

Radiative (non-radiative) accretion shock  $\Rightarrow \dot{M}_b = 6.5 \times 10^{11} \text{ (} Z=3, Z_{\odot} \text{)}$

$3.3 \times 10^{11} \text{ (} Z=0.1 \text{)}$

For the MW  $M_b \sim 1 - 1.5 \times 10^{12} M_\odot$  direct  
 $\sim 2 - 5 \times 10^{12} M_\odot$  abund. matching

$$\rightarrow M_b \sim 1.5 - 7 \times 10^{10} M_\odot$$

$$\text{Since } M_{\text{gas, MW}} = 6 \times 10^{10} M_\odot$$

$$M_{\text{CGM}} = 10 - 60 \times 10^{10} M_\odot$$

$$\text{Given } \langle Z \rangle_{\text{gas}} \sim Z_\odot \quad \langle Z \rangle_{\text{CGM}} \sim 0.1 - 0.5 Z_\odot$$

Approximate Steady

$$\frac{P}{r} \sim \frac{dP}{dr} \Rightarrow \rho \frac{d\Phi}{dr} \approx \rho \frac{V_c^2}{r}$$

$$\rightarrow \rho(c_s^2 + \langle v_{\text{wind}}^2 \rangle) + P_{\text{cr}} + \frac{1}{2} \frac{B^2}{\mu} \approx \rho V_c^2$$

$$\text{Rate} \quad \dot{M}_b \sim M_b / t_b \sim 15 - 70 M_\odot/\text{yr} \gtrsim 10 M_\odot$$

$$\dot{n}_{\text{cool}} (Z \sim 0.1 Z_\odot, \rho \sim r^{-3}, c_s \sim V_c) \approx 15 M_\odot/\text{yr} \gg \dot{n}_*$$

$$\dot{E}_{\text{cool}} \sim \dot{m}_{\text{cool}} V_c^2 \sim 10^{42} \text{ erg/s}$$

$$\dot{E}_{\text{SN}} \approx 3 \times 10^{41} (\dot{m}_*/1 M_\odot/\text{yr}) \text{ erg/s}$$

$$L_{x,\text{obs}} \approx 10^{41} \text{ erg/s for MW type galaxy}$$

$$L_{\text{dis, CGM}} \approx 3 \times 10^{42} \text{ erg/s}$$

## (d) motivation

- origin of turbulence in the CGM & disk?
  - substructure (mergers)
  - gas accretion from the IGM / CGM
  - feedback/outflows/winds (cen & sat)

- perspective: cosmo. hydro. sims  
EAGLE, Illustris [TNG], FIRE, ...

↳ goal: understand galaxy evo. in generality  
 explain the formation of #1] the typical galaxy,  
 at all mass scales  
 (dwarfs → clusters)

#2] outliers and rare phenomena

↳ typically: focused on the galaxy-population ( $\&$  stars)

- i.e. not trying to recreate any particular feature of the ICM,  
 but rather can look how the ICM develops within a  
 framework of a simple model which forms a "realistic"  
 BCG and satellite galaxy population

↳ gas structure (inc. atmospheres) particularly interesting  
 and predictive: further from the calibration regime

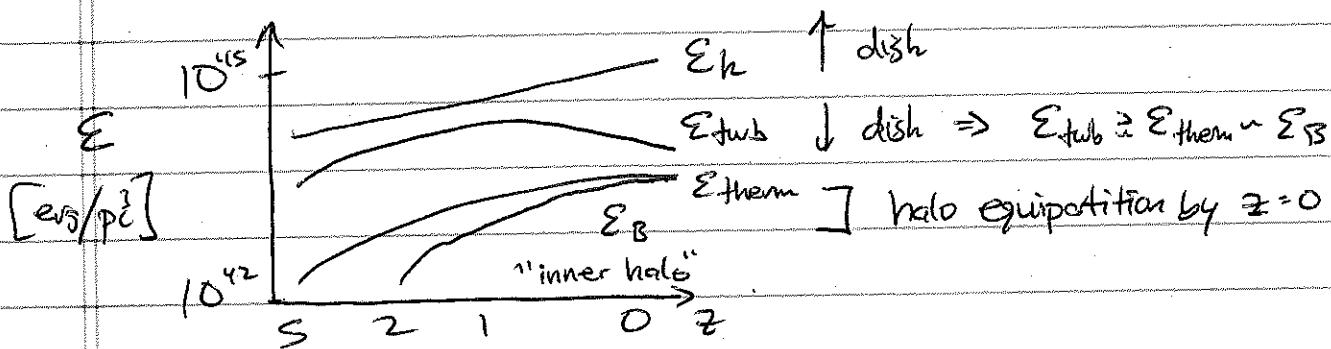
- for idealized work, provide strongly informative B.C.  
 (of the cosmological context)

## (1) halo turbulence

■ sims: AREPO, ideal MHD, cosmological, no CRs,

$$\vec{B}_0 = 10^{-14} \text{ cG}^{\frac{2}{3}} \text{ at } z=127$$

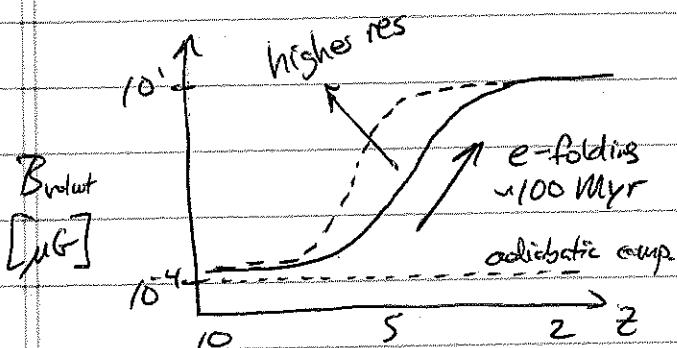
■ evolution of a  $\sim 10^{12} \text{ MW}$ -like halo (Pahnmor+17)



→ interpretation:  $B$  growth in halo = early exp. growth phase  
of a fast turbulent dynamo

$L_{\text{inj}} \propto r_{\text{vir}}$   
(KE injection scale)  
(+  $\alpha \Omega$  for the dish)

- so long as  $P_B > P_{\text{therm}}$ , exp. amplification on smallest scales first
- once  $E$  equipartition, "linear inverse cascade" transports magnetic energy to larger scales



- only occurs in collapsed structures ( $z_{\text{start}} =$  once turbulence resolved)
- reaches saturation state, all memory of  $\vec{B}_0$  lost
- $\Rightarrow E_B \approx 0.2 E_{\text{turb}}$  (small  $\rightarrow$  large scales)

■ does not occur in NR/adiabatic run: only mild growth above  $B \propto \rho^{2/3}$  in halos  $\Rightarrow$  need stirring from PB/fountain

■ no explicit subgrid-scale (SGS) turbulence model  
 $\Rightarrow$  numerical dissipation at  $\Delta x_{\text{grid}}$  is the end of any turbulent cascade

## (2) inflows

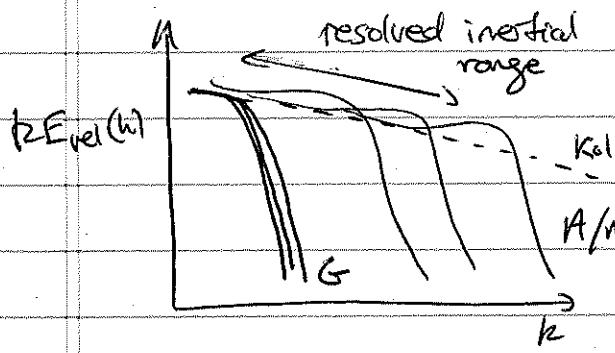
- turbulence key for halo B amplification

also: CGM thermal state, heating/cooling, baryon cycle

- numerically resolving subsonic turbulence = difficult

(particularly for SPH) [  $L_s$  halo volume filling from structure formation (Vincent filling)

- one of the more interesting things are realized in the first AREPO sims



■ Bauer+12 : driven, subsonic ( $M_{\odot} \text{ yr}^{-1}$ ) boxes, isothermal, solenoidal GZ vs. AREPO

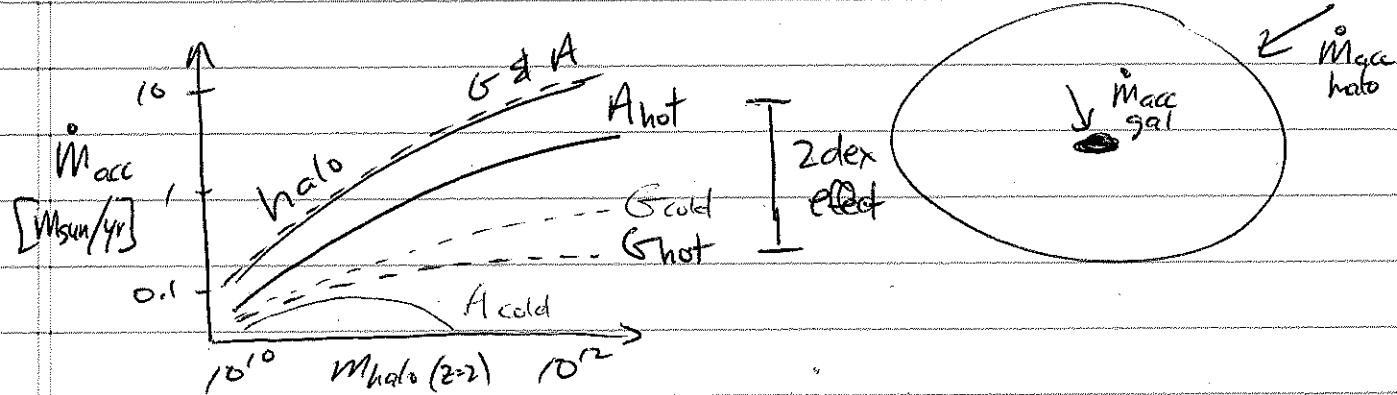
• issue: noisy SPH velocity field  
[ due to large errors in gradients  
(+ irregular particle distributions)

• result: majority of  $\dot{\epsilon}_{\text{diss}}$  on Linj (large)

$\Rightarrow$  artificial heating of the CGM

$\Rightarrow$  cooling suppression, "numerical quenching" of massive halos

Velзор + 13, vs. 14  
simulations, GZ



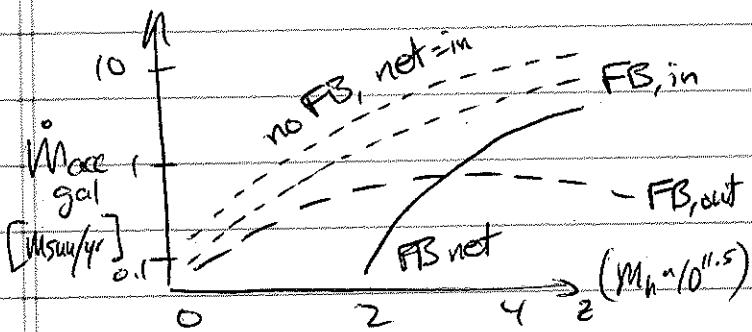
$\Rightarrow$  CGM turbulence also critical for galaxy formation

[gas accretion = outer B.C.]

### (3) outflows

- previous was "no FB" picture, but winds substantially alter accretion

Nelson + 15 (MHD)  
model



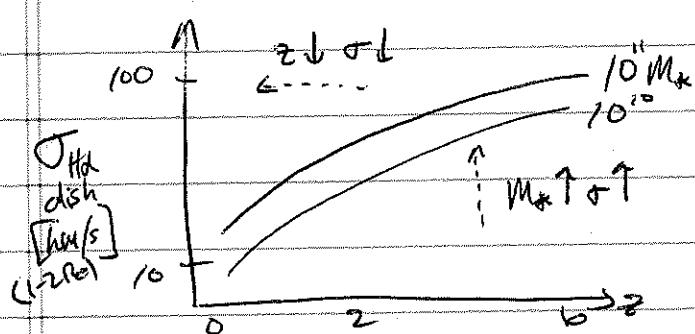
$$\dot{M}_{\text{net}} = \dot{M}_{\text{in}} - \dot{M}_{\text{out}}$$

- Feedback case:

$\dot{M}_{\text{out}}$  vs  $\dot{M}_{\text{in}}$  as  $2 \rightarrow 0$

- ⇒ suppress SF fuel
- ⇒ strong recycling/fountain flows

- connected directly to the star-forming disk:



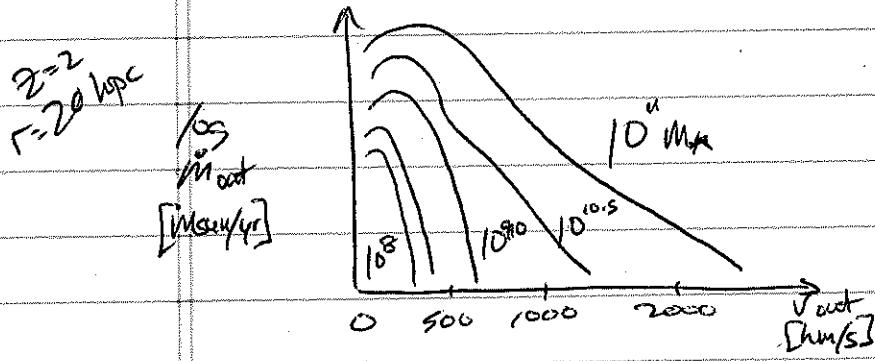
[ Pillepich + 19 TNG  
Cibler + 19 KMOS SD ]

- turbulent support of the star-forming disk as  $2 \rightarrow 0$

merger rate ↓  
 $\dot{M}_{\text{in ace}}$  ↓  
 $\dot{M}_{\text{out, Vout}}$  ↓  
SFR ↓  
 $f_{\text{SCS}}$  ↓

2  
0

- galaxy → halo impact through outflows: (Nelson + 19)



- SN-driven winds ⇒ low  $V_{\text{out}}$  core
- BH-driven winds ⇒ high  $V_{\text{out}}$  tail
- outflows span range of phases ( $e, T, z$ )

[ w/ different kinematics

- preferred orientations w.r.t. disks

- ⇒ injection of mass, energy, metals into the CGM
- from the galaxy, many non-trivial dependencies