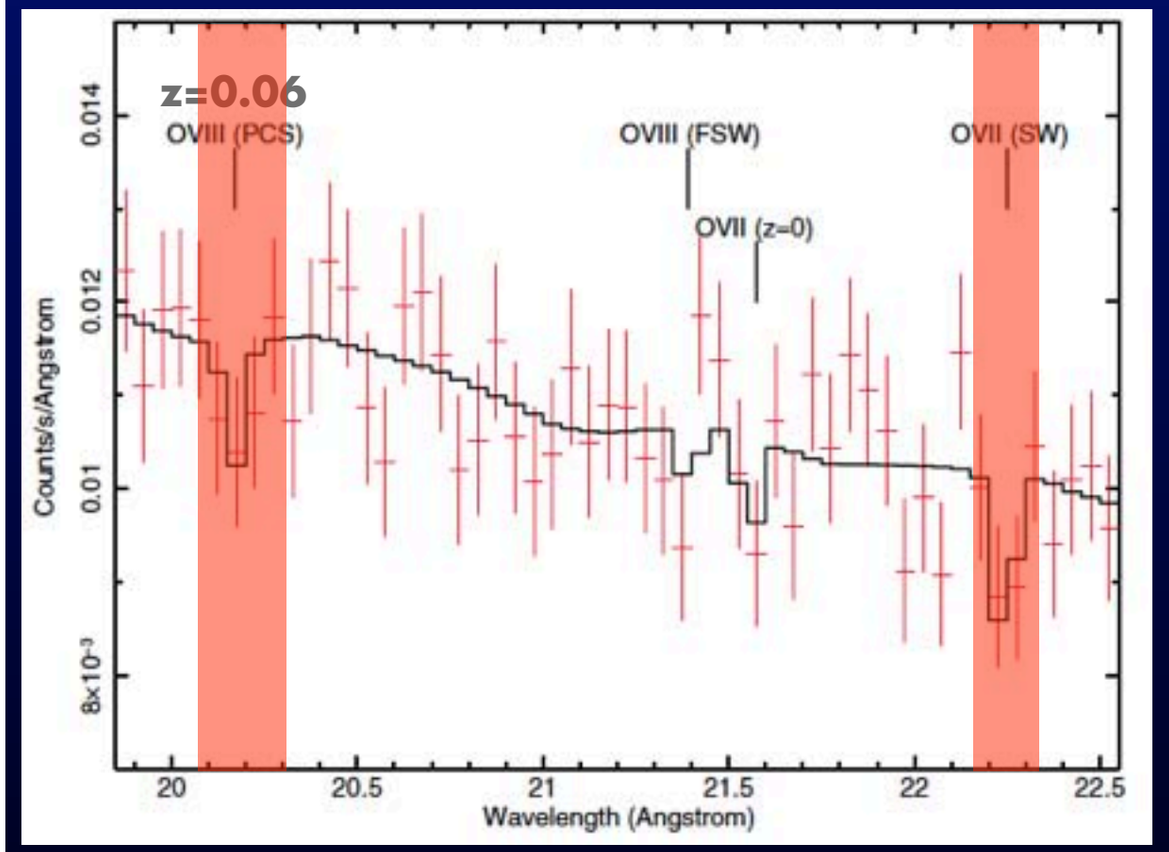


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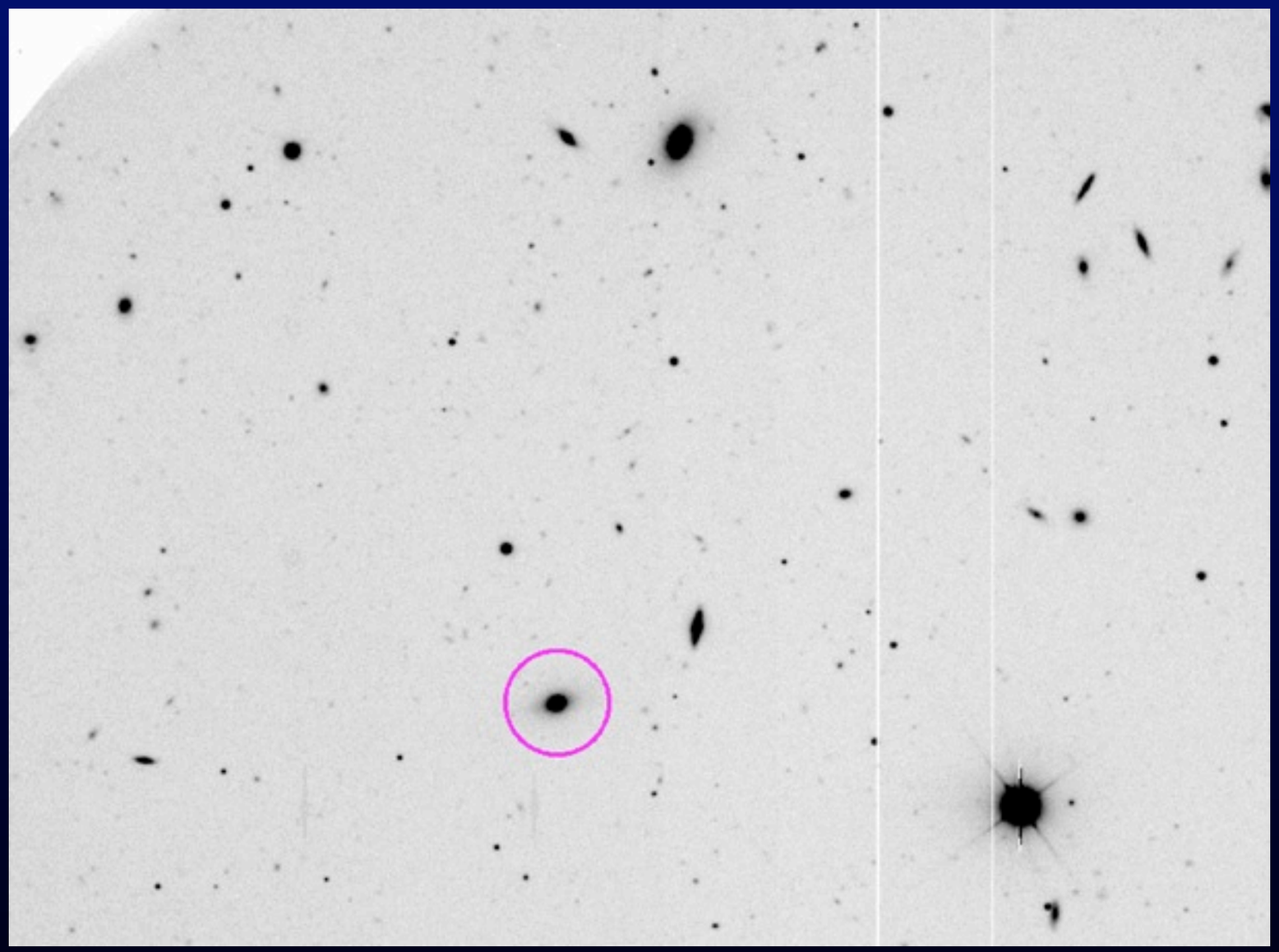

Williams, Mulchaey, & Kollmeier 2012

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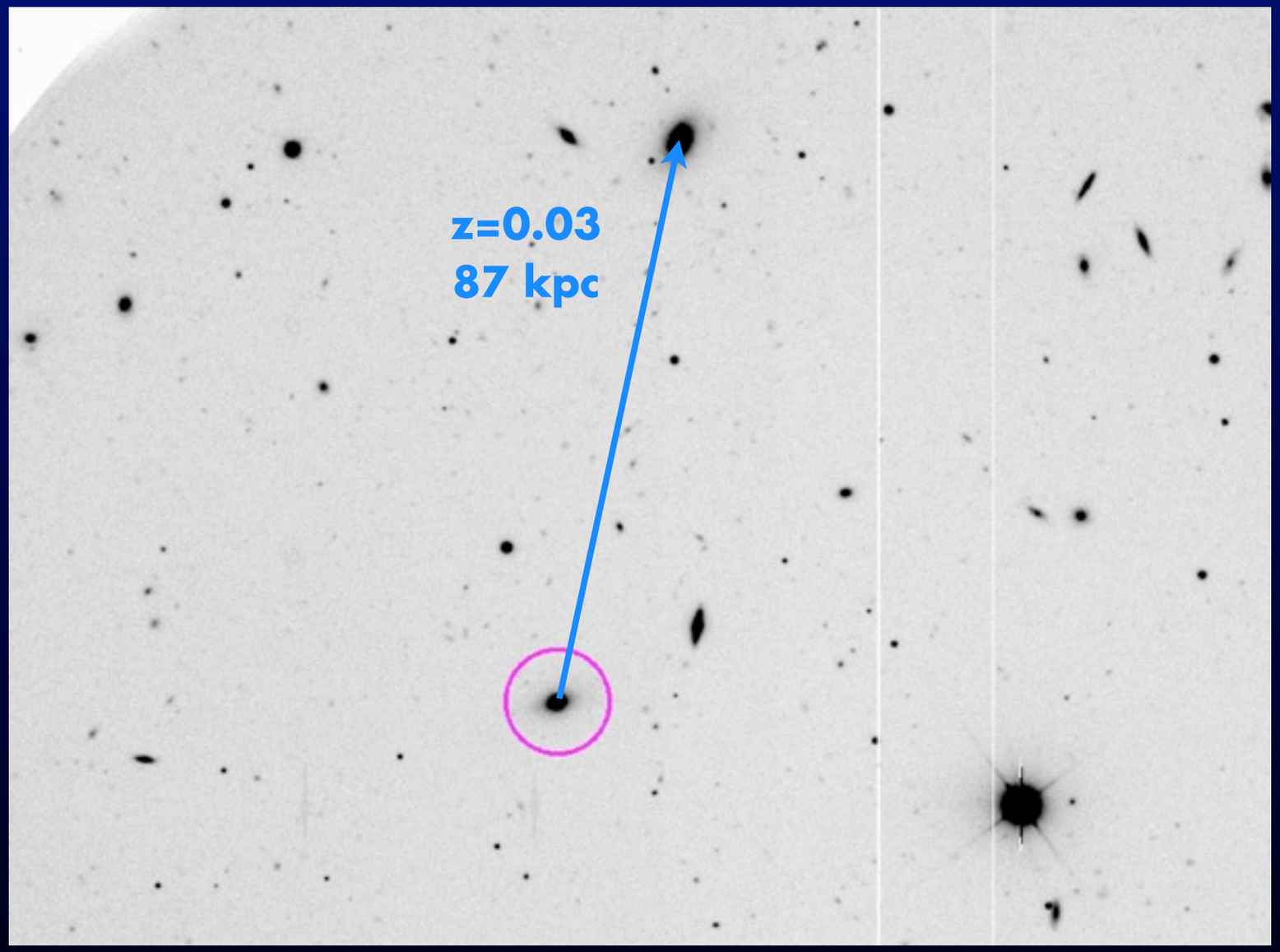


Williams, Mulchaey, & Kollmeier 2012

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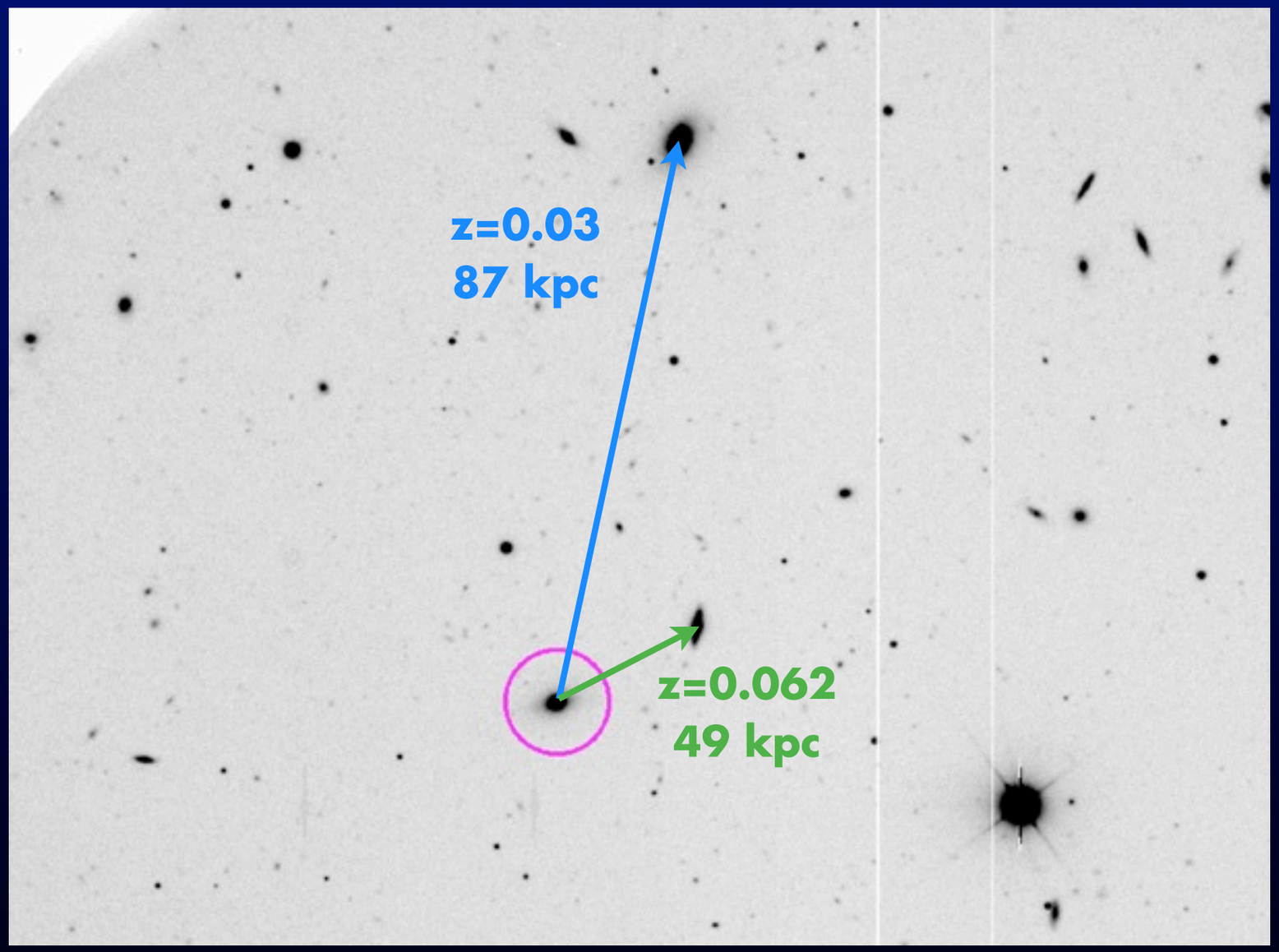


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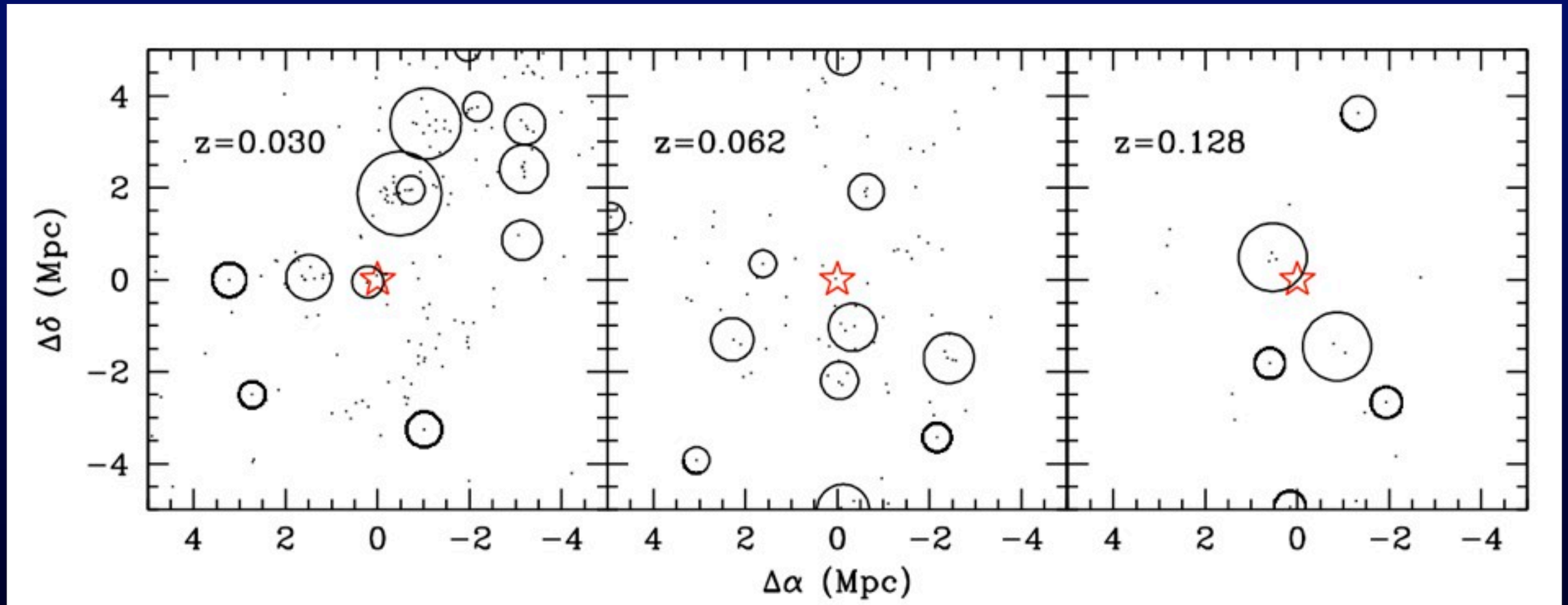


Williams, Mulchaey, & Kollmeier 2012

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To be continued...

# What's next?

- Elephant in the room: AGN quenching/feedback
  - X-ray and line diagnostics will be possible with full CSI data
  - Role of AGN in group and field galaxies

- Statistical sample of group velocity dispersions across masses and redshifts (upcoming Magellan program)

- Progenitors of z=2-3 massive quiescent galaxies: where did they come from?

- Probing lower density gas with X-ray/UV stacking; galaxies around COS-Halos absorbers (HST snapshots)

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- **Galaxy groups** grow dramatically during the thermal era, possibly accelerating the decline in star formation

- We may have detected the **hot gas** directly responsible for quenching star formation during the thermal era