A new unsolved problem: bright galaxies at z~10

Feedback-Free Starbursts at Cosmic Dawn

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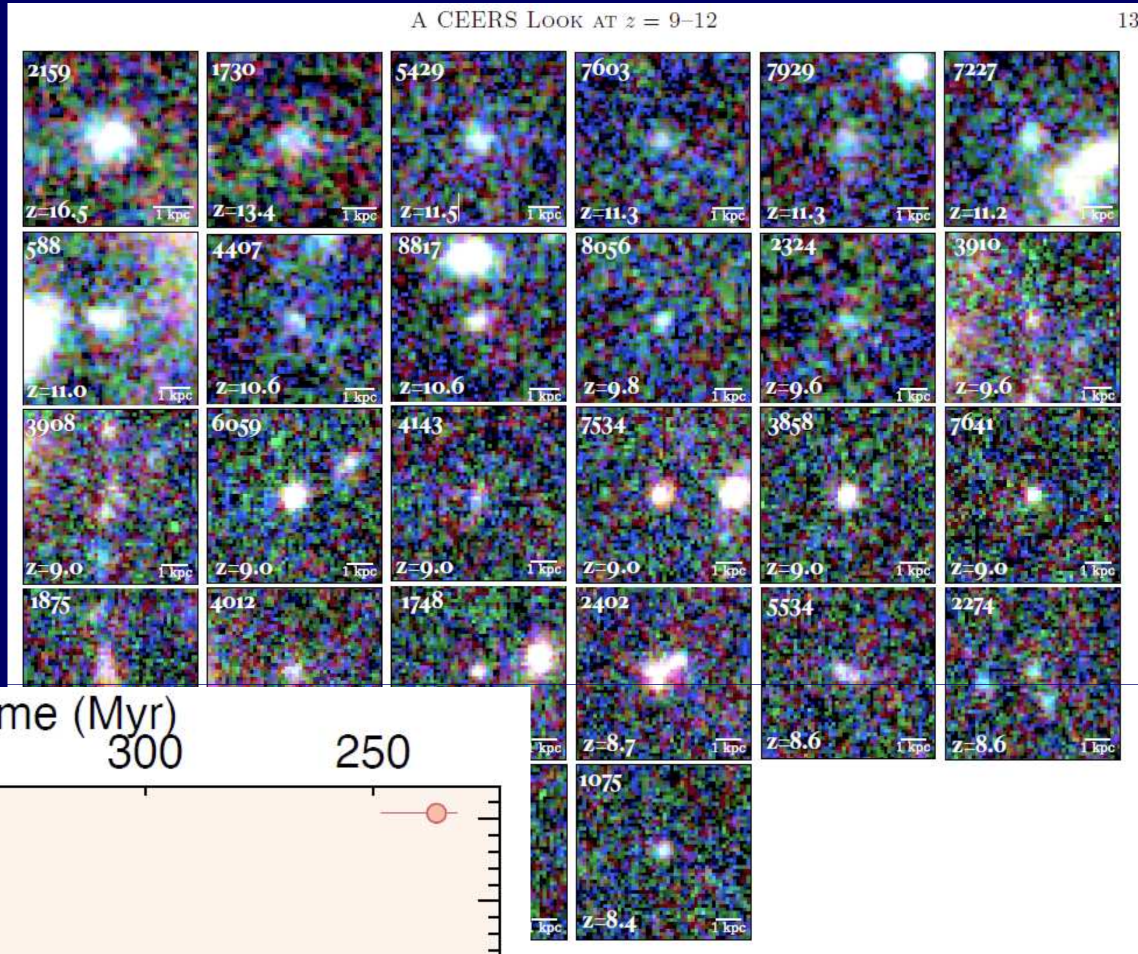
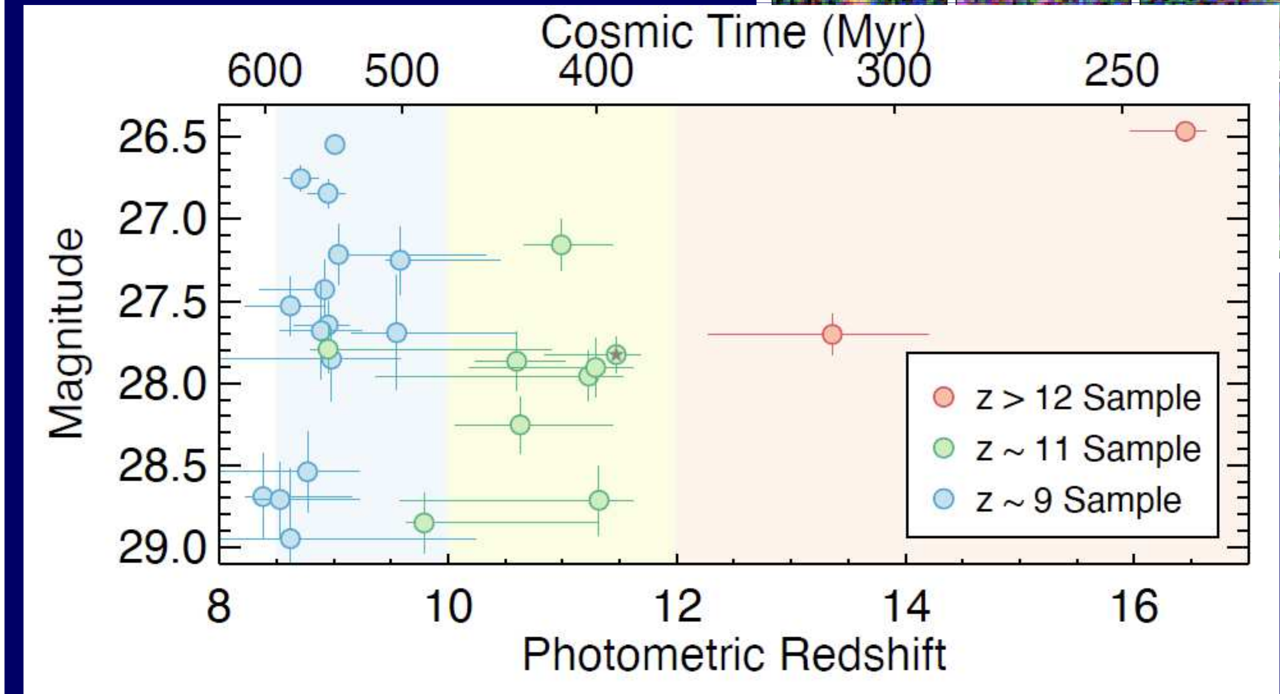
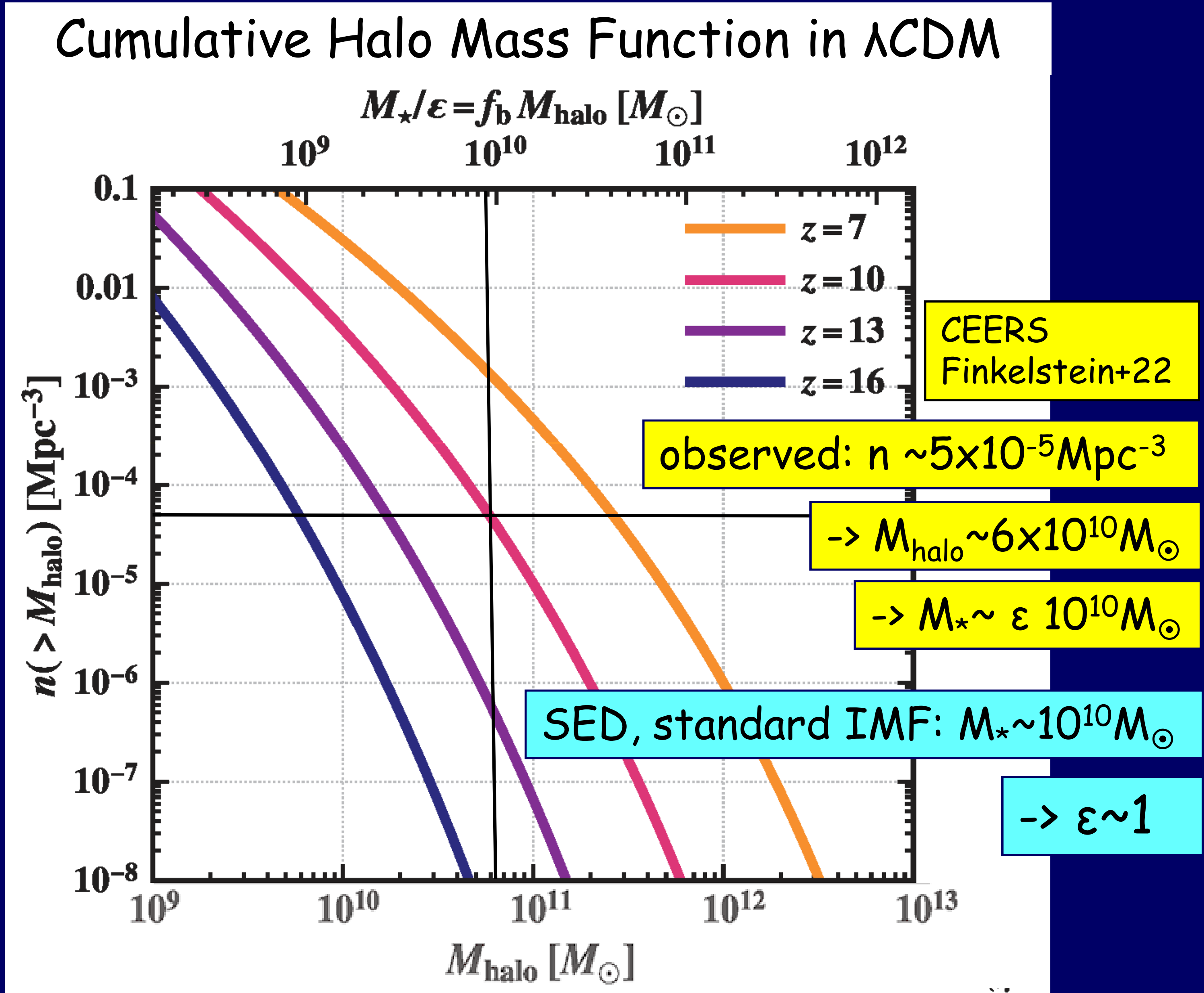
JWST

CEERS galaxies at z~9-12



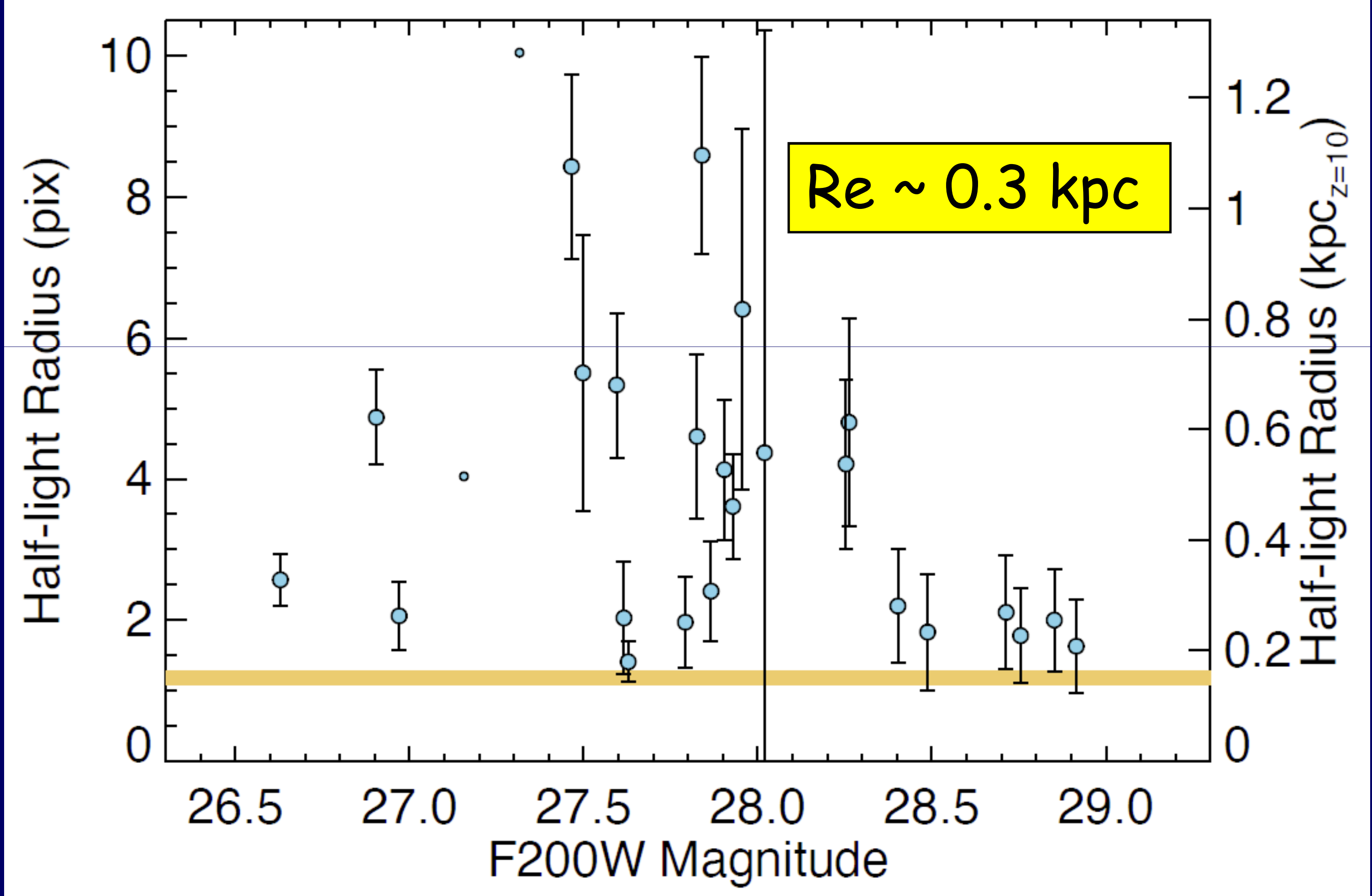


Too Many Too Bright Galaxies at z~10



The z~10 Galaxies are Compact

CEERS Finkelstein+22



Possible Solutions at z~10

1. The observations are totally off
   - calibration
   - photo-z
   - low dust extinction due to ejection (Ferrara+22)

   Left with x10 discrepancy with standard galaxy formation in ΛCDM

2. Number density of halos is higher than in Λ
   - Early Dark Energy (explains the Hubble tension, Klypin+21)

   But Occam's razor?

3. L_{UV}/M_* is higher than at low z
   - UV from accreting black holes (Inayoshi+22)
   - Top-heavy IMF (Harikane+22)

   Possile. Why no dust?

4. High efficiency $\varepsilon = M_*/f_b M_{halo} \sim 1$
   - Feedback-free starbursts

Necessary Requirements for $\varepsilon \sim 1$

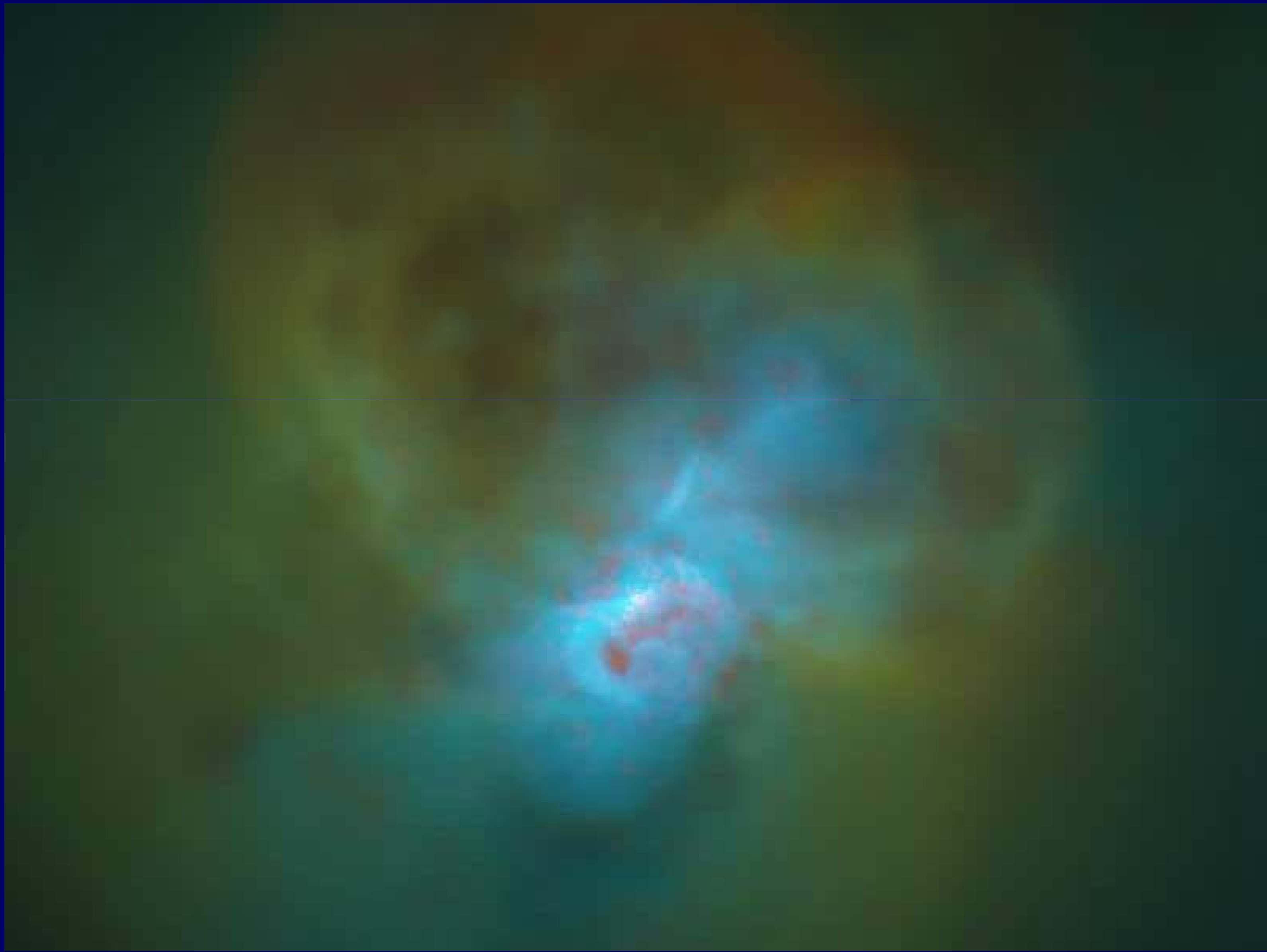
1. Efficient gas penetration through the halo into the galaxy

2. Most gas should reach the conditions for star formation (n,T)

3. Star formation not suppressed by feedback

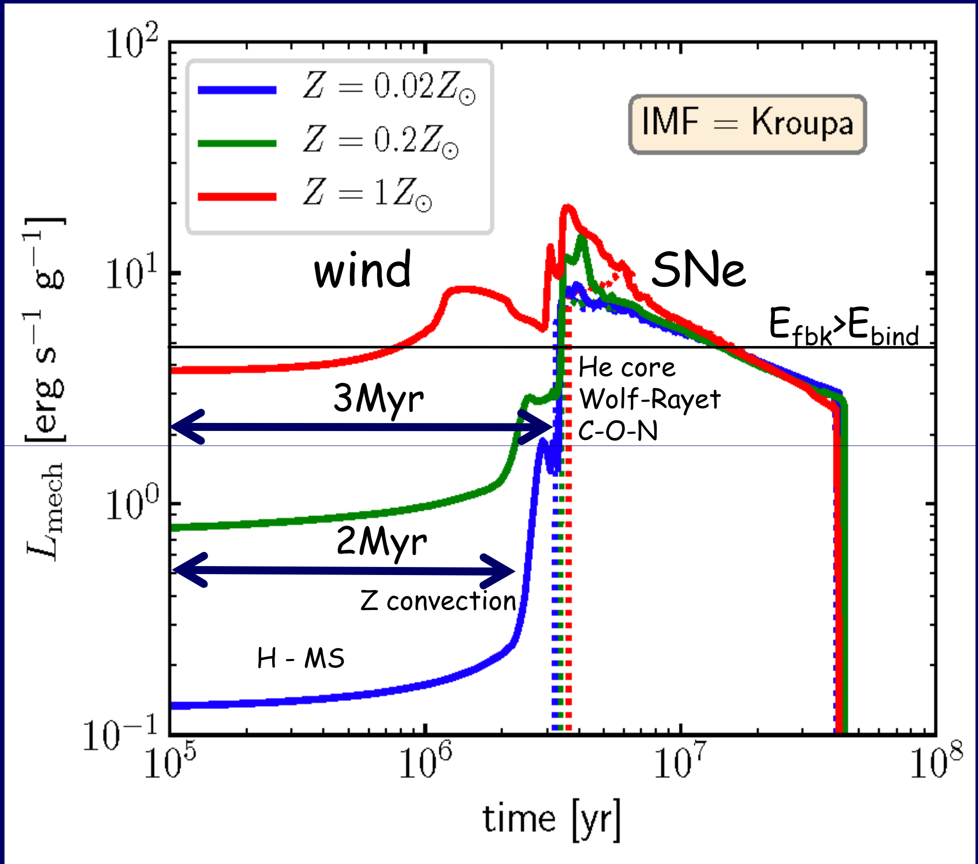
SNe Suppress Star Formation

NIHAO simulations: Maccio, Dutton+



Feedback-Free Starburst

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



Feedback-Free Starburst

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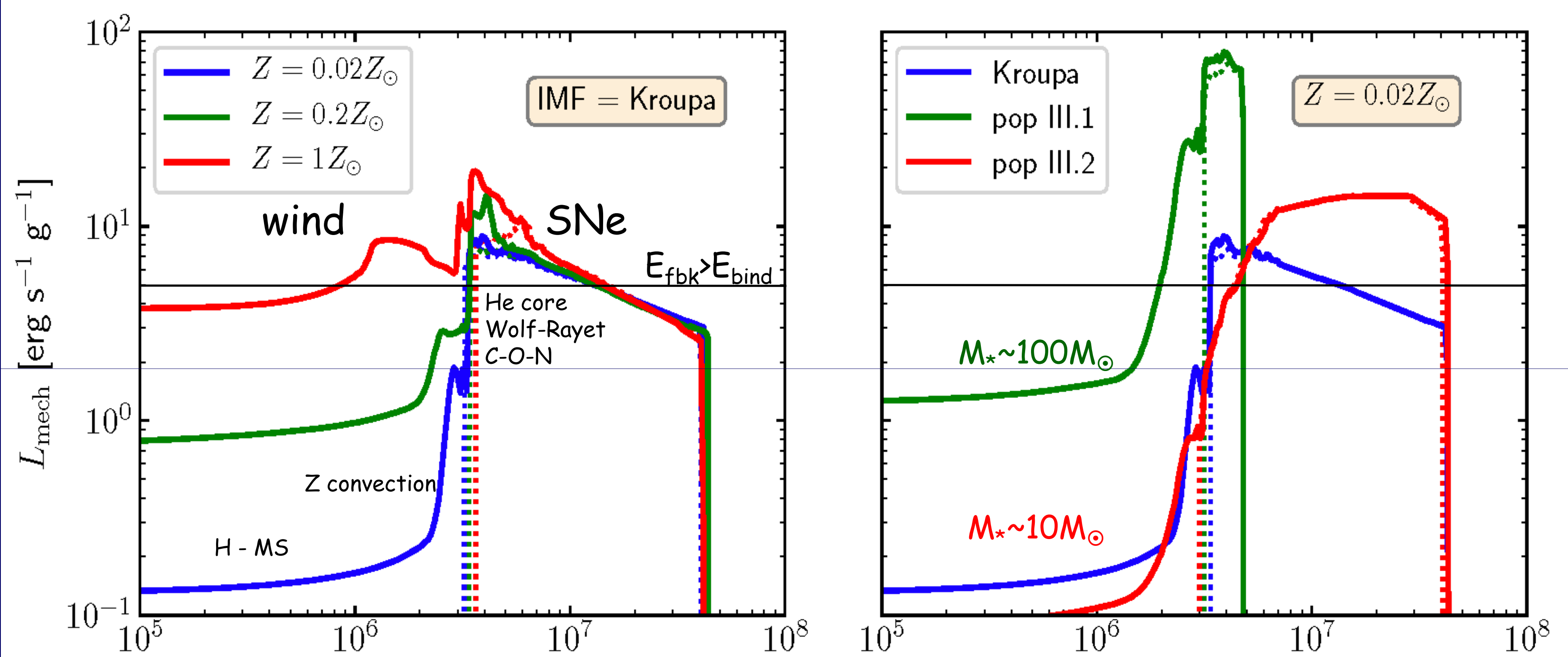


Robust SN delay t~3Myr

Wind delay for low Z t~2Myr

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

--> Feedback-free starburst if t_{ff} < 1 Myr

Feedback-Free Starburst at z~10

$$t_{\rm ff} < t_{\rm fbk} \approx 1\,{\rm Myr} \quad \Rightarrow \quad n > 2.7\times10^3\,{\rm cm}^{-3}\, t_{\rm fbk,1Myr}^{-2}$$

$$t_{\rm ff} \approx 52\,{\rm Myr}\, n^{-1/2}$$

Empirically

$$n_* \approx 4\times10^3\,{\rm cm}^{-3}\, c\, M_{*,10}\, R_{\rm e,0.3kpc}^{-3} \qquad M_{*,10} \approx \varepsilon\, M_{\rm v,10.8}$$

High-z galaxies

$$n_\lambda \approx c\,\lambda^{-3}\,\varepsilon\,\Delta\,\bar{n}_{\rm b,0}\,(1+z)^3 \approx 2\times10^3\,{\rm cm}^{-3}\, c\,\Delta_{200}\,\lambda_{0.03}^{-3}\,\varepsilon\,(1+z)_{10}^3$$

$$\lambda = R_{\rm e}/R_{\rm vir} \qquad \varepsilon = M_*/(f_{\rm b}\,M_{\rm vir}) \qquad c = \rho_{\rm sf}/\rho_{\rm gal}$$

The required high density and low metallicity for feedback-free star formation are natural at z~10

Necessary Requirements for $\varepsilon \sim 1$

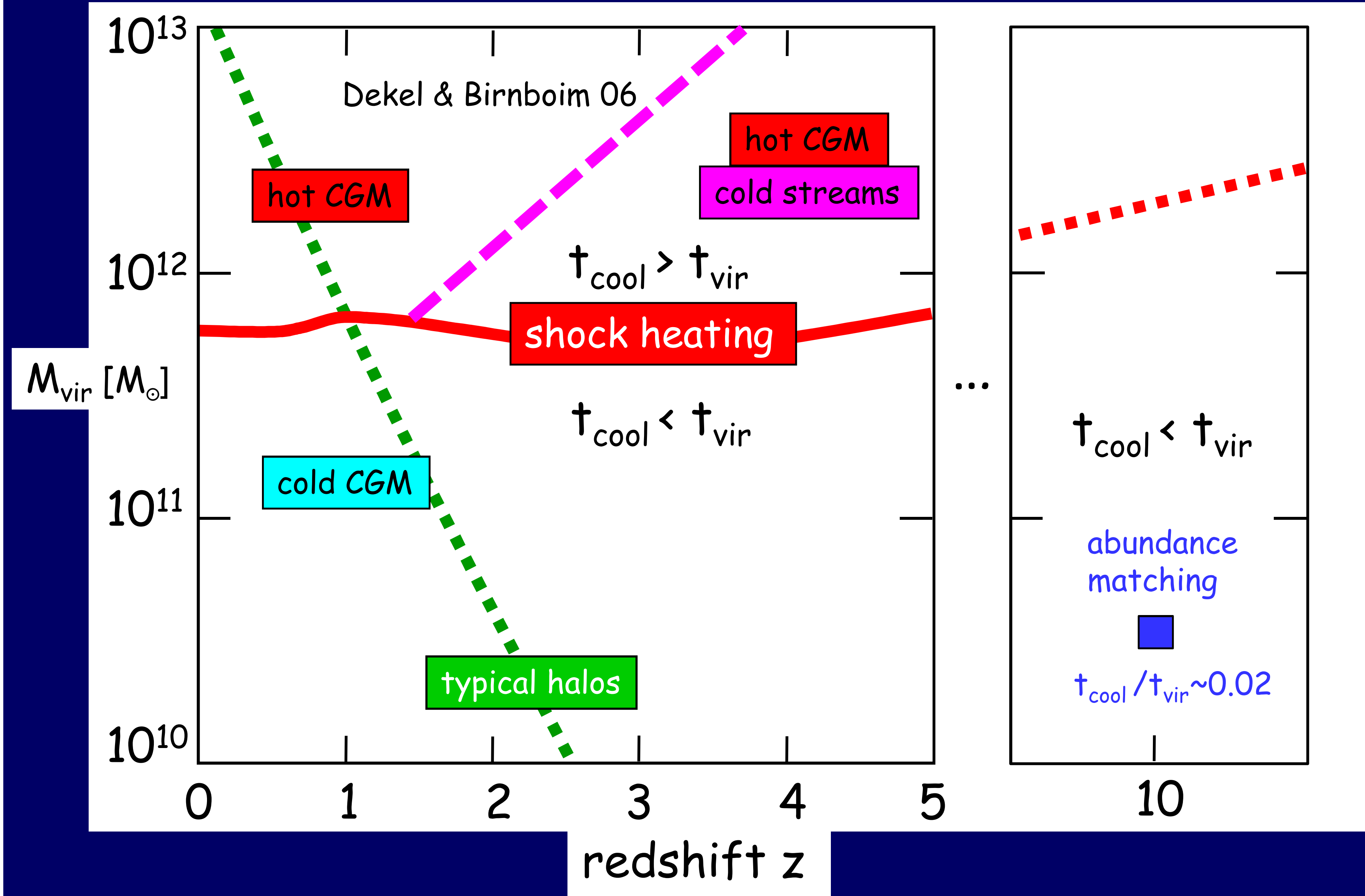
1. Efficient gas penetration through the halo into the galaxy

2. Most gas should reach the conditions for star formation (n,T)

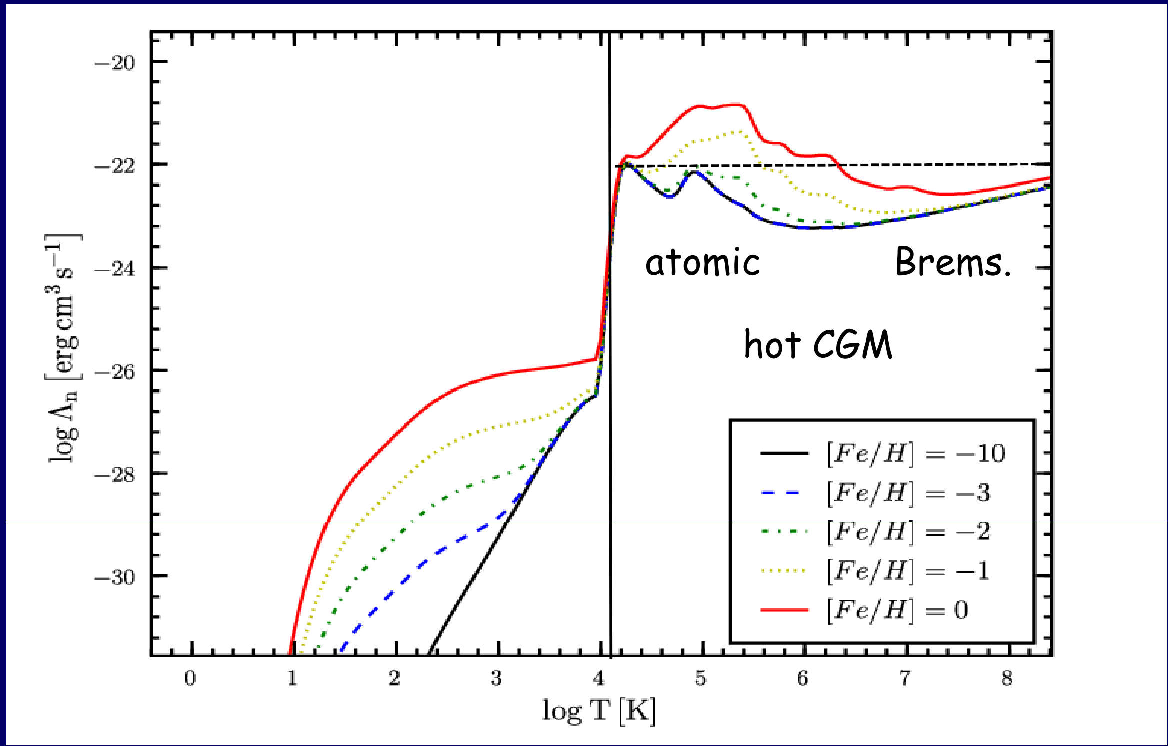
3. Star formation not suppressed by feedback

4. Star formation in bursts

Cold Inflow through the DM Halo



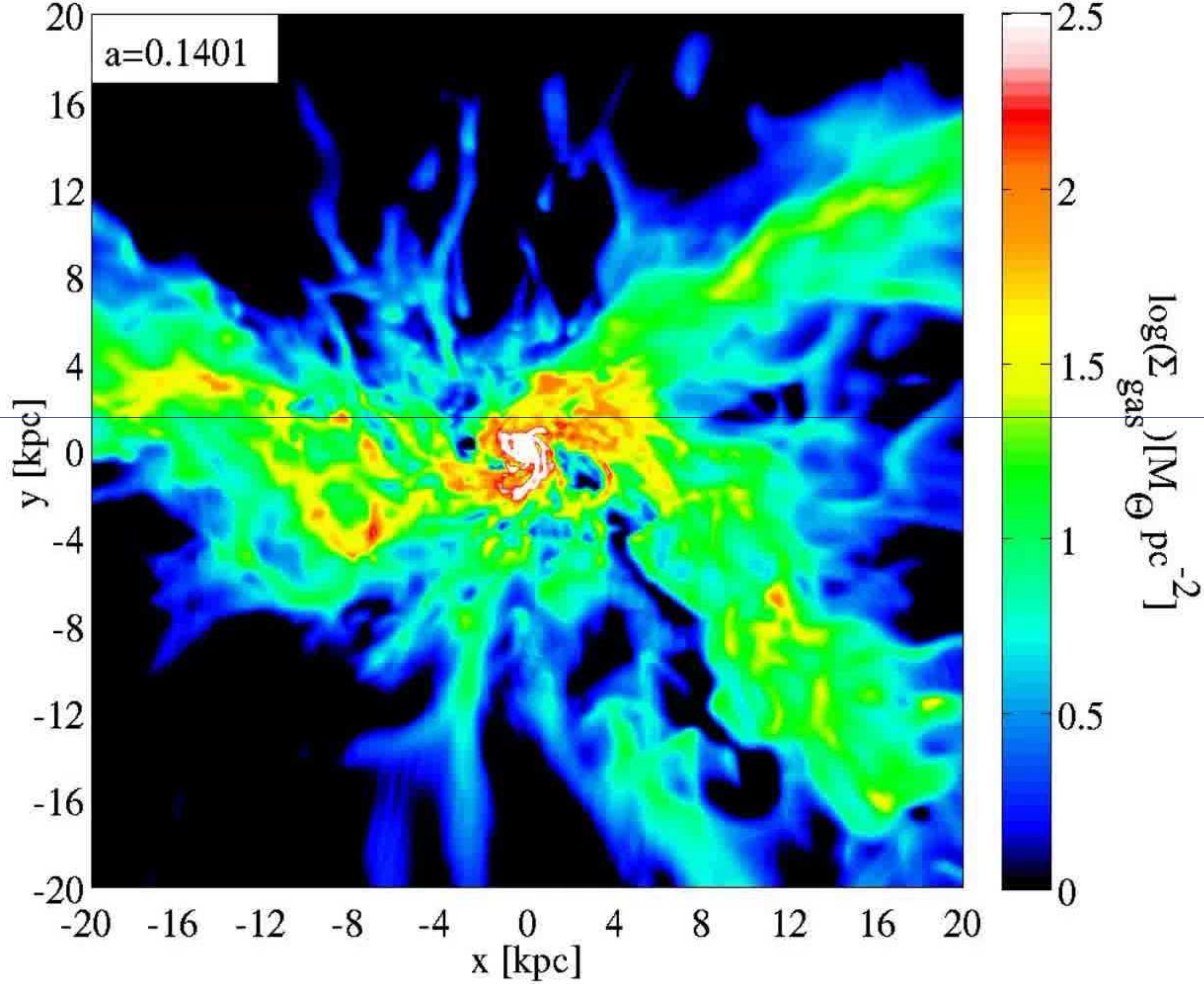
Rapid Cooling above T~10^{4}K



Atomic cooling: $t_{cool} \approx 0.16\,\mathrm{Myr}\,\Lambda_{-22}^{-1}\,T_6\,n^{-1}$ $\quad t_{ff} \approx 52\,\mathrm{Myr}\,n^{-1/2}$

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

Cold Streams feed Disks at Very High z



Streams - Galaxy Interface

Long inflow time $t_{vir} \approx 80\,\mathrm{Myr}(1+z)_{10}^{-3/2}$ >> t_{ff} in the galaxy

$V_{vir} \approx 170\,\mathrm{km\,s^{-1}} M_{vir,11}^{1/3} (1+z)_{10}^{1/2}$ $T \approx 10^4\,\mathrm{K}$ ⇨ supersonic streams Mach 20

$R_{vir} \approx 14\,\mathrm{kpc}\, M_{vir,11}^{1/3} (1+z)_{10}^{-1}$ $\bar{n}_{vir} \approx 5\times10^{-2}\,\mathrm{cm^{-3}} \Delta_{200} (1+z)_{10}^{3}$ ⇨ $n_{1kpc} \approx 10\,\mathrm{cm^{-3}}$

Streams halt at a shock around the galaxy ⇨ $n_{gal} \approx n_{1kpc} M^2 \approx 4\times10^3\,\mathrm{cm^{-3}}$

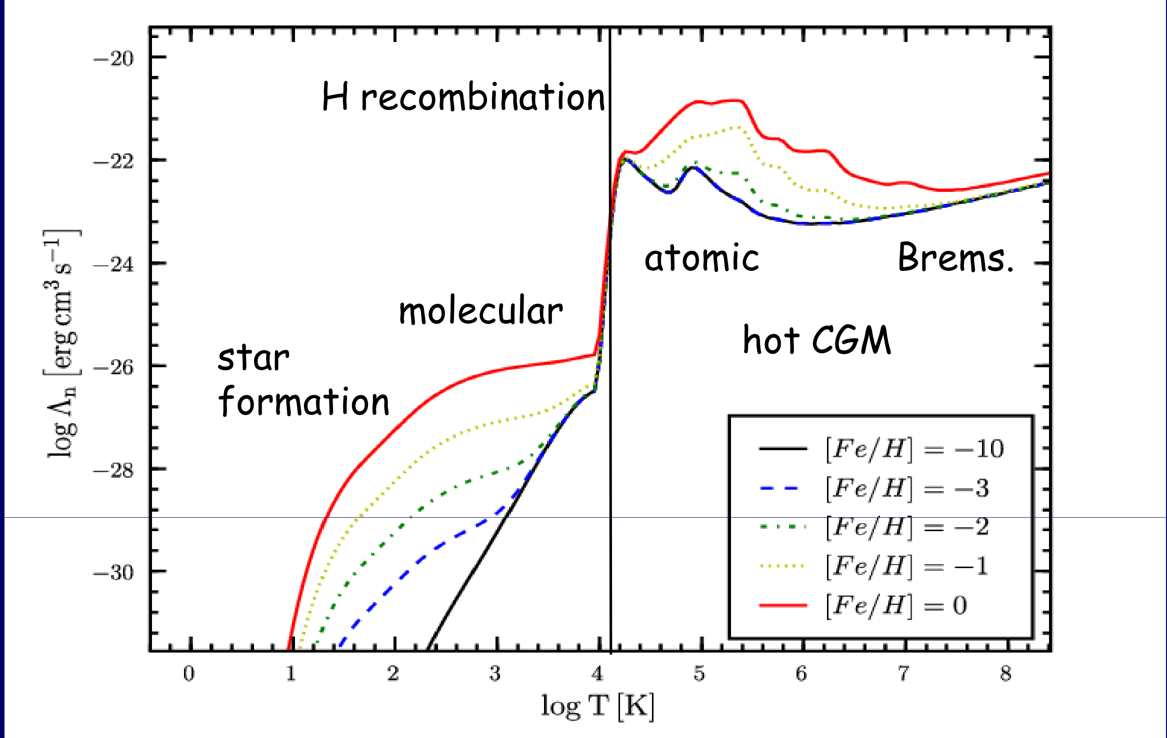
Starbursts

For a feedback-free period need a starburst:
a threshold for star formation ->
gas accumulation followed by a starburst

<u>Necessary conditions for star formation:</u>

- $t_{cool} < t_{ff}$ below 10^4K
- $M > M_{Jeans}$
- shielding against UV
- ...
- Mergers? Compactions?

Cooling below T~10^{4}K



At low Z, slow cooling by CII, OI, LyA: $t_{\rm cool} \approx 0.5\,{\rm Myr}\, Z_{-2}^{-1}\, T_4\, C^{-1}\, n_4^{-1}$

$$\frac{t_{\rm cool}}{t_{\rm ff}} \approx Z_{-2}^{-1}\, T_4\, C^{-1}\, n_4^{-1/2}$$

⇨ $t_{\rm cool}$~$t_{\rm ff}$ at $n_{\rm cool} \approx 10^4\,{\rm cm}^{-3}\, Z_{-2}^{-2}\, T_4^2\, C^{-2}$

Jeans mass and Shielding

$$M_{\text{Jeans}} \approx 10^6 \, M_\Theta \, T_4^{3/2} \, n_4^{-1/2}$$

-> multiple 1Myr bursts in $\sim 10^4$ globular cluster-like clumps

Multiple generations during t_{vir}~80 Myr

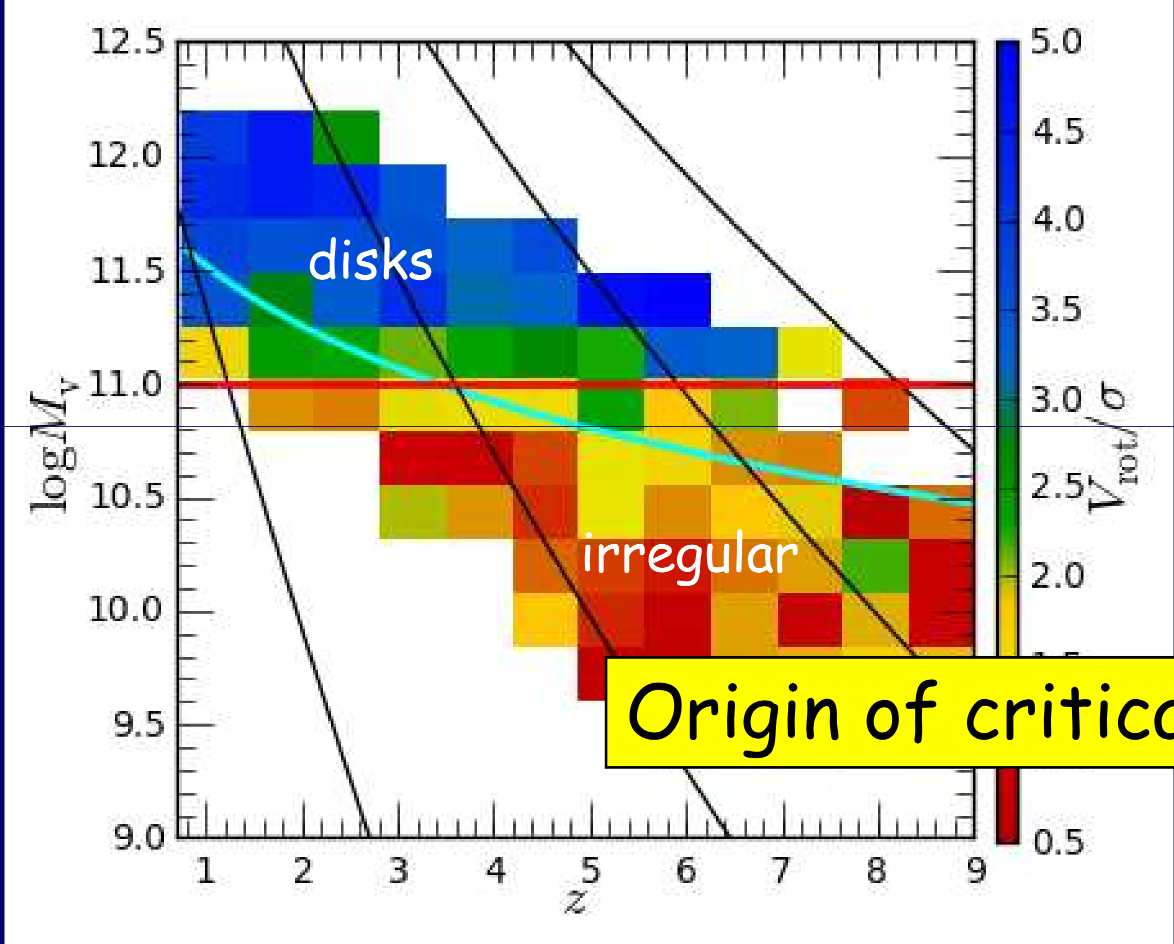
Generation duration ~ a few Myr required to accumulate M_{Jeans} locally

At $n \sim 10^4$ cm^{-3} the clumps are largely shielded against winds and UV from other clumps (& no external UV background)

After each generation, remaining gas is pushed to a bubble where internal pressure balances the supersonic inflow at r ~1 kpc with $n \sim 10^4$ cm^{-3}, ready for new bursts after accumulating M_{Jeans} locally

Morphology: High-z Massive Disks?

Dekel + 2020a VELA simulations and toy model



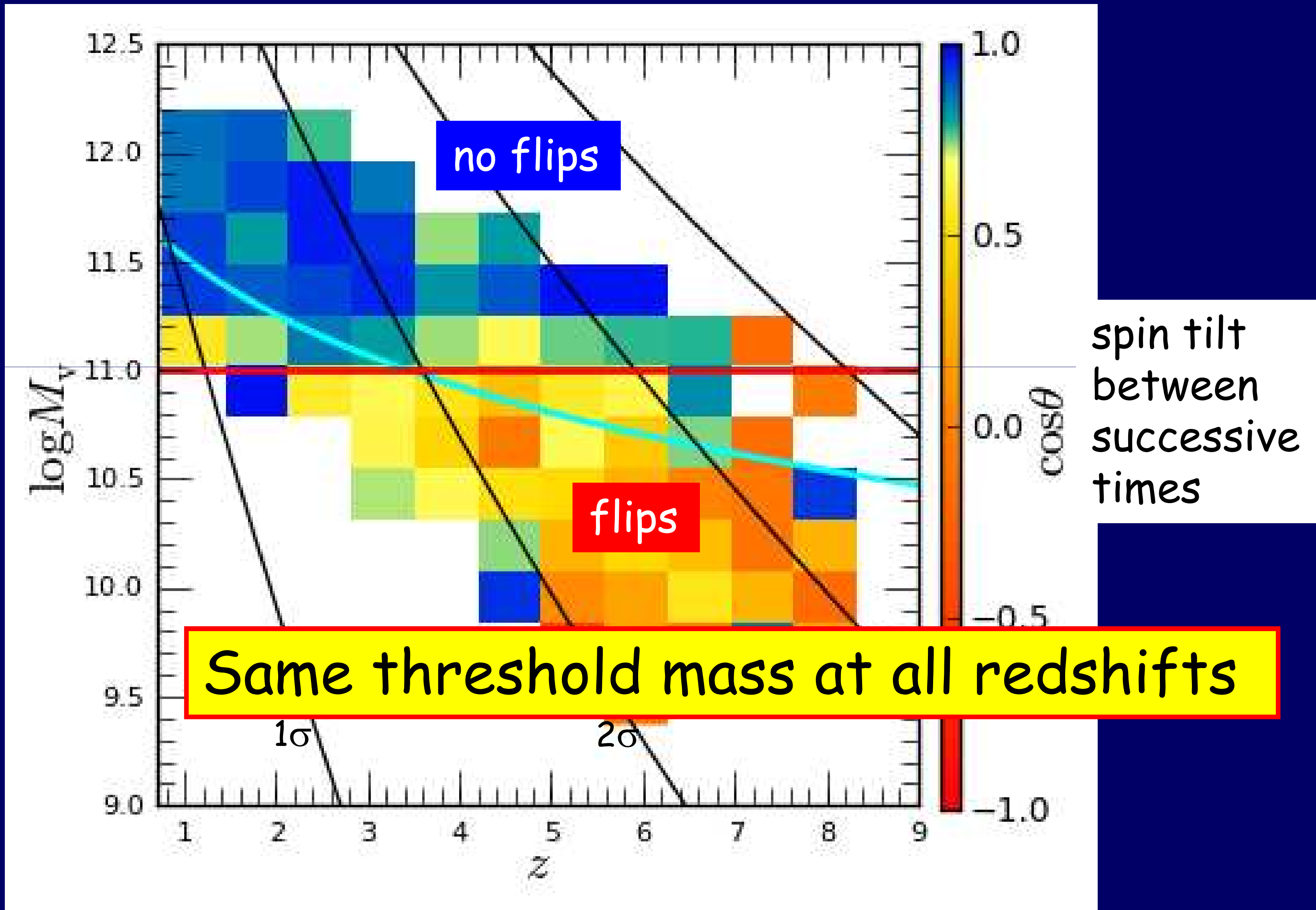
Origin of critical mass?

Disks in M_{vir}>2×10^{11} $M_\odot$

M_{star}>10^9 $M_\odot$

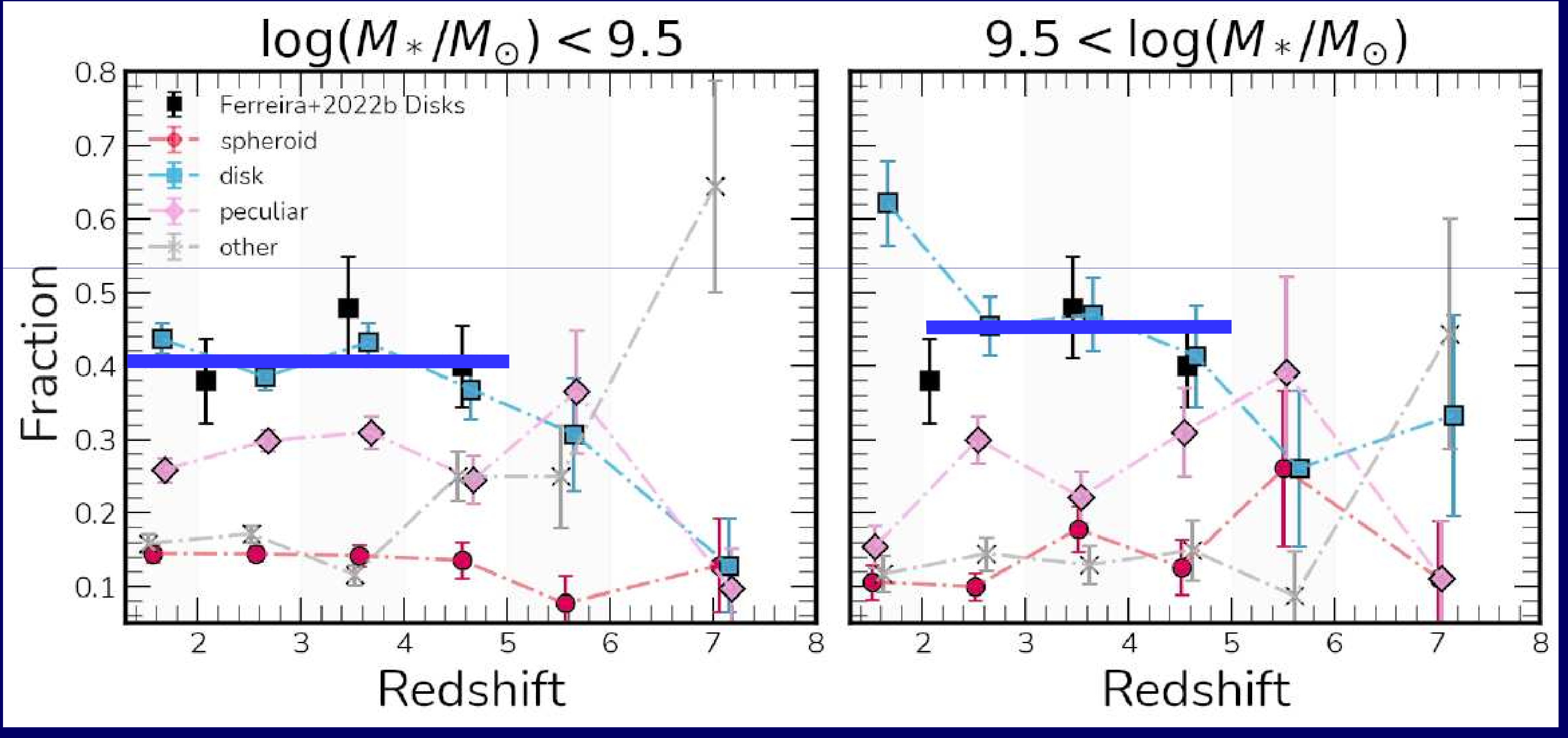
all redshifts!

Disks Disrupt Below a Critical Mass by Merger-Spin-Flips in an Orbital Time



Disk Fraction JWST

Ferreira+ 2022



Observable Predictions

For NIRSpec and MIRI, beyond images and SEDs from NIRCaam

- High number density and luminosities to be confirmed
- High stellar density n ~ 10^4 cm^{-1}
- Low metallicity
- Top-heavy IMF? Bursty star-formation history
- Bursty star-formation history
- Little gas, little dust attenuation
- No hot CGM, cold streams
- Globular cluster excess
- Disks? Rings? Clumps?

Conclusions

- Unsolved problem: $z\sim10$ galaxies may show x10 excess of bright galaxies compared to standard galaxy formation in ΛCDM

- Solutions to consider:
  - deviation from ΛCDM
  - high L/M top-heavy IMF
  - maximum efficiency $\epsilon=M_*/f_b M_{halo}\sim1$

- Efficient supersonic cold inflows through halos with no hot CGM at the indicated halo masses

- $\epsilon\sim1$ by feedback-free starbursts of ~1 Myr -> $n\sim10^4 cm^{-3}$ and $Z\ll1$

- Valid naturally in $z\sim10$ galaxies

- Starbursts after accumulation by a threshold for star formation:
  - $t_{cool} < t_{ff}$ -> $n\sim10^4 cm^{-3}$
  - $M > M_{Jeans} \sim 10^6 M_\odot$
  - self-shielding

- Galaxies as assemblies of "globular clusters"