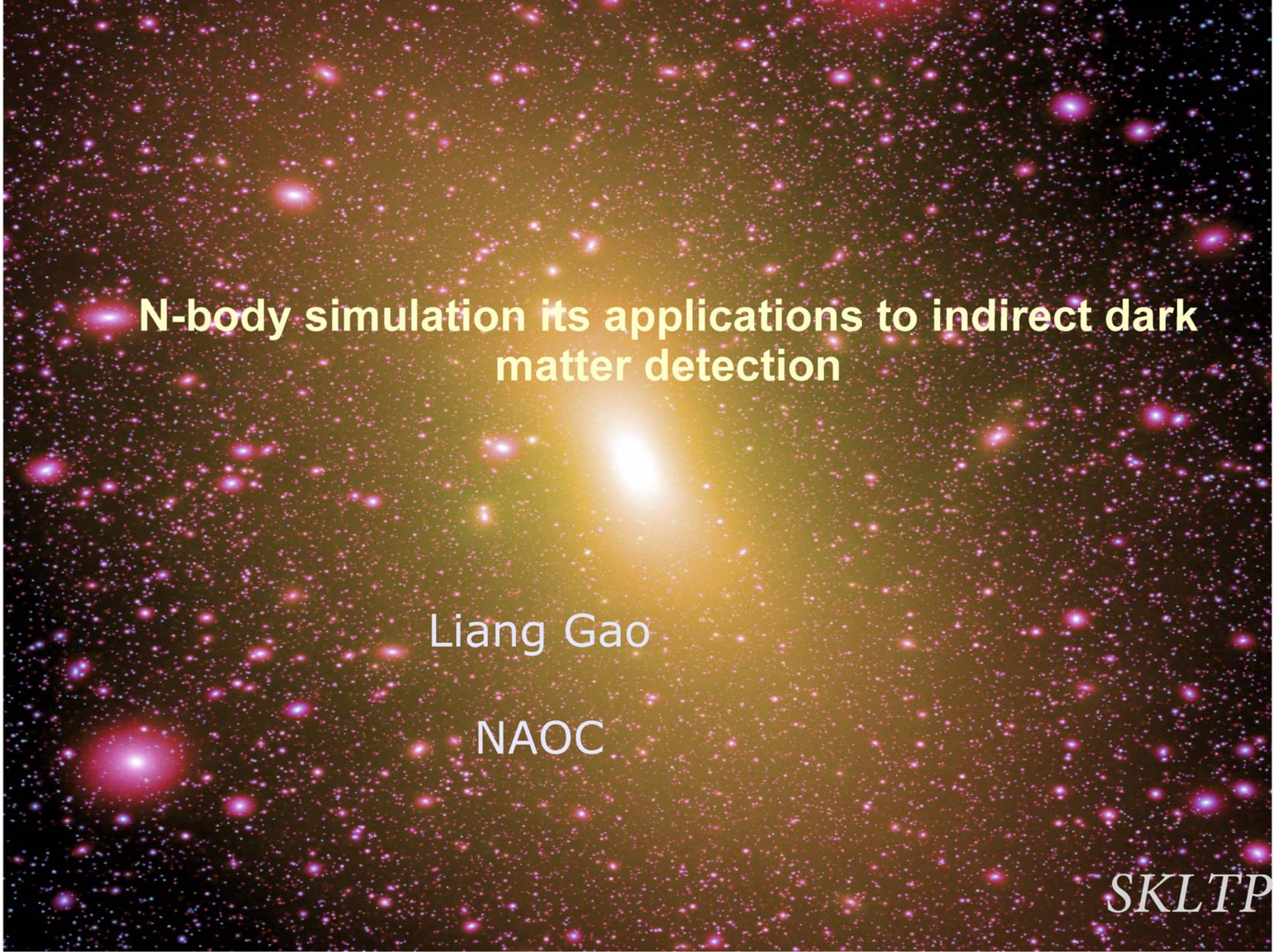

N-body simulation its applications to indirect dark matter detection

Liang Gao

NAOC

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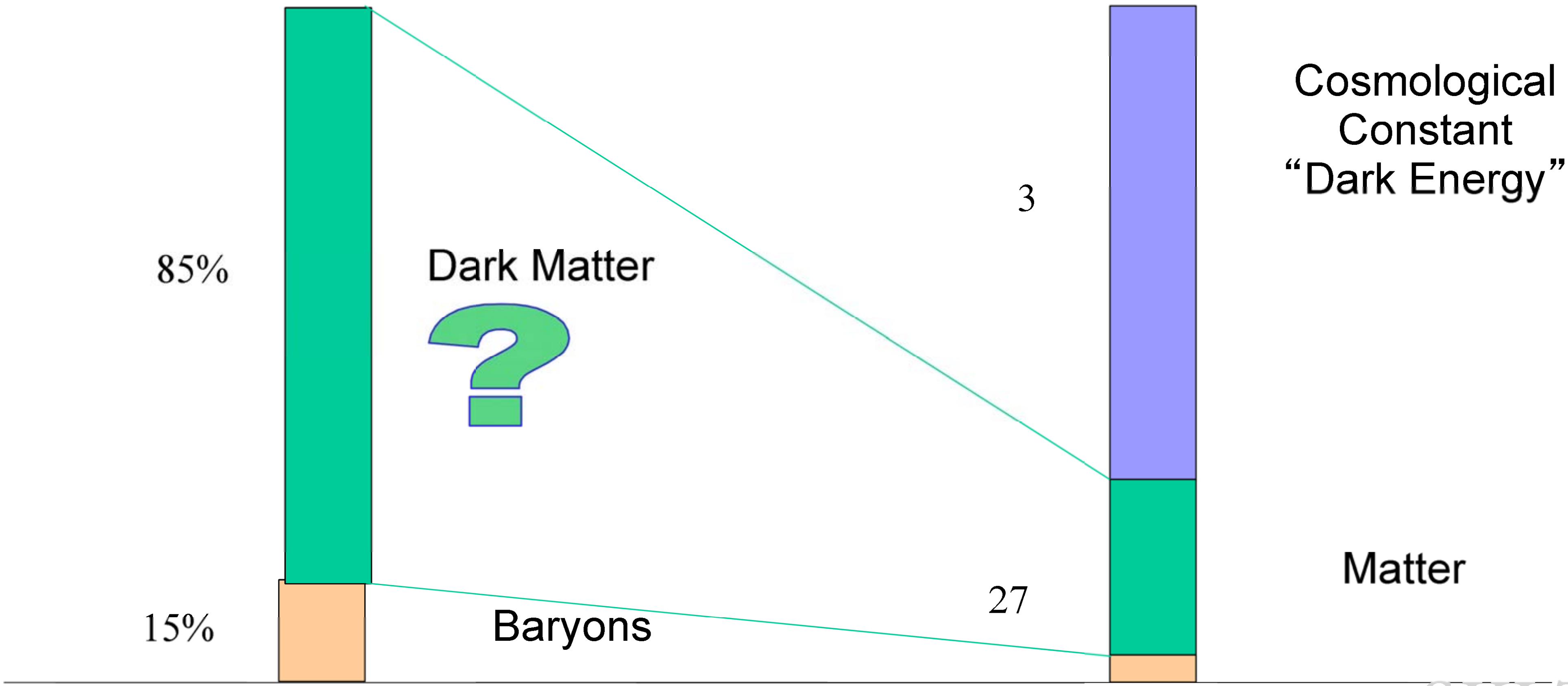
Simulations need to account for the full cosmic matter-energy content

MATERIAL IN THE UNIVERSE

tot = 1
flat space-time



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How did the primordial Universe produce galaxies/planets/people?

- Gravity Rules! Which drives the growth of all structure
- Microphysics of matter/radiations drives the formation of heavy elements and the generation of light
- Macrophysics of hydrodynamics and thermodynamics from stars, galaxies and larger structures.

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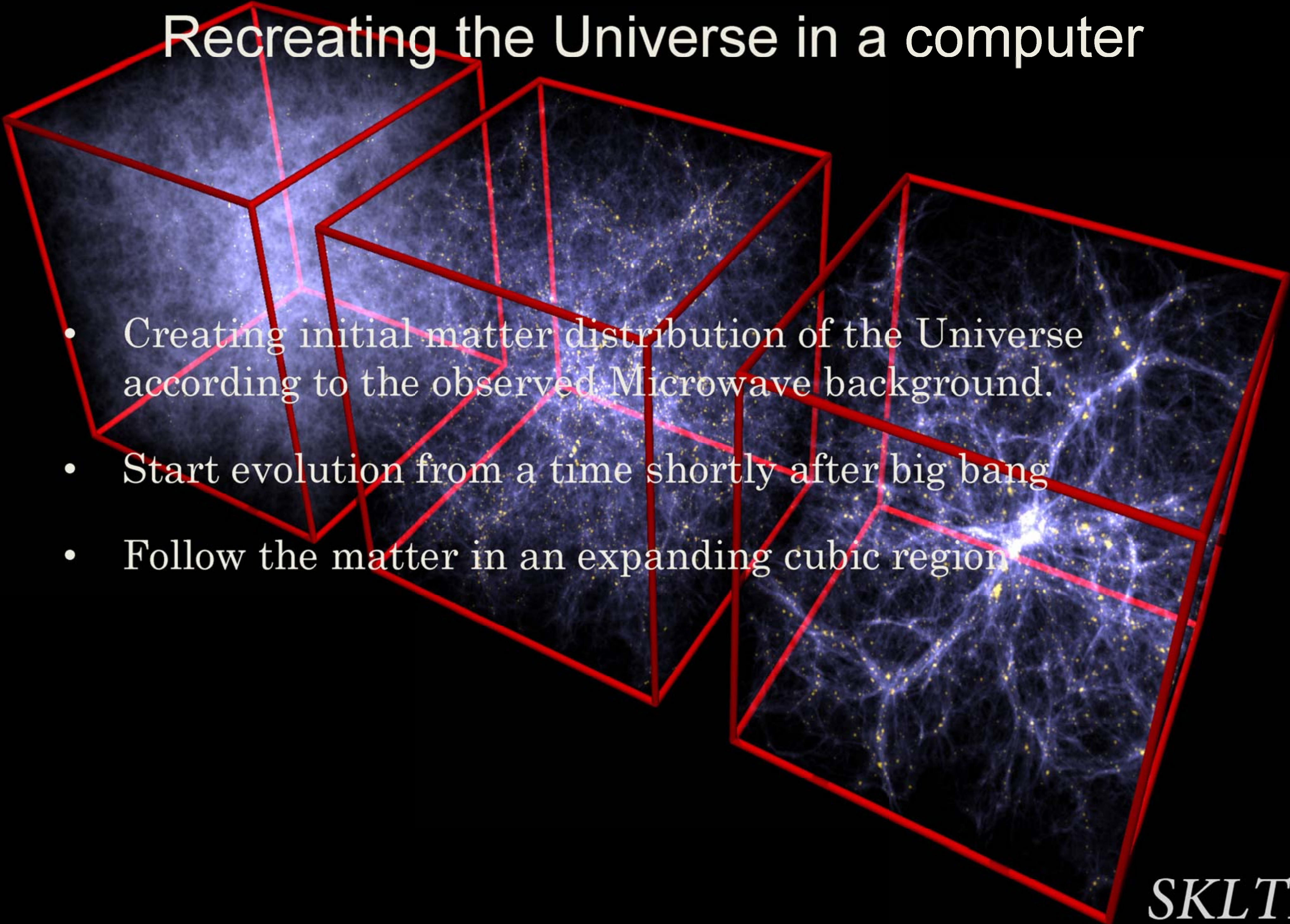
Recreating the Universe in a computer



- Creating initial matter distribution of the Universe according to the observed Microwave background.
- Start evolution from a time shortly after big bang
- Follow the matter in an expanding cubic region

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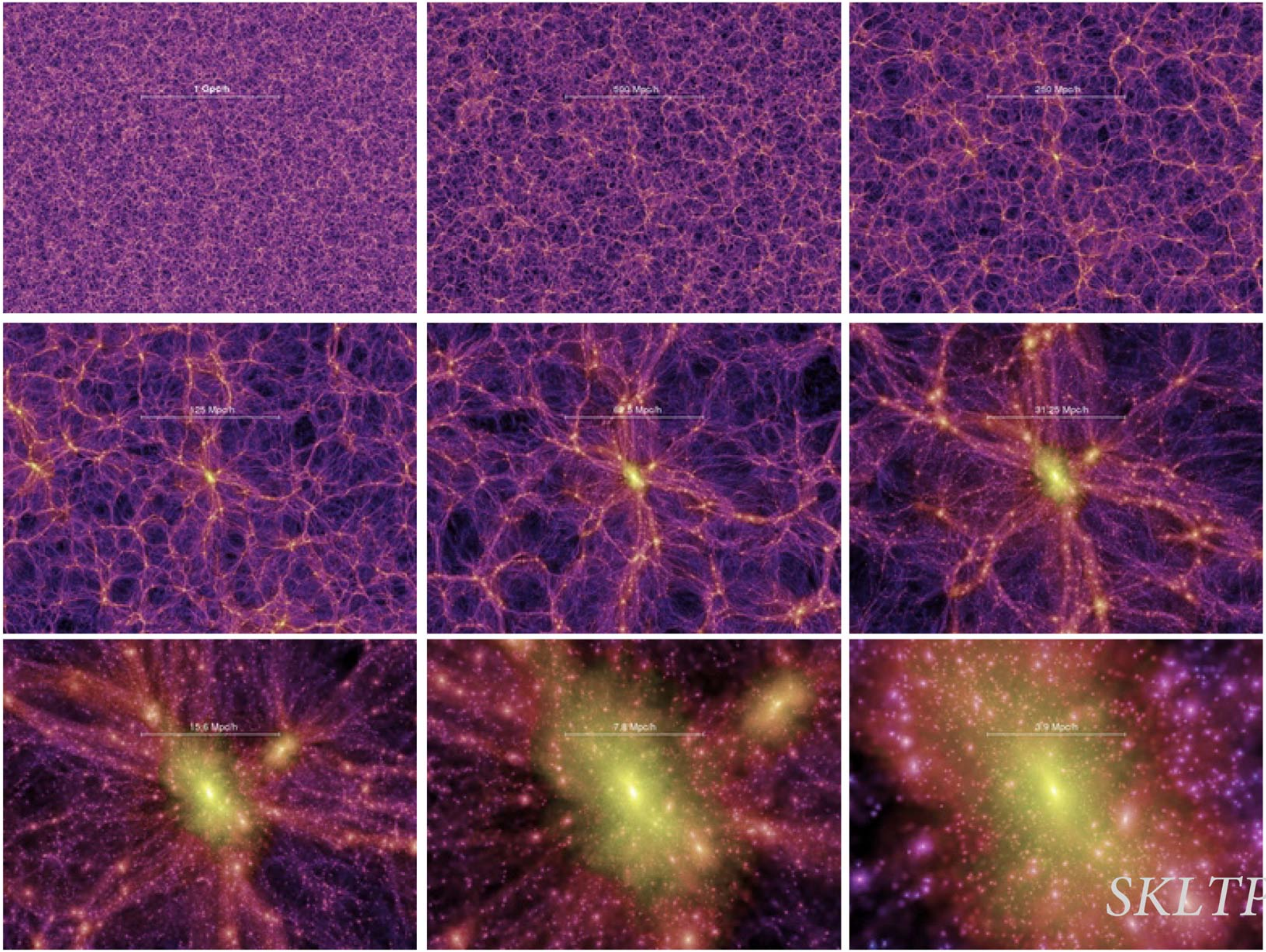
1 Gpc/h
500 Mpc/h
250 Mpc/h
125 Mpc/h
62.5 Mpc/h
31.25 Mpc/h
15.6 Mpc/h
7.8 Mpc/h
3.9 Mpc/h

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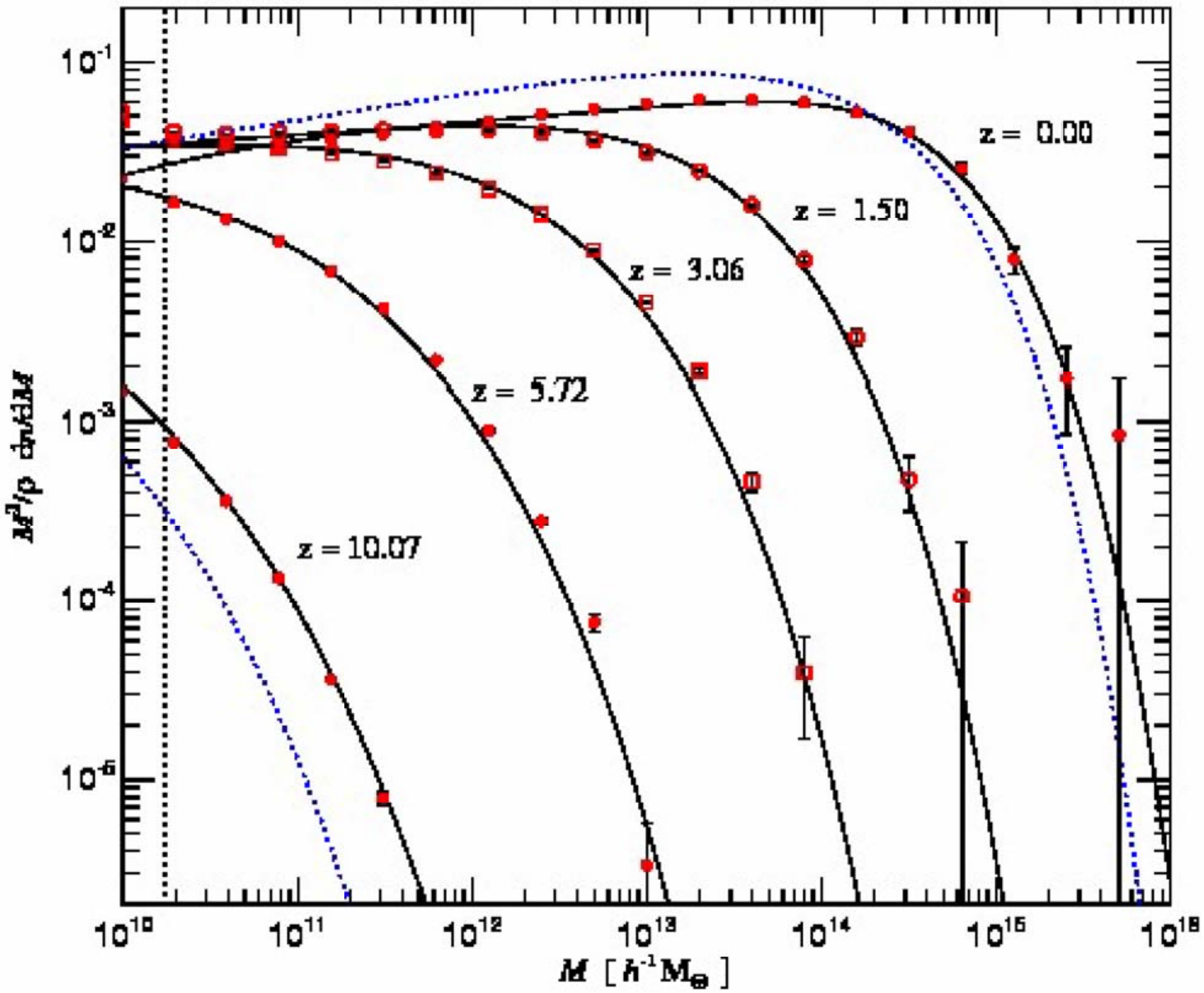
Halo mass function [number density of dark Matter halo as a function of halo mass]



Dark matter halo abundance is well described with Sheth-Torman form.
Springel et al. 2004

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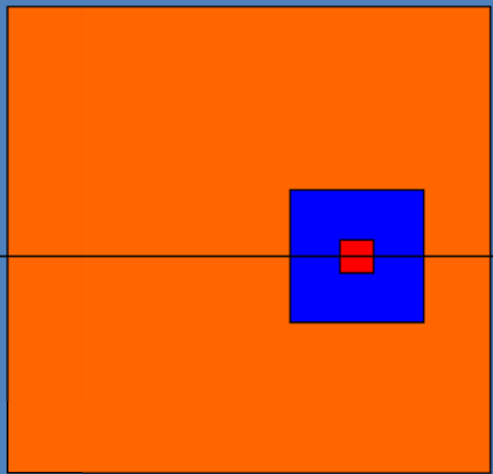
- The large N-body dark matter with uniform mass resolution like the MS may be not ideal to study internal structure of galaxy size halo ~1e12 solar masses.
- To reliably revolve inner structure of dark halo, one needs least million particles.
- We need a simulation 1000 times bigger than the Millennium simulation!

A resimulation will help here!



4 stages:

(1) Identify object of interest in existing simulation
(2) Create high resolution smooth mass distribution of the region the object originates from.
(3) Add old power keeping phases/amplitudes the same +add extra power
(4) Feed initial conditions to n-body code

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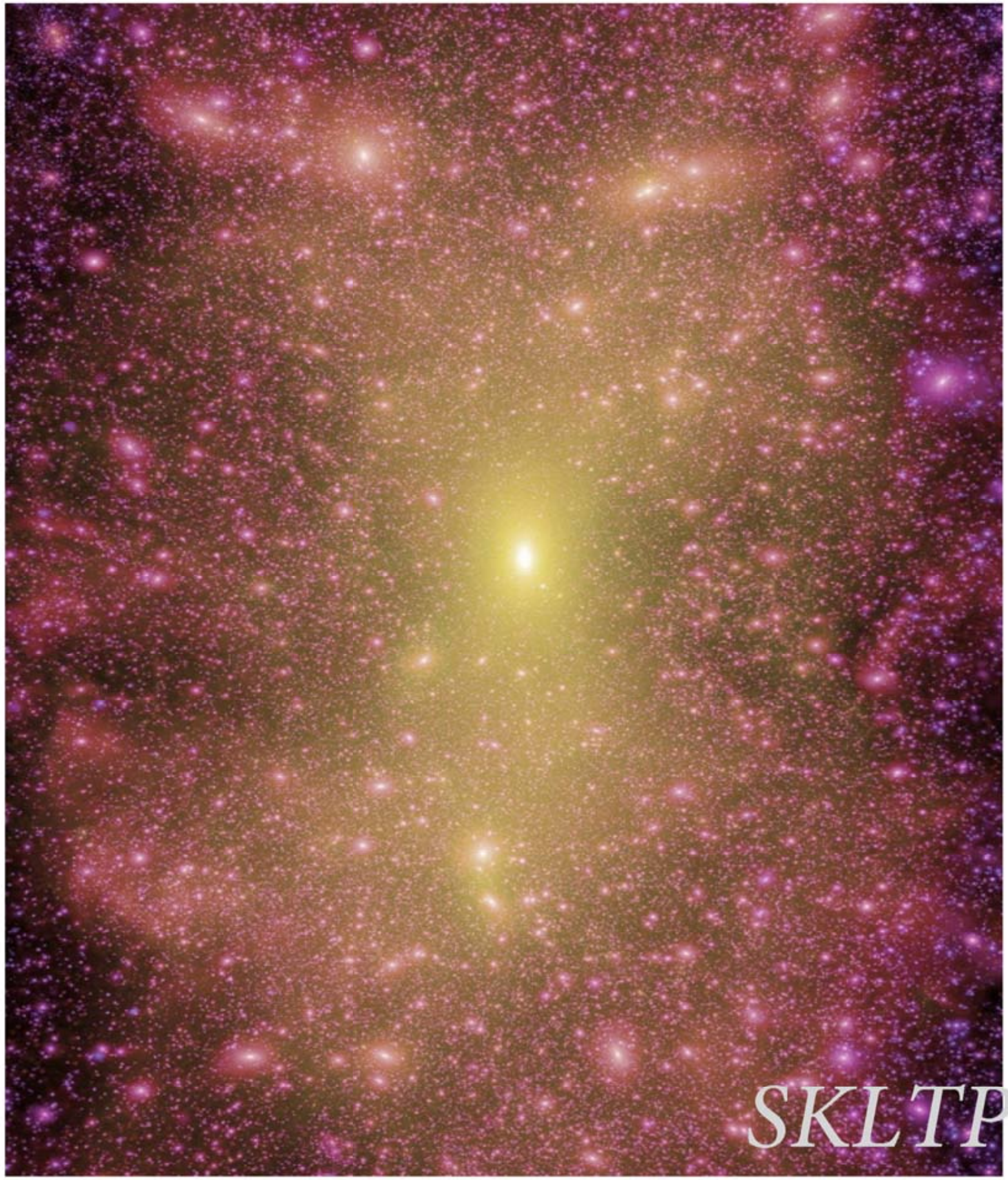
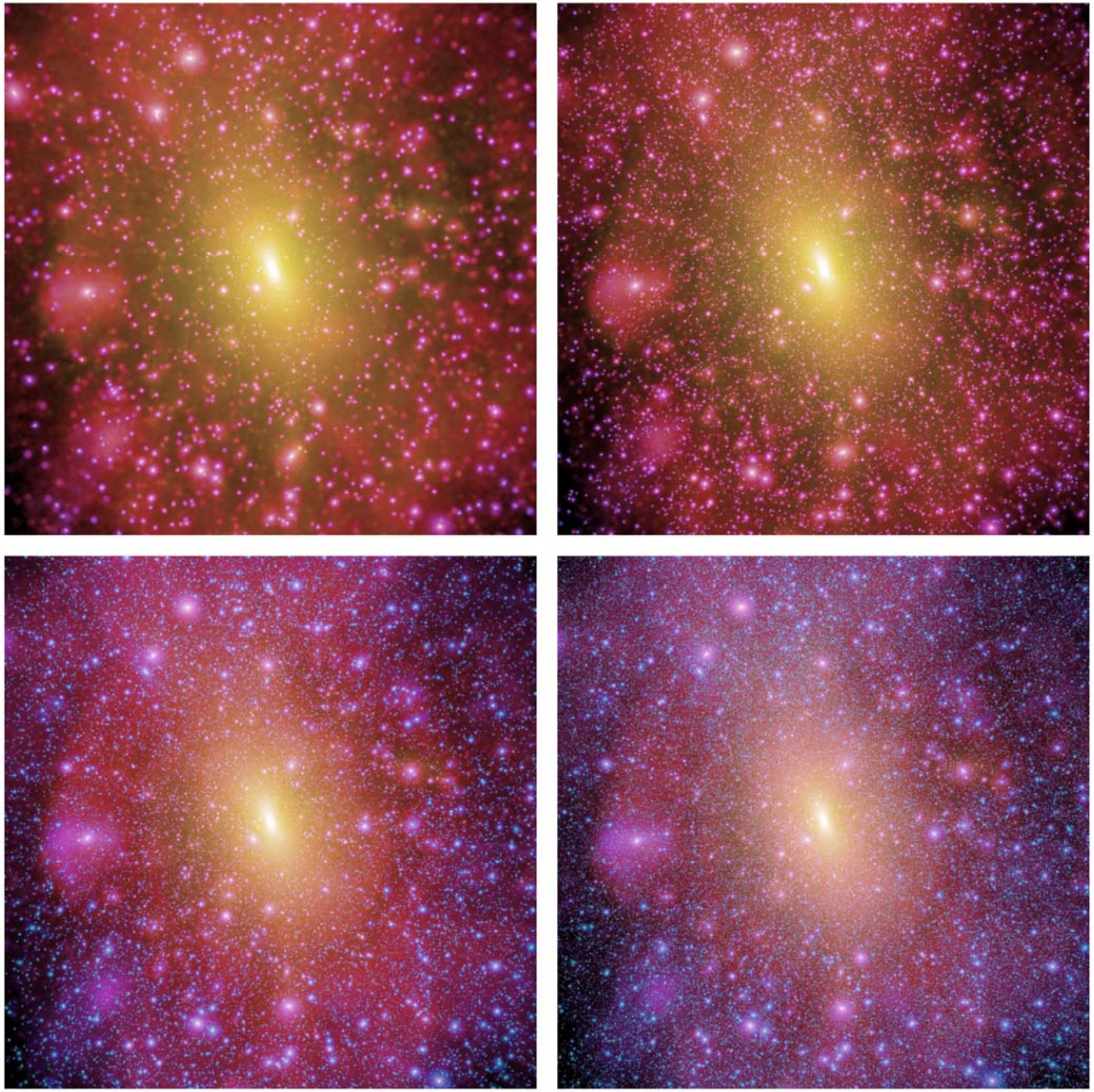
10^9 particles simulation of a galaxy sized halo

Springel et al. 2008



10^9 particles simulation of a cluster sized halo

Gao et al. 2012



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Structure of dark matter halos

- Halos extend to more than 10 times the visible radius of galaxies and contain more than about 10 times the mass in the visible regions
- Halo are not spherical but approximate triaxial ellipsoids
- Cuspy density profiles with outwardly increasing slopes.
- Substantial number of self-bound subhalos contain about 10% of the halo mass.

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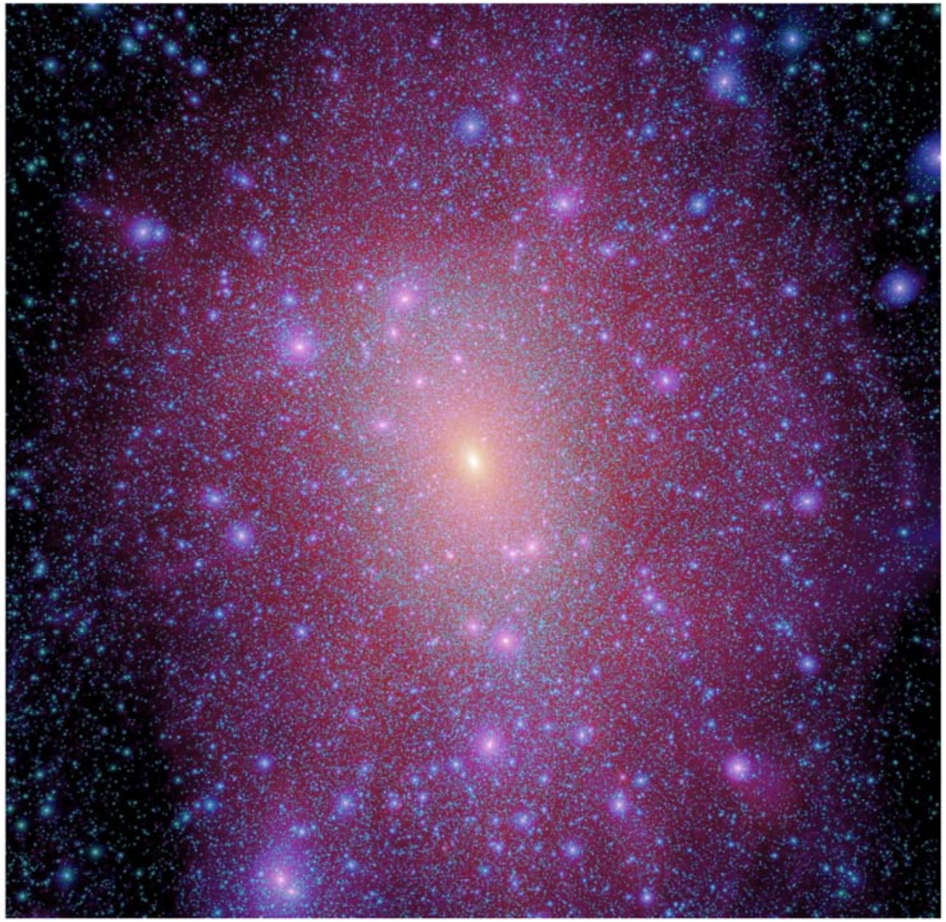
Small scale structure in halos

A 'Milky halo' Springel et al. 2008



A rich galaxy cluster halo Gao et al. 2012

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Dark halo tests of LCDM

- Measures of the shape and density profile of halos from Lensing and dynamics of visible tracers (stars, satellite galaxies)
- Limits on the central cusps from galaxy rotation curves
- Limits on amount of substructure from Observed satellites number counts and image distortion of background lensed objects.
- Detection of dark matter annihilation signal.
- Predictions for all these properties require simulations.

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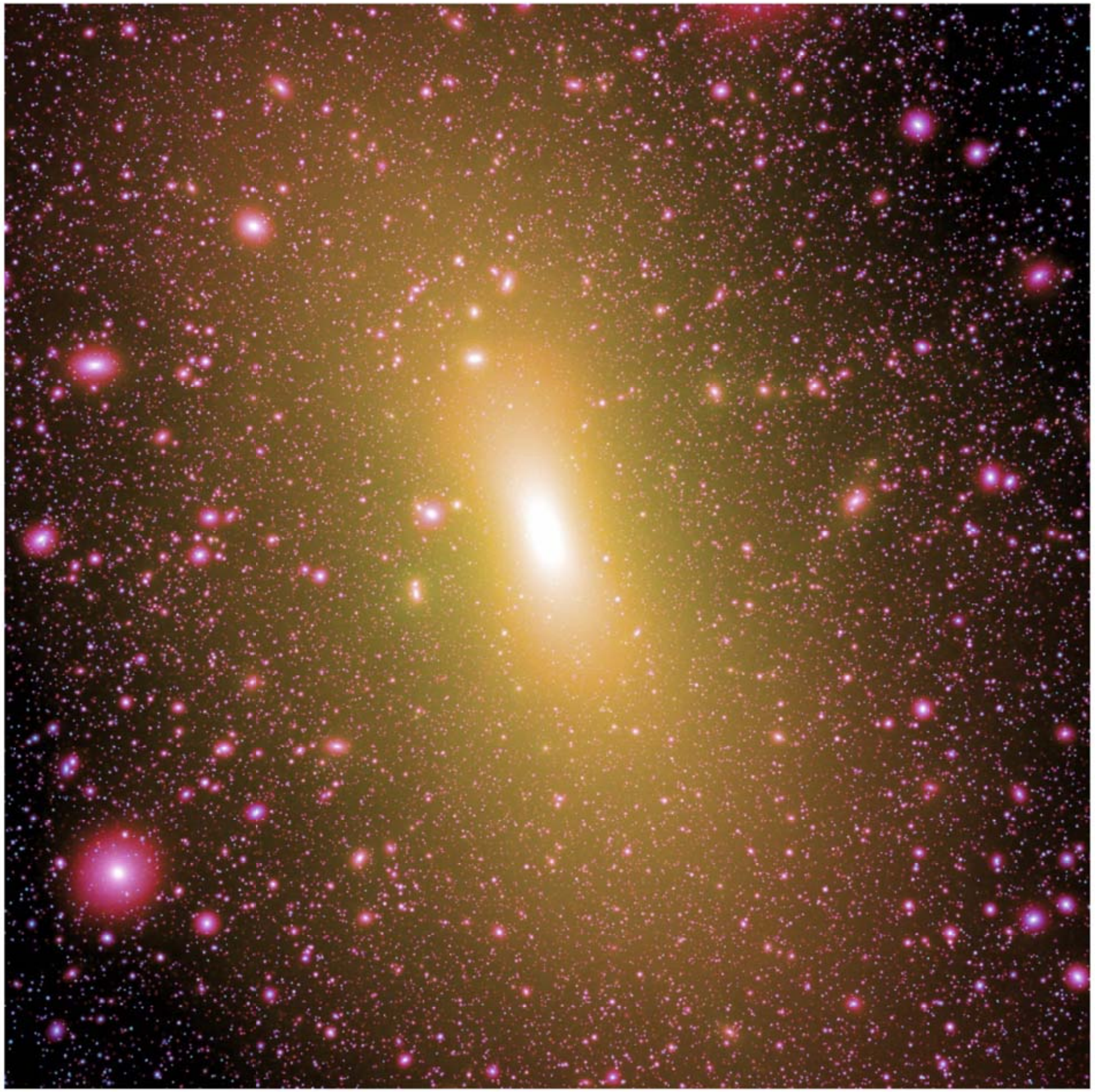
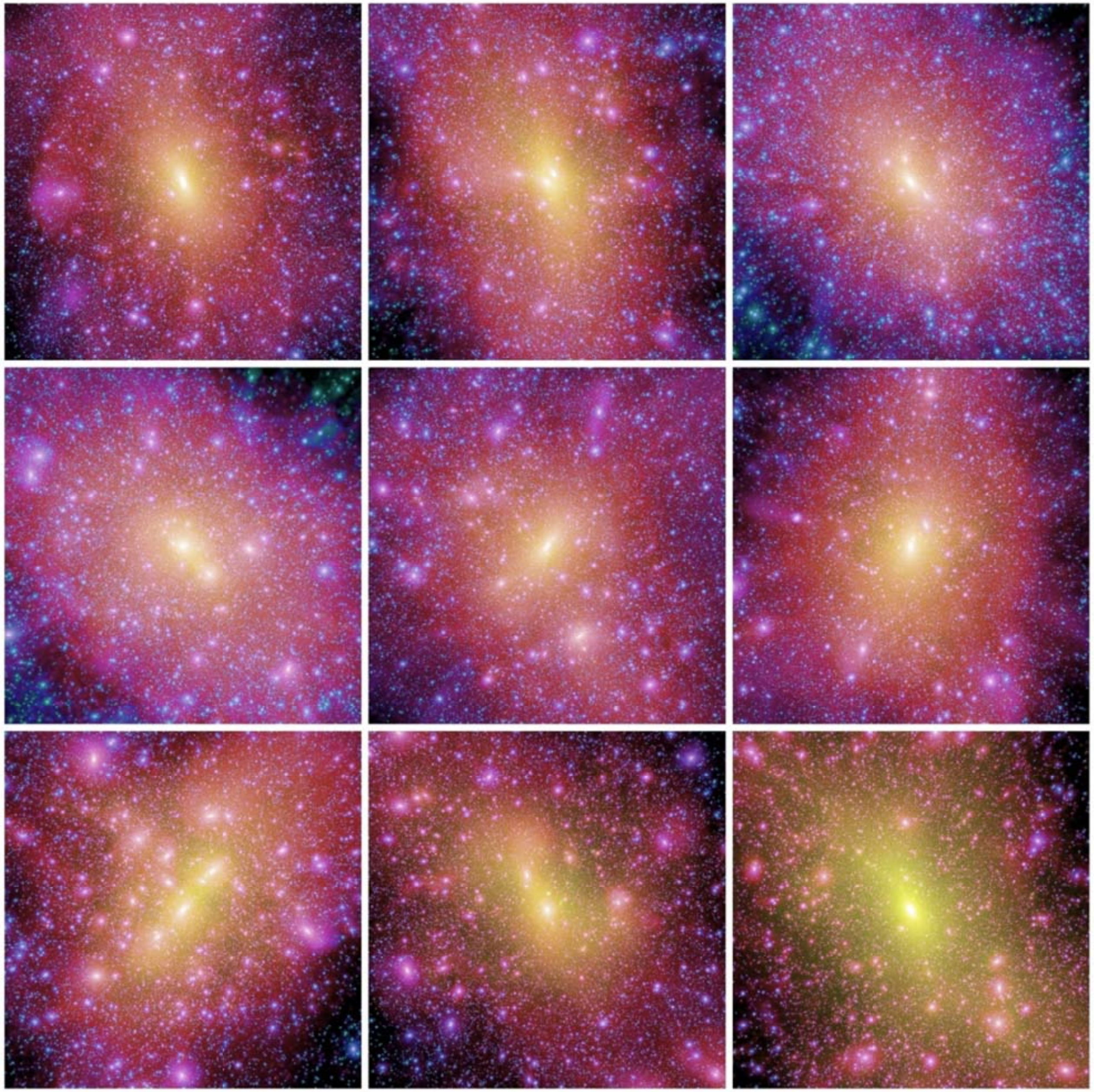


Unit Mpc/h across



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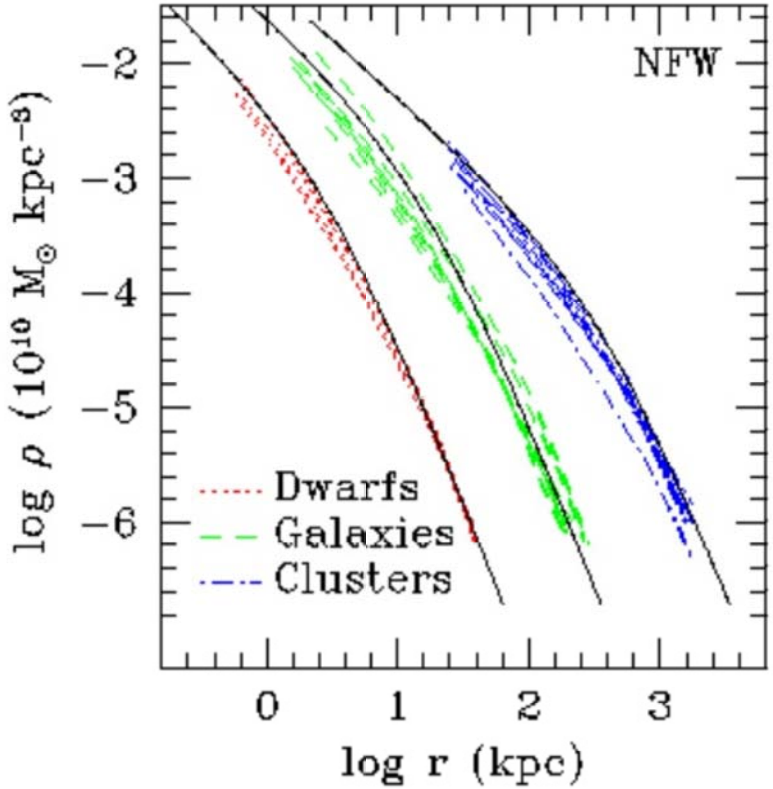
Density profiles of dark matter halos

$$\rho(r)/\langle\rho\rangle \approx \delta \; r_s \,/\, r(1 + r/r_s)^2$$



Navarro et al. 2003

An improved fitting formula

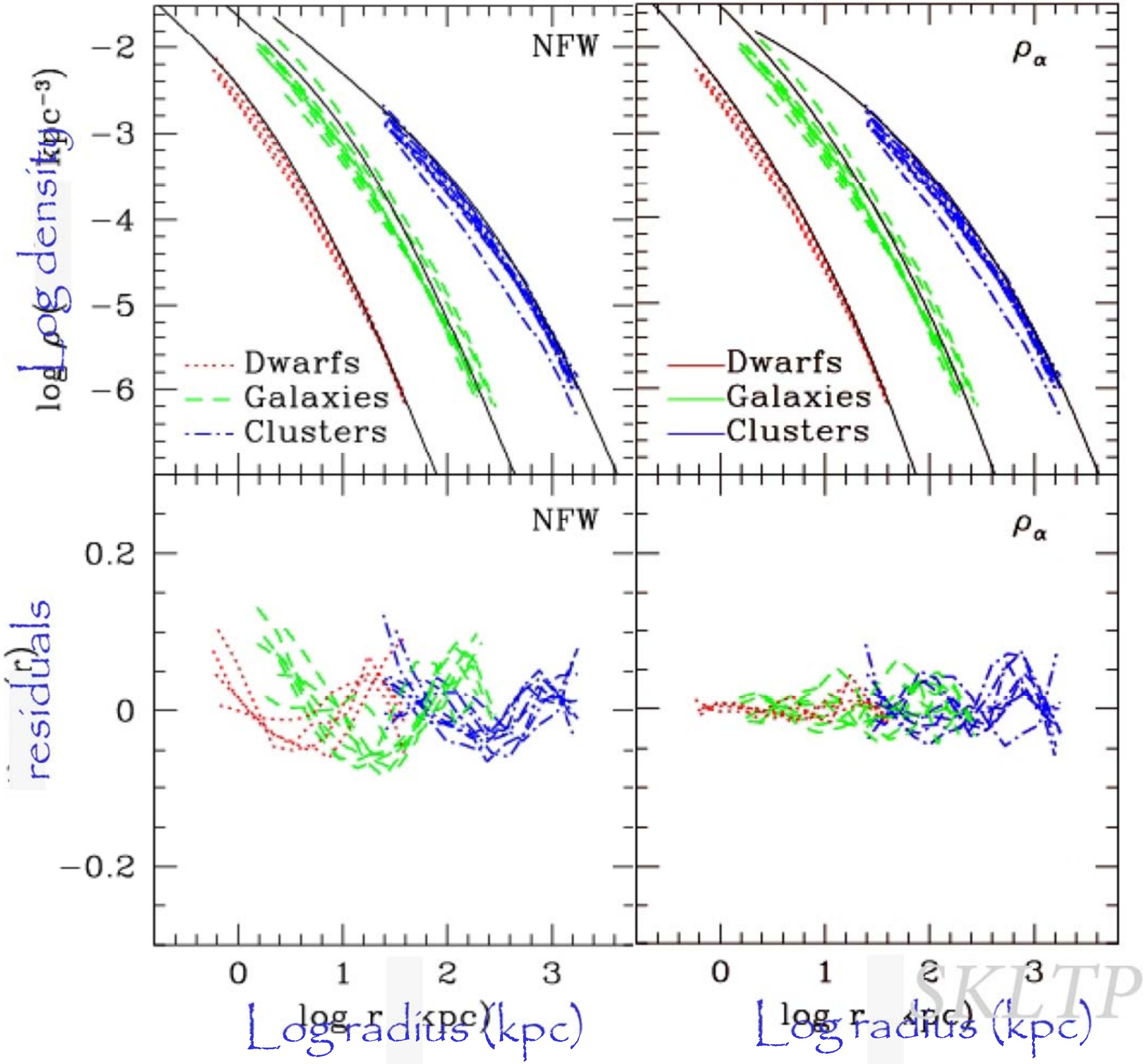
A profile whose slope is a power-law of r fits all halos to <5%

$$\frac{d\log\rho_\alpha}{d\log r} = -2\left(\frac{r}{r_{-2}}\right)^{\alpha}$$

Has extra param: α

(similar to stellar distribution in ellipticals - Einasto)

Navarro et al 04



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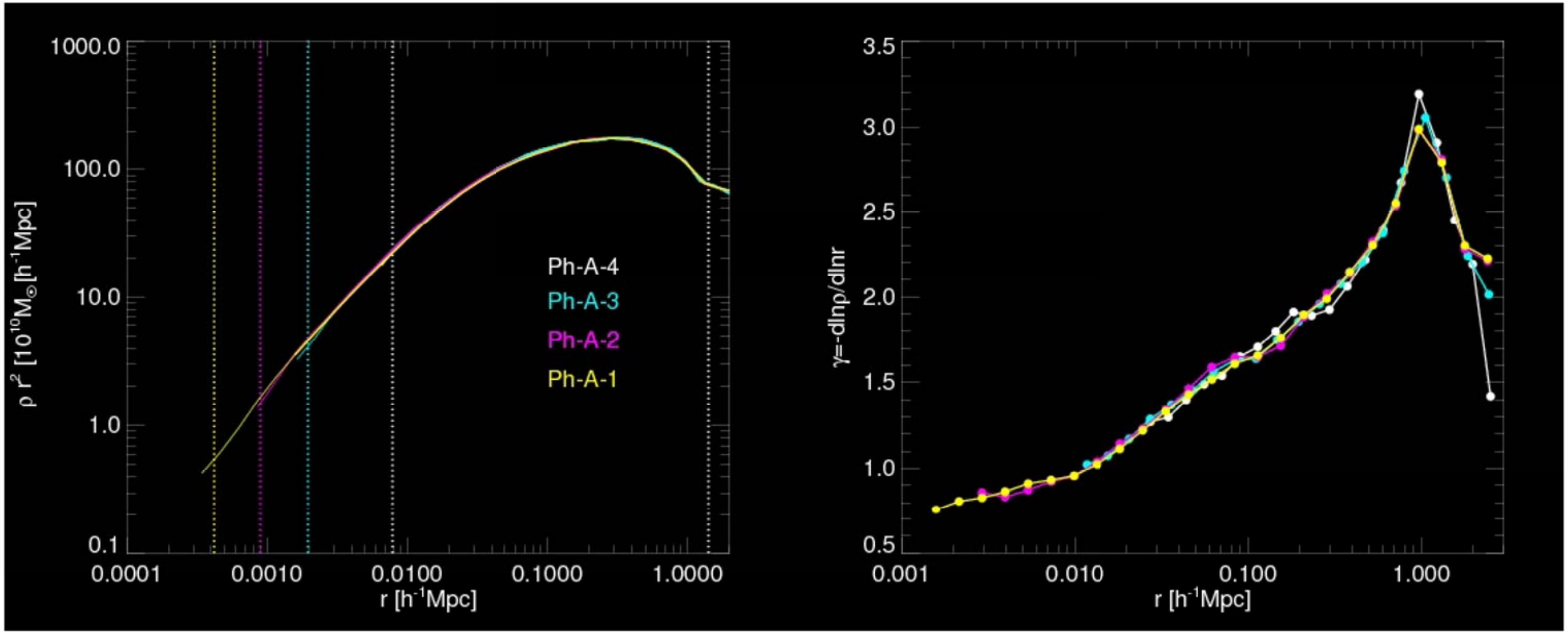
Numerical convergency



Gao et al . 2011

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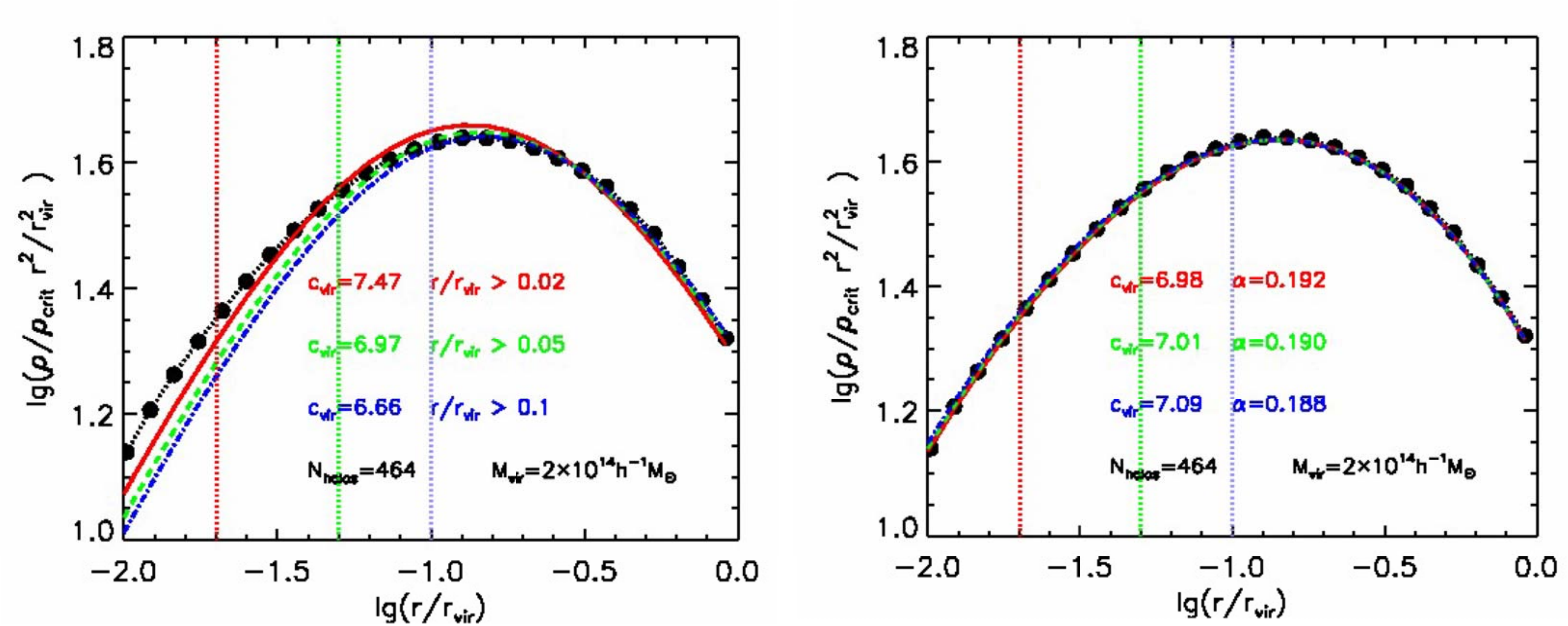
Einasto profiles

$$\ln(\rho/\rho_{-2}) = -(2/\alpha)[(r/r_{-2})^\alpha - 1].$$



Dark matter halo is more accurately described as Einasto fits

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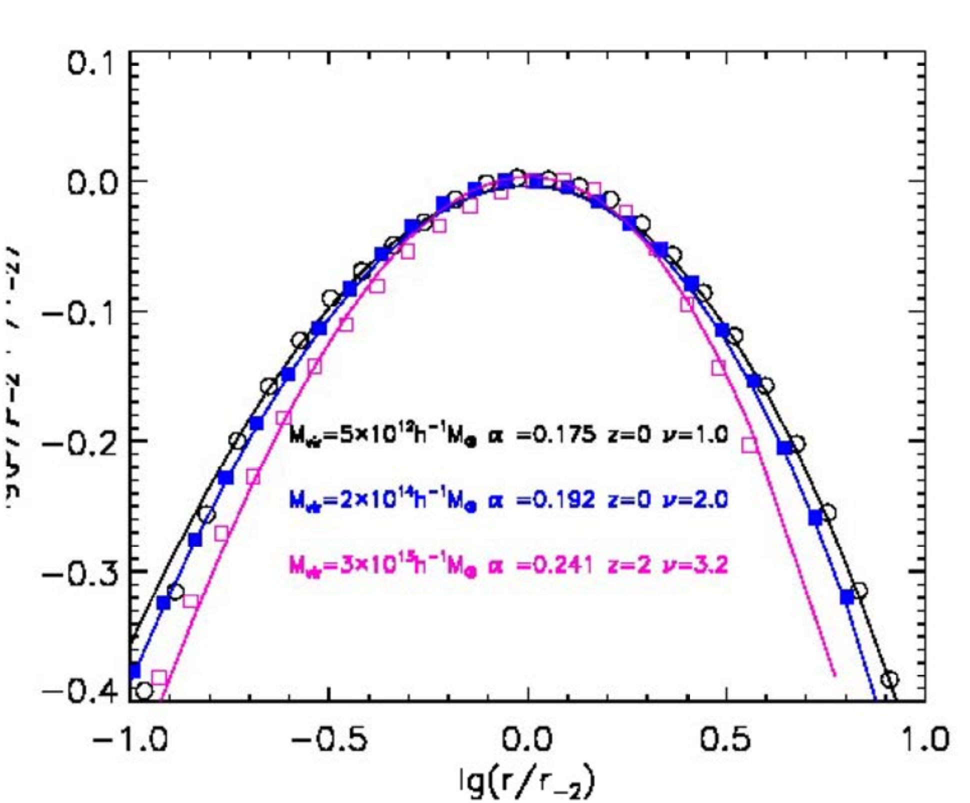
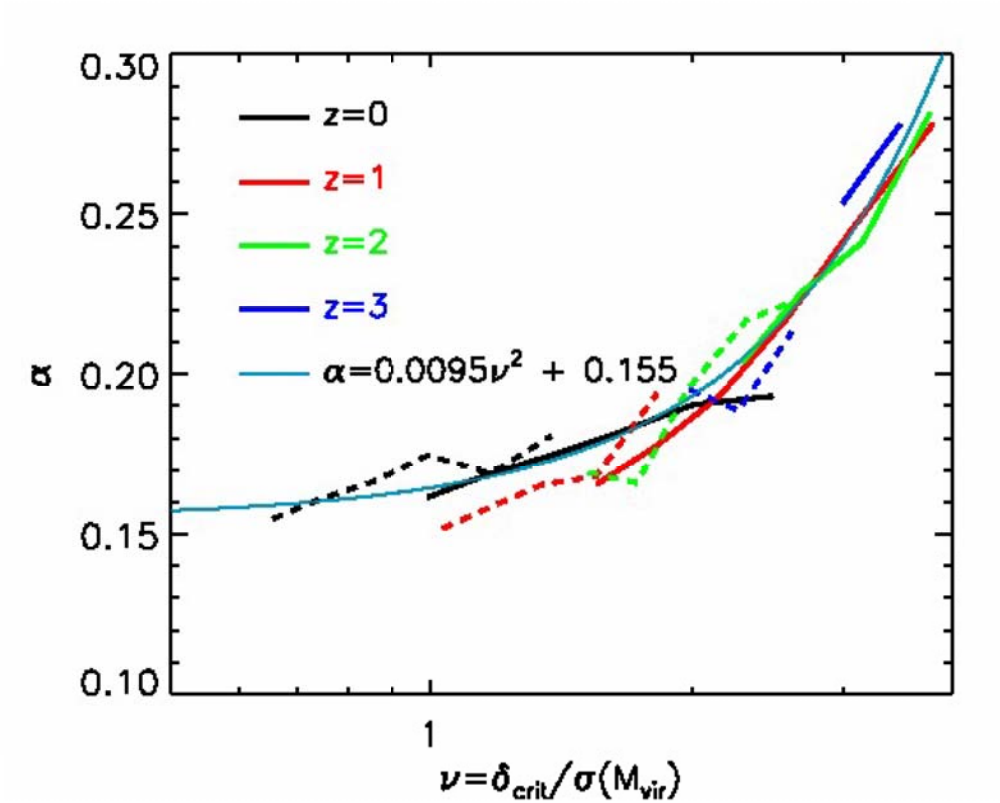
Mass dependence of halo structure





Gao et al. 2008

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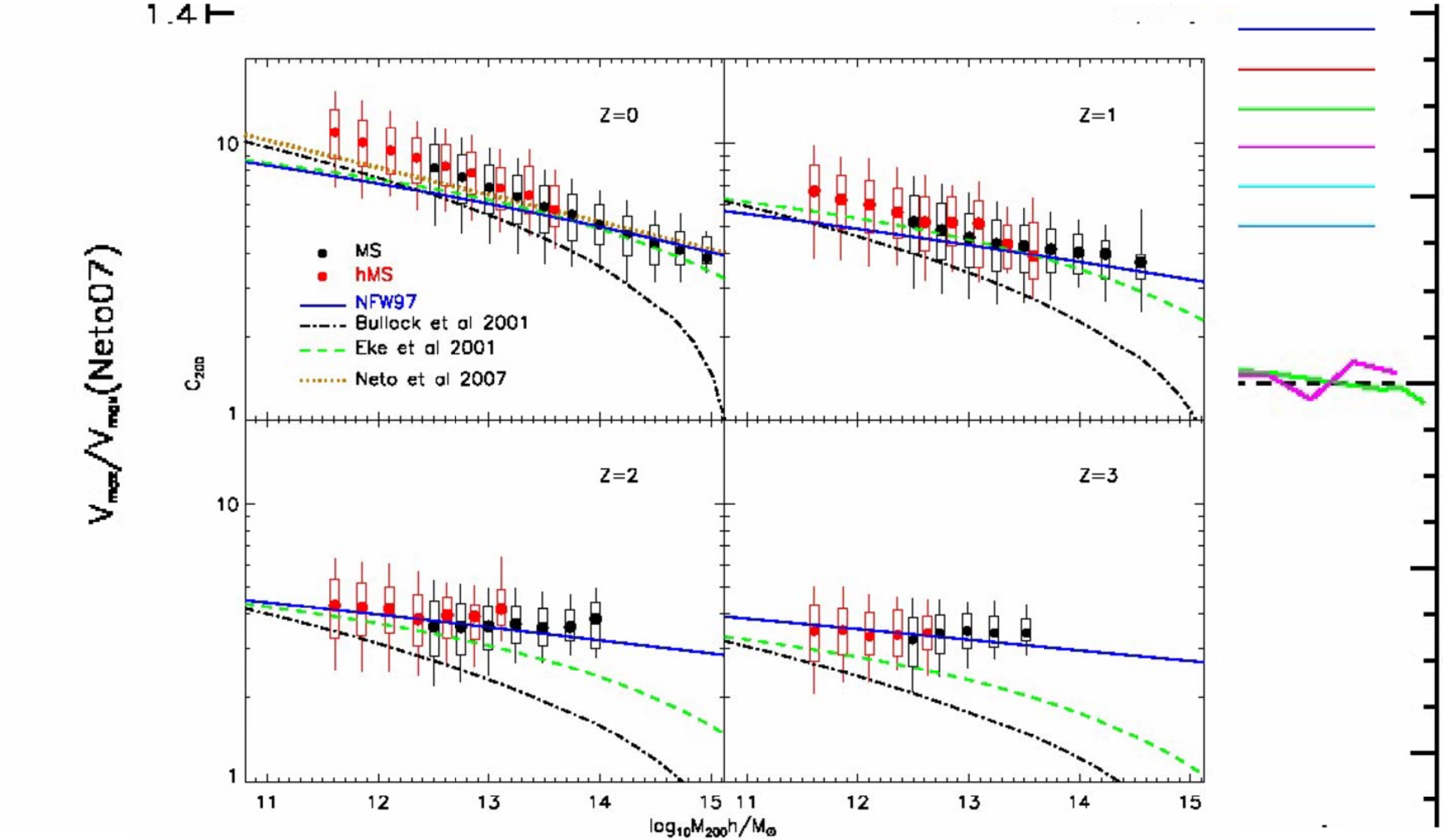
Halo concentration depends systematically and weakly on halo mass



Gao et a. 2008. Cao et al. 2011

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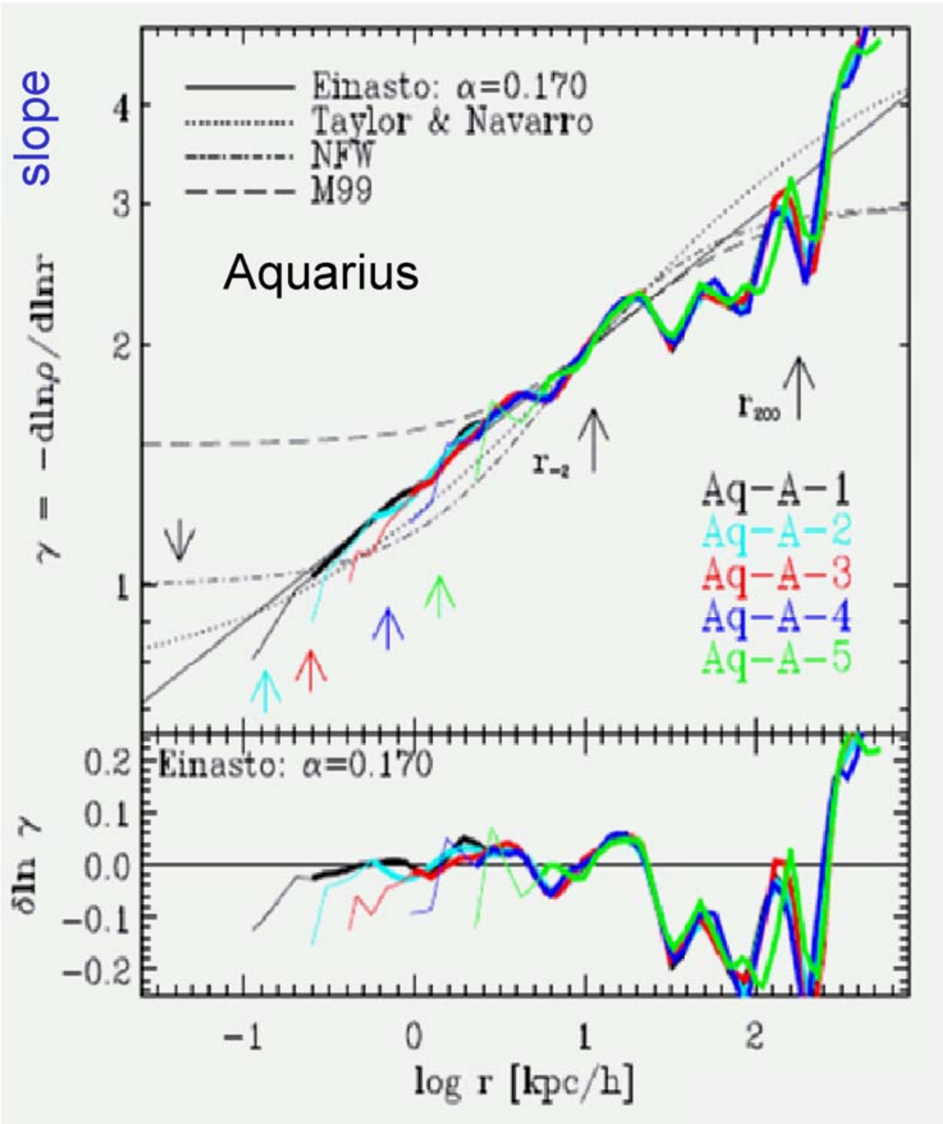
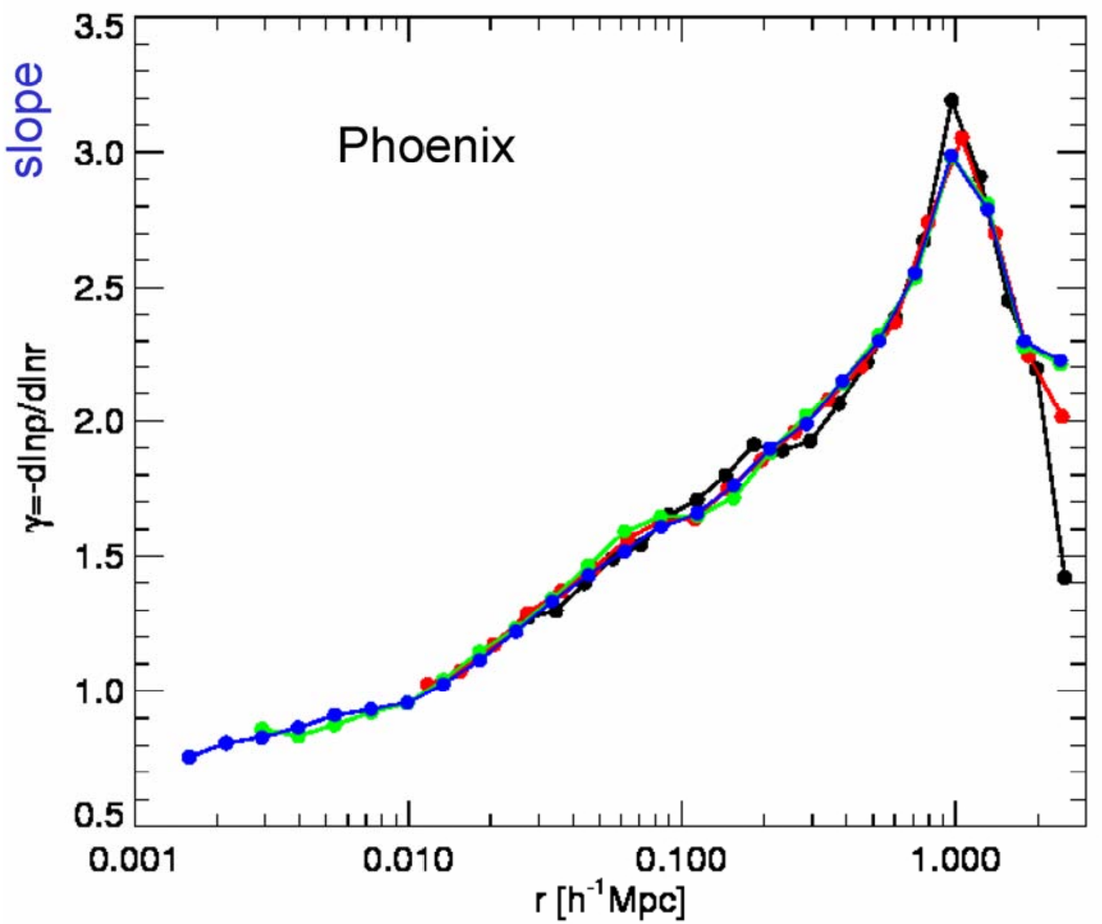
The structure of the cusp

NFW
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$





Asymptotic slope ≤ 1

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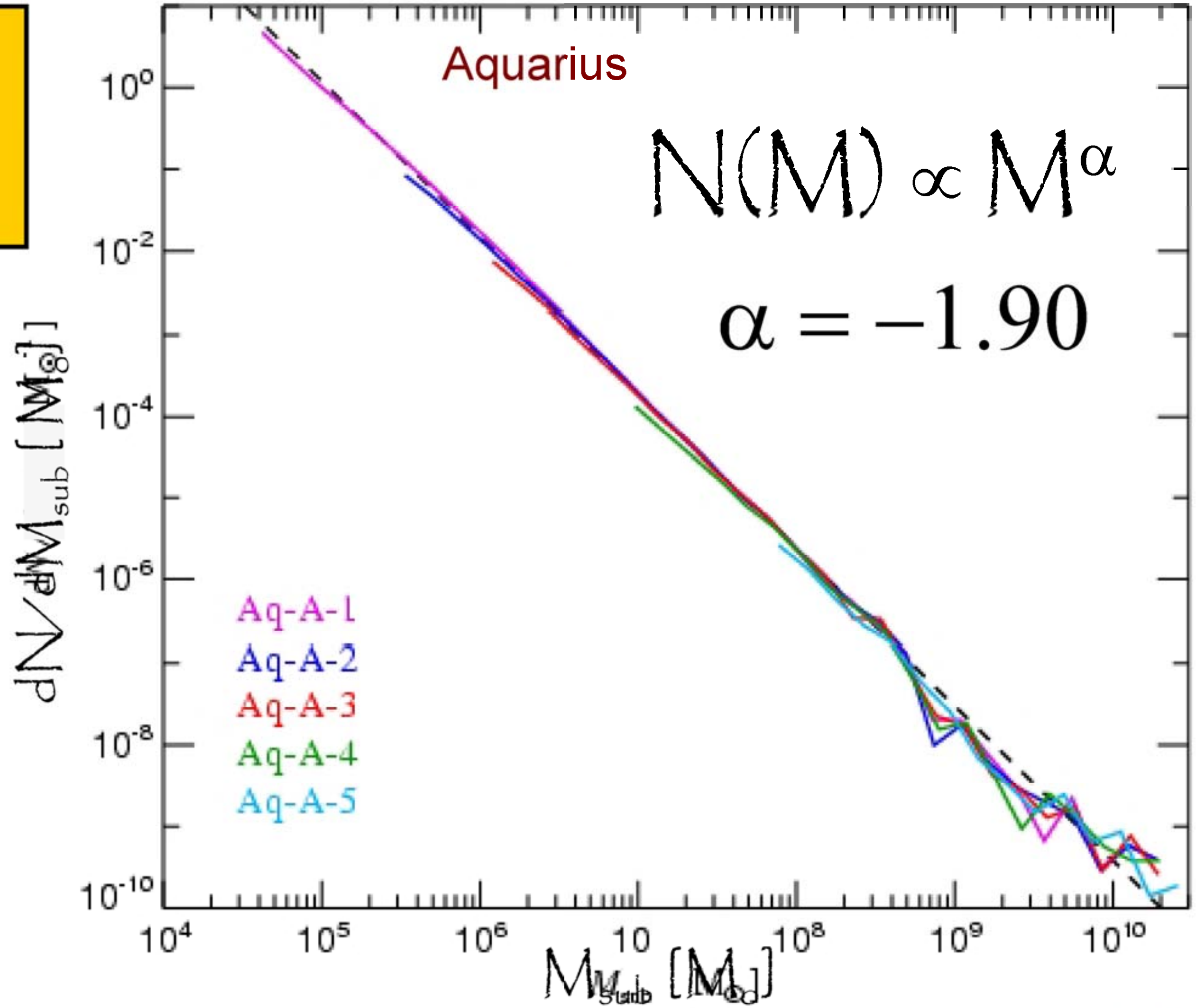
Substructures

Important for annhilation radiation

Intensity $\alpha \int \rho^2(\boldsymbol{x}) \langle \sigma v \rangle \, dV$

The mass function of substructures

The subhalo mass function is shallower than M^{-2}



Most of the substructure mass is in the few most massive halos

The total mass in substructures converges well even for moderate resolution

300,000 subhalos within virialized region in Aq-A-1

Virgo consortium
Springel et al 08

Springel, Wang, Vogelsberger, Ludlow, Jenkins, Helmi, Navarro, Frenk & White '08

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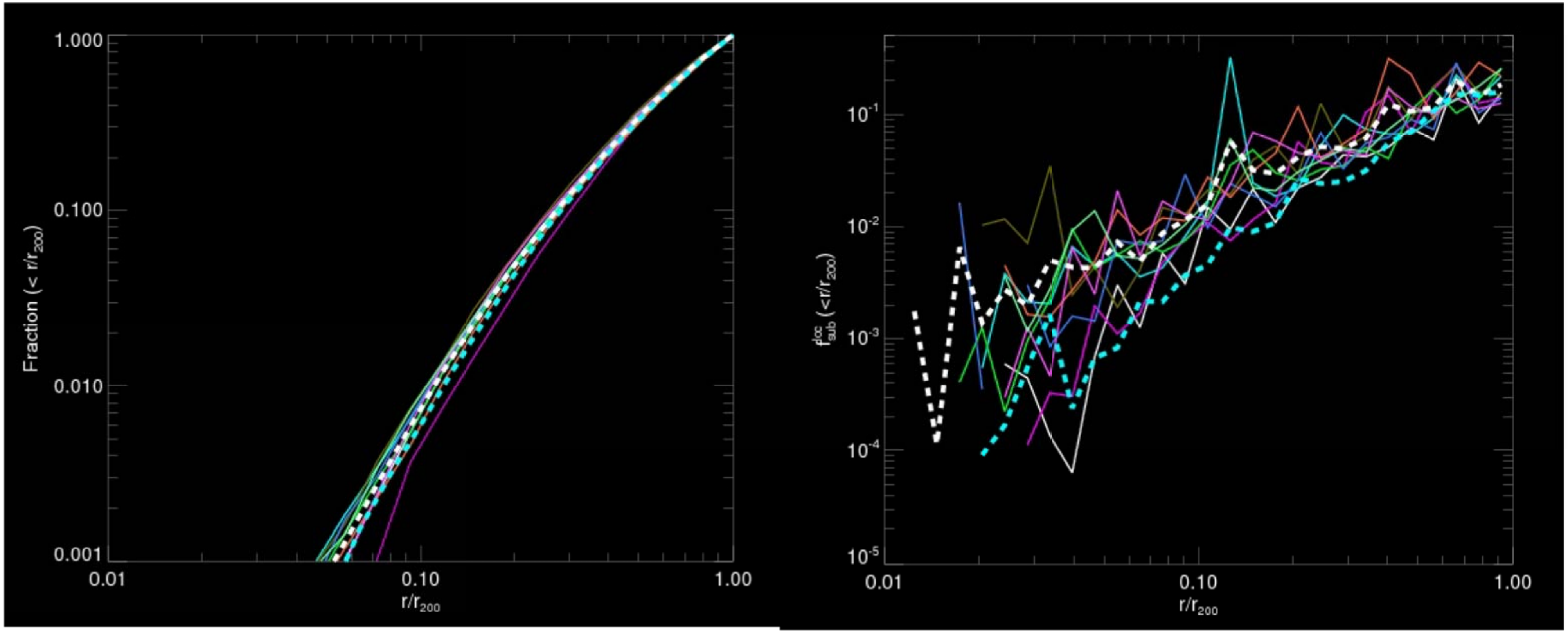
Subhalo spatial distribution



Subhalo radial distribution is almost identical for cluster and galaxy.
subhalo mass fraction is higher everywhere in clusters than in galaxies, especially in the innermost regions.

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The specific mass function of substructures

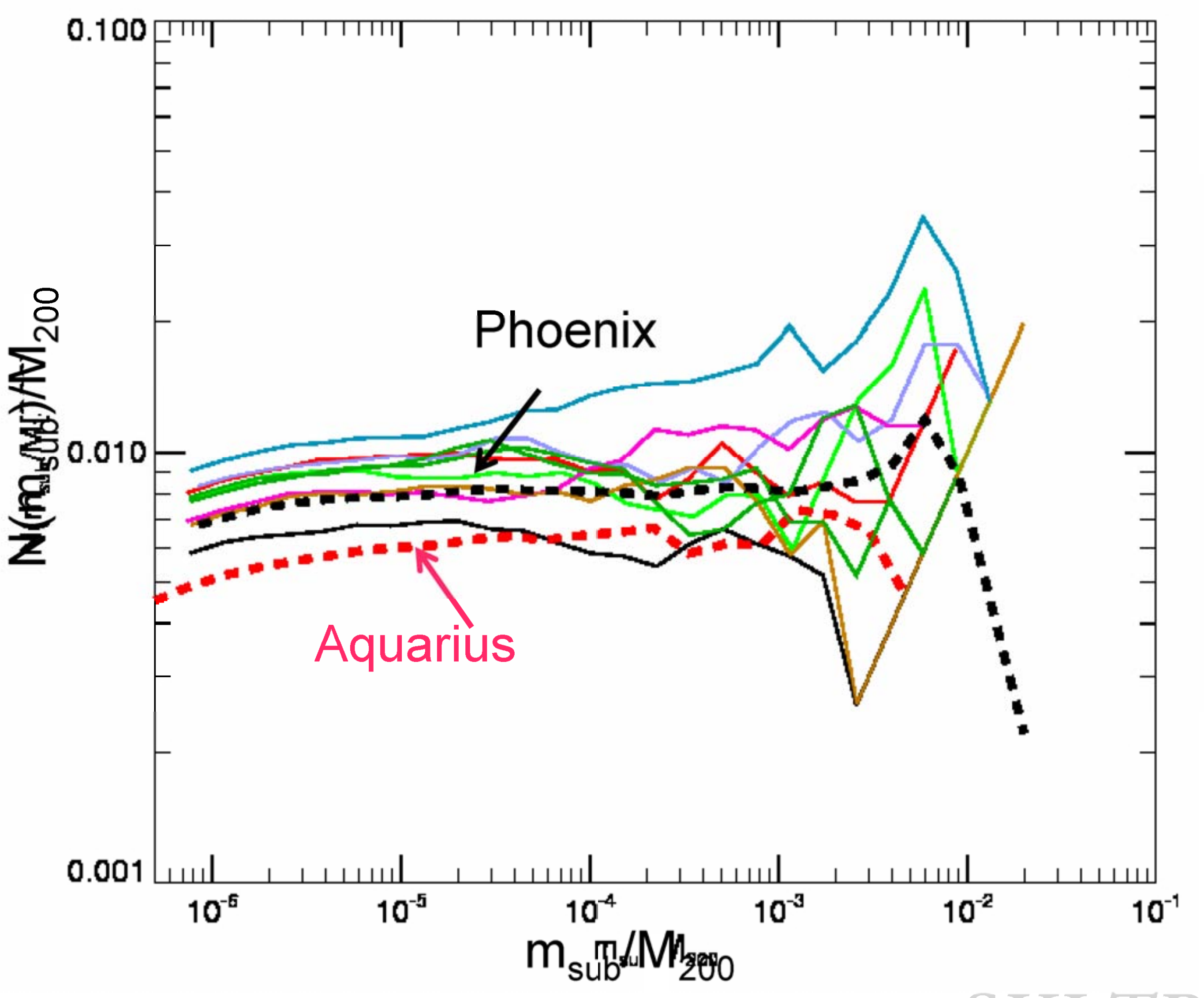
Subhalo mass function steeper

for galaxies than clusters

clusters: $N(>m) \sim M^{0.97}$ galaxies: $N(>m) \sim M^{0.90}$

~30% more subs per unit mass in clusters

Virgo consortium
Gao et al 2011



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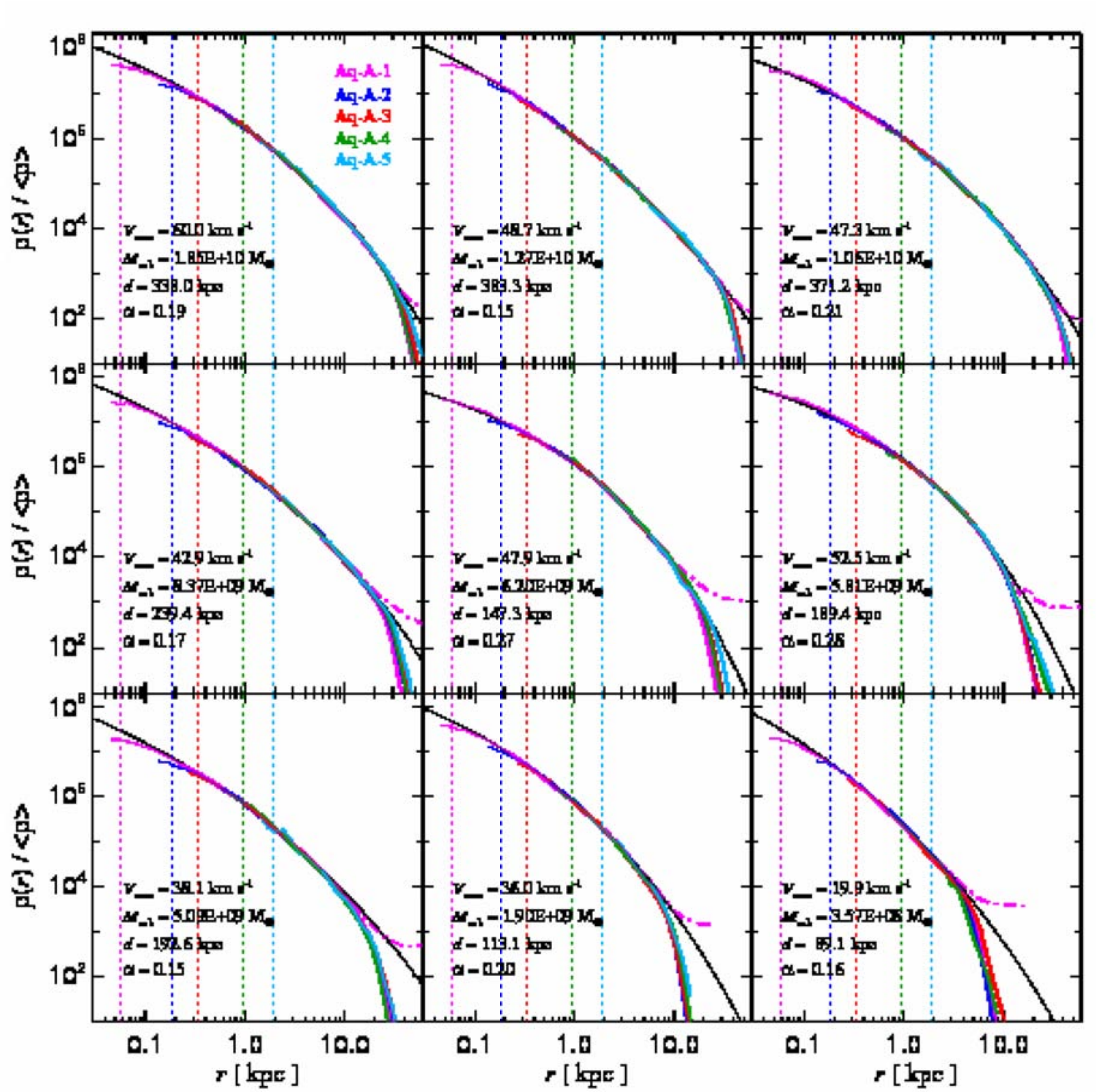
Structure of subhalo



Subhalos are Almost truncated DM halos

Springel et a. 2008

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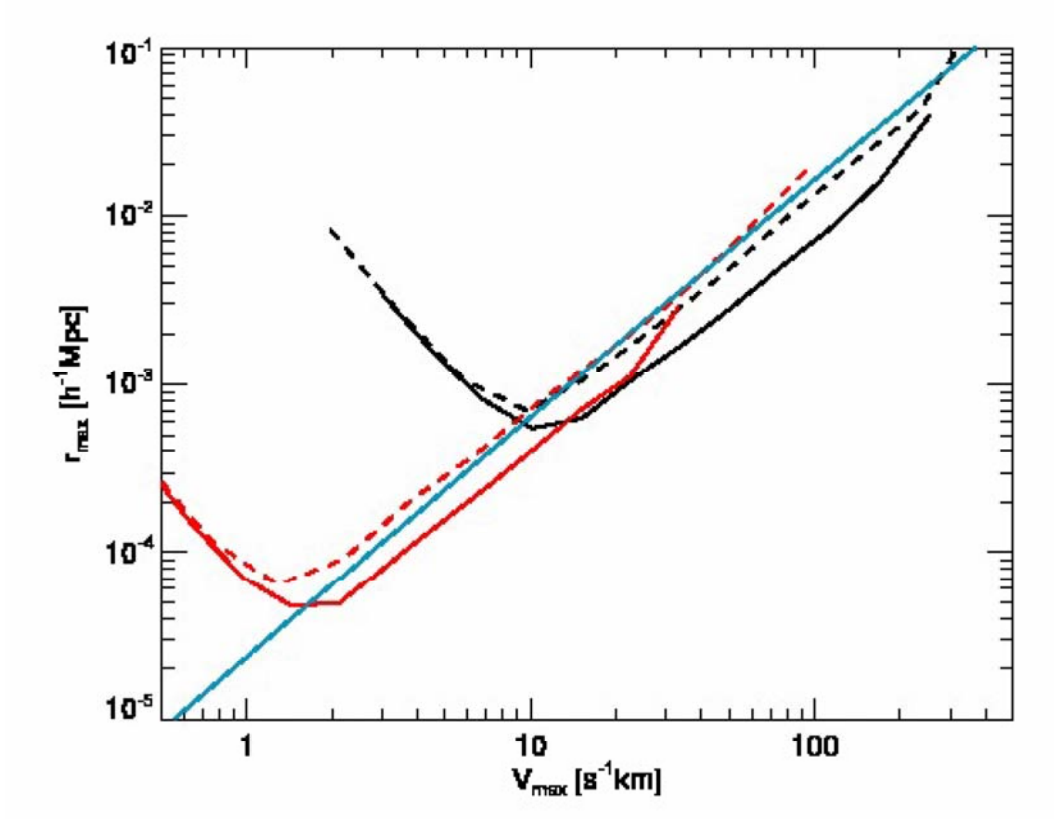
Concentration of subhalos



Gao et al. 2012

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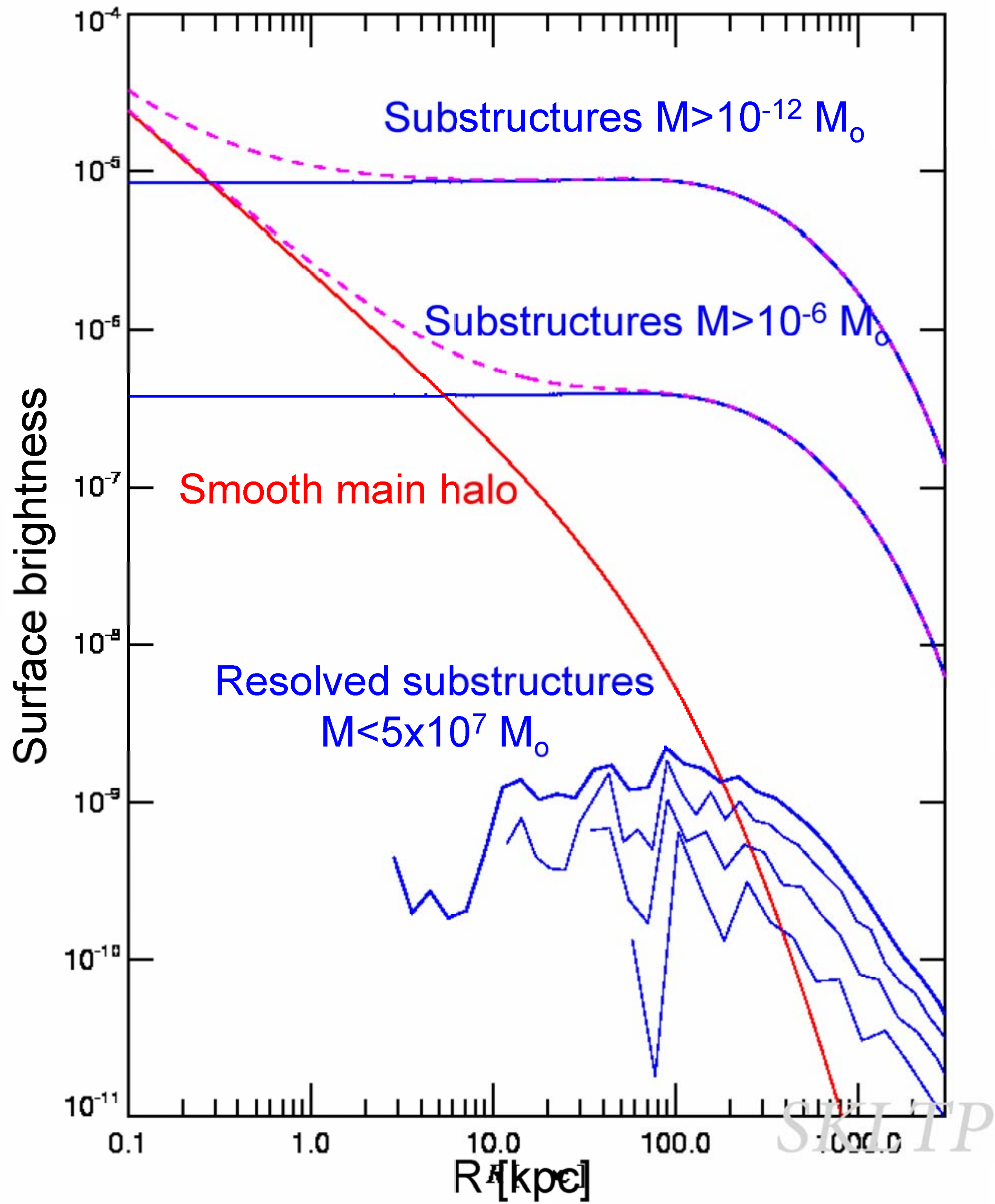
Annihilation radiation from cluster halos



Gao, Frenk, Jenkins, Springel & White '11

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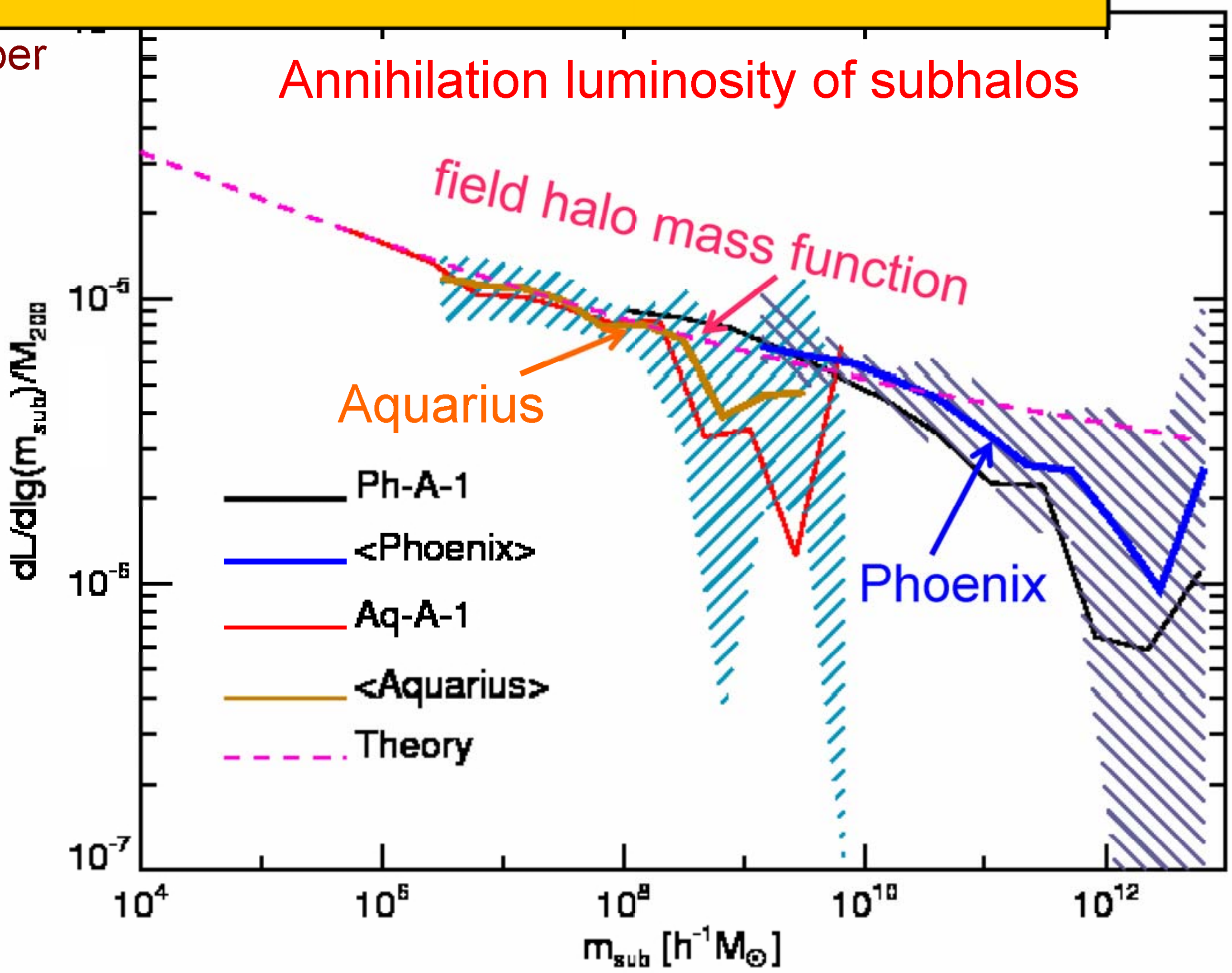
Extrapolation to Earth mass

Annihilation luminosity of subs. per unit mass

Subhalo L (per halo mass) similar to L of field halo mass fn.

Extrapolate using halo mass function (x1.5) + mass-concentration reln



Gao, Frenk, Jenkins, Springel & White ’11 (arxiv:1107.1916)

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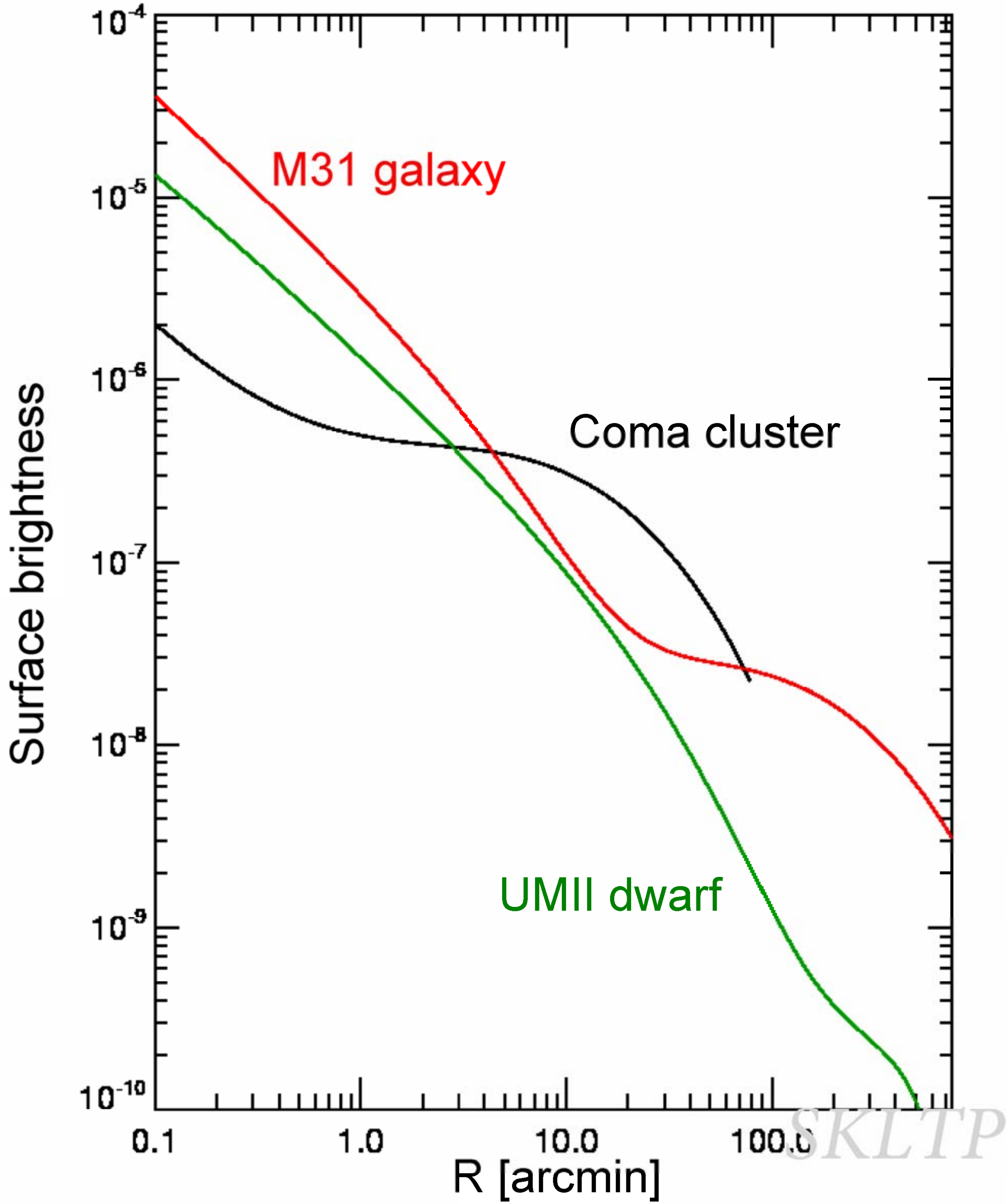
Substructure boost

Extrapolating luminosity down to $10^{-6}M_o$ (e.g. for 100 Gev WIMP)

For dwarf galaxy b~ few
For galactic halos b~100
For cluster halos b~1300 (Gao et al. '11)

Annihilation radiation

Surface brightness



Gao, Frenk, Jenkins, Springel & White '12

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Properties of nearby galaxy clusters, satellites of the Milky Way and M31

Object Name	Core radius [arcmin]	Distance [Mpc]	M_{200} [$M_\odot$] [$M_\odot$]	L [L_{mw}]	$F = L/(4\pi d^2)$ [F_{mw}]	S/N [$(S/N)_{mw}$]
AWM 7	35.5	67.0	4.2e14	3.8e4	3.2e-4	6.8e-3
Fornax Cluster	84.1	17.5	1.0e14	6.4e3	7.9e-4	7.3e-3
M49	59.6	18.2	0.4e14	2.1e3	2.4e-4	3.0e-3
NGC 4636	52.6	17.4	0.24e14	1.1e3	1.4e-4	2.0e-3
Centaurus (A3526)	40.1	50.5	2.6e14	2.1e4	3.1e-4	5.9e-3
Coma	36.1	95.8	1.3e15	1.5e5	6.4e-4	1.3e-2
Draco	16.4	0.082	N/A	2.8e-3	1.6e-5	6.3e-4
UMI	18.4	0.066	N/A	2.3e-3	2.0e-5	7.5e-4
LeoI	4.4	0.25	N/A	1.9e-3	1.2e-6	8.2e-5
Fornax dwarf	5.9	0.138	N/A	1.0e-3	2.1e-6	1.5e-4
LeoII	2.5	0.205	N/A	4.5e-4	4.1e-7	3.1e-5
Carina	4.6	0.101	N/A	3.8e-4	1.4e-6	1.0e-4
Sculpt	13.2	0.079	N/A	1.7e-3	1.0e-5	4.9e-4
Sext	3.3	0.086	N/A	1.6e-4	8.2e-7	6.1e-5
UMaII	28.8	0.032	N/A	1.4e-3	5.1e-5	1.3e-3
Comber	15.9	0.044	N/A	8.0e-4	1.7e-5	6.8e-4
WilI	17.7	0.066	N/A	2.1e-3	1.8e-5	7.0e-4
LMC	82.5	0.049	N/A	2.0e-2	3.3e-4	3.1e-3
SMC	45.5	0.061	N/A	1.0e-2	1.1e-4	1.7e-3
M31	352.0	0.807	6.8e11	2.4e2	1.4e-2	2.3e-2

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Conclusions

- Halos have nearly universal “cuspy" density profiles
- ~10% of halo mass is in substructures, primarily in outer parts

Annihilation radiation

- Emission from galaxies and clusters is extended boost factor is about one thousand for clusters, one hundred for galaxy and few for dwarfs
- Coma cluster has 10 × (S/N) of UMAII, thus with other nearby rich clusters, offer the best sits to detect dark matter annihilation

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- Fornax cluster is predicted to be 15 times brighter than the brightest dwarf spheroidal, UM_II, and 40-50 times brighter than UMA-1, Draco or Wilman-1.
- But Fornax cluster is too extended. Coma is slightly fainter but has large S/N thus offer the best place to detect dark matter annihilation.

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Evidence for extended excess emission in the centre of galaxy clusters

ABSTRACT

We report evidence for extended emission in Virgo, Fornax and Coma from maximum-likelihood analysis on 3-year Fermi-LAT data in these three cluster regions. For all three clusters, excess emission is observed within three degrees of the center, peaking around GeV scale. This can not be accounted for by known Fermi sources or the galactic and extra-galactic background emission. If interpretated in terms of annihilation emission from supersymmetric dark matter (DM), the data prefer a DM model with a particle mass in the range $20 - 60$ GeV annihilating into the $b\bar{b}$ channel, or $2 - 10$ GeV and > 1 TeV for $\mu^+\mu^-$ final states, coinciding with that found by a recent DM search in the galactic centre. An extended DM annihilation profile dominated by emission from substructures is preferred over a simple point source model to fit the data, giving a significance of 4.4σ in Virgo and lower in the other two clusters. We also consider the possibility that this excess is cosmic ray (CR) induced gamma-ray emission, yielding a CR level within a factor of three of that expected from analytical models. However, the significance for an additional CR component is lower than that for a DM component, and there's no need for such a CR component in the presence of a DM component in the preferred DM mass range. We also set flux and cross-section upper limits for DM annihilation into $b\bar{b}$ as well as $\mu^+\mu^-$ channels in all three clusters.

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