How do galaxies acquire their mass & when do they form their stars?

with

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Trinh THUAN
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Avishaï DEKEL
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Outline

Primer on galaxy formation

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Simulation methods

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Toy model of galaxy formation:

How do galaxies acquire their mass?

motivated by J. Ostriker

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motivated by J. Ostriker

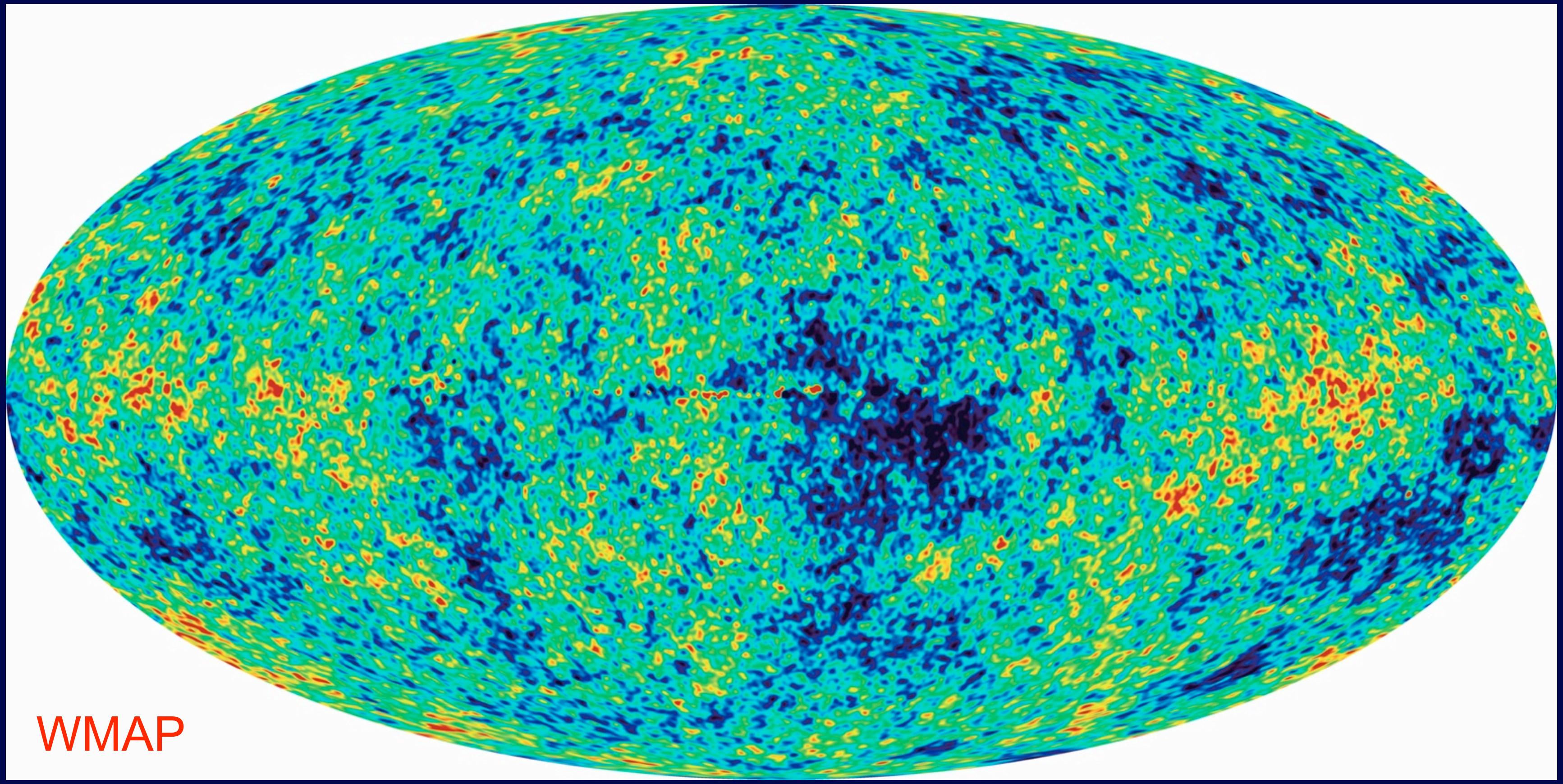
How frequent are young galaxies at z=0?

motivated by T. Thuan

Formation of dwarf spheroidal galaxies

A primer on galaxy formation

Nearly homogeneous early Universe



380 thousand years after Big Bang:
variations of 1 / 100 000 only!

How to build a galaxy?

1. Gas accretes into collapsing dark matter potential well
2. Gas cools into molecular clouds
3. Stars form

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details poorly understood!

How do galaxies evolve?
They grow:

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Softly:

by further gas accretion (monolithic collapse)

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In steps:

by mergers (hierarchical merging)

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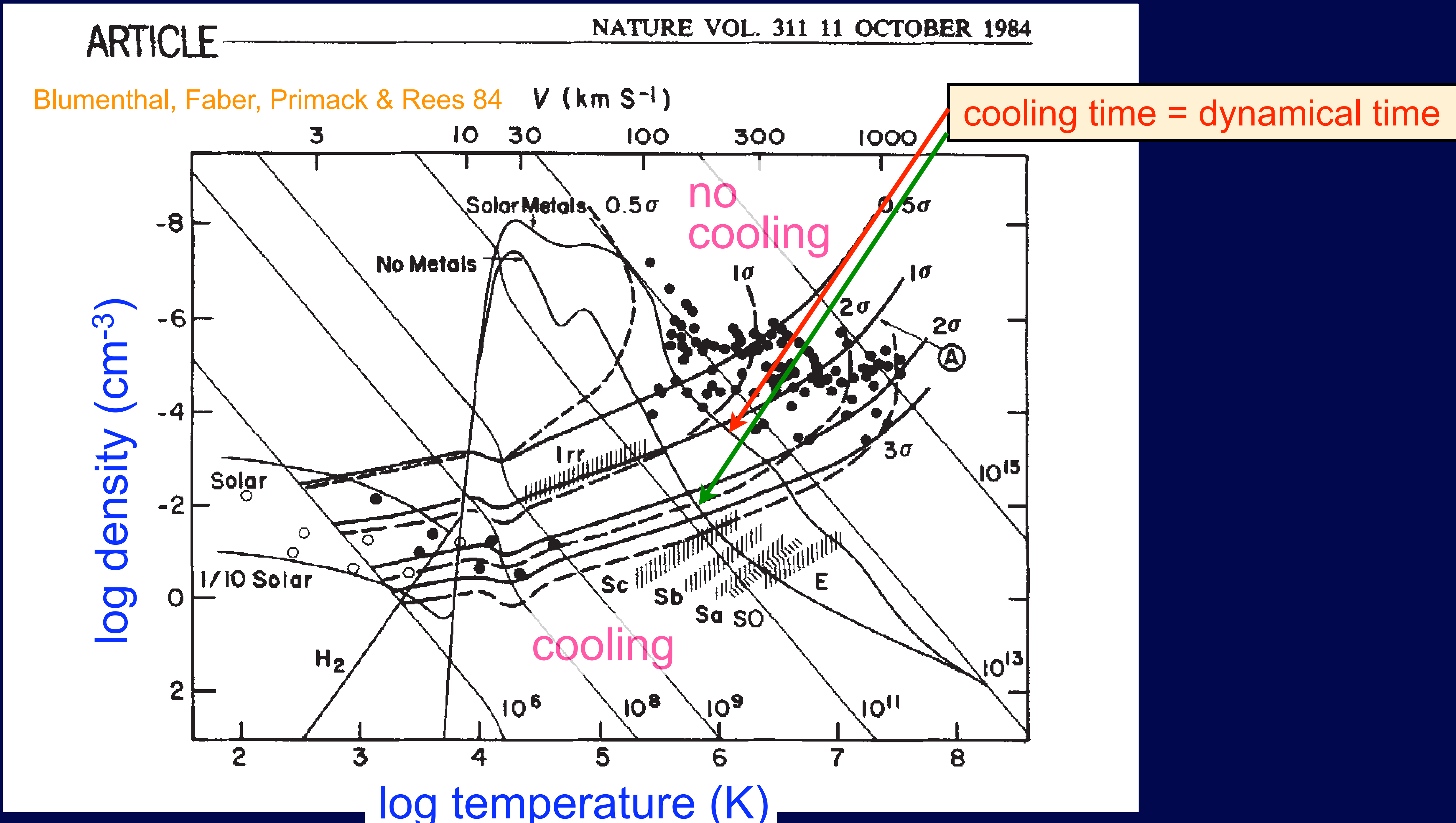
Both

Quenchers of galaxy formation

- long cooling time   Silk 77; Binney 77; Rees & Ostriker 78



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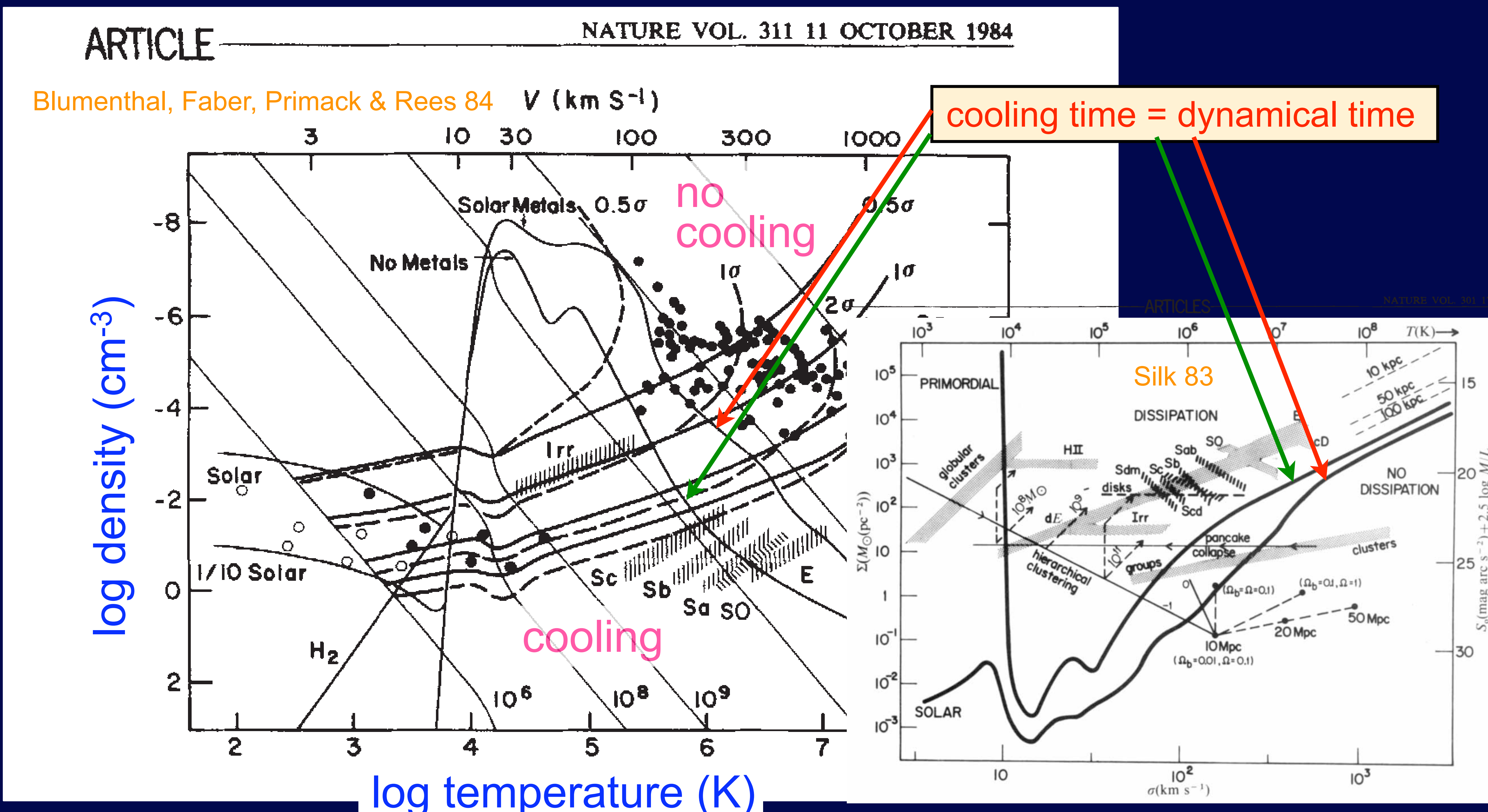

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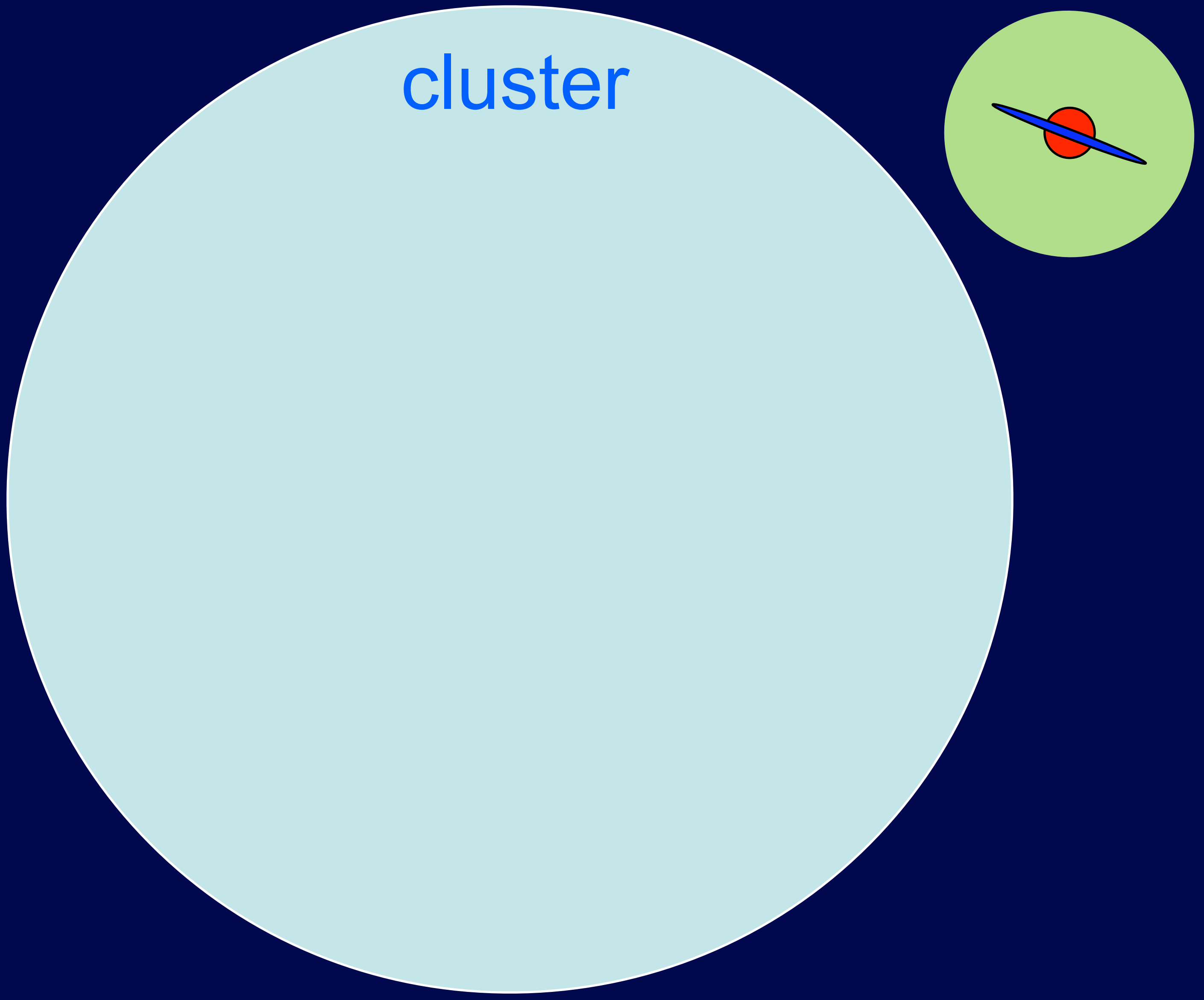

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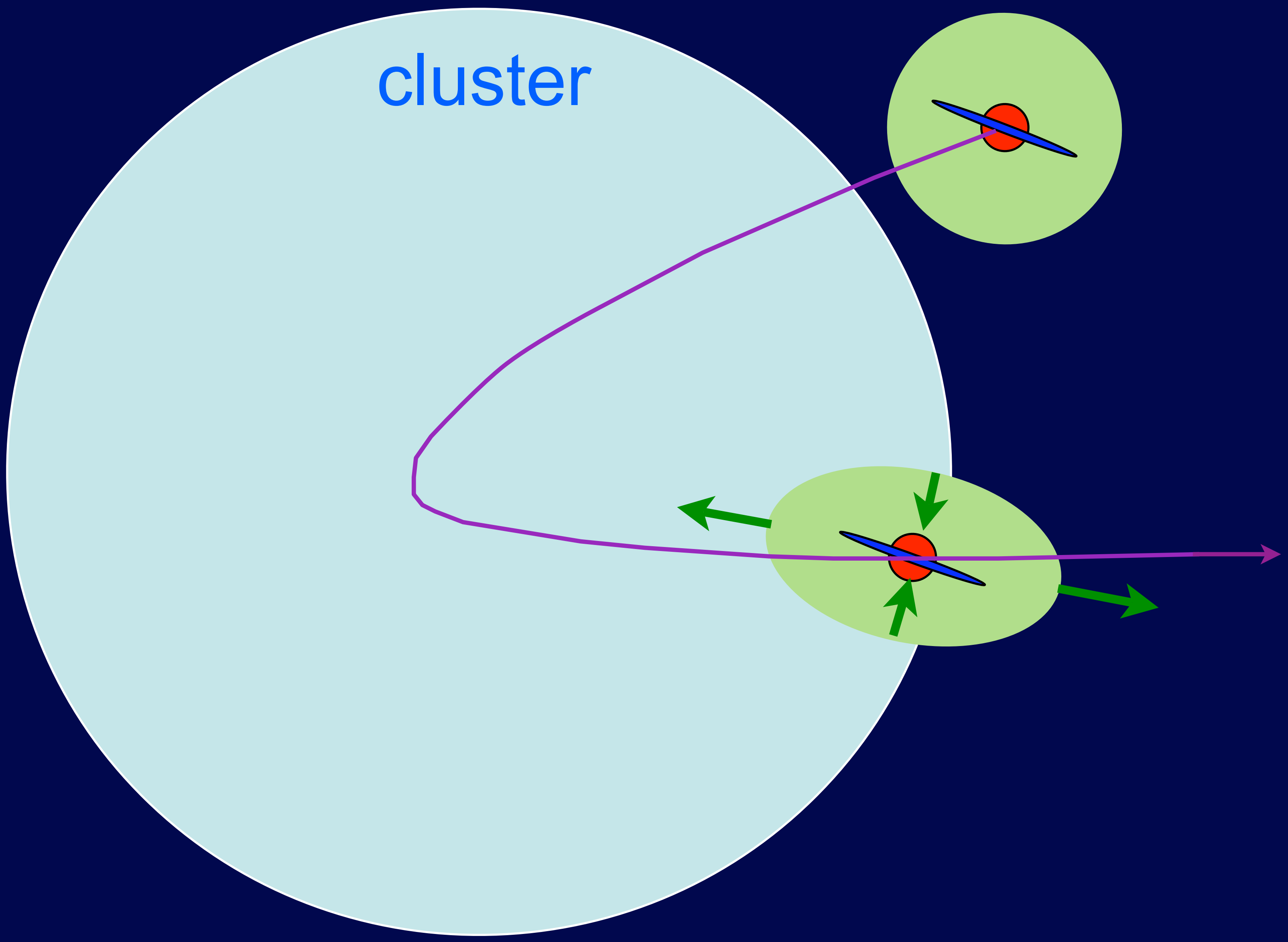

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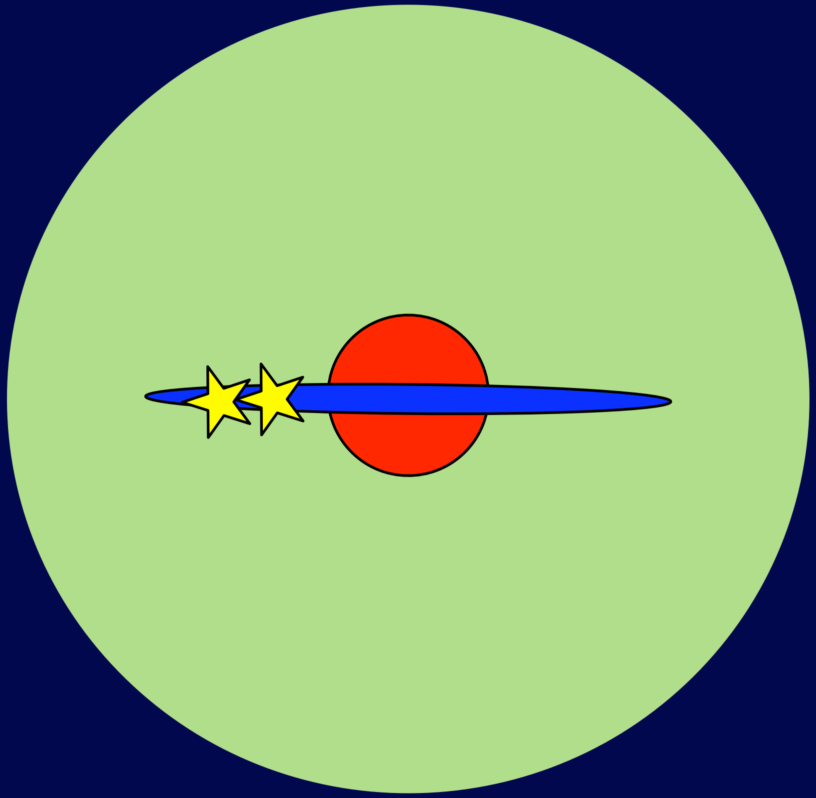

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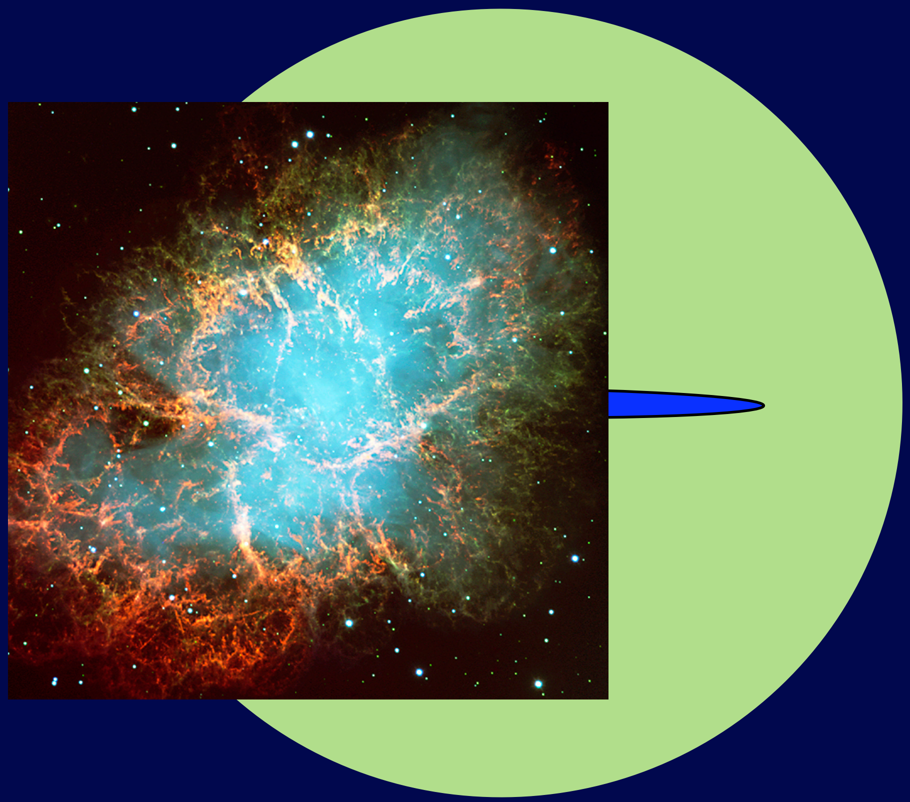

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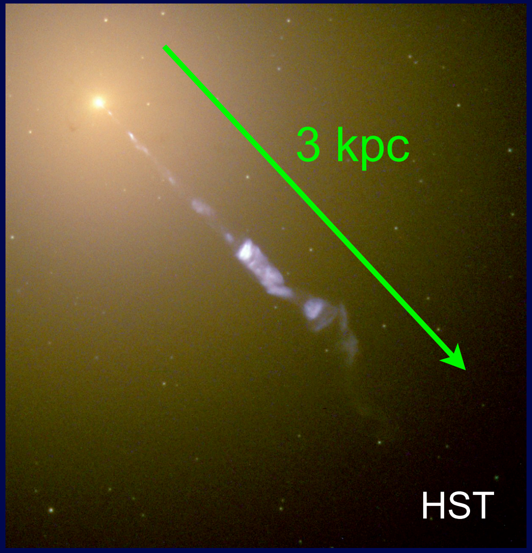

M87

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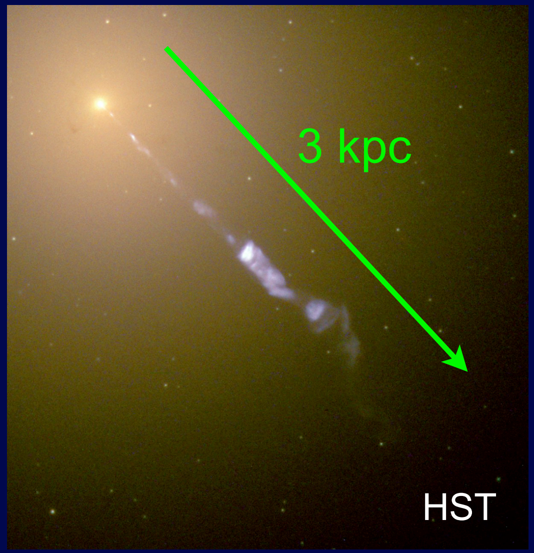

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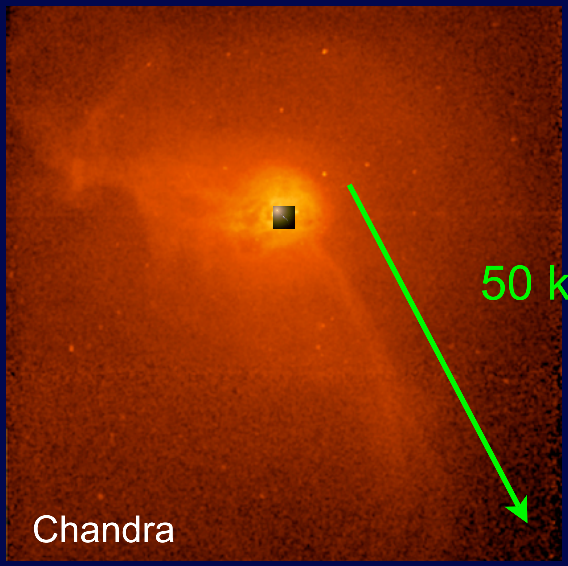

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- entropy barrier (photoionization of IGM) specific entropy ~ $T/n^{2/3}$

  Rees 86; Blanchard, Valls-Gabaud & Mamon 92

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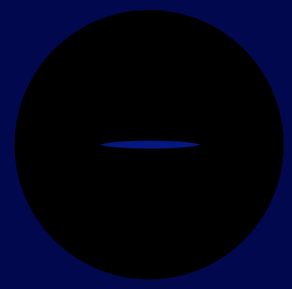
initial

mixed DM & baryons

final from cold IGM



DM & gas collapse
gas dissipates to disk

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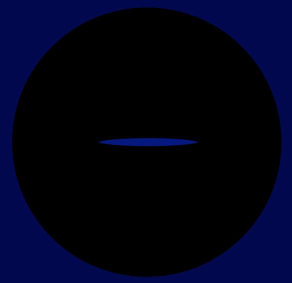
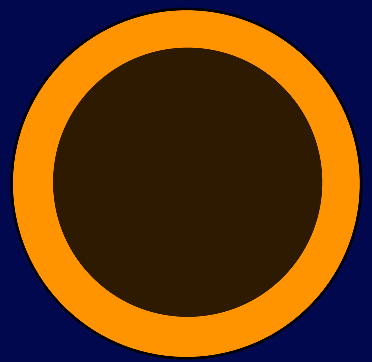


DM & gas collapse
gas dissipates to disk

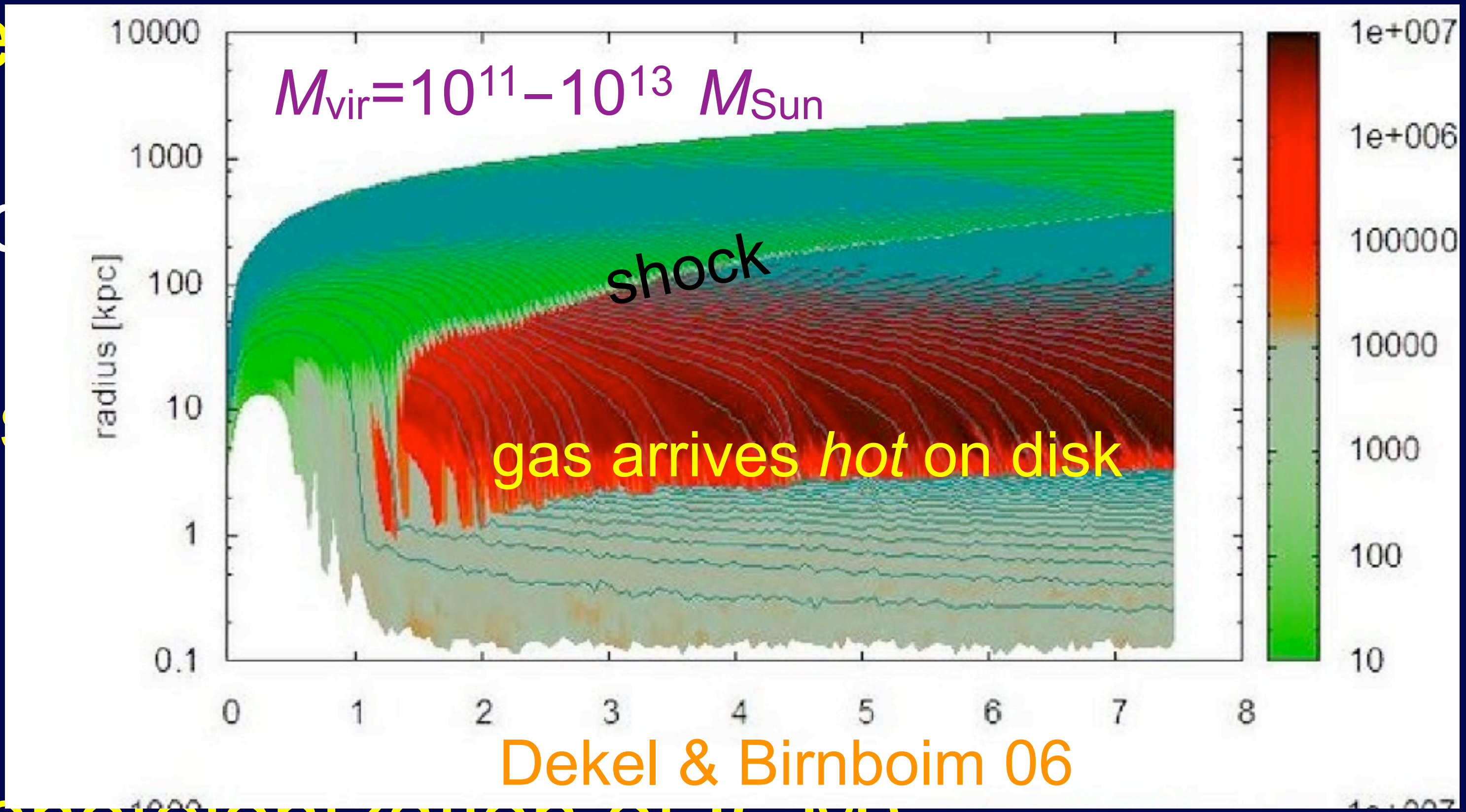
final from hot IGM



DM collapses
gas is held by entropy barrier

Quenchers of galaxy formation

- long cooling time
- tidal dissipation c
- supernova explos
- AGN jets Silk &



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- accretion shock Dekel & Birnboim 06

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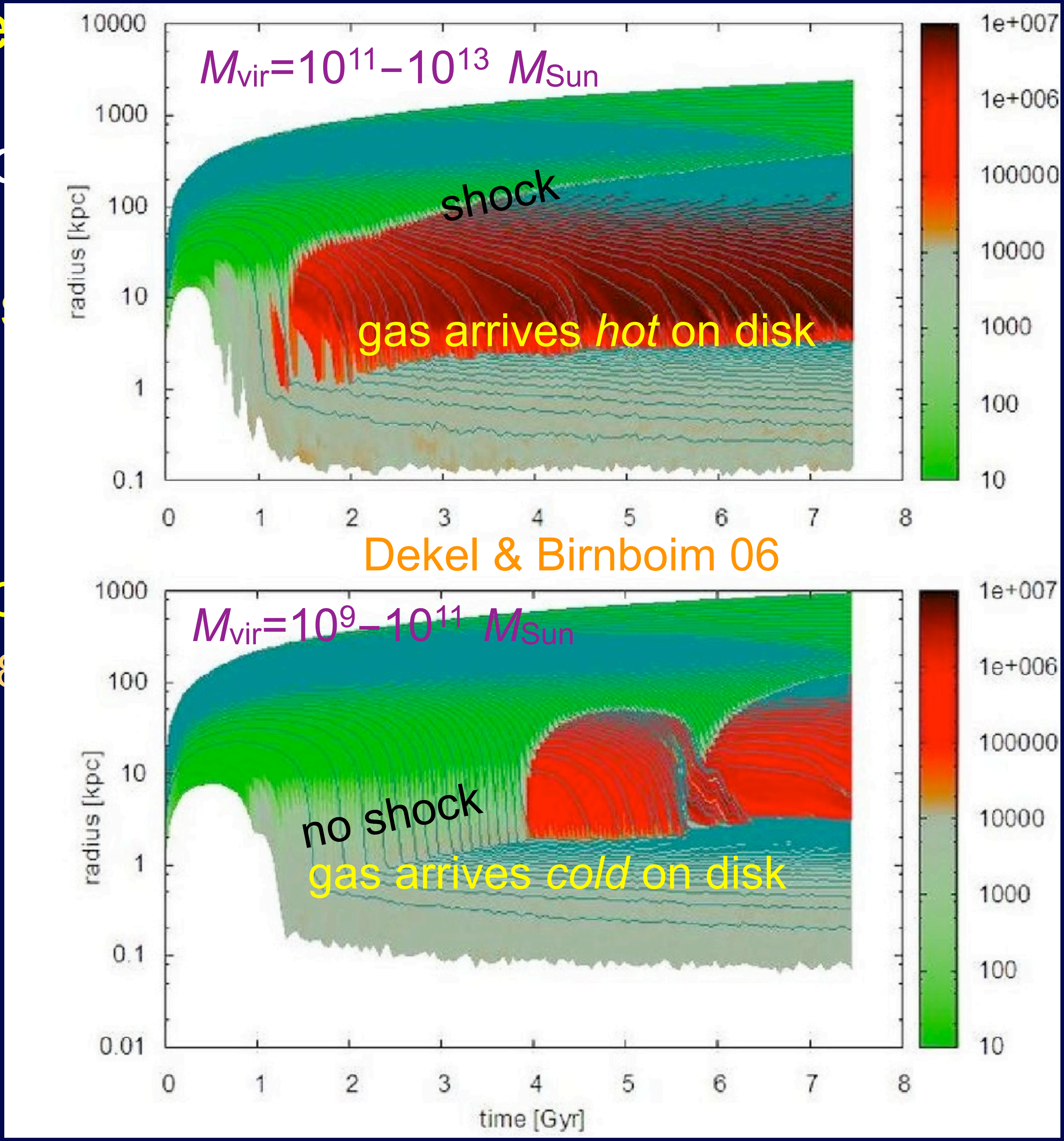

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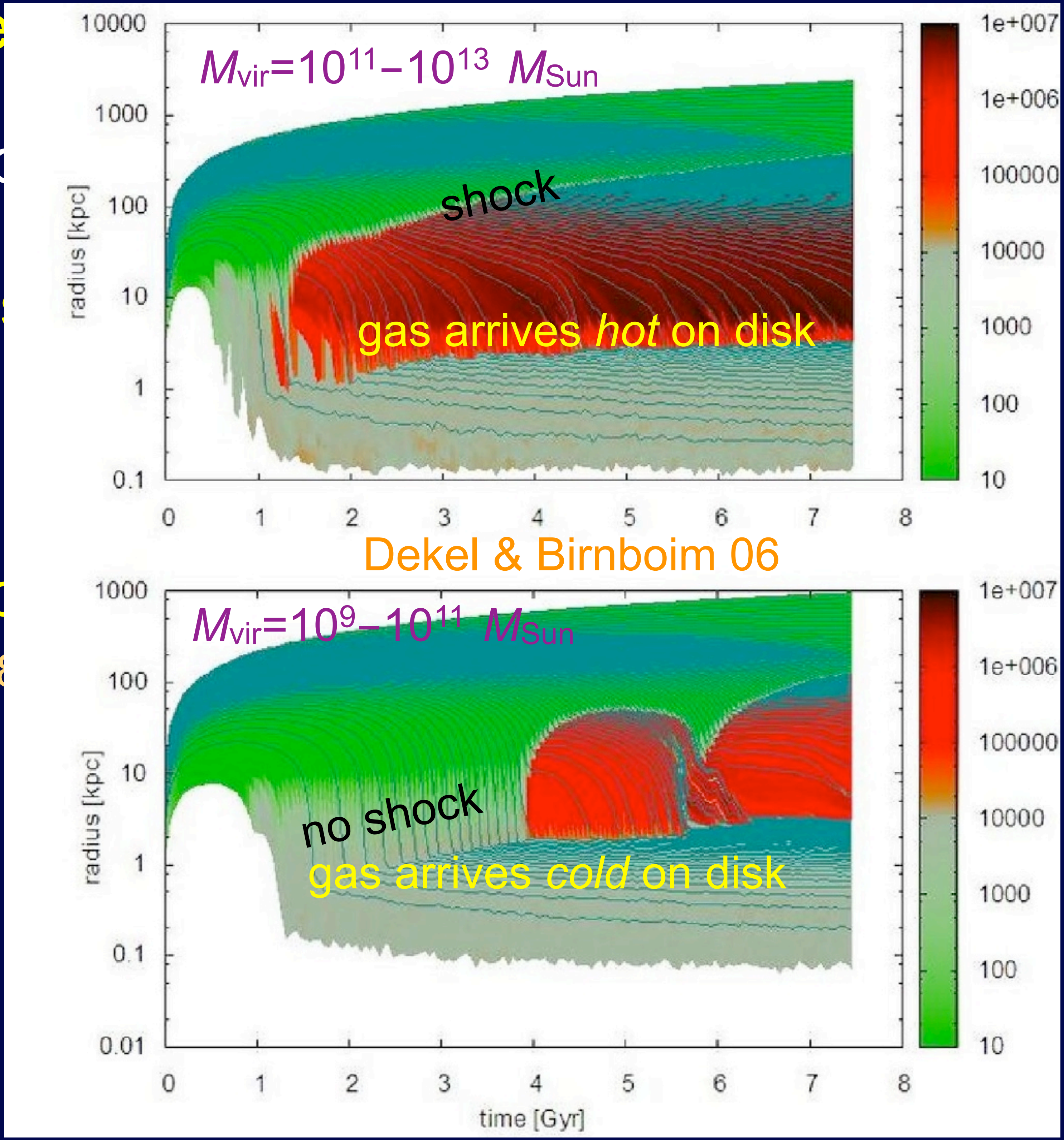


→ same constraint as cooling time = dynamical time

How do galaxies grow?

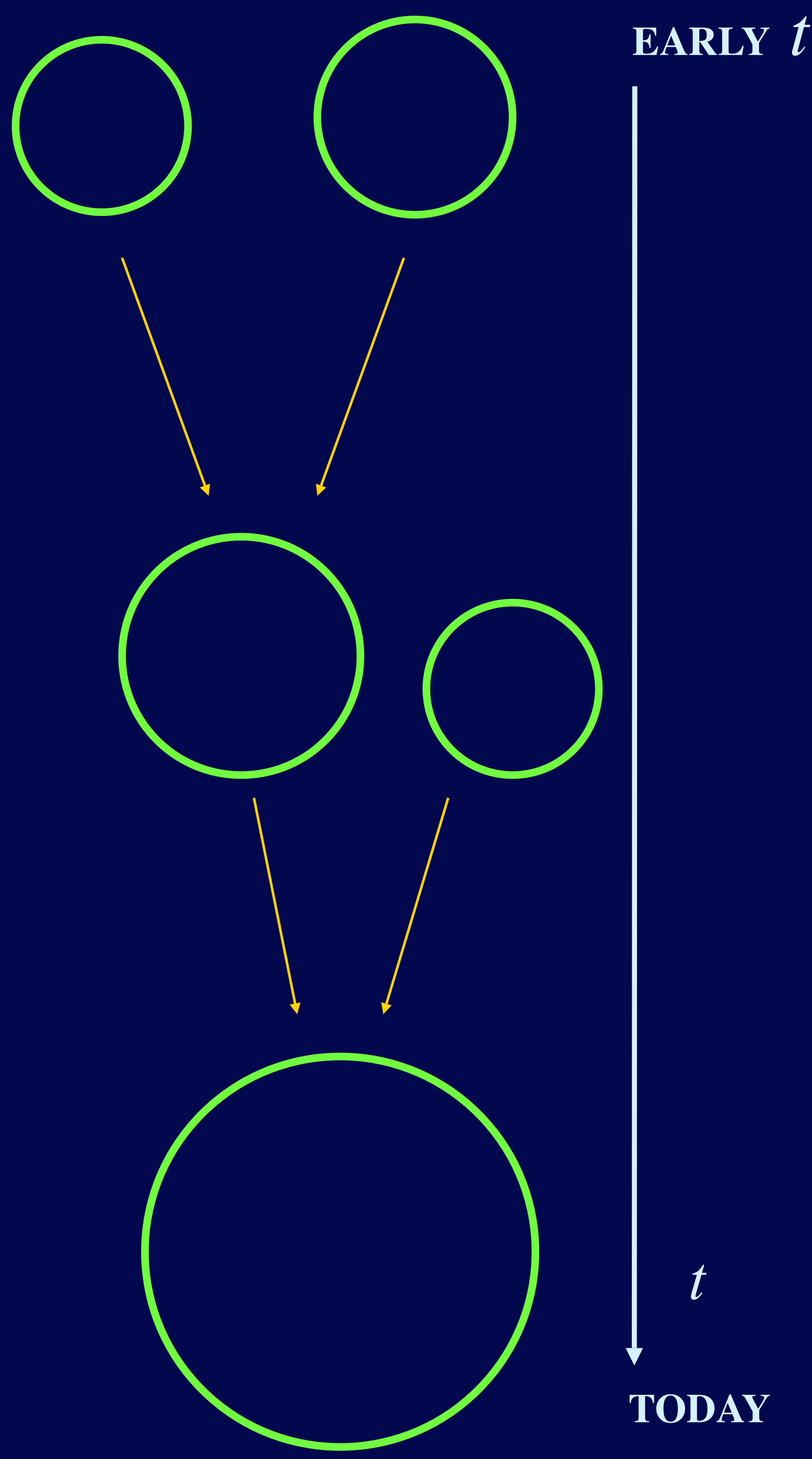
Semi-analytical modeling

Ab initio galaxy formation model
hierarchical structure formation
in a cold dark matter dominated Universe

Semi-analytical modeling

Ab initio galaxy formation model
hierarchical structure formation
in a cold dark matter dominated Universe

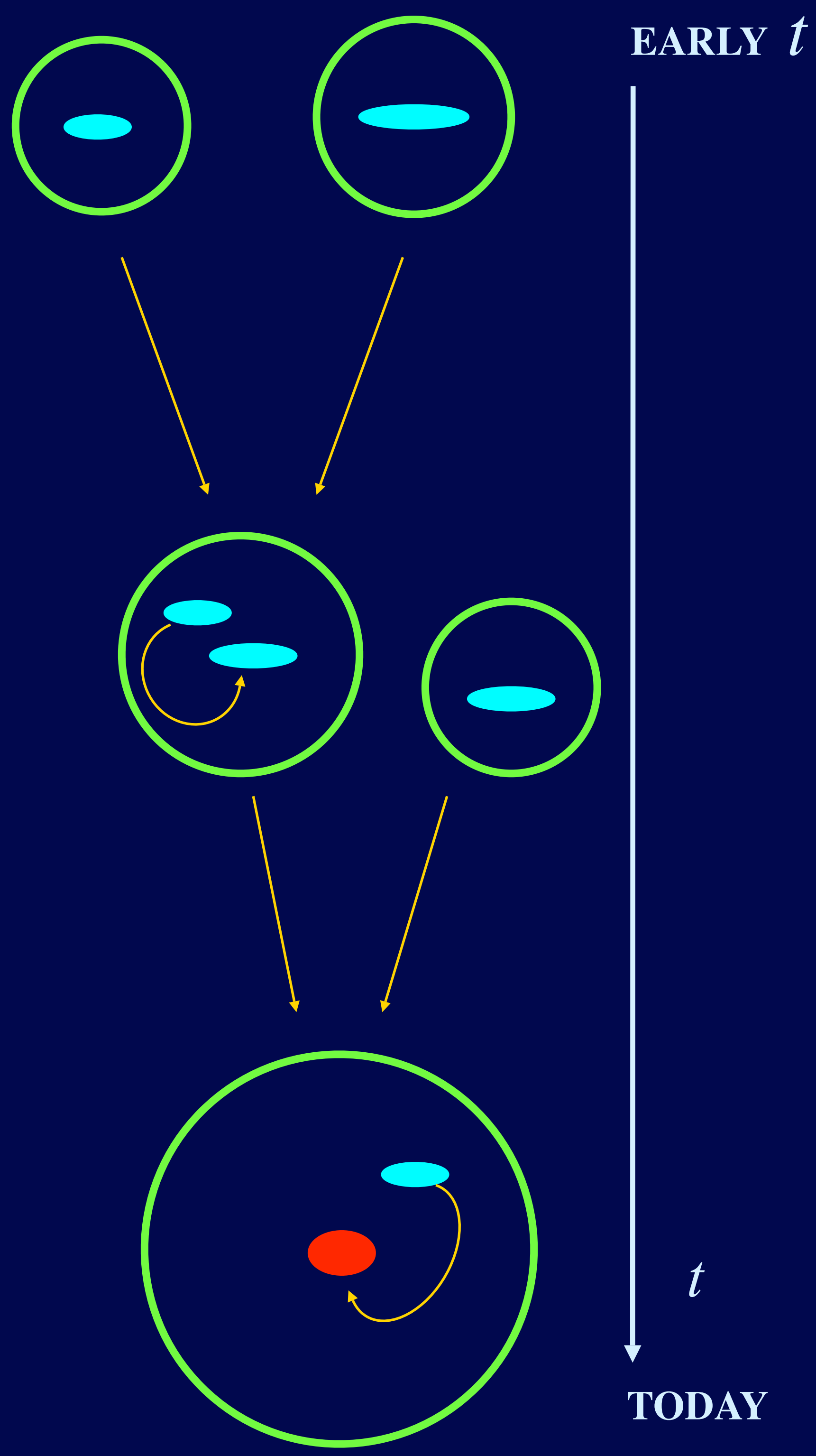
- (small) Dark matter halos form first
- small halos merge to larger halos



Semi-analytical modeling

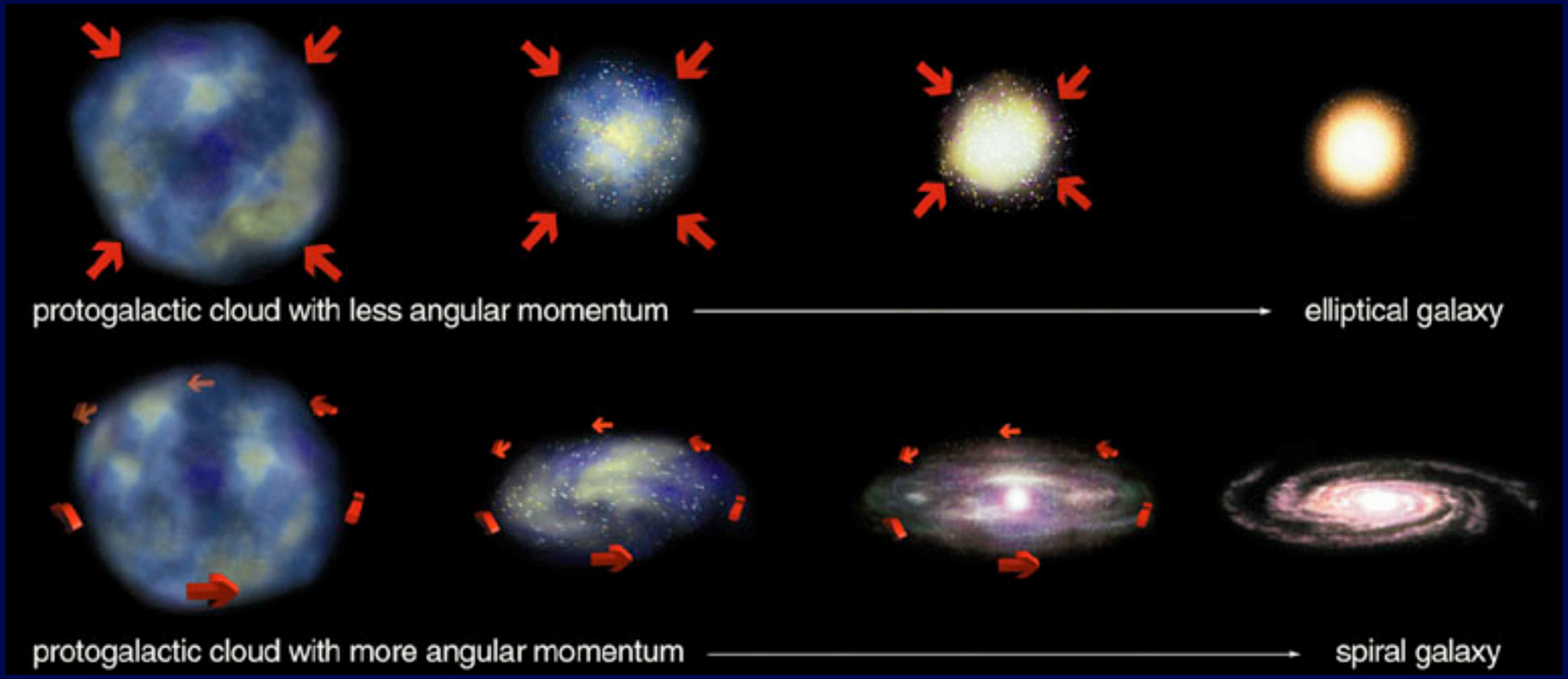
Ab initio galaxy formation model
hierarchical structure formation
in a cold dark matter dominated Universe

- (small) Dark matter halos form first
- small halos merge to larger halos
- Galaxies form and evolve within DM halos: gas cooling, star formation, galaxy mergers, ...



Soft galaxy formation: by gas accretion

- Progressively : *collapse and gas accretion*



Eggen, Lynden-Bell & Sandage 62

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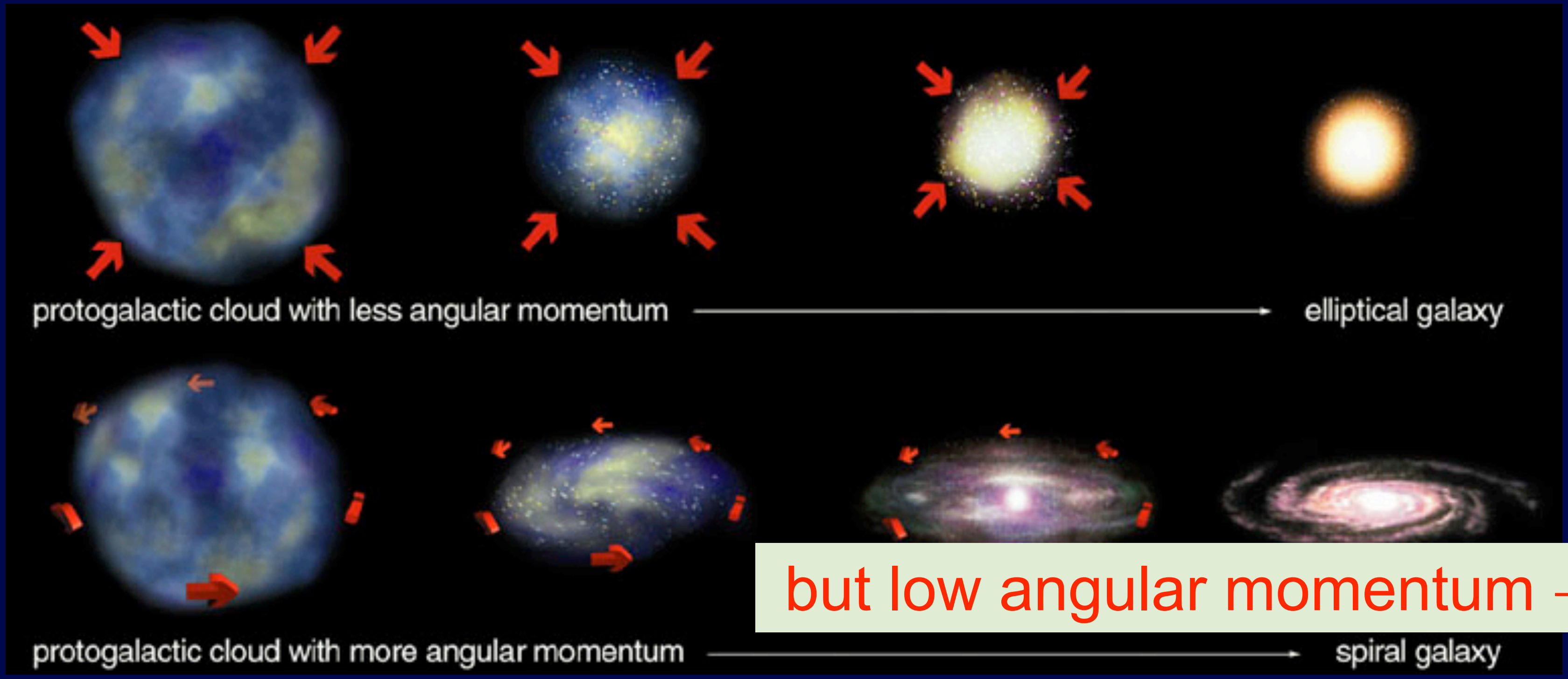

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but low angular momentum → small disks! Mo, Mao & White 98

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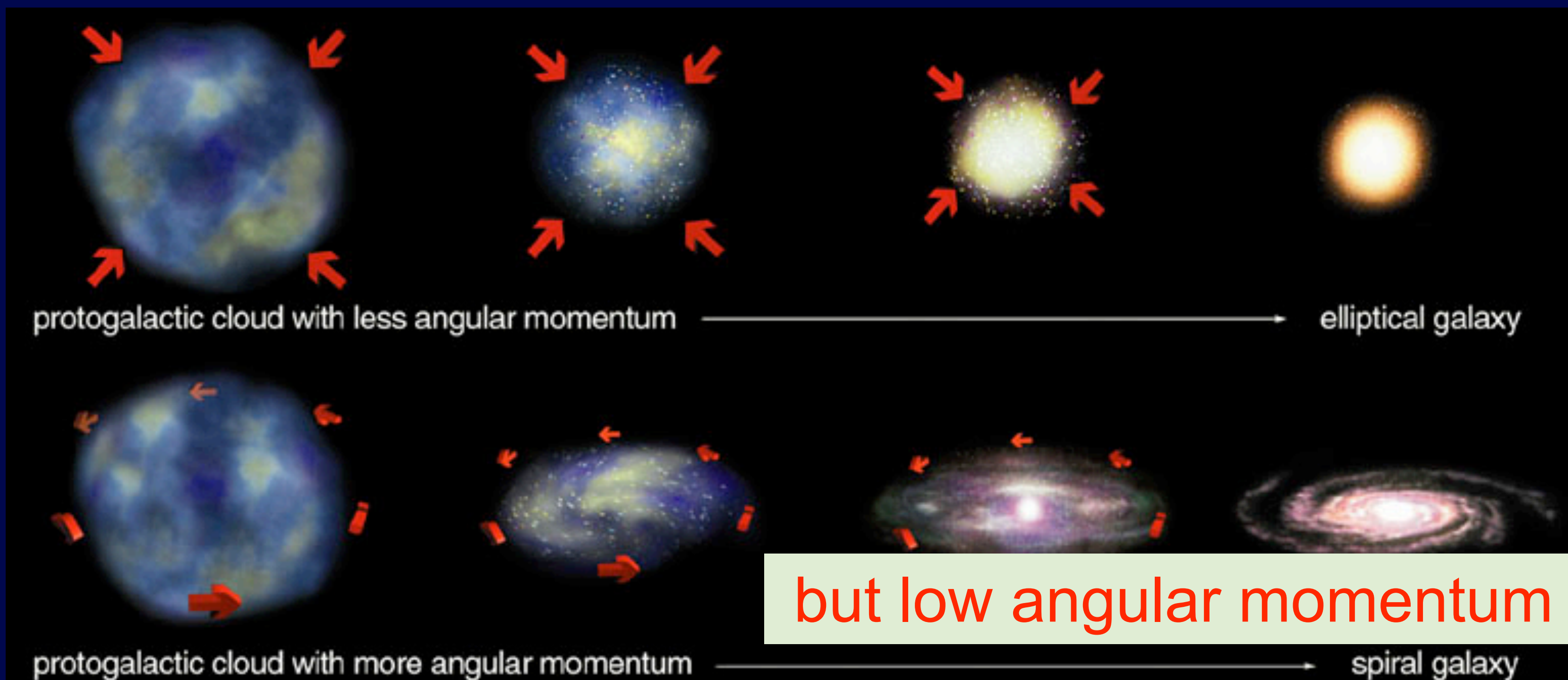

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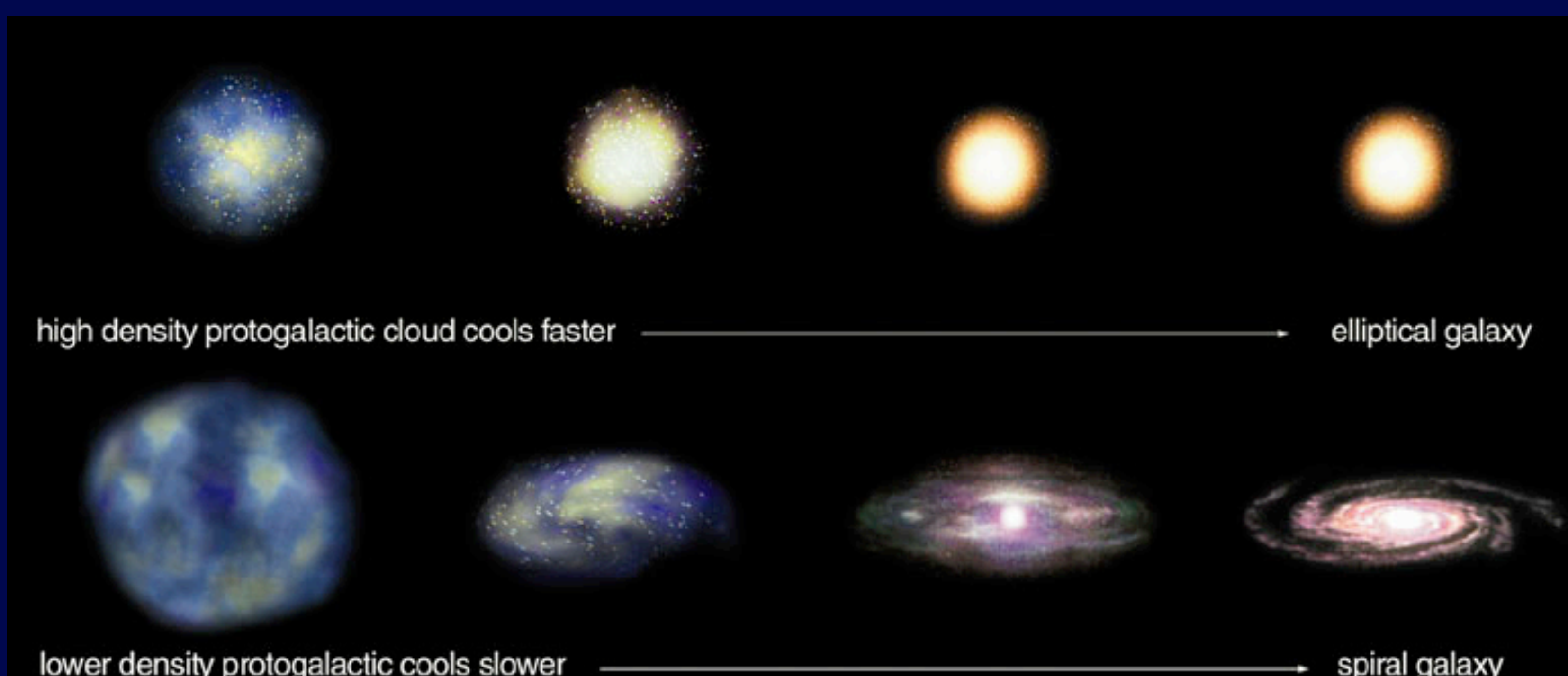

Gott & Thuan 76

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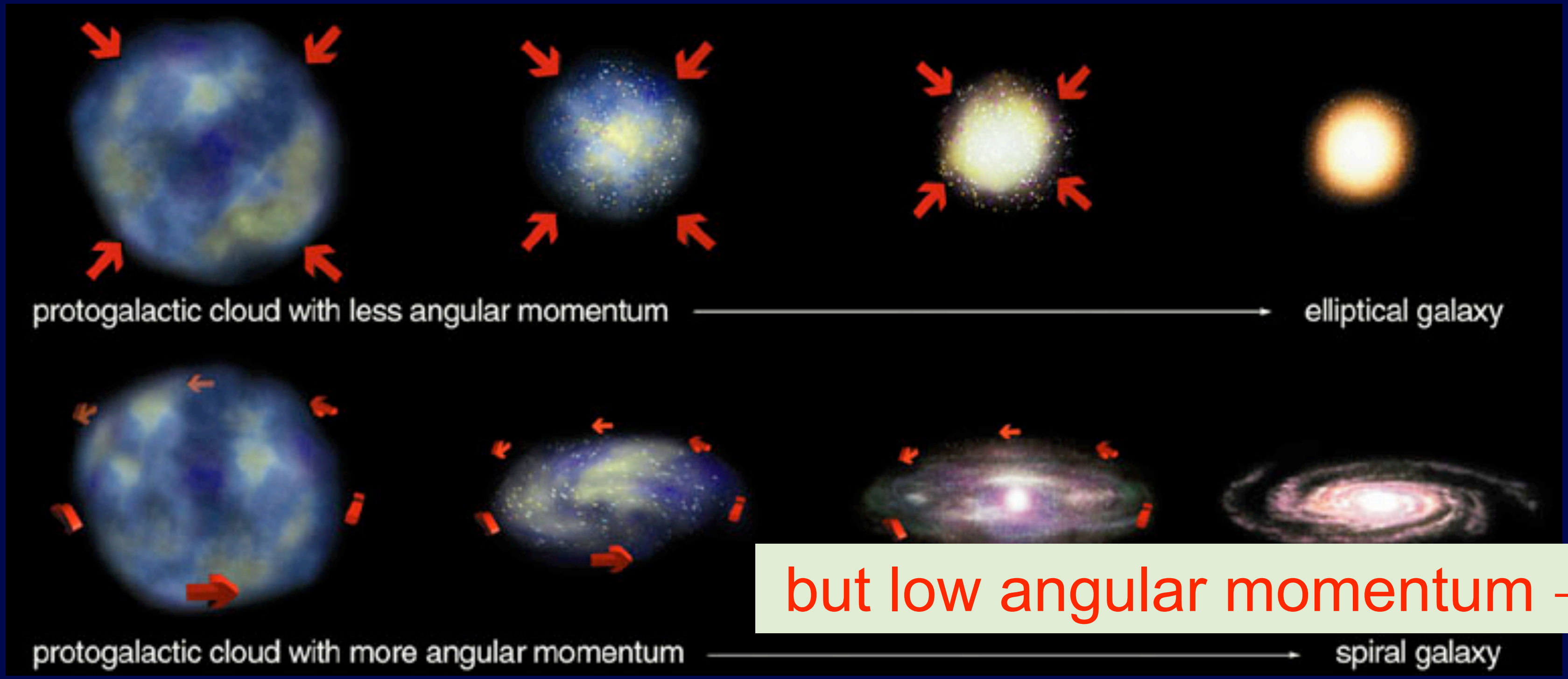

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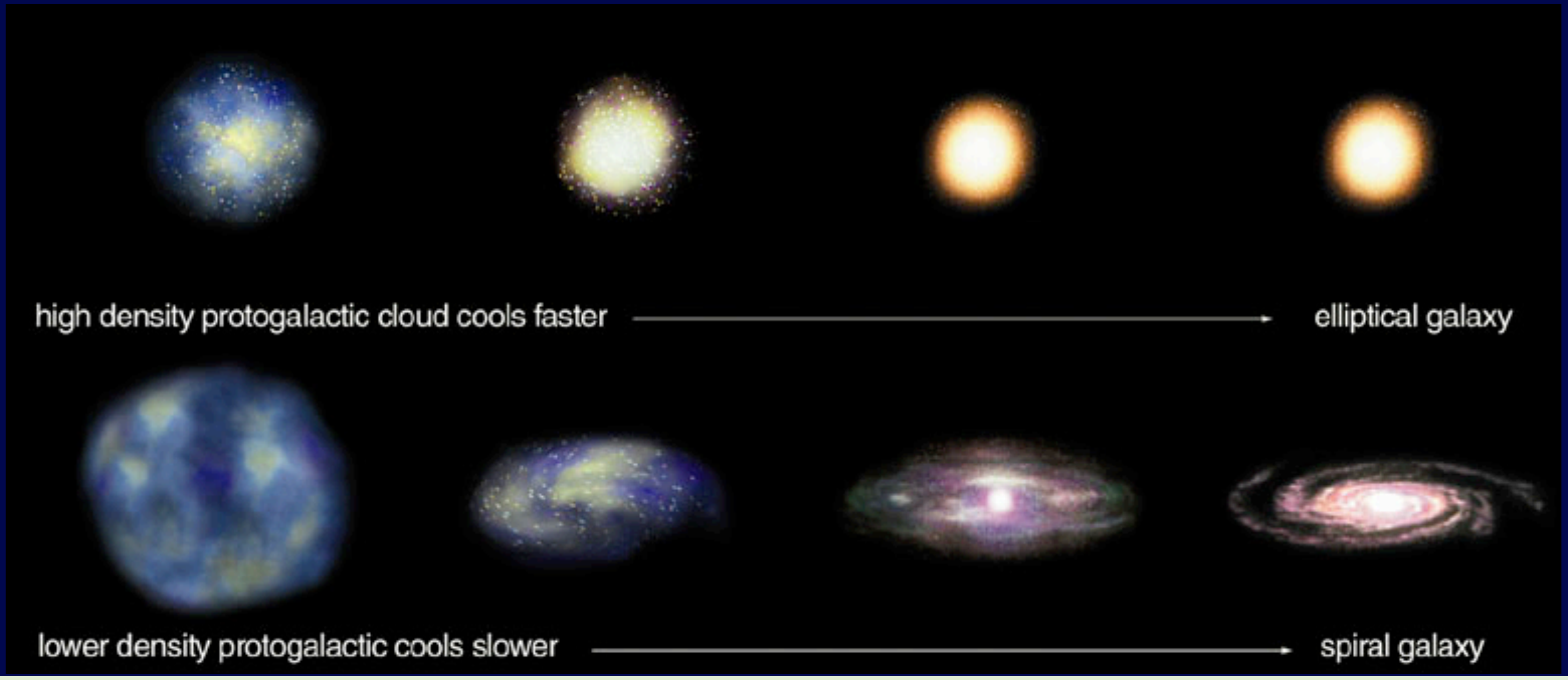
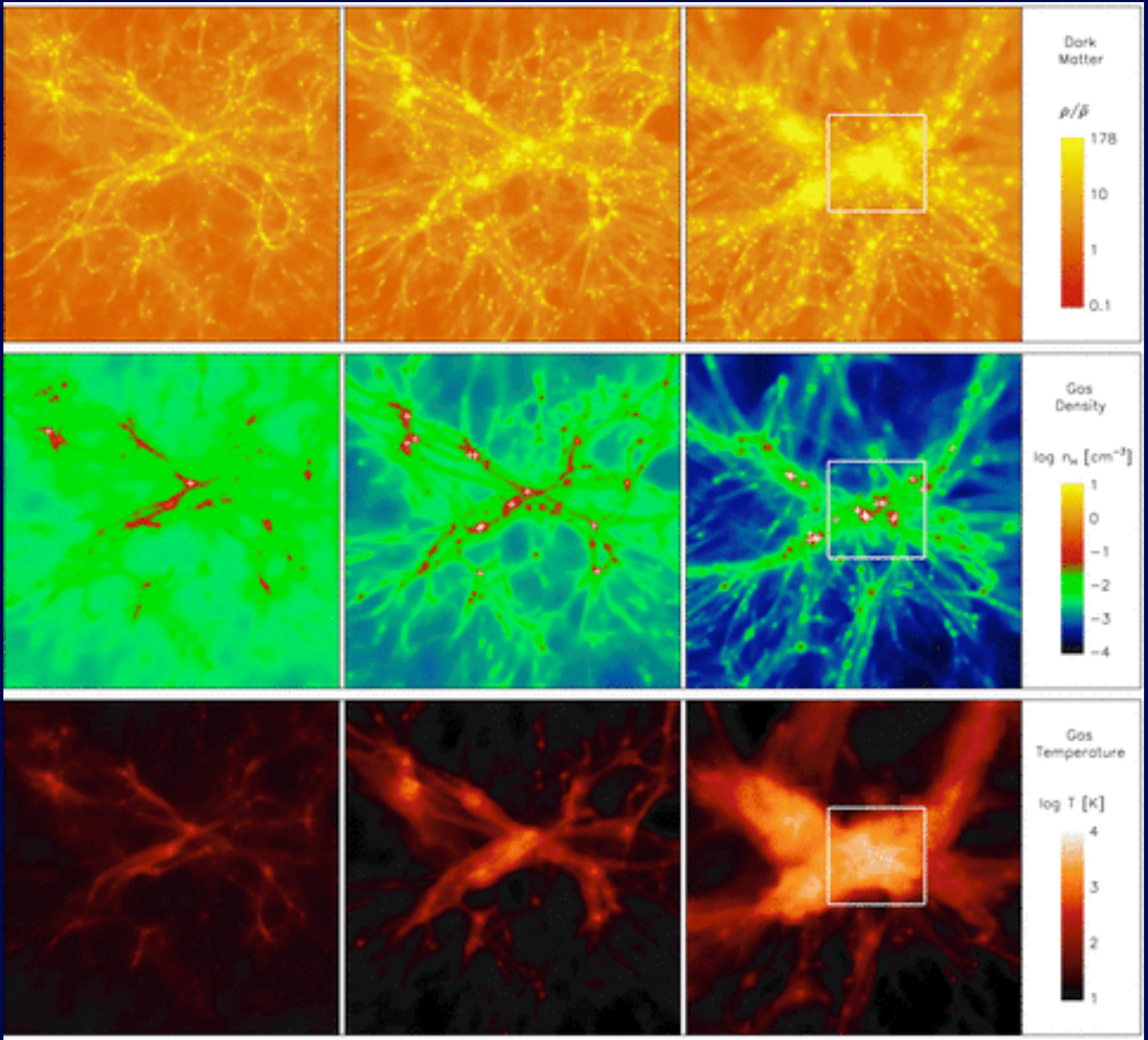


Gott & Thuan 76

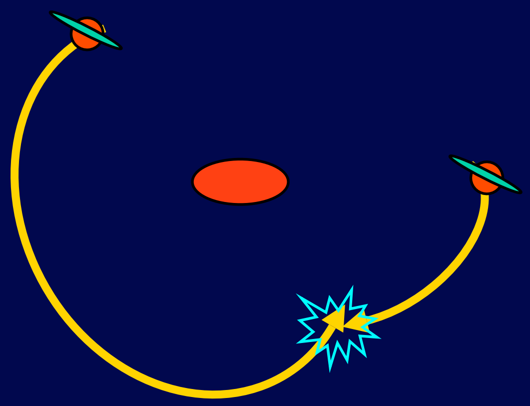
but ~ cst gas fraction & density within virial radius ⇒ cst ratio of cooling to collapse times!

Filamentary & clumpy accretion?



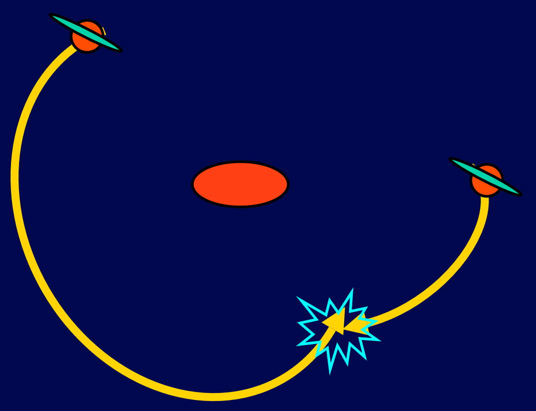
z=23 *z*=18 Greif et al. 2008 *z*=11

Galaxy Mergers

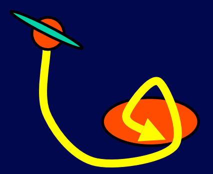


- Direct “satellite-satellite” mergers

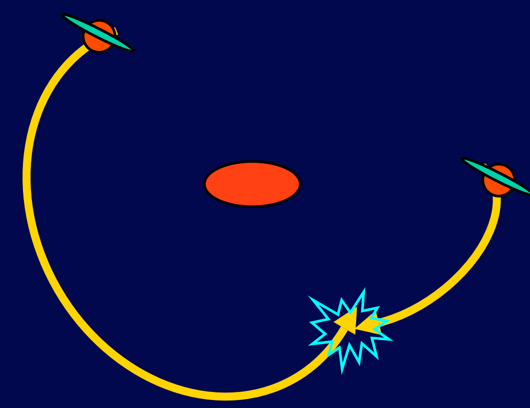
Galaxy Mergers



- Direct "satellite-satellite" mergers
- Mergers after obital decay by *dynamical friction*



Galaxy Mergers



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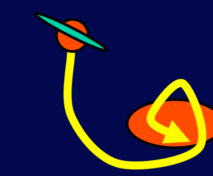
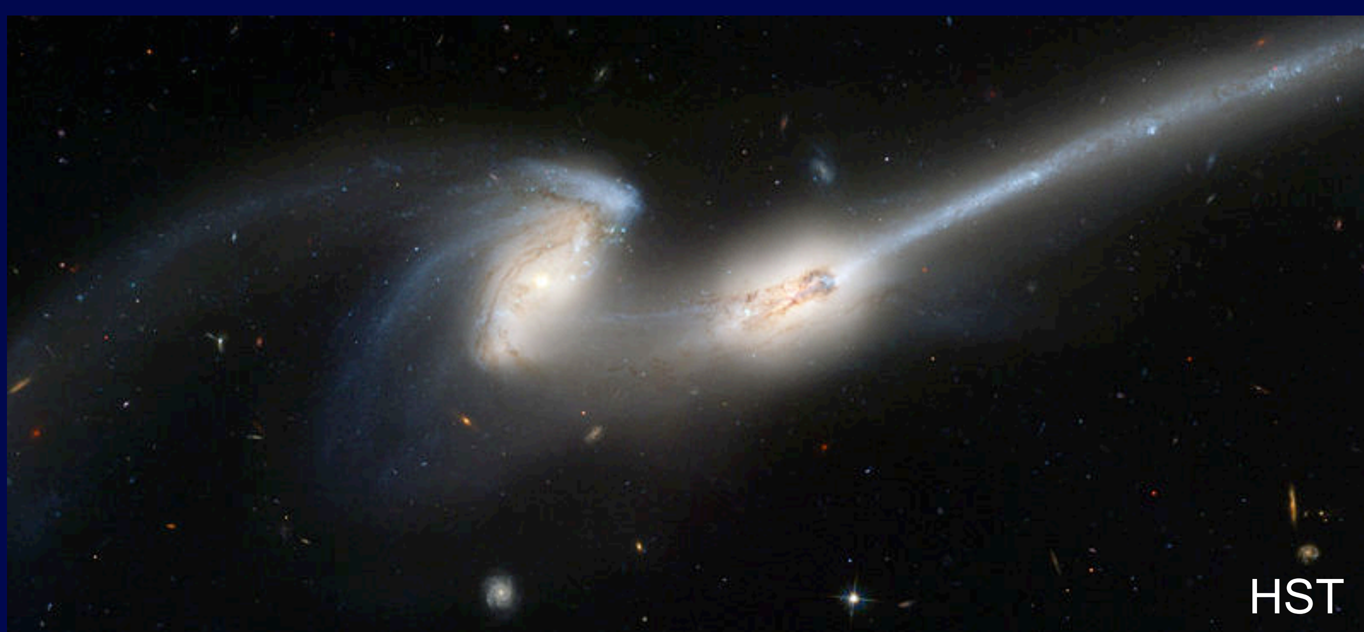
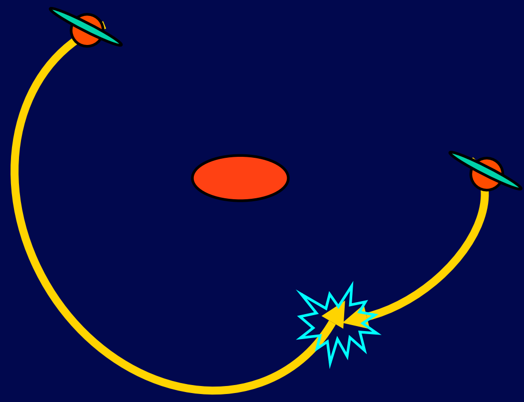


- Major mergers: comparable masses (1:1 to 3:1)



major merger: The Mice

Galaxy Mergers



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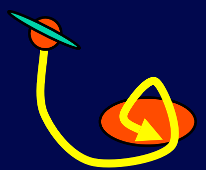
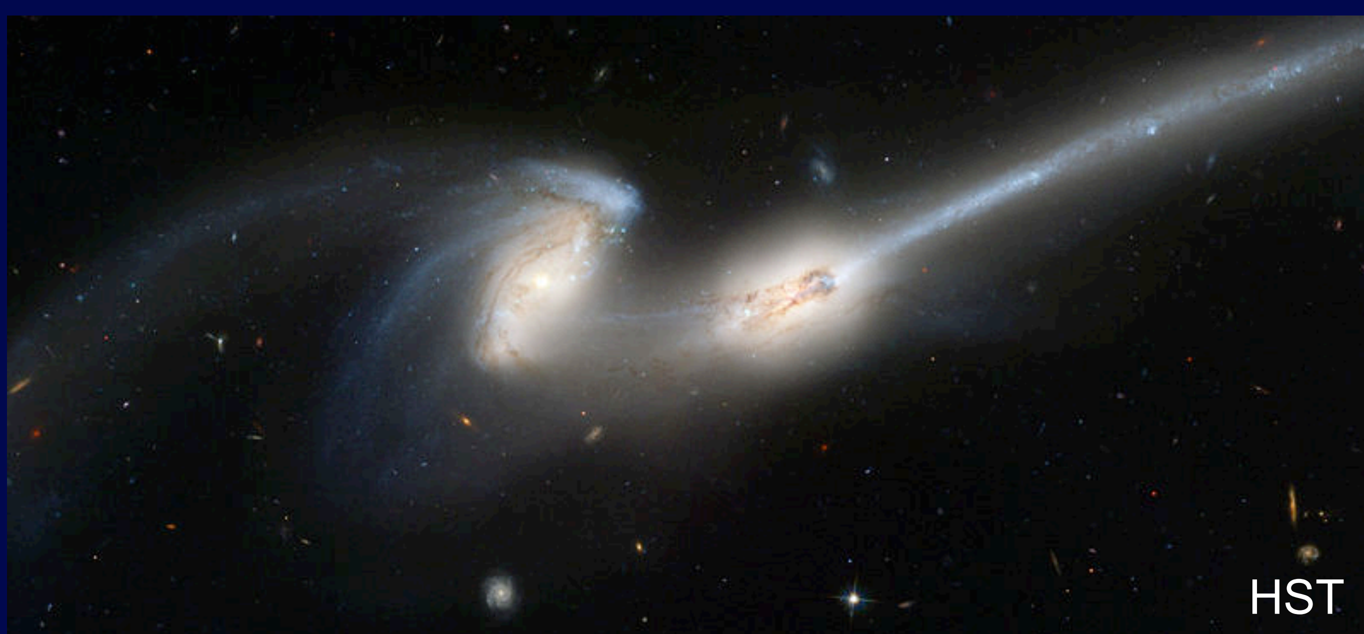


- Major mergers: comparable masses (1:1 to 3:1)
- Minor mergers: very unequal masses (3:1 to 100000...:1)



major merger: The Mice

minor merger: M51

Wet & Dry Mergers

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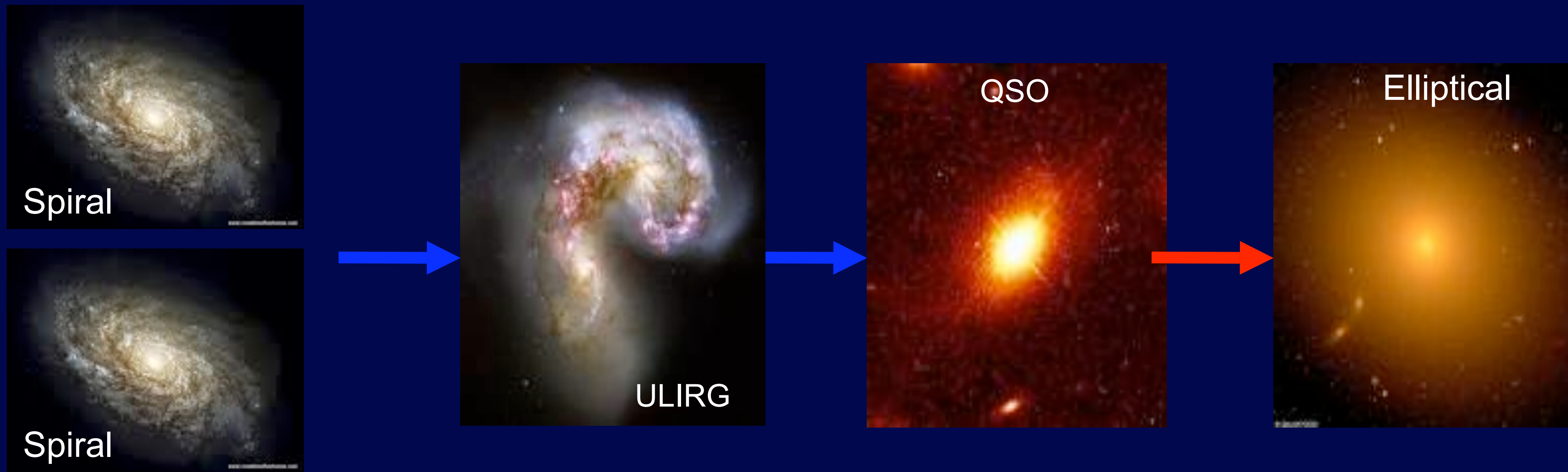
Spiral+Spiral → (wet merger) ULIRG → Quasar → Elliptical

Wet & Dry Mergers



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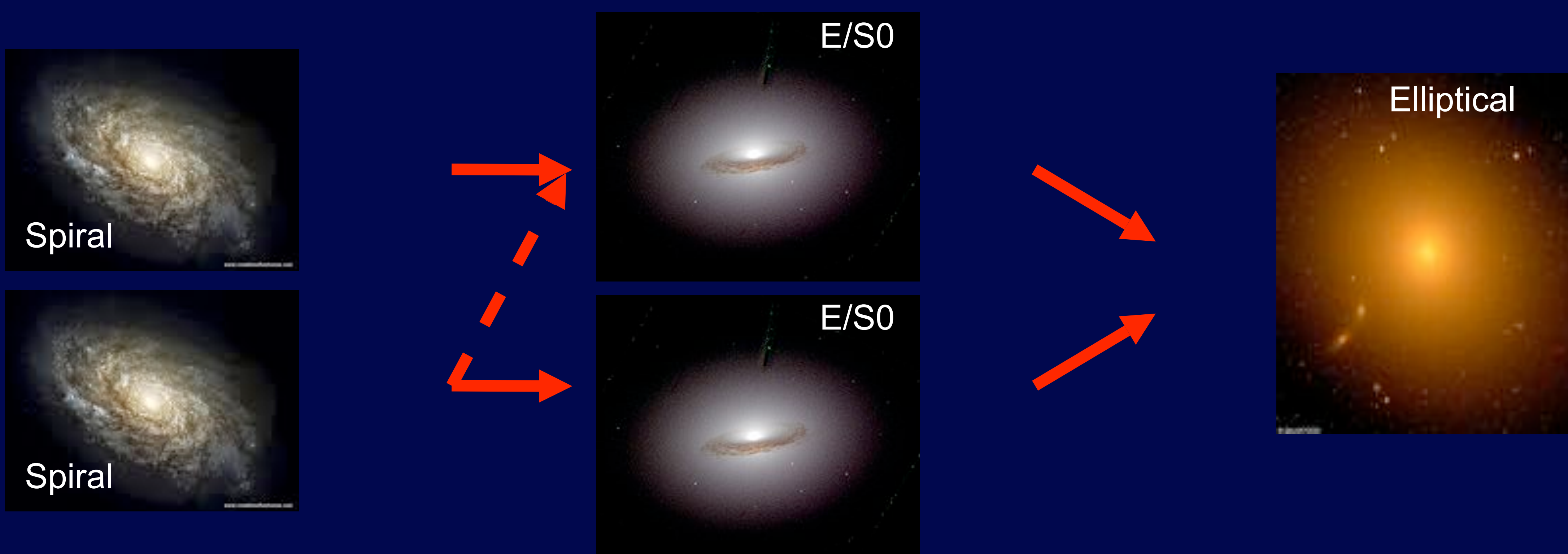
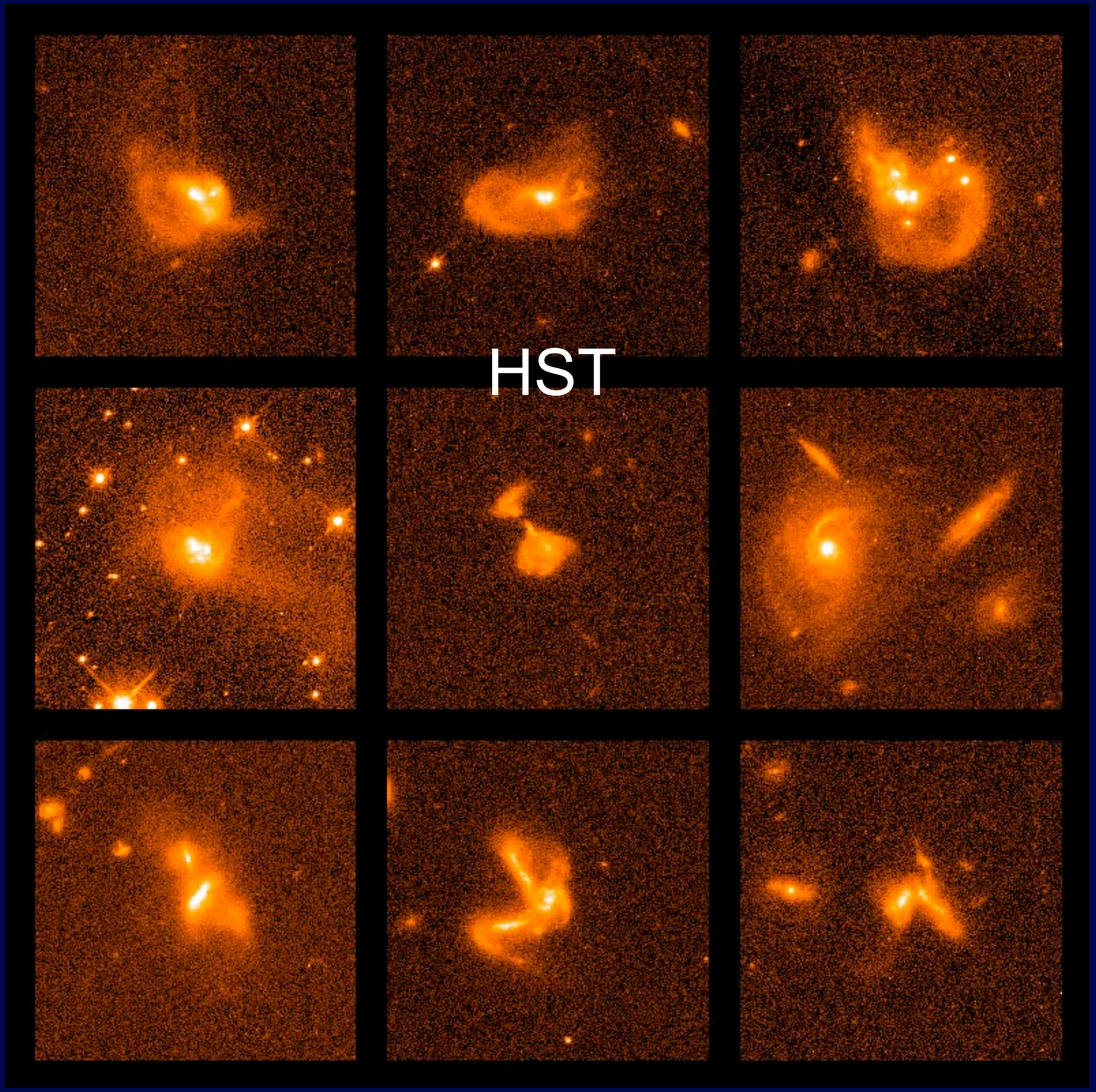


Spiral+Spiral → E/S0+E/S0 → (dry merger)

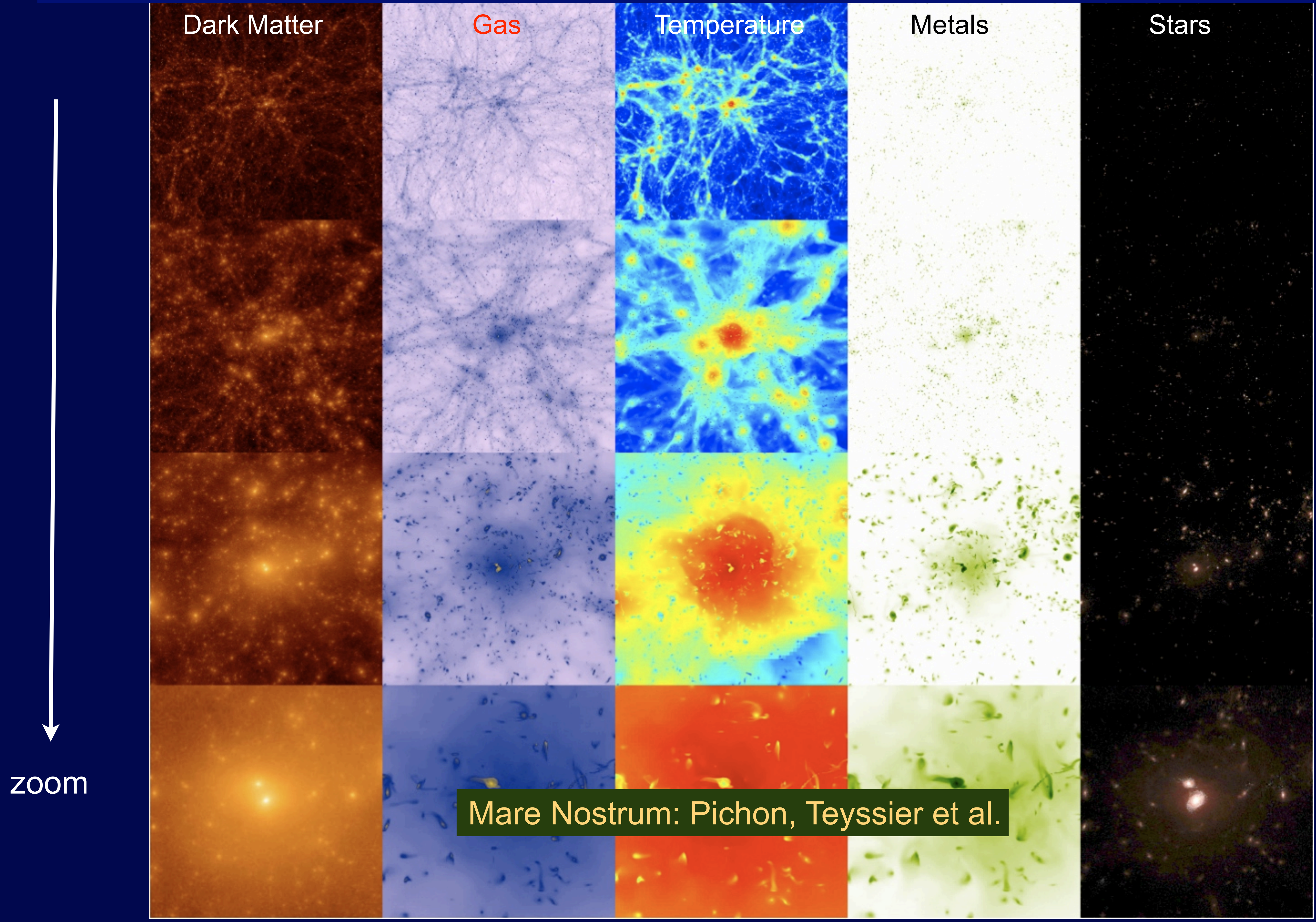
Ultraluminous Infrared Galaxies: sites of wet galaxy mergers

Borne et al. 99



Simulation Methods

Hydrodynamical Cosmological Simulations



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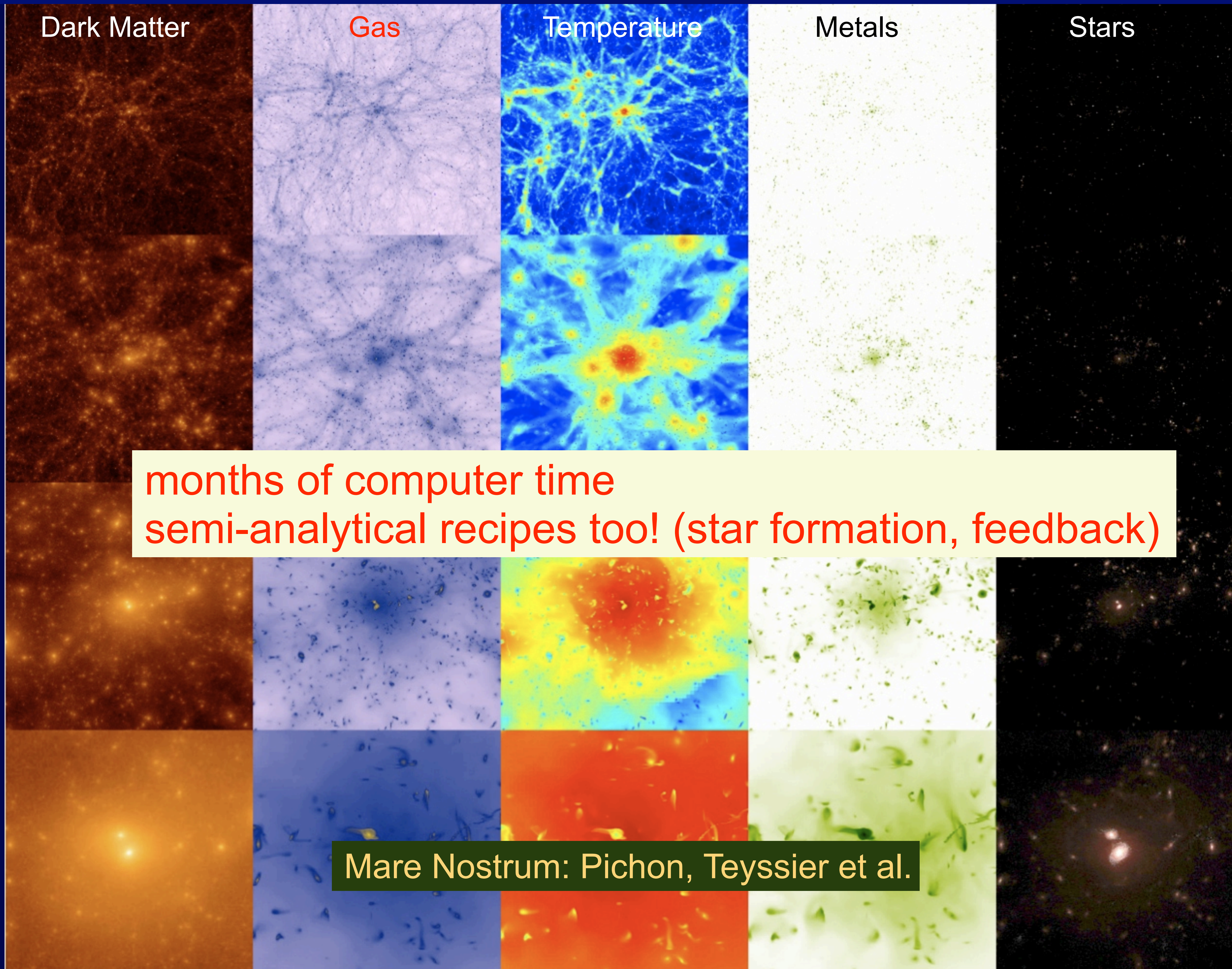


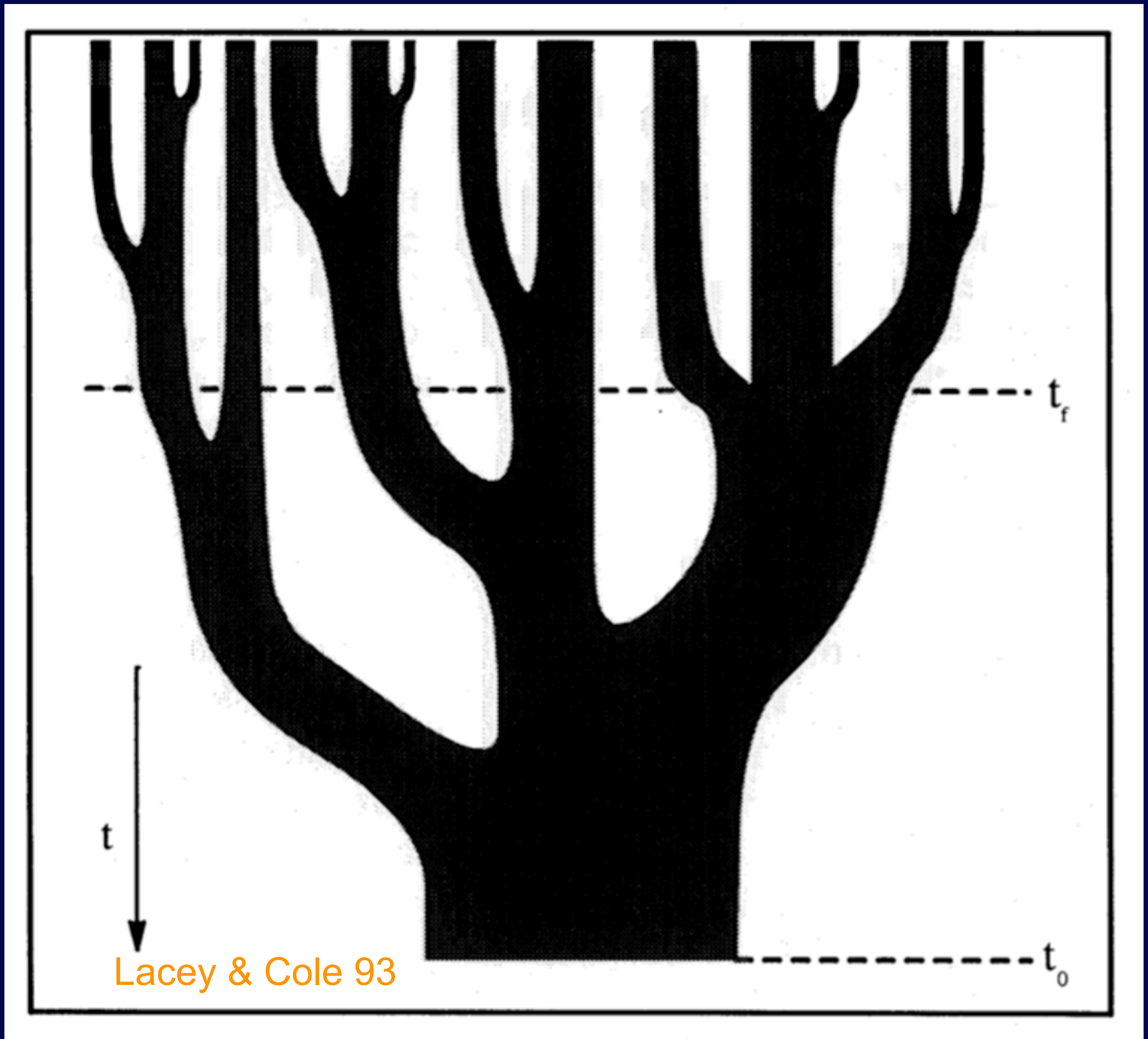
zoom

Semi-analytical models

Galaxy formation and evolution model on top of:

1) halo merger tree

2) astrophysics
cooling
star formation
feedback from
  SNe, AGN, shocks
galaxy mergers
chemical evolution
...



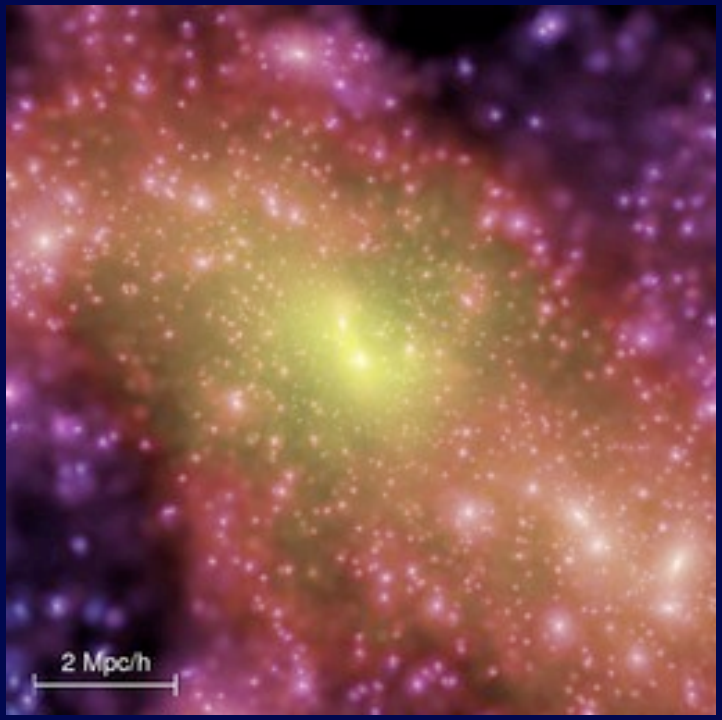
Semi-analytical models

Galaxy formation and evolution model on top of:

1) halo merger tree

2) dark matter cosmological simulation

Springel et al. 2005



dark matter

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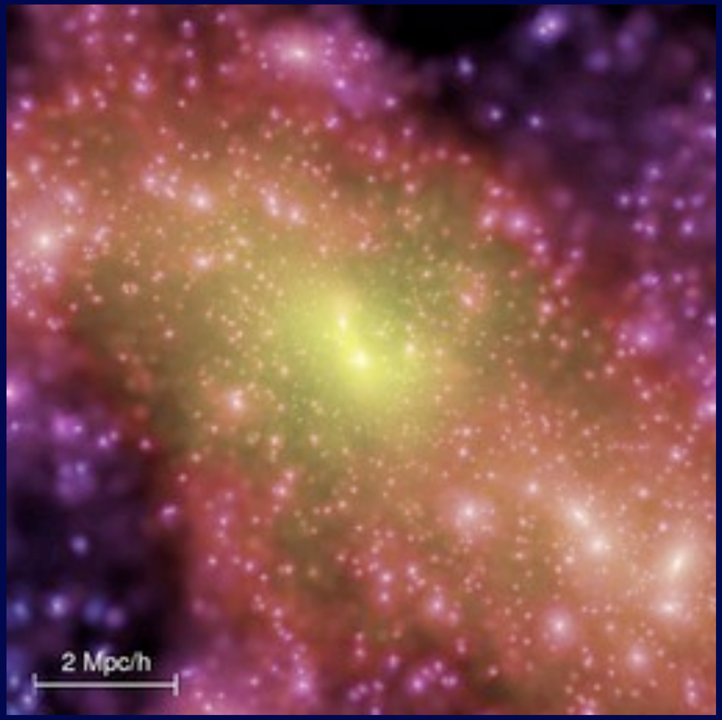
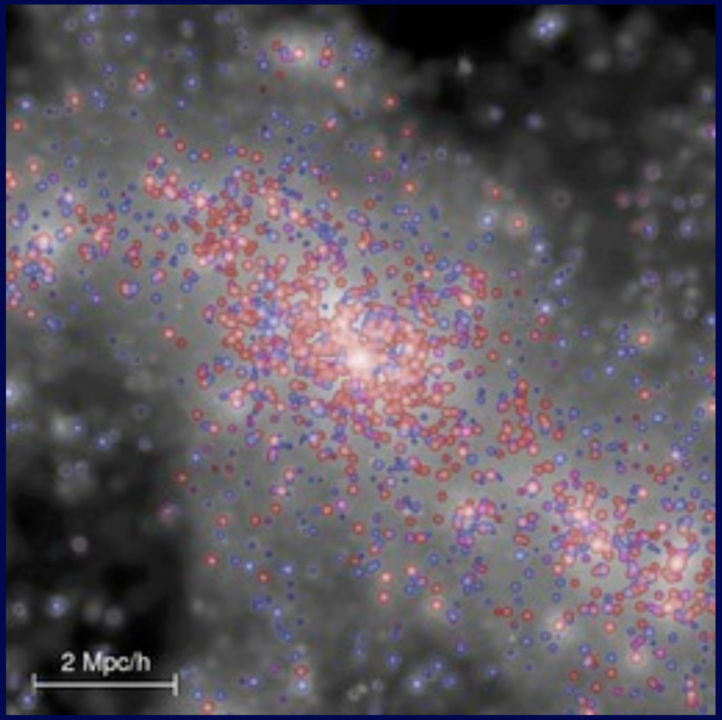
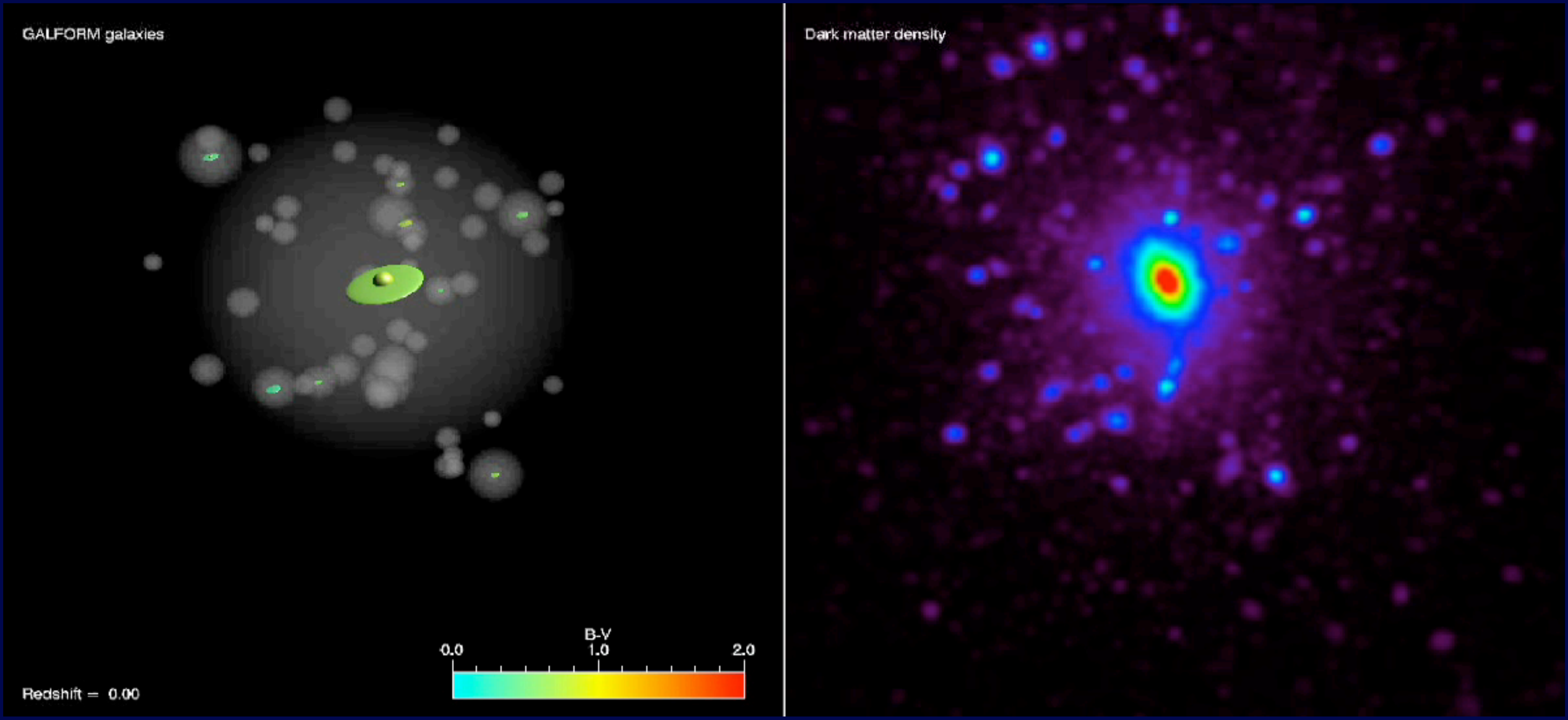


dark matter



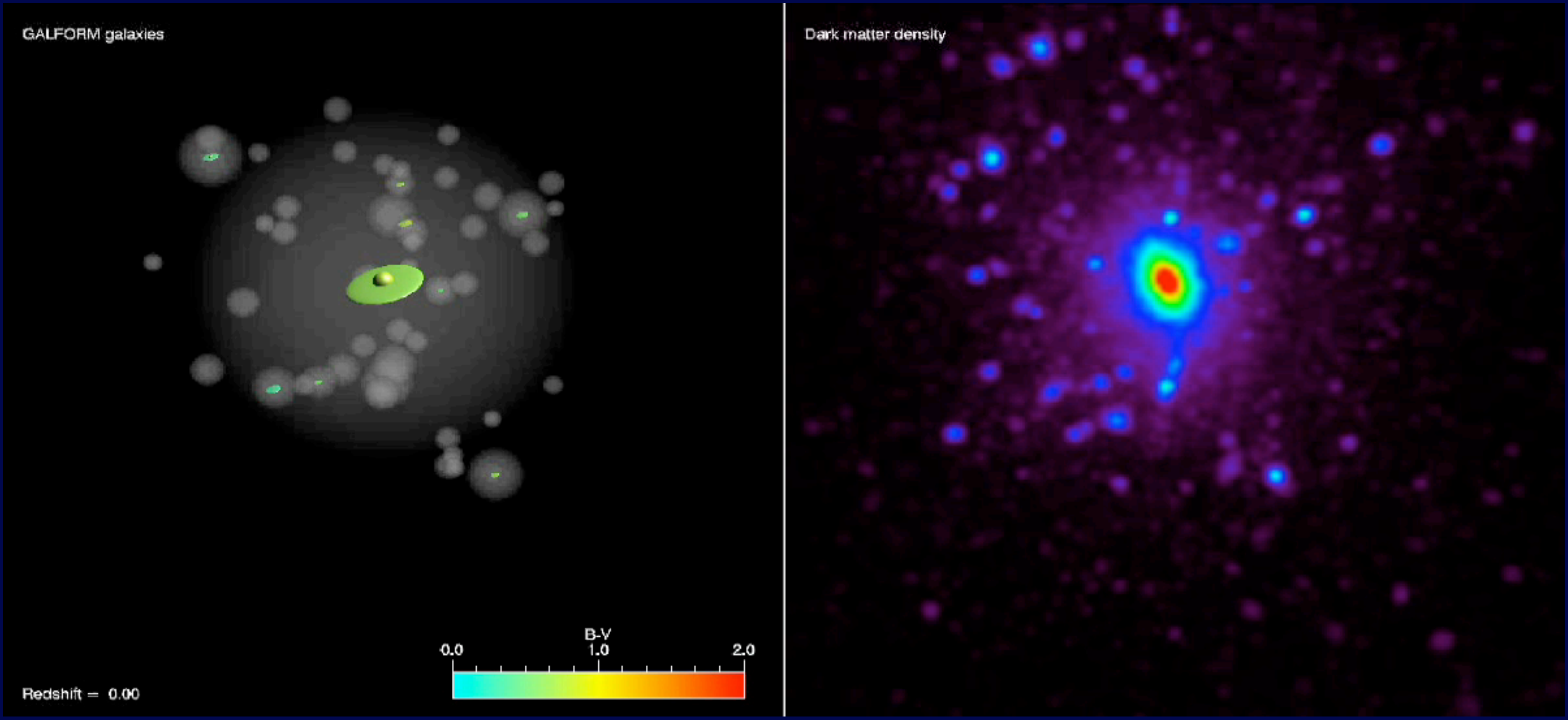
dark matter + galaxies

Semi-analytical models in motion!



Durham team

Semi-analytical models in motion!



Durham team

tens of thousands of lines of code
> 10 parameters

Halo Occupation Distribution

$$P(X|M_{\rm halo})$$

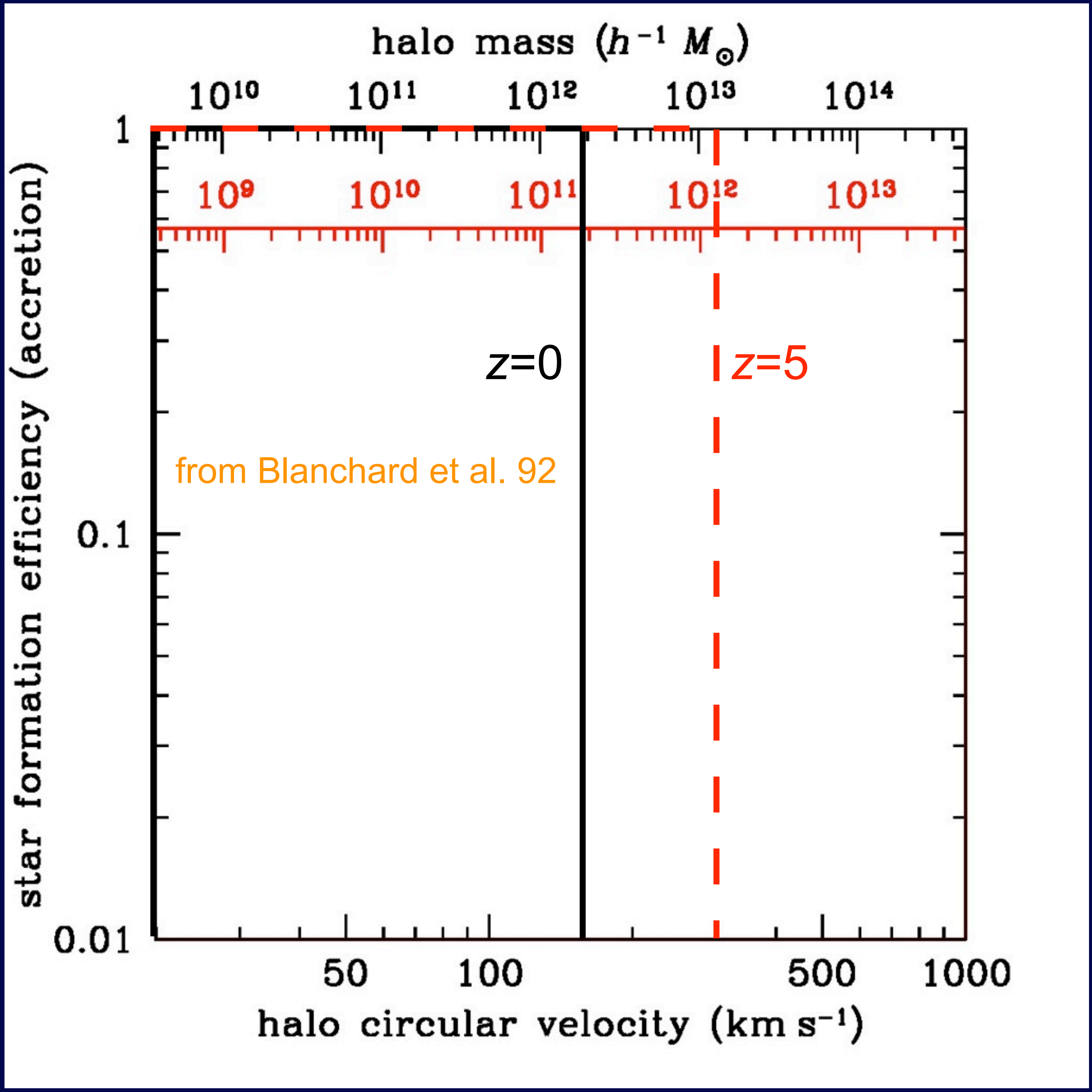
conditional luminosity function
Yang, Mo, van den Bosch 03, 05, 08, 09

How do galaxies acquire their mass?

Previous work

Toy model, back in 1992

naive galaxy formation:
too many stars Blanchard, Valls-Gabaud & Mamon 92
too massive and blue galaxies: Kauffmann et al. 96



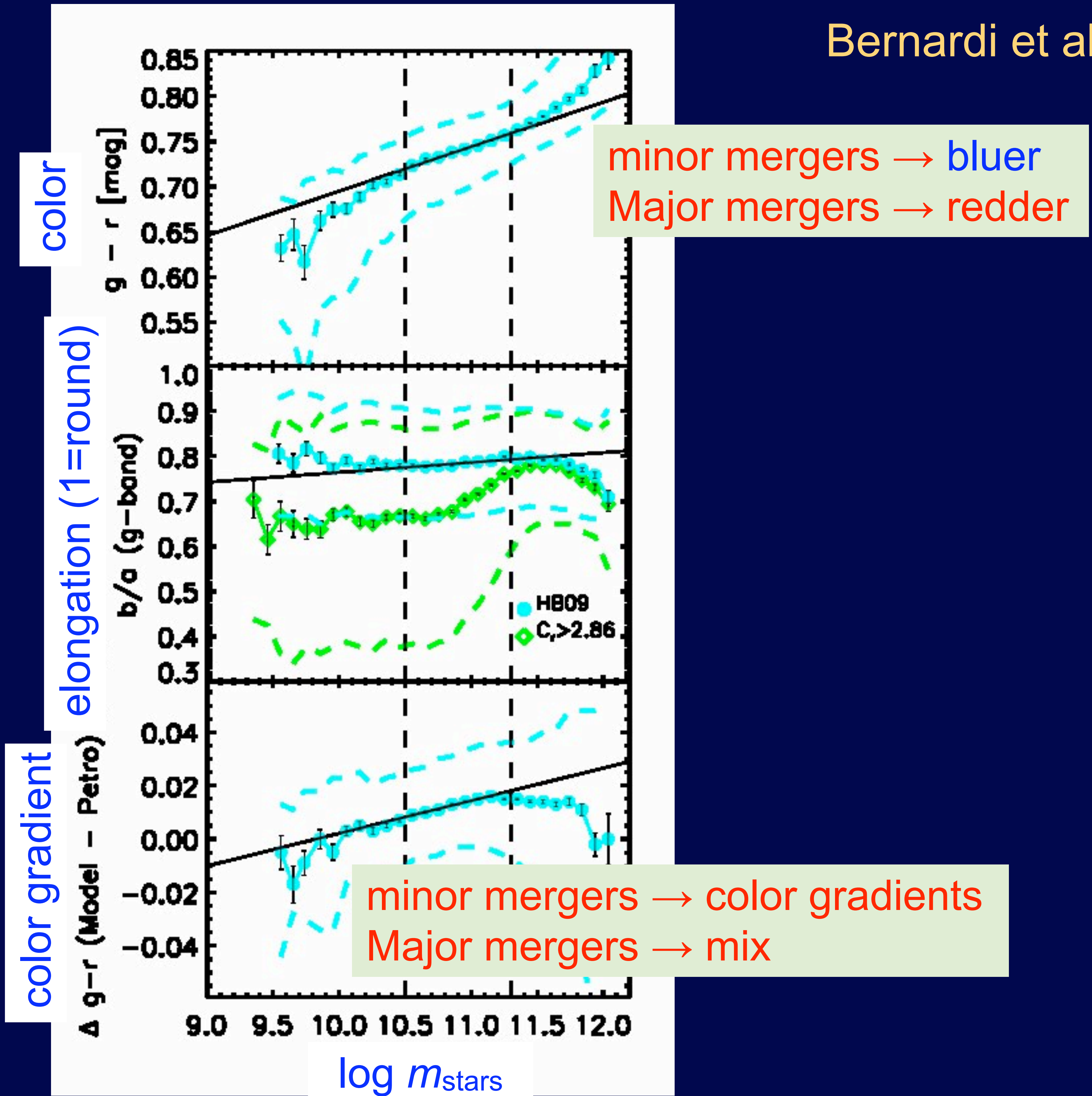
Recent work

(dry major) mergers dominate growth of massive ellipticals

Maller et al. 06; de Lucia et al. 06; Guo & White 08 (simulations)
Bernardi et al. 10ab (SDSS observations)

SDSS trends on ellipticals

Bernardi et al. 10b



SDSS trends on ellipticals

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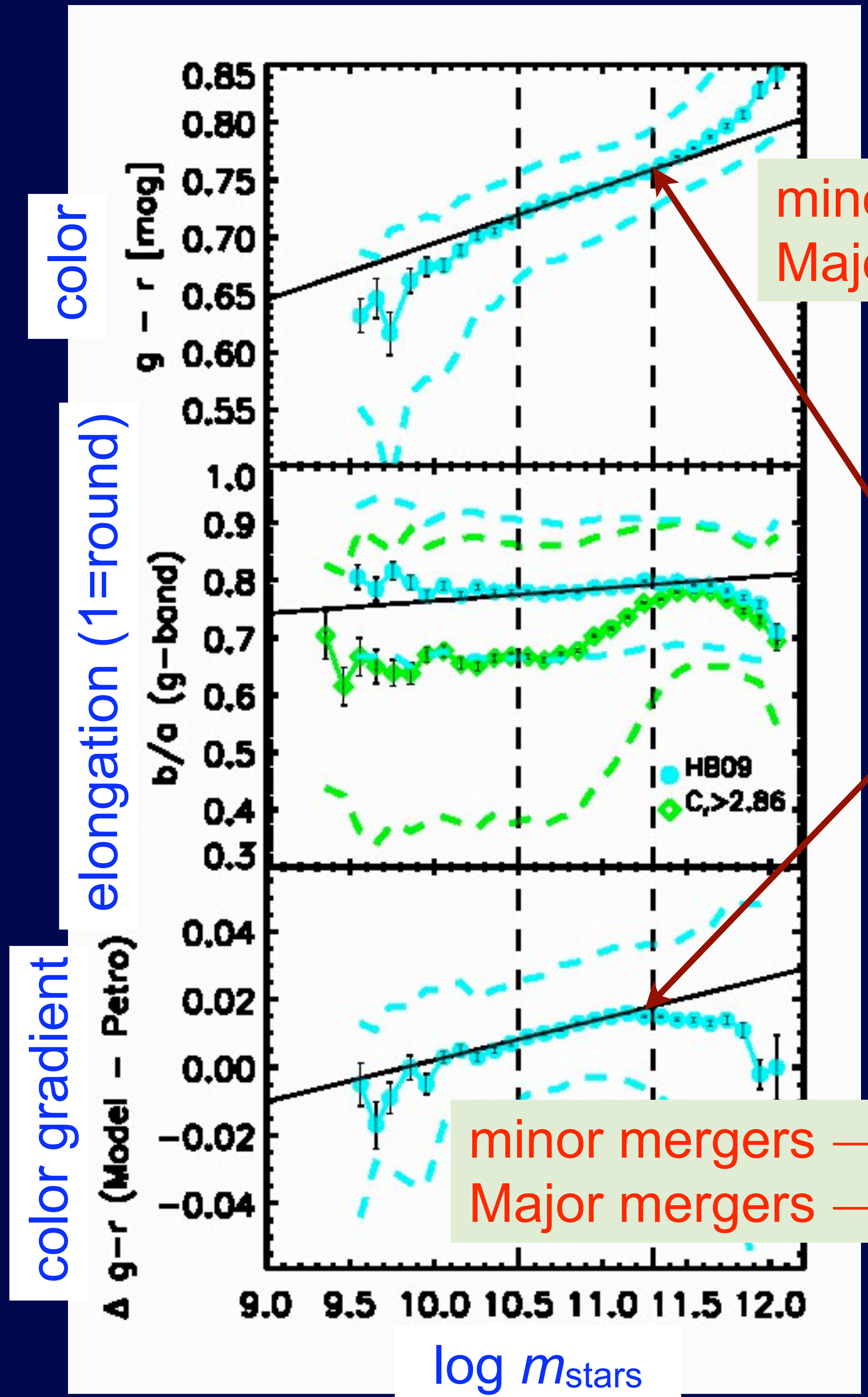

minor mergers → bluer
Major mergers → redder

transition at log $m_{\rm stars}$ = 11.3
i.e. log $h\ m_{\rm stars}$ = 11.0

minor mergers → color gradients
Major mergers → mix

Recent work

(dry major) mergers dominate growth of massive ellipticals

Maller et al. 06; de Lucia et al. 06; Guo & White 08 (simulations)
Bernardi et al. 10ab (SDSS observations)

but don't see growth by major mergers in high resolution hydro-cosmo simulations Naab et al. 07

How do galaxies acquire their mass?

A Toy Model of Galaxy Formation

with

Andrea CATTANEO

Obs. de Lyon

Toy model

Cattaneo, GM et al. 10

Suppress (smoothly) accretion when $M_{\rm halo} > M_{\rm shock}$

$m_{\rm accr}^{(1)} = f_{\rm baryons}\, M_{\rm halo} \,/\, (1 + M_{\rm halo} \,/\, M_{\rm shock})$ Dekel & Birnboim 06

Suppress (sharply) accretion when $v_{\rm halo} < v_{\rm reion}$

$m_{\rm accr} = [1-(v_{\rm reion}/v_{\rm halo})^2]\; m_{\rm accr}^{(1)}$ Thoul & Weinberg 96

Suppress (smoothly) star formation when $v_{\rm halo} < v_{\rm SN}$

$E_{\rm SN} \approx m_{\rm wind}\, v_{\rm halo}^2 \approx m_{\rm stars}\, v_{\rm SN}^2$

$m_{\rm wind} + m_{\rm stars} = m_{\rm accr}$

$\Rightarrow m_{\rm stars} = v_{\rm halo}^2 \,/ (v_{\rm halo}^2 + v_{\rm SN}^2)\; m_{\rm accr}$

Toy model

Cattaneo, GM et al. 10

Suppress (smoothly) accretion when $M_{\rm halo} > M_{\rm shock}$

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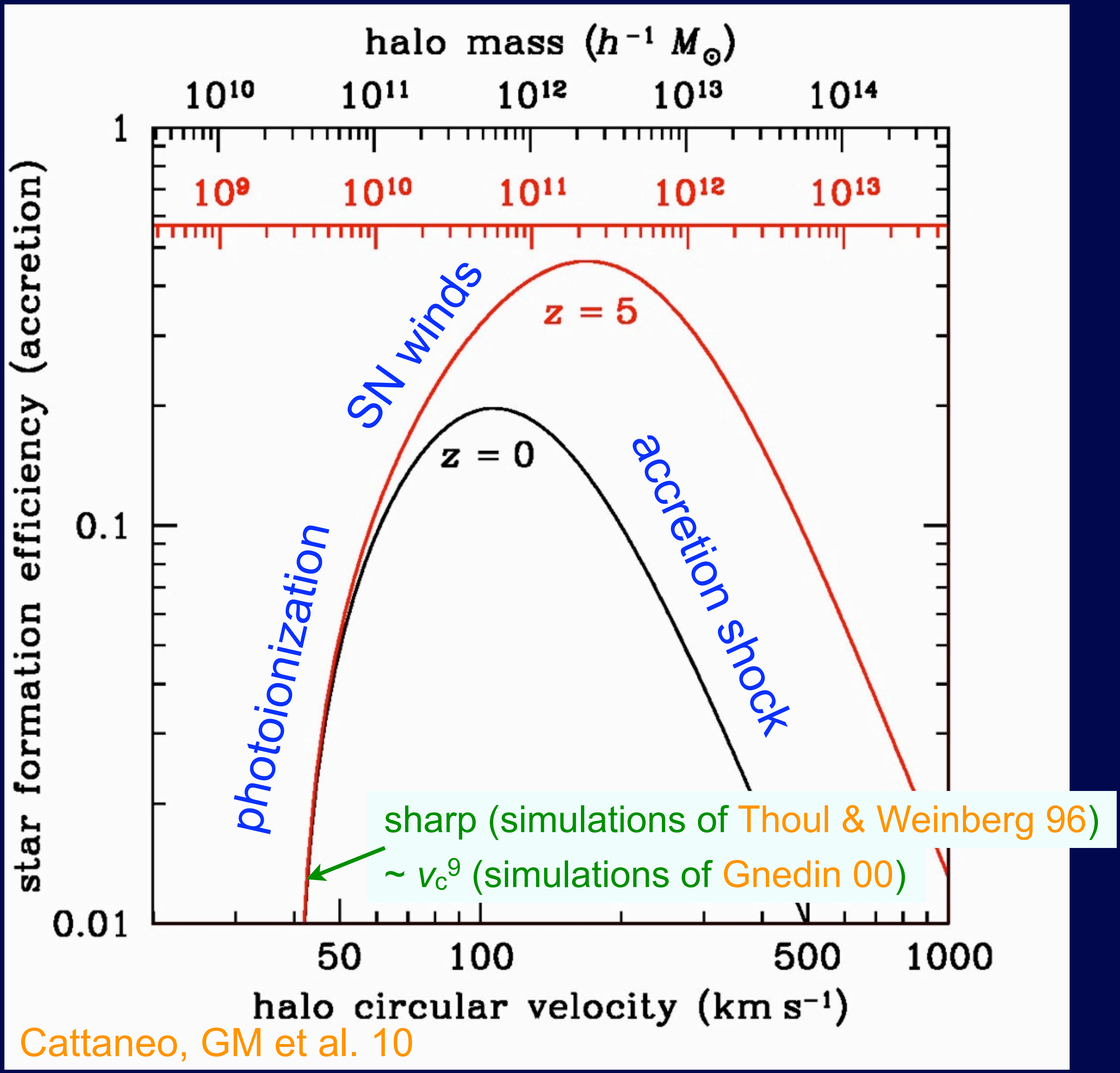
$\Rightarrow m_{\rm stars} = v_{\rm halo}^2 / (v_{\rm halo}^2 + v_{\rm SN}^2)\, m_{\rm accr}$

$m_{\rm stars} = f(M_{\rm halo}, z)$

Four-parameter toy model of galaxy formation

$$m_{\rm stars}^{\rm accr} \sim \frac{v_c^2(z) - v_{\rm reion}^2}{v_c^2(z) + v_{\rm SN}^2} \, \frac{f_{\rm b} M_{\rm halo}}{1 + M_{\rm halo}/M_{\rm shock}}$$

$$v_c(z) = \left[\frac{\Delta(z)}{2}\right]^{1/6} \left[G\,H(z)\right]^{1/3} M_{\rm halo}^{1/3}$$



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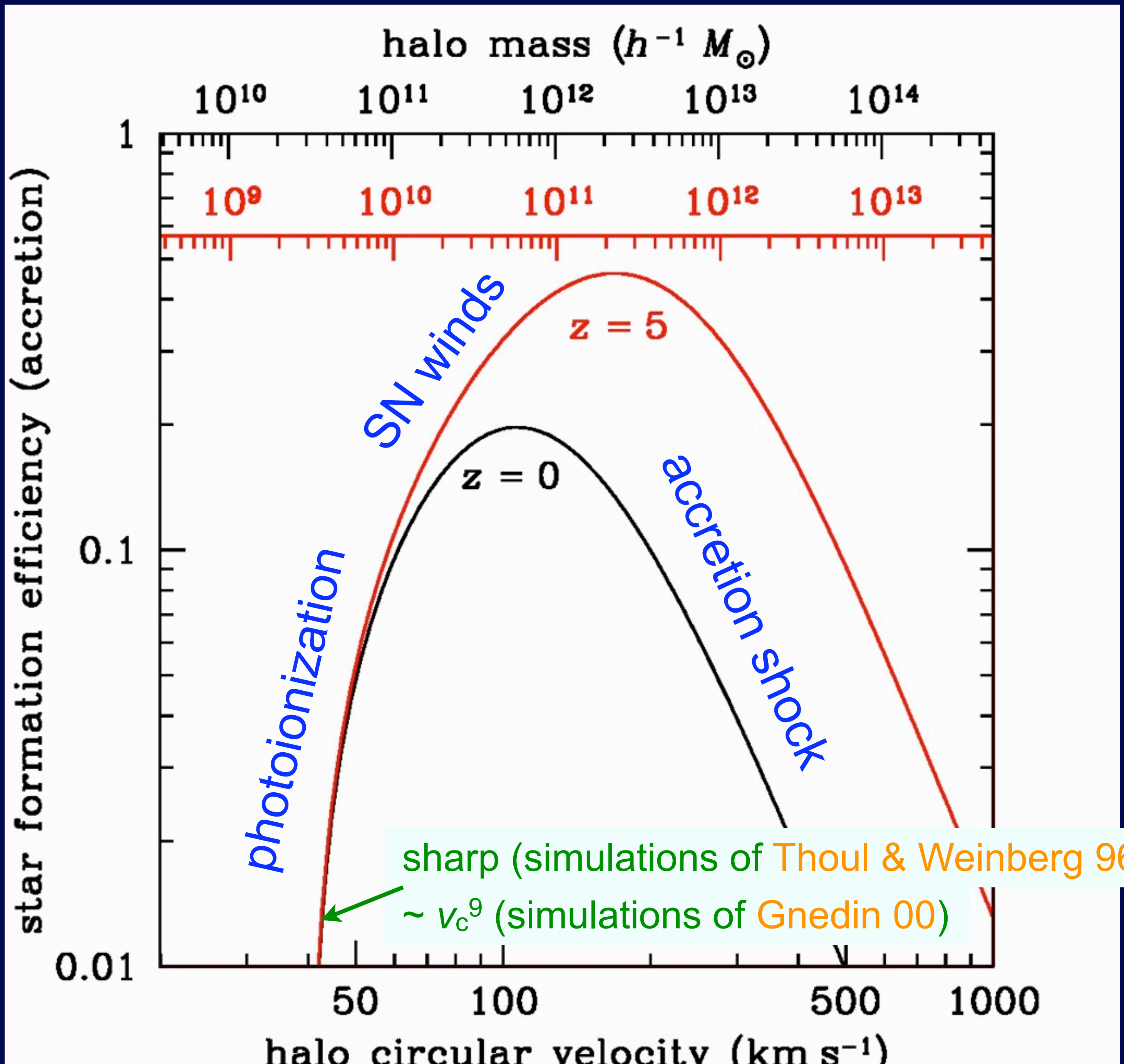
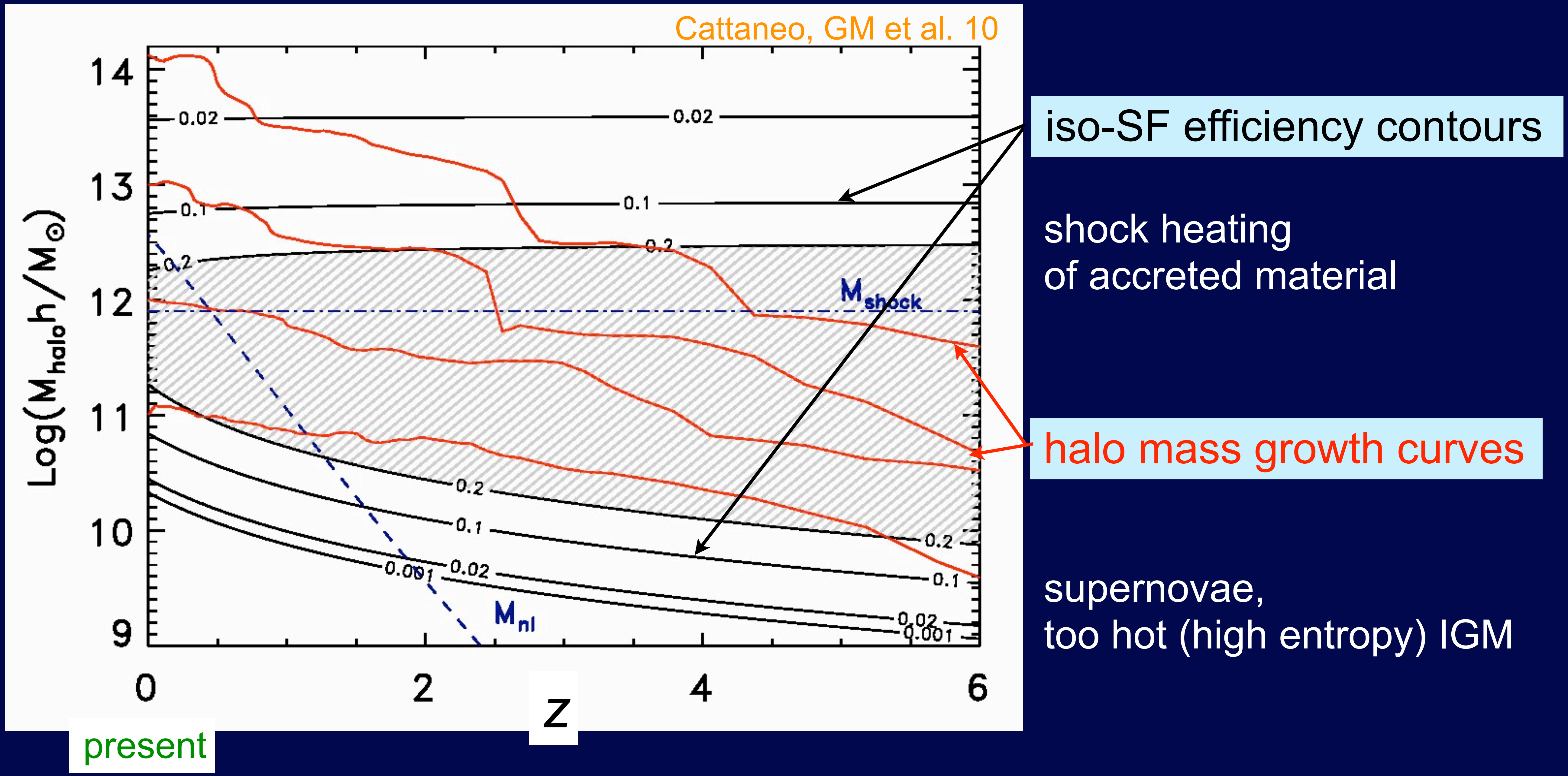


Cattaneo, GM et al. 10

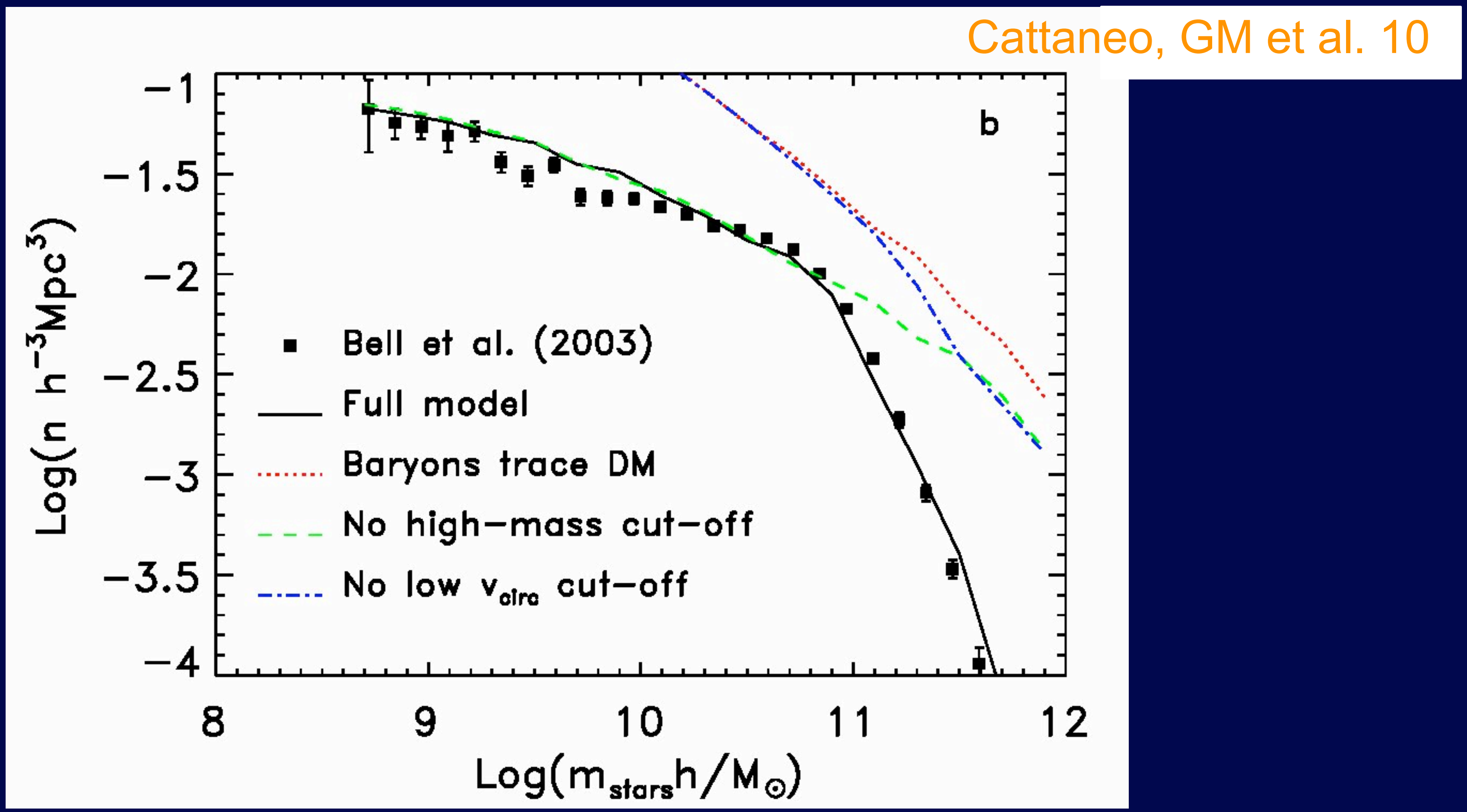
- run on top of 512^3 dark matter cosmological simulation particle mass = $7\times10^7\ M_{\rm sun}/h$
- build (sub-)halo merger tree AHF Knollmann & Knebe 09
- merge galaxies when subhalo merges into halo
- delay final merger of unresolved halos by dynamical friction time Jiang et al. 08
- apply toy model equation during quiescent phases prevent decrease of stellar mass
- tidal strip stellar mass at each orbit

Galaxy formation vs epoch

Accretion + Mergers (w/o starbursts)
+ quenching of SF by Supernovae, too hot IGM & accretion shock



Tests of Toy Model



Mass distribution:
parameters fit to
agree with observations

Tests of Toy Model

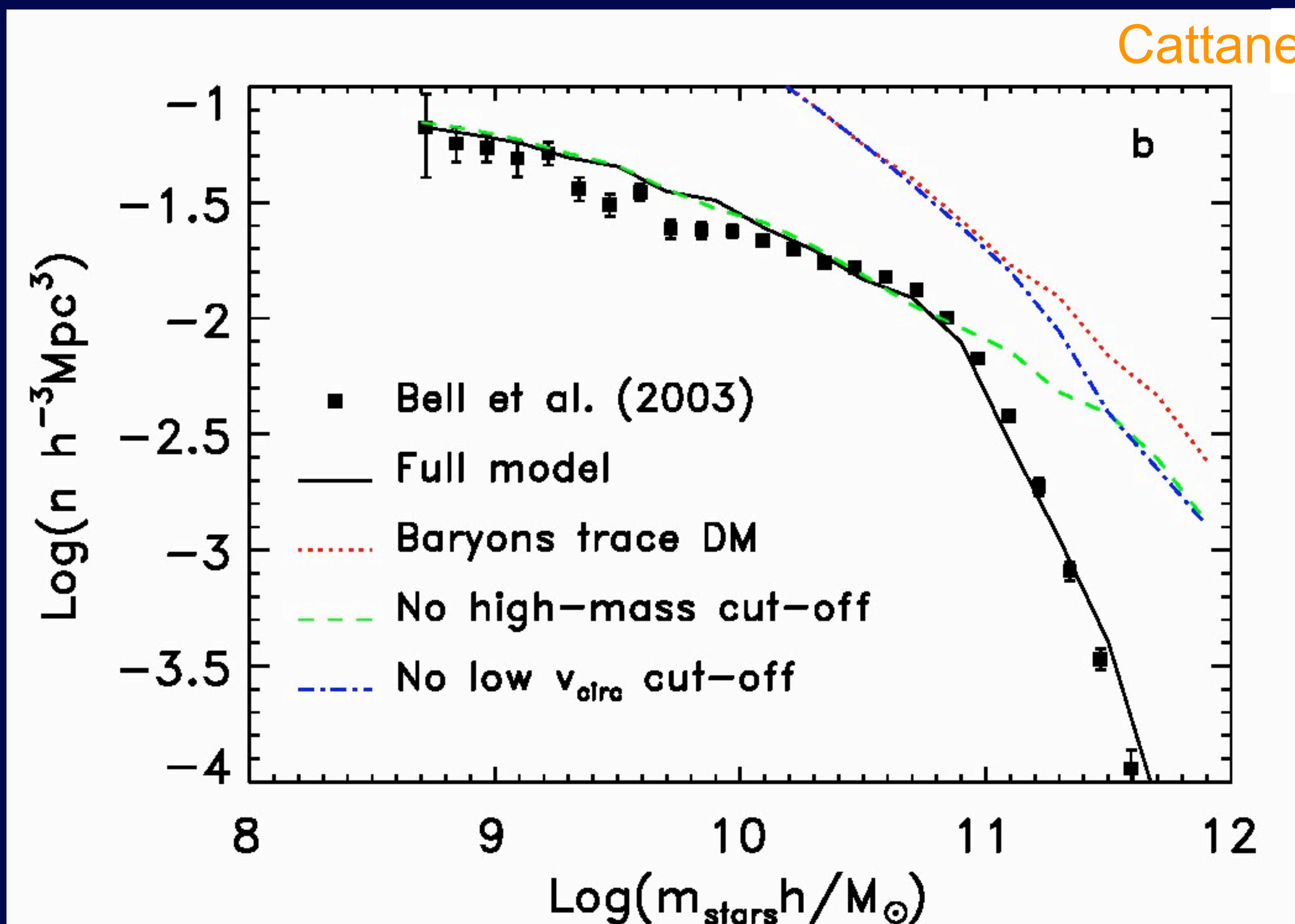
symbols: SFR vs z

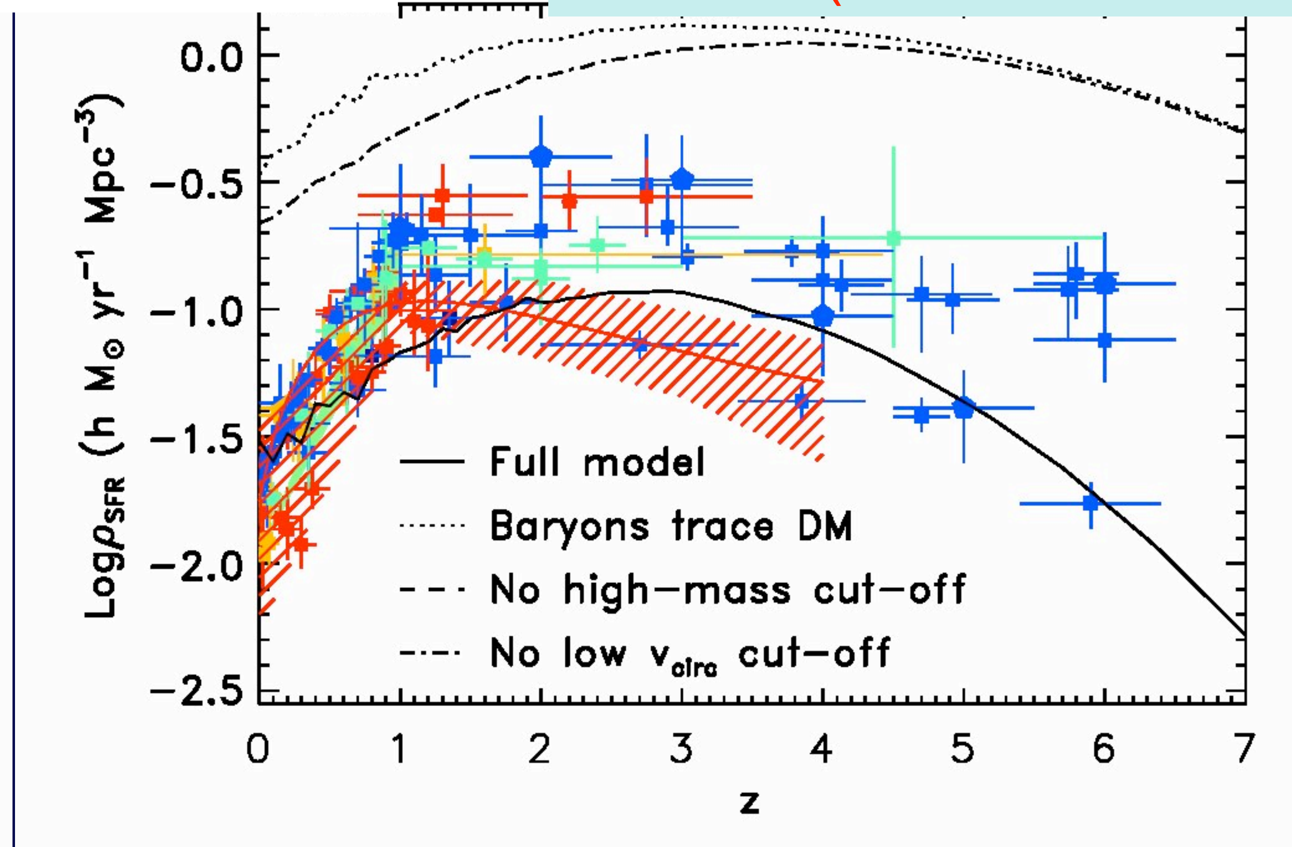
curves: $$\frac{d}{dt}\int_{m_{\min}}^{\infty} n(m,z)\,dm$$

black=toy model

red=obs (Wilkins et al. 08)

Cattaneo, GM et al. 10





Mass distribution:
parameters fit to
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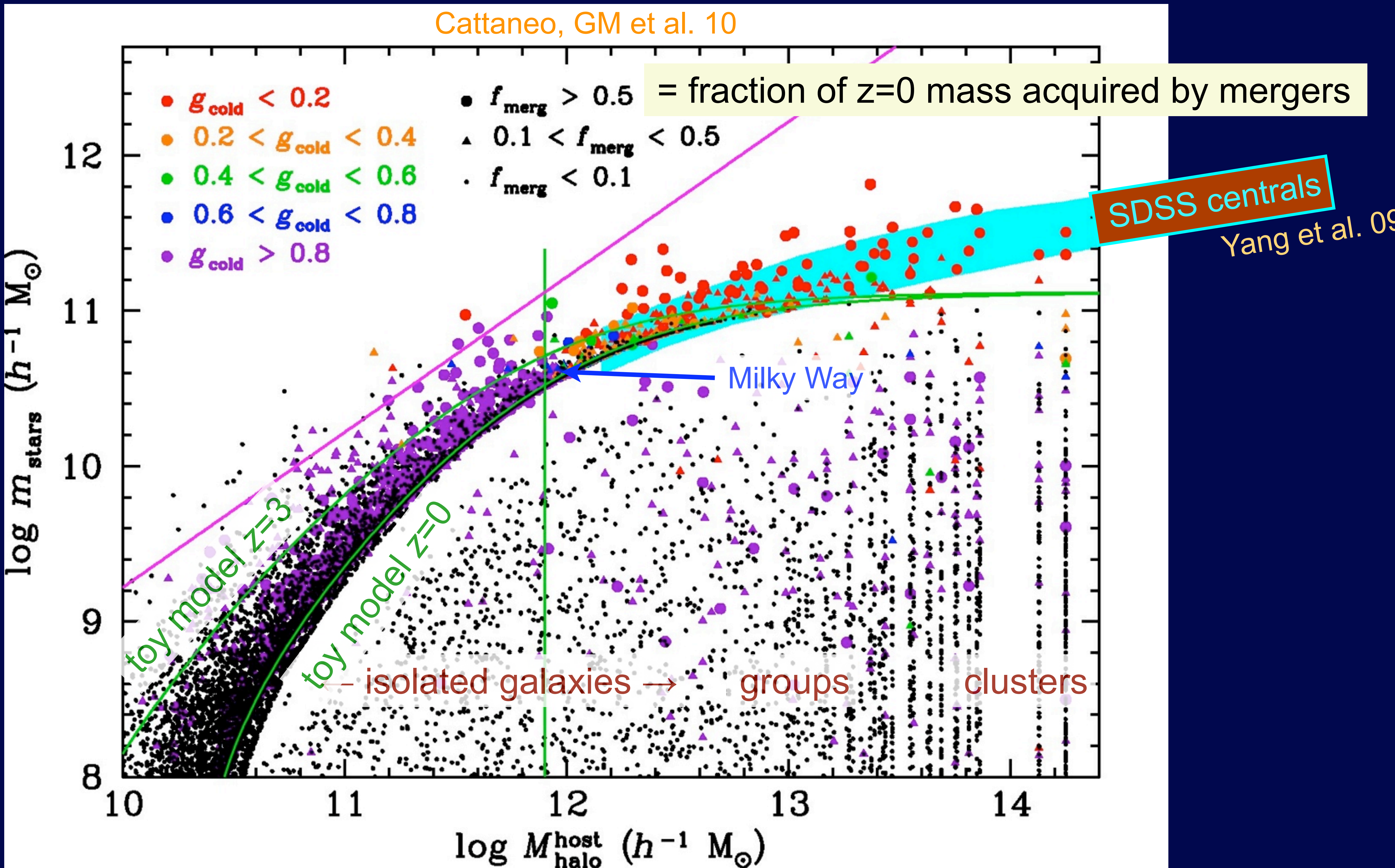
Evolution of cosmic Star Formation Rate:
fair agreement with Wilkins et al. 08

Present-day Galaxy mass vs. Halo (environment) mass



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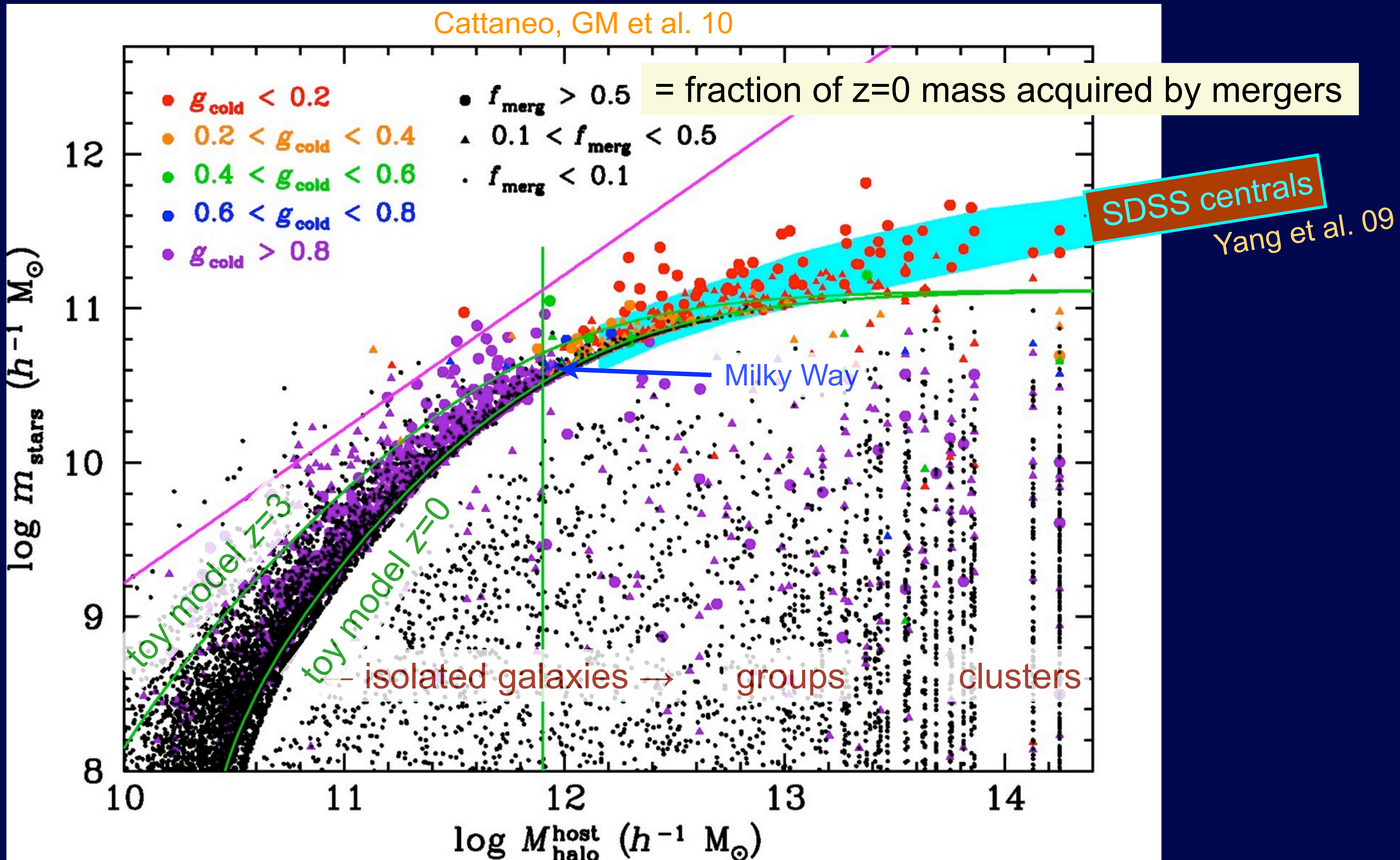
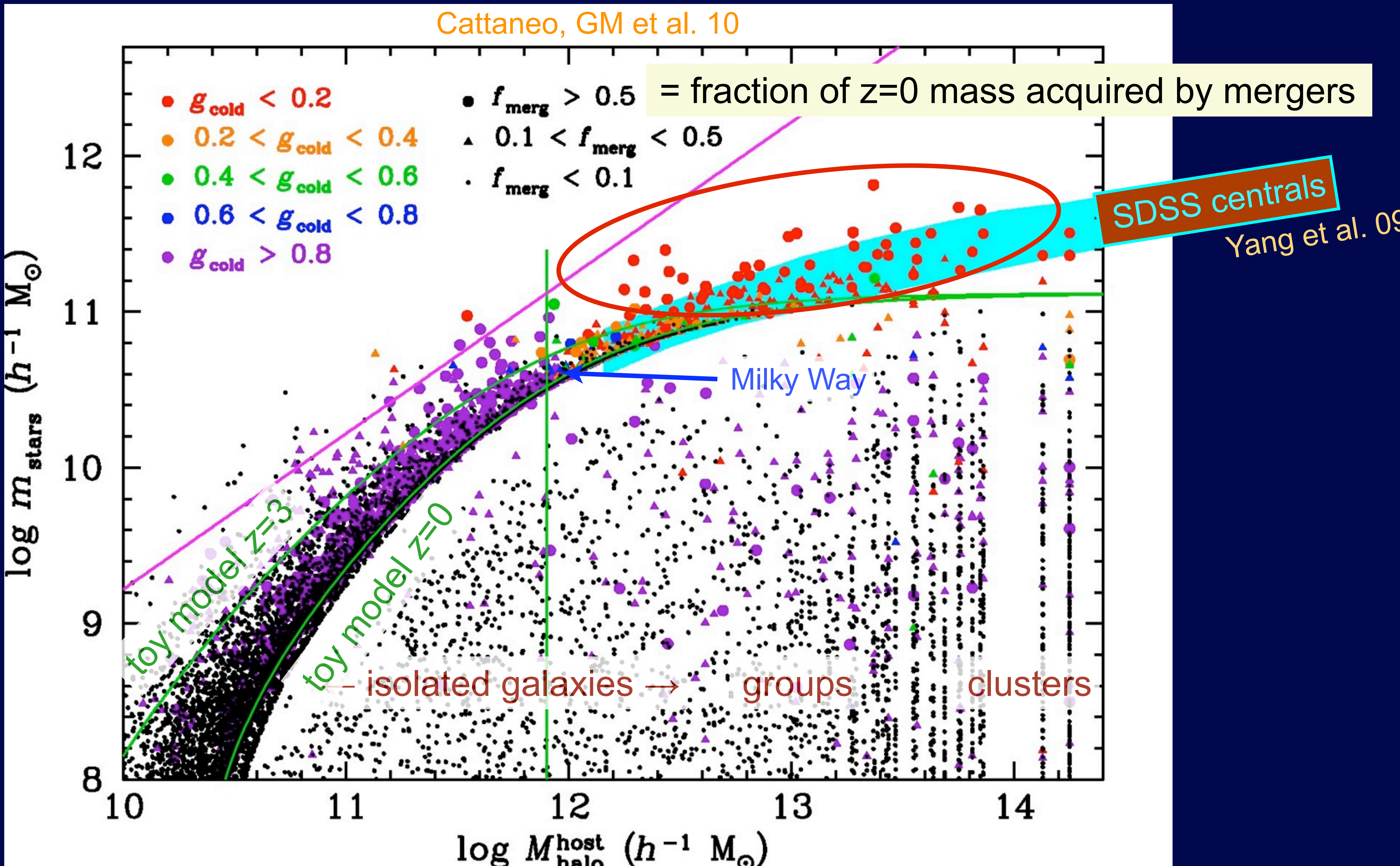


galaxy mass function =f(halo mass) & presents gap between centrals & satellites

Present-day Galaxy mass vs. Halo (environment) mass



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only massive galaxies acquire the bulk of their mass by mergers...

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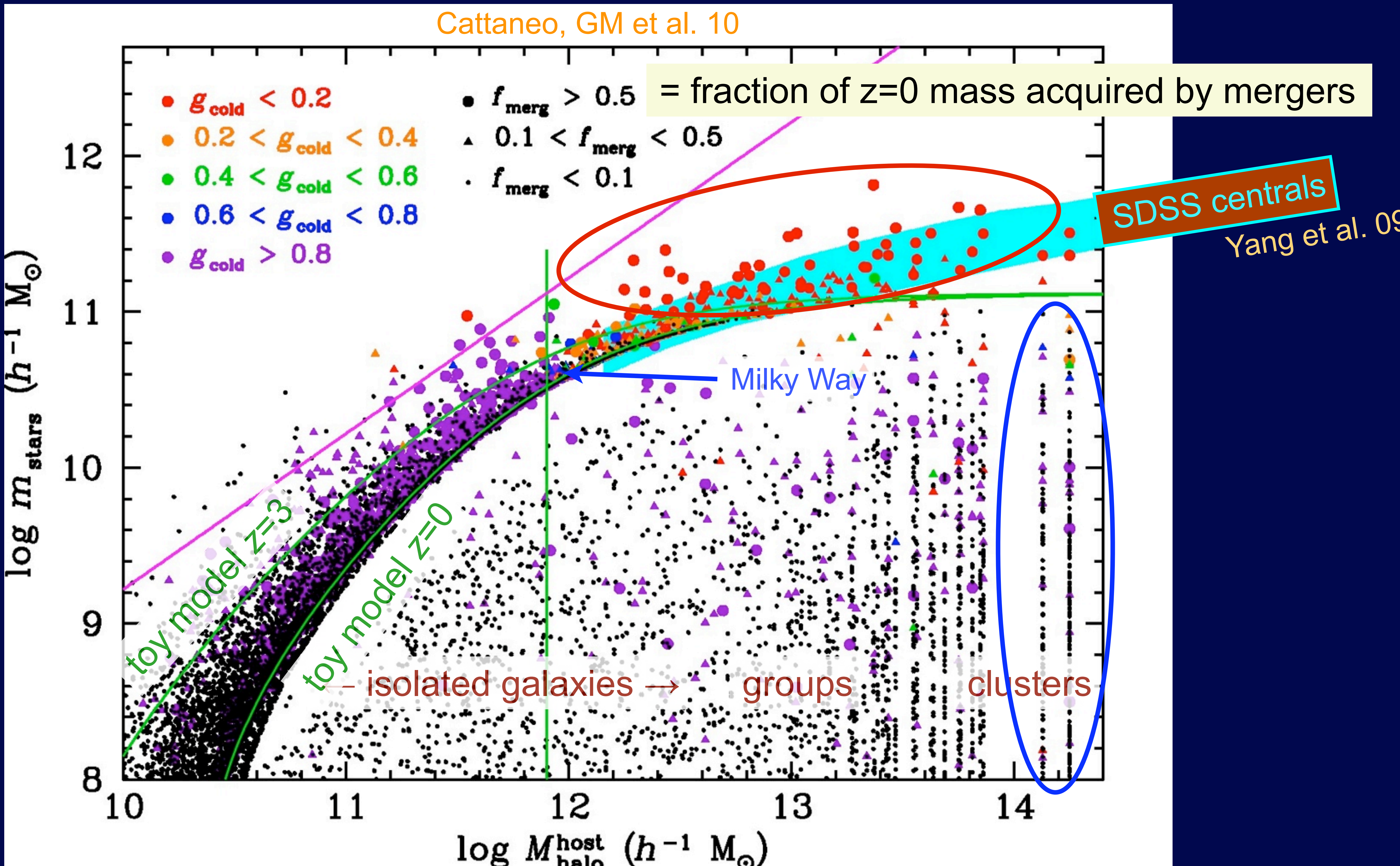
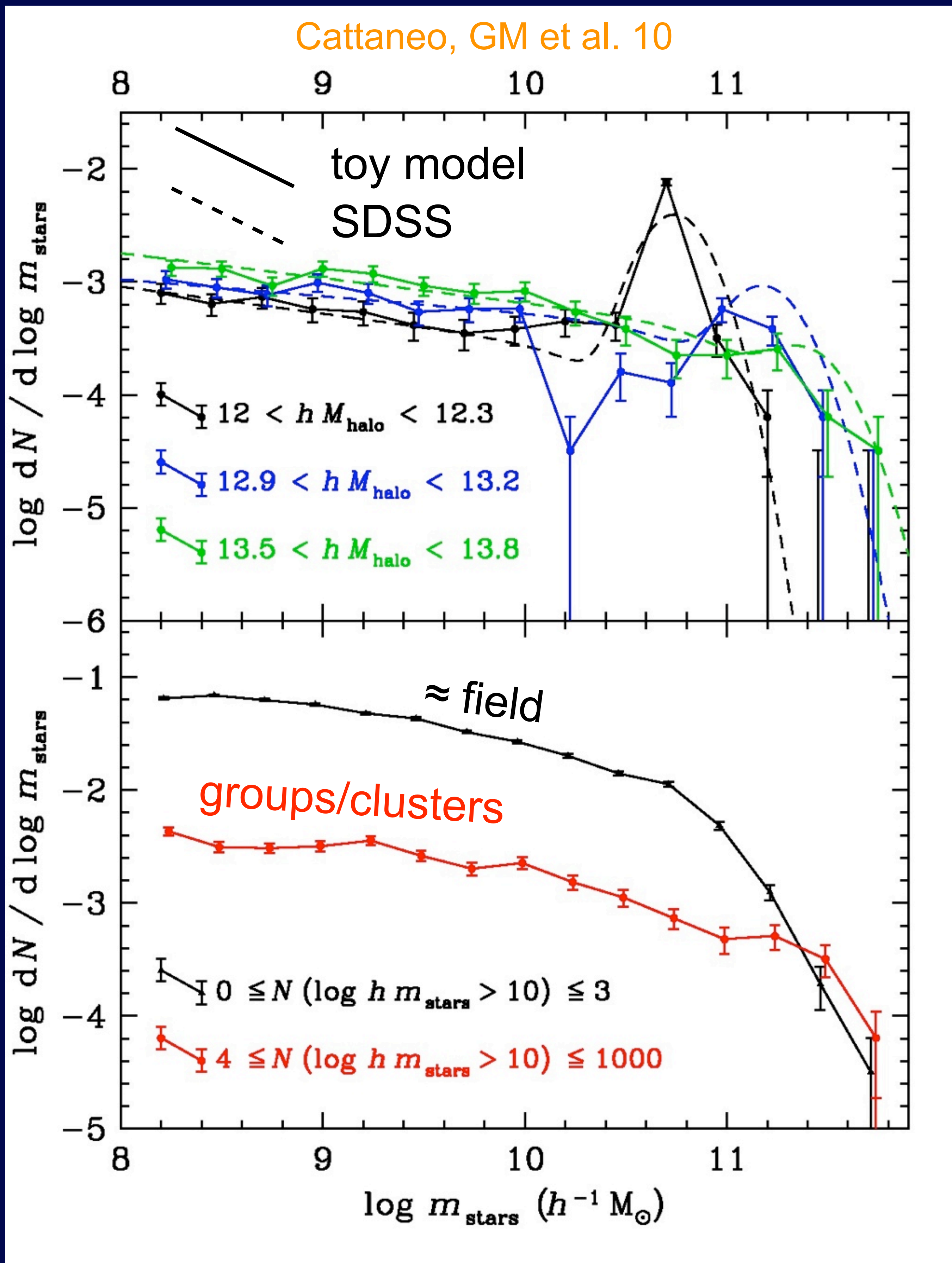


galaxy mass function =f(halo mass) & presents gap between centrals & satellites

only massive galaxies acquire the bulk of their mass by mergers...

... not cluster satellites! ⇒dEs usually not built by mergers!

Conditional galaxy mass functions



in narrow bins of $M_{\rm halo}$:

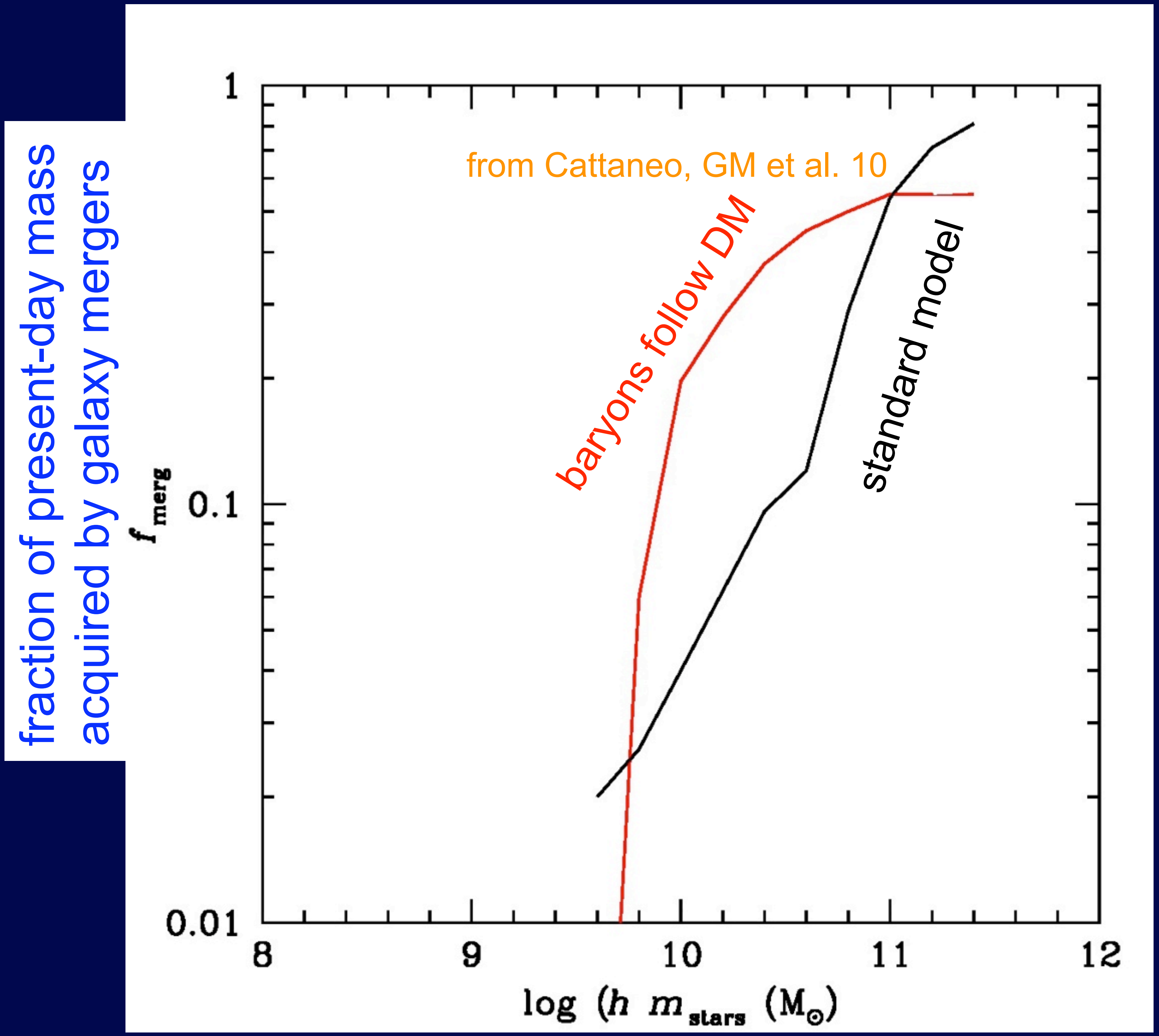
reproduces observed SDSS

Yang, Mo & van den Bosch 09

bump for centrals

amplitude & position = $f(M_{\rm halo})$

Is lack of mergers at low mass caused by limited mass resolution?



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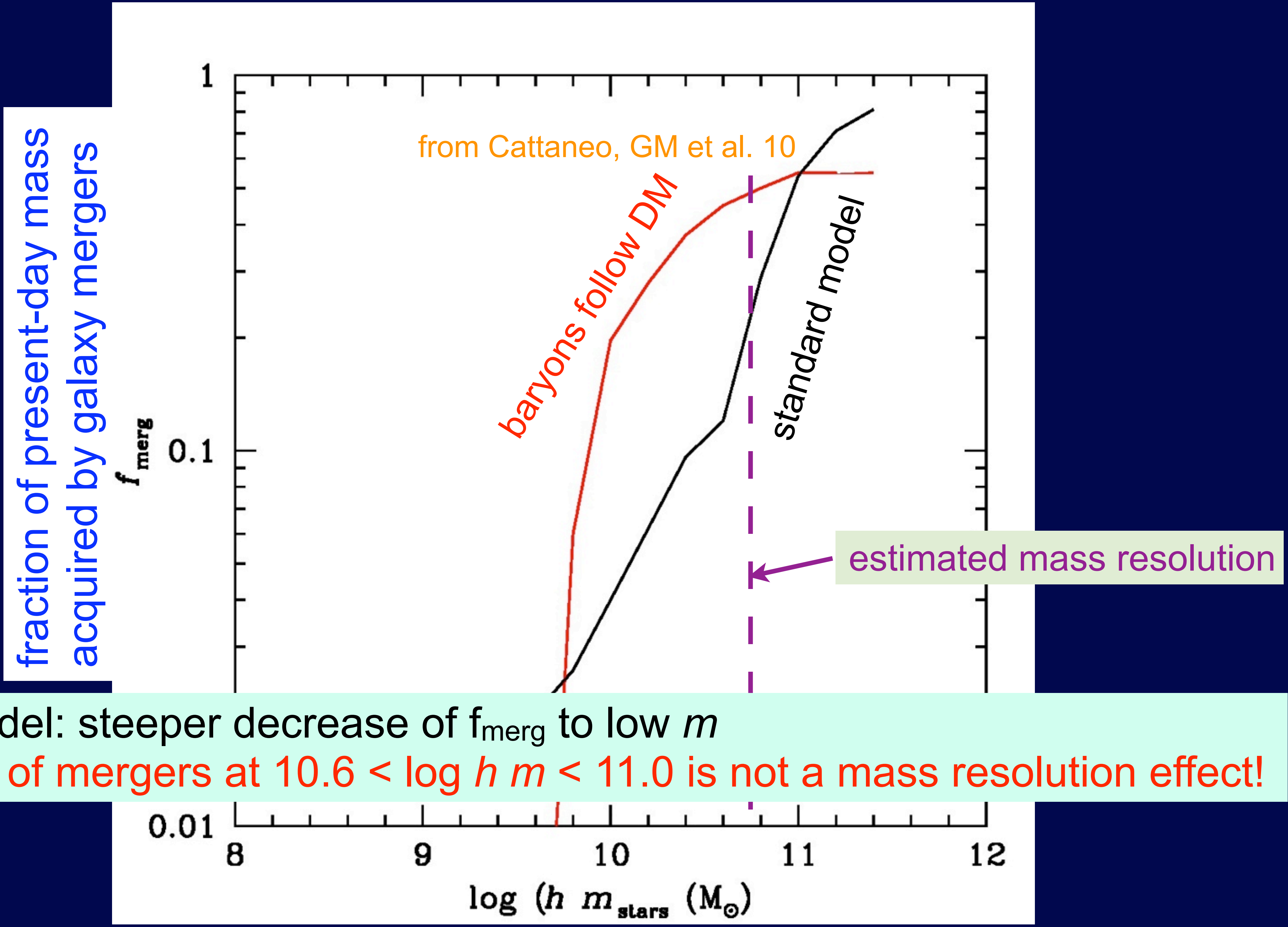
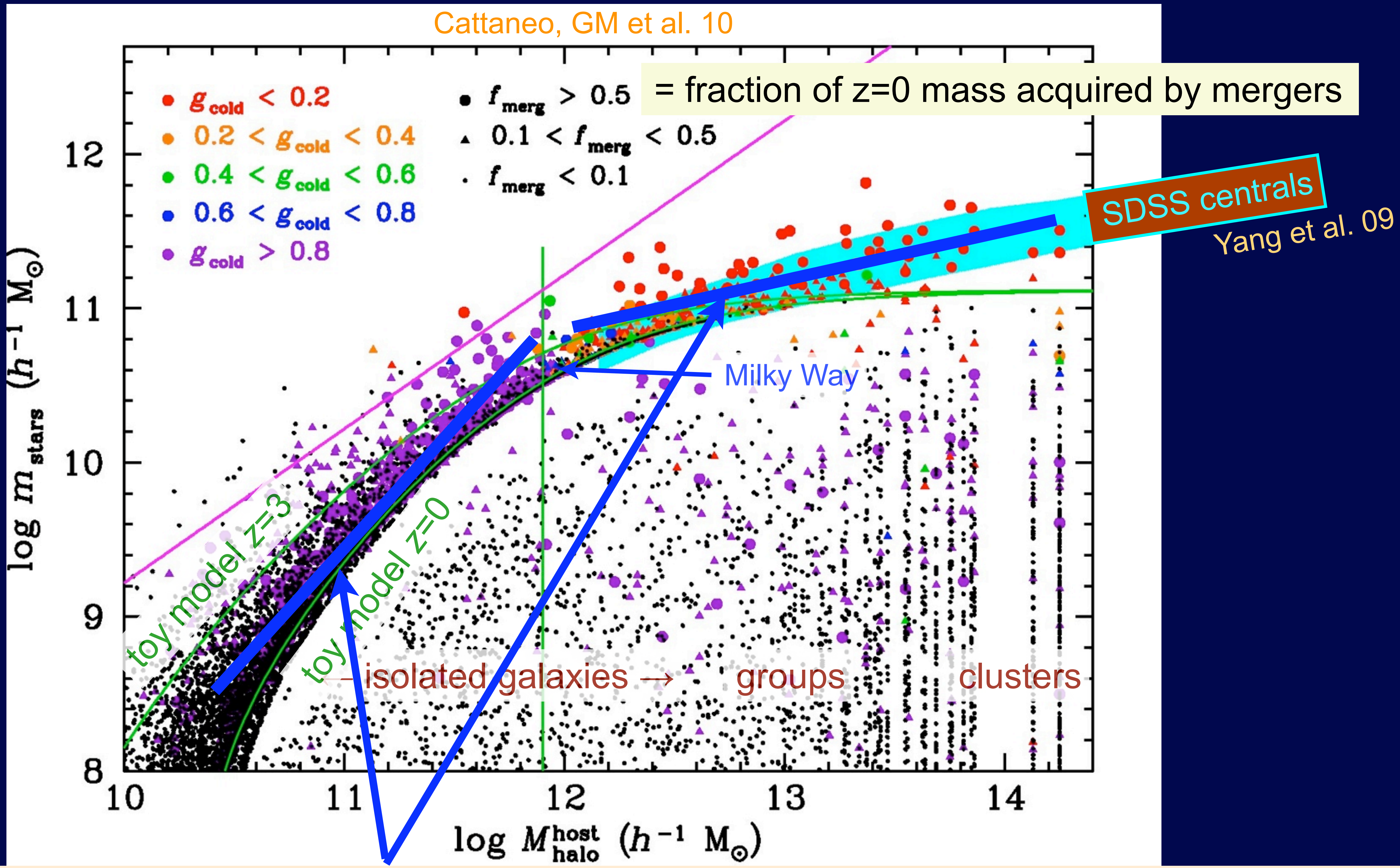


std model: steeper decrease of f_{merg} to low *m*

⇒ lack of mergers at 10.6 < log *h m* < 11.0 is not a mass resolution effect!

Why mergers are unimportant ay low mass?



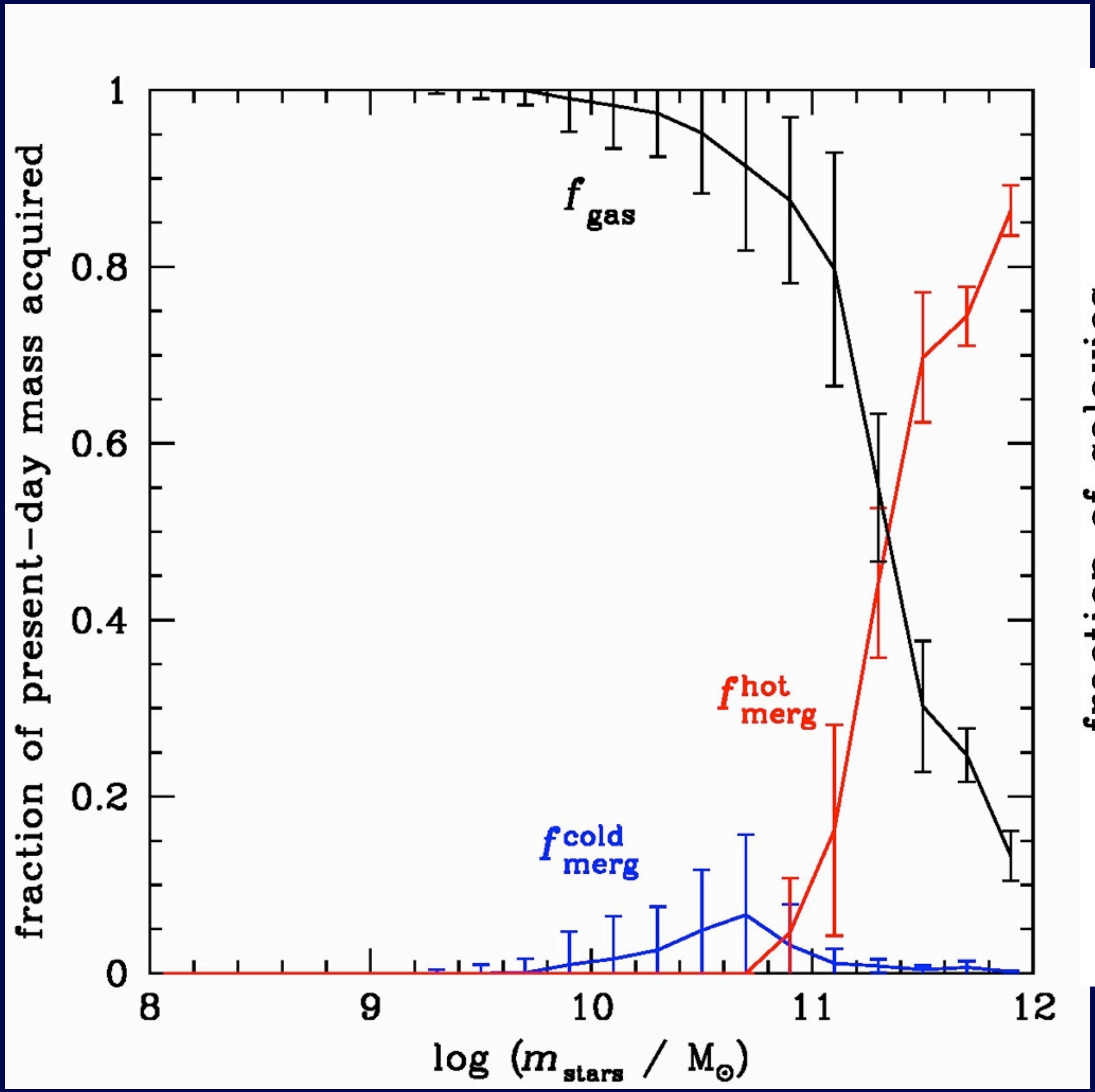
decreasing slope of m_{stars} vs M_{halo}

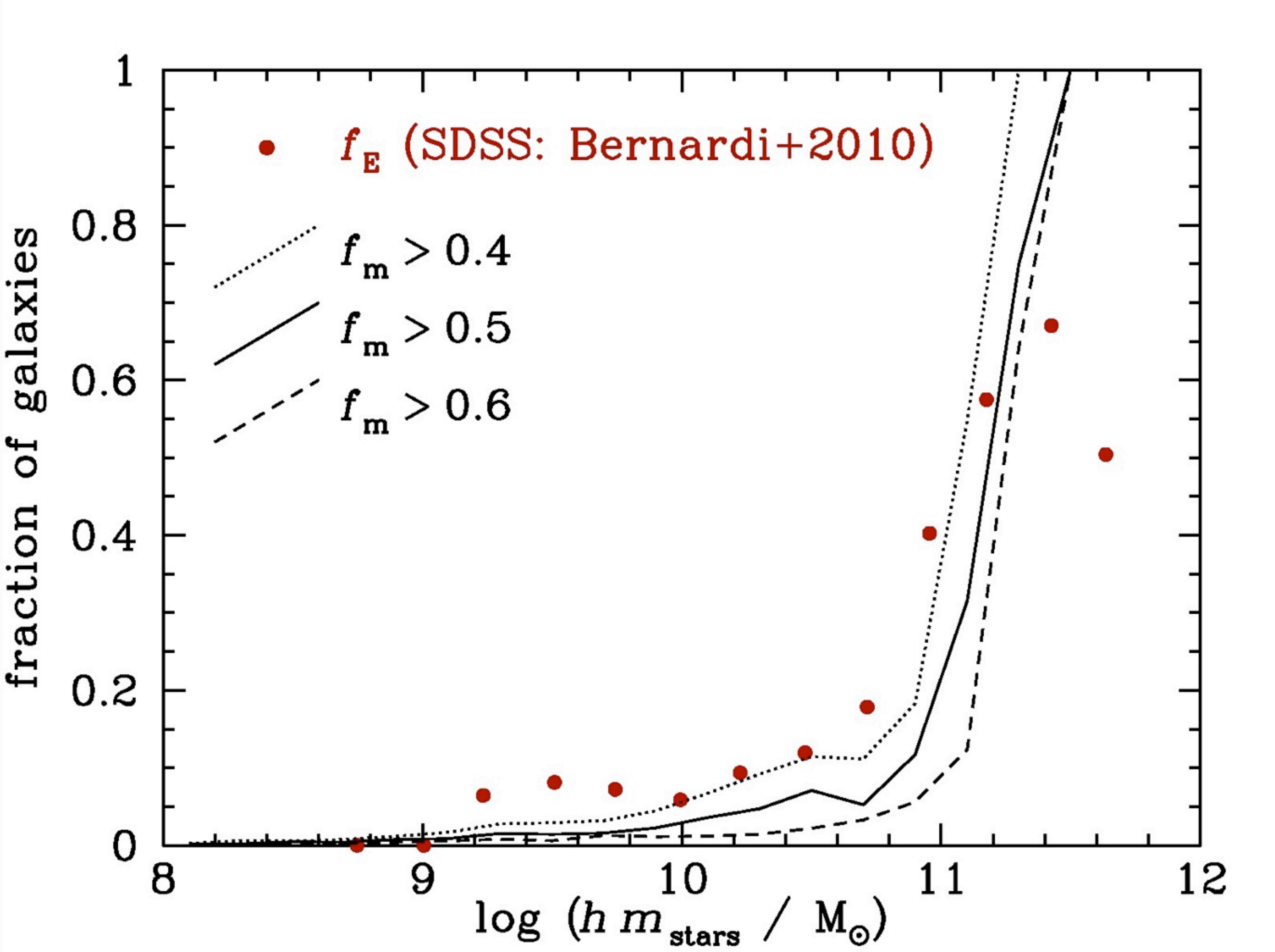
⇒ (low mass) centrals in low mass halos acquire relatively lower mass satellites

⇒ slower orbital decay by dynamical friction

⇒ mergers less important at low mass

Role of galaxy mergers



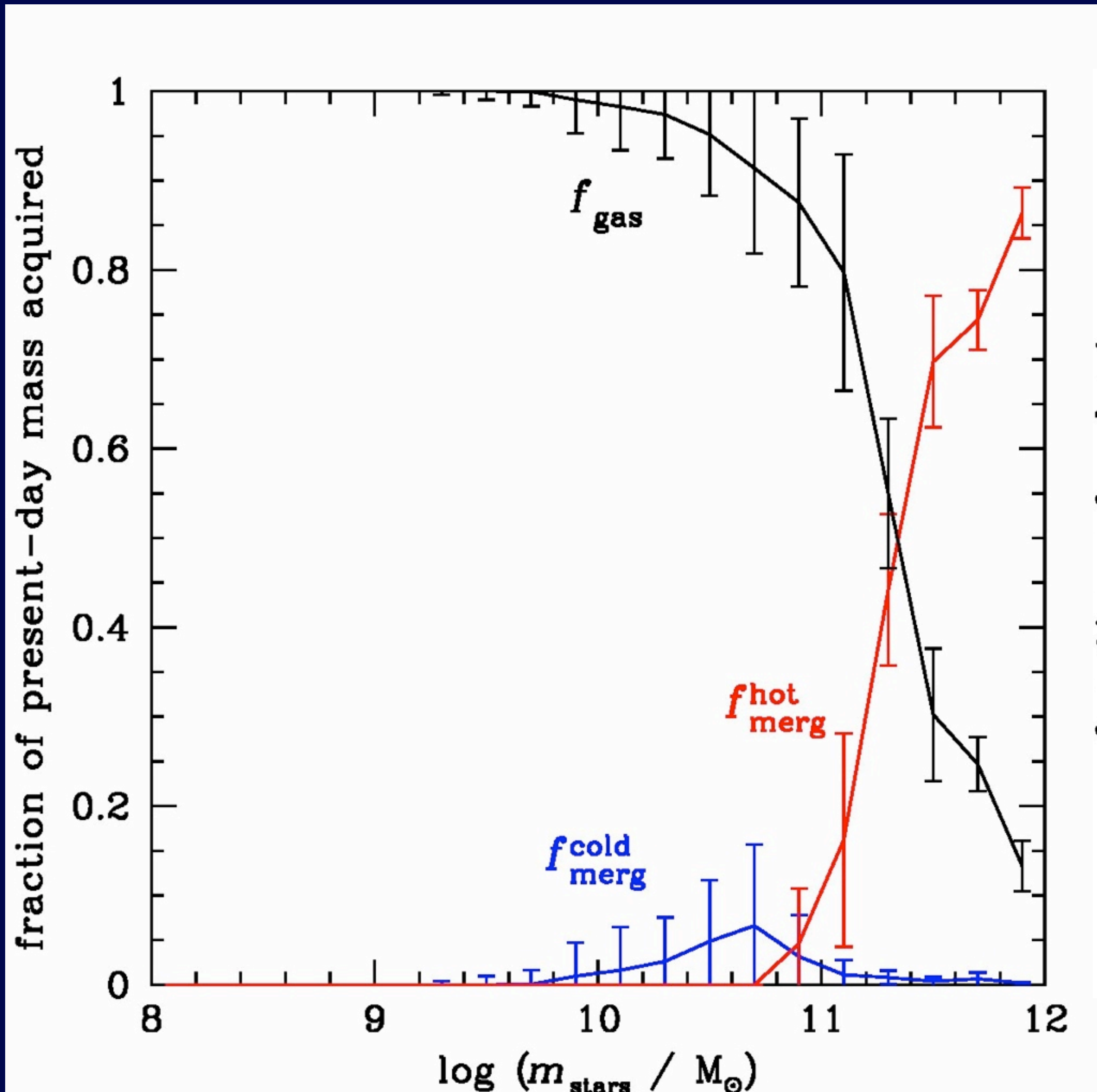


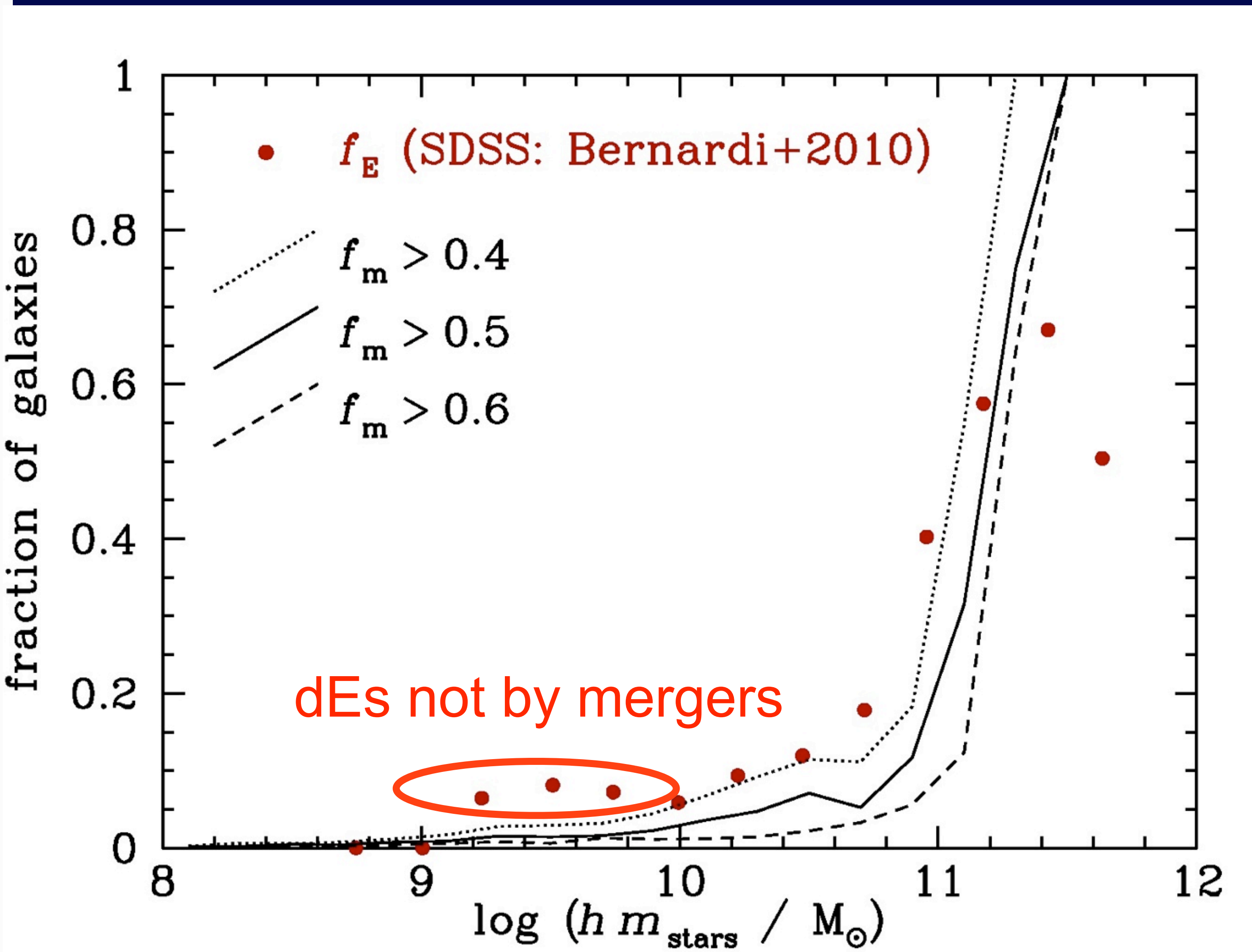
also De Lucia+06; Bernardi+10ab

small global role for wet (cold-mode) mergers!

important role for wet (cold-mode) mergers
making intermediate-mass ellipticals

Role of galaxy mergers





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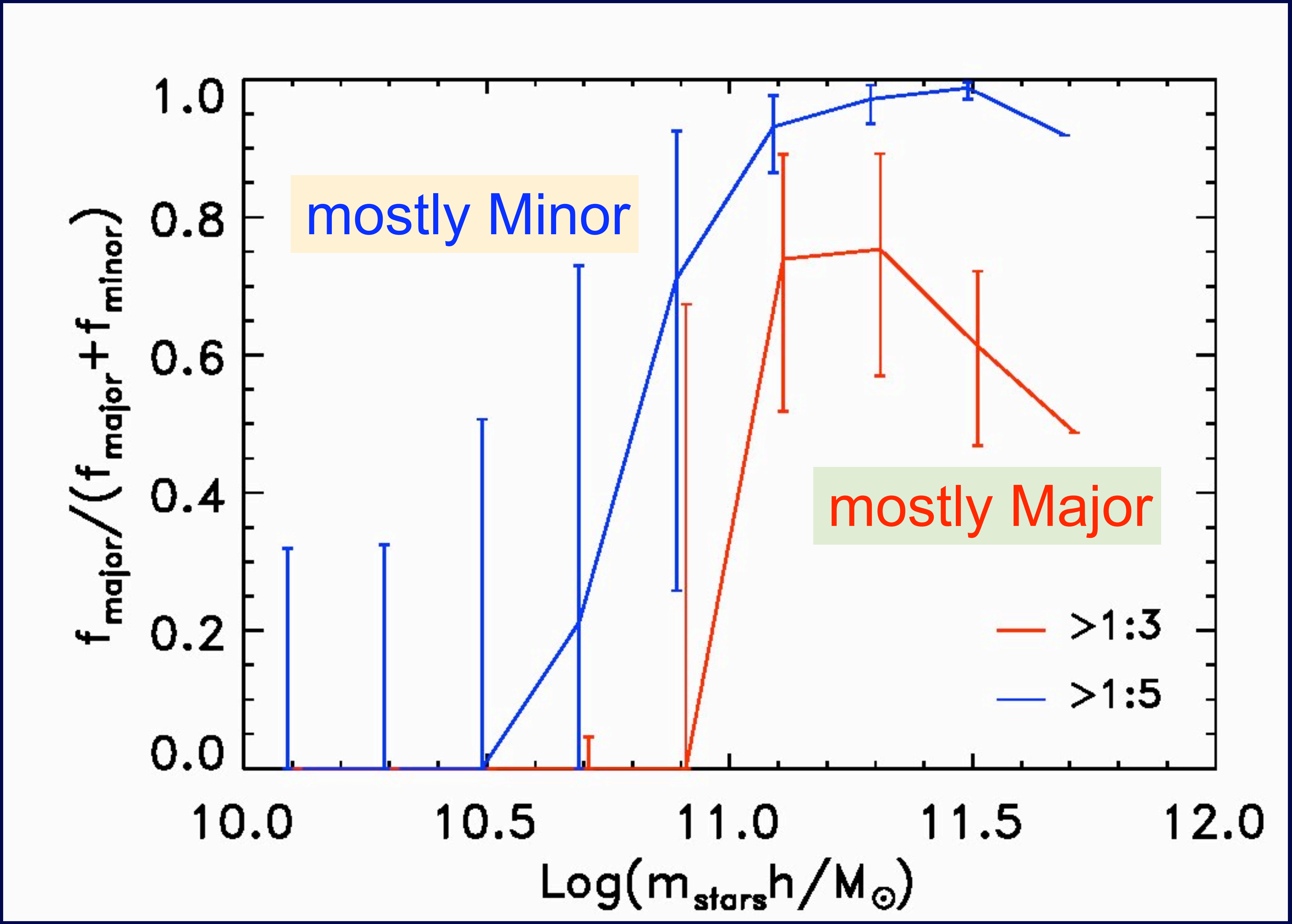
Major vs. Minor Mergers



Caveats & criticisms

Absence of gas accretion is built into Toy Model

Interacting galaxies and ULIRGs are frequent at $z \geq 0.7$

Greif et al. 08; Dekel et al. 09

Accreted gas contains clumps (subhalos) ⇒ mergers!

Chilingarian 09

Some Dwarf Ellipticals have Kinematically Decoupled Cores

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but these high z galaxies would be massive today

Chilingarian 09

Some Dwarf Ellipticals have Kinematically Decoupled Cores

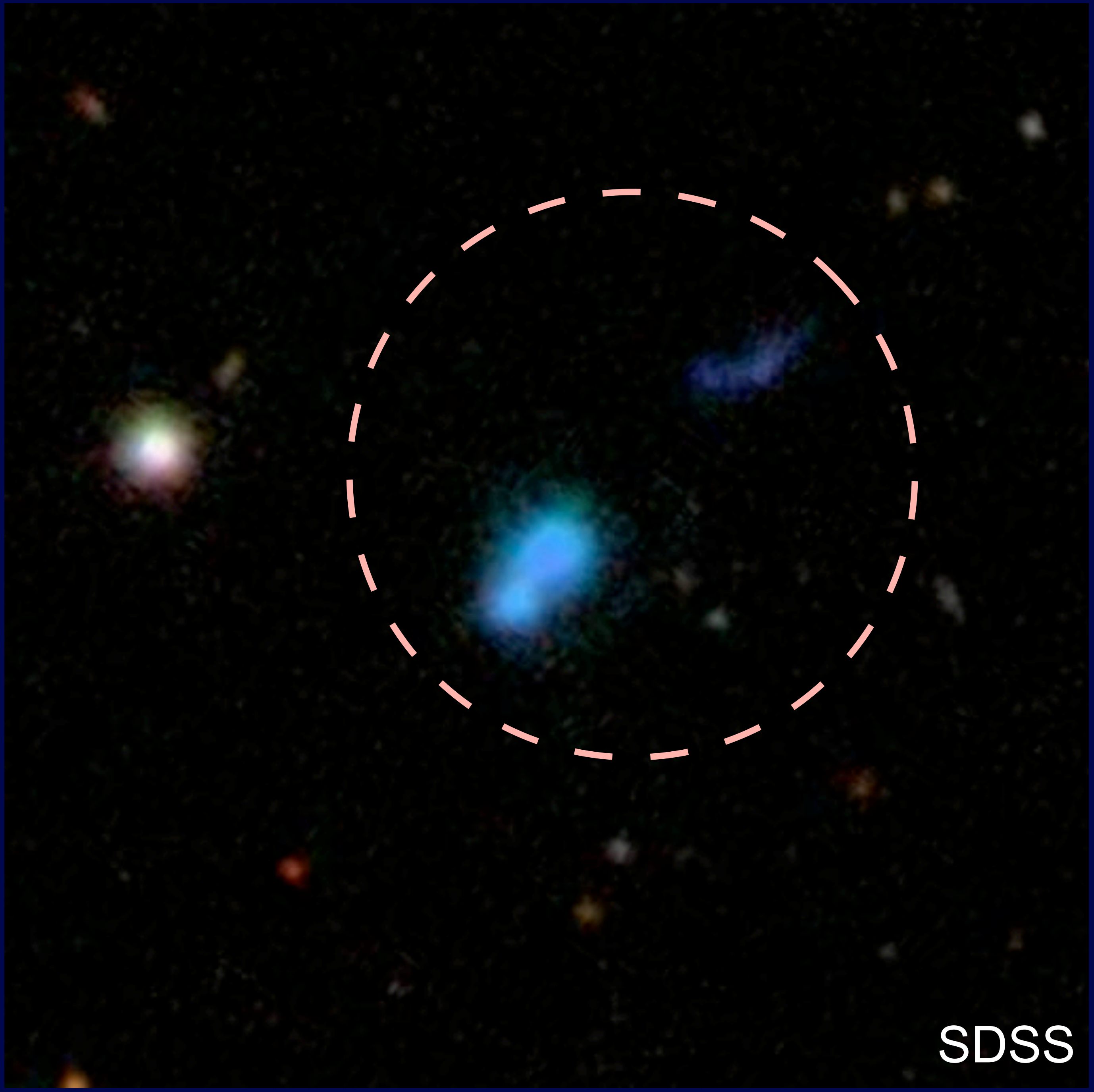
but most do not + presence of KDC $\not\Rightarrow$ bulk of mass by mergers

How frequent are Young Galaxies at z=0?

with

Dylan TWEED
IAS, Orsay

I Zw 18: a very metal-poor galaxy



$Z = Z_{sun}/50!$

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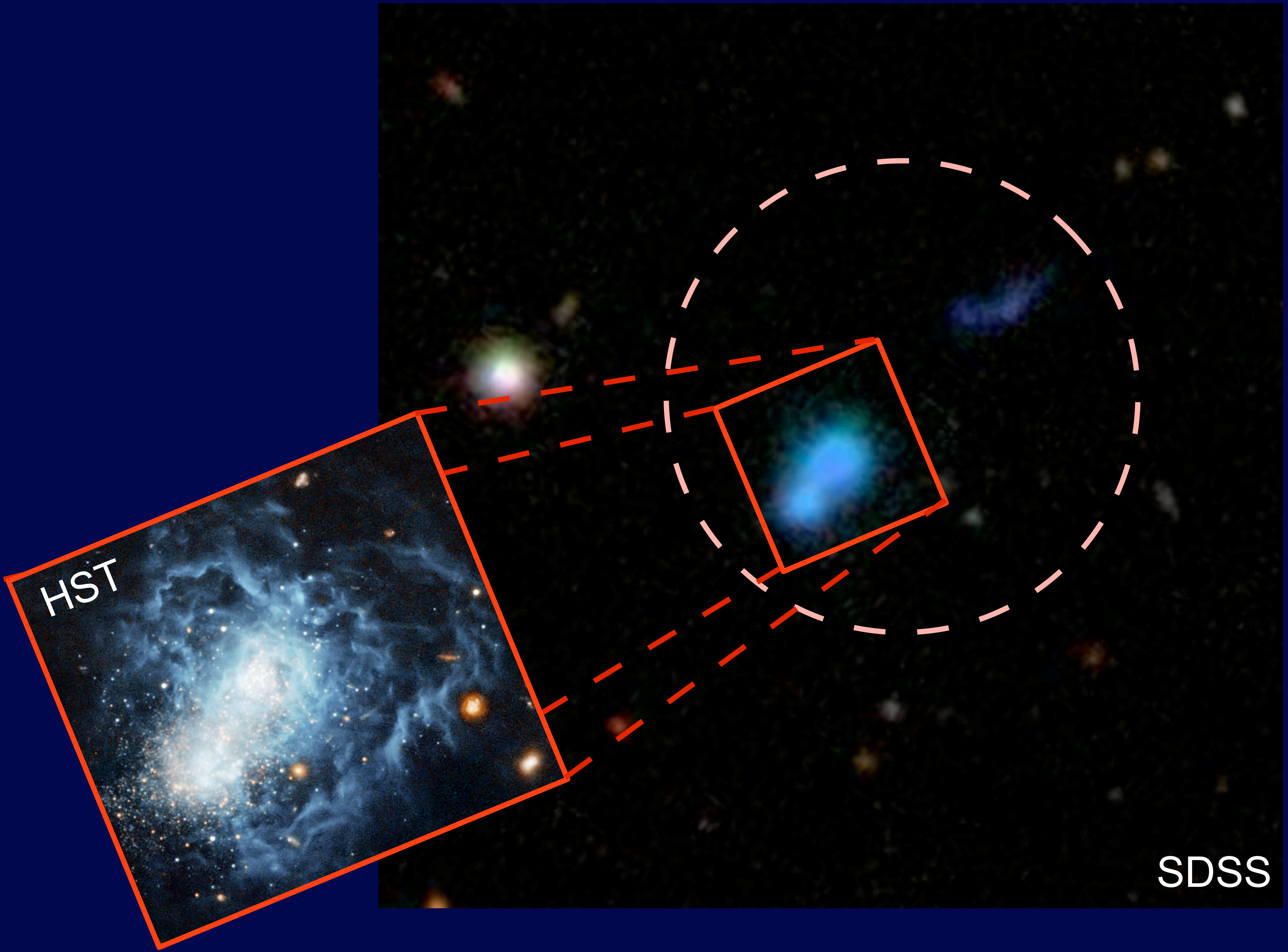

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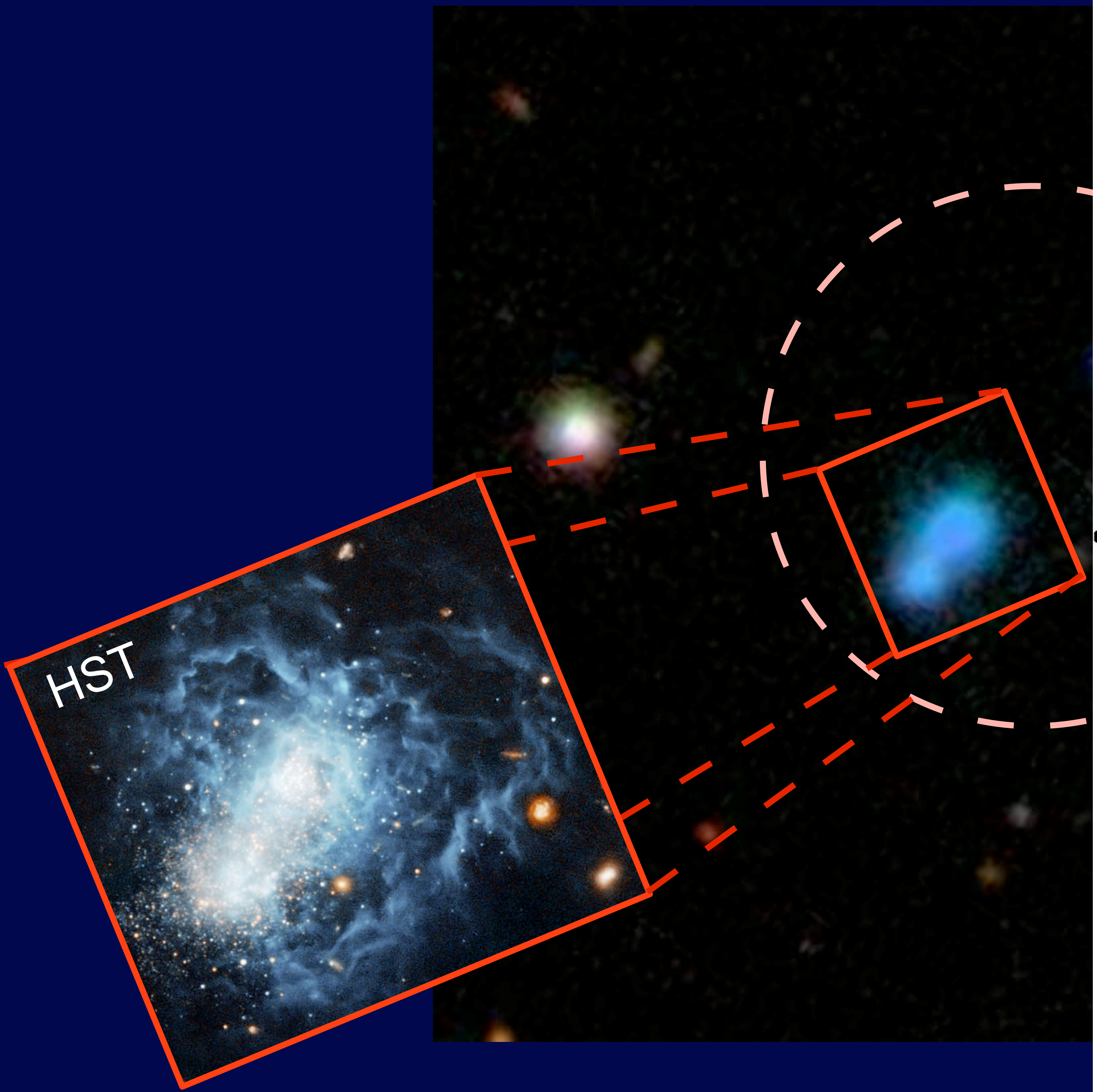

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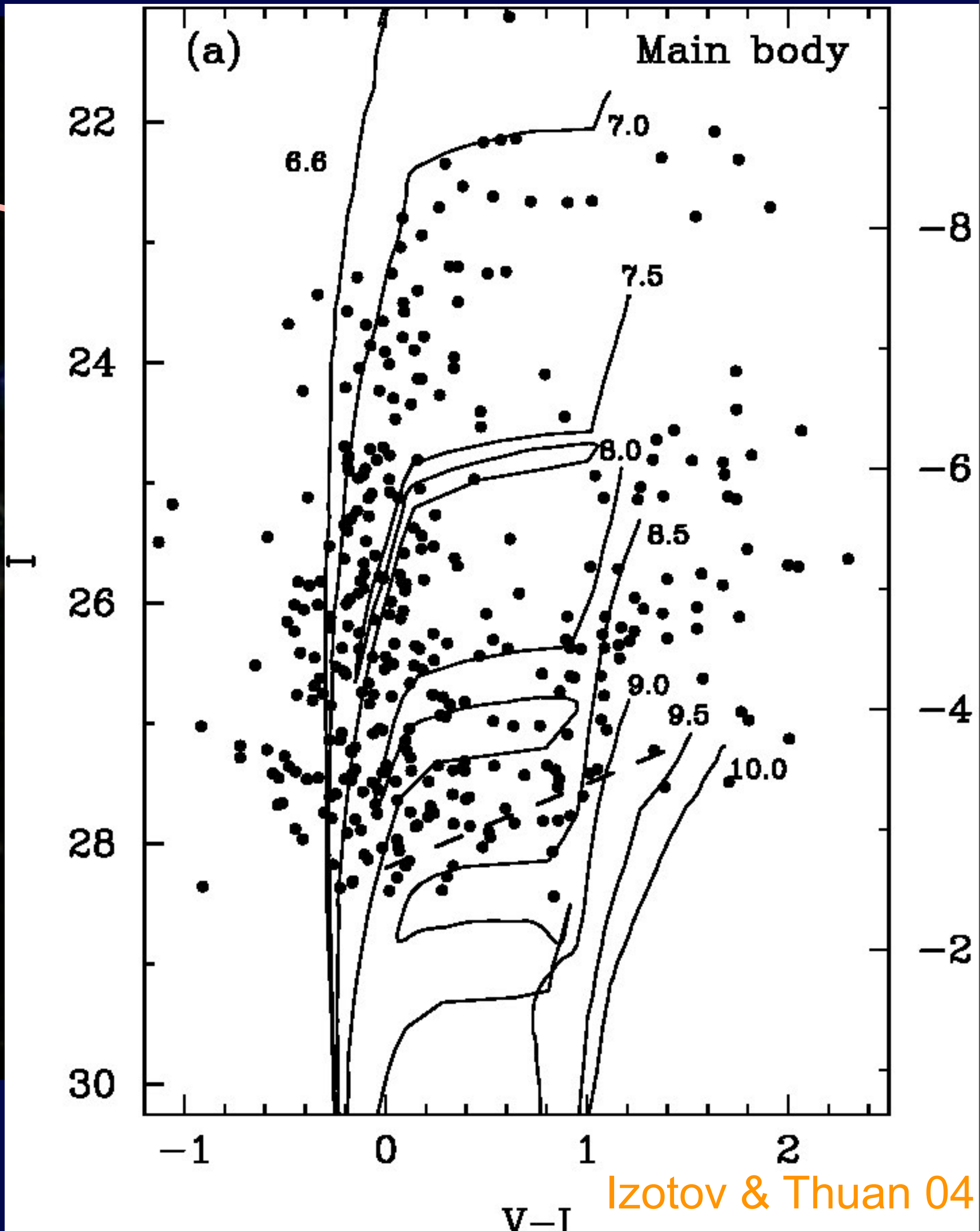

Izotov & Thuan 04

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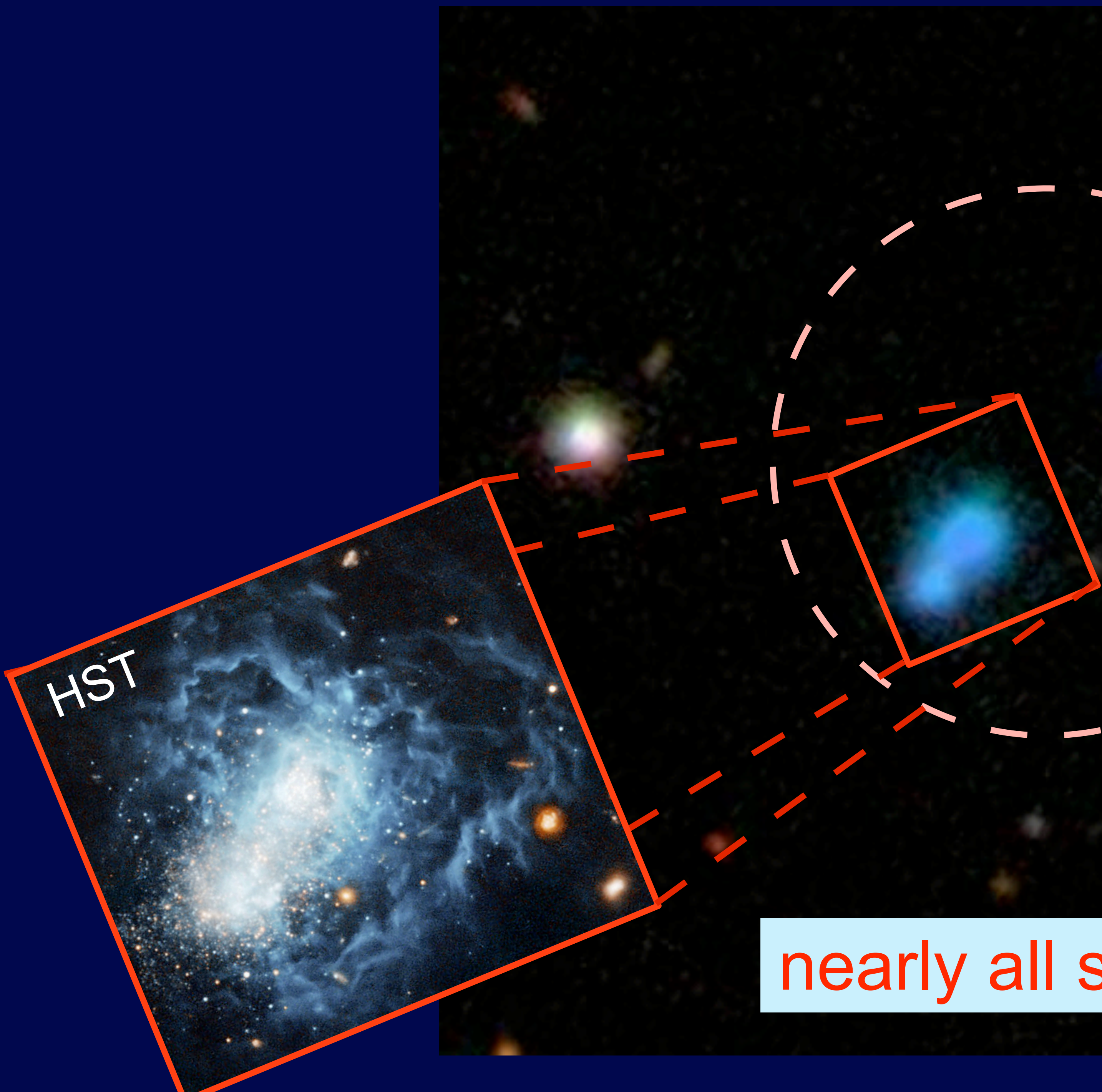
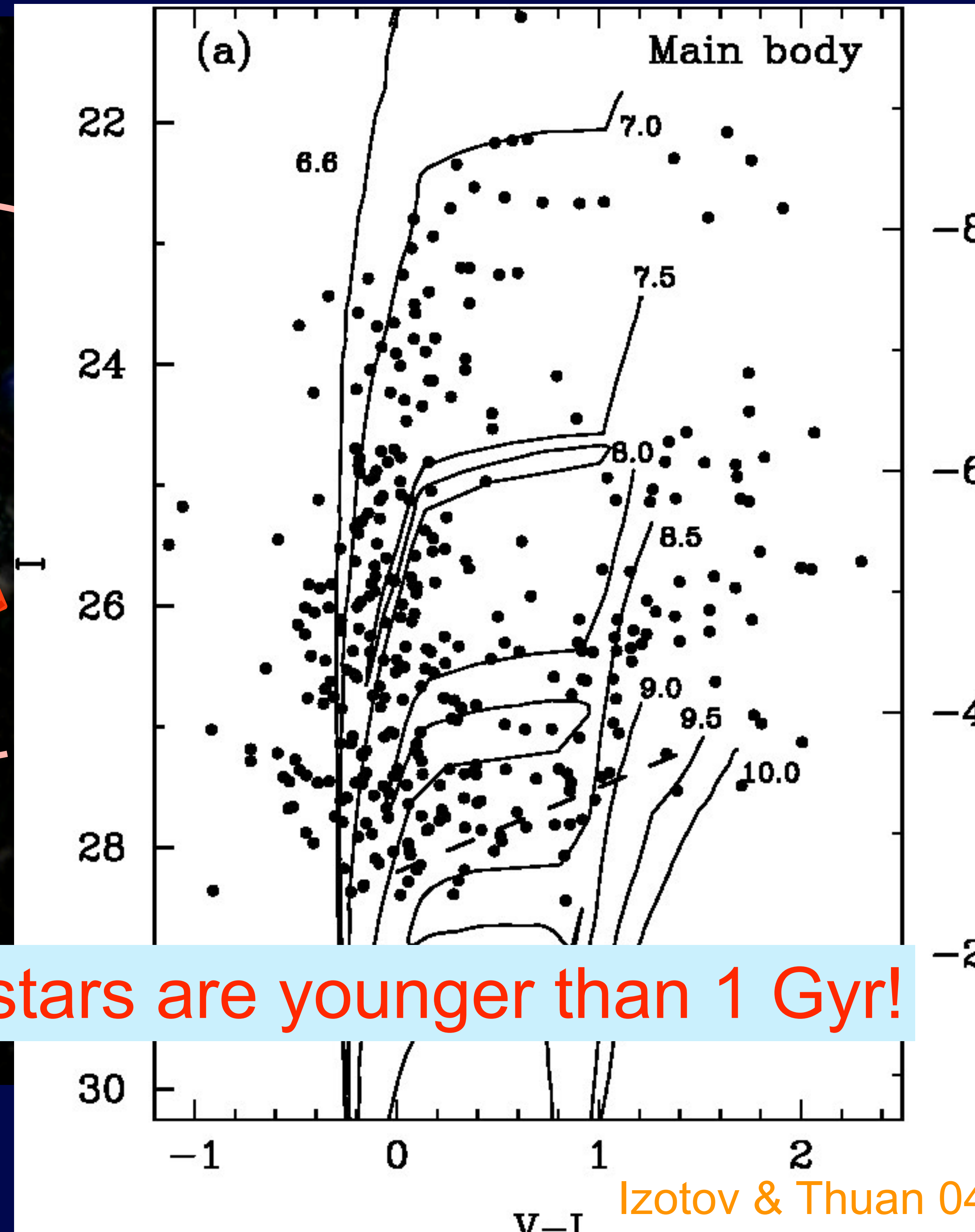


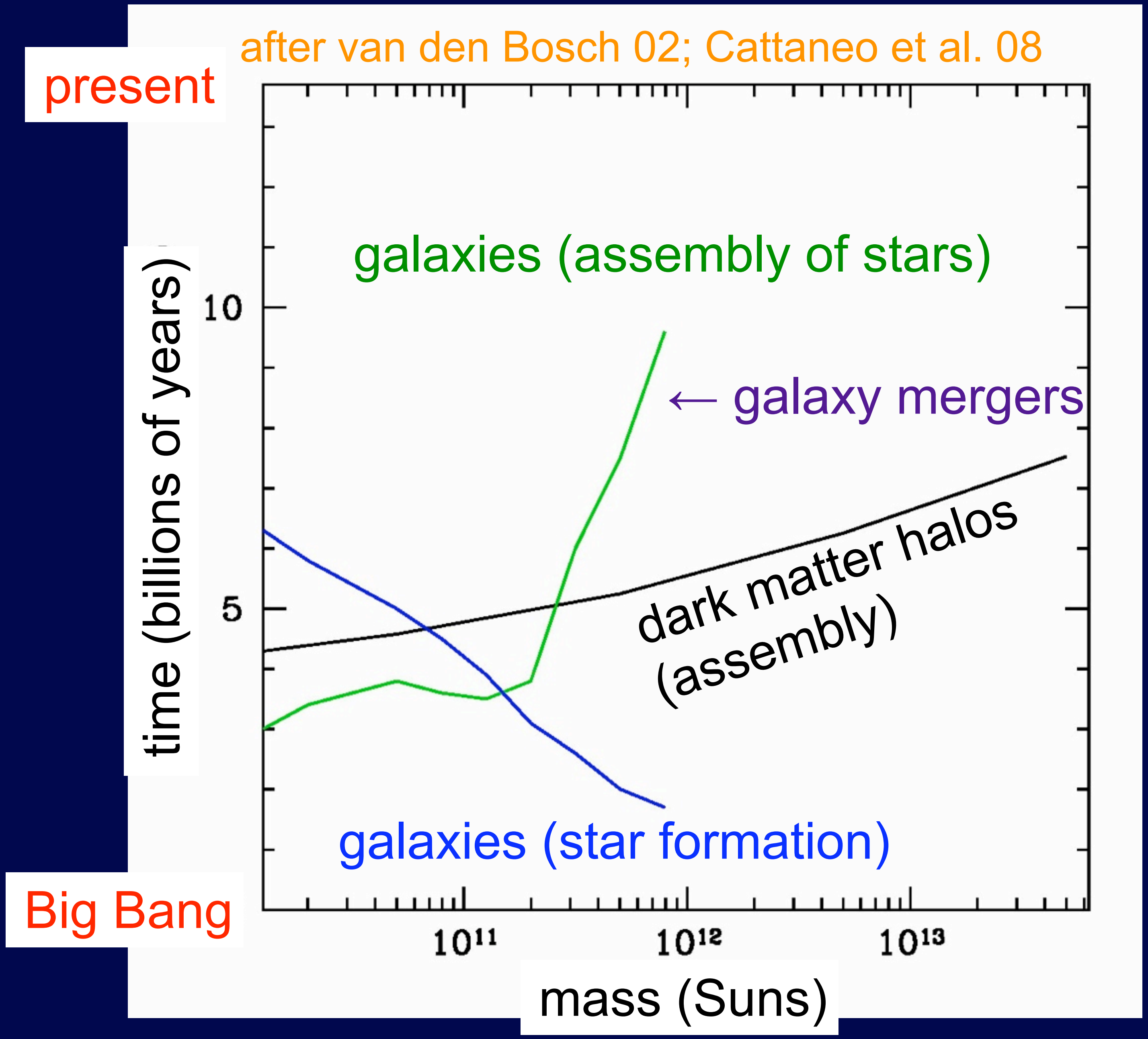


nearly all stars are younger than 1 Gyr!

$Z = Z_{sun}/50$!

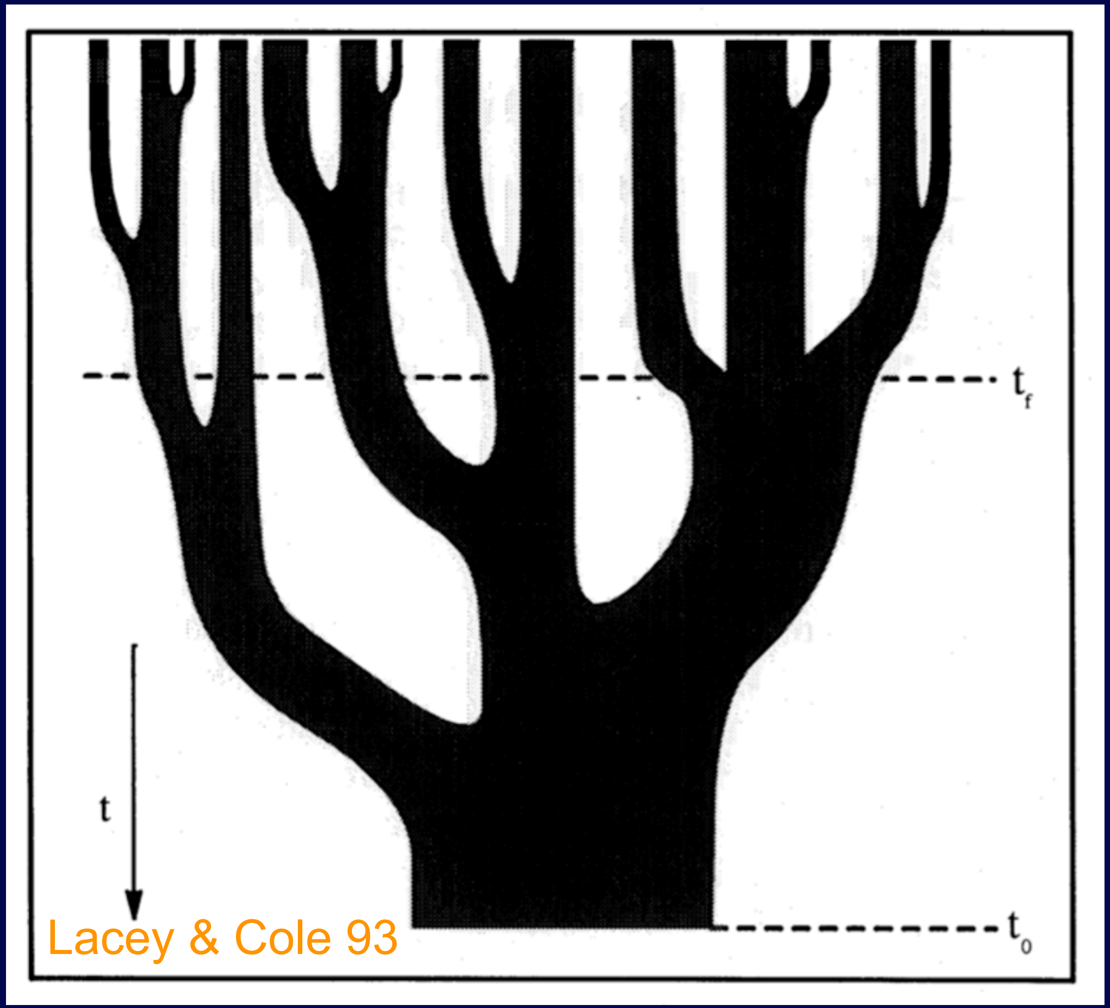
Izotov & Thuan 04

Upsizing of mass
Downsizing of star formation



see also De Lucia et al. 06

Hierarchical evolution of halos

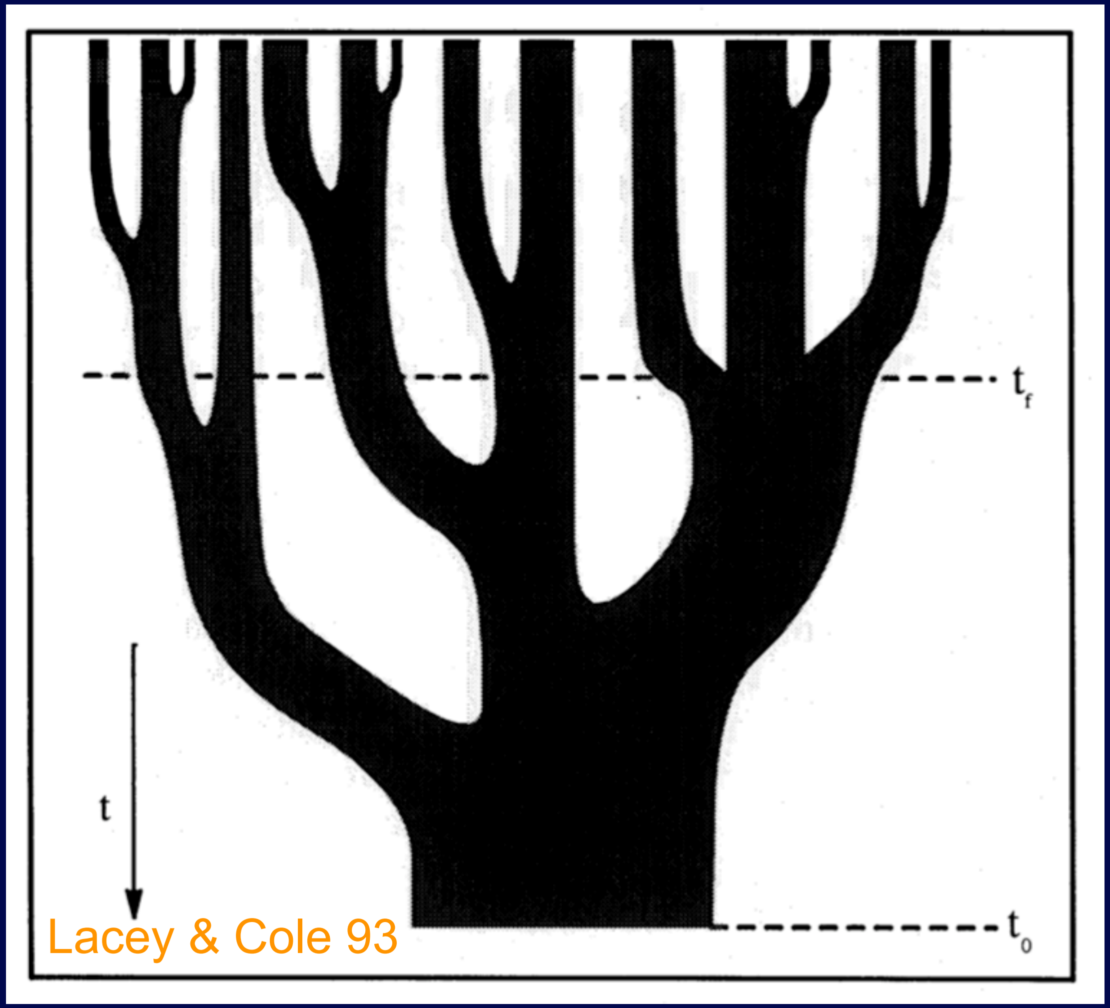


early Universe

present-day

use halo merger tree code by Neistein & Dekel 06

Hierarchical evolution of halos



early Universe

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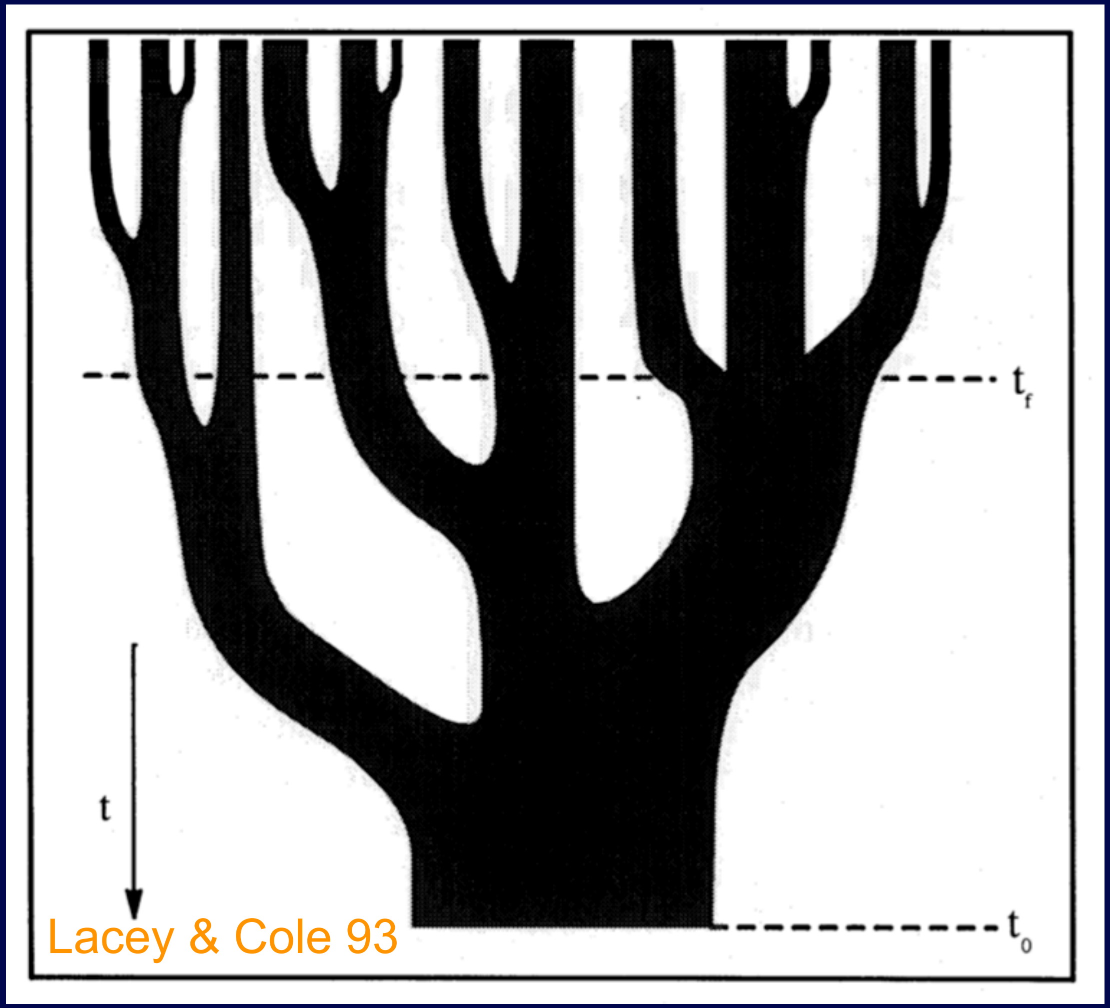
draw 10^4 trees for 24 final halo masses (7 < log M < 12.75 log spaced)
correct to final halo mass function from Millennium simulation

Hierarchical evolution of halos



early Universe

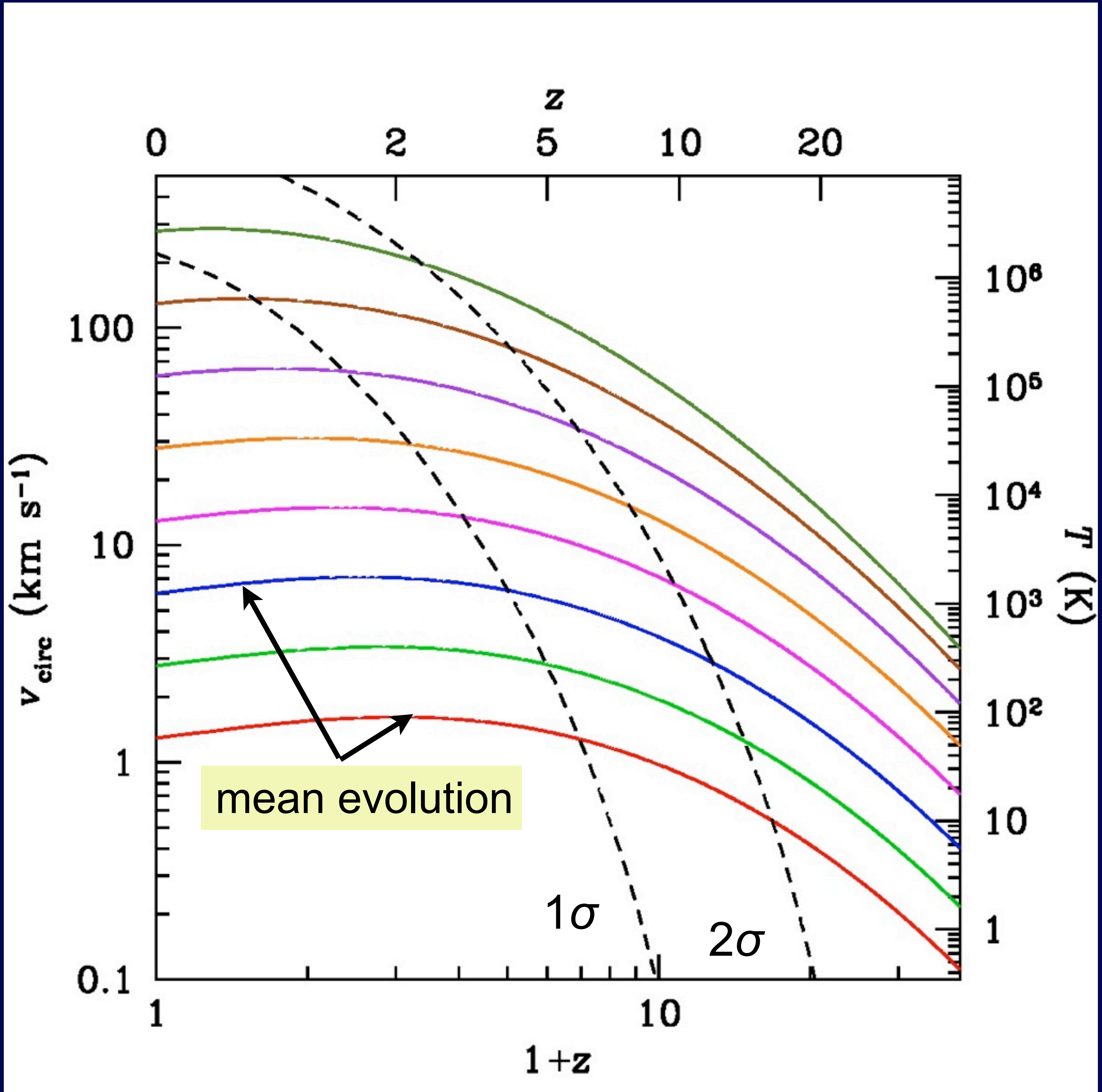
present-day

use halo merger tree code by Neistein & Dekel 06

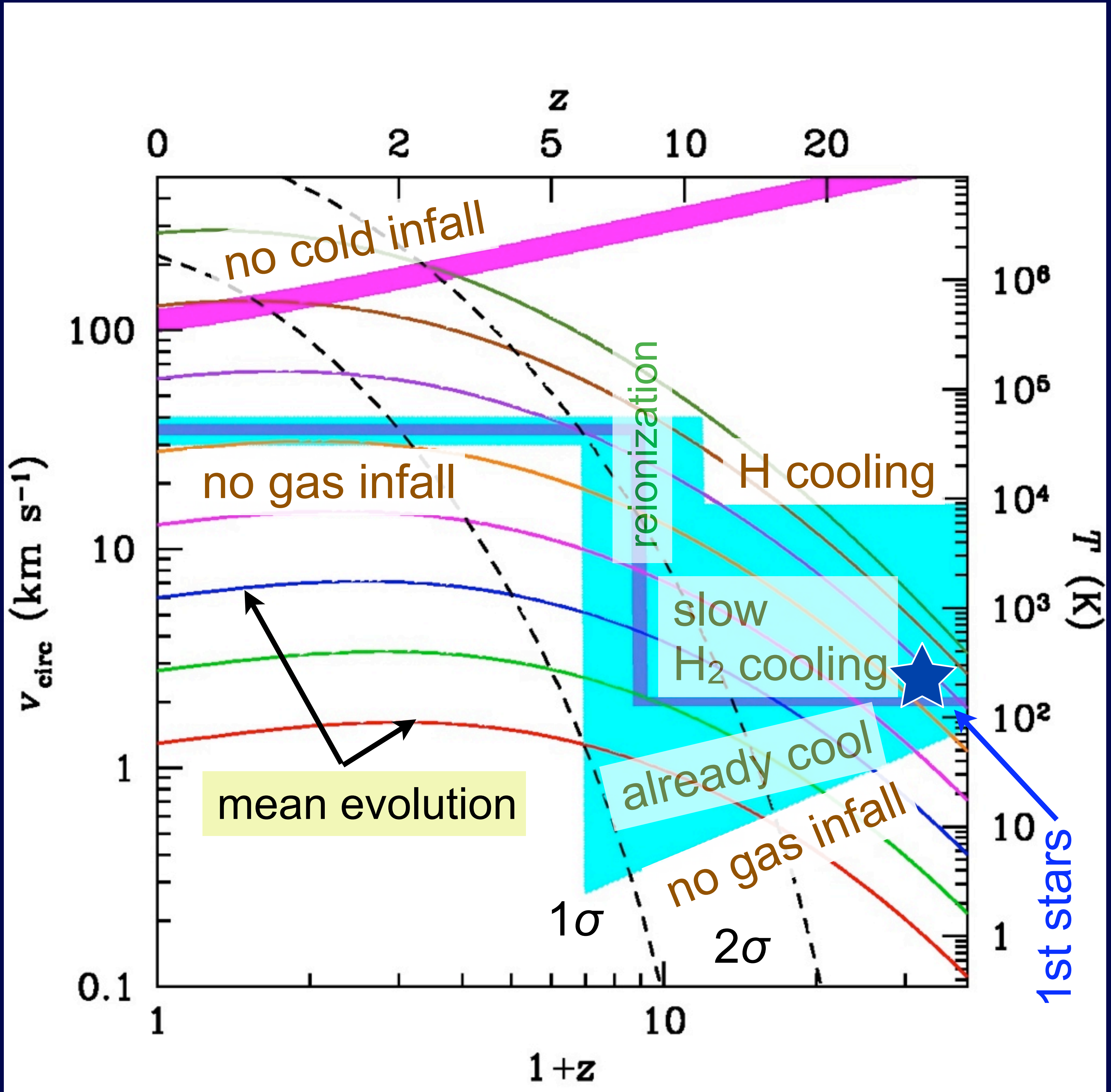
draw 10^4 trees for 24 final halo masses ($7 < \log M < 12.75$ log spaced)
correct to final halo mass function from Millennium simulation

avoid cluster final mass halos

halo circular velocity vs. time (main progenitor)



Minimum halo circular velocity vs. time for gas to overcome entropy barrier & collapse



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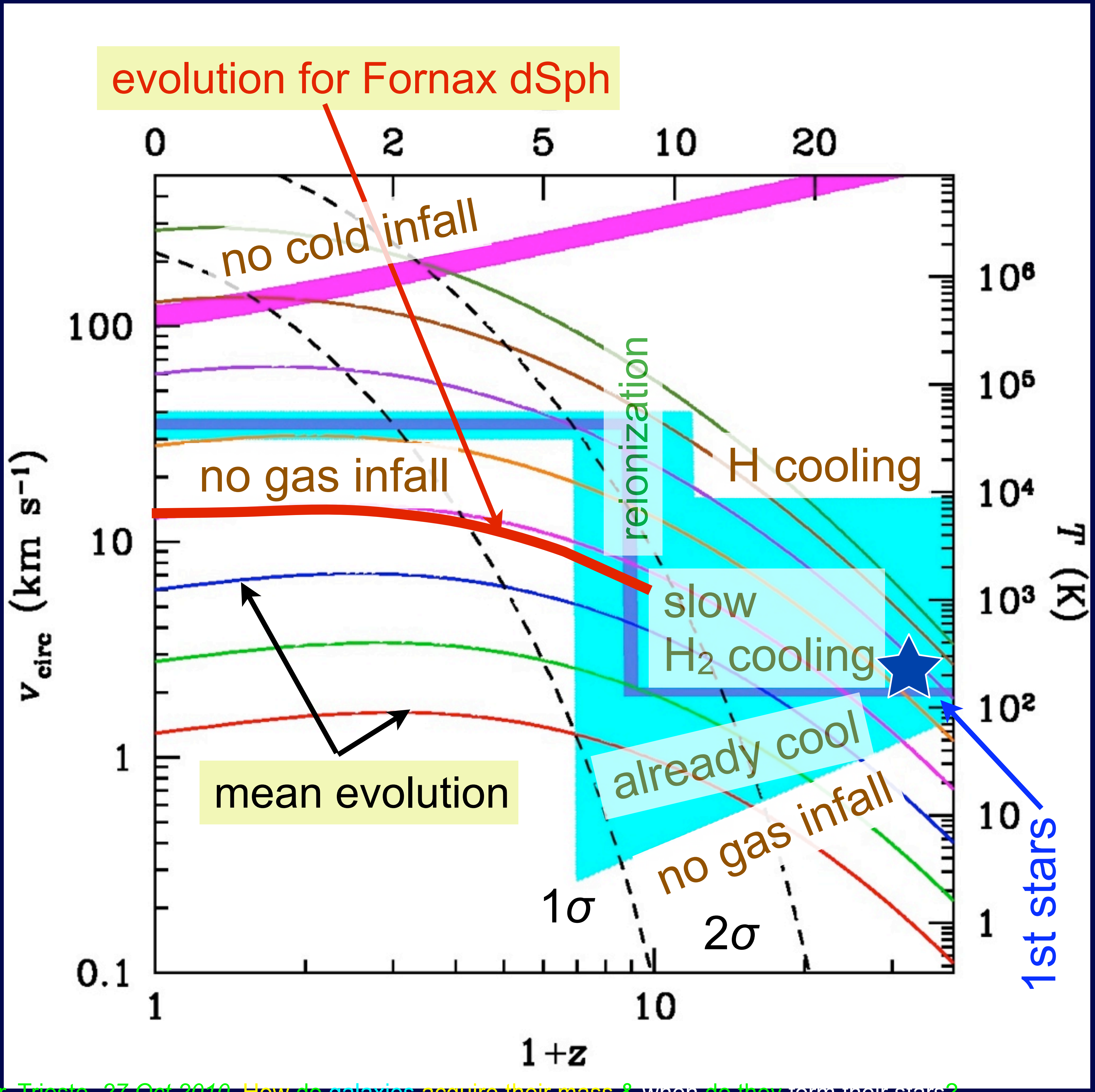

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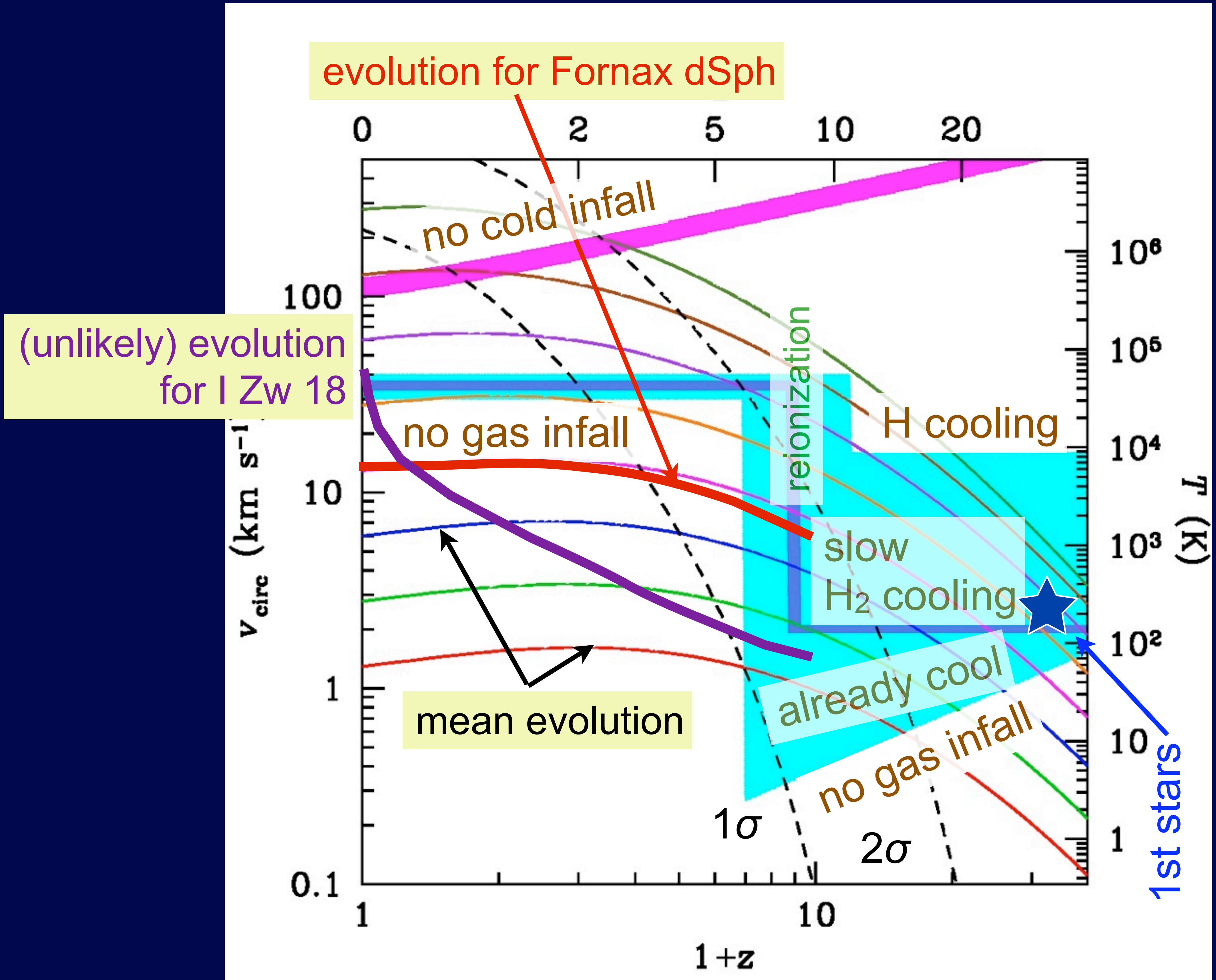

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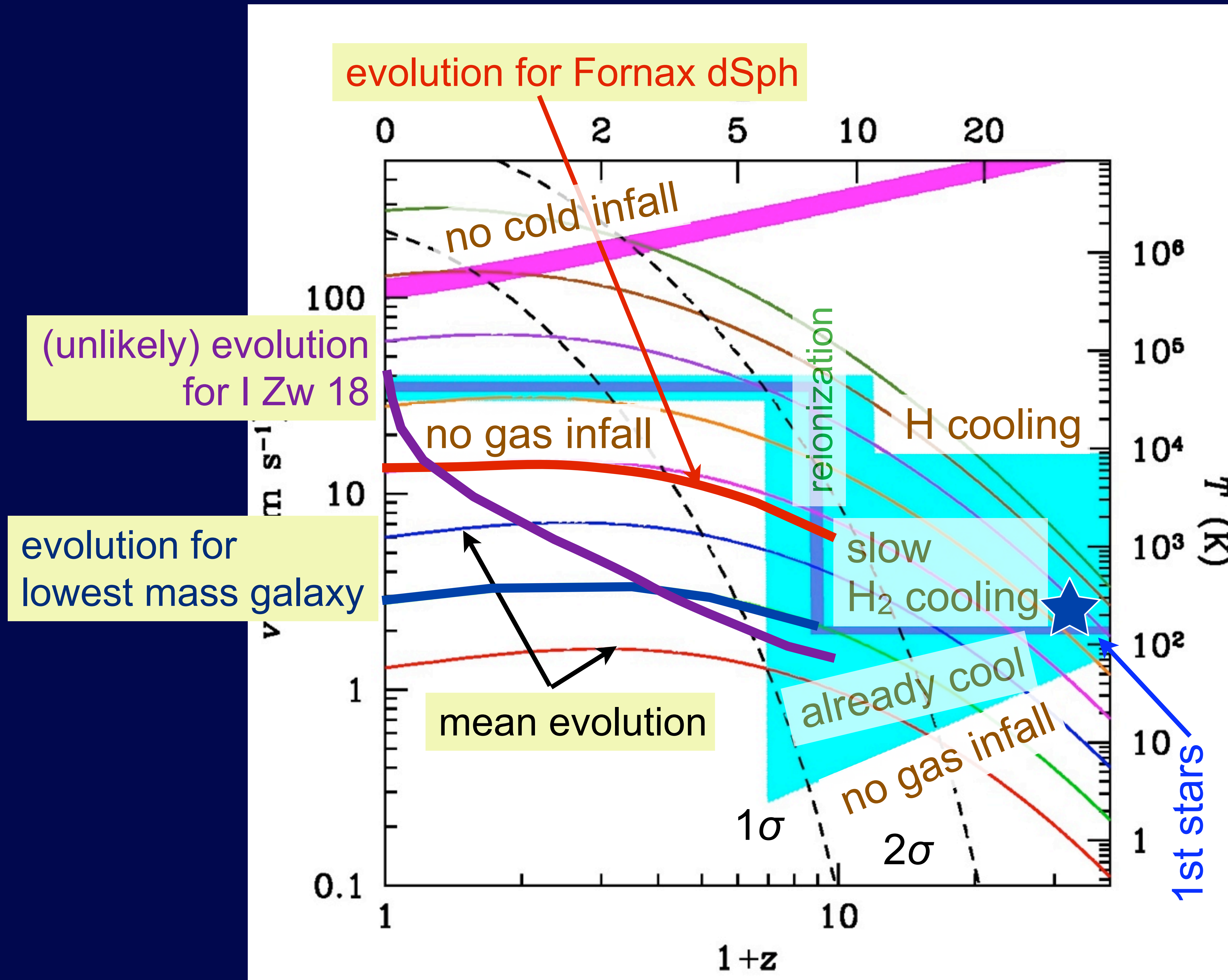
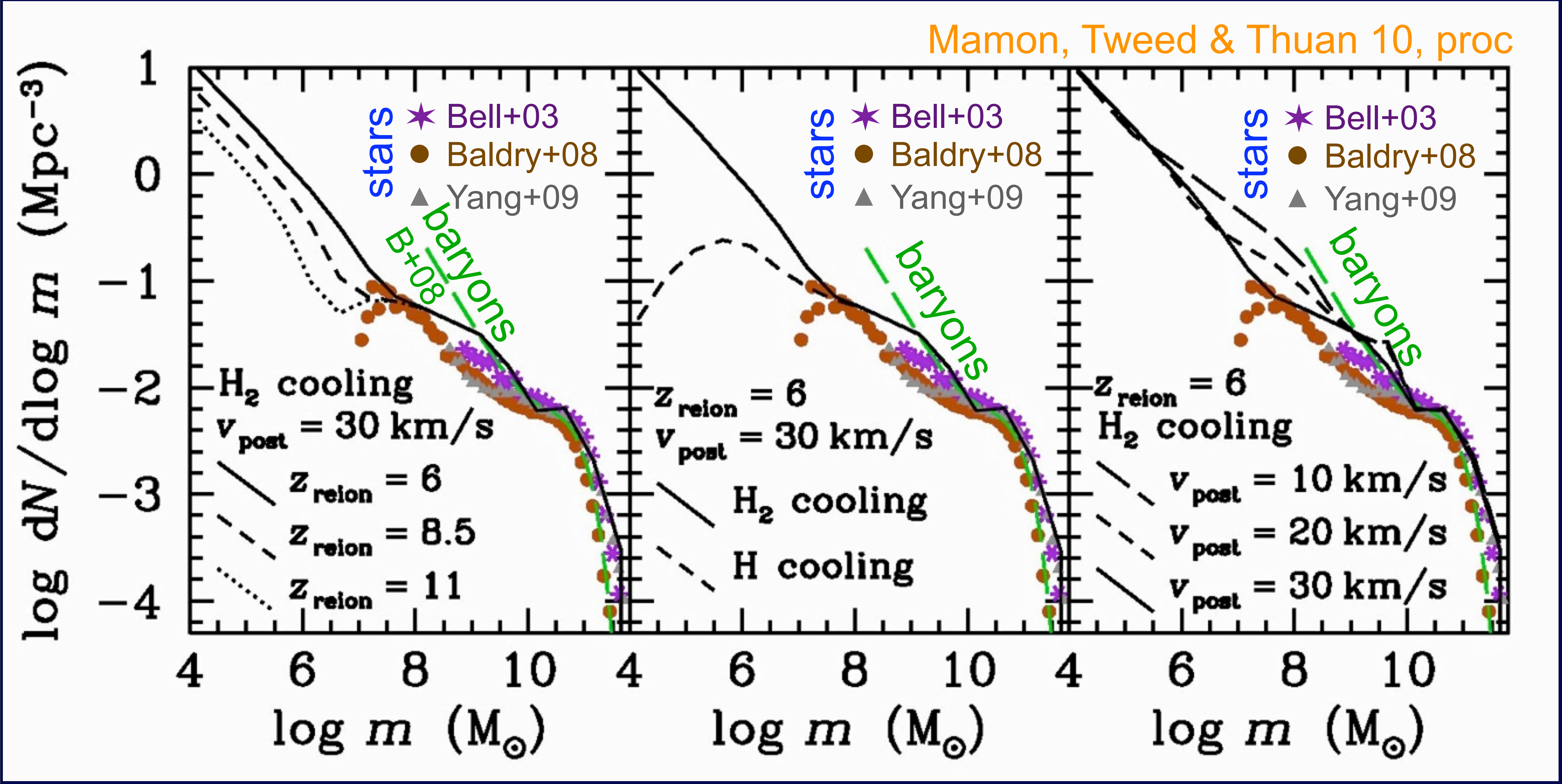


Baryon mass functions

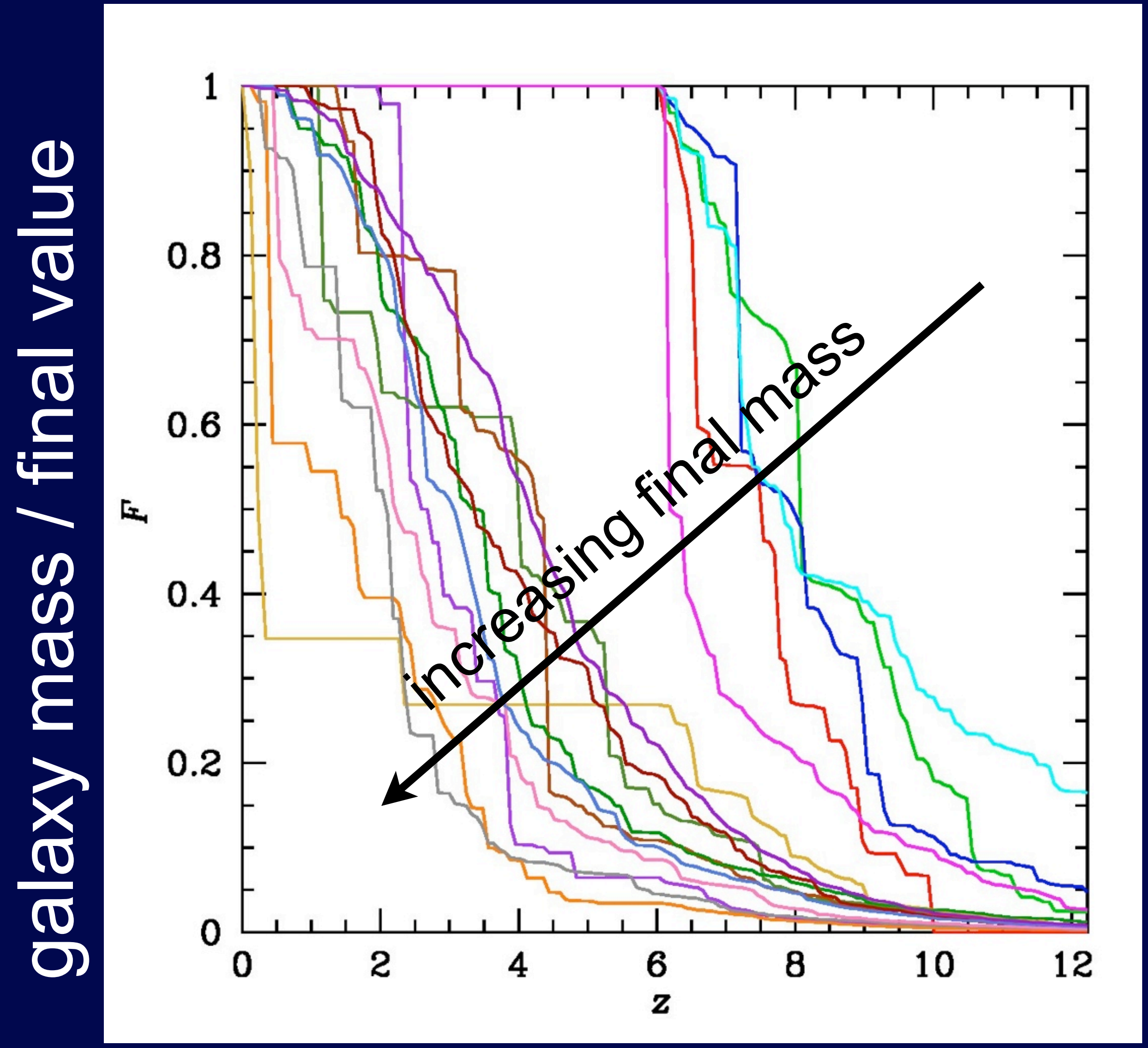
SDSS: stars
SDSS: baryons

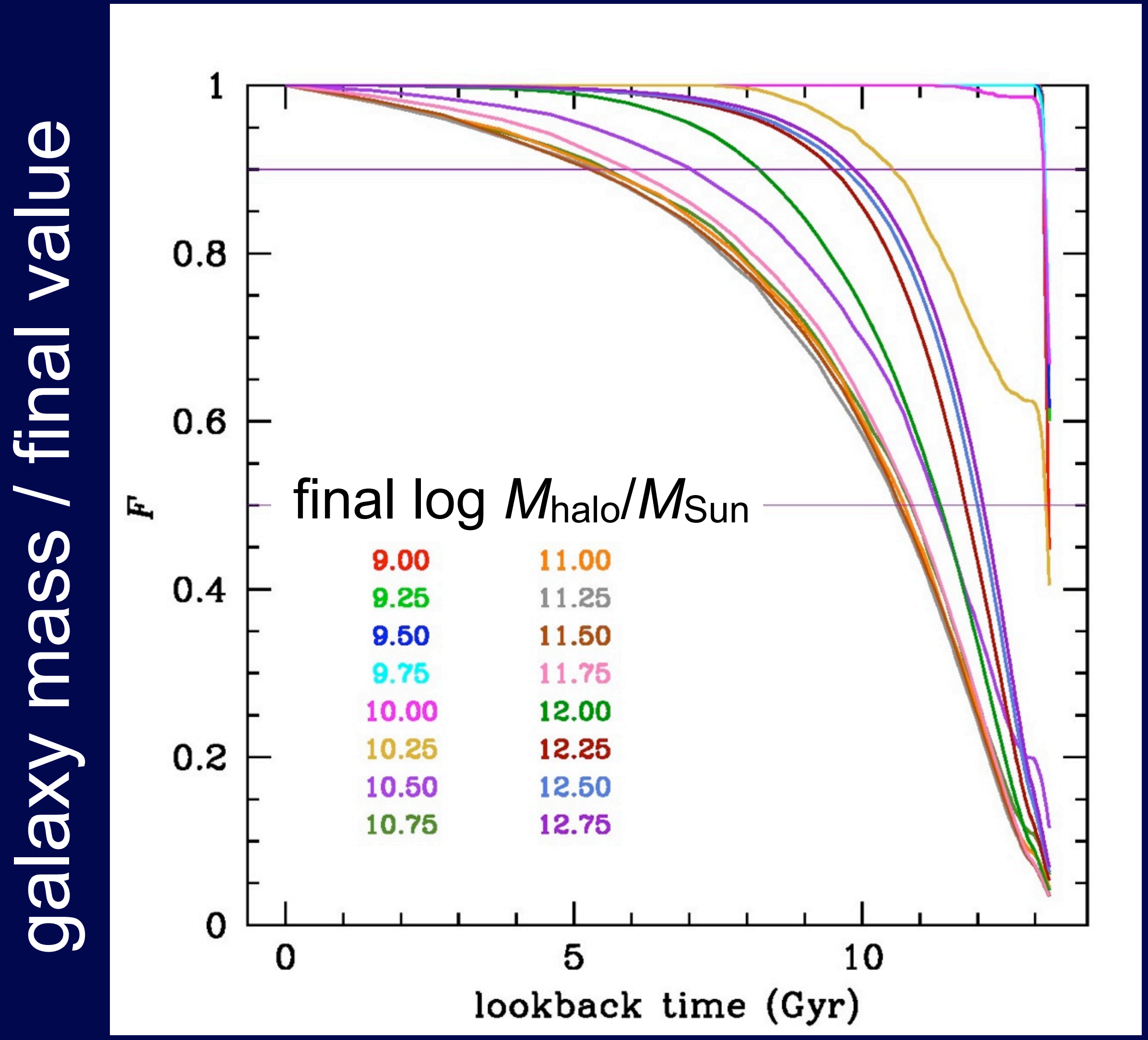


Galaxy mass accretion histories

individual vs redshift

mean vs lookback time





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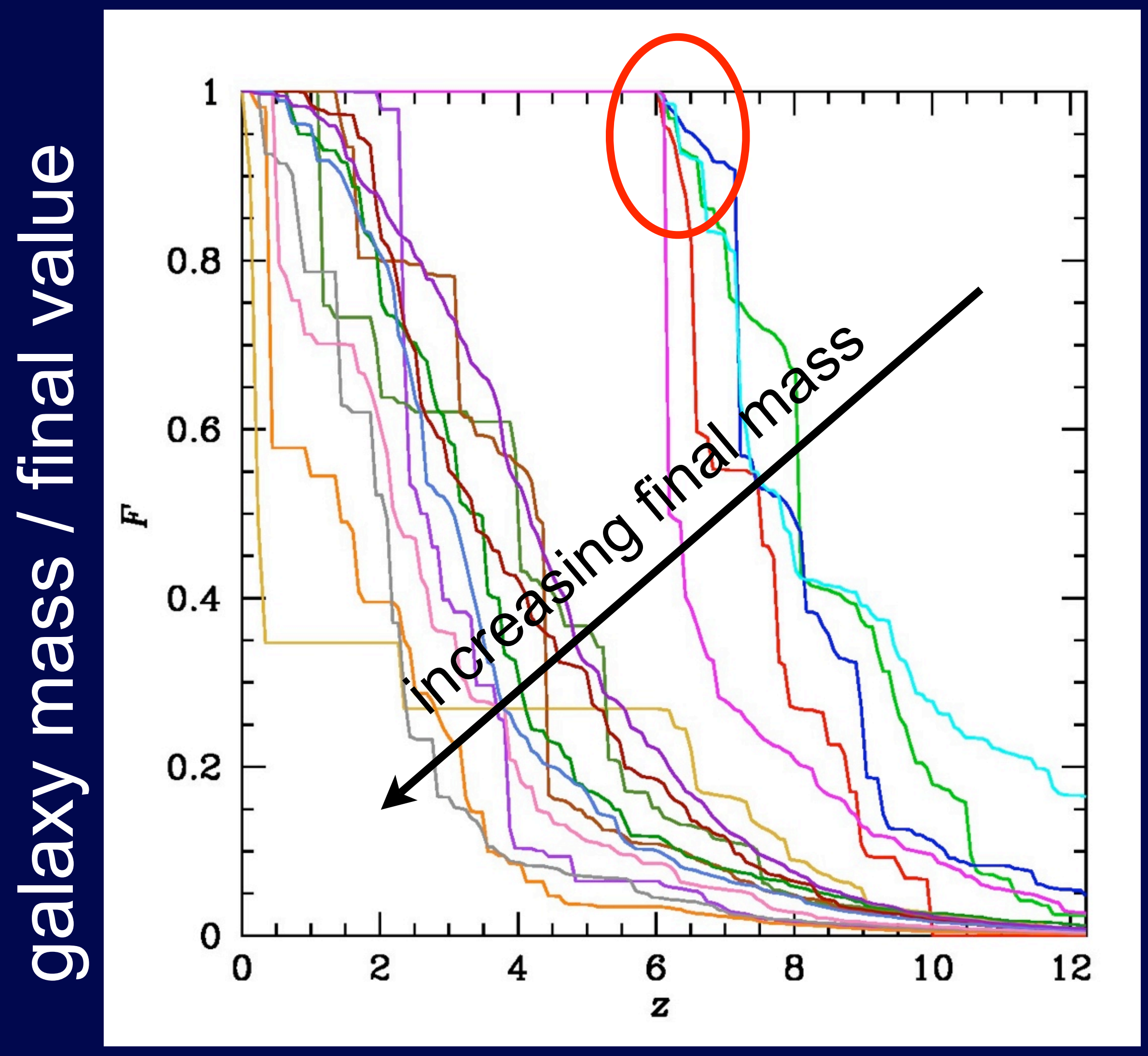

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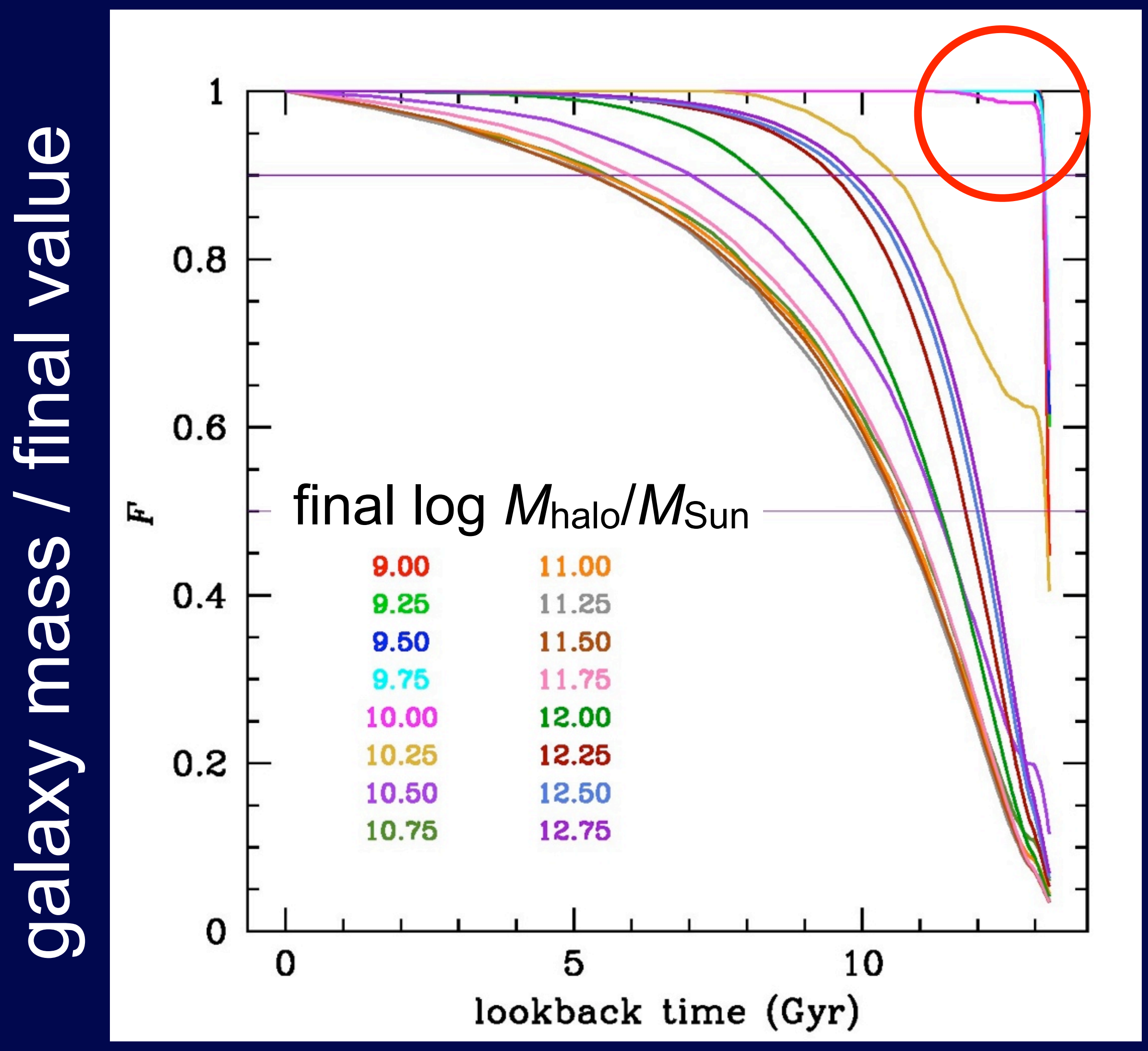
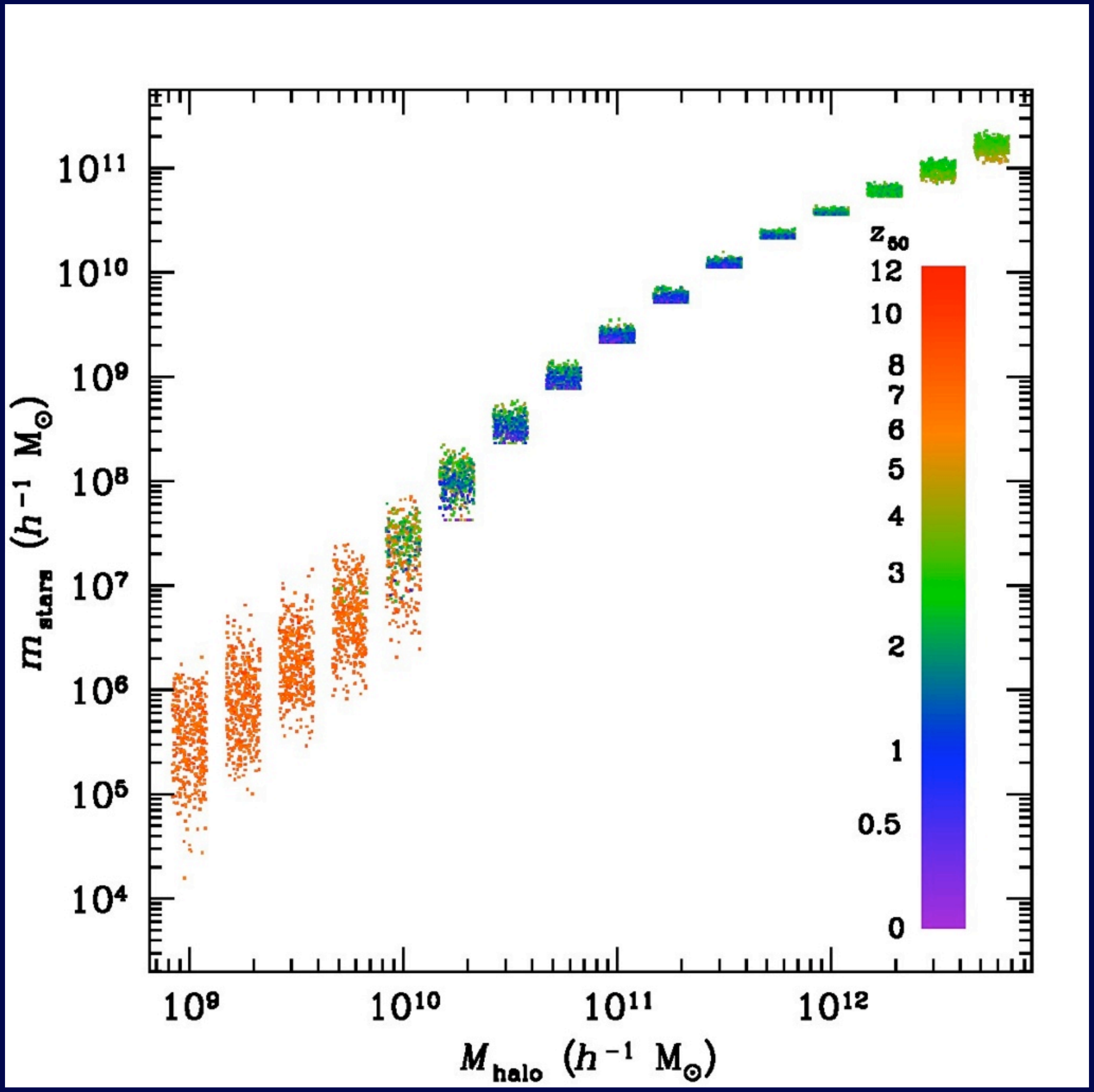


low mass galaxies stop accreting gas & forming stars at reionization

Half-mass-star formation epoch



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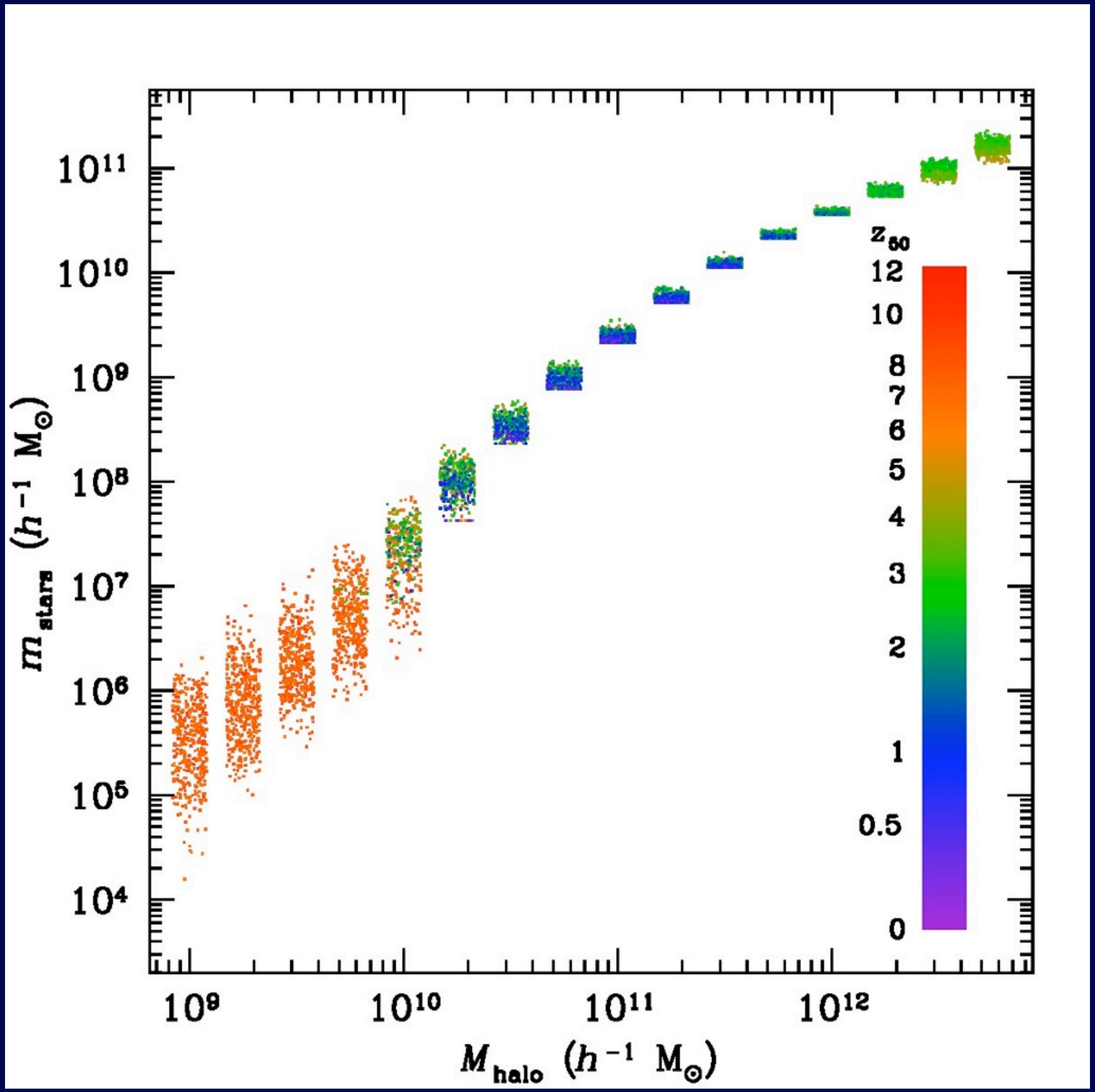

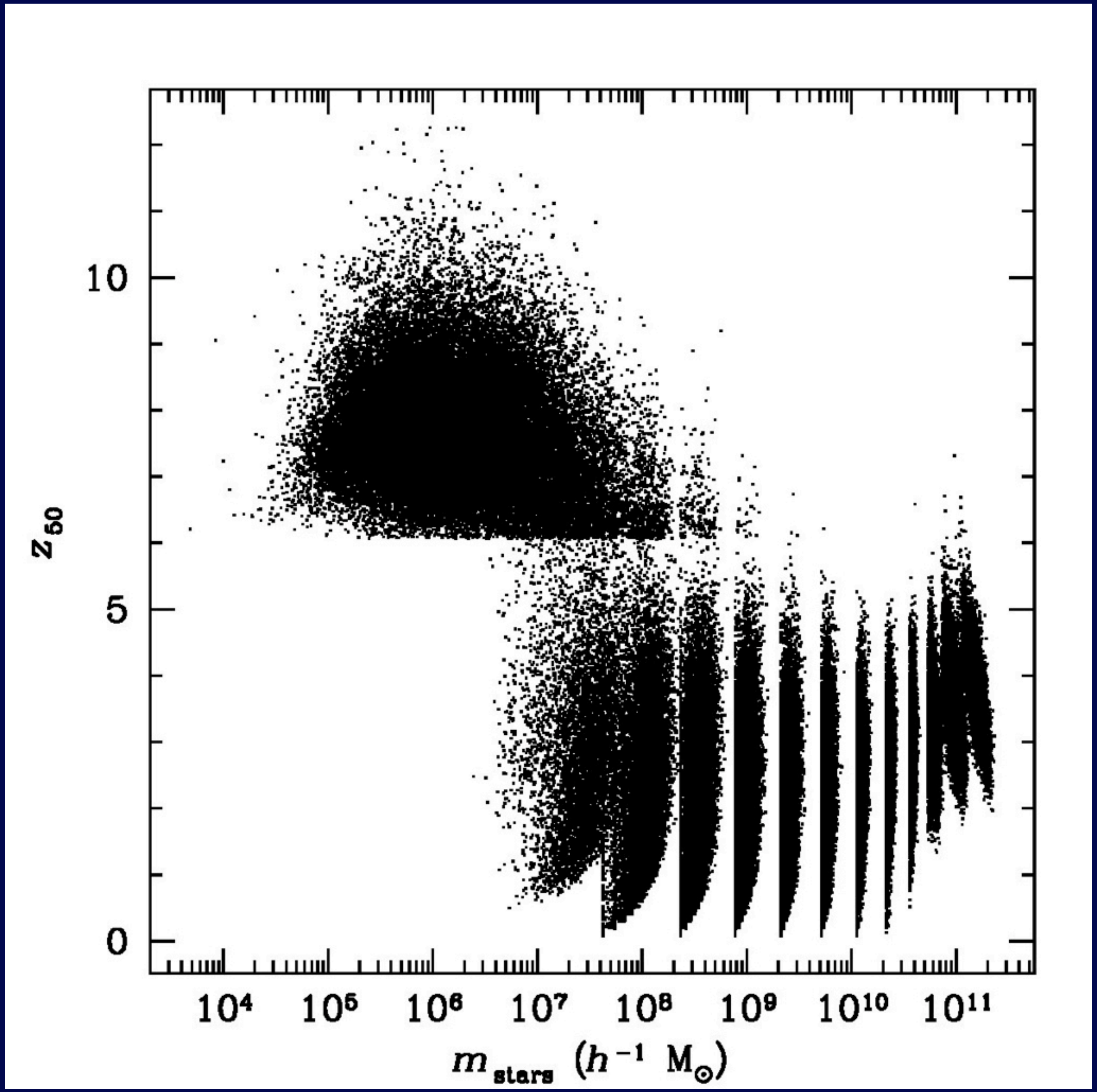

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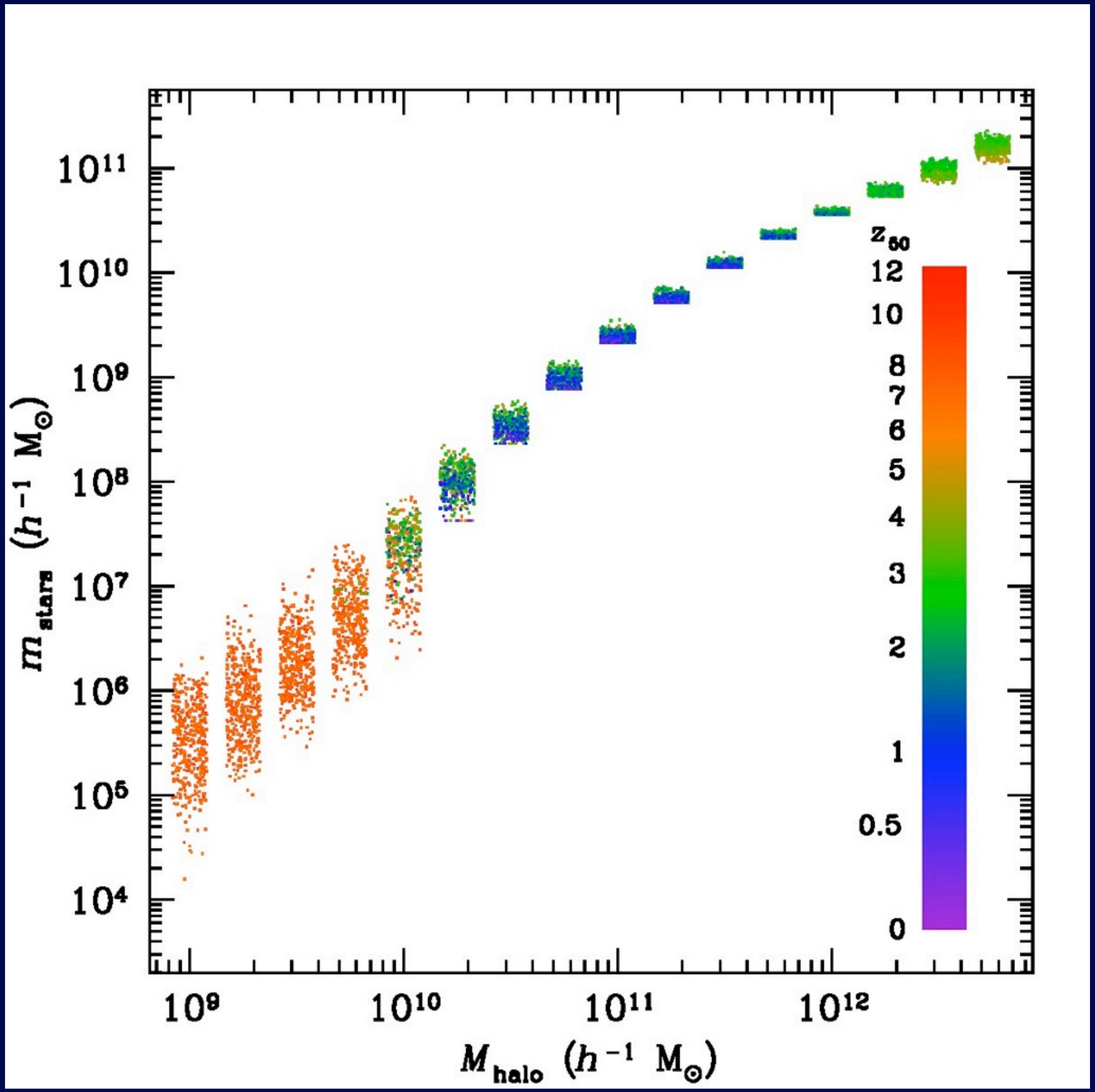

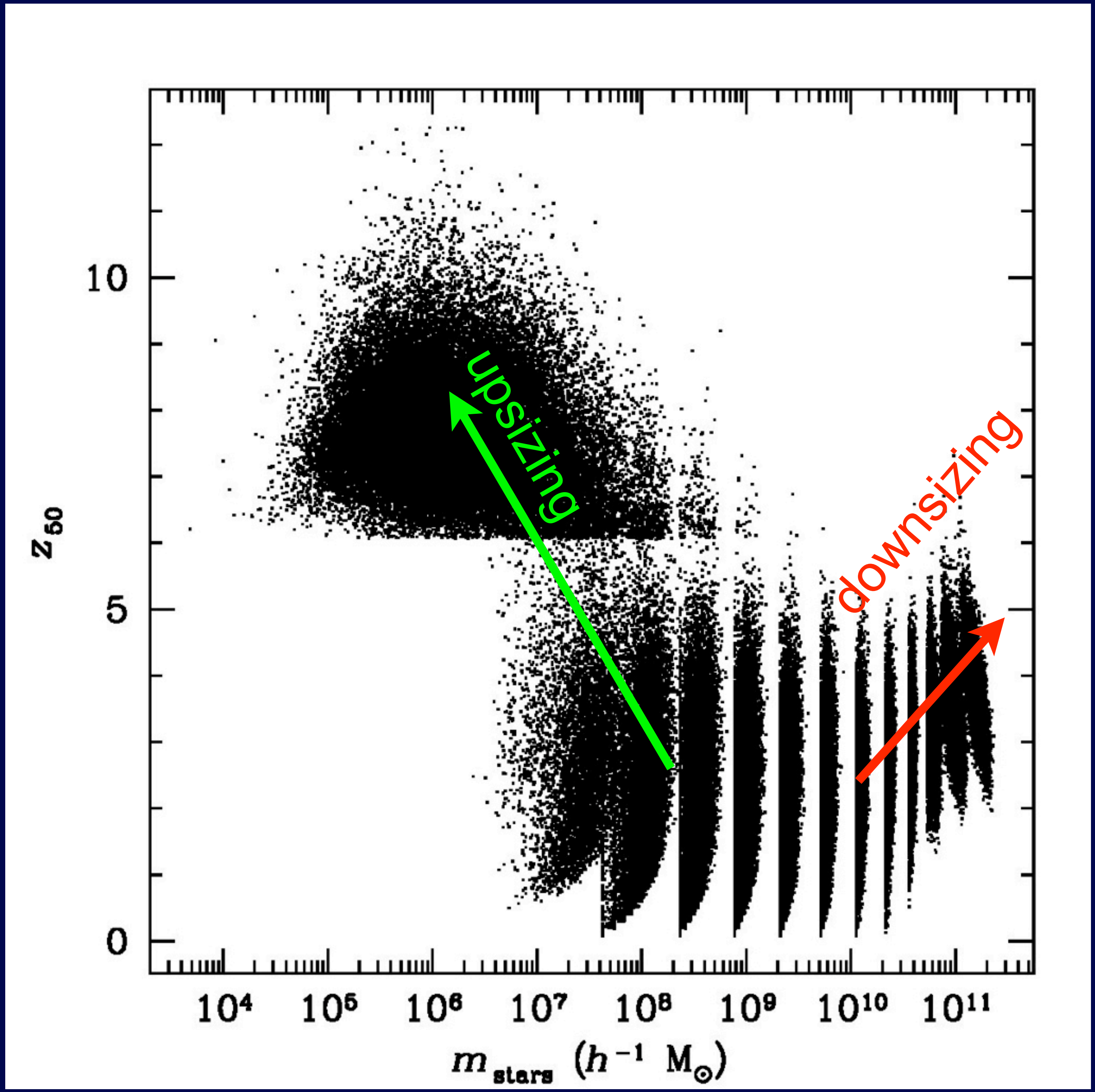

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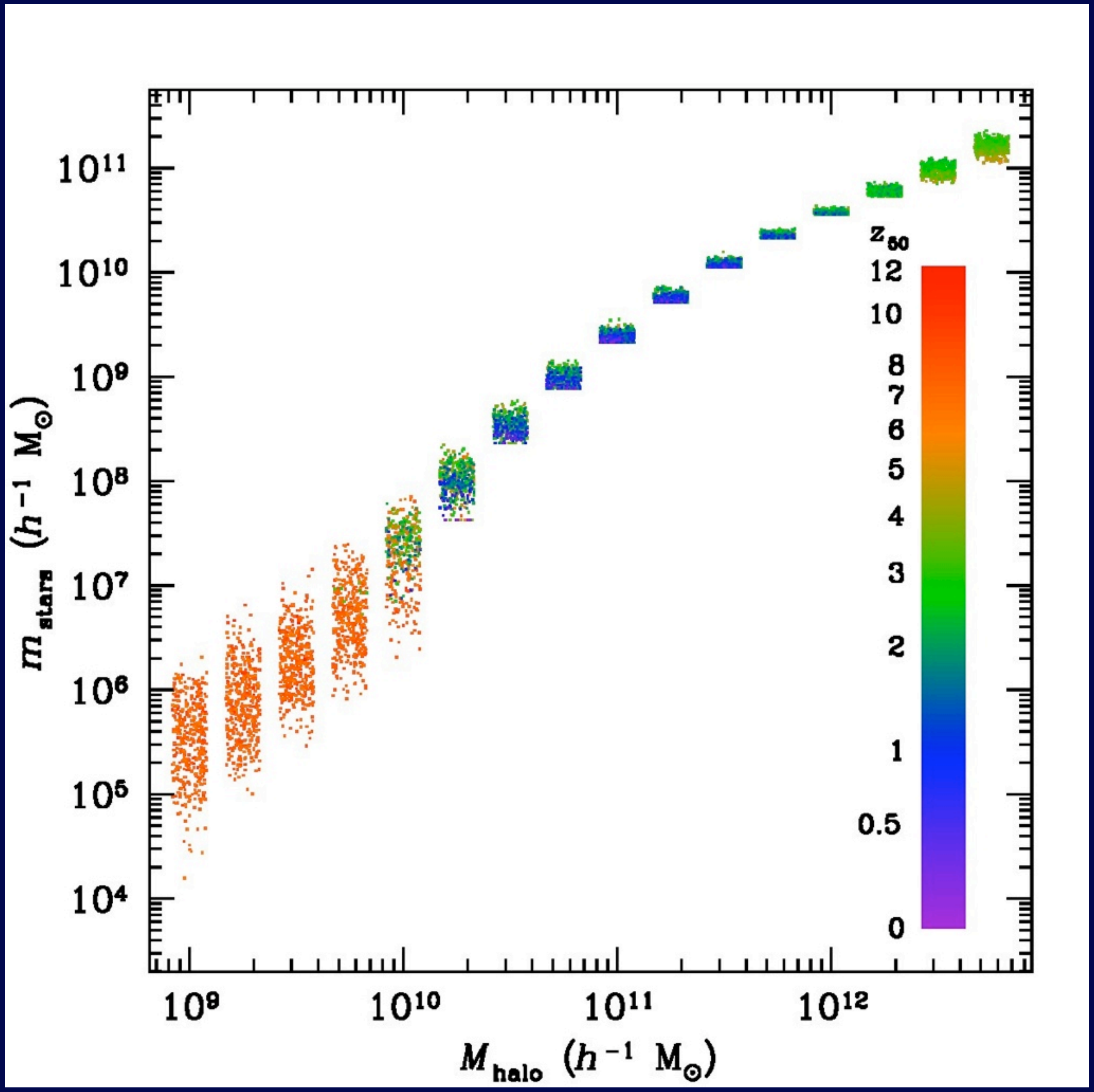
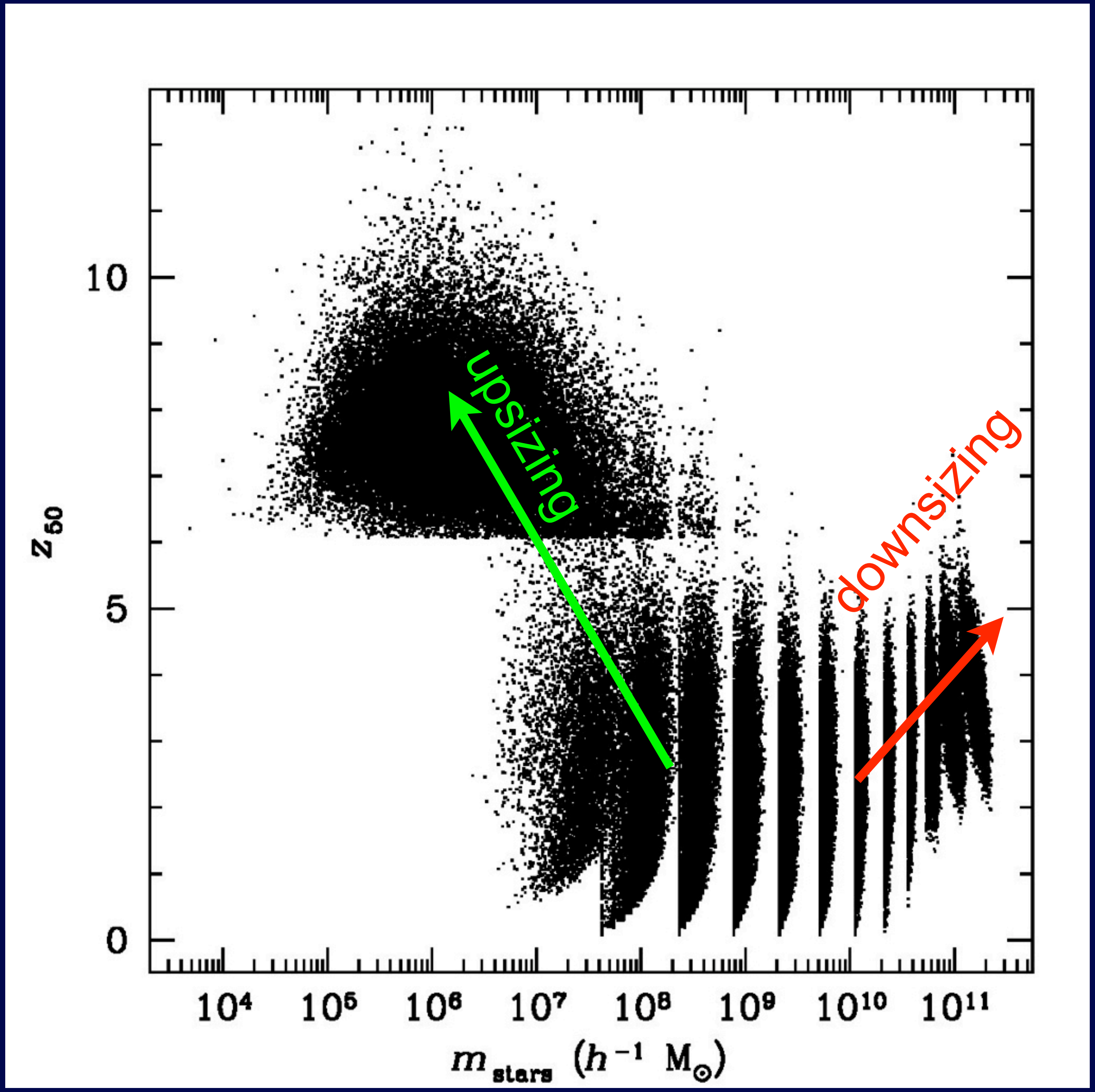
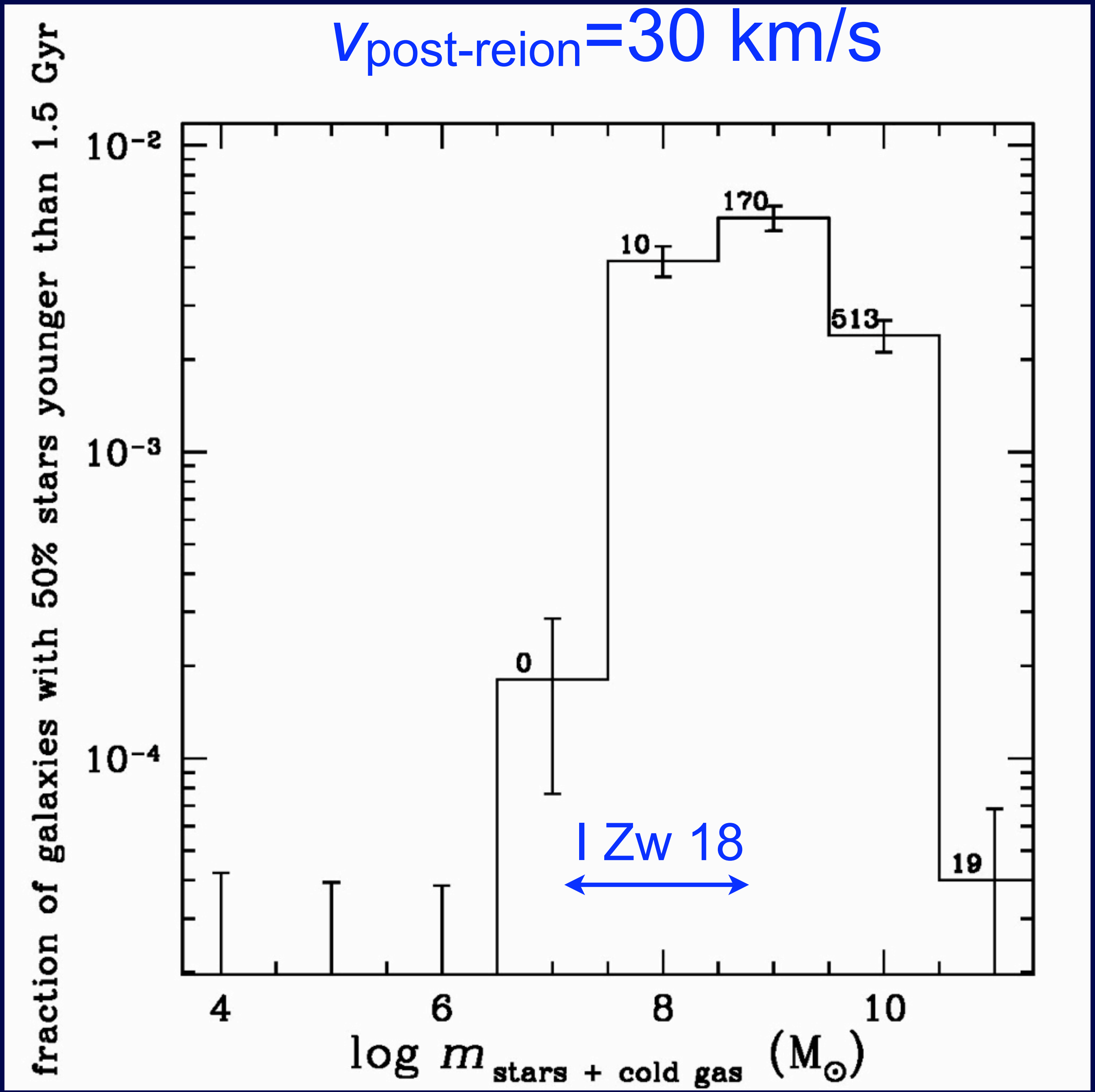




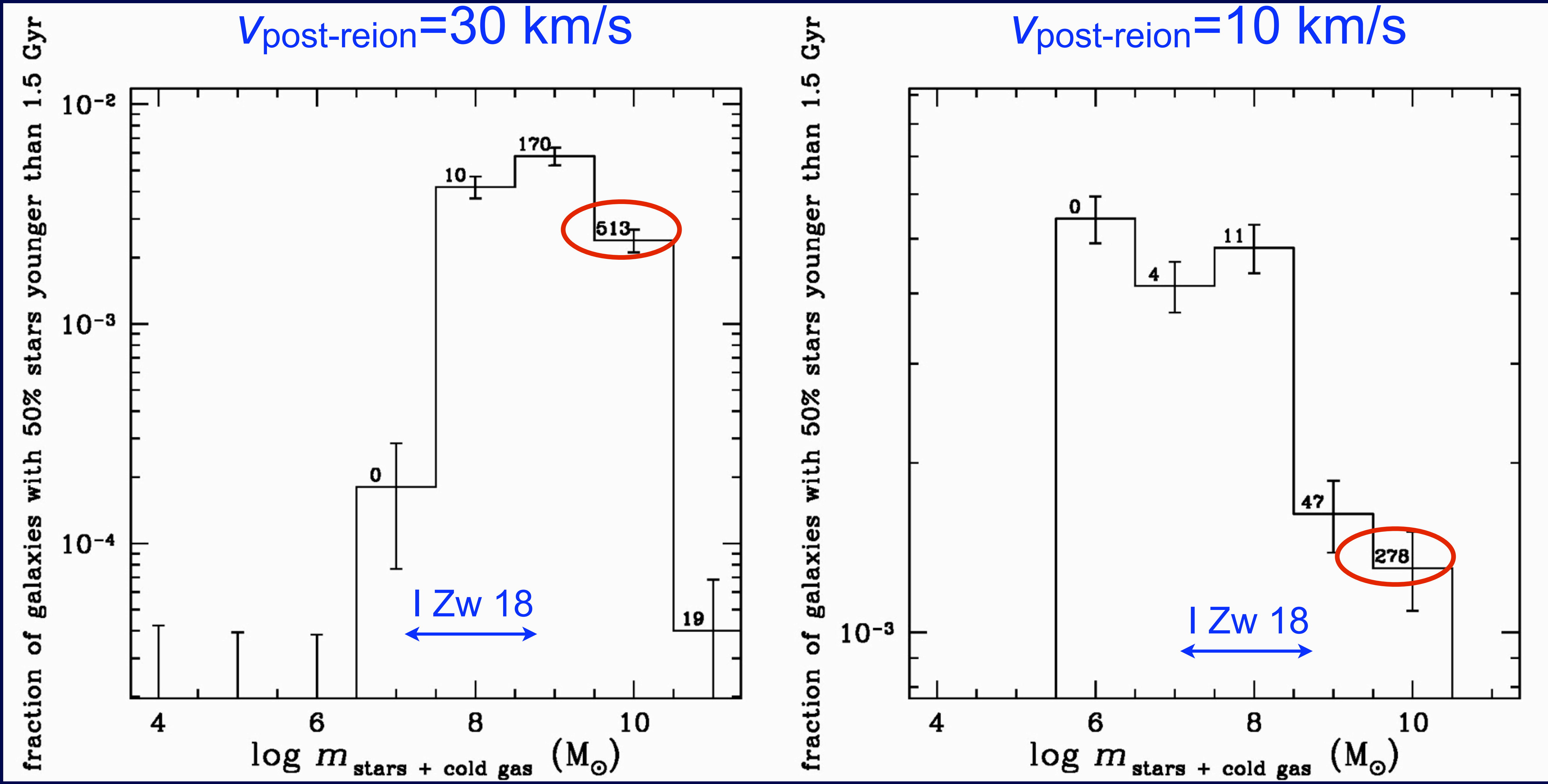
smallest galaxies must be old!

Fraction of young galaxies



up to 1% of young galaxies at $m_{\text{stars}} = 10^8\ M_{\text{Sun}}$

Fraction of young galaxies



up to 1% of young galaxies at $m_{\rm stars} = 10^8\ M_{\rm Sun}$

too many young galaxies in SDSS at $m_{\rm stars} = 10^{10}\ M_{\rm Sun}$

Conclusions

massive galaxies (ellipticals?) built up by dry major mergers

low mass galaxies built up by gas accretion

dEs in clusters: not built up by mergers...
... by harassment of small spirals? Mastropietro et al. 05

most intermediate galaxies not built by mergers
but (most?) intermediate ellipticals built by wet minor mergers

ULIRGs (cold-mode mergers) have log $m_{\rm stars} \sim 10.5 \pm 0.5$

galaxy stellar mass function suggests late reionization

young galaxies <1% at all masses, prefer log $m_{\rm stars} = 8$
but 100+ young galaxies expected at log $m_{\rm stars} = 10$...

less massive galaxies (dSph) are older: upsizing

Galaxy properties versus Mass

← upsizing

downsizing →

youngest galaxies

dSph BCD dIrr/dE Sp S0 gE, cD

some wet mergers → ULIRGs

dry major mergers

gas accretion

galaxy mass