Star formation and metal enrichment in a high-redshift cluster

Sesto, January 12th

How do galaxies affect the surrounding environment?

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(submitted to ApJ)

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- Higher activity = stronger feedback > ubiquitous outflows
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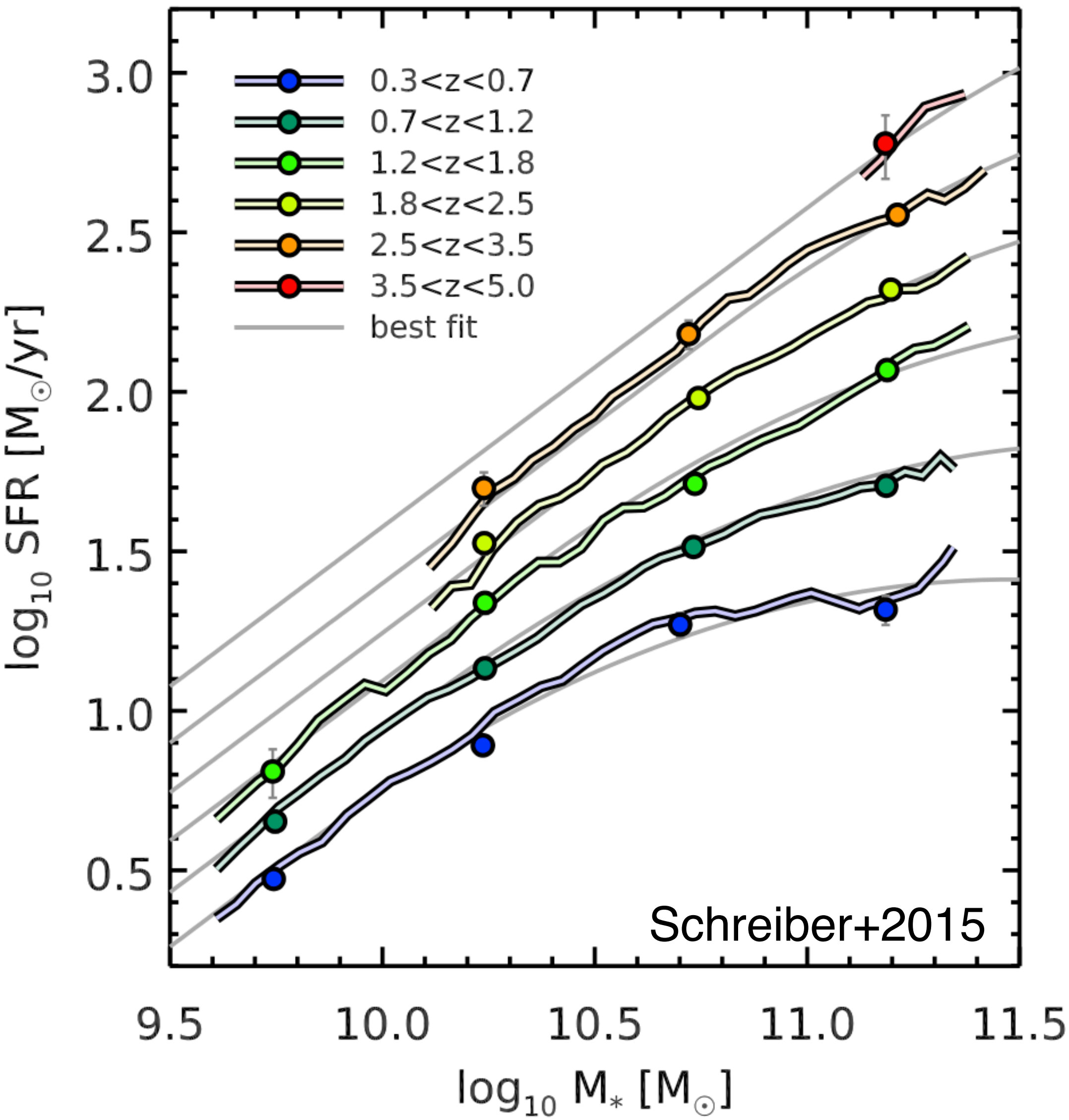
Galaxy activity rises with redshift

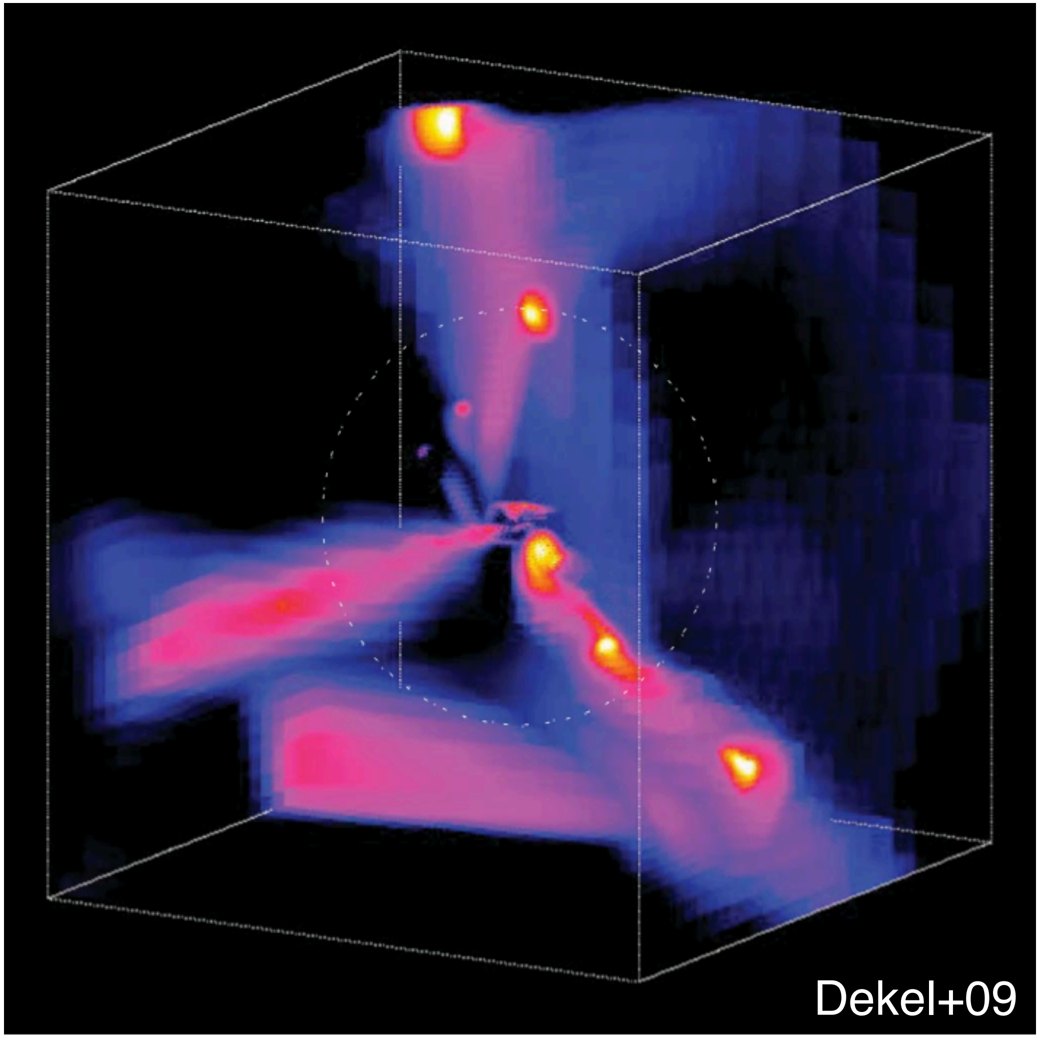


At z=1.5-2 galaxies:

- form stars at a rate 15-20× higher than in the local Universe (Sargent+2014, Schreiber+2015)
- their black hole activity increases accordingly (Mullaney+2012)
- their metal content drops (Erb+2006).

Gas regulation is the key

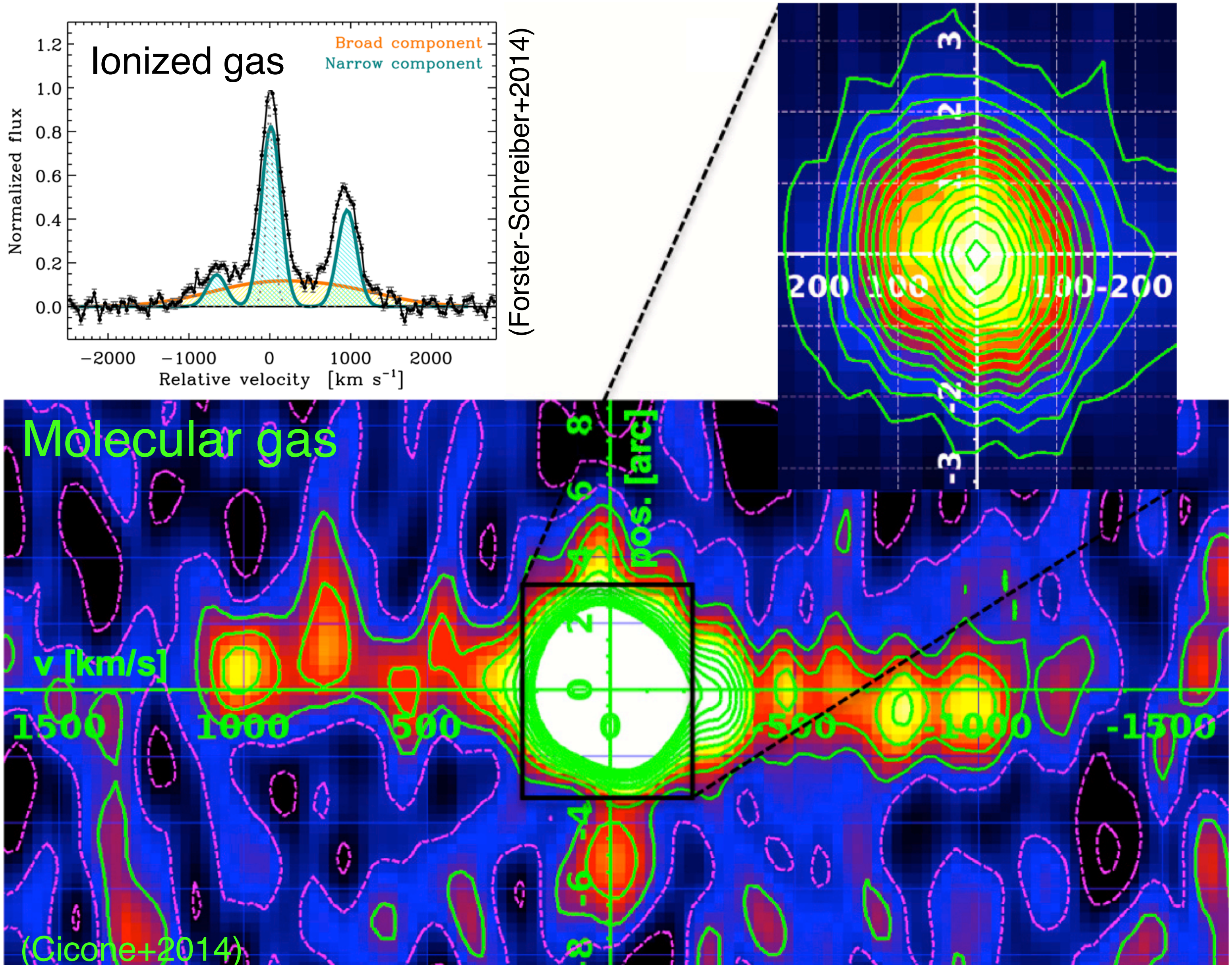
Galaxy activity rises with redshift



Higher gas fractions explain the rise in galaxy activity (i.e., Daddi+2010, with a moderate increase of star formation efficiencies).

Cosmological simulations show constant gas feeding from the cosmic web through dense **cold flows** (Dekel +2009).

Ubiquitous outflows



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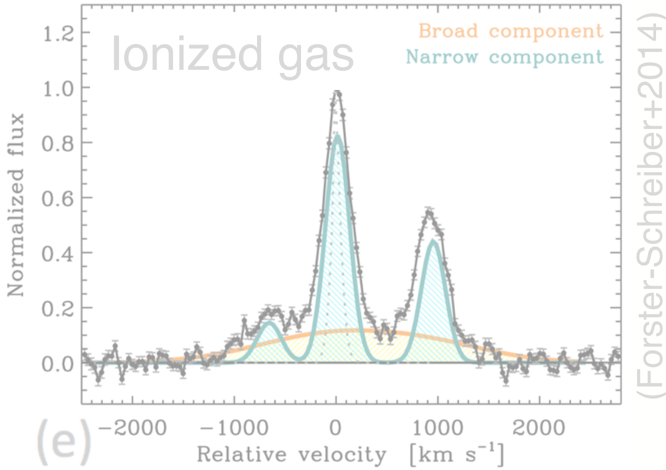
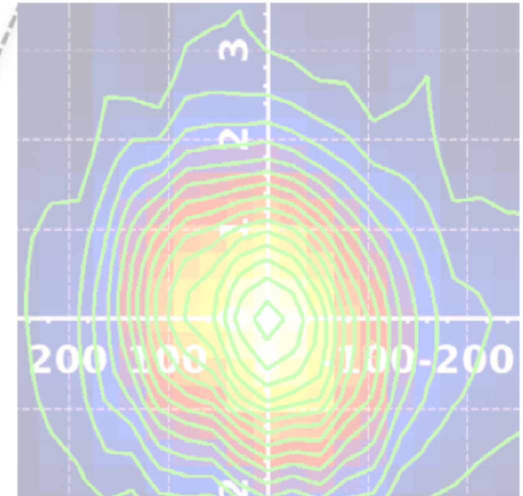
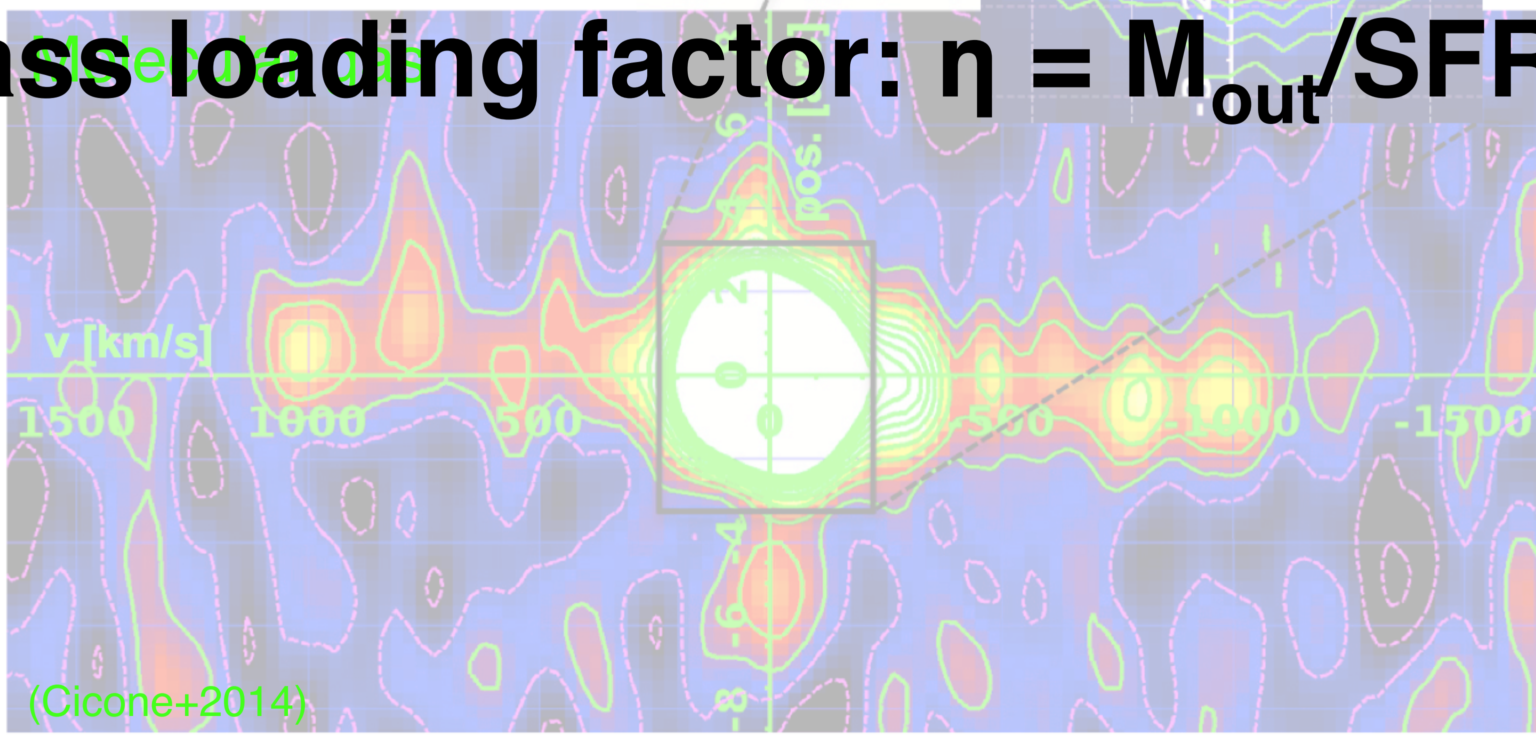
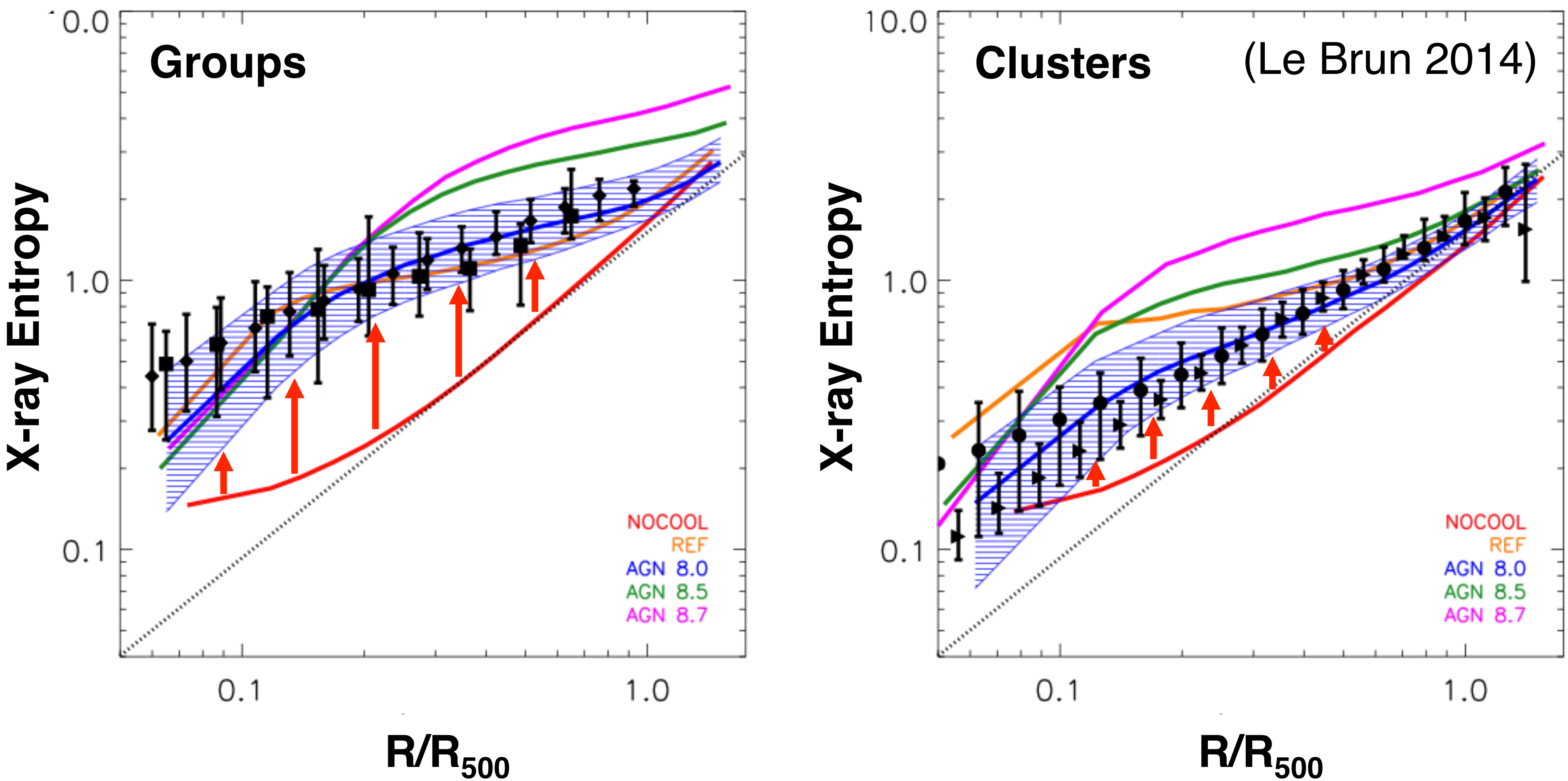






Mass loading factor: $\eta = \dot{M}_{out}/SFR \geq 1$

Energy injection into ICM



Galaxies are thought to **inject this energy** through outflows
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How much energy is supplied?

When does this occur?

For how long?

At what cluster evolutionary stage?

What is the fraction from AGN or SNe?

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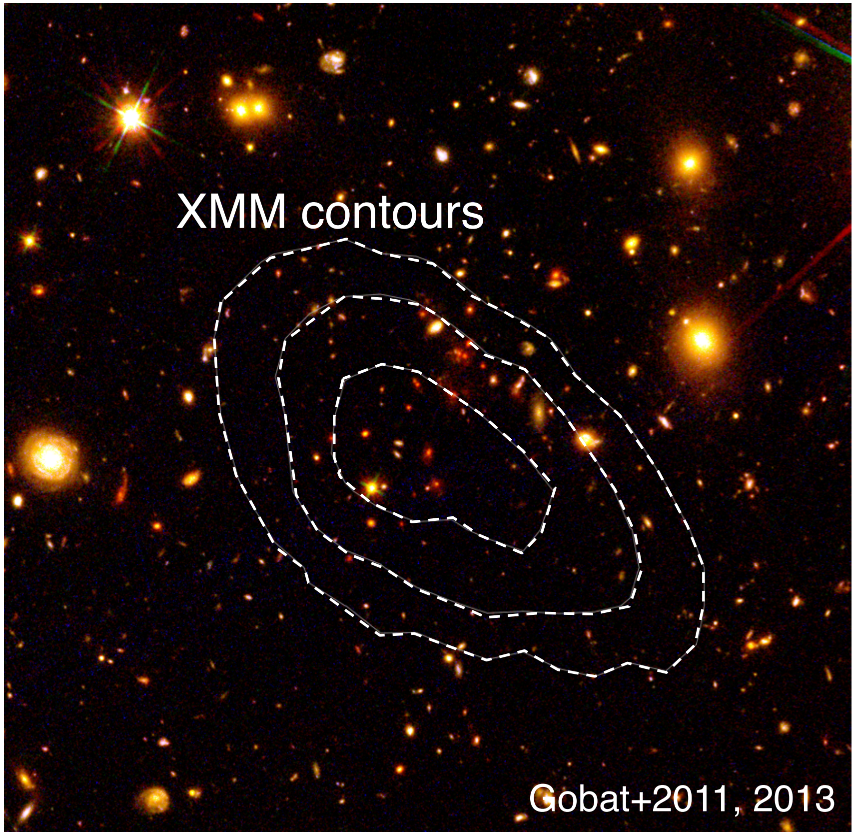
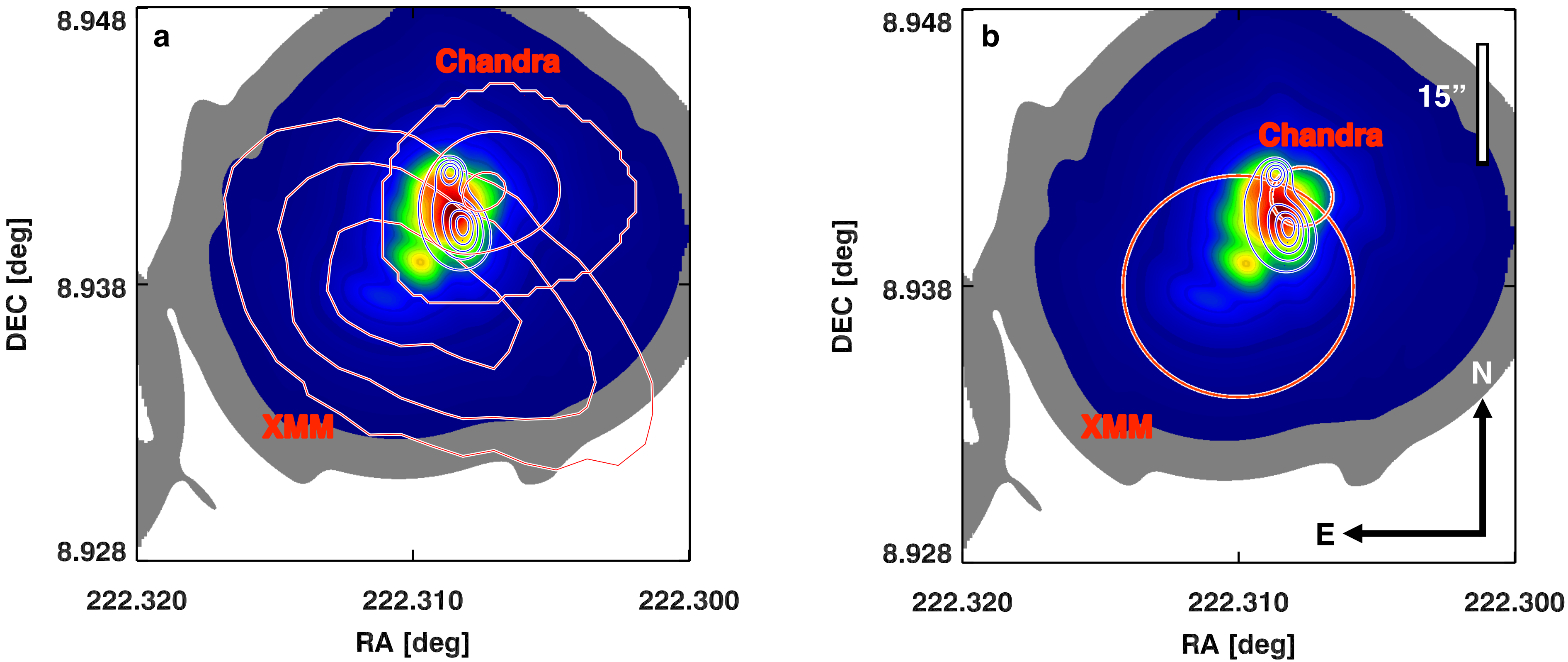
X-ray cluster at z = 1.99

- CL J1149+0856 at ***z* =1.99** is among the most distant clusters known to date, **the most distant X-ray detected** (Gobat +2011).
- Massive, red, quiescent members in its core (Strazzullo +2013, Gobat+2013)
- Yet, hosting a significant activity (**two X-ray AGN, several SFGs**, including the proto-BCG, Valentino+2015a)



X-ray cluster at $z = 1.99$

New Chandra 100ks: $L(x) = (9 \pm 3)\times10^{43}$ erg s^{-1} **$M_{halo} = (5 - 7)\times10^{13}M_{\odot}$**



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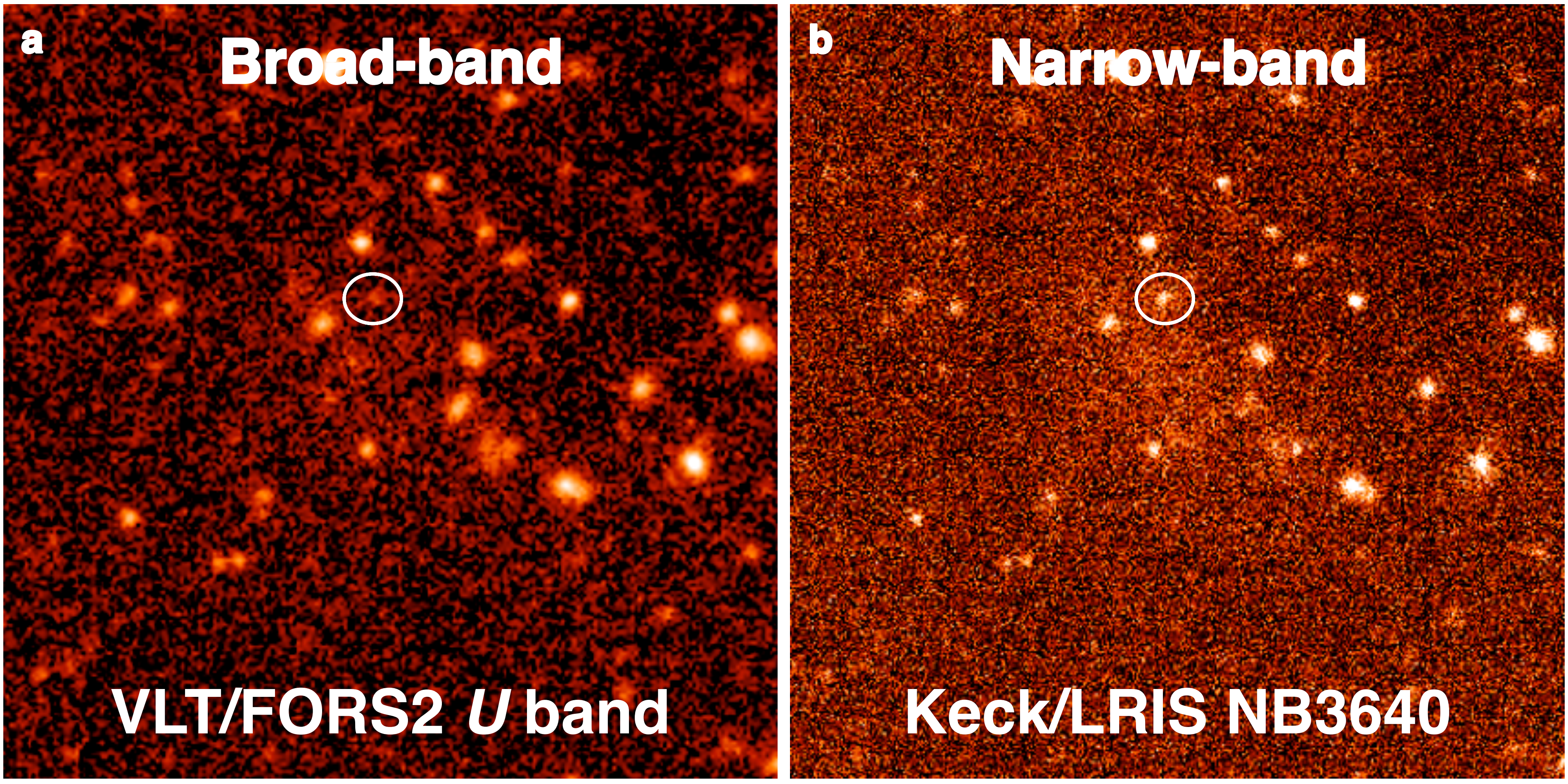
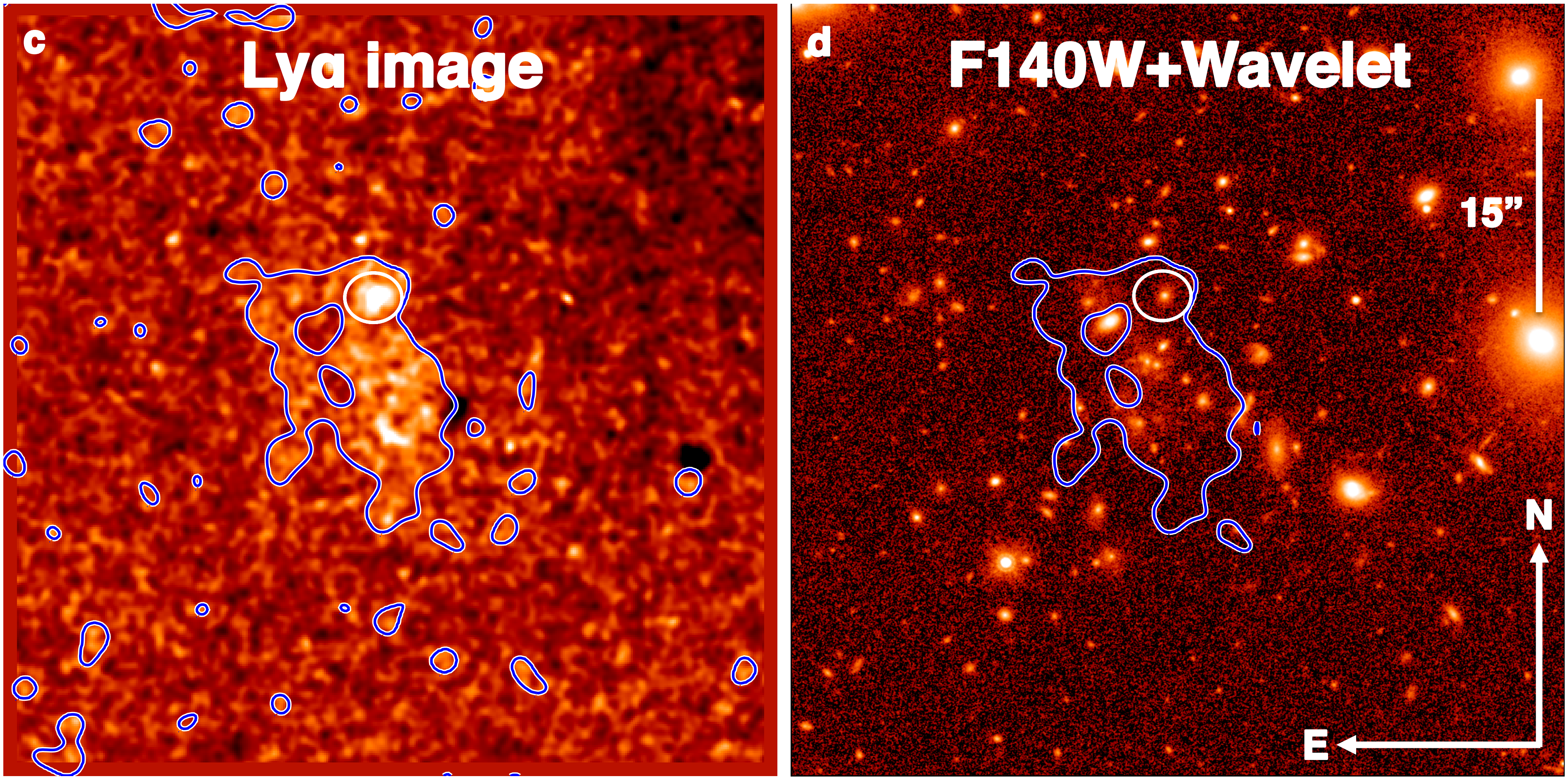
- Narrow-band imaging with Keck/LRIS to follow-up Lyα emitters/ absorbers

Lyα narrow-band follow-up



A giant Lyα nebula in the core



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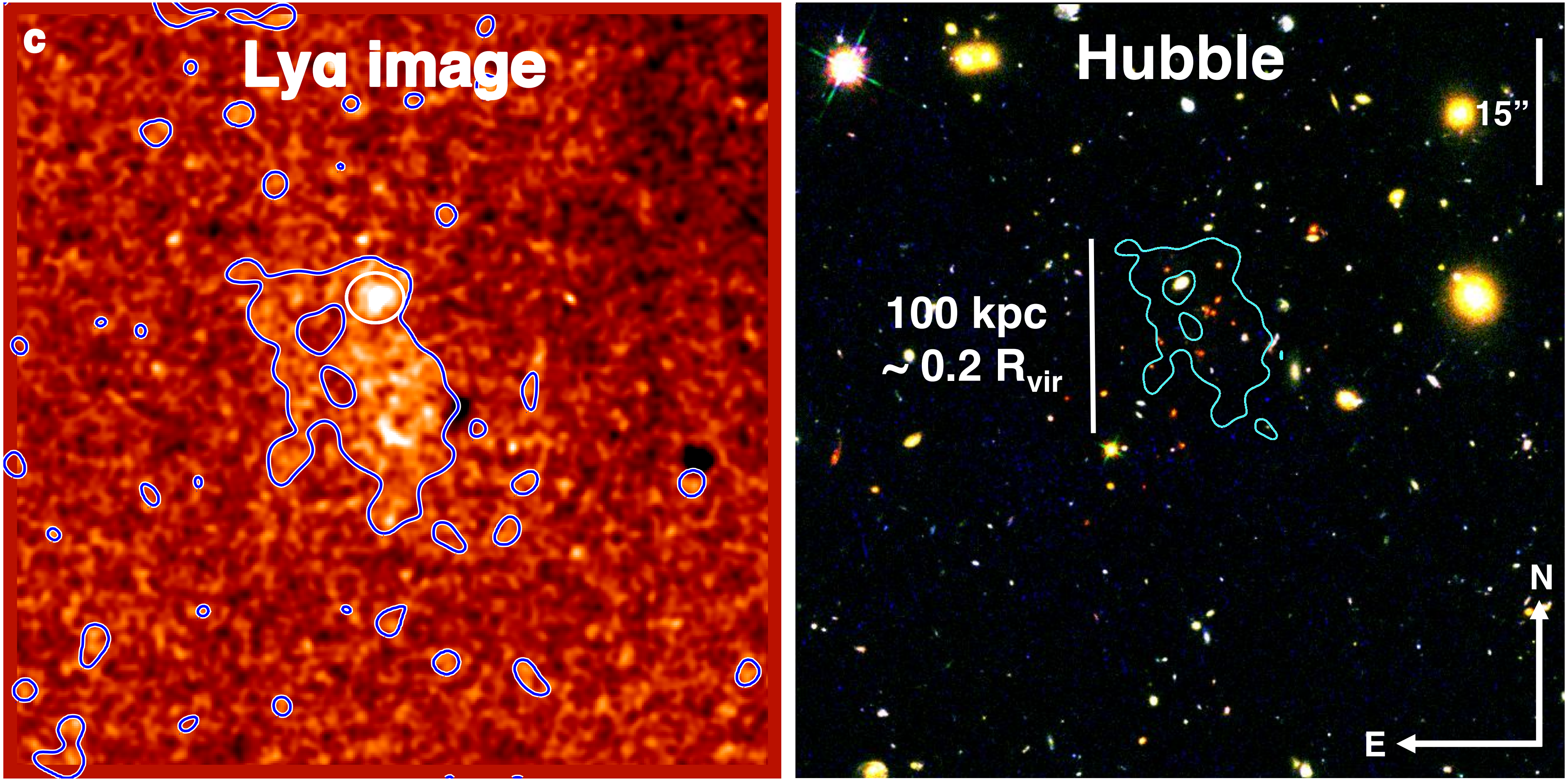

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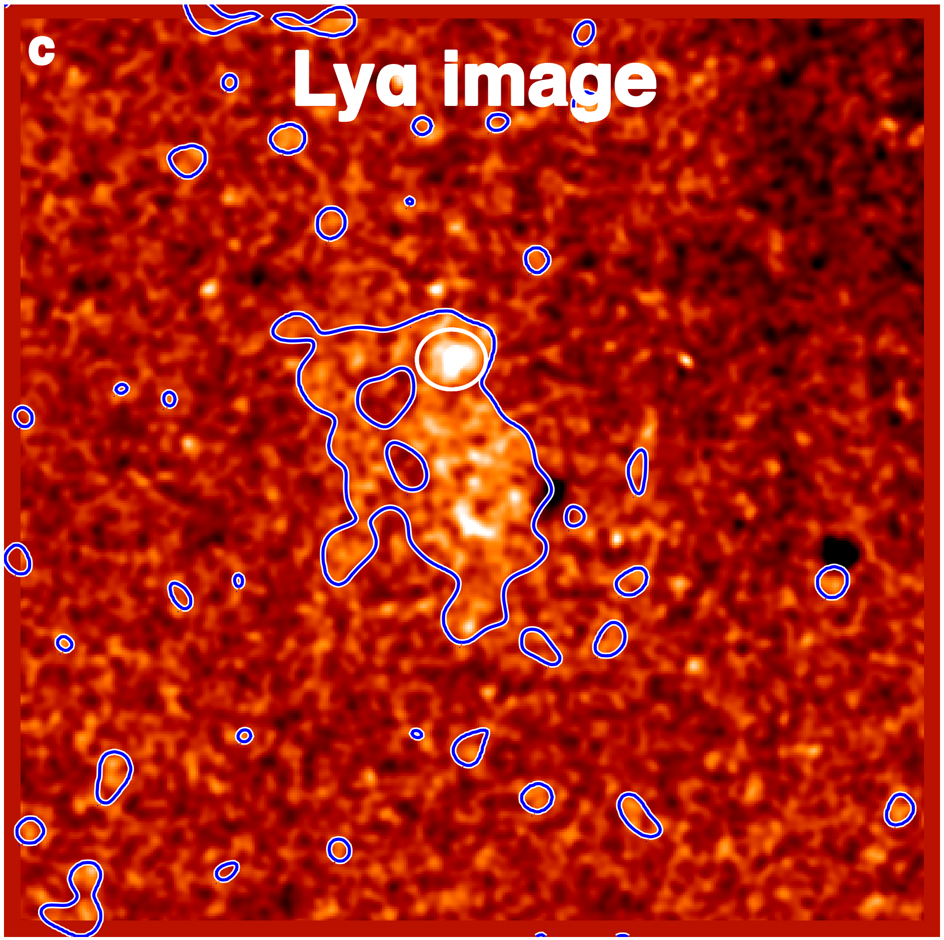

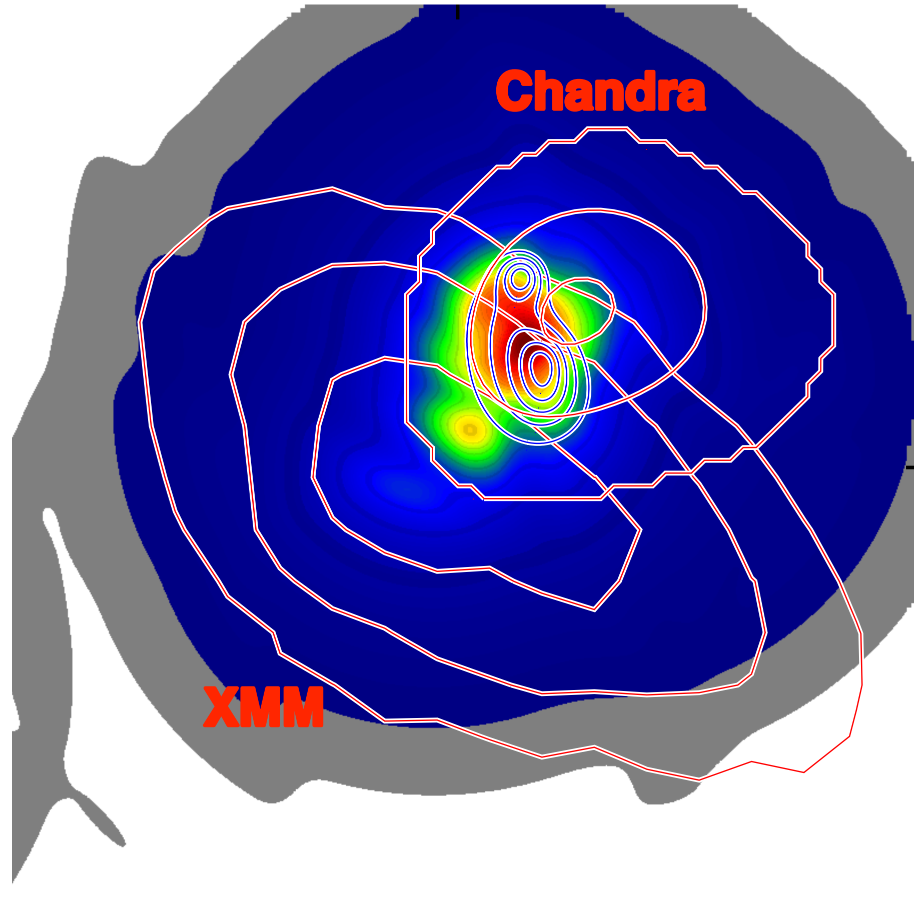

Cold 10^4 K plasma

Hot 10^7 K plasma

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- A ‘mature’ cluster at $z = 1.99$ is observed with XMM and Chandra: we see a **10^7 K, X-ray emitting extended plasma**
- Narrow-band imaging with Keck/LRIS reveals a 100-kpc extended **Lyα nebula (10^4 K)** in the cluster core
- Hot gas heats up cold gas: a ≥1000 $M_{\odot}$ yr^{-1} replenishment is needed to see the nebula

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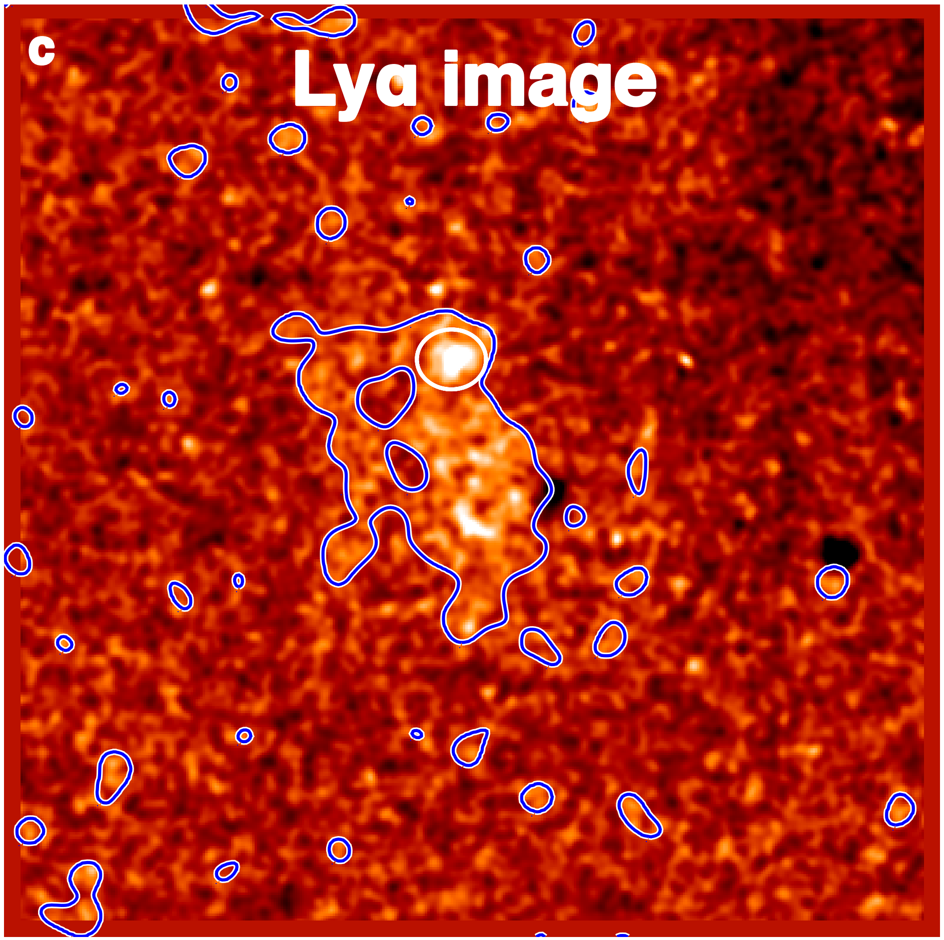
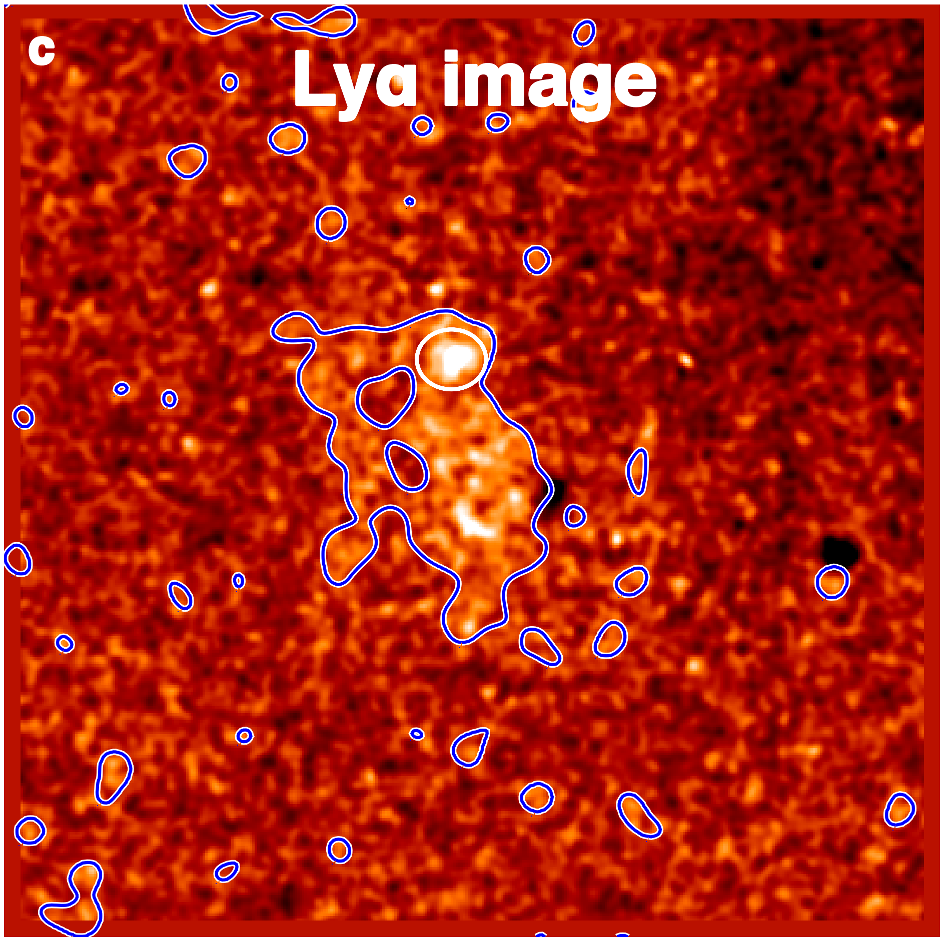


Luminosity = $(2.3\pm0.2)\times10^{43}$ erg s^{-1}
Radius ≈ 46 kpc
Mass = $(0.01 - 3.56) \times 10^{11}$ $M_\odot$
Electron density = $0.02 - 9$ cm^{-3}

Uncertainties from the **volume filling factor $f = 10^{-5} - 1$**

Powering mechanism:
✗ SFR (EW = (271 ± 88) Å, size)
✗ Cooling from X-ray (L(X)/L(Lyα) = 3, **>100x** less than observed locally)
✗ Cosmological cold flows
✓ **AGN**

A giant Lyα nebula in the core

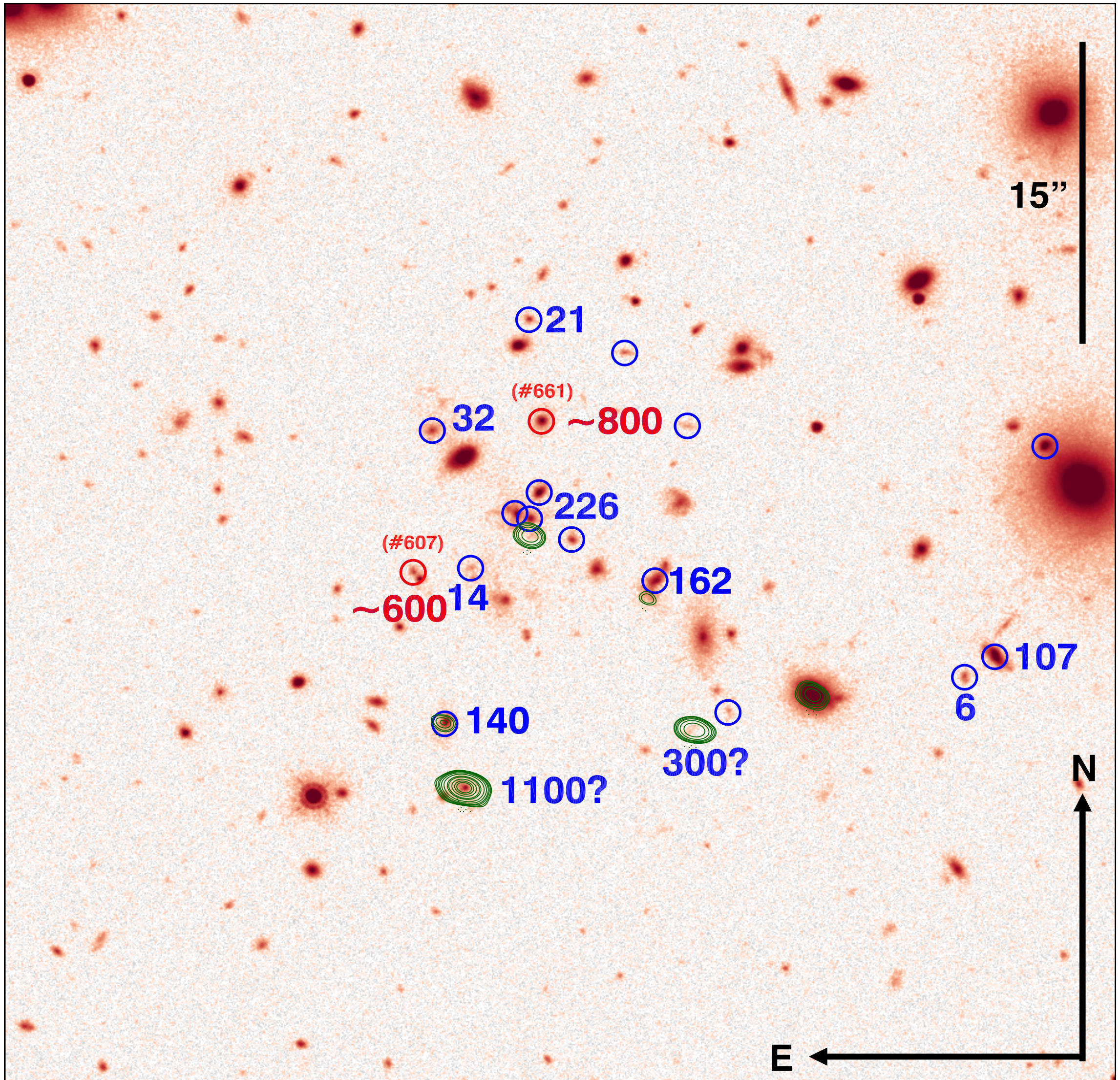


Time evolution:
Cooling time < 1 Myr
Free-fall time ≈ few 10 Myr
Evaporation time ≲ 100 Myr

Requires constant replenishment:
M_{repl} = M(Lyα) / t(evaporation)
$\gtrsim 1000\ M_{\odot}\ yr^{-1}$

Can outflows sustain the replenishment?

Outflows sustain the Lyα nebula



Huge mass outflow rates
(M_{out} ≈ SFR)

From SED modelling, Hα fluxes, and ALMA 870 μm continuum:
SFR ≈ 700 $M_{\odot}$ yr^{-1}

From SED modelling and X-ray luminosity (Cicone +2014):
AGN ≈ 1400 $M_{\odot}$ yr^{-1}

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- This cold gas comes from galaxies through outflows > There is enough from SF and AGN (from near-IR spectroscopy, SED modeling, ALMA maps)

A handle on a decade-standing issue

Instantaneous energy injection:

$$\dot{E}_{\rm kin} = \frac{1}{2}\dot{M}_{\rm out}v^2 = \ (4.9 - 5.3) \times 10^{44} \ \ {\rm erg \ \ s^{-1}}$$

≈ 75 - 85% from AGN (≈ 66% of the mass)

5× higher than L(X) > Offset cooling from X-ray

A handle on a decade-standing issue

Integrated energy injection:

$$E_{\mathrm{kin}} = \int_{t(z \geq 1.99)} \dot{E}_{\mathrm{kin}}\, dt \longrightarrow \dot{E}_{\mathrm{kin}} = \beta\, \mathrm{SFR}$$

A handle on a decade-standing issue

Integrated energy injection:

$$E_{\mathrm{kin}} = \int_{t(z \geq 1.99)} \beta \, \mathrm{SFR}(t) \, dt$$

$$\beta(z = 1.99) = 2.2 - 2.4 \times 10^{49} \ \mathrm{erg} \ \mathrm{M_{\odot}}^{-1}$$

A handle on a decade-standing issue

Integrated energy injection:

$$E_{\rm kin} = \int_{t(z\geq 1.99)} \beta\,\mathrm{SFR}(t)\,dt$$
$$= \frac{\beta}{1-R}\int_{t(z\geq 1.99)} \mathrm{SFR}(t)(1-R)\,dt$$

A handle on a decade-standing issue

Integrated energy injection:

$$E_{\mathrm{kin}} = \int_{t(z\geq 1.99)} \beta\, \mathrm{SFR}(t)\, dt$$

$$= \frac{\beta}{1-R} M_\star \quad \begin{cases} M_\star = 2\times 10^{12}\ \mathrm{M}_\odot \\ R = 0.4 \end{cases}$$

(Mass return fraction, Bruzual & Charlot 2003)

A handle on a decade-standing issue

Integrated energy injection:

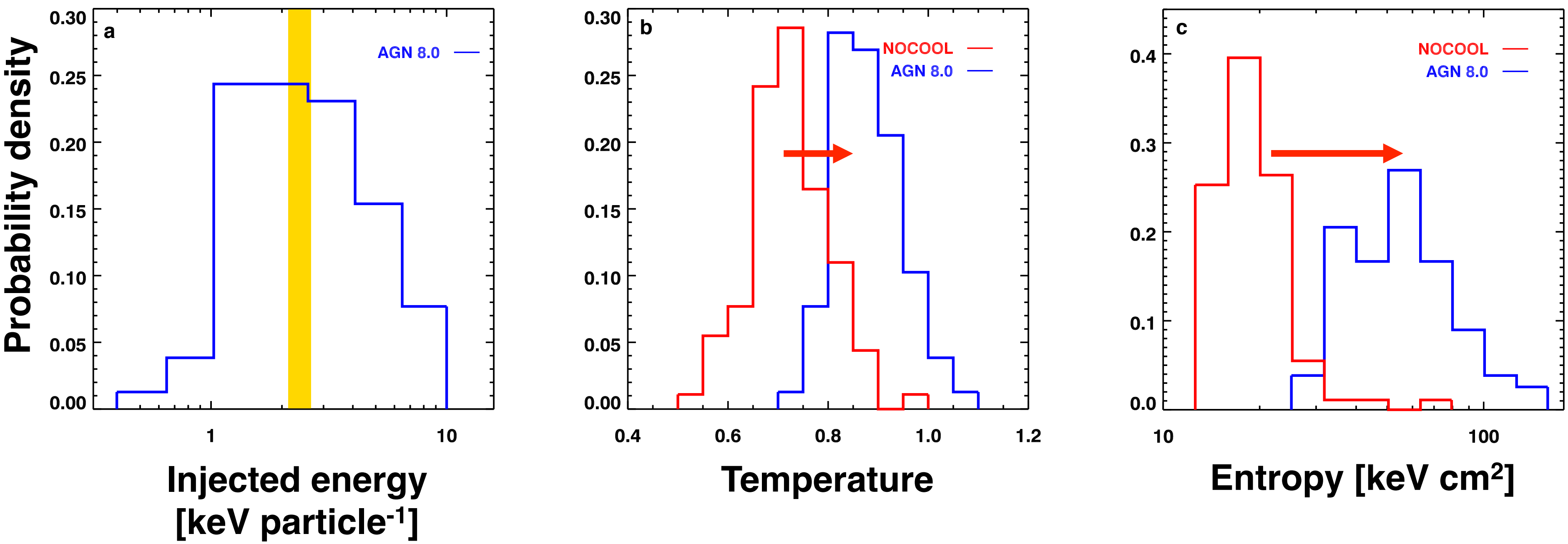
$$E_{\rm kin} = 4.4 - 4.8 \times 10^{61}\,{\rm erg}$$

$$2.5{-}2.7\,{\rm keV}$$

$$E_{\rm therm} = 2 - 2.8\,{\rm keV}$$

(per particle in the hot ICM, **depending on the gas fraction**)

A handle on a decade-standing issue



Suite of cosmological simulations **cosmo-OWLS** (Le Brun+2014):

NOCOOL model

Fiducial model with AGN feedback

Our observations (adopting a baryon fraction f_b = 0.15)

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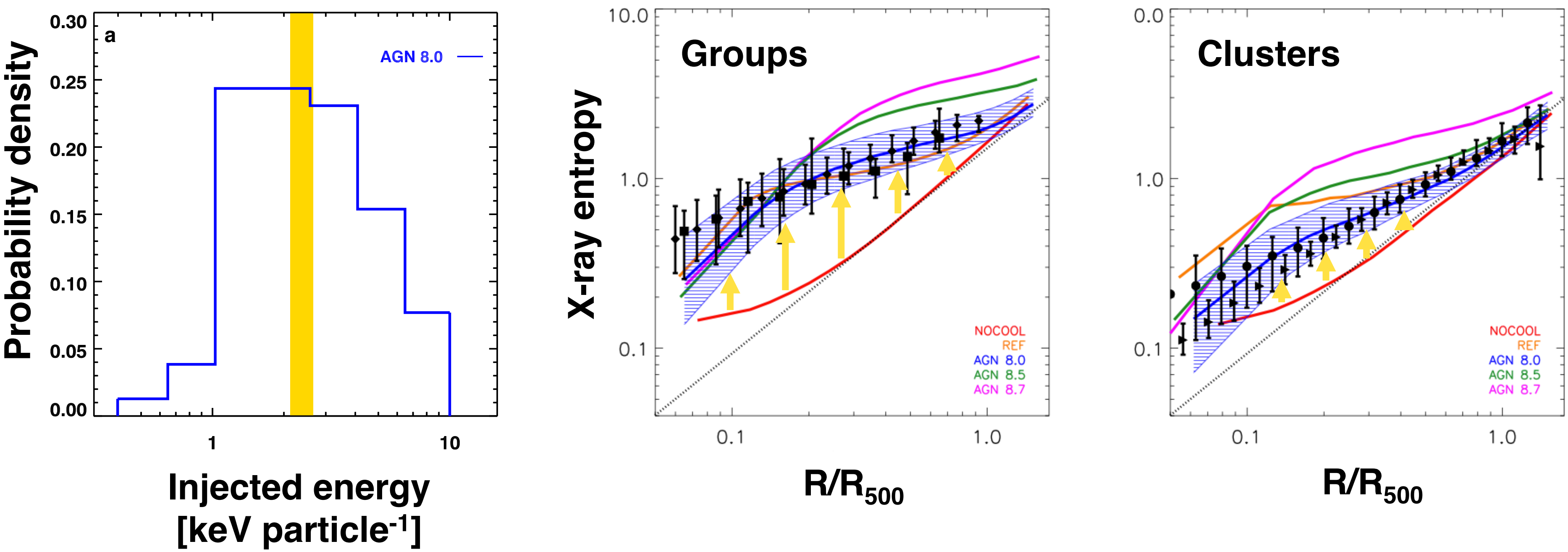

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- This cold gas comes from galaxies through outflows > There is enough from SF and AGN (from near-IR spectroscopy, SED modeling, ALMA maps)
- Outflows inject 2.5-2.7 keV $particle^{-1}$ in the intracluster medium, as predicted by cosmological simulations (cosmo-OWLS)

Lyα nebulae in cores of **X-ray clusters** at high-redshift signpost significant **energy injection into the intracluster medium**

Summary

Discovery of a **100 kpc Lyα nebula** in the core of an **X-ray cluster at z = 1.99**

It needs constant gas replenishment to survive

Huge outflow activity in the core **(SFR ≈ 700 $M_\odot$ yr^{-1}, AGN ≈ 1400 $M_\odot$ yr^{-1})** can supply the gas

Outflows inject 2.5-2.7 keV per particle in the hot ICM, as predicted by simulations