From the End of the Dark Ages to Now

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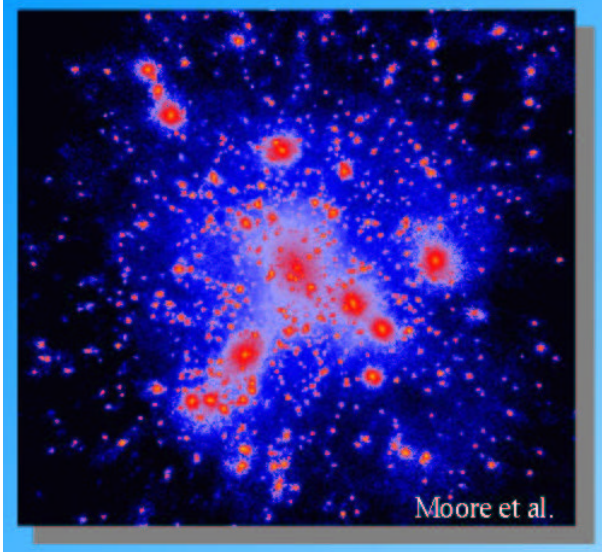
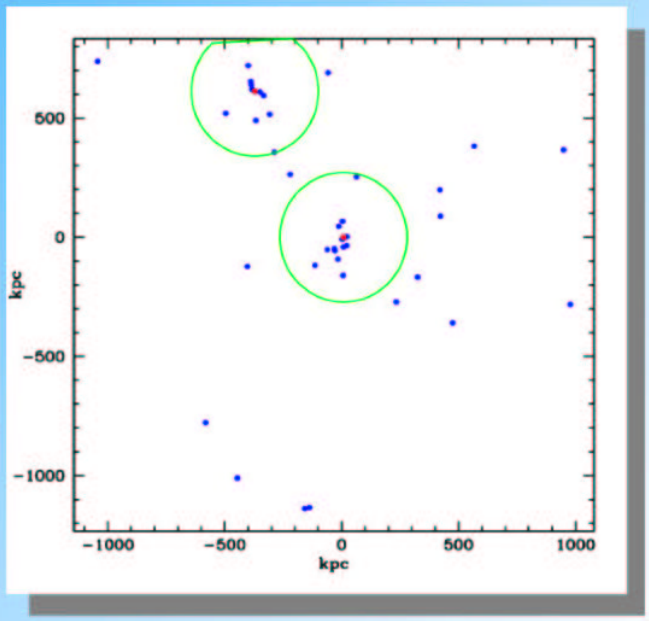
Talk Overview

- Dwarf galaxies and CDM (a crisis or not)
  - *A model of photoionization suppression (Ph.S.)*
  - *How many dwarfs in the Local Group?*
- Statistics of neutral regions close to reionization
  - *Frequency of neutral regions as a function of length*
  - *Cross- correlations of neutral regions and ionizing sources*
- Other consequences of Ph.S.
  - *Heating of galactic disks*
  - *Environmental variations.....?*
- Relation between galaxies and DM (a.k.a. bias)
  - *Voids*
  - *Halo Occupation Distributions*
- Conclusions
  - *What are the successes? Where do problems still exist?*

Subhalo Abundances in CDM



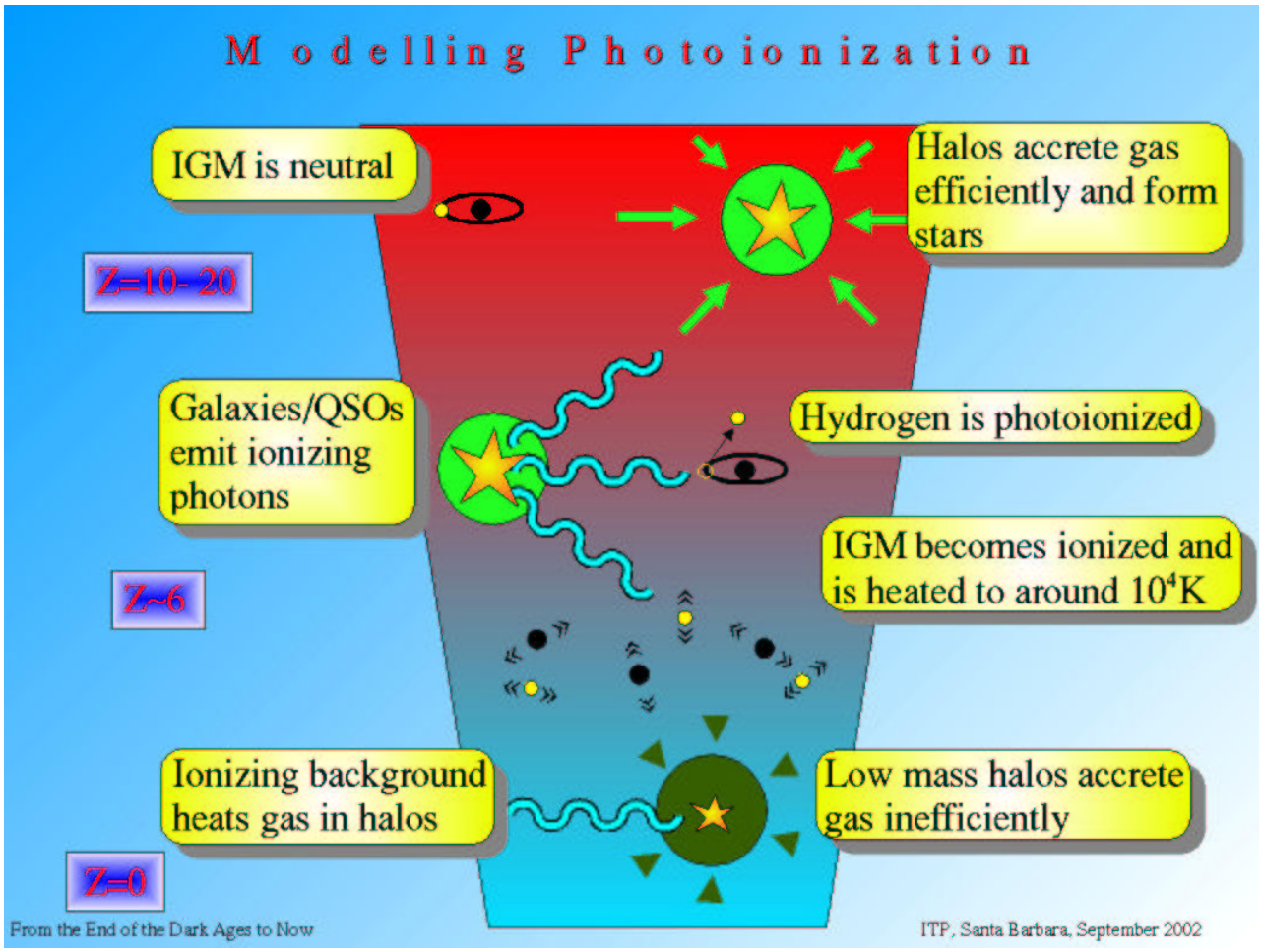
Simulated Galactic halo: Lots of substructure



Local Group: Not very much substructure...

Possible solutions

- Change the nature of the dark matter or the initial power spectrum to remove small- scale power
  - *WDM, SIDM, Broken scale invariance*
  - *Tight constraints from high- redshift Lyman- α forest*
  - *Would these match the observed velocity dispersions* (Stoehr et al.)*?*
- Supernovae explosions
  - *Standard ingredient in many galaxy formation models to produce a shallow LF*
  - *Needs to be much stronger than typically assumed to explain Local Group - problem with mass- to- light ratios?*
- Effects of reionization (e.g. Bullock, Kravtsov & Weinberg)
  - *Suppresses low- mass galaxies at low redshifts (only those forming at high- z are observed)*
  - *Simple calculations suggest this may work*
  - *Physics is well understood....*
  - *....and is unavoidable so should be accounted for!*


Modelling Photoionization
IGM is neutral
Halos accrete gas efficiently and form stars
Z=10-20
Galaxies/QSOs emit ionizing photons
Hydrogen is photoionized
IGM becomes ionized and is heated to around 10^4K
Z~6
Ionizing background heats gas in halos
Low mass halos accrete gas inefficiently
Z=0
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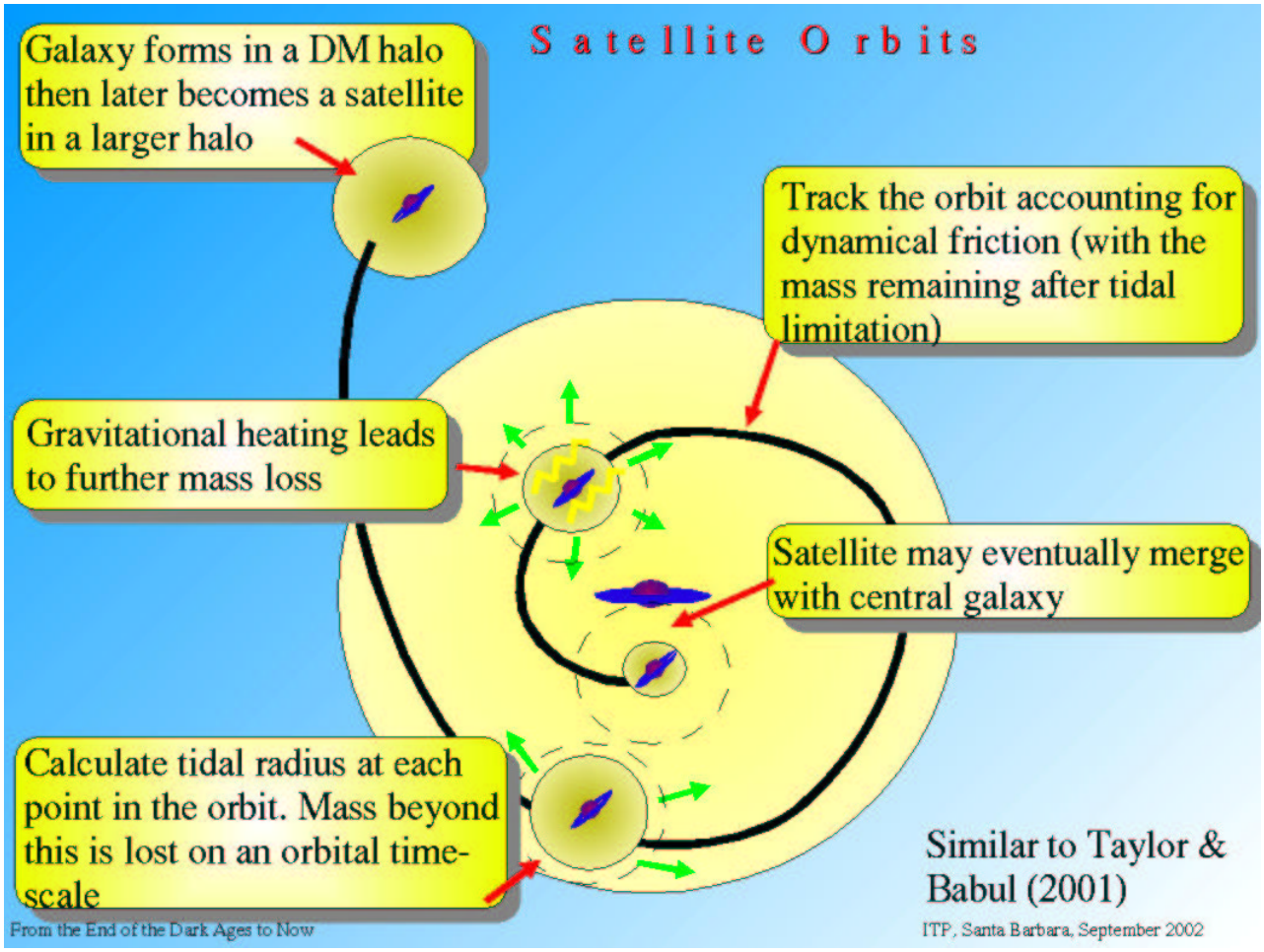
Satellite Orbits
Galaxy forms in a DM halo then later becomes a satellite in a larger halo
Track the orbit accounting for dynamical friction (with the mass remaining after tidal limitation)
Gravitational heating leads to further mass loss
Satellite may eventually merge with central galaxy
Calculate tidal radius at each point in the orbit. Mass beyond this is lost on an orbital time-scale
Similar to Taylor & Babul (2001)
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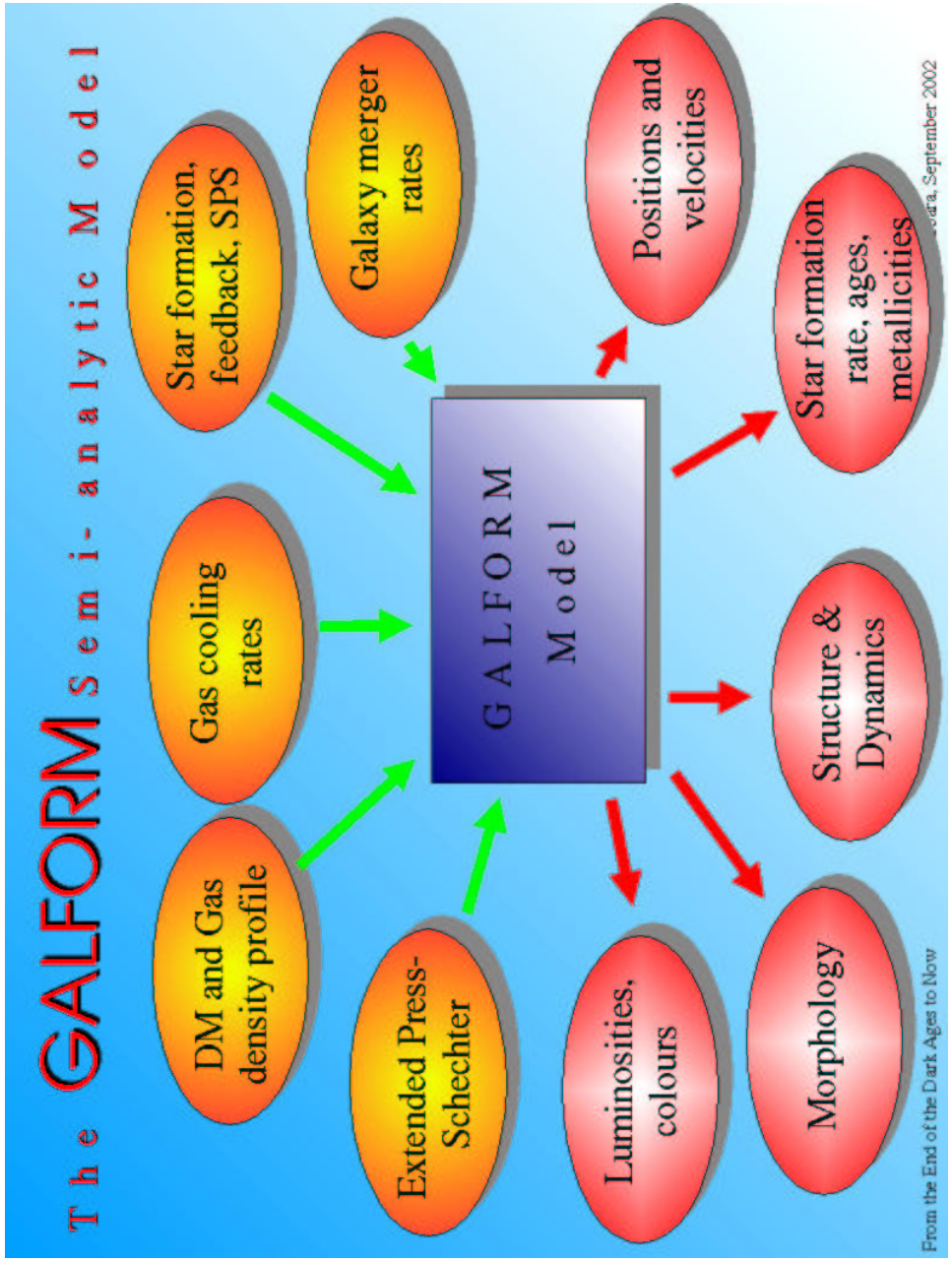
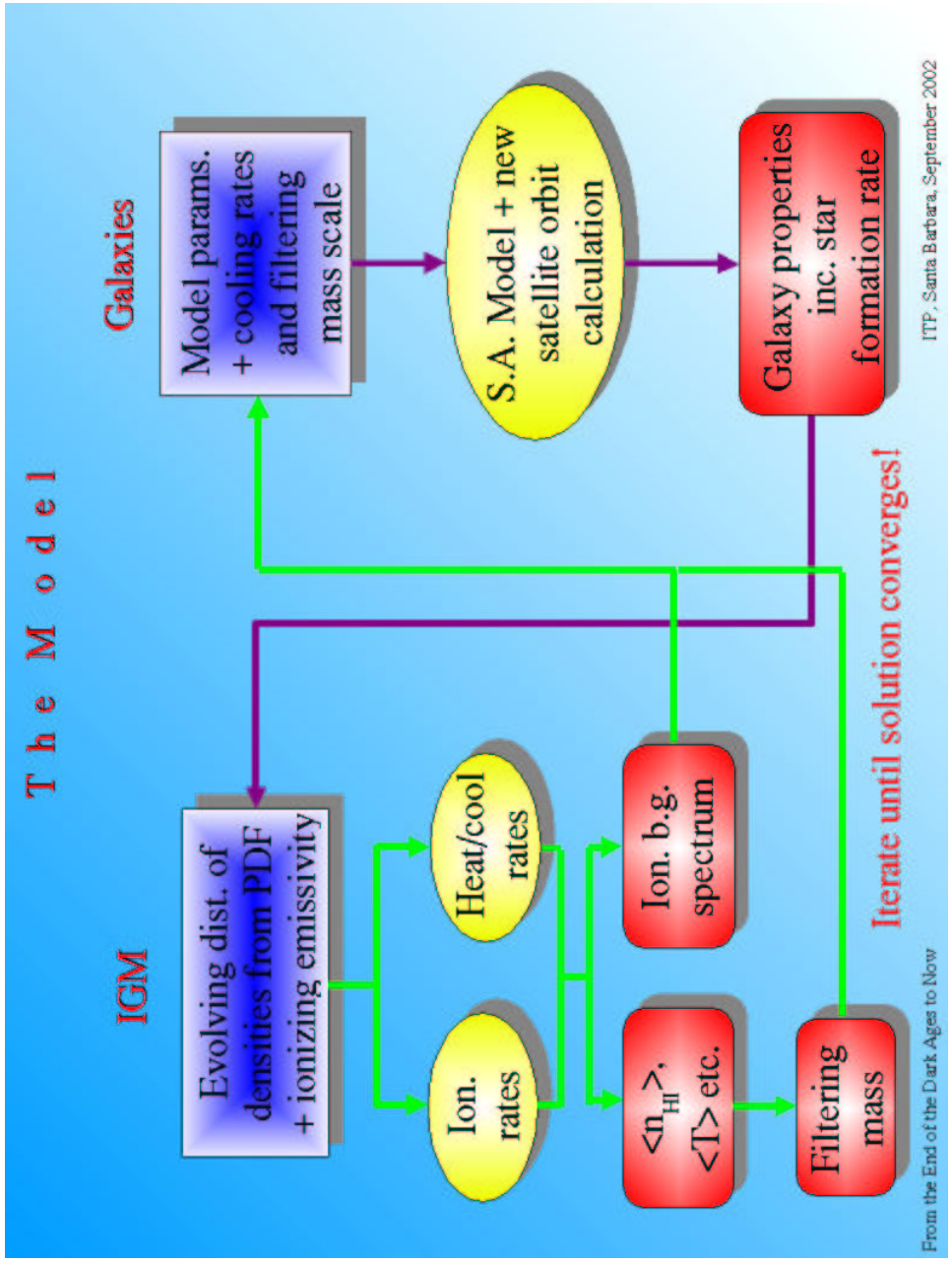

The GALFORM Semi-analytic Model
Star formation, feedback, SPS
Galaxy merger rates
Gas cooling rates
DM and Gas density profile
Extended Press-Schechter
GALFORM Model
Positions and velocities
Star formation rate, ages, metallicities
Structure & Dynamics
Luminosities, colours
Morphology
From the End of the Dark Ages to Now


The Model
IGM
Galaxies
Evolving dist. of densities from PDF + ionizing emissivity
Model params. + cooling rates and filtering mass scale
S.A. Model + new satellite orbit calculation
Galaxy properties inc. star formation rate
Heat/cool rates
Ion. rates
Ion. b.g. spectrum
<n_HI>, <T> etc.
Filtering mass
Iterate until solution converges!
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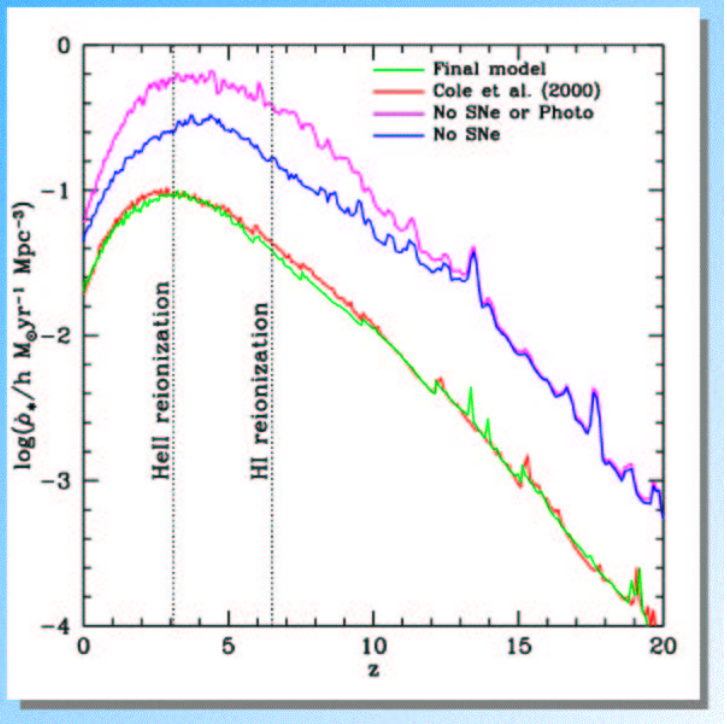
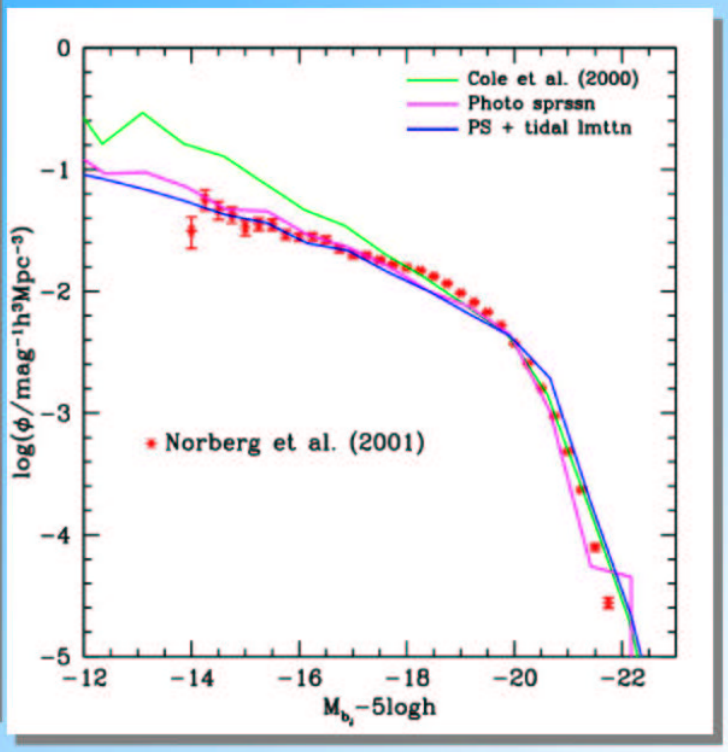
Global: Effects on the SFR

- Small (~10- 25%) reduction in SFR after each episode of reheating
- SFR then recovers to value with no reheating
- With no SNe or suppression feedback SFR is much higher
- Then photo- supression is much larger
  - *Low mass halos now contribute significantly to SFR*
  - *Photo- supression stops them forming stars, resulting in a large drop in SFR*



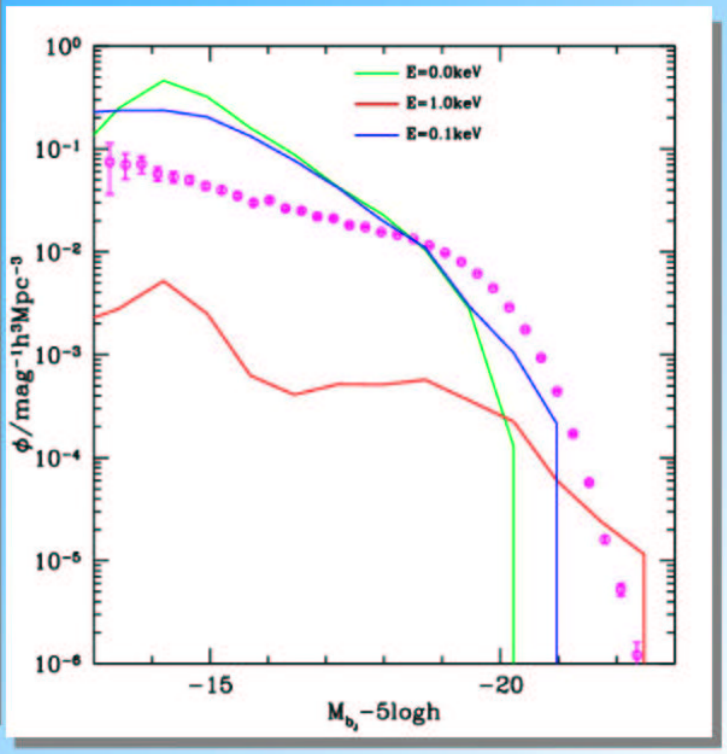
Global: Luminosity Functions at z = 0

- Previous model had LF slightly too steep
- Photo- supression flattens the faint end and has little effect on bright galaxies
- Adding in tidal limitation makes a further small flattening
- Results in good agreement with the data



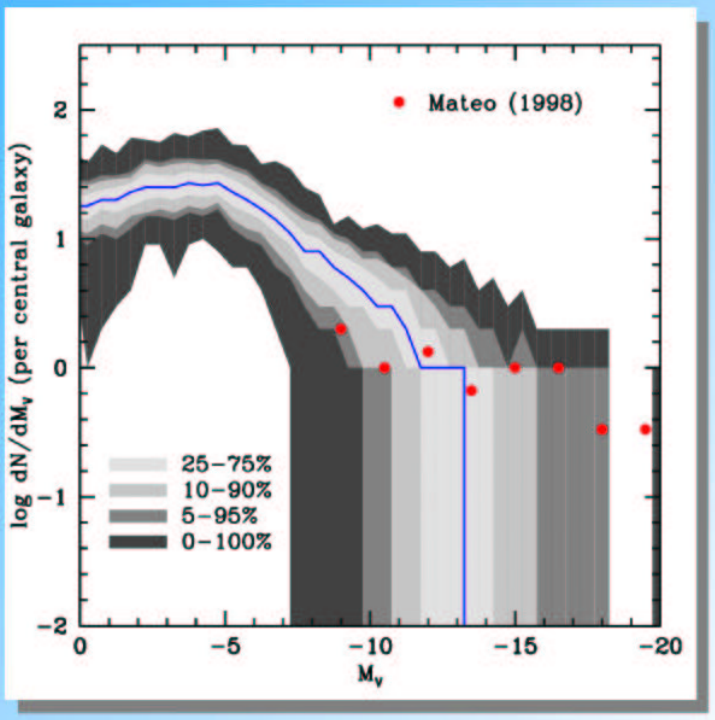
Global: Effects of Preheating

- Mori, Ferrara & Madau found IGM temperatures of 0.1- 1.0 keV at z~9.
- Track temperature evolution.....
- .....and filtering mass evolution
- Results in strong supression of the luminosity function

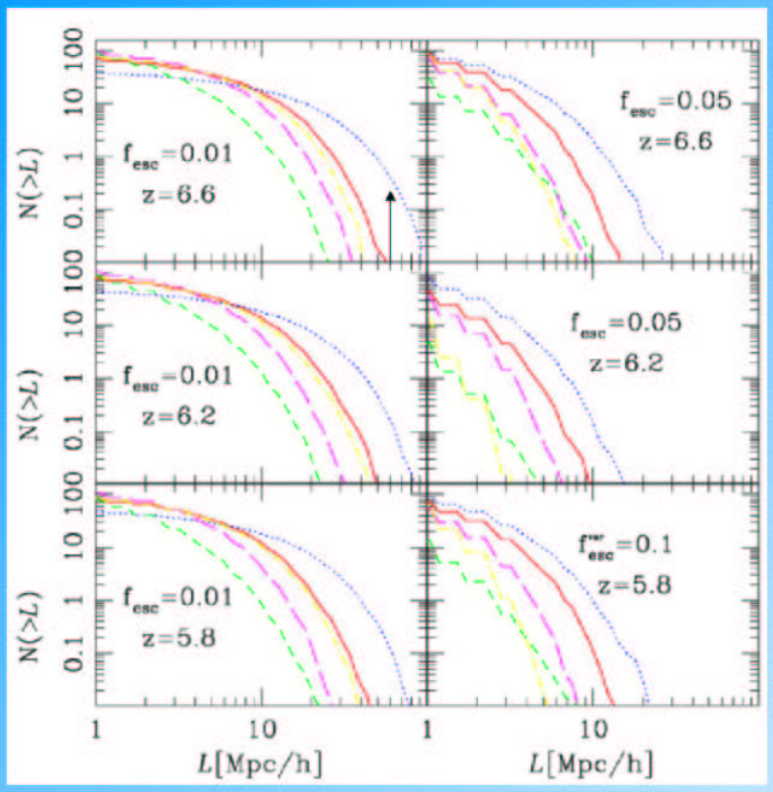


Local Group: Luminosity Function

- Luminosity function of galaxies within virial radius of MW or M31
- Previous model overpredicts abundances
- Tidal limitation a small effect
- Photo- supression greatly reduces abundances....
- ...but shape of luminosity function differs from data



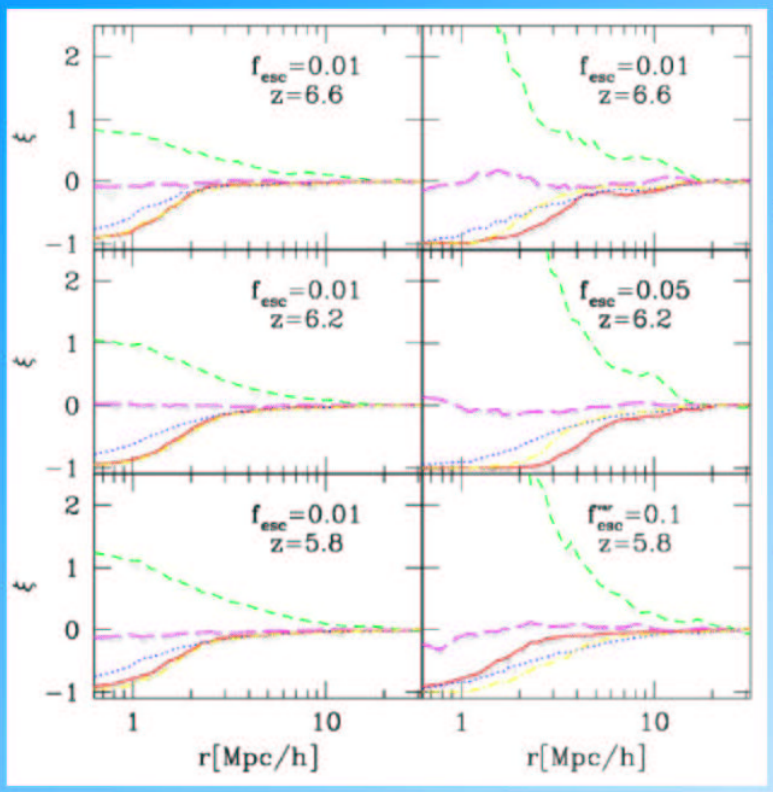
Approaching Reionization: HI Regions



High Density
Spheres
Boundary
Random
Low Density

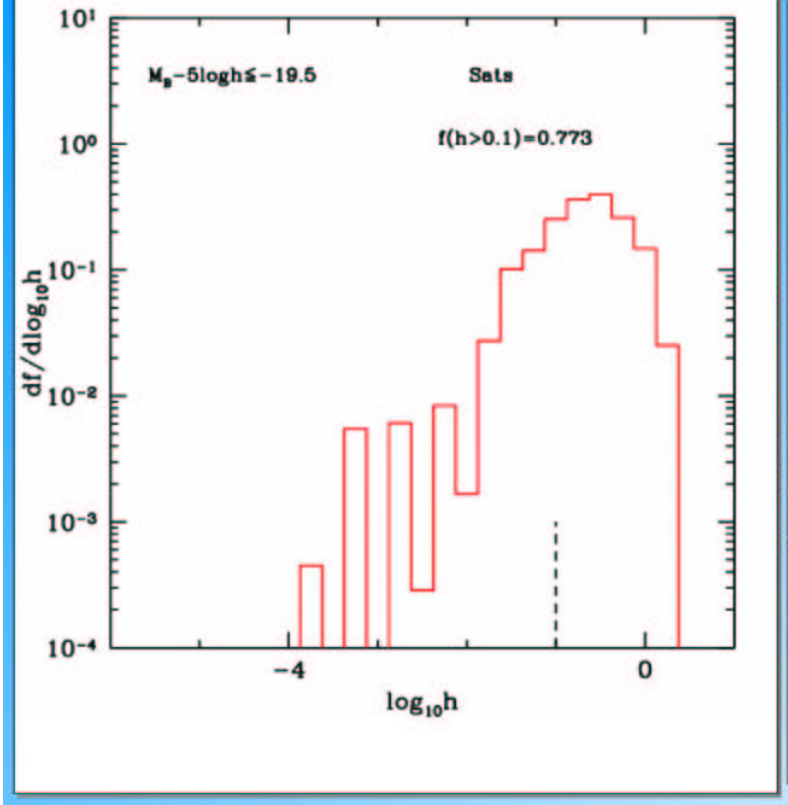
- Number of HI regions in 565Mpc/h length of a QSO spectrum
- Evolution of this function with redshift will constrain epoch of reionization...
- ...and the geometry of reionization

HI/Ionizing Source Cross Correlations



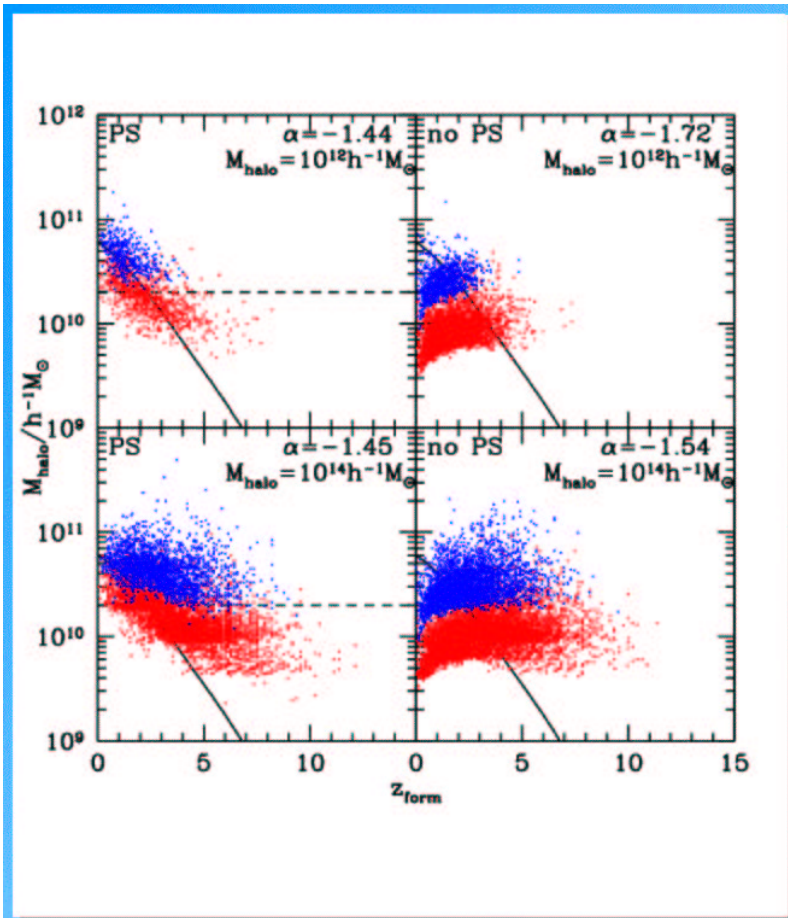
High Density
Spheres
Boundary
Random
Low Density

- Cross correlation of bright ionizing sources with neutral regions
- Shows a clear difference between high and low density models



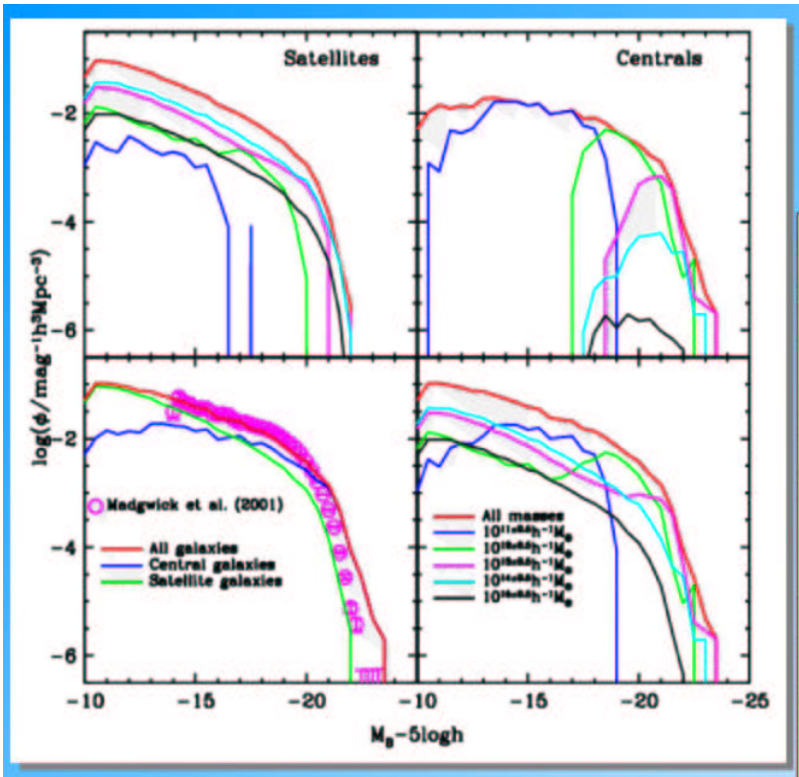
Disk Heating

- Can substructure be ruled out by its effects on thin galactic disks?
- Detailed orbit model allows heating rate to be calculated quite accurately
- Disk scale height distribution due to substructure heating...
- ...and including heating by star- cloud scattering (Lacey 1984)



Environmental Variations

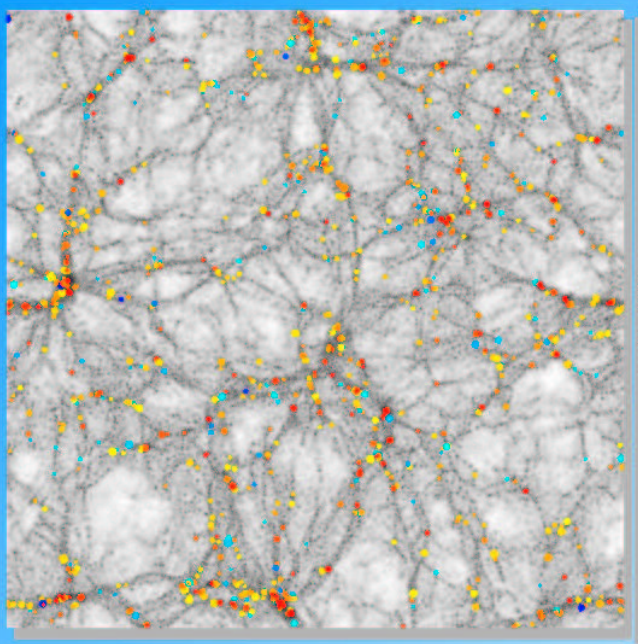
- Luminosity function slope seen to steepen in dense environments
  - *Photo- suppression effect?*
  - *Dwarfs in clusters form early - implies less suppression*
- No strong environmental variation
  - *Does reduce number of dwarf galaxies, but.....*
  - *....makes new ones as well*

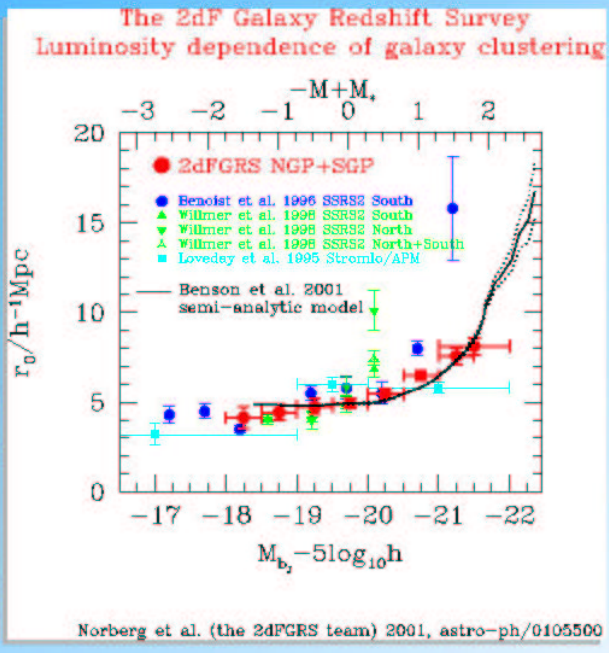


Building the LF

- Luminosity function split into satellite/central contributions
- Centrals dominate at bright magnitudes
- Faint end slope set by central luminosity/halo mass relation *not* by slope of satellite population LF

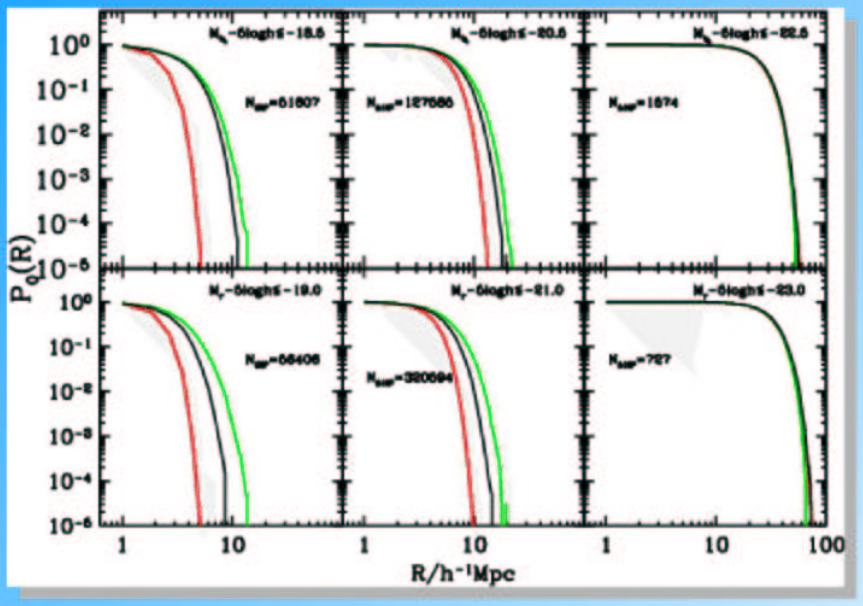
Galaxy Clustering





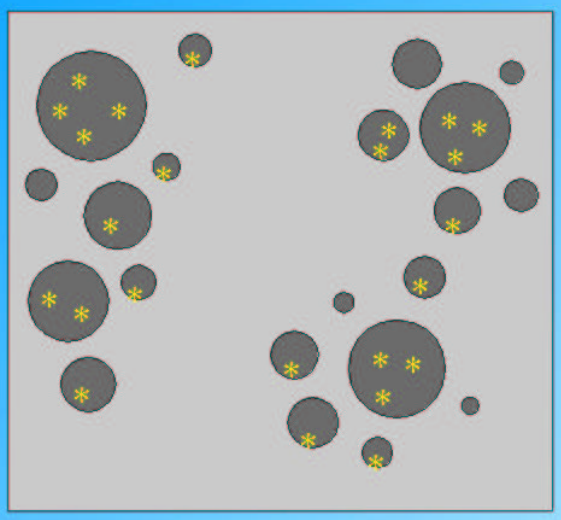
- Galaxy formation models describe where galaxies live in the LSS
- Great success at making *quantitative predictions*

Void Probability Function



- Made predictions for many void statistics (not clear which will prove most interesting)
- VPF is probability of a randomly placed sphere containing no galaxies

The Halo Model of Clustering



- Galaxies live in DM halos
- Spatial distribution and internal structure of halos known
- Given a model which tells us how many galaxies to place in each halo we can therefore build up the spatial distribution of galaxies
- Define $P(N;M)$ - probability to get N galaxies (of some particular type) in a halo of total mass M

- Use this to fill halos in N- body simulation with galaxies (e.g. Benson et al. 2000), or use in analytic calculations (see Cooray & Sheth review article)

What Can You Do With P(N;M)?

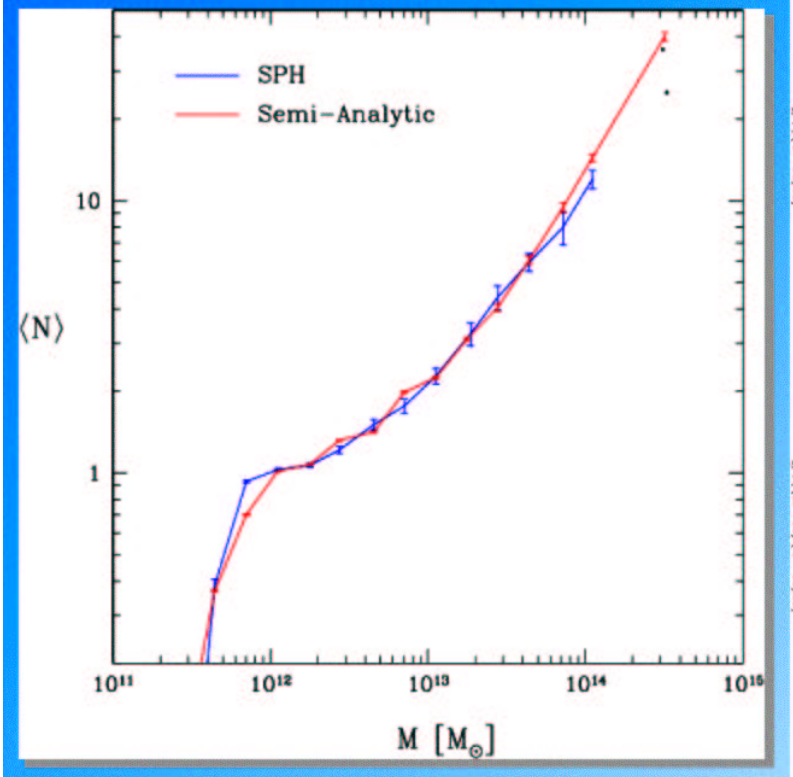
* Given P(N;M) and the distribution of dark matter halos you can predict *any* property depending on the spatial distribution of the galaxies. For example, the two-point correlation function is:

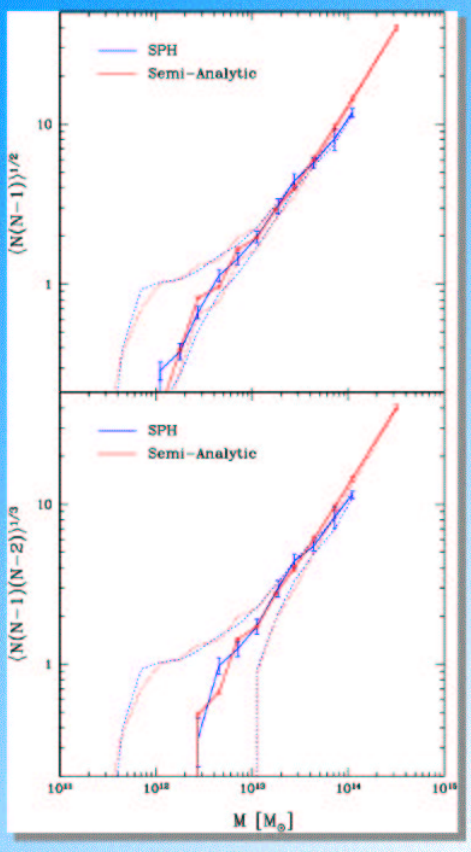
$$\xi(r) = \int_0^\infty \int_0^\infty \xi_{12}(r) \frac{\bar{N}(M_1)\bar{N}(M_2)}{n_{\rm gal}^2} \frac{{\rm d}n}{{\rm d}M}(M_1) \frac{{\rm d}n}{{\rm d}M}(M_2) {\rm d}M_1 {\rm d}M_2$$

$$\bar{N}(M) = \sum_{N=0}^{\infty} N P(N;M) \qquad \overline{N(N-1)}(M) = \sum_{N=0}^{\infty} N(N-1) P(N;M)$$

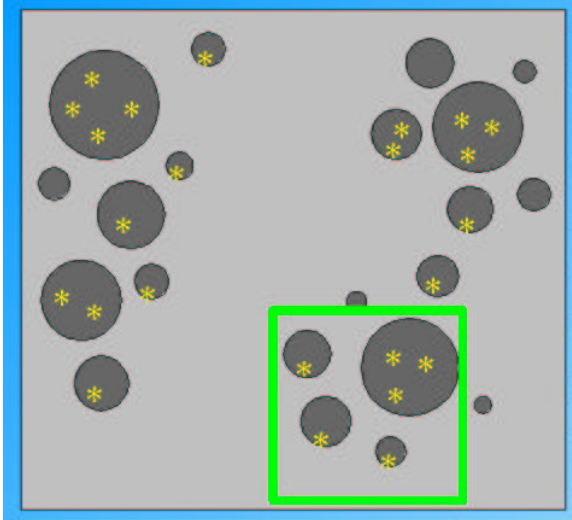
* P(N;M) is therefore a *complete* description of bias (fully describes any non-linearity, stochasticity, scale dependence, higher-order biases etc. etc.)
* Has a readily understandable physical meaning:
  - b_{gal}=1.3..... so what?
  - $P(1;10^{12}M_\odot)$=0.5..... so half of galactic-sized halos contain 1 galaxy

Theoretical Expectations - III





Direct Measurements of $P(N;M)$



- Counts- in- cells has a particularly simple relation to $P(N;M)$
- Measure probability to find N galaxies in a cell of volume V - $S_V(N)$
- Assume we know the distribution of DM halos, so probability to have N_1 of mass M_1, N_2 of mass M_2 etc. in the cell is $Q_V(N_1,N_2,.....)$
- Derive relationships between $S(N)$ and $P(N;M)$ and $Q_V(N_1,N_2,.....)$

Example:

$$S_V(0) = Q(0,0,\ldots) + Q(1,0,\ldots)P(0;M_1) + Q(0,1,\ldots)P(0;M_2) + Q(1,1,\ldots)P(0;M_1)P(0;M_2) + Q(2,0,\ldots)P(0;M_1)^2 + \ldots$$

$$S_V(0) = \sum_{N_1=0}^{\infty}\sum_{N_2=0}^{\infty}\cdots\sum_{N_n=0}^{\infty} Q(N_1,N_2,\ldots,N_n)\prod_{j=1}^{n} P_j^{N_j}(0)$$

- Similar (but more complex) expressions for $S(N>0)$
- Can solve for $P(N;M)$
- For N bins in mass, we need measurements of $S_V(N)$ for N different cell sizes

Conclusions: What's Been Done

- Self- consistent model for evolution of galaxies and the IGM
  - *Photoheating/ionization of IGM by galaxies*
  - *Suppression of galaxy formation*
  - *Dynamical effects on satellite galaxies*
- Flattens luminosity function slope - good agreement with latest observational data (+ constrains preheating)
- Photoionization does help resolve satellite abundance problem... but LF/VF shapes differ....
- Demonstrates how the global LF is built from those of individual halos

Conclusions: Successes & Failures

- Successes for CDM+photoionization suppression picture...
  - *Flattens global luminosity function - good agreement with data*
  - *Reduces abundances of Local Group satellites by a factor ~8*
  - *Heating rate of galactic disks predicts typical H/R≃0.2*
  - *Velocity dispersions of LG satellites accounted for* (Stoehr et al.)
  - *Lensing rates agree with those expected* (Metcalf & Madau, Dalal & Kochanek, Chiba)
- ...and its failures
  - *Doesn't produce a sufficiently flat Local Group luminosity function*
  - *Can't explain observed variation in LF slope with environment*
- Modelling is robust, but some problems remain. So...
  - *Still a need to modify our picture of dark matter?*
  - *Still missing important physics for faint galaxies (star formation...?)*

Conclusions: Clustering & Bias

- Voids and void galaxies
  - *New surveys will provide the first robust measurements of void statistics*
  - *Have computed a variety of void statistics from our model.....*
  - *....plus properties of void galaxies*
  - *Unclear which will provide strongest constraints on models*
- Halo Occupation Statistics
  - *Very powerful way to study/measure galaxy bias*
  - *Completely general and physically intuitive*
  - *Should be directly measurable from redshift surveys*