Cold Streams in the Hot Halo CGM of z~2-3 Galaxies

Han Aung

Collaborators: Nir Mandelker, Avishai Dekel,
Yuval Birnboim, Daisuke Nagai, and more …

KITP Cosmic Web Conference

האוניברסיטה העברית בירושלים
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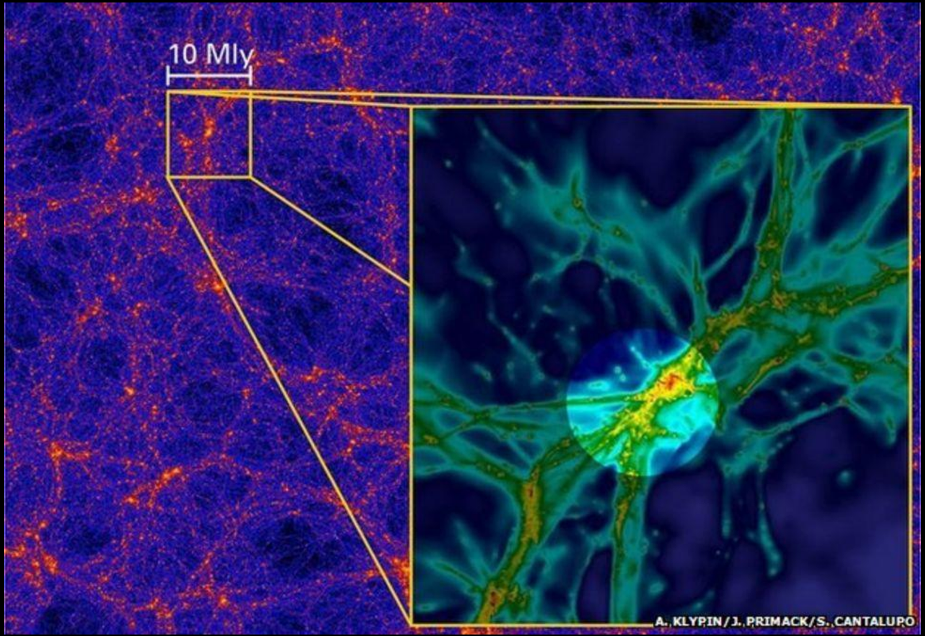
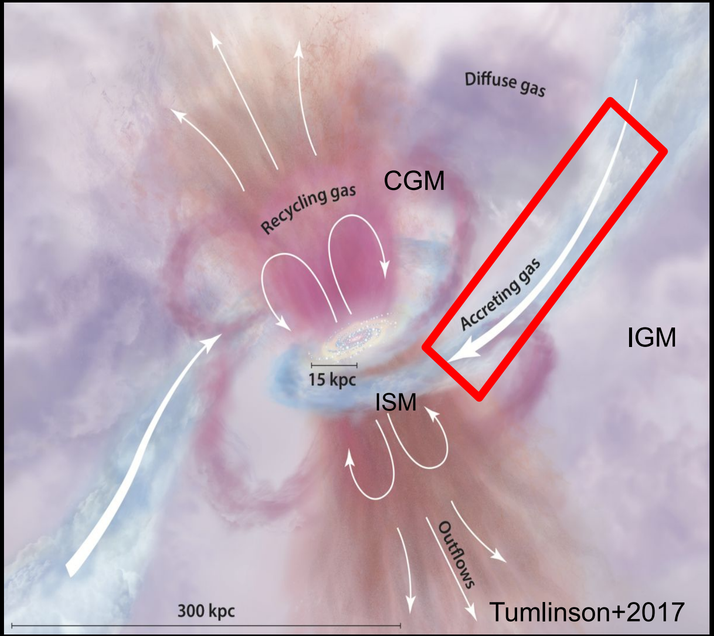
Cosmic Web and Galaxy Evolution



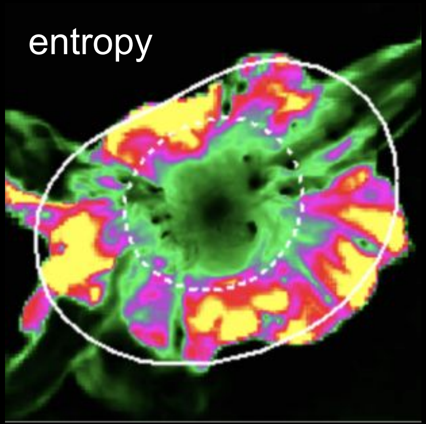


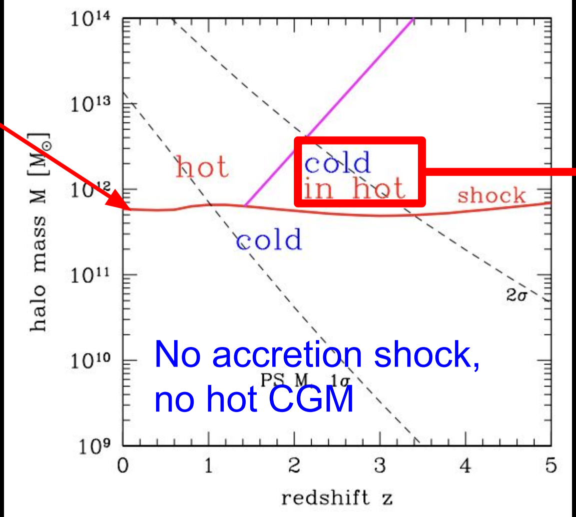
Star formation in galaxies is dictated by how accreted gas from the cosmic web is transported to the galaxy at the center of dark matter halos.

Cold Streams Feeding CGM at High-z

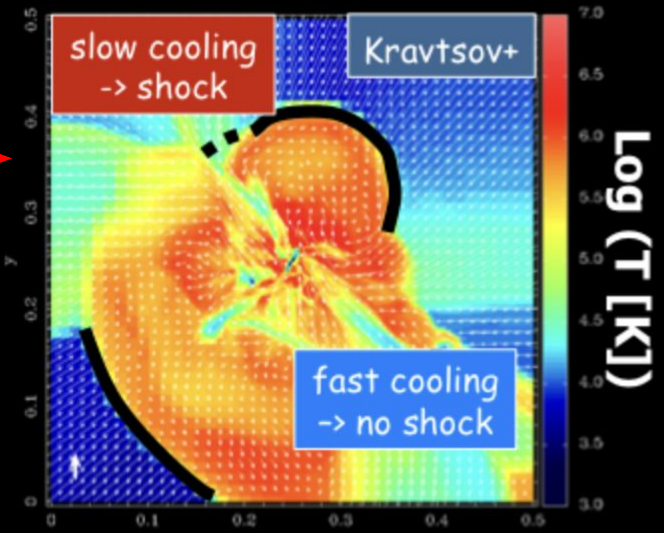
Massive galaxies at high-z (>$10^{12}M_\odot$, z>2) have cold streams penetrating hot shock-heated CGM as main mode of accretion.

Accretion shock formation at M>7e11$M_\odot$





No accretion shock, no hot CGM



slow cooling -> shock

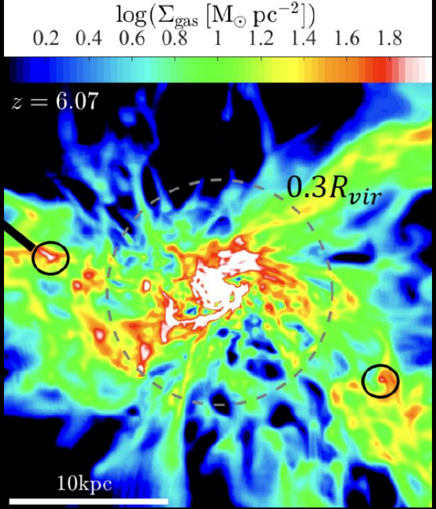
Kravtsov+

fast cooling -> no shock

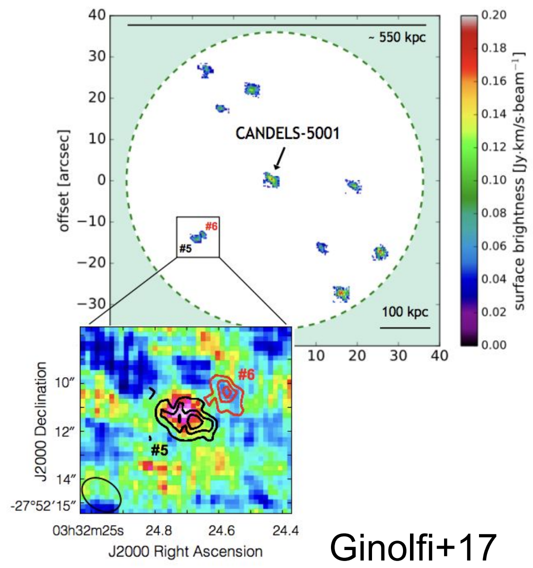
Accretion shock: outermost boundary of hot halo gas, analogous to dark matter splashback radius (Aung+21)

Birnboim & Dekel 03, Keres+ 05, Dekel & Birnboim 06, Fielding+ 17

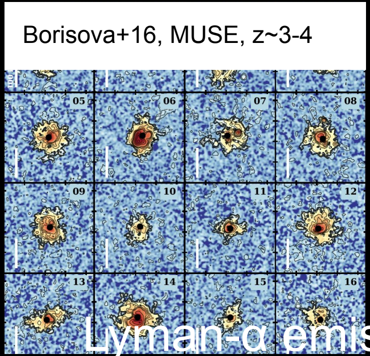
Simulated vs Observed CGM

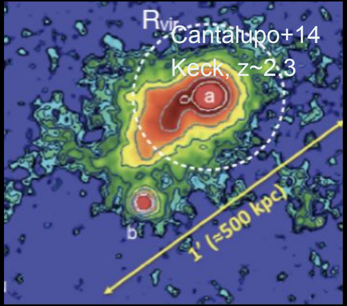


VELA simulations:
Ceverino+14, Zolotov+15

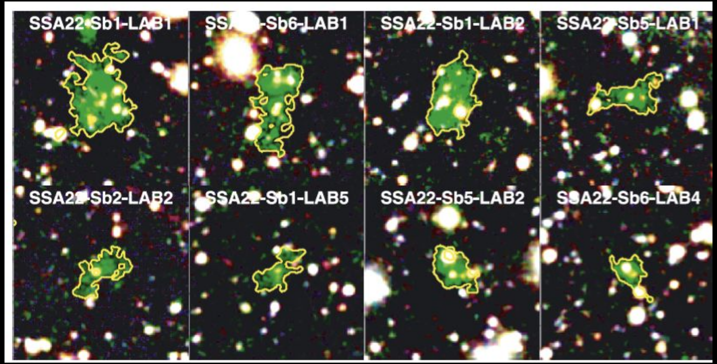


Ginolfi+17


Borisova+16, MUSE, z~3-4


Cantalupo+14
Keck, z~2.3

Lyman-α emissions in CGM

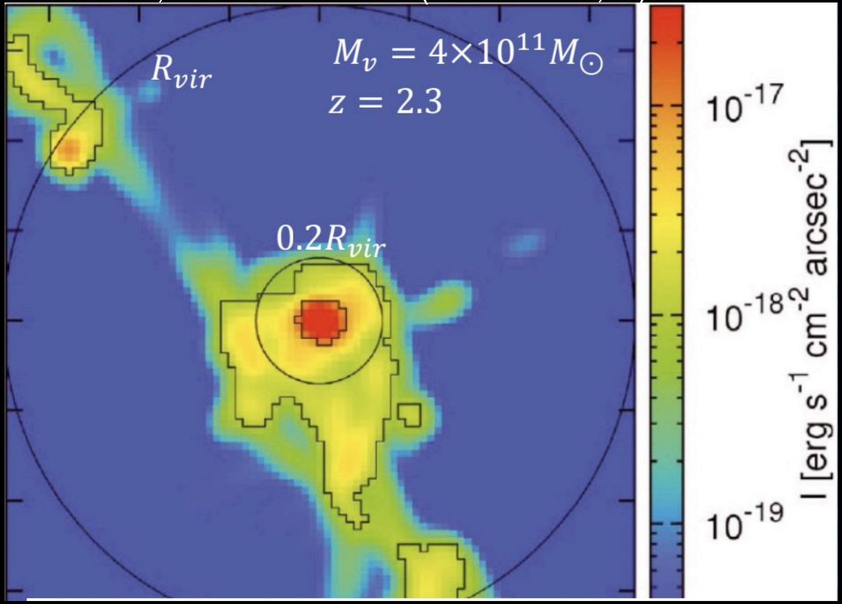


Matsuda+11 Subaru, z~3

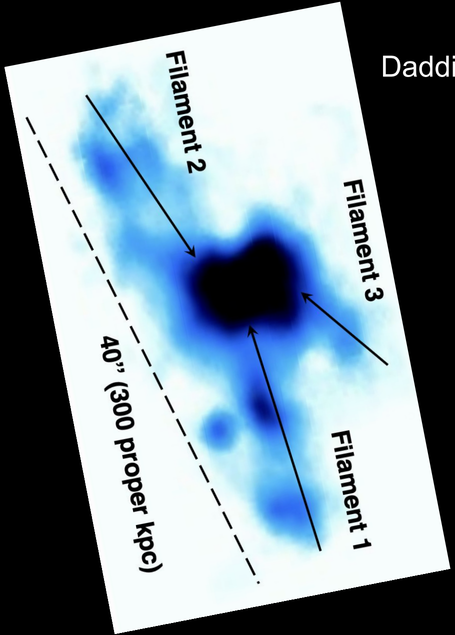
Observations of CGM show clumpy, dense, cold, Lyman-α emitting clouds.

SImulated vs Observed CGM- Lyman α

Goerdt+10, simulated at z=2.3 (Ceverino+09,10)



Daddi+21, z=2.91 by KCWI



Simulations suggest observed Lyman-α blobs may be powered by cold streams infalling and dissipating gravitational energy. (Dijkstra & Loeb 09, Goerdt+10, Steidel+00, Matsuda+06,11)

What is the mechanism for this dissipation?

Cold Gas Stream in Hot Halo

Dense streams cool efficiently:
T_s~10^4K form cooling curve

Dilute halo doesn't cool:
T_b~10^6K from shock heating

Pressure equilibrium sets $\rho_s/\rho_b=T_b/T_s$

DN1= $\boldsymbol{\delta}$ ~ρ_s/ρ_b ~ 30-300

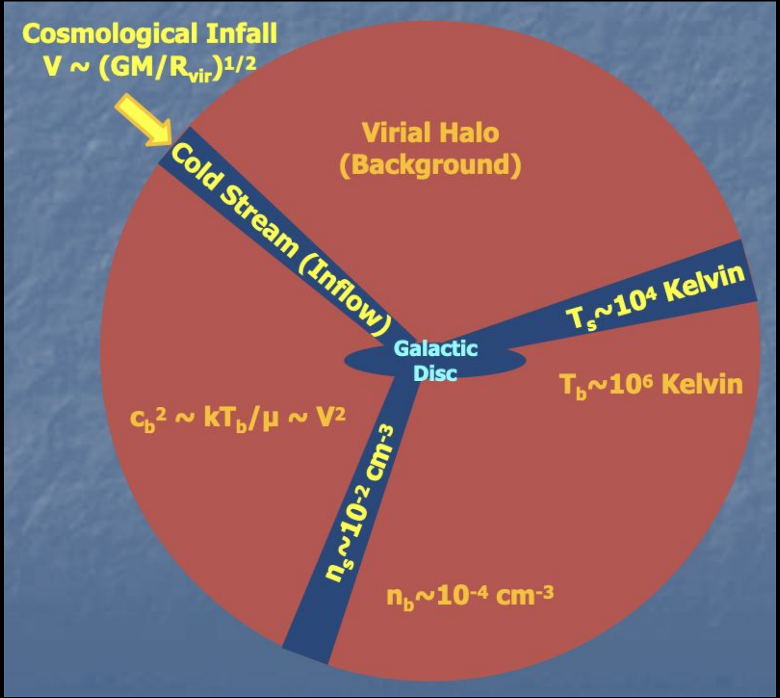
Stream is supersonic relative to halo

DN2= $\mathbf{M_b}$~ v/c_b ~0.5-2

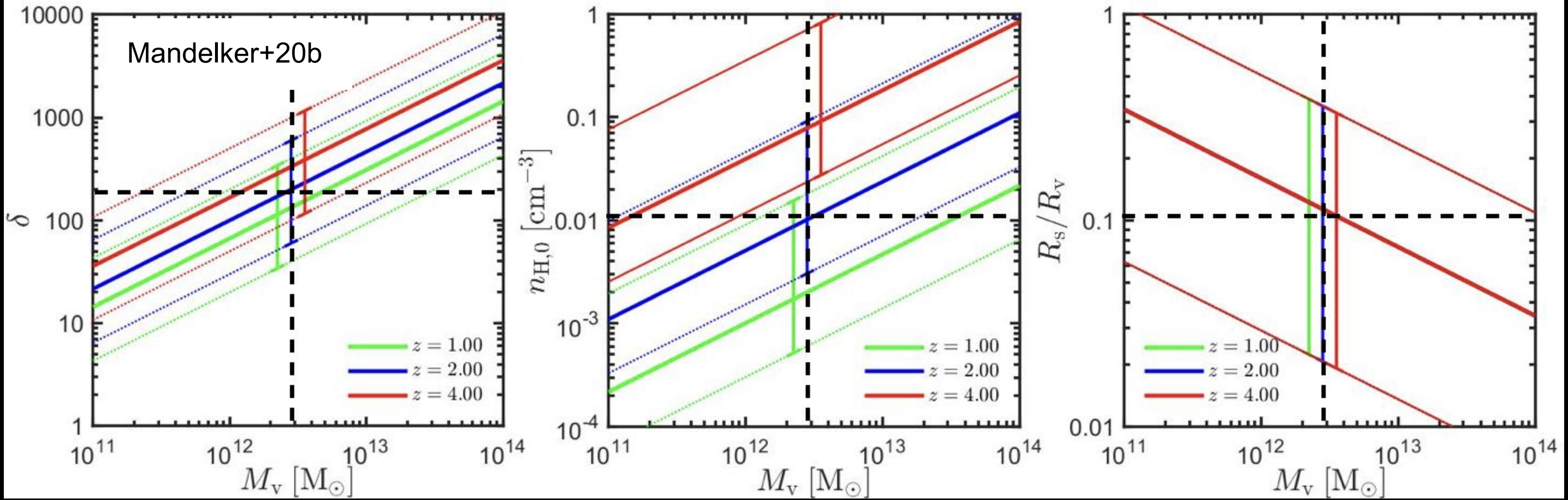
very supersonic relative to itself
v/c_s ~10

Stream radii constrained by cosmological accretion rate

DN3= $\mathbf{R_s/R_{vir}}$ ~ t_{sc}/t_v



Predicted Stream Parameters



$T_h \sim T_{vir}$

$T_s \sim 10^4$

Pressure equilibrium

δ

Halo density at R_{vir}

Hot gas mass fraction

n_s

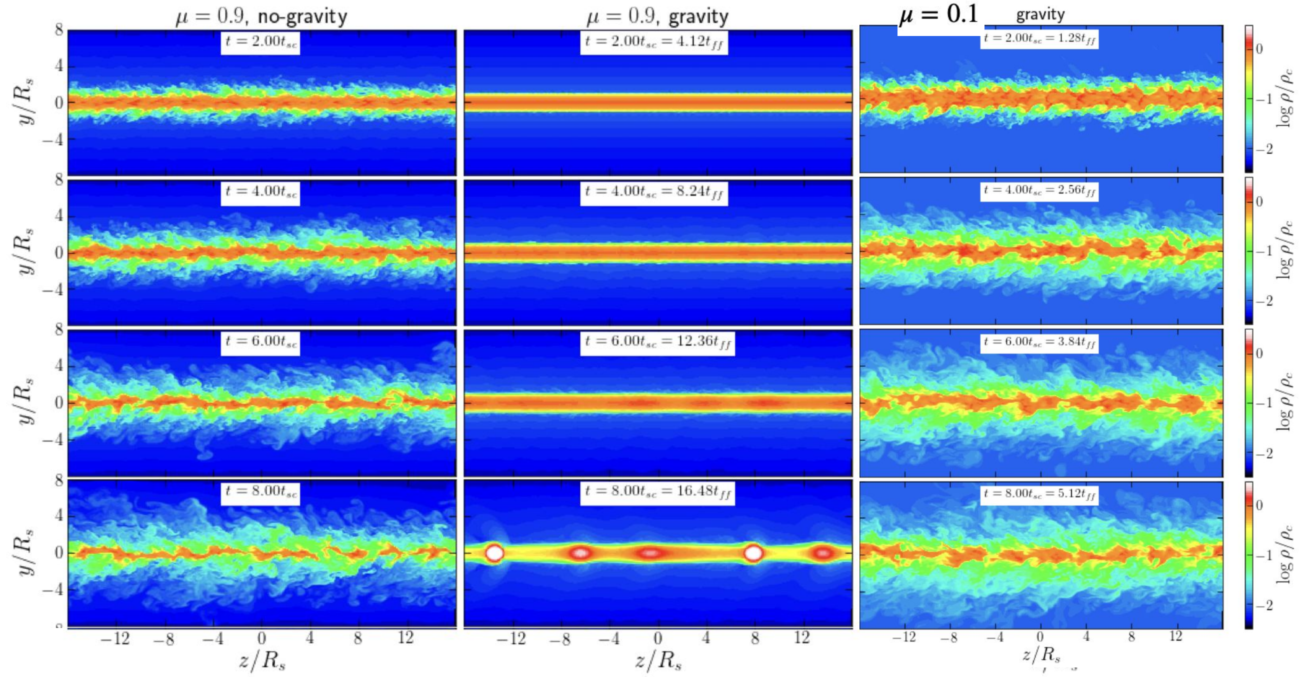
$V_s \sim V_{vir}$

$\dot{M}_{vir} \propto M_{vir}(1+z)^{2.5}$ (cosmology)

Fraction of accretion along stream

For $M_v=10^{12.5}M_\odot$ at z=2, δ~200, n_s~0.01cm^{-3}, R_s/R_v~0.1

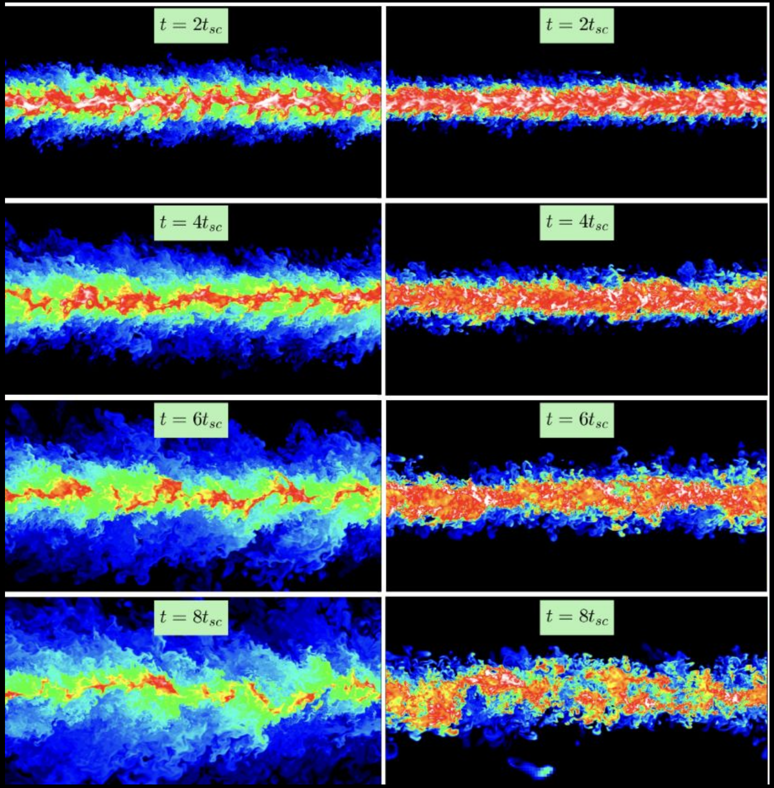
Kelvin Helmholtz Instability (KHI)



Adiabatic (Mandelker+16,19, Padnos+18): KHI disrupts and decelerates the stream.
Magnetic field (Berlok & Pfrommer 19, Mandelker+in prep): Suppresses KHI
Self-gravity (Aung+20): Suppresses KHI, but forms clumps at high gravity due to gravitational collapse.

KH Instability with Cooling

Mandelker+2020a



No cooling

Differences

- Stream expands into background
- Stream density decreases

Similarities

- Entrains mass
- Decelerates

Cooling

Depends on additional dimensionless number:

$\tau = t_{cool}/t_{dis}$ ratio of the cooling time in mixing region vs stream disruption time

$\tau<1$

Differences

- Background condenses onto stream
- Stream remains dense

Similarities

- Entrains mass
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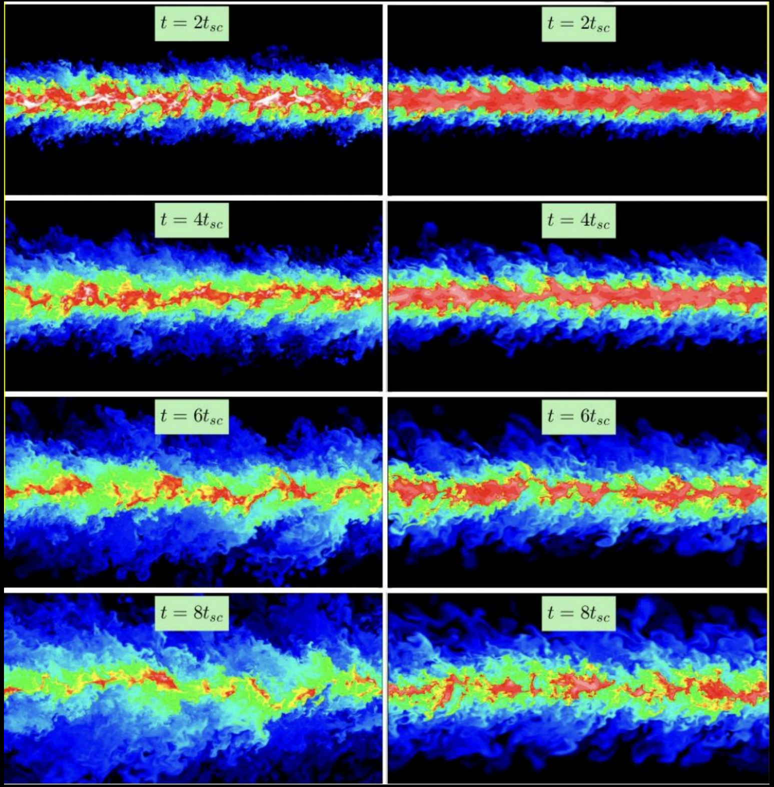
KH Instability with Cooling

Mandelker+2020a



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τ<1

Differences

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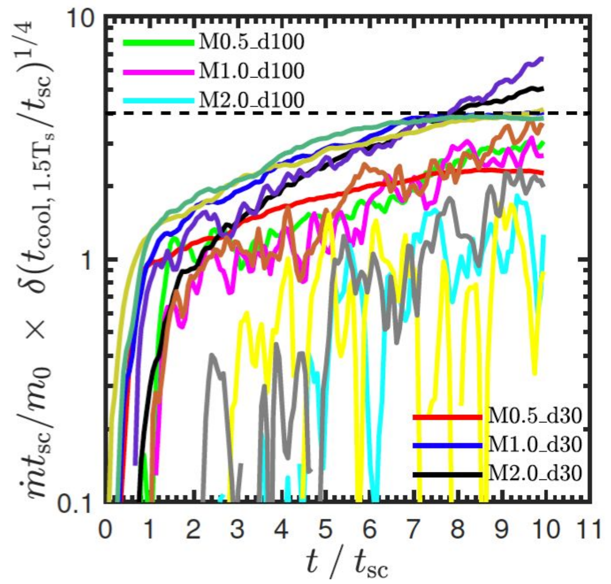
Similarities

- Entrains mass
- Decelerates

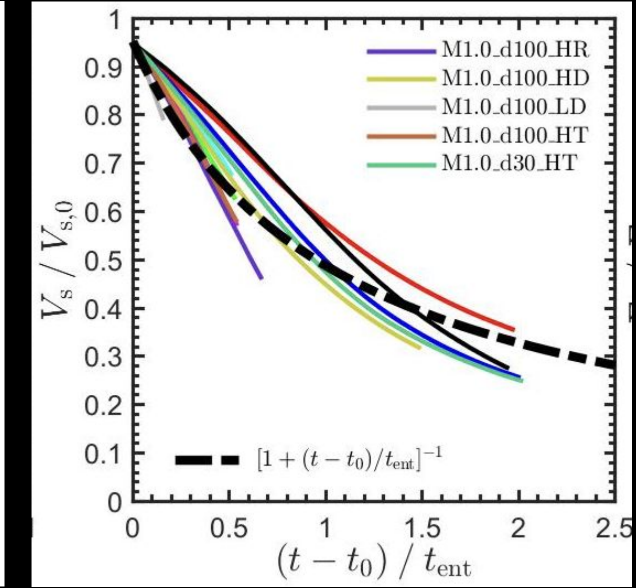
τ>1: same as no cooling

Evolution of Cooling Stream

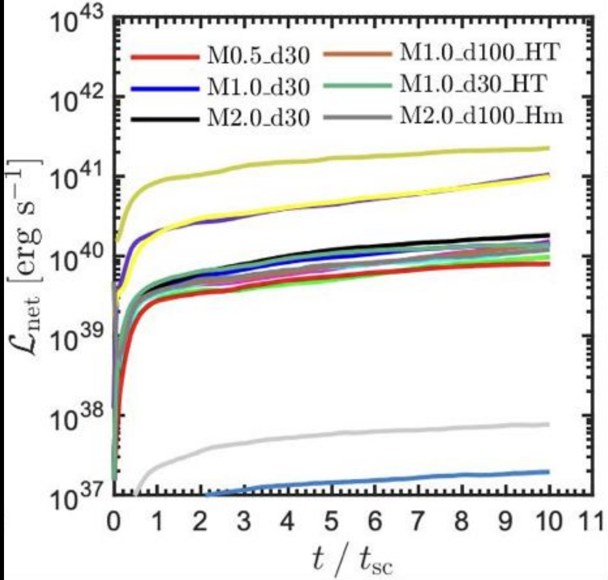
Mass Entrainment



Deceleration of Stream

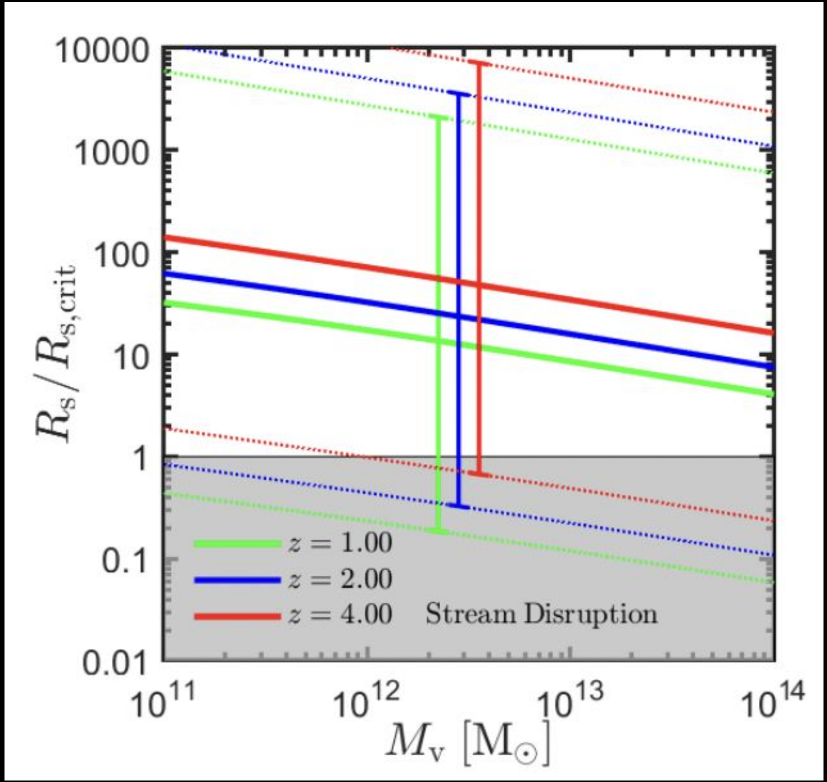


Lyman-α Emission



Cooling stream entrains mass, decelerates, and dissipated energy may be observed as Lyman-α (lower than observed luminosity of Lyman-α, but no halo potential yet).

Prediction for Cold Stream in High-z Galaxies



$t_{cool}<t_{dis}$ for the stream to survive.

$t_{dis} \propto t_{sc} \propto R_s$

There is a critical stream radius above which the stream will survive due to cooling. KHI below $R_{s,crit}$

$$R_s^2 \propto \frac{\dot{M}}{\rho_s v} \propto \frac{M(1+z)^{2.5}}{\delta \rho_{vir} v}$$

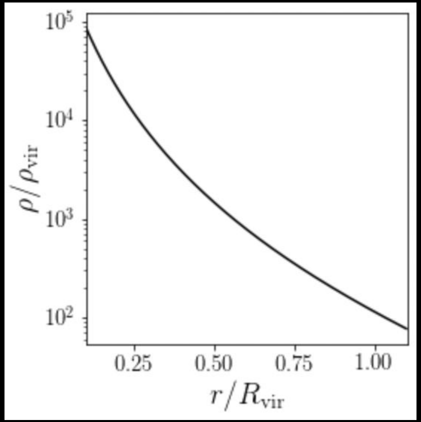
based on predicted stream parameters

At z=2, almost all streams are stable.

Analytic Model of Cold Stream in Halo Potential

Halo potential causes:

- stream to accelerate: counteract the deceleration of stream
- narrower stream: faster sound crossing and entrainment
- increased density: faster cooling and entrainment



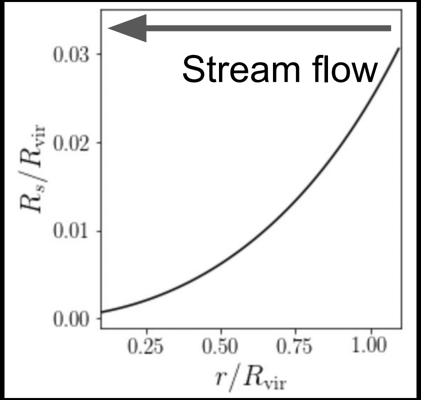
$$t_{sc} \propto r_s(r) \propto r^{\beta/2}$$

$$t_{cool} \propto \rho(r)^{-1} \propto r^{\beta}$$

$$t_{ent} \propto \left(\frac{t_{cool}}{t_{sc}}\right)^{1/4} t_{sc} \propto r^{5\beta/8}$$

β is 2 for conic stream, and constant density contrast with isothermal halo.

Varying β for isothermal stream in hydrostatic CGM within NFW halo



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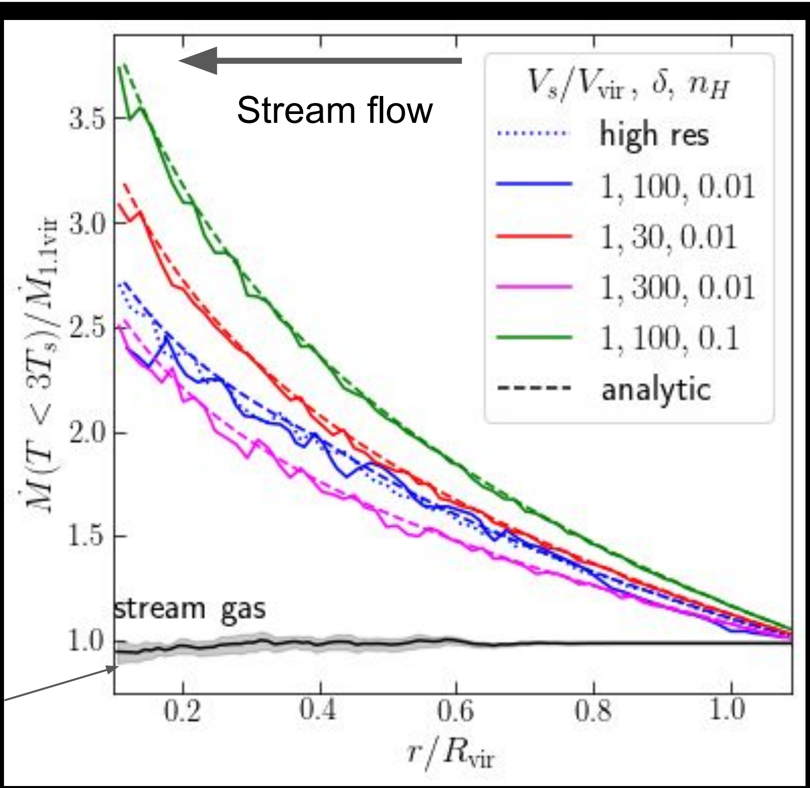
Dissipative power: $\mathcal{L}_{\rm diss} \simeq \left|\dot{E}_{\rm k}\right| + \frac{5}{3}\left|\dot{E}_{\rm th}\right|.$

Both energy: $\dot{E}_k, \dot{E}_{\rm th} \propto \frac{1}{t_{\rm ent}}$

Entrainment time scale controls both energy dissipation rates as the entrainment causes the deceleration and radiation of thermal energy.

Cooling Stream in Halo Potential

Radial mass flux of cold gas>1 implies additional source other than radial inflow from stream: Entrainment of cooling CGM gas onto cold stream



Mass flux of original stream gas

Faster entrainment and acceleration leads to more cold gas flowing into the galaxy than dark matter halo.

Implication for Galaxy Formation

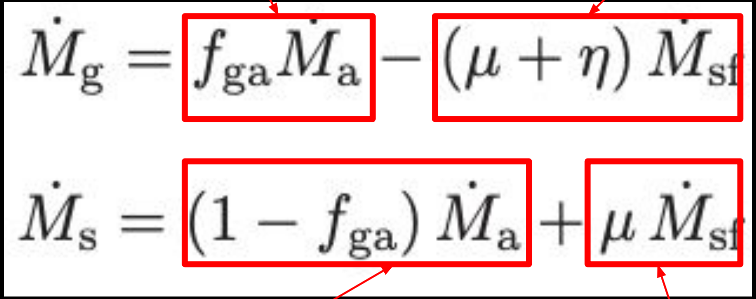
Bathtub/equilibrium model: Balancing the inflow, outflow of gas and formation of stars in ISM (Dave+12, Lilly+13, Dekel & Mandelker 2014)

Gas accreted

Gas loss to star formation & feedback

Change in gas mass

Change in stellar mass



$$\dot{M}_{\rm g} = \boxed{f_{\rm ga}\dot{M}_{\rm a}} - \boxed{(\mu+\eta)\,\dot{M}_{\rm sf}}$$

$$\dot{M}_{\rm s} = \boxed{(1-f_{\rm ga})\,\dot{M}_{\rm a}} + \boxed{\mu\,\dot{M}_{\rm sf}}$$

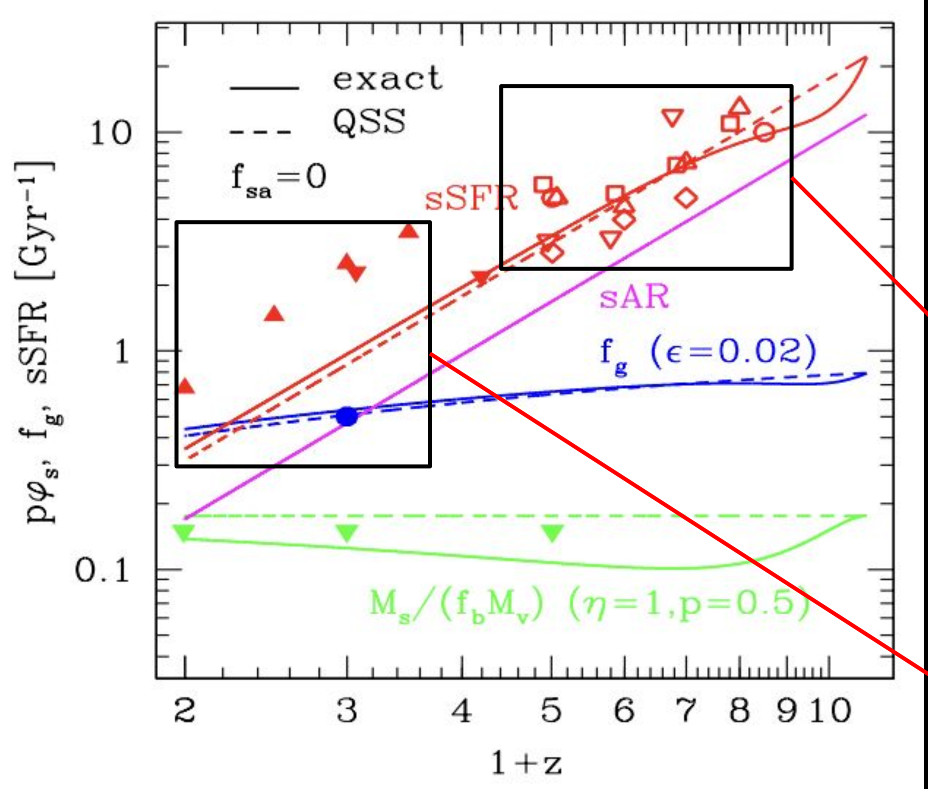
Stellar mass accreted

Star formation

μ = fraction of stars formed that are not lost to SN winds

η = mass loading factor, ratio of gas loss to SFR

Implication for Galaxy Formation

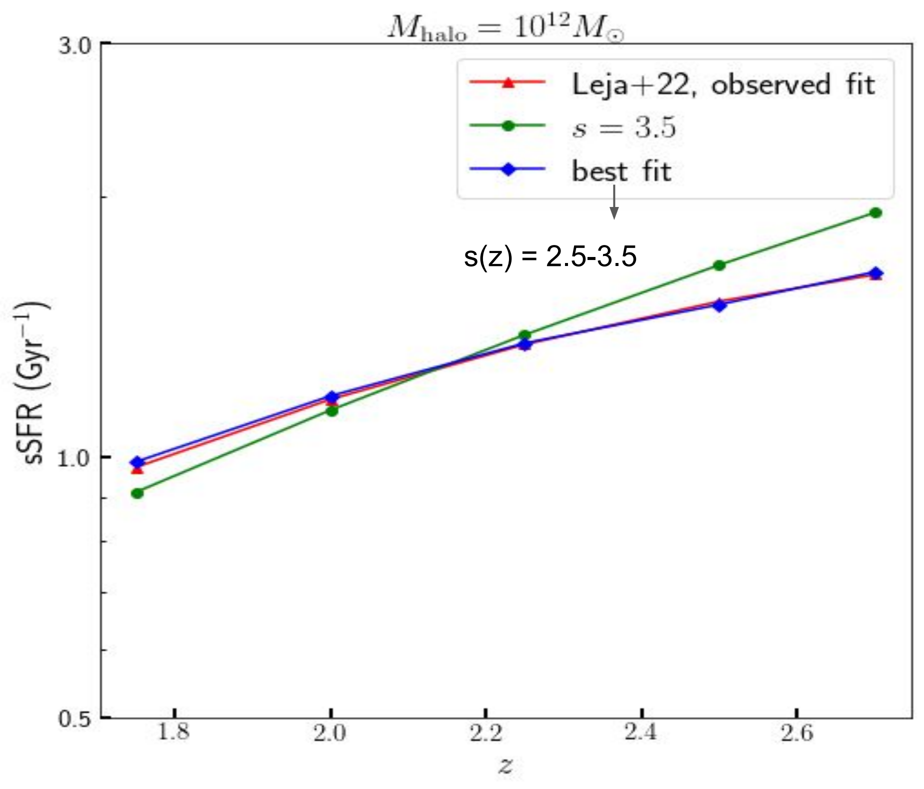


The model underpredicts sSFR of z=2-3 galaxies, but not z>5 (Dekel & Mandelker 2014).

Observations at z>3 for M<Mshock, no hot CGM, good agreement

Observations at z=1-3 for $10^{12}M_\odot$, can sustain hot CGM, disagreement

Implication for Galaxy Formation



s(z) = 2.5-3.5

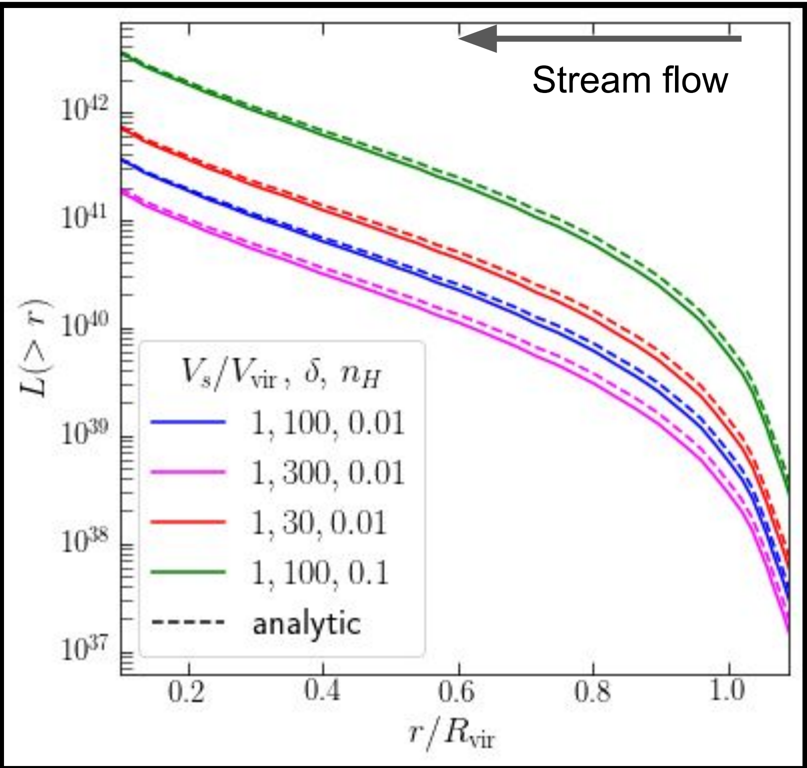
The model underpredicts sSFR of z=2-3 galaxies, but not z>5 (Dekel & Mandelker 2014).

The difference can be reconciled if the cold gas accretion onto the galaxy is boosted from cosmological accretion with s=[2-4]

$$\frac{\dot{M}}{M} = s\left(\frac{\dot{M}}{M}\right)_{\rm fiducial}$$

Lyman-α Emission of Cooling Stream in Halo Potential

Total luminosity integrated outside r



Emission from cold stream can explain the observed Lyman-α emission in CGM >10^{42}erg/s.

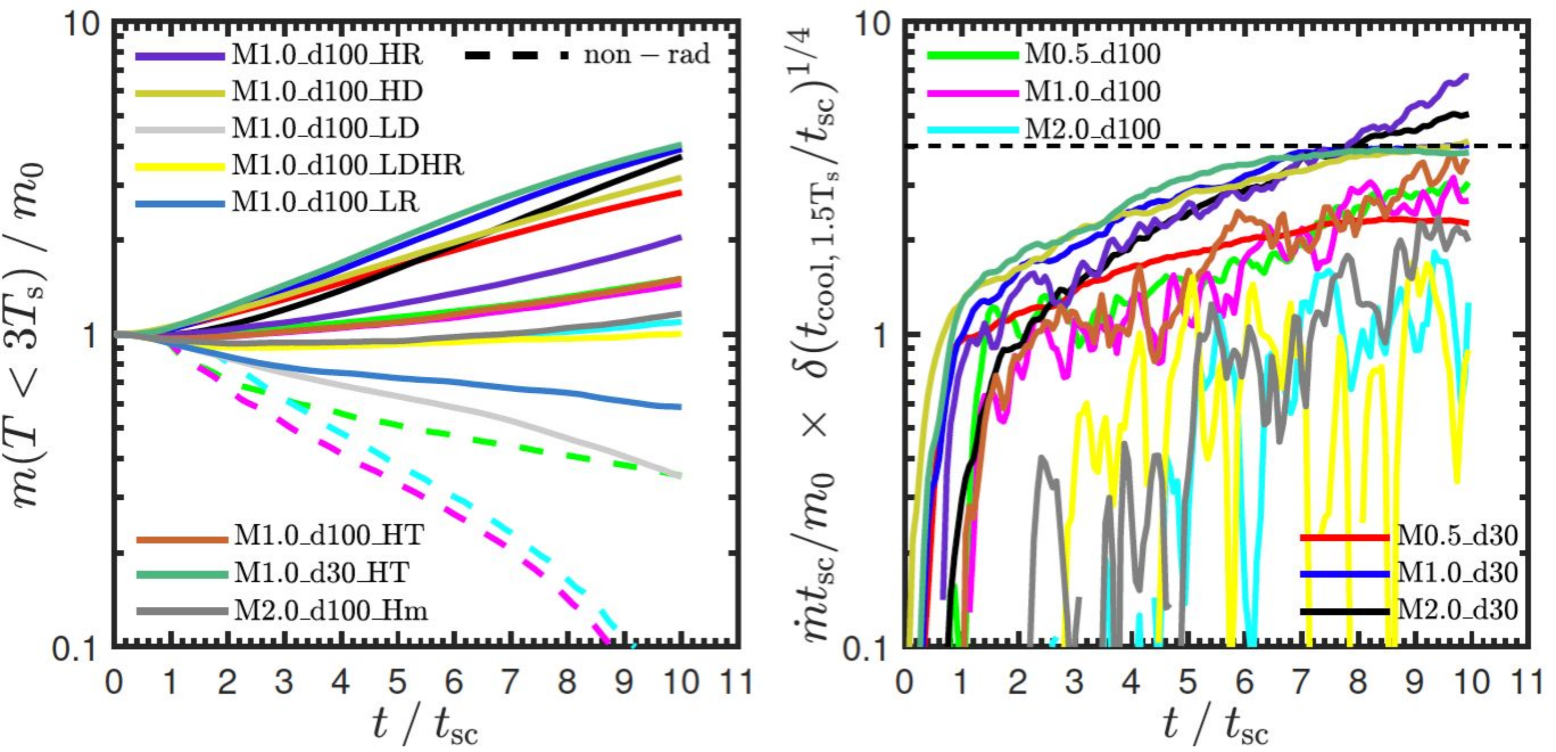
Summary

- Cold streams feeding high-z galaxies can dissipate kinetic and thermal energy and entrains mass as it mixes with hot CGM due to KHI.
- Halo potential causes stream to get narrower, accelerate, and increases the dissipation of energy and entrainment rate.
- Cold gas accretion onto the galaxy is boosted from cosmological accretion by a factor of [2-4], supplied by entrainment and cooling of CGM gas
- Lyman-α emission through the CGM can match the observed luminosity of Lyman-α blobs.

Next Steps

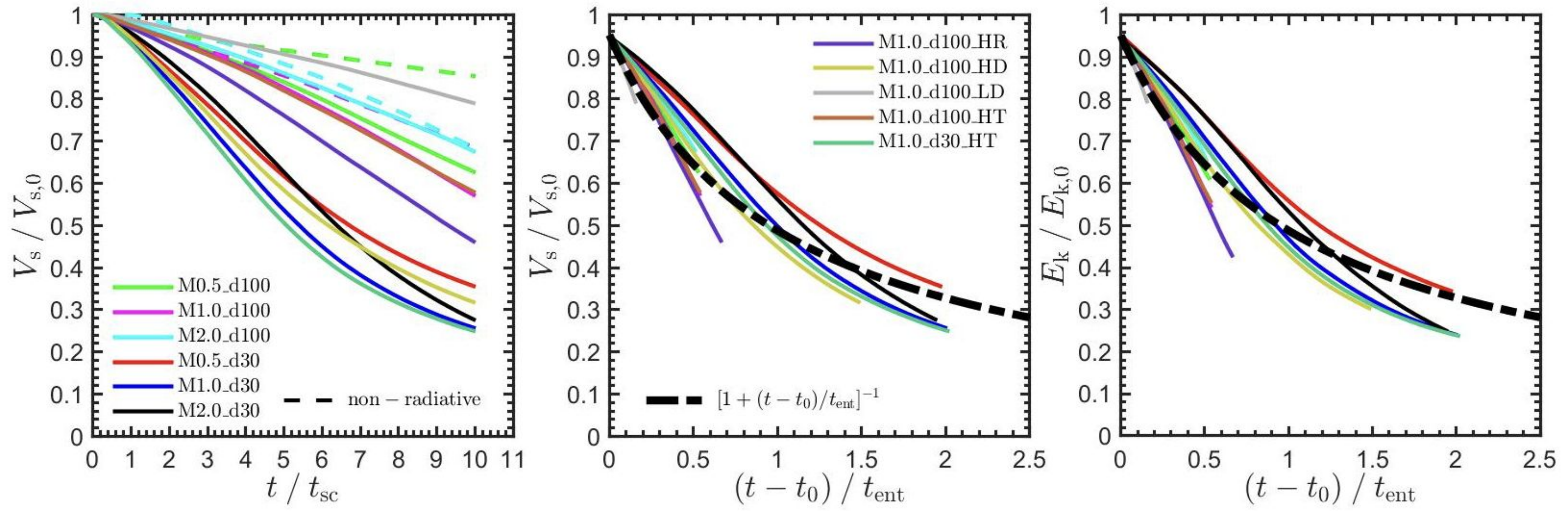
- Combine halo potential + cooling + self-gravity + MHD
- Cosmological simulations with refinements on stream

Mass Entrainment



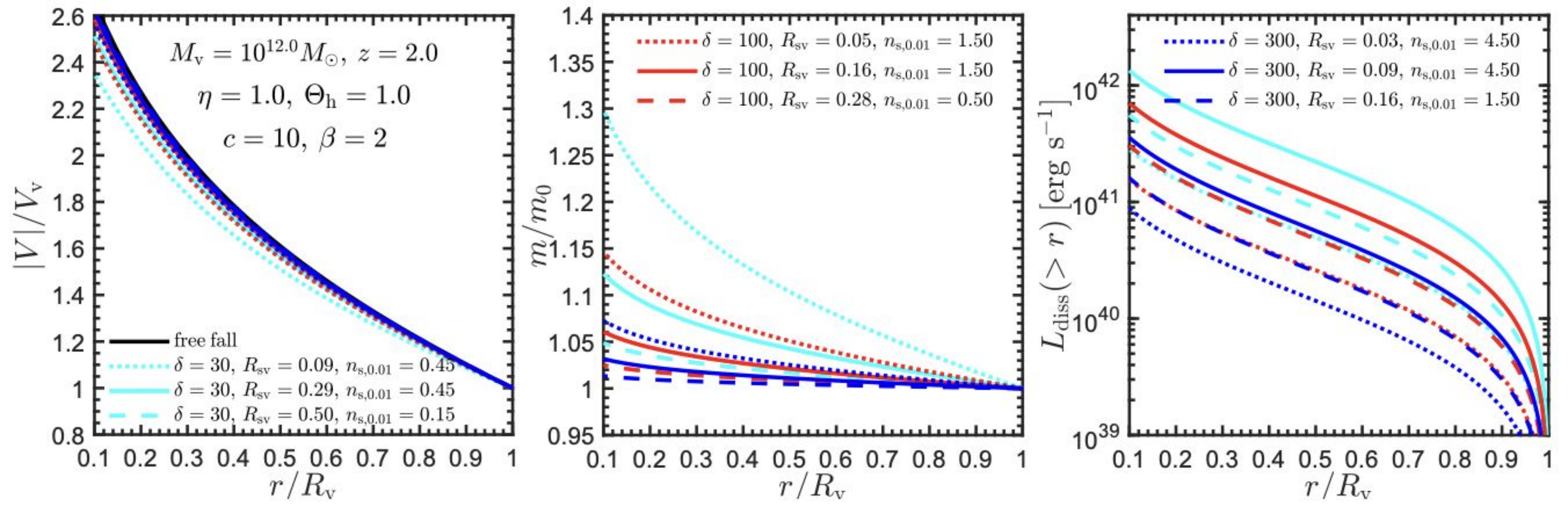
Hot gas mixes with cold gas, cools down and condenses onto stream.

Deceleration of Stream



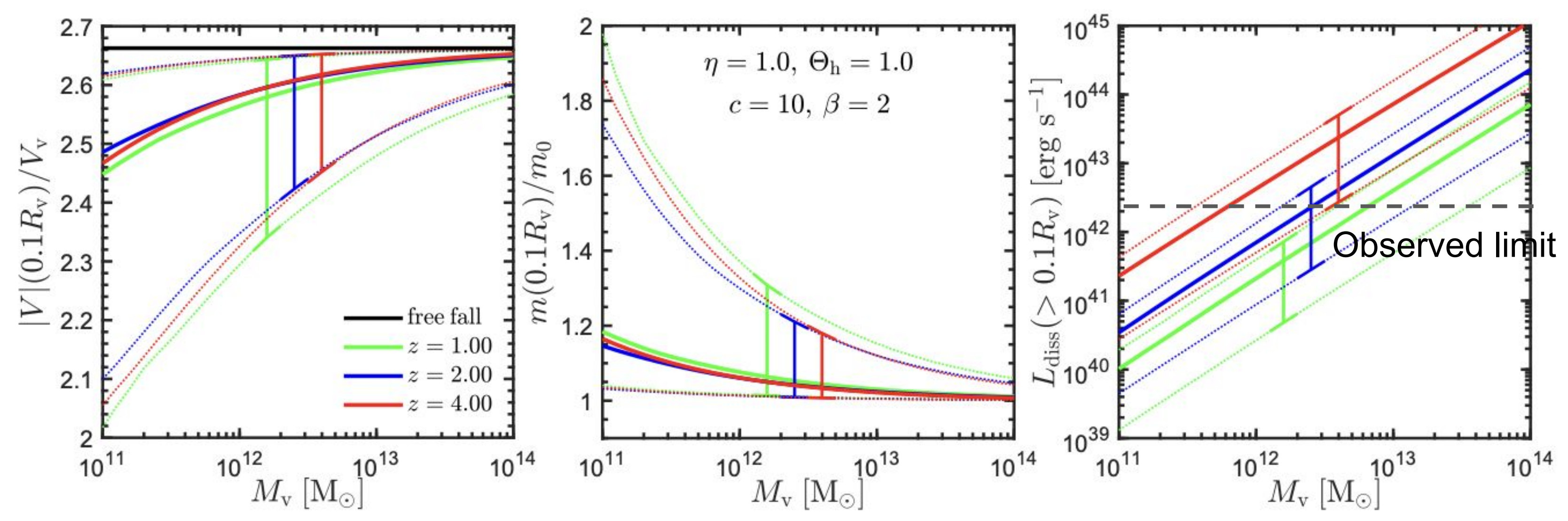
Inflowing stream mixes with background without momentum -> stream decelerates over time (no halo potential yet)

Lyman α with Halo Potential



As the stream falls into halo, and entrainment is faster, and emission is stronger

Lyman α with Halo Potential



Halo potential pushes Lyα luminosity above observed values (10^{42-44}) in inner region of the halo.