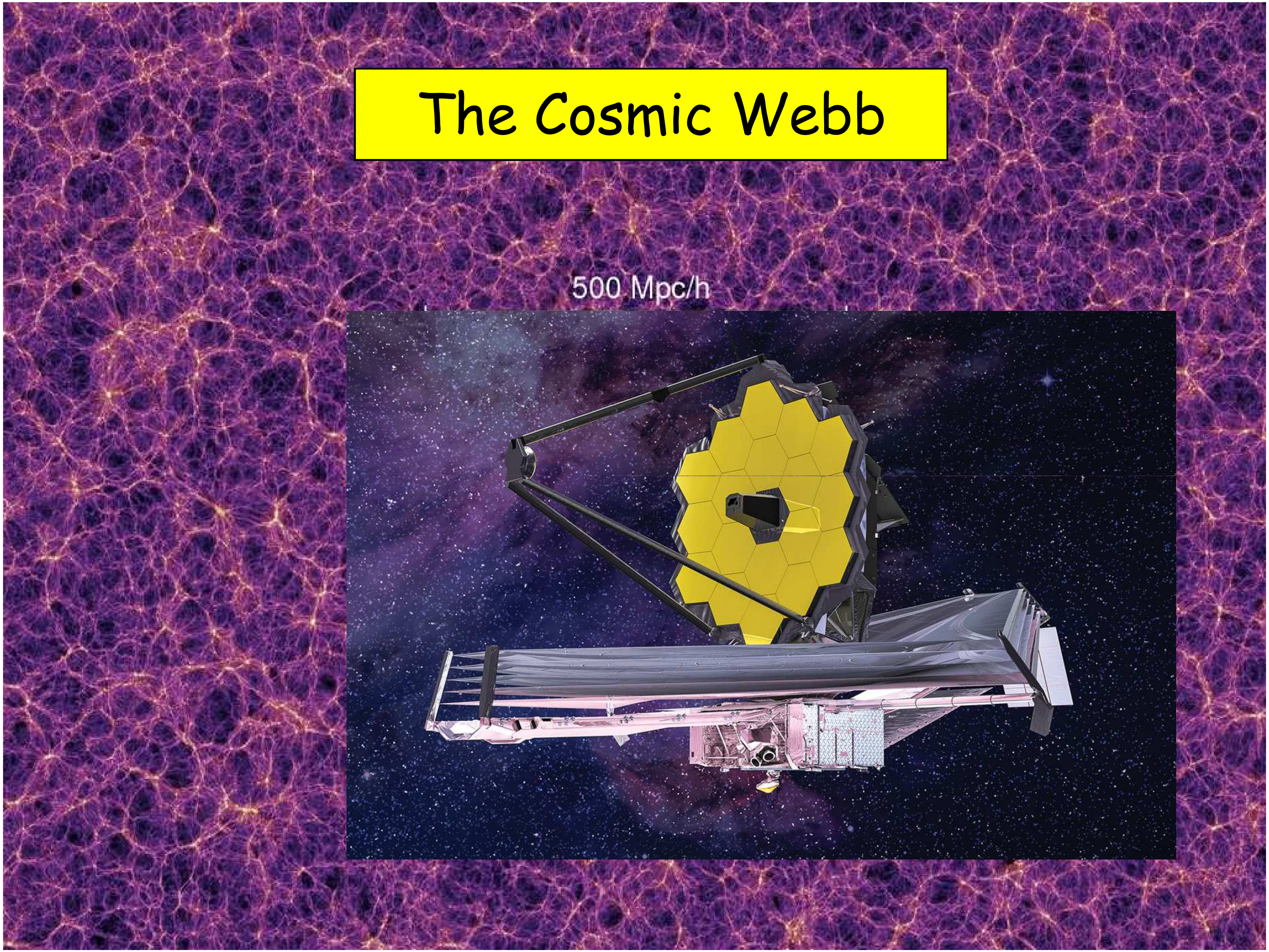
Origin of Excessively Massive Galaxies at Cosmic Dawn

Avishai Dekel
The Hebrew University of Jerusalem

Karick Sarkar, Yuval Birnboim, Nir Mandelker, Zhaozhou Li

KITP, The Cosmic Webb, February 2023

The Cosmic Webb

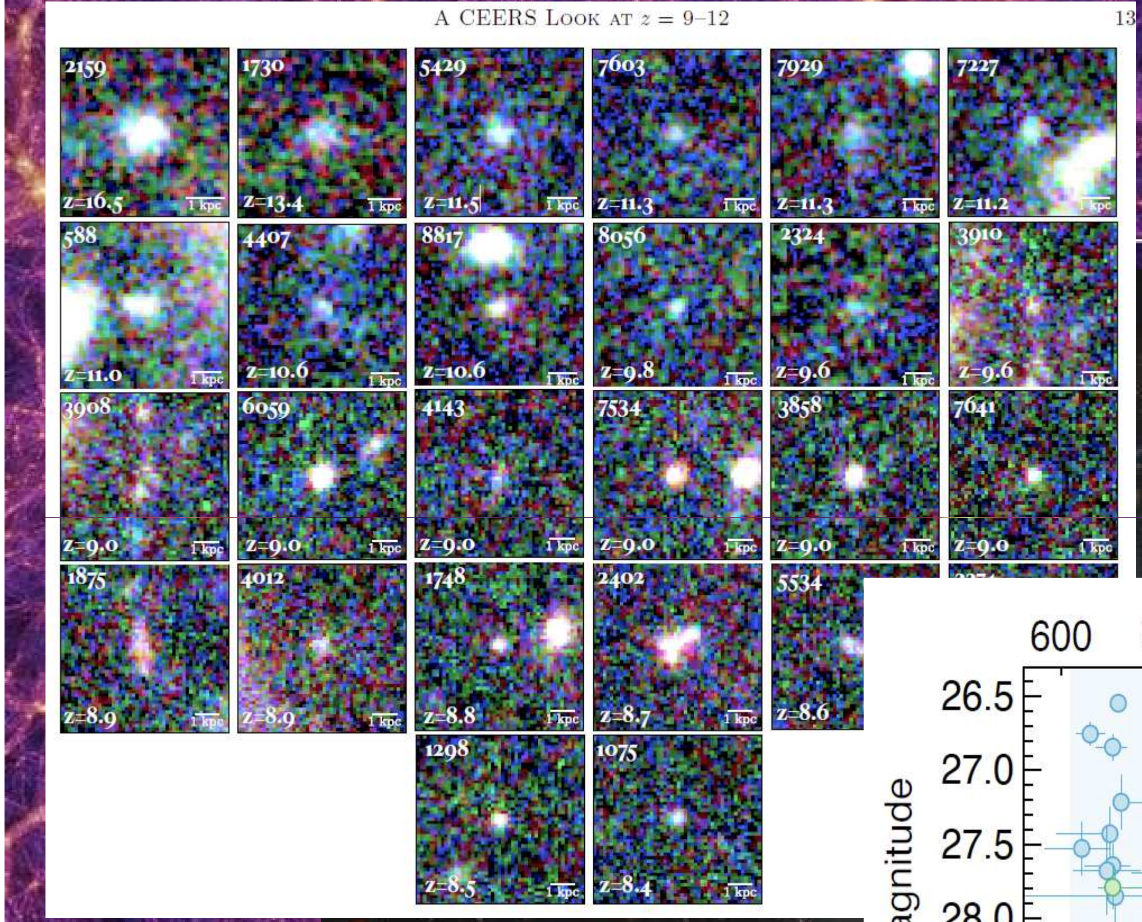


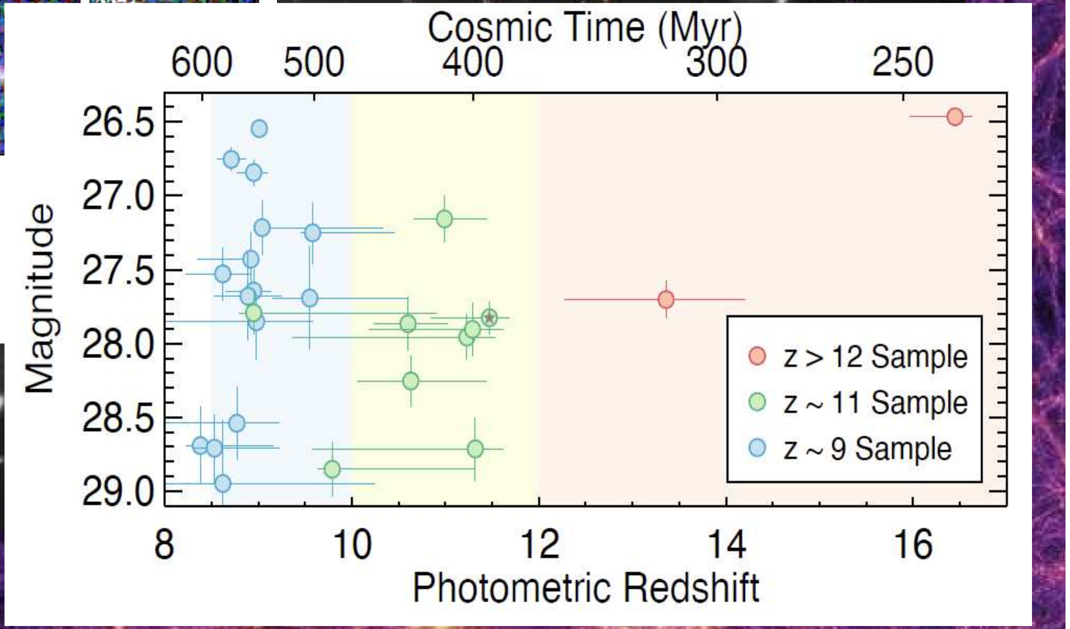
Outline

1. JWST reveals a puzzle
2. Feedback-free starbursts (FFB)
3. Massive galaxies at cosmic dawn

JWST/CEERS: 24 Galaxies at z~8.5-11.5

t ~ 400-600 Myr


A CEERS LOOK AT $z = 9$–12 13



A Puzzling Excess of Bright Galaxies at z~8-12

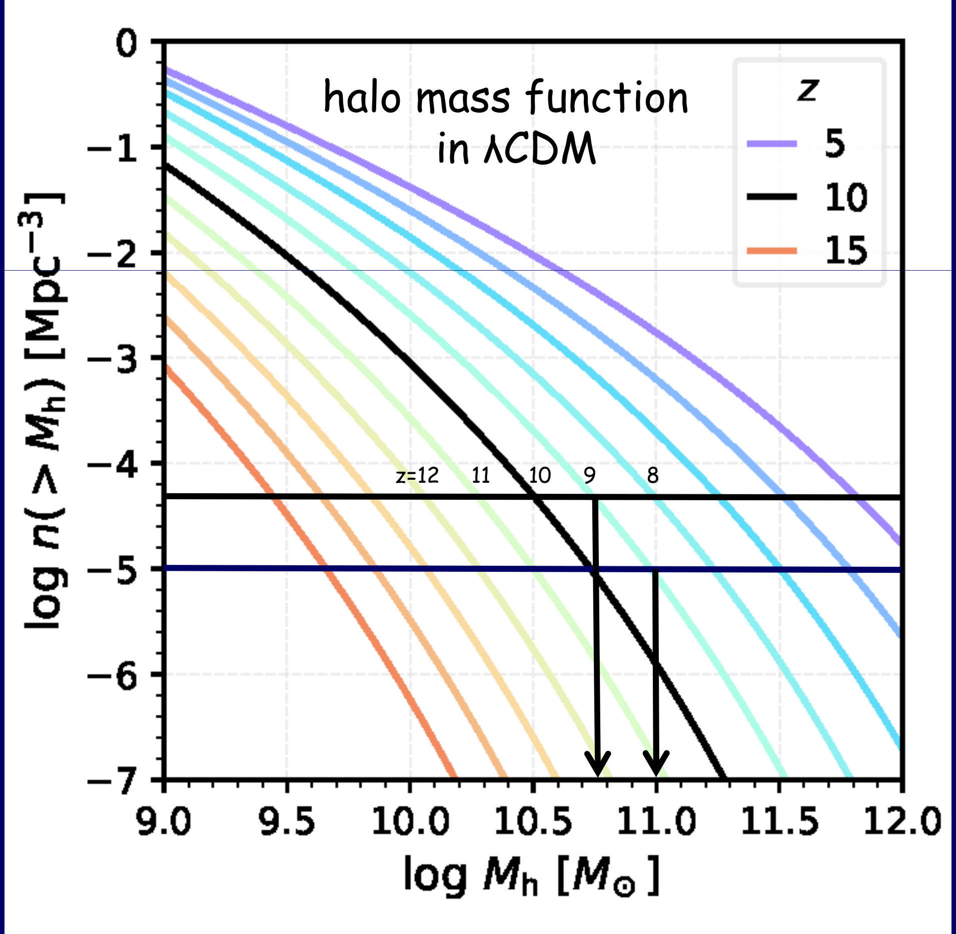
JWST/CEERS 24 galaxies at z=8.5-11.5   Finkelstein+22

Halo masses by abundance matching with luminosities

Effective volume ~ 10^5Mpc^3

5th galaxy

1st galaxy



5 brightest galaxies

$M_{halo} \sim 7\times10^{10} M_\odot$

SED (IMF, SFH)

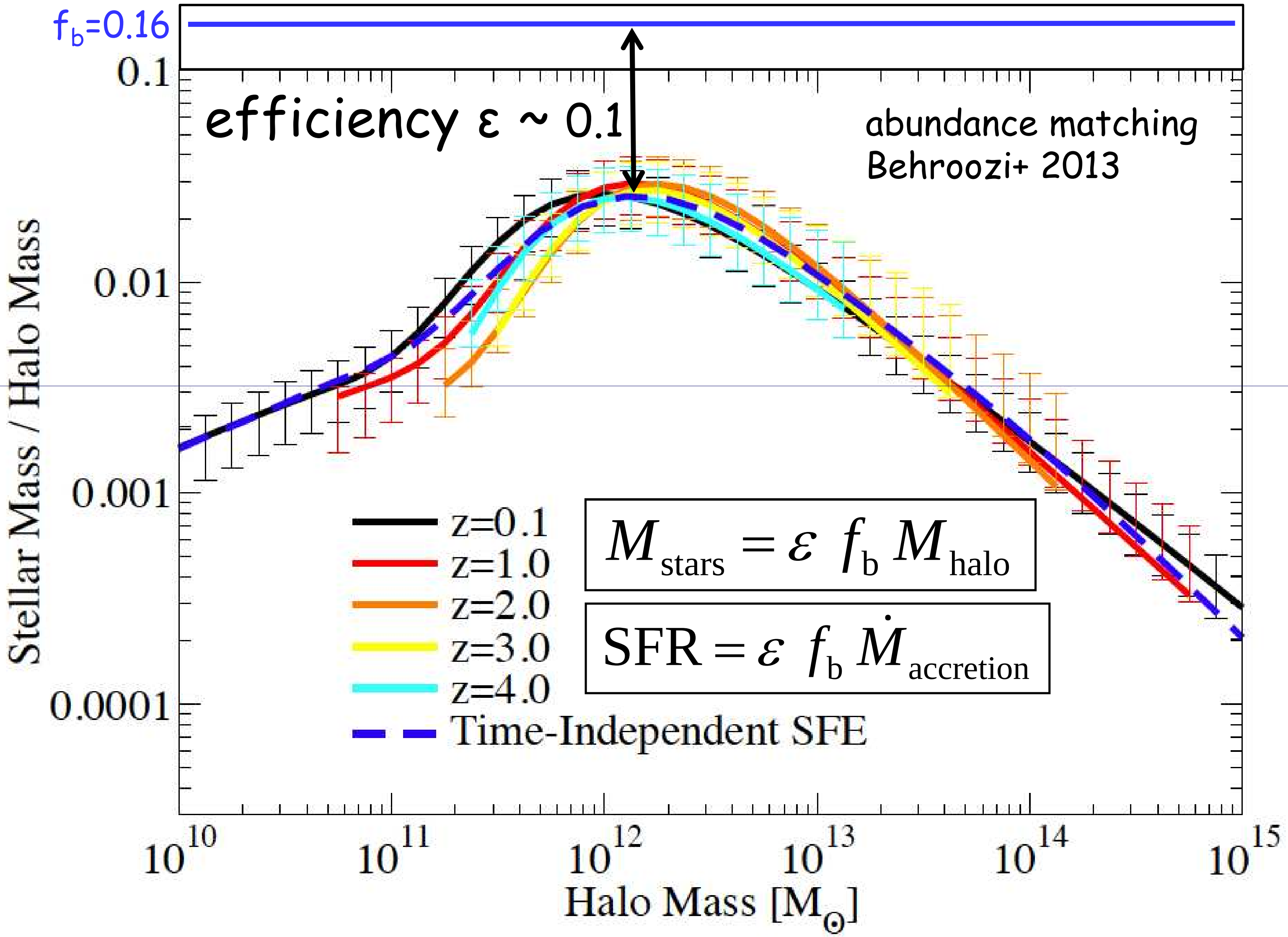
$M_{star} \sim 10^{10} M_\odot$

$M_{star} \sim \varepsilon\, f_b\, M_{halo}$

$\sim \varepsilon\, 10^{10} M_\odot$

max efficiency ε~1
of converting
accreted gas
to stars ?

Standard Lore: Inefficient Star Formation



$$M_{\rm stars} = \varepsilon\, f_{\rm b}\, M_{\rm halo}$$

$$\mathrm{SFR} = \varepsilon\, f_{\rm b}\, \dot{M}_{\rm accretion}$$

Possible Solutions at z~10

1. The observations are totally off
   - calibration
   - photo-z
   - wrong M_{star} (IMF, SFH, low dust extinction)

   Upcoming JWST observations (MIRI, NIRSpec) will tell

2. Number density of halos is higher than in ΛCDM
   - Early Dark Energy (Hubble tension, Karwal & Kamionkowski 16, Klypin+21)

   But Occam's razor?

$$H^2 = \frac{8\pi G}{3}\rho$$

3. L_{UV}/M_{star} is higher than at low z
   - UV from accreting black holes (but no AGN)
   - Top-heavy stellar initial mass function (IMF)

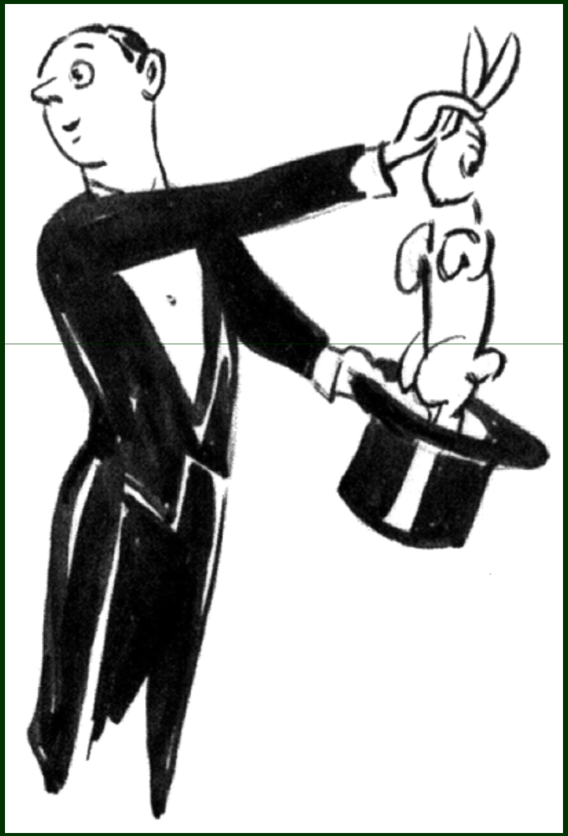
   Needs low metallicity. Dust attenuation. No mass dependence.

4. High efficiency of star formation $\varepsilon = M_{star}/f_b M_{halo} \sim 1$

   This talk.

2. Feedback-Free Starbursts

1. feedback-free: $t_{\text{free-fall}} < t_{\text{fdbk}} \sim 1$ Myr
2. starbursts: $t_{\text{cool}} < t_{\text{free-fall}}$
3. self-shielding



JWST: Supernova feedback at Low z

Robust prediction at high density and low metallicity

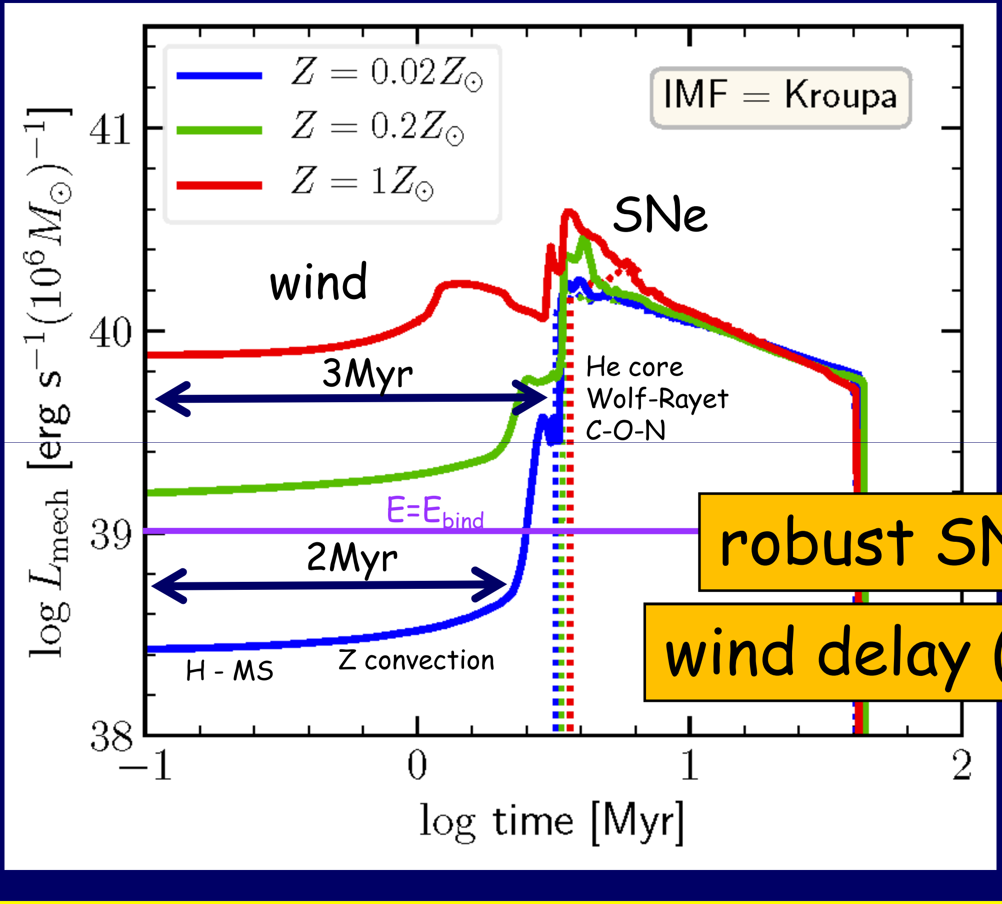
At $z\sim10$ and $M_{halo}\sim10^{10.8}M_{\odot}$: $\varepsilon\sim1$

Feedback-Free Starbursts

Characteristic timescale & density
$t\sim1$ Myr $n\sim3\times10^{3}$ cm^{-3}

2a. Feedback-Free Starburst

Starburst99: mechanical power of wind+SN feedback for a starburst



robust SN delay t~3Myr

wind delay (Z<0.2) t~2Myr

At low Z, a feedback delay of >1 Myr after a starburst

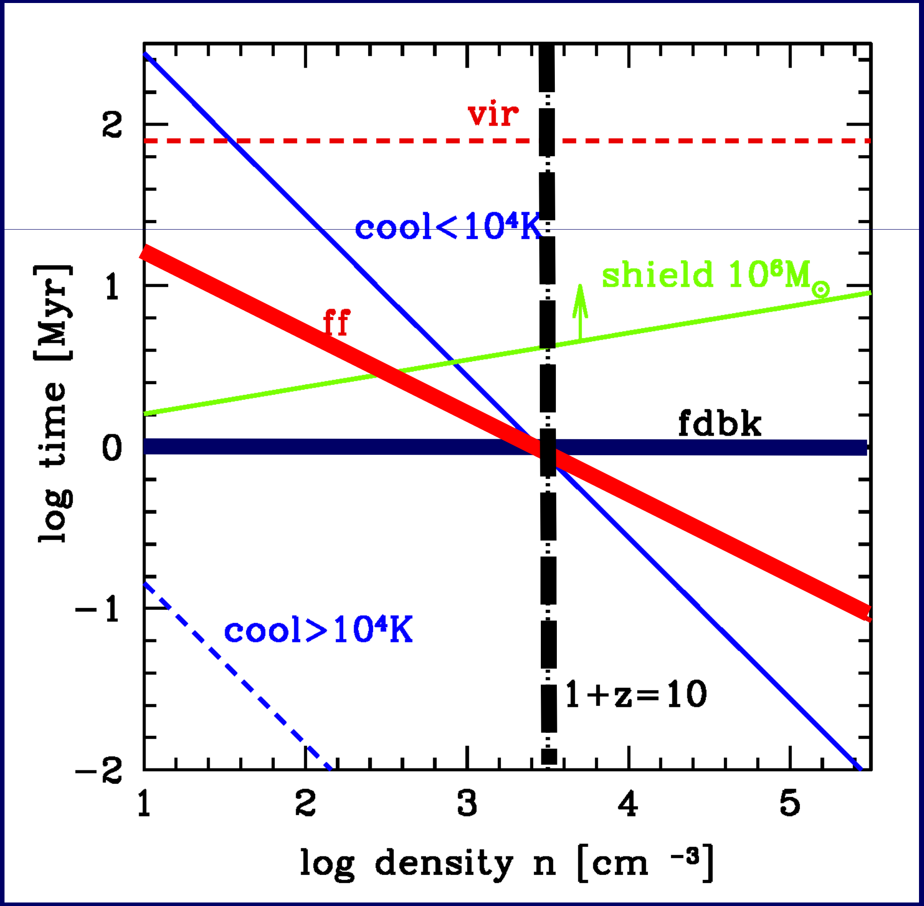
Feedback-free starburst ↔ t_{ff} < 1 Myr

Feedback-Free Starburst

$$t_{\rm ff} < t_{\rm fbk} \approx 1\,{\rm Myr}$$

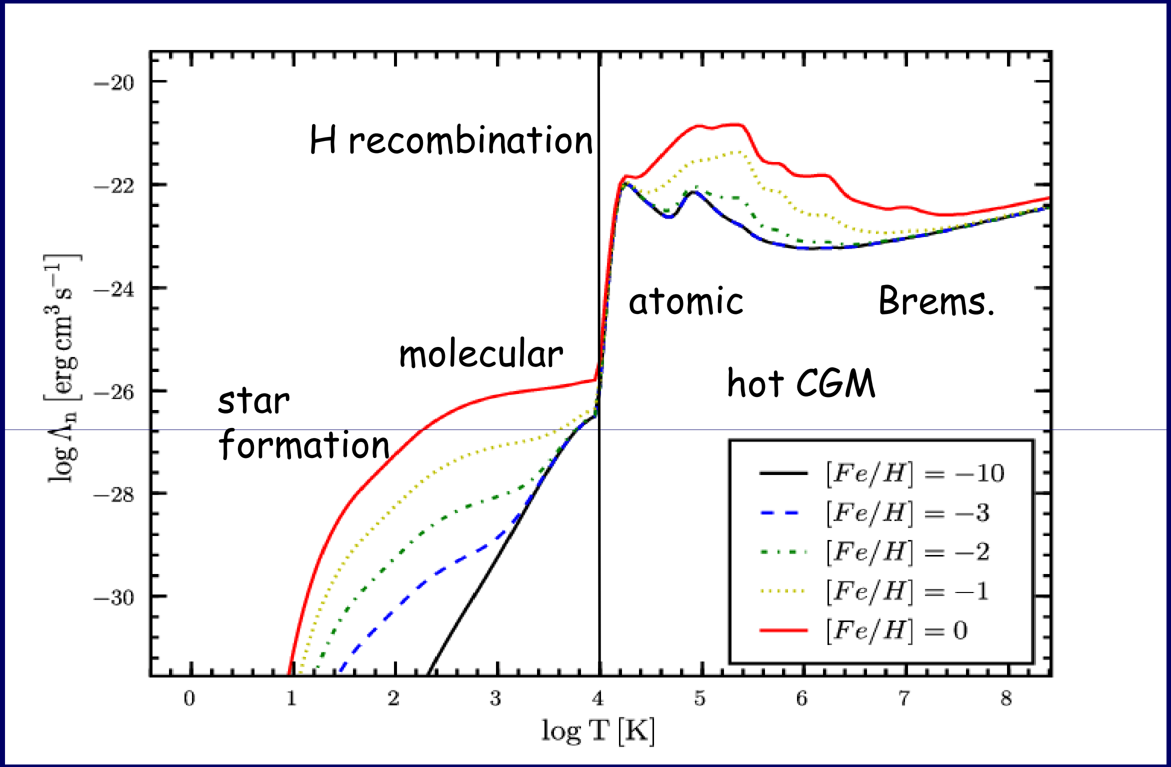
$$t_{\rm ff} = (3\pi/32G\rho)^{-1/2} \approx 0.84\,{\rm Myr}\, n_{3.5}^{-1/2}$$

$$\Rightarrow \quad n_{\rm fbk} \approx 2.3\times10^{3}\,{\rm cm}^{-3}$$



A necessary condition for a starburst

2b. Cooling on a free-fall time below T~10^4K



$$t_{\rm cool} = \frac{e}{\dot{e}} \approx \frac{kT}{n\,\Lambda(T,Z)}$$

At low Z, slow cooling by CII, OI, LyA: $t_{\rm cool} \approx 0.9\,{\rm Myr}\, n_{3.5}^{-1}\, Z_{-2}^{-1}\, T_4\, c^{-1}$

Krumholz 12

$t_{\rm ff} \approx 0.84\,{\rm Myr}\, n_{3.5}^{-1/2}$ ⇒ $t_{\rm cool}$~$t_{\rm ff}$ at $n_{\rm cool} \approx 3.4\times 10^3\,{\rm cm}^{-3}\, Z_{-2}^{-2}\, T_4^2\, c^{-2}$

Feedback-Free Starburst - Cooling

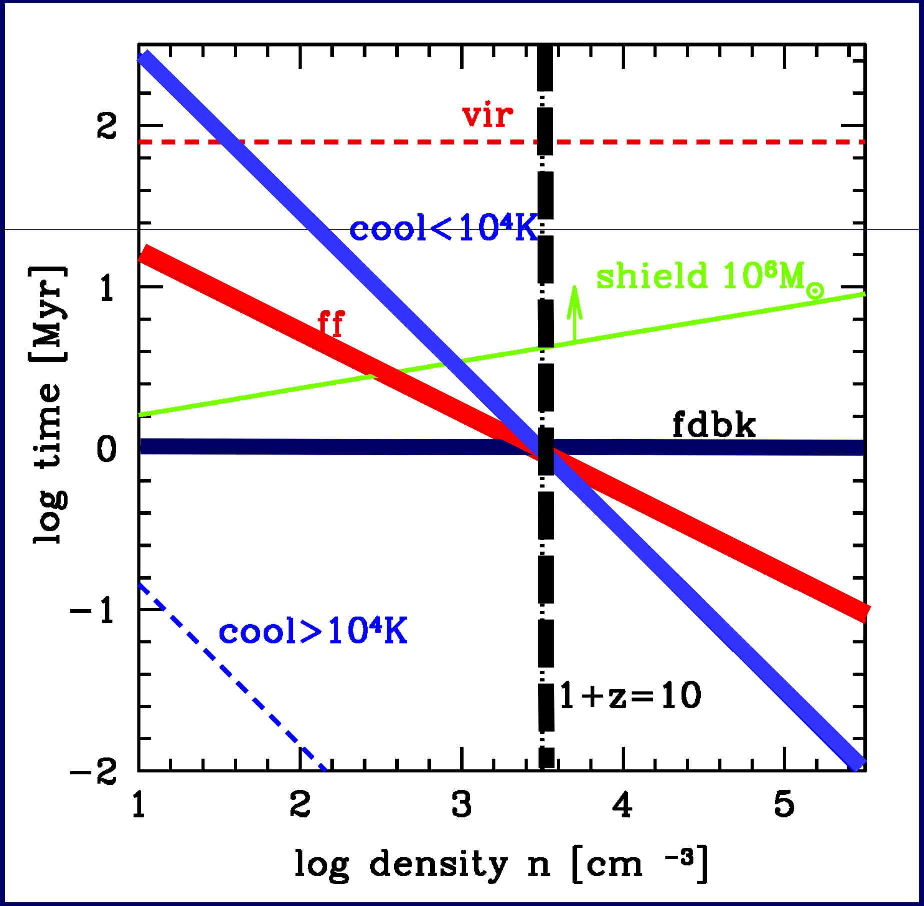
$t_{\rm fdbk} \approx 1\,{\rm Myr}$

$t_{\rm ff} \approx 0.92\,{\rm Myr}\, n_{3.5}^{-1/2}$

$t_{\rm cool} \approx 0.9\,{\rm Myr}\, n_{3.5}^{-1}\ Z_{-2}^{-1}\ T_4\ c^{-1}$

$n_{\rm fdbk} \approx 2.3\times10^{3}\,{\rm cm}^{-3}$

$n_{\rm cool} \approx 3.4\times10^{3}\,{\rm cm}^{-3}\ Z_{-2}^{-2}\ T_4^{2}\ c^{-2}$



2c. Self-Shielding of Starbursting Clouds

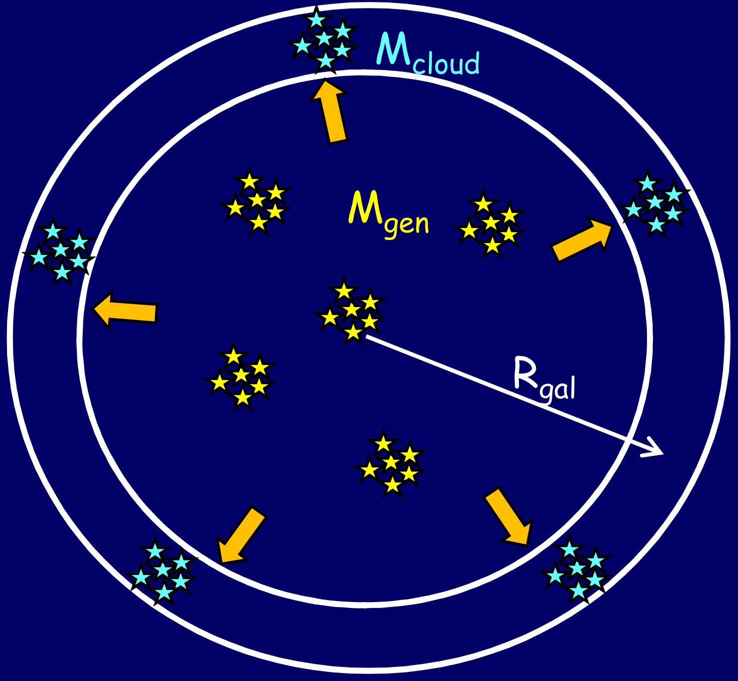
Cloud crushing by wind from an earlier generation of starbursts
Kelvin-Helmholtz instability (Klein, McKee, Colella 94)

$$t_{\rm crush} > 2\frac{R_{\rm cloud}}{V_{\rm wind}}\left(\frac{\rho_{\rm cloud}}{\rho_{\rm wind}}\right)^{1/2} \approx 4.2\,{\rm Myr}\, n_{3.5}^{1/6}\ M_{\rm cloud,6}^{1/3}\ R_{\rm gal,1kpc}\ M_{\rm gen,9}^{-1/2}$$

versus t_{ff}

Threshold for shielding against winds

$$M_{\rm cloud,\ shield} \approx 1.3\times10^4 M_\Theta\ n_{3.5}^{-1/2}\ R_{\rm gal,1kpc}^{-3}\ M_{\rm gen,9}^{3/2}$$



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versus t_{ff}

Threshold for shielding against winds

$$M_{\rm cloud,\,shield} \approx 1.3\times10^{4}\, M_{\Theta}\; n_{3.5}^{-1/2}\; R_{\rm gal,1kpc}^{-3}\; M_{\rm gen,9}^{3/2}$$

A generation of active winds

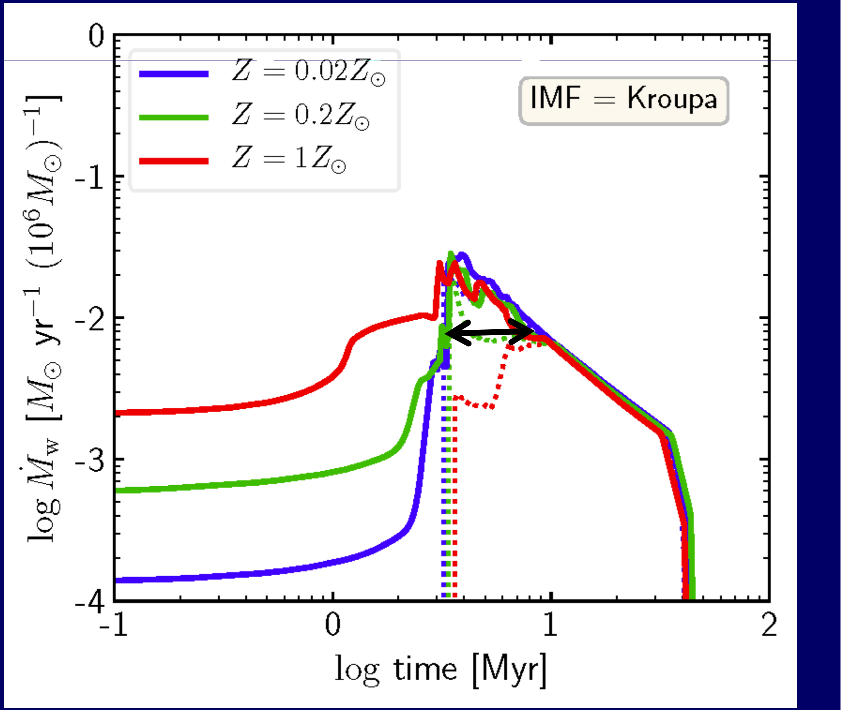
$$M_{\rm gen} \approx 1.3\times10^{9}\, M_{\Theta}\; \varepsilon\; M_{\rm vir,10.8}\; (1+z)_{10}^{3/2}$$

UV Shielding: flux vs recombination

$$\frac{f_{\rm OB}\, \nu_{\rm ionizing}\, M_{\rm gen}}{4\,\pi\, R_{\rm gal}^{2}} = \alpha\, n^{2}\, \Delta r$$

$$\Delta r \approx 0.1{\rm pc}\; f_{\rm OB,-2}\; M_{\rm gen,9}\; R_{\rm gal,1}^{-2}\; n_{3.5}^{-2}$$

shielded!



Feedback-Free Starburst - Shielding

$t_{\rm fdbk} \approx 1\,{\rm Myr}$

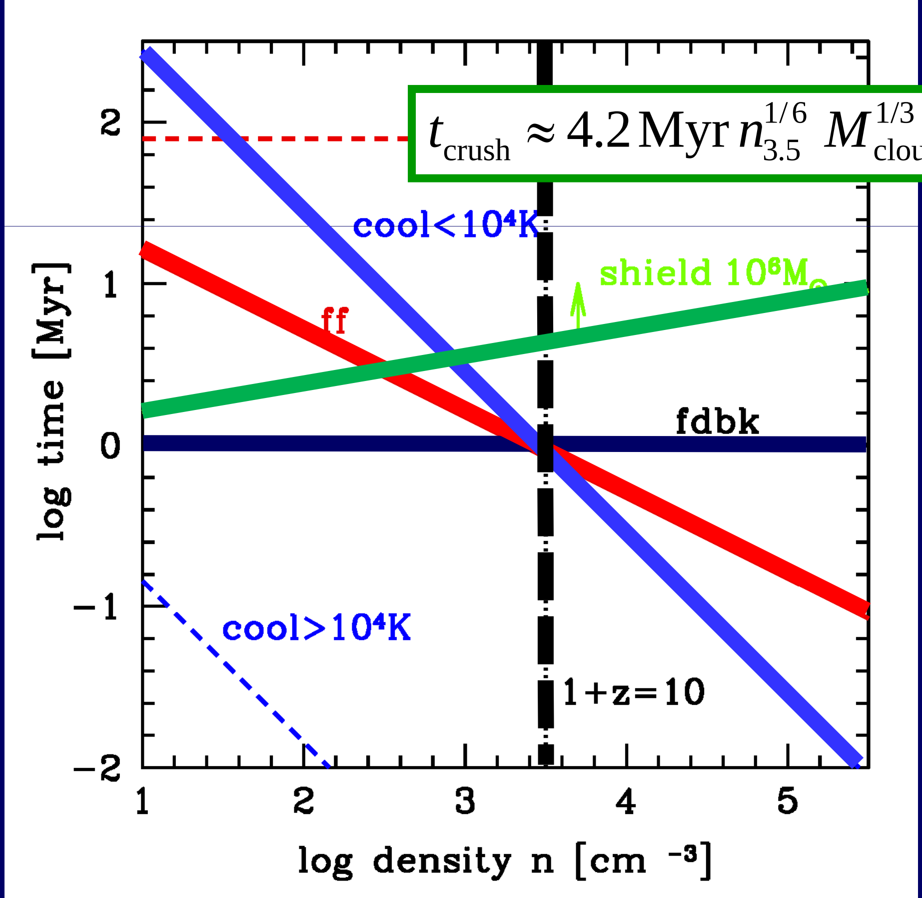
$t_{\rm ff} \approx 0.92\,{\rm Myr}\, n_{3.5}^{-1/2}$

$t_{\rm cool} \approx 0.9\,{\rm Myr}\, n_{3.5}^{-1}\ Z_{-2}^{-1}\ T_4\ c^{-1}$

$n_{\rm fdbk} \approx 3\times 10^3\,{\rm cm}^{-3}$

$n_{\rm cool} \approx 3.4\times 10^3\,{\rm cm}^{-3}\ Z_{-2}^{-2}\ T_4^2\ c^{-2}$

$t_{\rm crush} \approx 4.2\,{\rm Myr}\, n_{3.5}^{1/6}\ M_{\rm cloud,6}^{1/3}\ R_{\rm gal,1kpc}\ M_{\rm gen,9}^{-1/2}$



3. Massive Galaxies at Cosmic Dawn

a. Cold inflow through the halo

b. The critical density as a function of epoch and mass

c. Observable predictions

3a. Efficient Cold Inflow in DM Halos at z~10

$$t_{\rm univ} \approx 460\,{\rm Myr}\,(1+z)_{10}^{-3/2}$$

$$n_{\rm bary,univ} \approx 10^{-2}\,{\rm cm}^{-3}\,(1+z)_{10}^{3}$$

$$R_{\rm halo} \approx 12\,{\rm kpc}\,{\rm M}_{\rm halo,10.8}^{1/3}\,(1+z)_{10}^{-1}$$

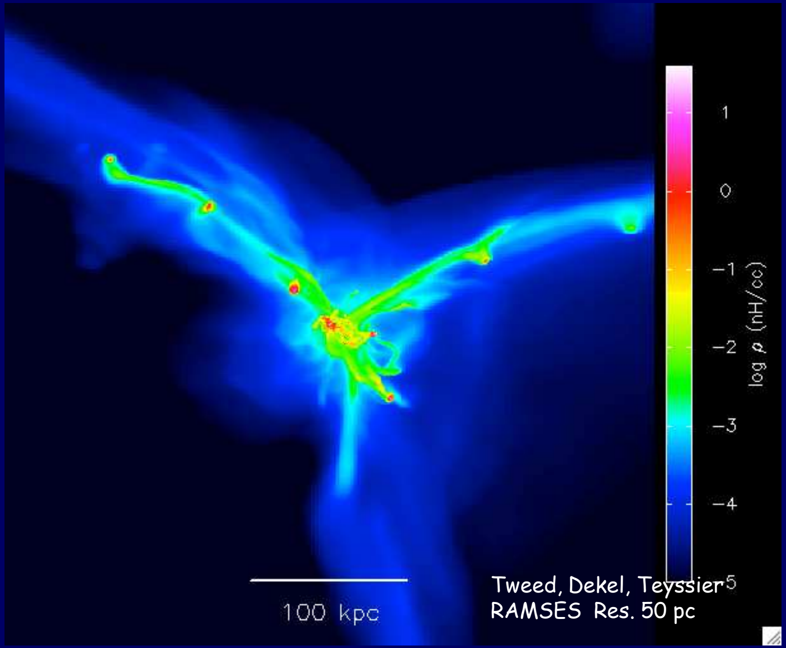
$$V_{\rm halo} \approx 150\,{\rm kms}^{-1}\,{\rm M}_{\rm halo,10.8}^{1/3}\,(1+z)_{10}^{1/2}$$

$$t_{\rm halo} \approx 80\,{\rm Myr}\,(1+z)_{10}^{-3/2}$$

$$n_{\rm bary,halo} \approx 5.5\times10^{-2}\,{\rm cm}^{-3}\,(1+z)_{10}^{3}$$

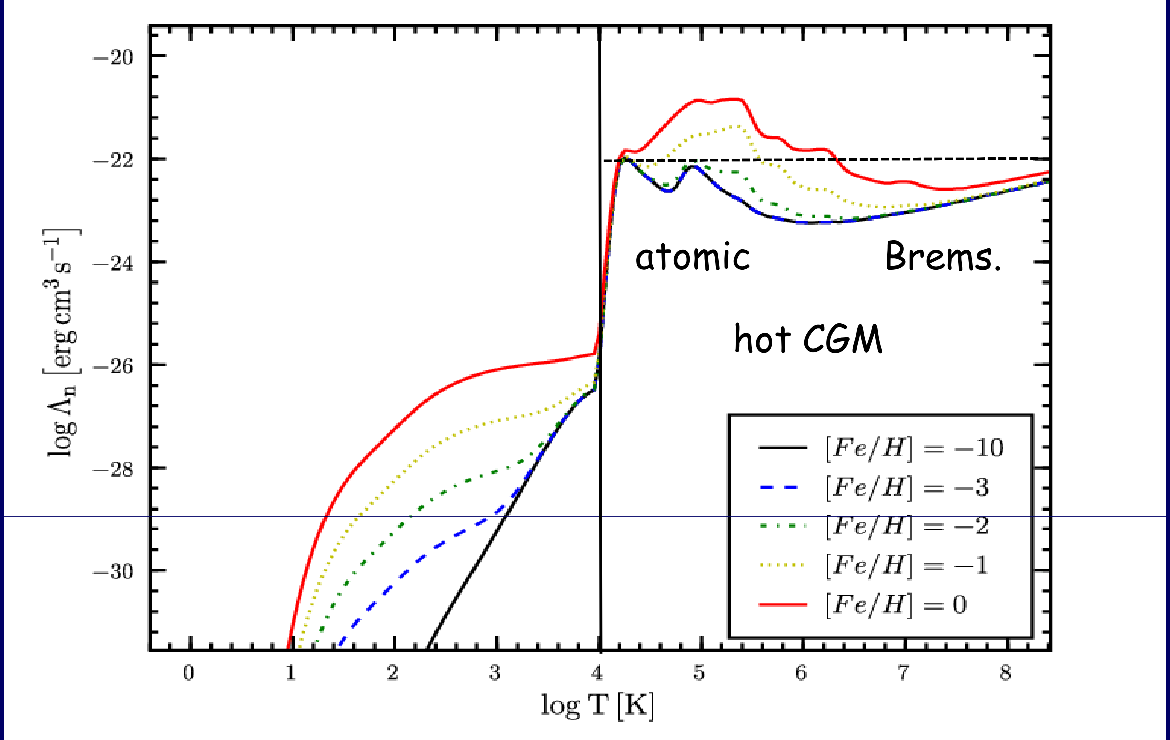
$$t_{\rm acc} = \frac{M}{\dot{M}} \approx 170\,{\rm Myr}\,M_{\rm halo,10.8}^{-0.14}\,(1+z)_{10}^{-5/2}$$

$$\dot{M}_{\rm bary,acc} \approx 65\,M_{\Theta}{\rm yr}^{-1}\,M_{\rm halo,10.8}^{1.14}\,(1+z)_{10}^{5/2}$$



Tweed, Dekel, Teyssier
RAMSES Res. 50 pc

Rapid Cooling above T~10^{4}K



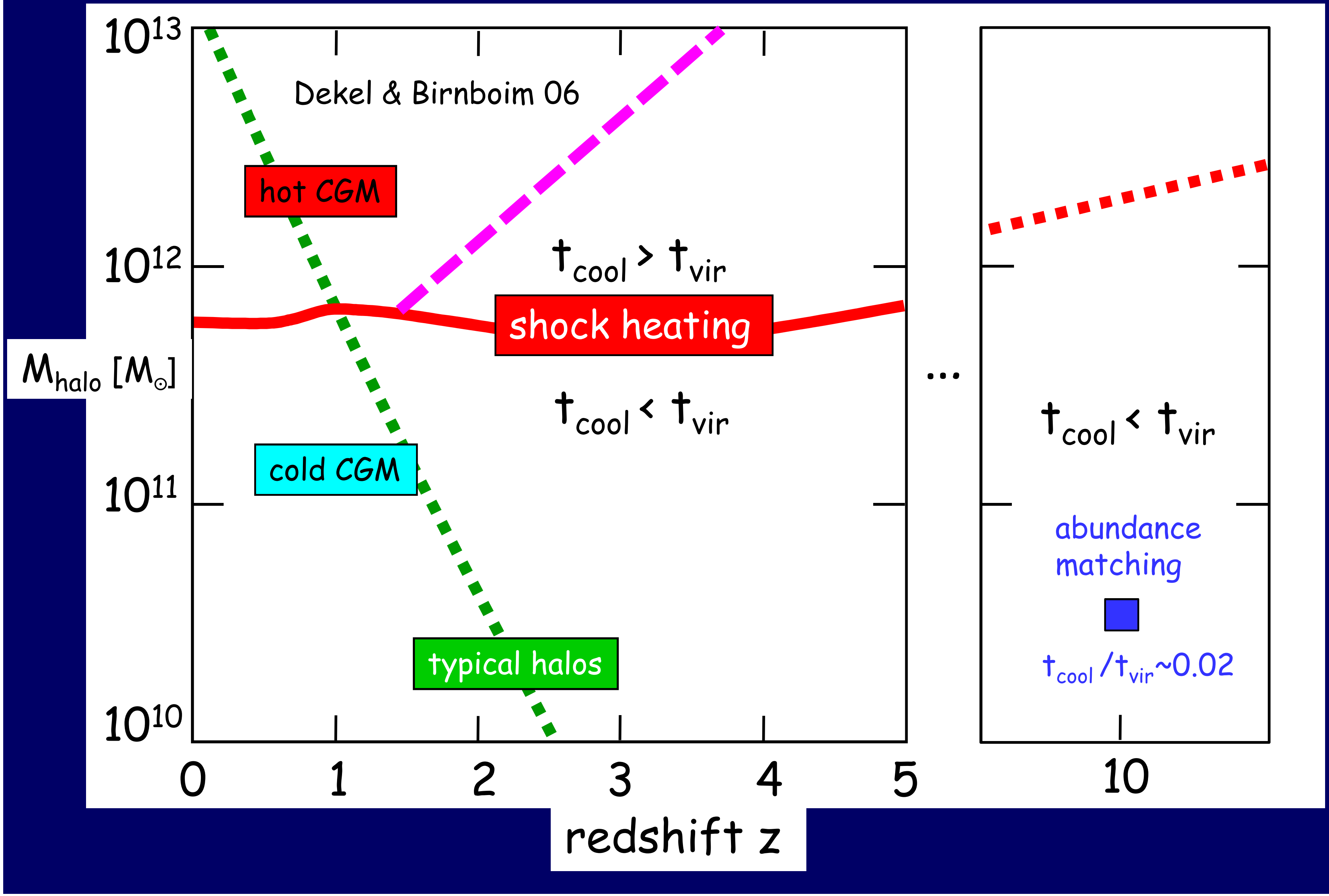
$$t_{\rm cool} = \frac{e}{\dot{e}} \approx \frac{kT}{n\,\Lambda(T,Z)}$$

Atomic cooling: $t_{\rm cool} \approx 1.3\times10^{-3}\,{\rm Myr}\,n^{-1}\,T_4\,\Lambda^{-1}_{-22}(T,Z) << t_{\rm ff}$

$t_{\rm cool} < t_{\rm vir}$ -> no virial shock

$t_{\rm cool} << t_{\rm ff}$ -> cold streams at T~10^{4}K

Cold Inflow in the DM Halo: no Viral Shock



Efficient Cold Inflow in DM Halos at z~10

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$$\dot{M}_{\rm bary,acc} \approx 65\,M_{\Theta}\,{\rm yr}^{-1}\,M_{\rm halo,10.8}^{1.14}\,(1+z)_{10}^{5/2}$$

Atomic cooling at $T>10^4$K

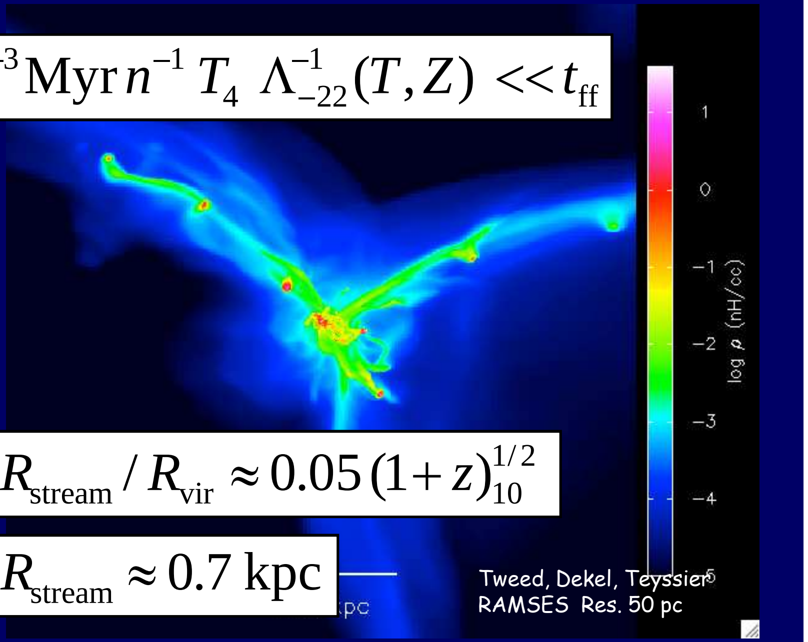
$$t_{\rm cool} \approx 1.3\times10^{-3}\,{\rm Myr}\,n^{-1}\,T_4\,\Lambda_{-22}^{-1}(T,Z) \ll t_{\rm ff}$$

$t_{\rm cool} < t_{\rm vir}$ -> no virial shock

$t_{\rm cool} \ll t_{\rm ff}$ -> cold streams at T~10^4K

Stream radius by cylindrical collapse & virialization conserving AM

Mandelker+18, Ramsoy+21 simulations

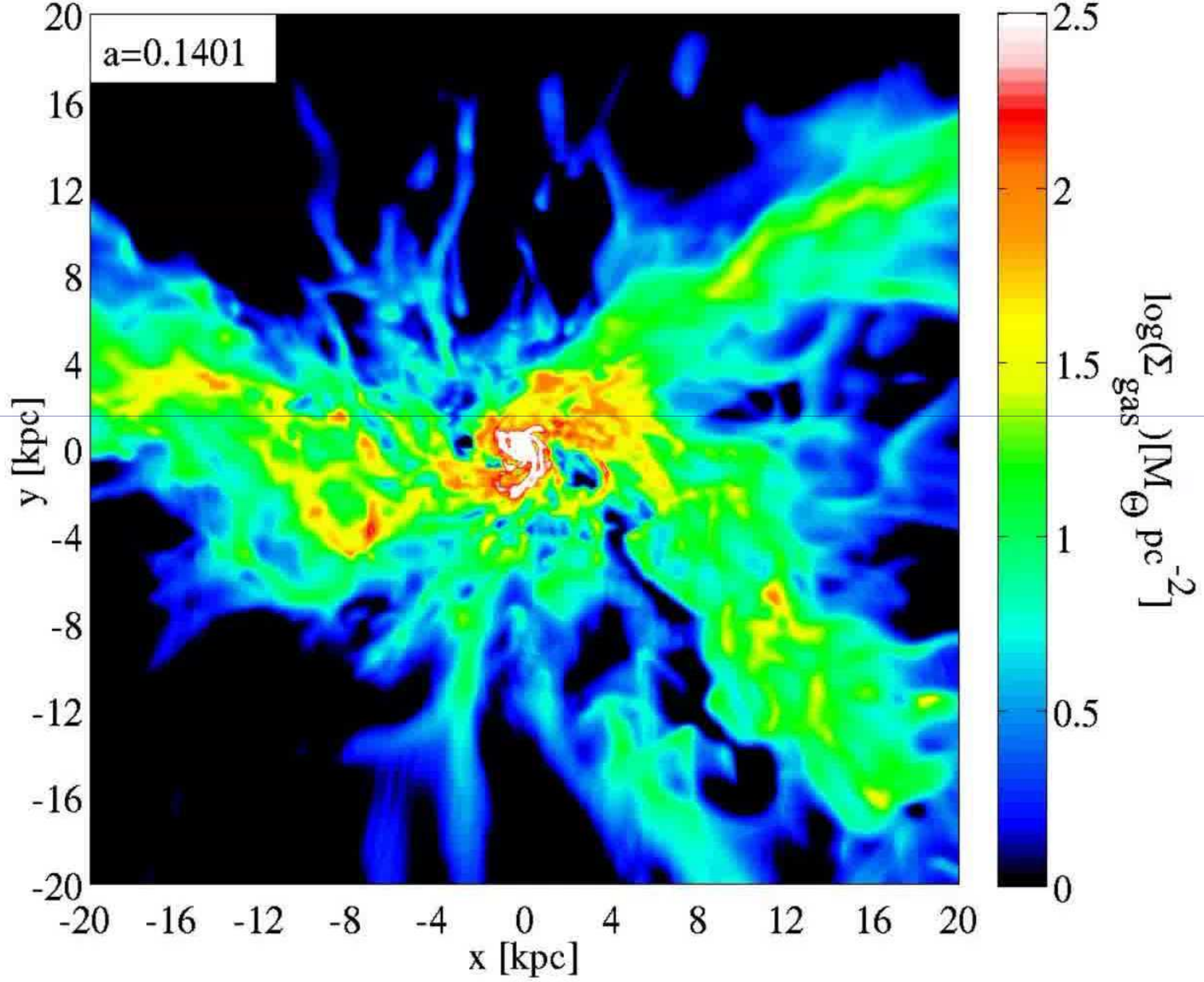


Tweed, Dekel, Teyssier
RAMSES Res. 50 pc

$$R_{\rm stream}/R_{\rm vir} \approx 0.05\,(1+z)_{10}^{1/2}$$

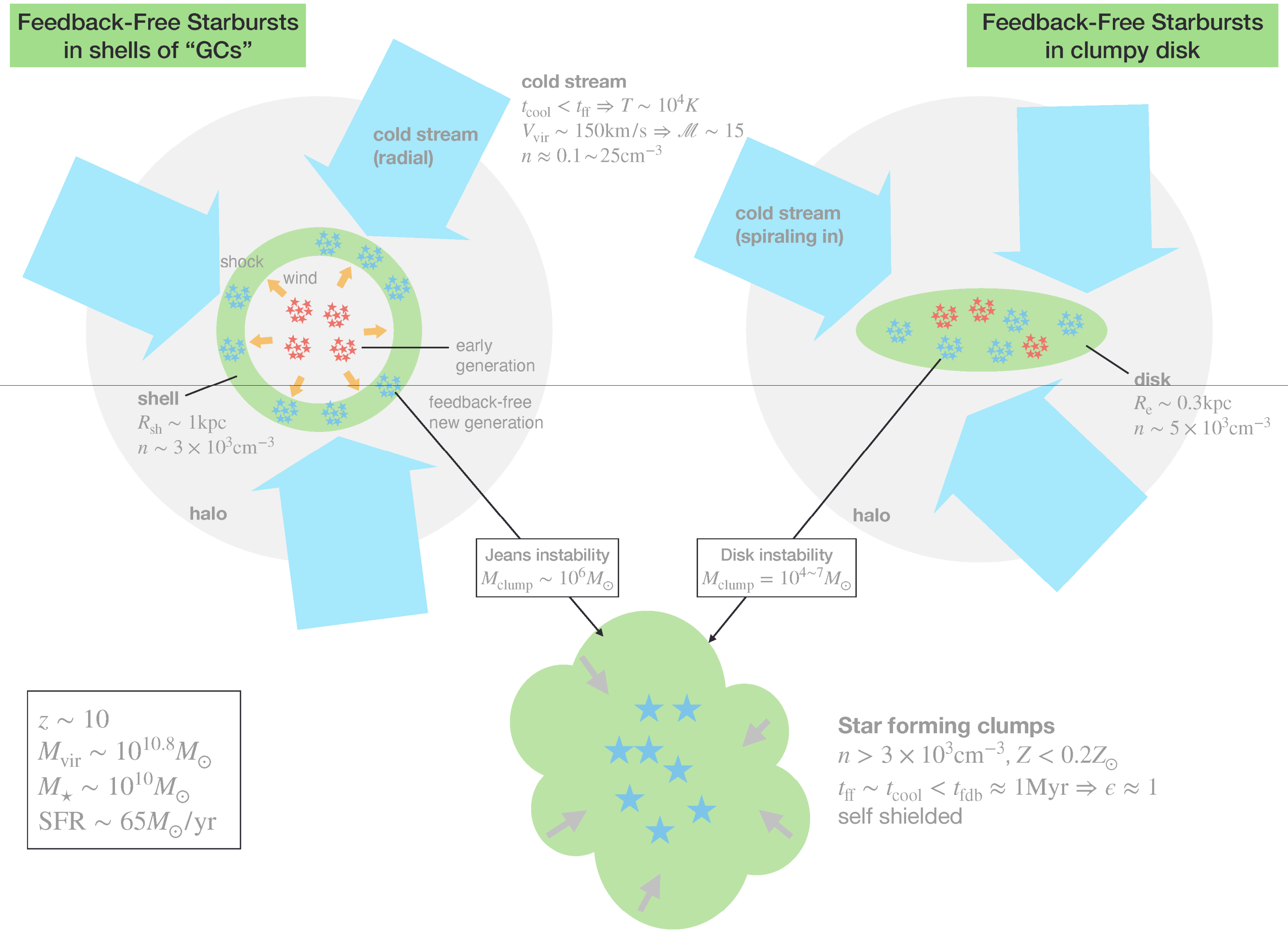
$$R_{\rm stream} \approx 0.7\,{\rm kpc}$$

Cold Streams feed Disks at Very High z



3b. At what epoch and mass do we expect the critical density for FFB?

Two Scenarios



Feedback-Free Starbursts in shells of “GCs”

Feedback-Free Starbursts in clumpy disk

cold stream

$t_{\rm cool} < t_{\rm ff} \Rightarrow T \sim 10^4 K$

$V_{\rm vir} \sim 150{\rm km/s} \Rightarrow \mathscr{M} \sim 15$

$n \approx 0.1 \sim 25{\rm cm}^{-3}$

cold stream (radial)

shock

wind

early generation

feedback-free new generation

shell

$R_{\rm sh} \sim 1{\rm kpc}$

$n \sim 3 \times 10^3{\rm cm}^{-3}$

halo

cold stream (spiraling in)

disk

$R_{\rm e} \sim 0.3{\rm kpc}$

$n \sim 5 \times 10^3{\rm cm}^{-3}$

halo

Jeans instability

$M_{\rm clump} \sim 10^6 M_\odot$

Disk instability

$M_{\rm clump} = 10^{4\sim7} M_\odot$

$z \sim 10$

$M_{\rm vir} \sim 10^{10.8} M_\odot$

$M_\star \sim 10^{10} M_\odot$

${\rm SFR} \sim 65 M_\odot/{\rm yr}$

Star forming clumps

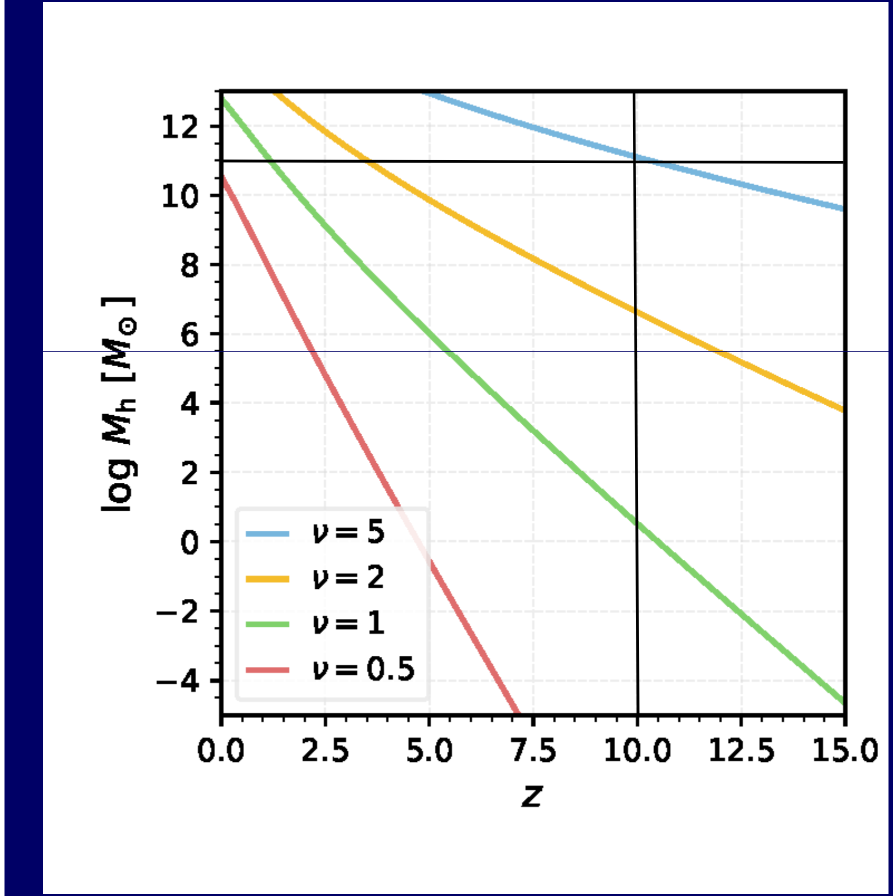
$n > 3 \times 10^3{\rm cm}^{-3}, Z < 0.2 Z_\odot$

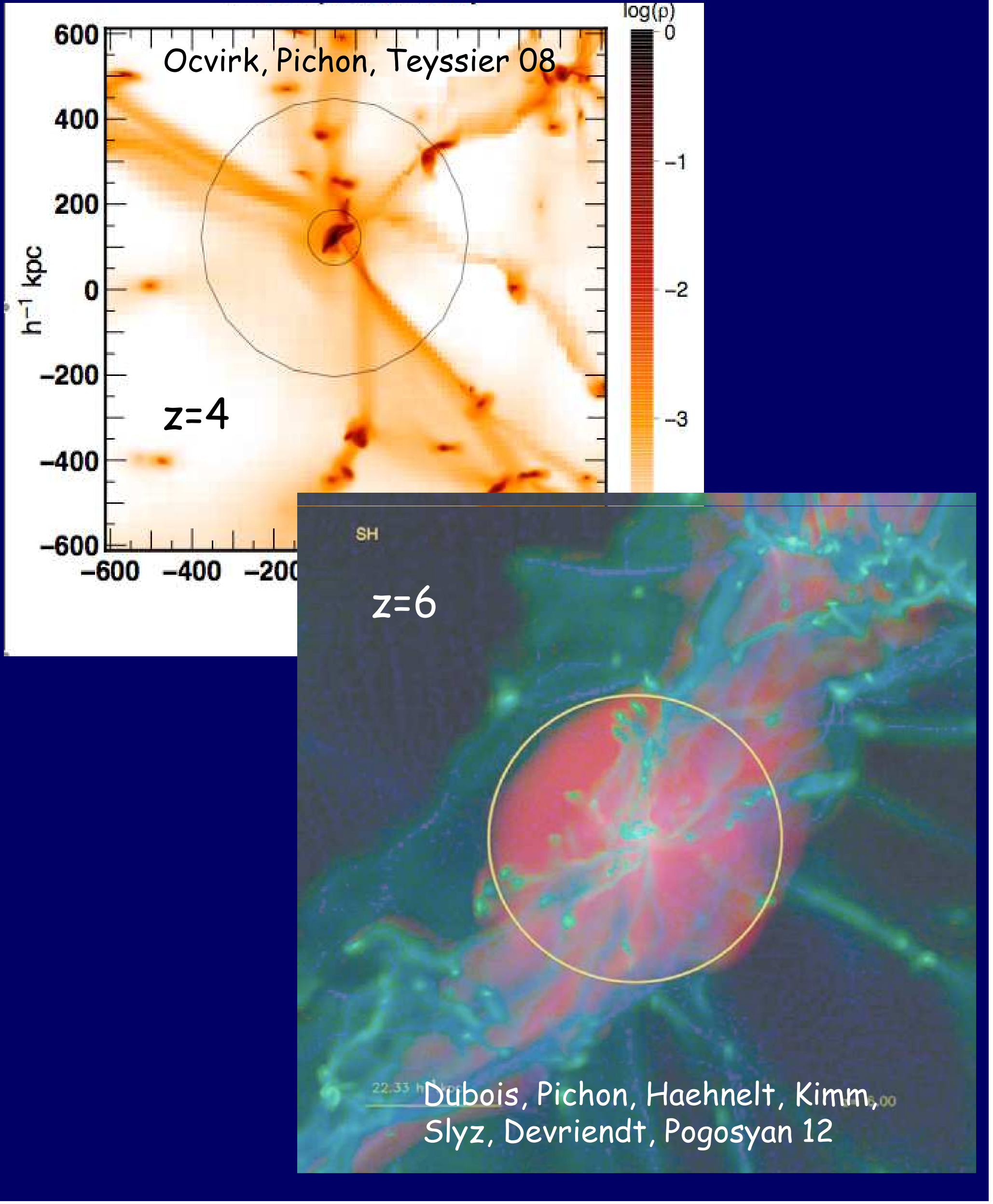
$t_{\rm ff} \sim t_{\rm cool} < t_{\rm fdb} \approx 1{\rm Myr} \Rightarrow \epsilon \approx 1$

self shielded

Case A: Radial Streams

High-sigma Peaks





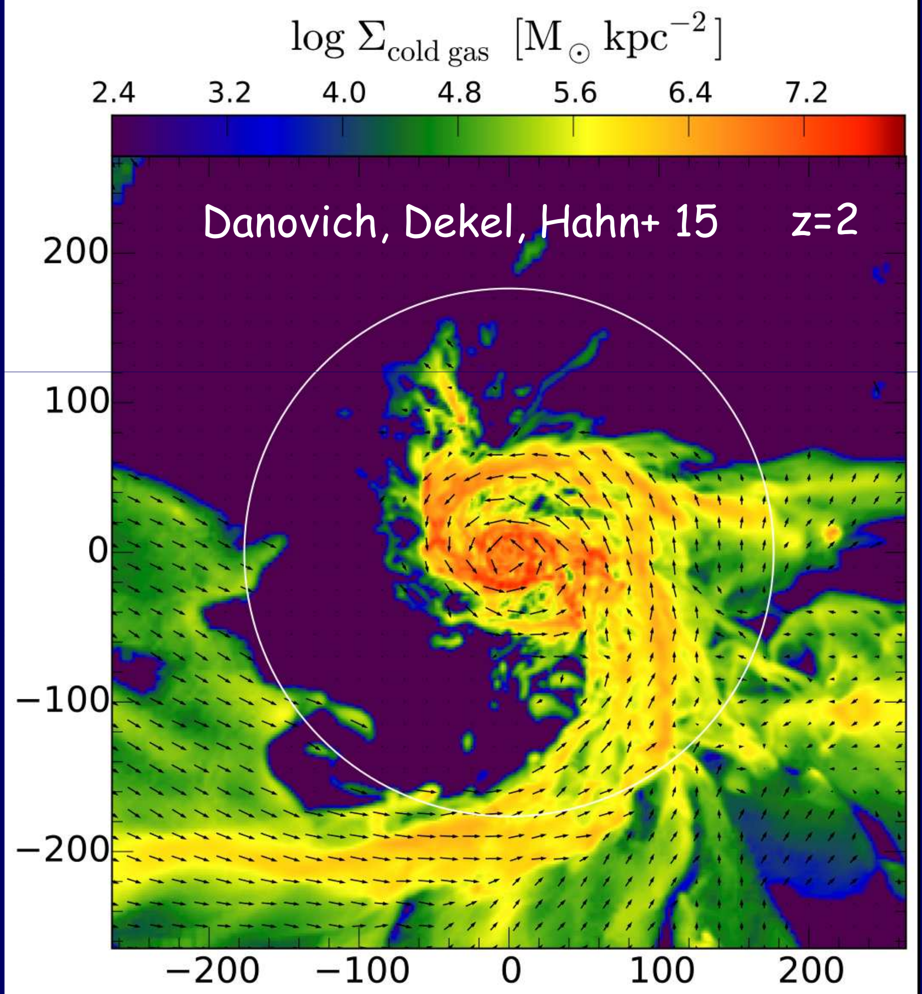
Ocvirk, Pichon, Teyssier 08

z=4

z=6

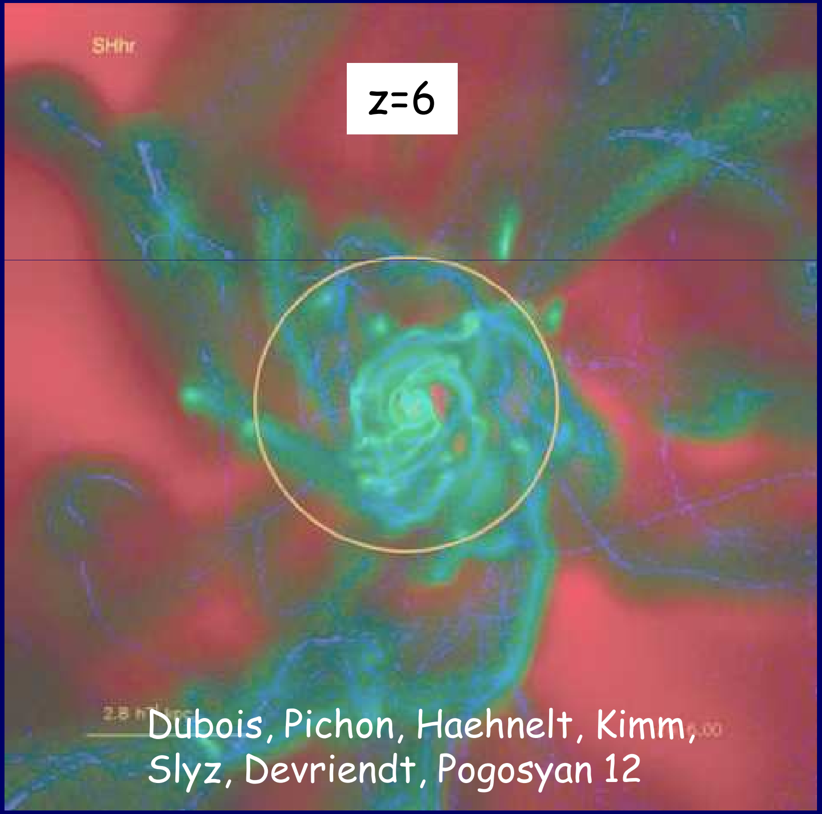
Dubois, Pichon, Haehnelt, Kimm, Slyz, Devriendt, Pogosyan 12

Case B: Disks by Stream's Angular Momentum



Danovich, Dekel, Hahn+ 15 z=2

Disk with ~low AM λ~0.02



z=6

Dubois, Pichon, Haehnelt, Kimm, Slyz, Devriendt, Pogosyan 12

Fdbk-Free Density at z~10 & $M_{\rm halo}$~$10^{11} M_\odot$

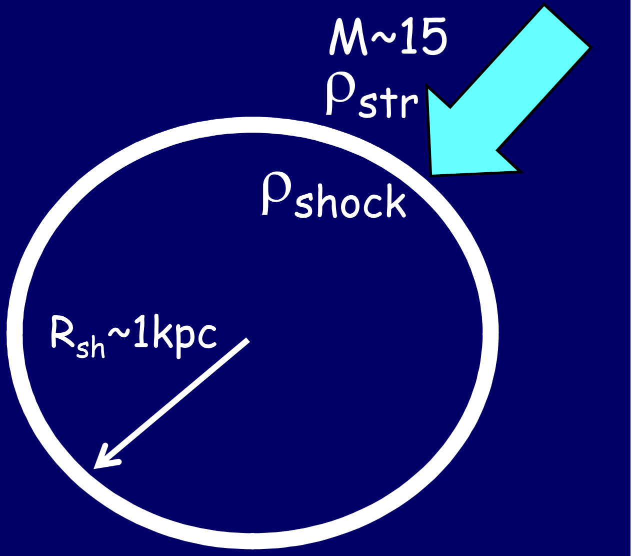
a. Radial Streams: post-shock Density

$$\rho_{\rm shock} \approx \rho_{\rm str}\, \mathbf{M}^2$$

Pre-shock $n_{\rm str} \approx 17\ {\rm cm}^{-3}\ R^{-2}_{\rm str,0.7kpc}\ M^{0.81}_{\rm halo,10.8}\ (1+z)^{2}_{10}$

Mach number $\mathbf{M} \approx 15\, M^{1/3}_{\rm halo,10.8}\ (1+z)^{1/2}_{10}\ T_4^{-1/2}$

$$n_{\rm shock} \approx 3.5\times 10^{3}\,{\rm cm}^{-3}\ R^{-2}_{\rm str,0.7kpc}\ M^{1.5}_{\rm halo,10.8}\ (1+z)^{3}_{10}$$



b. Streams with angular momentum: disc density

$$n_{\rm disc} \approx 2\, c\, \lambda^{-3}\ f_{\rm b}\, \Delta\, n_{\rm univ,0}(1+z)^{3}_{10}\ \approx 5.6\times 10^{3}\,{\rm cm}^{-3}\ c\ \lambda^{-3}_{0.025}\ (1+z)^{3}_{10}$$

contraction (spin?) $\lambda = R_{\rm e} / R_{\rm halo}$ clumping $c = \rho_{\rm sf} / \rho_{\rm gal}$

c. Observed

$$n_{\rm gal} \approx 1.7\times 10^{3}\,{\rm cm}^{-3}\ c\ \varepsilon\ M_{\rm halo,10.8}\ R^{-3}_{\rm e,0.3}$$

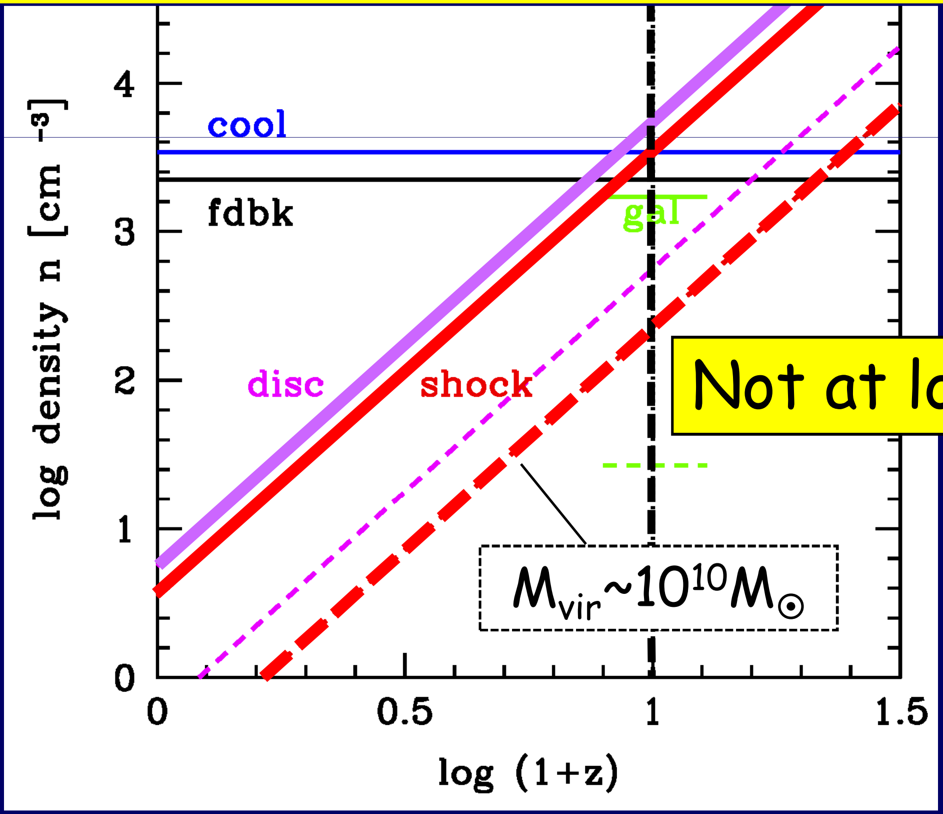
The density (and metallicity) for feedback-free starbursts arise naturally at z~10 & $M_{\rm vir}$~$10^{11} M_\odot$

Density at z~10 and M_{halo}~$10^{11}M_\odot$

$$n_{\rm shock} \approx 3.5\times10^3\,{\rm cm}^{-3}\; R_{\rm str,0.5kpc}^{-2}\; M_{\rm vir,10.8}^{1.5}\;(1+z)_{10}^{3}$$

$$n_{\rm disc} \approx 5.6\times10^3\,{\rm cm}^{-3}\; c\;\lambda_{0.025}^{-3}\;(1+z)_{10}^{3}$$

The density (and metallicity) for feedback-free starbursts arise naturally at z~10 & M_{halo}~$10^{11}M_\odot$



Not at lower masses

Clusters and Generations

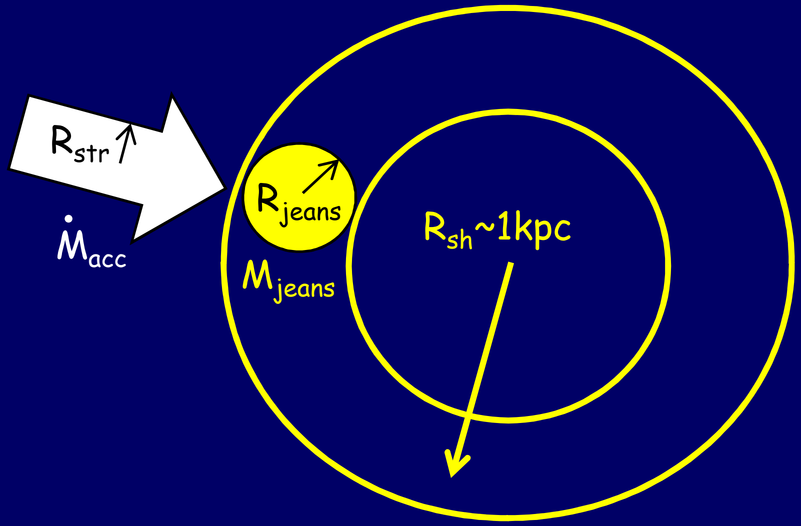
Jeans-Mass Clouds

$$R_{\rm jeans} = (\pi c_s^2 / 4G\rho)^{1/2}$$

$$M_{\rm jeans} \approx 1.1\times10^6 M_\Theta \, T_4^{3/2} \, n_{3.5}^{-1/2}$$

Accumulate $M_{\rm jeans}$ in $R_{\rm jeans}$

$$M_{\rm gen} \approx 4.9\times10^9 M_\Theta \, \varepsilon R^2_{\rm str,0.7kpc}$$



Disk Toomre Clumps

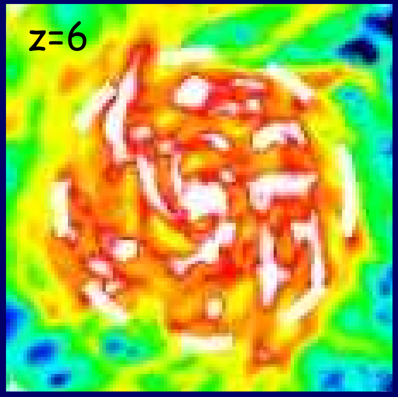
$$1 \approx Q(t) \approx \frac{\sigma\,\Omega}{\pi G \Sigma}$$

Accumulate $M_{\rm disk}$ for Q~1

$$M_{\rm clump} \approx 1.7\times10^6 M_\Theta \, \delta_{0.3}^2 \, \lambda_{0.025}$$

$$M_{\rm gen} \approx 1.1\times10^9 M_\Theta \, M_{\rm vir,10.8} \, \lambda_{0.025}$$

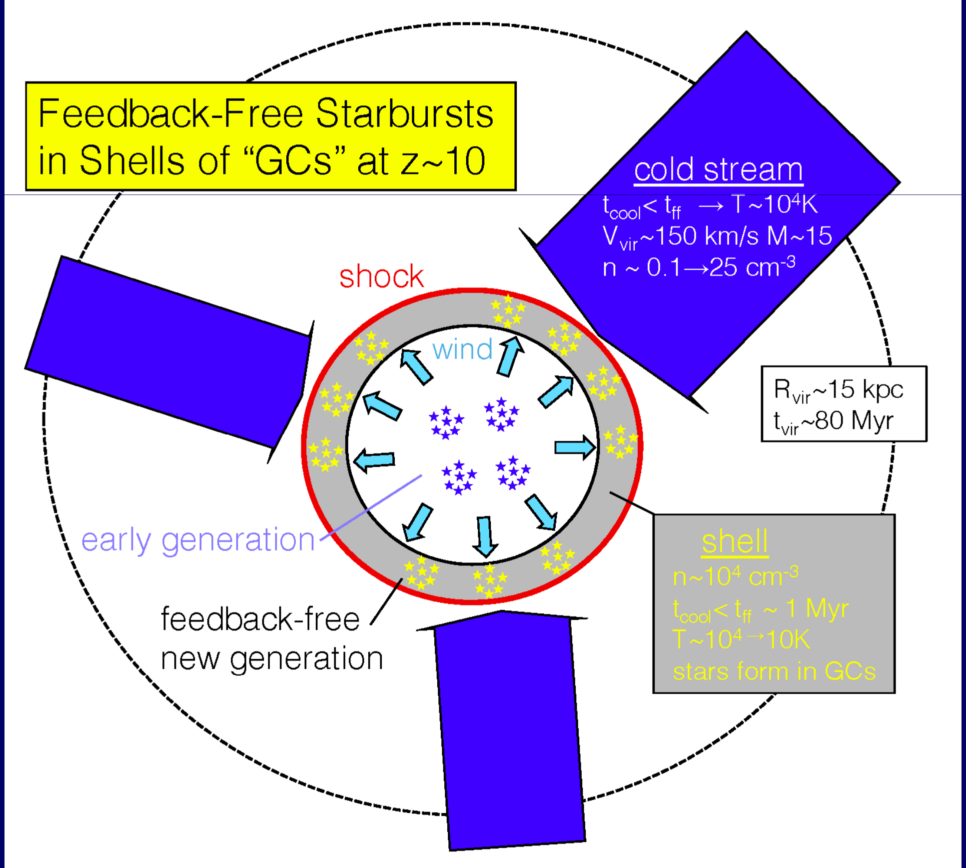
$$\delta = \frac{M_{\rm disk}}{M_{\rm tot}} \approx \frac{\sigma}{V}$$



Shell Radius < 1 kpc

Ram pressures $\rho_{\rm wind} V_{\rm wind}^2 = \rho_{\rm str} V_{\rm halo}^2$

$$\frac{R_{\rm sh}}{R_{\rm str}} = \left(\frac{V_{\rm wind} \; \dot{M}_{\rm wind}}{4 V_{\rm vir} \; \dot{M}_{\rm acc}} \right)^{1/2} \approx 1.25 \; M_{\rm halo,\,10.8}^{-0.73} \; (1+z)_{10}^{-3/2} \; M_{\rm gen,\,9}^{1/2}$$



Feedback-Free Starbursts in Shells of “GCs” at z~10

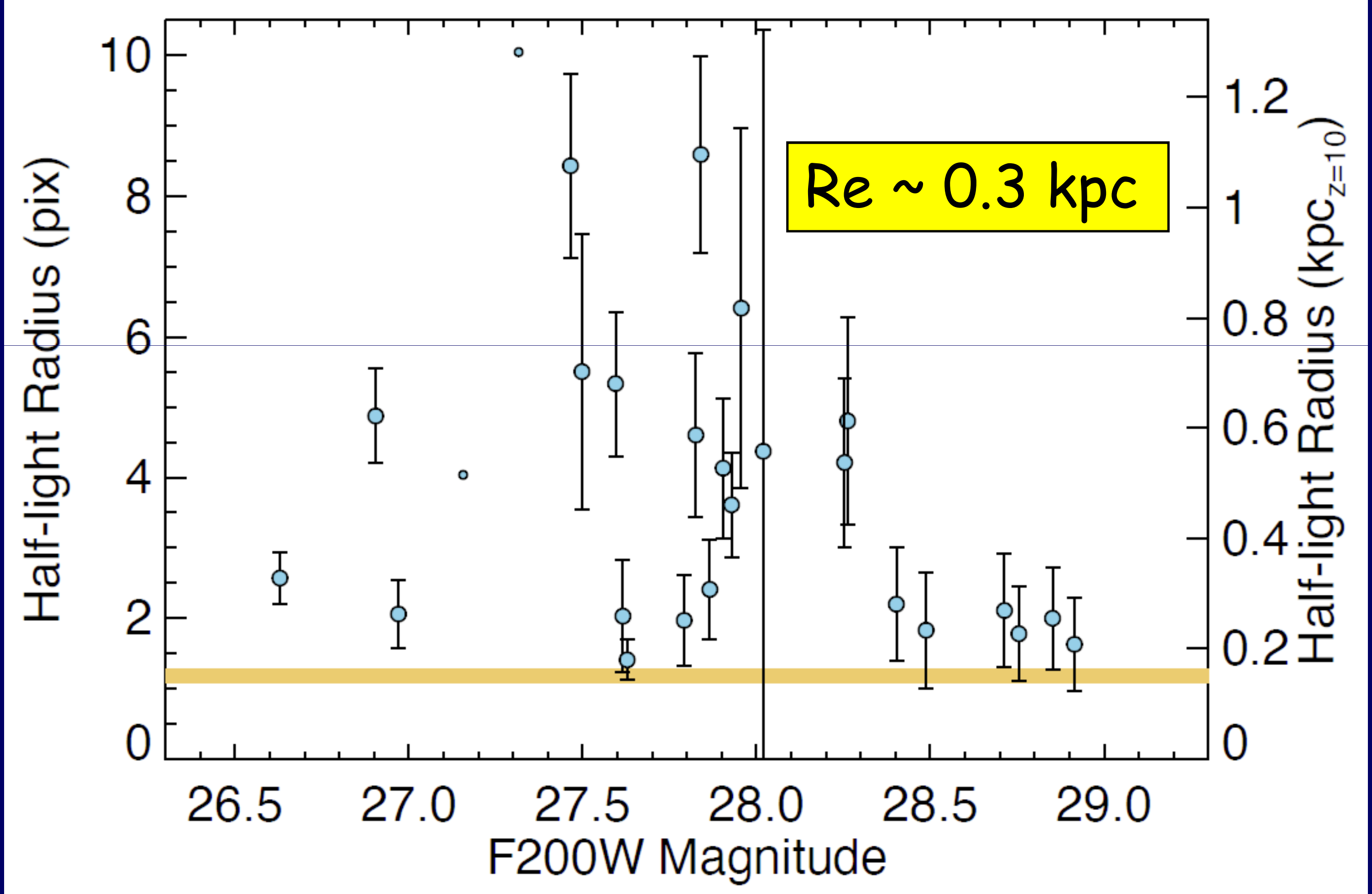
Observable Predictions at z~10

For NIRSpec and MIRI, beyond images and SEDs from NIRCam

- High efficiency $\varepsilon\sim 1$ in $M_{halo}\sim 10^{10.8}M_{\odot}$, $M_{star}\sim 10^{10}M_{\odot}$, SFR$\sim 65M_{\odot}yr^{-1}$
- $\varepsilon\sim 0.1$ in $M_{halo}<10^{10}M_{\odot}$
- Stellar density $n \sim 3\times10^{3}$ cm^{-3} in compact sub-kpc galaxies
- Metallicity $Z < 0.2Z_{\odot}$, little gas, little dust attenuation
- Top-heavy stellar mass function (IMF) possible but not necessary
- Star-formation history: bursts in generations
- Cold streams, little hot halo gas (CGM), little outflows
- Clumpy disks? Clumpy shells?
- Globular cluster excess?

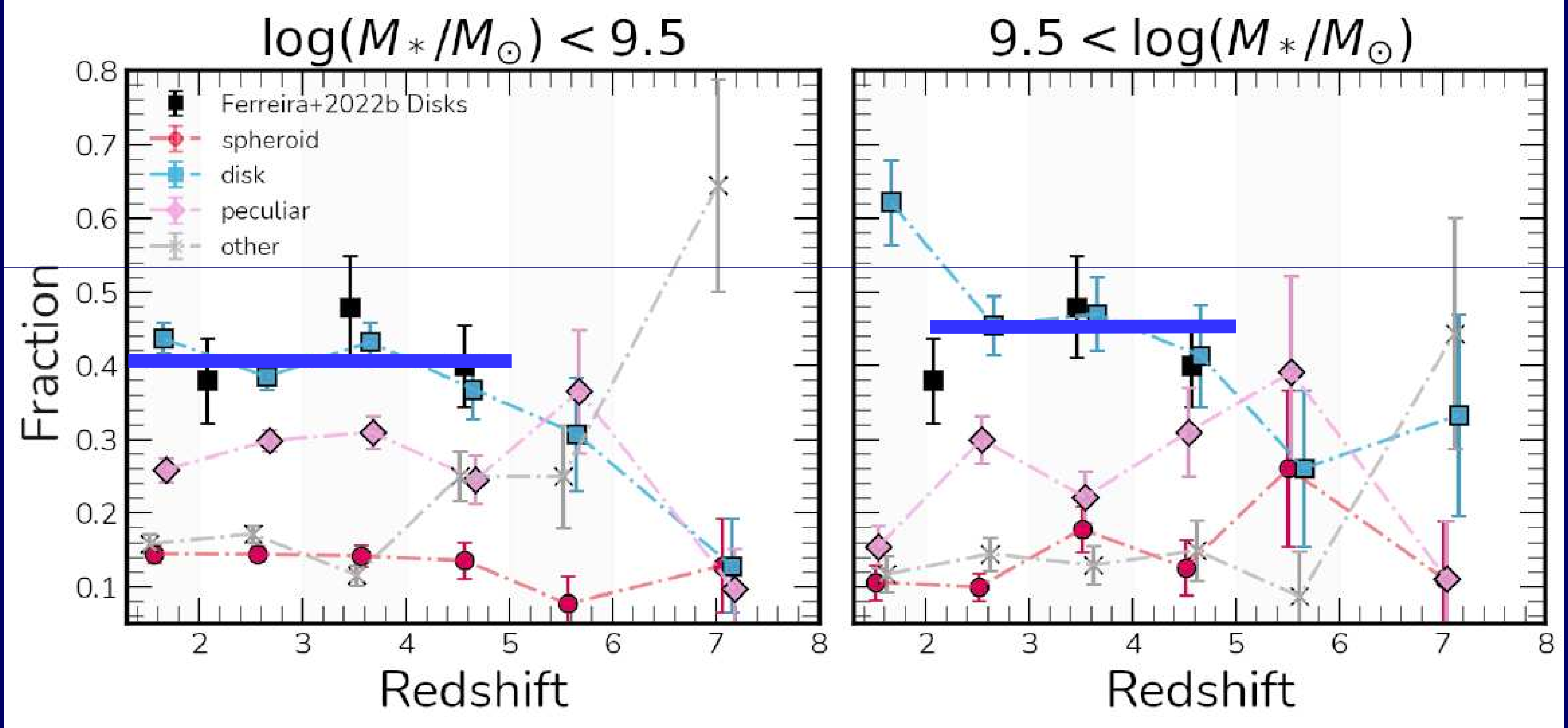
The z~10 Galaxies are Compact

CEERS Finkelstein+22

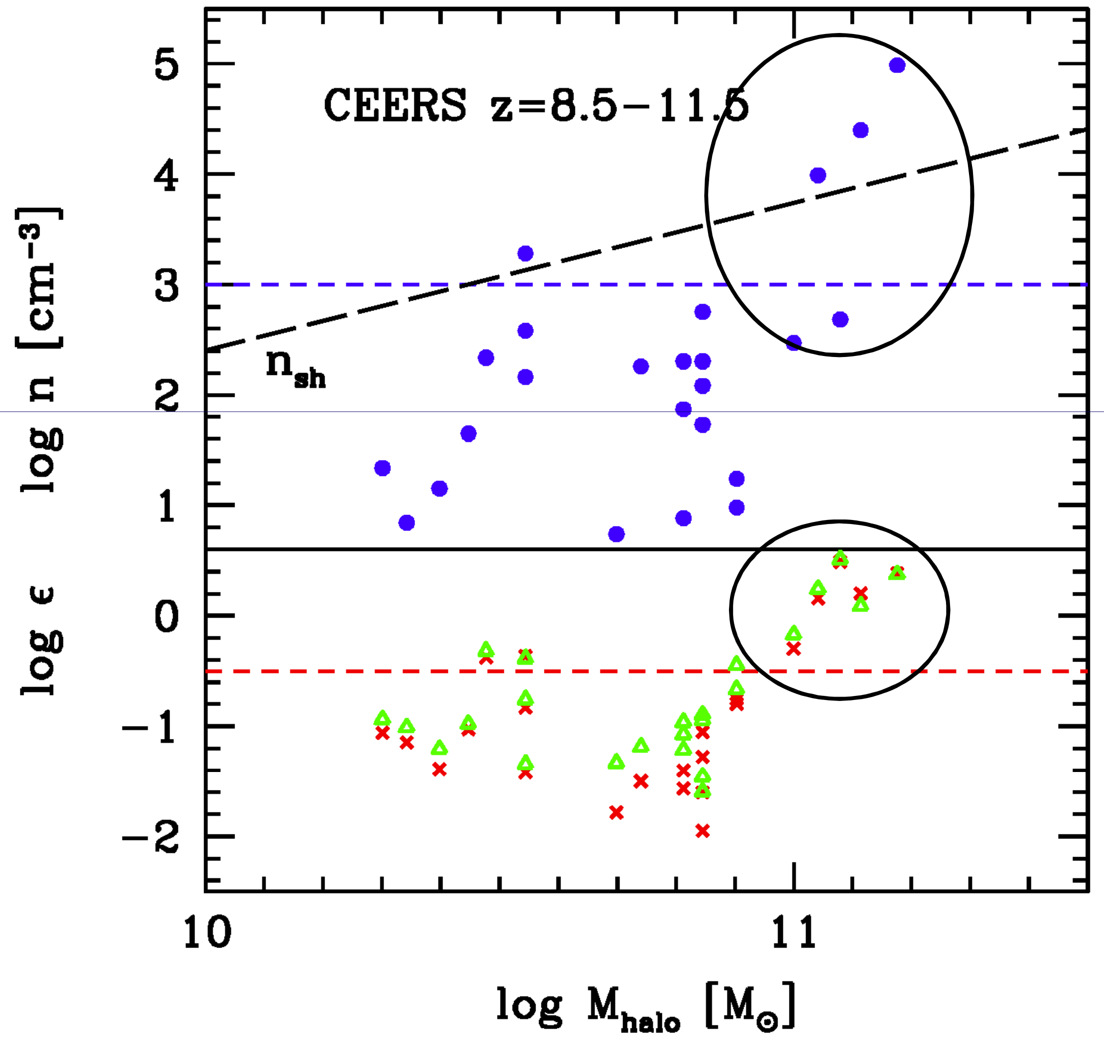


Disk Fraction JWST

Ferreira+ 2022



Tentative Stellar Masses



Conclusions

- Feedback-free starbursts with $\varepsilon\sim1$ when $n\sim3\times10^3$ cm^{-3}
  - $t_{ff} < t_{fbk} \sim 1$ Myr at low metallicity
  - starbursts: t_{cool} ($<10^4$K) $< t_{ff}$
  - self-shielding $M_{cluster} > 10^4 M_\odot$

- Valid at $z\sim10$ in halos $M_{halo} > 10^{10.5}\ M_\odot$
  - post-shock density in a shell, clusters $M_{jeans}\sim10^6 M_\odot$
  - unstable disks, clumps $< M_{toomre}\sim10^6 M_\odot$
  - $\sim$10 generations of $10^9 M_\odot$

- Efficient cold inflowing streams through halos with a little hot gas

- Observables by JWST:
  - $M_{halo}\sim10^{10.8}M_\odot$ $M_{star}\sim10^{10}M_\odot$ SFR$\sim65M_\odot$yr^{-1} R<1kpc
  - $Z < 0.2$ top-heavy IMF (?)
  - little gas and dust cold streams with little outflows & hot gas
  - clumpy disks or shells: assembly of star clusters

- A compact assembly of young stellar clusters -> seed black holes

To think about

- Evolution of a compact assembly of young stellar clusters
    - seed black holes
    - excess of globular clusters in BCGs

- The cosmic web at z~10 – still linear on galactic scales?
    - angular momentum of incoming streams