Dark Matter on the Smallest Scales

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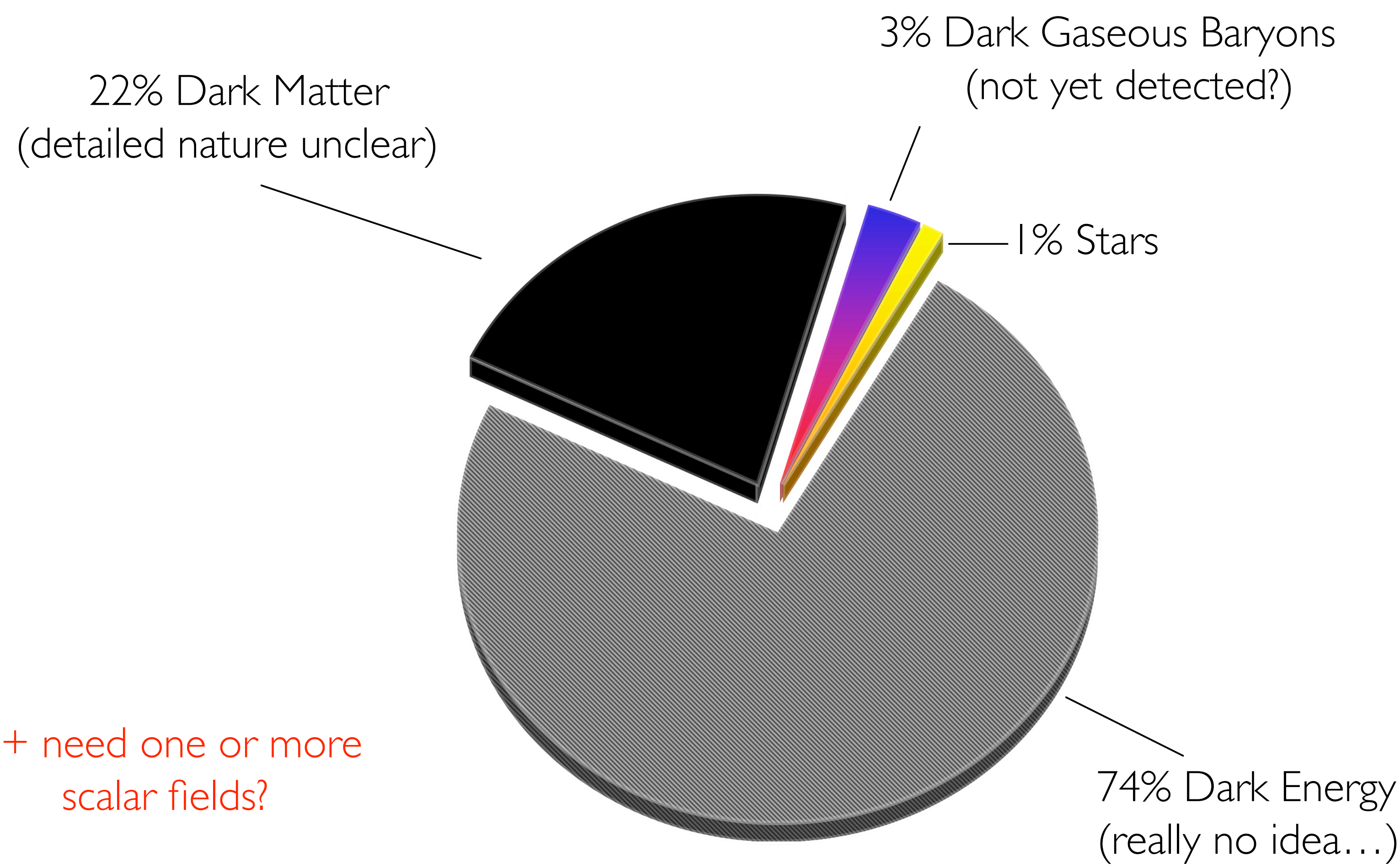
The Composition of the Universe (third quarter 2007)

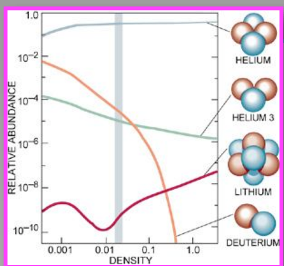


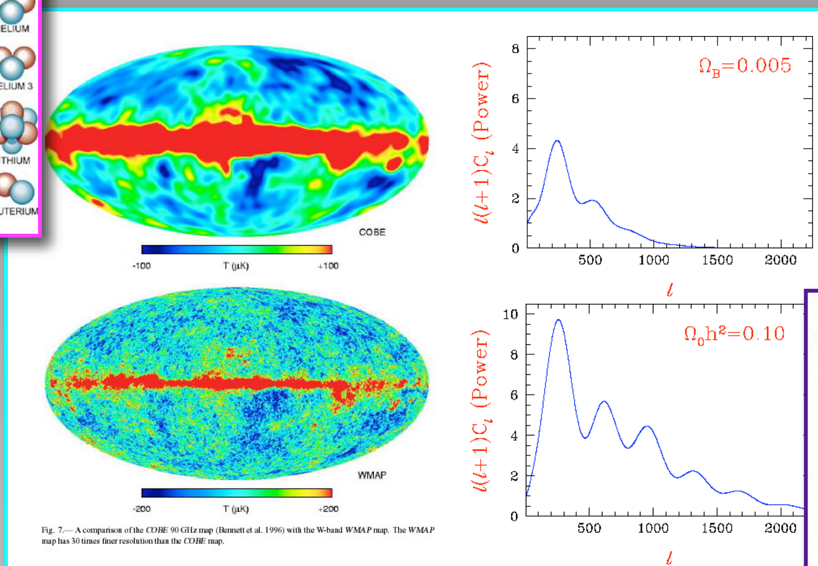
+ need one or more scalar fields?

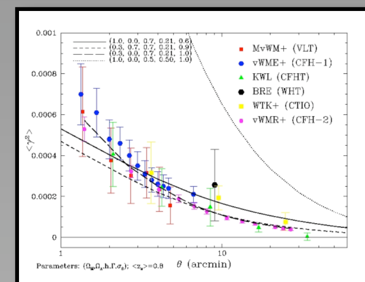
The Evidence for Non-baryonic Dark Matter

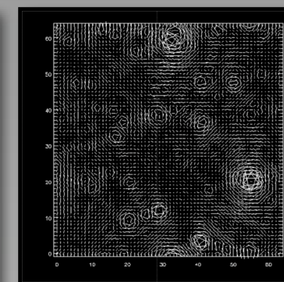
Over the past decade, growing evidence from many different scales and redshifts:

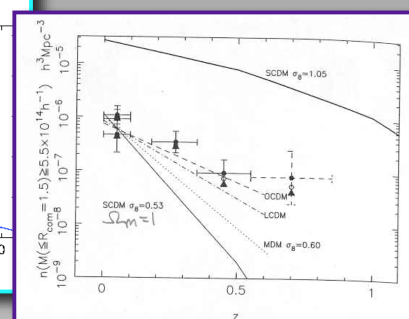
nucleosynthesis ; CMB ; local structure / cluster number counts / weak lensing

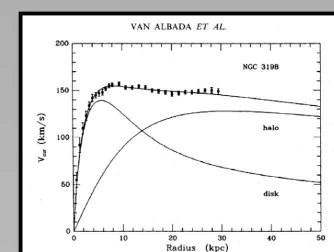








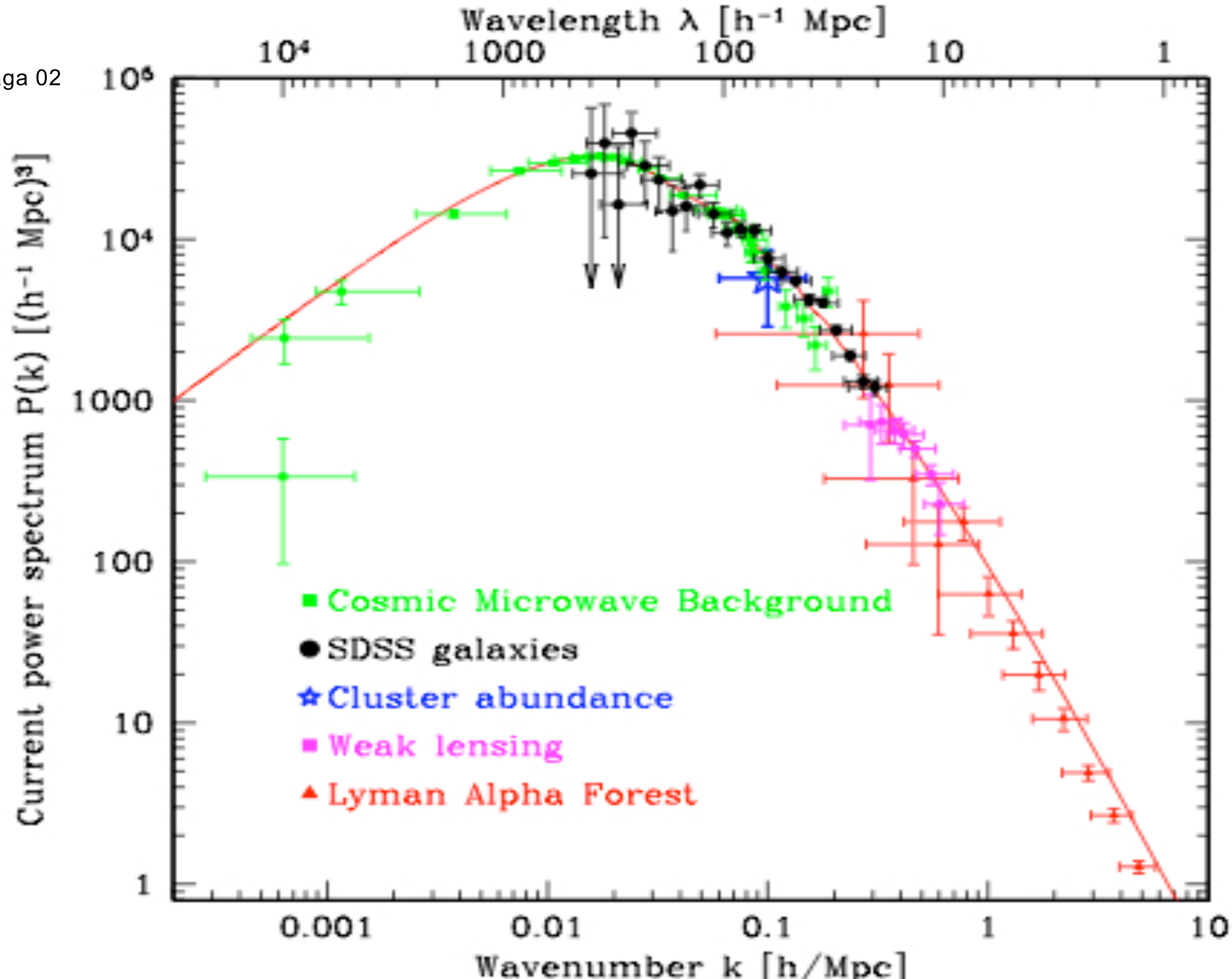




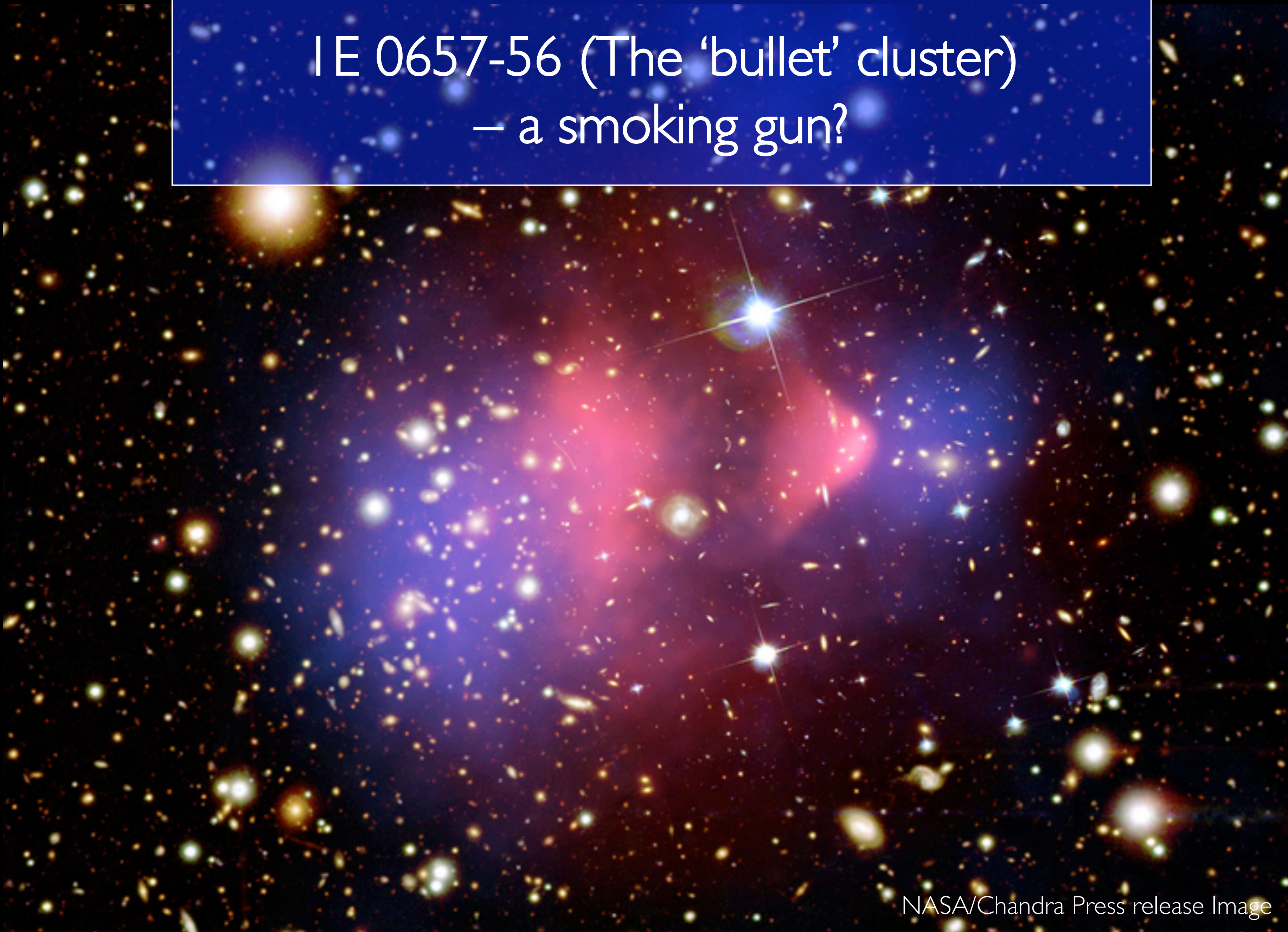
Ω_b	<<	Ω_m	<<	Ω_T
$0.0224h^{-2} \pm 0.0009$	<<	$0.135h^{-2} \pm 0.009$	<<	1.0
$0.04 \pm 4\%$		$0.27 \pm 7\%$		1.0

The spectrum of initial density perturbations P(k)

Tegmark & Zaldarriaga 02



1E 0657-56 (The ‘bullet’ cluster) – a smoking gun?



NASA/Chandra Press release Image

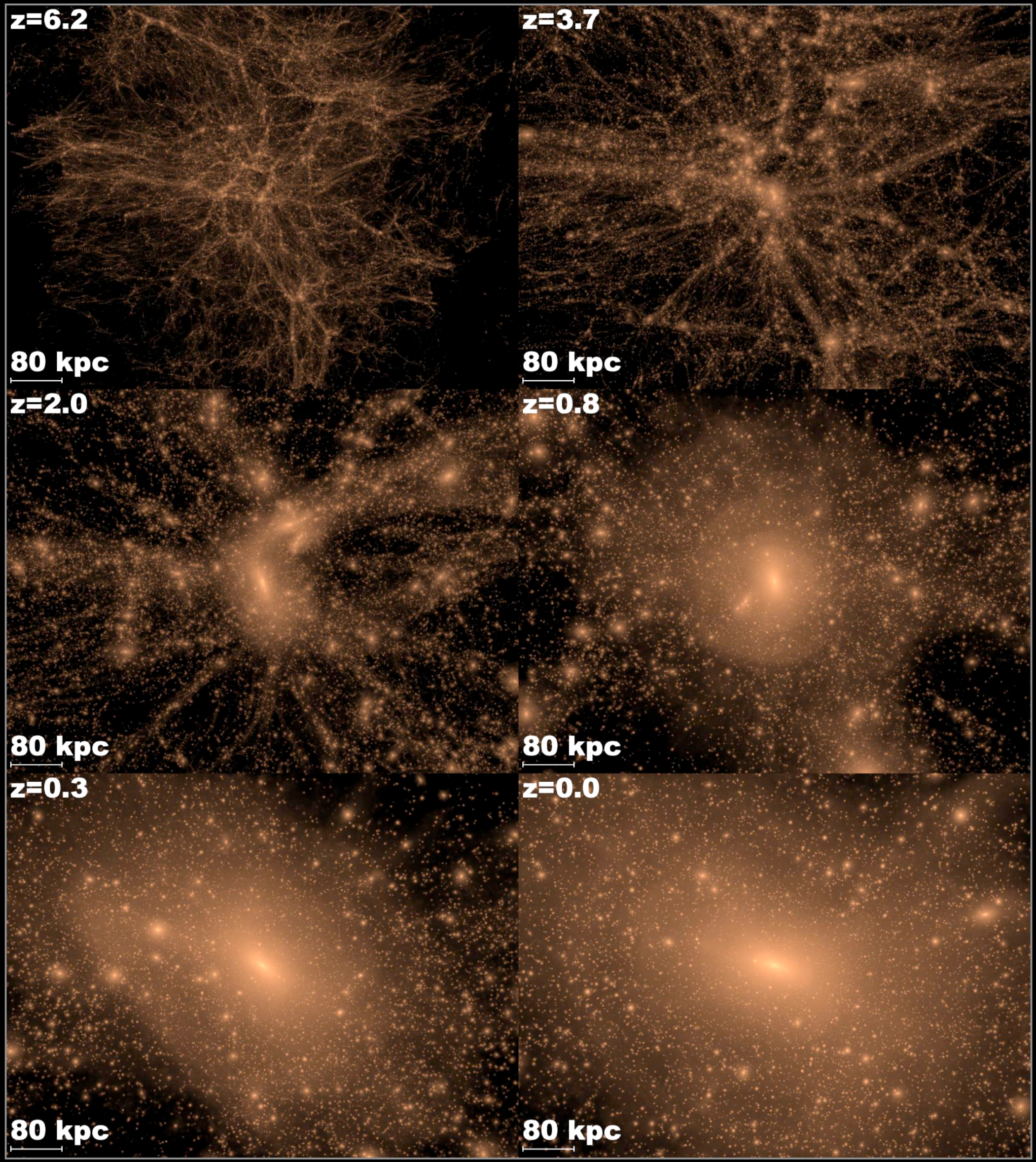
Dark Matter or MOND - does it really matter?

Horizon Scales:	excess energy density
100 Mpc scales:	LSS, clustering
Cluster scales:	deep potentials
Galaxy scales:	dark haloes
Subgalactic scales:	???

Clearly it matters to the rest of physics; the only strong astrophysical tests are now by default on small scales

How to model small scales

Fundamental resolution limit
⇐ mixing

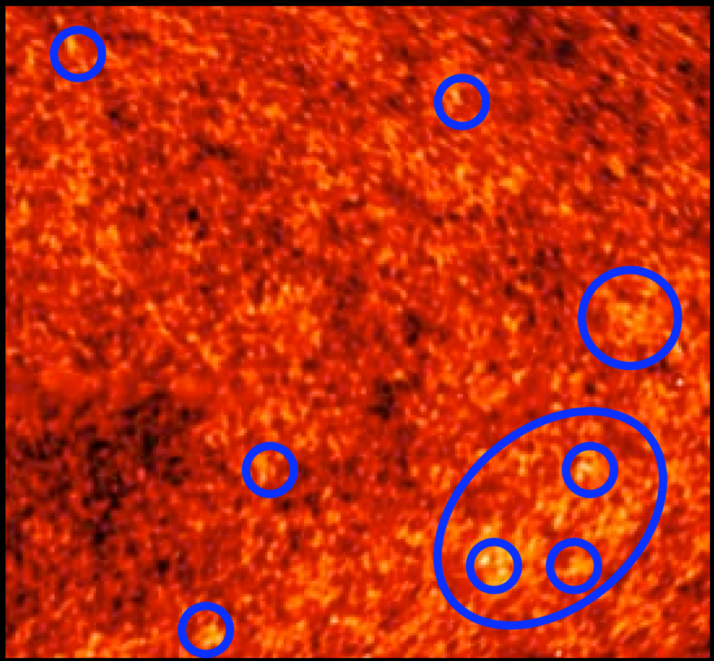


Via Lactea – Diemand, Kuhlen, Madau 2007

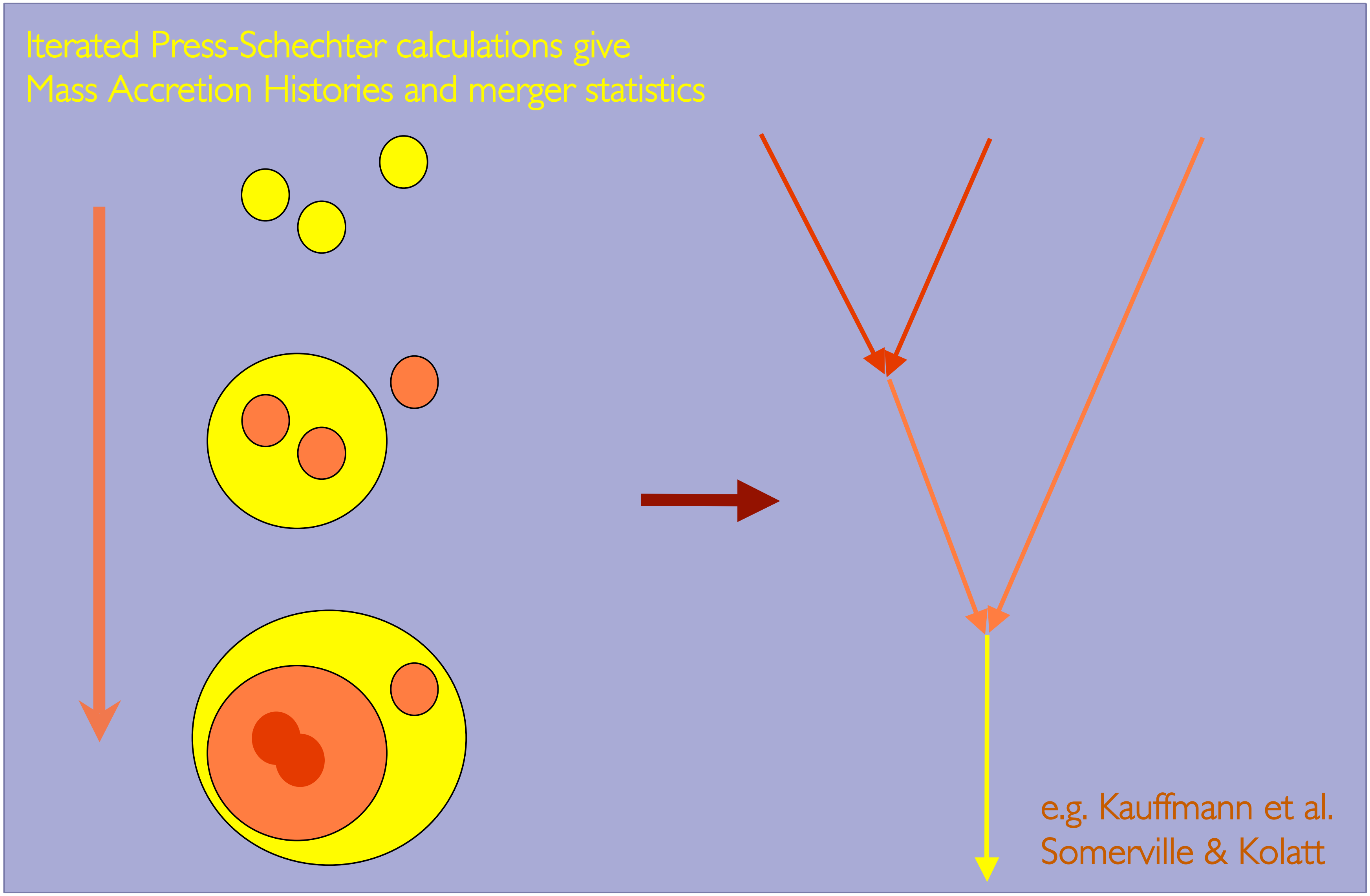
A statistical approach to the non-linear regime

Can't calculate full evolution of non-linear regime without N-body simulations, but can make statistical estimate of its extent: **Press-Schechter theory**

=> retain some of the power of linear theory to constrain parameters

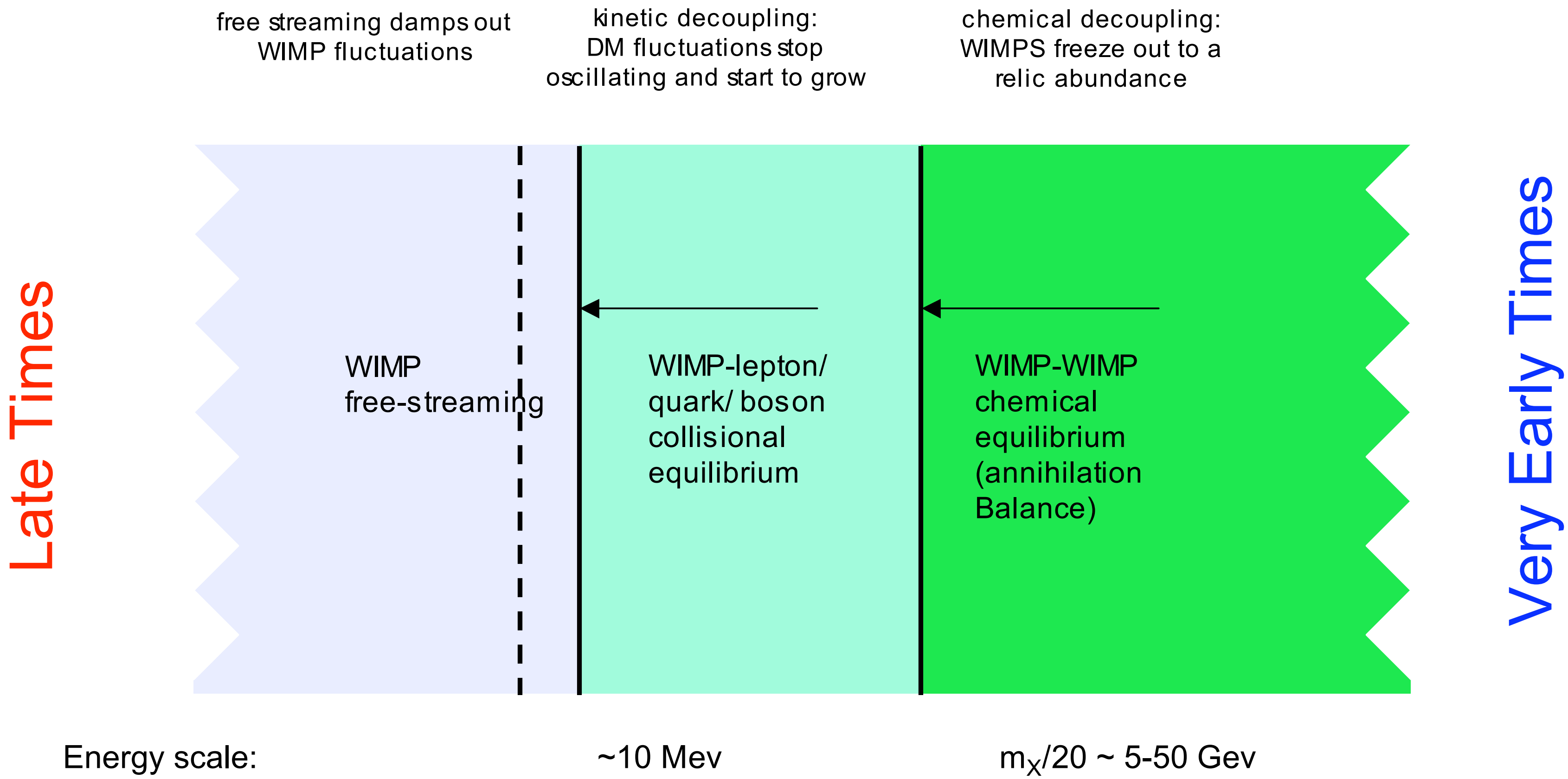


Representing hierarchical non-linear growth: semi-analytic merger trees



What is the initial linear input?

Consider specific example: supersymmetric WIMP



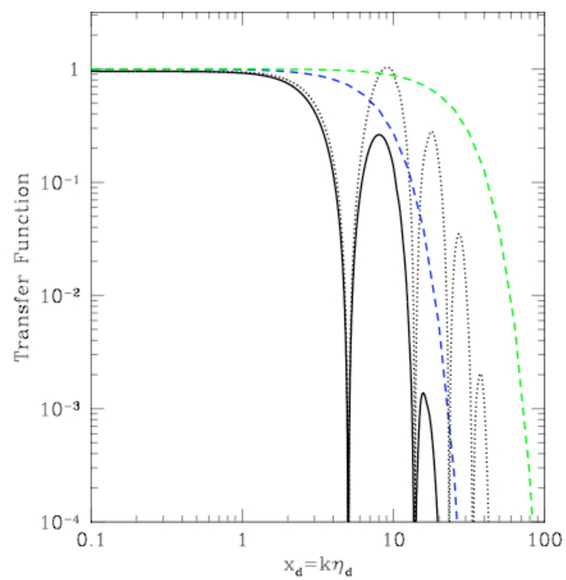
Basic answer: free streaming suppresses fluctuations below some scale, but acoustic oscillations also contribute $\Rightarrow$ minimum halo mass M_c

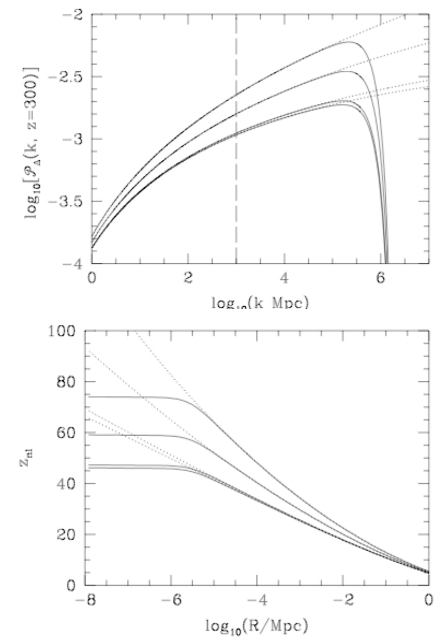
e.g. Loeb & Zaldarriaga (2005):

approximate calculation of transfer function due to collisional damping

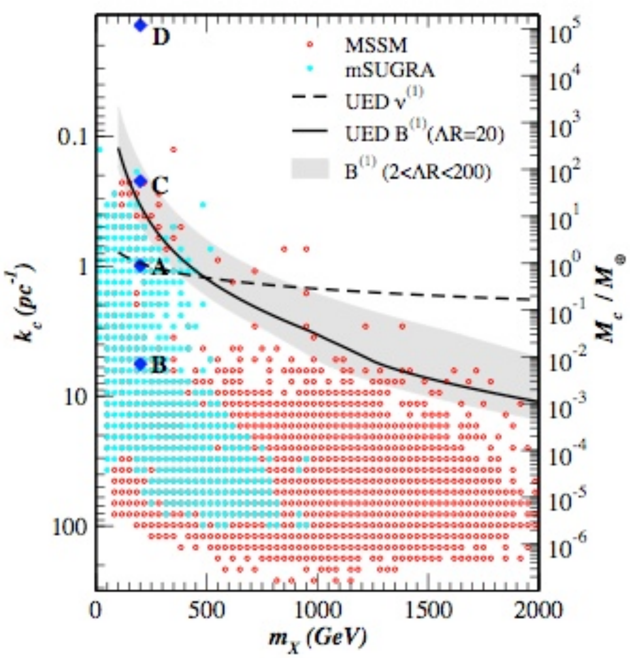
dominates over free streaming in case considered (100Gev WIMP w. T_d = 10Mev)

gives cutoff mass $\boxed{M_c = 10^{-4} - 10^{-5} M_\odot}$





Green, Hofmann & Schwarz 2005

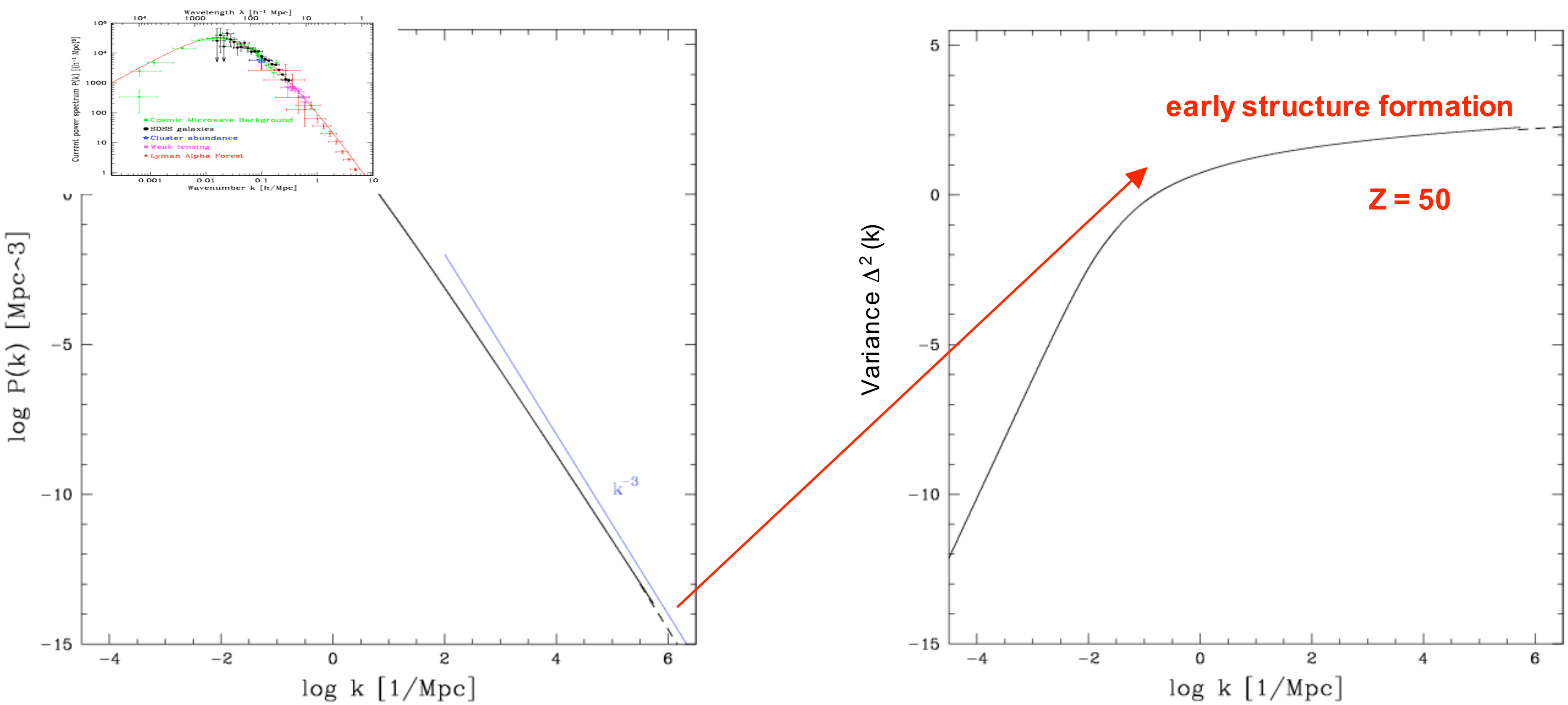


Profumo, Sigurdson & Kamionkowski (2006): Full calculation for a wide range of SUSY and extra-dimensional (Kaluza-Klein) WIMP candidates

Gives $\boxed{M_c = 10^{-4} - 10^{-12} M_\odot}$

So smallest scale dark matter structure encapsulates DM particle properties (via M_c) and possibly also inflaton properties (via ρ or z_f) (e.g. Zentner & Bullock 2002, 2003)

The Resulting Non-linear Power: Theoretical Expectations



From linear power spectrum and subsequent growth history, expect scale invariance over ~20 orders of magnitude in mass

But effect of flattening of variance vs. mass?

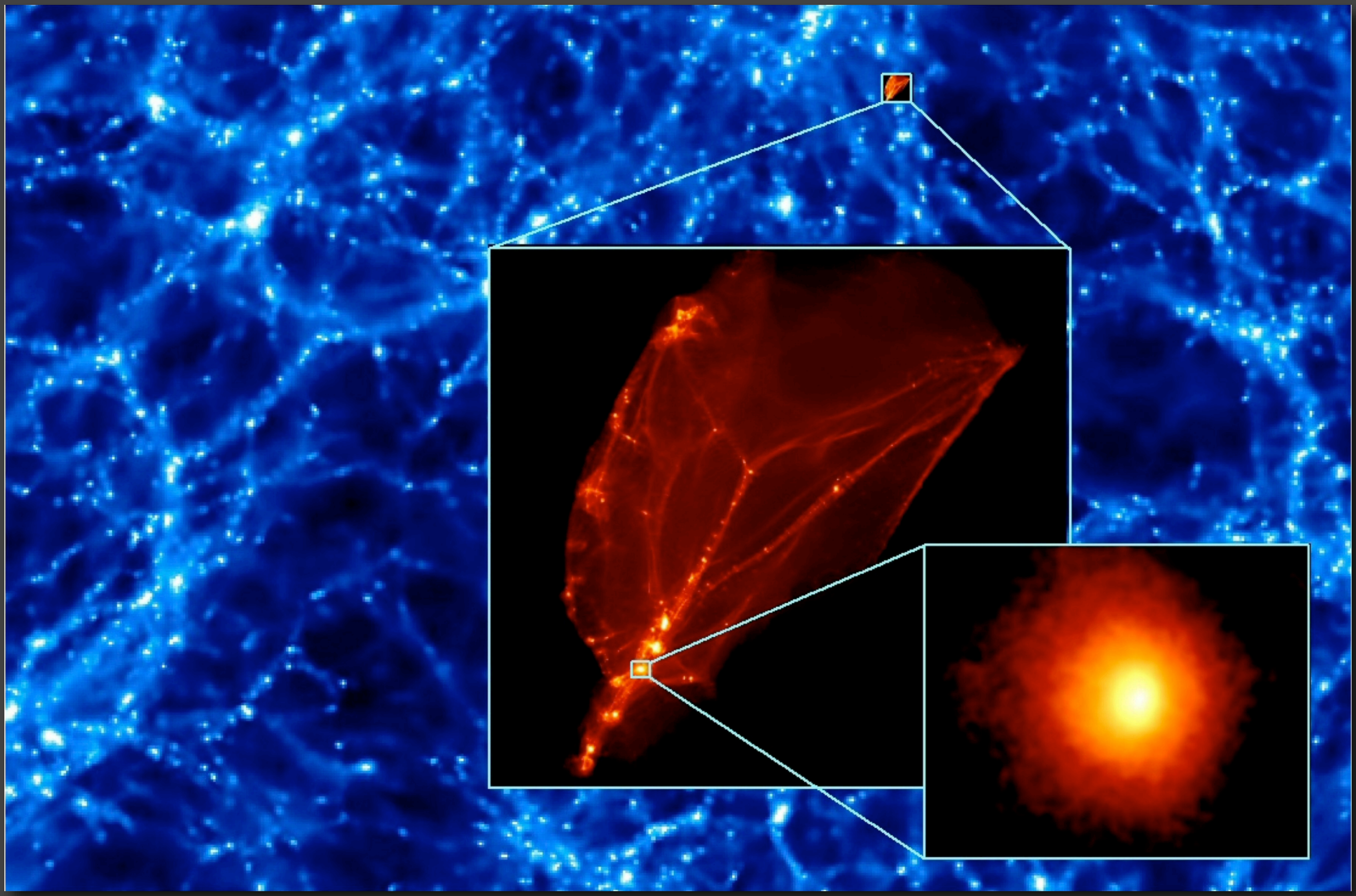
Diemand et al. (2005): first numerical attempt w. small box, stopping at high z

Consider linear power spectrum with
$M_c = 10^{-6}\ M_o$

Start at z=350

Zoom in:
Simulate $[3\ \text{kpc}]^3$ box, $[60\ \text{pc}]^3$ sub-box and $[0.024\ \text{pc}]^3$ sub-sub-box with $6\text{x}10^7$ particles of mass $10^{-10}\ M_o$ each

Find $10^{-6}\ M_o$ \`first' halo
With $M \sim M_c$



Profile, density as expected from theory

(Diemand et al. 2005)

Halo profile ~ universal;
Virial density ~ 200 mean,
even concentration ~ ok

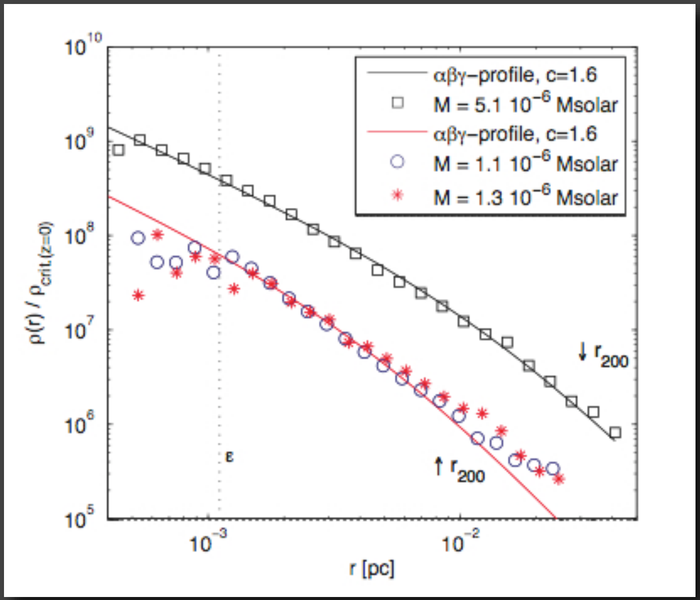
Also abundance matches
lower redshift results

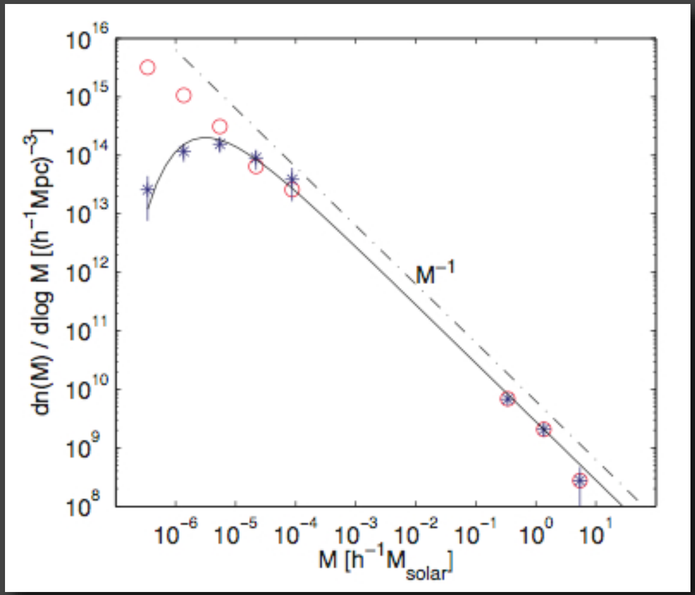
Implication: following scaling for more massive substructure, present-day MW halo should contain 10^{15} mcirohalos, or $500/pc^3$ locally, the nearest being within ~0.15pc away

Further implications for direct and indirect detection :

These objects move through solar system in ~100 years,
once every 10,000 years

Motion on sky ~ 1 arcmin/yr





Alternate Merger Tree Approach (w. Abel &Turk):

Basic resolution problem with trees:
Number of branches grows as ~Nlog(N), where N = M/M_{res}

Number of distinct redshift steps grows as N^2 or faster

So rather than following every branch, choose some preferentially,
e.g. with declining probability at low mass

e.g. branching probability = 1 for M > M1

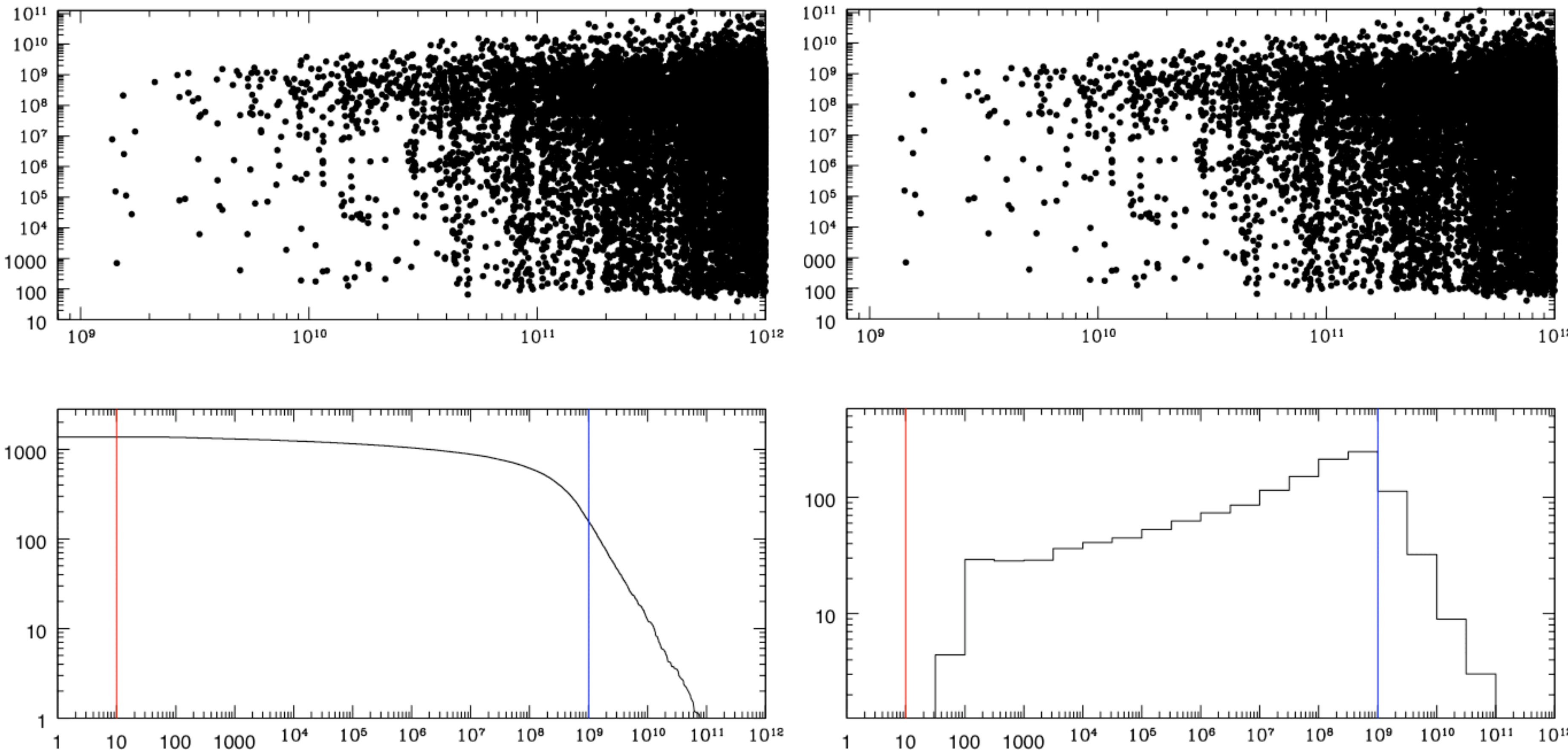
= M/M1 for M2 > M > M1

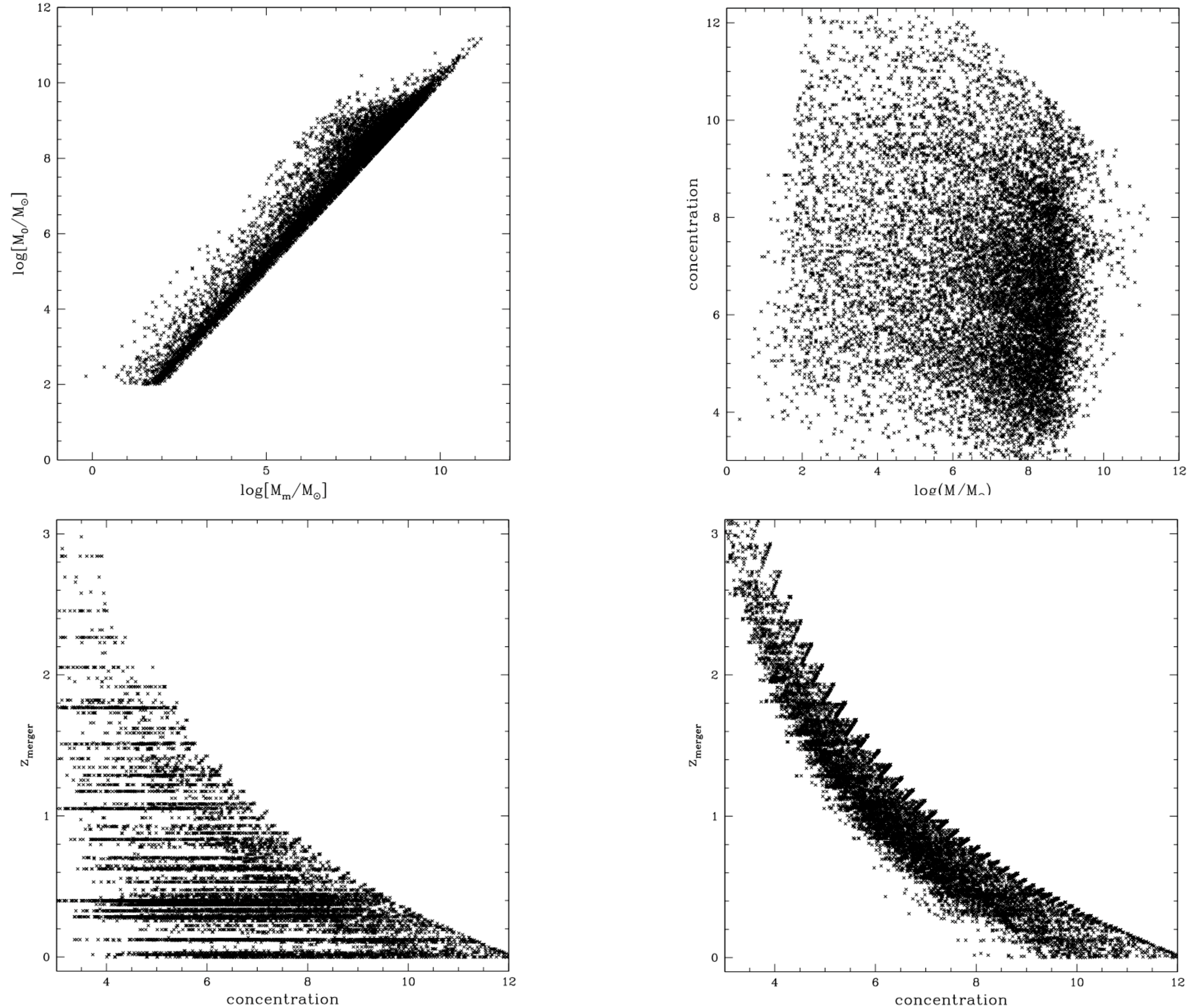
= 0 for M < M2

Get fast trees for Mf/M1 ~ 10^3, M1/M2 ~ 10^8

Use this as input to semi-analytic model of halo mergers and substructure evolution

Sparsely-sampled Trees:

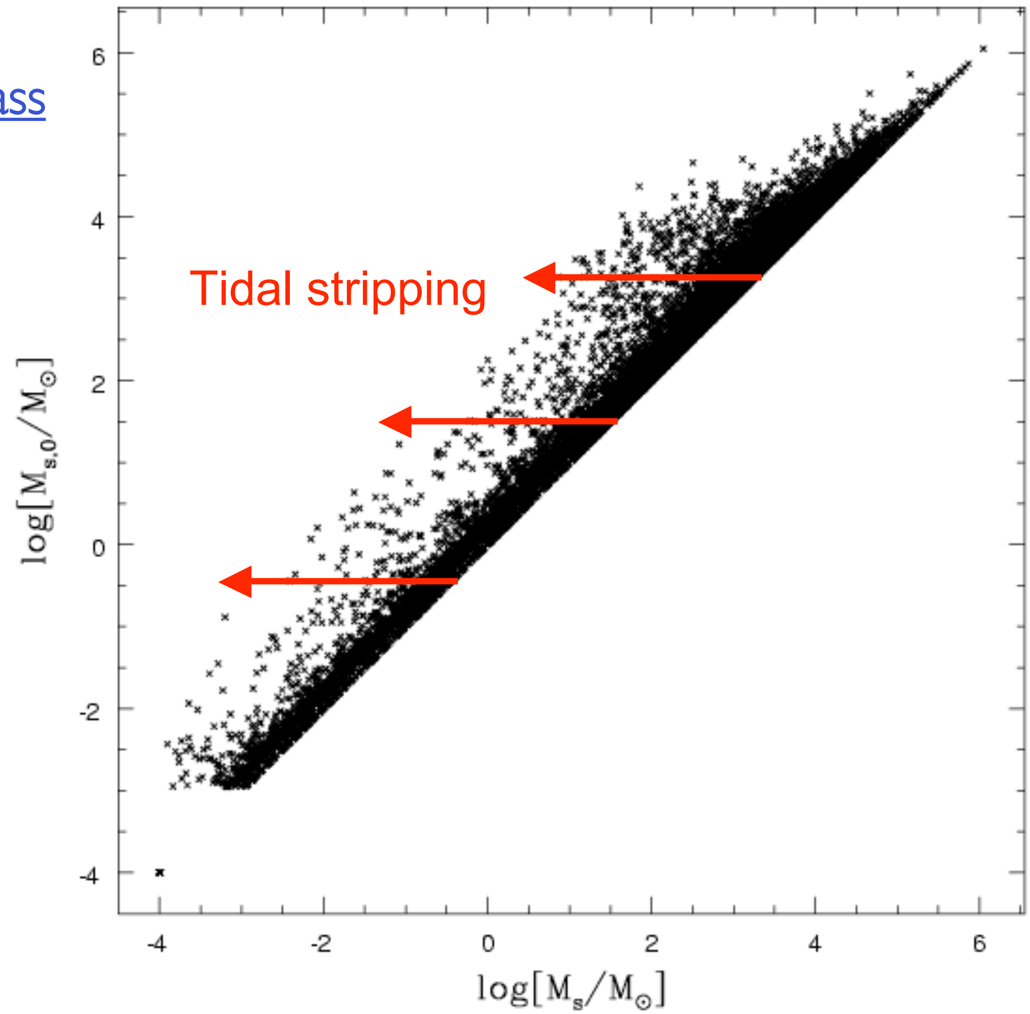



log[M_0/M_⊙]
log[M_m/M_⊙]
concentration
log(M/M_⊙)
z_merger
concentration
z_merger
concentration

Some Results from Small Scales (~ R < R_{Sun})

1: Final mass versus initial mass

⇒two orders of magnitude range in mass loss

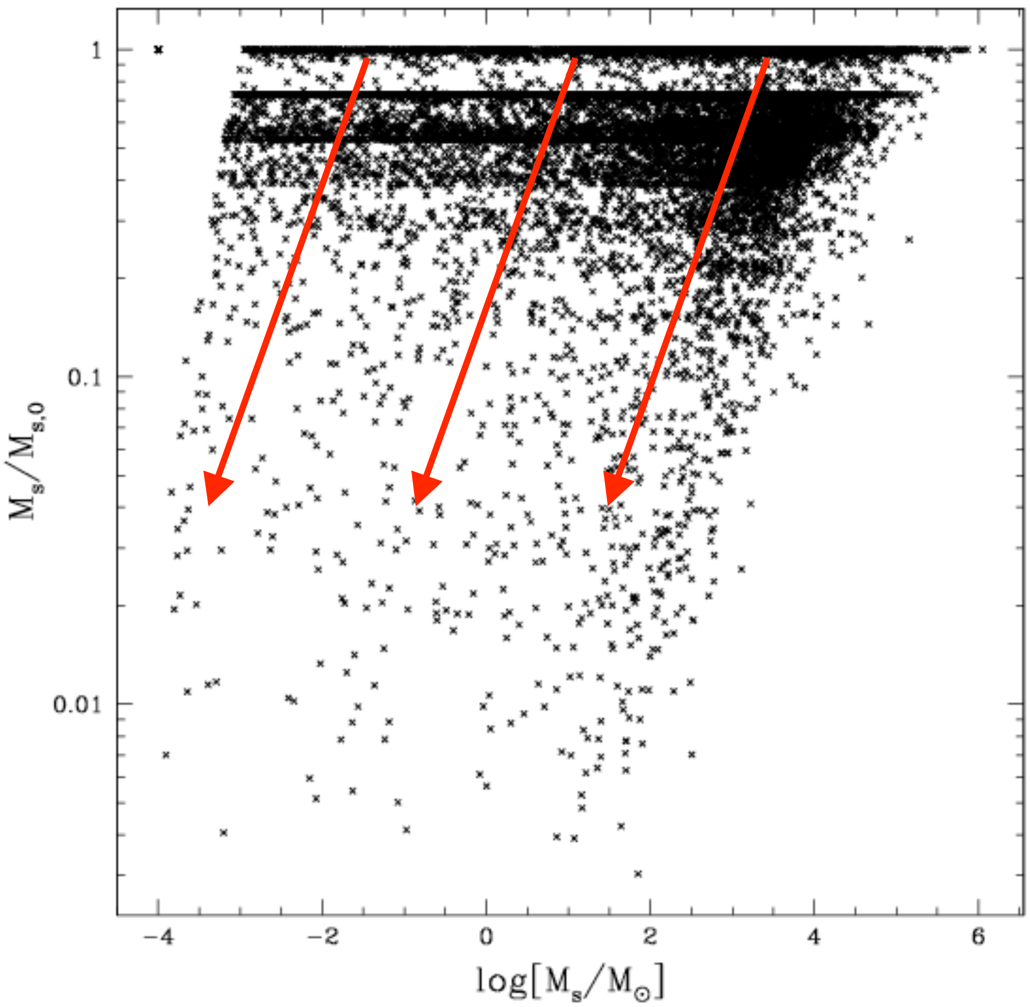


Some Results from Smaller Scales (~ $R < R_{Sun}$)

2: Mass loss vs. final mass

⇒ no major trend with mass

⇒ incompleteness in merger tree



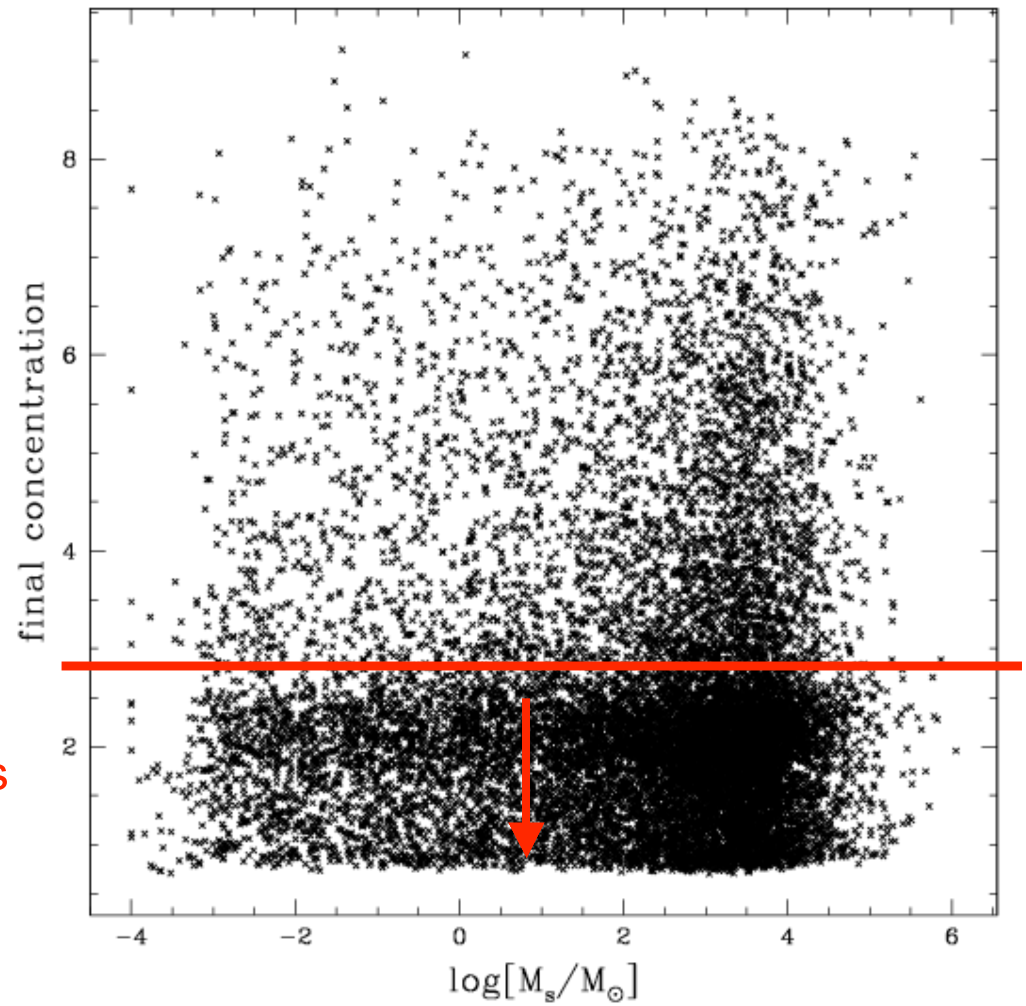
Some Results from Smaller Scales (~ R < R_{Sun})

3: concentration vs. final mass

⇒ no major trend with mass

⇒ most systems heavily stripped

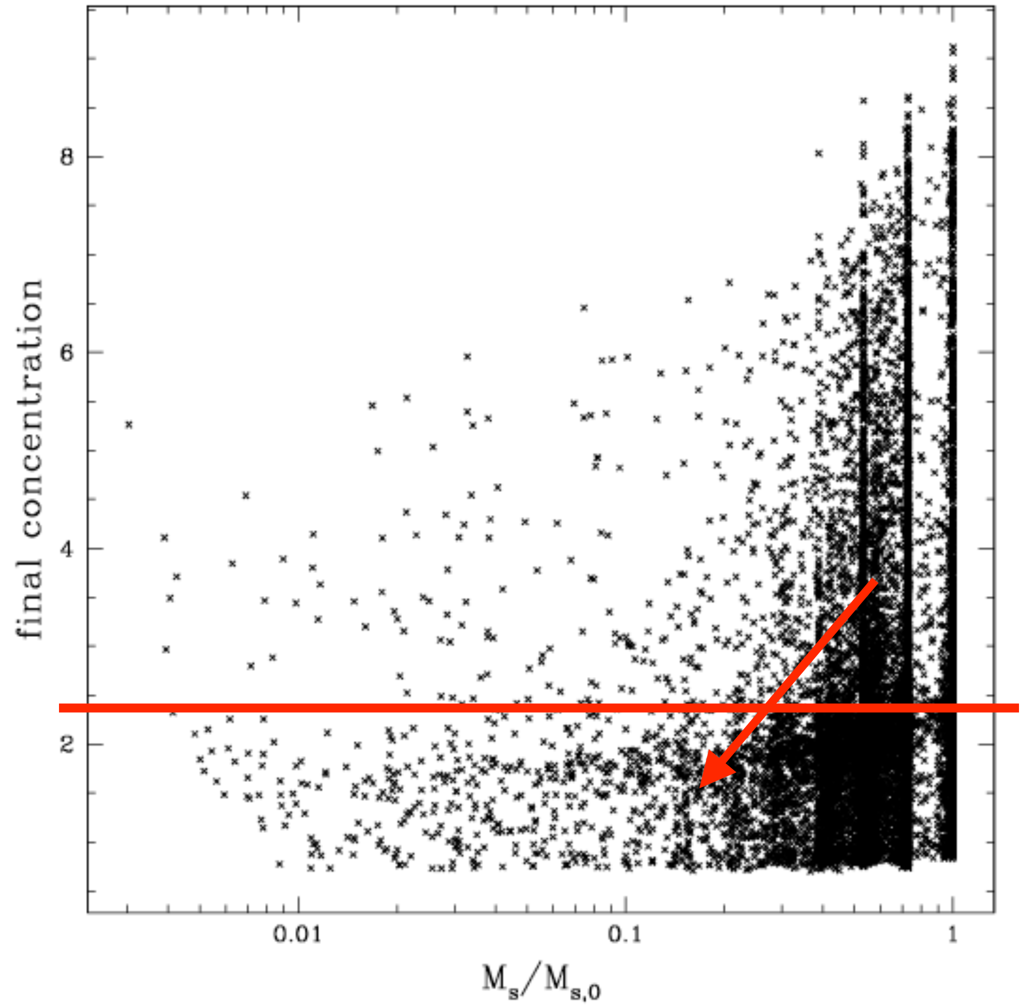
stripped systems



Some Results from Smaller Scales (~ $R < R_{Sun}$)

4: concentration vs. mass loss

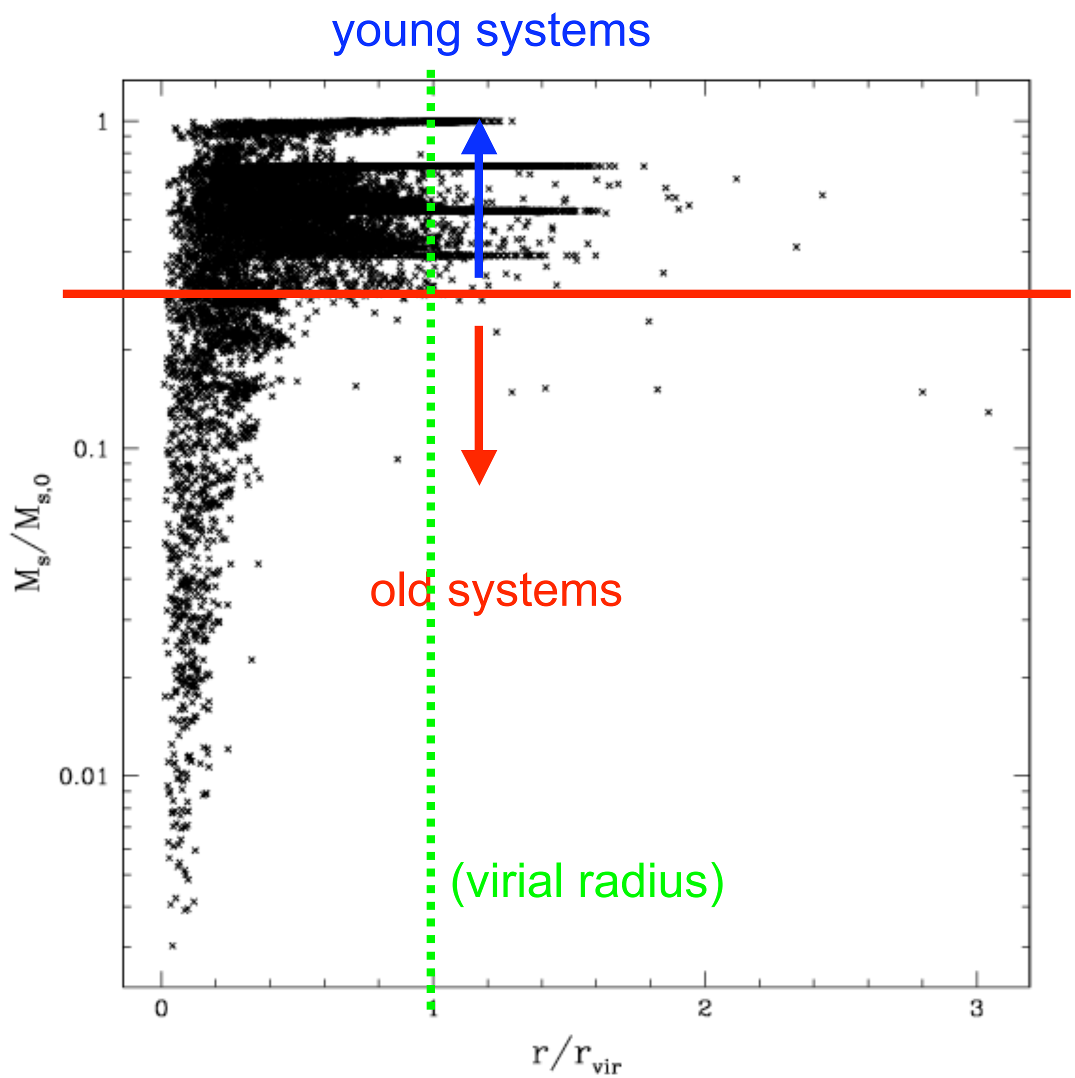
⇒ heavily stripped systems have concentrations close to 1



Some Results from Smaller Scales (~ R < R_{Sun})

5: mass loss vs. location

⇒ heavily stripped systems are only found at small radii (but need to be careful about incompleteness of tree)



Some Results from Smaller Scales ($\sim R < R_{Sun}$)

6: luminosity vs. mass

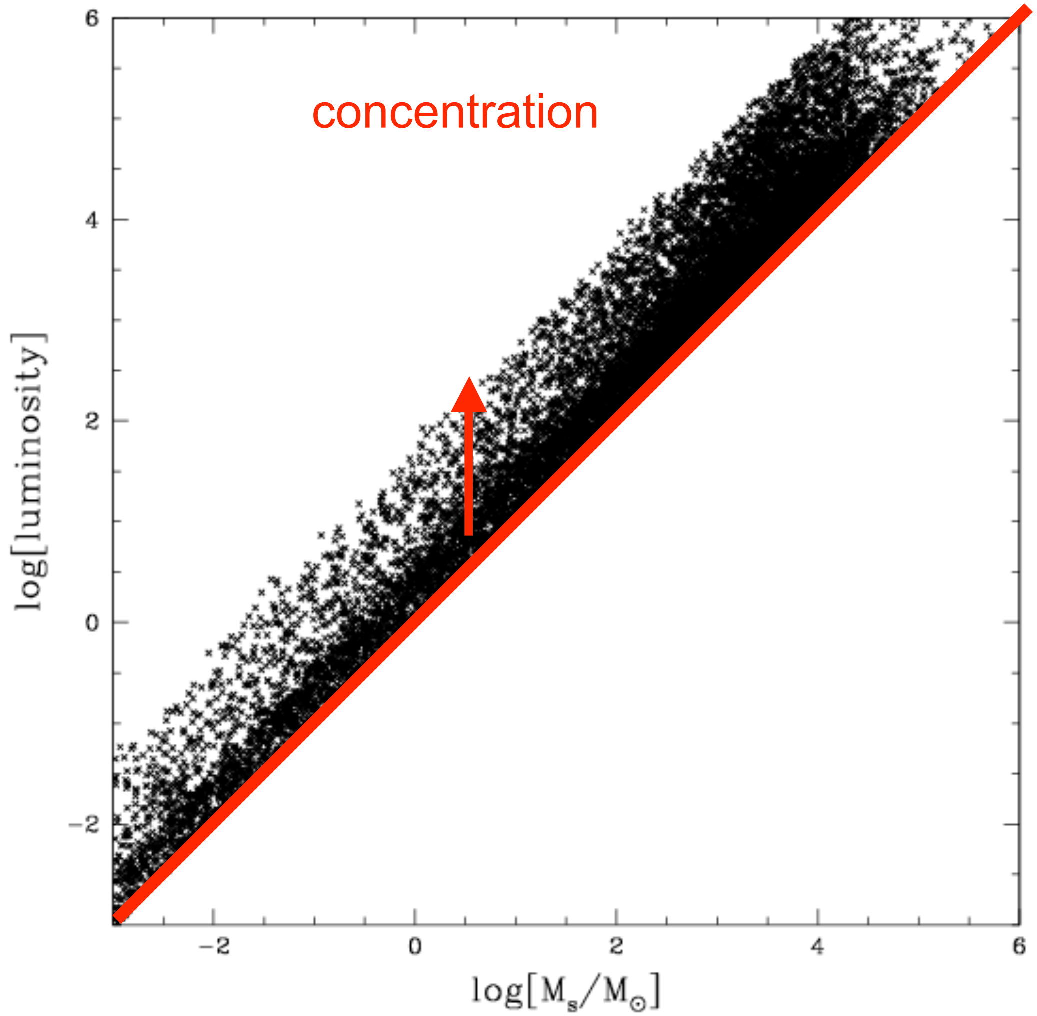
⇒ large scatter at fixed mass

⇒ massive systems dominate

however

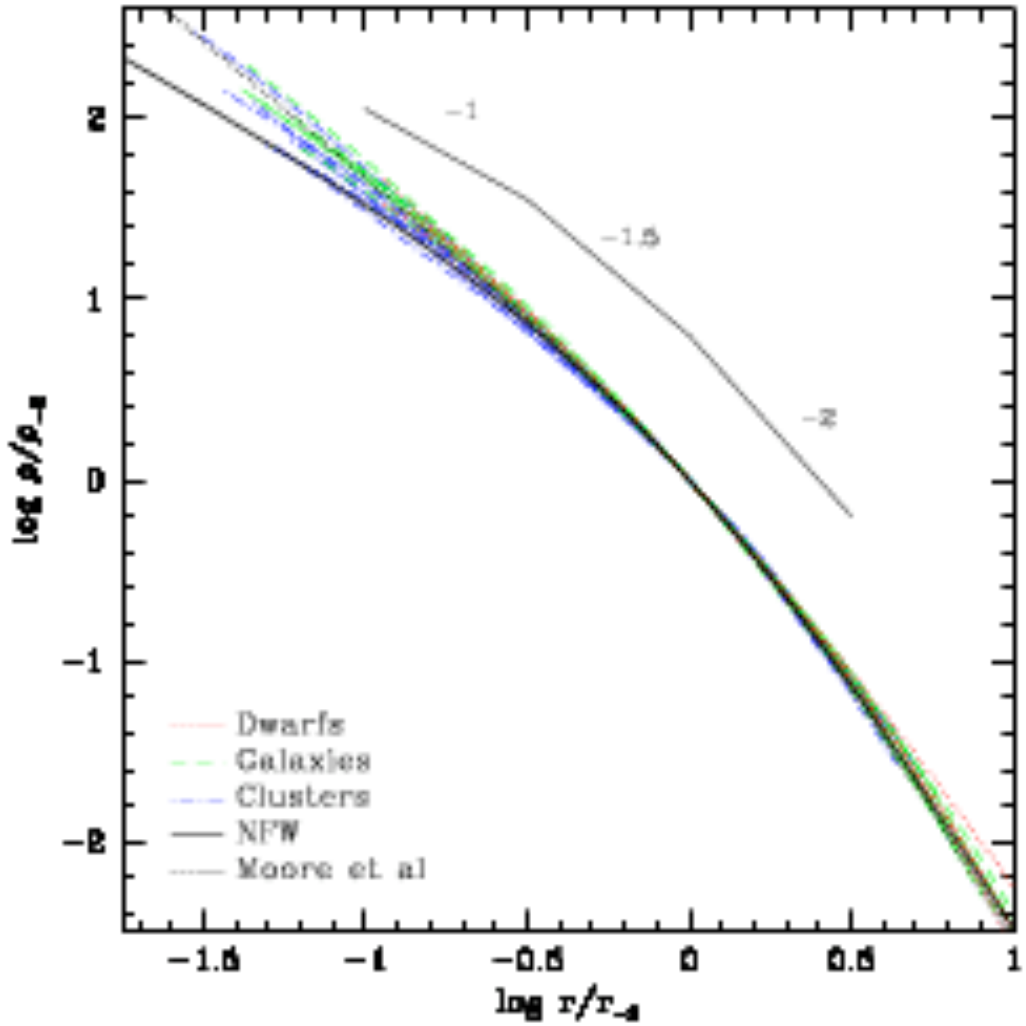
(N.b. distance $\propto n^{-1/3}$

so apparent luminosity $\propto n^{2/3}$)



Some Theoretical Issues

What are the density profiles for haloes and subhaloes, and how are they built up?



The Universal Density Profile (Navarro et al. 2004)

How to explain halo density profiles and concentrations?

Generic patterns in halo mass accretion histories (MAH - coloured lines),
cf. van den Bosch (2002), Wechsler et al. (2002), Yasitsiomi et al. (2004):

$M(a) = M(0) \exp[-2\ z\ a_c]$ or $M(a) = M(0)\ a^p \exp[-2\ z\ a_c]$

Rapid Growth:

When M is close to characteristic mass-scale M*(z)

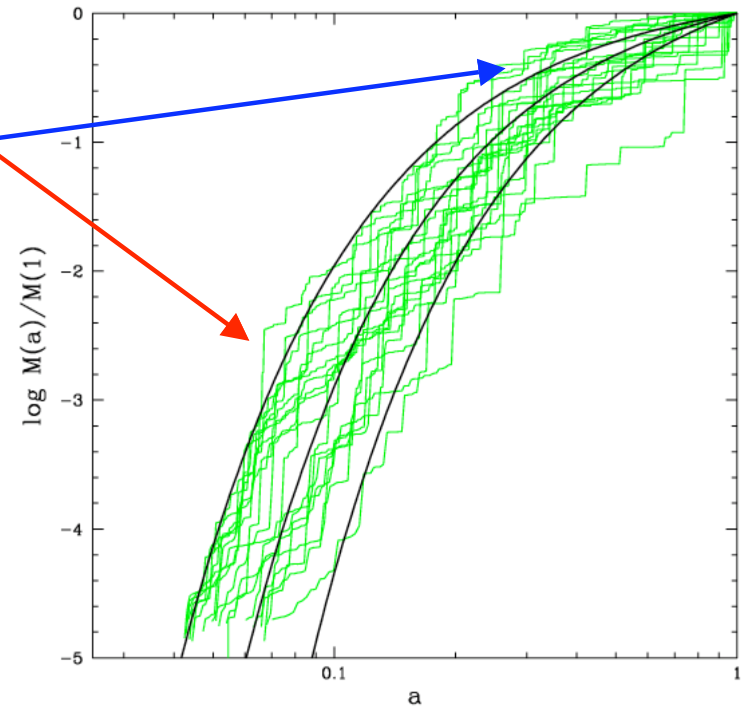
Slow Growth:

Once M*(z) has moved beyond M

Does the MAH determine the density profile?

e.g. concentration recipes of Wechsler et al.,

Zhao et al., Tasitsiomi et al. (solid black lines above)



Taylor 2005

How to explain halo density profiles and concentrations?

Consider the `Nusser Model'
(cf. Nusser & Sheth 1999)

- Simplest model for halo growth: assume

accreted material stays a given radius

- For a given mass M(z) at redshift z,

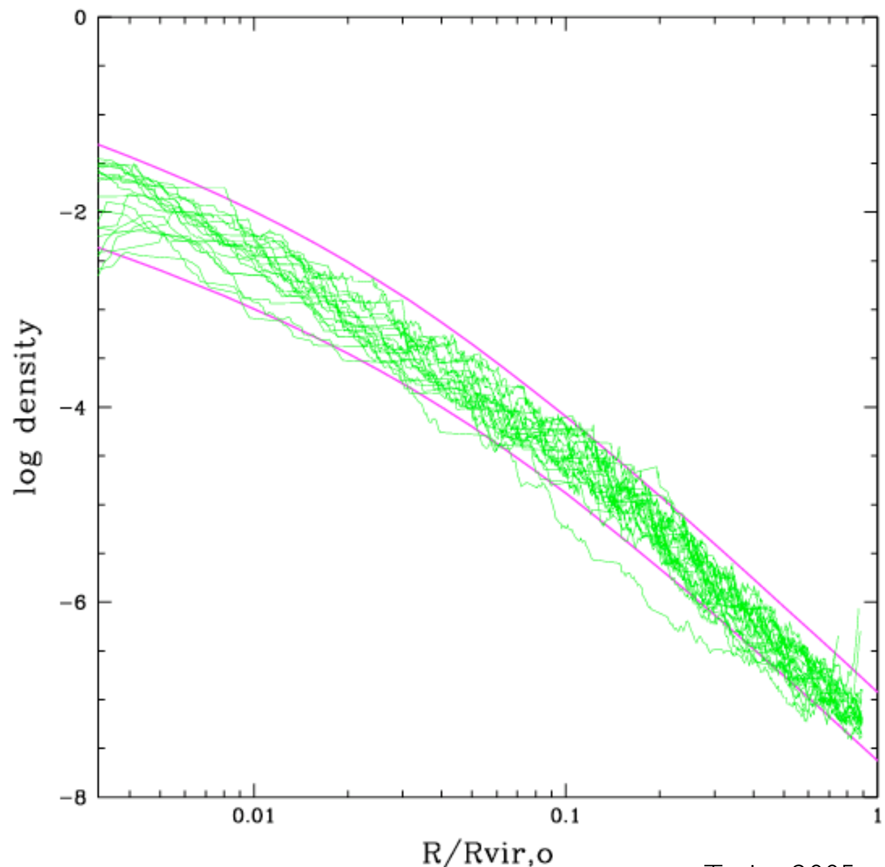
$r_{vir} = 3M/(4\pi\Delta_c\rho_c) = f(M,z,\text{cosmology})$

- For each step in MAH, compute

f(M, z and cosmology) to get r(z), $\Delta r(z)$

- density profile given by:

$\rho(r) = \Delta M(z)/(4\pi r(z)^2 \Delta r(z))$



Taylor 2005

- Assumes no transfer of energy or angular momentum to older material
- Halo profiles depend on cosmology/power spectrum in principle

NET RESULT: Without radial mixing haloes **too concentrated** by a factor of ~ 2

Another Major Issue:
substructure survival vs. heating and shocks

numerical results from several studies all in rough agreement (Hayashi et al. 2003, Kazantzidis et al. 2004, Goerdt et al. 2006)

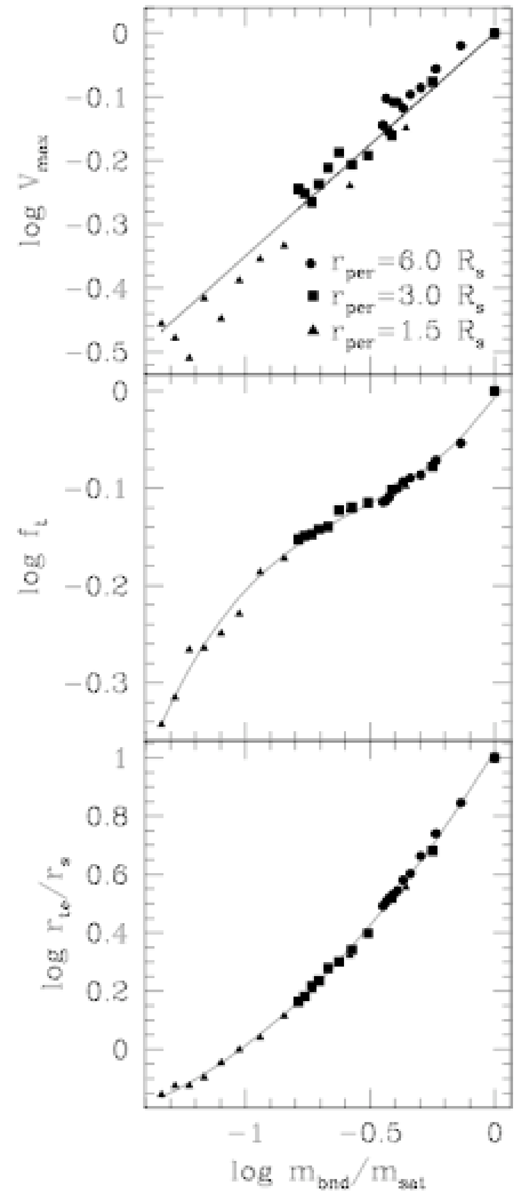
profile depends only on total mass-loss;

inner slope ~ stable

inner region simple $V_{max} \propto M^{1/3}$

outer region truncated as r^{-6}

Hayashi et al. 2004



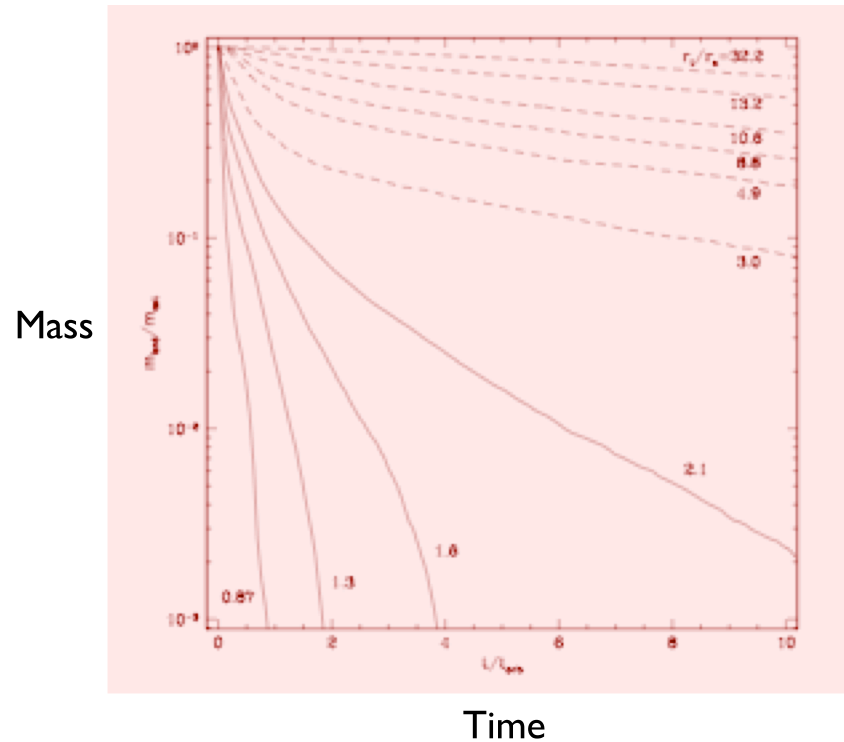
Theoretical Issues: The Disruption Criterion

Also not clear when (and if) substructure becomes completely unbound

Hayashi et al. 2003: bound systems that have lost ~0.1% on circular orbits, 1% on realistic orbits

for circular orbits, criterion: $r_t < 2\ r_{pos}$

but not clear what this should be for non-circular orbits (toy calculation suggests they never disrupt)



Hayashi et al. 2004

Disruption on subsolar scales

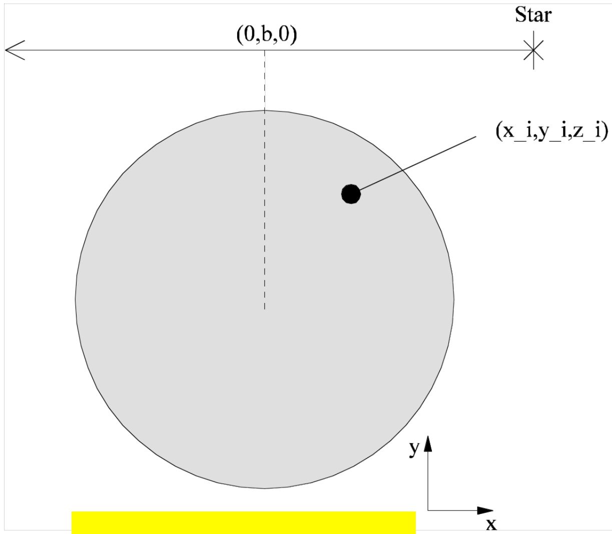
e.g. Diemand et al.: First halo has a density of $10^{-6}\ M_\odot/(0.01\mathrm{pc})^3 \sim 1 M_\odot/\mathrm{pc}^3$

This is ~10 times the local DM density (so microhalo survives halo formation), but corresponds to a restoring force less than the tidal field of the solar system within 1 pc

Thus, encounters with $1\ M_\odot$ stars at $b < 1$ pc will cause mass loss and/or disruption

These encounters should be common, since $\Sigma_d \sim 40\text{-}50\ M_\odot\ \mathrm{pc}^{-2}$ in the disk

Thus the grainy-ness of the local baryon distribution will shred small subhaloes.

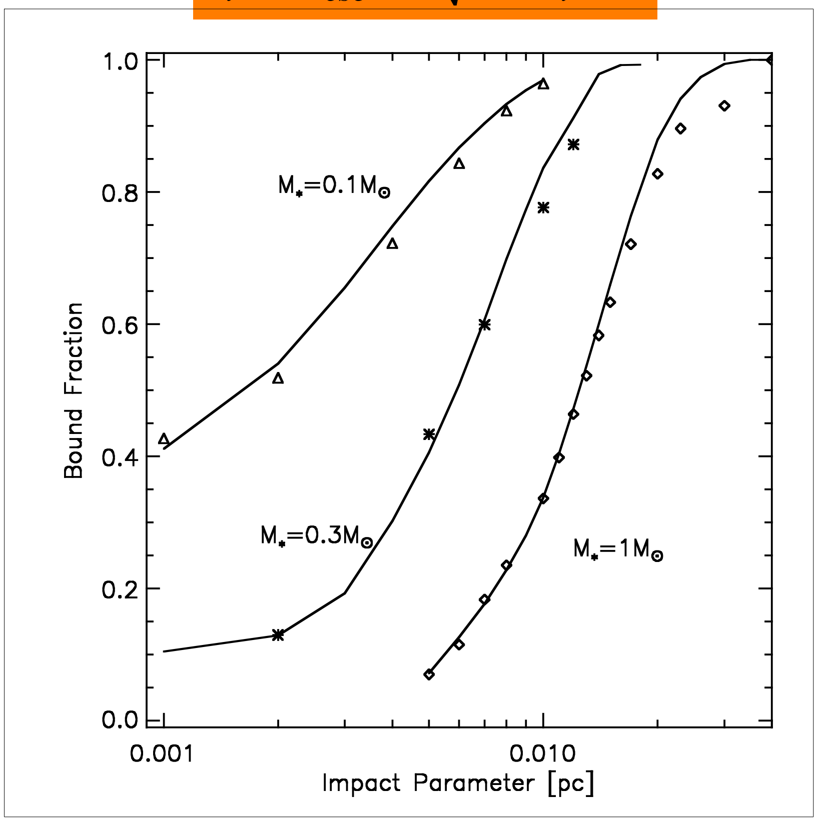


$$\rho = \frac{\rho_s}{r\left(r + r_s\right)^2}$$

What if a microhalo meets a star?

Angus & Zhao (2006):
ran tree-code N-body simulations with 10^5 particles to investigate, by considering the bound fraction of particles after a single encounter.

$$v_i < v_{esc} = \sqrt{-2\phi_i(r)}$$



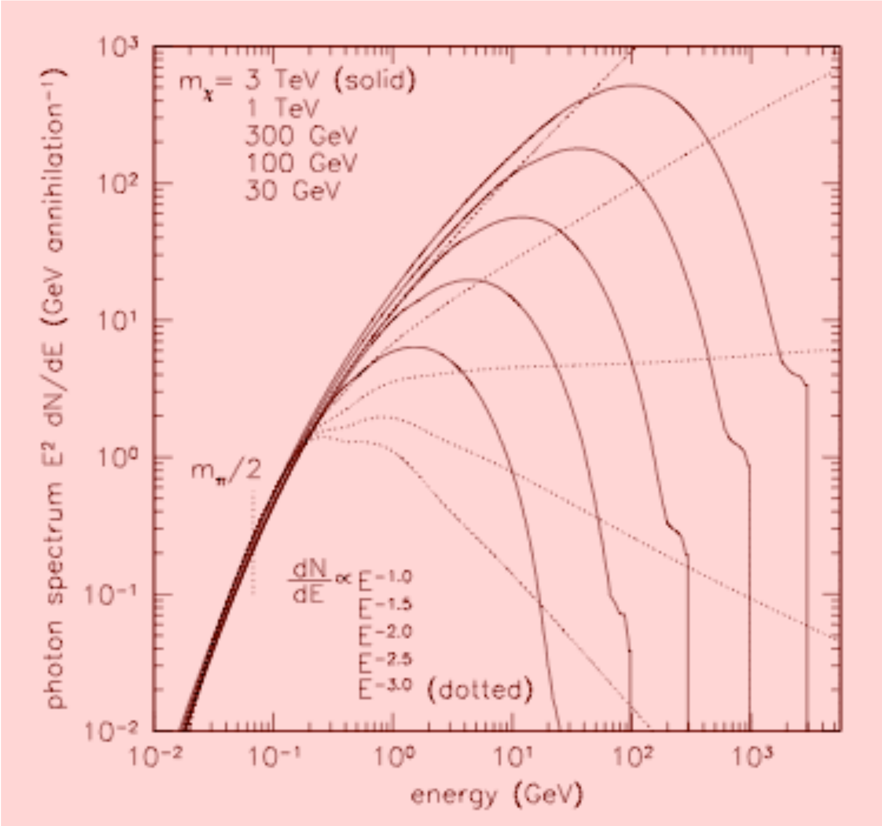
Compared with the impulse approximation

$$\Delta v \propto \frac{M_*}{bV_{rel}}$$

Looking for local Substructure

(Baltz, JET & Wai 2007) (astro-ph/0610731)

+ Consider supersymmetric neutralinos (~ vanilla CDM WIMP candidate)
+ Most gammas via (non-rel.) quark-antiquark pairs ⇒ hadronization ⇒ pions
+ Resulting pion bump at ~ $m_\chi/25$ ranges from 1-100 GeV depending on WIMP mass
+ Sharp energy cutoff, so very different from e.g. emission from power-law cosmic-ray proton spectrum



Baltz, Taylor & Wai 2007 - spectrum from DarkSUSY/Pythia

Local subhaloes as seen by GLAST

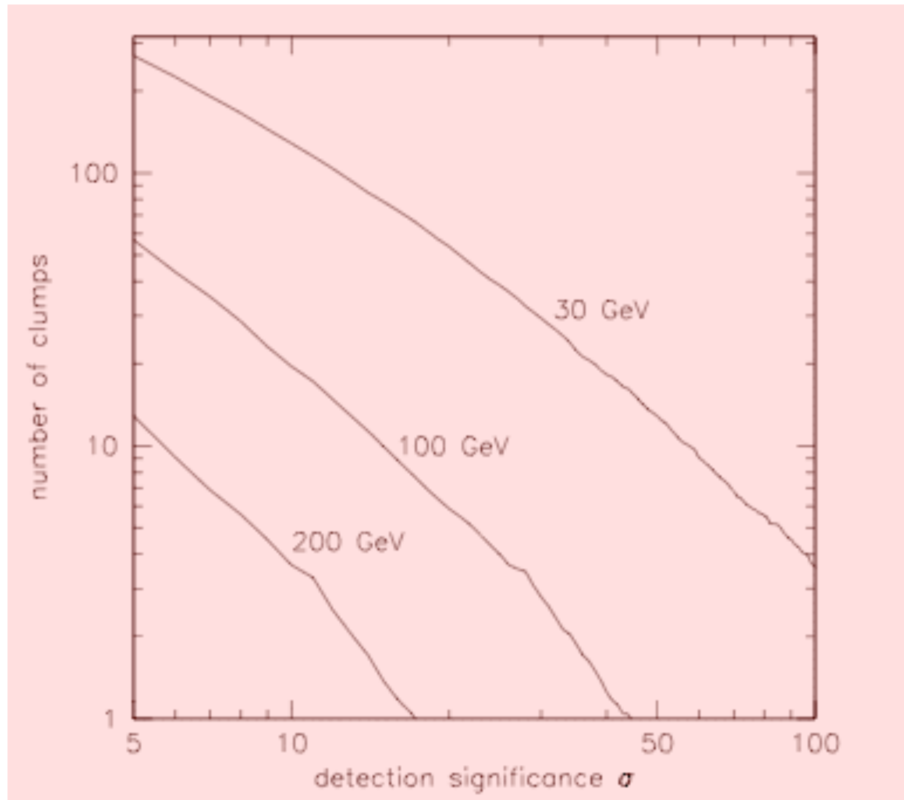
(astro-ph/0610731)

Brightness of local subhaloes depends on angular size (and thus distance) and on central density (and thus concentration and degree of stripping)

Scaling with mass/distance not trivial

At large masses, brightest sources are probably those that just fill the beam

Possibly tens or hundreds of sources detectable by GLAST over 5-year mission?



Baltz, Taylor & Wai 2007

Source Identification:

Source	Monoenergetic Quark Spectrum	Extended	Non-variable	High-latitude	No Counterparts
Subhaloes	✔	✔	✔	✔	✔
Molecular clouds	✖	✔	✔	✔	✖
Pulsars	~	✖	✖	~	✖
Plerions	✖	✔	✔	✖	✖
SNR	✖	✔	✔	✖	✖
Blazars	✖	✖	✖	✔	✖

Summary

Small scales are the only place to really test dark matter astrophysically

N-body simulations, the simplest theoretical models of non-linear structure formation, are still working with limited resolution

Merger tree models promise insights into small-scale CDM substructure, e.g.

- Subhaloes are typically stripped, with fairly low concentrations
- Mass function not exactly M^{-2}
- More massive subhaloes may dominate as sources
- Gamma-ray spectrum, variability, spatial extent all aid identification

Several important systematic uncertainties, including
net contraction/expansion history of halo contents.