Gas in Motion:
How Simulated Galaxies Control Their Star Formation

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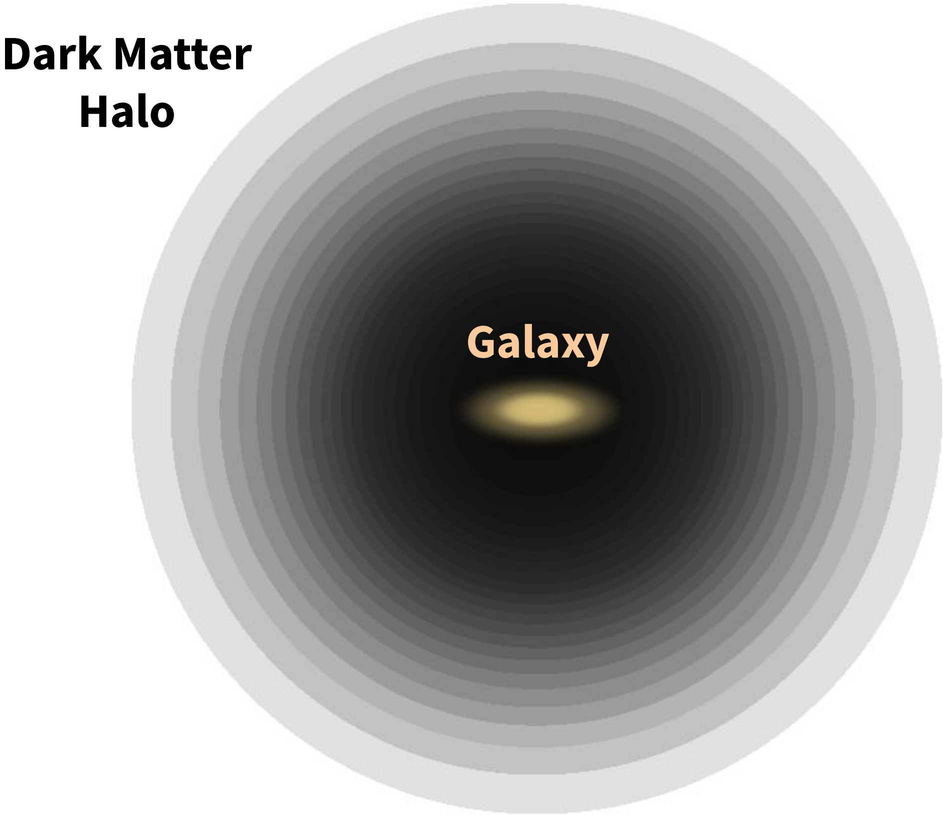
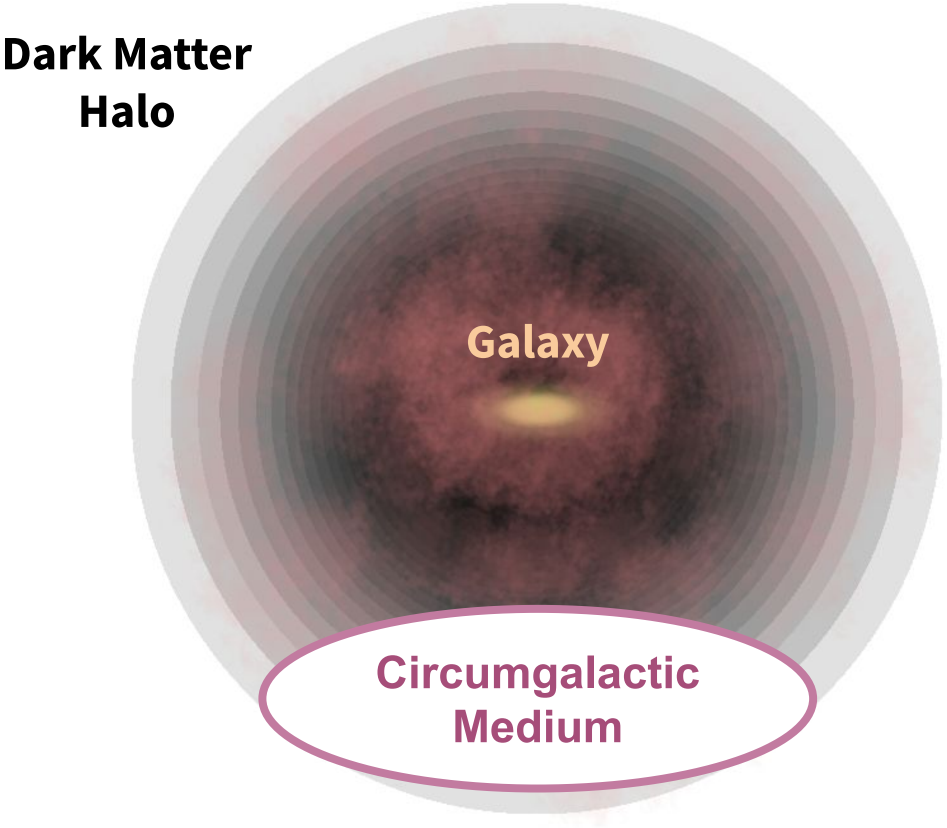
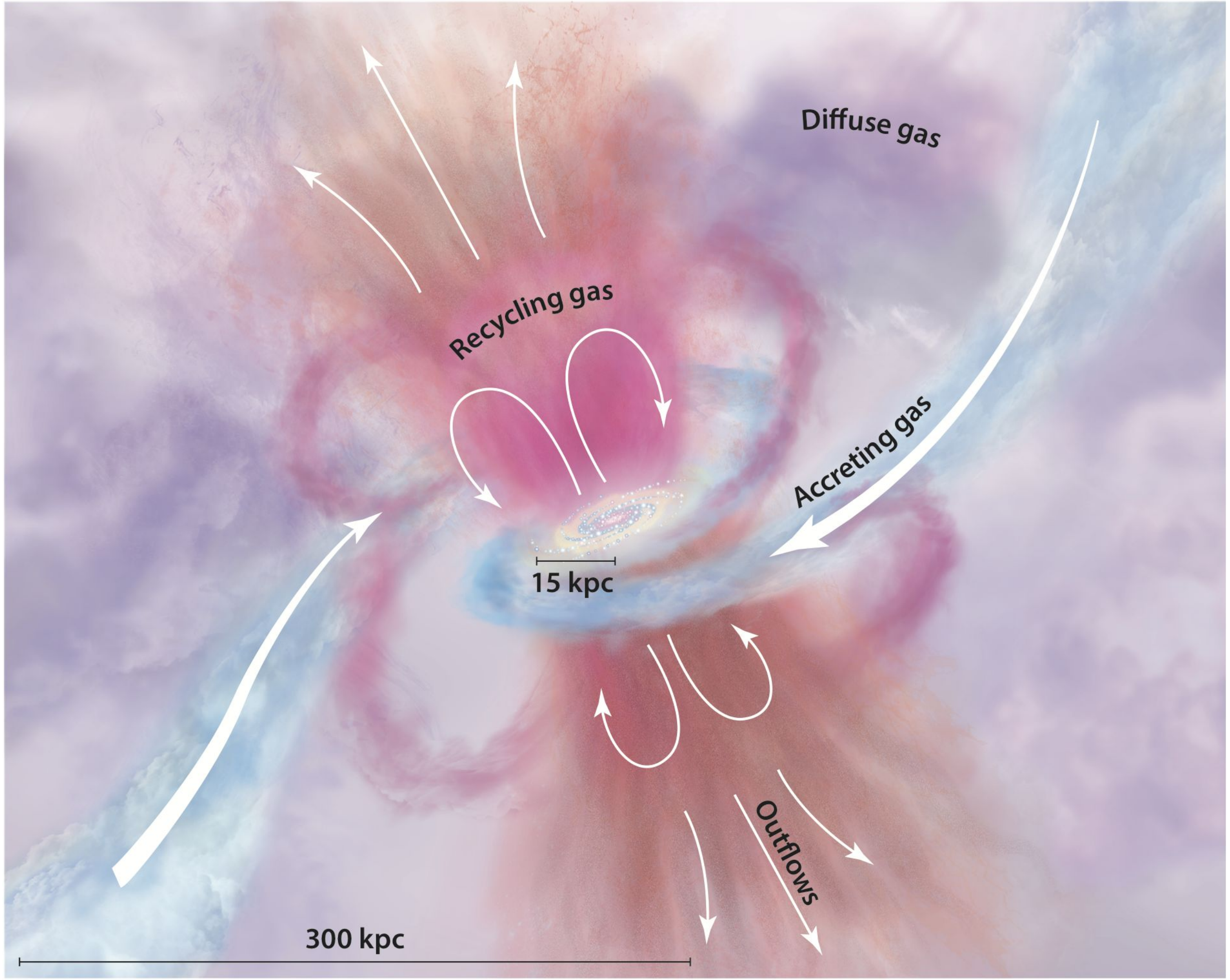

Dark Matter
Halo
Galaxy


Dark Matter Halo
Galaxy
Circumgalactic Medium

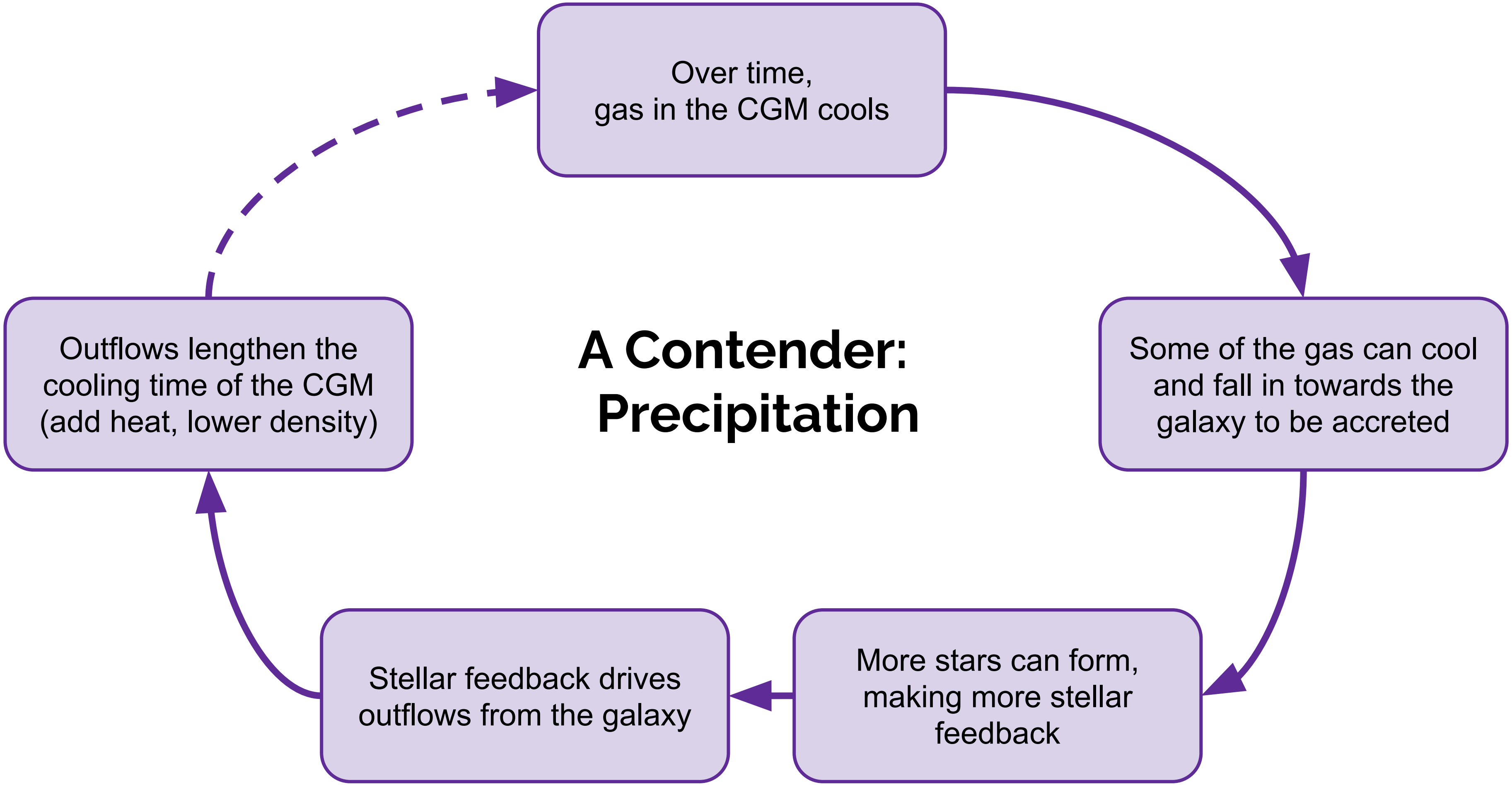


Tumlinson+17

The Situation

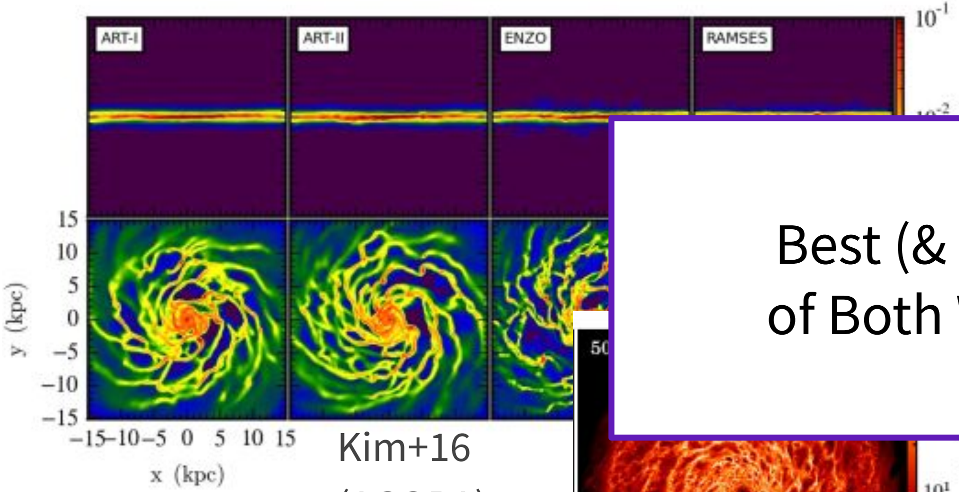
1. The CGM is a multiphase **gas reservoir & mediator**
2. **Gas must be accreted** to sustain star formation over cosmic time
3. Galaxies **tune their stellar mass** based on their dark matter mass

A Contender: Precipitation

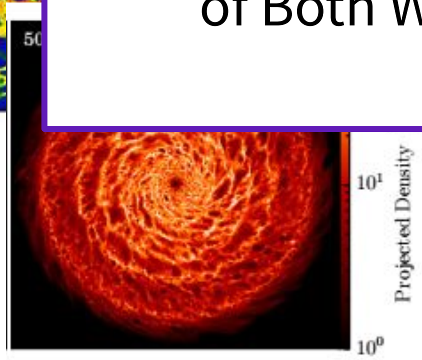


Previous Idealized Simulations

Star-Forming Disk, No CGM

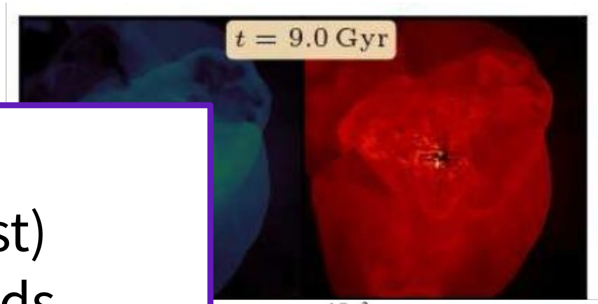


Kim+16 (AGORA)

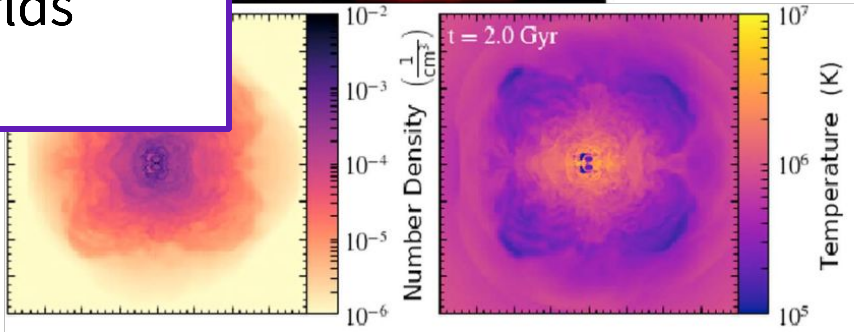


Benincasa+16

CGM, No Star-Forming Disk



Fielding+17



Li & Tonnesen 20

Best (& Worst)
of Both Worlds

The Sisyphus Suite

Target Questions

- Can we make a self-regulating system?
- Does it regulate according to the precipitation model?
- How robust is self-regulation to variations in initial conditions?

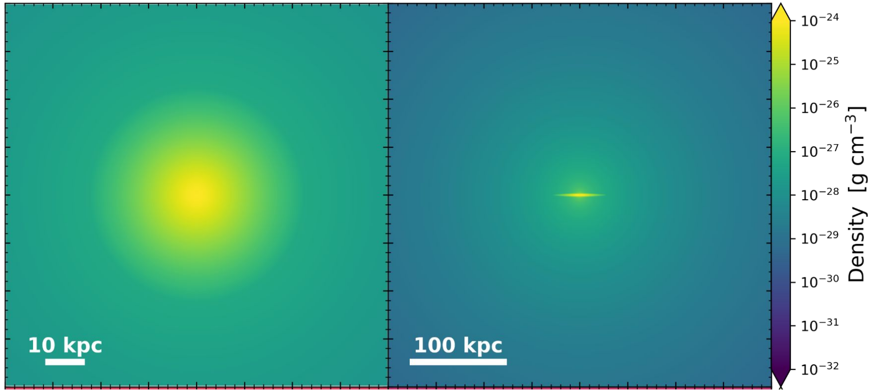
Numerical Test of Self-Regulation

Setup

- Milky Way-like idealized, isolated galaxy
- Gravitational potential
  - NFW dark matter
  - Stellar disk
- Star particles
- Rotation in both disk *and* CGM *(shiny!)*
- CGM set-up to match expectations of precipitation-regulation (Voit 2019)

Variants

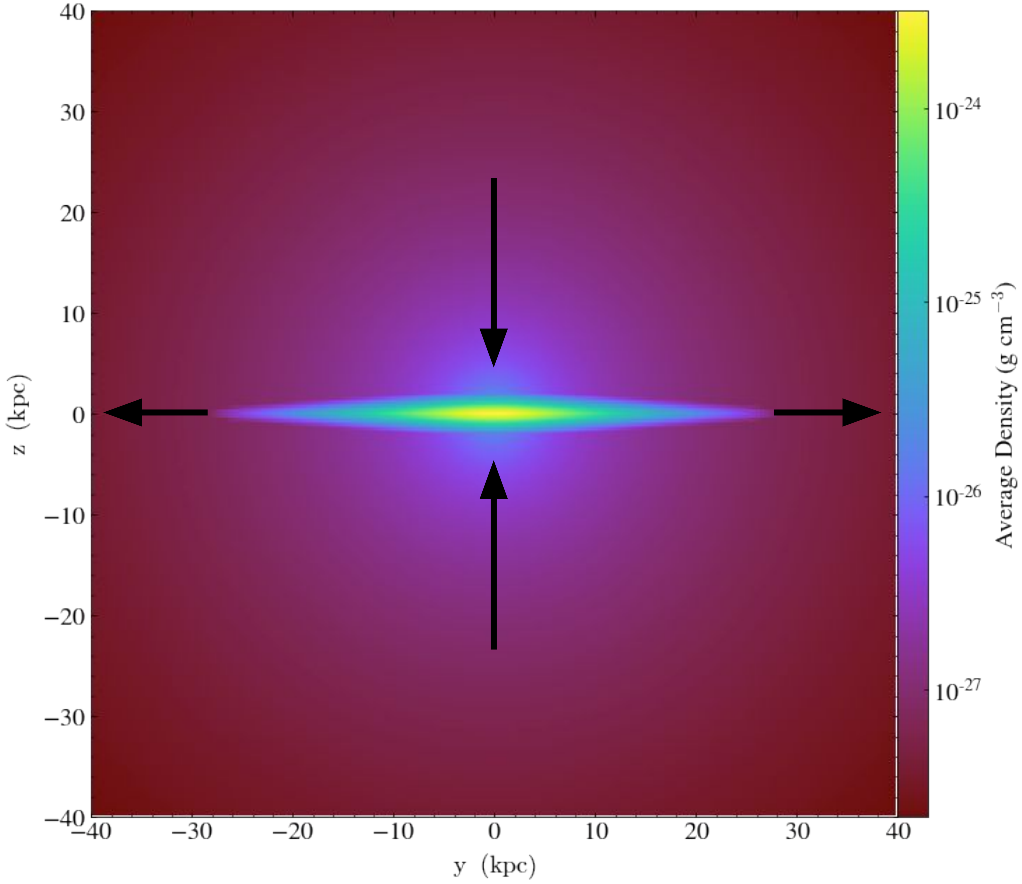
- Disable stellar feedback ("control")
- Initial t_{cool}/t_{ff}
  - 5, **10**, 20
- Initial CGM rotation
  - $\mathbf{v \propto r^{-2}}$, $v \propto r^{-1}$, and None



Simulations

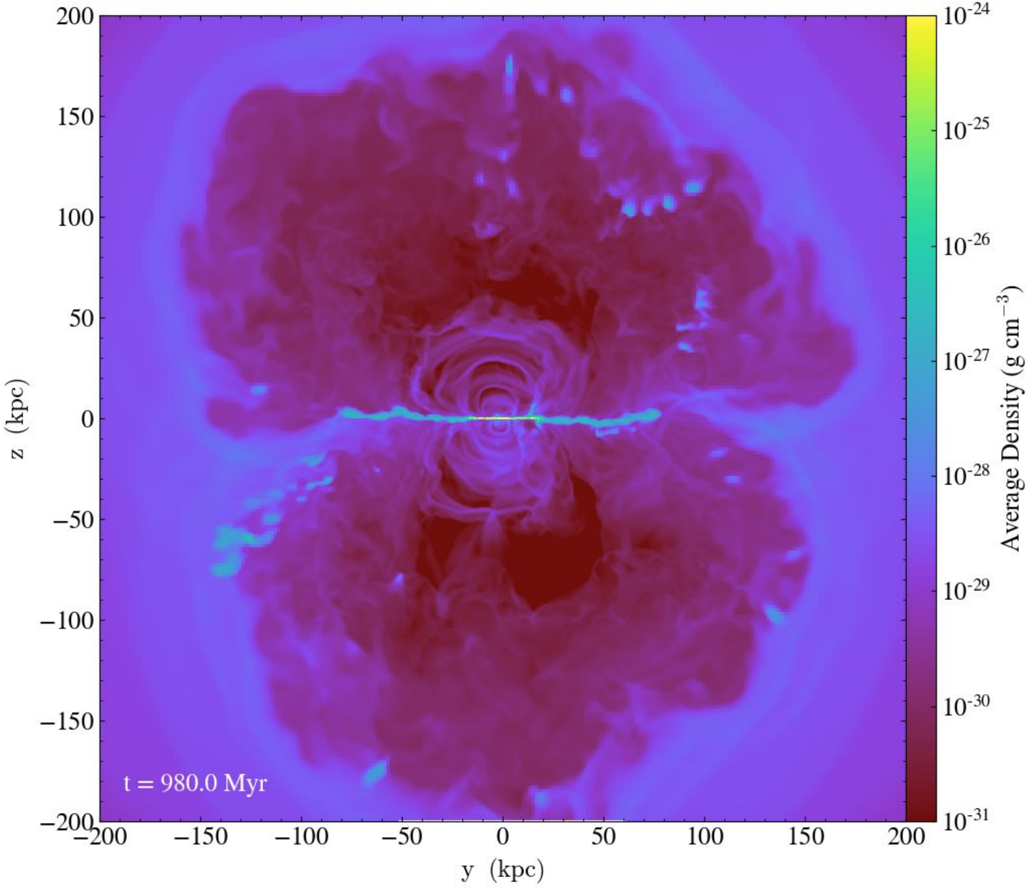
Initial Burst of Star Formation

- Gas rapidly collapses
- High density, Many stars, Much feedback



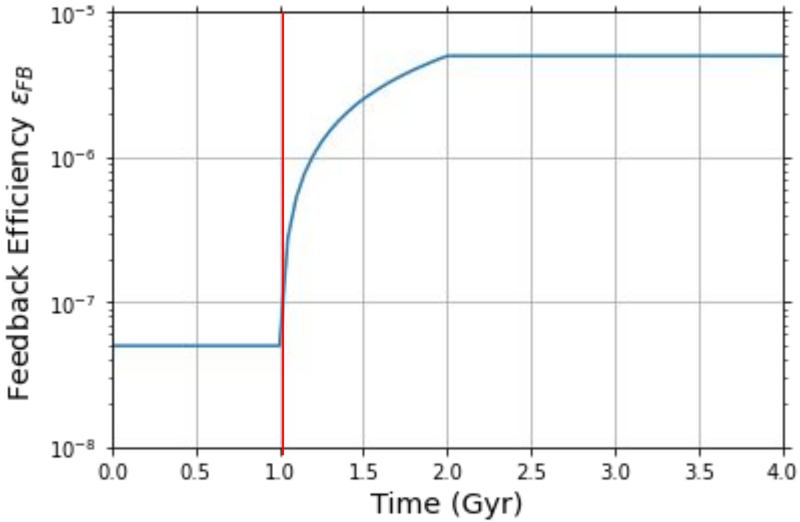
Initial Burst of Star Formation

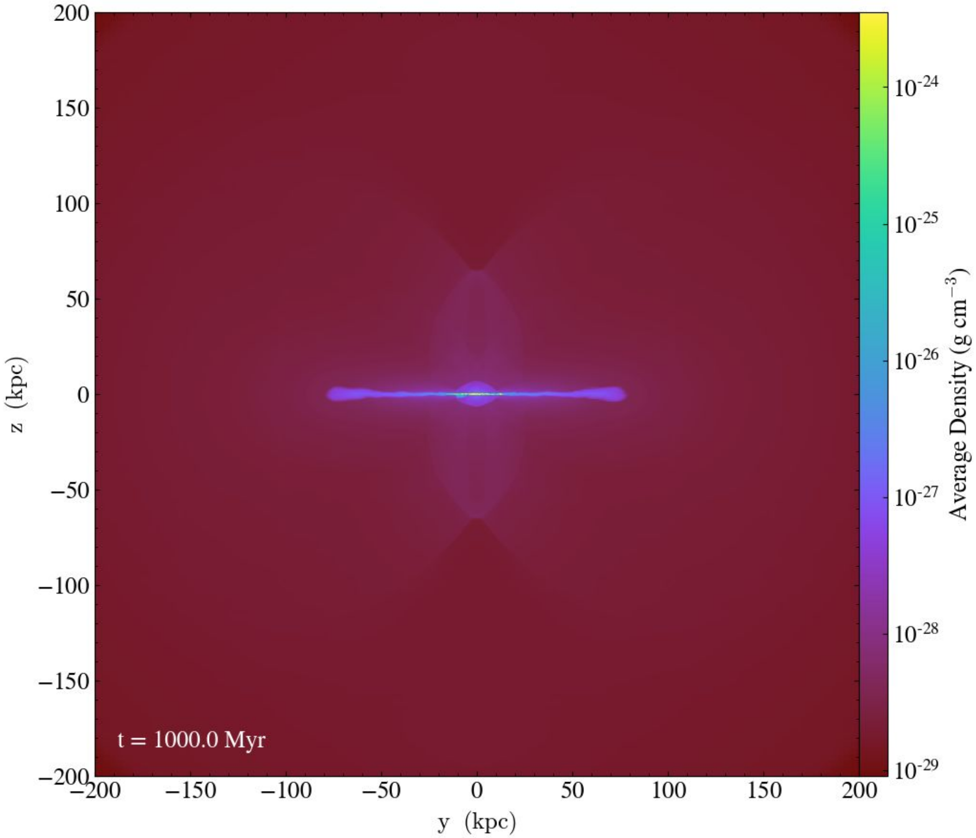
- Blow up your lovely CGM before gas can cool, infall
- Very low density near disk with continual strong SNe shocks



Solution:
Ramp FB Efficiency

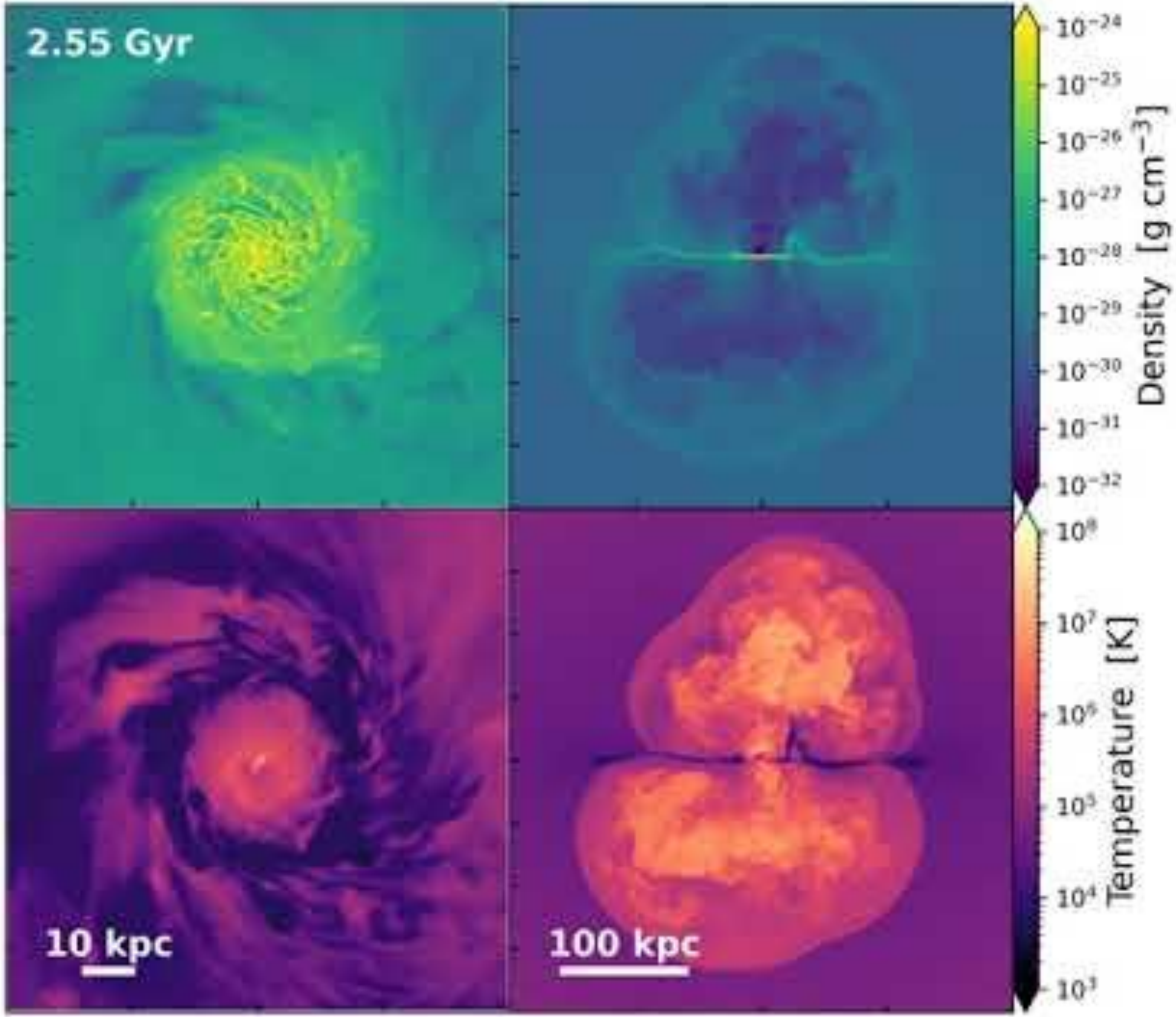
$$E_{\rm FB} = \epsilon_{\rm FB} \cdot \Delta M_{\rm SF} c^2$$





Simulations

Simulation Results

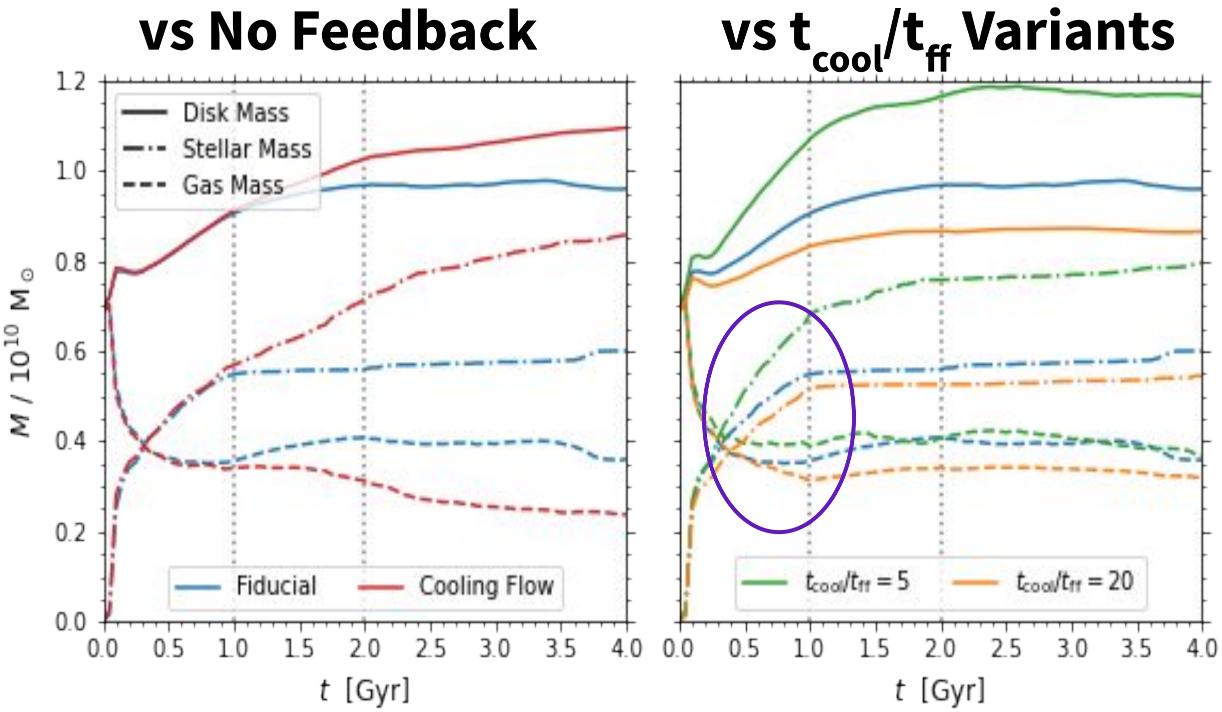


2.55 Gyr
10 kpc
100 kpc
Density [g cm^{-3}]
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
Temperature [K]
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}

Expectations

- Self regulating
  - ~Constant stellar mass over time
  - Gas infall (not just forming stars from initial gas content)
  - Long term stability of CGM structure/entropy profile
- Attractive equilibrium state
  - Slight variations in initial conditions should all become self-regulating
- Precipitation hallmarks
  - Median t_{cool}/t_{ff} ~ 10 in the CGM

Mass Growth



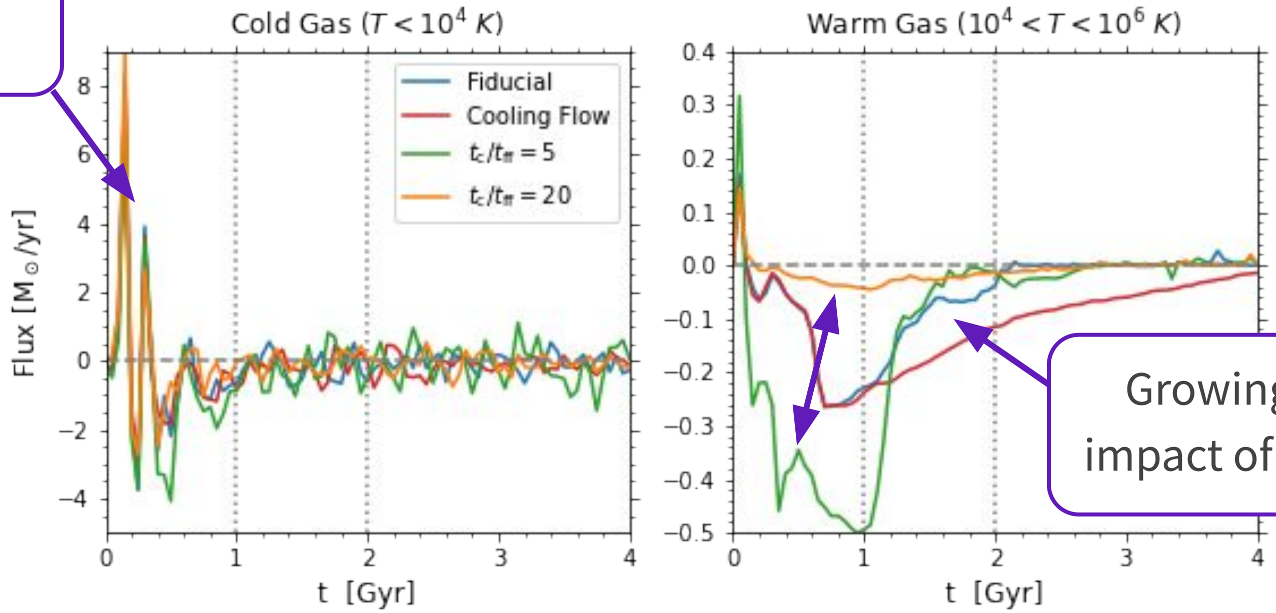
Asymptotic Stellar Mass

Preliminary Results

Radial Disk Accretion

Negative = Infalling

Initial disk "smoosh"



Growing impact of FB

Preliminary Results

Expectations

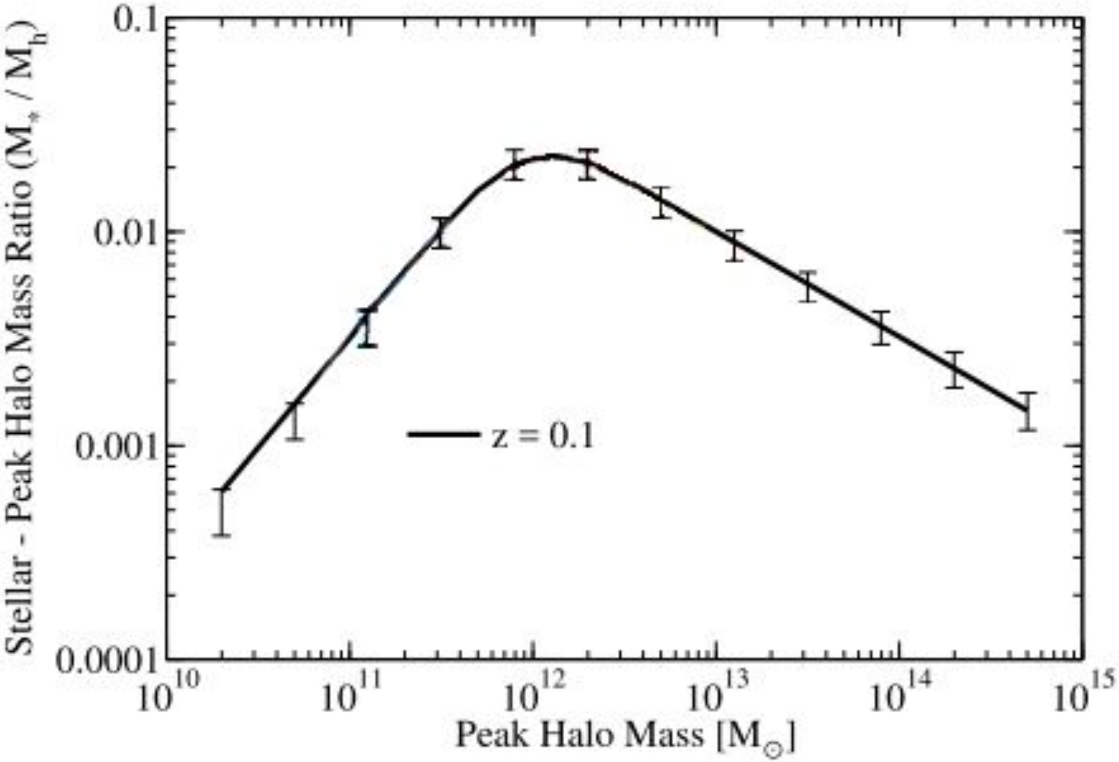
- Self regulating
  - ~Constant stellar mass over time ✔
  - Gas infall (not just forming stars from initial gas content) ✔
  - Long term stability of CGM structure/entropy profile ✔
- Attractive equilibrium state
  - Slight variations in initial conditions should all become self-regulating **Depends**
- Precipitation hallmarks
  - Median $t_{cool}/t_{ff} \sim 10$ in the CGM **Depends**

Summary

- Goal: make a model galaxy that self-regulates it's star formation through precipitation in it's circumgalactic medium (CGM)
- Simulations of isolated, idealized galaxies that directly model both the CGM *and* a dense, star-forming disk
  - The idealized nature creates unique challenges: initial star formation burst can undo carefully chosen CGM ICs
- Presented variations (with feedback) all achieve a steady late-time stellar mass
- However, only some variants are precipitation-regulated.
  - Others appear to shut off star formation by excessively heating the gas

Behroozi+19

Fraction of Mass in Stars



Behroozi+19

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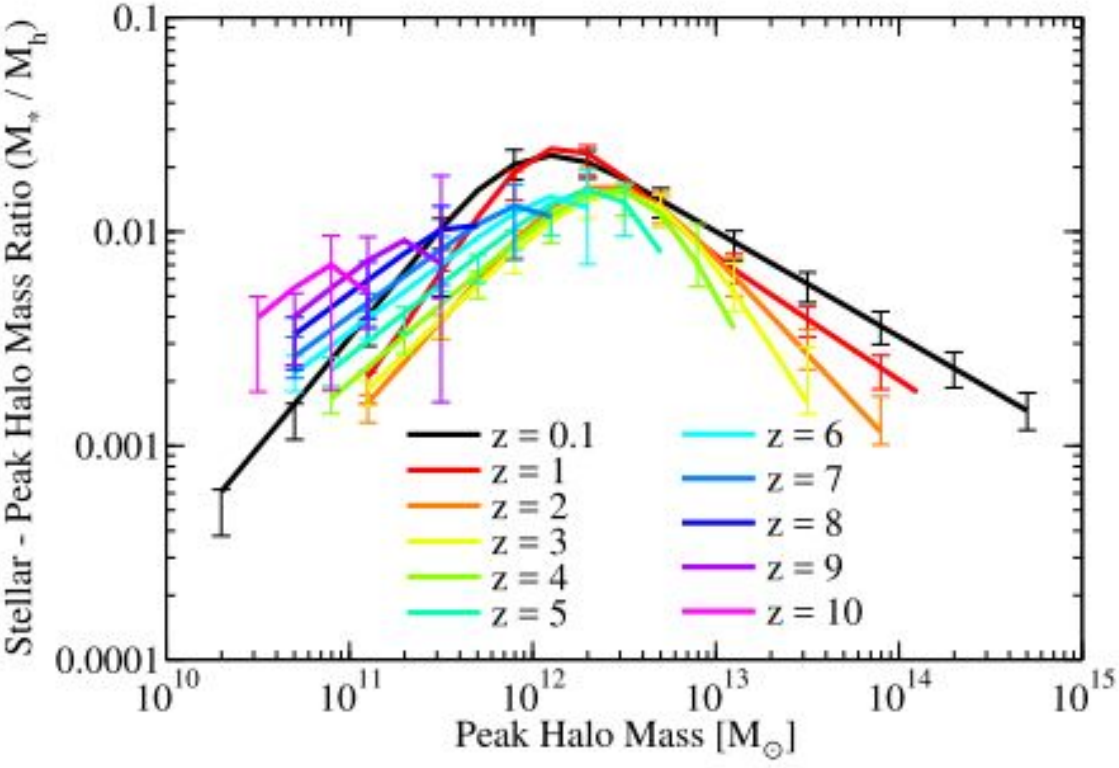
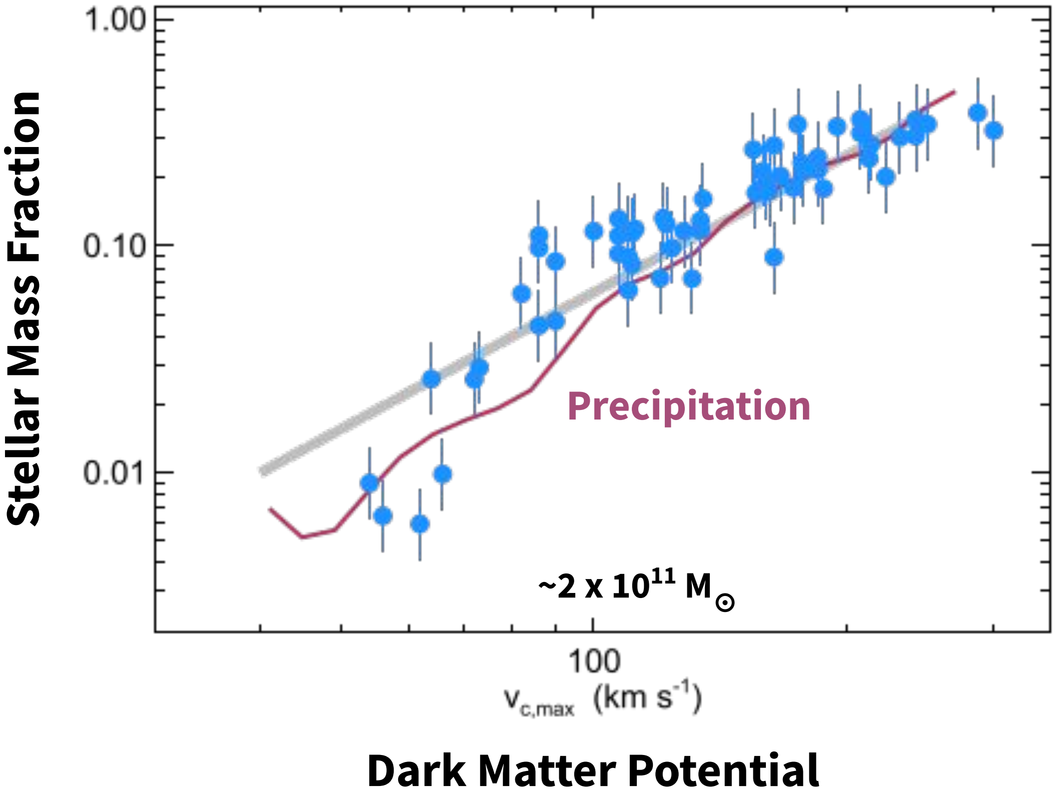


Stellar Mass relates to Halo Mass

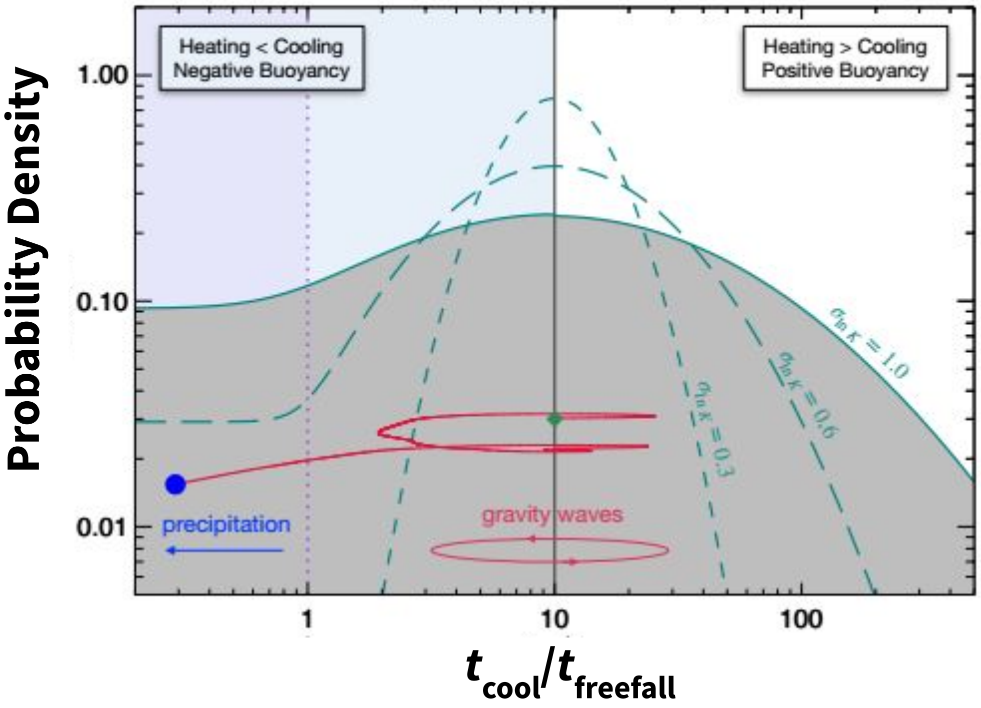
A Contender: Precipitation

- Cold gas clumps can fall onto galaxy if t_{cool}/t_{ff} distribution favorable (Median value ~ 10)
- Star form → Explode → lengthen cooling time, stopping infall
- Numerically & observationally tested for clusters & ellipticals
  - Physical principles should extent to smaller disk galaxies



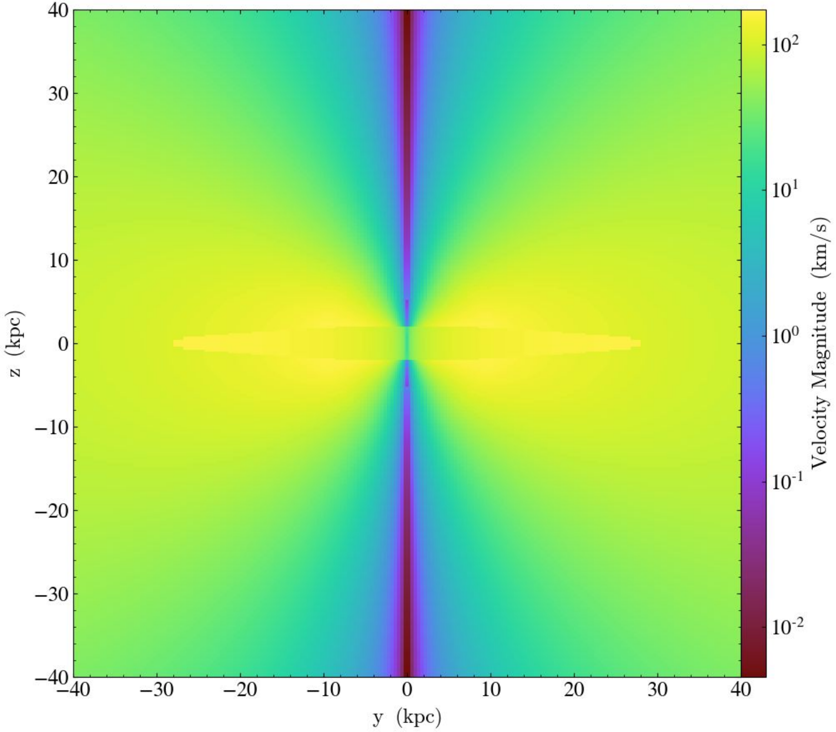
Voit+15 ApJL

A Contender: Precipitation



Numerical Test of Self-Regulation

- Milky Way-like idealized, isolated galaxy
- NFW dark matter potential
- Stellar disk potential
  (stars particles can form in addition)
- Rotation in both disk *and* CGM ⇒
- CGM set-up so system is
  ~precipitation-regulated (Voit 2019)

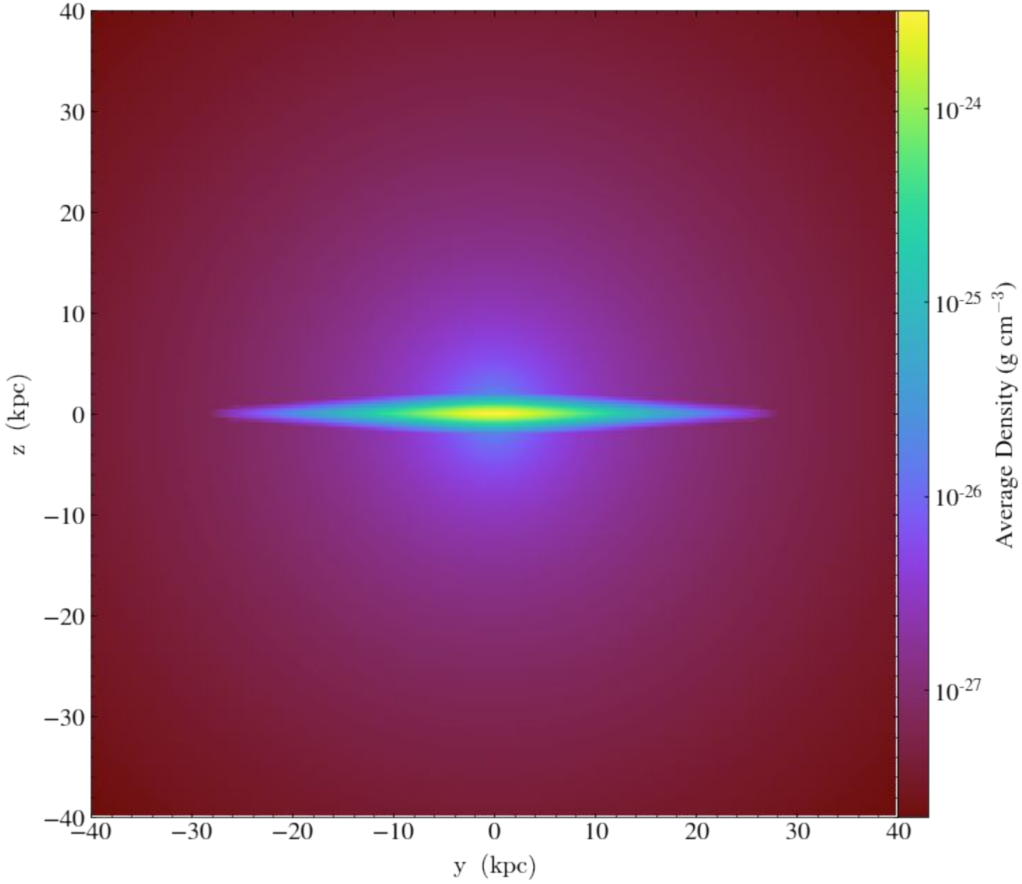


Defining ICs

Need density & temperature
ρ(x,y,z) & T(x,y,z)

1. Disk: ☐
2. CGM: **???**

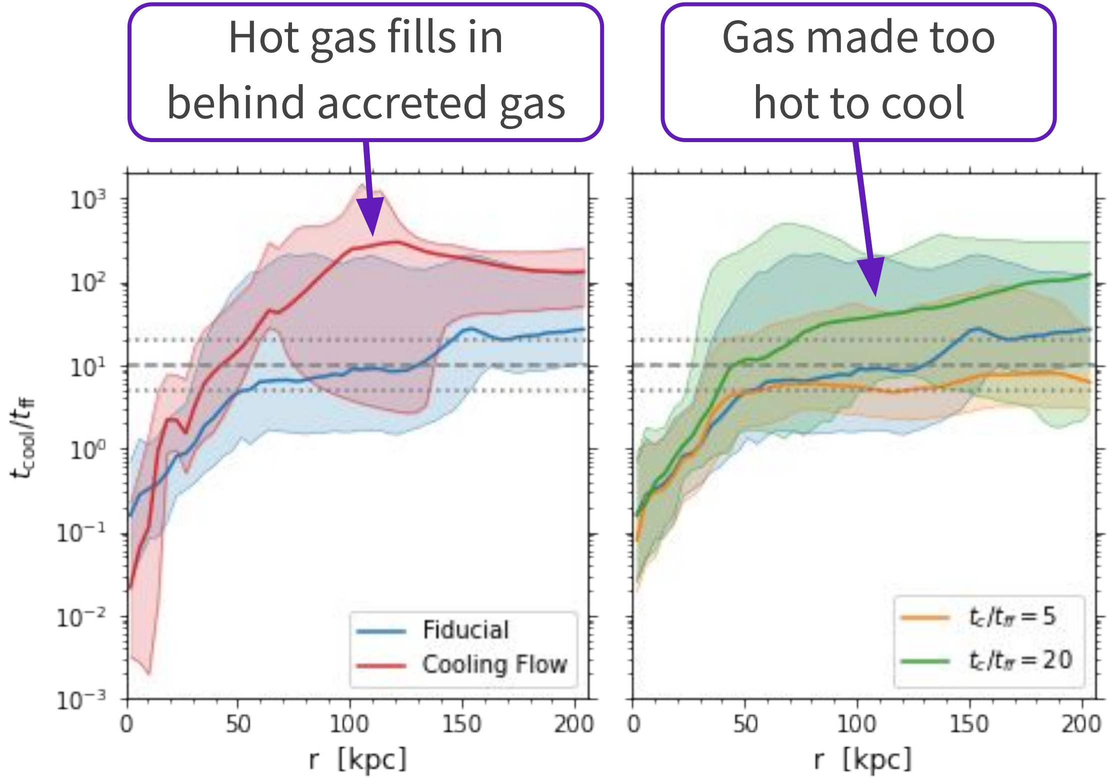
Voit 2019:
- Entropy vs radius
  - Dark matter
  - Precipitation conditions
- Hydrostatic equilibrium



Is it precipitation?

Find mass-weighted median in radial bins at each snapshot, then take the median over time in each bin.

Mass-weighted median traces the bulk of the mass without skewing towards high values.



Preliminary Results

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