Dark Matter at small scales: the lesson from Milky Way satellites

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Overview

1) How to study DM distribution -> Nbody Simulations

2) Satellites around galaxies Simulations vs. (old) Observations
The Missing Satellites problem

3) New satellites from SDSS-> Luminosity Function

4) Comparing apples with apples

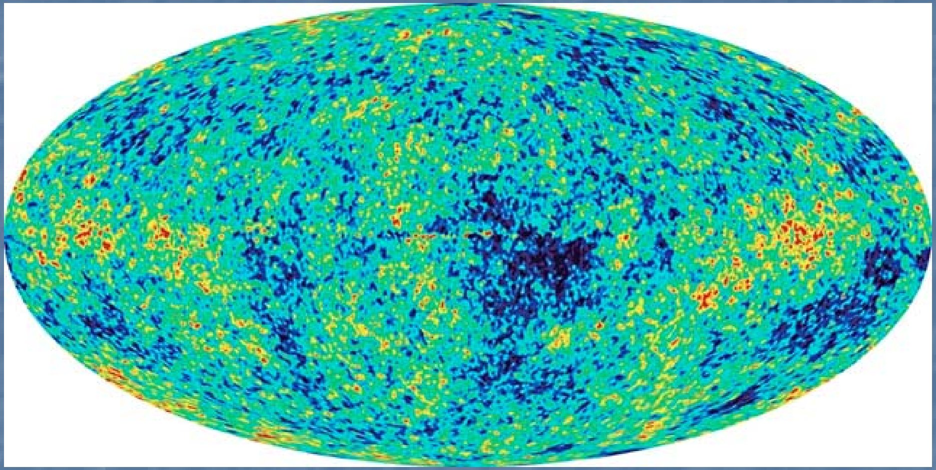
5) Is there a missing satellites problem?

6) Conclusions

7) Future work on (observationally) testing DM as small scales

How to study/follow the Universe: why numerical simulations?

Evolution is highly non linear: initial conditions from the CMB



$$\frac{\partial T}{T} \approx \frac{\partial \rho}{\rho} \approx 10^{-5}$$

$$\frac{\partial \rho}{\rho}(cluster\ \ center) \approx 10^{5}$$

10 orders of magnitude

(break down of linear theory)

-> Numerical simulations

Particles for a numerical cosmologist

Modern computer can handle more than 10^8 particles/elements

Simulation Volume: $200h^{-1}Mpc$

$$\rho_{cr} = 2.7755 \times 10^{11} h^2 M_{sun} Mpc^{-3}$$

$$m_p = \frac{V}{N_p} \times \rho_{cr} \times \Omega_m = 6.66 \times 10^9$$

Our particles have the same mass of a dwarf galaxy…

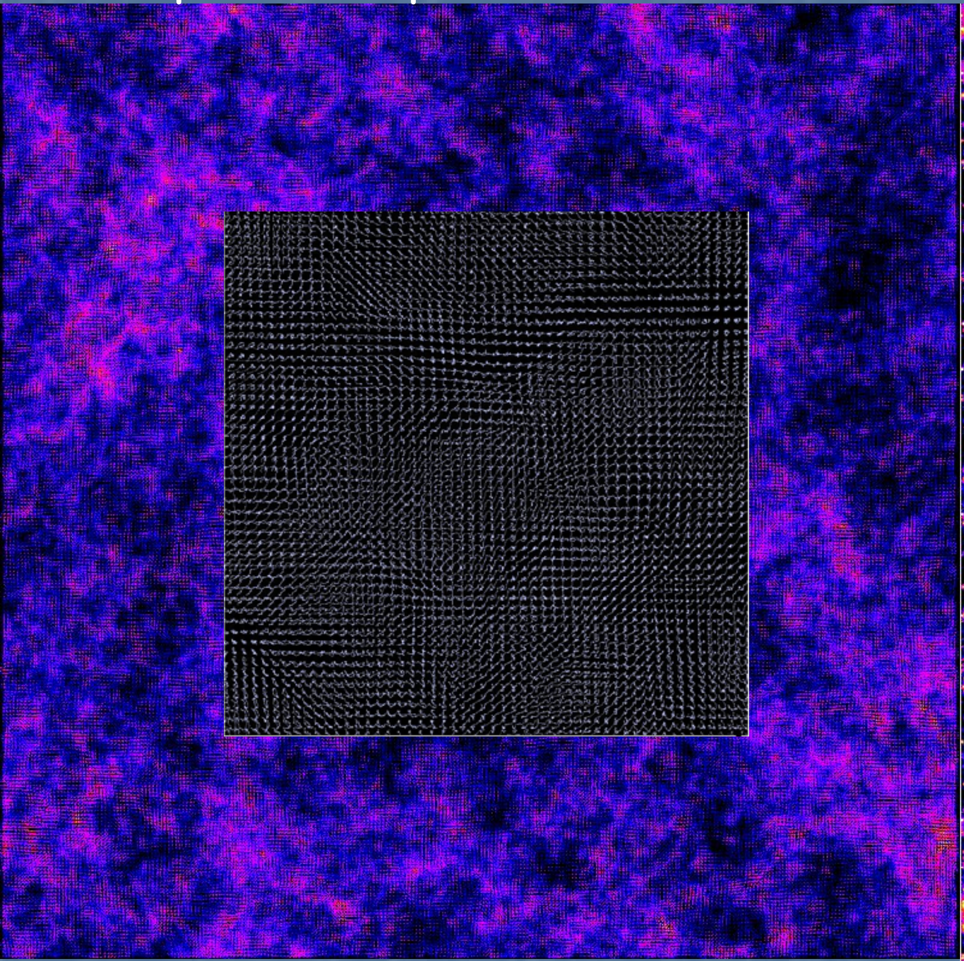
High resolution simulation of a single halo object:

$m_p \approx 10^5 M_{sun}$ Galaxies (recent simulations m_p~1000 Msun)

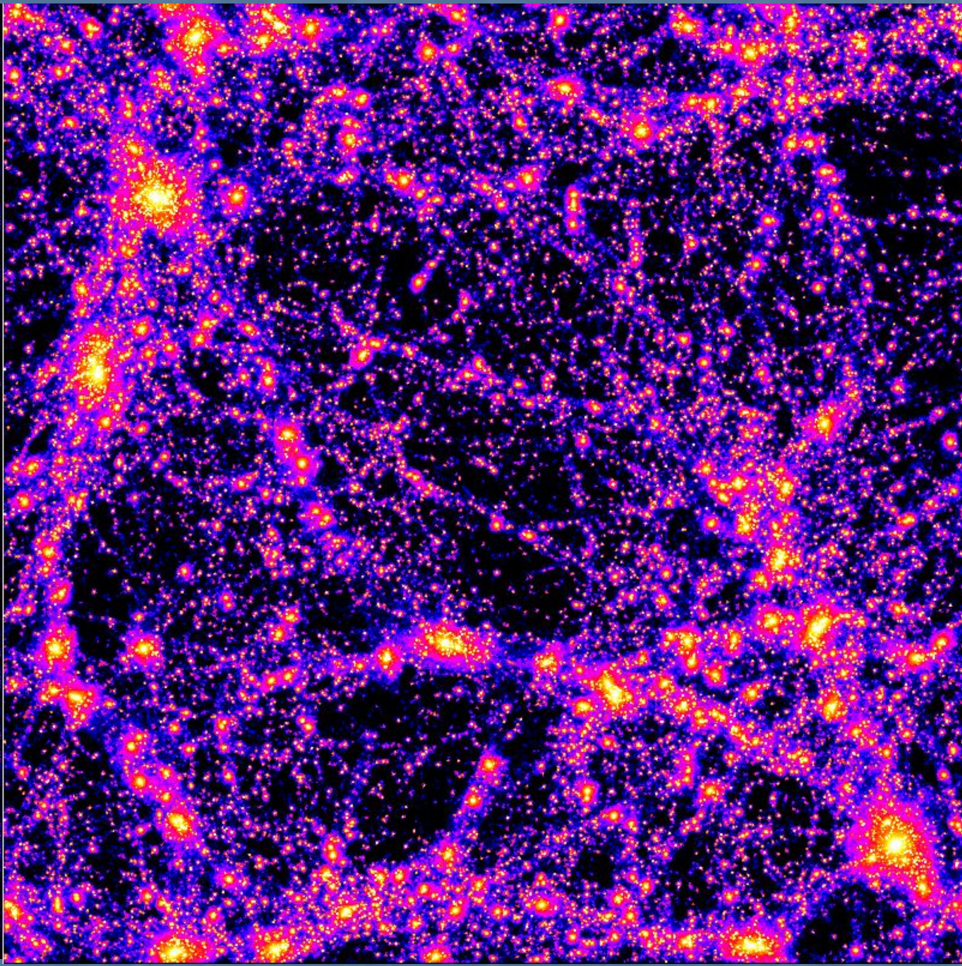
$m_p \approx 10^7 M_{sun}$ Clusters

Initial Conditions for Nbody Simulations

40 Mpc – 400^3 part   z=25



z=0



$$\log\left(\frac{\rho}{\bar{\rho}}\right) \propto [-1:0]$$

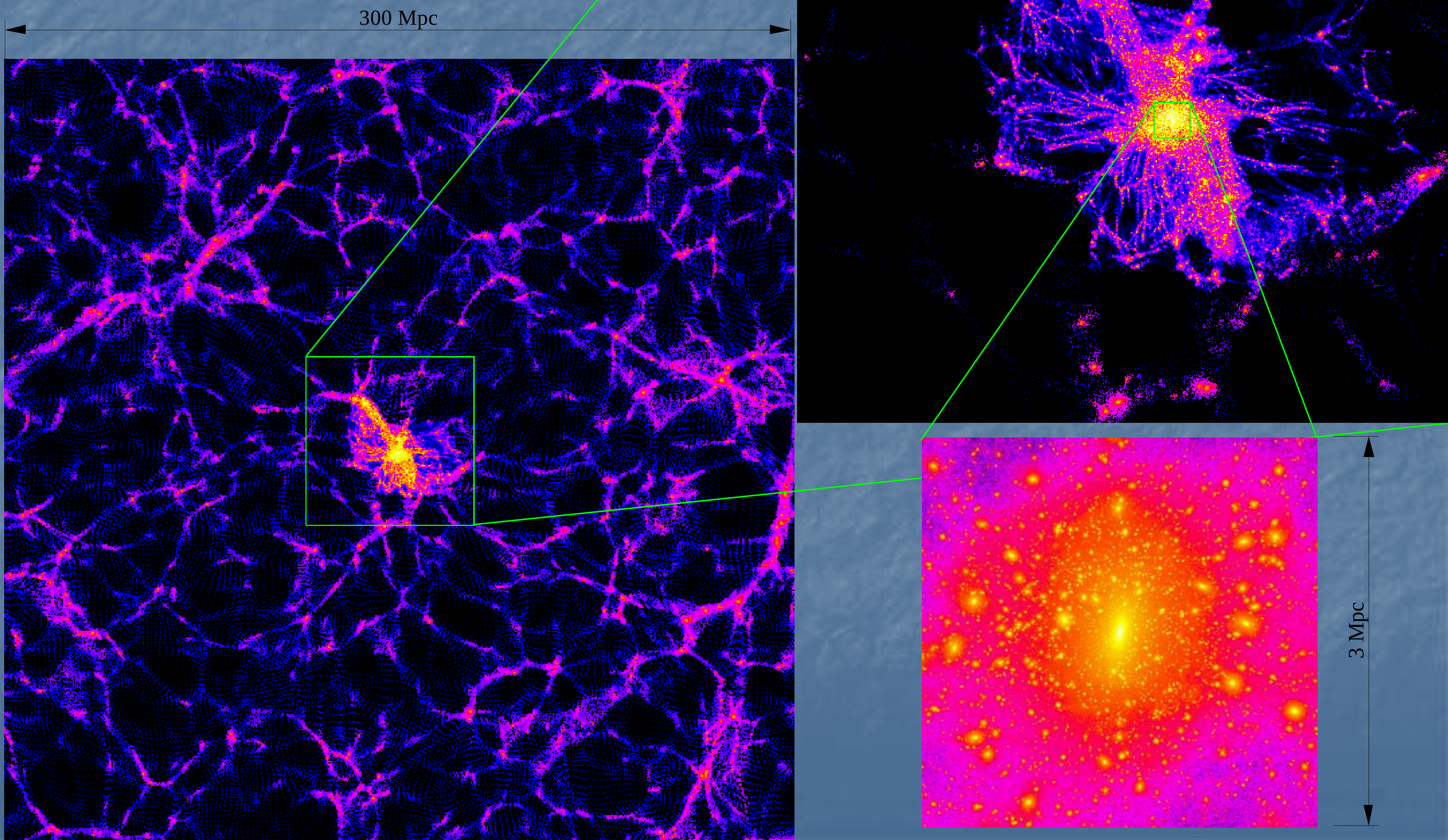
$$\log\left(\frac{\rho}{\bar{\rho}}\right) \propto [2:5]$$

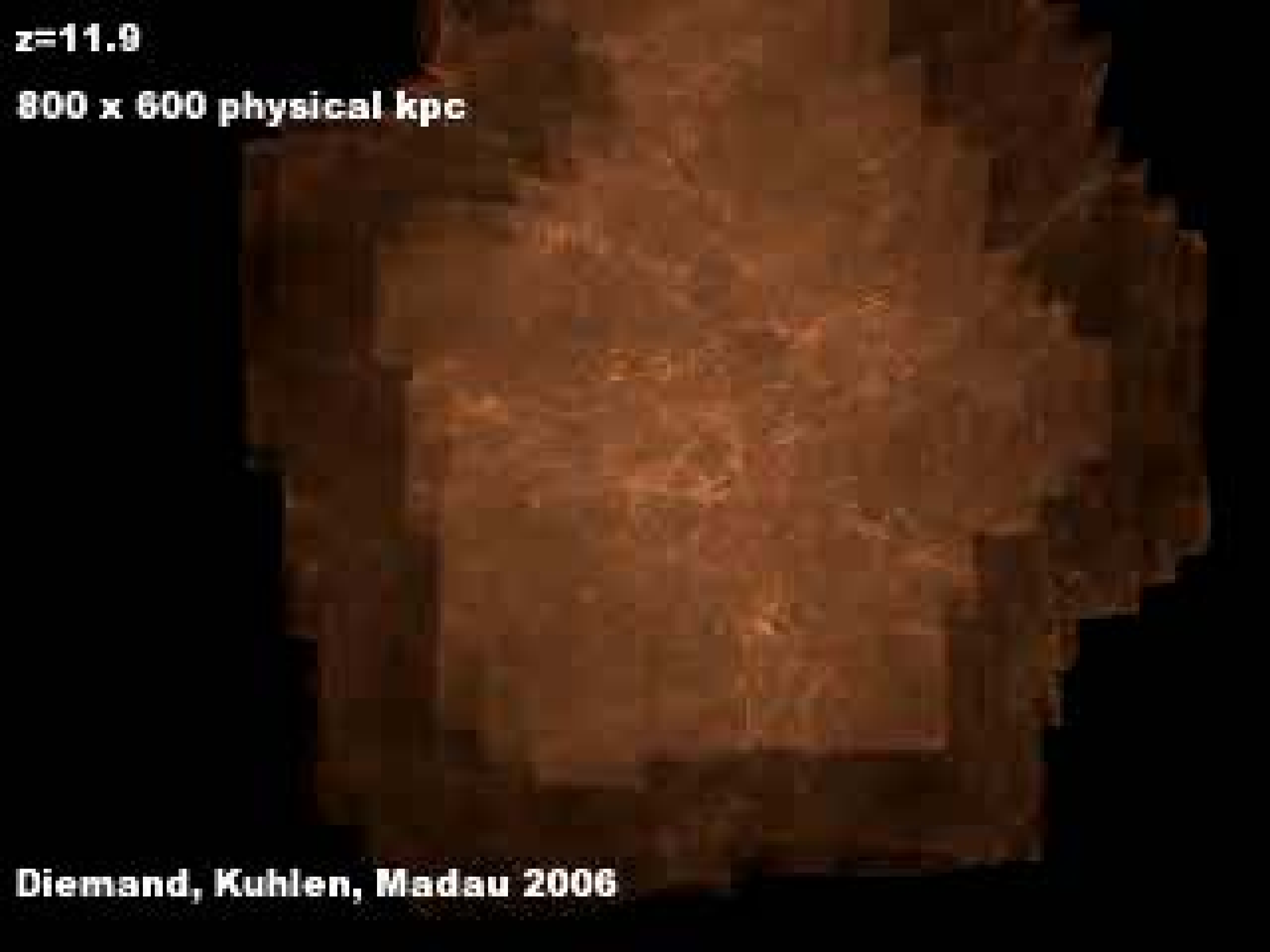
Maccio'+06

Formation of a cluster in the WMAP5 cosmology (comoving coordinates)

Refinement:

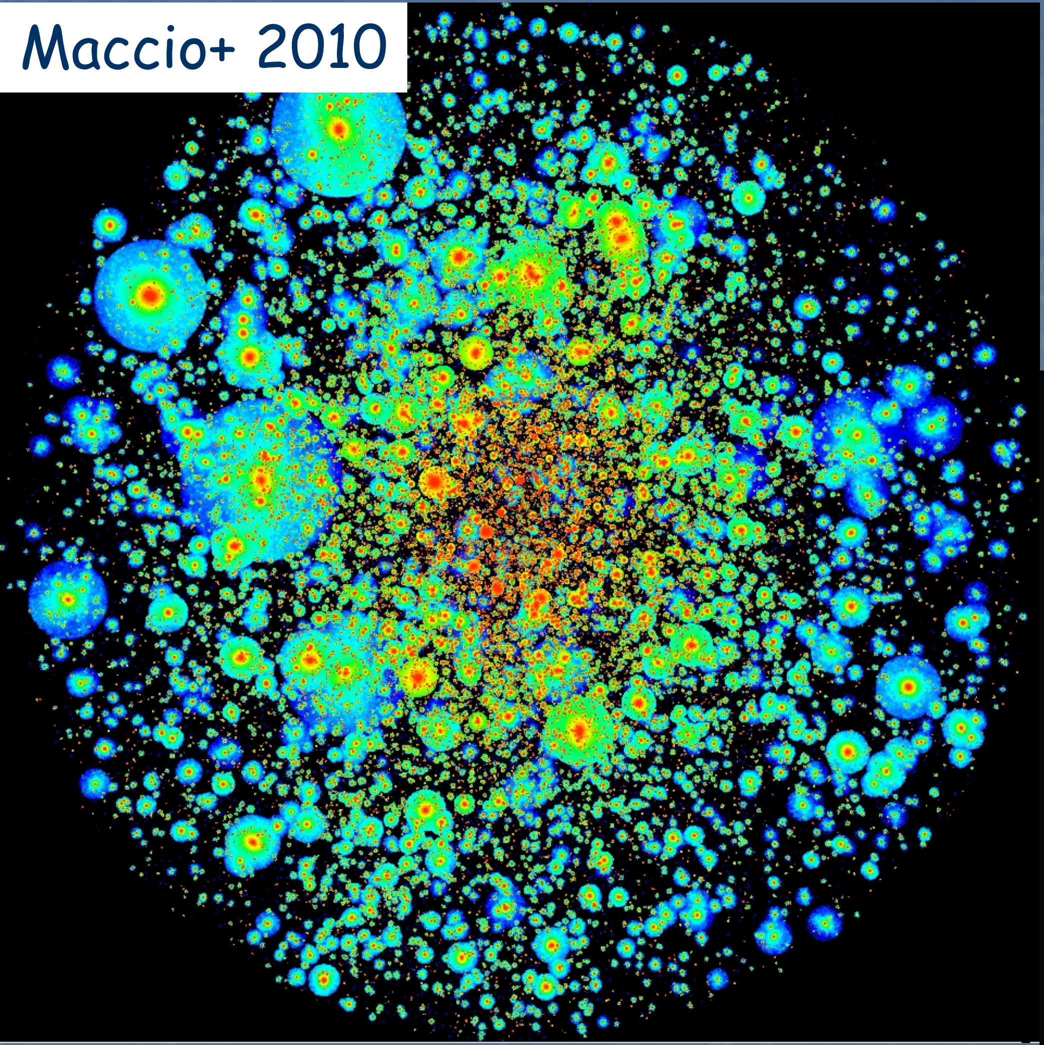
Re-simulating one halo with better mass resolution




z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006

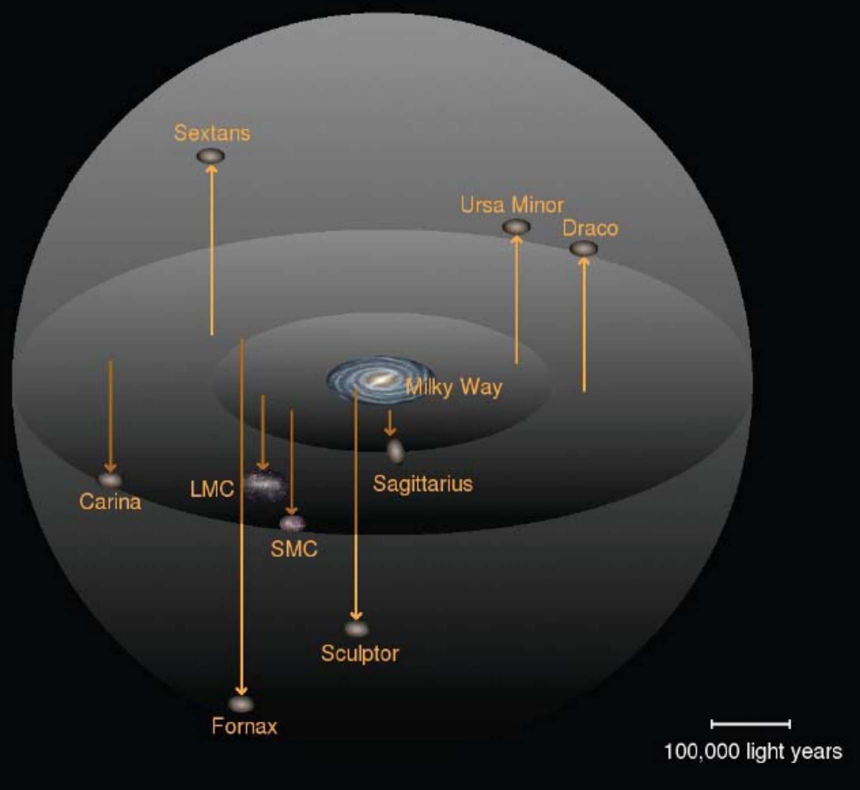
CDM at small scales – Satellites around the MW

Maccio+ 2010



Do we see the same amount of substructure (i.e. satellites) around our galaxy?

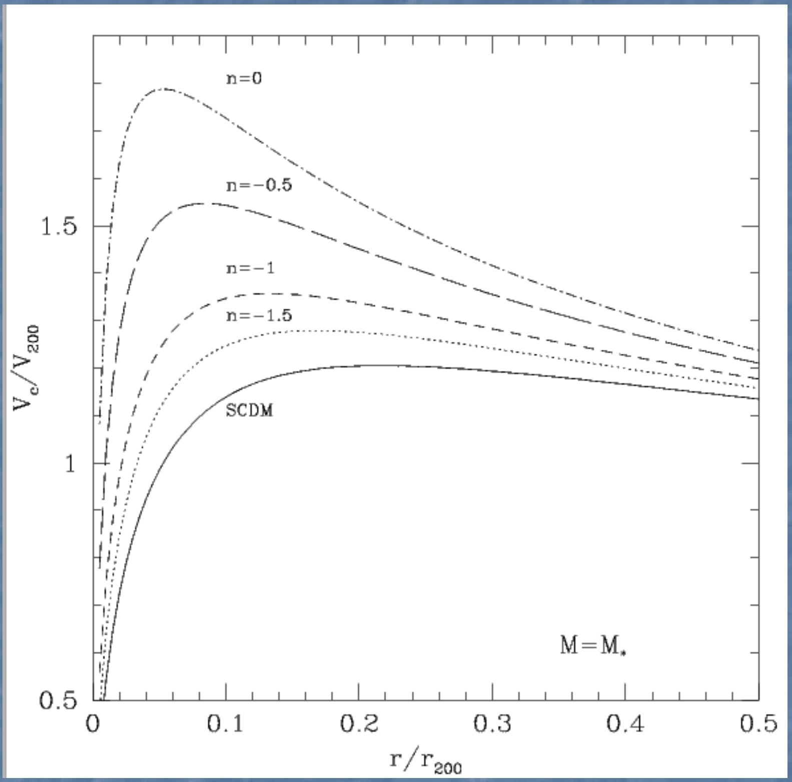
Courtesy of Jelte de Jong



Can we reconcile these two pictures?

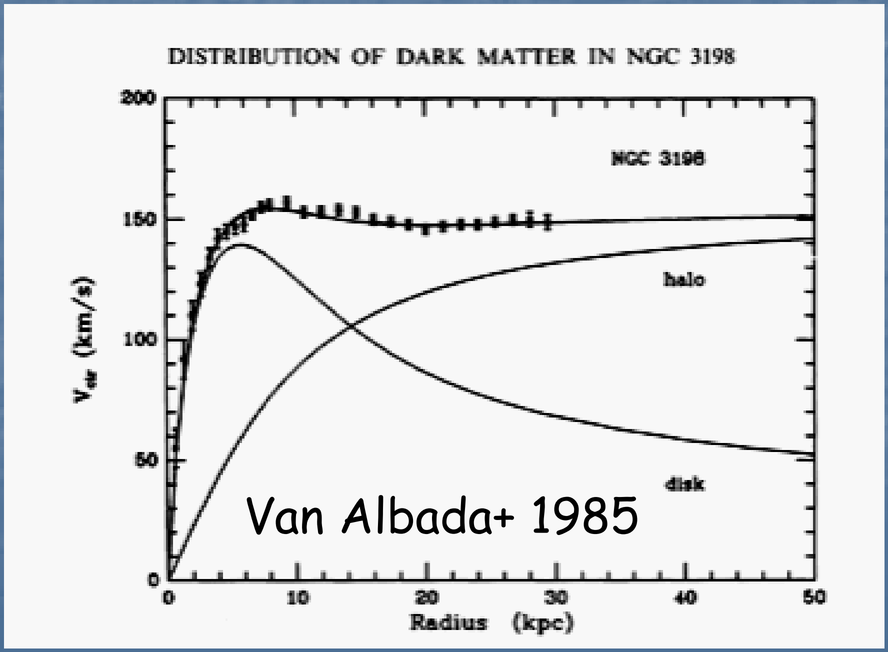
CDM at small scales – Satellites around the MW

How to compare sim. and obs?
Satellite Circular Velocity

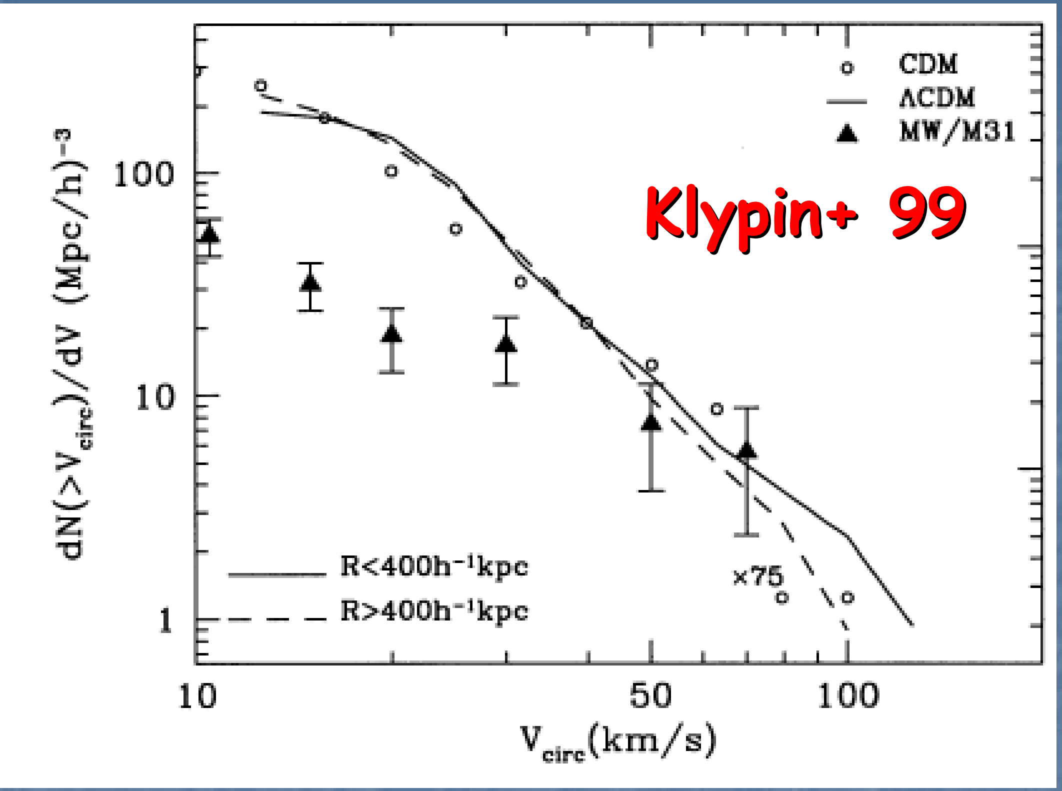


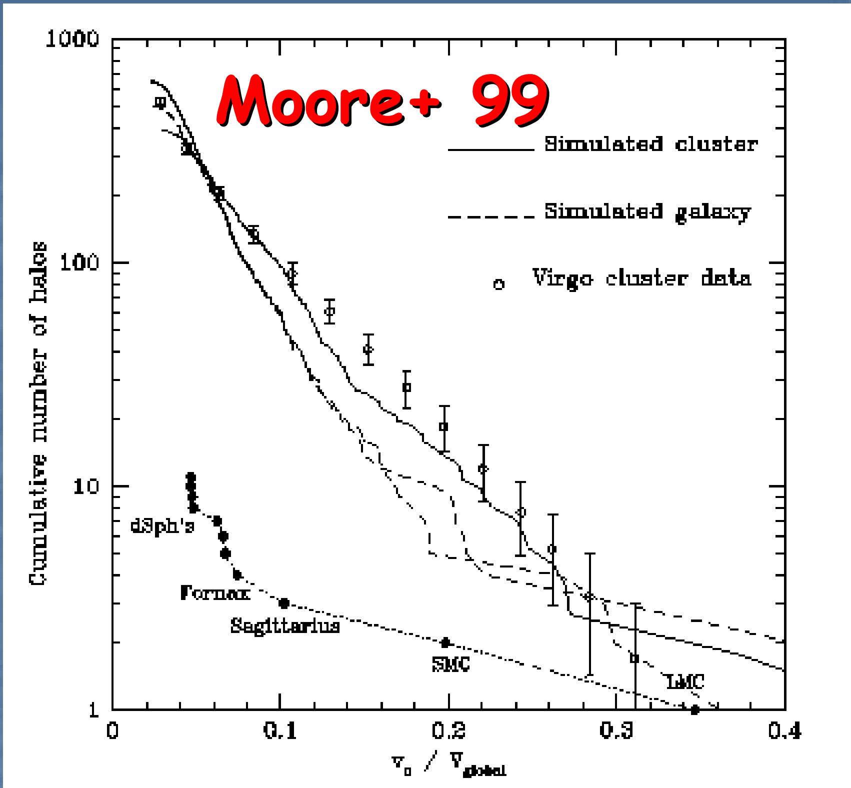
$$V_c(<R) = \sqrt{\frac{GM(<R)}{R}}$$

Vc from in observations
1 - directly
2 - assuming Vc=√3σ



Simulations vs. Observations





Almost one order of magnitude difference in number counts between observations and simulations.

The missing satellites problem, is CDM *wrong*?

Serious problem for CDM… more than 2000 citations

Cosmological solution
Replace Cold DM with Warm DM

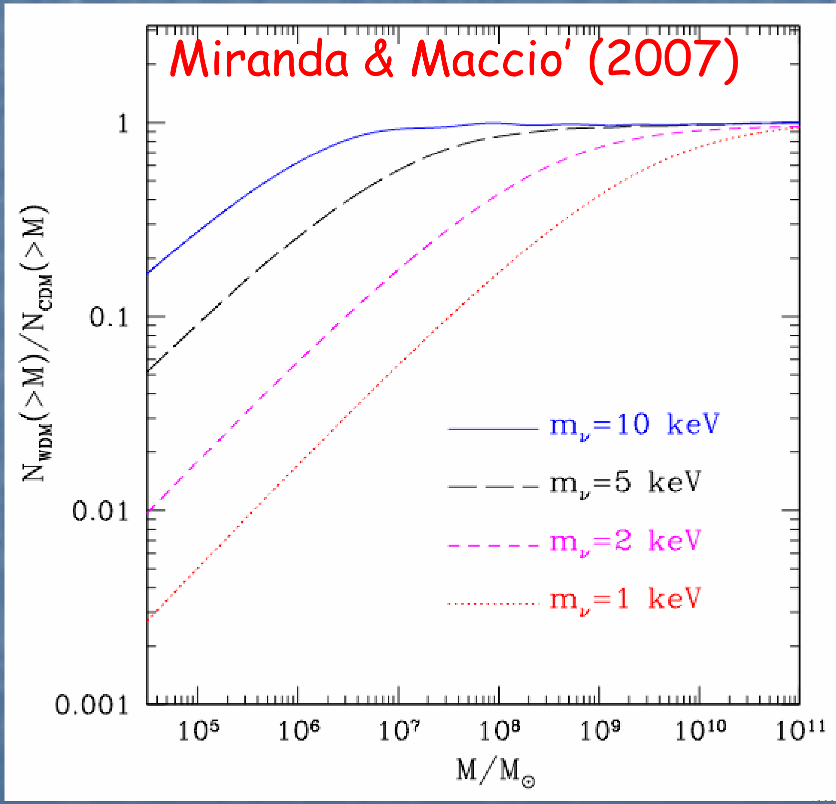
$$m_{WDM} \sim keV$$
$$m_{CDM} > GeV$$

Free-streaming smears out perturbations on small scales

Smoothing scale (Bode et al 2001)
P(wdm)/P(cdm) = 0.5

$$\frac{R_S}{Mpc} \approx 0.31\left(\frac{\Omega_X}{0.3}\right)^{0.15}\left(\frac{h}{0.65}\right)^{1.3}\left(\frac{keV}{m_X}\right)^{1.15}$$

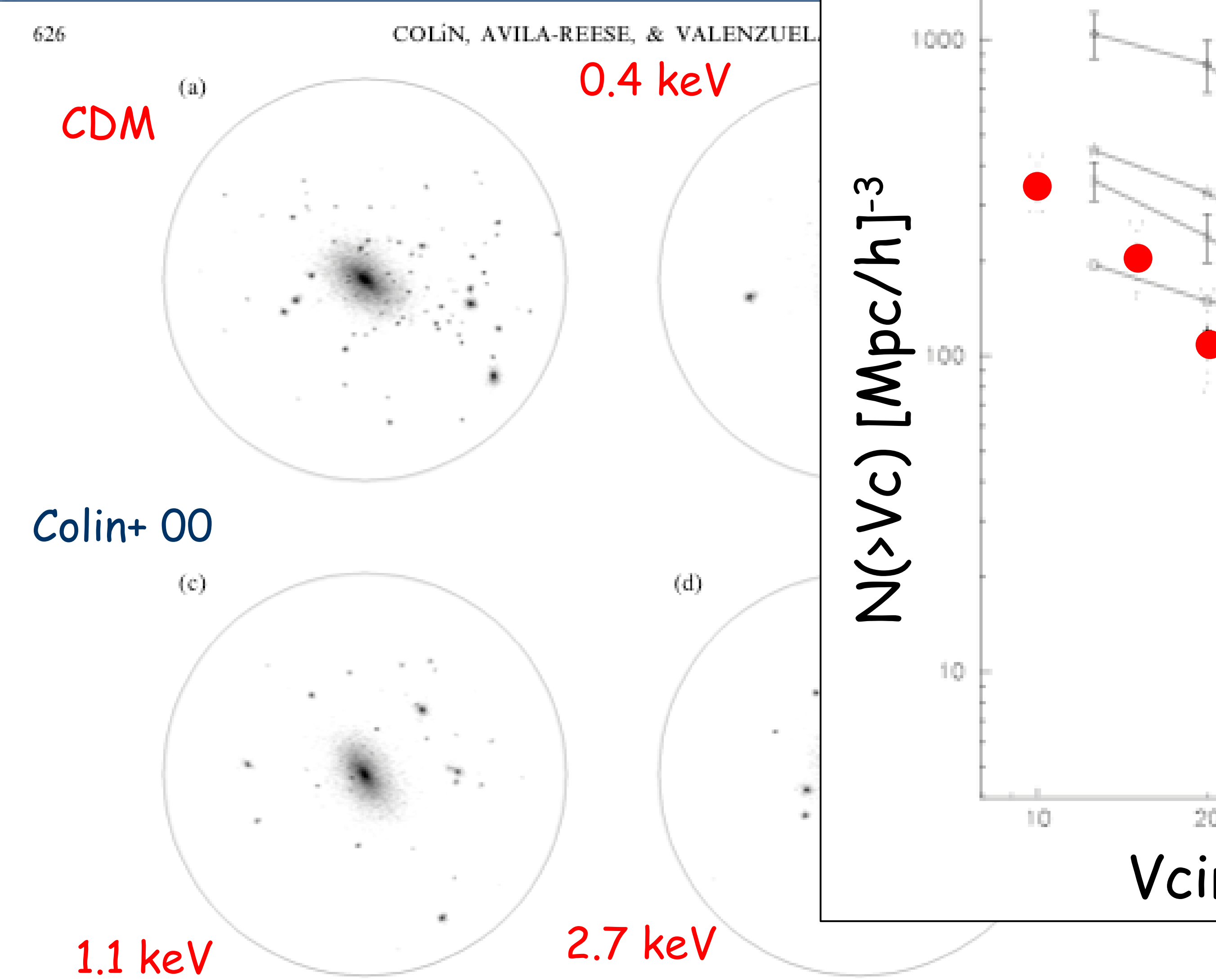
$$M_S = \frac{4\pi}{3}\bar{\rho}\left(\frac{R_s}{2}\right)^3$$

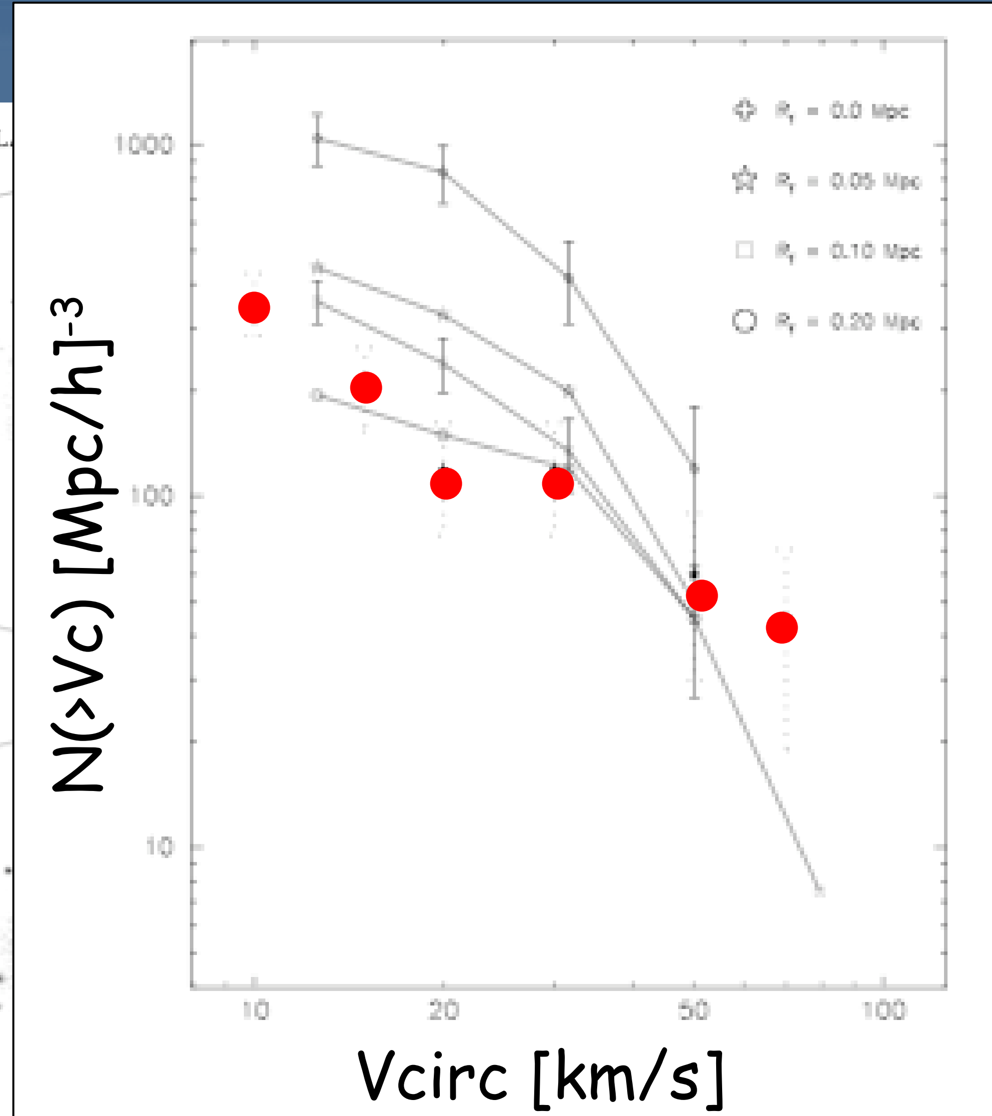


For m(WDM)= 0.5 keV ~ M_S~2 10^{10}

For CDM M_S ~ Earth Mass (Diemand et al. 2005)

Satellites in WDM



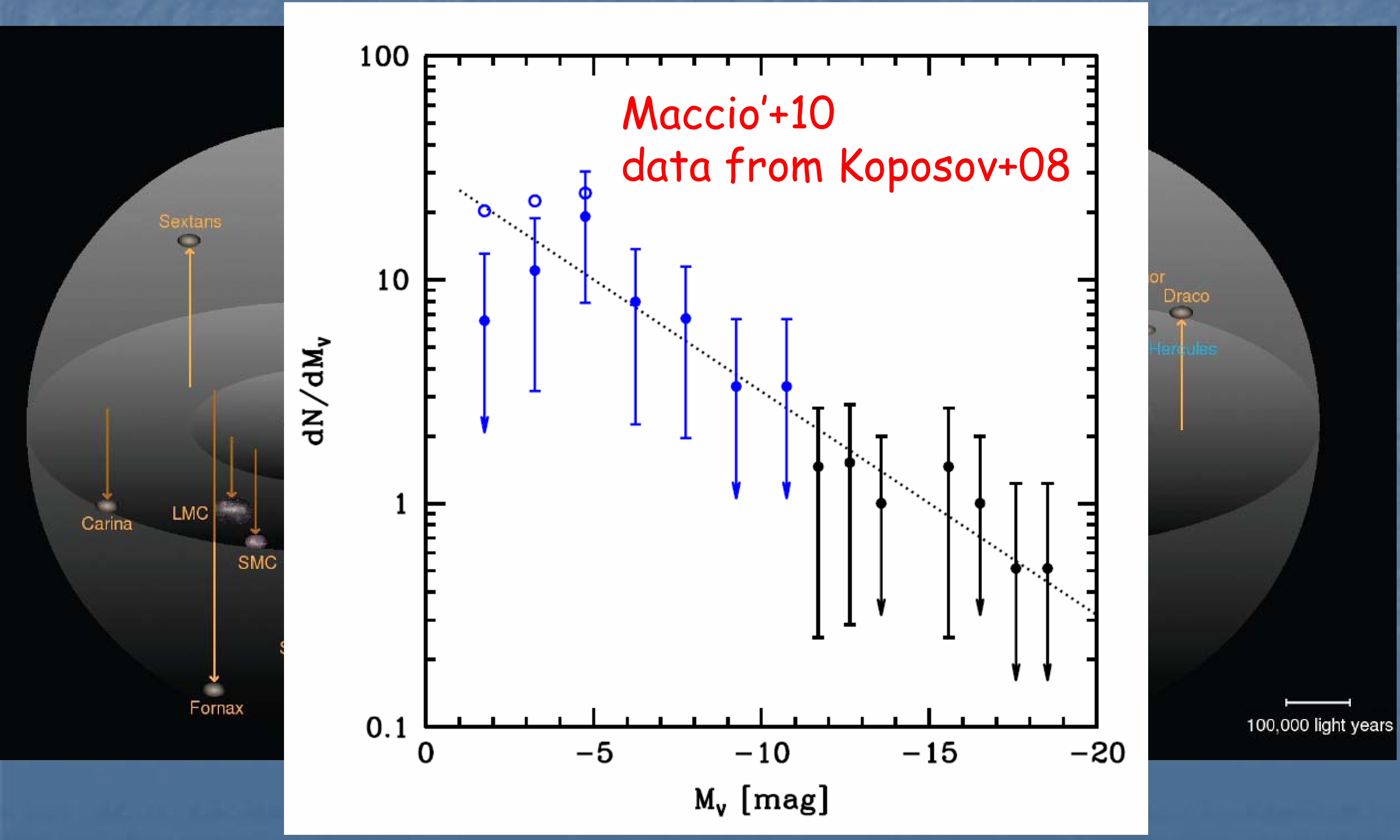


m ~ 0.5 -1 keV needed (Colin+ 2000)

New Satellites in the SDSS

16 new faint satellites discovered around Milky Way (1/5 of the sky)

Systematic coverage of the Sky-> Selection Function



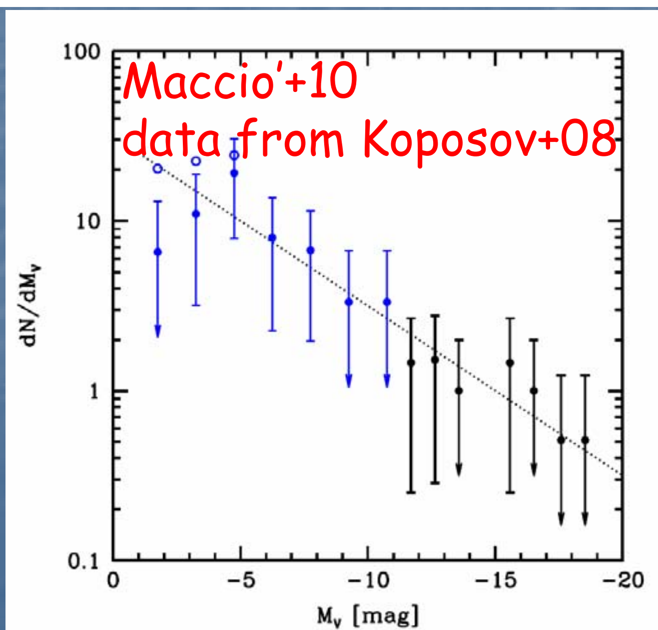
Three main questions

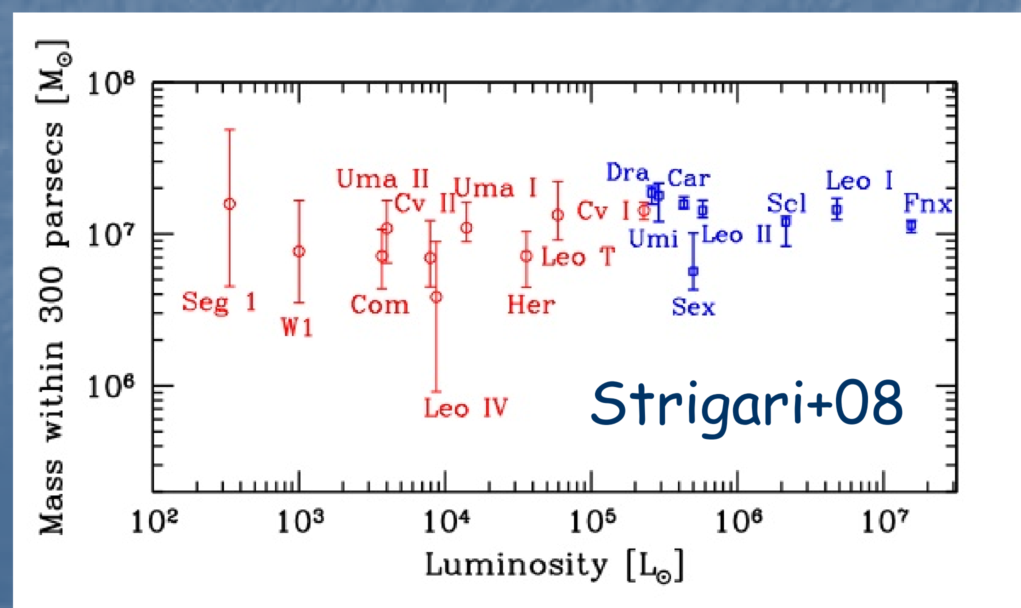
Can we reproduce in the LCDM model:

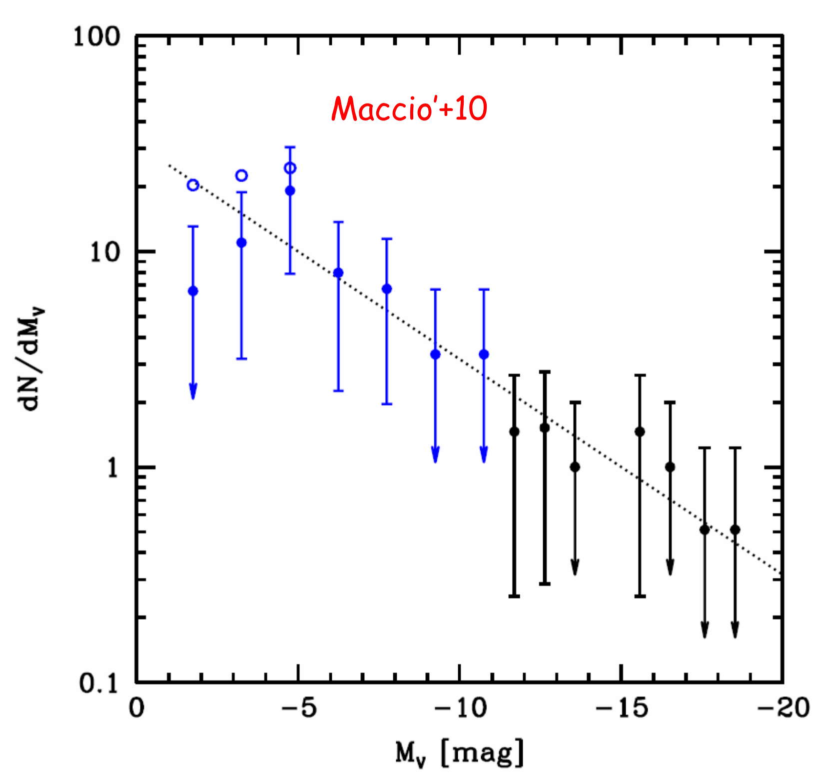
1) The MW satellites Luminosity function

2) The MW satellites radial distribution

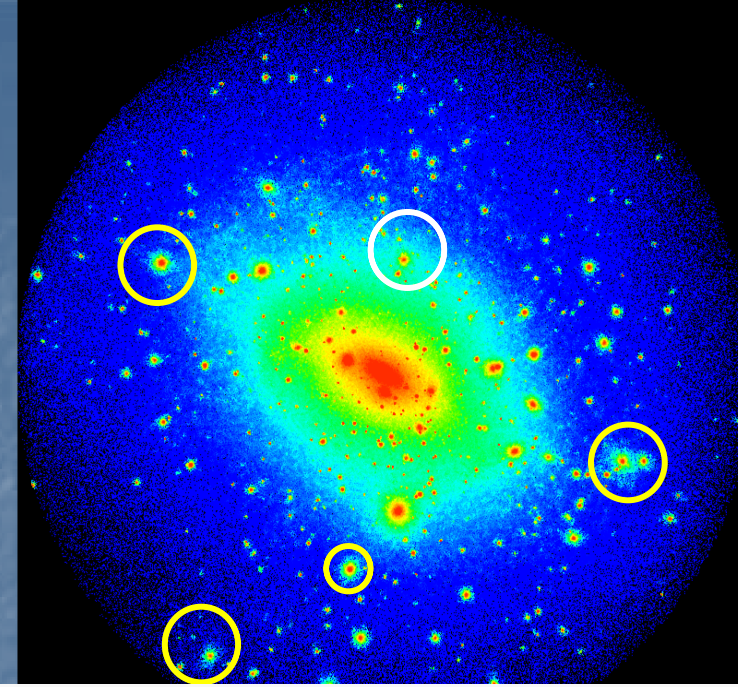
3) Relation between central mass and Lum.

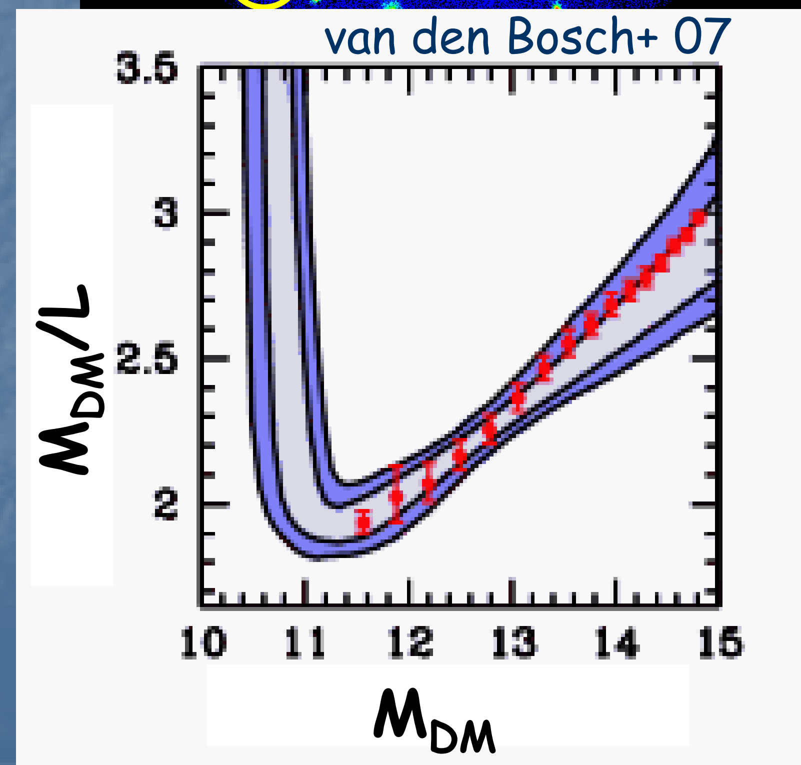






Mass vs Luminosity





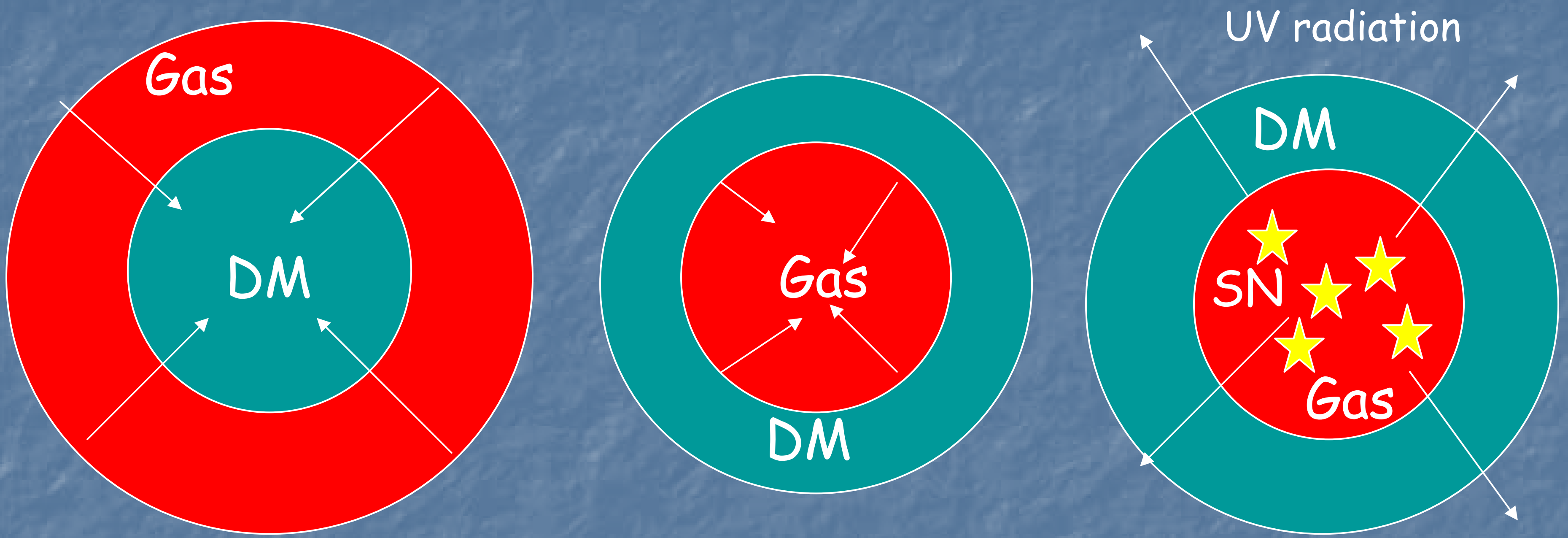
The missing satellite:
each dark matter sub-halo should host a (dwarf) galaxy.

M/L *is not constant!*

Small Dark Matter haloes can host really faint galaxies … if any!

Changing M/L: Super Novae and Reionization

Gas cools in the potential well of dark matter halos



Gas can cool on DM haloes only if $T_{gas} < T_{vir}$

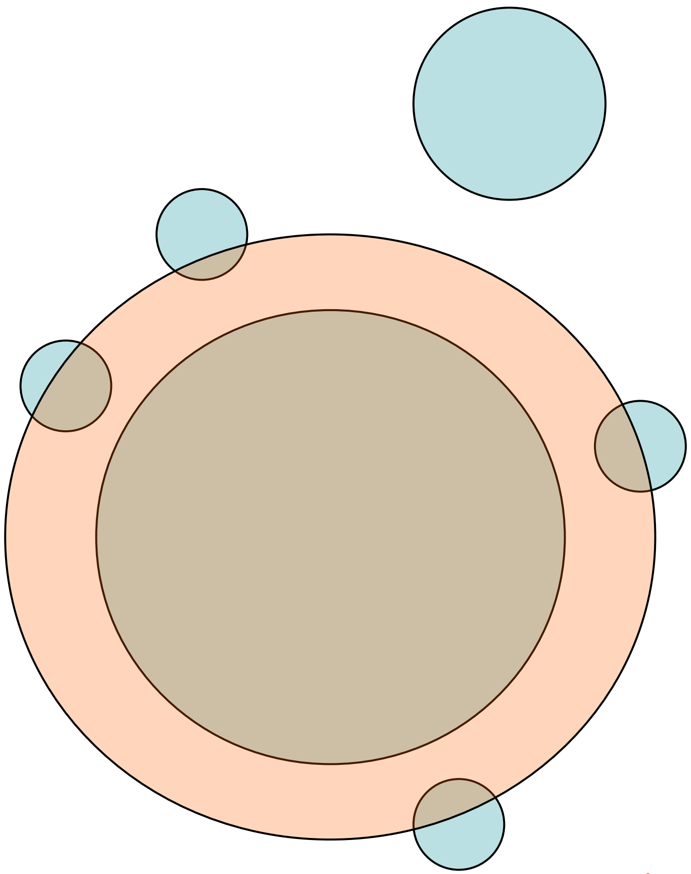
Star Formation:

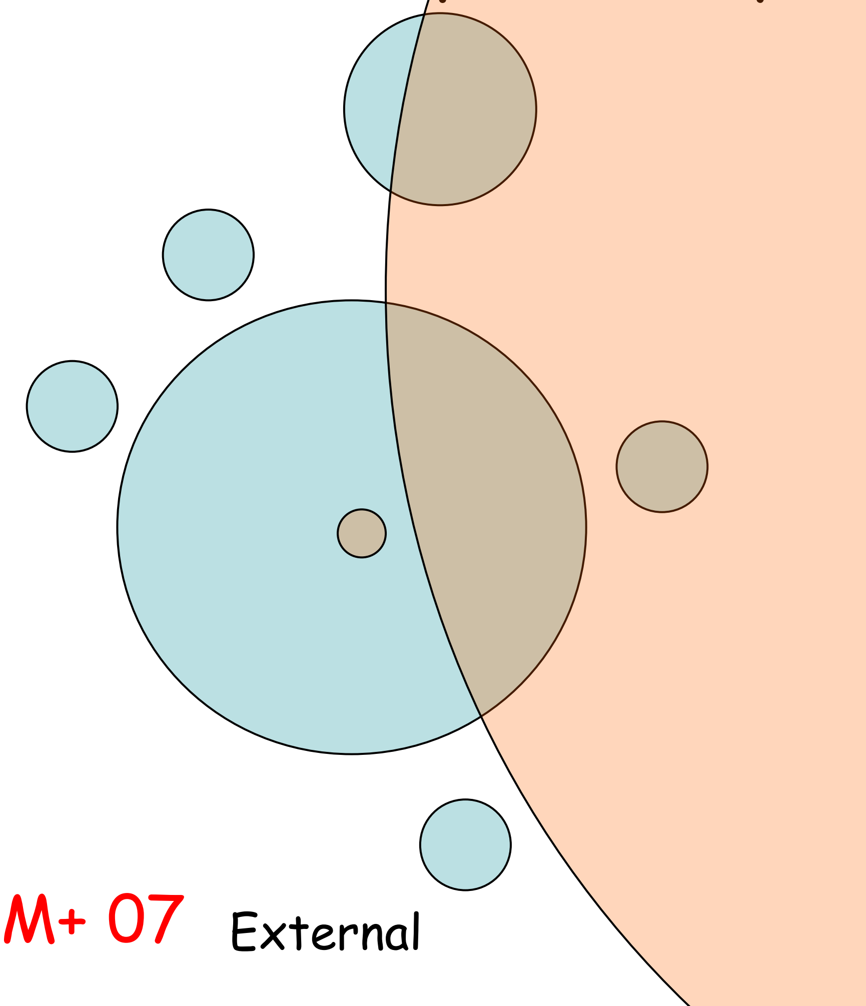
1. Energy from SN, heats the gas and removes it from the Halo (so subsequent star formation is delayed and/or quenched)

2. Produces UV background that reionizes the Universe (z~12-7), rising Tgas everywhere

Cosmic Reionization

- "Standard" picture
- Alternative possibility





Weinmann,AM+ 07

Before Reionization: $M_g / M_{dm} = \Omega_b / \Omega_m$

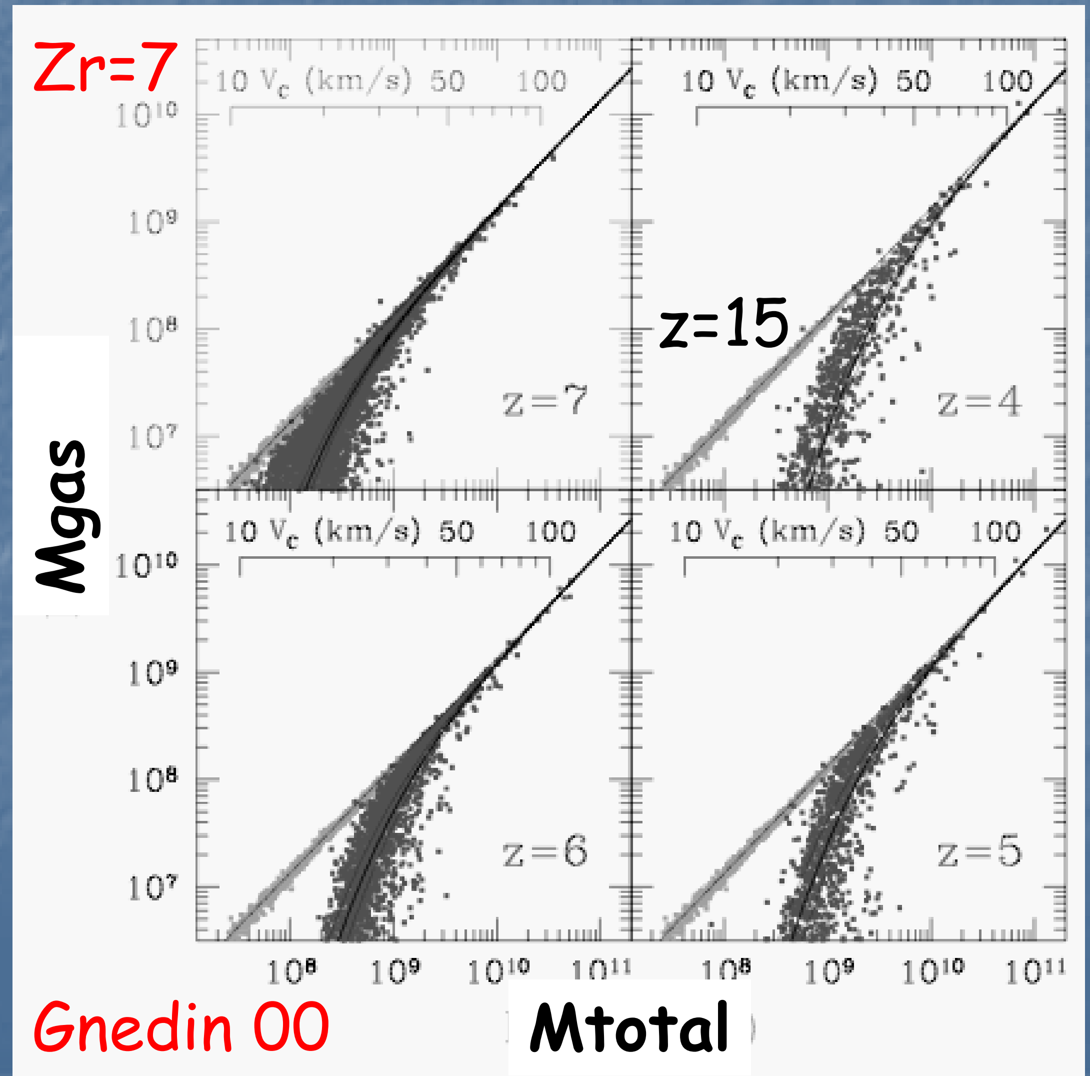
After reionization (higher T_{gas} due to UV background) baryon accretion is suppressed in haloes below a given mass M_F

$$M_F(a) = \frac{4\pi}{3}\bar{\rho}\left(\frac{2\pi a}{k_F}\right)^3$$

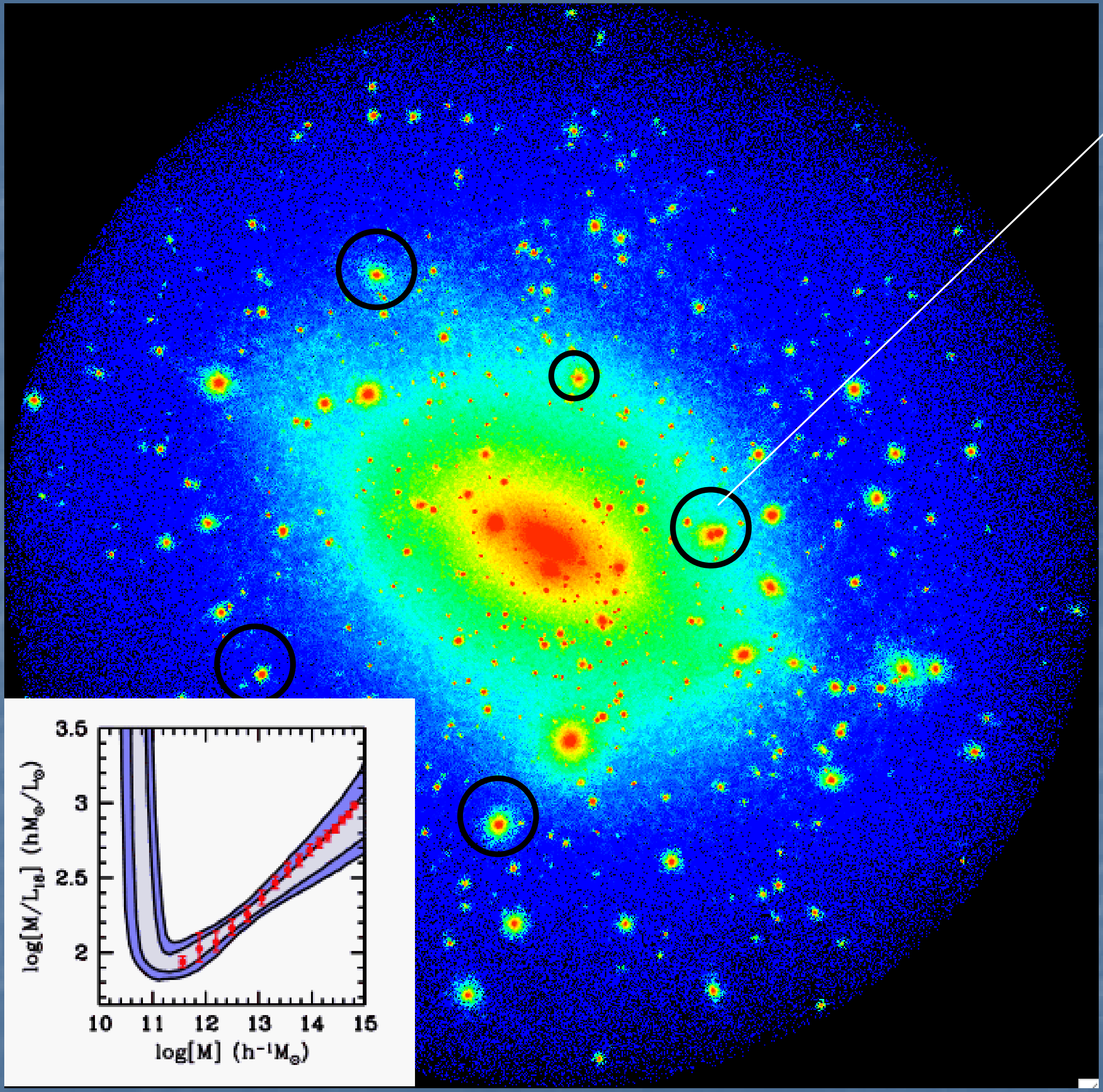
F: filtering scale: scale over which baryons perturbation are smoothed compared to DM.

For $M<M_F$ gas accretion is suppressed

$$M_F \approx 10^7 - 10^{10}$$

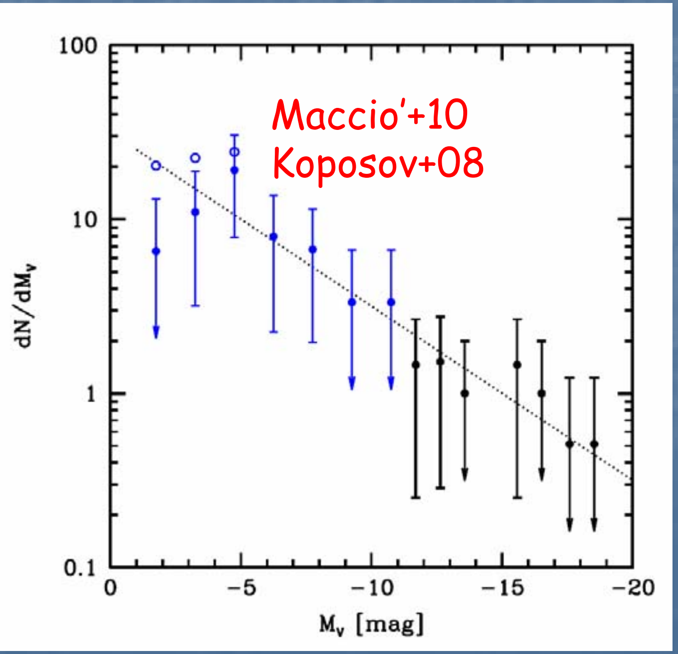


Comparing apples with apples



DM halo with V_c=20 km/sec
What kind of galaxy will it host
(if any)

Mass today
Mass at reionization
SN feedback
Reionization epoch
Orbital parameters

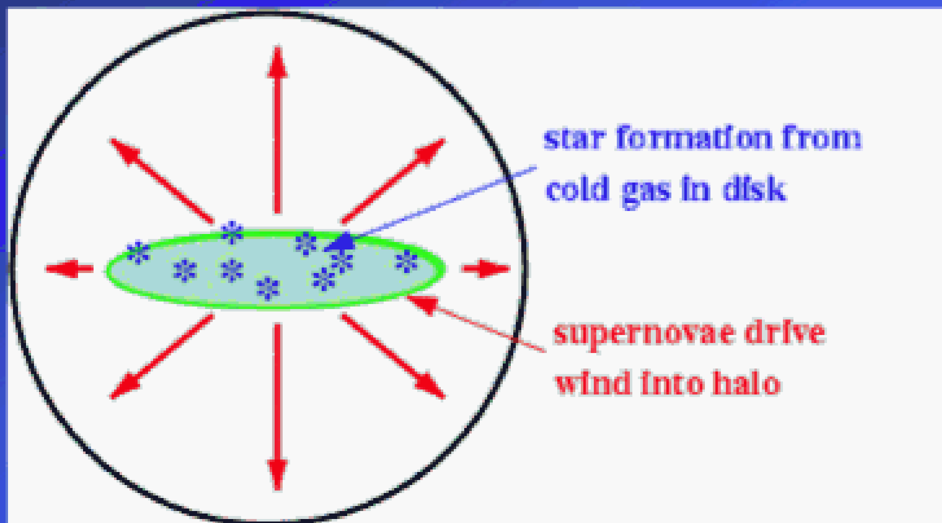


How to compute the Luminosity of DM haloes?

Semi Analytical Model

A series of approximated recipes are used to describe physical properties

Star formation & feedback



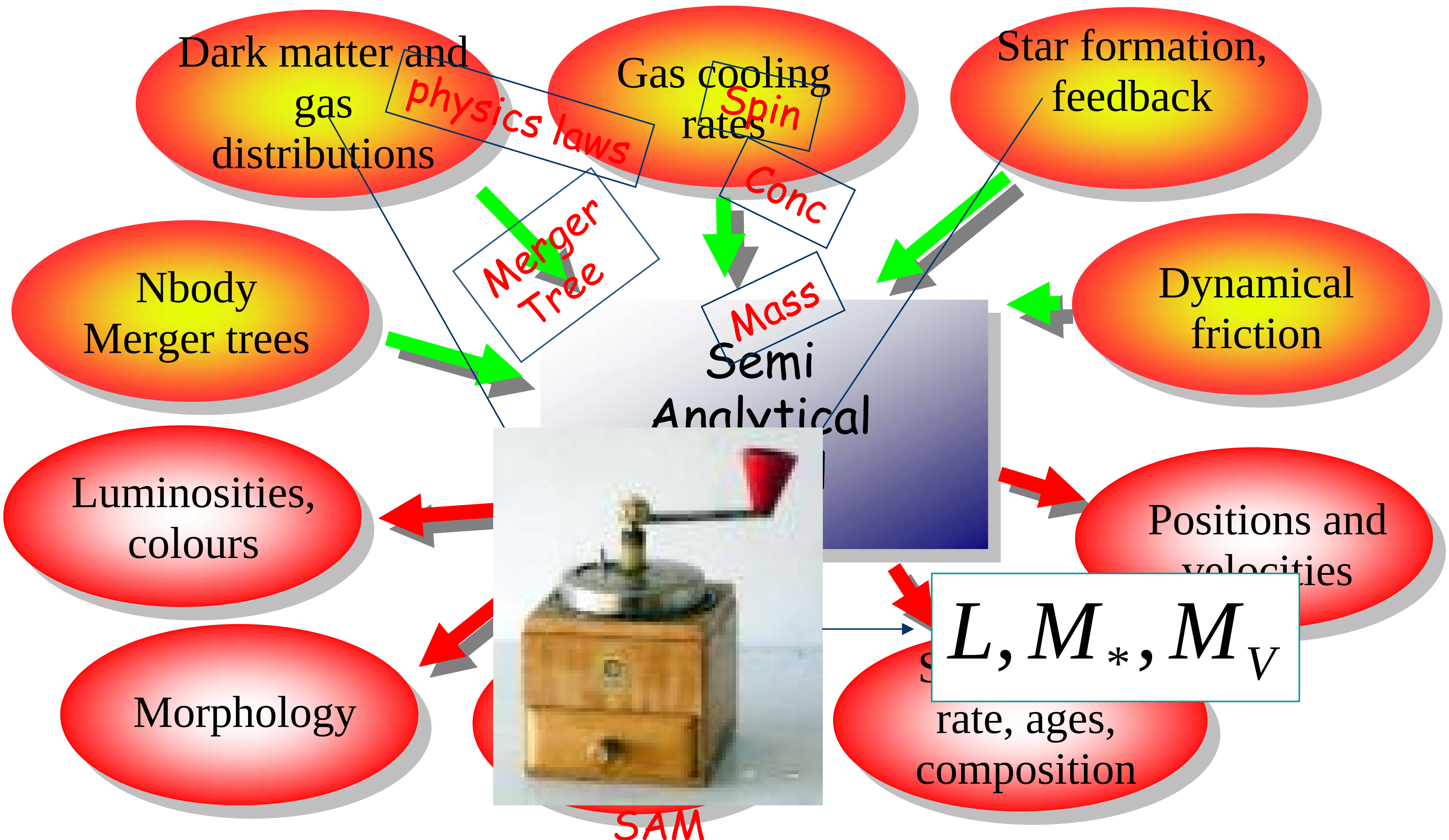
- stars form in disks

$$SFR = M_{gas} / \tau_*$$

- supernova feedback ejects gas from galaxies

$$\dot{M}_{eject} = \beta(V_c)\, SFR$$

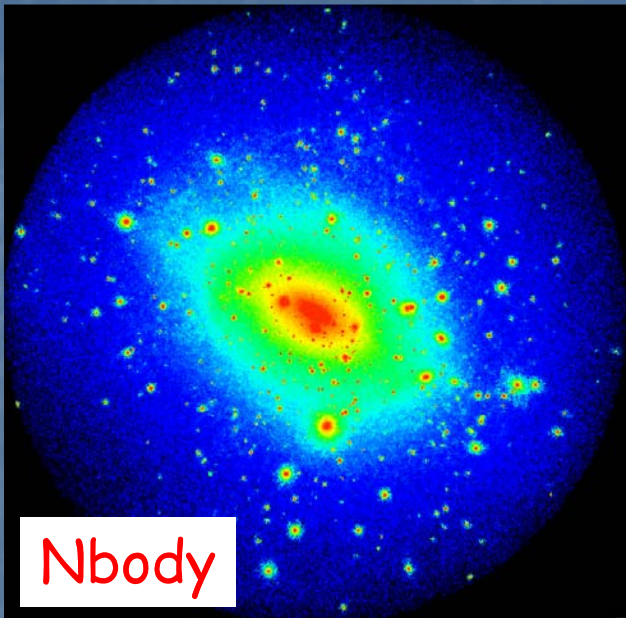
The Semi-analytic Model

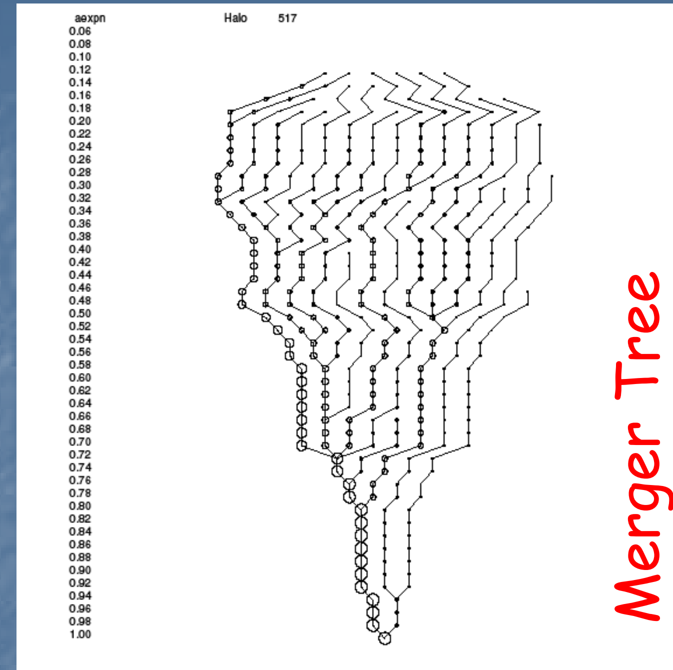


adapted from A. Benson's talk

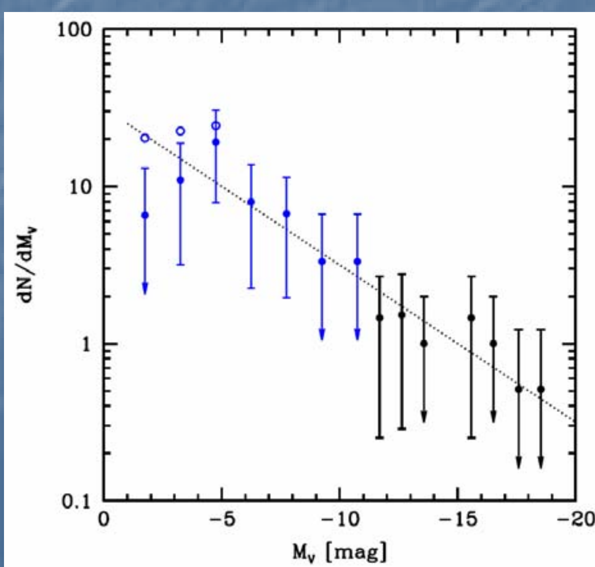
Rest of the world view

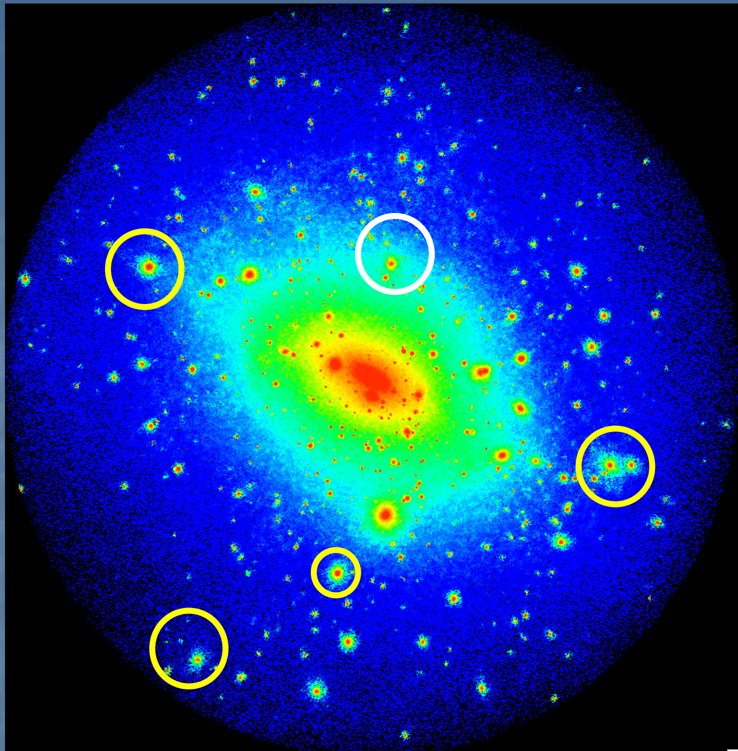
Method

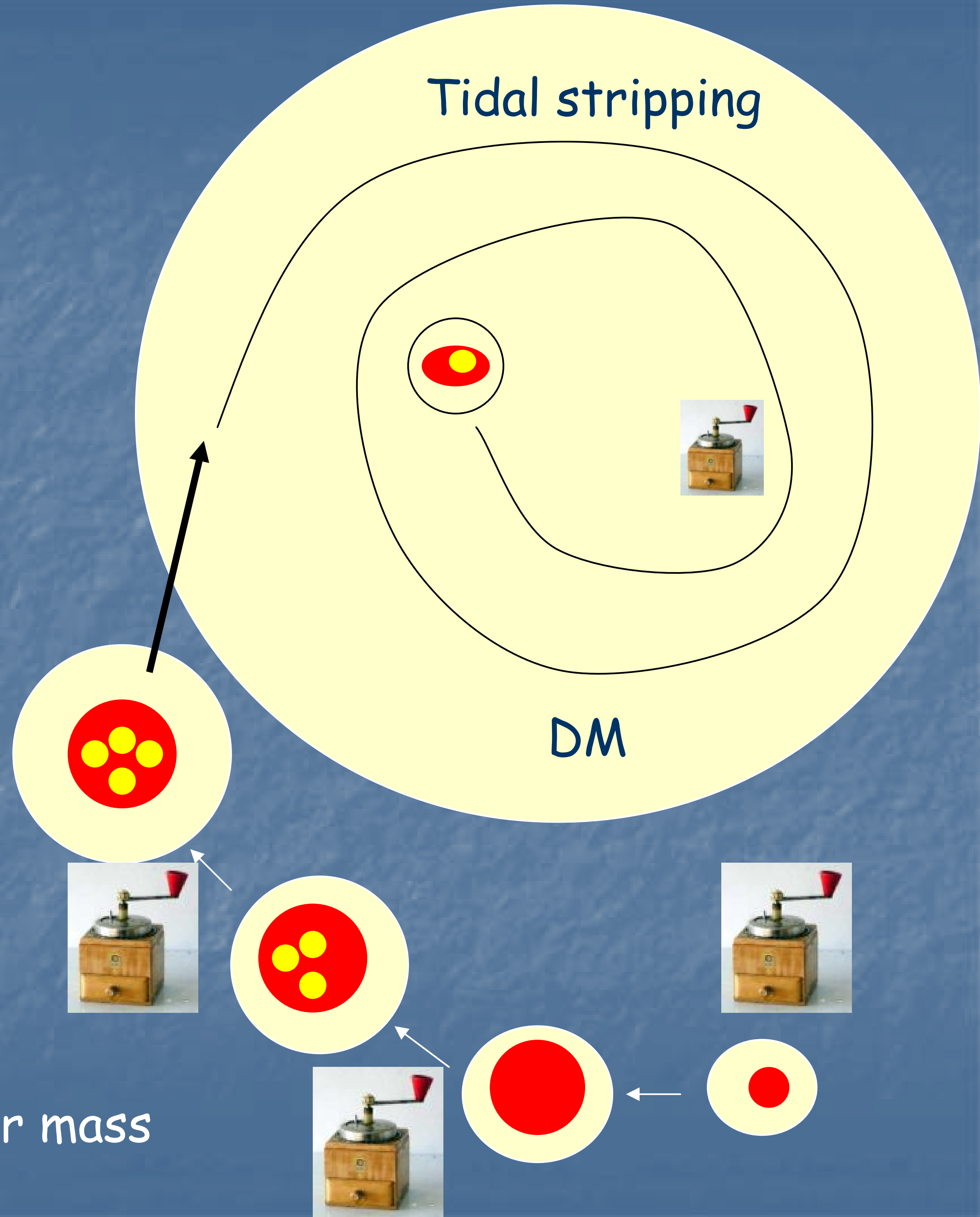

Nbody


aexpn
Halo 517
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
0.32
0.34
0.36
0.38
0.40
0.42
0.44
0.46
0.48
0.50
0.52
0.54
0.56
0.58
0.60
0.62
0.64
0.66
0.68
0.70
0.72
0.74
0.76
0.78
0.80
0.82
0.84
0.86
0.88
0.90
0.92
0.94
0.96
0.98
1.00
Merger Tree


SAMs


100
10
1
0.1
dN/dM_V
0
−5
−10
−15
−20
M_V [mag]





Gas Cooling
SFR
SN feedback
Tidal Stripping
Orbit evolution
=>
Luminosity (M_v) and Stellar mass

The Semi Analytical Models

Somerville et al 2008
Kang et al 2005, 2008
Morgana, Monaco et al 2006

Gas cooling (only for $T_{gas}>10^4$ K)
SN feedback
(AGN)
Cosmic Reionization
(Filtering Mass Gnedin00 Okamoto+08)
Tidal Stripping (DM only)
Tidal Distruction
Stellar Stripping (Morgana)

NO FINE-TUNING for this project

SAMs parameters from fit to galaxy LF red/blue dichotomy

Comparison Nbody and SAMs see our paper:
Maccio' et al 2010 arXiv 0903.4681

RESULTS

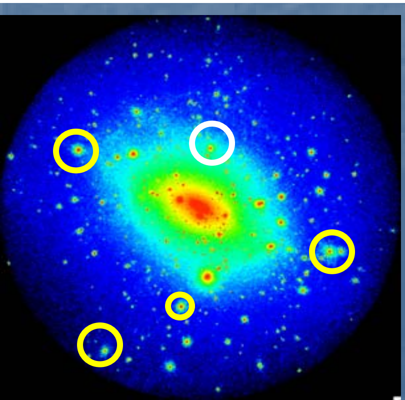
Maccio' Kang & Moore 2009, ApJL, 692, 109
Maccio' et al. 2010, MNRAS, 402, 1995

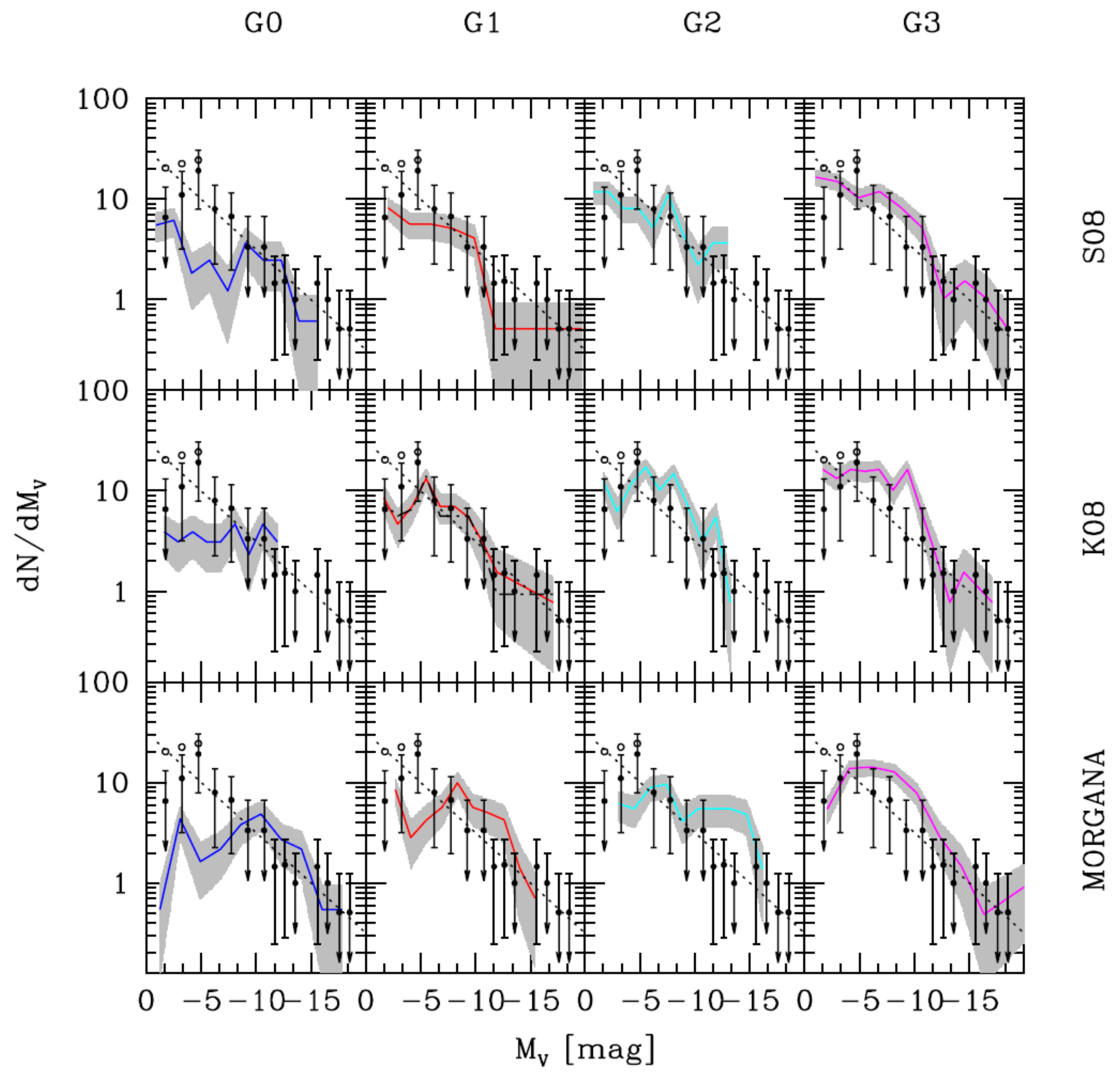
Table 1. Nbody Haloes

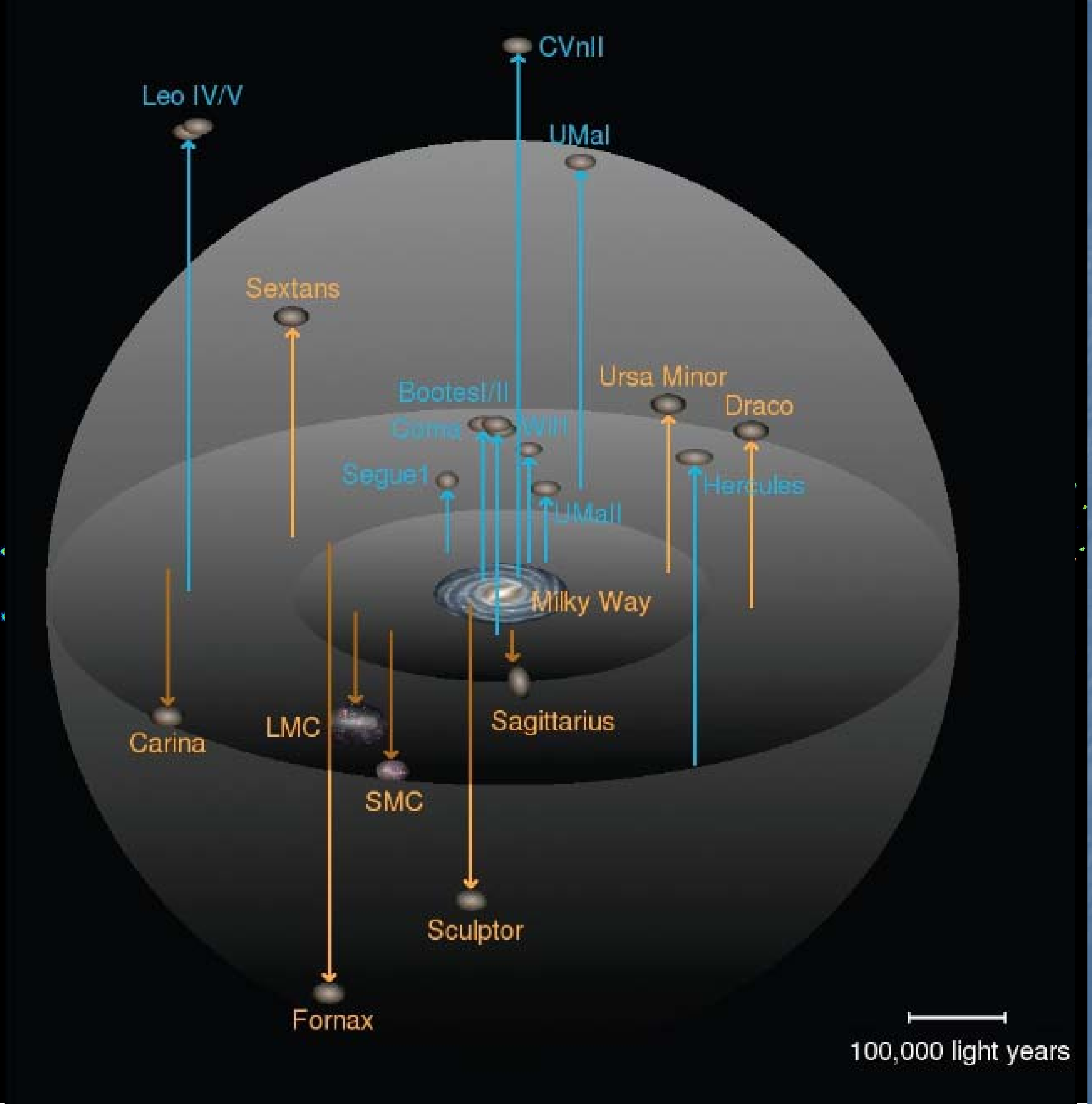
Halo	Mass ($10^{12} h^{-1}$ M$_\odot$)
G0	0.88
G1	1.22
G2	1.30
G3	2.63

Three SAMs

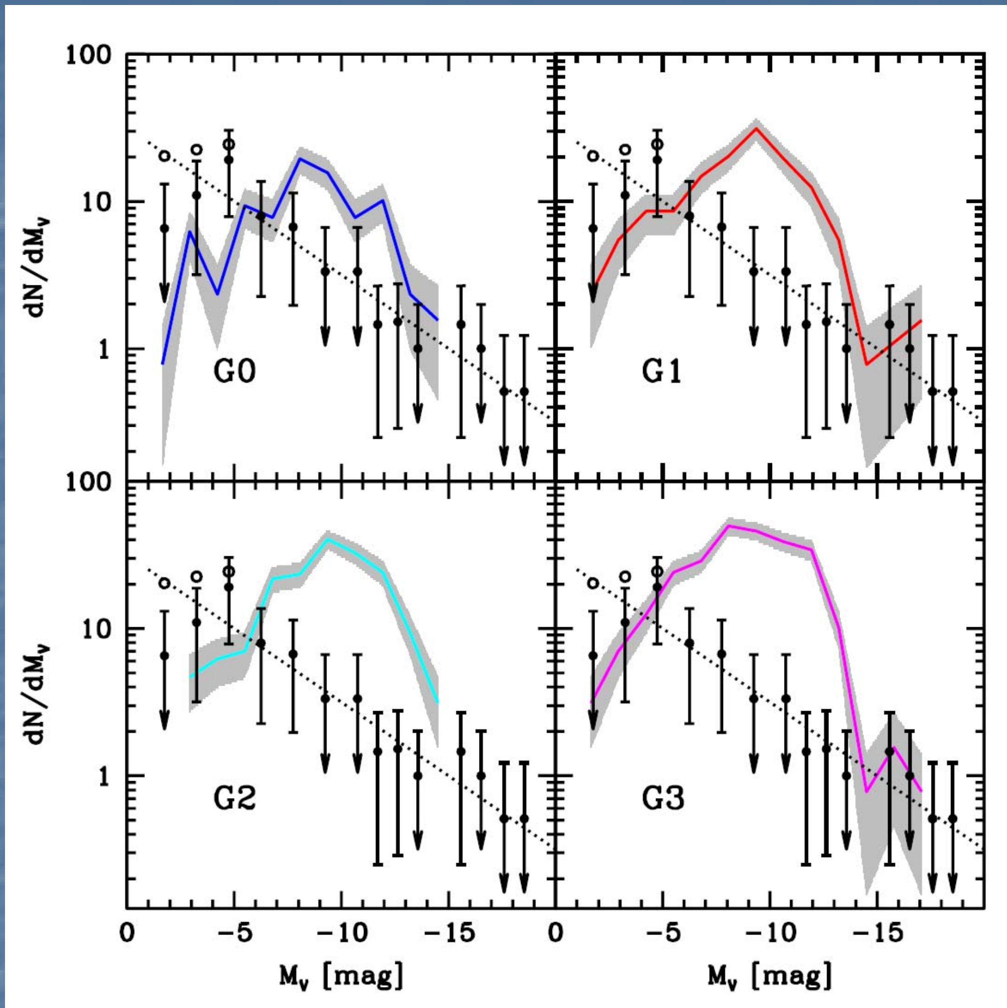
1) Somerville+ 08 (S08)
2) Monaco+ 06 (Morgana)
3) Kang+ 05,08 (K08)

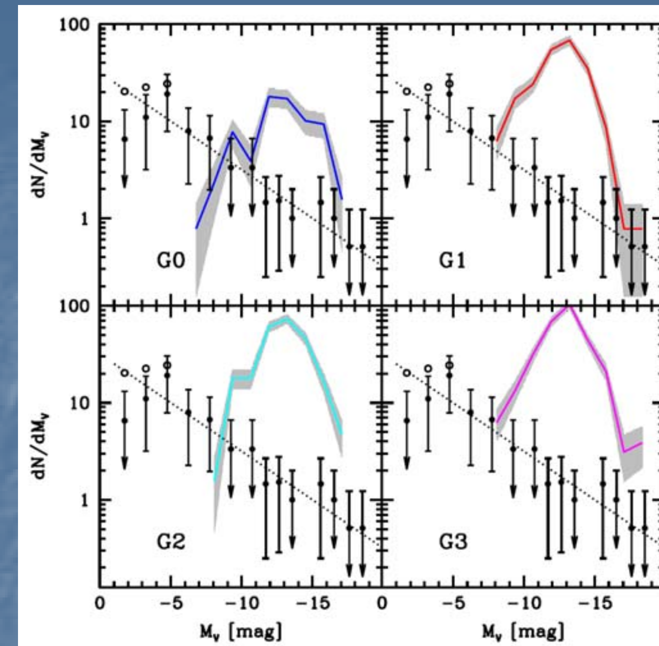


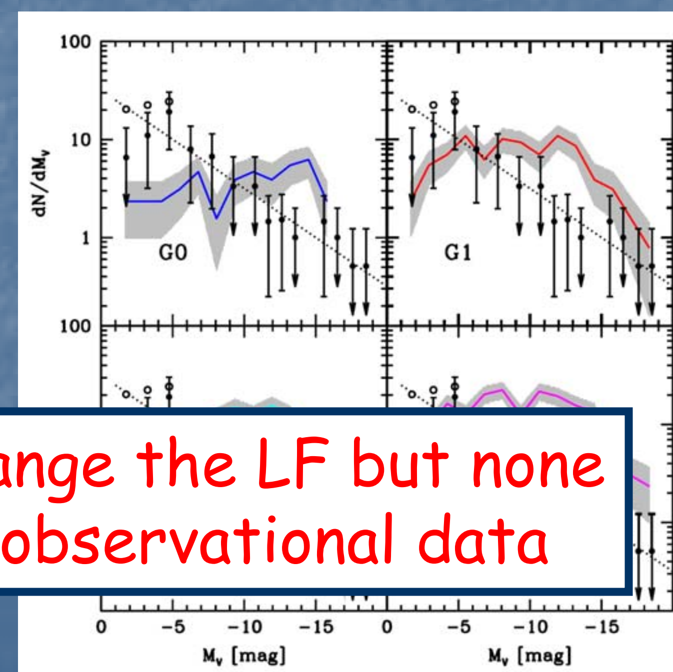



CVnII
Leo IV/V
UMaI
Sextans
Ursa Minor
BootesI/II
Draco
Coma
Willman1
Segue1
Hercules
UMaII
Milky Way
Sagittarius
LMC
Carina
SMC
Sculptor
Fornax
100,000 light years

Shaping the Luminosity Function (I)





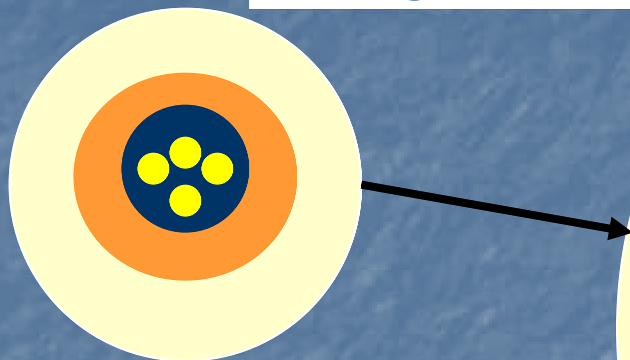


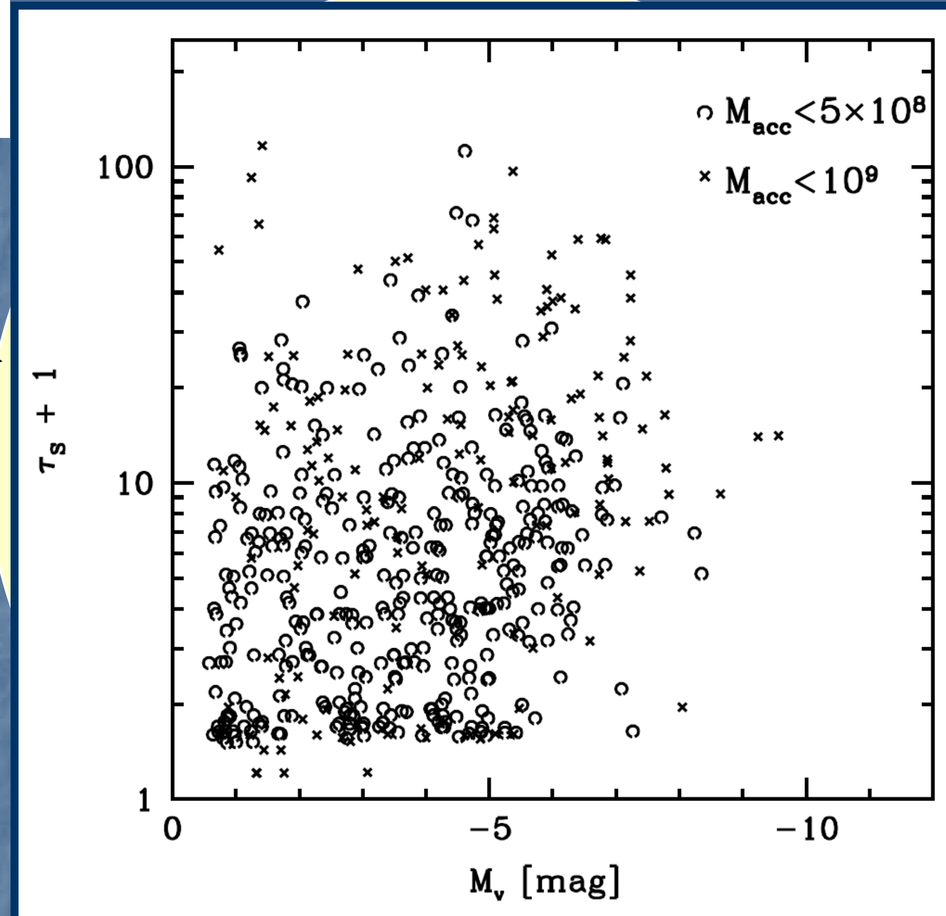
Both SN feedback and Reionization change the LF but none of them alone is able to reproduce the observational data

Shaping the Luminosity Function (II)

Gas removal

Hot gas halo
Cold gas halo





Hot gas component removed when a satellite is accreted
-> no more gas accretion
-> Star Formation quenched

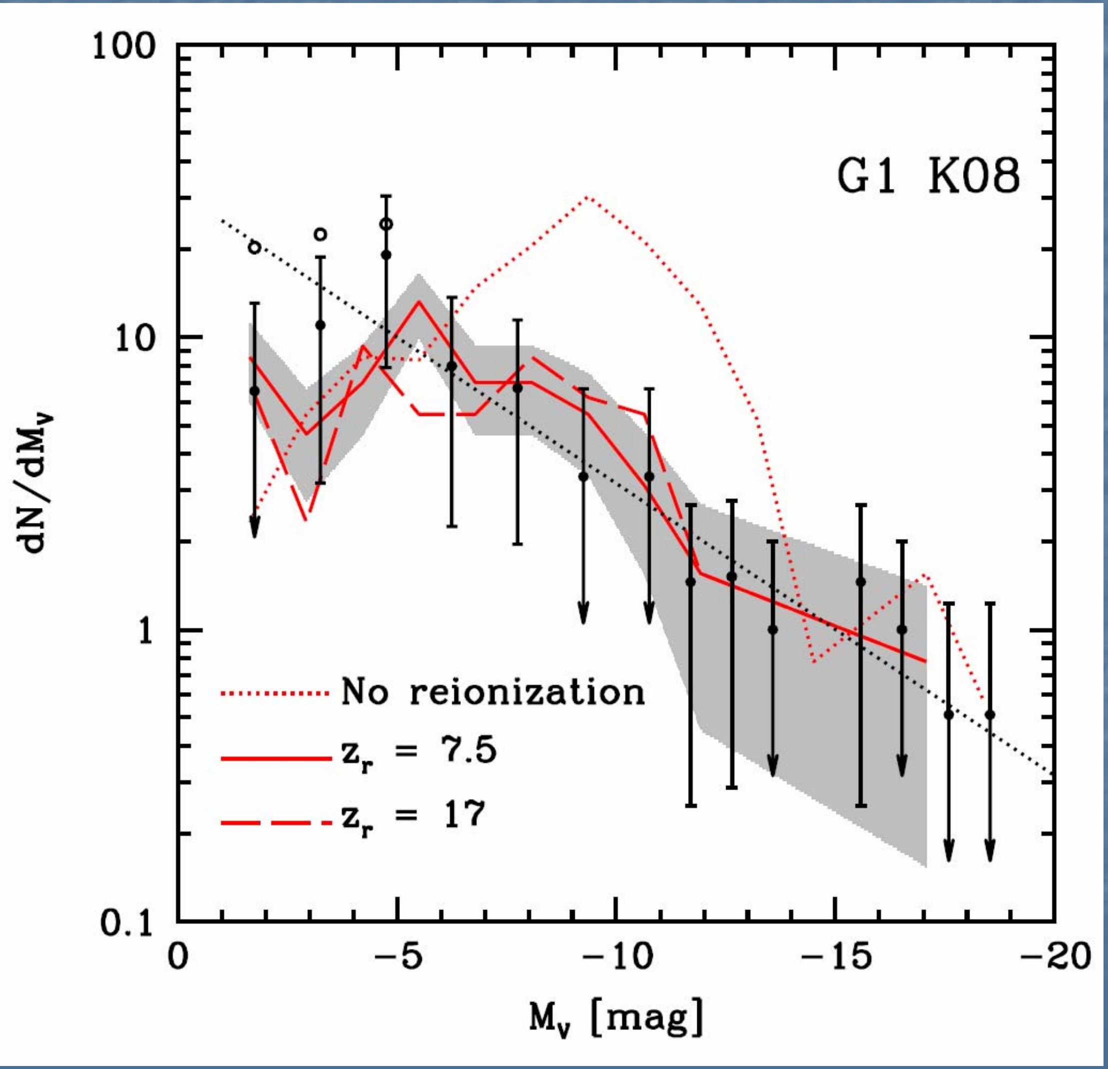
Formation Time
Cooling Time
Accretion Time

$$\tau_S = \frac{t_{acc} - t_{form}}{t_{cool}}$$

15% of the satel. with M_V>-5 didn't have enough time to make their stars
-> *strangulation*

Effects of Reionization (I)

What is the effect of changing z_r?

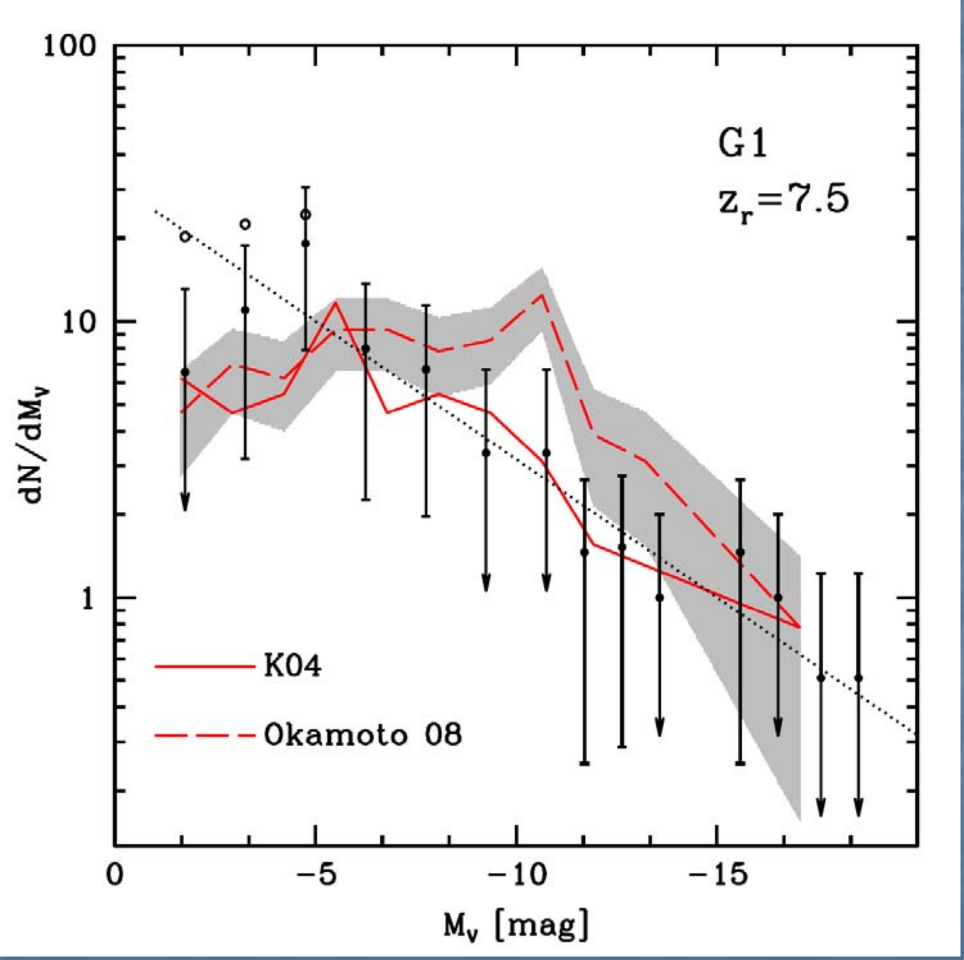


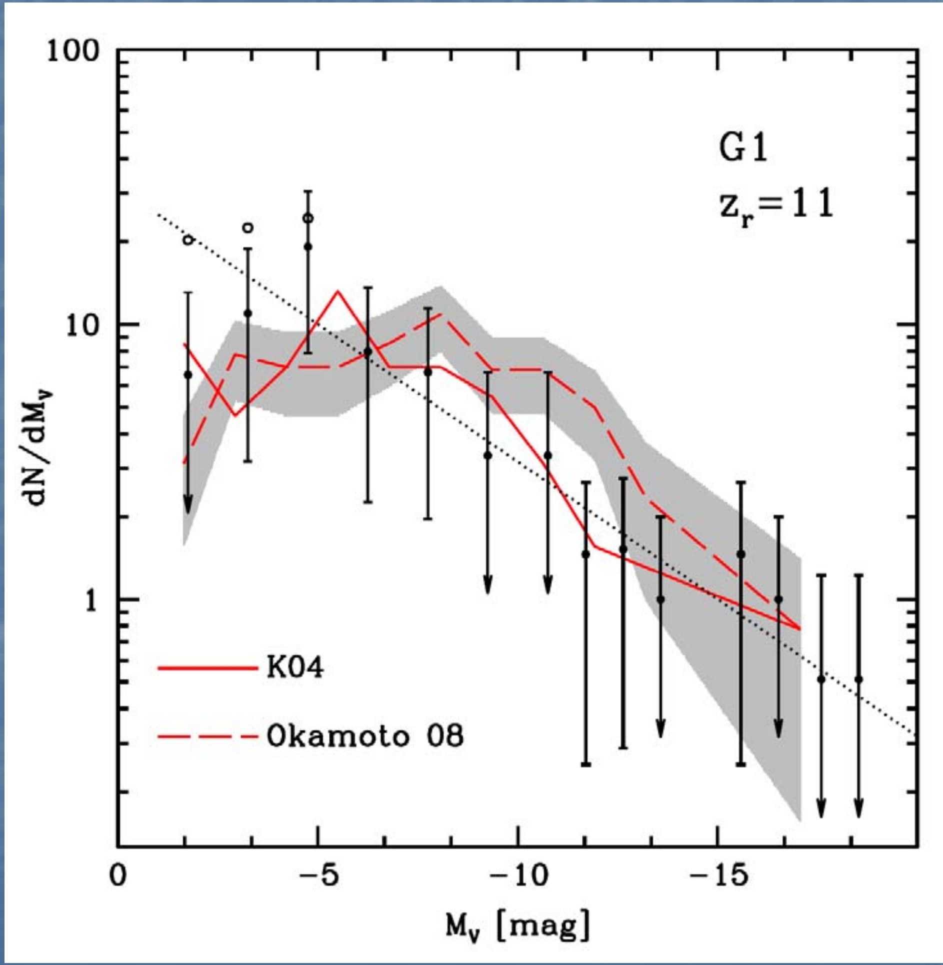
Using the Kravtsov+04 fitting formula for M_F

No dependence on reionization redshift

Effects of Reionization (II)

Over-estimation of M_F in Gnedin00 and Kravtsov+04 (Hoeft+07, Okamoto+08)

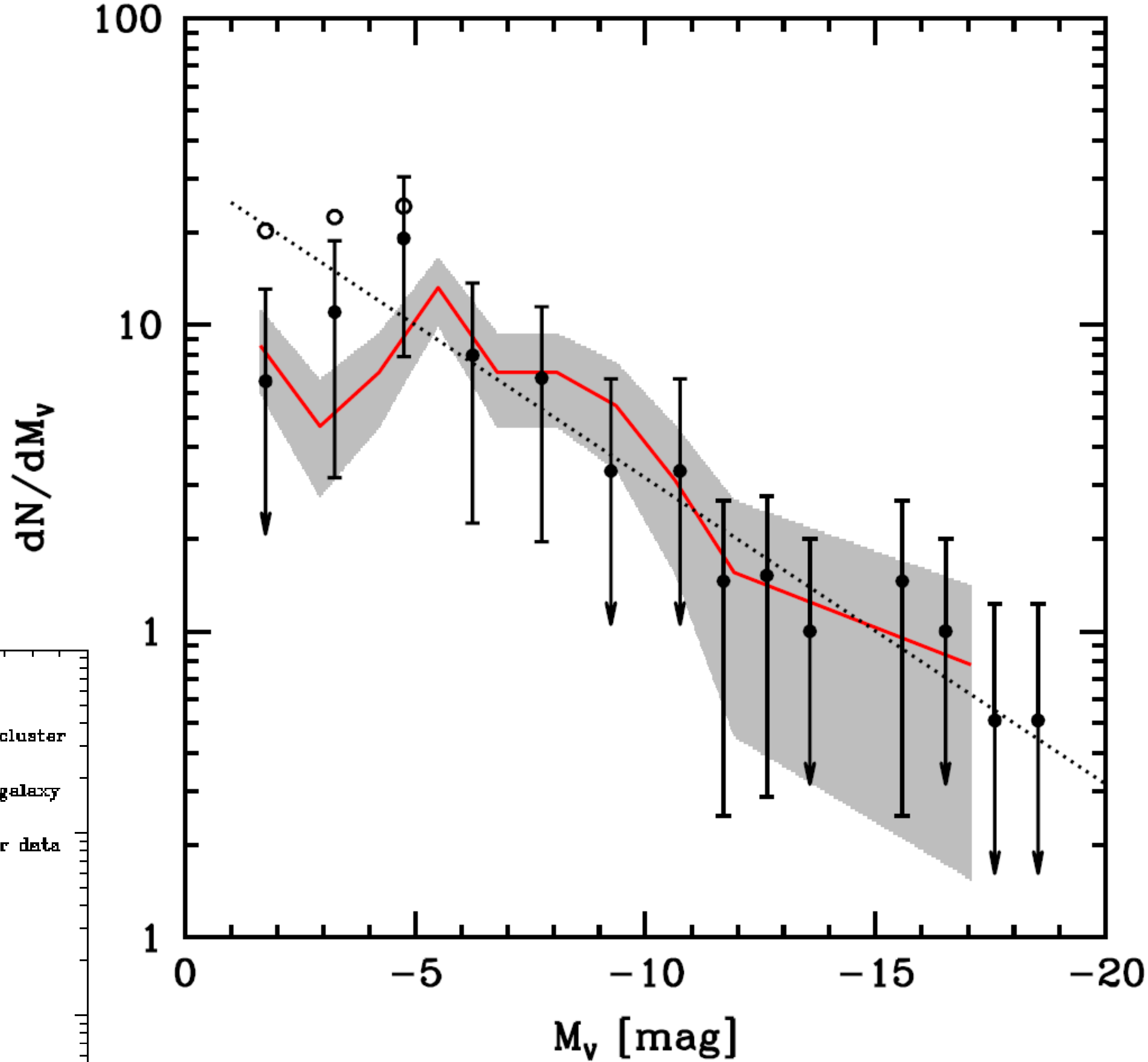


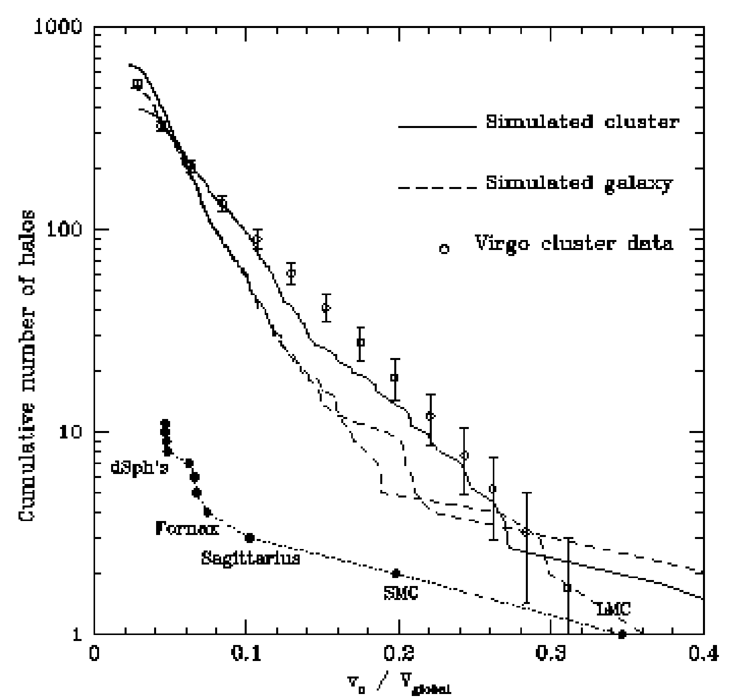


Okamoto+08 seems to favor a higher reionization redshift ~11

Solving the missing satellites problem:

SN feedback
+
Reionization
+
Strangulation



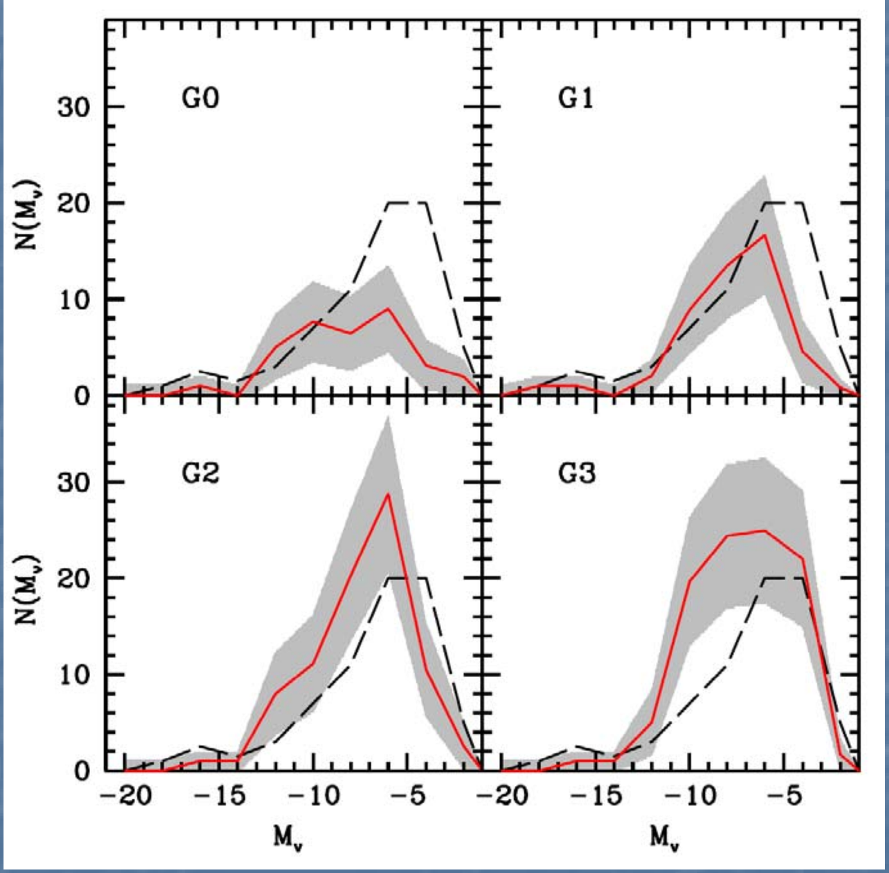


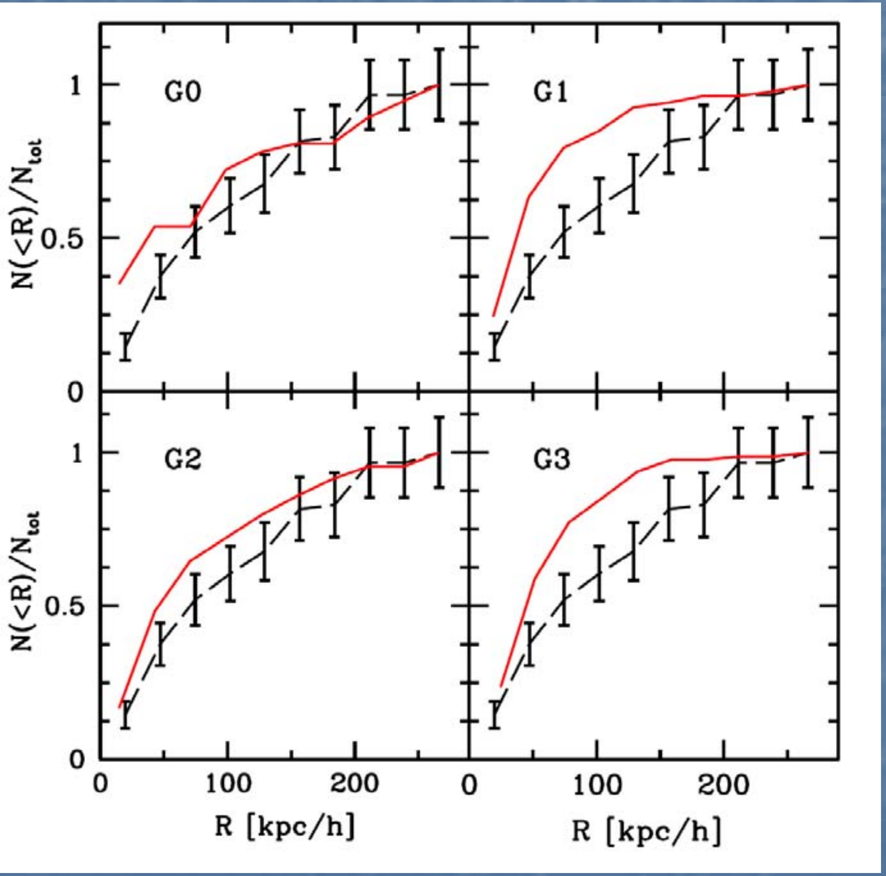
can be reproduces within (L)CDM model

Direct comparison with SDSS data

$$\log(R/kpc) < 1.04 - 0.228 \times M_V$$

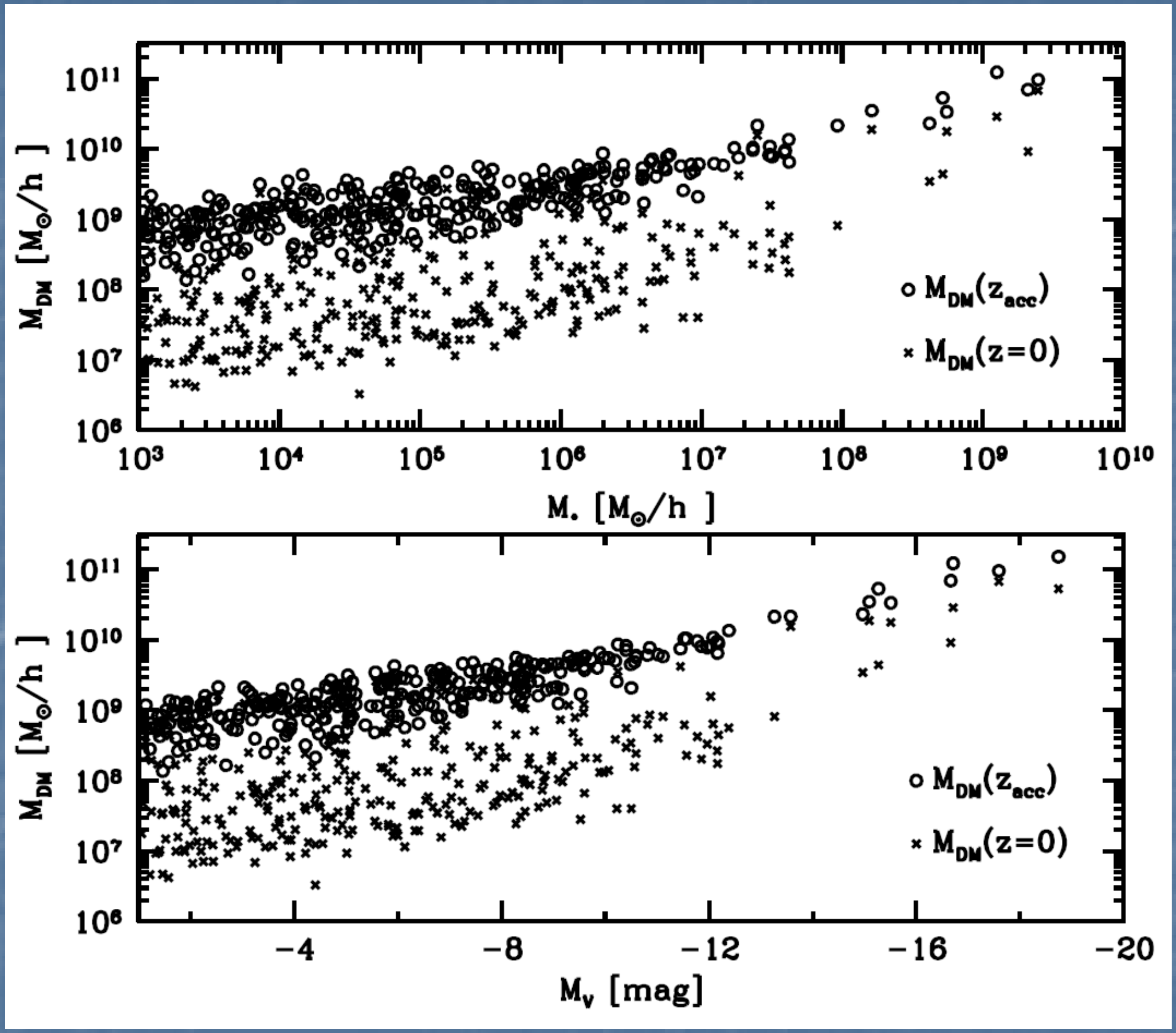
SDSS selection function criteria applied to simulations

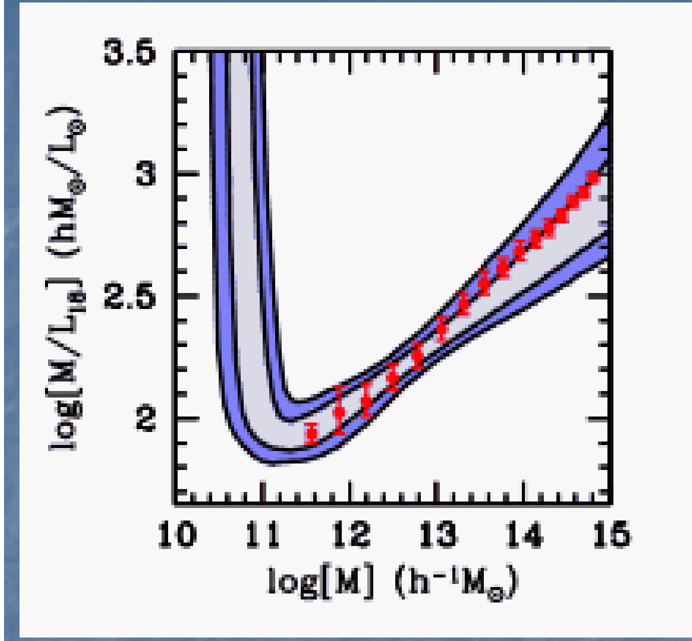




Radial distribution of MW correctly reproduced

Mass Luminosity relation for MW satellites

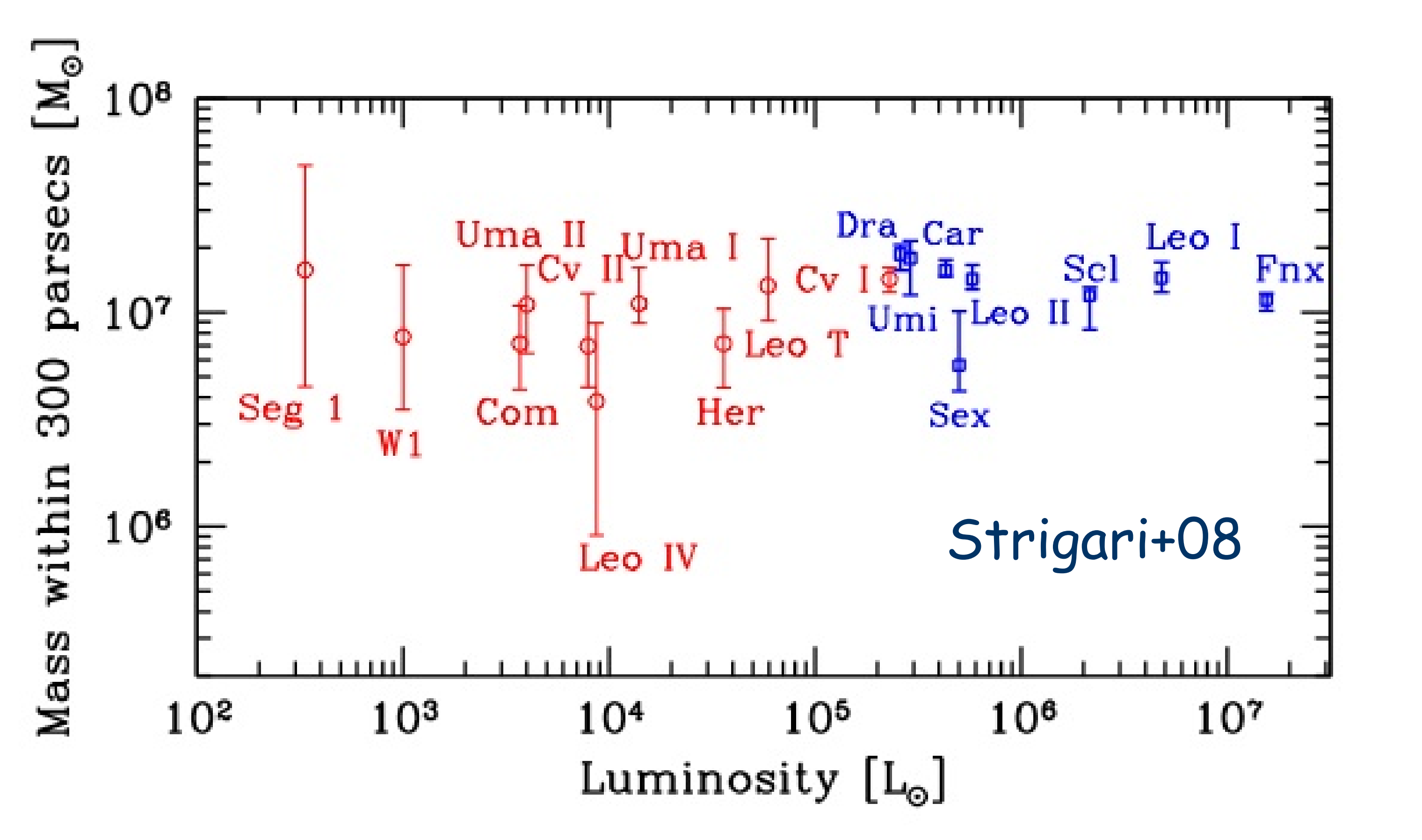




At a given M_{DM} more than 4 orders of magnitude in L/M_*

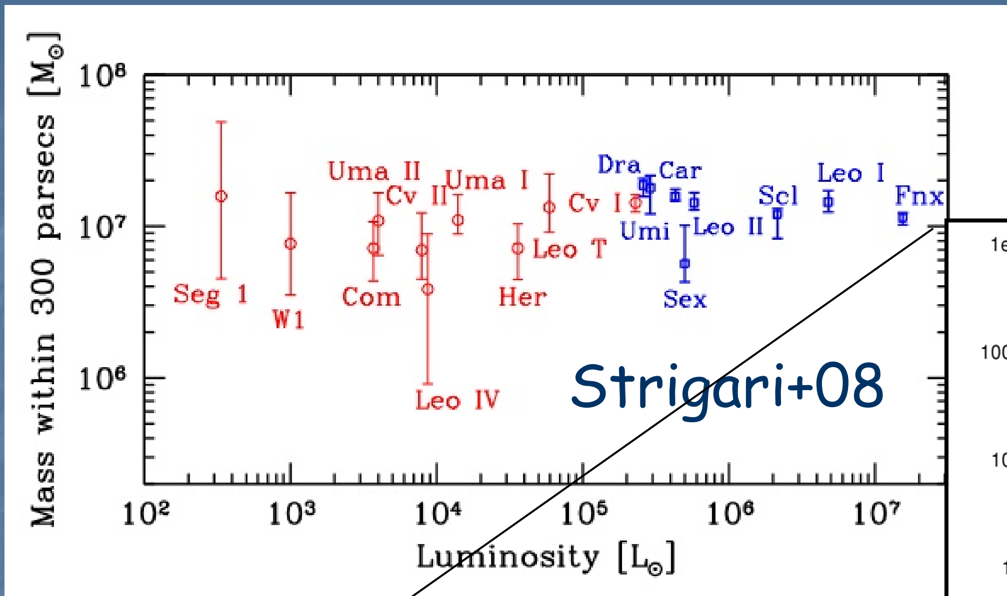
Central Mass of MW satellites

Maccio', Kang & Moore 2009, ApJL

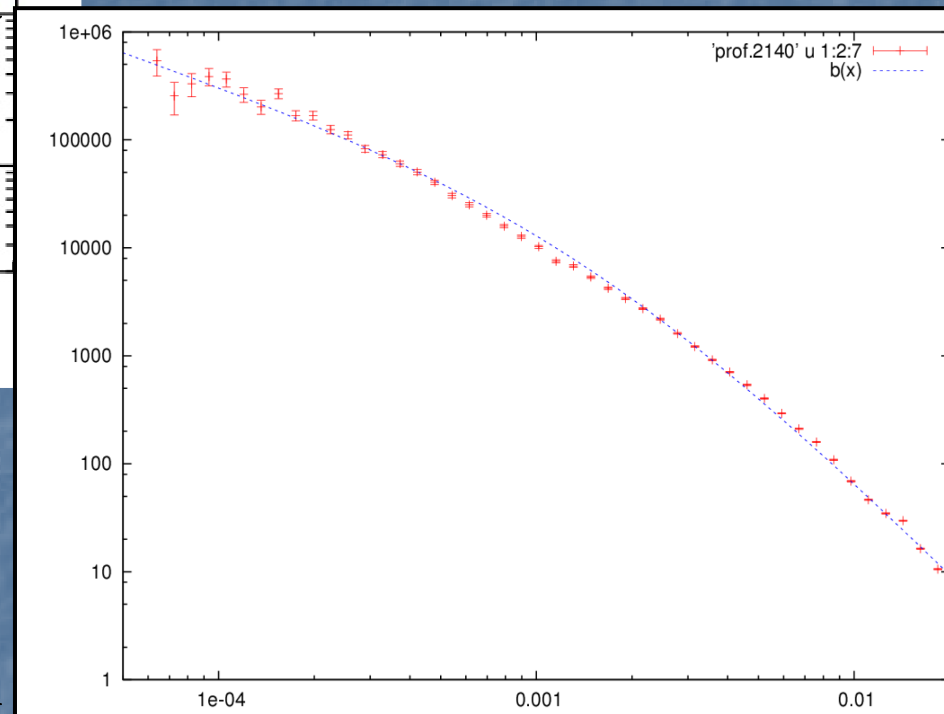


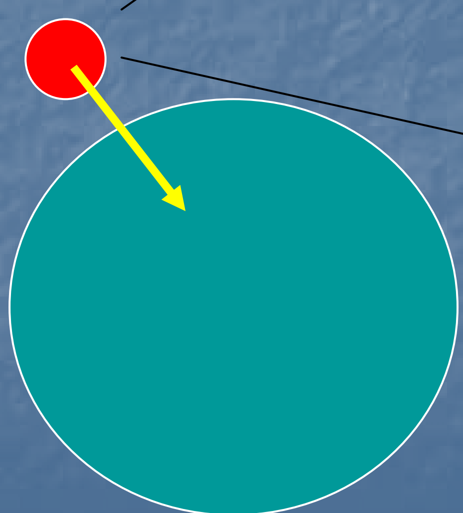
- A new mass scale in CDM?
- Evidence for WDM (e.g. Gilmore+08)
- Can CDM account for this result?

Central Mass of MW satellites



We do not have enough num. resolution ->
we use the density profile to compute the mass

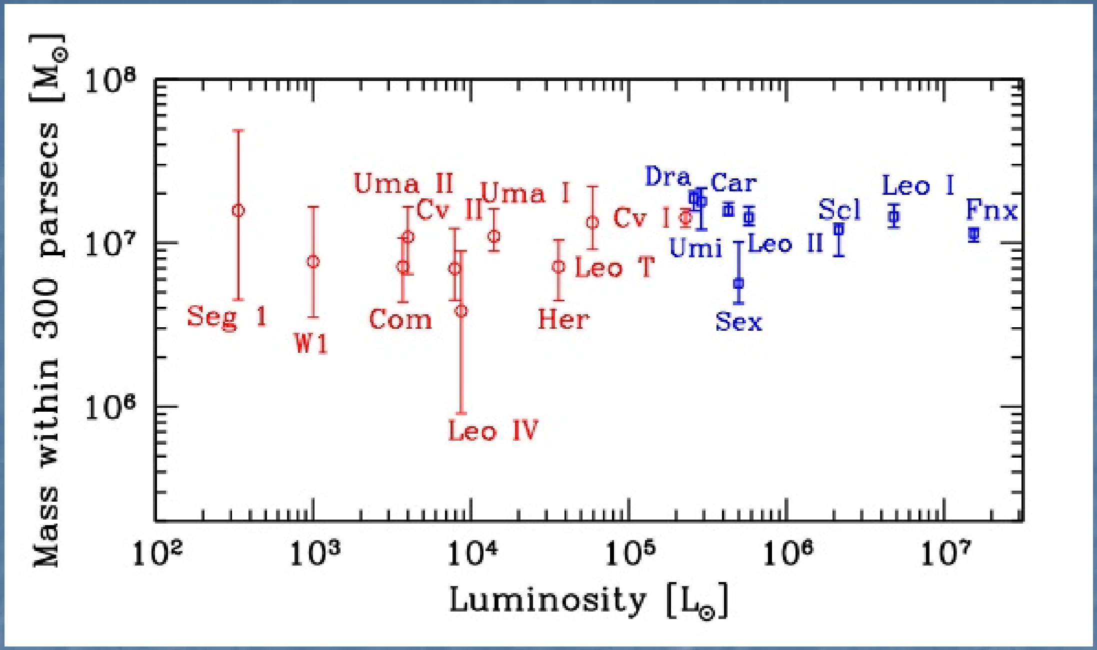




Compute r_s and δ_c at infall

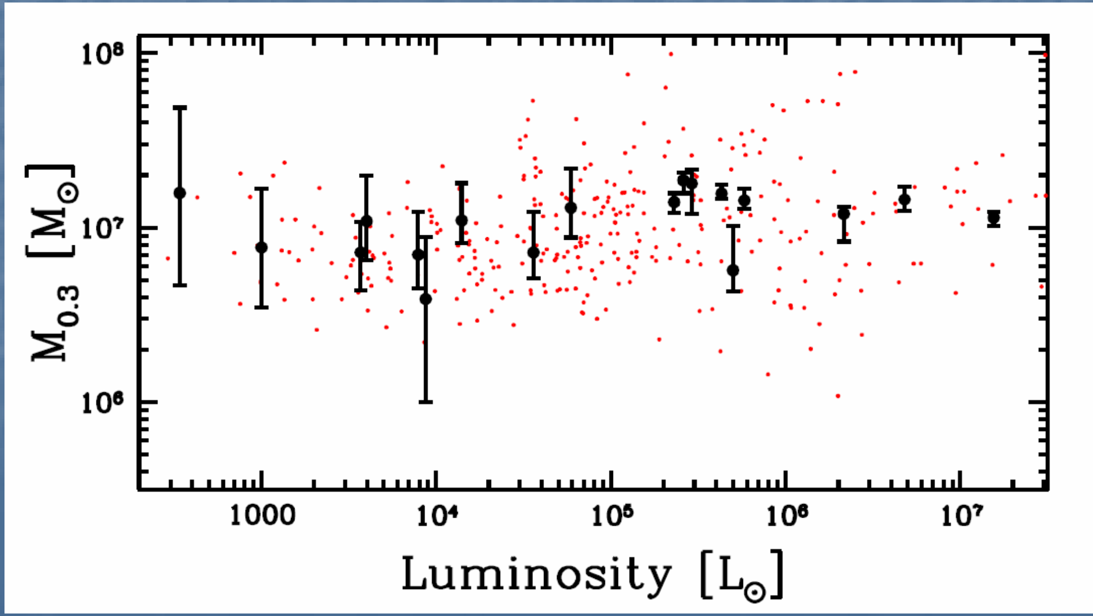
Under the assumption that r_s and δ_c do not change after accretion we can compute $M(<R_{0.3})$

For each satellite we have L and M(<$R_{0.3}$)



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

$$M(<R_{0.3}) = \int_0^{R_{0.3}} 4\pi r^2 \rho(r)\, dr$$



Origin of the $M_{0.3}/L$ relation

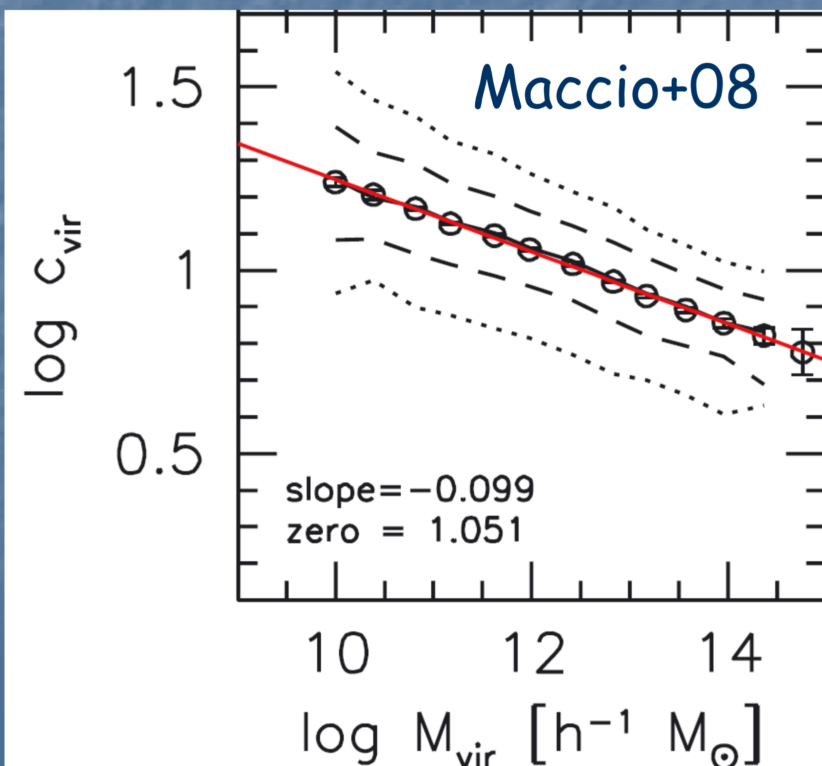
Maccio', Kang & Moore 2009, ApJL

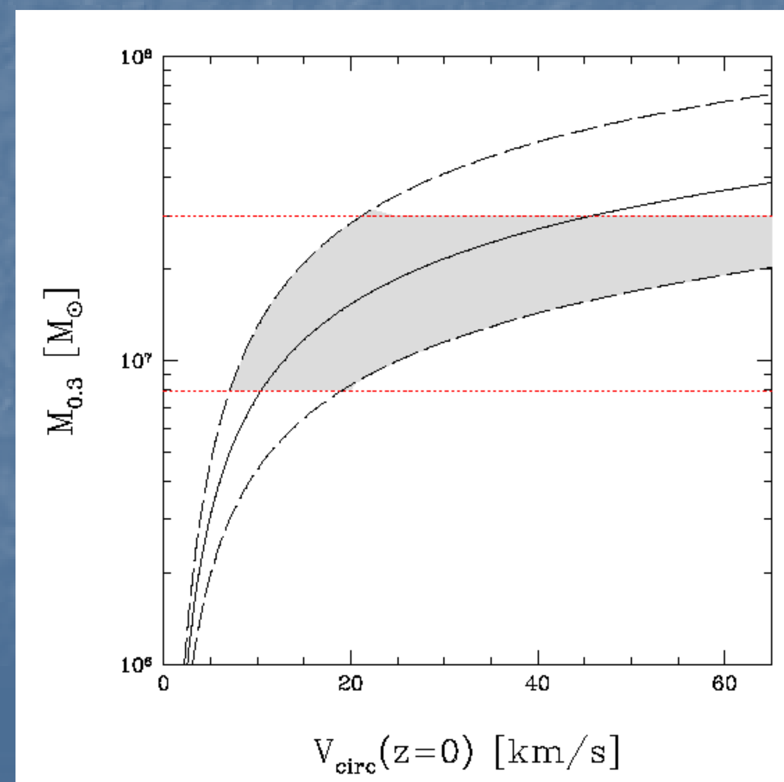
There is a well-known correlation between mass and concentration (e.g Maccio'+ 08)

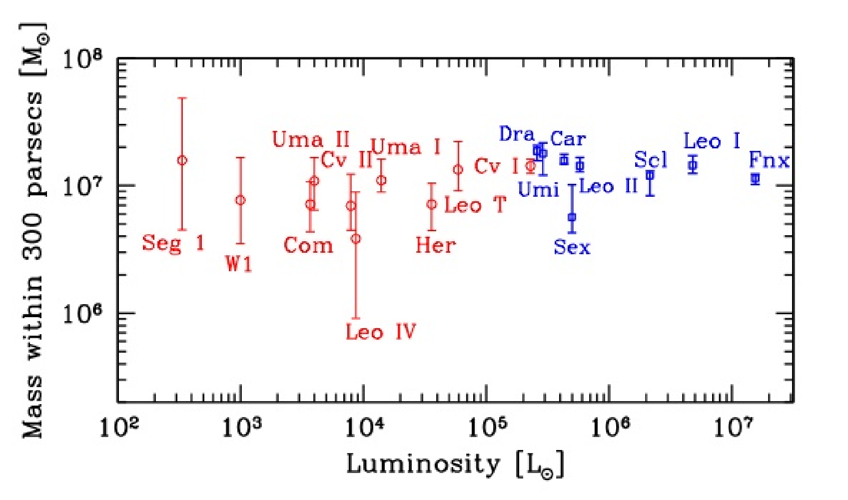
$$\frac{\rho(r)}{\rho_{cr}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

$$M(<R_{0.3}) = \int_0^{R_{0.3}} 4\pi r^2 \rho(r)\, dr$$

$$M_{vir} \Leftrightarrow \rho(r) \qquad c = \frac{R_{vir}}{r_s}$$

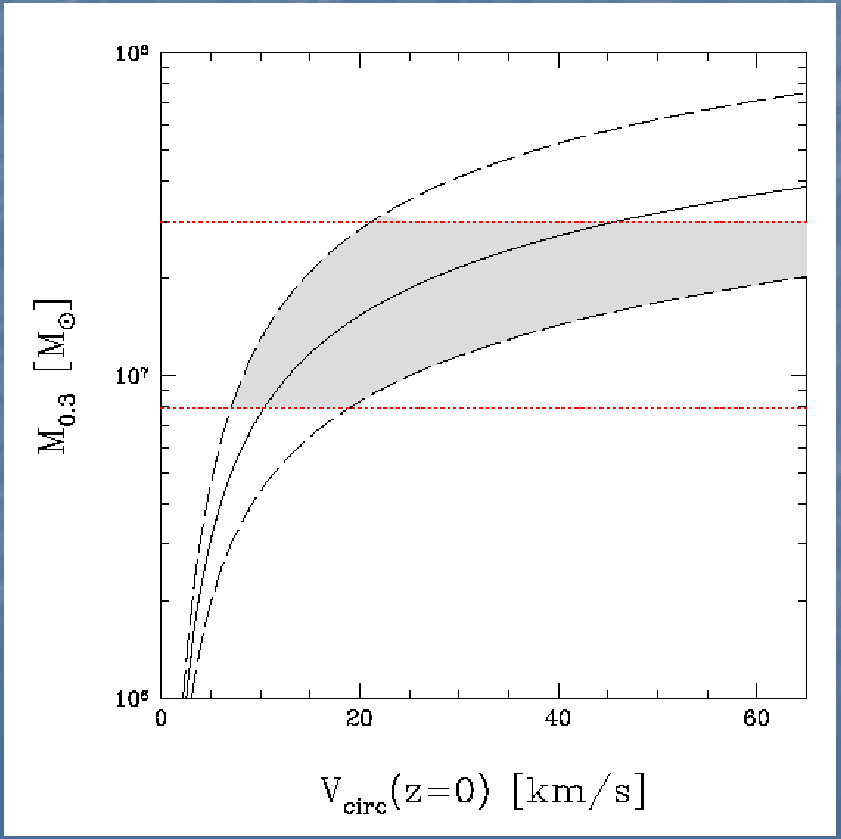


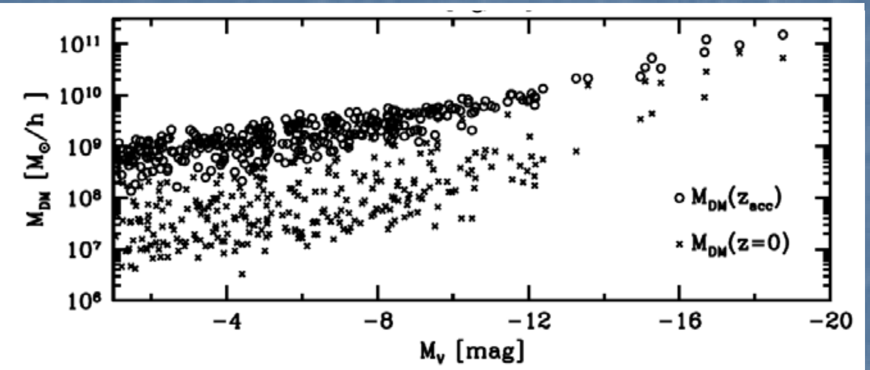


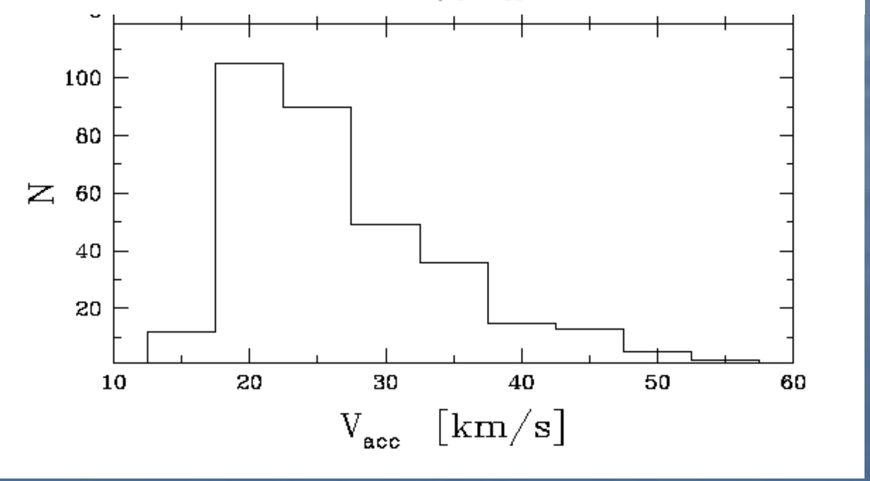


For a given Mass the Luminosity depends on mainly 3 factors:

- Formation Redshift Z_f
- Accretion Redshift Z_{acc}
- $M(z_r)$

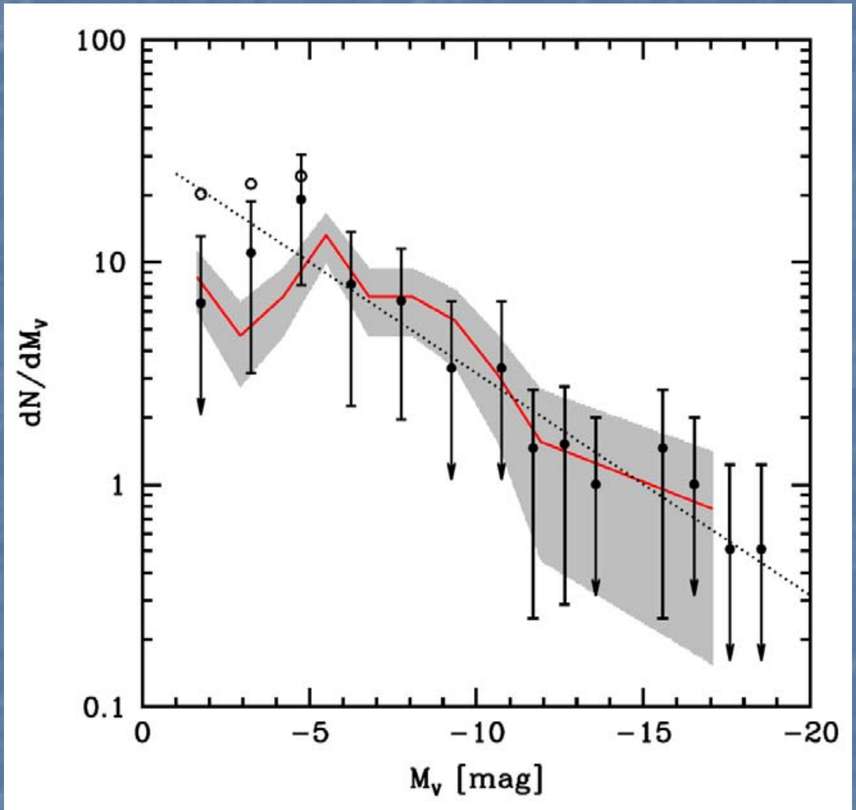


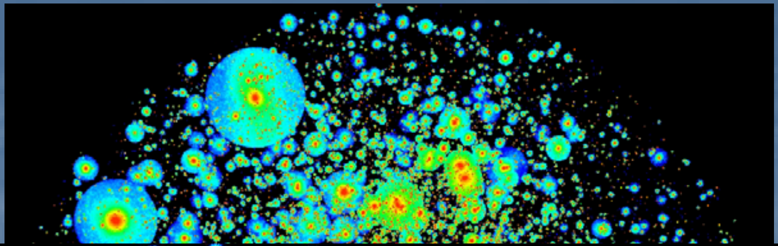


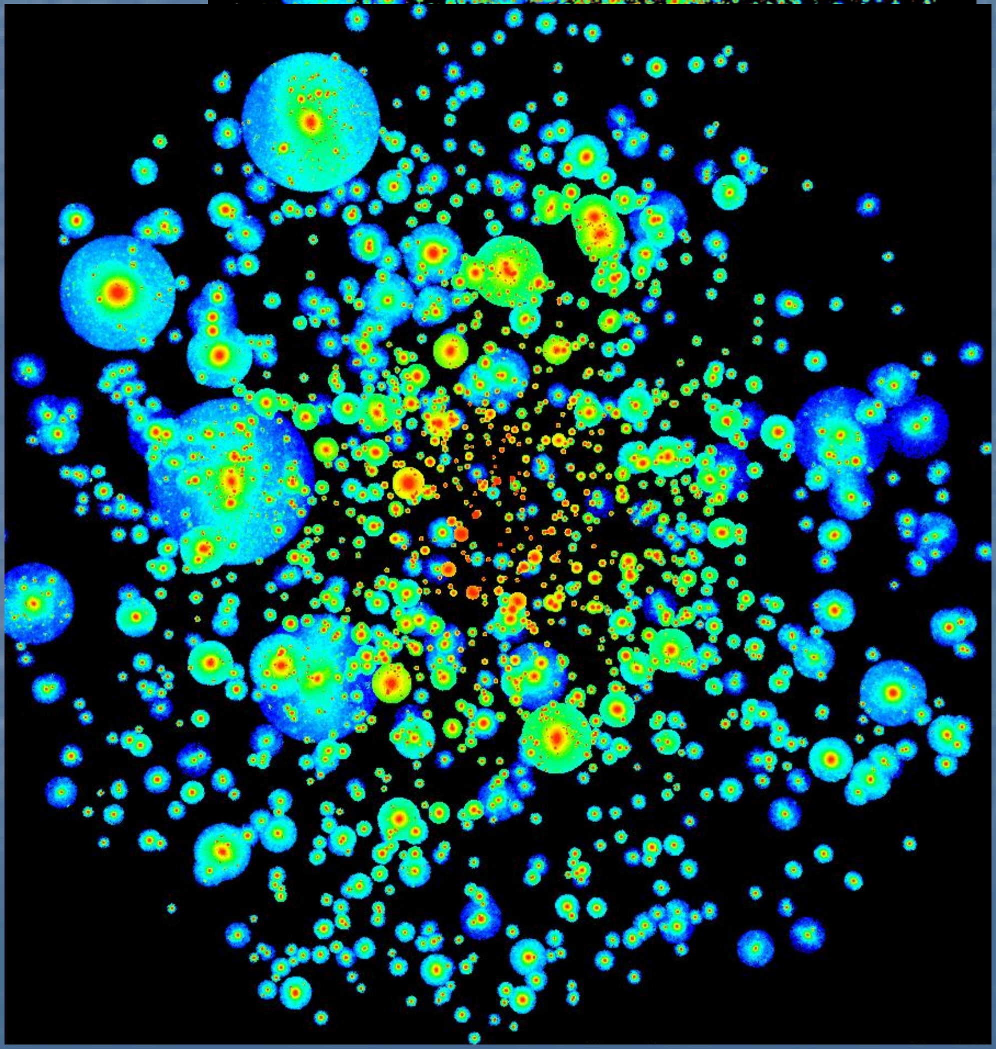


Milky way satellites and properties of DM

too many satellites in DM → WDM



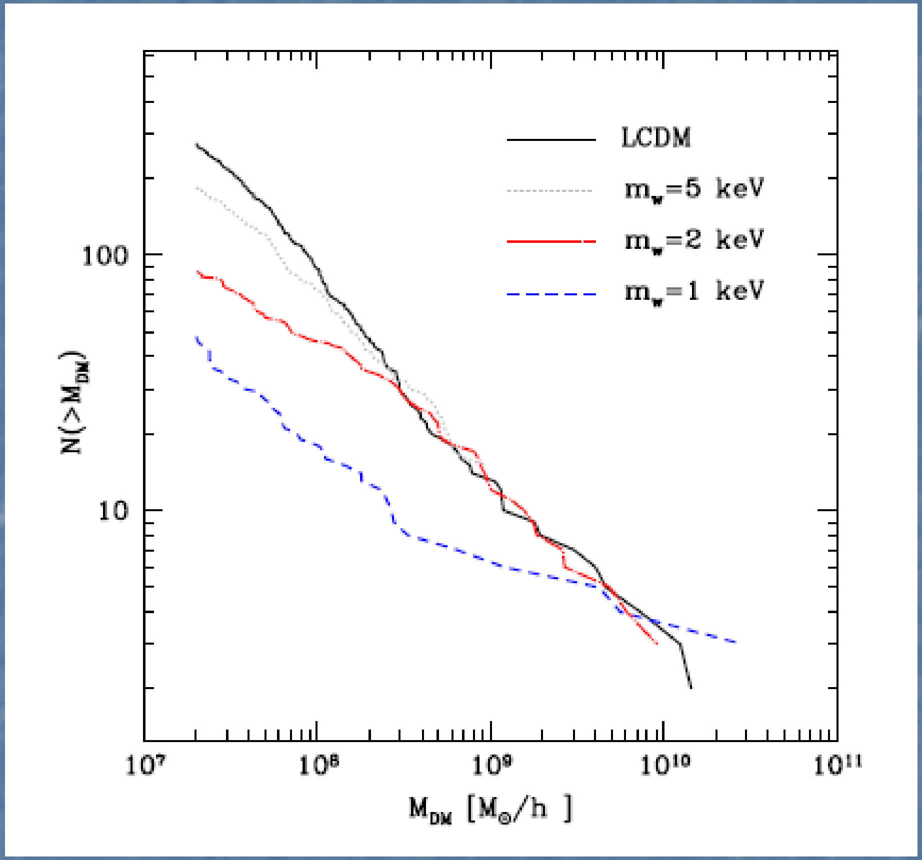


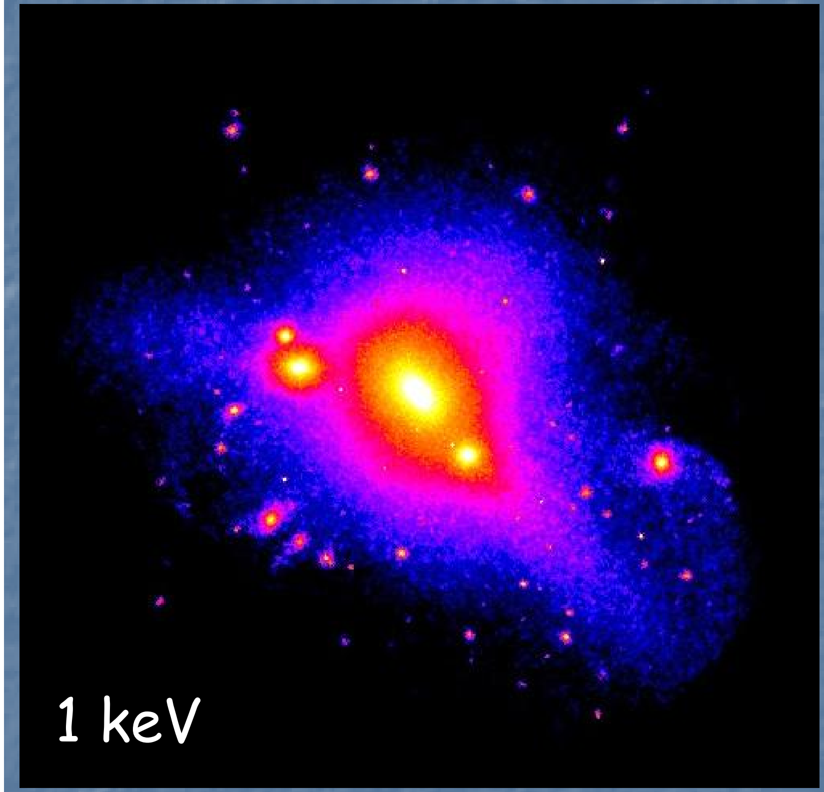


What happens if we REDUCE the number of small DM subhaloes?

Milky way satellites and properties of DM

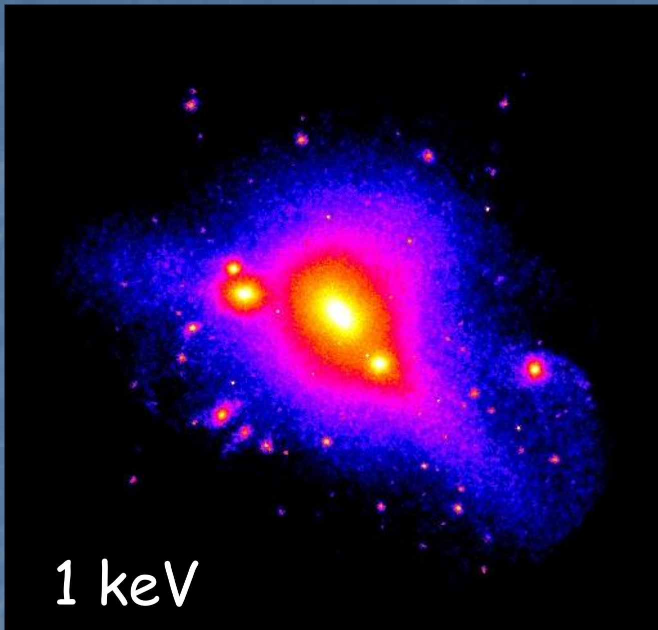
Can we constrain the minimum "temperature" of DM?

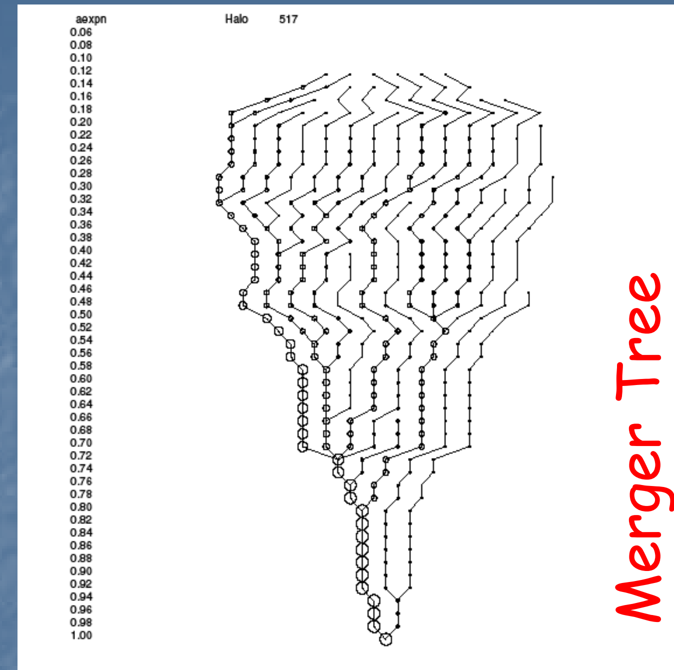


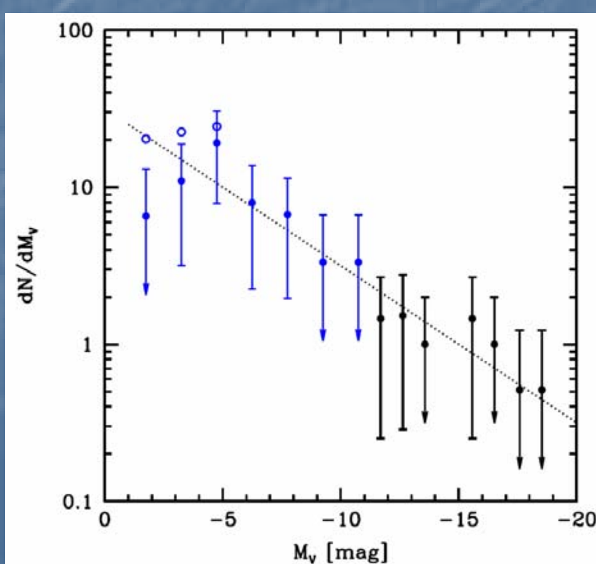


Maccio' & Fontanot 2010, MNRAS letters

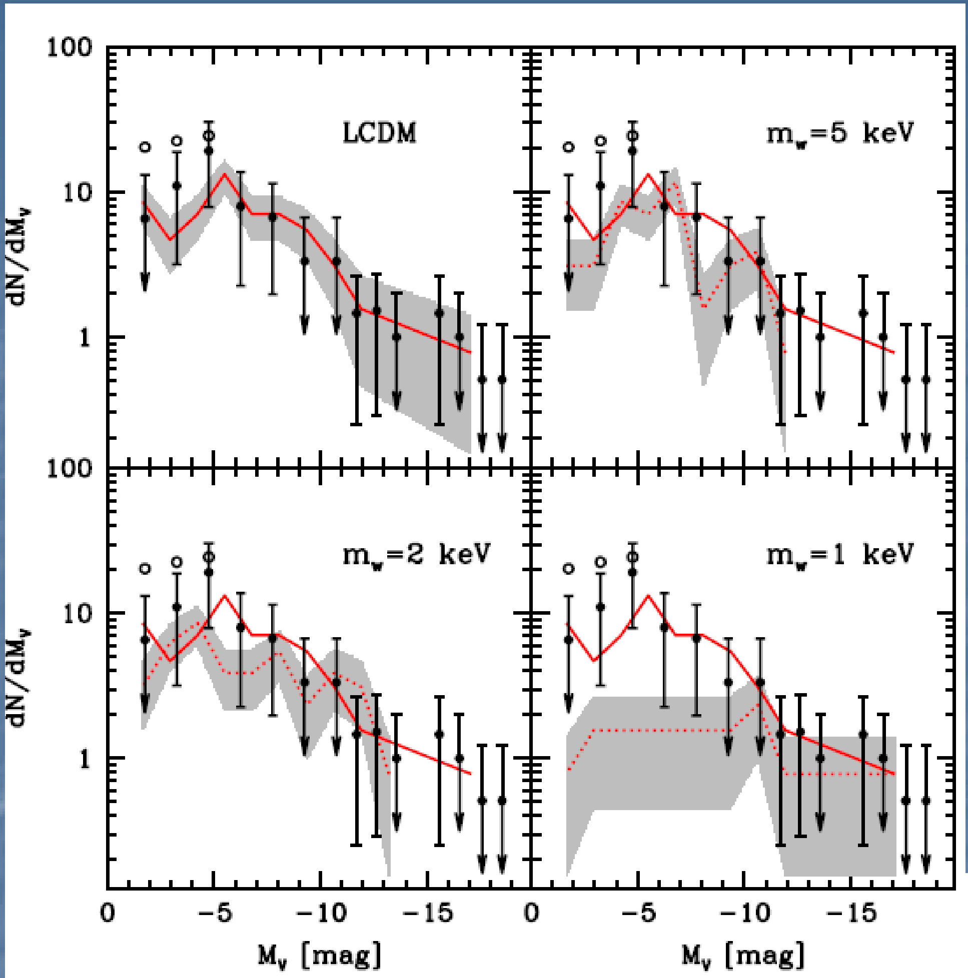
Method

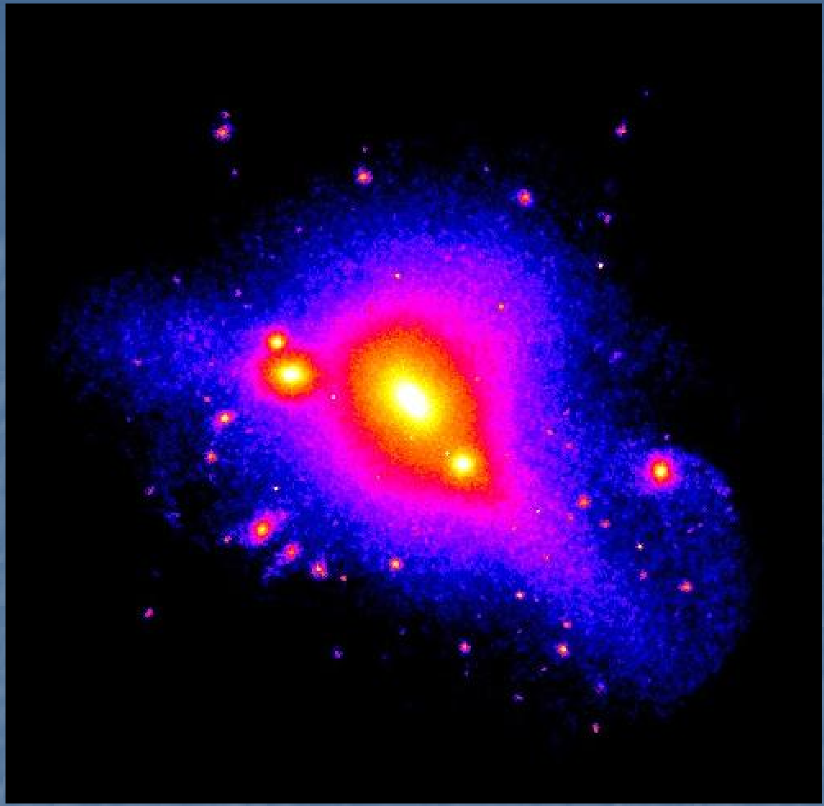

1 keV

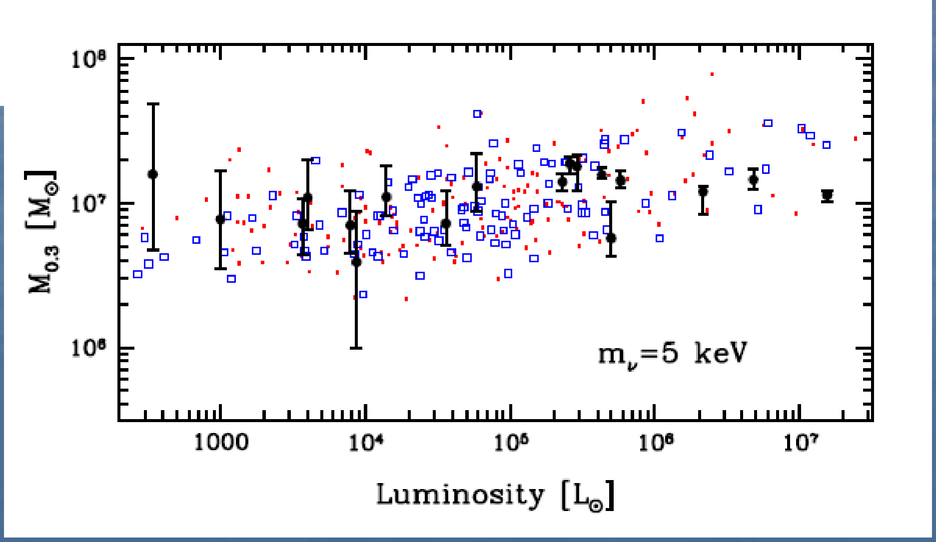

aexpn
Halo 517
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
0.32
0.34
0.36
0.38
0.40
0.42
0.44
0.46
0.48
0.50
0.52
0.54
0.56
0.58
0.60
0.62
0.64
0.66
0.68
0.70
0.72
0.74
0.76
0.78
0.80
0.82
0.84
0.86
0.88
0.90
0.92
0.94
0.96
0.98
1.00
Merger Tree


100
10
1
0.1
0
−5
−10
−15
−20
dN/dM_V
M_V [mag]


SAMs







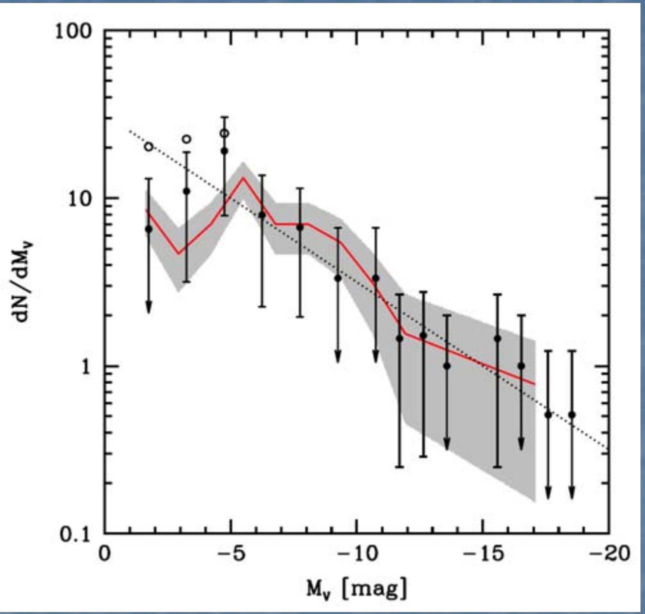
m_ν>1 keV
(thermal relic)

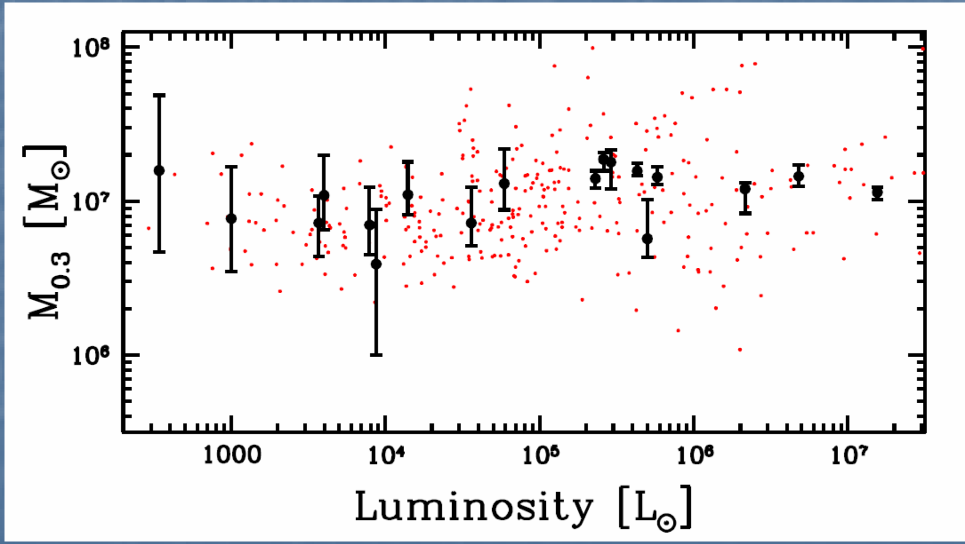
previous measurements
(L-alpha & QSO Lensing m_ν>4 keV)

Conclusions

Properties of MW satellites can be explained within (L)CDM
(with reasonable baryonic physics)

- Luminosity & Number Density
- Central Mass
- NO constraints for cold/warm



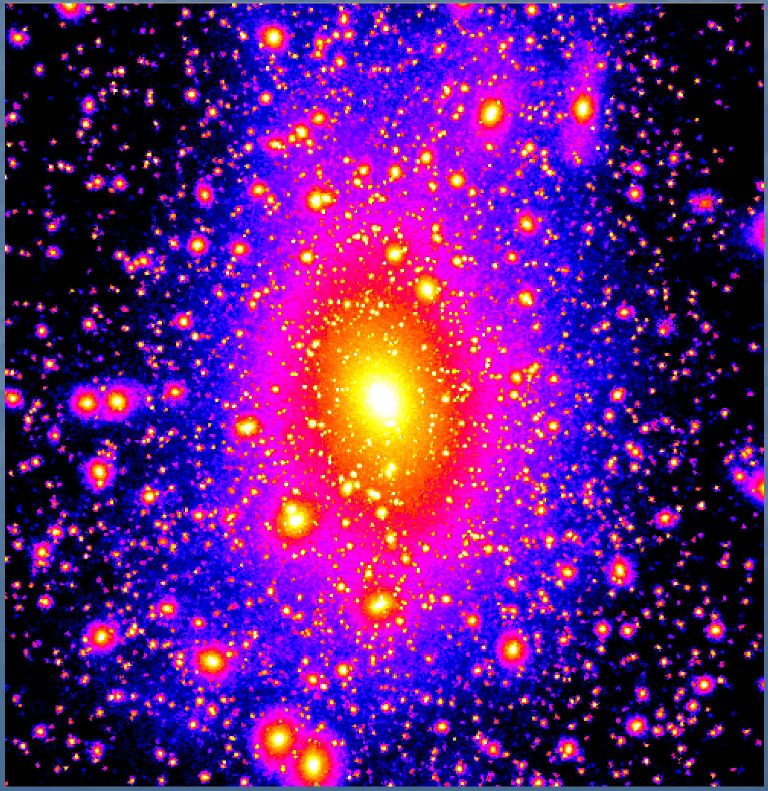


BUT...

The other side of the coin

¾ of the satellites with $M_{DM}>10^7\ M_{sun}$ are dark
They do not host any observable galaxies

The presence of this large population of satellites is a clear prediction of LCDM



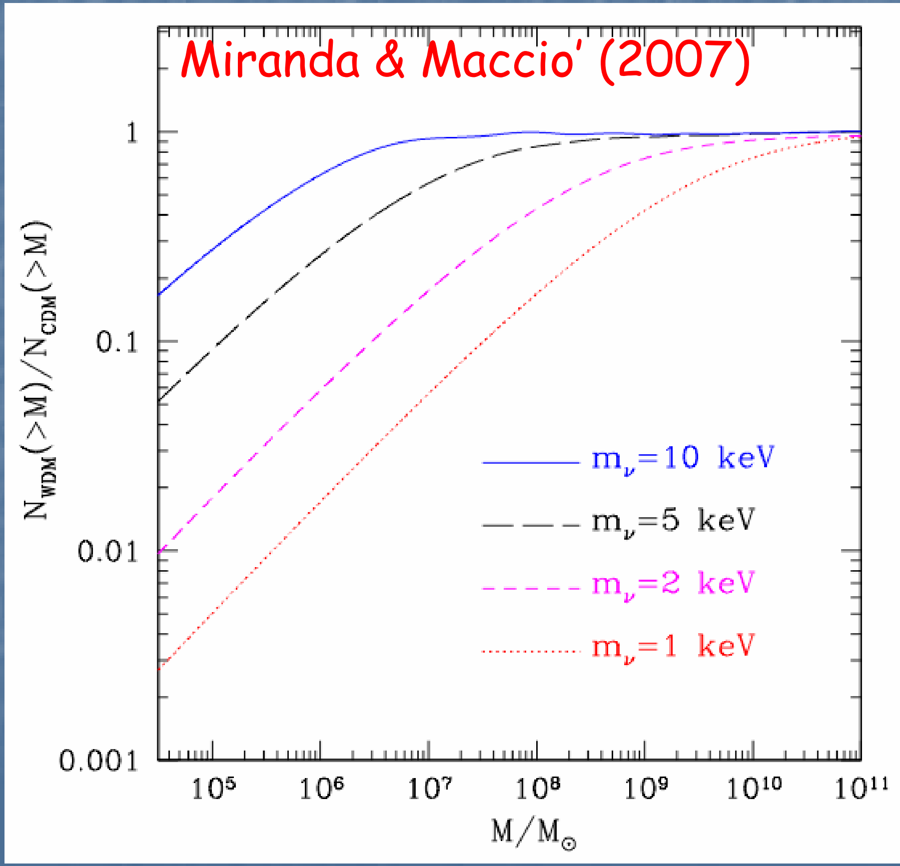
We need to "detect" them
to probe LCDM
to be correct

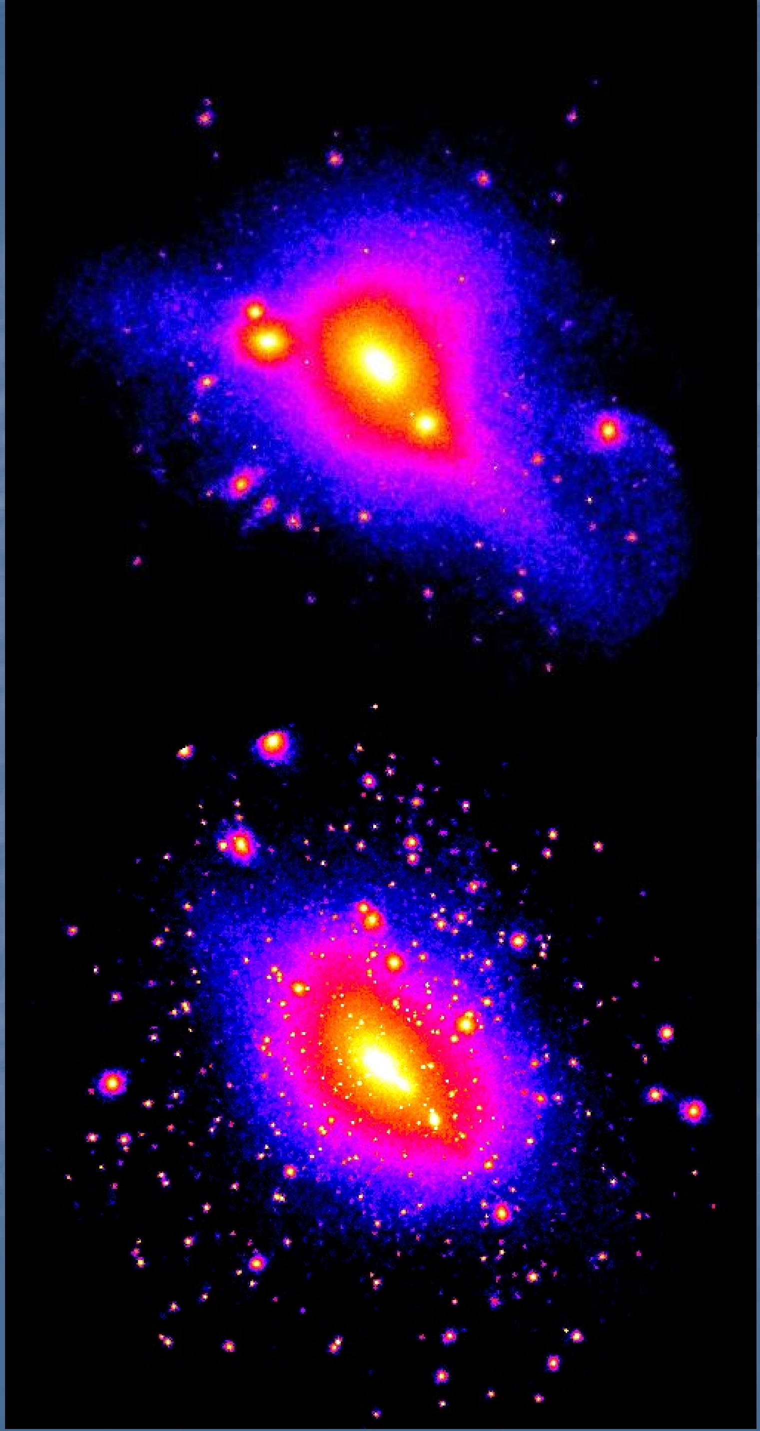
Lensing not really promising
(Maccio+06,07)
Gamma Rays (neither)

Key test to distinguish:

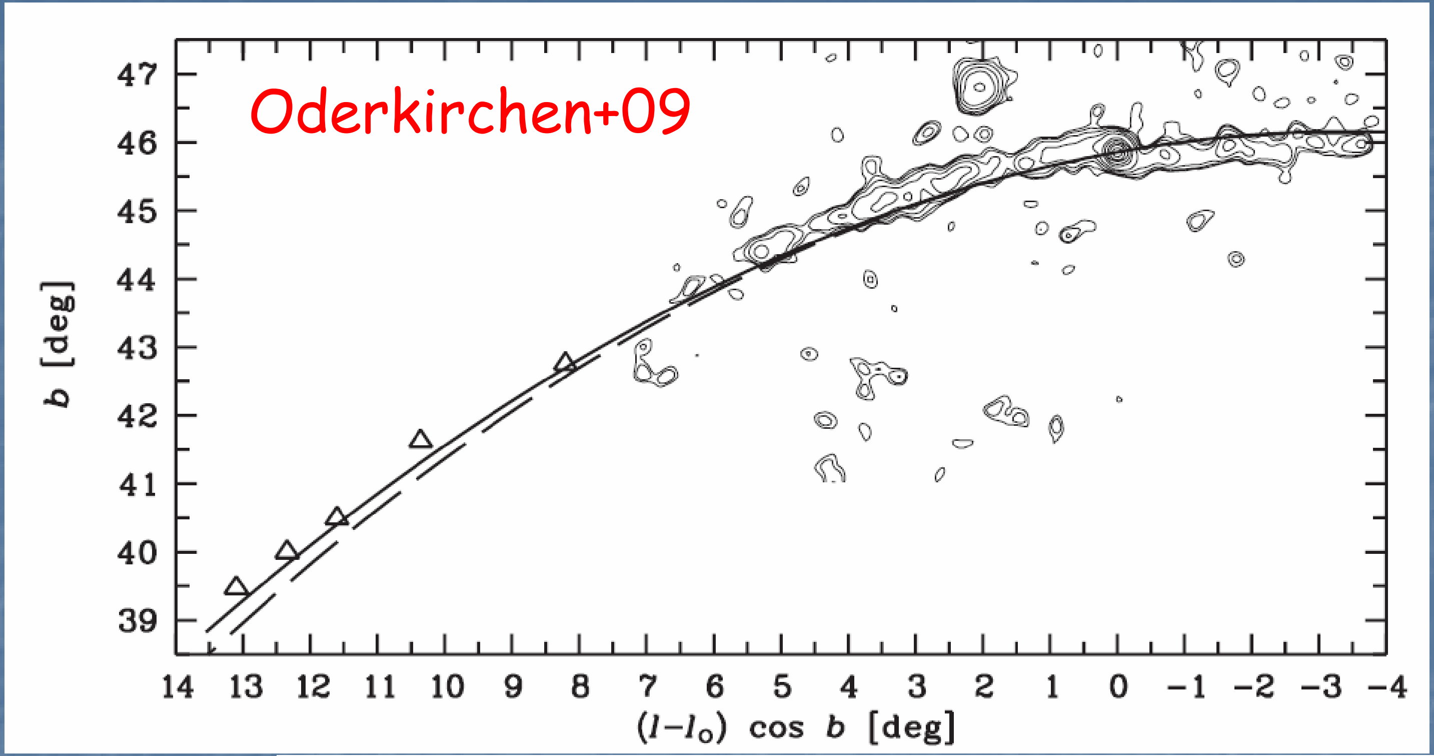
1 keV DM

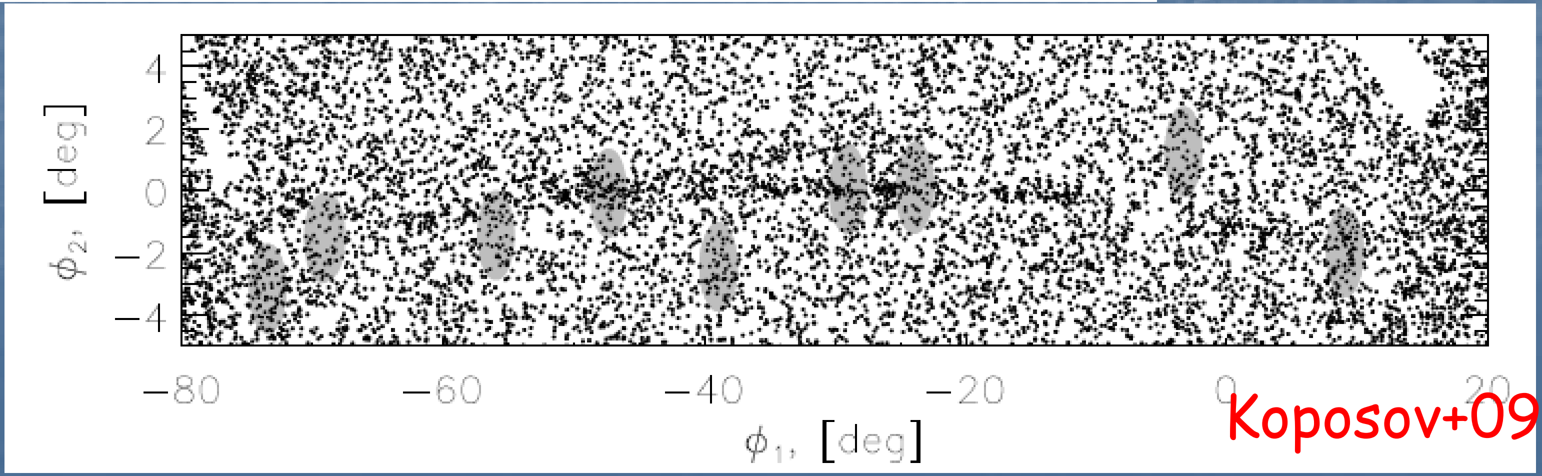
WIMP-like DM (GeV)





Heating of stellar streams



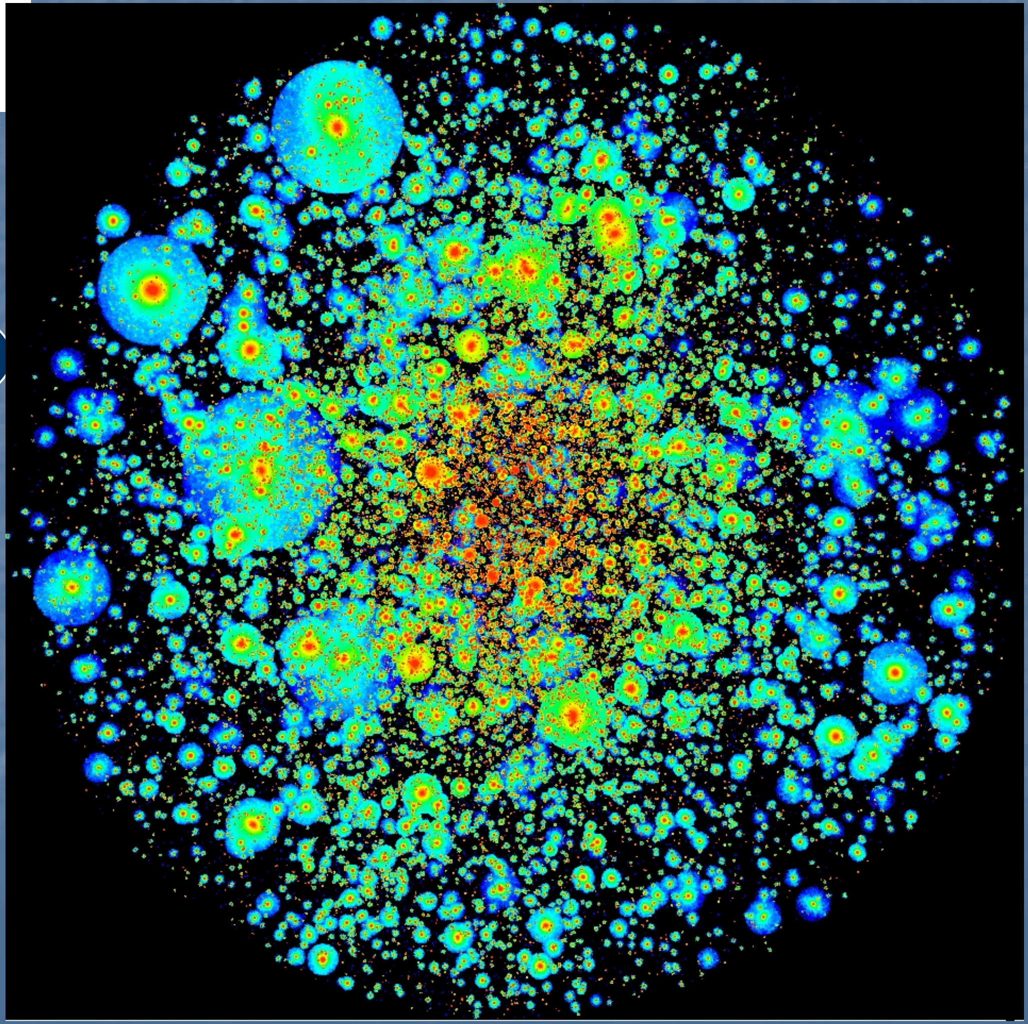


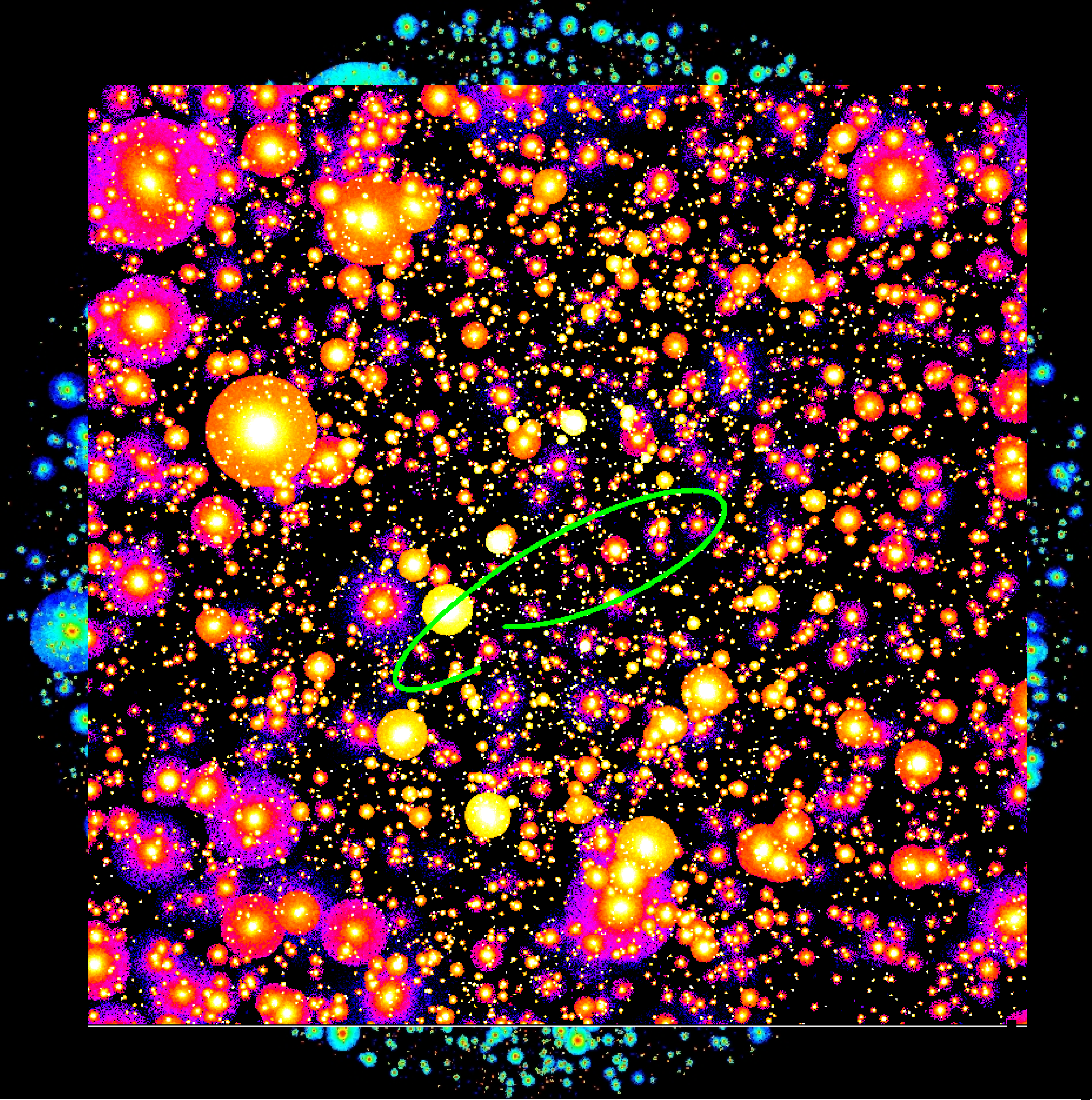
Heating of stellar streams (Maccio+10 in prep)

What is the effect of a large (undetected) population of dark satellites on thin stellar streams?

Satellite Distribution from Nbody

Miyamoto-Nagai disk
+
NFW DM halo

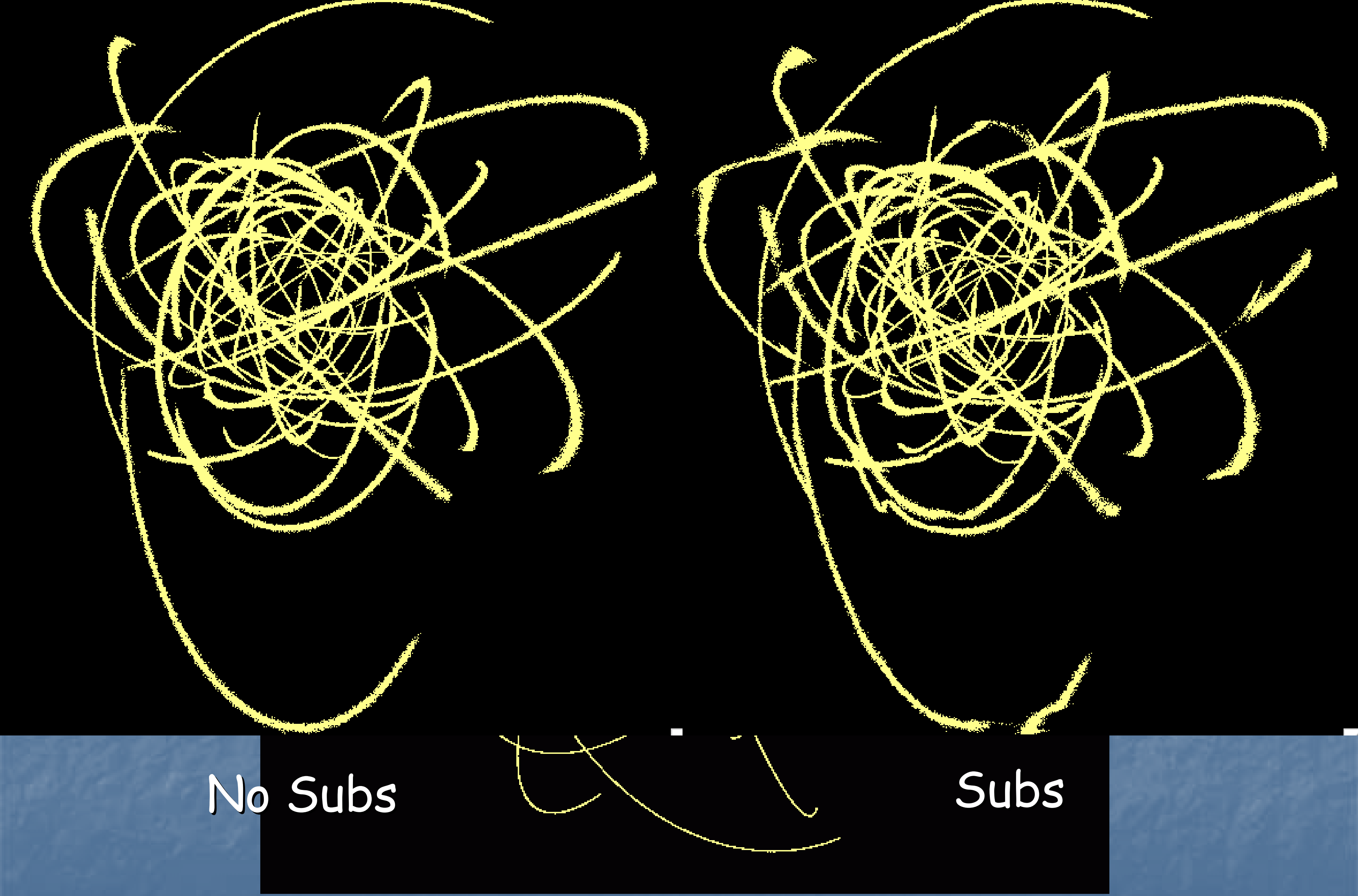




36.000
DM satellites
(within 300 kpc)

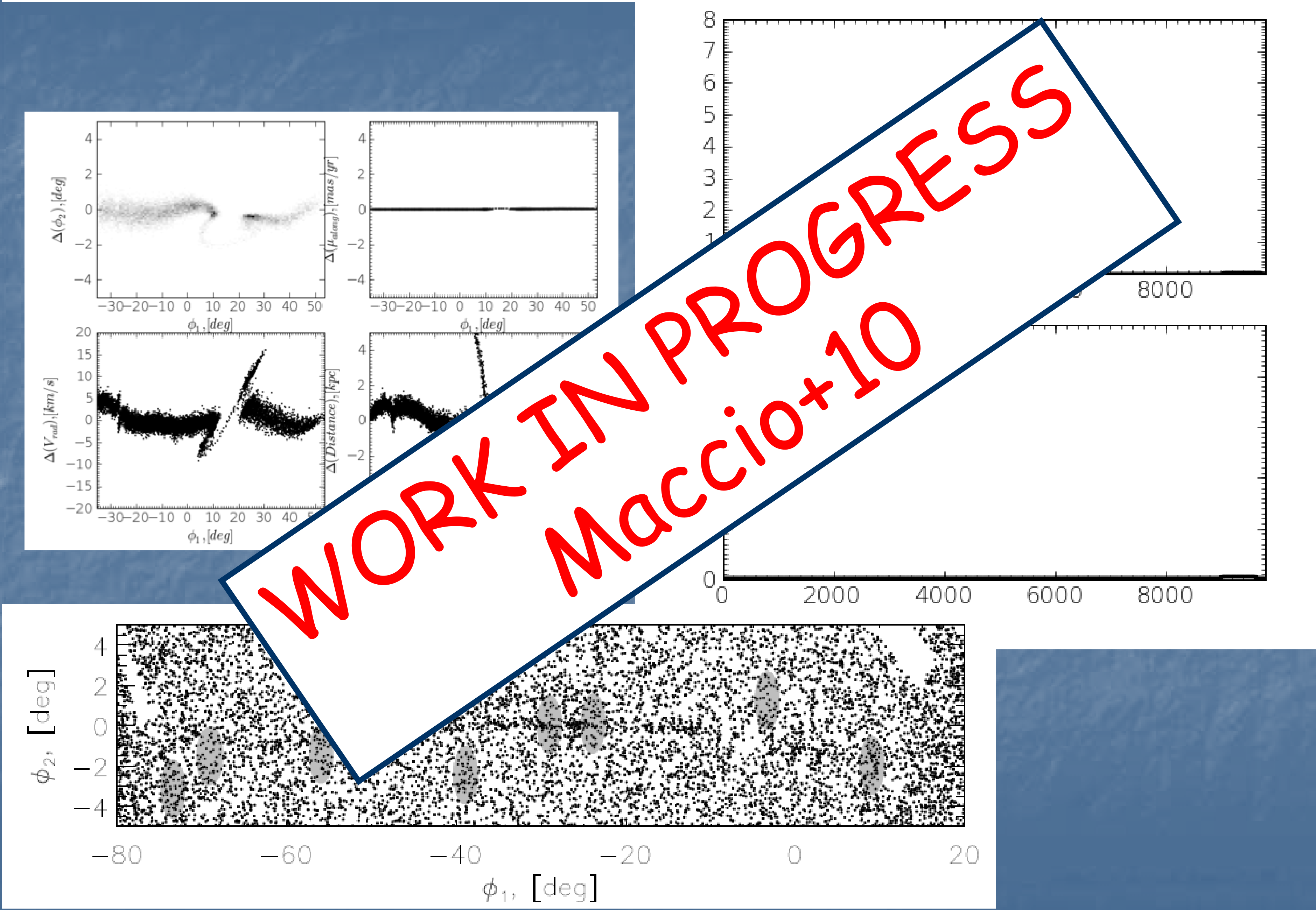
25 Millions part

Via Lactea II



Streams are in equilibrium with the NFW+Disk potential

DM satellites and stellar streams

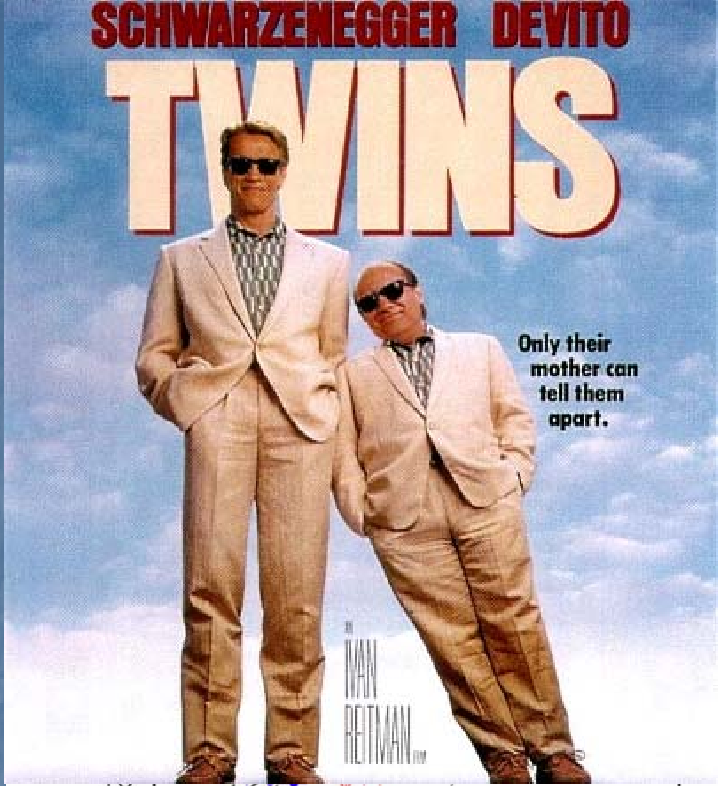


Even more work in progress:

N. Martin (MPIA)

Milky Way and Andromeda: which kind of twins?

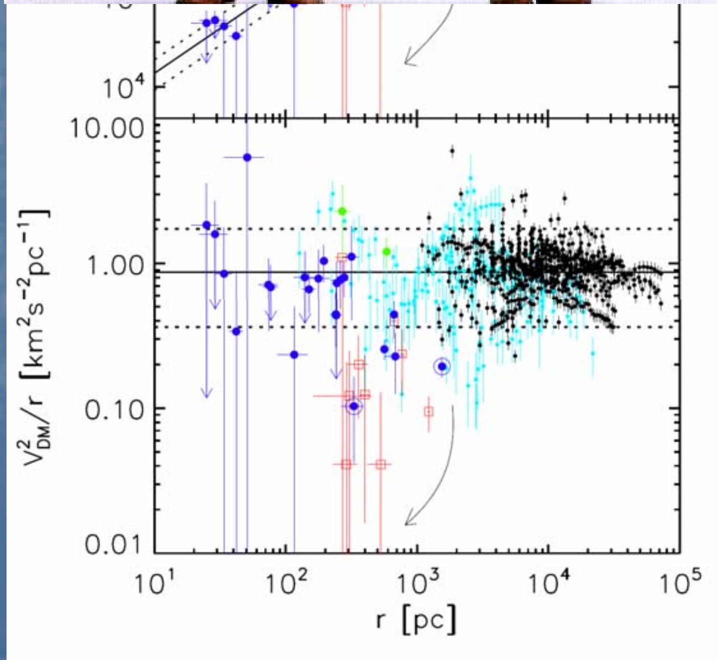
9 DM haloes + SAMs



$$M = 5\times10^{11}$$
$$M = 1\times10^{12}$$
$$M = 5\times10^{12}$$

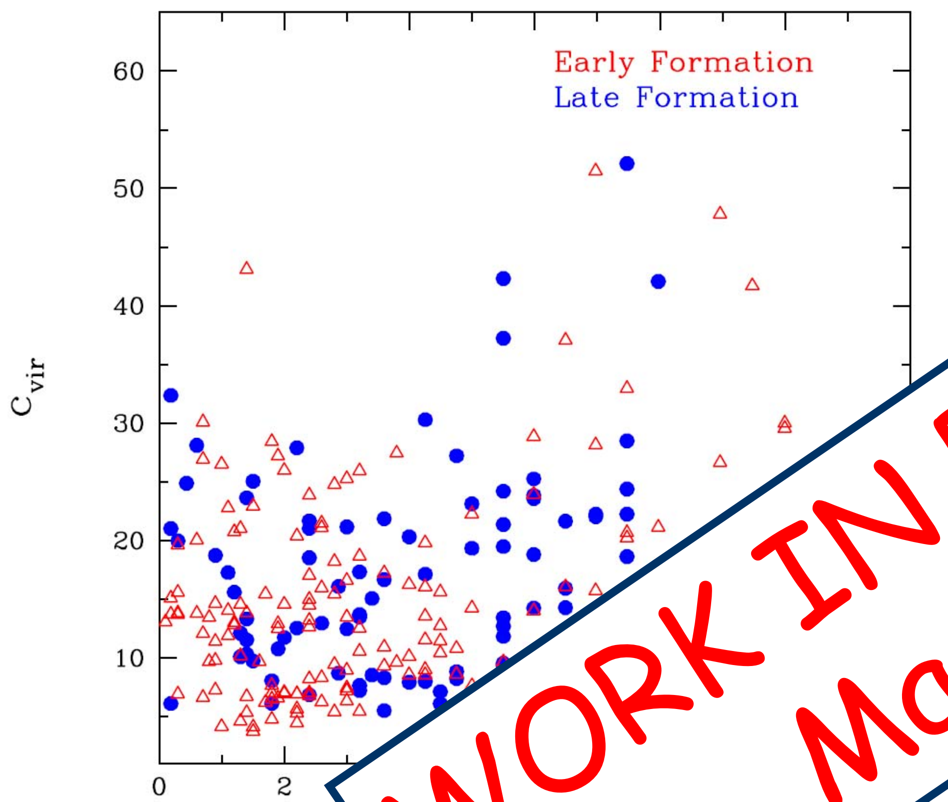
$\Leftrightarrow$

$$c = c(M_h)$$
$$c = c(M_h) + 1.5\sigma_c$$
$$c = c(M_h) - 1.5\sigma_c$$



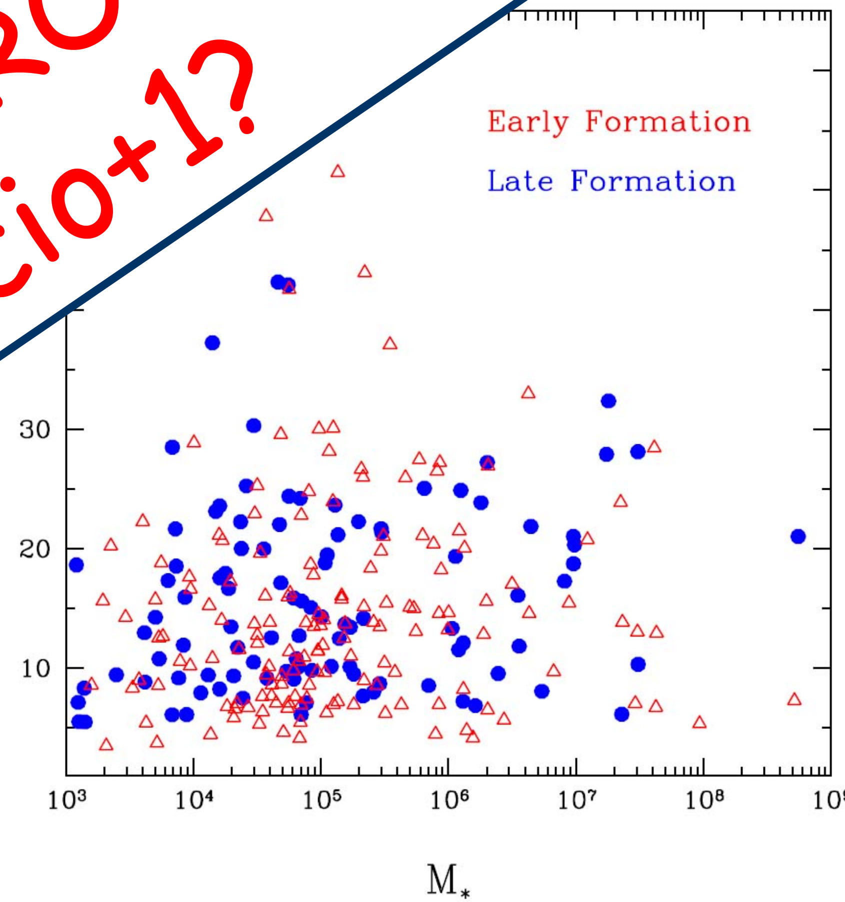
Do we see any systematic difference in satellites properties?

VERY PRELIMINARY



SAME HALO M…
DIFFERENT… TION TIME

WORK IN PROGRESS
Maccio+1?



No clear diffe… nces in the satellite concentration distribution

Conclusions

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(with reasonable baryonic physics)

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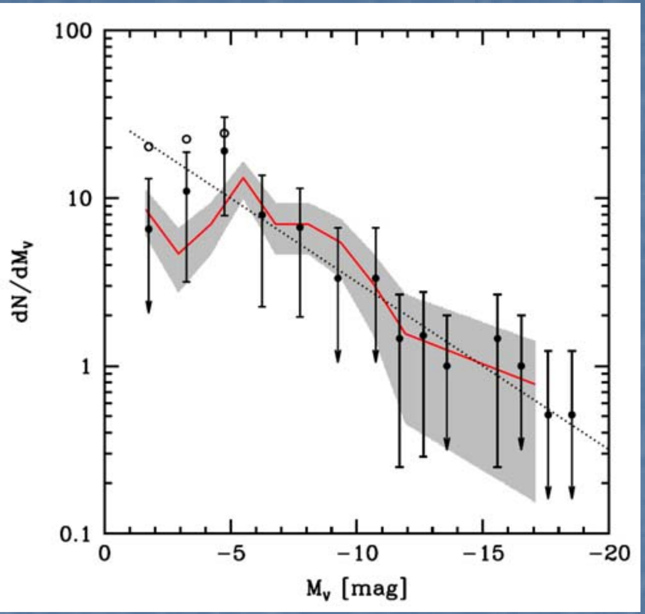
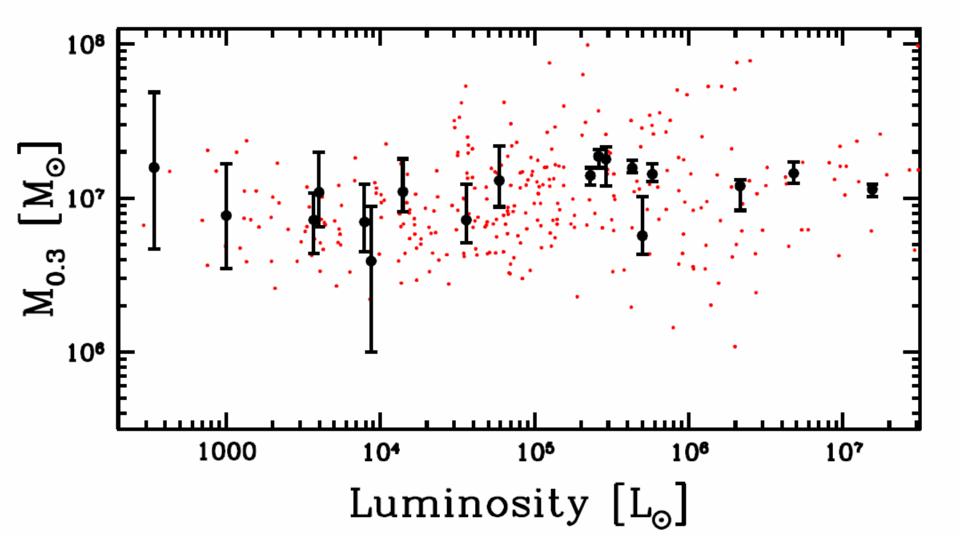
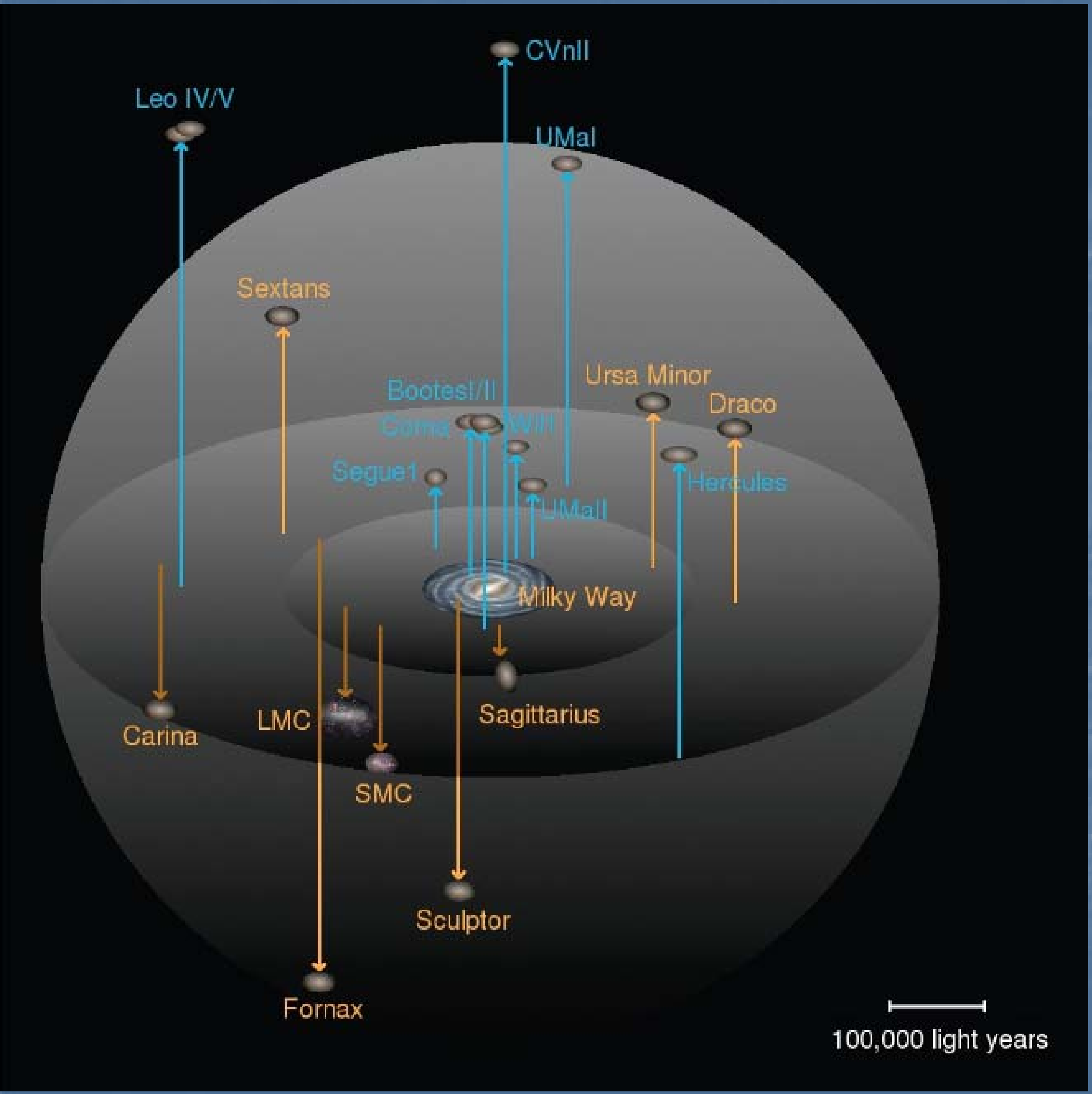
- Central Mass
- NO constraints for cold/warm





Detection of pure DM satellites through thin stellar streams


"That's all Folks"™
A WARNER BROS. CARTOON


CVnII
Leo IV/V
UMaI
Sextans
Ursa Minor
BootesI/II
Draco
Coma
WilI
Segue1
Hercules
UMaII
Milky Way
Carina
LMC
Sagittarius
SMC
Sculptor
Fornax
100,000 light years

The N-body: pure gravity

Cold Dark Matter: non relativistic, collisionless fluid of particles

$$\frac{\partial f}{\partial t} + \frac{\overline{p}}{ma^2}\nabla f - m\nabla\Phi\frac{\partial f}{\partial \overline{p}} = 0$$

Boltzmann collisionless equations
(Vlasov Equation)
in an expanding Universe

$$f = f(\overline{x}, \overline{p}, t)$$

Phase Space density

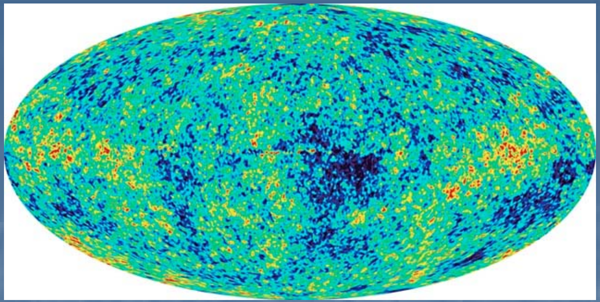
$$\rho(x,t) = \int f(x,p,t)d^3p$$

$$\nabla^2\Phi(x,t) = 4\pi G a^2[\rho(x,t) - \overline{\rho}(t)]$$

Matter density

We want to solve the equations of motions of N particles directly. The N particles are a Monte-Carlo realization of the true initial conditions.

Initial Conditions



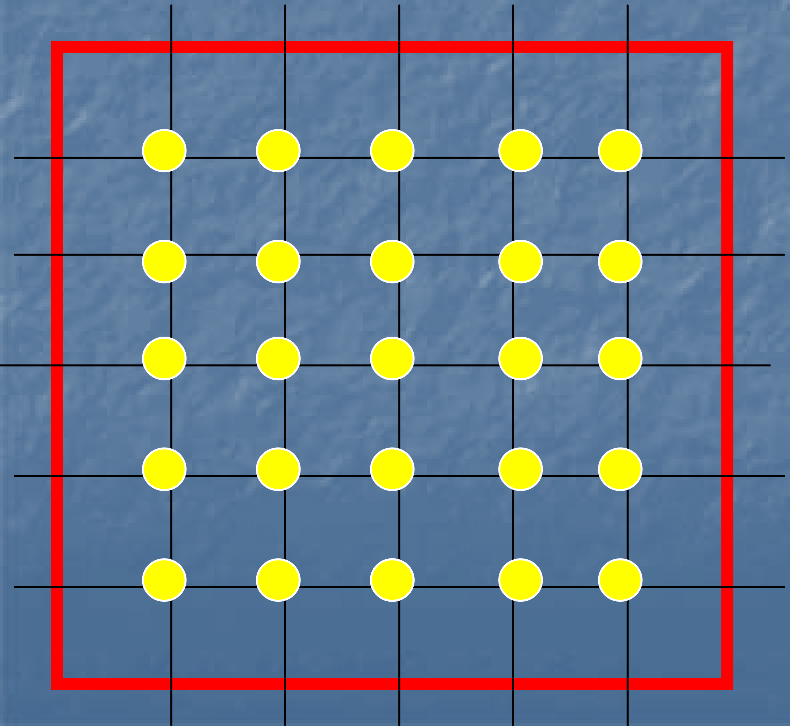
The Power Spectrum evolves according linear theory if δρ/ρ<0.2

$$P(k) = A\,k^n\,T^2(k,z)$$

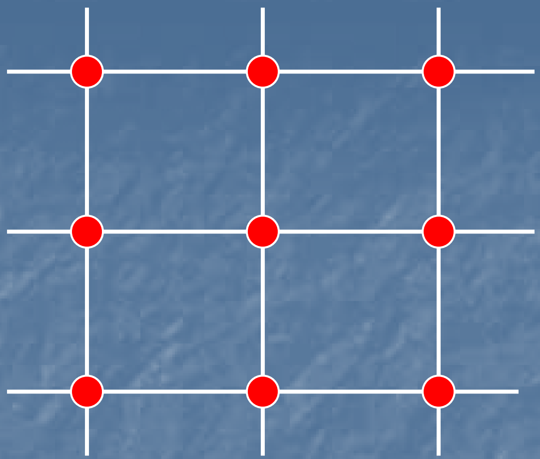
T(k,z) provided by linear theory

Then we should obtain a realization of this P(k) using particles:

Zel'dovich Approximation

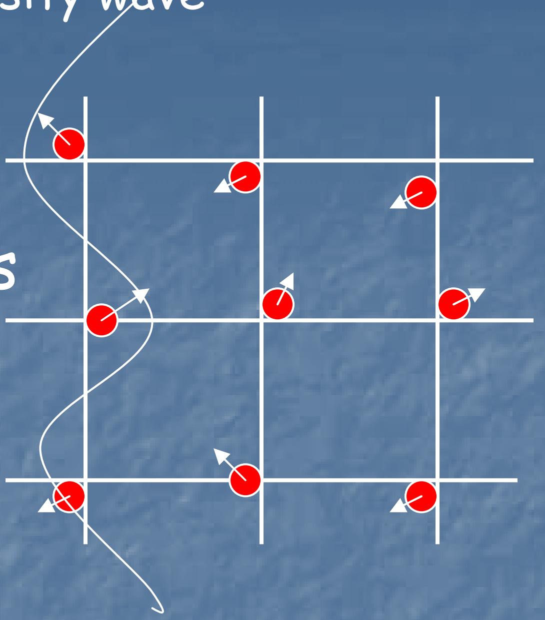


$$r(q,t) \propto P(k,t)$$



Zeldovich

Velocities and Positions
are linked together

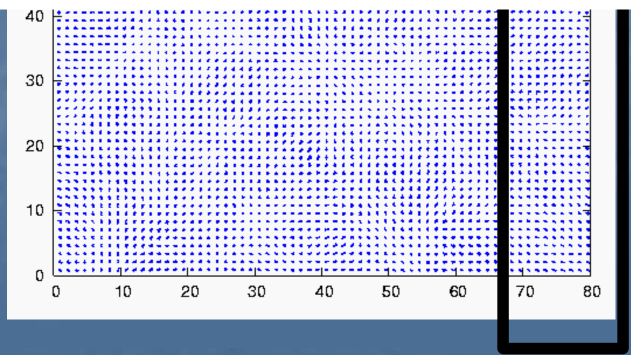


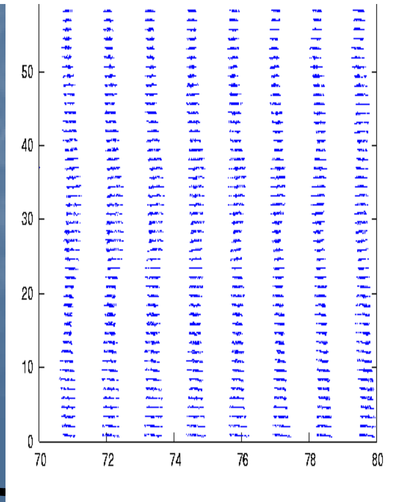
$$r(q,t) = a(t)\left[q + b(t)S(q)\right]$$

$$S(q) = \nabla \phi_0(q)$$

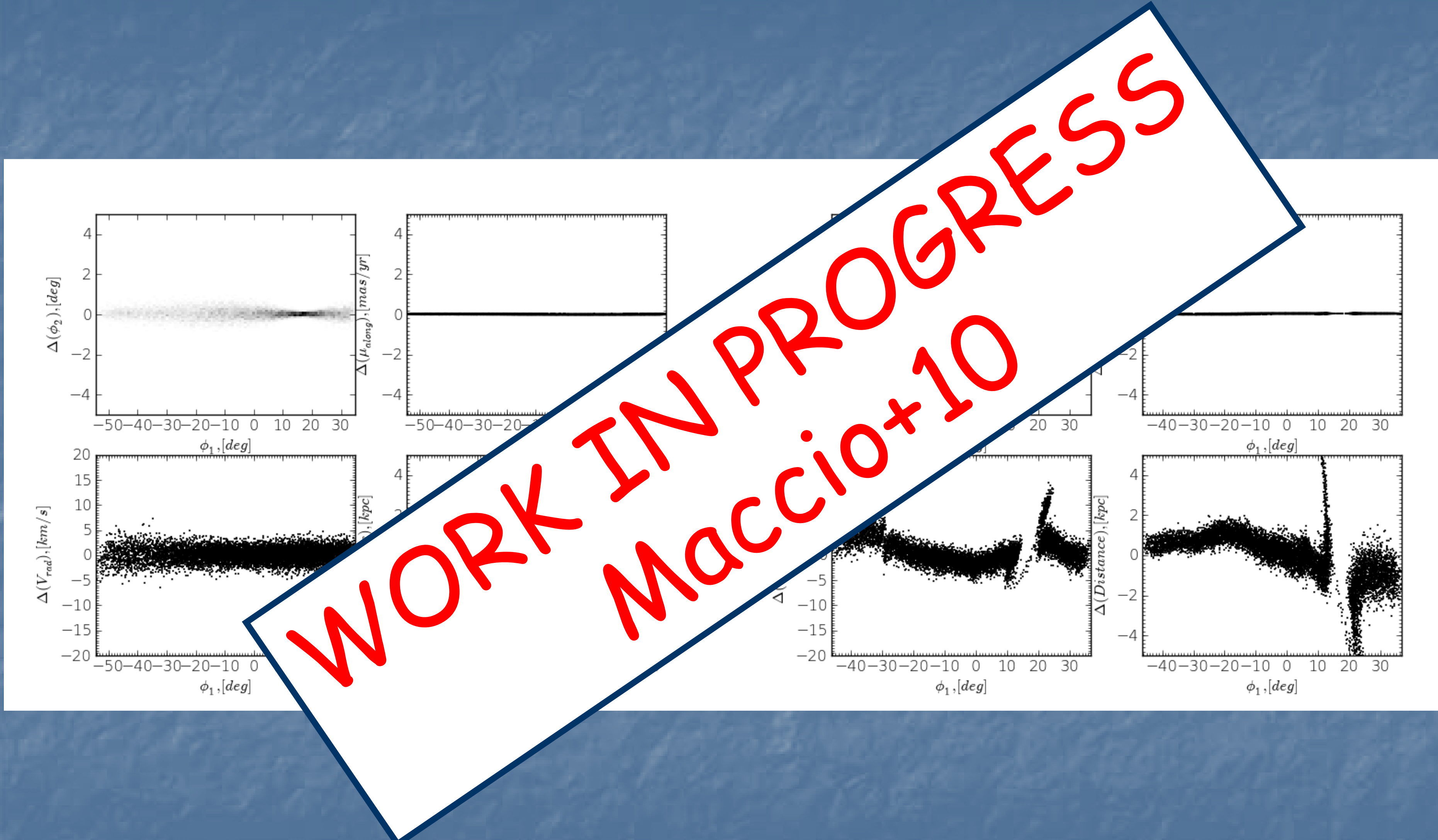
$$\phi_0(q) = \sum_k a_k \cos(kq) + b_k \sin(kq)$$

$$a_k, b_k = \sqrt{P(|k|)}\,\frac{Gauss(0,1)}{|k|^2}$$

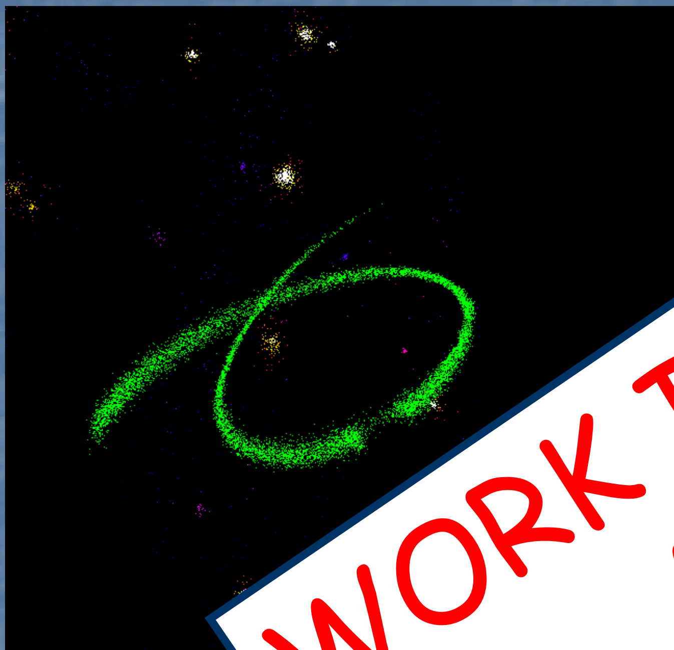


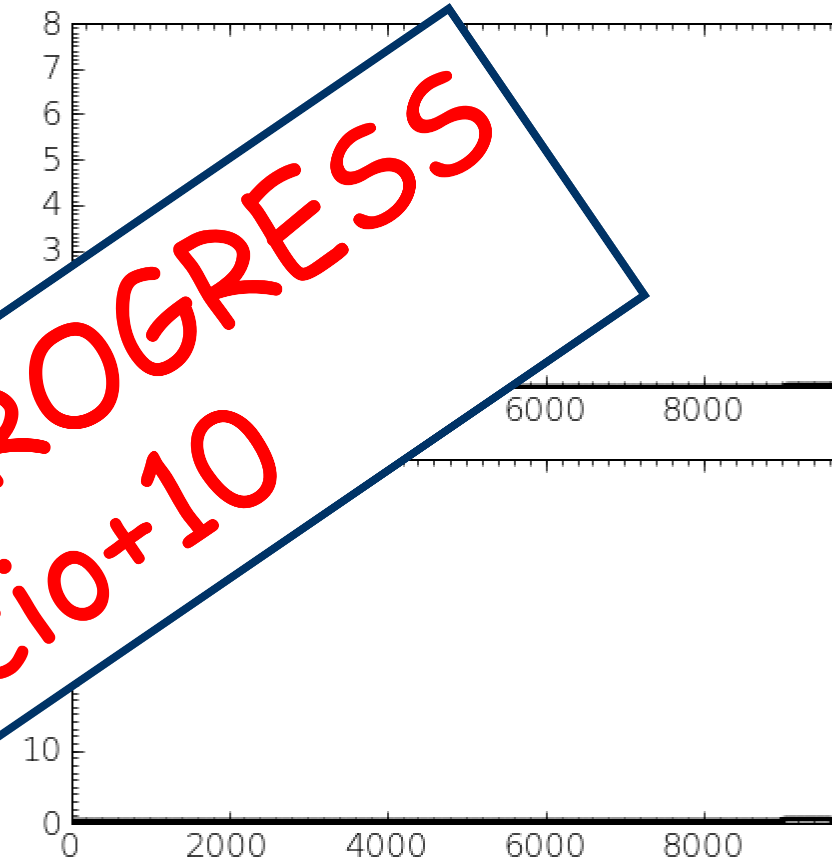


More stream perturbations



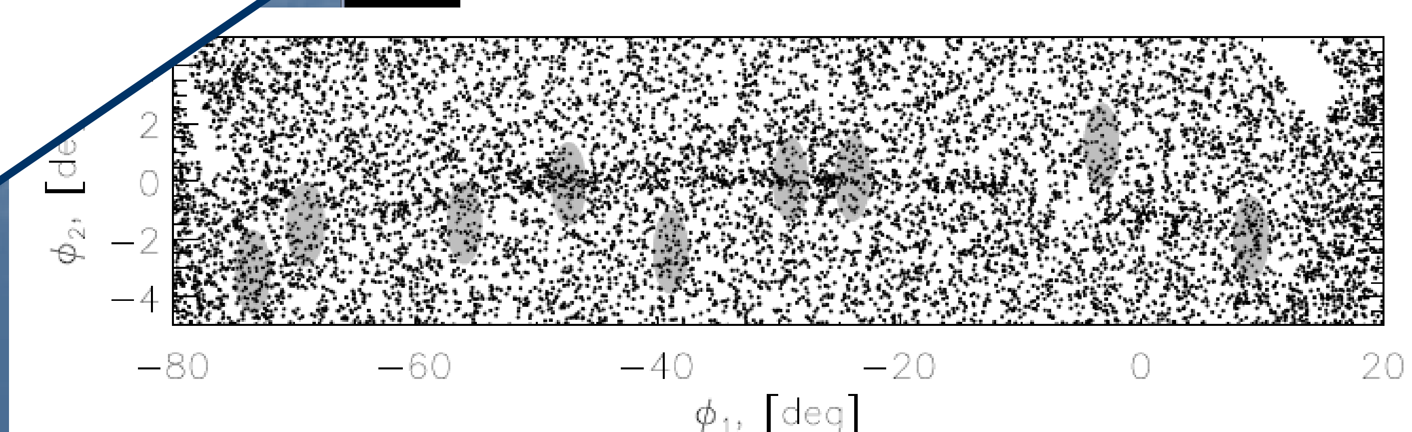
So far only tests at low resolution



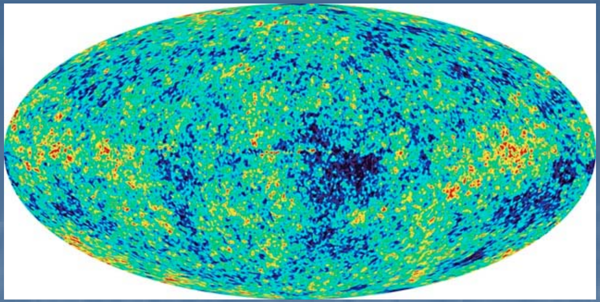


WORK IN PROGRESS
Maccio+10

Stream ev...
after 3 Gy...



Initial Conditions



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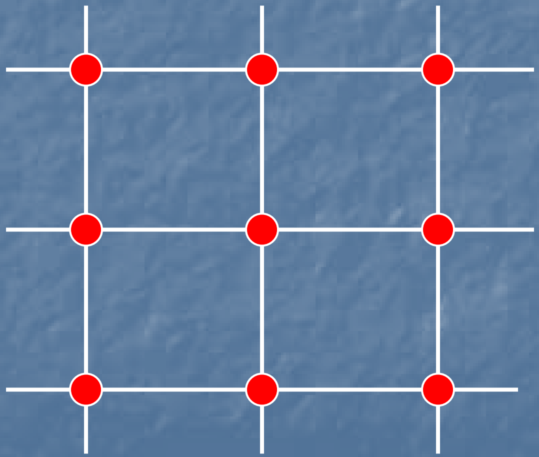

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$$S(q) = \nabla\phi_0(q)$$

$$\phi_0(q) = \sum_k a_k \cos(kq) + b_k \sin(kq)$$