Physics of Cooling Flows ('Hot Accretion')

1. ***<u>Some order in naming conventions</u>***

2. ***<u>Observations:</u>*** *is there a 'cooling flow problem' in galaxy-scale halos?*

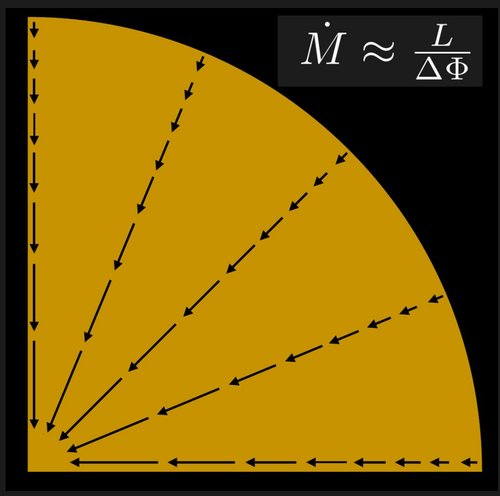
3. ***<u>Basic theory of cooling flows</u>***

4. ***<u>Theory of cooling flows with angular momentum:</u>***
   how do cooling flows accrete onto the disc?

answer depends
<u>qualitatively</u>
on halo mass

Naming Conventions: Cooling Flows vs. Cold Flows

'classic' Cooling Flows



An inflowing hot halo. Entropy drops inward, gas remains hot

also called Cooling Flows

High T

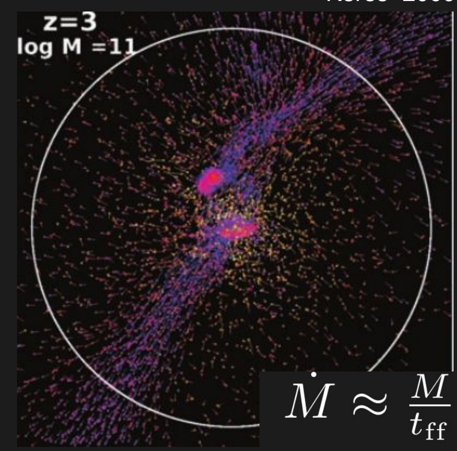
$$\dot{M} \approx \frac{L}{\Delta\epsilon_{\rm th}}$$

Low T

Gas losing thermal energy, no specifics of location

Cold Flows

Keres+2009

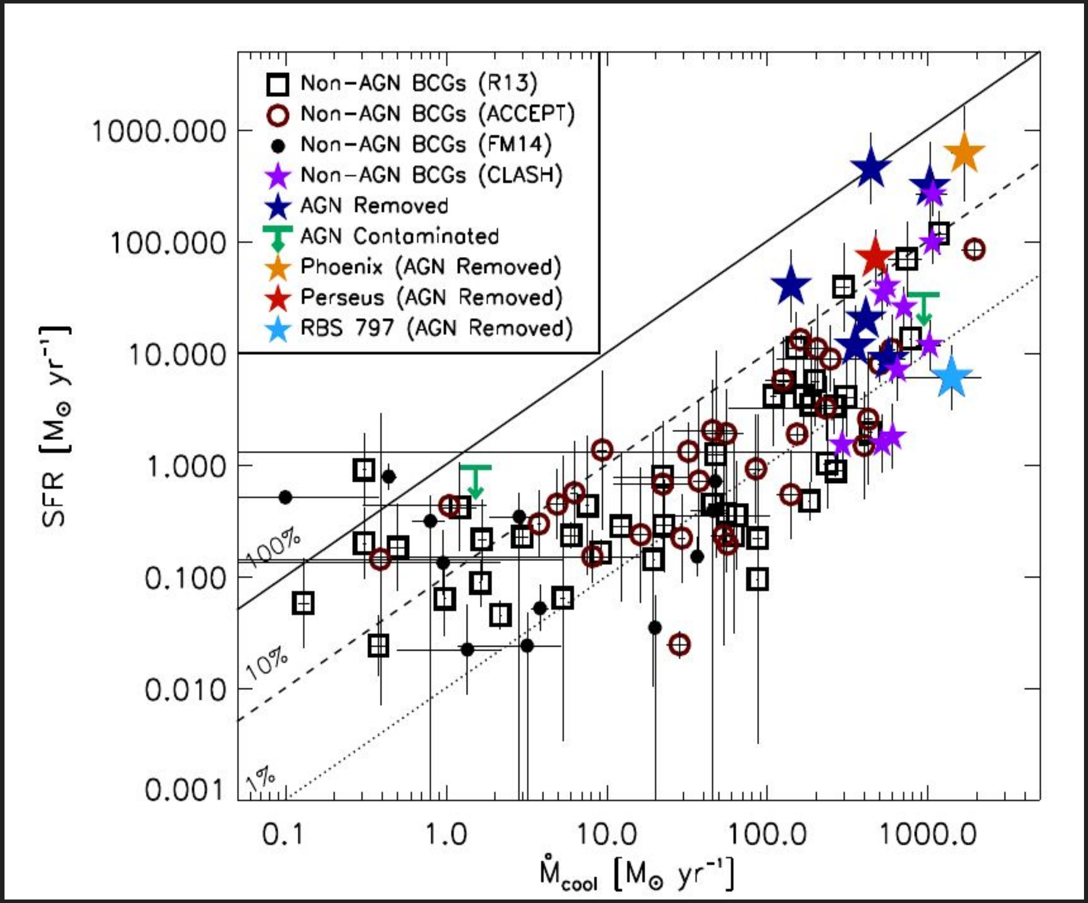


Free-falling ~10^4K gas, grav. energy radiated at ~10^4K or in shocks

very different things

Background: the ‘cooling flow problem’ in the ***ICM***

$$\dot{M}_{\rm cool} \approx \frac{L}{\Delta\Phi} \sim \frac{M_{\rm gas}(<r_{\rm cool})}{t_{\rm cool}}$$



McDonald et al. (2018)

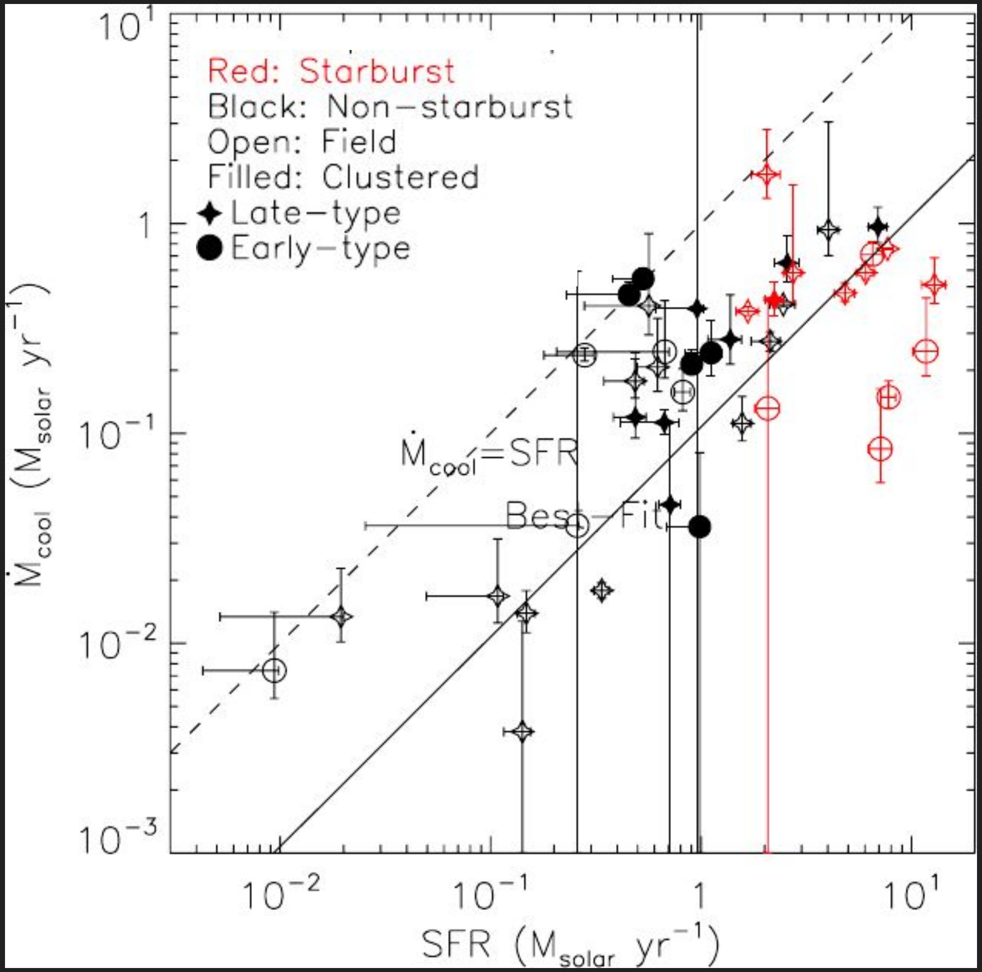
- *$\dot{M}_{cool} \gg$ SFR strongly suggests radiating gas is not inflowing*
- *Can be resolved with heating ~ cooling (‘thermal balance’)*

Is there a 'cooling flow problem' around ~*L** galaxies?

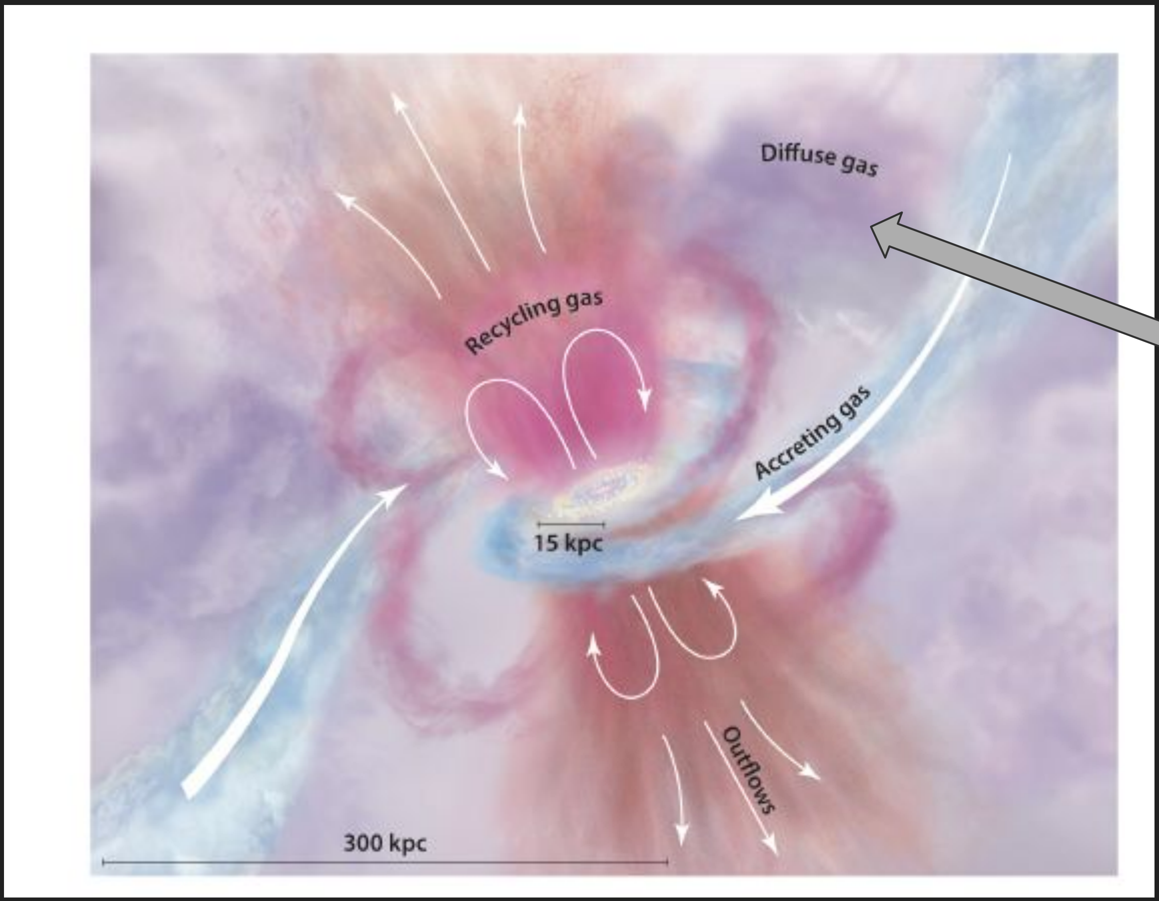
$SFR \gtrsim \dot{M}_{cool}$ -- no evidence for cooling flow problem in X-ray

Conclusion holds with simple extrapolation to large radii

Thermal balance <u>not required by data</u> -- is the hot gas inflowing?



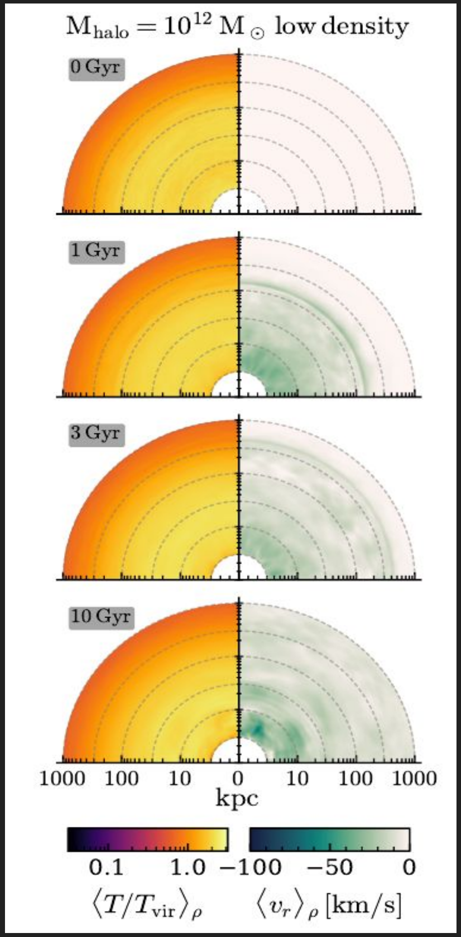
Li et al. (2014)
See also Benson+00; Rasmussen+09; Anderson+13; Li+16,+17,+18; Bregman+18; Das+20

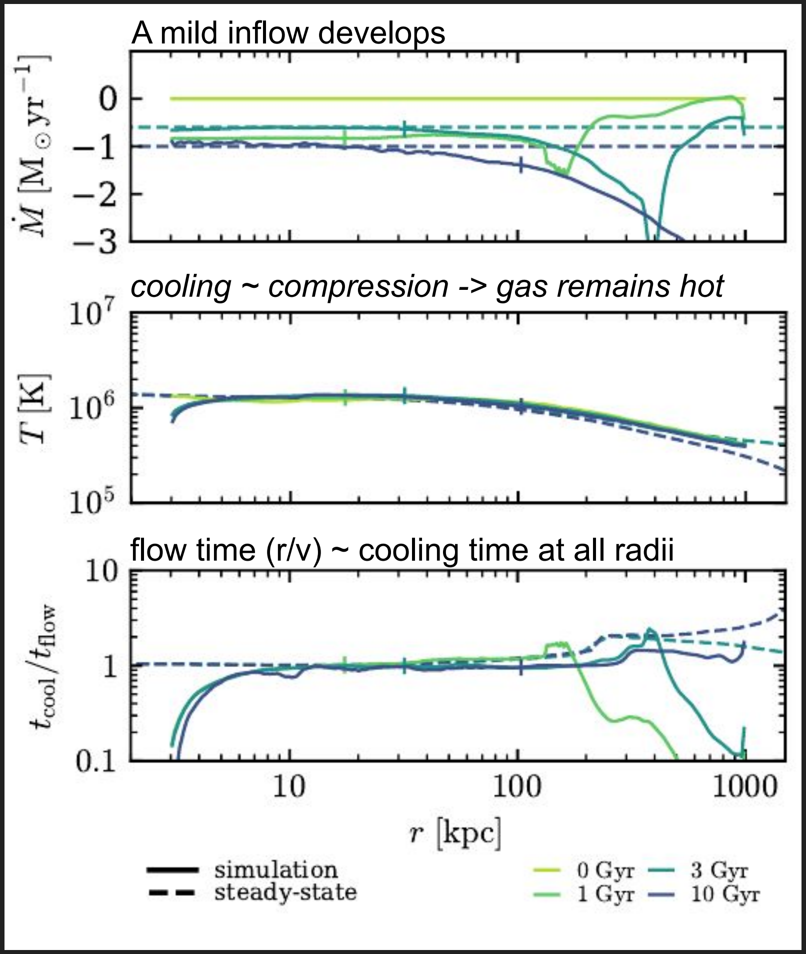


We should consider the possibility that the hot volume-filling phase is inflowing

Tumlinson, Peeples & Werk (2017)

Cooling Flows without Angular Momentum





Stern+(2019)
3D sims by the
amazing D. Fielding

initially hydrostatic gas turns converges to a cooling flow

(Mathews & Bregman 1978, Fabian+1984, Bertschinger 1989)

Cooling Flows without Angular Momentum

Additional properties:

1. Formation time of cooling flow is t_{cool} (only ~300 Myr in inner CGM!)

2. Subsonic flow ⟹ pressure profiles close to hydrostatic

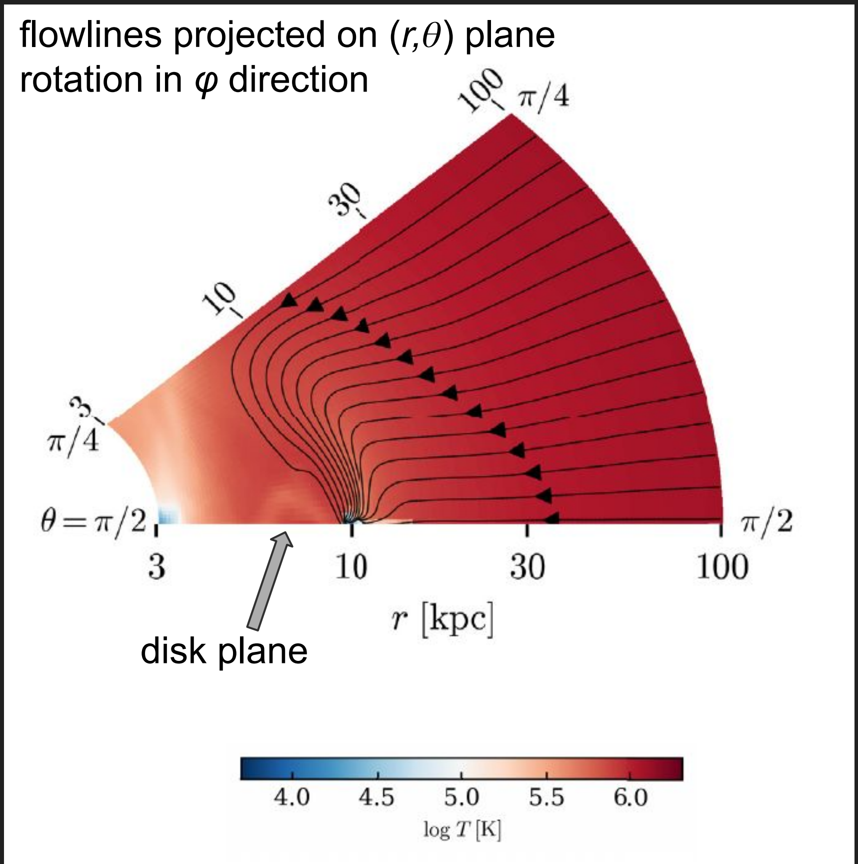
3. TIs advected with flow before growing
   ⟹ multi-phase structure only near satellites, filaments, disc, etc.

4. Prediction for observations: $n \sim r^{-1.5}$ ($\beta = 0.5$)

(see Mathews & Bregman 1978, Fabian+1984, Bertschinger 1989, Balbus & Soker 1989, McNamara & Nulsen 2007, Voit+2017, Stern+2019)

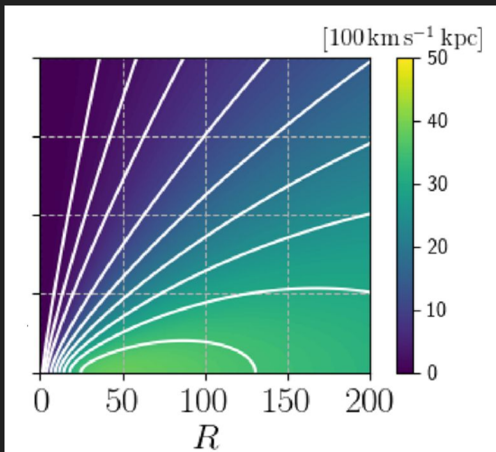
Cooling Flows *with* Angular Momentum

- *Angular momentum causes hot inflow to stall at disc radius*
- *Inner hot halo is rotating, consistent with MW hot halo (Hodges-Kluck+2016)*
- *Gas cools just before joining disc*
- *This accretion mode dominates in FIRE in low-z MW-mass halos (Hafen+, in prep.)*

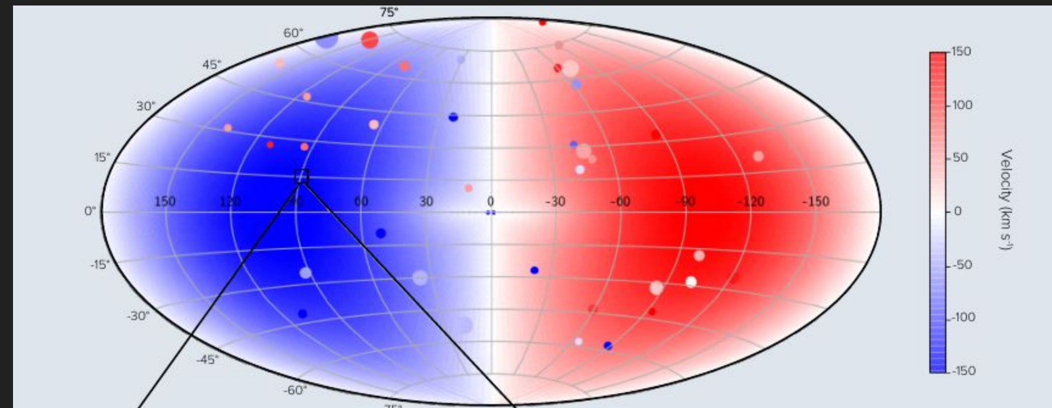


Stern+(2020a)

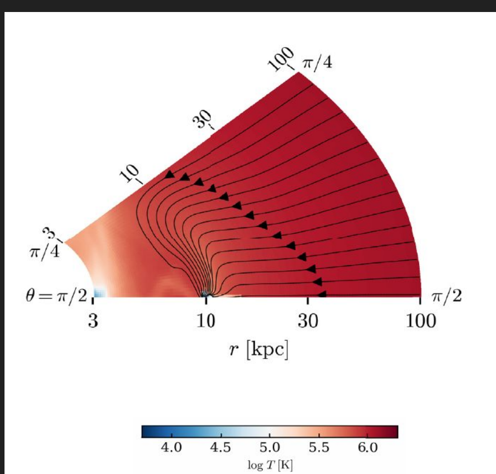
Rotating Hot Coronae



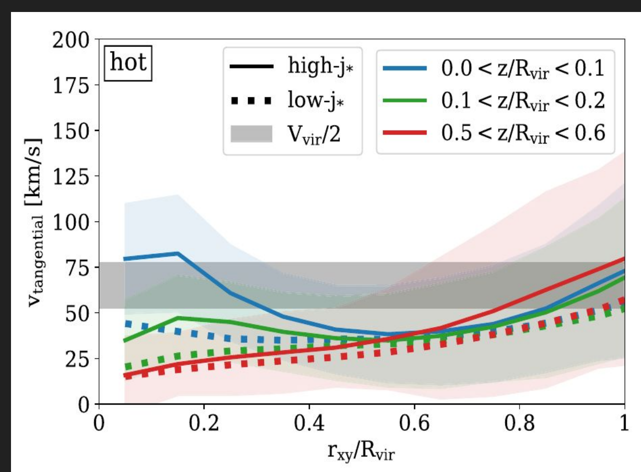
Hydrostatic models (Sormani+2018)
Contours: specific ang. mom.



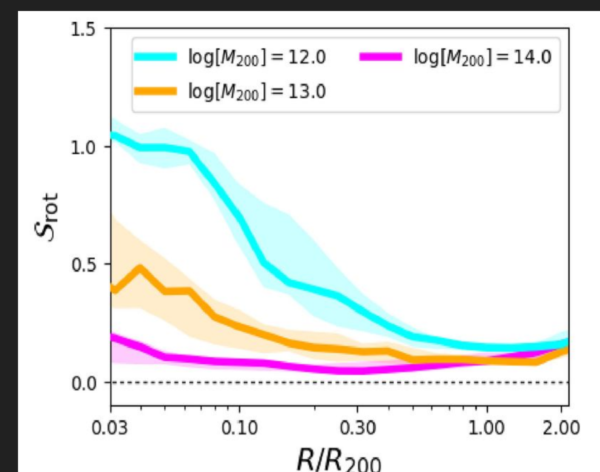
Milky-way model by Hodges-Kluck (2016). Fig. from Lynx concept study



Inflowing+rotating models (Stern+2020a)

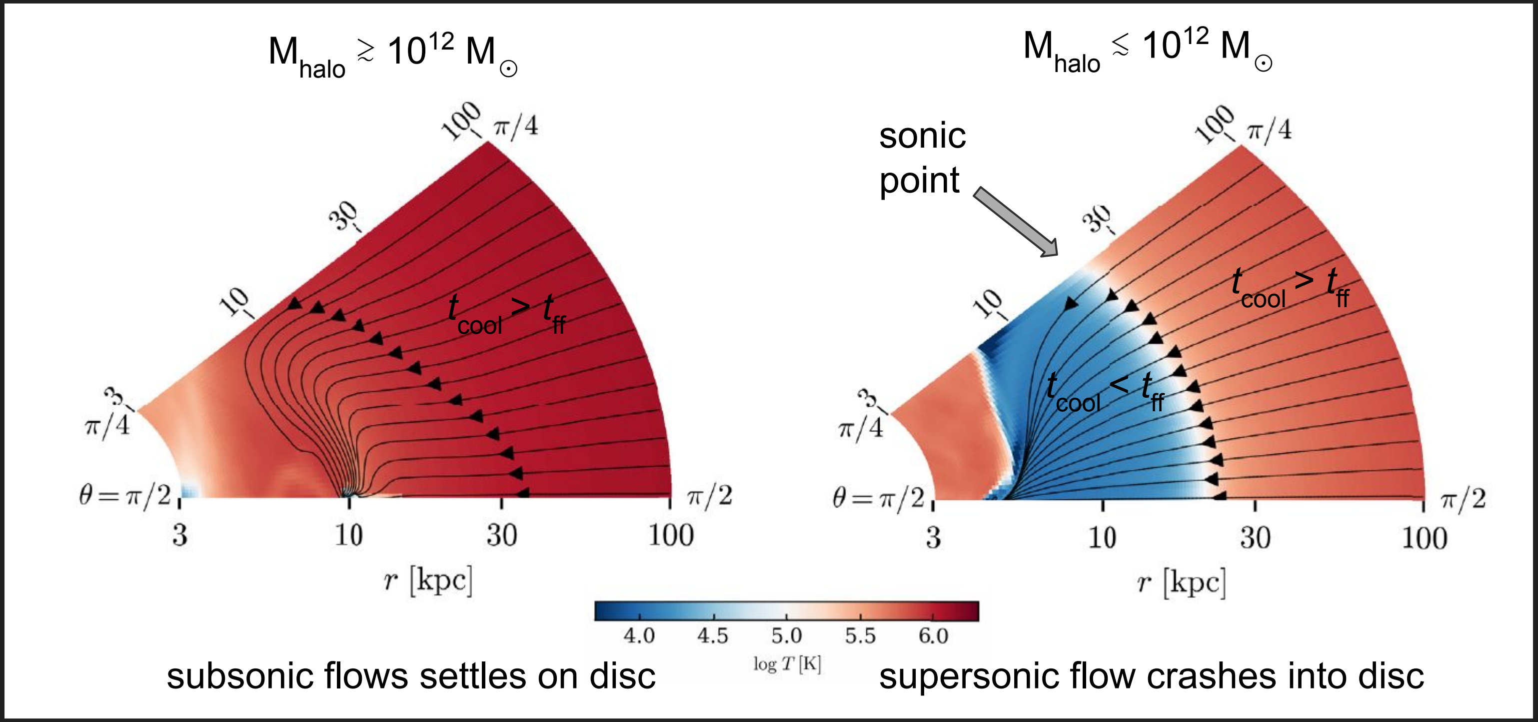


TNG100 (DeFilippis+2020)



EAGLE (Oppenheimer 2018)

Dependence of Cooling Flows on Halo Mass



Stern+(2020a)

In low mass halos, subsonic cooling flows turn into <u>supersonic cold flows</u>

Transition identified in FIRE! associated with suppression of outflows (Stern+2020b)

Physics of Cooling Flows -- Summary

1. No evidence for ‘cooling flow problem’ in X-ray emission around ~L* galaxies => *hot CGM may be inflowing*

2. Simulators/observers: use cooling flows as *baseline for estimating feedback* effects on hot CGM

3. Hot inflow will *rotate and cool onto disc* when angular momentum support becomes significant

4. *Qualitative transition* in cooling flow solutions at $\sim 10^{12}\ M_\odot$