The dynamics and time-dependent mass accretion rates of protostars

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The FIRE collaboration
Stars, Planets, & Galaxies, 16 April 2018

Outline

- Introduction: Star formation and giant molecular clouds (GMCs)
- A new GMC catalog, capturing 98% of the flux in the Dame map
- Large scatter in $F_{free-free}/F_{CO}$ and F_{FIR}/F_CO, inconsistent with a constant star formation rate
- Feedback from stars is crucial to halt a runaway
- Feedback will likely also drive winds
- FIRE simulations find winds; reproduce the M_{star}—M_{halo} relation
- FIRE predicts large variations in $L_{CO}(z)$; Intensity Mapping will test this
- Conclusions

Stars Form in GMCs

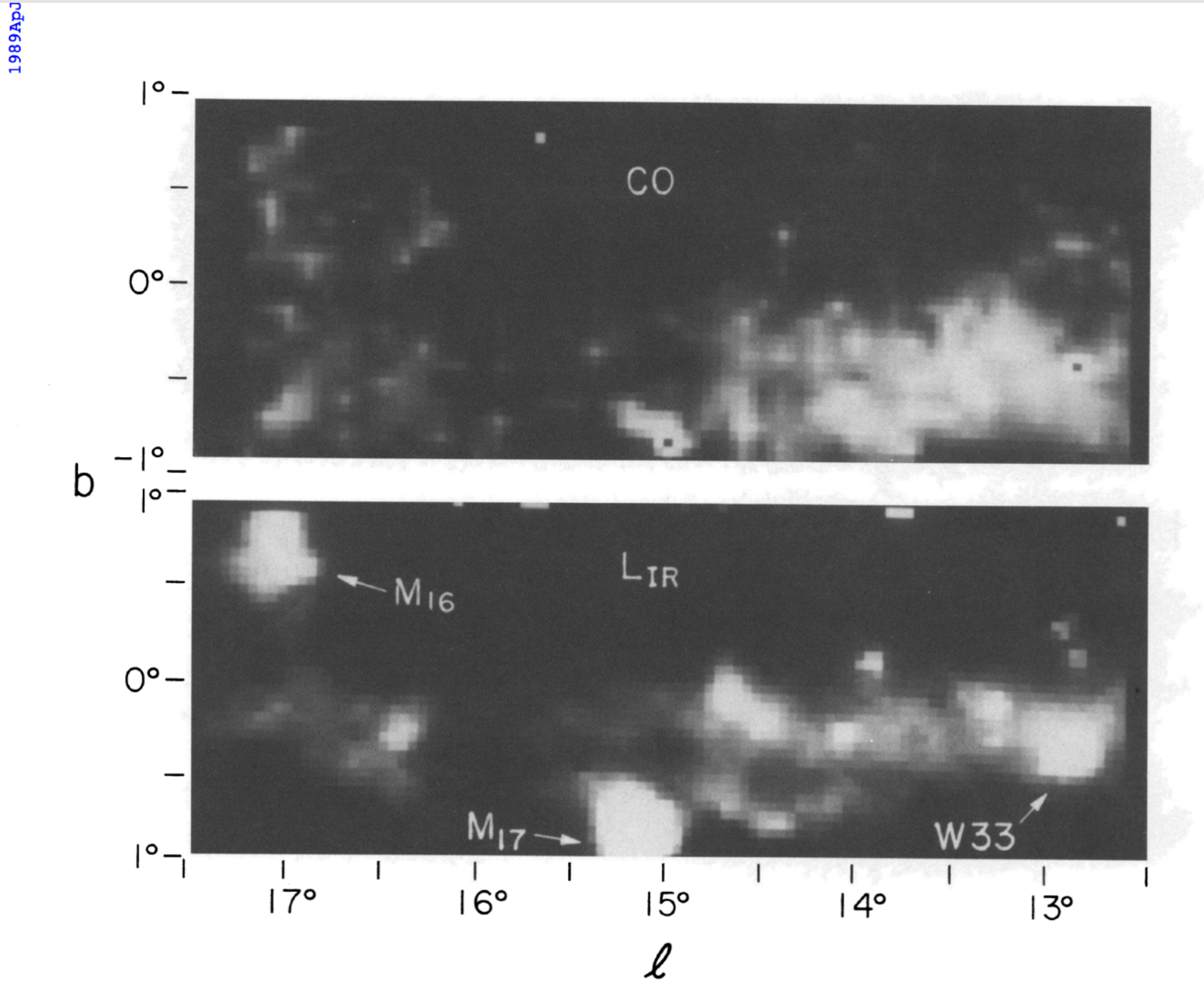


FIG. 1.—Infrared luminosity (λ = 1–500 μm) and integrated CO (v = 10–40 km s^{-1}) distributions are shown for a 2° × 2° area of the galactic plane including the H II regions M16, M17, and W33. The image clearly demonstrates that the bulk of the far-infrared luminosity in this region originates from the molecular clouds and their associated H II regions. Pixels are 3′ × 3′.

SCOVILLE AND GOOD (*see* **339**, 150)

Scoville & Good 1989

The star formation rate

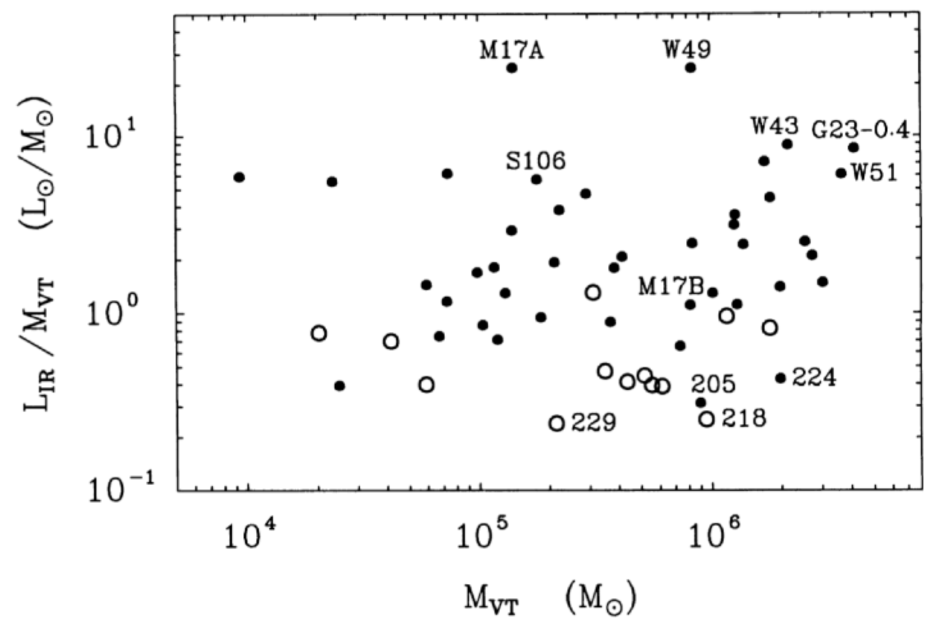


FIG. 2.—The ratio of far-infrared luminosity to cloud mass as a function of cloud mass. The solid and open circles are the same as in Fig. 1. The star formation rate per unit of available molecular mass as measured by L_{IR}/M_{VT} is independent of the mass of the cloud.

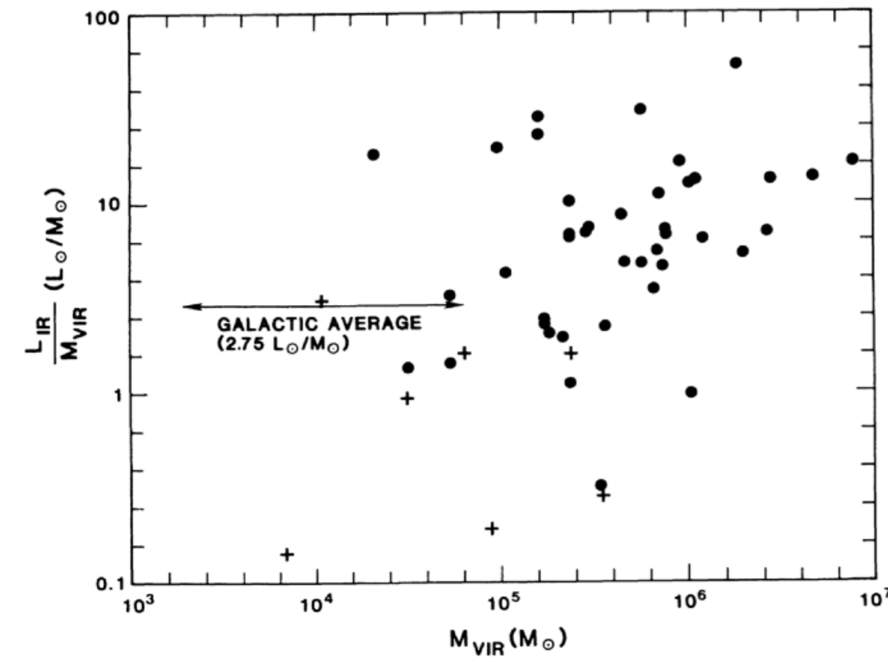
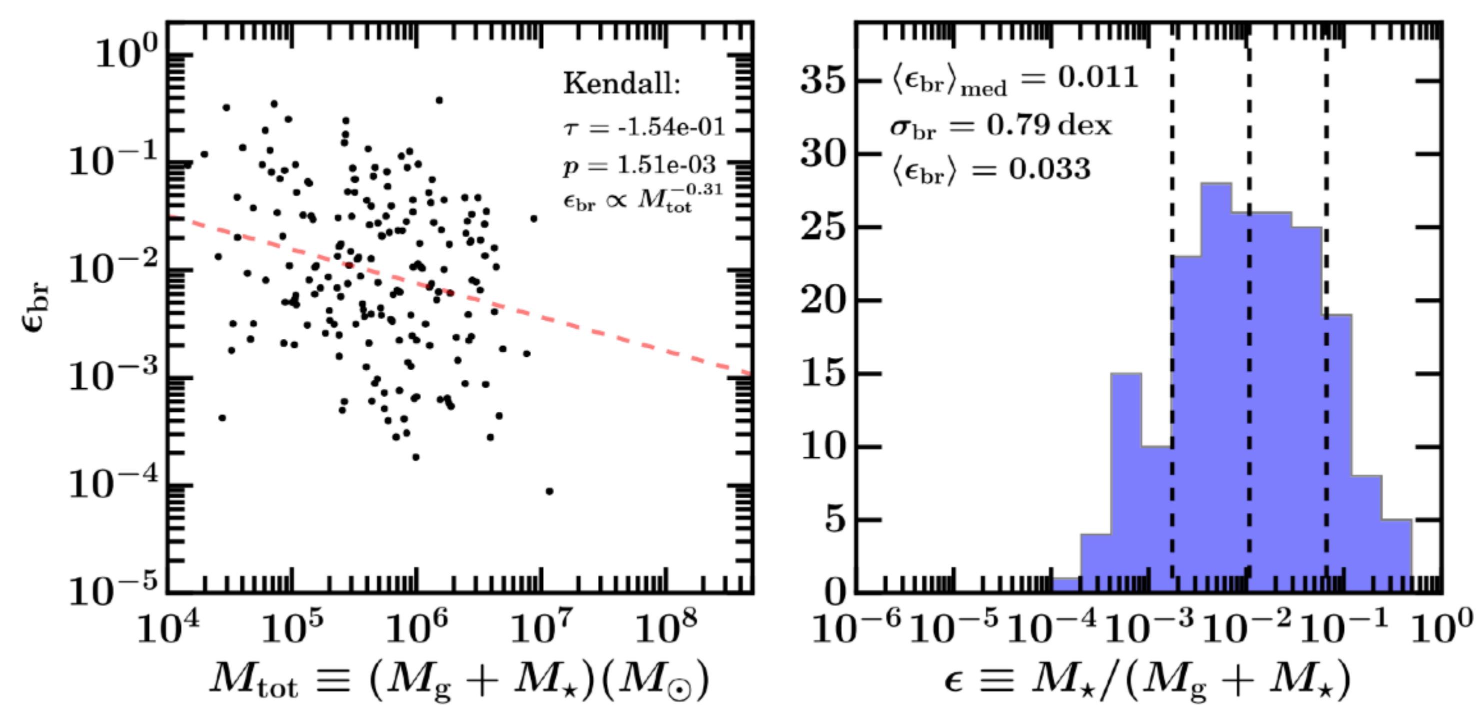


FIG. 9.—The luminosity-to-mass ratio L_{IR}/M_{VIR} is shown as a function of virial mass for both cloud samples. No correlation is found between the luminosity-mass ratio and cloud masses.

Mooney & Solomon 1988

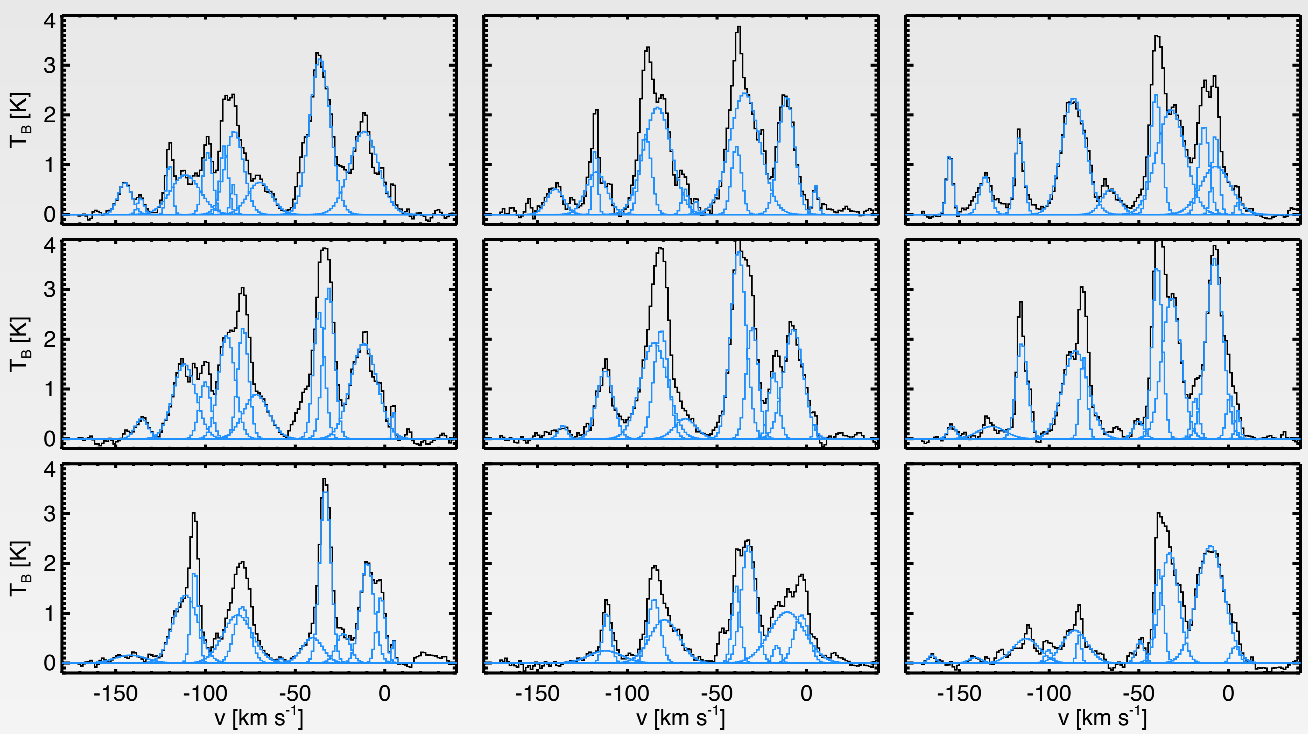
Scoville & Good 1989

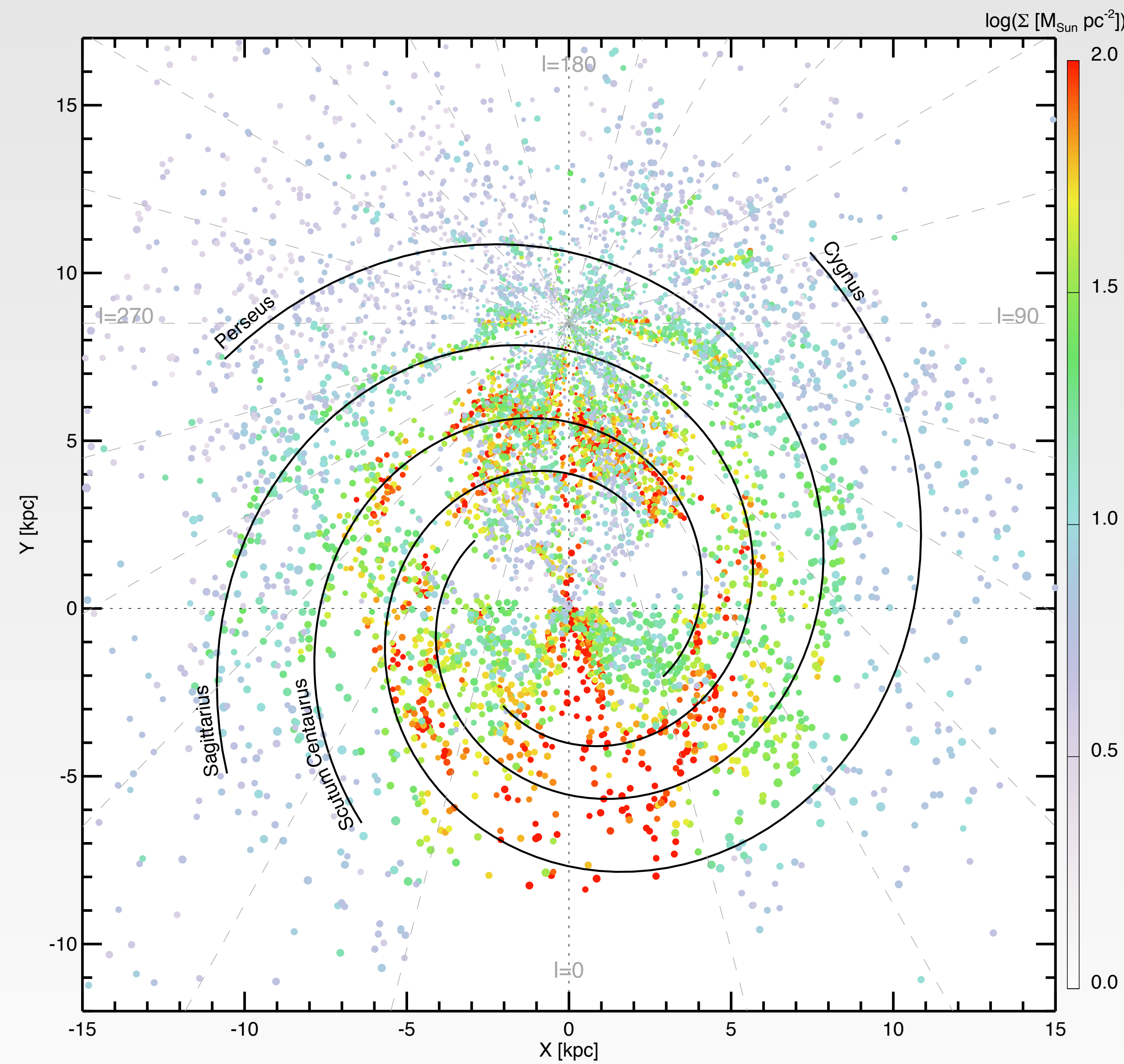
THE ASTROPHYSICAL JOURNAL, 833:229 (15pp), 2016 December 20



Is dM_*/dt constant?

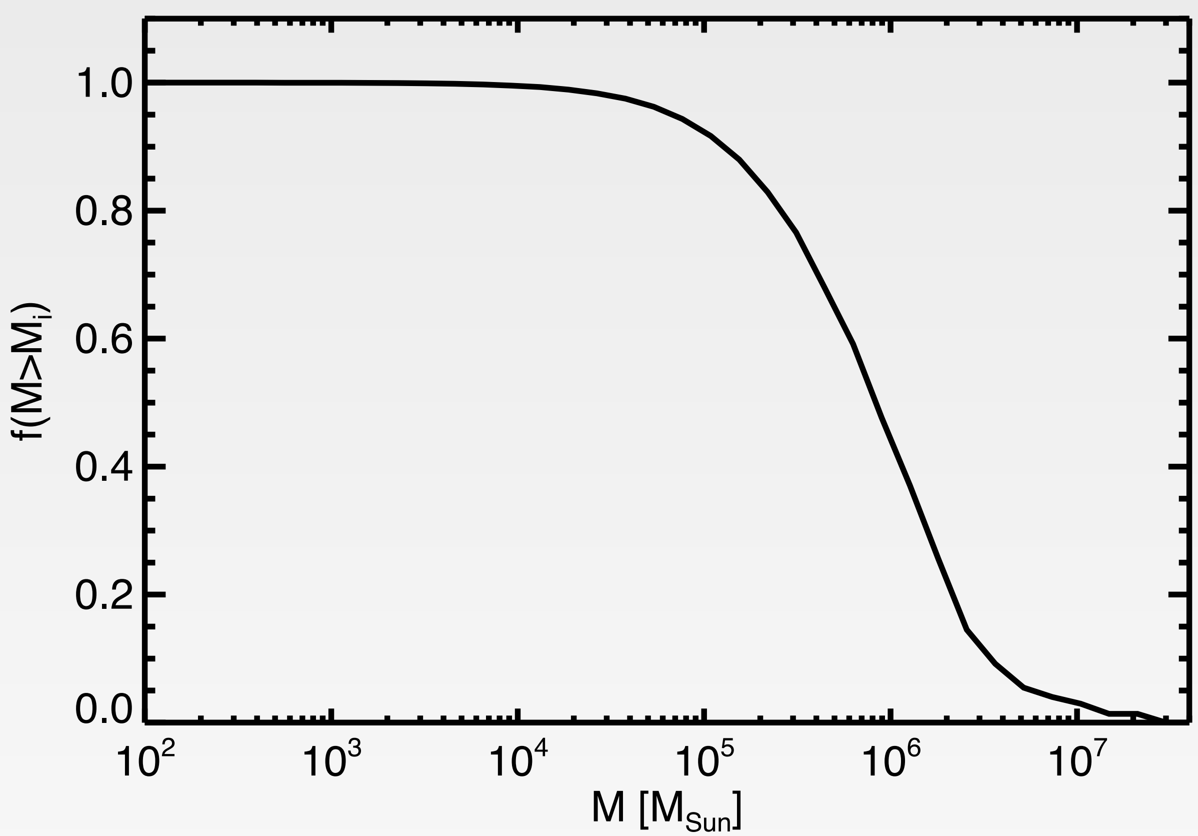
Introducing a new Milky Way GMC catalog

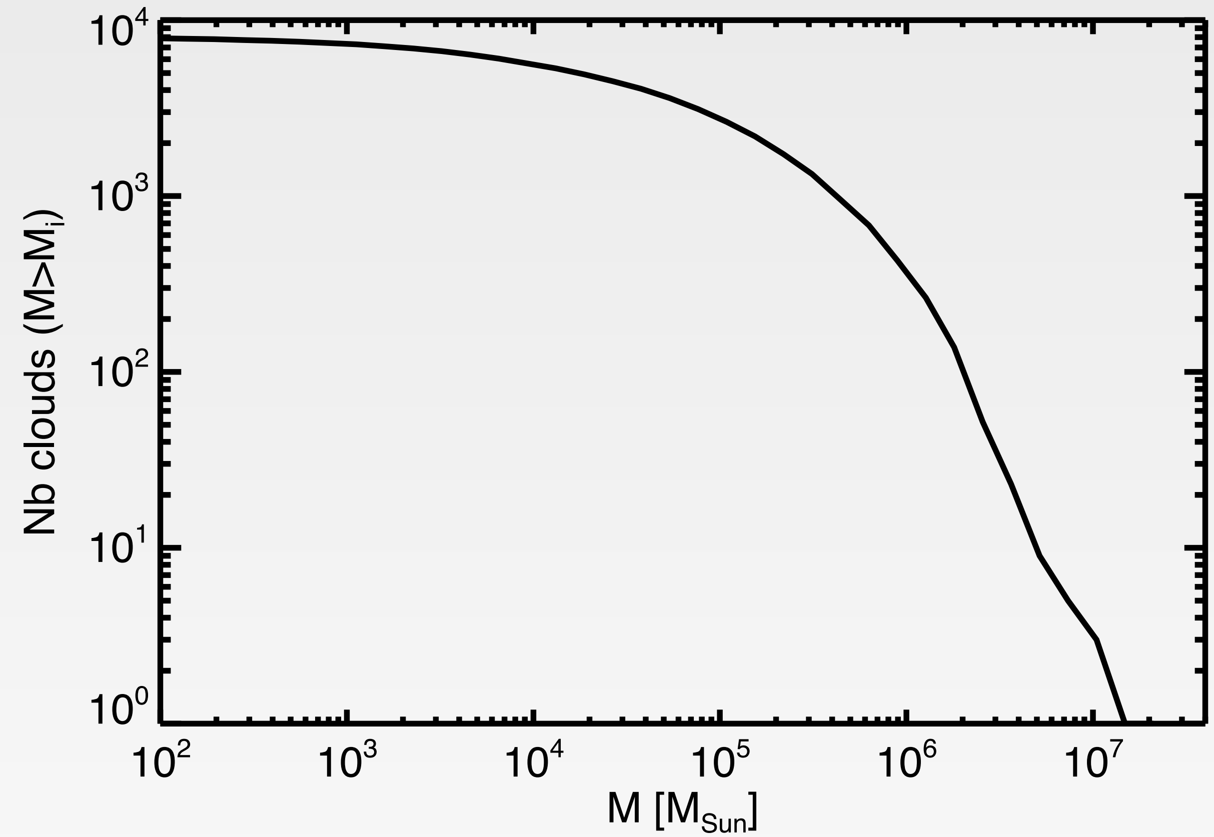




Mivilles-Deschene, Murray, & Lee (2017) ApJ **834** 57

Most of the molecular gas is in about 500 massive clouds



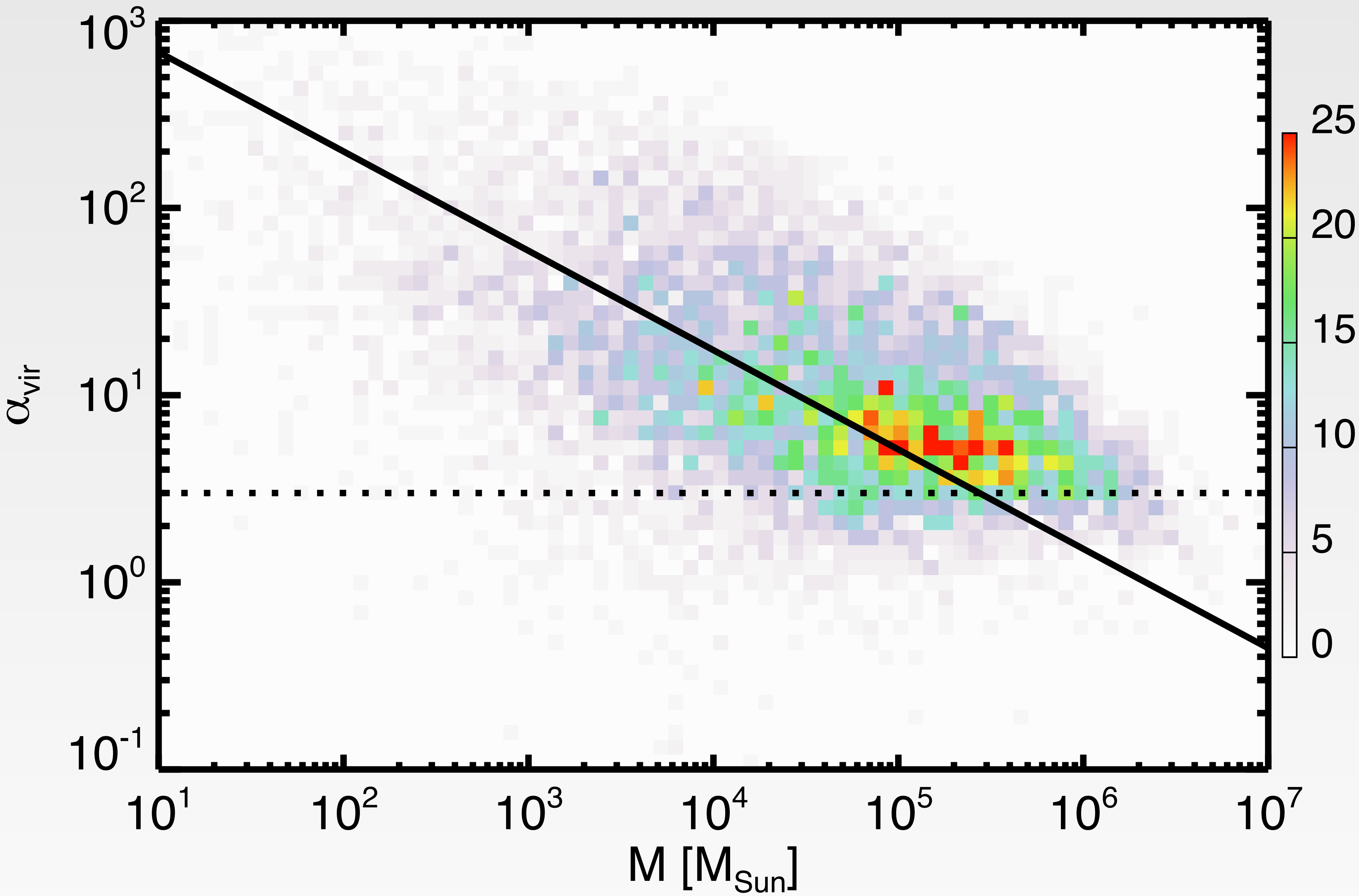


Half the molecular mass is in clouds with $M>8.4\times10^5\ M_\odot$

There are about 500 such clouds, out of ~9000 total

The catalog recovers 98% of the CO flux in the map

Miville-Deschenes, Murray, & Lee



The GMC virial parameter decreases with increasing GMC mass. Many of the 10^6 $M_\odot$ GMCs are gravitationally bound

Variations with R_{gal}

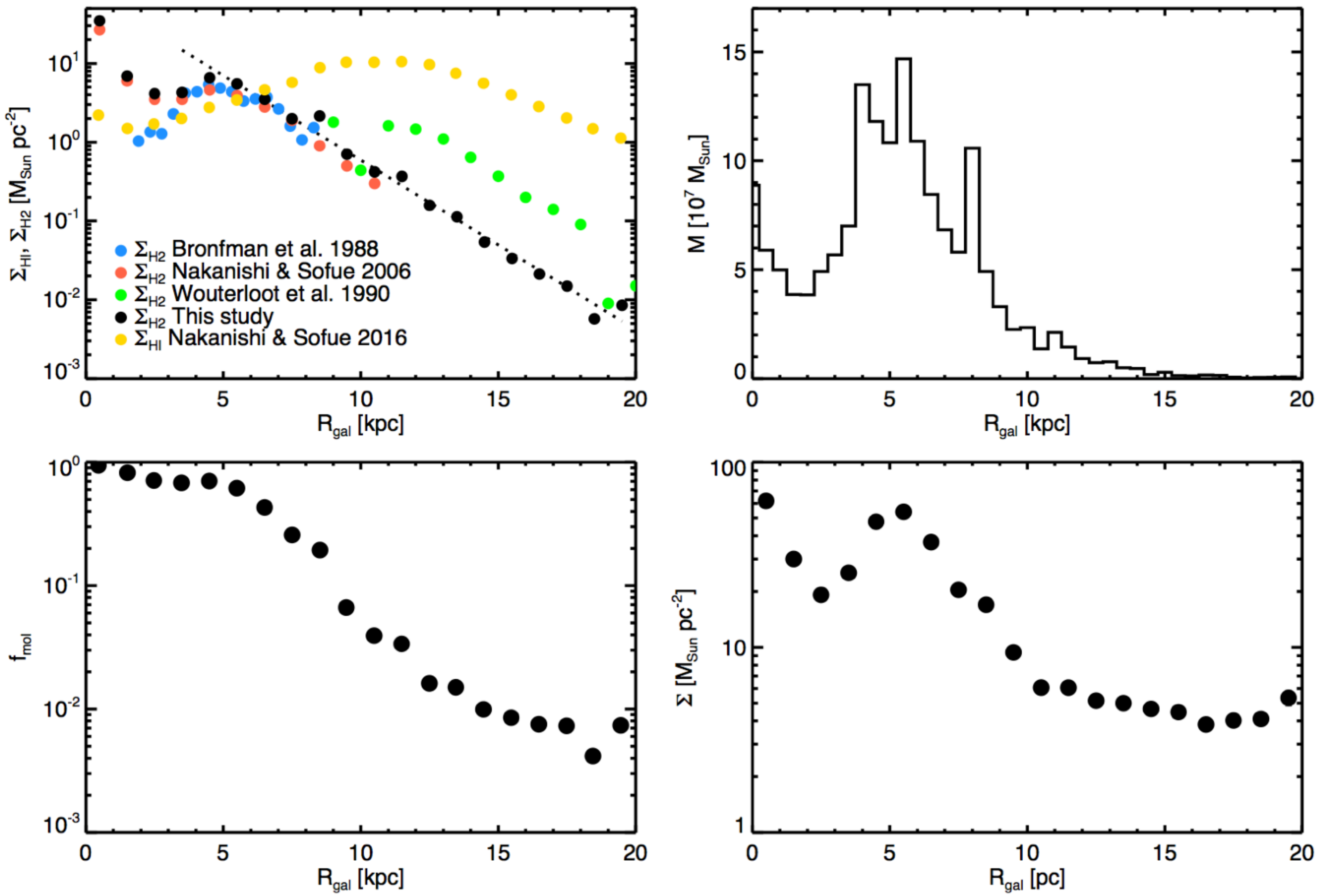


Figure 9. Top left: Surface density of H_2 mass as a function of galacto-centric radius (black points). The blue, red and green points correspond respectively to the estimate of Bronfman et al. (1988), Nakanishi & Sofue (2006) and Wouterloot et al. (1990). The dotted line is the exponential fit over the range $4 < R_{gal} < 17$ kpc: $\Sigma = 83 \exp(-R_{gal}/2.0)$. The yellow points correponds to the HI surface density of Nakanishi & Sofue (2016). **Top right:** Total mass of clouds in Galacto-centric rings (thickness 0.5 kpc), as a function of R_{gal}. **Bottom left:** Molecular fraction $f_{mol} = \Sigma_{H2}/(\Sigma_{HI} + \Sigma_{H2})$ built using our estimate of Σ_{H2} and Σ_{HI} from Nakanishi & Sofue (2016). **Bottom right:** Variation of the median cloud mass surface density Σ as a function of Galactocentric radius.

Mean line width versus R_{gal}

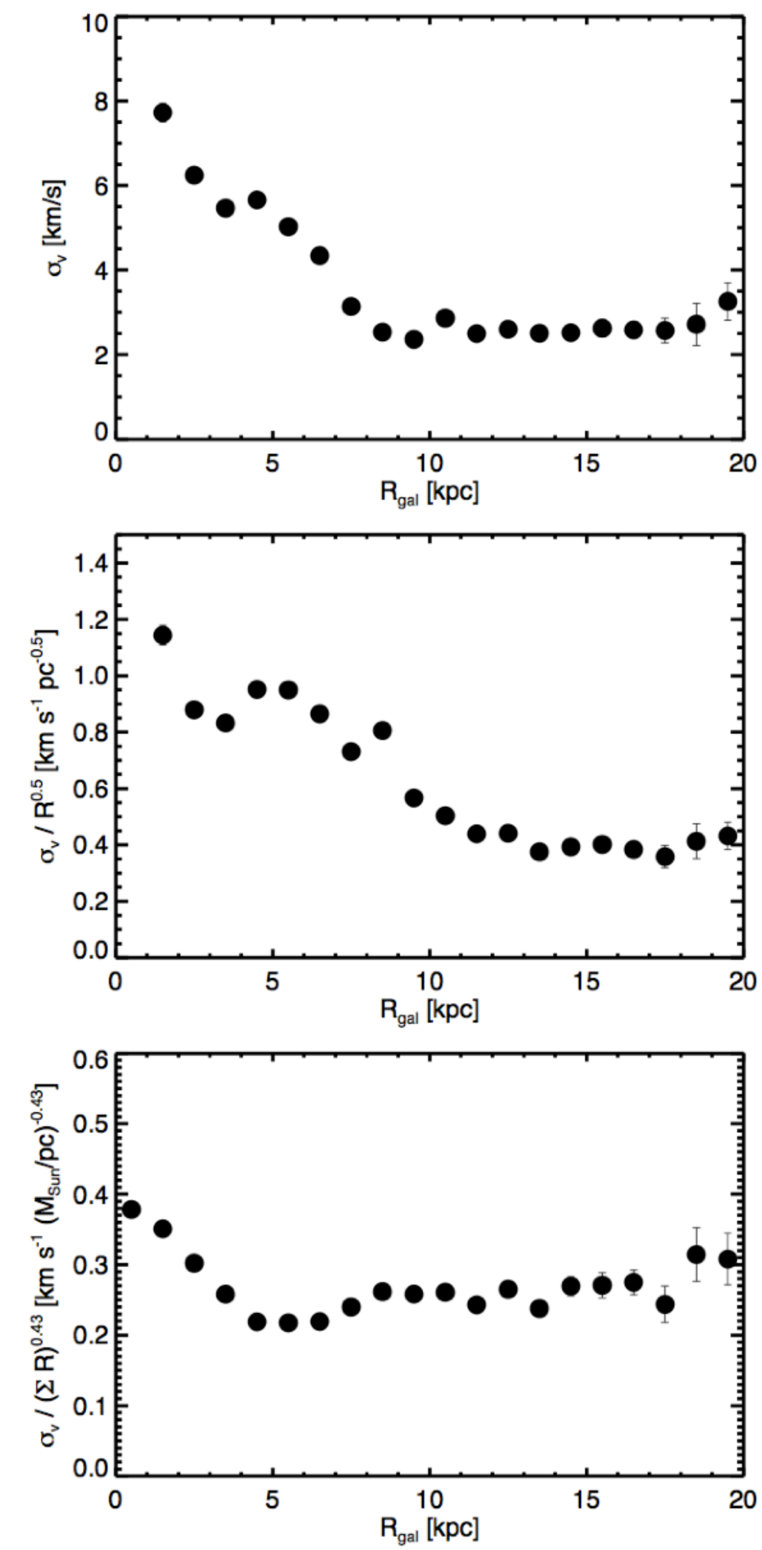
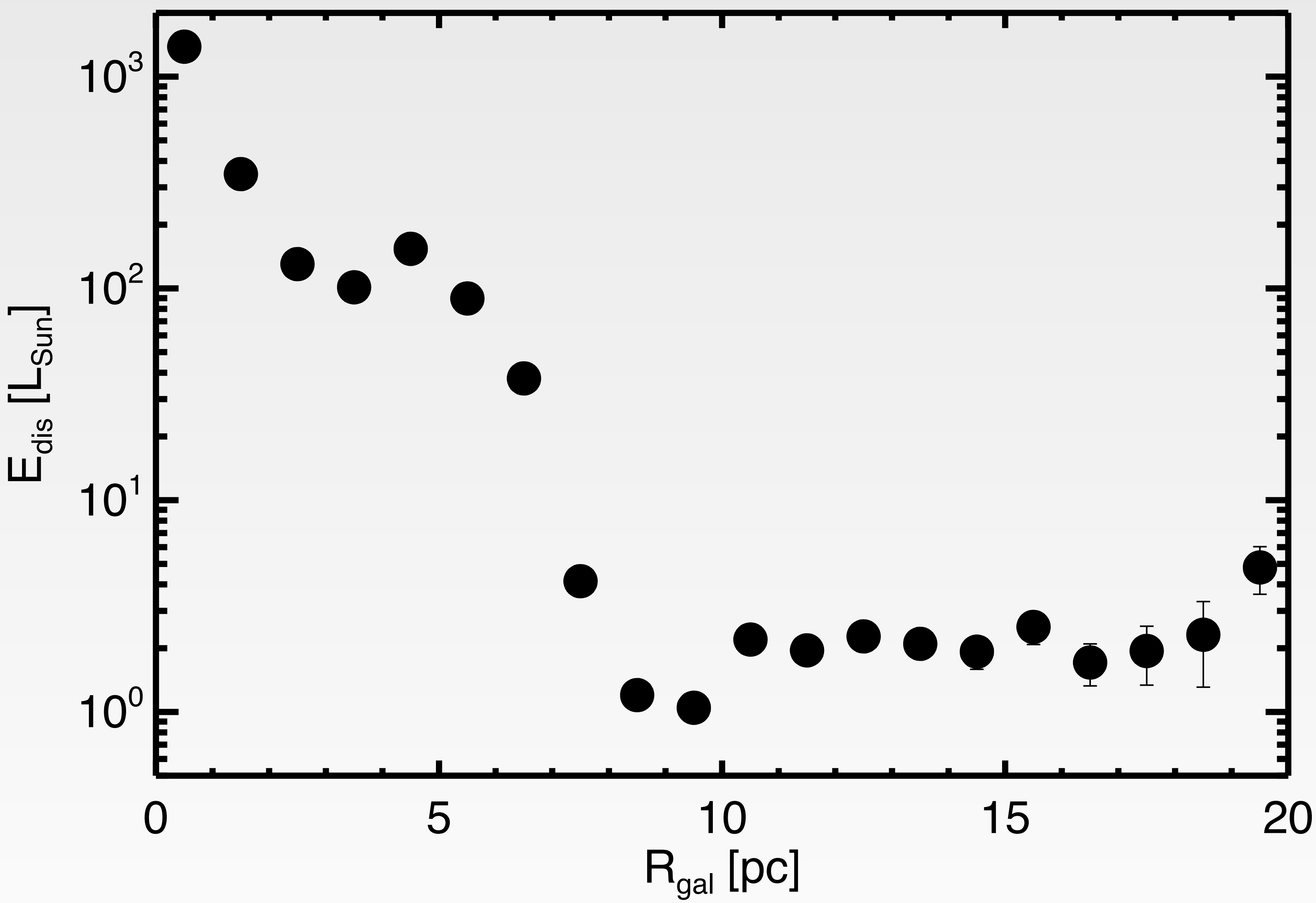


Figure 13. Variation of σ_v (top), $\sigma_v/R^{1/2}$ (middle) and $\sigma_v/(\Sigma R)^{0.43}$ (bottom) as a function of Galactocentric radius. In all panels each dot and its associate error bar indicate respectively the median and 1σ dispersion of the values in a bin of R_{gal}.

Turbulent Luminosity

$$\dot{E}_{\rm dis} = \frac{1}{2}\frac{M\sigma_v^3}{R}$$

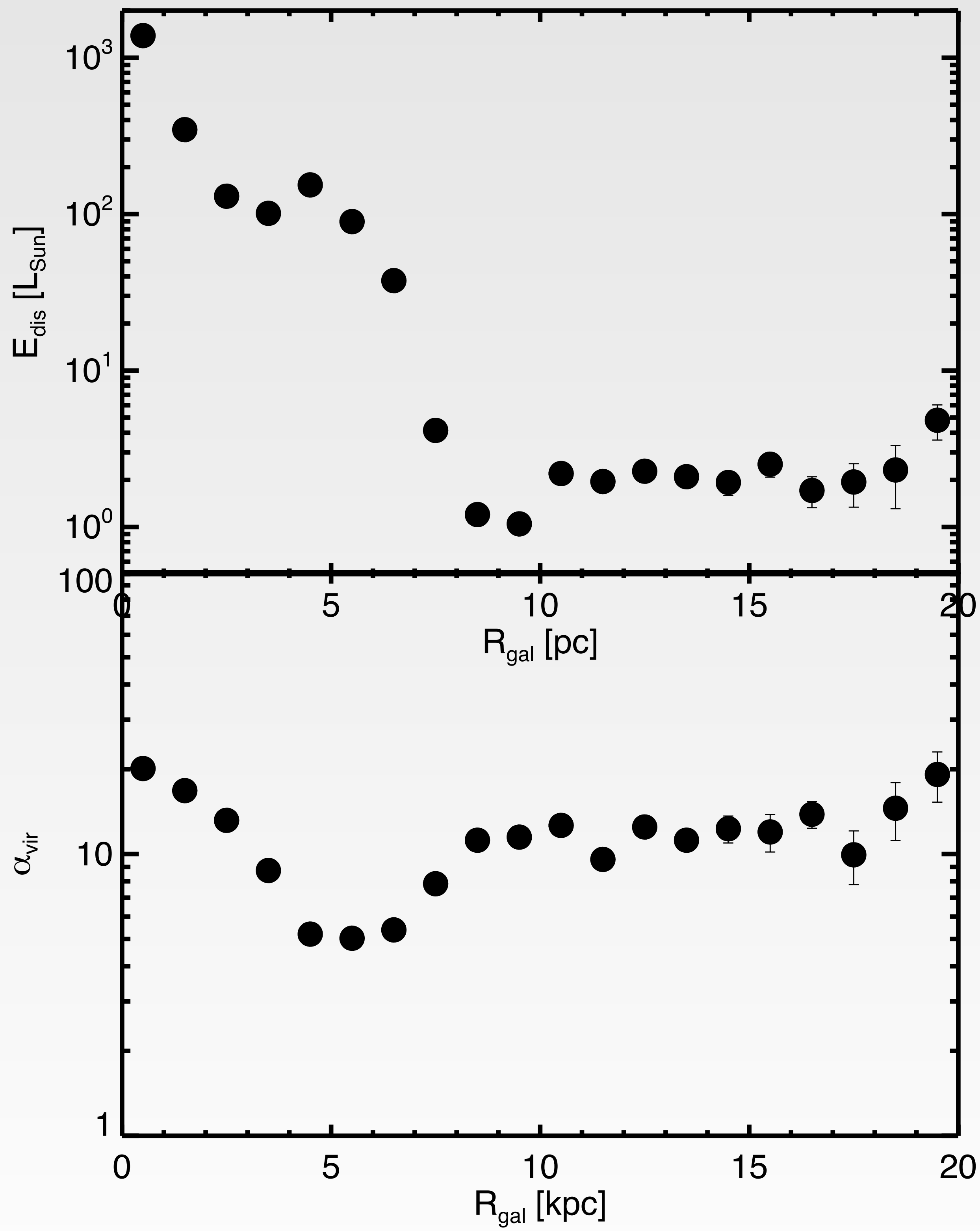


The average energy dissipation rate in annuli. In the outer Galaxy, the dissipation rate $L_{Turb}=2L_{\odot}$ can be supplied by the flows that create the GMCs. The inner Galaxy is another story, since $L_{Turb}=100L_{\odot}$; assembly of GMCs does not supply enough power.

What powers the turbulence in individual GMCs?

- Accretion through the Galactic disk (its an accretion disk!) driven by the MRI, or by gravitational torques due to spiral arms
- Accretion onto GMCs
- Contraction of GMCs
- Stellar feedback: protostellar jets, radiation pressure, HII region, stellar winds, supernovae

Virial Parameter vs R_{Gal}



Lee, Murray, & Miville-Deschenes (2016)

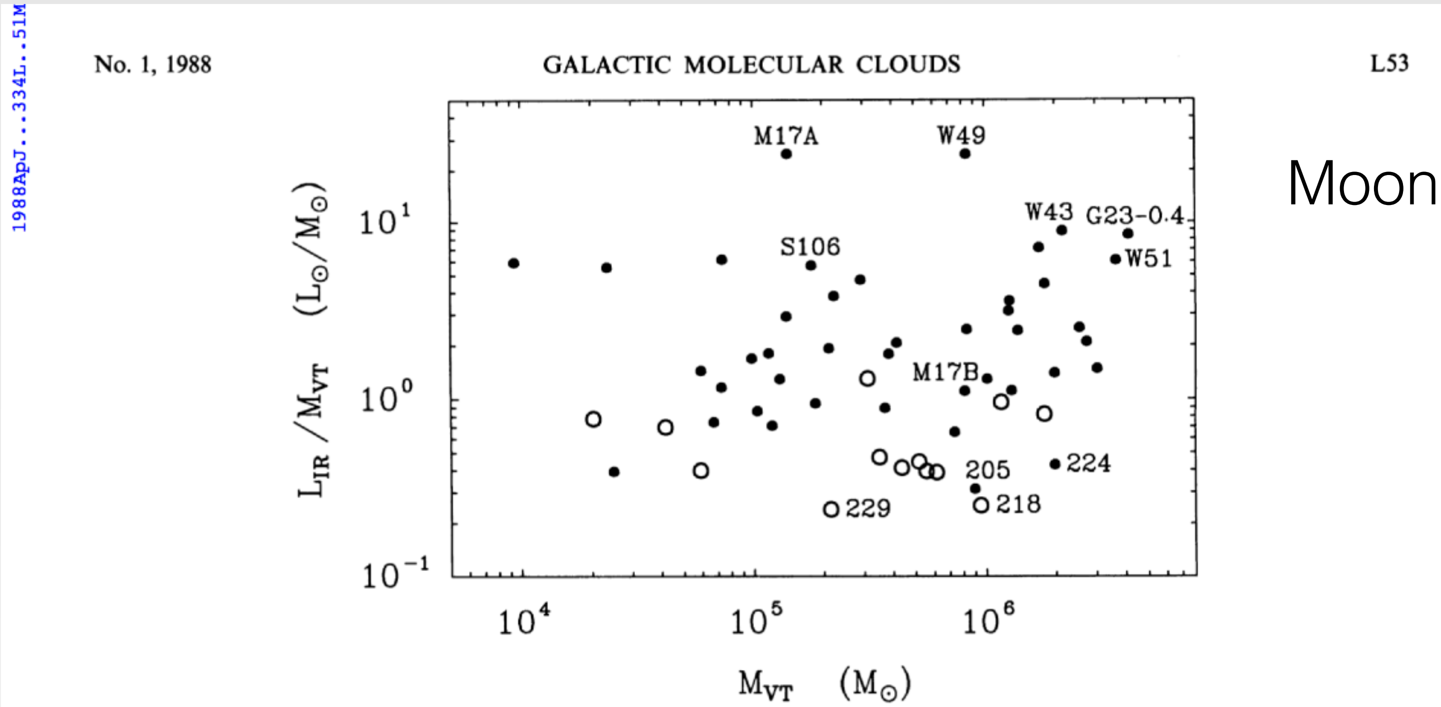
Contraction powers the turbulence in the molecular ring GMCs,
Accretion through the disk R_{gal}<3kpc

If massive GMCs are bound or collapsing, why don't they all show star formation?

If massive GMCs are bound or collapsing, why don't they all show star formation?

They are collapsing, but the star formation rate starts small, then increases with time

The mass accretion rate



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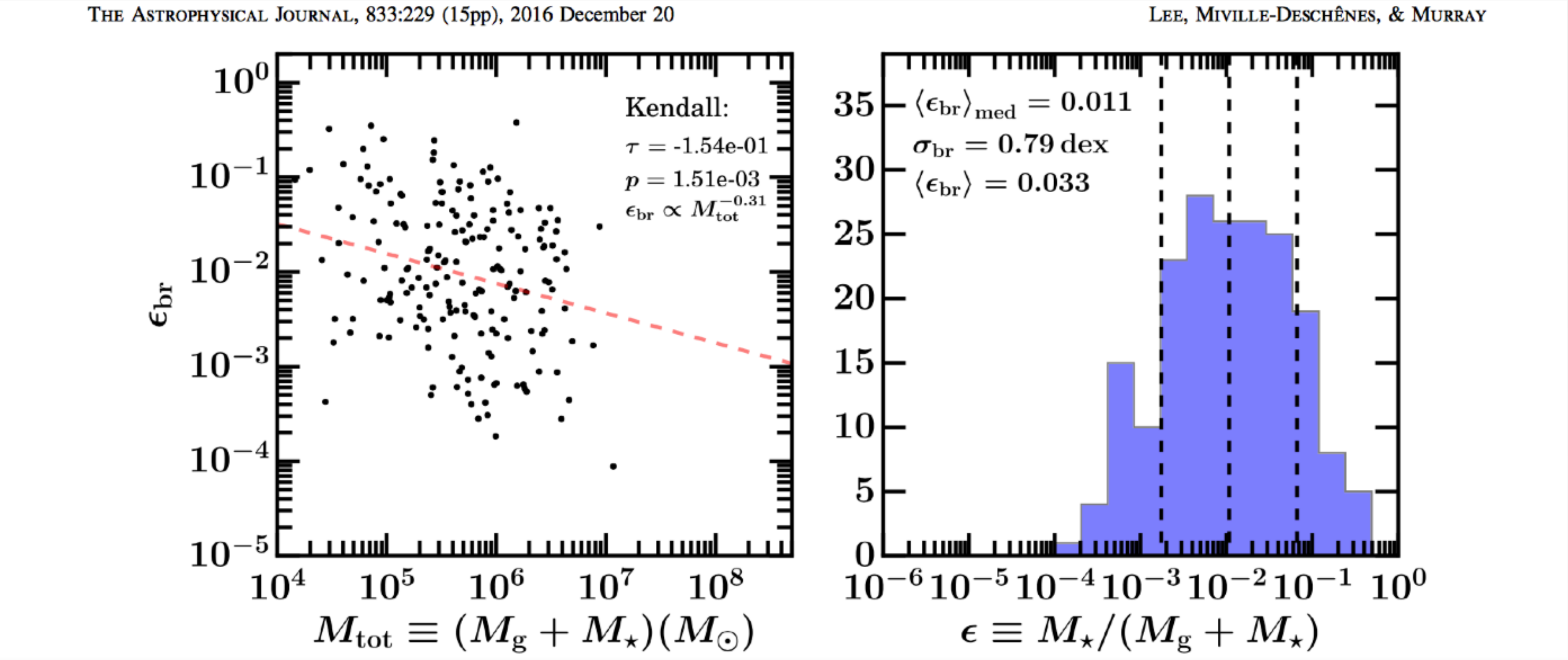
Mooney & Solomon 1988



Is dM⁎/dt nearly constant?

Spherical Collapse Model

Murray & Chang (2015) ApJ 804 44

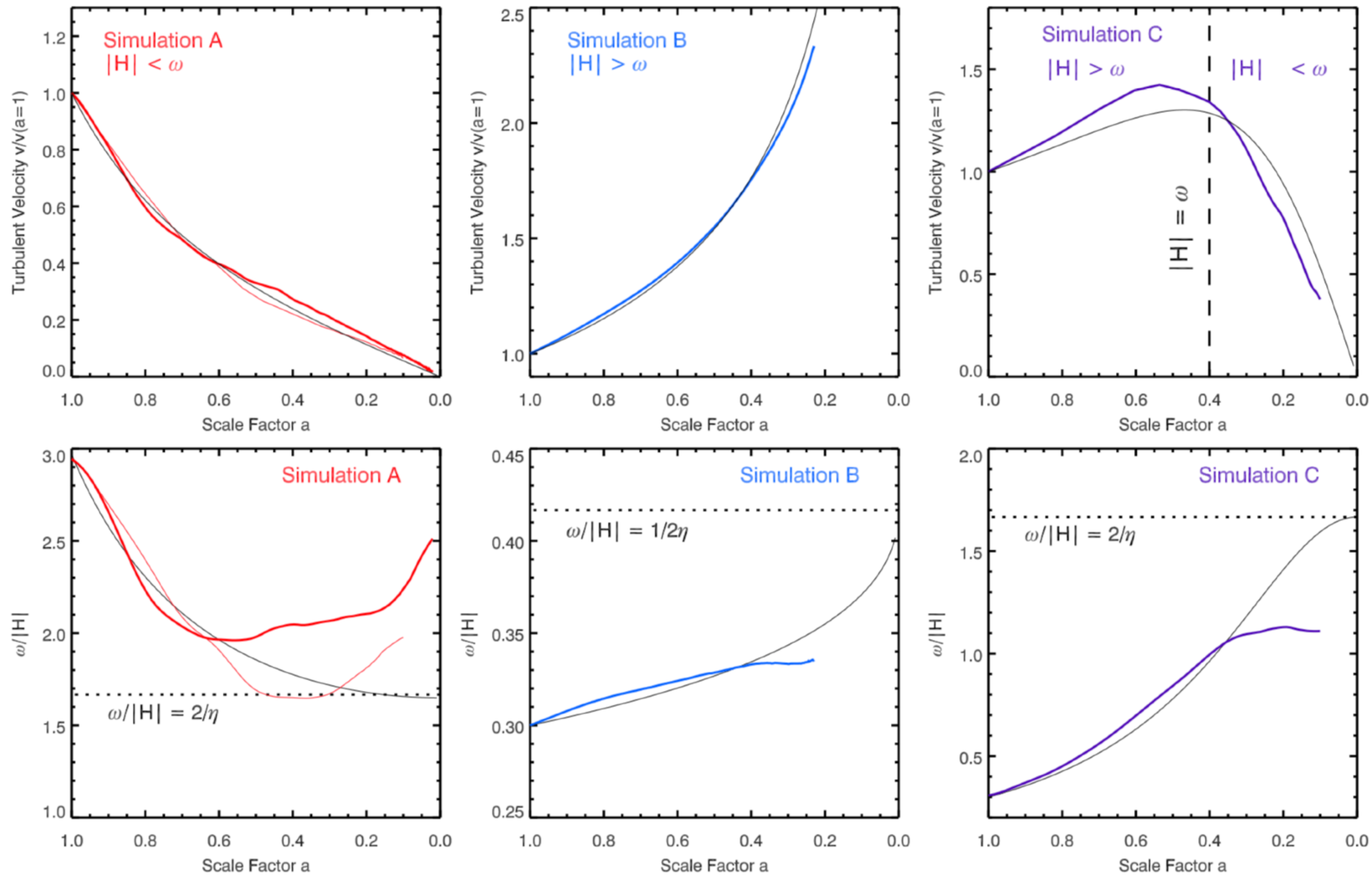
$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 u_r \rho) = 0,$$

$$\frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + \frac{1}{\rho}\frac{\partial \rho v_T^2(r,t)}{\partial r} + \frac{GM(r,t)}{r^2} = 0,$$

$$\frac{\partial v_T}{\partial t} + u_r \frac{\partial v_T}{\partial r} + \left(1 + \eta \frac{v_T}{u_r}\right)\frac{v_T u_r}{r} = 0.$$

$$M(r,t) = 4\pi \int r^2 \rho(r,t) dr.$$

Robertson & Goldreich



Spherical Collapse Model Feedback Loop

Murray & Chang (2015) ApJ 804 44

$$\frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} = -\frac{1}{\rho}\frac{\partial \rho v_T^2}{\partial r} - \frac{GM(r,t)}{r^2},$$

$$\frac{\partial v_T}{\partial t} + u_r \frac{\partial v_T}{\partial r} = +\frac{v_T |u_r|}{r} - \eta \frac{v_T^2}{r}.$$

As a result :

$$v_T(r,t) \approx |u_r(r,t)|$$

Spherical Collapse Model: Stellar sphere of influence

- Star or Star cluster sphere of influence: breaks simple self-similarity

$$M_g(r_*(t), t) \equiv 4\pi \int_{0^+}^{r_*(t)} r^2 \rho(r,t) dr = M_*(t)$$

- Solutions for $r_{disk} < r < r_*(t)$ differ from those for $r_*(t) < r < R$

Spherical Collapse Model

Murray & Chang (2015) ApJ 804 44

$$\frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + \frac{1}{\rho}\frac{\partial \rho v_T^2}{\partial r} + \frac{GM_*(t)}{r^2} = 0,$$

since

$$v_T \sim |u_r|$$

$$|u_r| \sim r^{-1/2}$$

for $r << r_*$.

Spherical Collapse Model: the density attractor.

$$\rho(r,t) \sim r^{-k_\rho}\tilde{\rho}(t)$$

$$u_r(r,t) \sim r^p \tilde{u}(t)$$

$$\frac{\partial\tilde{\rho}(t)}{\partial t} r^{-k_\rho} + \tilde{\rho}(t)\tilde{u}(t) r^{p-k_\rho-1}\left[2+p-k_\rho\right] = 0,$$

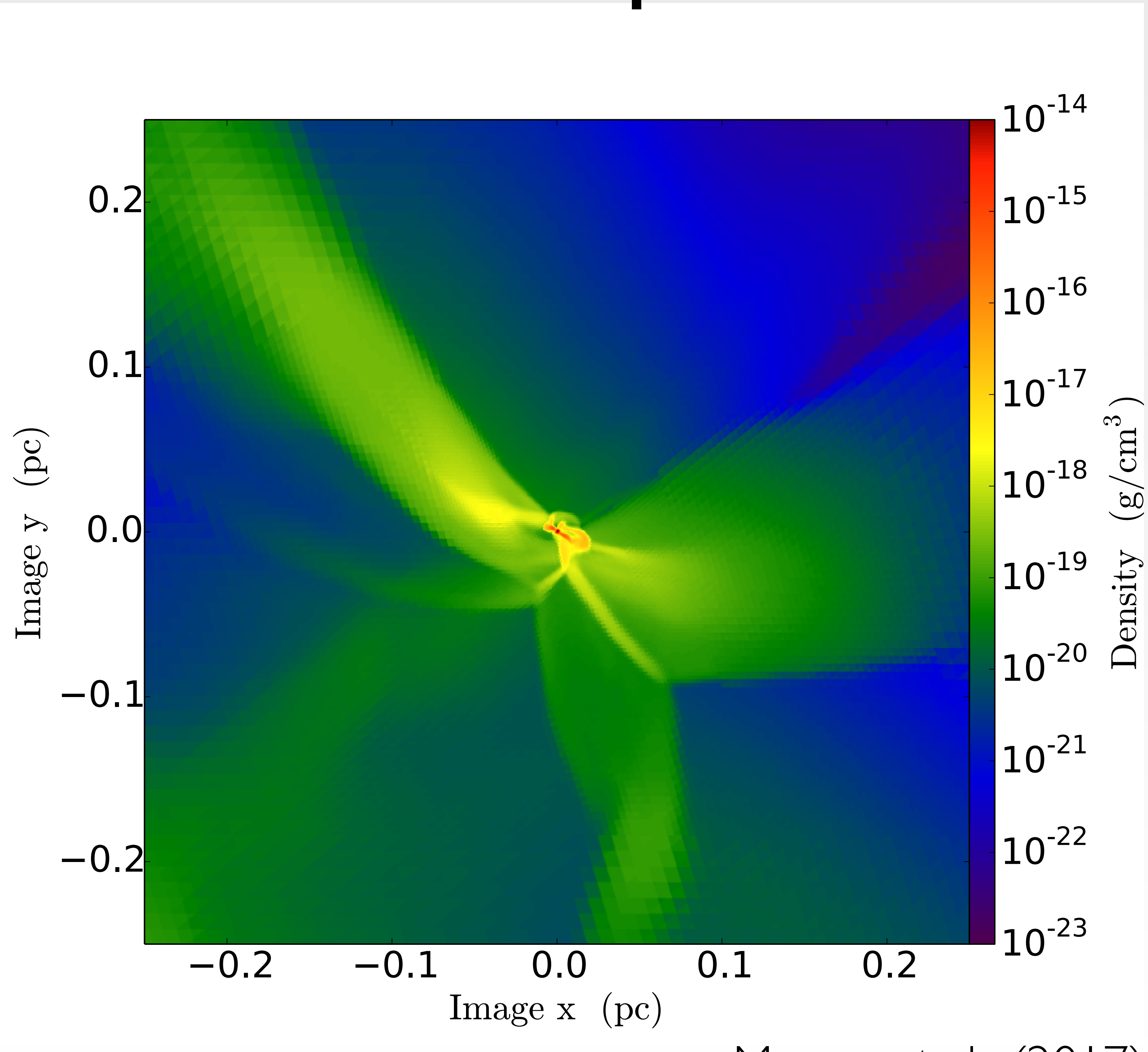
since $p < 0$, at small r the second term grows much faster than the first, so

$$k_\rho = 2+p, \text{ and}$$

$$\frac{\partial\tilde{\rho}(t)}{\partial t} = 0, \text{ i.e., } \rho(r,t) \to \rho(r).$$

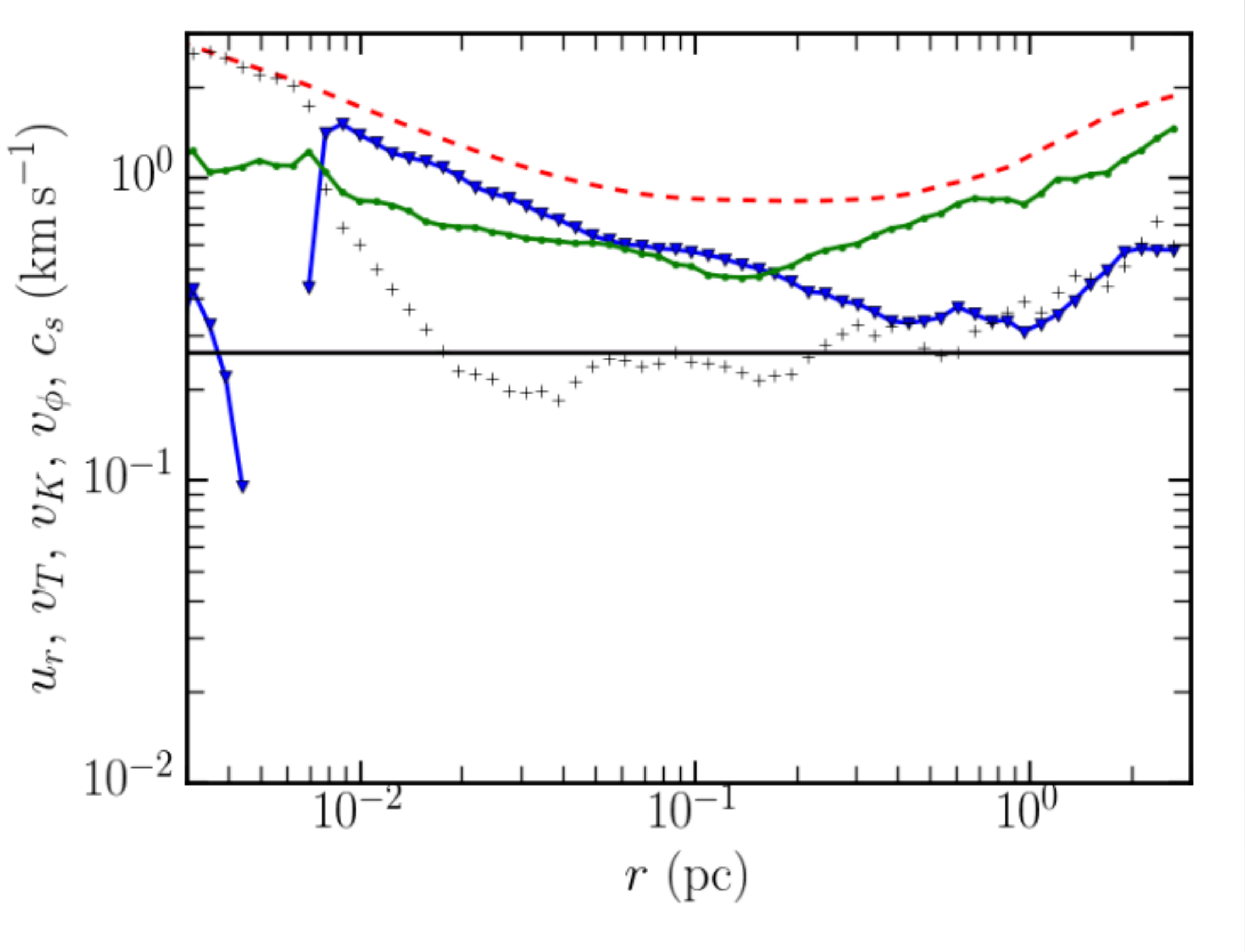
Murray & Chang (2015) ApJ 804 44

Simulations of Turbulent Collapse



Murray et al. (2017) MNRAS 465 1316

Infall, turbulent, & rotational velocity

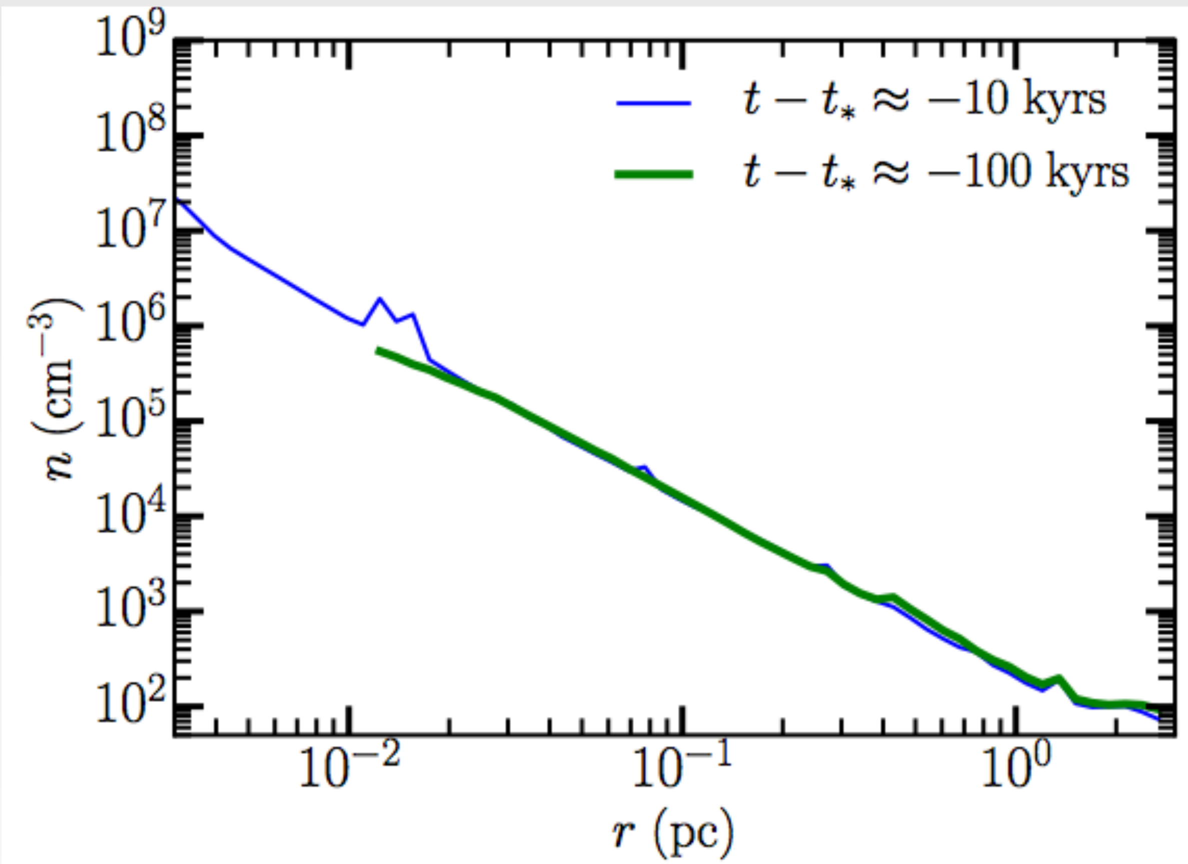


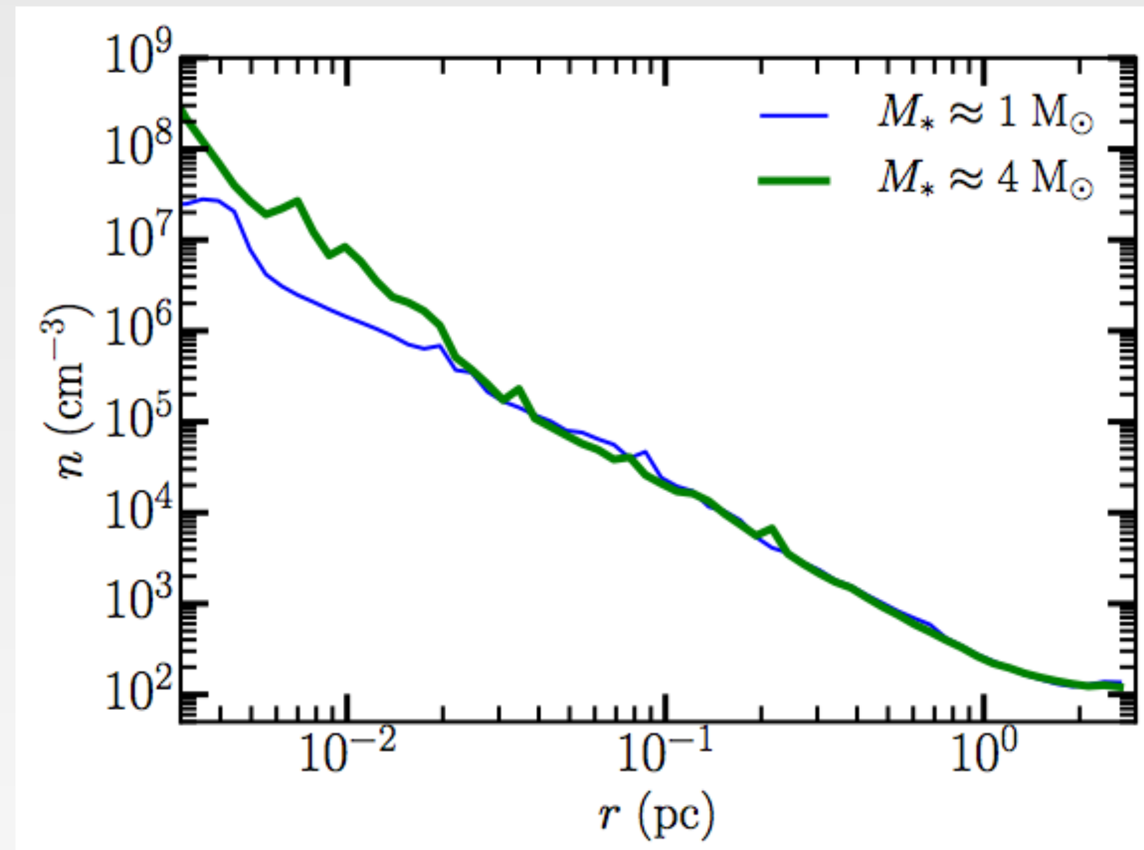
Supersonic infall, at ~1/3-1/2 v_K (blue line); not HSE

v_T (green line) increases inward for $r>r_*$, increases inward for $r<r_*$

This is when the star has $M_* \approx 3M_\odot$

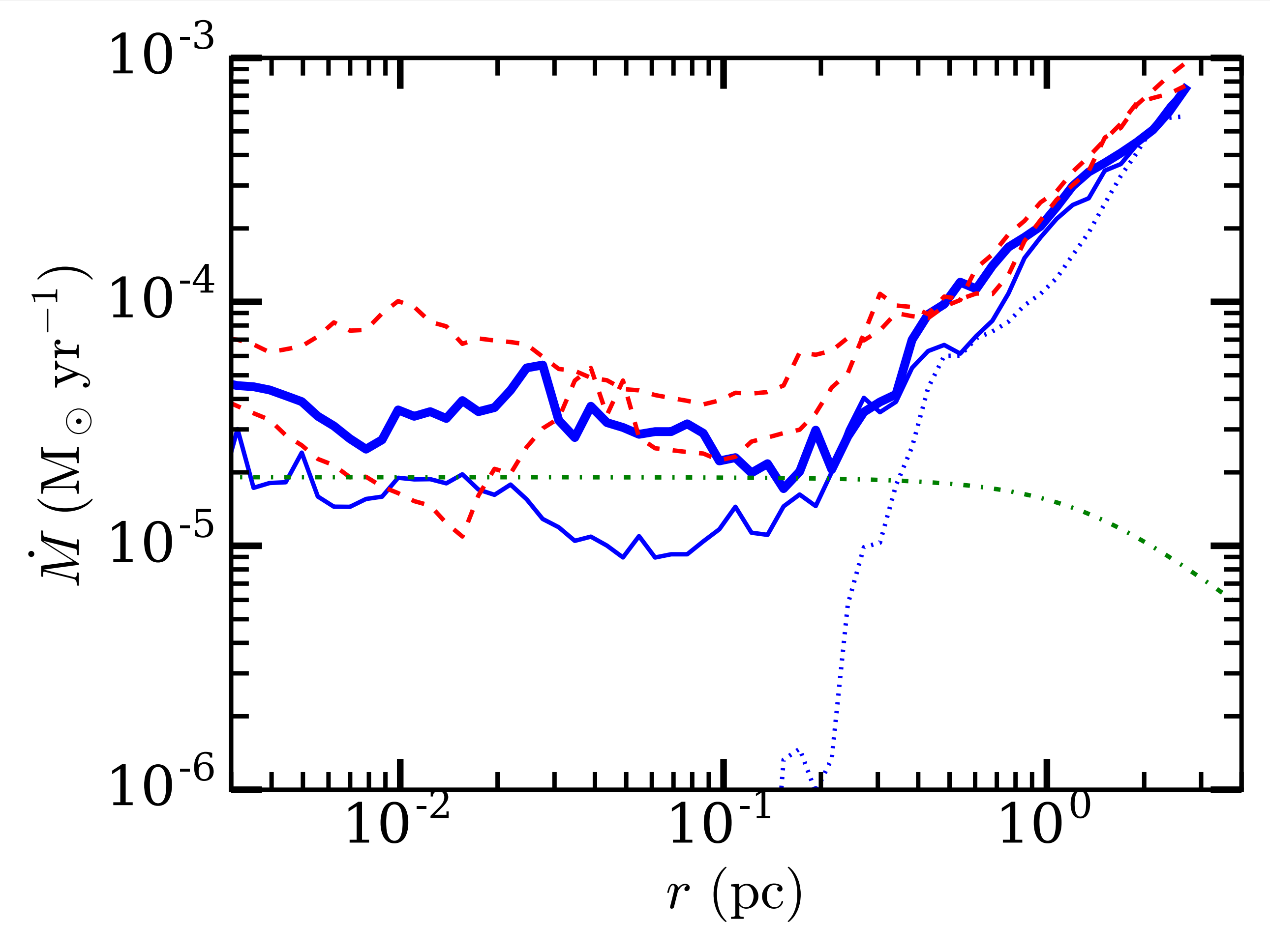
The density attractor

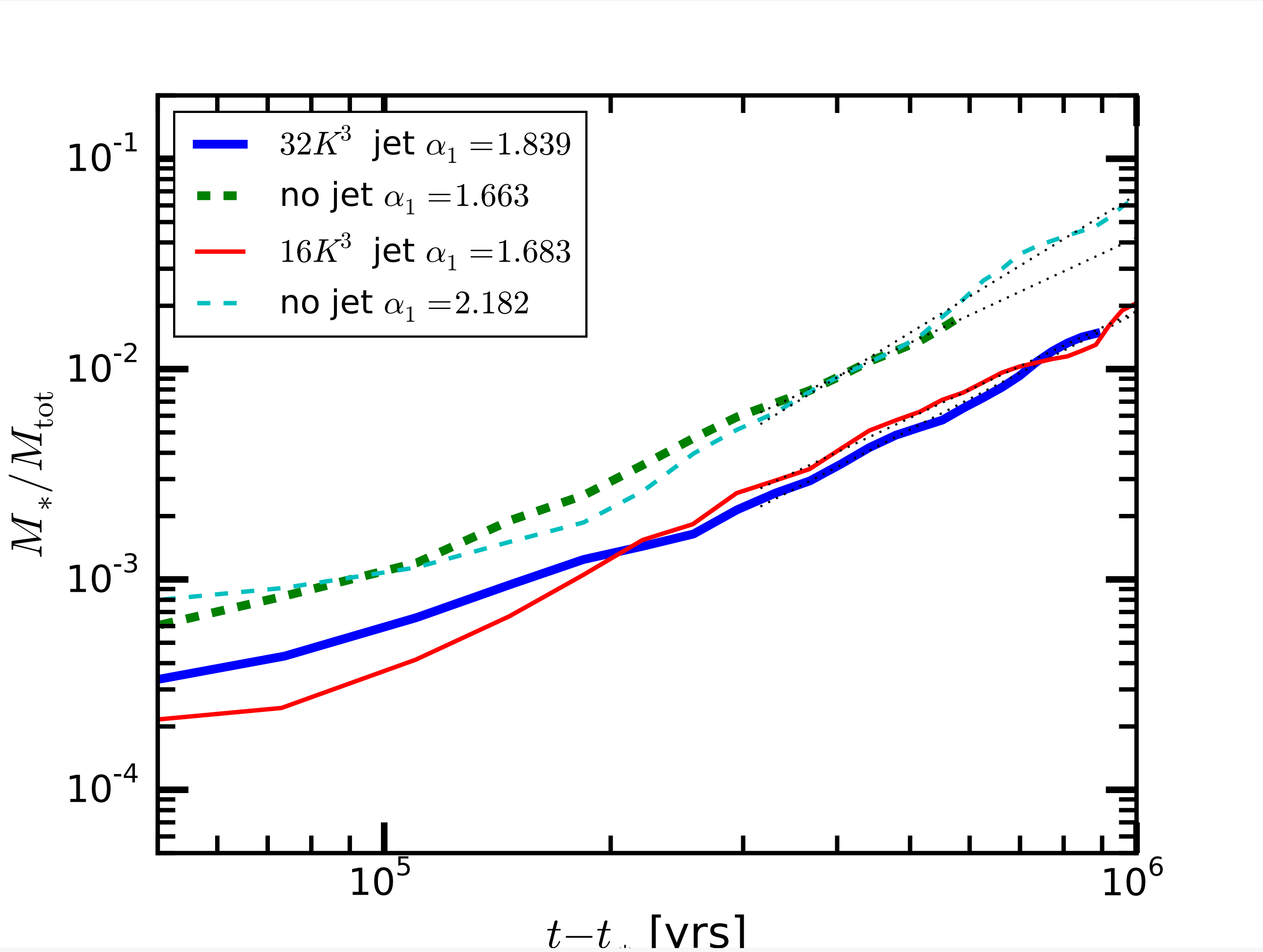




The density does not vary with time for at least 1/3 of a large scale dynamical time for $r > r_d$

The mass accretion rate



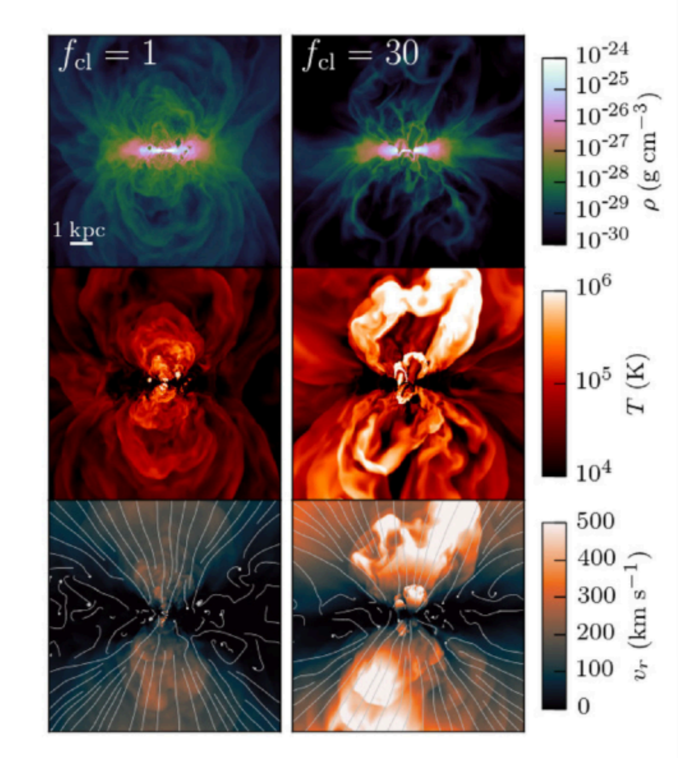


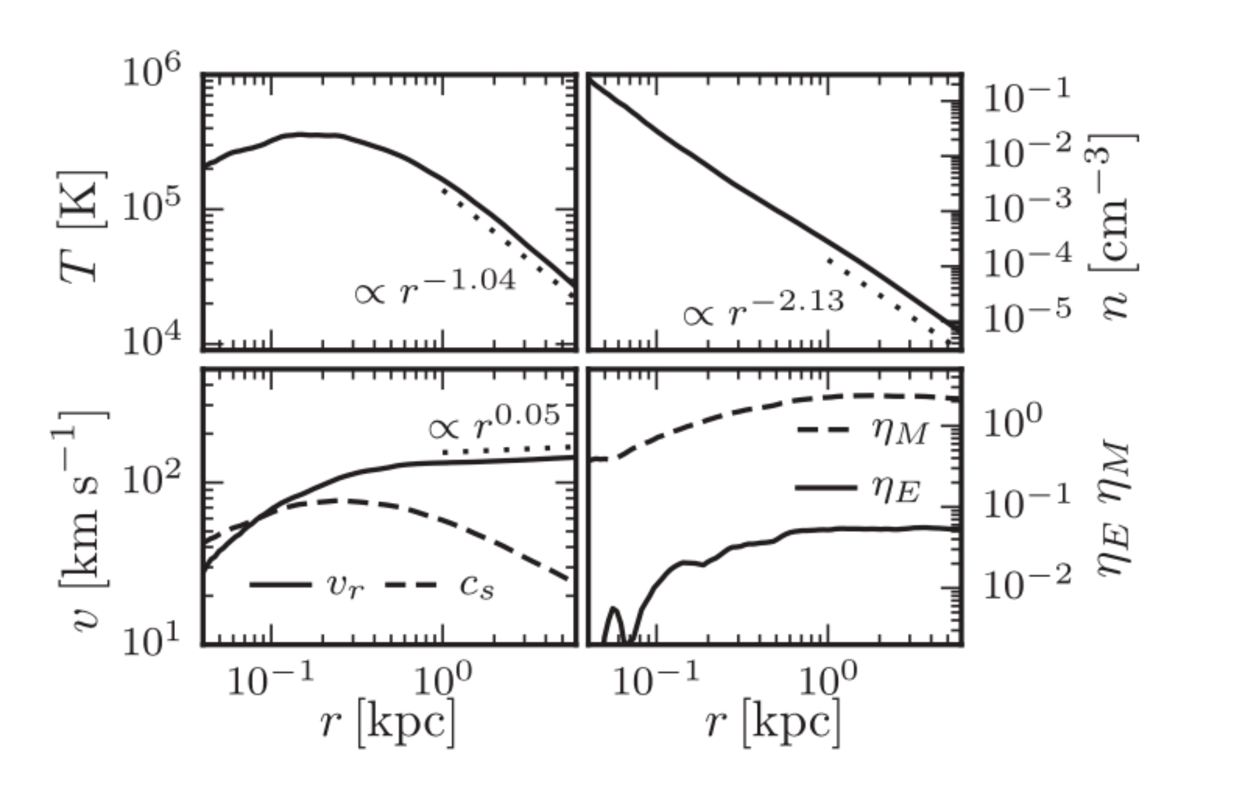
dM/dt (r) is nearly constant for r<r✷

M✷(t) ~ $t^{1.8}$

Stellar Feedback in action

Moving to Larger Scales: 1KPC disk, resolved Sedov-Taylor phase

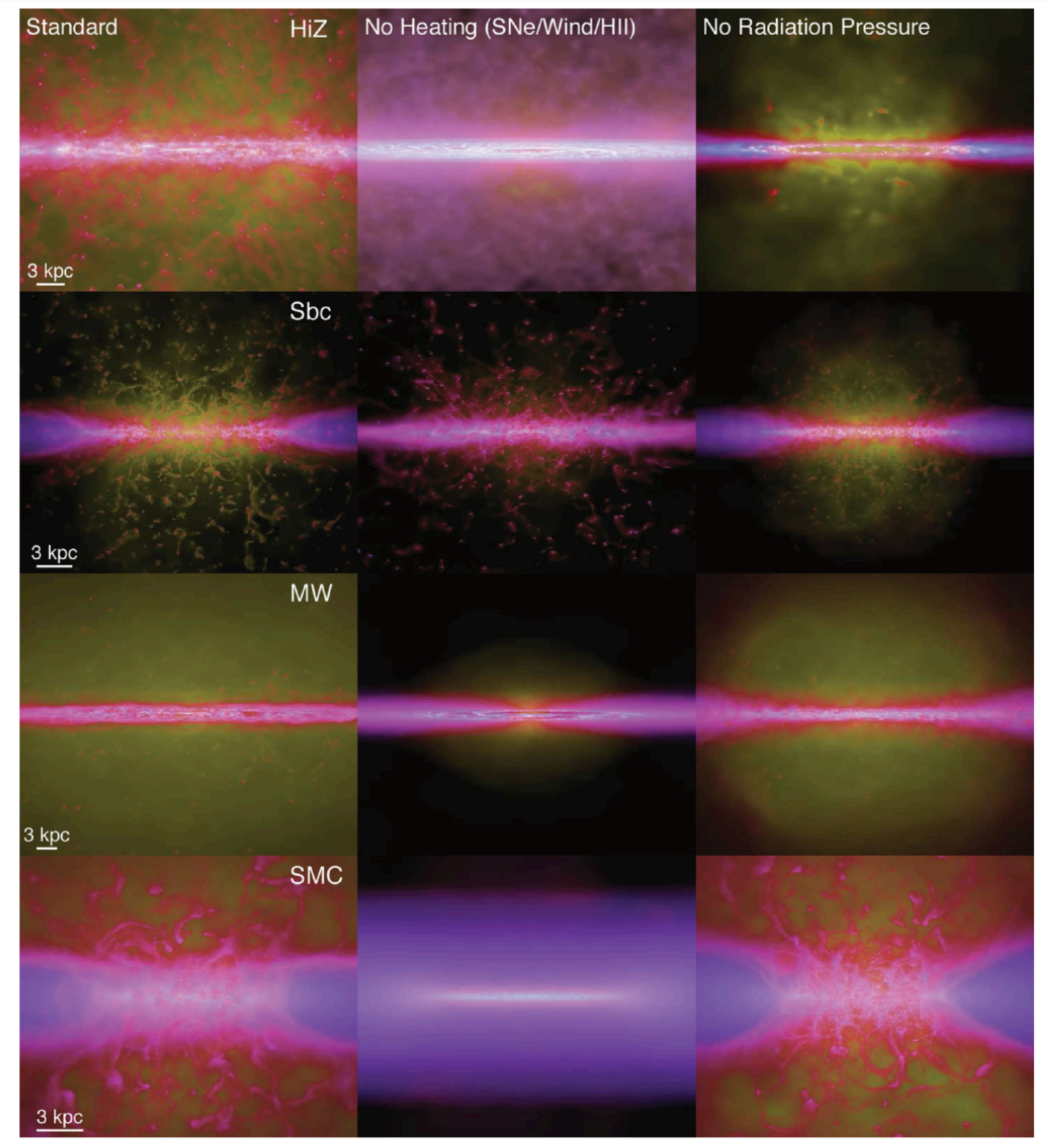




Fielding et al. (2017) MNRAS **470** 39

Moving to Larger Scales:
isolated galaxies, mostly resolved Sedov-Taylor phase

resolution 3pc
100-1000$M_\odot$



Hopkins, Quataert, & Murray (2012)

Moving to Larger Scales: isolated galaxies, mostly resolved Sedov-Taylor phase

resolution 3pc
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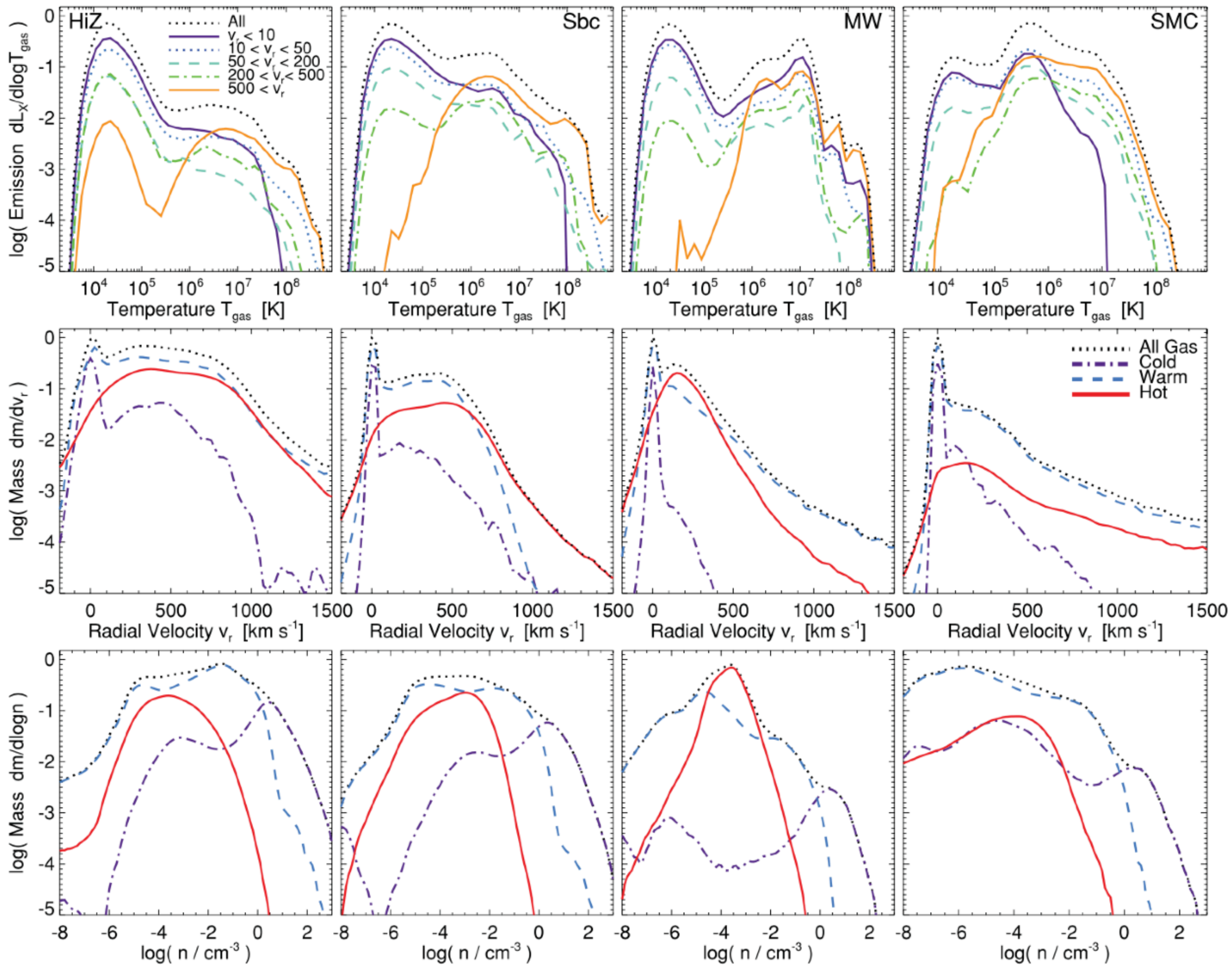
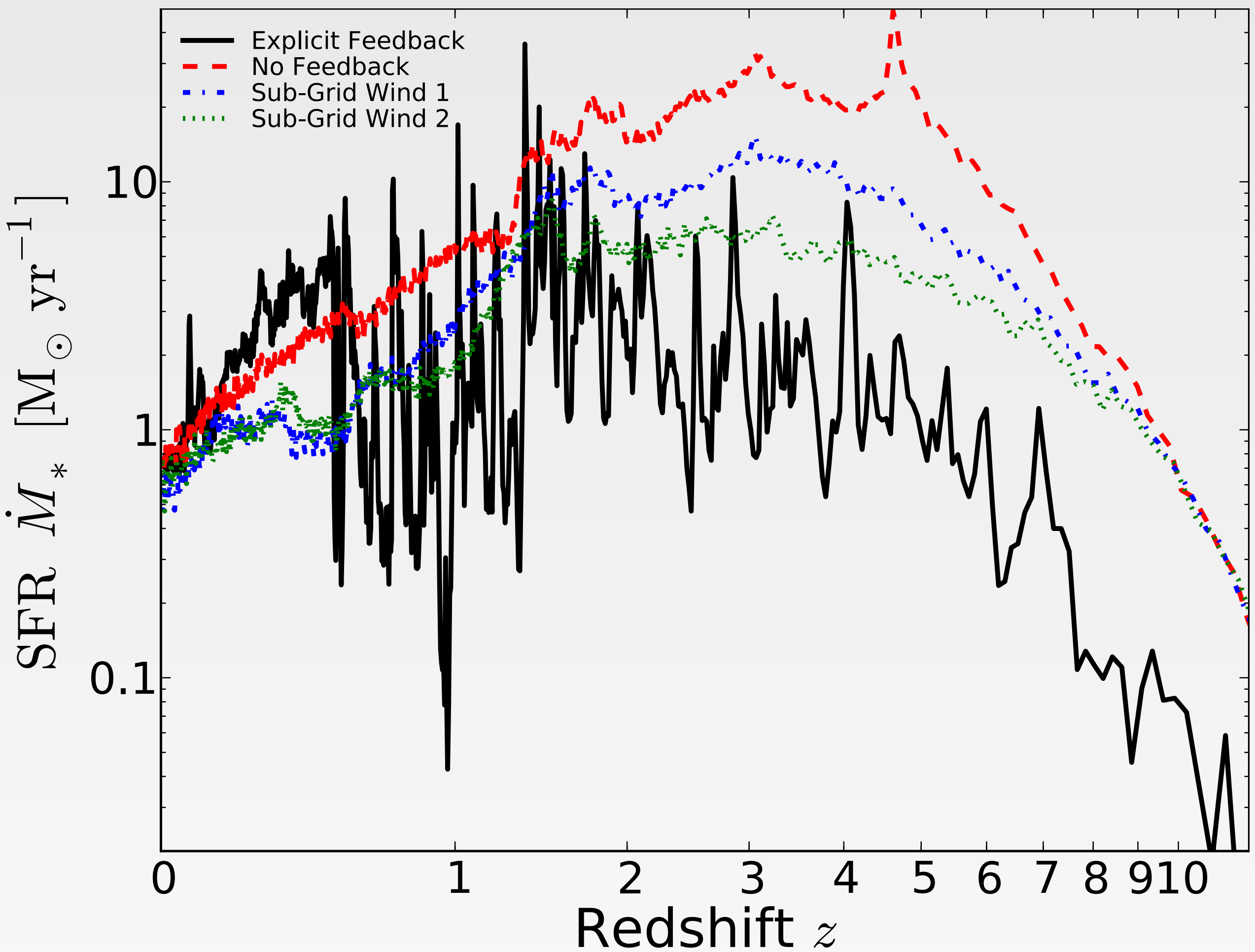


Hopkins, Quataert, & Murray (2012)

Moving to Larger Scales: cosmological zoom galaxies (FIRE)



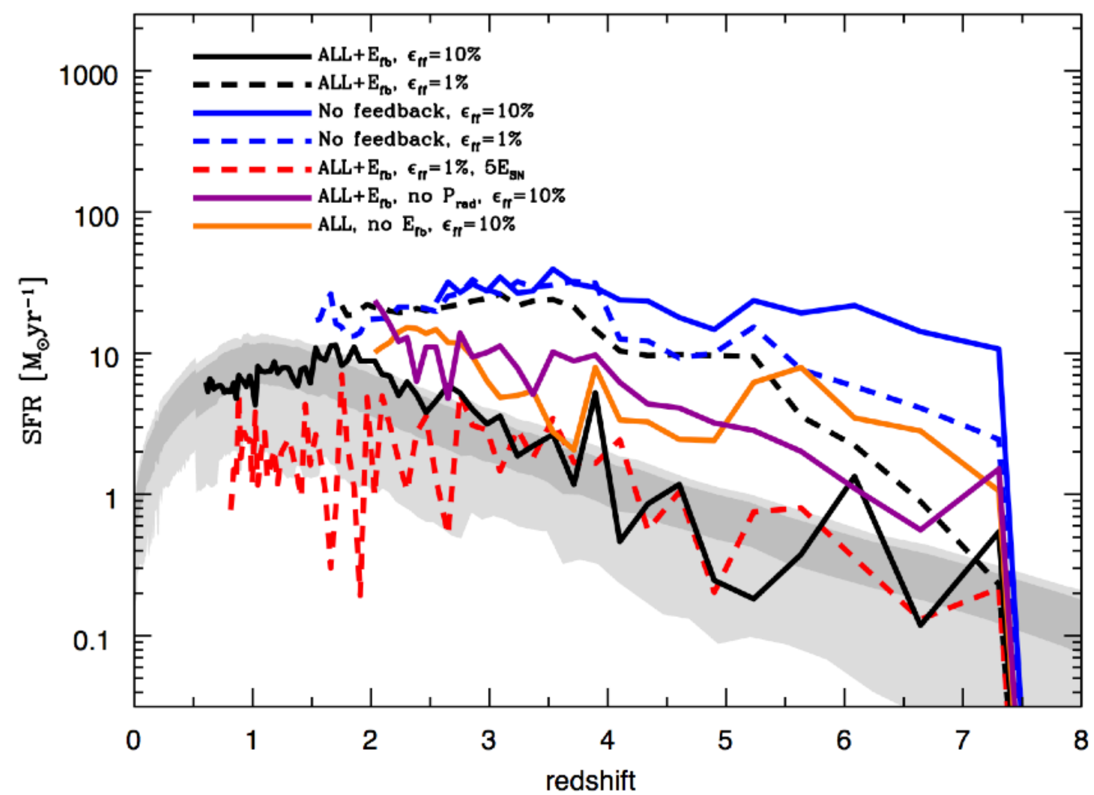
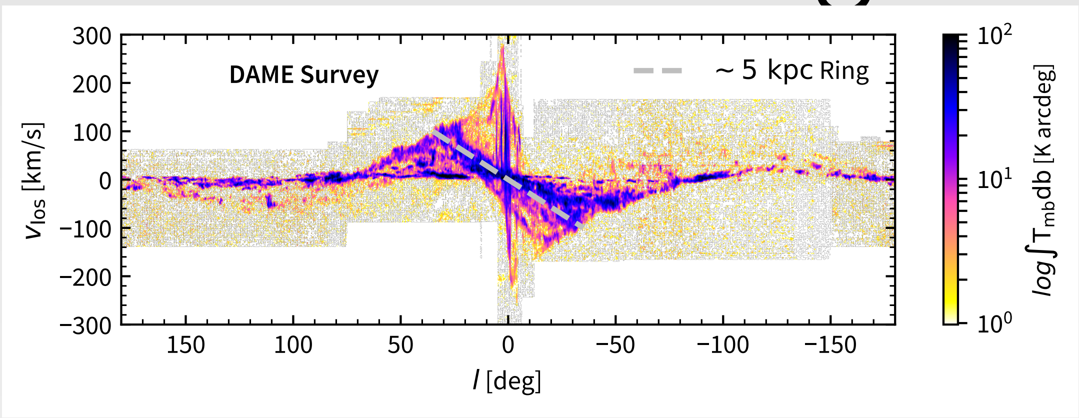


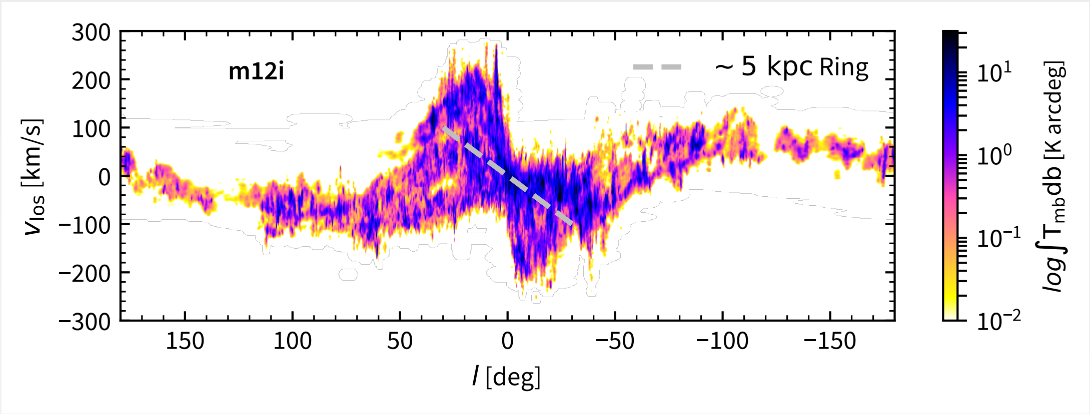
FIG. 4.— Simulated star formation histories compared to the Behroozi et al. (2013) data for $M_{vir}(z = 0) = 10^{12} M_\odot$. Dark and light gray shaded areas one-and two-sigma confidence regions respectively. We adopt bins of size Δt_{SF} = 100 Myr for the simulated SFHs. Without feedback, SFRs are overpredic by at least one order of magnitude at $z > 1$. Efficient feedback in conjunction with $\epsilon_{ff} \gtrsim 10\%$ (ALL_Efb_e010) renders a star formation history in agreem with the Behroozi et al. data. In simulations with low star formation efficiency of $\epsilon_{ff} = 1\%$, the effectiveness of feedback diminishes and SFRs is $\sim$ 1 dex hig than expected. Boosting the available SNe feedback (ALL_Efb_e001_5ESN) alleviates this, but leads to a significantly stronger suppression of star format at $z \lesssim 2.5$. Both radiation pressure and efficient SN feedback appear crucial, as removing any of these feedback sources offsets the SFH by up to $\sim$ 1 dex discussed in the text.

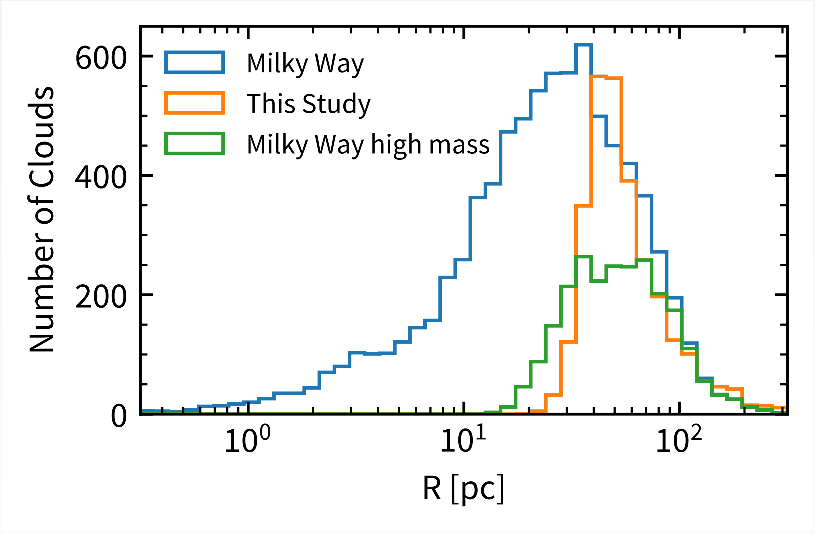
Mostly not resolved S-T phase

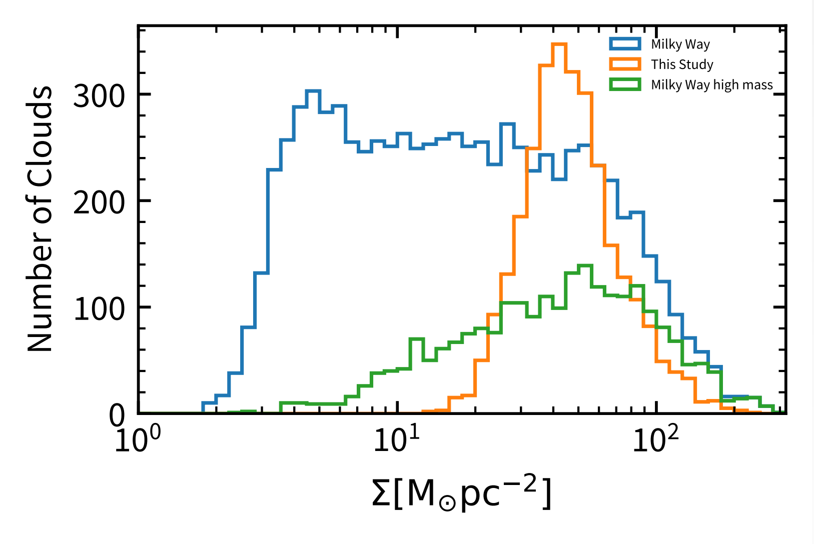
Hopkins et al. (2014); Agertz & Kravtsov (2016)

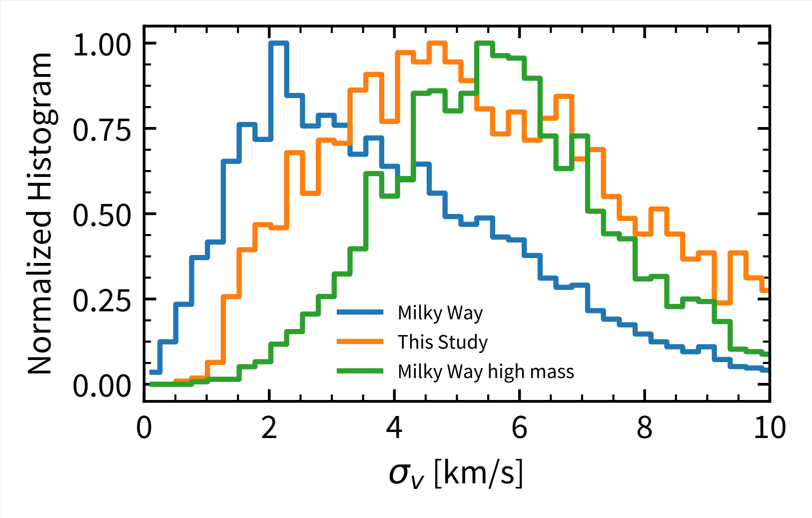
Moving to Larger Scales: cosmological zoom galaxies (FIRE)





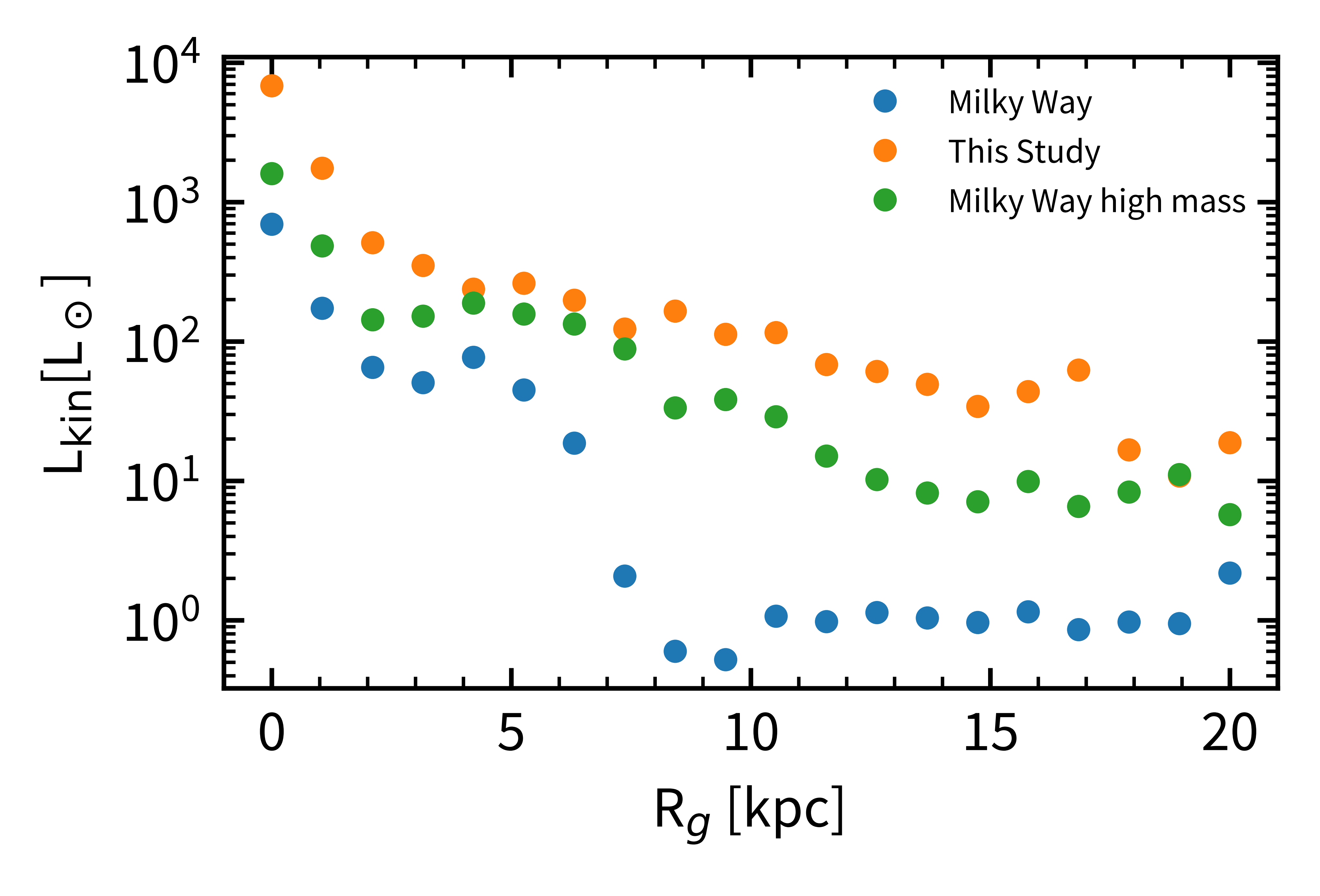






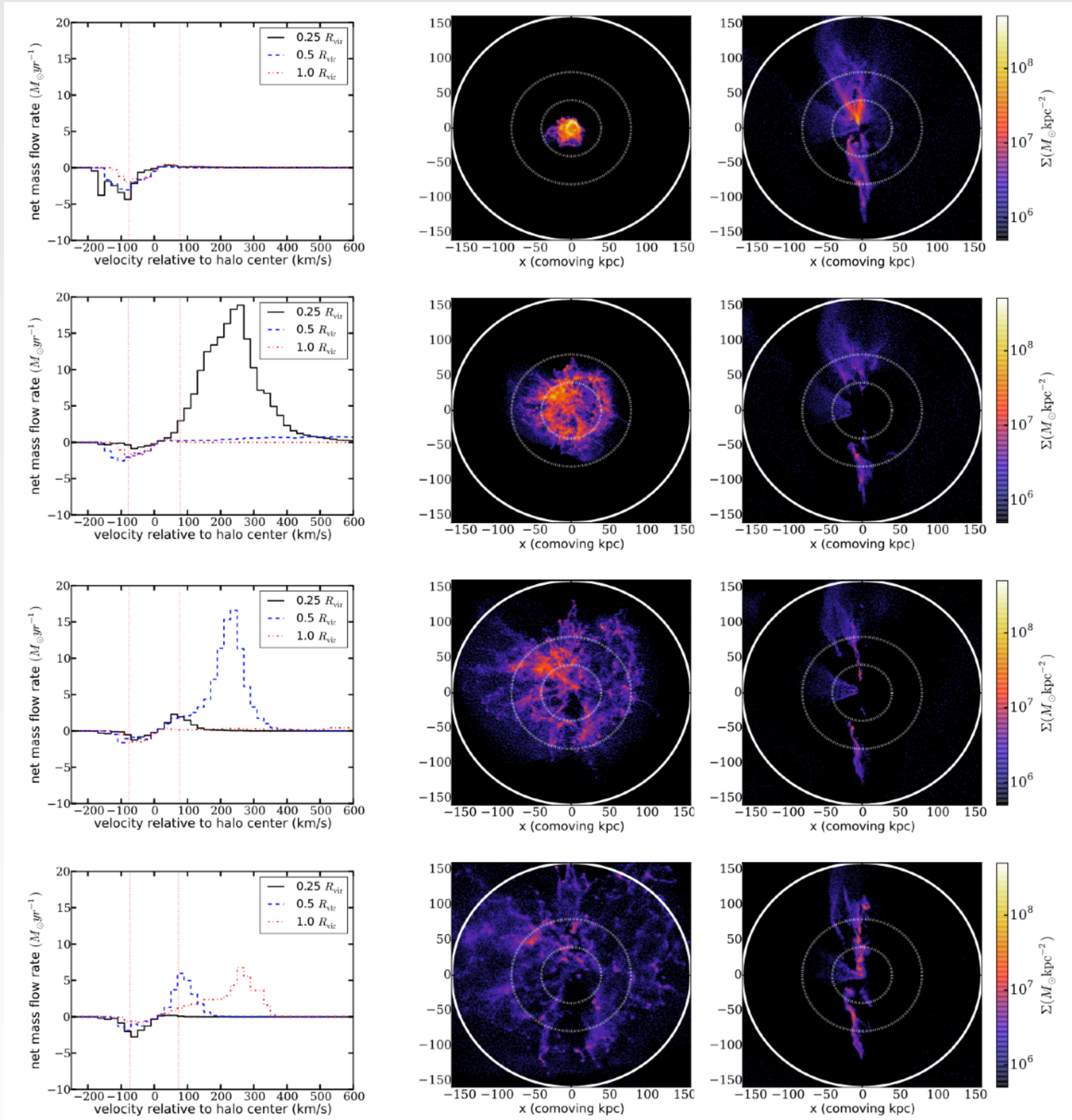
Lakhlani et al. (2018)

Moving to Larger Scales: cosmological zoom galaxies (FIRE)



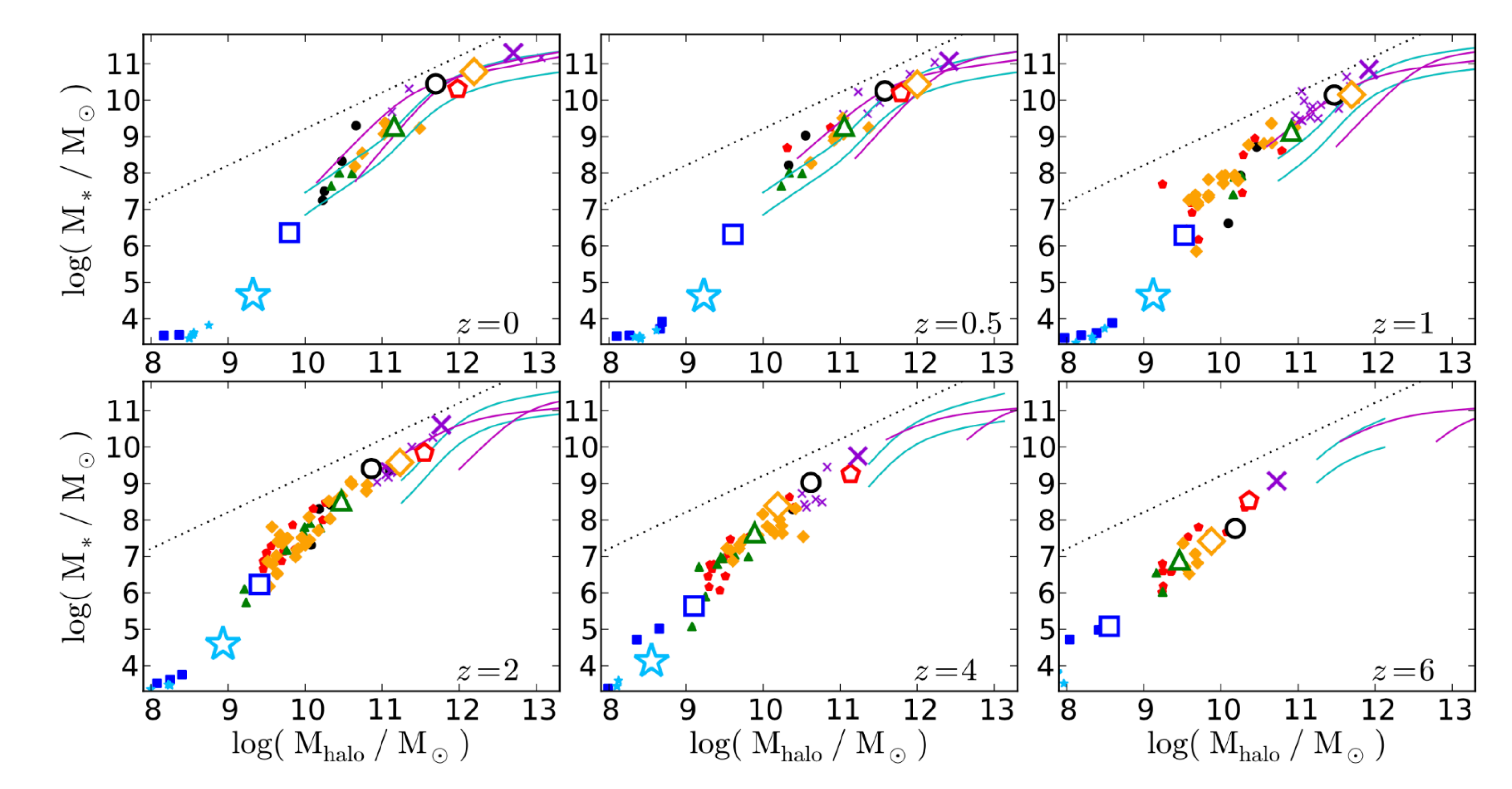
Lakhlani et al. (2018)

Moving to Larger Scales: cosmological zoom galaxies (FIRE)



Muratov et al. (2015) MNRAS **454** 2691

Moving to Larger Scales: cosmological zoom galaxies (FIRE)



Hopkins et al. (2014)

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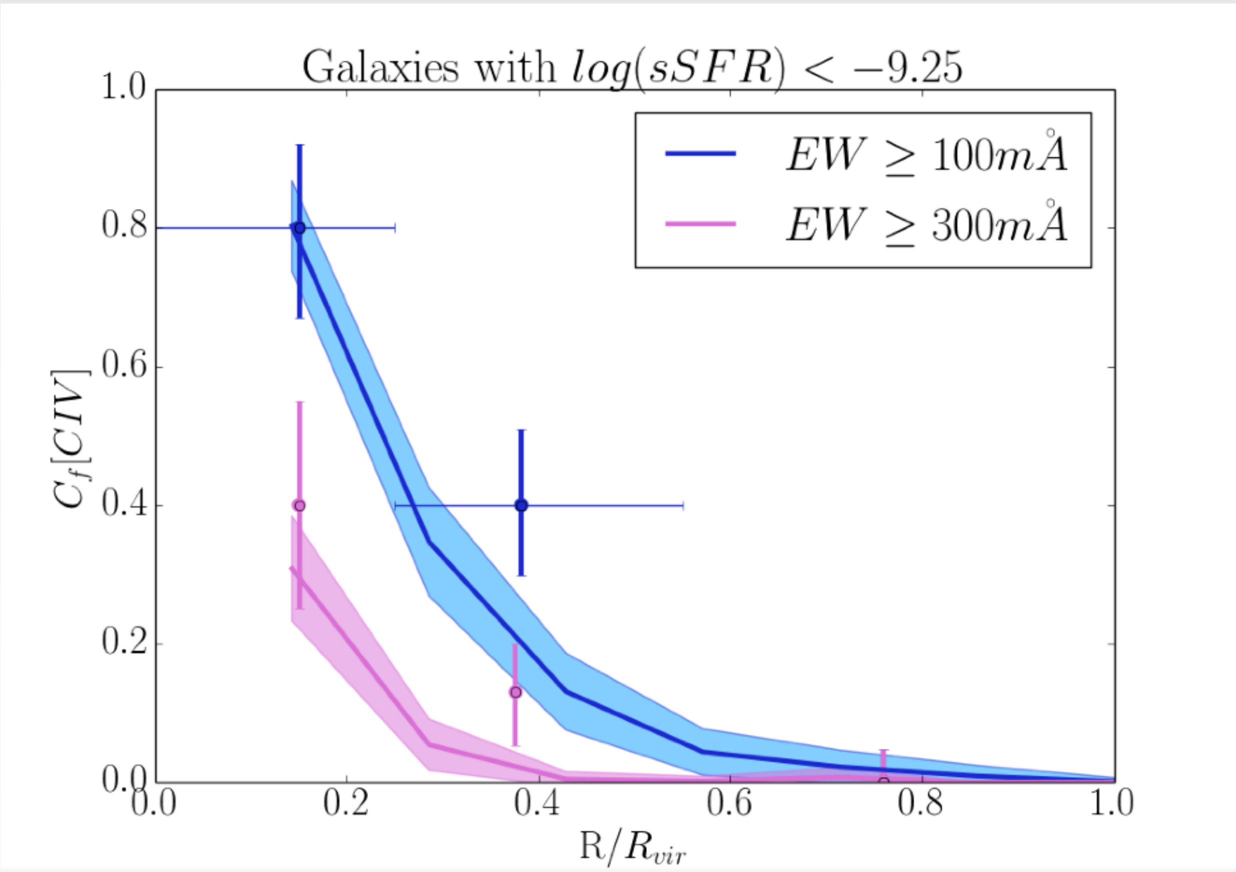
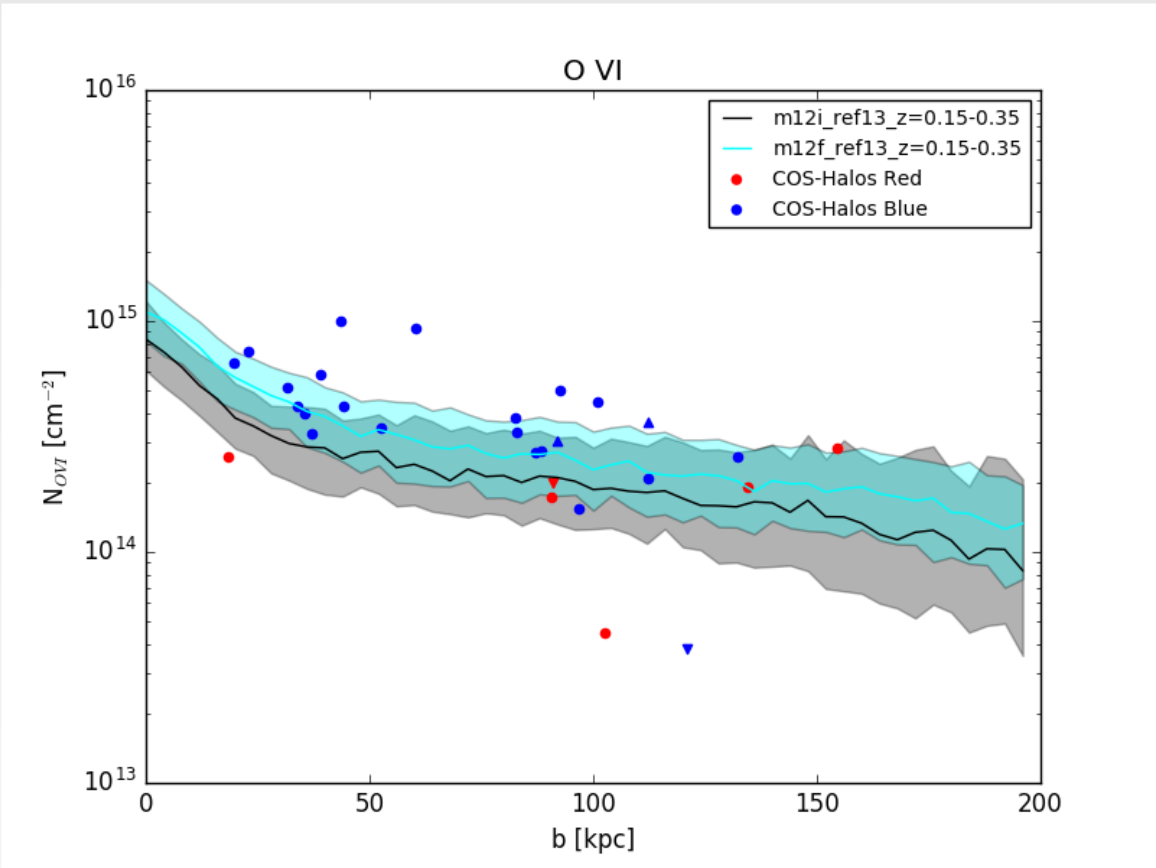
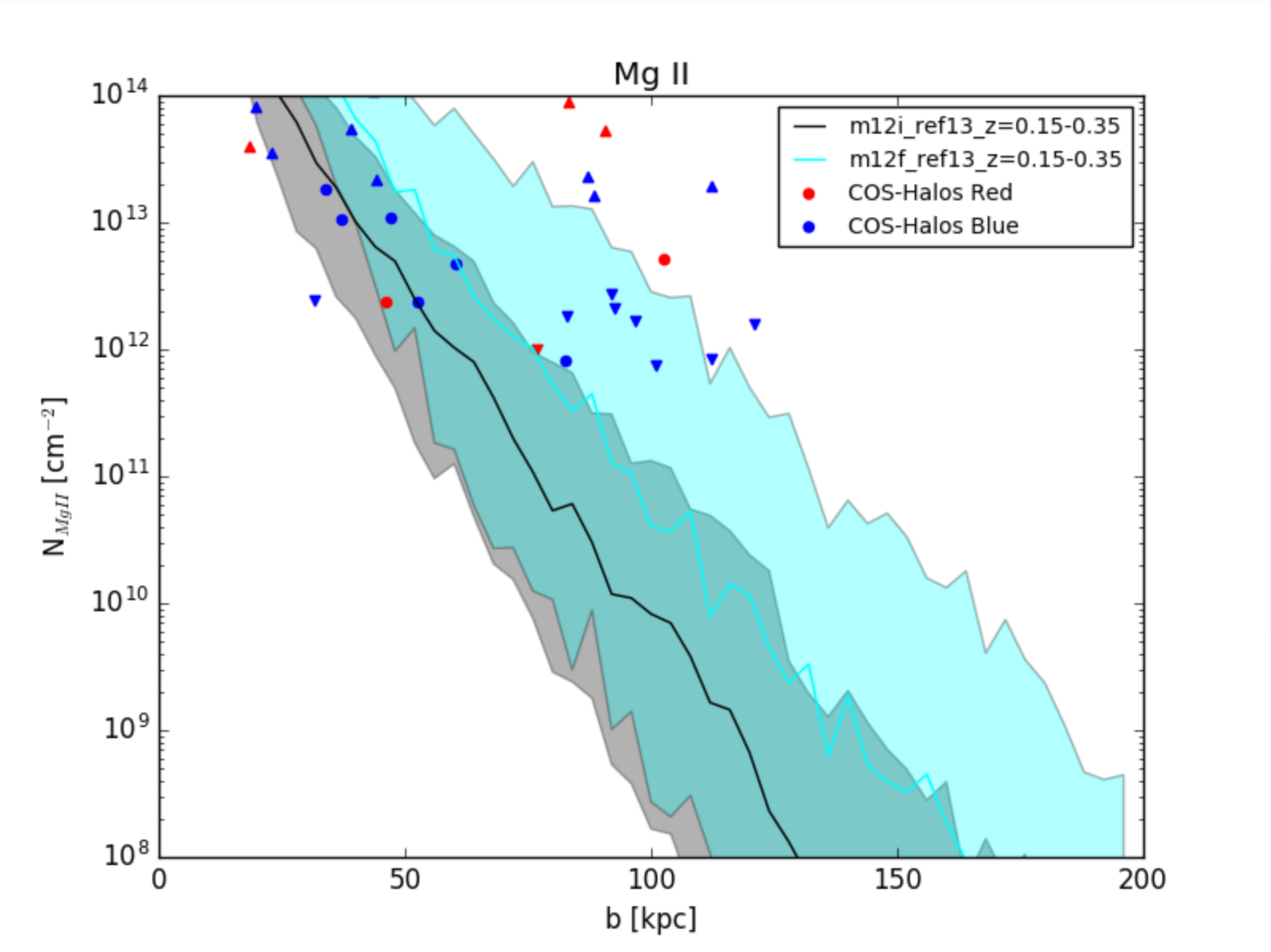




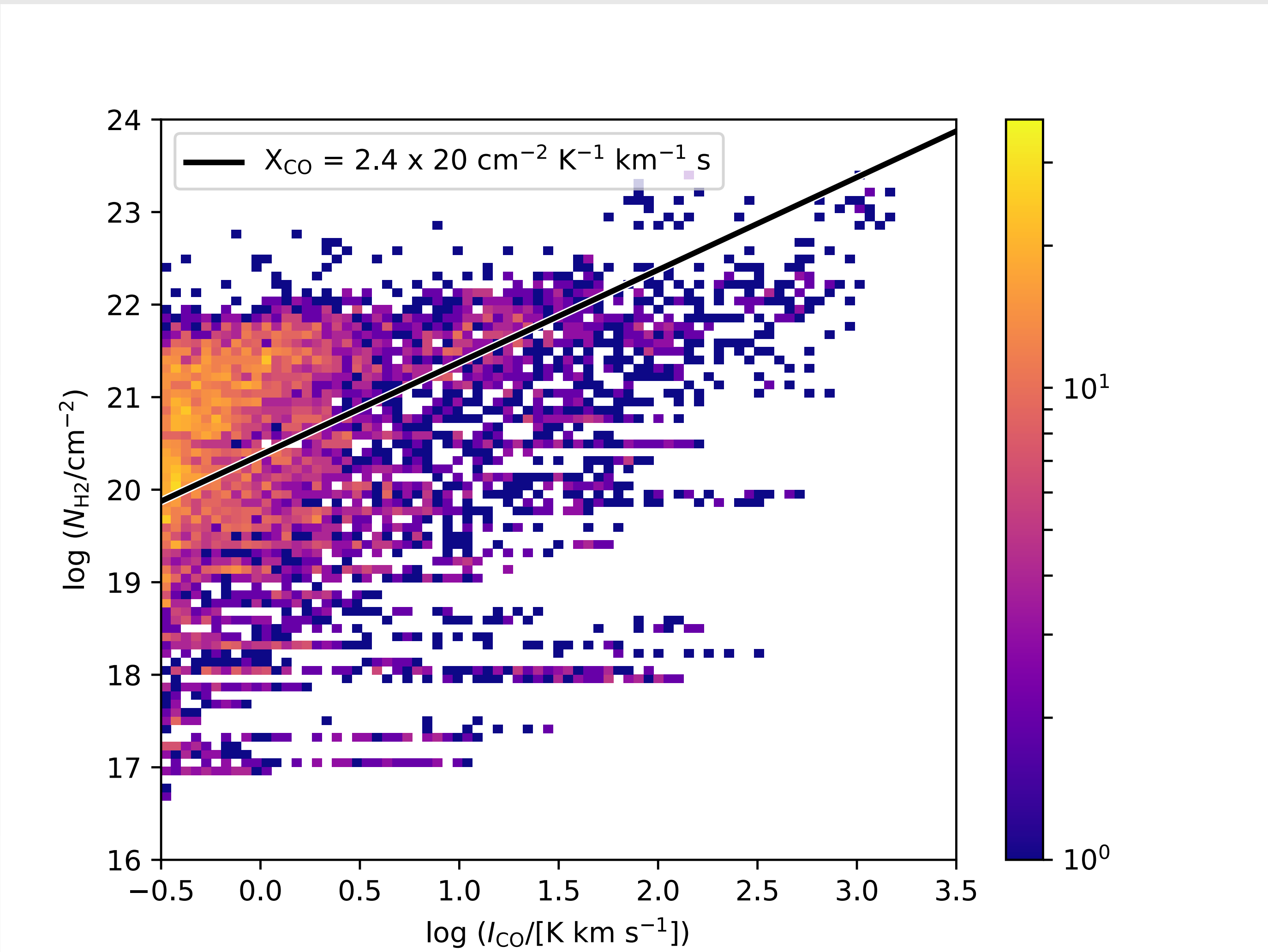
Fei Li, NWM, et al; Hummels, NWM, et al. in prep

Moving to Larger Scales: cosmological zoom galaxies (FIRE)

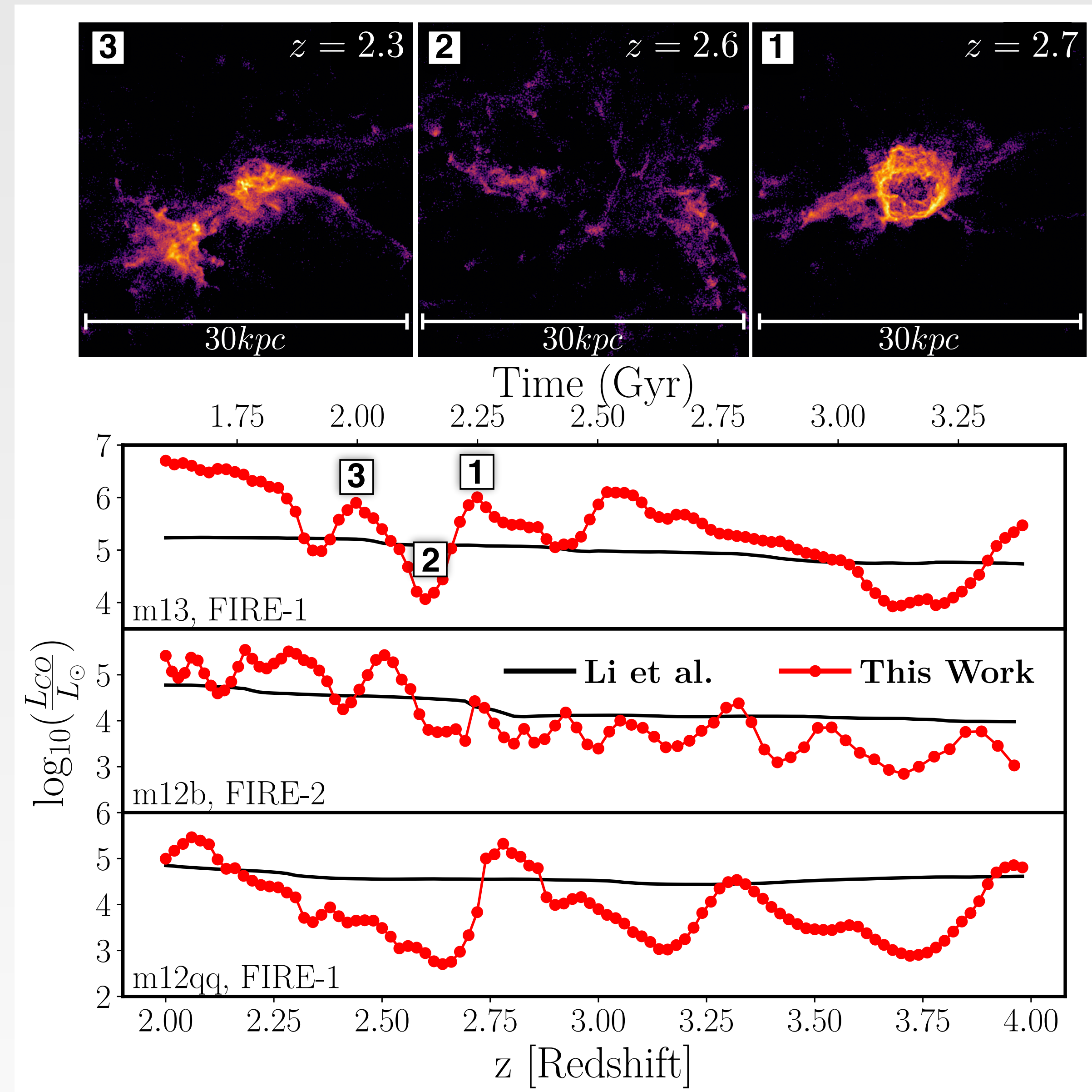


Hummels et al. in prep

CO Luminosity vs z



Laura Keating, Alex Richings



Lakhlani et al (2018b)

L_{CO} in a FIRE simulation

Conclusions

- A new, complete GMC catalog is now available
- Turbulence in inner galaxy GMCs driven by contraction; most GMCs are not forming stars
- These two results suggest that feedback must disrupt the cloud rather than slowing the collapse
- SN feedback drives winds in simulations with a range of resolution; need to resolve S-T, or sub-grid model
- The resulting galaxies have realistic ISMs
- The resulting galaxies lie on the M_{star}-M_{halo} relation
- The CGM is not resolved; despite that, CIV, OVI looks ok; MgII does not
- The IGM may be expelled entirely—this can be checked by intensity mapping.