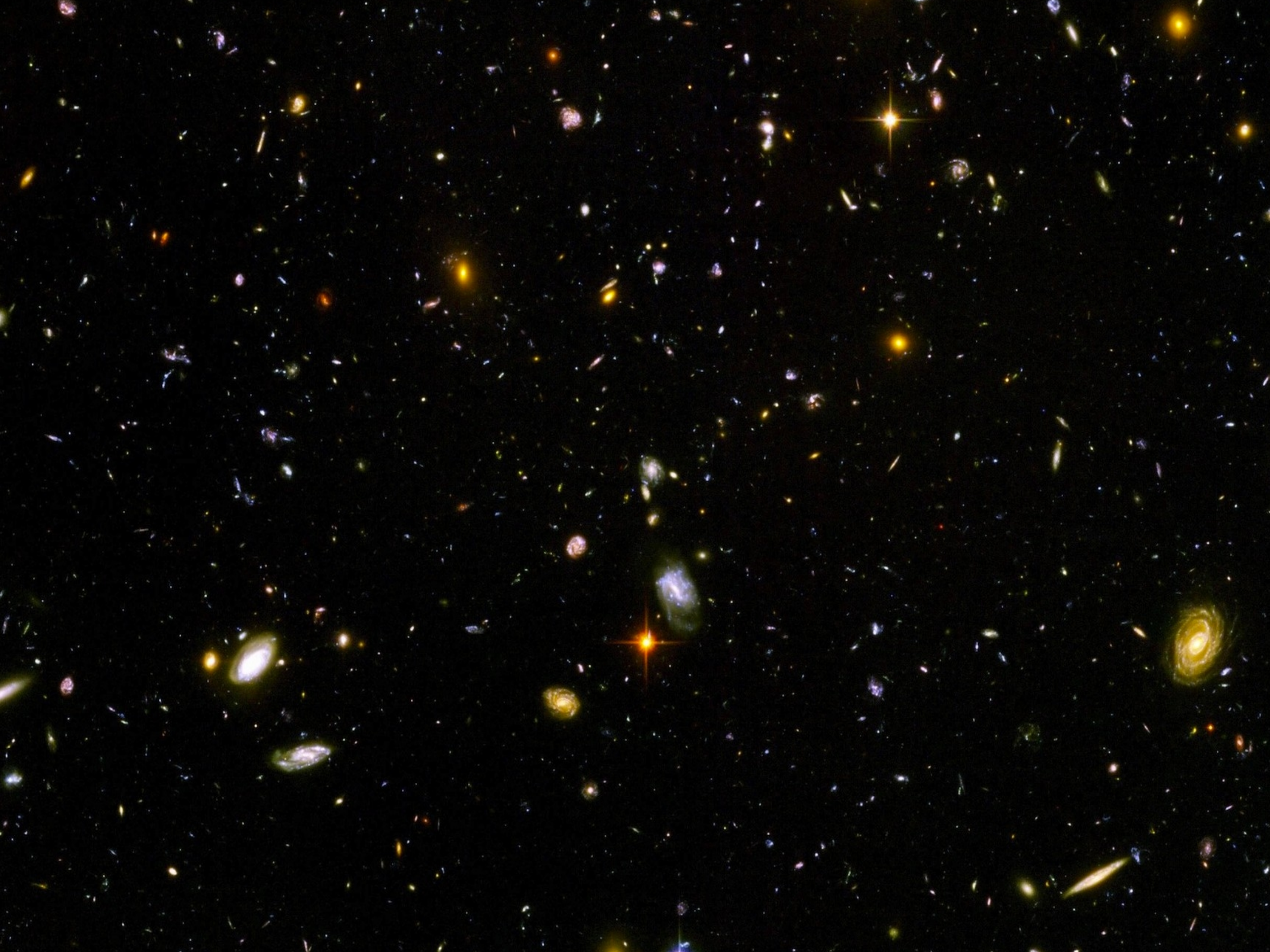
Where are galaxies feeding from?

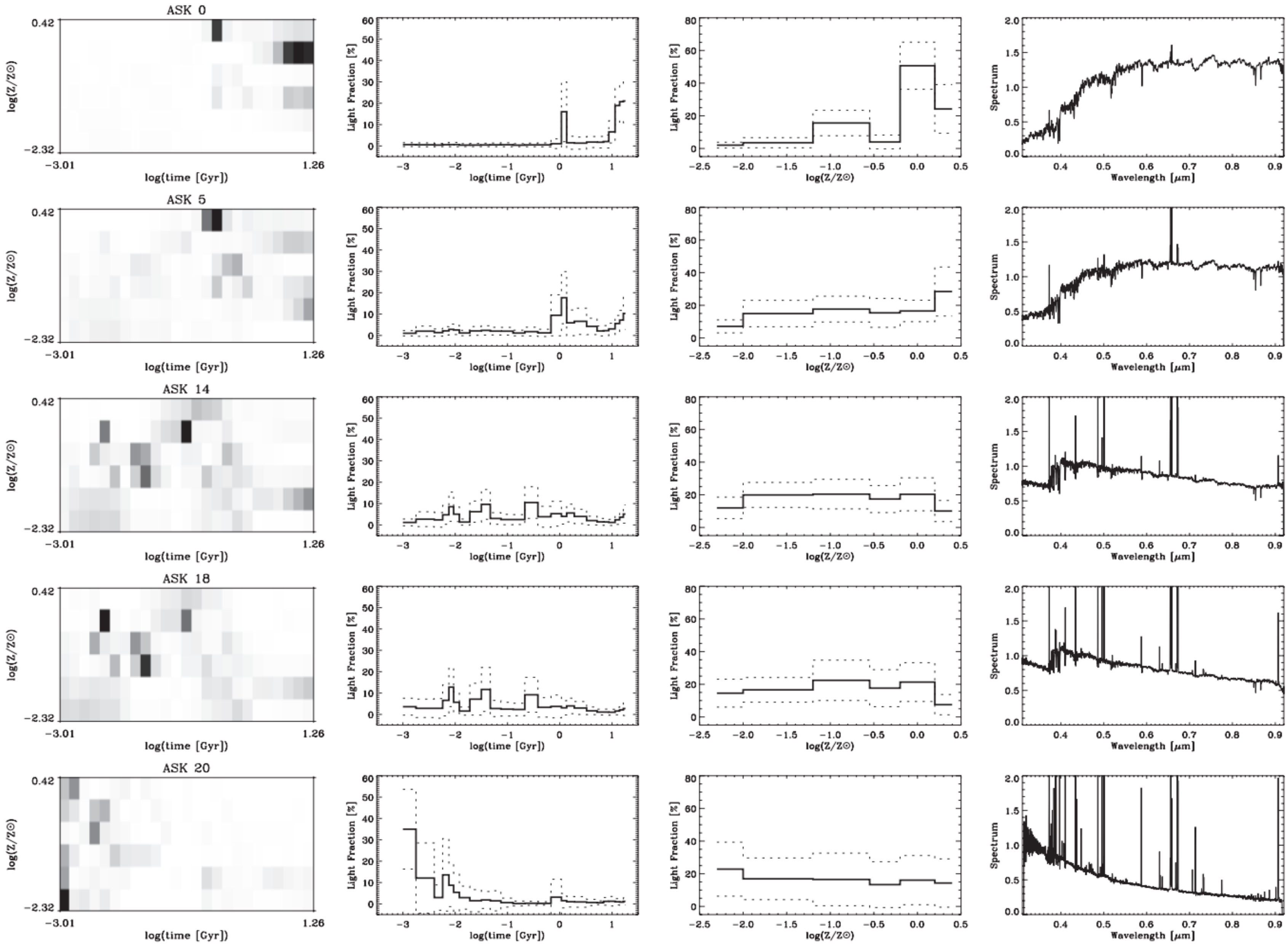
J. Sánchez Almeida

In collaboration with
B. G. Elmegreen
C. Muñoz Tuñón
D. M. Elmegreen
M. Filho,
et al.

Instituto de Astrofísica de Canarias

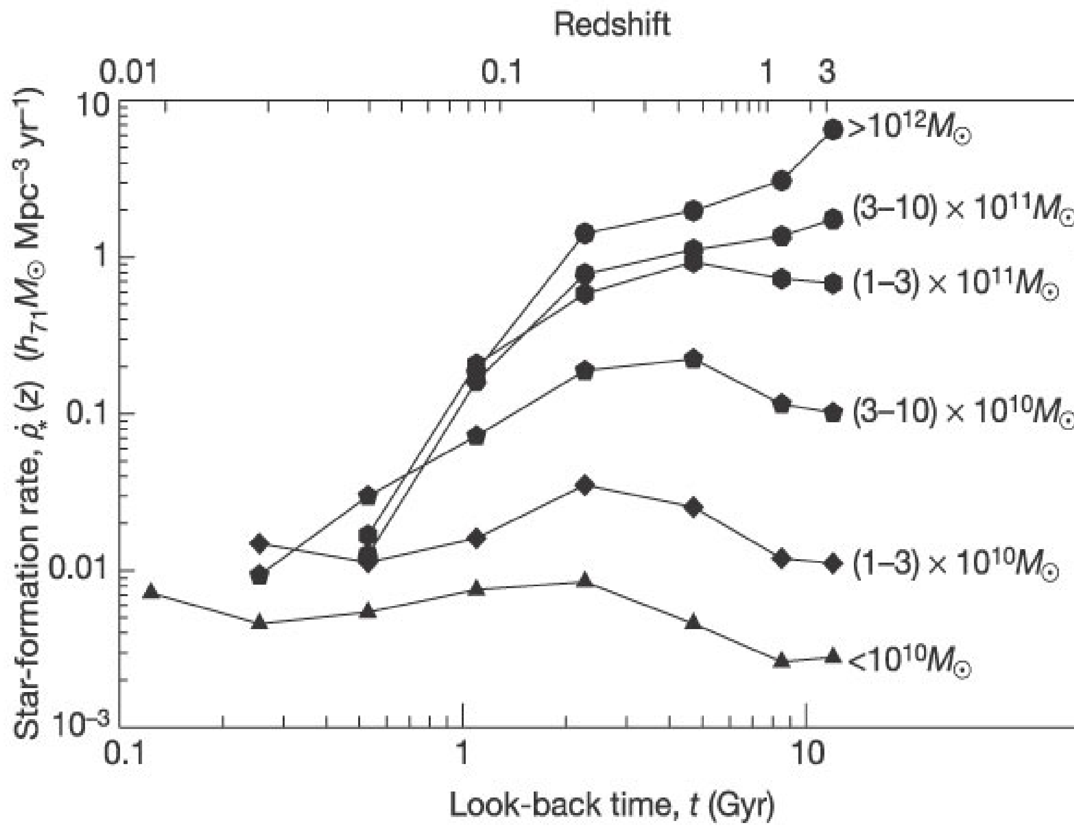


The star-formation history can be inferred from the galaxy spectra



From SA+12, ApJ

Galaxies were born very early in the Universe, and they continue forming stars today



Heavens et al. 2004, Nat

Outline

- Galaxy formation from Cosmological numerical simulations
- Why is gas accretion so important?
- Expected properties of the accreted gas
- Evidence for cosmological gas accretion
- Summary: take-home message

Galaxy Formation from Cosmological Numerical Simulations

- Initial conditions, set by the cosmology (ΛCDM)
- Stars, Gas, and Dark Matter
- Gravity + Hydro-forces (gas pressure forces)

Basic equations ruling the dynamics (plus expansion)

$\frac{\partial f}{\partial t} + \mathbf{u}.\nabla f - \nabla\Phi.\nabla_u f = 0$	Vlasov : dark matter, stars
$\frac{\partial \rho_b}{\partial t} + \nabla.(\rho_b \mathbf{u}) = 0$	Continuity : gas
$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}.\nabla).\mathbf{u} = -\nabla\Phi - \frac{\nabla p}{\rho_b}$	Euler : gas
$\frac{\partial \varepsilon}{\partial t} + \mathbf{u}.\nabla\varepsilon = -\frac{p}{\rho_b}\nabla.\mathbf{u}$	Energy : gas
$p = (\gamma - 1)\varepsilon\rho_b$	Equation of state : gas
$\nabla^2\Phi = 4\pi G\left[\int f d^3u + \rho_b\right]$	Poisson : everything

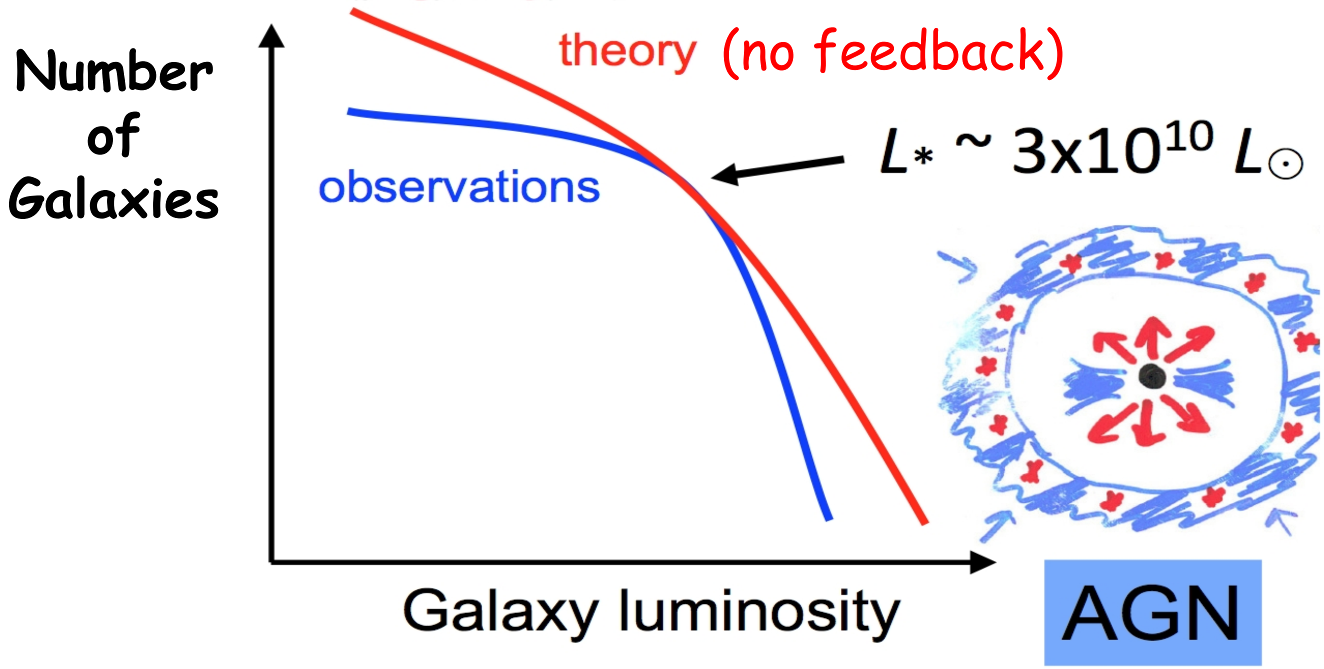
(Devriendt 12)

- Sub-grid physics (critically important): resolution 1kpc and 10^6 $M_\odot$ and so impossible to resolve the physically relevant scales.

Full equations in Bertschinger 98, ARA&A

Sub-grid physics: feedback processes

The energy (momentum and mass) released by stars (SNe) and super-massive black holes (AGN) quench star-formation.

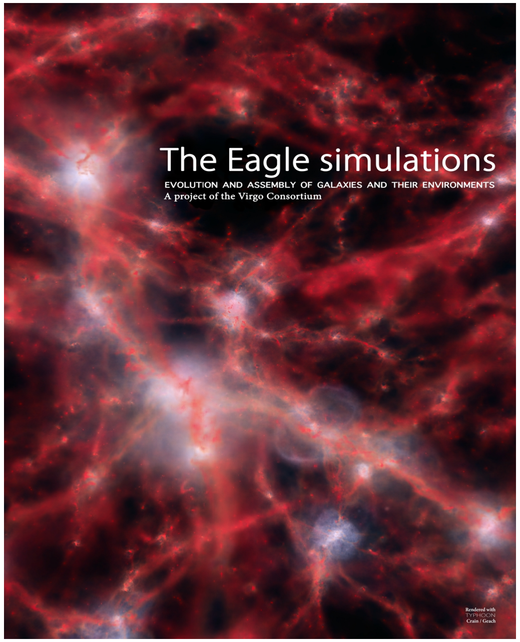


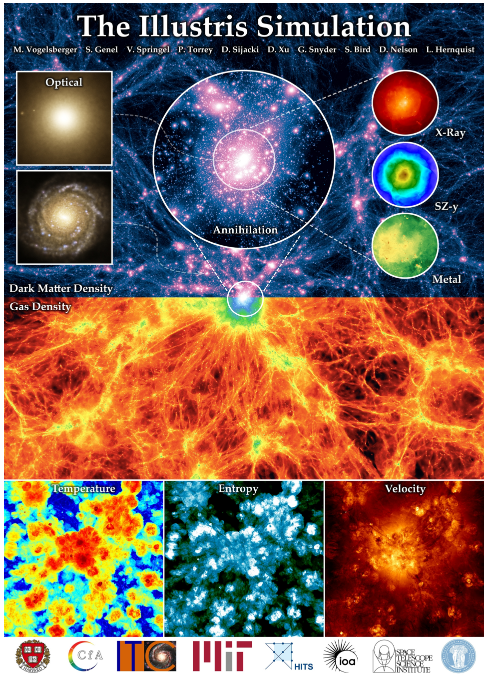
(schematic adapted from Silk & Mamon 12, RAA)

Examples of state-of-the-art cosmological numerical simulations

I will show movies from

EAGLE (Schaye+15, MNRAS) Illustris (Vogelsberger+14, Nat)





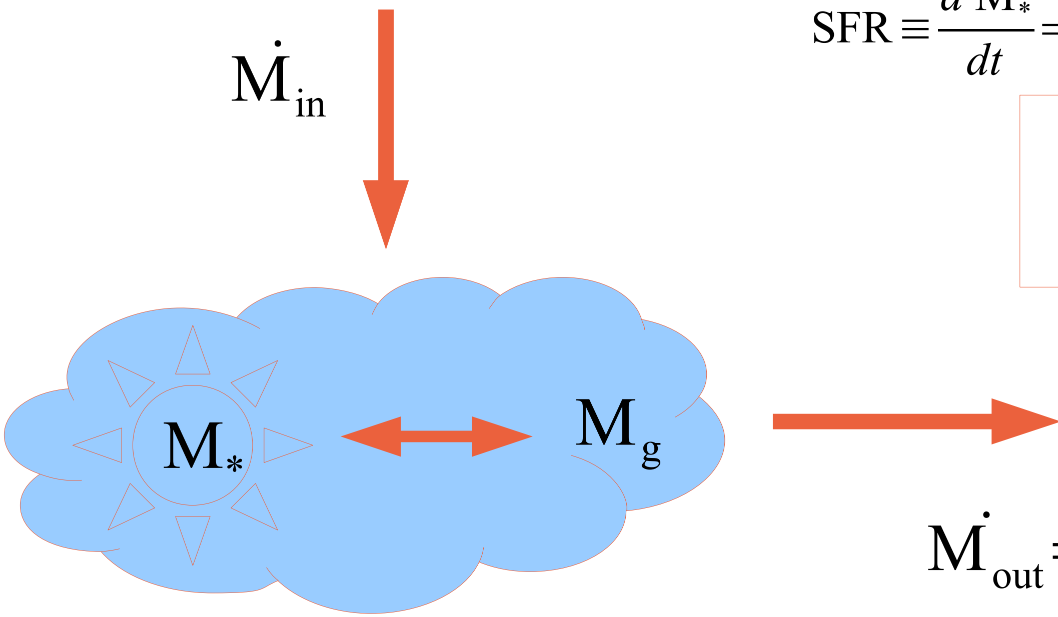
Why is gas accretion so important?

$$\mathrm{SFR} \equiv \frac{d\,\mathrm{M}_*}{dt} = \frac{\mathrm{M_g}}{\tau_\mathrm{g}}$$

Kennicutt-Schmidt law

$$\tau_\mathrm{g} = M_\mathrm{g} / \mathrm{SFR}$$

Gas depletion time-scale



$$\dot{\mathrm{M}}_{\mathrm{out}} = \omega\,\mathrm{SFR}$$

returned mass fraction R

'**Bathtub' model** or the gas regulator model or ....Tinsley80; Edmunds90; ... Peeples+Shankar11; Dave+12, Brisbin&Harwit12, Dayal+13, Lilly+13, Pipino+14; Ascasibar+14; SA+14; Dekel & Mandelker14, Forbes+14; Peng&Maiolino 14; Harwitt&Brisbin15, Somerville&Dave15; Rodriguez-Puebla+15; ....

$$\frac{d\mathrm{M_g}}{dt} \equiv \dot{\mathrm{M}}_\mathrm{g} = -(1-R)\,\mathrm{SFR} + \dot{\mathrm{M}}_\mathrm{in} - \dot{\mathrm{M}}_\mathrm{out},$$

mass conservation

R return fraction

$\dot{\mathrm{M}}_\mathrm{in}$ gas infall rate - the driver of the system

$$\mathrm{SFR} = \epsilon\,\mathrm{M_g} = \frac{\mathrm{M_g}}{\tau_\mathrm{g}}.$$

KS law

$$\dot{\mathrm{M}}_\mathrm{out}(t) = w\,\mathrm{SFR}(t),$$

gas outflow rate

w mass loading factor

Then

$$\mathrm{SFR}(t) = \mathrm{SFR}(0)\,\mathrm{e}^{-t/\tau_\mathrm{in}} + \int_0^t \dot{\mathrm{M}}_\mathrm{in}(t')\,\mathrm{e}^{-(t-t')/\tau_\mathrm{in}}\,dt'/\tau_\mathrm{g},$$

$$\tau_\mathrm{in} = \tau_\mathrm{g}\,/(1-R+w).$$

Since τ_g is very small $\dot{\mathrm{M}}_\mathrm{in}$ can be pulled out of the integral and

$$\mathrm{SFR}(t) \simeq (1-R+w)^{-1}\,\dot{\mathrm{M}}_\mathrm{in}(t),$$

SFR is set the infall rate only (corrected by outflows)

$$\mathrm{SFR}(t) \simeq (1 - R + w)^{-1}\, \dot{\mathrm{M}}_{\mathrm{in}}(t),$$

SFR is set the infall rate only (corrected by outflows)

$$\mathrm{M_g}(t) \simeq \tau_{\mathrm{g}}\, \mathrm{SFR}(t) \simeq \frac{\tau_{\mathrm{g}}}{1 - R + w}\, \dot{\mathrm{M}}_{\mathrm{in}}(t).$$

The mass of gas is set by infall rate: is just needed to maintain the SFR given by the infall rate

$$\frac{\mathrm{SFR_{gf}}}{\mathrm{SFR}} \simeq \frac{1 - R + w}{1 + w}. \qquad \frac{\mathrm{SFR_{gf}}}{\mathrm{SFR}} \simeq 1$$

The fraction of star formation produced by fresh gas (fg) is very large

$$Z \simeq Z_i + y\,(1 - R)/(1 - R + w).$$

The metallicity *Z* of the gas in a galaxy is independent of time, SFR and infall rate !!!

It is set only by **stellar physics** (the yield *y*, and the return fraction *R*) and by **gas outflows** (through the mass loading factor *w*).
Z_i stands for the metallicity of the infalling gas

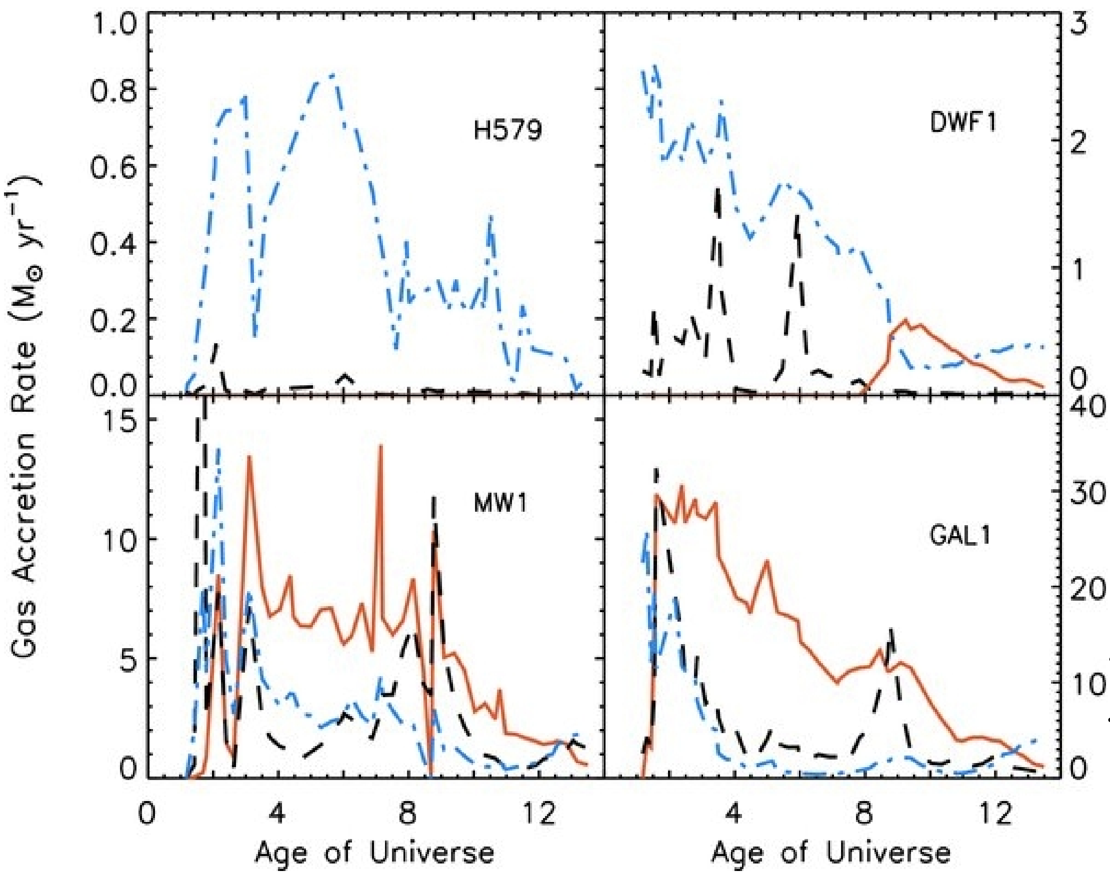
Since *Z* varies from galaxy to galaxy, and *y*, *R* are set, w >> 1

Why is gas accretion so important?

It is like 'the one ring' of 'the lord of the rings'

One ring to rule them all

Expected properties of the accreted gas



Accretion is clumpy

The galaxy mass increases from top to bottom and left to right

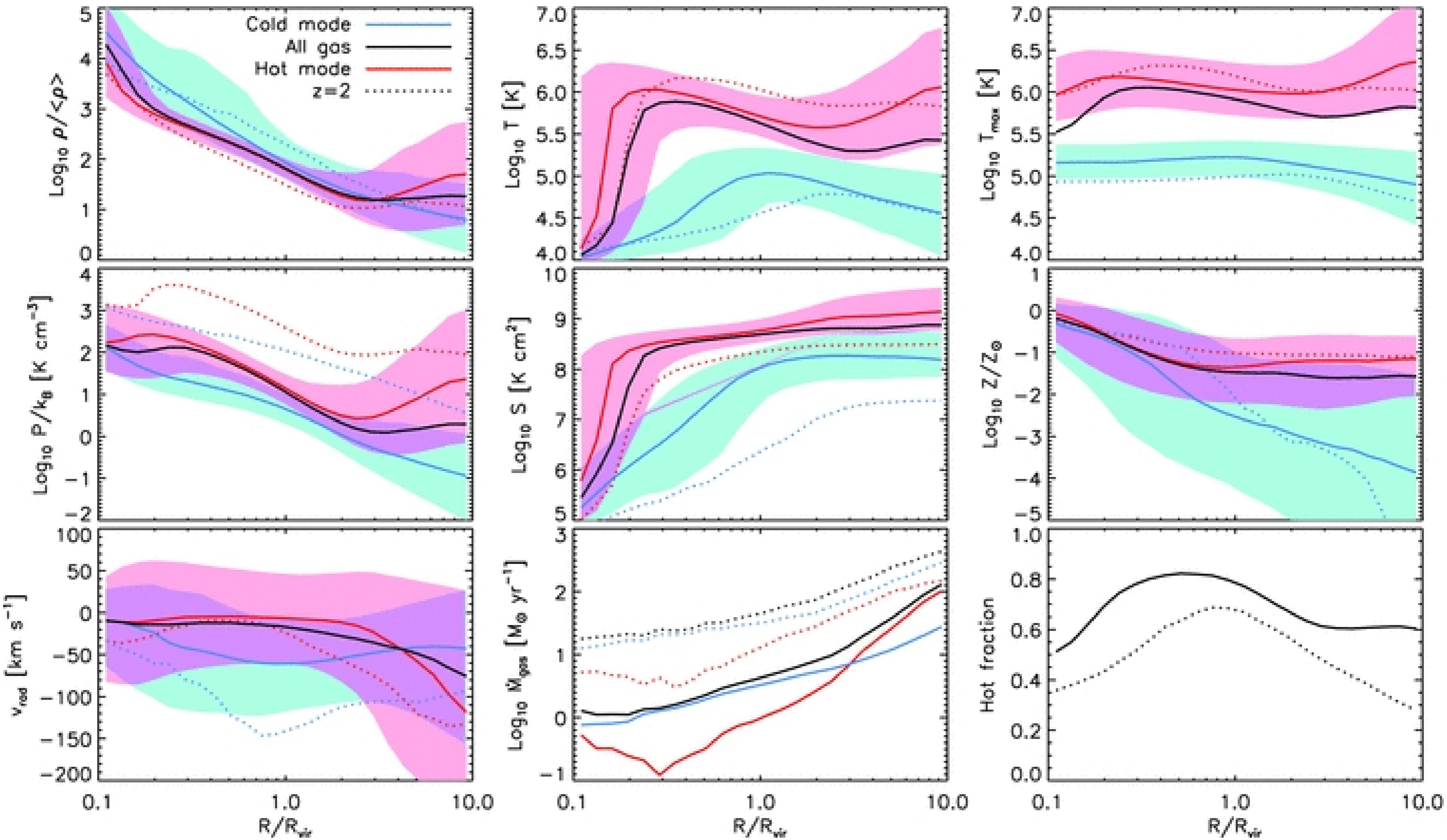
mergers

hot accretion

cold accretion

z=0

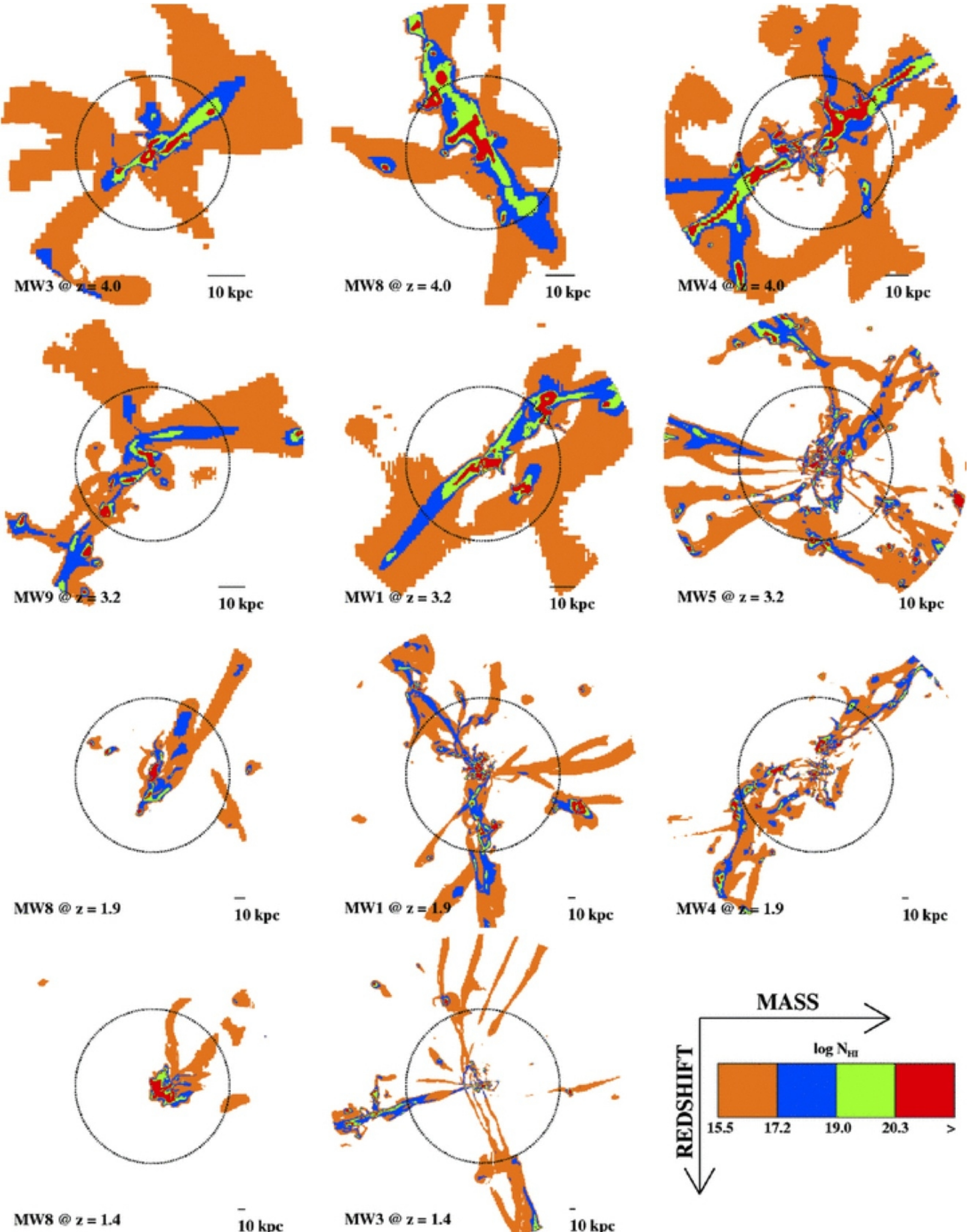
from Brooks+09



van de Voort & Schaye 12   MW-like haloes at z=0

R_{vir} is the virial radius, much larger than the optical radious (70 times larger than the half-light radius; Kartsov 13)

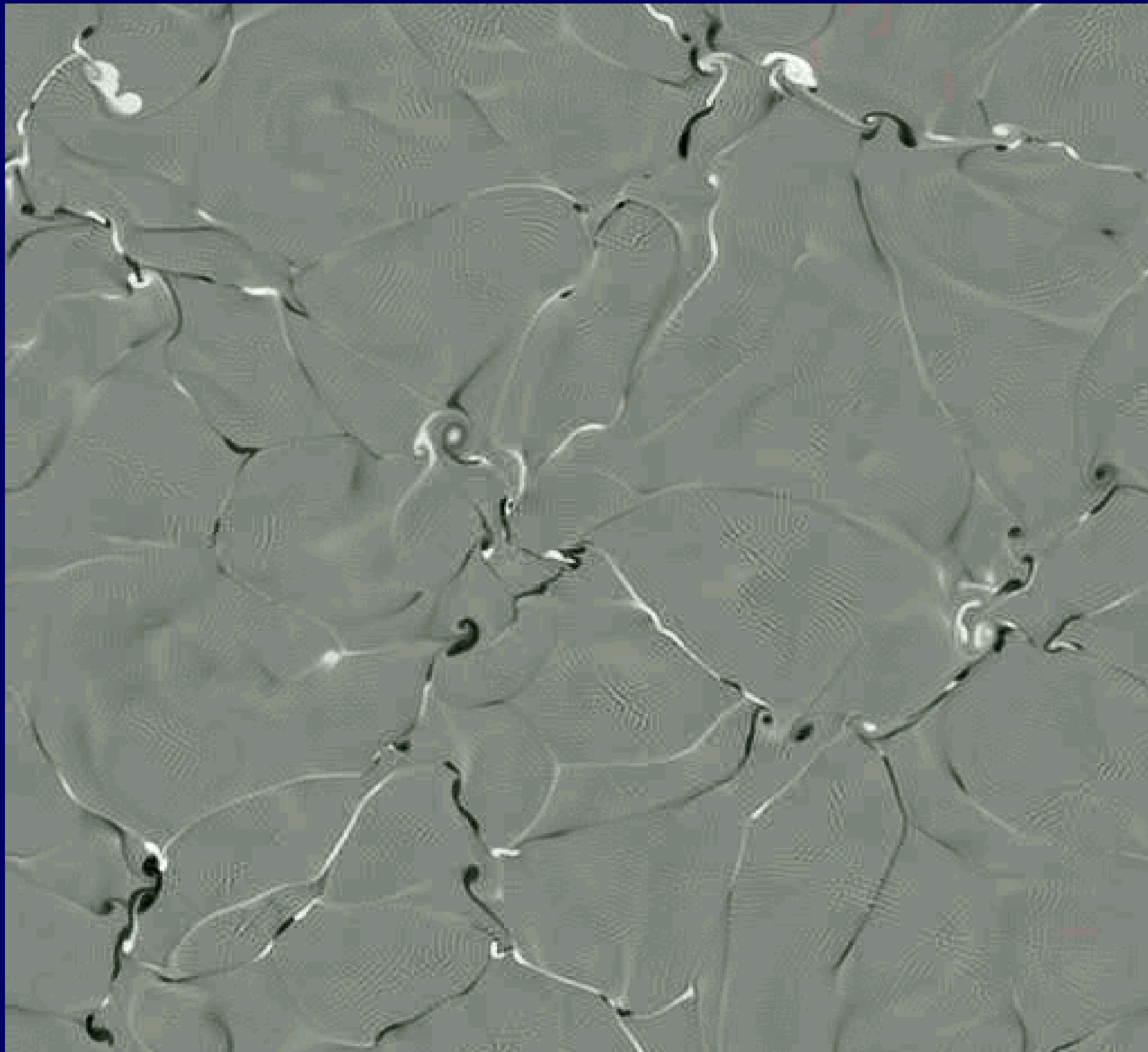
Lys systems: model predictions by Fumagalli+11

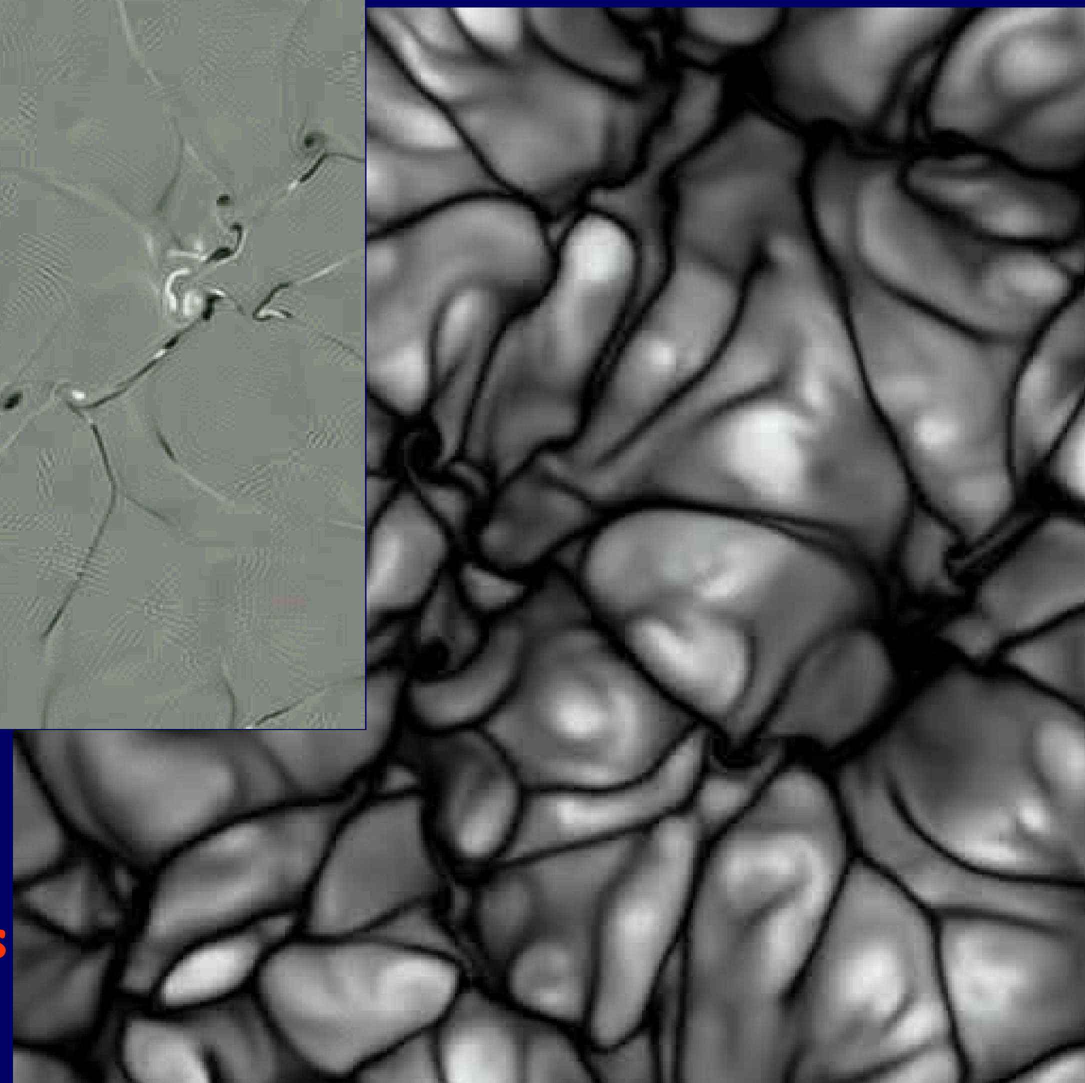


Damped Lyman Alpha absorbers (DLAs) have $N_{HI} > 10^{20}$ cm^{-2}

Lyman Limit Systems (LLS) have $N_{HI} > 10^{17}$ cm^{-2}

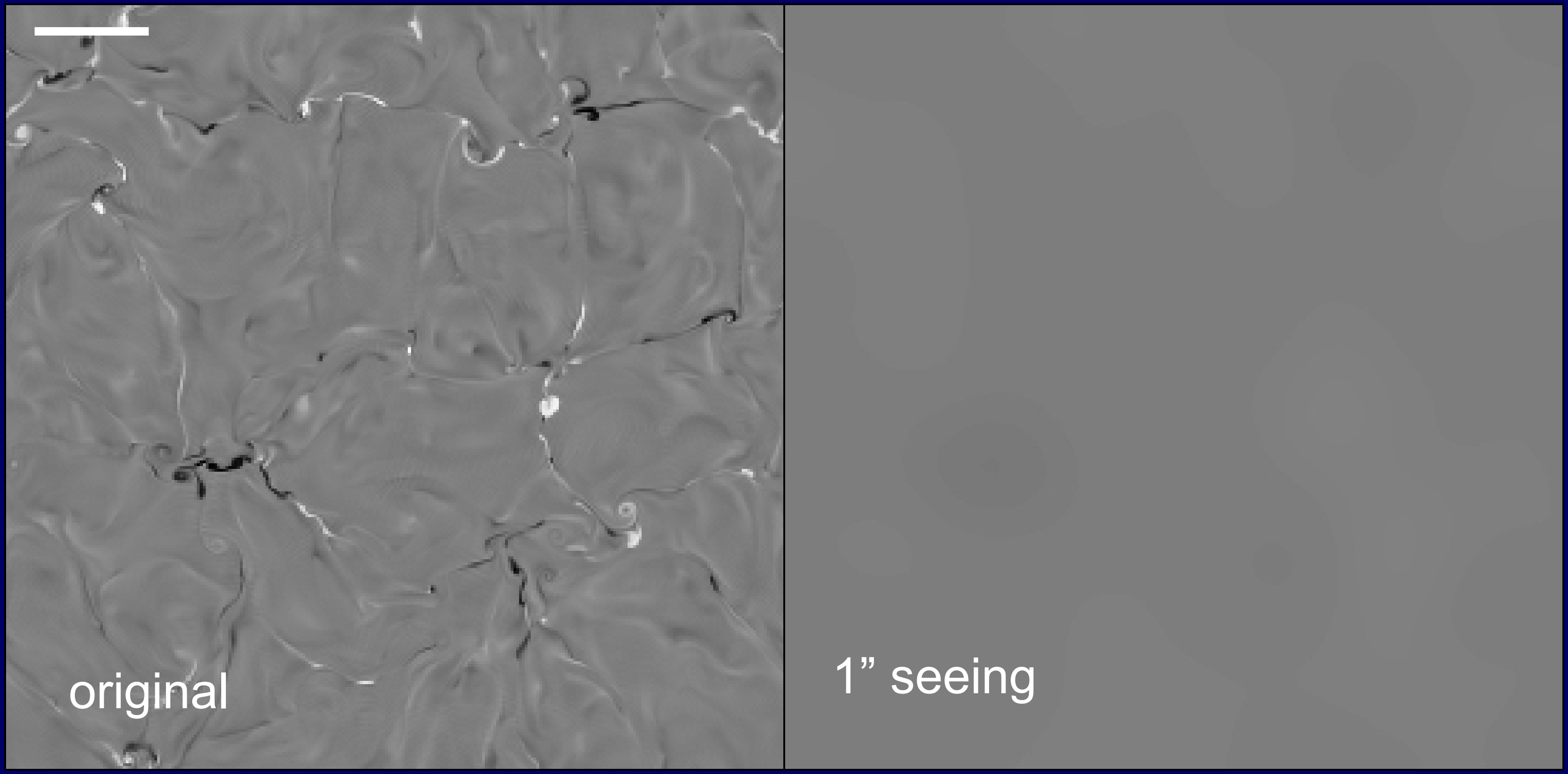
[...





1”

Turbulent Dynamo Simulations by Cattaneo 1999



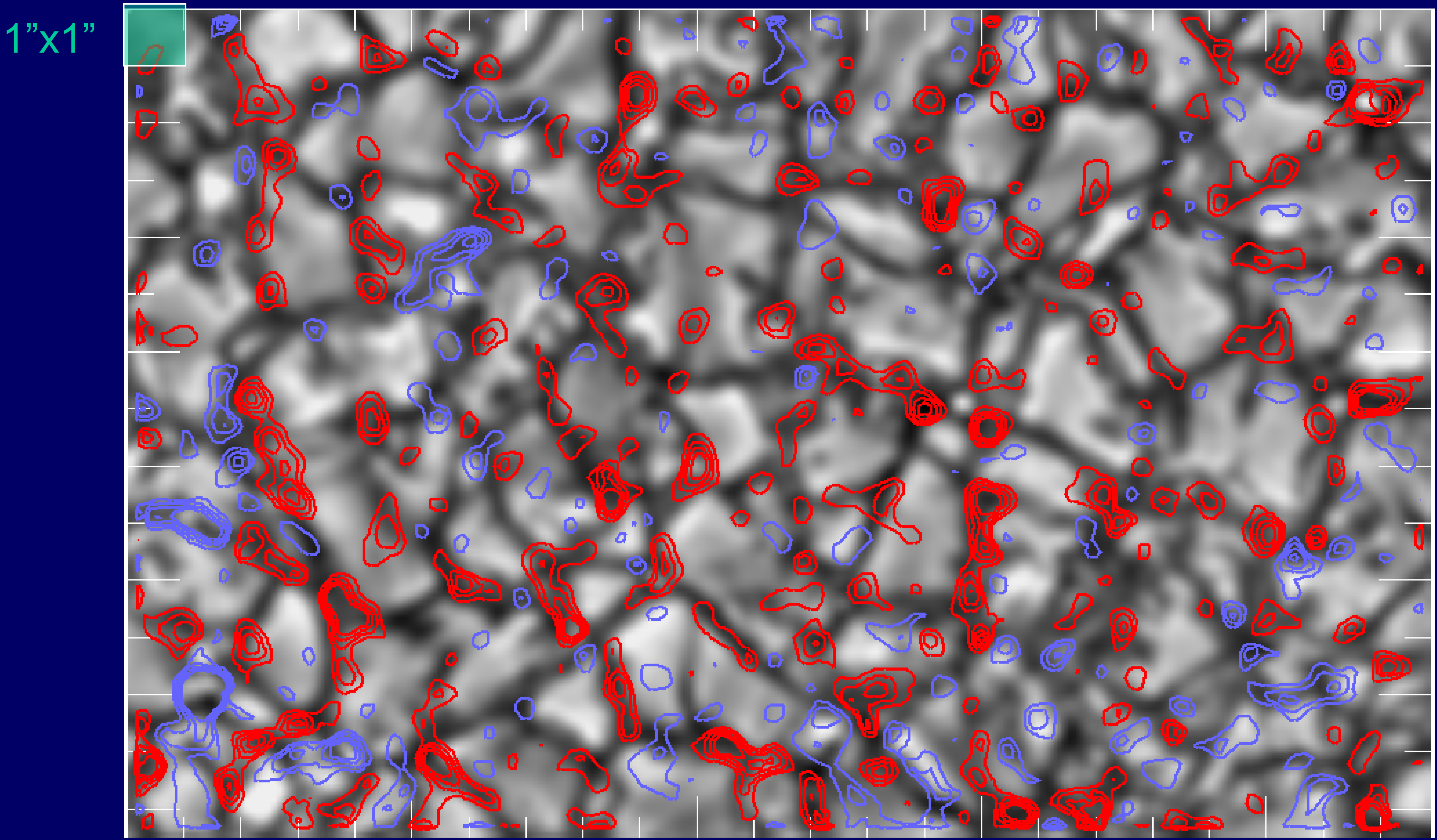
Effects of insufficient angular resolution

- the intrinsic polarization is largely reduced
- a residual is left
- the structures becomes large (seeing-size)
- all structures have sub-resolution mixed polarities

SA et al. (03)

Quiet Sun

- angular resolution mag. 0.5”
- sensitivity 21 G
- VTT (obs. Teide), speckle reconstructed



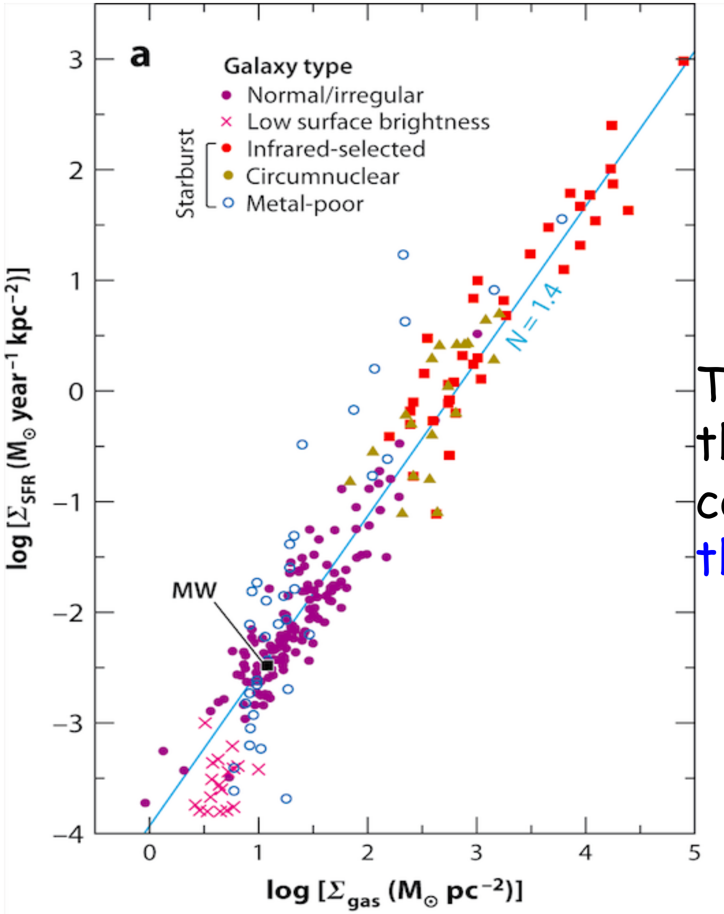
Domínguez Cerdeña et al. (03)

...]

Evidence for cosmological gas accretion

Short gas-consumption time-scale

SA+14, A&ARev



Kennicutt RC Jr, Evans NJ II. 2012.

Kennicutt-Schmidt (KS)-like law

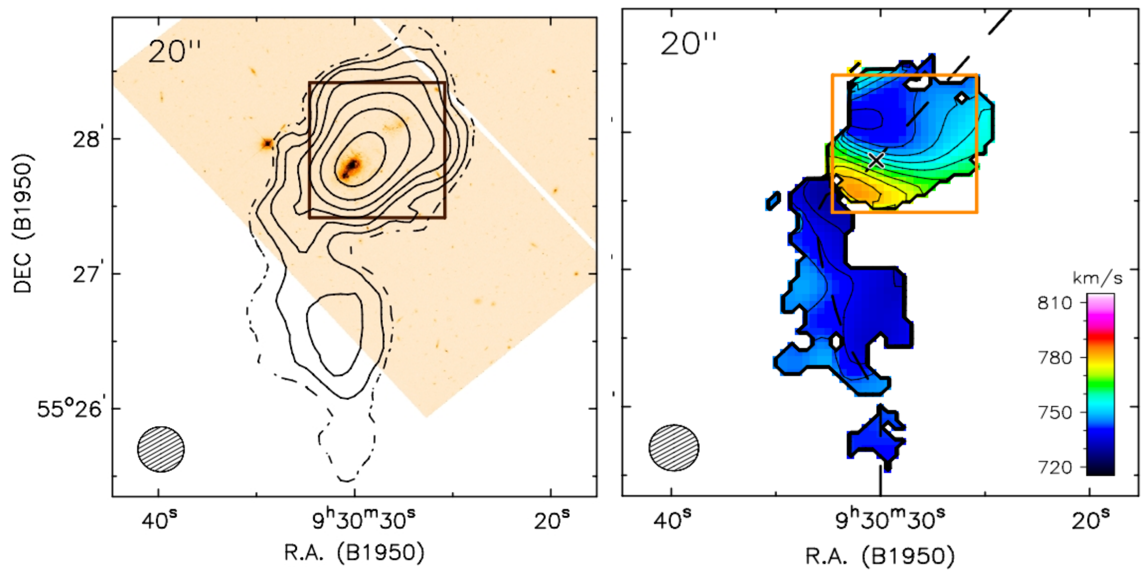
$$\mathrm{SFR} = \epsilon\, \mathrm{M_g} = \frac{\mathrm{M_g}}{\tau_{\mathrm{g}}}.$$

The star formation rate (SFR) is proportional to the mass of gas available to form stars, with a (gas consumption) time scale smaller than the rest of the important timescale,

$$\tau_g < 1\,\mathrm{Gyr}$$

... and decreases with increasing z

Plumes of gas neutral falling into galaxies



Star forming galaxies all have pools of neutral gas often with very suggestive, as the case of the extremely metal poor (XMP) I Zw18

Lelli+12

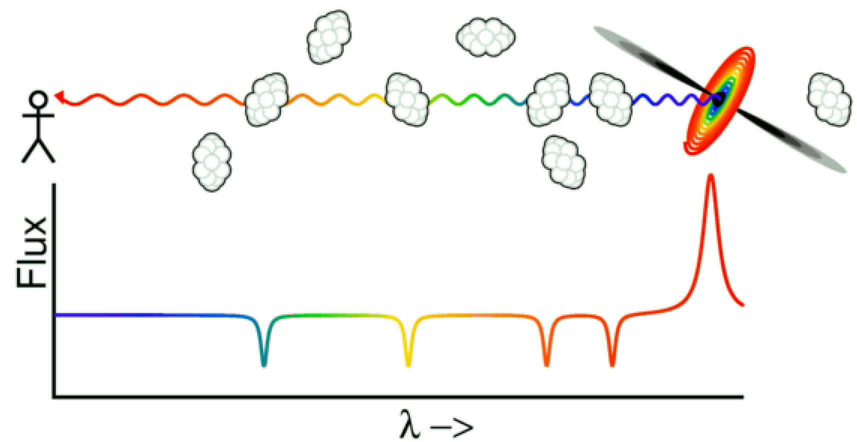
As inferred from line absorptions on the continuum emission of the galaxy, the HI gas around I Zw18 is a factor of 2 more metal poor than the HII regions (Lebouteiller+13).

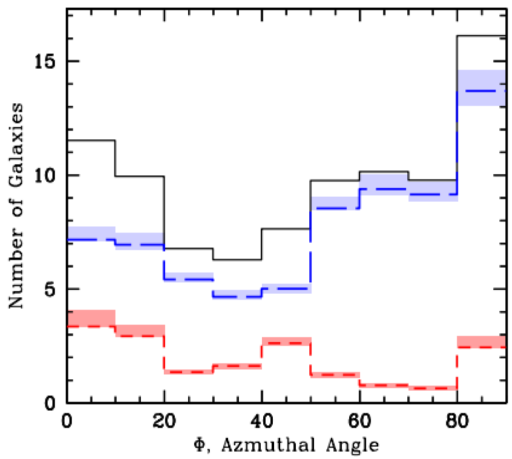
- A large discrepancy between HI and HII metallicities is also present in Pox 36 (Lebouteiller+13)

- In XMPs Mg/M*~10, and the gas metallicity << 1/10 solar (Filho+13)

The cosmic web in absorption

(multi-phase) gas absorption observed on the spectrum of a background source, typically a QSO

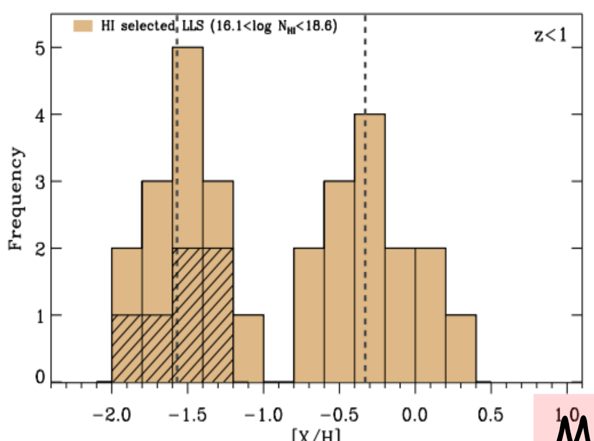




The MgII absorption occur perferentially at 0° and 90° (Kacprzak+12)

0°

90°



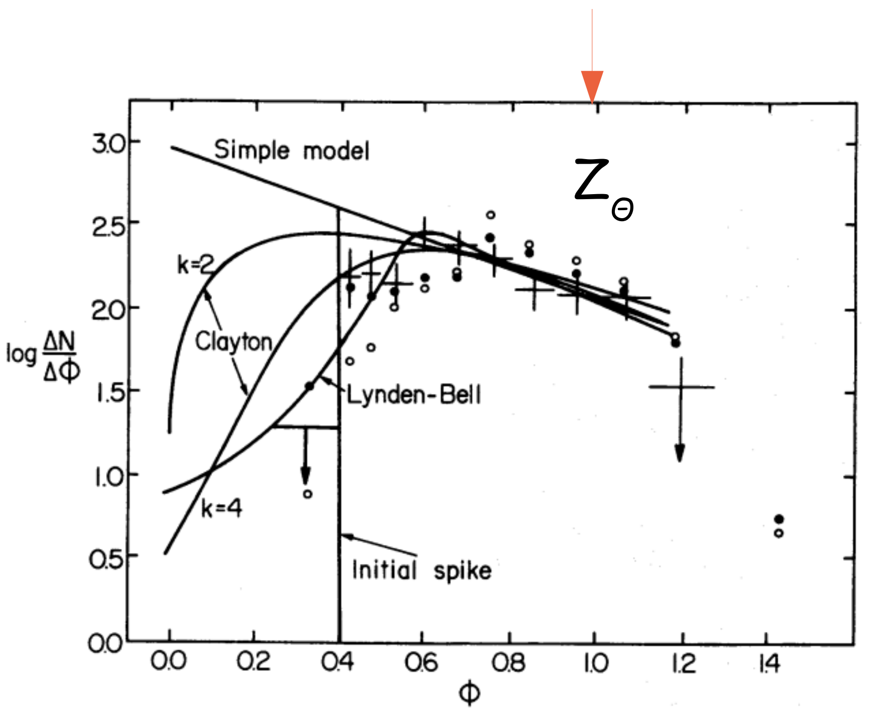
The metallicity distribution of DLA absorption systems is bimodal, $Z_\odot$ and 3%$Z_\odot$, (Lehner+13). z < 1

The two components represent inflows and outflows

MgII outflows faster in face-on galaxies (Bordoloi+14)

The G-dwarf problem

There is a notorious deficit of sub-solar metallicity G-dwarf stars in the solar neighborhood (van den Berg 62; Schmidt 63), as compared with the distribution expected in closed-box evolution where every new population is less numerous than the preceding one.



Φ is metallicity in linear scale

(from Rocha-Pinto & Maciel 96)

The deficit is actually and excess of G-dwarfs with solar metallicity, easy to explain in the stationary state gas infall model (Larson 72)

$$Z \simeq Z_i + y\,(1 - R)/(1 - R + w).$$

$$y \approx Z_\Theta$$

The same deficit occurs in other galaxies as well (Worthey+96)

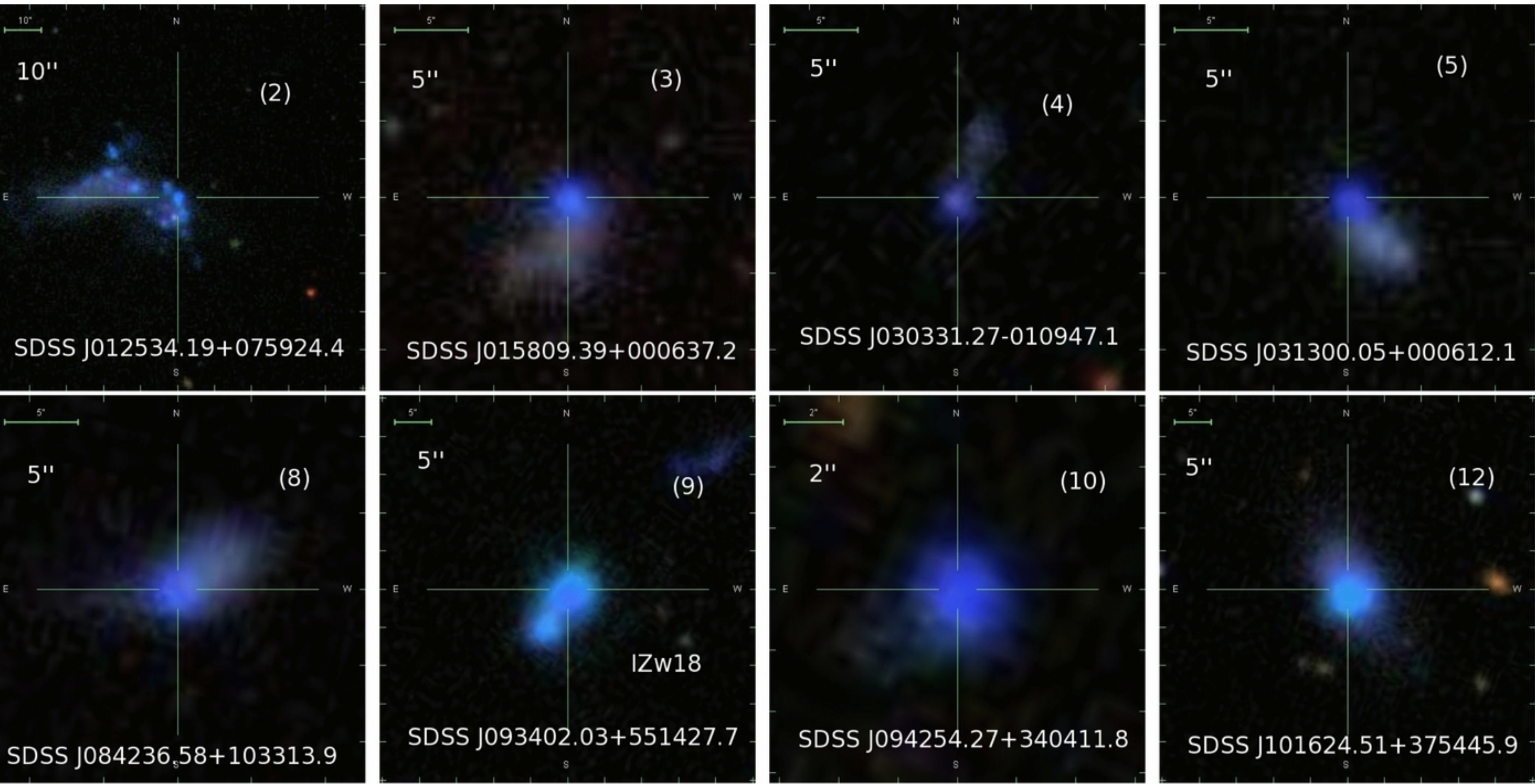
Polar ring galaxies

Often the morphology of the galaxies as observed in broad band (thus tracing stars) is distorted with signs of recent accretions of large amounts of gas in a single episode.

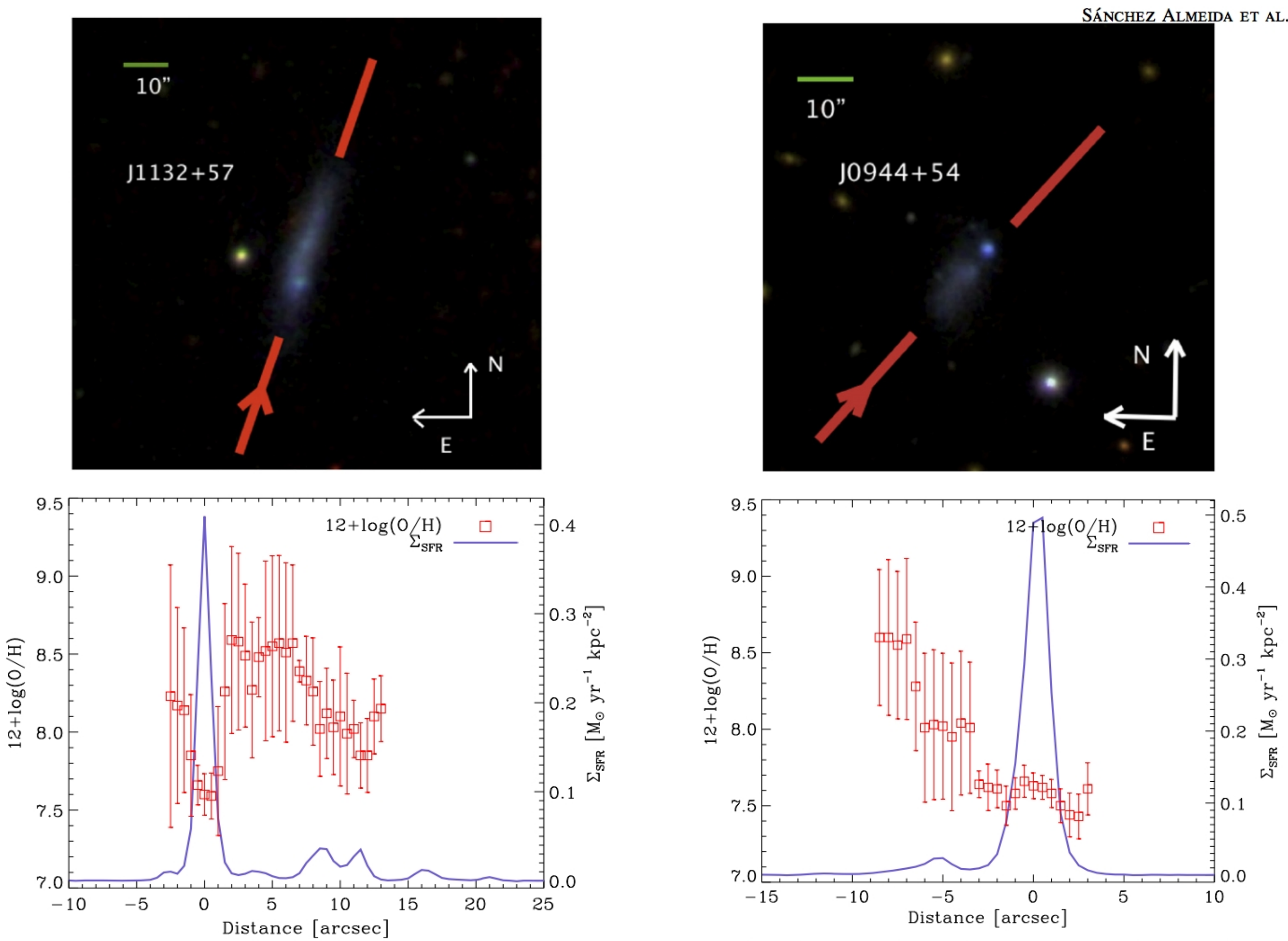
The polar ring galaxies are extreme cases (e.g., Combes+13)

Metallicity Drops in XMPs

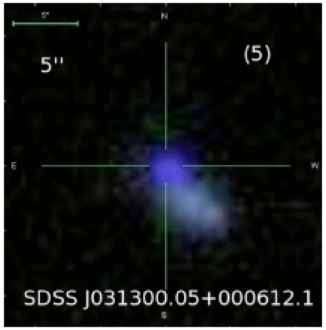
Extremely Metal Poor (XMP) galaxies of the local Universe turns out to be tadpole or cometary (Morales-Luis+11, ApJ; Filho+13, A&A). With a big off-center starburst.



XMPs present metallicity inhomogeneities so that the larger the SFR the more metal poor (SA+13, 14, ApJ; 15, ApJL)



Local **Tadpoles-cometary-XMP** galaxies:



- the heads are giant star-forming regions

- rotate, with the heads displaced with respect to the rotation centers

- the head has a lower metallicity than the rest of the galaxy, which must be a short lived phase (ISM mixing in 100 Myr)

These observations are consistent with the heads being a star-formation episode triggered by the recent and localized inflow of pristine gas

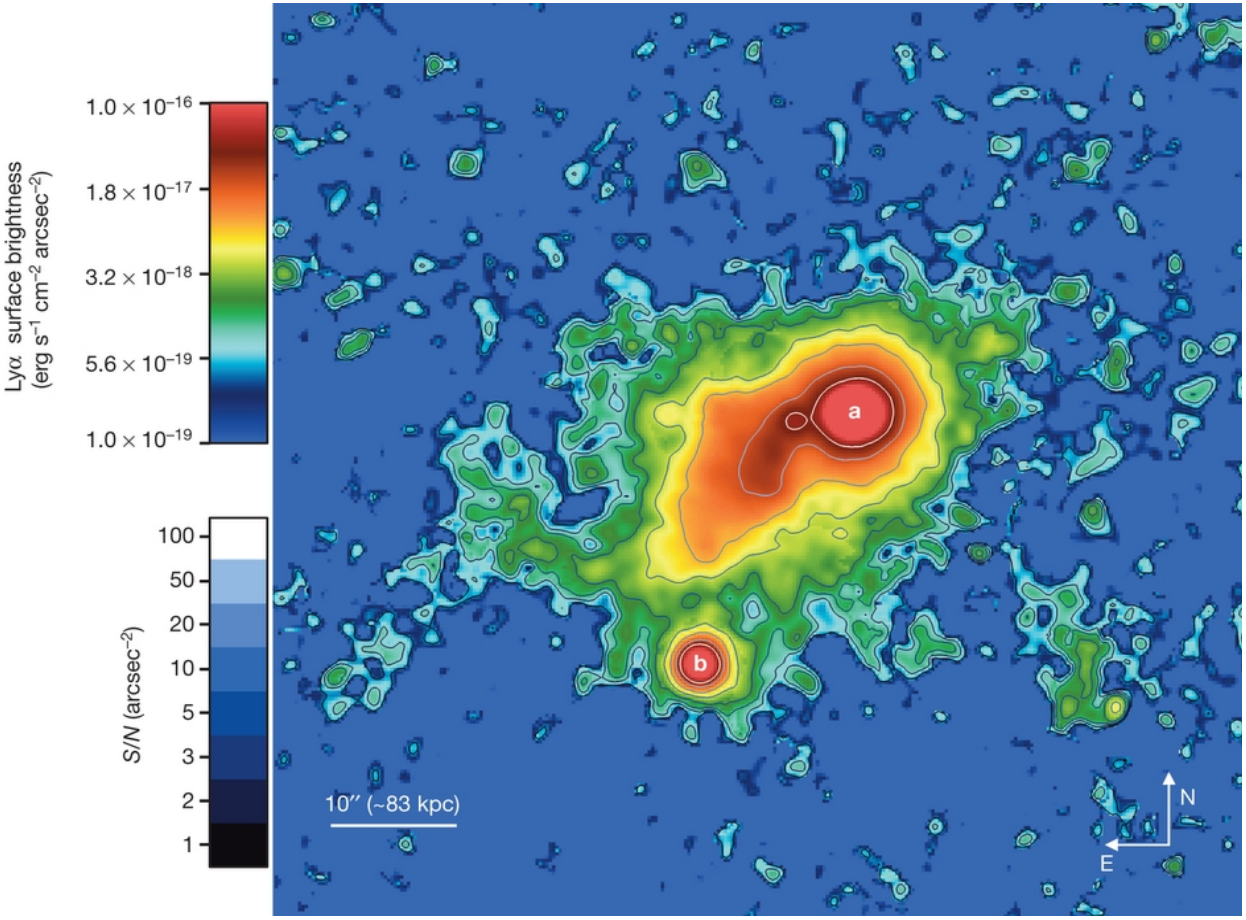
↓

We are witnessing a cold-flow accretion episode

The cosmic web in emission

Lya emission that extends further out of the virial radius of the galaxy hosting the QSO UM287 (a). z=2.3.

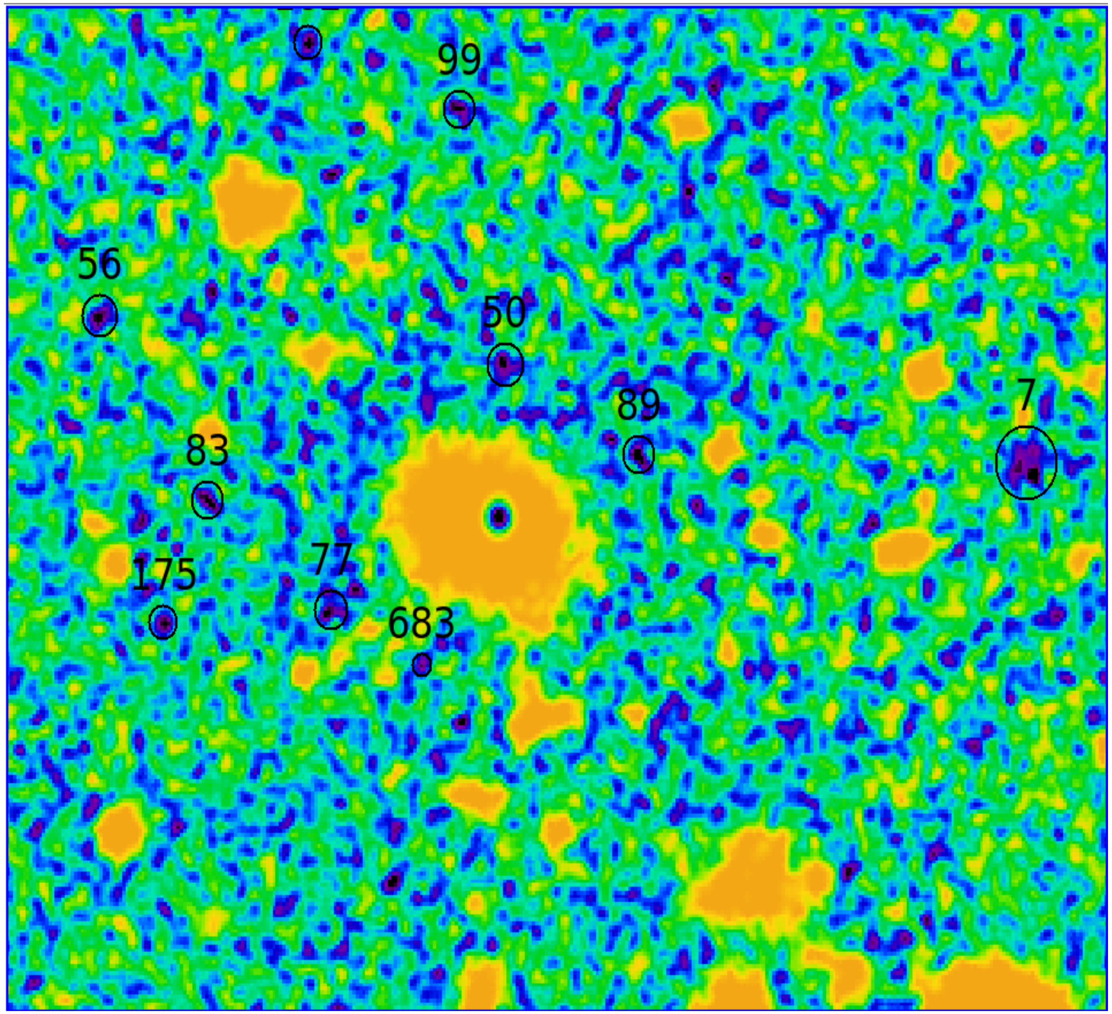
Fluorescence of Lya photons originally emitted by the QSO (a)



Cantalupo+14, Nature

We are in the way to detect these gas by deep imaging in Ha.

8 hour integration with the 10m GTC, which leads to a depth of 27.5 mag/arcsec^2 (Olmo-Garcia et al. 2017).



Summary: take-home messsage

0.- Galaxies transform gas into stars.

1.- **Disk galaxies are still forming.**

2.- What are galaxies feeding from?

Theory: the **star-formation** at all redshift **is driven by gas accretion from the cosmic web**.

Observations: the observational **characterization** of this central ingredient in galaxy astrophysics is still **in its infancy**