

# How Do GALAXIES GROW?

Context: HIERARCHICAL  
STRUCTURE EVOLUTION

Bottom-up sequence for dark matter  
is well established over  $10^6 - 10^{22} M_{\odot}$

SEMI-ANALYTICAL GALAXY  
FORMATION THEORY

is it dead?

Fundamental theory  $\rightarrow$  generic predictions

phenomenological theory  $\rightarrow$  data modelling

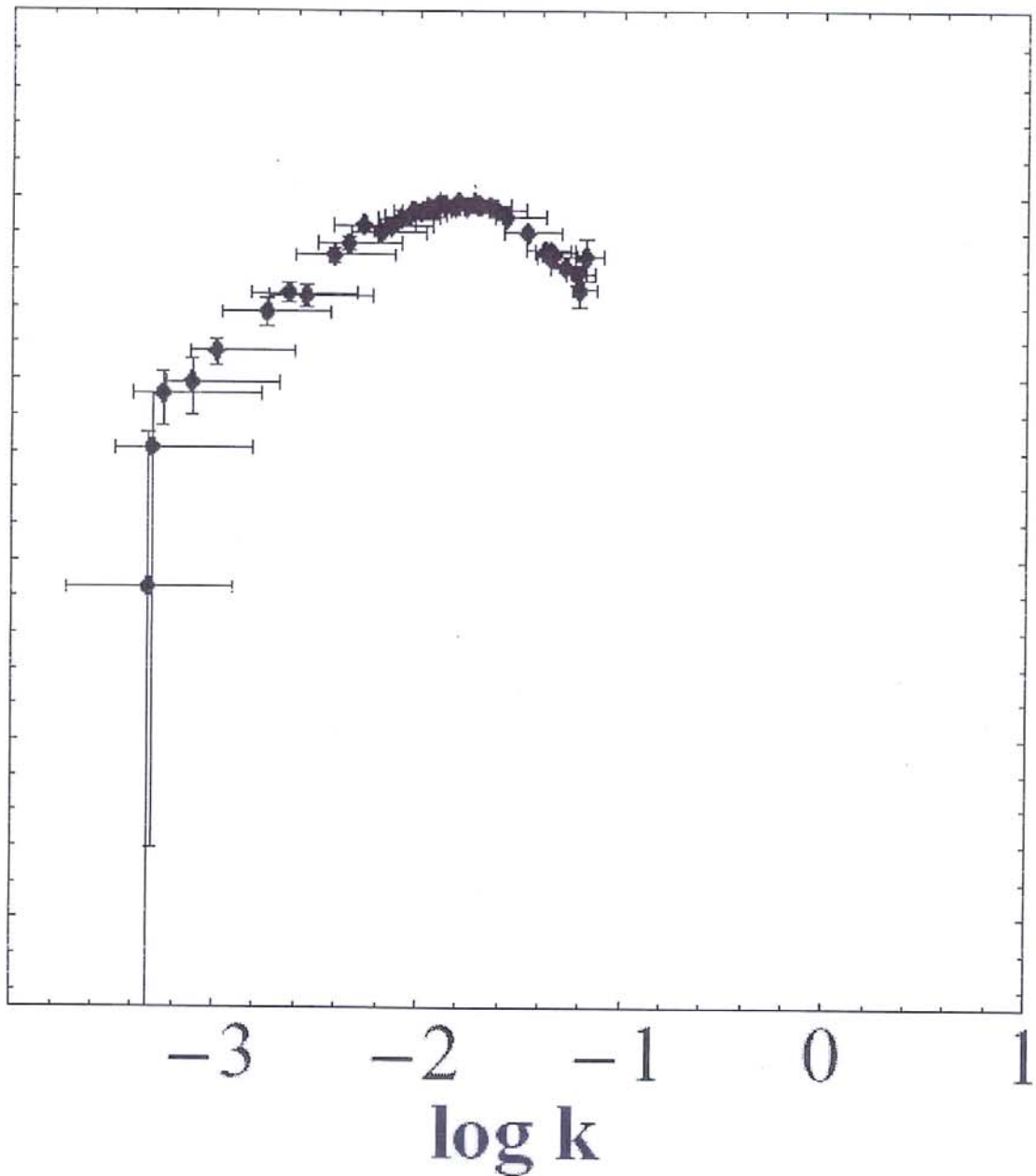
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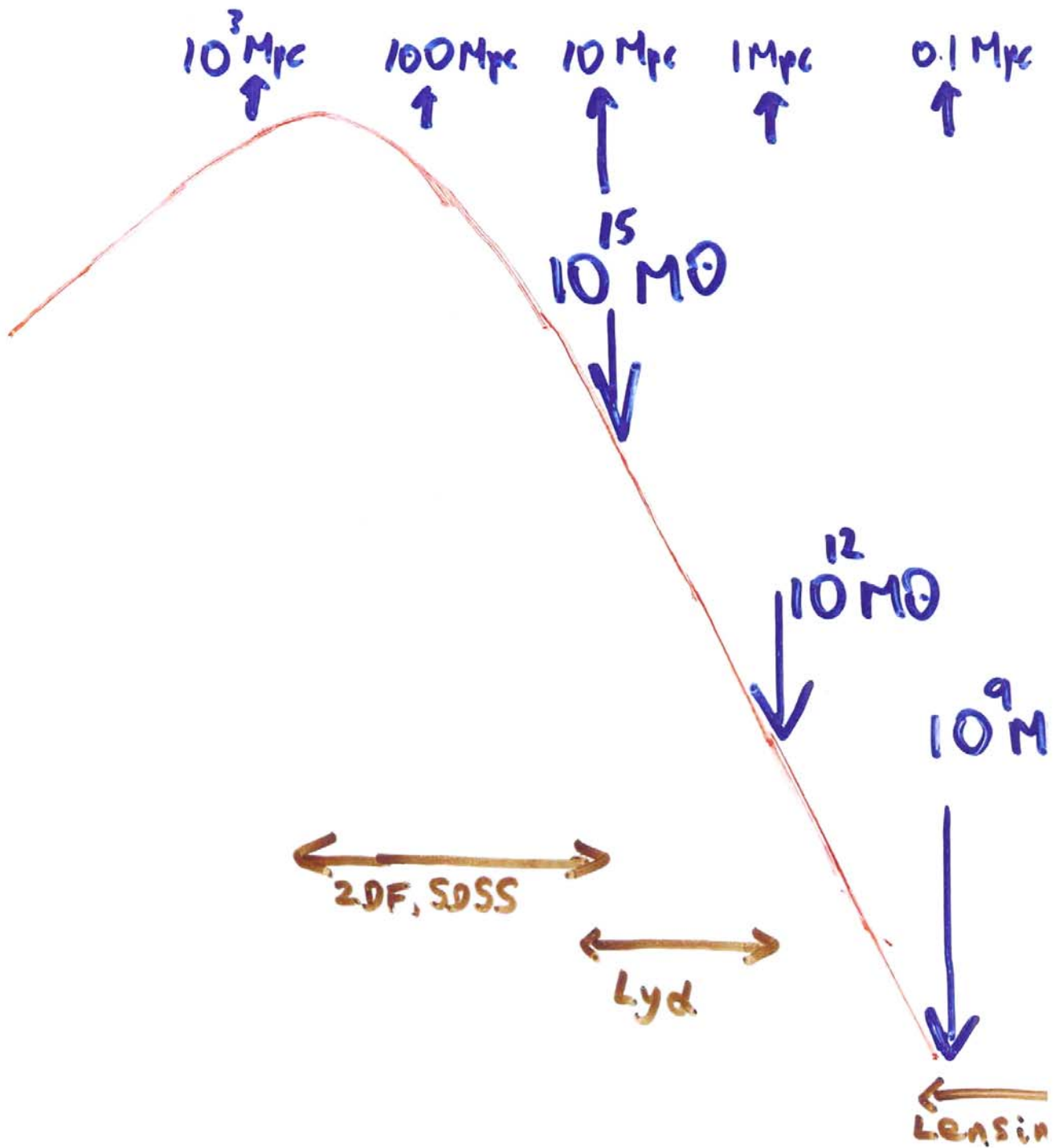


data simulation.

D. Tocchini-Valenti, M. Doustis, J.S (2003)

POWER SPECTRUM of mass fluctuations  
from band power inversion of WMAP data





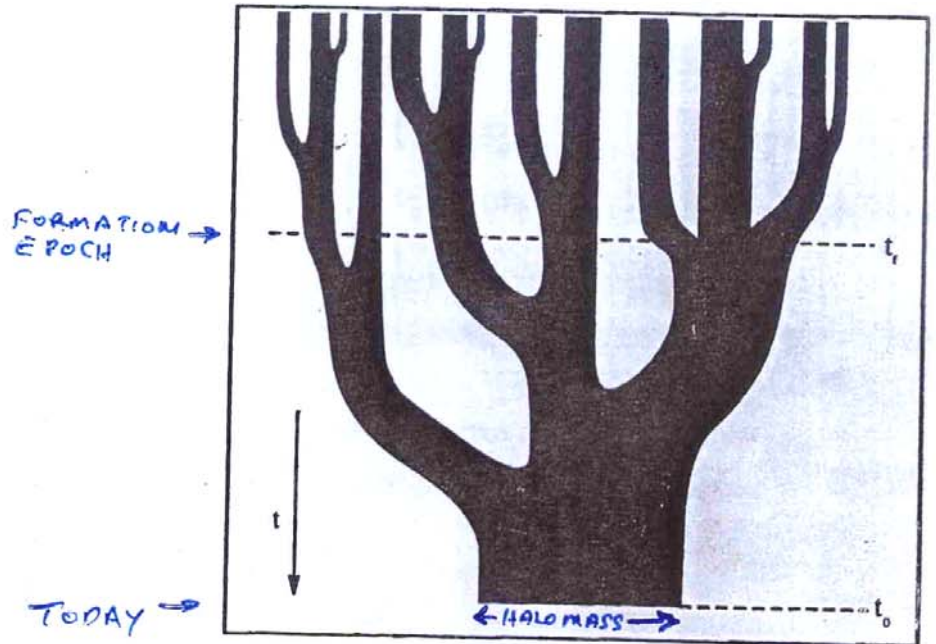


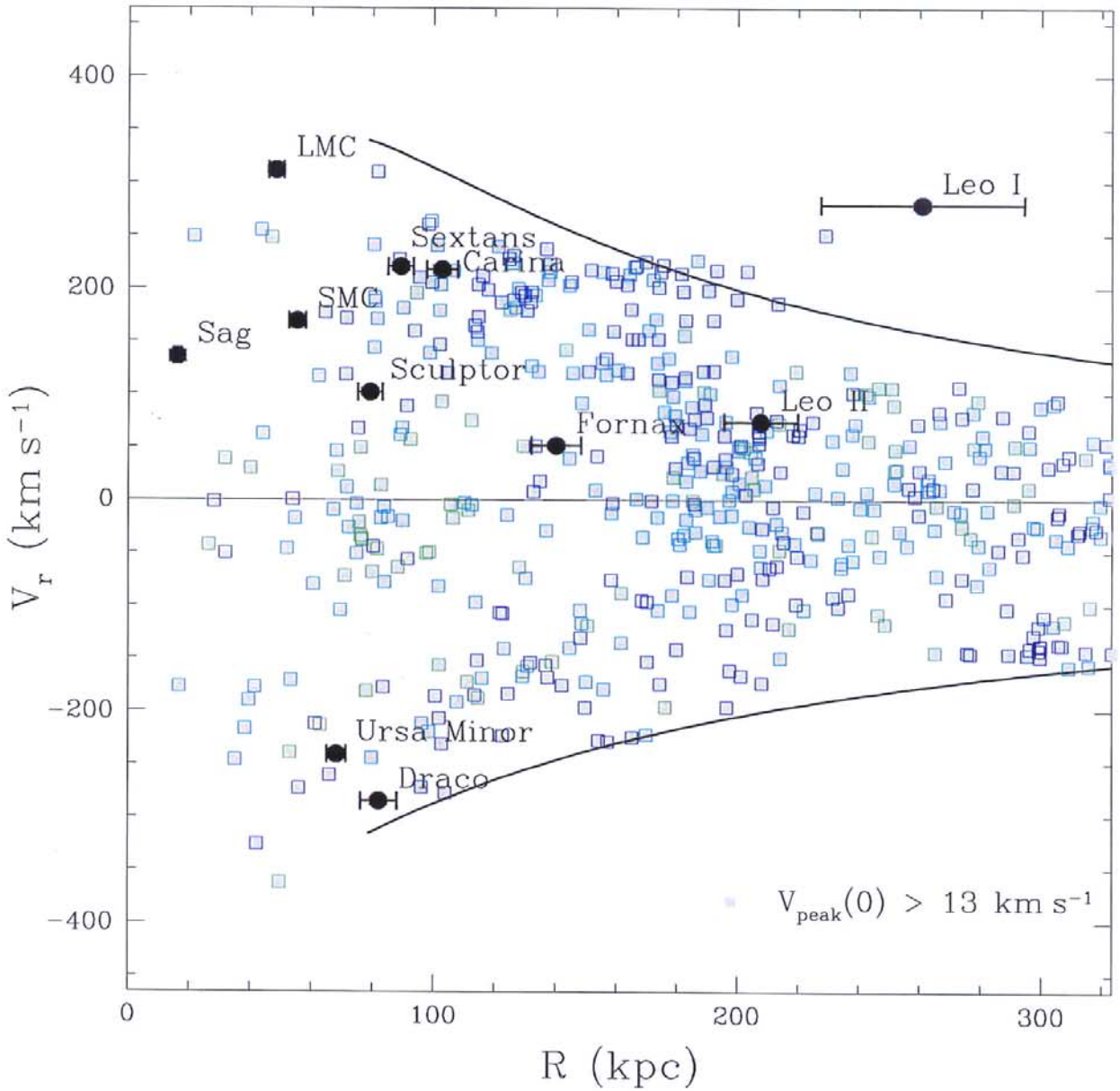
Figure 6. A schematic representation of a 'merger tree' depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent haloes. A slice through the tree horizontally gives the distribution of masses in the parent haloes at a given time. The present time  $t_0$  and the formation time  $t_f$  are marked by horizontal lines, where the formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.

Lacey and Cole  
 MNRAS 262 627 (1993)

# GENERIC PREDICTIONS

- merging of dark matter clumps
- halo substructure
  - minicaustics
  - satellites
  - tidal streams
- halo profiles and concentration
  - subject to modification
  - e.g. by bar heating or massive outflow
- galaxy clusters
  - substructure
  - profiler

J. Taylor, A. Babul, J.S. (2003)



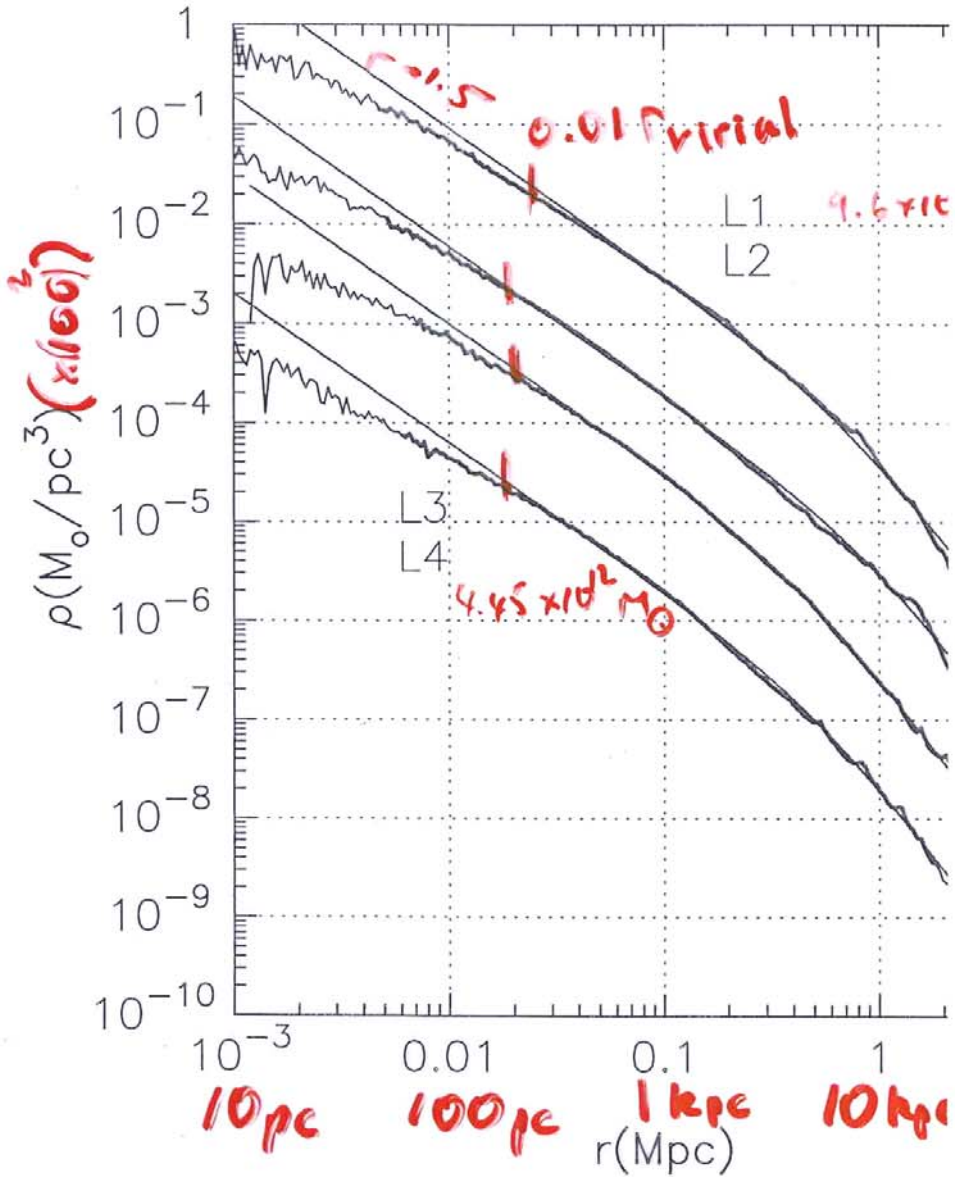
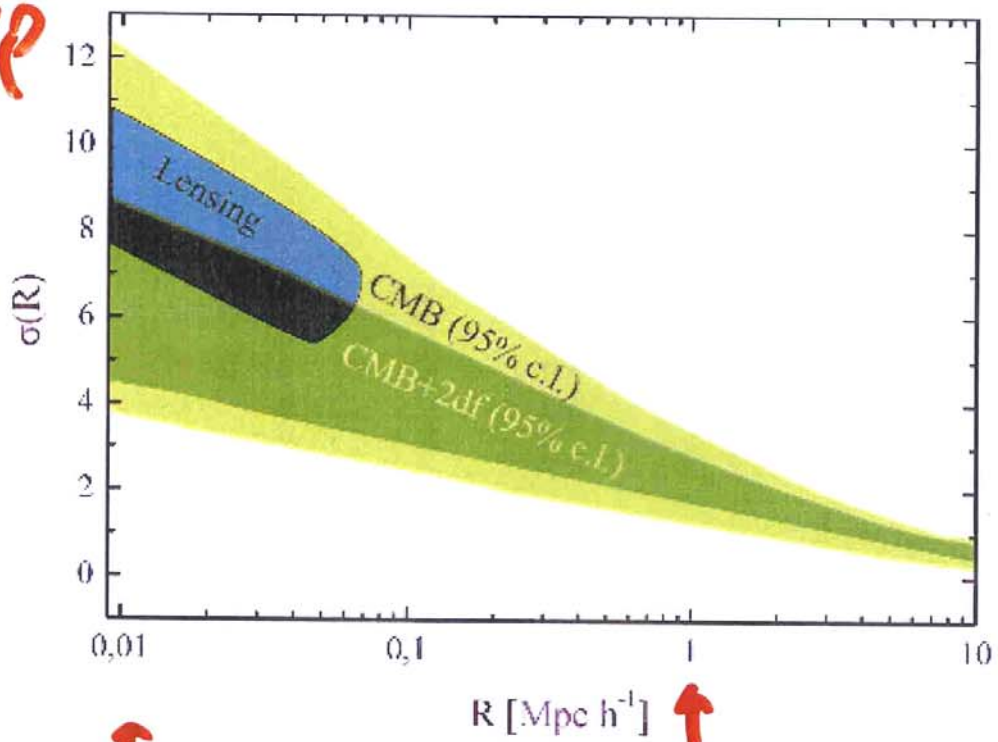


Fig. 4.— Same as Figure 3, but for the LCDM model.

Fukushige(etal) astrophy

" $\delta\rho/\rho$ "



$\uparrow$   
 $10^6 M_{\odot}$

$\uparrow$   
 $10^{12} M_{\odot}$

- first star formation at  $z \sim 20$ 
  - WMAP
- disk galaxies form inside out
  - phenomenological star formation rate
  - disk instability theory
  - angular momentum distribution of cold gas
- galaxies are smaller in the past
  - HST
- mergers were more frequent in the past
  - IRAS
- disk galaxies form by gas accretion + minor mergers
  - HI
- massive spheroids form by gas-rich major mergers
  - ULIRGs

WE ARE UNABLE TO  
MAKE THE STEP FROM  
PHENOMENOLOGY  
TO  
FUNDAMENTAL THEORY



Semi-analytical galaxy formation  
implements these predictions  
by adding  
phenomenologically-motivated  
but simplistic rules for star formation  
to N-body simulations

It has been known for a decade  
that the resulting galaxy formation  
theory is NOT bottom-up

THE DARK MATTER HIERARCHY MUST  
BE INVERTED  
massive galaxies are red, old and  
metal-rich

dwarfs are blue, young and  
metal-poor

Conversion of baryons into stars is a complex, poorly understood process.

Key ingredients of star formation theory are

Initial Mass Function

Star Formation Efficiency

Star Formation Rate

Chemical Yields

No theory.  
Local data.

Phenomenology

Phenomenology

Theory  
+ data.



# YIELDS

Is there a Pop III signature?

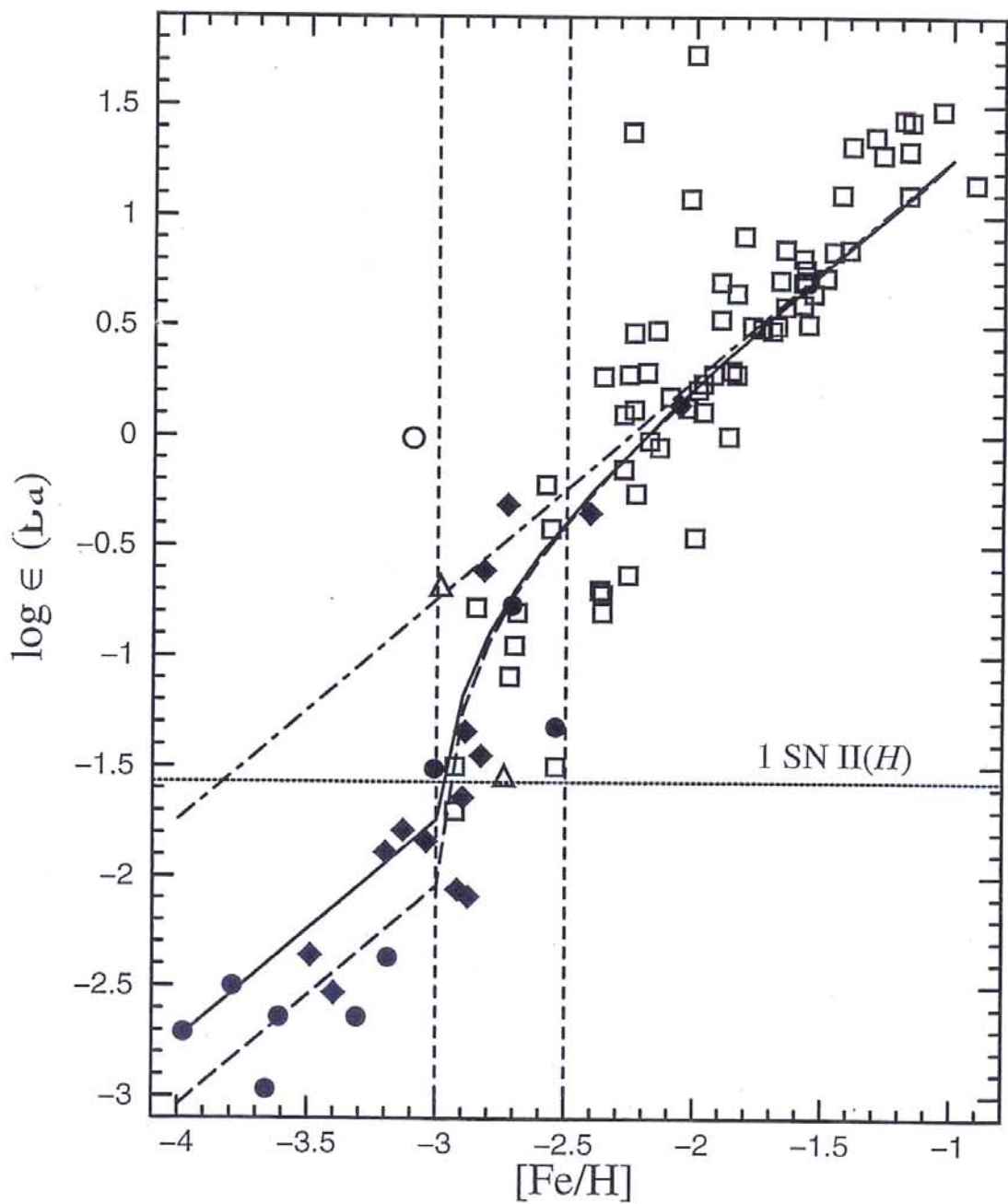
Signature of 100  $M_{\odot}$   $Z=0$  stars  
is not seen in metal poor halo

But what possibly is seen

is a hypernova signature

enhanced  $Zn, Cr$  at

$[Fe/M] \sim -3$  produced by  $E \sim 10^{53}$   
one  $\sim 30 M_{\odot}$  stars that form b.h.  $10^{51}$  ergs  
and a  $\Gamma$  process signature  
(produced by ?)



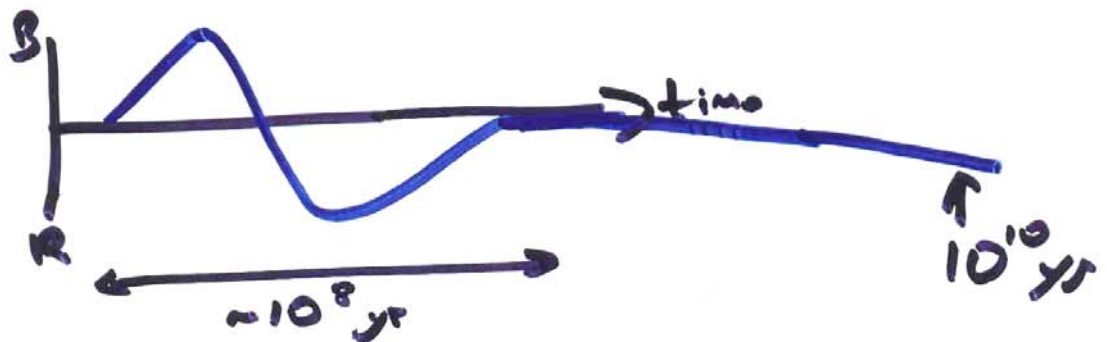
Qian & Wasserburg  
Astrophys. J. 567 (2002)

# IMF

what is it in the early universe?

Solar neighbourhood may be a poor guide  
with new surveys, we  
can probe a top-heavy IMF

at  $z \approx 2-3$  since galaxy colours change



- excessively red (AGB) briefly
- accelerated return to 'normal' colour
- could even leave 'ghost' galaxy
- ultraluminous starburst
- holes in HI disks in outer galaxy

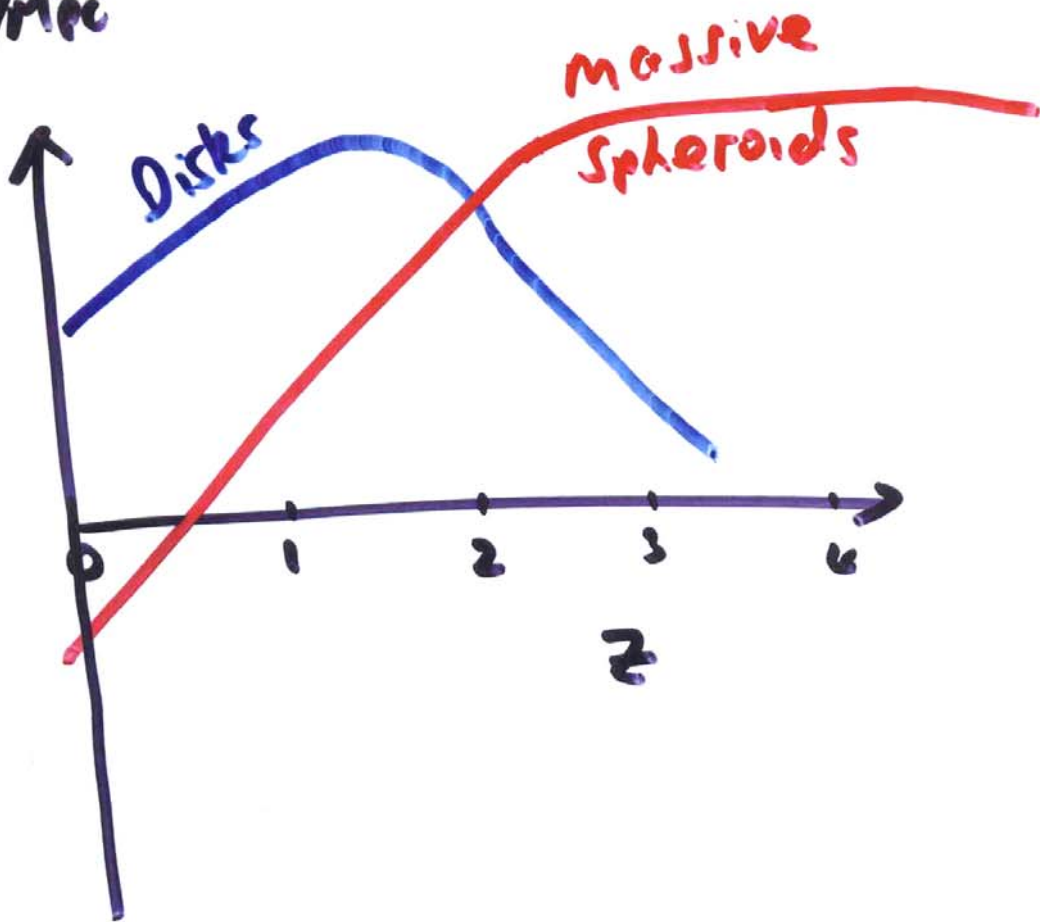
# SFR

is cosmic star formation history  
in conflict with passive evolution  
& nearly constant (to  $\times 2$ ) stellar mass  
over  $z = 0-2$ ?

- Disk and spheroidal colours motivated bimodal star formation
- Revisit this - motivated by merger history
- K band selection may not be enough to get total star formation rate - need FIR too

# MERGER-INSPIRED SFR HISTORY

SFR/Mpc<sup>3</sup>



- rapid rise of the AGN
- severe bias if sampling depends on SFR mode



# SFE

fraction of gas forming stars  
per dynamical time

- needs to be high in massive galaxies to account for red colours at  $z \sim 1-2$  but low in dwarfs: from  $\sim 1$  to  $\sim 0.01$

- SFE increase in massive spheroids suggested at  $z \sim 0$  (SDSS)

- A challenge for theory:

Negative feedback from

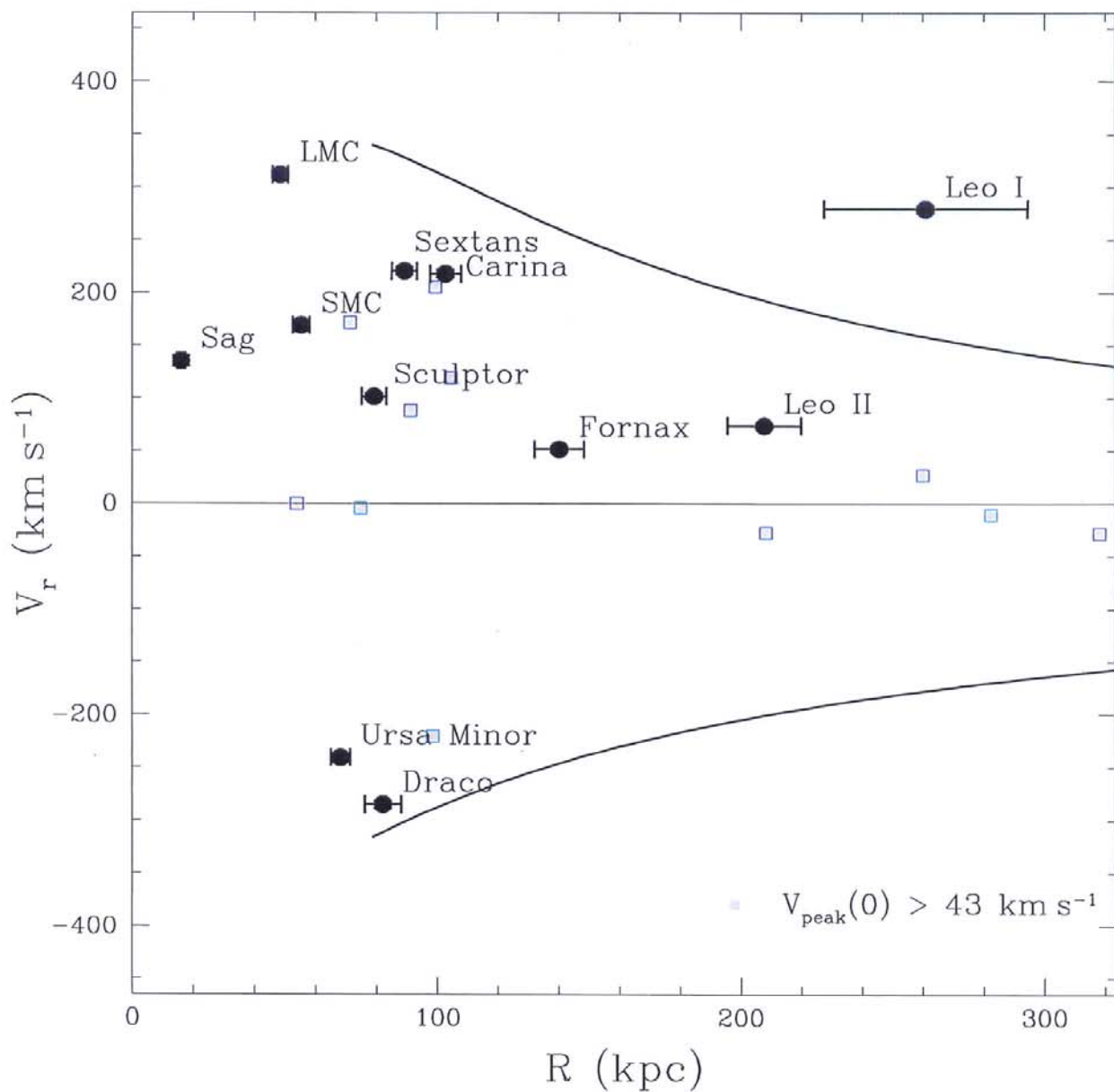
SN-driven winds works for low SFE in dwarfs

multiphase porosity of  $\propto \sigma^{-2.7}$

Positive feedback may be needed in massive galaxies

This could come from  
SMGH-accretion driven outflows

J. Taylor et al. (2003)



# ~~THE AGN CONNECTION~~ THE AGN CONNECTION I

- SMBH growth saturates the

$$M_{\text{SMBH}} \propto \sigma^{4-5} \text{ relation}$$

- Positive feedback on star formation produces a burst that reduces dispersion in  $M_{\text{SMBH}}, \sigma$  relation

- Expect a wind with

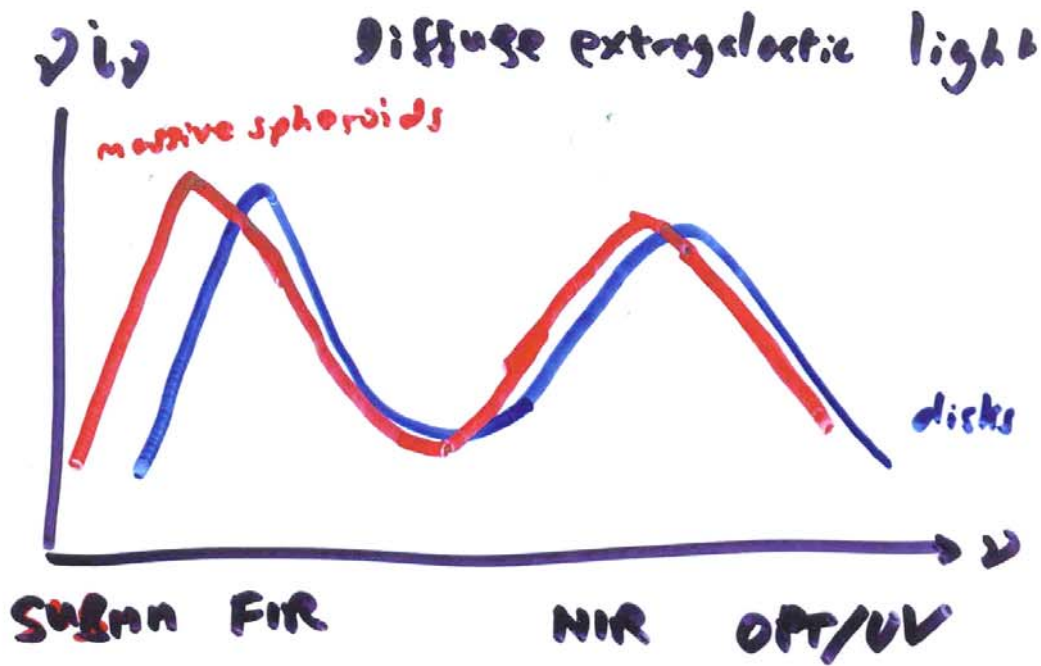
$$\dot{M}_{\text{outflow}} \sim \dot{M}_* \text{ which}$$

will solve 2 problems (if ejection from b

- where are  $\sim 1/2$  the baryons?

- overcooling in massive holes

# WHERE ARE THE STARS?



stellar mass:

$$\propto \nu I_\nu \times (1 + z_{95})$$

$$\Omega_* = 0.007$$

7.5%

$$\Omega_* = 0.0015$$

4%

compared to  $\Omega_b = 0.04$

I COBE  
FRAS  
?  
SIRTF  
π

DIRGE  
I I HST  
ø  
I ISO

I ROSAT

most baryons today are in

ICM 10%

Ly $\alpha$  Forest 20%

WHIM  $\sim$ 40%

GALAXY FORMATION WAS

AN INEFFICIENT PROCESS

YET MASSIVE GALAXIES

FORMED EFFICIENTLY