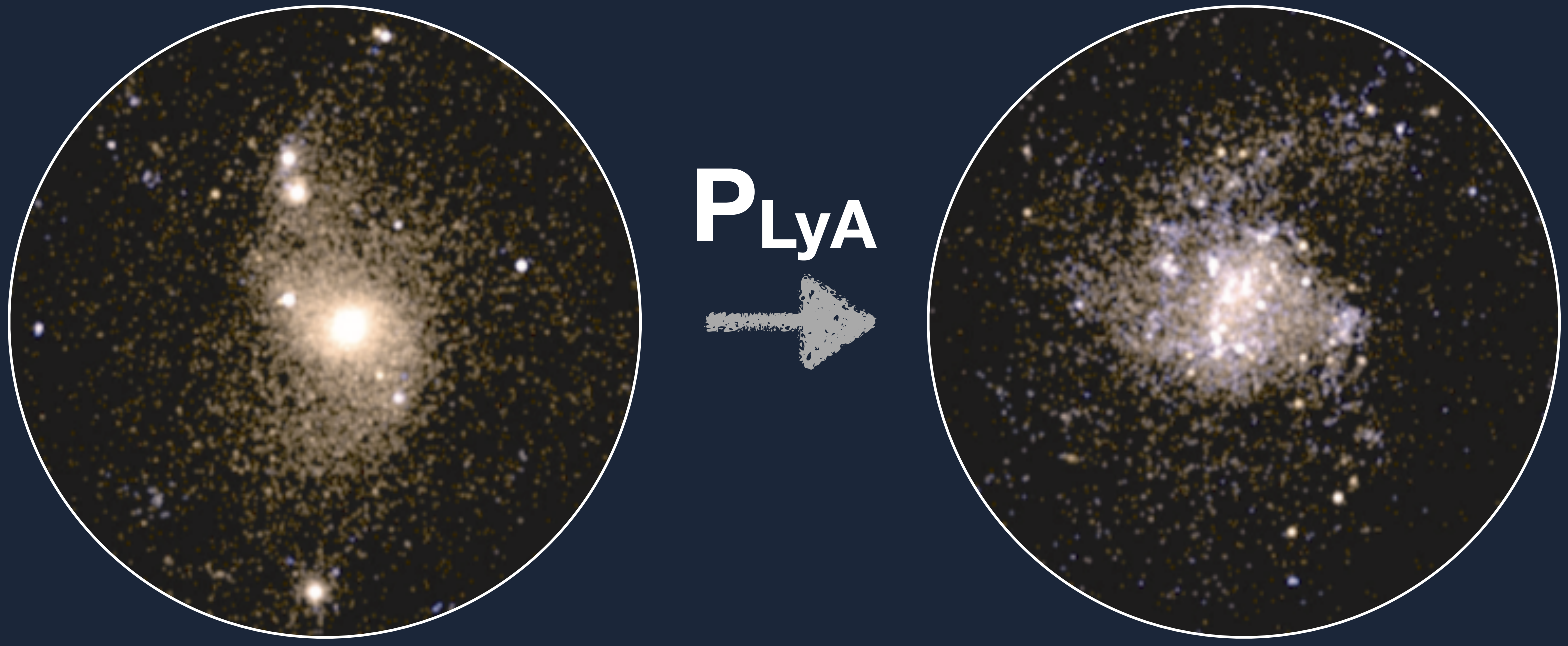
IMPACT OF LYMAN-α PRESSURE ON METAL-POOR DWARF GALAXIES

Taysun Kimm (Yonsei University)



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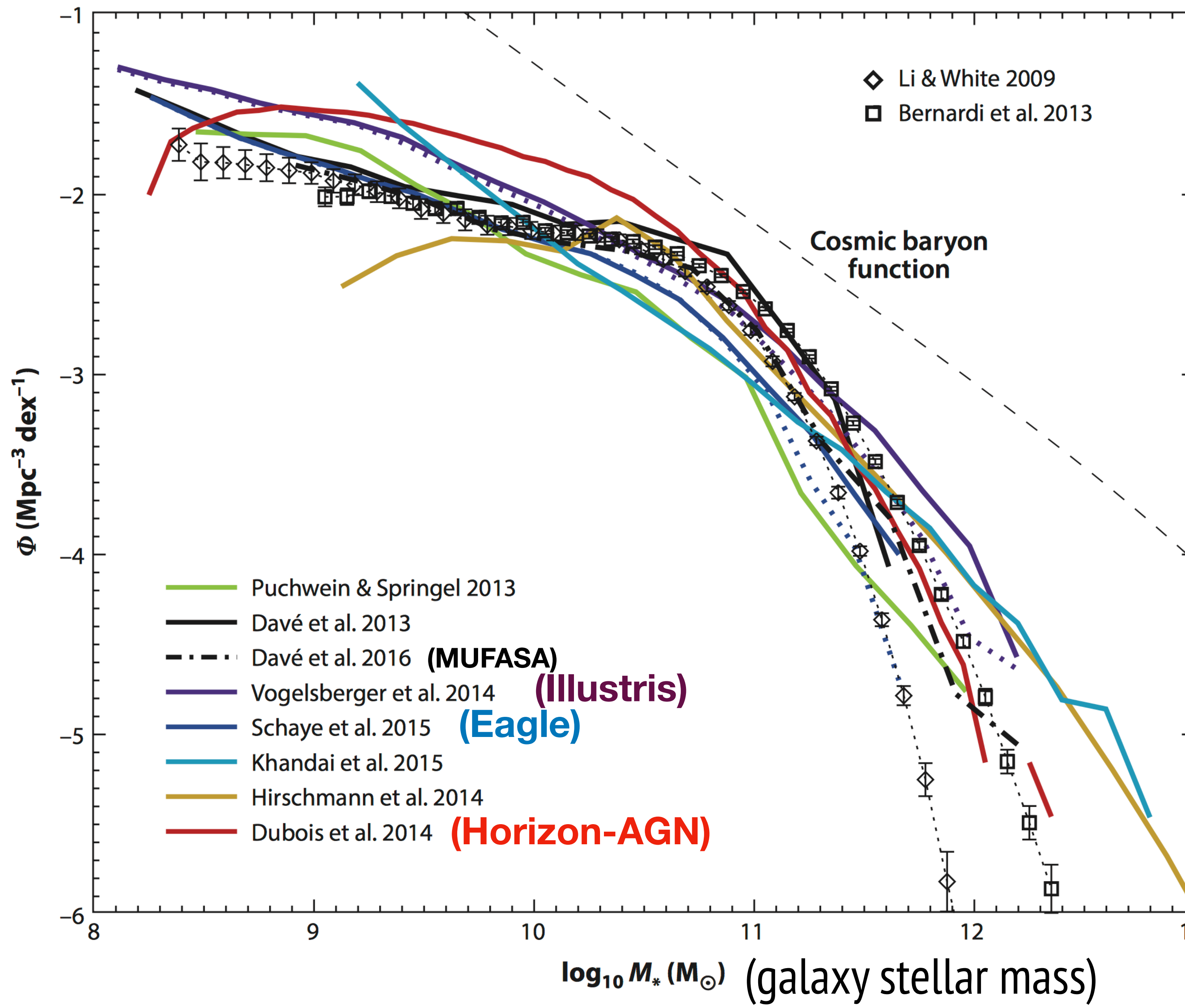
Thibault **Garel** LYON
Leo **Michel-Dansac** LYON
Harley **Katz** OXFORD
Romain **Teyssier** ZURICH

Galaxy Formation

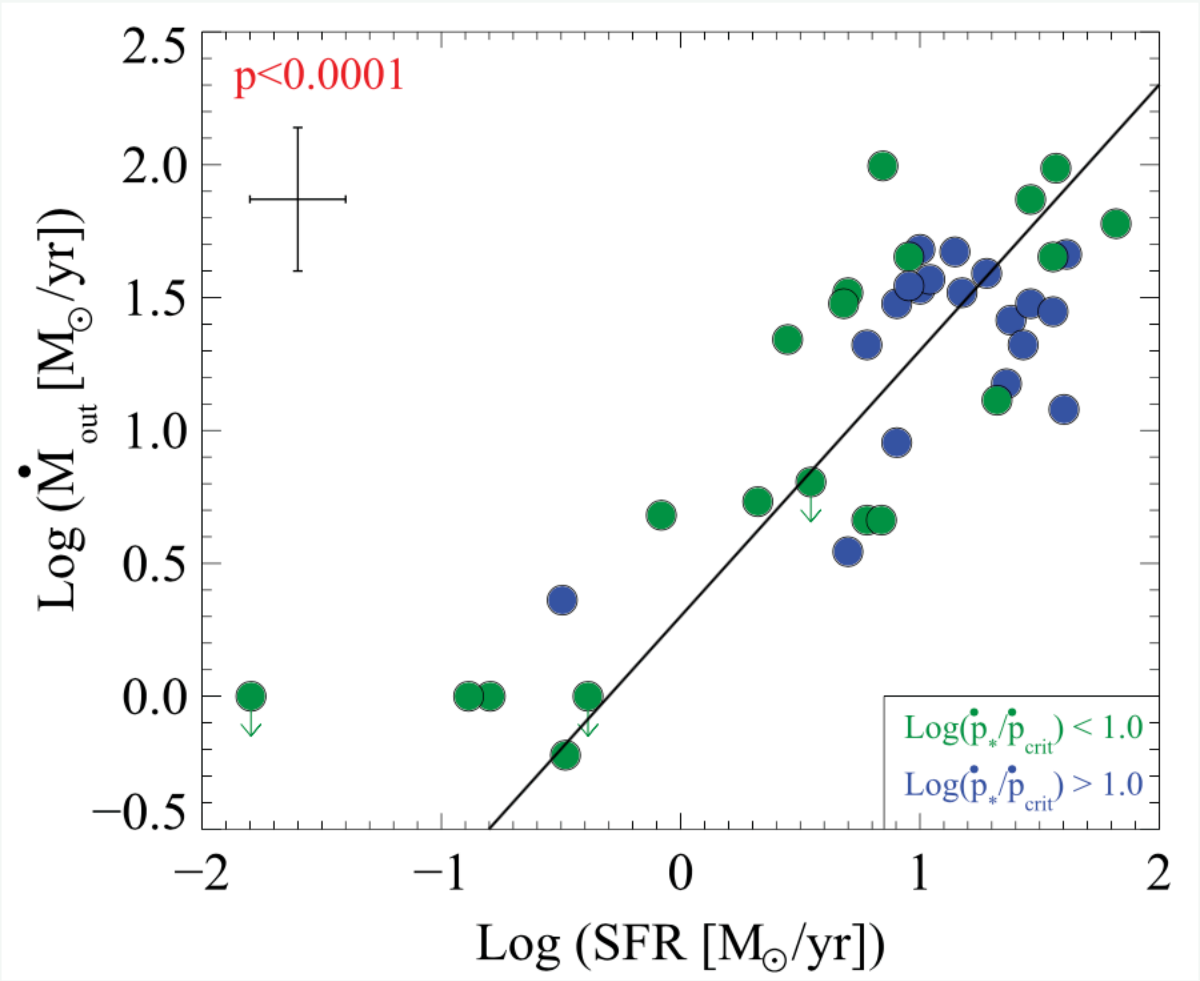
One of the most important goals of galaxy formation theory is to understand the suppression of star formation

Enough to control it? or do we need to actually blow gas out from galaxies?

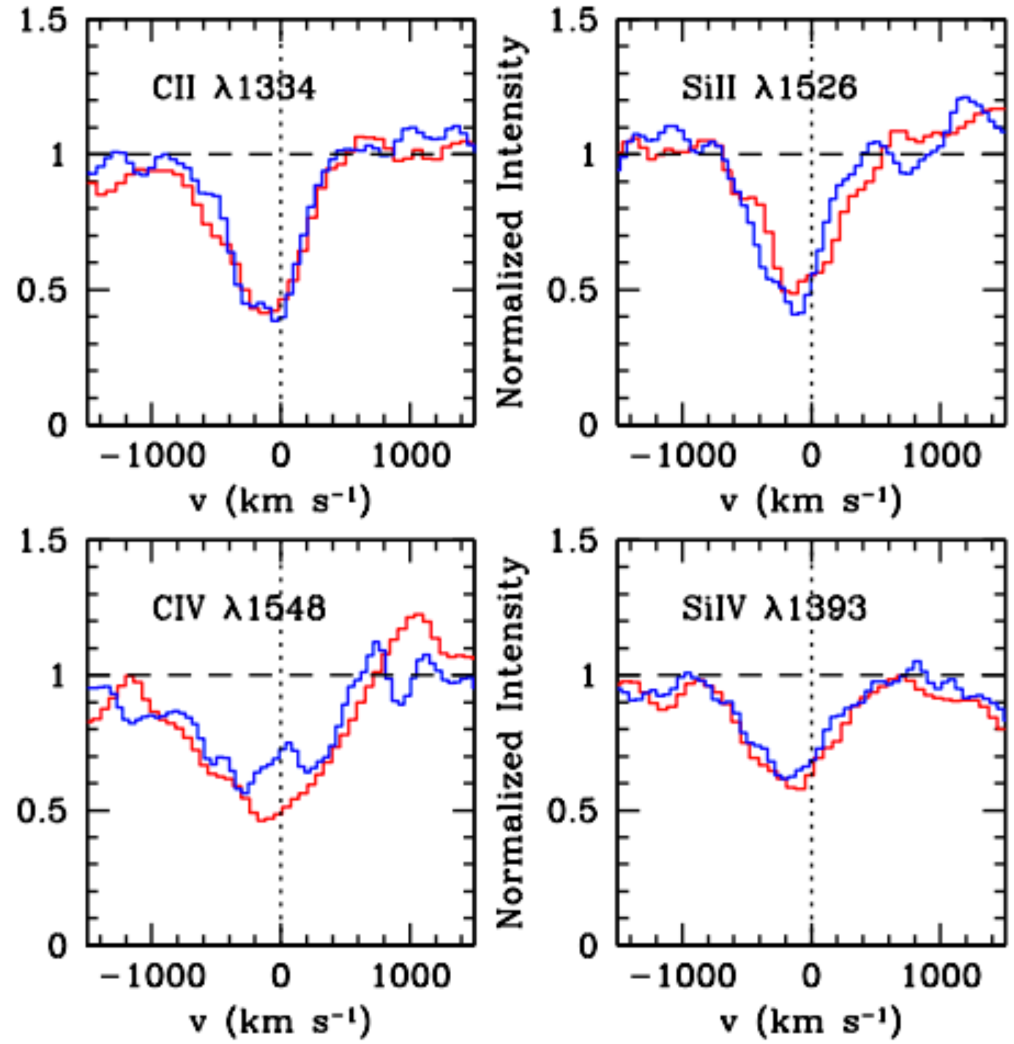


Naab & Ostriker (2017, ARAA)

Large mass loading (Heckman+15; z~0 starbursts)



Ubiquitous **Outflows** in LBGs at z~2 (Steidel+10)



Strong galactic outflows

Star forming galaxies show galactic outflows ubiquitously.
Question is how do they do that?

Stellar Feedback Processes

Stellar winds

$$\left\langle \frac{p_{\rm wind}}{M} \right\rangle \sim 20 - 100\,{\rm km/s}$$

(e.g. Leitherer et al. 1999)

Direct Radiation Force

$$\left\langle \frac{p_{\rm rad}}{M} \right\rangle = \int \frac{L_{\rm UV}}{c} dt \sim 180\,{\rm km/s}$$

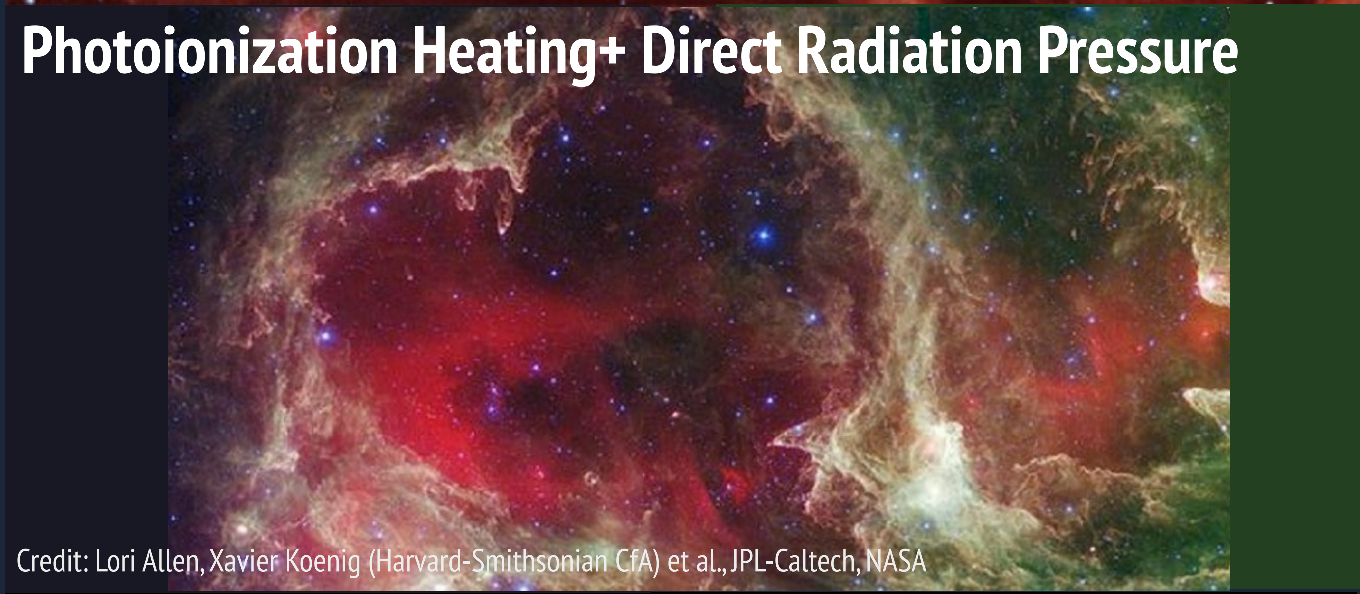
Photoionization Heating

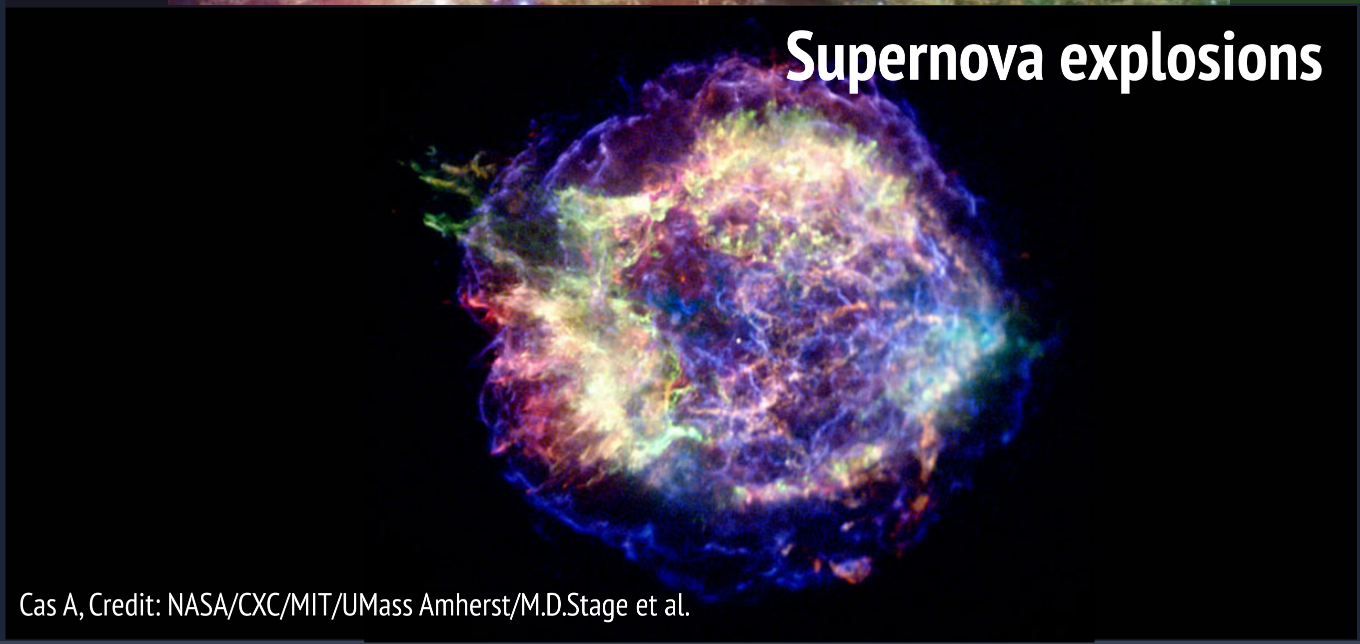
$$\left\langle \frac{p_{\rm HII}}{M} \right\rangle = M_{\rm sh}\dot{r}_i = 10^5\,{\rm km/s}\,M_{\odot} n_2^{-1/7} T_{i,4}^{-8/7} S_{49}^{4/7} t_6^{9/7}$$

$$\sim 3000\,{\rm km/s}$$

Supernova (final)

$$\left\langle \frac{p_{\rm SN}}{M} \right\rangle \sim 3000\,{\rm km/s}\ n_H^{-2/14}\, Z^{-0.14}\, E_{51}^{15/16}$$



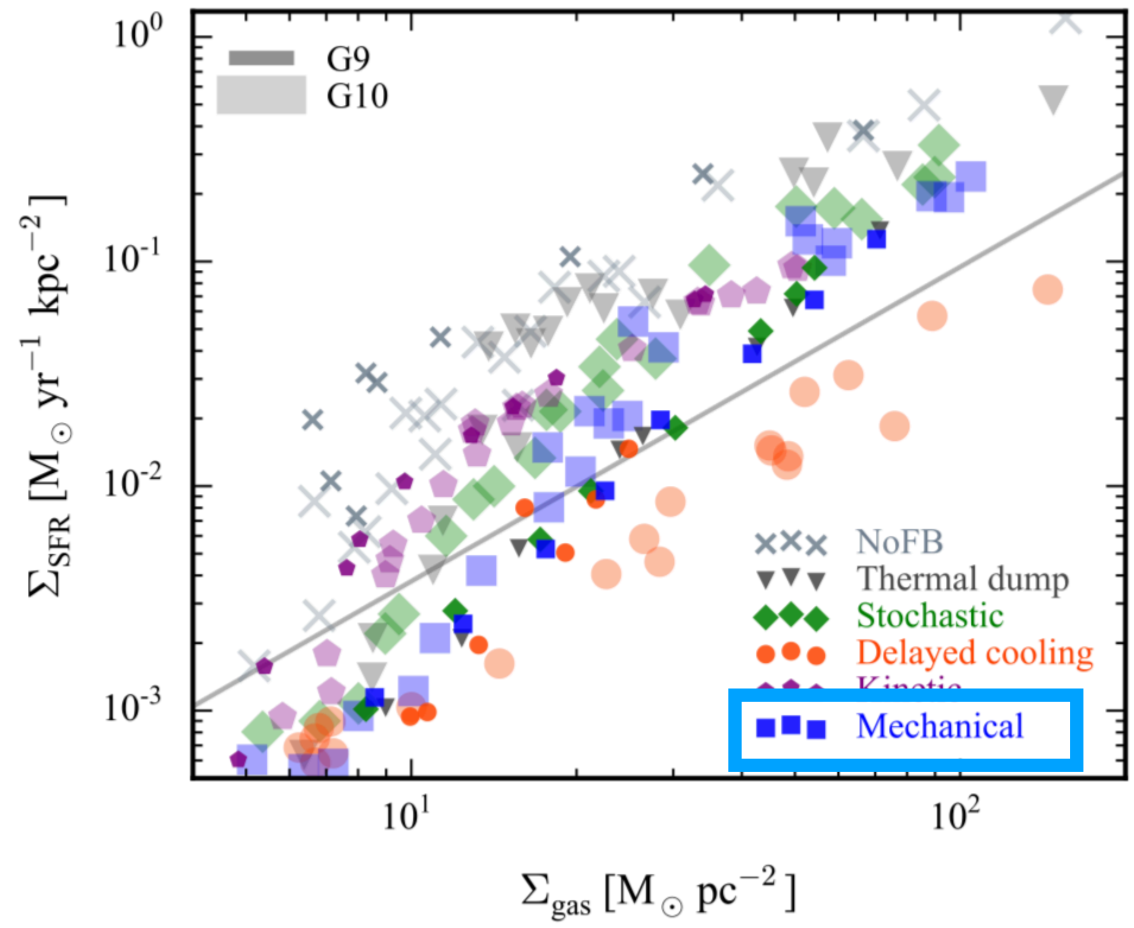


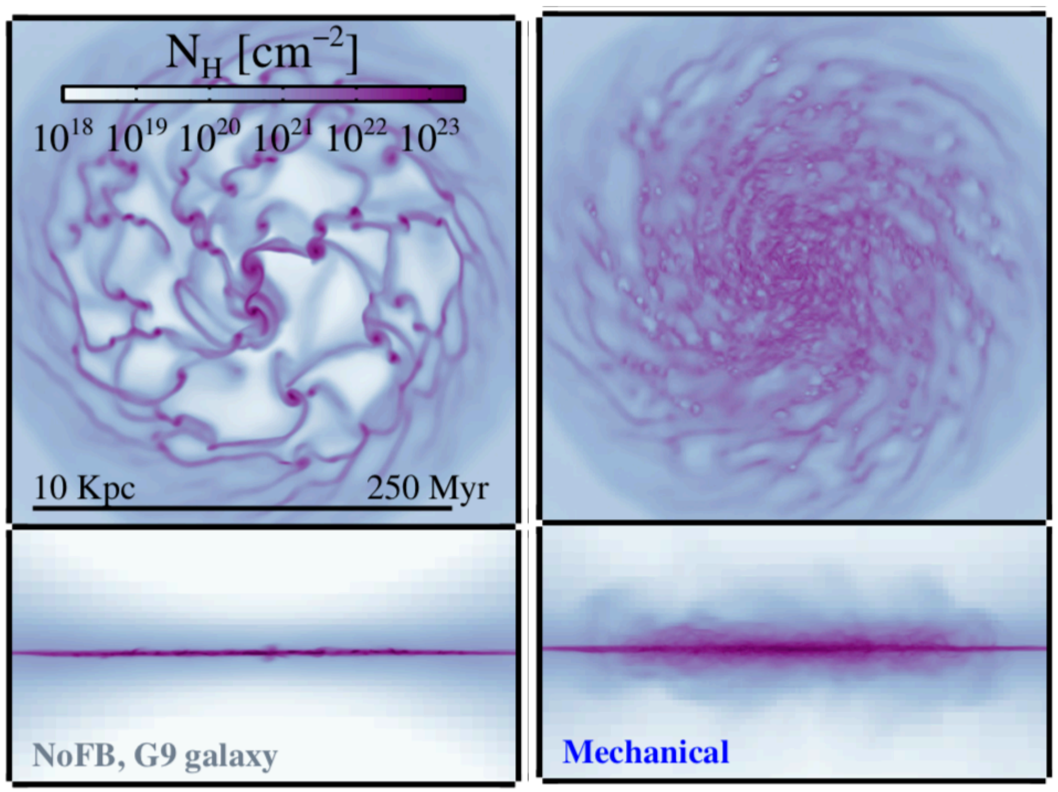
SN feedback: not enough

- cannot control star formation in dense regions

$$p_{\rm SN} \sim 3\times10^5\,{\rm km/s}\ M_\odot\, n_H^{-2/17}\, E_{51}^{16/17} Z^{-0.14}$$

Rosdahl, TK+(17)





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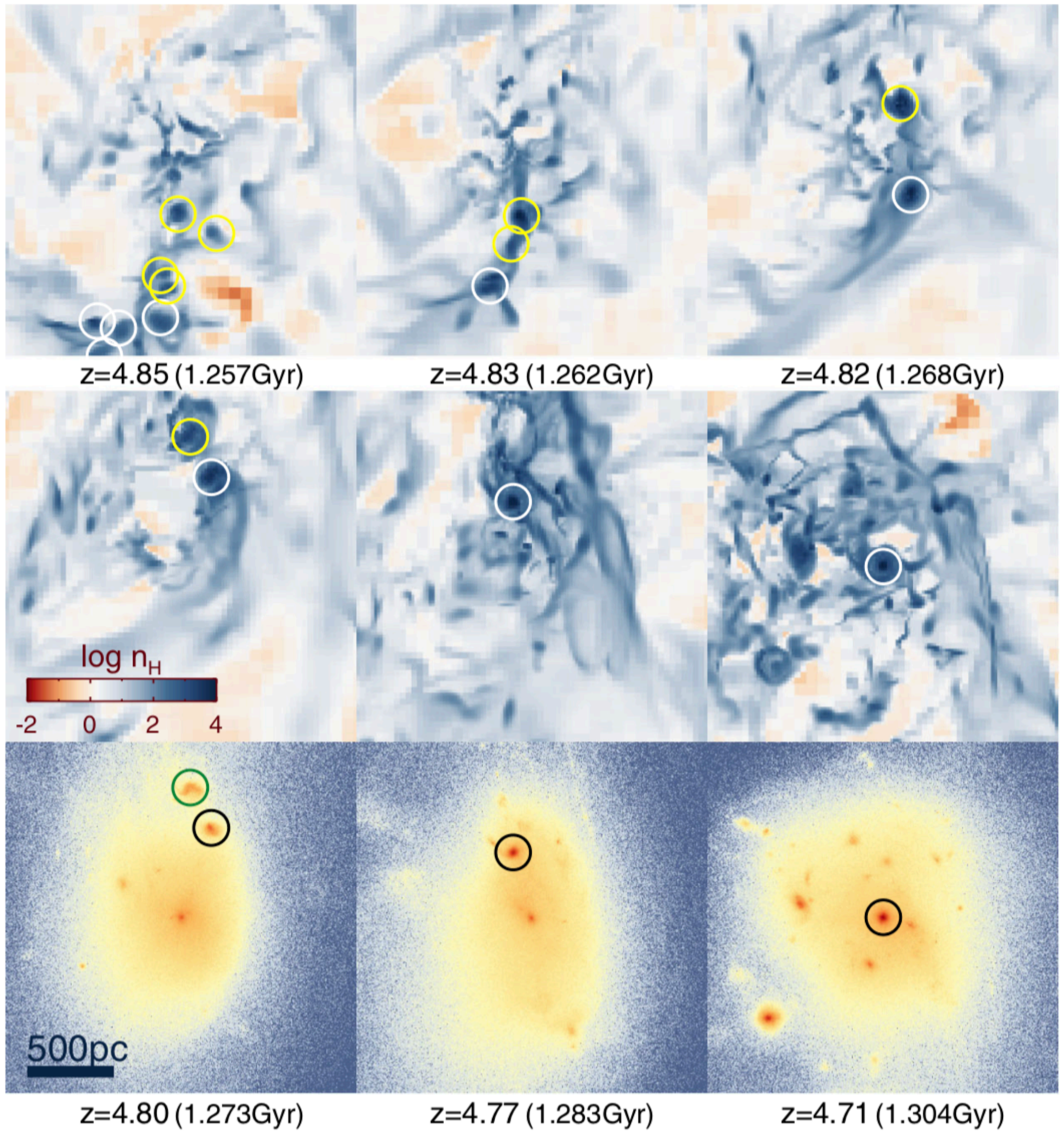
- enormous RAM pressure from accretion onto the galaxy centre

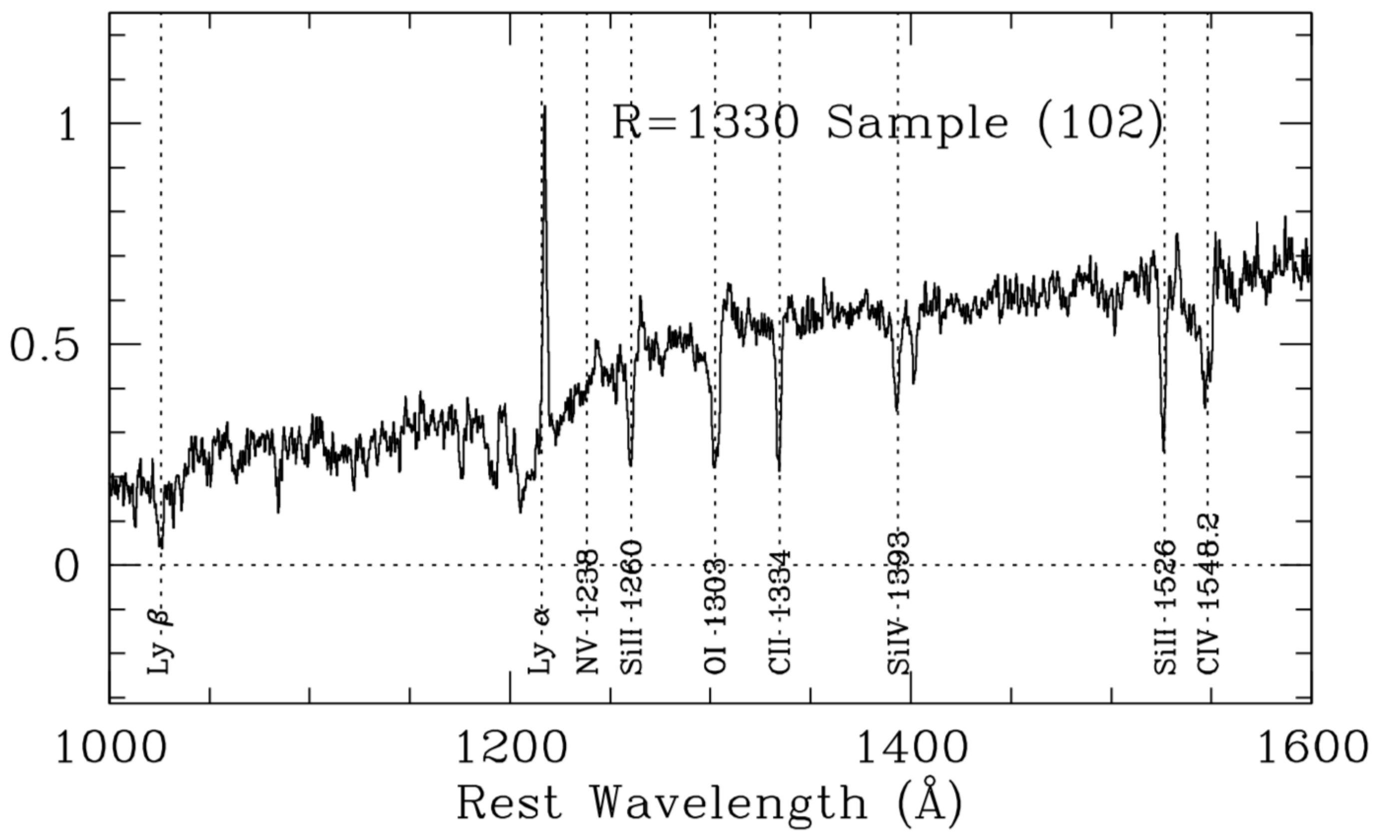
Q: How do we destroy the dense clumps?
Maybe IR pressure? -> optical depth is not very large though…

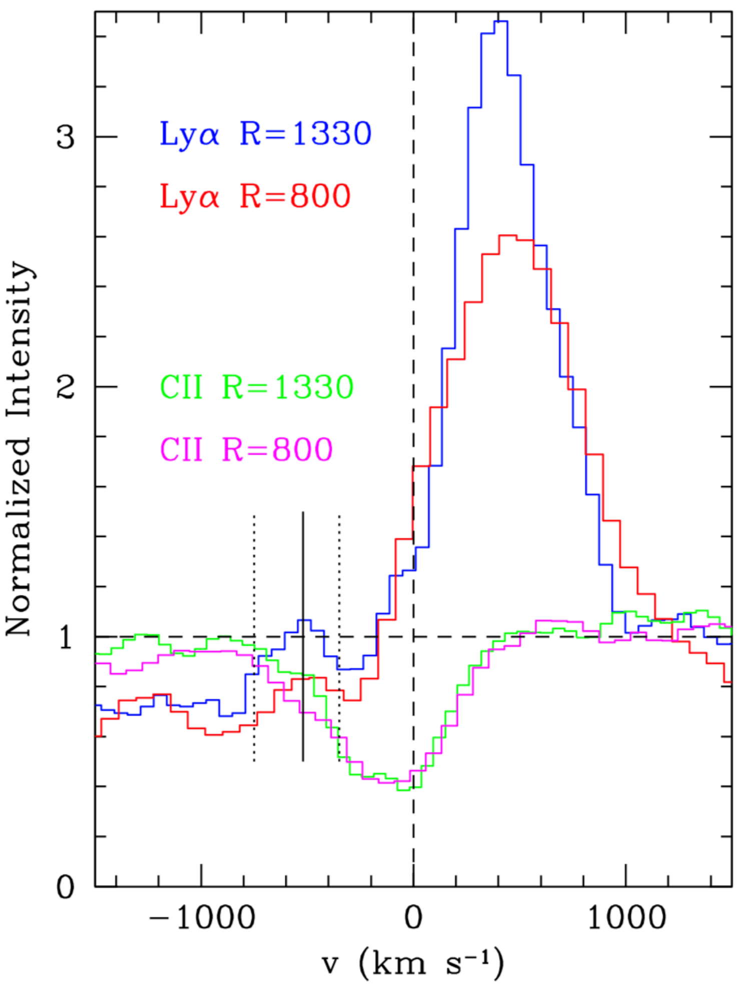
TK, Cen et al. (2015)



Onset of the **over-cooling problem** in a cosmological simulation

Composite spectrum of z~2 LBGs (Steidel+10)

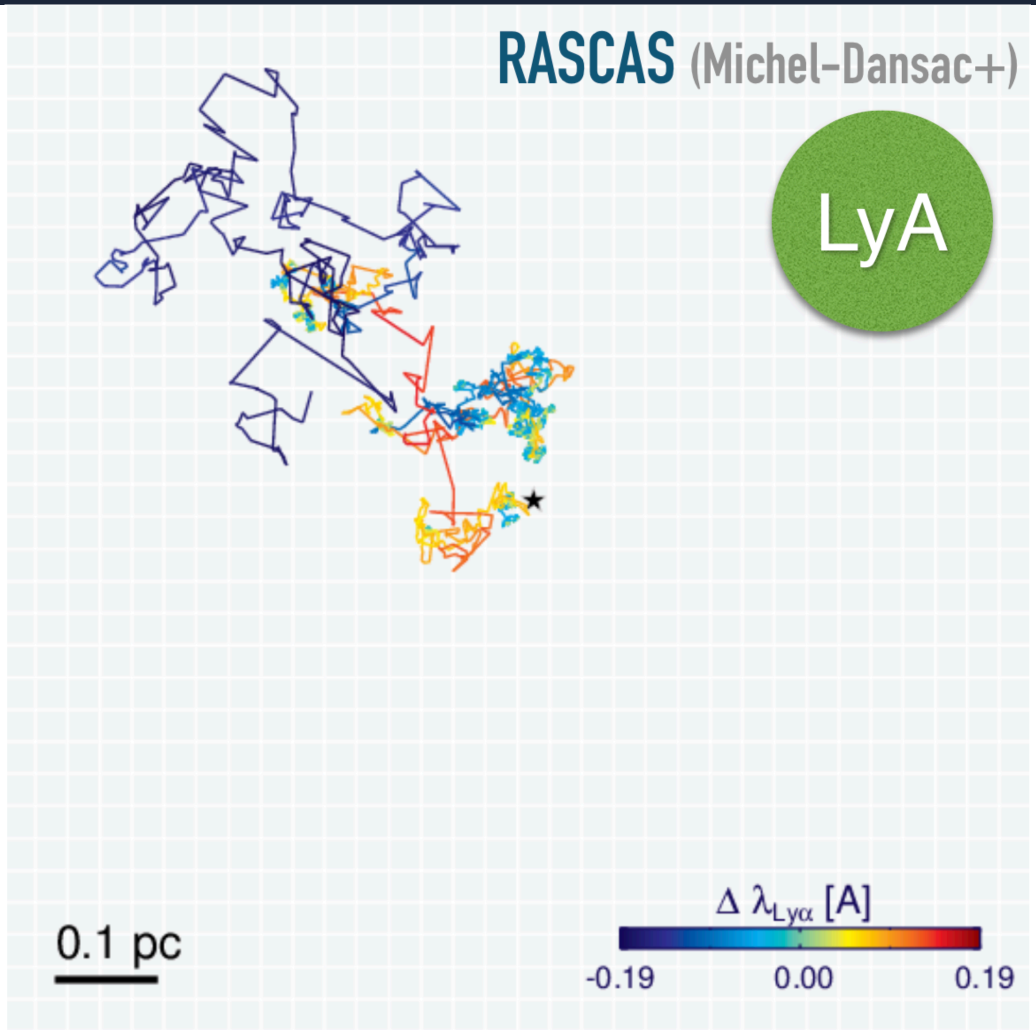




Lyman alpha profile of LBGs

Large velocity offset from the line centre means that

Lya photons experience a large number of scattering events



RASCAS: Monte-Carlo Lyman alpha Radiative Transfer code

Momentum transfer $$\Delta\vec{p} = \frac{h_p}{c}\left(\nu_{\rm in}\hat{n}_{\rm in} - \nu_{\rm out}\hat{n}_{out}\right)$$

Multiplication factor $$F_{Ly\alpha} = M_{\rm F}\frac{L_{Ly\alpha}}{c}$$

See also Dijkstra & Loeb (08), Smith et al. (16)

Scattering of LyA photons transfers momentum to the surroundings

Why do we care?

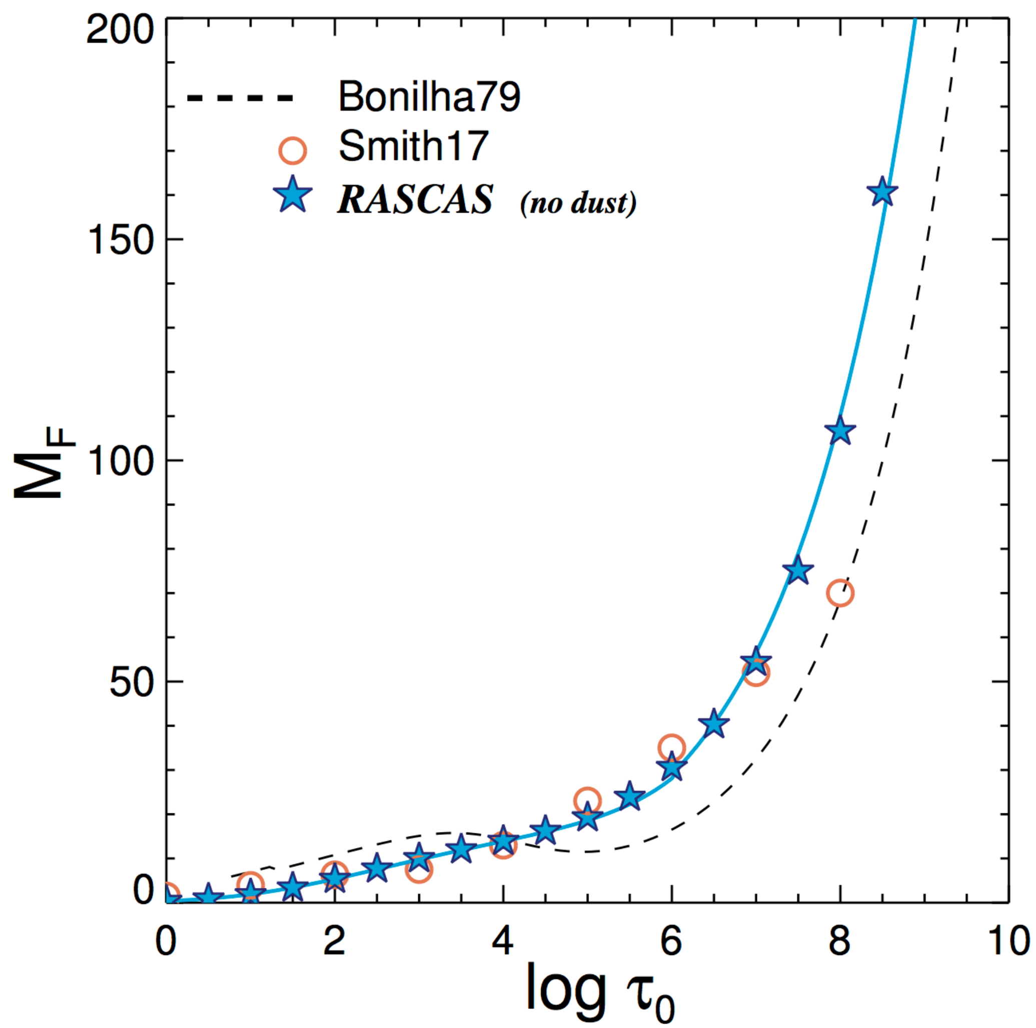
Because Optical Depth to Lya Is Huge!

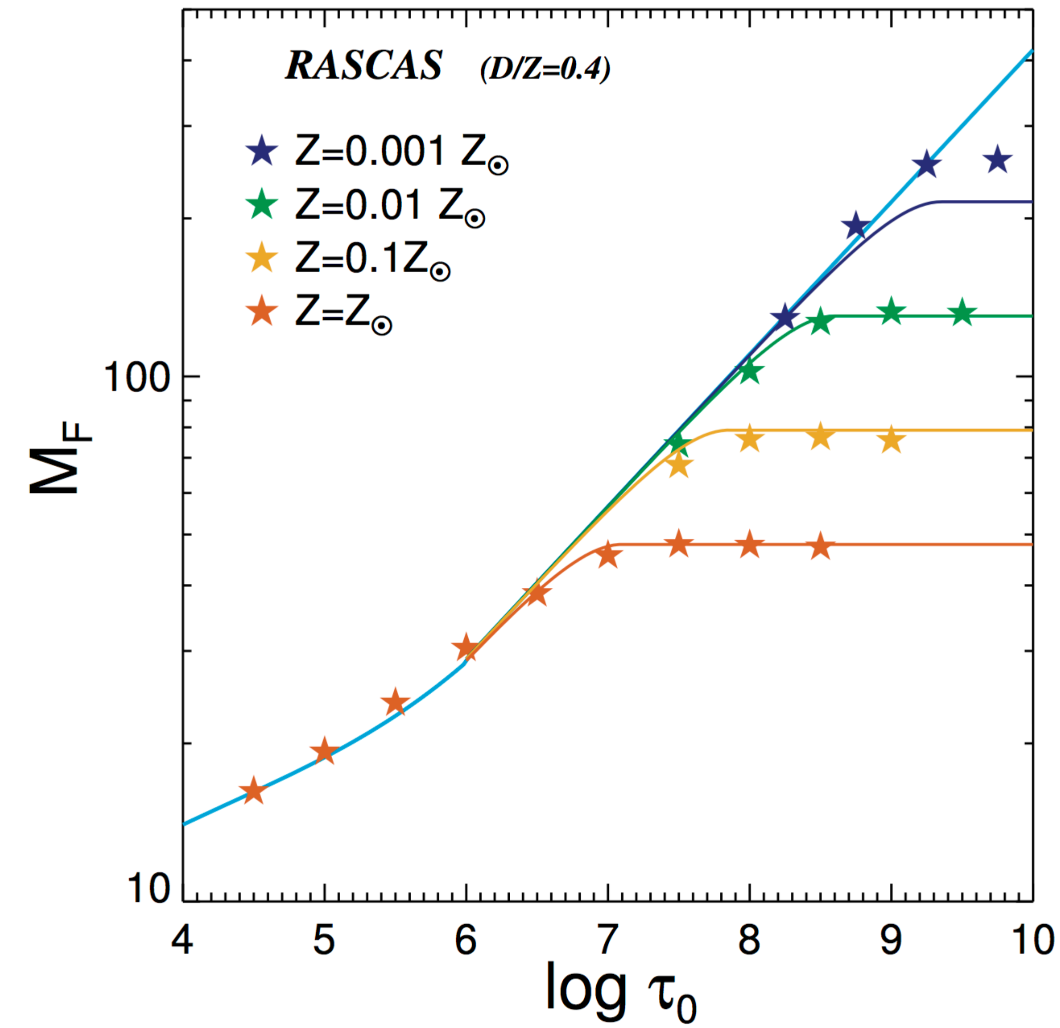
(~10^7-10^{10})

$$\tau_{\rm Ly\alpha} = \left(\frac{N_{\rm HI}}{2\times10^{13}\,{\rm cm^{-2}}}\right)\left(\frac{T}{10^4\,{\rm K}}\right)^{-1/2}$$

Dust-free

Dusty





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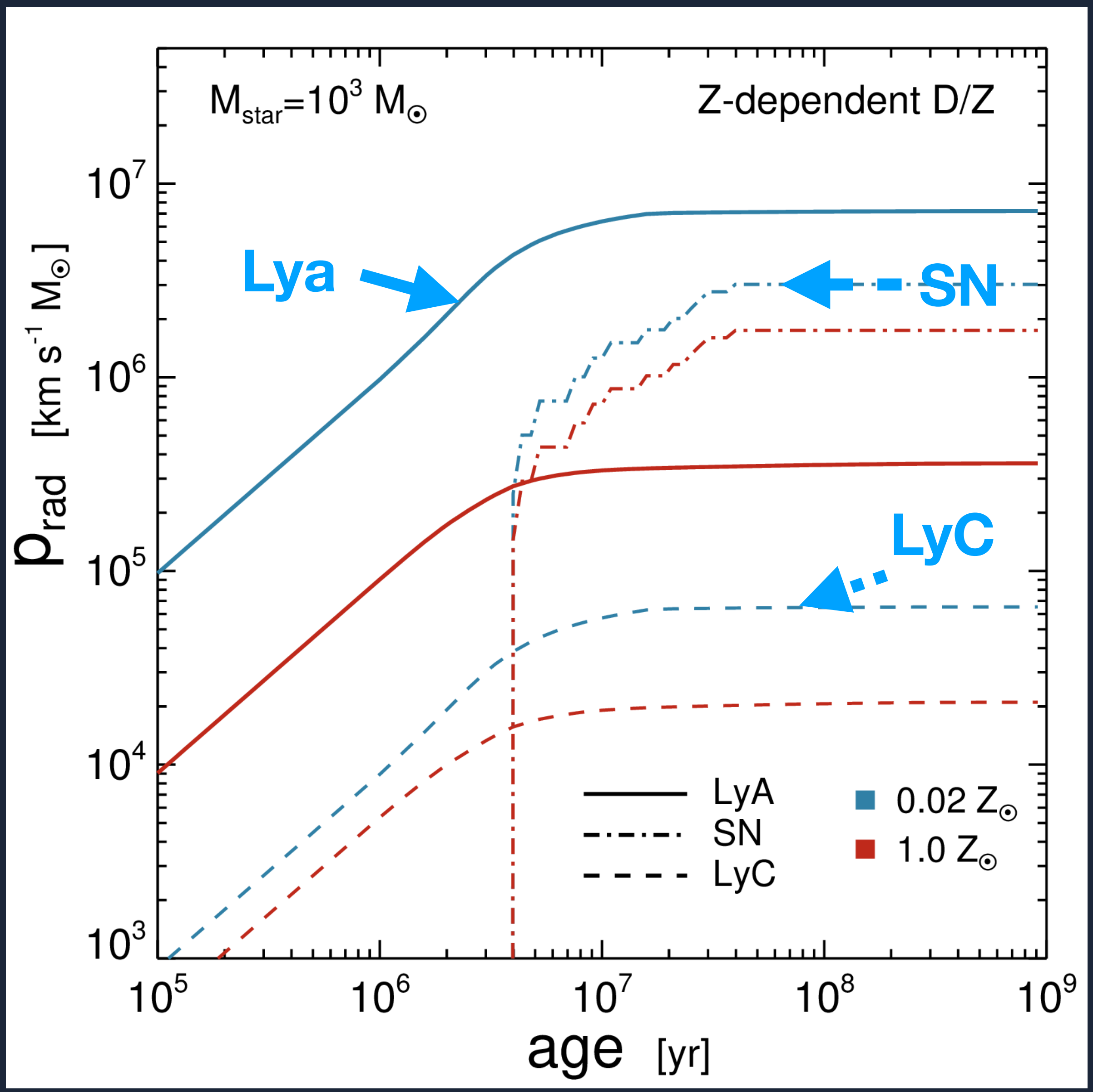
Momentum budget from Lya pressure



(assuming $n_{H,bg}$ = 100 cm^{-3})

Photo-ionization heating

$$n_{\rm H,ion} T_{\rm ion} = n_{\rm H,0} T_0$$

$$r_{\rm PH} \approx 26\,{\rm pc} \left(\frac{m_{\rm star}}{10^3\,{\rm M_\odot}}\right)^{1/3} \left(\frac{P/k_{\rm B}}{10^5\,{\rm cm^{-3}\,K}}\right)^{-3/2} \left(\frac{T_{\rm ion}}{10^4\,{\rm K}}\right)^{2/3}$$

Lyman alpha pressure

$$n_{\rm H} k_B T = \frac{M_F L_\alpha}{4\pi r_\alpha^2 c}$$

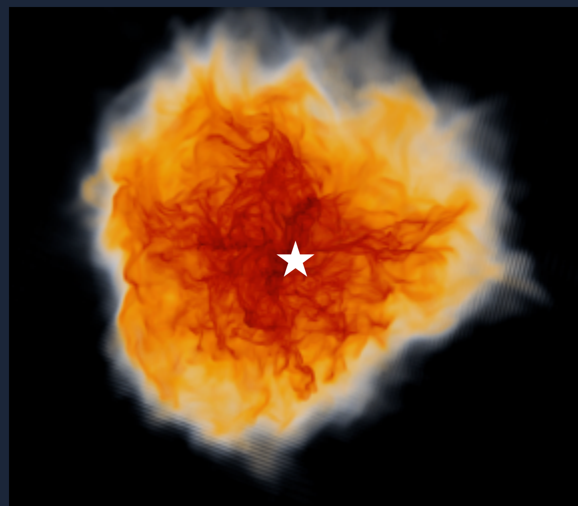
$$r_\alpha = 37\,{\rm pc} \left(\frac{M_{\rm F}}{100}\right)^{1/2} \left(\frac{m_{\rm star}}{10^3\,{\rm M_\odot}}\right)^{1/2} \left(\frac{P/k_{\rm B}}{10^5\,{\rm cm^{-3}\,K}}\right)^{-1/2}$$

- The momentum from Lya is comparable or more significant than that of SNe
- Lya pressure is advantageous from a computational viewpoint as well

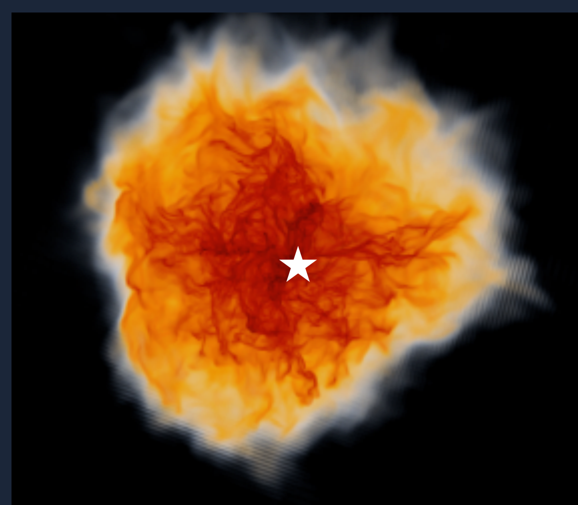
RHD sims with limited res

(i.e. Stromgren sphere unresolved)

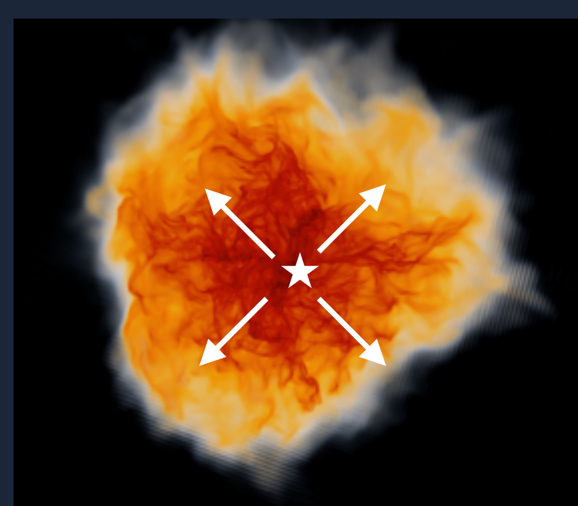
t~0 Myr



t<3 Myr



t>3 Myr



w/ strong LyA feedback

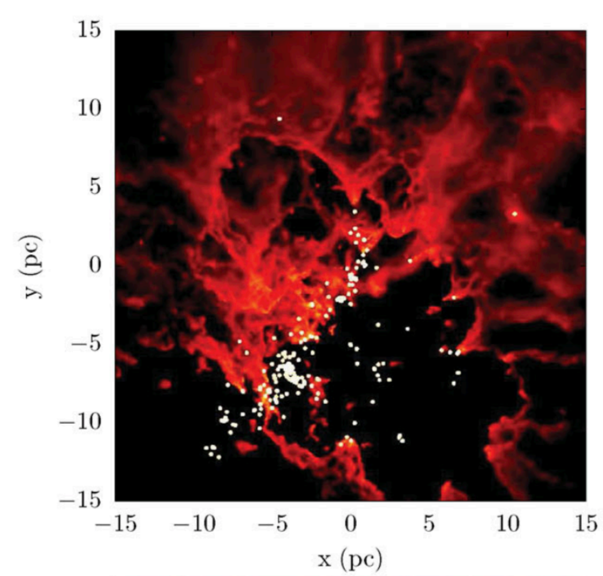
initially molecular

1. Lyman-Werner: H_2 -> HI

t < 1 Myr: Direct radiation pressure due to UV and optical + Lya feedback

t ~ 1 Myr: Photo-ionization heating

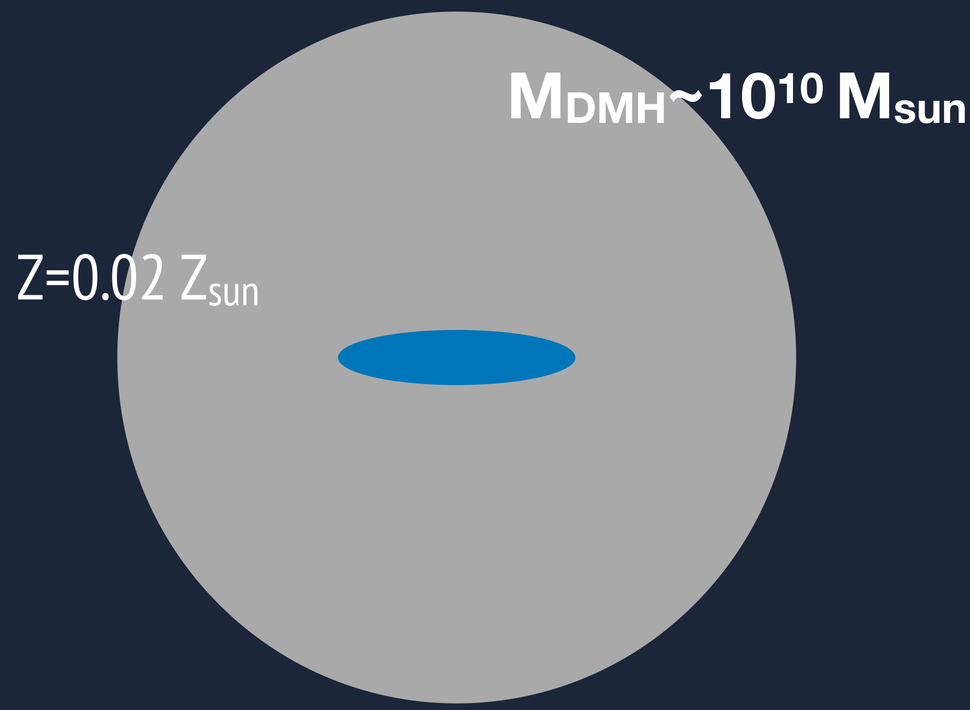
t > 3 Myr: Supernova explosions



Dale+(13);
(NB. w/ photo-ionization heating)

Radiation-hydrodynamic simulations of an isolated disk

Simulation set-up



- Initial stellar mass = 2 x 10^8 M_{sun}
- Initial gas mass = 1.7 x 10^8 M_{sun}
- Max Resolution: 2 - 5 pc

Input physics

RAMSES-RT (Teyssier 02; Rosdahl+13)

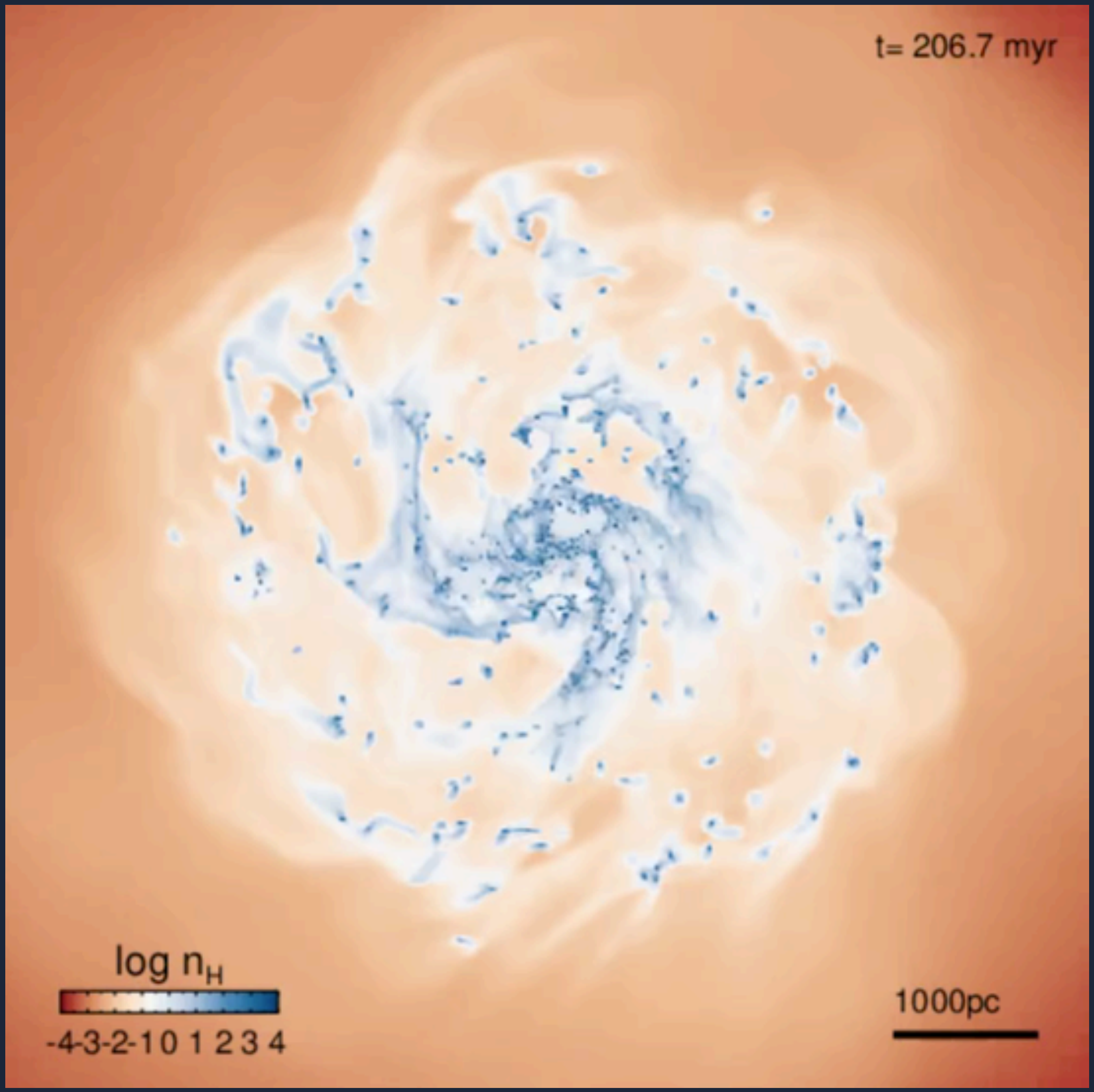
- Thermo-turbulent star formation scheme (Devriendt+; Kimm+17)
- Momentum-conserving SNe (Kimm & Cen 14, Kimm+15)

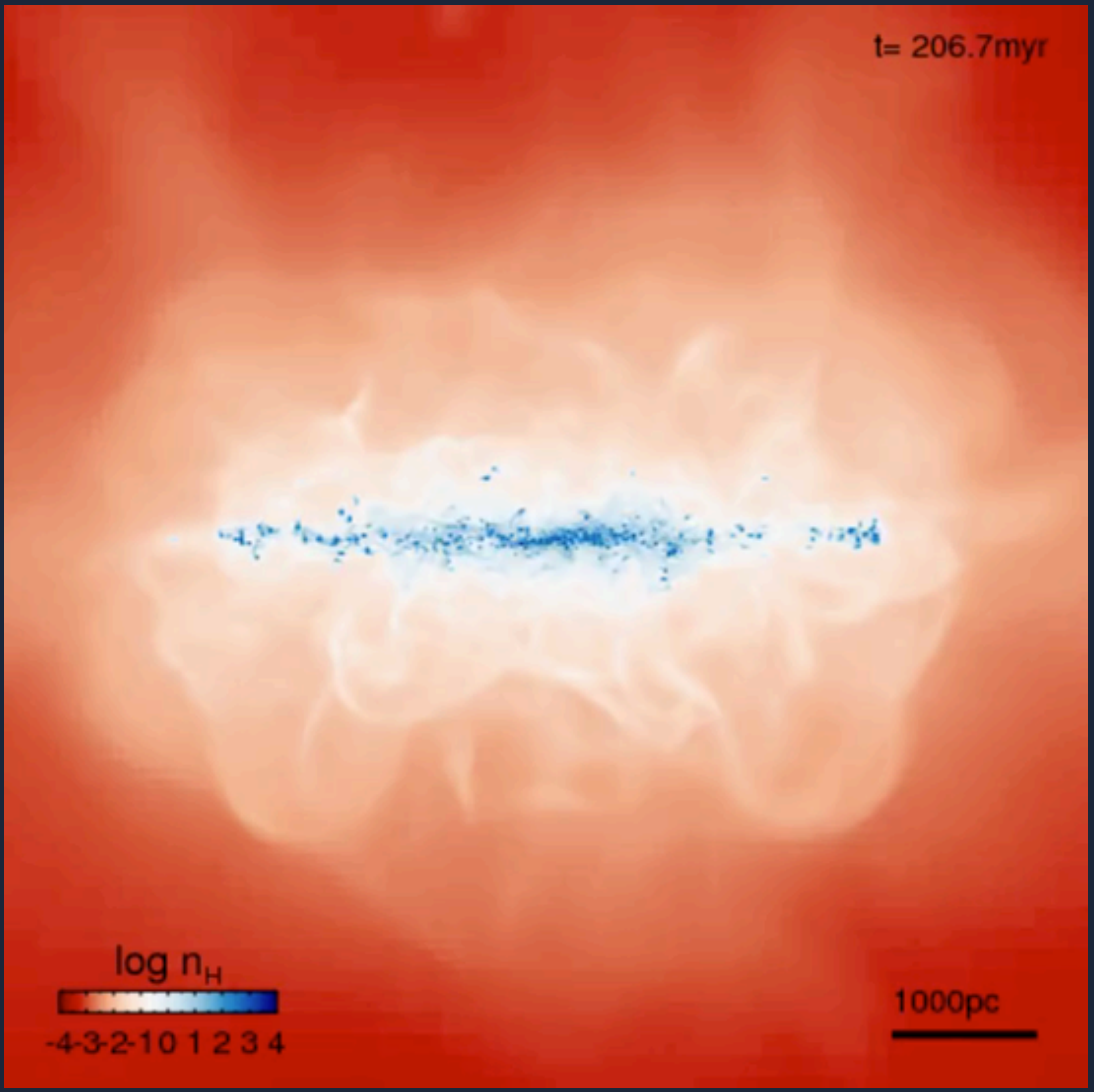
- Non-equilibrium photo-chemistry with H_2 (Katz,Kimm+17)
- Photo-ionisation heating (Rosdahl+13)
- Direct radiation pressure (Rosdahl+13)
- RP by reprocessed IR photons (Rosdahl & Teyssier 15)
- Photoelectric heating on dust (Kimm+17)

- Lya pressure (Kimm+18) - a simplified model for P_{Lya} based on M_F
(more accurate calculations require on-the-fly MC Lya RT)

Photon group	ϵ_0 [eV]	ϵ_1 [eV]	κ [cm^2/g]	Main function
EUV_{HeII}	54.42	∞	10^3	HeII ionisation
EUV_{HeI}	24.59	54.42	10^3	HeI ionisation
$EUV_{HI,2}$	15.2	24.59	10^3	HI and H_2 ionisation
$EUV_{HI,1}$	13.6	15.2	10^3	HI ionisation
LW	11.2	13.6	10^3	H_2 dissociation
FUV	5.6	11.2	10^3	Photoelectric heating
Optical	1.0	5.6	10^3	Direct RP
IR	0.1	1.0	5	Radiation pressure (RP)

Radiation-hydrodynamic simulations of an isolated disk





PhotoHeating + Direct Radiation Pressure by UV + IR Pressure + SN explosions + Lya Pressure

NOTE: Large-scale, fast outflows are driven by SN, not by Lya

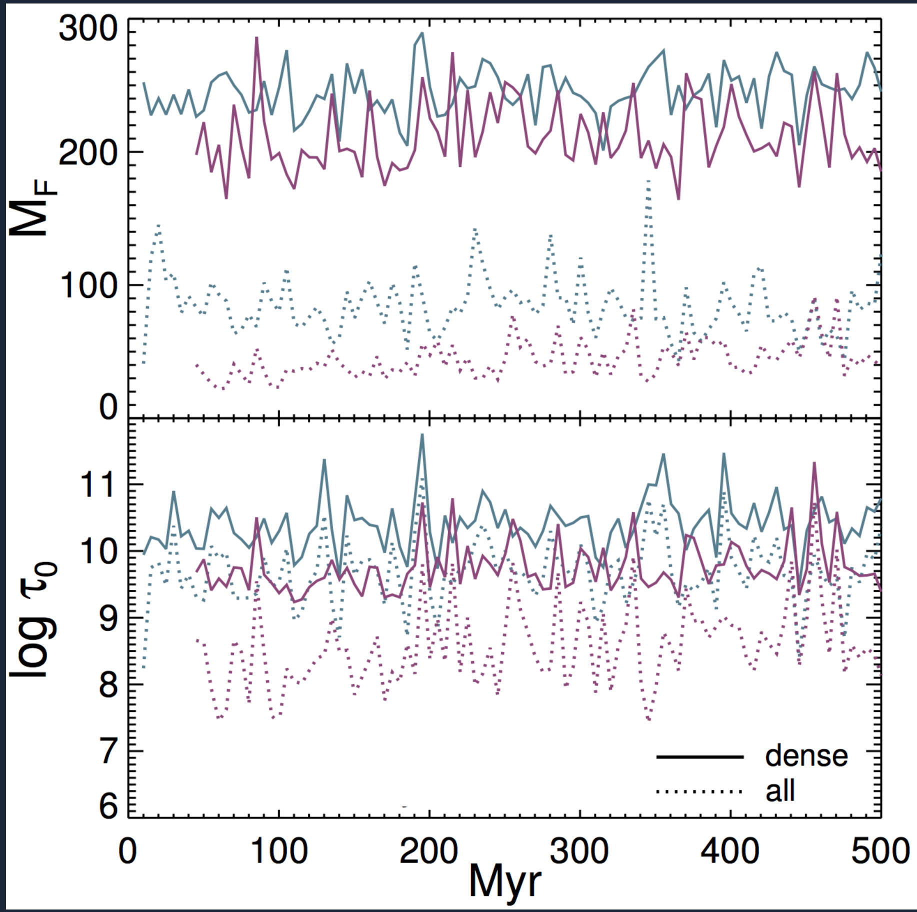
Where does Lya operate?

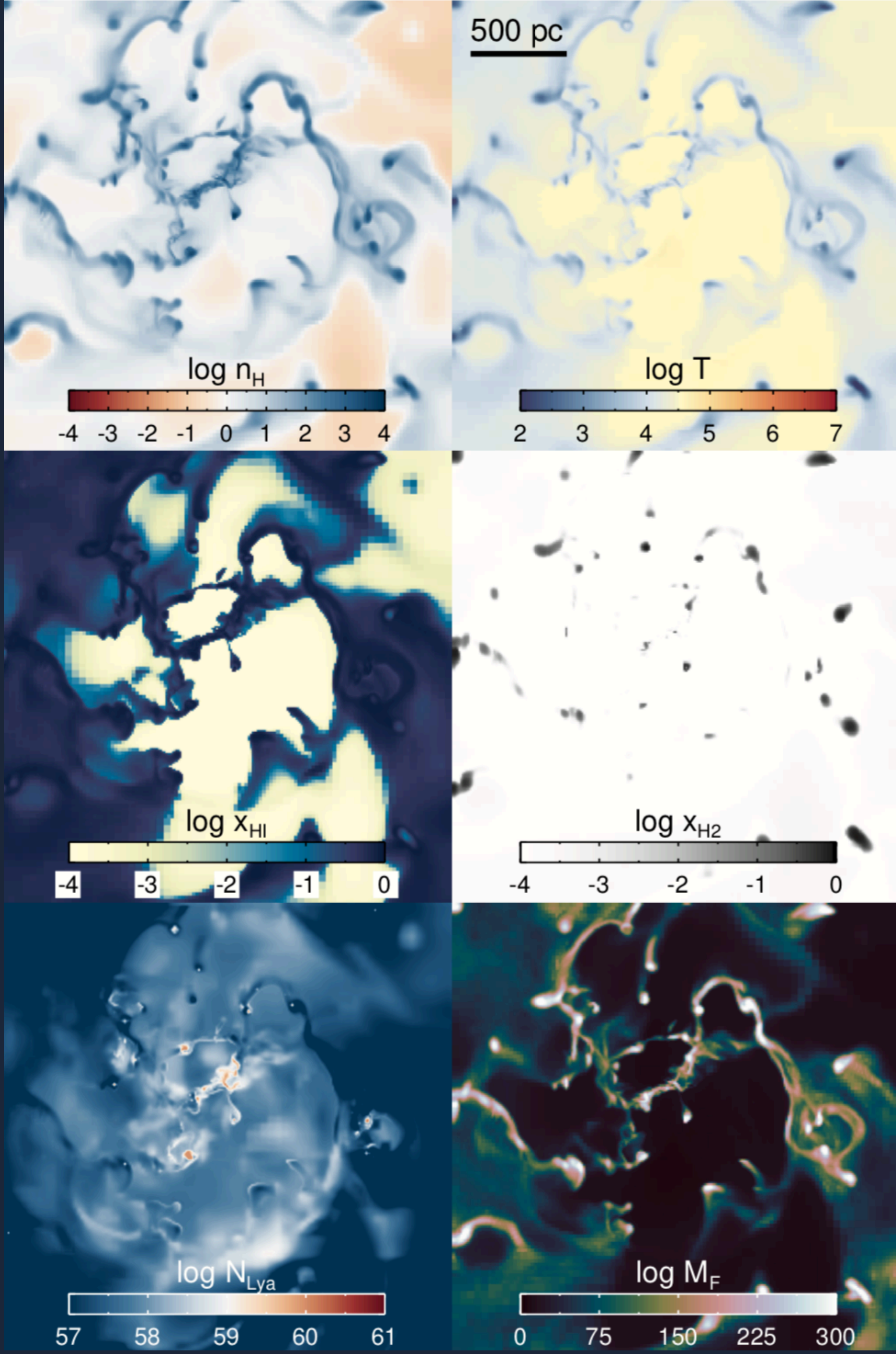
- Requirement for strong Lya pressure
  - Luminous ionizing source
  - Large N_{HI} density

→ around young stars

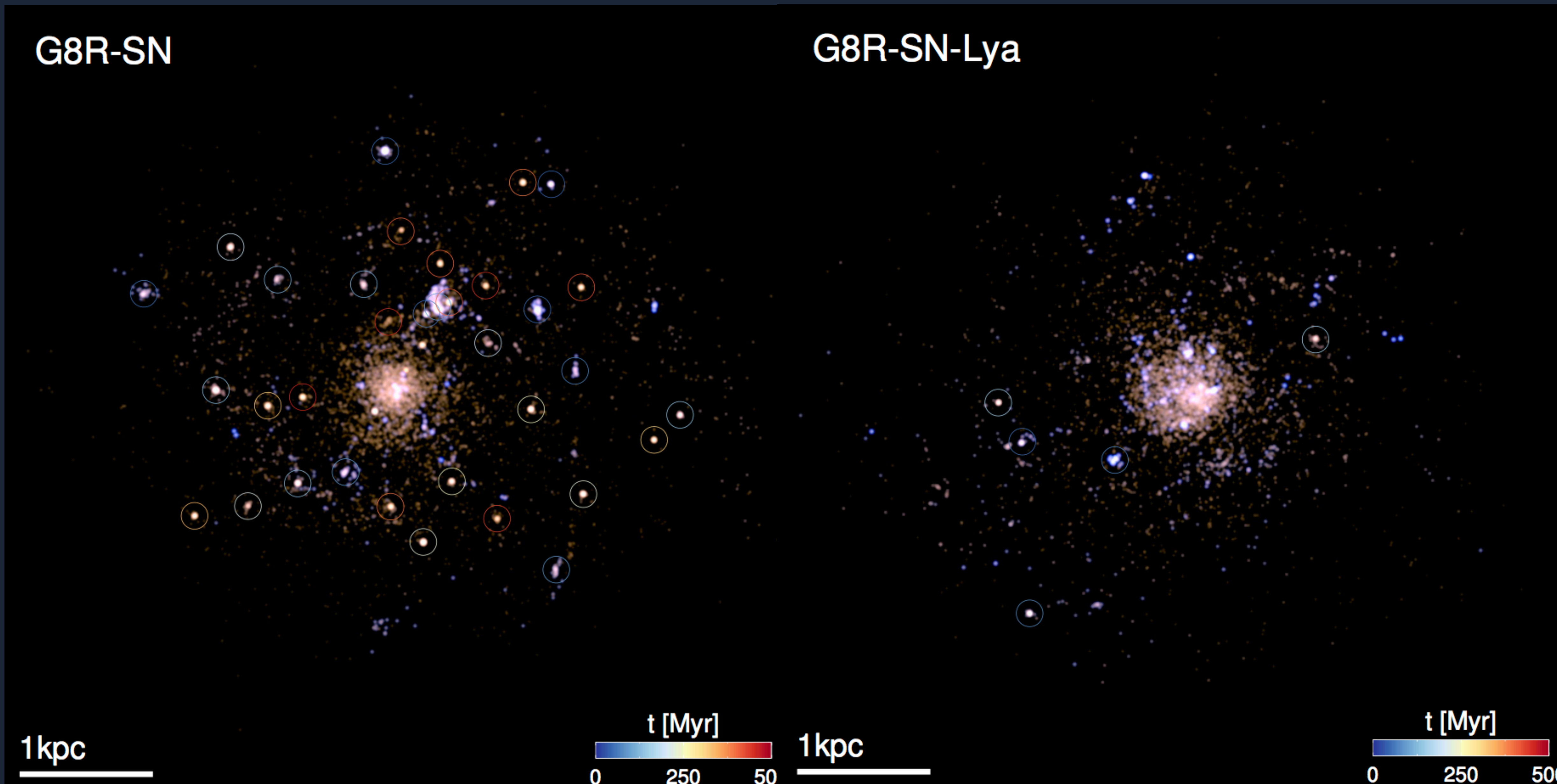
→ interrupt SF quickly (<5Myr)

- Effective M_F ~ 200-300 in dense regions





Cluster Formation with LyA Feedback

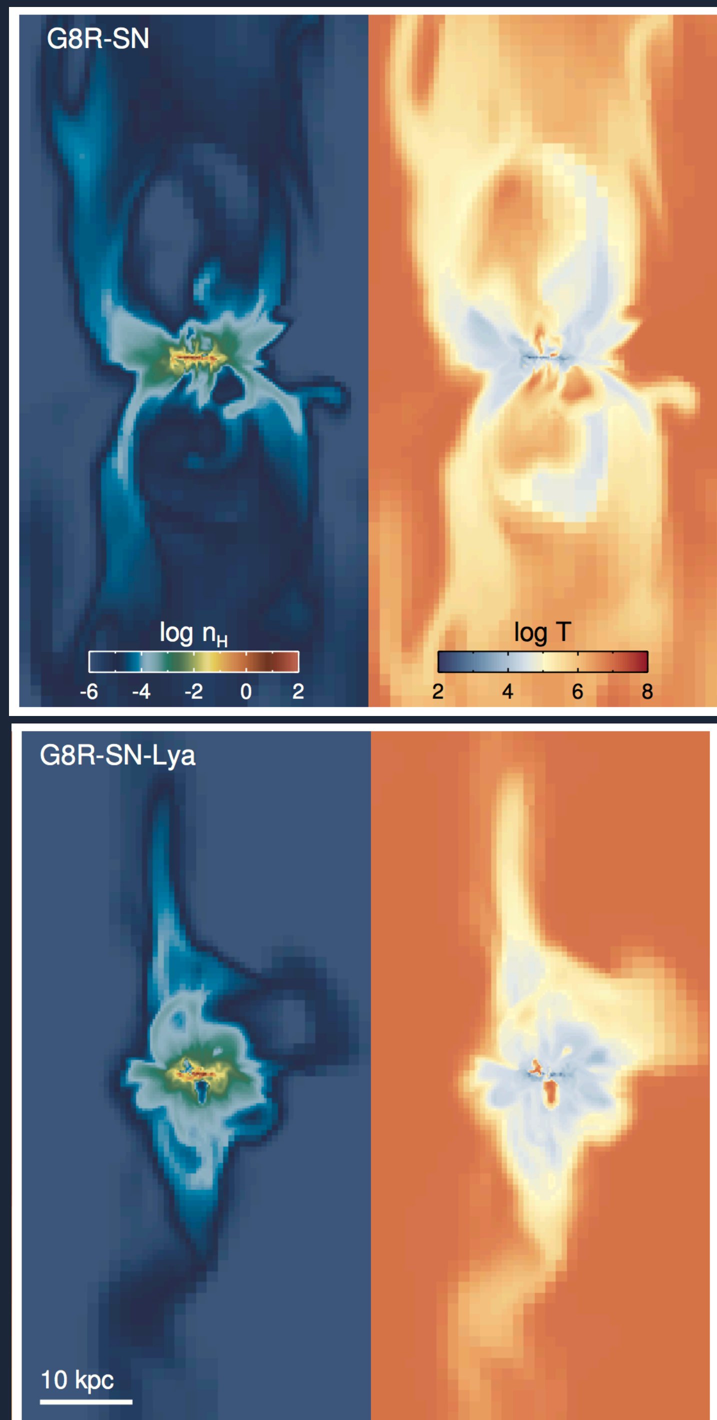


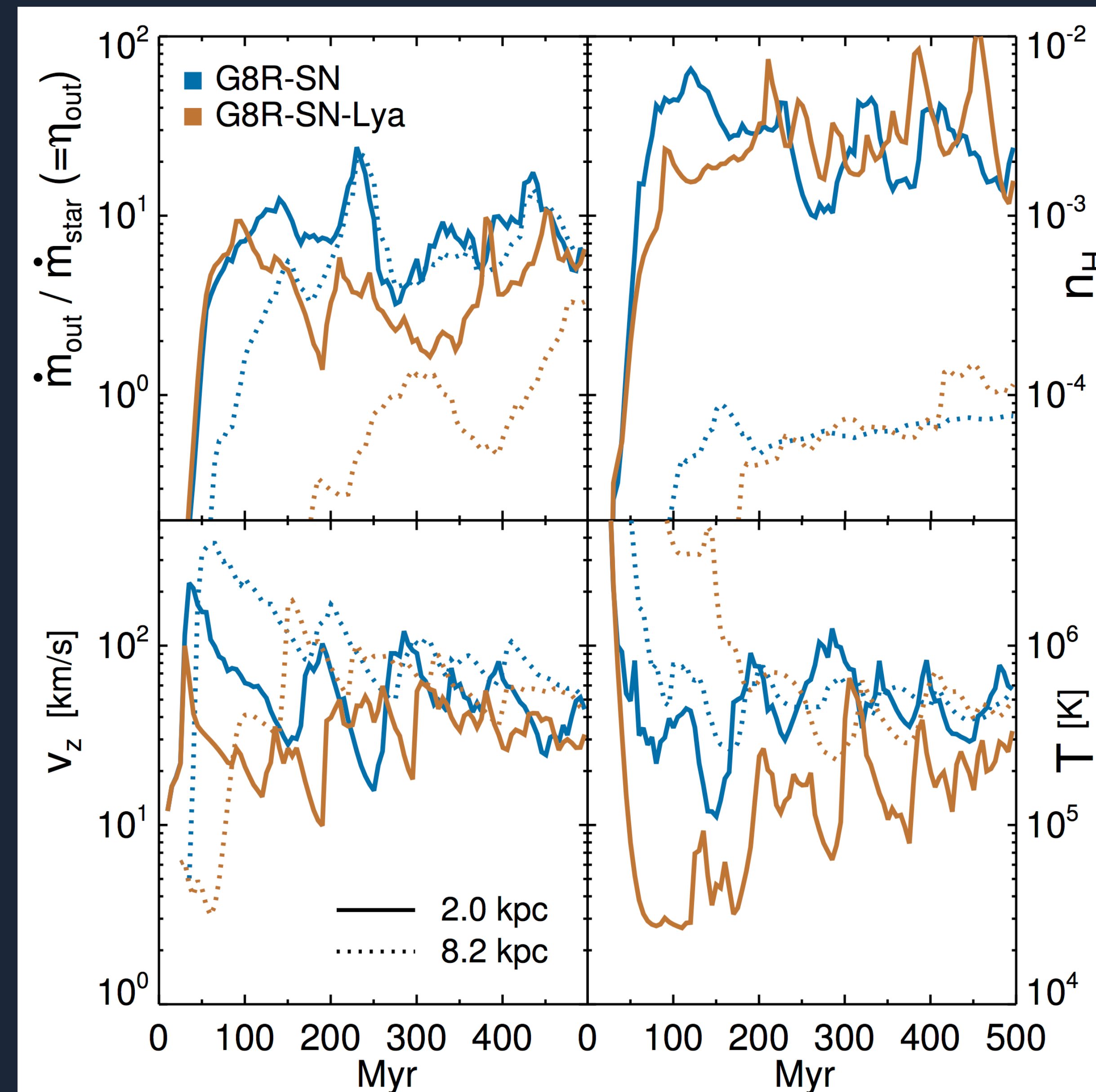
- Fewer clusters form and survive when strong radiation feedback is present
  (caution: cluster formation in HD simulations…)

Weaker outflows with Lya pressure

w/o Lya

w/ Lya

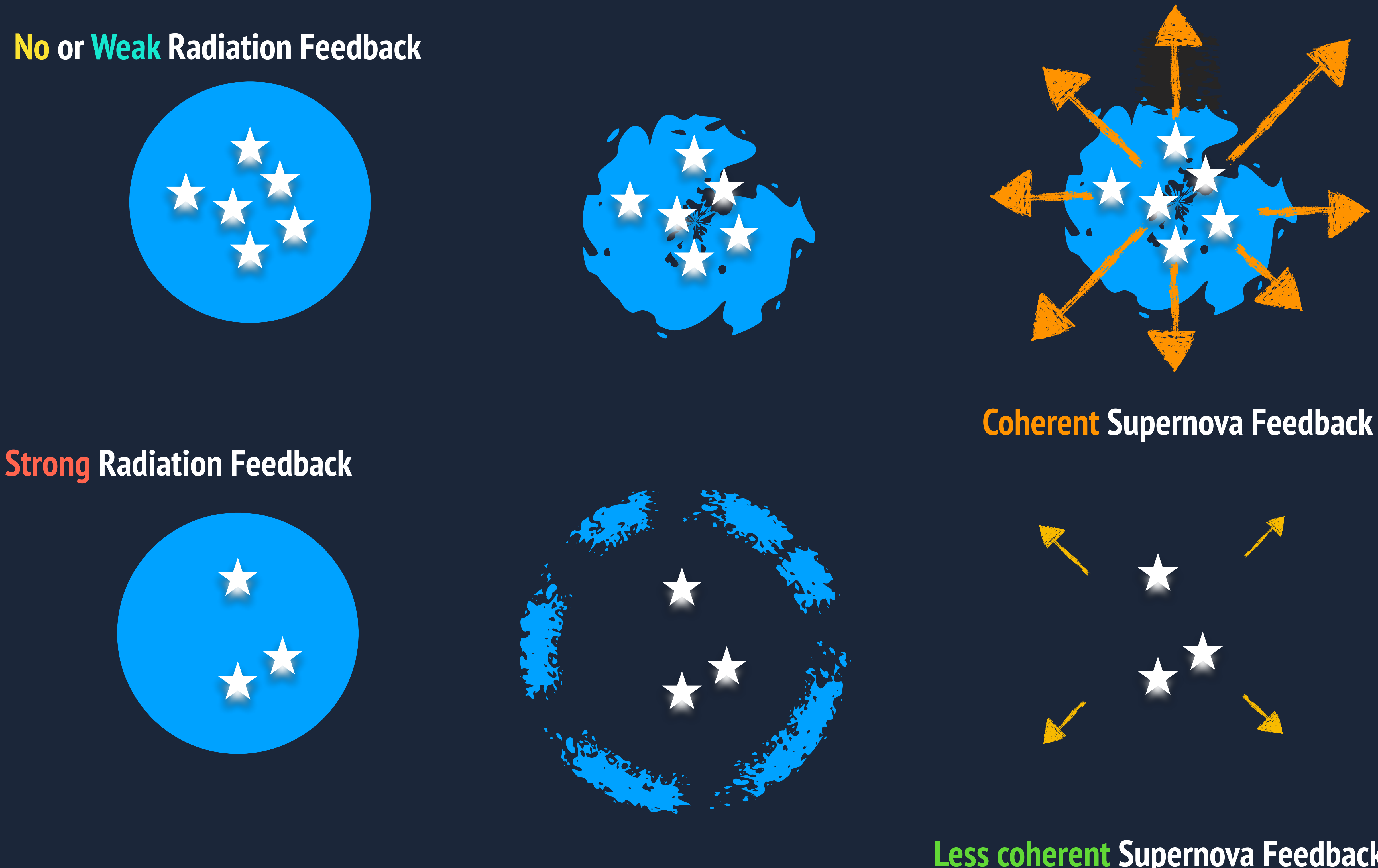




W/ Lya pressure

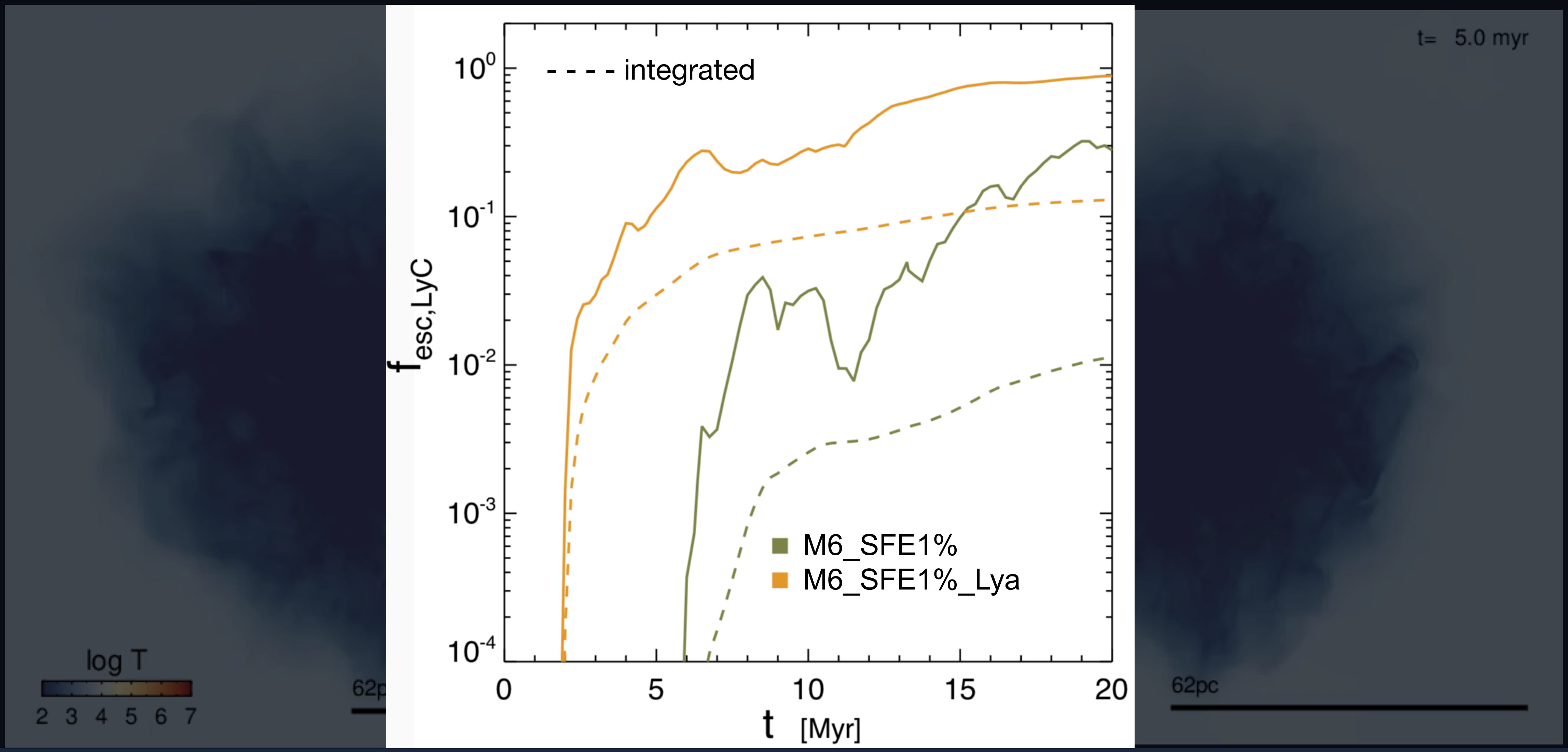
- Mass-loading factor is decreased
- Outflows become cooler and slower

Picture with strong radiation feedback



Preliminary results: Lya pressure in metal-poor clouds

$M_{cloud}=10^6\,M_{sun}$ / $M_{star}=10^4\,M_{sun}$ / $Z = 0.1\,Z_{sun}$



PH+RP+IR+SN

PH+RP+IR+SN+Lya

total box size = 512pc

* Star particles are placed in dense regions

Summary

- LyA photons resonantly scatter with HI, and impart 100-300 times more momentum than the single-scattering case (L_{Lya}/c) in the metal-poor regime ($Z \sim 0.02\ Z_{sun}$)

- Isolated gas-rich, metal-poor dwarf galaxy test:
  - Total stellar mass : suppressed by a factor of ~2
  - weaker outflows (mass loading~a few at 0.2 Rvir)
  - Star clusters are more difficult to form and survive -> important for GC formation

  - Strong RP does not necessarily lead to stronger outflows (due to self-regulated SF)

- (Partial) Solution to the over-cooling problem in galaxy formation simulations
- Important for cloud evolutions and reionization