Escape of LyC and LyA from PRALINE & G9 simulations

Preliminary results
Kimm et al. (2021, in prep)
Song et al. (2021, in prep)

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+RASCAS Team + ?

RASCAS/SPHINX/TRIPLE Meeting, 2 Feb 2021

Motivation

Why do we care small-scale propagation of LyC photons?

1. Propagation of LyC from GMCs: Reionization ($f_{esc,LyC}$~10%)
2. Cloud disruption: photo-ionization heating -> galactic outflows
3. LyA spectrum from GMCs -> galaxy kinematics

This talk will cover 1 and 3

Previous attempts: Dale+, Howard+,Kim+

Understanding the escape of LyC and Lyα photons from turbulent clouds

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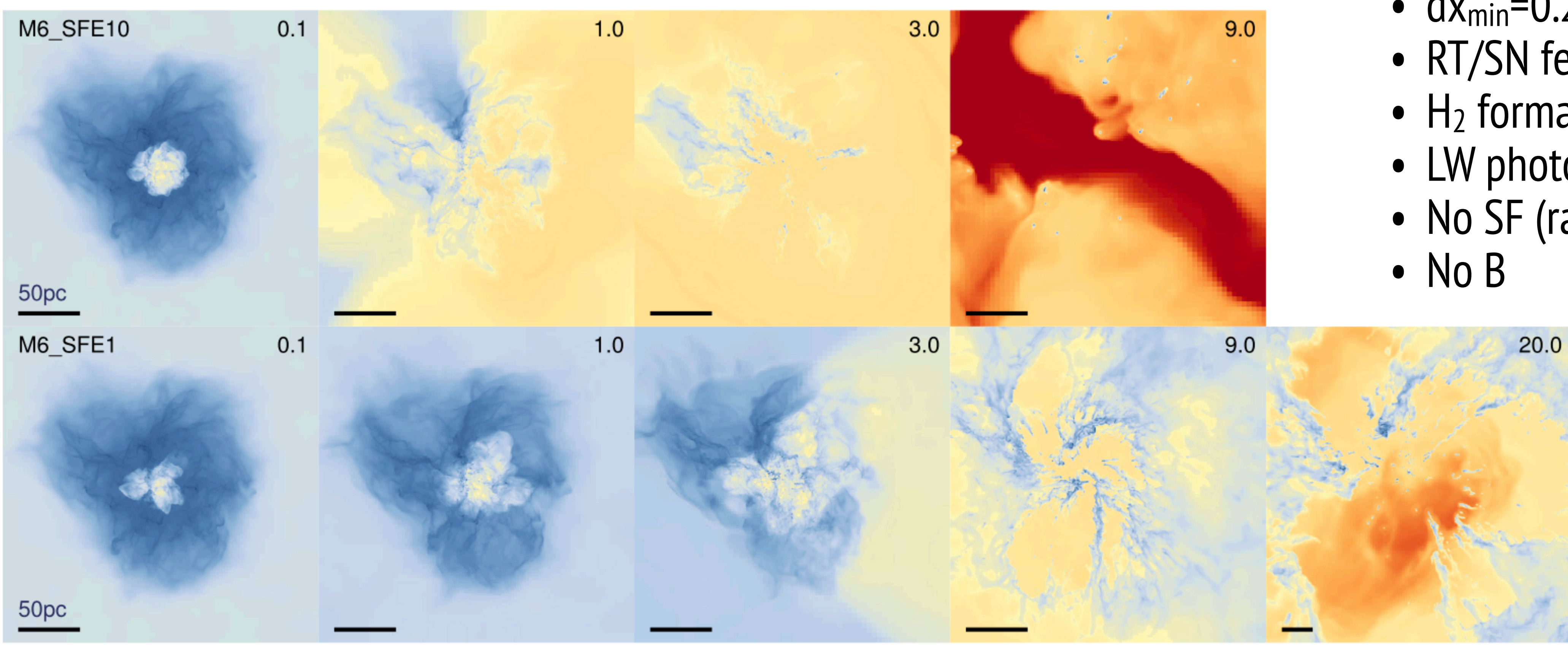
SFE=10%
(f_{LyC}~50-70%)

SFE=1%
(f_{LyC}~5-20%)



RAMSES-RT

- dx_{min}=0.25pc
- RT/SN feedback
- H_2 formation
- LW photons
- No SF (random)
- No B

Kimm et al. (2019)

Limitations

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

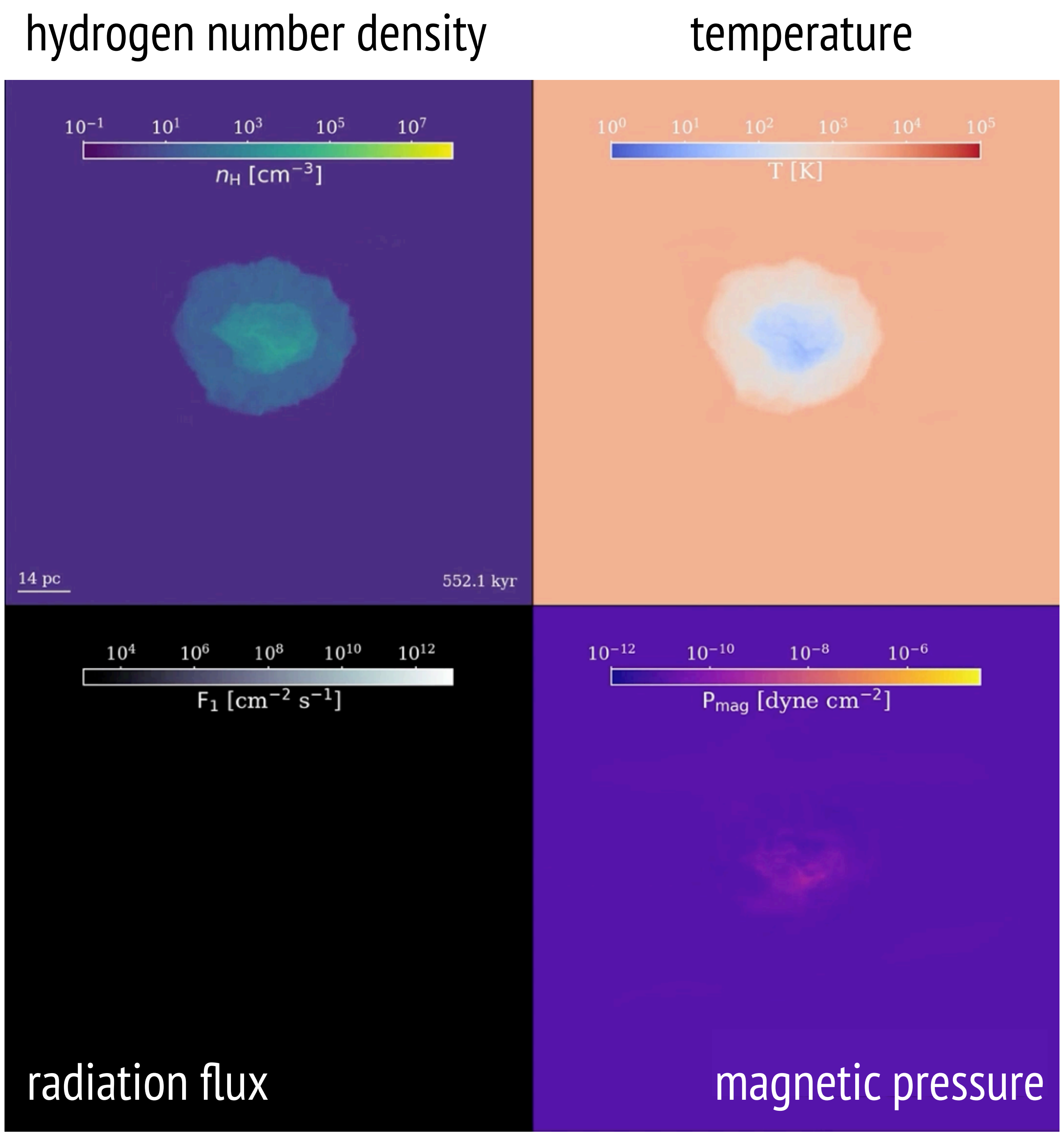
PRALINE simulations

RAMSES-RT

- dx_{min}=0.25 -> 0.02-0.08 pc
- RT/SN fbk -> No IR/thermal SN fbk
- ~~H_2 formation~~
- ~~LW photons~~
- No SF -> Sink particle algorithm
- No B - > Magnetic fields
- Various morphologies
- Two different surface densities
- Two different turbulent strength
- Metallicity
- Cloud mass
- Resolution

Total 20+ simulations so far

MPA (Germany)
Lyocca (France)
KISTI (Korea)
Cartesius (Netherlands)



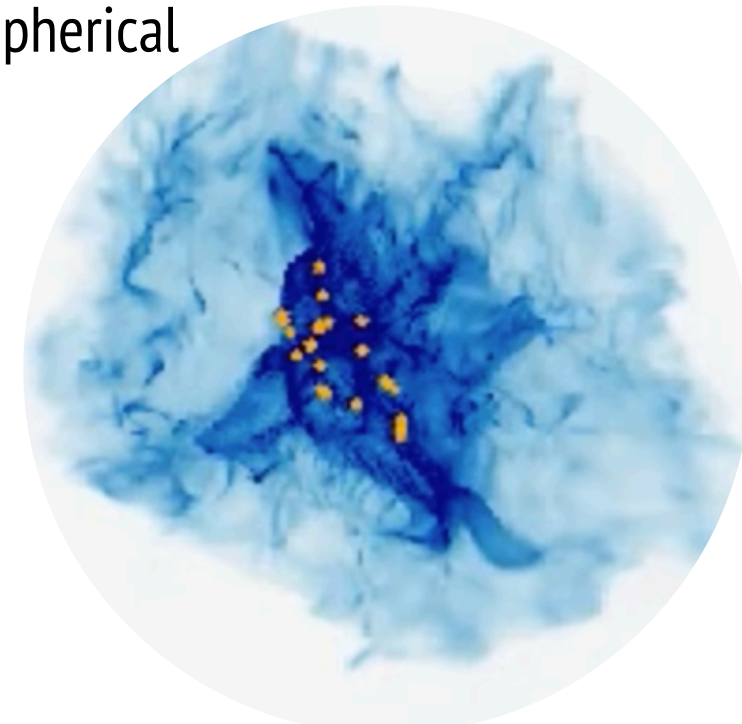
RMHD simulations of a GMC

PRALINE simulations

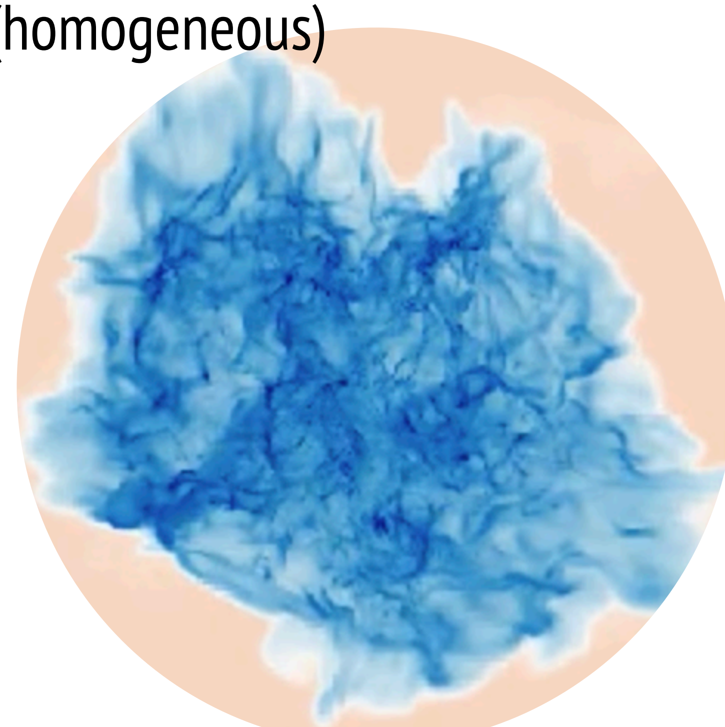
No	Name	$M_{\rm cloud}$ [$M_\odot$]	$\Sigma_{\rm gas}$ [$M_\odot$/pc^2]	Geometry	$Z_{\rm gas}$	$L_{\rm box}$ [pc]	$\Delta x_{\rm min}$ [pc]	β	SN	σ_v [km s^{-1}]	$t_{\rm final}$ [Myr]	SFE	Remark
01	`SM5_Z002`	10^5	90	Spherical	0.002	173	0.04	0.31	–	2.9	8.4	0.26	
02	`SM5_Z014`	10^5	90	Spherical	0.014	173	0.04	0.31	–	2.9	8.4	0.26	
06	`SM5_Z002_HR`	10^5	90	Spherical	0.002	173	0.02	0.31	–	2.9	8.4	0.24	
07	`SM5_Z002_LR`	10^5	90	Spherical	0.002	173	0.08	0.31	–	2.9	8.4	0.19	
04	`SM5_Z002_BW`	10^5	90	Spherical	0.002	173	0.04	2.89	–	2.9	8.4	0.22	
05	`SM5_Z002_BS`	10^5	90	Spherical	0.002	173	0.04	0.03	–	2.9	8.4	0.16	
117	`SM6_Z002`	10^6	200	Spherical	0.002	317	0.08	0.11	–	11.5	8.3	0.51	
17	`SM6_Z002_SN`	10^6	200	Spherical	0.002	317	0.08	0.11	✓	11.5	8.3	0.51	
23	`SM6_Z014_SN`	10^6	200	Spherical	0.014	317	0.08	0.11	✓	11.5	8.3	0.64	
26	`SM6_Z002_SNHR`	10^6	200	Spherical	0.002	317	0.04	0.11	✓	11.5	8.3	0.55	
10	`SM6D_Z002`	10^6	650	Spherical	0.002	208	0.05	0.01	–	11.4	4.5	0.87	
08	`SM6D_Z014`	10^6	650	Spherical	0.014	208	0.05	0.01	–	11.4	4.5	0.95	
11	`SM6D_Z002_SN`	10^6	650	Spherical	0.002	208	0.05	0.01	✓	11.4	4.5	0.86	
03	`FM5_Z002`	10^5	90	Filamentary	0.002	173	0.04	0.31	–	2.7	8.4	0.18	
20	`FM6_Z002_SN`	10^6	200	Filamentary	0.002	317	0.08	0.11	✓	10.3	8.3	0.44	
12	`FM6D_Z002_SN`	10^6	650	Filamentary	0.002	208	0.05	0.01	✓	11.5	4.4	0.68	
128	`HM6_Z002_SN`	10^6	200	Homo-sph	0.002	320	0.08	0.24	✓	9.1	8.3	0.17	
28	`HM6_Z002_SNST`	10^6	200	Homo-sph	0.002	320	0.08	0.11	✓	16.3	8.3	0.01	

Various morphologies from PRALINE

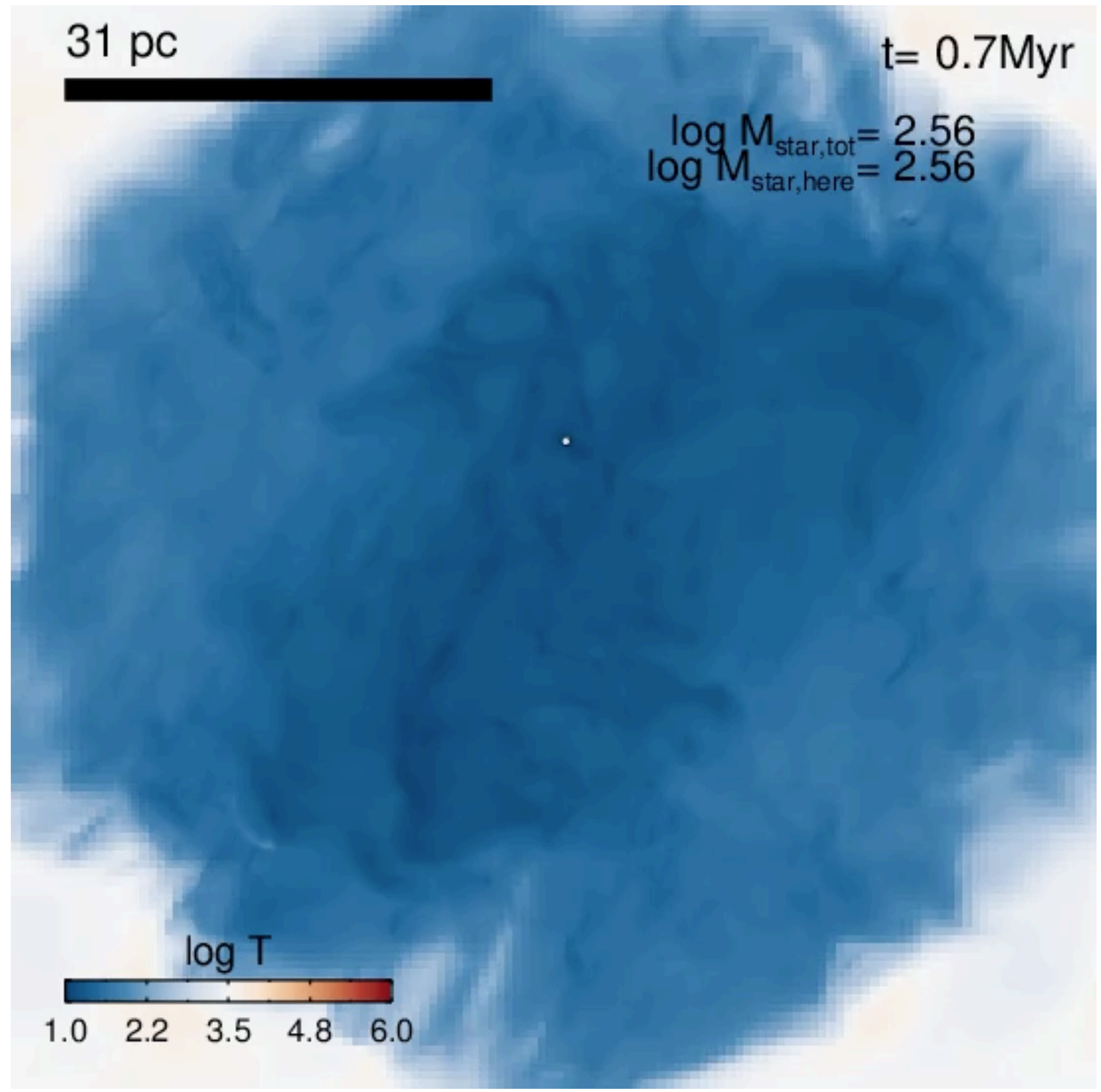
Spherical



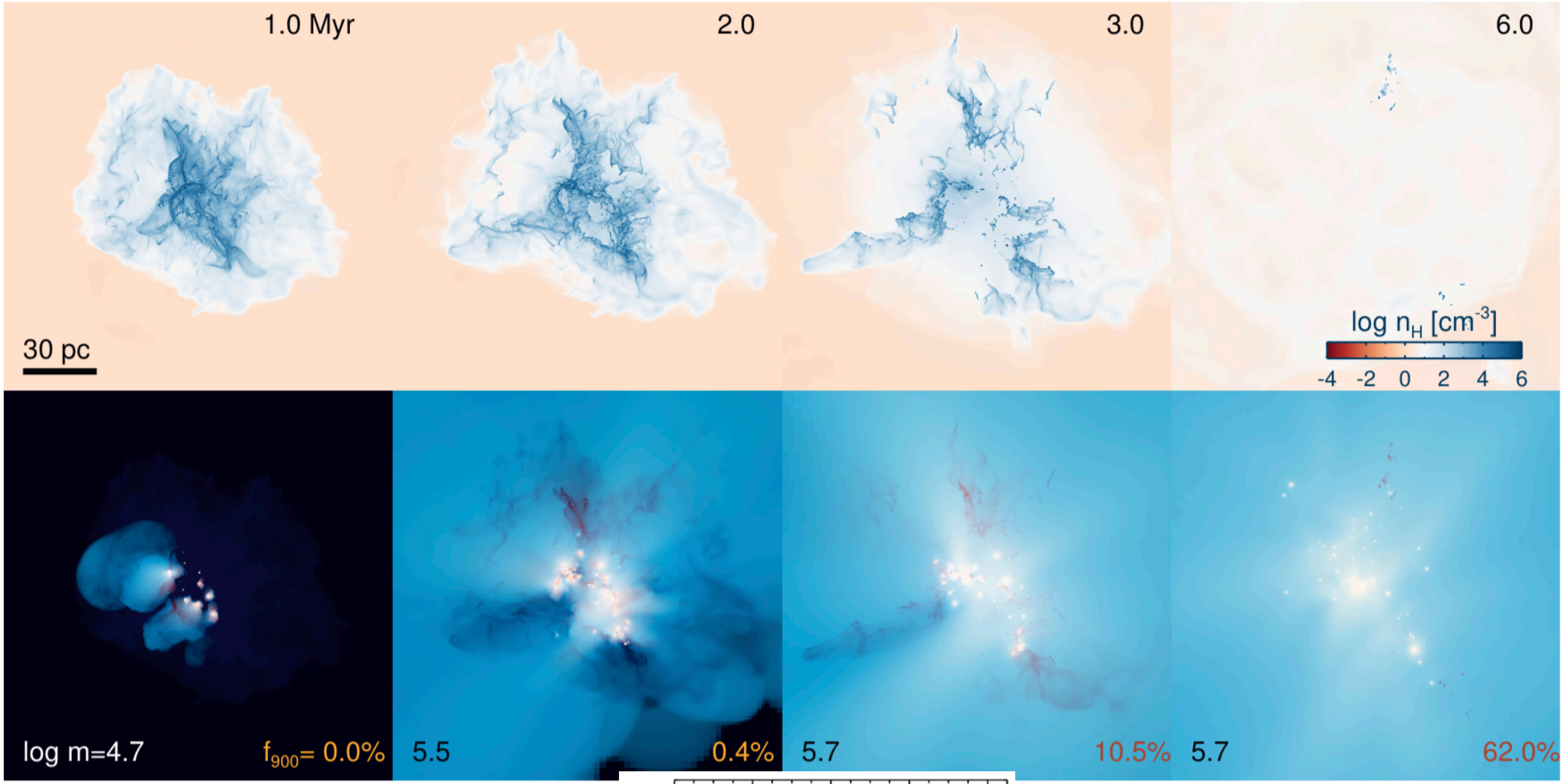
Spherical (homogeneous)

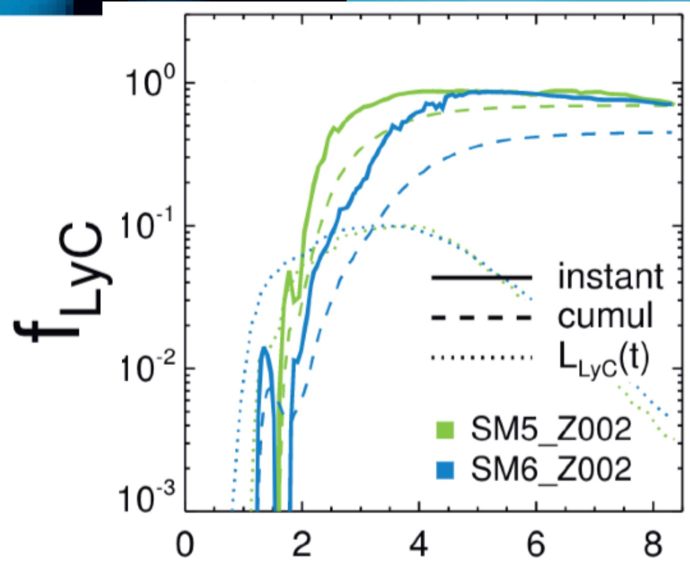


Filamentary

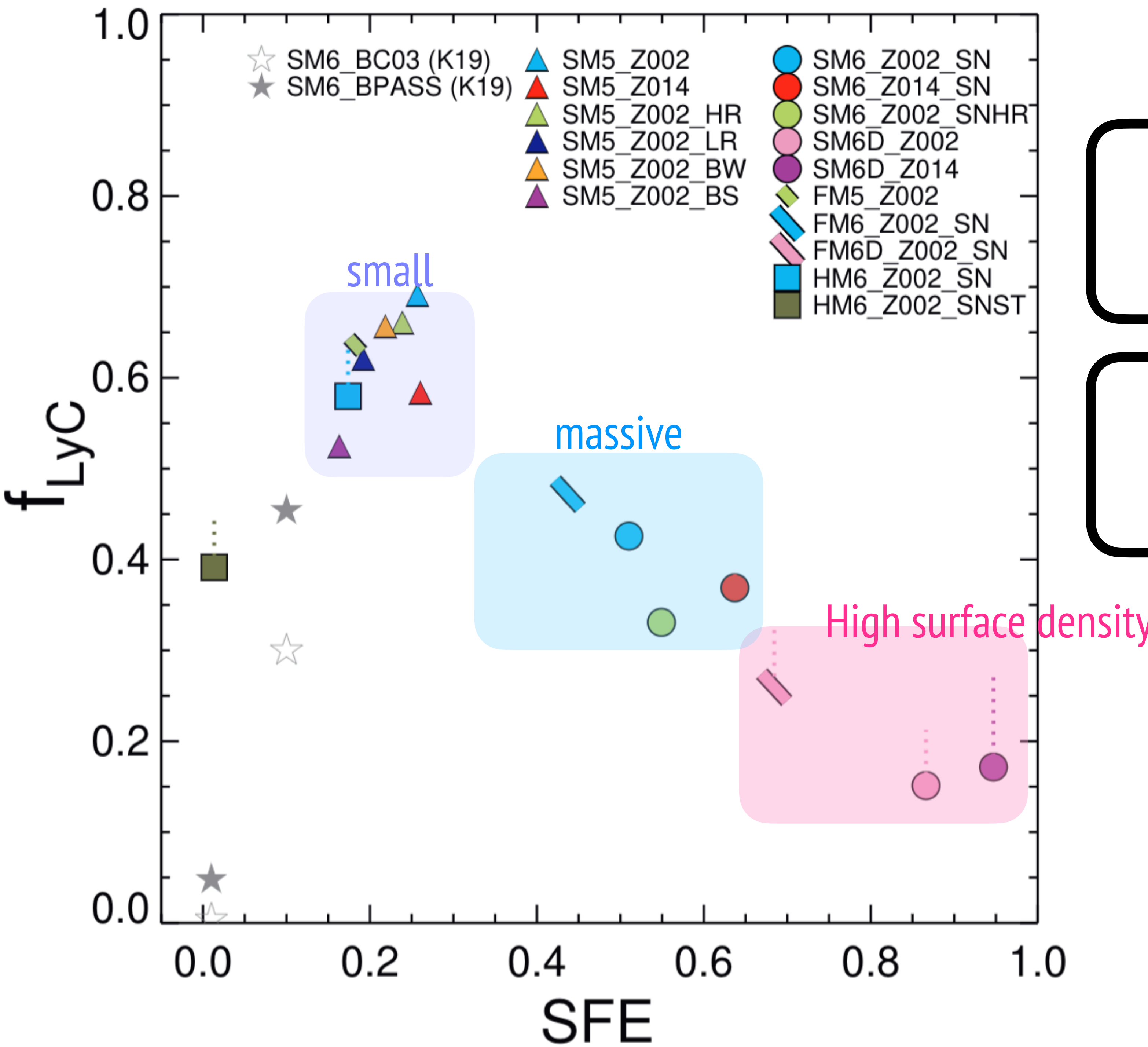


General evolutionary trend from PRALINE





What determines $f_{esc,LyC}$?

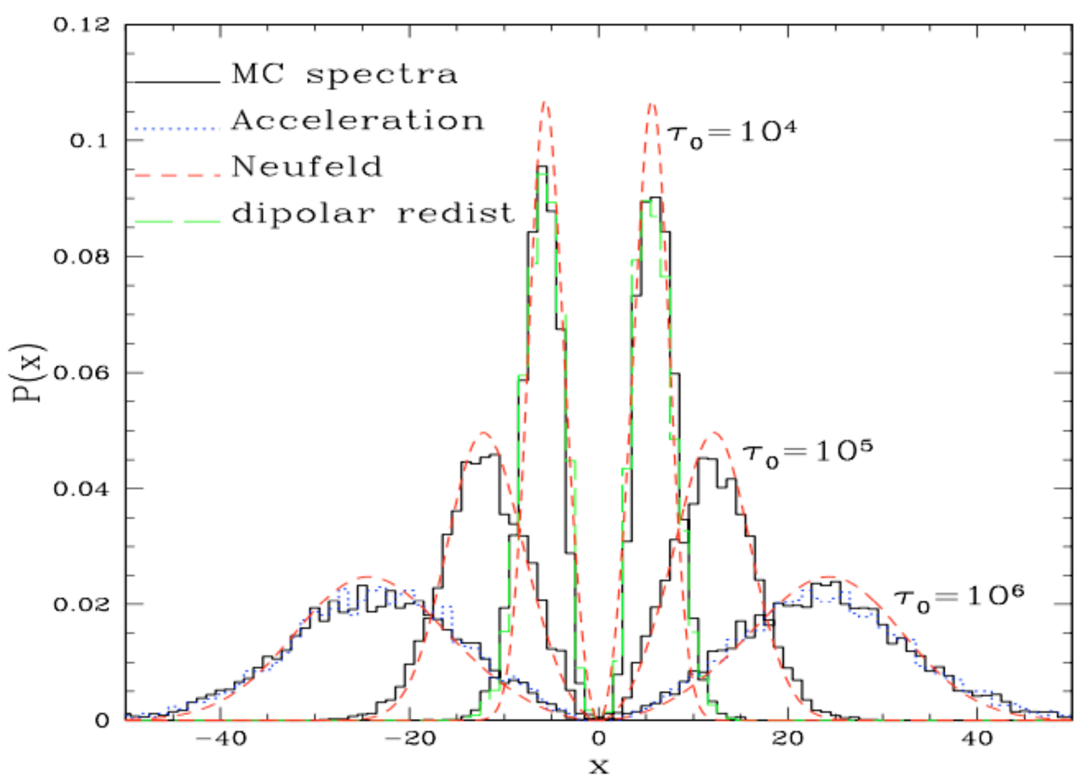


f_{LyC} is high ~20-70% in GMCs

Escape of LyC is most efficient in clouds with ~20% SFE

Connection between LyC and LyA photons

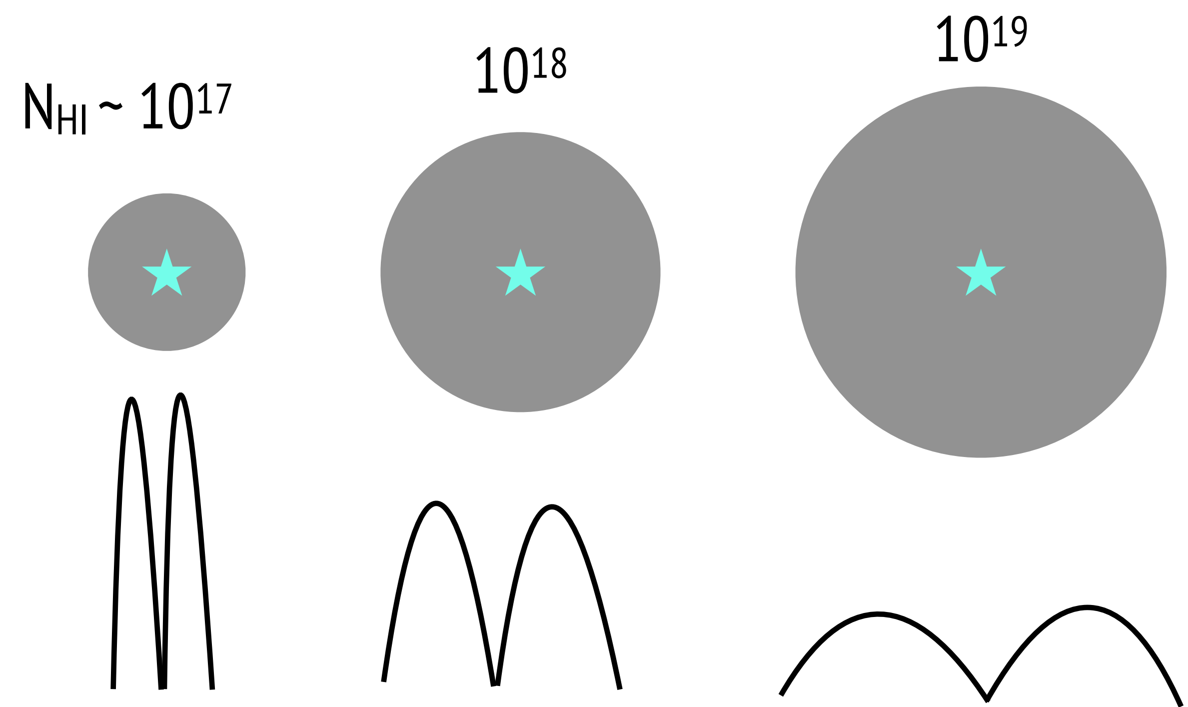
- LyC photons: non-resonant; reionization, absorbed by $N_{HI} > 10^{17}$ cm^{-2}
- LyA photons: resonant; galaxy kinematics, scattered by $N_{HI} > 10^{14}$ cm^{-2}



Verhamme+(06)

Vsep

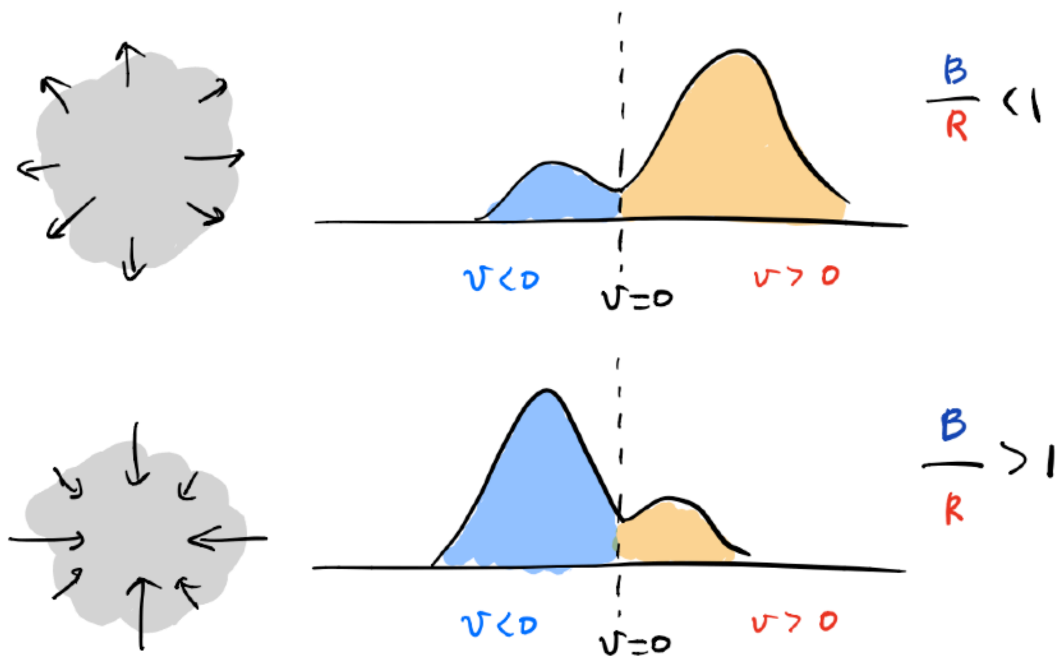
$$x \equiv -\frac{v}{b}$$

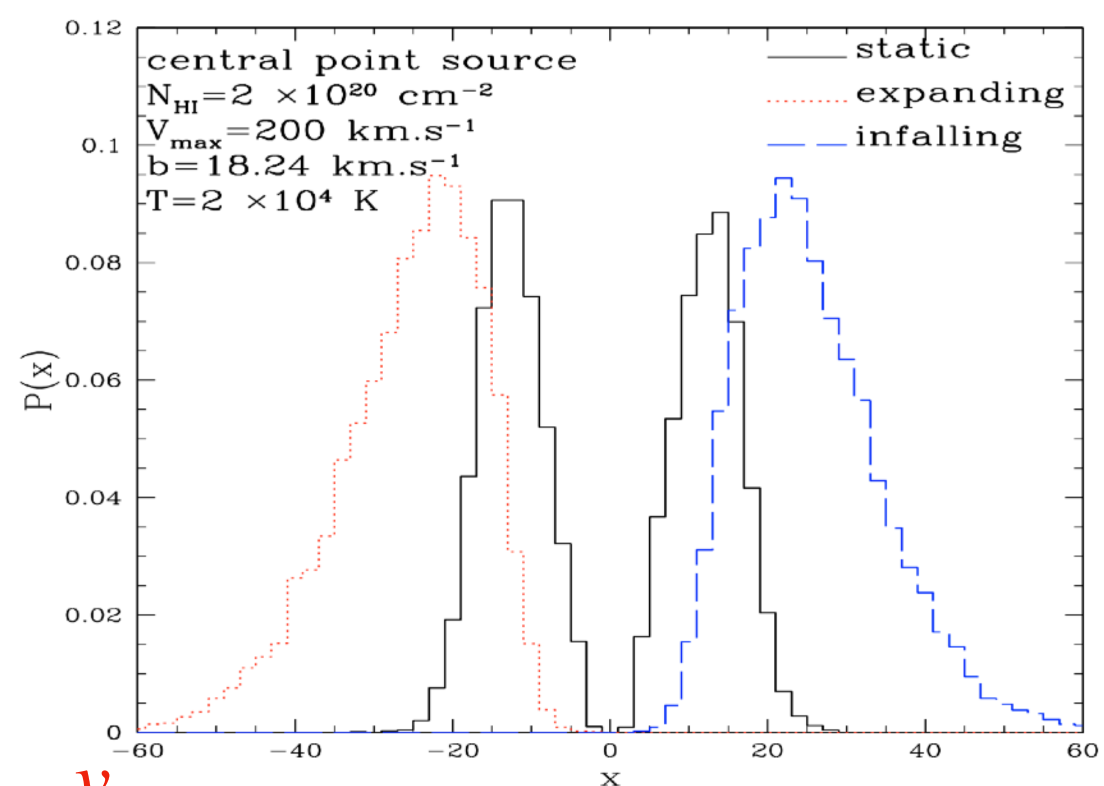


Vsep: measure of N_{HI}

Connection between LyC and LyA photons

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





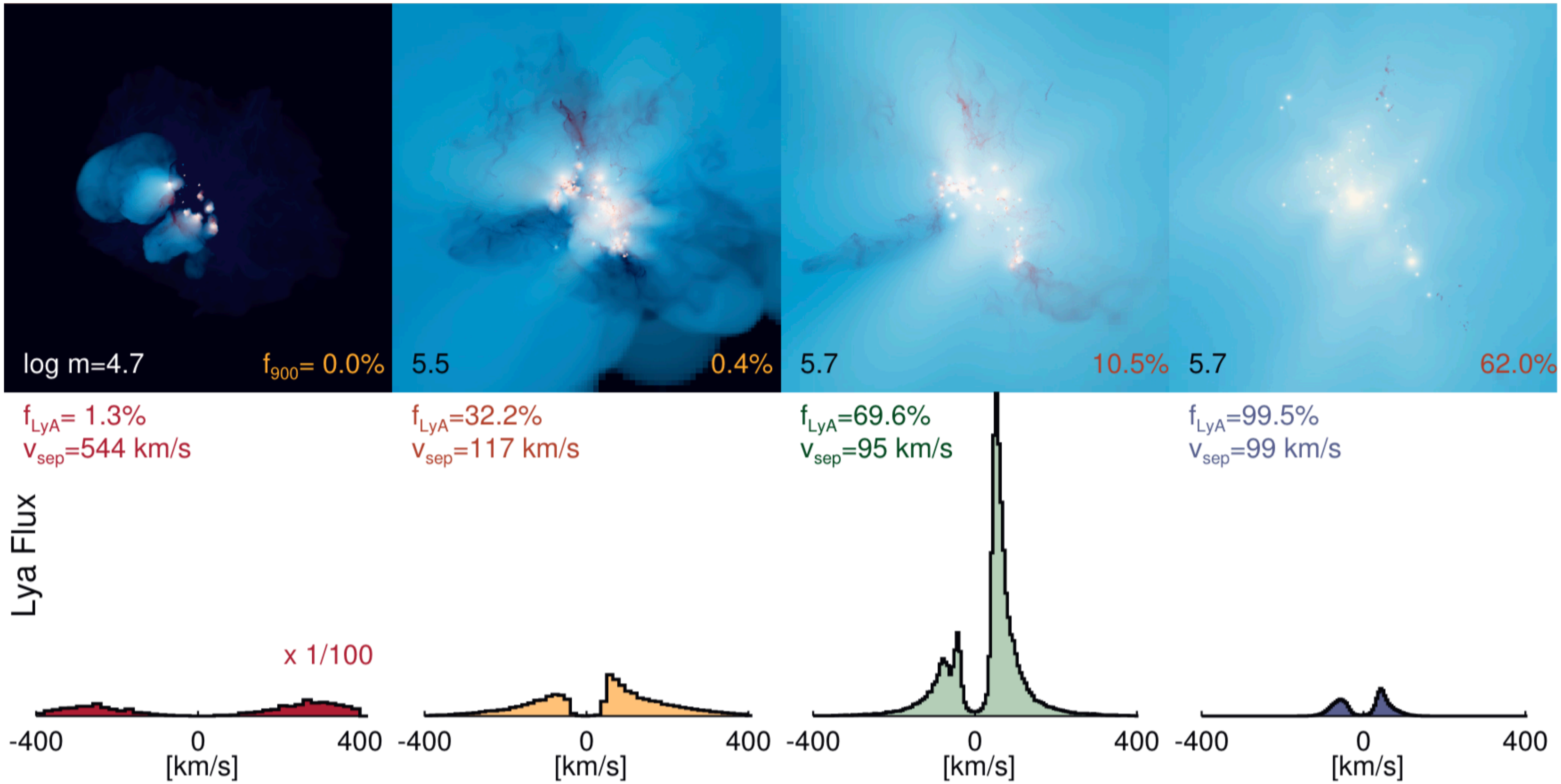
$$x \equiv -\frac{v}{b}$$

Verhamme+(06)

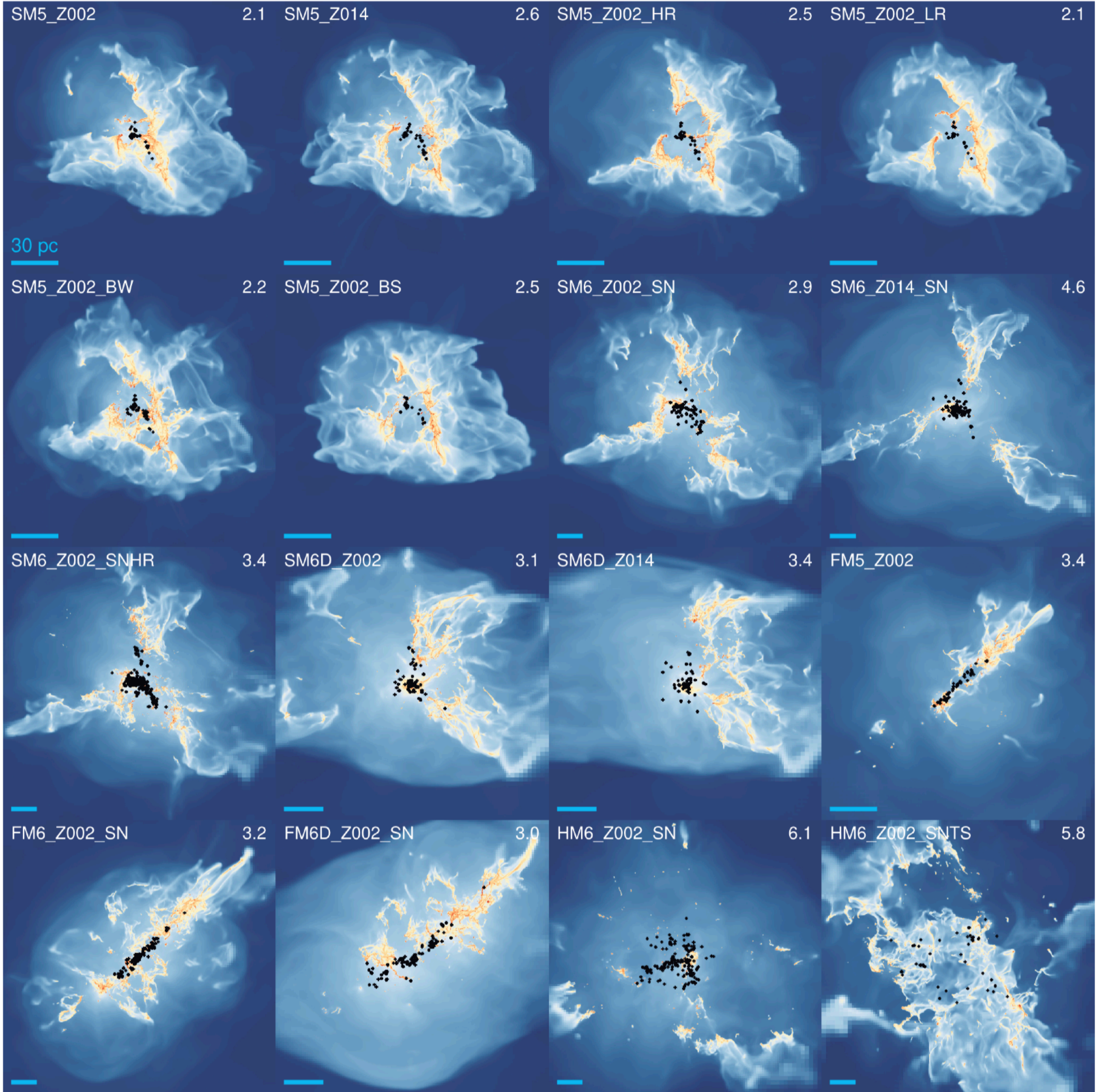
Blue-to-red flux: measure of kinematics

PRALINE + RASCAS

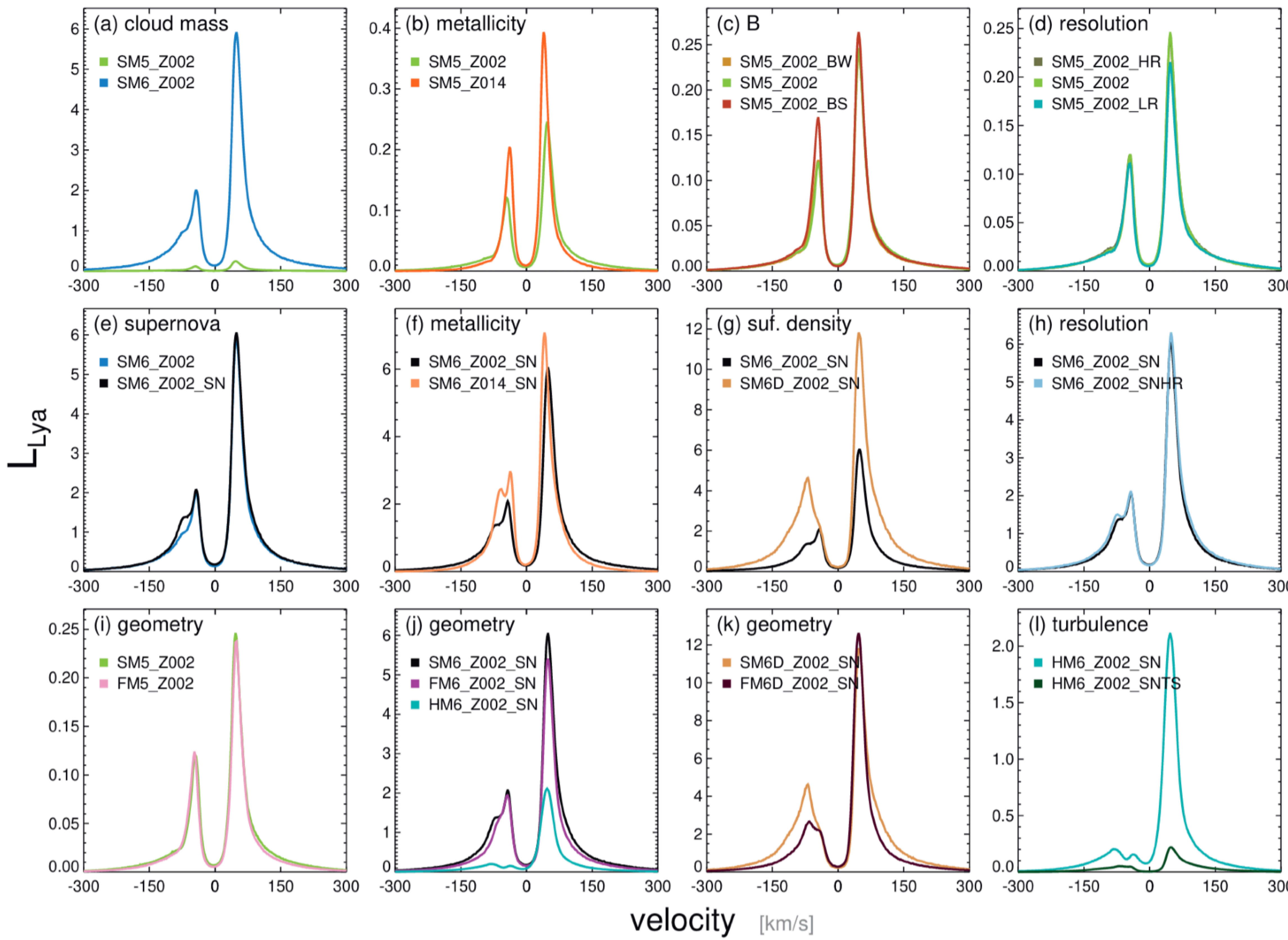
RASCAS: RAdiation SCattering in Astrophysical Simulations (Lya radiative transfer) (Michel-Dansac+20)



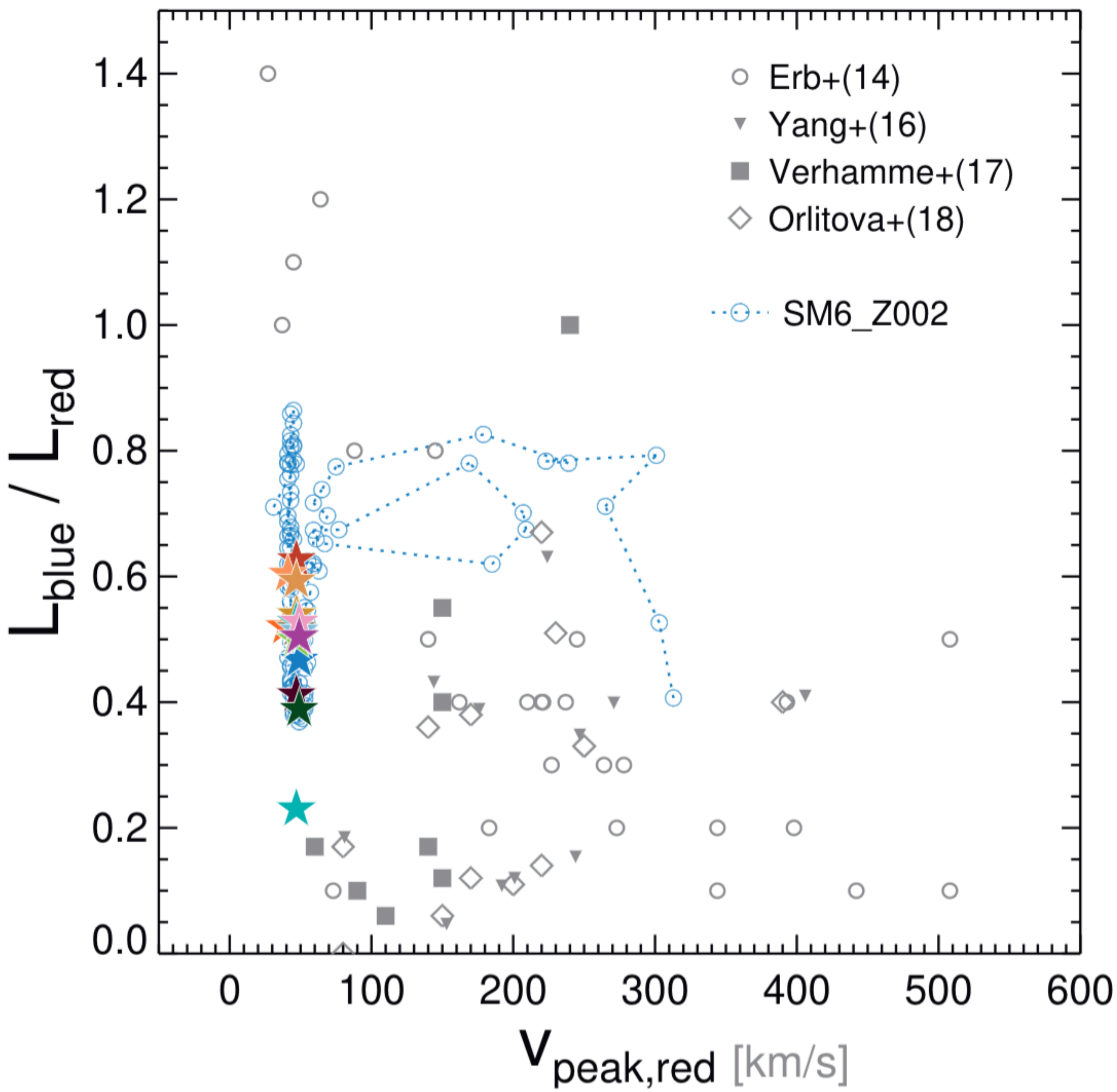
Clouds are bright in Lya when they are being destroyed efficiently


SM5_Z002 2.1
SM5_Z014 2.6
SM5_Z002_HR 2.5
SM5_Z002_LR 2.1
30 pc
SM5_Z002_BW 2.2
SM5_Z002_BS 2.5
SM6_Z002_SN 2.9
SM6_Z014_SN 4.6
SM6_Z002_SNHR 3.4
SM6D_Z002 3.1
SM6D_Z014 3.4
FM5_Z002 3.4
FM6_Z002_SN 3.2
FM6D_Z002_SN 3.0
HM6_Z002_SN 6.1
HM6_Z002_SNTS 5.8

Lya spectra from simulated GMCs



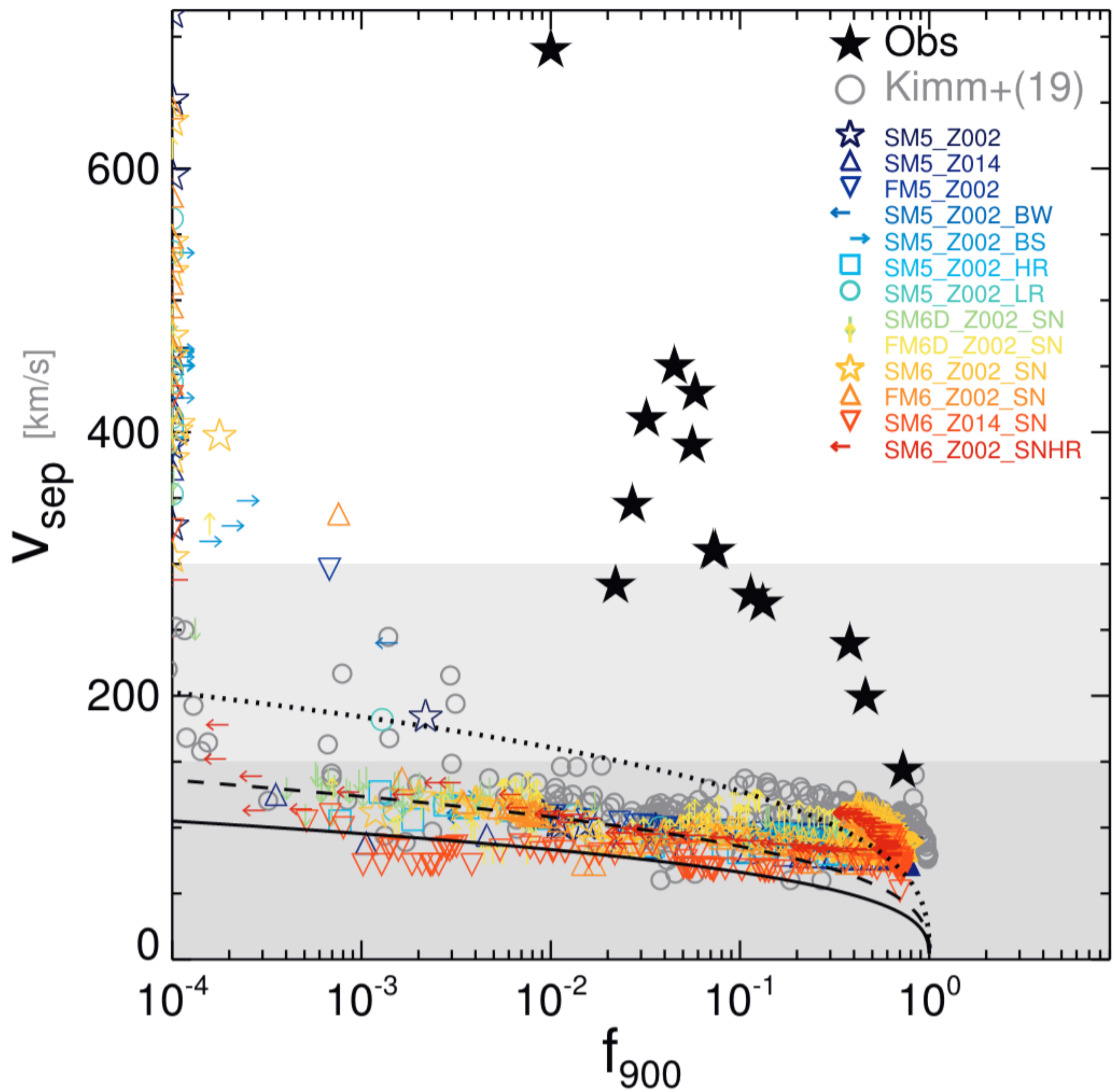
Lya properties from GMCs



Lya properties are very similar on GMC scales

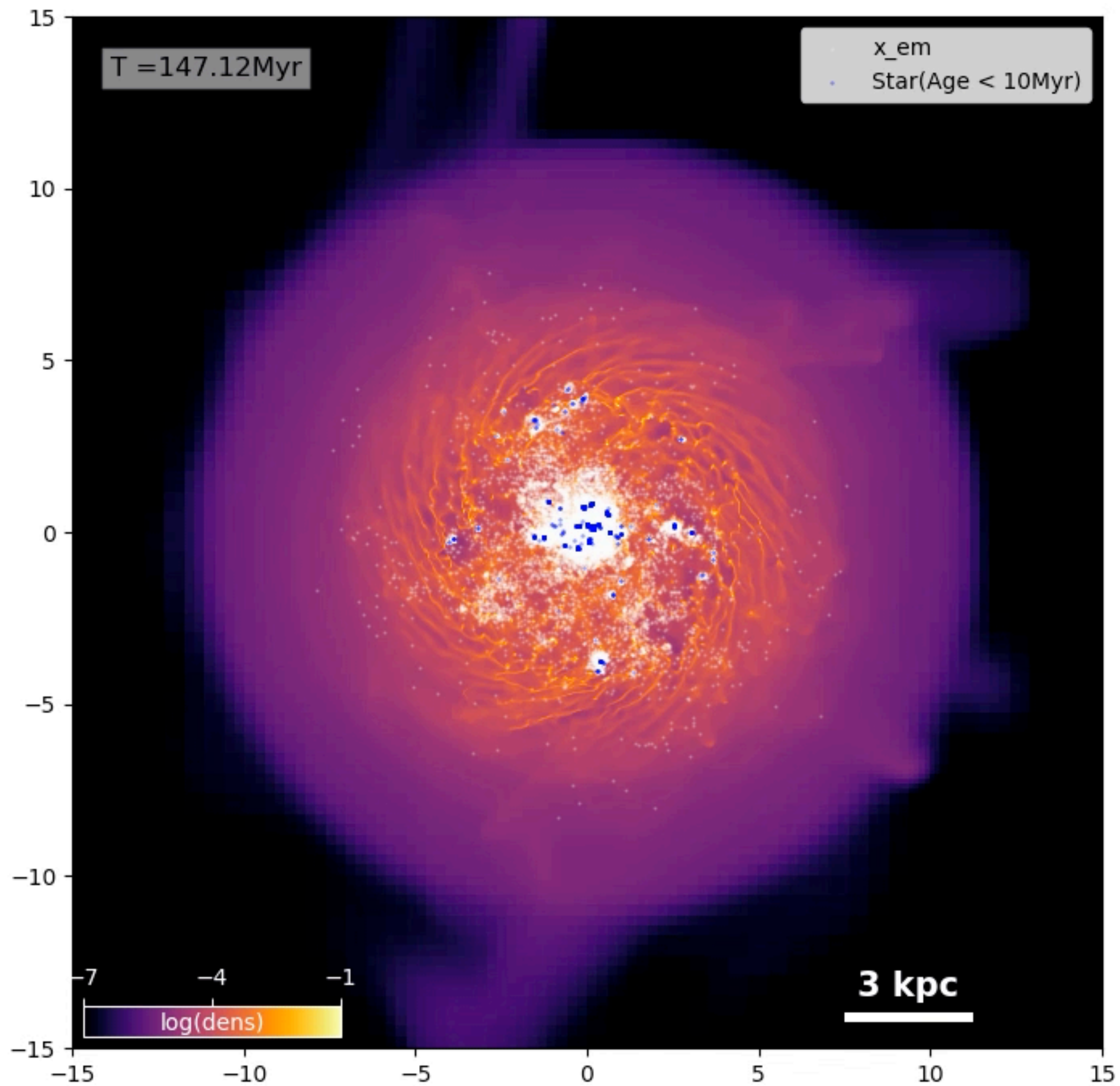
Relation between V_{sep} and f_{900}

f_{900}: escape fraction at 900A



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

Lya spectra from isolated galaxies

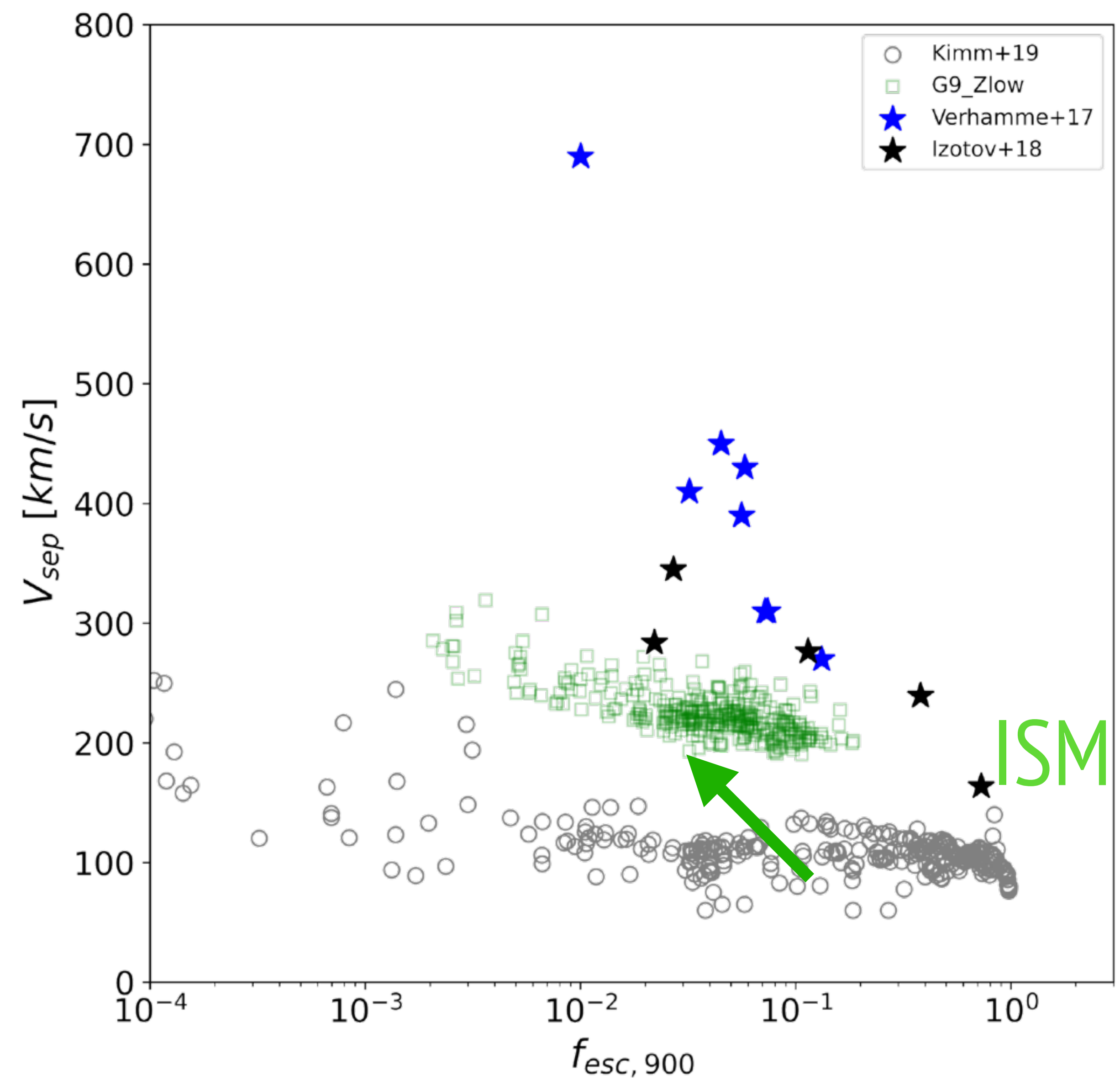


White: Lya source position

RHD simulation of an isolated galaxy embedded in a 10^{11} M_{sun} DMH

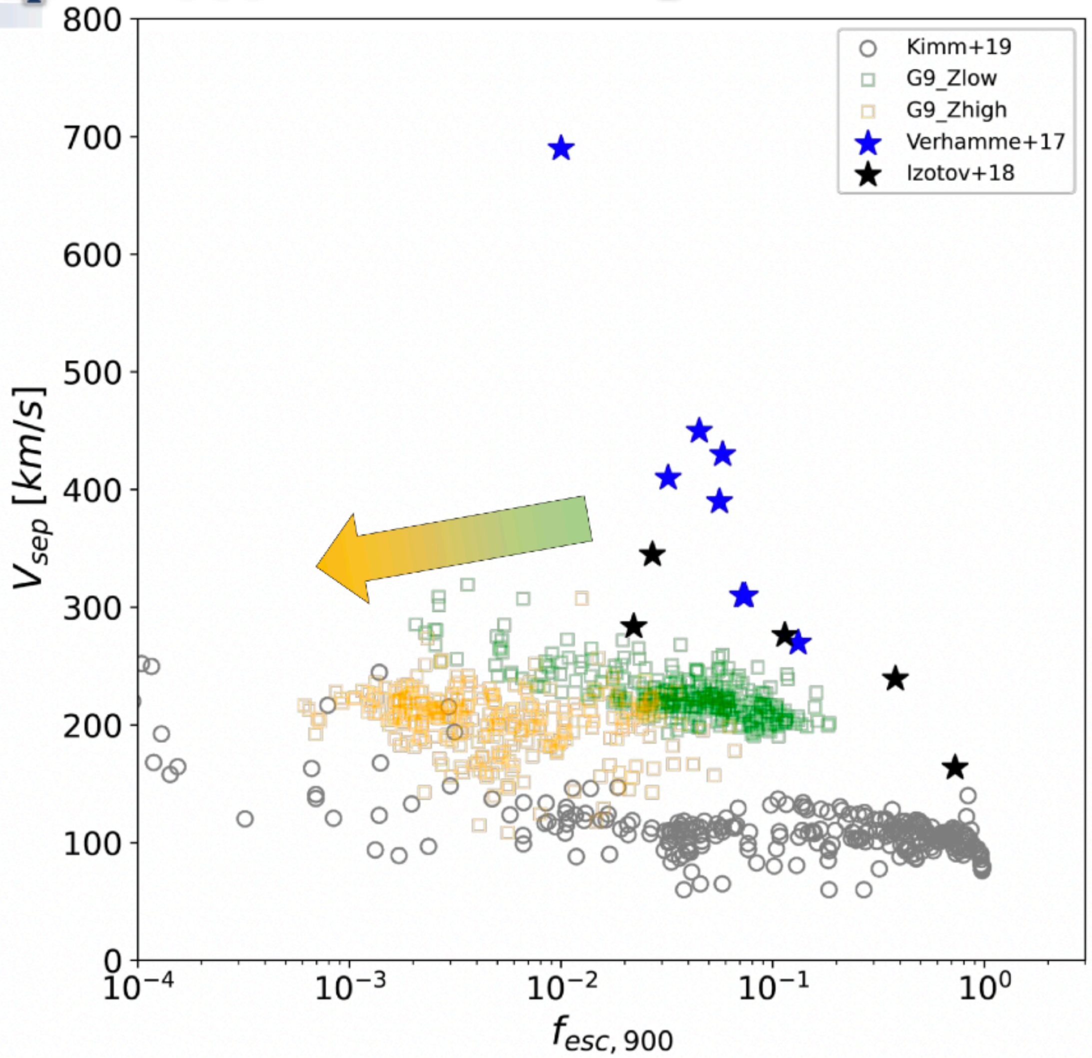
Do Woon Lee

Hyunmi Song

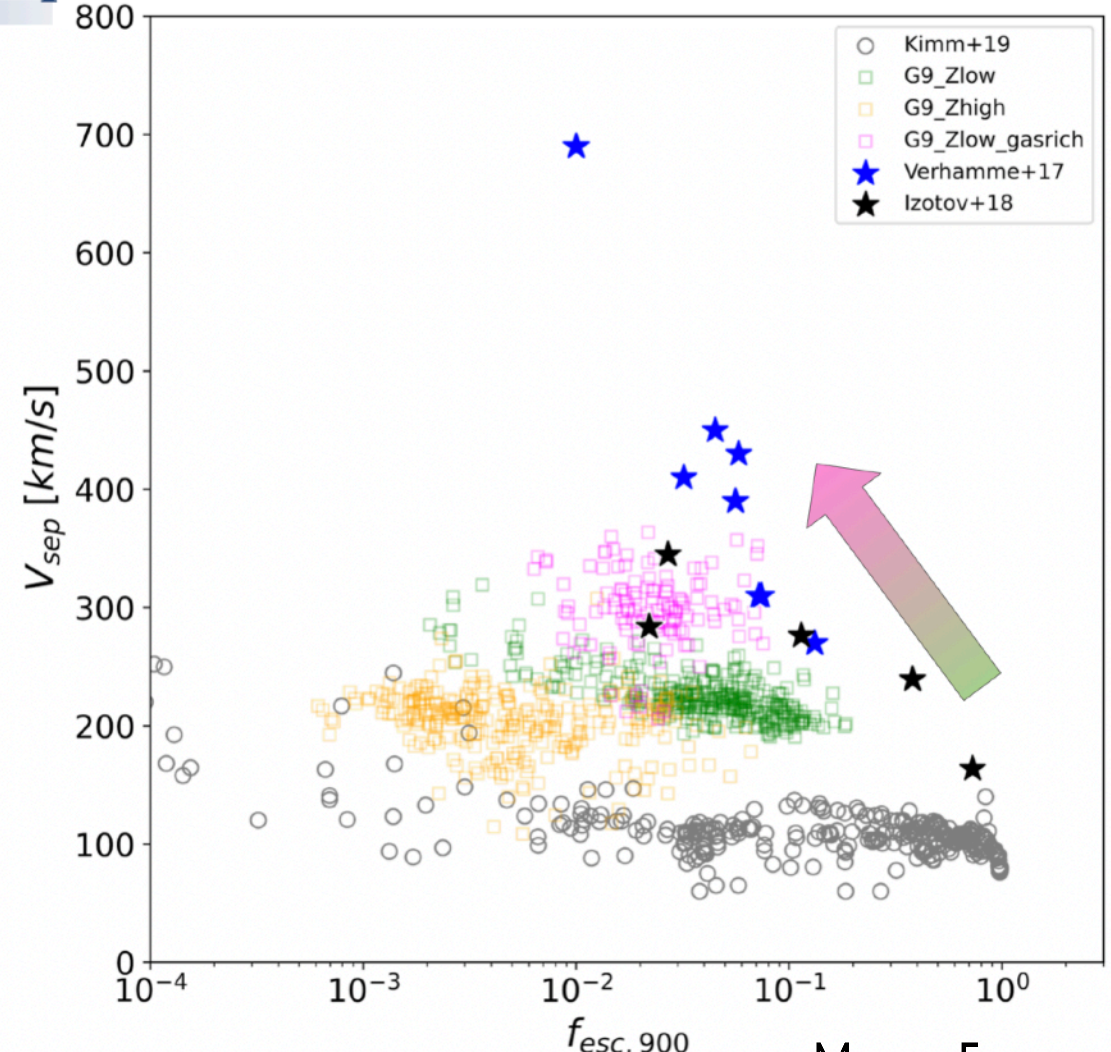


Lya spectra from isolated galaxies

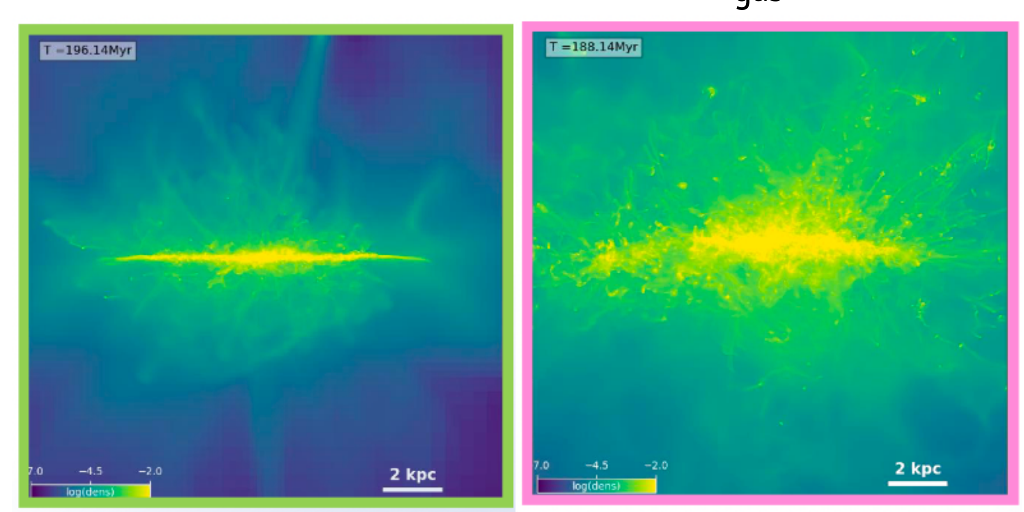
$V_{sep} - f_{900}$: Metallicity



$V_{sep} - f_{900}$: Gas fraction



M_{gas} x 5

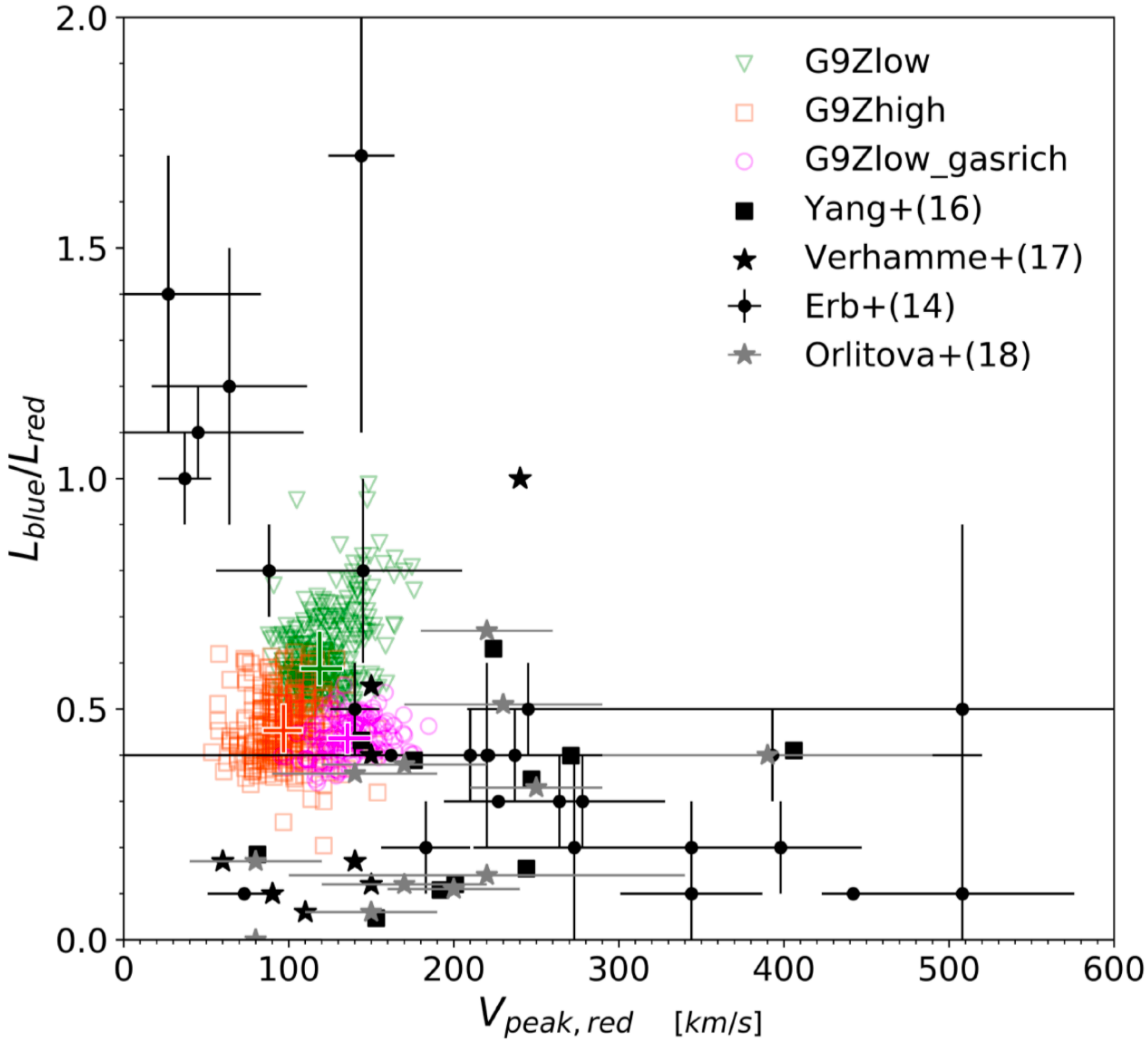


- Metallicity ↑ -> dust ↑ -> Vsep ↓
- dust ↑ -> difficult to destroy GMCs -> f900 ↓

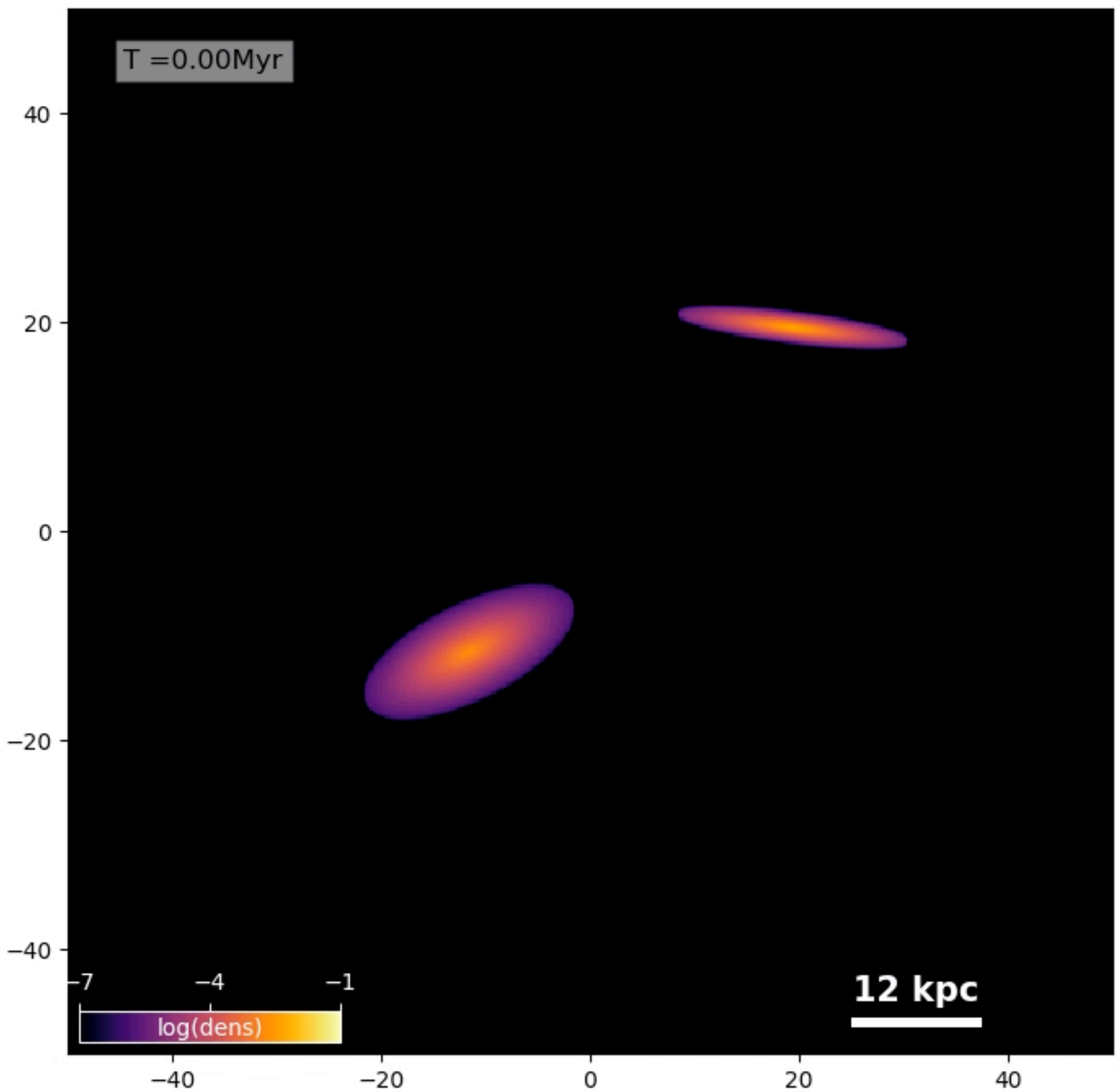
Reasonable agreement? Maybe not

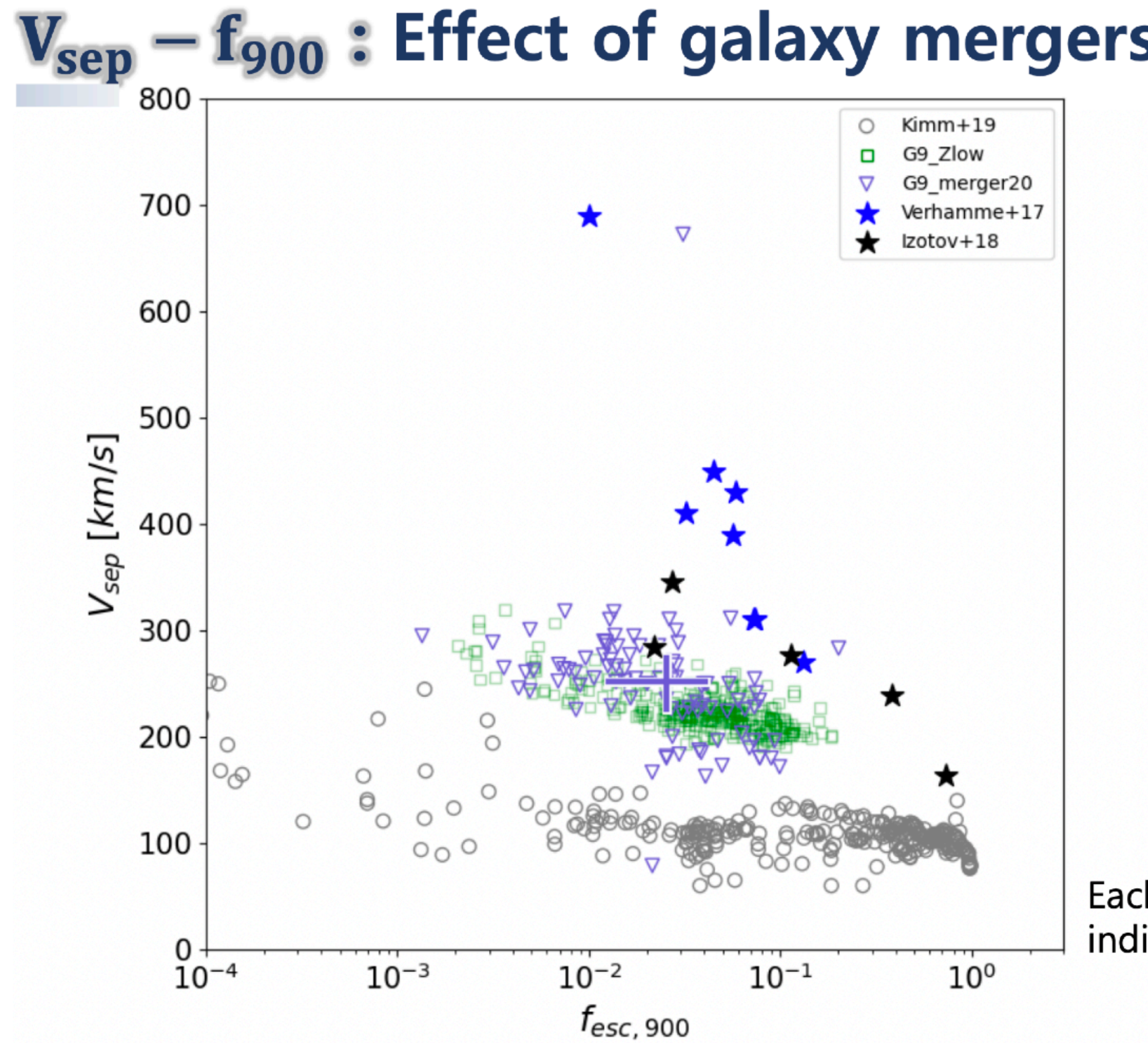
infalling

outflowing



Lya spectra from a merging galaxy

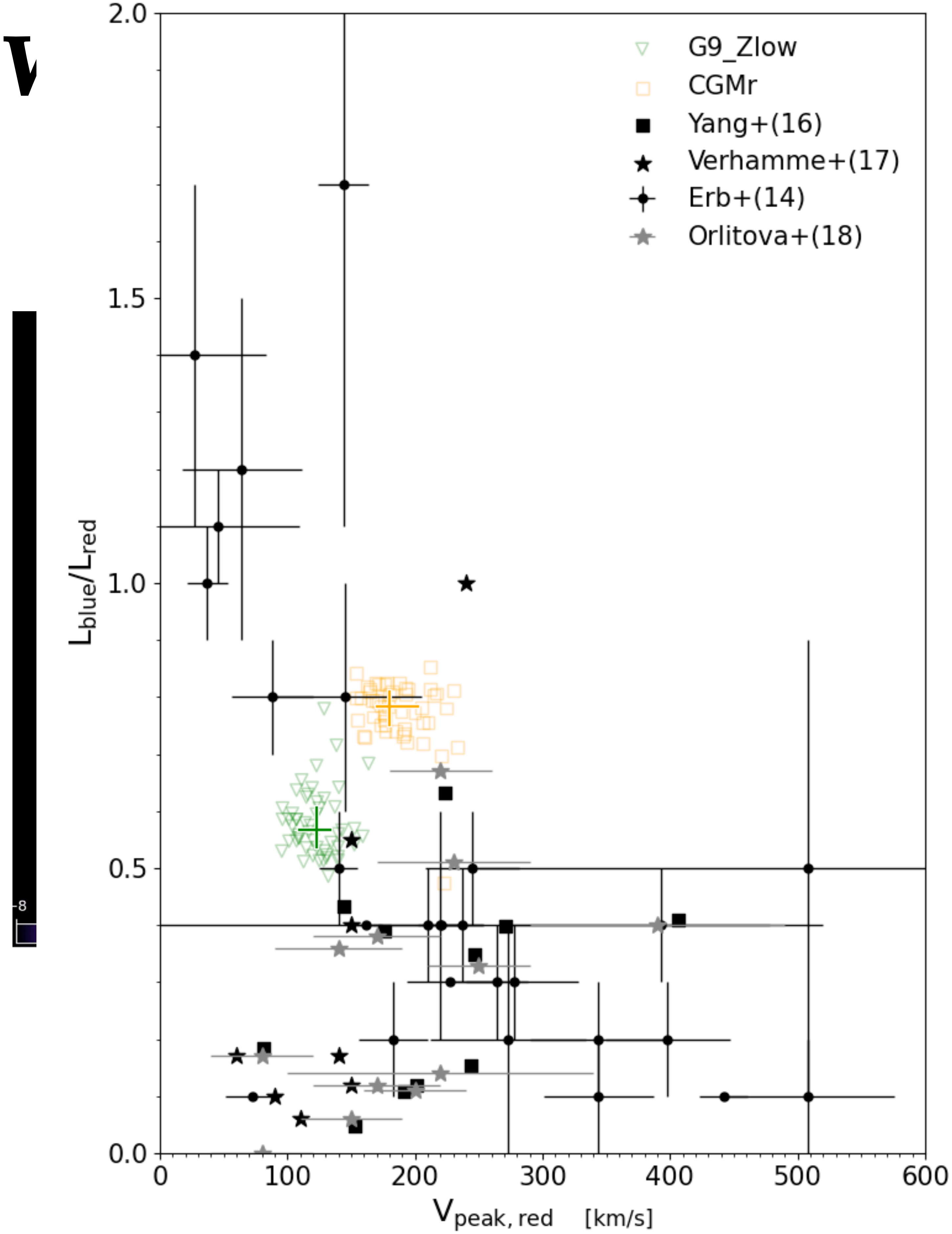


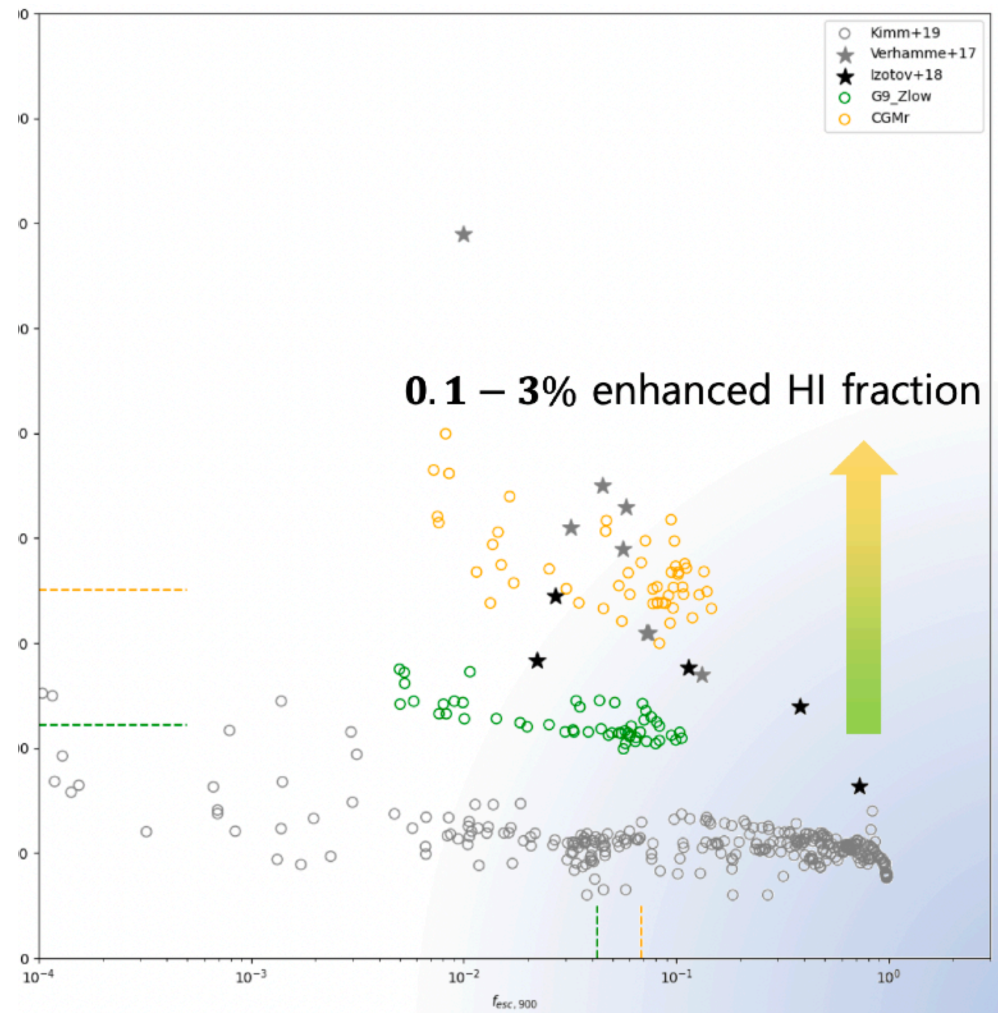


Each
indiv

Same physics, but with 20 pc resolution

… CGM?



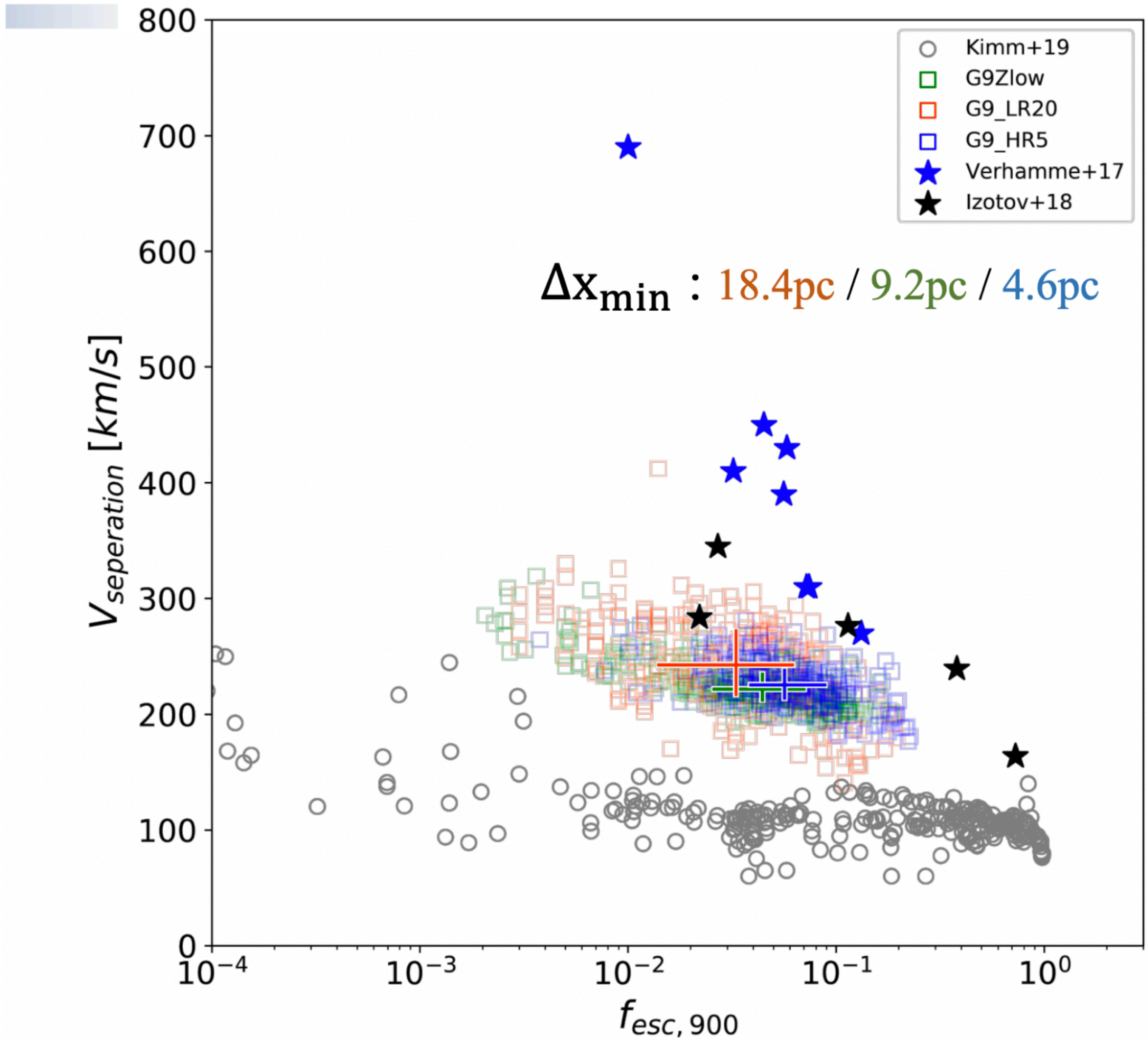


…. How do we produce strong outflows while keeping the CGM neutral?

Summary

1. PRALINE show that LyC escape is efficient on GMC scales (~20-60%), most efficient in clouds with ~ 20% SFE
2. Simulated GMCs show very similar Lya features in terms of Vsep, B/R
3. Galaxy simulations (isolated or merging) did not reproduce the Verhamme results of f_{900}-V_{sep}
4. Orientation effects help a bit, but not entirely
5. Presence of neutral CGM seems like an easy solution to large Vsep, but questions remain how we can actually produce neutral outflows (need to check with runs with extreme feedback)

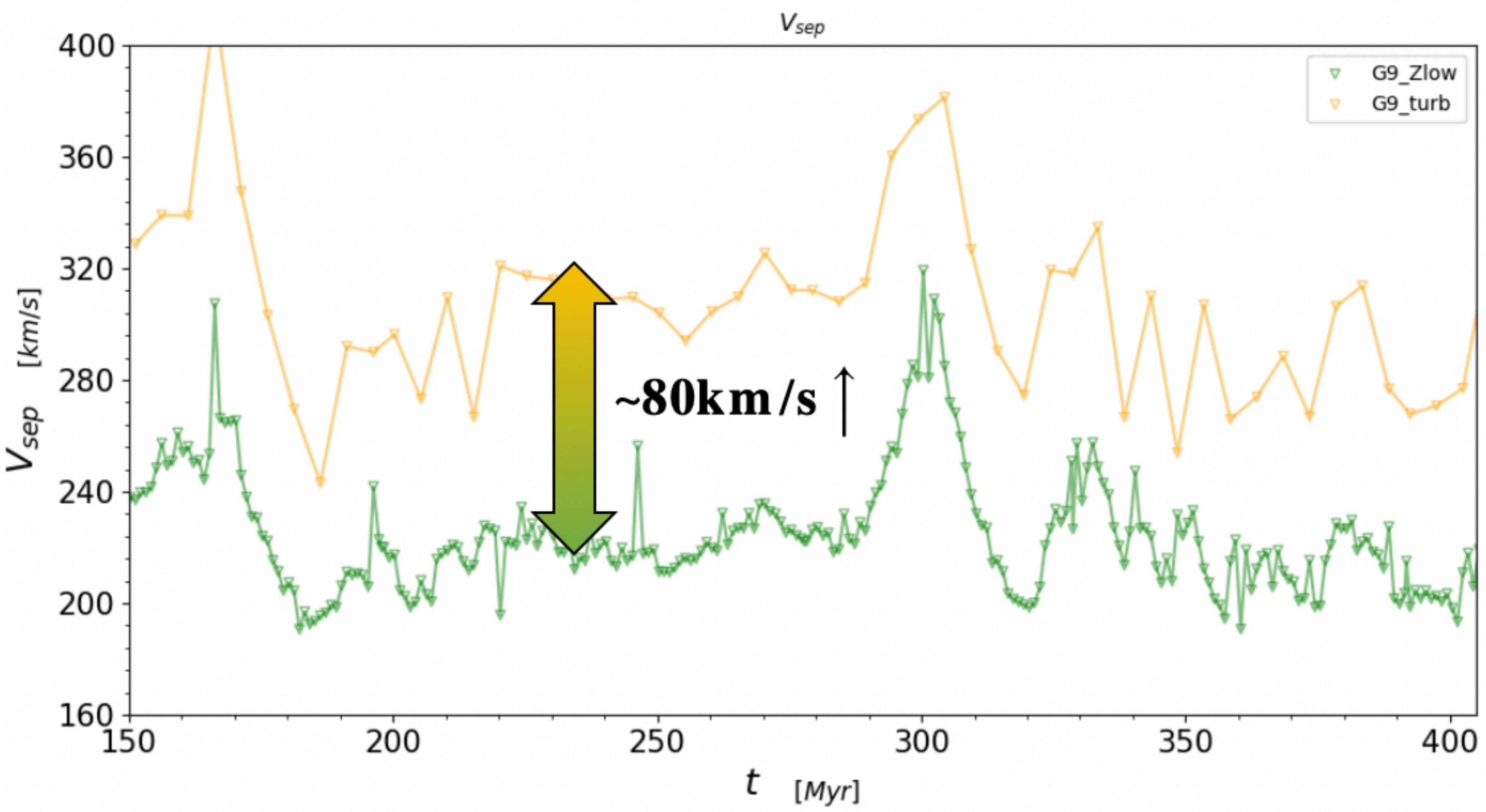
Effect of numerical resolution

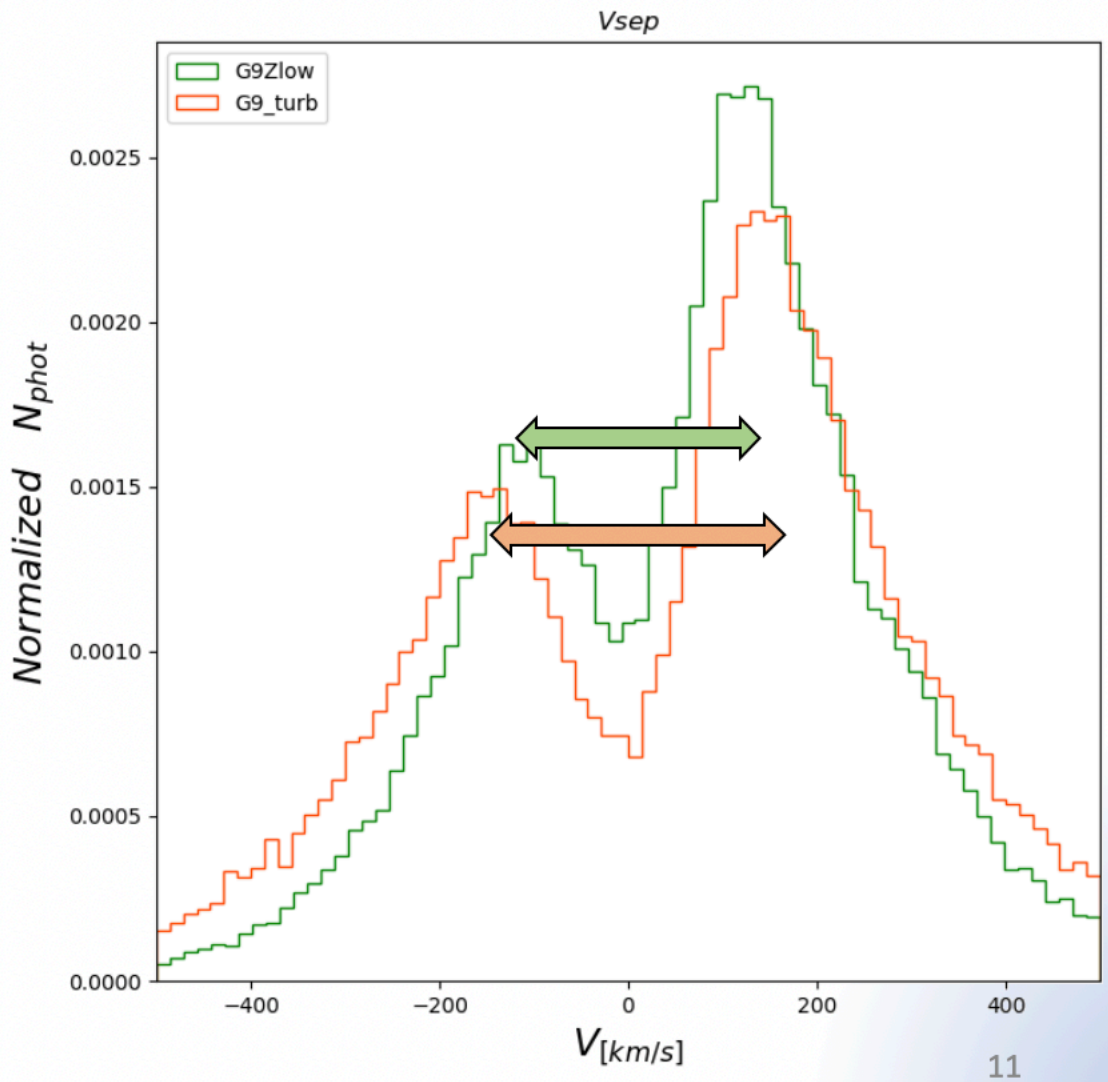


Effect of turbulence

In RASCAS,

Doppler width = $\sqrt{2k_BT/m_p}$ => $\sqrt{2k_BT/m_p + v_{turb}^2}$





Effect of Orientation from merging galaxies