Title: Observational Probes of Early Universe Cosmology - Lecture 3

Date: Jun 26, 2009 11:30 AM

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Abstract:

This lecture:
Dark matter clustering and galaxy surveys

1. The dark matter power spectrum P(k)
2. Understanding the shape of P(k)
3. σ_8
4. The galaxy power spectrum $P_g(k)$ and bias
5. Historical measurements of $P_g(k)$
6. Recent measurements of $P_g(k)$
7. Future measurements of $P_g(k)$

An Introduction to Observational Cosmology

Olivier Doré, CITA

Lect 1: Dynamics of the Universe as probed by distance measurements (SNe)
Lect 2: Baryonic Acoustic Oscillations
Lect 3: Dark matter clustering and galaxy surveys
Lect 4: Gravitational lensing
Lect 5: The cosmic microwave background radiation

With material from
Sarah Bridle and Martin White

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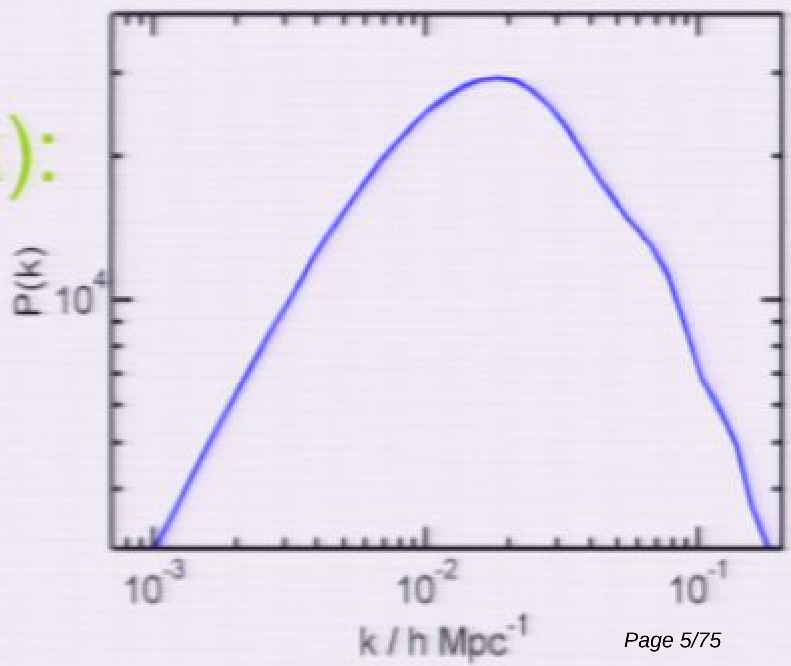
Definition of P(k)

- Fourier Transform of 3d matter distribution
- Average over all directions
  - $k=(k_x^2 + k_y^2 + k_z^2)^{0.5}$

- Present day universe P(k):



Why study P(k)?

- Shape depends on
  - Ω_m total matter content
  - Ω_b baryon content
  - Ω_{DE} dark energy content
- Probed by galaxy surveys: 2dFGRS, SDSS
- Theory underpins
  - CMB (Lecture 5)
  - Cosmic shear (Lecture 4)
  - Lyman-α forest…

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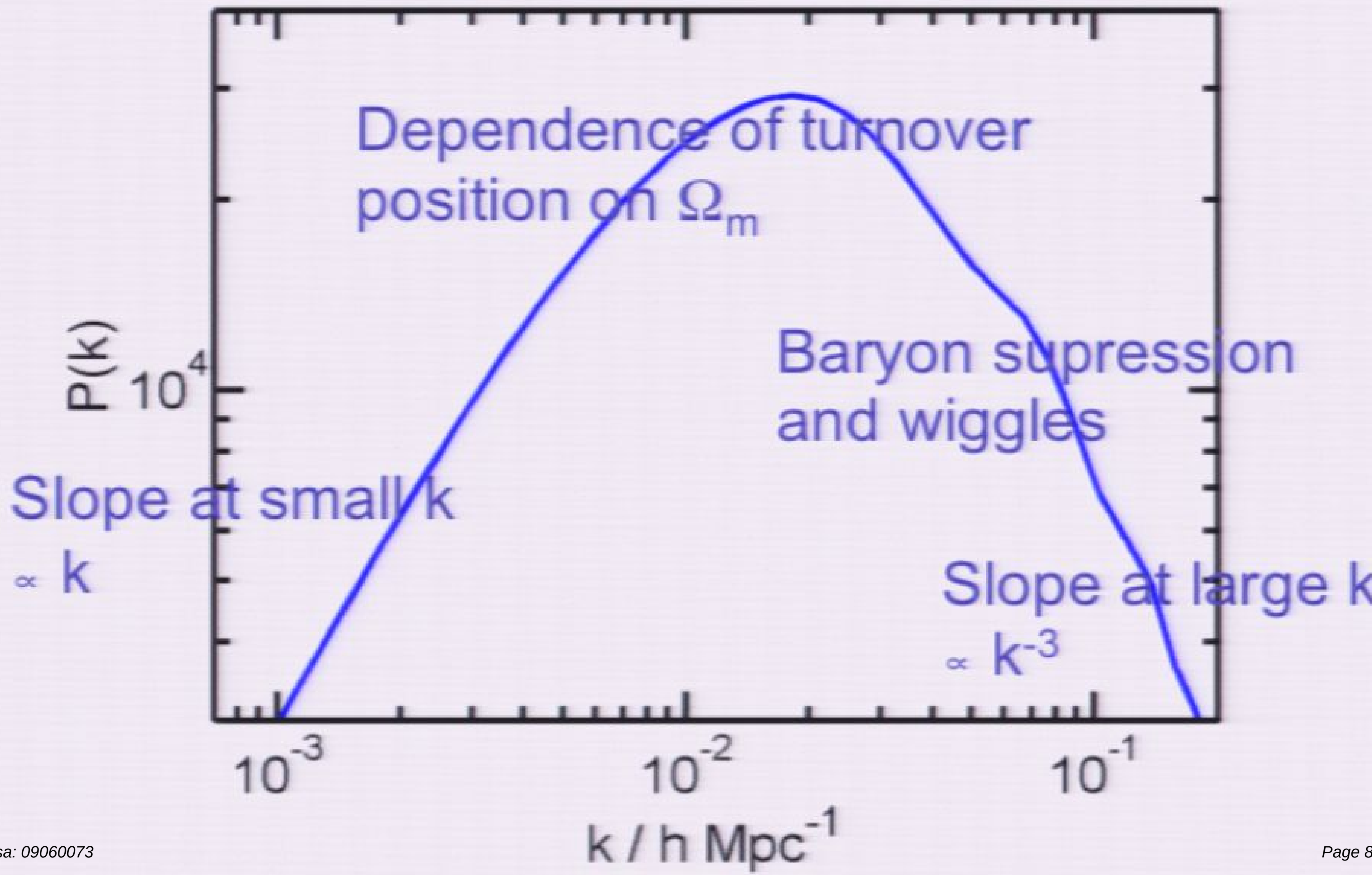
Key features



Primordial fluctuations

- Just after inflation, expected to be:
- Roughly scale-invariant
  - $P_i(k) \propto k$
- Gaussian
  - Consider histogram of densities
- Adiabatic
  - but could also have isocurvature components
- Scalar, tensor and maybe even vortical

Linear theory

- = Assume all fluctuations are very small
- Expand all equations to first order
  - $\rho(\mathbf{x})$ ' $\rho_0 (1 + \delta(\mathbf{x}))$
- Solve numerically (CMBFAST/CAMB)
- Cannot be valid today since $\delta >> 1$
- Expected to work
  - at early times
  - on large scales

Ingredients for understanding overall shape

- Expansion rate in
  - radiation dominated universe $a \propto t^{1/2}$
  - matter dominated universe $a \propto t^{2/3}$
- Jeans length
  - radiation dominated universe
  - matter dominated universe
- Growth rate of fluctuations in
  - radiation dominated universe
  - matter dominated universe

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Jeans length

- Gravity causes collapse
  - Collapse time for structure of size λ_J
  - t» $1/(G\rho)^{1/2}$
- Pressure resists collapse
  - Time for pressure to act over distance λ_J
  - t» λ_J / c_s
  - where c_s = sound speed
- Defn of Jeans length: when these times are equal
  - solving gives $\lambda_J = c_s /(G\rho)^{1/2}$

Significance of the Jeans length

- Fluctuations with $\lambda > \lambda_J$
  - large scales
  - grow under gravity

- Fluctuations with $\lambda < \lambda_J$
  - small scales
  - oscillate between collapsing and expanding

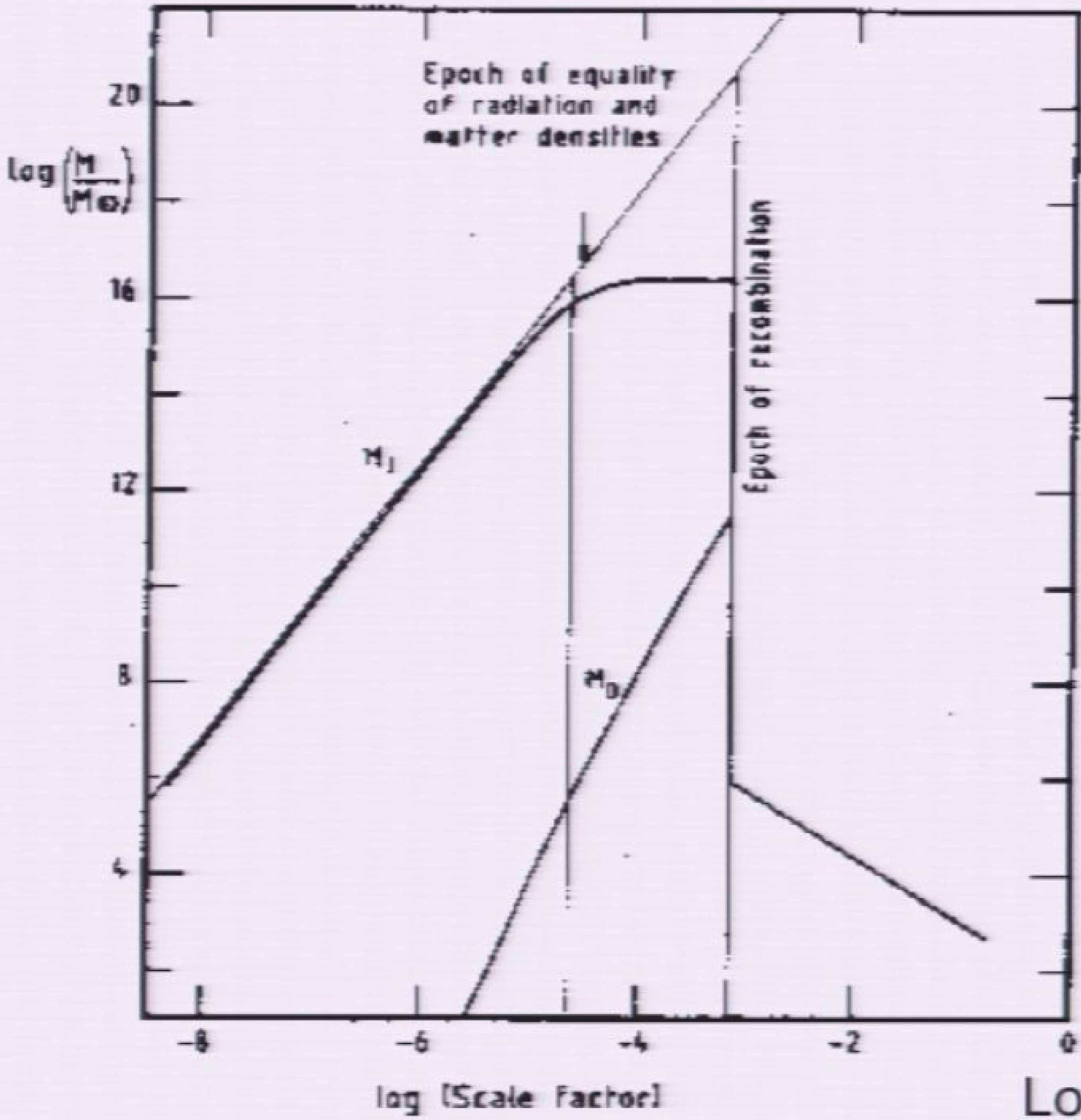
Picture the oscillations

- Radiation dominated Universe:
  - clumping of the radiation provides the gravity
  - squashing of the radiation resists further clumping
- Matter dominated Universe:
  - the amount of radiation is dynamically negligible
  - clumping of the dark matter provides the gravity
  - nothing provides the pressure to stop the dark matter from collapsing…

How does λ_J change with time?

- Radiation dominated era:
  - $\lambda_J \propto \rho^{-1/2}$
  - $\rho \propto a^{-4}$
  - so $\lambda_J \propto a^2$

- Matter dominated era:
  - no pressure so $\lambda_J = 0$



Longair Fig 12.1

Ingredients for understanding overall shape

- Expansion rate in
  - radiation dominated universe $a \propto t^{1/2}$
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- Jeans length
  - radiation dominated universe $\lambda_J \propto a^2$
  - matter dominated universe $\lambda_J = 0$
- Growth rate of fluctuations in
  - radiation dominated universe
  - matter dominated universe

Growth rate of fluctuations

- Radiation dominated era
  - $\lambda > \lambda_J$ grow $\propto a^2$
  - $\lambda < \lambda_J$ oscillate, ~ no growth

- Matter dominated era
  - $\lambda > \lambda_J$ (ie. all scales) grow $\propto a$
  - ie. grow as $1/(1+z)$

Consider large wavelengths

- Wavelength λ
  - Large in the sense that $\lambda > \lambda_J$ always
- Grows $\propto a^2$ in radiation dominated
- Grows $\propto a$ in matter dominated
- Amount grown is independent of λ

- Primordial power spectrum shape is retained

Consider smaller wavelengths λ

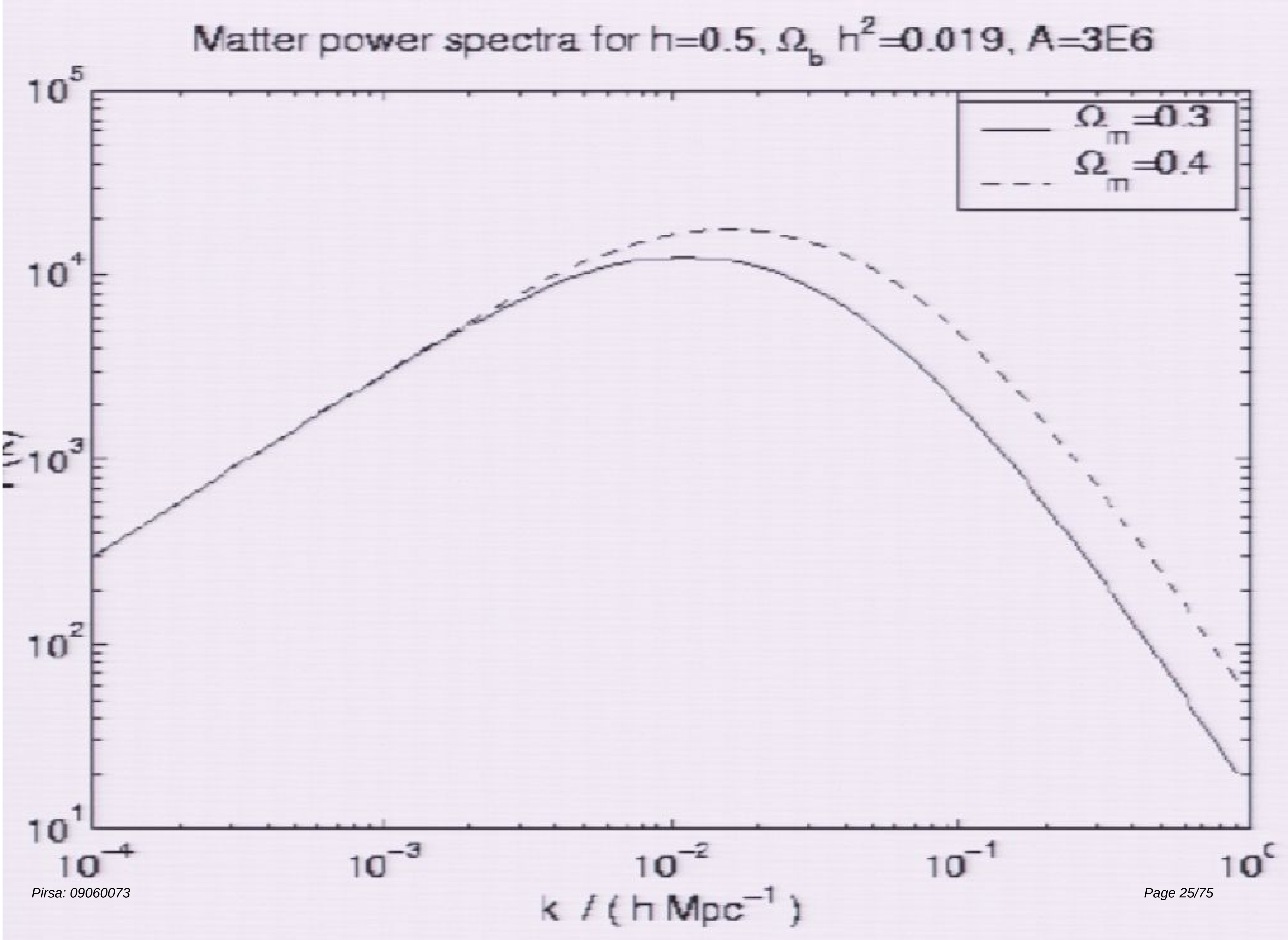
- Very early on, $\lambda > \lambda_J$
- Grows as a^2
- But λ_J is increasing with time $\lambda_J \propto a^2$
  - So there comes a time when $\lambda<\lambda_J$
- Stops growing
- Then after matter-radiation equality all fluctuations on all scales grow the same

Where is the turnover?

- Critical scale is Jeans length at matter-radiation equality, λ_{eq}
  - corresponding wavenumber k_{eq}
- Scales larger than this grew always
- Scales smaller wen progressively longer periods of stagnation (oscillation)

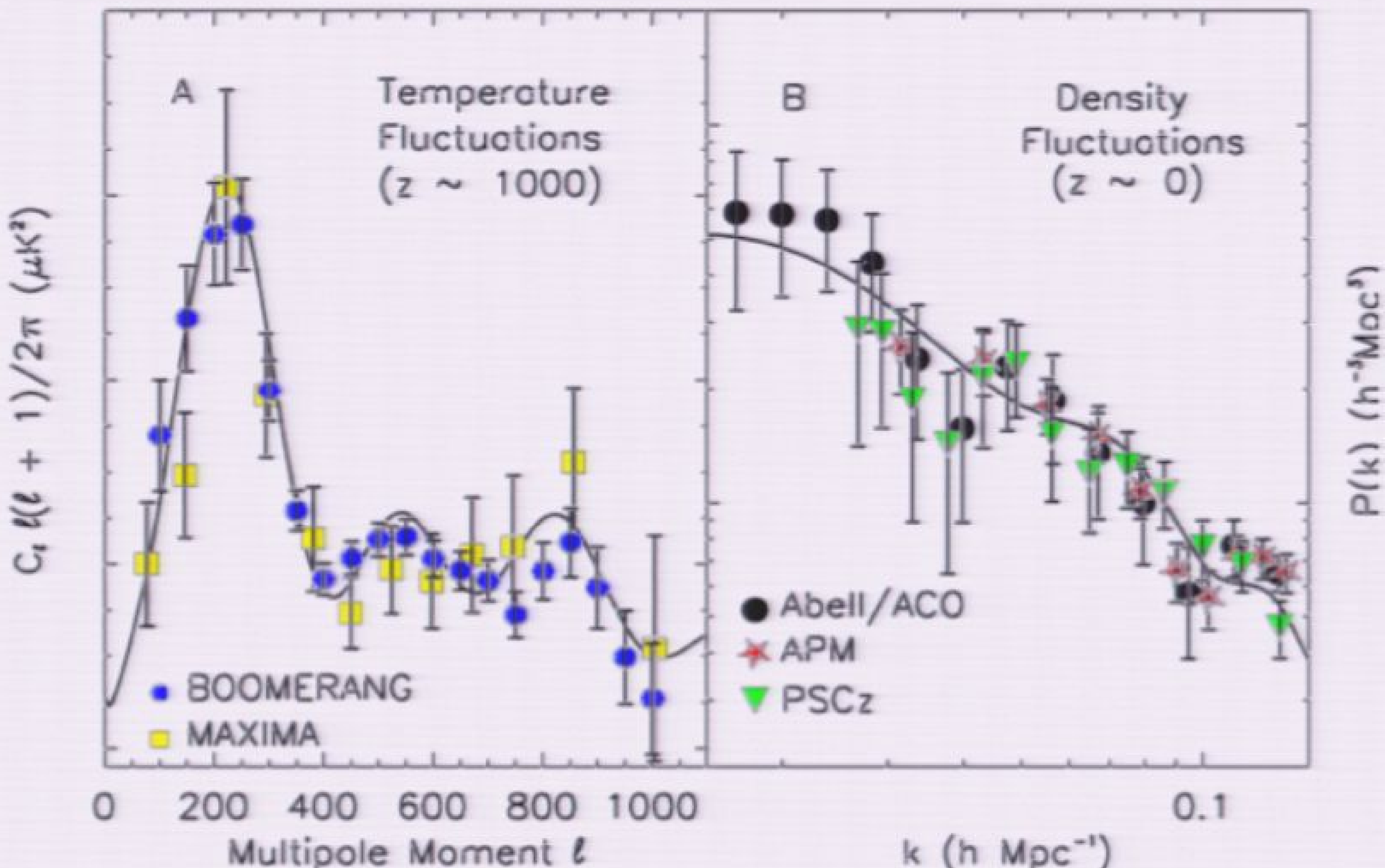
How does turnover depend on Ω_m ?

- How does Ω_m affect when matter-radiation equality occurs?
- Larger $\Omega_m \rightarrow$ earlier matter-radiation equality
  - Less chance for oscillation/stagnation
- Turnover moves to the ...



Matter power spectra for h=0.5, Ω_b h²=0.019, A=3E6
Ω_m=0.3
Ω_m=0.4
10⁵
10⁴
10³
10²
10¹
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
k / (h Mpc⁻¹)

Baryon oscillations



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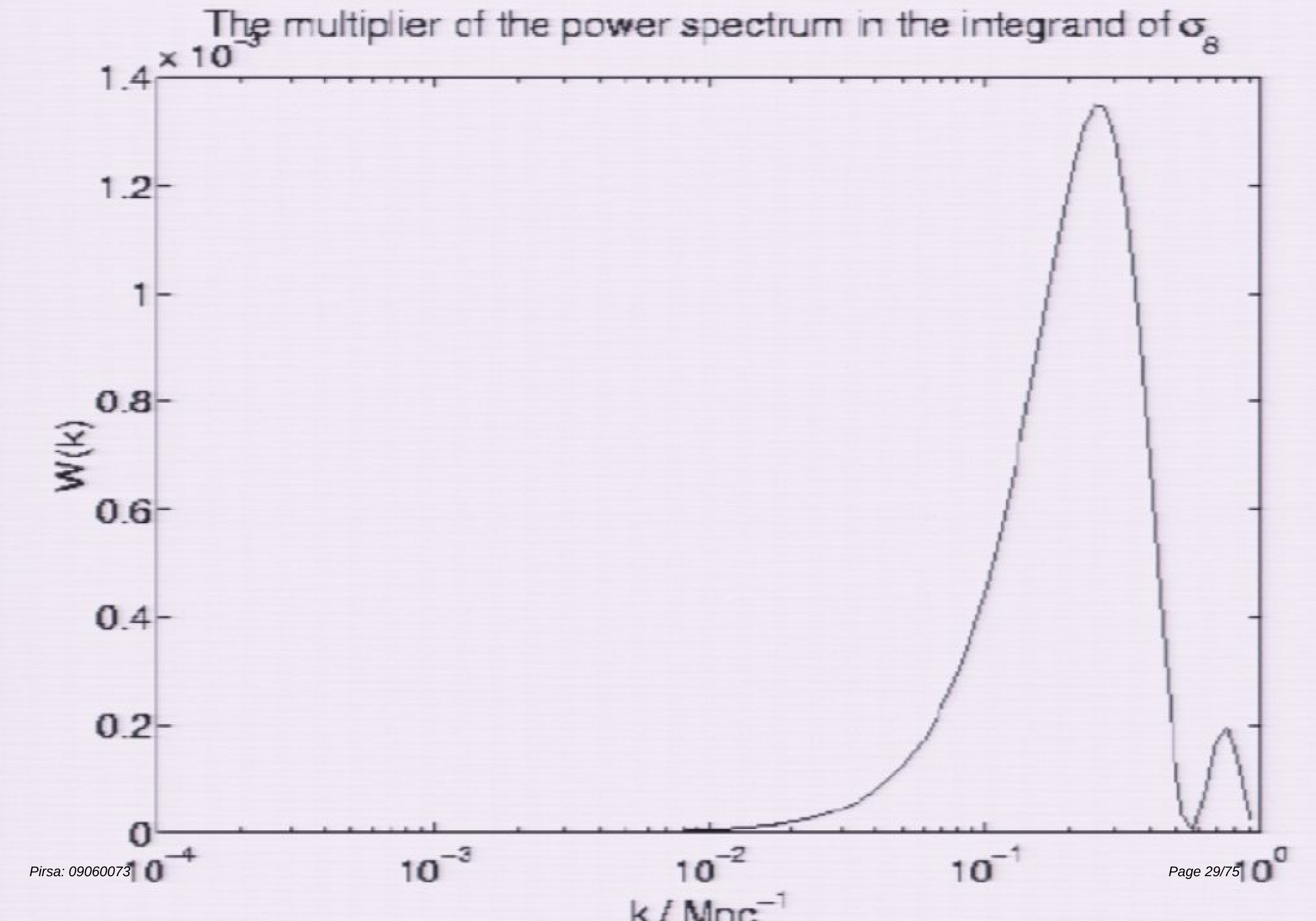
What is σ_8 ?

- $\sigma_R \equiv$ rms mass fluctuation in spheres of radius R Mpc
- R=8 was chosen since gave $\sigma_8 \sim 1$
- $\sigma_R^2 = s\, W(k,R)\, P(k)\, dk$
  - Using linear theory P(k)
- $\sigma_8 \sim$ amplitude of P(k) at $k \sim 2\pi/8\ \mathrm{Mpc}^{-1}$
- Often used to fix amplitude of primordial fluctuations, A in $P_i(k) = A\, k^n$



The multiplier of the power spectrum in the integrand of σ8
× 10^-3
1.4
1.2
1
0.8
0.6
0.4
0.2
0
W(k)
10^-4
10^-3
10^-2
10^-1
10^0
k / Mpc^-1

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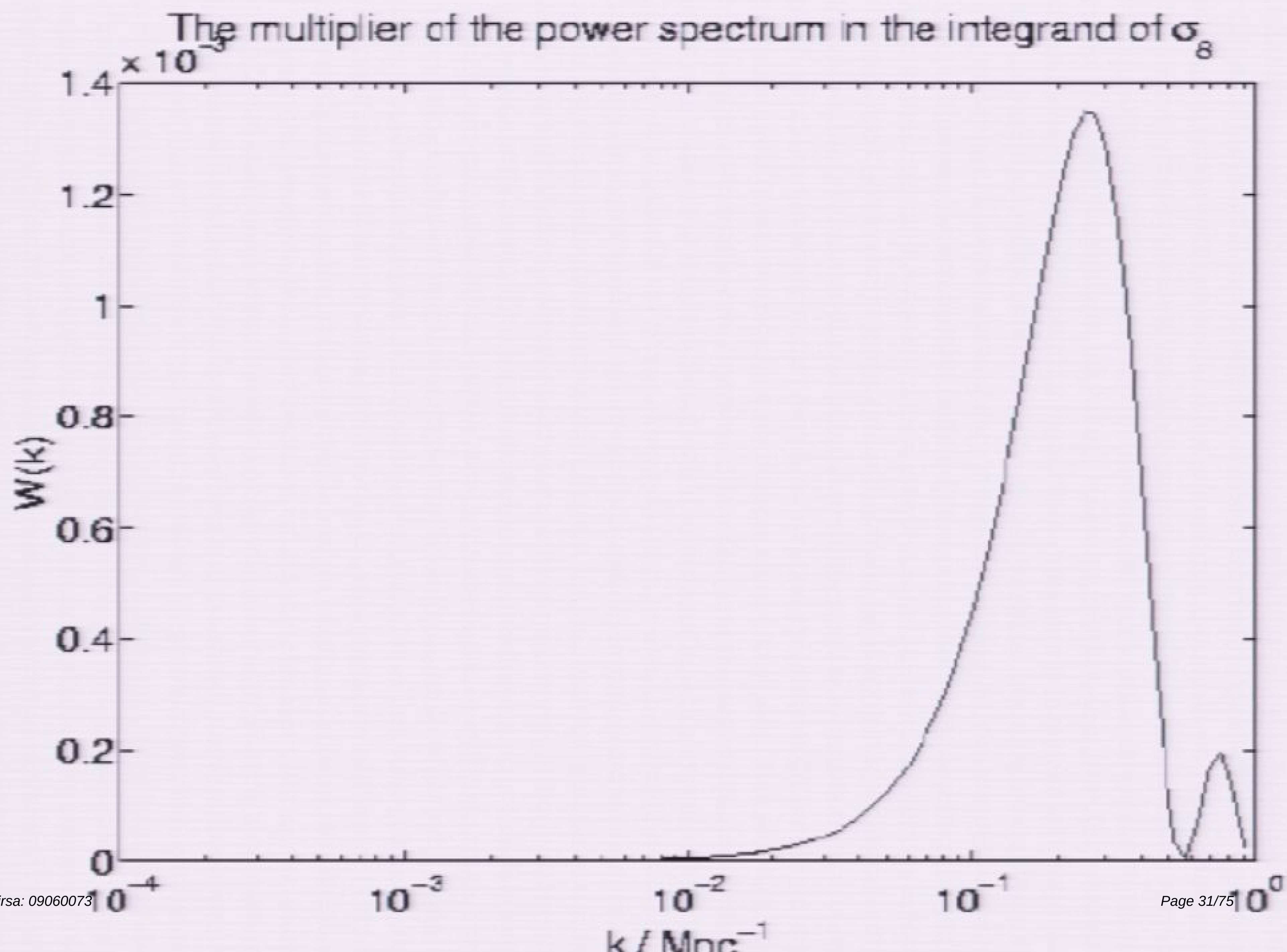
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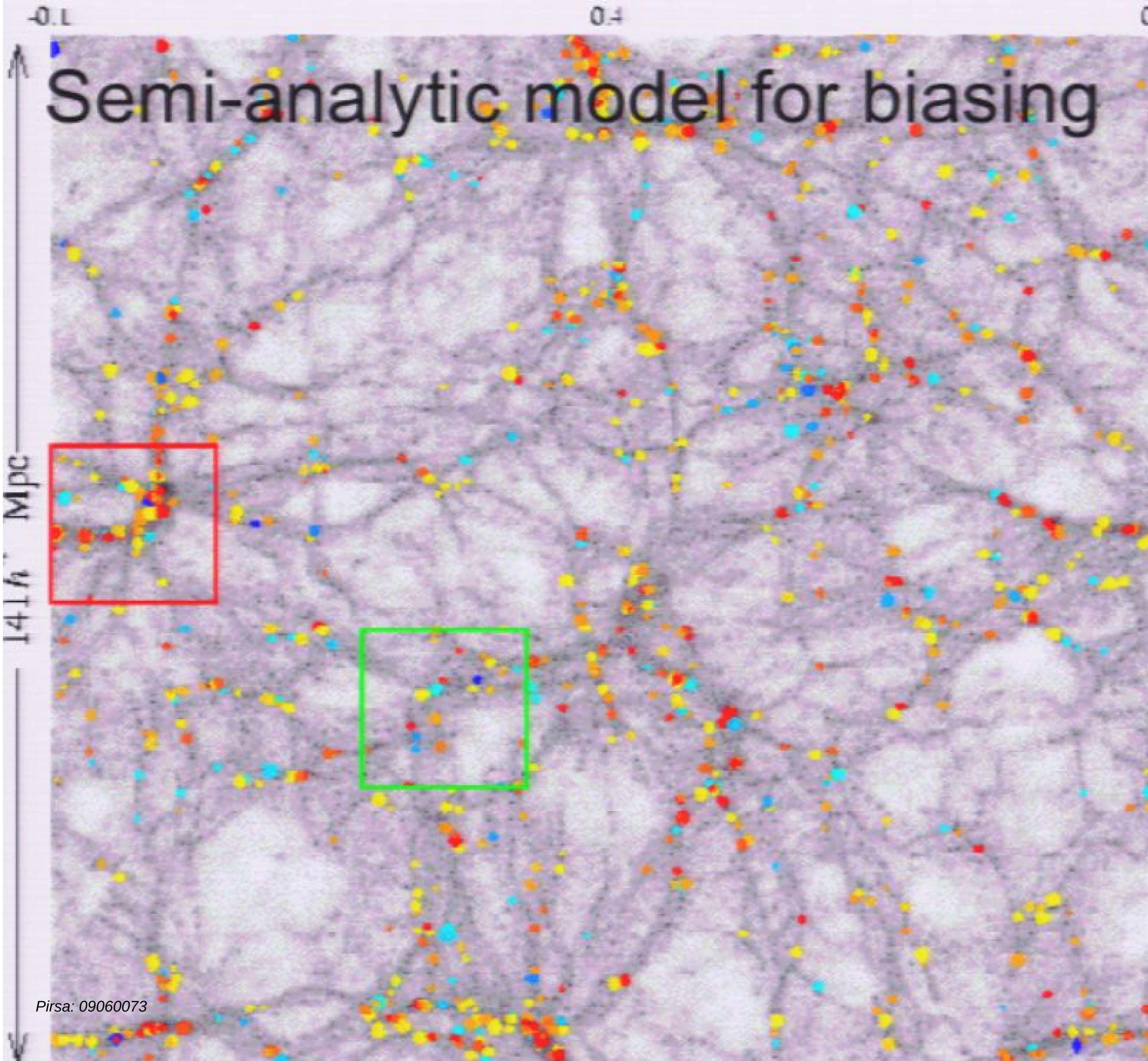
Biasing

- Relation of galaxies to mass ≡ "bias"
- Comparison of different galaxy types
  - ⇒ there must be some bias
- Theoretical models speculative
- Do galaxies tell us about cosmology…
  - – or about galaxy formation??

Semi-analytic model for biasing



Benson et al MNRAS 311, 793

Linear Bias

≡ galaxy power spectrum is a constant multiple of the matter power spectrum

– $P_g(k) = b^2 P(k)$

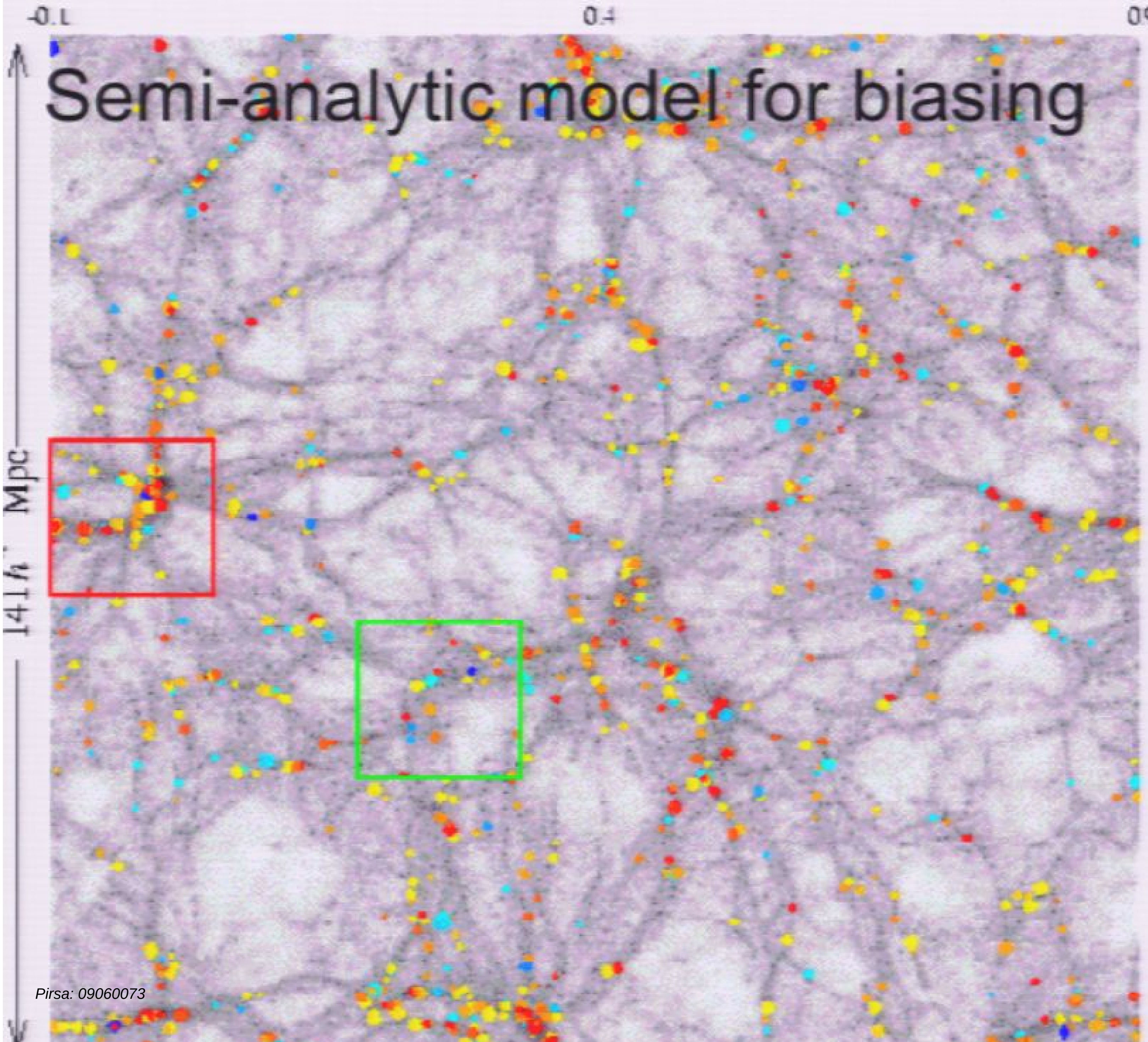
– $\sigma_{8g} = b\ \sigma_8$

- Assumed for 2dFGRS and SDSS cosmological parameter analyses

- Could more generally have b(k)

= non-linear bias eg. $b=b_0 + b_1 k$

Semi-analytic model for biasing



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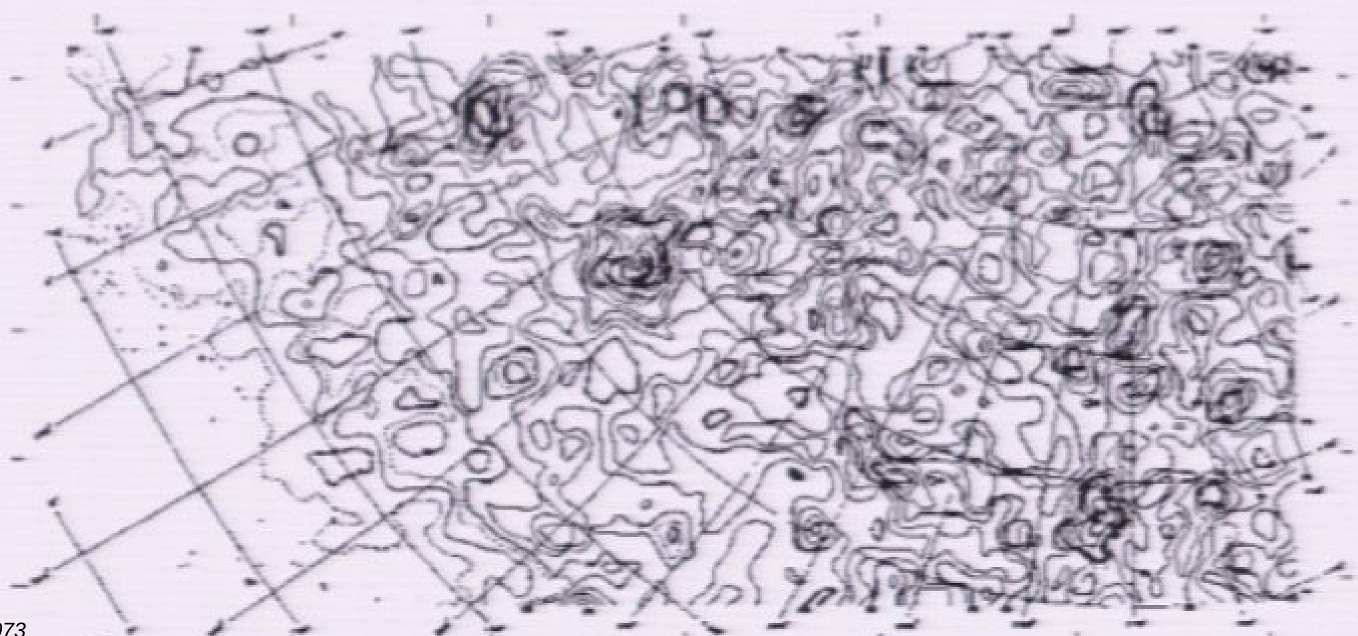
Past galaxy surveys

Name	N_{obj}	Ref.
Cat. of Neb. and Clusters	1000's	Herschel (1864)
New General Catalogue	11,475	Dreyer (1888, 1895, 1908)
Heidelberg Nebular Lists	10,000+	Wolf (1901-1916), Reinmuth (1916-1940)
Hubble	44,000	[Hubble, 1934]
Shapley	392,870	[Shapley, 1938]
Abell clusters	~3,000	[Abell, 1958]
Lick	1,000,000+	[Shane and Wirtanen, 1967]
CGCG	30,700	[Zwicky et al., 1968]
Jaggelonian Field	10,000	[Rudnicky and et al., 1973]
Texas Radio Sources	65,208	[Douglas, 1987]
Edinburgh/Durham	40,000	[Heydon-Dumbleton et al., 1988]
ACO clusters	~3,000	[Abell et al., 1989]
APM	2,000,000	[Maddox et al., 1990a]
IRAS PSC	~14,000	[Saunders, 1996]

Lick catalogue

- Visual inspection of plates
- Limiting magnitude ~ 18.5
- Effective depth 300 h^{-1} Mpc



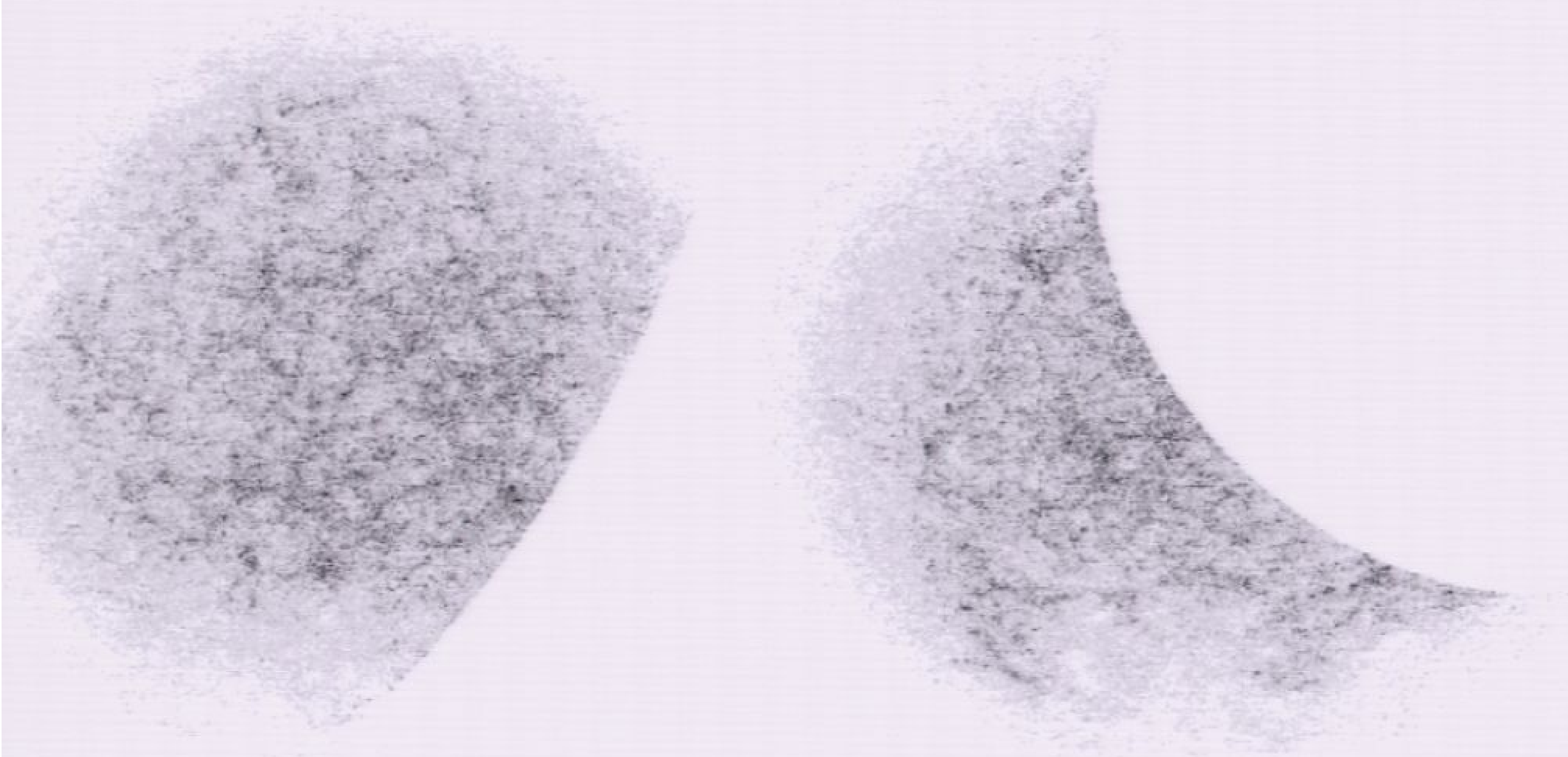
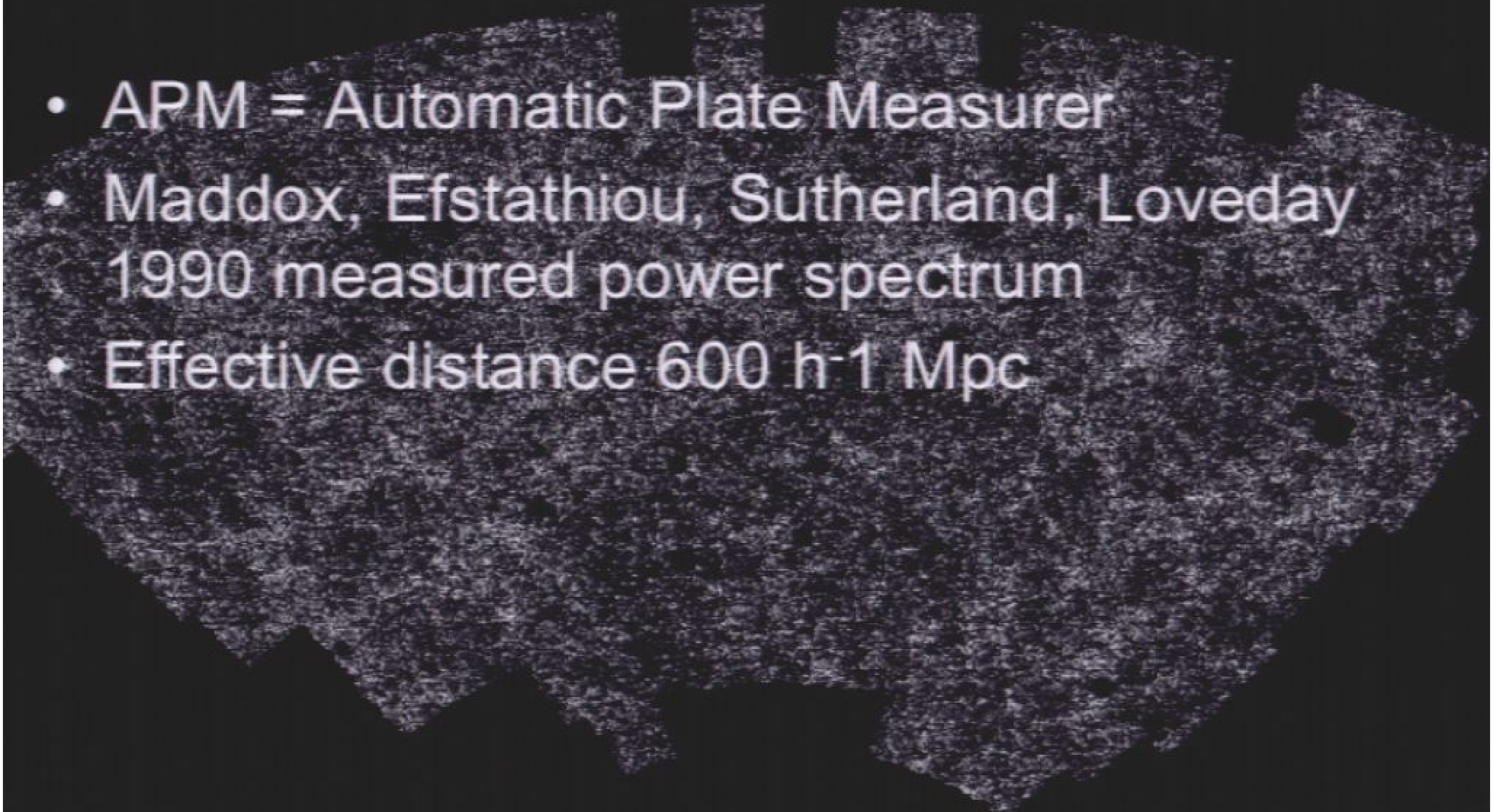
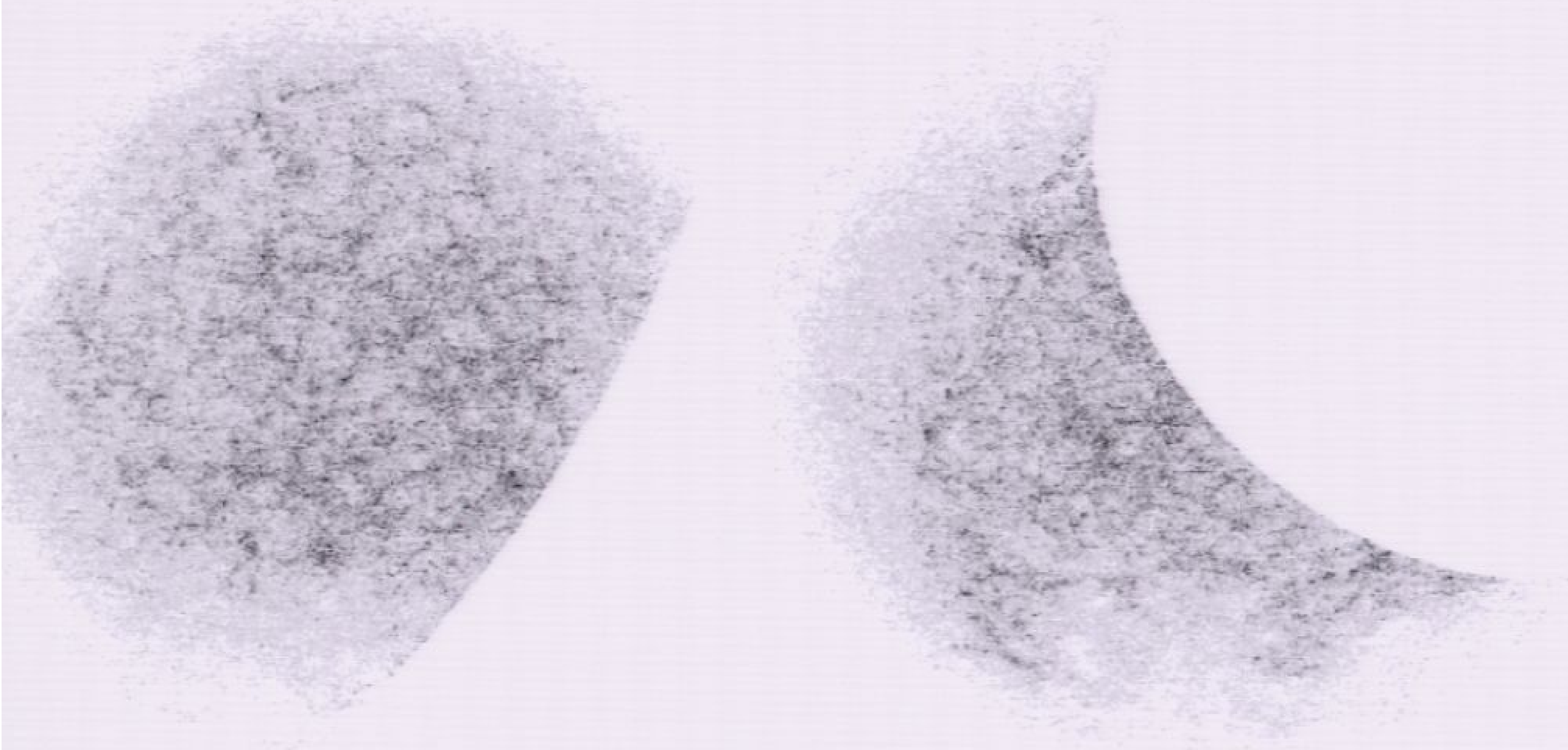


Figure 4.1: Lick survey in the Princeton representation made by [Seldner et al., 1977].

APM

- APM = Automatic Plate Measurer
- Maddox, Efstathiou, Sutherland, Loveday 1990 measured power spectrum
- Effective distance 600 h^{-1} Mpc





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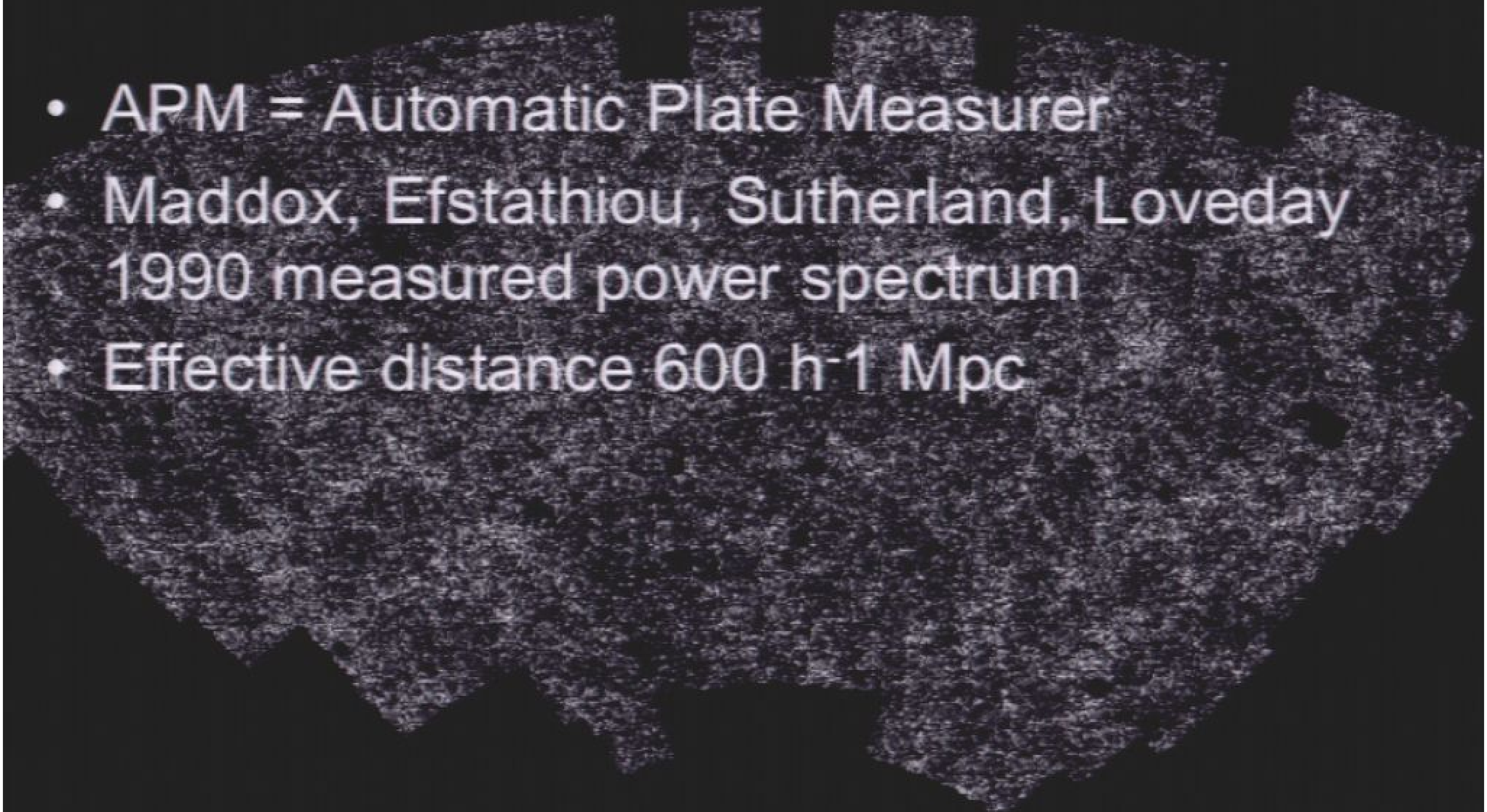

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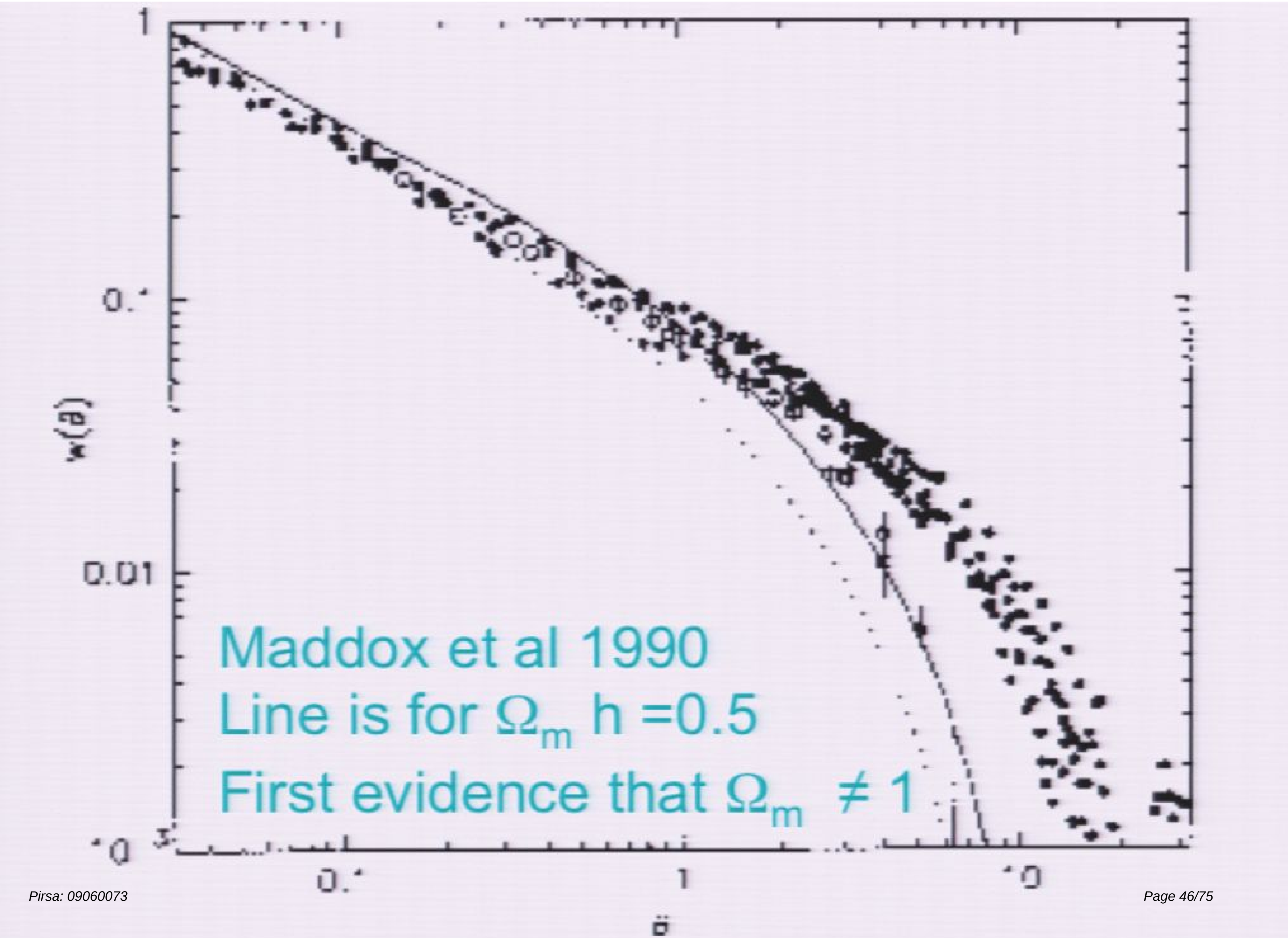
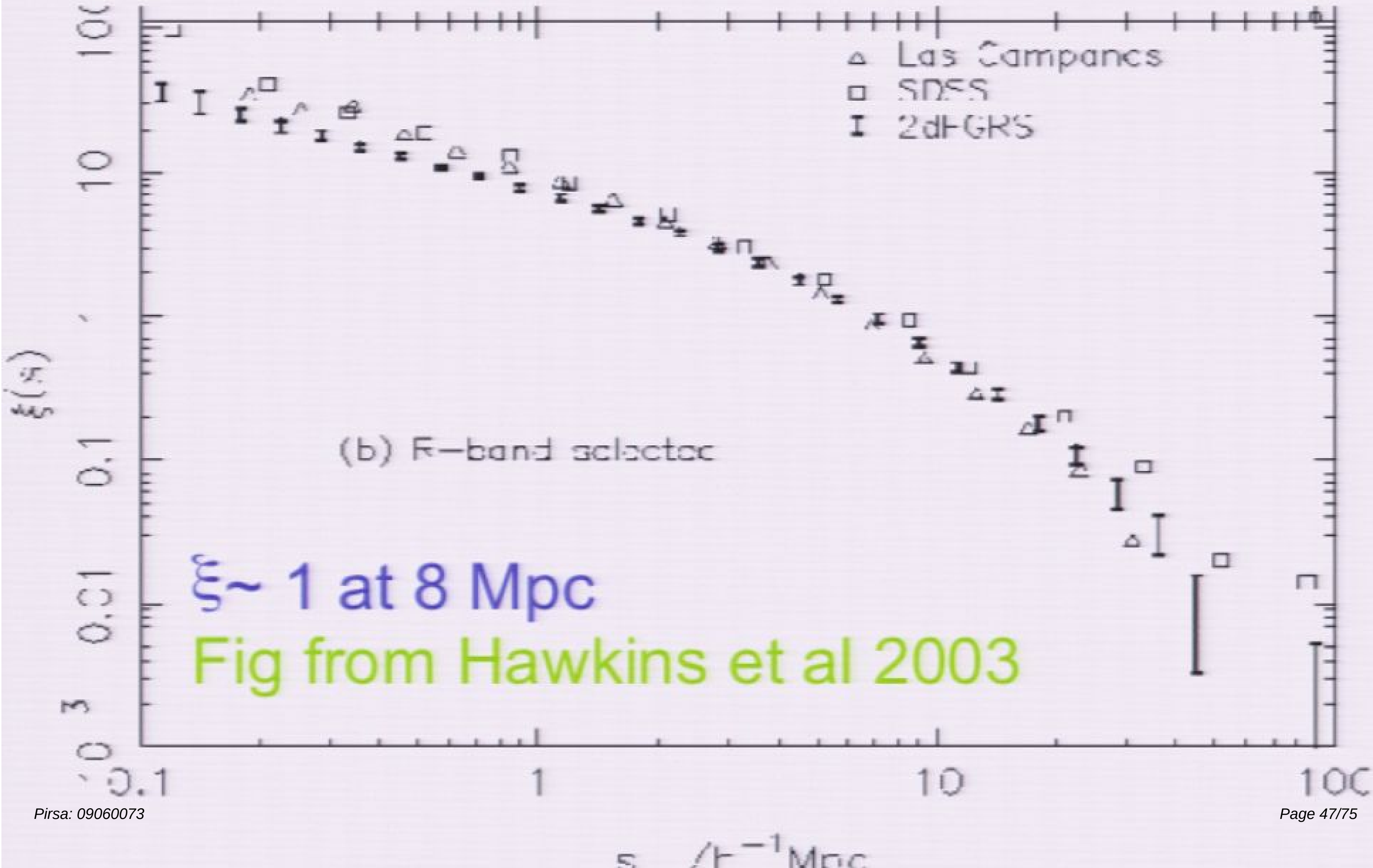
Galaxy 2-point correlation fn

- $dP = n^2 \, dV_1 \, dV_2 \, [1+\xi \, (r)]$
- The traditional measure of clustering
- Simply related to P(k)
- Angular correlation function
  - Even easier to measure:
- $dP = n^2 \, d\,\Omega_1 \, d\,\Omega_2 \, [\, 1 + w(\theta)]$
- ξ (r) and $w(\theta)$ related through "Limber's equation"



1
0.1
0.01
w(θ)
0.1
1
10
θ
Maddox et al 1990
Line is for Ω_m h =0.5
First evidence that $\Omega_m \neq 1$

Why 8 Mpc?

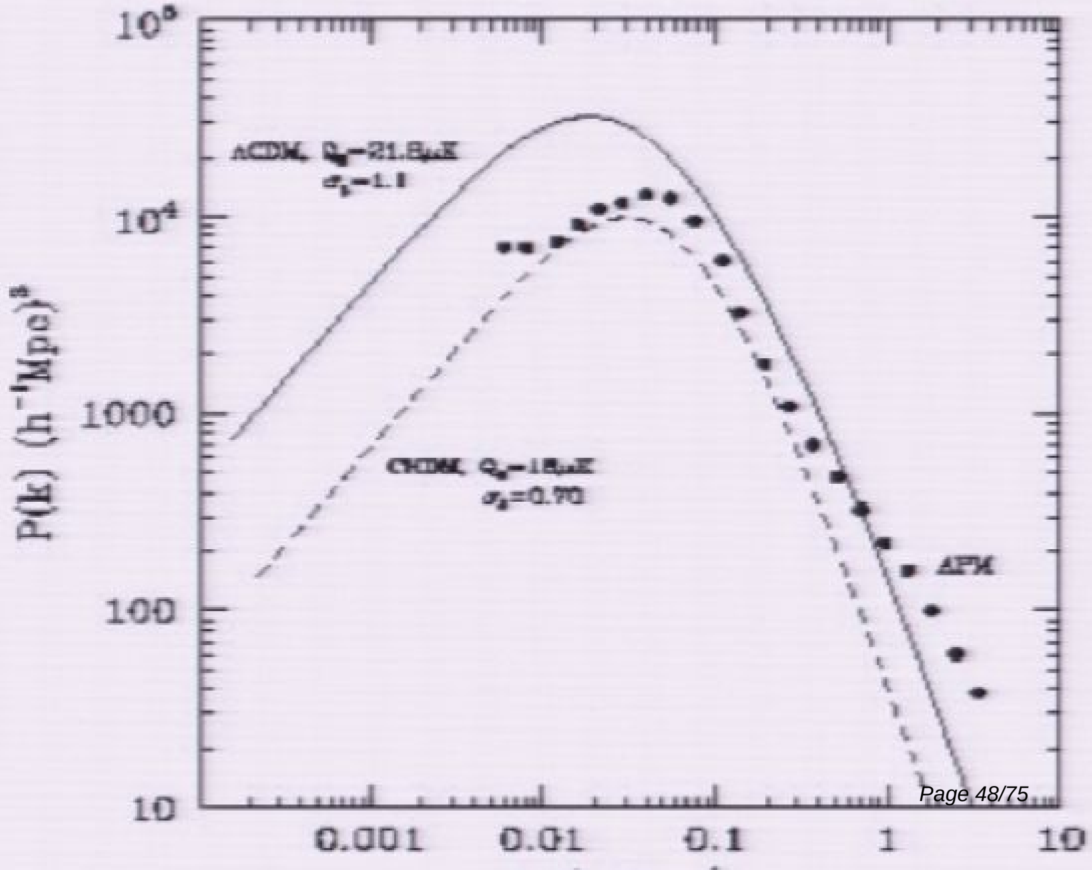


ξ~ 1 at 8 Mpc

Fig from Hawkins et al 2003

Galaxy power spectrum

- Simply related to ξ – contains same info
- Isolates physics occurring on different scales
- Used nowadays
- Harder to extract



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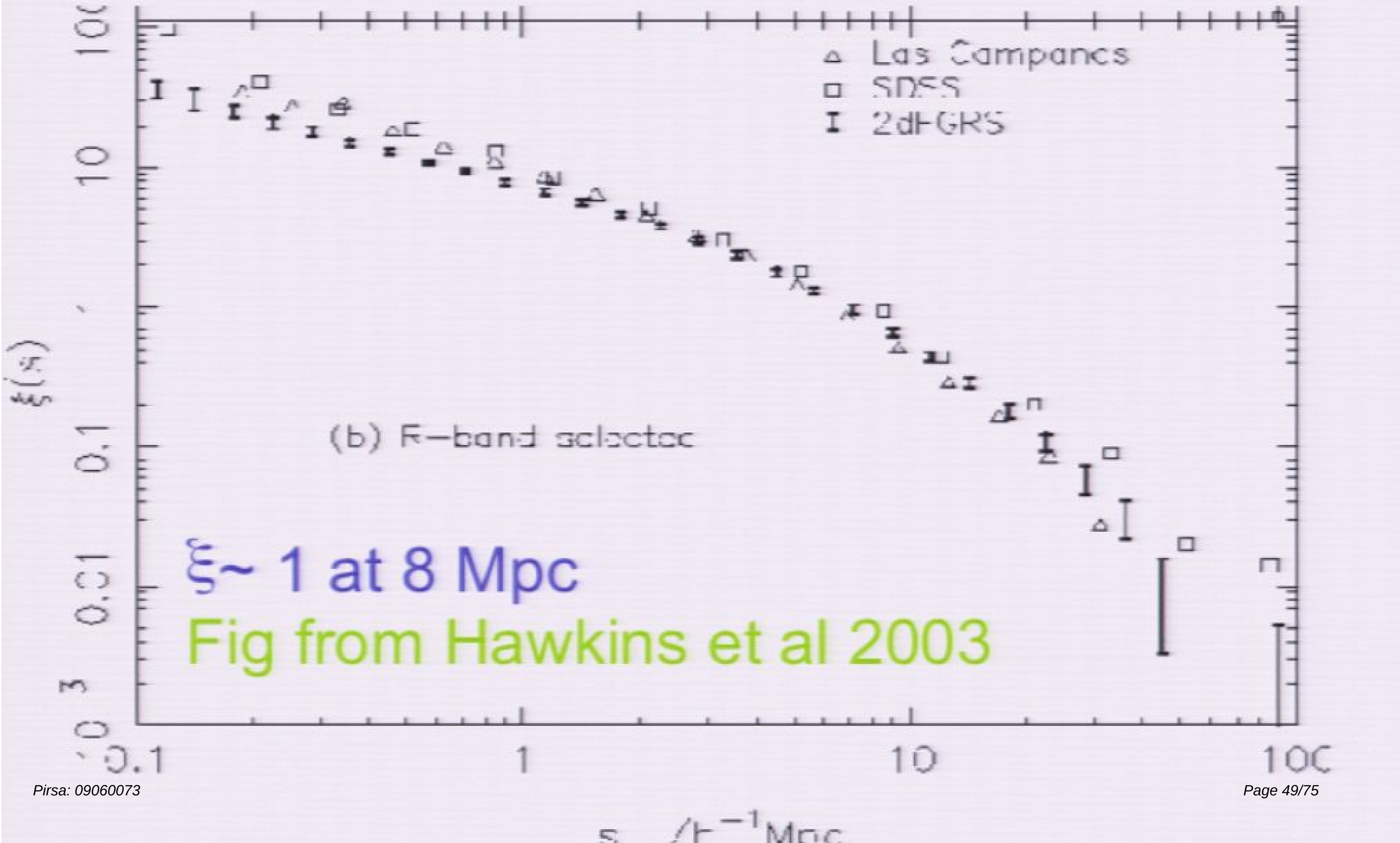

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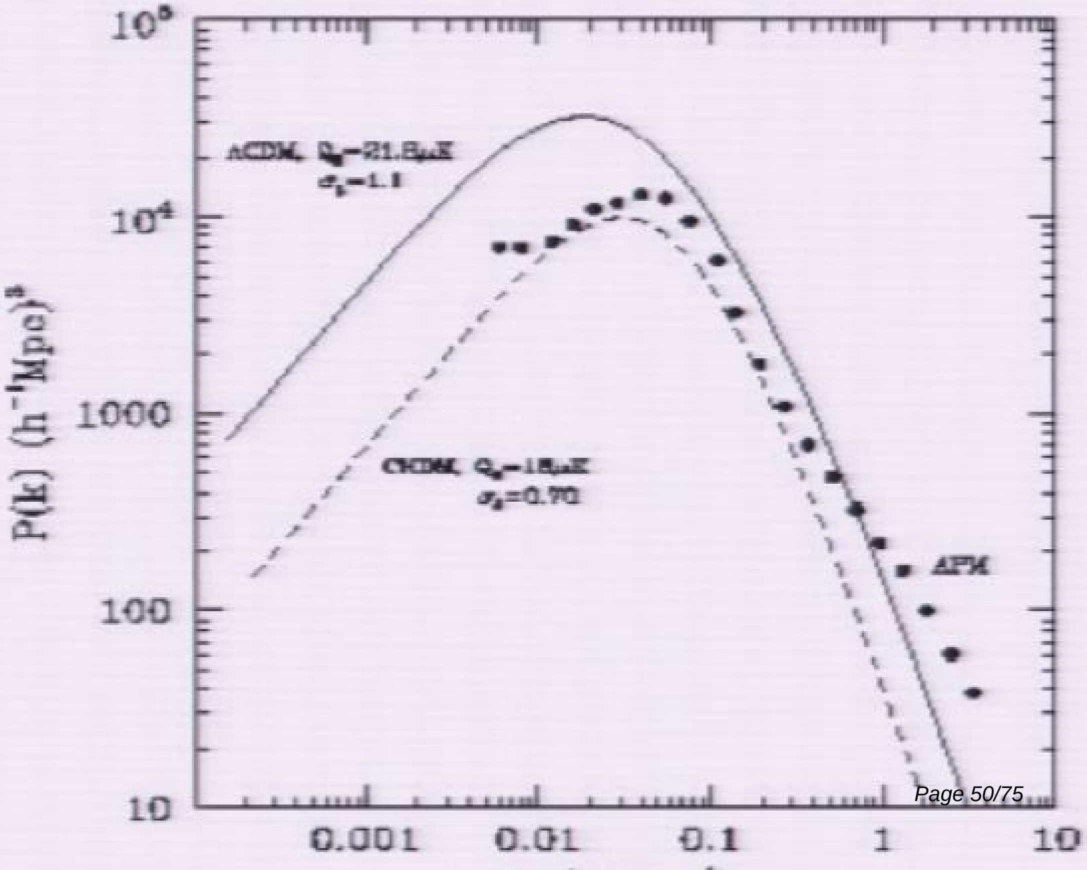

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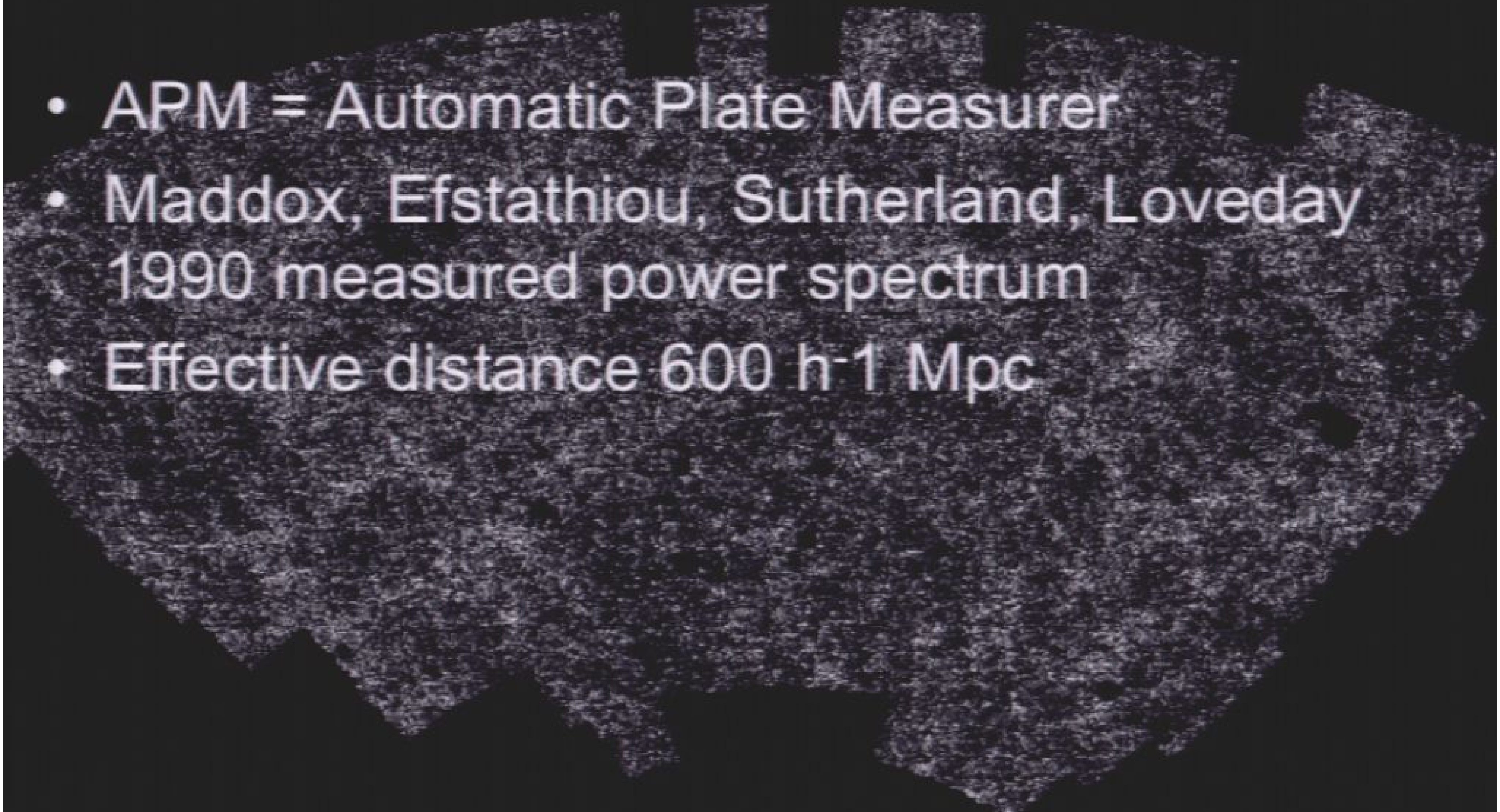

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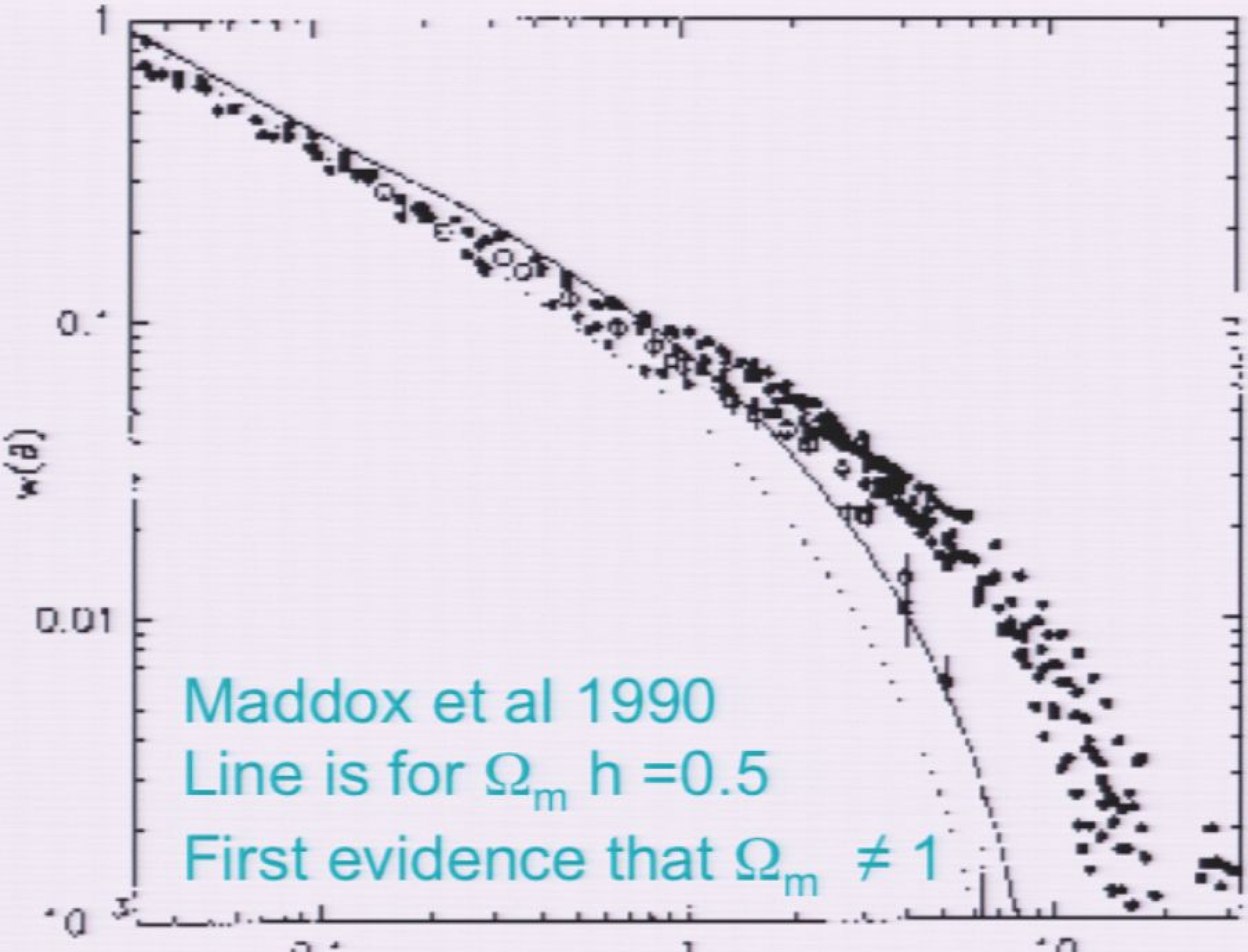

Maddox et al 1990

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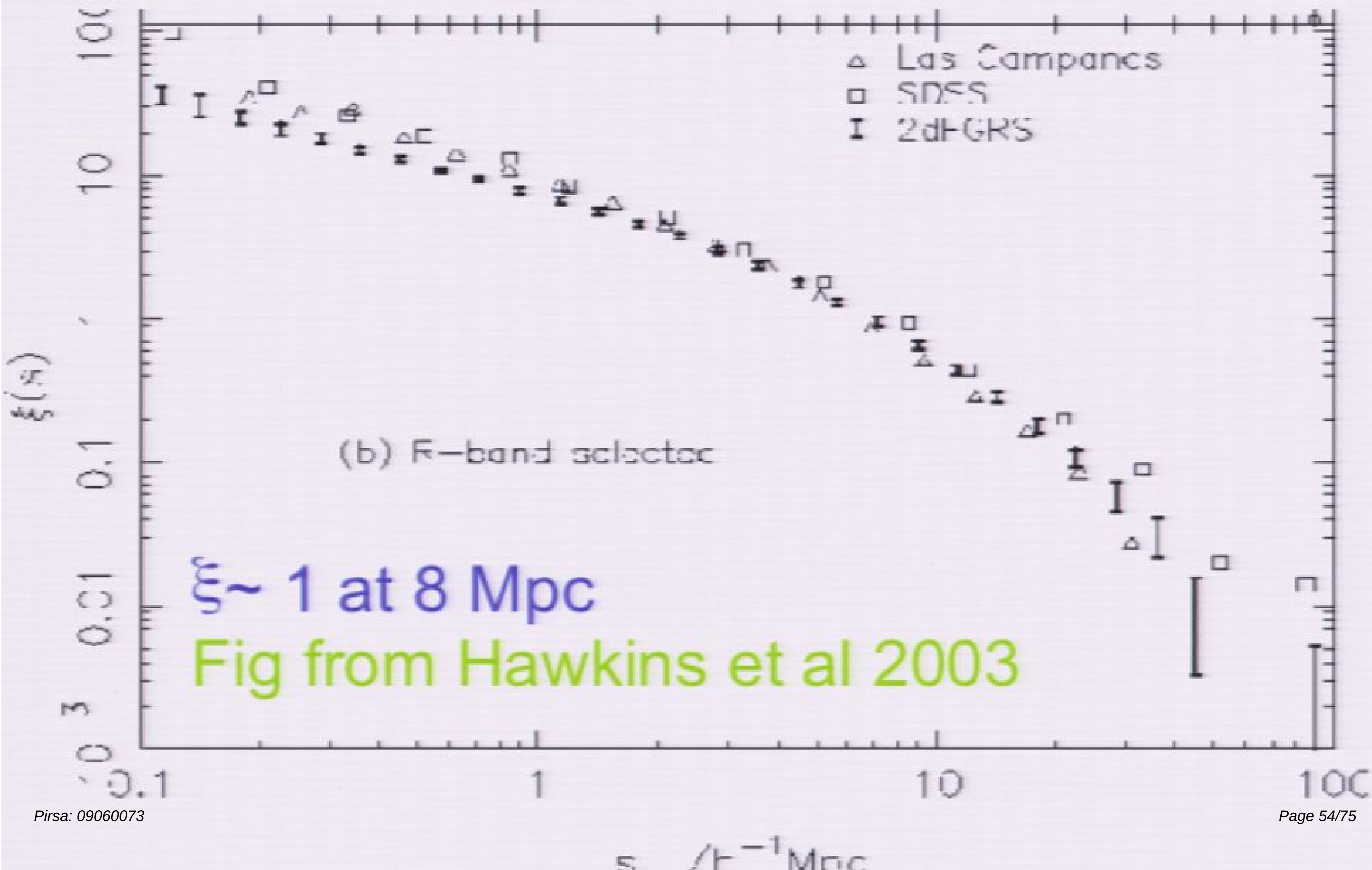

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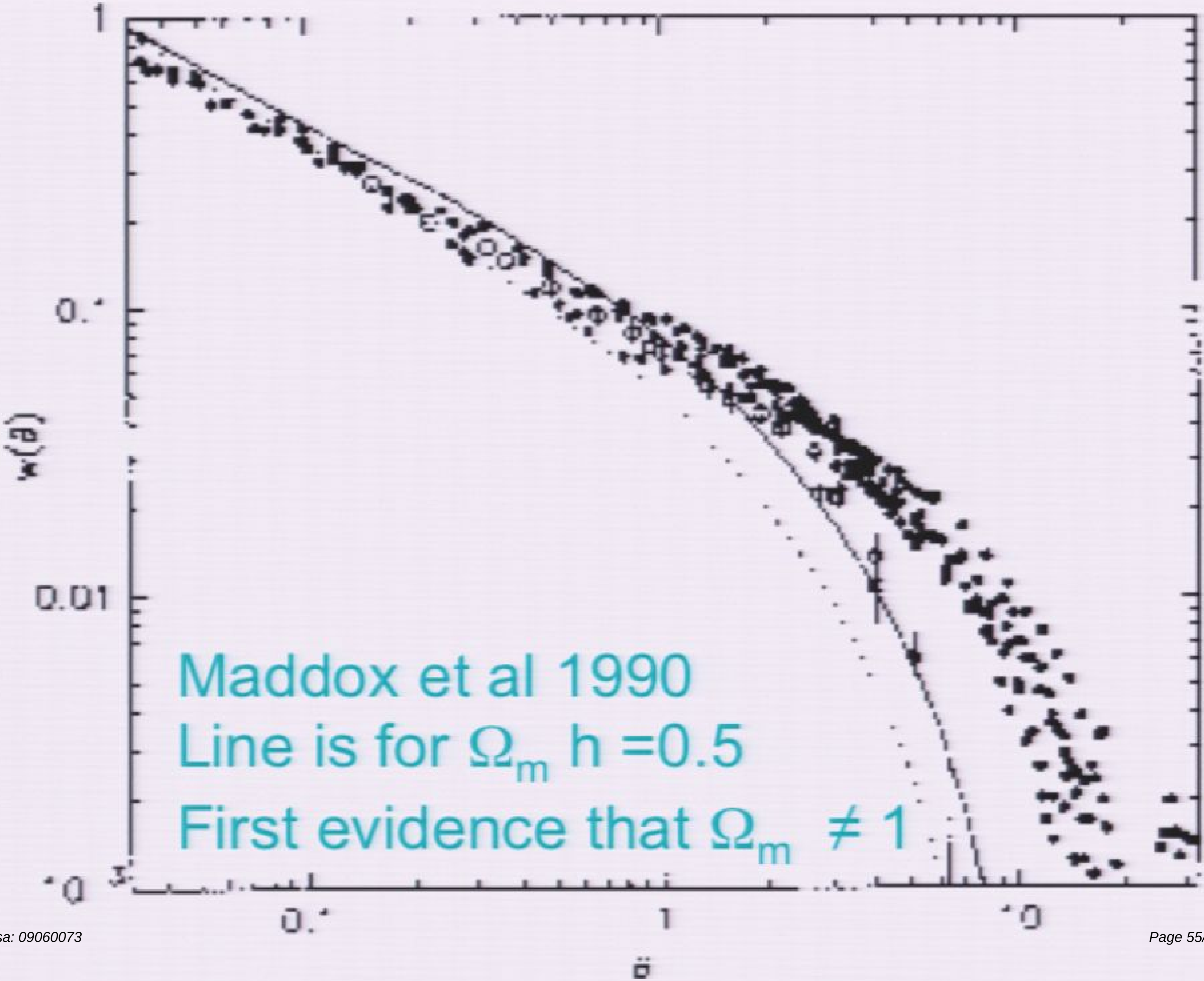

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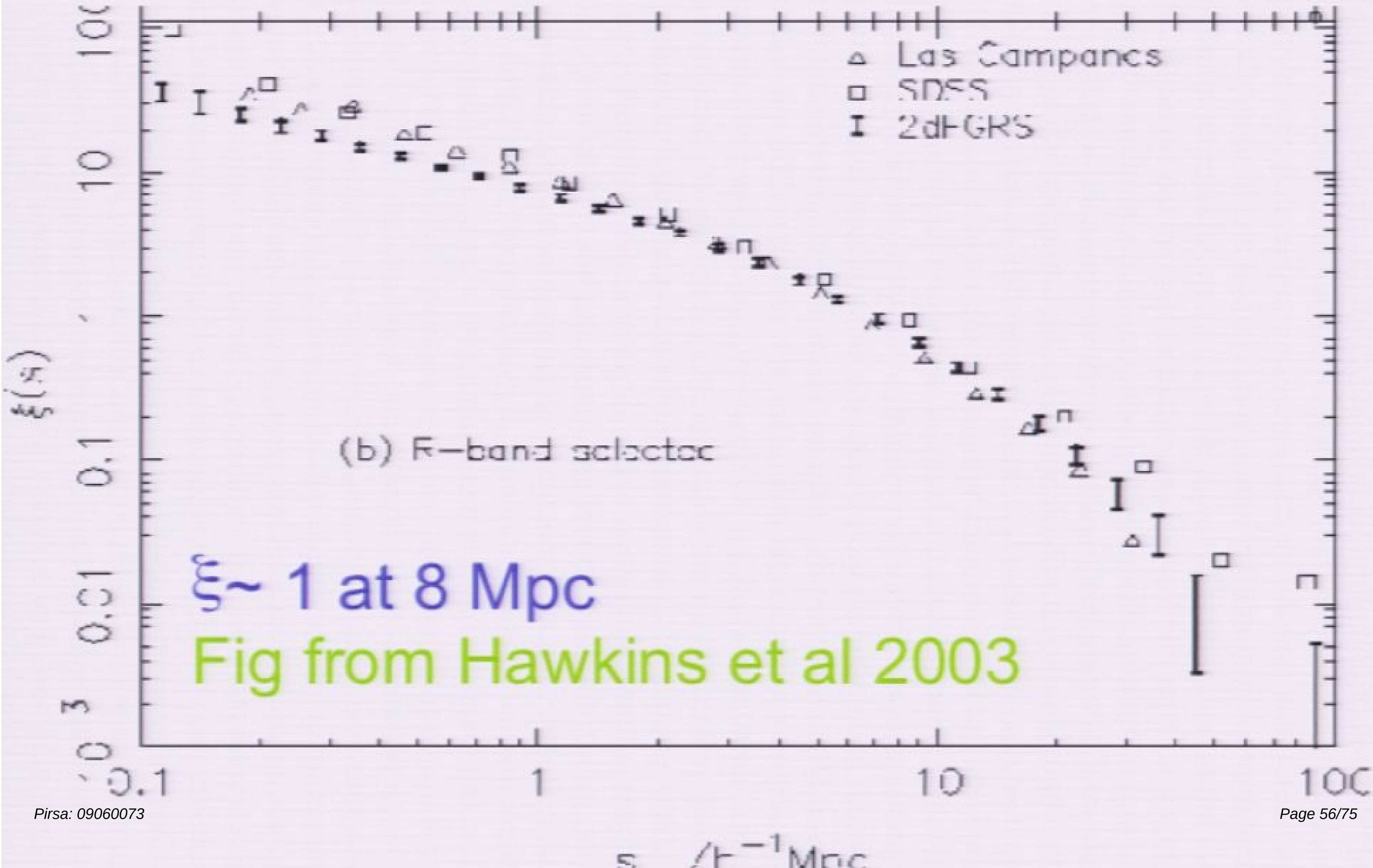

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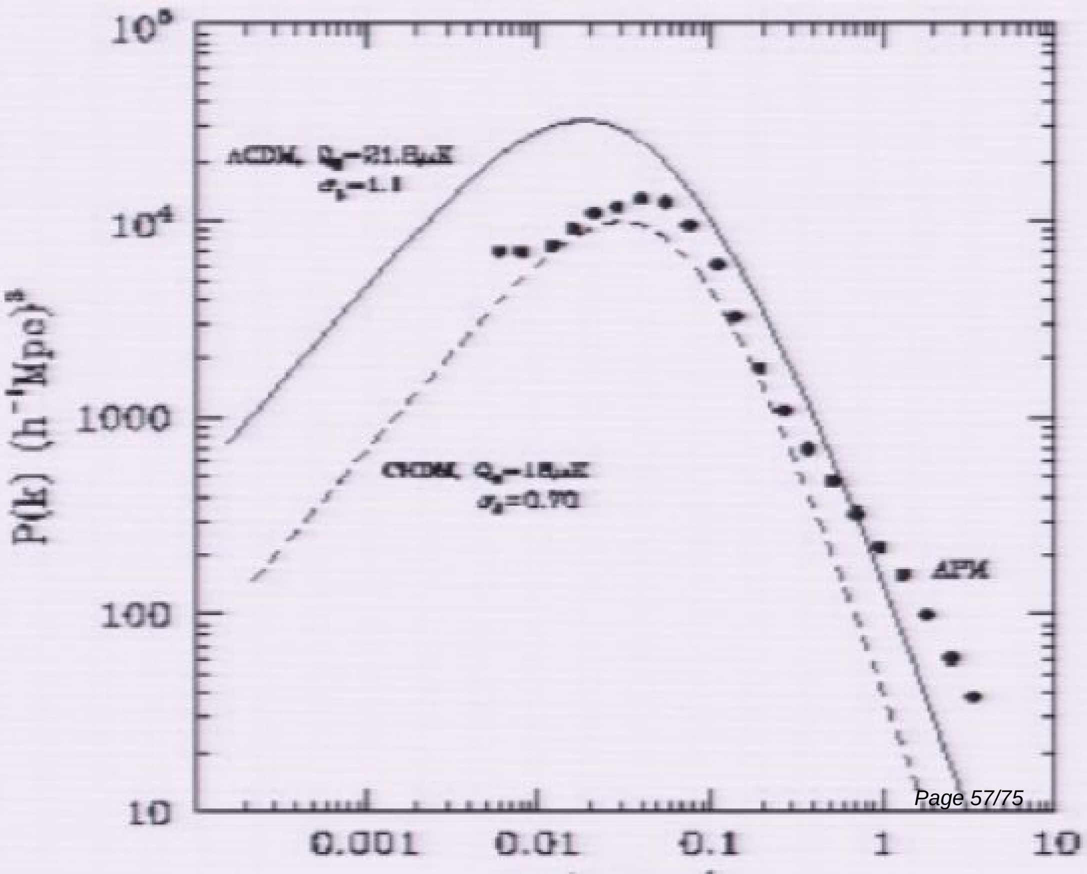

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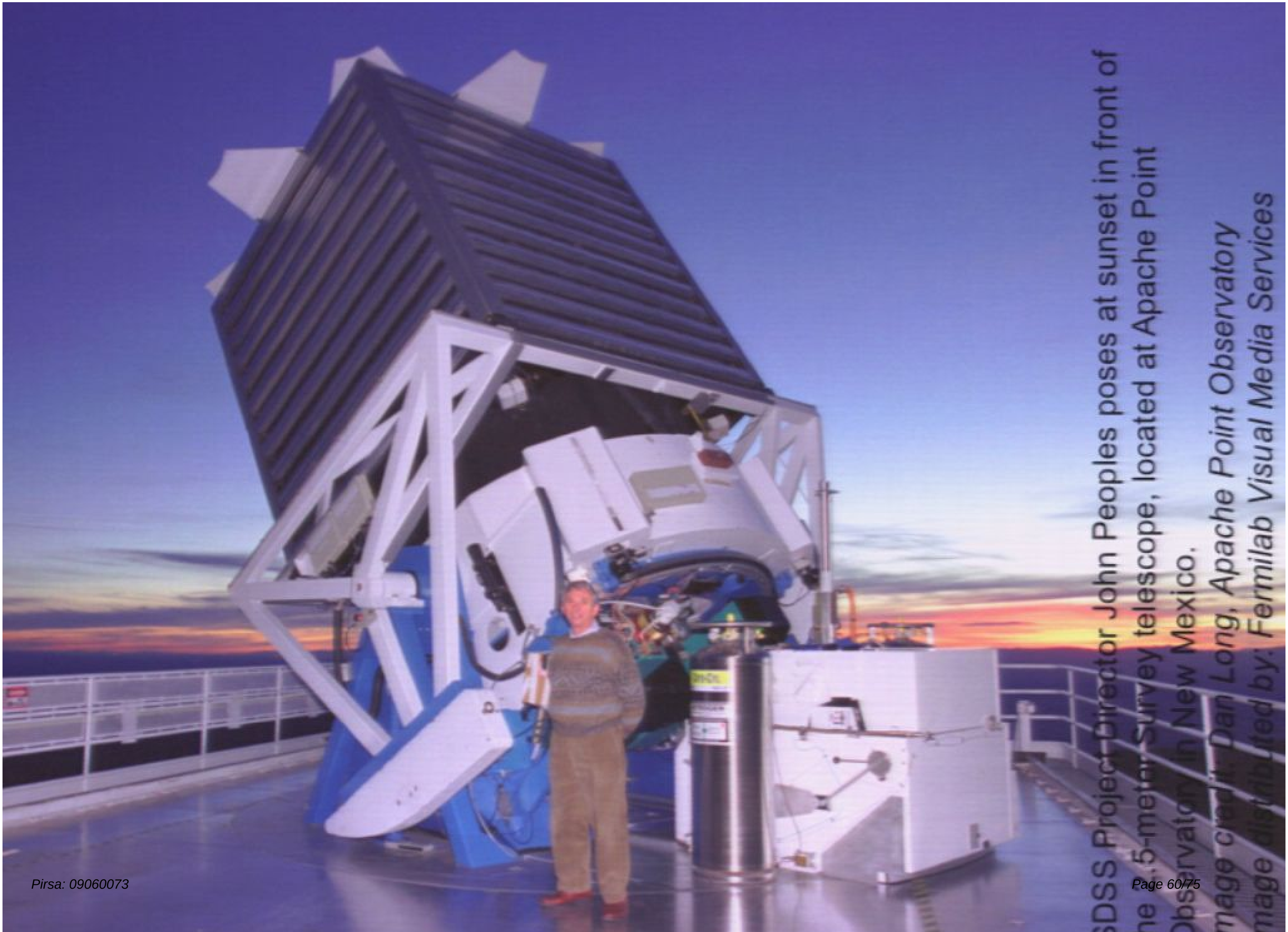
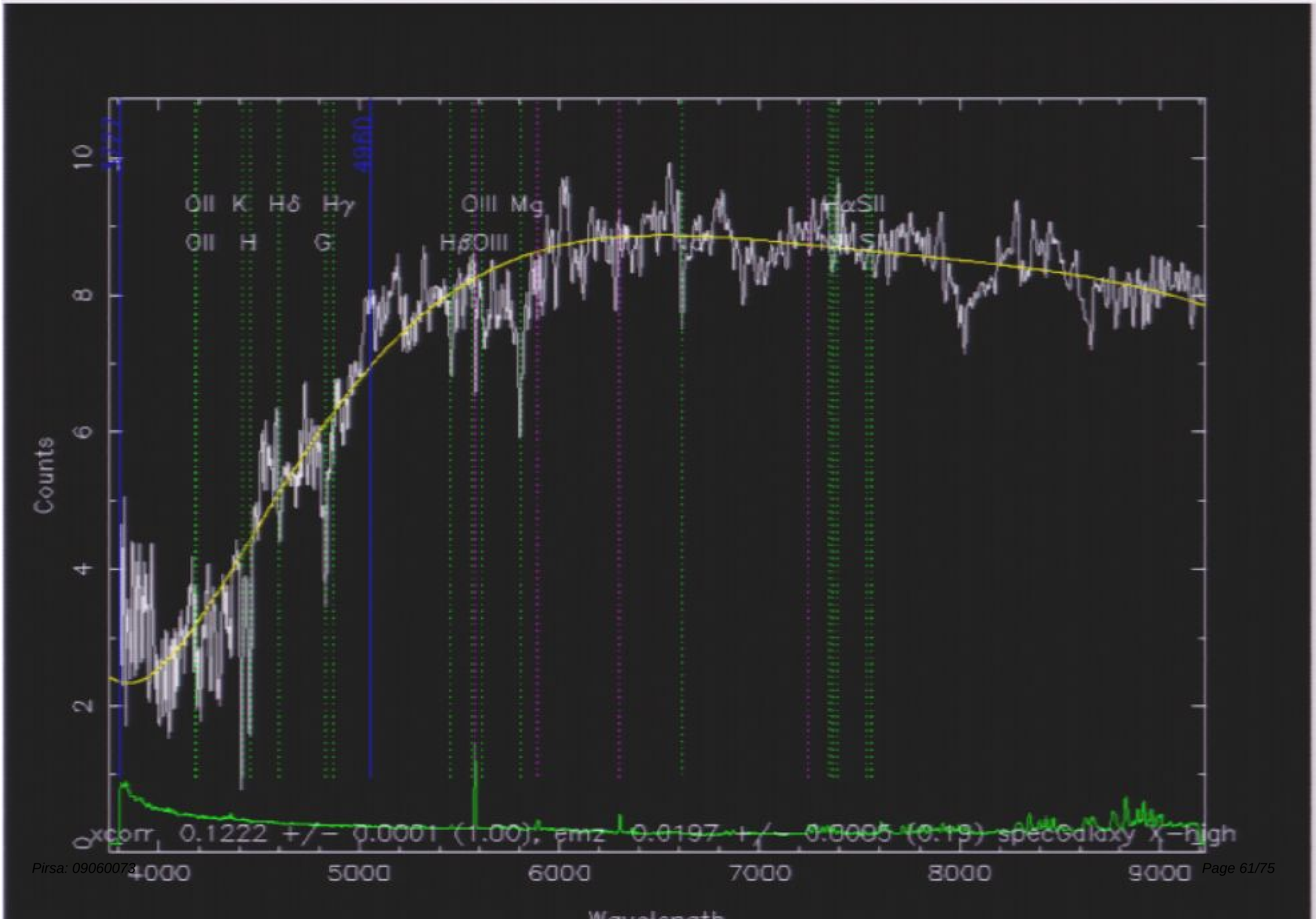
The latest: 2dF and SDSS

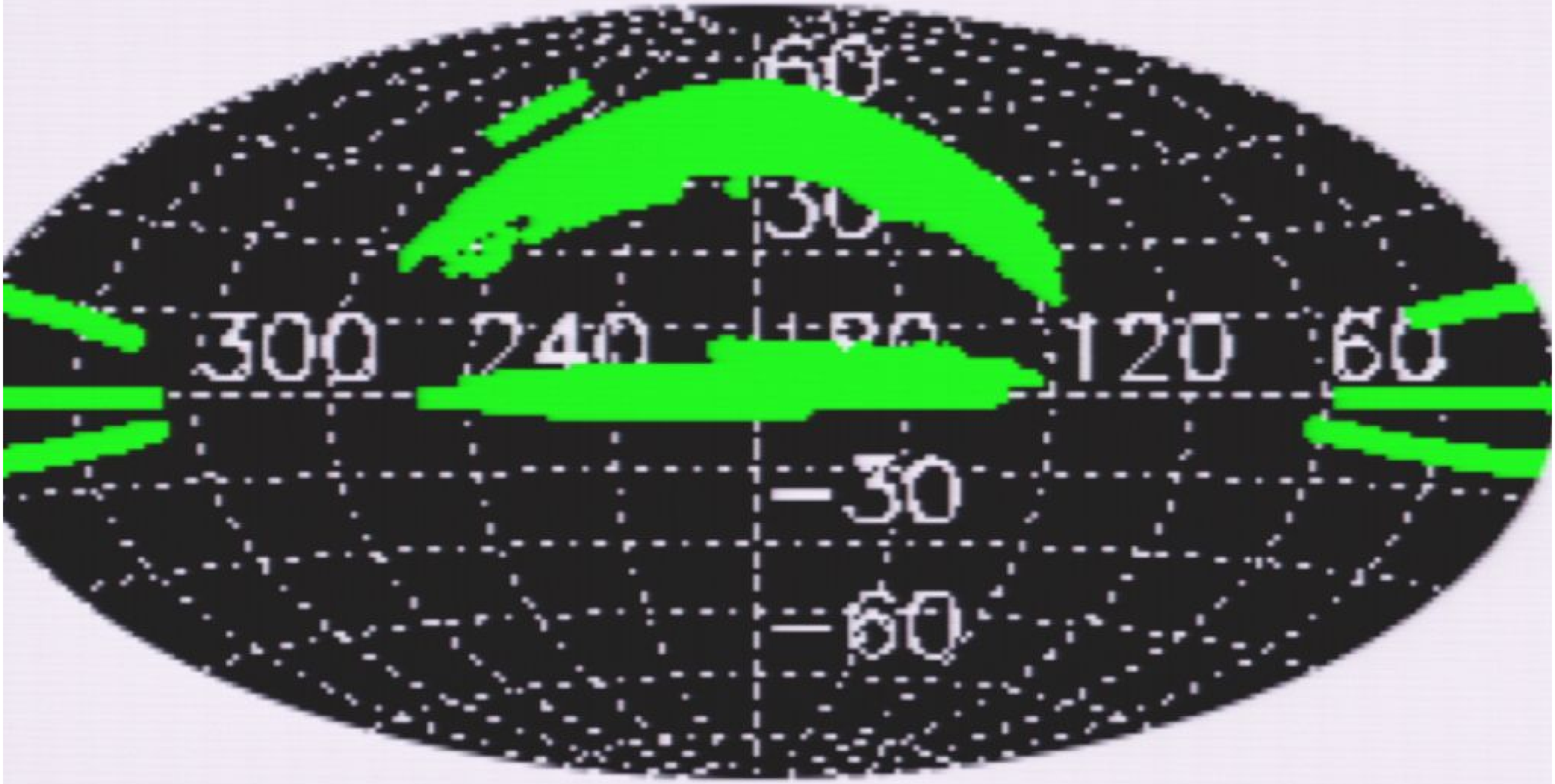
- 2dFGRS:
  - 250,000 galaxies with redshifts
  - galaxies selected from APM
  - Median redshift 0.17
  - Final data released in summer 2004
- SDSS GRS
  - aims at 1,000,000 redshifts
  - DR3 was 11 days ago
  - >5000 square degrees
  - 141,000,000 objects
  - 374,000 galaxy spectra


SDSS Project Director John Peoples poses at sunset in front of
Survey telescope, located at Apache Point
New Mexico.
Apache Point Observatory
Fermilab Visual Media Services

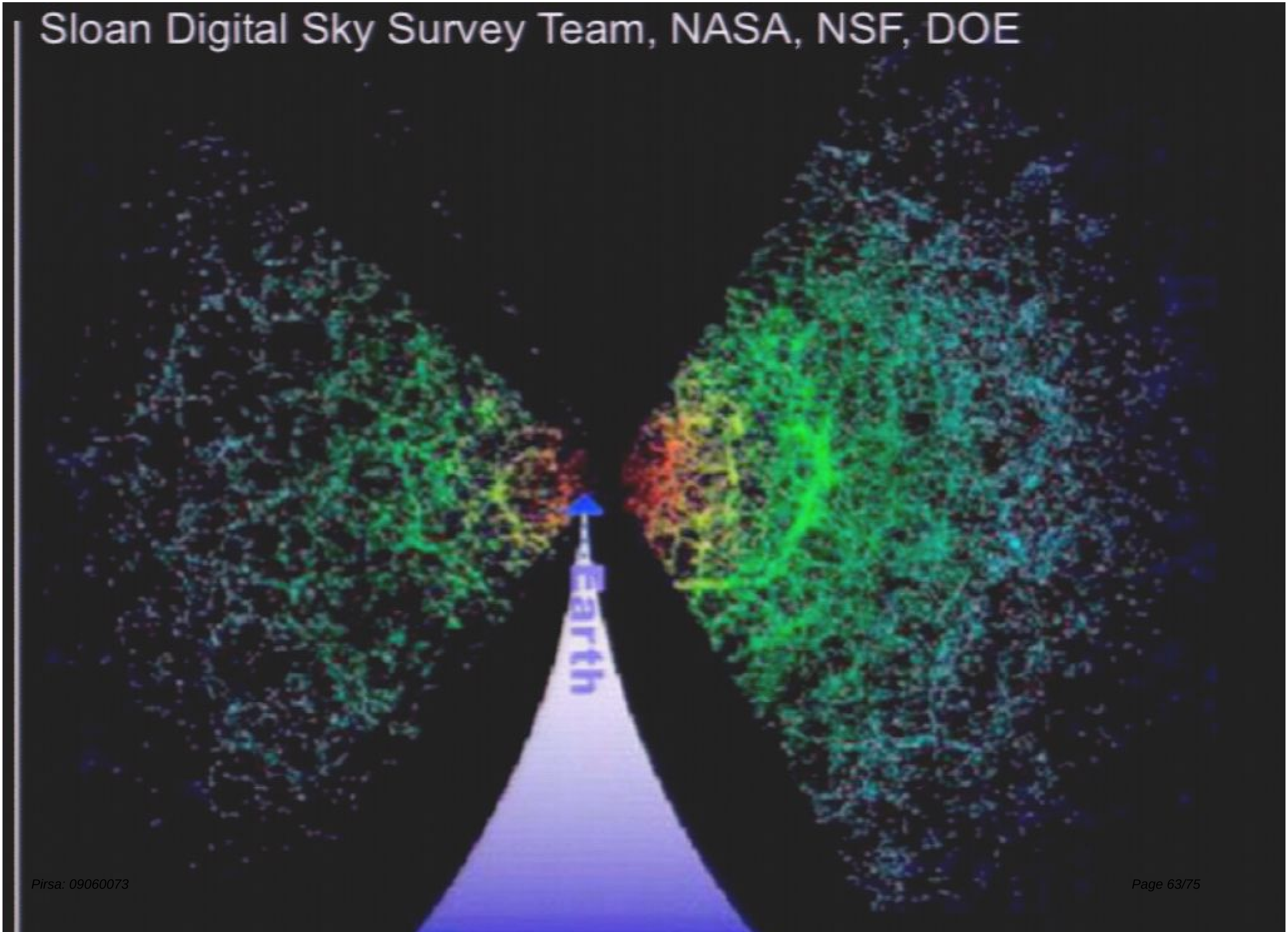


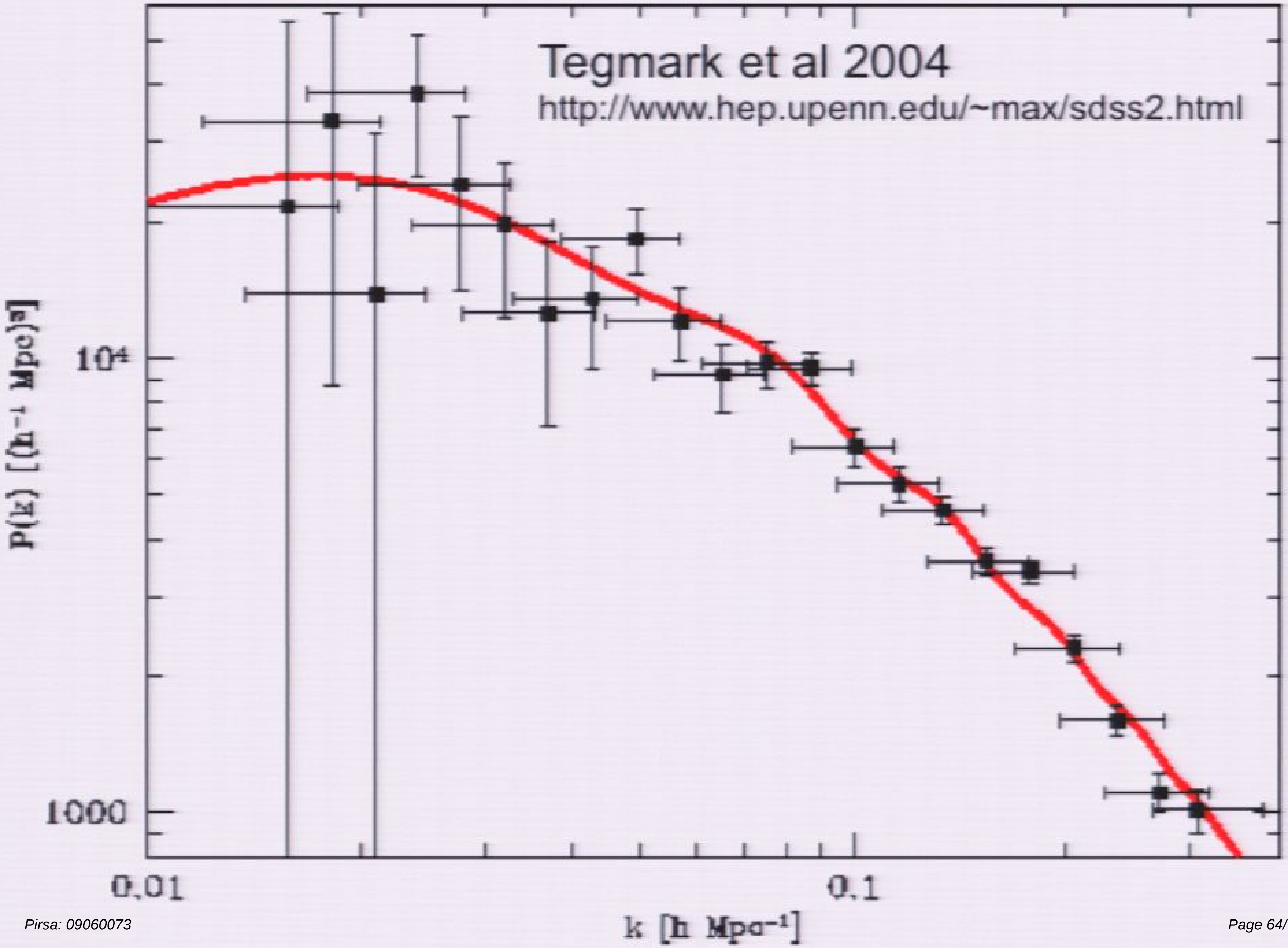
Counts
OII K Hδ Hγ
OII H G
OIII Mg
HβOIII
HαSII
xcorr, 0.1222 +/- 0.0001 (1.00), emz 0.0197 +/- 0.0005 (0.19) specGalaxy X-high
4000 5000 6000 7000 8000 9000
0 2 4 6 8 10

SDSS spectroscopic survey area



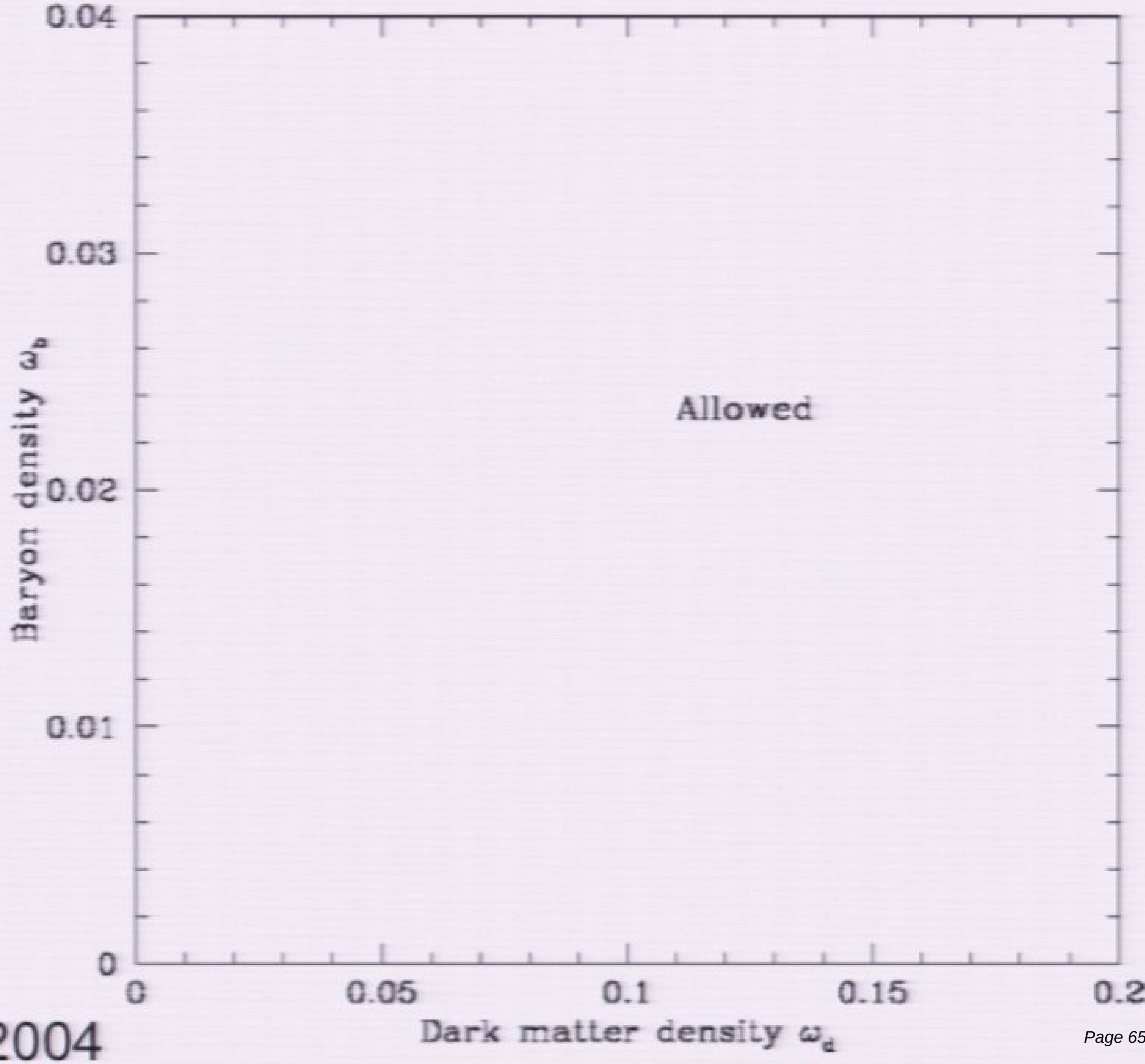
http://www.sdss.org/dr3/


Sloan Digital Sky Survey Team, NASA, NSF, DOE
Earth



Tegmark et al 2004
http://www.hep.upenn.edu/~max/sdss2.html
P(k) [(h⁻¹ Mpc)³]
10⁴
1000
0.01
0.1
k [h Mpc⁻¹]

How much dark matter is there?



egmark et al 2004

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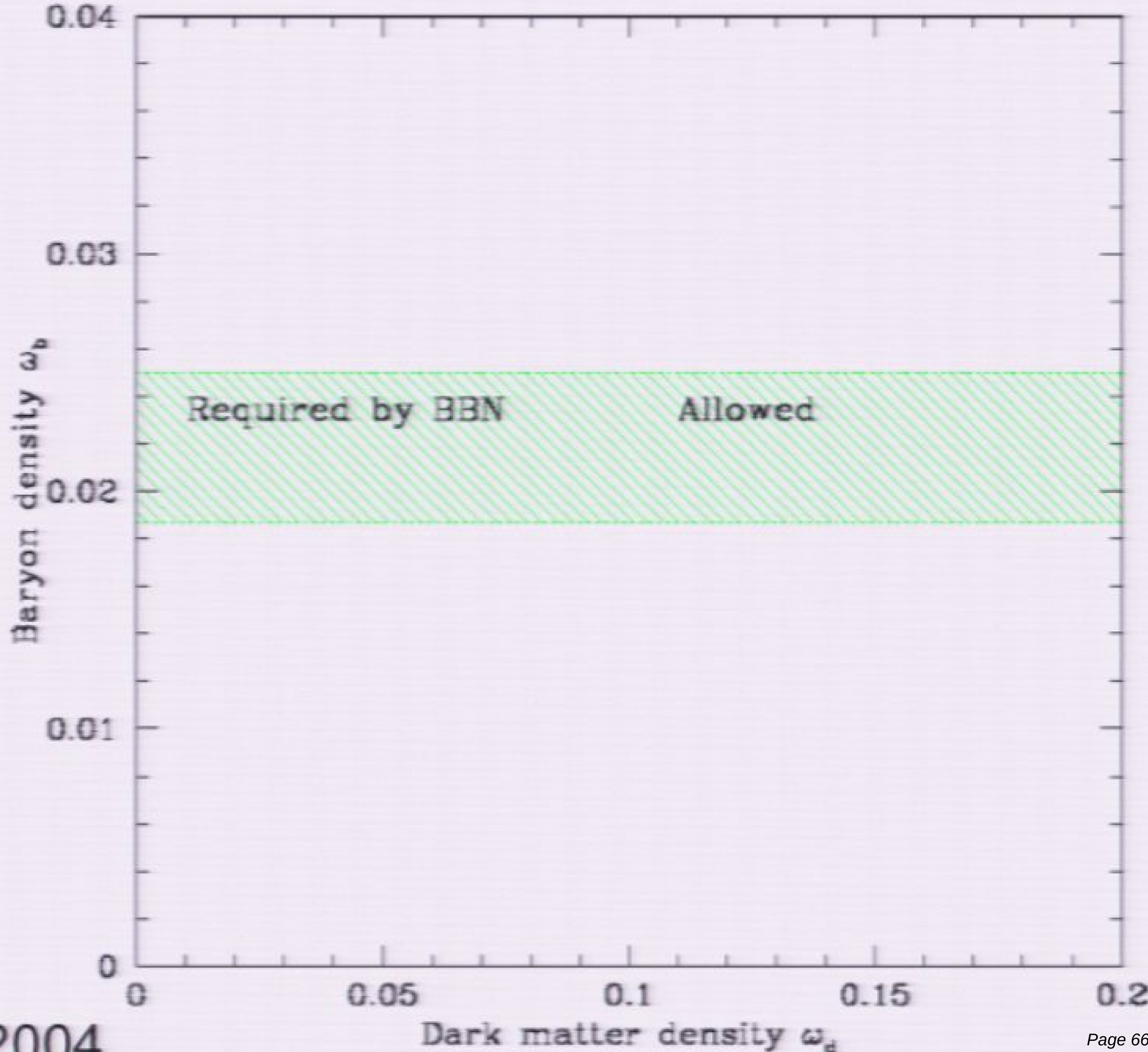

egmark et al 2004

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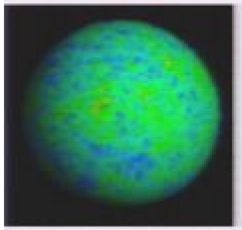
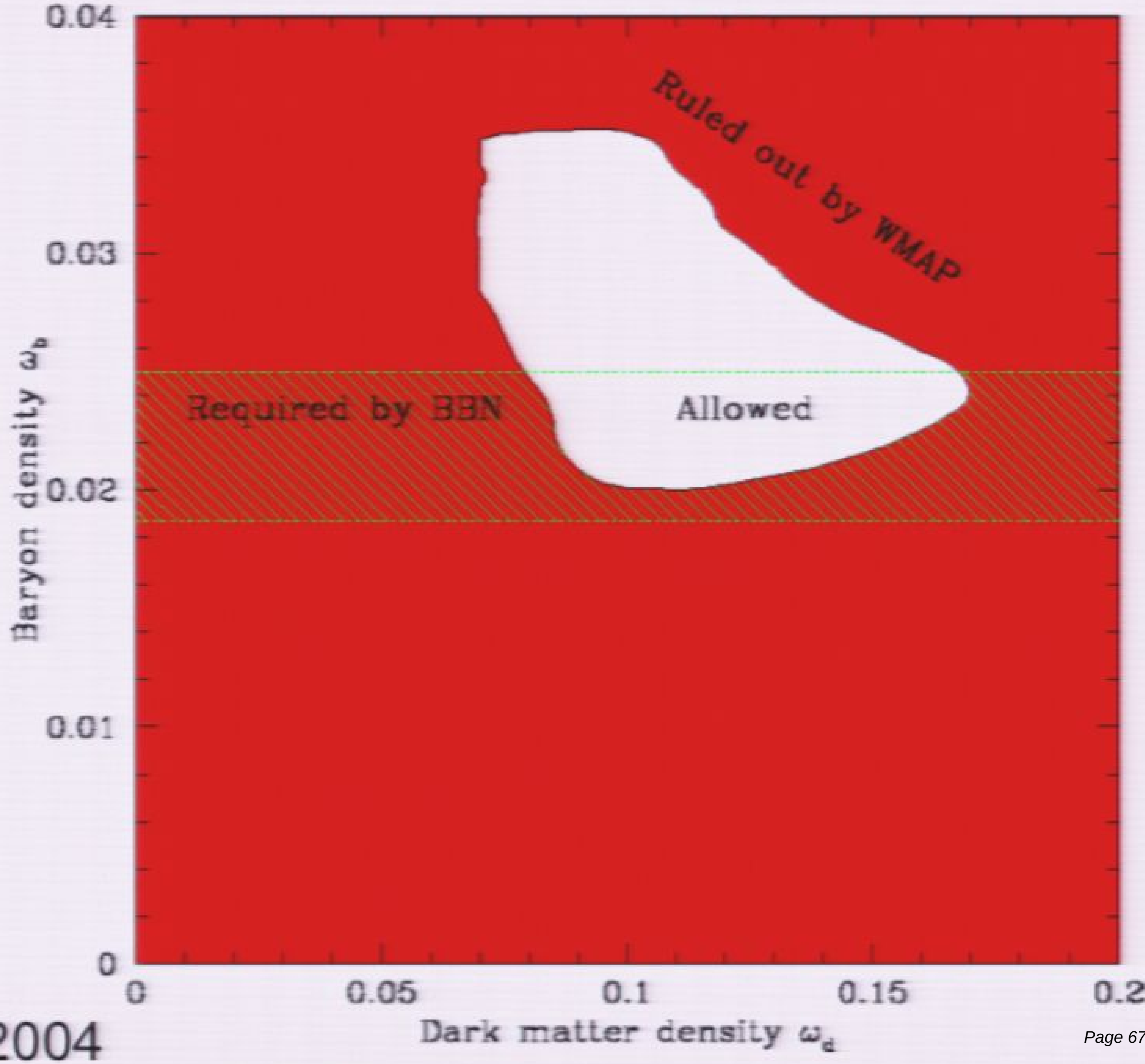


CMB

How much dark matter is there?



egmark et al 2004

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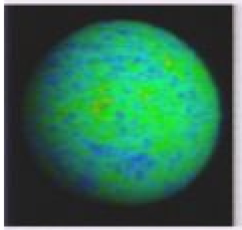
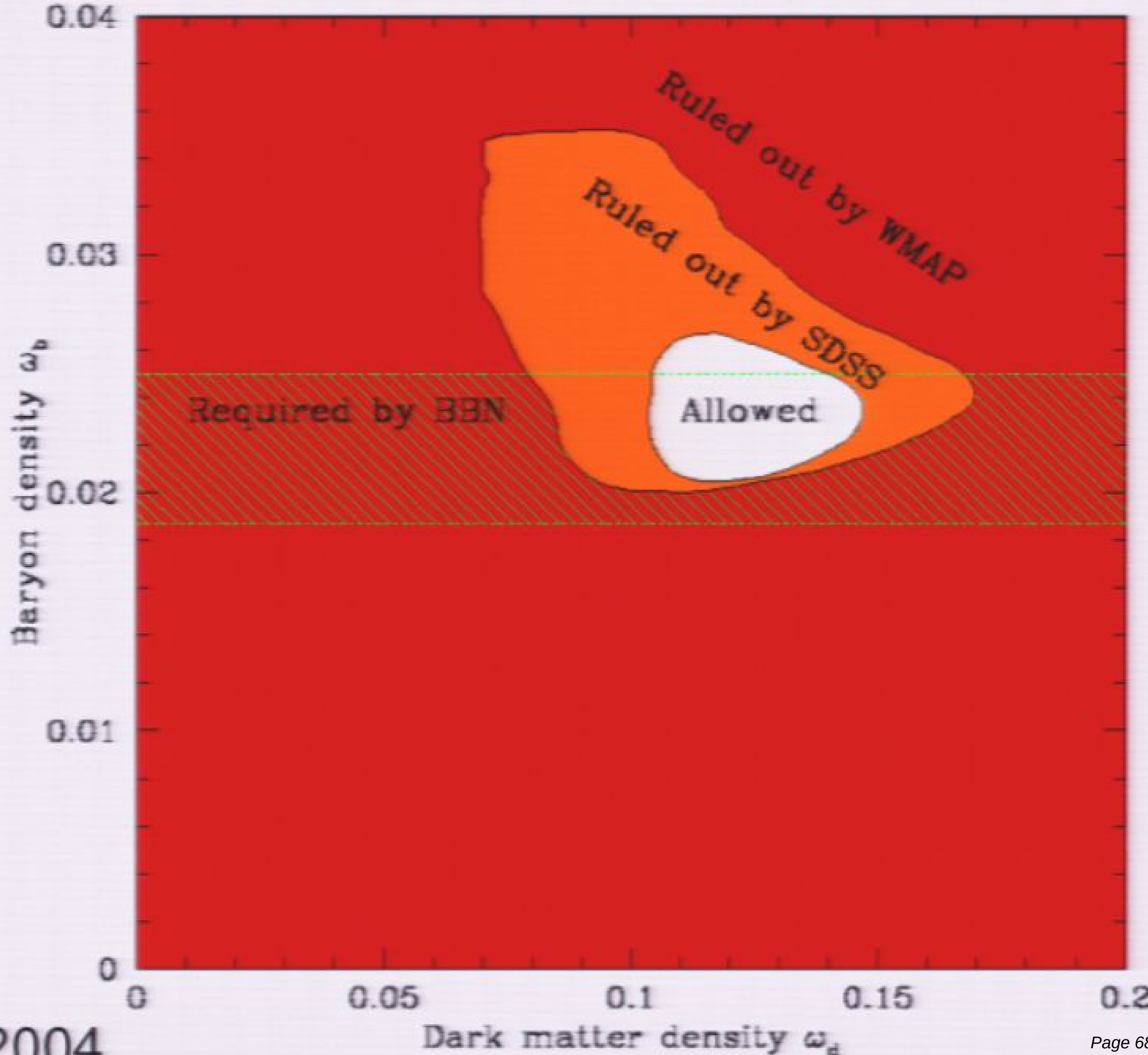


CMB

+

LSS



egmark et al 2004

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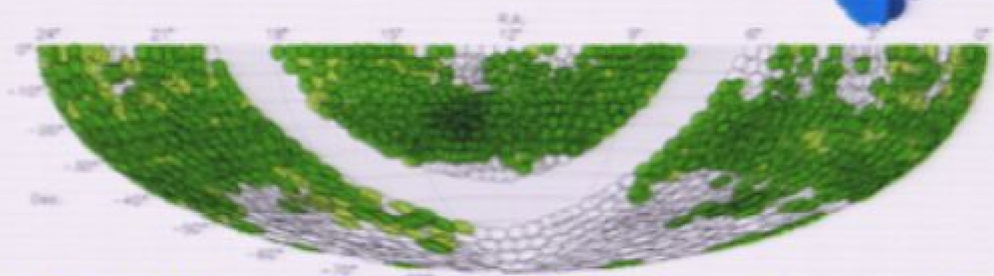
This lecture:
Dark matter clustering and galaxy surveys

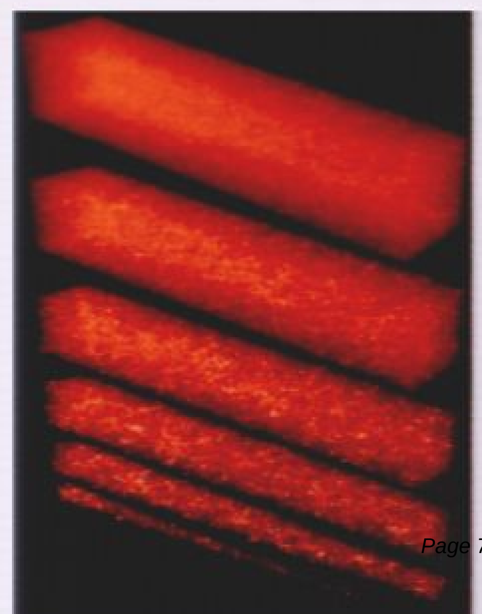
1. The dark matter power spectrum P(k)
2. Understanding the shape of P(k)
3. σ_8
4. The galaxy power spectrum $P_g(k)$ and bias
5. Historical measurements of $P_g(k)$
6. Recent measurements of $P_g(k)$
7. Future measurements of $P_g(k)$

Ongoing galaxy redshift surveys

- Completion of SDSS
- 6dF



- DEEP 2 (like 2dFGRS at z~1)
- VIRMOS VLT Deep Survey
  – (VVDS)
- UKIDSS



Future galaxy surveys

- KAOS (Kilo-aperture optical spectrograph)
- LSST (large-aperture synoptic survey telescope)
- SNAP (supernova/acceleration probe)
  - all >2010

- ~300 million photometric redshifts from
  - DES, VISTA, PanSTARRS ~ 2008

The long term future

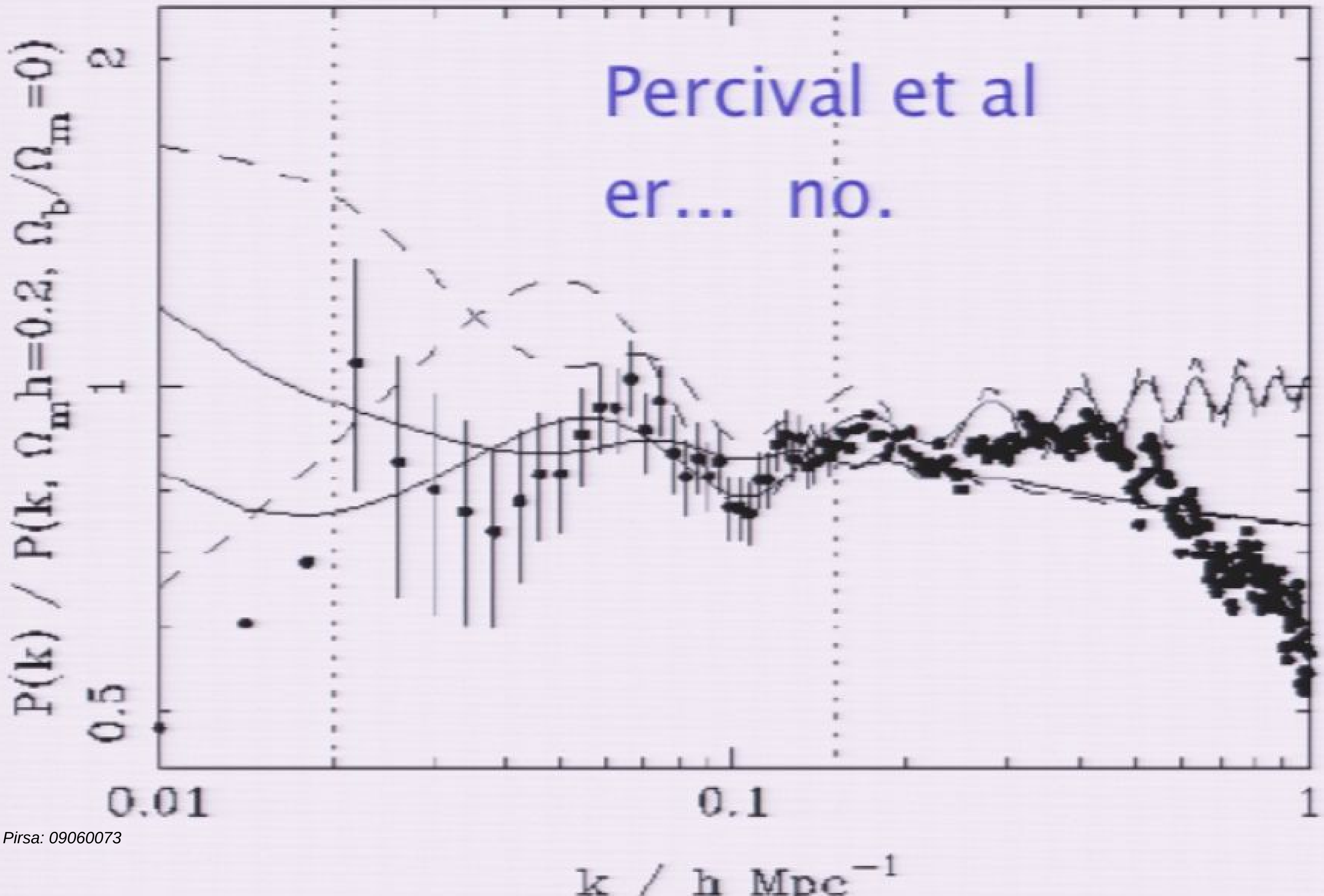
- CMB (next lecture)
- plus cosmic shear (final lecture), velocities
- will tell us all about dark matter, dark energy, early universe
- Galaxy surveys will tell us about galaxy formation.

- But any departures from standard picture may well show up first in galaxy surveys…

Summary

- Now understand turnover in matter power spectrum
  - turnover scale = Jeans length at matter-radiation equality
- Can explain its location as fn of Ω_m
- Defined σ_8 and discussed bias
- Historical and up to date view of galaxy surveys

Baryonic wiggles?



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