Galaxy Evolution in Clusters:

Exploring the Role of
Ram Pressure Stripping
U   ns

VIRGO

S

STRASBOURG C

COYPU!!

St

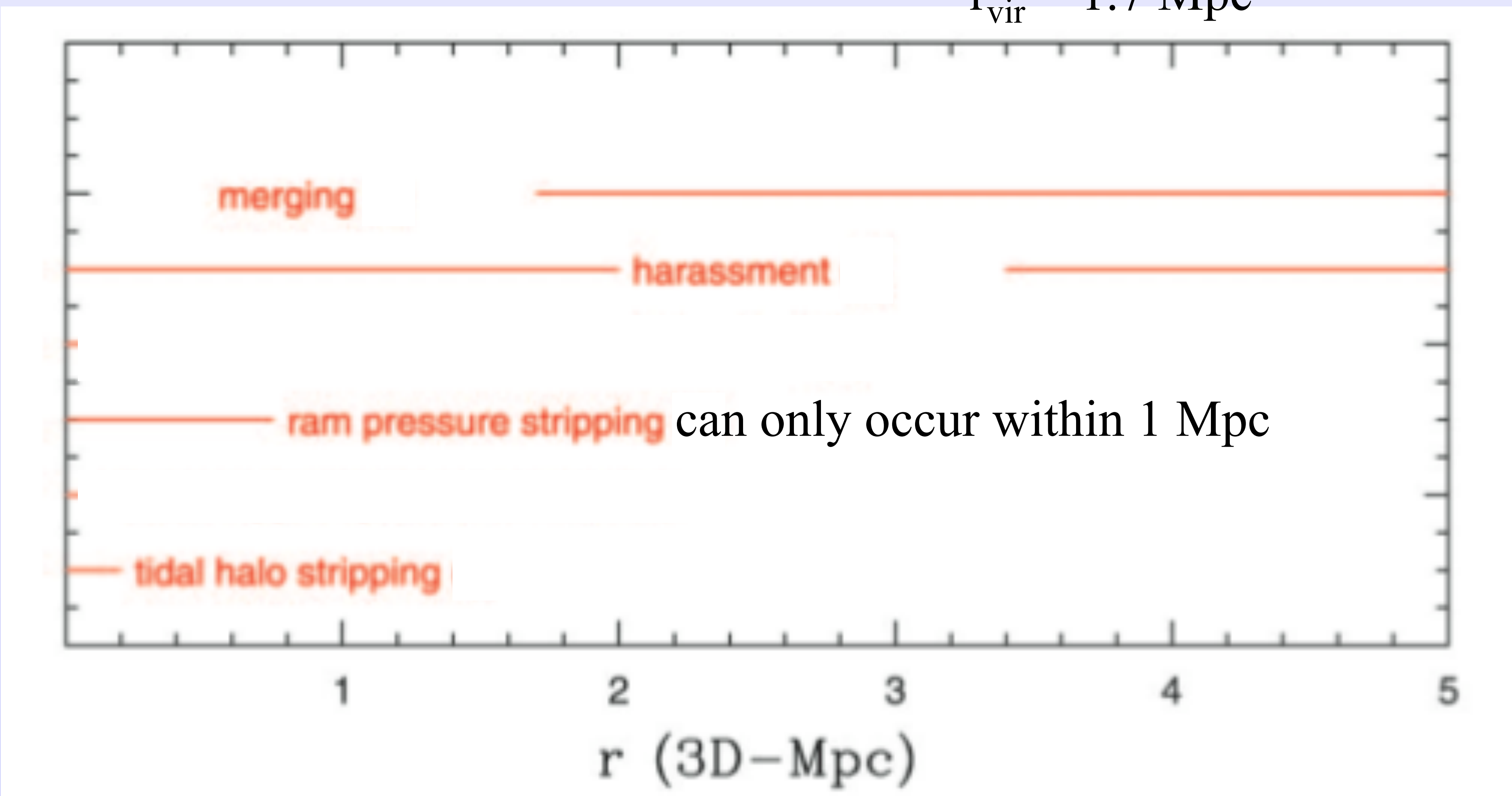
Myocastor coypus in Avaré

Which Mechanisms Act to Drive the Evolution of galaxies, and Where do they act in a Cluster?

A WIDE-FIELD *HUBBLE SPACE TELESCOPE* STUDY OF THE CLUSTER Cl 0024+1

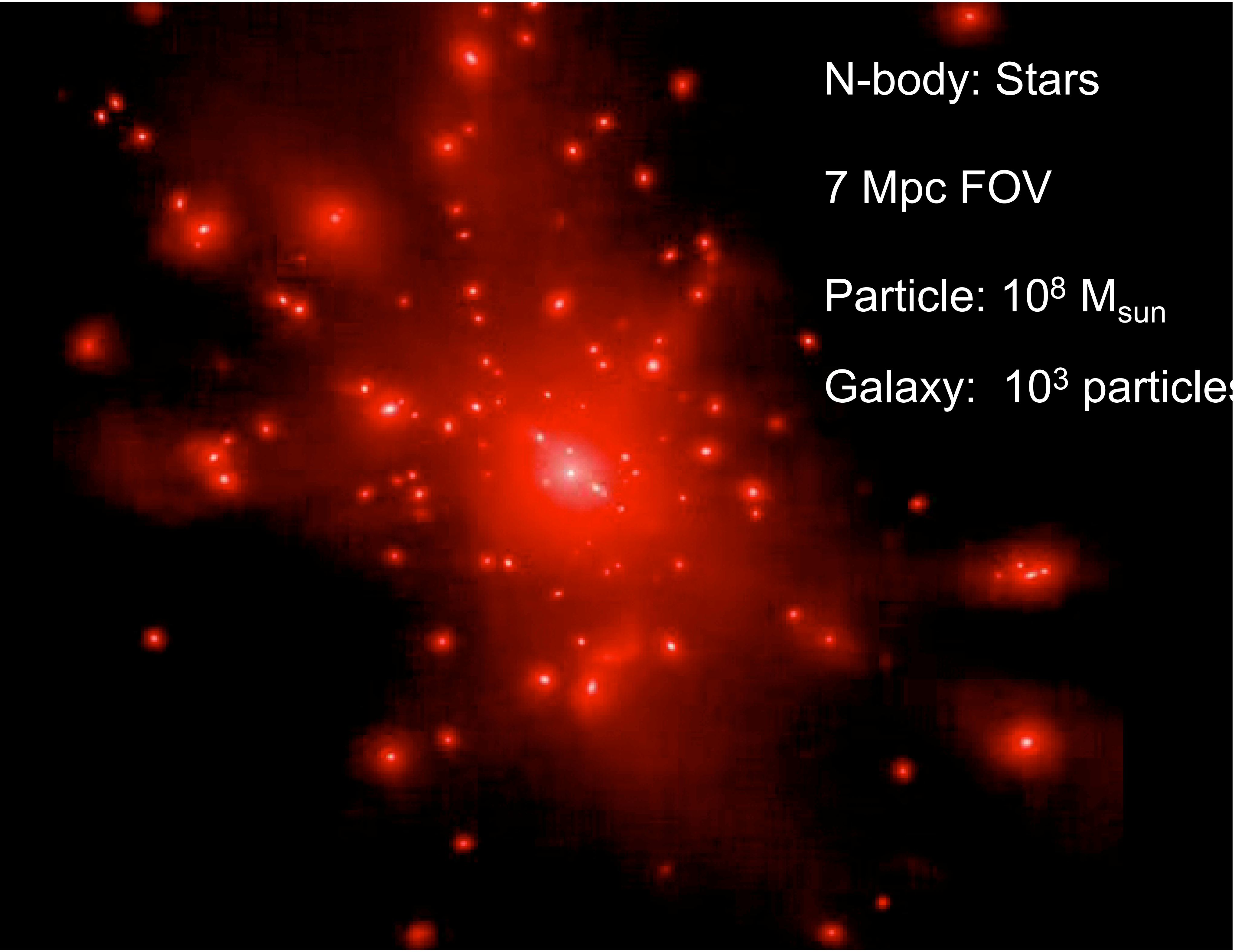
Treu et al. 2003

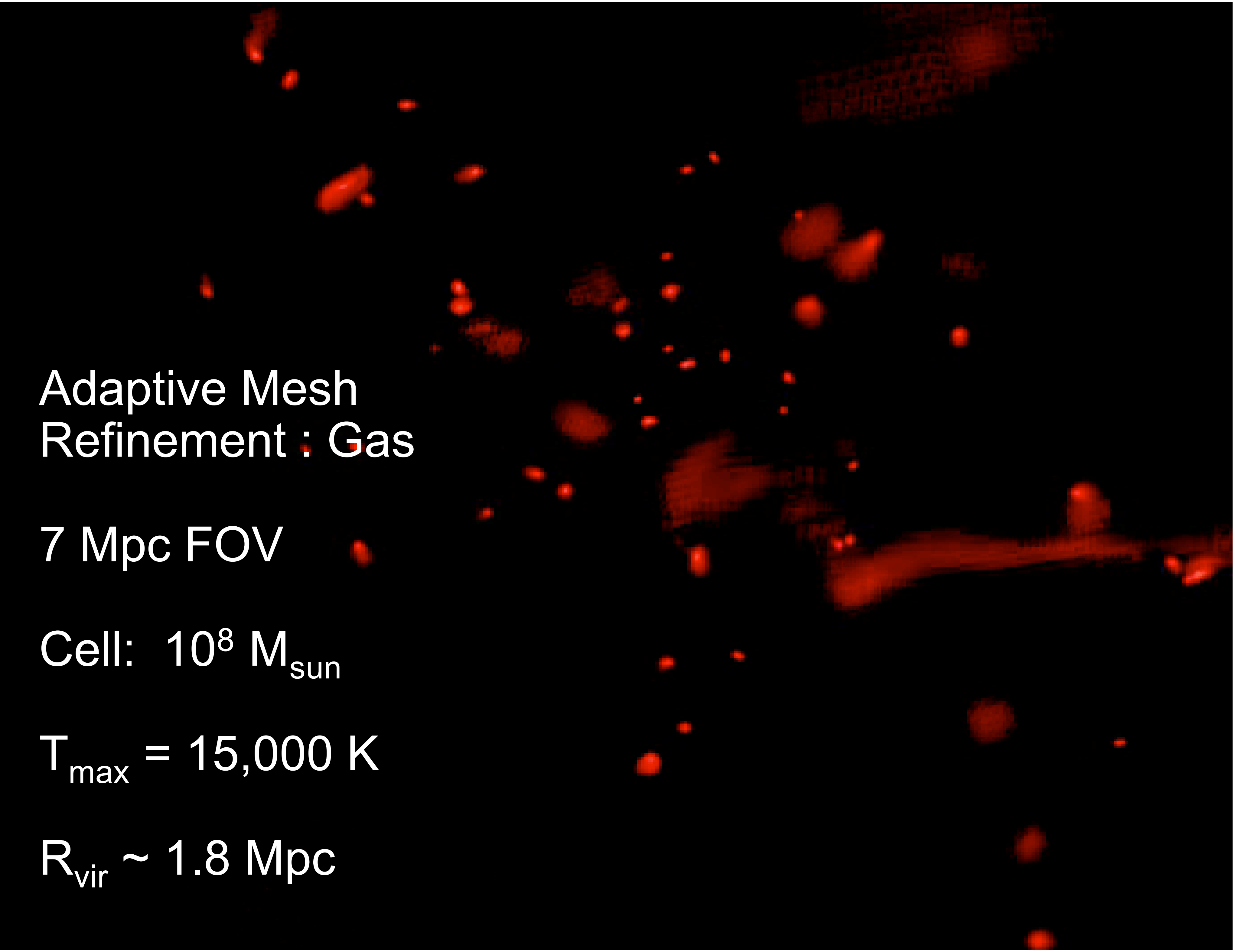
$r_{vir} = 1.7$ Mpc



can only occur within 1 Mpc

Fig. 10


N-body: Stars
7 Mpc FOV
Particle: 10^8 M_{sun}
Galaxy: 10^3 particles


Adaptive Mesh
Refinement : Gas
7 Mpc FOV
Cell: 10^8 M_{sun}
T_{max} = 15,000 K
R_{vir} ~ 1.8 Mpc

Initial Approach

A vital part of a galaxy's evolution from a late type to an earlier type is the loss of cool gas

Gravitational Interactions

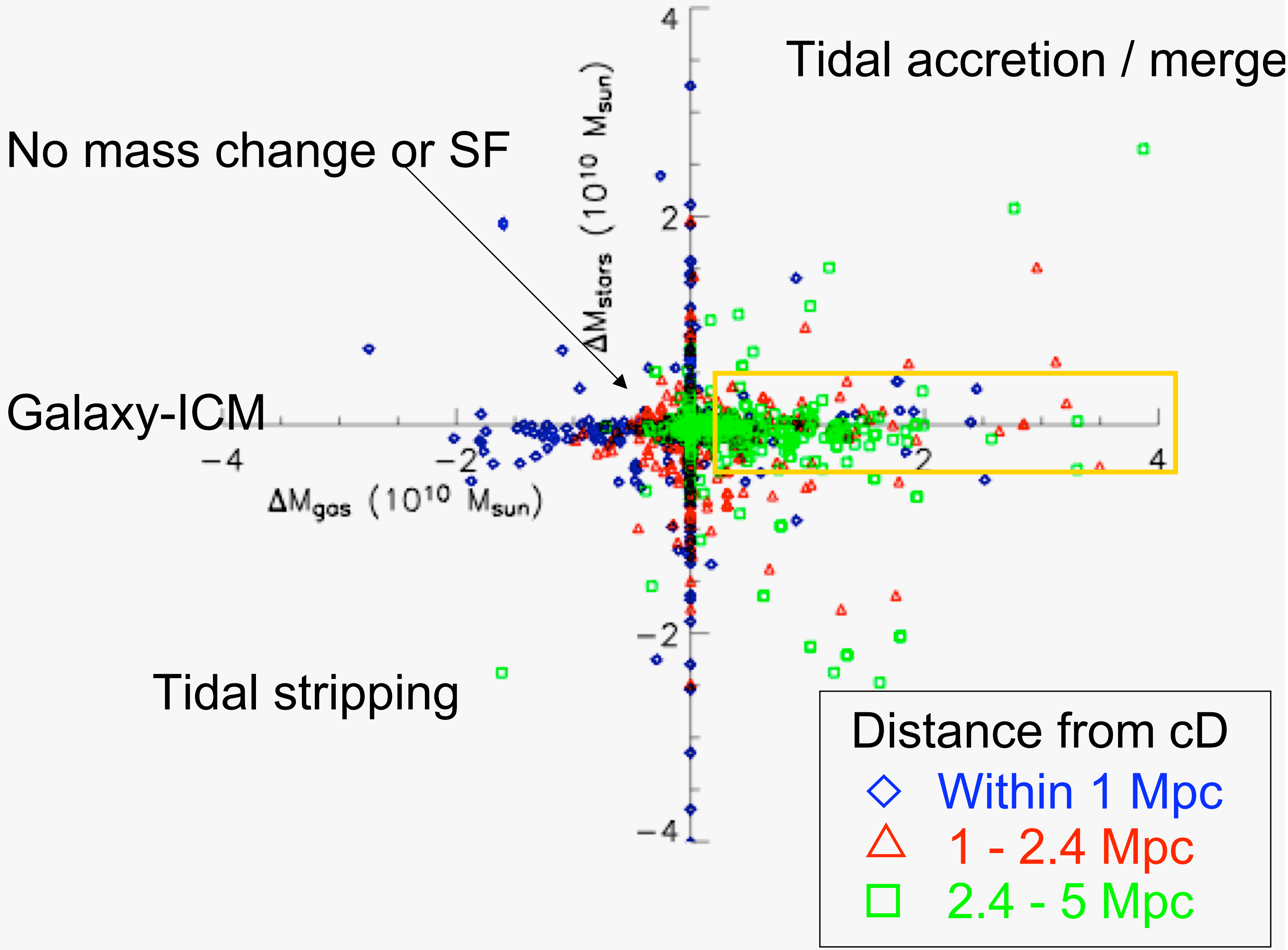
- Affect both gas and stars

Galaxy-ICM Interactions

- Affect only gas

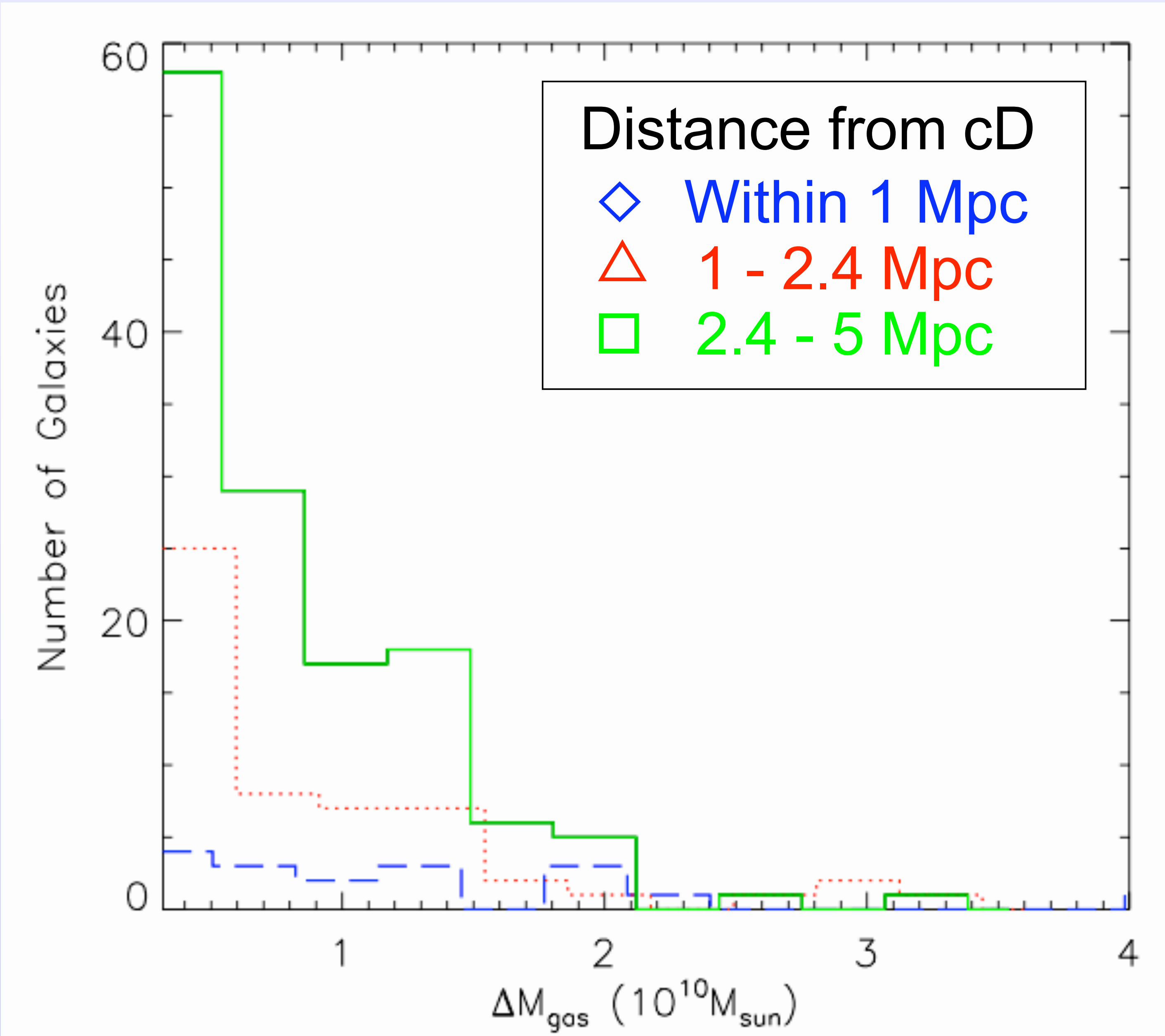
Our Sample

- 132 Galaxies
- Spheres with radius = 26.7 kpc
- 15 timesteps of .244 Gyr
- Examine changes in gas and stellar mass



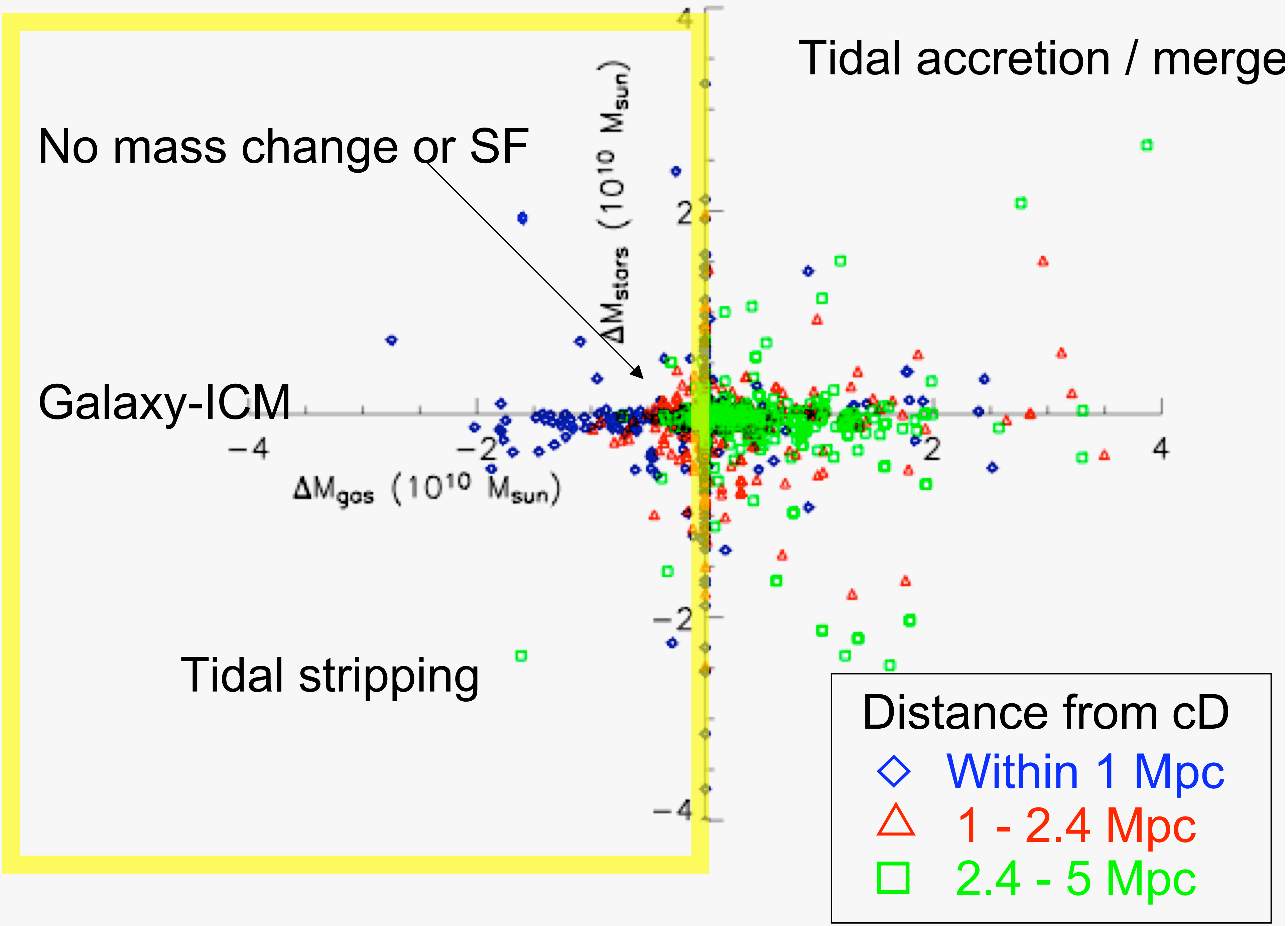
Distance ranges are chosen to correspond to Treu et al. 2003

Histogram comparing the gain of cool gas mass (T<15 000 K for the galaxies that have no change in their stellar mass.



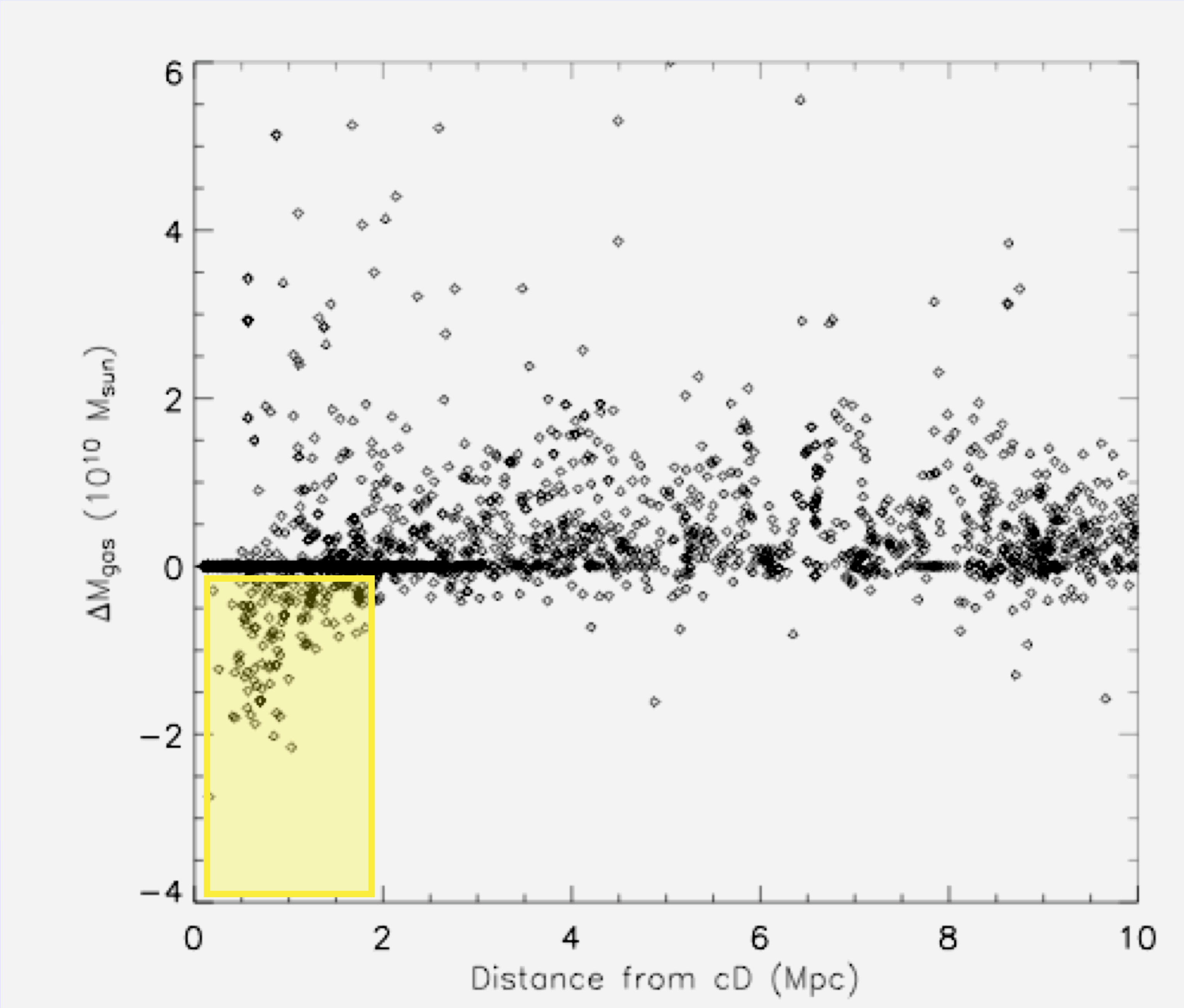
Galaxies are able to accrete cool gas from their surroundings in the outer regions of the cluster

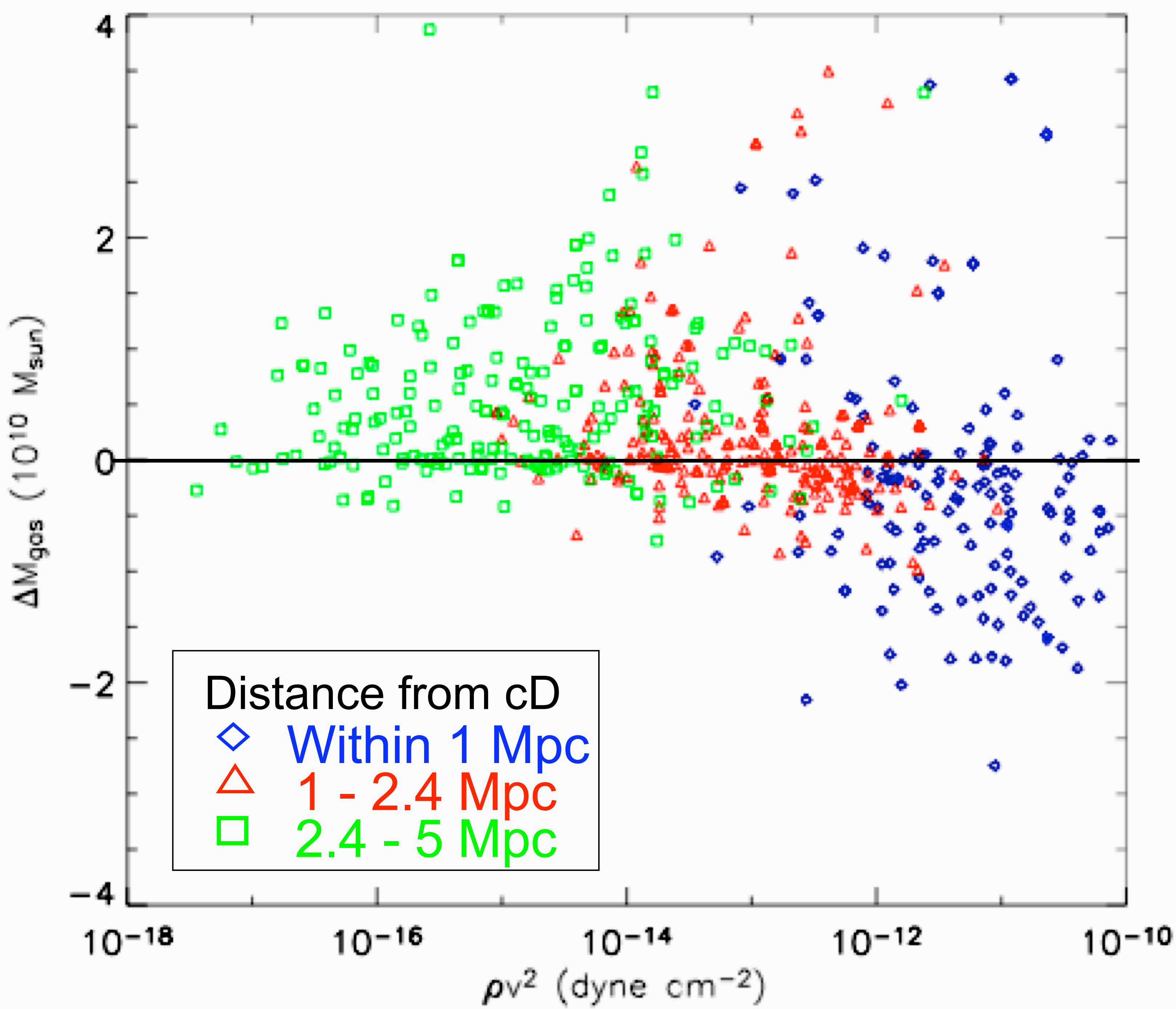
Closer to the cluster center, can see the onset of starvation (Larson et al. 1980)



Distance ranges are chosen to correspond to Treu et al. 2003

Change in Gas Mass vs Distance from cD





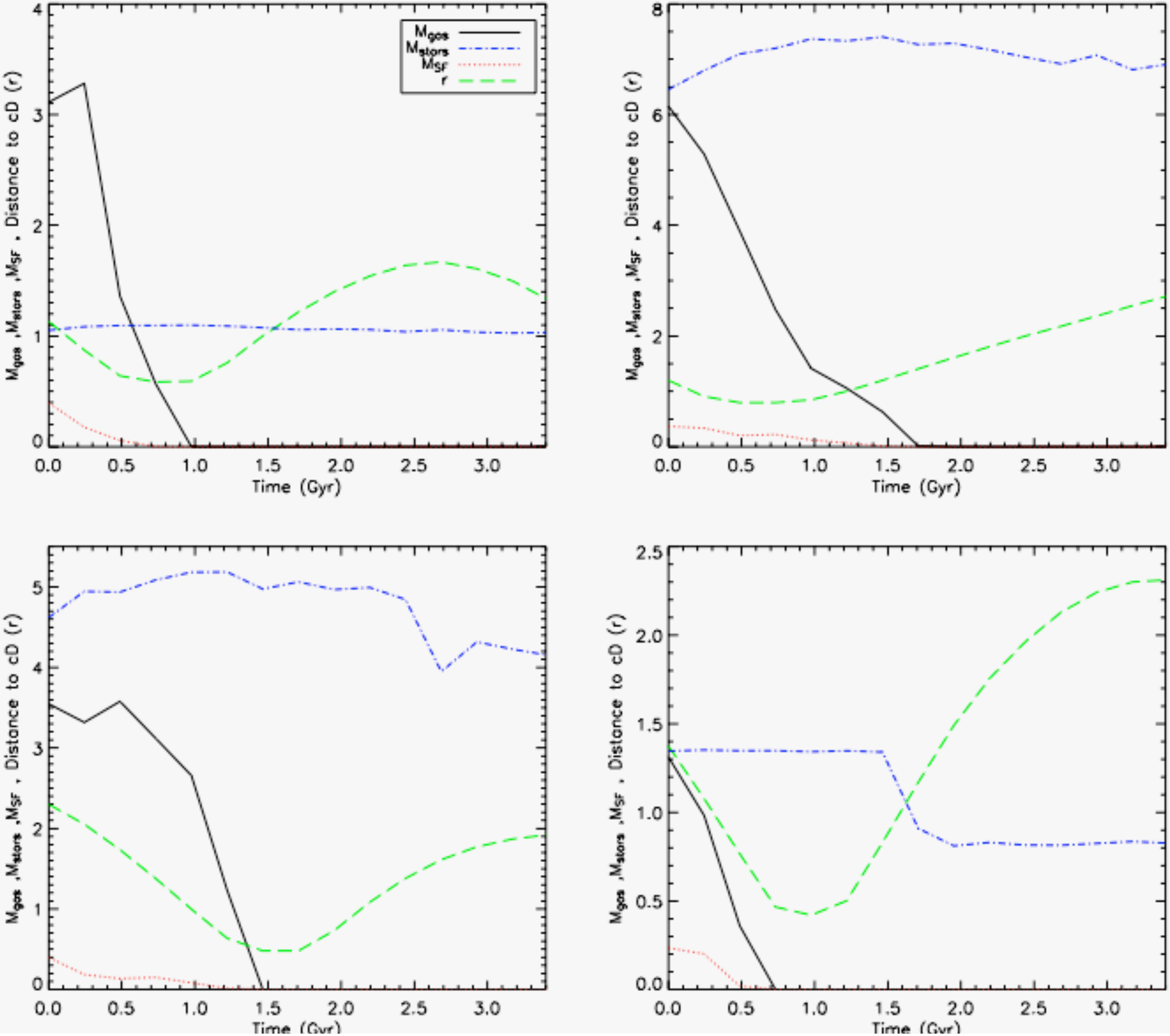
4
2
0
−2
−4
ΔM_{gas} (10^{10} M_{sun})
10^{-18}
10^{-16}
10^{-14}
10^{-12}
10^{-10}
ρv^2 (dyne cm^{-2})
Distance from cD
Within 1 Mpc
1 - 2.4 Mpc
2.4 - 5 Mpc

But…

Just because there are a number of instances of ram pressure stripping, can ram pressure really strip a galaxy of enough gas to change it into an earlier type?

The Stripped Sample

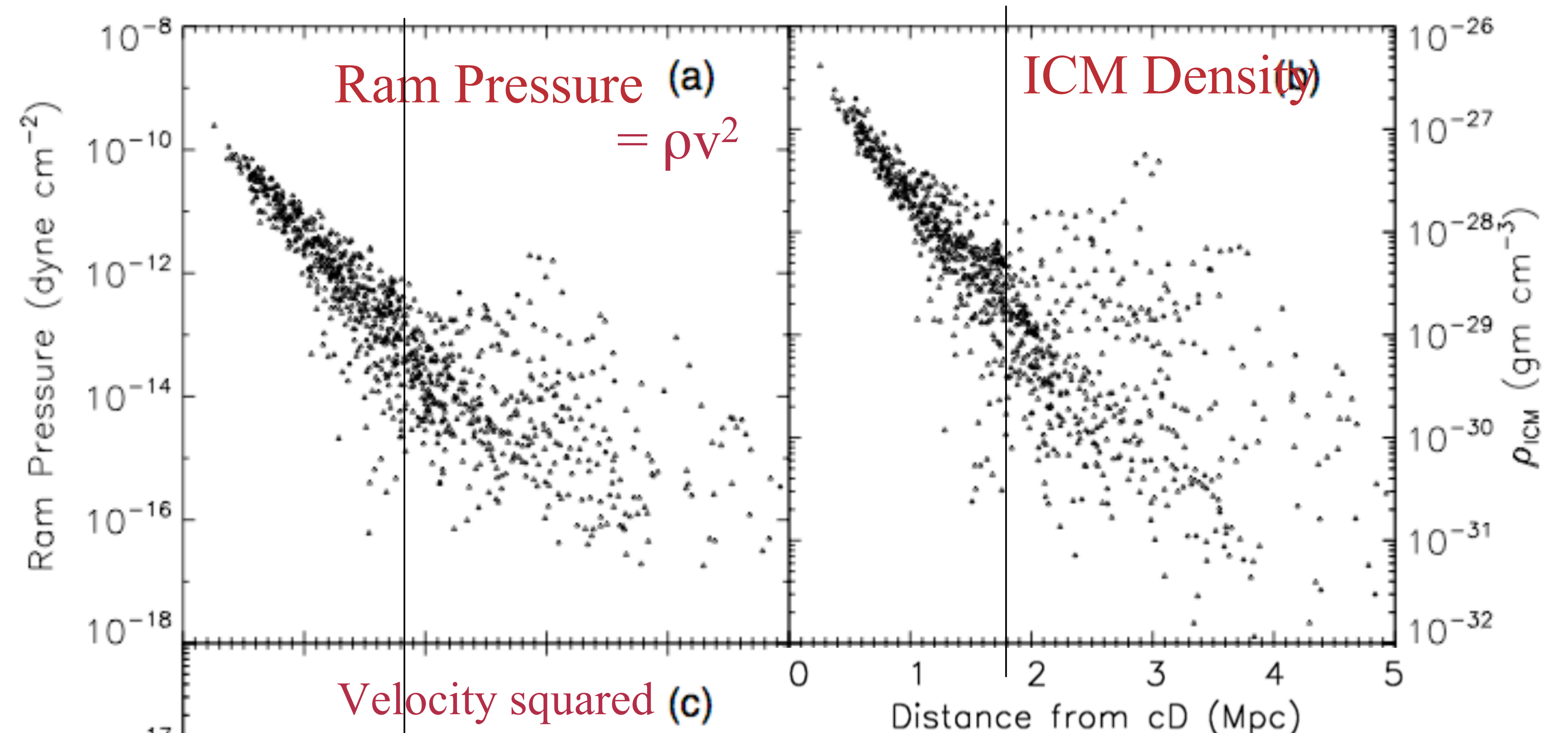
- 16 galaxies lose all their gas
- 75% of them lose their gas through a galaxy-ICM interaction (no tidal stripping)
- 58% of galaxies that undergo a galaxy-ICM interaction start before entering 1 Mpc.

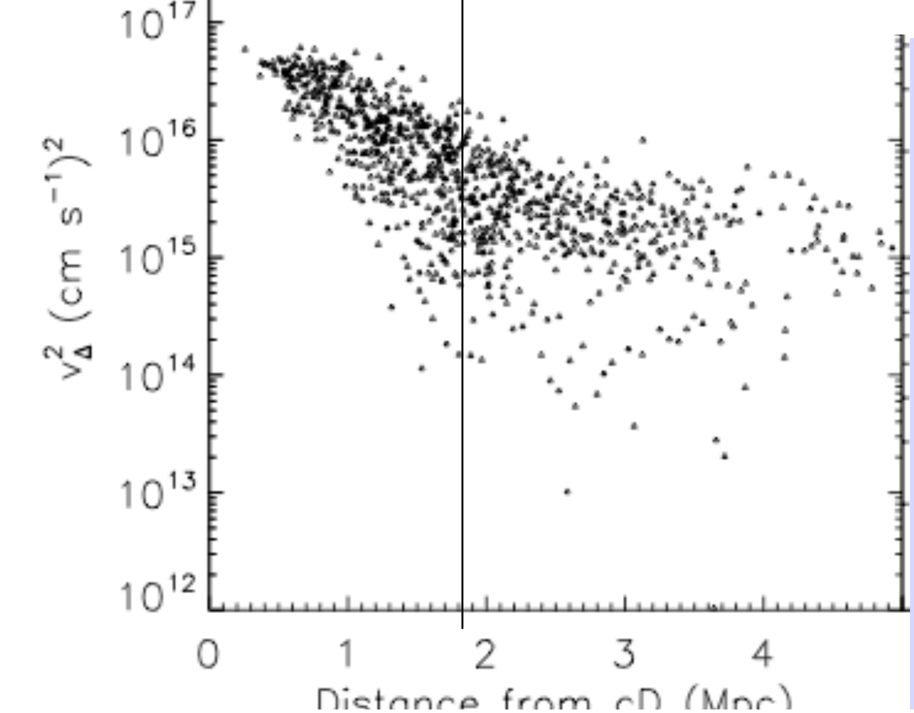


M_gas
M_stars
M_SF
r
M_gas ,M_stars ,M_SF , Distance to cD (r)
Time (Gyr)

Cluster Simulation Summary

- Galaxy-ICM interactions are the most common interaction that can strip a galaxy of its gas
- Ram pressure stripping occurs out to the virial radius of the cluster

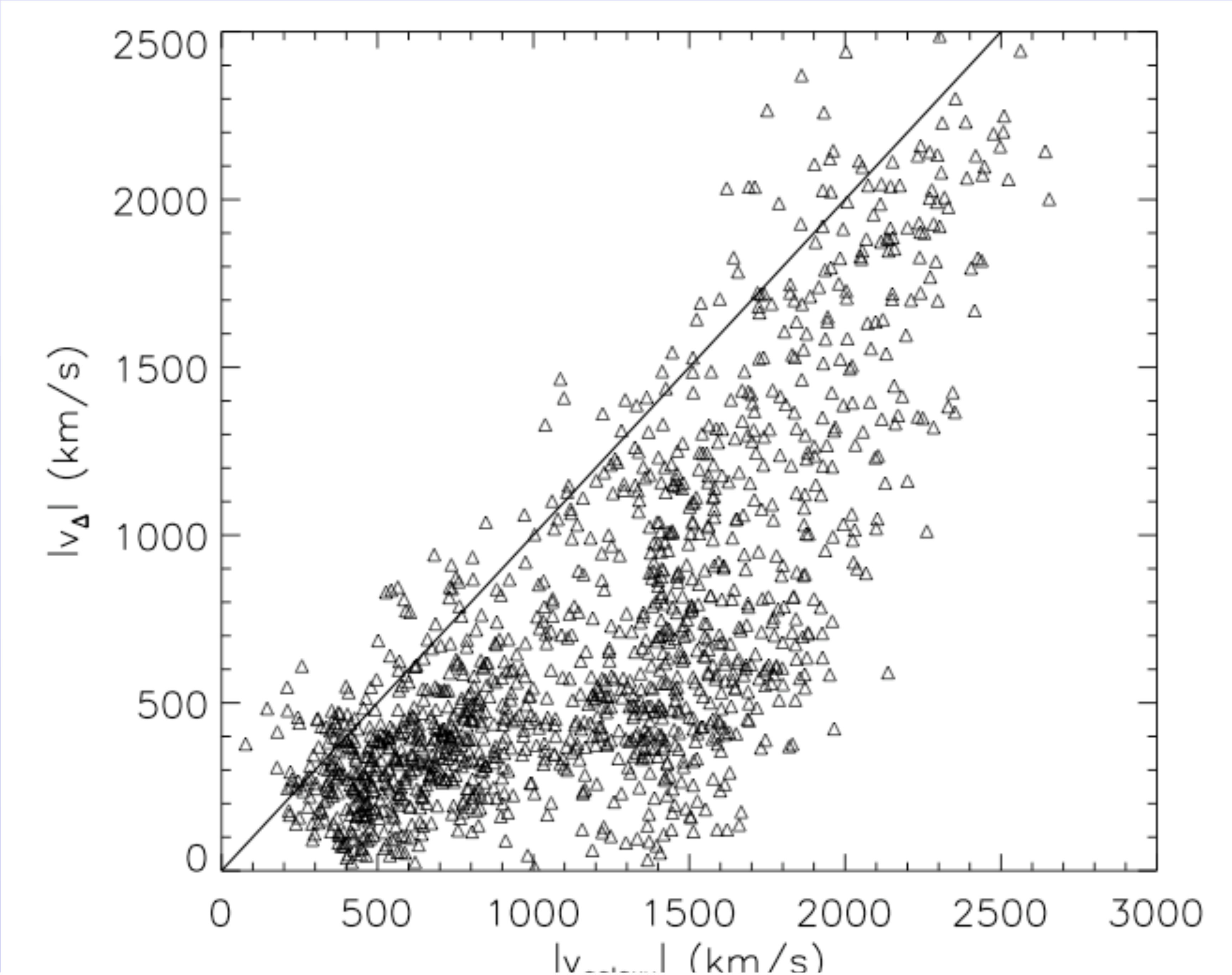




At the virial radius:

- ram pressure spans 2 orders of magnitude,
- ICM density varies by more than an order of magnitude
- velocity squared varies by more than an order of magnitude

Gas Falls in Along Filaments



Part

Zooming in to Highly Resolved Simulations of Ram Pressure Strippin

93 kpc

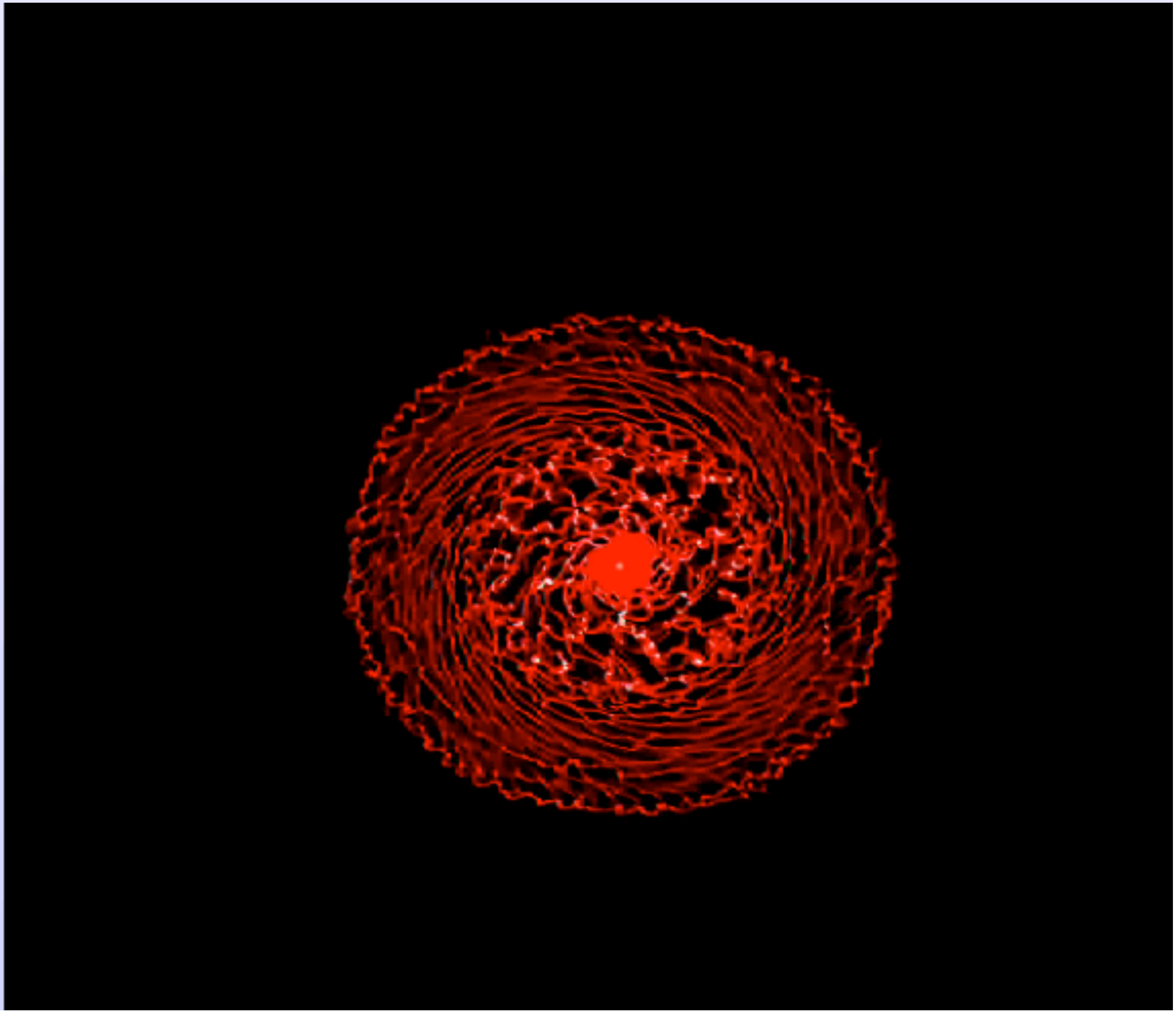
Resolution 38 pc

Cooling to 8,000 K

or

Cooling to 300 K

No Star Formation



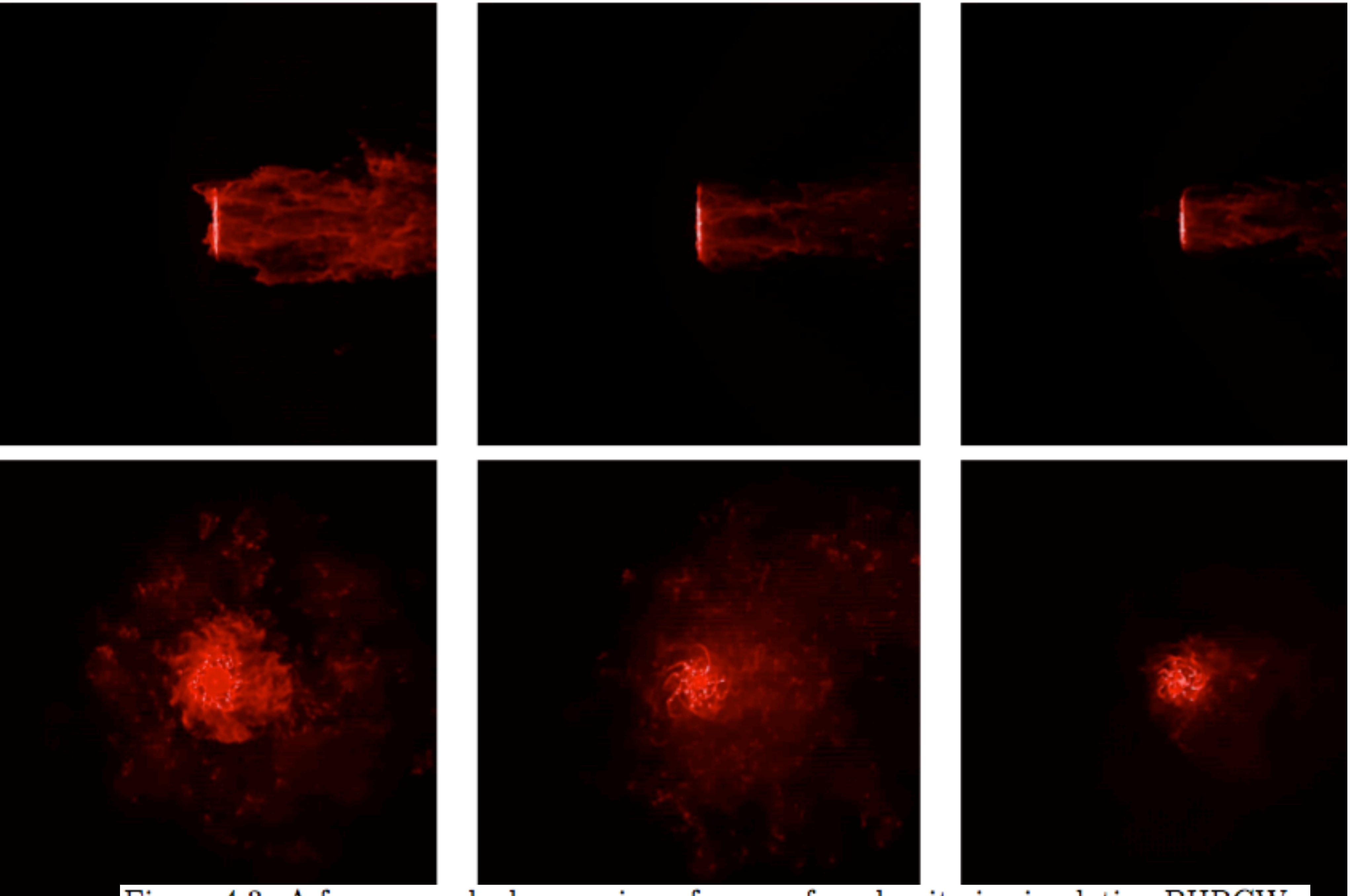
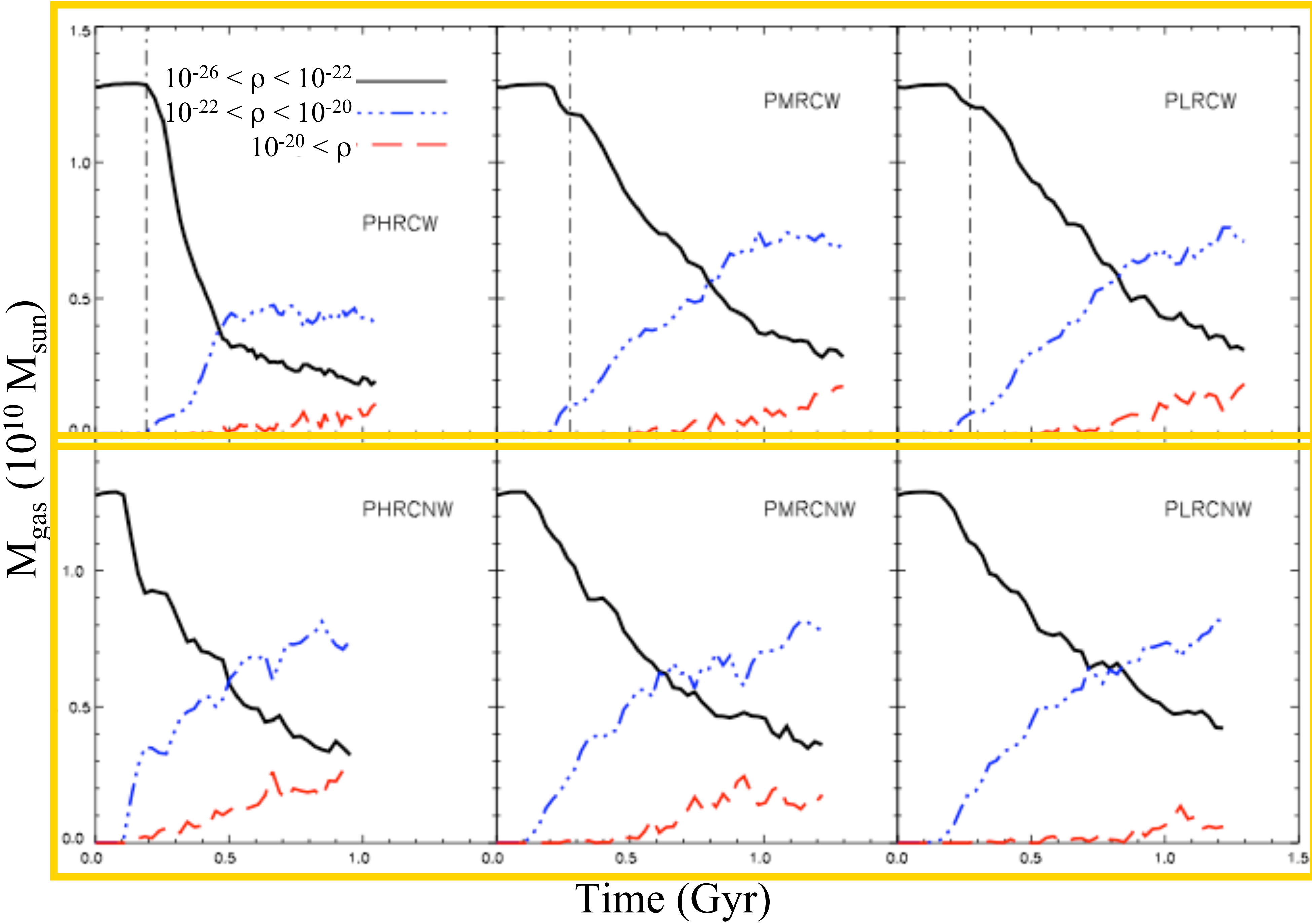


Figure 4.3: A face-on and edge-on view of gas surface density in simulation PHRCW, 250, 500, and 750 Myr after the wind has hit the galaxy. Note the substructure both in the disk and in the stripped gas. Each image side is 103.7 kpc



$10^{-26} < \rho < 10^{-22}$
$10^{-22} < \rho < 10^{-20}$
$10^{-20} < \rho$
PHRCW
PMRCW
PLRCW
PHRCNW
PMRCNW
PLRCNW
M_{gas} (10^{10} M_{sun})
Time (Gyr)

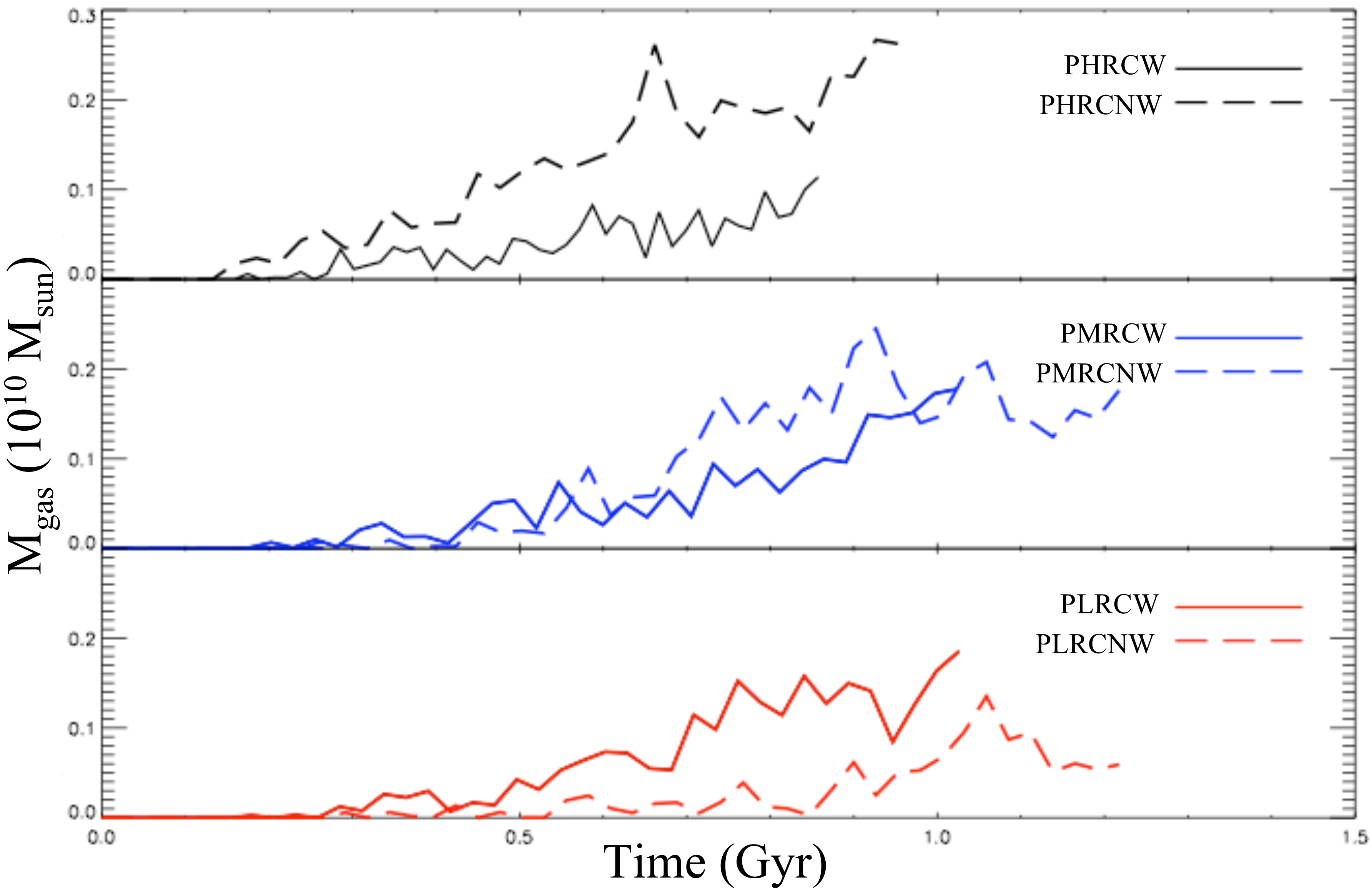
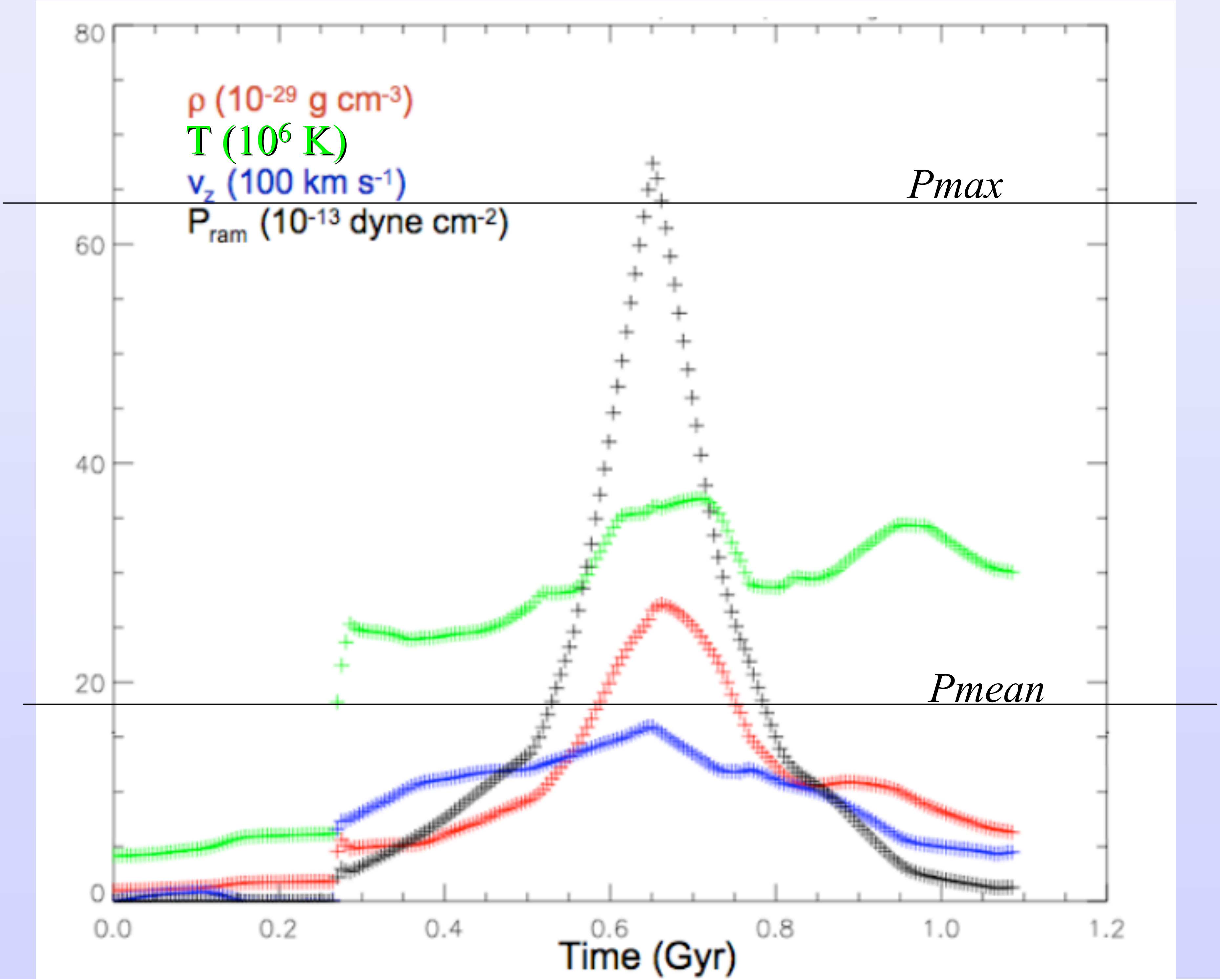


Figure 4.8: This focuses on the most dense gas in each of the radiatively cooled cases. The runs with an ICM wind have been shifted in time by the amount of time before the wind hits them (190 Myr, 274 Myr, and 271 Myr, respectively). High ram pressure results in less high density gas, while low ram pressure increases the amount of high density gas.



ρ (10-29 g cm-3)
T (106 K)
vz (100 km s-1)
Pram (10-13 dyne cm-2)
Pmax
Pmean
80
60
40
20
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Time (Gyr)

Focus on the Disk

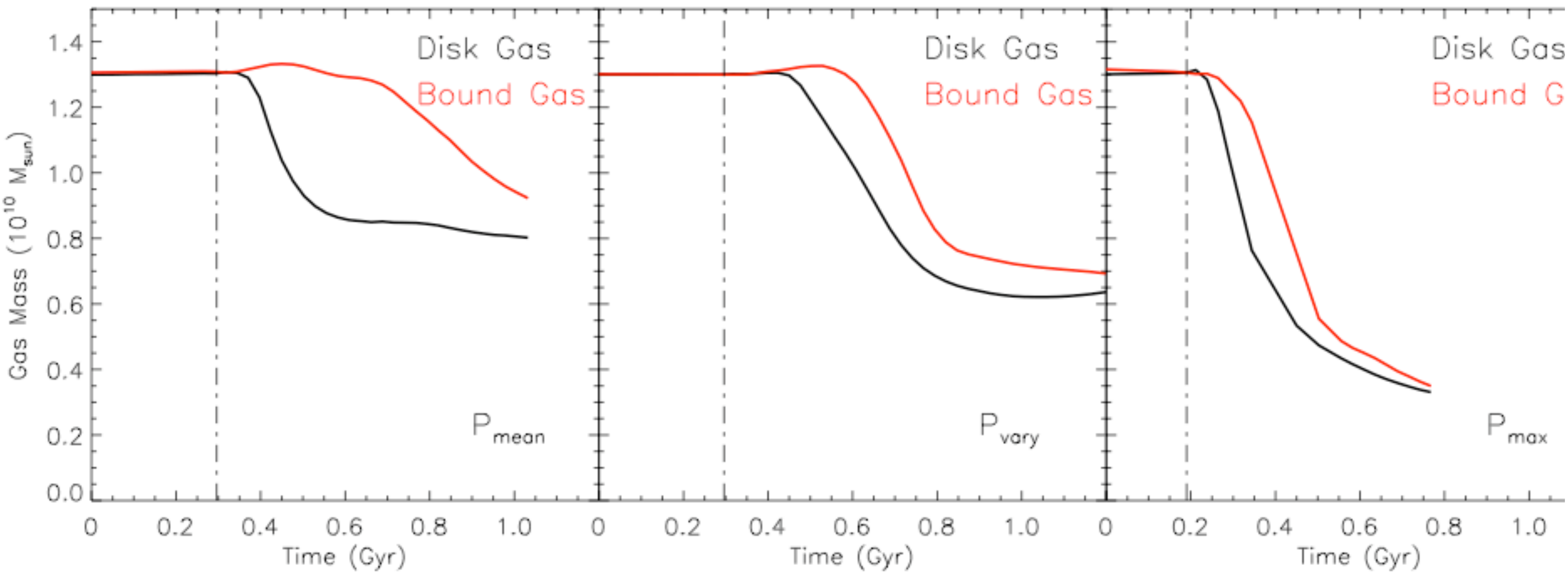


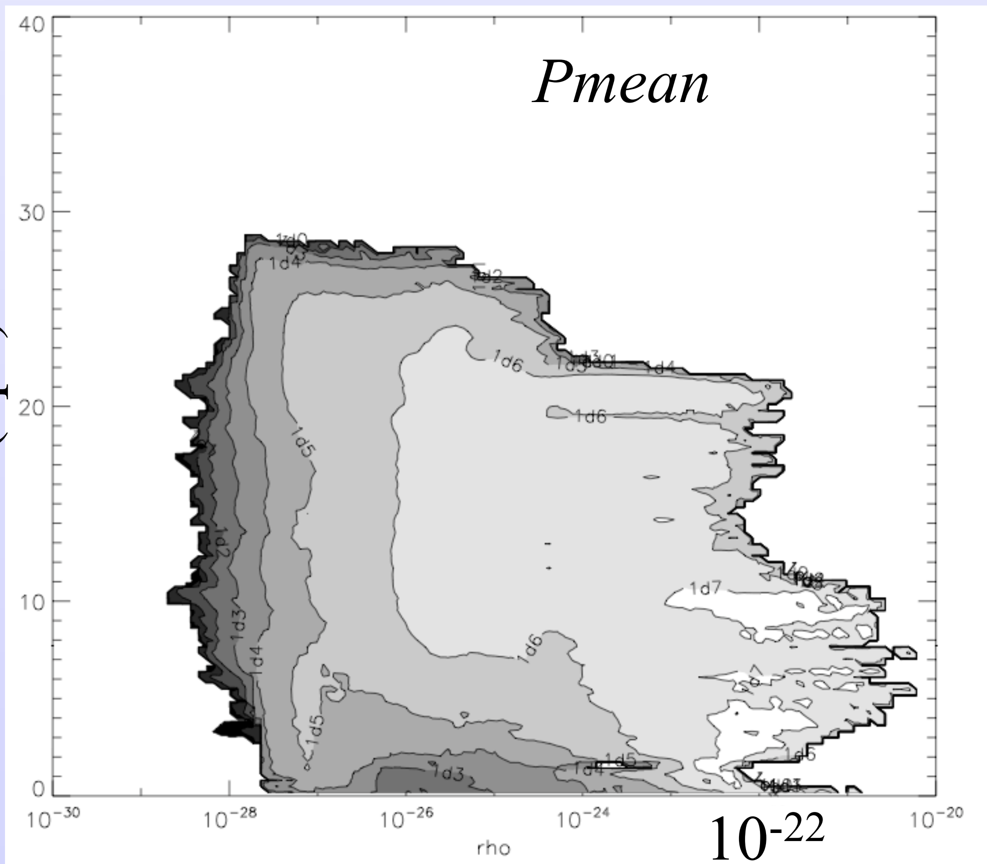
Table 7.2: Comparison Between Disk Radii

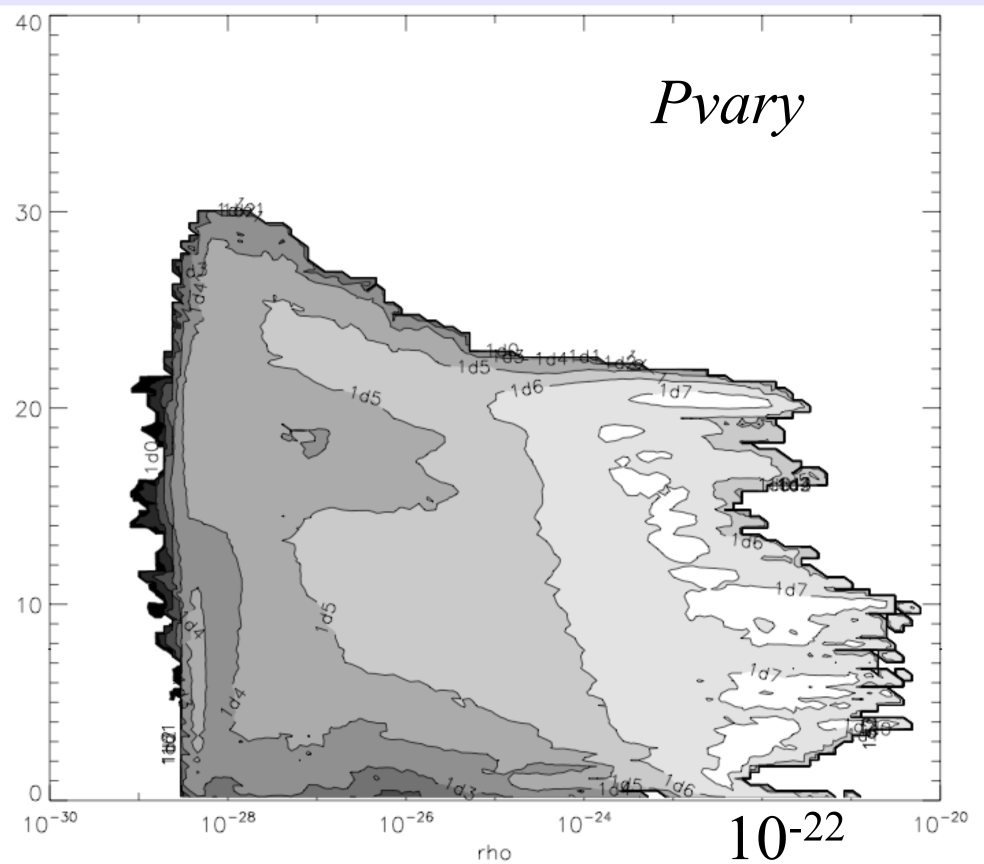
Run	r_{disk} (t = 390 Myr)	r_{disk} (final)	t_{final}
Pvary	16.5 kpc	13 kpc	975 Myr
Pmax	10.5 kpc	9 kpc	605 Myr
Pmean	16 kpc	11.5 kpc	765 Myr

Table 7.2: Comparison Between Disk Radii

Run	r_{disk} ($t = 390$ Myr)	r_{disk} (final)	t_{final}
Pvary	16.5 kpc	13 kpc	975 Myr
Pmax	10.5 kpc	9 kpc	605 Myr
Pmean	16 kpc	11.5 kpc	765 Myr

Radius (kpc)

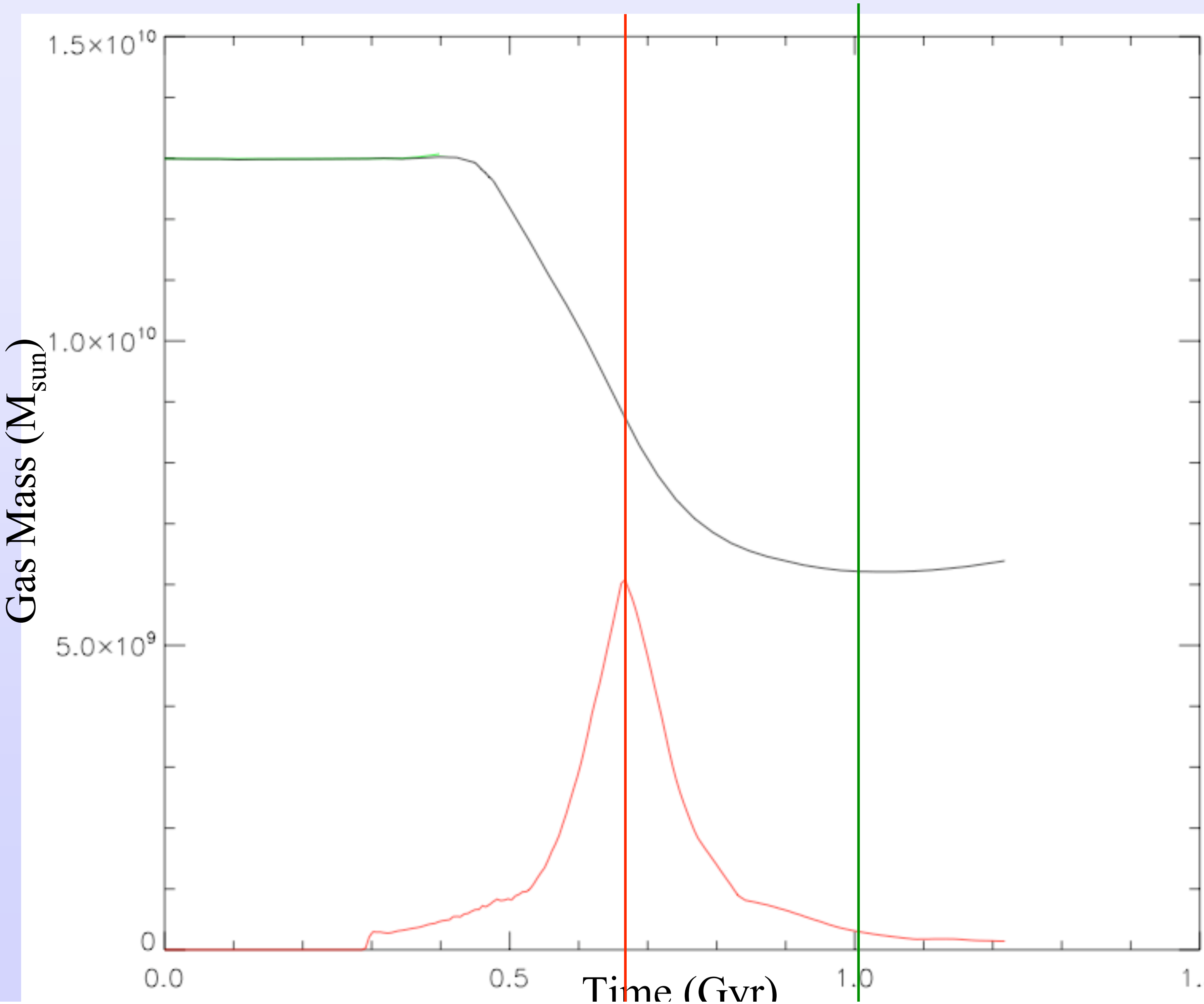




10^{-22} 10^{-22}

Gas Density (g cm^{-3}) Gas Density (g cm^{-3})

100 Myr after the wind has hit the disk



1.5×10¹⁰
1.0×10¹⁰
5.0×10⁹
0
0.0
0.5
1.0
1.5
Gas Mass (M_sun)
Time (Gyr)

Where Does Fallback Happen?

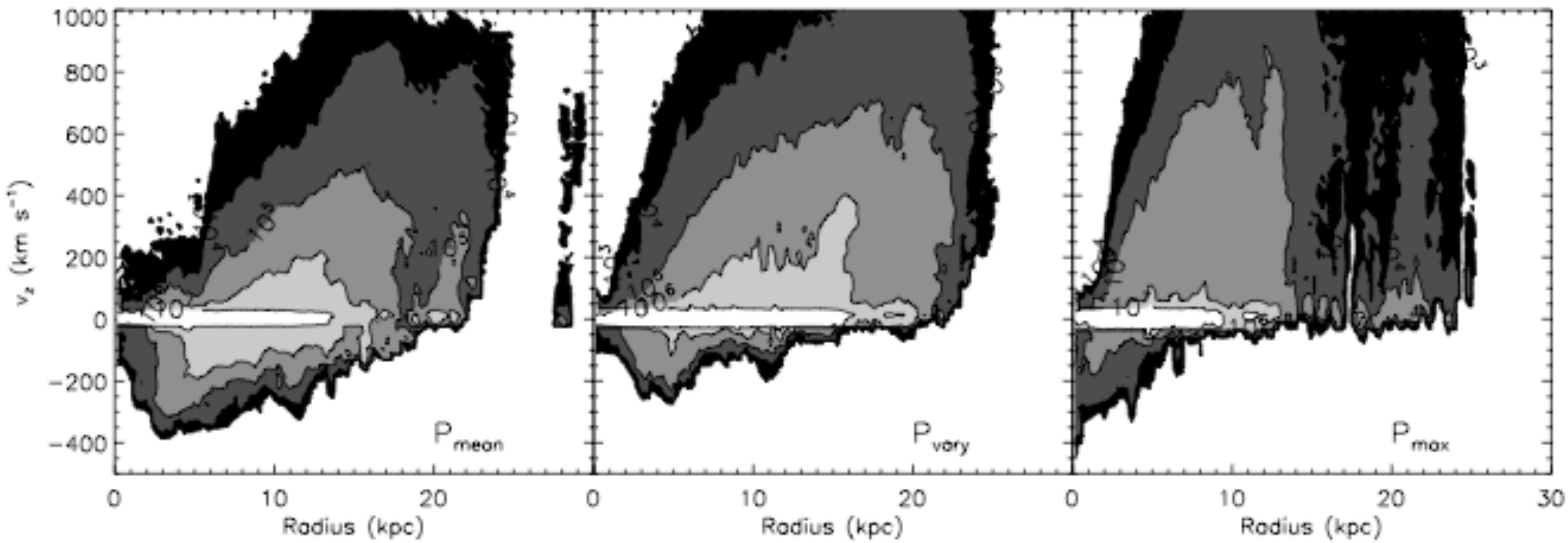
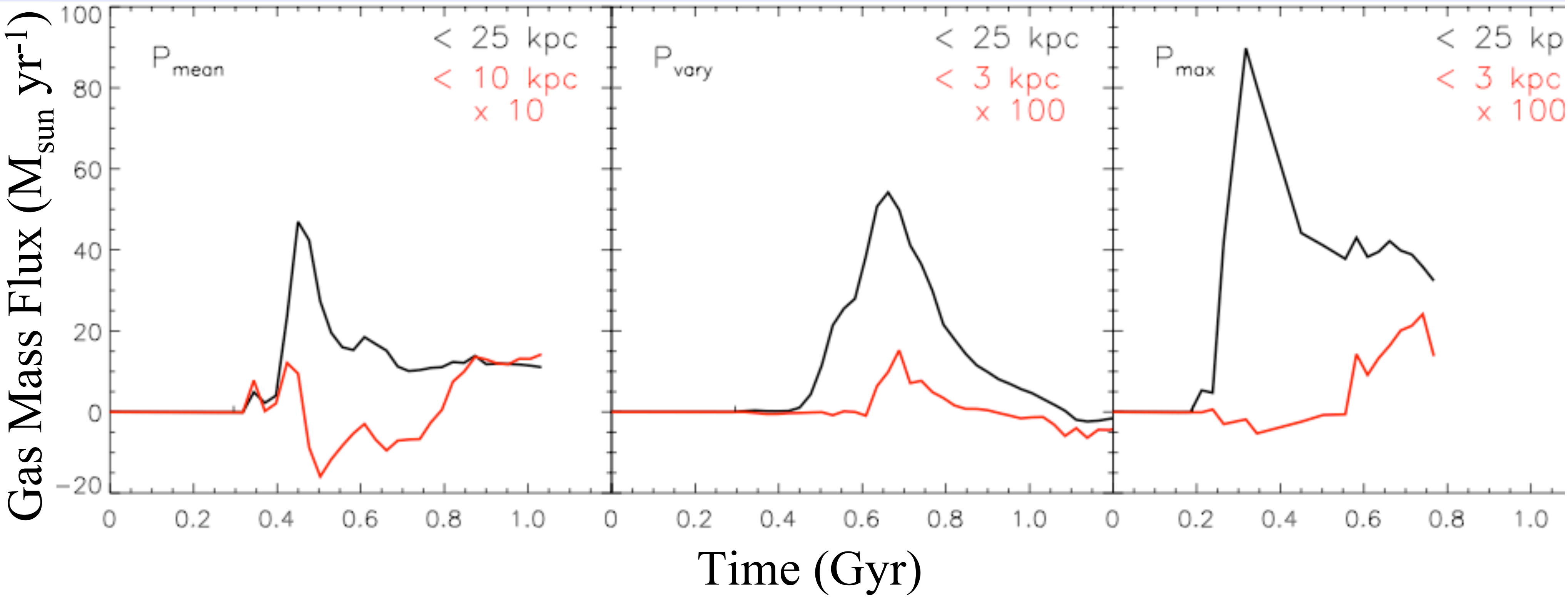


Figure 7.3: This is gas with a tracer fraction of at least 25% within 10 kpc of the plane of the galactic disk, plotting mass contours as a function of z-velocity (velocity in the wind direction) and radius (in the disk plane). Each panel is 315 Myr after the wind has begun stripping each galaxy. Fallback generally occurs in the center of the disk (although disordered motion can result in negative z velocities at larger radii).

Are the negative velocities from disordered motion, or can we find net fallback?



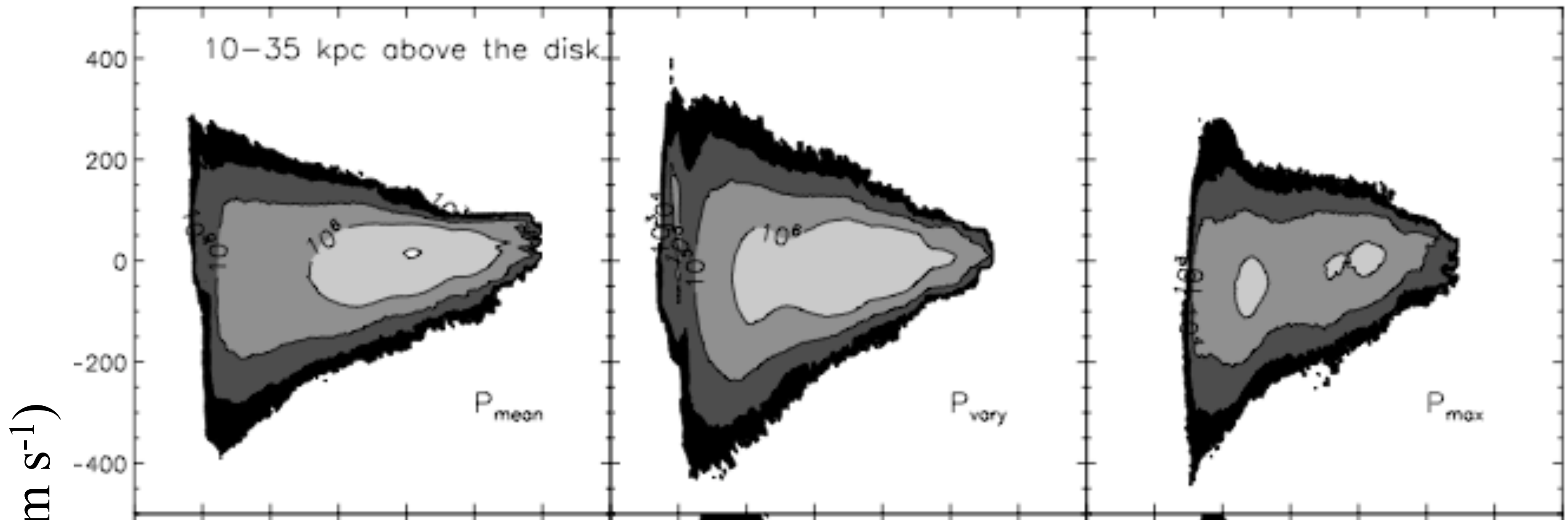
Compares the total net flux to the largest radius with negative net flux at any time.

What might cause stripped gas to fallback?

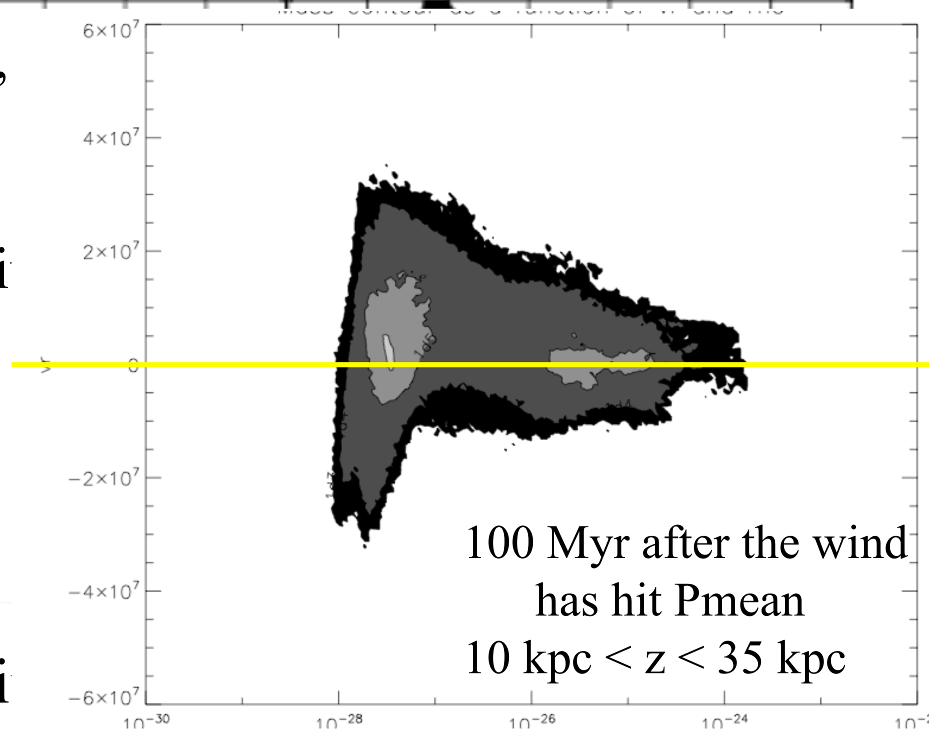
In other words, what might cause gas to move laterally into the shadow of the disk?

- Drag from ICM slowing down cloud rotational velocity, and gravity drawing gas towards the center
- A Pressure gradient with a low pressure pocket behind the disk along which gas flows
- Turbulence, which will randomly move some gas into the shadow at which point it can fallback

Why Does Gas Fallback?

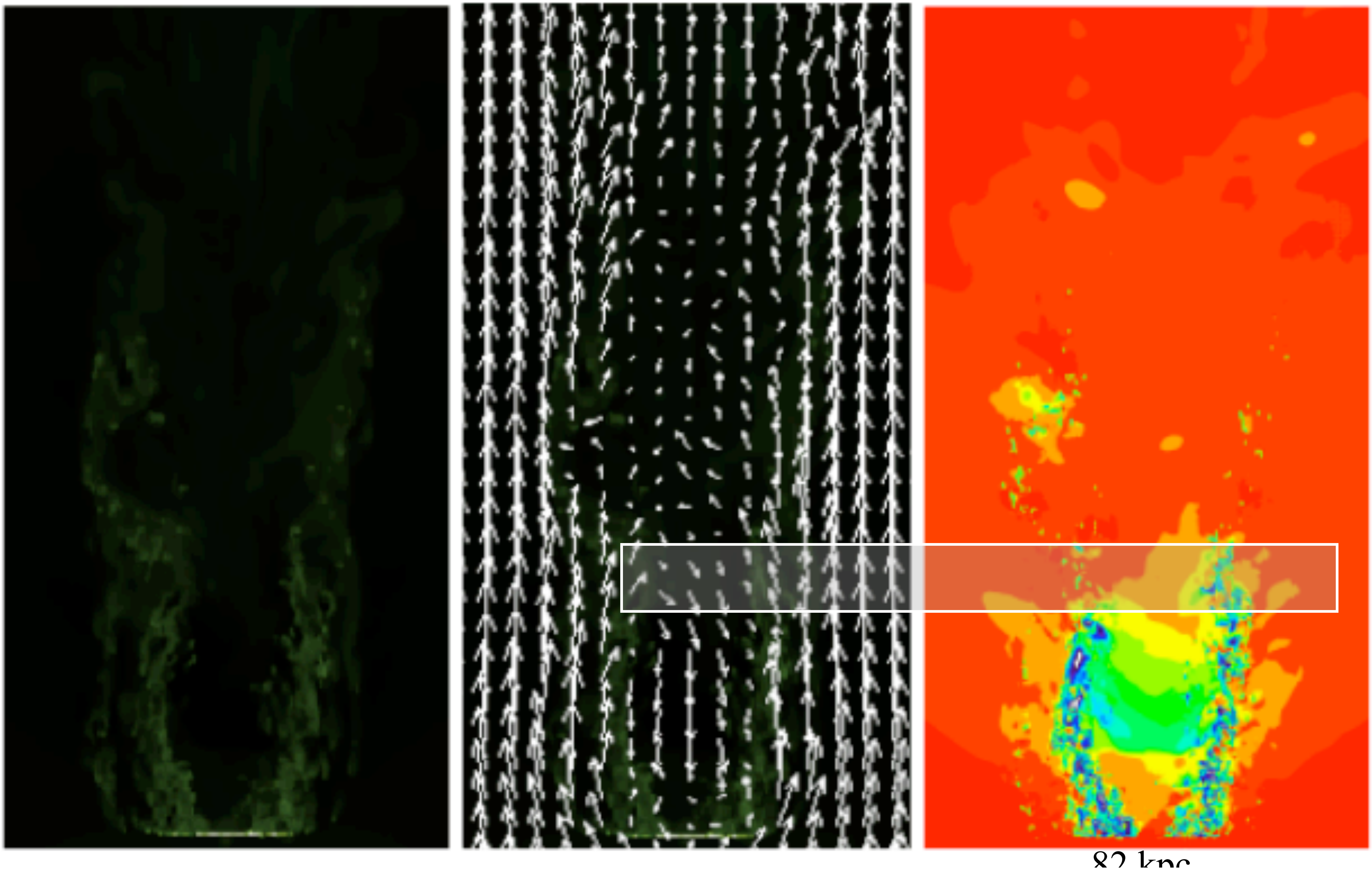


Between 10-35 kpc above the disk, 315 Myr after the wind has hit the disk:
The skew is inwards, and grows wi
time.
Therefore, gas is flowing towards the center along an increasingly steep pressure gradient.

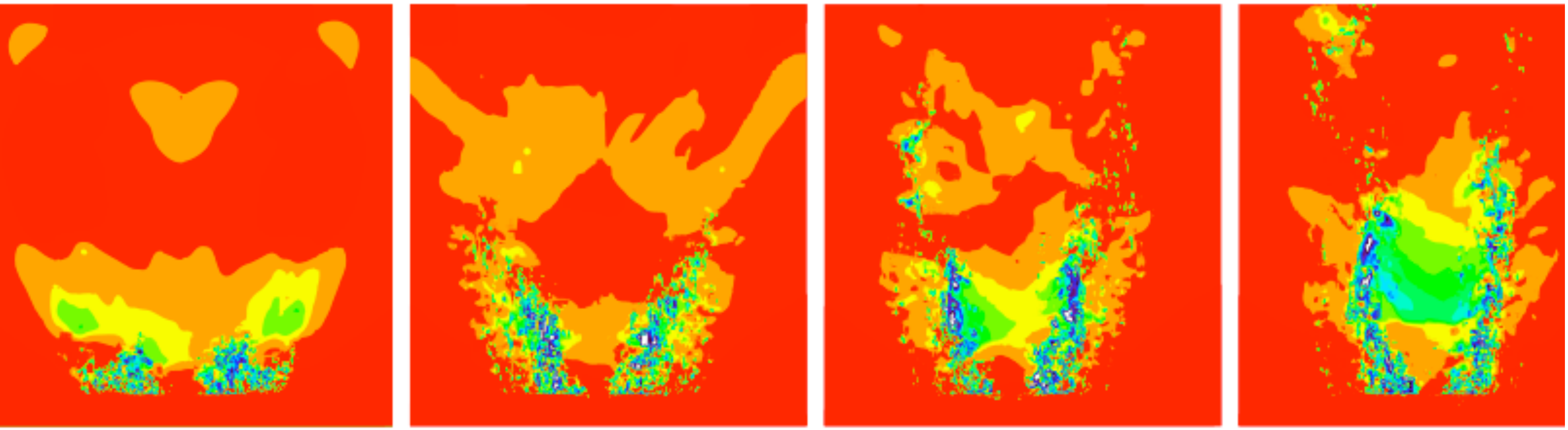


100 Myr after the wind has hit Pmean
10 kpc < z < 35 kpc

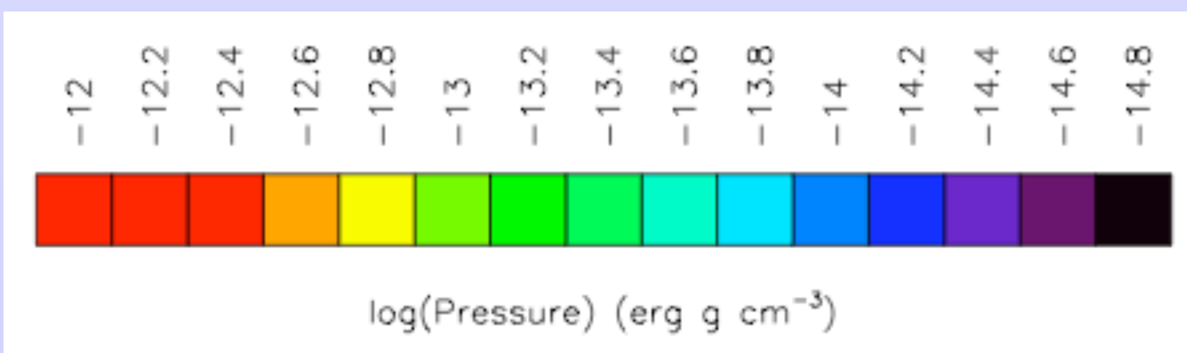
Turnover to Fallback occurs where pressure decreases



The Pressure Gradient Grows with Time

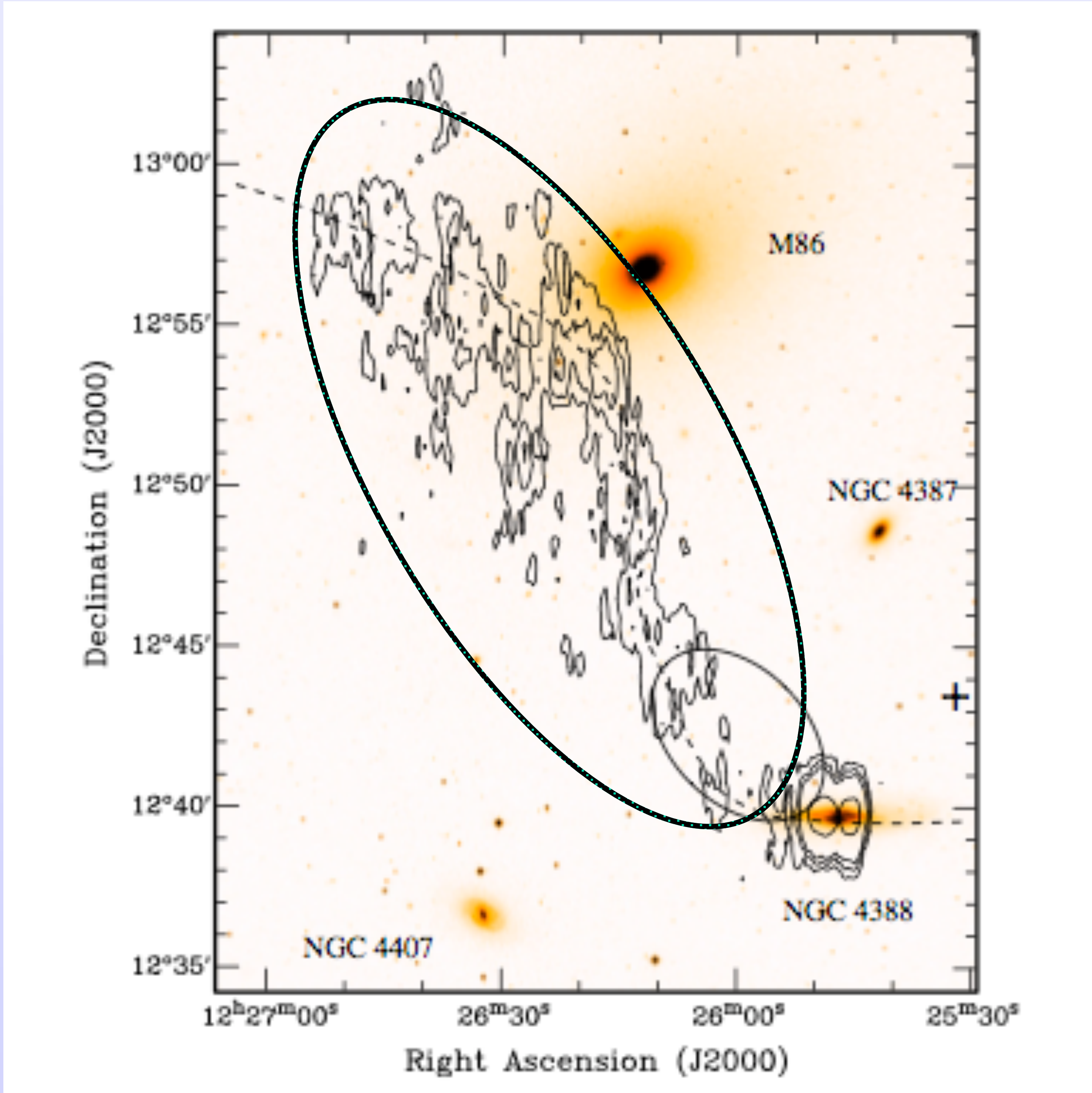


100 Myr 200 Myr 260 Myr 315 Myr



Long tails have been observed in HI, X-rays, and Hα

~110 kpc tail



Oosterloo & van Gorkom 20

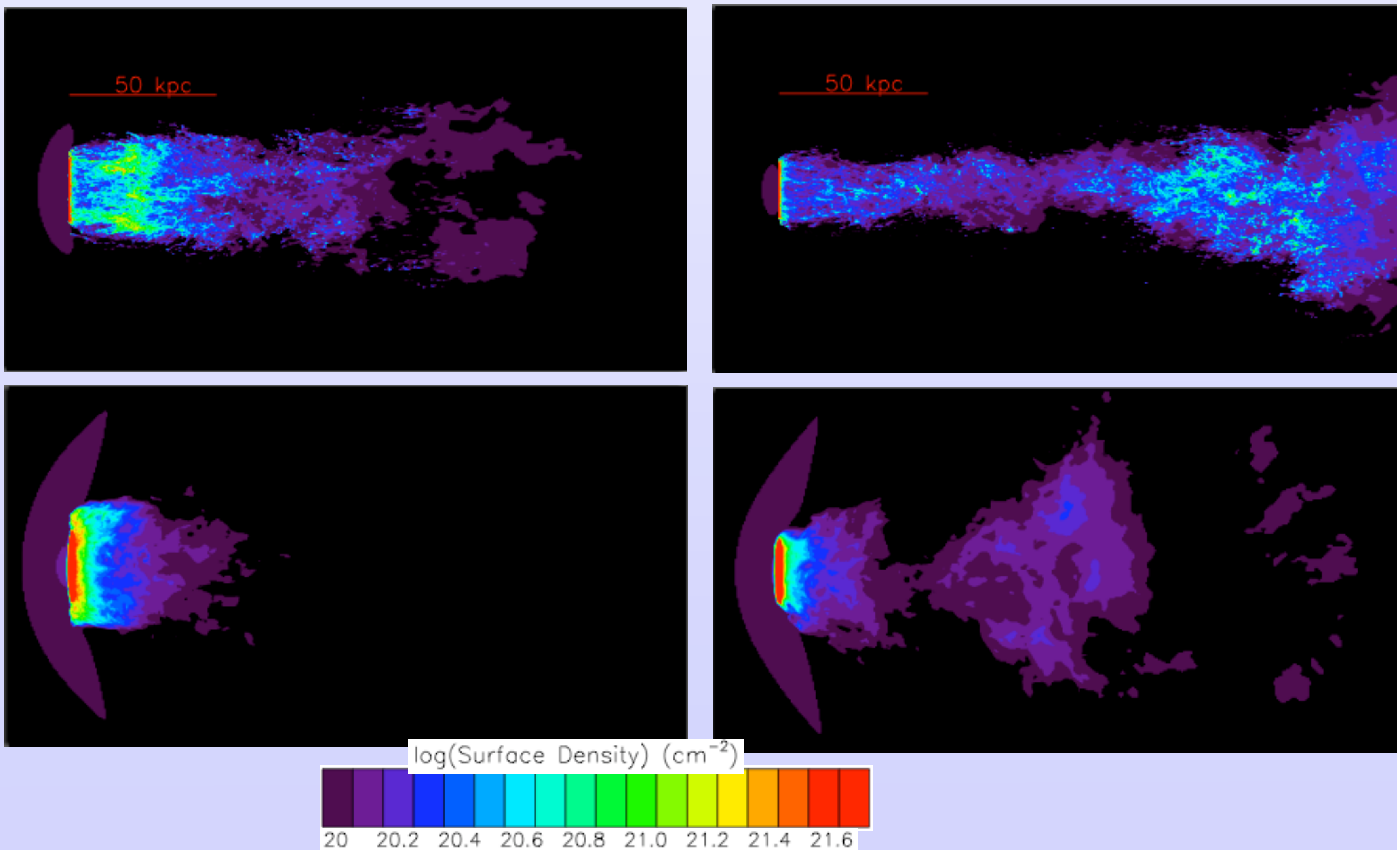
Including cooling changes the morphology of the tails

250 Myr

500 Myr

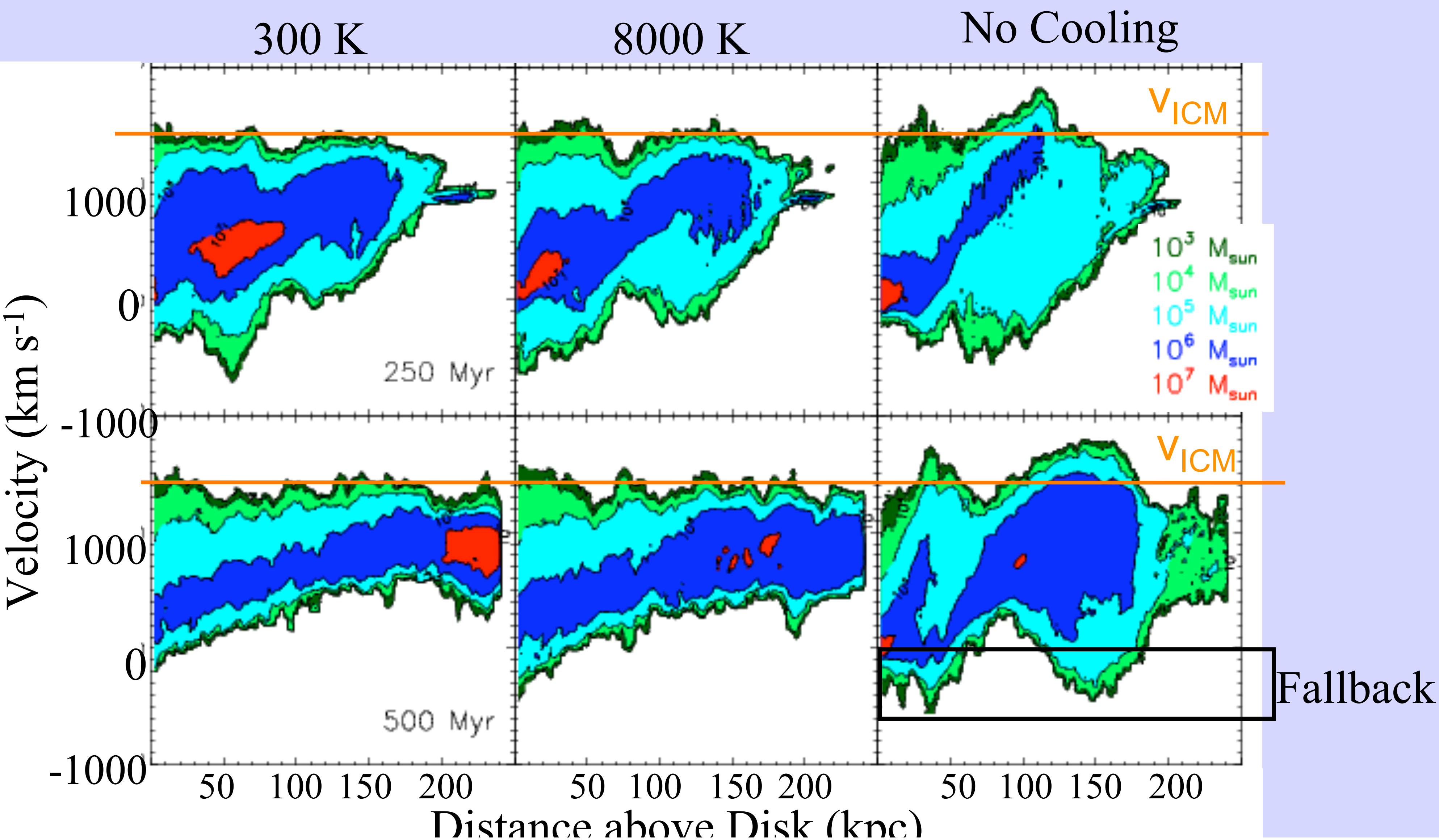
T_{min} = 8000 K

No Cooling



Cold dense clouds are hard to accelerate

The wind velocity is 1413 km s^{-1}, but most of the tail gas remains less than 1000 km s^{-1}, especially in the cooled cases.

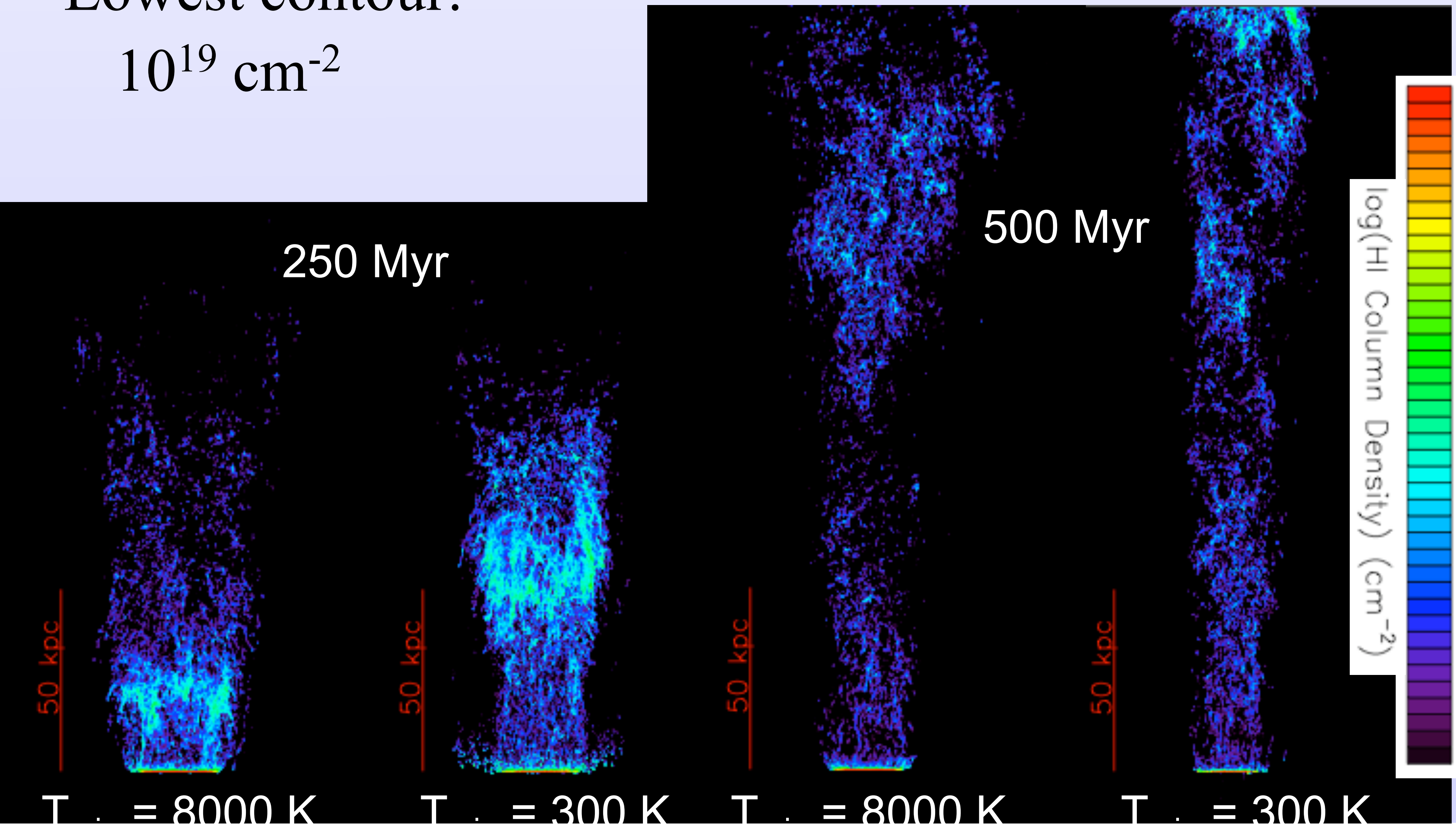


HI Column Density

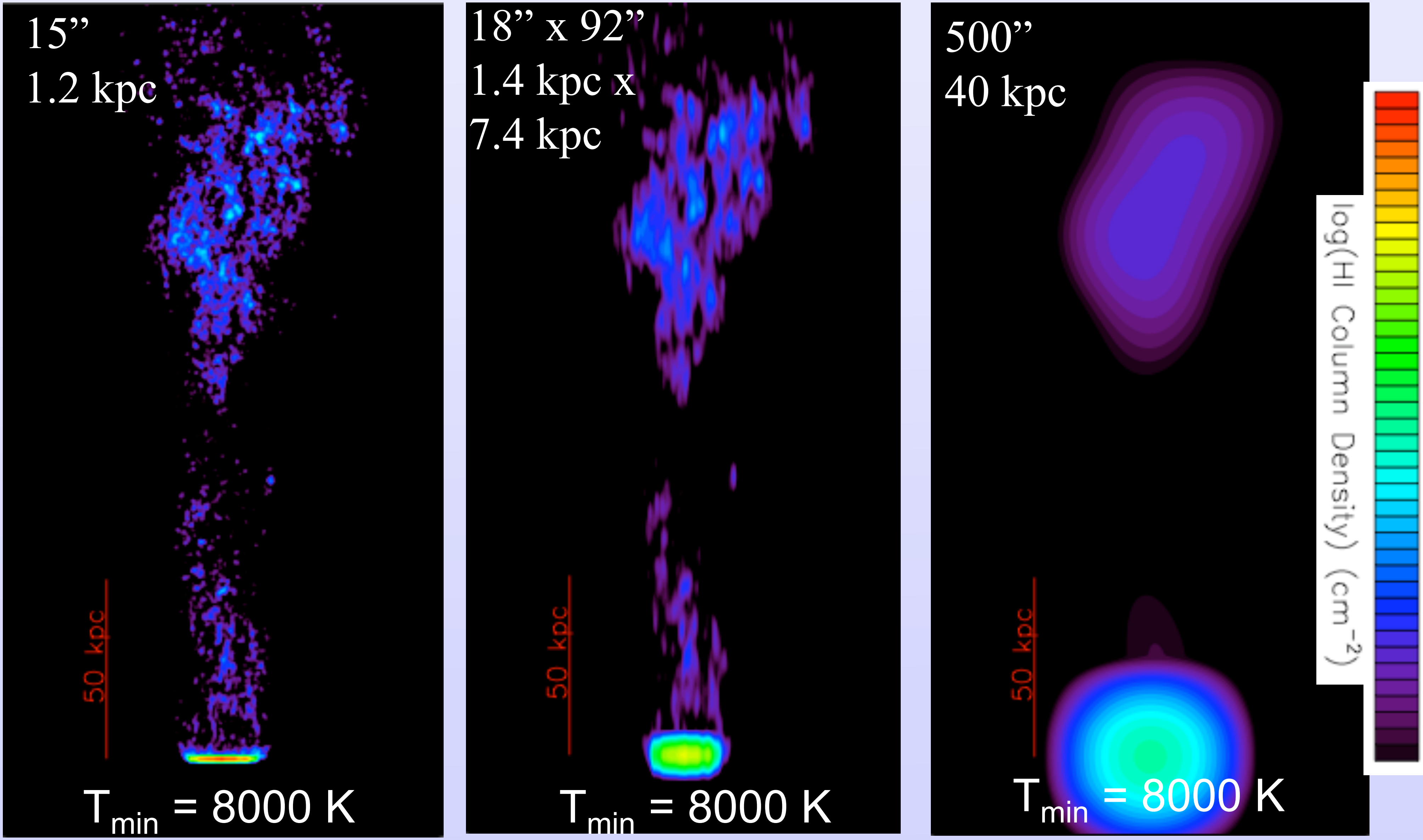
40 pc resolution

Lowest contour:

10^{19} cm^{-2}



HI at the resolution of current observations



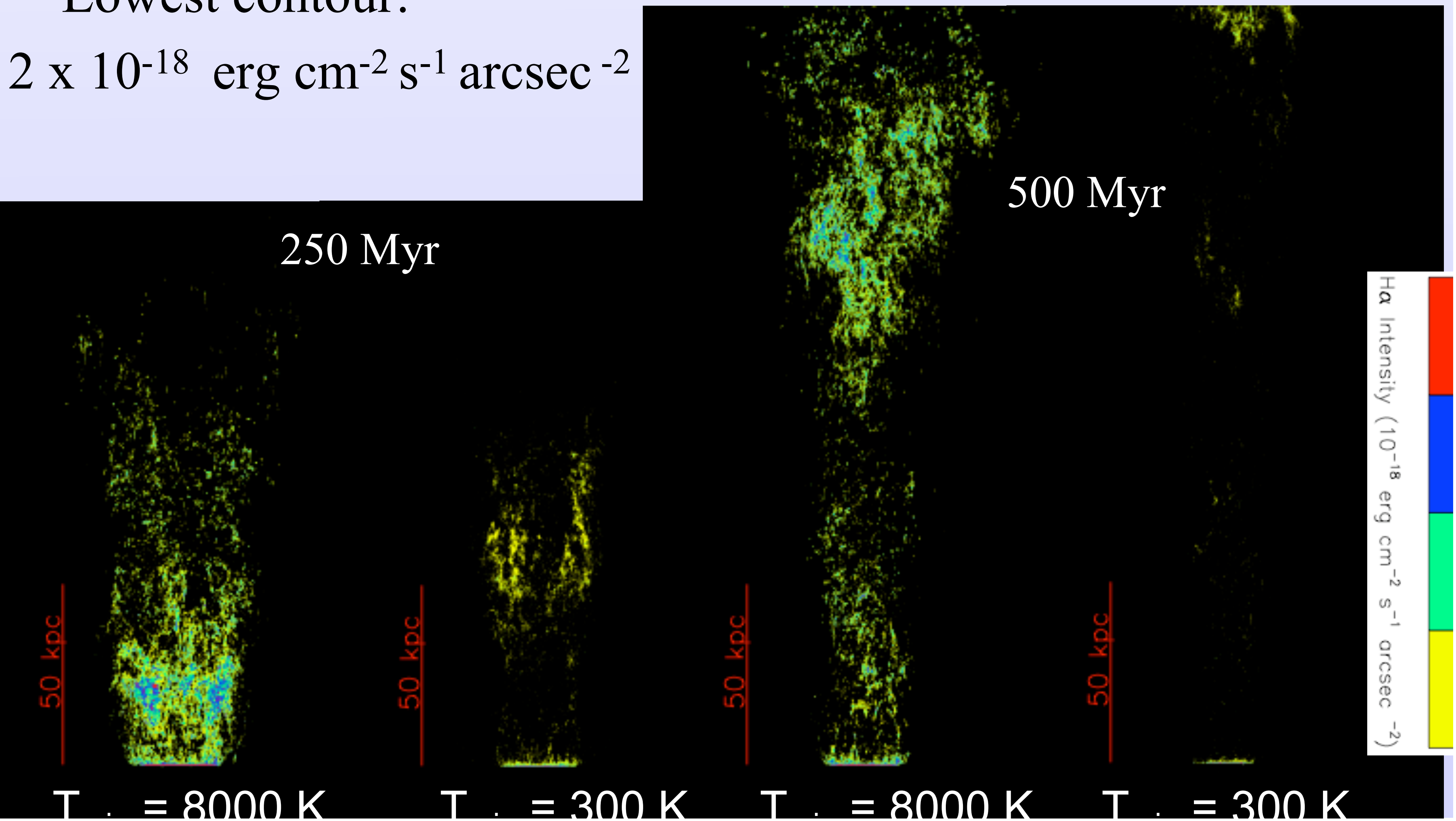
Chung et al (2007) | Oosterloo & van Gorkom (2005) | Vollmer & Huchtmeier (2007)

Hα intensity

40 pc resolution

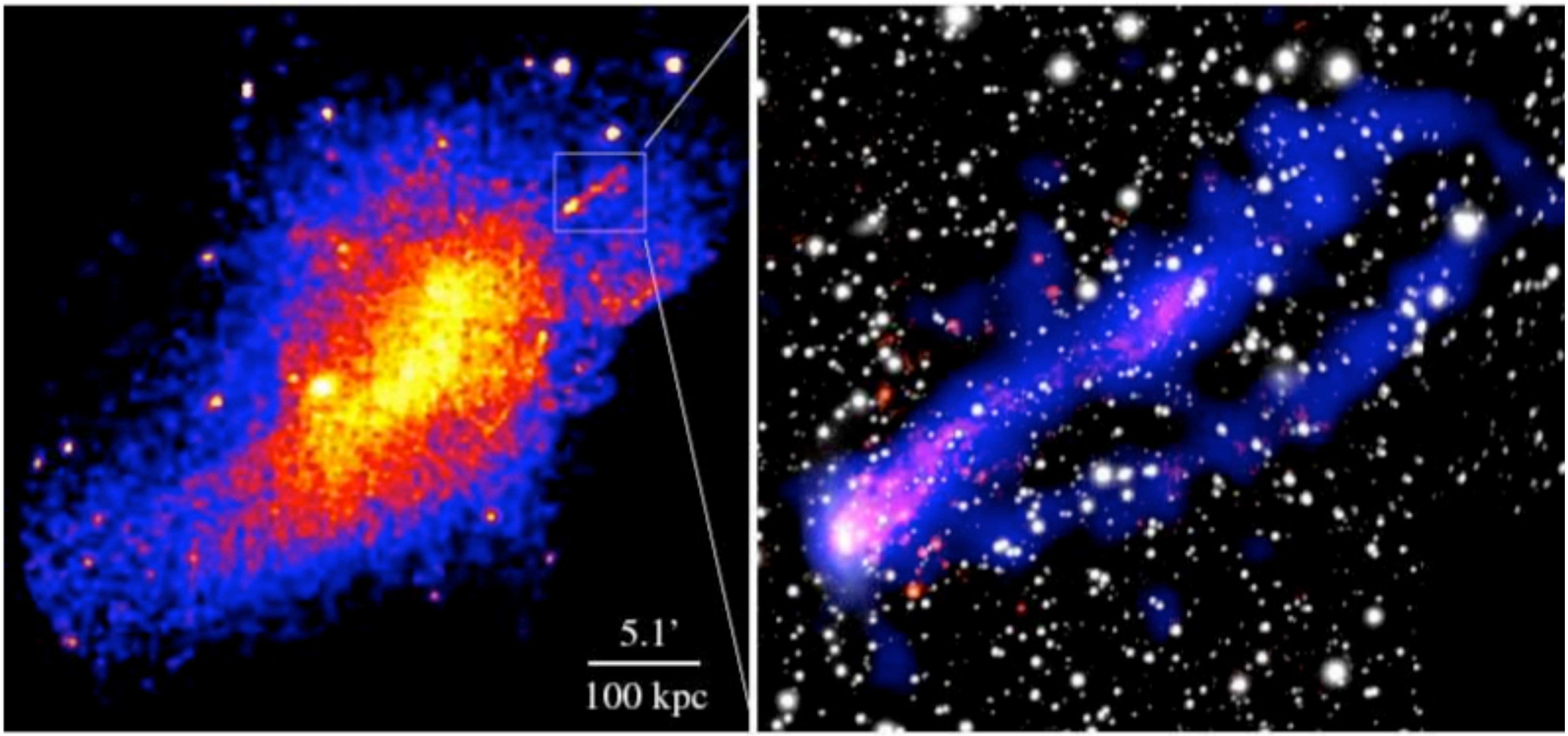
Lowest contour:

2×10^{-18} erg cm^{-2} s^{-1} $arcsec^{-2}$



ESO 137-001 in A3627 (Norma cluster)

Sun et al. 2009

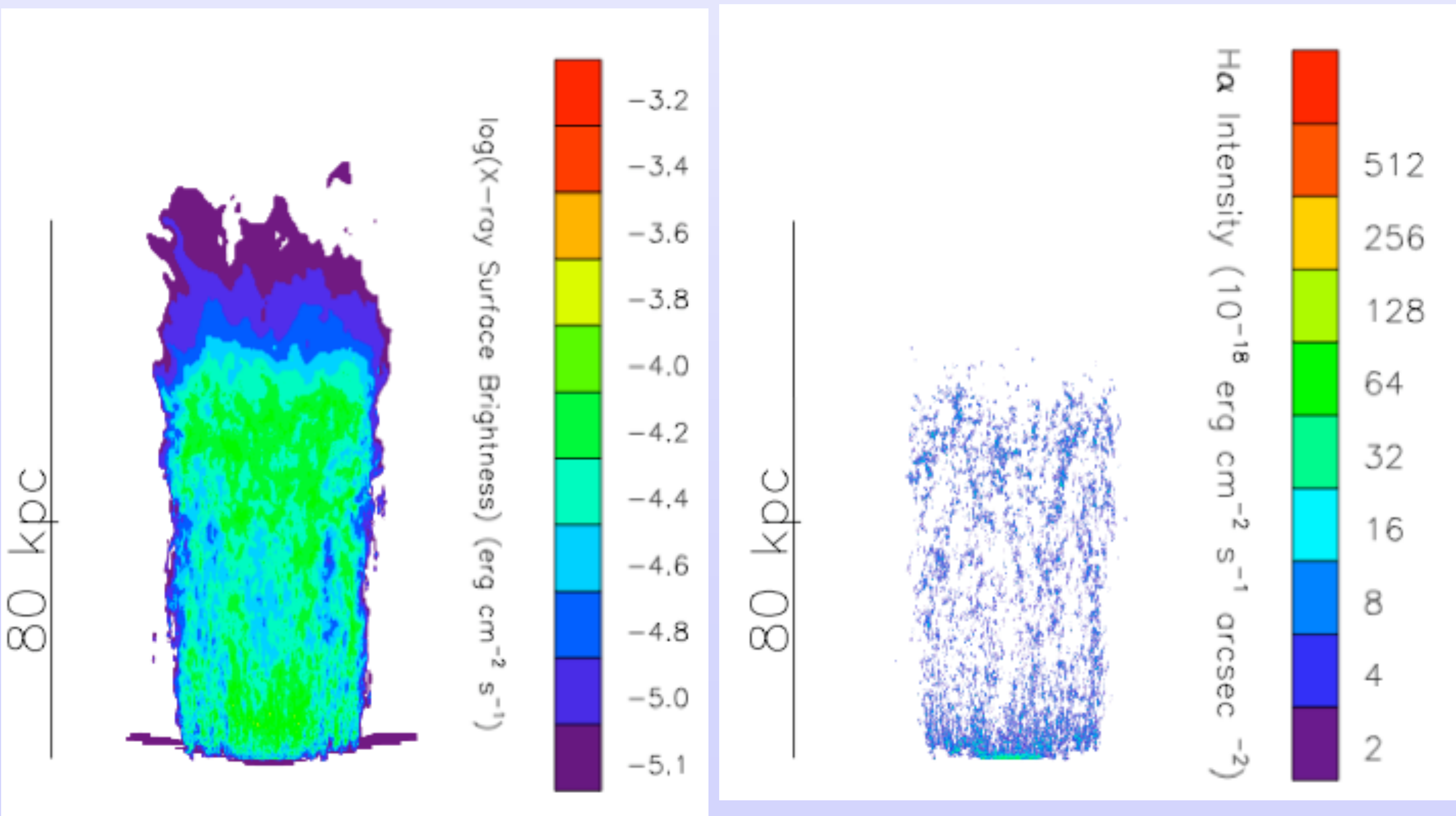


XMM-Newton 0.5-2.0 keV image

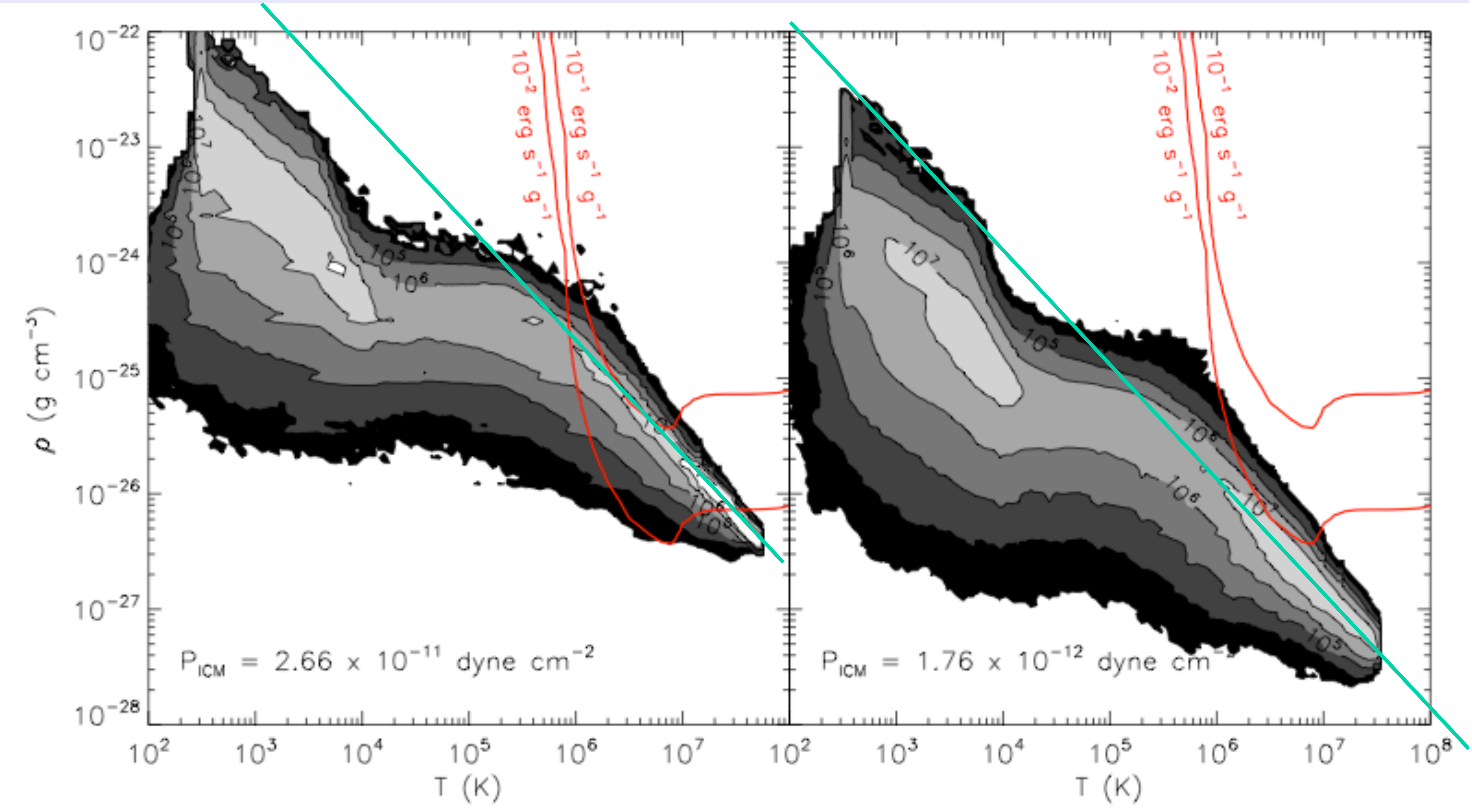
Blue: Chandra 0.6-2.0 keV image
Red: Hα image

The X-ray Surface Brightness and Hα Intensity projections from a comparison simulation

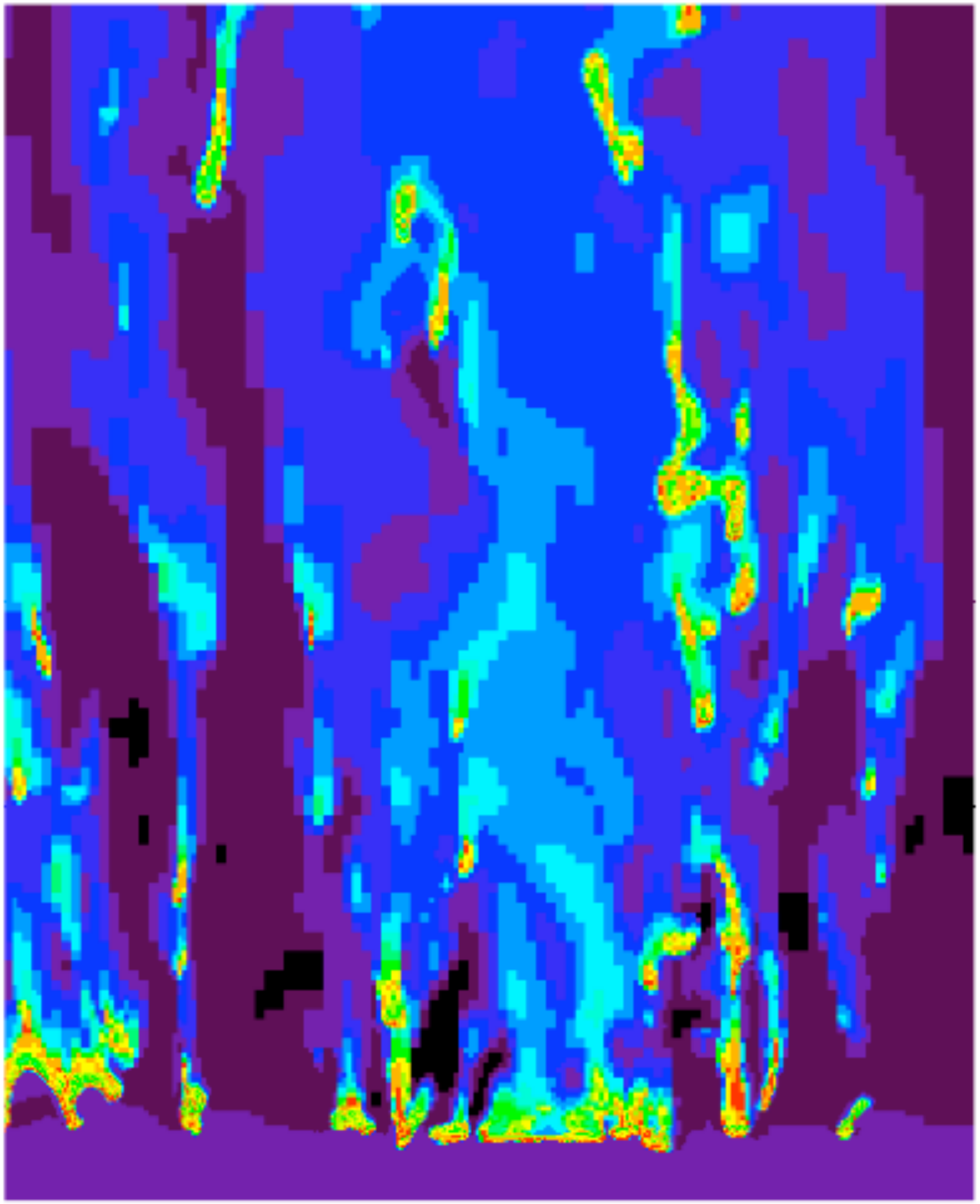
T3vh



Why are some tails X-ray bright?

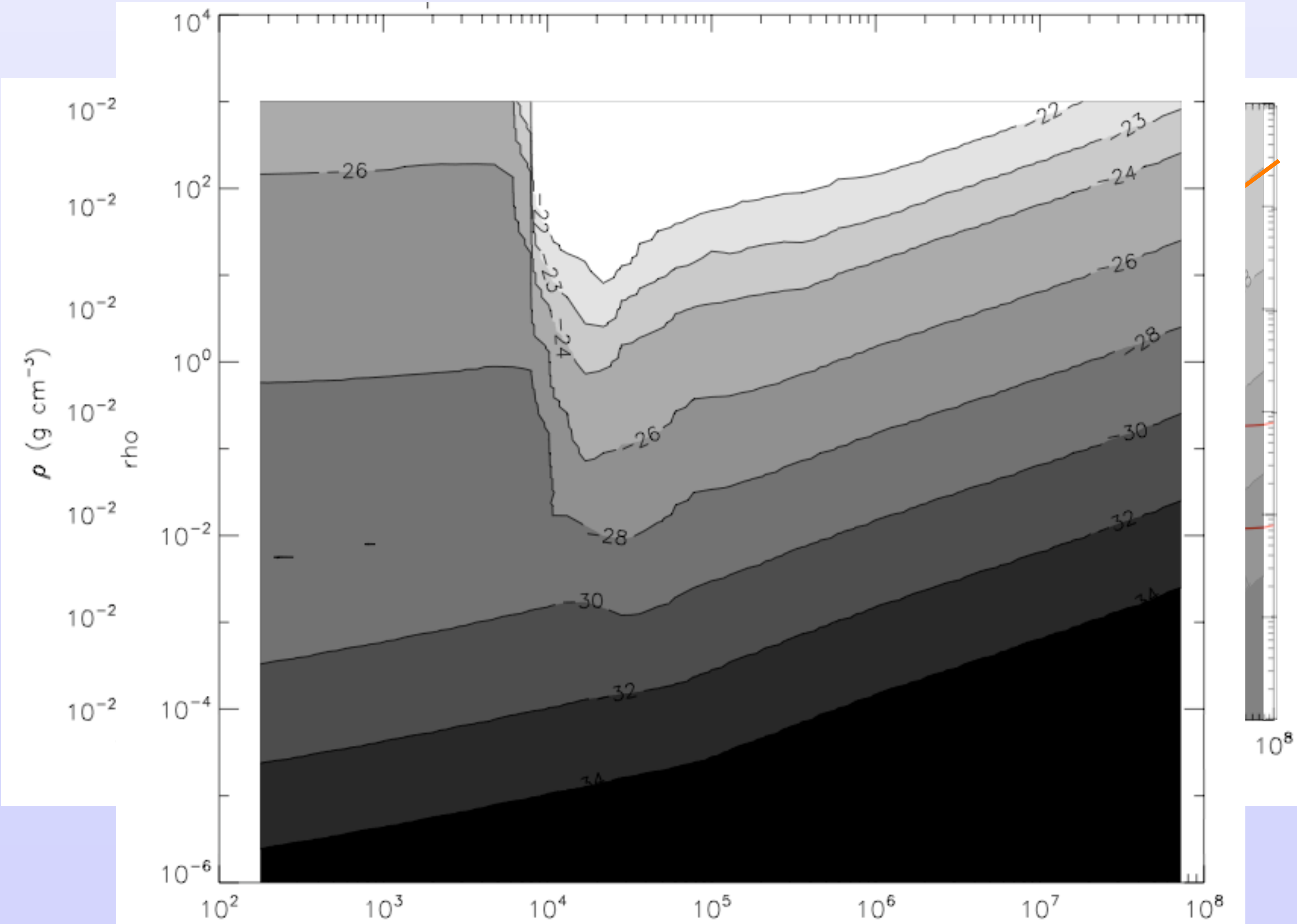


Does this tail have any HI?



Hα emission is produced at the edges of dense cold clouds.

What about Hα?



In total

- Ram pressure stripping can happen throughout a cluster
- Ram pressure can strip a galaxy of (nearly) all its gas
- Ram pressure results in small gas disks, as observed in Virgo
- Ram pressure simulations including radiative cooling agree well with tails observed in HI, Hα, and X-ray emission.
- X-ray bright tails are produced by galaxies stripped in high pressure ICMs
- HI and Hα emission are linked
- Fallback of stripped gas onto galaxy disks may occur after peak ram pressure, or during constant ram pressure. There is no net fallback during constant ram pressure.