Forming molecules in a violent environment: outflows in starburst nuclei

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"Local gas in Galaxies" Talk

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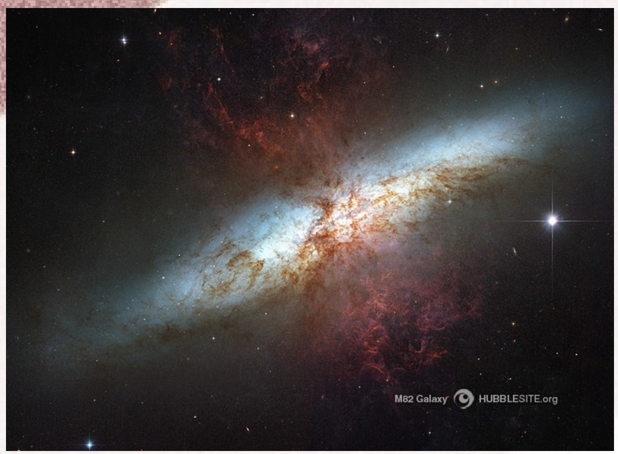
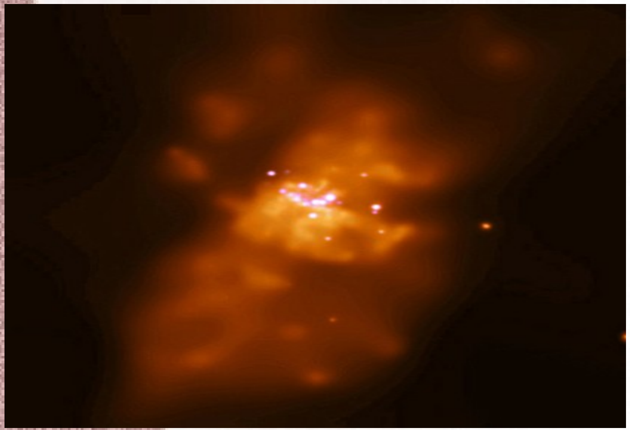
Observations of nearby and high redshift galaxies → star-formation → galactic winds.

For example, M82



M82 Optical - HST

M82 Infrared-Spitzer



M82X-ray-CHANDRA

M82 Composite Image

Strong shock → moving through ISM → sweeps up matter → slows down → post shock temperature falls → **radiative cooling → becomes weak !**

To cross **3-4 scale heights (z_0) and beyond → needs a very high velocity at z_0** → needs the shock not to become weak due to cooling

SN coherency condition

SN coherency condition: $$\frac{4\pi}{3} R_a^3 t_a \nu_{SN} > 1$$

R_a => $$R_a = 50\left(\frac{E_{51}}{n}\right)^{1/3} pc$$

t_a => $$t_a = 3\text{x}10^5\left(\frac{E}{n}\right)^{1/3} yr$$

Roy, A., Nath, B. B., Sharma, P., Shchekinov, Y., MNRAS, 2013

gives rough estimate of **SFR surface density** ~ 0.3 M_o yr^{-1} kpc^{-2}

Heckman 2002 -- **threshold SFR surface density ~ 0.1 M_o yr^{-1} kpc^{-2}**

-- galactic winds

Realistic simulations:

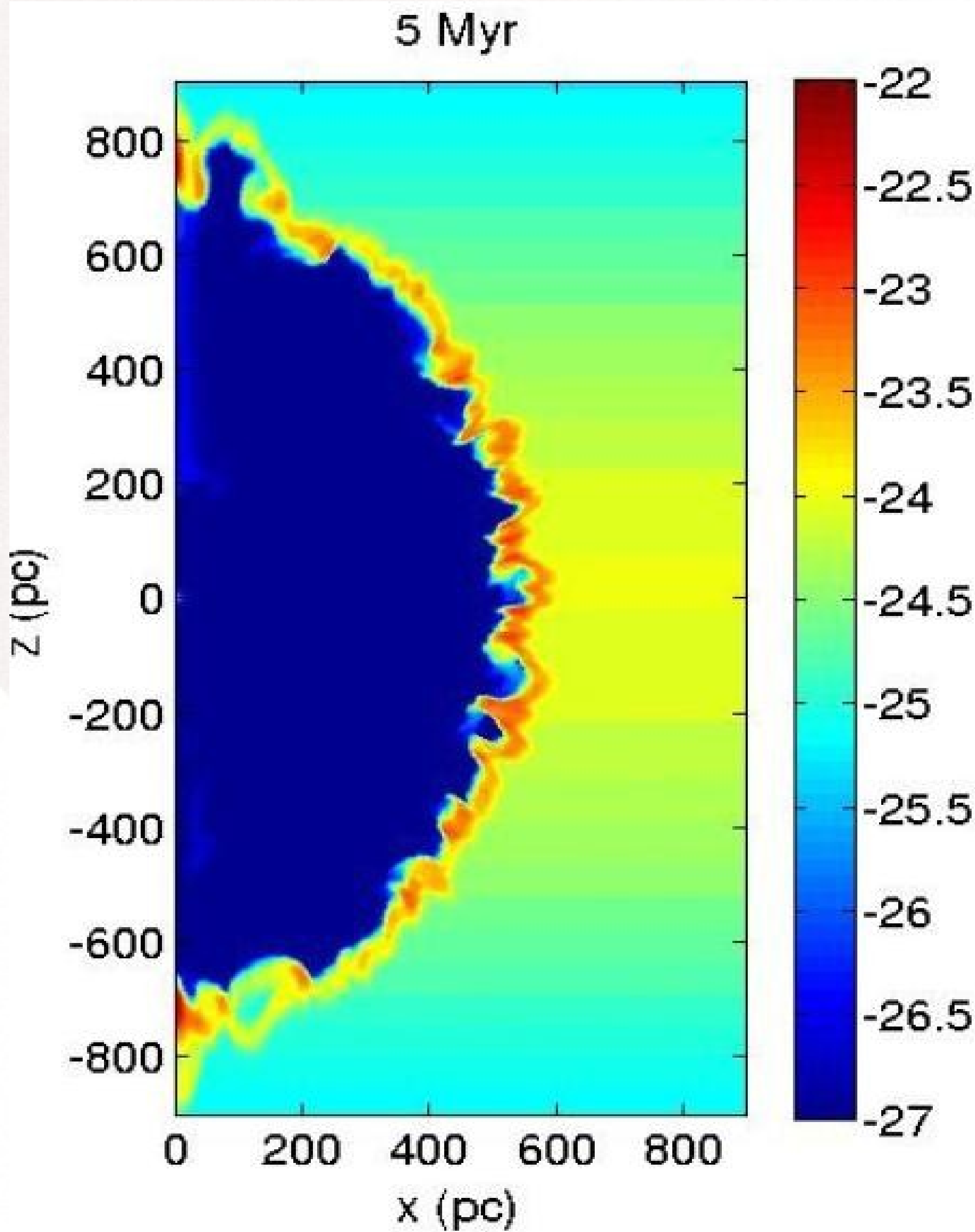
- radiative cooling
- SN input energy → constant luminosity
- disk gravity (hydrostatic equilibrium) – disk temperature ~ 10^4 K

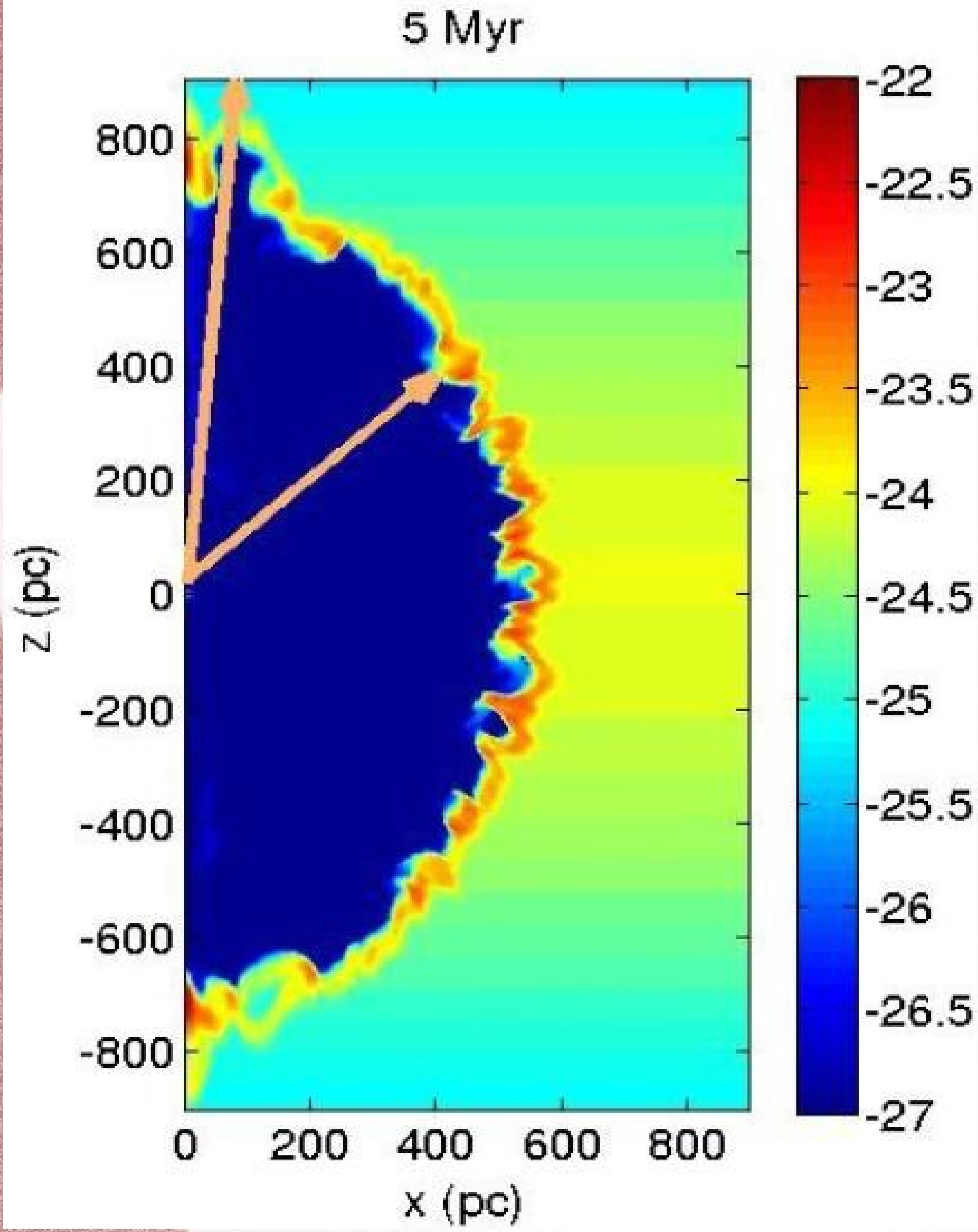
ZEUS-MP simulations.

N_{OB}=10^4, n_0=0.5 cm^{-3}, z_0=300 pc

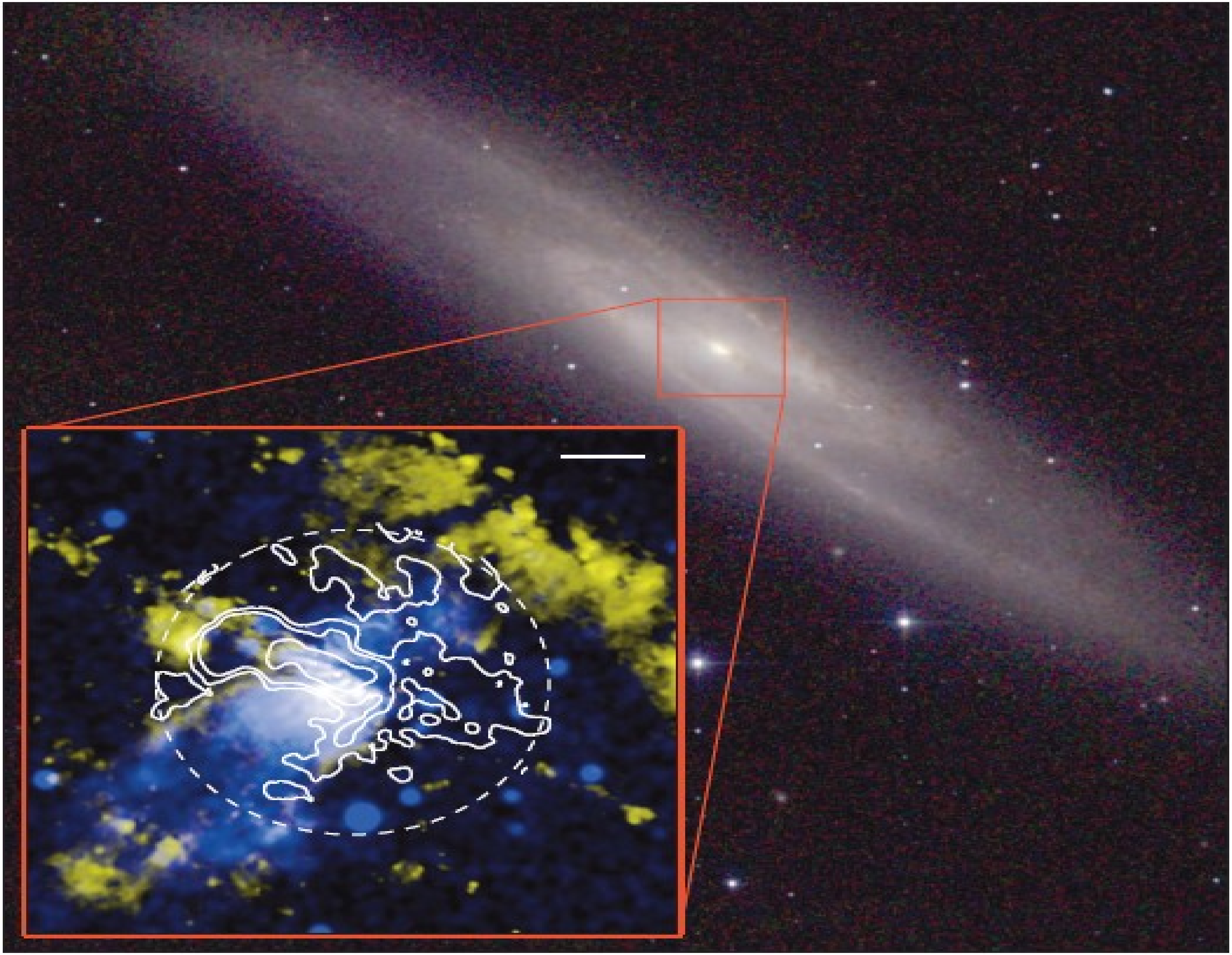
- Thermal instability, Rayleigh Taylor Instability (RTI)
- clumping in shells and channels
- helps the **material to come out** and also helps the **ionizing photons to escape**

Roy et. al., 2013

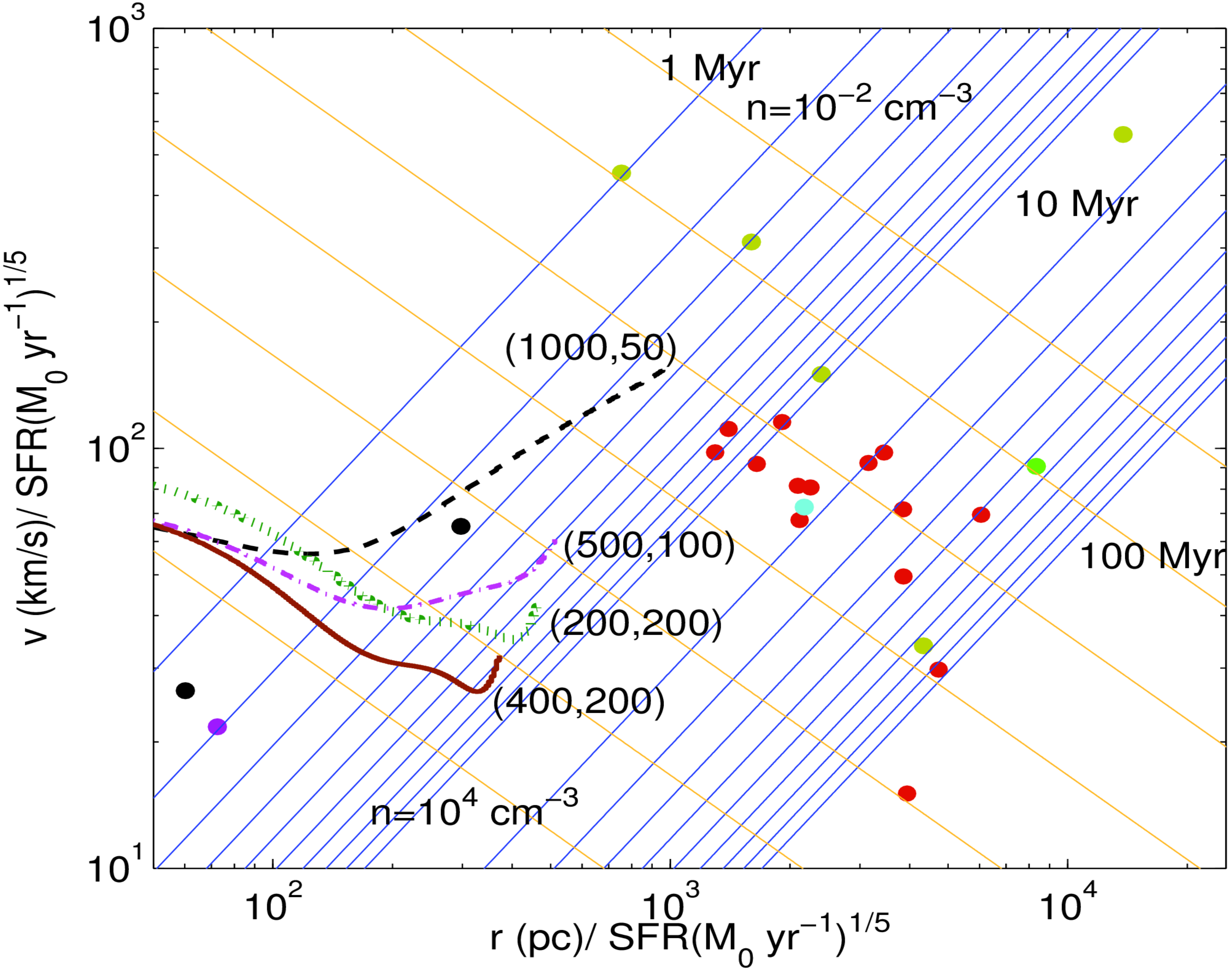




Roy, A., Nath, B. B., Sharma, P., MNRAS, 2015



NGC 253, Bolatto et. al., 2013, doi:10.1038/nature12351



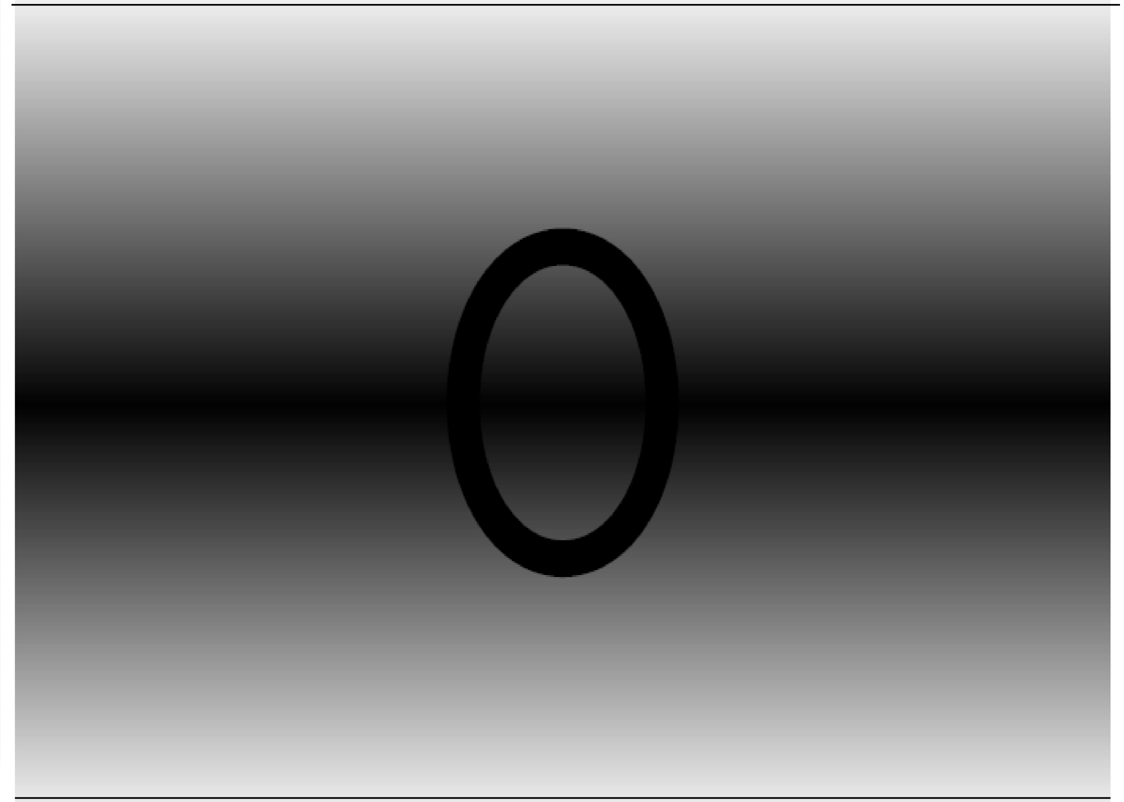
1 Myr
n=10^-2 cm^-3
10 Myr
(1000,50)
(500,100)
(200,200)
(400,200)
100 Myr
n=10^4 cm^-3
v (km/s)/ SFR(M_0 yr^-1)^1/5
r (pc)/ SFR(M_0 yr^-1)^1/5
10^3
10^2
10^1
10^2
10^3
10^4

Galaxy Name	r (kpc)	v (km/s)	SFR ($M_\odot yr^{-1}$)	state of the outflow and Others	Reference
M82	0.1	30 (average)	~ 5–8	Molecular, mass $\sim 2 \times 10^8$ $M_\odot$, Momenta $\sim 4 \times 10^9$ $M_\odot$ km/s, Energy $\sim$ (1–10) $\times 10^{52}$ erg	Galaz et. al., 2014, arXiv:1410.6329
NGC 253	0.06–0.09	23–42	~ 3	Molecular, mass $\sim$ (0.3–1) $\times 10^7$ $M_\odot$, momenta $\sim$ (8.5–40) $\times 10^7$ $M_\odot$ km/s, Energy $\sim (2$–$20) \times 10^{52}$ erg	Bolatto et. al., 2013, arXiv:1307.6259
NGC 3628	0.37–0.45	90 ± 10	$\sim$ 5 (Zhao et. al., 1997, ApJ, 482, 186)	Molecular, mass $\sim 3 \times 10^7$ $M_\odot$, momenta $\sim 3 \times 10^9$ $M_\odot$ km/s, Energy $\sim (1.8$–$2.8) \times 10^{54}$ erg	Tsai et. al., 2012, ApJ, 752, 38
M82	3	~ 100	~ 5	Molecular (Warm, T$\sim$ 2000 K)	Veilleux et. al., 2009, ApJ, 700, L149

Whether the molecules are entrained from MC (molecular clouds)??

OR,

Are the molecules form in-situ?



Roy et. al., in preparation

What are the disk parameters or number of supernovae explosions to form molecules in-situ?

- Molecular outflow at ~ 100 pc with a mass ~ 10^7-10^8 M_0 ⟶ $n_0 \geq 100$ cm^{-3}

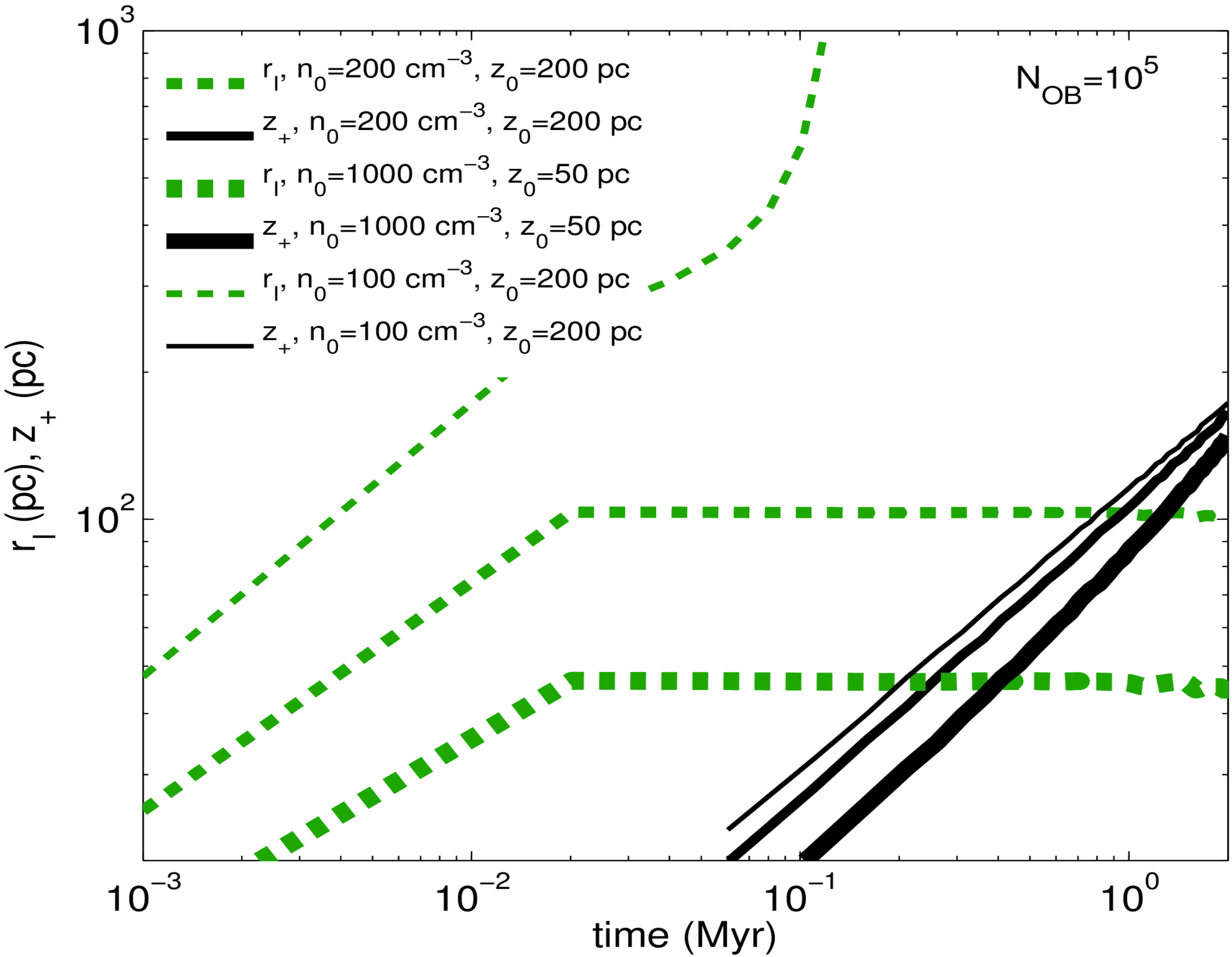
- Velocity ~ few tens of km/s,

$$\mathcal{L} \approx (5/3)^3 \rho\, v^3 r^2$$

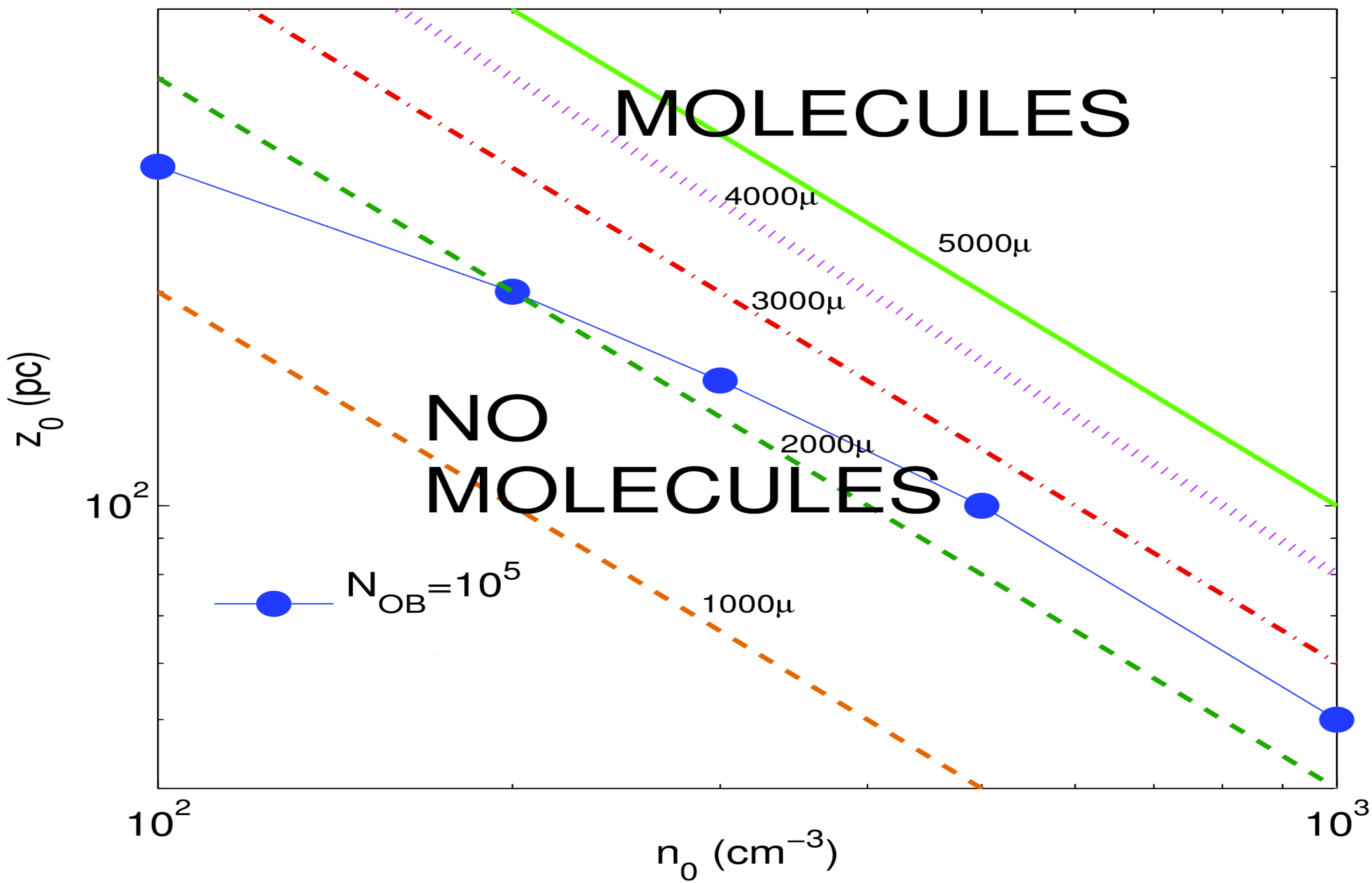
Mechanical luminosity ≥ $3*10^{41}$ erg/s ⟶

$N_{OB} \geq 10^5$

- Shell radius (z_p) & ionization radius (r_I) crossing over ⟶ threshold scale height (z_0)

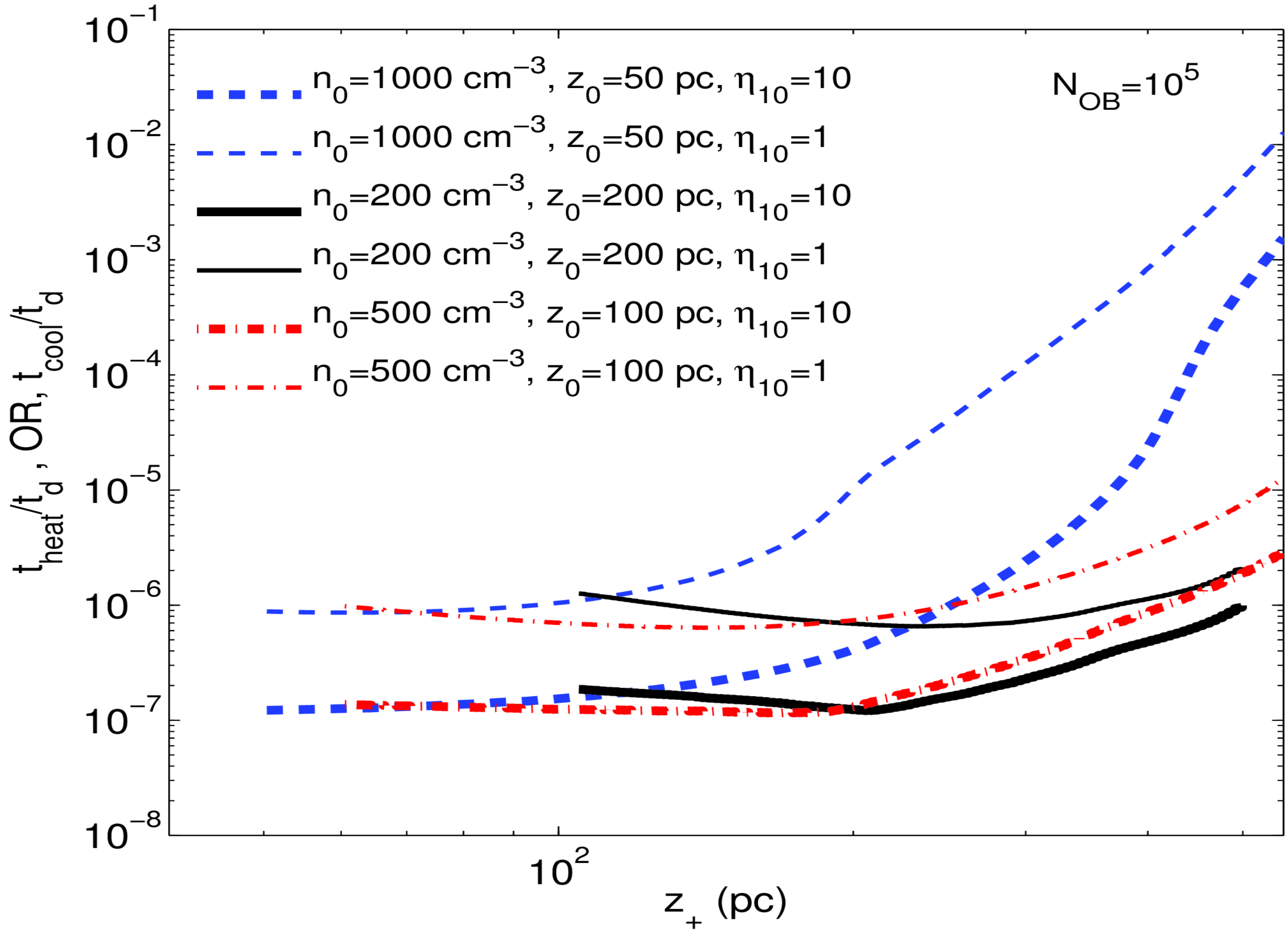


Roy et. al., in preparation



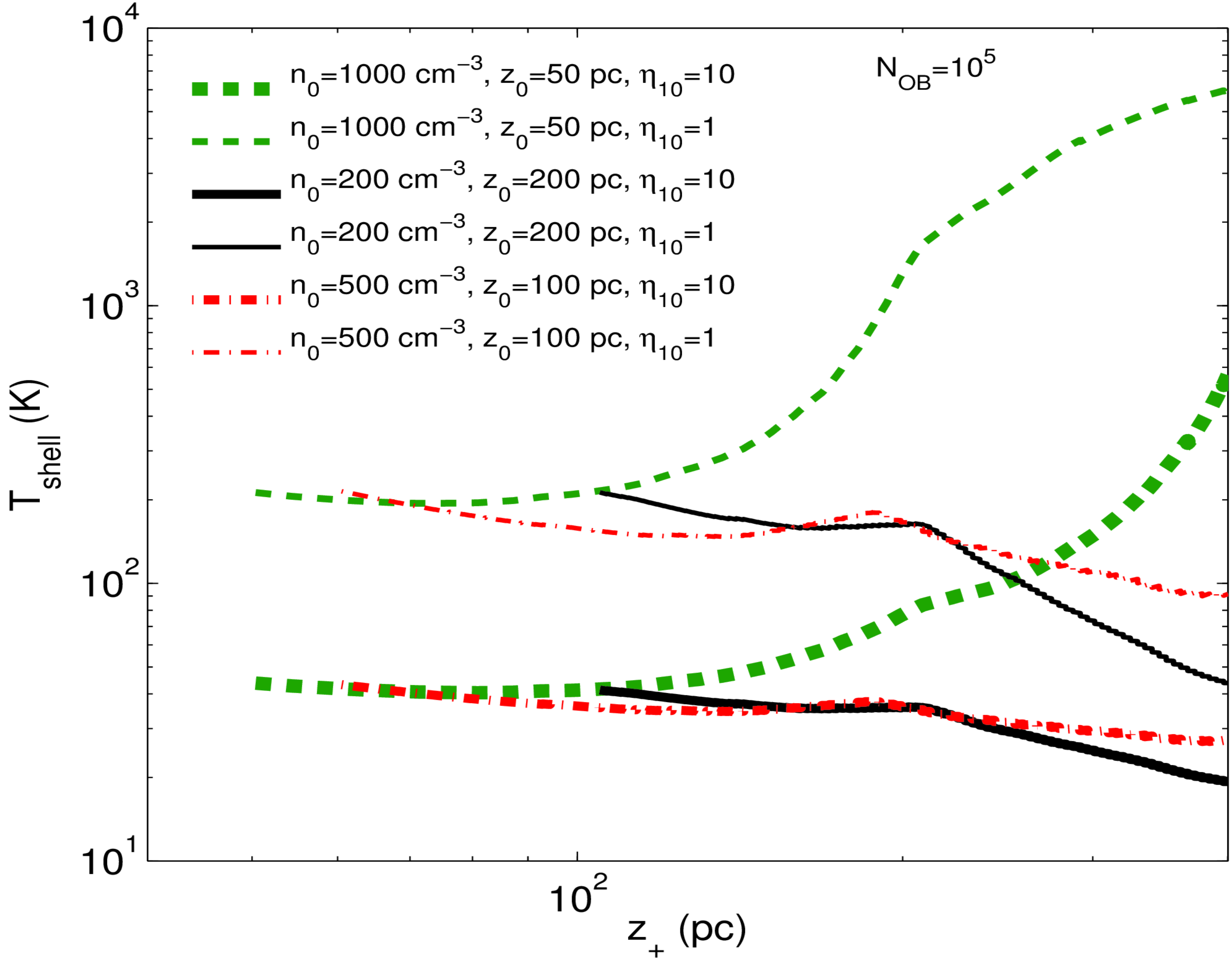
$$1000\mu\left(\frac{\mathrm{SFR}}{\mathrm{M_\odot yr^{-1}}}\right)\frac{\mathrm{M_\odot}}{\mathrm{pc^2}}$$

Outflow (Nath & Shchekinov 2013) →
surface density ~ 1000 M_0/pc^2



Thermal equilibrium calculation ⟶ balancing PE heating with cooling ($n^2\Lambda$)

Roy et. al., in preparation



Roy et. al., in preparation

Formation & Destruction Processes of molecules :

$$\frac{dn_{H_2}}{dt} = R_f n n_{HI} - R_{d,thin} f_{dust,H_2} f_{shield,H_2} n_{H_2} - k_D n n_{H_2}$$

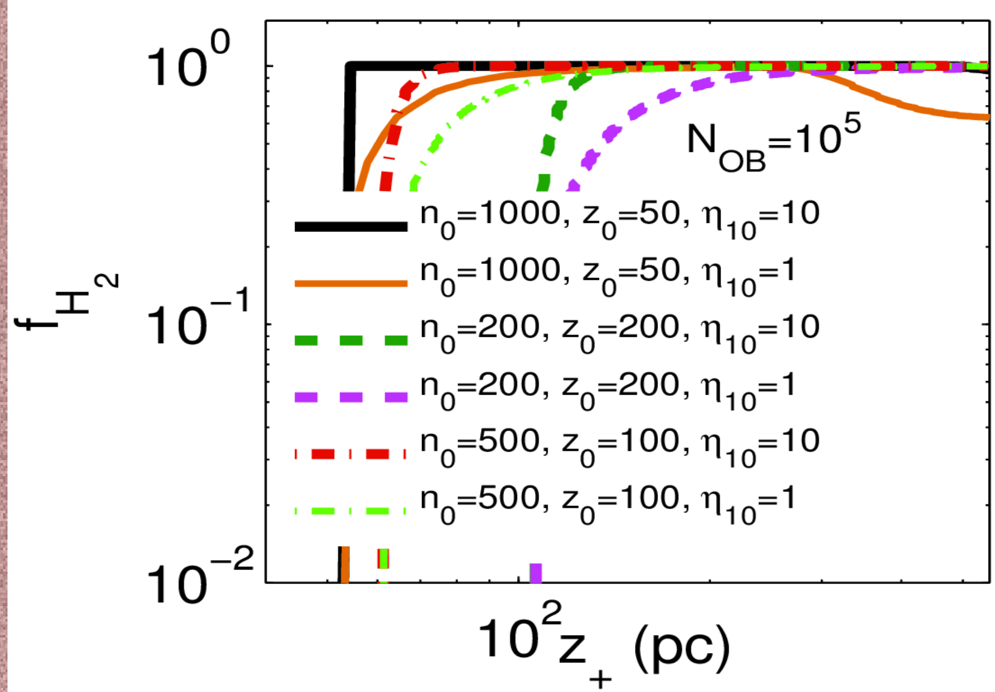
Formation term

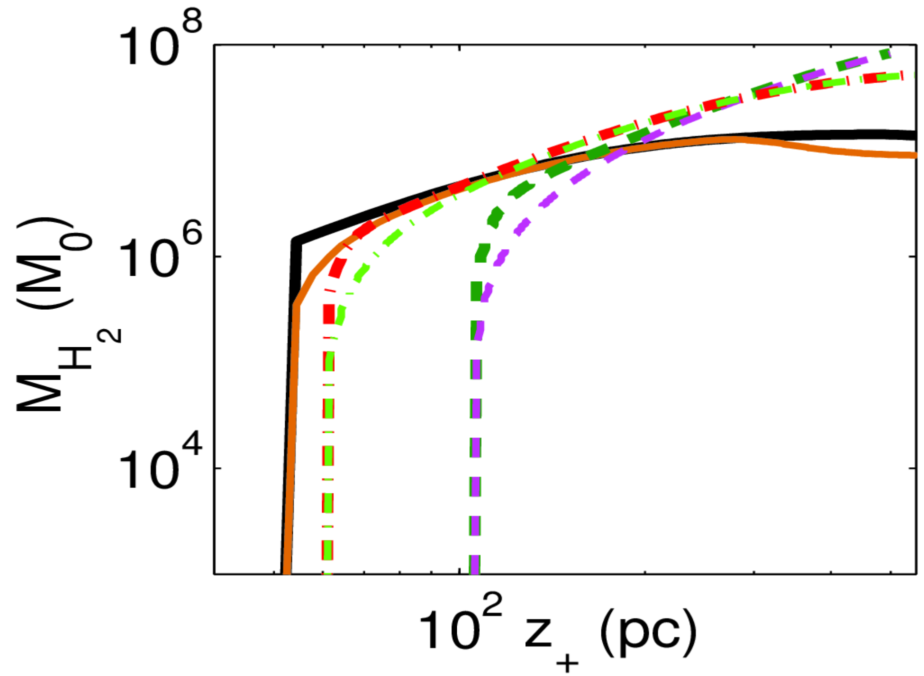
Destruction term

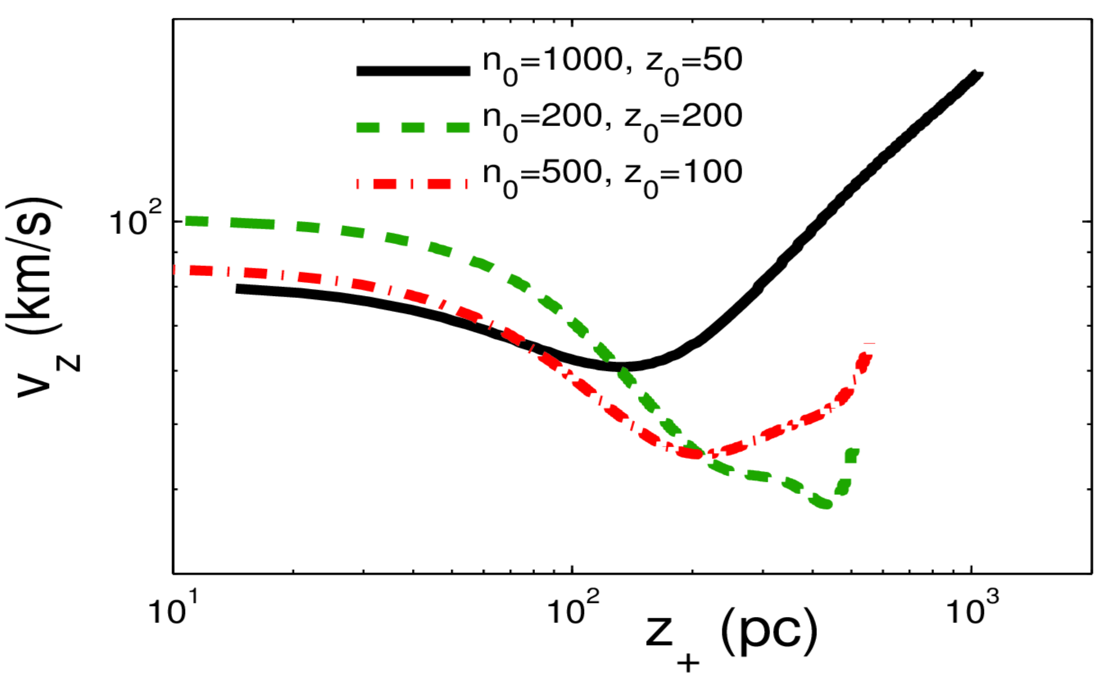
R_f: Rate coefficient of H_2 formation on grain surface

$R_{d,thin}$: photo-dissociation rate in optically thin gas

k_D : the collisional dissociation rate co-efficient







Roy et. al., in preparation

Conclusions :

- Molecules can form in-situ in dense superbubble shell.

- Threshold condition for n_0-z_0 below which molecules can not form.

- Molecules can be destroyed at larger radii (due to collisional dissociation (as temperature rises), and thus can become warm molecules (M82 ~ 2000 K).

- We can explain the molecule formation with molecular mass ~ 10^7-10^8 M_0, velocity ~ few tens of km/s, momentum ~ 10^8-10^9 M_0 km/s, energy ~ 10^{53}-10^{54} erg/s and radii ~ 100-300 pc, consistent with observations.

Thank You.