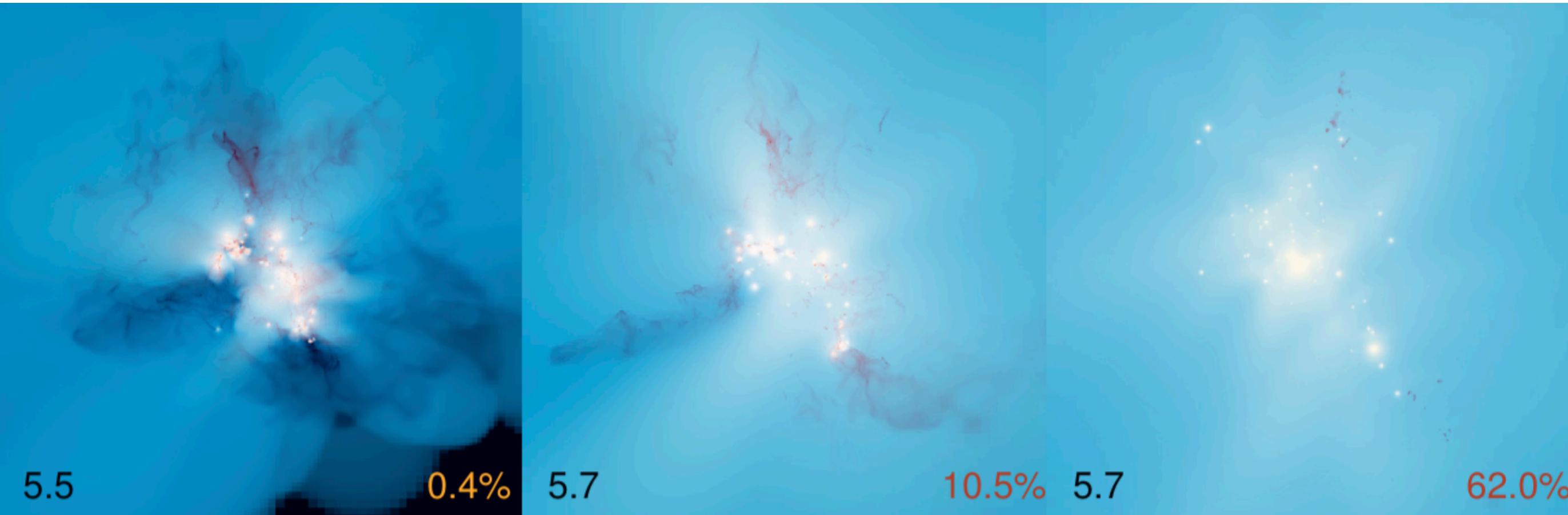


PRALINES: LyC and LyA Escape from GMCs



Taysun Kimm (Yonsei)

RAMSES User Meeting 2021 / 09 / 27

Sam **Geen** (Amsterdam), Rebekka **Bieri** (MPA)
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Leo **Michel-Dansac** (CRAL)
Thibault **Garel**, Anne **Verhamme** (Geneva)

Reionization driven by dwarf galaxies

SPHINX simulation

- Cosmological RHD
- $(10 \text{ Mpc})^3$ or $(20 \text{ Mpc})^3$
- $10^8 \leq M_{\text{vir}} \leq 10^{11} M_{\odot}$
- Maximum of $\sim 10 \text{ pc}$
- SN + radiation feedback that can model star formation cycles
- Thermo-turbulent star formation scheme

Dwarf galaxies can reionize the universe, provided...



PI: J. Rosdahl

Blaizot (CRAL)

Chuniaux (CRAL)

Garel (Geneva)

Haehnelt (Cambridge)

Katz (Oxford)

Kimm (Yonsei)

Mauerhofer (Geneva)

Martin-Alvarez (Cambridge)

Michel-Dansac (CRAL)

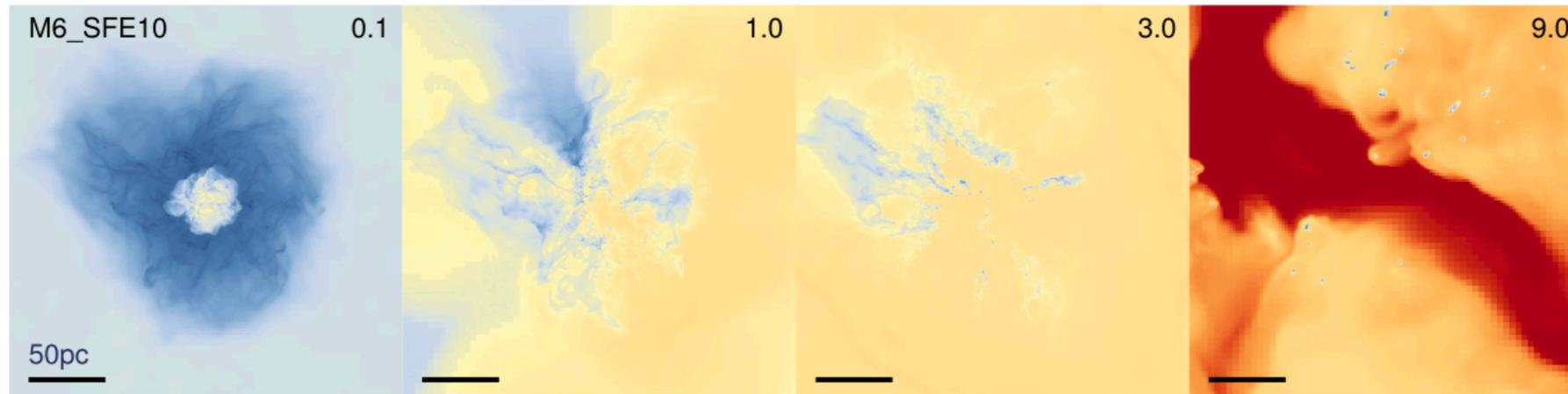
Ocvirk (Strasbourg)

Teyssier (Zurich)

Credit: the SPHINX collaboration

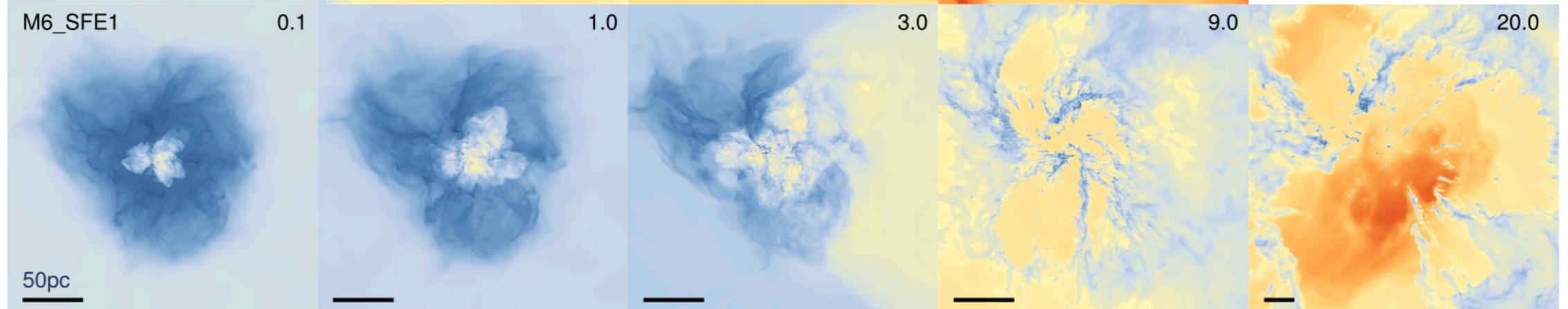
Escape of LyC photons in GMC simulations

$SFE_{\text{tot}}=10\%$



Kimm et al. (2019)

$SFE_{\text{tot}}=1\%$



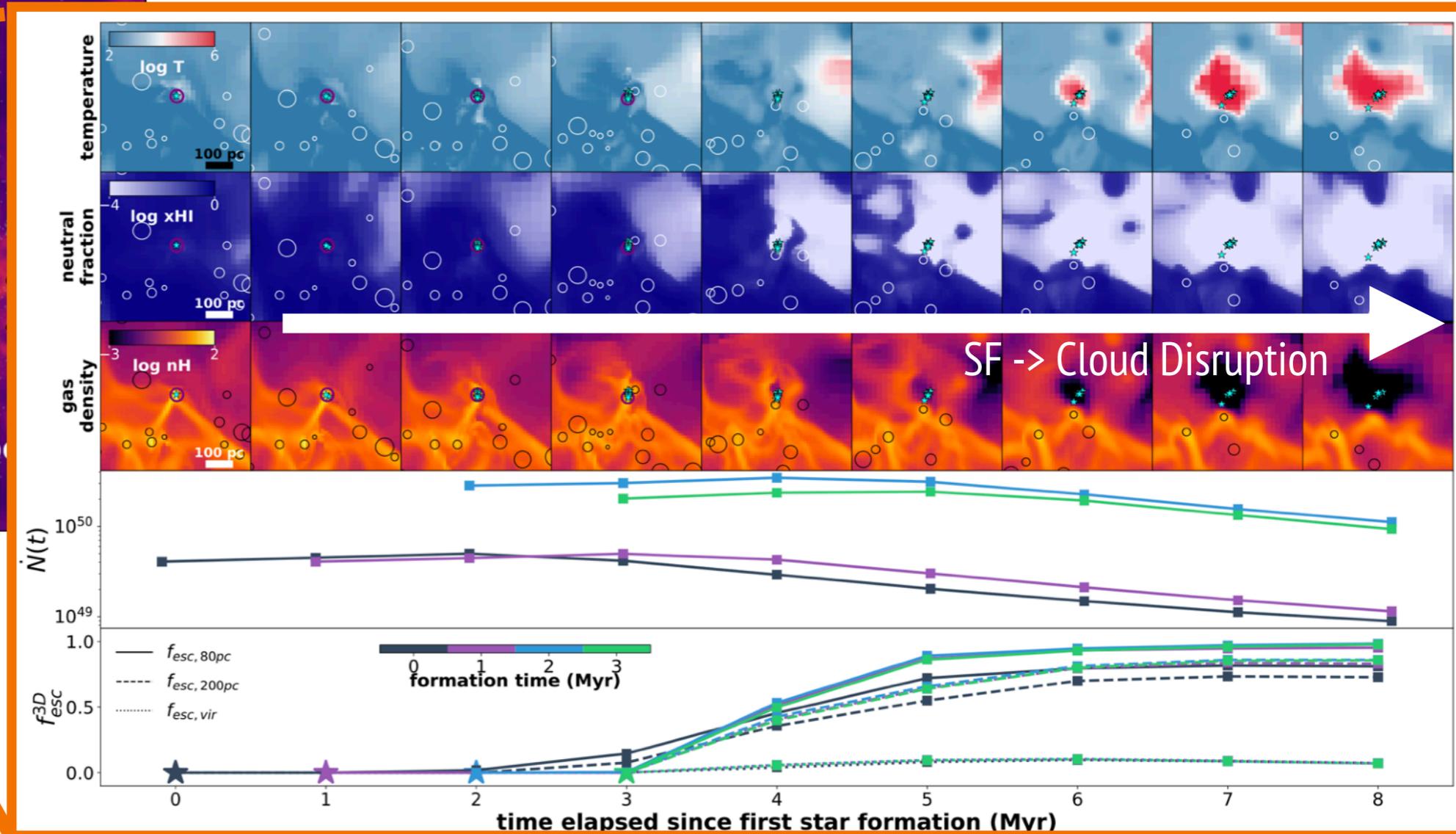
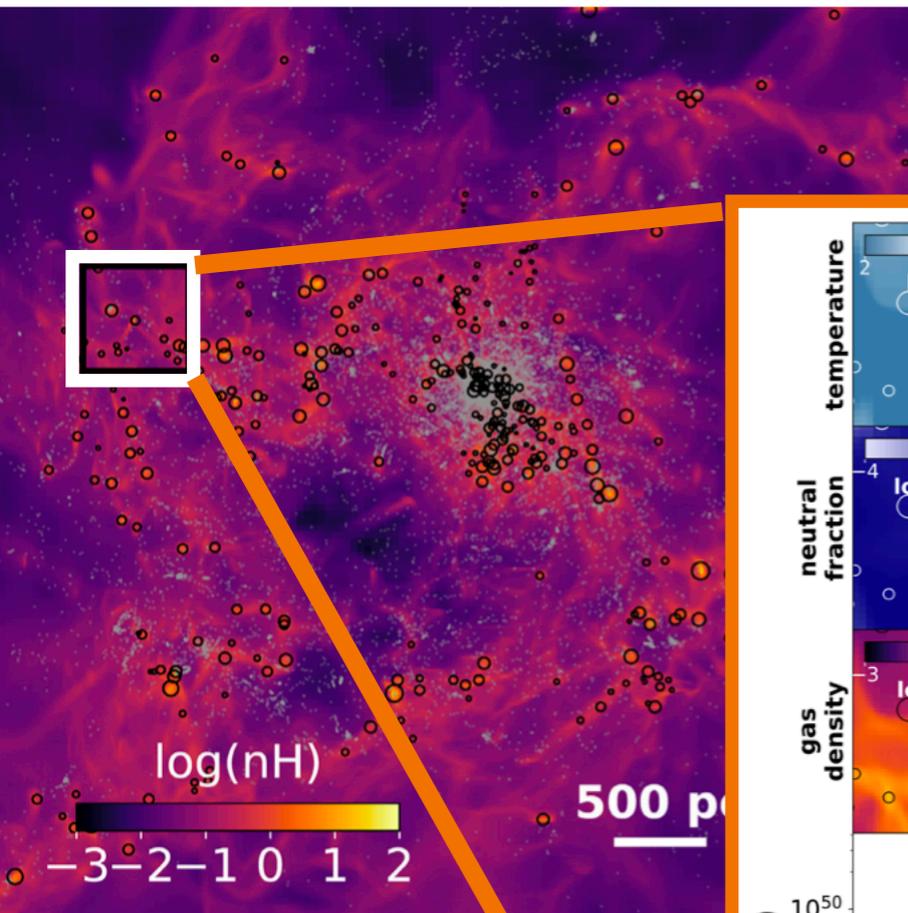
RAMSES-RT

- $dx_{\text{min}}=0.25\text{pc}$
- Photo-ionization + radiation pressure
- SN feedback
- Simple H_2 formation
- Lyman-Werner photons
- **Different SEDs (BC03 or BPASS)**

An example of f_{esc} from galactic-scale sim

Yoo, Kimm, Rosdahl (2020)

<- not SPHINX, but isolated disk

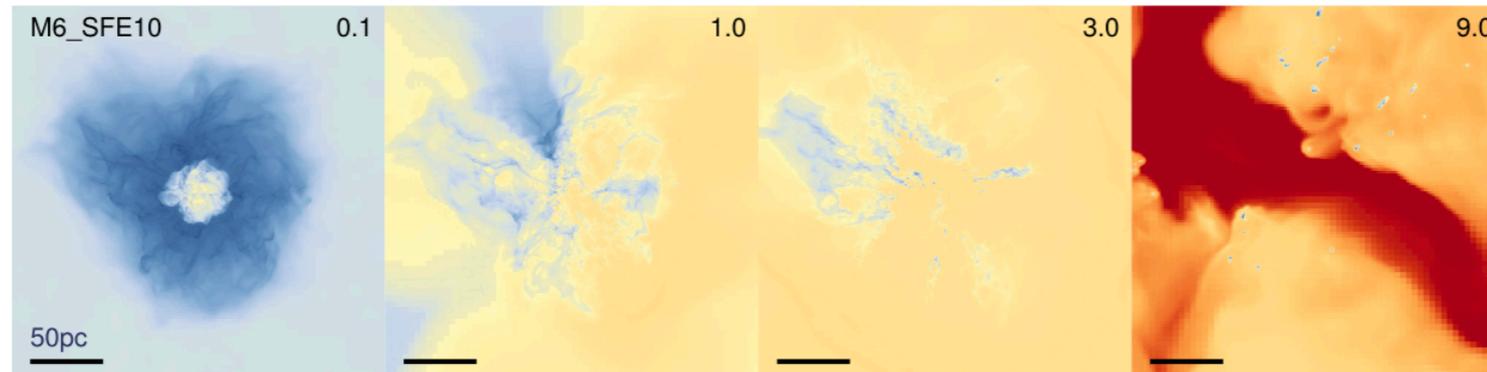


Taehwa Yoo

The escape fraction of LyC photons tend to increase monotonically, as star-forming clumps are disrupted

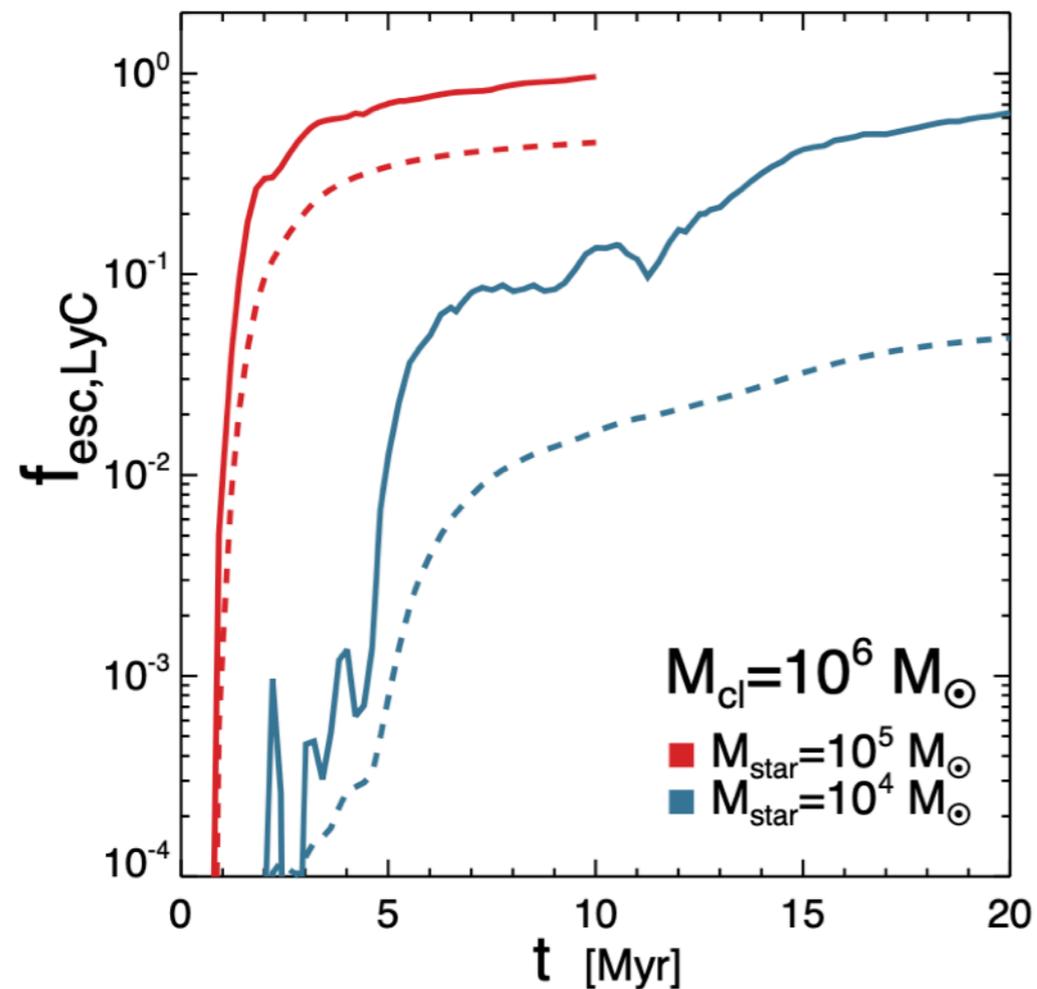
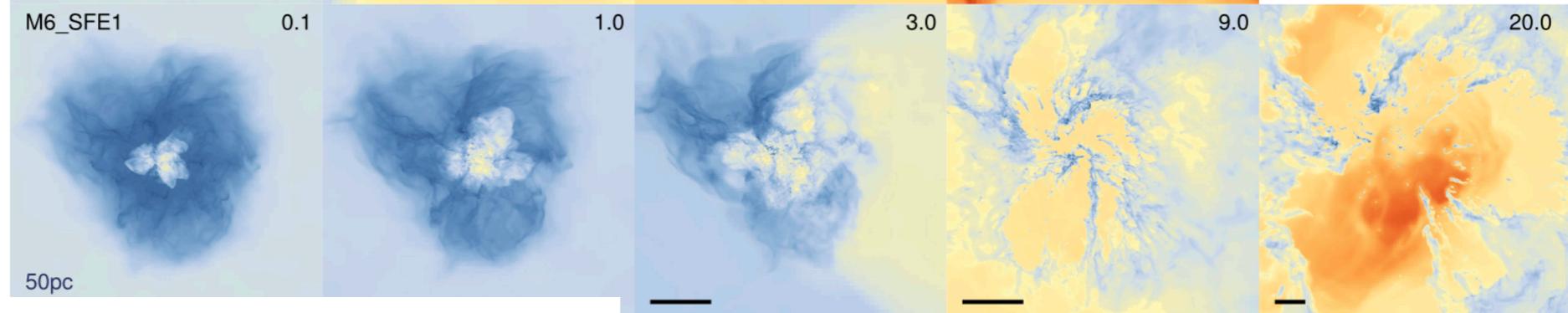
Fluctuation of escape fraction on GMC scales?

$SFE_{\text{tot}}=10\%$



Kimm et al. (2019)

$SFE_{\text{tot}}=1\%$



Limitations

- 1) No self-consistent star formation
- 2) Only spherical clouds
- 3) No magnetic fields

After Ramses User Meeting 2018 in Lyon



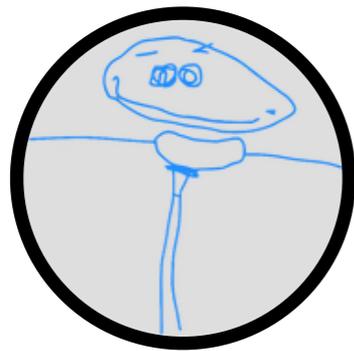
Sam Geen

Interested in more GMCs?

Sure, but your GMCs ($10^{4-5}M_{\text{sun}}$)
may be a bit small for high- z systems?



Taysun Kimm



Jeremy Blaizot

Ok, why don't we run new GMC simulations?

PRALINE Simulations

RAMSES-RT

- $dX_{\min}=0.02-0.08$ pc
- Photoionization heating
- SN Feedback (thermal)
- Sink particle algorithm
(Bleuler & Teyssier 14)
- Magnetic fields
- Various morphologies
- Different surface densities
- Different turbulent strength
- Different metallicities
- Cloud masses
- Resolutions

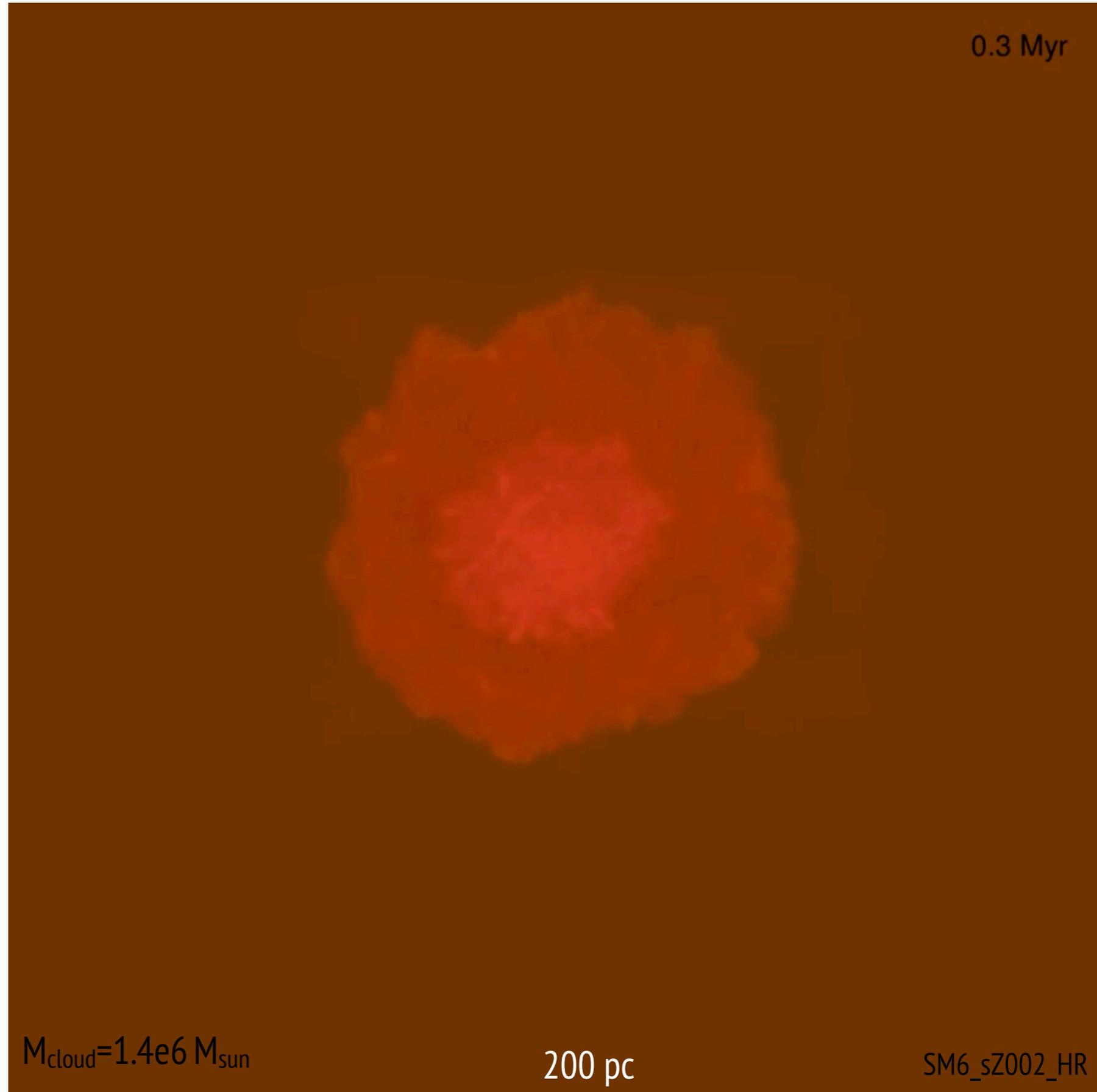
Total 20+ simulations so far

MPA (Germany)

Lyocca (France)

KISTI (Korea)

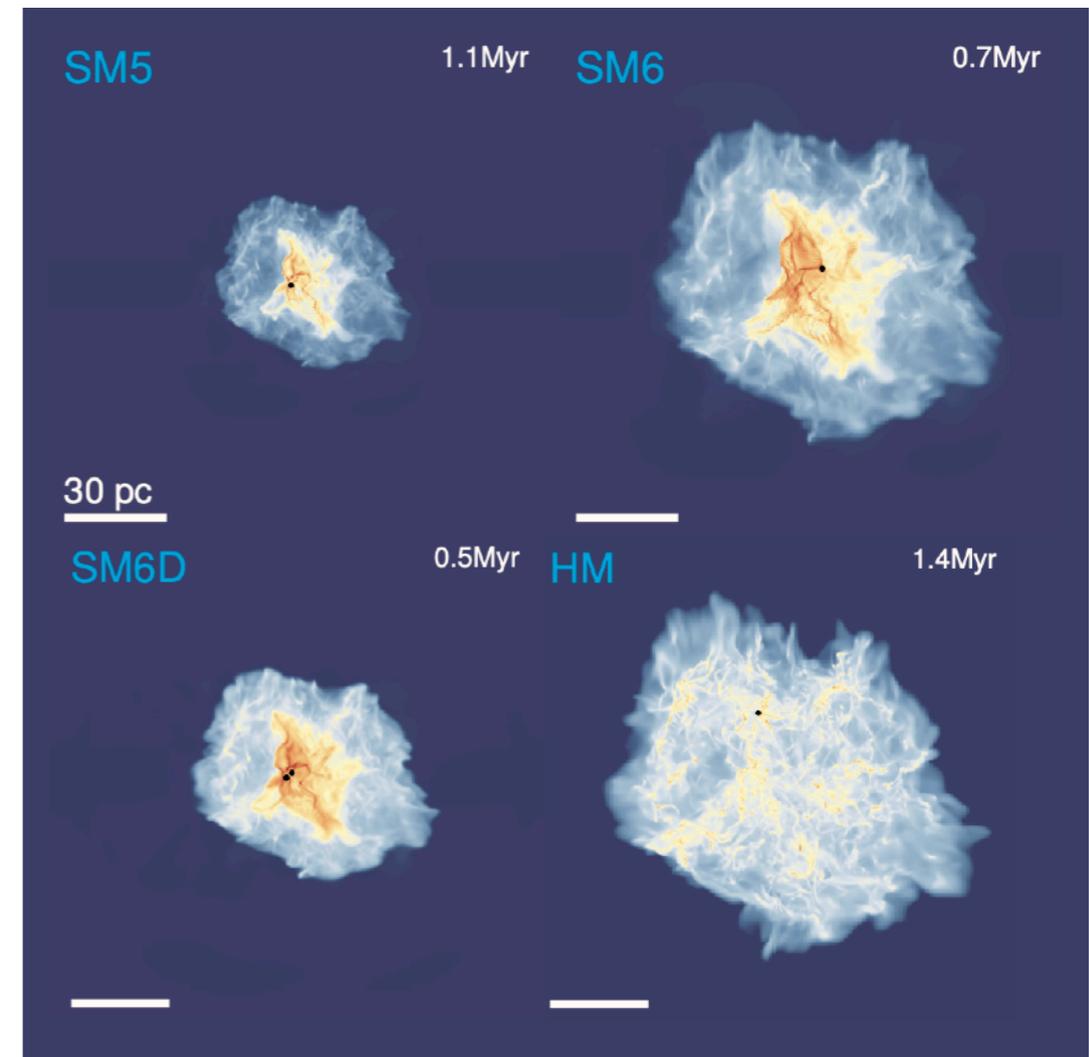
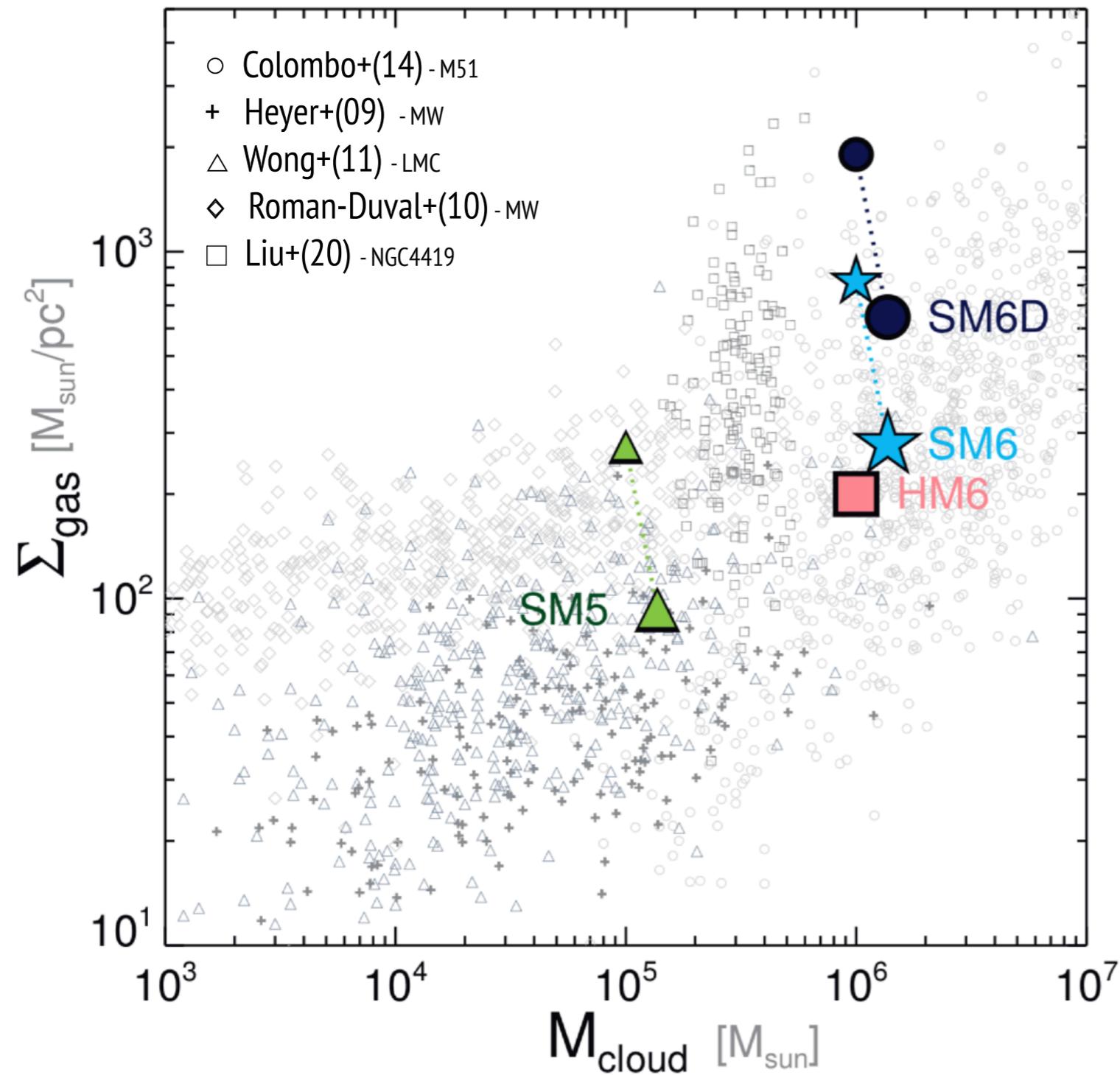
Cartesius (Netherlands)



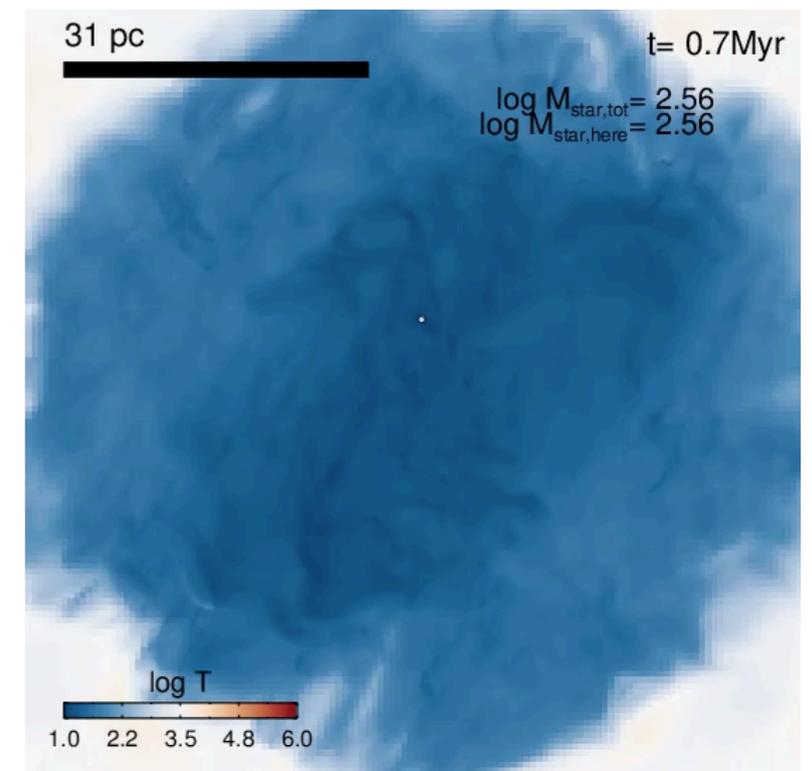
Comparison with previous work

	Kimm+19	PRALINES
Cloud mass	$10^5 - 10^6 M_{\text{sun}}$	$10^5 - 10^6 M_{\text{sun}}$
Resolution	0.25 pc	0.02 - 0.08 pc
Radiation Feedback	Photo-ionization heating Direct radiation pressure IR radiation pressure	Photo-ionization heating
Supernova	Mechanical	Thermal
Chemistry	Primordial + metal cooling + simple H ₂	Primordial + metal cooling
ICs	Cloud mass, metallicity, SEDs	Cloud mass, metallicity, B, morphology, surface density, turbulence
Star formation	Random	Sink particle algorithm

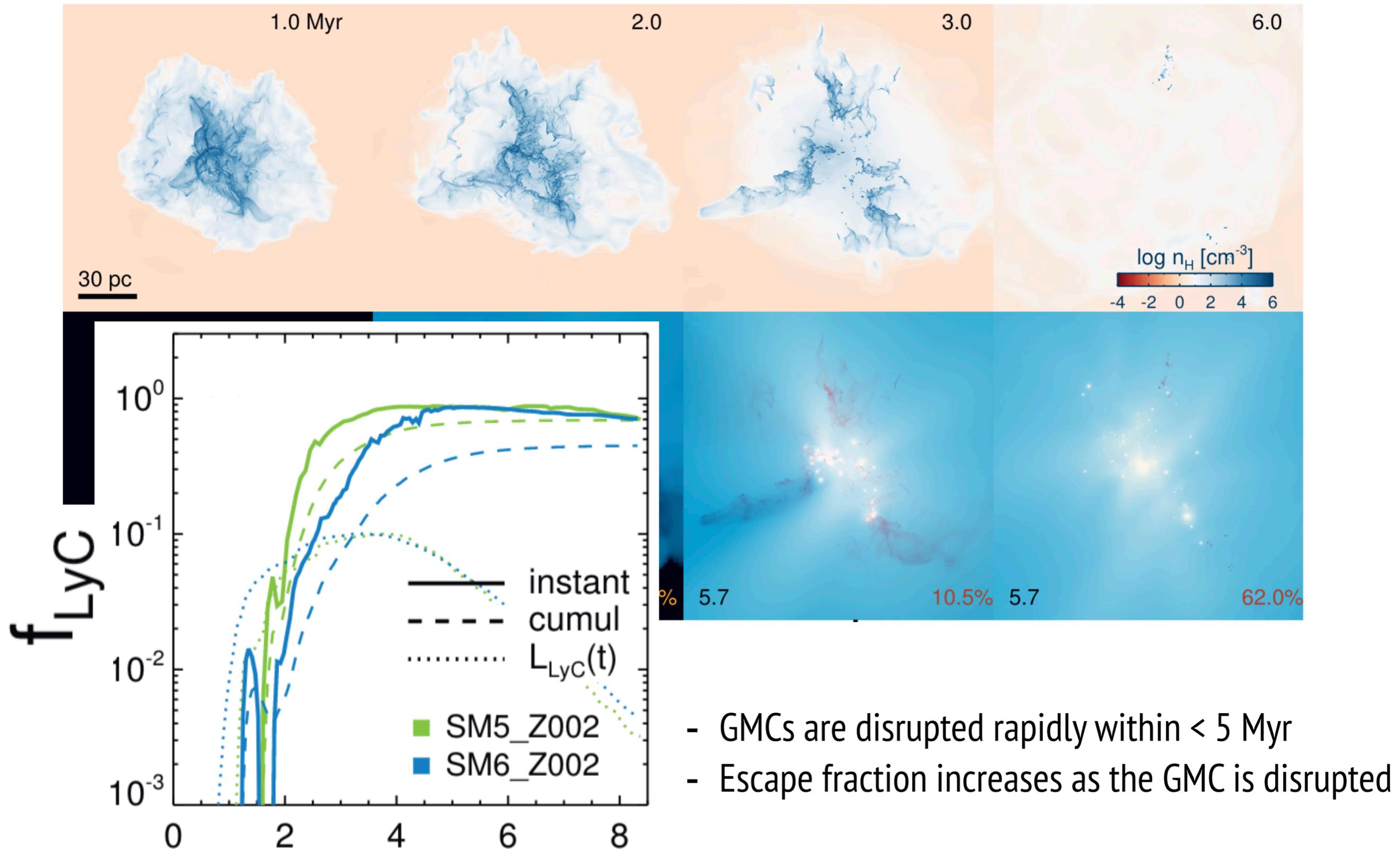
PRALINE simulations



Filamentary
Case

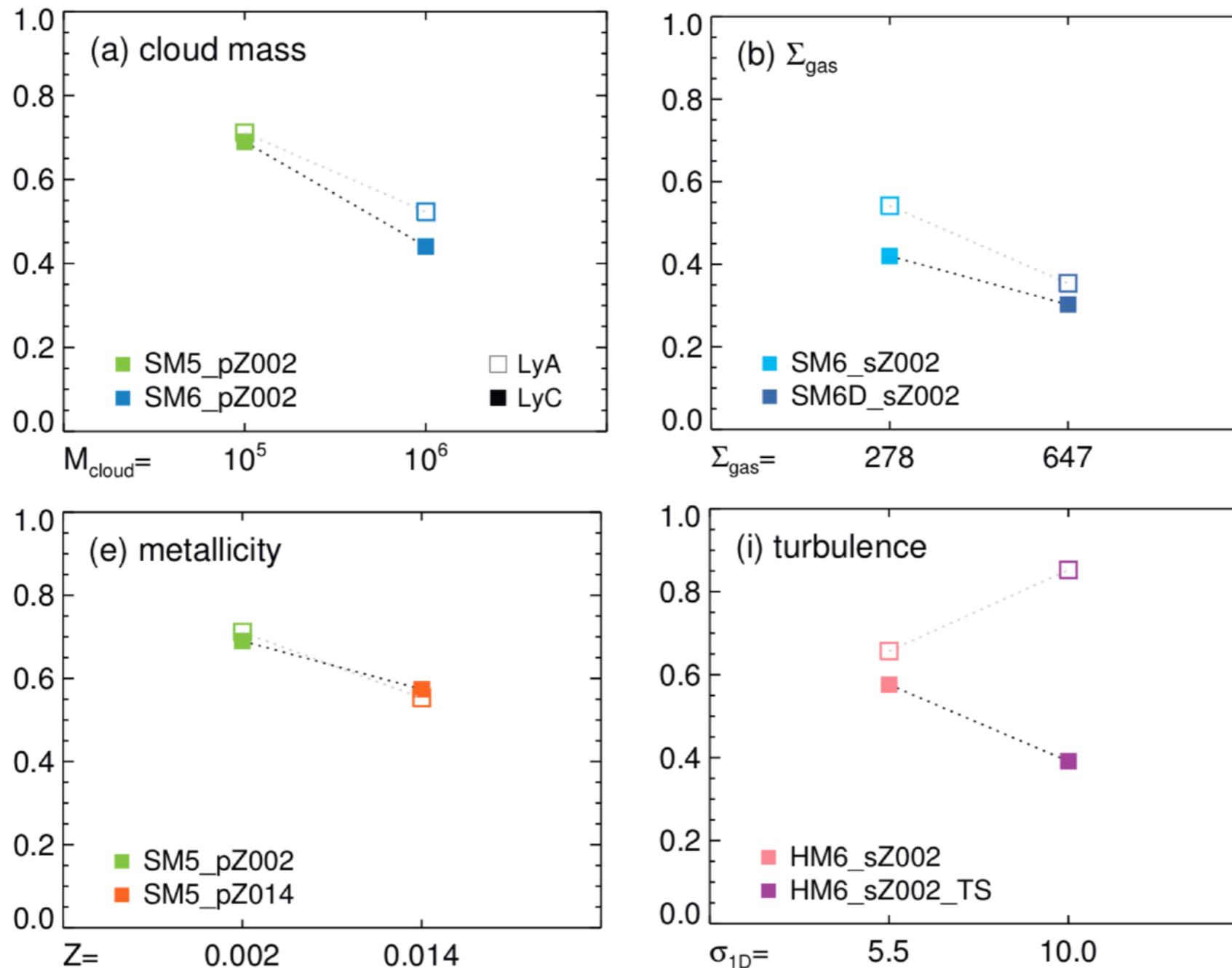


General evolutionary trend of GMCs



- GMCs are disrupted rapidly within < 5 Myr
- Escape fraction increases as the GMC is disrupted

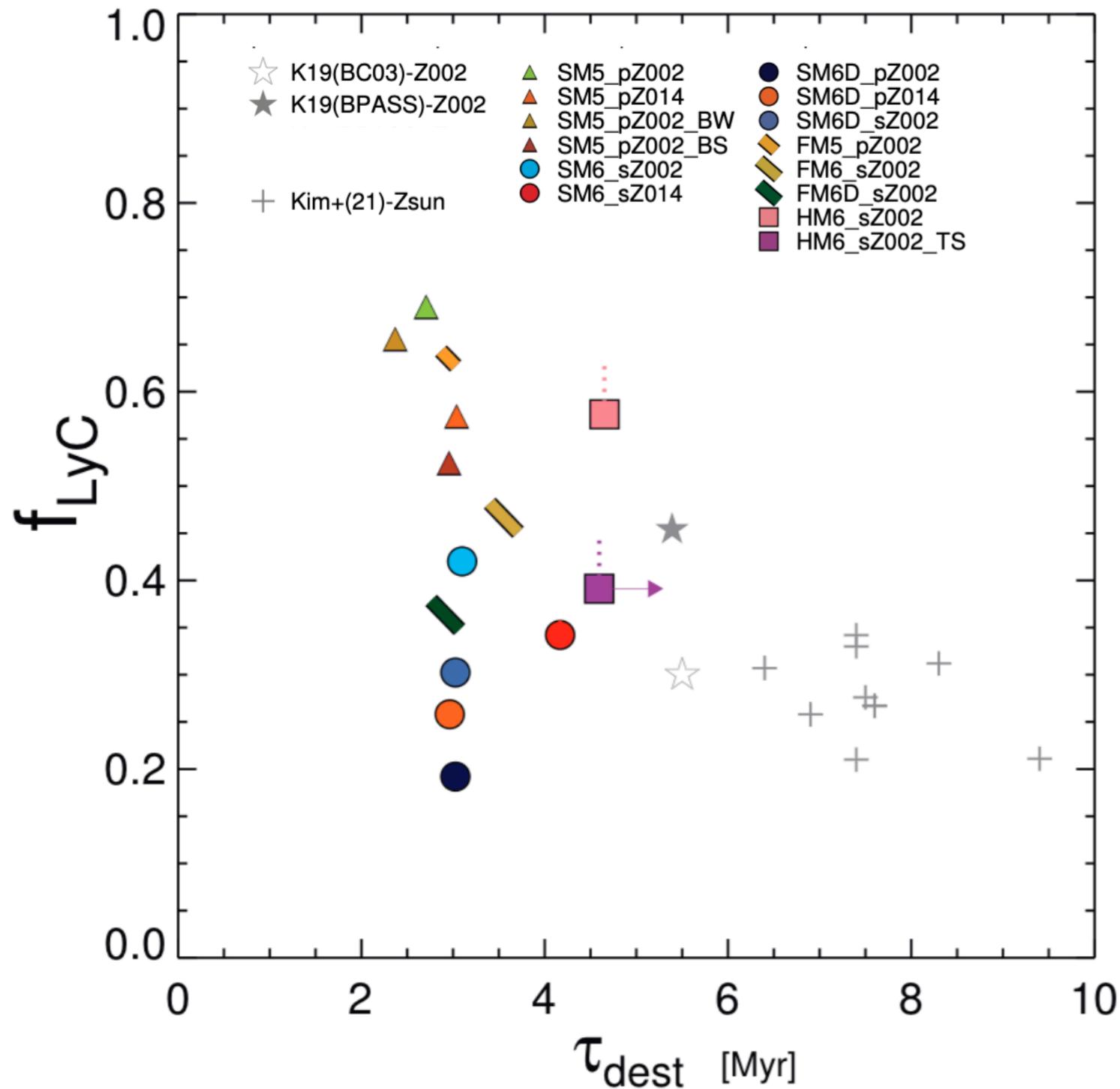
Favorable conditions for LyC escape



Escape of LyC is more efficient if the GMC is **less massive, less dense, less metal-rich, and less turbulent**

(No clear correlation with B and morphology)

Connection between f_{LyC} - τ_{dest}

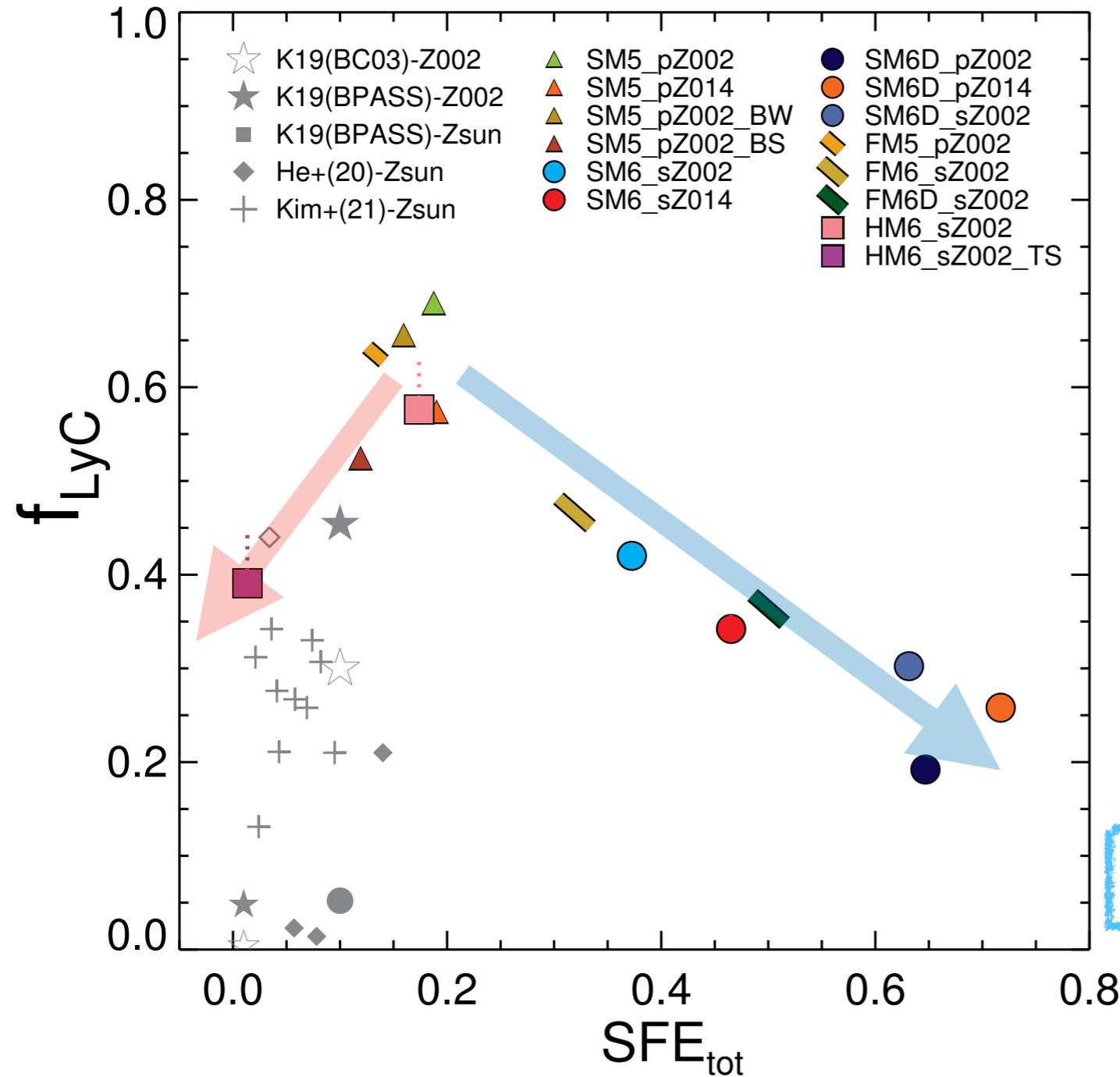


τ_{dest} : timescale at which 90% of the dense gas with $n_{\text{H}} > 100$ is dispersed

More rapid disruption = Higher escape fraction?
(Not necessarily)

(Taken together with results from other studies, perhaps too some extent)

Connection between f_{LyC} - SFE_{tot}



When Σ_{gas} is high, stars form very efficiently, but the high density gas delays the propagation of the LyC radiation $\rightarrow f_{\text{esc}} \downarrow$

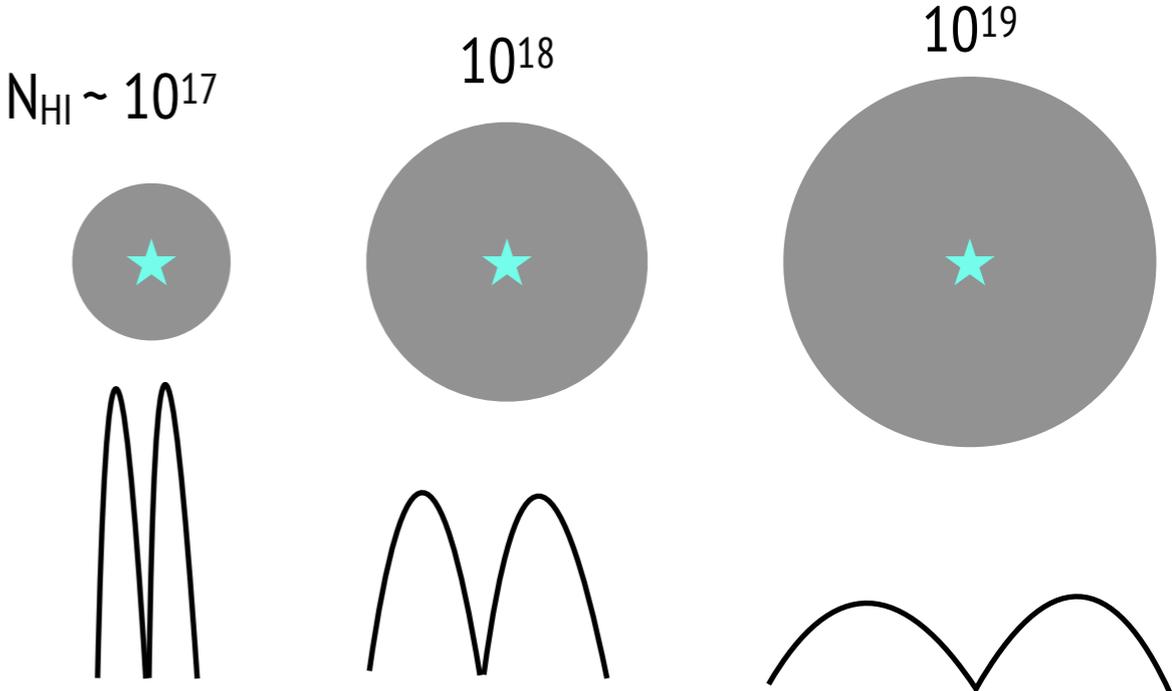
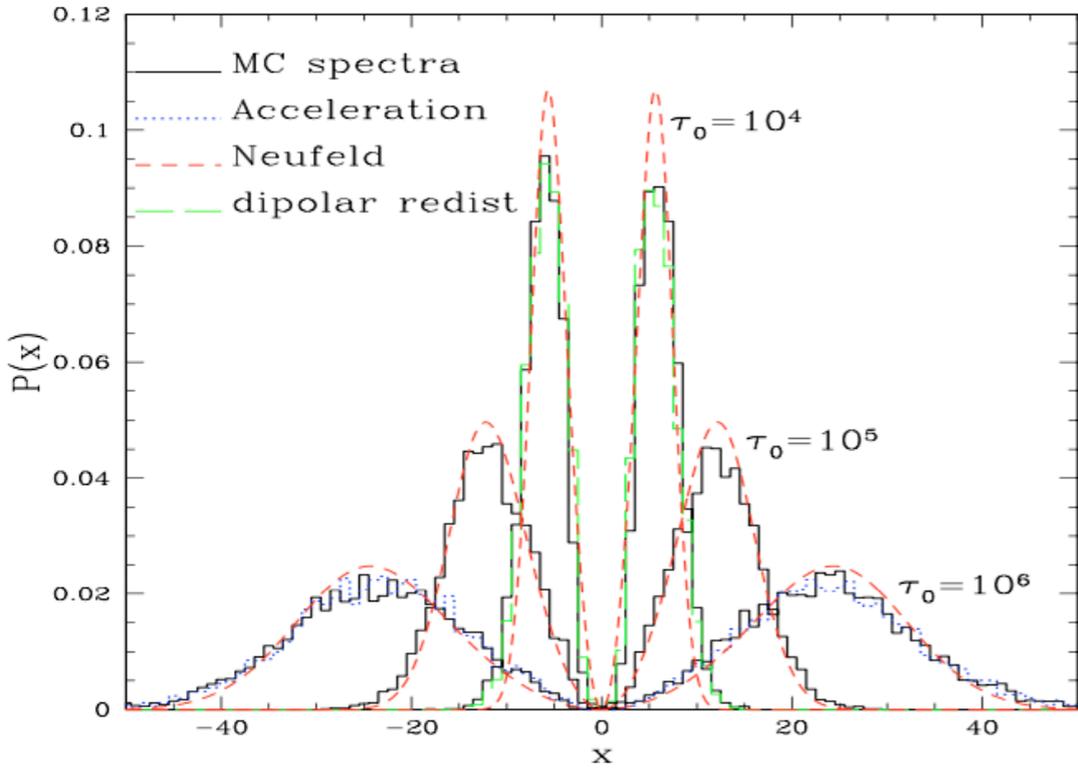
Because of limited number of LyC, the leakage becomes inefficient with decreasing SFE

Not all of the SF bursts would lead to a high f_{esc}

The escape of LyC on GMCs is very efficient (20~70%)
 -> too high to explain cosmic reionization?

Connection between LyC and LyA photons

- LyC photons: non-resonant; reionization, absorbed by $N_{\text{HI}} > 10^{17} \text{ cm}^{-2}$
- LyA photons: resonant; galaxy kinematics, scattered by $N_{\text{HI}} > 10^{14} \text{ cm}^{-2}$



Verhamme+(06)

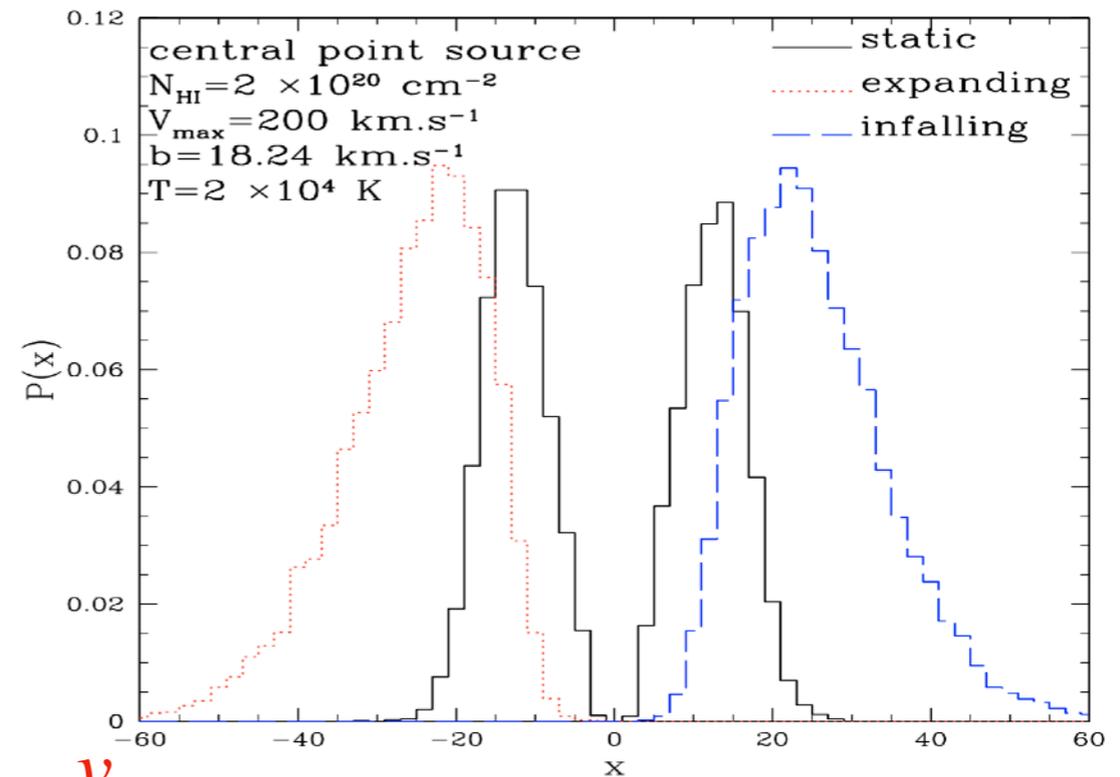
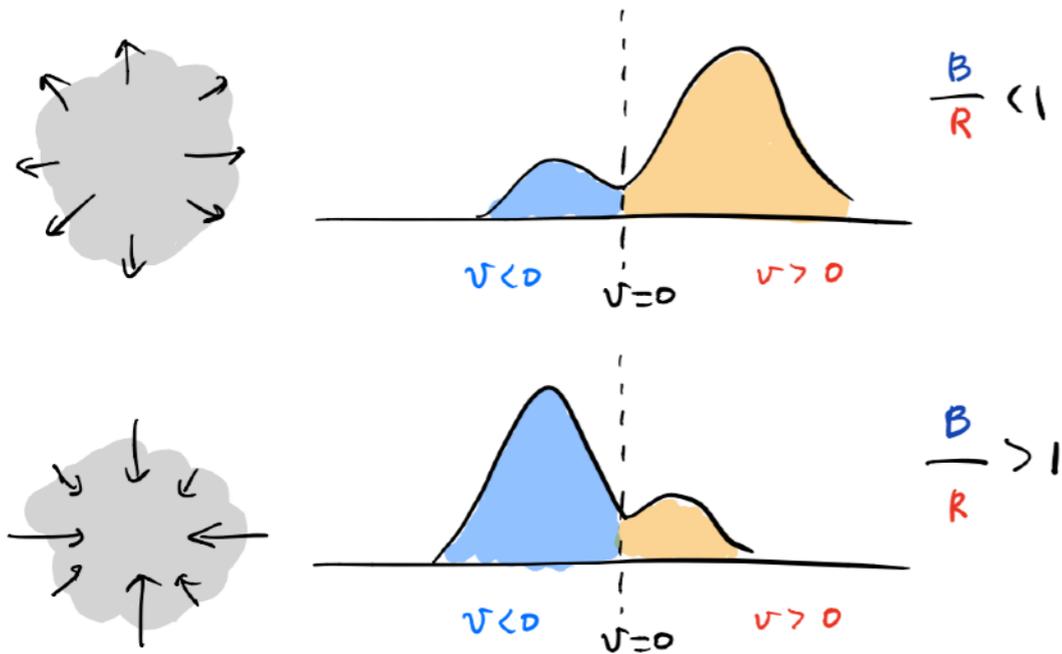


$$x \equiv -\frac{v}{b}$$

Vsep: measure of N_{HI}

Connection between LyC and LyA photons

- LyC photons: non-resonant; reionization, absorbed by $N_{\text{HI}} > 10^{17} \text{ cm}^{-2}$
- LyA photons: resonant; galaxy kinematics, scattered by $N_{\text{HI}} > 10^{14} \text{ cm}^{-2}$



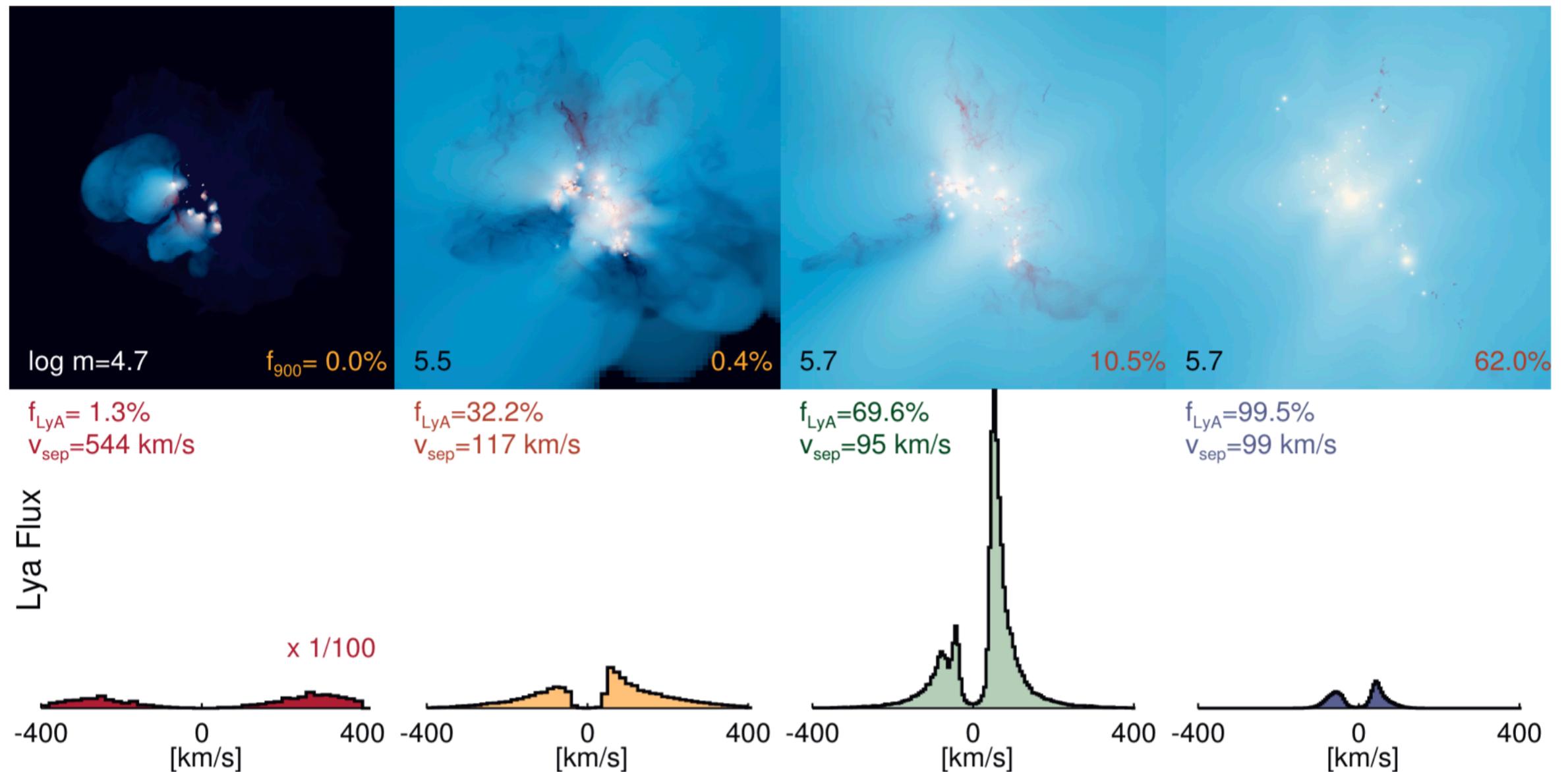
Verhamme+(06)

$$x \equiv -\frac{v}{b}$$

Blue-to-red flux: measure of kinematics

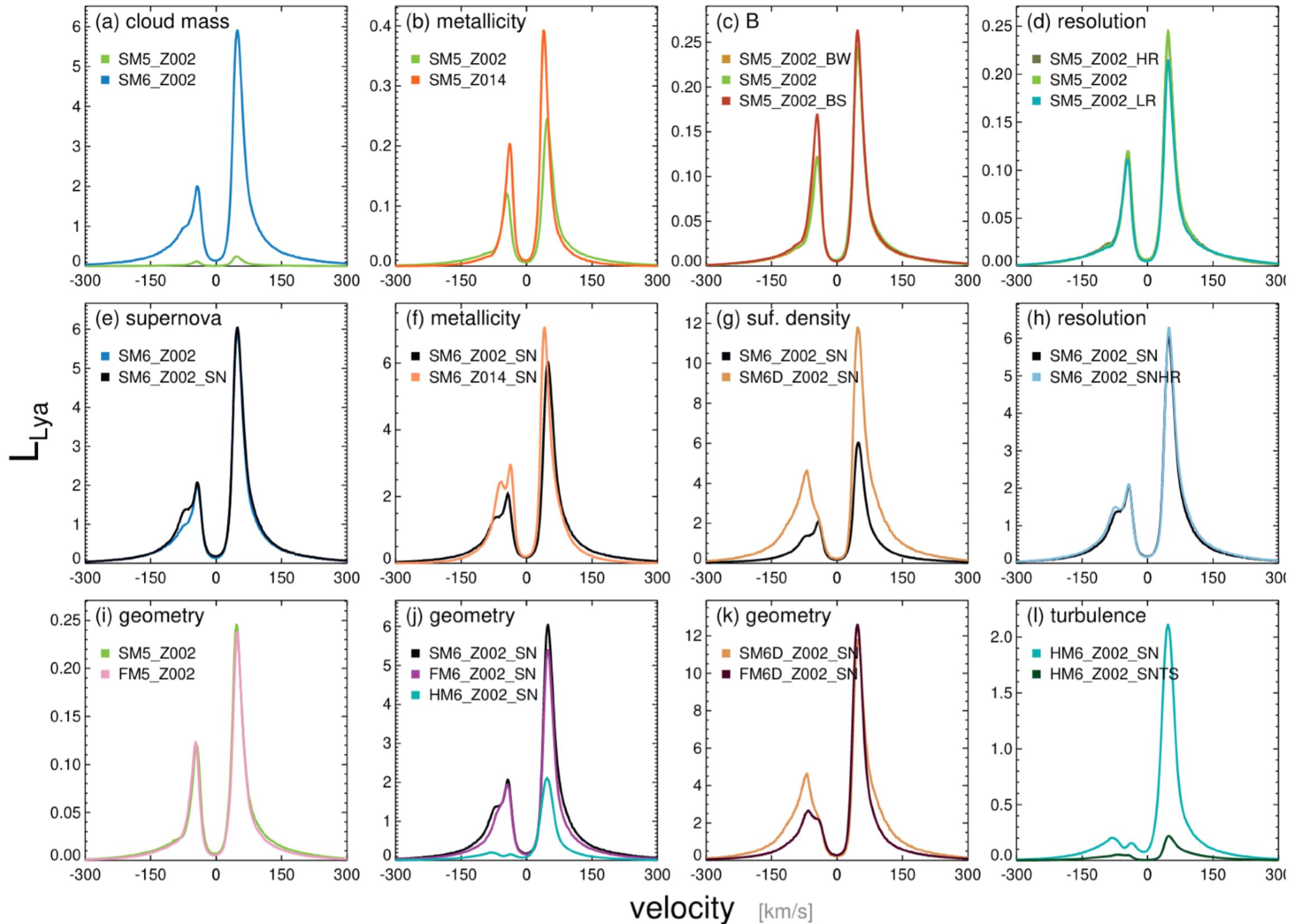
PRALINES + RASCAS

RASCAS: RAdiation SCattering in Astrophysical Simulations (Ly α radiative transfer) (Michel-Dansac+20)



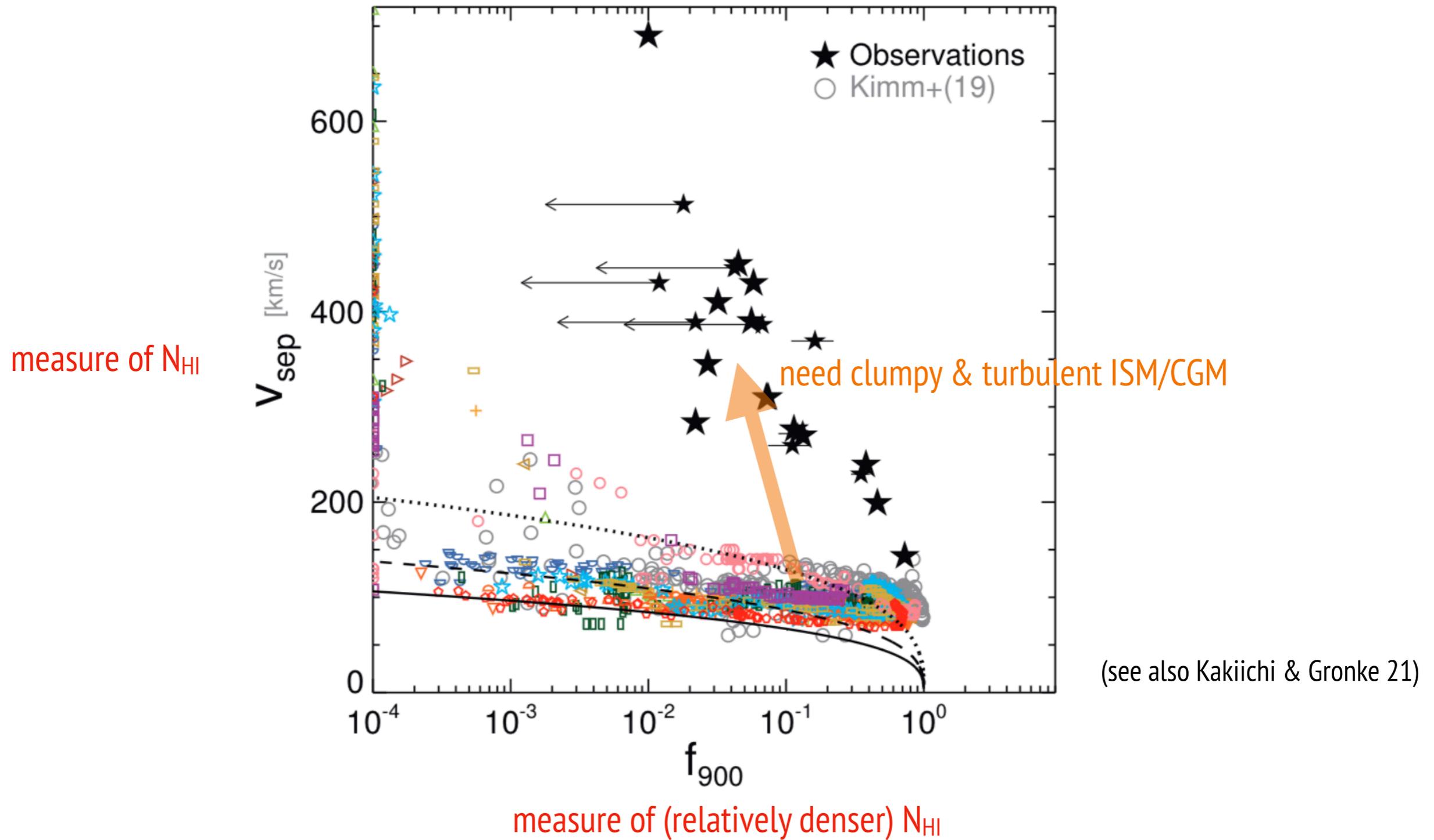
Clouds are bright in Ly α when they are being destroyed efficiently

Ly α spectra from simulated GMCs



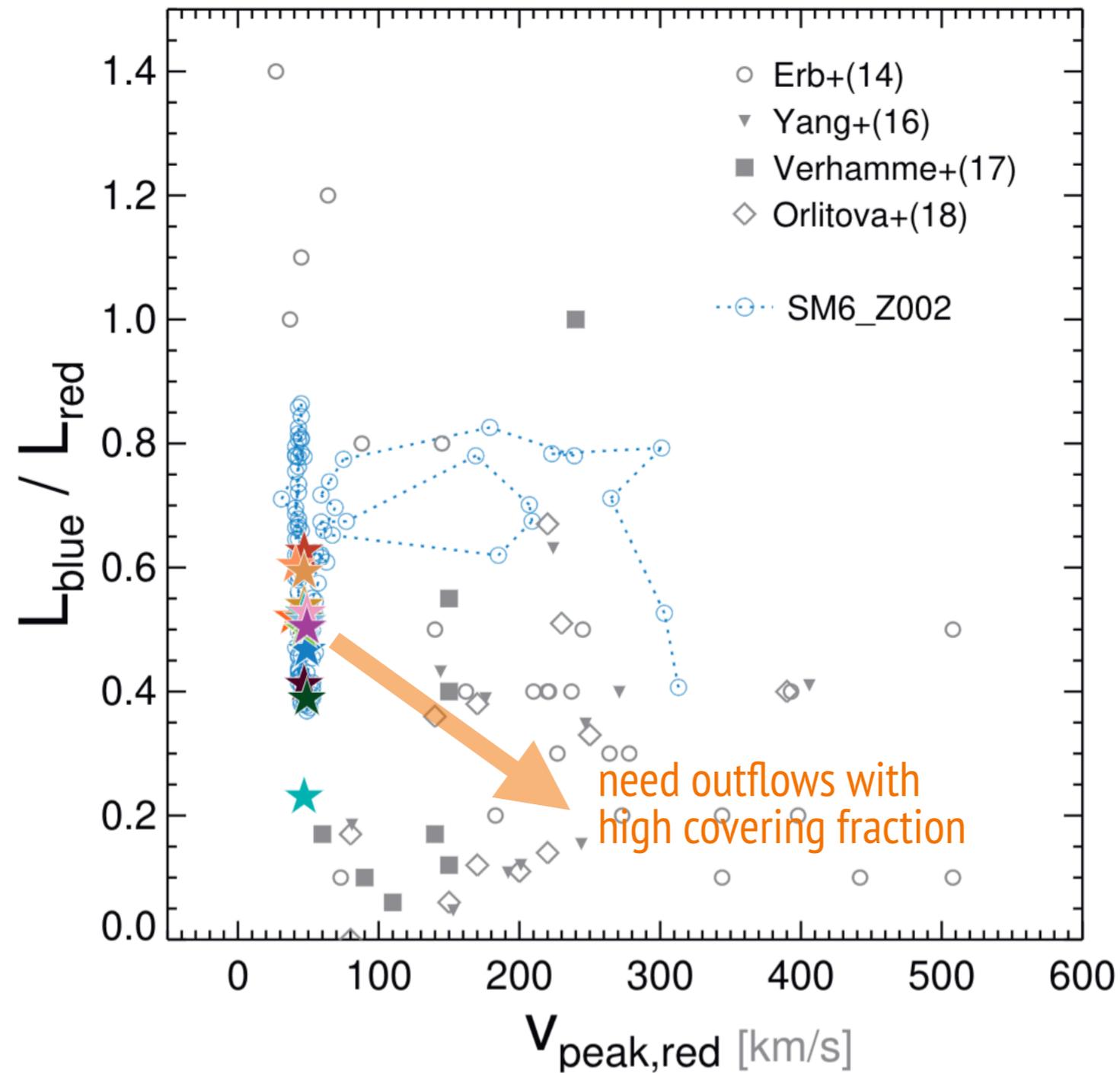
Relation between V_{sep} and f_{900}

f_{900} : escape fraction at 900Å



Solid, dashed, dotted lines: analytic v_{peak} with $T=20,000$ K and $\sigma_t = 0, 15, 30$ km/s

L_{α} properties from GMCs

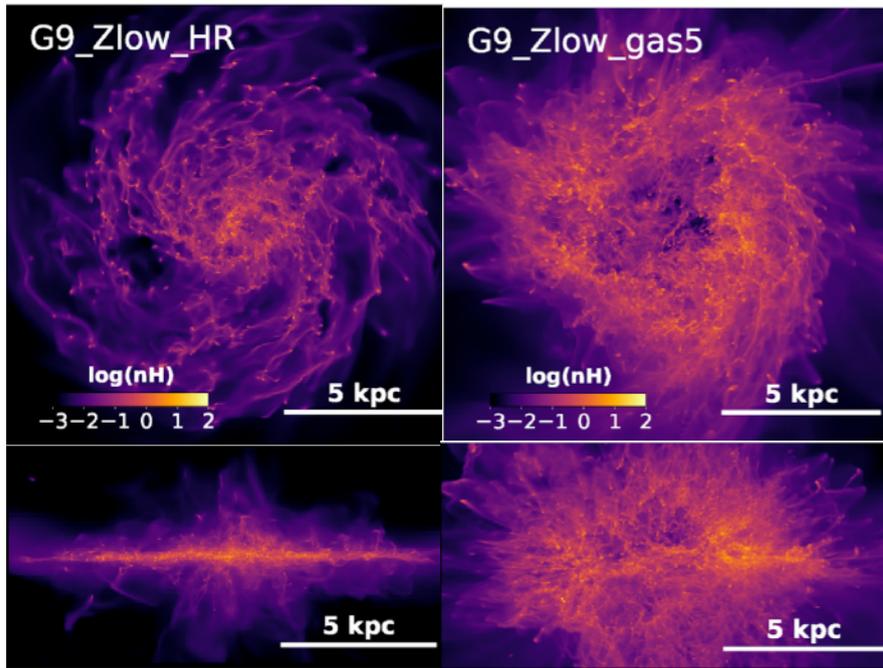


L_{α} properties are very similar on GMC scales

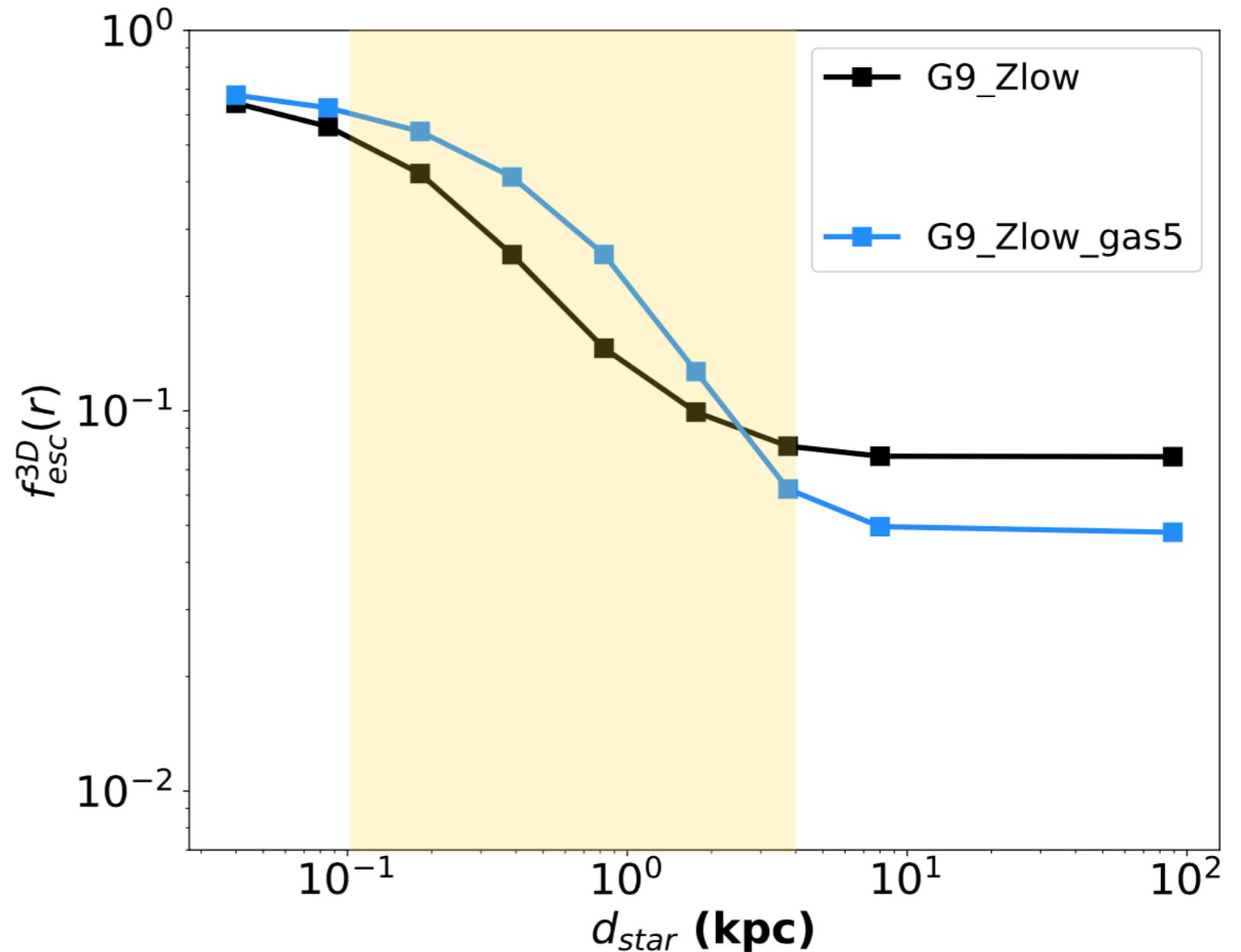
Summary

1. We have a little more understanding on the dependence of fesc on the physical properties of GMCs
-> Escape of LyC is more efficient if the GMC is **less massive, less dense, less metal-rich, and less turbulent**
2. PRALINE show that fesc is generally high on GMC scales ($\sim 20-70\%$), **maximal in clouds with $\sim 20\%$ SFE**
3. Dense clouds are not necessarily most efficient in the escape of LyC
4. Simulated GMCs show **very similar Ly α features** in terms of V_{sep} , B/R
-> may provide a useful window to study the ISM/CGM kinematics

Absorption of LyC due to the ISM



Yoo, Kimm, Rosdahl (20)



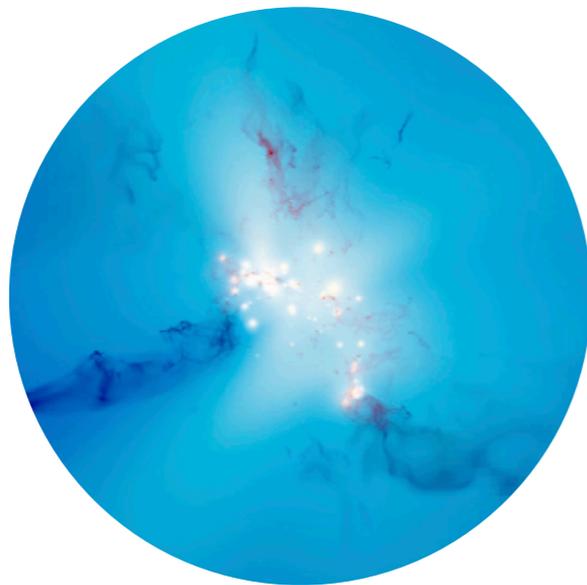
distance from each LyC source (i.e. star)

In galaxies with a well defined disk, a significant fraction of LyC radiation is absorbed between ~ 100 pc and ~ 4 kpc \rightarrow **reduction by a factor of $\sim 5-10!$**

A view on the propagation of LyC photons

Reionization theory with the current constraints (z_{reion}, τ_e) requires the escape fraction of 0.05 - 0.1

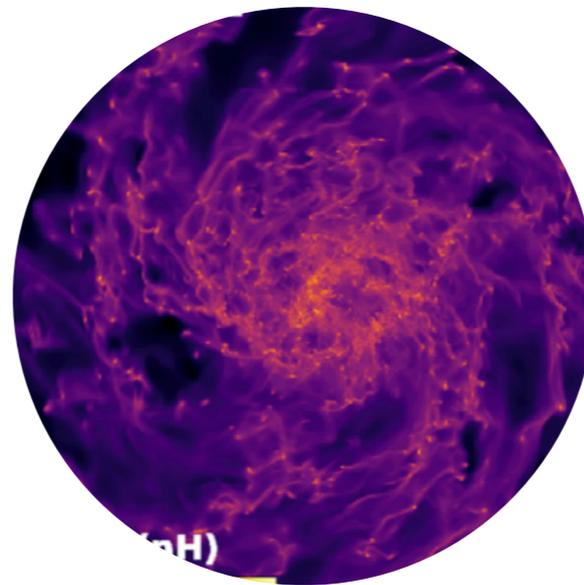
GMC



$$f_{\text{esc}} \sim 0.2 - 0.7$$

Radiation feedback

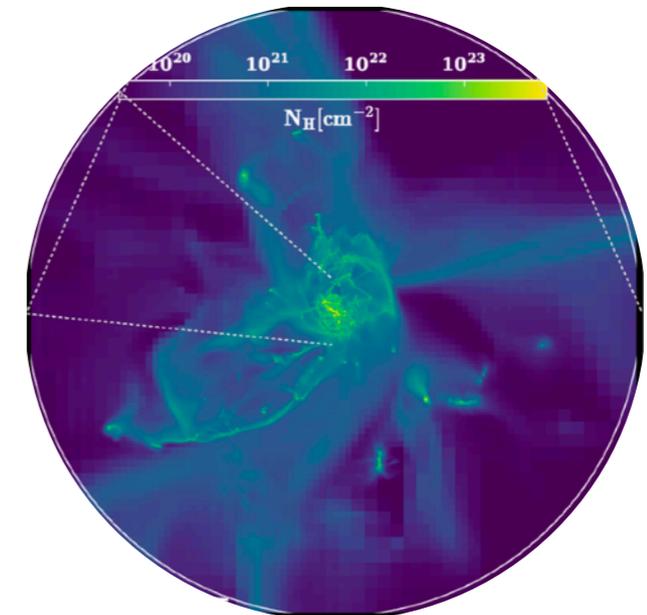
Galactic



$$f_{\text{esc}} \sim 0.05 - 0.2$$

Supernova feedback

Dark matter halo



$$f_{\text{esc}} \lesssim 0.05 - 0.1?$$

(Little absorption due to CGM?)

PRALINES?



Brioche aux pralines
(Praline-filled brioche)