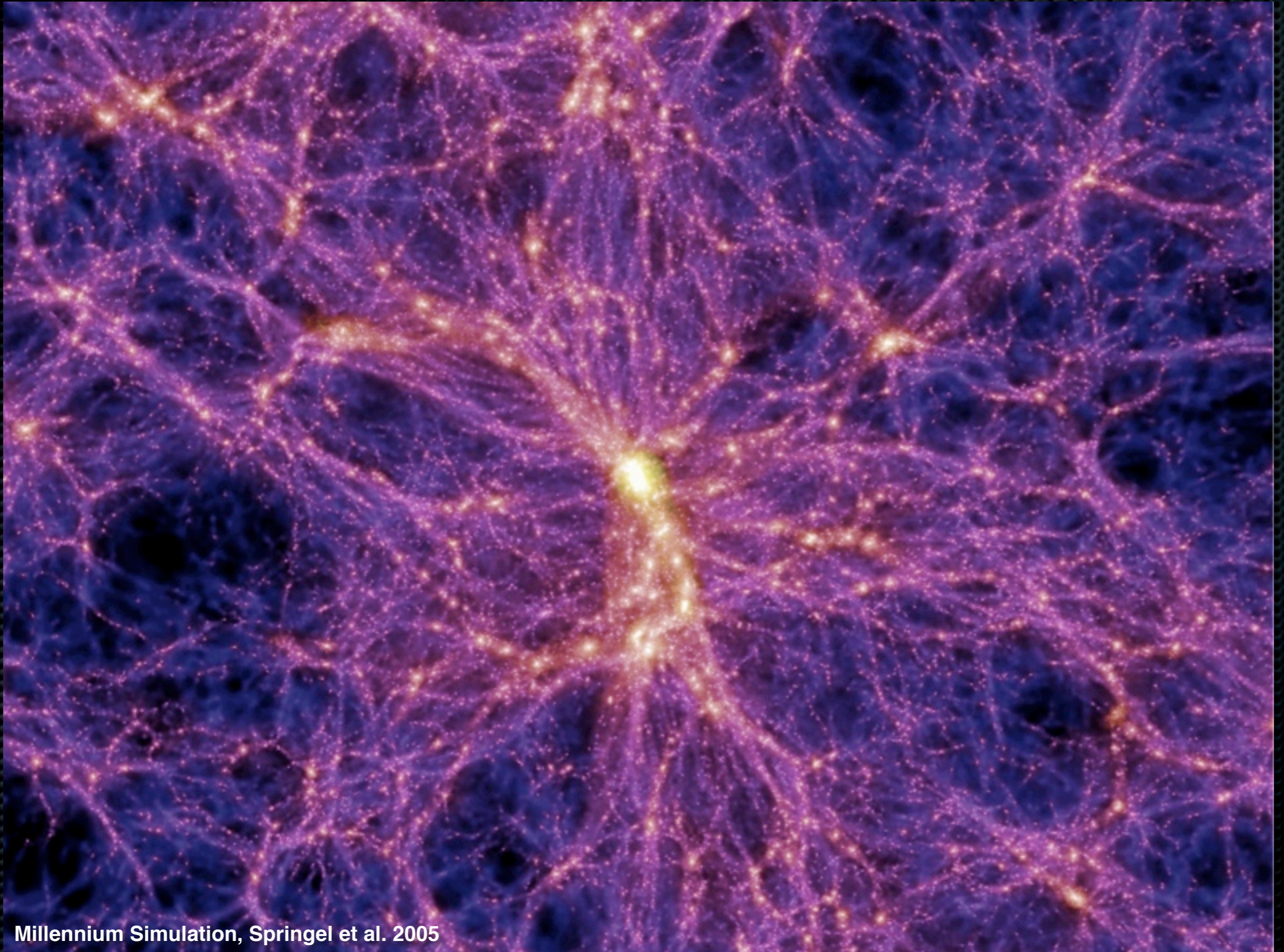


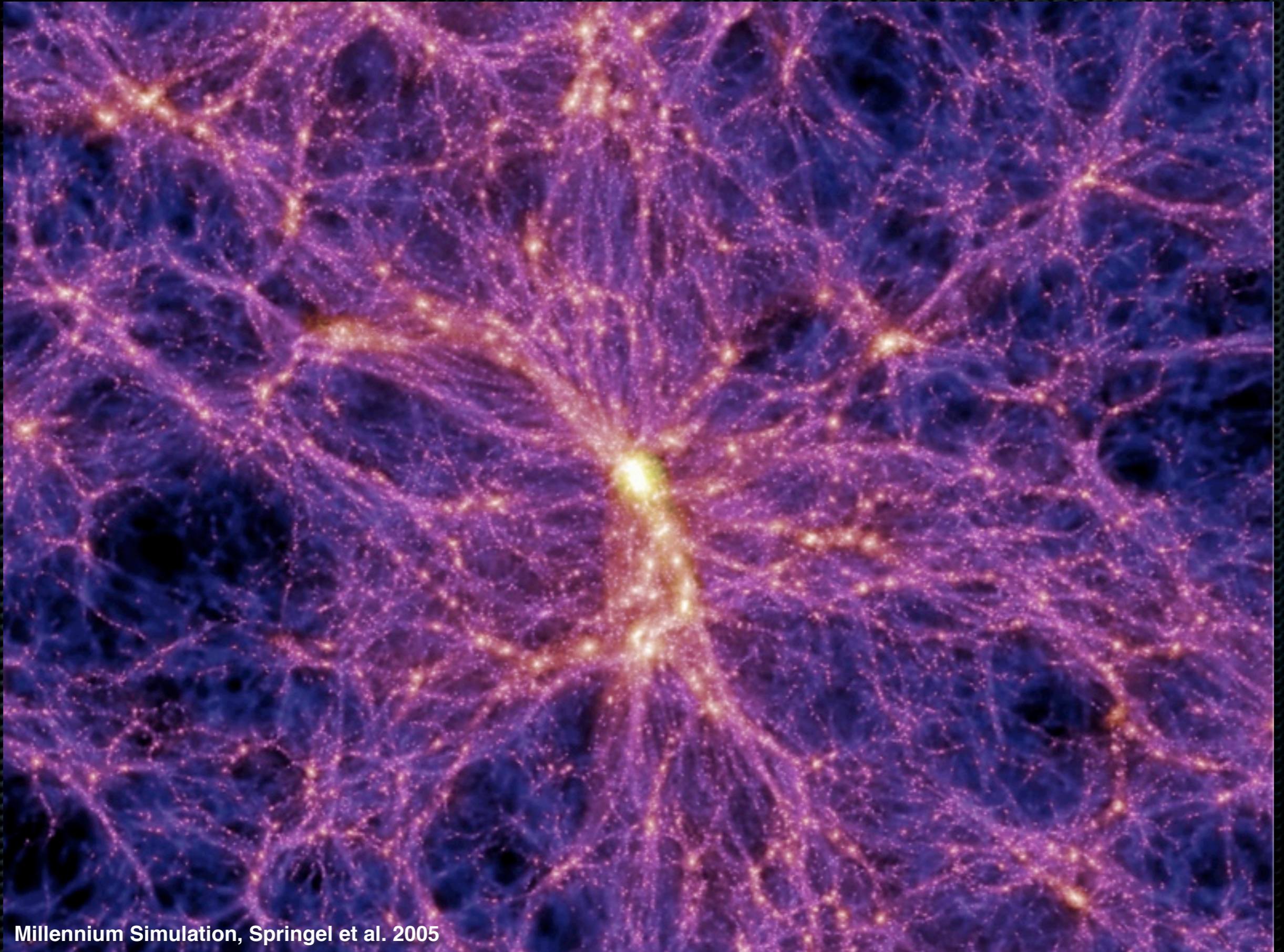
# Caught in the Cosmic Web: Testing Models of Giant Ly $\alpha$ Nebulae

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(UC Santa Barbara)

Arjun Dey (NOAO), Paul Smith (UofA), Gary Schmidt (NSF), Mark Brodwin (CfA), Fred Chaffee (Gemini), Vandana Desai (CalTech,SSC), Peter Eisenhardt (JPL), Emeric Le Floc'h (IfA), James Houck (Cornell), Buell Jannuzi (NOAO), Nobunari Kashikawa (NAOJ), Yuichi Matsuda (Durham), Marcia Rieke (UofA), Tom Soifer (CalTech,SSC)

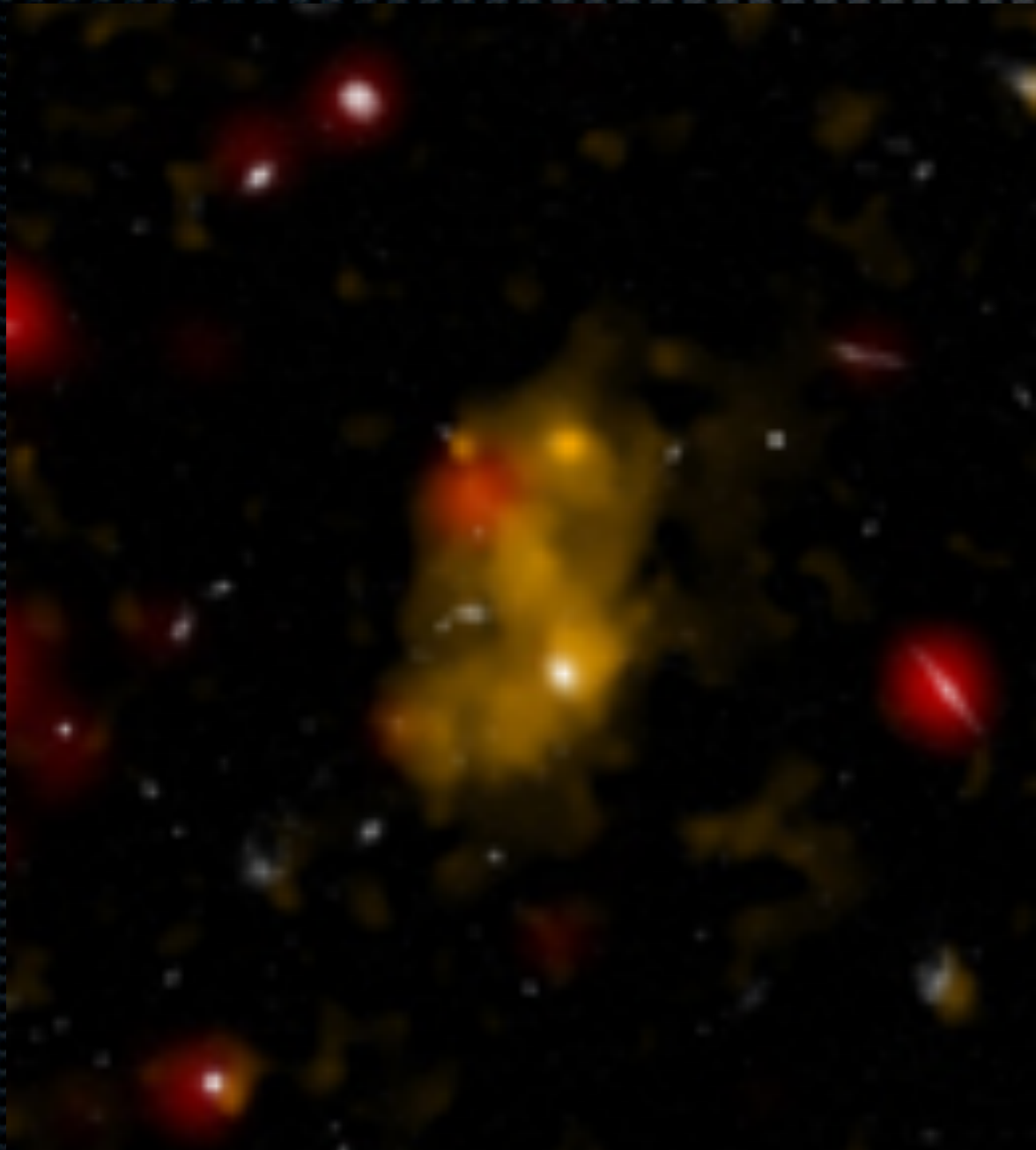


Millennium Simulation, Springel et al. 2005

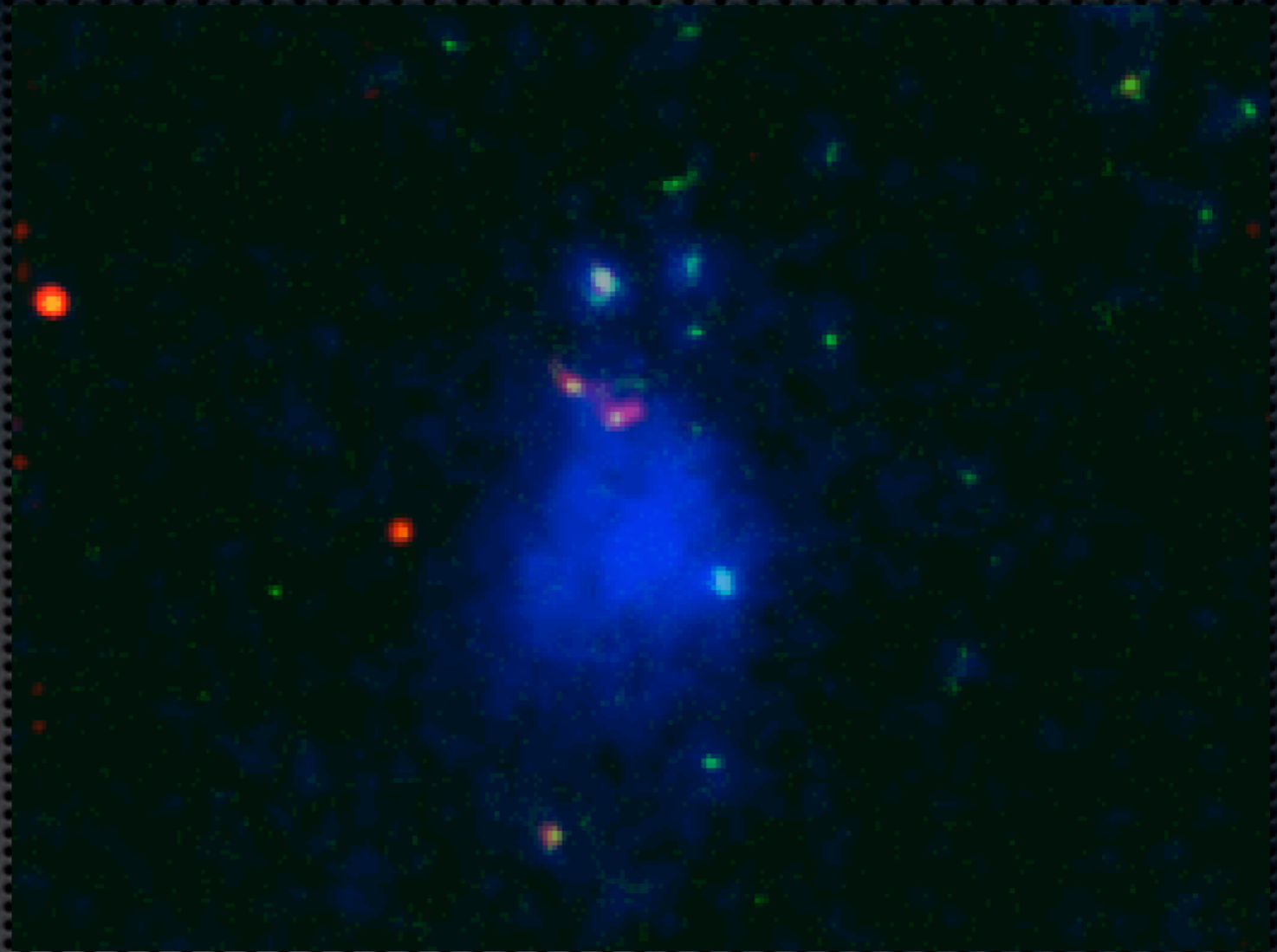


Millennium Simulation, Springel et al. 2005

# Lya Nebulae



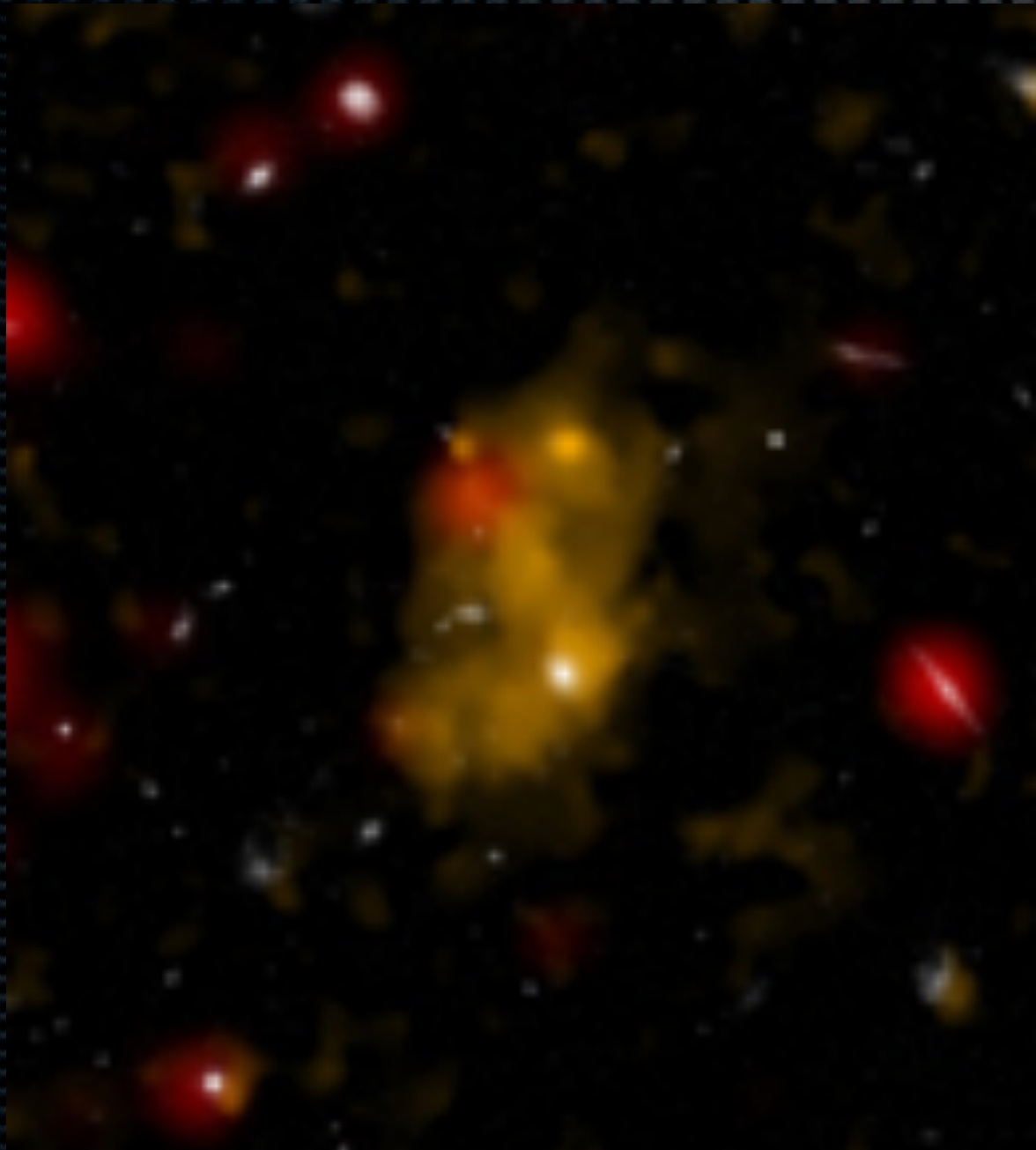
Credit: NASA/CXC/SAO



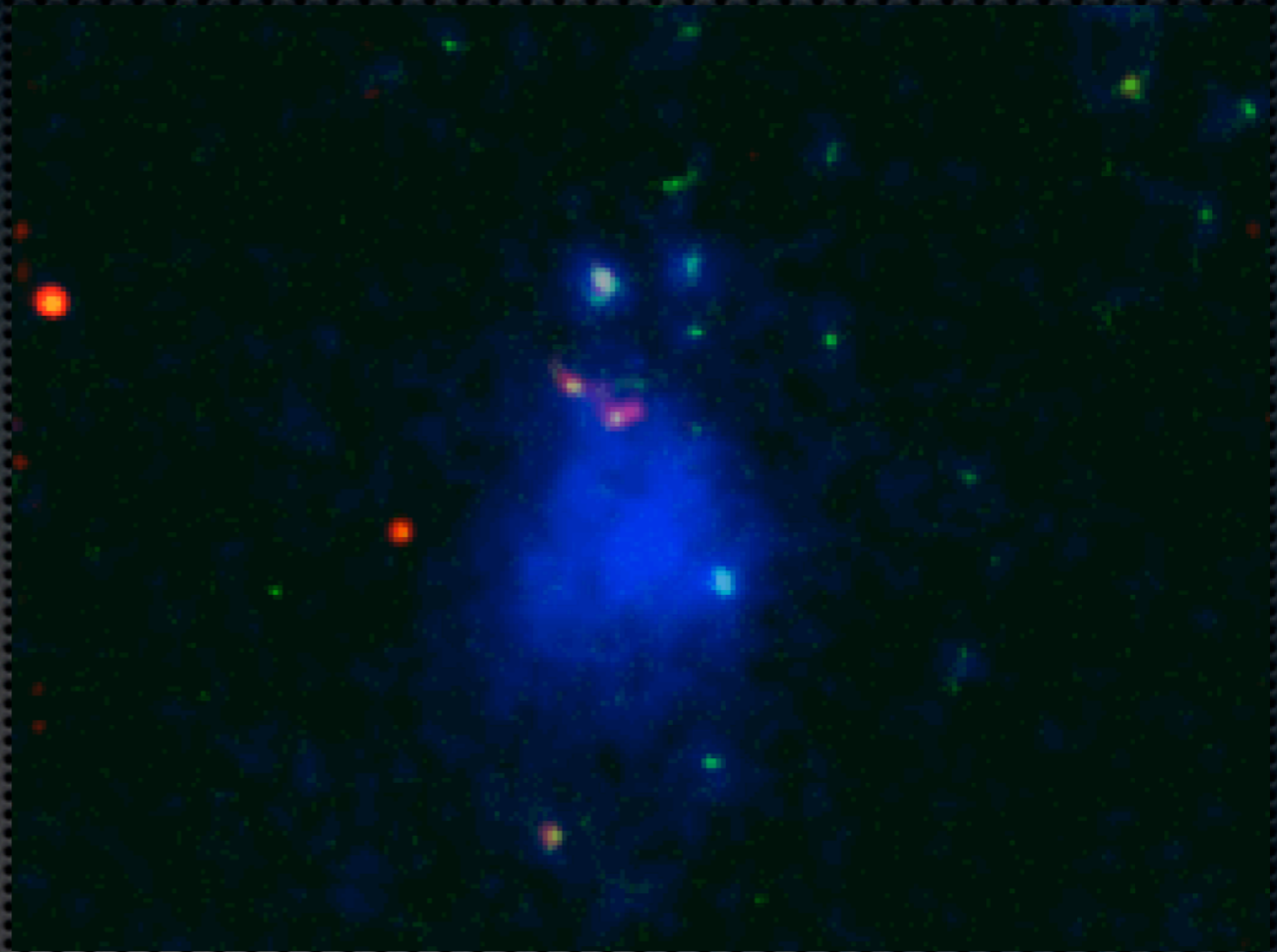
Credit: M. Prescott & A. Dey 2010

- Highly energetic phenomenon ( $\sim 10^{44}$  erg/s)
- Enormous spatial extent ( $\sim 100$  kpc)
- Regions of ongoing galaxy formation?

# Lya Nebulae



Credit: NASA/CXC/SAO



Credit: M. Prescott & A. Dey 2010

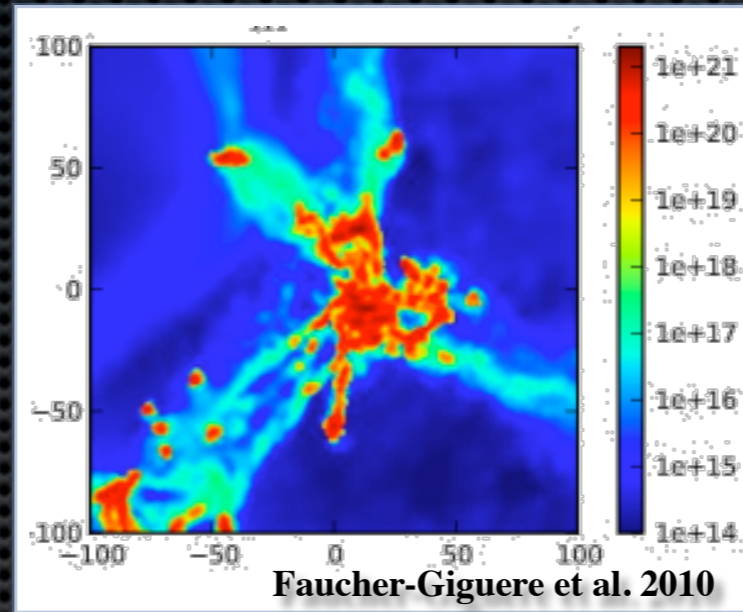
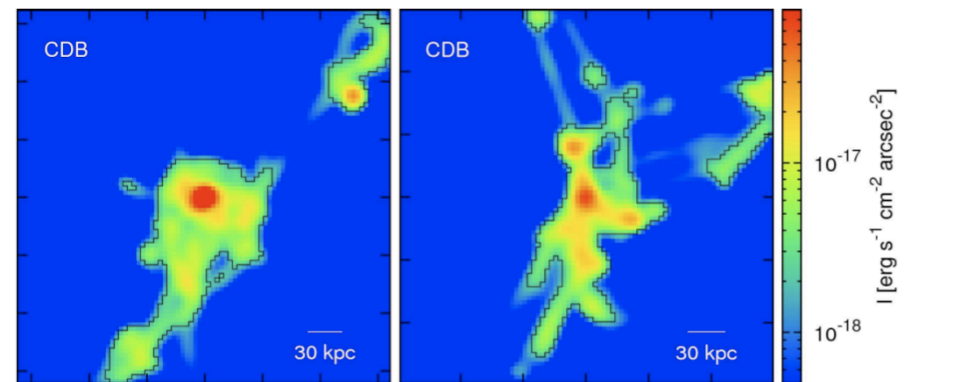
- Highly energetic phenomenon ( $\sim 10^{44}$  erg/s)
- Enormous spatial extent ( $\sim 100$  kpc)
- Regions of ongoing galaxy formation?

What powers Ly $\alpha$  nebulae?

# What powers Ly $\alpha$ nebulae?

Goerdt et al. 2009

*Cold streams as Lyman-alpha blobs*



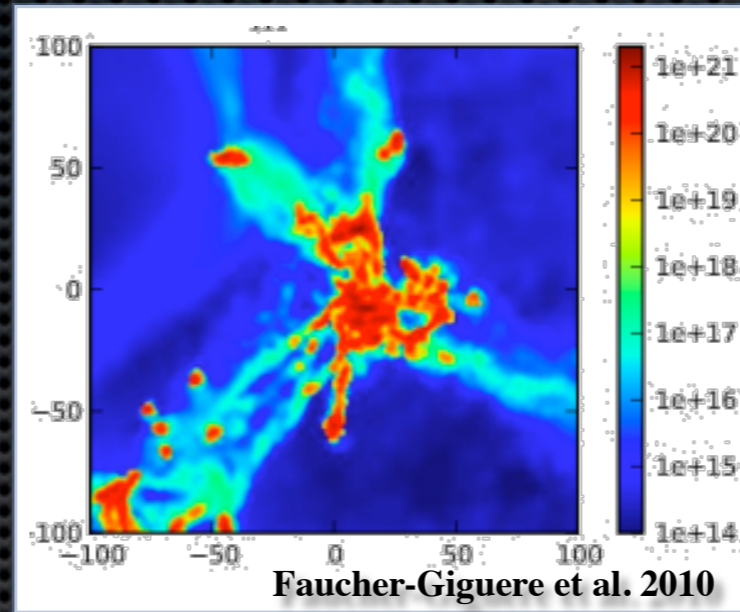
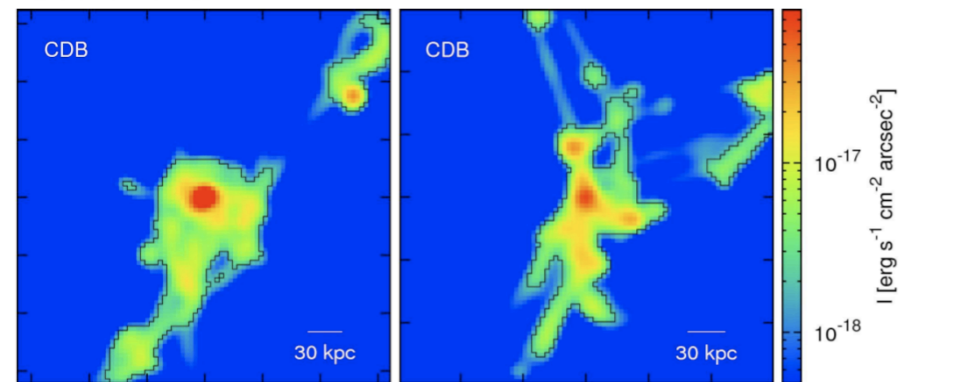
✦ Cold flows

- Also work by Dijkstra, Rosdahl

# What powers Ly $\alpha$ nebulae?

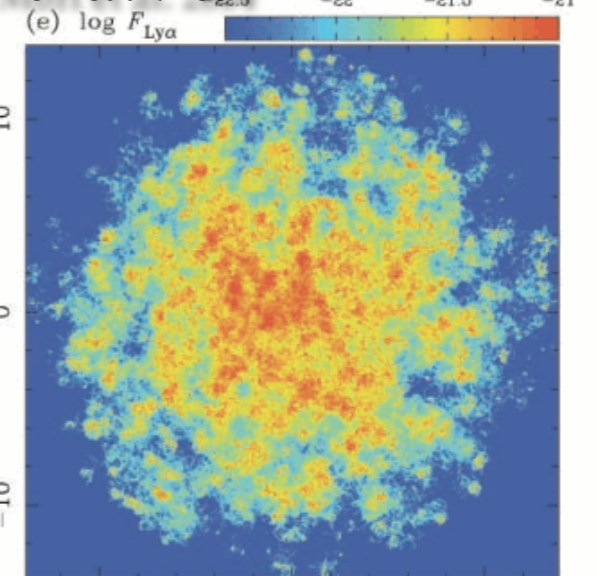
Goerdt et al. 2009

*Cold streams as Lyman-alpha blobs*



Faucher-Giguere et al. 2010

Mori et al. 2004



- ✦ Cold flows
- ✦ Superwind outflows

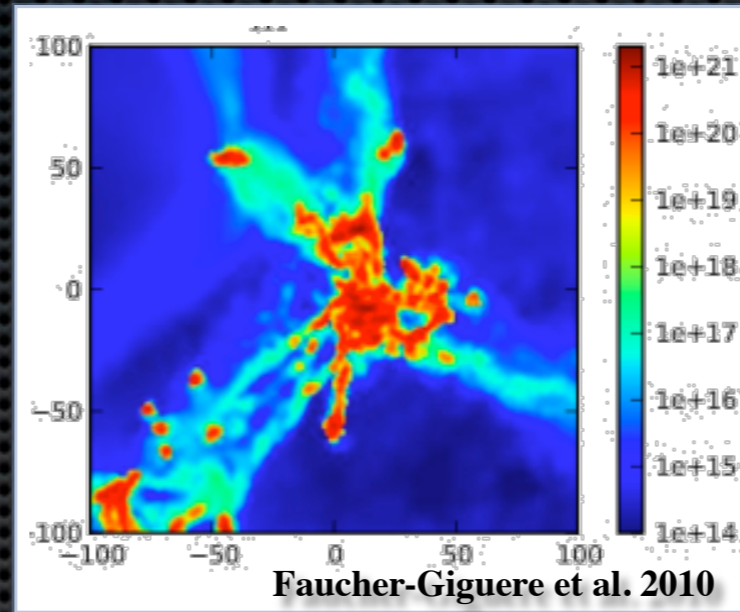
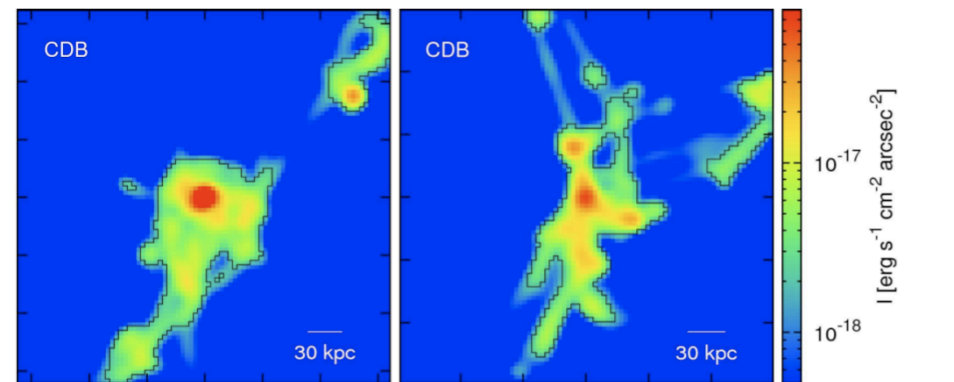
- Also work by Dijkstra, Rosdahl, Taniguchi, Shioya



# What powers Ly $\alpha$ nebulae?

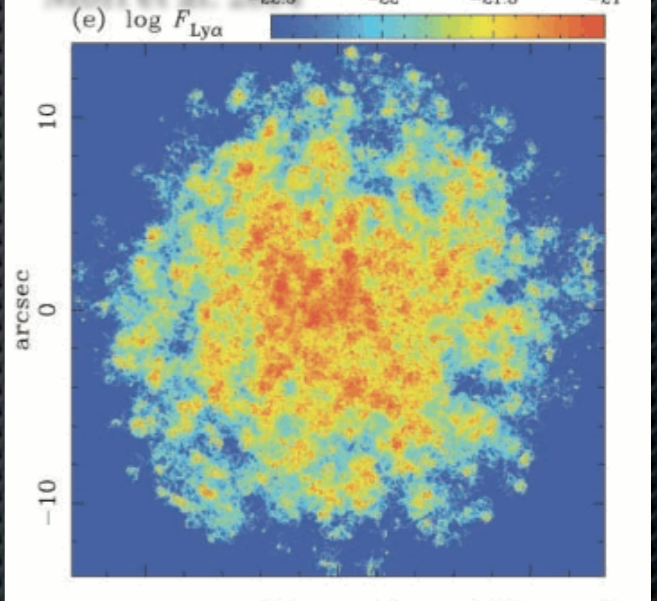
Goerdt et al. 2009

Cold streams as Lyman-alpha blobs

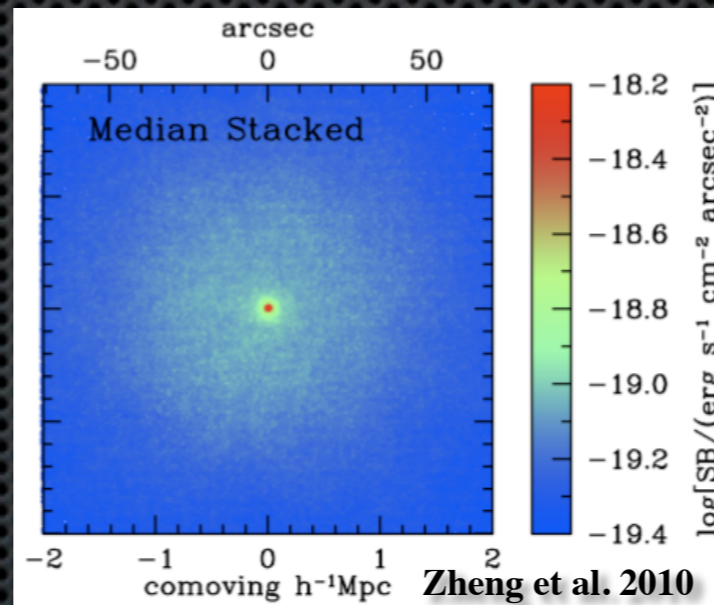


Faucher-Giguere et al. 2010

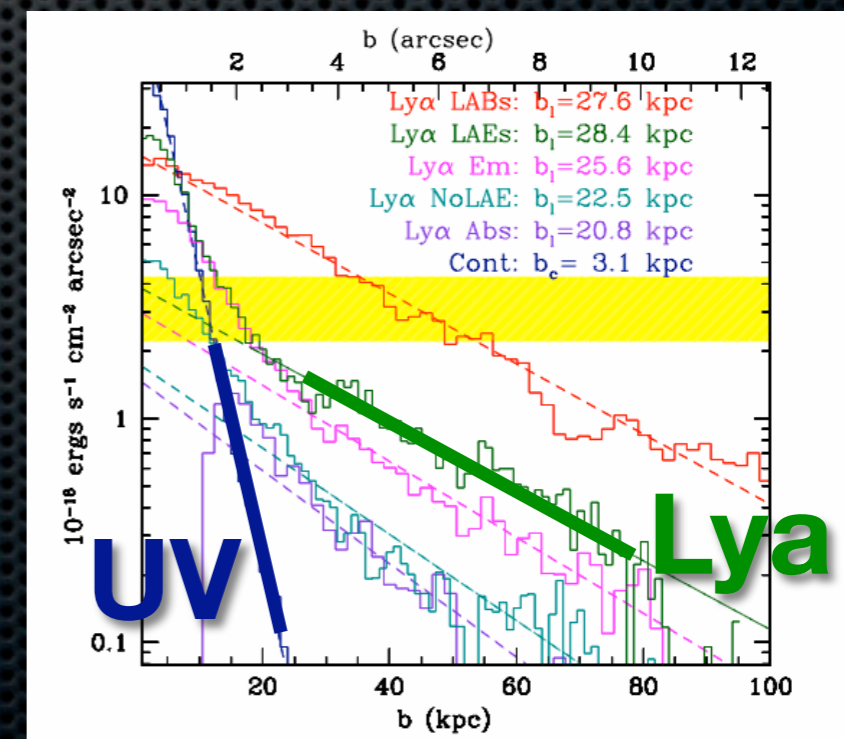
Mori et al. 2004



- ✦ Cold flows
- ✦ Superwind outflows
- ✦ Resonant scattering



Zheng et al. 2010

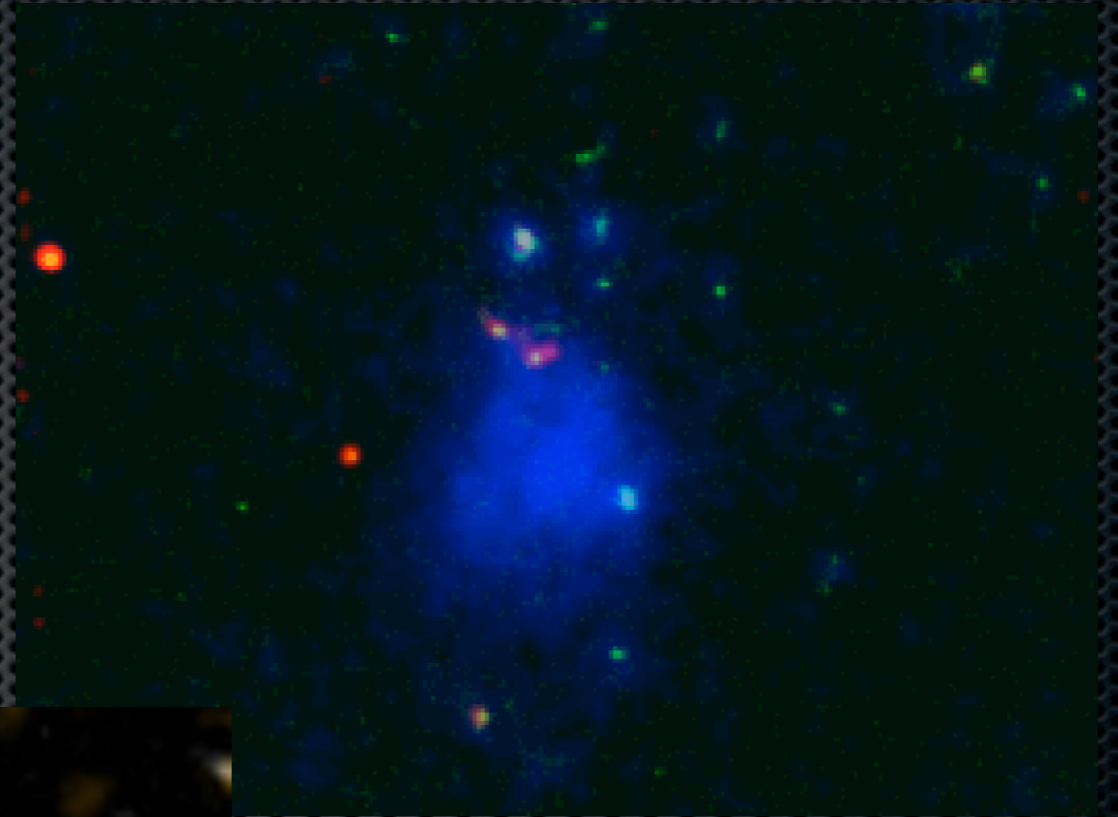


- Also work by Dijkstra, Rosdahl, Taniguchi, Shioya

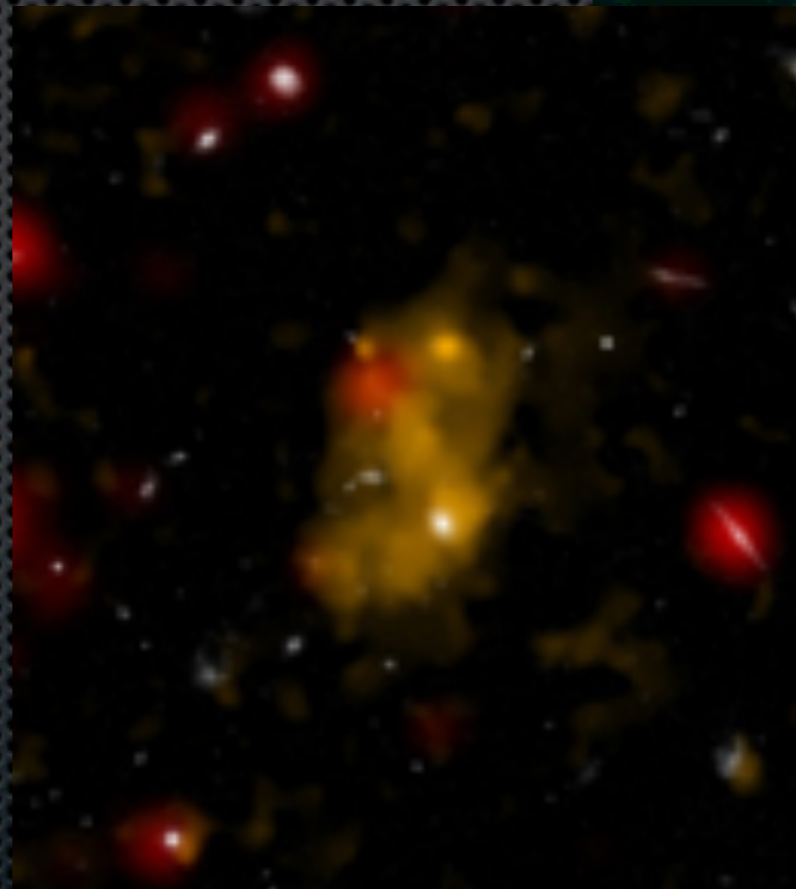
Steidel et al. 2011

# On the observational side...

- ✦ Ly $\alpha$  nebulae are complex regions, challenge simple explanations
- ✦ Need a full range of observational constraints



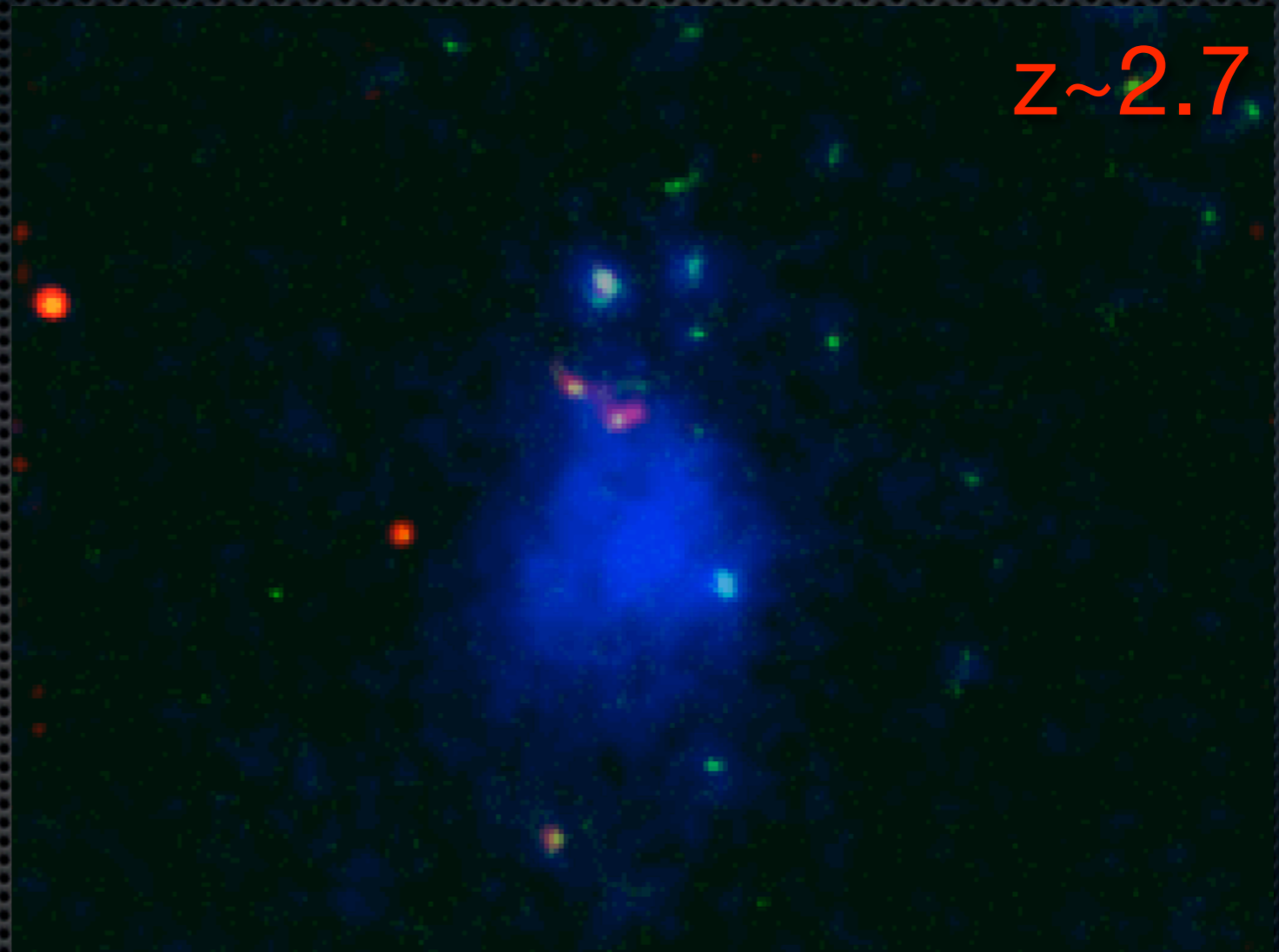
Credit: M. Prescott & A. Dey 2010



Credit: NASA/CXC/SAO

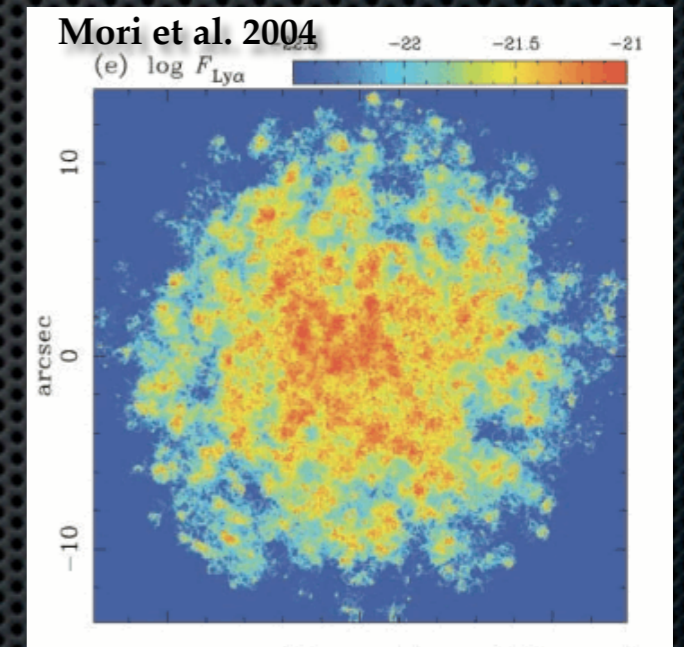
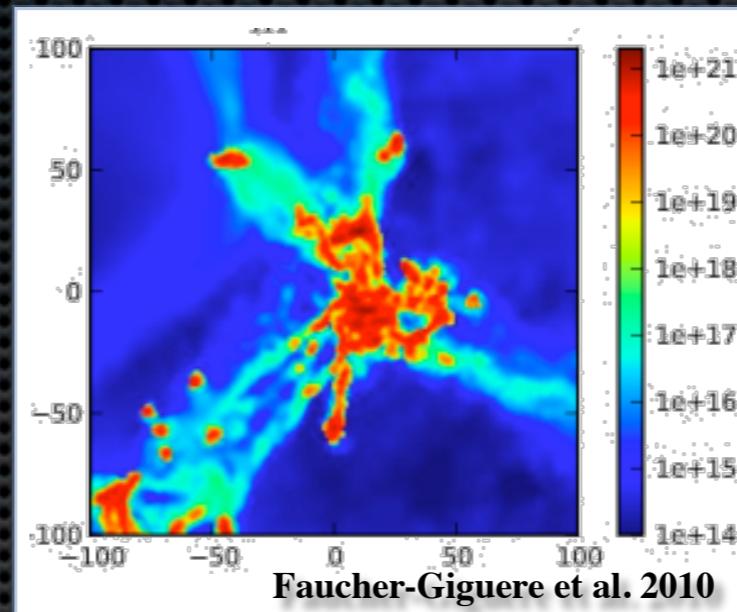
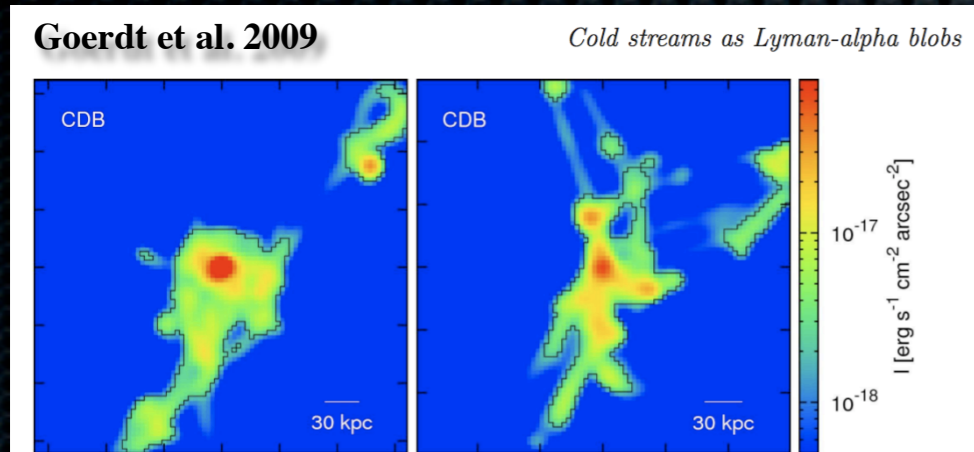
# Outline

- Small-scale Morphology
- Ly $\alpha$  polarization
- Properties of galaxies within a Ly $\alpha$  nebula

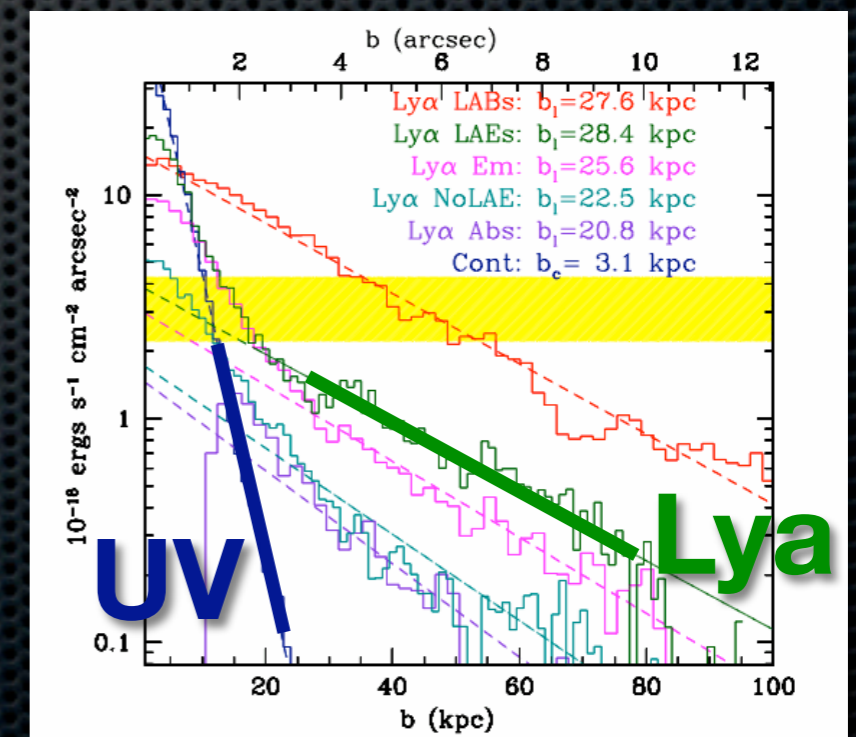
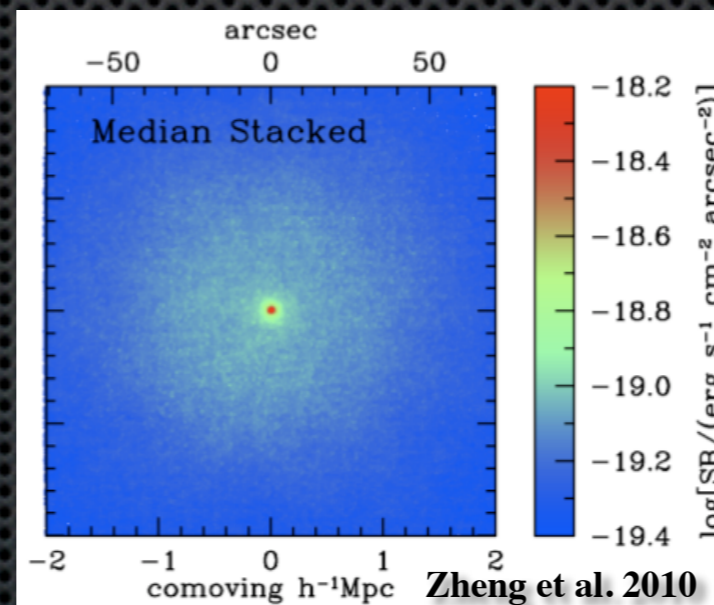


Credit: M. Prescott & A. Dey 2010

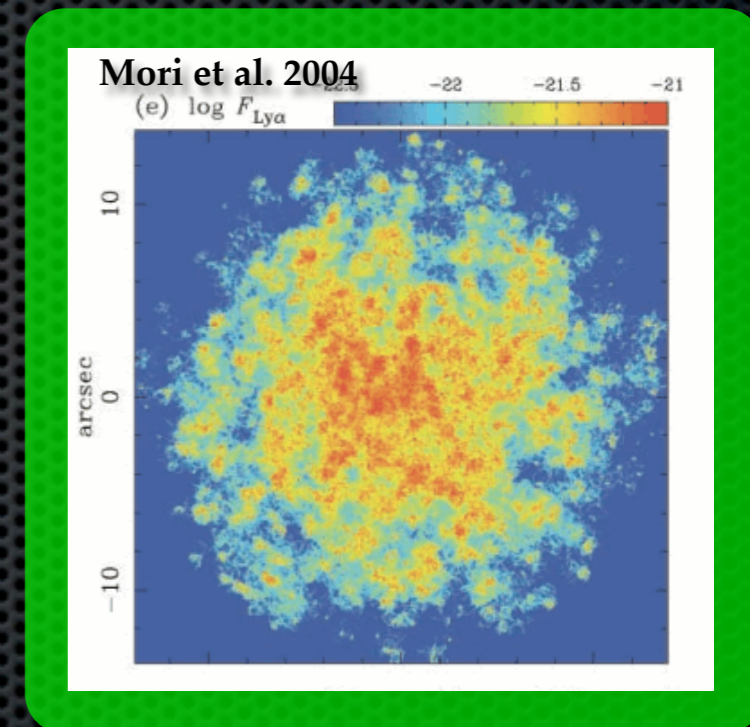
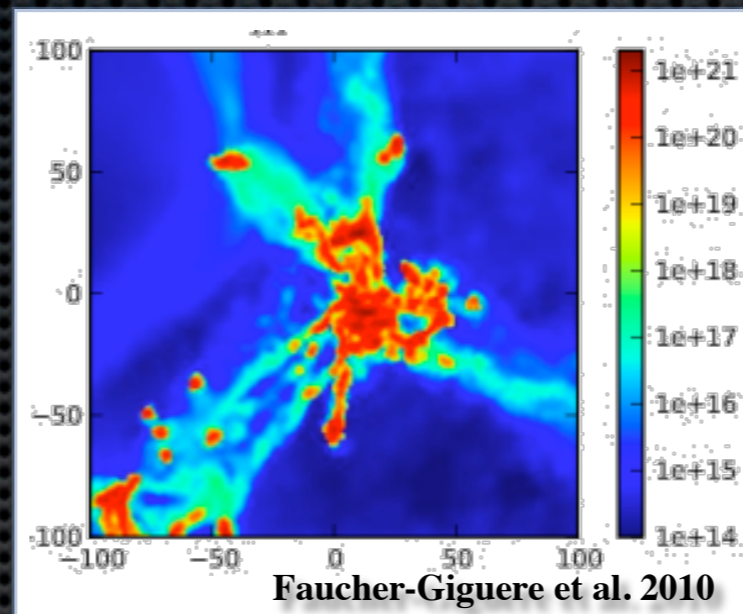
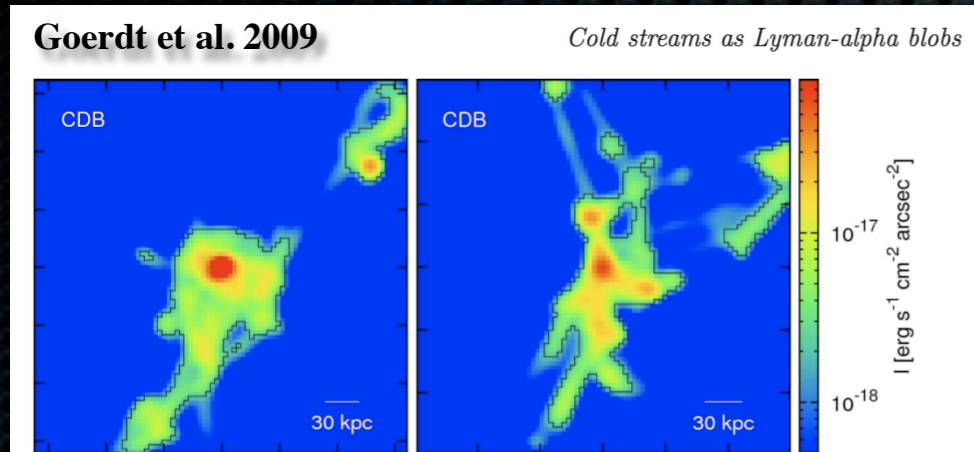
# What would we expect?



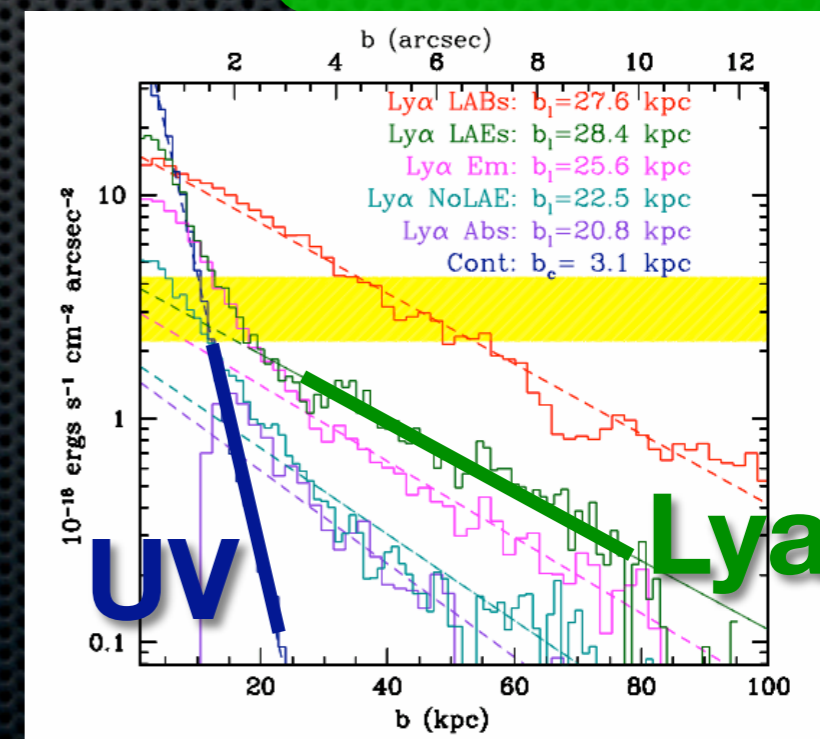
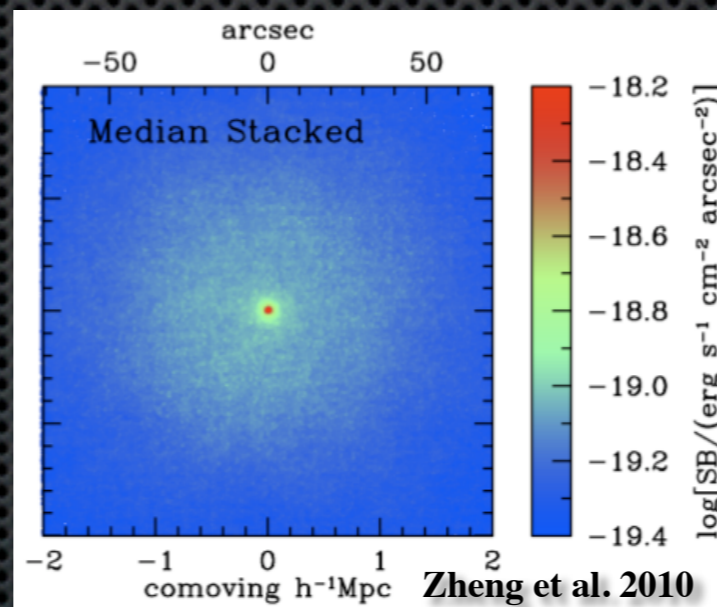
- ✦ Central galaxy
- ✦ Clumpy, filamentary structure
- ✦ Ly $\alpha$  profile larger than the UV profile
- ✦ Polarized Ly $\alpha$



# What would we expect for **Outflows**?



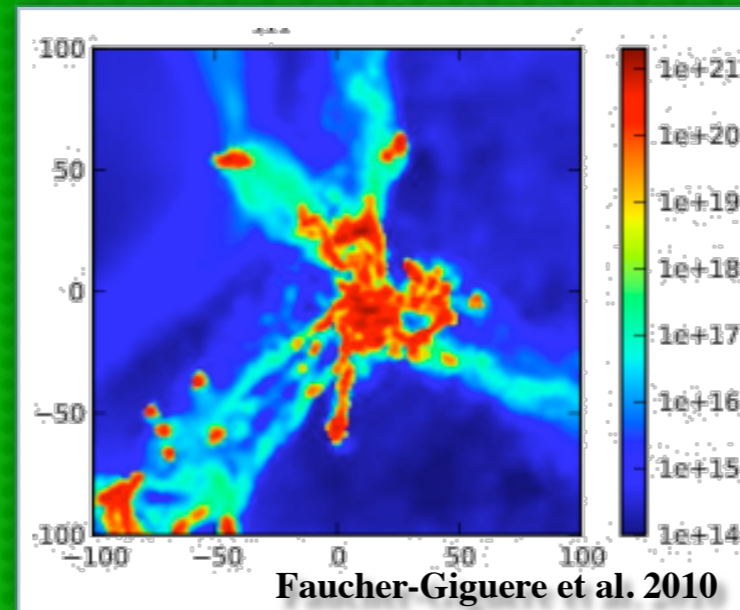
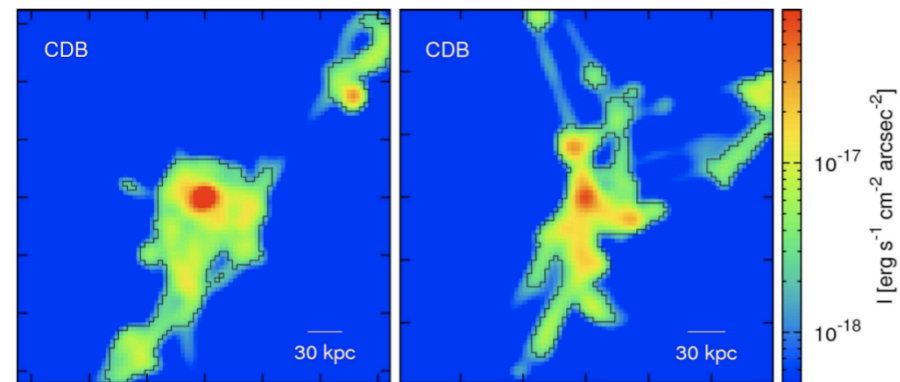
- ✦ **Central galaxy**
- ✦ Clumpy, filamentary structure
- ✦ Ly $\alpha$  profile larger than the UV profile
- ✦ Polarized Ly $\alpha$



# What would we expect for Cold Flows?

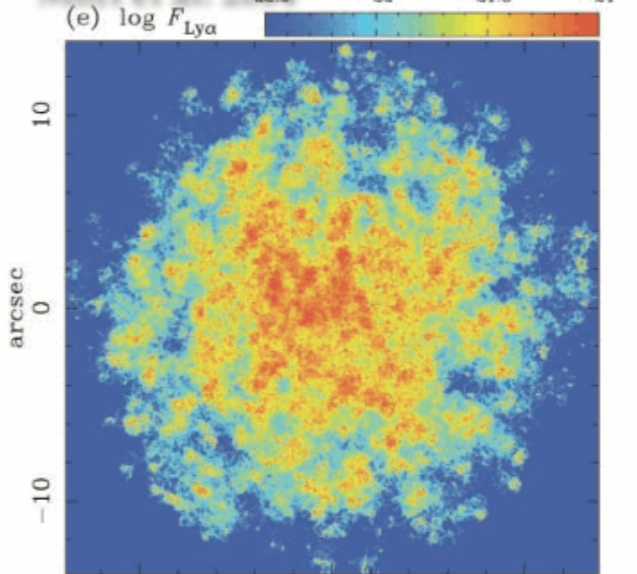
Goerdt et al. 2009

Cold streams as Lyman-alpha blobs



Faucher-Giguere et al. 2010

Mori et al. 2004

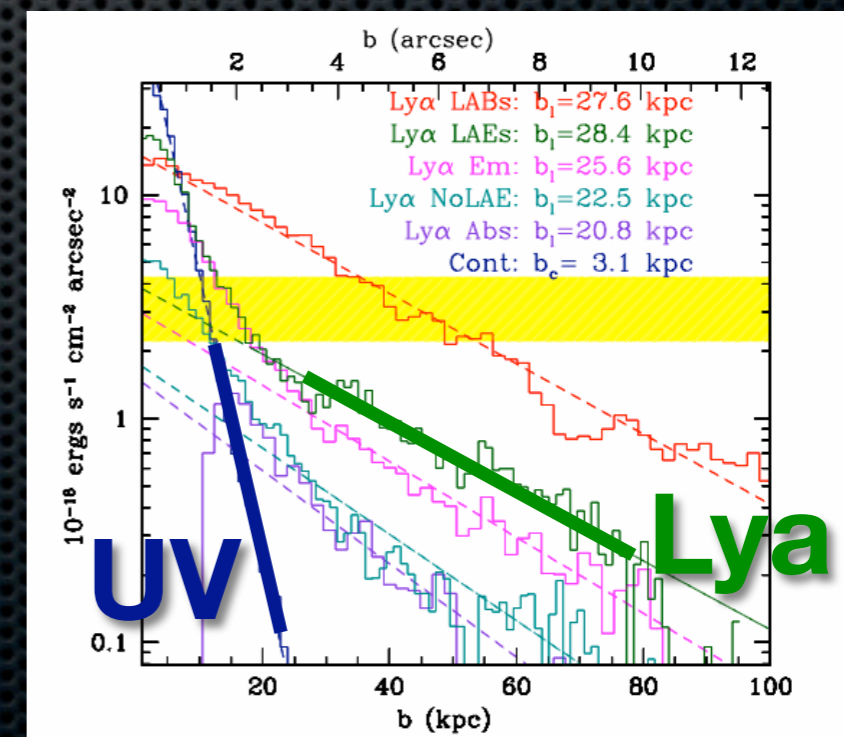
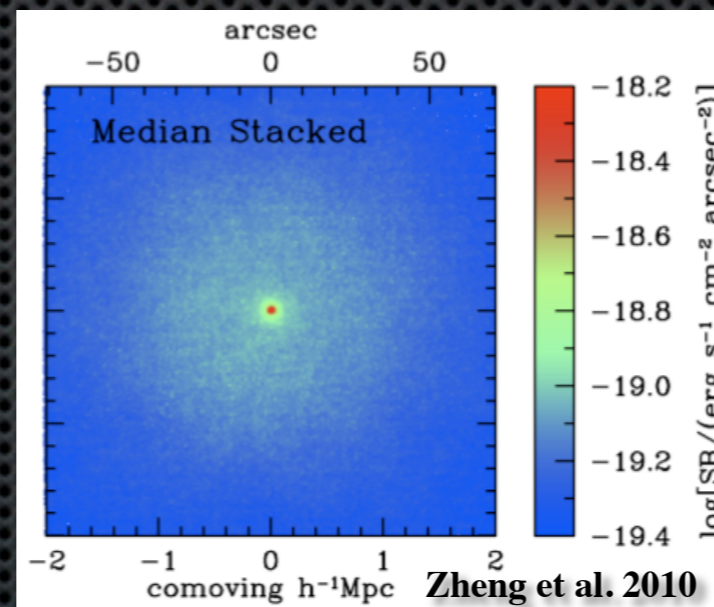


- Central galaxy

- Clumpy, filamentary structure

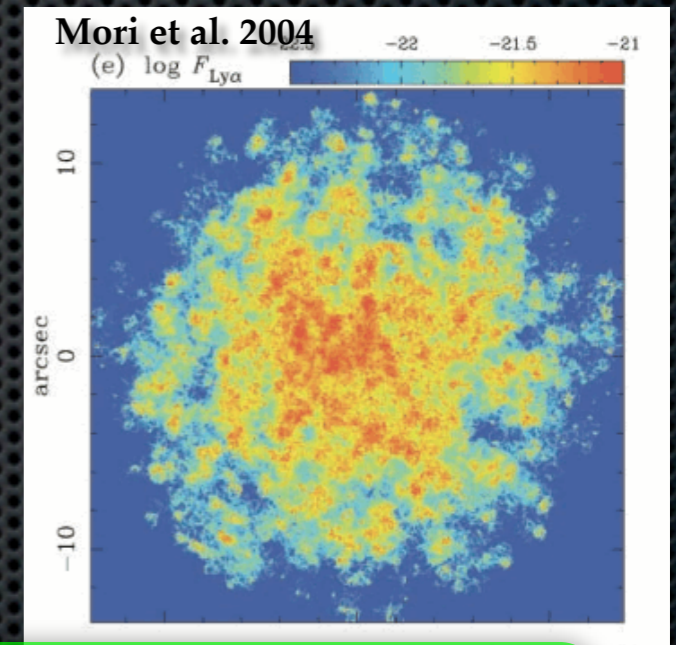
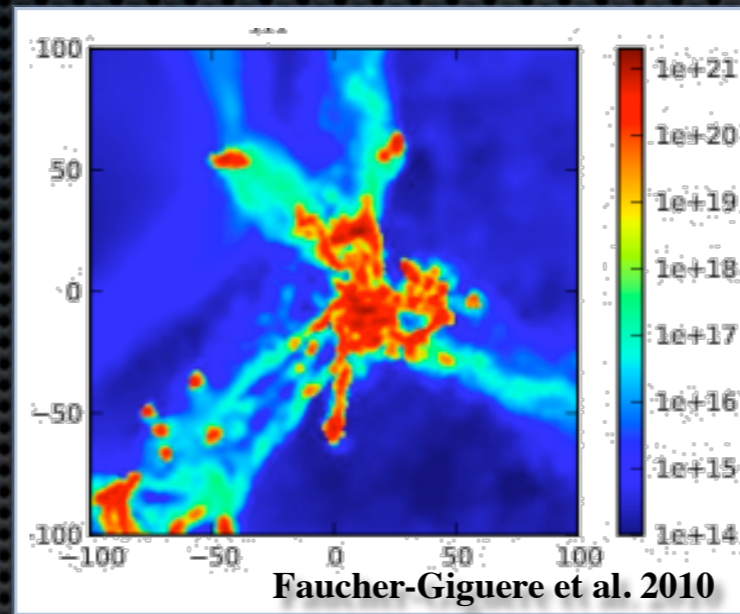
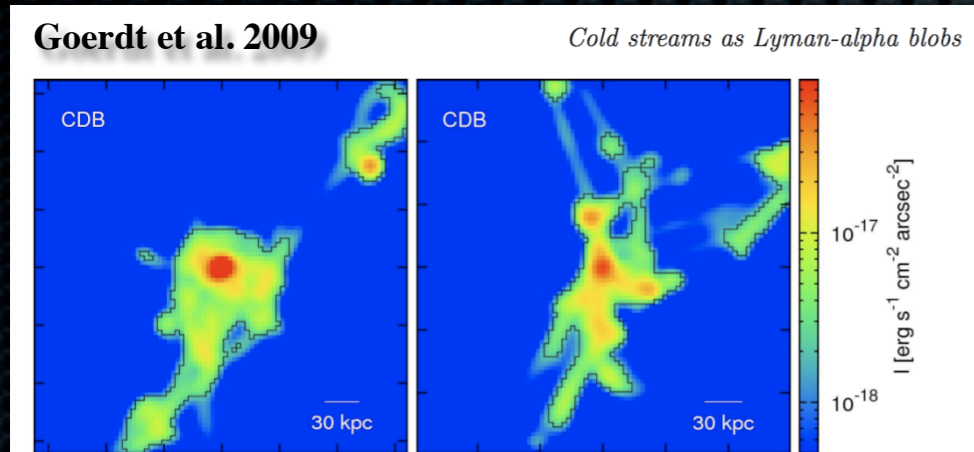
- Ly $\alpha$  profile larger than the UV profile

- Polarized Ly $\alpha$



Steidel et al. 2011

# What would we expect for **Scattering**?

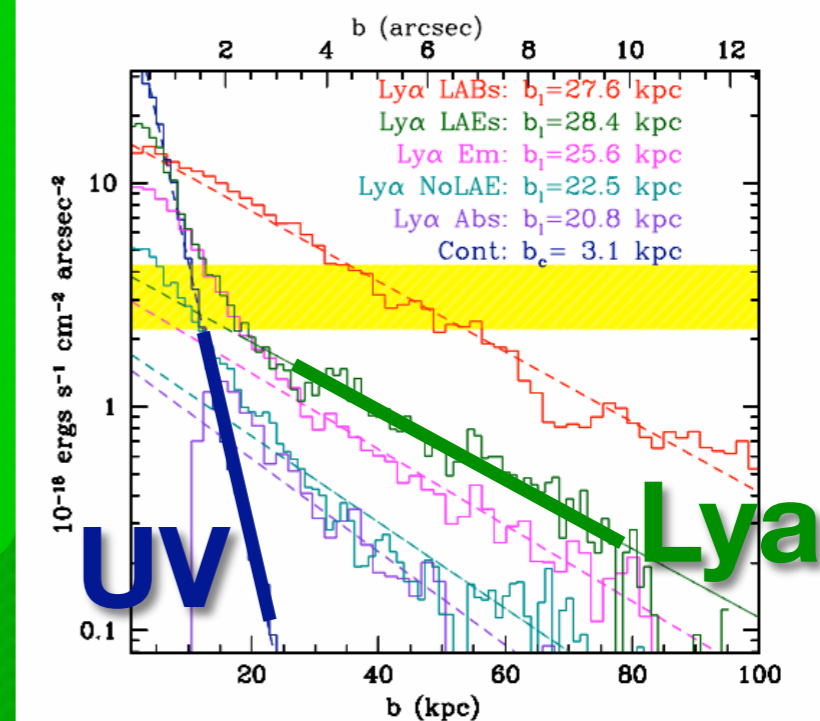
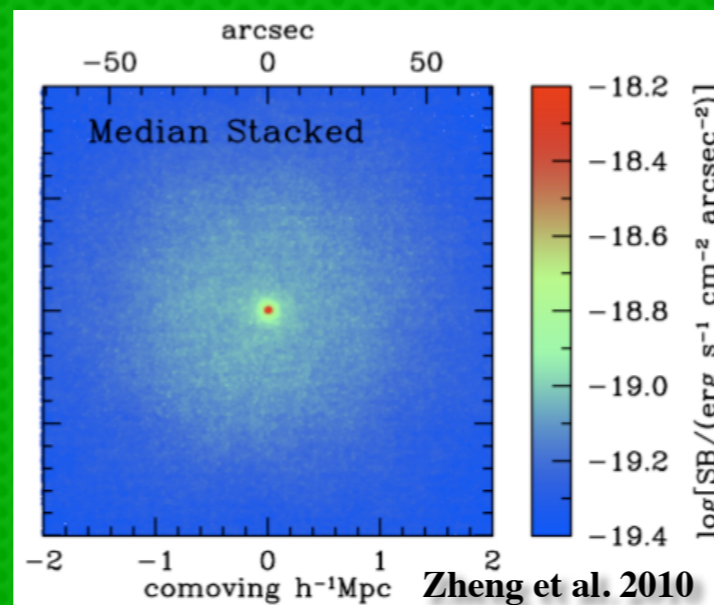


- Central galaxy

- Clumpy, filamentary structure

- Ly $\alpha$  profile larger than the UV profile

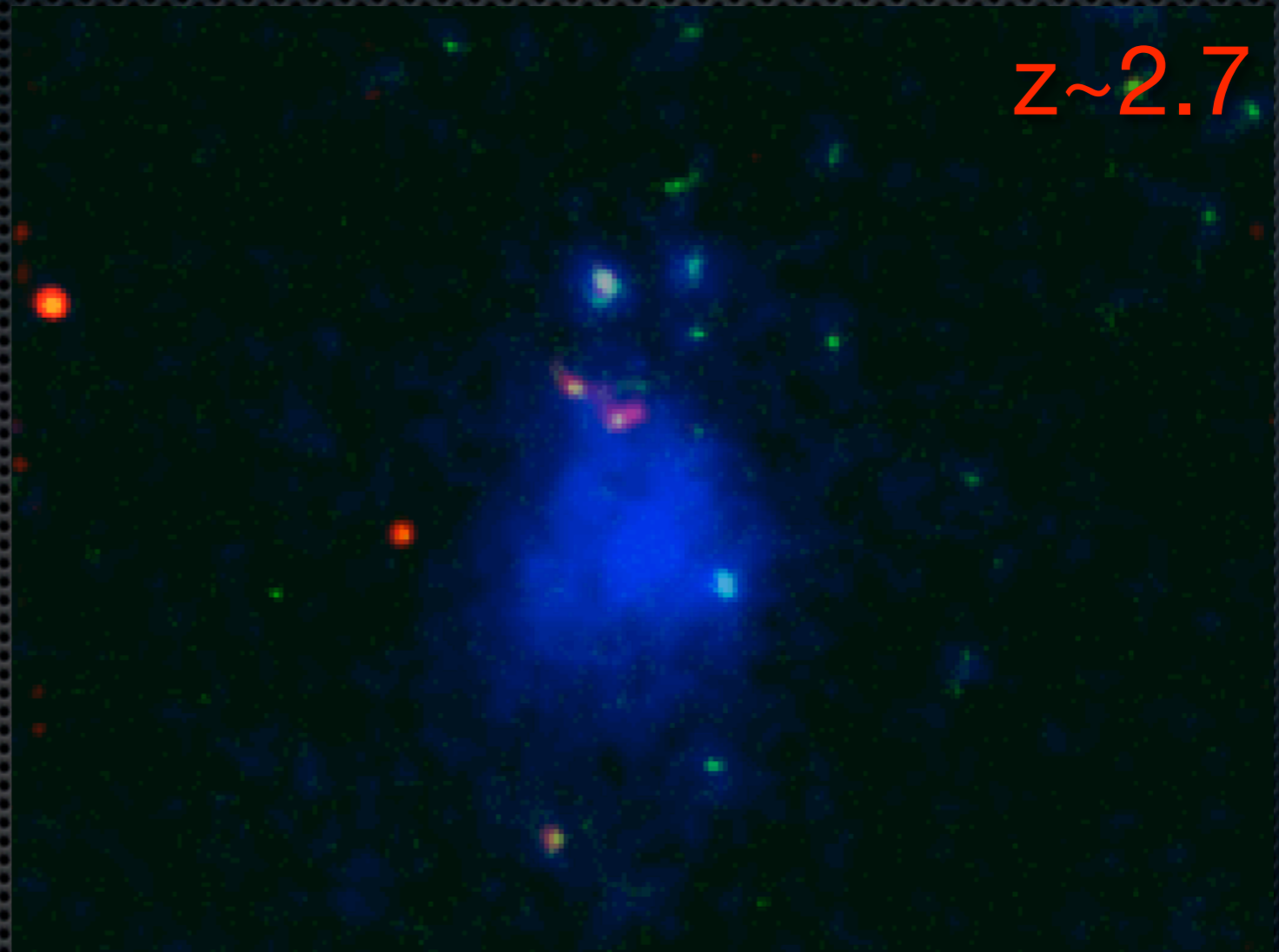
- Polarized Ly $\alpha$ ?



Steidel et al. 2011

# Outline

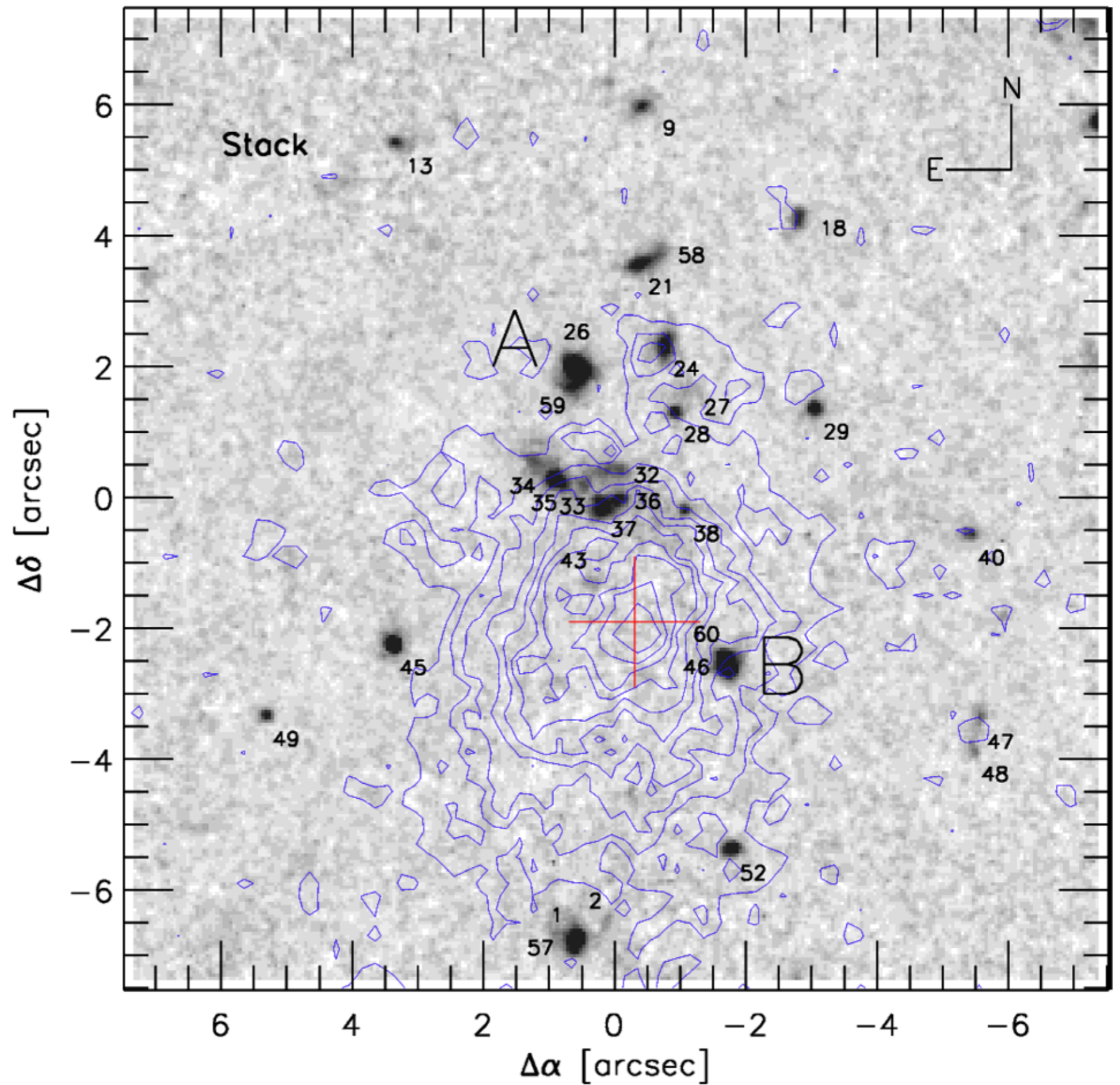
- **Small-scale Morphology**
- Ly $\alpha$  polarization
- Properties of galaxies within a Ly $\alpha$  nebula



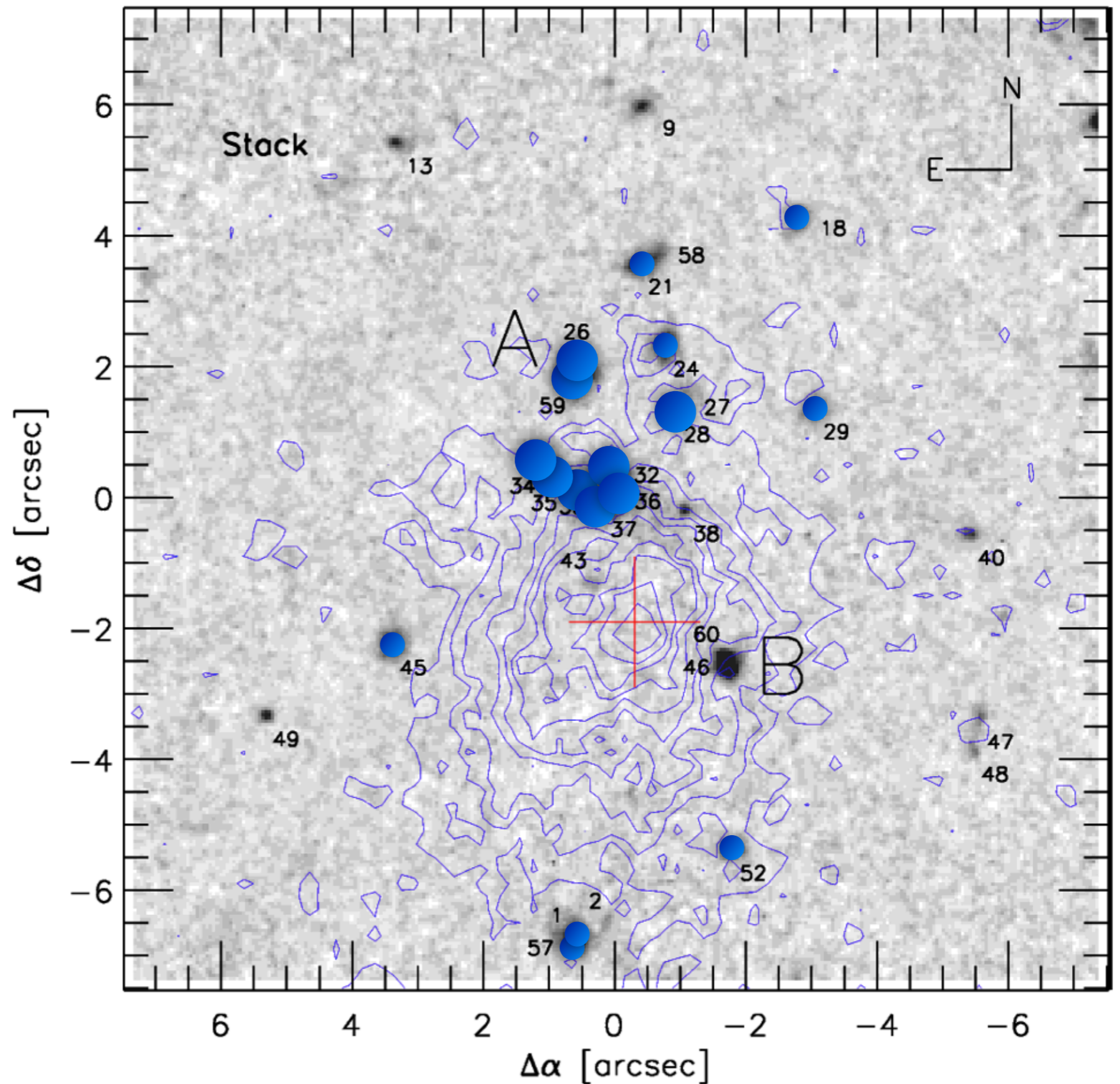
Credit: M. Prescott & A. Dey 2010



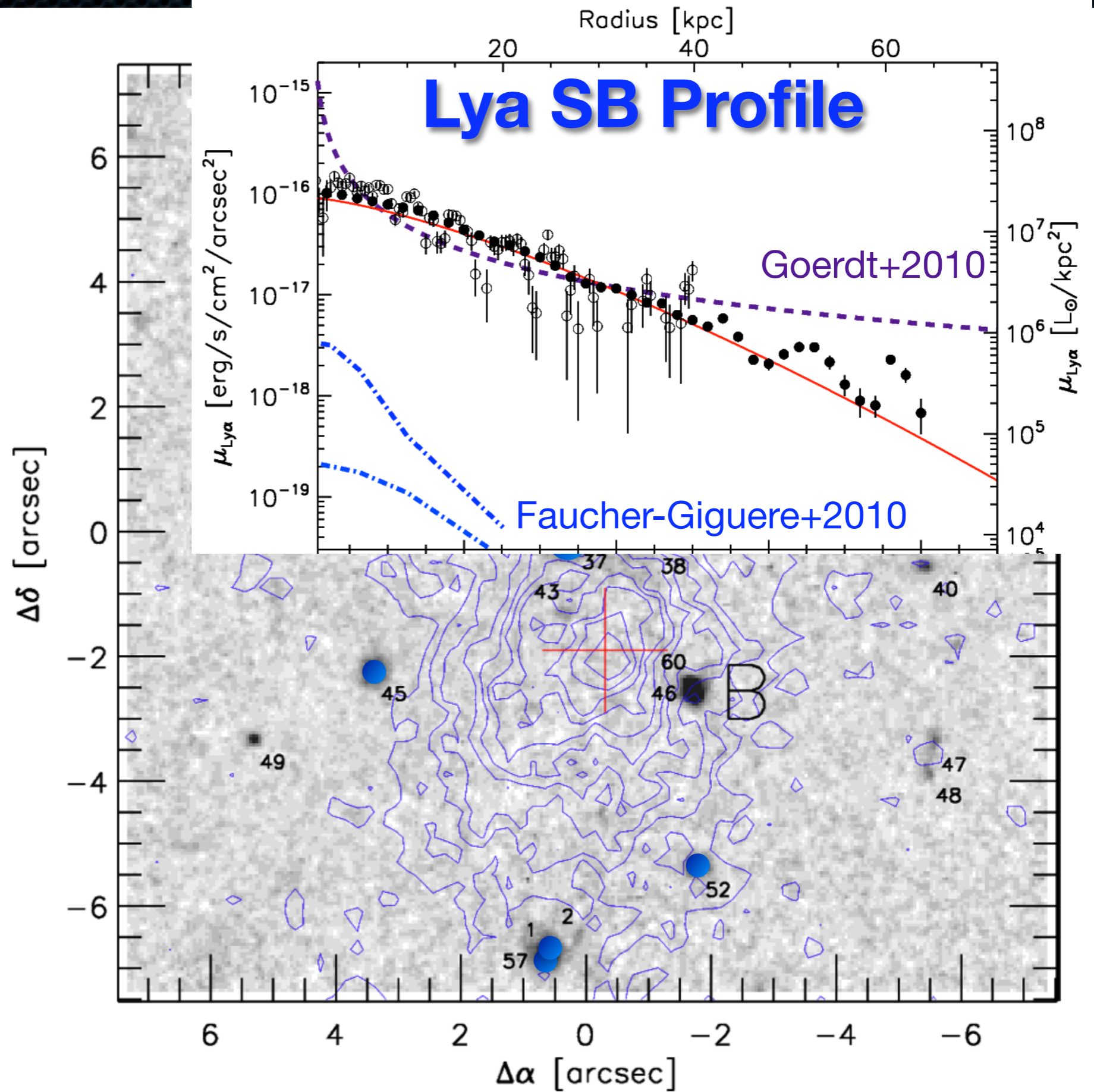
- Use spec-z and NIR colors to select member galaxies



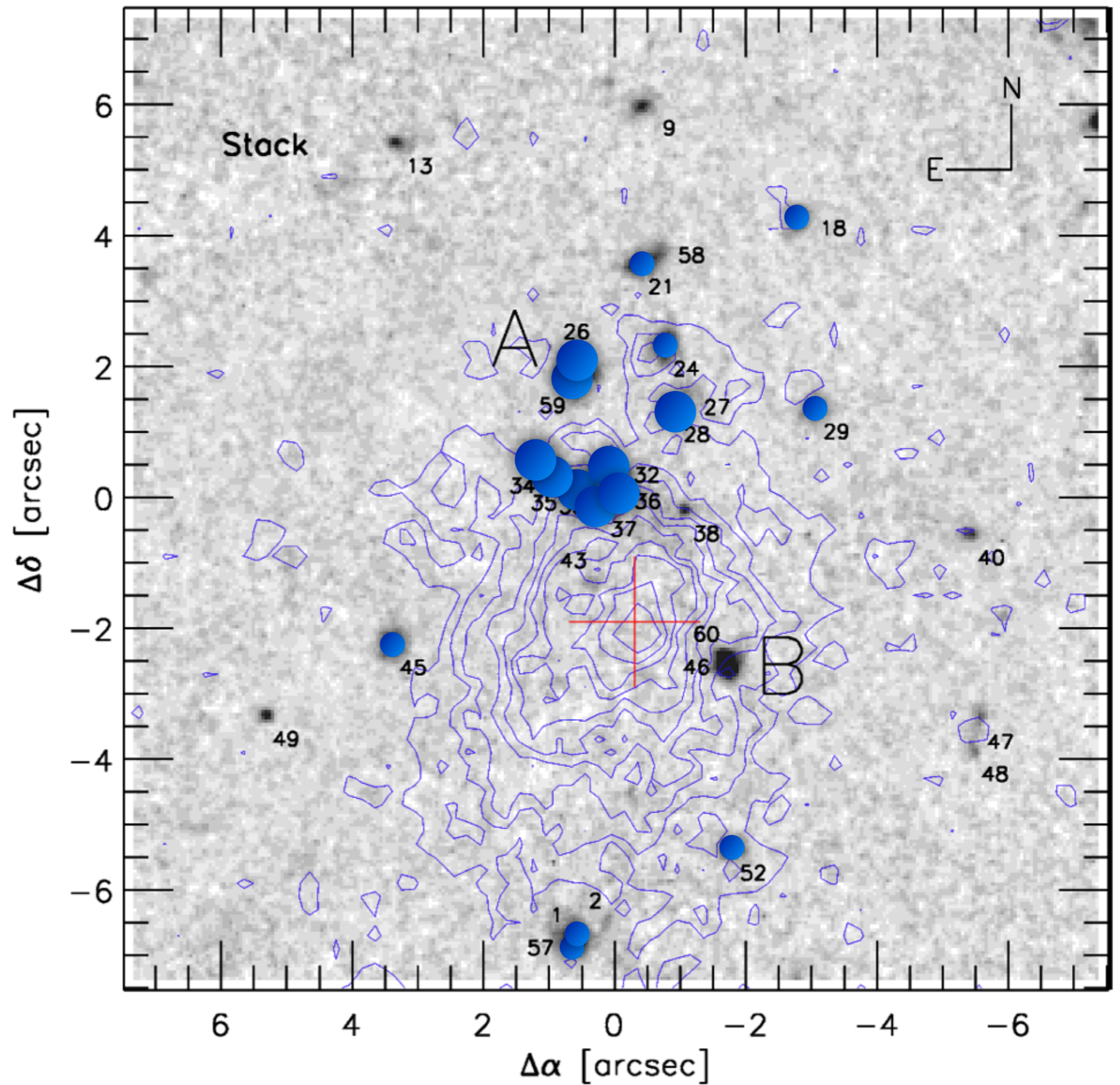
- ✦ No central galaxy in Ly $\alpha$ , UV, optical, or infrared
- ✦ Member galaxies offset from the Ly $\alpha$  nebula peak by  $\sim 20$  kpc
- ✦ **Challenges all three models**



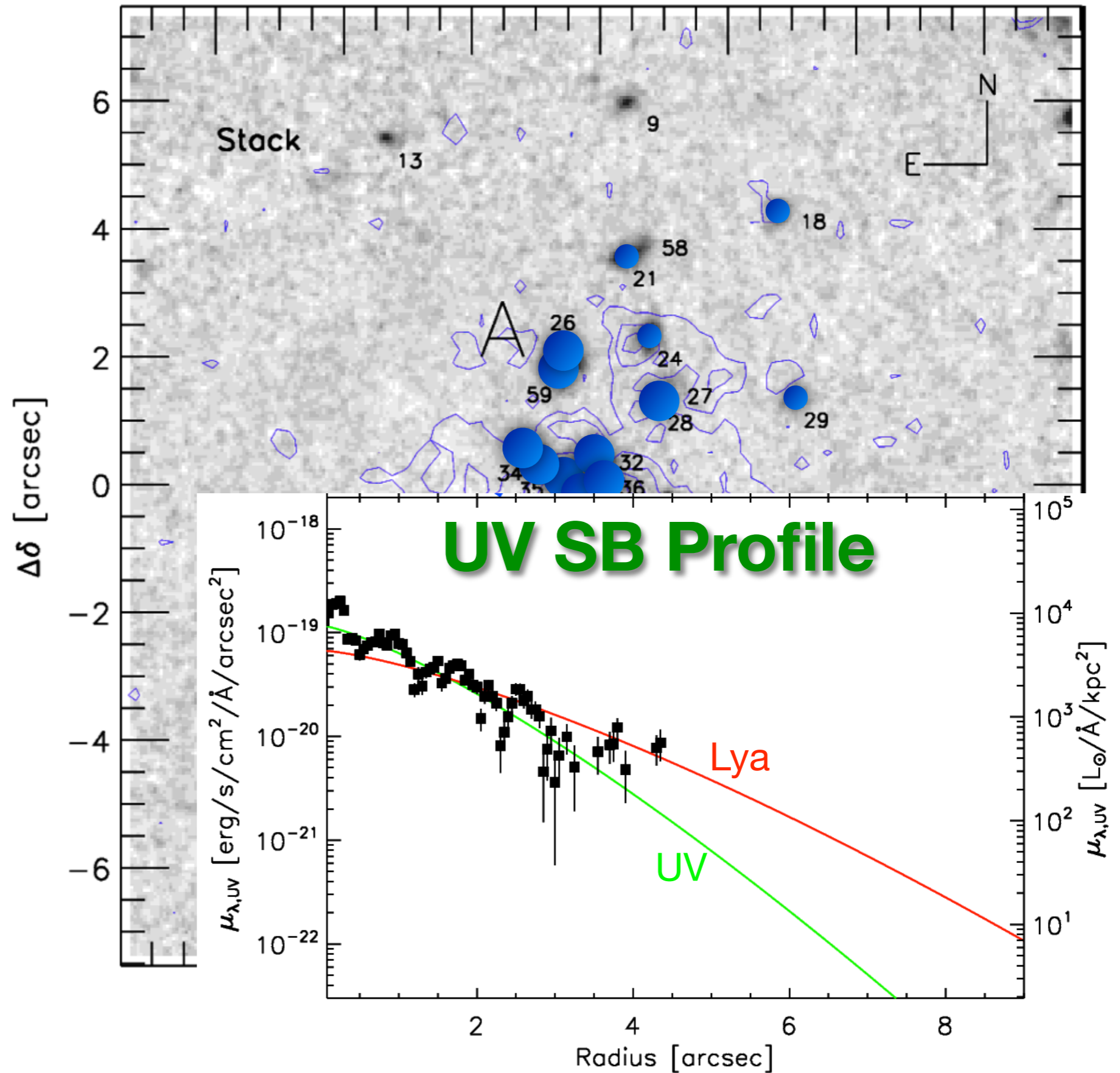
- ✦ Ly $\alpha$  surface brightness profile differs in shape/luminosity
- ✦ **Challenges cold flow model**



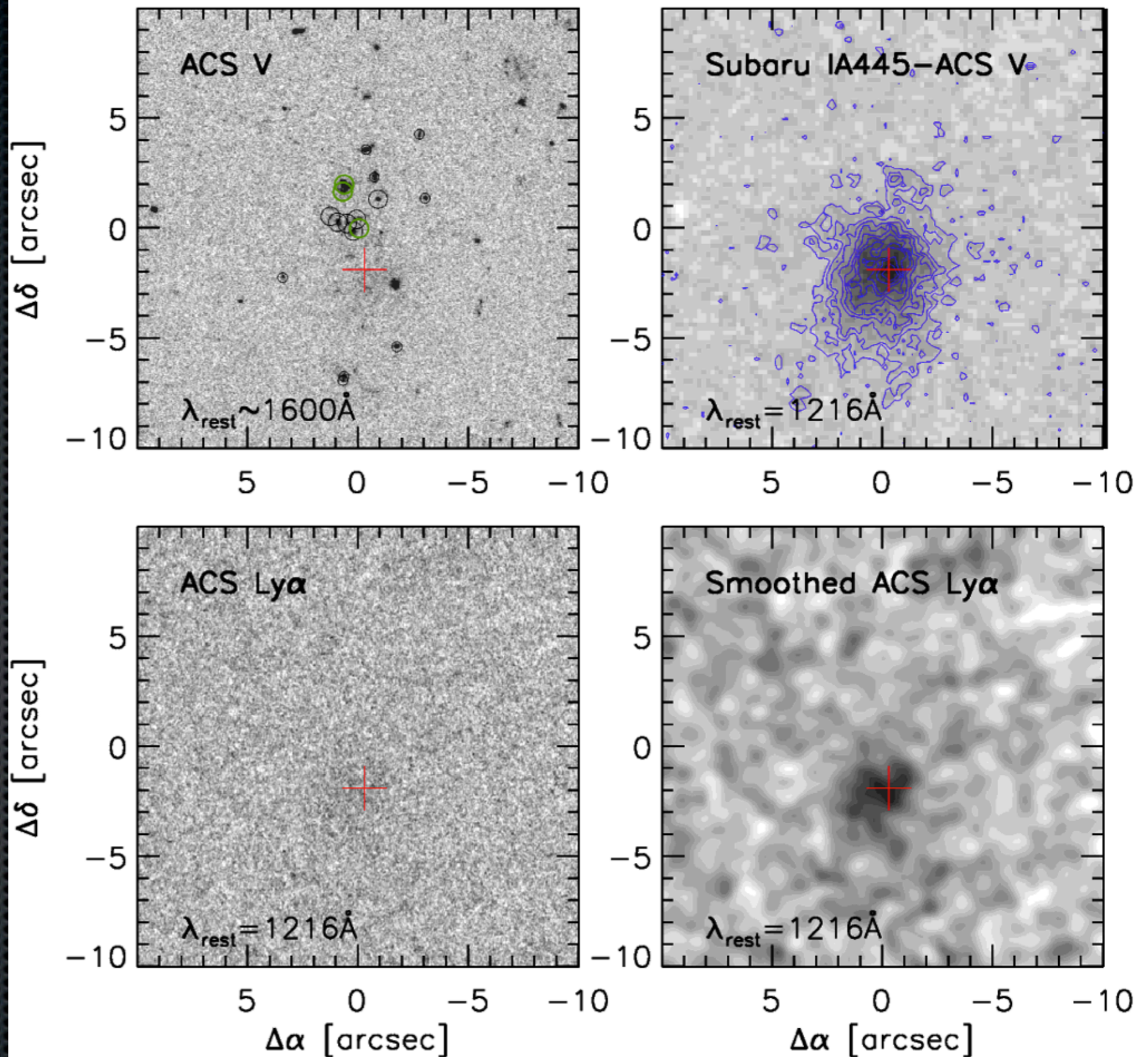
- ✦ No central compact UV source ( $M < 3 \times 10^7 M_{\text{sun}}$ )
- ✦ However, there is faint *diffuse* UV emission within nebula



- ✦ UV profile nearly as extended as Ly $\alpha$  profile
- ✦ **Challenges resonant scattering model**



- Ly $\alpha$  is smooth (SFR < 1 Msun/yr)
- Ly $\alpha$  best fit as an exponential disk with  $b/a \sim 0.7-0.8$
- Not particularly filamentary or clumpy
- **Challenges cold flow model**



# Small-scale morphology

- ✦ While outflows, cold flows, resonant scattering no doubt present, **none** of these processes is favored as the sole explanation for:

➔ **powering** the Ly $\alpha$  emission

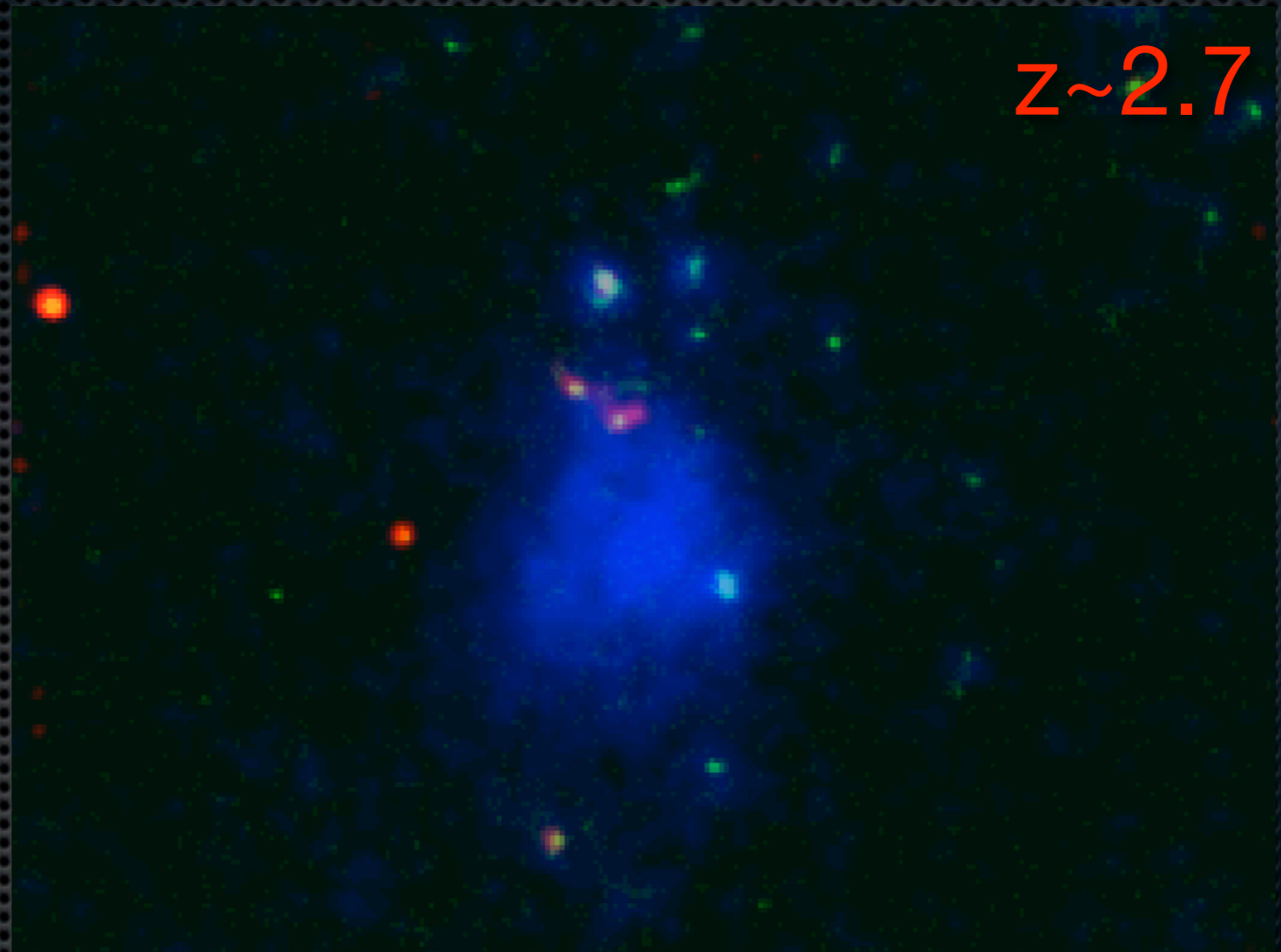
or

➔ producing the **large Ly $\alpha$  extent**

- ✦ Photoionization by AGN / SF most likely dominates

# Outline

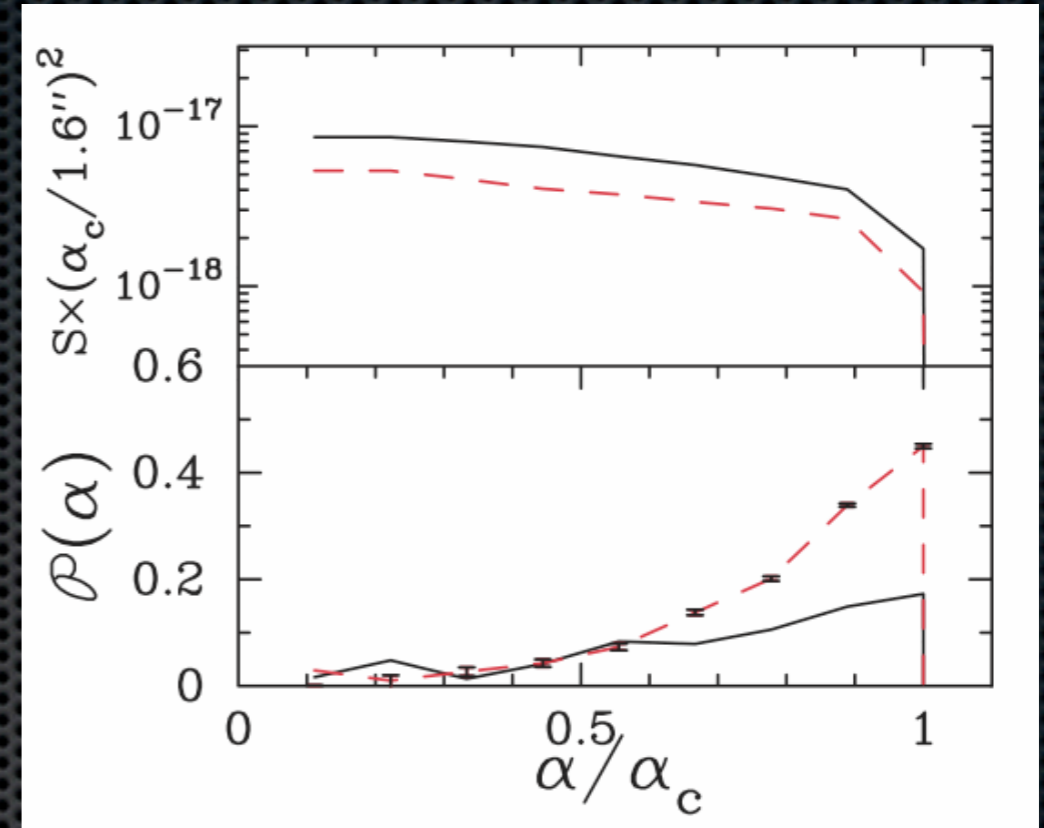
- Small-scale Morphology
- **Lya polarization**
- Properties of galaxies within a Lya nebula



Credit: M. Prescott & A. Dey 2010



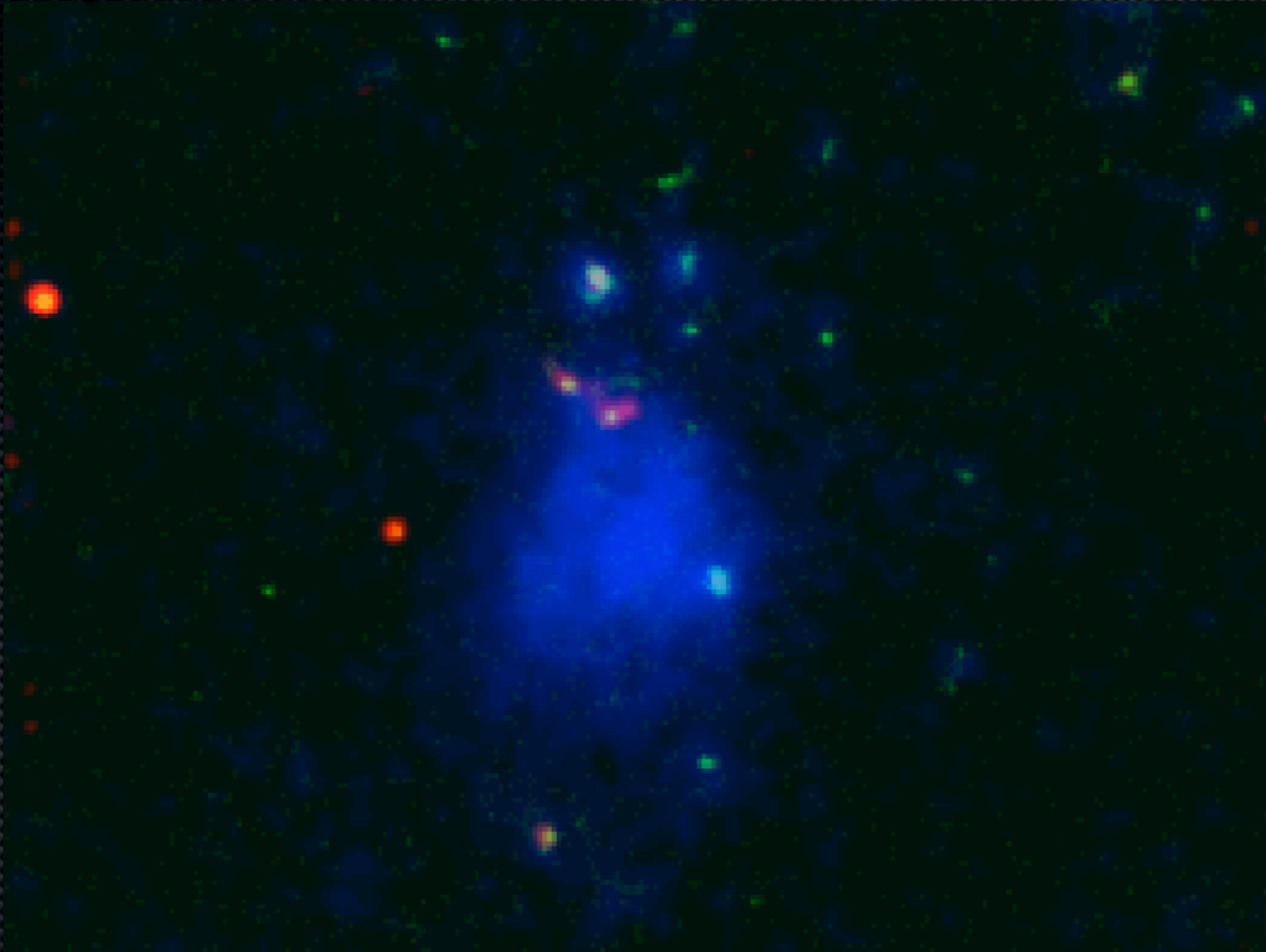
# Lya polarization



Dijkstra & Loeb 2008

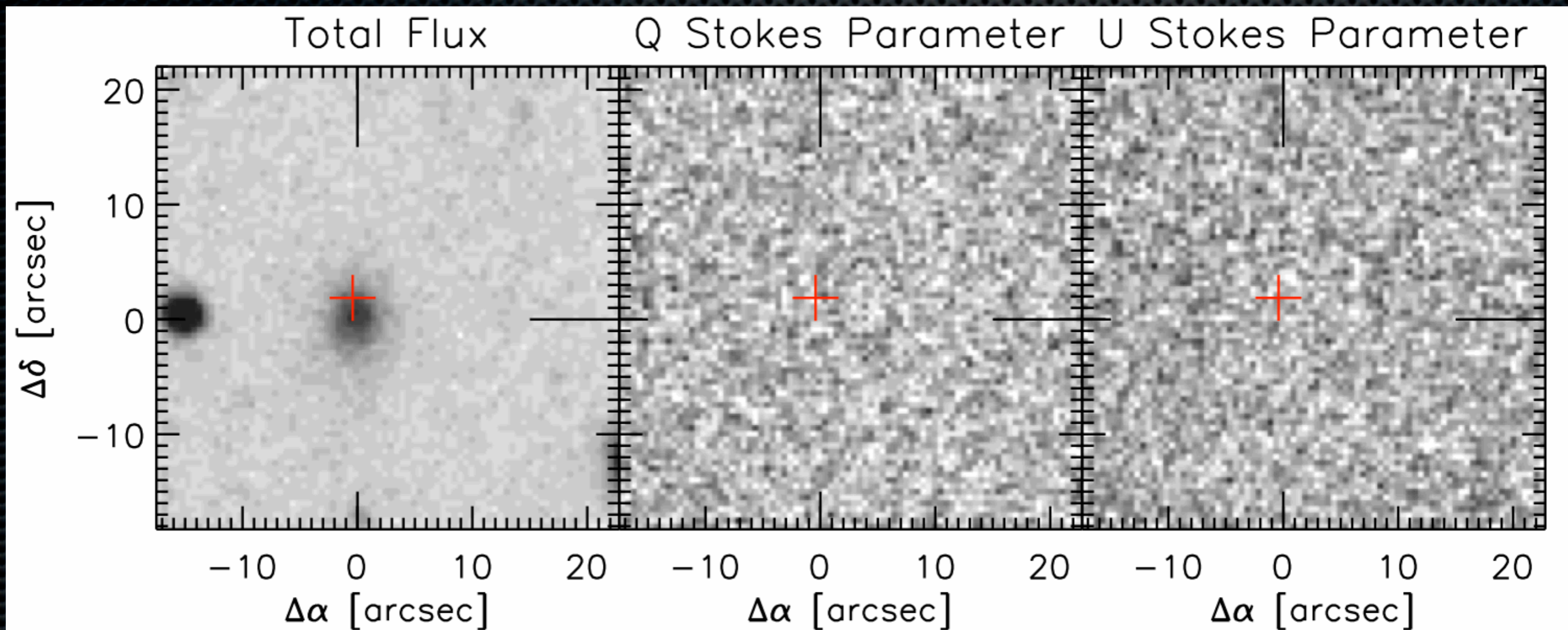
- Ly-alpha polarization observations can provide a constraint on:
  - ➔ whether scattering of Ly-alpha is important
  - ➔ where Ly-alpha photons are being generated
- Theoretical predictions suggest that Ly-alpha nebulae may be polarized:
  - ➔ show a rising radial polarization gradient
  - ➔ reach polarizations as high as  $\sim 40\%$
  - ➔ details depend on gas geometry, density, and velocity gradient

# First polarization constraints



Credit: M. Prescott & A. Dey 2010

# First polarization constraints

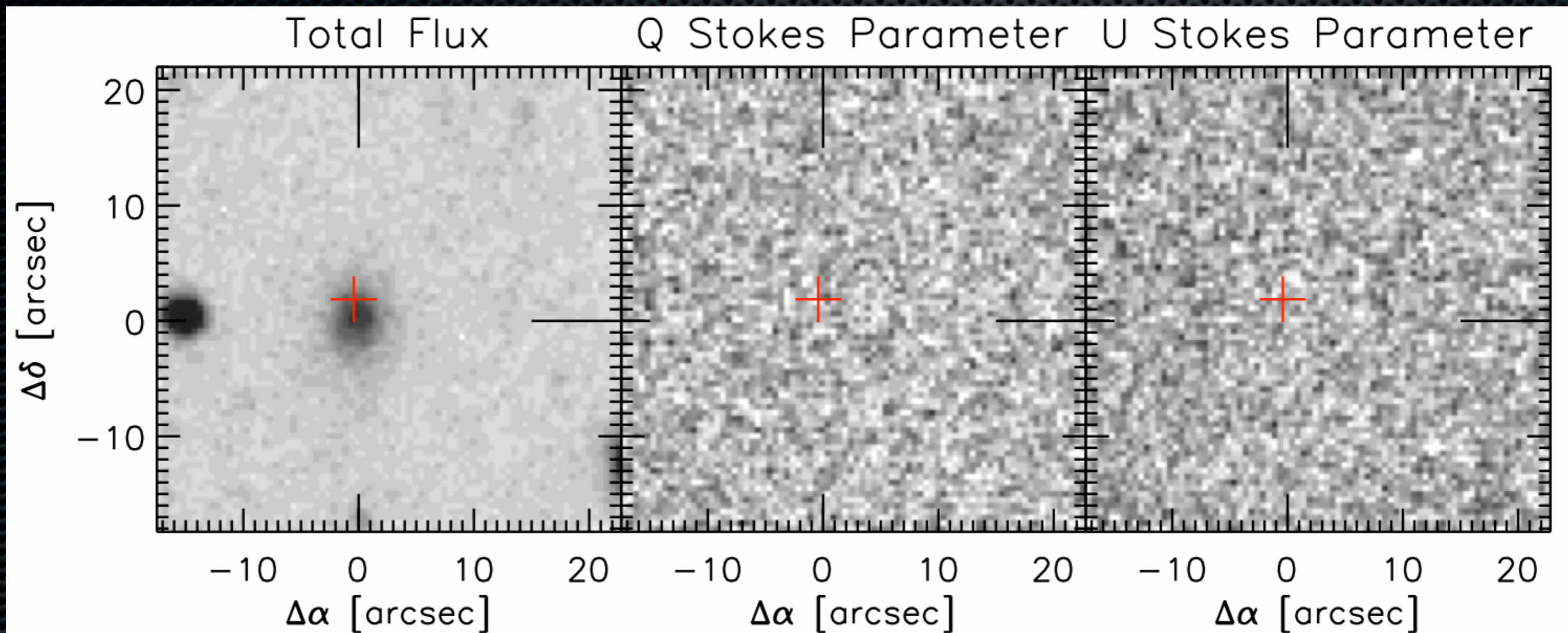


Prescott et al. 2011a

$$P^2 = q^2 + u^2$$

- $P = 2.6 \pm 2.8\%$  over entire nebula

# First polarization constraints

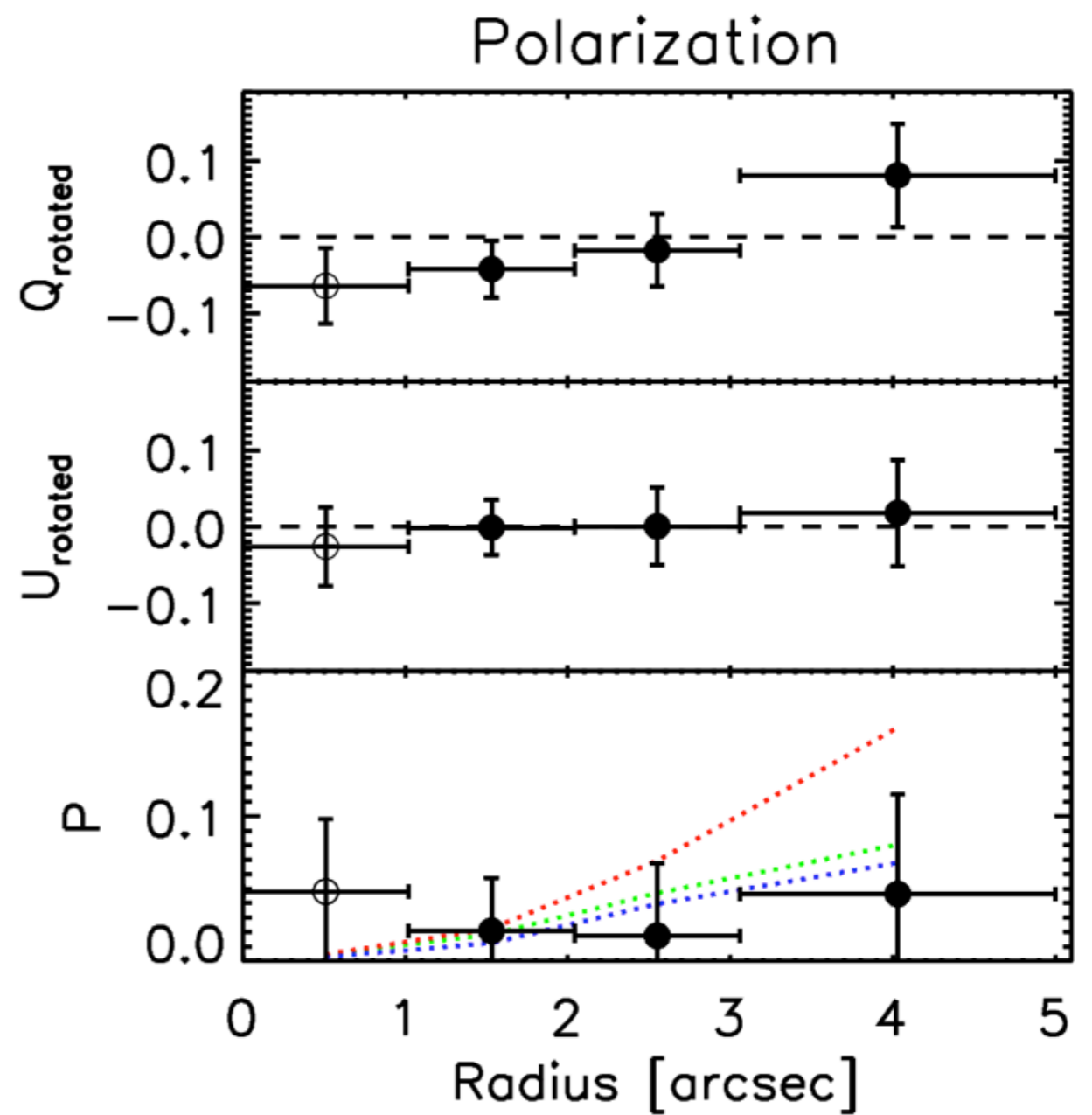
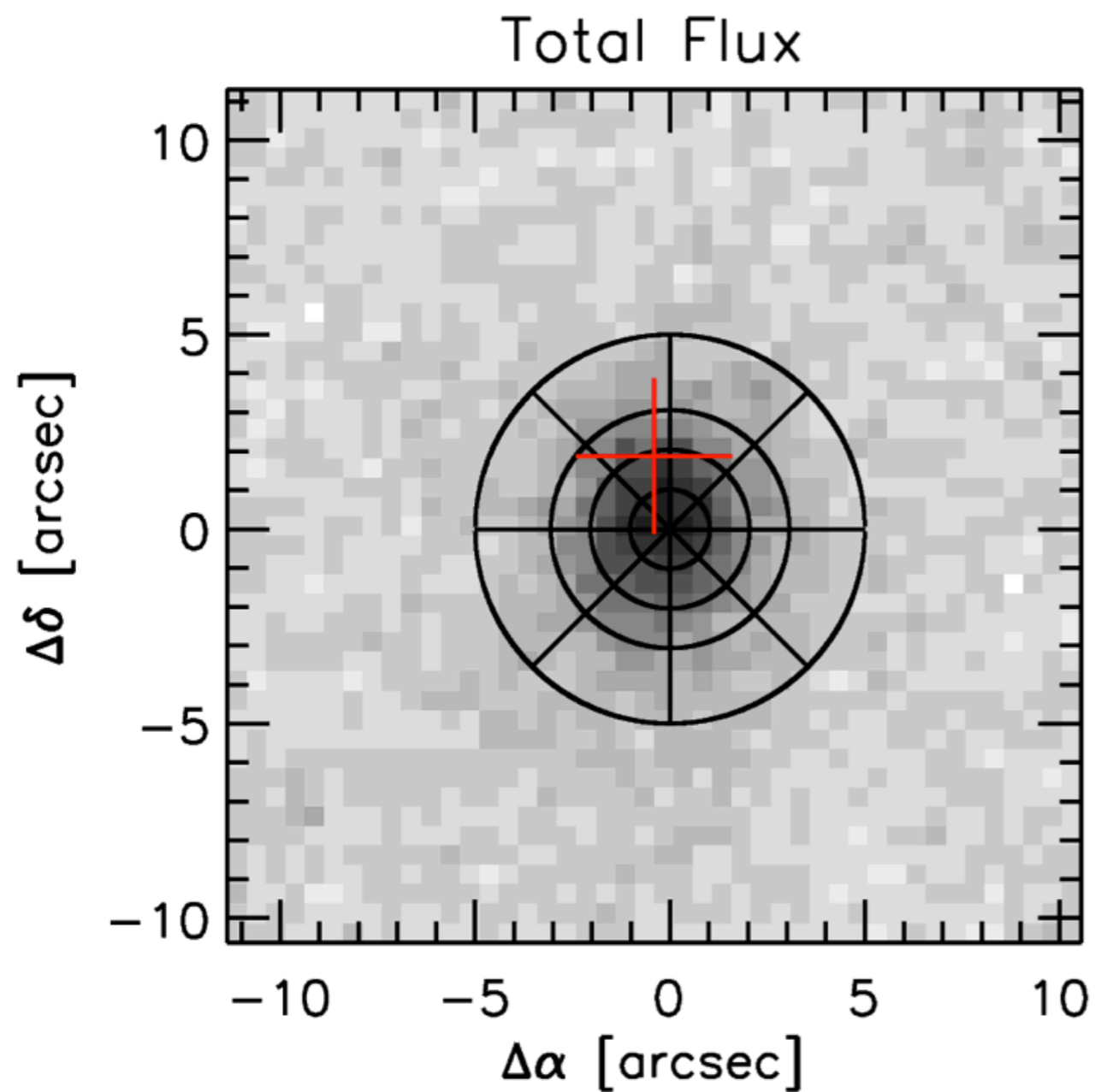


Prescott et al. 2011a

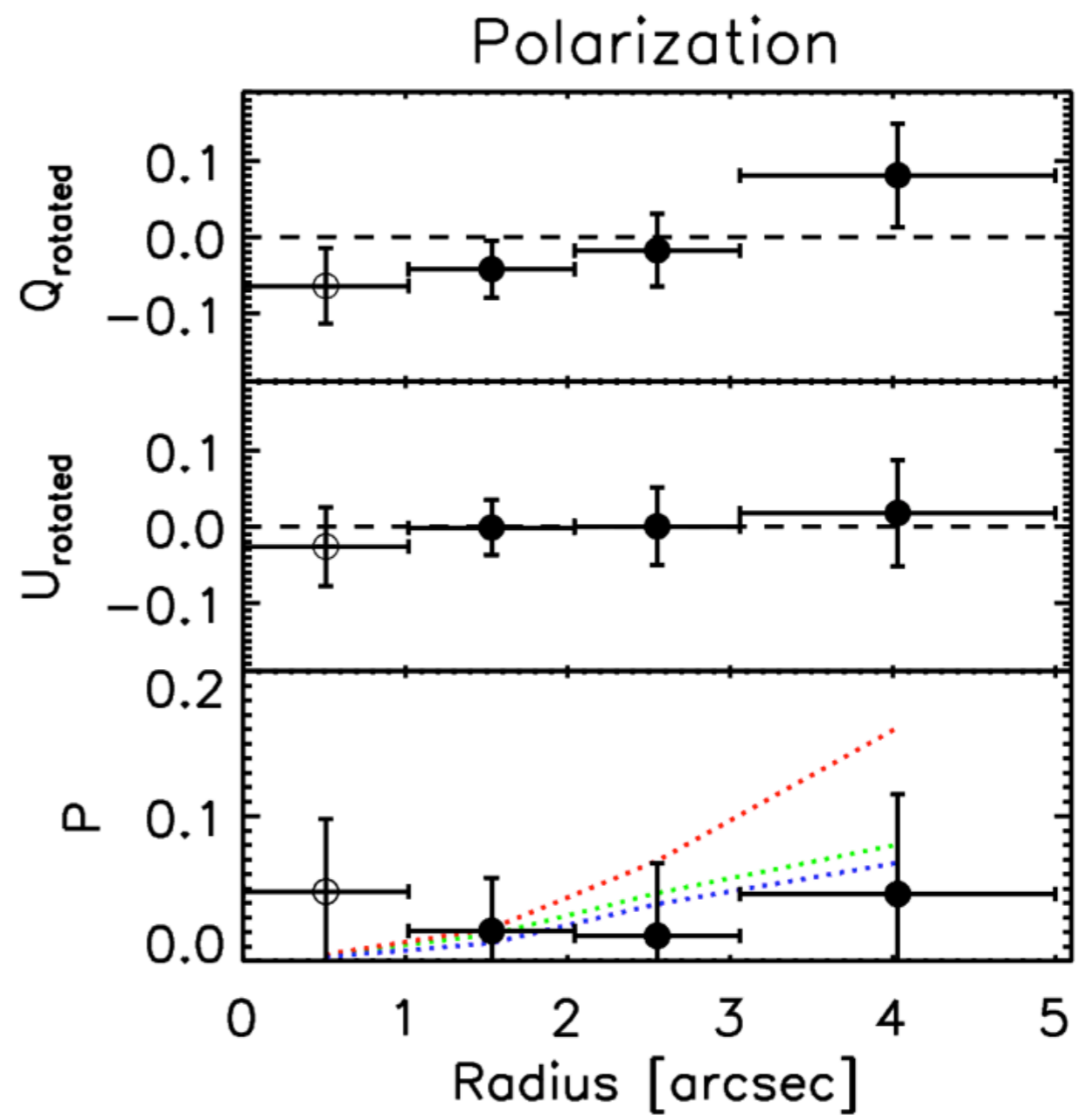
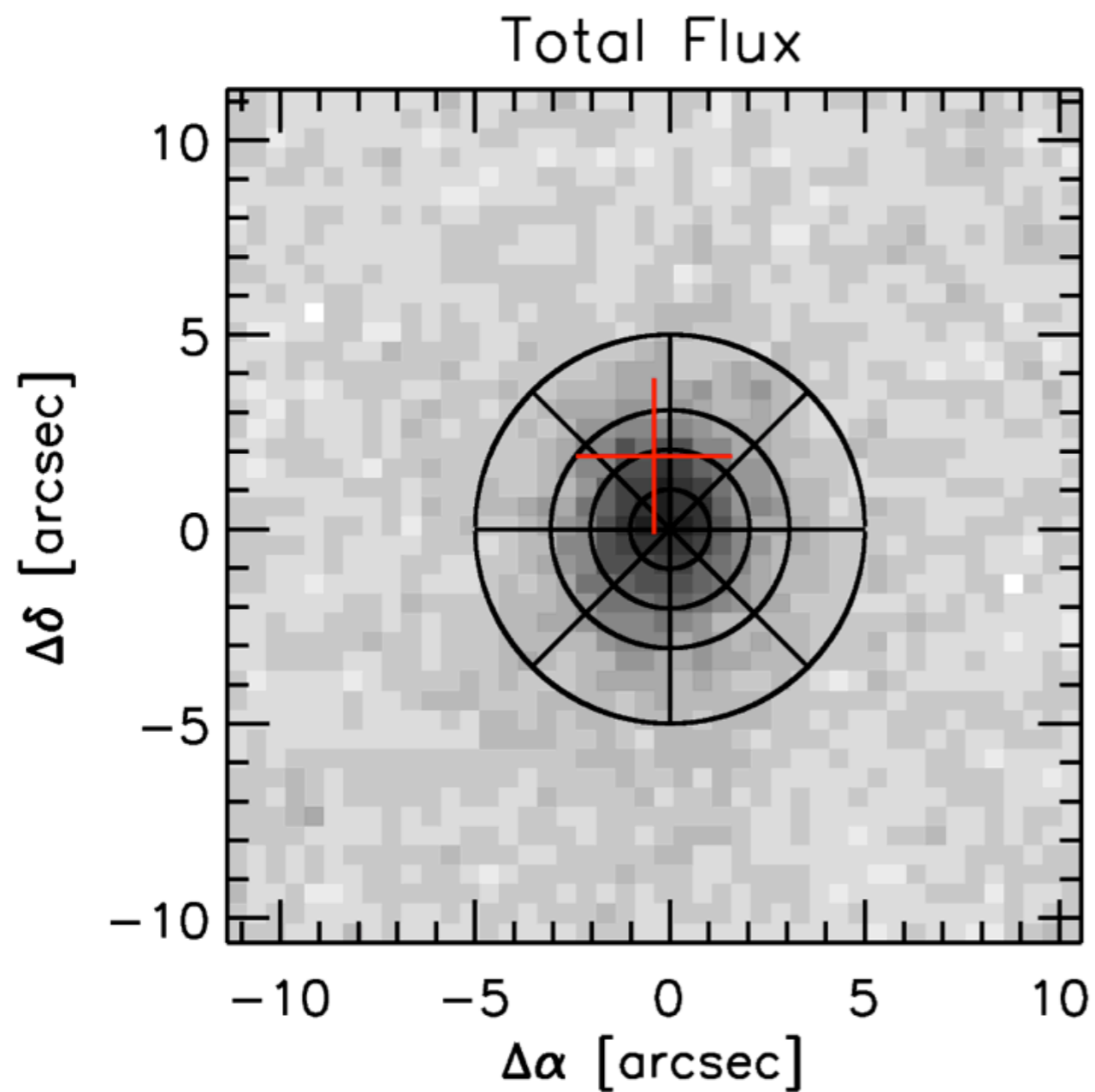
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# First polarization constraints



# First polarization constraints



# Lya Polarization

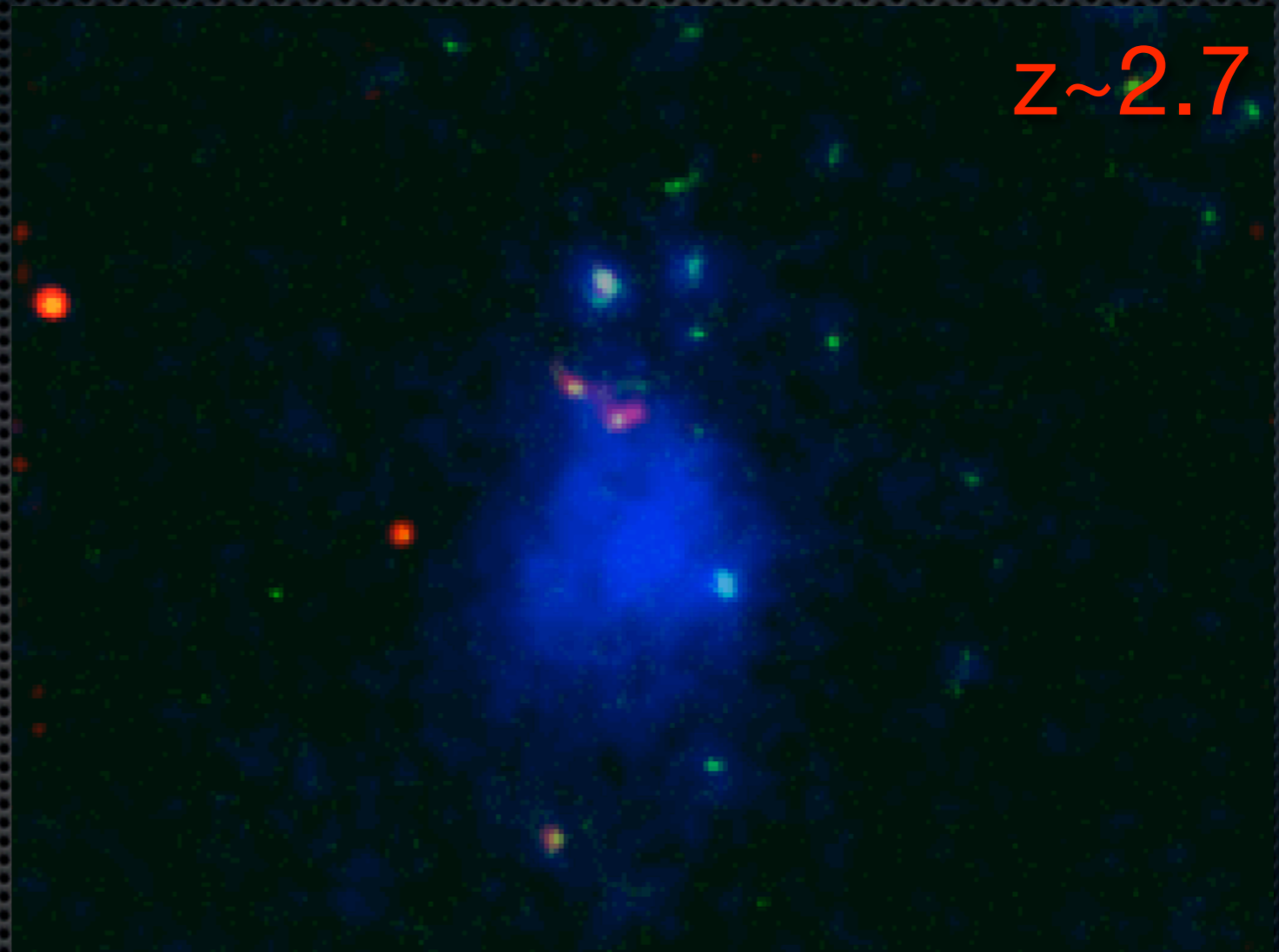
- ✦ First observational constraint on the polarization of a Lya nebula (<5% overall or <20% at large radius)
- ✦ Puts limits on the contribution of scattered Lya

but

- ➔ Need deeper and higher spatial resolution observations of **multiple Lya nebula systems**

# Outline

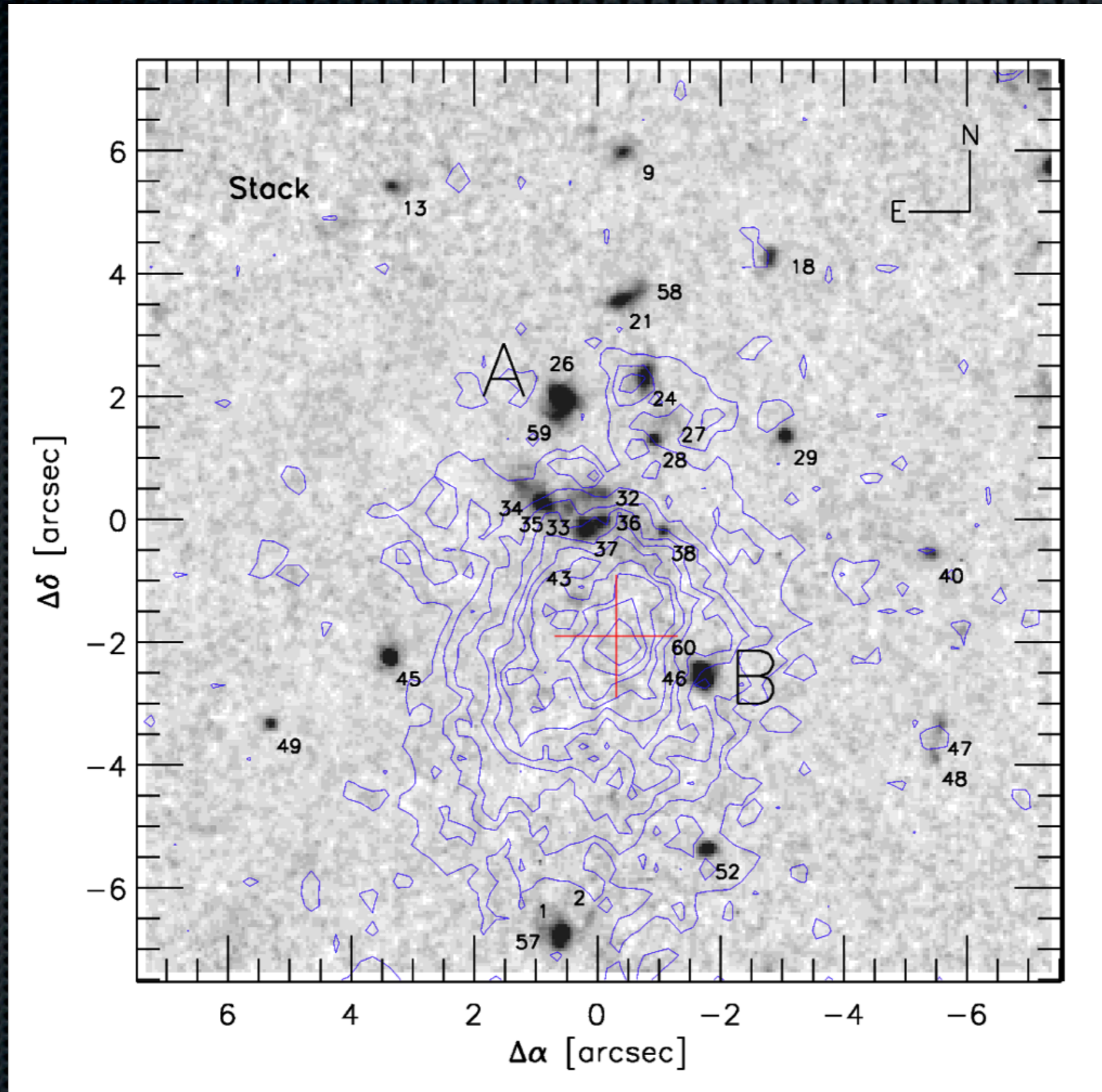
- Small-scale Morphology
- Ly $\alpha$  polarization
- **Properties of galaxies within a Ly $\alpha$  nebula**



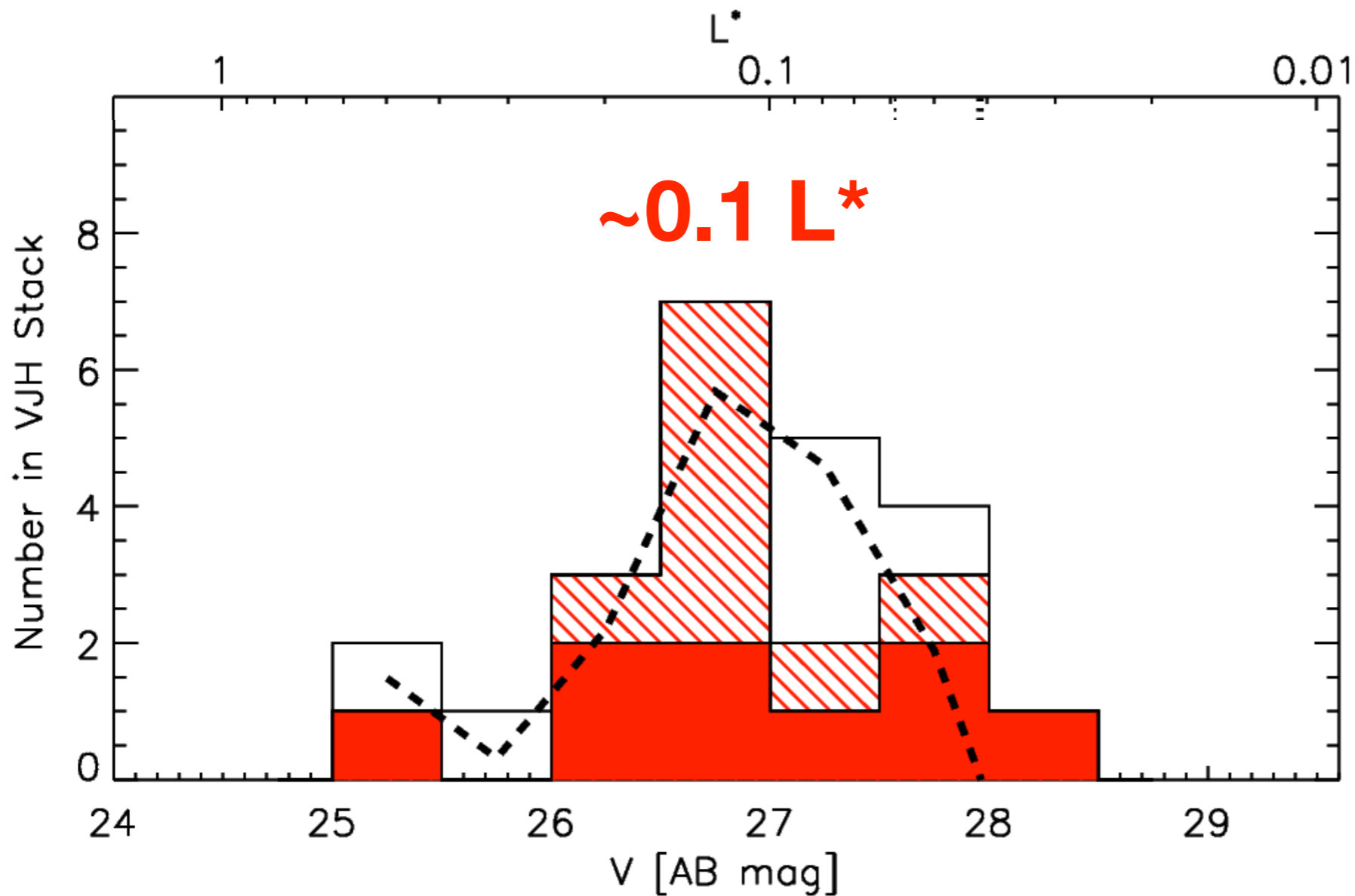
Credit: M. Prescott & A. Dey 2010



# The galaxies within...



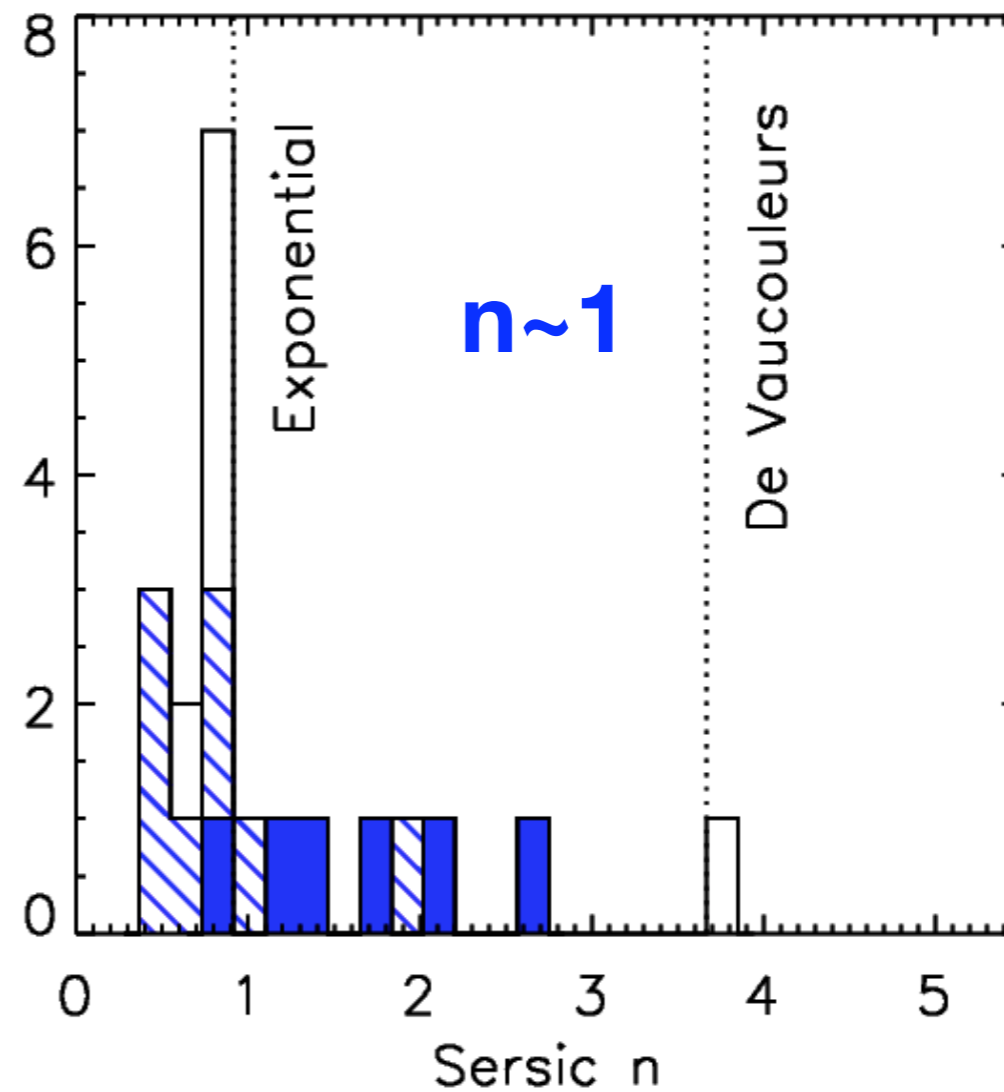
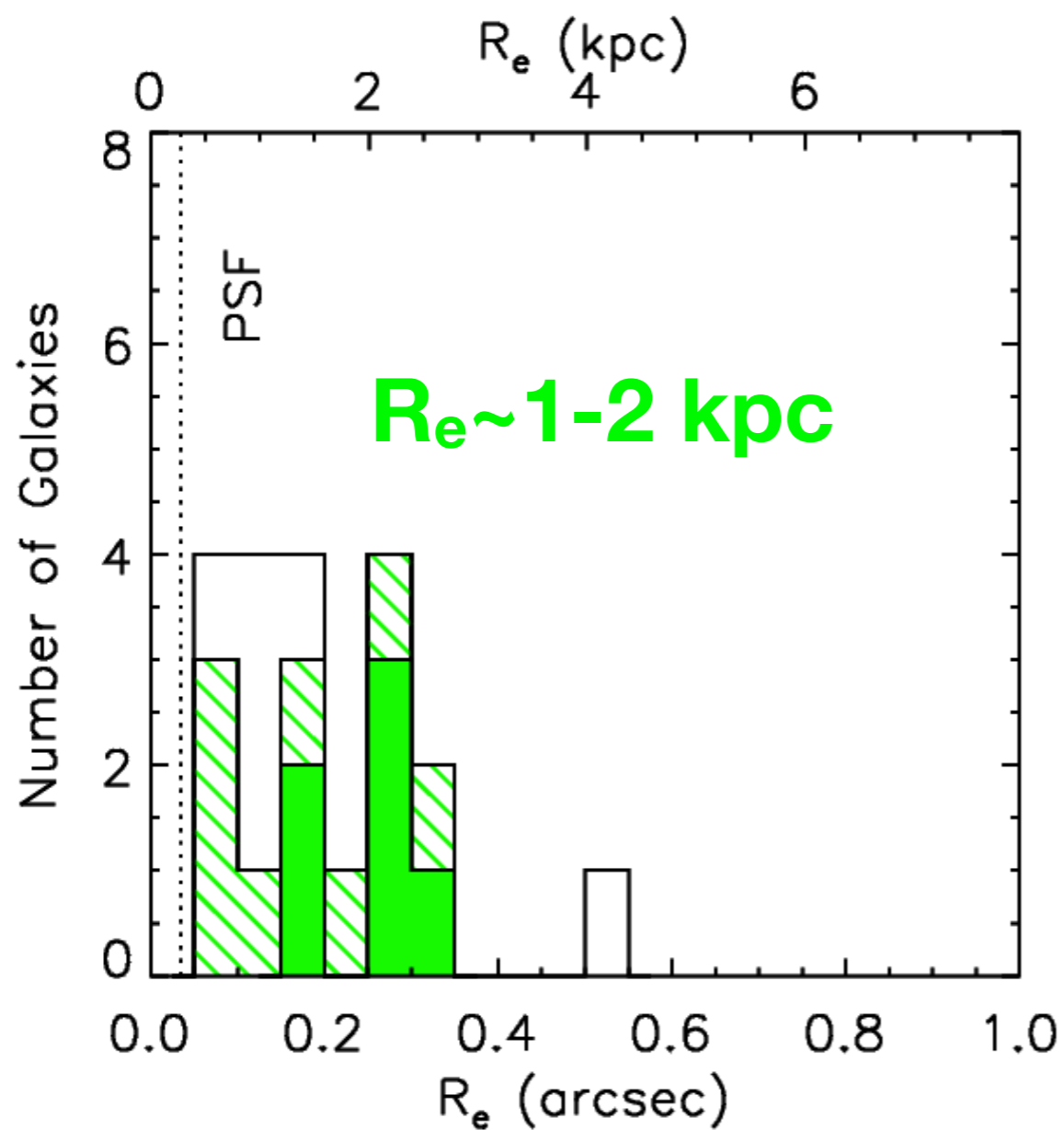
# Many low luminosity galaxies...



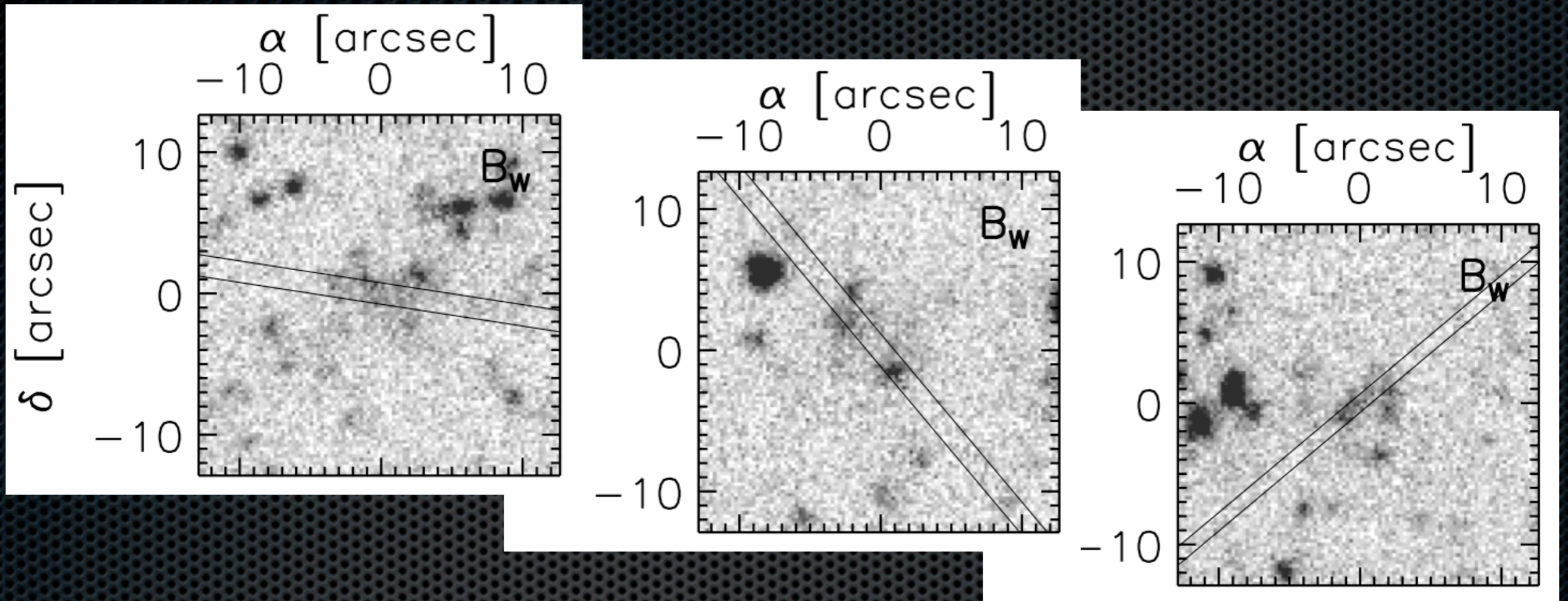
Prescott et al. 2011b, submitted

- ✦ Assign membership based on spec-zs and NIR colors
- ✦ Approximate “Luminosity Function” for galaxies ***within*** the Ly $\alpha$  nebula system

... that are small and disk-like.



# Future plans



- Accepted Cycle 19 HST/ACS+WFC3 program to image a sample of “low redshift” ( $z < 2.5$ ) Ly $\alpha$  nebulae for which we can constrain membership
  - ➔ Future prospects for measuring ensemble luminosity function of galaxies in Ly $\alpha$  nebulae and doing a full energetic analysis

# Summary

- ✦ Small-scale morphology of the Ly $\alpha$  nebula:
  - ➔ morphology diverges from outflow, cold flow, and resonant scattering scenarios
- ✦ First constraint on the Ly $\alpha$  polarization (<5% overall)
- ✦ The properties of galaxies within the Ly $\alpha$  nebula:
  - ➔ numerous small ( $\sim 1$  kpc), disk-like ( $n \sim 1$ ), low luminosity ( $\sim 0.1 L^*$ ) galaxies
  - ➔ first estimate of LF of galaxies in a Ly $\alpha$  nebula system
  - ➔ a forming galaxy group?