How galaxies acquire their gas

perspectives from modern cosmological simulations

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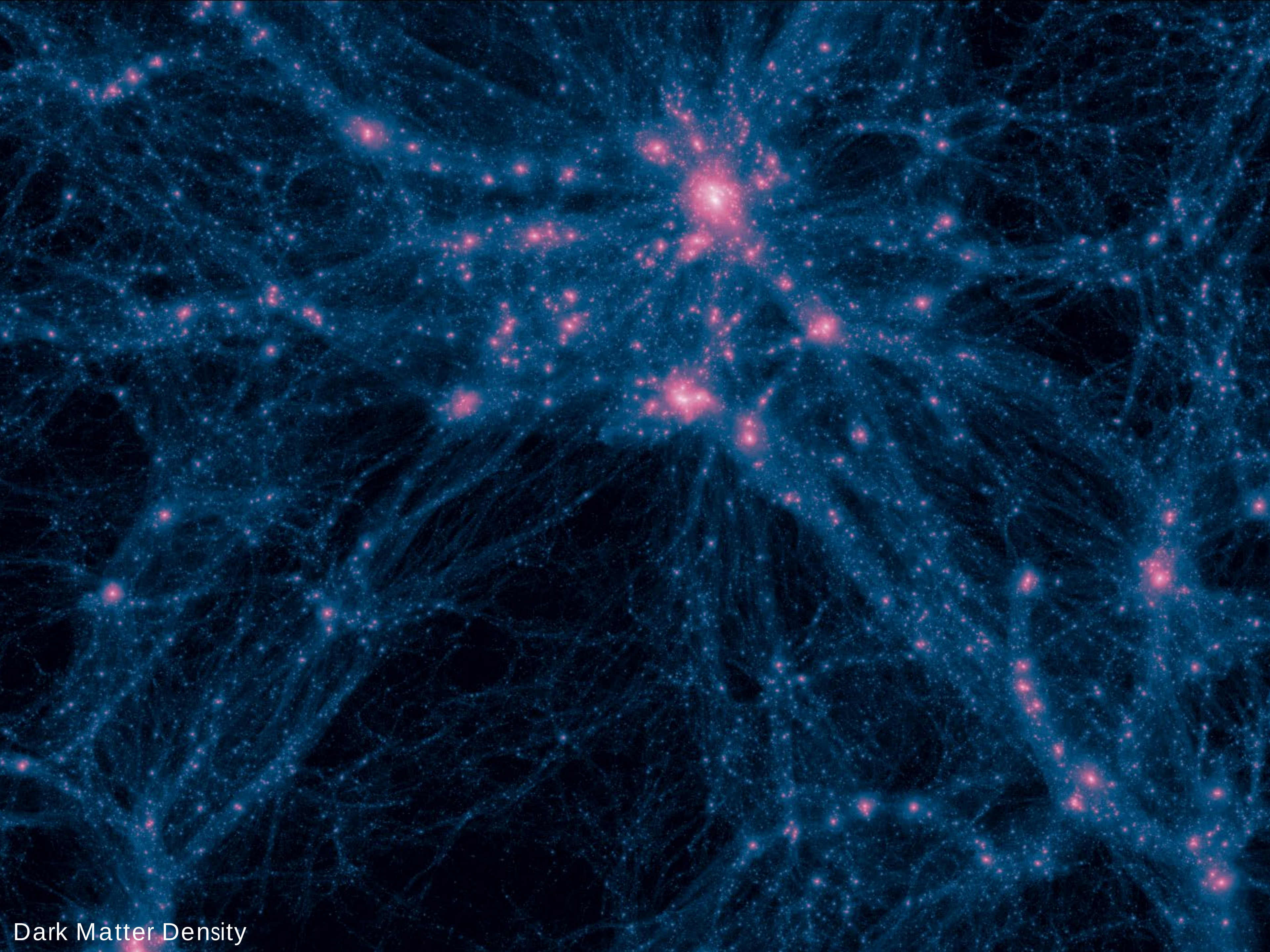
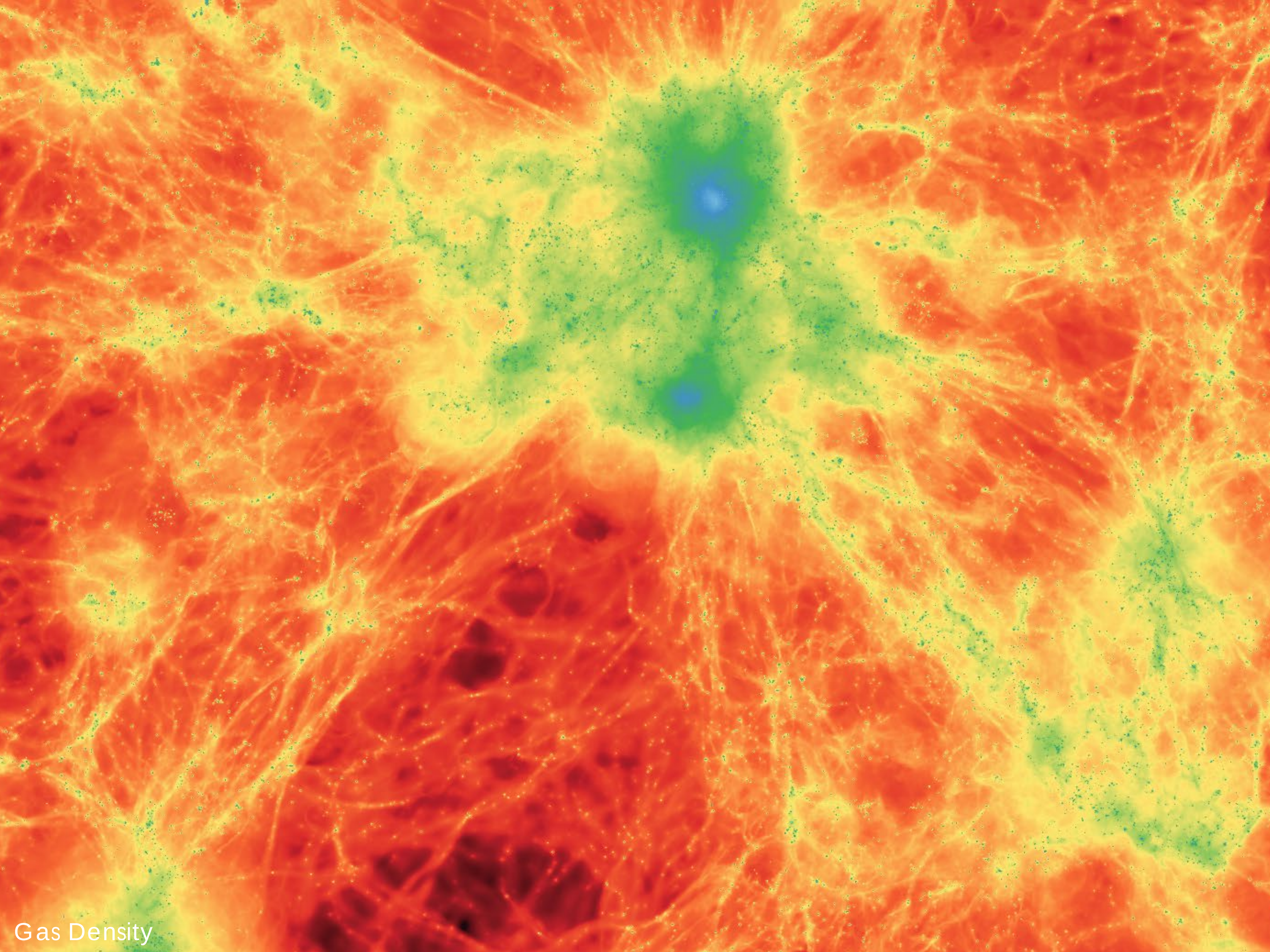
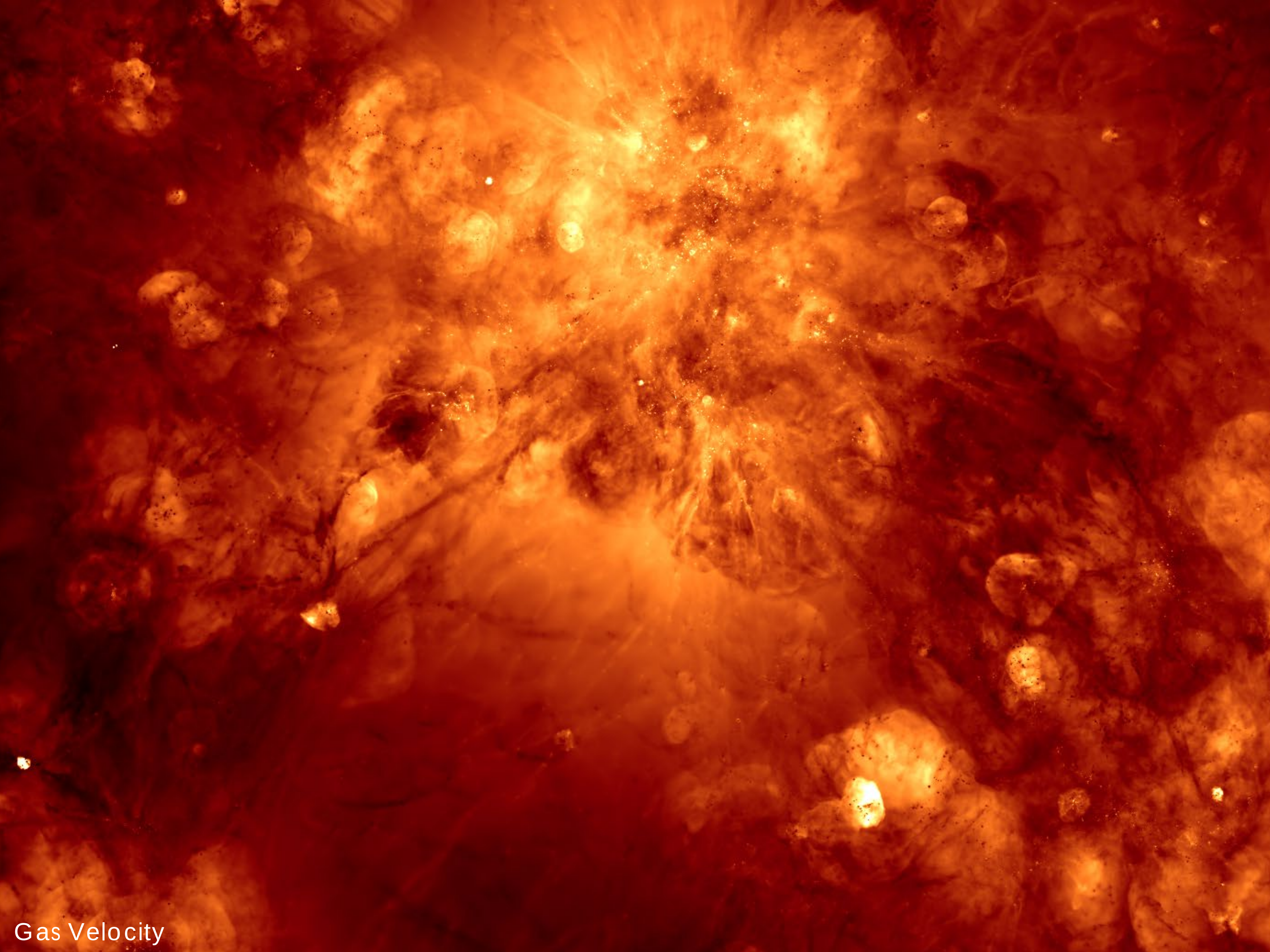
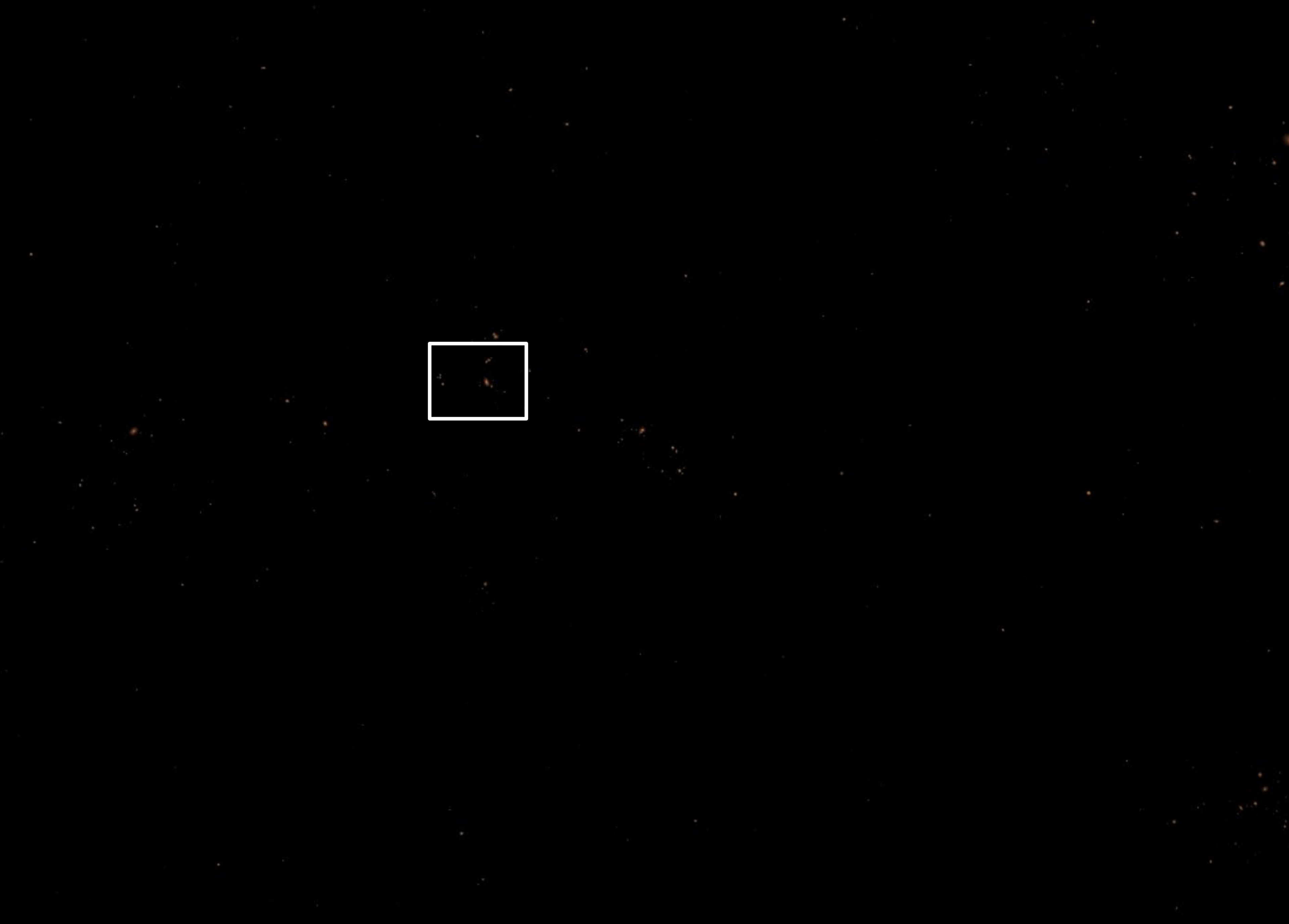

Dark Matter Density

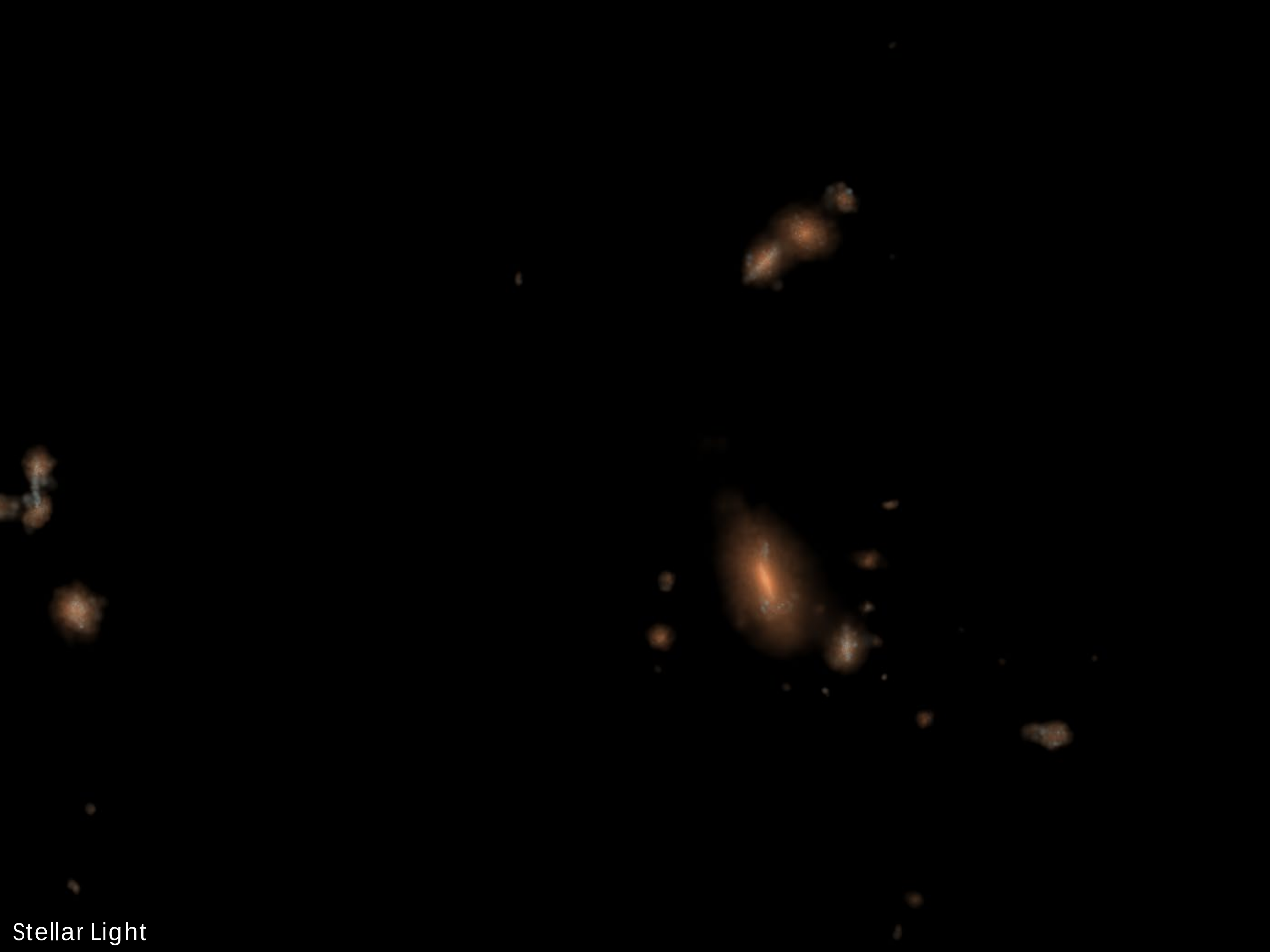

Gas Density

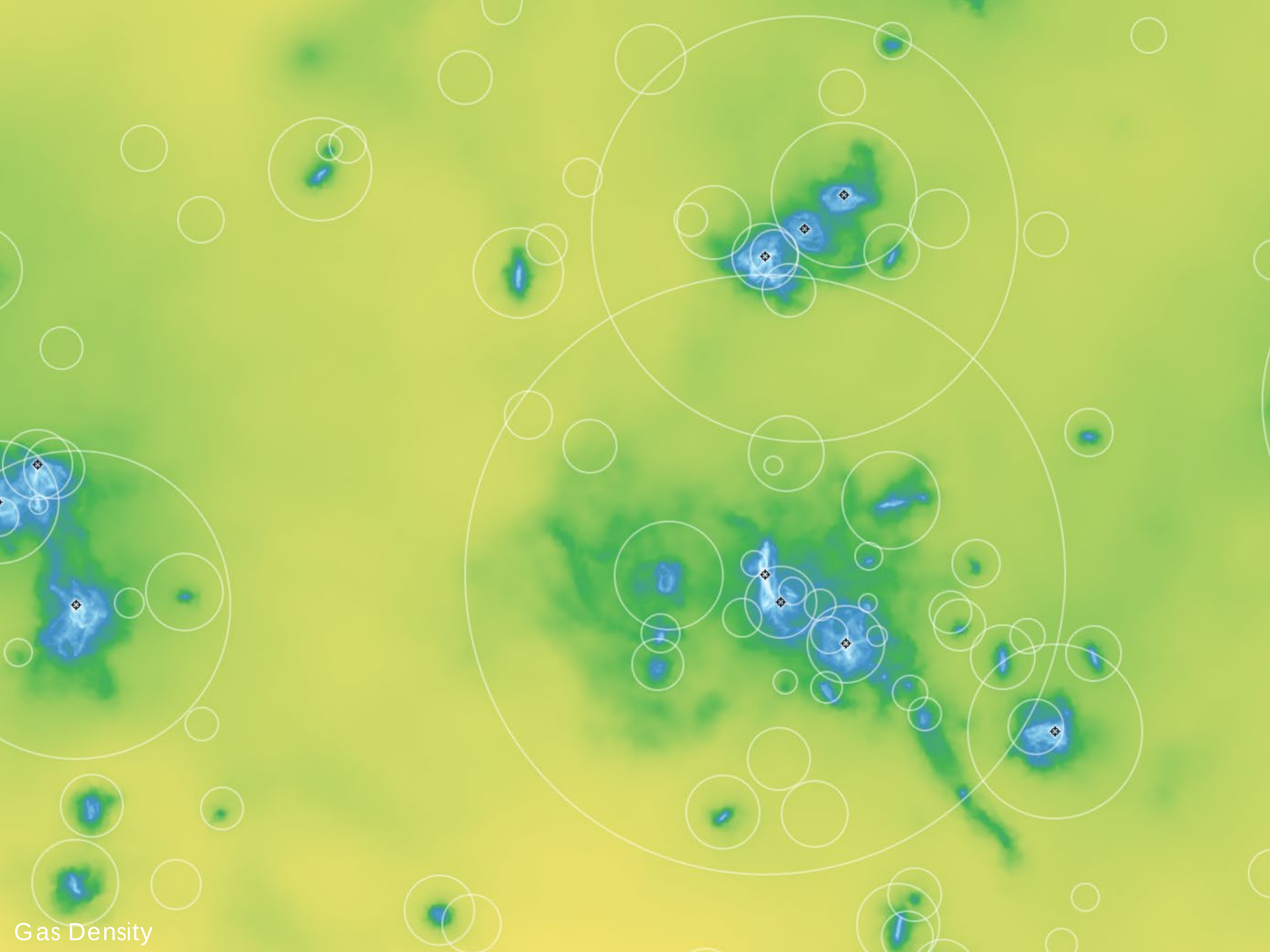

Gas Velocity

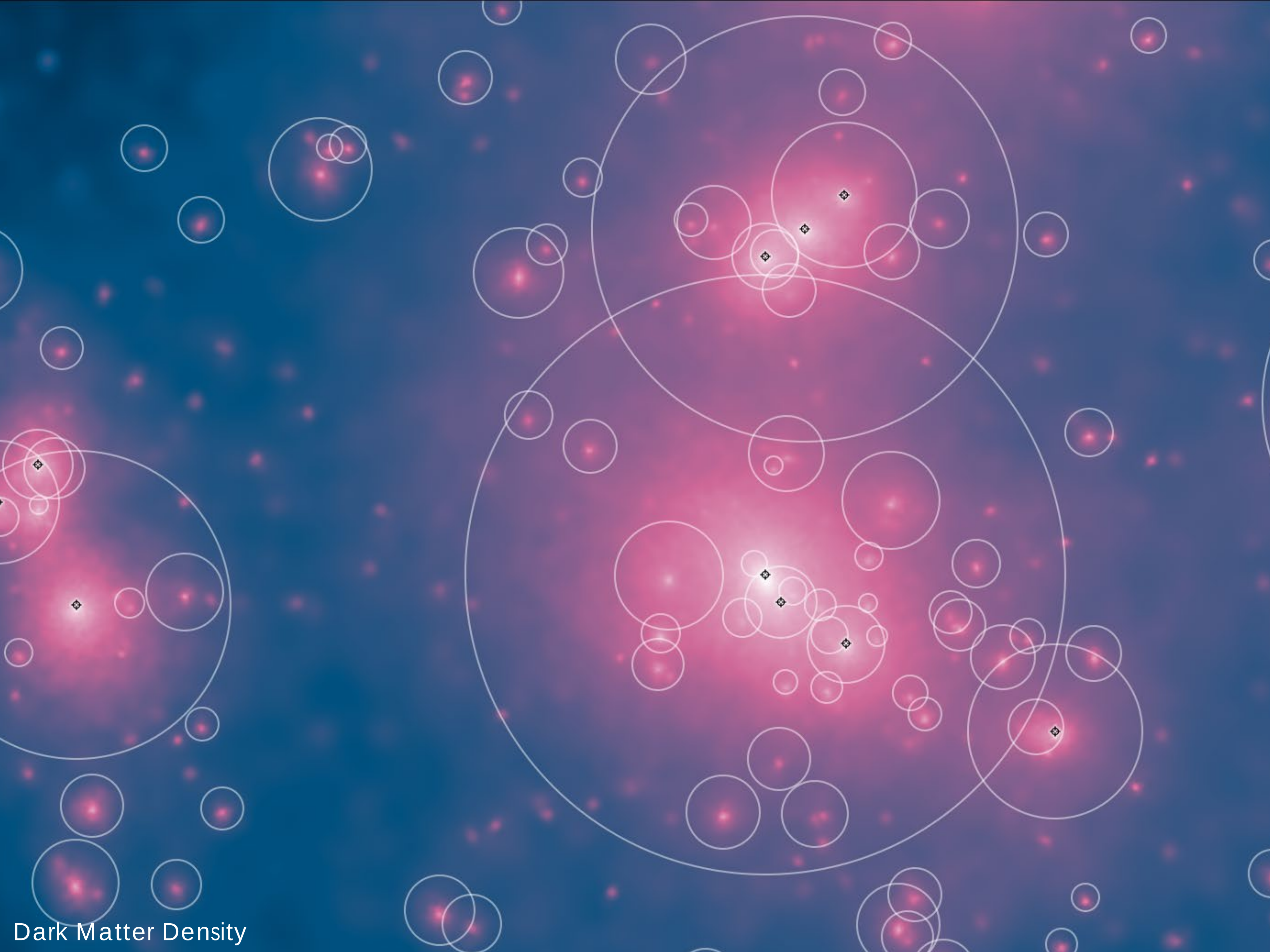
Stellar Light



Stellar Light


Stellar Light

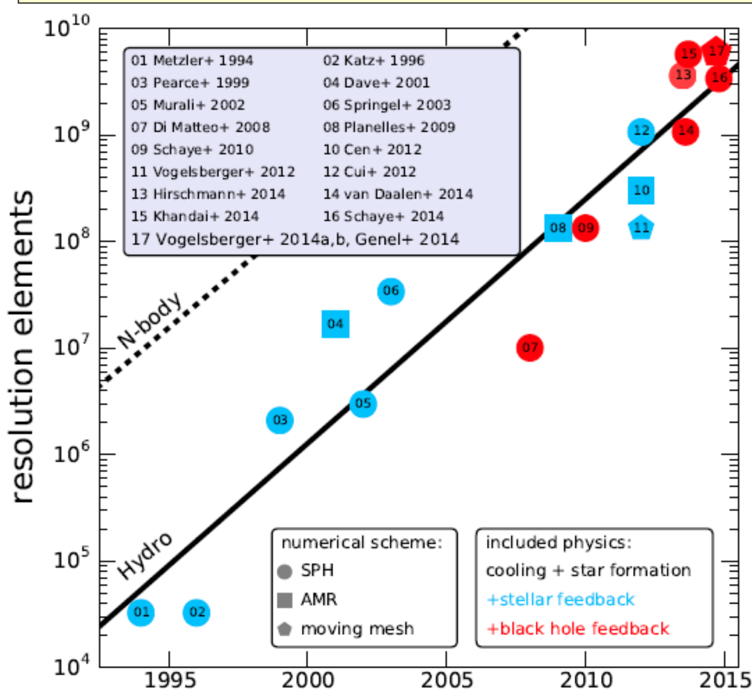

Gas Density


Dark Matter Density

SUPERMUC usage in 2013 according to field

	#Jobs %	CPU-time %
Astrophysics/Cosmology	8.9	28.2
Computational Fluid Dynamics	17.4	17.2
Biophysics/Biology/Bioinformatics	10.2	14.6
Physics - High Energy Physics	7.0	11.2
Chemistry	18.2	8.0
Physics - others	3.2	6.4
Engineering - others	2.3	6.3
Geophysics	8.3	3.0
Support/Benchmarking	9.0	2.1
Engineering - Electrical Engineering	0.9	1.4
Physics - Solid State	3.2	0.7
Informatics/Computer Sciences	10.3	0.6
Meteorology/Climatology/Oceanography	1.1	0.3
Engineering - Sturctural Mechanics	0.0	0.0
Medicine	0.1	0.0
Sum	100.0	100.0

(data courtesy V. Springel)



Genel+ (14)

Astrophysics is a dominant user of HPC!

Cost of a fixed amount of computation has dropped by 10^8 in the last 30 years

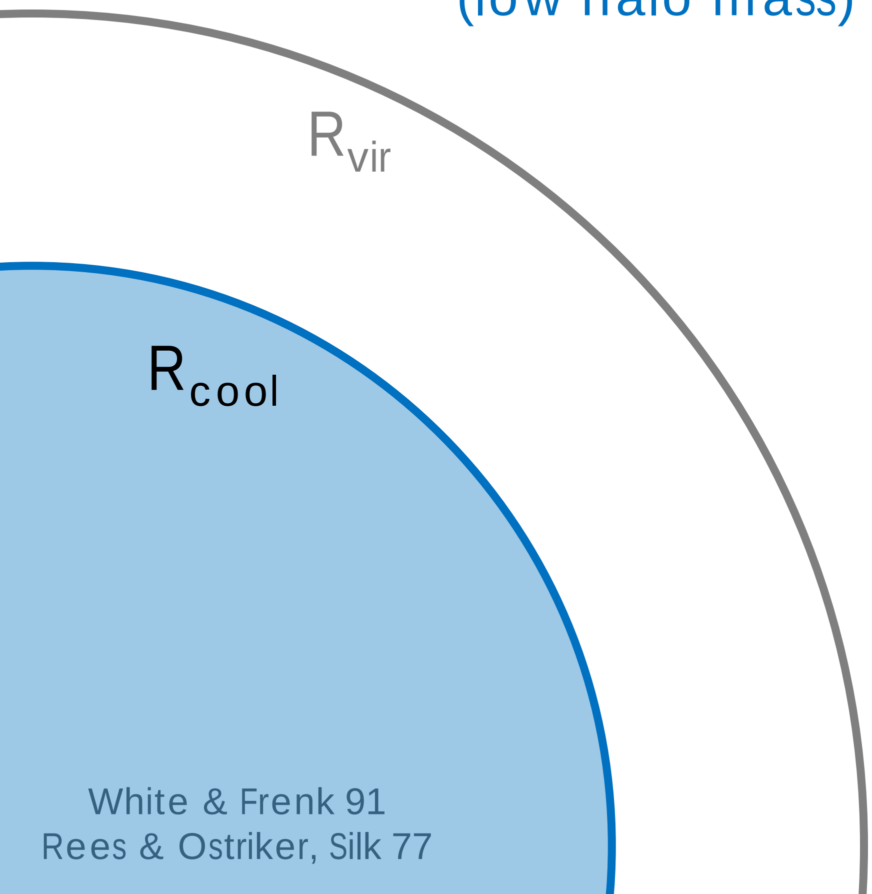
Simulation size increasing exponentially

Wikipedia

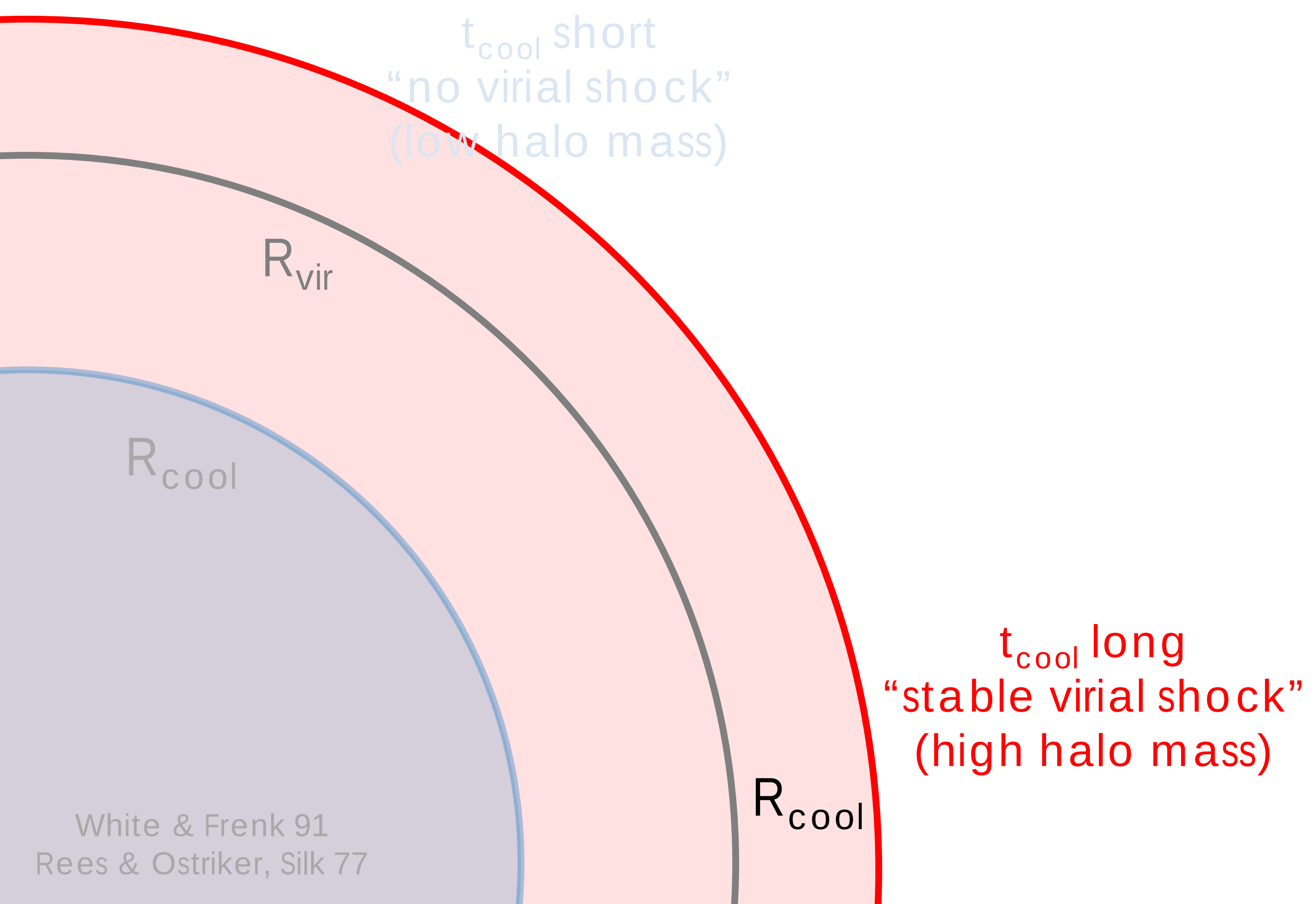
Date	Approximate cost per GFLOPS	Approximate cost per GFLOPS inflation adjusted to 2013 US dollars[45]	Platform providing the lowest cost per GFLOPS
1961	US $1,100,000,000,000 ($1.1 trillion)	US $8.3 trillion	About 17 million IBM 1620 units costing $64,000 each
1984	$18,750,000	$42,780,000	Cray X-MP/48
1997	$30,000	$42,000	Two 16-processor Beowulf clusters with Pentium Pro microprocessors[47]
April 2000	$1,000	$1,300	Bunyip Beowulf cluster
May 2000	$640	$836	KLAT2
August 2003	$82	$100	KASY0
August 2007	$48	$52	Microwulf
March 2011	$1.80	$1.80	HPU4Science
June 2013	$0.22	$0.22	Sony Playstation 4
November 2013	$0.16	$0.16	AMD Sempron 145 GeForce GTX 760 System
December 2013	$0.12	$0.12	Pentium G550 R9 290 System

Gas accretion: classic virial shocking or cold flows and streams?

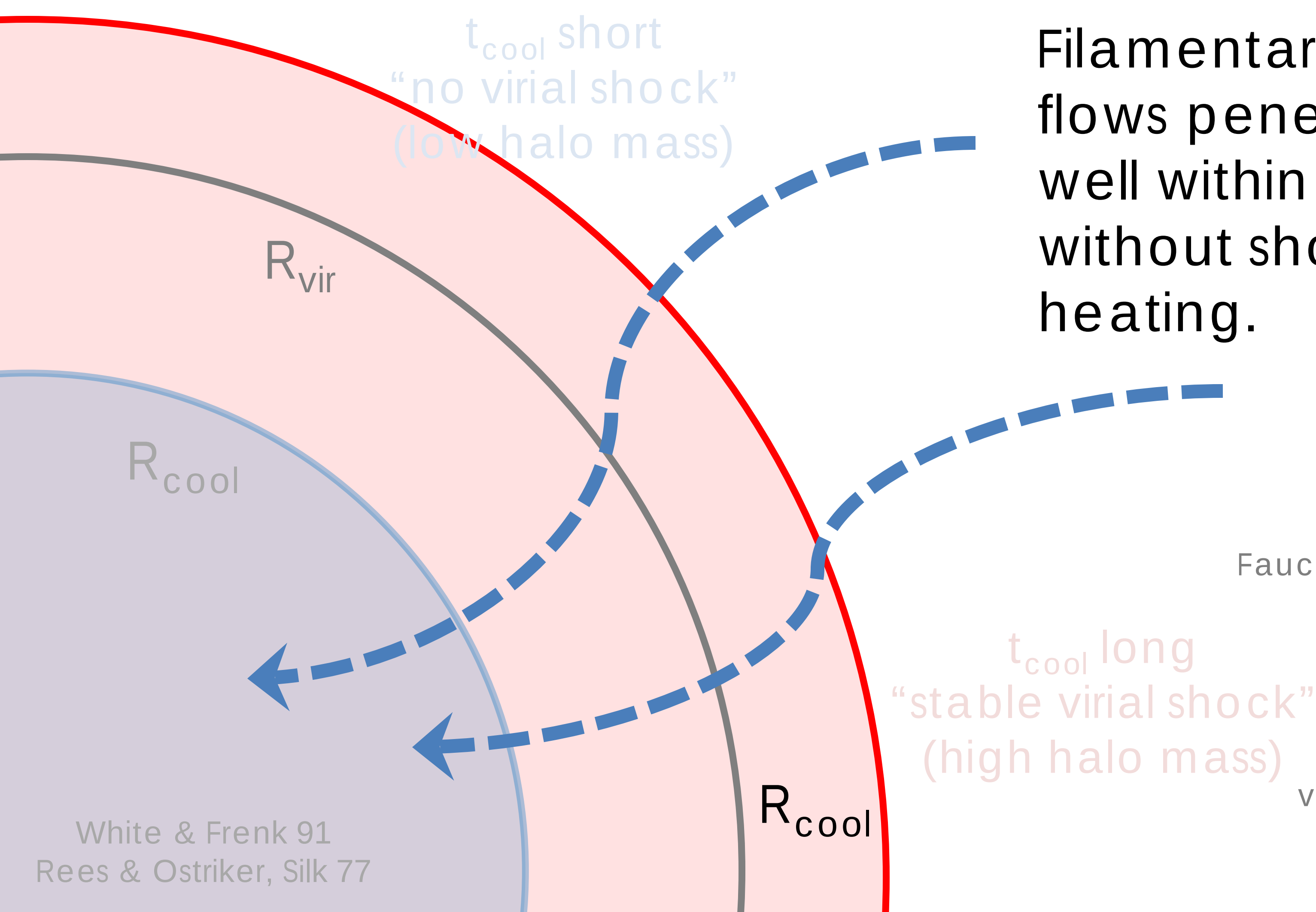
t_{cool} short
"no virial shock"
(low halo mass)



Gas accretion: classic virial shocking or cold flows and streams?



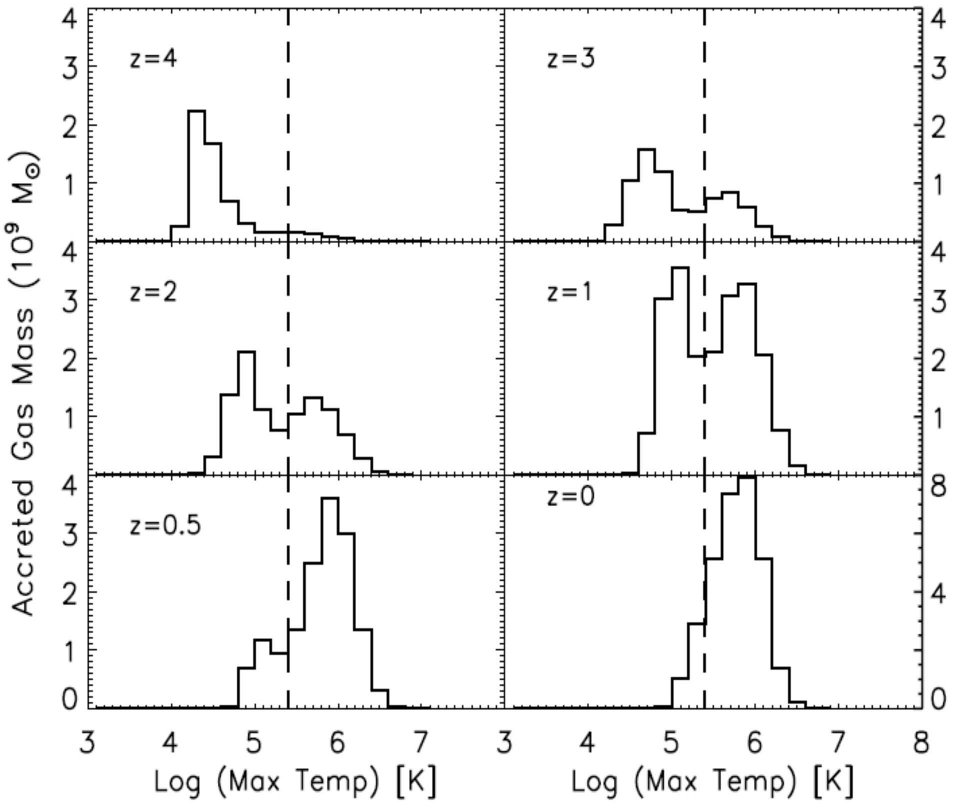
Gas accretion: classic virial shocking or cold flows and streams?



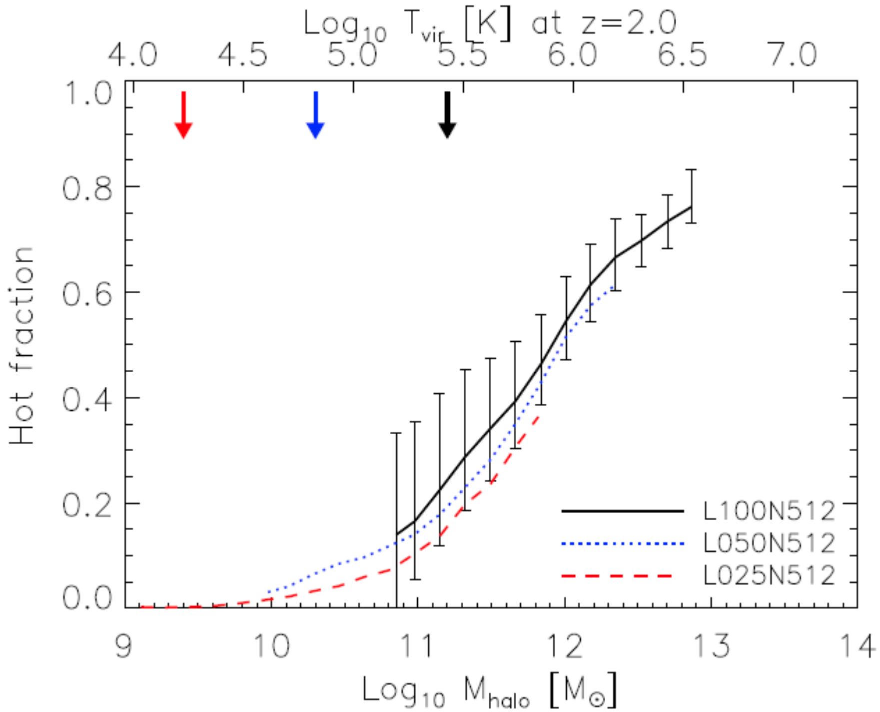
Filamentary gas flows penetrate well within hot halo without shock heating.

Keres 05,09
Birnboim 03
Brooks 09
Cen 14
Danovich 11,14
Dekel 06,09
Dubois 12
Faucher-Giguere 11,14
Joung 12
Murante 12
Ocvirk 08
Sales 12
Stewart 11
van de Voort 11,12

Simulations identified a separate ‘cold mode’ accretion channel, whereby gas avoids shock heating to ~the virial temperature.



Brooks+ (09)

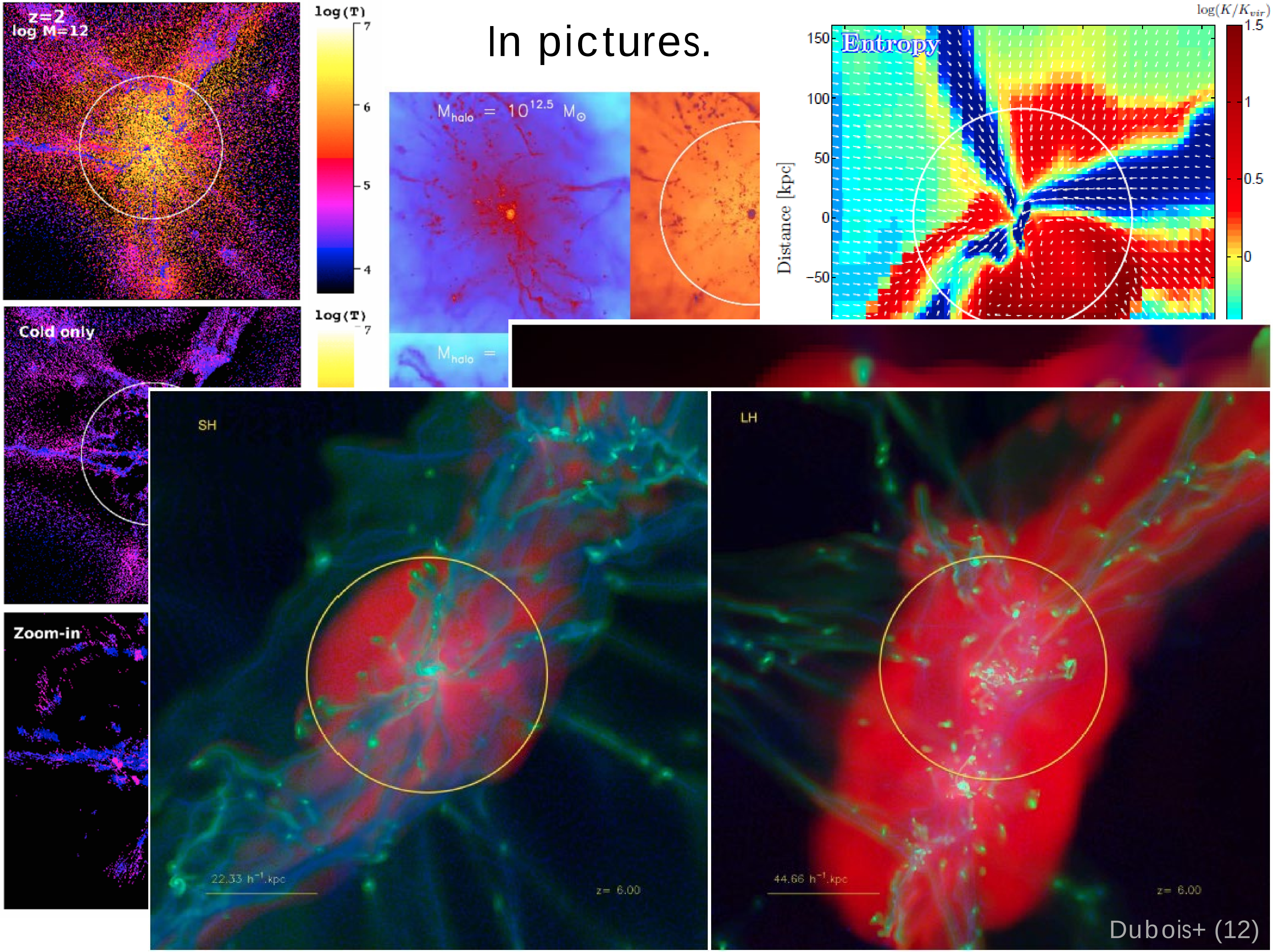


van de Voort+ (11)

Bimodal distribution of T_{max} for smooth accretion.

Transition point in halo mass from cold to hot mode dominated.

In pictures.


z=2
log M=12
log(T)
Cold only
Zoom-in
M_{halo} = $10^{12.5}$ $M_\odot$
M_{halo} =
Entropy
Distance [kpc]
log(K/K_{vir})
SH
LH
22.33 h^{-1}.kpc
44.66 h^{-1}.kpc
z= 6.00
Dubois+ (12)

I. Monte Carlo tracer particles

(or, *how do we follow the flow?*)

II. Comparing to SPH

(or, *have we gotten it correct in the past?*)

III. Impact of feedback

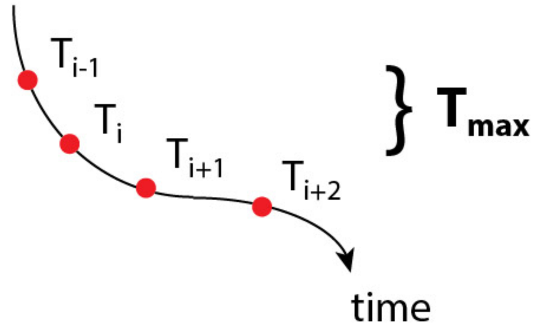
(or, *does more realistic physics change things?*)

IV. Zooms

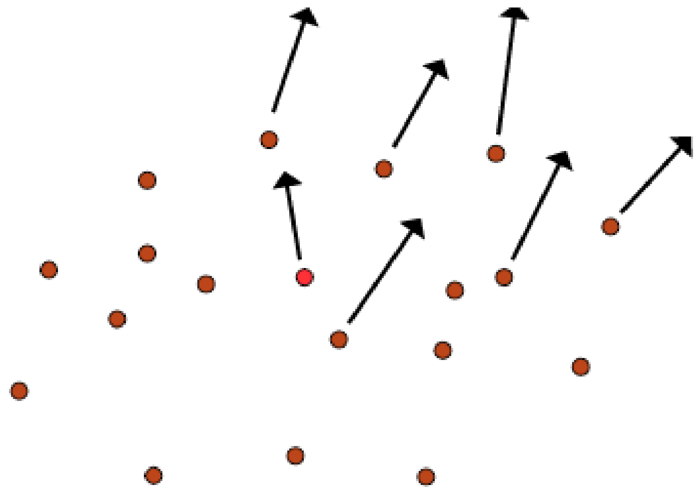
(or, *are we resolving the circumgalactic regime?*)

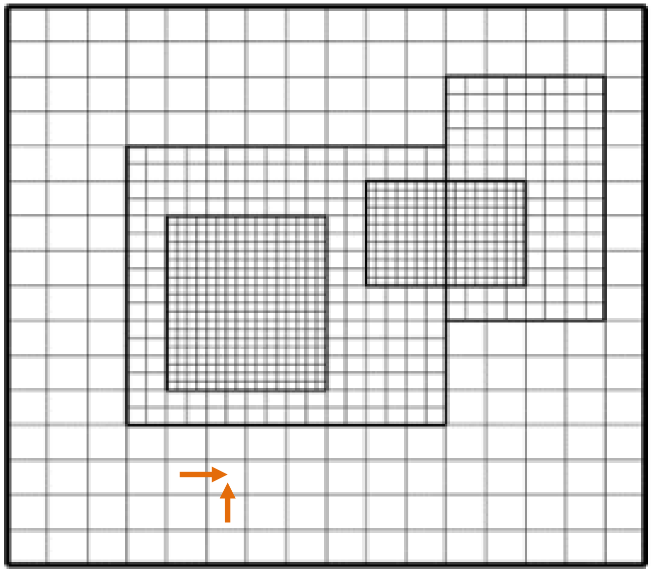
Genel+ (2013)

To determine the thermodynamic history of accreting gas, we need to follow individual fluid elements through time.



Can easily follow the history of gas elements in SPH.



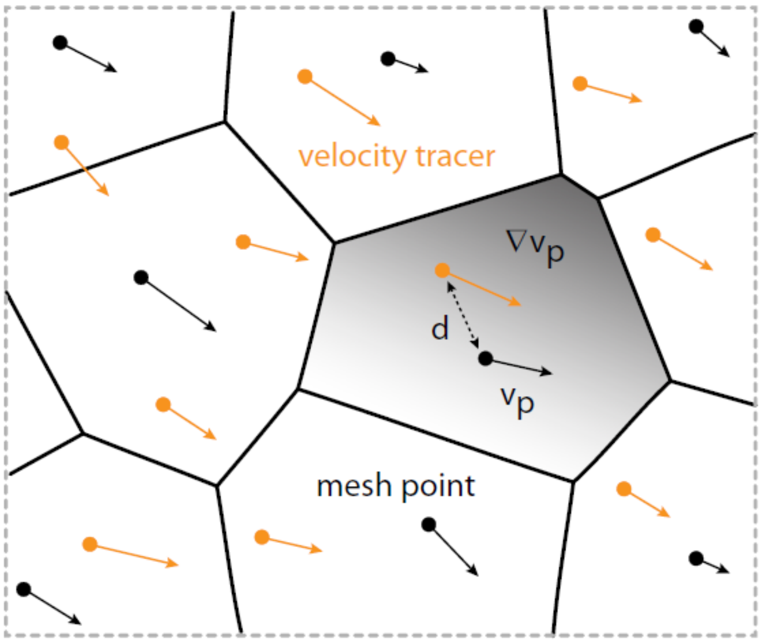


Tracer particles are required in any grid-based code to follow a Lagrangian history.

Typical solution: ‘velocity field’ tracers.

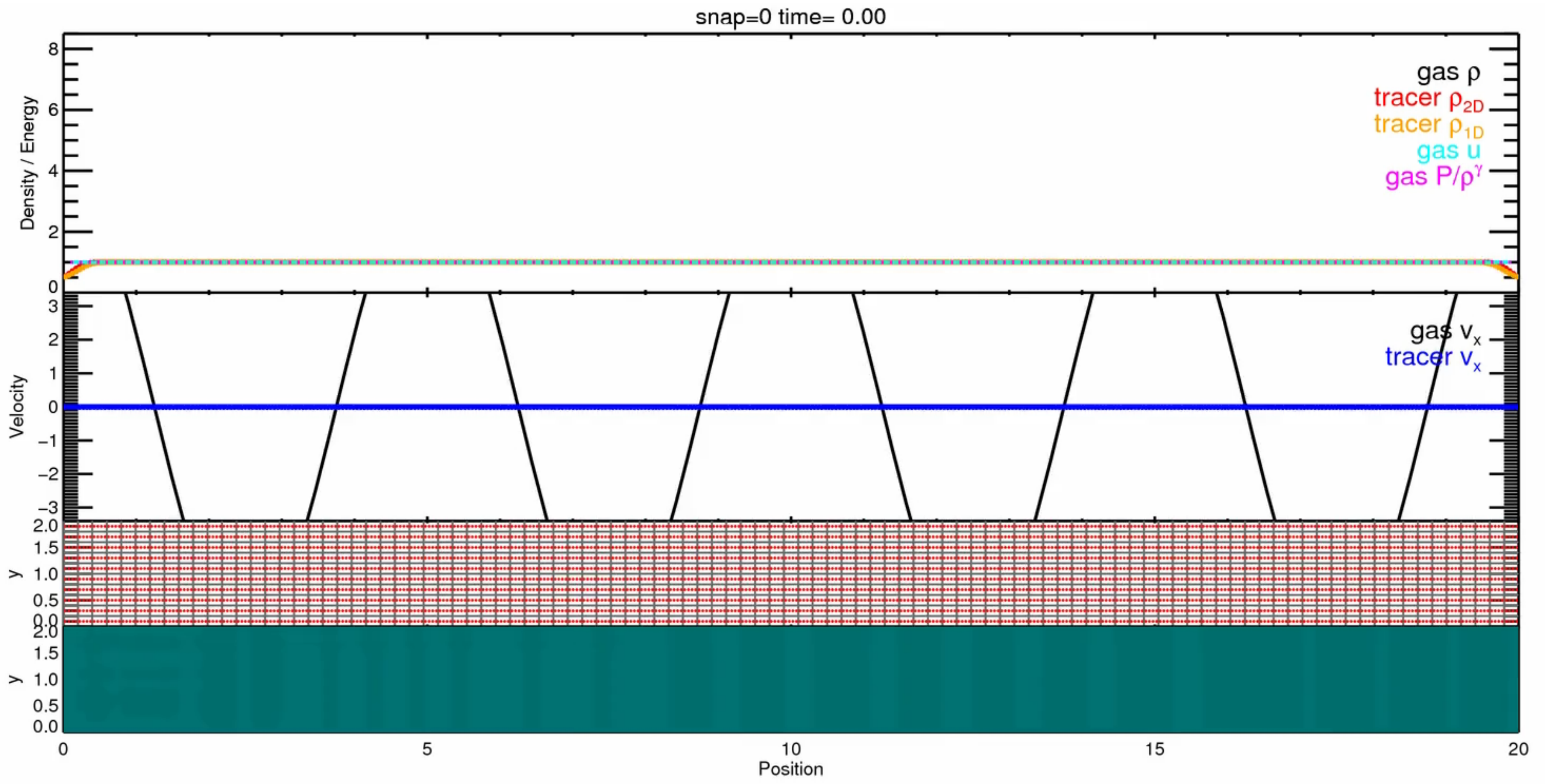
vs. ‘Monte Carlo’ Tracer Particles

Tracers are massless, passive particles advected using the same time integrator as hydro simulation.



Have phase space coordinates (x,y,z,v_x,v_y,v_z), velocities interpolated from the grid.

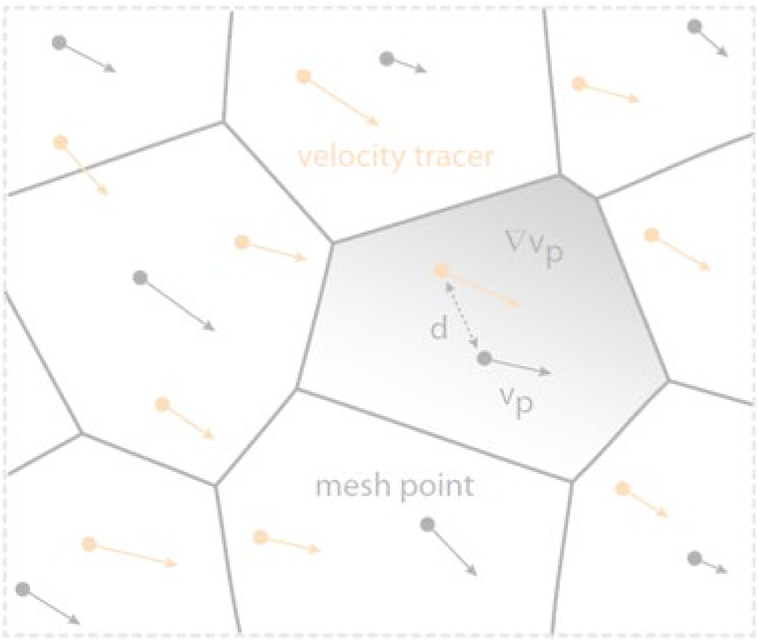
1D converging flow: velocity field tracers



Each hydro timestep is a sequence of three steps:
Reconstruction -> Evolution -> Averaging

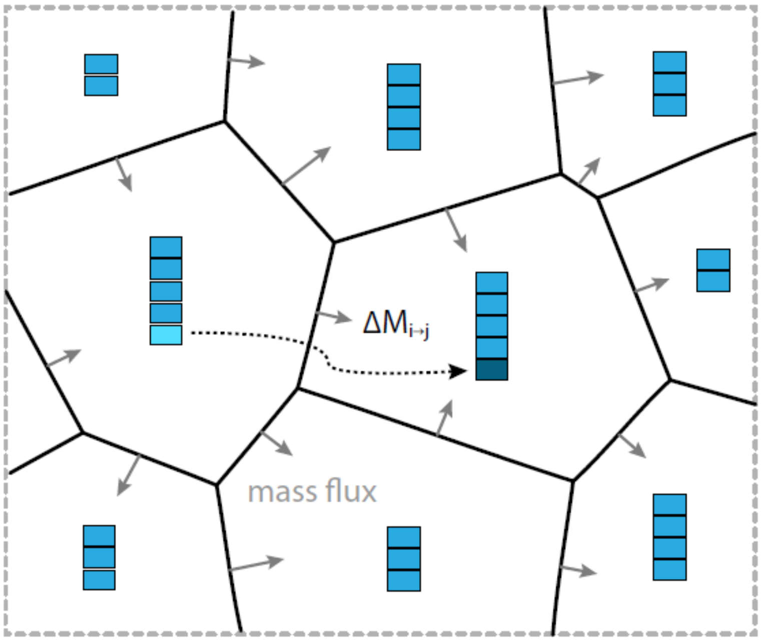
Typical solution: ‘velocity field’ tracers.
vs. ‘Monte Carlo’ Tracer Particles

Tracers are massless, passive particles advected using the same time integrator as hydro simulation.



Have phase space coordinates (x,y,z,v_x,v_y,v_z), velocities interpolated from the grid.

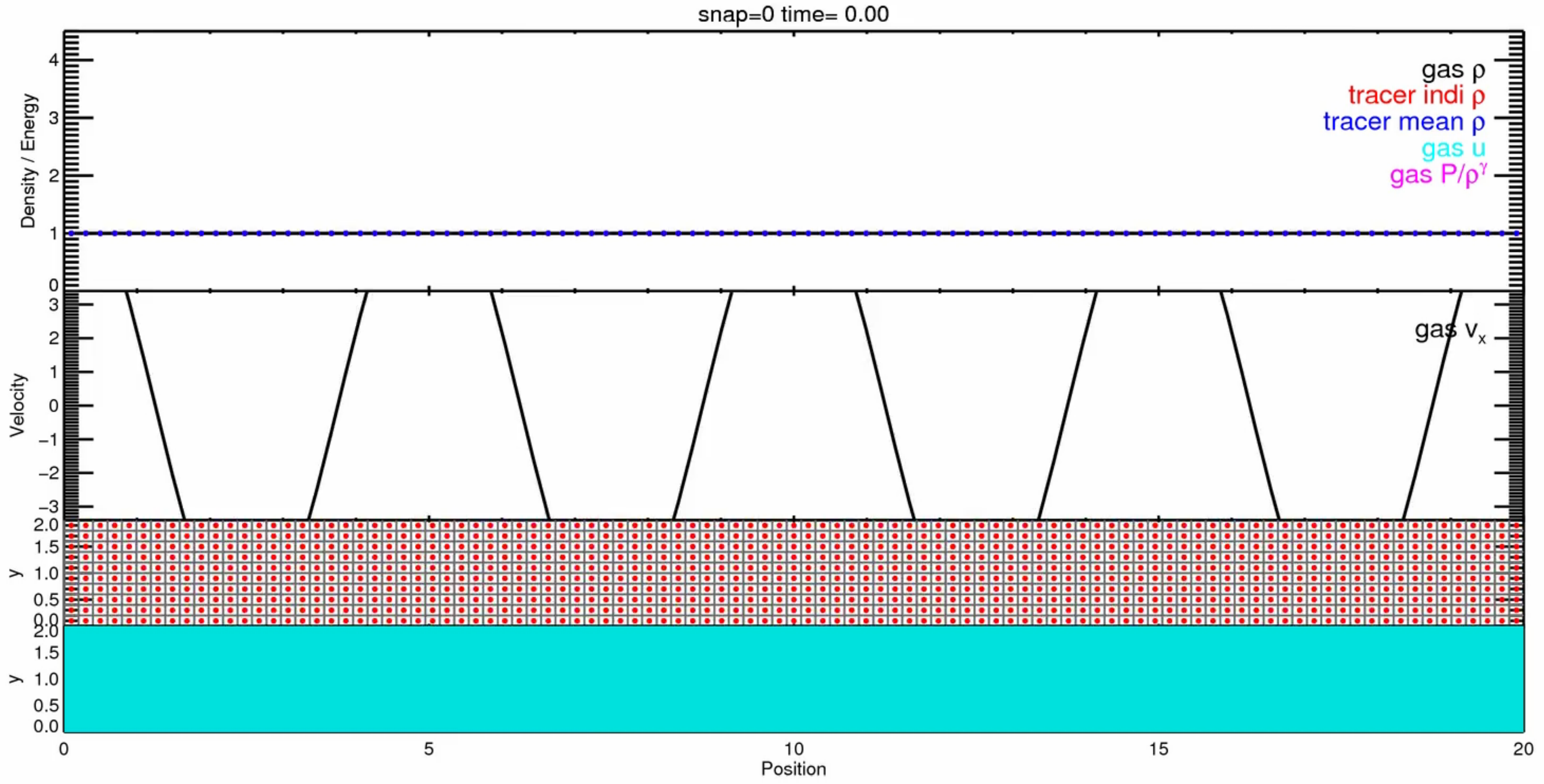
Tracers are ‘unique tags’ which exist only as children of gas cells.



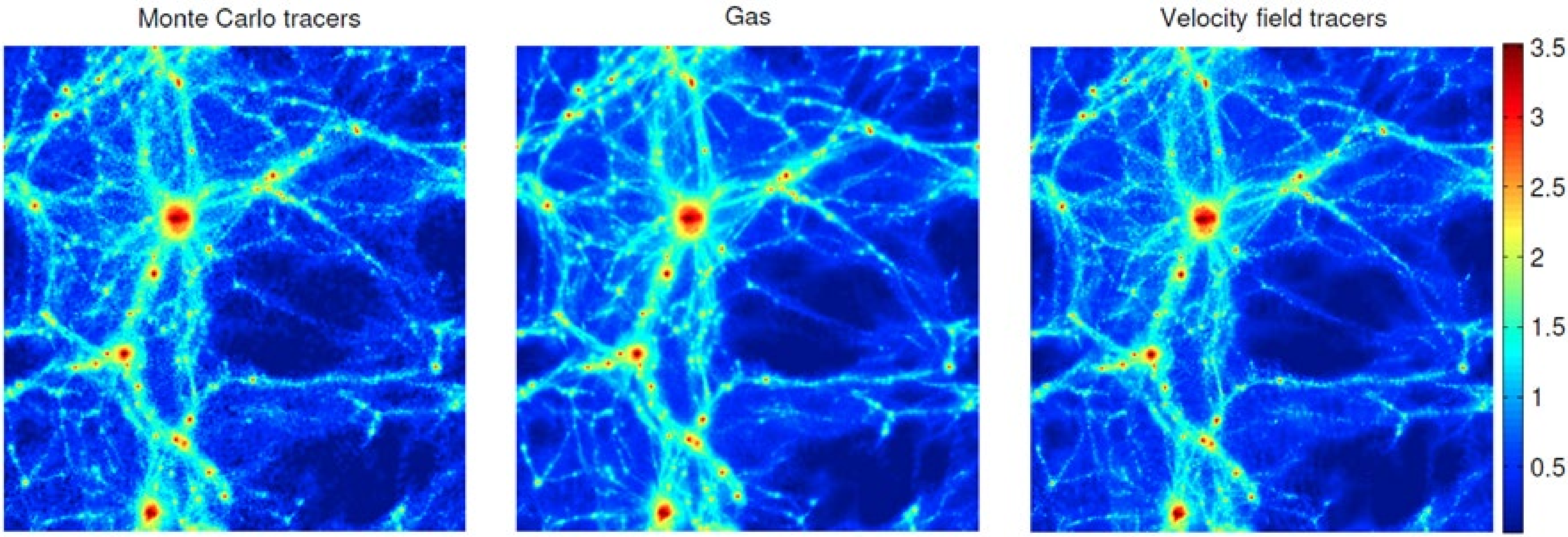
Exchanged probabilistically between cells based explicitly on mass-fluxes.

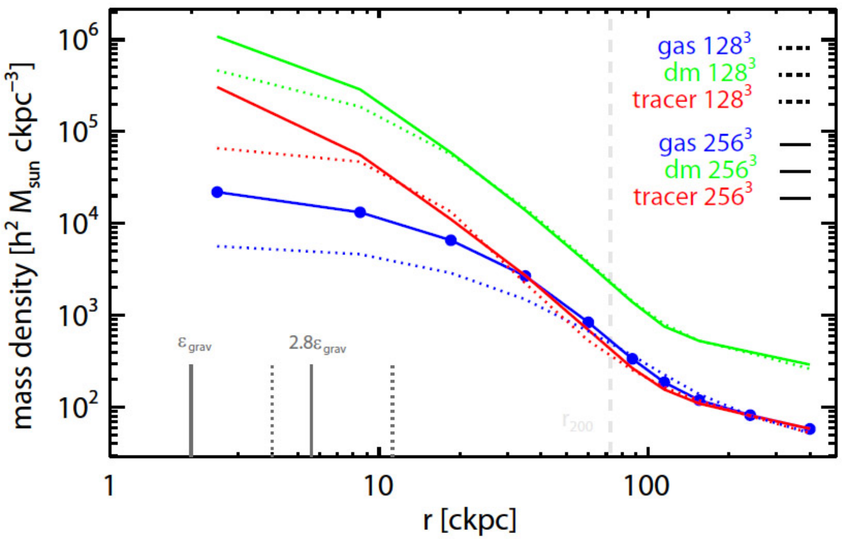
$$p_{i,j}^{\mathrm{flux}} = \frac{\Delta M_{i,j}}{\widetilde{M_i}}$$

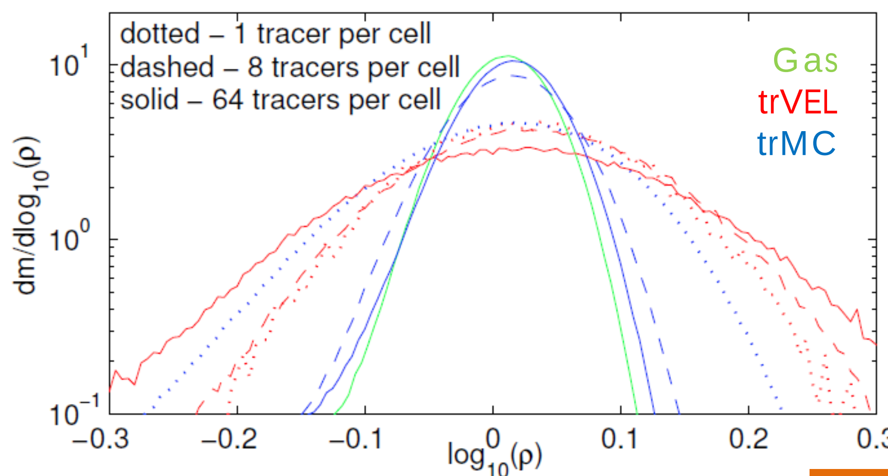
1D converging flow: Monte Carlo tracers



In cosmological volumes, the problem manifests as a pile-up of tracers in the centers of halos.







I. Monte Carlo tracer particles

(or, *how do we follow the flow?*)

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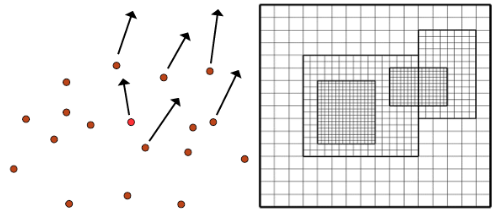
GADGET (SPH)



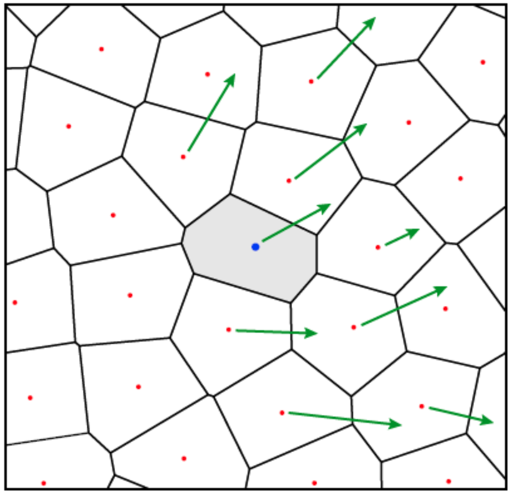
AMR (Eulerian)

vs.

AREPO (quasi-Lagrangian Moving Mesh)

Same initial conditions.
Same gravity solver.
Same implemented physics.

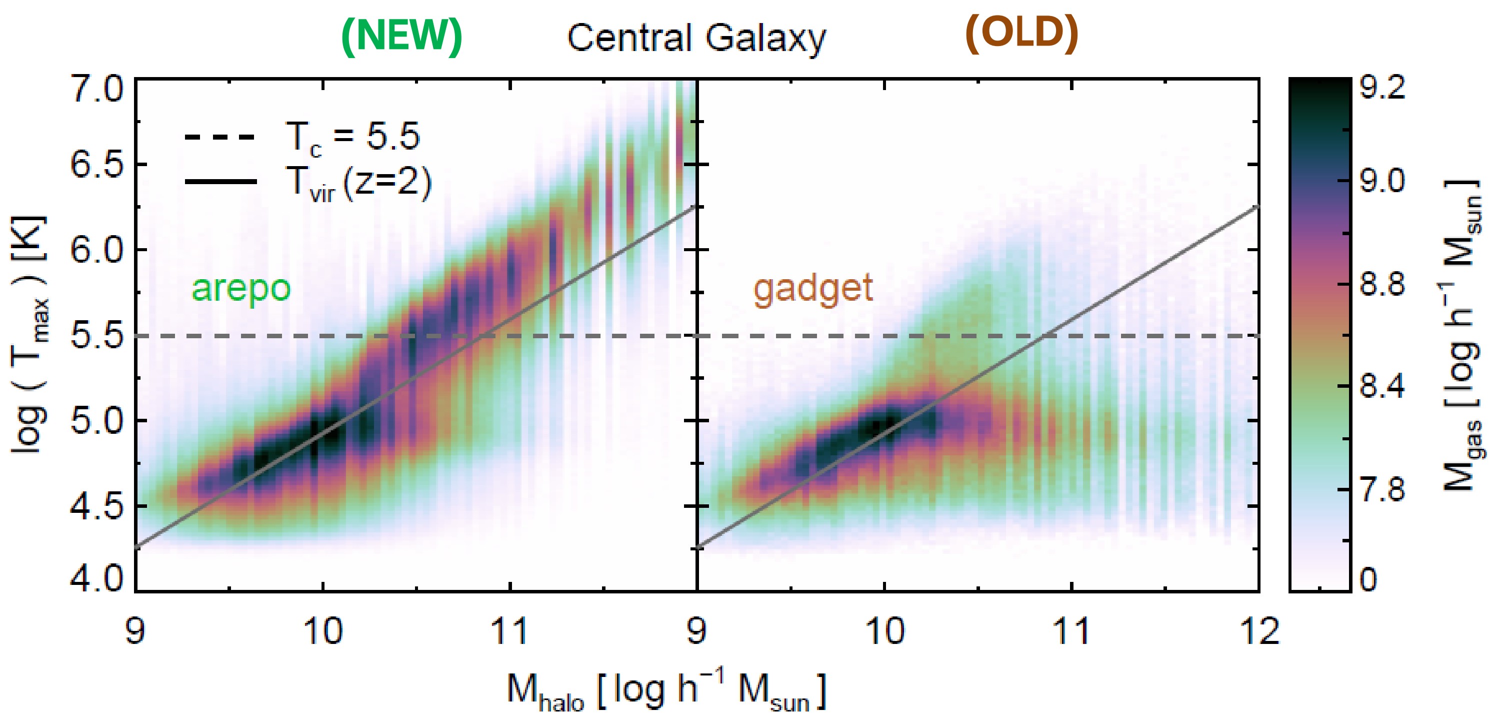
20/h Mpc box, WMAP-7 cosmology
Radiative cooling + UVB (primordial H,He)
Subgrid K-S type star formation recipe
No stellar/AGN feedback (no winds/outflows)



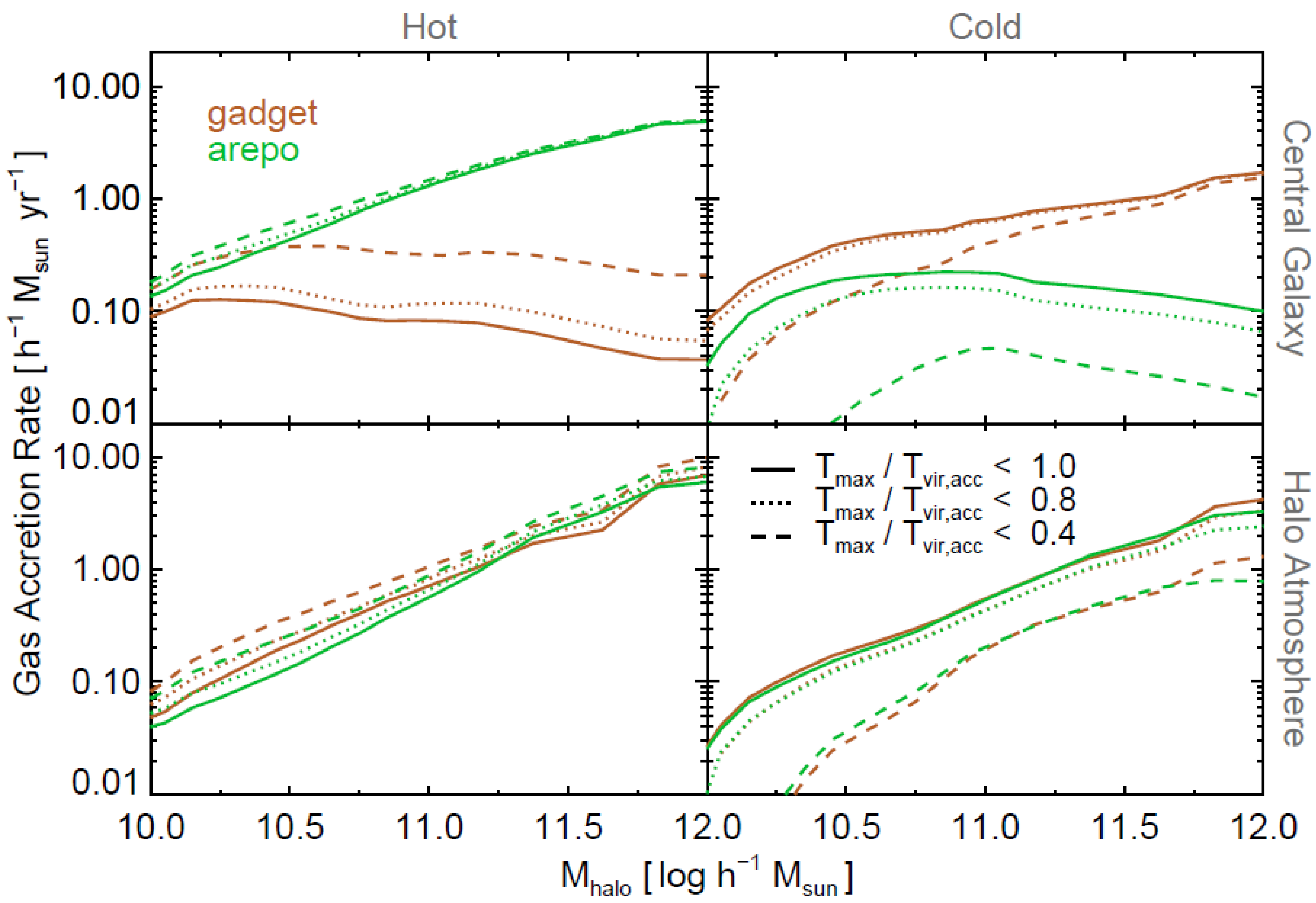
V. Springel 09

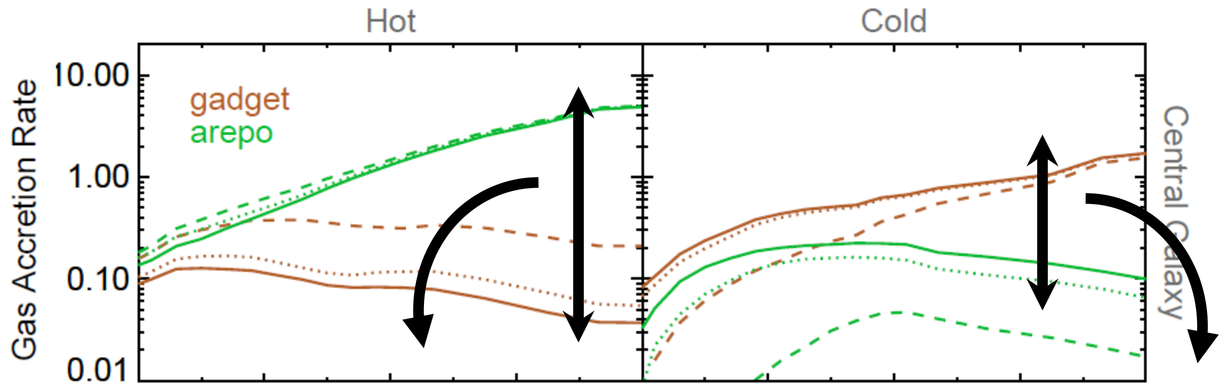
Gas Elements	DM Particles	Vel Tracers	MC Tracers	$m_{\mathrm{target/SPH}}$ $[h^{-1}M_\odot]$	m_{DM} $[h^{-1}M_\odot]$	ϵ $[h^{-1}$ kpc$]$
128^3	128^3	1 x 128^3	10 x 128^3	4.8 x 10^7	2.4 x 10^8	4.0
256^3	256^3	1 x 256^3	10 x 256^3	6.0 x 10^6	3.0 x 10^7	2.0
512^3	512^3	1 x 512^3	10 x 512^3	7.4 x 10^5	3.7 x 10^6	1.0

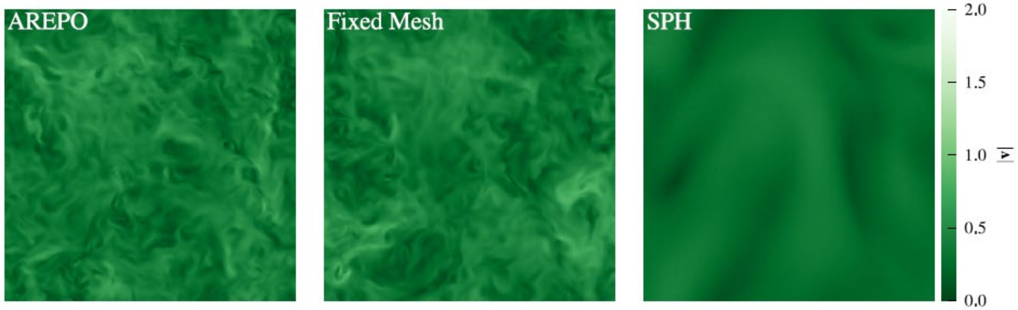
There are significant differences in the thermal history of gas accreted onto massive galaxies.



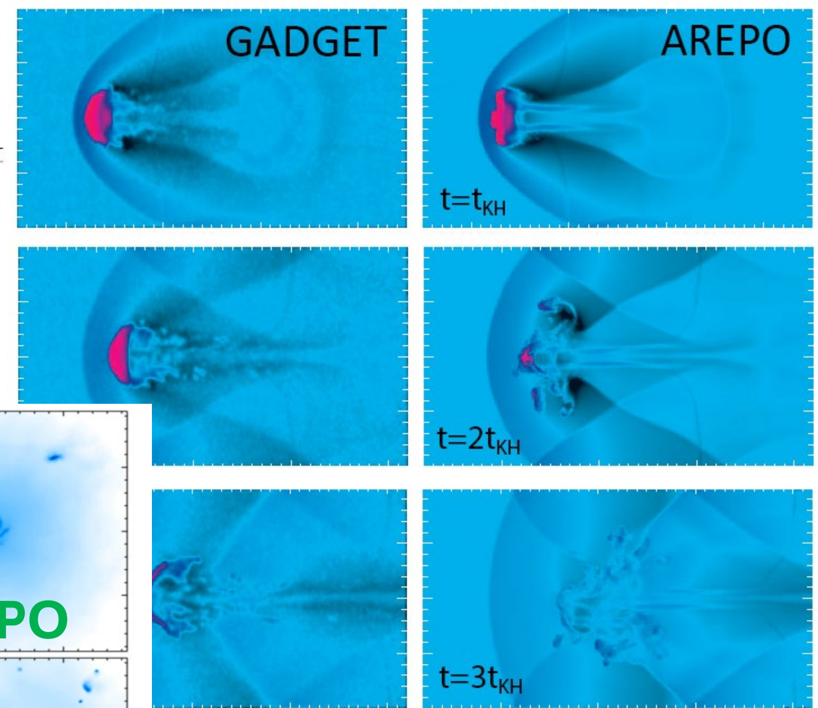
Relative importance of hot vs. cold accretion modes is strongly modified.





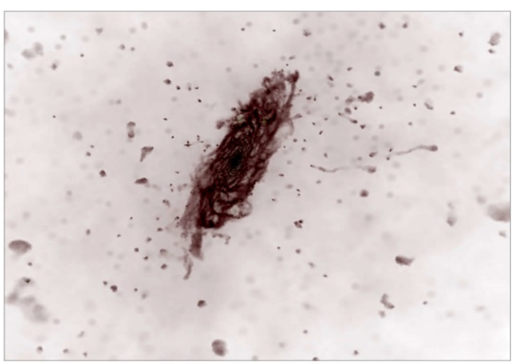


Bauer+ 11

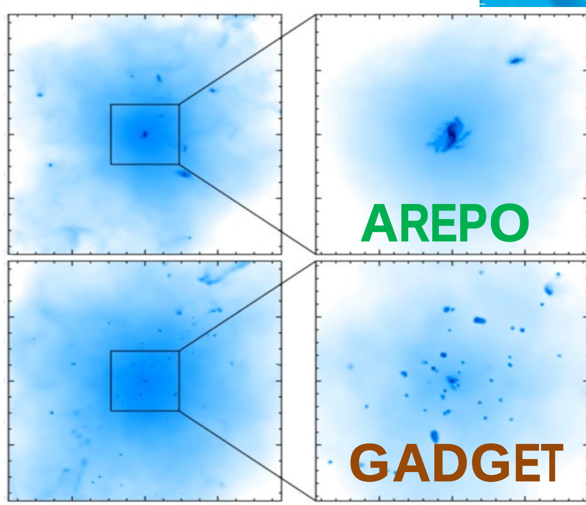


Sijacki+ 12

1. SPH does not dissipate subsonic turbulence c



Eris Simulation

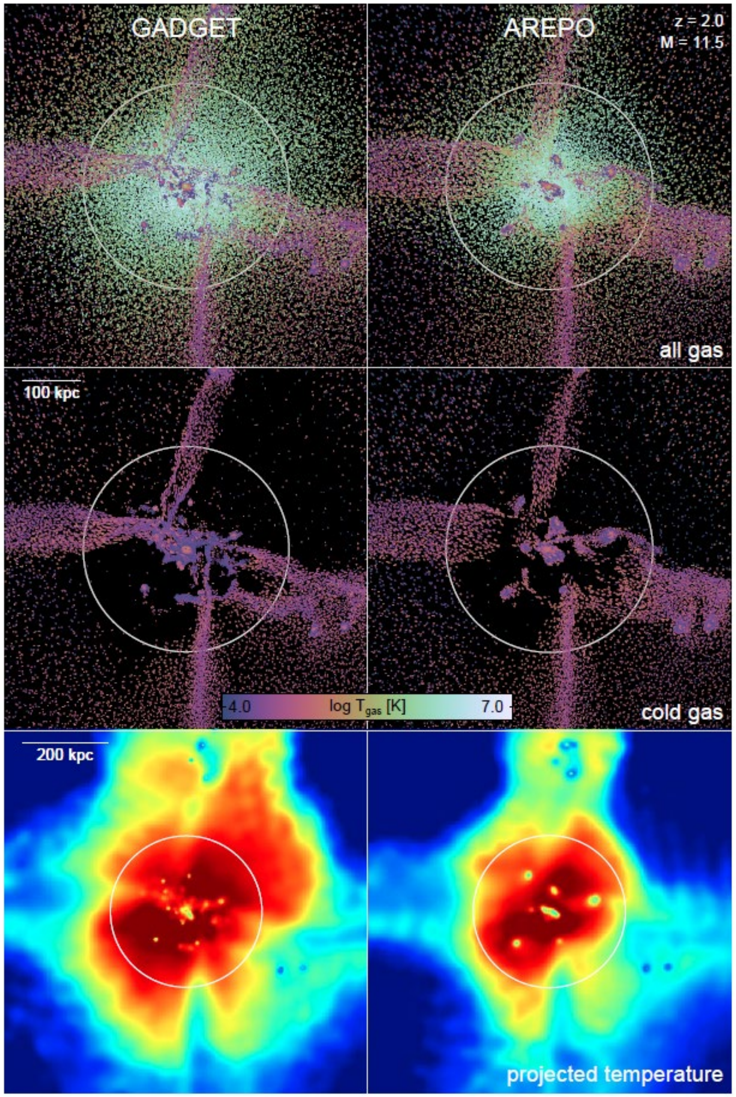


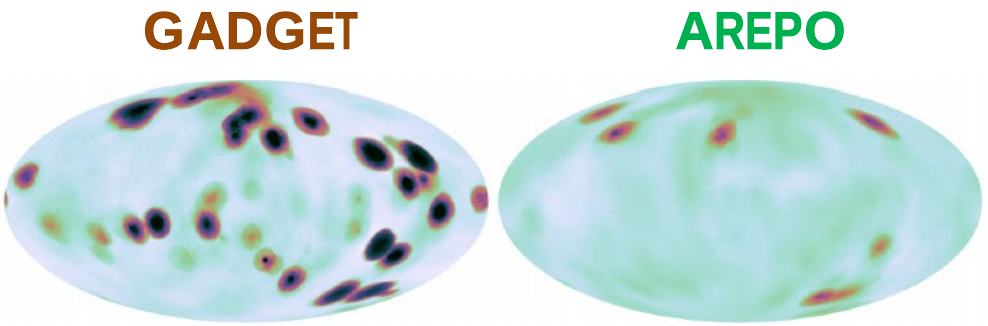
Torrey+ 12

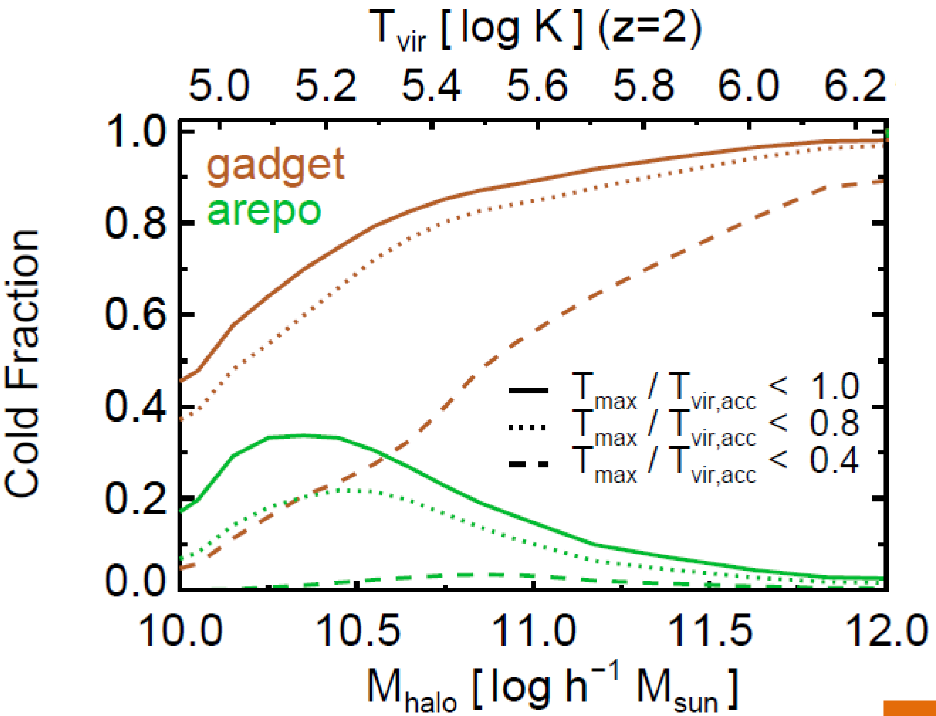
2. SPH prevents proper mixing.

3. SPH suffers from artificial clumping.

Significant differences in gas morphology and behavior within the halo.







Part II - Conclusions

1. Compared to an identical SPH simulation, the moving mesh run shows significant physical differences in the thermodynamic history of accreted gas.

2. With order of magnitude differences at z=2, hot mode accretion in AREPO is larger than in GADGET, while cold mode accretion is smaller.

3. Cold streams do not survive (cold) to the galaxy, but are instead heated/disrupted within the halo.

4. The causes are purely numerical in origin.

I. Monte Carlo tracer particles

(or, *how do we follow the flow?*)

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(or, *have we gotten it correct in the past?*)

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NO FEEDBACK vs. FEEDBACK
(Fiducial Illustris Model)

"simple physics"

- 20/h Mpc box
- WMAP-7 cosmology
- Radiative cooling + UVB heating (primordial H,He)
- Subgrid K-S type star formation recipe
- No stellar/AGN feedback (no winds/outflows)

"minimally comprehensive, standard state of the art"

- Stellar evolution: mass/metal return
- Metal line cooling contributions
- Chemical enrichment: H, He, C, N, O, Ne, Mg, Si, Fe
- Stellar feedback: SNIa, SNII, AGB
- Kinetic wind treatment -> galactic-scale outflows
- Black hole feedback (quasar/radio mode), nearby radiation effects

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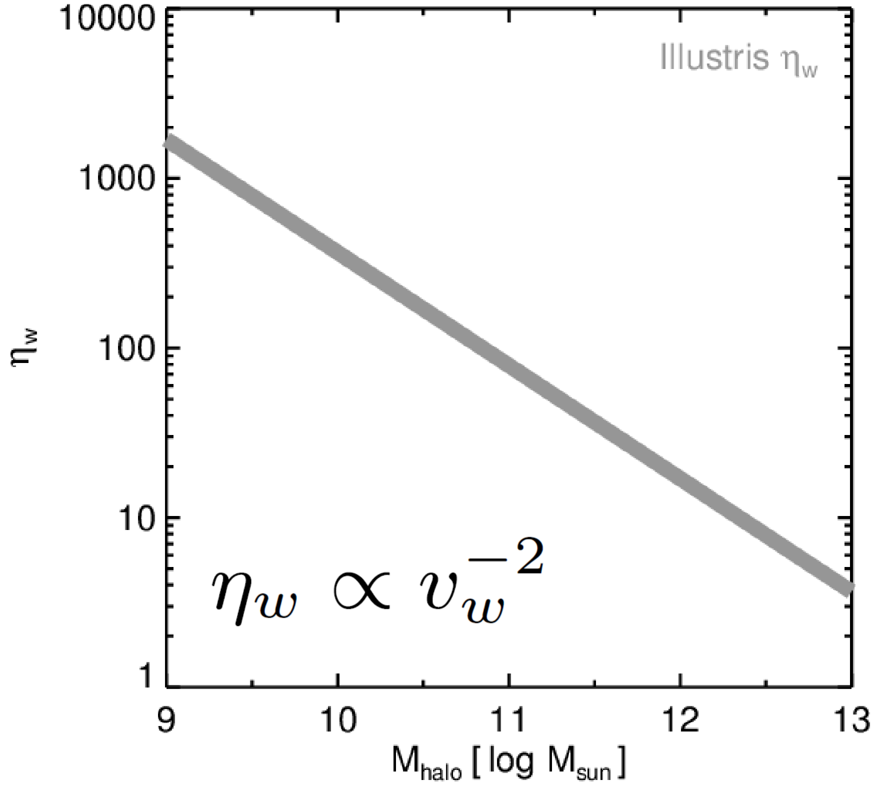
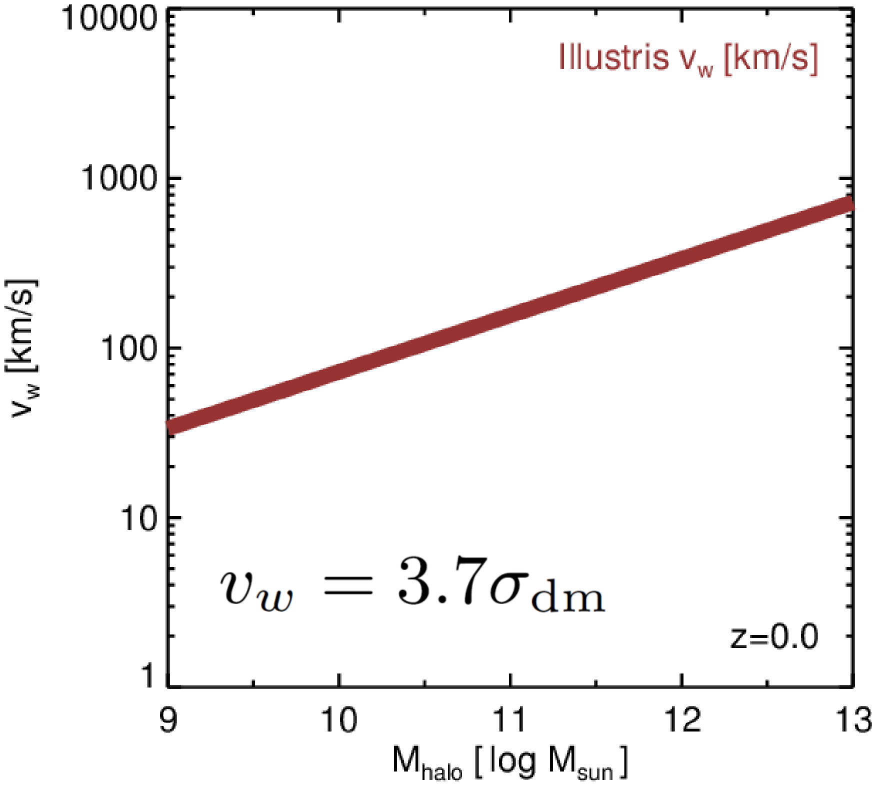
NO FEEDBACK vs. FEEDBACK

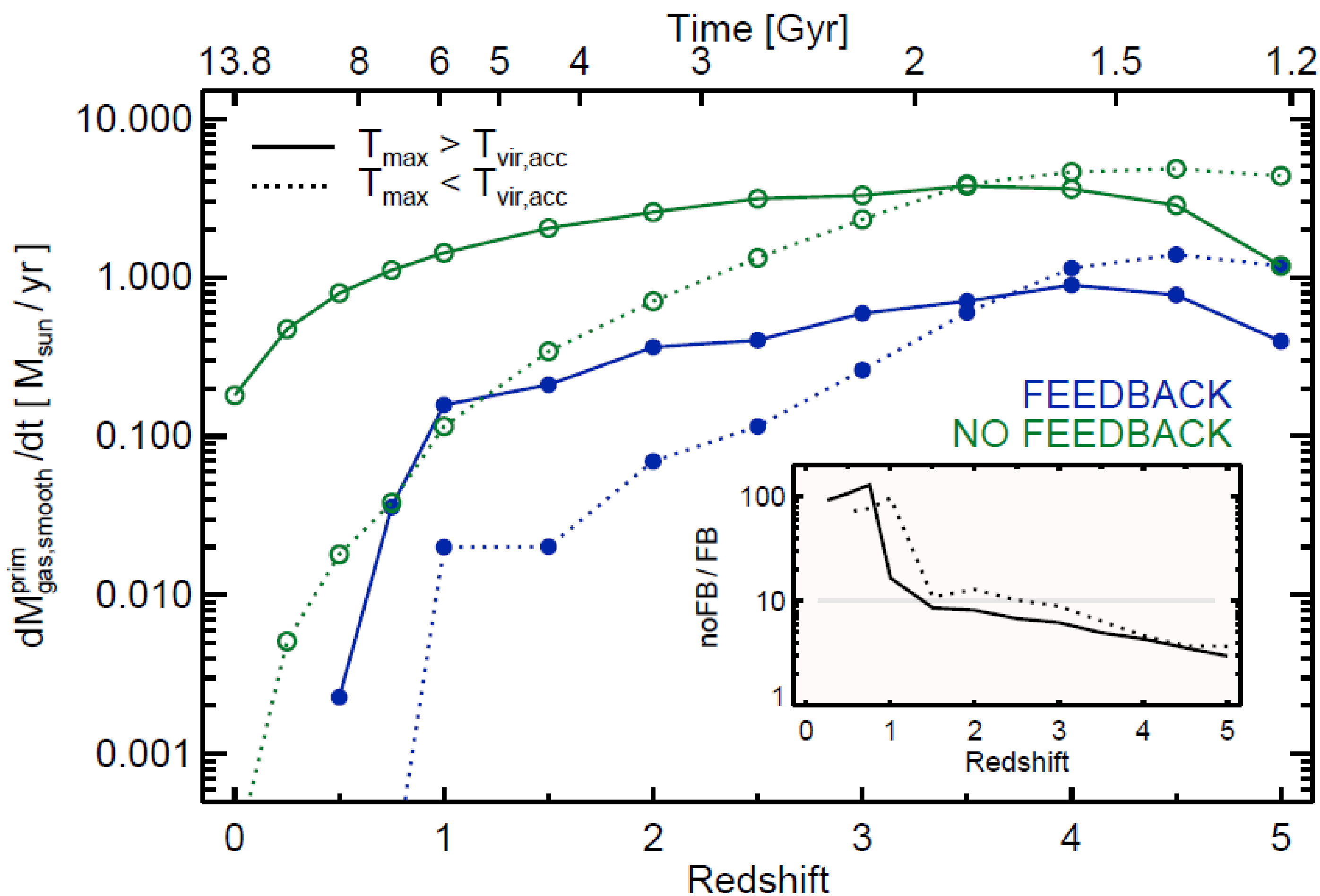
(Fiducial Illustris Model)

"minimally comprehensive, standard state of the art"



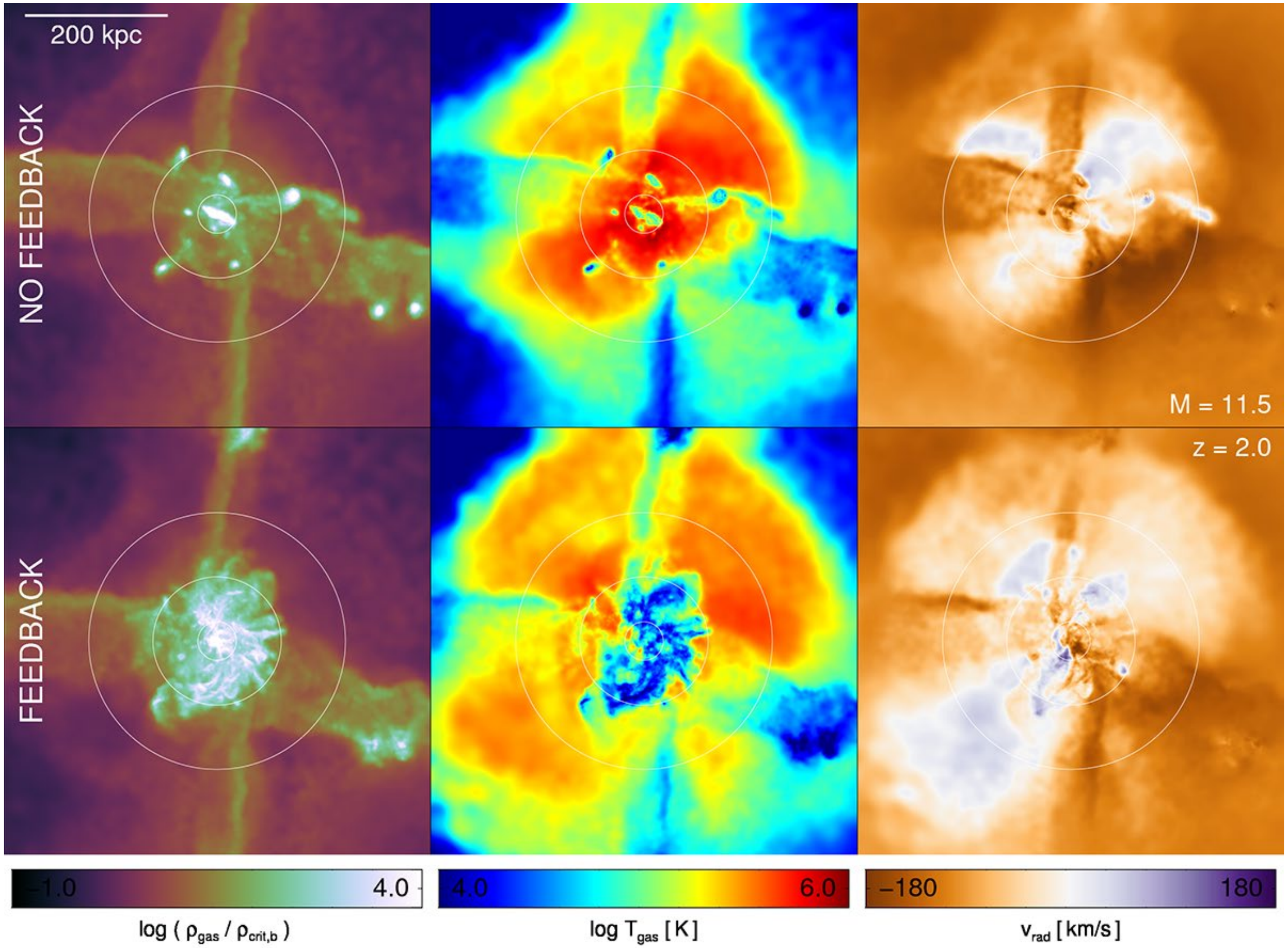


Accretion rate of smooth, primordial gas suppressed by feedback for ~$10^{11.5}$ halos, regardless of T_{max} / T_{vir}.

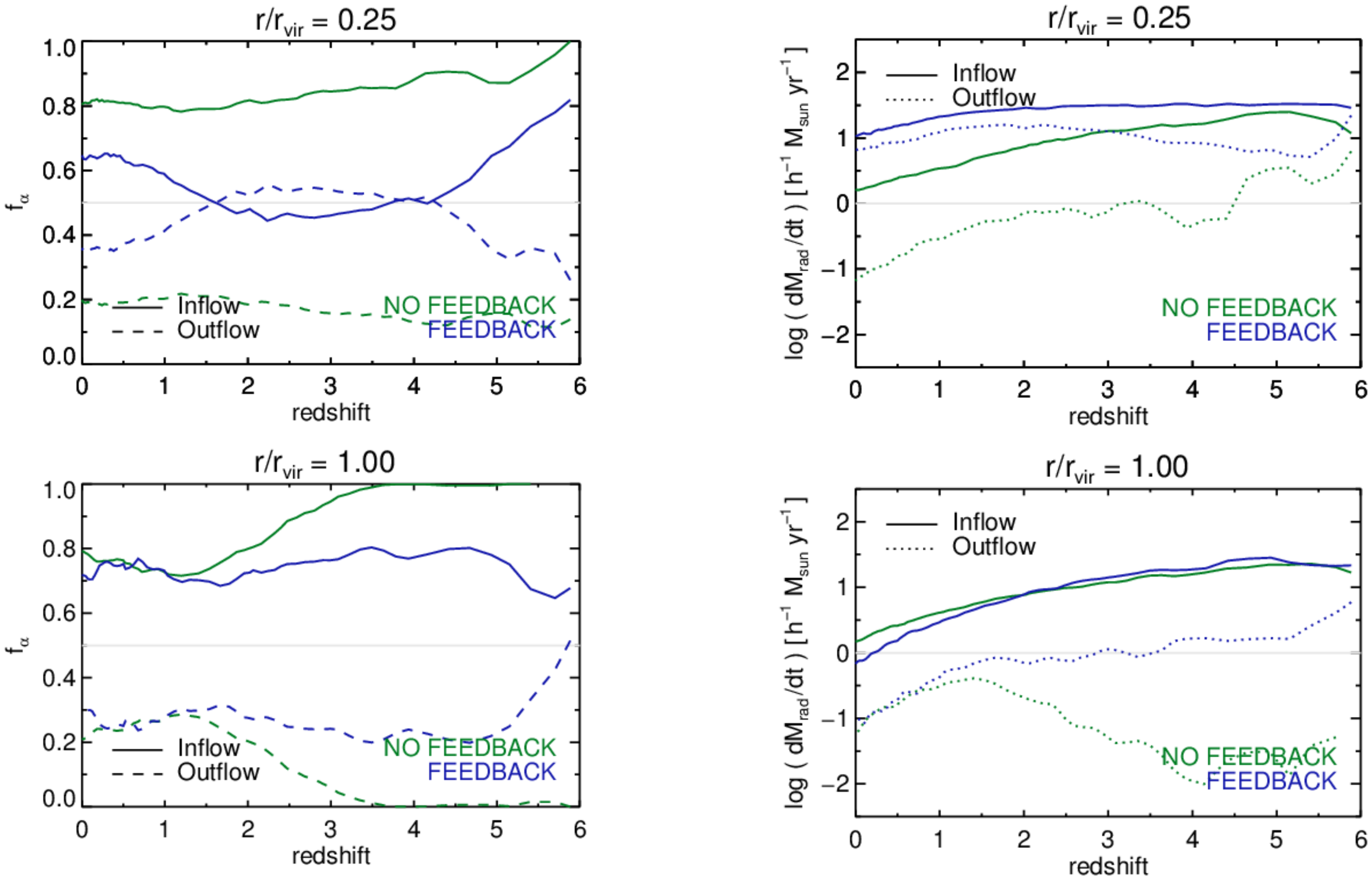


1. “net”: (inflow-outflow).
2. “primordial” only: (entering galaxy for the first time).

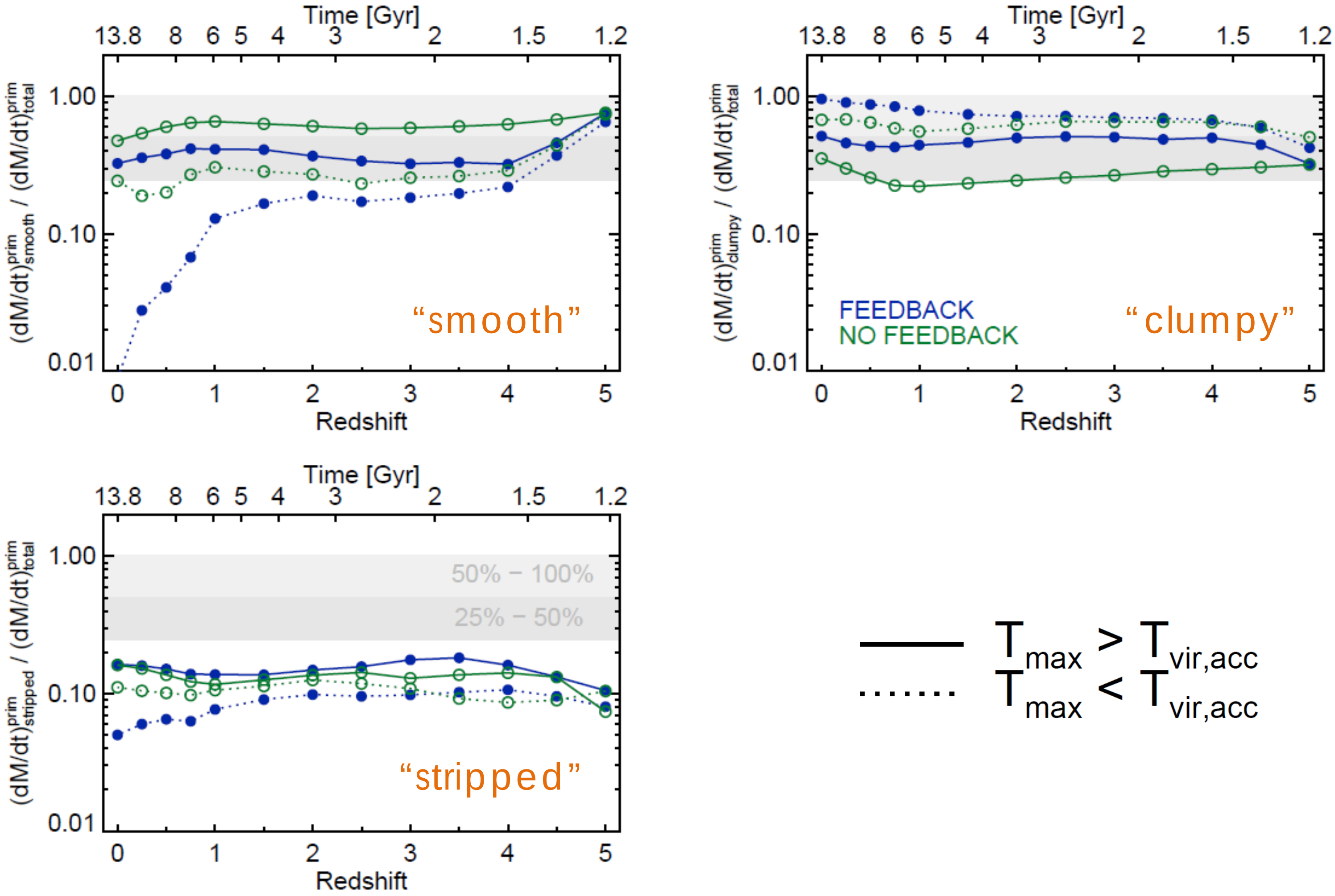
Cold winds reach to ~0.5 r_{vir} with substantial influence, but gas inflow largely unaffected at the virial radius.



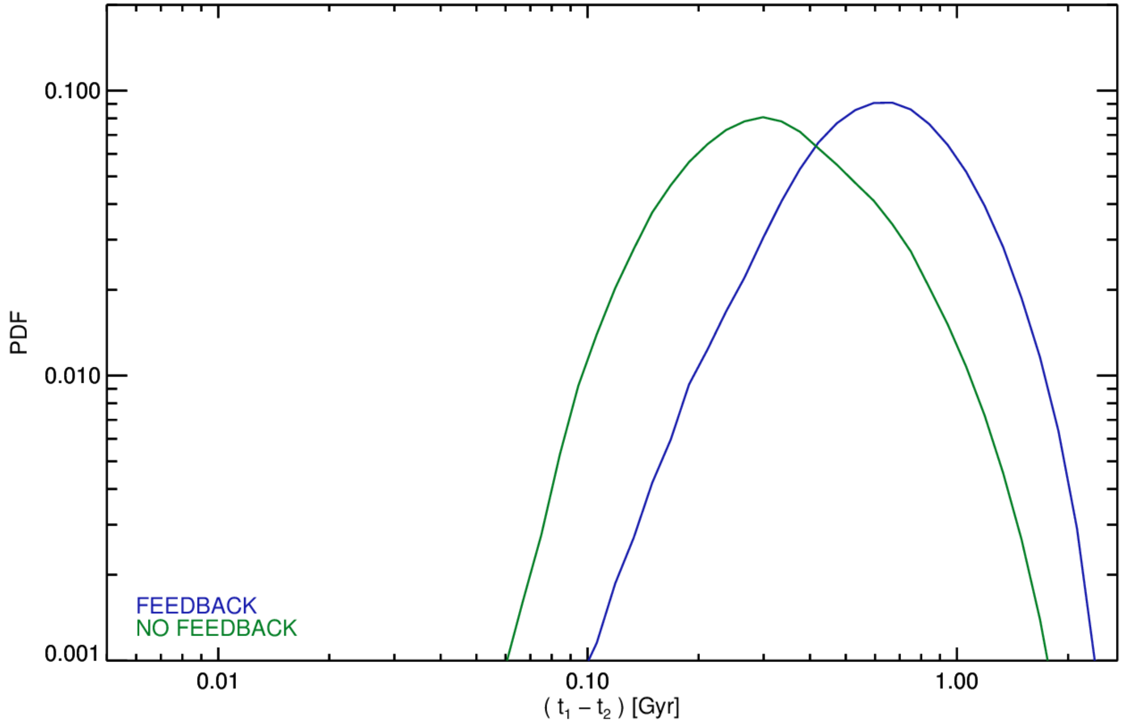
Feedback boosts spherical covering fractions of outflow as well as outflow rates, strongly at 0.25 r_{vir}, somewhat at 1.0 r_{vir}.



The fractional contribution of smooth accretion is suppressed across all redshifts, and particularly so for T_{max} / T_{vir} material at z < 1.



The presence of feedback increases the time taken by gas to transit from the virial radius to the galaxy.



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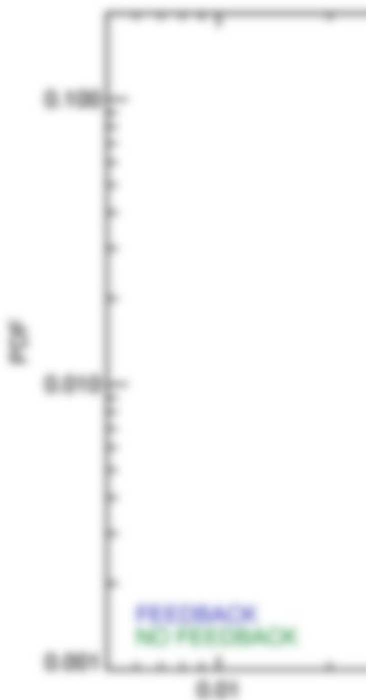
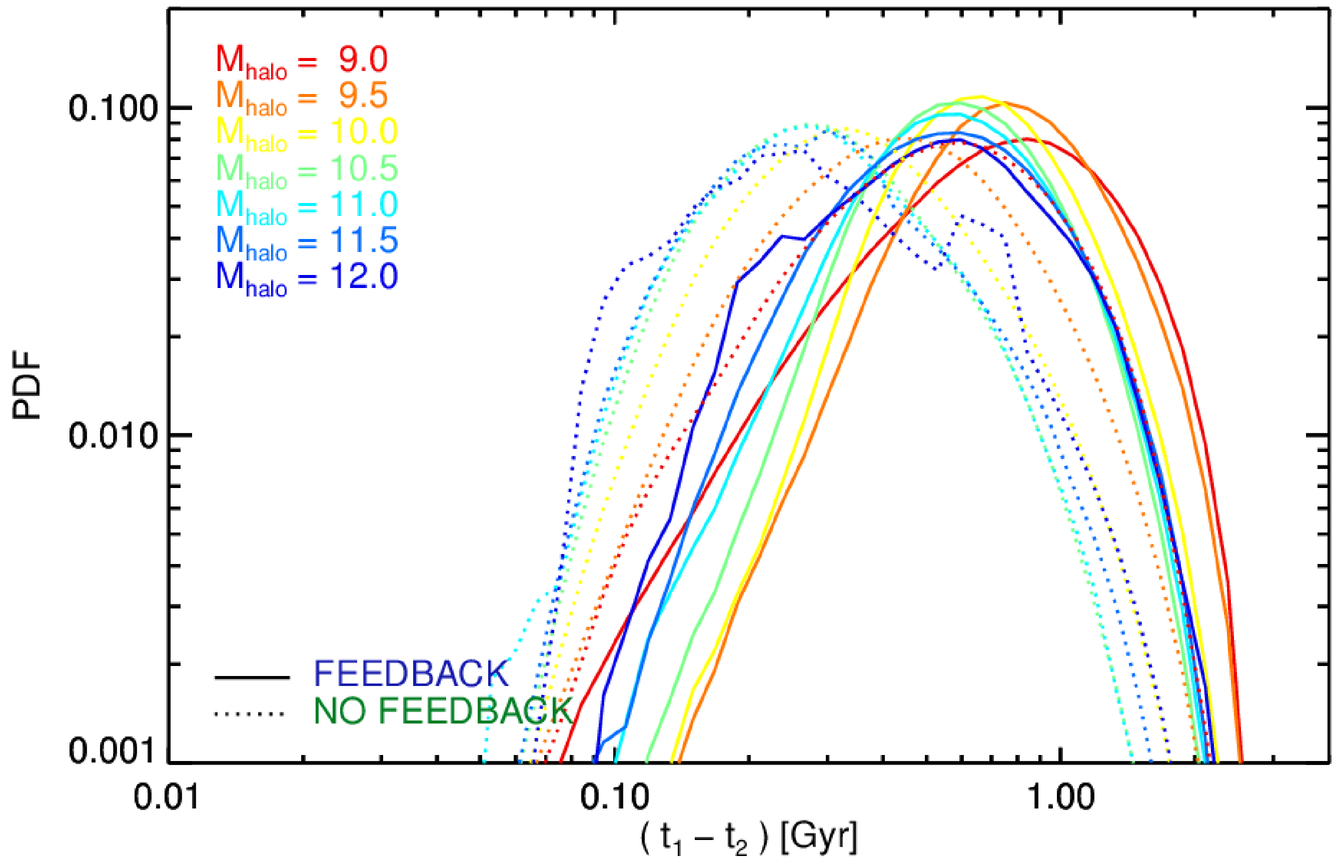
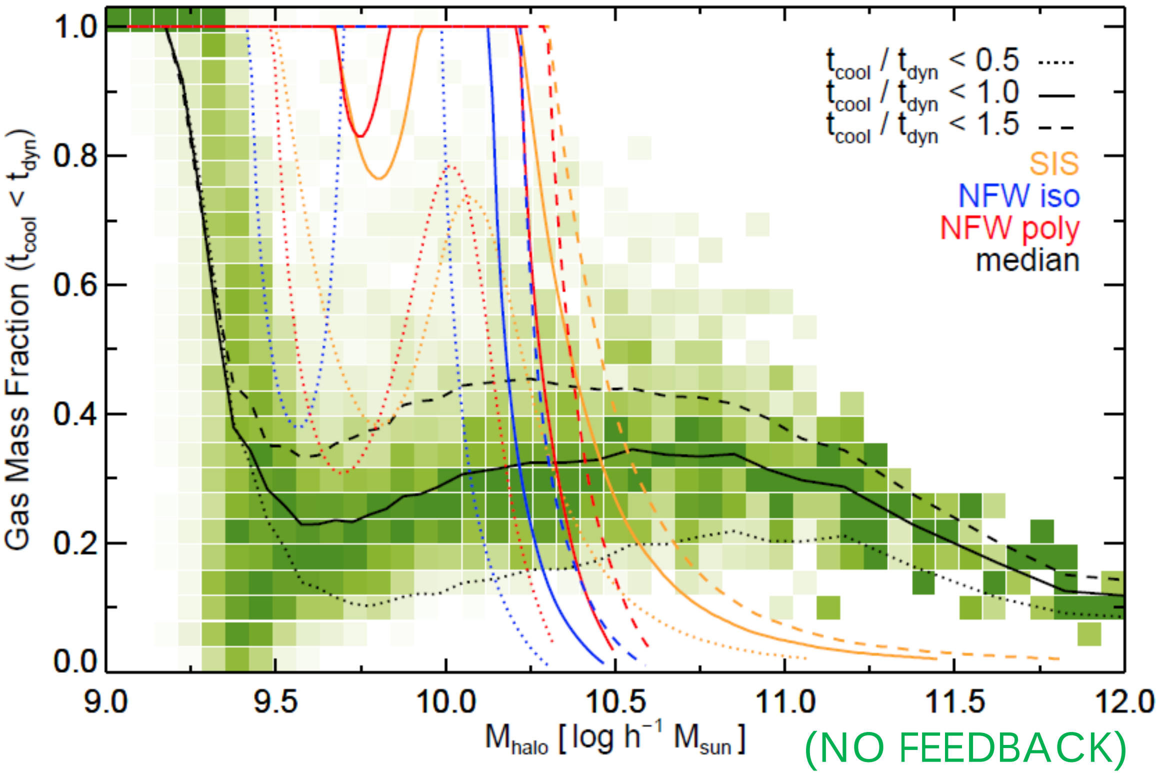




The fraction of hot halo gas "eligible" to cool onto the galaxy also remains relatively flat from 10^{10} to 10^{12}.



(NO FEEDBACK)

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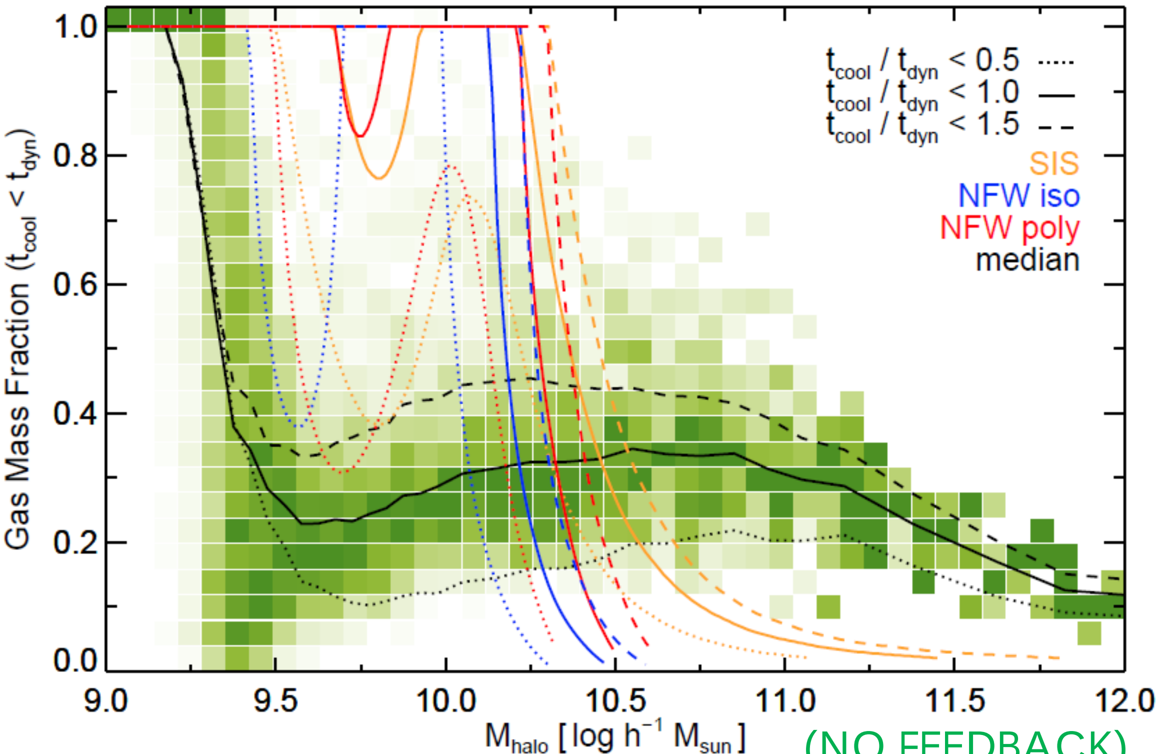
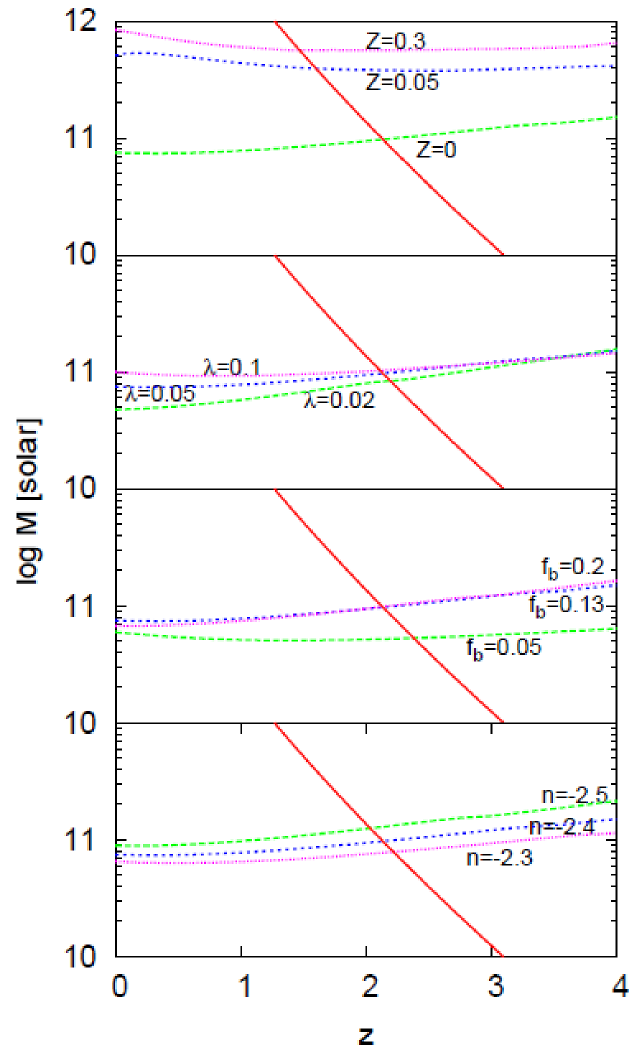


(NO FEEDBACK)



Analytic/1D stability of a virial shock (pressure vs. grav+radiative cooling) gives a "critical halo mass" of ~10^{11}.

Part III - Conclusions

1. Rate of smooth, primordial gas accretion suppressed by feedback for ~$10^{11.5}$ halos (by ~10 at z=2, increasing towards z=0).

2. Spherical covering factor of inflowing gas at 0.25 r_{vir} decreases, while the rates of both inflow and outflow increase.

3. The fractional contribution of smooth accretion is lower across all redshifts, and particularly so for T_{max} / T_{vir} material at z < 1.

4. The "halo transit time" of smooth accretion increases, but neither it (nor the fraction of gas with $t_{cool} < t_{dyn}$) vary strongly with halo mass.

I. Monte Carlo tracer particles

(or, *how do we follow the flow?*)

II. Comparing to SPH

(or, *have we gotten it correct in the past?*)

III. Impact of feedback

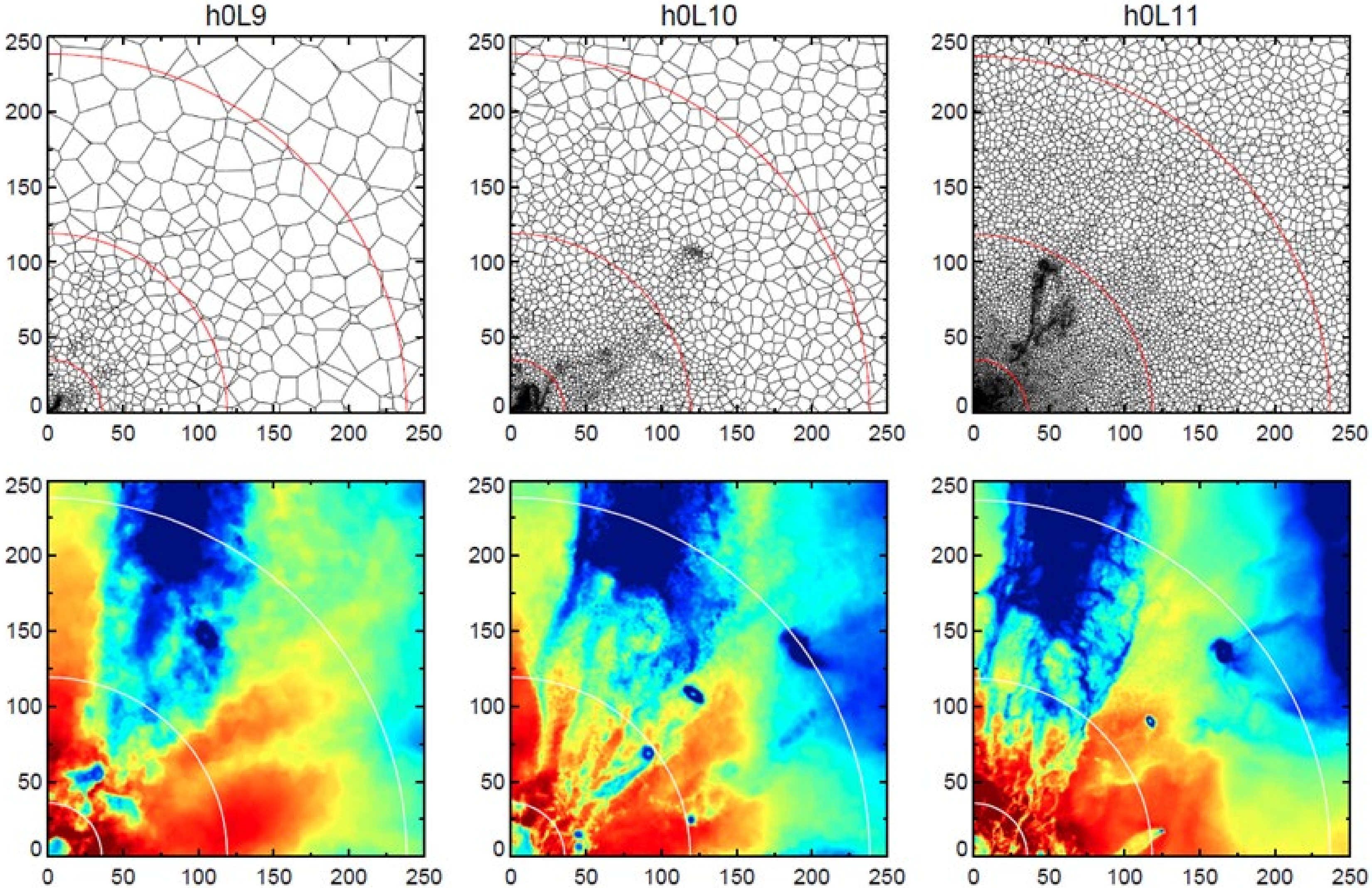
(or, *does more realistic physics change things?*)

IV. Zooms

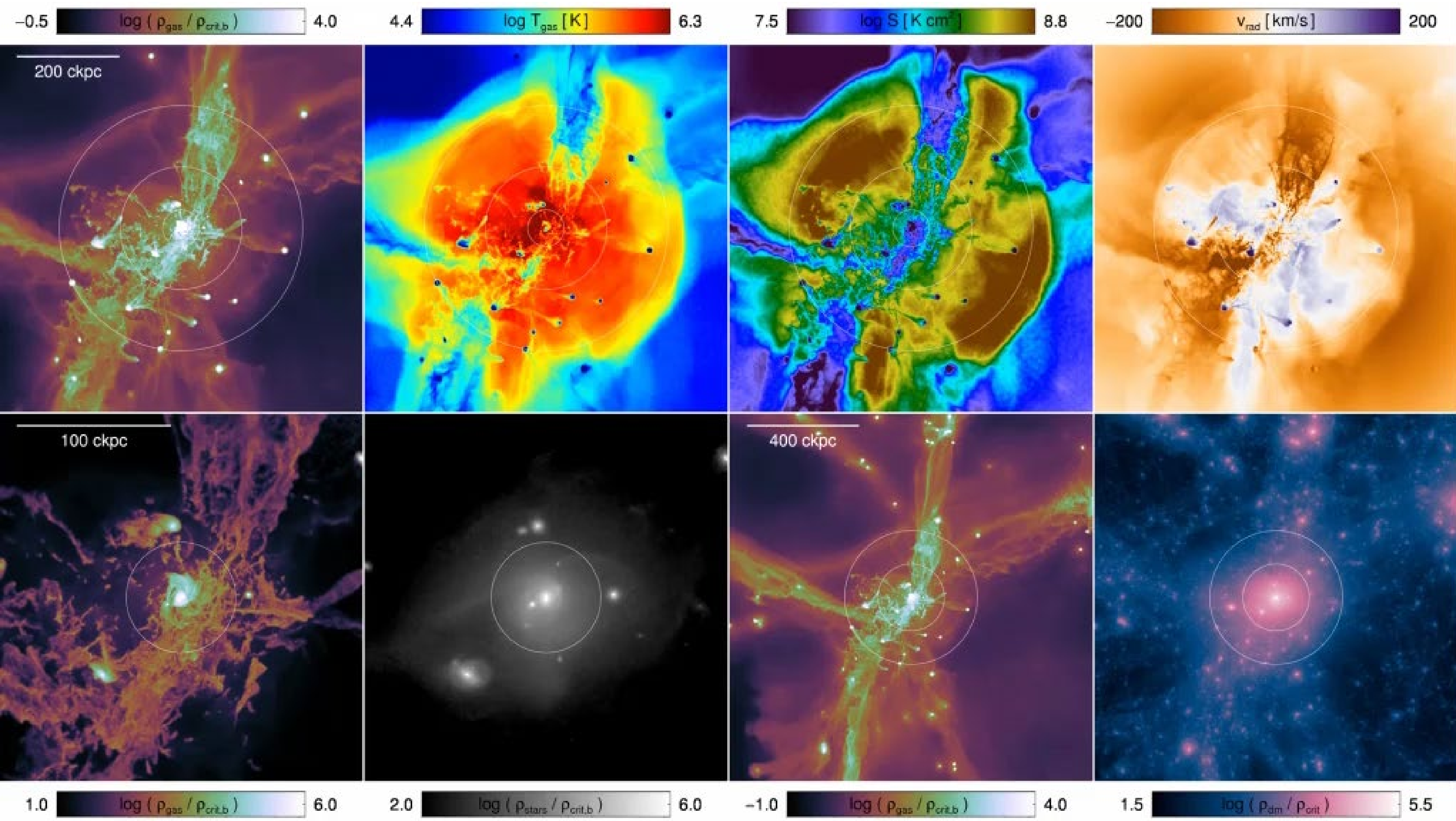
(or, *are we resolving the circumgalactic regime?*)

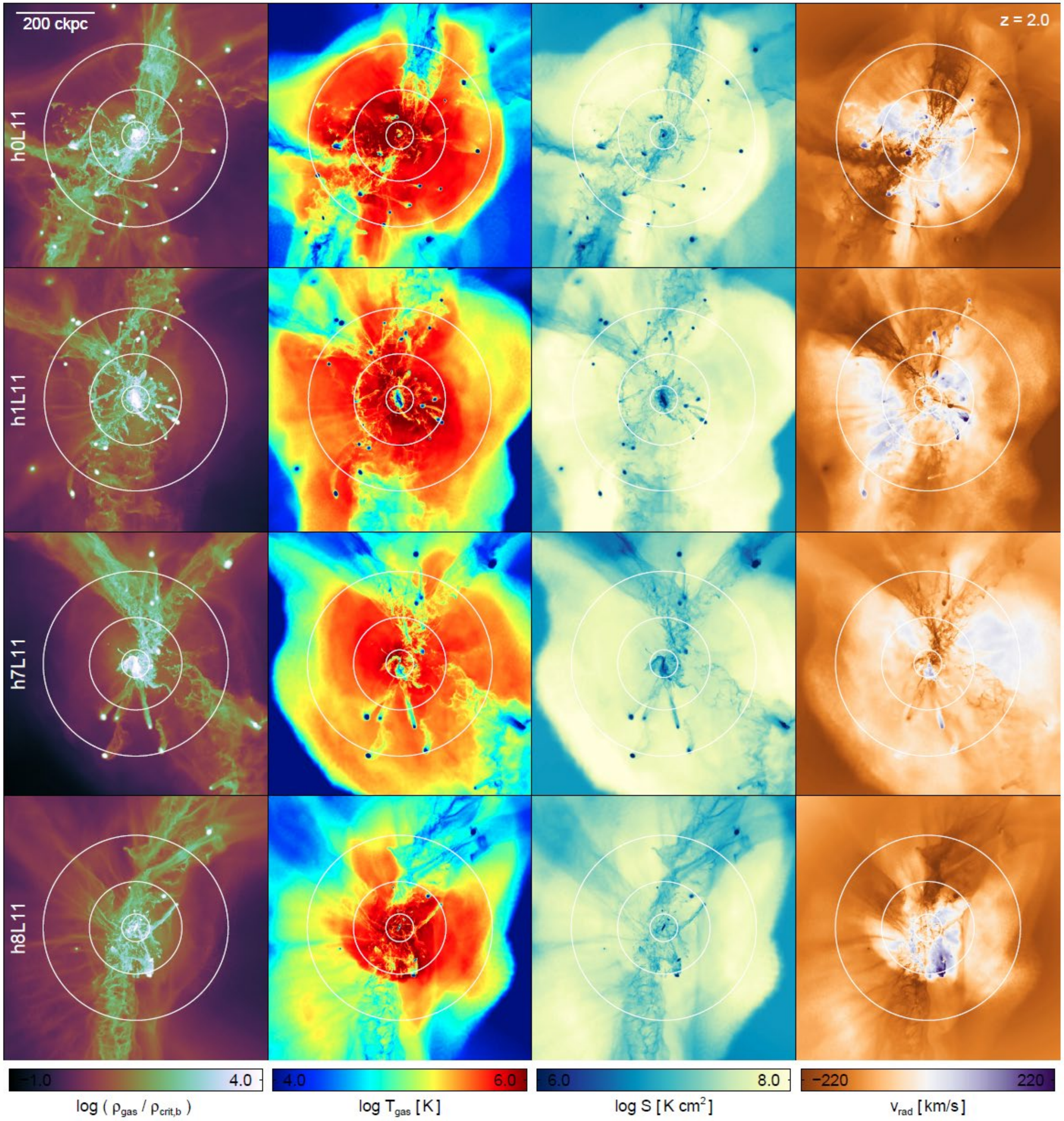
Nelson+ (in prep)

Res	N_{part}^{eff}	N_{part}^{HR}	m_{baryon} [$M_\odot$]	m_{DM} [$M_\odot$]	$\epsilon_{grav}^{comoving}$ [pc]	$\epsilon_{grav}^{z=2}$ [pc]	r_{cell}^{min} [pc]	r_{cell}^{halo} [kpc]
L9	512^3	800,000	1.0×10^6	5.1×10^6	1430	480	31	2.7
L10	1024^3	7,000,000	1.3×10^5	6.4×10^5	715	240	11	1.6
L11	2048^3	64,000,000	1.6×10^4	8.0×10^4	357	120	3.3	0.8



Gas flows connect from Mpc scales of large-scale structure through the halo and the 'messy region' to the disk.

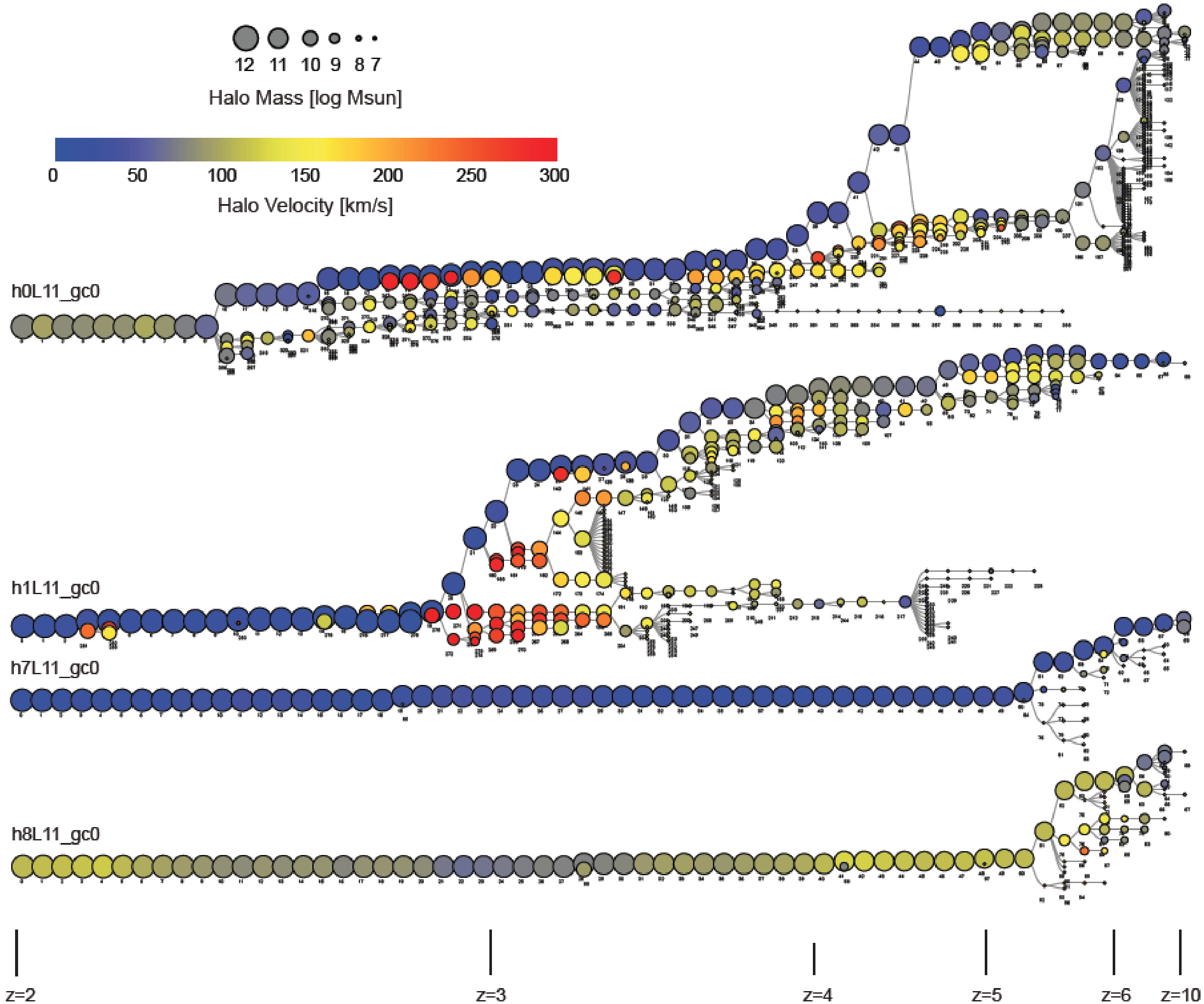


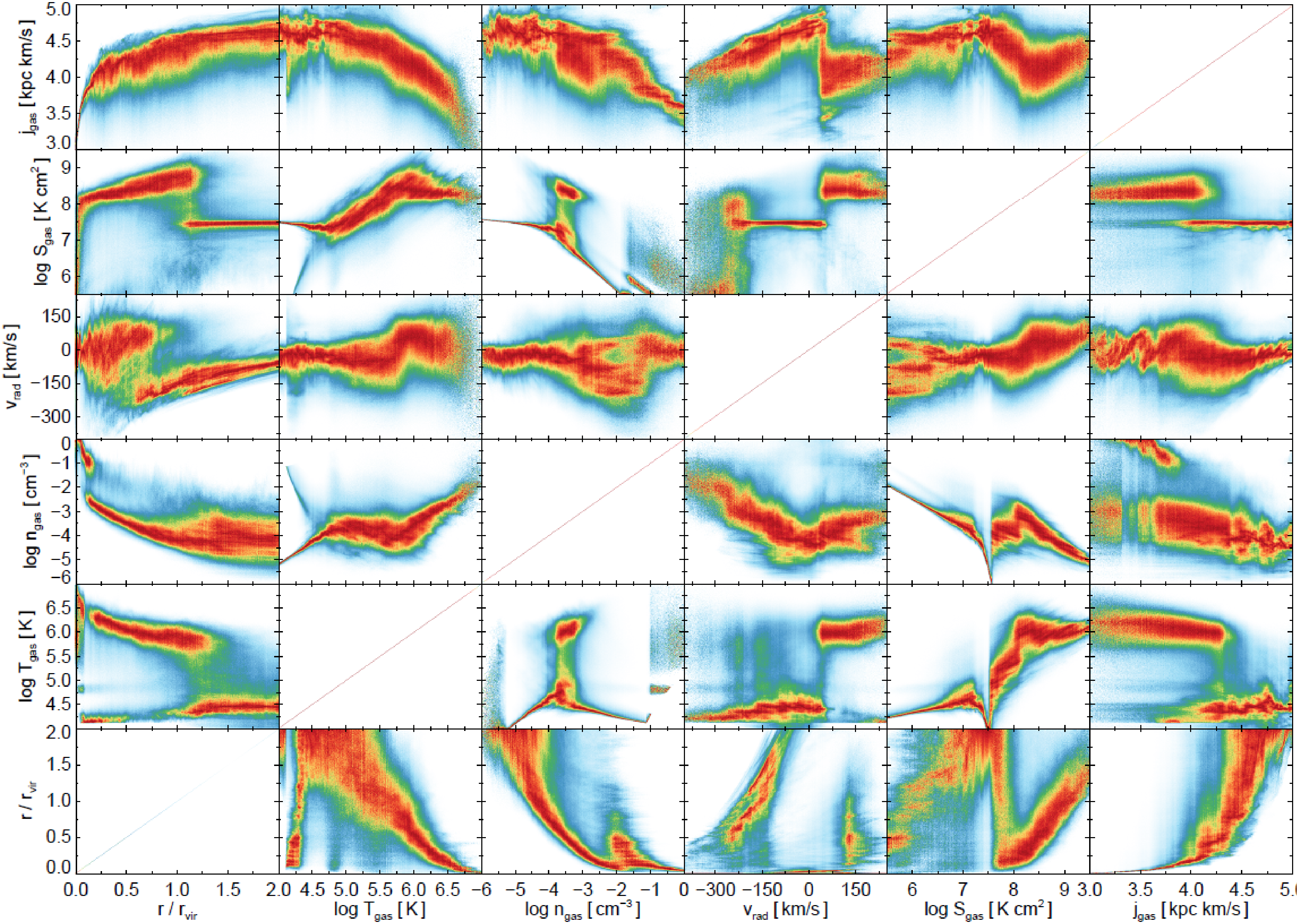


Coherent flows can penetrate 0.5 r_{vir}, maintain over-density (and low entropy?) while heating.

Orbiting substructures experience strong stripping. Mixing with CGM enhances cooling and fallback onto central. But: gravitational heating processes.

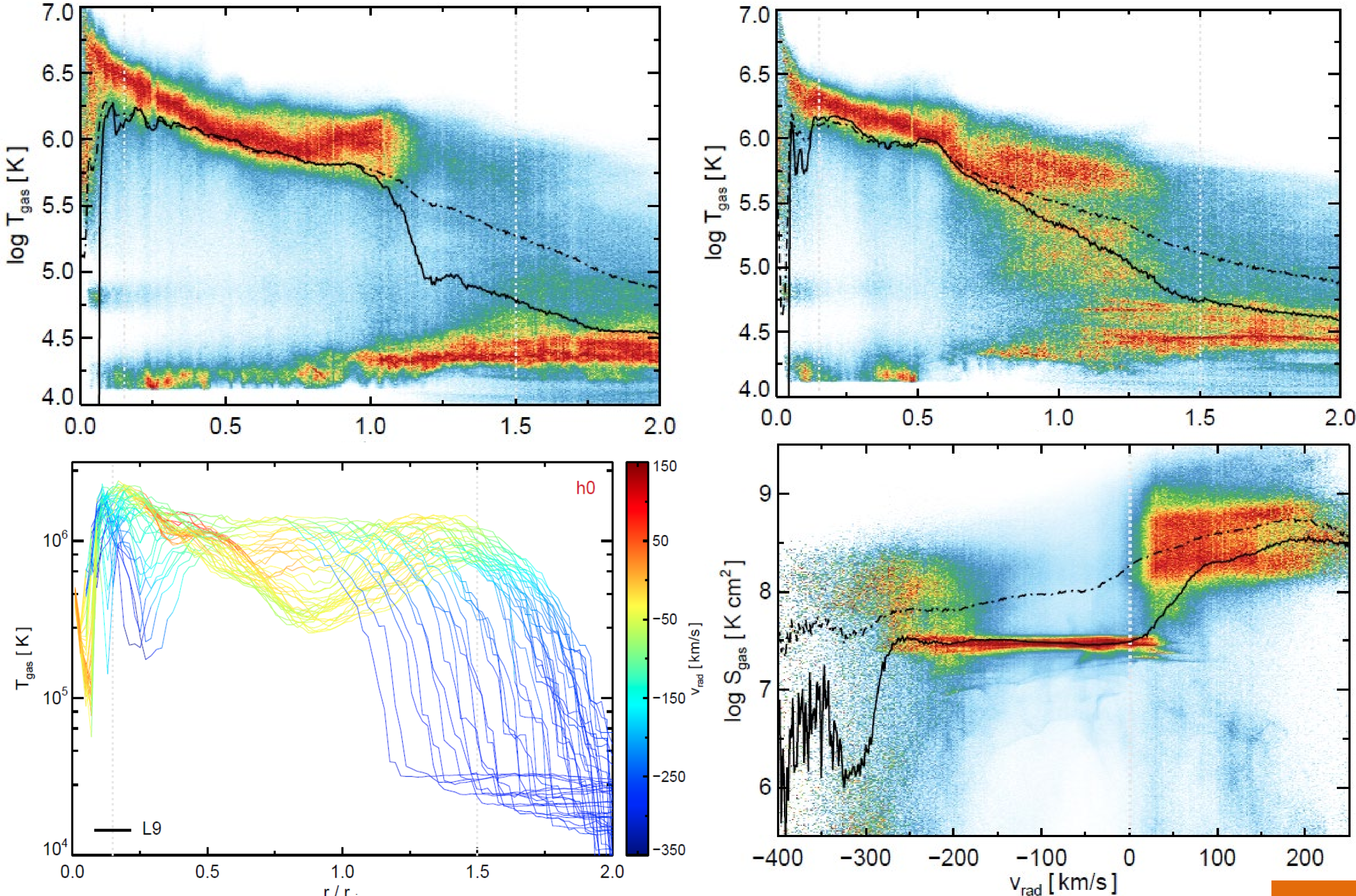
Variety of assembly histories affects how ‘quasi-static’ the hot halo gas is, and the spherical symmetry of the virial shock.





j_gas [kpc km/s]
log S_gas [K cm^2]
v_rad [km/s]
log n_gas [cm^-3]
log T_gas [K]
r / r_vir
r / r_vir
log T_gas [K]
log n_gas [cm^-3]
v_rad [km/s]
log S_gas [K cm^2]
j_gas [kpc km/s]

Characterizing the transition from IGM infall to virialized halo gas.



Lots of open questions we can address:

1. Look at evolution of tracer entropy, what heating is due to shocks and what arises from the virial shock?
   - How does the virial shock form at high z?
   - How spherically symmetric is it (closed surface?)
2. Does the interaction of filamentary inflow and quasi-static hot halo gas change as we better resolve the interface?
3. Are the accretion rates of gas robust @ typical cosmological simulation resolutions (and balance of 'hot'/'cold')
4. Orbiting substructures ("cosmological context")
   - Energy input via gravitational heating processes vs.
   - Stripping, mixing and enrichment of the hot halo gas
5. Angular momentum acquisition of the galaxy
   - Contribution from ~spherical hot halo cooling vs. streams
6. Observational puzzles
   - E.g. metal-line absorption studies, prevalence of cold metal enriched gas in massive systems

Some broad conclusions.

1. The Monte Carlo tracer scheme as a robust way to trace the Lagrangian history of gas in cosmological simulations.
2. Numerical (hydro) methods can significantly alter the scientific conclusions drawn in certain regimes – gas accretion and the circumgalactic regime being particularly difficult.
3. The presence of strong stellar feedback sets up strong recycling motions in the inner halo. The accretion rate of smooth, primordial material is suppressed, although the morphology of inflow at the virial radius is largely unaffected.
4. Focus on the formation of the hot halo and its interaction with filamentary inflow in higher resolution zoom simulations.