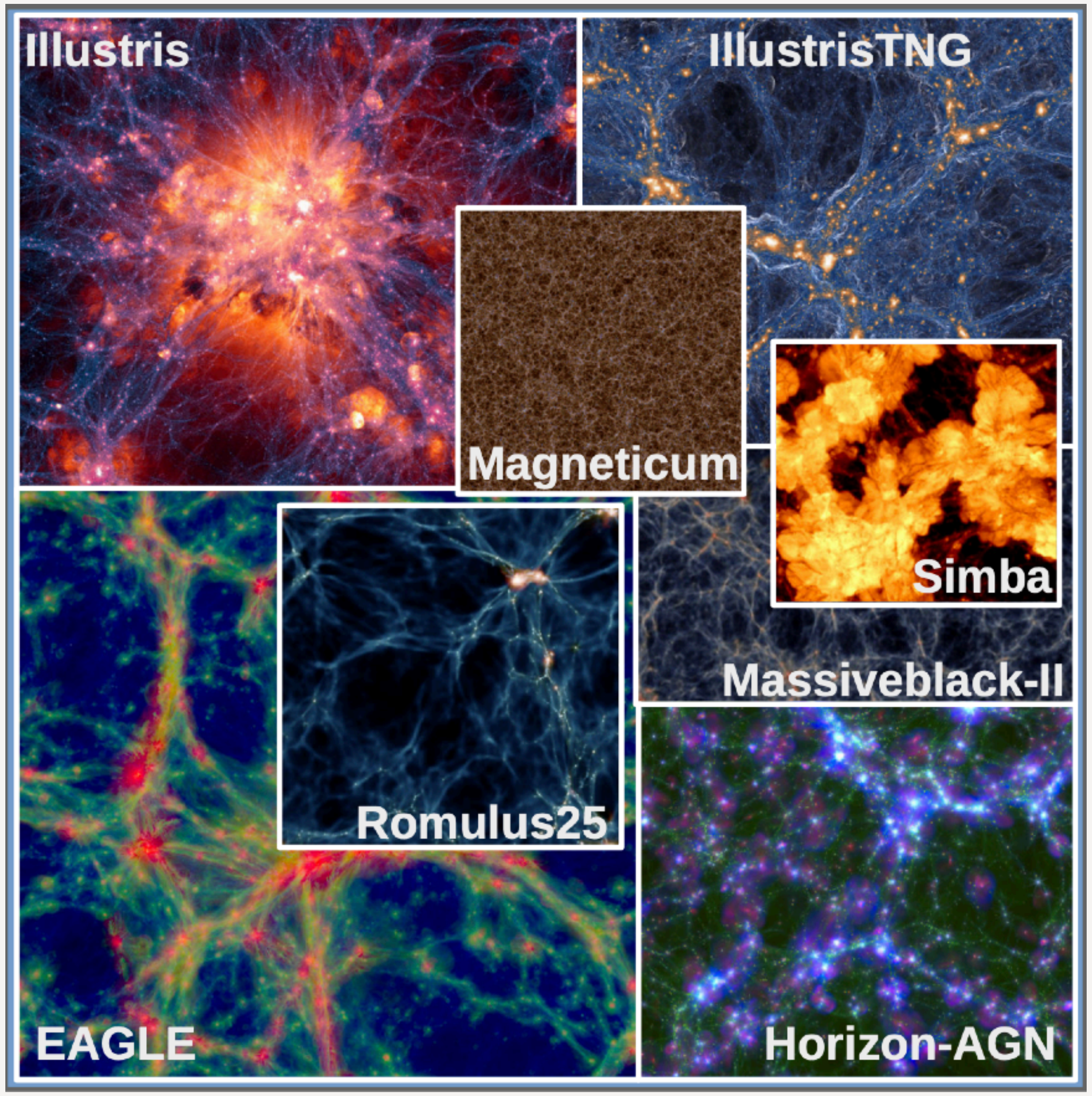
# Emergence of Lyman-α Emission from GMCs to Galactic scales

Taysun Kimm (Yonsei University, South Korea)

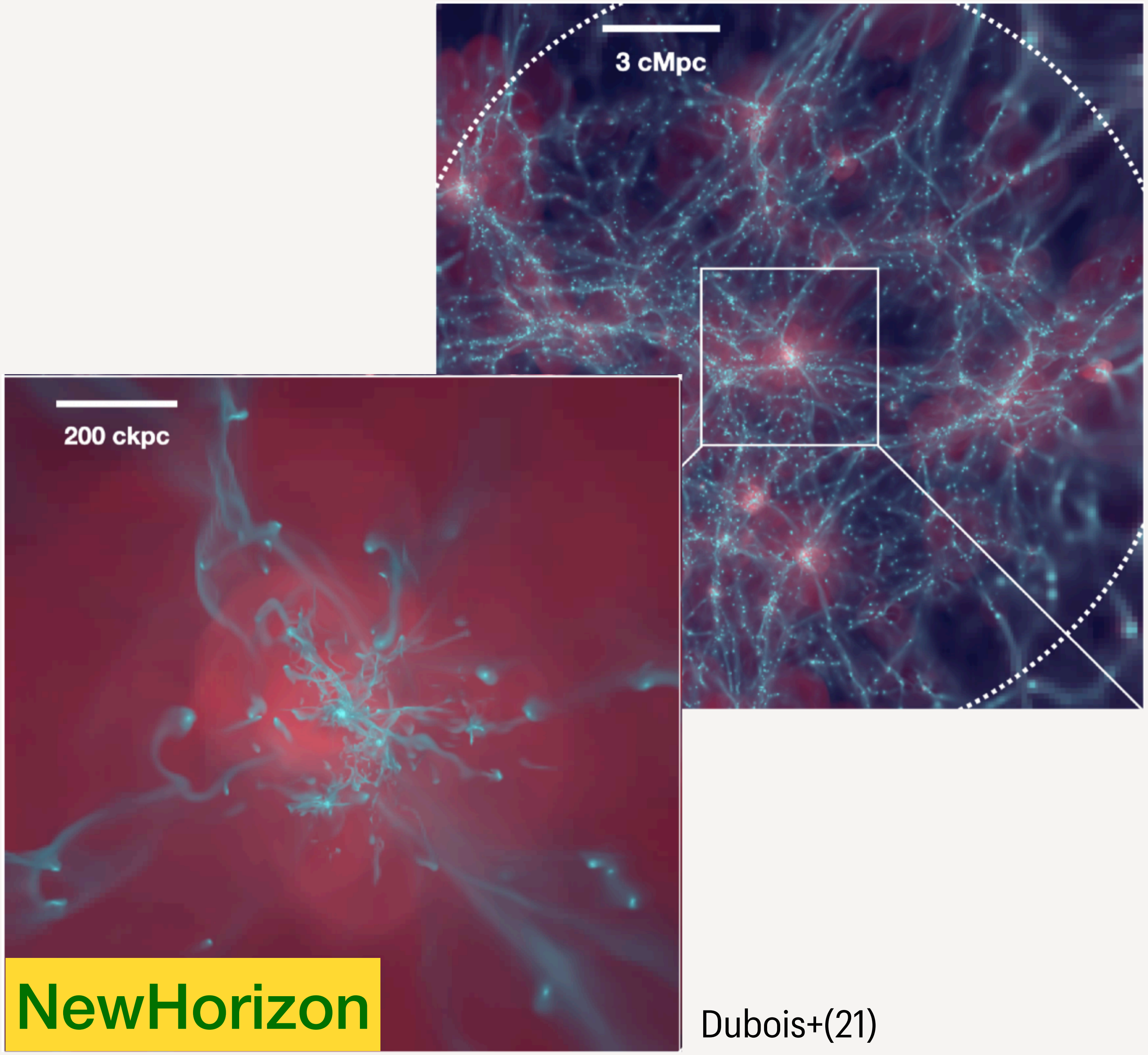
with

Hyunmi Song (Chungnam National University), Harley Katz (Oxford),
Jeremy Blaizot, Joakim Rosdahl, Leo Michel-Dansac (Lyon), Taehwa Yoo (Florida)
Martin Haehnelt (Cambridge), Anne Verhamme, Thibault Garel (Geneva),
Sam Geen (Amsterdam), Rebekka Bieri (MPA)

# Galaxy Formation Simulations



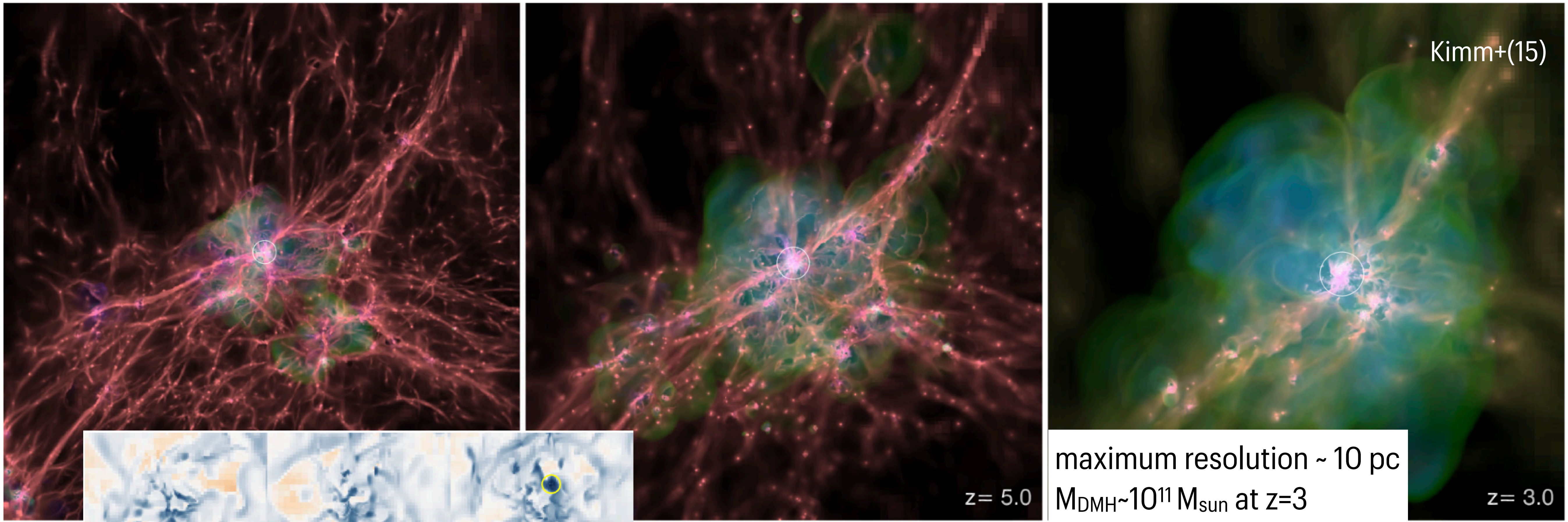

Vogelsberger+(20)



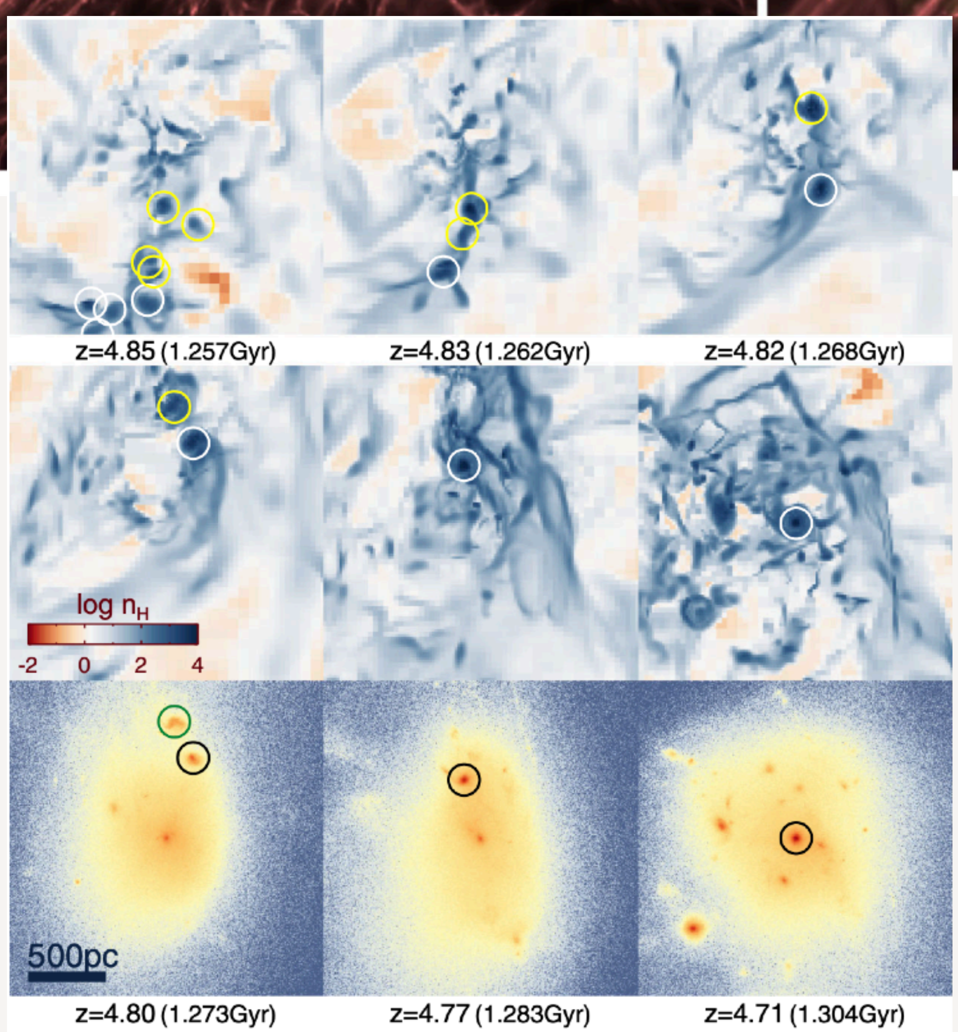

Dubois+(21)

"Recent hydrodynamical simulations reproduce galaxy populations that agree remarkably well with observational data. However, many detailed predictions of these simulations are still sensitive to the underlying implementation of baryonic physics. "

# Galaxy formation from the large-scale structure




maximum resolution ~ 10 pc
$M_{DMH}$~$10^{11}$ $M_{sun}$ at z=3




Even w/ supernova feedback

- star formation is not well controlled
- over-cooling is easy to develop

(when strong gas accretion takes place at the galaxy center)

(c.f. Star formation is self-regulated in the local ISM simulations
where max res ~ 4 pc; e.g., Kim et al. 15, 18.. )

# Various models for stronger stellar feedback

**Super-bubble Feedback**
+ Bursty Star Formation

**Momentum boost in SN explosion**

**Radiation Feedback**

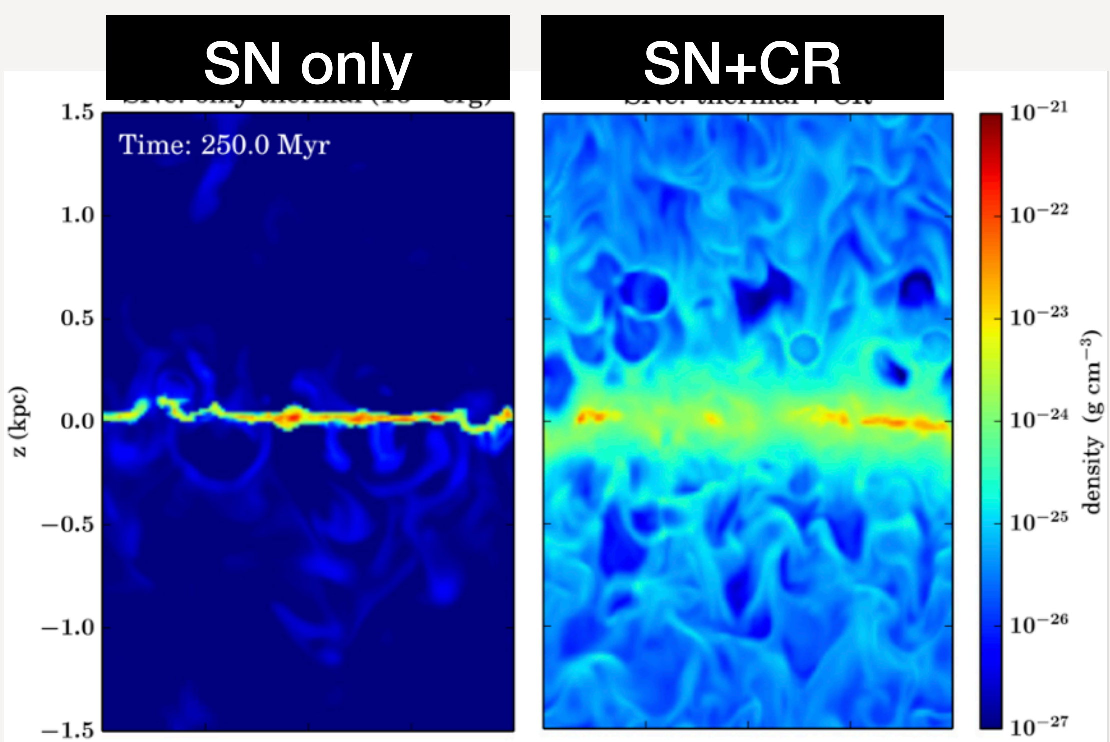
**Cosmic Ray Pressure**

- SN clustering ⬆
- drive stronger (hot) outflows

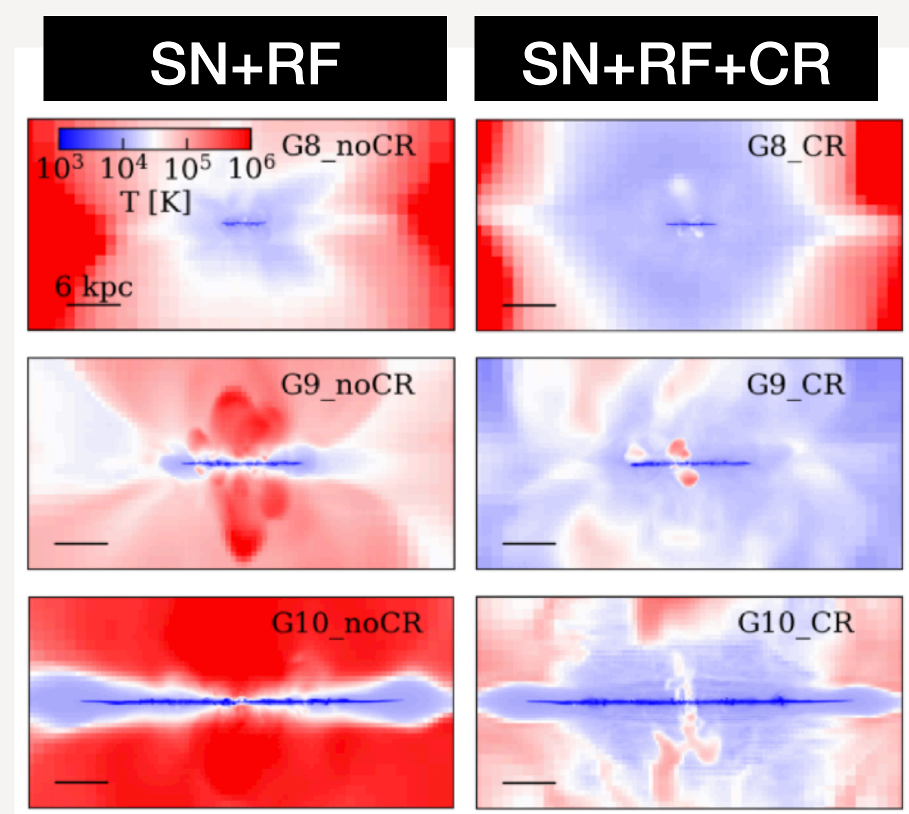
(e.g., Keller+14; Agertz+2015; Gentry+17; Rodriguez Montero+22)

- radiation: suppress SF (but SN clustering ⬇)
- CRs: more warm outflows

(e.g., Girichidis+16; Kimm+18; Smith+20; Farcy+22)



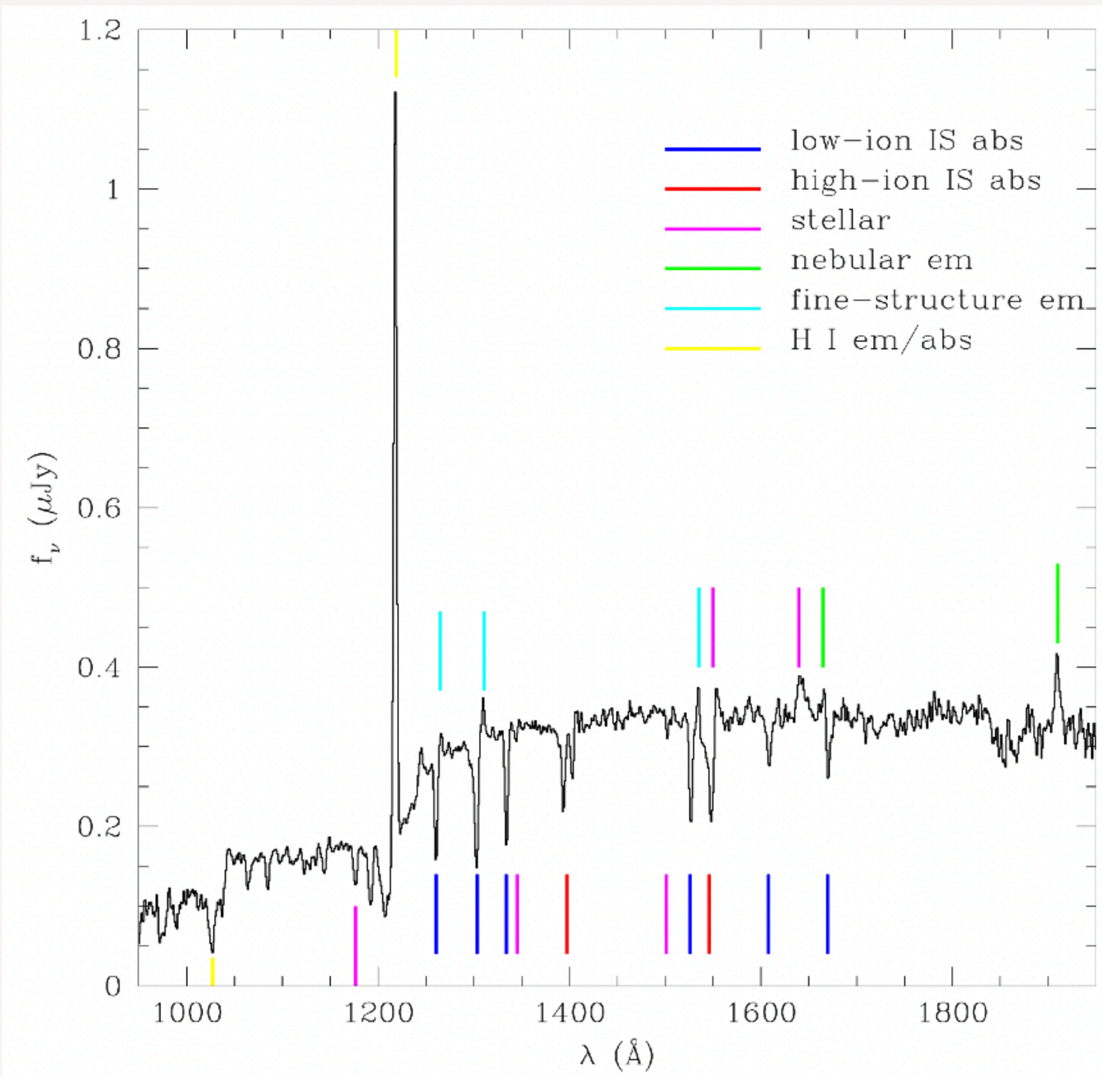

Girichidis+(16)




Farcy+(22)

# A metric to test theoretical models : Lyman-$\alpha$

H Lya: 2P->1S resonant line at 1215.67A




(Shapley+03)

Recombinative radiation

$$H + \gamma_{>13.6} \rightarrow H^{+} + e^{-}$$

$$H^{+} + e^{-} \rightarrow H + \gamma_{\alpha} + ..$$

Collisional (cooling) radiation

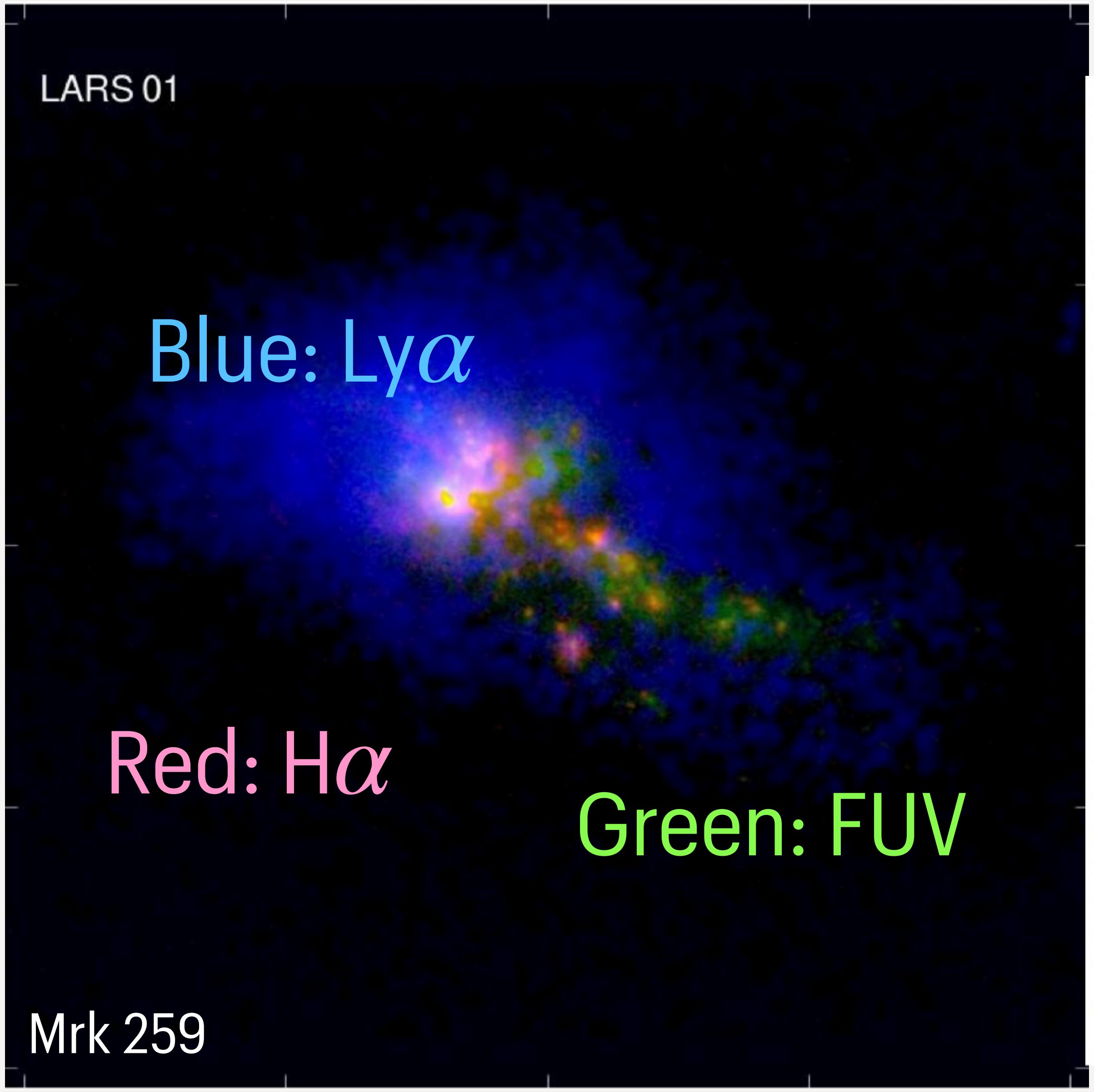
$$H + e^{-} \rightarrow H + \gamma_{\alpha} + e^{-}$$

Lyman-$\alpha$ is strong in star-forming galaxies because

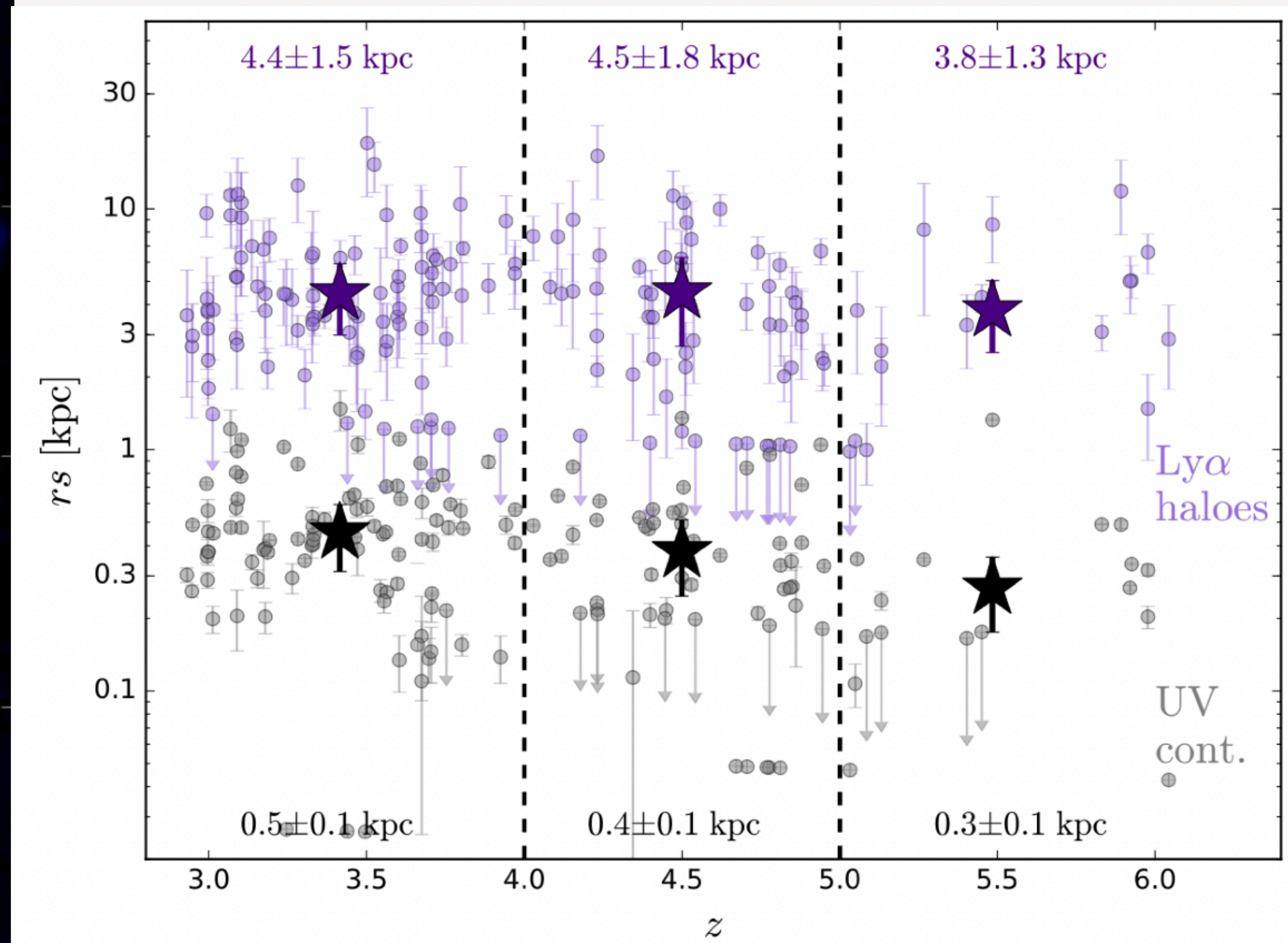
1) hydrogen is abundant

2) warm ISM is at the right temperature range (T~10,000 K)

# Lyman-$\alpha$ halo around star-forming galaxies




Hayes et al. (2013)
(GALEX+HST, 0.03<z<0.18, -22 < $M_{UV}$<-15)

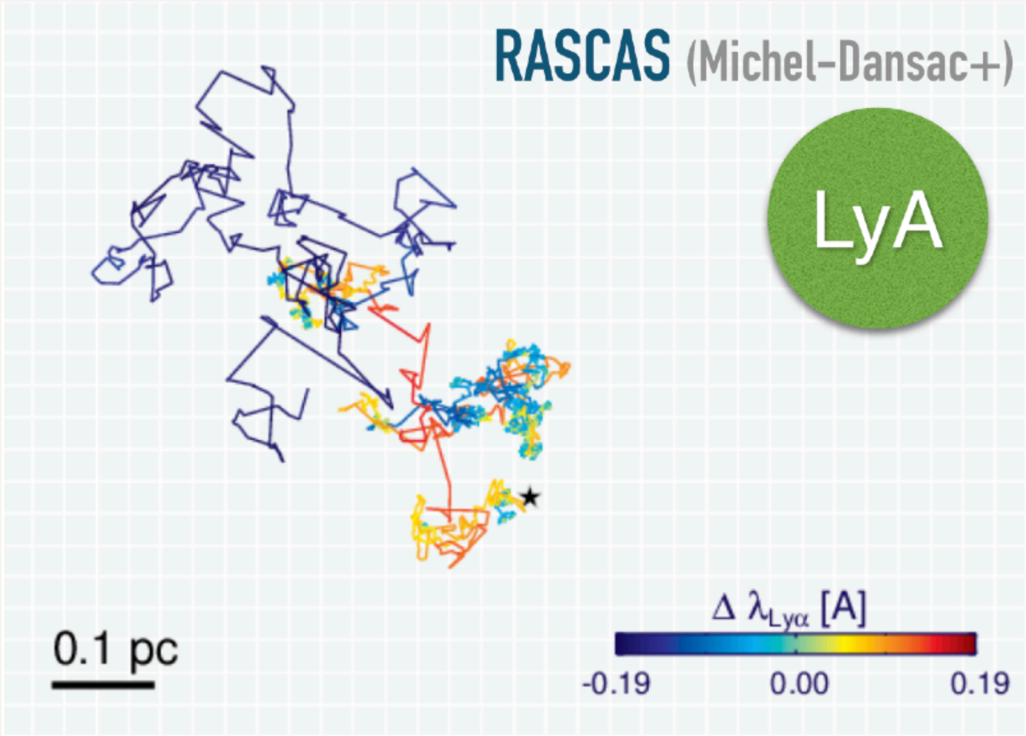



Leclercq et al. (2017)
(MUSE, 3<z<6, -22 < $M_{UV}$<-15)

80% of Lyman alpha emitters reveal extended Lyman alpha halos

Implication: extended warm/neutral H

# Lyman-$\alpha$ scattering



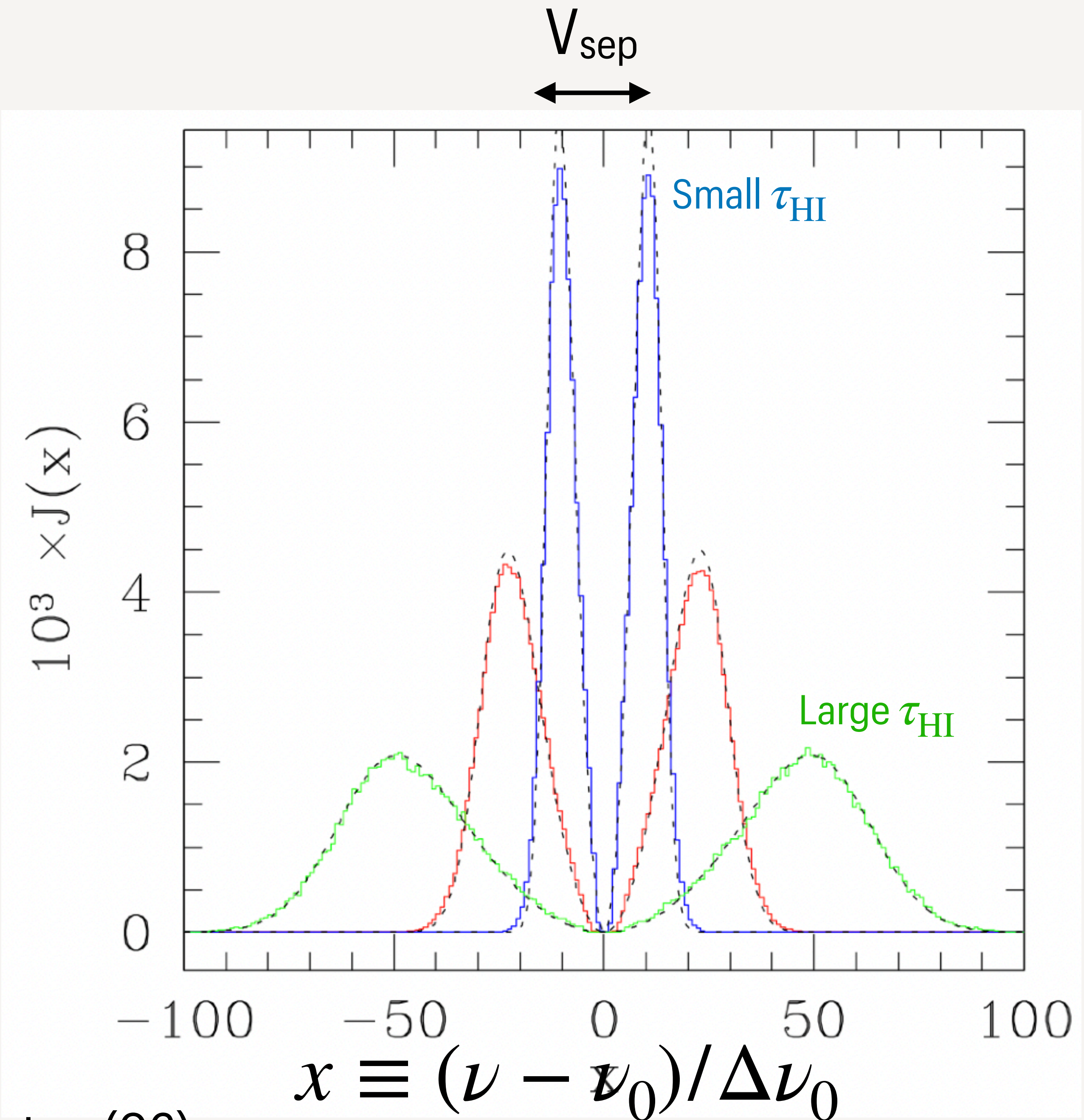

Optical depth to Ly-$\alpha$ is extremely large in SFGs

$$\tau_\alpha = \sigma_0 N_{HI} \sim 10^7 \left(\frac{T}{10^4\,\mathrm{K}}\right)^{-1/2} \left(\frac{L}{500\,\mathrm{pc}}\right) \left(\frac{n_H}{1\,\mathrm{cm}^{-3}}\right)$$

Large optical depth

-> a large number of scattering

-> more redistribution of Lyman $\alpha$ in space and frequency domain




**Large $\tau_{HI} \rightarrow v_{sep} \uparrow$ or $v_{red} \uparrow$**

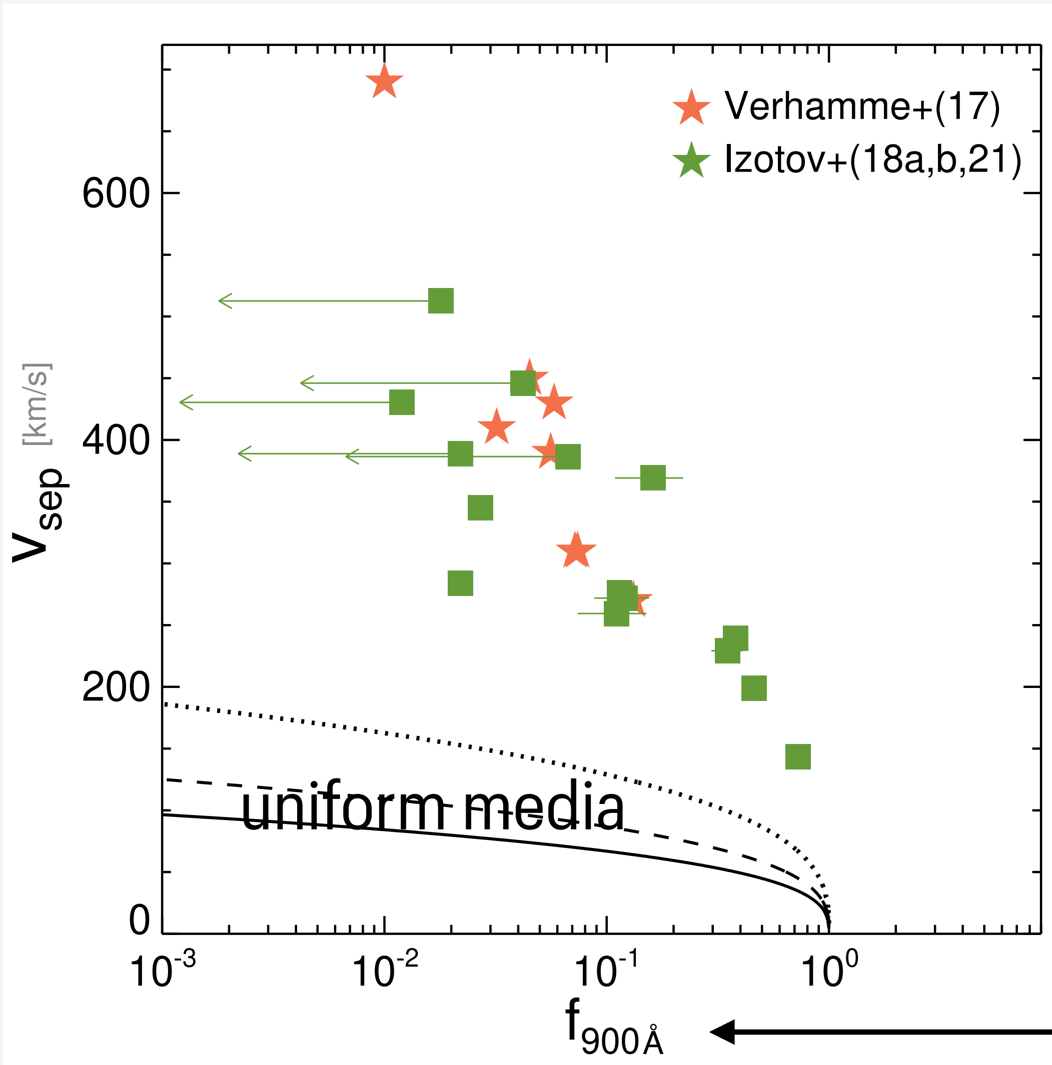
See also Ahn+(02); Verhamme+(06), Michel-Dansac+(20); Seon & Kim (20); Park+(22)

Dijkstra+(06)

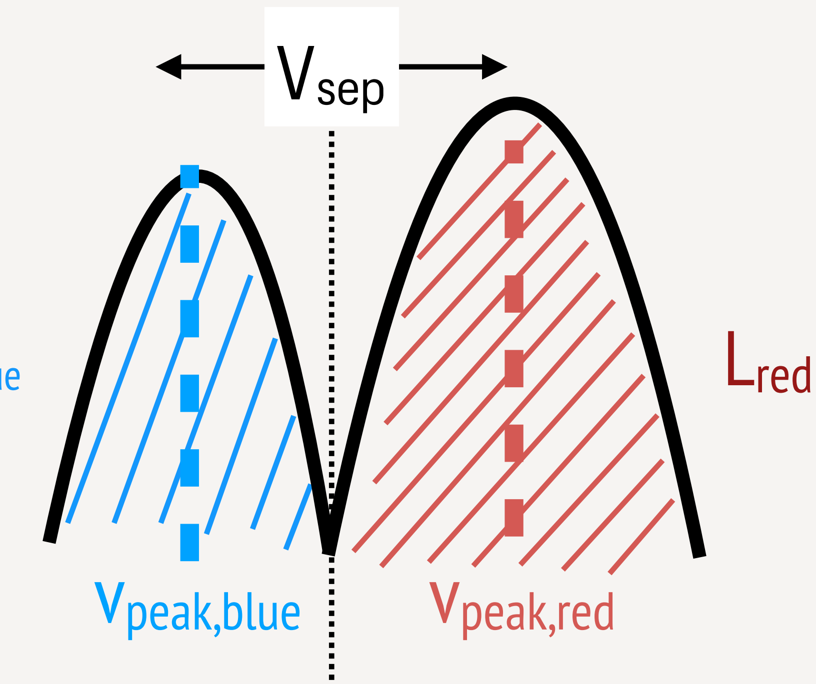
$\Delta\nu_a = \nu_a \sqrt{v_{th}^2 + v_{turb}^2}/c$

# Interesting features in Lyman-$\alpha$

measure of optical depth to HI




Lyman alpha profile in velocity space

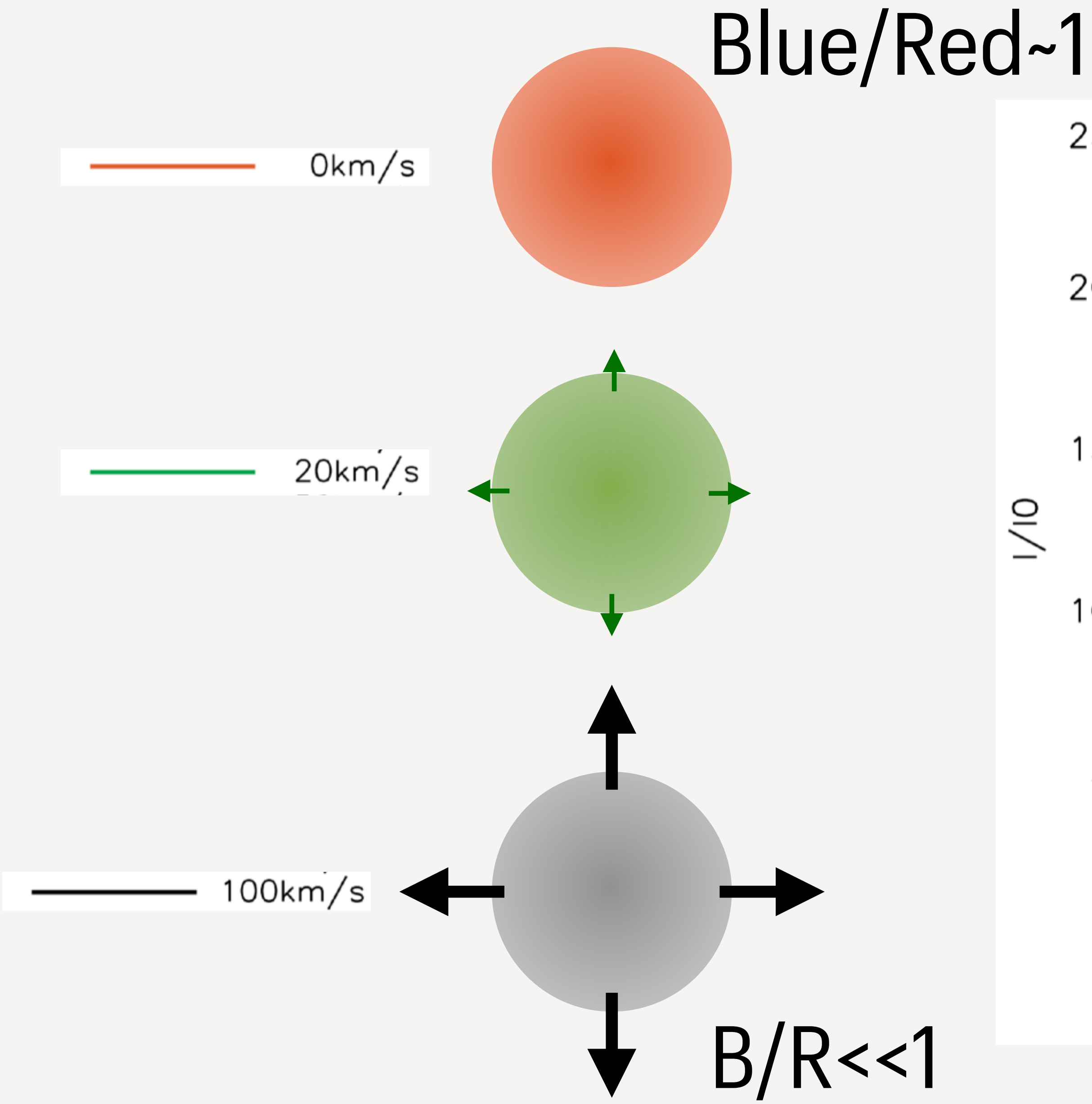



escape fraction at 900A

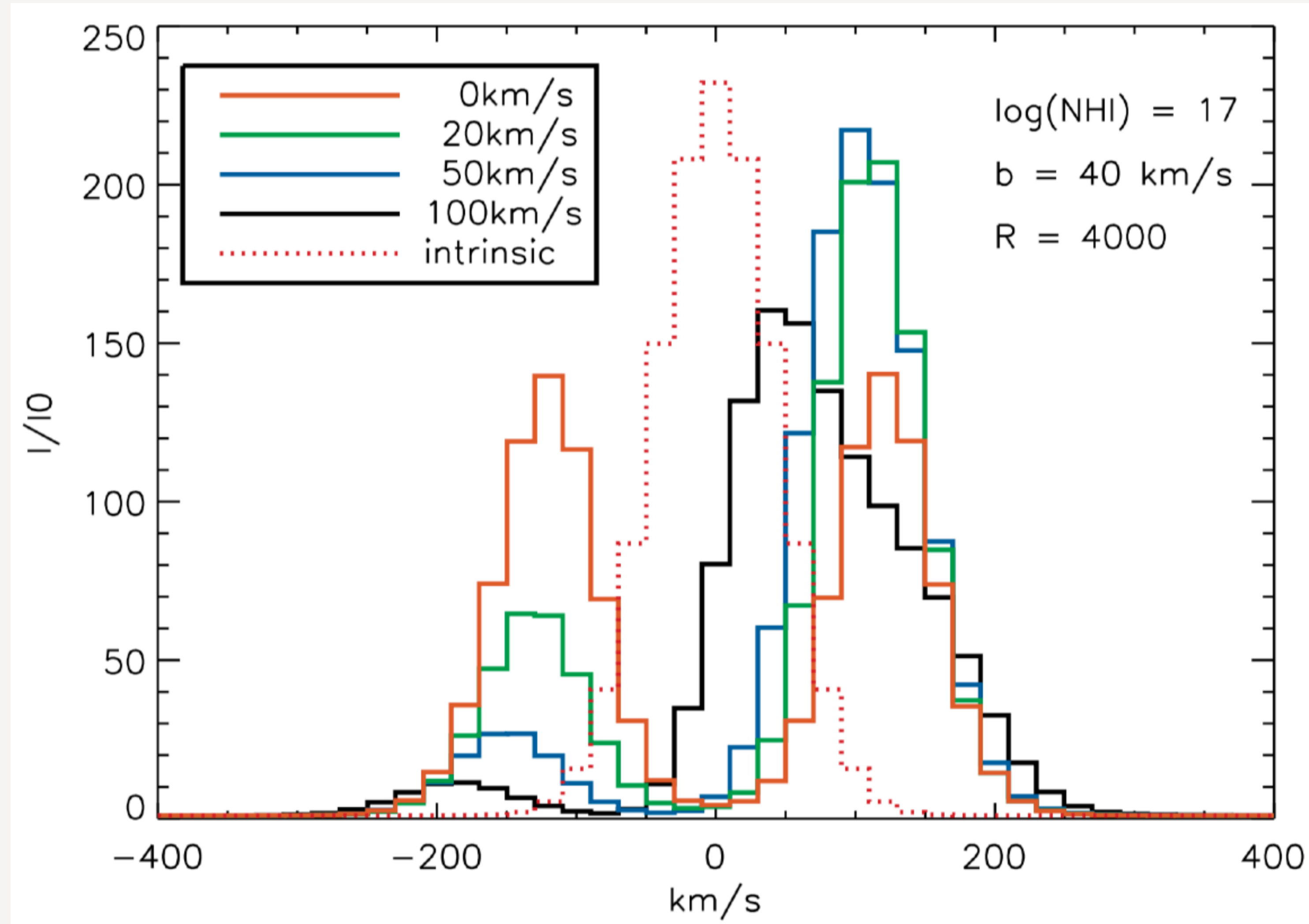
measure of optical depth to HI

$$\tau_{900\text{Å}} \sim 6 \times 10^{-18}\,\text{cm}^{-2} \times N_{\text{HI}}$$

# Blue-to-Red ratio of Lyman-$\alpha$ : sensitive to kinematics



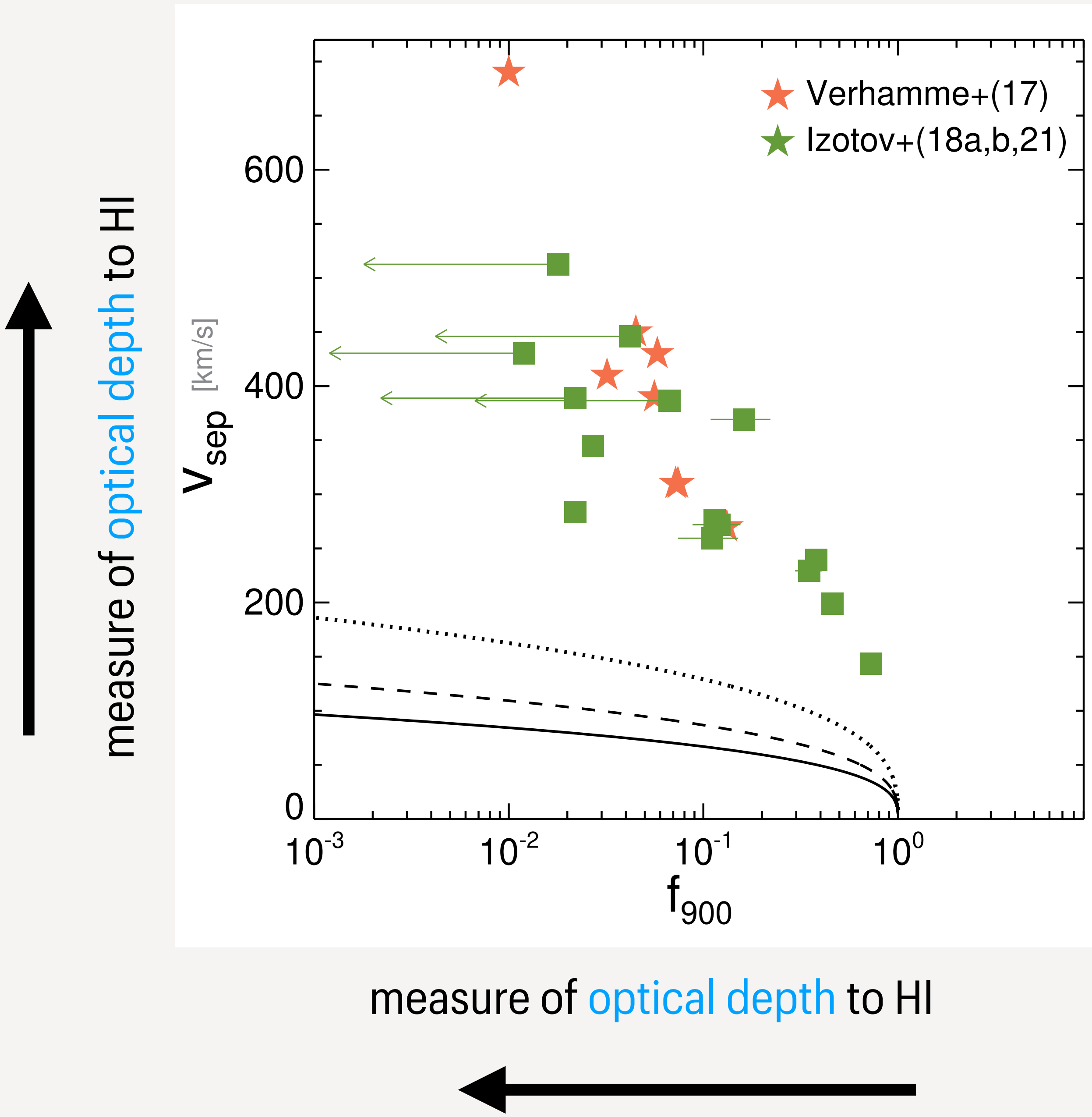

Lyman-$\alpha$ spectra

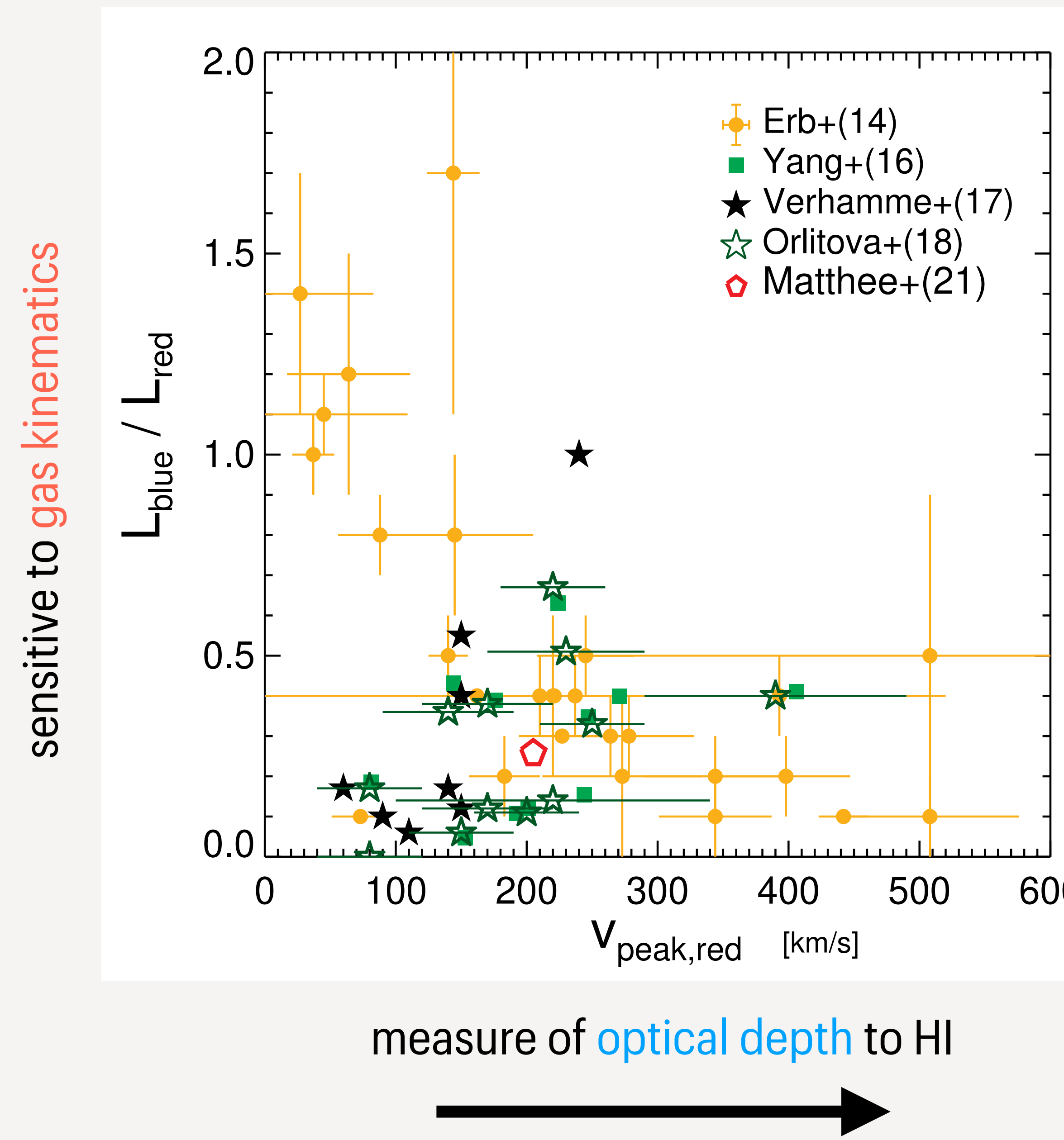



Verhamme+(15)

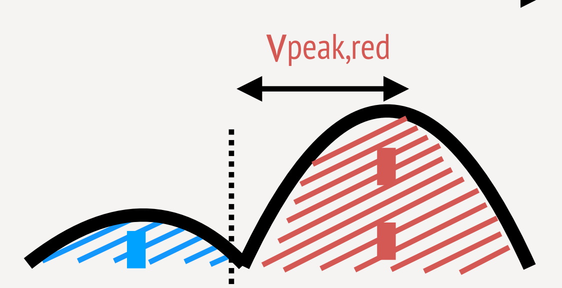
Red peak is more pronounced in Lyman-$\alpha$ if a medium is expanding

# Observed features from Lyman-$\alpha$



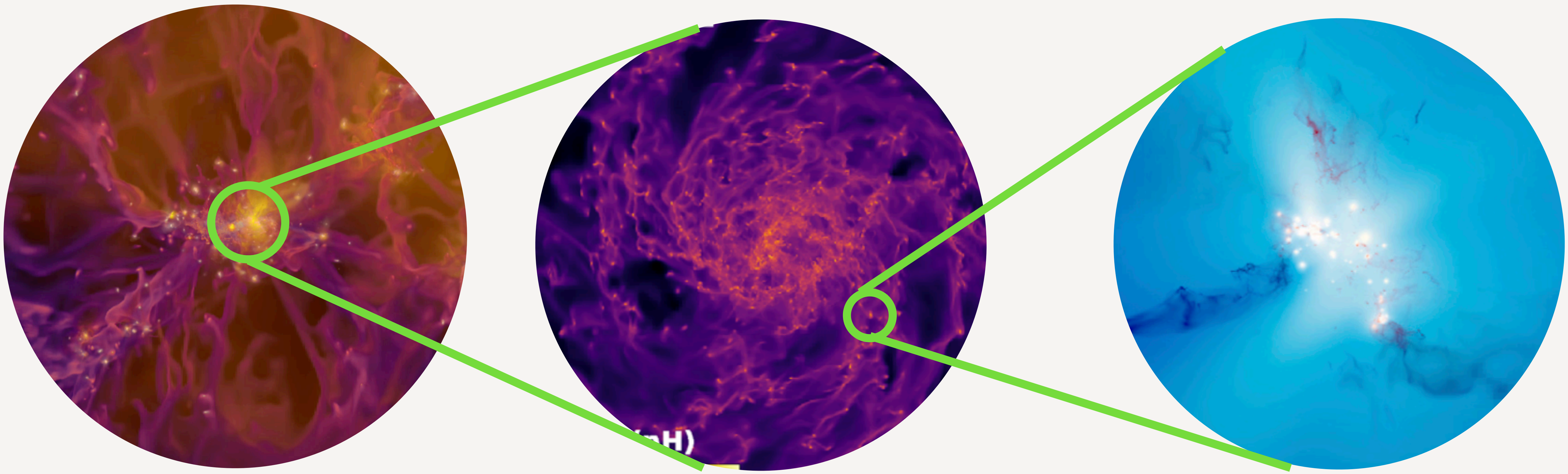

Ly$\alpha$ should scatter with the medium of $10^{14} \lesssim N_{HI} \lesssim 10^{18}\,\mathrm{cm}^{-2}$




Strong outflows in high-z SFGs

# Gas distributions from GMC to CGM

CGM+IGM | Galactic scale | Individual GMC



~100-1000 kpc
(Rosdahl+18; Katz+21)

(see also NewHorizon, NH2)
(Dubois+21, Yi+in prep)

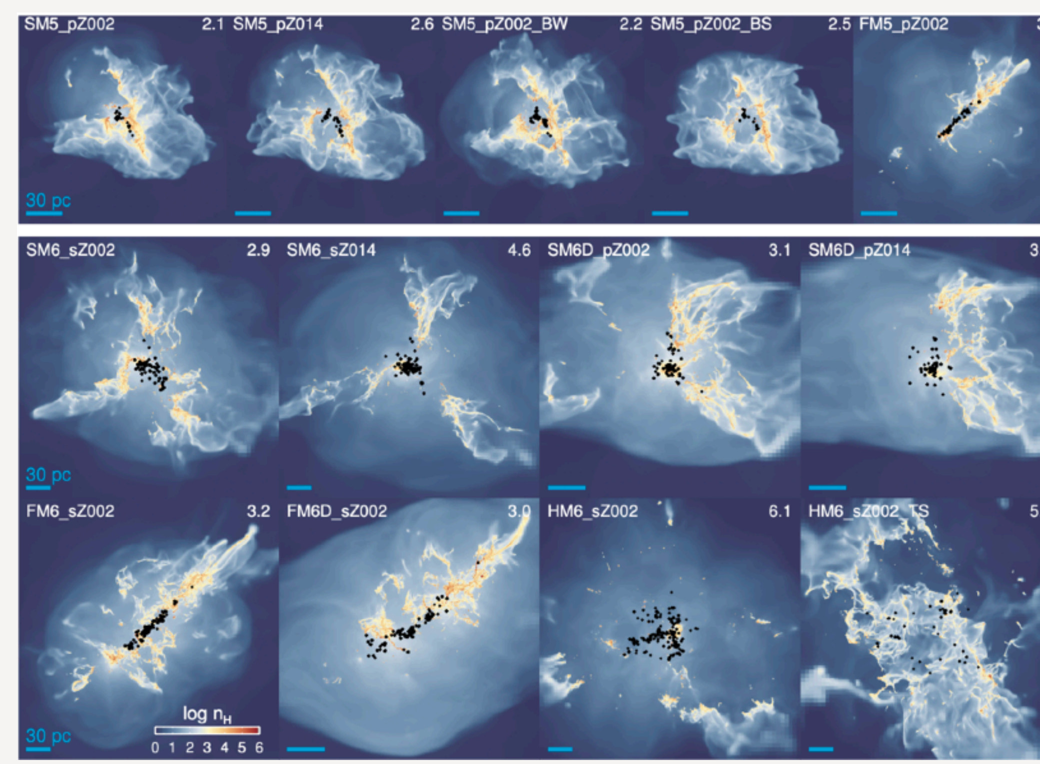
~5 kpc
(Yoo, Kimm, Rosdahl 20)

~100 pc
(Kimm+19, 22)

# A suite of GMC simulations

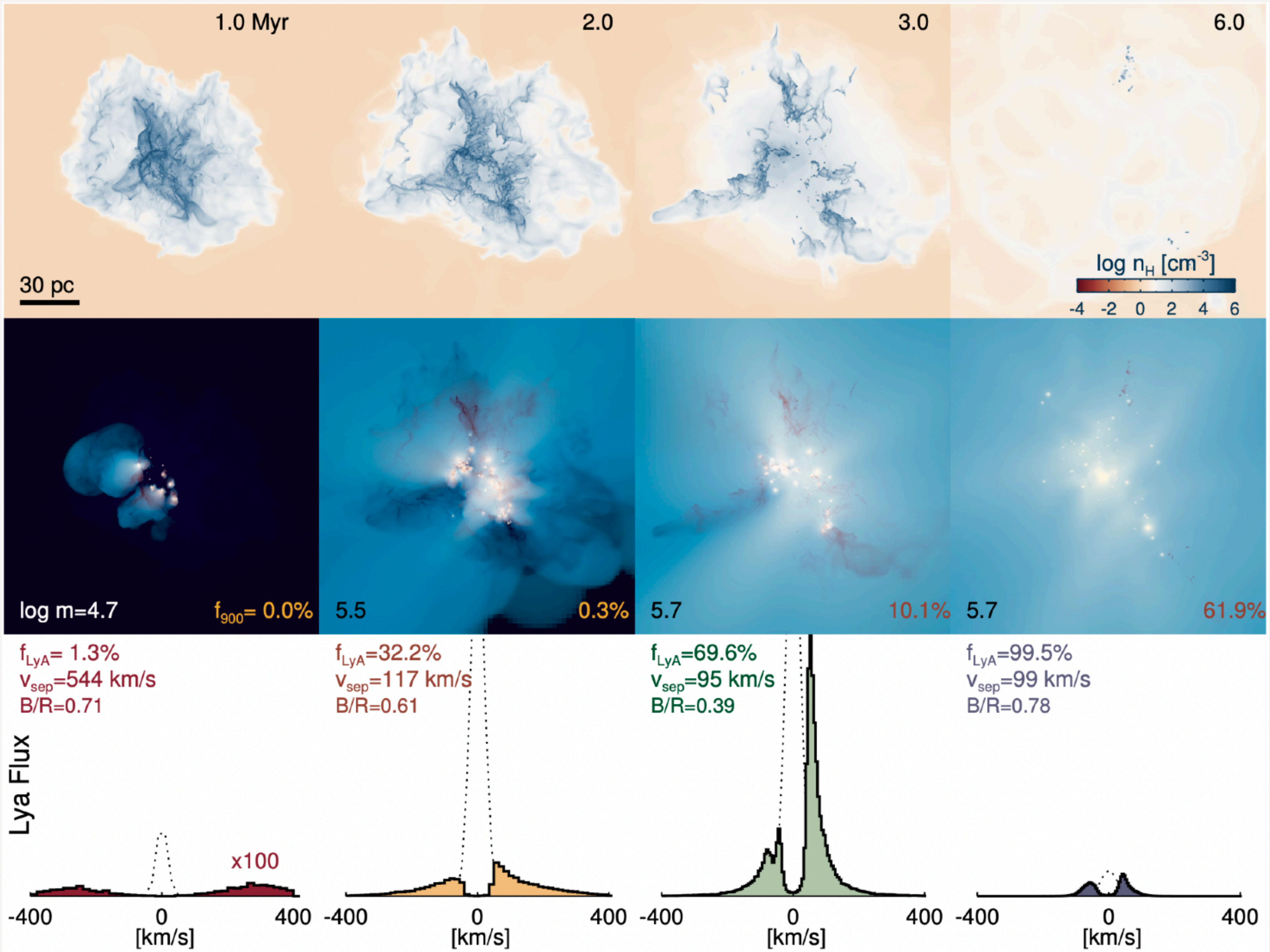

RAMSES-RT

- $dx_{min}$=0.02-0.08 pc
- Photoionization heating
- Type II Supernova
- Star formation via sink particle
- Magnetic fields
- Various morphologies
- Different surface densities
- Different turbulent strength
- Different metallicities
- Cloud masses
- Resolutions




Radiation-magneto-hydrodynamic simulations of GMCs (Kimm+22)

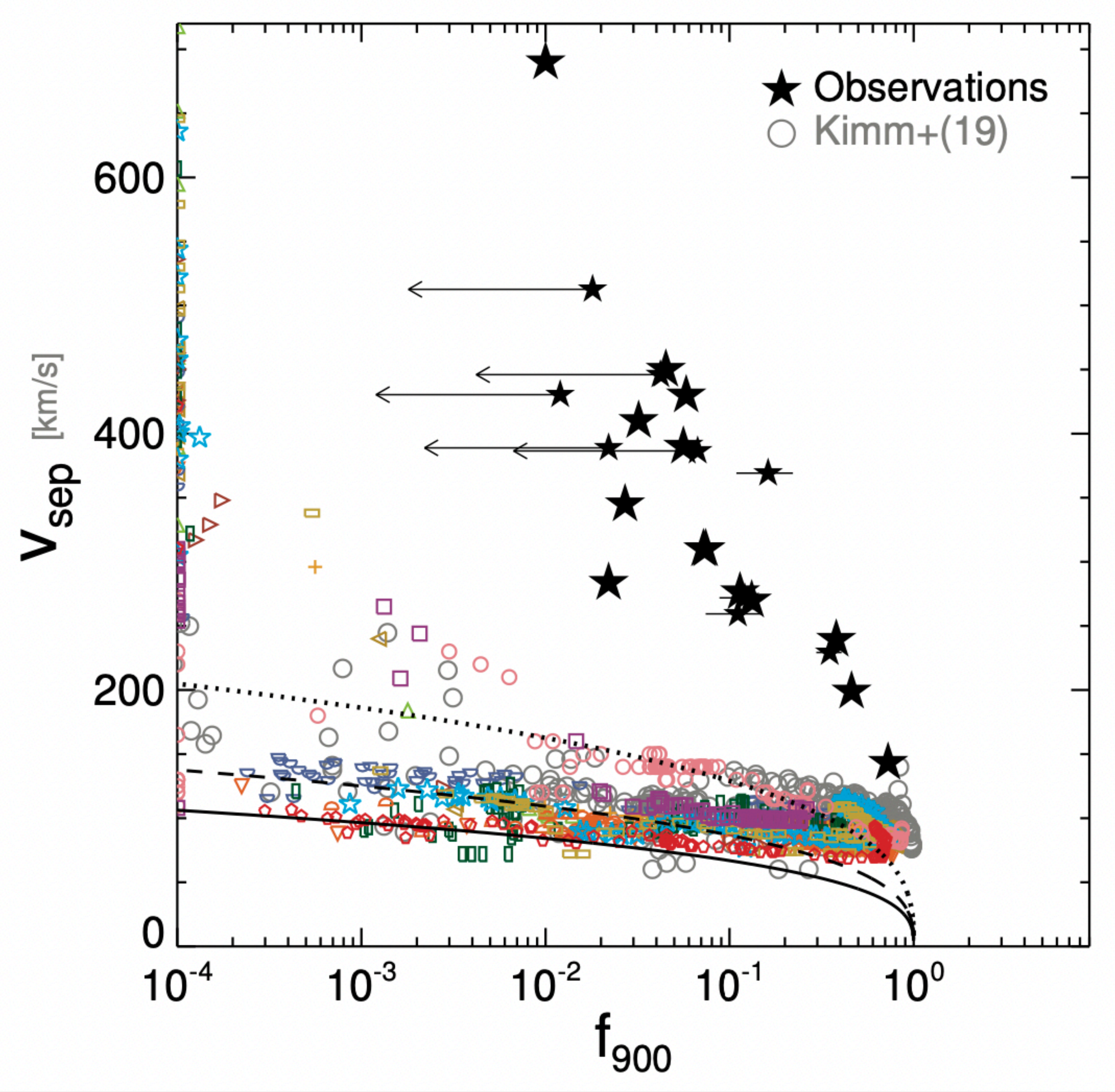
# Evolutionary Lya features from GMC simulations




Kimm+22
(see also Kakiichi & Gronke 21)

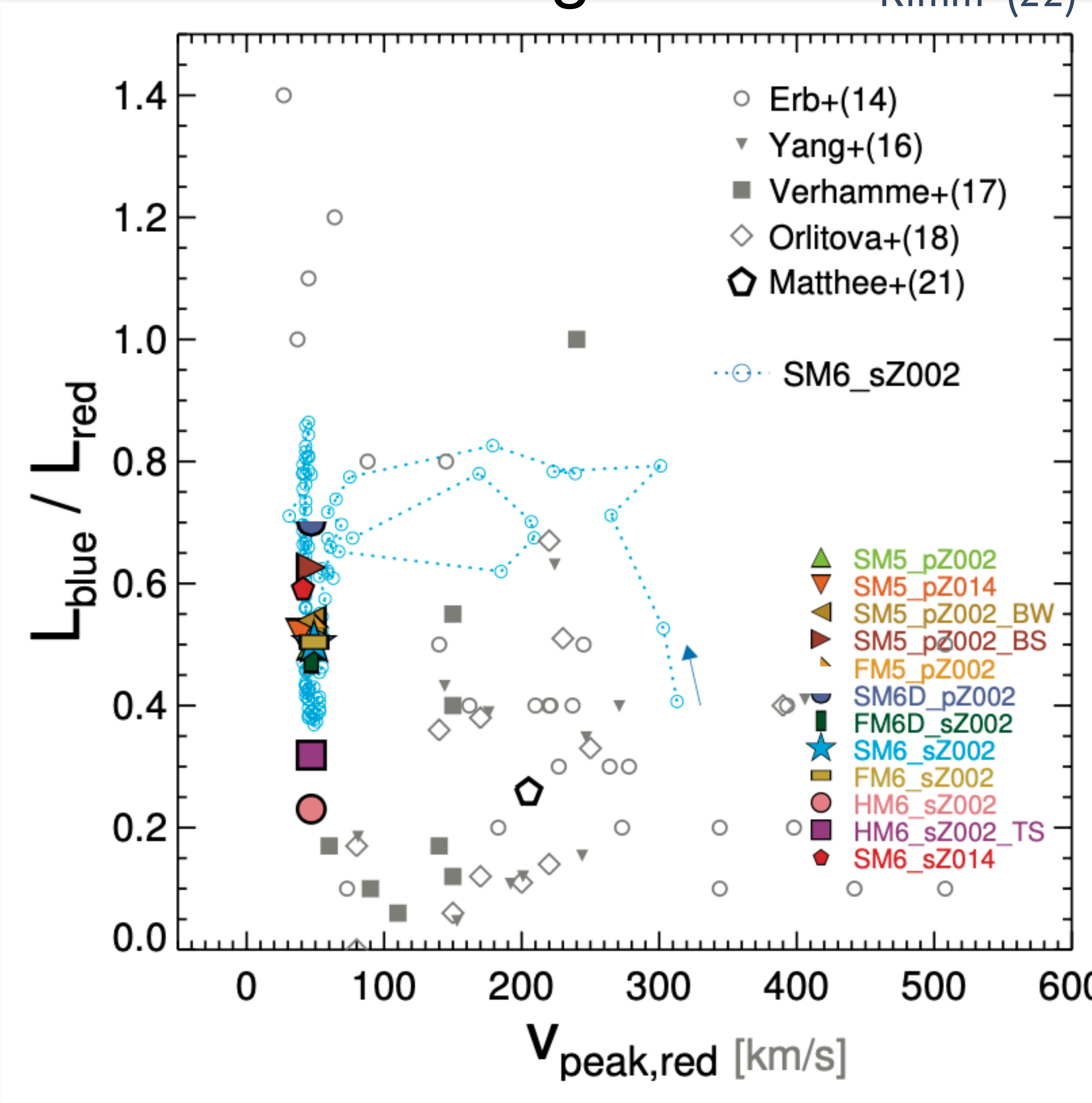
Lyman alpha emissions are brightest when GMCs are being dispersed by radiation feedback
Once destroyed, ionizing radiation (LyC) will interact with the ISM

# Lyman-a properties from GMCs




L-weighted

Kimm+(22)

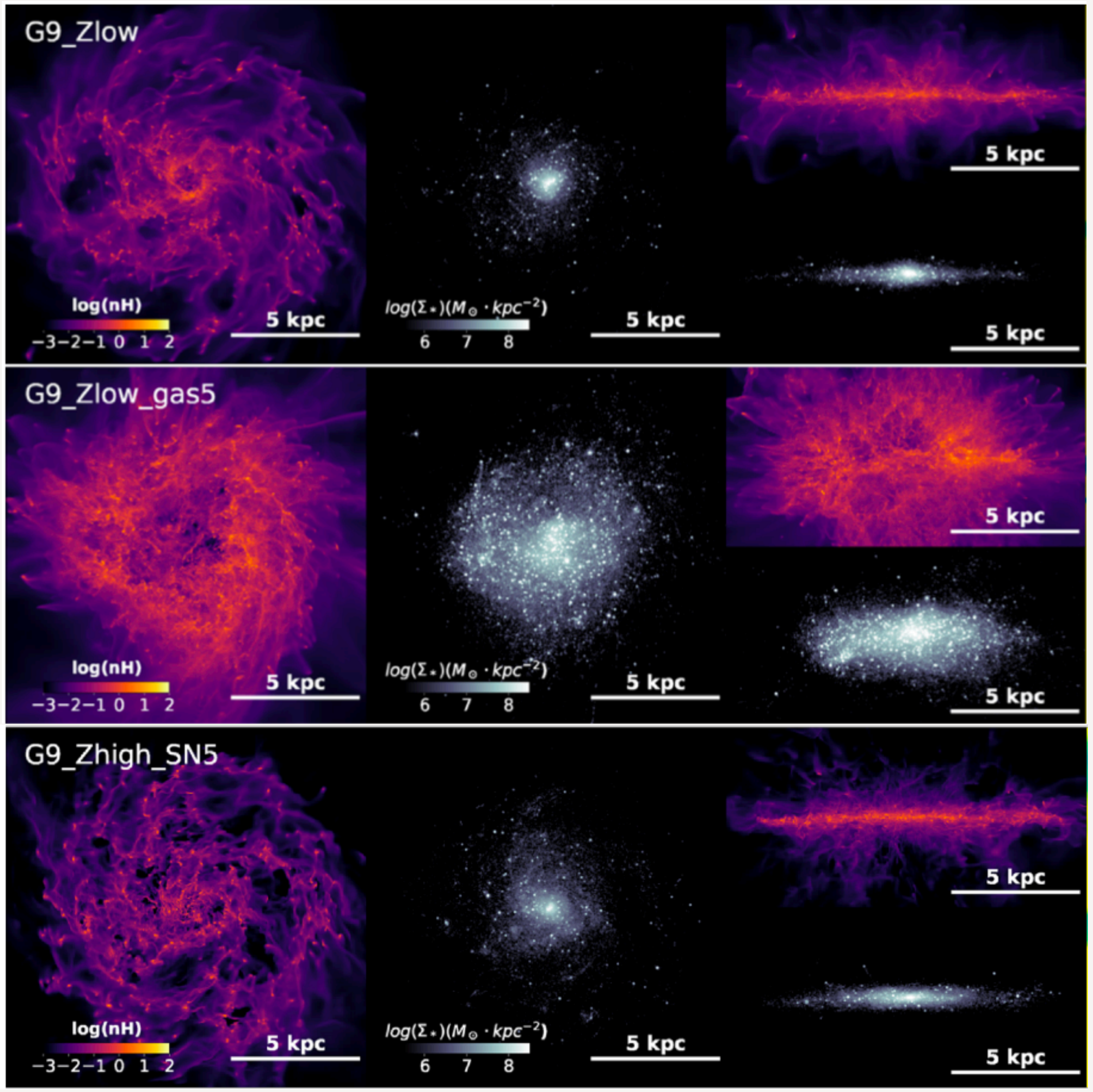



Lyman alpha emissions are not broad compared to observations, indicating that more scattering is needed outside the GMCs

# Lyman-a in disk galaxies with different physical properties

Isolated disk sim with $M_{DMH}$ ~ $10^{11}$ $M_{sun}$,   $M_{star}$ ~ $10^{9}$ $M_{sun}$

Hyunmi Song, Kimm+(in prep)

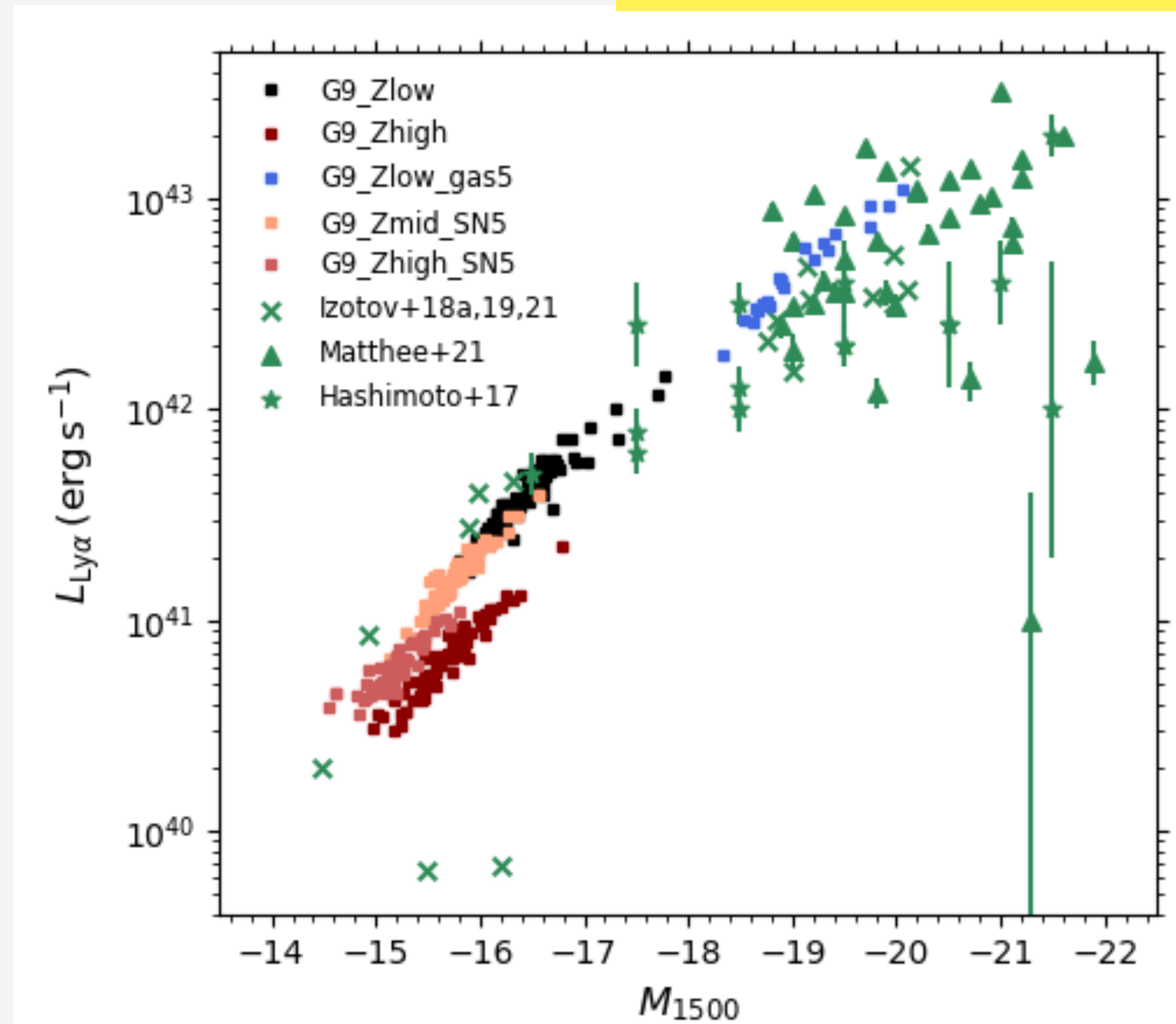



Z=0.1 Zsun
$M_{gas}/M_{star}$=1

Z=0.1 Zsun
$M_{gas}/M_{star}$=5

Z=1 Zsun
$M_{gas}/M_{star}$=1

Yoo, Kimm, Rosdahl (20)

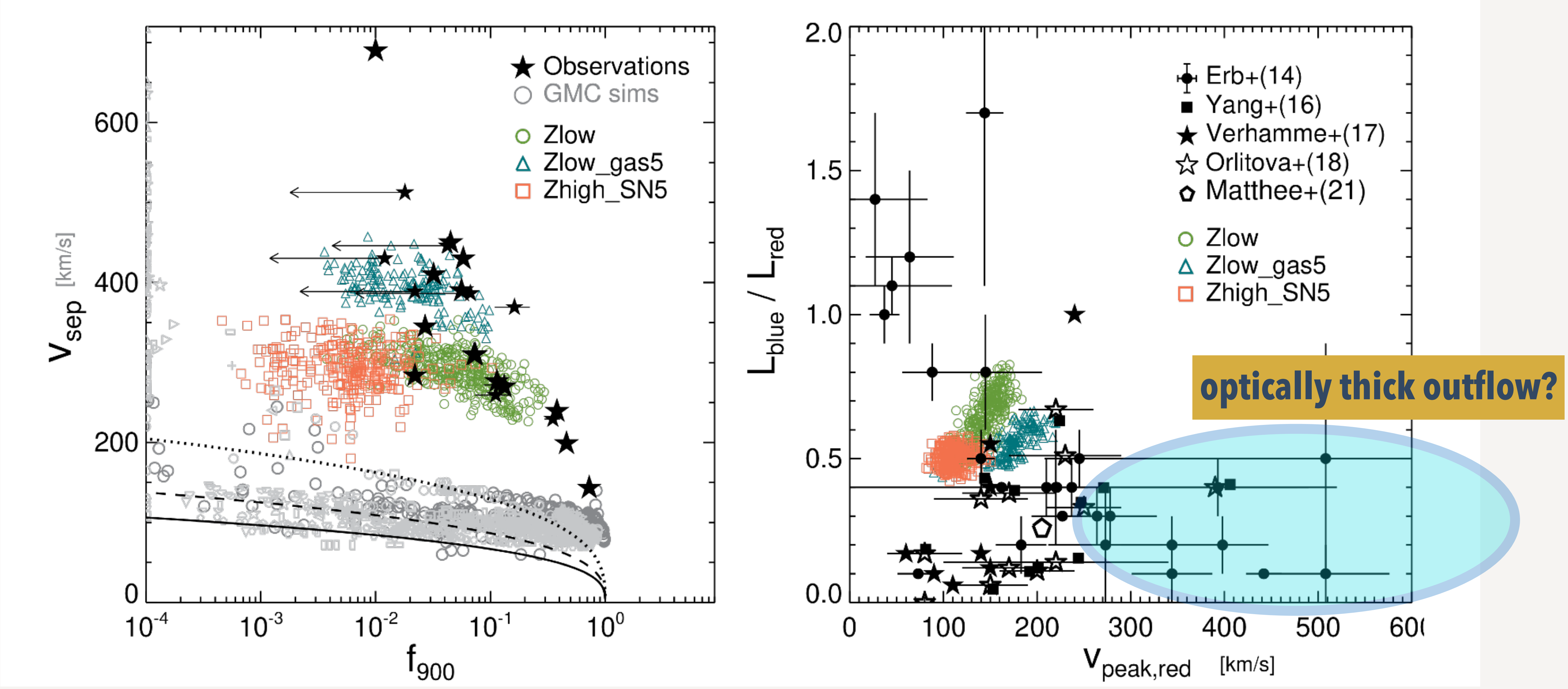



n.b. our samples with a normal gas fraction may be biased towards galaxies with well-defined disk structures

RHD simulations with SN + Radiation Feedback
(max res ~ 4.5 - 9 pc)

# Lyman-a in disk galaxies with different physical properties

Hyunmi Song, Kimm+(in prep)

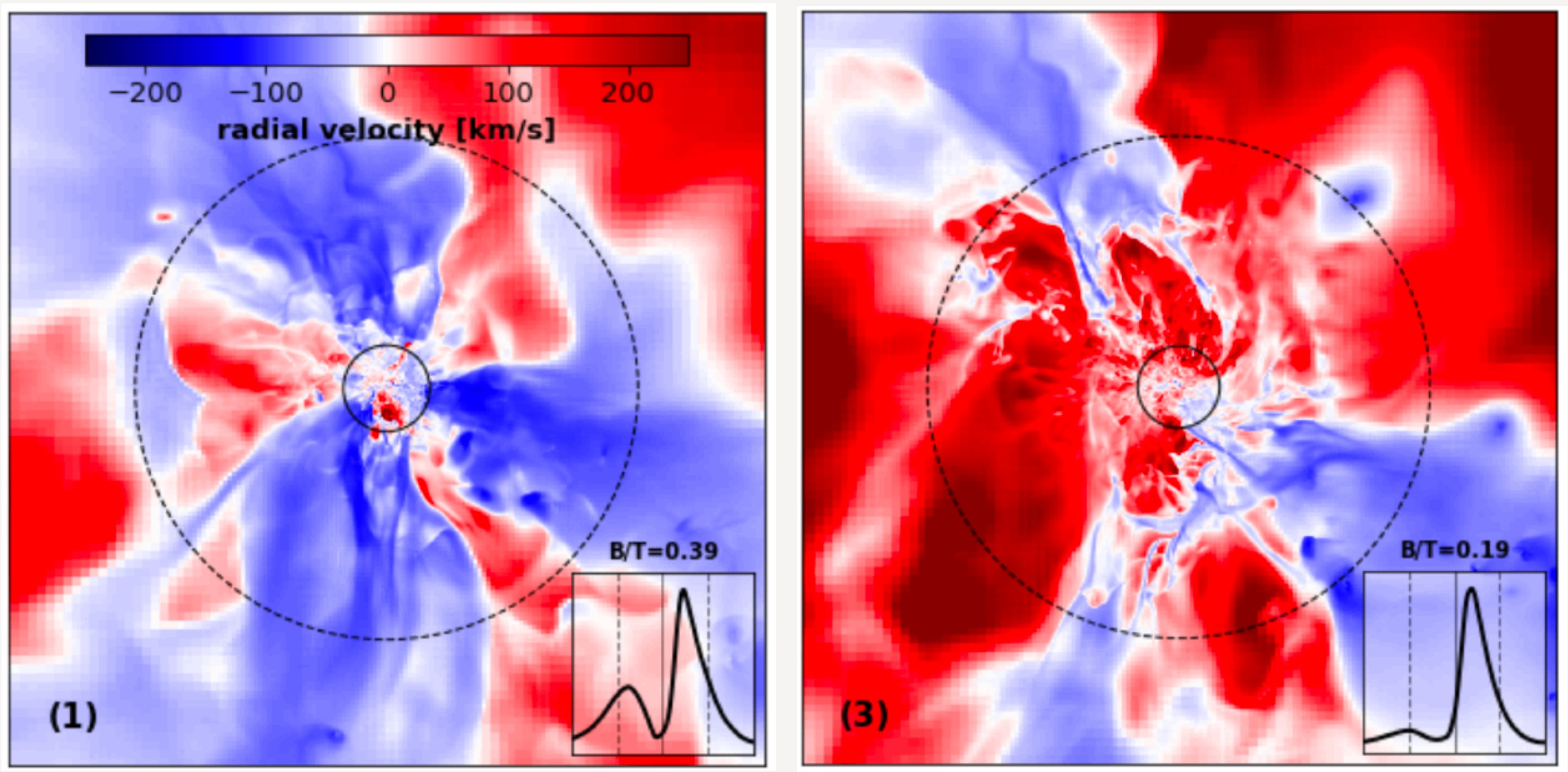



Scattering with the ISM can explain galaxies with $V_{sep}$ < 500 km/s, but we may be still missing galaxies with strong (neutral) outflows

# A galaxy in a cosmological setting

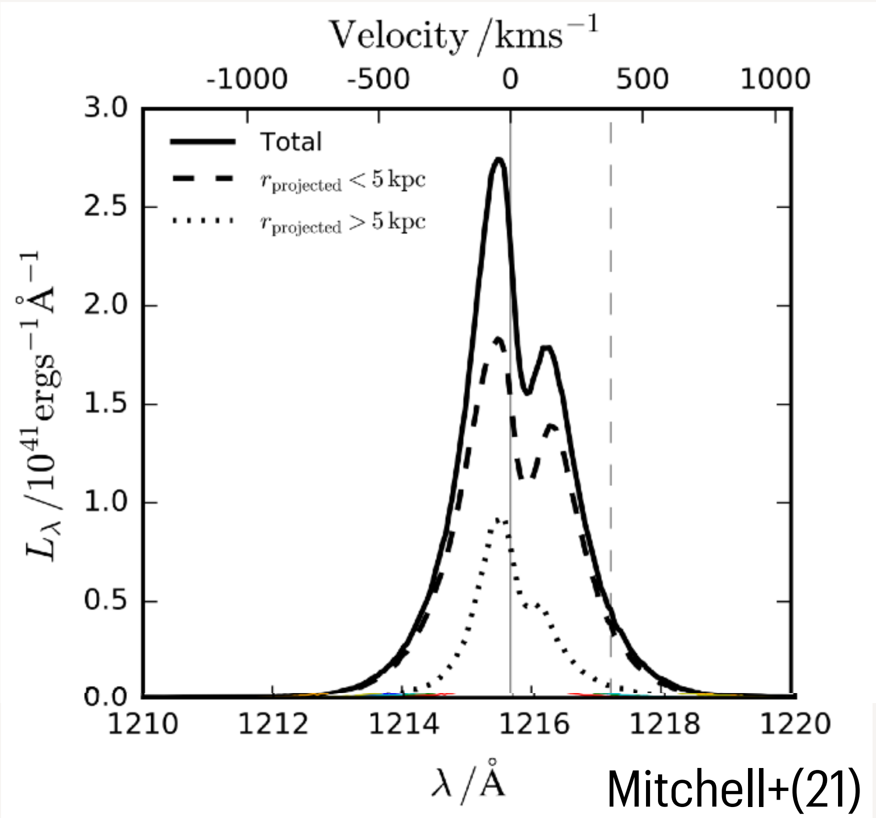
Blaizot, Kimm+(23)

Cosmological RHD simulation of a galaxy in **5x10^10 M_sun DMH at z=3** (max res ~ 15 pc)




same galaxy, different epoch

(Feedback: SN x 4)




Mitchell+(21)

run with weak SN feedback

(n.b. reproduced Lya surface bright profiles!)

Lyman-a is more sensitive to volume-filling outflows

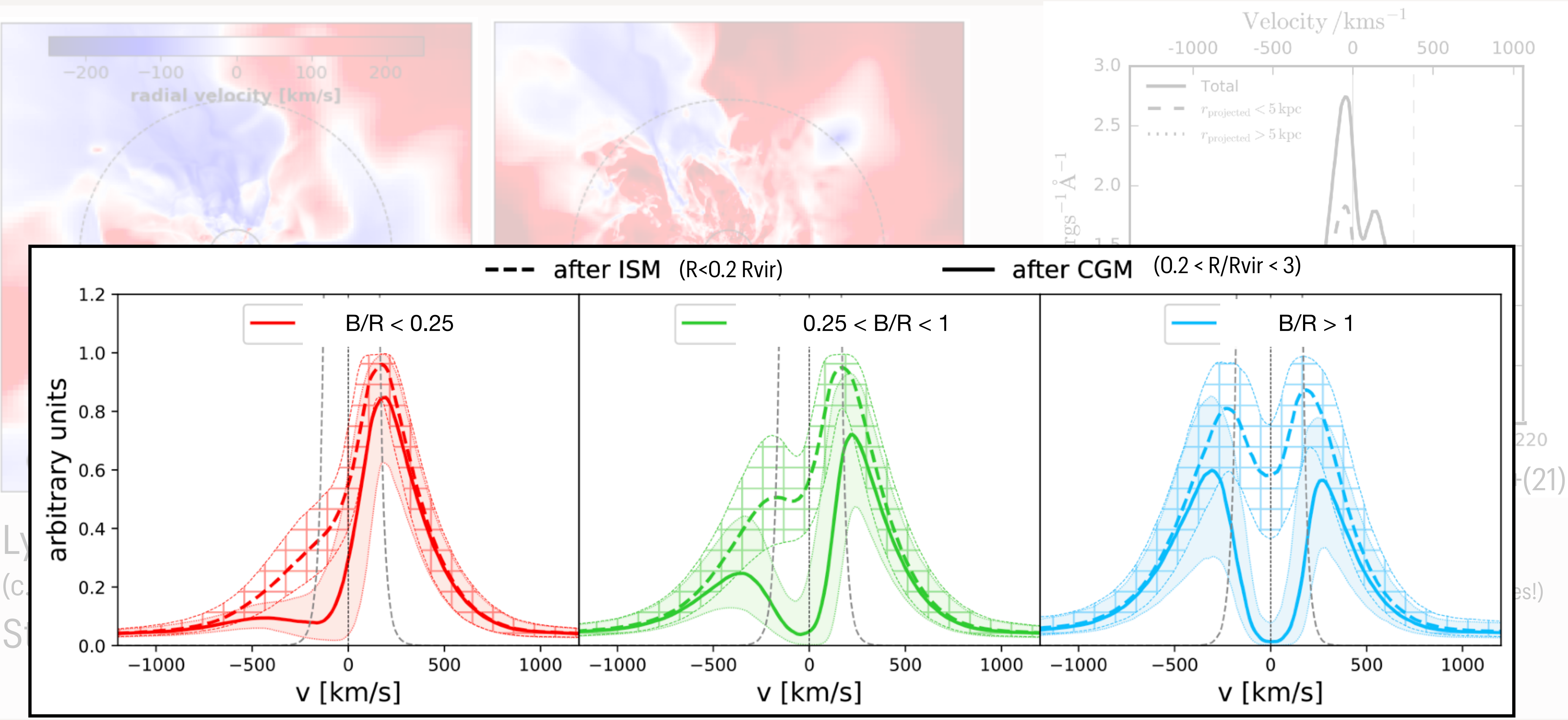
(besides inflow phases are fainter in Lyman-a)

Strong red peak ($L_{blue}$<$L_{red}$) is successfully reproduced

# A galaxy in a cosmological setting

Blaizot, Kimm+(23)

Cosmological RHD simulation of a galaxy in $5 \times 10^{10}$ $M_{sun}$ DMH at z=3

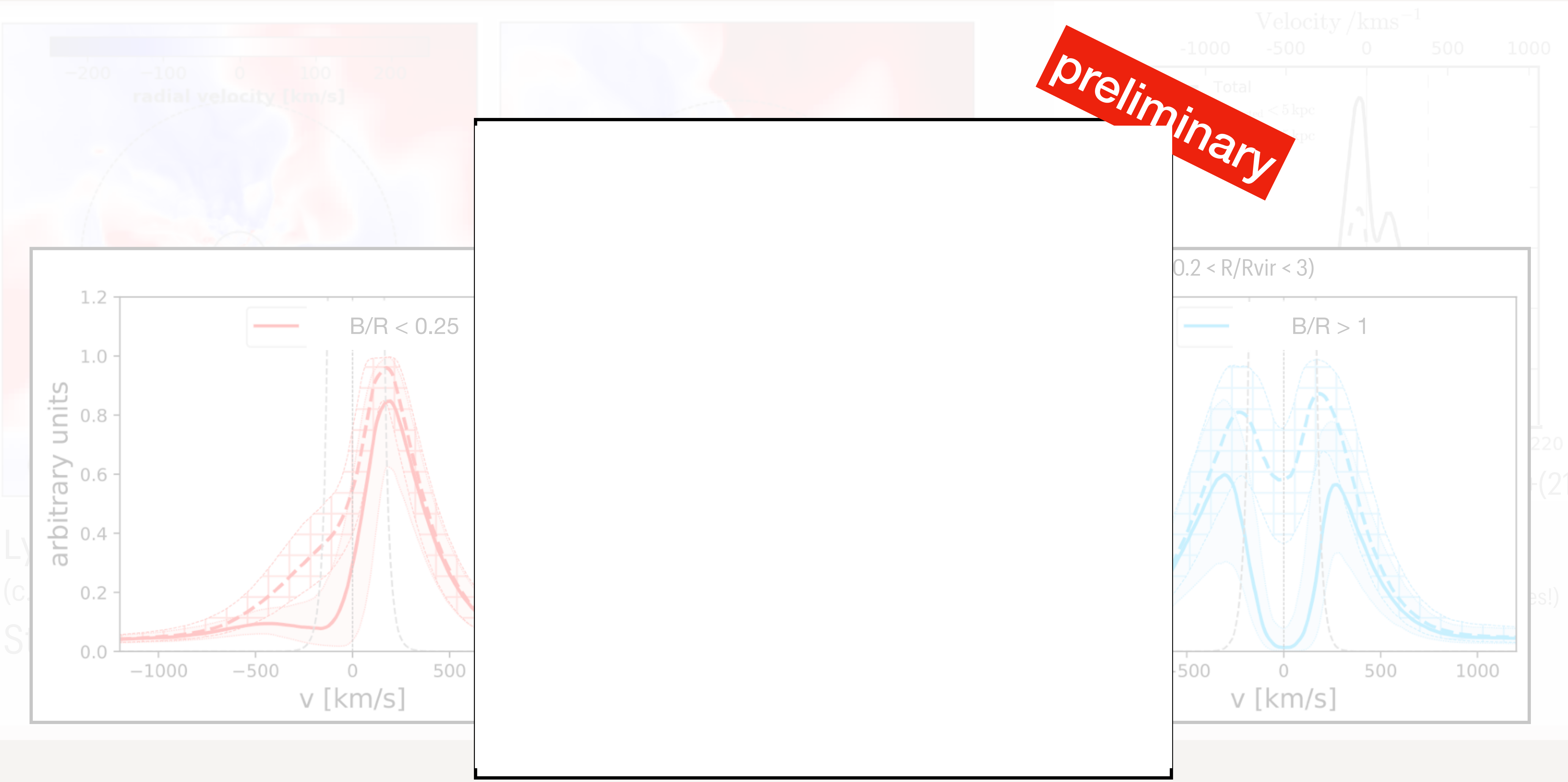



- CGM tends to scatter off Lyman-a from the line of sight, resulting in absorption in the blue spectrum
- $V_{sep}$ seems to be largely determined on ISM scales

# A galaxy in a cosmological setting

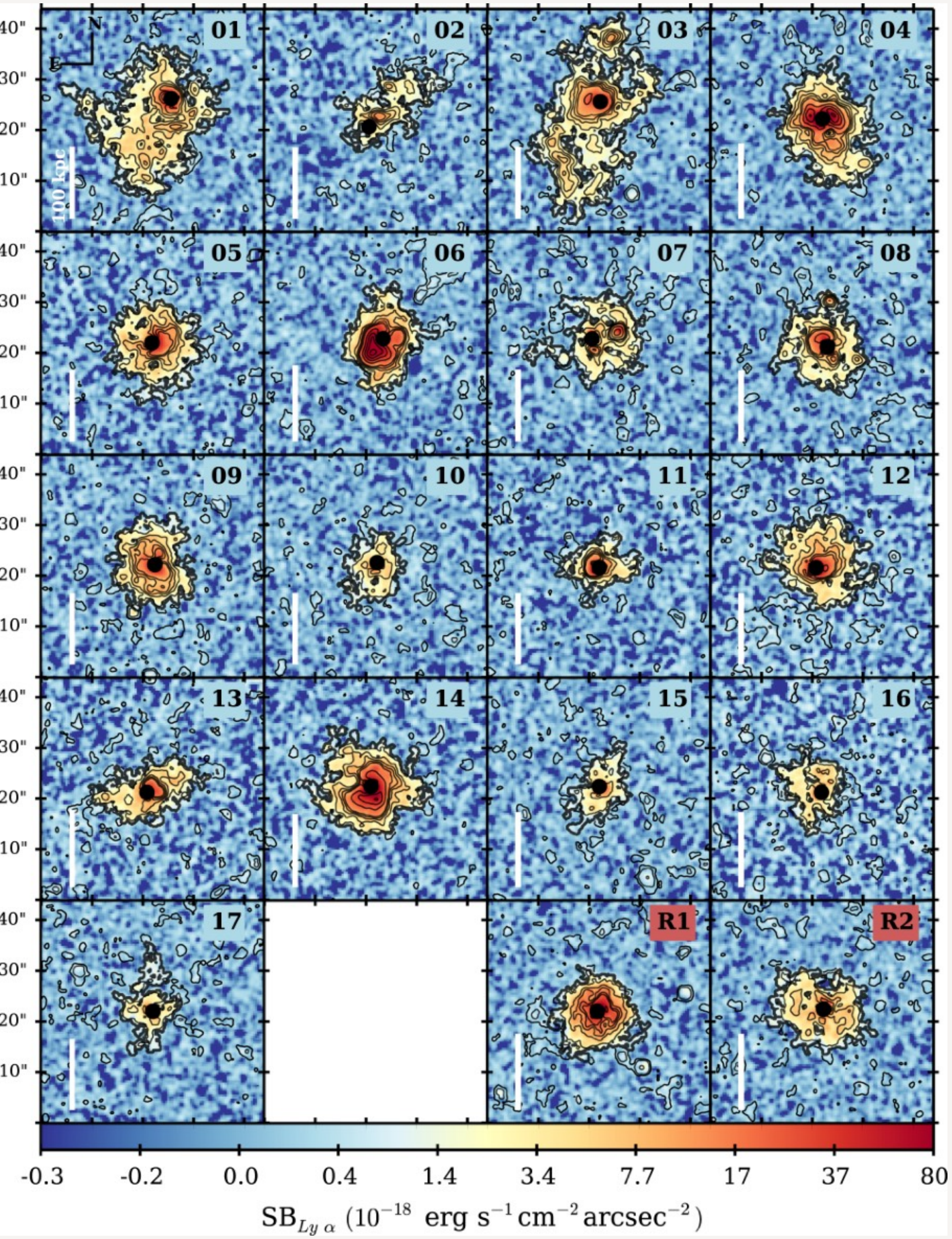
Blaizot, Kimm+(23)

Cosmological RHD simulation of a galaxy in $5 \times 10^{10}$ $M_{sun}$ DMH at z=3




- Need more starburst galaxies in the sample
- May be missing galaxies with strong (neutral) outflows

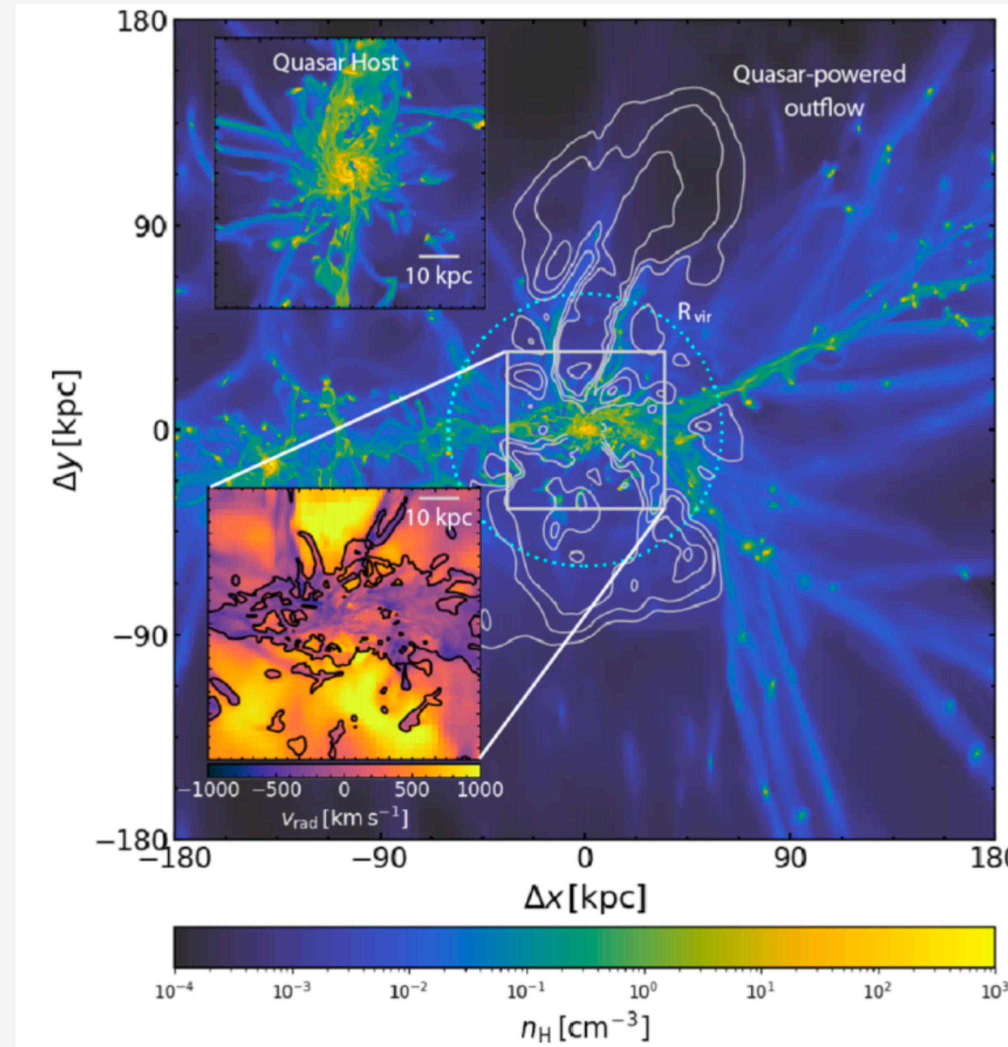
# Lyman-$\alpha$ halo around Quasar

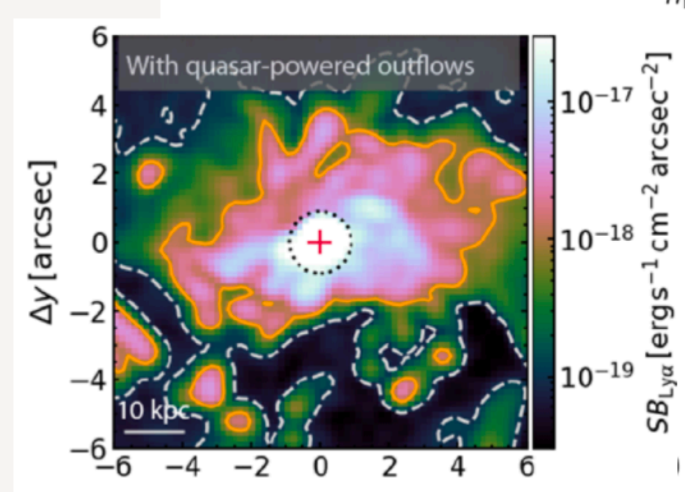



Borisova et al. (2016)

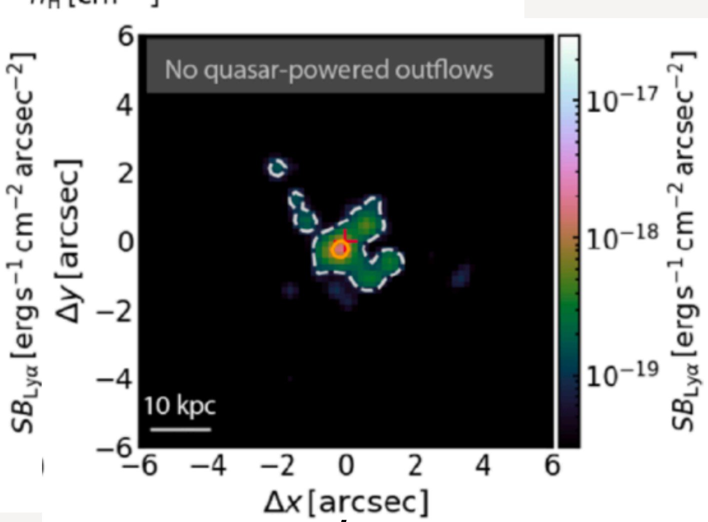
UBIQUITOUS GIANT Ly$\alpha$ NEBULAE AROUND THE BRIGHTEST QUASARS AT $Z \sim 3.5$ REVEALED WITH MUSE

Costa, Kimm+(22)




w/ AGN




w/o AGN

# Summary

**Lyman-a from GMC**

- Lyman-a in GMCs is mostly formed during the disruption phase, and its evolution in $V_{sep}$-$f_{900}$ plane is largely similar regardless of GMC properties
- Scattering is **not sufficient enough to explain the double-peak profile** observed in star-forming galaxies : needs more scattering

**Lyman-a from GMC**

- The presence of the ISM increases $V_{\rm sep} \sim 400\,{\rm km/s}$, but still galaxies with a large $V_{\rm sep} > 500\,{\rm km/s}$ are not reproduced
- The CGM acts as a screen and scatter off the blue photons, leading to $L_{blue}/L_{red} << 1$
- Seems to be lacking **volume-filling neutral outflows in the models with SN boost**

**Future direction**

- Need to examine simulations with cosmic rays and other physics