The study of cold streams in galaxy formation

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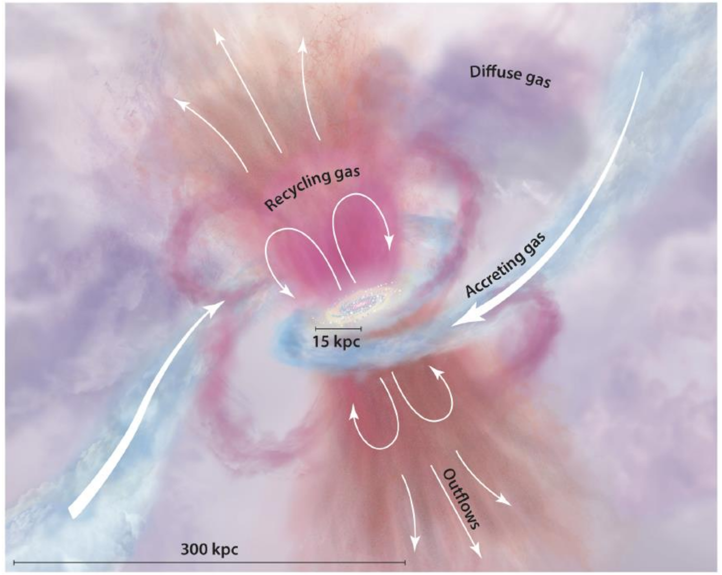
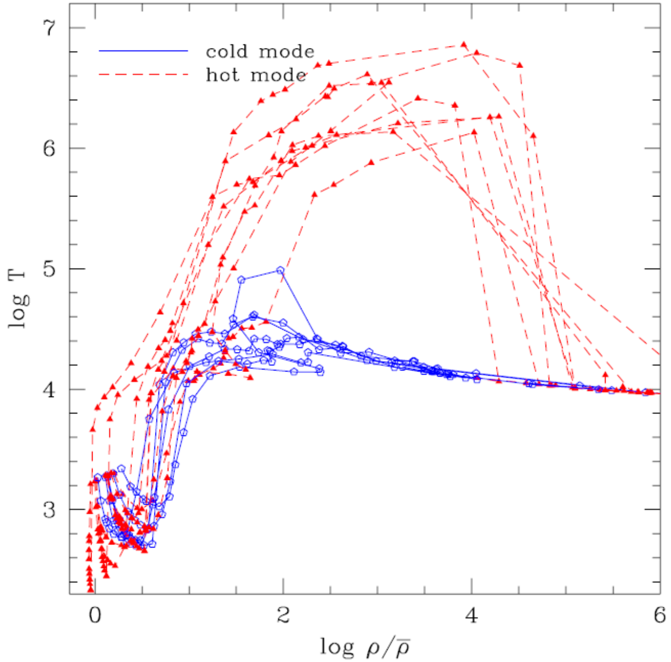
Gas accretion onto galaxies

- Accreting gas onto galaxies is an essential part of cosmic baryon cycle.
- Two modes of accretion (Keres et al. 2005)
    - Hot-mode: shock-heated to $T\sim10^6\ K$. Ambient accretion.
    - Cold-mode: stay cold $T\sim10^4\ K$ without the virial shock. Filamentary accretion.



Tumlinson et al. (2017)



Keres et al. (2005)

Cold streams

- Accrete onto galaxies along the cosmic filaments
- Fuel star formation on the galaxies
- The criteria of the virial shock and cold streams, depending on halo mass and redshift. (Dekel & Birnboim 2006)

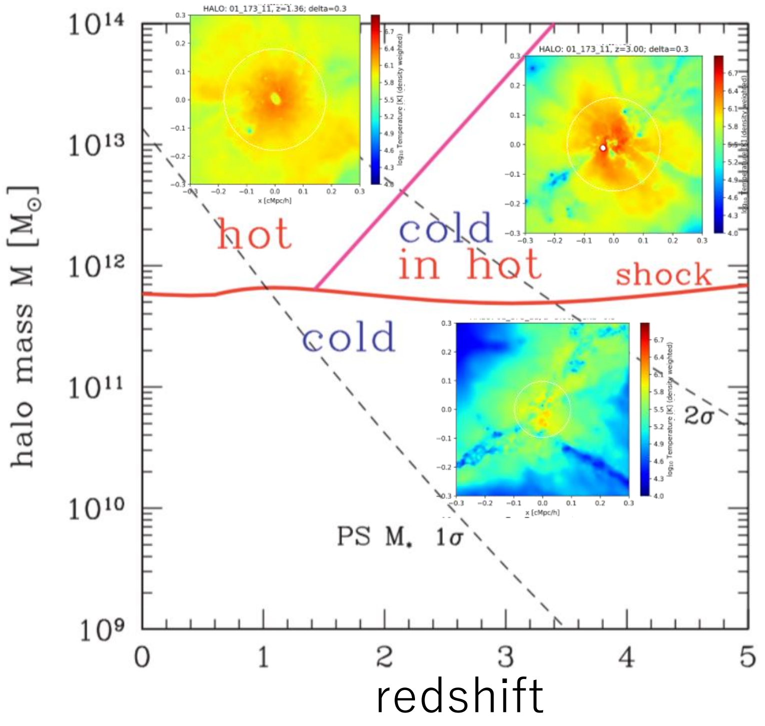
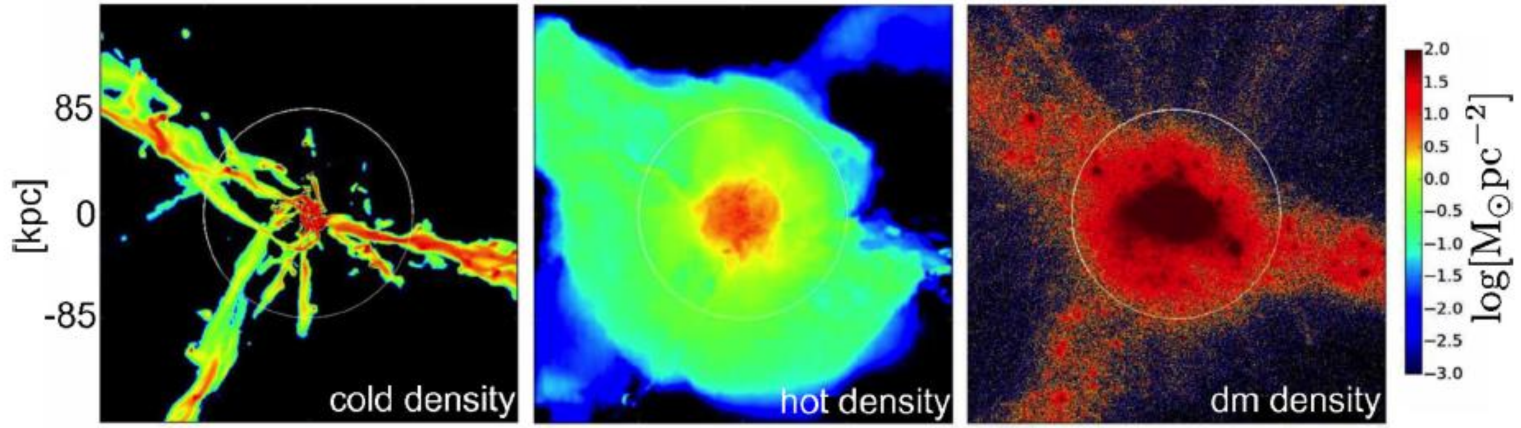


Diagram: Dekel & Birnboim (2006)
Temperature plot: Nakamura-san's master thesis



Danovich et al. (2015)

Motivation

- To understand the properties of cold streams in galaxy formation at $z > 2$.
  - Cold streams are efficiently feeding gas into galaxies which is the key ingredient for star formation.

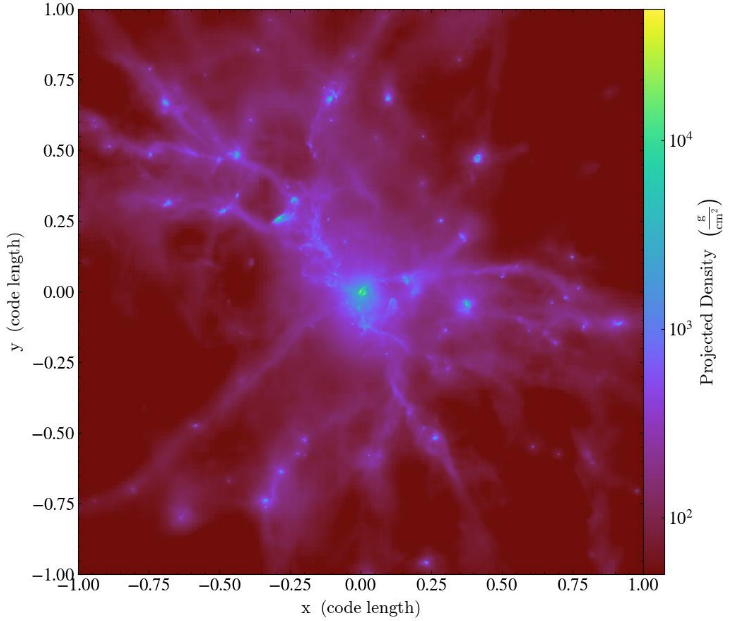
Method

- Cosmological zoom-in simulations

Simulation details

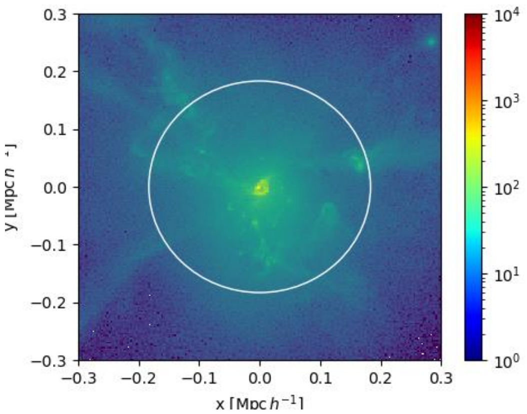
- Cosmological hydrodynamical simulation code: **GADGET3-Osaka** (Aoyama et al. 2017; Shimizu et al. 2019)
- Algorithm for making initial condition: **MUSIC** (Hahn & Abel 2011)
- Cosmological parameter from **WMAP 7/9 results** (Komatsu et al. 2011; Hinshaw et al. 2013)
  - $\Omega_m = 0.272, \Omega_\Lambda = 0.728, \Omega_b = 0.0455, H_0 = 70.2\ [\mathrm{km\,s^{-1}\,Mpc^{-1}}]$
- Box size: $\left(\boldsymbol{60\, h^{-1} cMpc}\right)^{\boldsymbol{3}}$, Zoom-in region: $\sim\left(\boldsymbol{4\, h^{-1} cMpc}\right)^{\boldsymbol{3}}$
- Zoom-in region and initial random numbers from **AGORA project** (Kim et al. 2014)
- Effective numbers of particle: $N_p = 4096^3$ (Level 12)
  - DM particle: $1.98 \times 10^5\ M_\odot$, gas particle: $3.97 \times 10^4\ M_\odot$
- Halos are identified by **SUBFIND** (Springel et al. 2001)

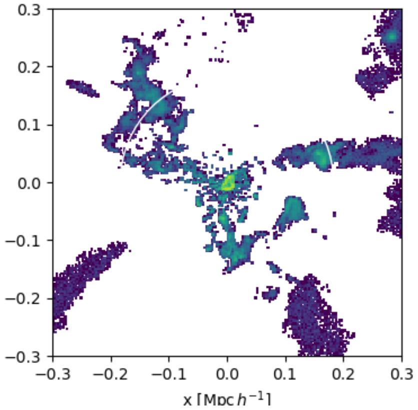
Gas density distribution

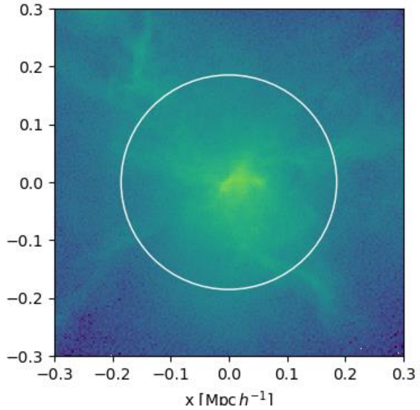


About the selected halo

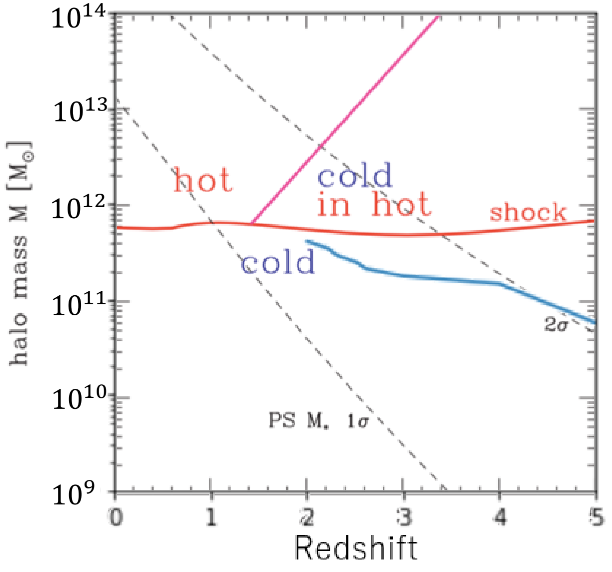
- Located at the node of the cosmic filaments.
- Halo mass: $M_h = 4 \times 10^{11}\ M_\odot$ at $z = 2.0$
- Set temperature threshold to capture cold streams. (Strawn et al. 2021)
  - Cold gas: $10^{3.8} < T < 10^{4.5}\ K$
  - Hot gas: $10^{4.5} < T < 10^{6.5}\ K$


Gas


Cold gas


Hot gas

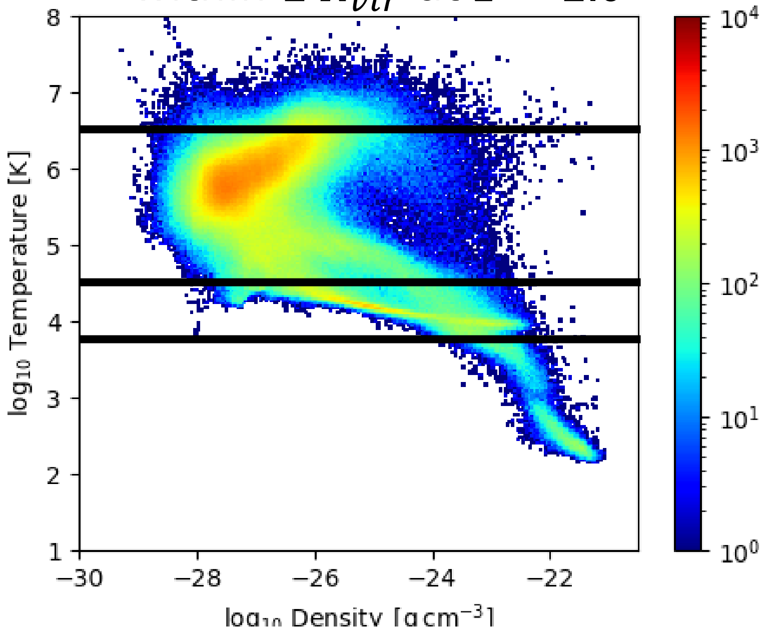
Halo mass evolution



Phase diagram
within $2\ R_{vir}$ at $z = 2.0$

Hot

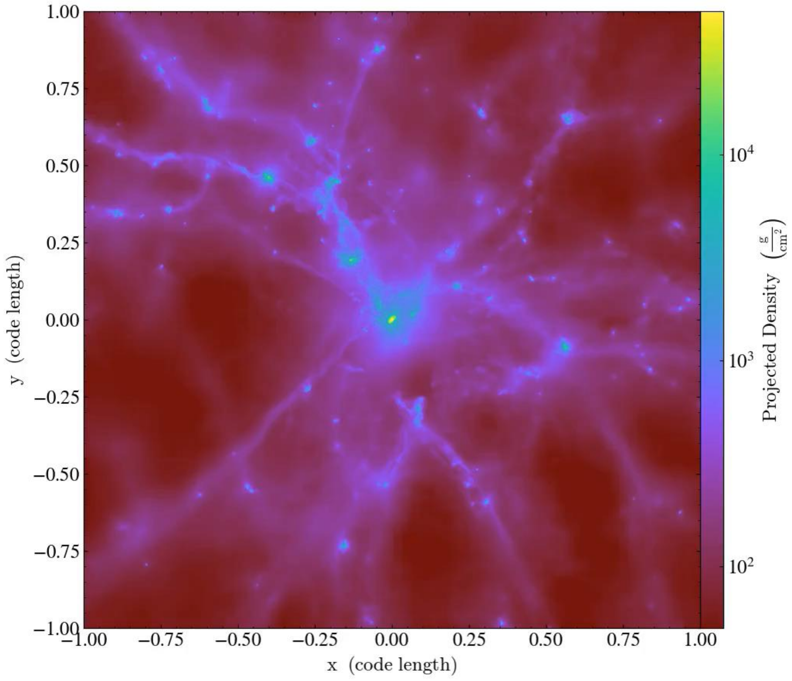
Cold



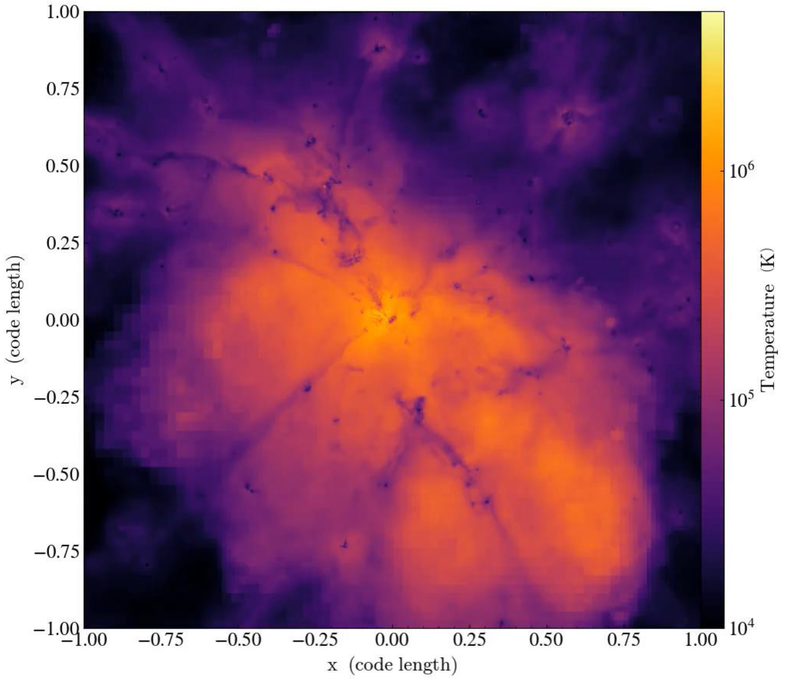
Distributions of density, temperature and metallicity

Cold, dense and metal-poor gas is fed into the central galaxy.

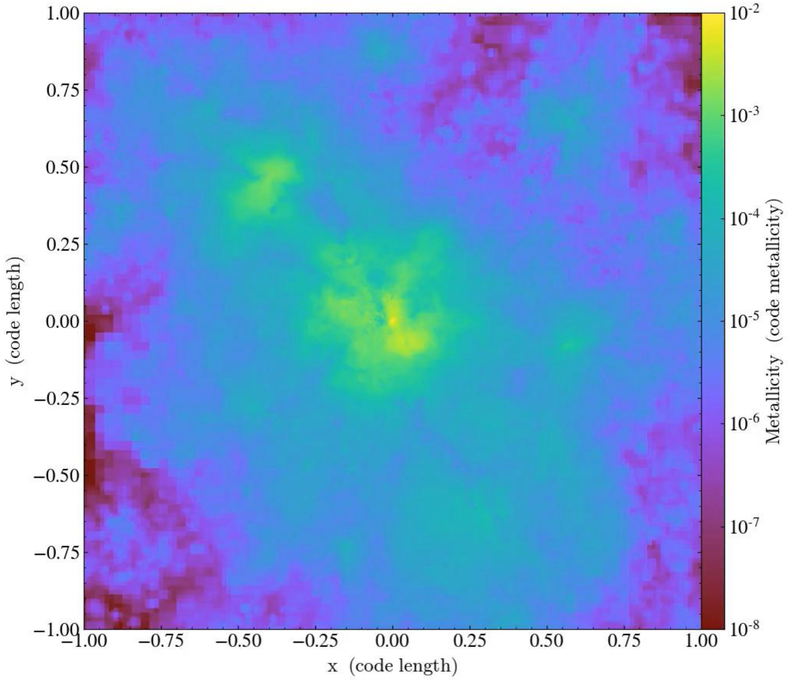
Density



Temperature



Metallicity

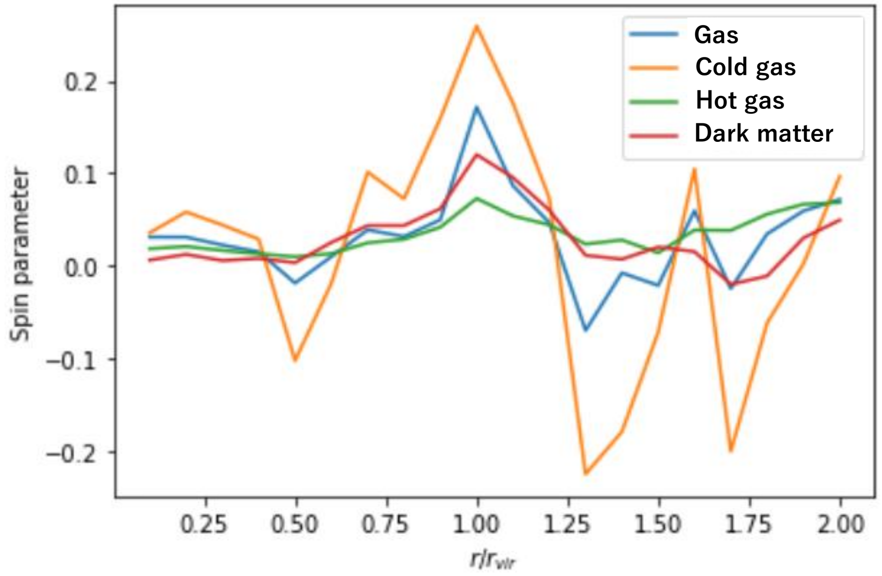


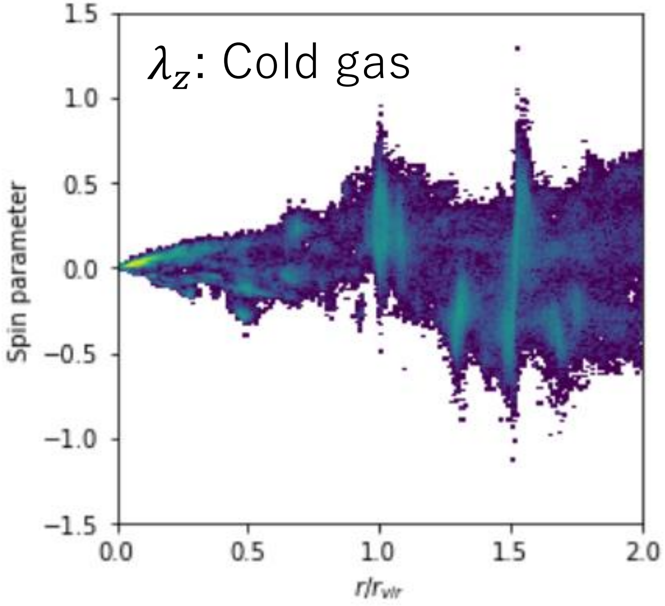
$2\ h^{-1}$ cMpc

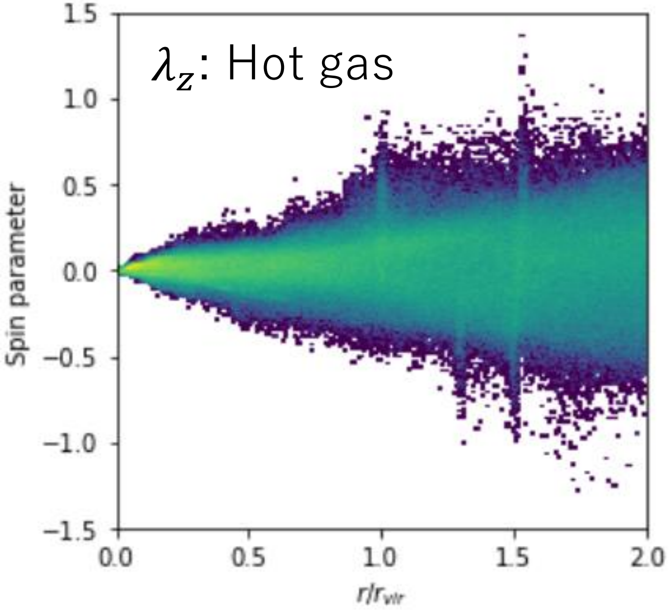
Redshift from $z = 3$ to $z = 2$

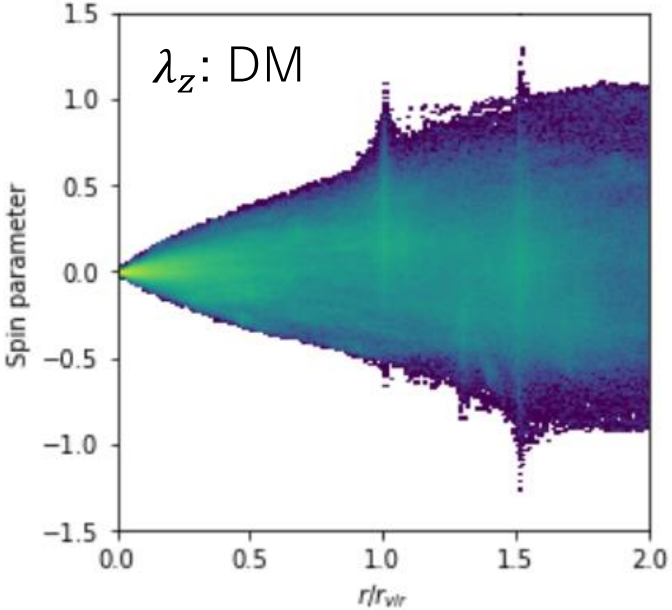
Axis of spin parameter

- Spin parameter of disk axis
  - $\lambda_z = \frac{xv_y - yv_x}{\sqrt{2GM}}$
- The fluctuation of cold gas is the largest.





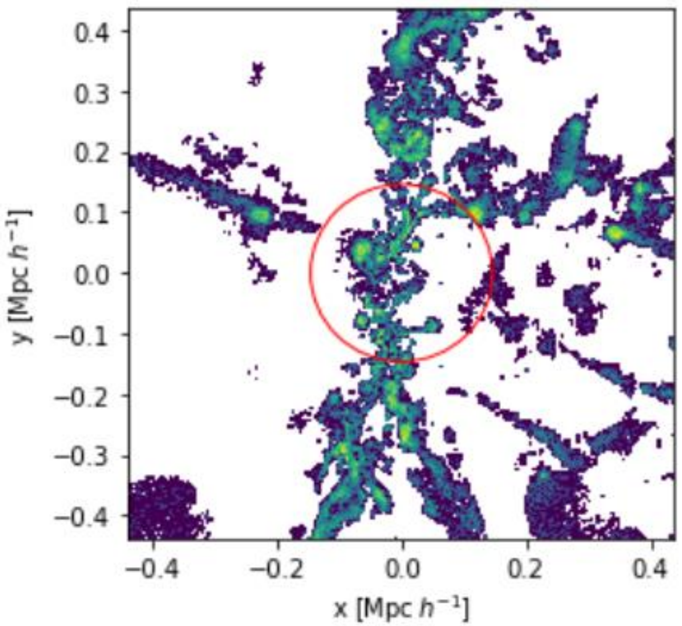




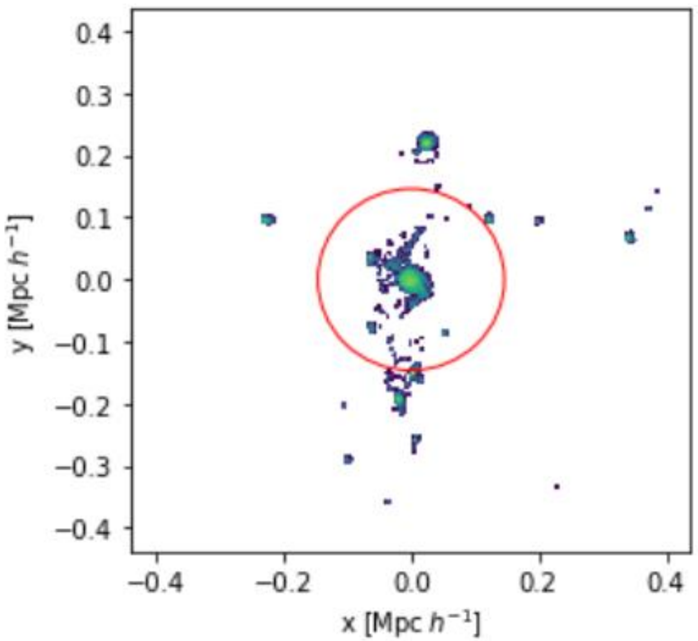
Clump and smooth components of cold gas

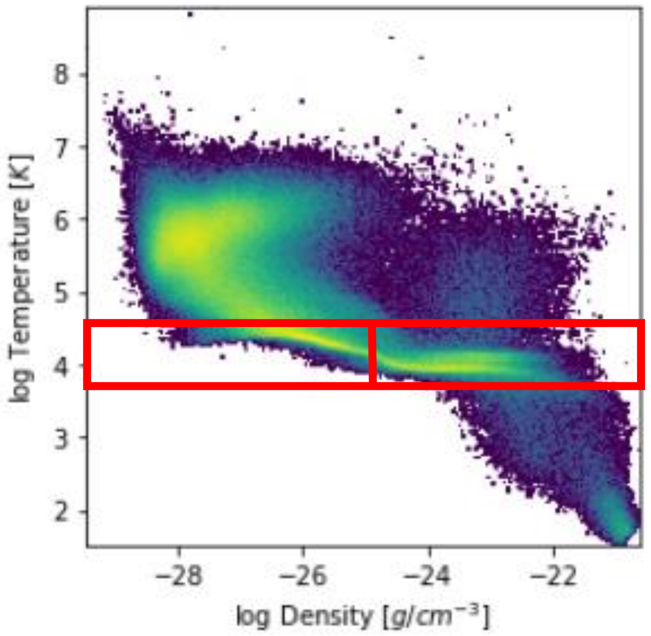
- Spin parameter of cold gas looks strongly affected by clump
- Threshold: $\rho = 10^{-25}$ [g cm^{-3}]

Smooth

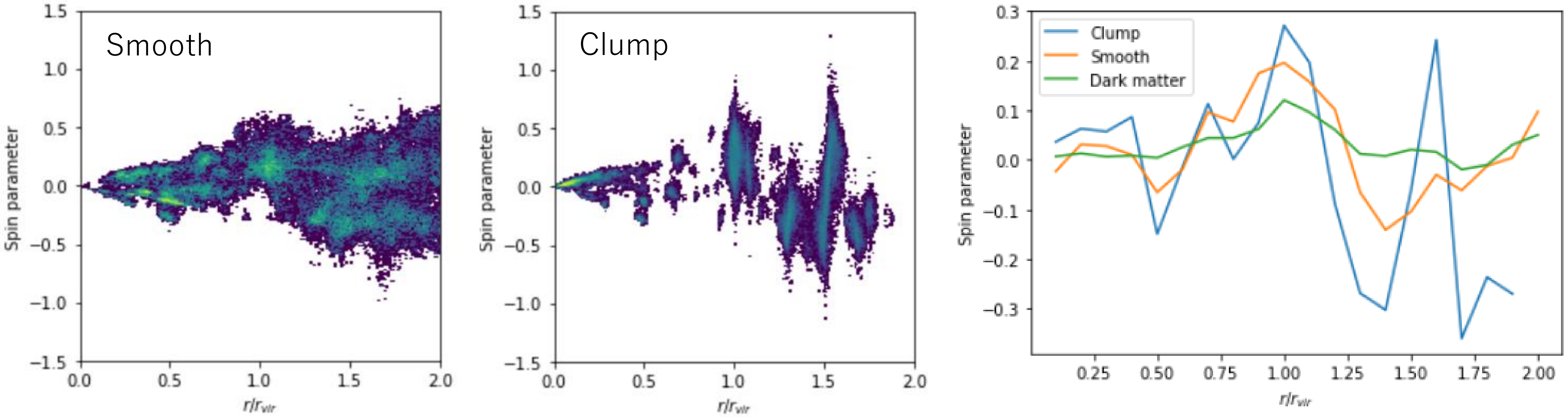


Clump





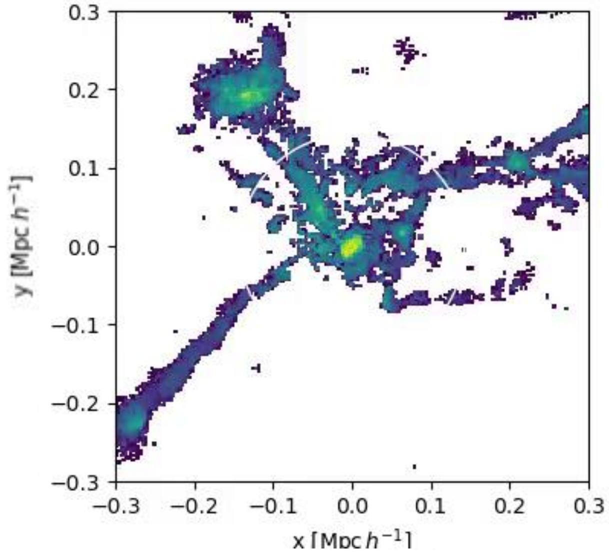
Spin parameter of clump and smooth gas



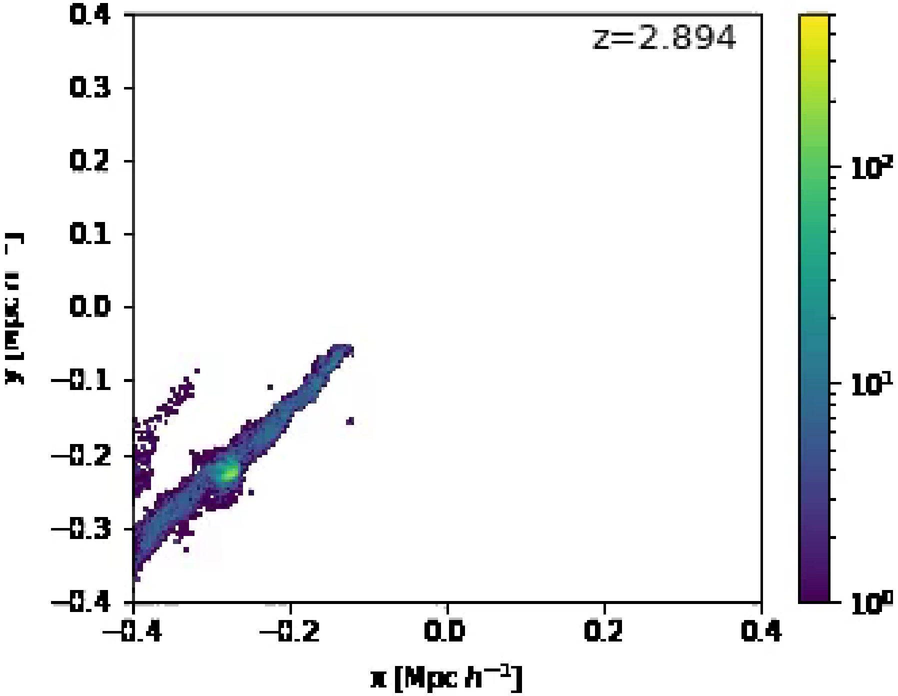
- Spin parameter of cold gas fluctuates due to gas clumps.

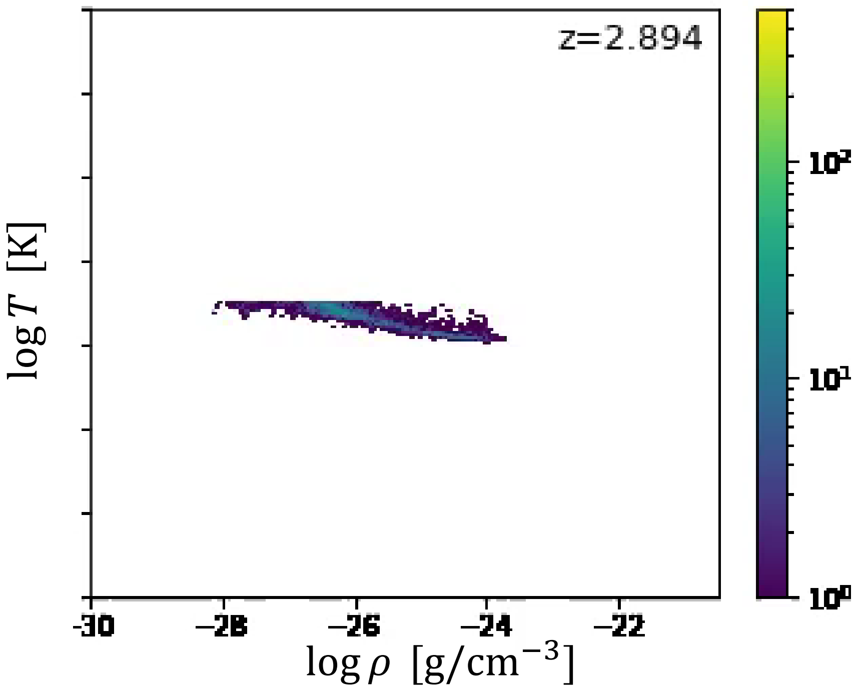
Tracking cold flow gas
- using SPH particle ID tracking

- Extract cold gas outside R_{vir} and track the particles until $z\sim2$.
- Accreting to the center and then outflowing.
- Cold gas evolves to hot gas or $T < 10^{3.8}\ K$.



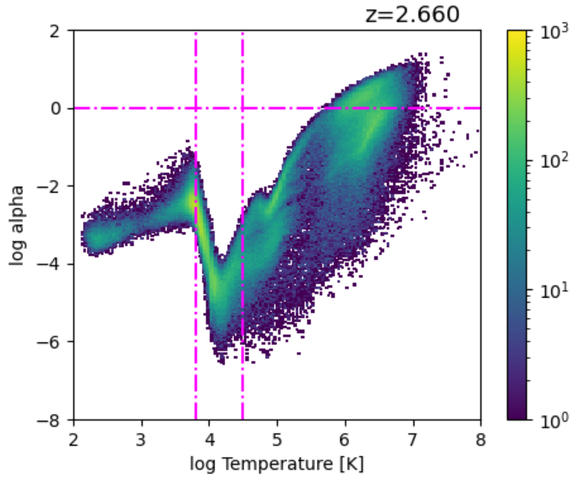
Cold gas



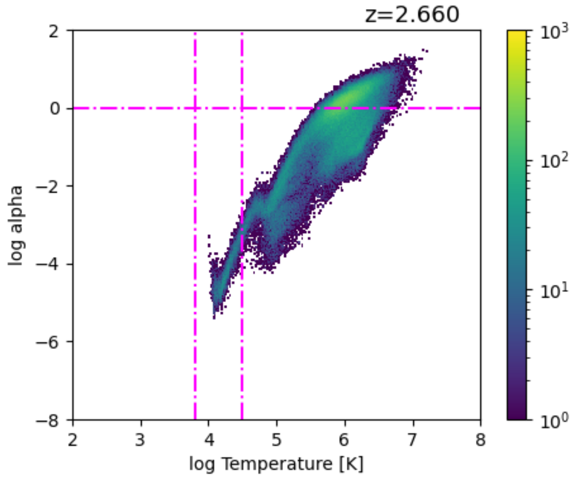


Cooling and compression time scale

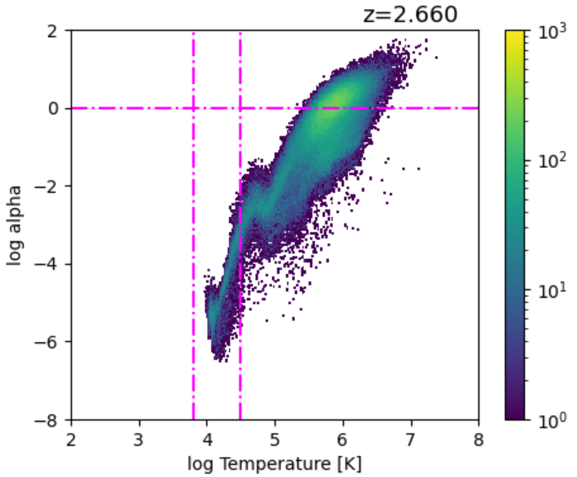
- Shock stability criterion
  - $\alpha = \frac{t_{cool}}{t_{comp}} > 1,\quad t_{cool} \simeq \frac{3}{2}\frac{n k_B T}{n_H^2 \Lambda(T, Z)}\qquad t_{\rm comp} \simeq \frac{28}{5} t_{\rm ff}$
- Cooling function (Sutherland & Dopita 1993; Koyama & Inutsuka 2002)
- Cold mode accretion is dominant if $\alpha < 1$.
- The shock condition is satisfied by a few parts of gas of $T > 10^{5.7}$



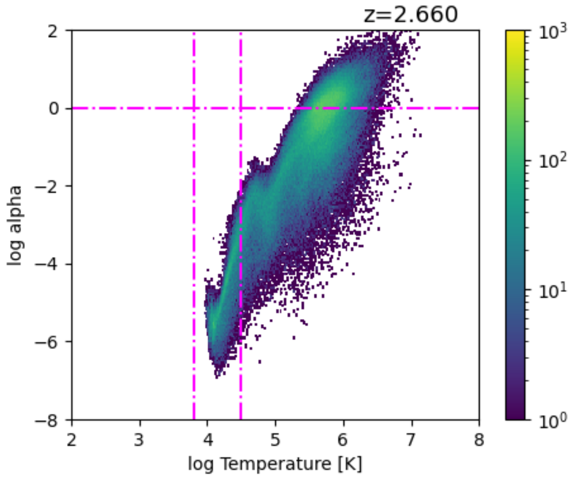
$0 < r < 0.5\ R_{vir}$



$0.5\ R_{vir} < r < 1.0\ R_{vir}$



$1.0\ R_{vir} < r < 1.5\ R_{vir}$



$1.5\ R_{vir} < r < 2.0\ R_{vir}$

Summary

- Run zoom-in cosmological hydrodynamical simulation.
- Cold, dense and metal-poor gas accretes onto galaxy with filamentary structures and fuel star formation while heated.
- The ratio of cooling time scale to compression time scale represents the criterion of the shock stability.

Future plan

- Explore the relation between star formation and disc rotation, and the cold streams.
- Run zoom-in runs of $M_h = 10^{10}, 10^{12}\ M_{\odot}$.
- Examine halo mass dependency, resolution effects and environmental effects.