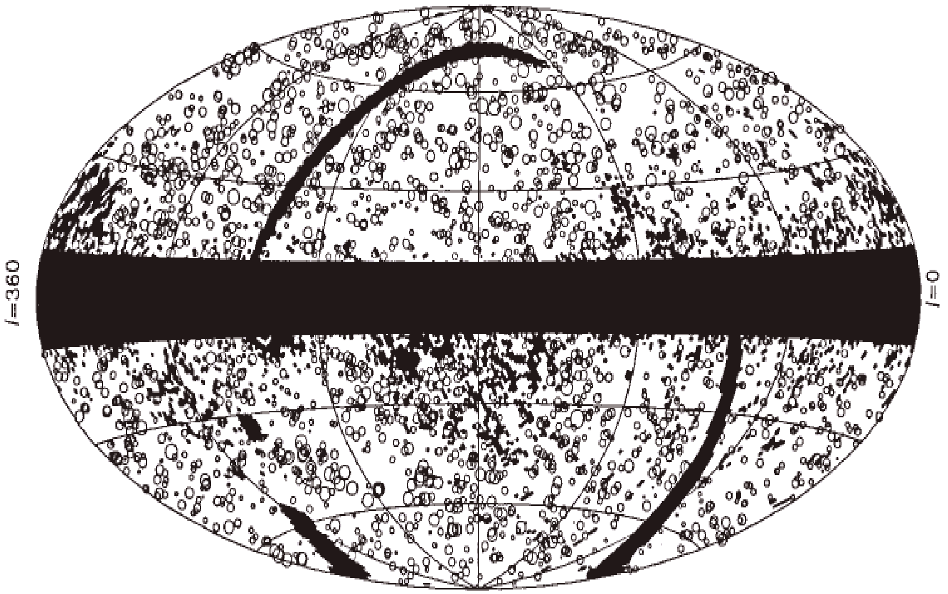
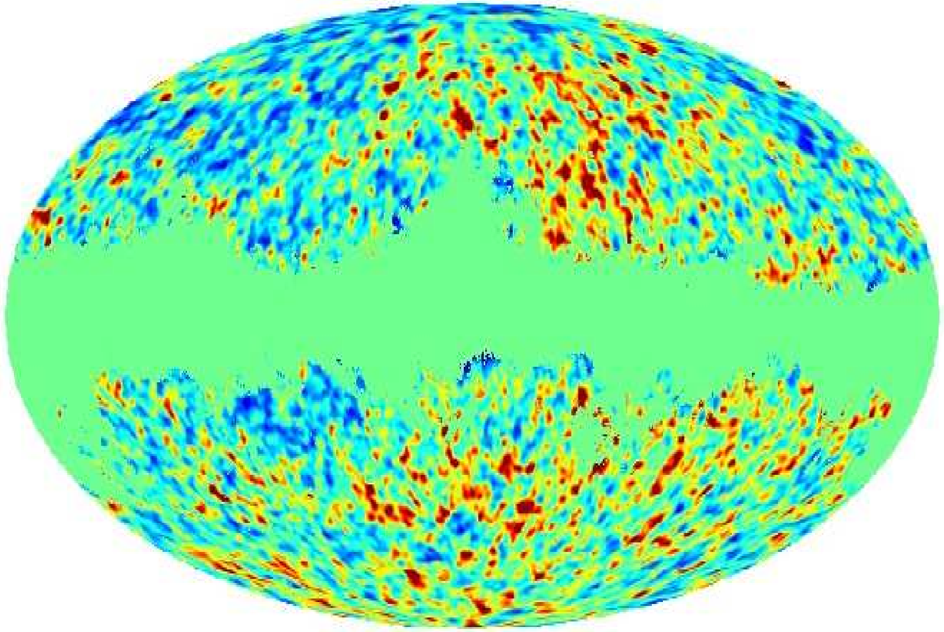
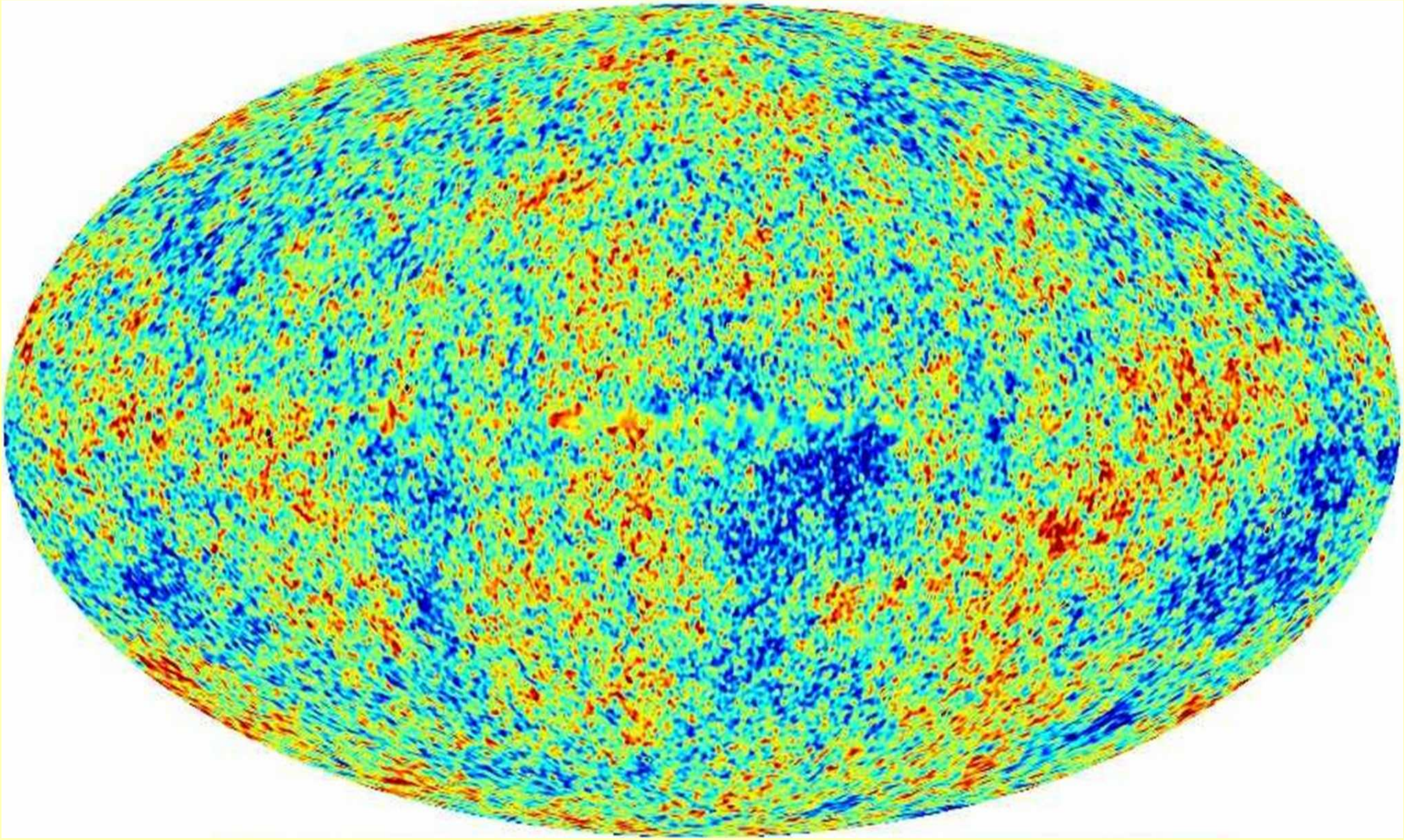
Aspects of large-scale structure



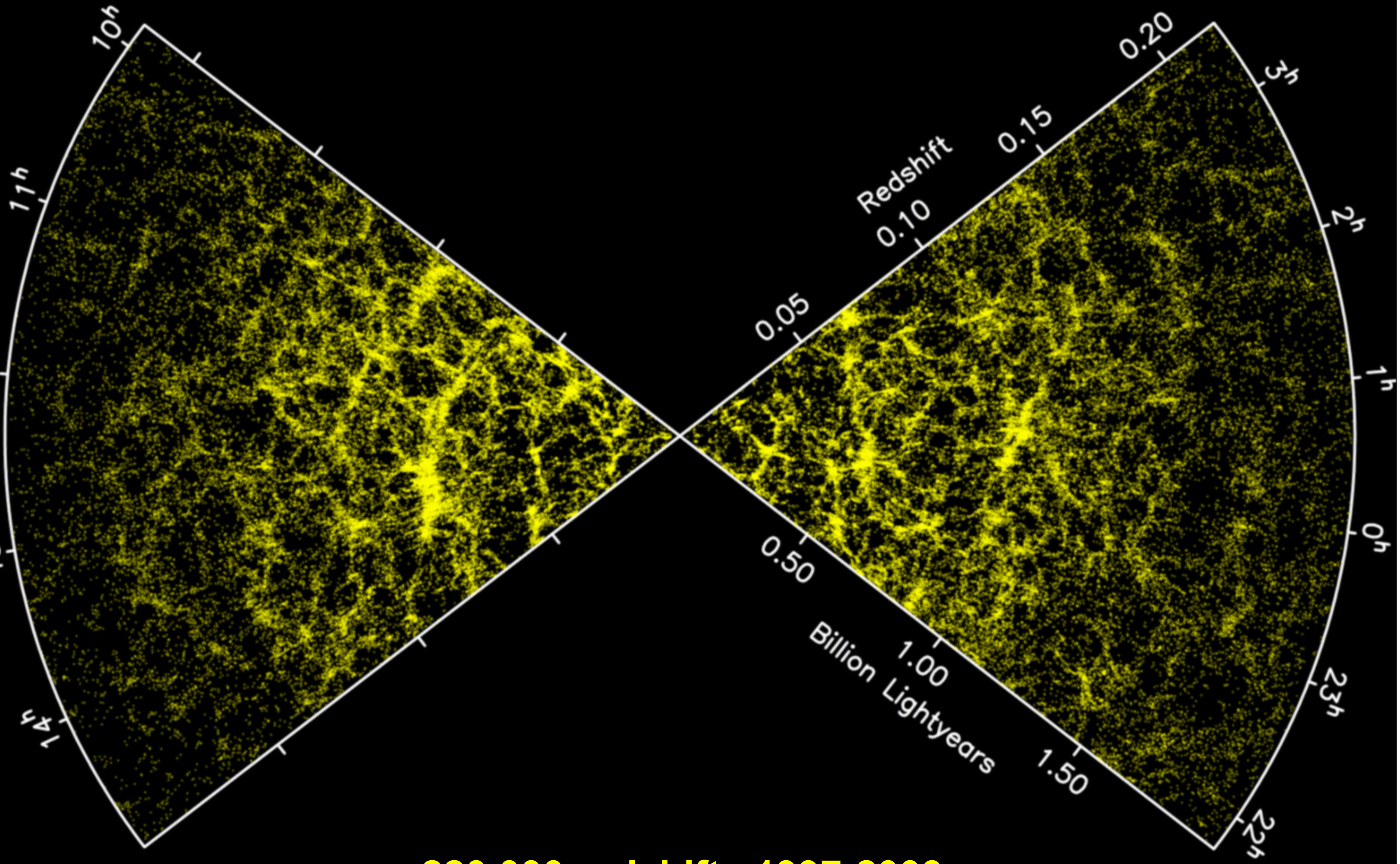


John Peacock **UniverseNet** **Mytilene Sept 2007**

WMAP 2003

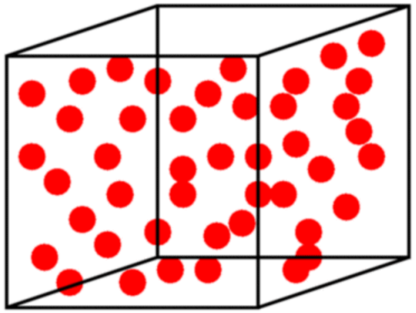


2dFGRS cone diagram: 4-degree wedge

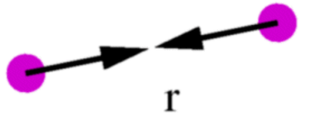


220,000 redshifts 1997-2003

Simulating structure formation



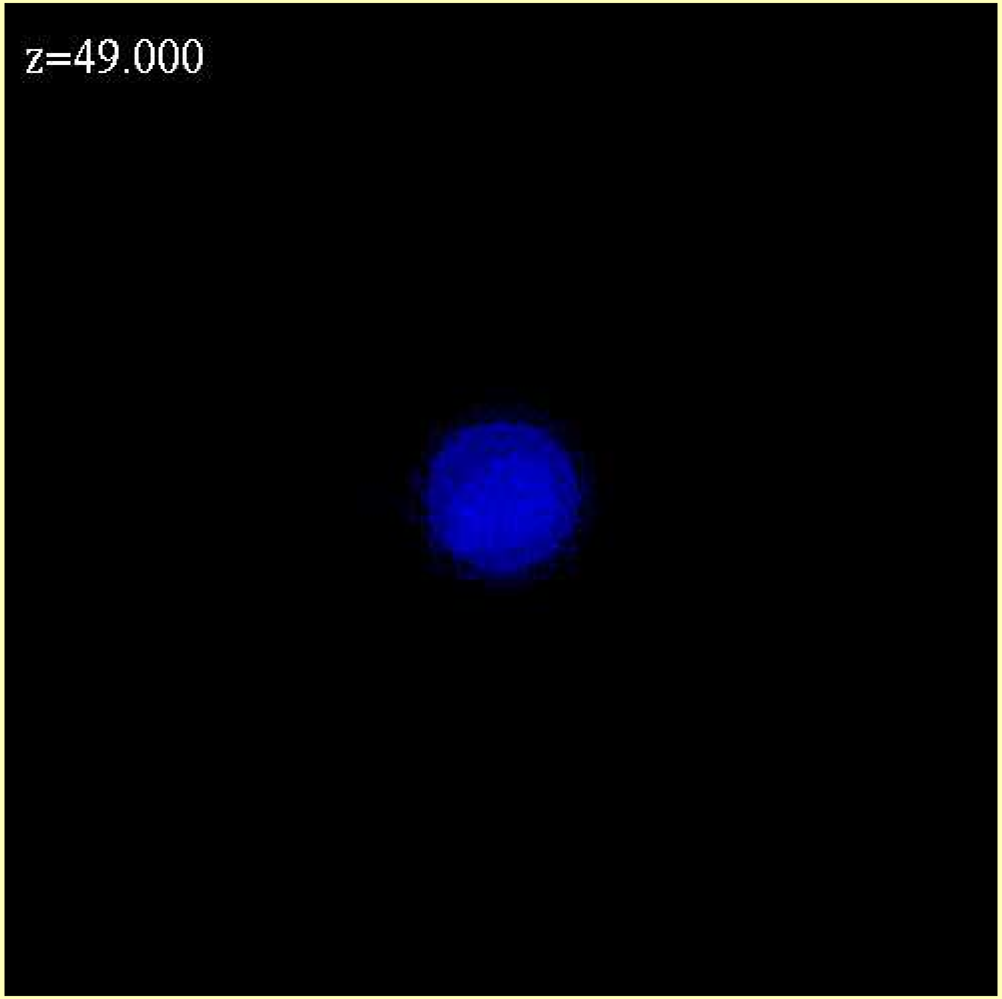
Use a supercomputer to follow the trajectories of 10 million - 1 billion imaginary particles

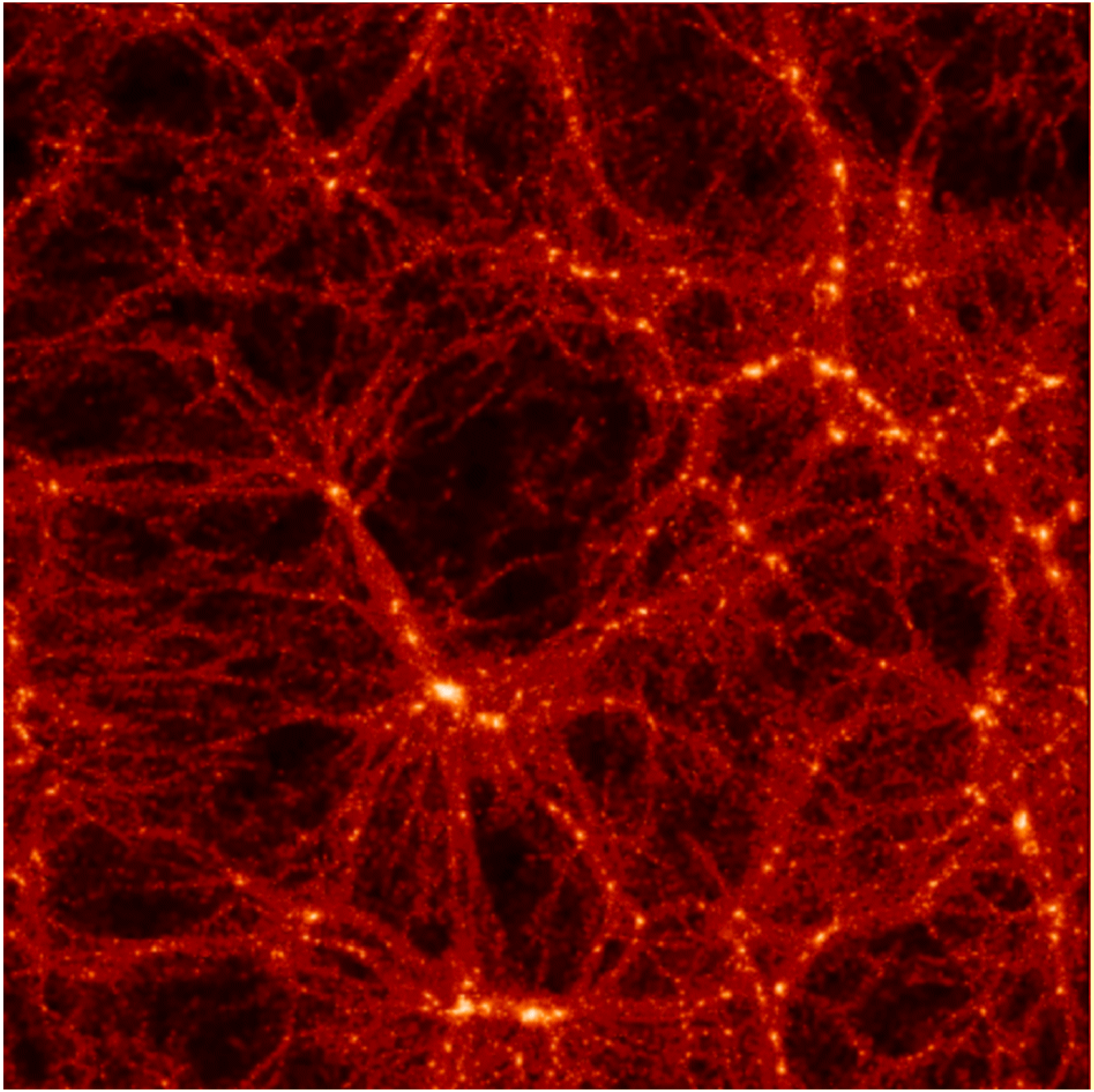


$$F = \frac{G\,m\,m}{r^2}$$

VIRGO

The Virgo consortium uses supercomputers in Durham, Edinburgh & Munich to simulate the growth of cosmological structure


z=49.000



Forming superclusters (comoving view)

redshift z=3

(1/4 present size)

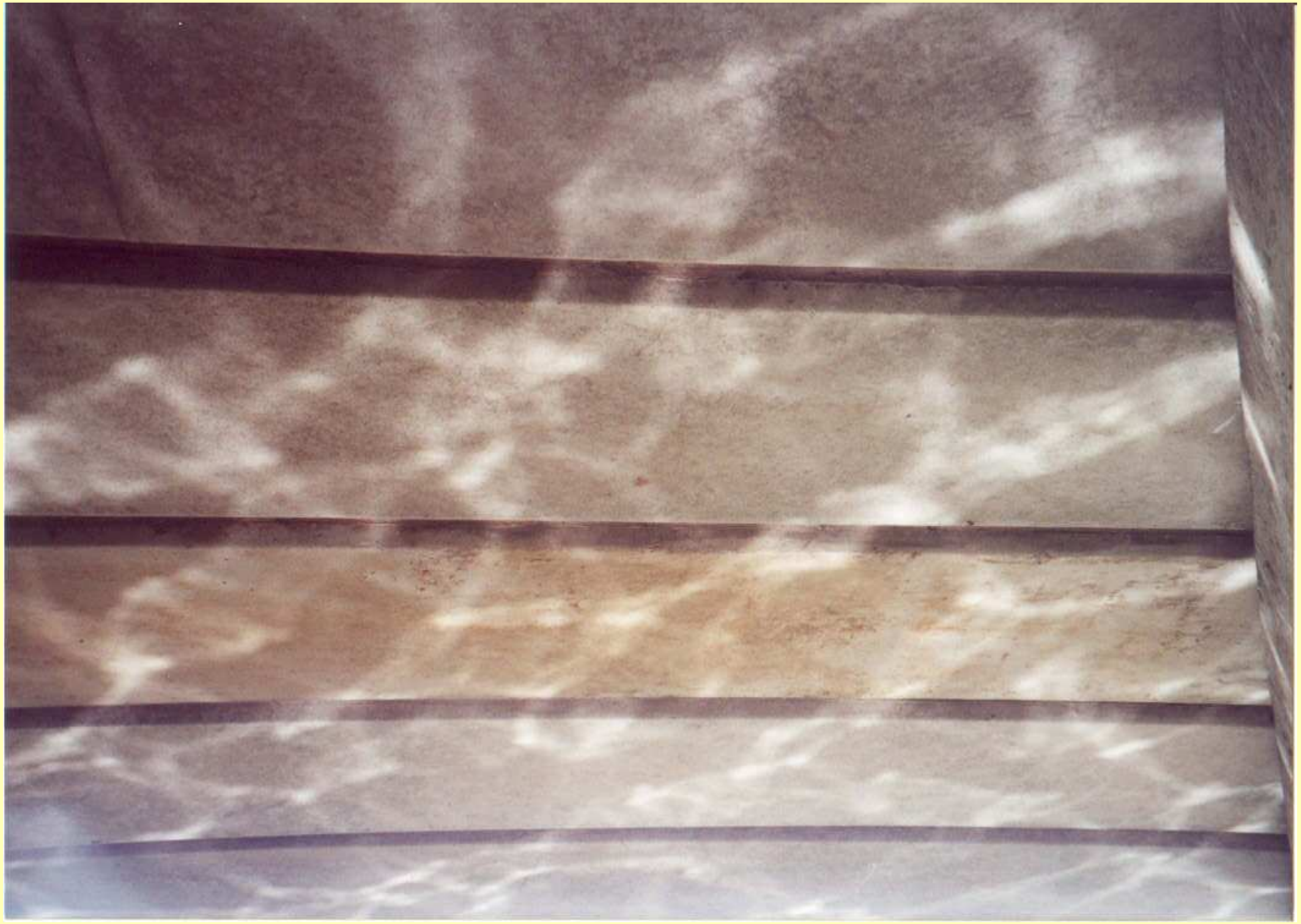
redshift z=1

(1/2 present size)

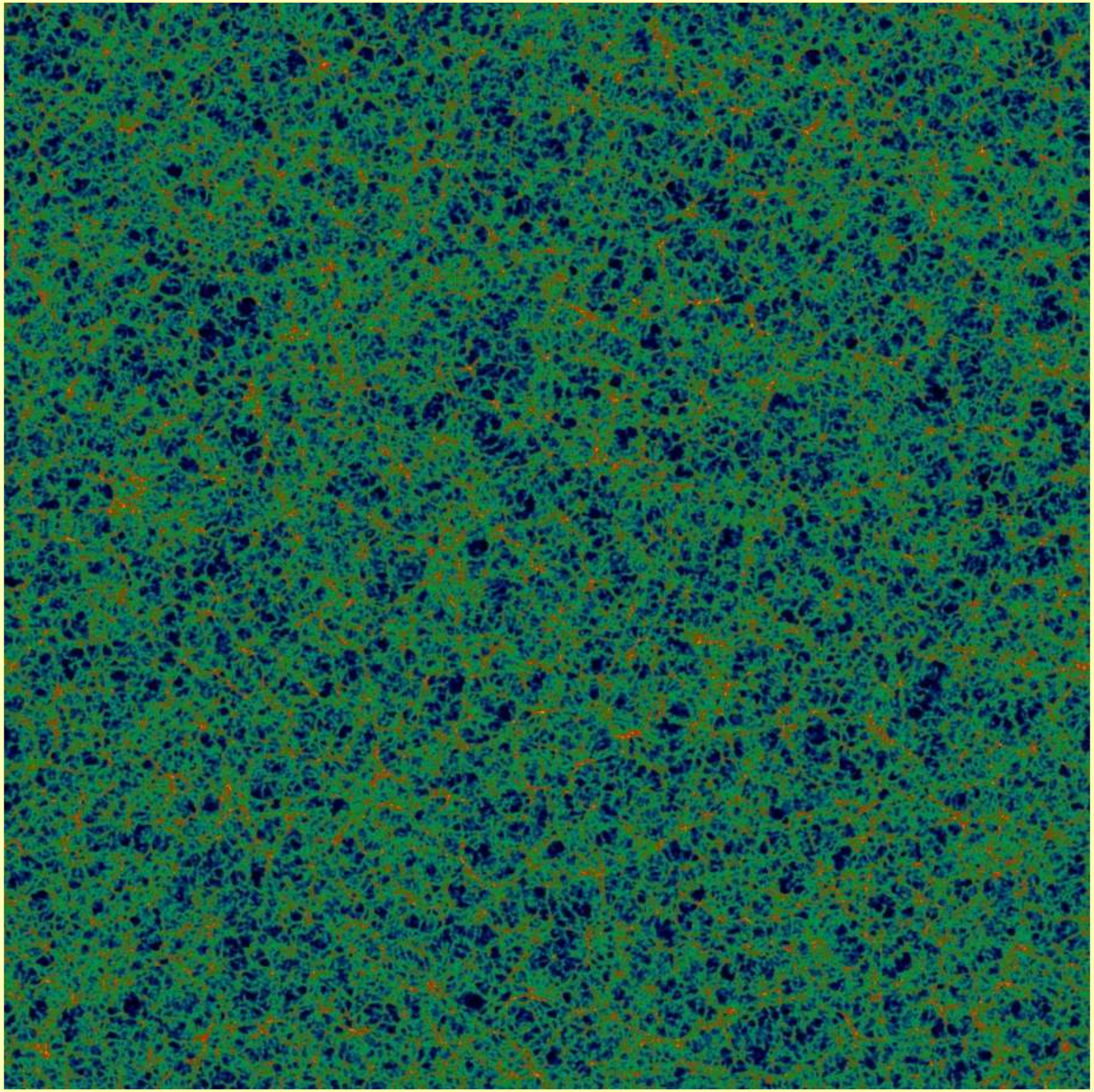
Redshift z=0

(today)

Non-gravitational caustics

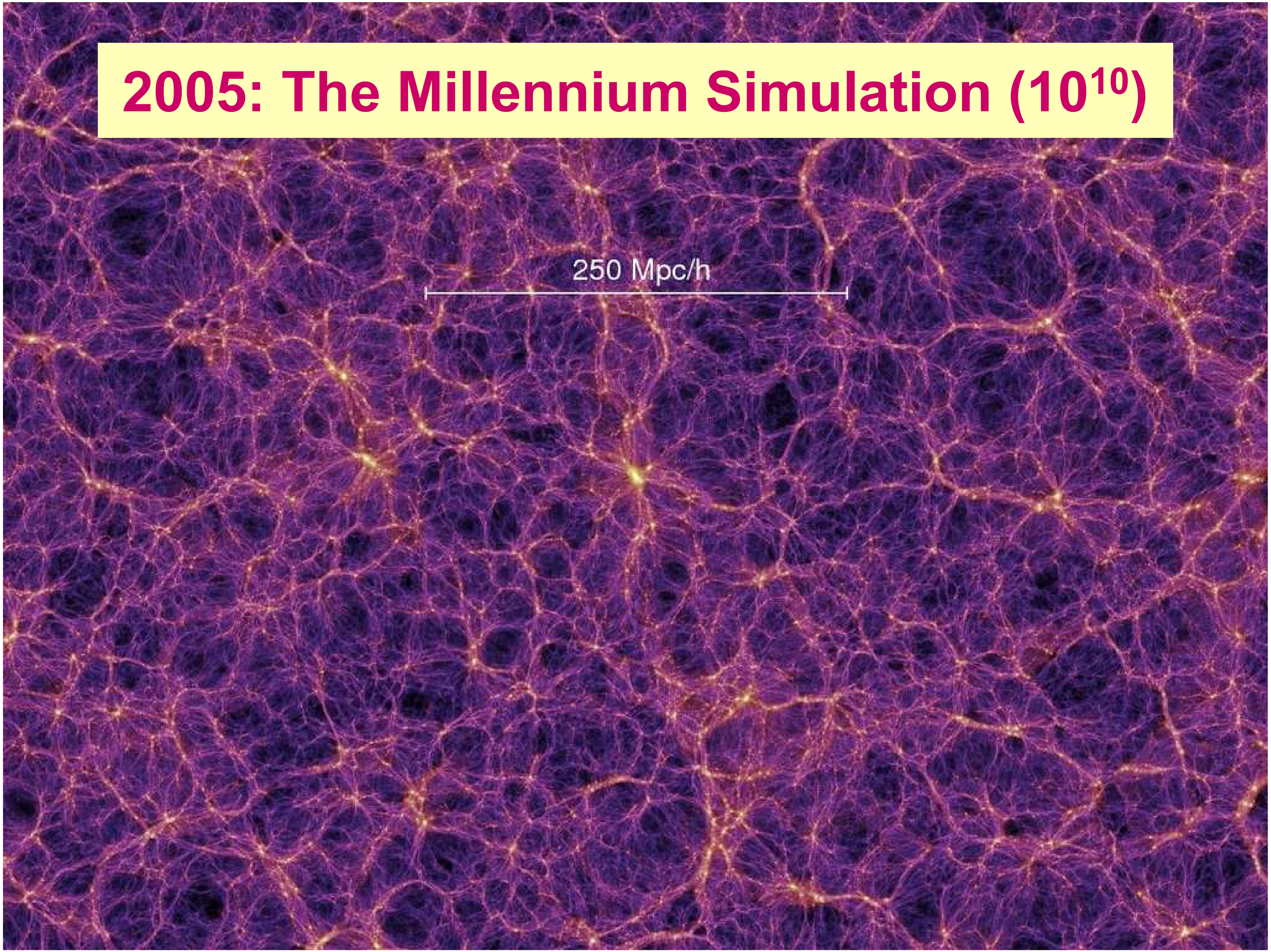


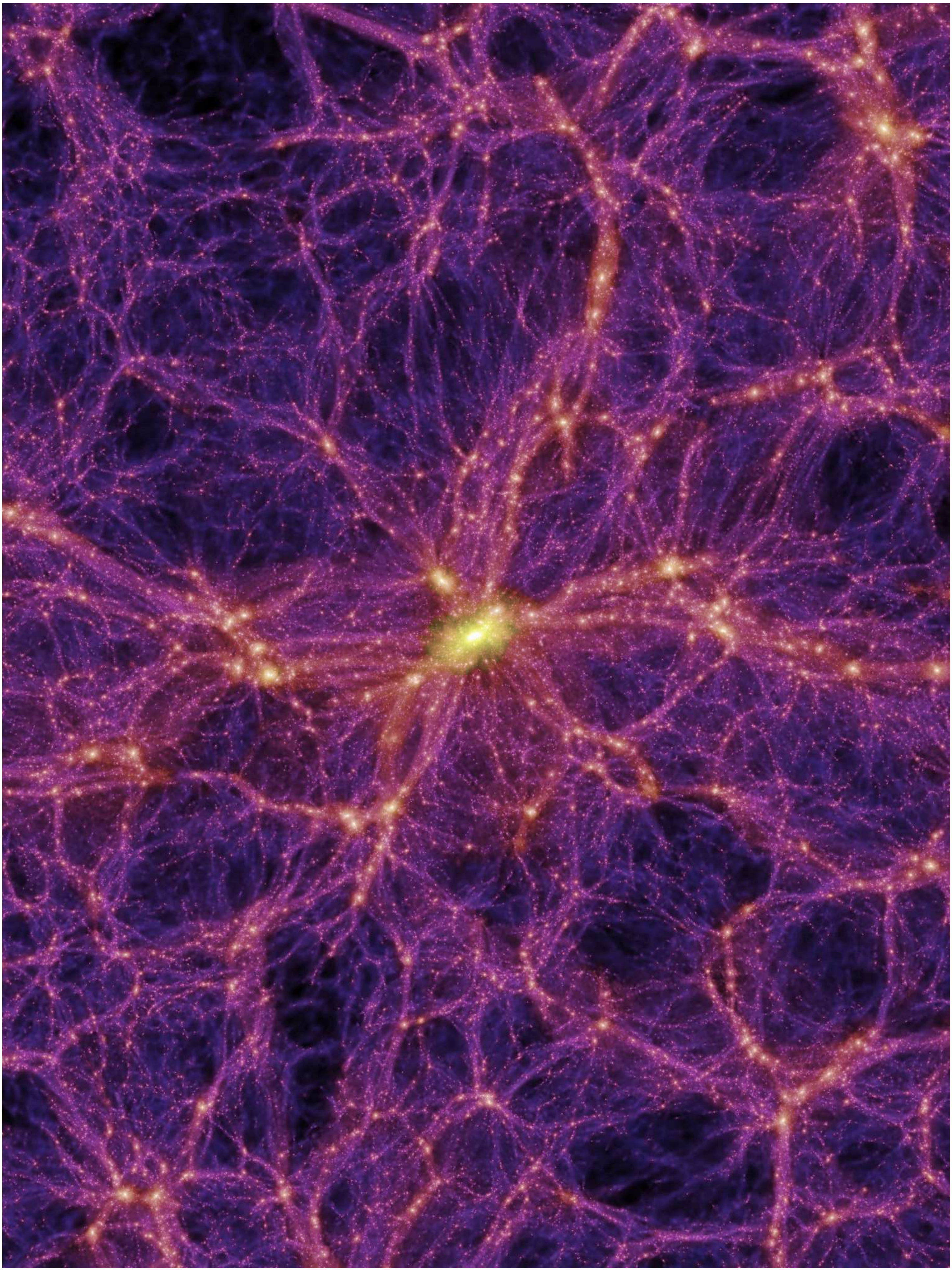
1998: The Hubble Volume Simulation (10^9)

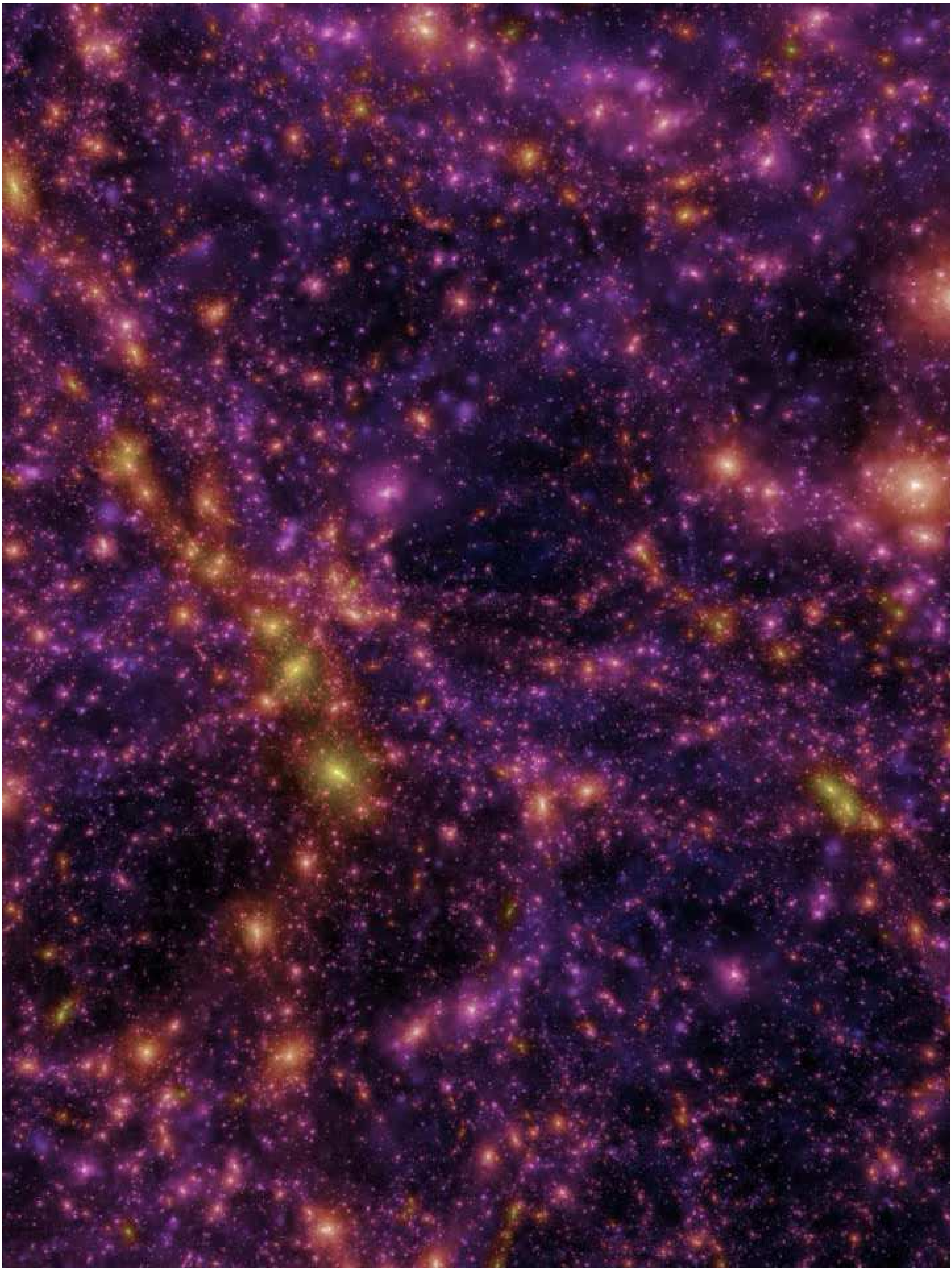


2 h^{-1} Gpc

2005: The Millennium Simulation (10^{10})

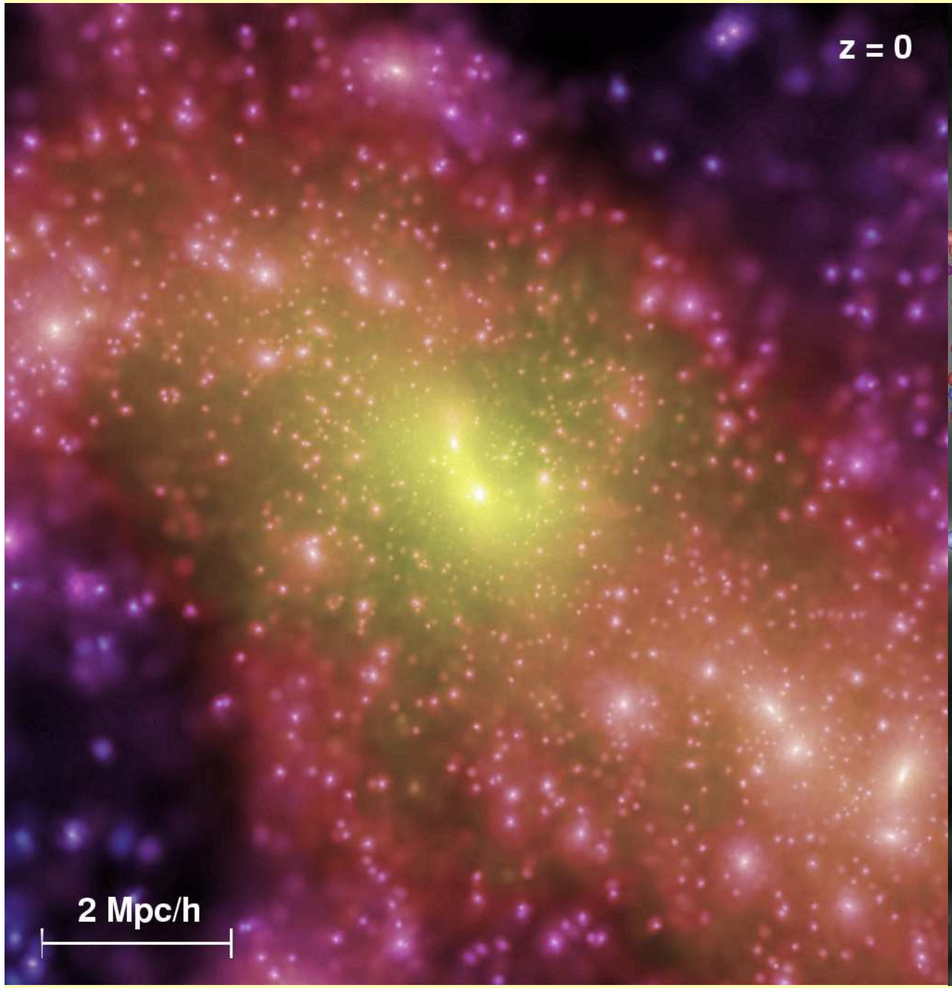




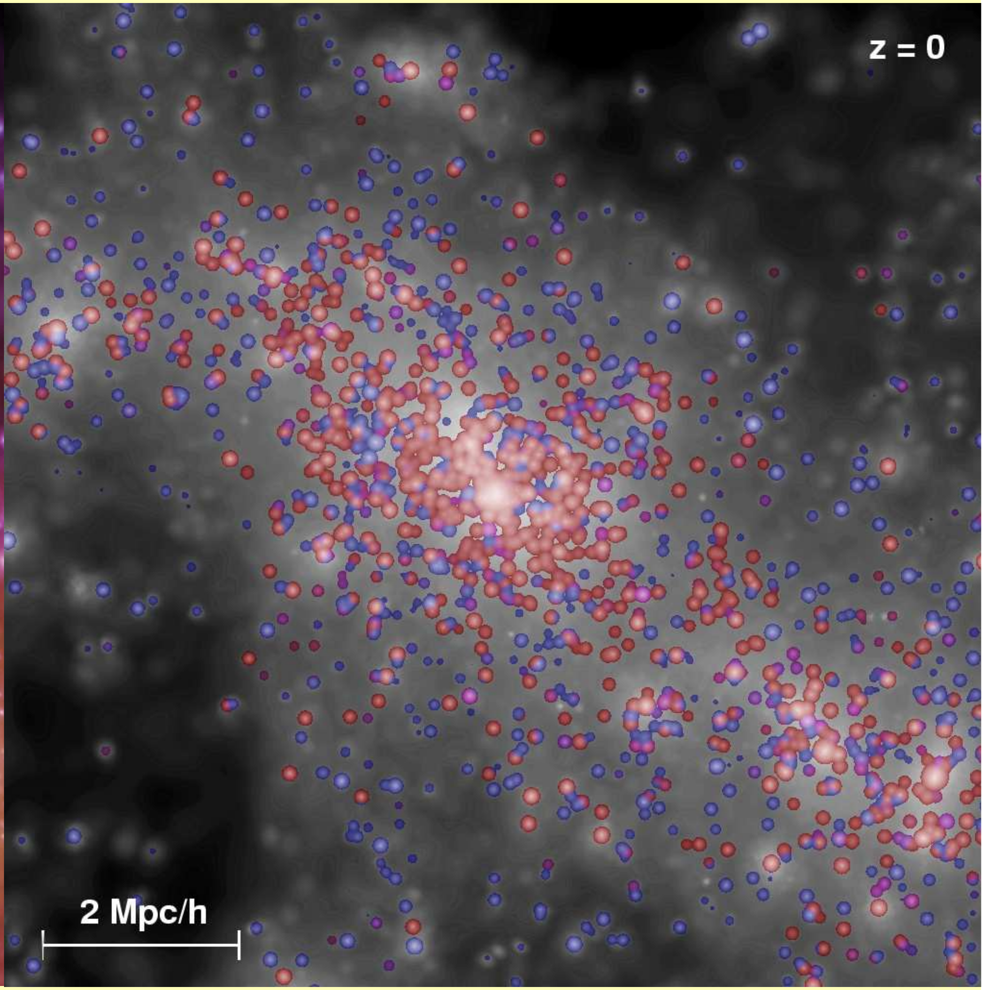


Dark matter halo: $10^{14}M_\odot$

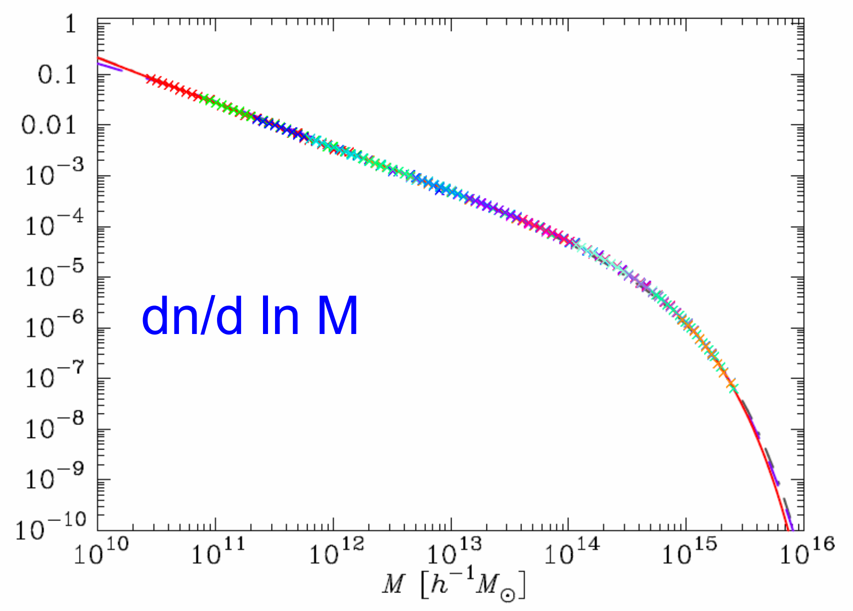
Dark matter



Galaxies



The mass function of halos (= systems with 200x mean density)



(e.g. Warren et al. 2006)

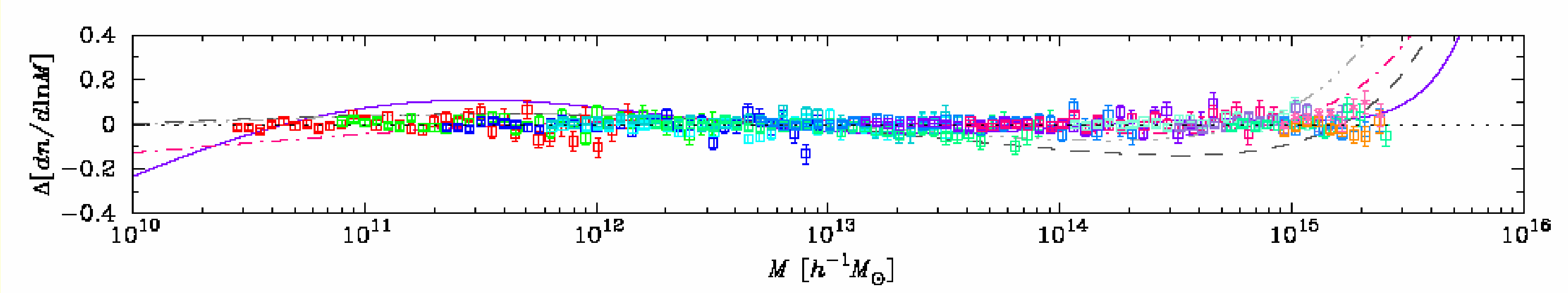


FIG. 2.— Shown are the residuals from the binned simulation data to the fit presented in this work as square data points of different colors per simulation. The Jenkins fit is the solid (purple) line, ST original fit the dashed (dark gray) line, the ST fit with parameters A, a, p free with dot-dashed line (red), and the ST fit with a, p free and amplitude A set to require all dark matter in halos as a triple-dot-dashed line (light gray). The binned mass function from the Virgo Hubble Volume simulation are the asterisk points with errors (pink).

Universal in $\nu = 1.686 / \sigma(R)$

Collapse fraction $F(>\nu) = (1 + a\nu^{b})^{-1} \exp(- c\nu^{2})$

A brief history of large-scale structure

- The glory days
- Where we are now
- Next-generation goals

The Universe in ~ 1989

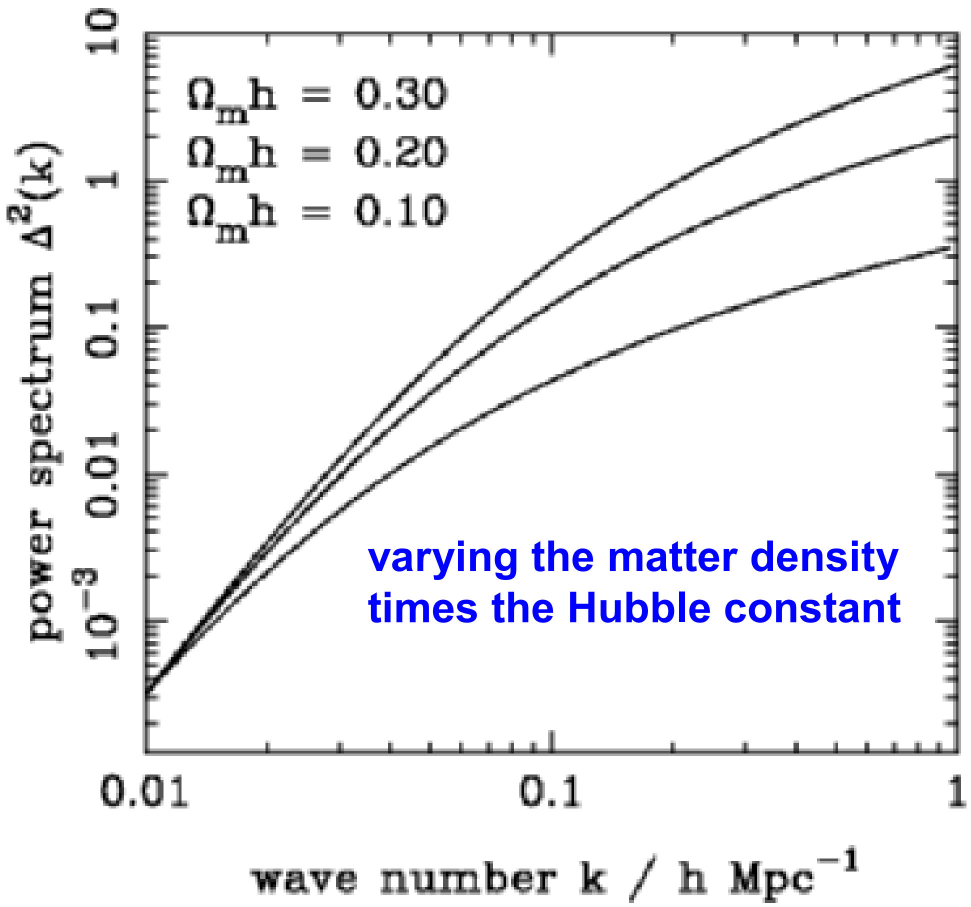
$$\left.\begin{array}{l}\Omega_m = 1 \\ \\ \Lambda = 0\end{array}\right\} \quad \textbf{CDM model ~1984}$$

$$\Delta T/T < 10^{-4}$$

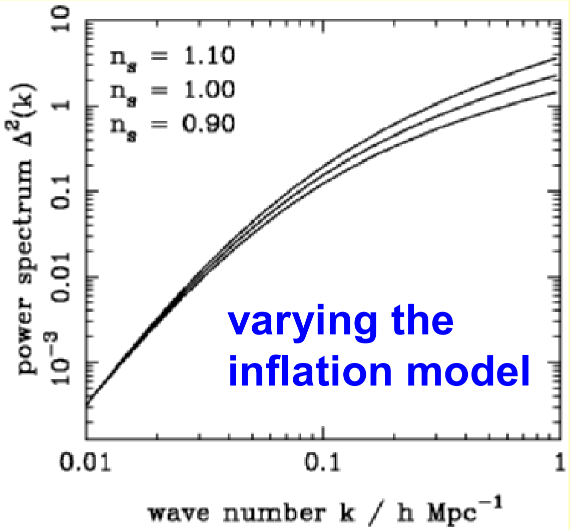
CDM predictions for the linear mass P(k)

$$\delta = \sum \delta_k e^{(-ikx)}$$

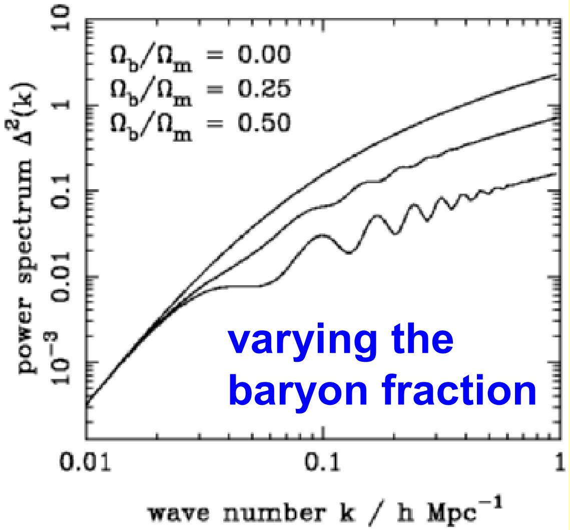
$$\Delta^2(k) = d\sigma^2/d\ln k = |\delta_k|^2 \times (k^3/2\pi^2)$$



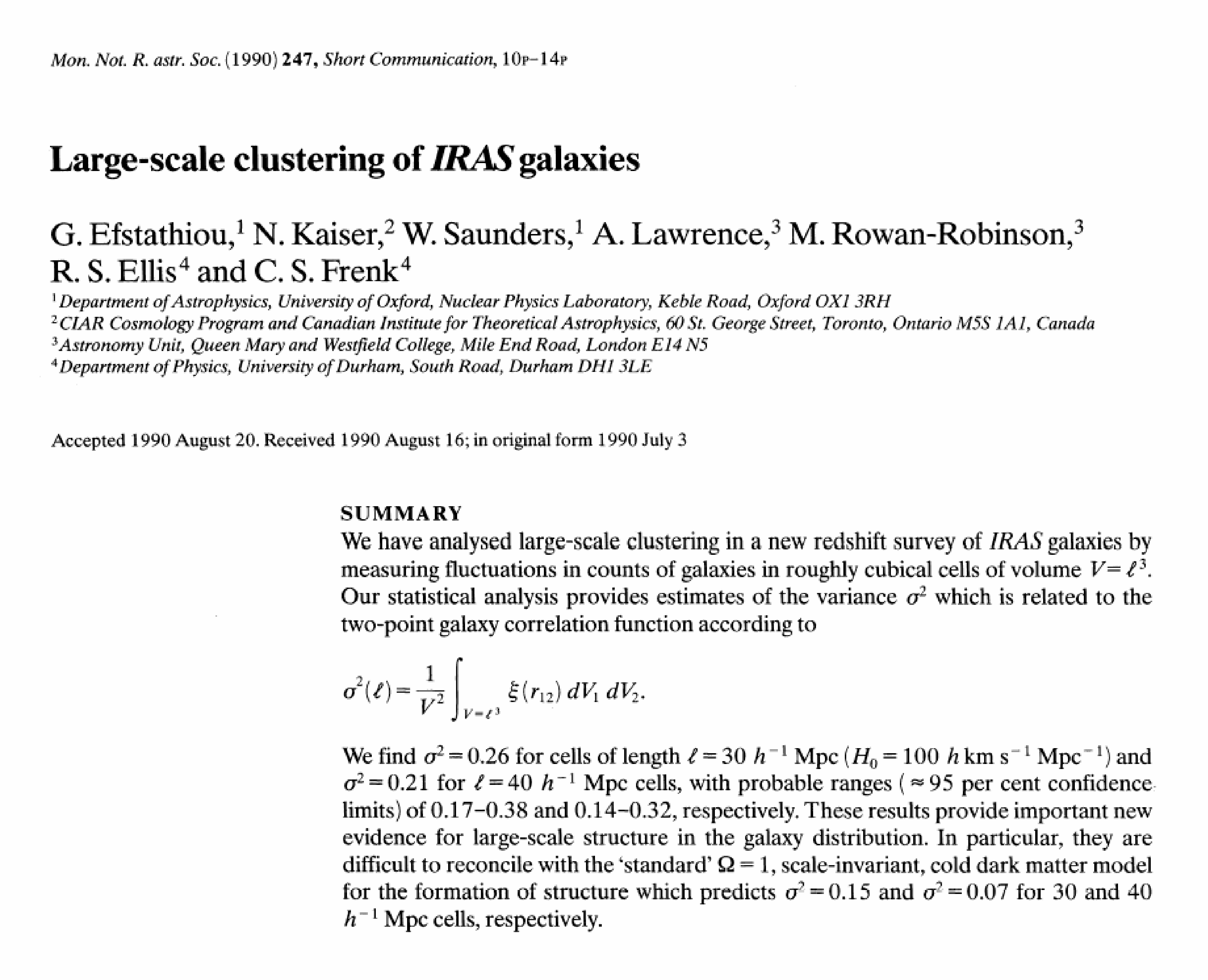
varying the matter density times the Hubble constant



varying the inflation model



varying the baryon fraction



Mon. Not. R. astr. Soc. (1990) **247**, *Short Communication*, 10P–14P

Large-scale clustering of *IRAS* galaxies

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R. S. Ellis[4] and C. S. Frenk[4]
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[2] *CIAR Cosmology Program and Canadian Institute for Theoretical Astrophysics, 60 St. George Street, Toronto, Ontario M5S 1A1, Canada*
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Accepted 1990 August 20. Received 1990 August 16; in original form 1990 July 3

SUMMARY

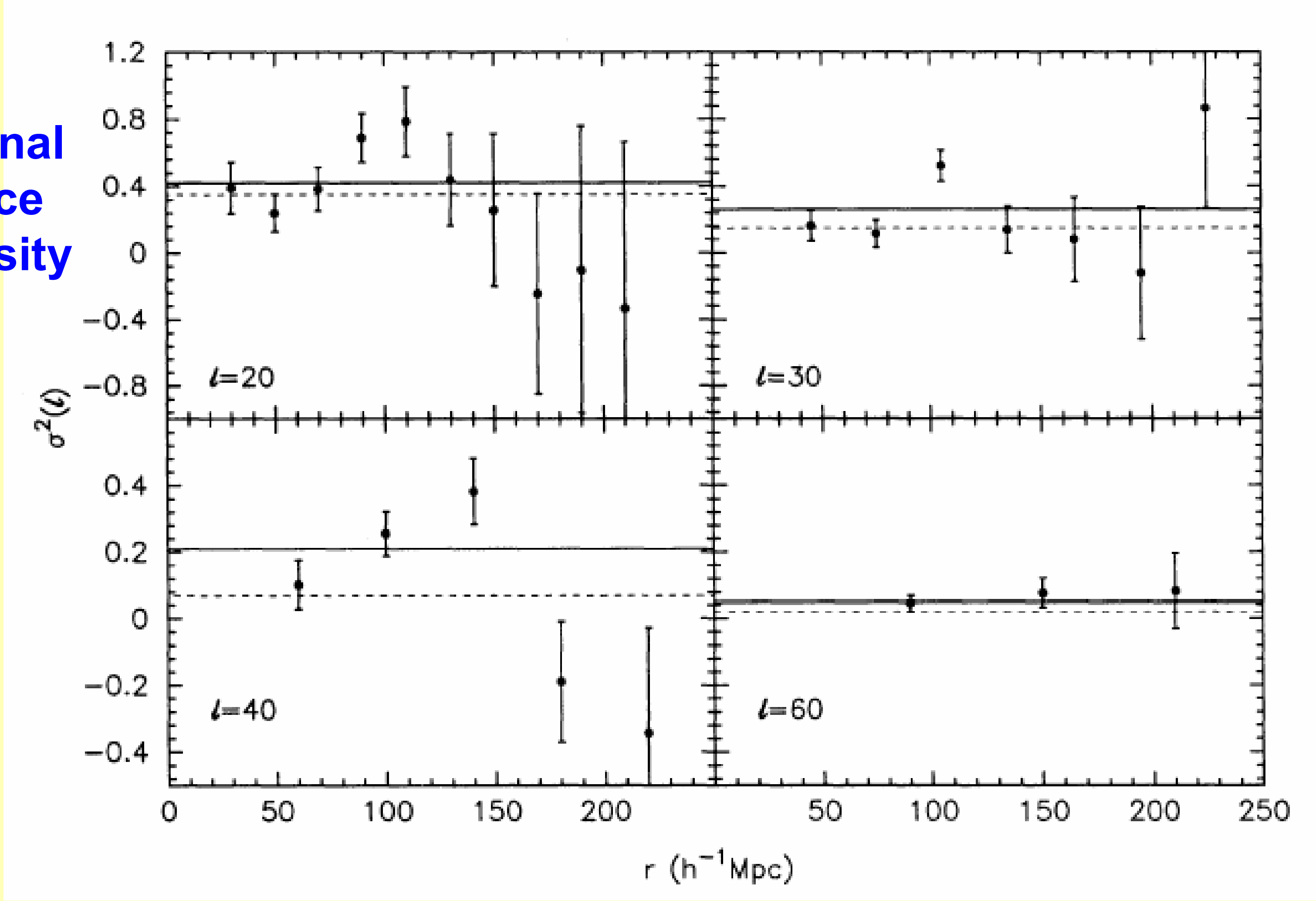
We have analysed large-scale clustering in a new redshift survey of *IRAS* galaxies by measuring fluctuations in counts of galaxies in roughly cubical cells of volume $V = \ell^3$. Our statistical analysis provides estimates of the variance σ^2 which is related to the two-point galaxy correlation function according to

$$\sigma^2(\ell) = \frac{1}{V^2} \int_{V=\ell^3} \xi(r_{12})\, dV_1\, dV_2.$$

We find $\sigma^2 = 0.26$ for cells of length $\ell = 30\ h^{-1}$ Mpc ($H_0 = 100\ h$ km s^{-1} Mpc^{-1}) and $\sigma^2 = 0.21$ for $\ell = 40\ h^{-1}$ Mpc cells, with probable ranges (≈ 95 per cent confidence limits) of 0.17–0.38 and 0.14–0.32, respectively. These results provide important new evidence for large-scale structure in the galaxy distribution. In particular, they are difficult to reconcile with the 'standard' $\Omega = 1$, scale-invariant, cold dark matter model for the formation of structure which predicts $\sigma^2 = 0.15$ and $\sigma^2 = 0.07$ for 30 and 40 h^{-1} Mpc cells, respectively.

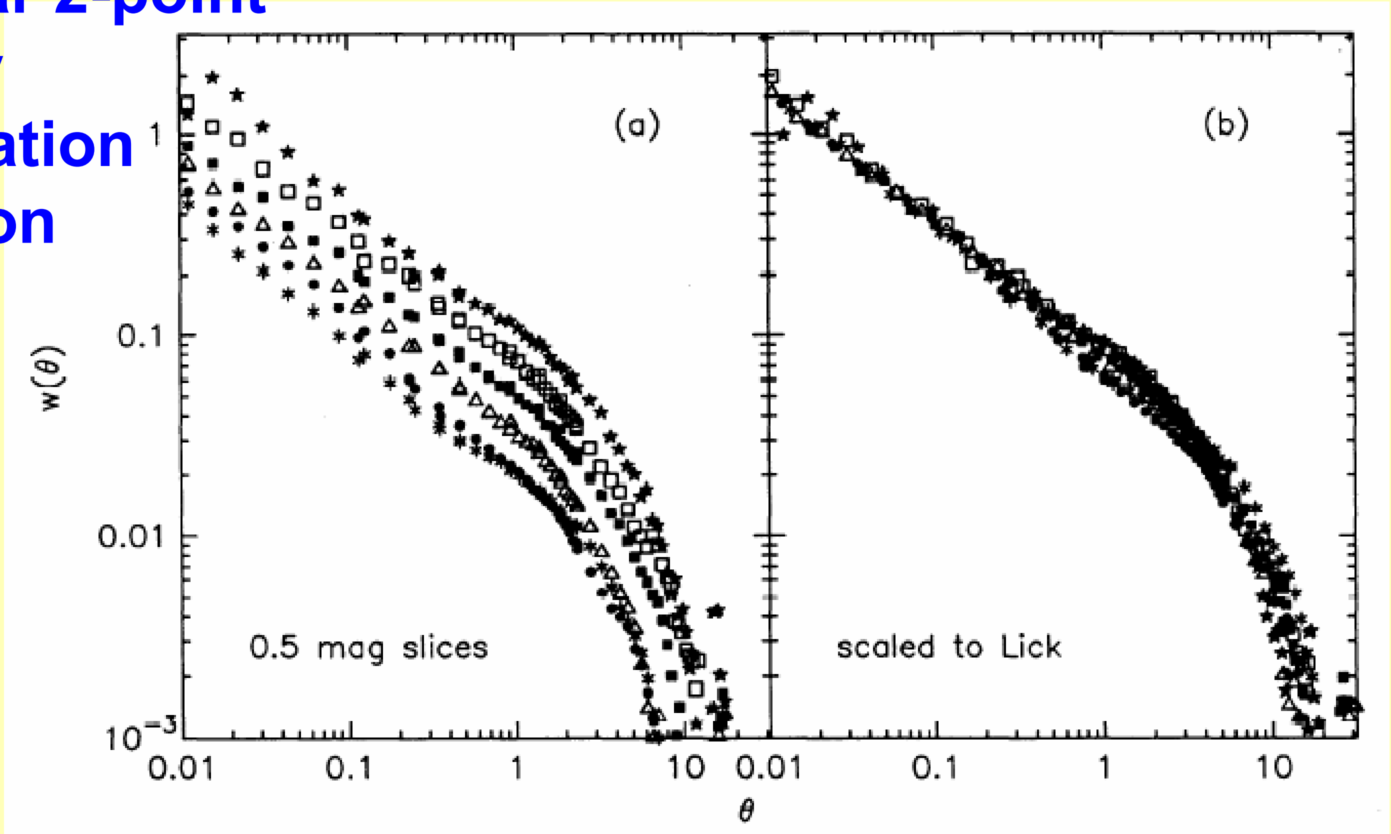
QDOT: 2163 z's rule out 'standard CDM'

fractional variance in density



1990: APM w(θ)

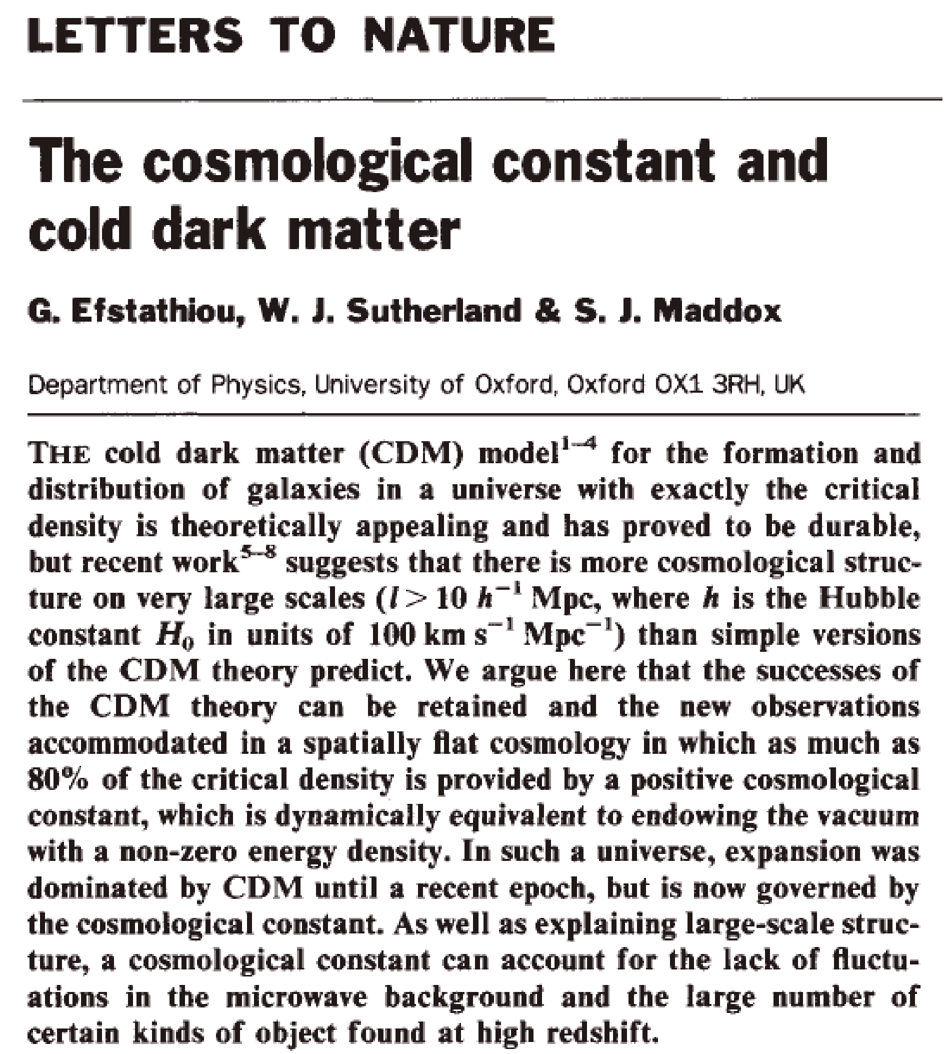
angular 2-point galaxy correlation function



$\Omega_m h \simeq 0.2$ (and argument for Λ)

deprojected to P(k) by Baugh & Efstathiou (1993)

The argument for Λ: 1990 LSS + CMB limits $\Rightarrow$ low density but not open



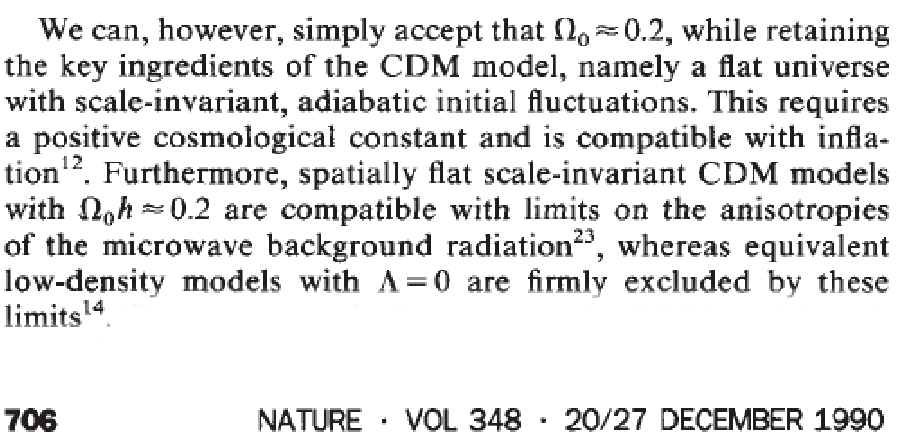
LETTERS TO NATURE

The cosmological constant and cold dark matter

G. Efstathiou, W. J. Sutherland & S. J. Maddox

Department of Physics, University of Oxford, Oxford OX1 3RH, UK

THE cold dark matter (CDM) model[1–4] for the formation and distribution of galaxies in a universe with exactly the critical density is theoretically appealing and has proved to be durable, but recent work[5–8] suggests that there is more cosmological structure on very large scales ($l > 10\ h^{-1}$ Mpc, where h is the Hubble constant H_0 in units of 100 km $\mathrm{s^{-1}}$ $\mathrm{Mpc^{-1}}$) than simple versions of the CDM theory predict. We argue here that the successes of the CDM theory can be retained and the new observations accommodated in a spatially flat cosmology in which as much as 80% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background and the large number of certain kinds of object found at high redshift.



We can, however, simply accept that $\Omega_0 \approx 0.2$, while retaining the key ingredients of the CDM model, namely a flat universe with scale-invariant, adiabatic initial fluctuations. This requires a positive cosmological constant and is compatible with inflation[12]. Furthermore, spatially flat scale-invariant CDM models with $\Omega_0 h \approx 0.2$ are compatible with limits on the anisotropies of the microwave background radiation[23], whereas equivalent low-density models with $\Lambda = 0$ are firmly excluded by these limits[14].

706 NATURE · VOL 348 · 20/27 DECEMBER 1990

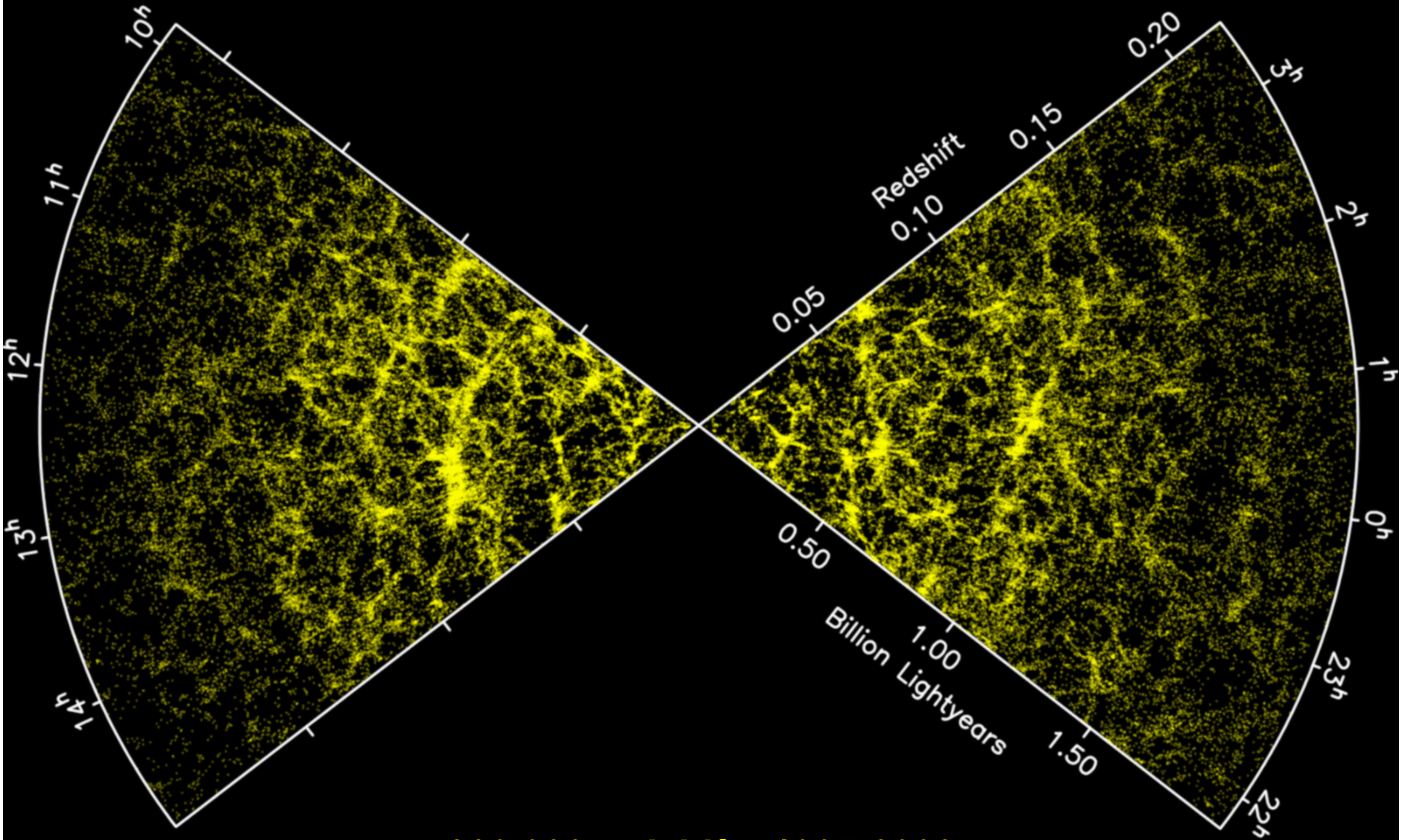
cf. Perlmutter et al. 1996:

SNe Ia $\Rightarrow$ Λ-dominated models excluded

Fast forward 10 years

-100 times as many redshifts (for a factor 3 in team size)

2dFGRS cone diagram: 4-degree wedge

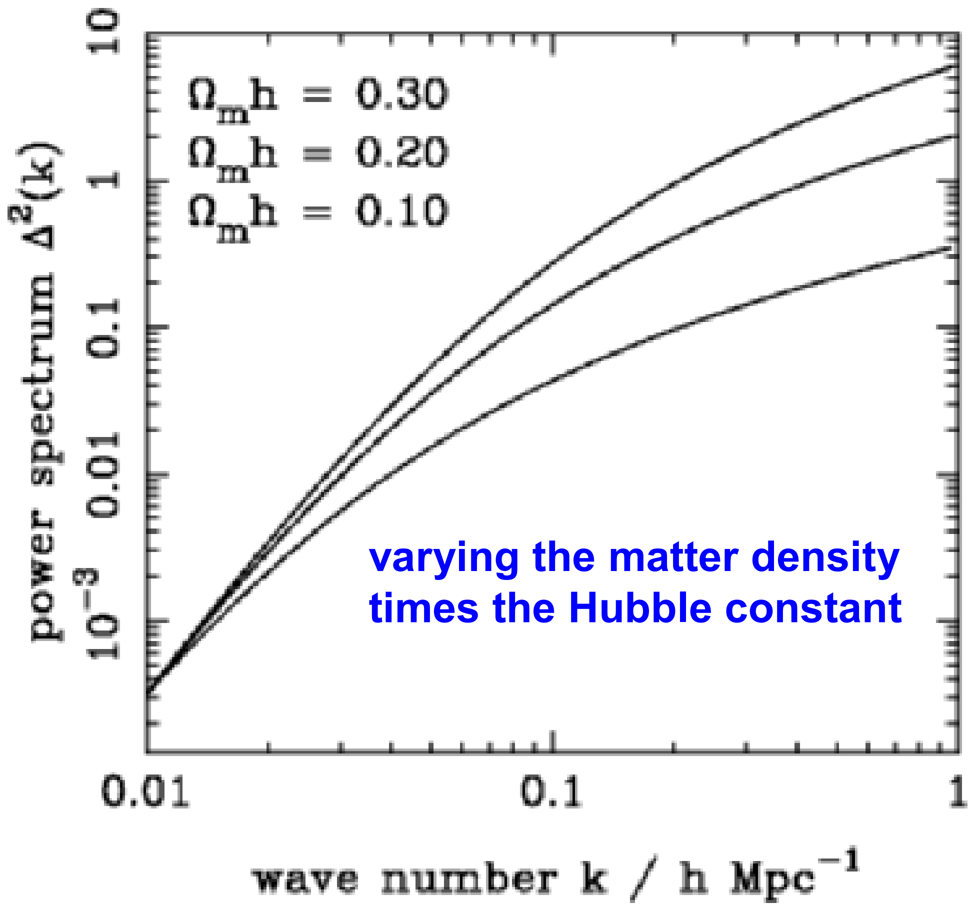


220,000 redshifts 1997-2003

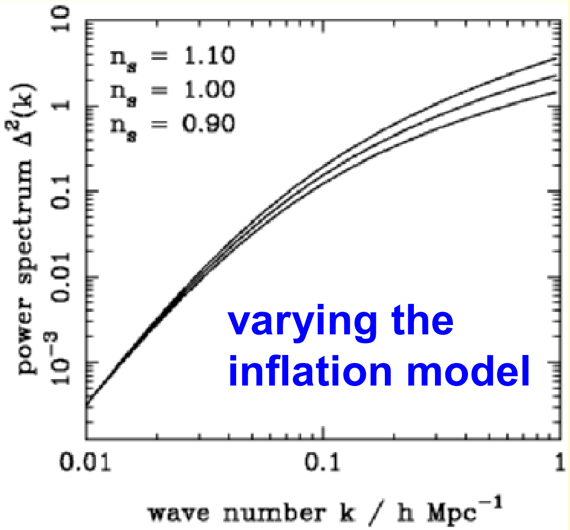
CDM predictions for the linear mass P(k)

$\delta = \sum \delta_k e^{(-ikx)}$

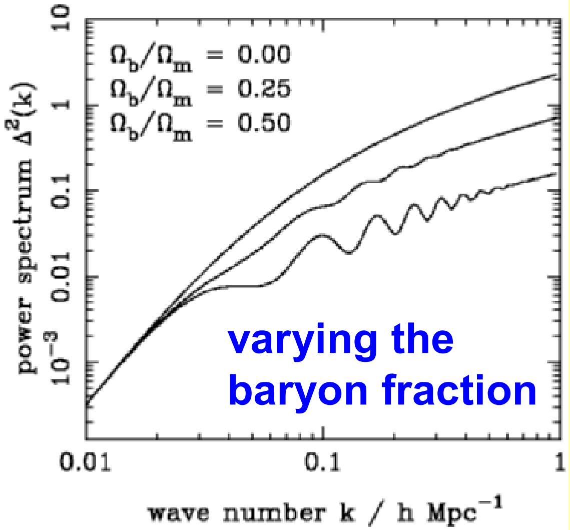
$\Delta^2(k) = d\sigma^2/d \ln k = |\delta_k|^2 \times (k^3/2\pi^2)$



varying the matter density times the Hubble constant

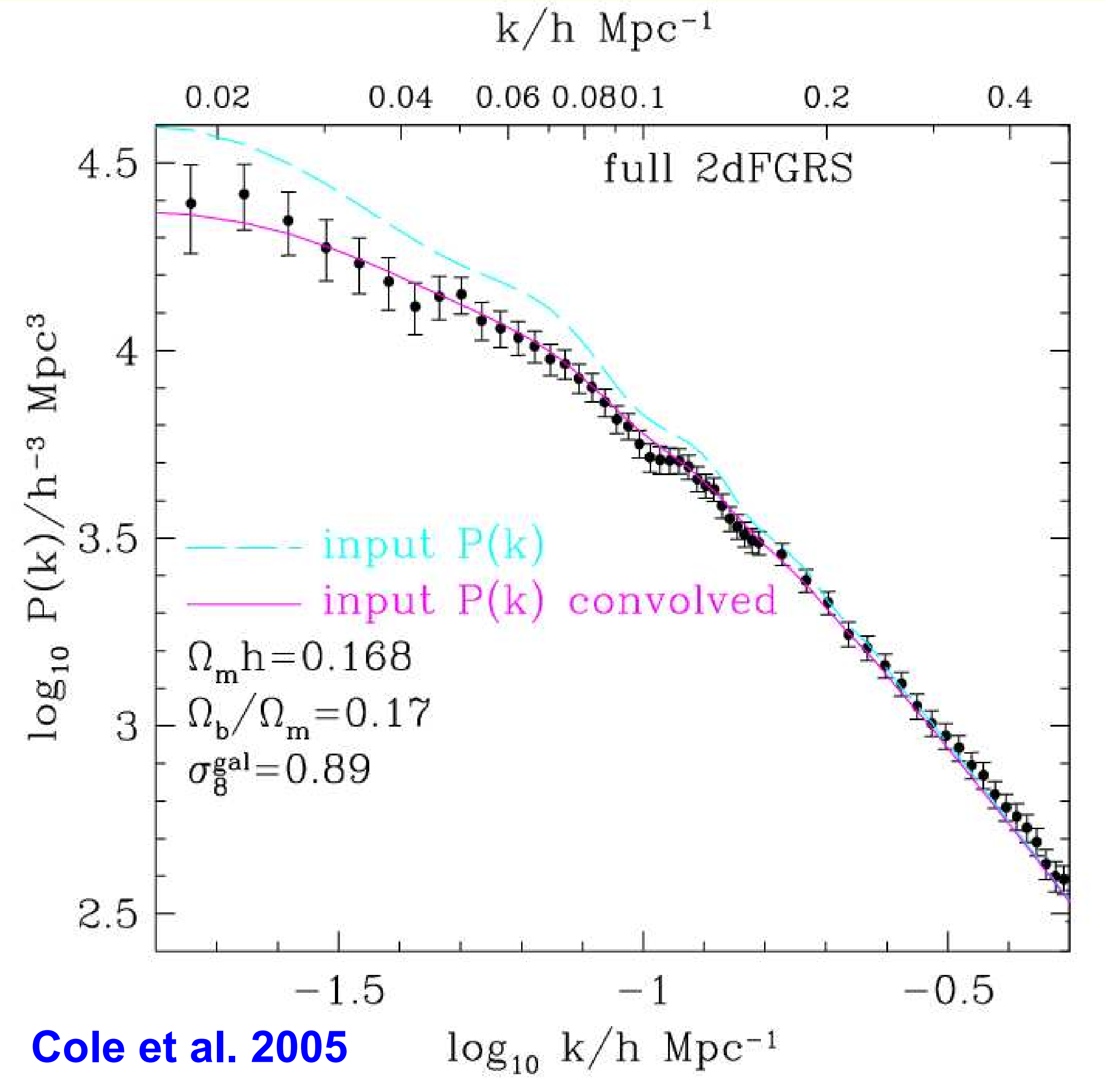


varying the inflation model

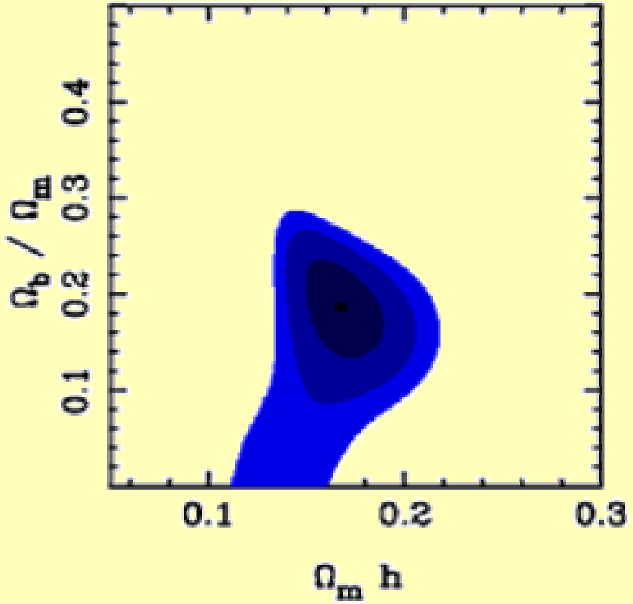


varying the baryon fraction

The final 2dFGRS Power Spectrum



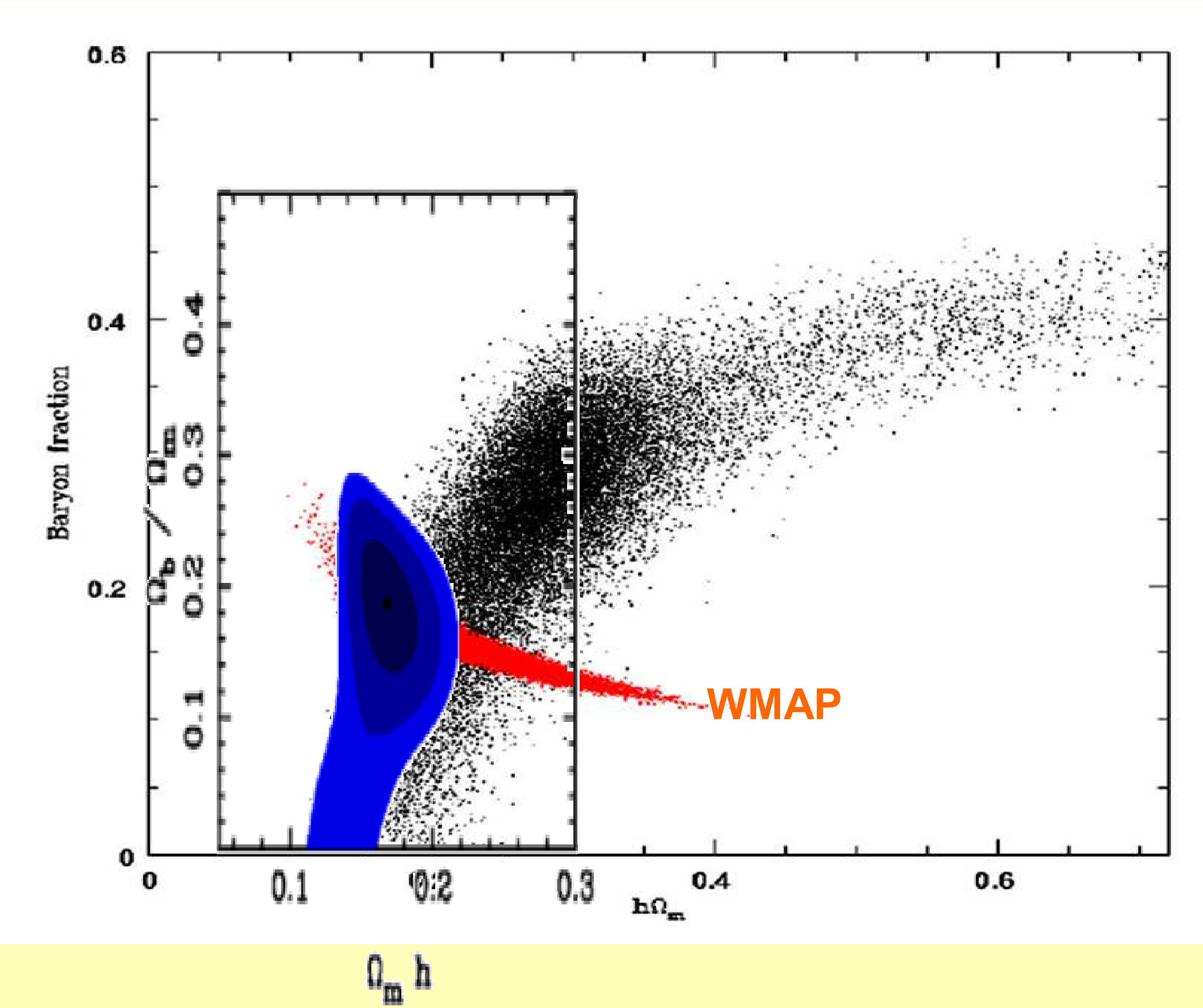
Cole et al. 2005



$\Omega_m h$ = 0.168 ± 0.016

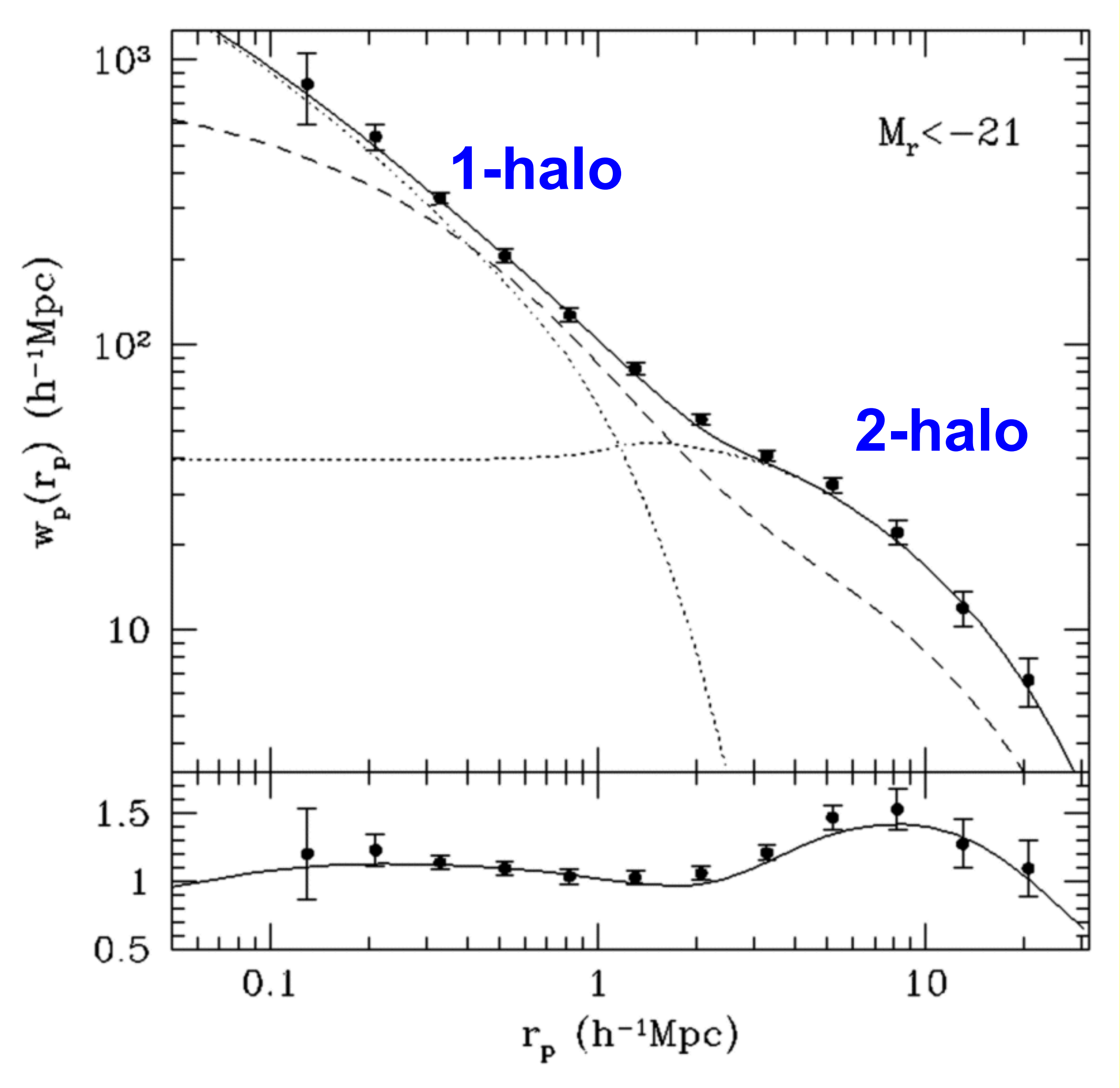
Ω_b/Ω_m = 0.185 ± 0.046

2dFGRS-SDSS comparison



Tegmark et al. **vs Cole et al.**

Halo model: Prediction matches correlation data

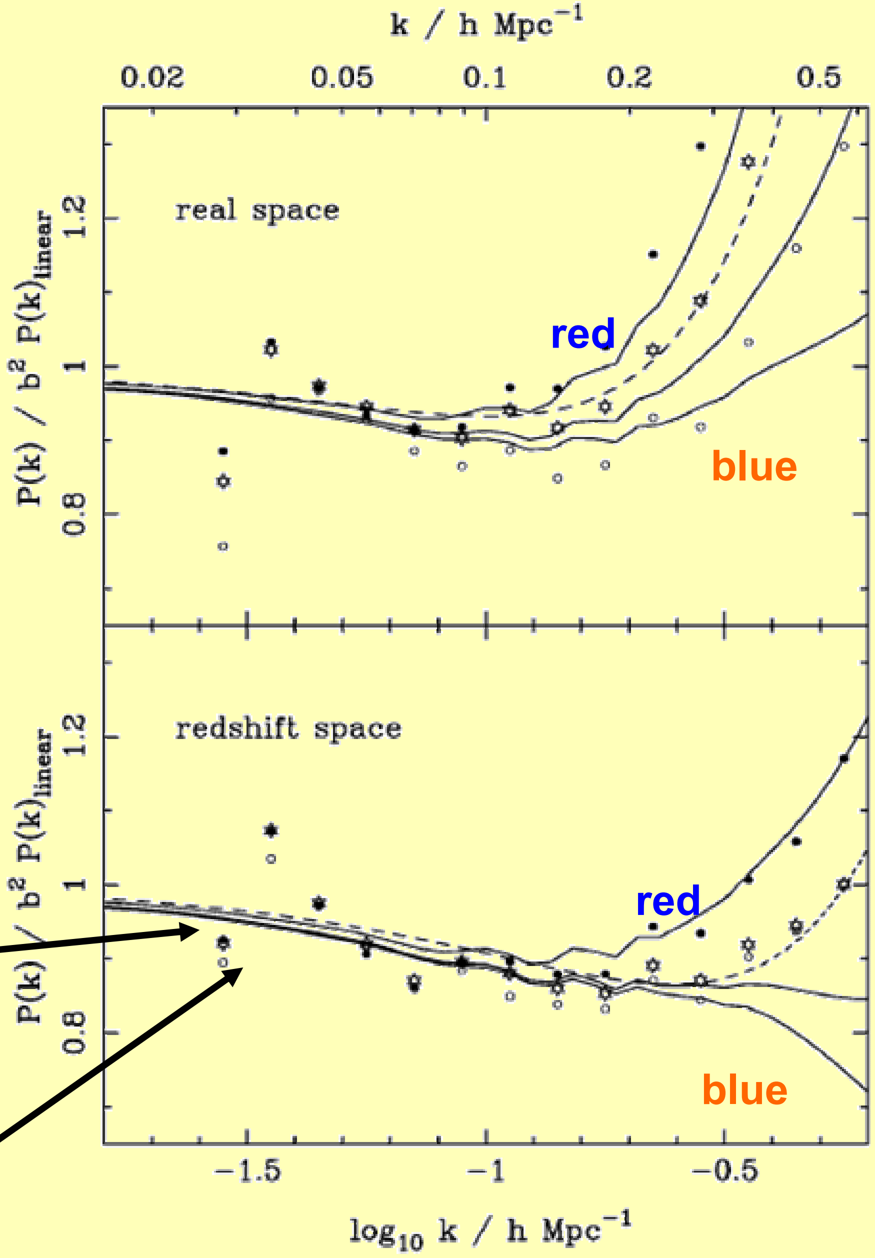


Zehavi et al.
astro-ph/0301280

Luminous SDSS galaxies need weight $M^{-0.11}$ for $M > M_{min} = 10^{13.6}$

Scale dependent bias: stronger for red galaxies

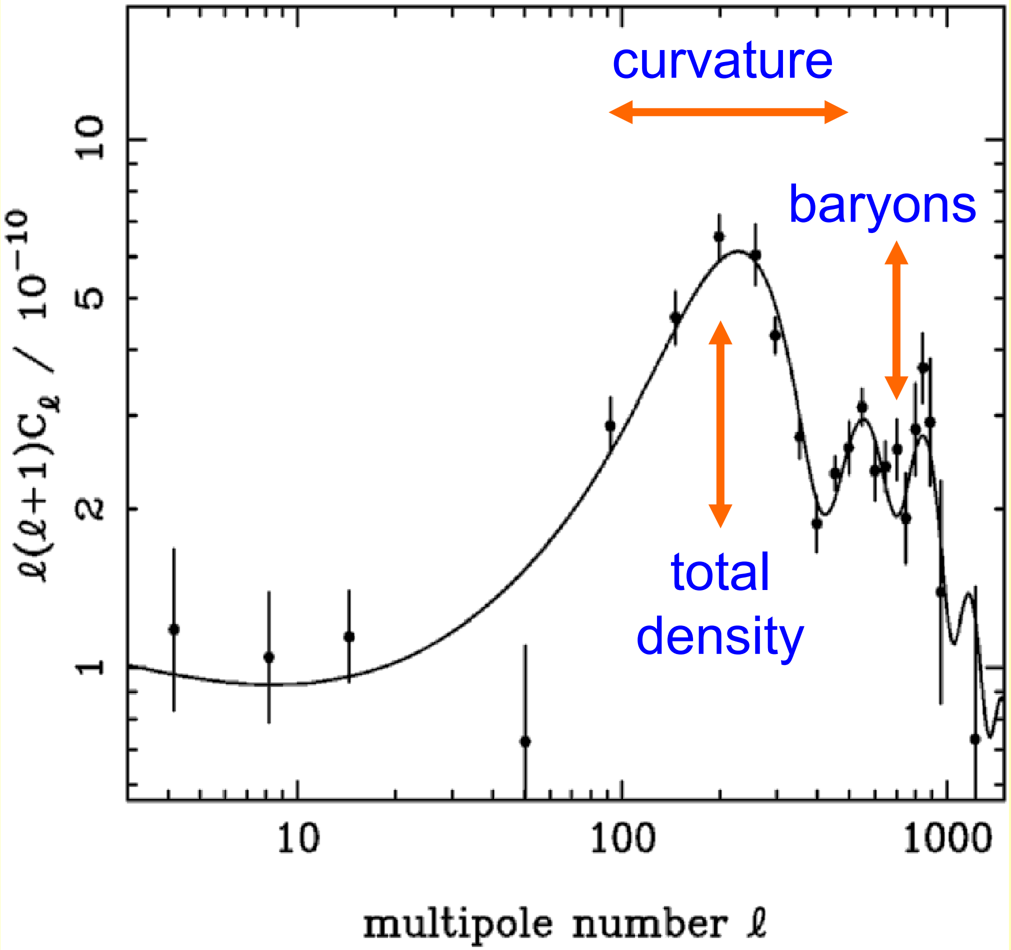
- Consider spherical average redshift-space power, ratioed to linear theory
- Evaluate via halo model and via semianalytic simulation
- Thus systematic correction (at <1σ in parameters) used up to k=0.2



lines: results from the halo model

symbols: results from semi-analytic models

from Cole et al. (2005)



Relation of LSS to CMB results

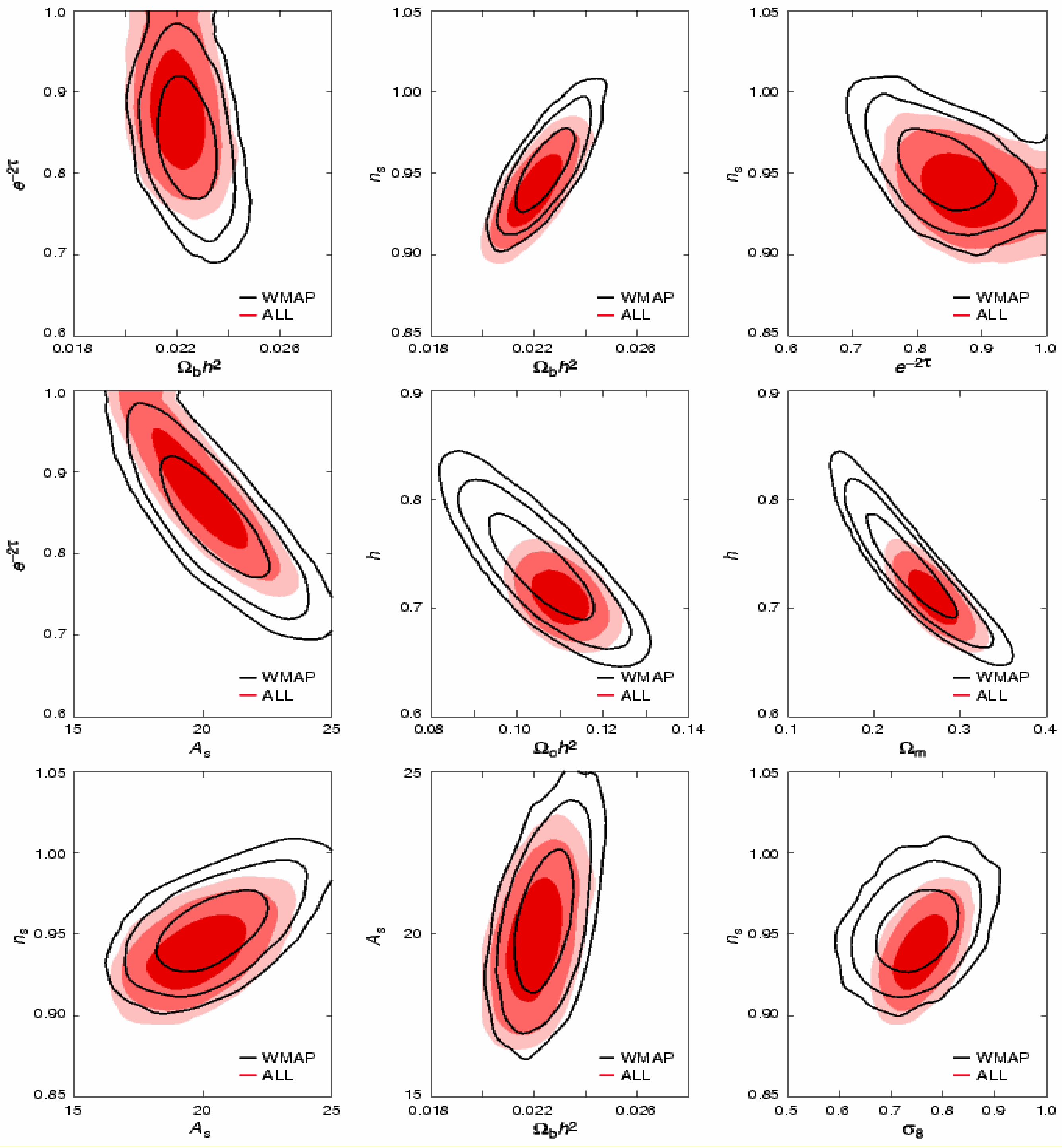
Approx scaling of peak locations:

$$\boxed{\theta_H \propto (\Omega_m h^{3.4})^{0.14} \; \Omega_{tot}^{1.4}}$$

Combining LSS & CMB breaks degeneracies:

LSS measures $\Omega_m h$ only if power index n is known

CMB measures n and $\Omega_m h^3$ (only if curvature is known)



Additional LSS information important in complementing CMB, especially for Ω_m and h, but also for rejection of n=1

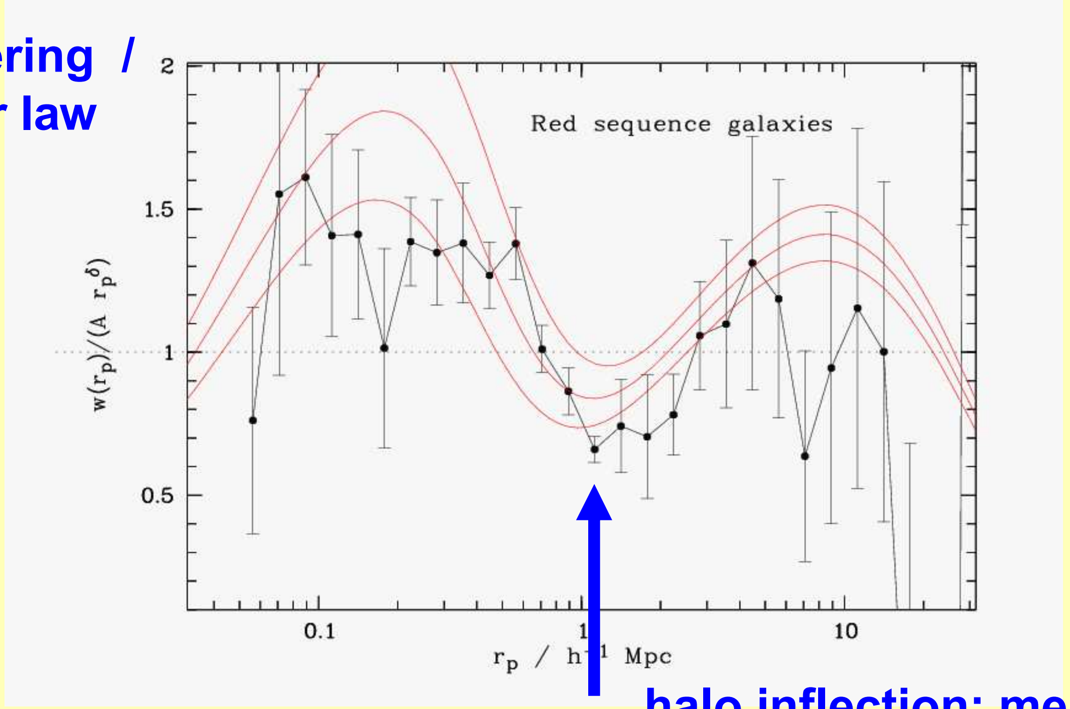
Parameter	WMAP Only	WMAP +CBI+VSA	WMAP+ACBAR +BOOMERanG	WMAP + 2dFGRS
$100\Omega_b h^2$	$2.233^{+0.072}_{-0.091}$	$2.203^{+0.072}_{-0.090}$	$2.228^{+0.066}_{-0.082}$	$2.223^{+0.066}_{-0.083}$
$\Omega_m h^2$	$0.1268^{+0.0073}_{-0.0128}$	$0.1238^{+0.0066}_{-0.0118}$	$0.1271^{+0.0070}_{-0.0128}$	$0.1262^{+0.0050}_{-0.0103}$
h	$0.734^{+0.028}_{-0.038}$	$0.738^{+0.028}_{-0.037}$	$0.733^{+0.030}_{-0.038}$	$0.732^{+0.018}_{-0.025}$
A	$0.801^{+0.043}_{-0.054}$	$0.798^{+0.047}_{-0.057}$	$0.801^{+0.048}_{-0.056}$	$0.799^{+0.042}_{-0.051}$
τ	$0.088^{+0.028}_{-0.034}$	$0.084^{+0.031}_{-0.038}$	$0.084^{+0.027}_{-0.034}$	$0.083^{+0.027}_{-0.031}$
n_s	$0.951^{+0.015}_{-0.019}$	$0.945^{+0.015}_{-0.019}$	$0.949^{+0.015}_{-0.019}$	$0.948^{+0.014}_{-0.018}$
σ_8	$0.744^{+0.050}_{-0.060}$	$0.722^{+0.044}_{-0.056}$	$0.742^{+0.045}_{-0.057}$	$0.737^{+0.033}_{-0.045}$
Ω_m	$0.238^{+0.027}_{-0.045}$	$0.229^{+0.026}_{-0.042}$	$0.239^{+0.025}_{-0.046}$	$0.236^{+0.016}_{-0.029}$

Parameter	WMAP+ SDSS	WMAP+ LRG	WMAP+ SNLS	WMAP + SN Gold	WMAP+ CFHTLS
$100\Omega_b h^2$	$2.233^{+0.062}_{-0.086}$	$2.242^{+0.062}_{-0.084}$	$2.233^{+0.069}_{-0.088}$	$2.227^{+0.065}_{-0.082}$	$2.247^{+0.064}_{-0.082}$
$\Omega_m h^2$	$0.1329^{+0.0057}_{-0.0109}$	$0.1337^{+0.0047}_{-0.0098}$	$0.1295^{+0.0055}_{-0.0106}$	$0.1349^{+0.0054}_{-0.0106}$	$0.1410^{+0.0042}_{-0.0094}$
h	$0.709^{+0.024}_{-0.032}$	$0.709^{+0.016}_{-0.023}$	$0.723^{+0.021}_{-0.030}$	$0.701^{+0.020}_{-0.026}$	$0.686^{+0.017}_{-0.024}$
A	$0.813^{+0.042}_{-0.052}$	$0.816^{+0.042}_{-0.049}$	$0.808^{+0.044}_{-0.051}$	$0.827^{+0.045}_{-0.053}$	$0.852^{+0.036}_{-0.047}$
τ	$0.079^{+0.029}_{-0.032}$	$0.082^{+0.028}_{-0.033}$	$0.085^{+0.028}_{-0.032}$	$0.079^{+0.028}_{-0.034}$	$0.088^{+0.021}_{-0.031}$
n_s	$0.948^{+0.015}_{-0.018}$	$0.951^{+0.014}_{-0.018}$	$0.950^{+0.015}_{-0.019}$	$0.946^{+0.015}_{-0.019}$	$0.950^{+0.015}_{-0.019}$
σ_8	$0.772^{+0.036}_{-0.048}$	$0.781^{+0.032}_{-0.045}$	$0.758^{+0.038}_{-0.052}$	$0.784^{+0.035}_{-0.049}$	$0.826^{+0.023}_{-0.035}$
Ω_m	$0.266^{+0.025}_{-0.040}$	$0.267^{+0.017}_{-0.029}$	$0.249^{+0.023}_{-0.034}$	$0.276^{+0.022}_{-0.036}$	$0.301^{+0.018}_{-0.031}$

Where next for LSS?

- **Understanding galaxy formation (i.e. can semianalytics predict HOD at high z?)**

clustering / power law

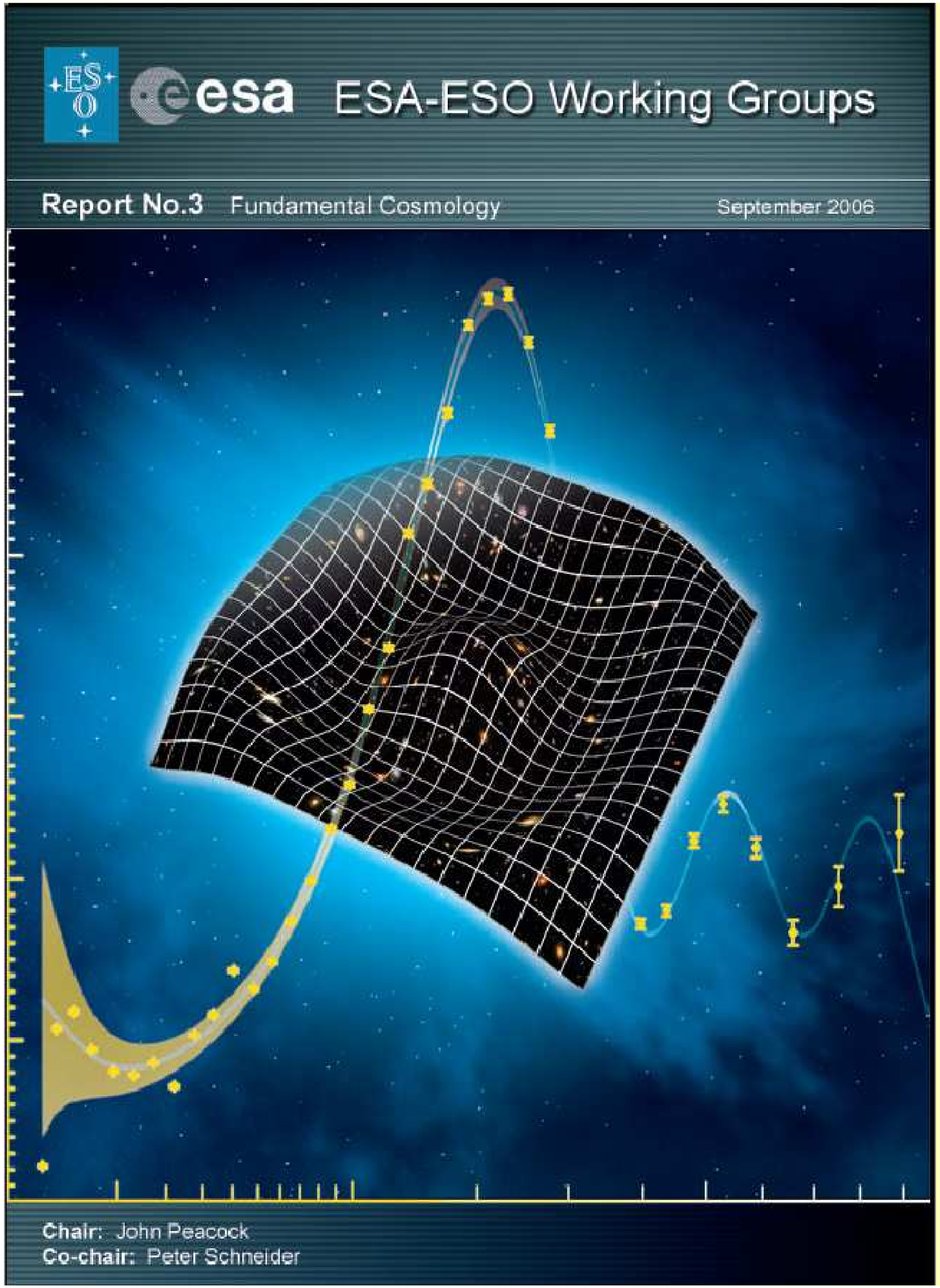


halo inflection: measure host masses

Phleps et al.:

20,000 COMBO-17 galaxies at <z> = 0.6

- **Dark energy**



ESA-ESO Working Groups

Report No.3 Fundamental Cosmology September 2006

Chair: John Peacock
Co-chair: Peter Schneider

ESA-ESO Working Group on Fundamental Cosmology

John Peacock (Chair)
Peter Schneider (Co-Chair)
George Efstathiou
Jonathan R. Ellis
Bruno Leibundgut
Simon Lilly
Yannick Mellier

Major contributors:

Pierre Astier, Anthony Banday, Hans Boehringer, Anne Ealet, Martin Haehnelt, Guenther Hasinger, Paolo Molaro, Jean-Loup Puget, Bernard Schutz, Uros Seljak, Jean-Philippe Uzan

Measuring the vacuum

Vacuum affects H(z):

$$H^2(z) = H^2_0\ \left[\ \underset{\text{matter}}{\Omega_M (1+z)^{3}} + \underset{\text{radiation}}{\Omega_R (1+z)^{4}} + \underset{\text{vacuum}}{\Omega_V (1+z)^{3(1+w)}}\ \right]$$

Alters D(z) via $r = \int c\, dz/H$

And growth via $2H\, d\delta/dt$ term in growth equation

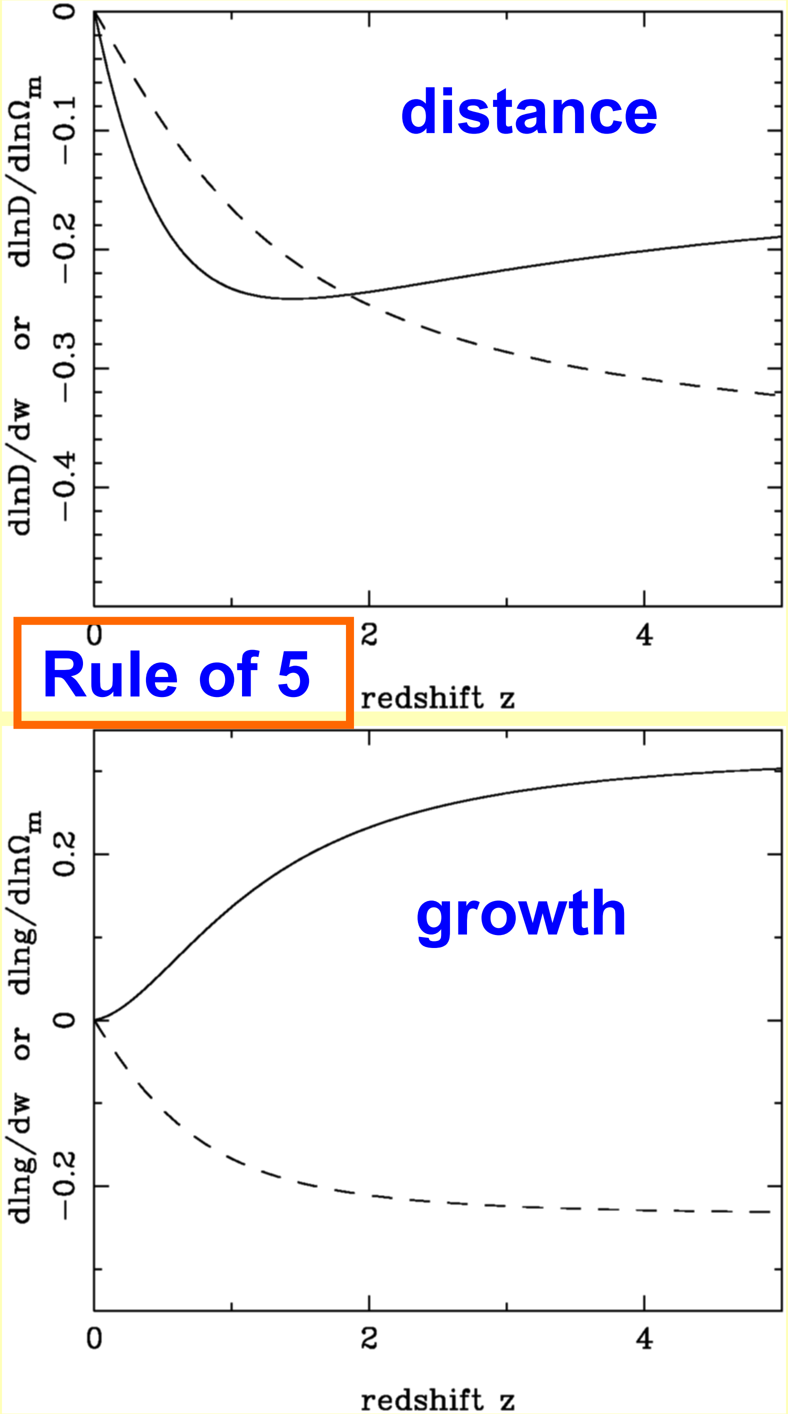
Both effects are

(1) Small (need D to 1% for w to ± 0.05)

(2) Degenerate with changes in Ω_m

Redshift surveys of ~ 10^6 galaxies over ~ 1000 deg^2 can measure w to 3-5% but systematics are challenging

Now: AAΩ (2dF++) 2012: WFMOS



Rule of 5

P(k) as a standard ruler

(1) Matter-radiation horizon:

123 $(\Omega_m h^2 / 0.13)^{-1}$ Mpc

(2) Acoustic horizon at last scattering :

147 $(\Omega_m h^2 / 0.13)^{-0.25} (\Omega_b h^2 / 0.024)^{-0.08}$ Mpc

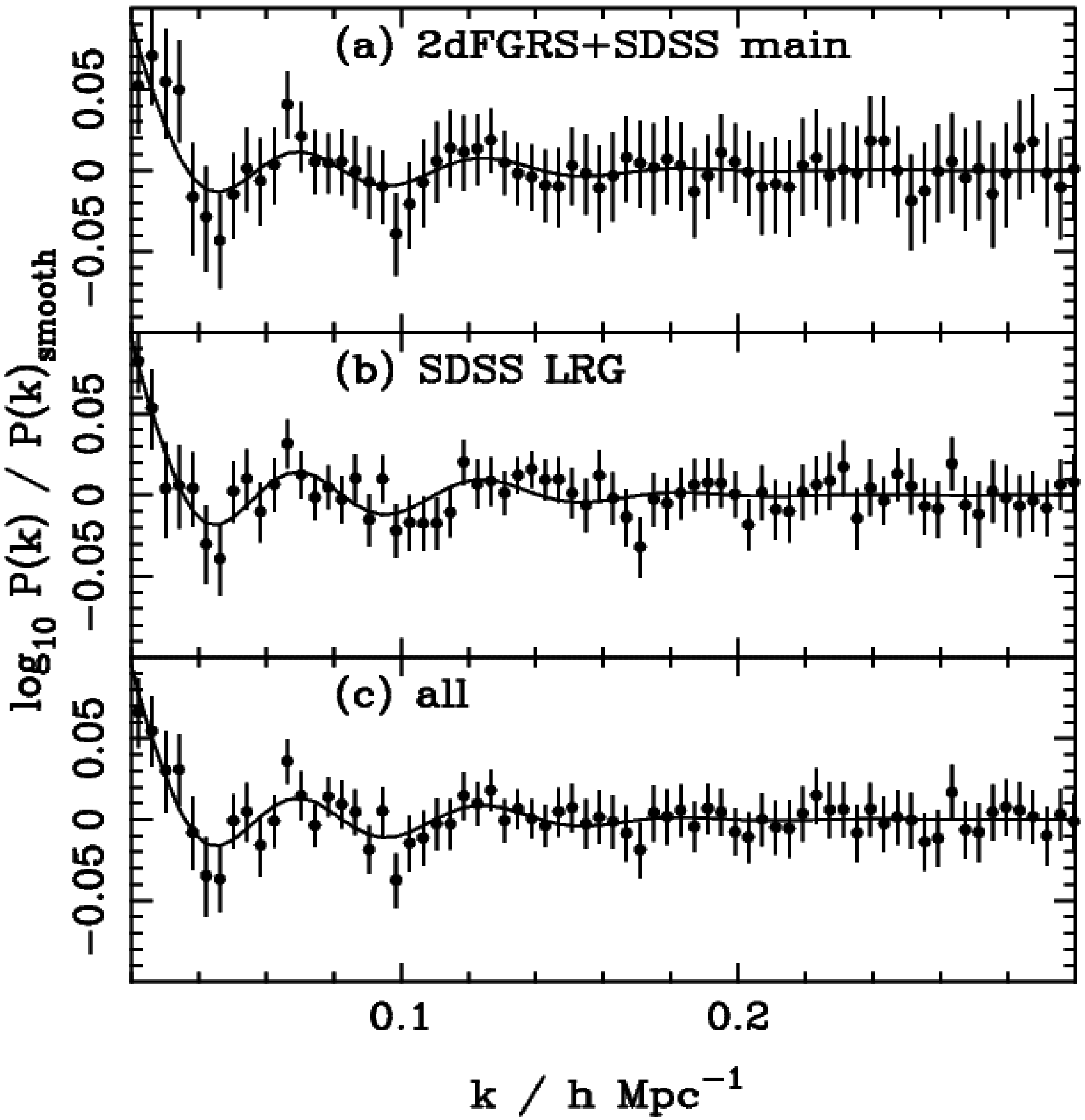
Acoustic horizon can be seen in CMB and baryon wiggles:

Use to probe distance-z relation

$$D(z) = \frac{c}{H_0} \int_0^z \frac{dz}{[(1-\Omega_m)(1+z)^{3+3w} + \Omega_m (1+z)^3]^{1/2}}$$

can measure w for vacuum ($P/\rho c^2$)

BAO: state of the art

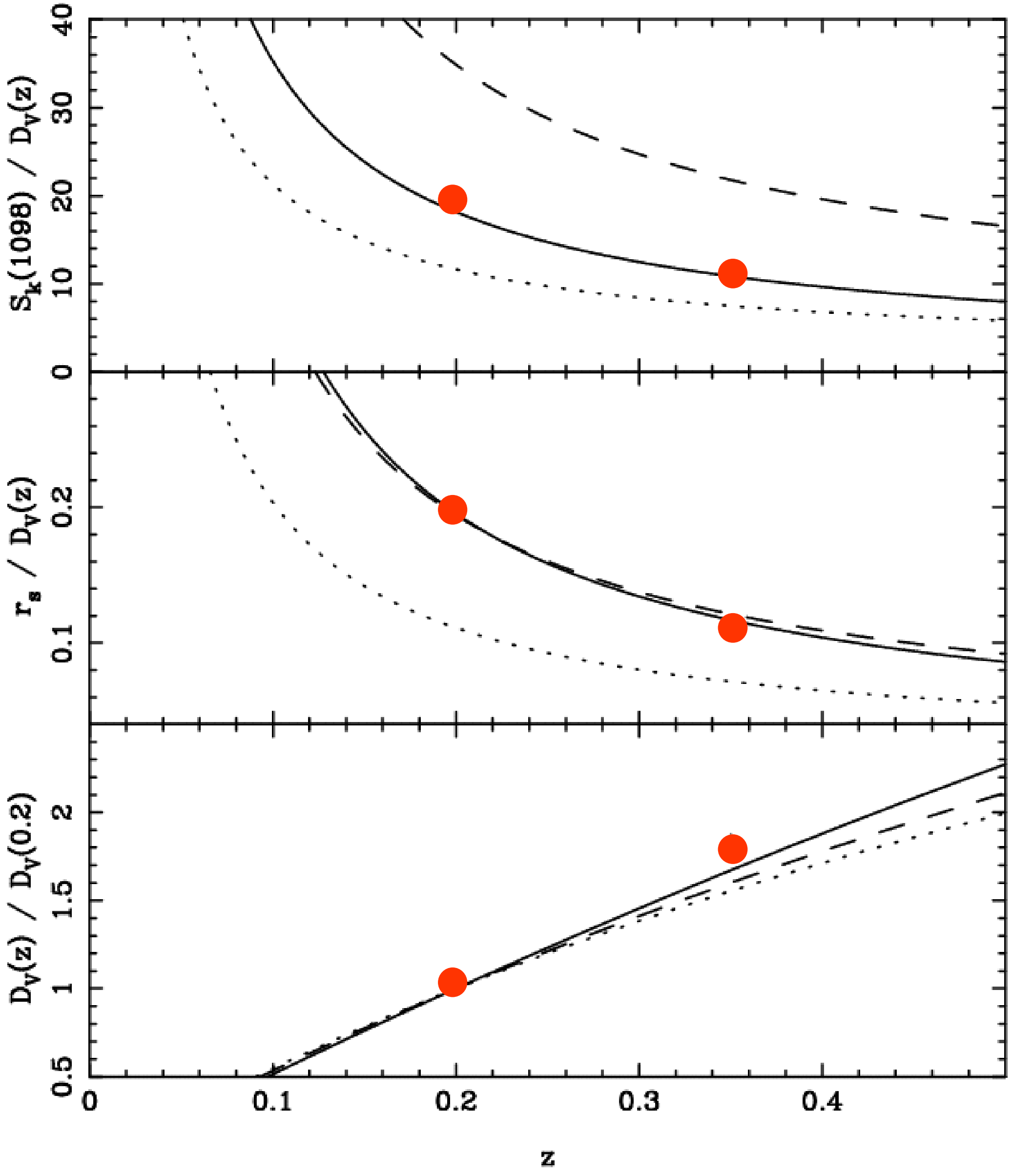


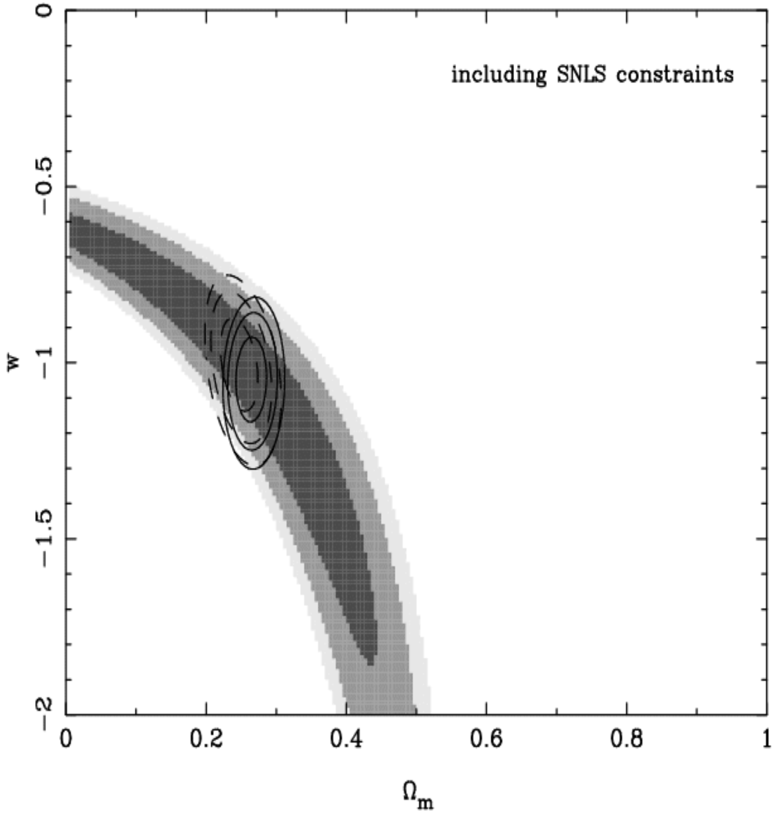
Percival et al. 2007 arXiv: SDSS + 2dFGRS

590,000 G’s at <z> = 0.2

78,000 LRG’s at <z> = 0.35

BAO: state of the art





10% error on w using BAO + SNe

S/N for P(k): cosmic variance vs shot noise

$$\sigma_{\ln P} = \frac{(2\pi)^{3/2}/V_k^{1/2}}{\left(\int \frac{(nP)^2}{(1+nP)^2}\, dV\right)^{1/2}}$$

n(z) falls fast at z > 1, but near <n>P=1, can treat as const. Exact density unimportant near n ~ 0.001 h^3 Mpc^{-3}

Error scales as $(k_{max})^{-3/2}$ so understanding of nonlinearities is critical. Larger k_{max} at higher z?

But oscillation signal falls as 1/k, so overall BAO sensitivity goes as $(k_{max})^{1/2}$

In practice: % error in D =

$(V / 5\ h^{-3}\ \mathrm{Gpc}^3)^{-1/2}$

$\times\ (k_{max} / 0.2\ h\ \mathrm{Mpc}^{-1})^{-1/2}$

Volumes and numbers

- DEEP2-like: $0.7 < z < 1.3$: 1 $(h^{-1}\mathrm{Gpc})^3$ = 540 deg^2
- LBG UGR: $2.5 < z < 3.5$: 1 $(h^{-1}\mathrm{Gpc})^3$ = 254 deg^2
- Thus 1% distance accuracy (V=5) at z=1 or z=3 needs about 5,000,000 redshifts over 2000 or 1000 deg^2
- And this is 5% in w: should aim for >10,000,000 z's

Main current/future BAO surveys

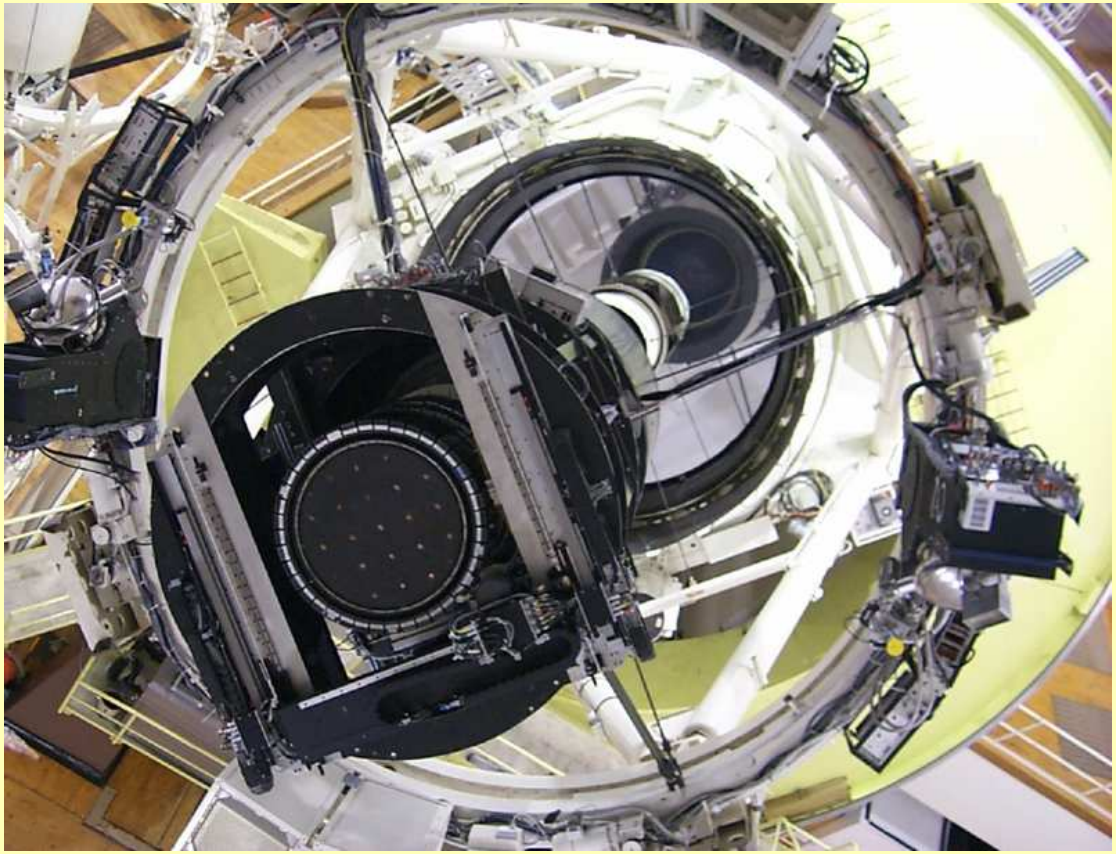
Name	Telescope	N(z) / 10^6	Dates	Status
SDSS/2dFGRS	SDSS/AAT	0.8	Now	Done
WiggleZ	AAT(AAOmega)	0.4	2007-2011	Running
FastSound	Subaru(FMOS)	0.6	2009-2012	Proposal
BOSS	SDSS	1.5	2009-2013	Proposal
HETDEX	HET(VIRUS)	1	2010-2013	Part funded
WFMOS	Subaru	>2	2013-2016	Part funded
ADEPT	Space	>100	2012+	JDEM
SKA	SKA	>100	2020+	Long term

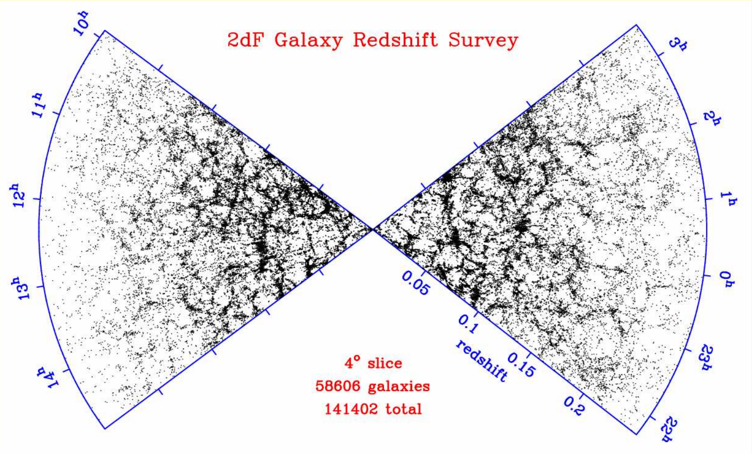
Most data will come at $z \sim 1$ (U-band bottleneck for LBGs)

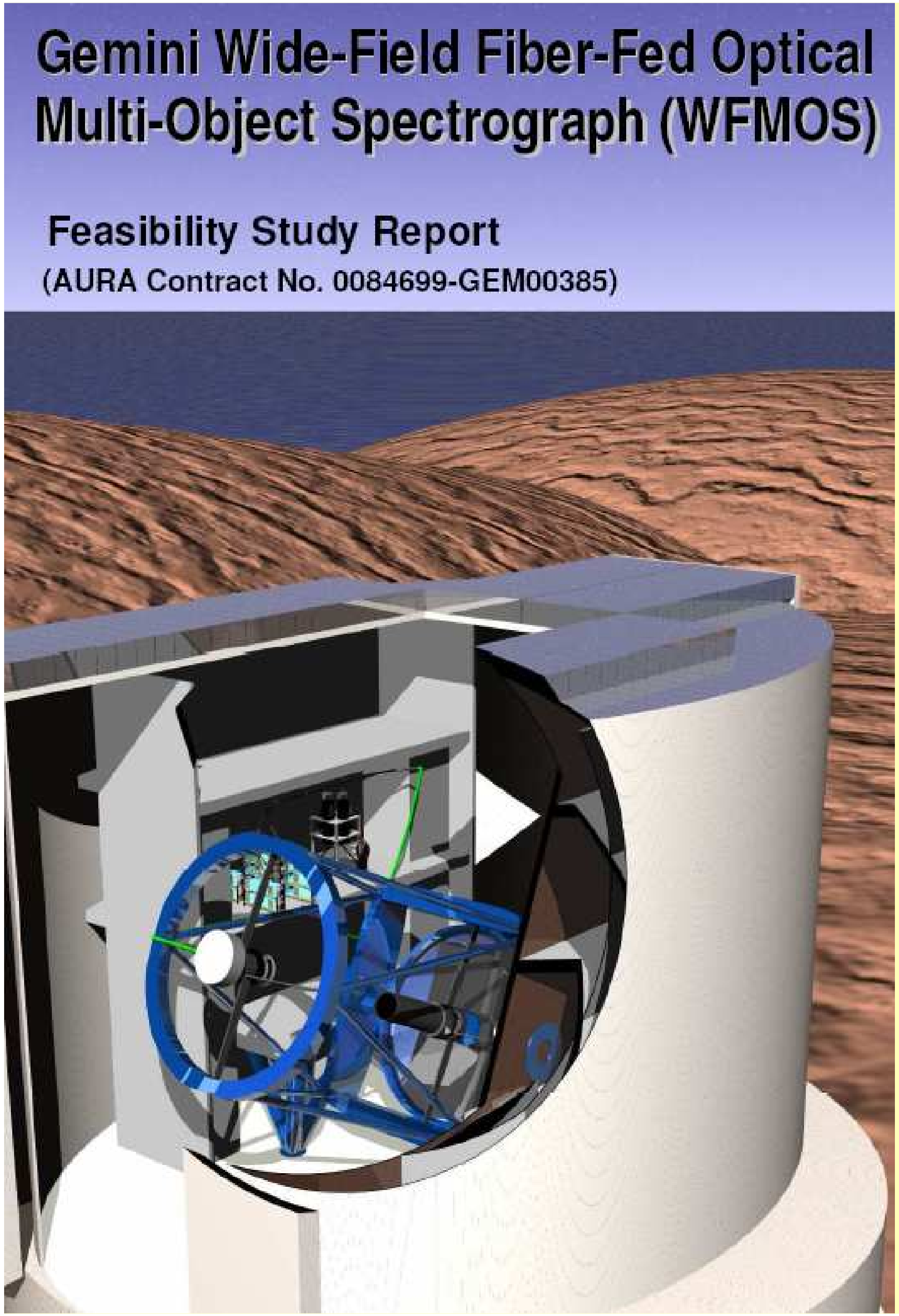
Σ WiggleZ/FastSound/BOSS = 2m by ~2012 (~7% on w)

AAΩ
The Two Degree Field (2dF)


Anglo-Australian 4m Telescope
Coonabarabran, NSW







Gemini Wide-Field Fiber-Fed Optical Multi-Object Spectrograph (WFMOS)

Feasibility Study Report

(AURA Contract No. 0084699-GEM00385)

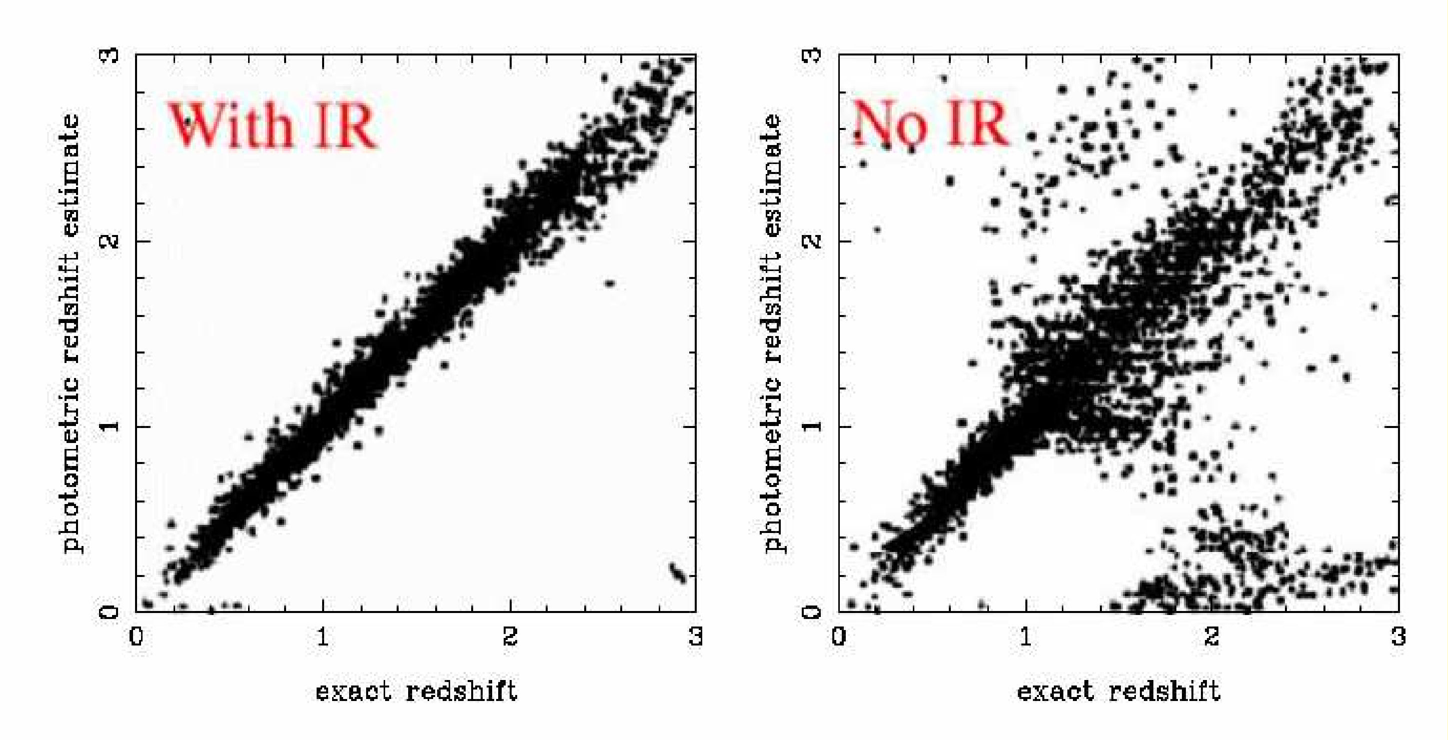
Gemini-Subaru collaboration

Motivated by 1.5 – 2 deg HyperSuprimeCam field on Subaru

2 competing design studies underway: hope for a decision on construction by end 2008

Original concept: 4000 fibres

Going faster: photometric redshifts



Broad-band data can give $\delta z/(1+z) \simeq 0.04$

But expect catastrophic failures for z>1 with optical only

Sufficiently deep near-IR (K $\simeq$ 22) needs space

Pan-STARRS

Panoramic Survey Telescope and Rapid Reponse System

The world's leading survey telescope, sited on Haleakala, Maui, Hawaii

- 1.8m mirror
- 7 deg^2 fov and 1.4 Gpixel CCD

Survey (5-band grizy) operations from end of 2007, for 3.5 years

- All-sky to r = 24.6 (above dec -30)
- 70 deg^2 to r = 27.4 (variability)

Conclusions

- Huge progress in efficiency of surveying universe:
  - QDOT: 10 scientists for 2163 z's
  - 2dFGRS: 33 scientists for 220k z's
  - Pan-STARRS: 160 scientists for 1 billion (photo)z's
  - $\Rightarrow$ 500 scientists for all universe in 2020
- What have we learned?
  - First evidence for flat vacuum-dominated universe
  - $\Omega_m = 0.25$, $n<1$ in combination with CMB
- What will we learn?
  - w to 1%
  - Too high a price for one number: need to make sure datasets are suitable for broader astrophysics