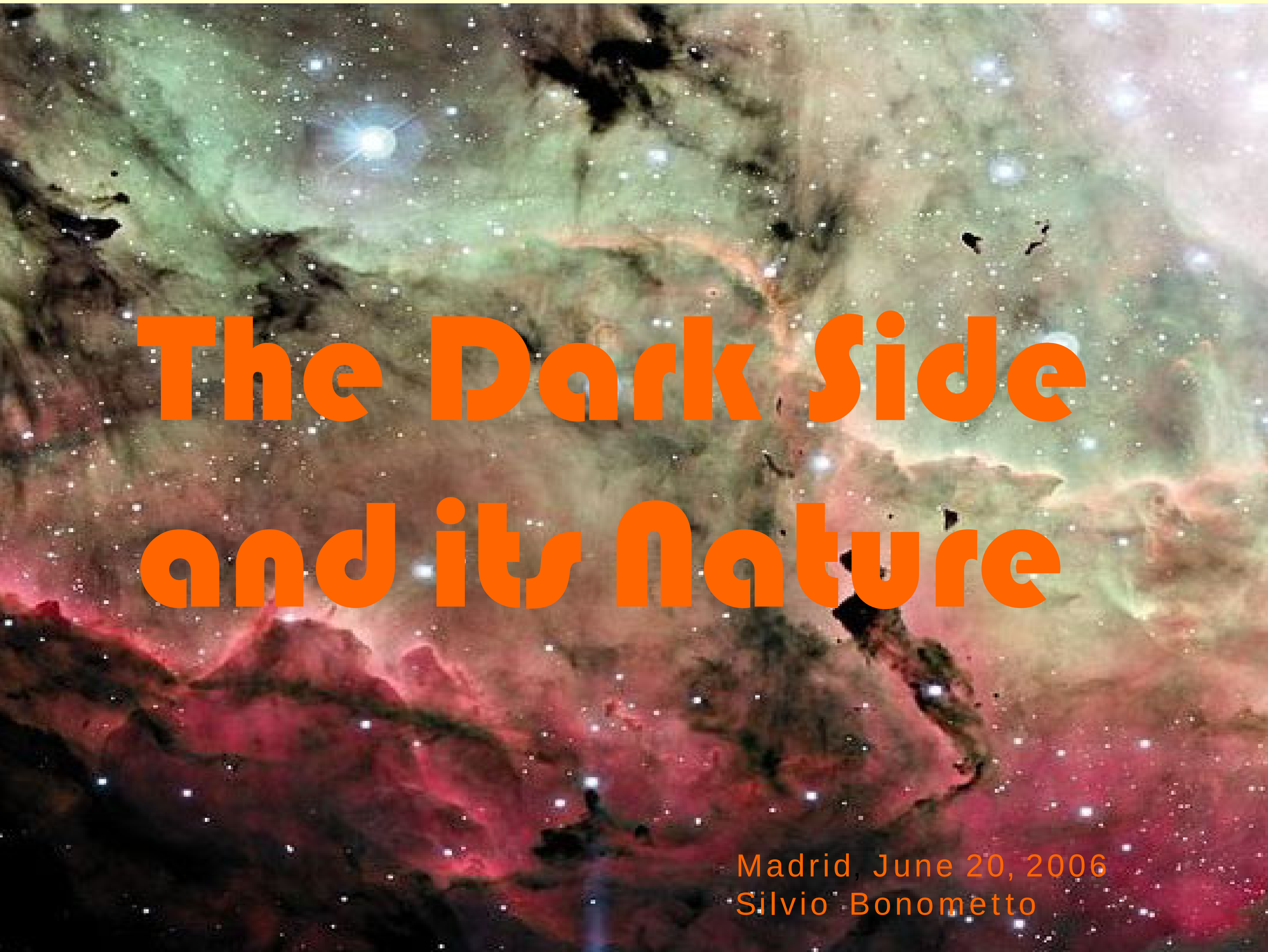


The Dark Side and its Nature

Madrid, June 20, 2006

Silvio Bonometto

The density quest in the 90's

$q_o \sim 0$

$\Omega_m = 0.2\text{-}0.3$ or $\Omega_m \sim 1$?

0CDM vs SCDM

$q_o \sim 0.5$

Supported by apparent slow evolution

Inflationary models can make it acceptable without fine tuning

Supported by CMB (COBE) data

Generic inflationary prediction

Riess et al, 1998, AJ116, Perlmutter et al, 1999, ApJ 517

SN Ia as standard candles gave an unexpected reply

$q_o \sim$ -- 0.6-0.7

$\Omega_m = 0.2\text{-}0.3$ & $\Omega_o \sim 1$

the gap is covered by Dark Energy

SNIa

cosmic expansion is accelerated

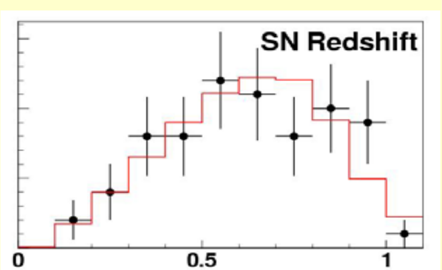
SNLS: *Astier et al (2005) A&A*

Only acceptable model with sound historical records

LCDM

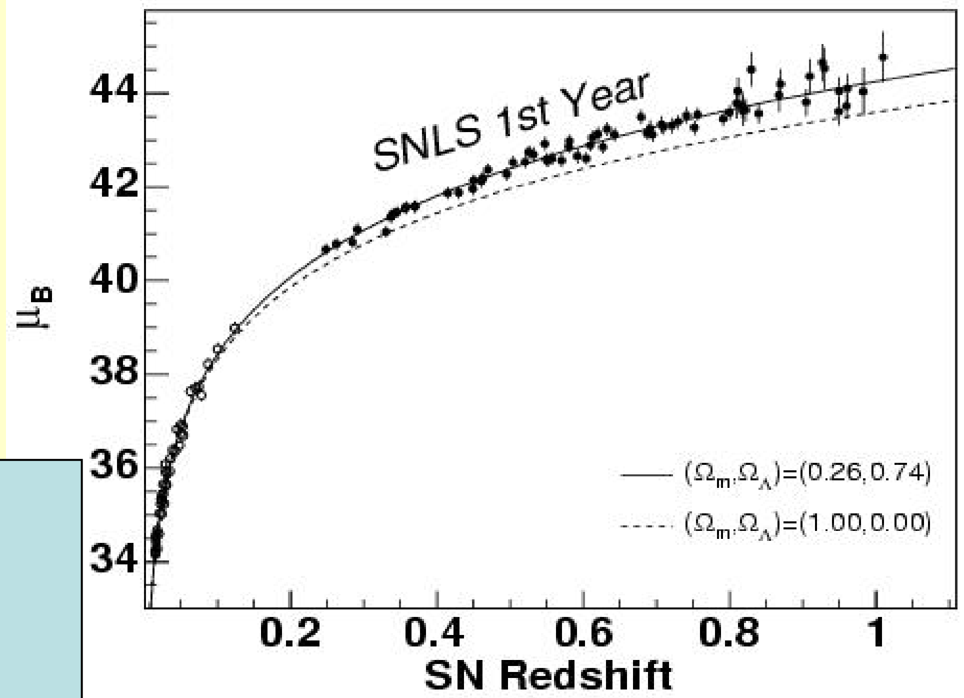
$$d_L H/c \cong z + z^2(1-q)/2 + \ldots$$

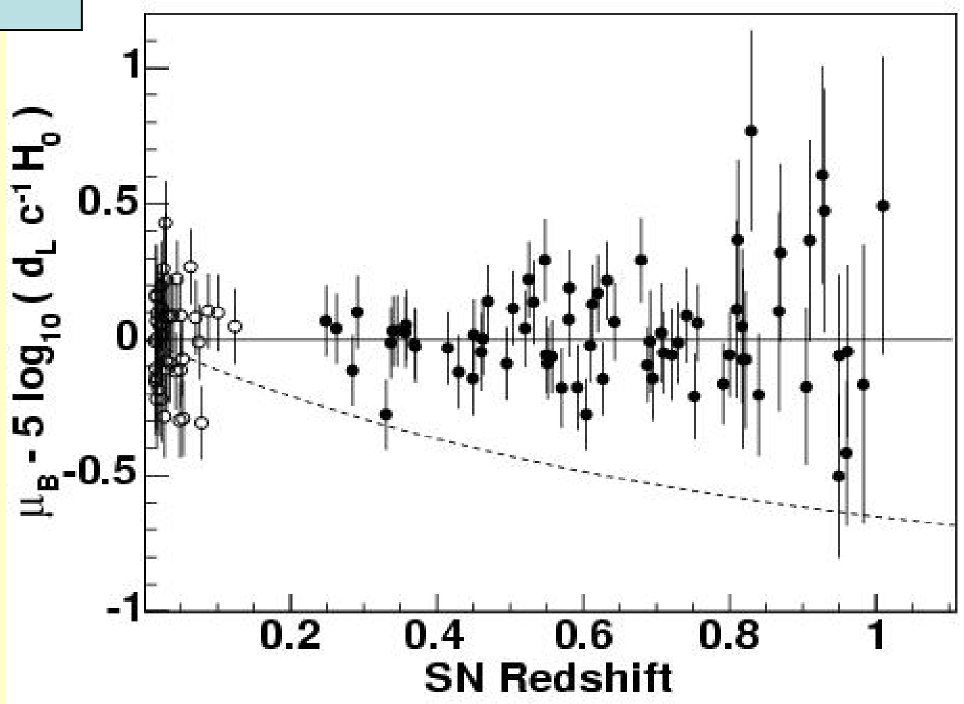
$$q = \Omega_m/2 - \Omega_\Lambda$$



$$\Omega_m = 0.26$$

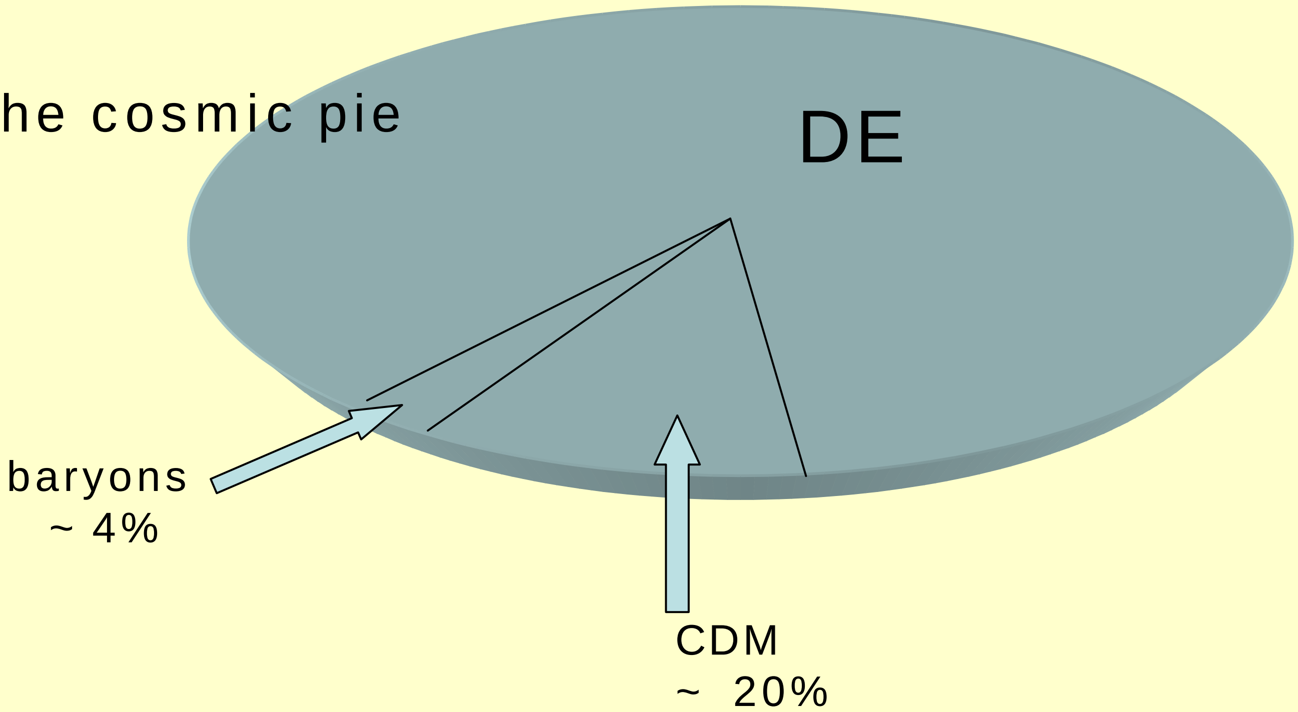
$$\Omega_{de} = 0.74$$





- DE, what is that ?
- Dont' worry, its' just cosmological constant

The cosmic pie

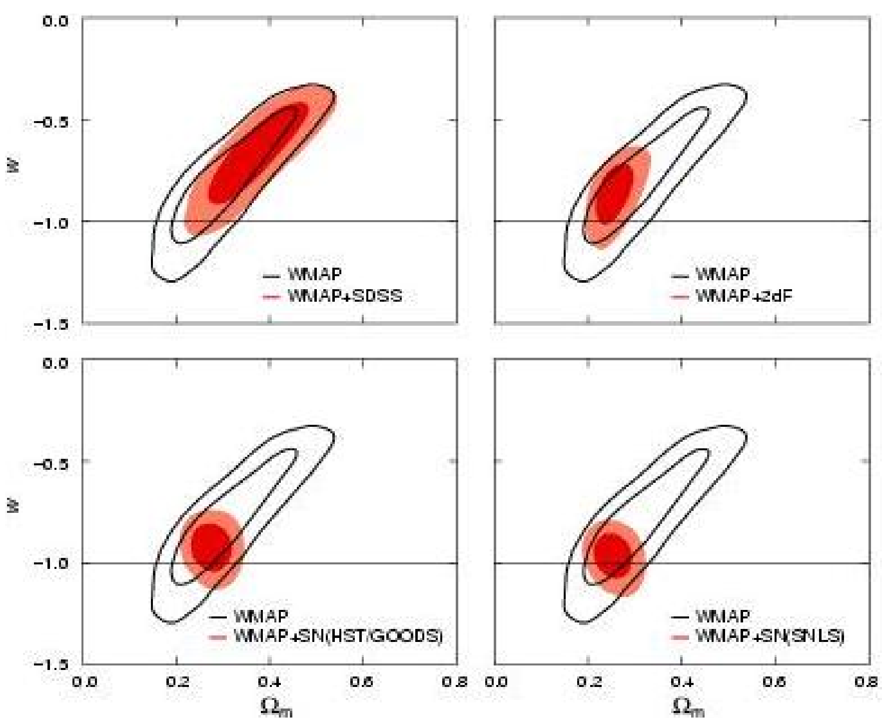


- Fire, fire !
- Dont' worry, its' just incendescent plasma

Table 5: ΛCDM Model: Joint Likelihoods

Parameter	*WMAP Only*	*WMAP +CBI+VSA*	*WMAP+ACBAR +BOOMERanG*	*WMAP+ 2dFGRS*
$\Omega_b h^2 (\times 10^2)$	$2.233^{+0.072}_{-0.091}$	$2.212^{+0.066}_{-0.084}$	$2.231^{+0.070}_{-0.088}$	$2.223^{+0.066}_{-0.083}$
$\Omega_m h^2$	$0.1268^{+0.0072}_{-0.0095}$	$0.1233^{+0.0070}_{-0.0086}$	$0.1259^{+0.0077}_{-0.0095}$	$0.1262^{+0.0045}_{-0.0062}$
h	$0.734^{+0.028}_{-0.038}$	$0.743^{+0.027}_{-0.037}$	$0.739^{+0.028}_{-0.038}$	$0.732^{+0.018}_{-0.025}$

WMAP2+ parameter values



WMAP2+ contours on the w-Ω_m plane

The most immediate candidate: VACUUM ENERGY
however .....

as $\rho_o \approx (10\,T_o)^4$ and $\rho_{vac,EW} \approx T_{EW}^{\;4}$

CMB temp.

$10\ T_o : T_{EW} \sim 1 : 10^{14}$

$\rho_\Lambda : \rho_{EW} \sim 1 : 10^{56}$

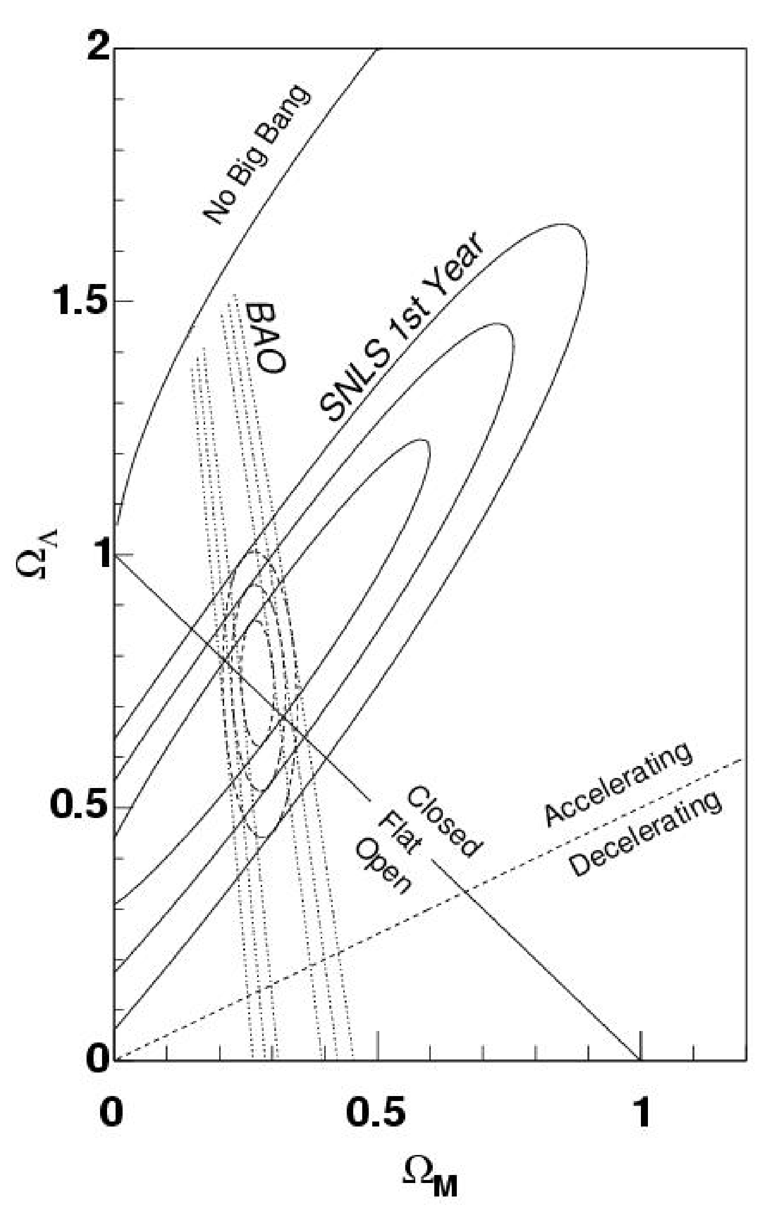
horrible fine tuning

But, recall that $T_{EW} : T_{GUT} \sim 1 : 10^{14}$

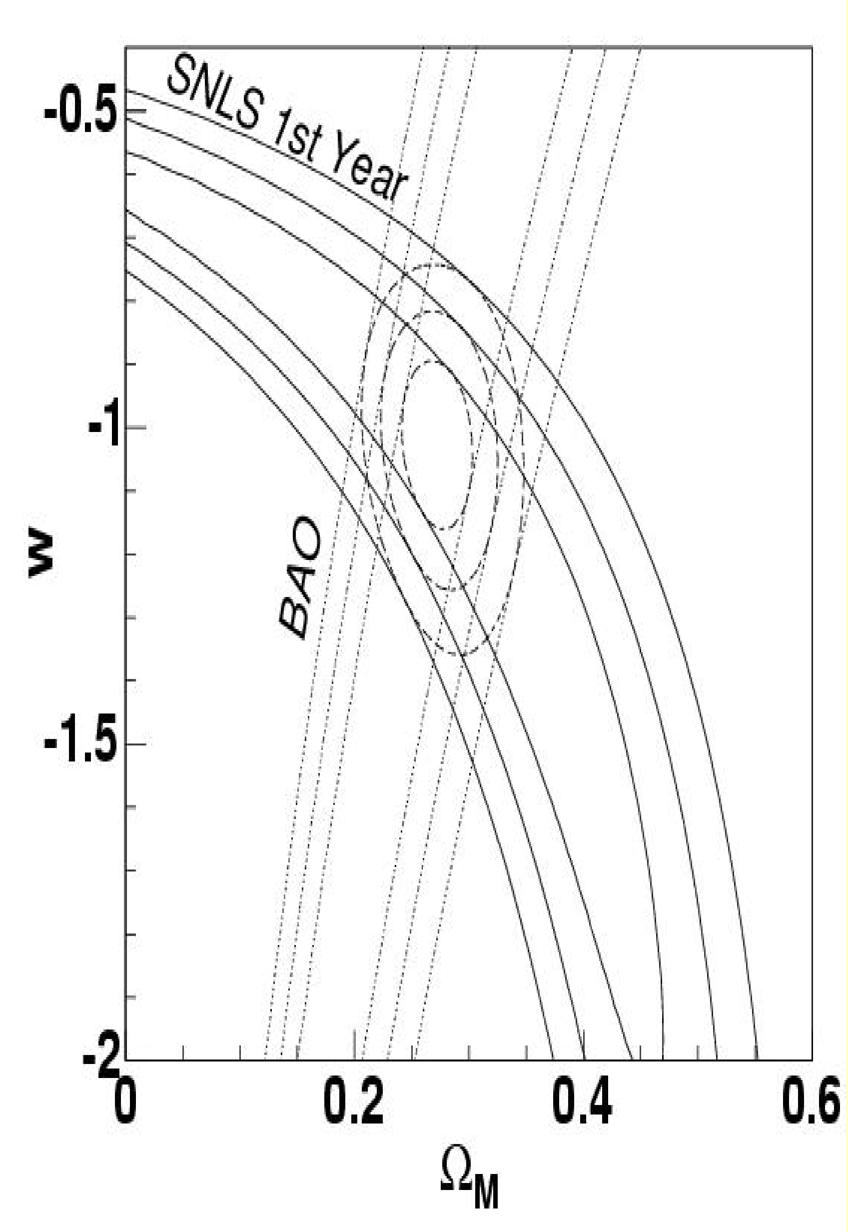
A recent and still unfinished phase transition ?
perhaps concerning the neutrino sector ....

Frieman et al, 1995 P.R.L. 75
Weiss, 1987 P.L. B 42
Amendola & Barbieri CERN-PH-TH/2005-163

Matter-DE constrnts



pressure/density ratio



Otherwise
DE is a scalar field

$$\rho = \dot{\phi}^2 / 2 + V(\phi)$$

$$p = \dot{\phi}^2 / 2 - V(\phi)$$

$$w = p / \rho \sim -1$$

dDE: Wetterich,1988, N.P.B302
Ratra&Peebles, 1988, P.R.D37

if $V(\phi) >> \dot{\phi}^2$, potential energy >> kinetic energy

This depends on the choice of V(ϕ)
& of "initial conditions" on ϕ' and ϕ''

Tracking potentials preferred, so getting rid of I.C. dependence

dDE apparently eliminates fine-tuning

$$V(\phi) = \Lambda^{\alpha+4} / \phi^{\alpha}$$ RP potential

Scale Λ
in the energy range of EW transition
or SUSY break

$$V(\phi) = (\Lambda^{\alpha+4} / \phi^{\alpha}) \exp[4\pi(\phi / m_P)^2]$$ SUGRA potent.

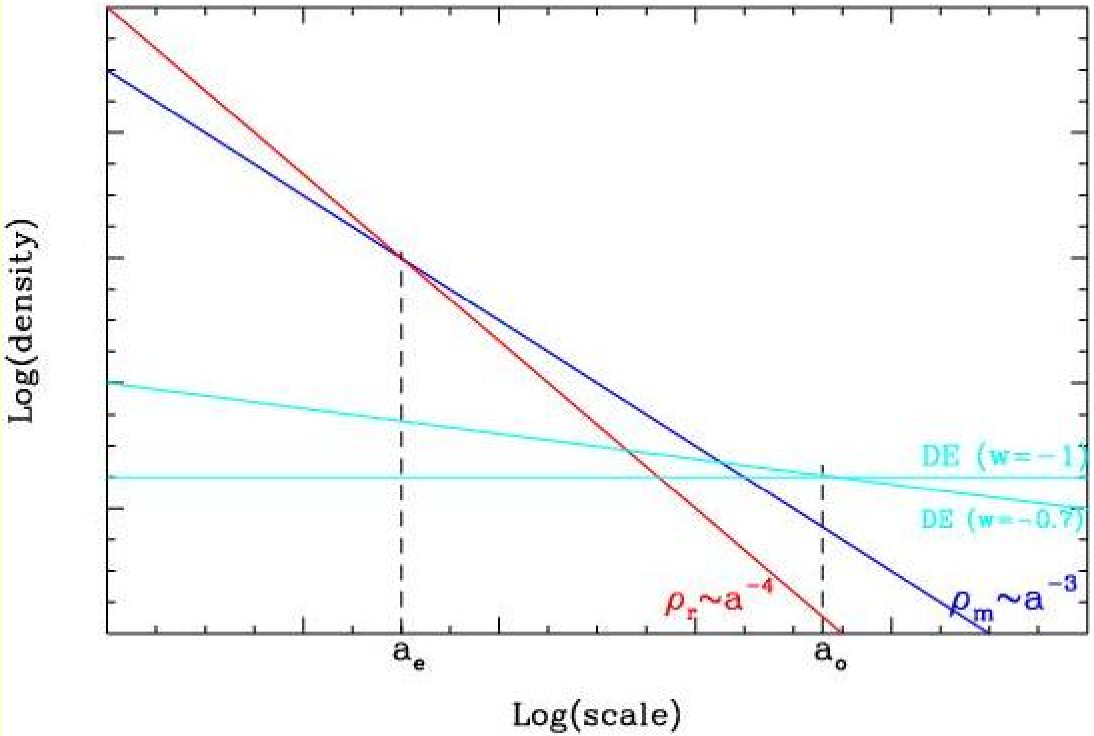
fine tuning hidden in
why we use "field" representation
instead of N (number of particles) representation
N is diagonal → w positive

Brax&Martin, 1999, P.L.B468
and 2001, P.R.D62
+Riazuelo, 2000, P.R.D61

Dynamical Dark Energy may ease the fine tuning problem, but it does not eliminate

The coincidence problem

DE emerges, as significant cosmic component, just at the eve of our epoch



A possible way out: DE & DM coupled

Say it otherwise:
The Dark Substance has a complex eq of state: partially it clusters (DM) partially it doesn't (DE)...

... and we try to appoach phaenomenologically such substance using DM-DE coupl.

$$ds^2 = a^2(\tau)(-d\tau^2 + dx_i dx^i)\ , \qquad (i = 1, .., 3)$$

conformal time

Coupling intensity set by β value

$$\ddot{\phi} + 2\frac{\dot{a}}{a}\dot{\phi} + a^2\frac{\partial V}{\partial \phi} = \frac{4}{m_p^2}\sqrt{\frac{\pi}{3}}\beta a^2 \rho_c$$

$$\dot{\rho}_c + 3(\dot{a}/a)\rho_c = -\frac{4}{m_p^2}\sqrt{\frac{\pi}{3}}\beta \rho_c \dot{\phi}$$

Energy flow from DM to DE

Wetterich, 1995, A&A 301; Amendola, 1999, P.R.D60; Bartolo & Pietroni, 2000, P.R.D61; Bean & Magueijo, 2001, P.L.B 517; Gasperini, Piazza & Veneziano, 2002,, P.R.D65; Comelli, Pietroni & Riotto, 2003, P.L.B571; etc.

$$\theta_{c,b} = i\frac{\mathbf{k}\cdot\mathbf{v_{c,b}}}{\mathcal{H}}\ , \qquad \mathcal{H} = \dot{a}/a\ , \qquad \mathbf{k}:\ wavenumber$$

$'$: differentiation with respect to $\alpha = \ln a$, $\quad X = \sqrt{4\pi/3}\,\dot{\phi}/(m_p\mathcal{H})$

$$\delta_c{}'' = -\delta_c{}'(1 + \frac{\mathcal{H}'}{\mathcal{H}} - 2\beta X) + \frac{3}{2}(1 + \frac{4}{3}\beta^2)\Omega_c\delta_c + \frac{3}{2}\Omega_b\delta_b$$

$$\delta_b{}'' = -\delta_b{}'(1 + \frac{\mathcal{H}'}{\mathcal{H}}) + \frac{3}{2}(\Omega_c\delta_c + \Omega_b\delta_b)$$

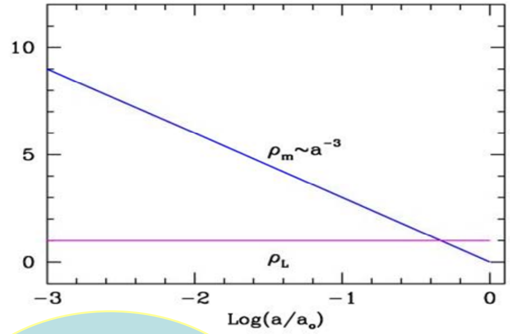
$$\theta_c{}' = -\theta_c(1 + \frac{\mathcal{H}'}{\mathcal{H}} - 2\beta X) - \frac{3}{2}(1 + \frac{4}{3}\beta^2)\Omega_c\delta_c - \frac{3}{2}\Omega_b\delta_b,$$

$$\theta_b{}' = -\theta_b(1 + \frac{\mathcal{H}'}{\mathcal{H}}) - \frac{3}{2}(\Omega_c\delta_c + \Omega_b\delta_b)\ .$$

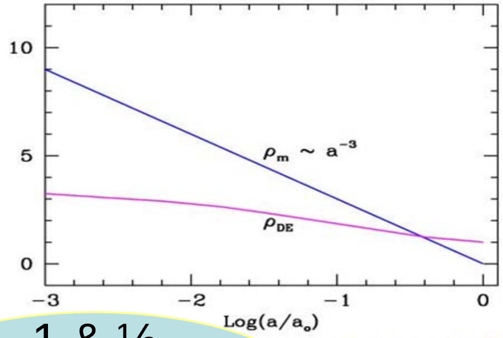
eqs. for fluctuation evolution

+ usual ones for baryon & radiative components

From LCDM to dDE & cDE

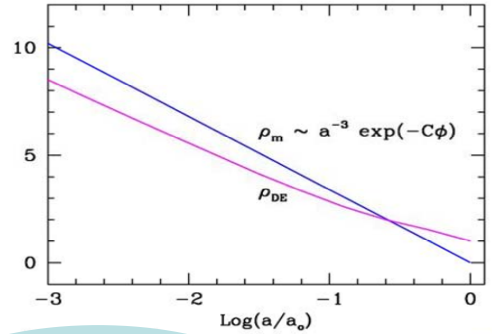


2 problems: fine tuning, coincidence



cost: Λ par. in DE pot.

1 & ½ problems: fine tuning eased; coincidence remains



cost: Λ par. in DE pot. + coupling par. C

fine tuning & coincidence: both eased

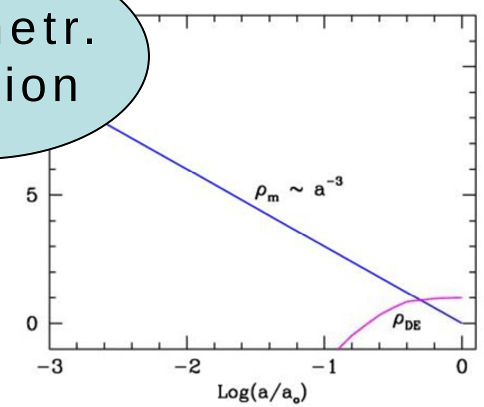
An alternative view (Kolb,Riotto,Matarrese,…2005 see also Buckert 1980, Ellis 1990 …)

$g_{\mu\nu}=\eta_{\mu\nu}+h_{\mu\nu}$

standard $\eta_{\mu\nu}$ defined by $a(\tau)$ & κ coming from ass. state eqs. ($p=w\rho$); $h_{\mu\nu}$ initially linear, then developing non-linearities

new $h_{\mu\nu}$ initially linear when extreme non-linearities developped backg.state eqn modified

Geometr. solution



ρ_{DE} growth together with heavy non-linearities

Coupling compatible with data ?

Seeking limits on β

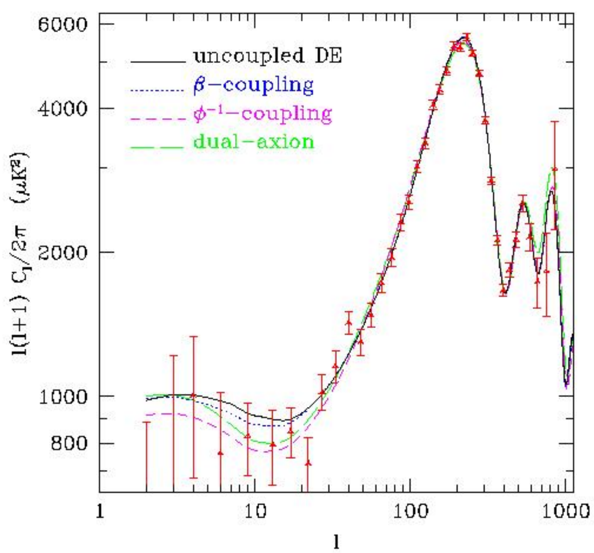
e.g., baryons could not be coupled to DE, this would cause unacceptable changes in their effective gravity

CMB data

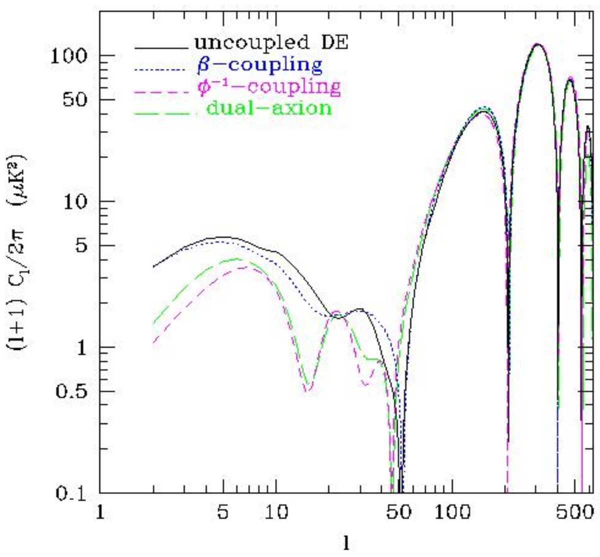
	χ^2	probability	
ΛCDM	1.066	4.7 %	
dDE	1.064	5.0 %	(SUGRA)
β-coupling	1.066	4.7 %	(SUGRA)
ϕ^{-1}-coupl.	1.074	2.9 %	(SUGRA)

from Colombo, Mainini & B., 2005, ApJ632 WMAP1 data

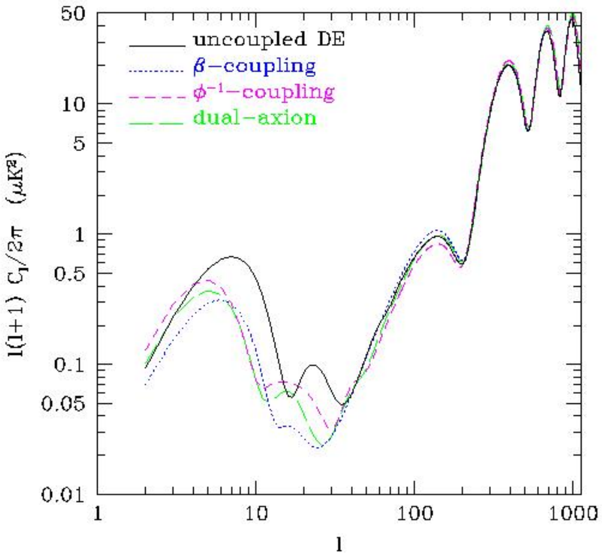
anisotropy spectrum



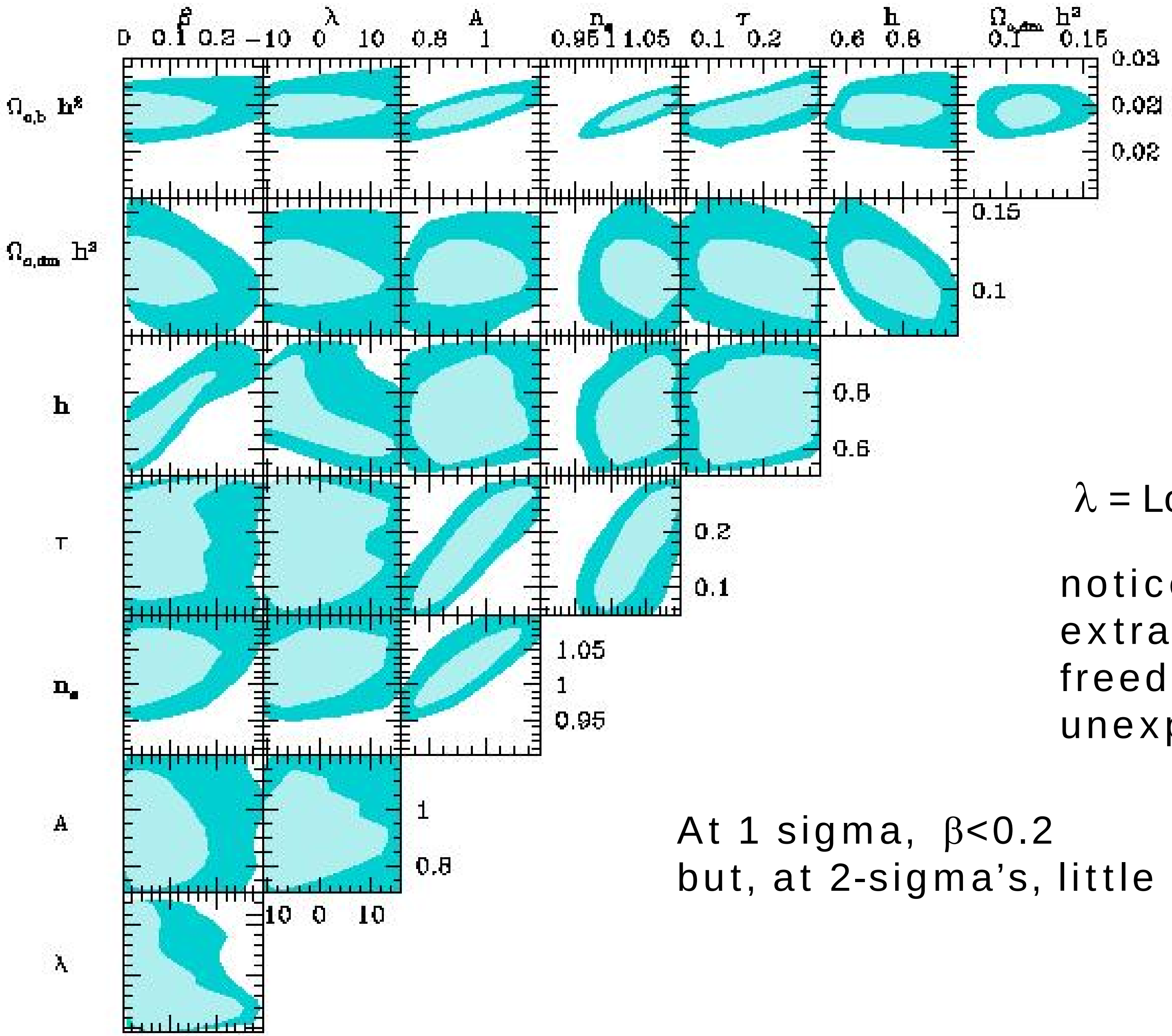
T-E correlation spectrum



E-mode spectrum



Cosmological parameters for cDE with β-coupling



β < ~0.2

λ = Log(Λ/GeV)

notice that this extra degree of freedom is almost unexploited

At 1 sigma, β<0.2
but, at 2-sigma's, little restrictions

Structure formation
PS formalism

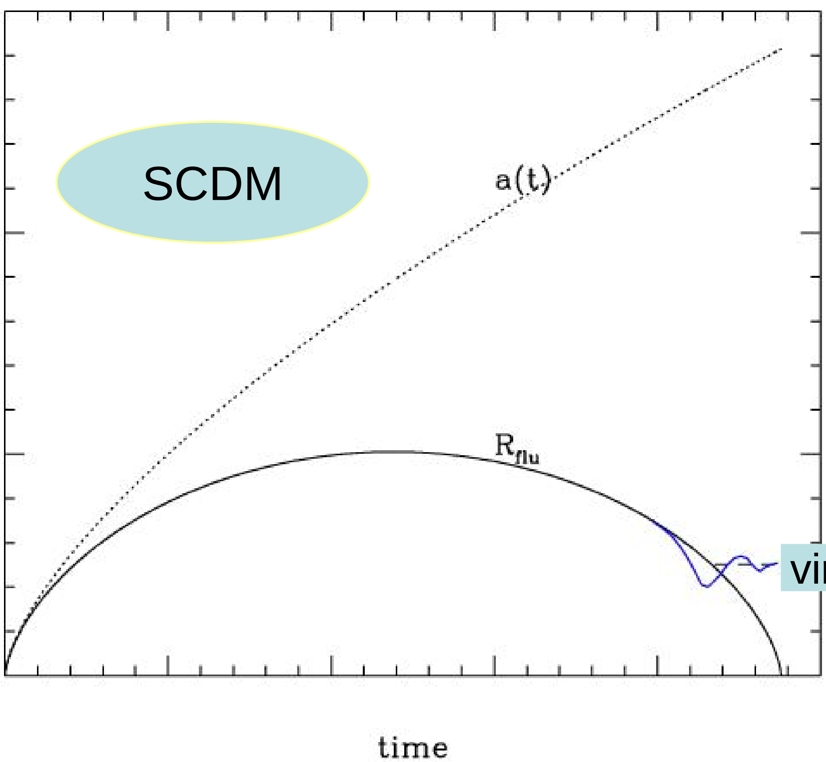
Press& Schechter 1974, ApJ 187
Improved by
Sheth&Tormen 1999, MNRAS; Jenkins et al., 2001, MNRAS 321

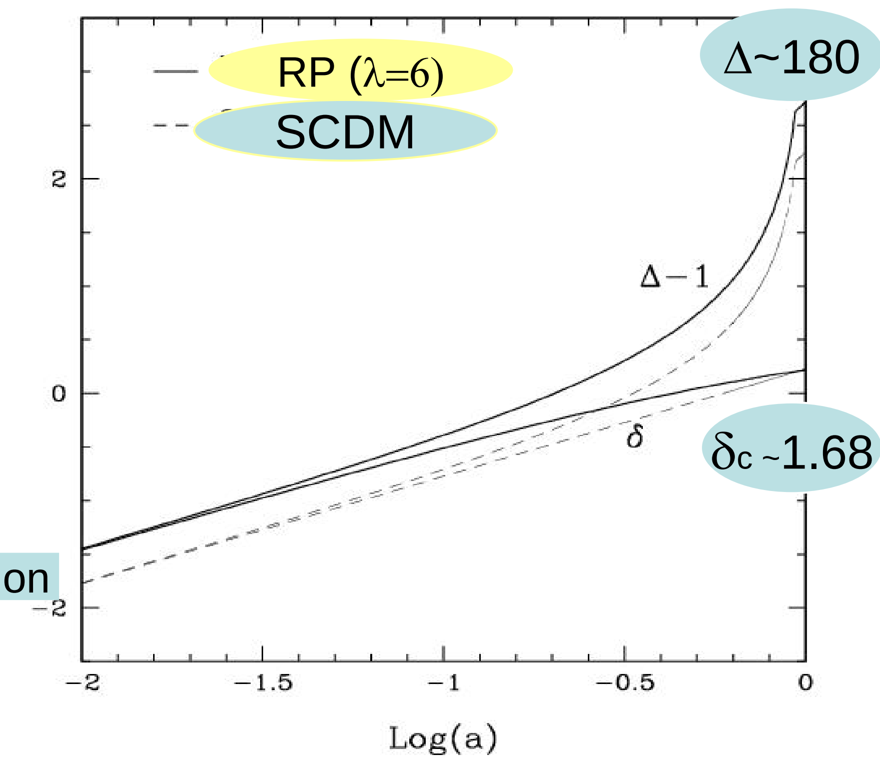
allows to find which linear δ_c would have fluctuations virializing today

Starting point: spherical top-hat fluctuation growth

Fluct. radius (R_{flu}) expands and recontracts while the scale factor a(t) drives cosmic exp.

non-linear density contrast growing more fastly than linear fluctuation





The PS expression

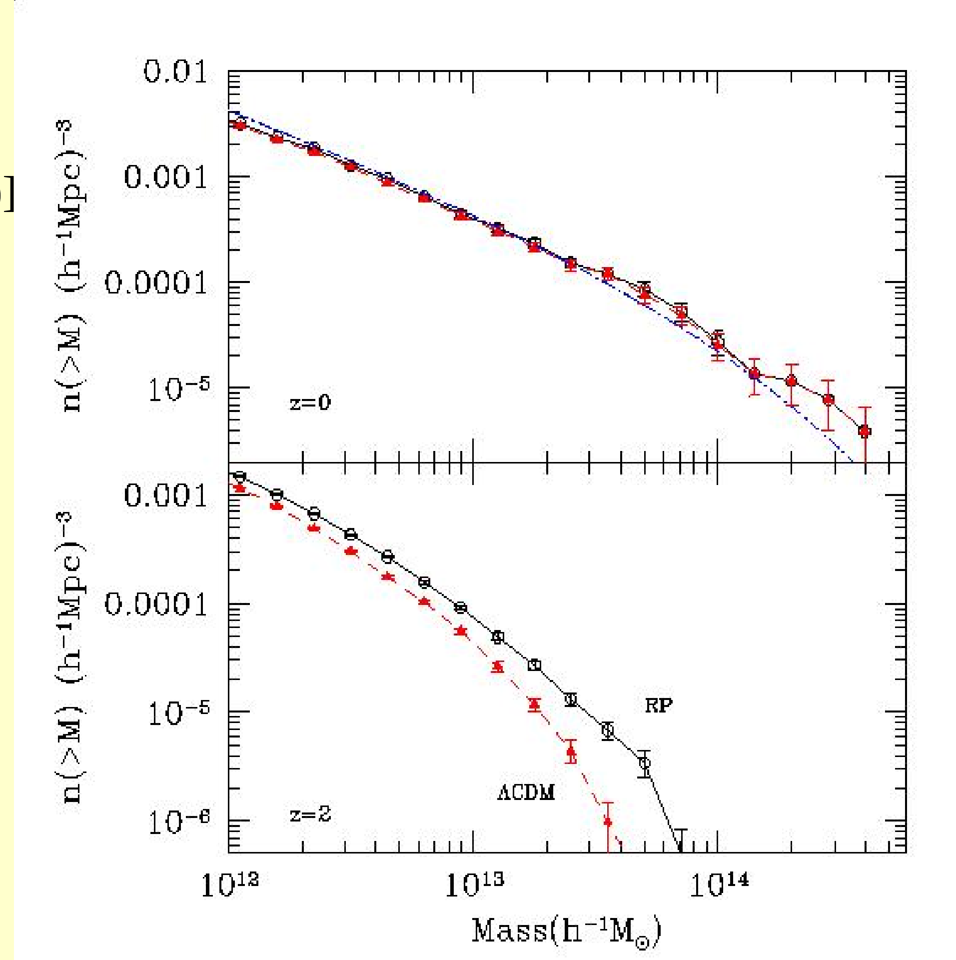
$$n(M)MdM \cong \rho_m[P(>\delta_c, M) - P(>\delta_c, M+dM)]$$

$$P(\delta) = (2\pi)^{-1/2} \int_{\delta_c/\sigma_M}^{\infty} dx e^{-x^2/2}$$

$$\frac{dP}{dM}(>\delta_c, M) = \frac{\delta_c}{\sigma_M^2}\frac{d\sigma_M}{dM} e^{-\frac{1}{2}(\frac{\delta_c}{\sigma_M})^2}$$

$$n(>M) = \frac{\rho_m}{M}\int_M^{\infty} dM \frac{\delta_c}{\sigma_M^2}\frac{d\sigma_M}{dM} e^{-(\delta_c/\sigma_M)^2/2}$$

PS is a fair
fit to simulations
ST takes partially into account
non-sphericity in real fluct.
growth, and provides
even better
fits



ST vs simulations
ST: dashed blue line
error bars: poisson noise

From Klypin, Maccio', Mainini & B. 2003, ApJ 599 (dDE simulations)

PS formulation for cDE

Based on a newtonian description of DM-DE interactions

(i) DM particle masses to vary :

$$M_c(\tau) = M_c(\tau_i)\exp[-C(\phi - \phi_i)].$$

(ii) Gravitational constant between DM particles : $G^* = \gamma G$.

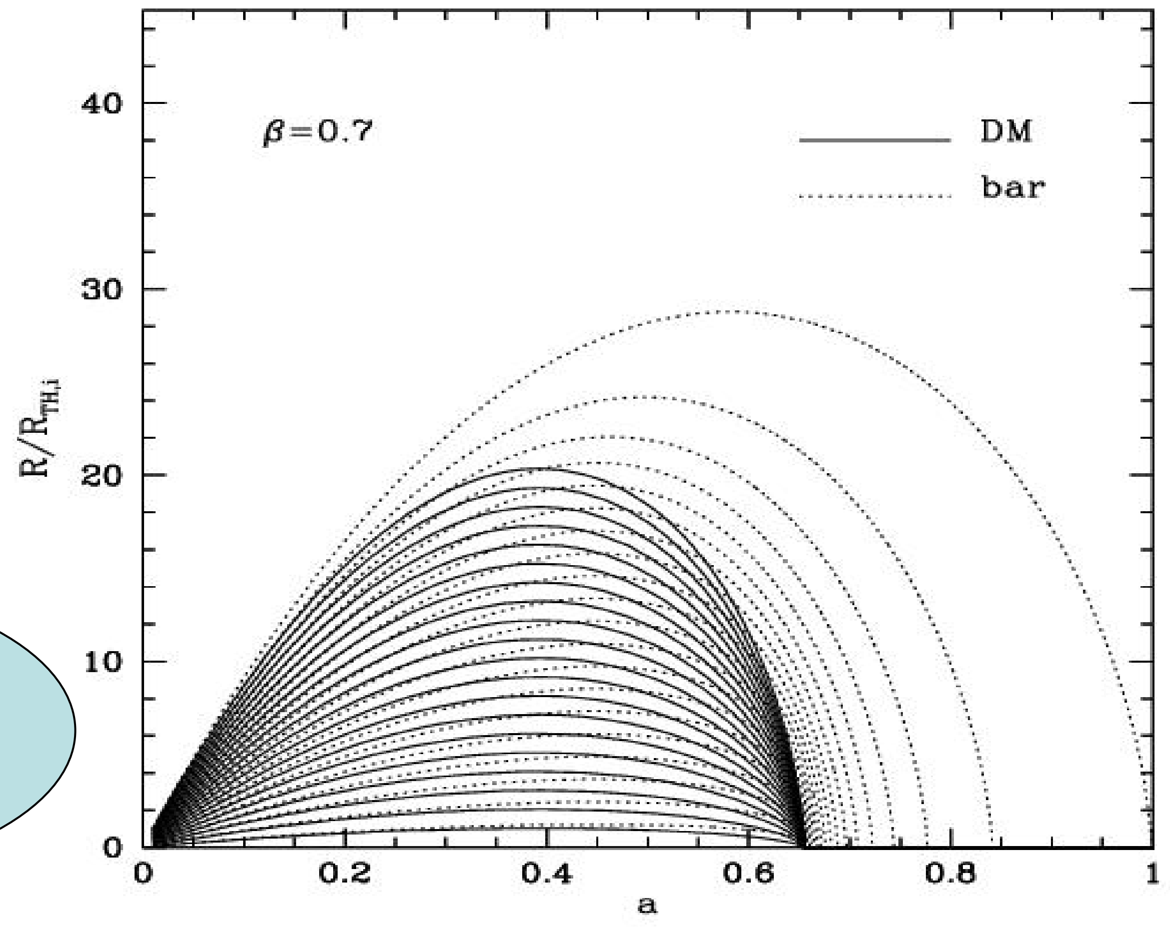
$$C = \sqrt{16\pi G/3}\,\beta \;, \qquad \gamma = 1 + 4\beta^2/3$$

(Maccio' et al. , 2004, P.R.D69)

Valid
well below
horizon &
for negligible
radiative
comp.

The Φ-field carries a long-range interaction which appears as a correction to newtonian gravity, but only for DM-DM interactions
B-DM interactions untouched

Model with
$\beta = 0.7$
from Mainini, 2005, P.R.D 72



Effective DM gravity is stronger

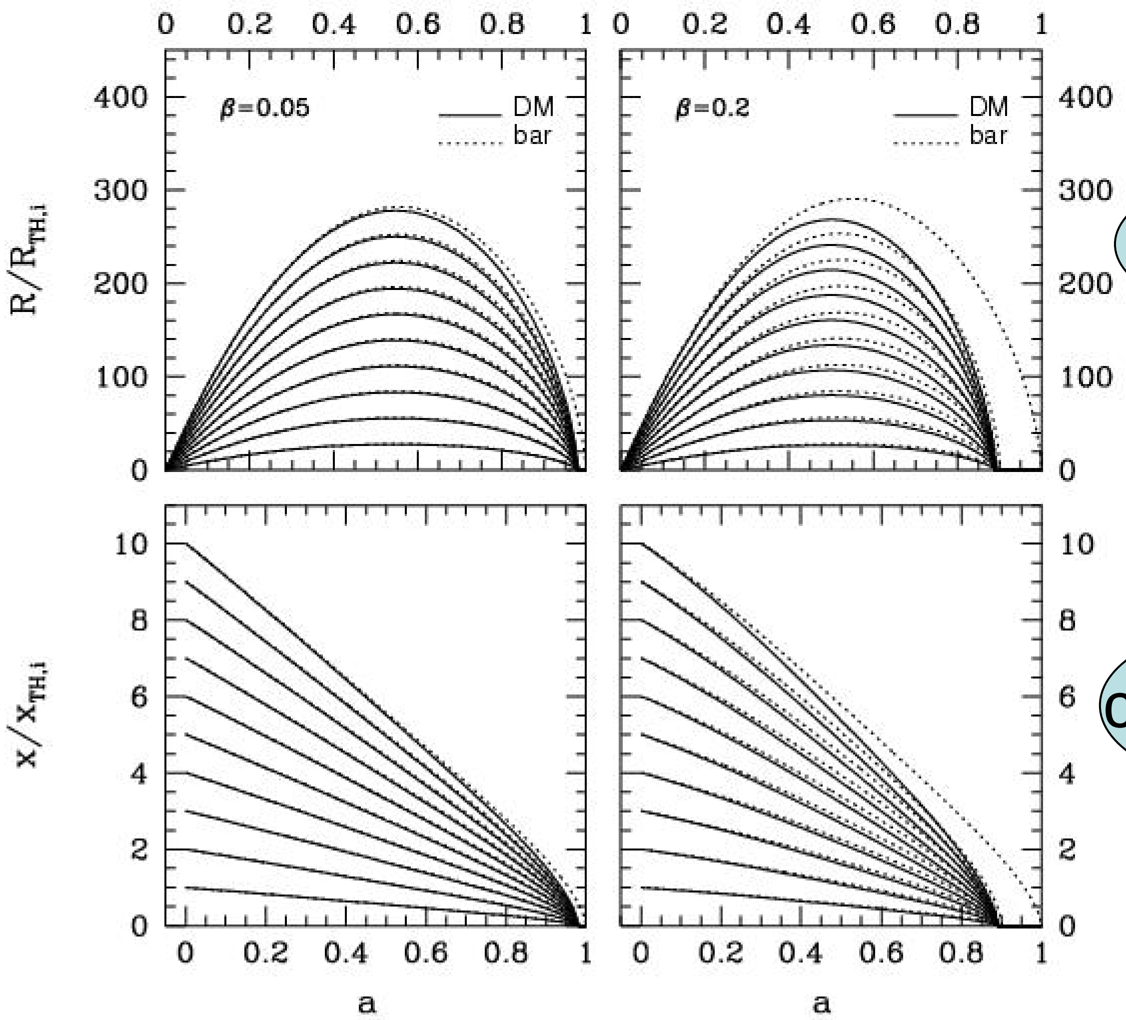
DM shells evolve more rapidly

A sampling of spherical shells (~1000 used)

Shell radii (bar & DM)

Models of this paper

Mainini & Bonometto, PRD 2006



physical

comoving

Our model's parameters

Ω_m=0.25

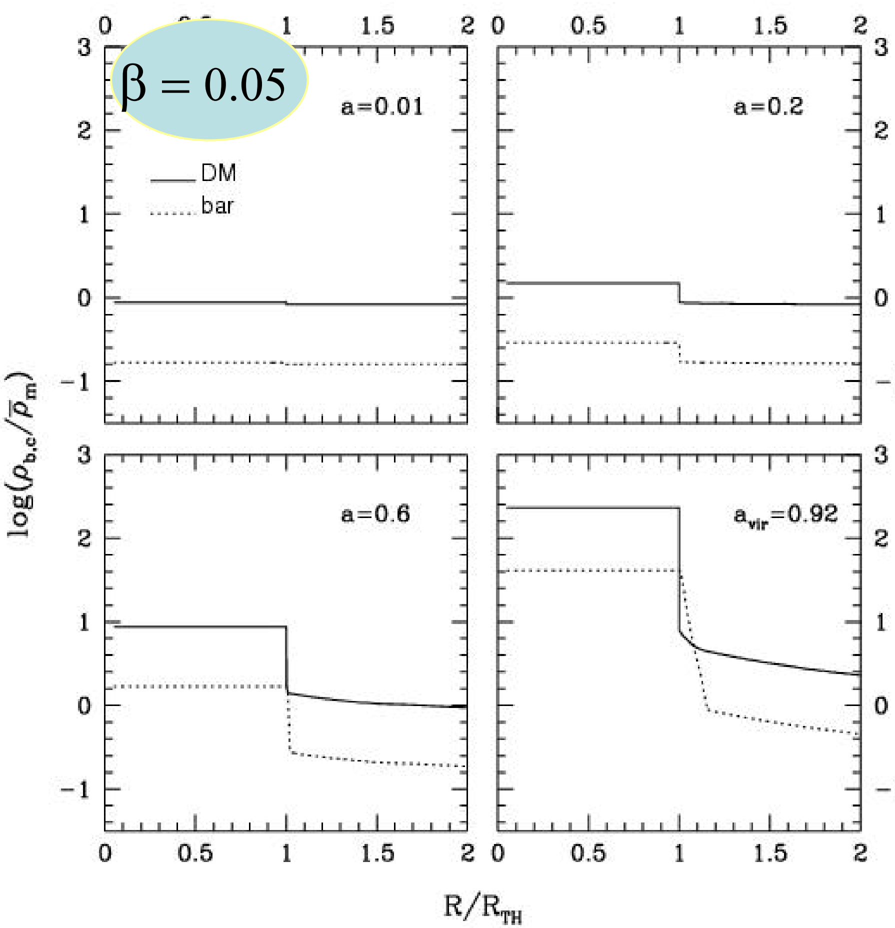
Ω_b=0.042

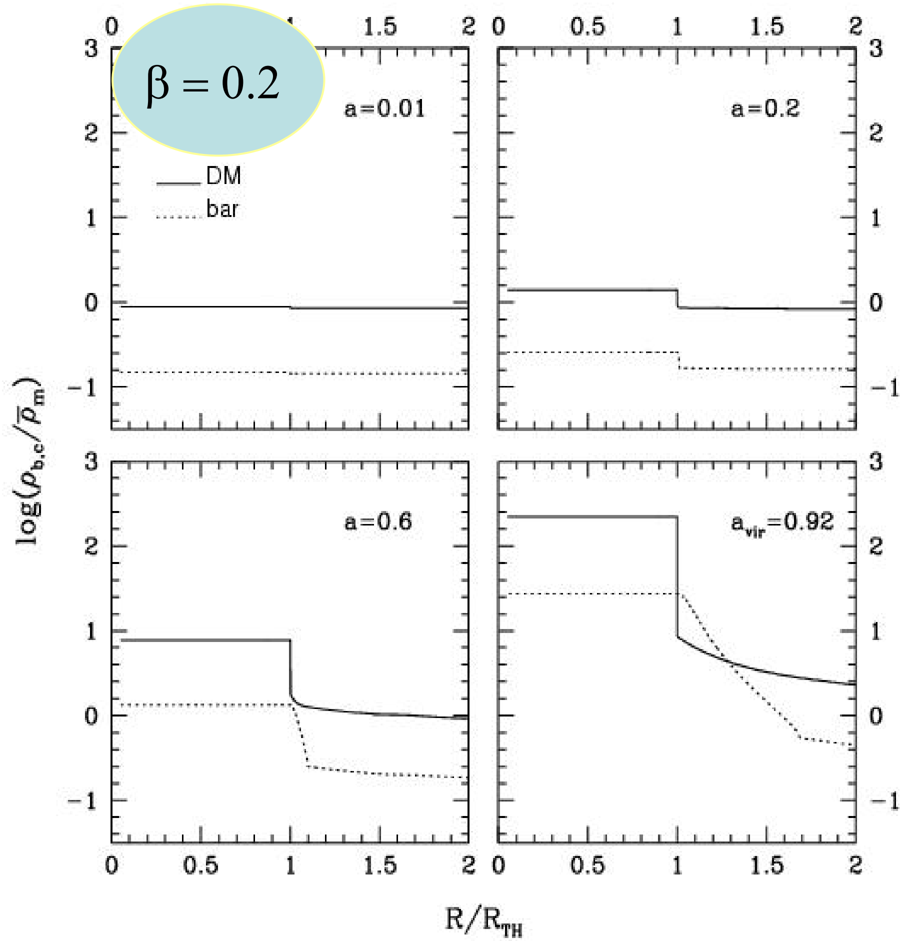
h=0.73

WMAP1

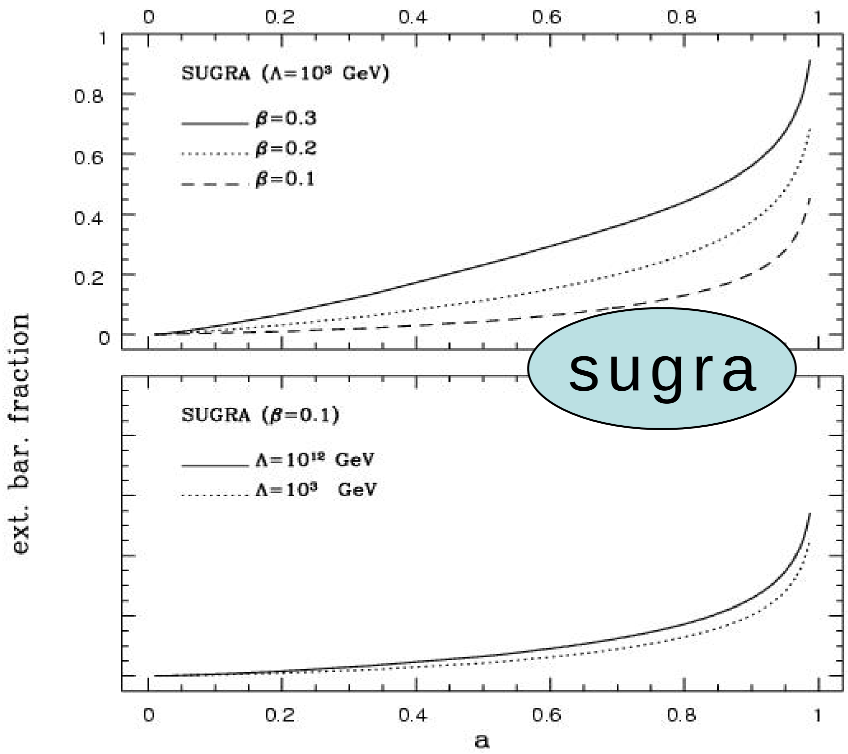
Profile evolution, in bar. & DM until virialization

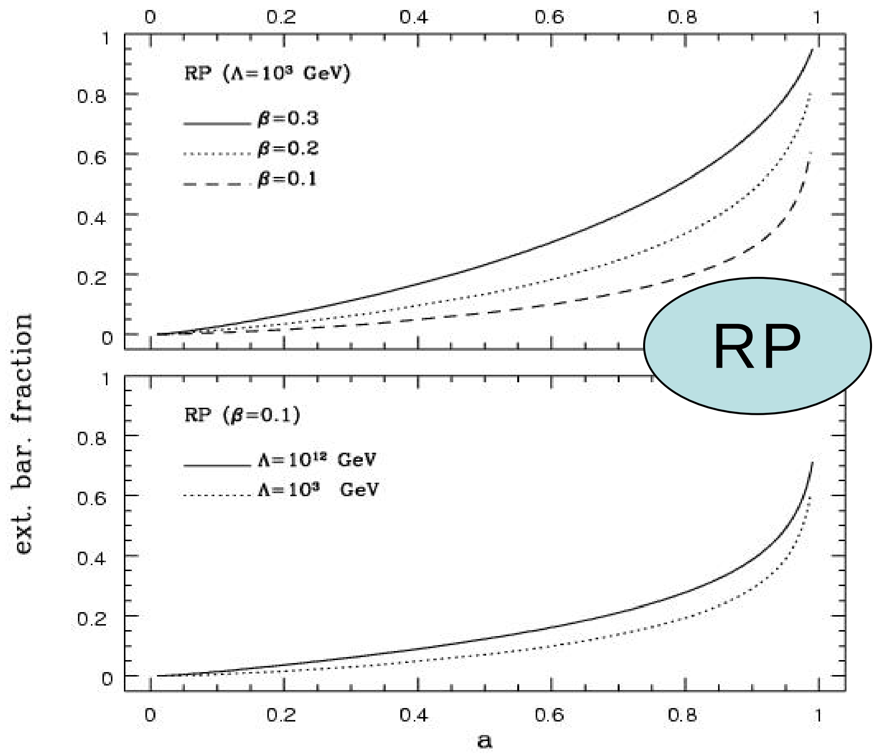
How small can be β, to yield appreciable shifts ?





Baryon fraction leaking DM bulk





fraction increases with β
almost independent from Λ

RP fraction greater

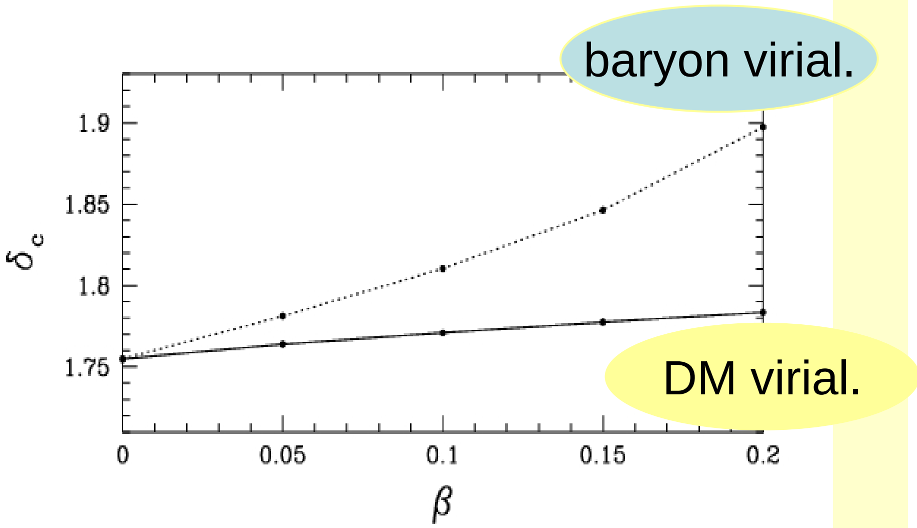
Linear amplitudes (SUGRA)

to be used in PS or ST espressions

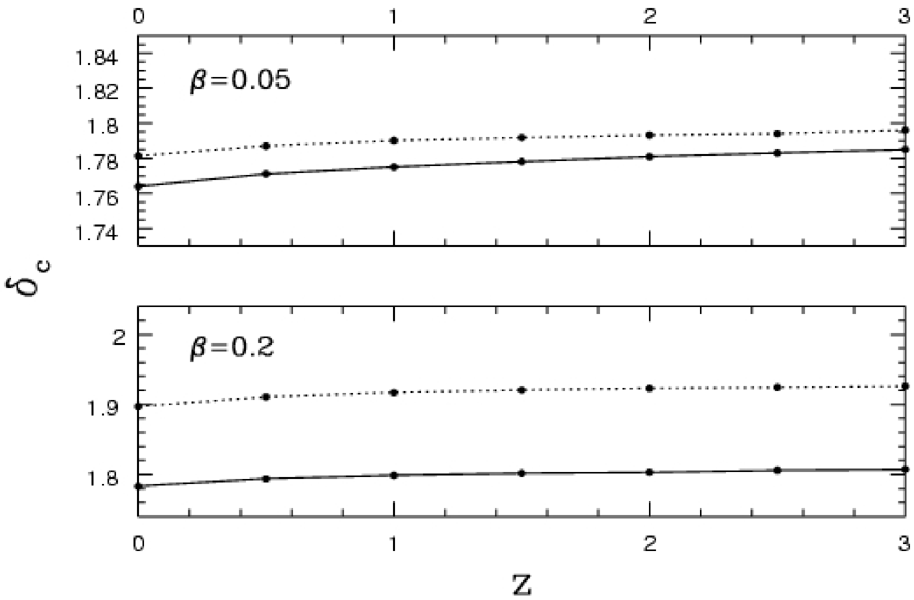
2 different values for δ_c

fluct. ampl → DM virial.

Fluct.ampl → baryon virial.

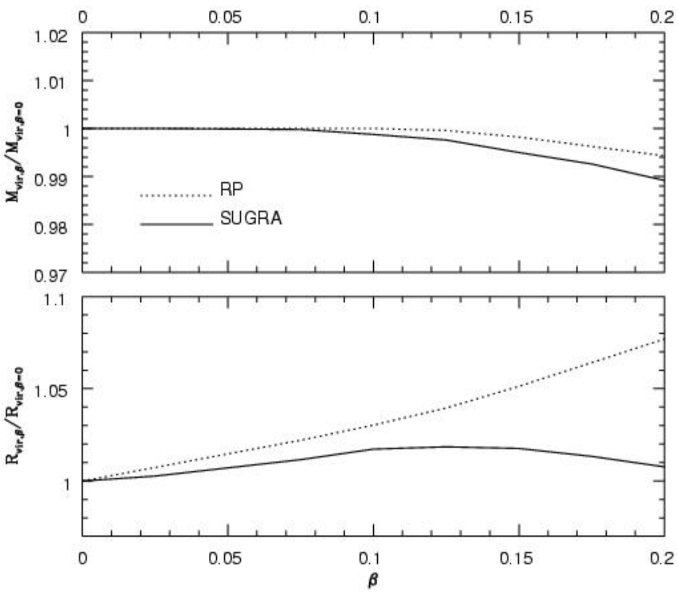


β dependence at z=0

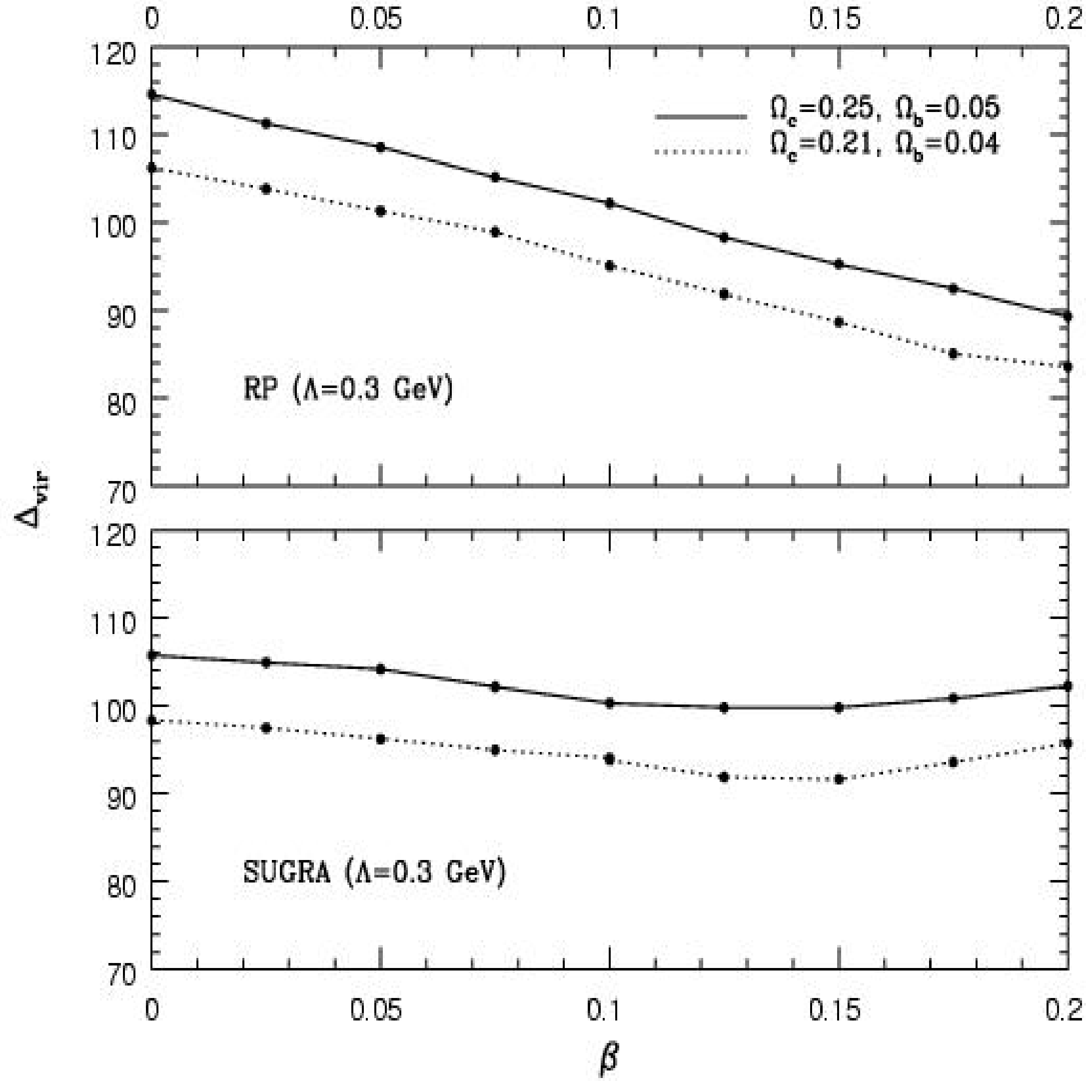


z dependence for model's β

M_{vir} & R_{vir} vary because of coupling



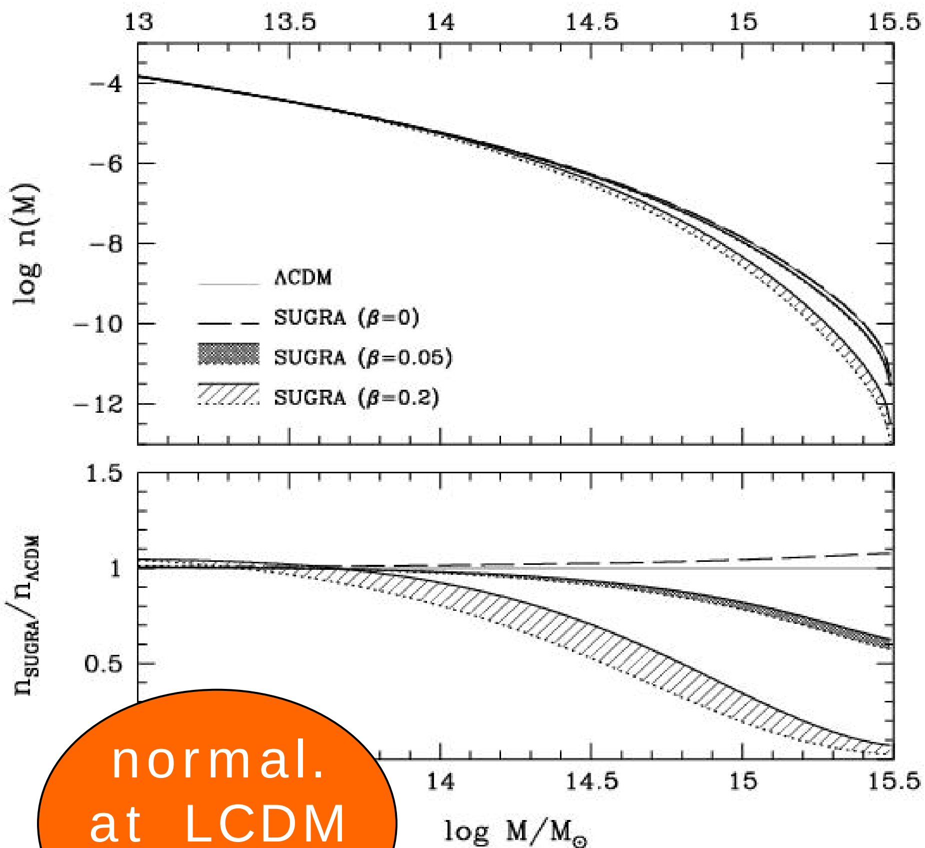
Δ_{vir}

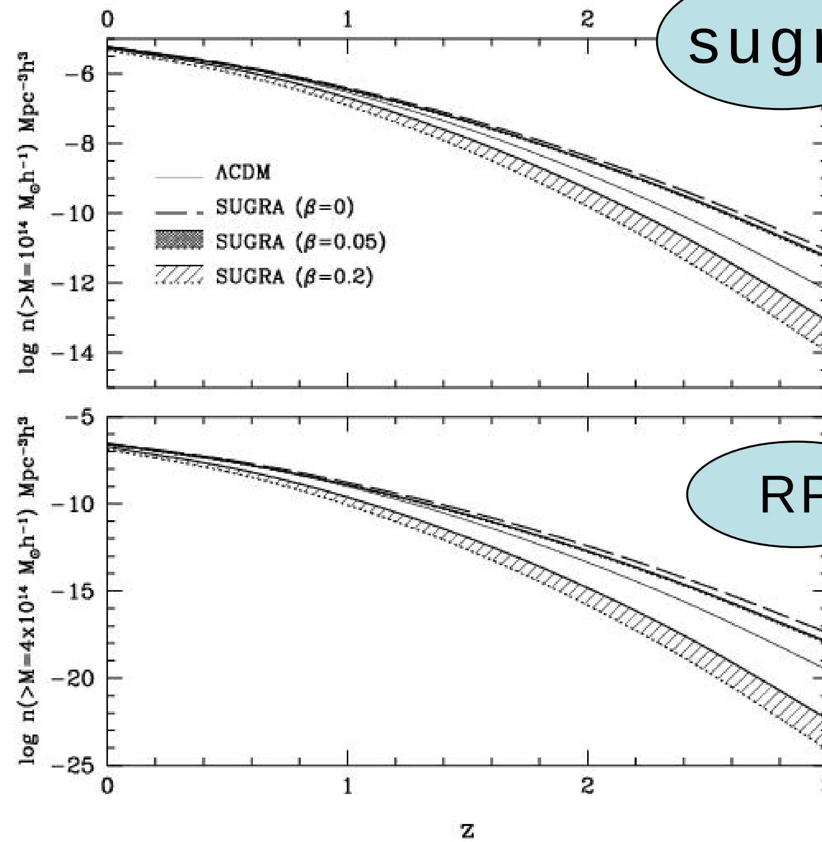


to be used to find halos in simul.

PS mass functions
at z=0

N vs redshift
in comoving volumes





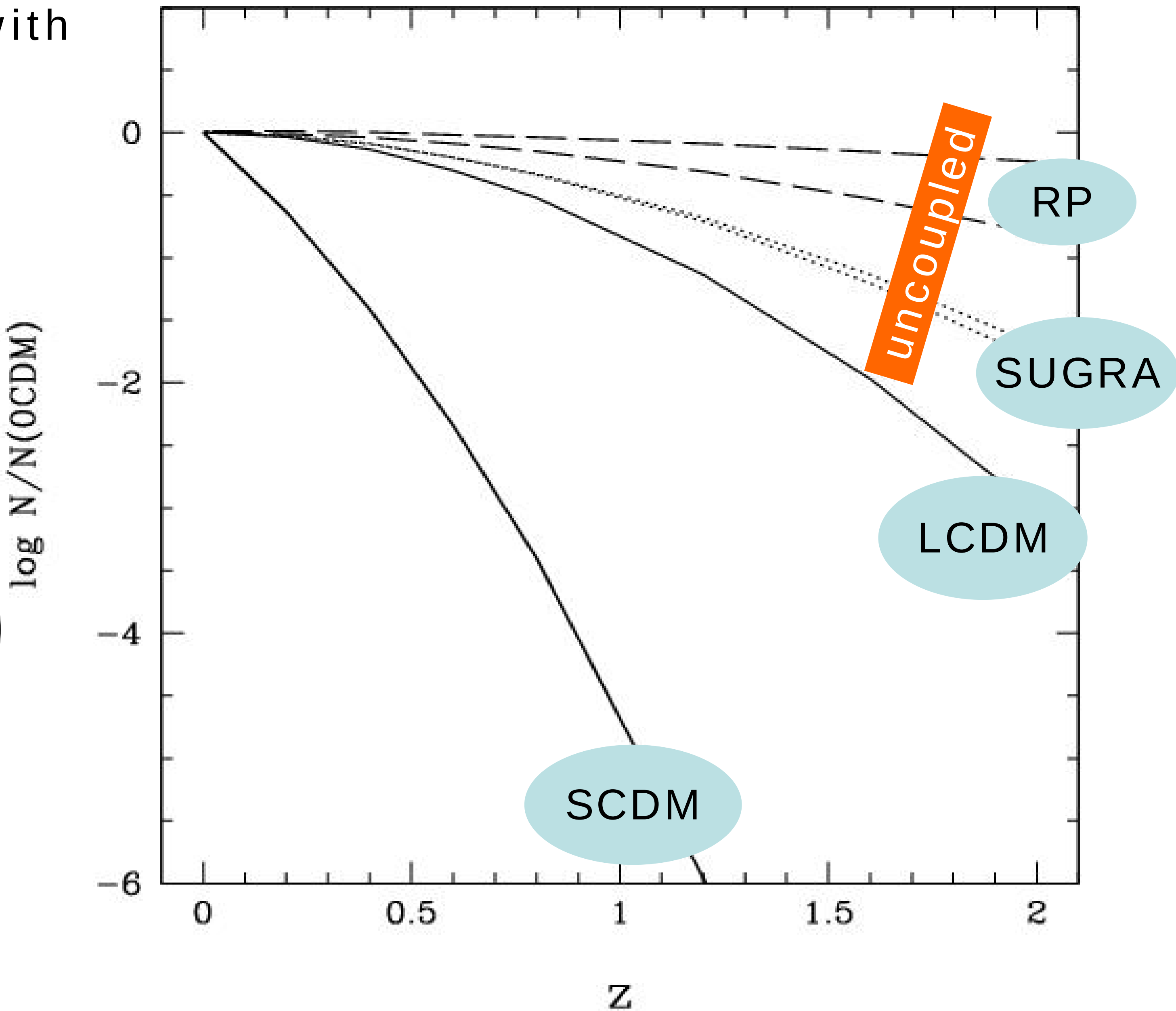
sugra

RP

normal.
at LCDM
values

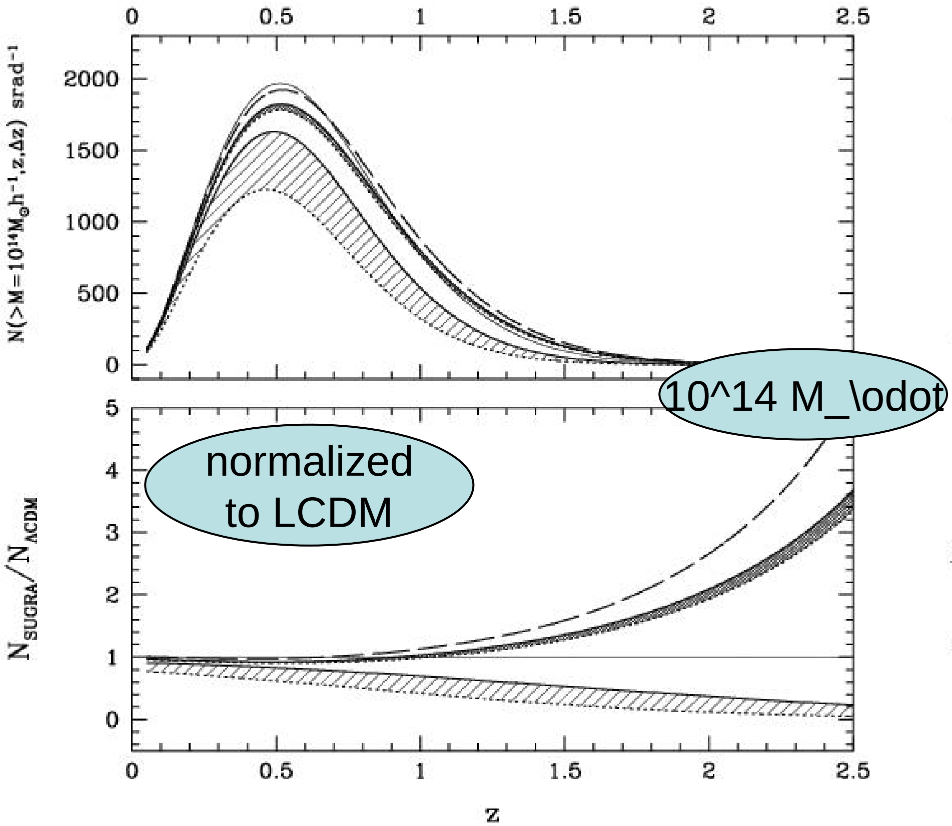
signal of coupling at z=0,
expected if $\beta \sim 0.2$

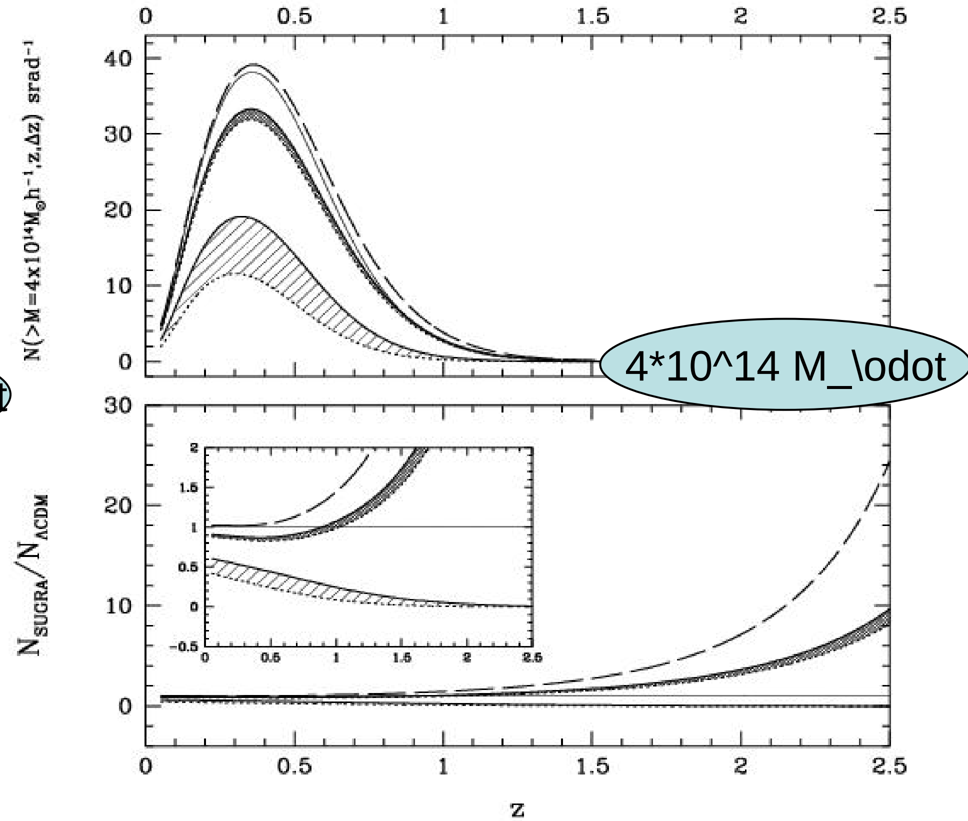
halo # evolution compared with 0CDM



plots M=5.6*10^14 h^-1 M_sun

of expected halos in fixed Δz and solid angle

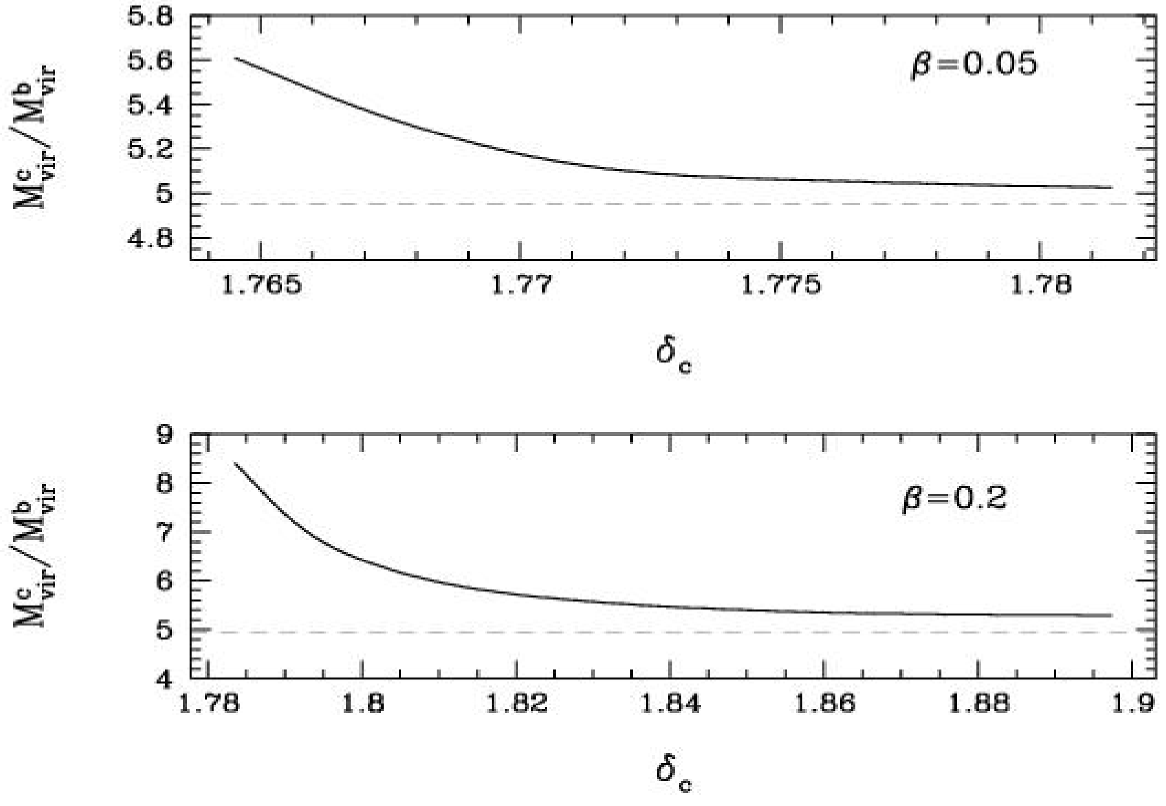




dDE evolves
more slowly than
LCDM

coupling can invert
dDE displacement

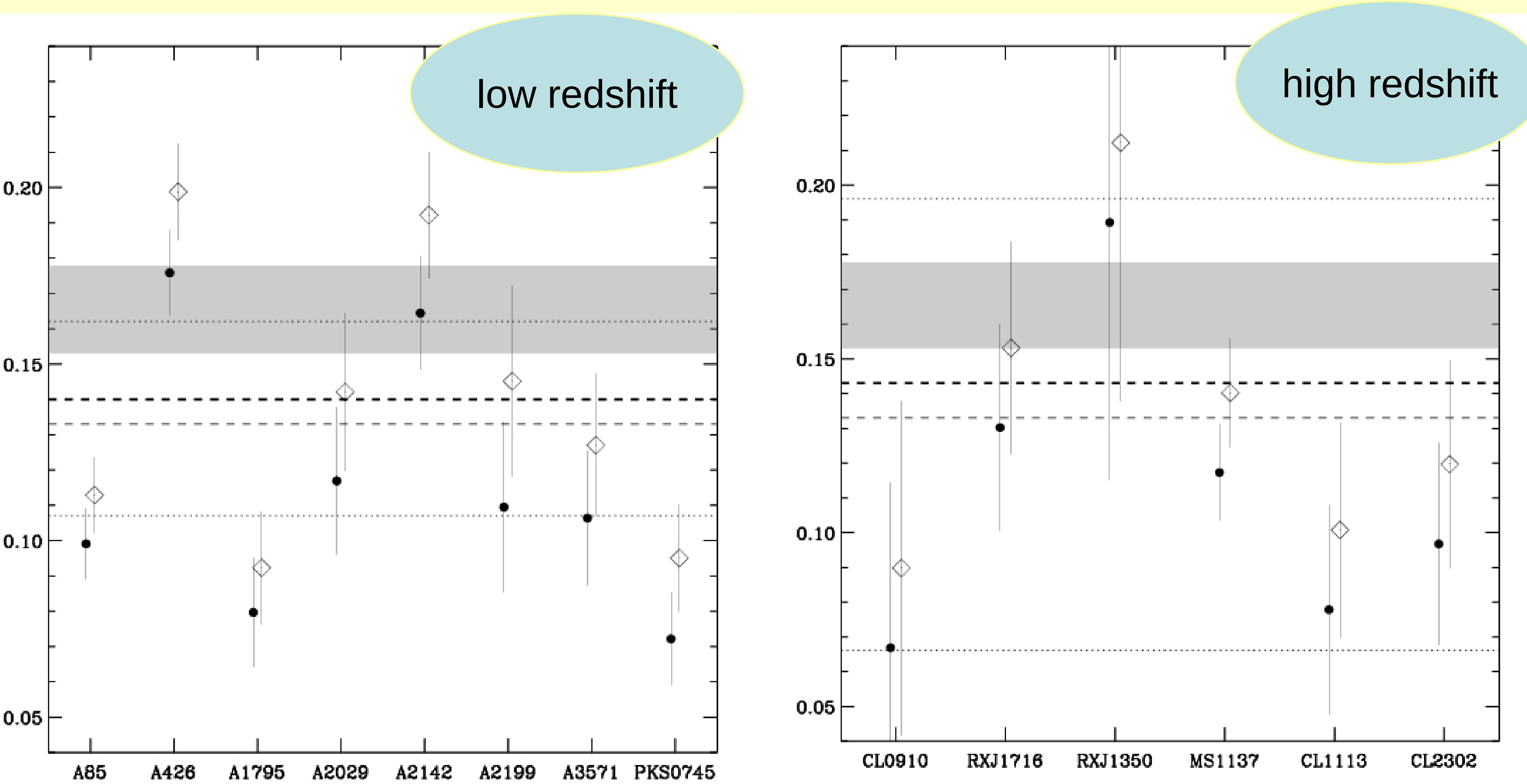
Halos are however baryon impoverished



Baryons in galaxy clusters

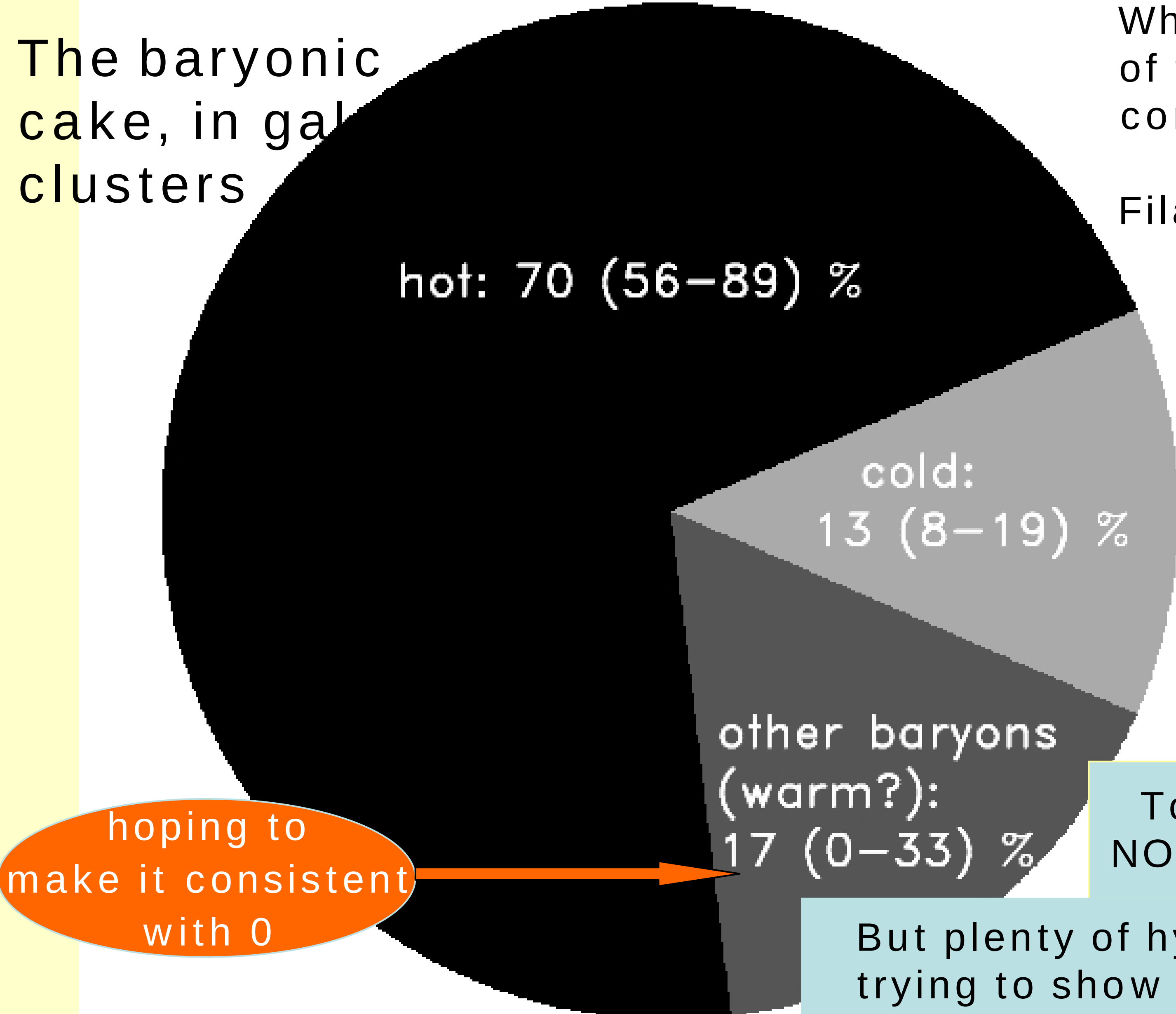
Ettori, 2003, MNRAS 344

grey band: WMAP1 data interval



black dots: intracluster gas emitting X-rays
diamonds: total baryon budget

The baryonic cake, in galaxy clusters



Which evidence of the warm component ?

Filaments emitting:

Soft x-rays :
Kaastra et al.,2003, A&A397
Finoguenov, Briel & Henry,2003,A&A410

UV :
Mittaz, Lieu & Lockman, 1998, ApJL 498
Maloney & Bland-Howthorn, 2001, ApJL 553

To my knowledge
NO more recent data

But plenty of hydro simulations trying to show that:

- Warm phase forms
- Baryons expelled by early SNe

cDM simulation

$\Omega_m = 0.3$

$\Omega_b = 0.026$

H = 70 km/s/Mpc

SUGRA potential

$\Lambda = 100$ GeV

$\beta = 0.16$

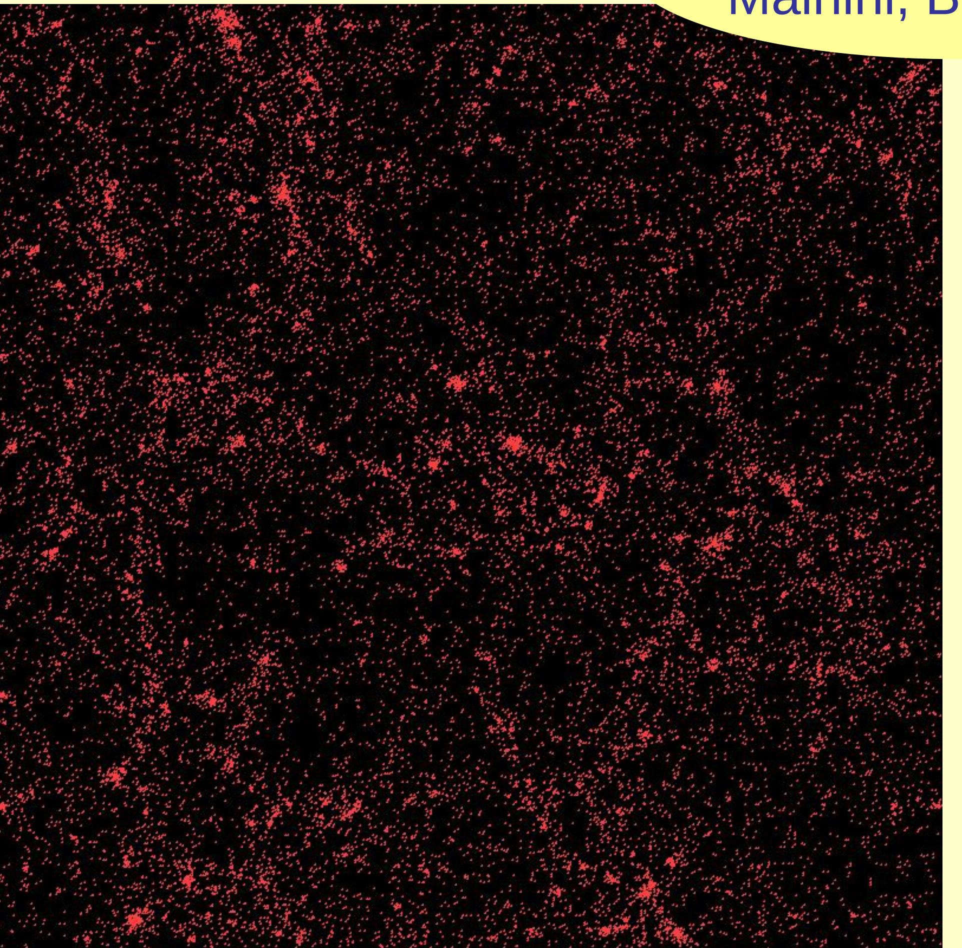
ART program modified

Box: 90 Mpc

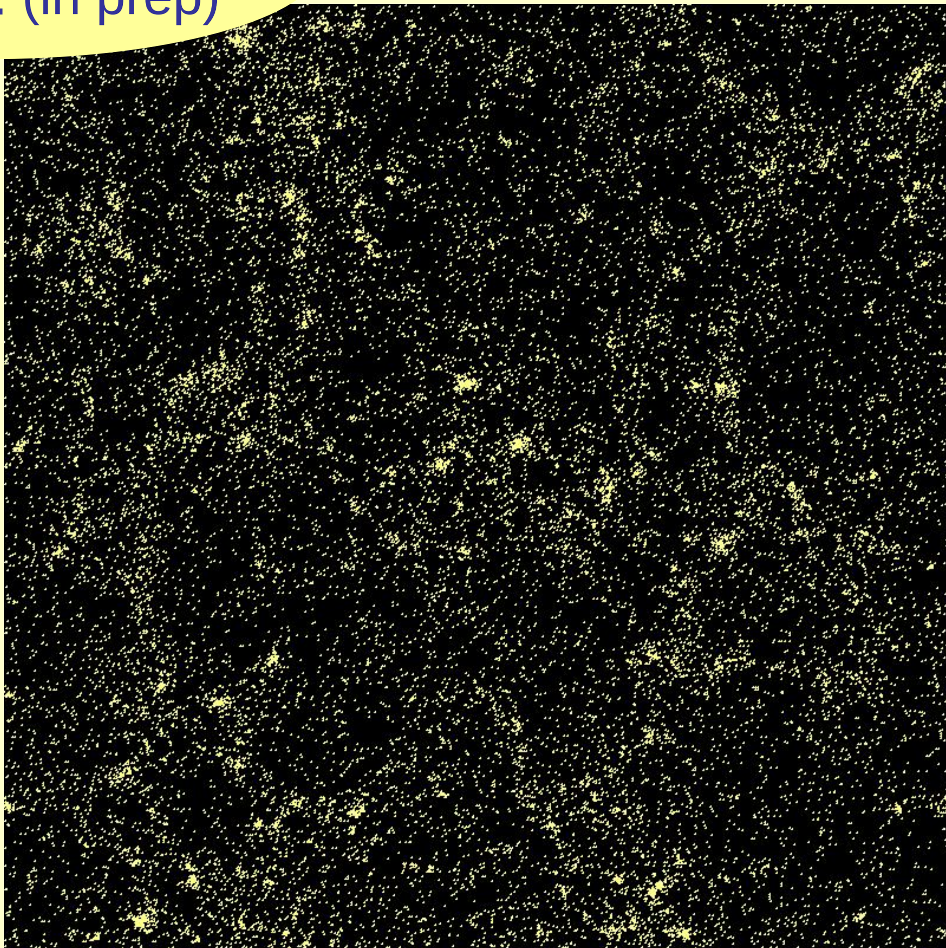
64^3 part./8 ref.lev.

Maccio', Casarini, Mainini, B. (in prep)

dm



bar



Former simulation performed in 2004 with RP potential

Maccio',Quercellini,Mainini,Amendola,B., 2004, P.R.D69

Principal findings: limits on coupling
In RP models the ϕ field is always increasing
Corrections to DM gravity stronger in the past
→highly concentrated halos

Only for $\beta < 0.2$ concentration acceptable

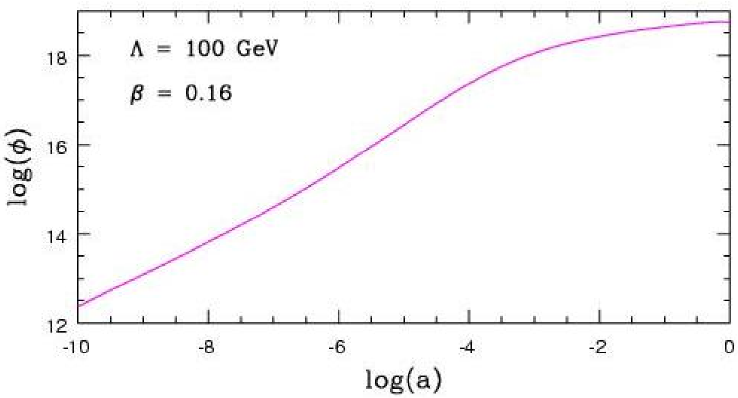
NO test on baryon depletion made on it

RP potential

$$V(\phi) = \Lambda^{4+\alpha} / \phi^{\alpha}$$

Main difficulty with ART implementation: agreement btwn finite step lenth and continuous M and G variat.

An easy solution for monotonic field variation

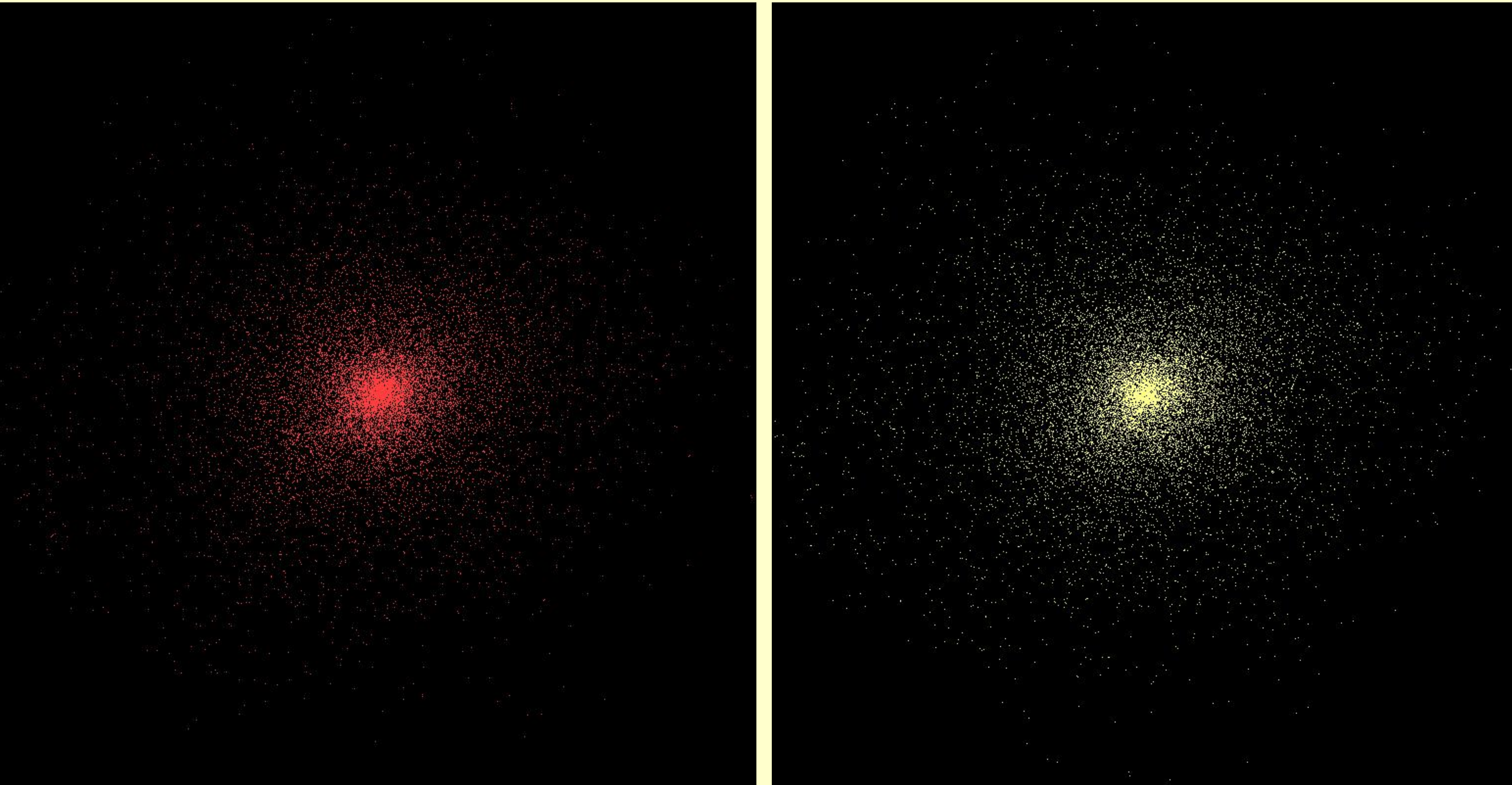


With SUGRA potential, ϕ increase stopped by exp factor; with selected parameters, the recent ϕ behavior almost flat
Halo concentration no longer a problem

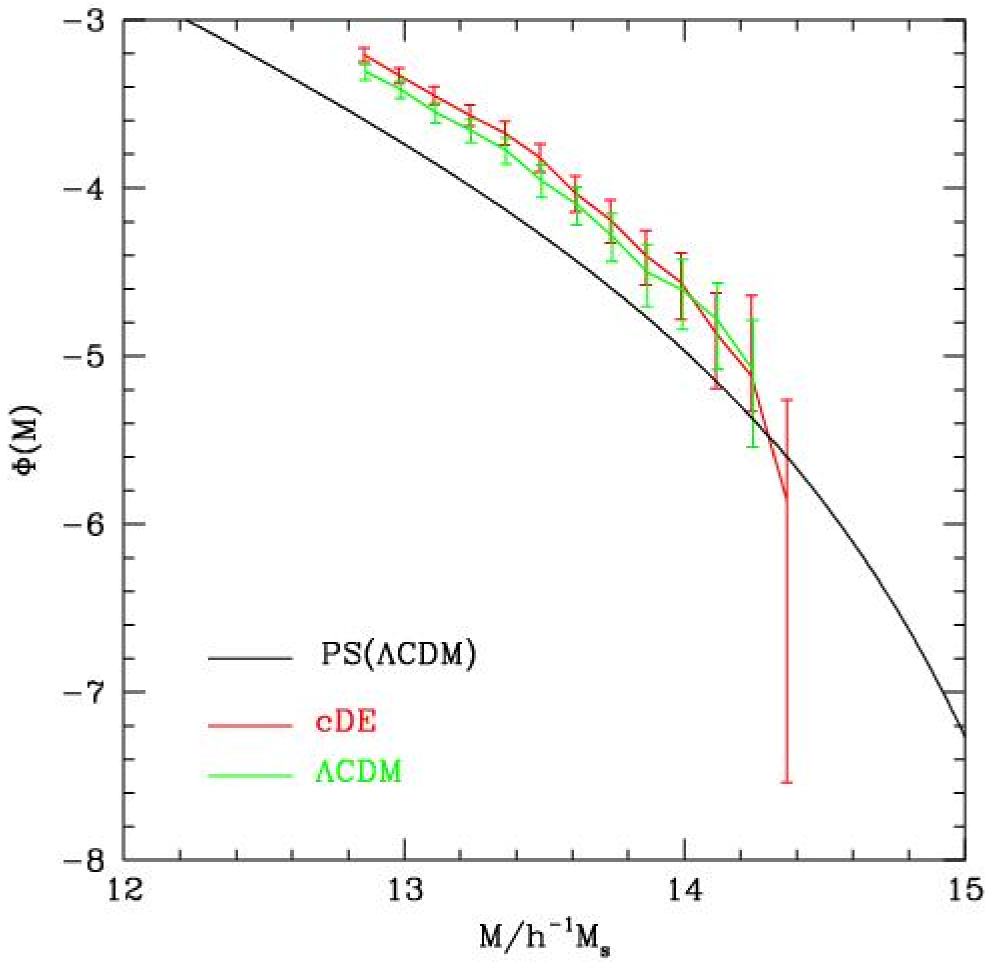
Box contains
153 halos in mass interval:
2.3e13 M_\odot (100 part) -
2.5e14 M_\odot (1089 part)

8 halos magnified
8 levels in mass
5 levels in force

dm bar



Mass function



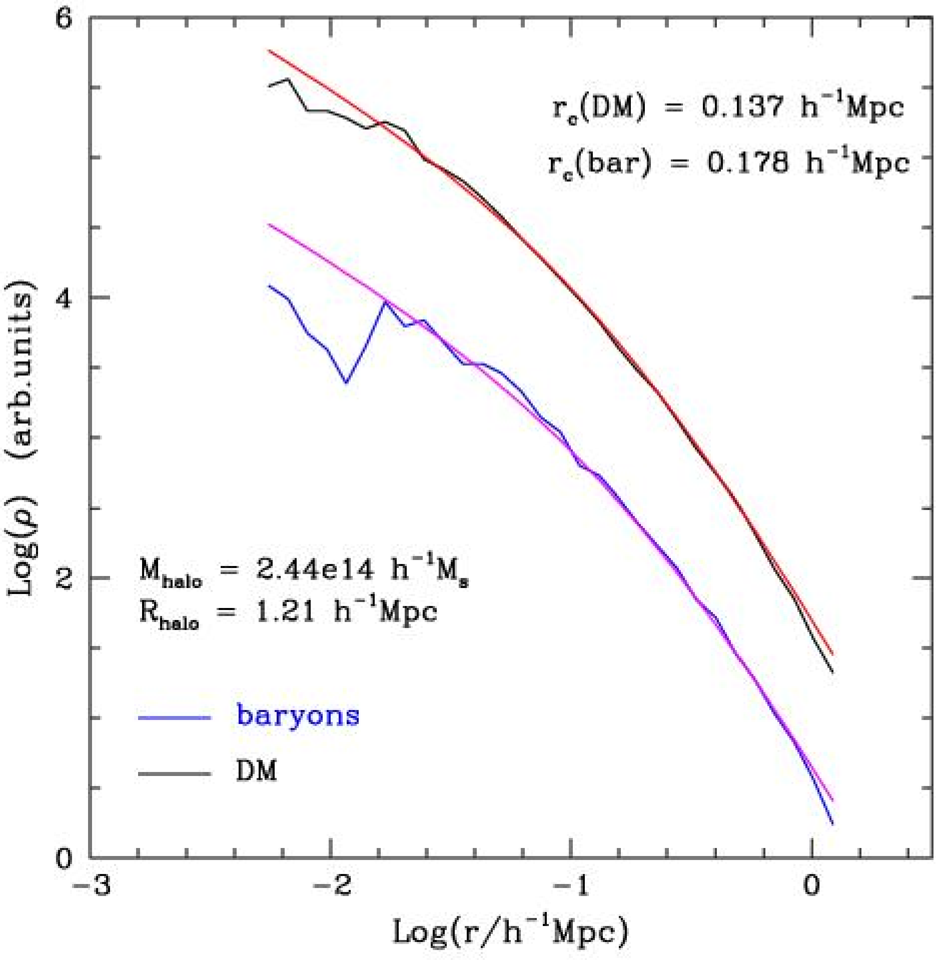
Same σ_8
for coupled SUGRA
and LCDM

369 halos in LCDM
470 halos in cDE

>30 particle halos

Mild disagreement with PS
ST fits better

Halo profile for DM and baryons, NFW fits

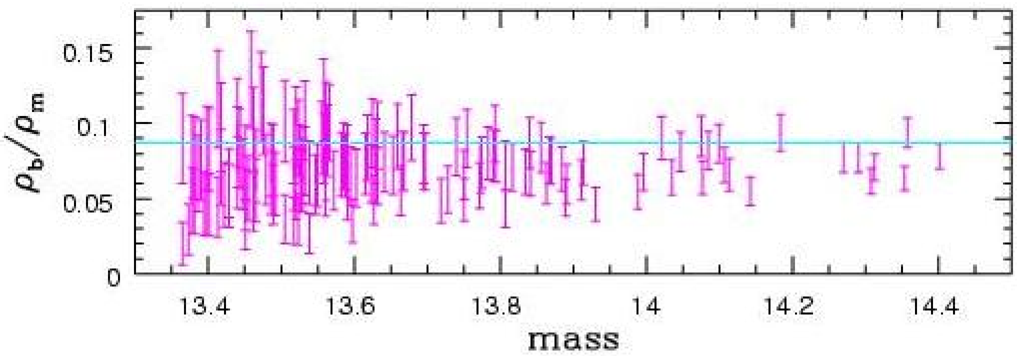


Different concentrations for DM & bar.

baryon depletion

Blue line is the background abundance

All halos
Error bars are poisson noise

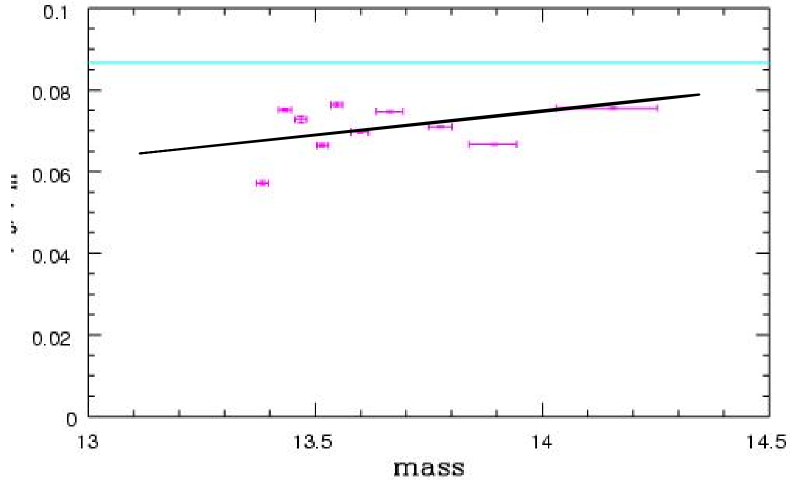


average depletion ~17 %

(all halos with >31 particles)

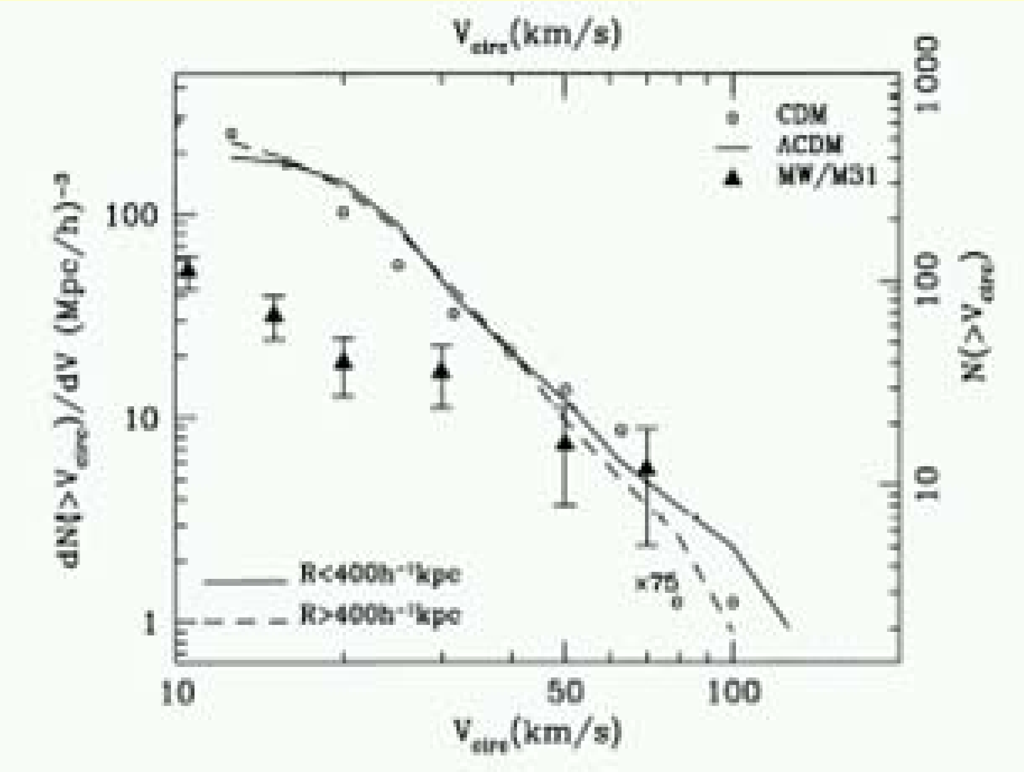
Sets of 15 halos
Error bars are 1-σ standard deviation

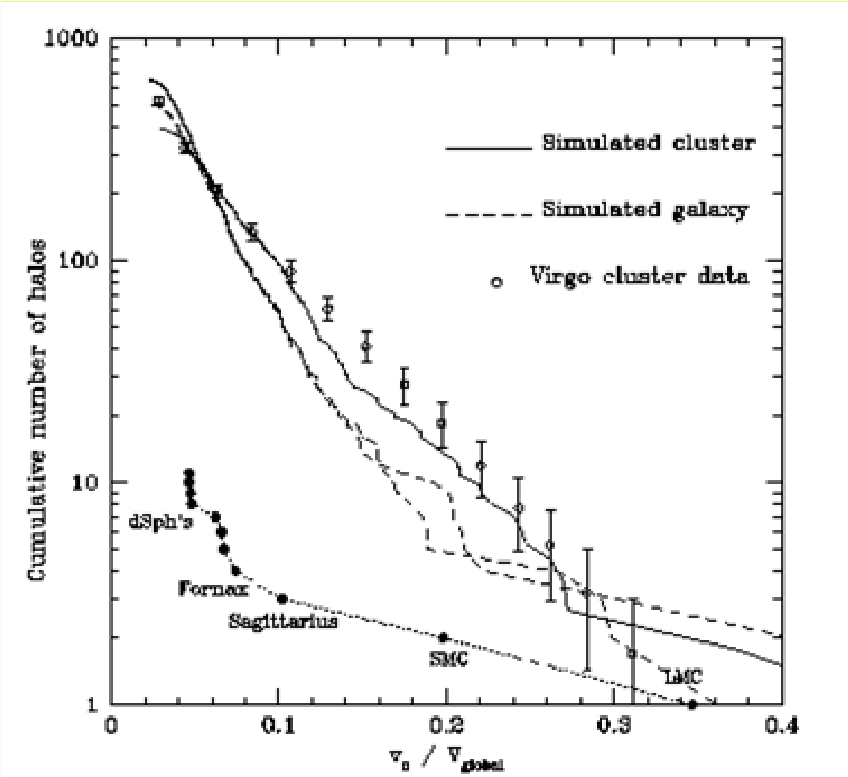
Only halos with >100 particles



A trend
in baryon
depletion ?

ANDROMEDA SATELLITES





Klypin et al., 1999, ApJ 522

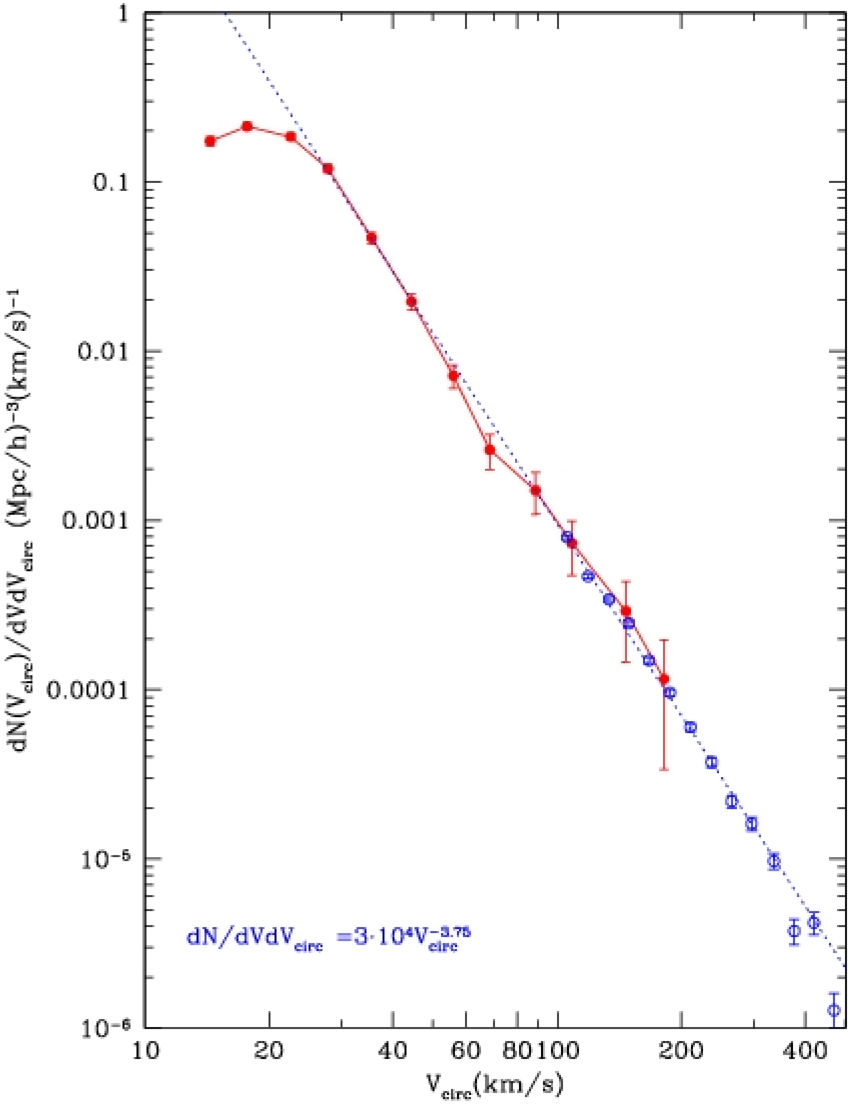
Moore et al., 1999, ApJ 524

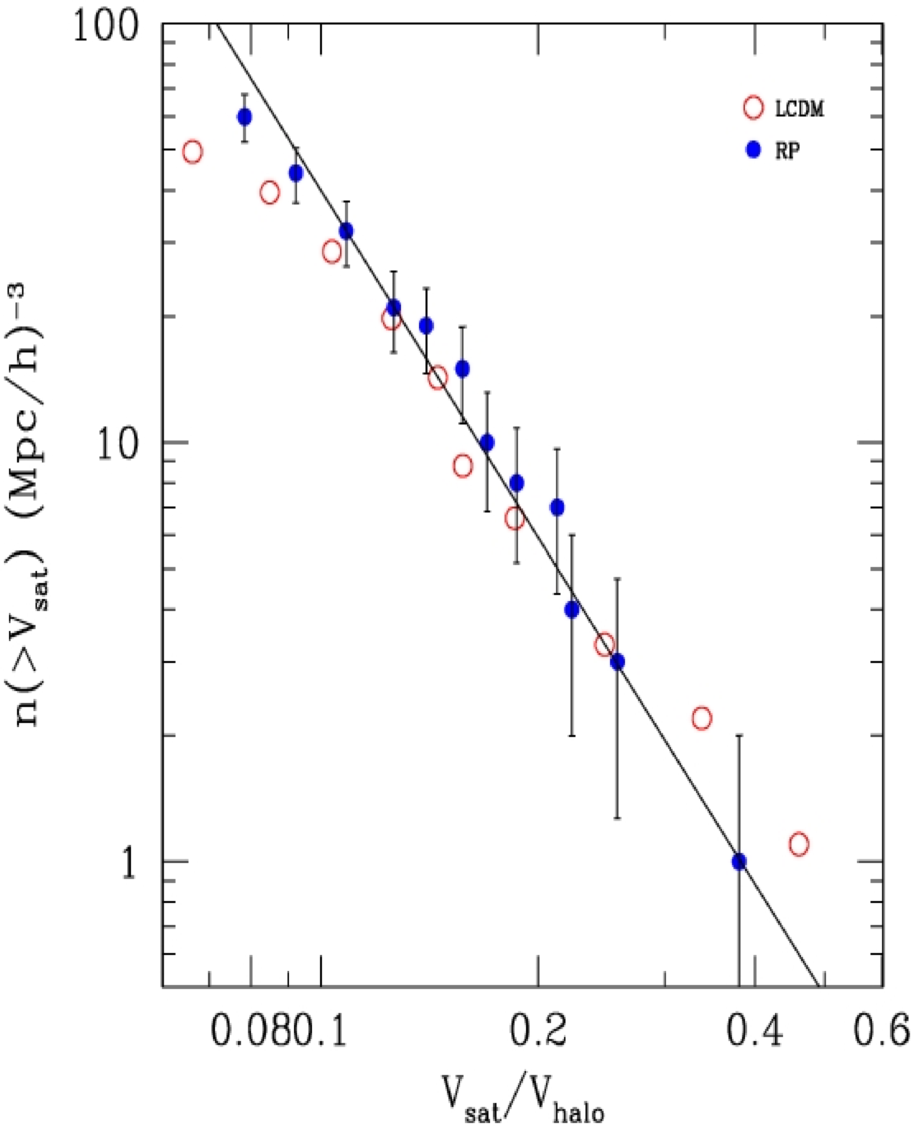
Where are the missing galaxy satellites ?

Metcalf & Madau, 2001, ApJ 563

2 solution: missing satellites did not form
missing satellites are there, but invisible...

DARK SATELLITES





Klypin, Kravtsov, Valenzuela & Prada,1999, ApJ 522
see also Moore et al, 1999, ApJL 524

dDE, # of satellites predicted the same as for LCDM
Klypin et al, 2003, ApJ 599

CONCLUSIONS

DM+LAMBDA models
are an excellent 'caloric' description
of the Dark Substance, but...

N-body simulations of cDE cosmologies
yield promising results
with fairly acceptable coupling strenths

already
$\beta \sim 0.05$
yields fair
effects

In the sensitive areas
a number of data require different dynamics
for DM & baryons; here we considered
baryon depletion in clusters

Similar patterns to be explored
whenever hydrodynamics does not provide
bar-DM segregation mechanism acting early enough
In turn, this can provide rich information
on DM-DE relations