Title: 9,000,000,000 years of gravity at work in the cosmic factory

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URL: http://pirsa.org/07080000

Abstract: The Origin of the Large Scale Structure is one of the key issue in Cosmology. A plausible assumption is that structures grow via gravitational amplification and collapse of density fluctuations that are small at early times.
The growth history of cosmological fluctuations is a fundamental observable which helps in hunting for evidences of new physics, currently missing from our picture of the universe, but potentially crucial to explain its past, present and future history.
I'll show how we investigated if the gradual growth of structures observed over a period of nearly 9 billion years can be used to discriminate between different gravitational models. I'll also discuss how the measurement of the cosmic growth rate provides an alternative independent probe to understand the origin of the accelerated expansion of the universe.

9,000,000,000 years of gravity at work in the cosmic factory

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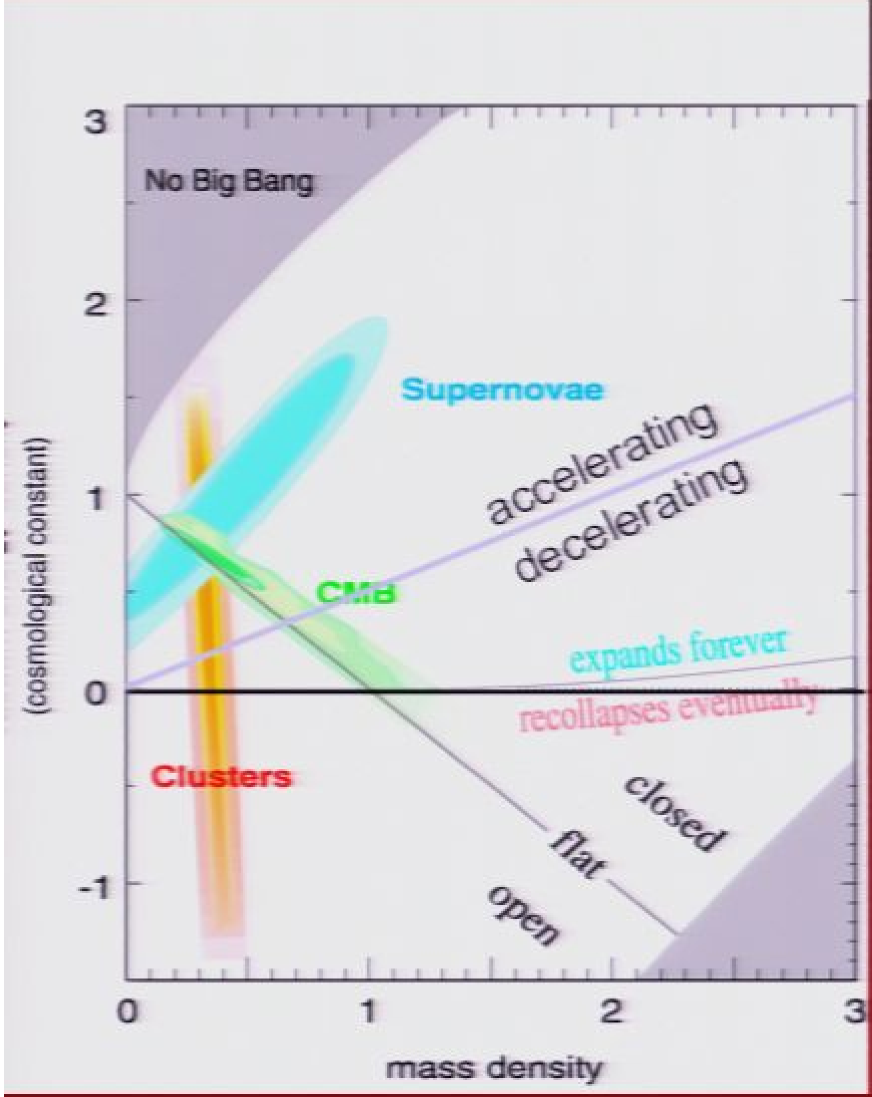
Un unprecedent convergence of results in cosmology over the last few years indicates that we live in a universe where:



- ordinary matter is a minority (1/6) of all matter
- matter is a minority (1/4x) of all energy
- geometry is spatially flat
- Expansion is presently accelerated

The big picture is in place, but the major constituents and many of the detailed physical mechanisms remain to be understood.

The outstanding problem : Dark Energy

What do we know ? { Dark
Smooth on cluster scales
Accelerating the Universe

- The Cosmological Constant Problem

  Particle physics theory currently provides no understanding of why the vacuum energy density is so small: $\rho_{DE}^{(Theory)} / \rho_{DE}^{(obs)} = 10^{120}$

- The Cosmic Coincidence Problem

  Theory provides no understanding of why the Dark Energy density is just now comparable to the matter density.

- Nature : What is it?

  Is dark energy the vacuum energy? a new, ultra-light particle? <u>a breakdown of General Relativity</u> on large scales? Evidence for extra dimensions?

Outline

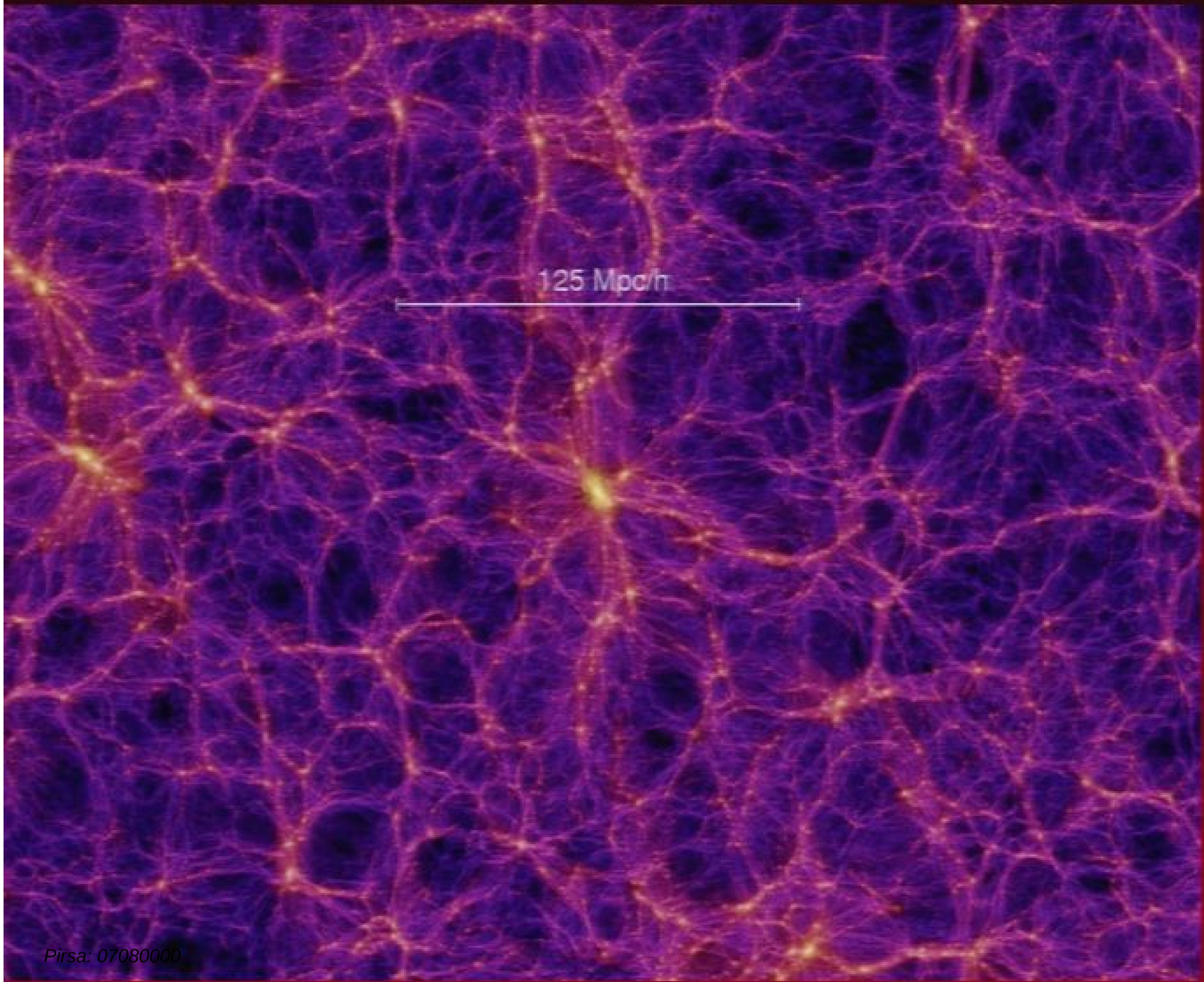
- **Matter-Galaxy bias**
  - Biasing from a theoretical & observational perspective
  - Our approach to the extraction of the biasing function across different cosmic epochs

- **Testing the consistency of Gravitational Instability as described by GR**
  - statistical approach : moments of the PDF of matter fluctuation
  - dynamical approach : redshift space distortions caused by density fluctuations

- **Purely geometrical, gravity independent, test of the accelerated expansion of the universe**
  - method and preliminary results

$\delta = \frac{\rho - <\rho>}{<\rho>}$ Fundamental variable describing the LSS structure

Complete understanding of δ on larges scales

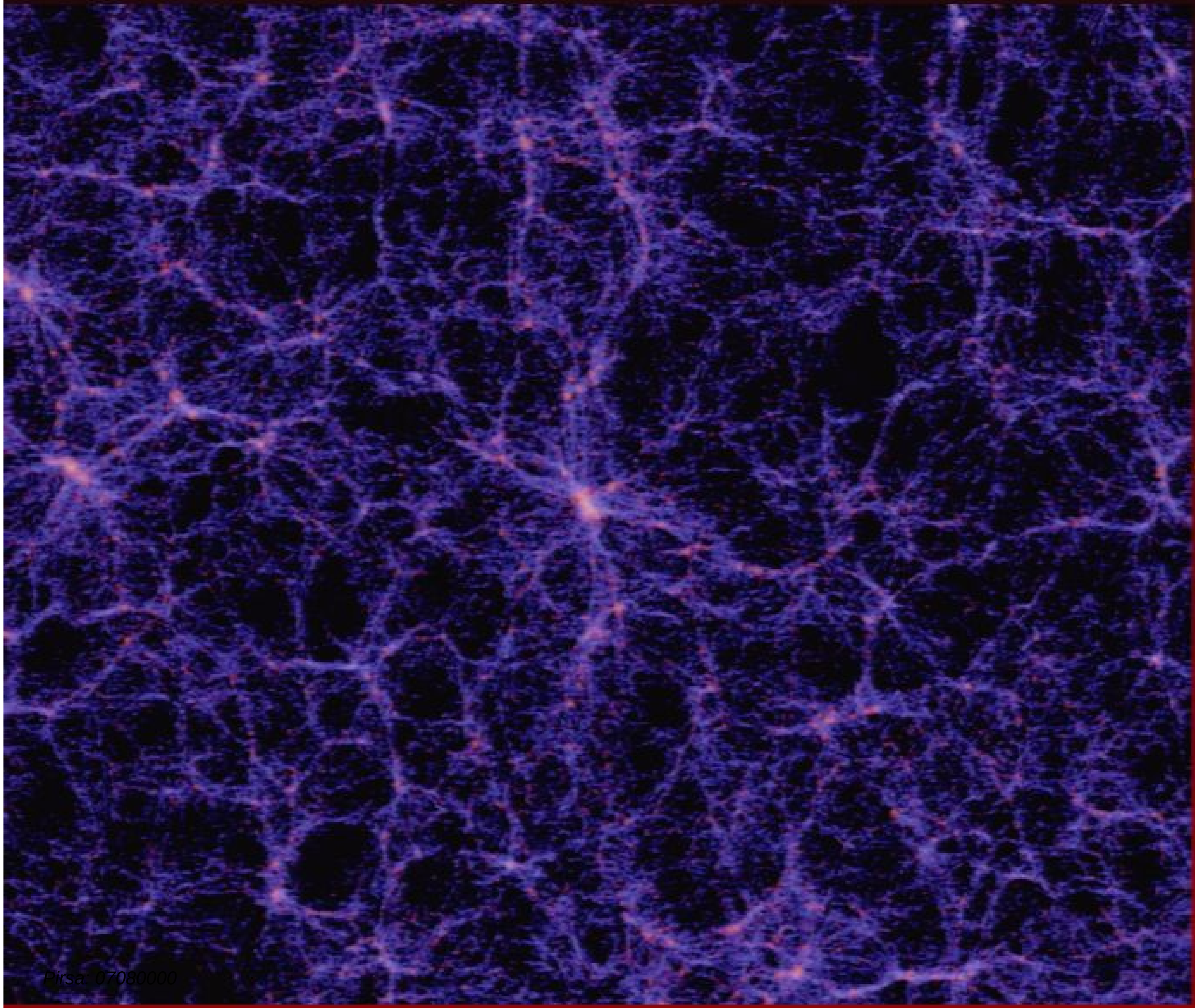


- Cosmology is phrased in the ΛCDM frame
- Initial conditions of cosmological structure formation almost unambiguously known
- Gravitational evolution is known (collisionless)

Springel et al. Nature 2005 Millenium Simulation

Formation and evolution of luminous matter

Dynamics of galaxy fluctuations δ_g



- Where and when did galaxies form?
- How do they evolve w.r.t. DM?

Springel et al. 2005, Millenium Simulation

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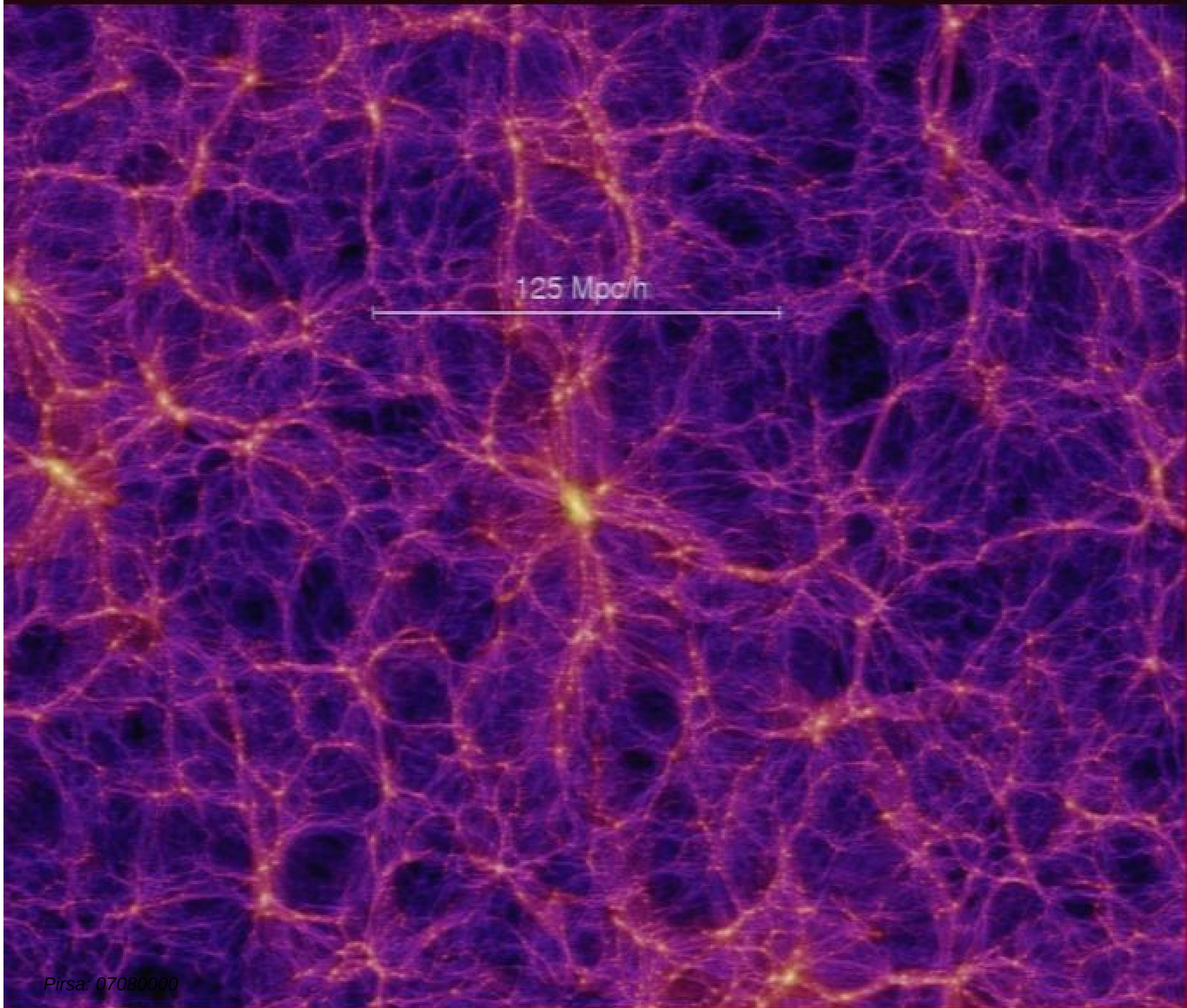

- Formal problem:

$$\delta_g = \delta_g(\delta, z)$$

Biasing scheme

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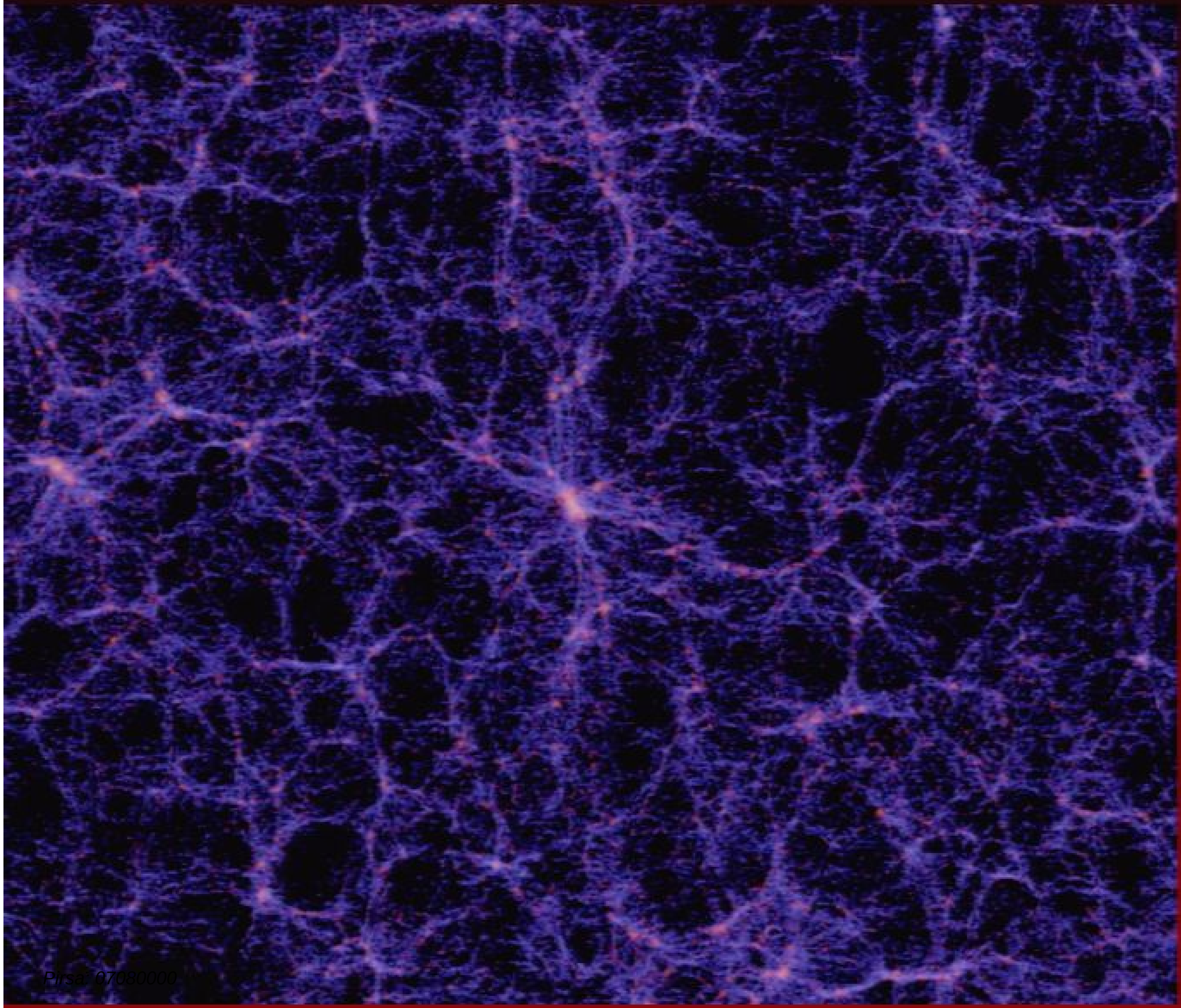

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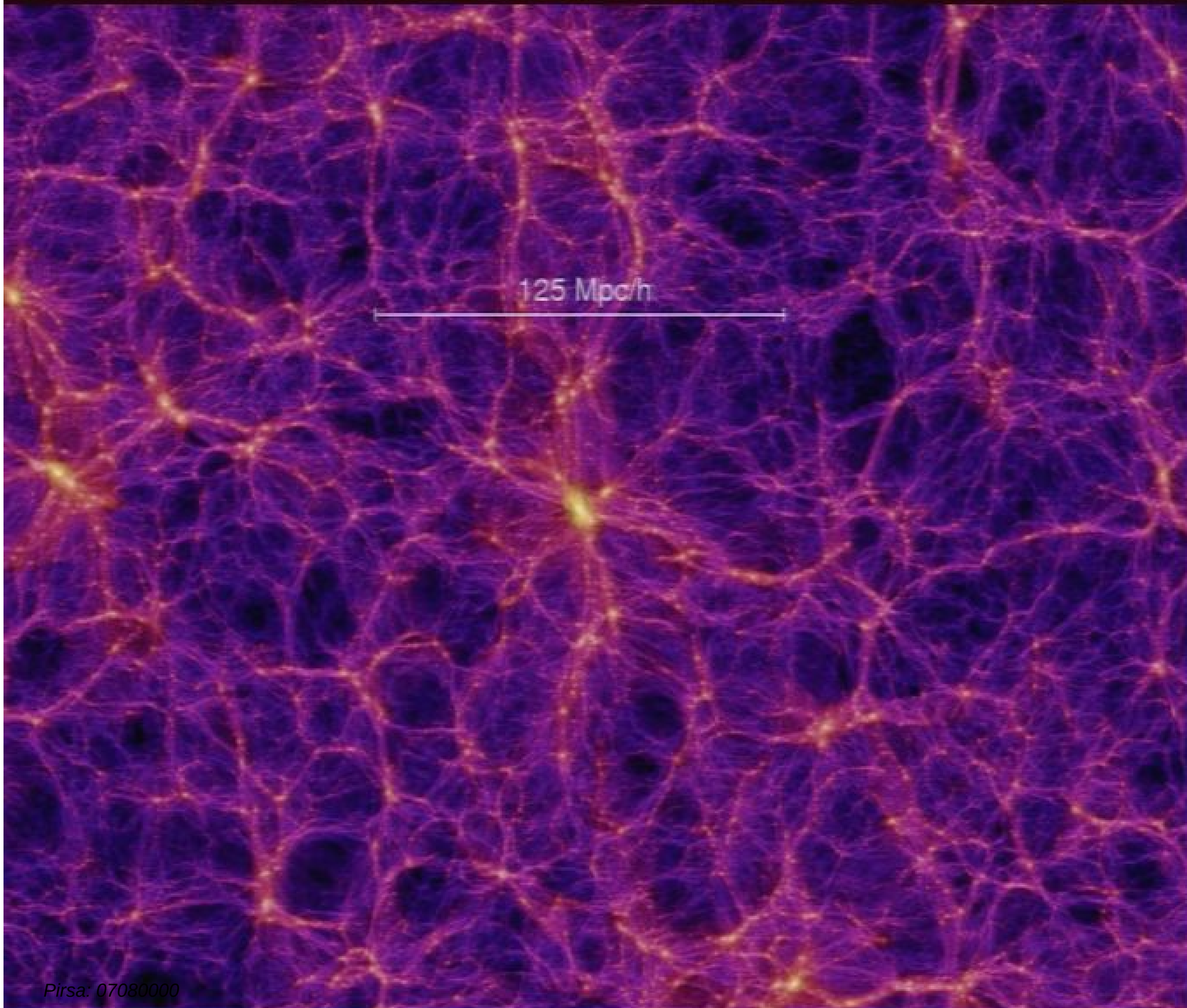

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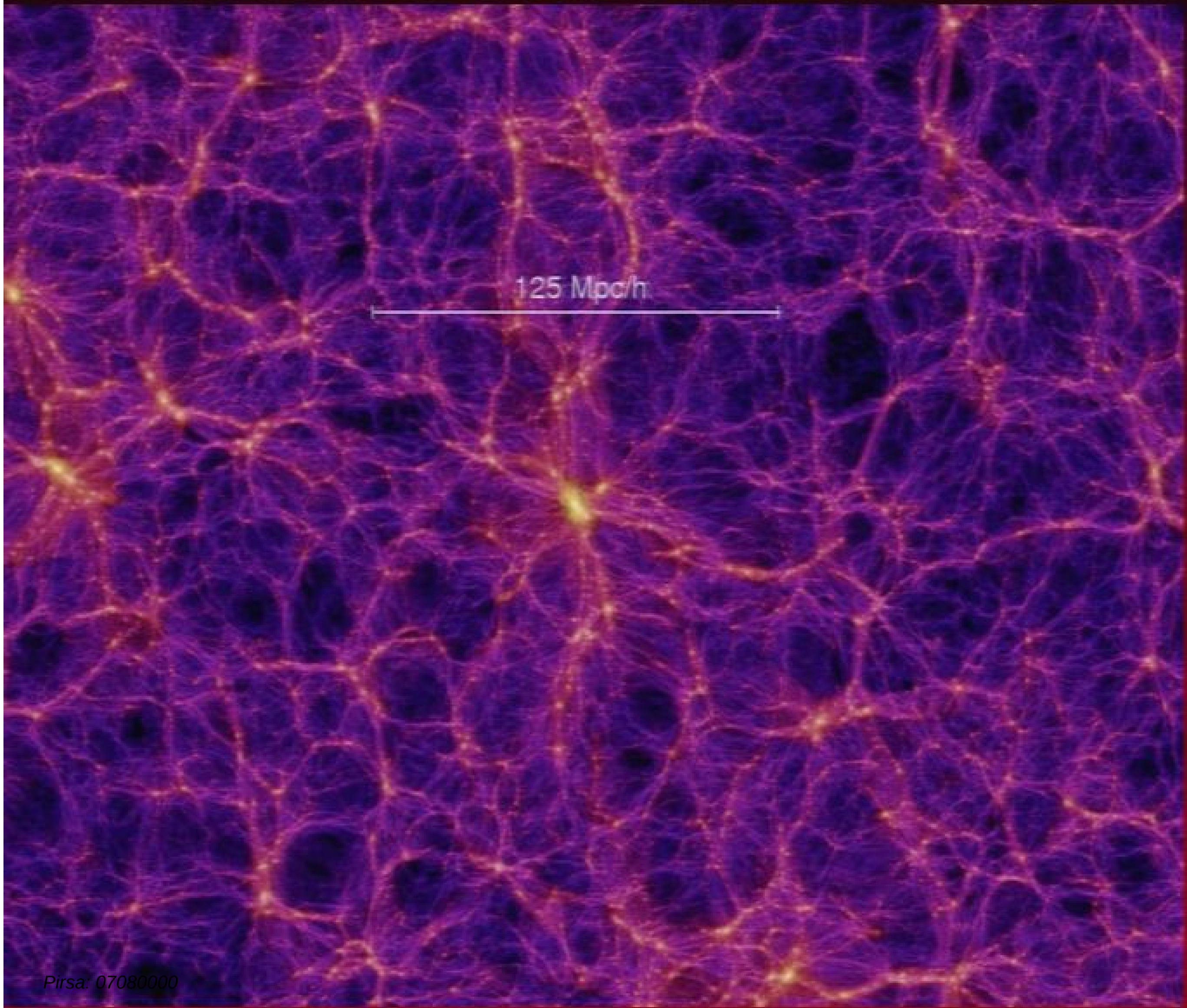

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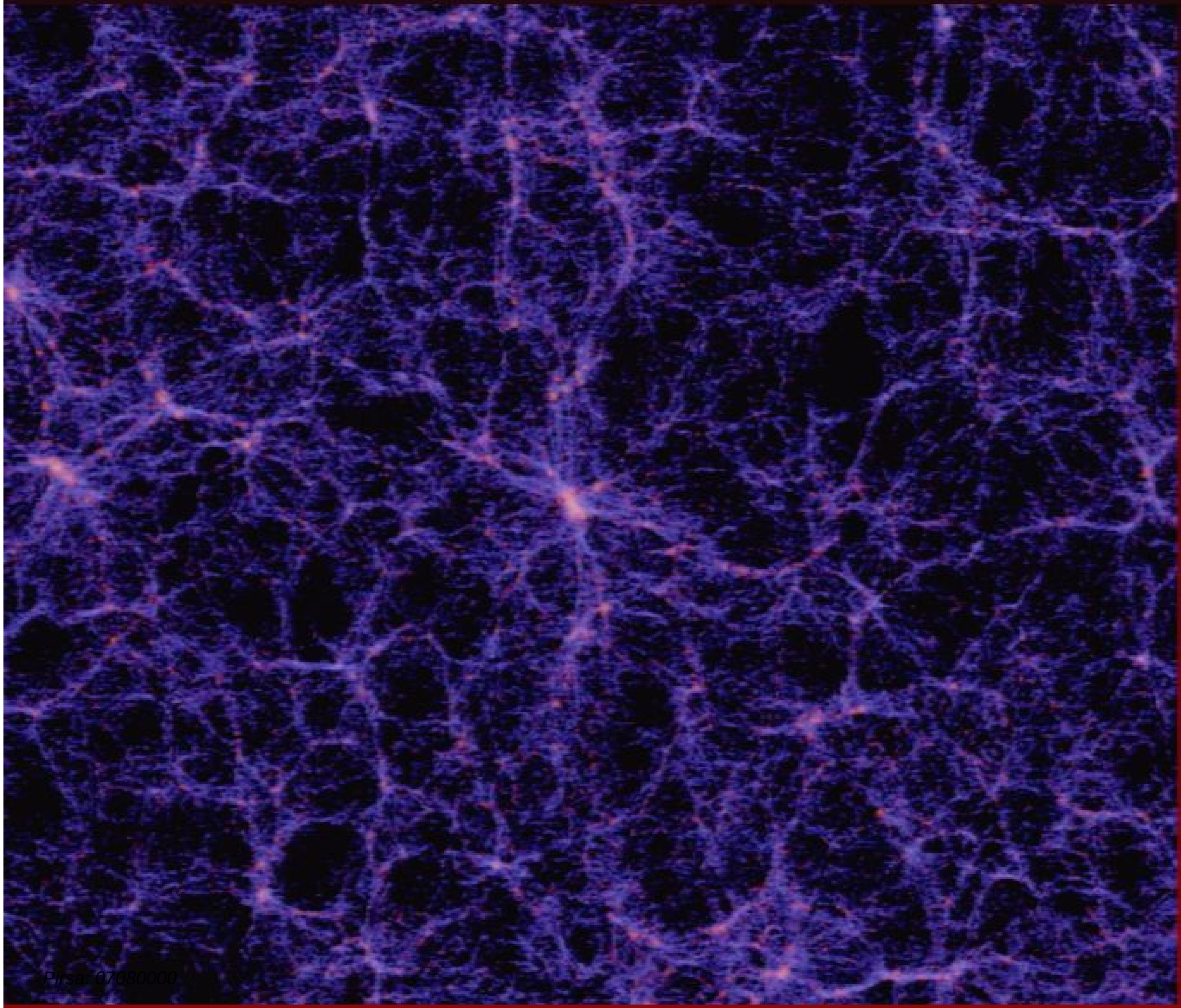

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What do we know about biasing? The theorist point of view....

- Bias must exist on small scales
  - Halo and galaxy profiles differs
  - Void phenomenon

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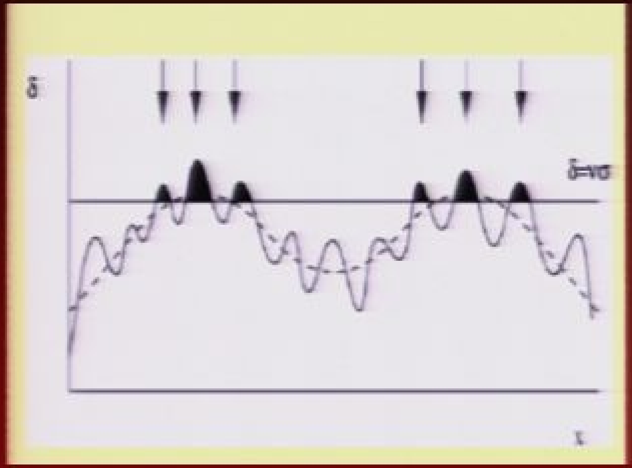
- ......and also on large cosmological scales!

$$Hp: \; P(\delta, \delta', r) = Gaussian$$

$$Hp: \; \delta_\nu(\vec{x}) \geq \nu\sigma_R \qquad \nu \in \Re^+$$

$$< \delta_\nu(\vec{x})\delta_\nu(\vec{x}+\vec{r}) > \approx \nu^2 < \delta(\vec{x})\delta(\vec{x}+\vec{r}) >$$



Peaks (galaxies) are more correlated than the field (Dark Matter)

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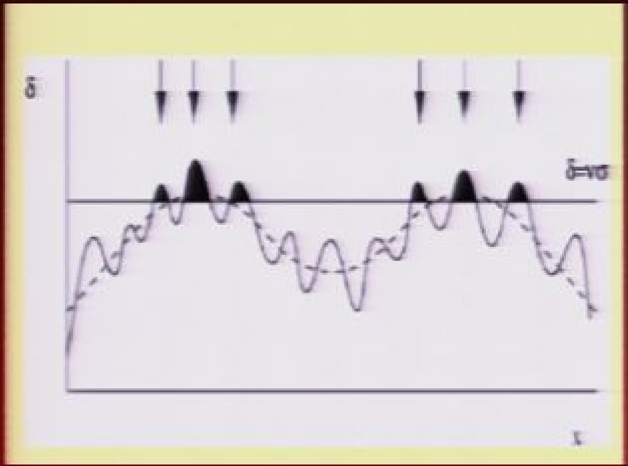

Peaks (galaxies) are more correlated than the field (Dark Matter)

- It might evolve with time!

galaxies are initially biased ($\delta_g = b\delta$) and satisfy continuity (they are neither formed nor estroyed during evolution) then there is a natural gravitational debiasing mechanism

$$\dot{\delta}_g + \nabla \cdot \vec{v} = 0$$

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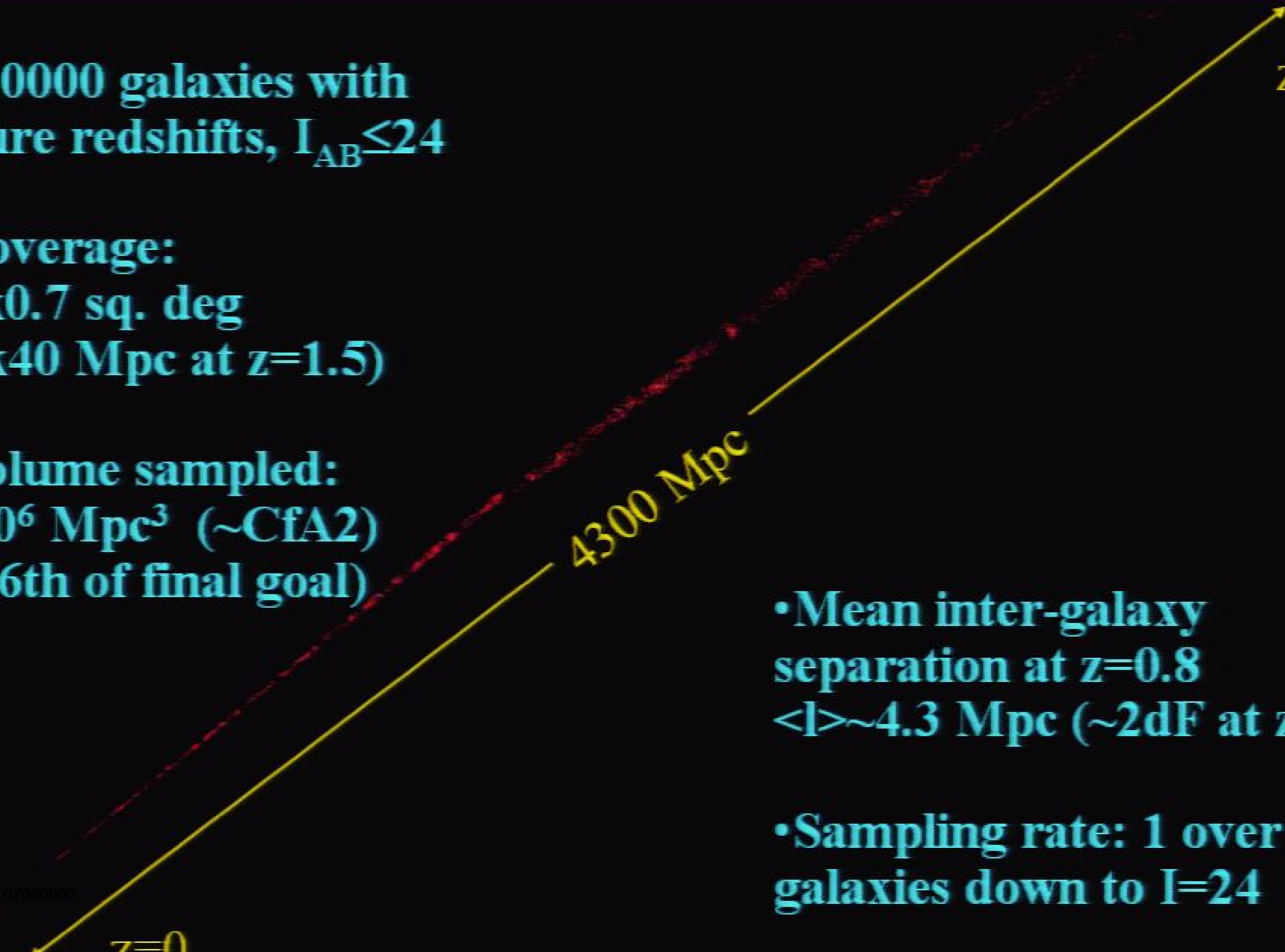
$$b(t) - 1 \propto \delta^{-1}$$

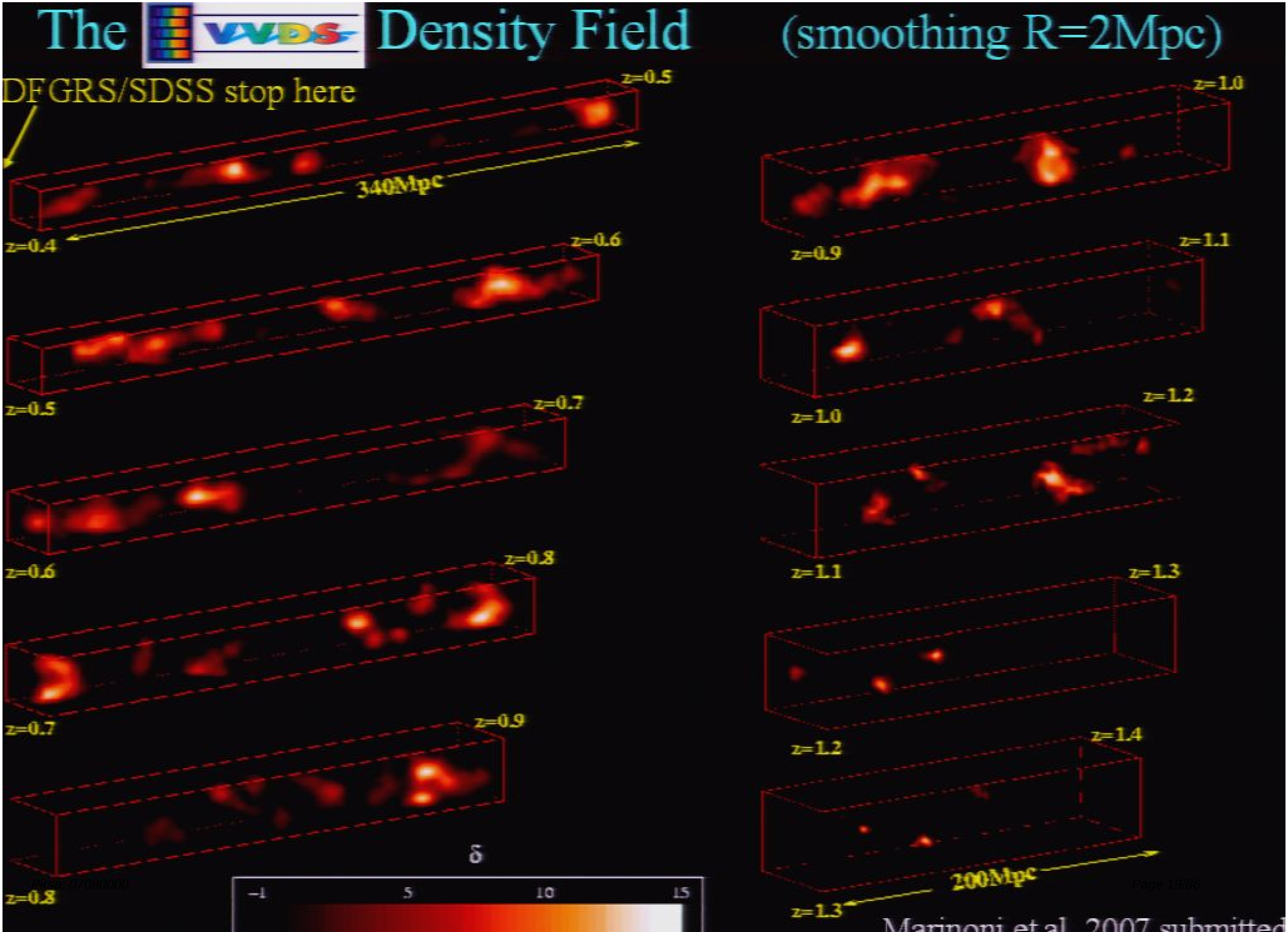
Bias decrease in time while remaining constant in space

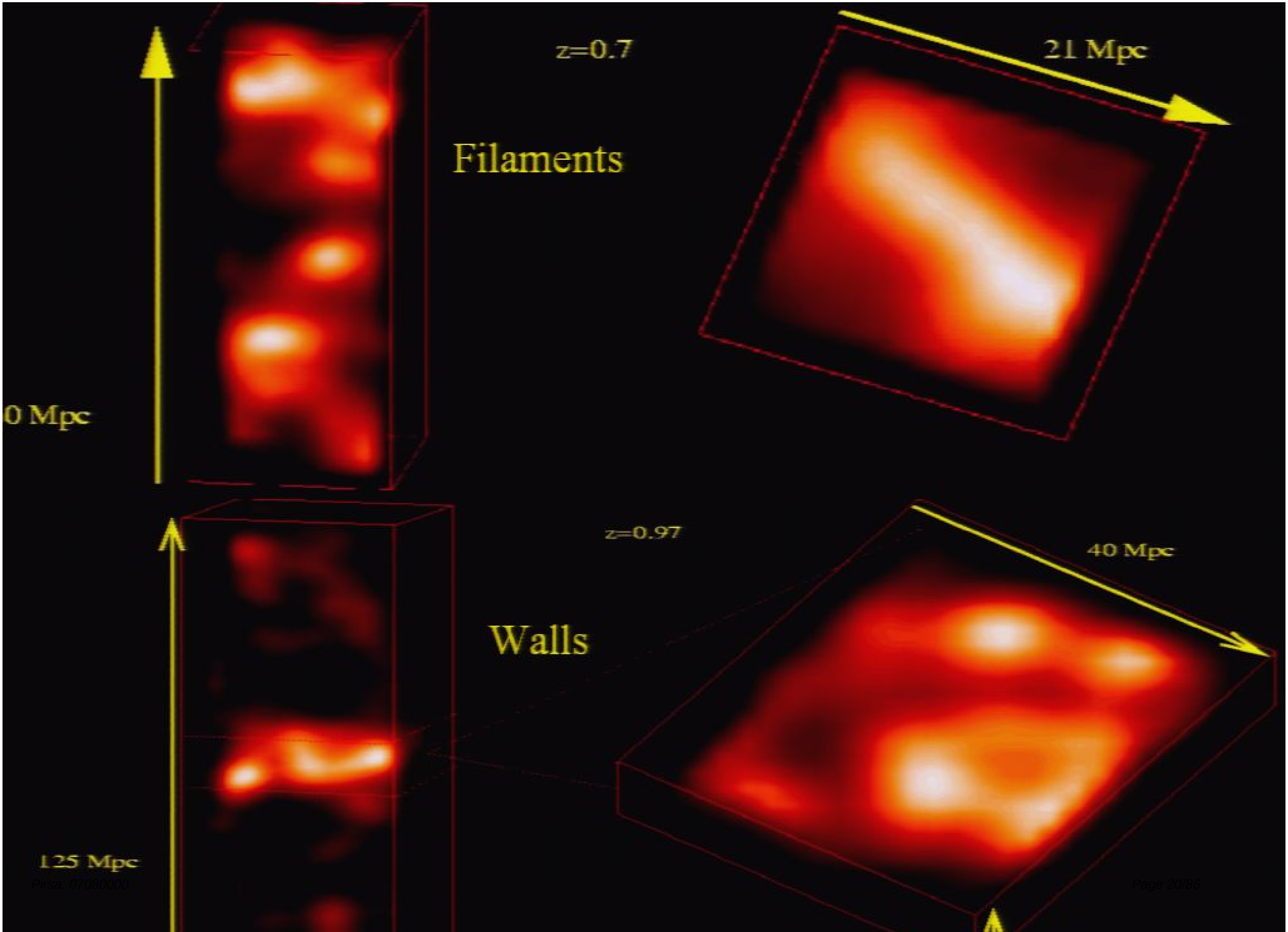
Sample: VVDS Deep "cone"
(2h Field: first-epoch data)

- ~10000 galaxies with secure redshifts, $I_{AB} \leq 24$
- Coverage: 0.7x0.7 sq. deg (40x40 Mpc at z=1.5)
- Volume sampled: 2×10^6 Mpc^3 (~CfA2) (1/16th of final goal)

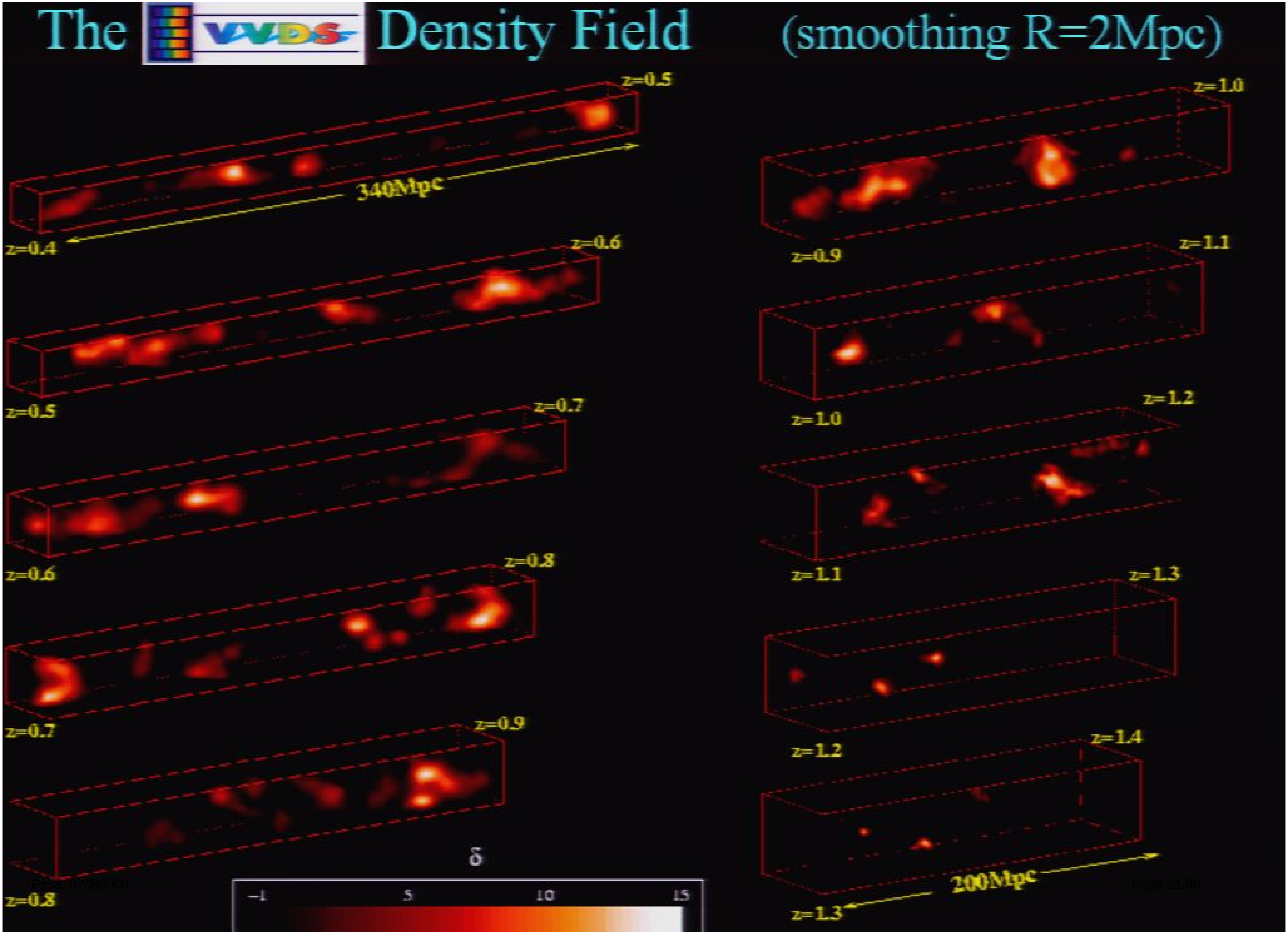


- Mean inter-galaxy separation at z=0.8 <l>~4.3 Mpc (~2dF at z=0.1)
- Sampling rate: 1 over 3 galaxies down to I=24


The VVDS Density Field (smoothing R=2Mpc)
DFGRS/SDSS stop here
340Mpc
200Mpc
z=0.4
z=0.5
z=0.6
z=0.7
z=0.8
z=0.9
z=1.0
z=1.1
z=1.2
z=1.3
z=1.4
δ
-1
5
10
15
Marinoni et al. 2007 submitted



z=0.7
21 Mpc
Filaments
0 Mpc
z=0.97
40 Mpc
Walls
125 Mpc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z=1.3
z=1.4
200Mpc
δ
-1
5
10
15

The VVDS Density Field (smoothing R=2Mpc)

Traditionally the density field has been characterized in terms of the auto-correlation function

$$\xi(\vec{r}) = < \delta(\vec{x})\delta(\vec{x}+\vec{r}) >$$

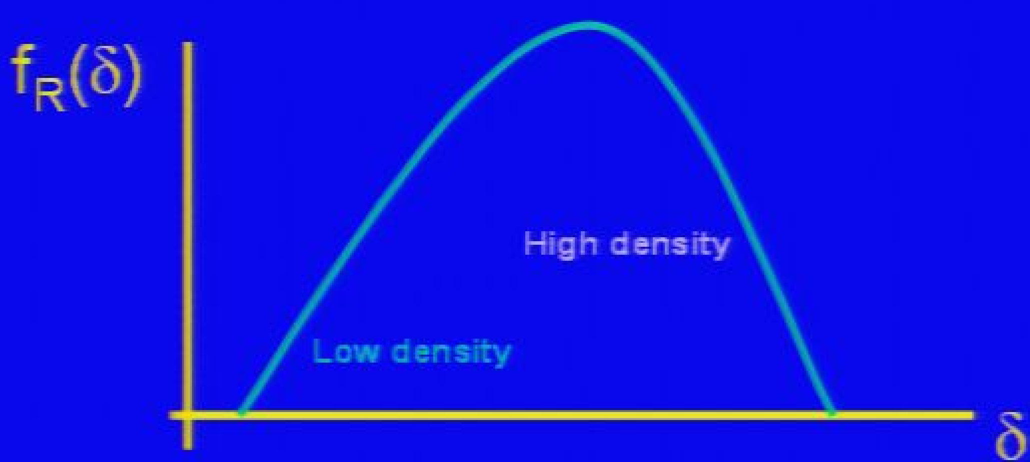
Excess probability, with respect to random, of finding two fluctuations with separation r

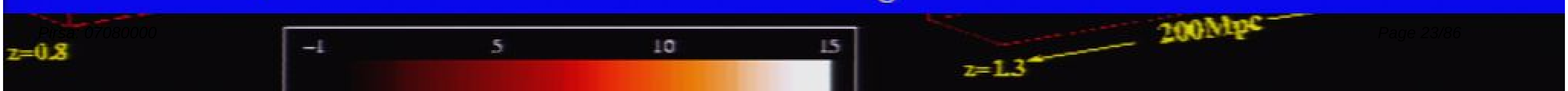
If the distribution is gaussian then the statistical properties of the delta field are completely determined by the 2point correlation function

The VVDS Density Field (smoothing R=2Mpc)

The Probability Distribution Function (PDF) of galaxy overdensities

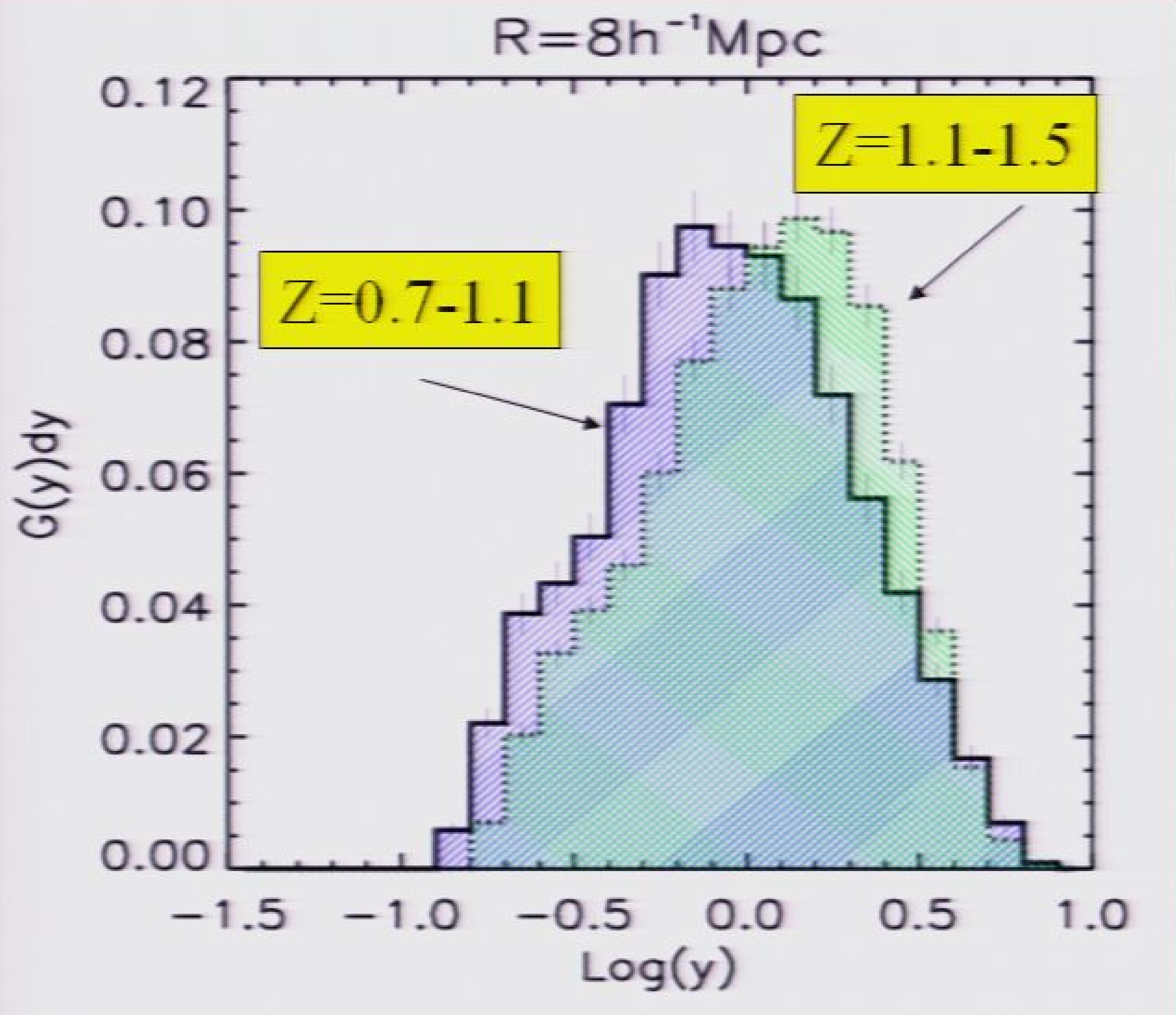
Probability of having a density fluctuation in the range $(\delta,\delta+d\delta)$ within a sphere of radius R randomly located in the survey volume





Time Evolution of the galaxy PDF

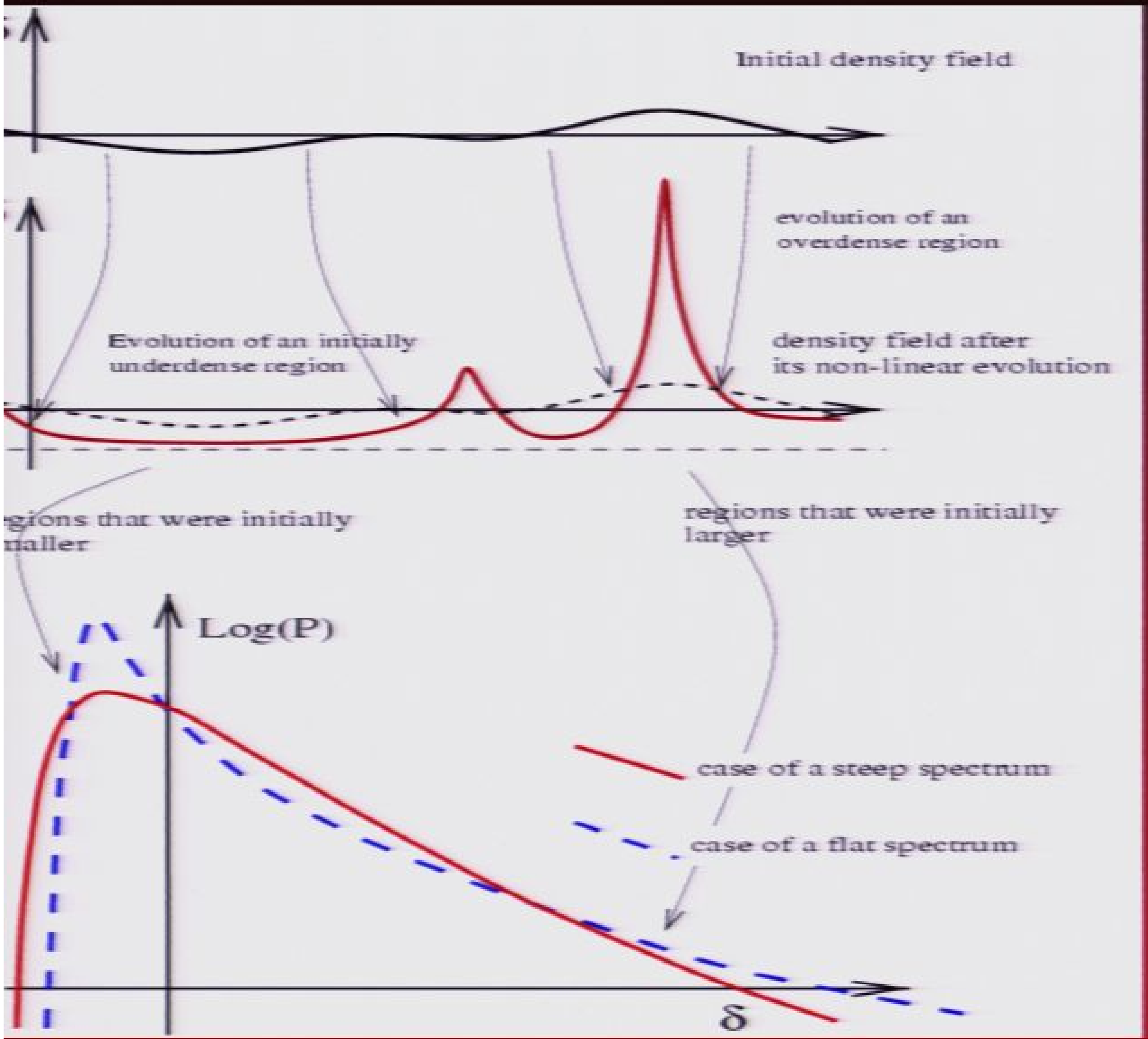
The 1P-PDF of galaxy overdensities $g_R(\delta)$



- The PDF is different at different cosmic epochs
- Systematic shift of the peak towards low density regions as a function of cosmic time
- Cosmic space becomes dominated by low density regions at recent epochs

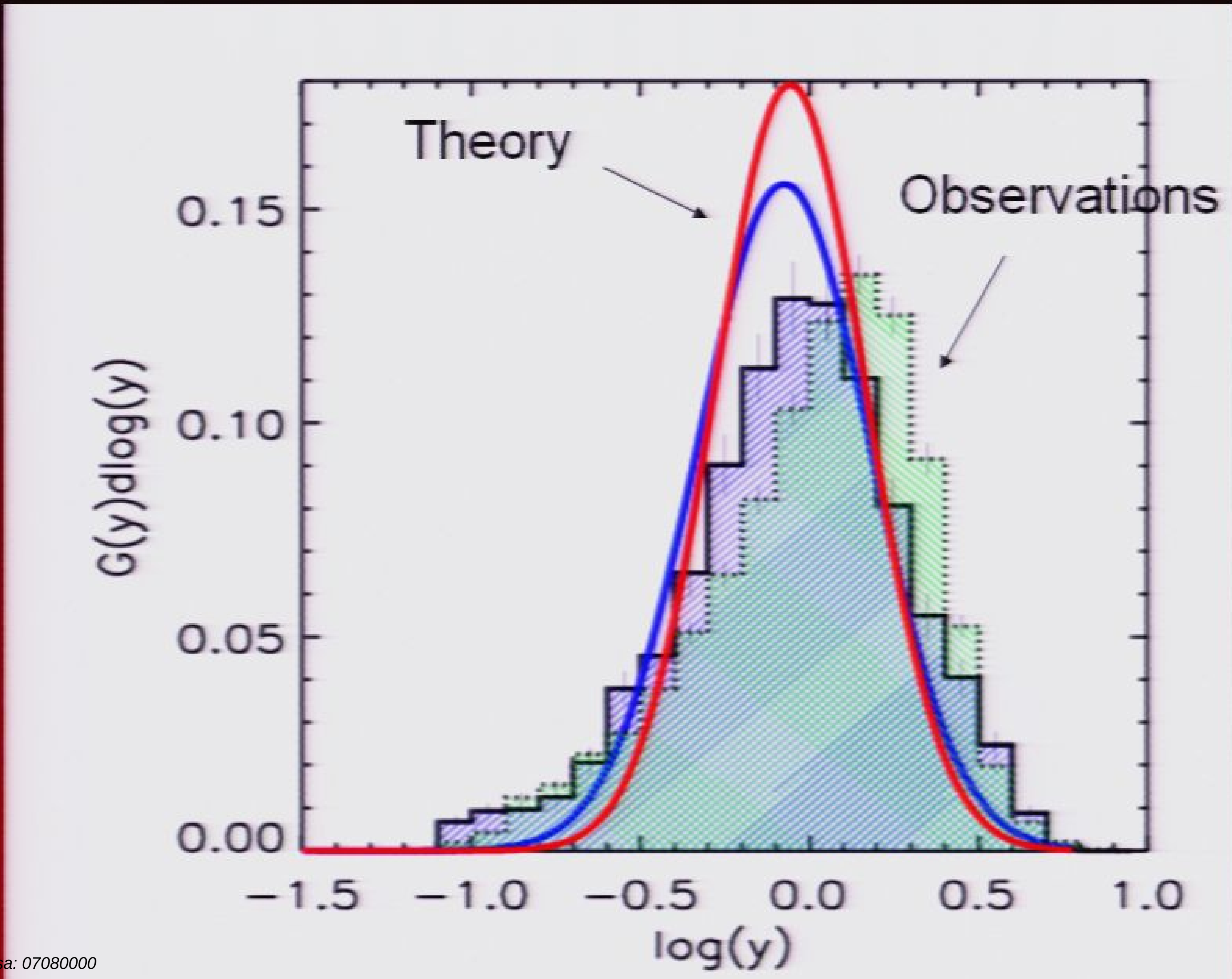
Volume limited sample M<-20+5log h

A possible Interpretation

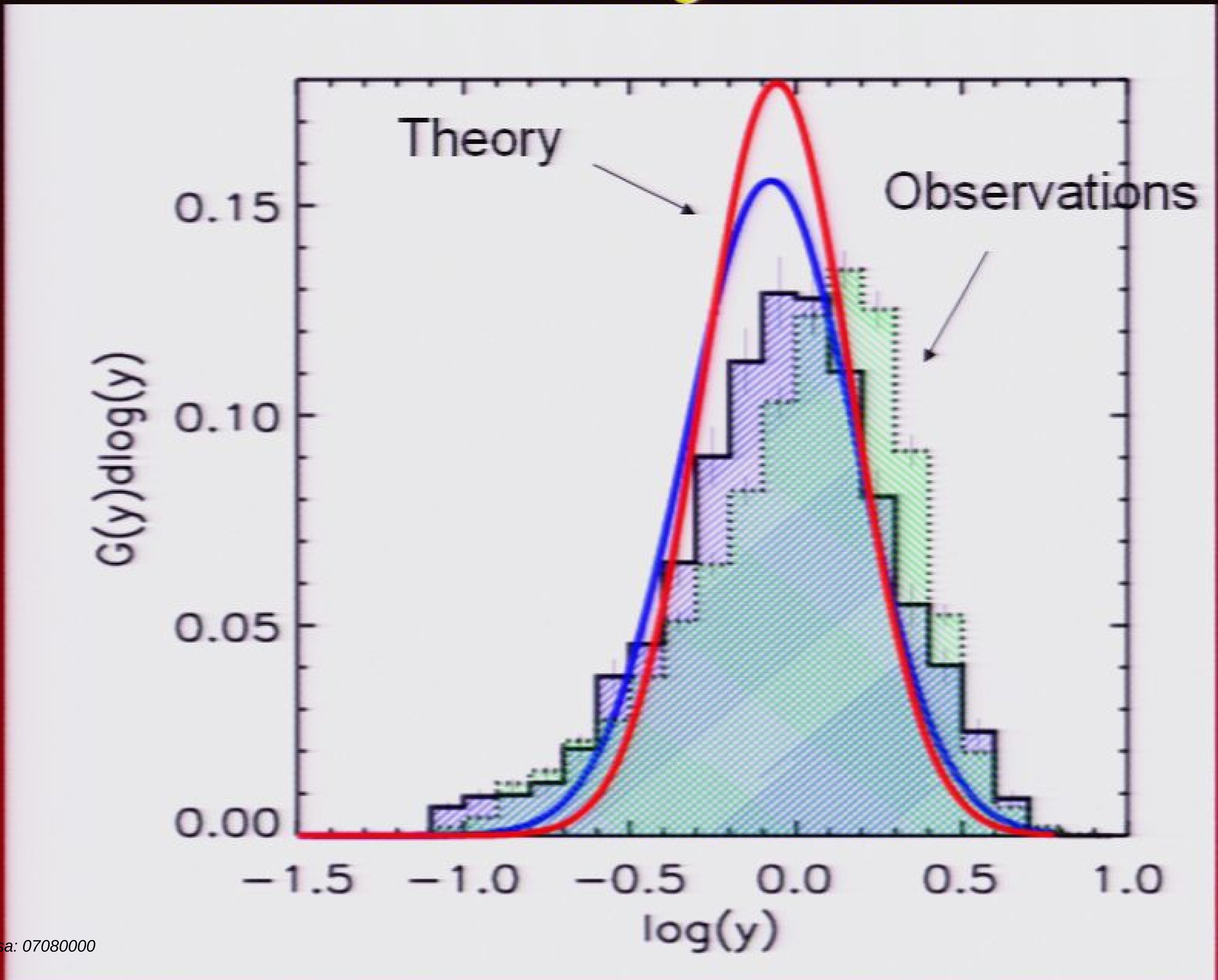


Gravitational instability in an <u>expanding</u> universe

$$\vec{v}(\vec{r}) \propto \int_V \delta(\vec{r}\,') \frac{\hat{r}-\hat{r}'}{|\vec{r}-\vec{r}\,'|^2} d^3\vec{r}\,'$$


Theory
Observations
0.15
0.10
0.05
0.00
G(y)dlog(y)
−1.5
−1.0
−0.5
0.0
0.5
1.0
log(y)

Light fluctuations does not trace mass fluctuations on large scales!!



Measuring galaxy bias

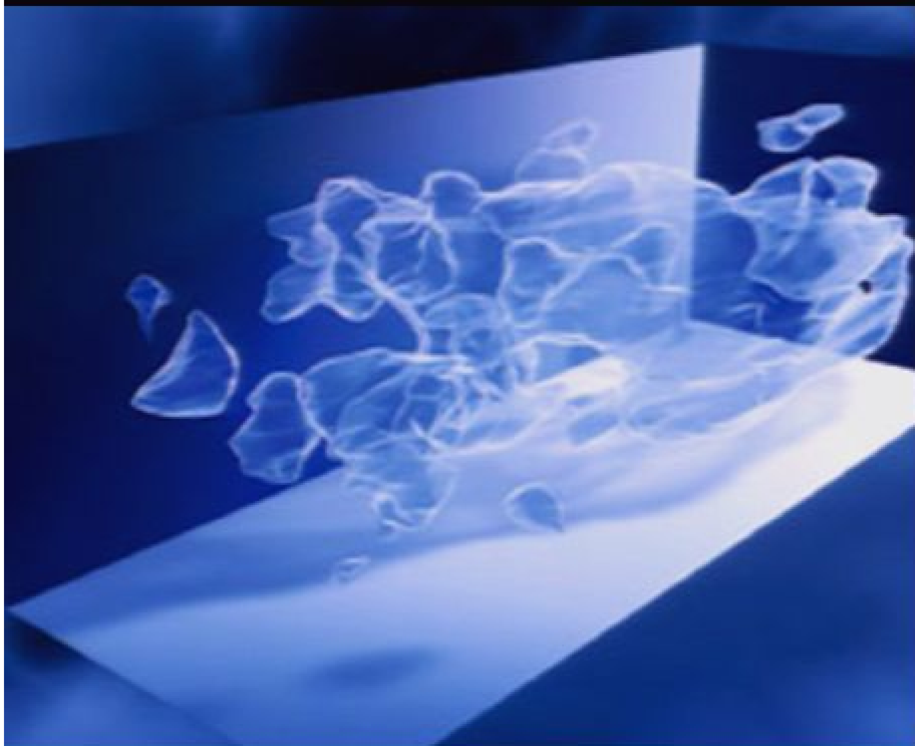
Bias: difference in distribution of DM and galaxy fluctuations

Linear Bias Scheme: $\delta_g = b\,\delta$ (Kaiser 1984)

Our goal: $\delta_g = \delta_g(z, \delta, R)$

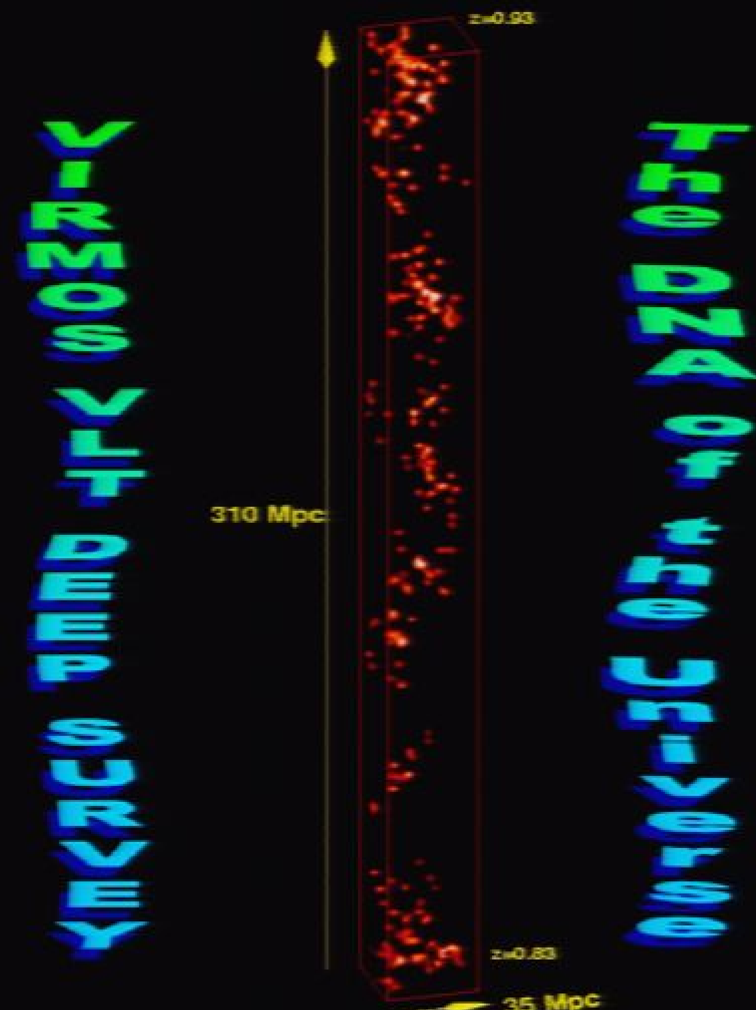
- Redshift evolution
- Non linearity
- Scale dependence

…BUT THE TIMES THEY ARE A-CHANGIN'



Massey et al. 2007 (ACS/COSMOS)

www.spacetelescope.org/news/html/heic0701.html



Marinoni et al. 2006 (VIMOS/VLT)

http://www.eso.org/outreach/press-rel/pr-2006/pr-45-06.htm

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Strategy $g(\delta_g)\,d\delta_g = \varphi(\delta)\,d\delta$ Marinoni & Hudson 2002; Ostriker et al. 2003

The PDF of mass: $\psi(\delta)$

Real Space Lognormal Model (Cole & Jones 1991, Springel et al. 2005)

$$\psi(y) = \frac{1}{\sqrt{2\pi\omega^2}} \frac{1}{y} Exp\left[-\frac{(\ln y + \omega^2/2)^2}{2\omega^2} \right]$$

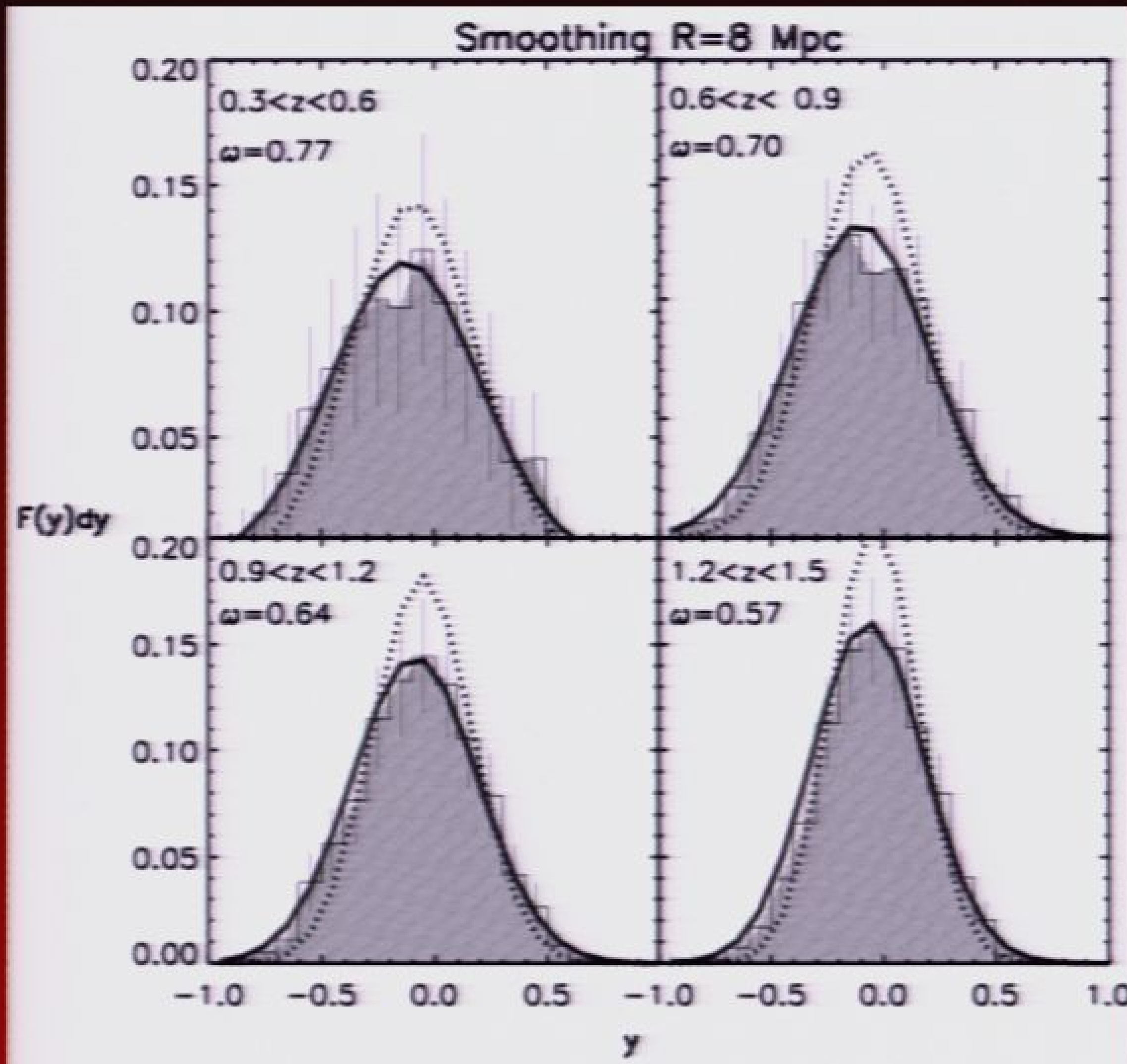
$$y = 1 + \delta \qquad \omega^2 = \ln[1 + \sigma_r(R,z)^2]$$

$$\sigma_r(z,R) = \sigma_r(0,R) D(z)$$

Problem: we measure the PDF of galaxies in redshift space!

$$\sigma_z(R,z)$$

Is the z-space lognormal PDF a good model ?



ΛCDM Millenium Simulation (Virgo consortium)

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- **Derive the biasing function** $\delta_g = \delta_g(\delta)$

The PDF of galaxy overdensities g(δ): Shape

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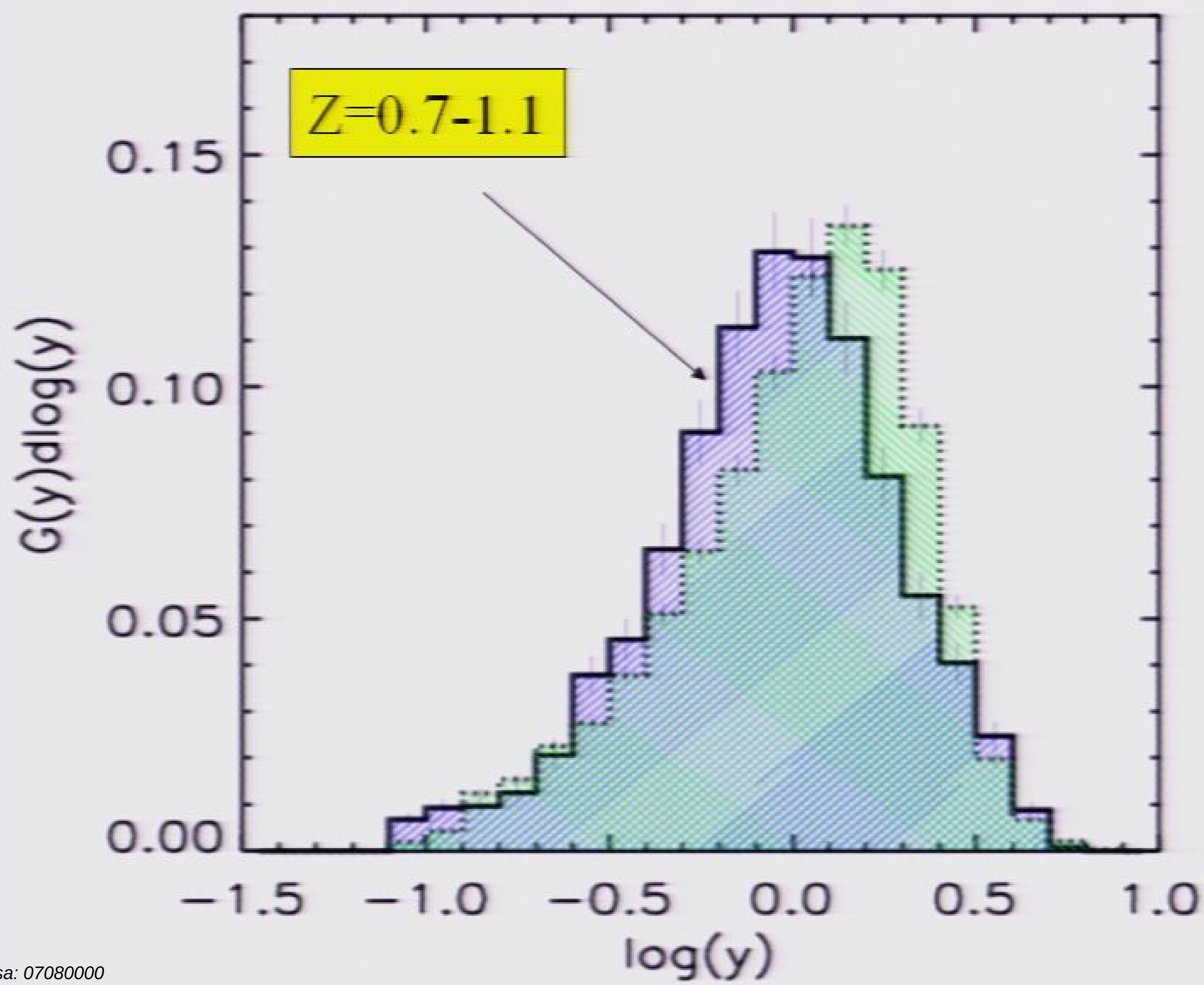

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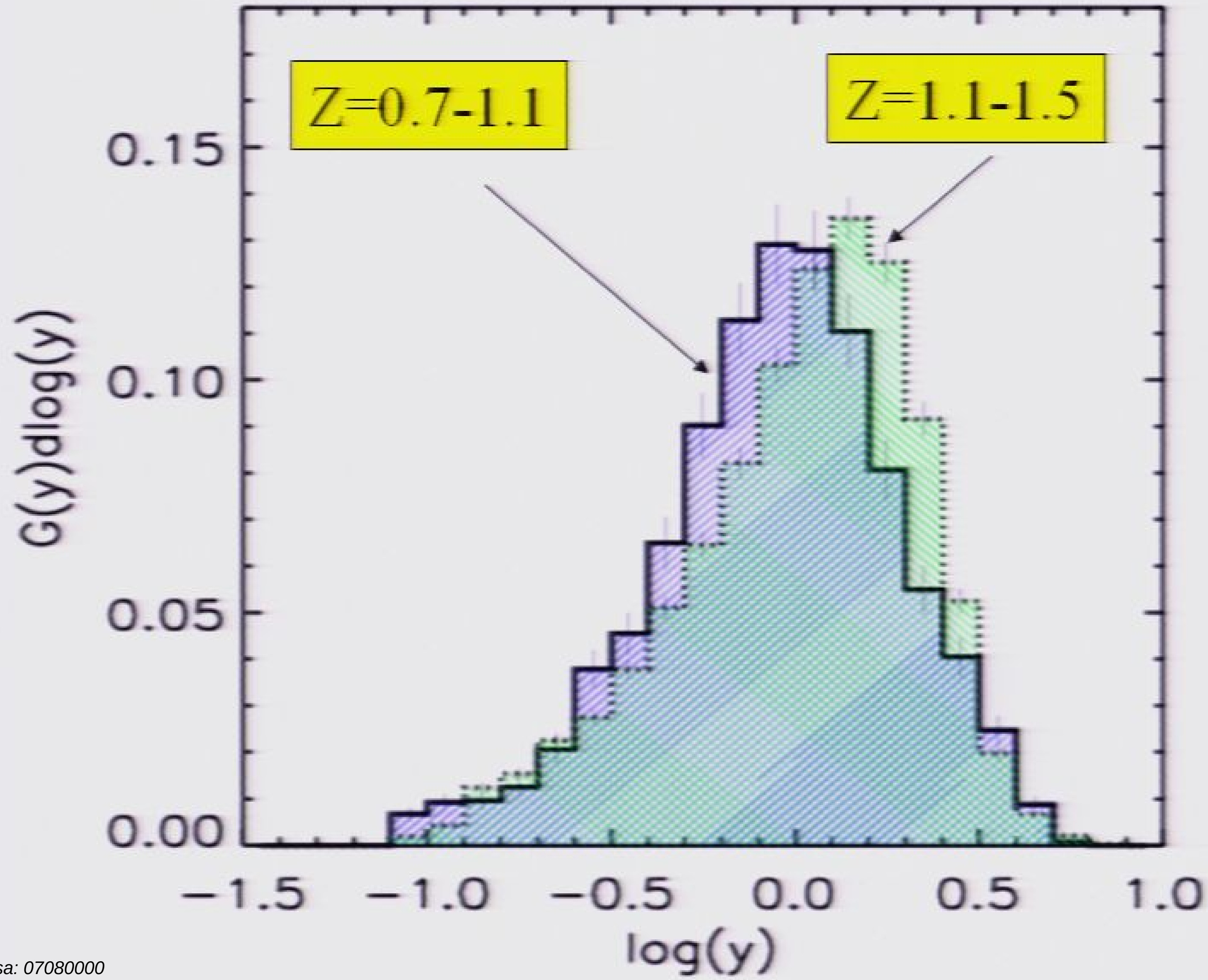

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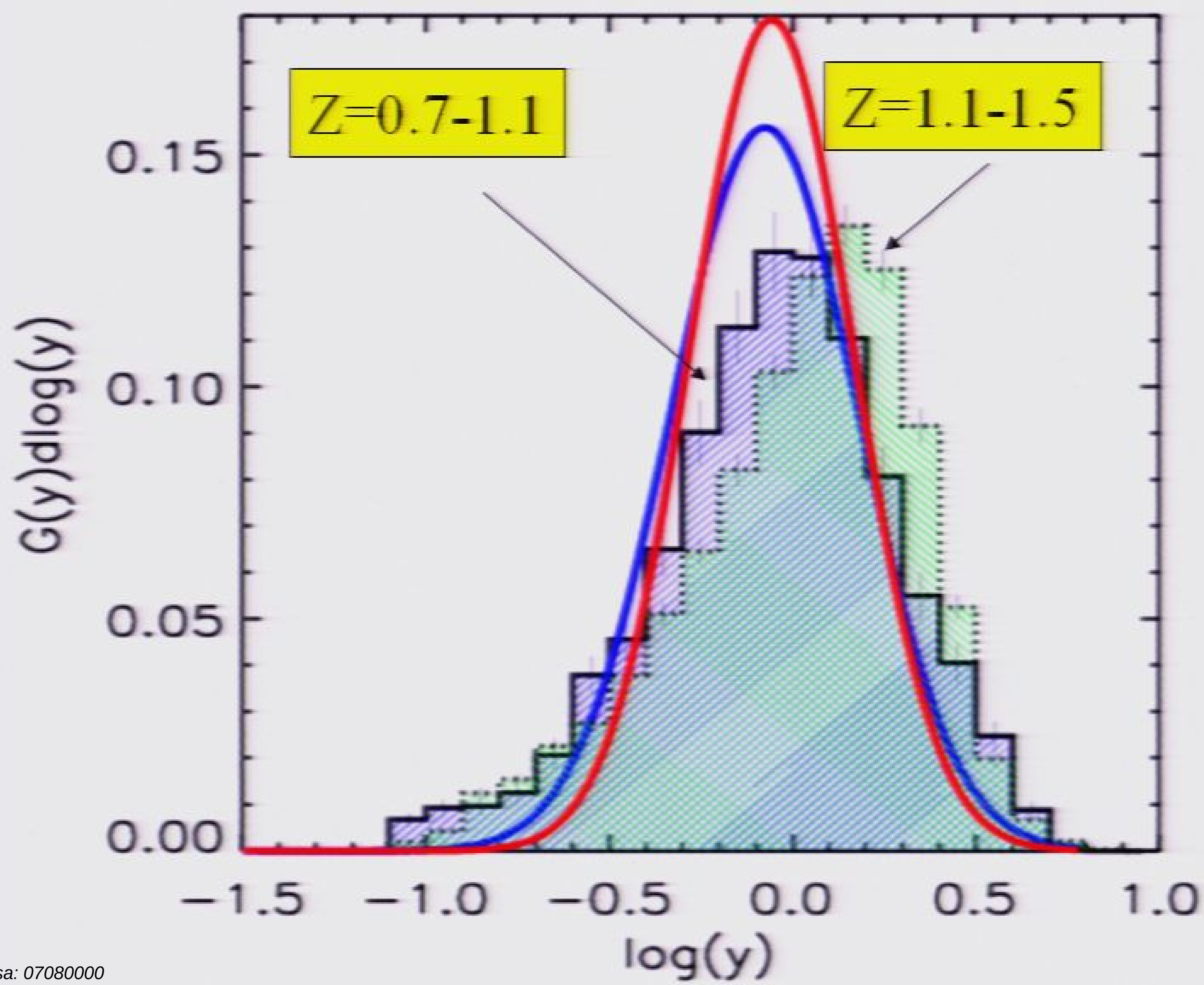

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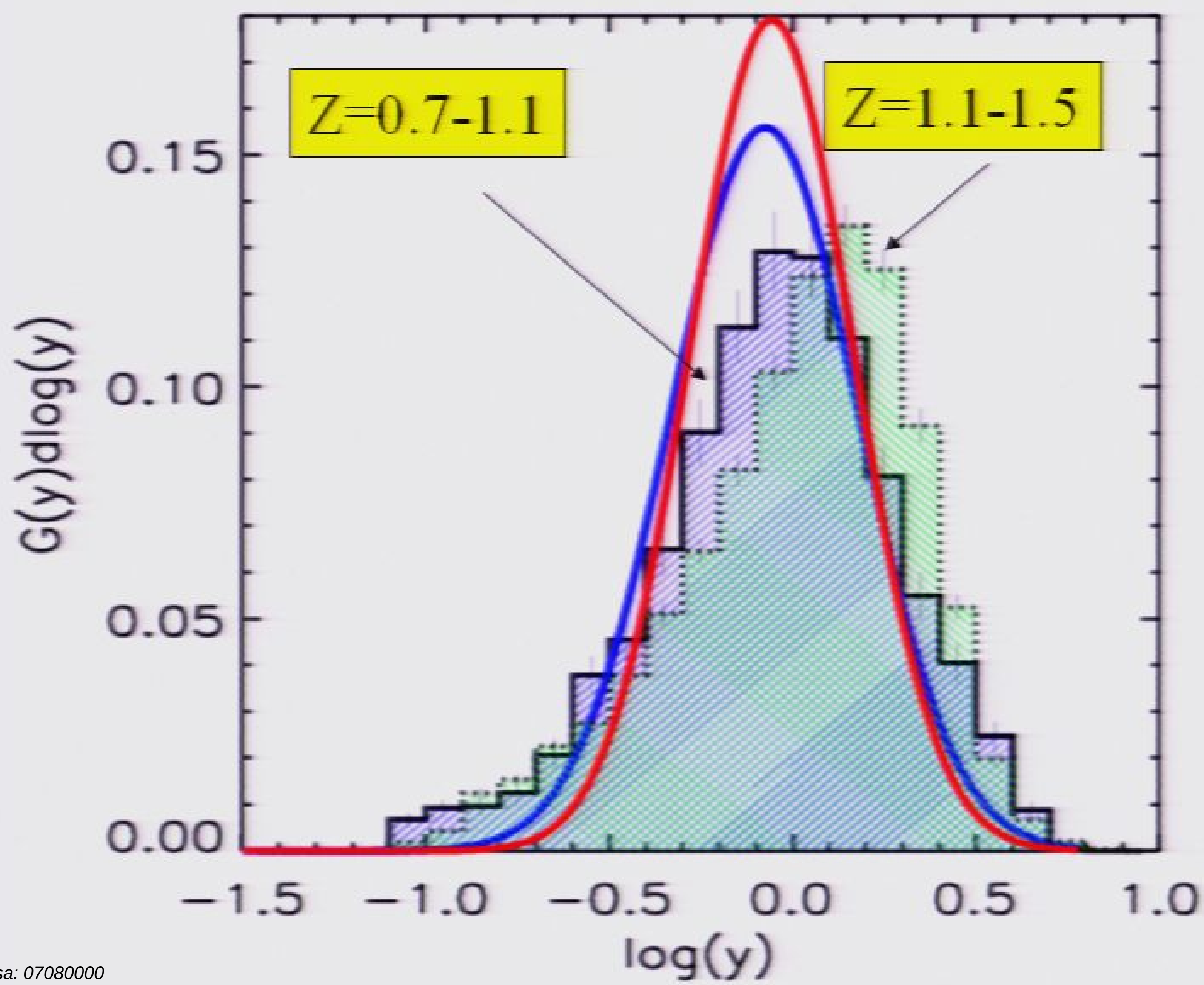

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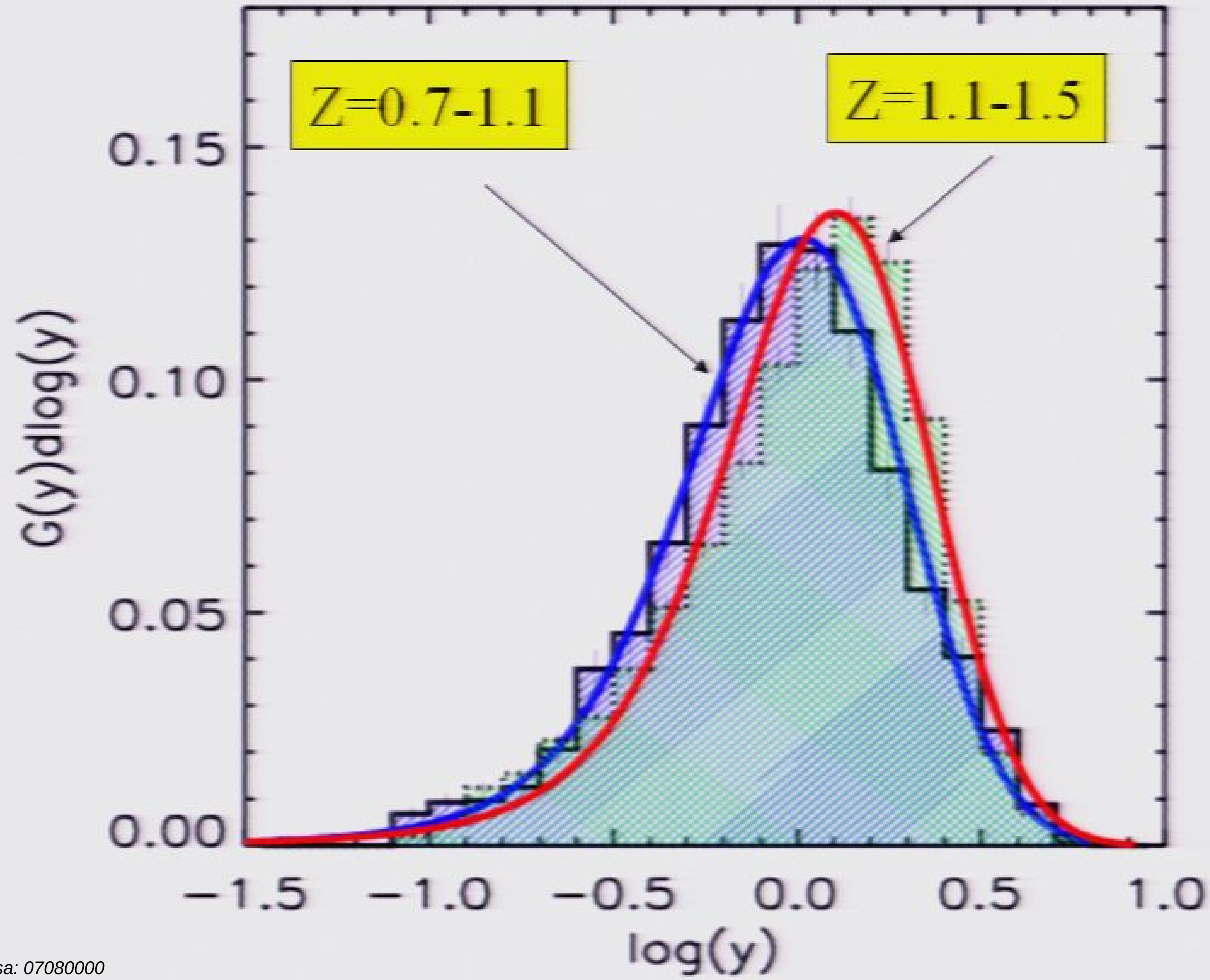

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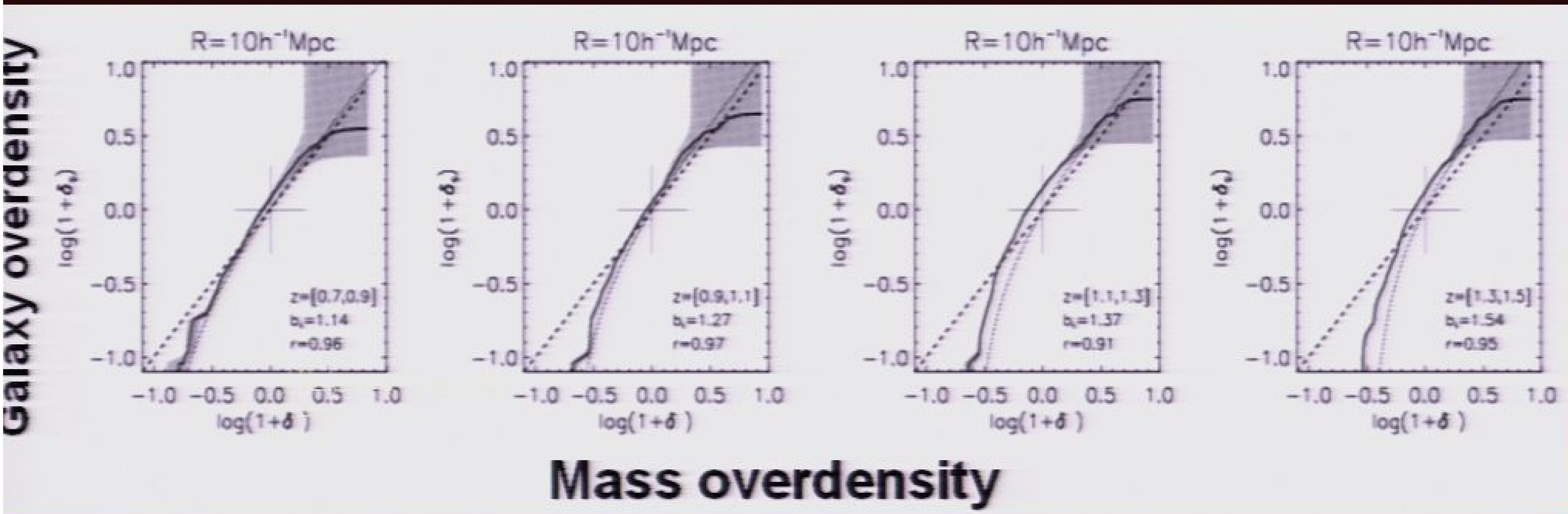
The biasing function: Shape

Redshift evolution

olume limited sample (M<-20+5log h)

z



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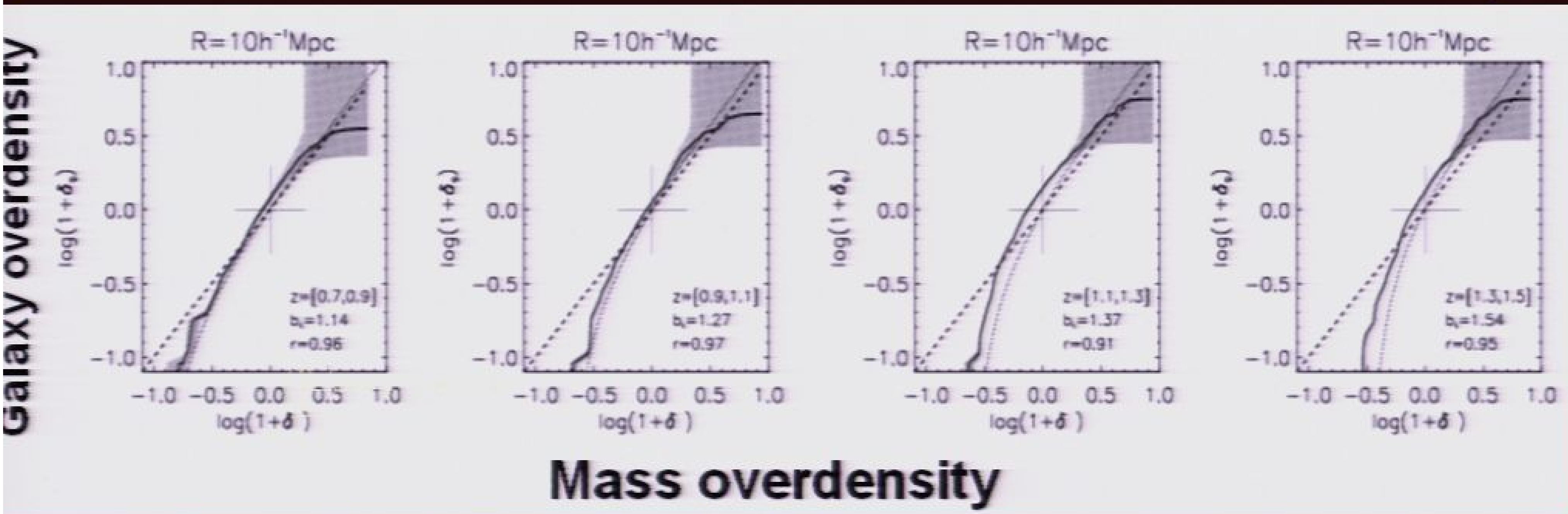

Non linearity at a level <10% on scales 5<R<10 Mpc

(Local slope is steeper (bias stronger) in underdense regions)

$$\delta_g = \sum_k \frac{b_k}{k!}\delta^k \qquad \left\langle \frac{b_2}{b_1} \right\rangle = -0.19 \pm 0.04$$

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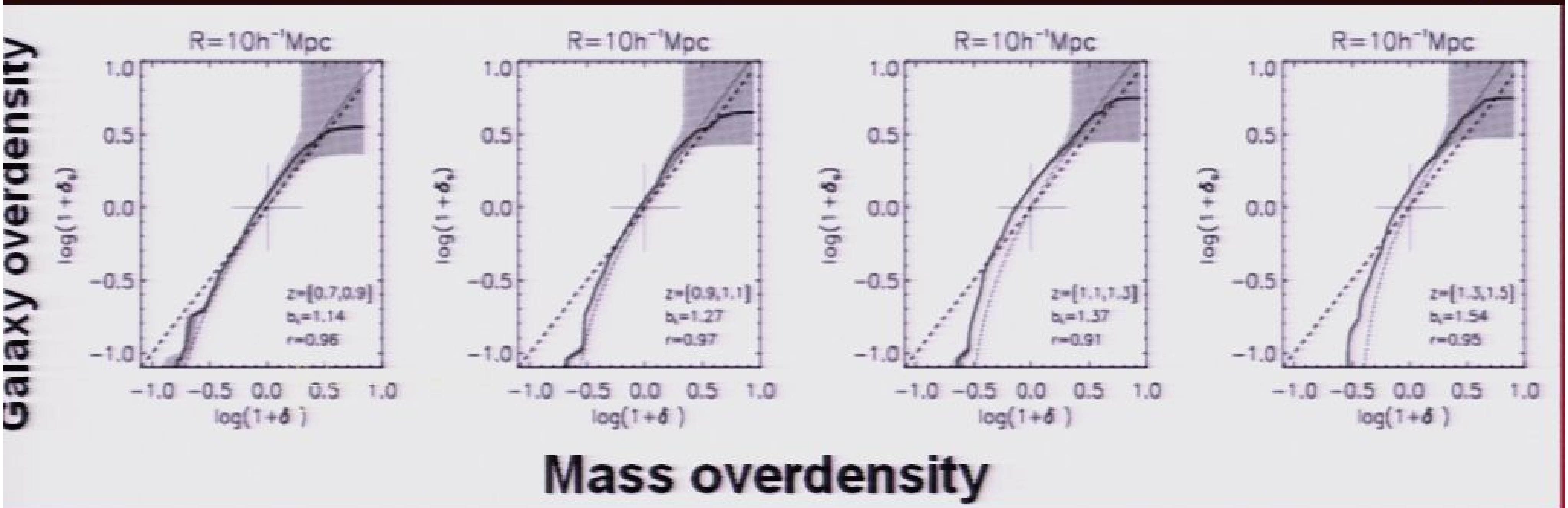

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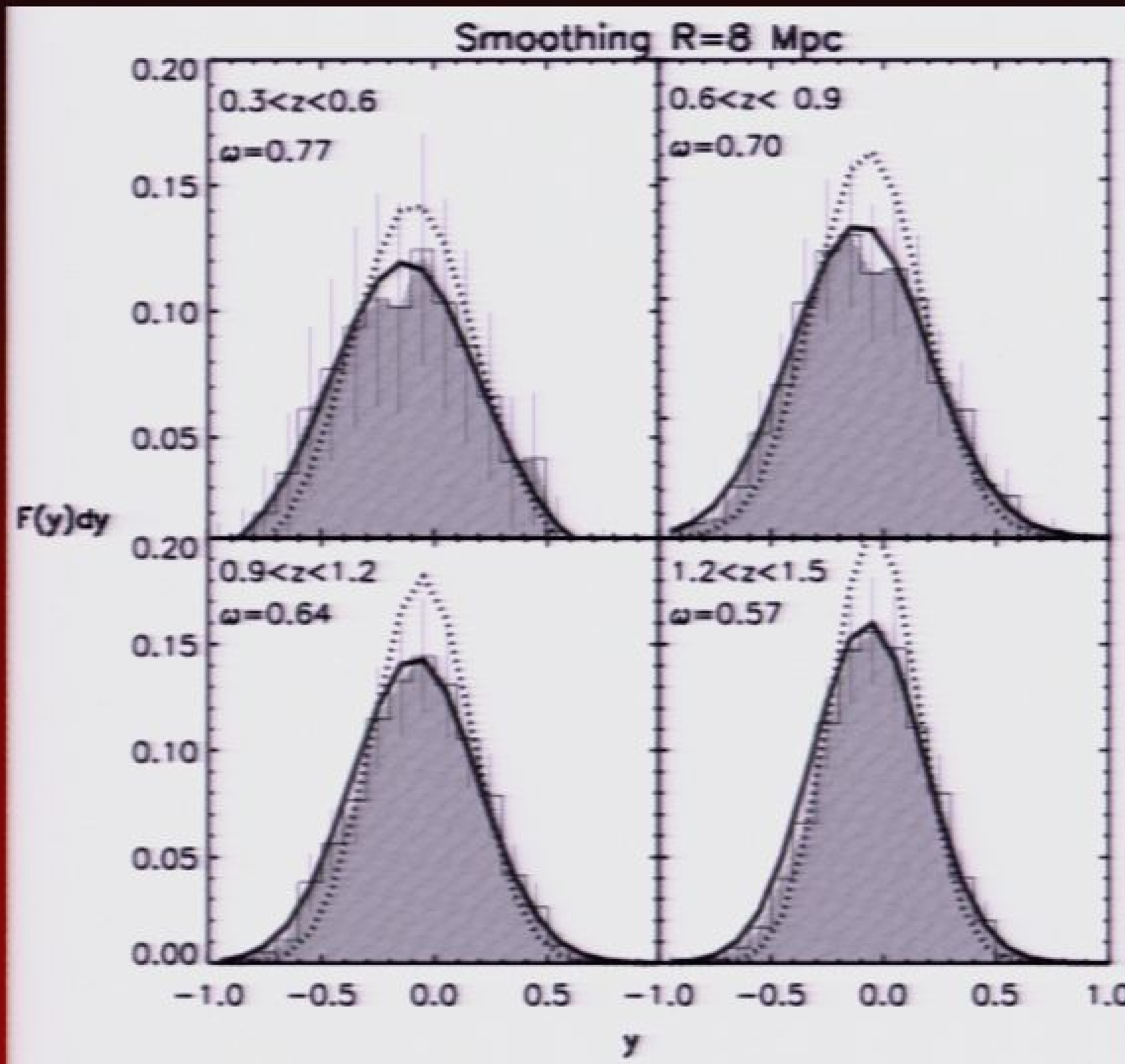

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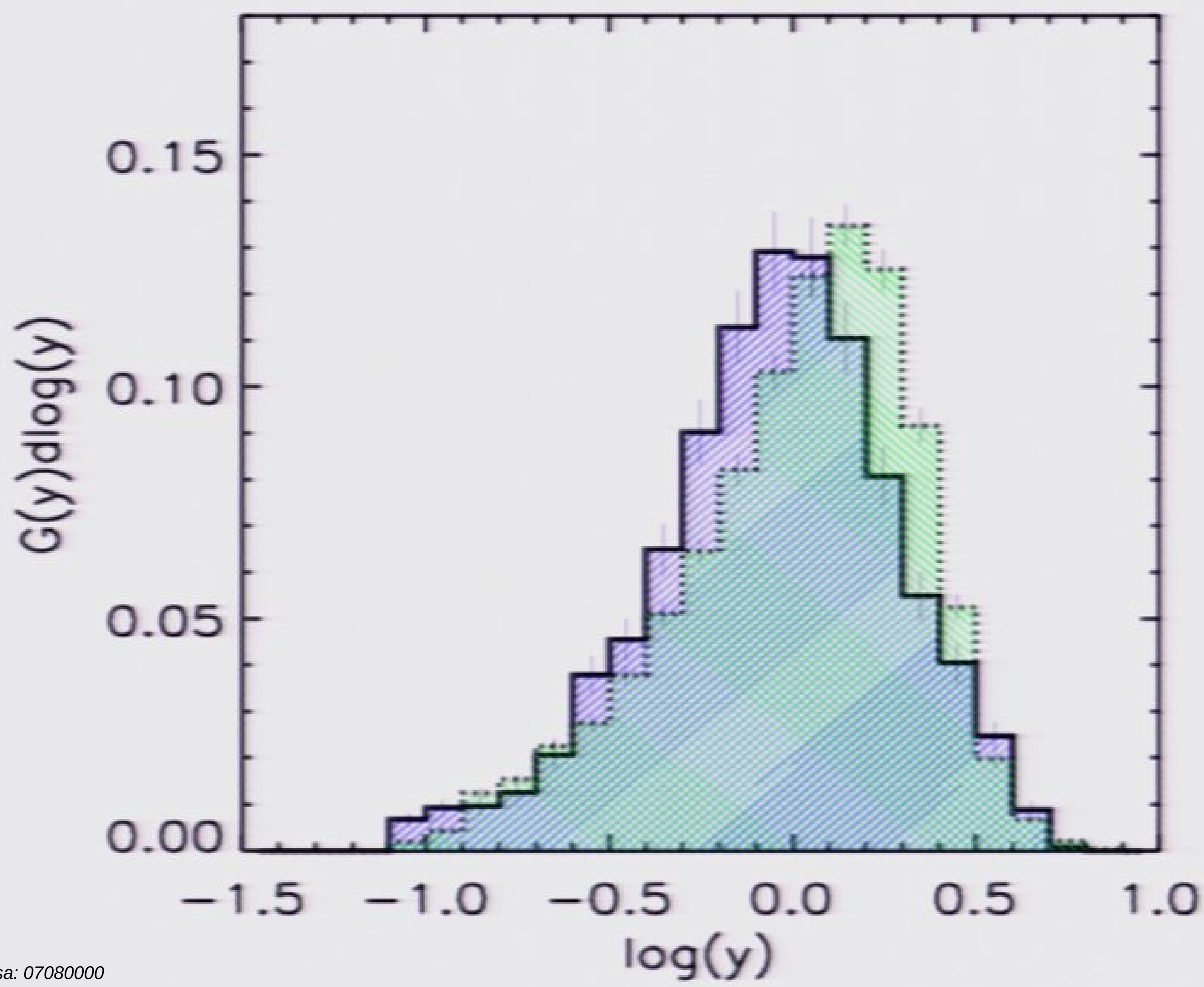

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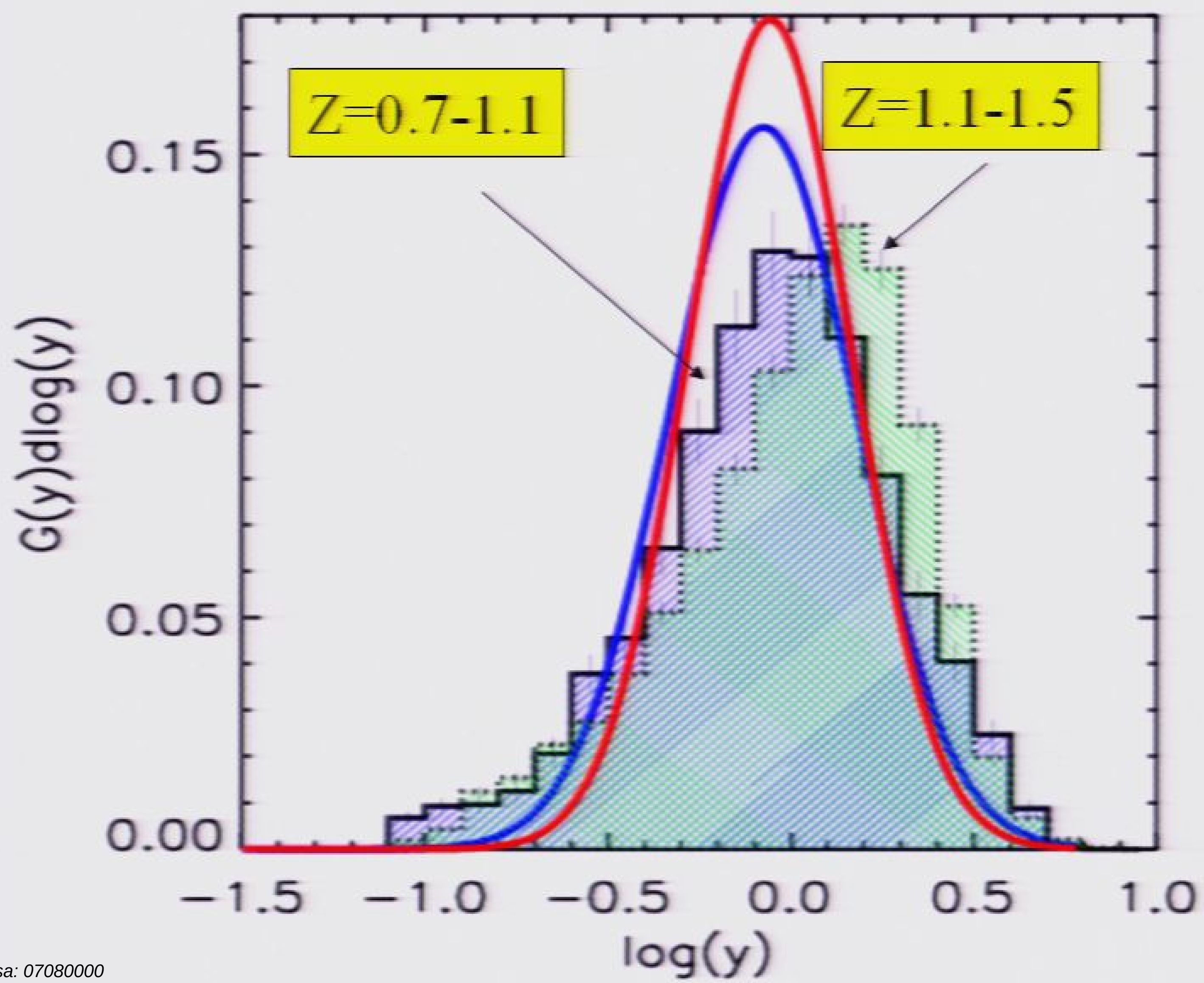

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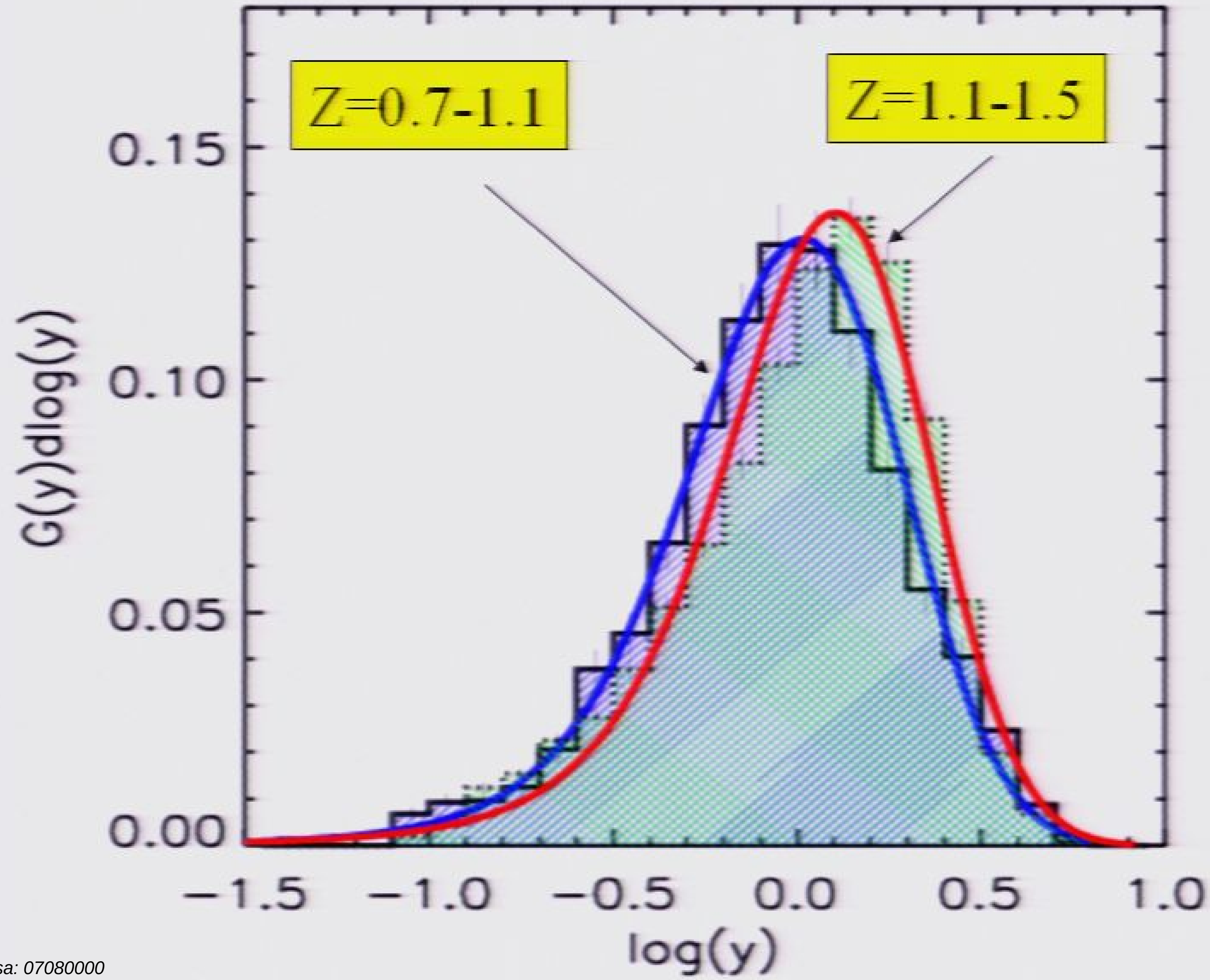

$$\delta_g = \delta_g(\delta)$$

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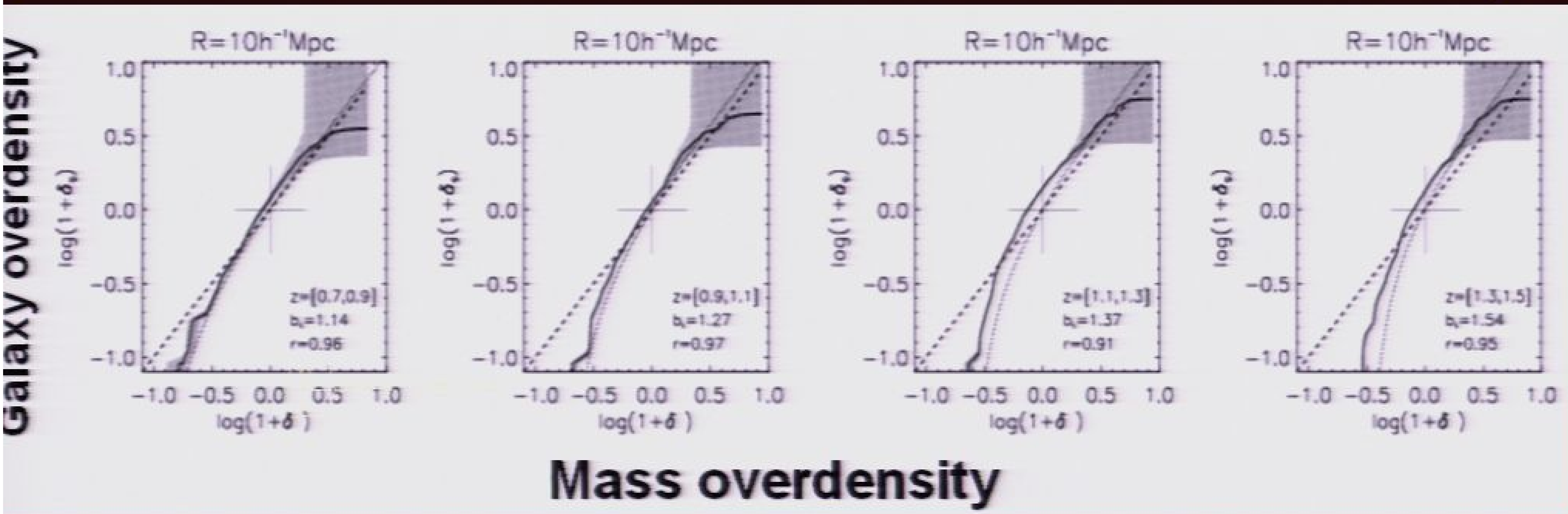

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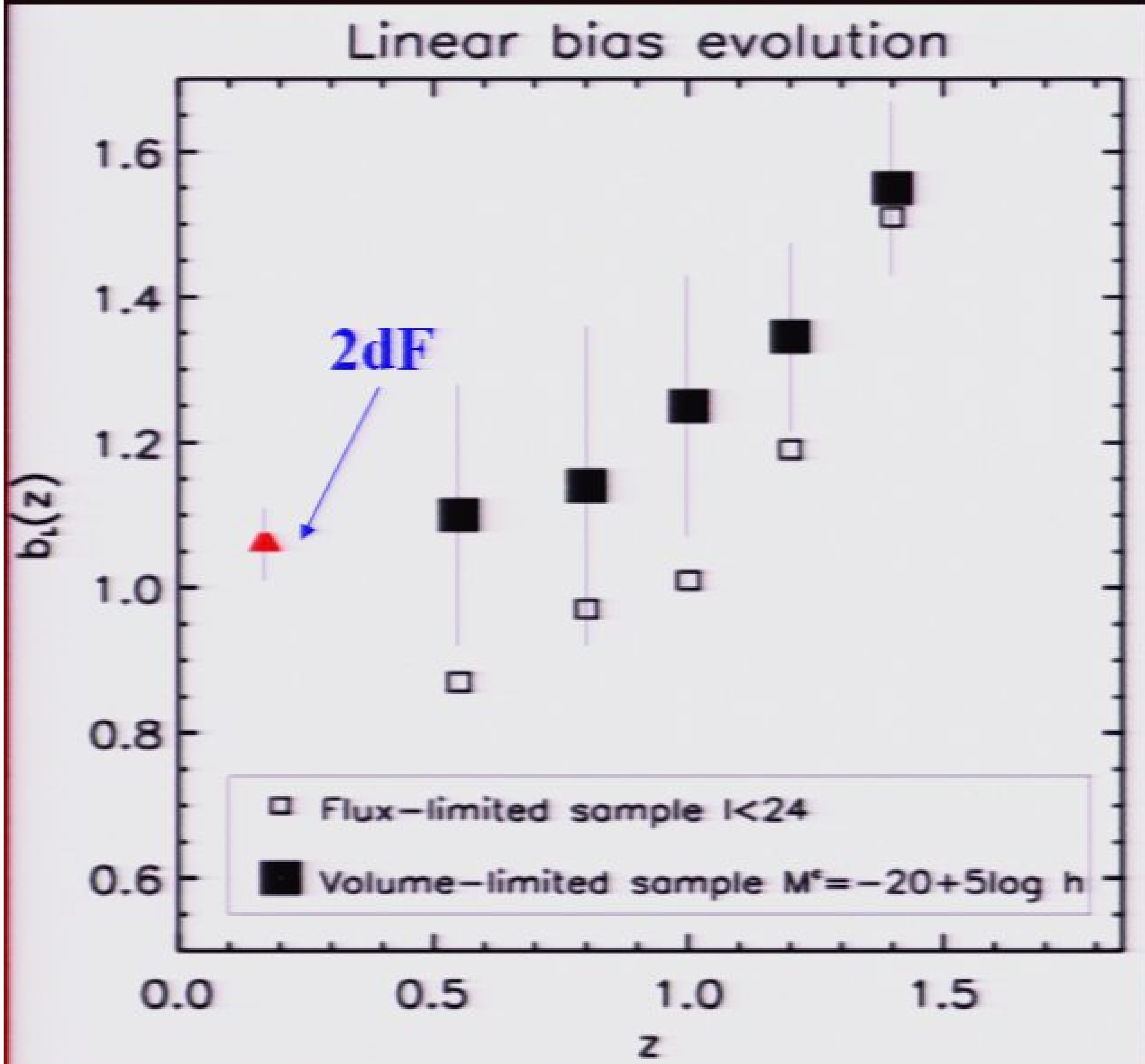
At recent epochs luminous galaxies form also in low density regions, while
t high z the formation process is inhibited in underdensities

The linear biasing function: Time evolution



The most natural linear bias indicator is related to second moments

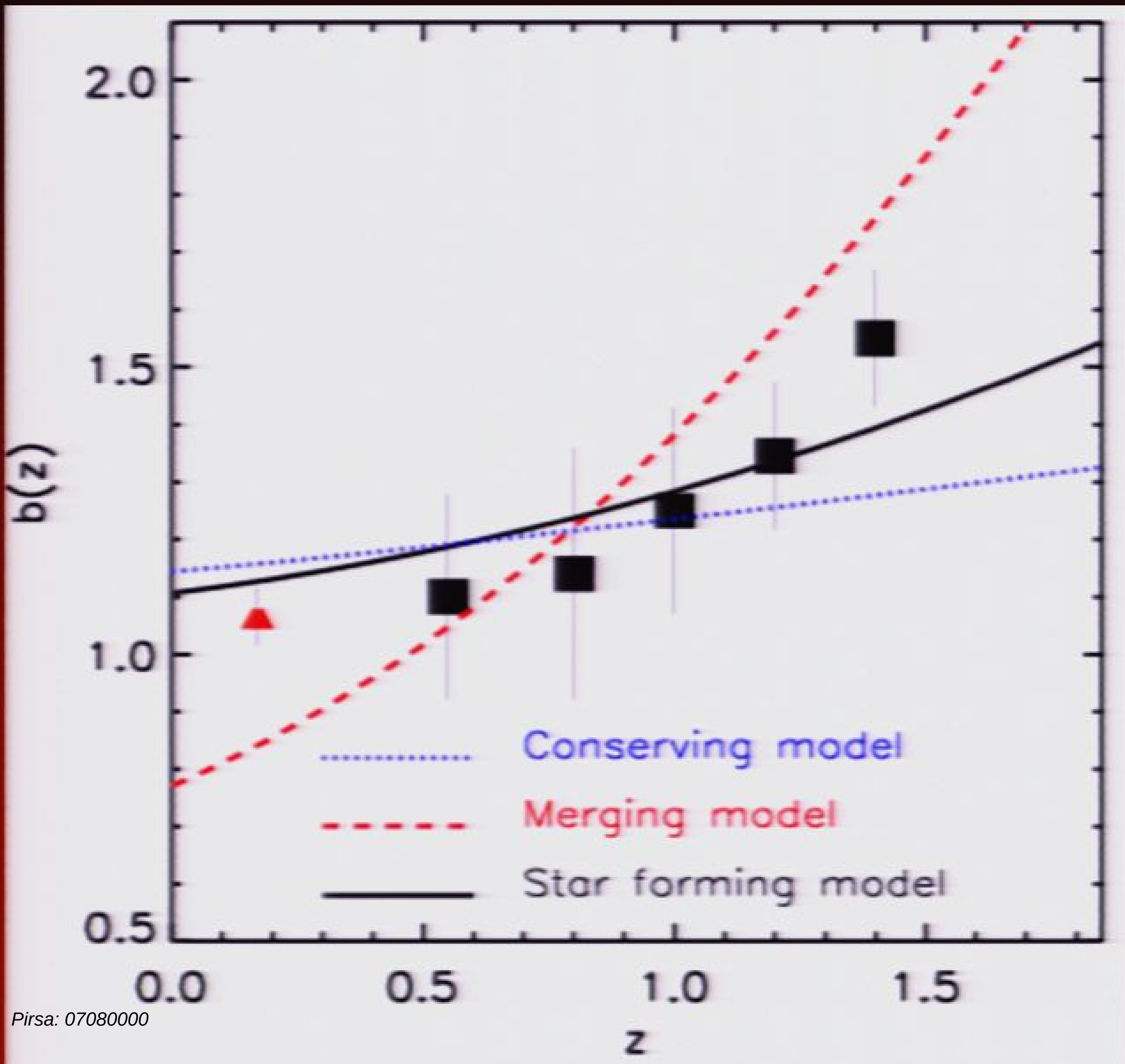
$$b_L = \frac{< b^2(\delta)\delta^2 >}{< \delta^2 >}$$

- Galaxies were progressively more biased mass tracers in the past
- Evolution:
  weak for z < 0.8
  stronger for z > 0.8

$$b_L = 1 + (0.03 \pm 0.01)(1+z)^{3.3\pm 0.6}$$

Volume limited sample (M<-20+5log h)   C.M., Le Fèvre, Meneux et al. 2005

Theoretical Interpretation: Which is the physical mechanism governing biasing evolution?



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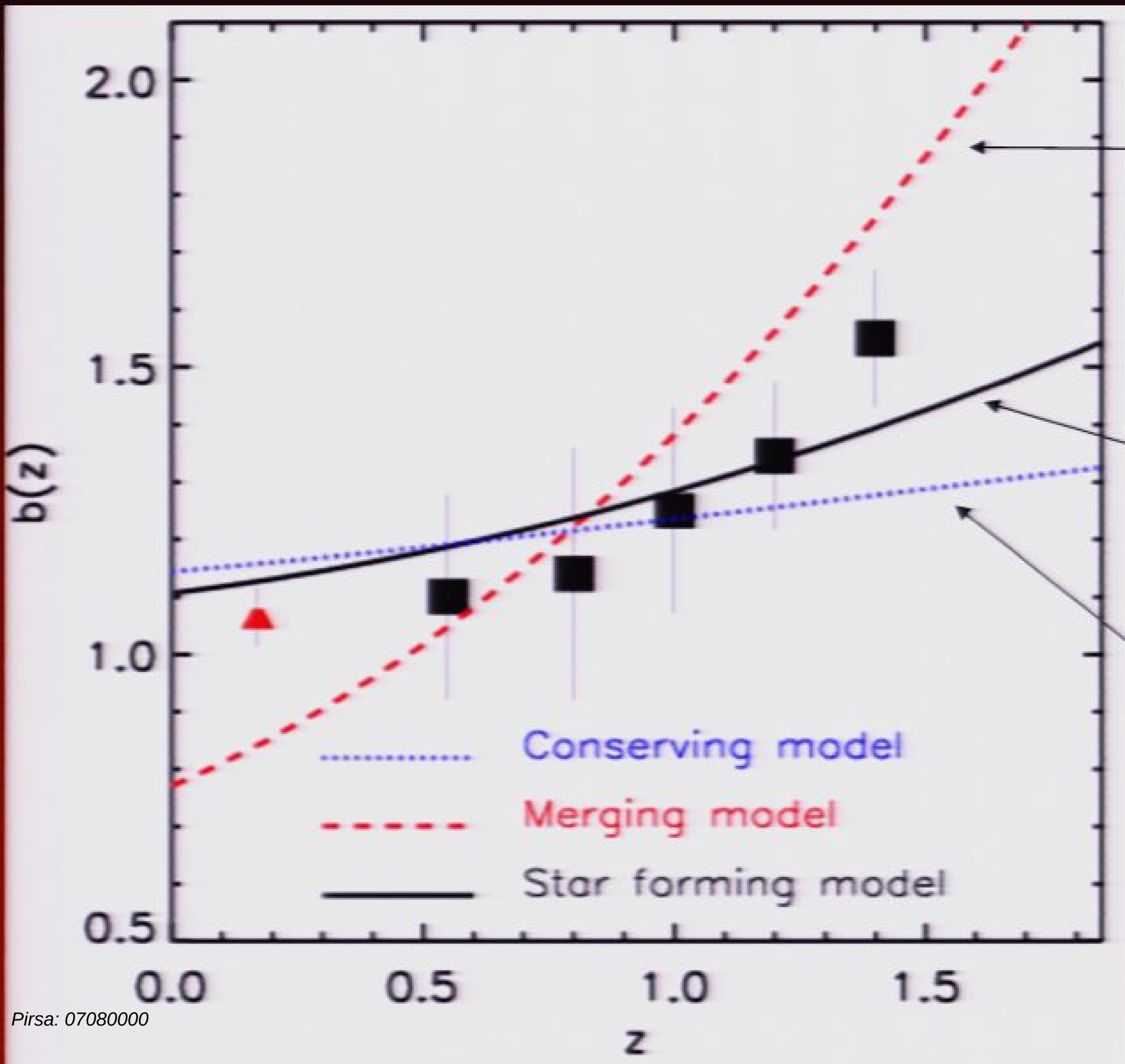


Merging
(Mo & White 96
Matarrese et al 97)

Istantaneous Star Formation
(Blanton et al 02)

Gravity
(Dekel and Rees 88
Tegmark & Peebles 98)

Outline

Matter-Galaxy bias

- Biasing from a theoretical & observational perspective
- Our approach to the extraction of the biasing function across

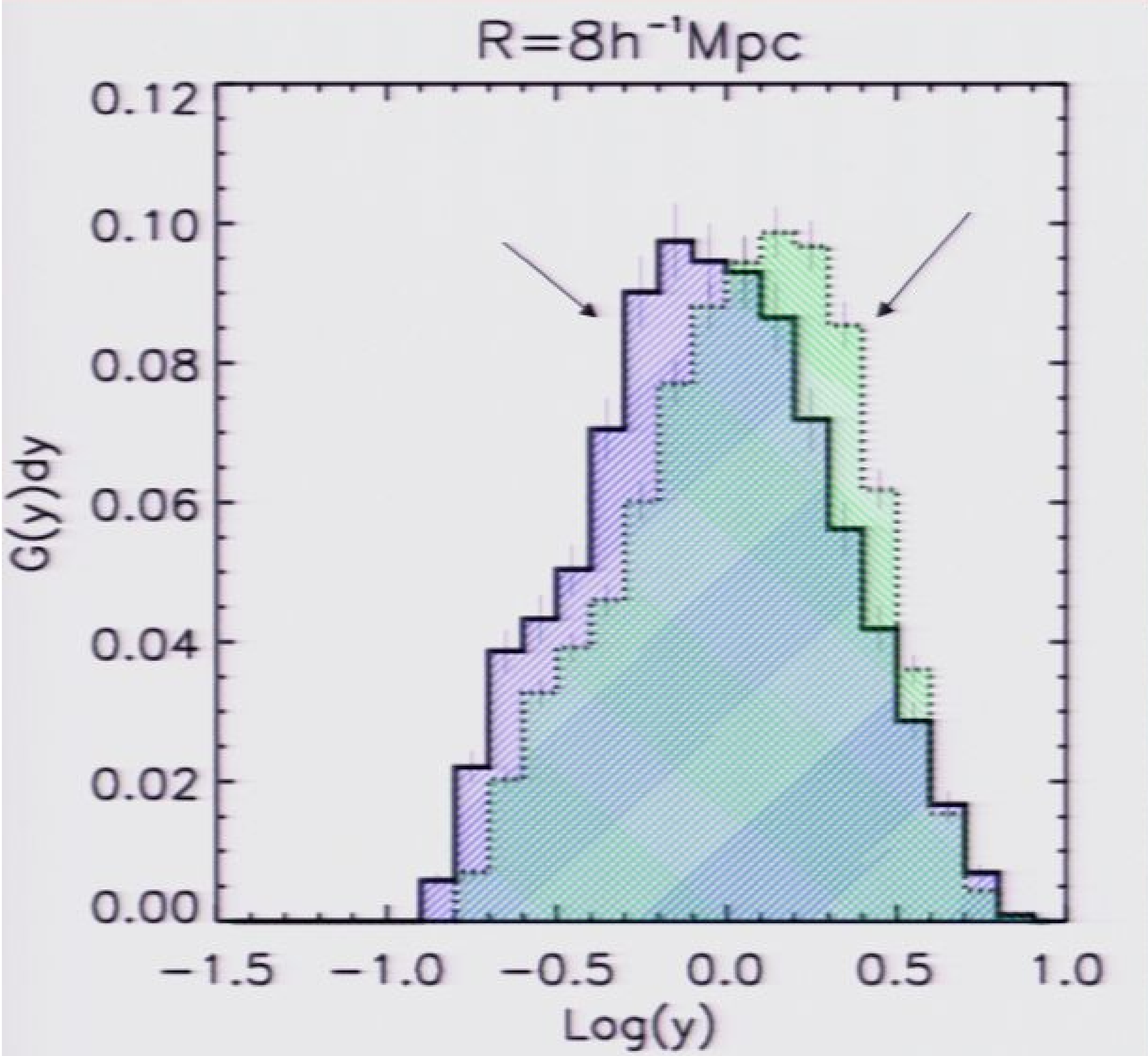
Tesing the consistency of the Gravitational Instability Paradigm (GIP)

- Statistical approach : moments of the PDF of matter fluctuation
- Dynamical approach : redshift space distortions caused by density fluctuations

Purely geometrical, gravity independent, test of the accelerated expansion of the universe

- method and preliminary results

Test of the Gravitational Instability Paradigm



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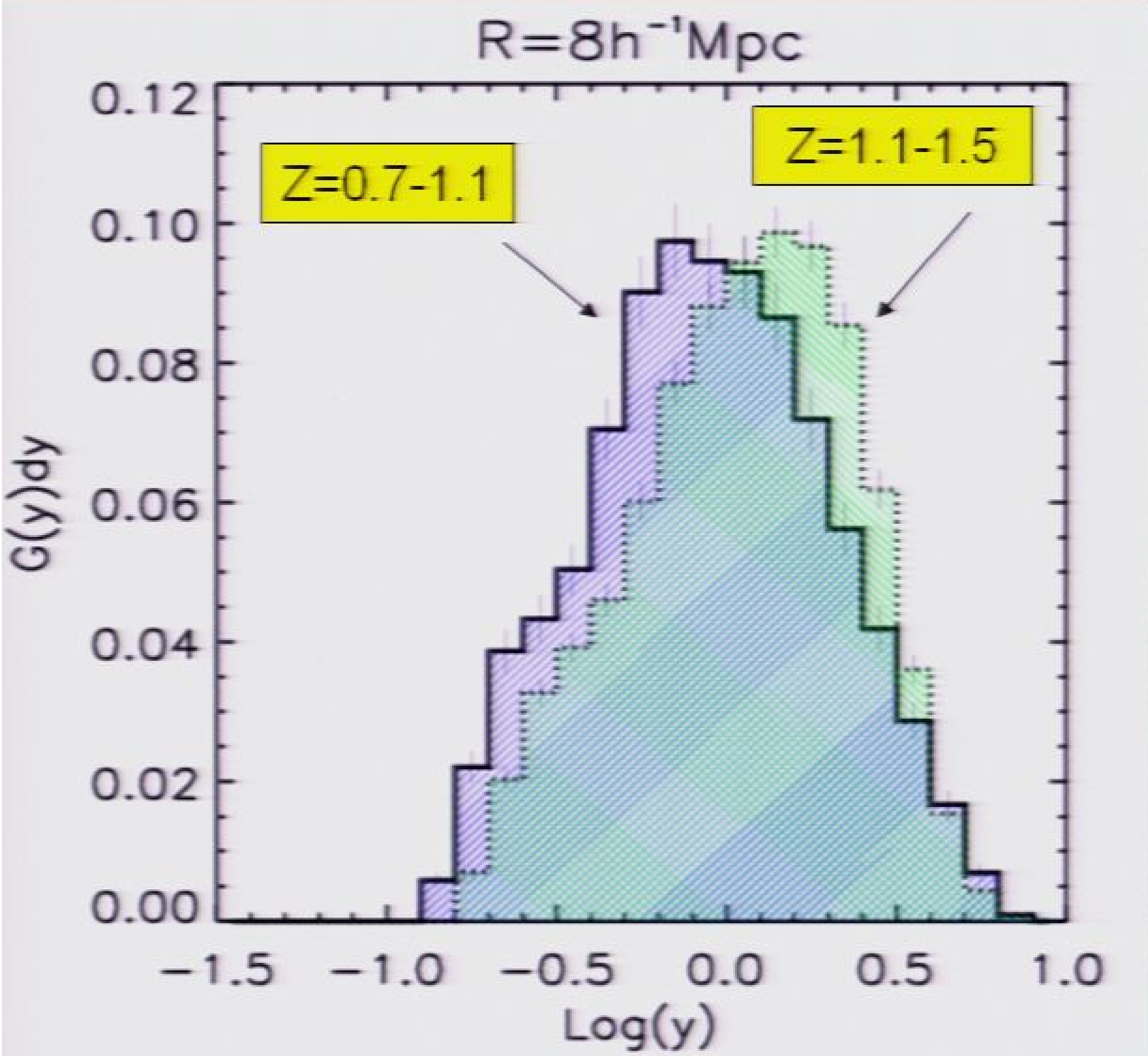

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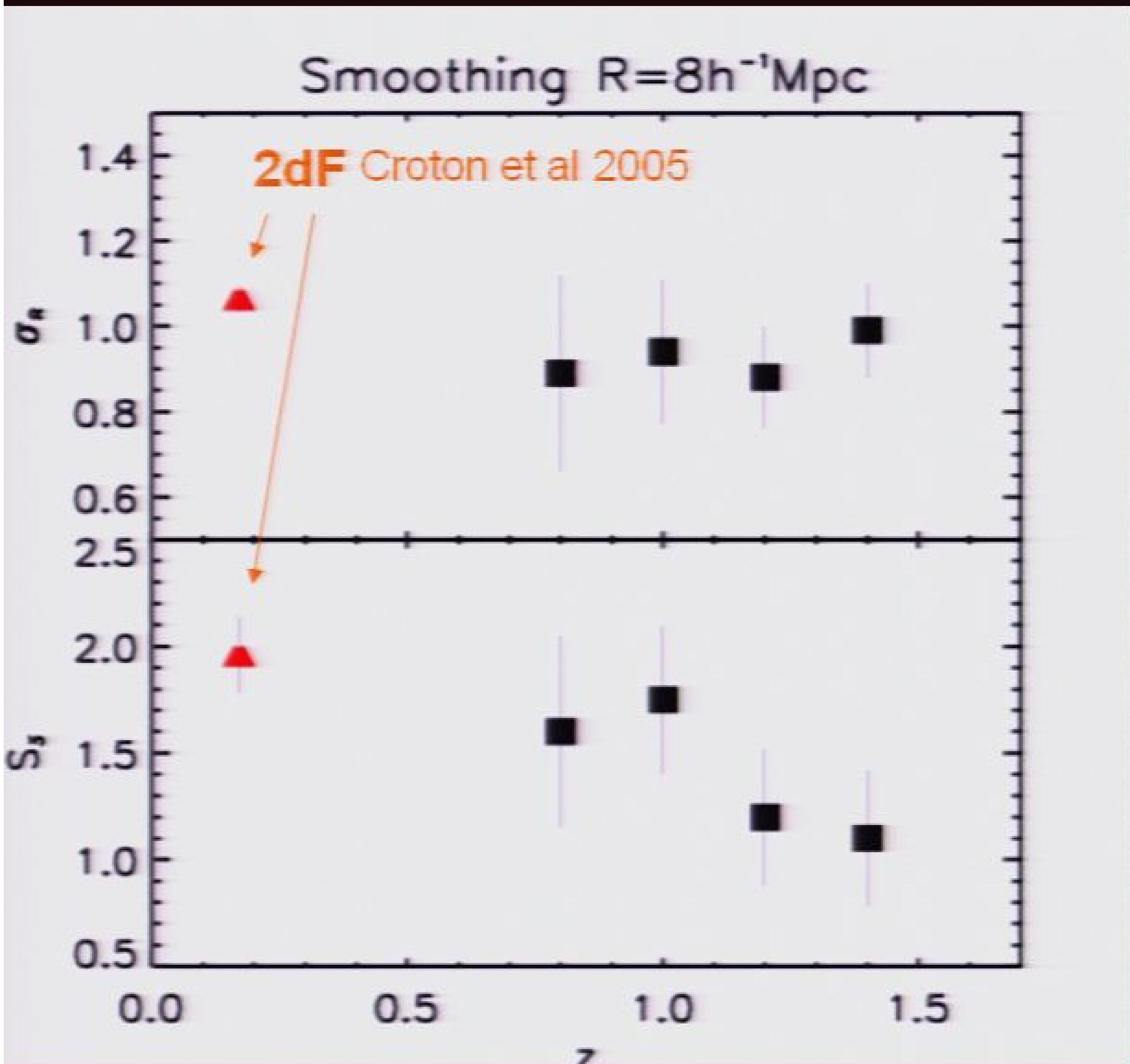

Measure deviations from homogeneity

~ costant with z

$$\sigma_8 = 0.94 \pm 0.07$$

Volume limited sample M< -20+5 log h

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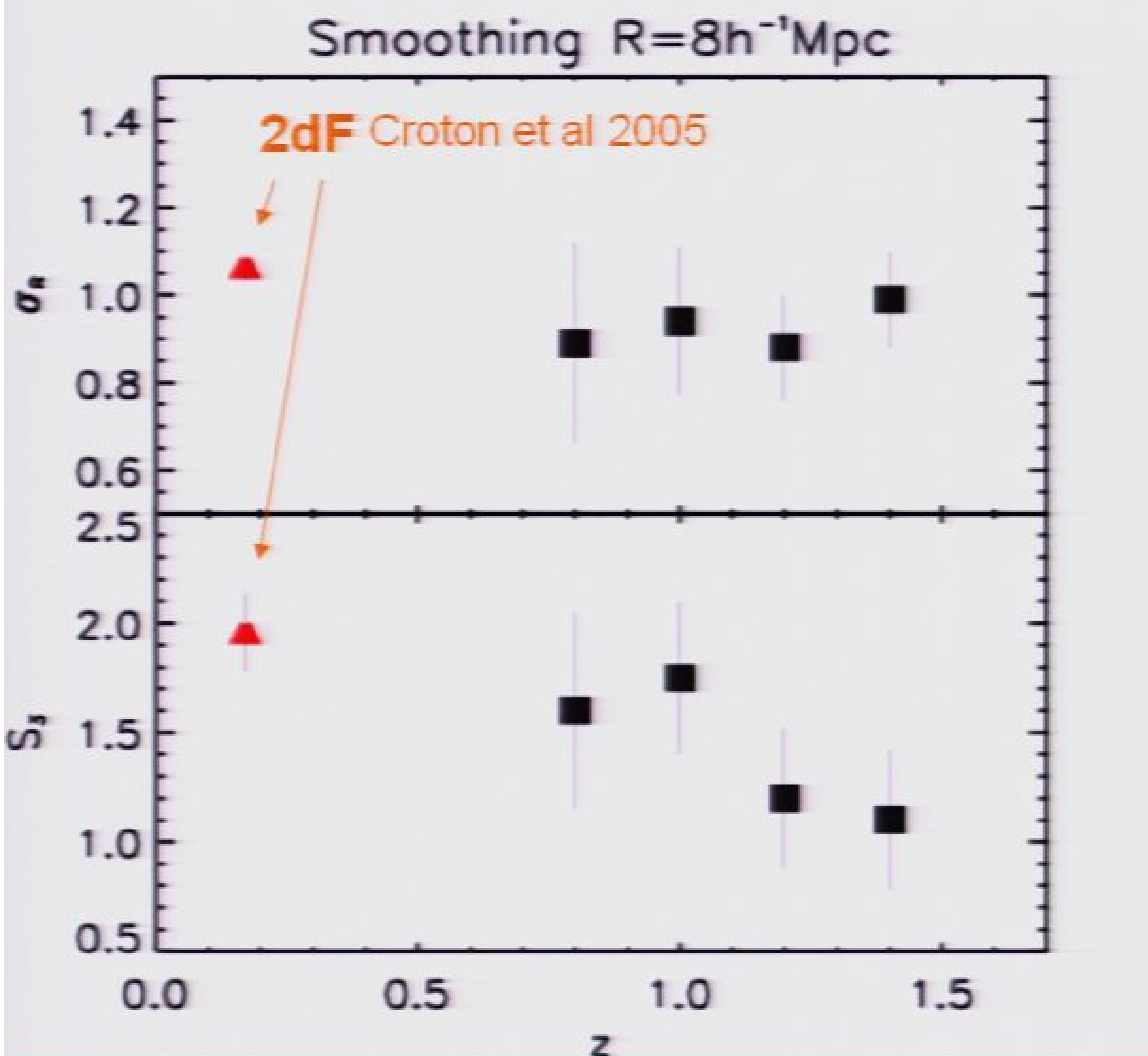

Measure deviations from homogeneity

~ costant with z

$\sigma_8 = 0.94 \pm 0.07$

Measure deviations from Gaussianity

decrease with z

Volume limited sample M< -20+5 log h

Growth of CDM structures

Linear Approximation
Newtonian Regime
Pressureless Matter fluid
Adiabatic perturbation

$$\ddot{\delta} + 2\mathrm{H}\dot{\delta} = 4\pi \mathrm{G}\bar{\rho}\delta$$

Growth of CDM structures

Linear Approximation
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$$\ddot{\delta} + 2\mathrm{H}\dot{\delta} = 4\pi G\bar{\rho}\delta$$

It exists an unstable growing solution $\delta(x,t) = \delta_i(x)D(t)$

Predictions for the PDF moment evolution

(Peebles 1980)

$$\sigma^2(t) = \langle \delta^2 \rangle$$

$$S_3(t) = \langle \delta^3 \rangle / \langle \delta^2 \rangle^2$$

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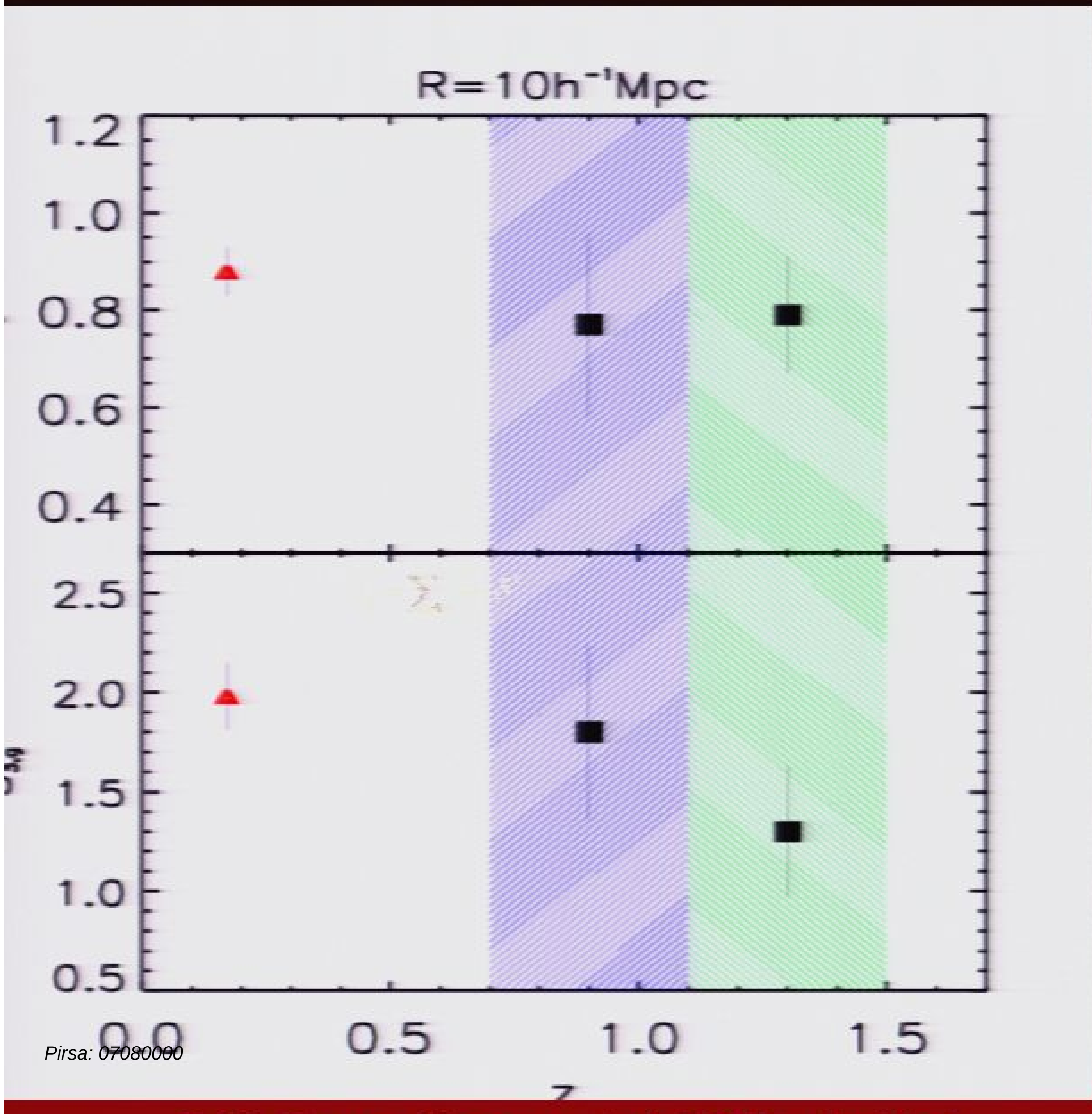

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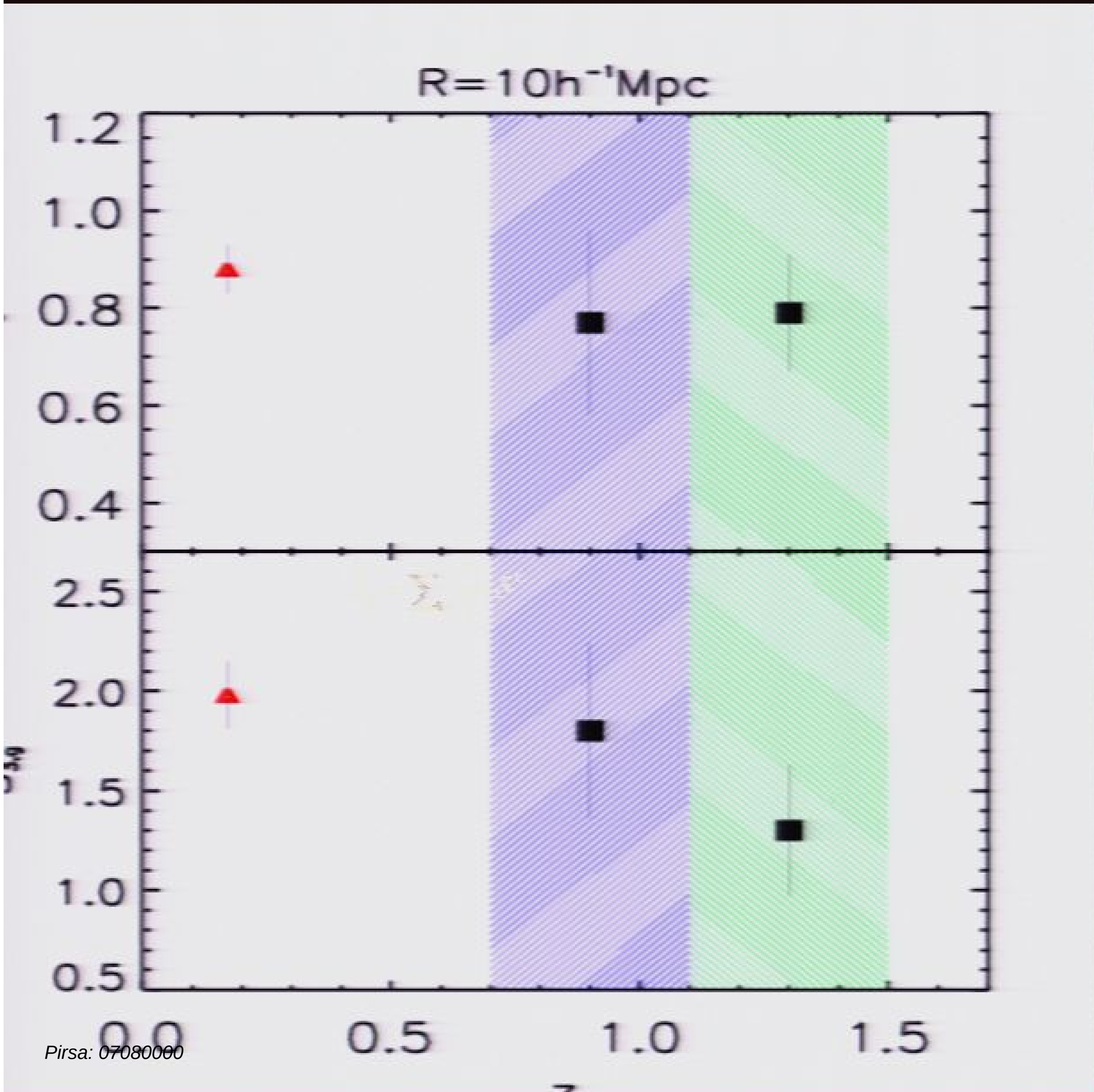

$$\sigma^g(z) = b_L(z)D(z)\sigma(0)$$

Peebles 1980

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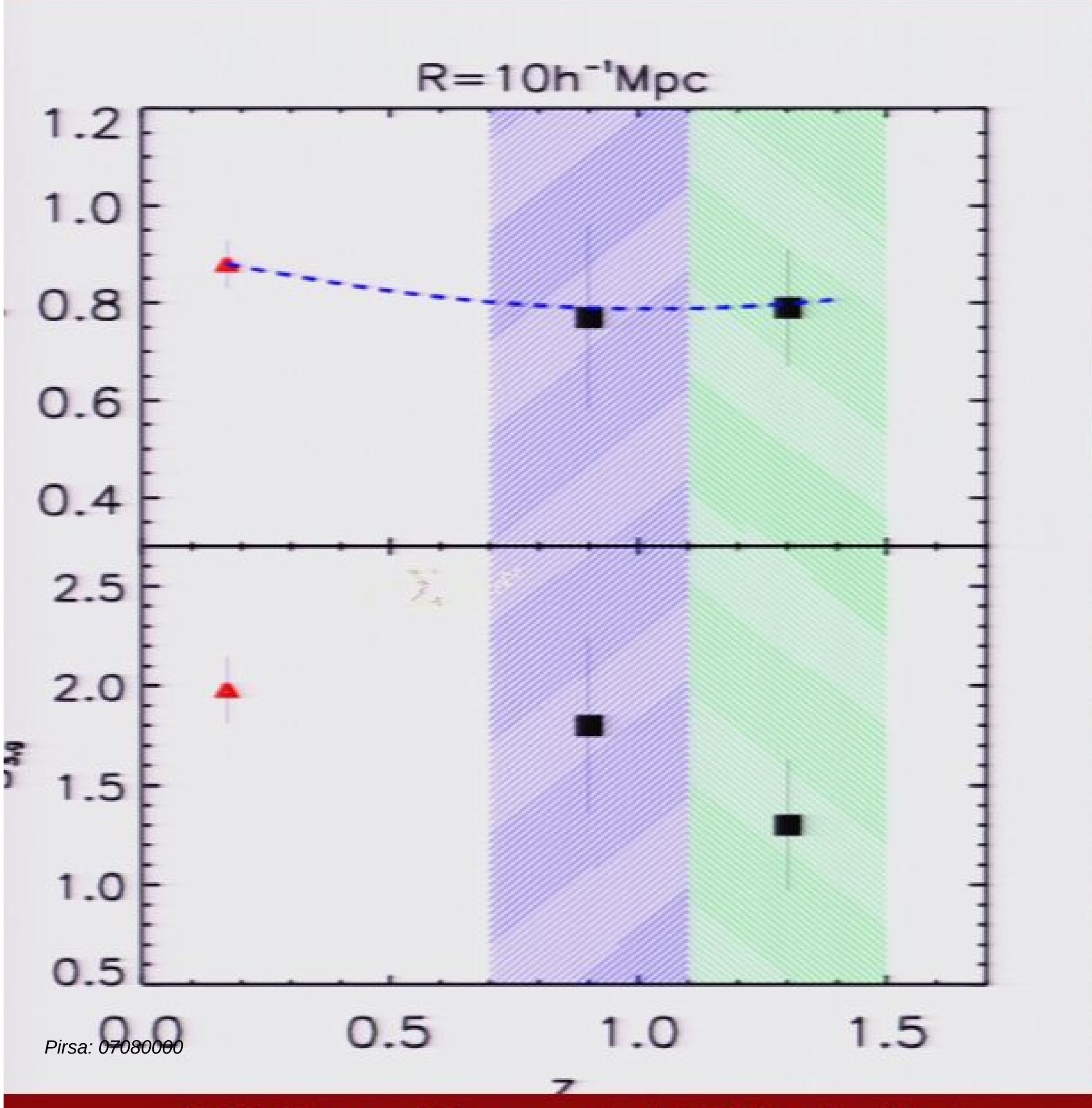

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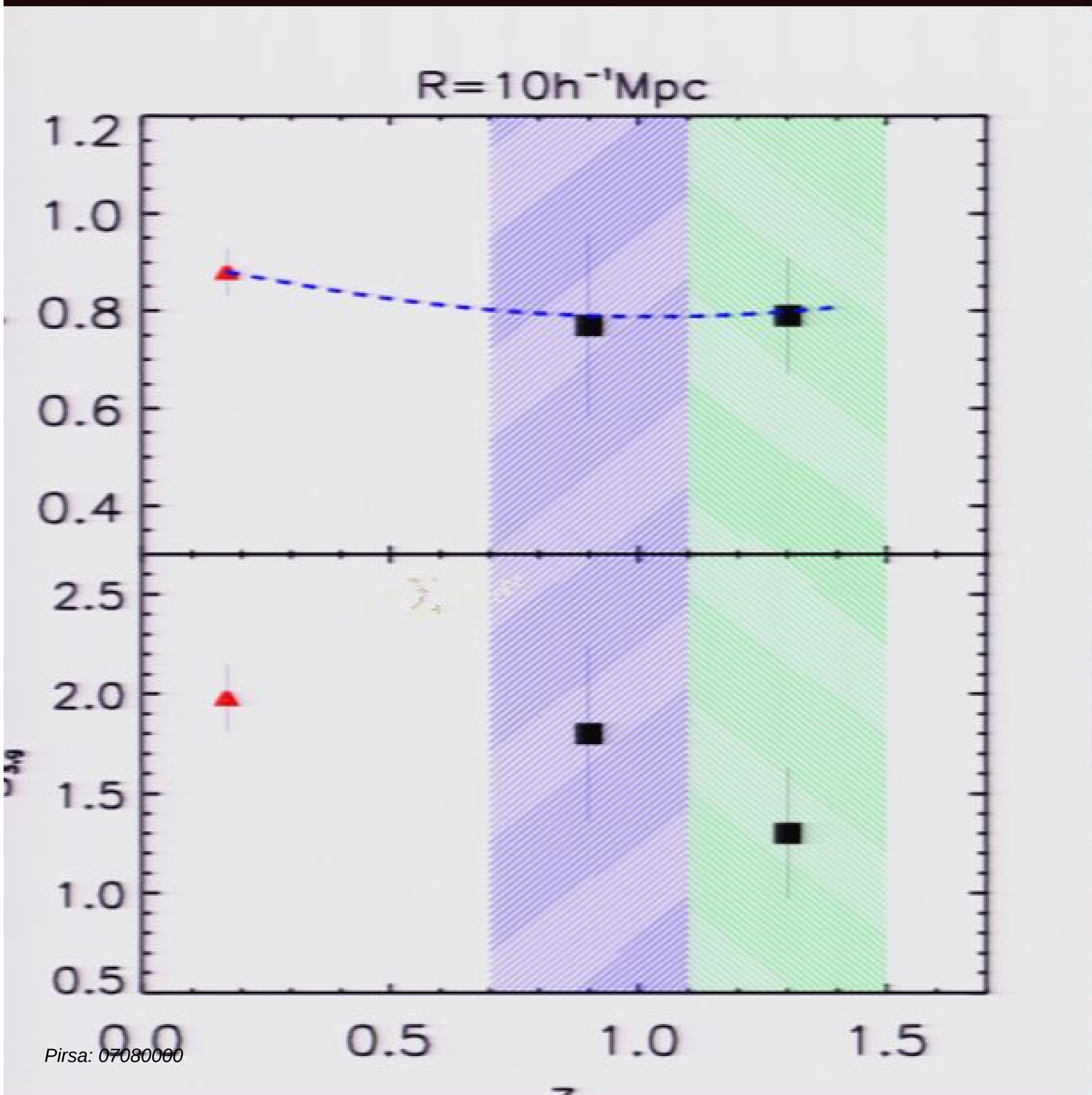

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$$S_3^g(z) = b_1^{-1}(z)\left[S_3 + 3\frac{b_2}{b_1}\right]$$

$$S_3 = 34/7 - (n+3)$$

Juskiewicz et al. 1992

$$\delta_g = \sum_k \frac{b_k}{k!}\delta^k \qquad \left\langle \frac{b_2}{b_1} \right\rangle = -0.19 \pm 0.04$$

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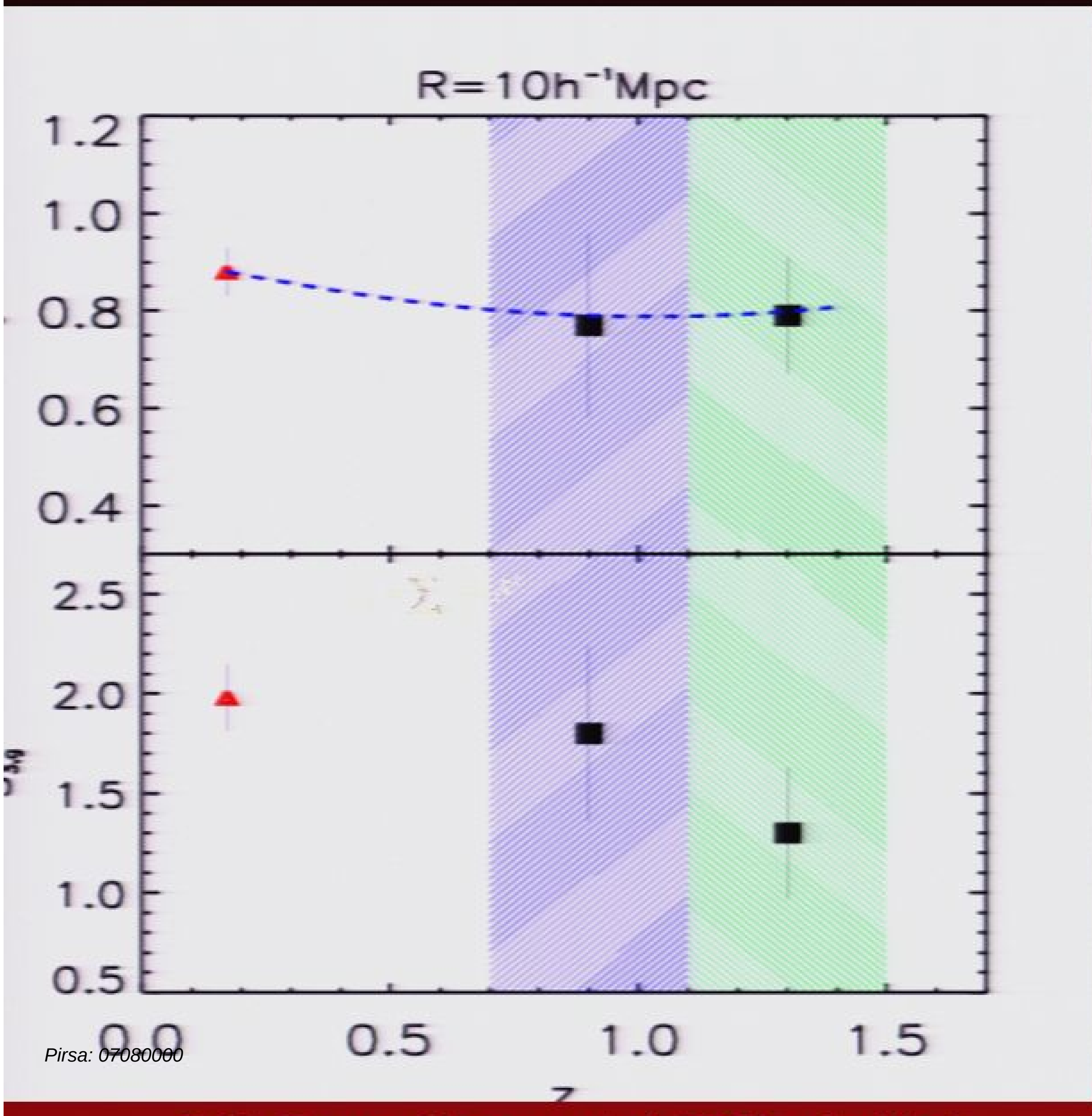

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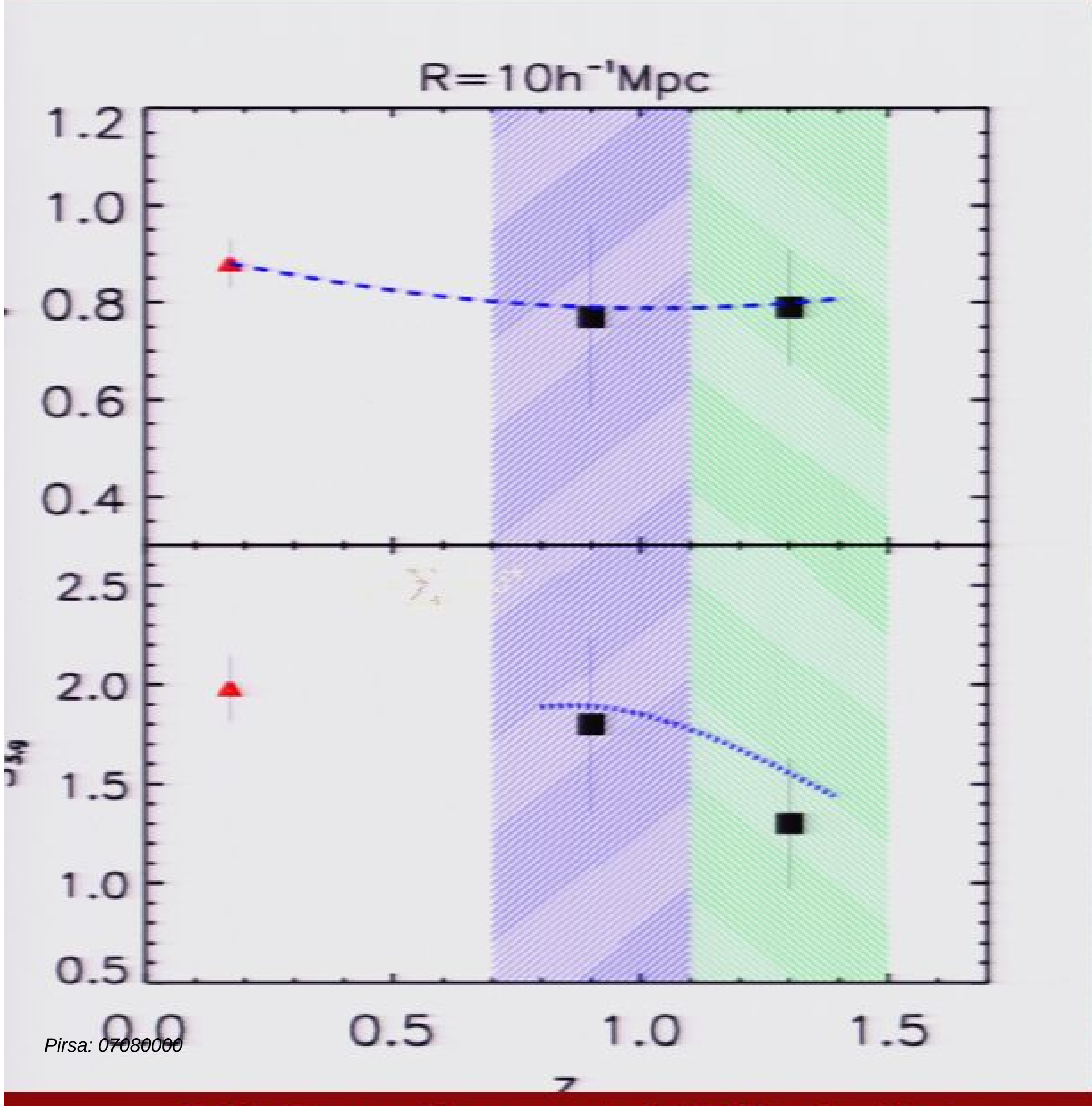

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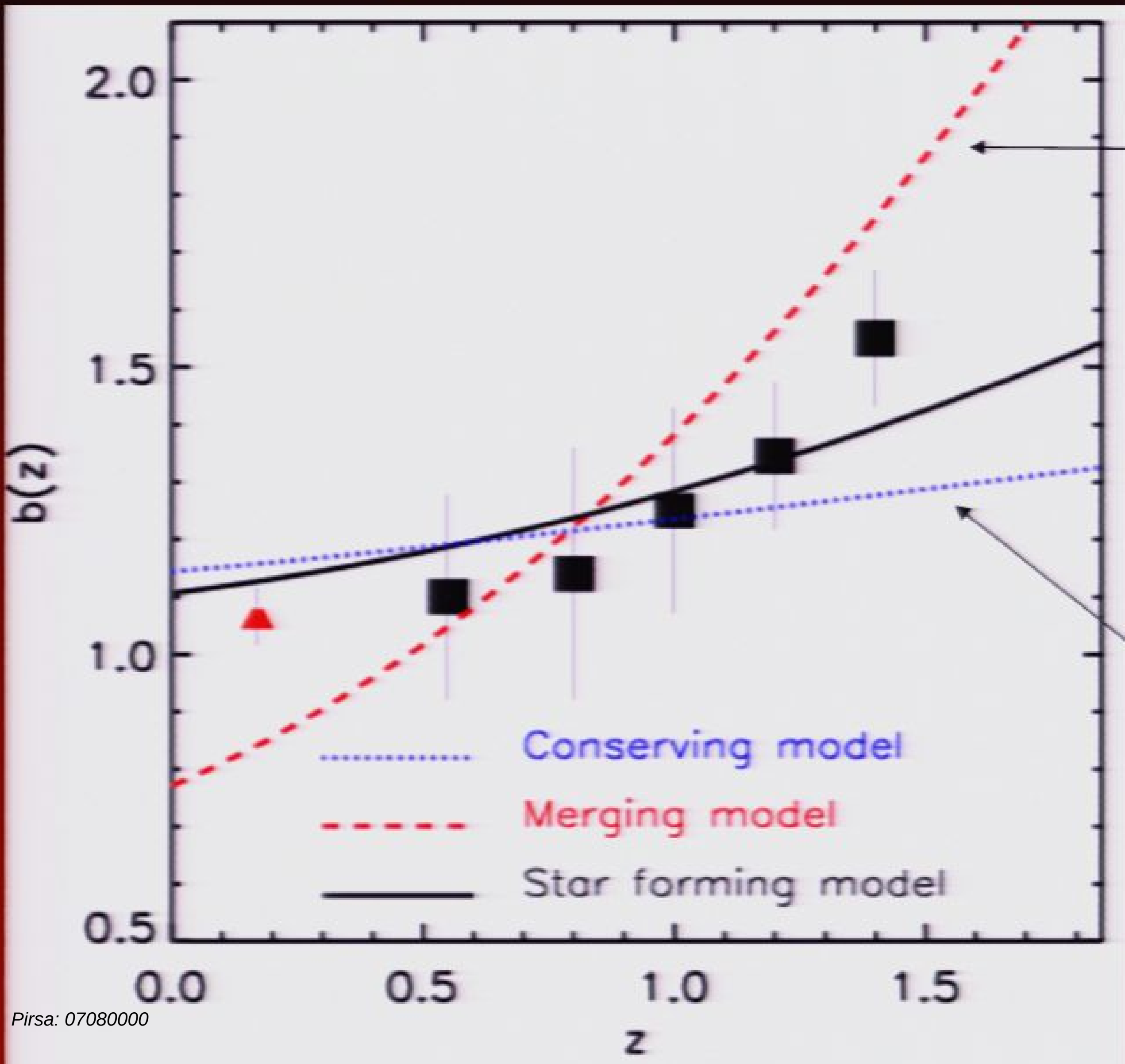
Theoretical Interpretation: Which is the physical mechanism governing biasing evolution?



Merging
(Mo & White 96
Matarrese et al 97)

Gravity
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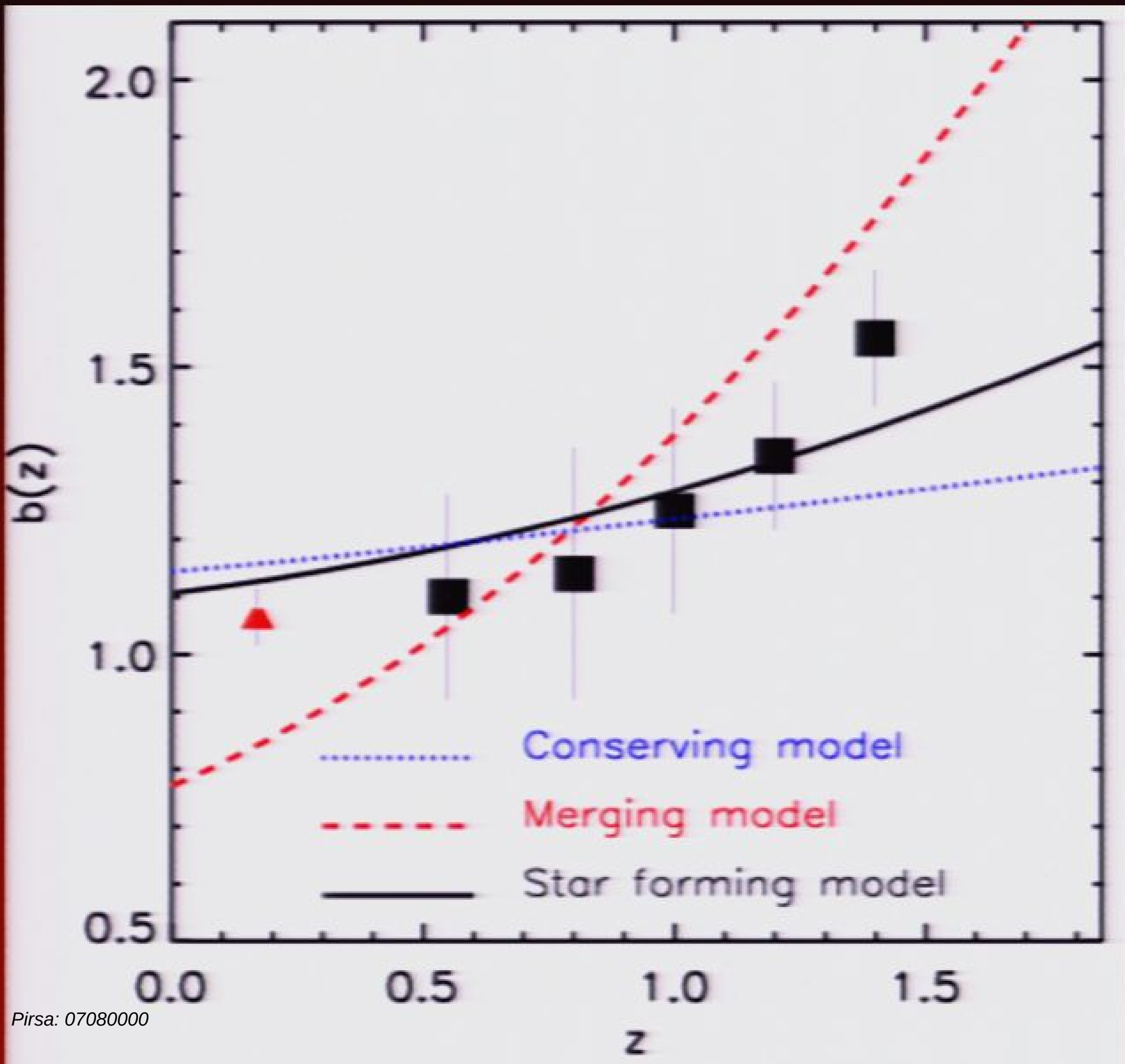

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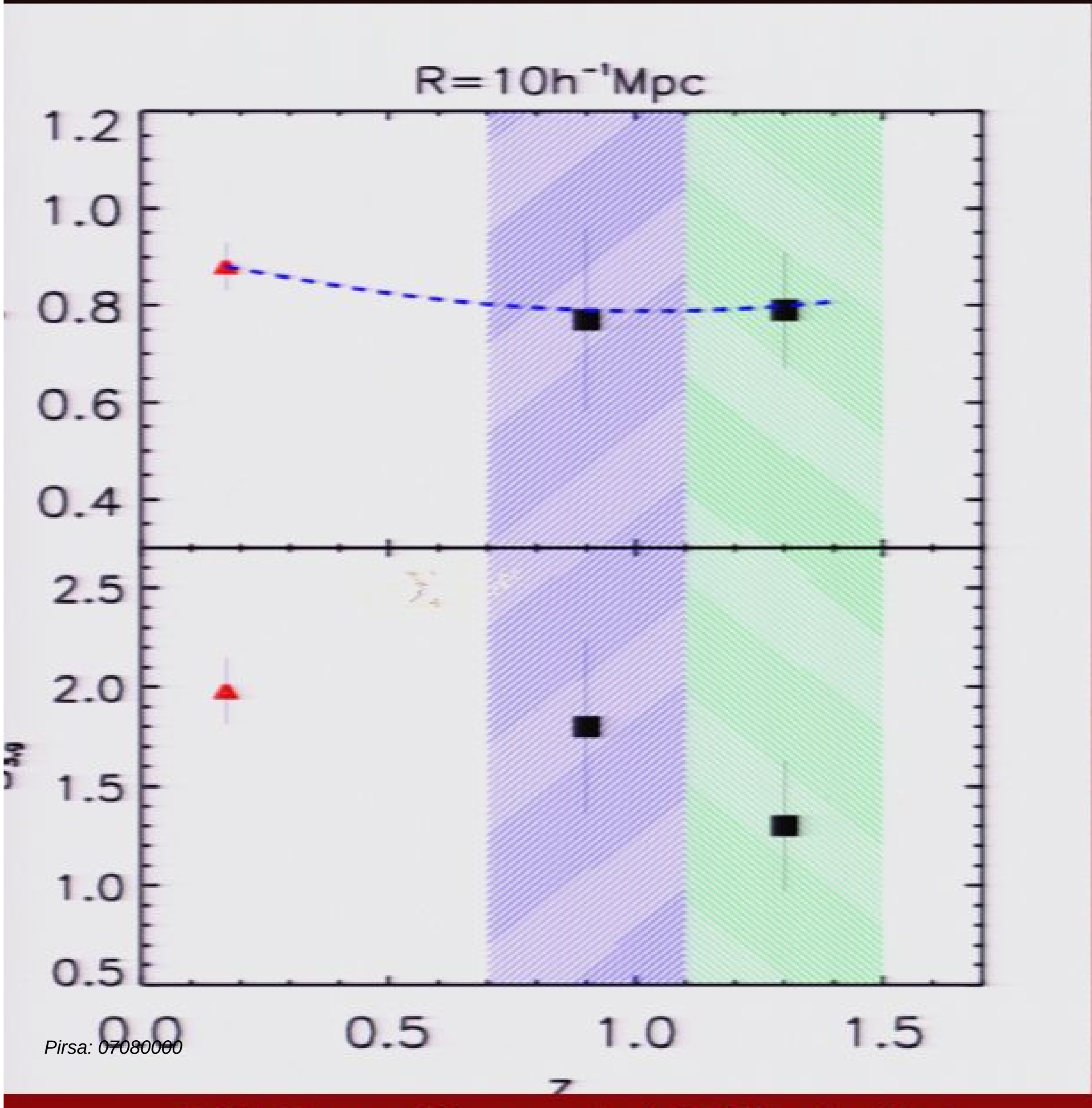

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Growth of CDM structures: A direct probe of D(t)

$$f(t) \equiv \frac{d \ln D}{d \ln a}$$

- f depends only on the present day matter density and the expansion rate of the universe (Hubble parameter)

$$\Omega_m(t) = \frac{\Omega_m^0 a^{-3}}{H^2}$$

$$f(t) \approx \Omega_m(t)^{\gamma}$$

Wang & Steinhardt (1998)
Linder (2005)

$$(H(t)/H_0)^2 = \Omega_M^0 a^{-3} + \Omega_X^0 a^{-3} \exp\left[-3\int_1^a w_X(a') d\ln a'\right]$$

$$w = \frac{p_x}{\rho_x}$$

-Growth of perrturbations is damped in low matter density or accelerated universes

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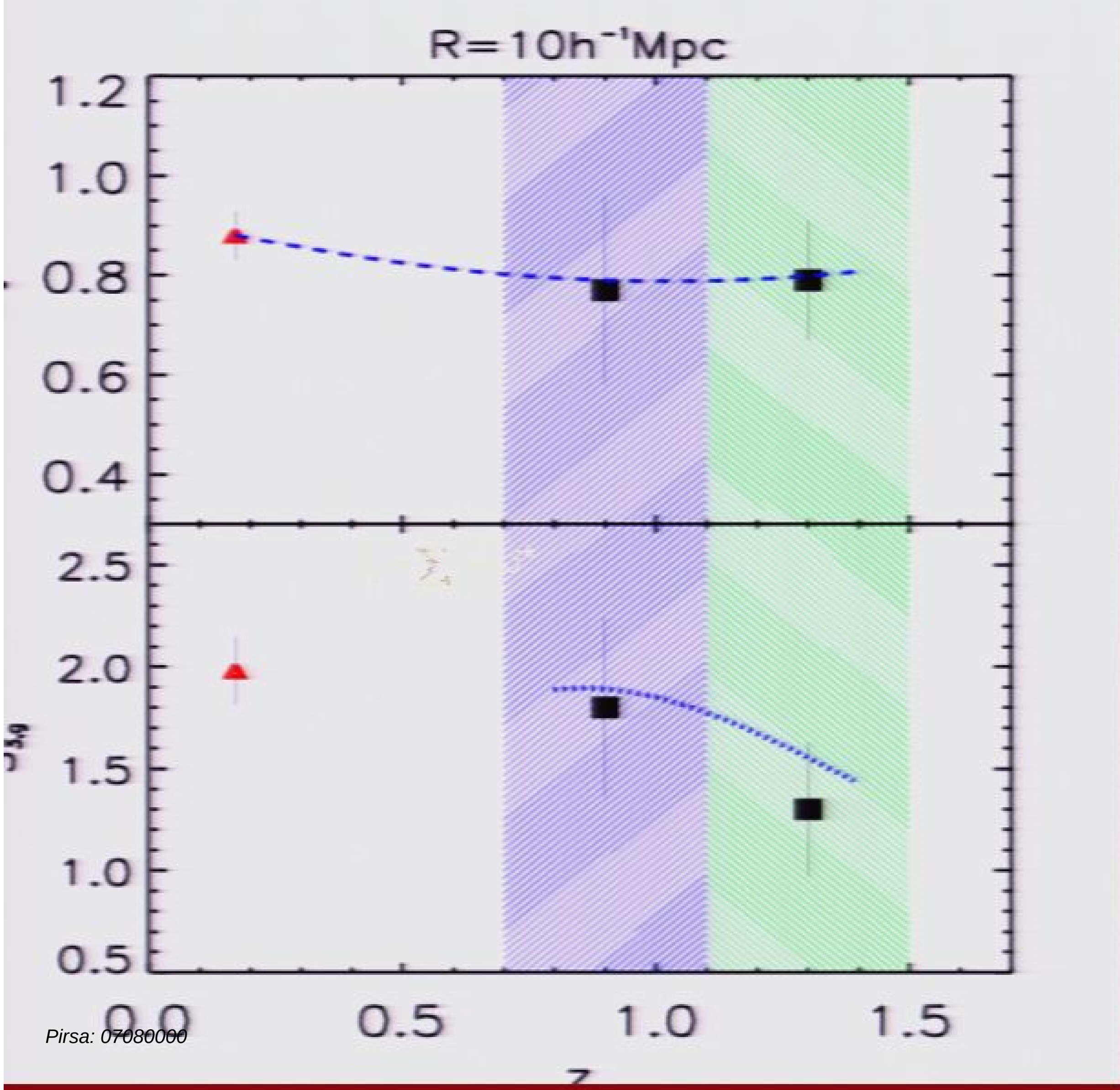

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Within the Standard Model, one can use f to constrain cosmological parameters

Note that most of the cosmological tests (CMB, SNIa) probe the integral of H

$$Obs(z) \propto \int \frac{H_0}{H(z)} dz$$

An alternative view : F is a diagnostic to test if the accelerated expansion originates from a non minimal modification of GR

Inhomogeneous Matter Gravity

$$f(t) \approx \Omega_m(t, \vec{p})^\gamma$$

Homogeneous Background Expansion

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Inhomogeneous Matter Gravity

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Homogeneous Background Expansion

Different models are tuned to reproduce the same expansion history H(z).
By analyzing the growth history we can break this degeneracy
Models with the same expansion history (same Ω at all redshift) but different gravitational theories, will have different index γ.

$$\text{Standard } \Lambda \text{ Paradigm} \quad \rightarrow \quad \gamma = 6/11$$

$$DGP \text{ (Dvali et al. 2000, Lue et al. 2004)} \quad \rightarrow \quad \gamma = 2/3$$

f can in principle reveal the physical origin of the acceleration

A new theory or a new component?

Finding Our Way in the Dark with Dynamics

A new theory or a new component?

Finding Our Way in the Dark with Dynamics

Track record:

Inner solar system motions $\rightarrow$ General Relativity

Outer solar system motions $\rightarrow$ Neptune

Galaxy rotation curves $\rightarrow$ Dark Matter

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Finding Our Way in the Dark with Dynamics

Track record:

Inner solar system motions → General Relativity

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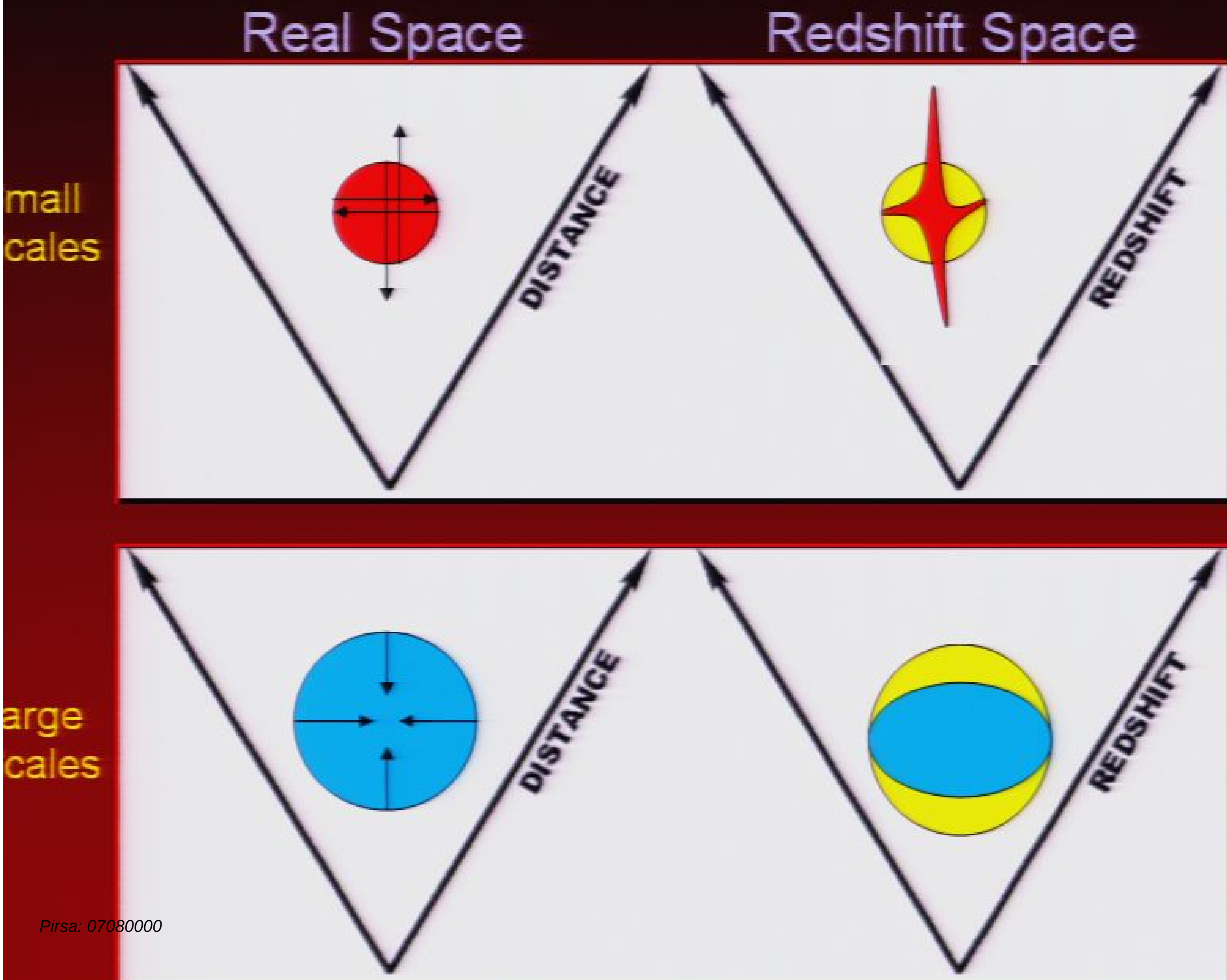
Use galaxy dynamics on large scales to resolve the degeneracy

How to extract f with large scale galactic dynamics?

How big a fluctuation is ? Interpret distortion signatures introduced by motions toward density maxima



Random motions increase power on small scales along the L.o S.

Bulk motions increase power on large scales Perpendicular To the L. o S.

Method : Measure correlation of fluctuations in radial and transverse direction

$$\xi(\vec{r}) = < \delta(\vec{x})\delta(\vec{x}+\vec{r}) >$$

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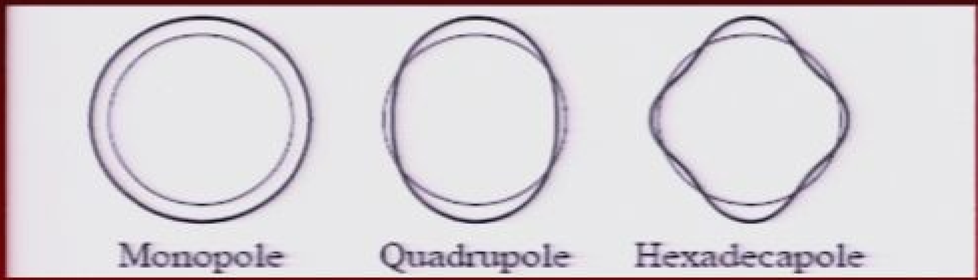
Linear Theory

$$\xi_L(r_p,\pi) = \sum_{even}^{4} a_l(s) P_l(\mu) \qquad r=\sqrt{r_p^2+\pi^2} \qquad \mu = \hat{s}\cdot\hat{\pi}$$

Legendre Polynomials



$$a_0 \propto (1+\frac{2}{3}\beta+\frac{1}{5}\beta^2)$$

$$a_2 \propto (\frac{4}{3}\beta+\frac{4}{7}\beta^2)$$

$$a_4 \propto \frac{8}{35}\beta^2$$

$$\beta = \frac{f}{b}$$

Hamilton 1998

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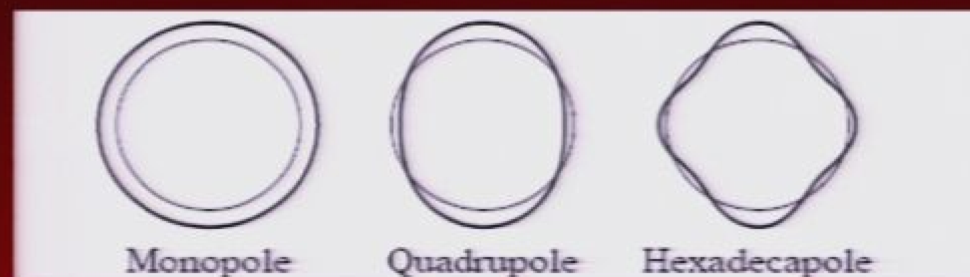

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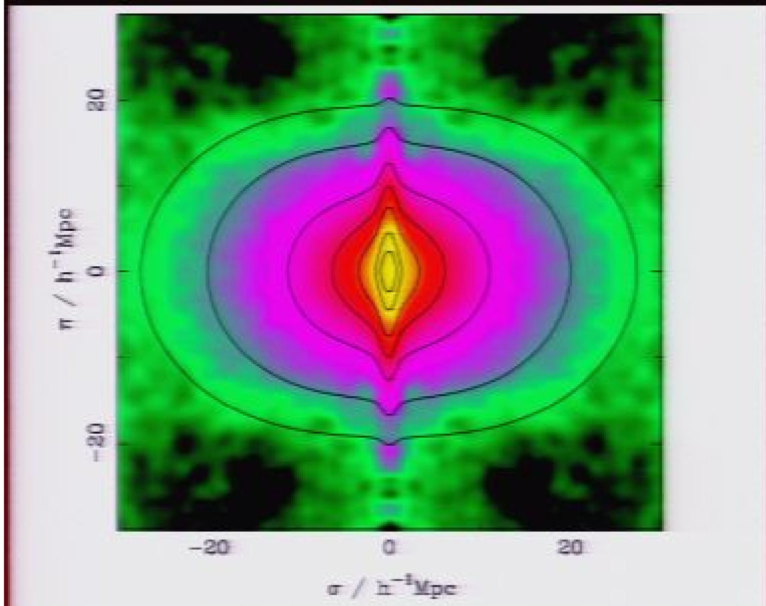
Non Linear Model

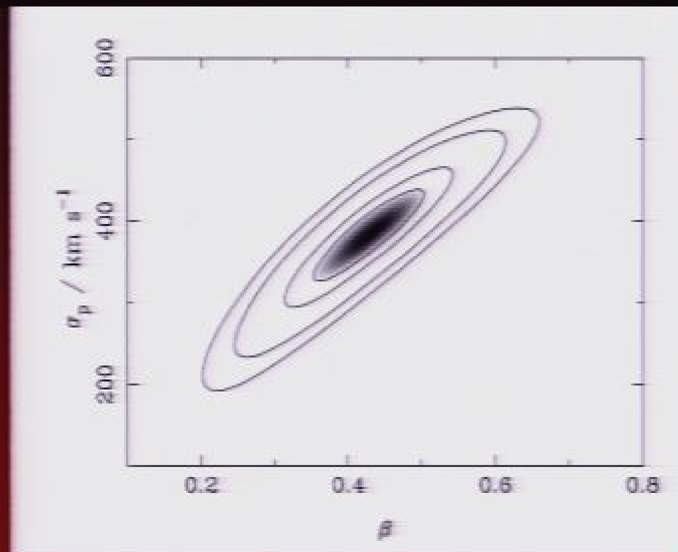
$$\xi(r_p,\pi) = \int_{-\infty}^{+\infty}\xi_L\left(r_p, \pi - \frac{v(1+z)}{H(z)}\right)f(v)dv$$

$$f(v) = \left(\sigma_{12}\sqrt{2}\right)^{-1}\exp\left(-\sqrt{2}\,|v|/\sigma_{12}\right)$$

f = PDF of relative velocityies of galaxy pairs
σ = describes small-scale thermal random motion

Redshift distortions in the correlation maps : Results

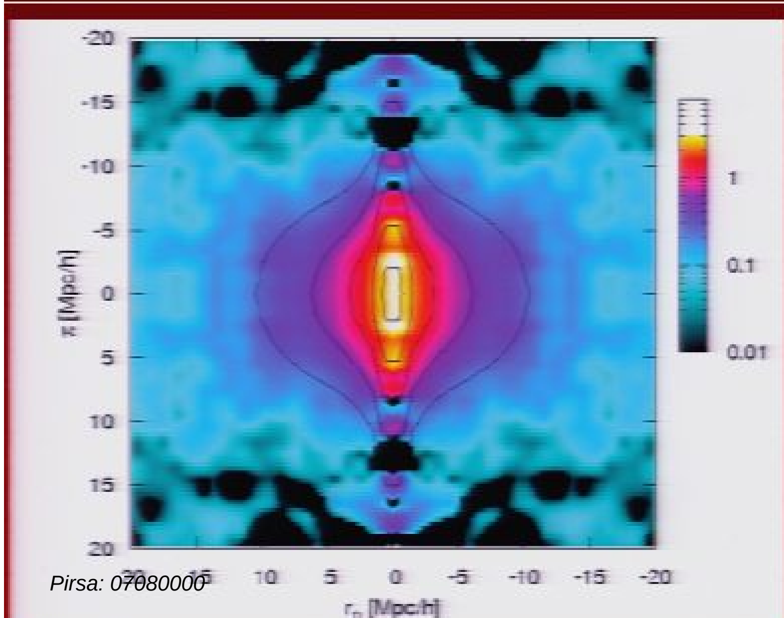


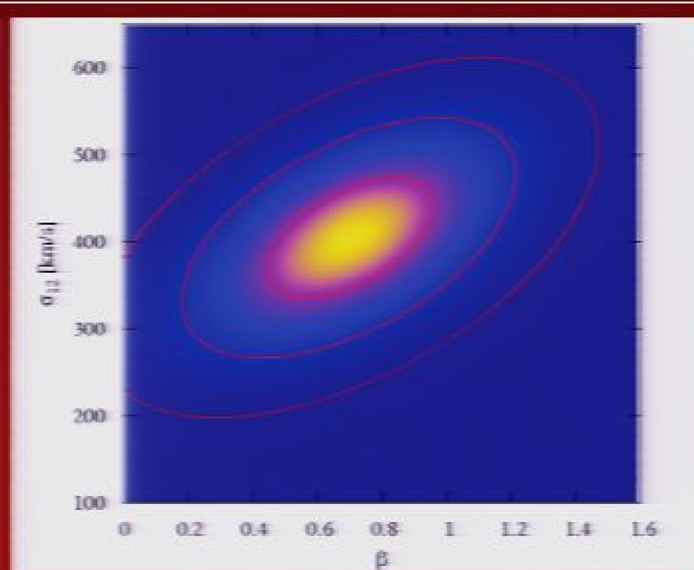


2dFGRS
(Colless et al. 00)

<Z>=0.1
250,000 galaxies
f=0.5±0.1
σ=390±50 km/s

(Peacock et al. 2001, Nature)





VVDS
LeFevre et al. 05

<Z>=0.75
10,000 galaxies
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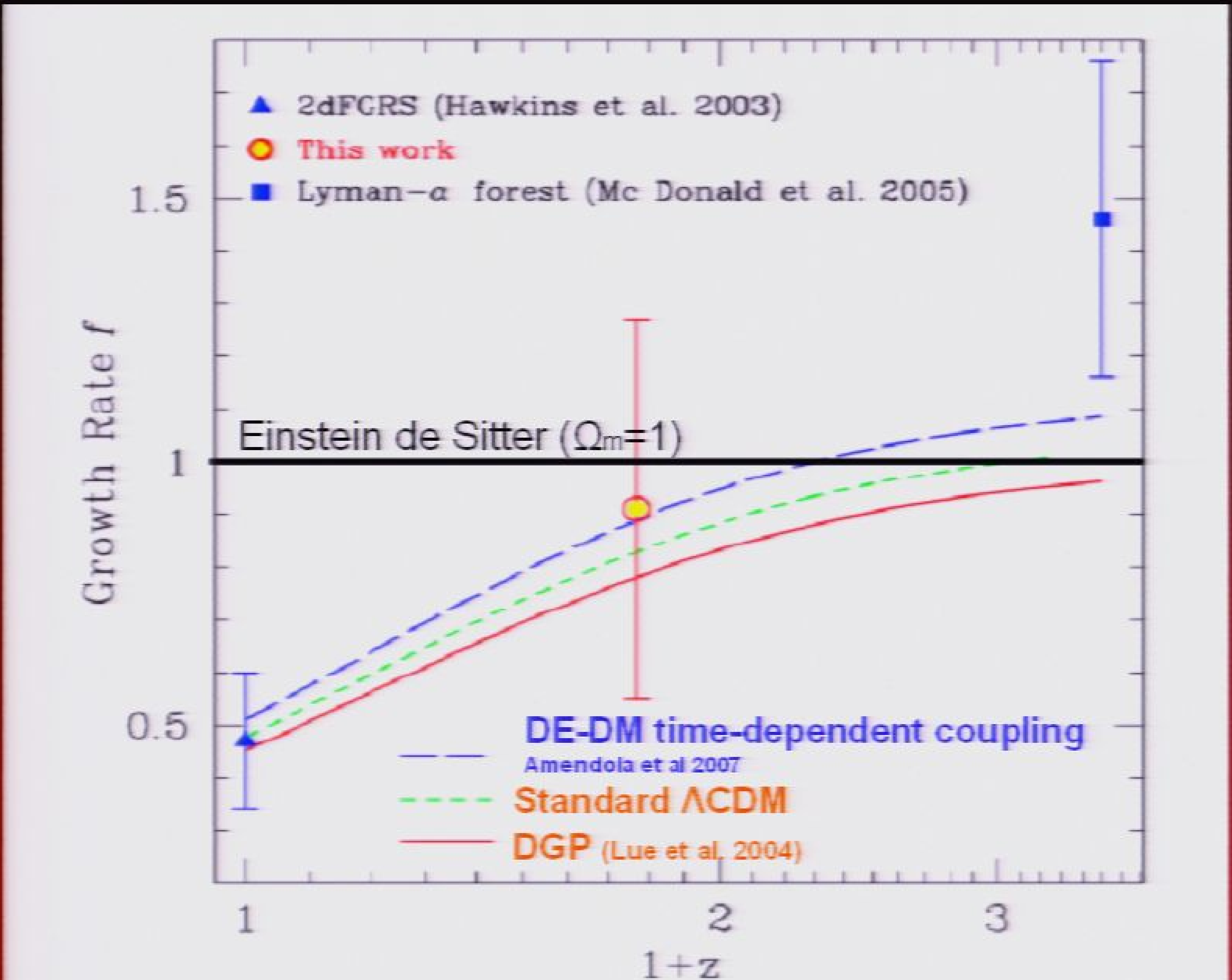
(Guzzo, Branchini, C.M. et al. 2007 submitted)

Constraining the physics behind acceleration



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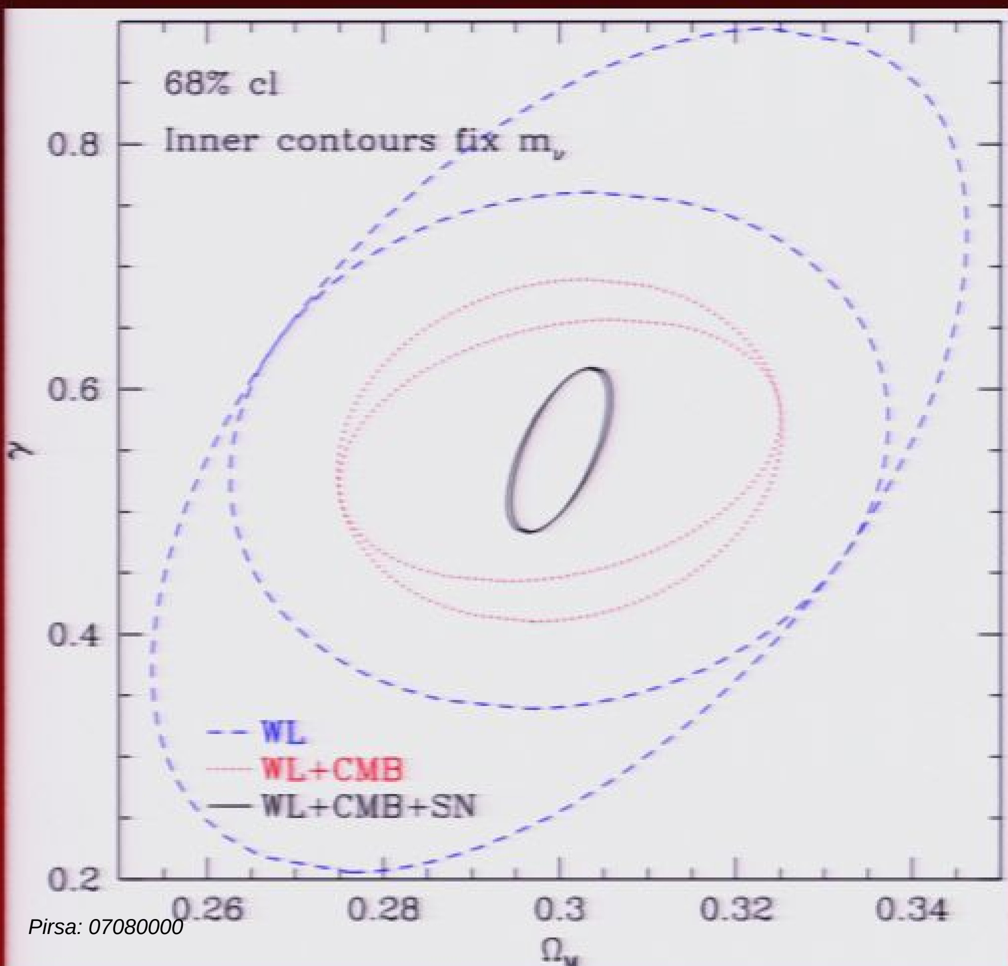
Going Beyond Einstein

To test Einstein gravity (γ), we need growth (f) and expansion (H)
...No wait! we need superb data.

How well can we fit gravity?



WL (1/4 of sky)

+

SN (2000 up to z=2)

+

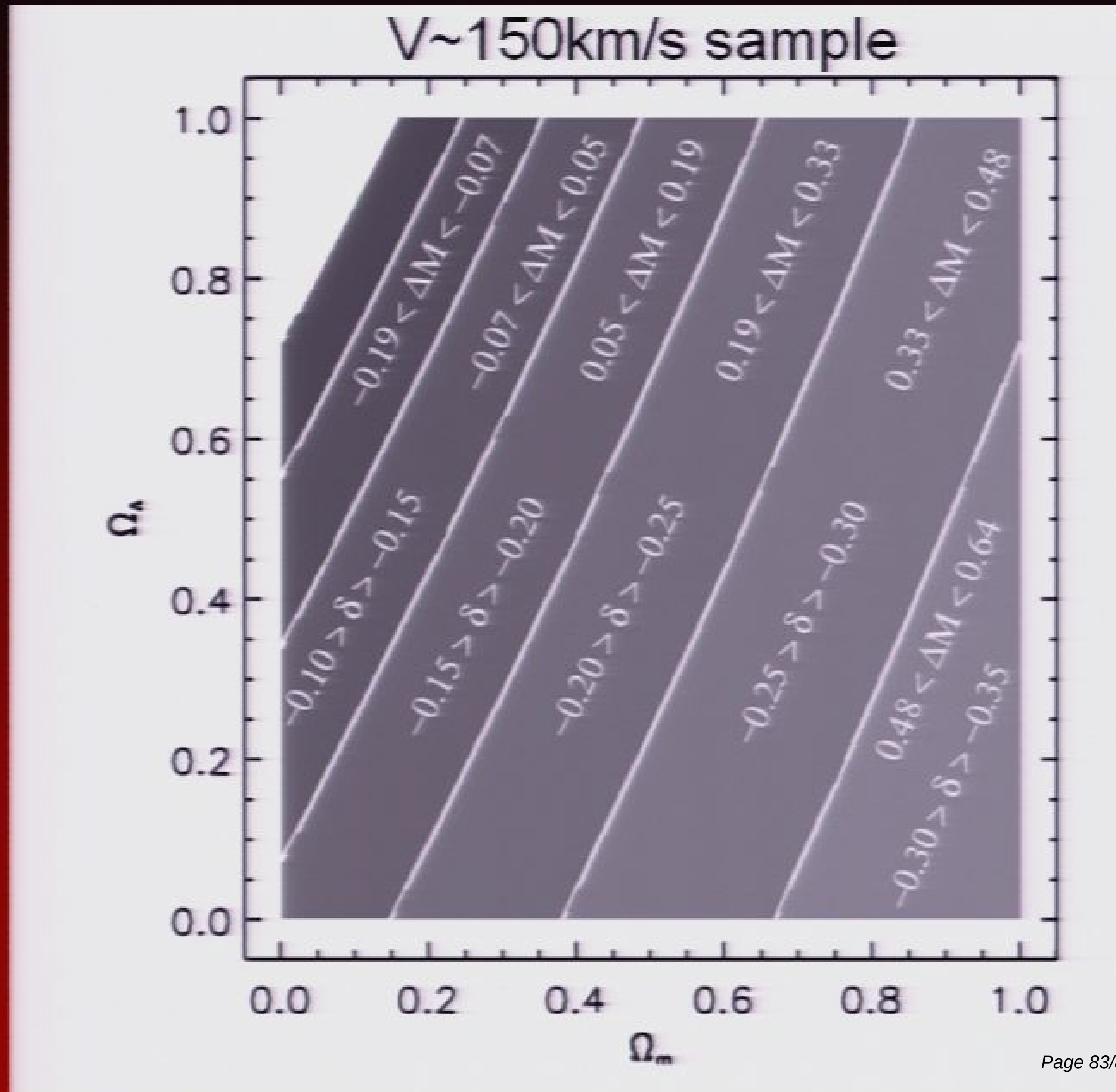
CMB (Planck)

can determine γ to 8%.

Cosmology - Evolution Diagram at z=1

- Extract cosmology once the amount of disc/luminosity evolution is known at some given redshift.

- Extract evolution in structural parameters once cosmology is known



Conclusions

Ve can use the kinematics of the homogeneous universe to accurately measure he expansion rate of the universe (constraining cosmological parameters)
Ve must use the dynamics of the inhomogeneous universe to break he degeneracy between different models (constraining the physics behind cceleration)

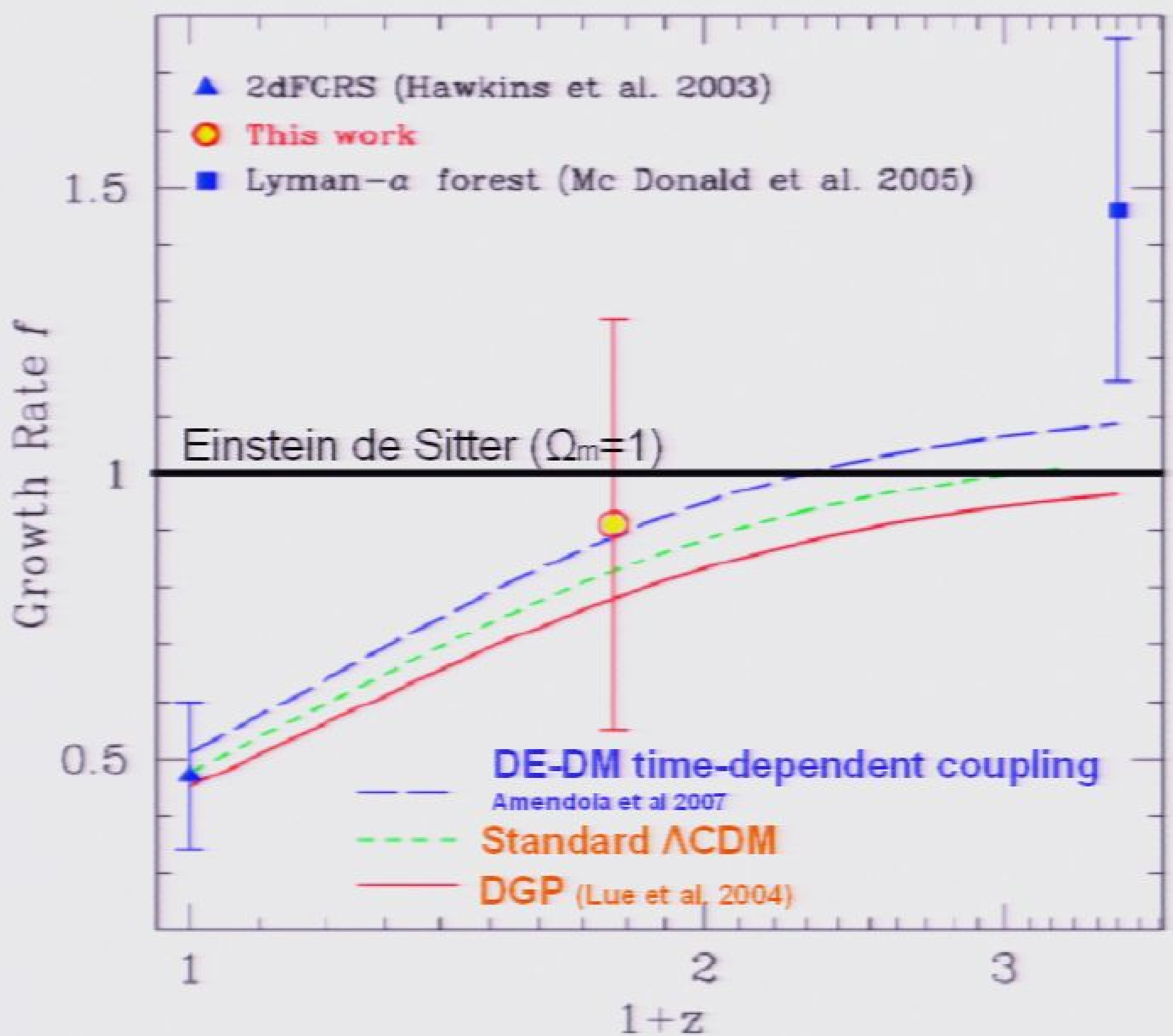
Preliminary studies at z~1 indicates:

- The PDF of galaxy fluctuations evolves over the range 0.5< z <1.5
  → matter-galaxy biasing is <u>non-linear on large scale</u> and it was <u>significantly higher in the past</u>

- Low order moments of the galaxy PDF evolve as predicted by the linear and second order perturbation theory.

- The amplitude of the growth rate function D(t) at z=0.75 is consistent with what expected within the standard model (ΛCDM)

Constraining the physics behind acceleration



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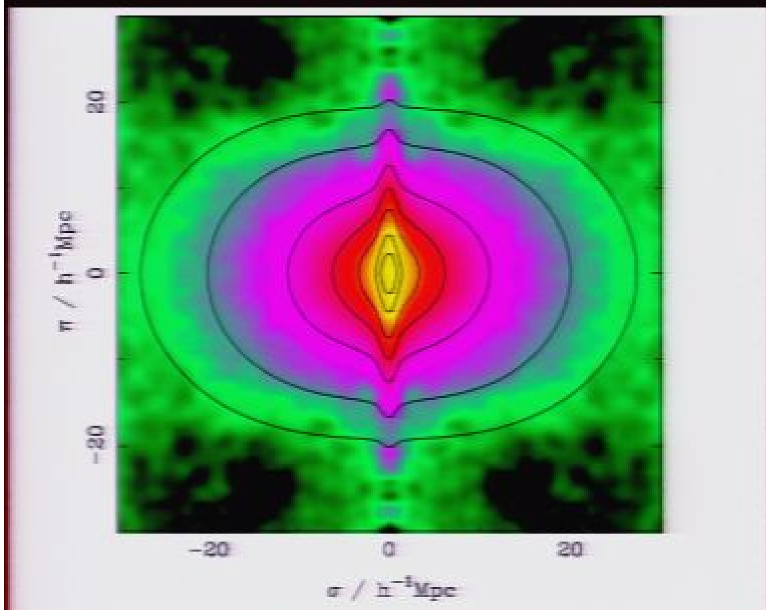

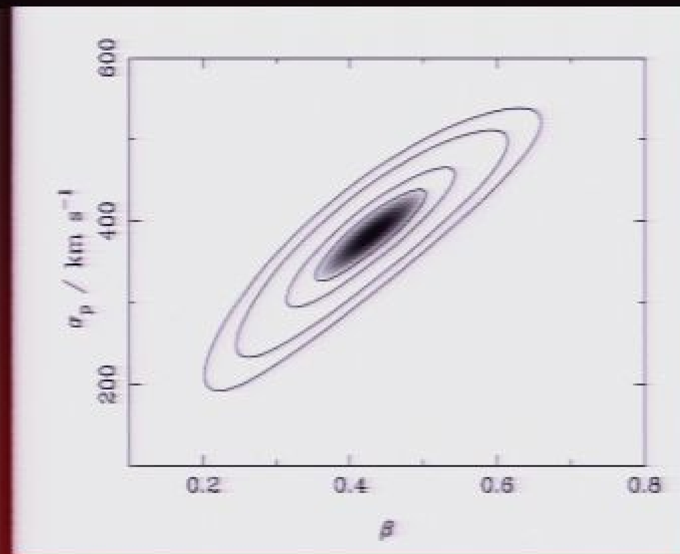

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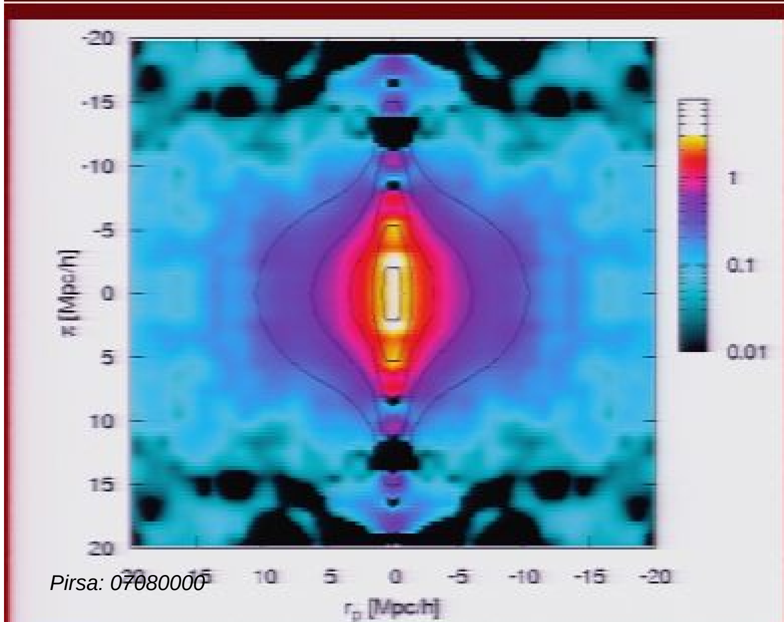

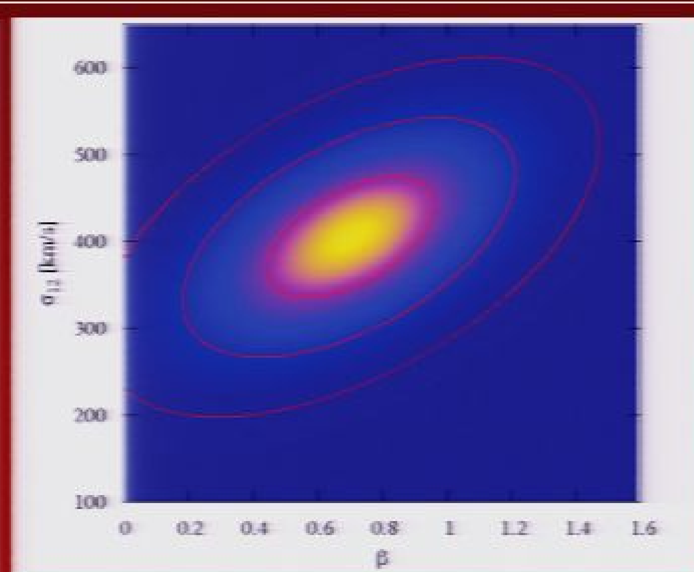

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