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

Andrea CATTANEO
Obs. de Marseille

Kristin WARNICK
AIP, Postdam

Alexander KNEBE
Univ. Autonoma, Madrid
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Hebrew Univ.

Trinh THUAN
Univ. of Virginia

Avishaï DEKEL
Hebrew Univ.
Outline

Primer on galaxy formation
Outline

Primer on galaxy formation

Simulation methods
Outline

Primer on galaxy formation

Simulation methods

Toy model of galaxy formation:
How do galaxies acquire their mass?

*motivated by J. Ostriker*
Outline

Primer on galaxy formation

Simulation methods

Toy model of galaxy formation:
How do galaxies acquire their mass? *motivated by J. Ostriker*

How frequent are young galaxies at $z=0$? *motivated by T. Thuan*
Outline

Primer on galaxy formation

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Toy model of galaxy formation:
How do galaxies acquire their mass? *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
How to build a galaxy?

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

details poorly understood!
How do galaxies evolve?
They grow:
How do galaxies evolve?
They grow:

Softly:
by further gas accretion \(\text{(monolithic collapse)}\)
How do galaxies evolve?

They grow:

Softly:
by further gas accretion (monolithic collapse)

In steps:
by mergers (hierarchical merging)
How do galaxies evolve?

They grow:

Softly:

by further gas accretion (monolithic collapse)

In steps:

by mergers (hierarchical merging)

Both
Quenchers of galaxy formation

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

Blumenthal, Faber, Primack & Rees 84

Cooling time = dynamical time

<table>
<thead>
<tr>
<th>Log density (cm⁻³)</th>
<th>Log temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cooling</td>
<td>Cooling</td>
</tr>
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- tidal dissipation of baryonic reservoirs  
  Shaya & Tully 84
Quenchers of galaxy formation

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- **AGN jets**  Silk & Rees 99

3 kpc  M87  HST
Quenchers of galaxy formation

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- **entropy barrier (photoionization of IGM)**  
  specific entropy $\sim T/n^{2/3}$  
  Rees 86; Blanchard, Valls-Gabaud & Mamon 92
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Mixed DM & baryons

Initial

Final from cold IGM

DM & gas collapse

gas dissipates to disk
Quenchers of galaxy formation

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

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Quenchers of galaxy formation

- long cooling time
- tidal dissipation of baryonic reservoirs
- supernova explosions
- AGN jets
- entropy barrier (photoionization of IGM)
- accretion shock

Rees 86; Blanchard, Valls-Gabaud & Mamon 92; Dekel & Birnboim 06

\[ M_{\text{vir}} = 10^{11} - 10^{13} M_{\text{Sun}} \]

Gas arrives hot on disk

Dekel & Birnboim 06
Quenchers of galaxy formation

- long cooling time
- tidal dissipation of baryonic reservoirs
- supernova explosions
- AGN jets
- entropy barrier (photoionization of IGM)
- accretion shock

$M_{\text{vir}} = 10^{11} - 10^{13} M_{\text{Sun}}$

gas arrives hot on disk

$M_{\text{vir}} = 10^9 - 10^{11} M_{\text{Sun}}$

no shock
gas arrives cold on disk
Quenchers of galaxy formation

- long cooling time
- tidal dissipation of baryonic reservoirs
- supernova explosions
- AGN jets
- entropy barrier (photoionization of IGM)
- accretion shock

\[ M_{\text{vir}} = 10^{11} - 10^{13} \ M_{\odot} \]

\[ M_{\text{vir}} = 10^{9} - 10^{11} \ M_{\odot} \]

→ 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, ...

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
Soft galaxy formation: by gas accretion

- Progressively: collapse and gas accretion

Eggen, Lynden-Bell & Sandage 62
Soft galaxy formation: by gas accretion

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Eggen, Lynden-Bell & Sandage 62

but low angular momentum → small disks! Mo, Mao & White 98
Soft galaxy formation: by gas accretion

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Eggen, Lynden-Bell & Sandage 62

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Gott & Thuan 76

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
Soft galaxy formation: by gas accretion

- Progressively: *collapse and gas accretion*

  - but low angular momentum $\rightarrow$ small disks! *Mo, Mao & White 98*
  - but $\sim$ cst gas fraction & density within virial radius $\Rightarrow$ cst ratio of cooling to collapse times!
Filamentary & clumpy accretion?

Greif et al. 2008

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

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
Galaxy Mergers

- Direct “satellite-satellite” mergers
Galaxy Mergers

- Direct “satellite-satellite” mergers
- Mergers after orbital decay by *dynamical friction*
Galaxy Mergers

- Direct “satellite-satellite” mergers
- Mergers after orbital decay by dynamical friction
- Major mergers: comparable masses (1:1 to 3:1)

major merger: The Mice
Galaxy Mergers

- Direct "satellite-satellite" mergers
- Mergers after orbital decay by *dynamical friction*
- **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
How do galaxies acquire their mass & when do they form their stars?

Wet & Dry Mergers

Spiral + Spiral $\rightarrow$ (wet merger) ULIRG $\rightarrow$ Quasar $\rightarrow$ Elliptical
**Wet & Dry Mergers**

Spiral+Spiral \( \rightarrow \) (wet merger) ULIRG \( \rightarrow \) Quasar \( \rightarrow \) Elliptical

Spiral+Spiral \( \rightarrow \) E/S0+E/S0 \( \rightarrow \) (dry merger)
Ultraluminous Infrared Galaxies: sites of wet galaxy mergers

Borne et al. 99

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

Hydrodynamical Cosmological Simulations

Dark Matter  Gas  Temperature  Metals  Stars

zoom

Mare Nostrum: Pichon, Teyssier et al.
Hydrodynamical Cosmological Simulations

months of computer time
semi-analytical recipes too! (star formation, feedback)

Mare Nostrum: Pichon, Teyssier et al.
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
   ...

Lacey & Cole 93
Semi-analytical models

Galaxy formation and evolution model on top of:

1) halo merger tree

2) dark matter cosmological simulation

Springel et al. 2005
Semi-analytical models

Galaxy formation and evolution model on top of:

1) halo merger tree

2) dark matter cosmological simulation

Springel et al. 2005
Semi-analytical models in motion!

Durham team
Semi-analytical models in motion!

Durham team

tens of thousands of lines of code
> 10 parameters

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
Halo Occupation Distribution

\[ P(X|M_{\text{halo}}) \]

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

Graph showing halo mass and star formation efficiency versus halo circular velocity.
**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

- **Minor mergers → bluer**
- **Major mergers → redder**

- **Minor mergers → color gradients**
- **Major mergers → mix**

---

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
How do galaxies acquire their mass & when do they form their stars?

SDSS trends on ellipticals

Bernardi et al. 10b

- Minor mergers → bluer
- Major mergers → redder
- Transition at log $m_{\text{stars}} = 11.3$
  i.e. log $h m_{\text{stars}} = 11.0$

- 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 $M_{\text{halo}} > M_{\text{shock}}$

\[
m_{\text{accr}}^{(1)} = f_{\text{baryons}} \frac{M_{\text{halo}}}{(1 + \frac{M_{\text{halo}}}{M_{\text{shock}}})}
\]

Dekel & Birnboim 06

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

\[
m_{\text{accr}} = [1 - (\frac{v_{\text{reion}}}{v_{\text{halo}}})^2] \, m_{\text{accr}}^{(1)}
\]

Thoul & Weinberg 96

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

\[
E_{\text{SN}} \approx m_{\text{wind}} \, v_{\text{halo}}^2 \approx m_{\text{stars}} \, v_{\text{SN}}^2
\]

\[
m_{\text{wind}} + m_{\text{stars}} = m_{\text{accr}}
\]

\[
\Rightarrow m_{\text{stars}} = \frac{v_{\text{halo}}^2}{(v_{\text{halo}}^2 + v_{\text{SN}}^2)} \, m_{\text{accr}}
\]
**Toy model**

Cattaneo, GM et al. 10

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

$$m_{\text{accr}}^{(1)} = f_{\text{baryons}} \frac{M_{\text{halo}}}{(1 + M_{\text{halo}}/M_{\text{shock}})}$$

Dekel & Birnboim 06

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

$$m_{\text{accr}} = [1-(v_{\text{reion}}/v_{\text{halo}})^2] m_{\text{accr}}^{(1)}$$

Thoul & Weinberg 96

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

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

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

$$\Rightarrow m_{\text{stars}} = \frac{v_{\text{halo}}^2}{(v_{\text{halo}}^2 + v_{\text{SN}}^2)} m_{\text{accr}}$$

$$m_{\text{stars}} = f(M_{\text{halo}}, z)$$
Four-parameter toy model of galaxy formation

\[ m_{\text{accr}}^{\text{stars}} \sim \frac{v_c^2(z) - v_{\text{reion}}^2}{v_c^2(z) + v_{\text{SN}}^2} \frac{f_b M_{\text{halo}}}{1 + M_{\text{halo}}/M_{\text{shock}}} \]

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

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
**Four-parameter toy model of galaxy formation**

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m_{\text{accr}}^{\text{stars}} \sim \frac{v_c^2(z) - v_{\text{reion}}^2}{v_c^2(z) + v_{\text{SN}}^2} \frac{f_b M_{\text{halo}}}{1 + M_{\text{halo}}/M_{\text{shock}}}
\]

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

Cattaneo, GM et al. 10

run on top of $512^3$ dark matter cosmological simulation
particle mass = $7 \times 10^7 M_{\odot}/h$

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

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
Galaxy formation vs epoch

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

Cattaneo, GM et al. 10

iso-SF efficiency contours
shock heating of accreted material
halo mass growth curves
supernovae, too hot (high entropy) IGM

 present
Mass distribution:
parameters fit to
agree with observations

Cattaneo, GM et al. 10
Tests of Toy Model

Mass distribution: parameters fit to agree with observations

Evolution of cosmic Star Formation Rate: fair agreement with Wilkins et al. 08

Symbols: SFR vs z
Curves: \[
\frac{d}{dt} \int_{m_{\text{min}}}^{\infty} n(m, z) \, dm
\]
Black = toy model
Red = obs (Wilkins et al. 08)

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
Present-day Galaxy mass vs. Halo (environment) mass

Cattaneo, GM et al. 10

- $g_{\text{cold}} < 0.2$
- $0.2 < g_{\text{cold}} < 0.4$
- $0.4 < g_{\text{cold}} < 0.6$
- $0.6 < g_{\text{cold}} < 0.8$
- $g_{\text{cold}} > 0.8$
- $f_{\text{merg}} > 0.5$
- $0.1 < f_{\text{merg}} < 0.5$
- $f_{\text{merg}} < 0.1$

= fraction of z=0 mass acquired by mergers

SDSS centrals

Yang et al. 09

Toy model $z=3$

Toy model $z=0$

Isolated galaxies → groups → clusters

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
**Present-day Galaxy mass vs. Halo (environment) mass**

Cattaneo, GM et al. 10

<table>
<thead>
<tr>
<th>$g_{\text{cold}} &lt; 0.2$</th>
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= fraction of $z=0$ mass acquired by mergers

Galaxy mass function = $f(\text{halo mass})$ & presents gap between centrals & satellites

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars? 37
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Milky Way

toy model $z=3$

toy model $z=0$

isolated galaxies → groups → clusters

SDSS centrals

Yang et al. 09

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

only massive galaxies acquire the bulk of their mass by mergers...
Present-day Galaxy mass vs. Halo (environment) mass

Cattaneo, GM et al. 10

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SDSS centrals
Yang et al. 09

Milky Way

toy model $z=3$

toy model $z=0$

isolated galaxies → groups → clusters

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

... not cluster satellites! $\Rightarrow$ dEs usually not built by mergers!
Conditional galaxy mass functions

in narrow bins of $M_{\text{halo}}$: reproduces observed SDSS bump for centrals amplitude & position $= f(M_{\text{halo}})$
Is lack of mergers at low mass caused by limited mass resolution?

from Cattaneo, GM et al. 10

fraction of present-day mass acquired by galaxy mergers

baryons follow DM

standard model

log (h m_{stars} (M_\odot))

f_{met}

0.01

0.01

0.1

1

1

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
Is lack of mergers at low mass caused by limited mass resolution?

from Cattaneo, GM et al. 10

fraction of present-day mass acquired by galaxy mergers

\[ f_{\text{merg}} \]

baryons follow DM

standard model

estimated mass resolution

std model: steeper decrease of \( f_{\text{merg}} \) to low \( m \)

\[ \Rightarrow \text{lack of mergers at } 10.6 < \log h m < 11.0 \text{ is not a mass resolution effect!} \]
Why mergers are unimportant at low mass?

Cattaneo, GM et al. 10

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fraction of $z=0$ mass acquired by mergers

Toy model $z=0$

Toy model $z=3$

Milky Way

SDSS centrals

Yang et al. 09

Decreasing slope of $m_{\text{stars}}$ vs $M_{\text{halo}}$

→ (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

Important role for wet (cold-mode) mergers

Making intermediate-mass ellipticals

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

Also De Lucia+06; Bernardi+10ab

Galaxies acquire their mass & when do they form their stars?
Major vs. Minor Mergers

- Mostly Minor
  - $f_{\text{major}}/(f_{\text{major}}+f_{\text{minor}})$
- Mostly Major
  - $>1:3$
  - $>1:5$

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
Caveats & criticisms

Absence of gas accretion is built into Toy Model

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

Accreted gas contains clumps (subhalos) $\Rightarrow$ mergers!

Some Dwarf Ellipticals have Kinematically Decoupled Cores

Greif et al. 08; Dekel et al. 09
Chilingarian 09
Absence of gas accretion is built into Toy Model

but need to quench accretion by shock and/or SF by AGN to avoid blue gEs & cDs

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Interacting galaxies and ULIRGs are frequent at $z \geq 0.7$
but most of these galaxies later grow by dry mergers

Accreted gas contains clumps (subhalos) $\Rightarrow$ mergers!
but these high $z$ galaxies would be massive today

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Accreted gas contains clumps (subhalos) $\Rightarrow$ mergers!

but these high $z$ galaxies would be massive today

Some Dwarf Ellipticals have Kinematically Decoupled Cores

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

Greif et al. 08; Dekel et al. 09

Chilingarian 09
How frequent are Young Galaxies at $z=0$?

with

Dylan TWEED
IAS, Orsay
I Zw 18: a very metal-poor galaxy

$Z = Z_{\text{sun}}/50!$
I Zw 18: a very metal-poor galaxy

\[ Z = \frac{Z_{\text{sun}}}{50!} \]
I Zw 18: a very metal-poor galaxy

$Z = Z_{\text{sun}}/50!$

Izotov & Thuan 04
I Zw 18: a very metal-poor galaxy

$Z = Z_{\text{sun}}/50!$

nearly all stars are younger than 1 Gyr!

Izotov & Thuan 04
Upsizing of mass
Downsizing of star formation

after van den Bosch 02; Cattaneo et al. 08

present

Big Bang

galaxies (assembly of stars)
galaxies (star formation)

galaxy mergers

dark matter halos

mass (Suns)
time (billions of years)

see also De Lucia et al. 06
Hierarchical evolution of halos

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

use halo merger tree code by Neistein & Dekel 06
Hierarchical evolution of halos

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
Hierarchical evolution of halos

early Universe

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)

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

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
Minimum halo circular velocity vs. time for gas to overcome entropy barrier & collapse.
How do galaxies acquire their mass & when do they form their stars?

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

- Evolution for Fornax dSph
- (unlikely) evolution for I Zw 18
- No cold infall
- No gas infall
- Mean evolution
- Slow H2 cooling
- Already cool
- No gas infall
- 1st stars
- Reionization
- H cooling

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
**Minimum halo circular velocity vs. time for gas to overcome entropy barrier & collapse**

- Evolution for Fornax dSph
- No cold infall
- No gas infall
- Mean evolution
- First stars

(unlikely) evolution for I Zw 18

Evolution for lowest mass galaxy

No gas infall

H cooling

Reionization

Slow H$_2$ cooling

Already cool

No gas infall

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
How do galaxies acquire their mass & when do they form their stars?

Baryon mass functions

SDSS: stars
SDSS: baryons

Mamon, Tweed & Thuan 10, proc

Baryon mass functions

SDSS: stars
SDSS: baryons

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Baryon mass functions

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Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?

**Galaxy mass accretion histories**

- **individual vs redshift**
- **mean vs lookback time**

**Graphs:**
- Left: galaxy mass / final value vs redshift ($z$) showing increasing final mass.
- Right: final log $M_{\text{halo}}/M_{\text{Sun}}$ vs lookback time (Gyr) with labels for different redshifts (e.g., 9.00, 9.25, 9.50, etc.).
Galaxy mass accretion histories

individual vs redshift

mean vs lookback time

Low mass galaxies stop accreting gas & forming stars at reionization.
Half-mass-star formation epoch

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
Half-mass-star formation epoch

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Half-mass-star formation epoch

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**Half-mass-star formation epoch**

- **smallest galaxies must be old!**

- Graph showing the relationship between $M_{\text{halo}}$ and $m_{\text{stars}}$ with green and red downsizing and upsizing arrows.

- The graph indicates that the smallest galaxies must be old.
**Fraction of young galaxies**

$v_{\text{post-reion}} = 30 \text{ km/s}$

Fraction of galaxies with 50% stars younger than 1.5 Gyr

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

Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010; How do galaxies acquire their mass & when do they form their stars?
**Fraction of young galaxies**

- For $v_{\text{post-reion}} = 30 \text{ km/s}$:
  - Up to 1% of young galaxies at $m_{\text{stars}} = 10^8 \, M_{\odot}$

- For $v_{\text{post-reion}} = 10 \text{ km/s}$:
  - Too many young galaxies in SDSS at $m_{\text{stars}} = 10^{10} \, M_{\odot}$

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Gary Mamon (IAP), Oss. Astr. Trieste, 27 Oct 2010, How do galaxies acquire their mass & when do they form their stars?
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 $m_{stars} \sim 10.5 \pm 0.5$

galaxy stellar mass function suggests late reionization

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

less massive galaxies (dSph) are older: upsizing
Galaxy properties versus Mass

← upsizing

youngest galaxies

<table>
<thead>
<tr>
<th>dSph</th>
<th>BCD</th>
<th>dIr/dE</th>
<th>Sp</th>
<th>S0</th>
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gas accretion

some wet mergers → ULIRGs

dry major mergers

galaxy mass