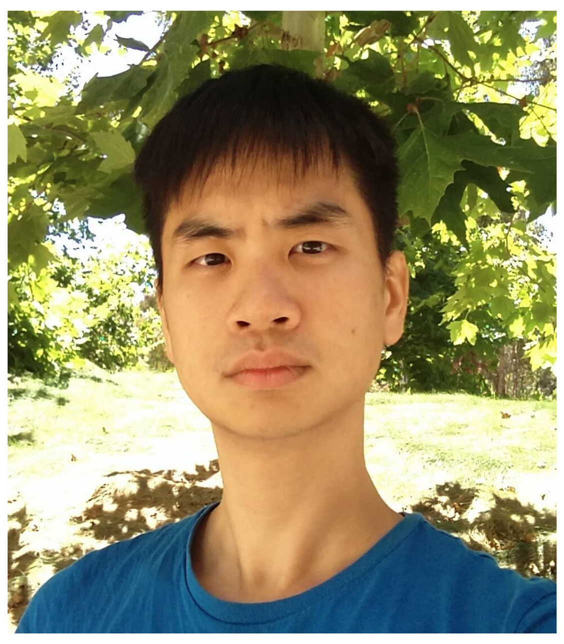
Cosmic Ray feedback in FIRE:
Constraint from γ ray emission & Cosmic ray driven outflow[1]



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Introduction

We show the first implementation of the cosmic ray (CR) physics in the GIZMO code coupled with the FIRE (Feedback In Realistic Environments) feedback physics applied to idealized galaxy simulations. We constrain CR propagations with the observed pionic γ ray emissions. We find that the addition of CR feedback significantly modifies the properties of galactic winds, which are cooler ($10^{4\text{-}5}$ K) and slower (100 km/s) than winds driven by mechanical feedback alone.

The FIRE 2 simulations[2,△]

MFM: Meshless Finite Mass hydro-solver (Hopkins 15)
Gravity solver: updated version of the PM+Tree algorithm from Gadget-3
Comprehensive baryonic physics:
a. ionized+atomic+molecular cooling
b. star formation in dense bound molecular gas
c. physical stellar feedback, e.g. radiation pressure, supernovae, stellar wind, photo-ionization, and photo-electric heating
d. Magnetohydrodynamics (MHD)
Simulation set:
Isolated galaxies: dwarf, dwarf starburst and L star (LSG) galaxies

CR physics and numerical implementation:

Two fluid model: gas +CR
Injection: 10% supernova (SN) energy (S_{cr});
Loss: hadronic and Coulomb losses (Γ_{cr});
Propagation: isotropic/anisotropic diffusion & streaming (*Table 1*);
Numerical scheme: two moment method similar to Jiang & Oh 2018 with the reduced speed of light (c_{red}) (*Equation 1*).

$$\frac{1}{c_{\rm red}^2}\frac{\partial \mathbf{F}_{\rm cr}}{\partial t}+(\gamma_{\rm cr}-1)\,\hat{\mathbf{B}}\,(\hat{\mathbf{B}}\cdot\nabla e_{\rm cr}) = -\frac{\gamma_{\rm cr}-1}{\kappa^*_{\rm di}}\mathbf{F}_{\rm cr} \qquad \frac{\partial e_{\rm cr}}{\partial t}+\nabla\cdot\mathbf{F}_{\rm cr} = (\mathbf{v}+\mathbf{v}_{\rm st})\cdot\nabla P_{\rm cr}+S_{\rm cr}-\Gamma_{\rm cr}$$

Equation 1: Two moment method for CR diffusion and streaming; e_{cr} & F_{cr} are the CR energy density and flux respectively; κ^*_{di} is the effective diffusion coefficient, which also takes streaming into account.

		noCR	BnoCR	ADV	DC27	DC28	DC29	STREAM	BDC28	BDC28STR
MHD		Off	On	Off	Off	Off	Off	On	On	On
Stream		Off	Off	Off	Off	Off	Off	On	Off	On
κ_{di}	[cm²/s]	-	-	0	3×10^{27}	3×10^{28}	3×10^{29}	0	3×10^{28}	3×10^{28}
c_{red}	[km/s]	-	-	-	500	1000	2000	500	1000	1000

Table 1: Various CR propagation models ; κ_{di} is the diffusion coefficient; Stream is CR streaming.

Simulating γ ray emission and Constraints on CR propagation:

Method: CRs collide with nuclei in interstellar medium (ISM) and produce pions, some of which decay and produce pionic γ rays. We calculated the luminosity of pionic γ rays with *Equation 2* and determine the fraction of CRs which escape the galaxies by comparing the γ ray and total star formation luminosities with *Equation 3*.

Main results:
Figure 1: we compare our ratios between γ ray and total SF luminosity with observations. Our comparison suggests that $\kappa_{di} \sim 3\times10^{28\text{-}29}$ in order to enable enough CRs to escape;
Figure 2: we show that the low γ ray emission at low gas surface density is *mainly* due to the escape of CRs but not adiabatic losses.

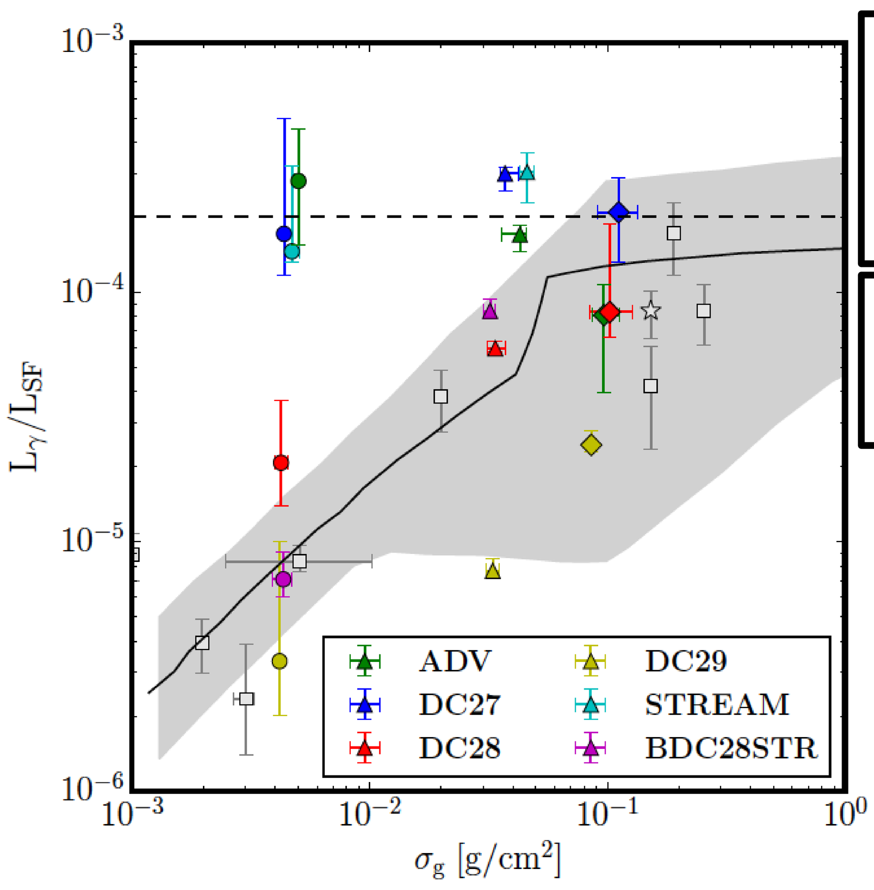

Figure 1: Ratio between high energy γ ray and total SF luminosity as a function of gas surface density. Points are observations listed in Lacki+11; soilid line and shaded region are the Lacki+11 prediction; dashed line shows the calorimetric limit when no CR can escape.

$$L_\gamma(\geq {\rm GeV}) \approx \sum_{\rm gas} 1.08\times10^{-16} e_{\rm cr}\left(\frac{n_{\rm H}}{\rm cm^{-3}}\right)\,{\rm s}^{-1}$$

Equation 2: Luminosity of high energy γ ray emission by CRs, which is proportional to both CR energy and ISM density (Guo&Oh 08; Lacki+11)

$$L_{\rm SF} \approx 3.5\times10^{43}\frac{\rm SFR}{[{\rm M_\odot/yr}]}{\rm erg/s}$$

Equation 3: Total star formation (SF) luminosity.

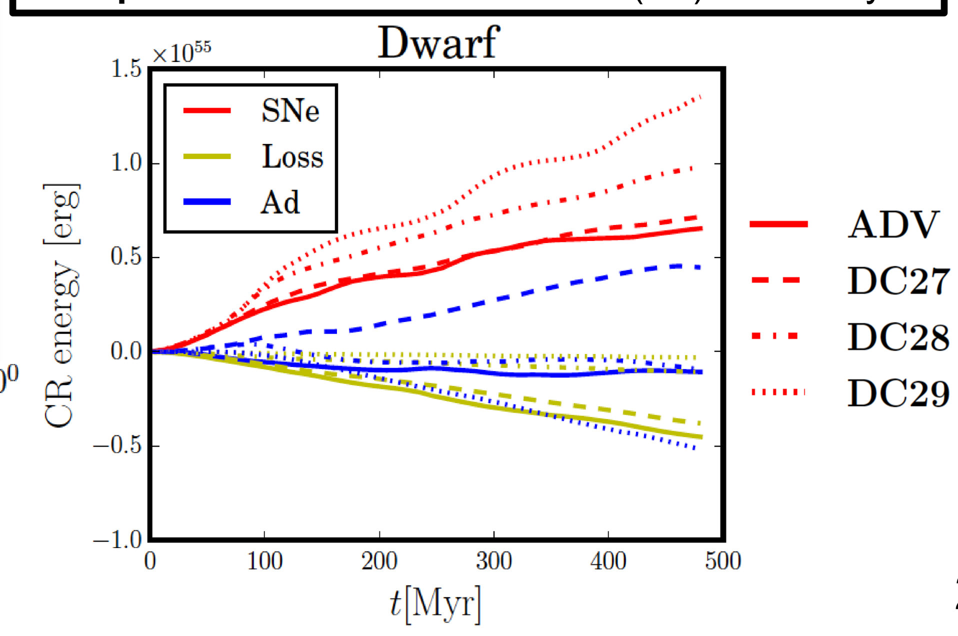

Figure 2: Different cumulative CR energy contributions in different propagation models. SNe is CR injection from SN; Loss includes both hadronic and Coulomb loss; Ad is adiabatic energy.

CR driven winds – Cooler and Slower[‡]

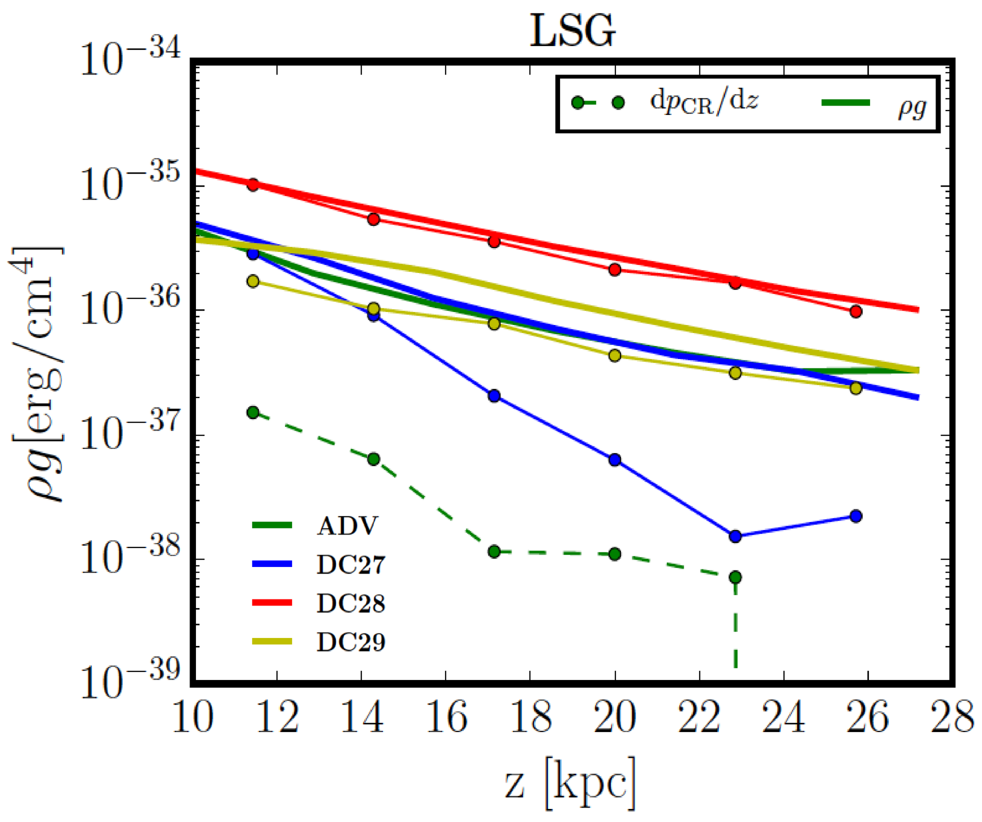

Figure 3: A comparison between gravity and CR pressure gradient after 500 Myr of evolution:

(1) CRs with active transport, e.g. diffusion and streaming, can develop a significant pressure gradient against gravity;

(2) CRs diffuse too fast in DC29, so they cannot balance gravity without the help of thermal pressure.

Figure 5 & 6:
(1) Strong CR pressure gradients allow galactic winds to launch without high thermal pressure and initial velocities;
(2) Colder and slower gas can be ejected from the galaxies with CRs and diffusion or streaming.

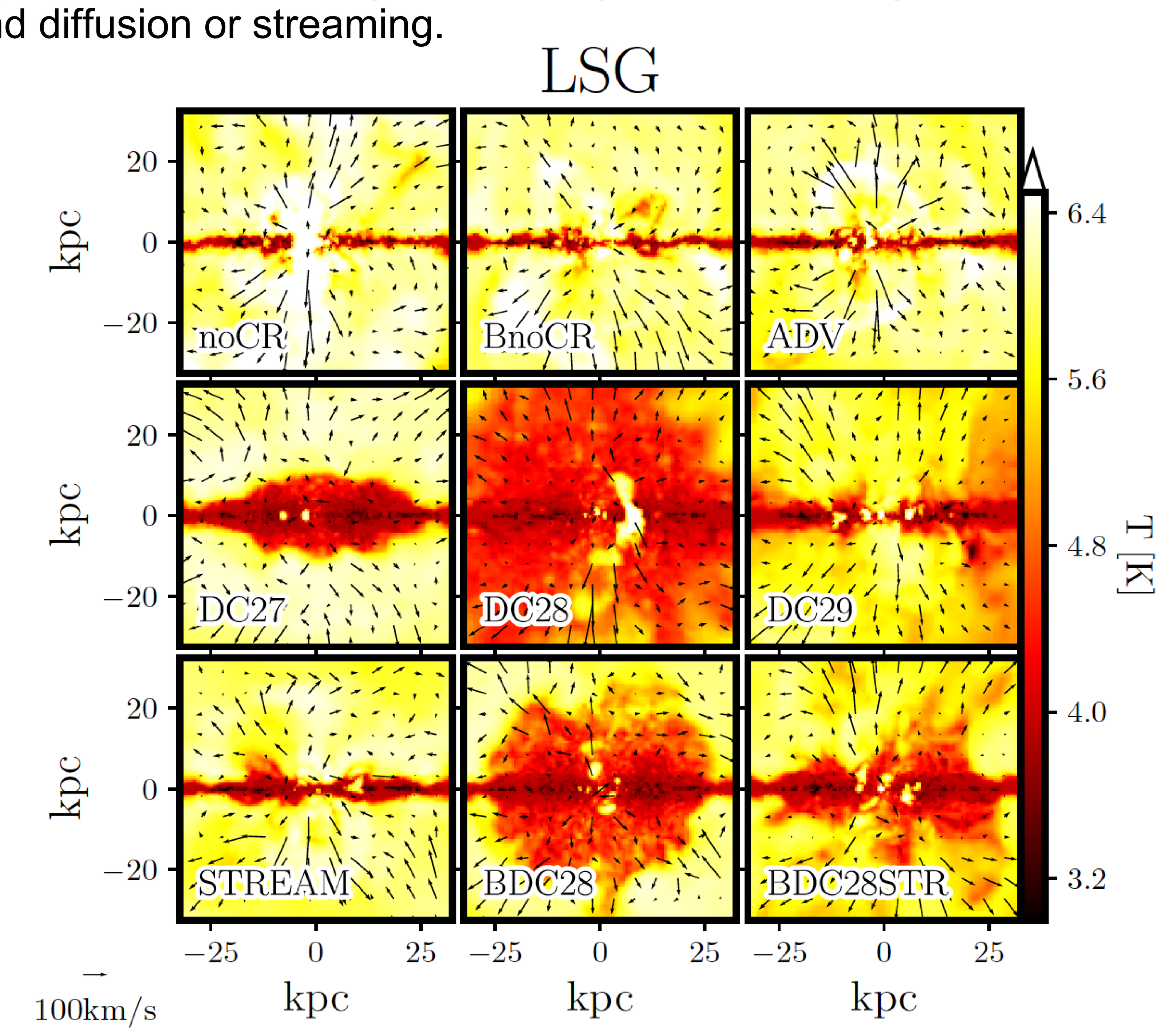

Figure 5: Slide plots of edge-on temperature profiles after 500 Myr evolution.

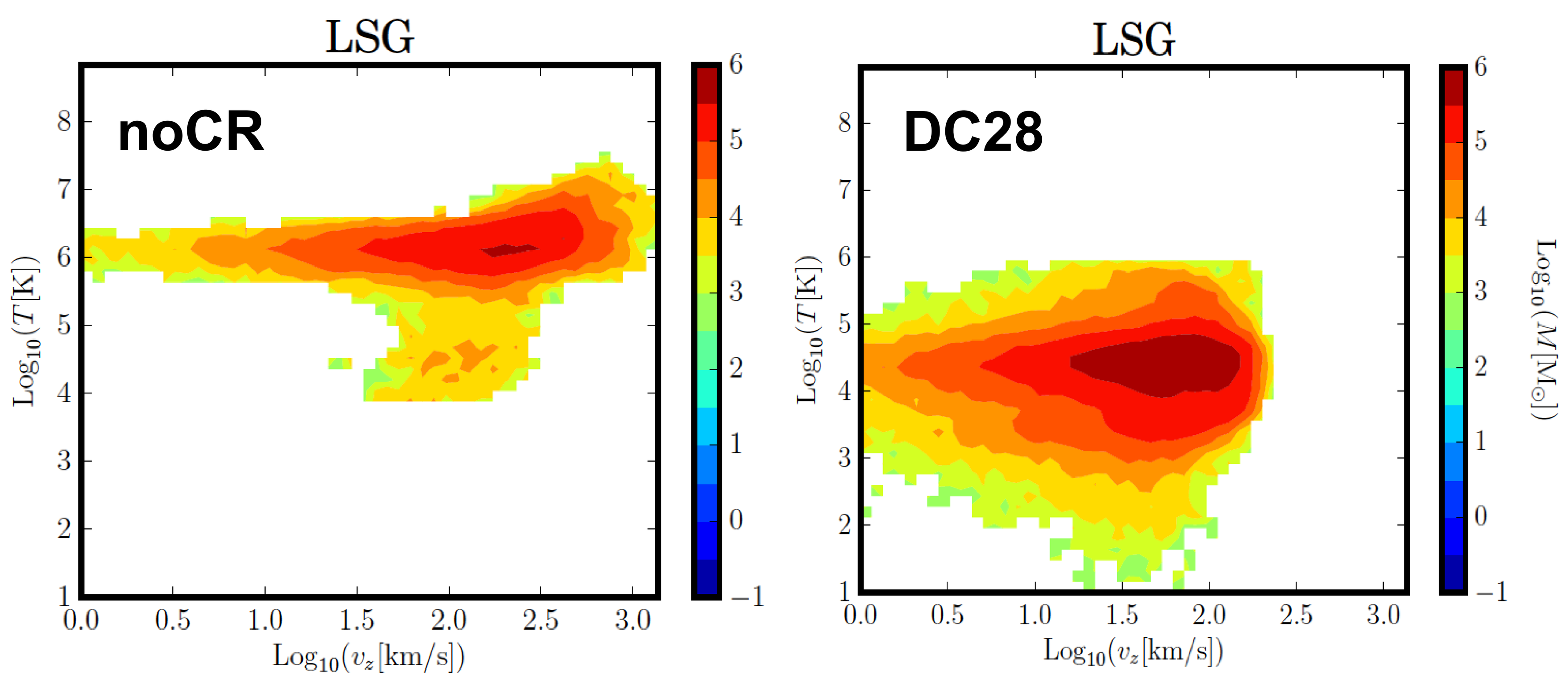

Figure 6: The mass distributions of outflowing gas particles as a function of temperature and vertical velocity after 500 Myr of evolution. We only consider gas particles with 15 kpc < z < 25 kpc, r < 20 kpc and moving away from the galactic disk plane.

Major References

1. Chan T. K., Kereš D., Hopkins P. F., Quataert E., et al., in prep
2. Hopkins P.F., et al., 2018, MNRAS, 480, 800

△ the FIRE website: fire.northwestern.edu ‡ see movies at tsangkeungchan.com

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