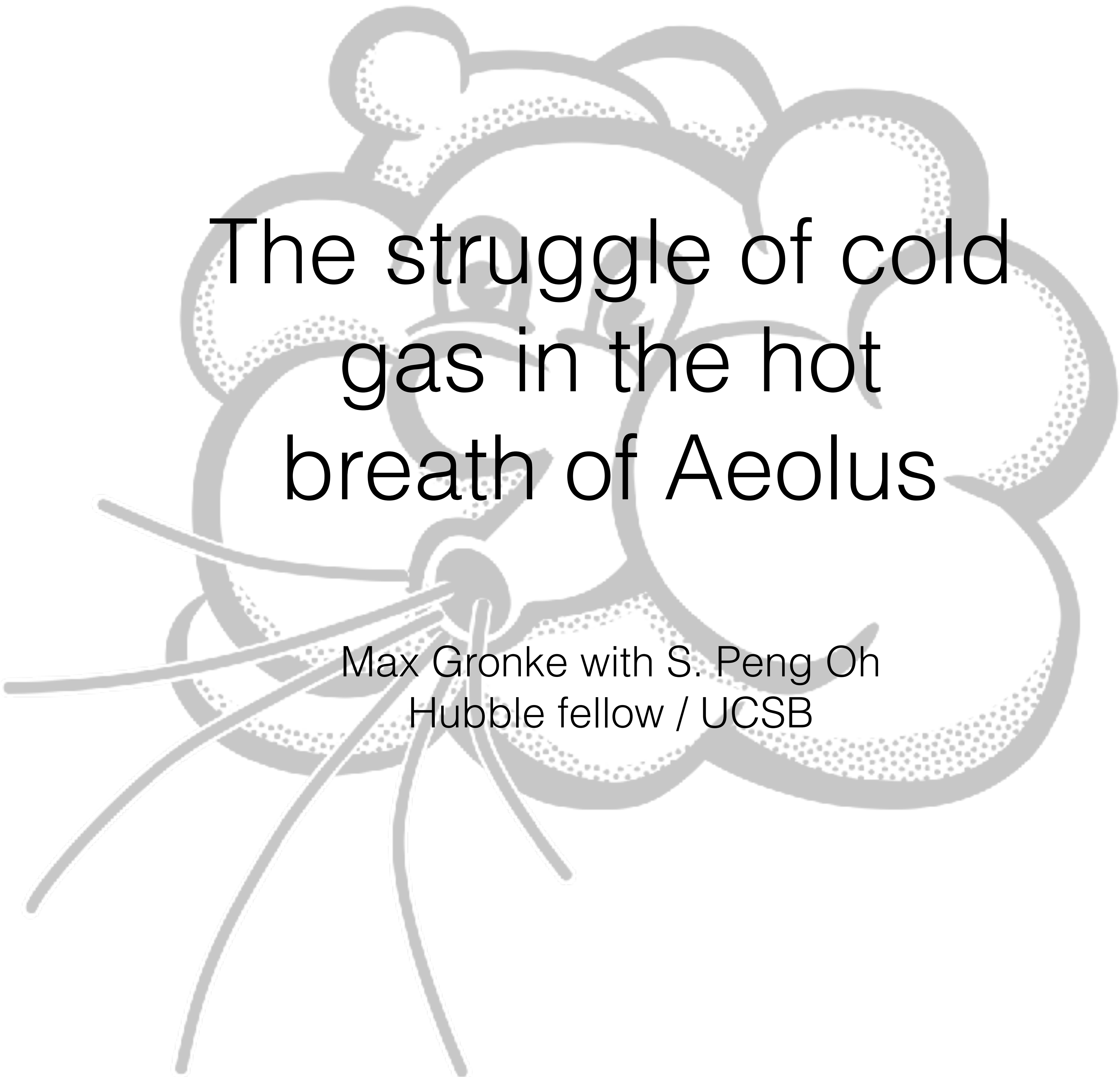
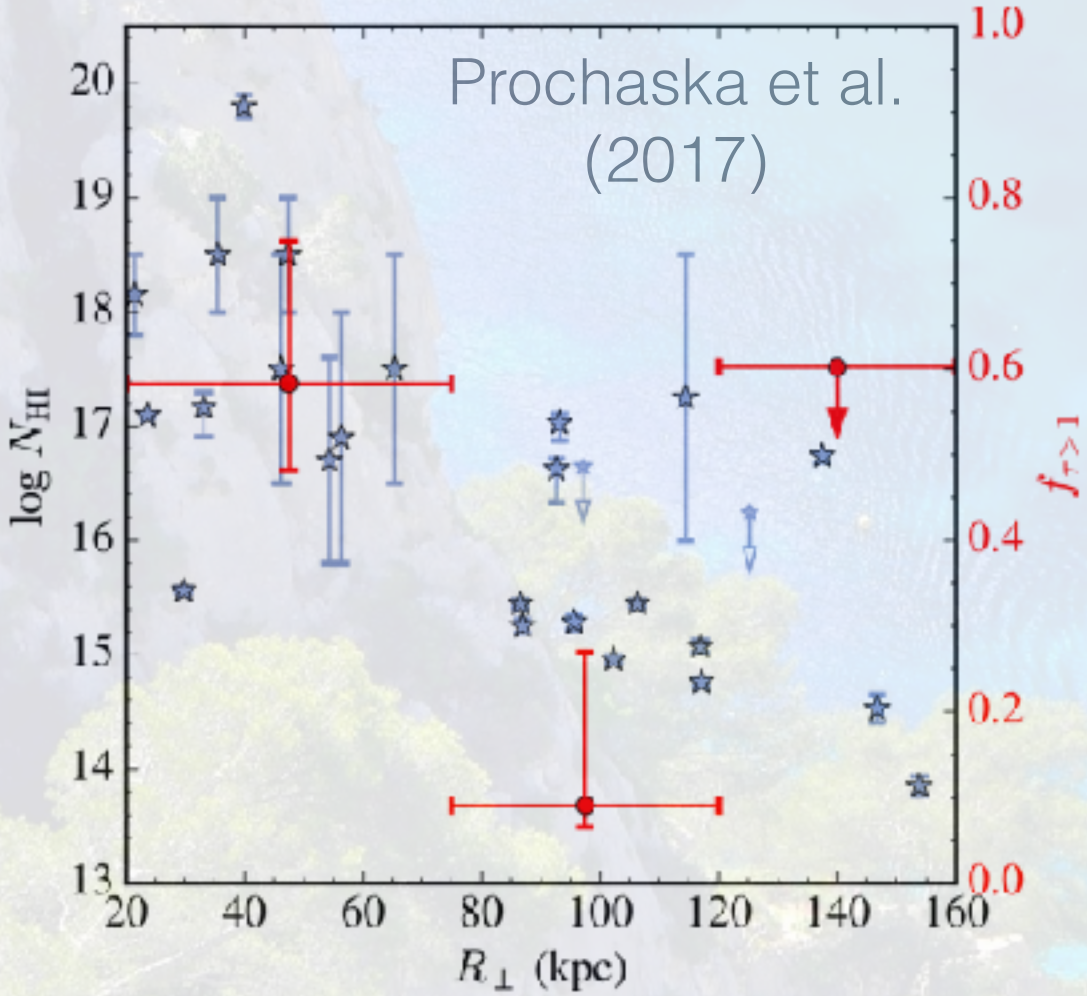
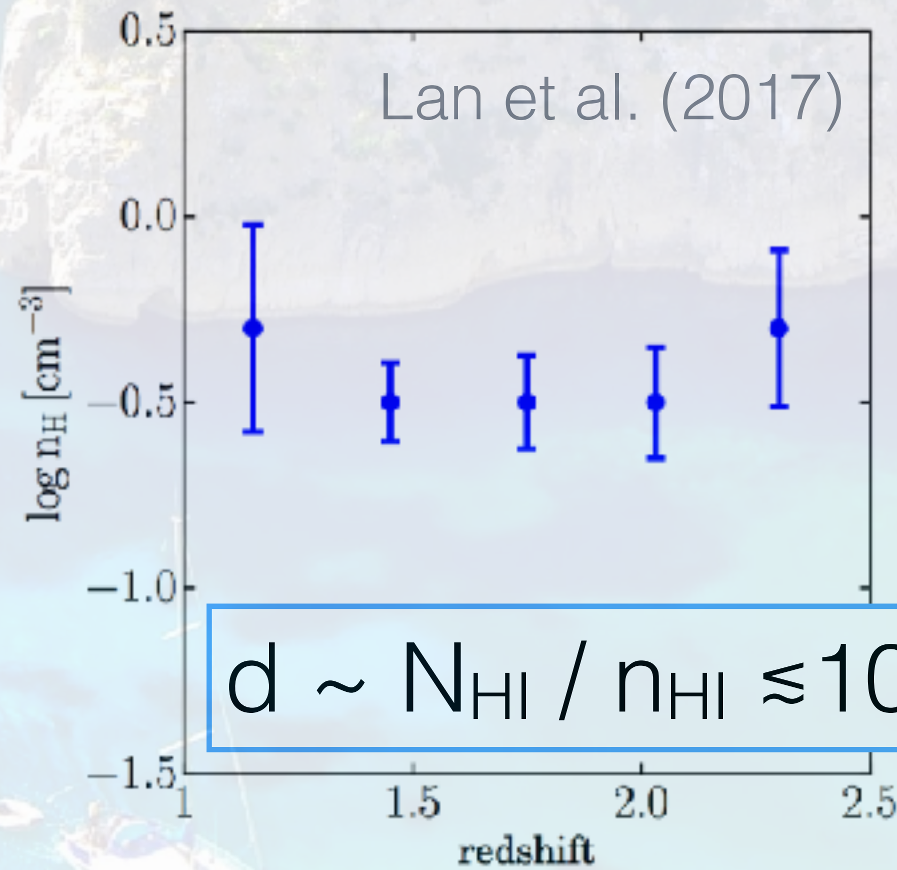


# The struggle of cold gas in the hot breath of Aeolus

Max Gronke with S. Peng Oh
Hubble fellow / UCSB

# The ubiquity of (small-scale) cold gas in the CGM




$d \sim N_{HI} / n_{HI} \lesssim 100\text{pc}$

also:
Rauch et al. (1999)
Rigby et al. (2002)
Shaye et al. (2007)
Lau et al. (2015)
Crighton et al. (2015)
…

*Generally: Large $f_A$, small $f_V$.*

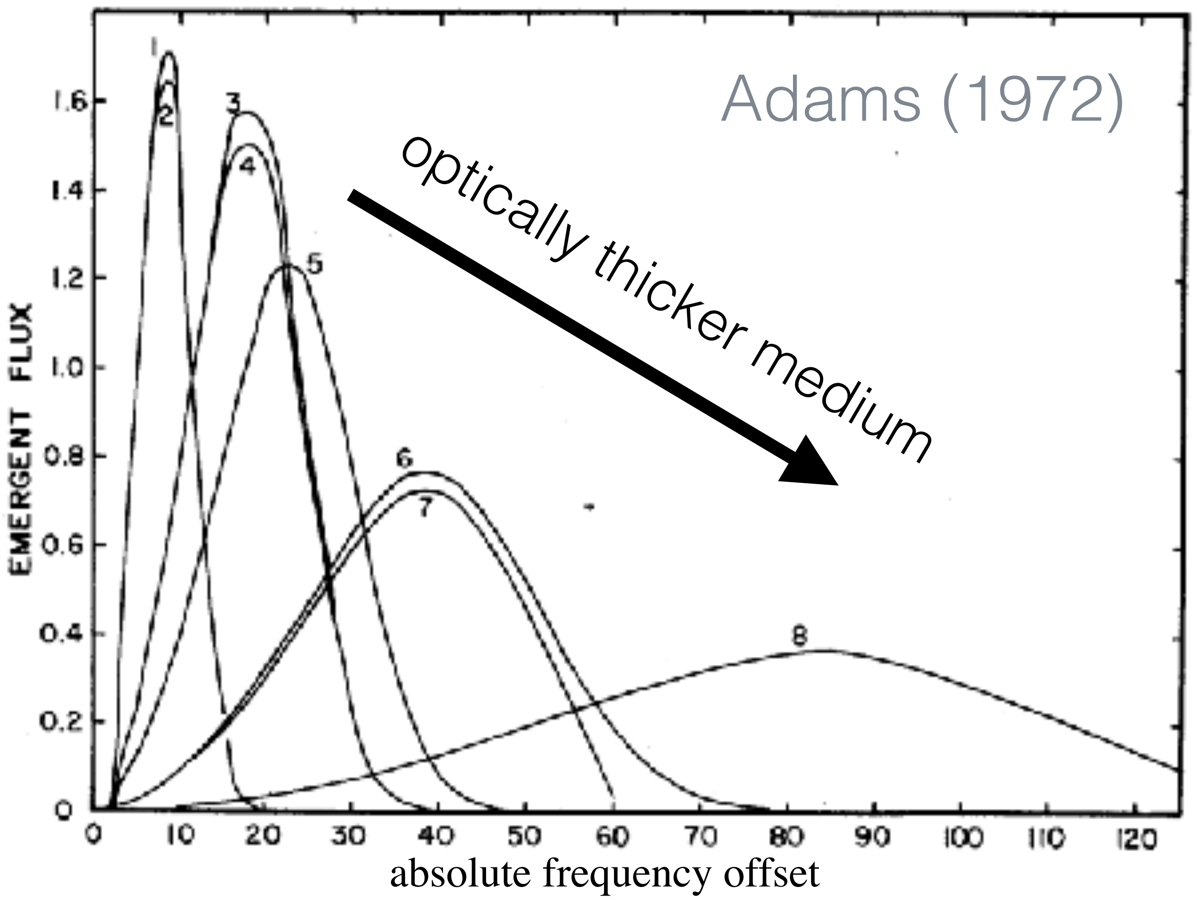
*+ kinematic information, neighbouring quasar nightlines, …*

e.g., Churchill et al.(2003) e.g., Rauch et al. (1999)

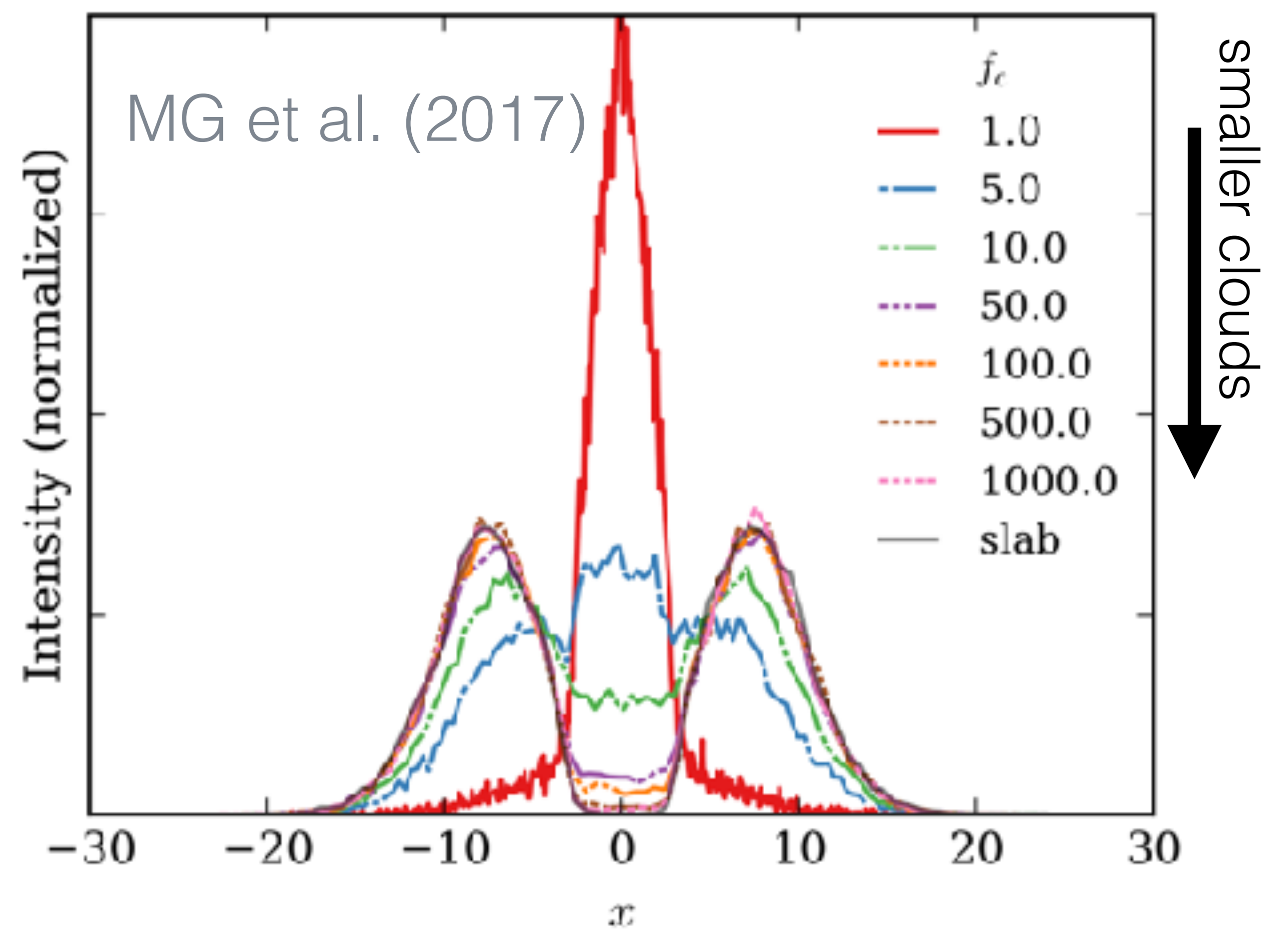
## Why should we care…?

# Lya cares!

…about the amount of HI.




…it's structure.




…, & its kinematics.

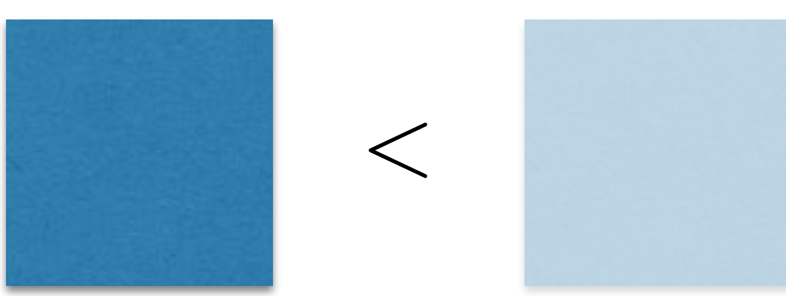
e.g., Bonilha et al. (1979), Verhamme et al. (2006, 2008), Dijkstra et al. (2006a,b, 2009, 2012), …

## Why should we care…?

# LyC cares!

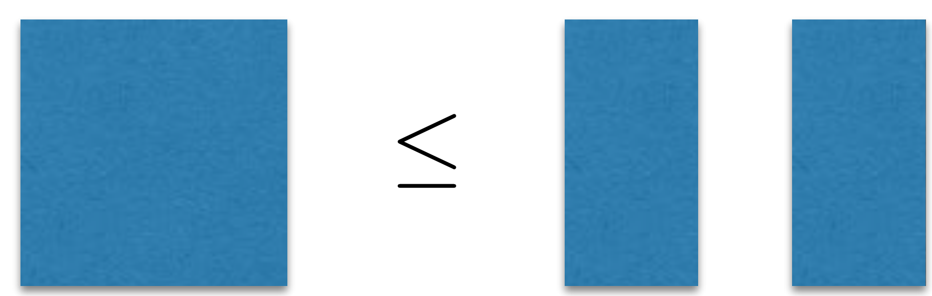
…about the amount of HI.

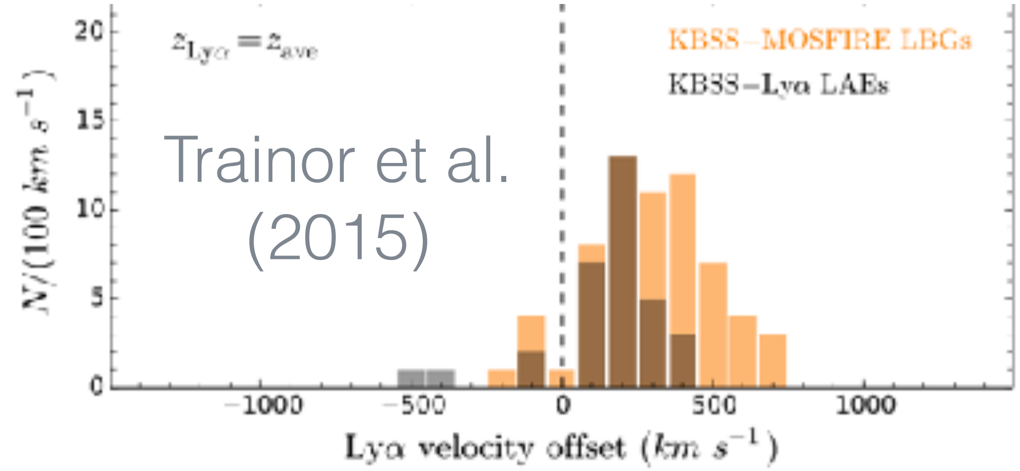
$$f_{\rm esc} \propto e^{-\sigma N_{\rm HI}}$$



…it’s structure.

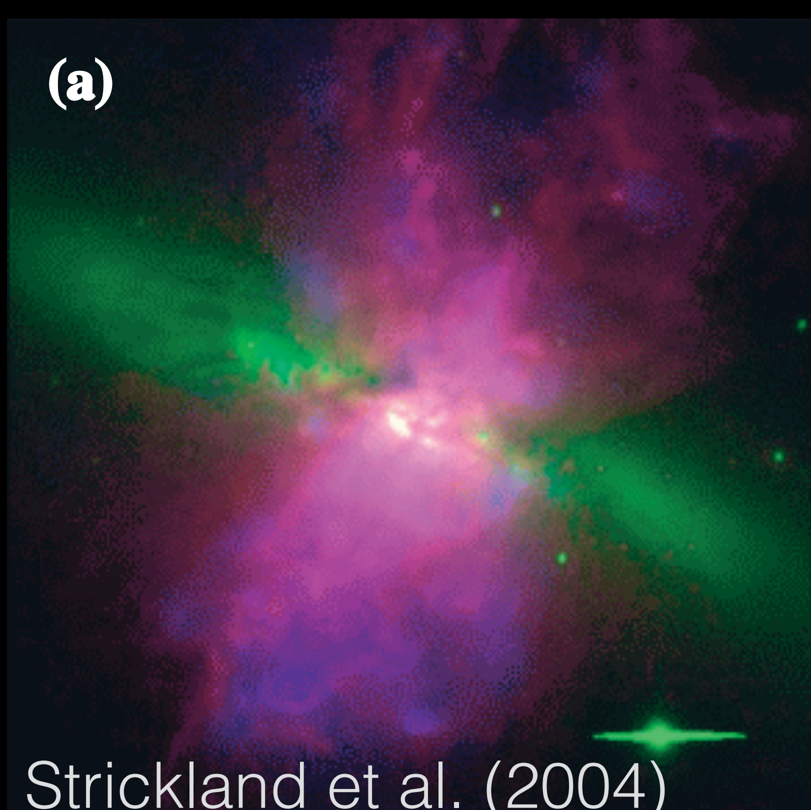
$$\exp(-\langle\tau\rangle) \leq \langle\exp(-\tau)\rangle$$



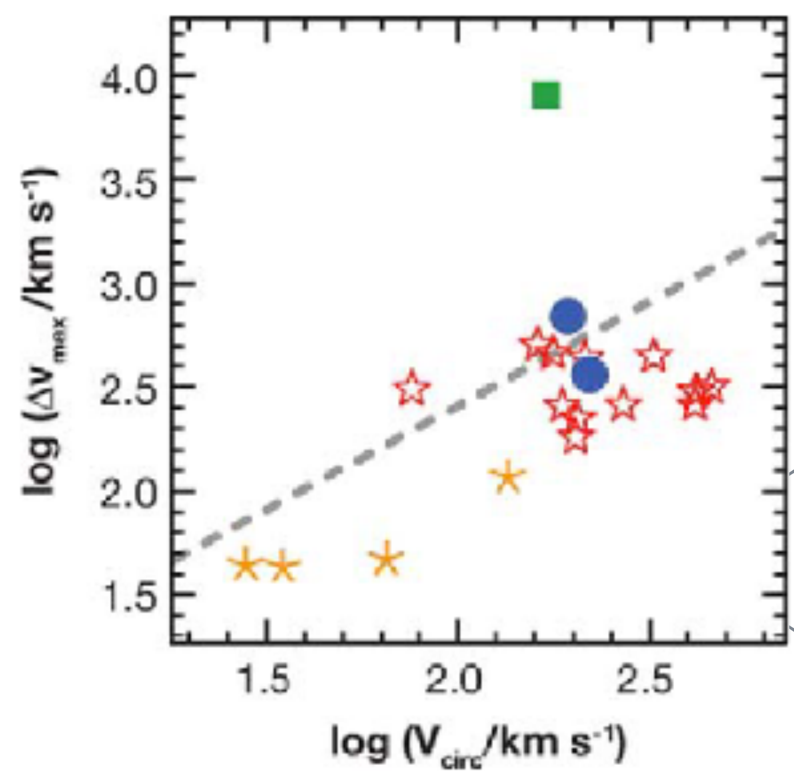



also:
Kunth et al. (1998),
Steidel et al. (2000),
Erb et al. (2014), …

1. How does cold gas get into the CGM?
2. Why does it move?
3. How does it affect Lyα / LyC escape?

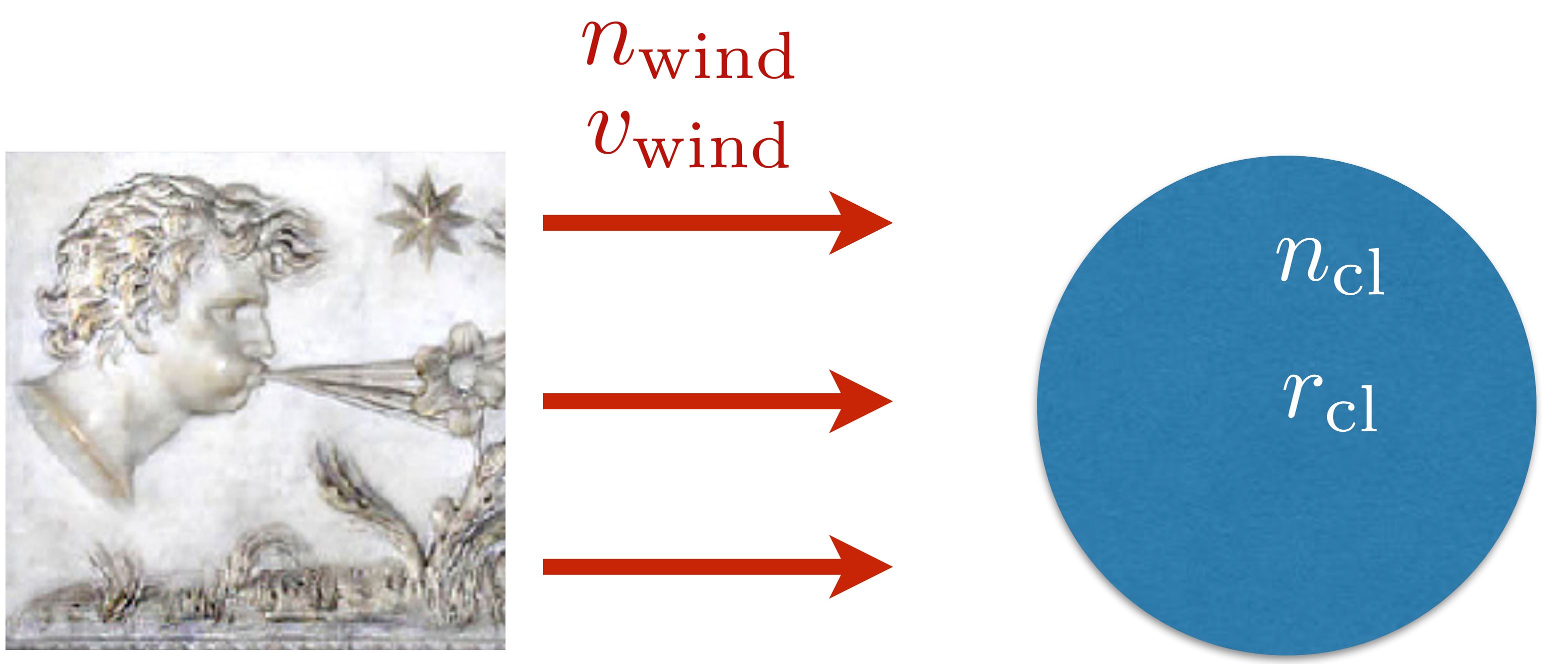



Hα
X-ray
UV




Veilleux et al. (2005)

# Cold gas survival (in a hot wind)




$$t_{\rm cc} \sim \chi^{1/2} \frac{r_{\rm cl}}{v_{\rm wind}}$$

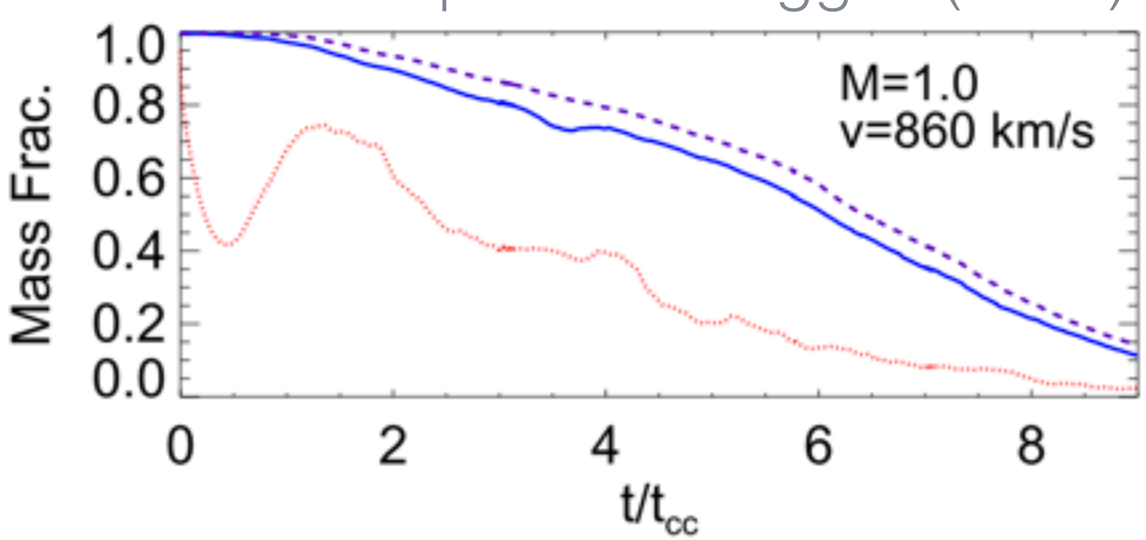
$$\text{with } \chi \equiv \frac{n_{\rm cl}}{n_{\rm wind}}$$

$$t_{\rm drag} \sim \chi \frac{r_{\rm cl}}{v_{\rm wind}}$$

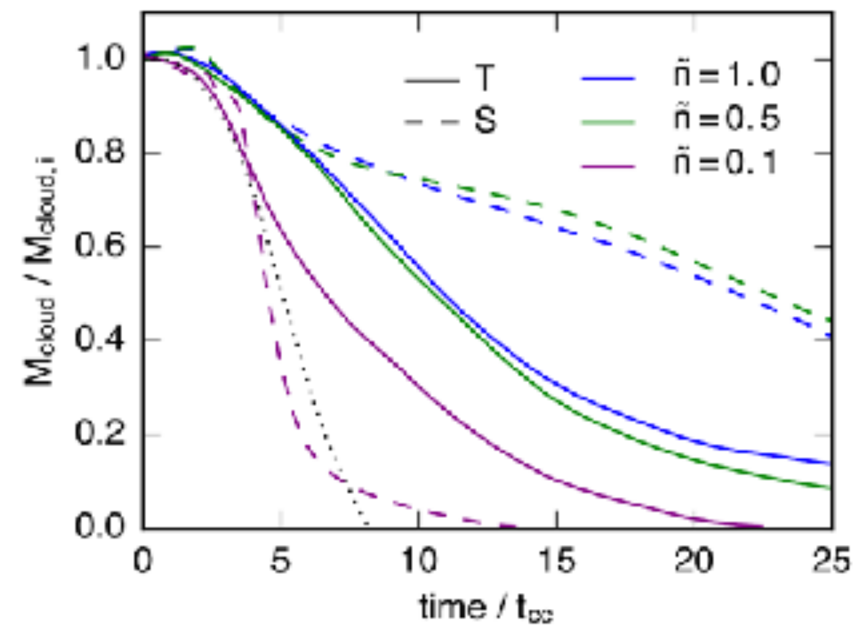
*Problem:* $t_{\rm drag} \gg t_{\rm cc}$*! How does the cold gas survive?*

# Cold gas survival (in a hot wind)

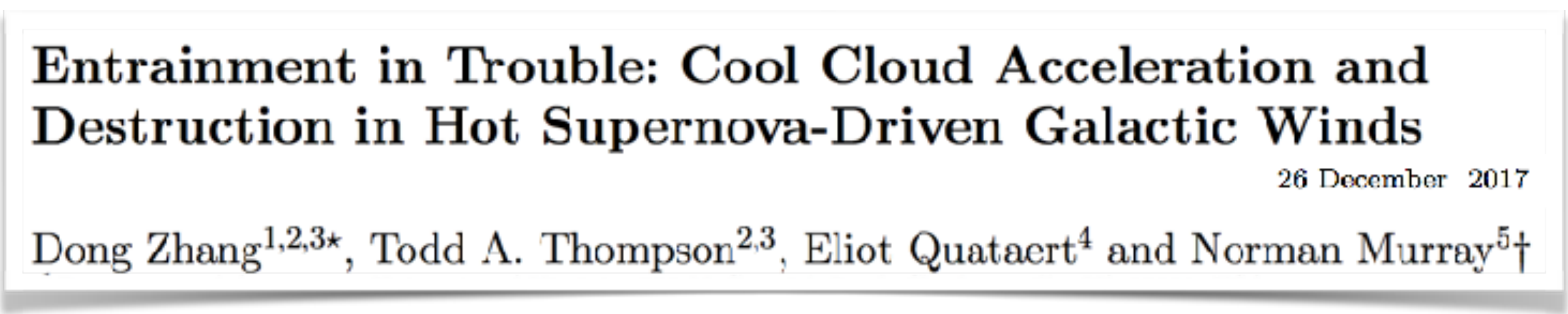
Scannapieco & Brüggen (2015)




Schneider & Robertson (2017)




*Also:*
Klein+94
Mellema+02
Pittard+05,10
Cooper+09
McCourt+15
Armillota+17
…



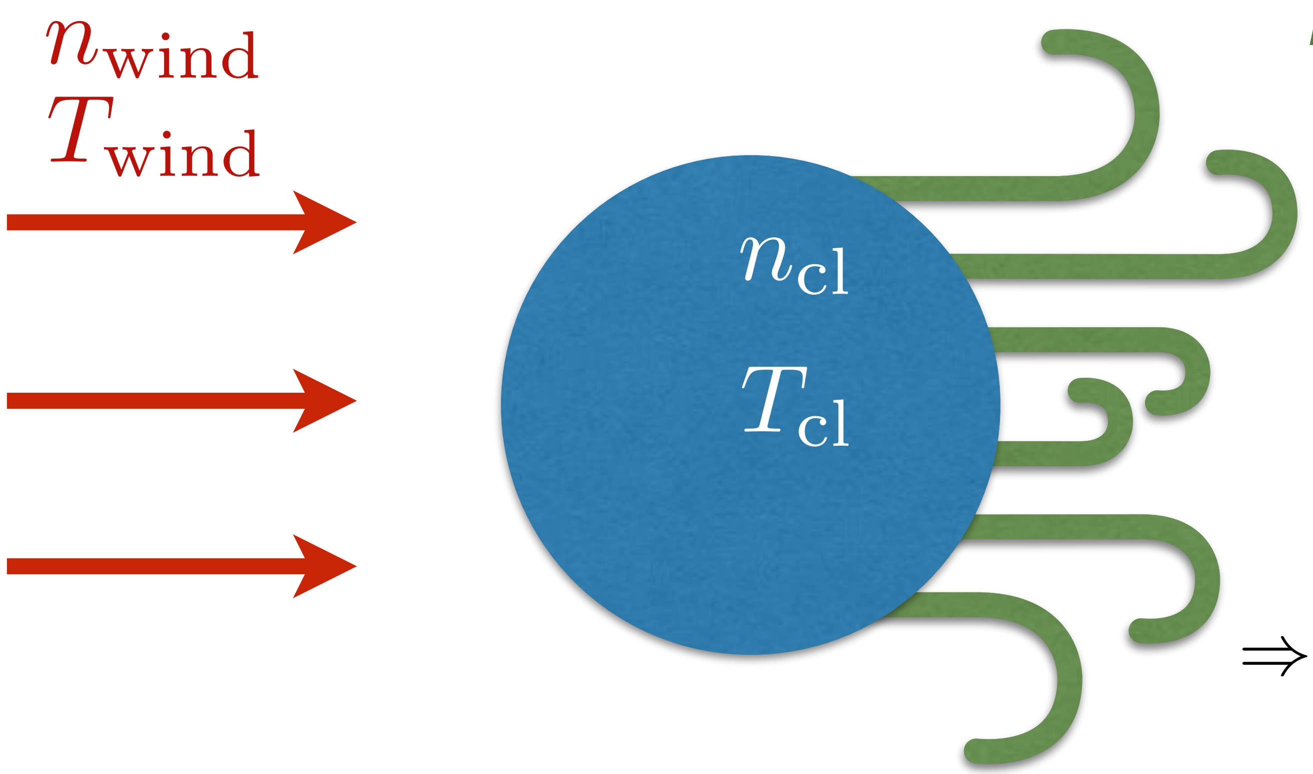
**Entrainment in Trouble: Cool Cloud Acceleration and Destruction in Hot Supernova-Driven Galactic Winds**

26 December 2017

Dong Zhang[1,2,3⋆], Todd A. Thompson[2,3], Eliot Quataert[4] and Norman Murray[5]†

*Problem:* $t_{\rm drag} \gg t_{\rm cc}$ *! How does the cold gas survive?*

# (I) Mixing is your foe – but also your friend




*Turbulent mixing layer*

Begelman & Fabian (1990)

(cf. Ji & Oh, in prep.)

$$T_{\rm mix} \sim \sqrt{T_{\rm wind} T_{\rm cl}}$$

$$n_{\rm mix} \sim \sqrt{n_{\rm wind} n_{\rm cl}}$$

$$\Rightarrow t_{\rm cool,mix} \sim 10 t_{\rm cool,cl} \frac{\chi}{100} \frac{\Lambda(T_{\rm mix})/\Lambda(T_{\rm cl})}{0.1}$$

***Require:*** $t_{\rm cool,mix} < t_{\rm cc}$

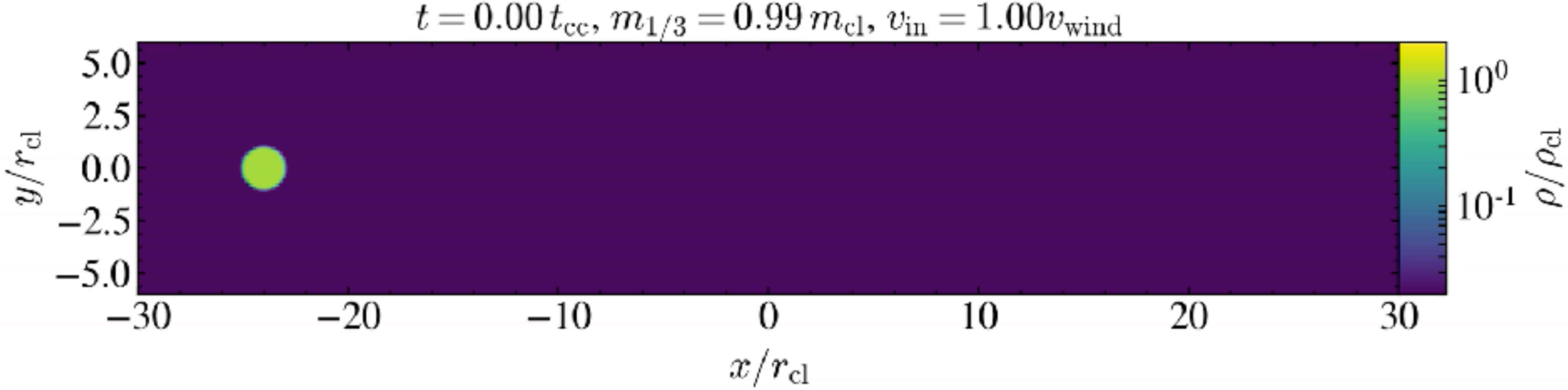
$$r_{\rm cl} > r_{\rm cl,crit} \equiv \frac{v_{\rm wind} t_{\rm cool,mix}}{\chi^{1/2}} \approx 2\,{\rm pc}\,\frac{T_{\rm cl,4}^{5/2} \mathcal{M}_{\rm wind}}{P_3 \Lambda_{\rm mix,-21.4}} \frac{\chi}{100}$$

$$T_{\rm cl,4} \equiv (T_{\rm cl}/10^4\,{\rm K})$$

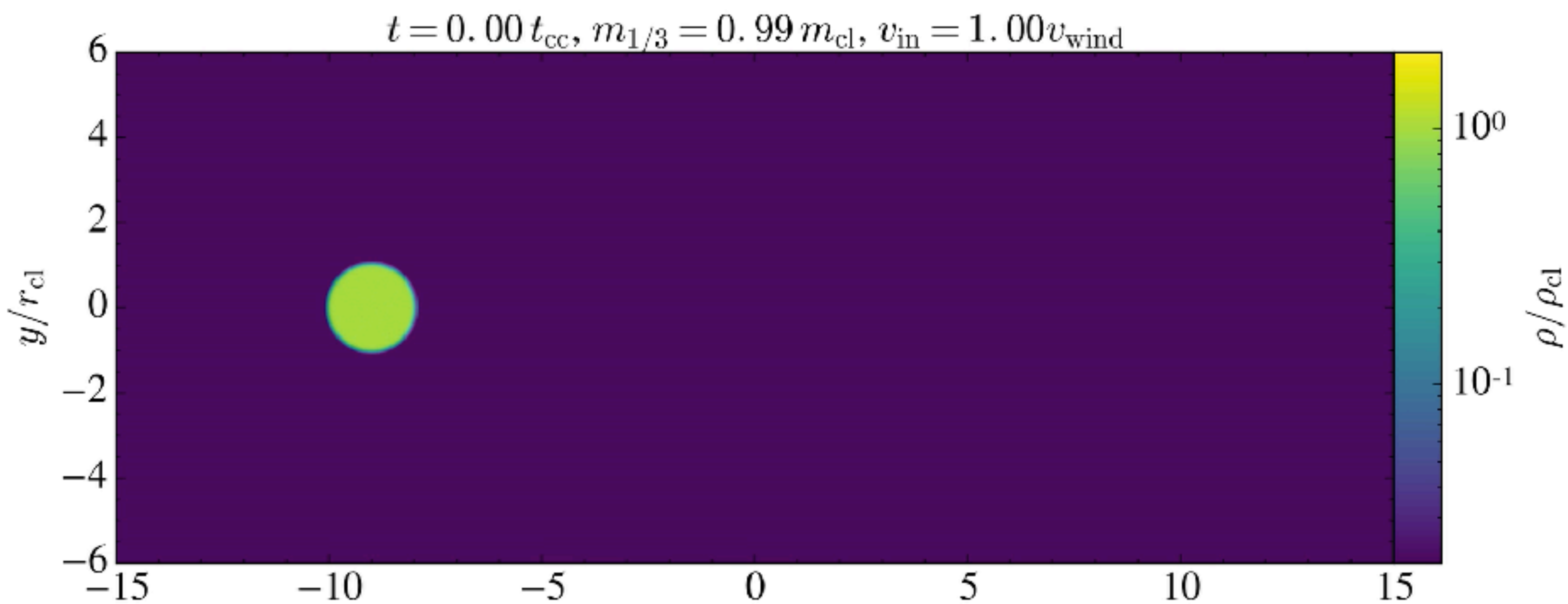
$$P_3 \equiv nT/(10^3\,{\rm cm}^{-3}\,{\rm K})$$

$$\Lambda_{\rm mix,-21.4} \equiv \Lambda(T_{\rm mix})/(10^{-21.4}\,{\rm erg\,cm^3\,s^{-1}})$$

$t_{\rm cool,mix}/t_{\rm cc} \sim 8$ $(r_{\rm cl} < r_{\rm cl,crit})$

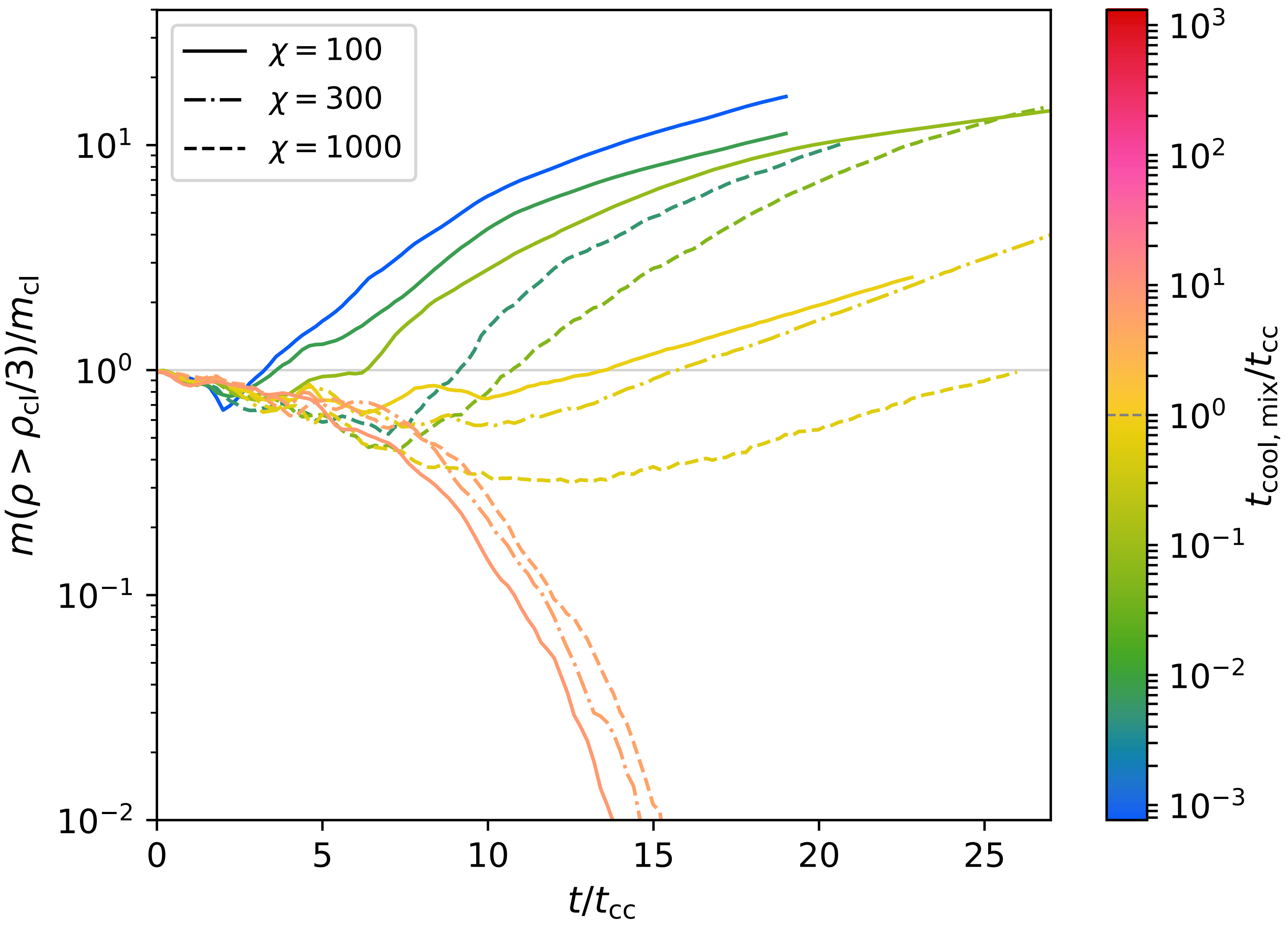



$t_{\rm cool,mix}/t_{\rm cc} \sim 0.08$ $(r_{\rm cl} > r_{\rm cl,crit})$



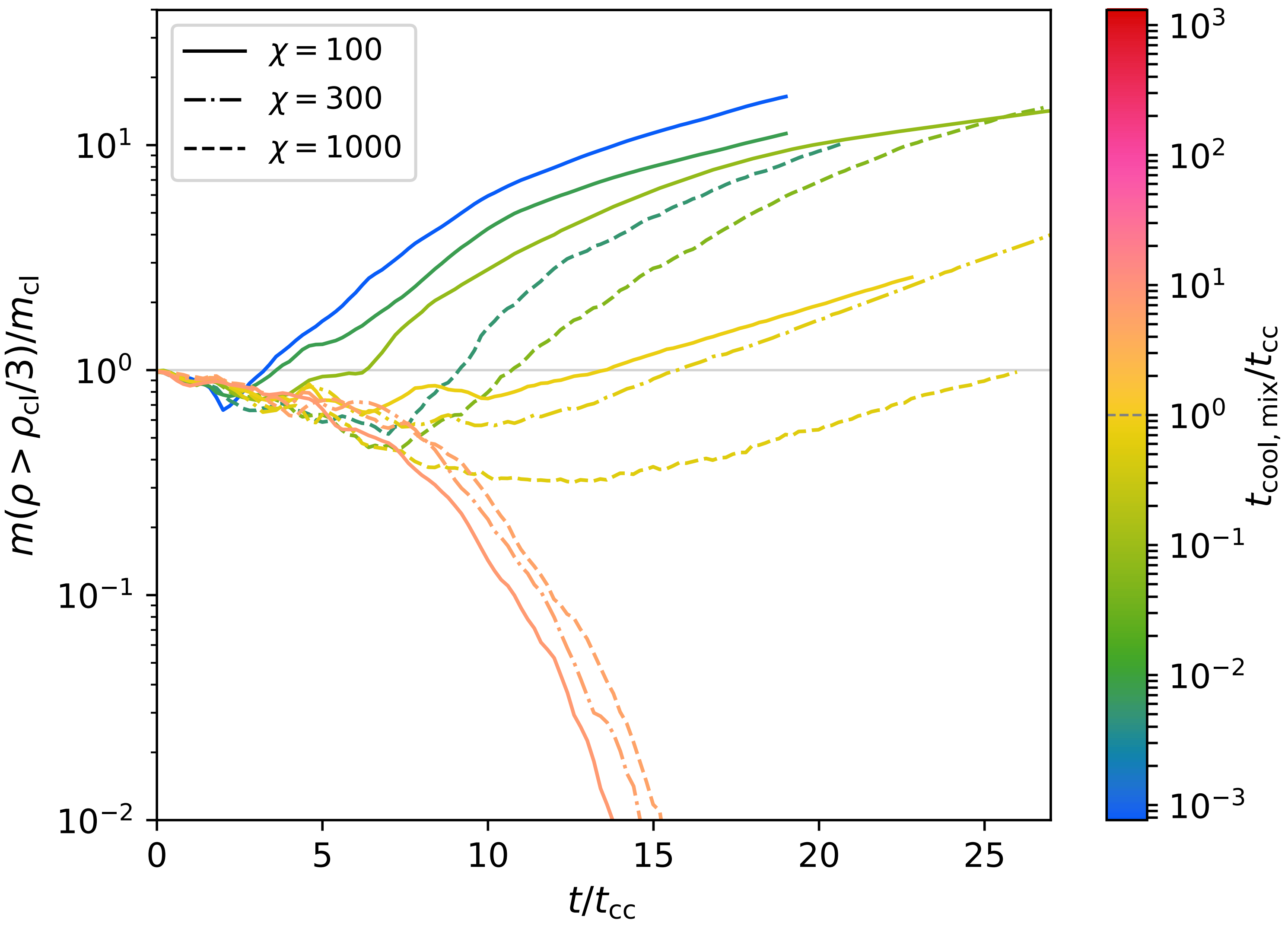
# Large enough clouds *survive*

$t_{\mathrm{cool,mix}} < t_{\mathrm{cc}}$ ➔mass growth

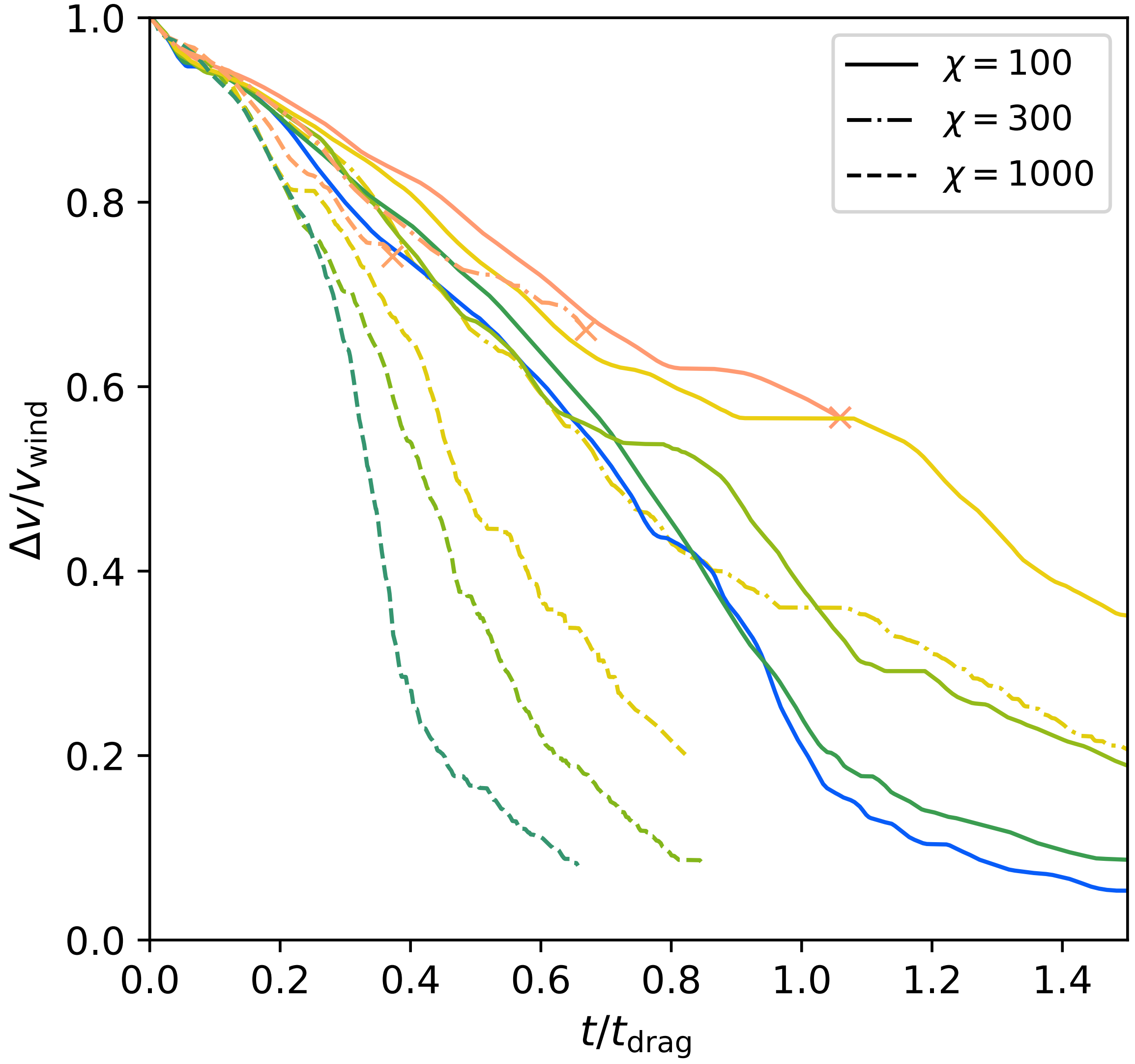


# Large enough clouds *survive* and become *comoving*

$t_{\rm cool,mix} < t_{\rm cc}$ ➔mass growth

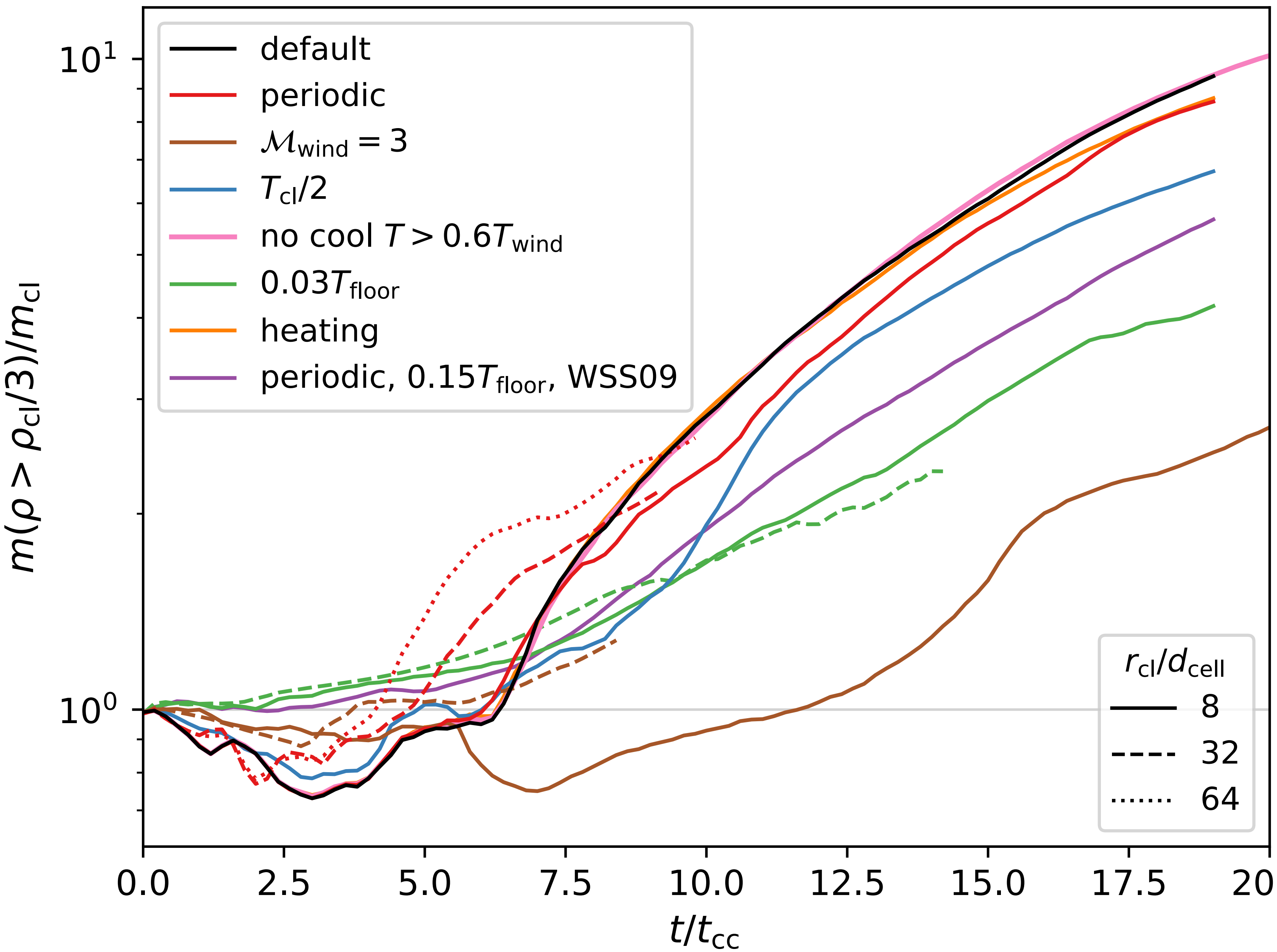



*Bonus:* momentum transfer



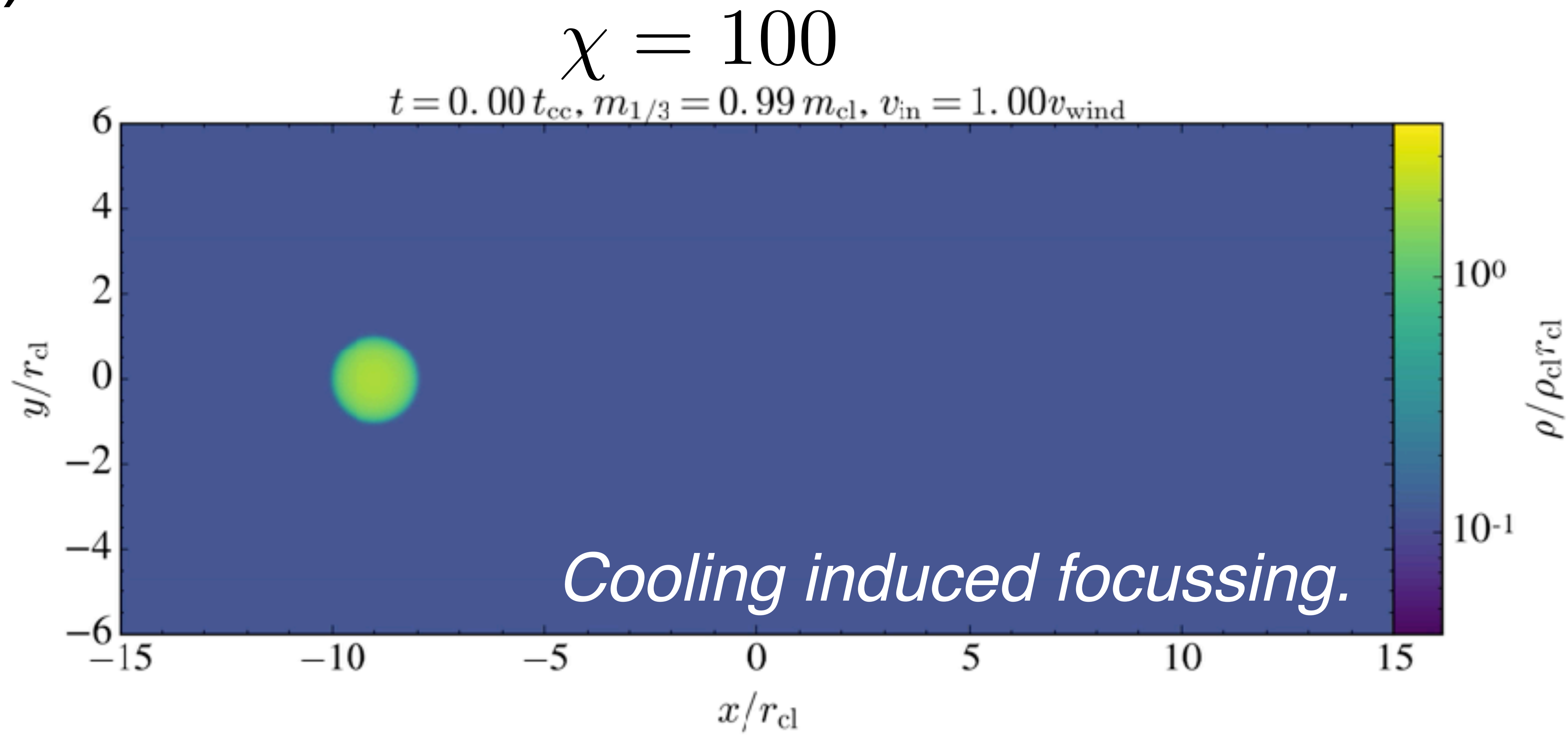

$$\frac{\Delta v}{v_{\rm wind}} \rightarrow \frac{m_{\rm cl}}{m_{\rm cl} + m_{\rm new}}$$

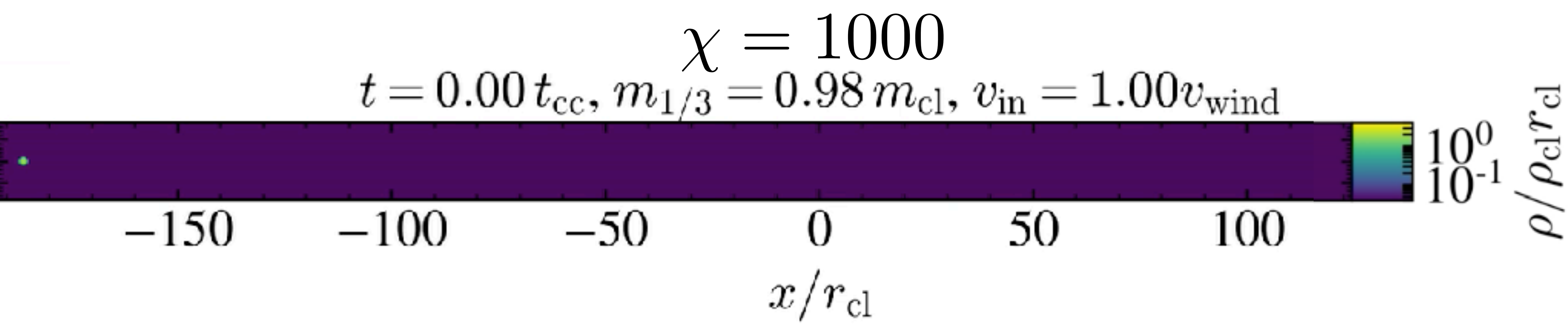
# Large enough clouds *survive* and become *comoving*




Works for different wind speeds, boundary conditions, cooling curves, cloud geometries…

# (II) The action is in the tail.

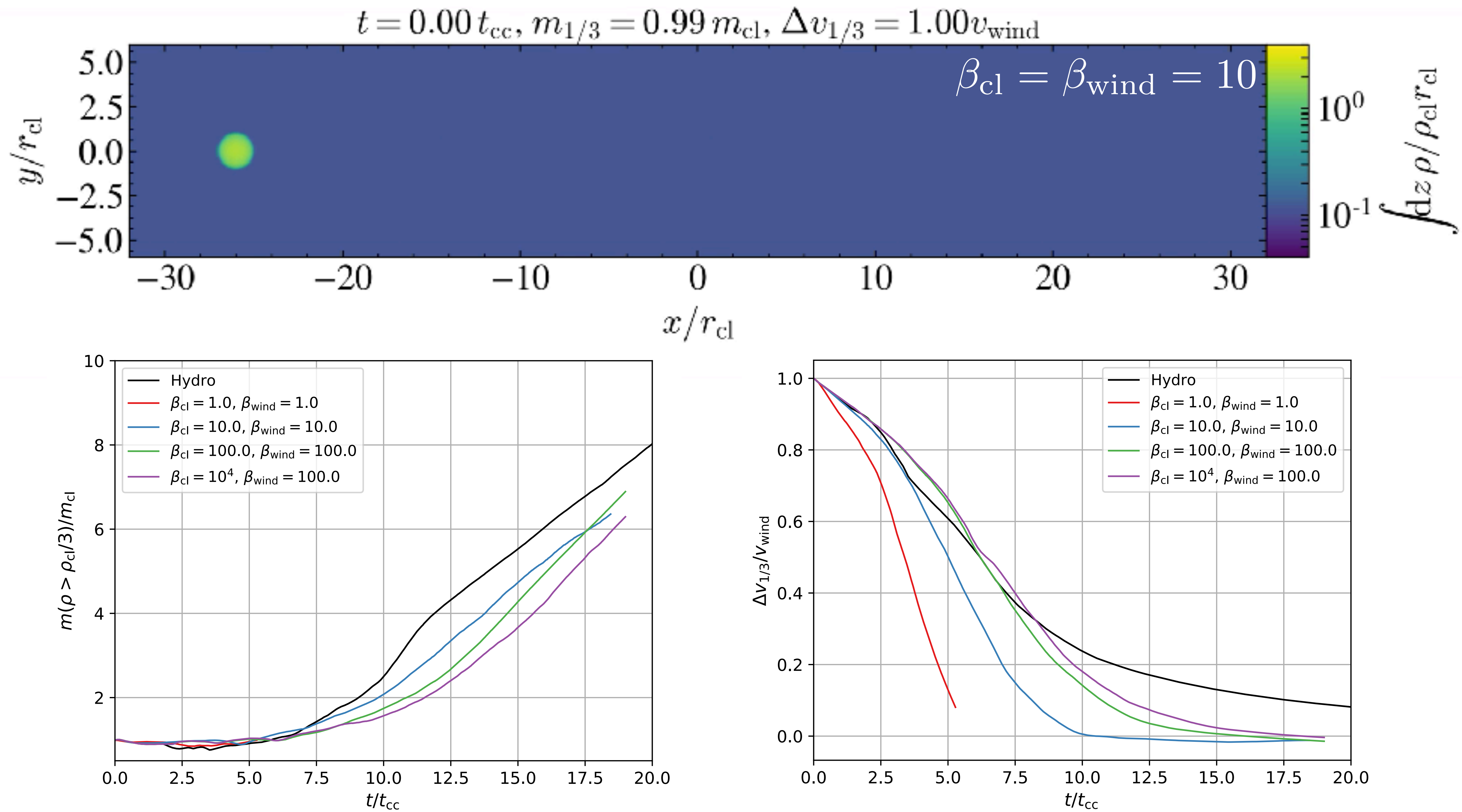



*Required box size: ~0.2 - 0.5 $\chi$ $r_{cl}$*

(work in progress)

# What about magnetic fields?
# Also works with magnetic fields!



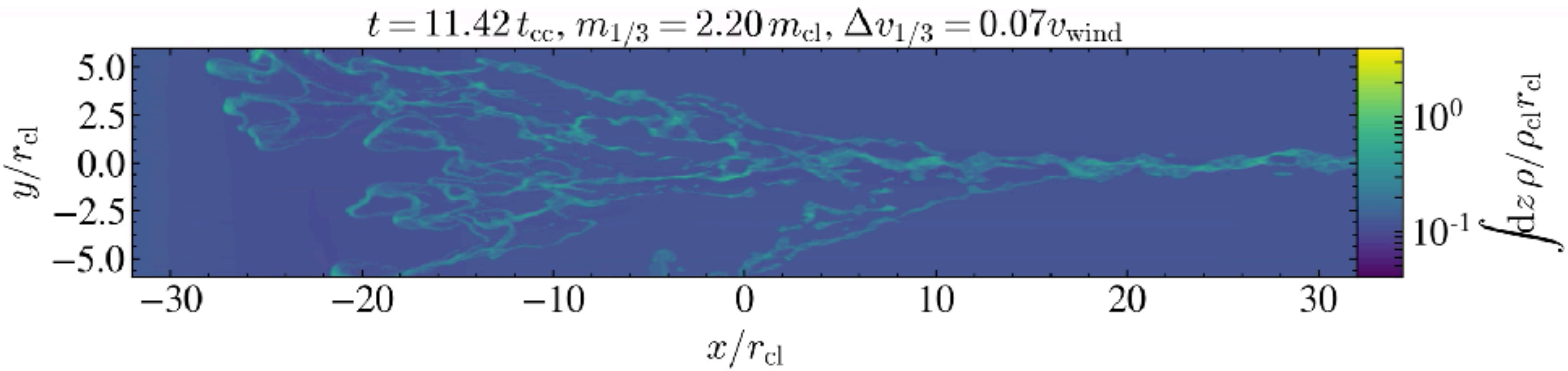

faster entrainment (➔ magnetic draping), similar growth

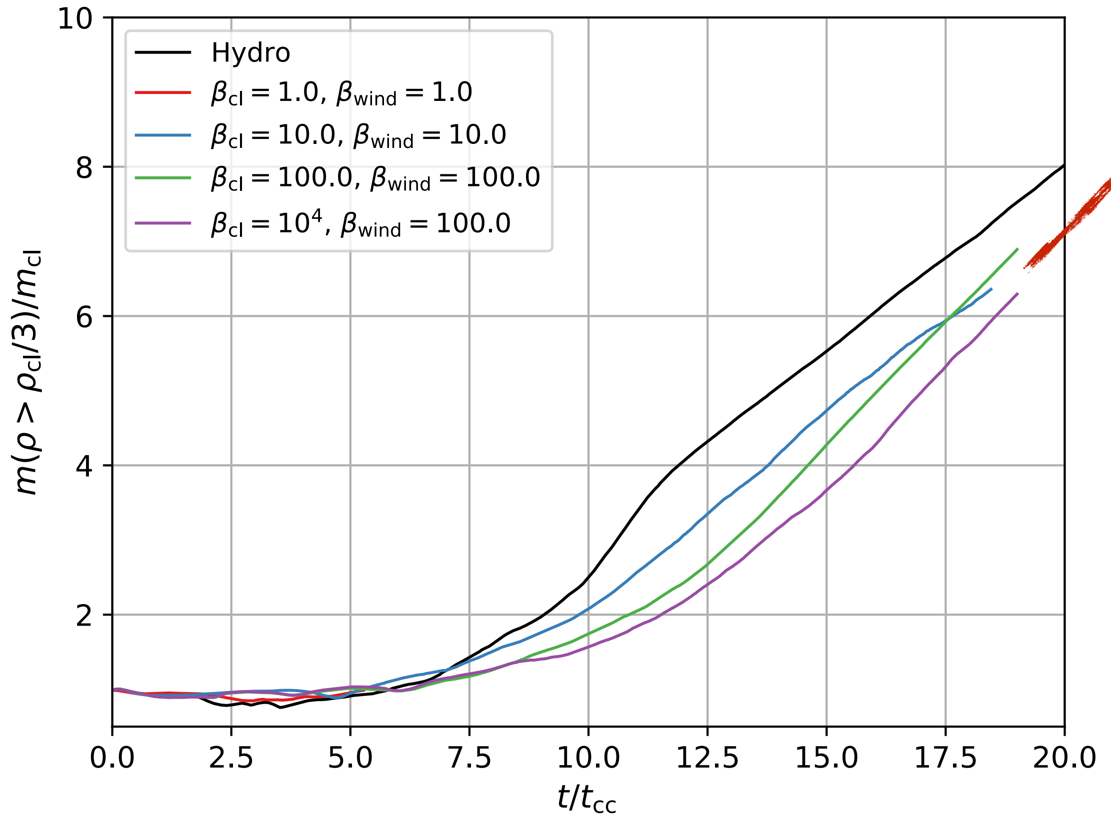
*but* very different morphology!

↳ *connection to observations (OVI!)*

(work in progress)

# Significant mass growth



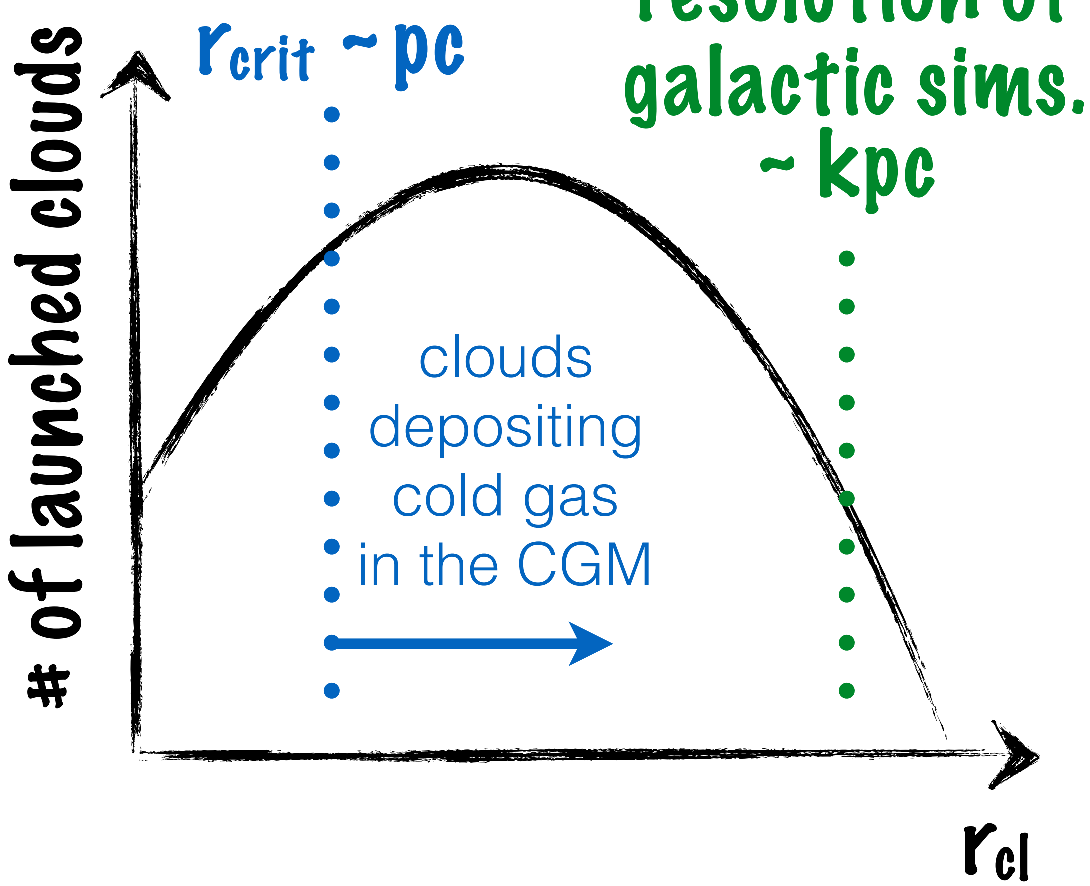

**Mass growth does not cease when cloud is entrained!**

↳not caused by *shear* but *cooling*!

(work in progress)

# 1. How does cold gas get into the CGM?

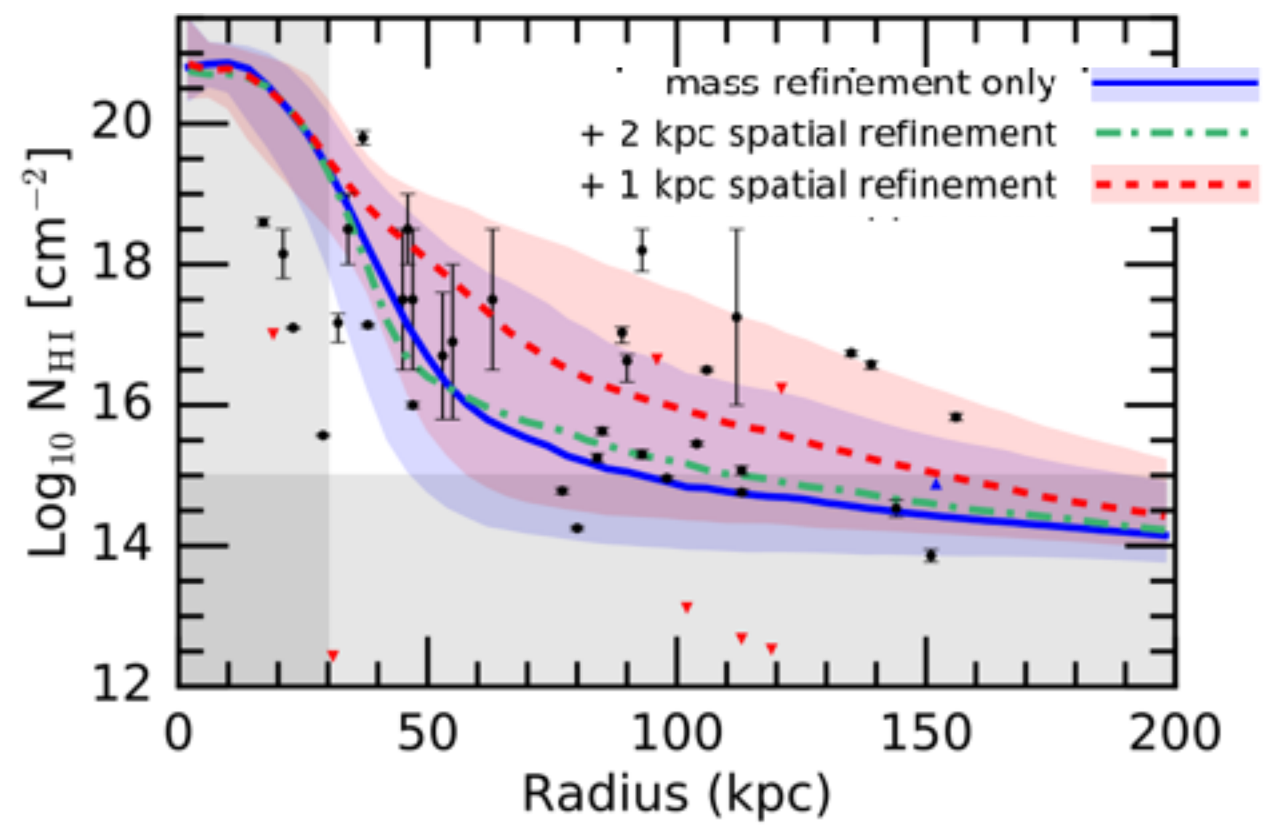
**Clouds with $r_{cl} > r_{crit}$**
***grow substantially***




## Effect in galactic simulations?

**Cosmological simulations of the circumgalactic medium with 1 kpc resolution: enhanced H I column densities**


Freeke van de Voort,[1,2★] Volker Springel,[3,1] Nir Mandelker,[2,1] Frank C. van den Bosch[2] and Rüdiger Pakmor[3,1]


standard simulation with only mass refinement. However, the median neutral hydrogen column density is much higher in the 1 kpc spatially refined simulation, by up to 1.6 dex. The H I column density could potentially increase even further, because the results are not yet converged. The scatter between H I sightlines is large in all simulations, especially

1. How does cold gas get into the CGM?
2. Why does it move?

Clouds with

$$r_{\rm cl} > \frac{v_{\rm wind} t_{\rm cool,mix}}{\chi^{1/2}} \approx 2\,{\rm pc}\,\frac{T_{\rm cl,4}^{5/2} \mathcal{M}_{\rm wind}}{P_3 \Lambda_{\rm mix,-21.4}} \frac{\chi}{100}$$

grow & become entrained.

3. **How does it affect Lyα / LyC escape?**

↳ see Marius' and other great talks this week! :)

Lya and LyC care about cold gas in the CGM

# How does it get into the CGM & why does it move?

*The answer is blowing in the wind!*

## (I) Mixing is your foe – but also your *friend*.

$$t_{\rm cool,mix} < t_{\rm cc}$$

$$r_{\rm cl} > \frac{v_{\rm wind} t_{\rm cool,mix}}{\chi^{1/2}} \approx 2\,{\rm pc}\, \frac{T_{\rm cl,4}^{5/2} \mathcal{M}_{\rm wind}}{P_3 \Lambda_{\rm mix,-21.4}} \frac{\chi}{100}$$

## (II) The action is in the tail.

*Large boxes* required to capture "focussing" effect.

## (III) Mass growth does not depend on shear.