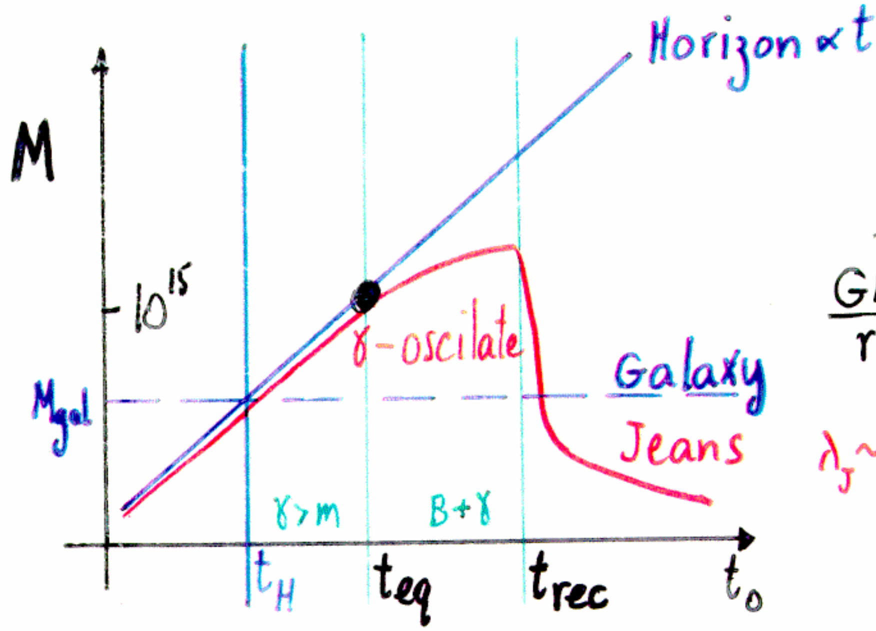
Galaxy Formation

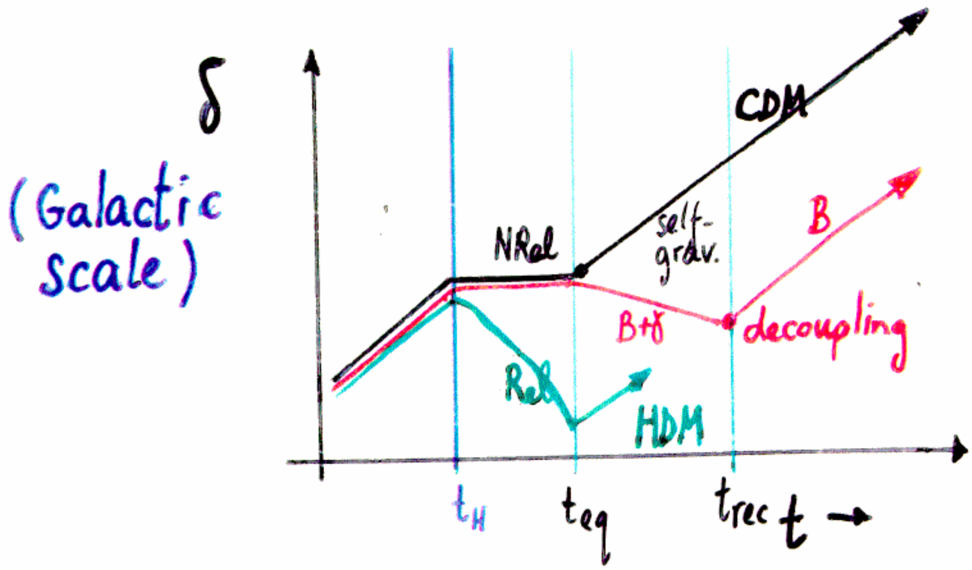
Formation of Structure in the Universe

Filtering by Dark Matter



$$\frac{GM}{r^2} \sim \frac{1}{\rho}\frac{\partial p}{\partial r}$$

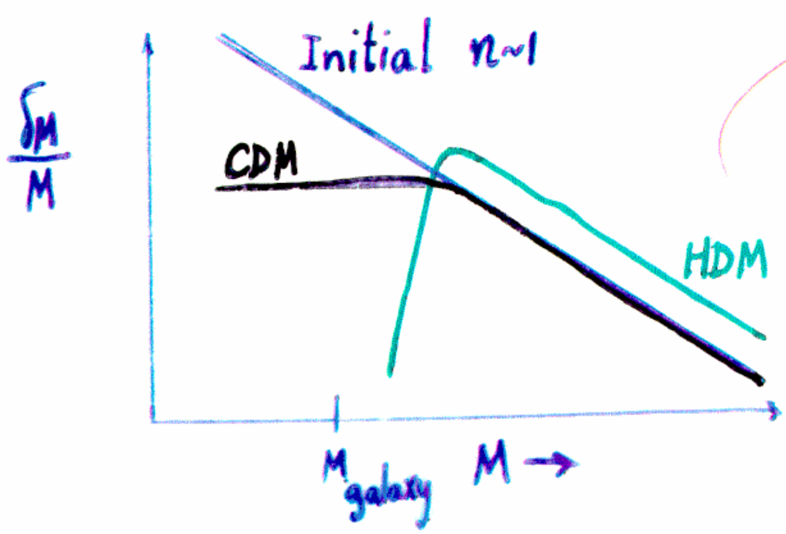
$$\lambda_J \sim \left(\frac{p}{G\rho^2}\right)^{1/2} \sim c_s t$$



Growth suppressed by radiation

t_{eq} t_{rec}

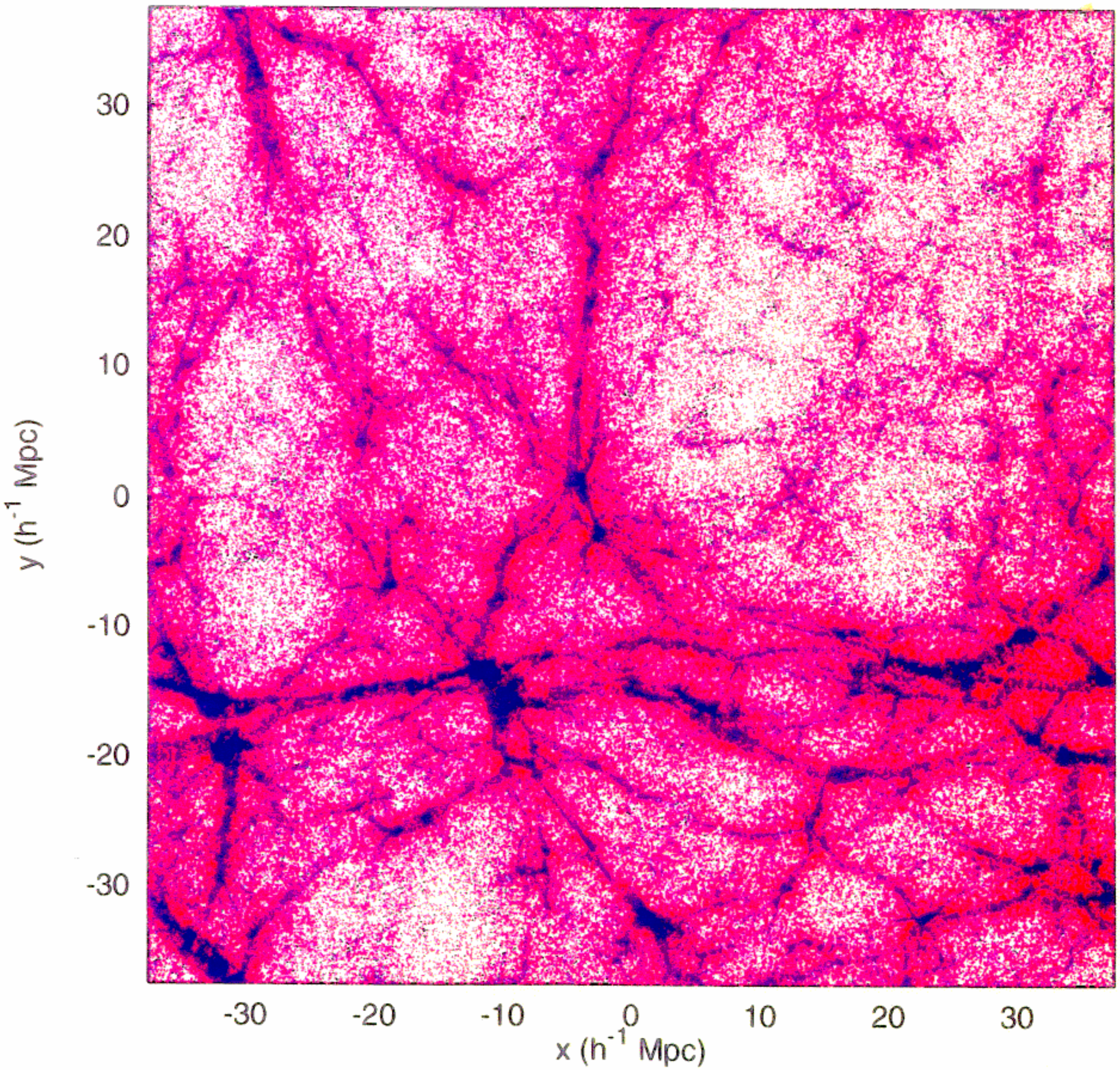
free streaming



Bottom→up

Top→down

0.5 h^{-1} Mpc slice of **CHDM** simulation, $z=0$



Gross

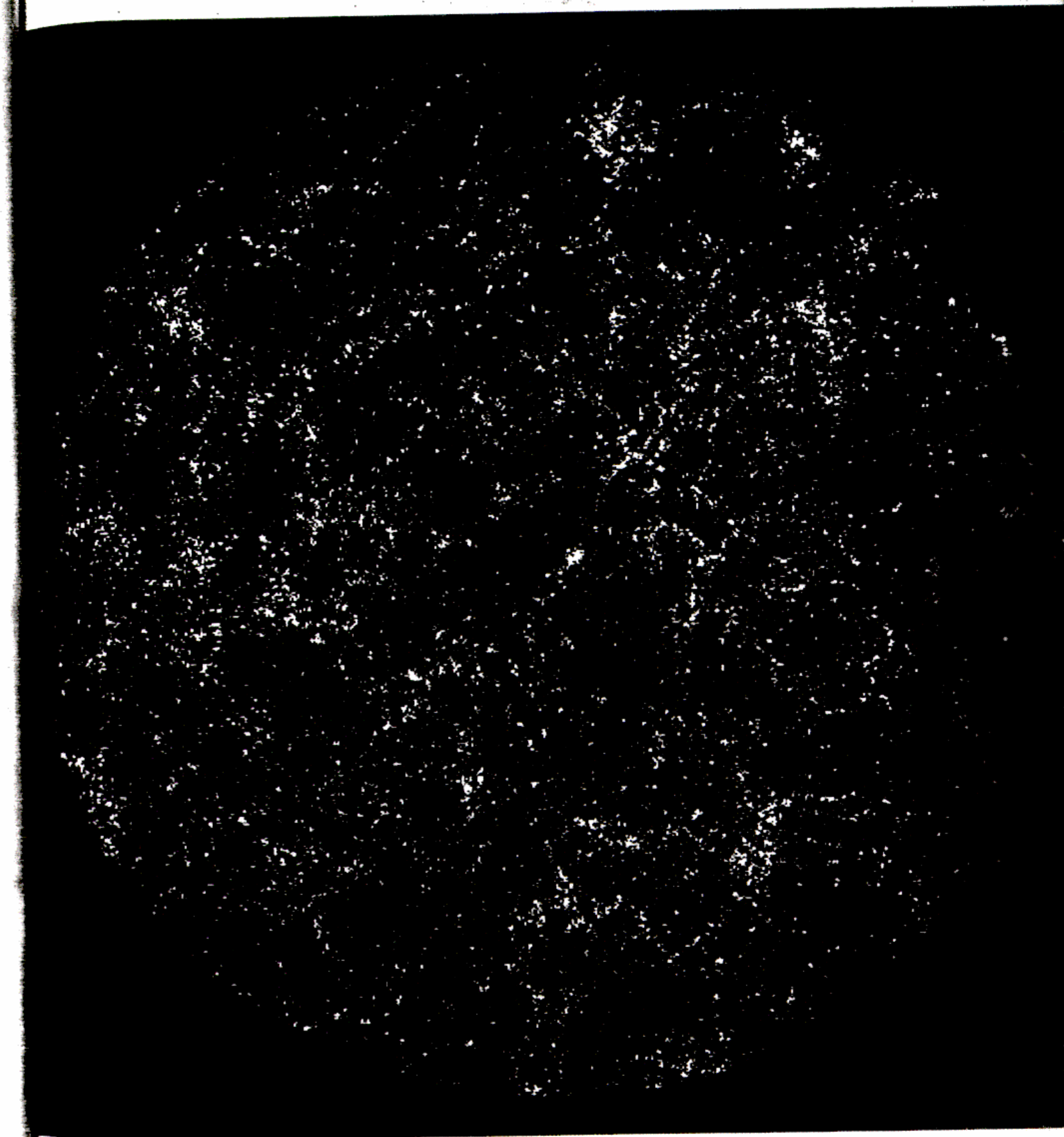


Figure 3.9. The Lick galaxy counts in a circle of radius 50° centered on the north galactic pole (Seldner et al. 1977).

IRAS (strauss, Davis, Yahil, Huchra 1990)

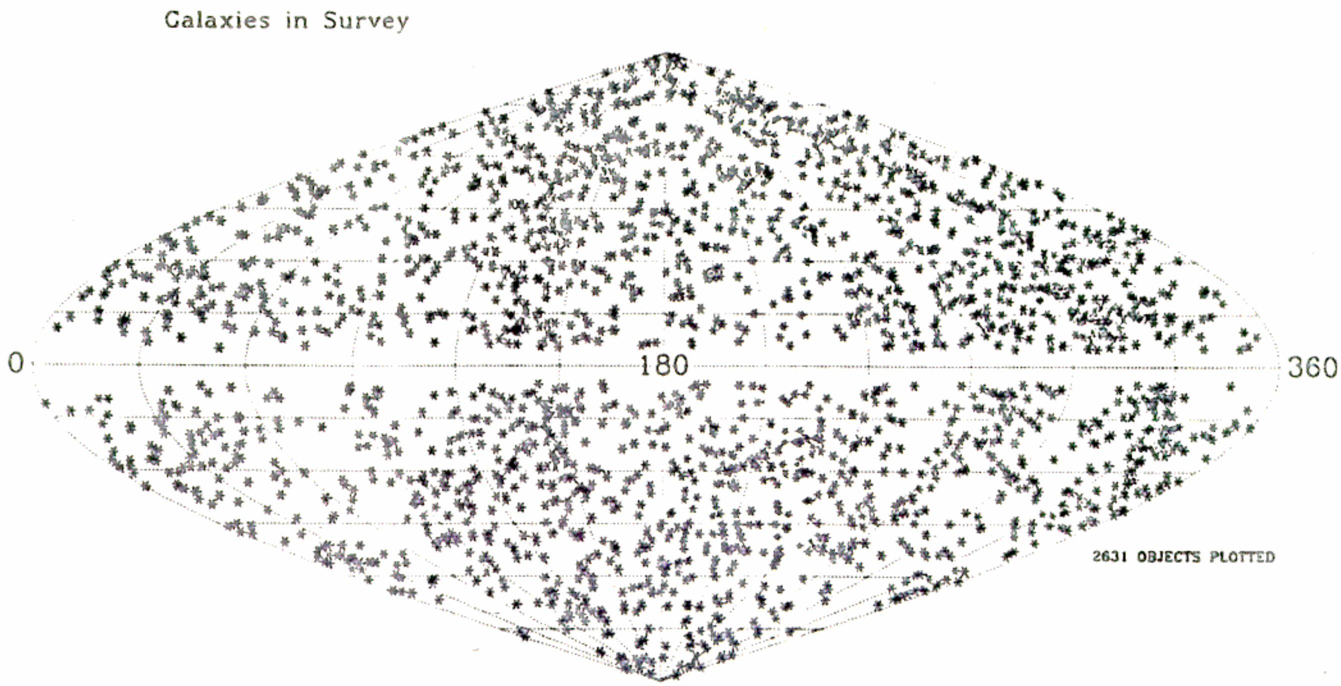


Fig. 16. The sky distribution of galaxies in the sample.

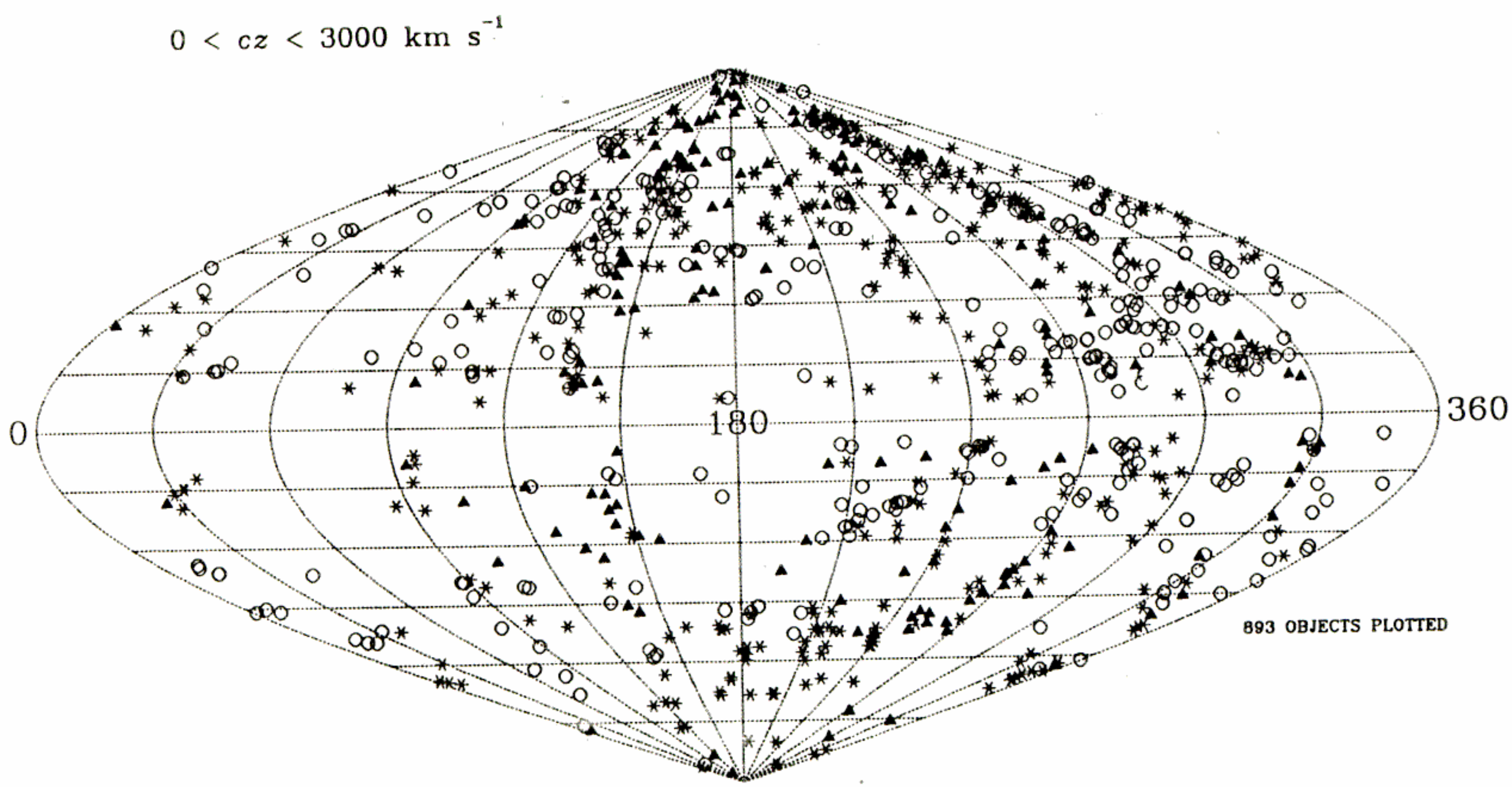


Fig 1a

$3000 < cz < 6000$ km s^{-1}

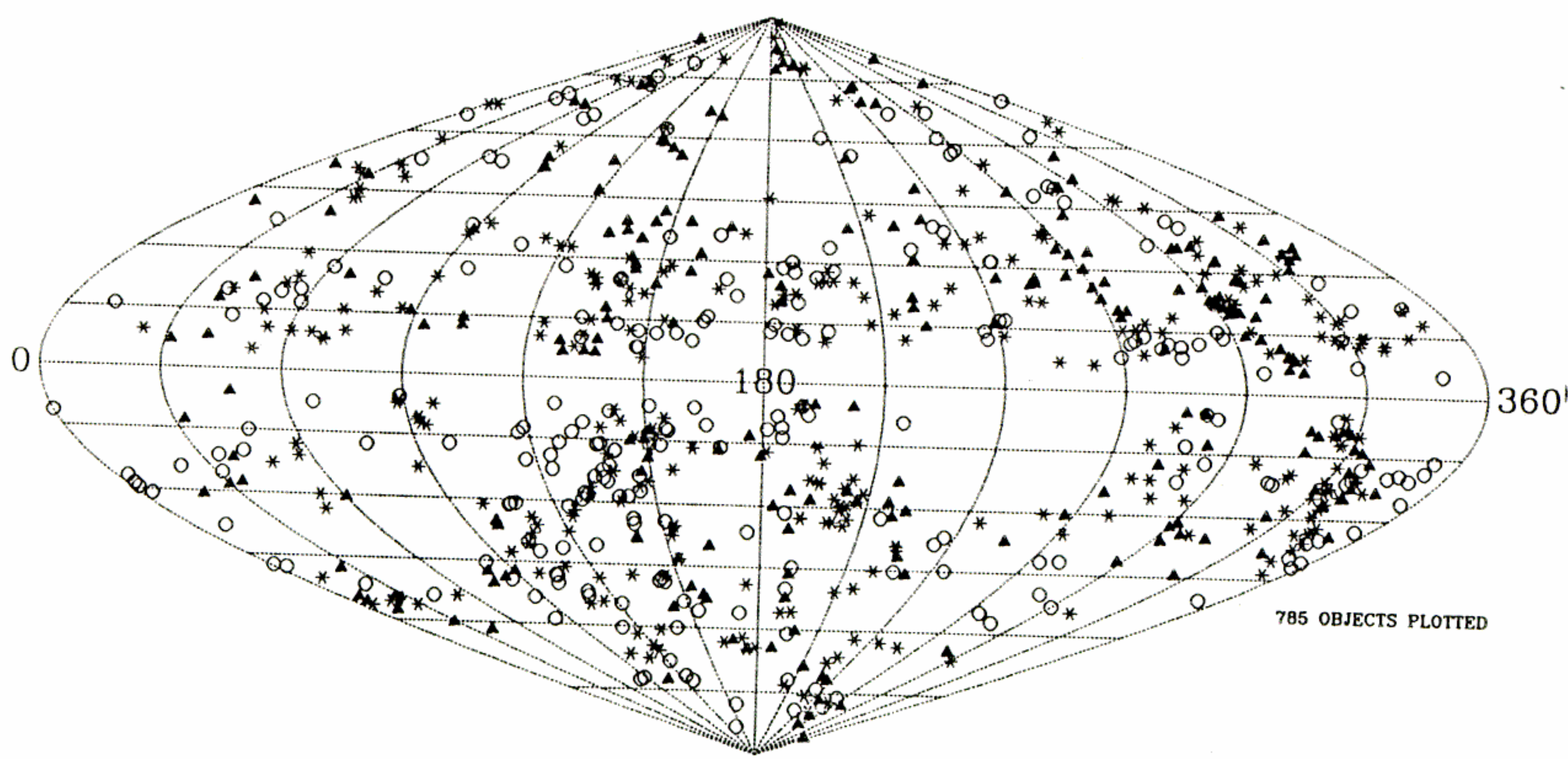


Fig 1b

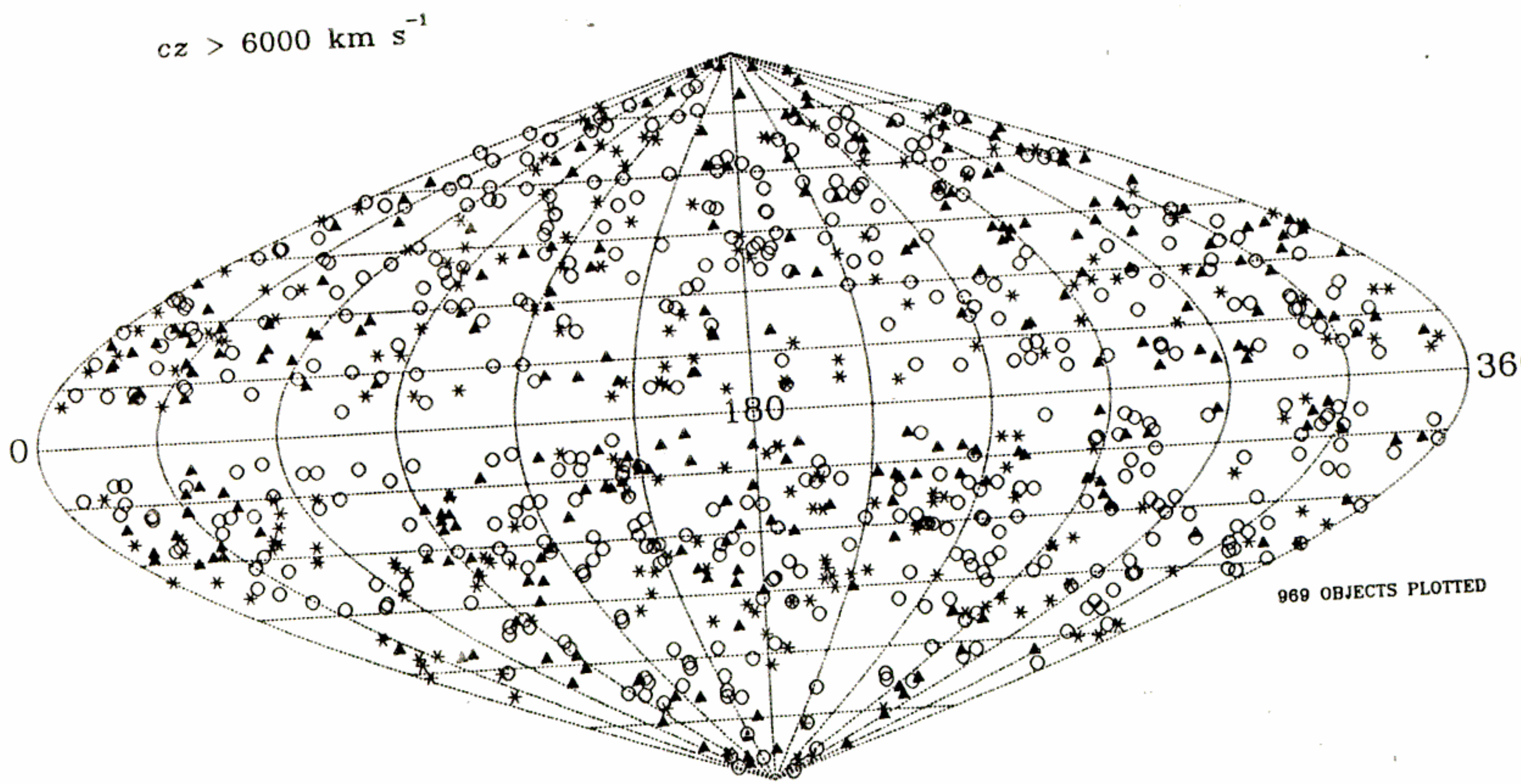
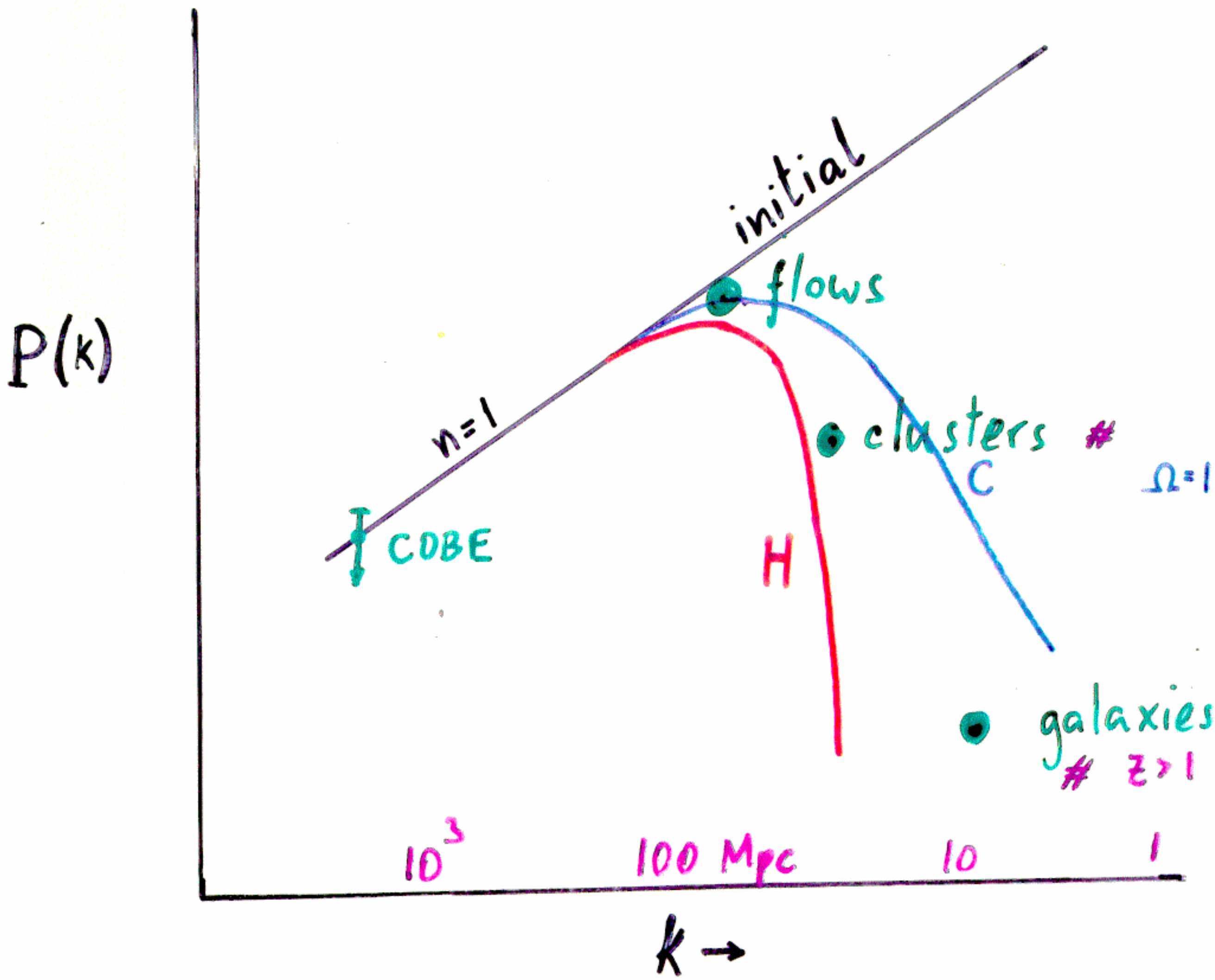
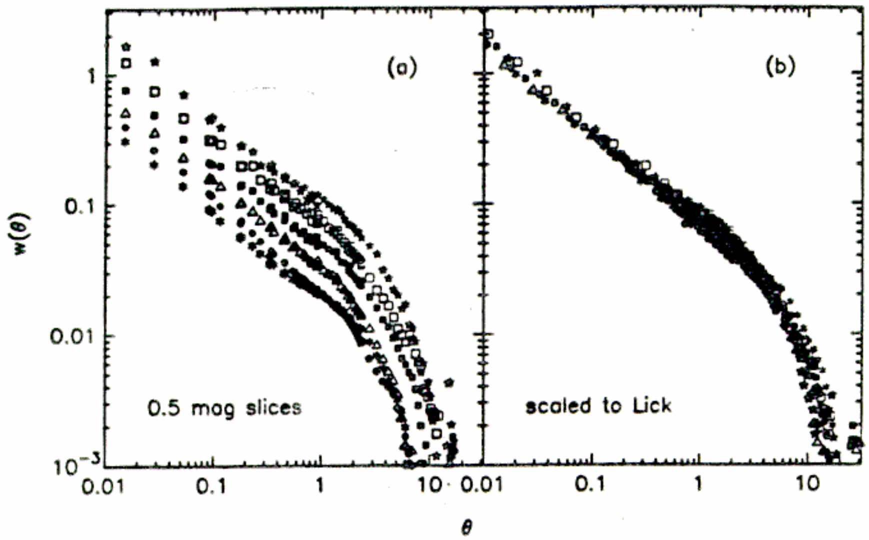
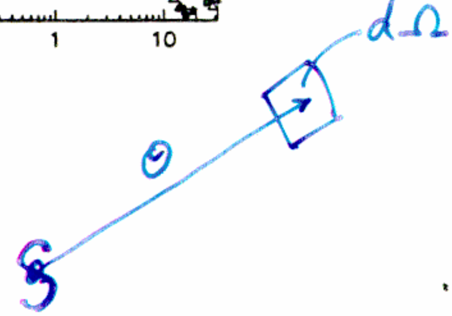


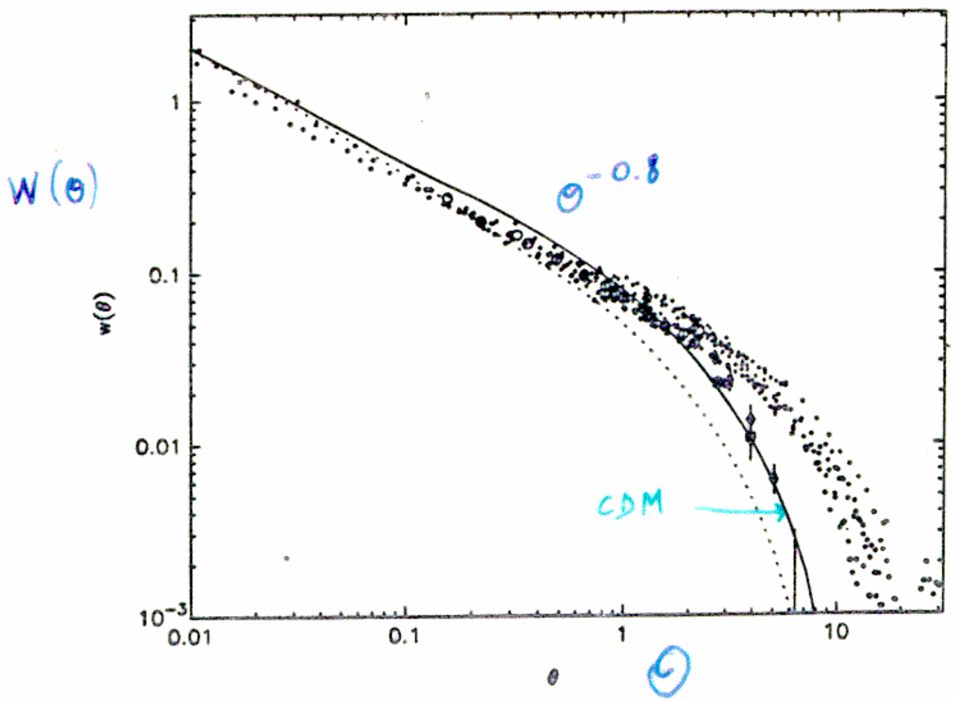
Fig 1c


P(k)
initial
flows
n=1
clusters
#
C
Ω=1
COBE
H
galaxies
z>1
10^3
100 Mpc
10
1
k →





$$d\Omega \cdot P(\theta) = [1 + w(\theta)] \cdot d\Omega \cdot \sigma$$



APM: Maddox, Efstathiou, Sutherland, Loveday '90

Mixed models that ~ work

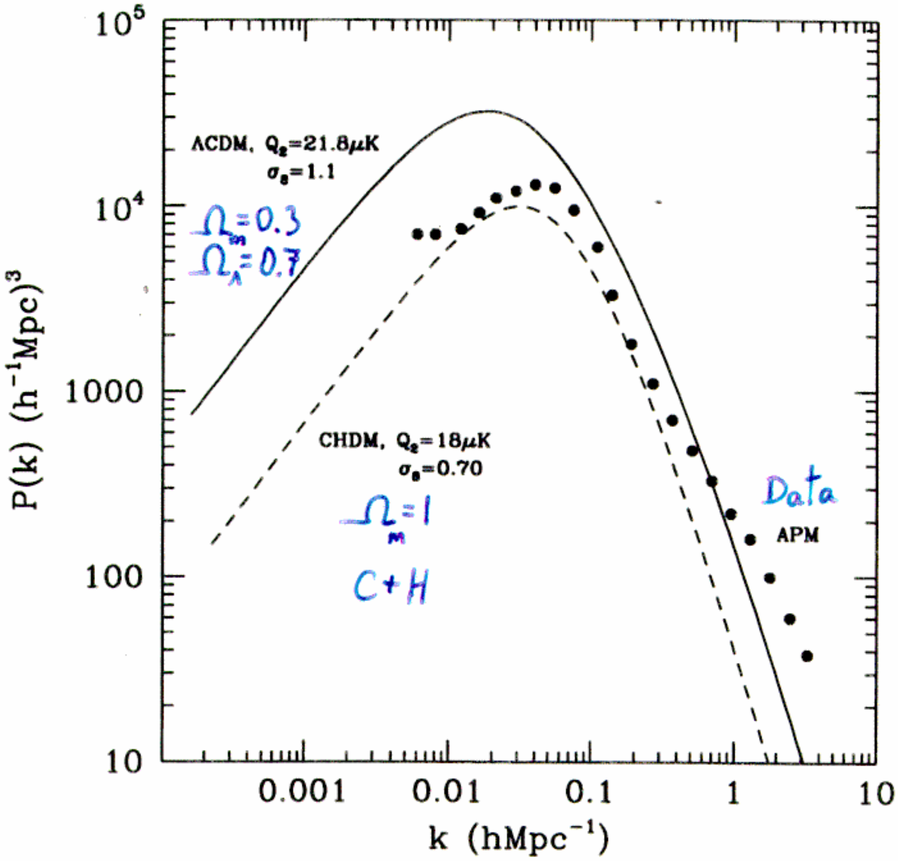
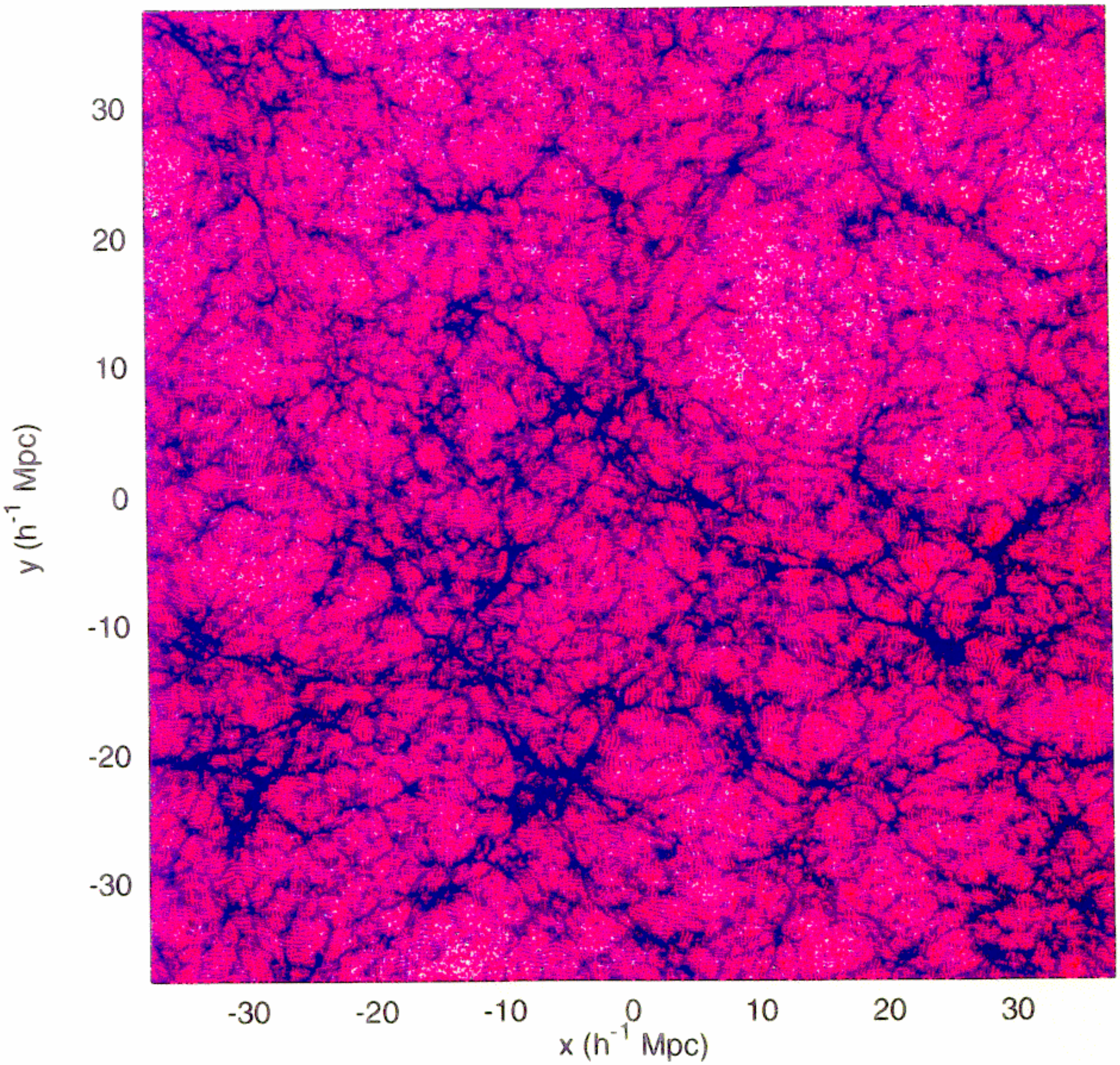
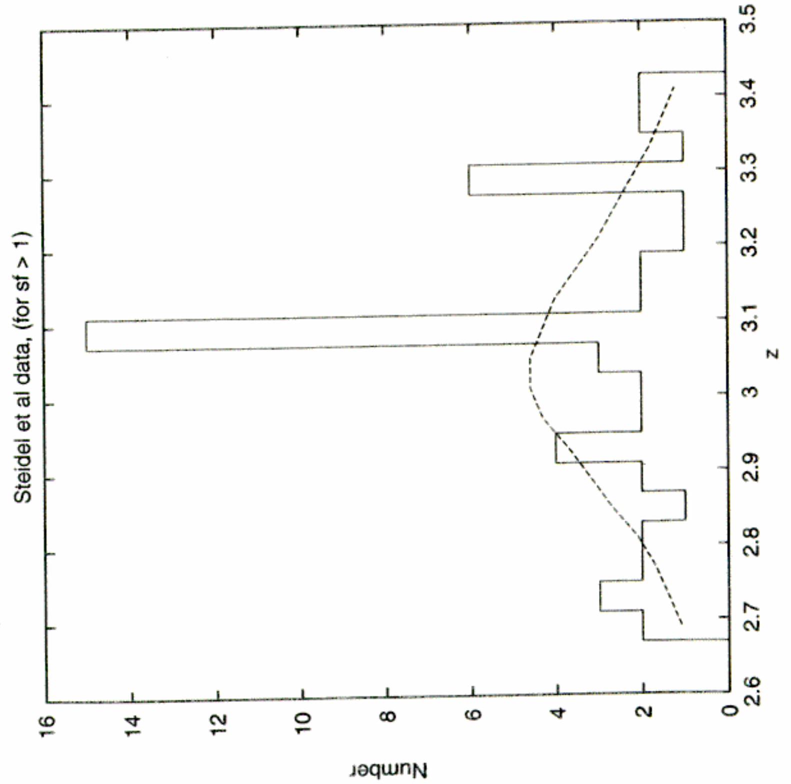
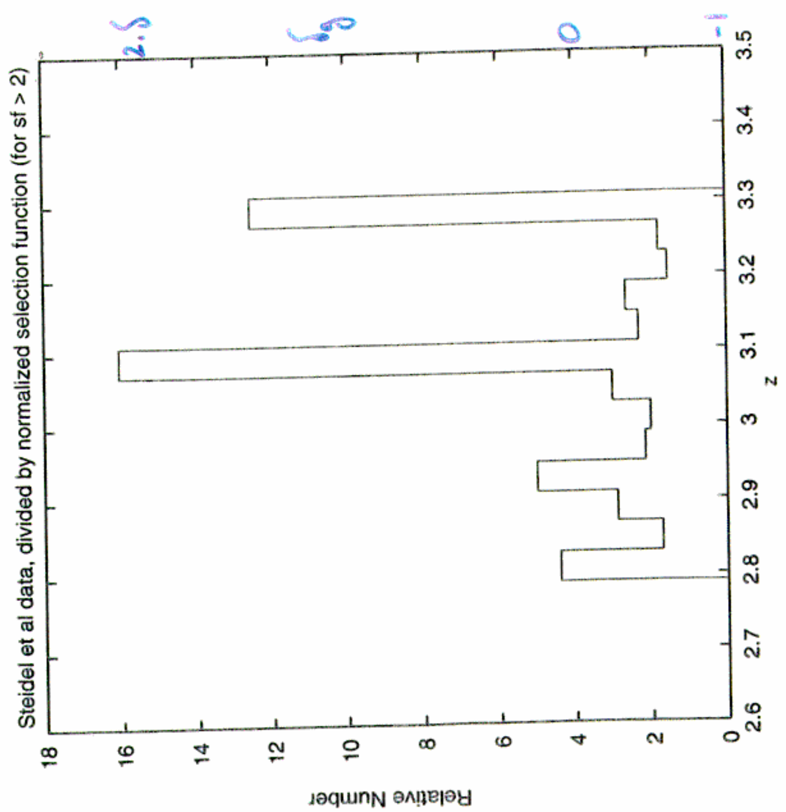


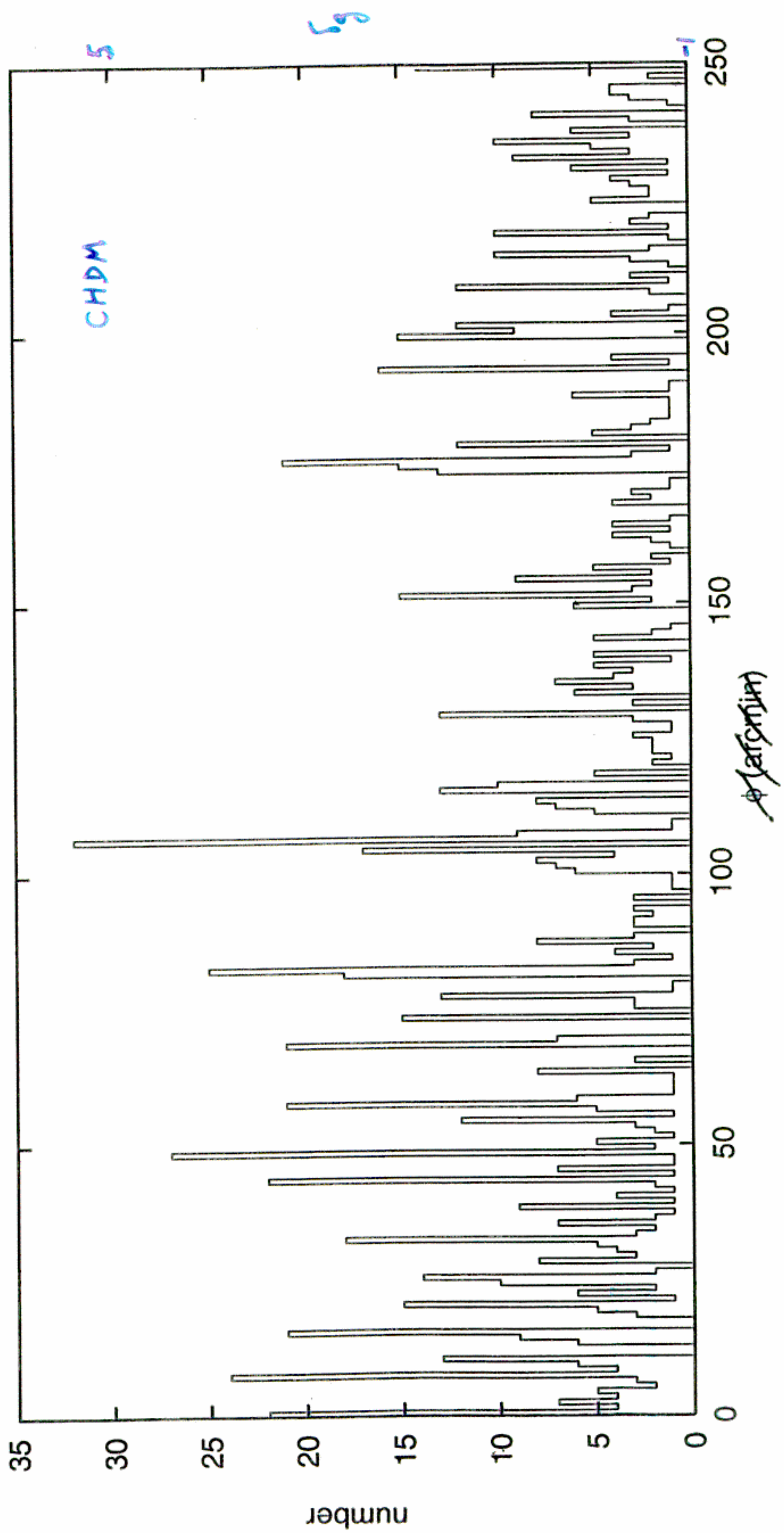
Fig. 1.8. Power spectrum of dark matter for ΛCDM and CHDM models considered here, both normalized to COBE, compared to the APM galaxy real-space power spectrum. (ΛCDM: $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, thus $t_0 = 13.4$ Gy; CHDM: $\Omega = 1$, $\Omega_\nu = 0.2$ in $N_\nu = 2$ ν species, $h = 0.5$, thus $t_0 = 13$ Gy; both models fit cluster abundance with no tilt, i.e., $n_p = 1$. (From Primack & Klypin 1996.)

0.5 h^{-1} Mpc slice of CHDM simulation, $z = 2.7$




Steidel et al data, (for sf > 1)
Number
z
0
2
4
6
8
10
12
14
16
2.6
2.7
2.8
2.9
3
3.1
3.2
3.3
3.4
3.5


Steidel et al data, divided by normalized selection function (for sf > 2)
Relative Number
z
0
2
4
6
8
10
12
14
16
18
2.6
2.7
2.8
2.9
3
3.1
3.2
3.3
3.4
3.5

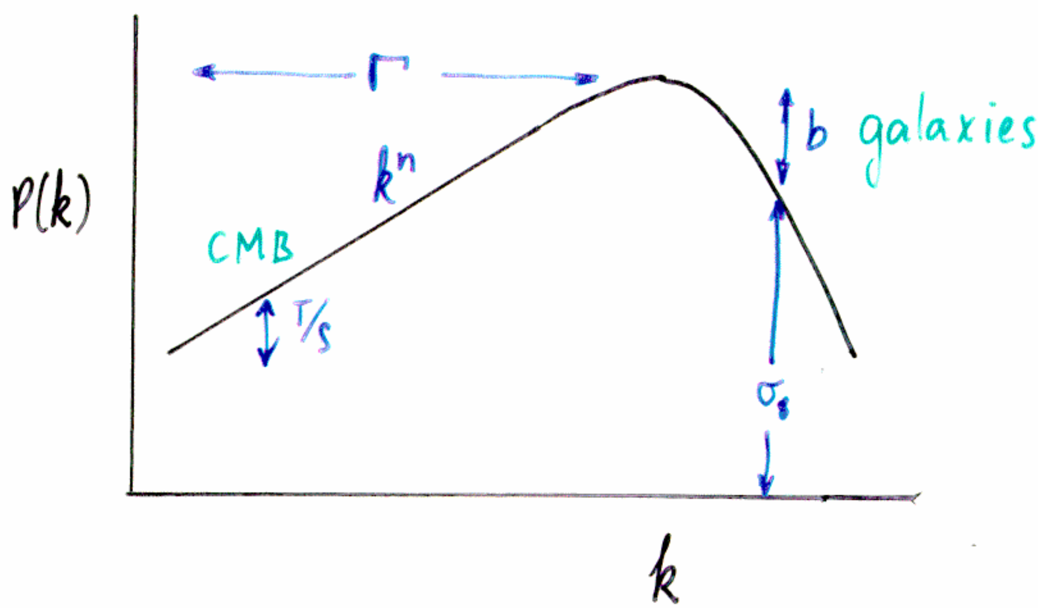

CHDM
number
0
5
10
15
20
25
30
35
0
50
100
150
200
250

Cosmological Parameters

- $\Omega_m \quad \Omega_\Lambda \quad H_0$ — bound/unb.
  - $\Omega_{tot} = \Omega_m + \Omega_\Lambda \qquad \Omega_k = 1 - \Omega_{tot}$ — open/closed
  - $q_0 = \frac{1}{2}\Omega_m - \Omega_\Lambda$ — deceleration
  - $t_0 H_0 = f(\Omega_m, \Omega_\Lambda)$

- $\Omega_m = \Omega_b + \Omega_c + \Omega_\nu + \ldots$

- Fluctuations: n, T/S, Γ, σ_8, b, ...



	Ω	Λ	Ω_ν	Ω_b	n	h	t_0
SCDM	1	0	0	0.01	1	50	
TCDM	1	0	0	0.01	0.8	50	
ΛCDM	0.4	0.6	0	0.01	1	75	
OCDM	0.4	0	0	0.01	1	>75	
CHDM	1	0	0.2	0.01	1	50	
strings+HDM	1	0	1	0.01	1	50	
PIB	0.1	0.9	0	0.01	2	75	

SVD
(Something Very Different)

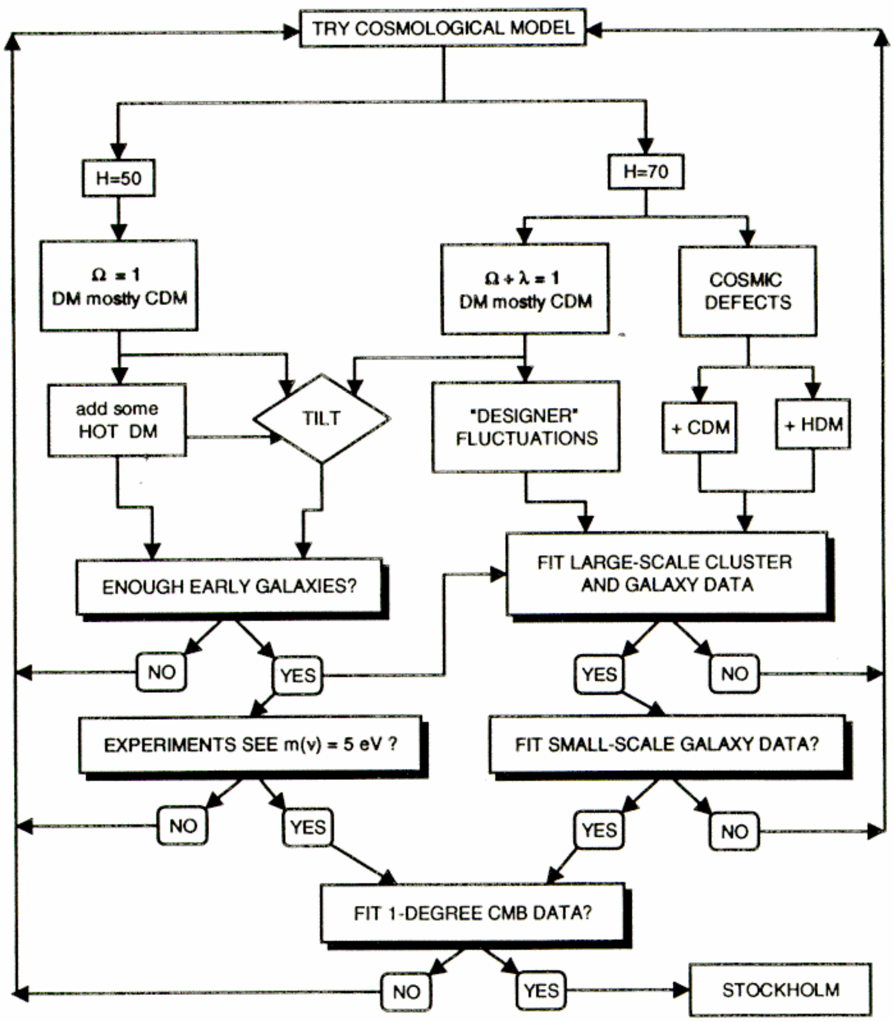
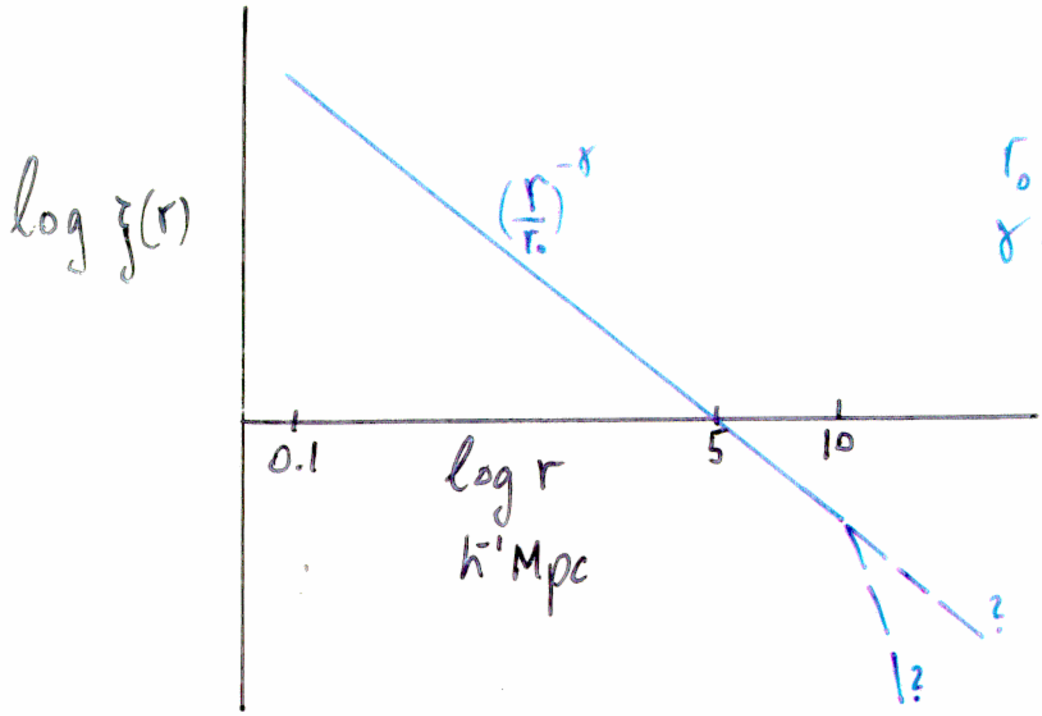


Fig. 1.3. Building a Cosmological Model. (This figure was inspired by similar flow-charts on inventing dark matter candidates, by David Weinberg and friends, and by Rocky Kolb.)

• Galaxy-Galaxy Correlation Function

$$P(r)\,dV = [1 + \xi(r)]\,n\,dV$$

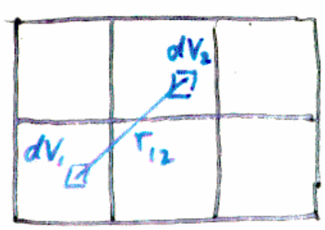


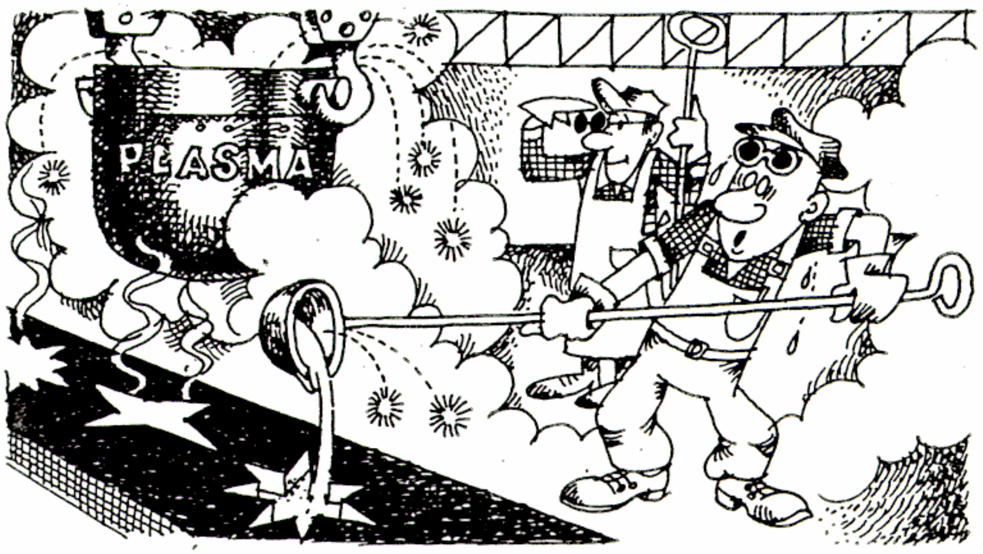
$r_0 \sim 5\ h^{-1}\mathrm{Mpc}$

$\gamma \sim 1.8$

• Counts in Cells

$$\sigma^2(V) = \frac{1}{V^2}\int_V \xi(r_{12})\,dV_1\,dV_2$$





3: The hot Universe

Physics of the initial stage of expansion

The preceding chapters introduced the reader to the mechanics of the expansion of the Universe. Actually, mechanics is not the only aspect of interest. A great number of processes took place in the Universe at its early moments. We know that at the instant of the Big Bang, 15 billion years ago, the density of matter in the Universe was tremendously high. Hence, the physical processes at that stage were quite dissimilar to those we observe now. These past processes predetermined the current state of the world and, among other things, contained the possibility for the appearance of life.

The physics of processes at the outset of expansion is the focus of extreme attention. However, are we really able to say anything about these processes? This is a legitimate question since we mean the very first moment of expansion, and that moment was 15 billion years ago.

In fact, we really *are* able to infer some things.

The point is that the process during the first seconds of the Big Bang had such important consequences for today's Universe and left 'traces' so obvious, that the processes themselves can be reconstructed.

The most important among them were nuclear reactions among elementary particles, occurring at very high particle densities. Such

Dekel & Shaham 1979

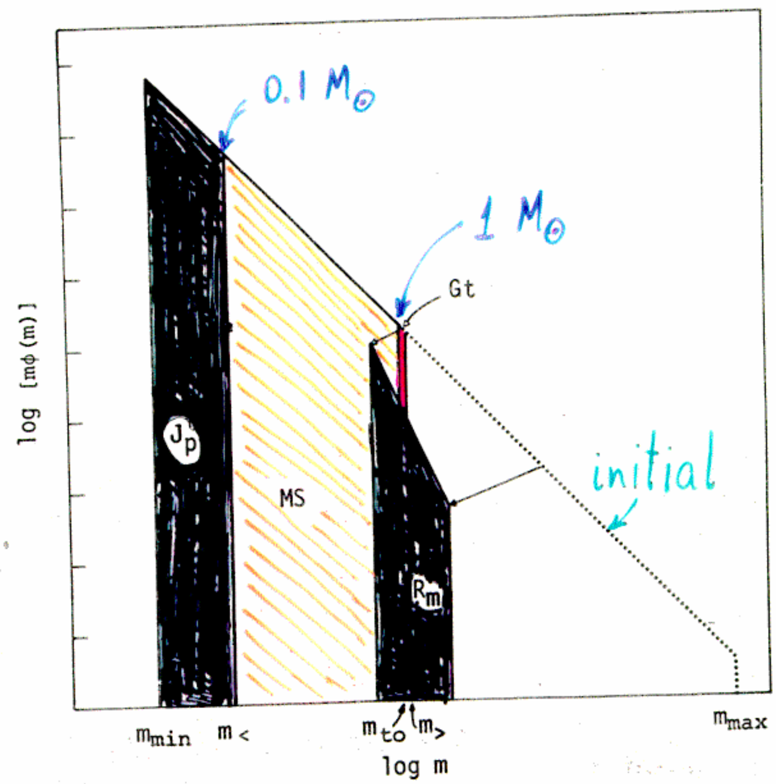
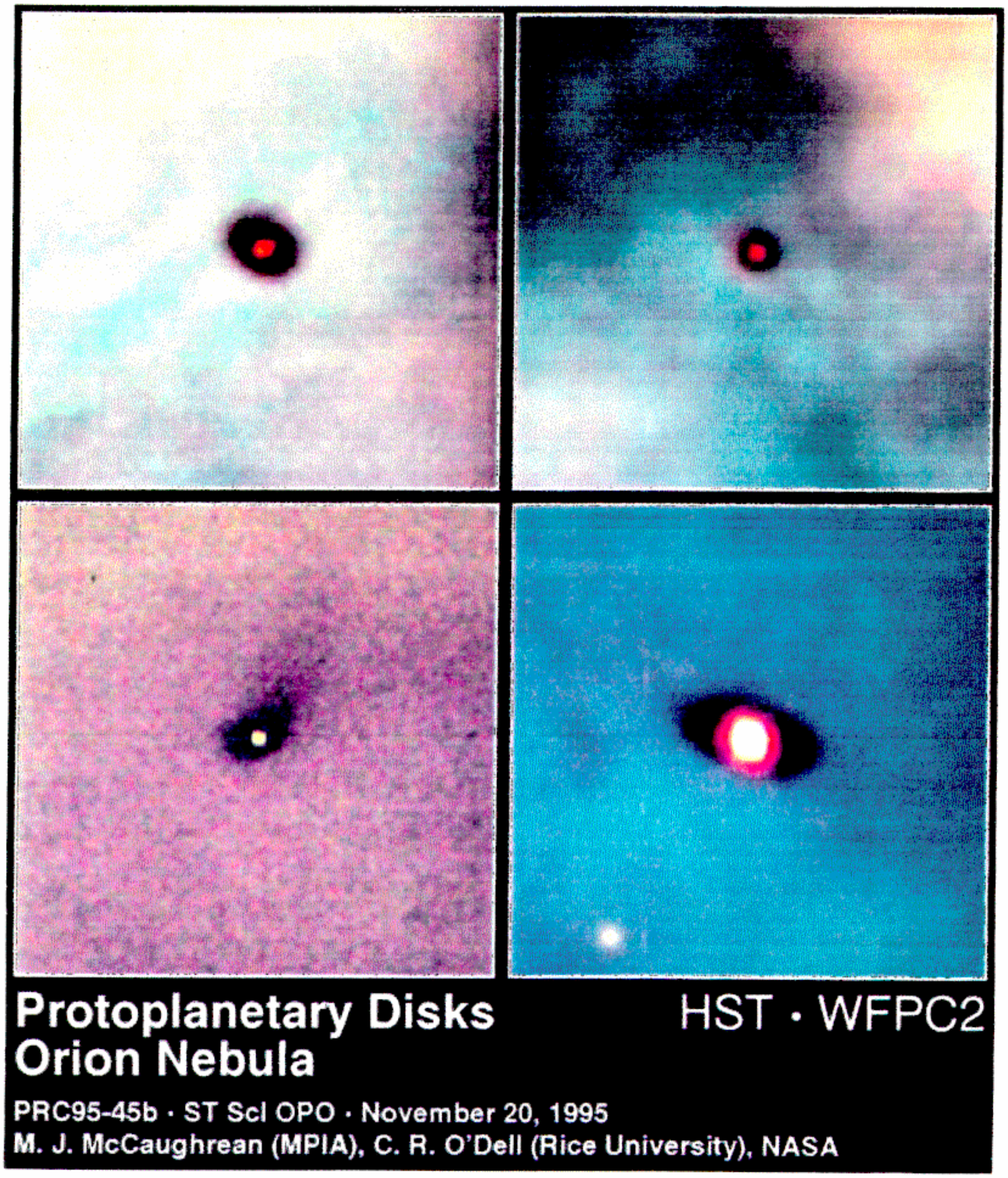
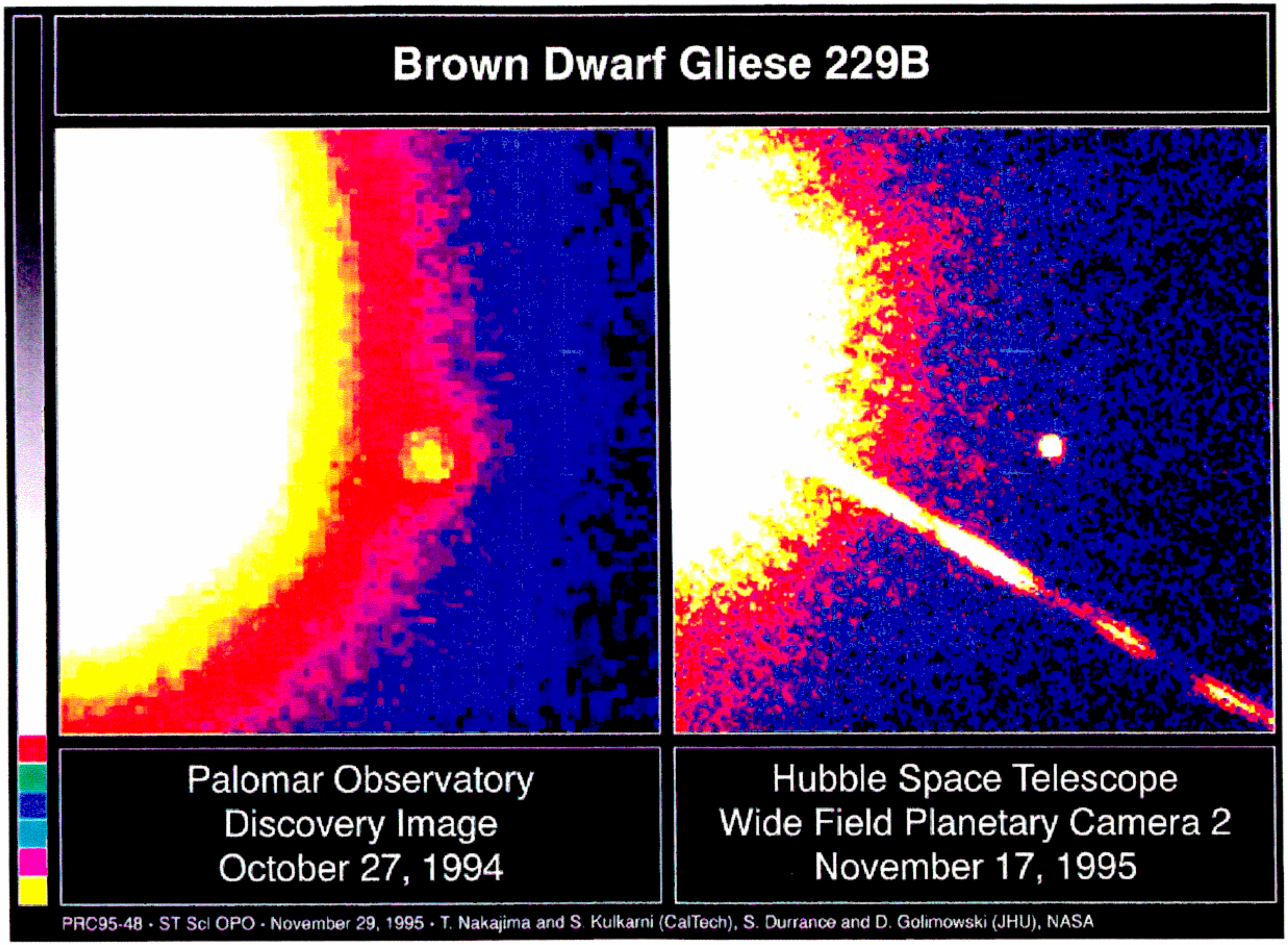
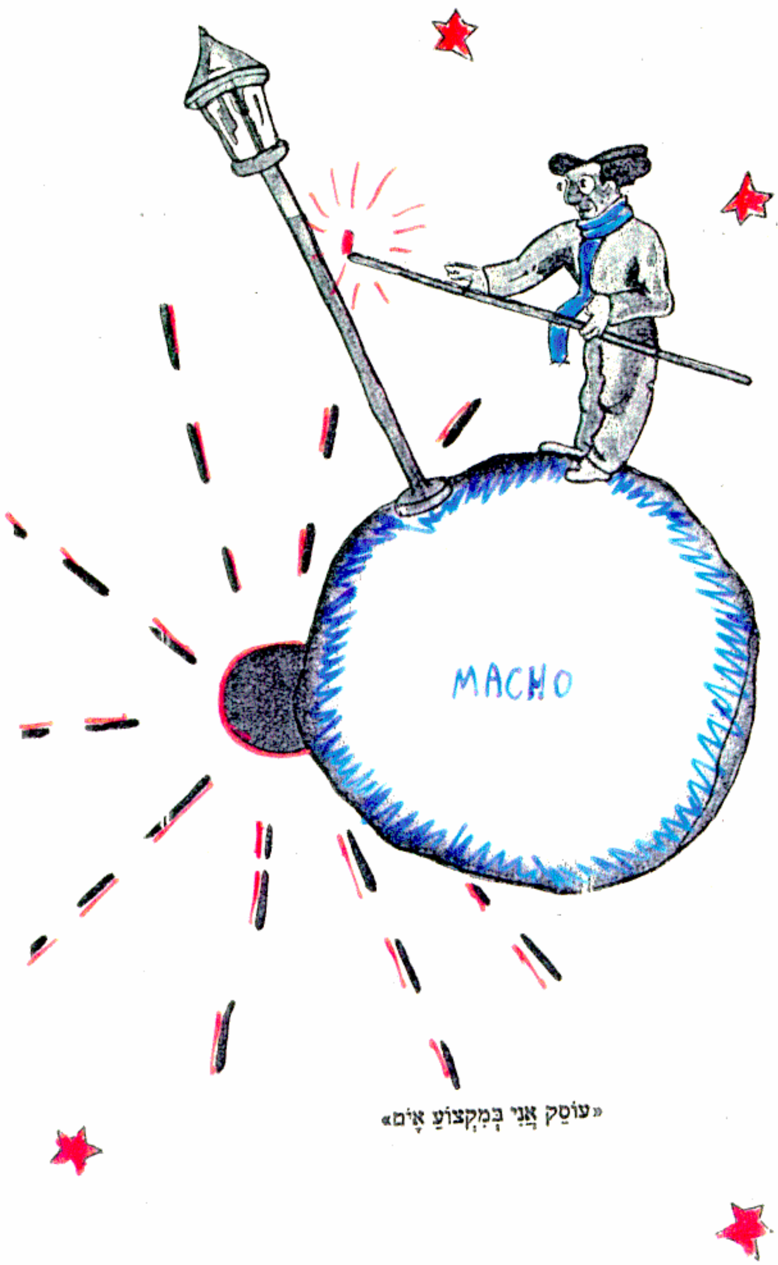


Fig. 3. *The model mass function* at a given radius, divided into four classes, namely: Jupiters (Jp), main-sequence stars (MS), red giants (*Gt*) and dead-remnants (*Rm*). $\phi(m)$ is the number density of stars per unit mass, having the form $\phi(m) \propto m^{-n}$. For the various notations see text. The dashed line correspond to heavy stars of the original population before they have shed their envelope and left as dead remnants. The parameters chosen for this figure are: $n=3.5$, $m_{\min}=0.03\ M_\odot$, $m_<=0.08\ M_\odot$, $m_{t0}=0.790\ M_\odot$, $m_>=0.805\ M_\odot$, and $m_{\max}=60\ M_\odot$. Ordinate divisions represent logarithm differences of unity

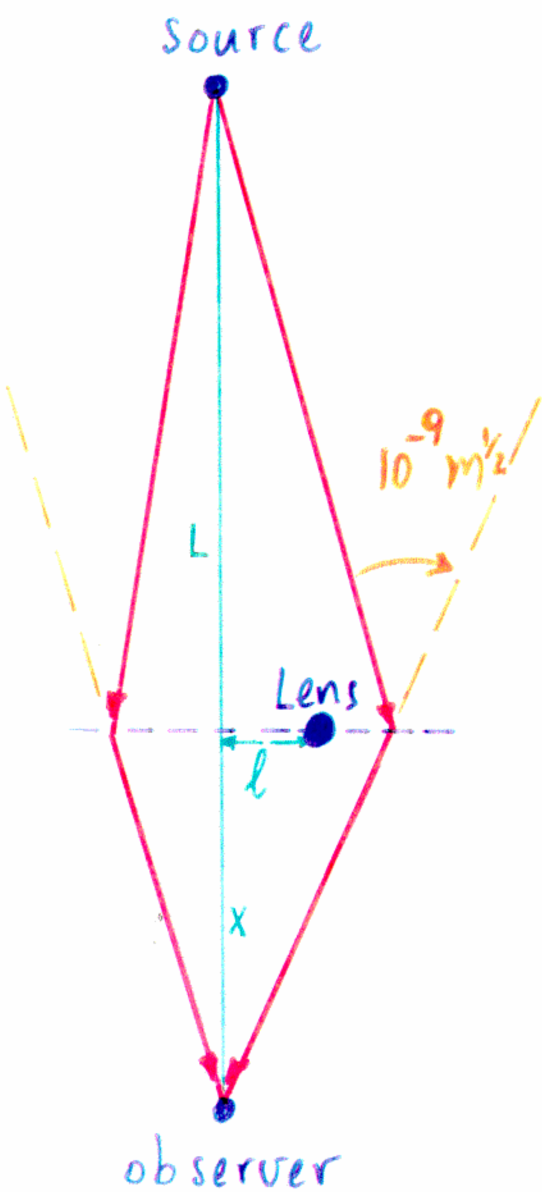

Protoplanetary Disks
Orion Nebula
HST • WFPC2
PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

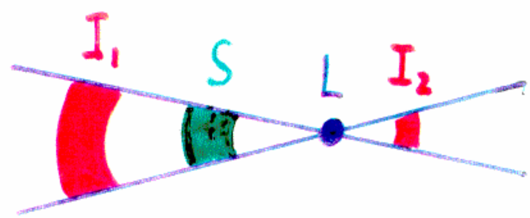

Brown Dwarf Gliese 229B
Palomar Observatory
Discovery Image
October 27, 1994
Hubble Space Telescope
Wide Field Planetary Camera 2
November 17, 1995
PRC95-48 · ST ScI OPO · November 29, 1995 · T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA



«עוֹסֵק אֲנִי בְּמִקְצוֹעַ אָיֹם»

Microlensing → Amplification

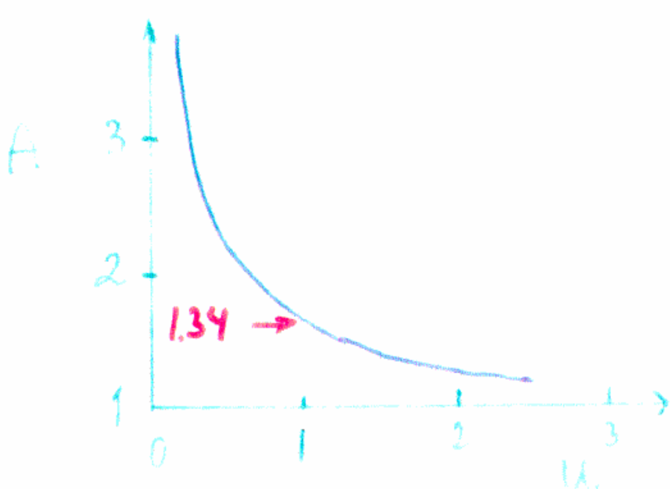




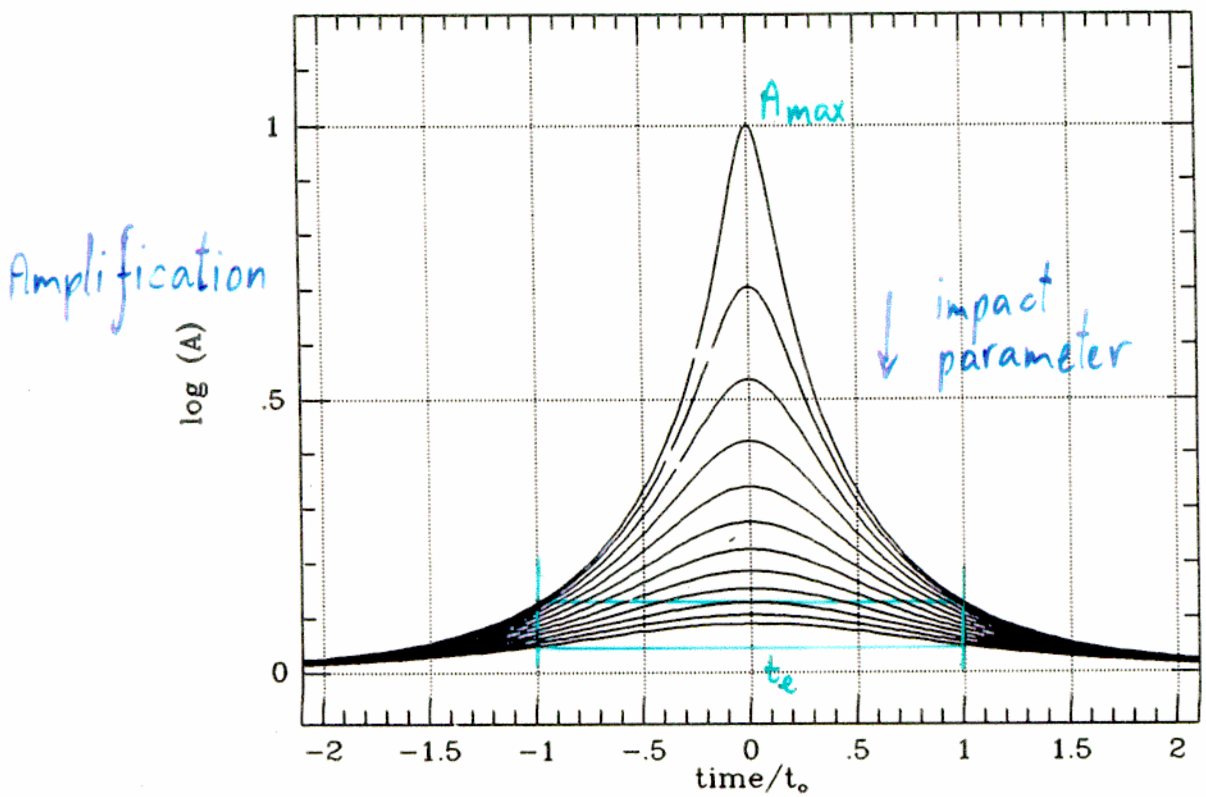
$$R_E^2 = \frac{4G}{c^2}\, m\, L\, x(1-x)$$

Impact p. $u \equiv \ell / R_E$

$$A = \frac{u^2+2}{u\,(u^2+4)^{1/2}}$$



Light Curve A(t)

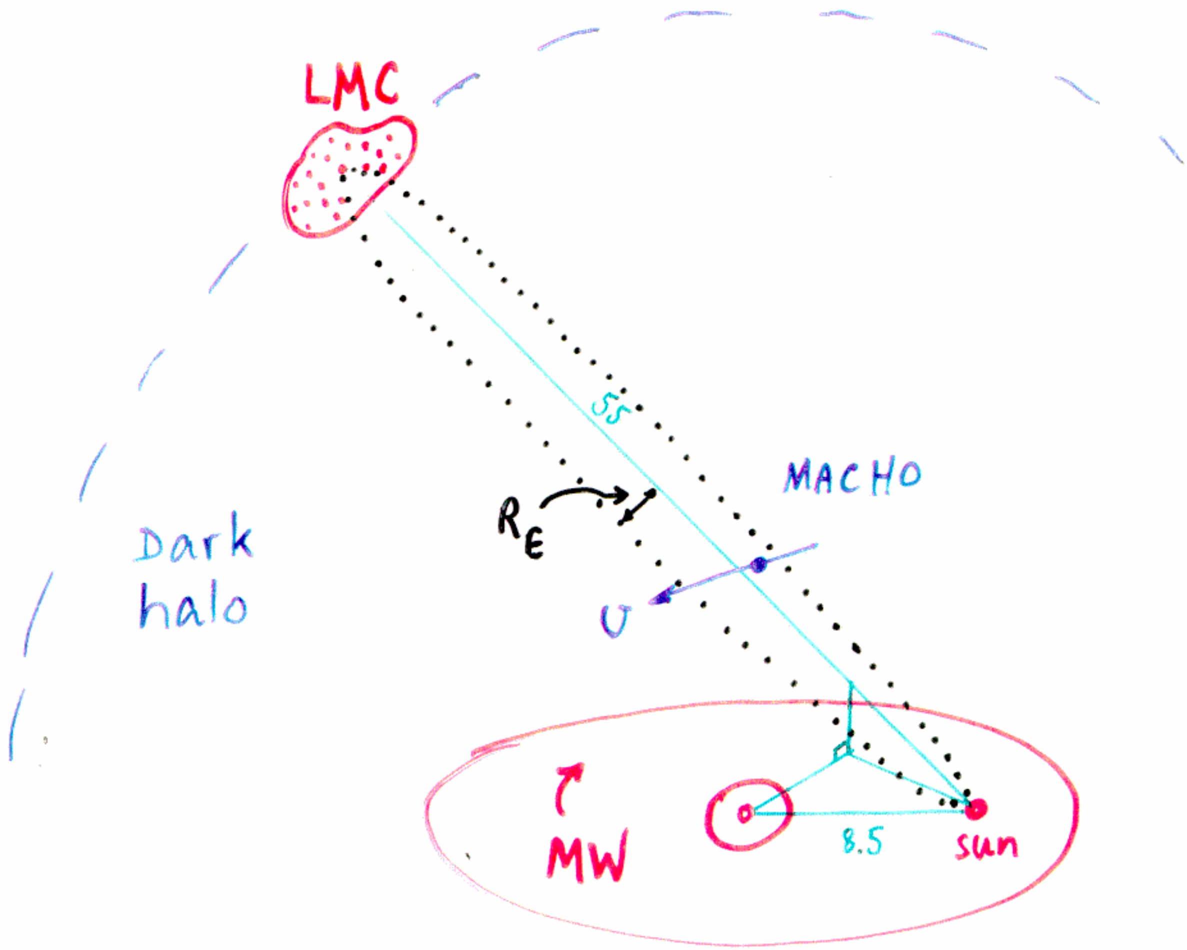


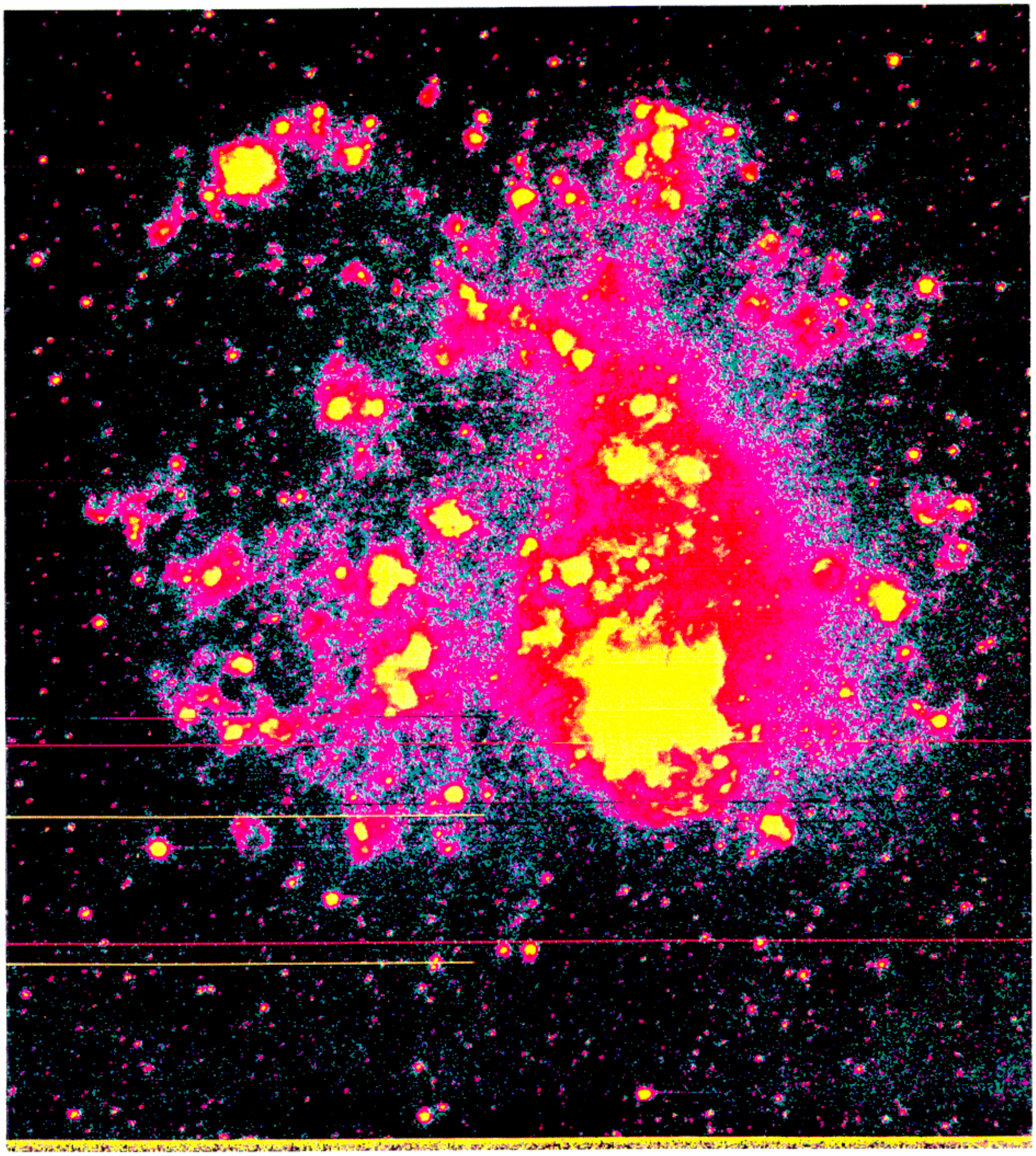
$t_0 = R_E/v$

FIG. 2.—Time variation of the amplification due to gravitational microlensing for events with the impact parameter d/R_0 equal 0.1, 0.2, . . . , 1.1, 1.2. The largest amplitude corresponds to the smallest impact parameter. The unit of time is given as $t_0 \equiv R_0/v$, where R_0 is the radius of ringlike image formed when the source, the lensing mass, and the observer are perfectly aligned (see eq. [2] and [16]) and v is the relative tangential velocity of the lensing object.

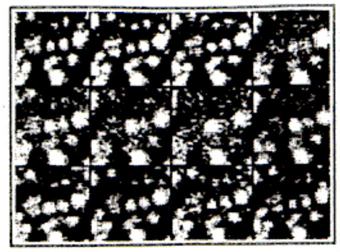
- Symmetric
- Achromatic
- 2 parameters
- distribution
- All types of *

MACHO Experiment

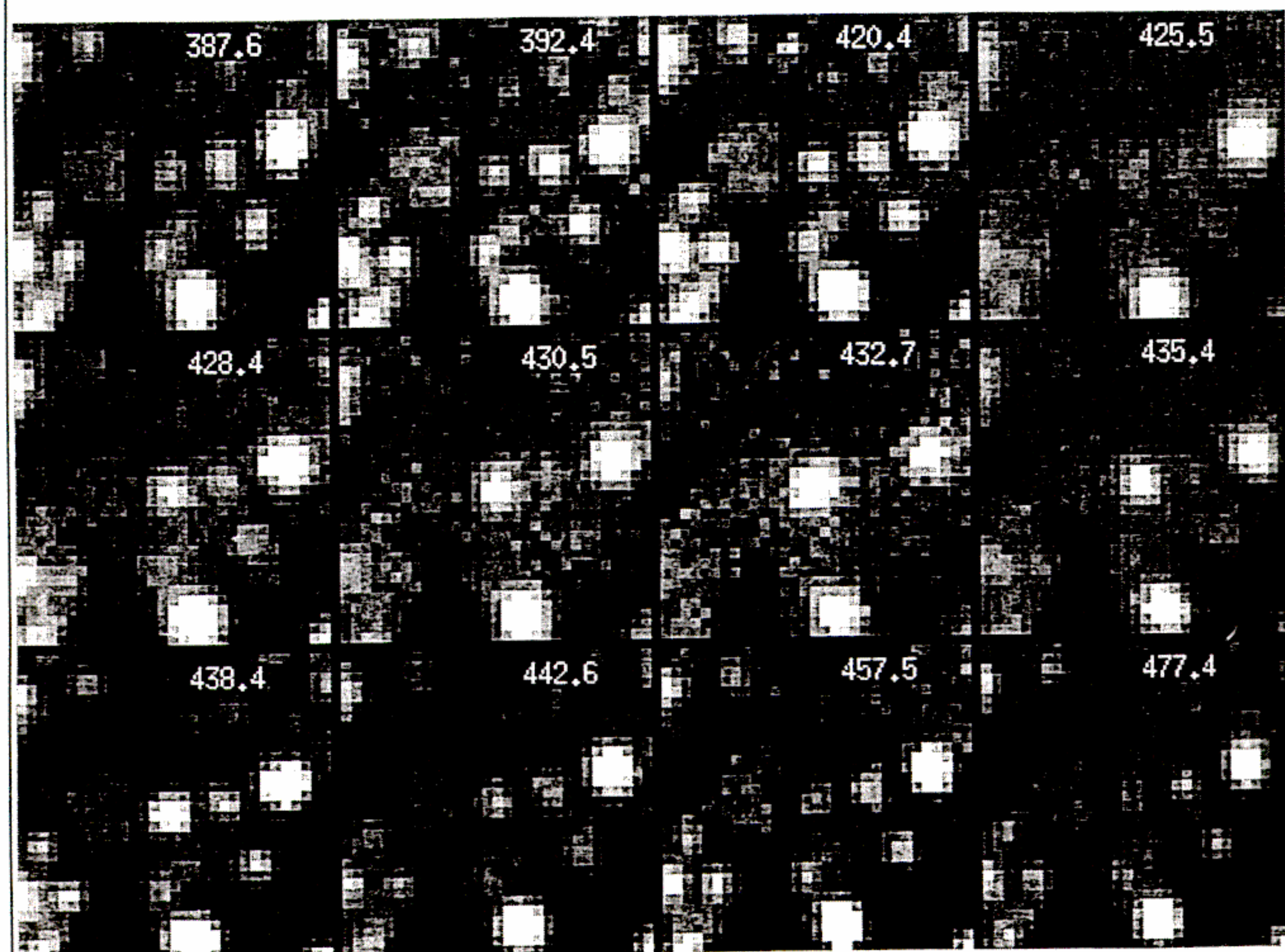




file: test4.fit
dir: /macho21/macho/stuart

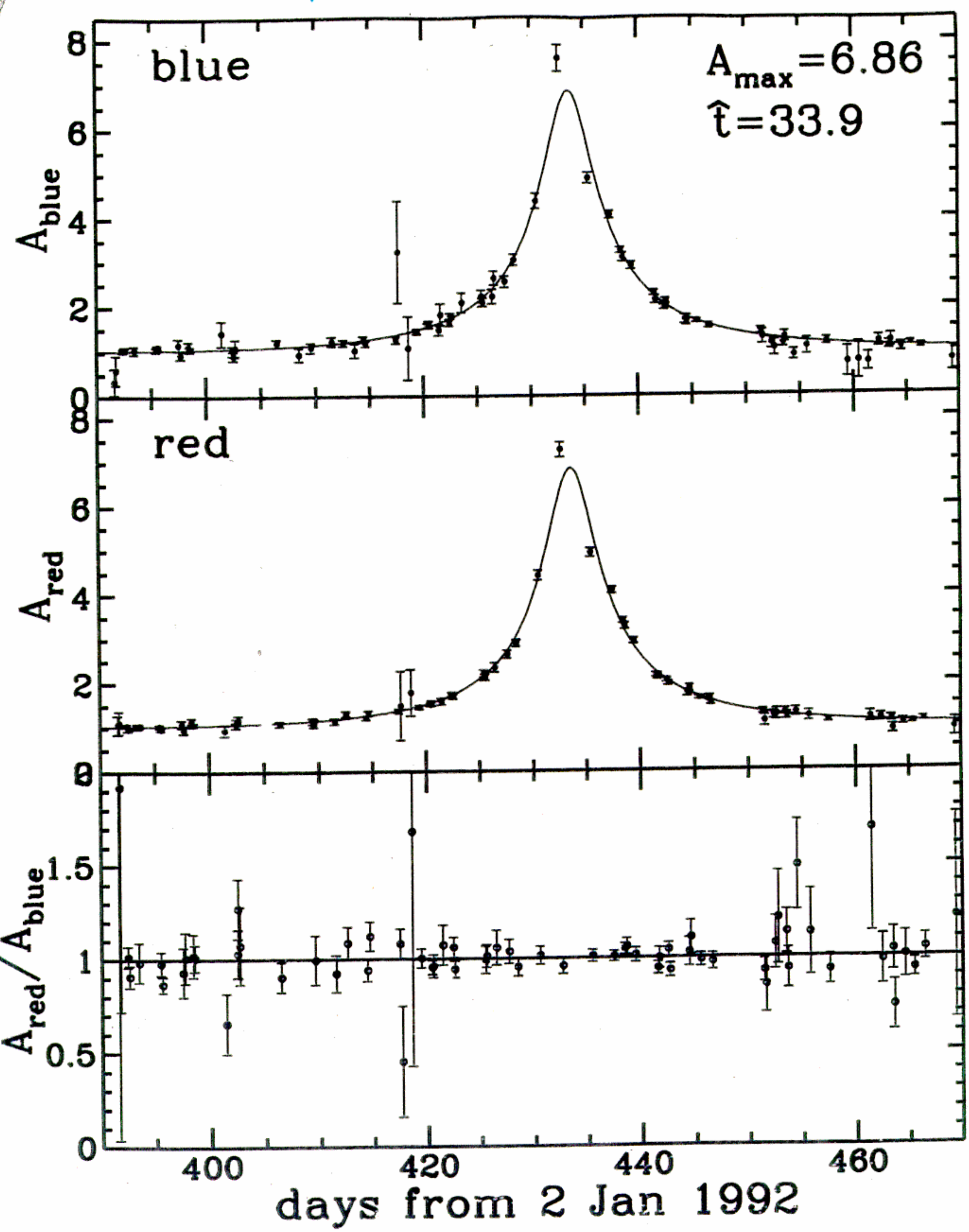


85.5 112.0 x



MACHO Collaboration

Massive Astrophysical Compact Halo Object = MACHO



Experience de Recherche d'Objets Sombres = EROS

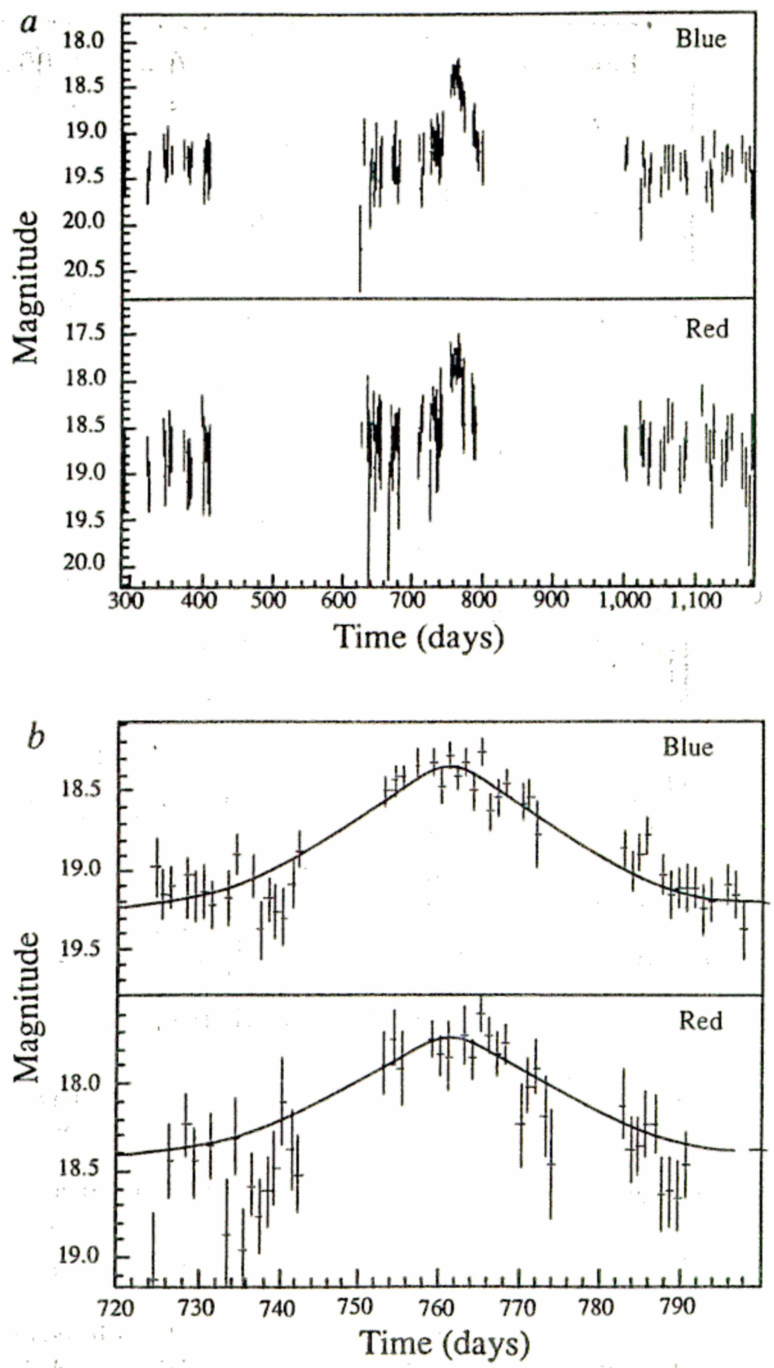


FIG. 1 *a*, The measured magnitudes for candidate 1 as a function of time. The time is counted from 1 January 1990. The error bars correspond to the estimated 1σ errors. *b*, The light-curve of candidate 1 on an expanded scale. The curve shows the best fit for the microlensing hypothesis. The parameters of the best fit are shown in Table 1.

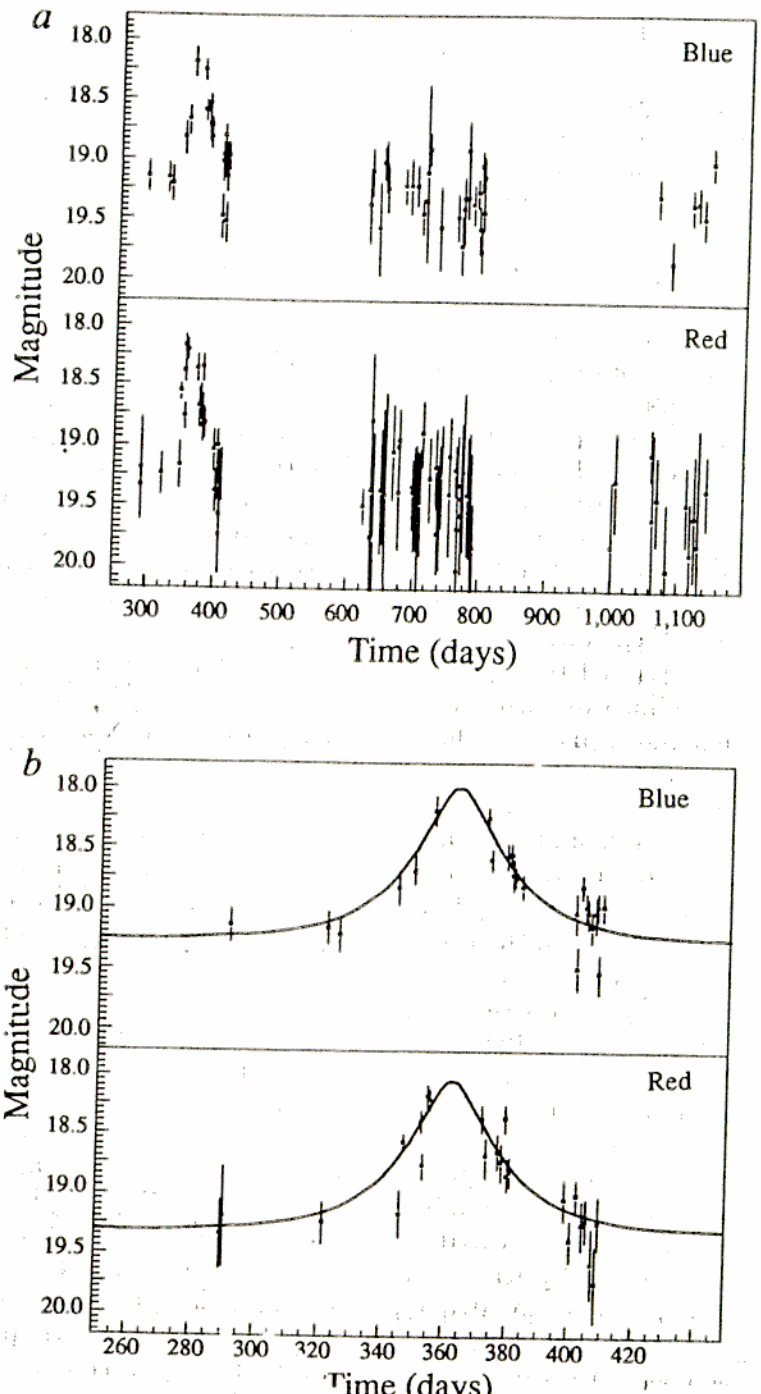


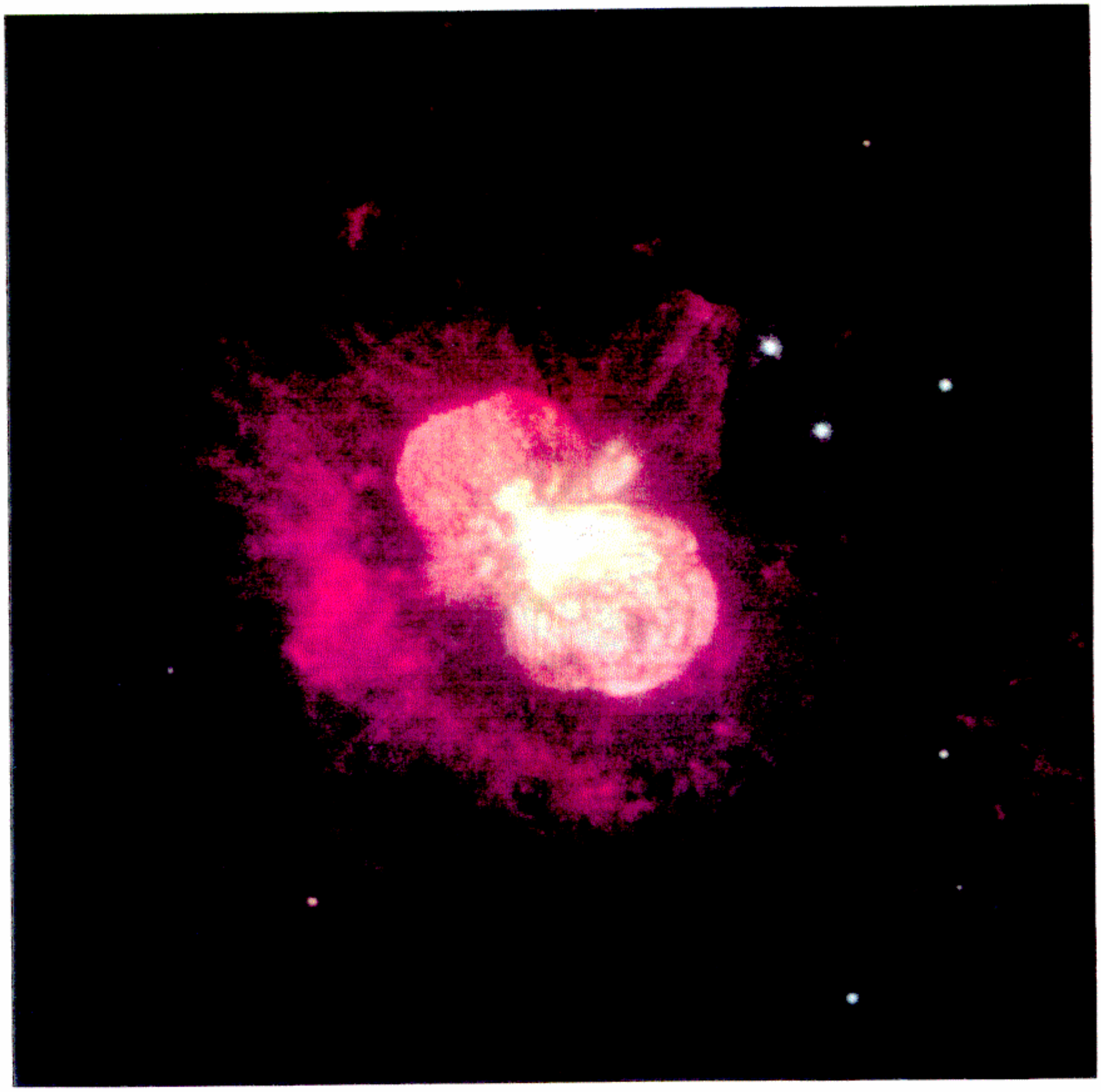
FIG. 2 As Fig. 1, for candidate 2.

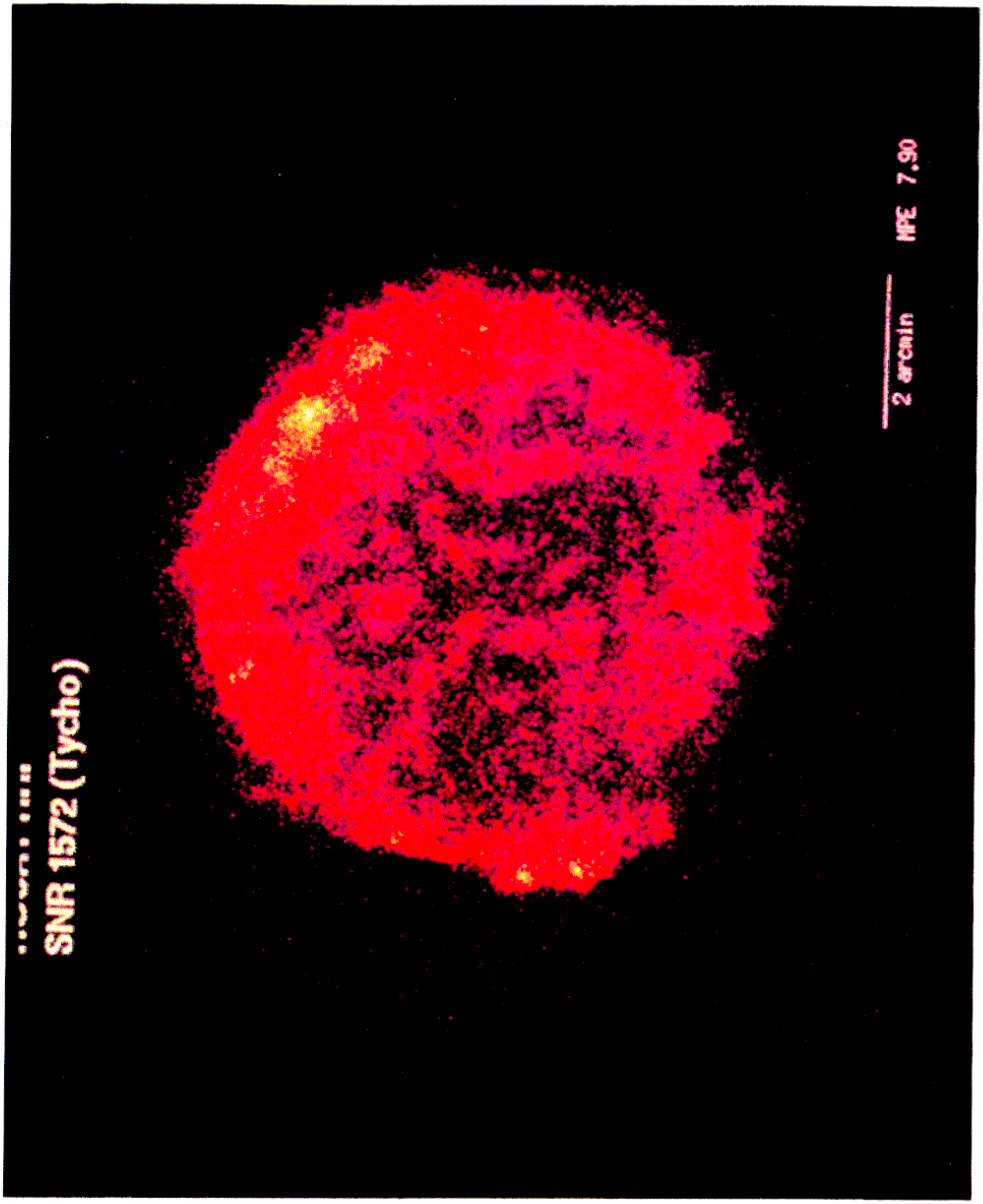
Two-year MACHO results :

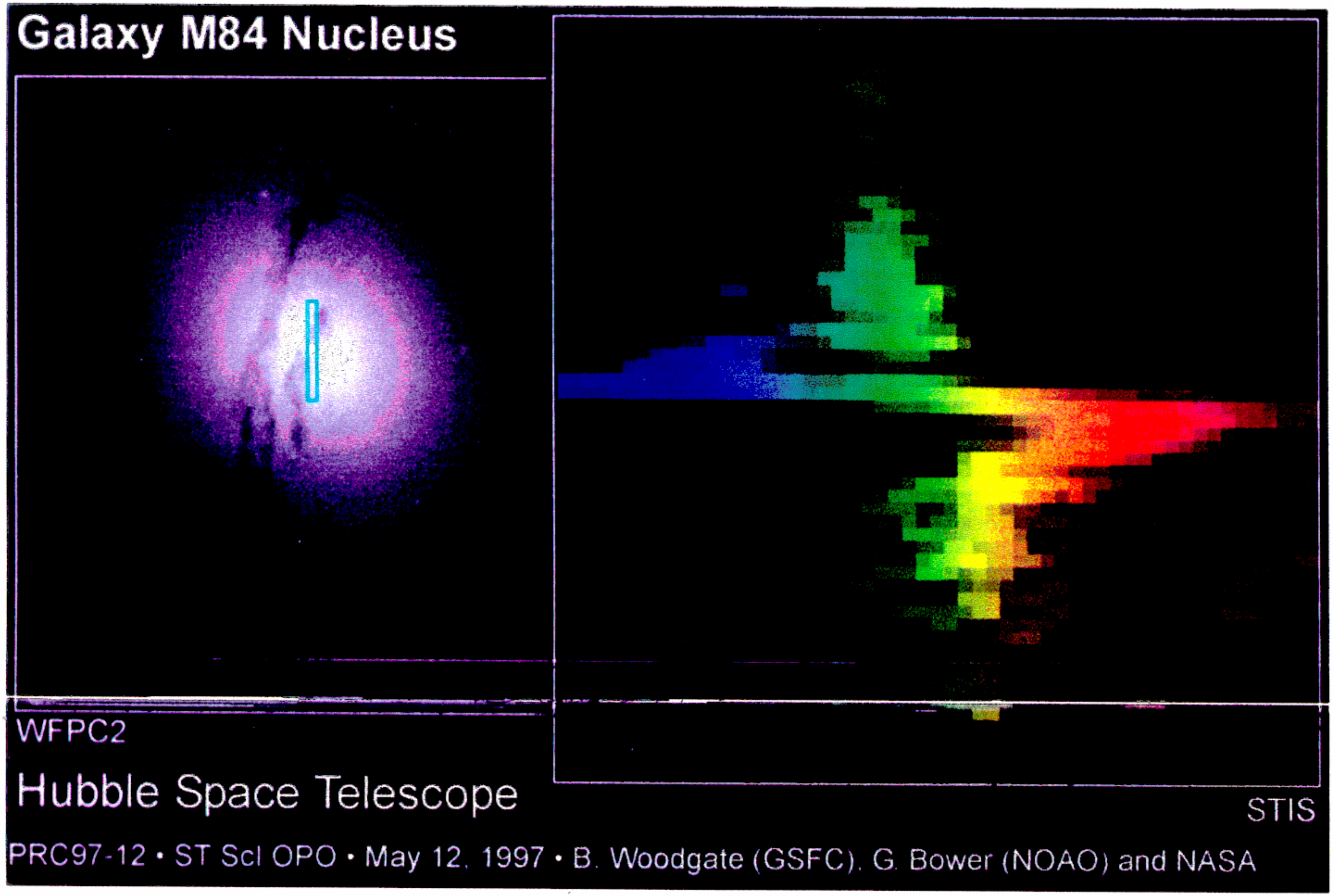
6-8 events in halo towards LMC

$m \sim 0.3 \pm 0.2$

fraction $\sim$ <u>0.5 ± 0.2</u>




SNR 1572 (Tycho)
2 arcmin
MPE 7.90


Galaxy M84 Nucleus
WFPC2
Hubble Space Telescope
STIS
PRC97-12 • ST ScI OPO • May 12, 1997 • B. Woodgate (GSFC), G. Bower (NOAO) and NASA

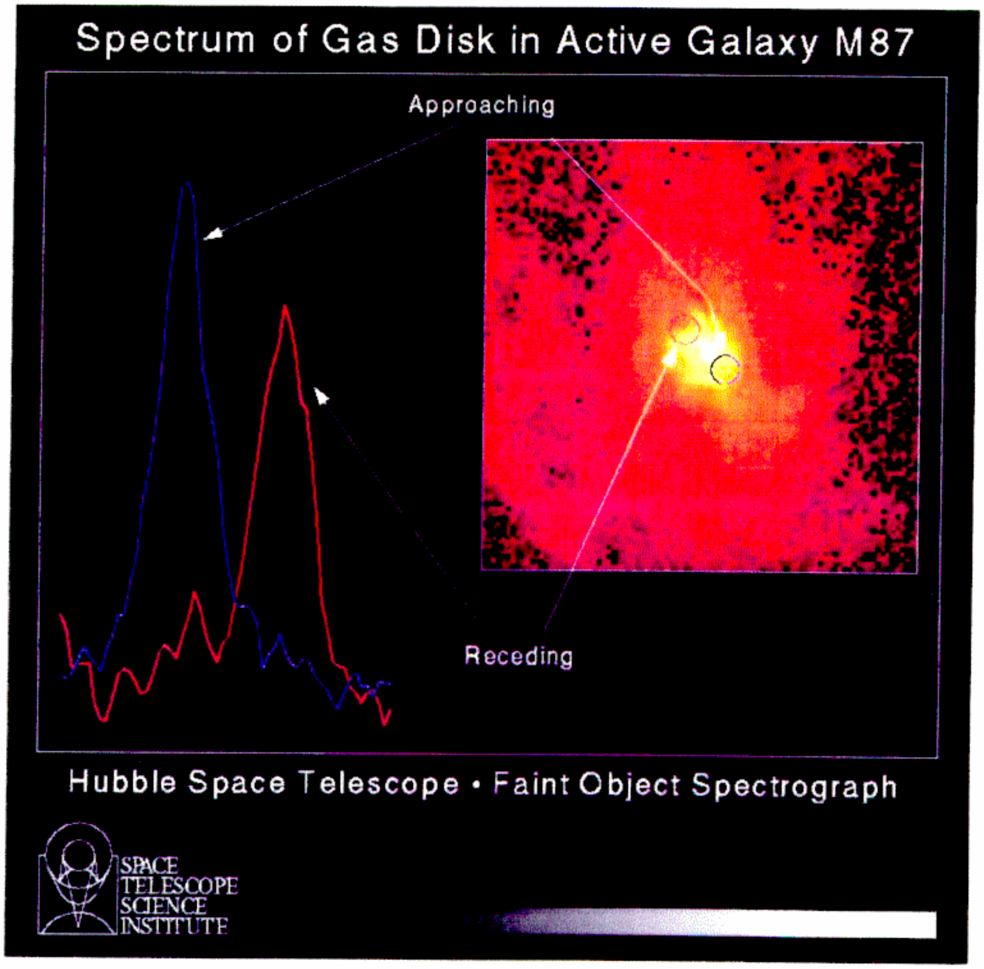

Spectrum of Gas Disk in Active Galaxy M87
Approaching
Receding
Hubble Space Telescope • Faint Object Spectrograph
SPACE TELESCOPE SCIENCE INSTITUTE

Table 1.3. *Dark Matter Candidates*

axion SUSY LSP neutralino technibaryon pseudo Higgs ⋮ shadow matter topological relics non-top. solitons	Weakly Interacting Massive Particles	COLD DARK MATTER
Primordial BH jupiters brown dwarfs white dwarfs neutron stars stellar BH massive BH	Massive Astrophysical Compact Halo Objects	
neutrinos ν_e ν_μ ν_τ (ν_s?) majorons?	HOT DARK MATTER	
gravitino right-handed ν	WARM DM	
decaying dark matter ⋮	VOLATILE DM	

Table 1.4. *Supersymmetry*

A hypothetical symmetry between boson and fermion fields and interactions

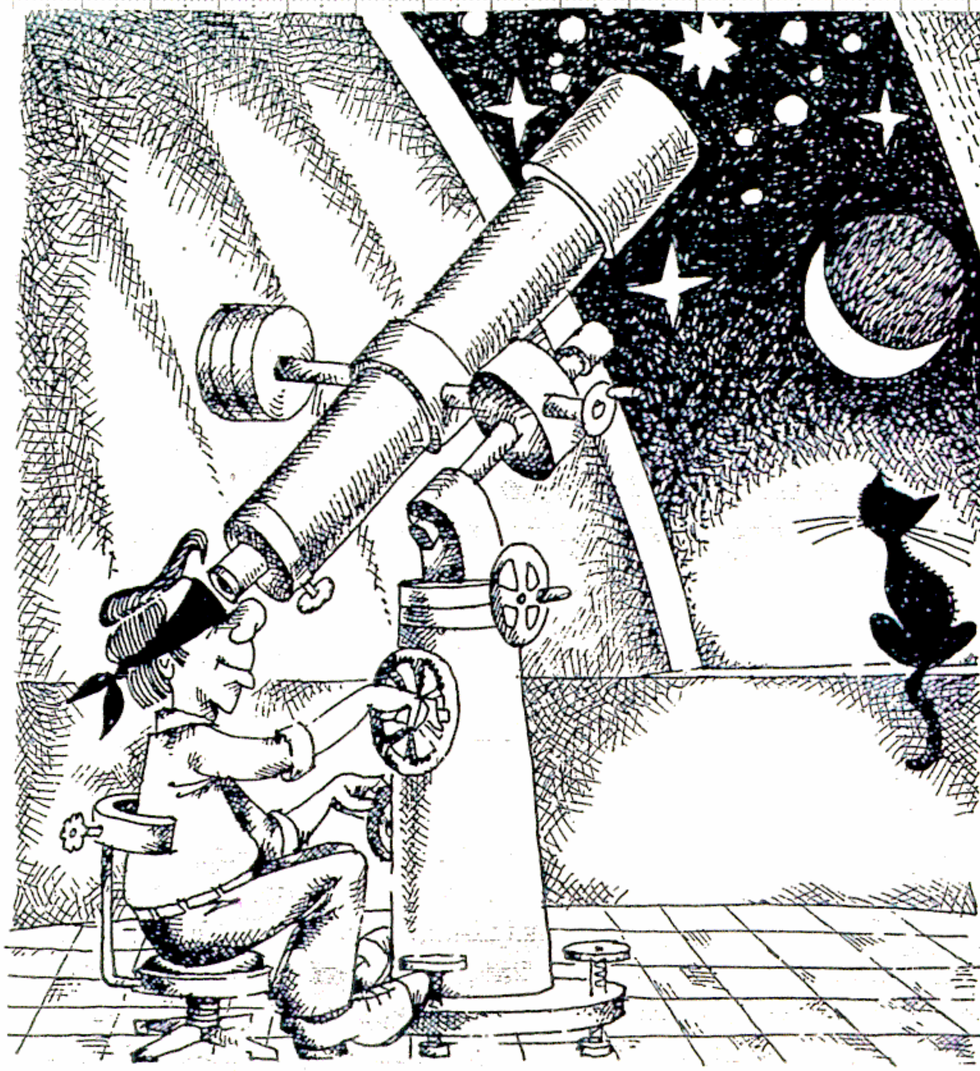
Spin	**Matter** (fermions)	**Forces** (bosons)	**Hypothetical Superpartners**	**Spin**
2		graviton	gravitino	3/2
1		photon, $W^{\pm}, Z^0$ gluons	photino, winos, zino, gluinos	1/2
1/2	quarks u,d,... leptons $e, \nu_e, \ldots$		squarks $\tilde{u}, \tilde{d}, \ldots$ sleptons $\tilde{e}, \tilde{\nu}_e, \ldots$	0
0		Higgs bosons axion	Higgsinos axinos	1/2

Note: Supersymmetric cold dark matter candidate particles are underlined.

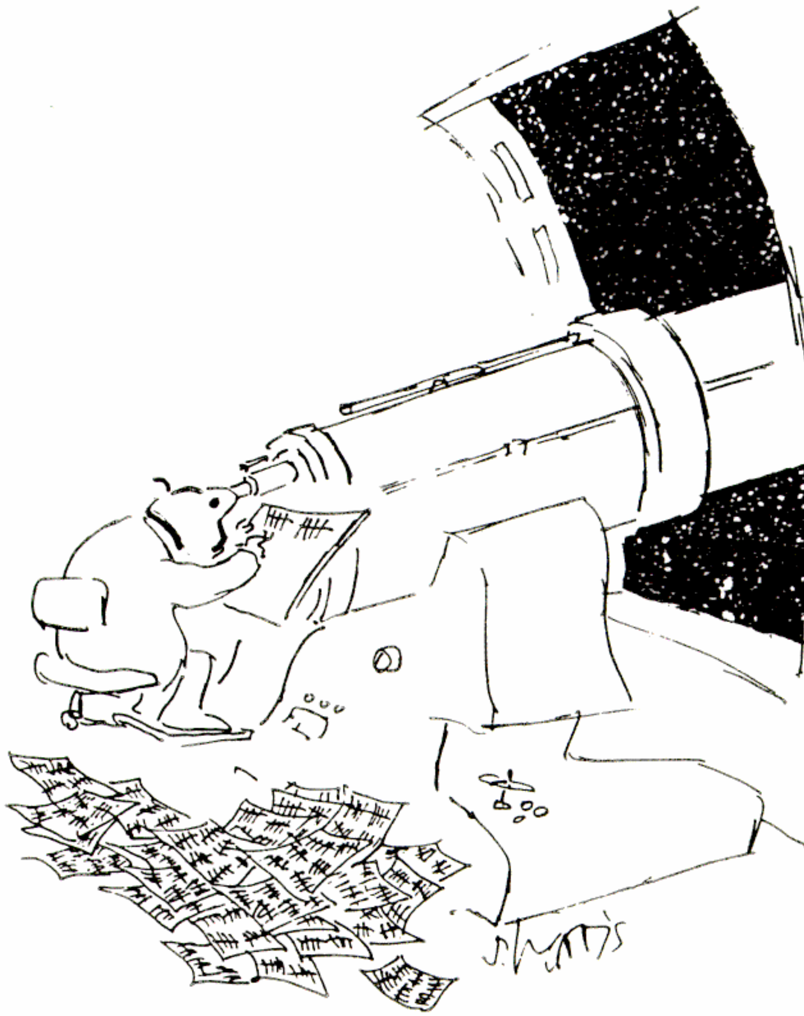
COSMOLOGICAL PARAMETERS FROM COSMIC FLOWS

Avishai Dekel

- Reconstruction from V_{pec}
- Ω — cosmology
- $P_k - C_\ell$ — $\Omega, n, \sigma_8, \Omega_b$ — fluctuations
- $\beta \equiv \Omega^{0.6}/b$ — mass/light
- H — Hubble bubble

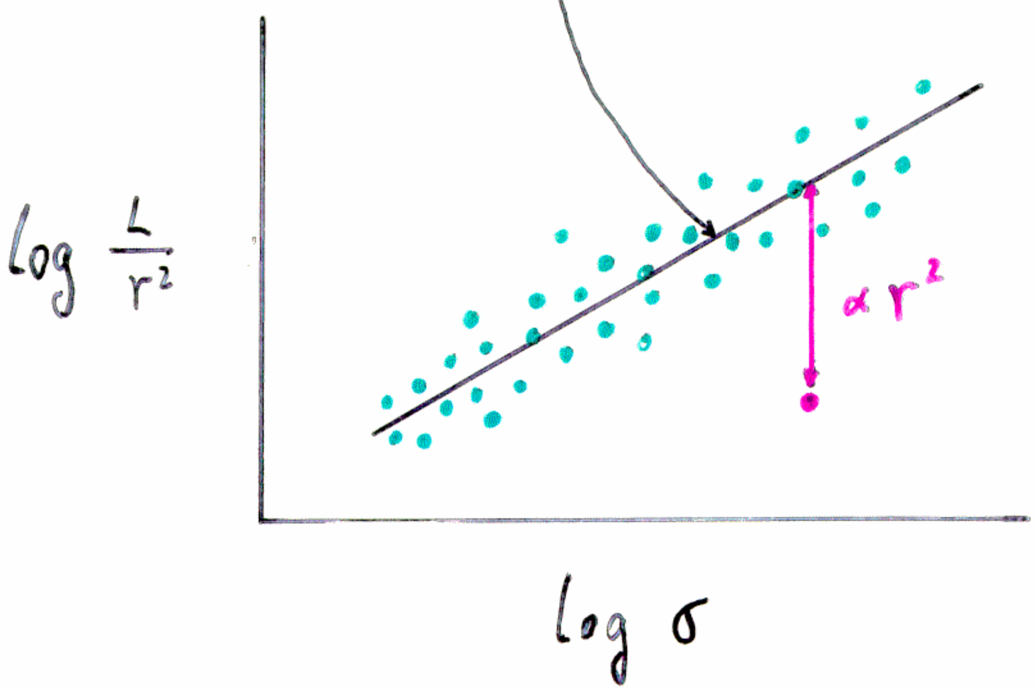


The search for Dark Matter



Peculiar Velocities

Distance: $L \propto \sigma^{\beta}$ Tully-Fisher, FP



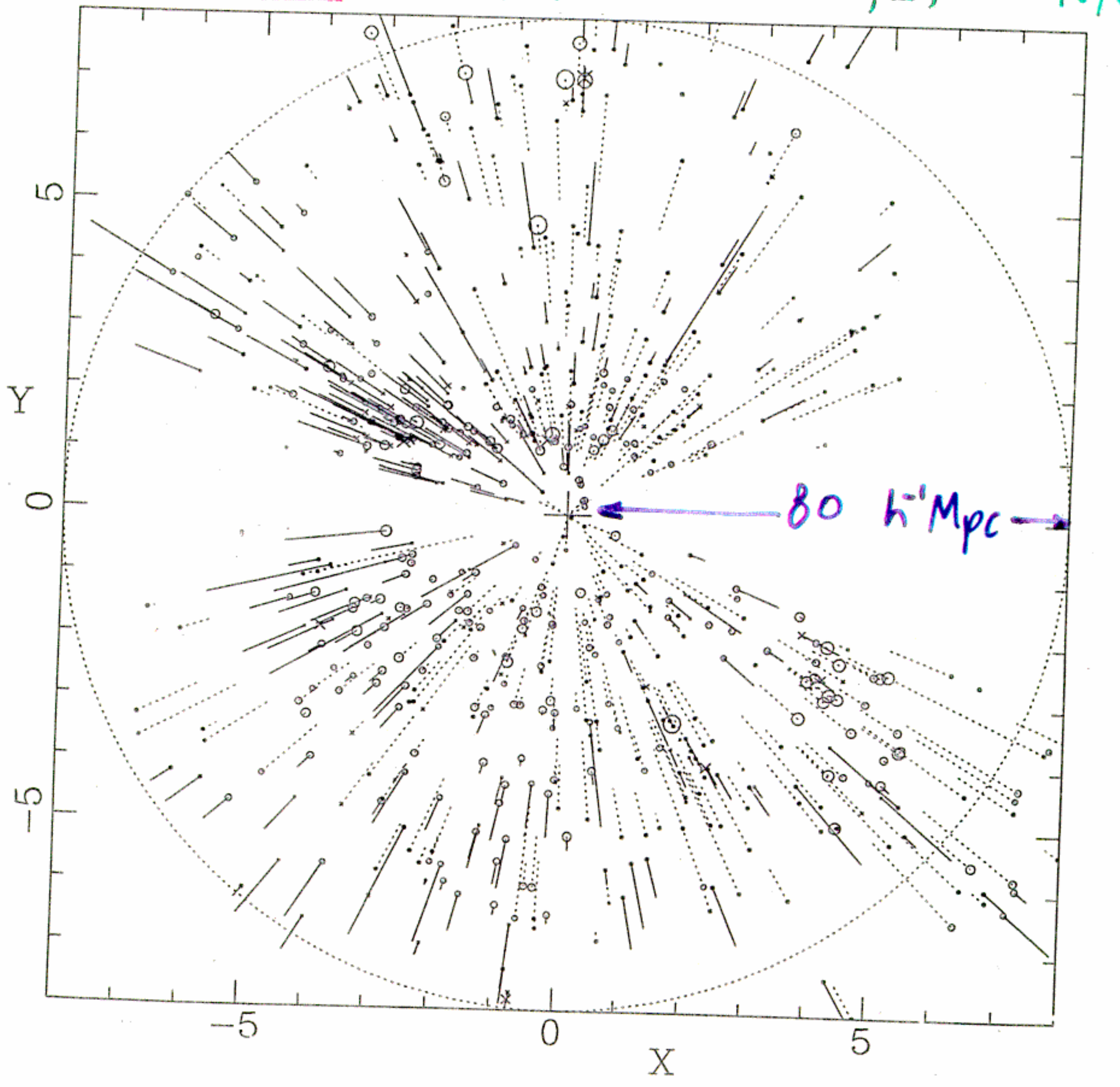
$\Delta r = 15\text{-}20\%$

Peculiar Velocity Data

		Δ	N	R
→ Mark III	TF/$D_n\sigma$	~18%	~3400	<70 h^{-1}Mpc
→ SFI	TF	~18%	~2000	<70
clusters	TF/$D_n\sigma$	~18% /$\sqrt{N}$	~50	50→200
clusters	BCG	<20%	150→500	50→240
→ SNe Ia		~7%	44	20–300
SBF		~7%		<40
shell	TF	~18%		50-70
E-FAR	$D_n\sigma$	~20%		<100
E-NEAR				

Mark III Catalog of Peculiar Velocities

Willick et. al. I, II, III 95/6



3,400 galaxies

Willick, Courteau, Faber, Burstein, Dekel

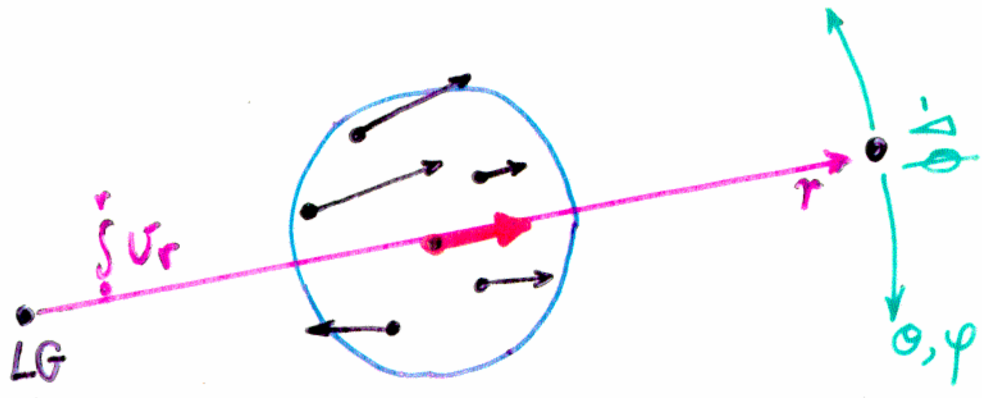
POTENT

Bertschinger & Dekel

- $v_r \rightarrow \vec{v}$

$$\vec{v} = -\nabla\phi$$

$$\phi(\vec{r}) = -\int_0^{\vec{r}} v_r(r,\theta,\varphi)\, dr$$



- Sparse, noisy data

  → smoothing $W_i \propto n_i^{-1} \sigma_i^{-2} e^{-\Delta r_i^2 / 2R^2}$

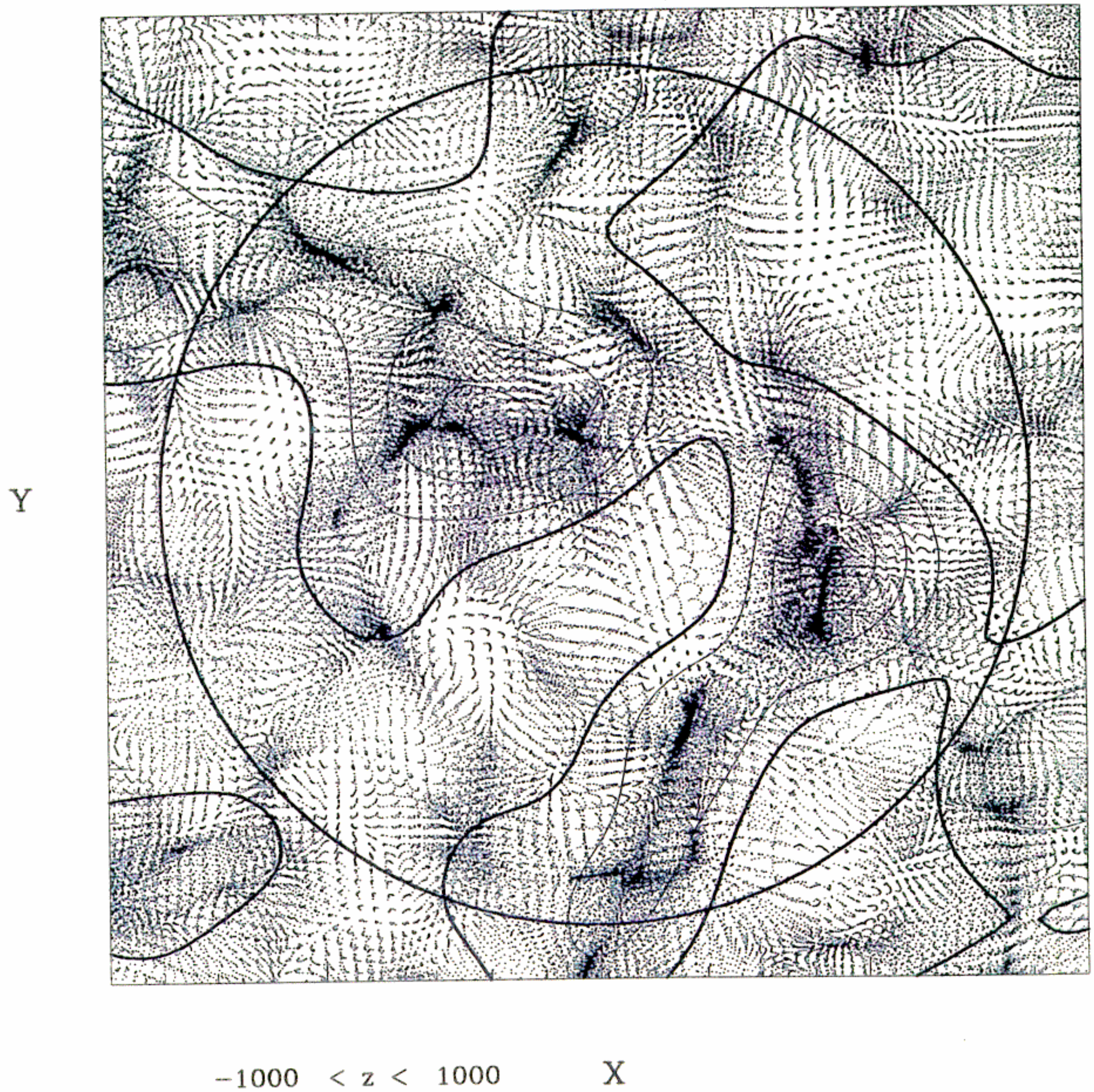
- $\delta \simeq -f^{-1}(\Omega)\, \nabla\cdot v$

  $\rightarrow \left\| I - f^{-1}\, \partial v_i / \partial x_j \right\| - 1$ Nusser et al 91

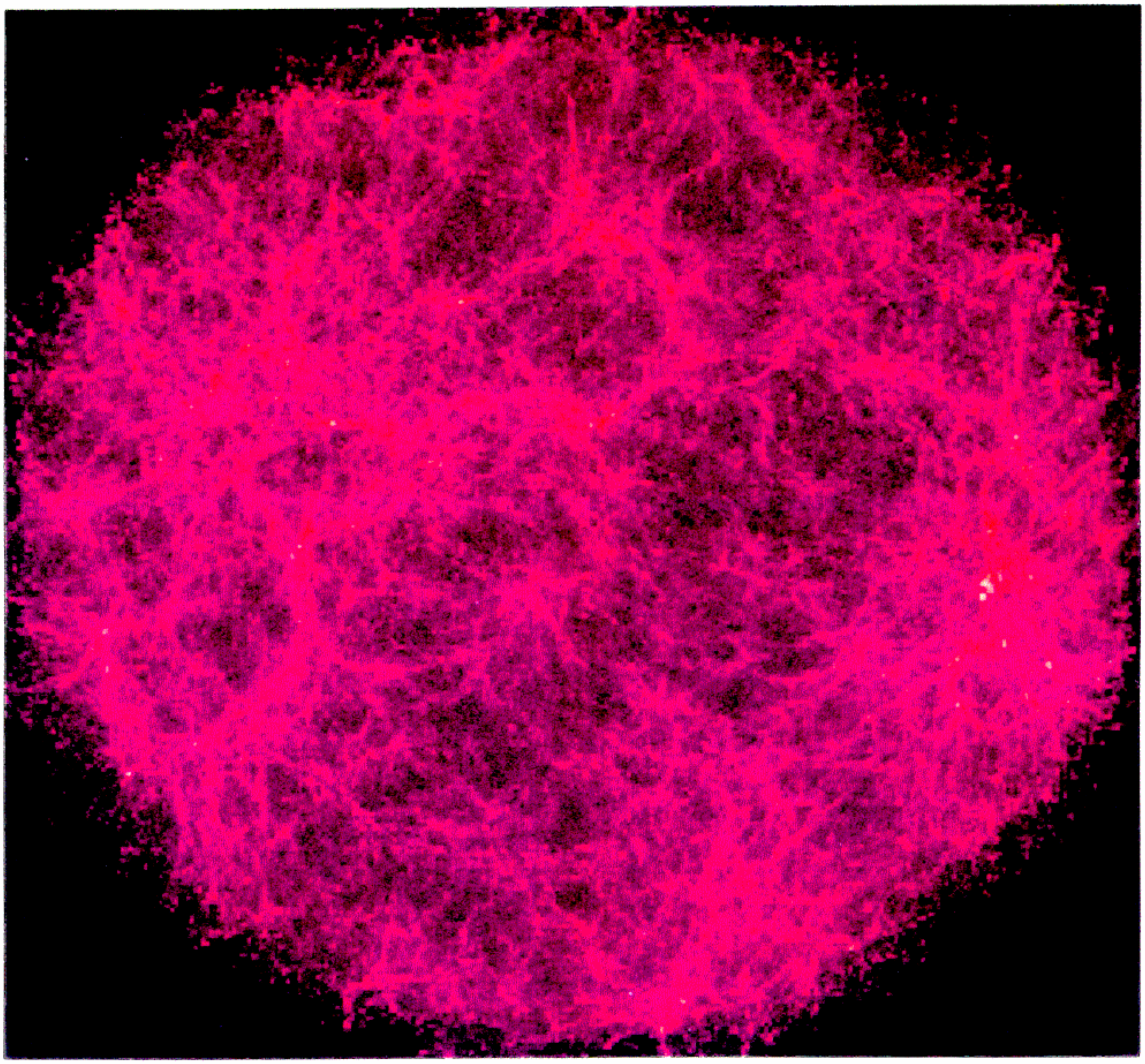
$\delta = \delta\rho / \rho$

Simulating the Real Universe

Kolatt, Dekel, Ganon, Willick 95



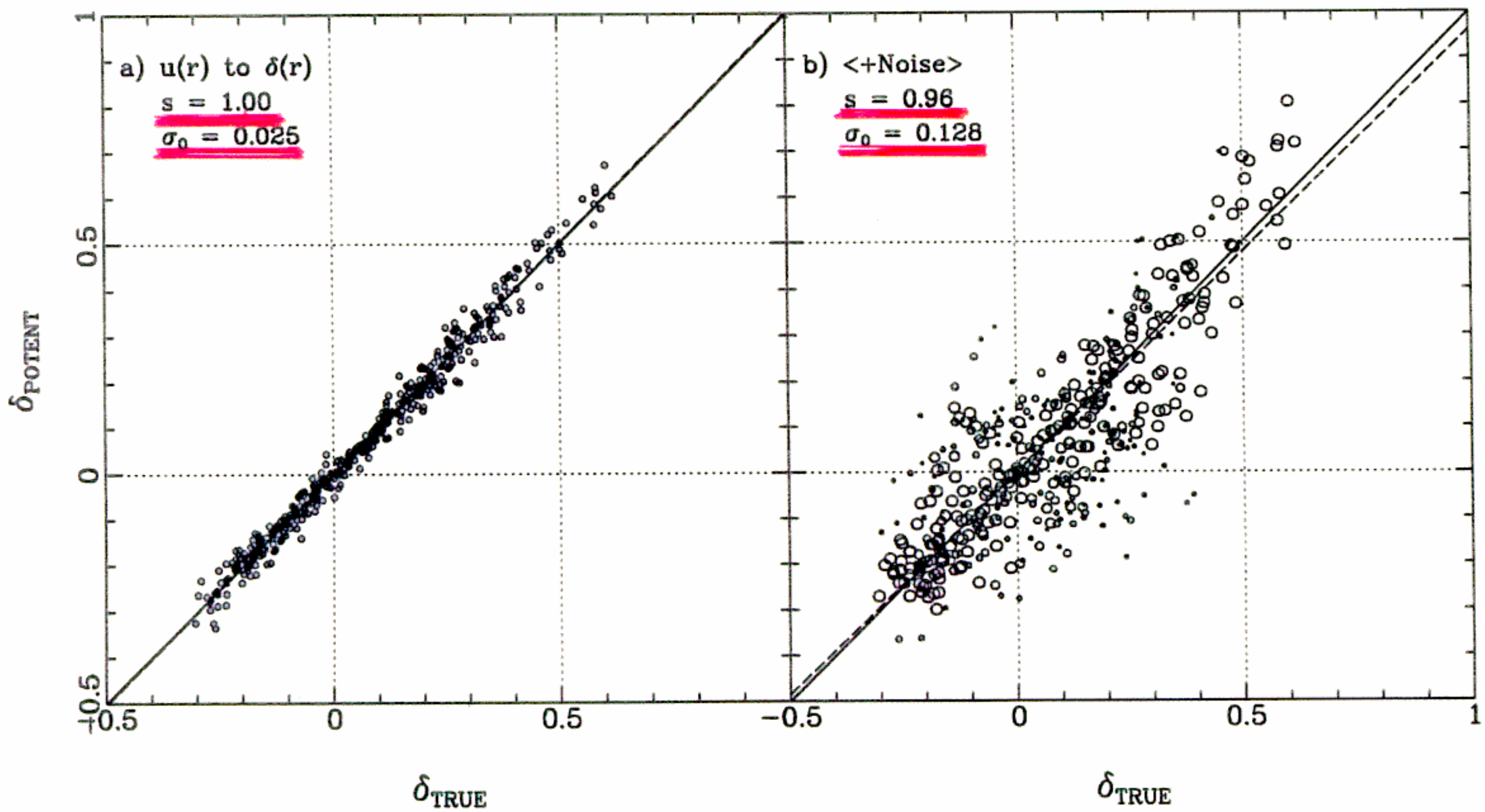
Constrained Simulation of our Local Neighborhood

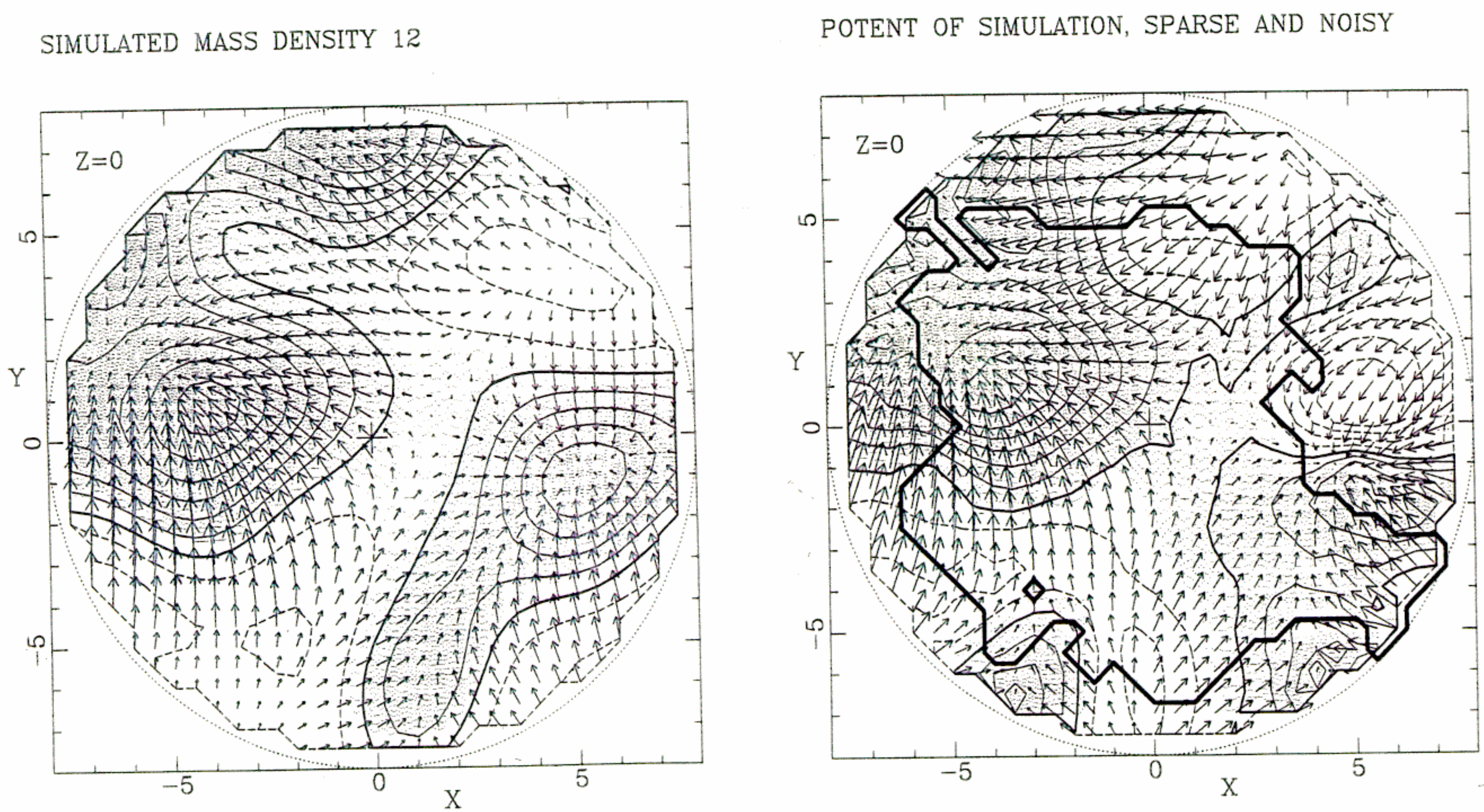


GIF: Lemson, Colberg, Kauffmann, White, Dekel

Testing POTENT w Mock Catalogs

Ideal data | Sparse, Noisy Data



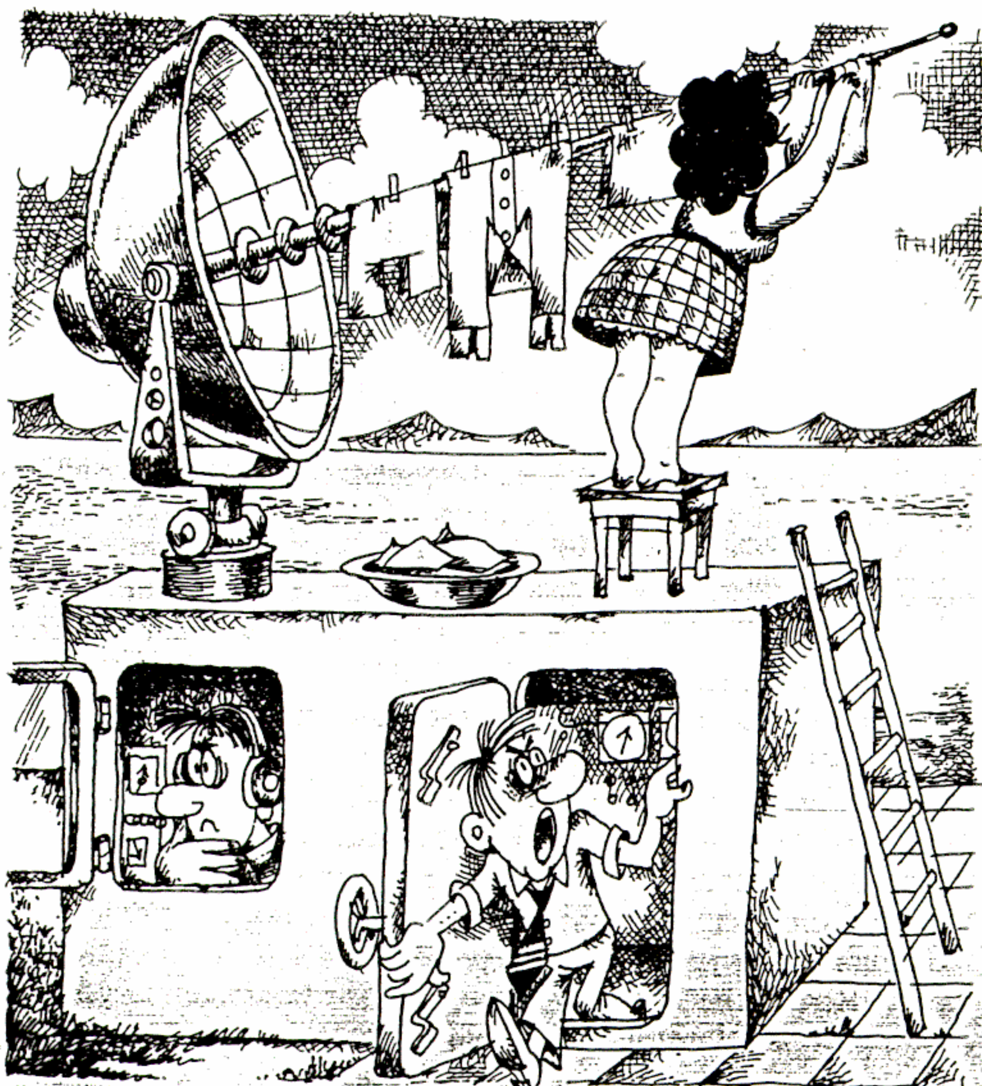


Kolatt AD, et al Eldar

them. About 0.3 seconds after the Big Bang, the entire matter of the Universe, including electrons and positrons, becomes transparent for neutrinos, that is, they stop interacting with the rest of matter. Their number does not change after this, and they survive until today, with their energy reduced by the red shift just as the temperature of electromagnetic radiation quanta is reduced by it.

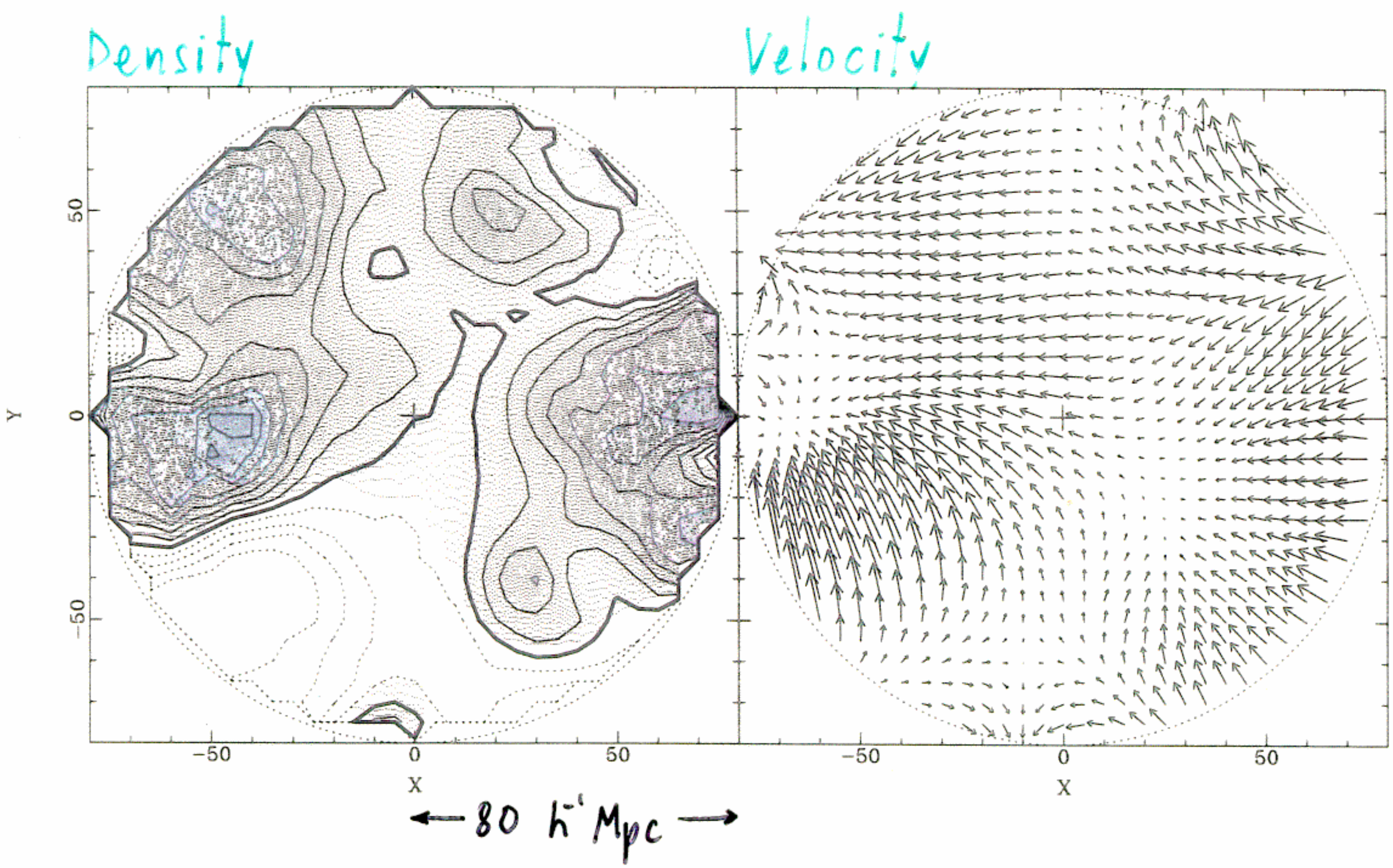
We conclude that in addition to the cosmic microwave background, the Universe must now also contain relict neutrinos and antineutrinos. The energy of these particles must be approximately equal to the energy of quanta of today's cosmic electromagnetic radiation background, and their concentration is also little different from that of relict quanta.

Experimental detection of relict neutrinos would be an extremely

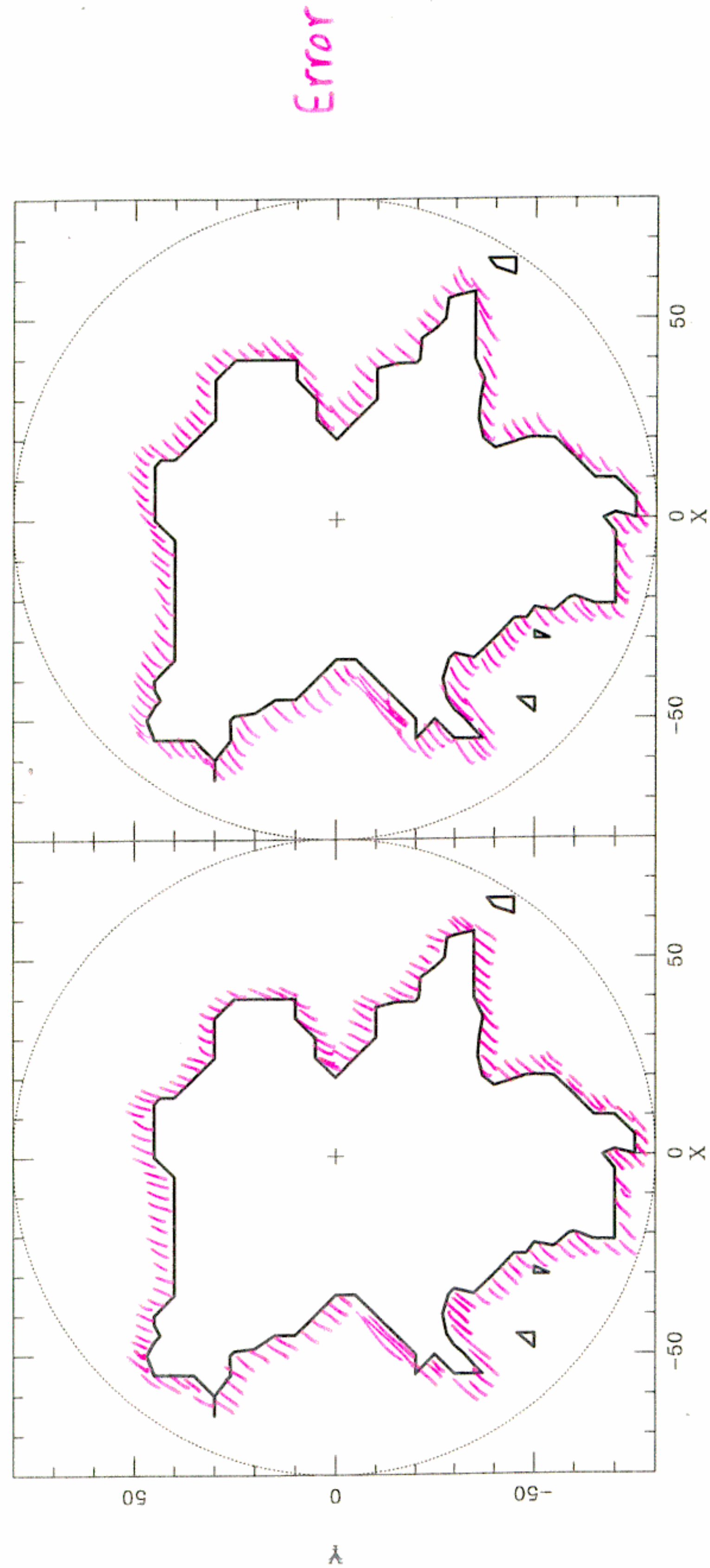


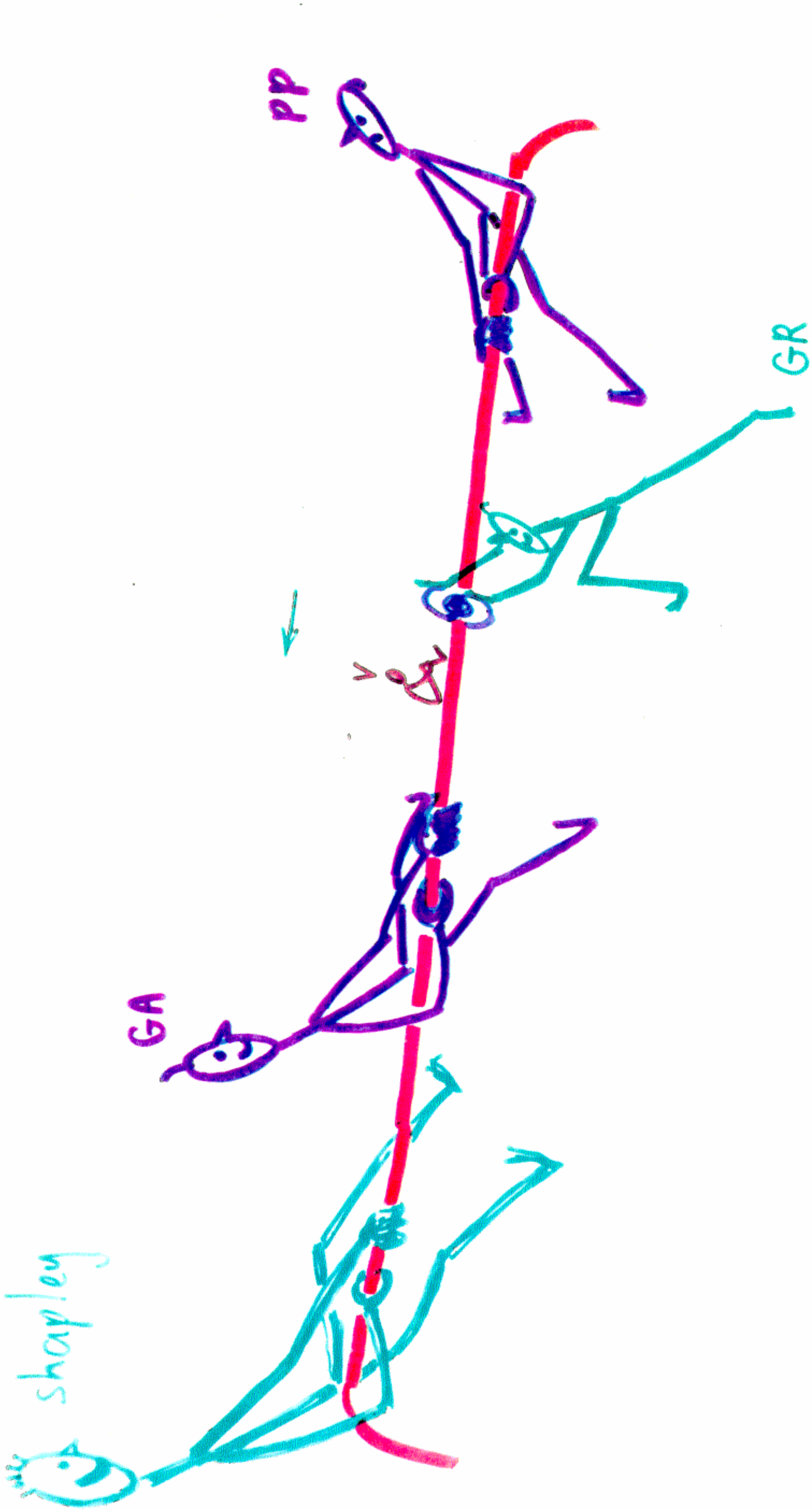
Error Analysis

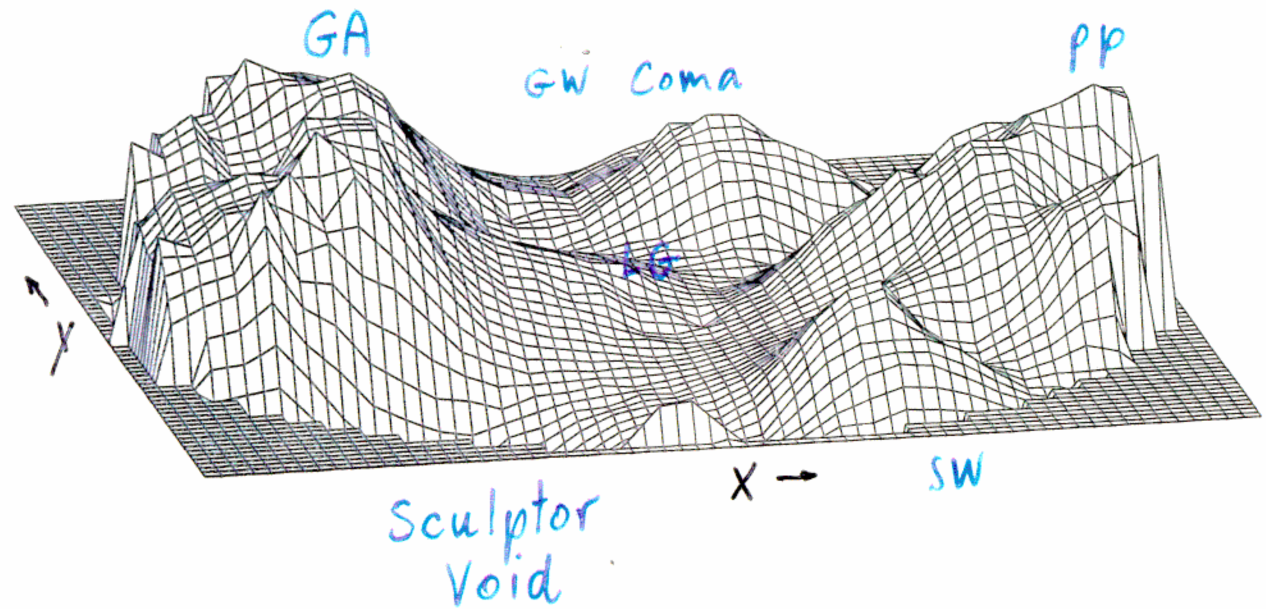
POTENT Mark III



Dekel, Eldar, Willick, ... 98
Faber, Courteau, Burstein


Error
50
0
−50
X
Y

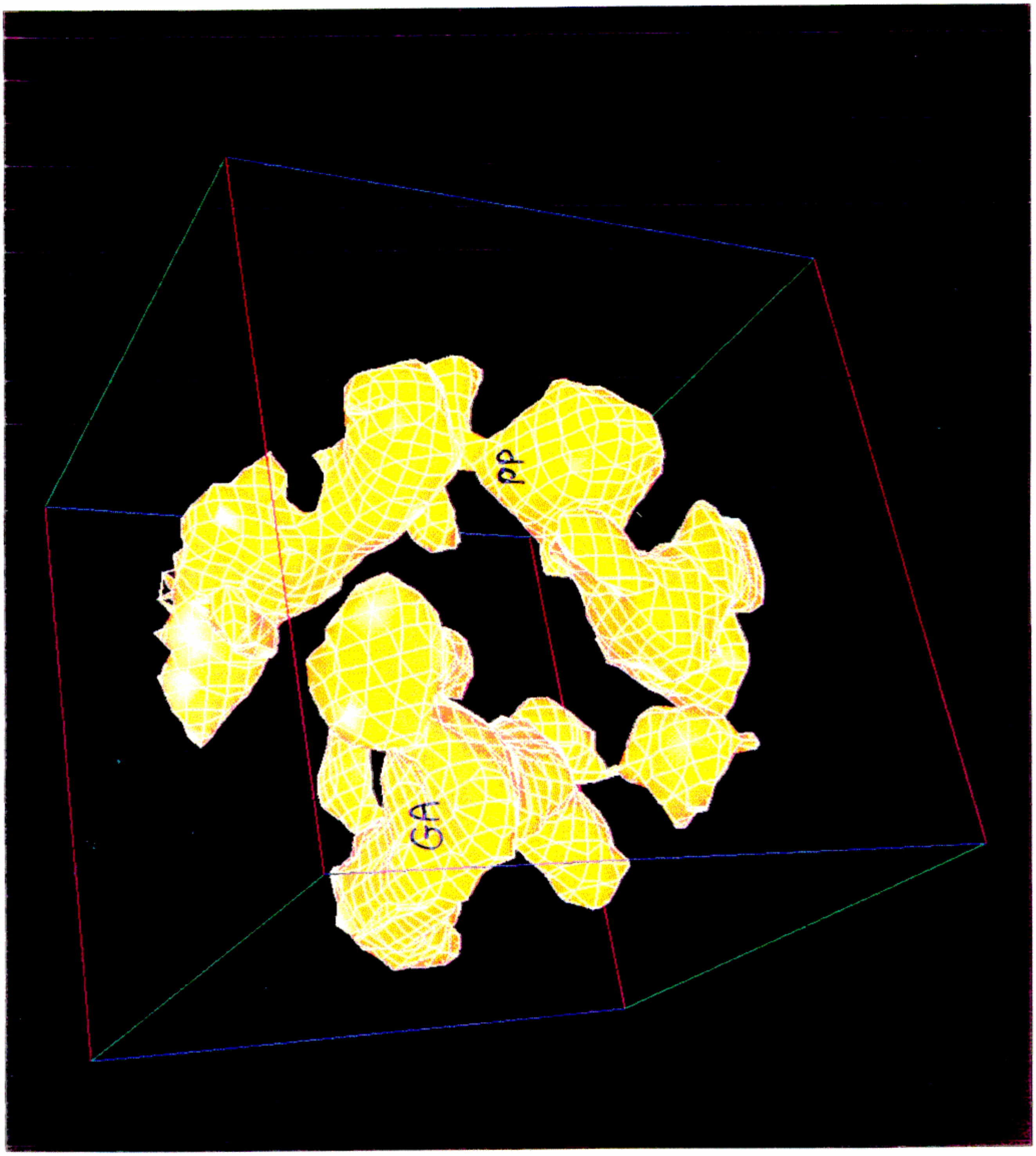

PP
GR
GA
shapley



POTENT Mass Density in Supergalactic Plane

Dekel et al 97

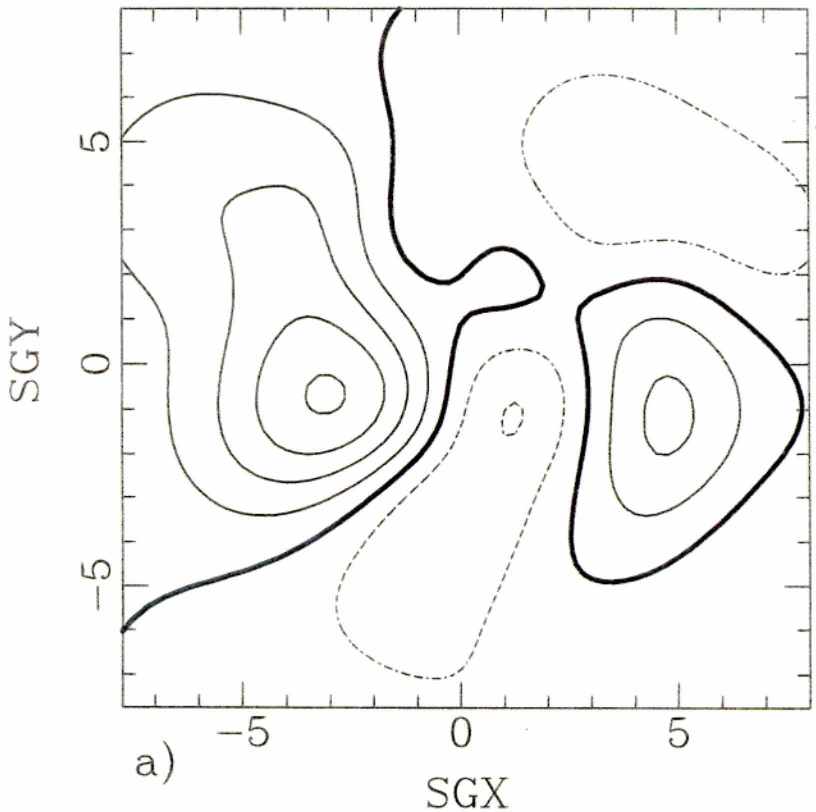
A. Dekel, SSI 1998



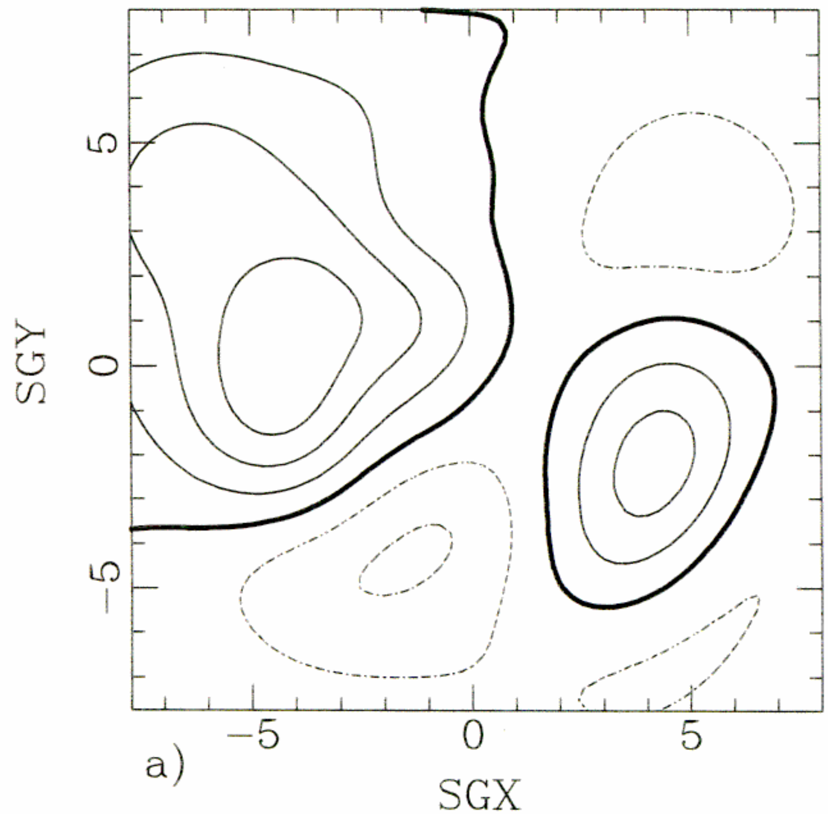
Wiener,

Wiener Filter

SFI G12

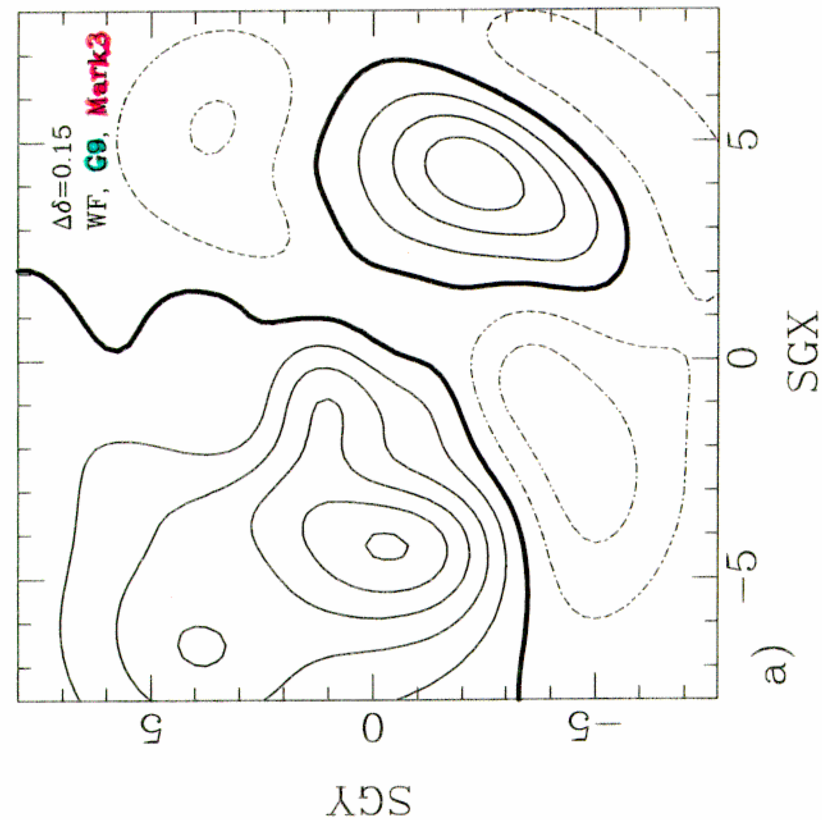


M3 G12

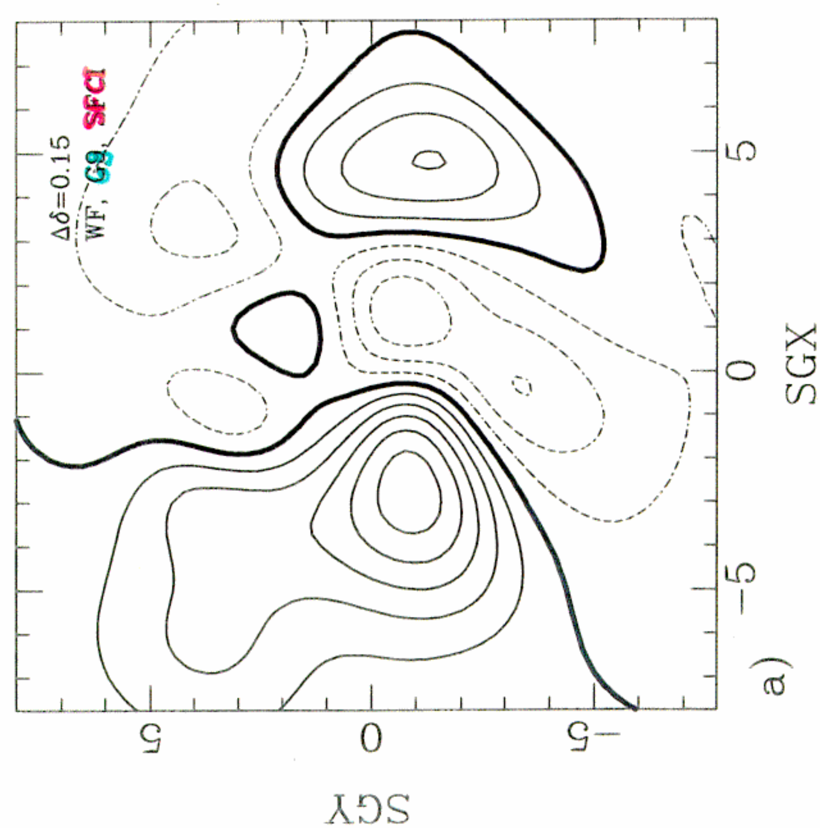


Zaroubi, Dekel, Hoffman ; Mark III, SFI

Giovanelli, Haynes, daCosta, Freudling
Wegner, Salzer

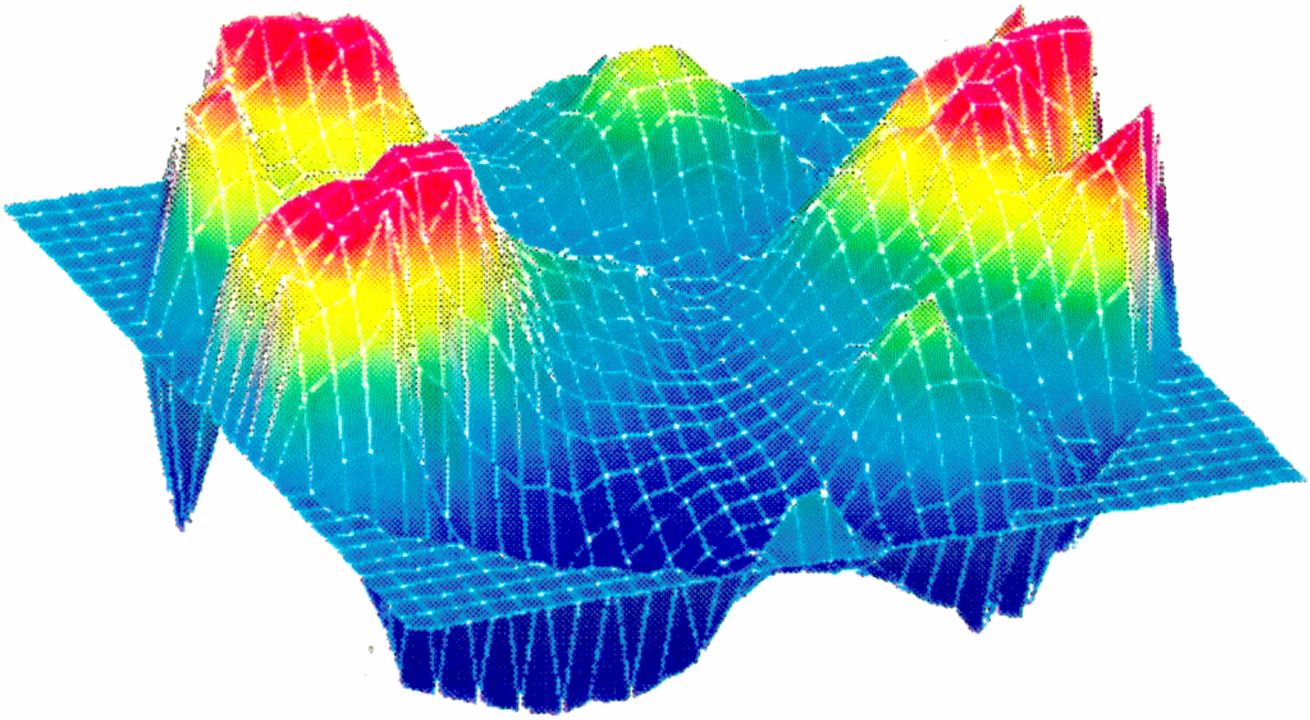


Δδ=0.15
WF, G9, Mark3
a)
SGX
SGY
−5
0
5



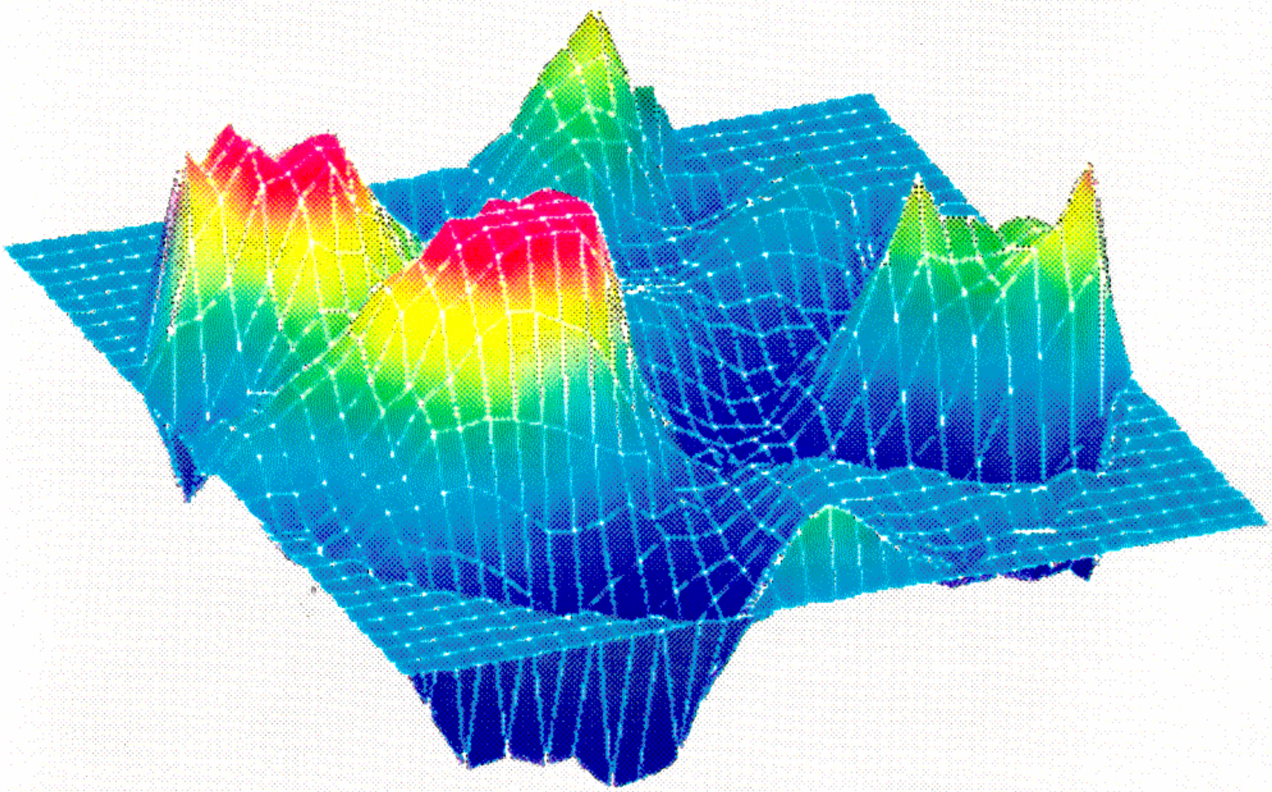
Δδ=0.15
WF, G9, SFCI
a)
SGX
SGY
−5
0
5

POTENT
MarkIII



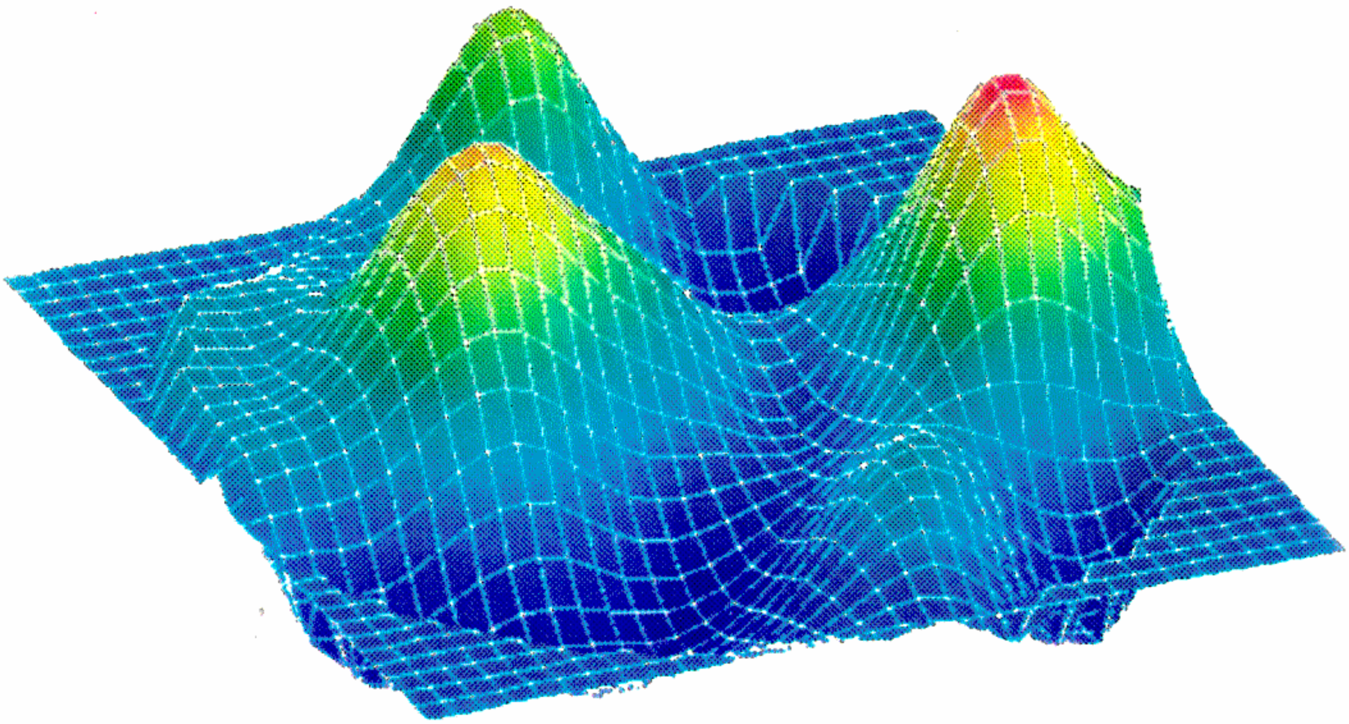
POTENT

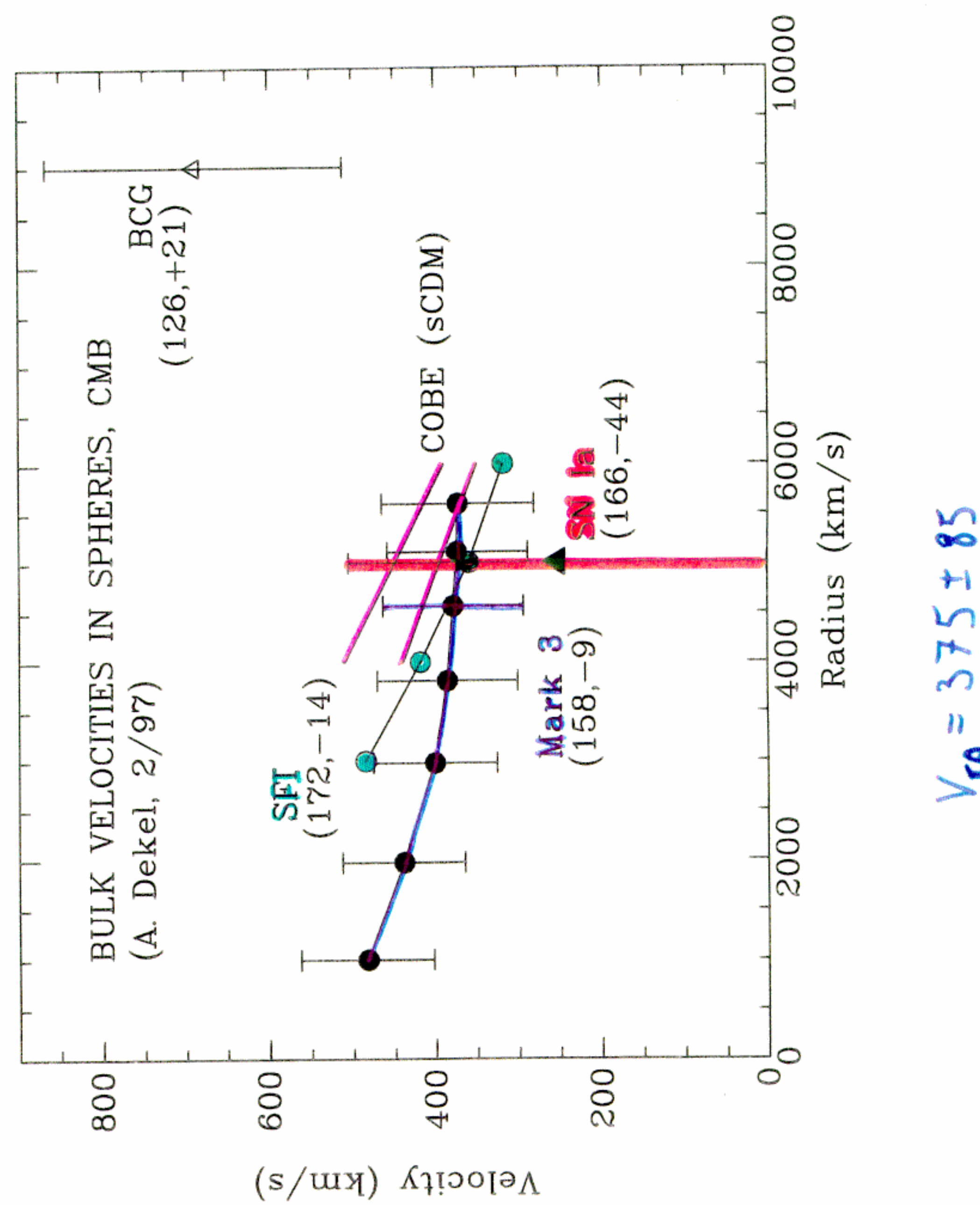
SFI

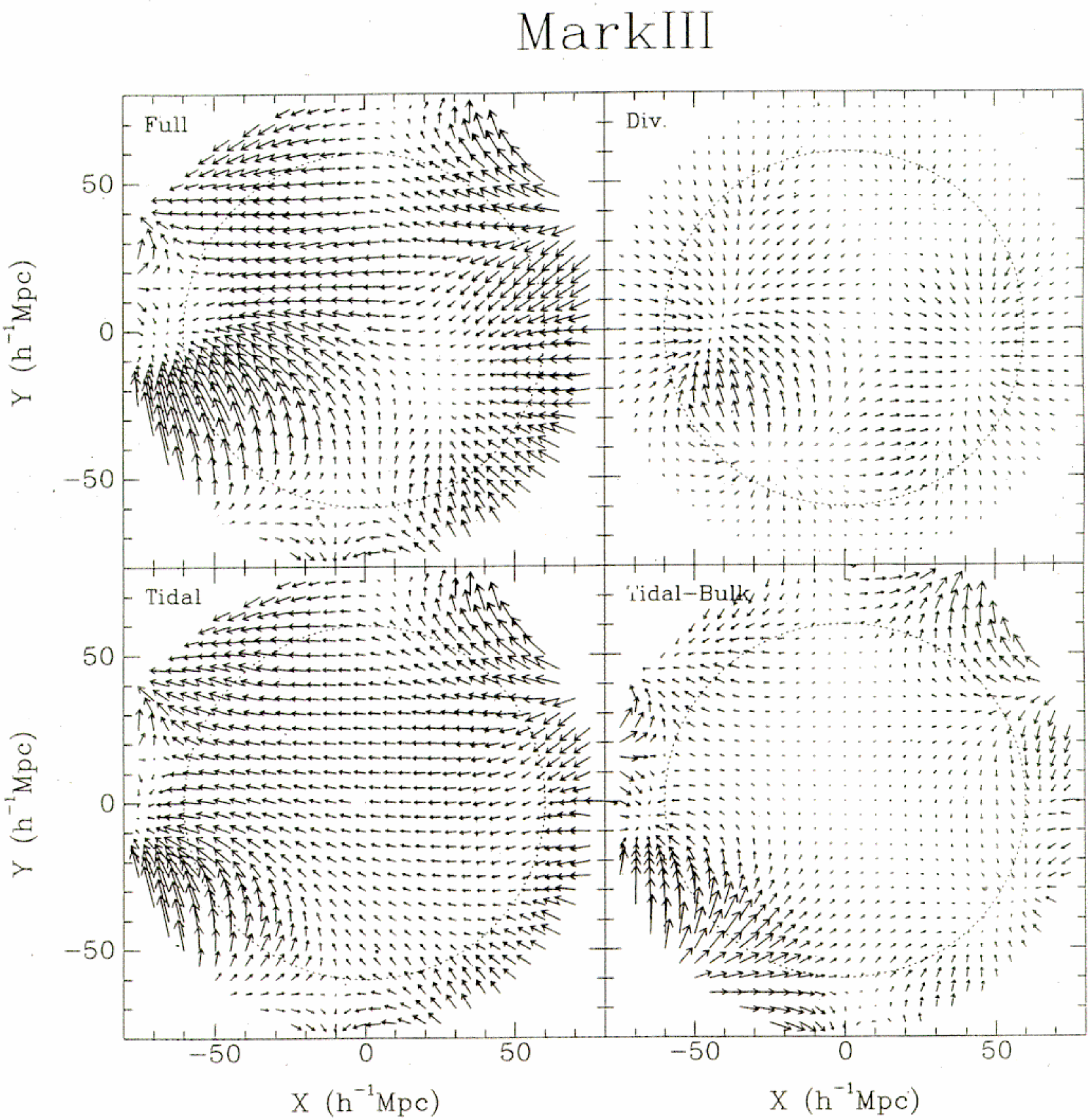


Eldar, Zehavi, Dekel, Freudling, daCosta, ... (SFI)

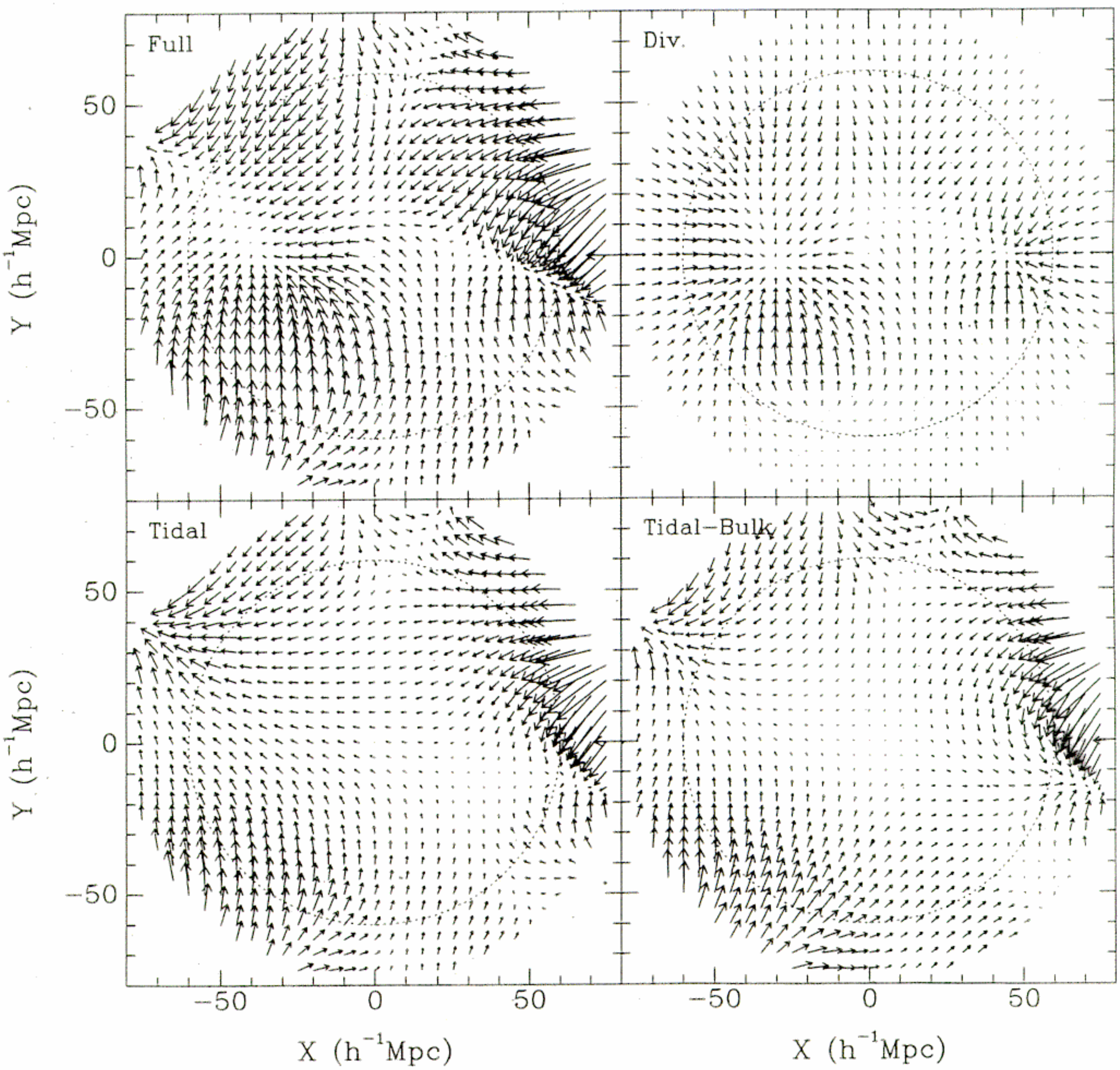
IRAS 1.2 Jy

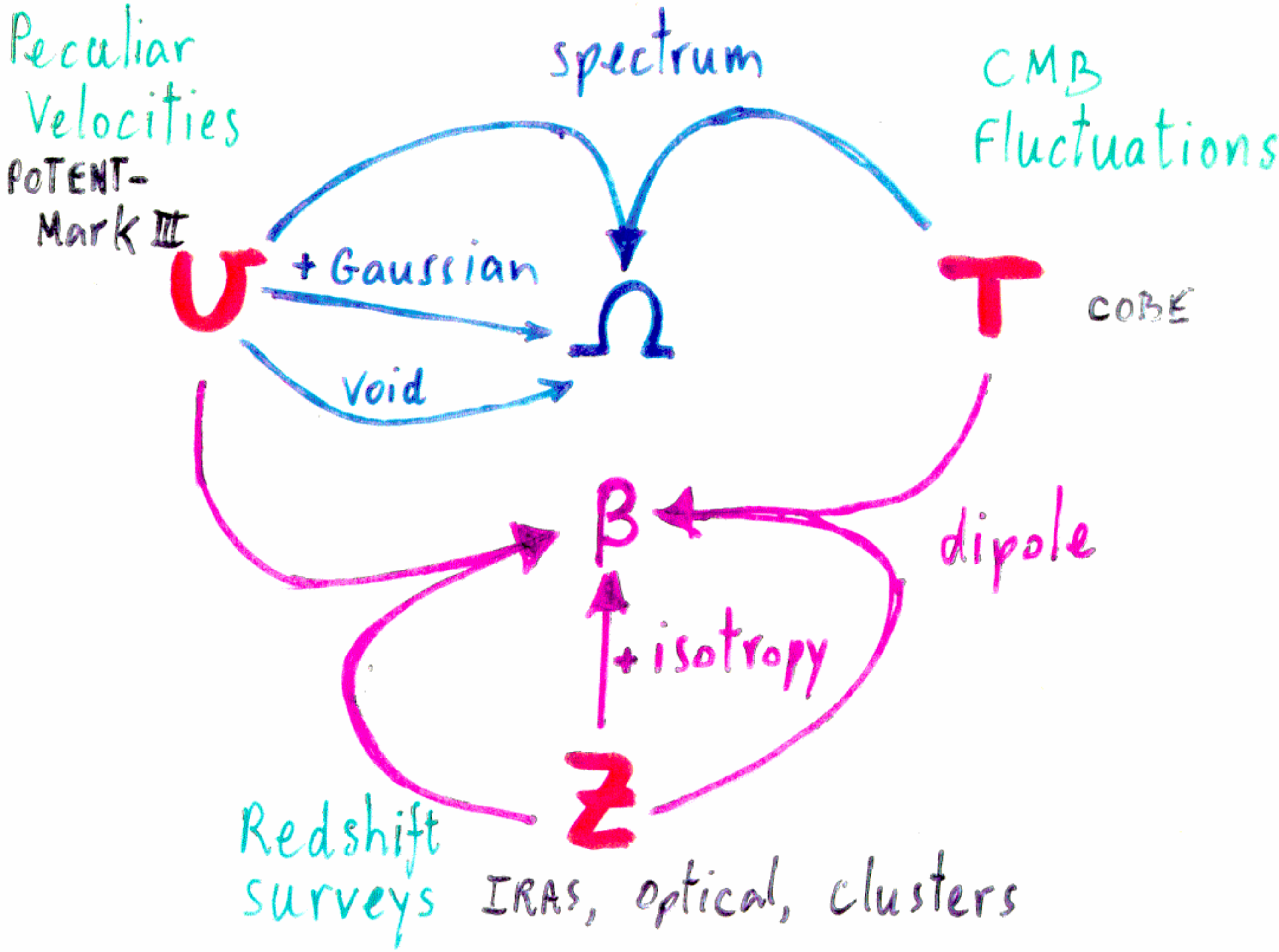



BULK VELOCITIES IN SPHERES, CMB
(A. Dekel, 2/97)
BCG
(126,+21)
COBE (sCDM)
SFI
(172,−14)
Mark 3
(158,−9)
SN Ia
(166,−44)
Velocity (km/s)
Radius (km/s)
0
200
400
600
800
2000
4000
6000
8000
10000
$V_{50} = 375 \pm 85$


MarkIII
Full
Div.
Tidal
Tidal-Bulk
Y (h^-1 Mpc)
X (h^-1 Mpc)
50
0
-50

SFI





Assuming: G.I. linear or quasi-linear

Linear biasing

Measuring Ω from Cosmic Flows

- v_{pec} + Gaussian i.c. $\longrightarrow$ Ω

  voids, $P(\rho)$, $P(\nabla\cdot v)$

- v_{pec} + $\delta T/T$ + model P_k $\longrightarrow$ Ω, n, T/S, h, σ_8

  CDM+, likelihood

- v_{pec} + $\vec{n}_{gal}$ $\longrightarrow$ $\beta_x = \Omega^{0.6}/b_x$

  δ-δ, v-v

- $\delta T/T$ + $\vec{n}_{gal}$ $\longrightarrow$ β_x

  dipole, P_k

- $\vec{n}_{gal}$ + isotropy $\longrightarrow$ β_x

  z-distortions

From V_{pec} alone

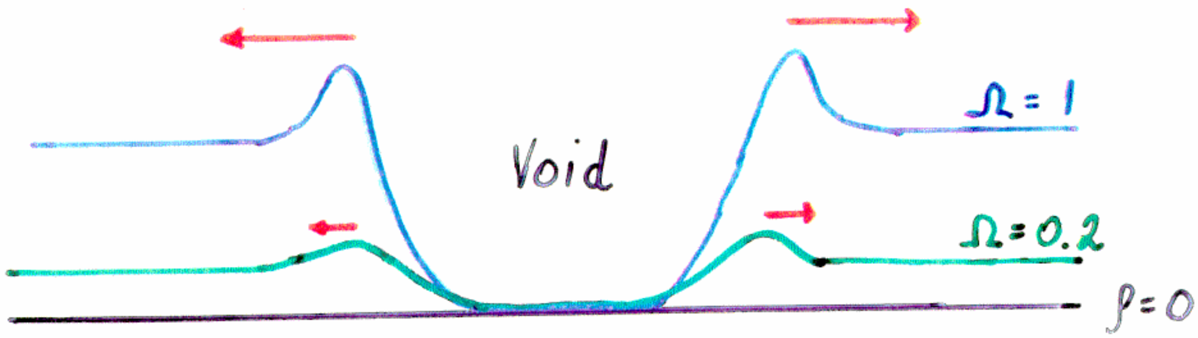
(independent of biasing)
but Gaussian I.C.

$\Omega > 0.3$ at $> 2\sigma$

- Divergence in Voids — Dekel & Rees 94
- Skewness of $\nabla \cdot v$ — Bernardeau et al 95
- IPDF — Nusser & Dekel 93

Ω from Velocities in Voids

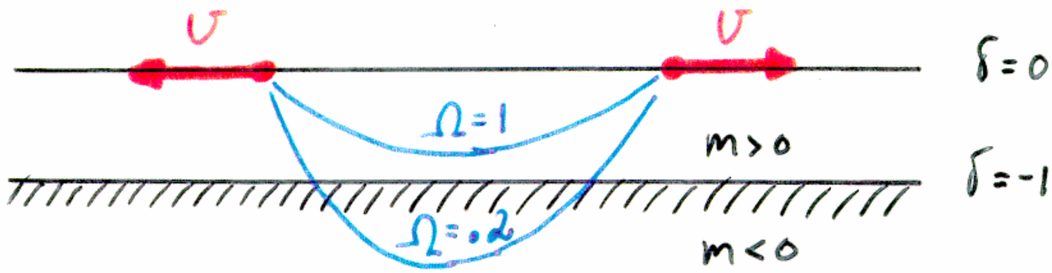
Dekel + Rees 94



$$\nabla \cdot v \simeq -\Omega^{0.6}\,\delta$$

Ω from Velocities near Voids

Dekel & Rees 94



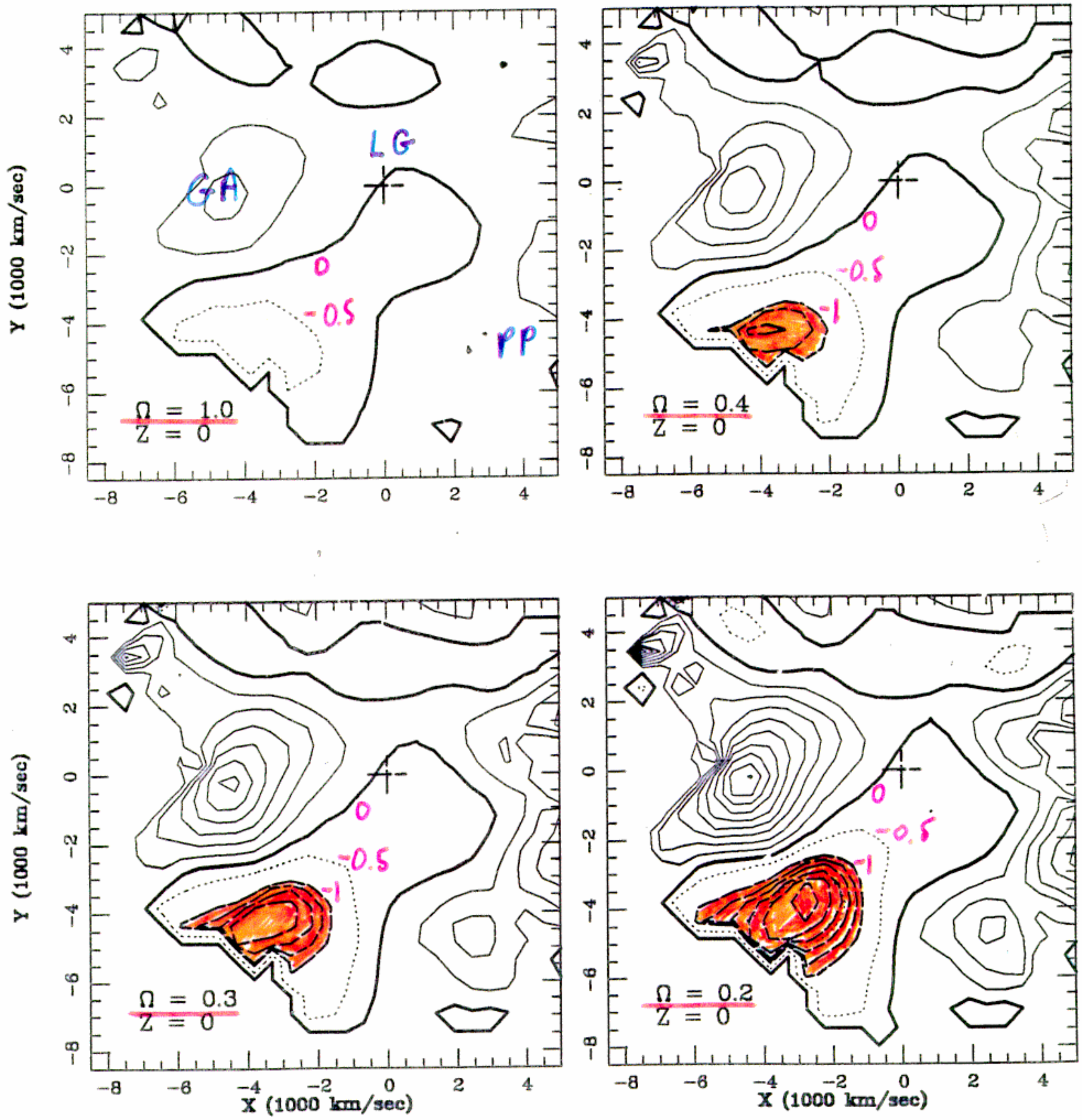
$$\delta = -\Omega^{-0.6}\,\nabla\cdot v \quad < \delta_{true}$$

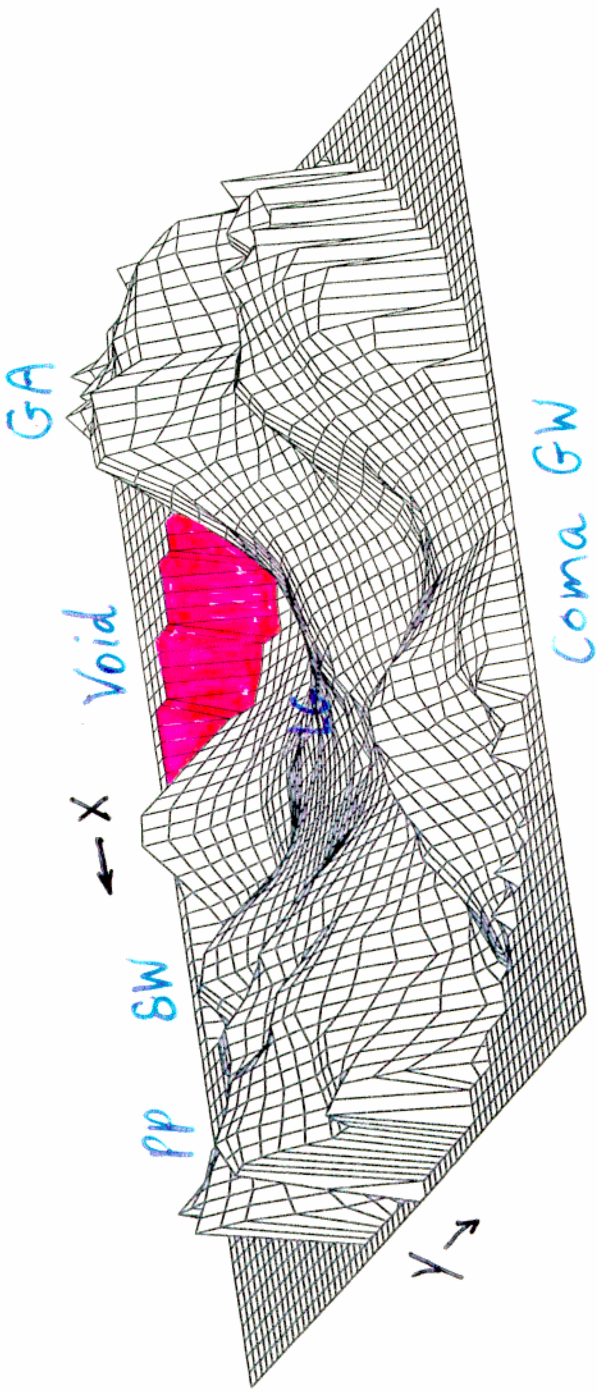
$$\delta(\partial\vec{v}/\partial\vec{x},\ \Omega) \ > \ \delta_{true} \qquad > 99\%$$

Independent of "biasing" !

$\delta\rho/\rho$ Supergalactic Plane

$\Delta\delta = 0.5$ $\Delta\sigma = 0.5$




GA
Void
LG
X
SW
PP
Coma
GW
Y

N.Y. Times Jan. 96

Masters of the Universe

Dark Matter Lights the Void

By GEORGE JOHNSON

MANY moons from now, when extraterrestrial archeologists sift through the records of our brief civilization, they might be ꞏed to stumble across the proceedings annual convention of stargazers called ꞏmerican Astronomical Society. They l be right in concluding that 1996 was, ꞏ way or another, a landmark year.

ꞏt week, at this cosmological jamboree ı Antonio, astronomers unveiled photoꞏs from the Hubble Space Telescope were so jammed with stars that the ꞏated number of galaxies in the uniꞏ quintupled overnight, to 50 billion. ꞏe we earthlings had time to absorb this ꞏing revelation, we were hit with still

ꞏ analyzing the wobble of distant stars, ꞏnomers found deviations that could be ꞏd by large, orbiting planets. Scrutinizꞏne wiggles within the wobbles, they dared speculate that the two unseen ꞏts would be close enough to their suns ꞏk up the rays needed for life.

perhaps the single revelation that the ꞏ would find most amusing involves a ꞏe hypothetical substance called dark ꞏr, which by its very nature cannot be Over the years it has become clear ꞏ the prevailing cosmological theories ꞏght, some 90 percent of the universe be made up of dark matter. Last week, ꞏomers said they may have identified ꞏ this unseen stuff. But the implicaꞏemain as mysterious as ever.

ꞏ the aliens might wonder: How was it his ancient race was forced to conꞏ that almost all of the universe is ꞏle?

ꞏble in the Galaxy

earthlings, the anthropologists might ꞏ, kept track of time by counting the ꞏheir planet had taken around its sun ꞏhe time of a highly regarded prophet ꞏ Jesus. It was after about 1,930 of revolutions that the planet's stargazꞏgan to notice something seriously ꞏ with the galaxies. Even their own ꞏ Way was violating what earthlings, with characteristic lack of humility, called a Law of the Universe. This particular law had been laid down by another prophet called Newton. Newton's law did such a fine job describing how apples fell from trees and arrows flew through the air that the earthlings were sure that the stars themselves must obey it.

Gravity Defied

How shocking then that the Milky Way seemed to be spinning much faster than Newton decreed — so fast, in fact, that it should have flown apart long before. Could it be that the great prophet was wrong, that his laws were no more universal than such earthly concoctions as British cor and the Internal Revenue Code?

But these stargazers were far r er than that. Perhaps, they propo kind of unseen cosmic glue is h Milky Way together. If 90 perc galaxy consists of this invisible ꞏ Newton's laws would again reign

In the annals of astronomy, thiꞏ recorded as the "discovery" of da

This dark matter — whatever turned out to be quite useful. Late Earth's inhabitants were having with their creation myth, the Big ꞏ took was a hefty dose of dark mat straight.

The elders had taught that th began 10 billion earth orbits ear great explosion that still reverbe one problem. The debris from the — all this hurtling star stuff — w been flying too fast to clump t form galaxies and clusters of ga prophet Newton's gravity just wa enough.

Then dark matter came to the

Stuart Goldenberg

Something big was missing from space. Newton couldn't find it. Luckily, it turned up in scientists' brains.

Where's the Mass?

most of the universe had simply e astronomers' notice, then there enough mass — and therefore en ity — to cause the congealing.

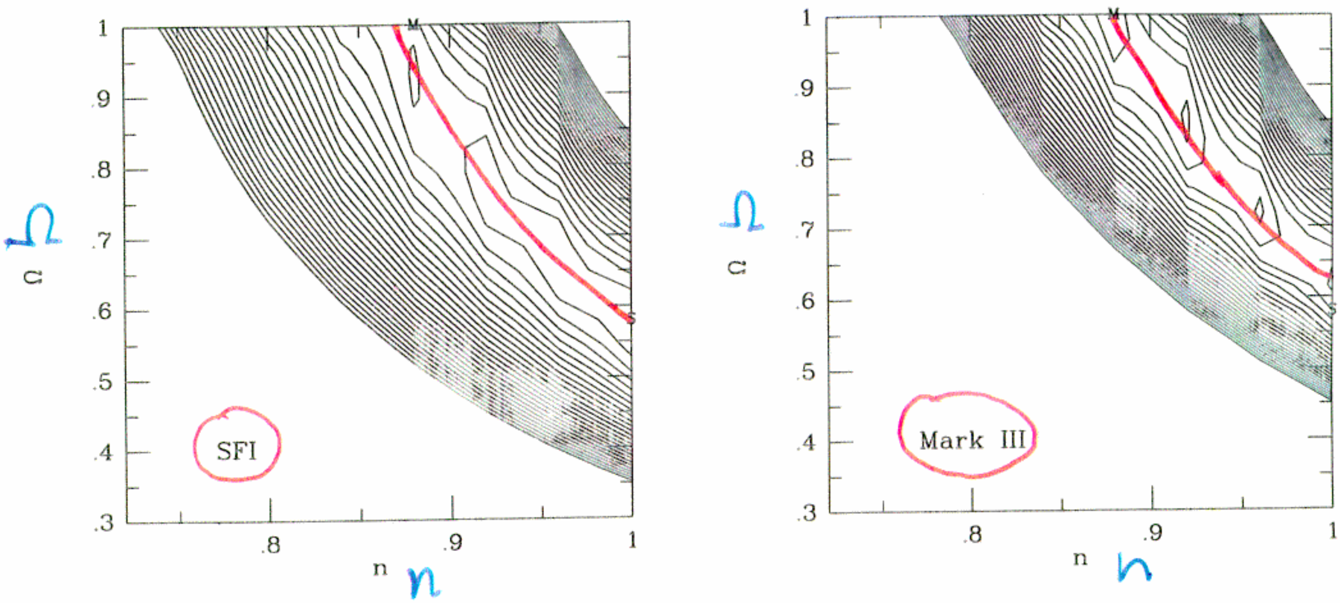
Before long, nearly every st earth had joined the cult of dark r then there came a schism. Tw called the Wimps and the Mach war over the true nature of th cosmic glue.

"Wimp" stood for Weakly I Massive Particles. No one had such things. But the believers in V the radical view that these exotic which would neither emit nor ab accounted for most of the da According to this daring heresy, made from "normal" matter, in earthlings themselves, was a m tion.

Against this disheartening vi

Continue

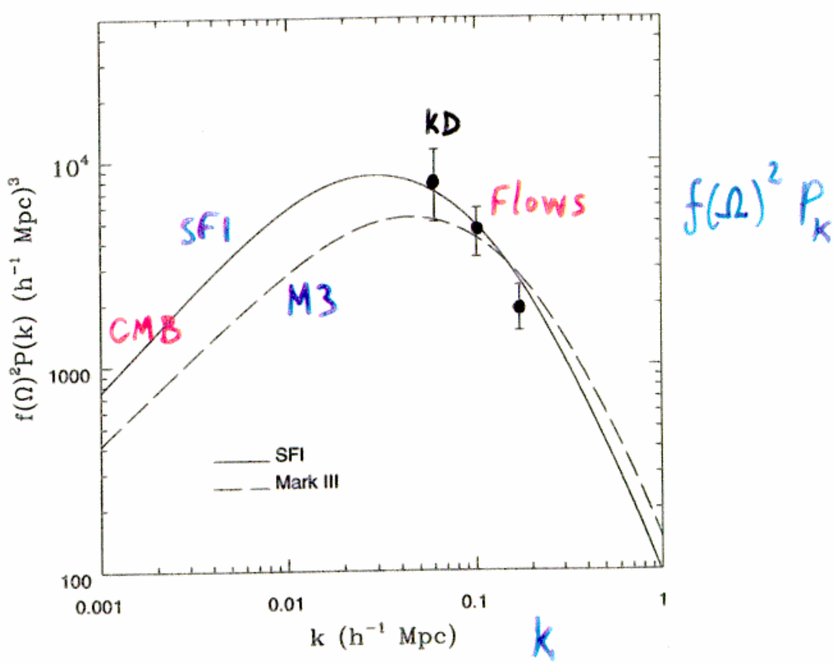
Likelihood



h=0.65

Tilted+Λ CDM

Vel. + COBE

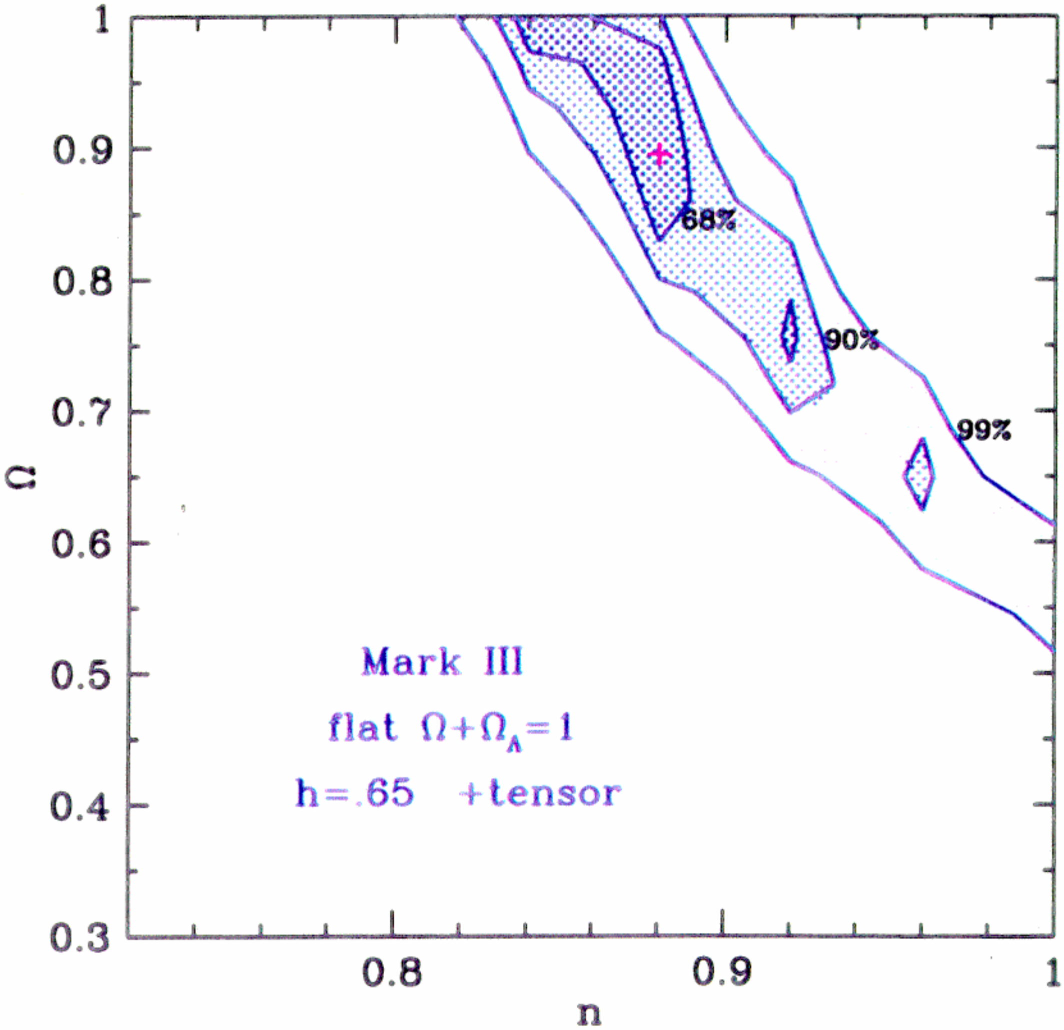


- Zaroubi et al
- Λ Zehavi et al
- Freudling

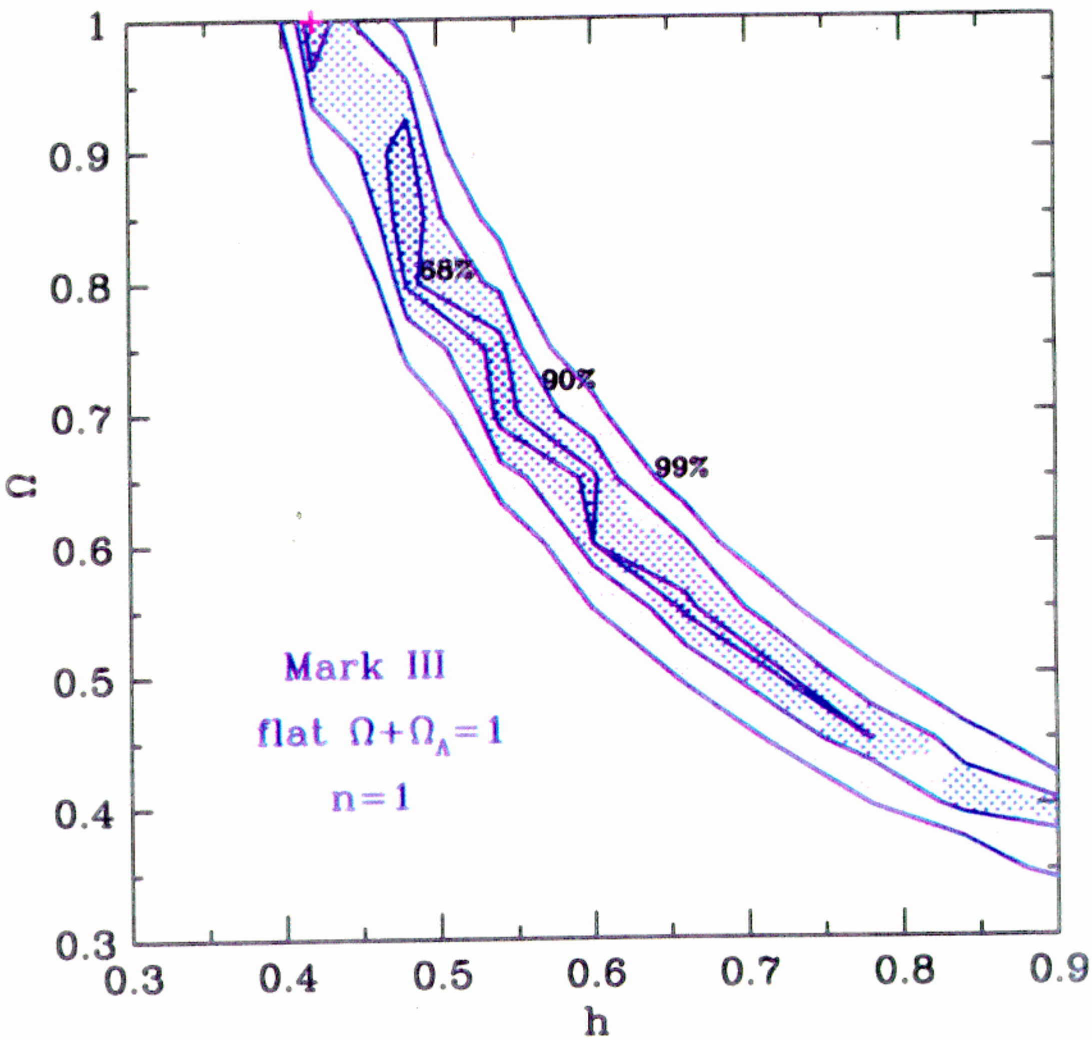
$$\Omega h_{60}^{1.2} n^2 \simeq 0.6 \pm 0.2 \quad \text{SFI}$$

$$\Omega h_{60}^{1.2} n^2 \simeq 0.7 \pm 0.2 \quad \text{M3}$$

$$\sigma_8 \Omega^{0.6} = 0.8 \pm 0.2$$

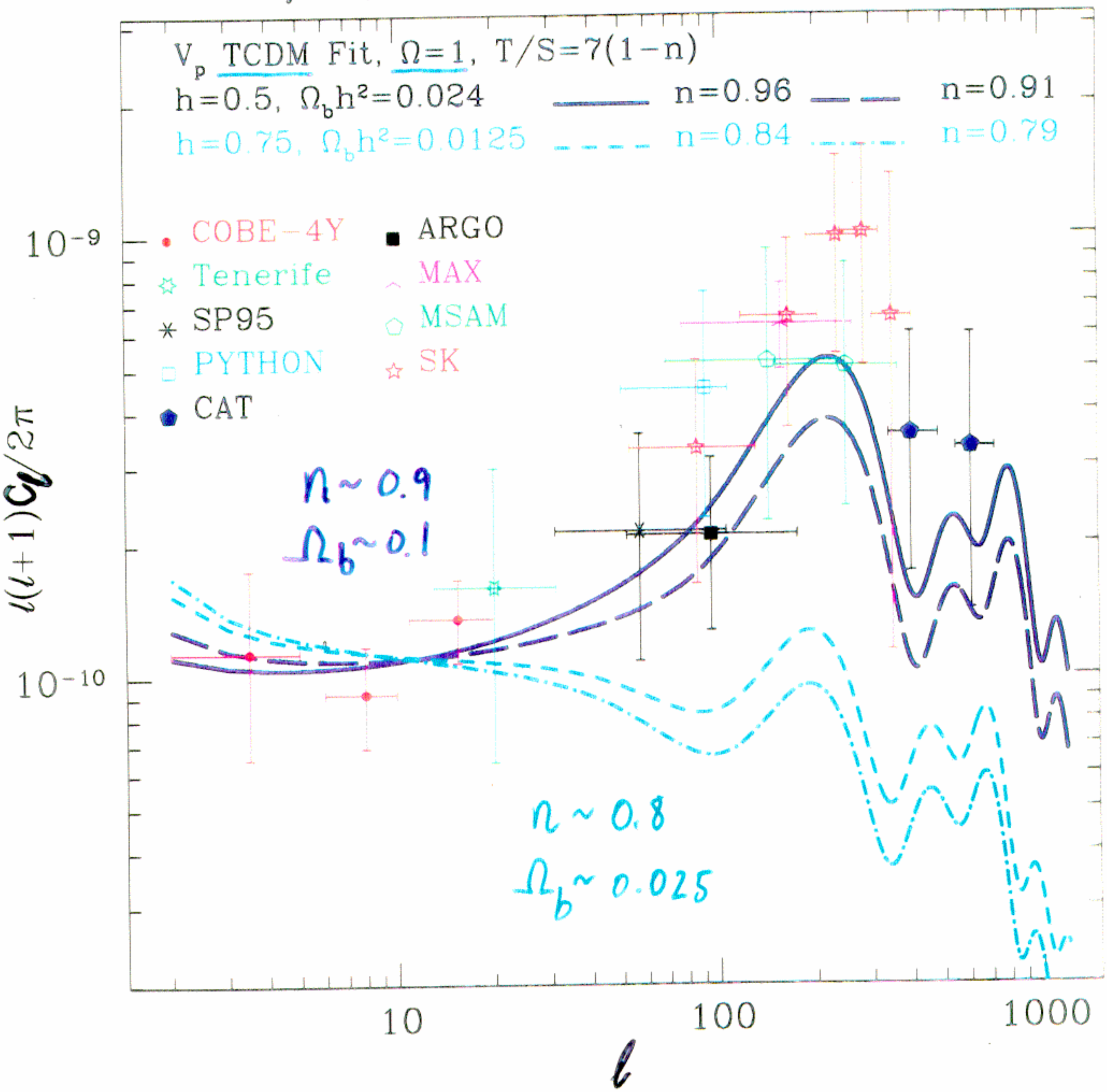


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Ω
0.8
0.9
1
n
68%
90%
99%
Mark III
flat Ω+Ω_Λ=1
h=.65 +tensor



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Ω
0.3
0.4
0.5
0.6
0.7
0.8
0.9
h
68%
90%
99%
Mark III
flat Ω+Ω_Λ=1
n=1

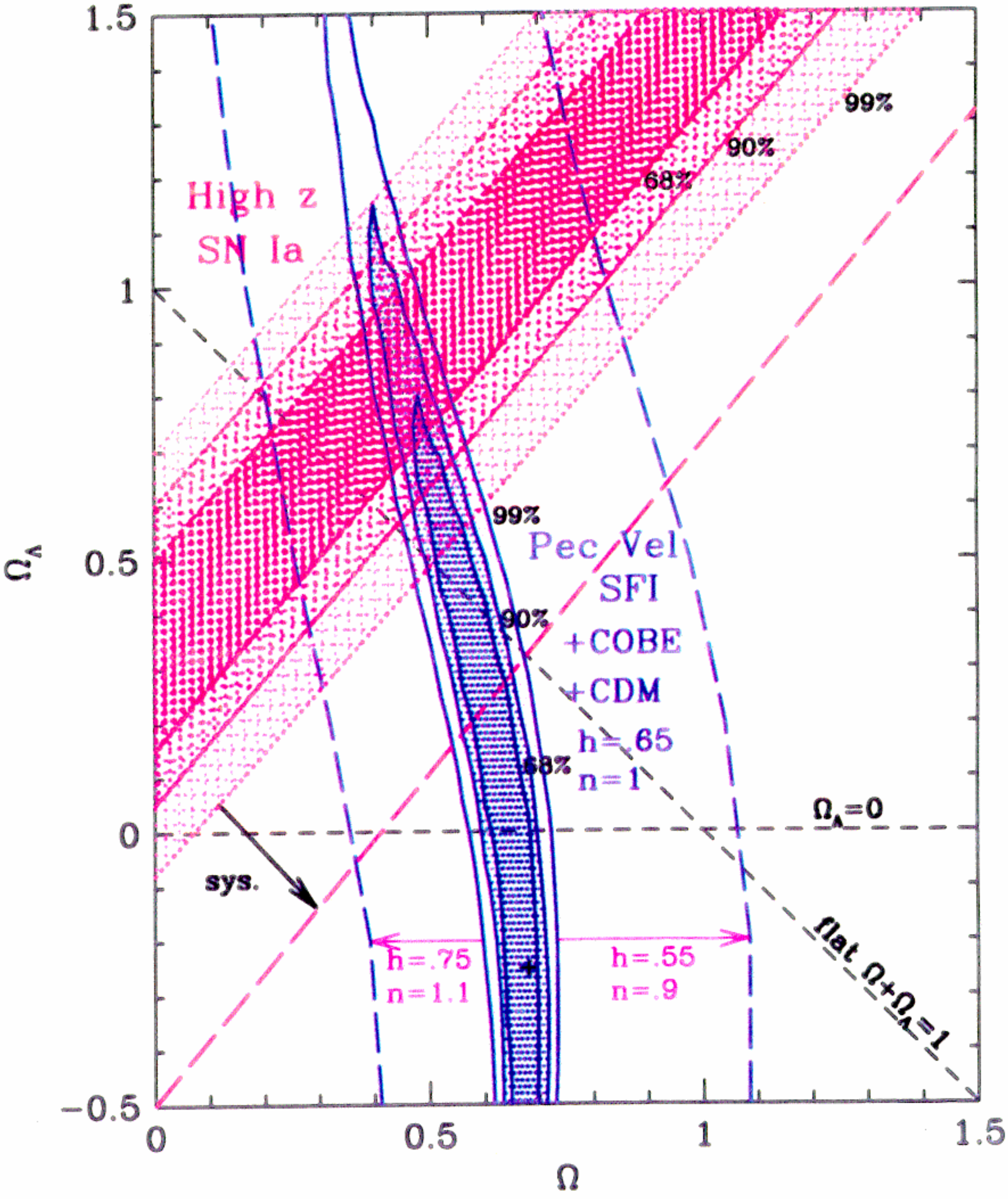
Velocity P_k → CMB C_ℓ



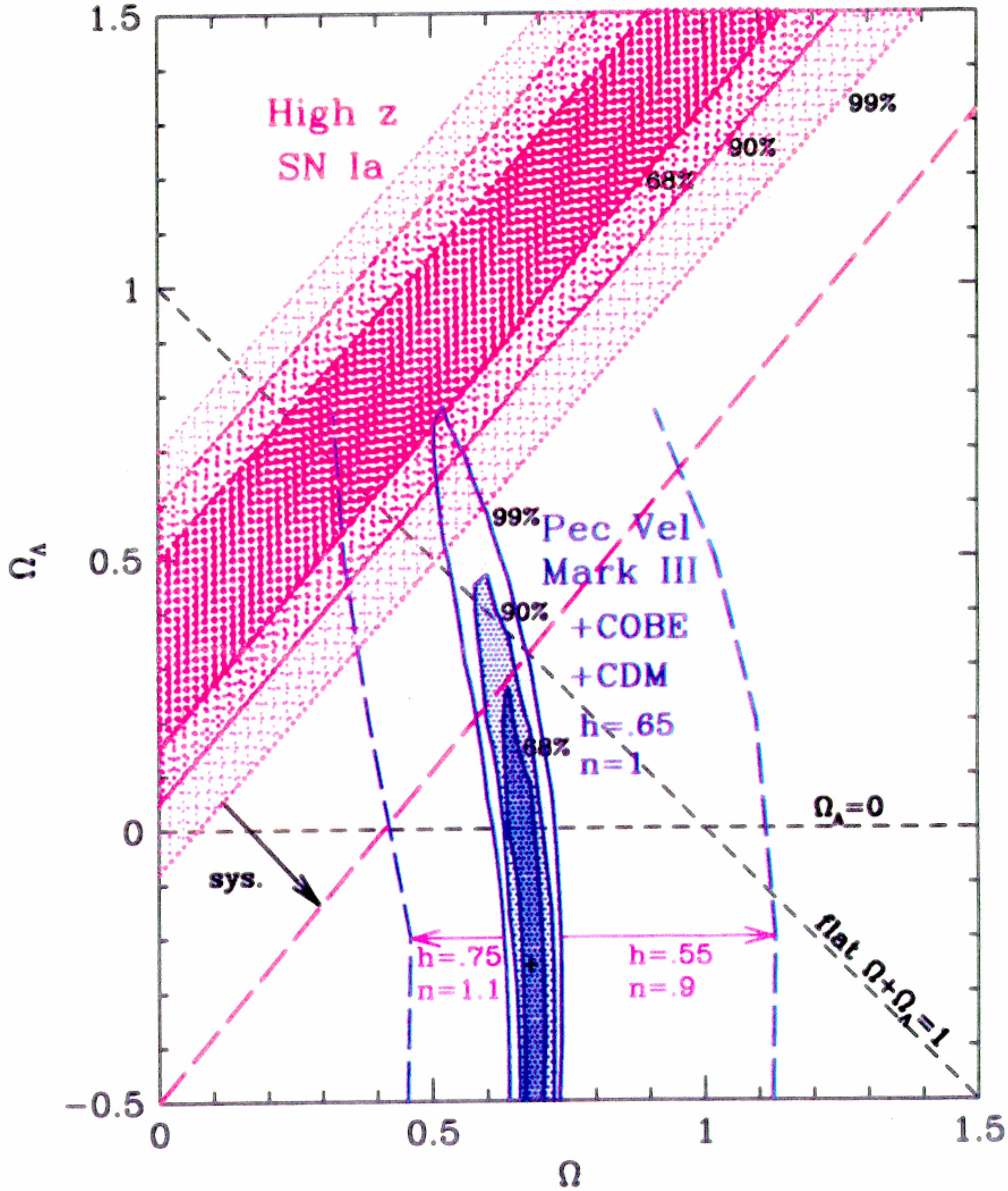
Zaroubi, Sugiyama, Silk, Hoffman, Dekel 97

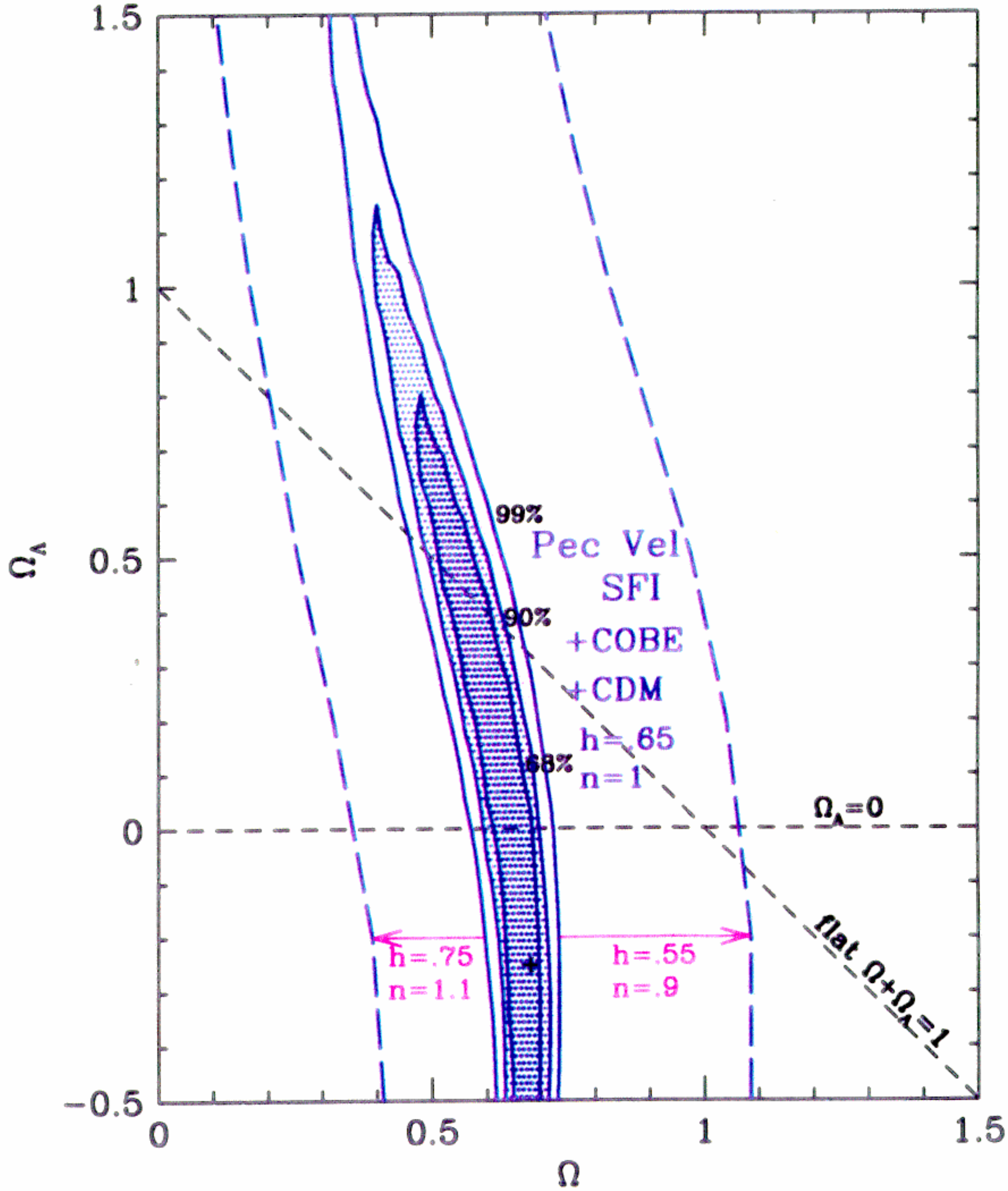
Flows + CMB for CDM models

- $V \sim 300$ $\quad \delta T/T \sim 10^{-5}$ $\rightarrow$ Gravitational growth
- $\sigma_8 \Omega^{0.6} = 0.8 \pm 0.2$ $\quad \Gamma \sim 0.3 - 0.4$ Flows
- $\Omega h_{60}^{1.2} n^2 \simeq 0.7 \pm 0.2$ Flows + COBE + CDM
  0.6 ± 0.2
- $n \gtrsim 0.9$ $\quad C_\ell$ at 1°

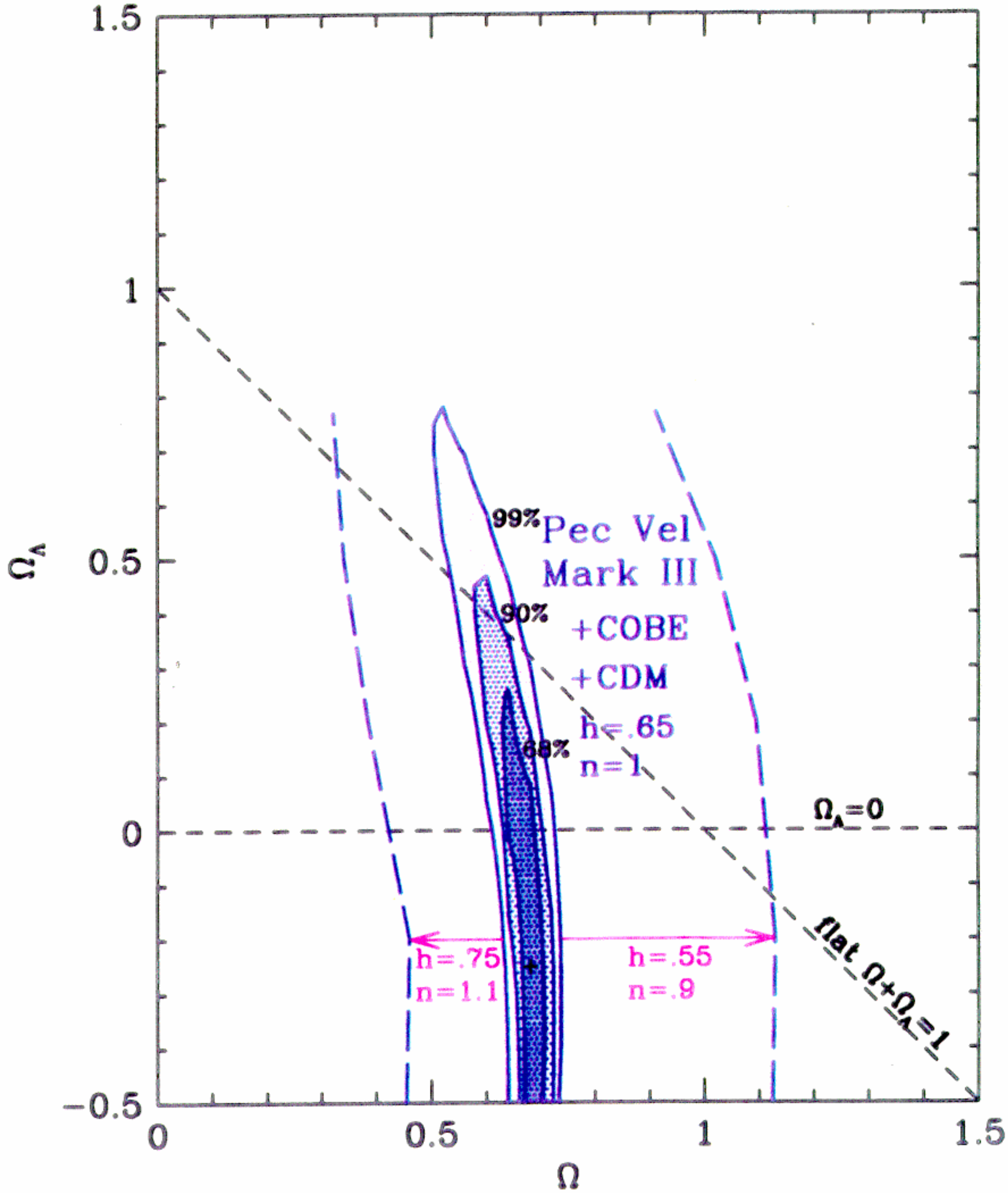


1.5
1
0.5
0
−0.5
Ω_Λ
0
0.5
1
1.5
Ω
High z
SN Ia
99%
90%
68%
99%
Pec Vel
SFI
90%
+COBE
+CDM
h=.65
n=1
68%
Ω_Λ=0
sys.
h=.75
n=1.1
h=.55
n=.9
flat $\Omega+\Omega_\Lambda=1$

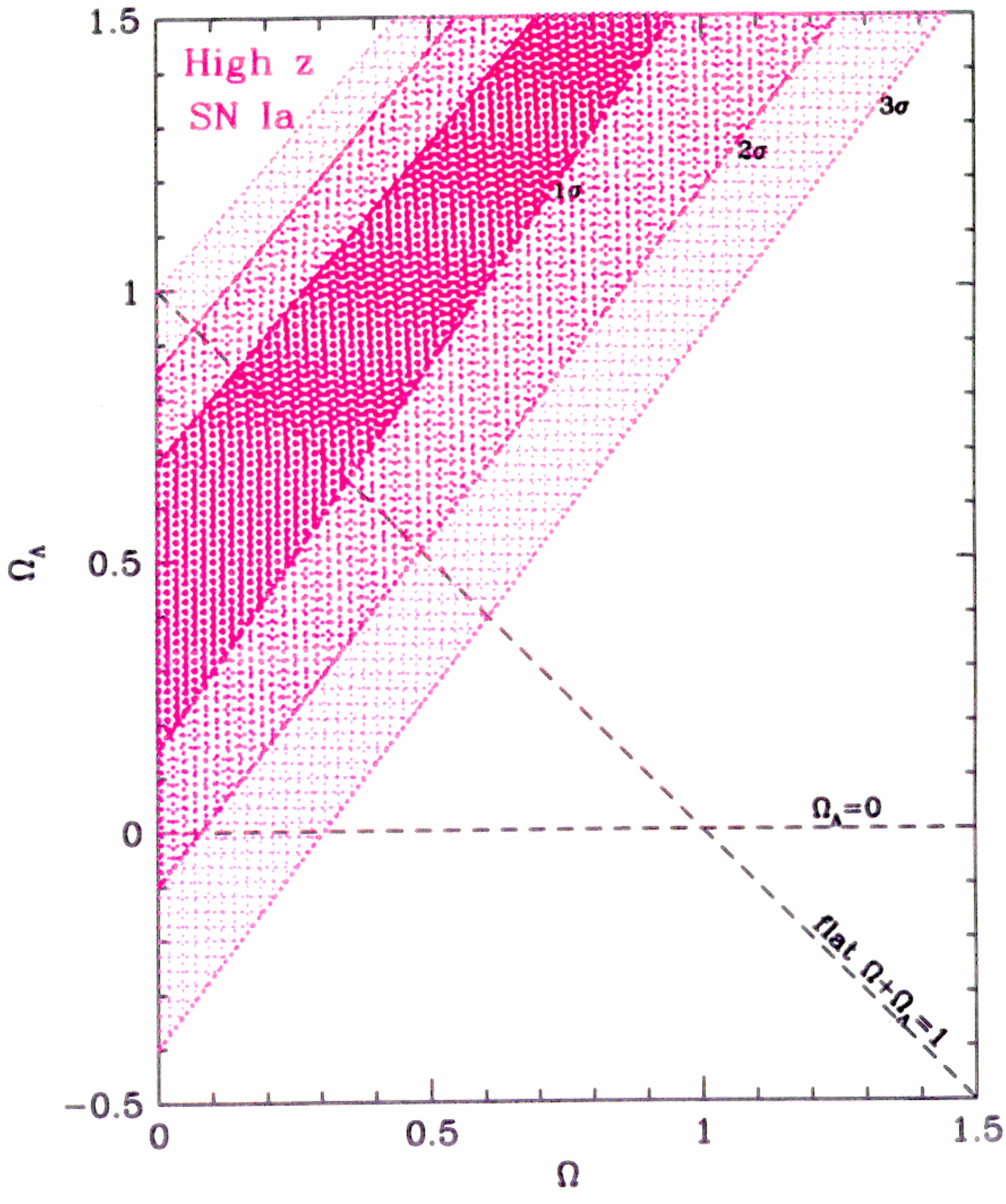

High z
SN Ia
99%
90%
68%
99%
Pec Vel
Mark III
90%
+COBE
+CDM
h=.65
68%
n=1
Ω_Λ=0
sys.
flat $\Omega+\Omega_\Lambda$=1
h=.75
n=1.1
h=.55
n=.9
1.5
1
0.5
0
−0.5
0
0.5
1
1.5
Ω_Λ
Ω



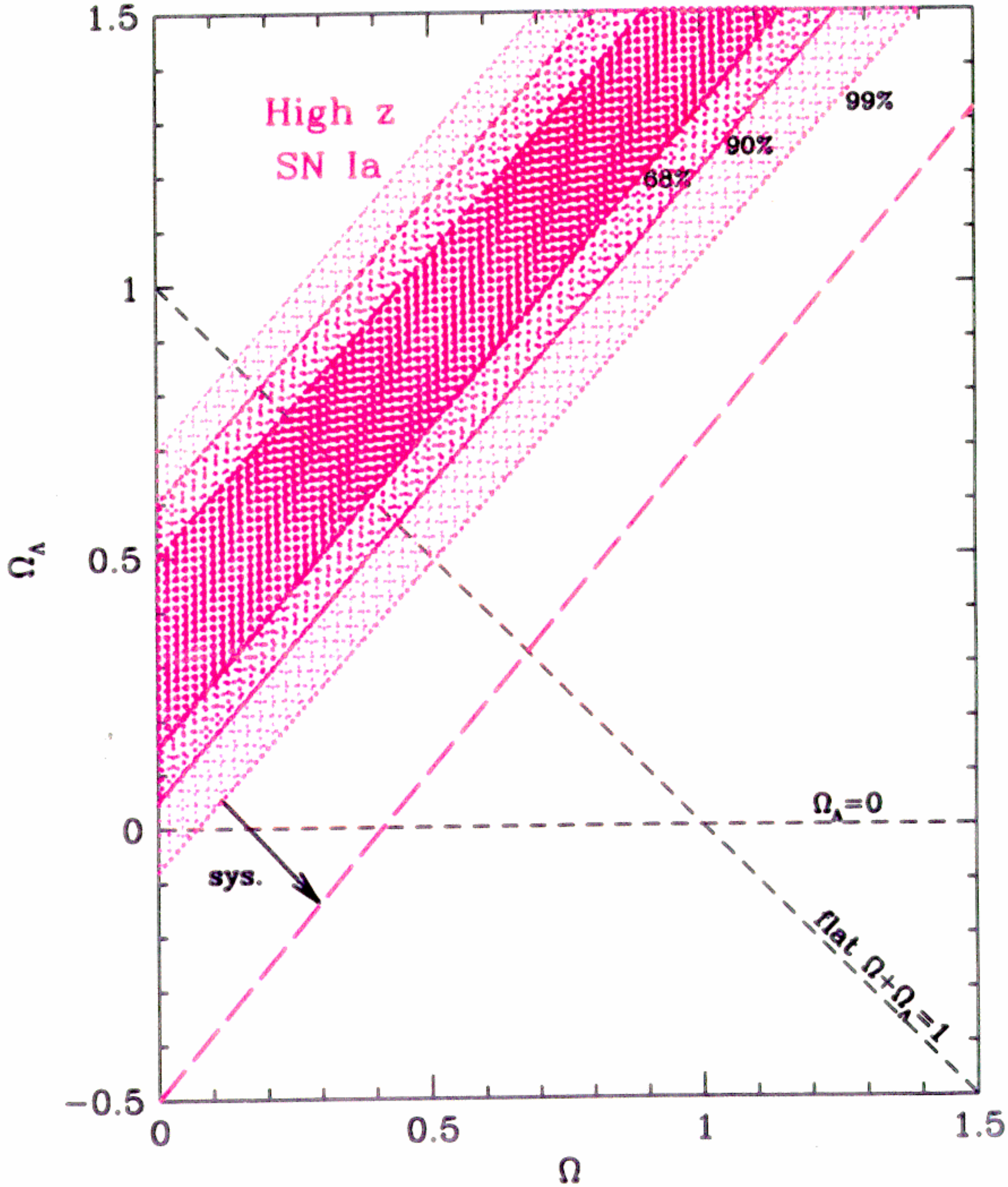
1.5
1
0.5
0
−0.5
0
0.5
1
1.5
Ω_Λ
Ω
99%
90%
68%
Pec Vel
SFI
+COBE
+CDM
h=.65
n=1
Ω_Λ=0
flat $\Omega+\Omega_\Lambda$=1
h=.75
n=1.1
h=.55
n=.9



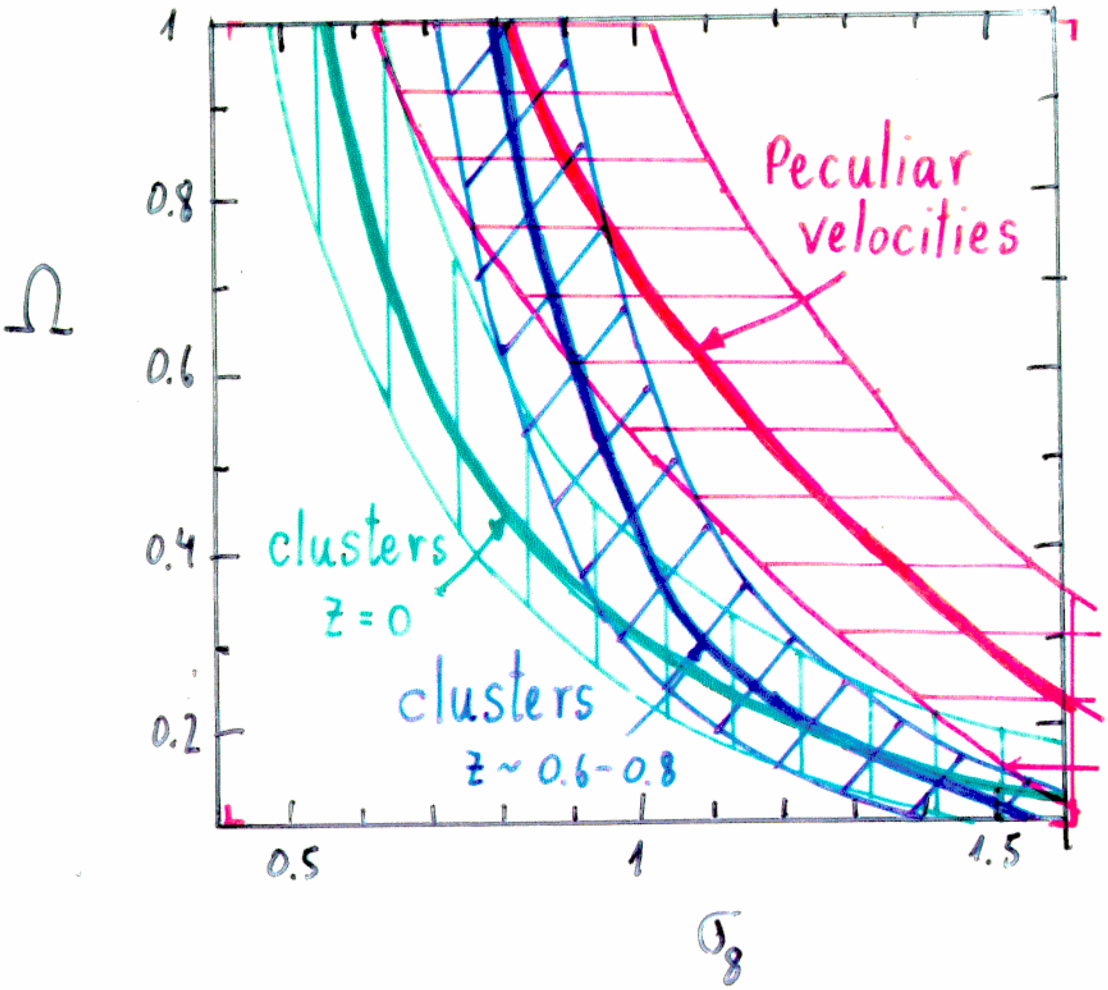
1.5
1
0.5
0
−0.5
0
0.5
1
1.5
Ω_Λ
Ω
99%
90%
68%
Pec Vel
Mark III
+COBE
+CDM
h=.65
n=1
Ω_Λ=0
flat $\Omega+\Omega_\Lambda$=1
h=.75
n=1.1
h=.55
n=.9


High z
SN Ia
1σ
2σ
3σ
Ω_Λ=0
flat $\Omega+\Omega_\Lambda$=1
1.5
1
0.5
0
−0.5
0
0.5
1
1.5
Ω_Λ
Ω

A. Dekel, SSI 1998



$$n \propto \frac{\delta_c}{\sigma} e^{-\delta_c^2/2\sigma^2}$$



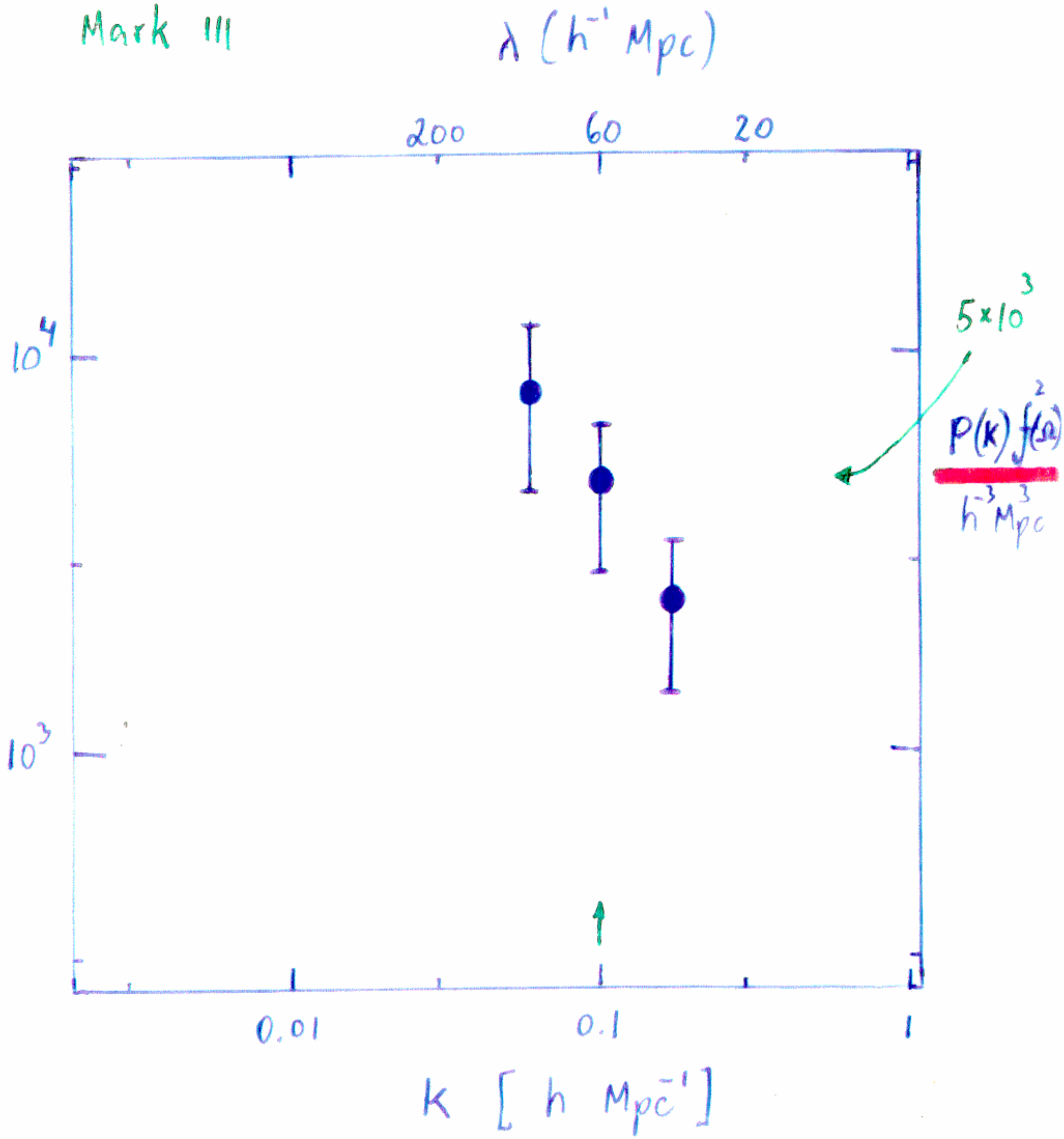
$\sigma_8 \Omega^{0.5} = 0.55 \pm 0.1$ White etal 93, Eke etal 96,

$\sigma_8 \Omega^{0.3} = 0.8 \pm 0.1$ Bahcall & Fan 98

$\sigma_8 \Omega^{0.6} = 0.8 \pm 0.2$ Zaroubi etal 98
Freudling etal 98

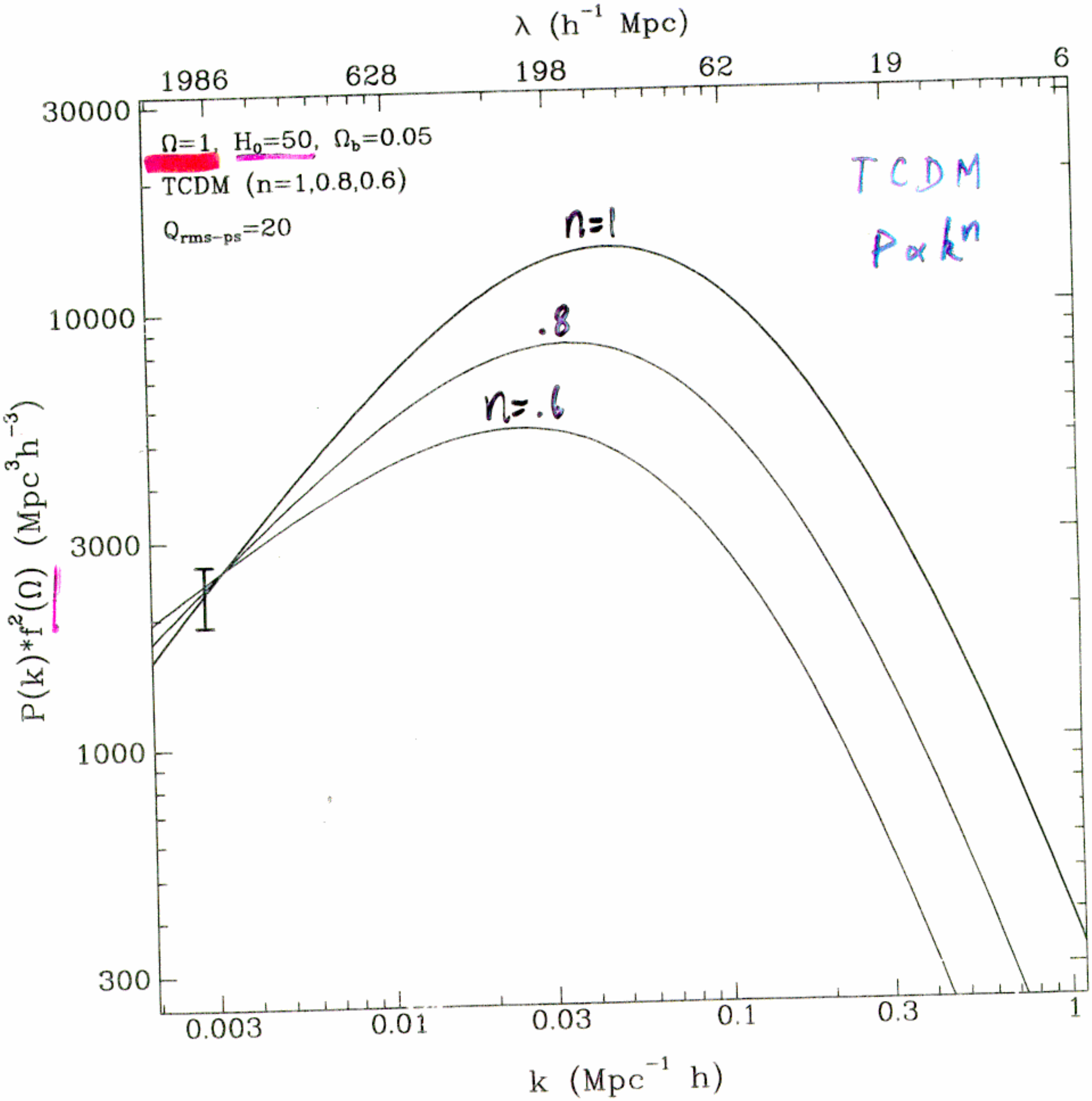
Mass-Density Power Spectrum

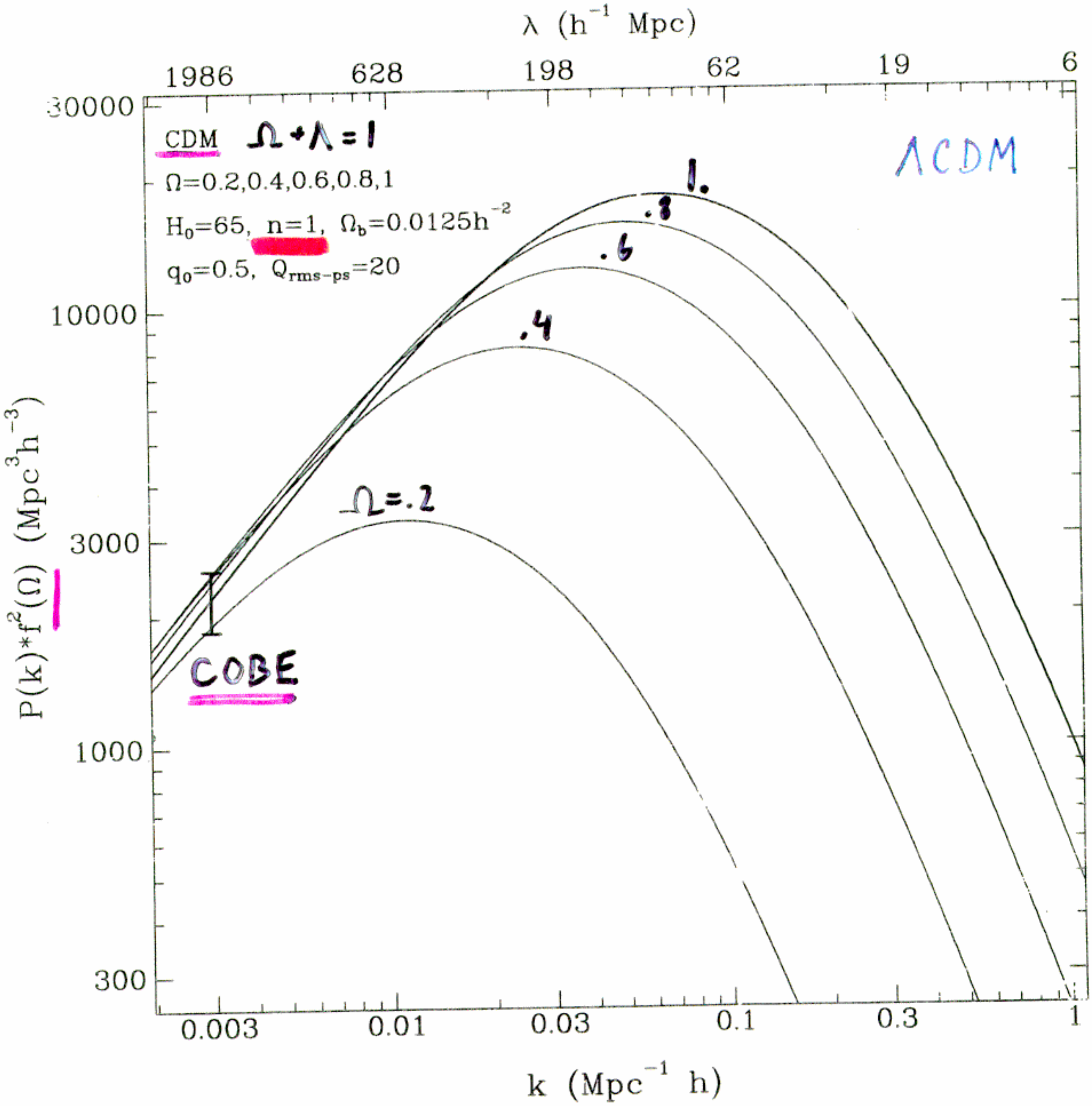
Mark III



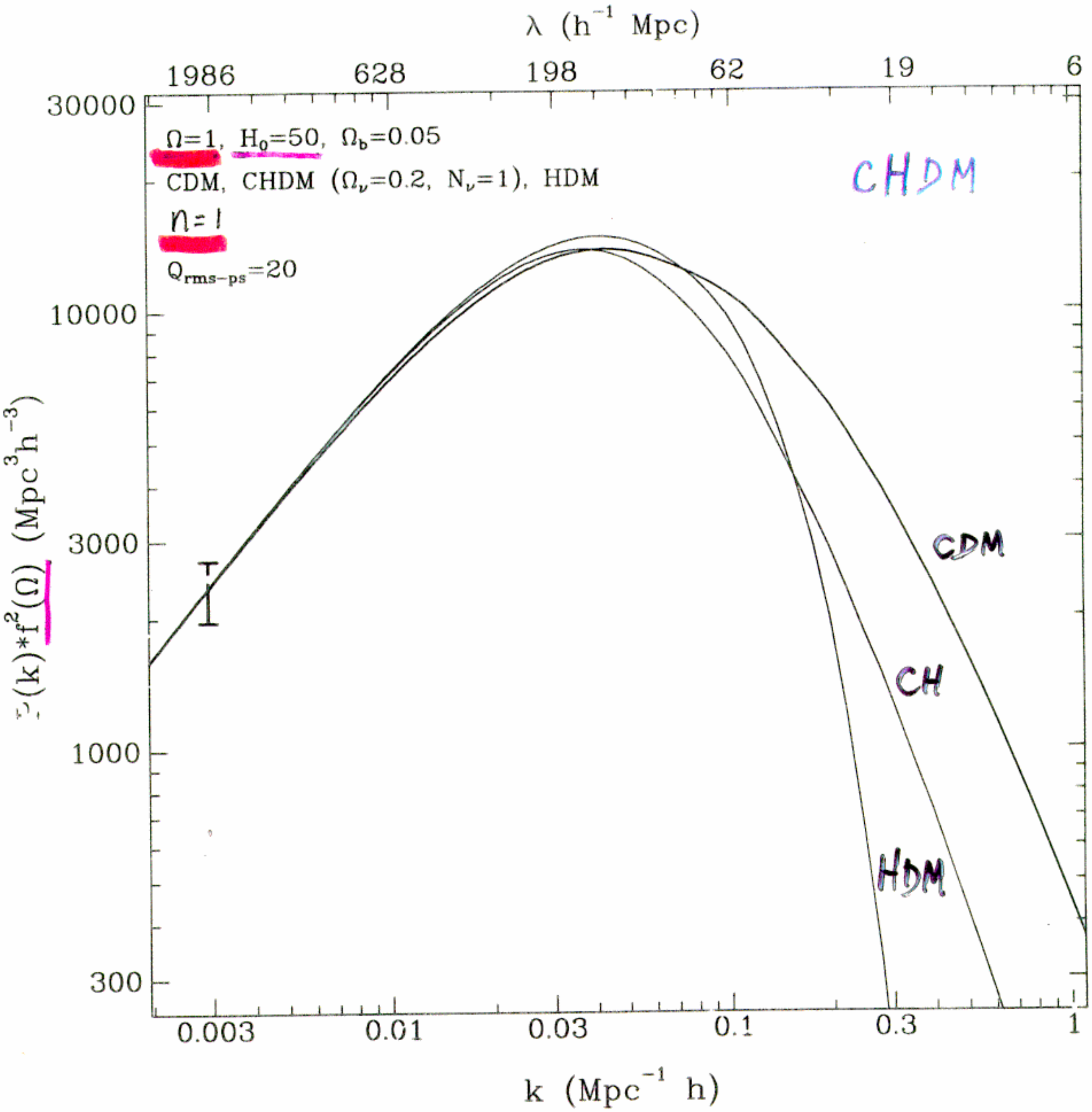
Kolatt + Dekel 96 $P(k) = (5 \pm 2) \times 10^{3}\, \Omega^{-1.2} \left(\frac{k}{0.1}\right)^{-1.4 \pm .2}$

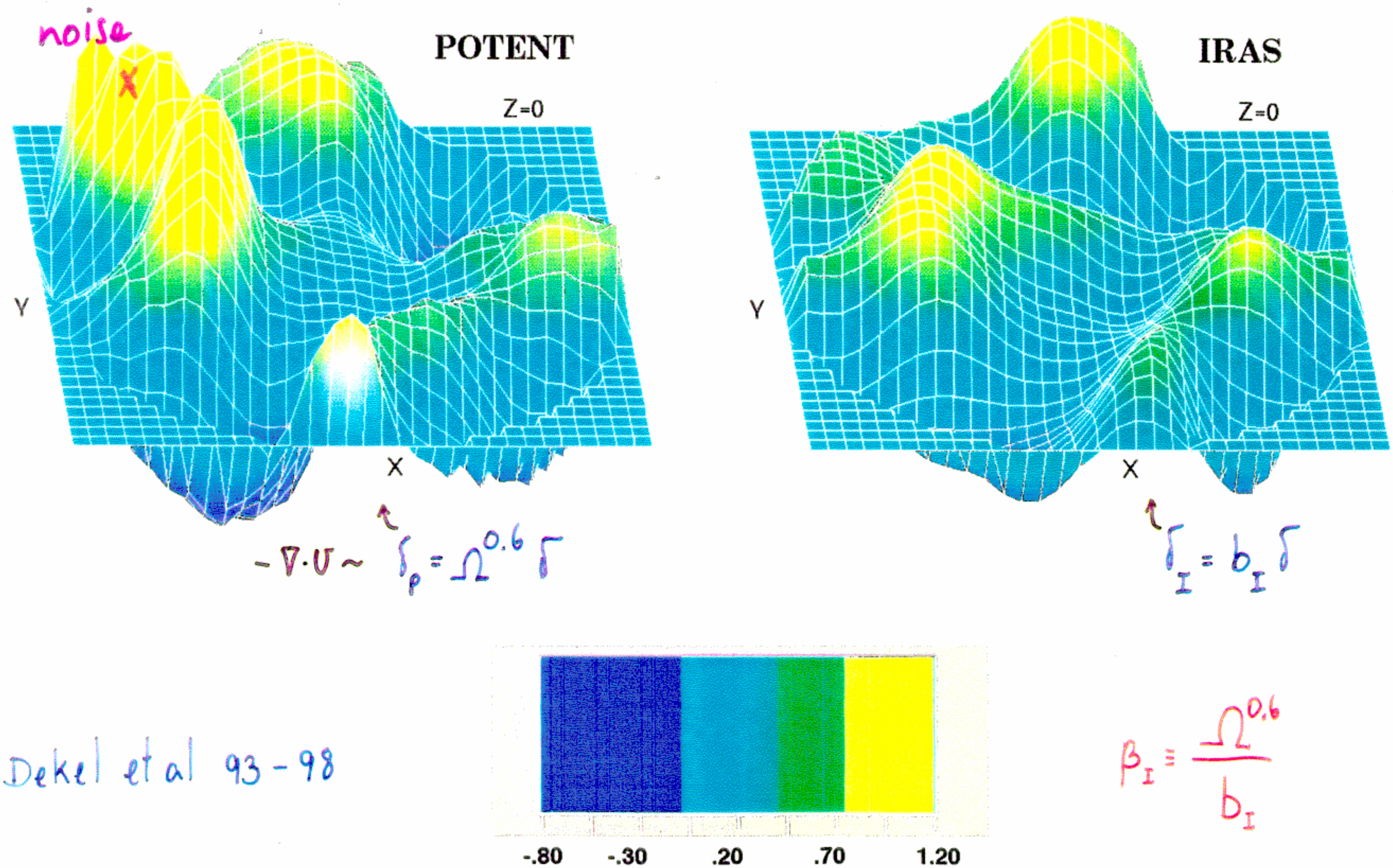
Zaroubi, Dekel, Hoffman 96 $\sigma_8 \Omega^{0.6} = 0.80 \pm .2$


λ (h⁻¹ Mpc)
1986
628
198
62
19
6
30000
10000
3000
1000
300
Ω=1, H₀=50, Ω_b=0.05
TCDM (n=1,0.8,0.6)
Q_rms-ps=20
TCDM
P ∝ k^n
n=1
.8
n=.6
P(k)*f²(Ω) (Mpc³h⁻³)
0.003
0.01
0.03
0.1
0.3
1
k (Mpc⁻¹ h)


λ (h^-1 Mpc)
1986
628
198
62
19
6
30000
10000
3000
1000
300
CDM Ω+Λ=1
Ω=0.2,0.4,0.6,0.8,1
H0=65, n=1, Ωb=0.0125h^-2
q0=0.5, Qrms-ps=20
ΛCDM
1.
.8
.6
.4
Ω=.2
COBE
P(k)*f²(Ω) (Mpc³h^-3)
0.003
0.01
0.03
0.1
0.3
1
k (Mpc^-1 h)

A. Dekel, SSI 1998





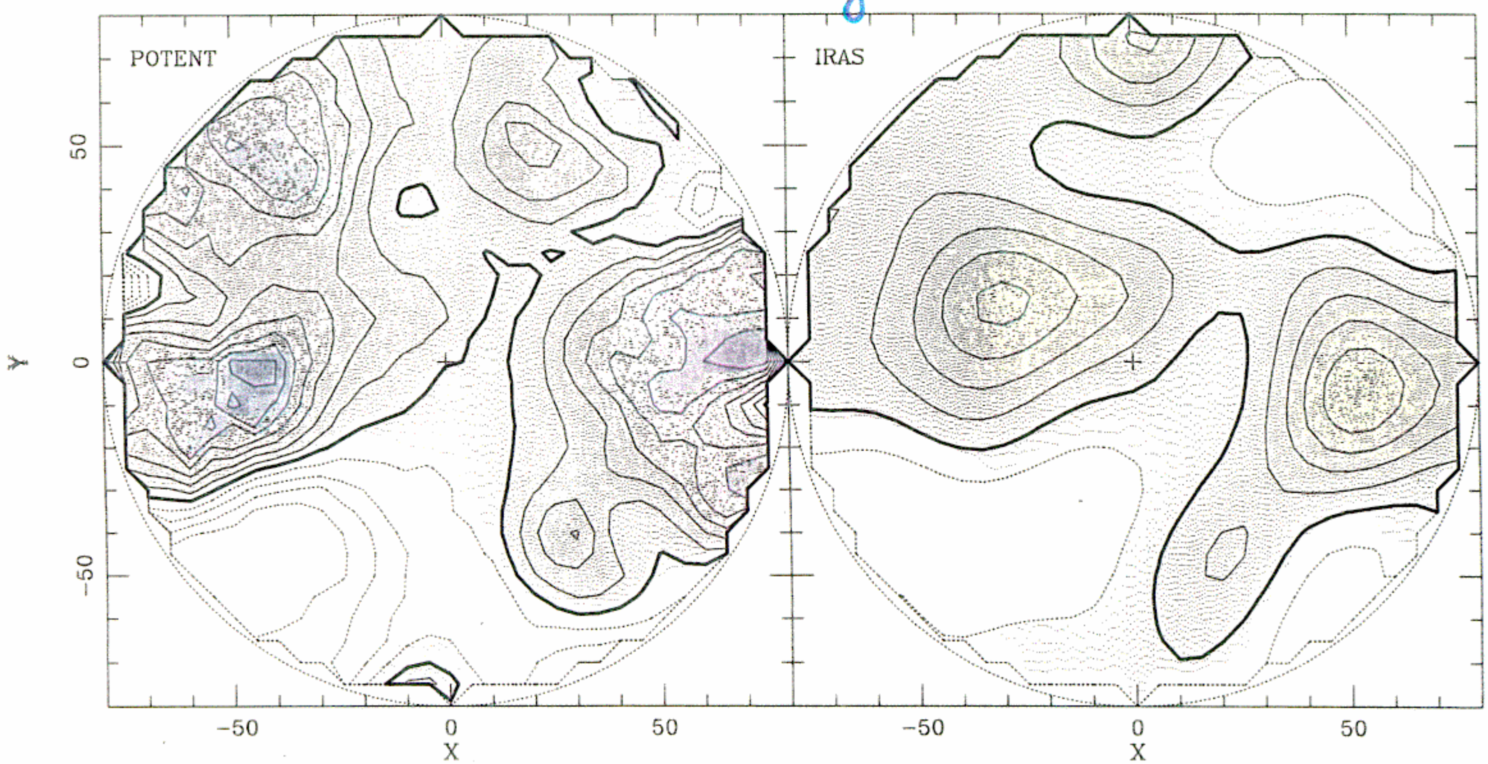
$-\nabla\cdot v \sim \delta_p = \Omega^{0.6}\delta$

$\delta_I = b_I \delta$

$\beta_I \equiv \frac{\Omega^{0.6}}{b_I}$

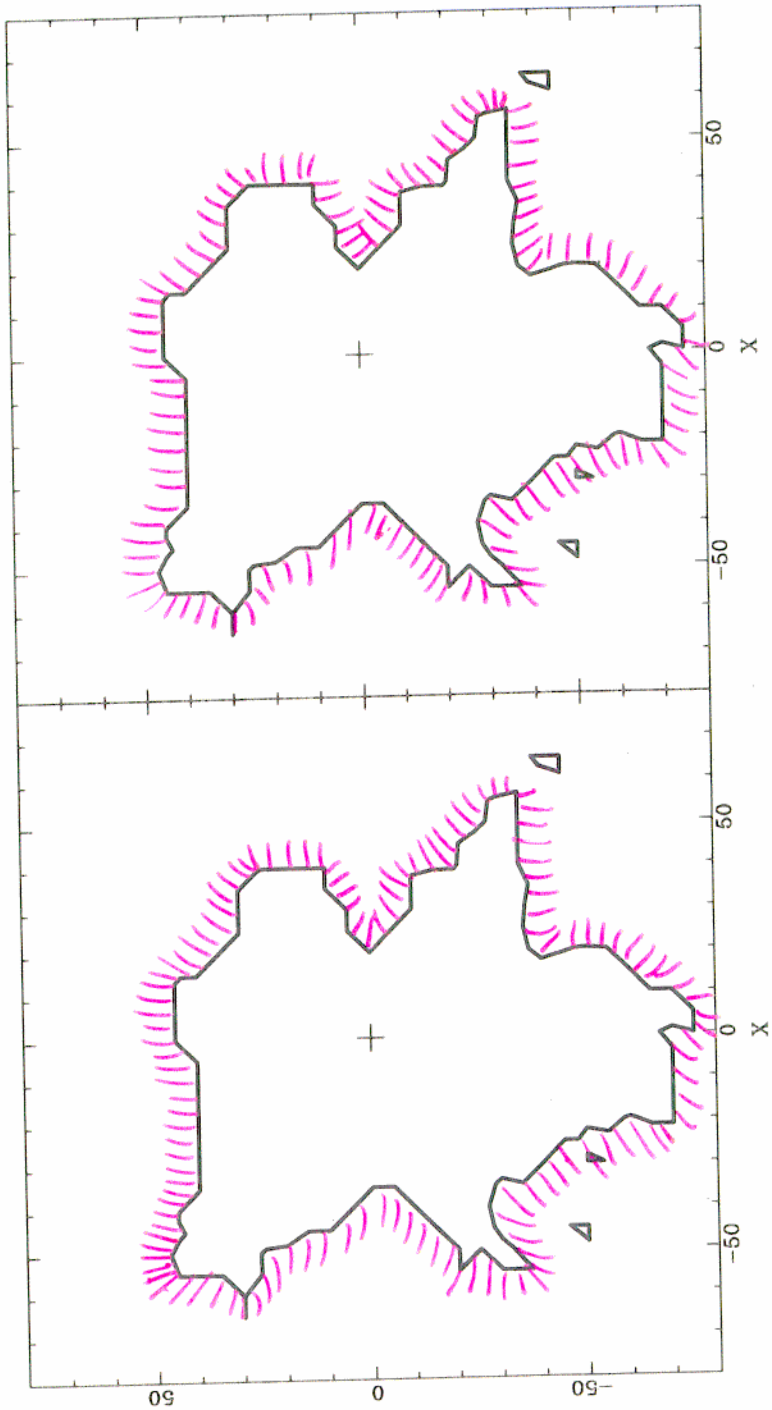
Dekel et al 93-98

Mass Light

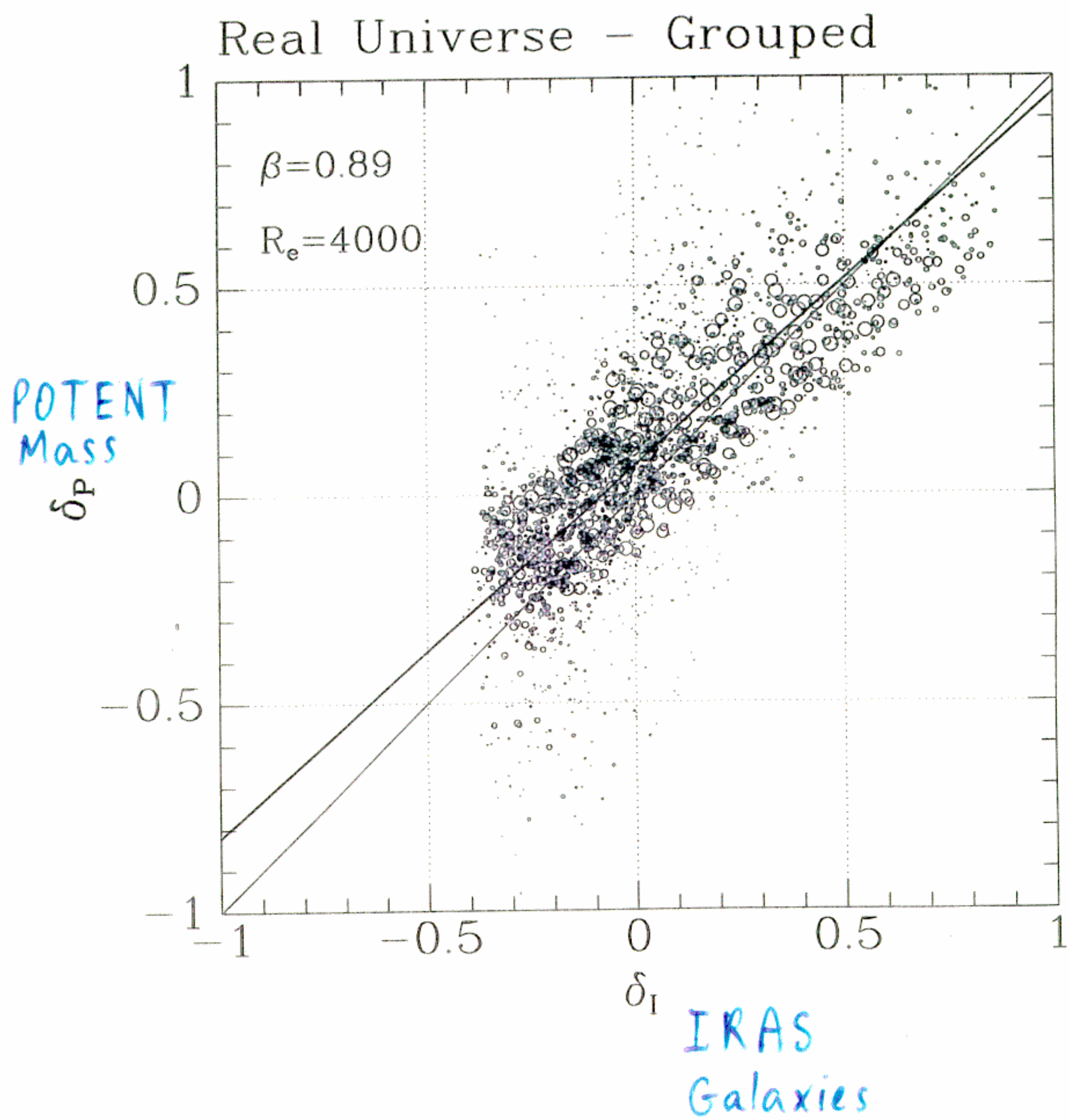


$$-\nabla \cdot v = \Omega^{0.6} \delta \qquad \delta_{gal} = b_{gal} \delta$$

$$\rightarrow \beta \equiv \frac{\Omega^{0.6}}{b_{gal}}$$

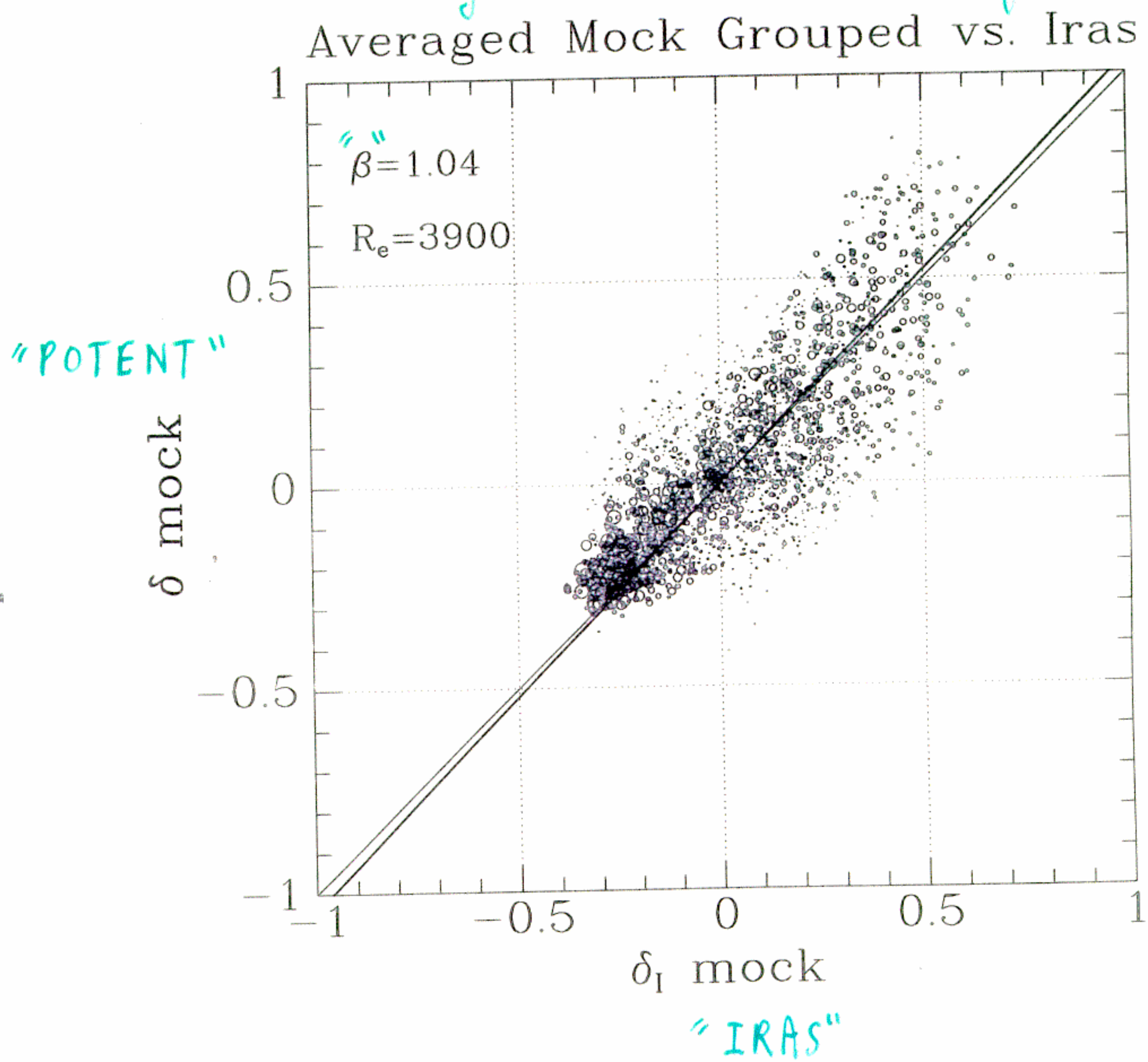


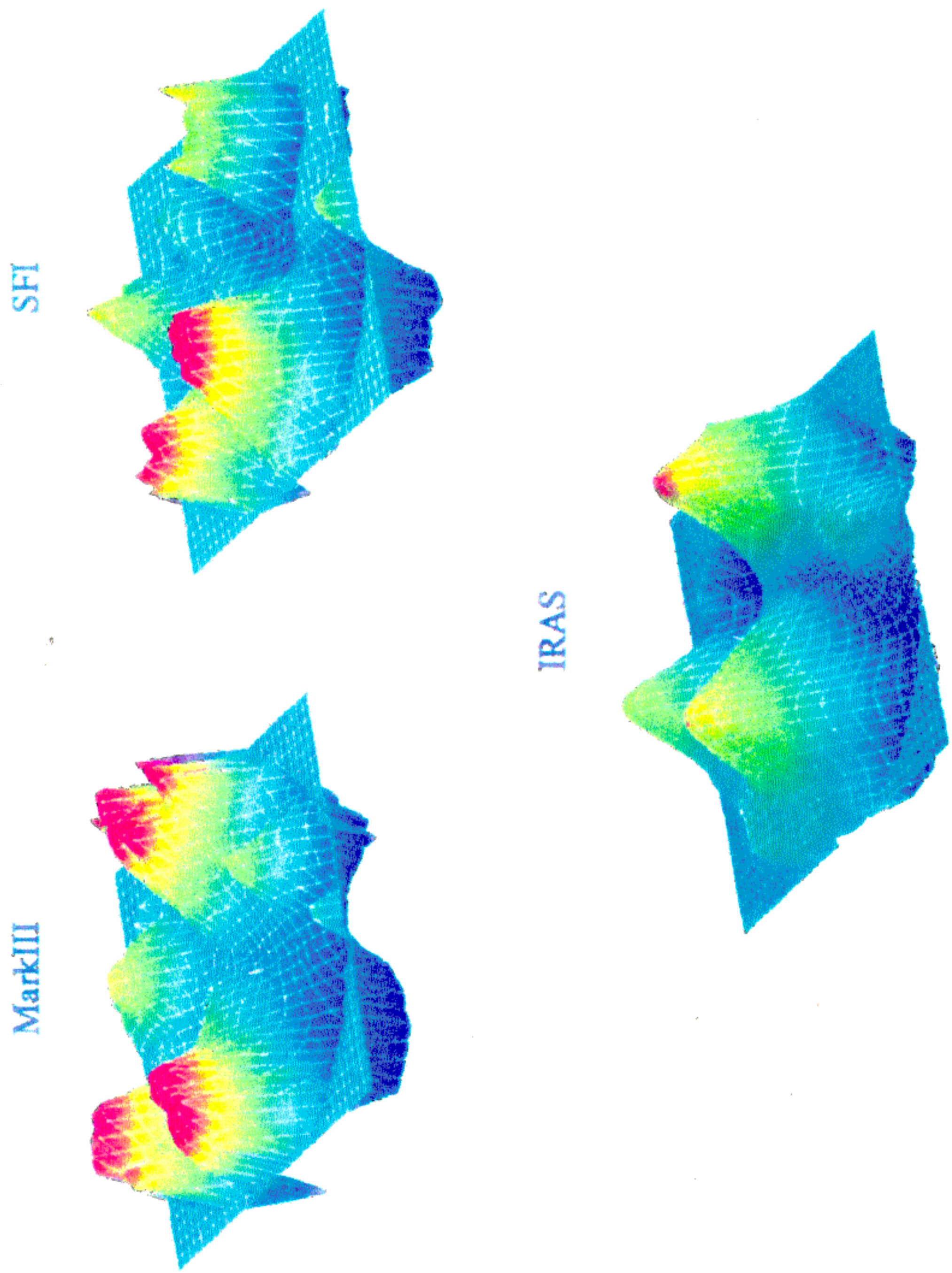
50
0
−50
X



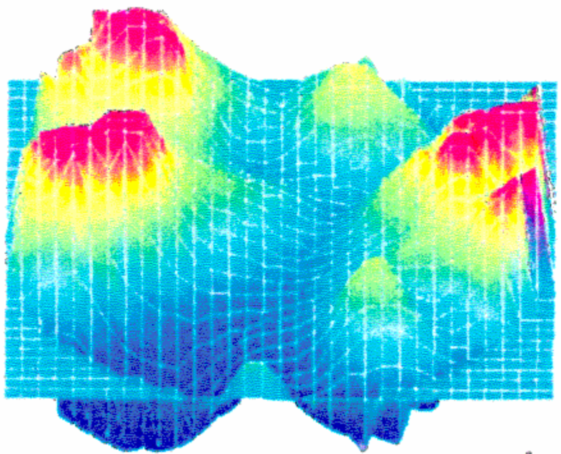
Eldar Sigad, Dekel, Strauss, Yahil 98

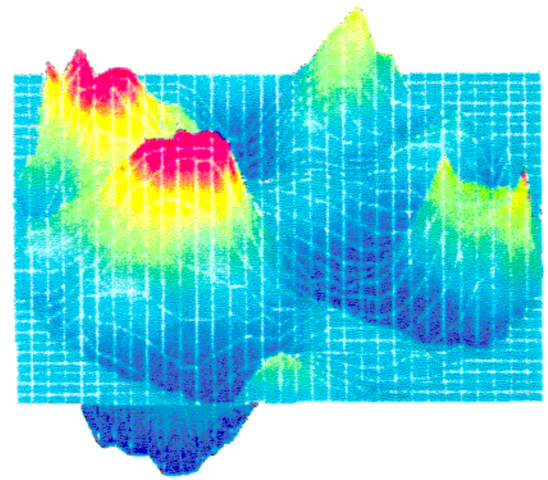
Testing with Mock Catalogs




SFI
MarkIII
IRAS

MarkIII POTENT → Mass SFI



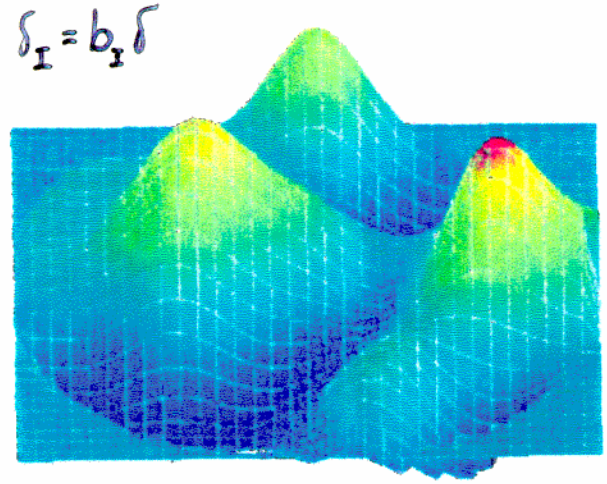


$-\nabla \cdot U \sim \delta_p = \Omega^{0.6} \delta$

$\beta_I \equiv \frac{\Omega^{0.6}}{b_I}$ ⇐

IRAS Galaxies

$\delta_I = b_I \delta$



V_{pec} vs. ρ_{gal} → $\beta \equiv \Omega^{0.6}/b$

Mark III   IRAS 1.2 Jy

- $\delta - \delta$ 12 h^{-1}Mpc   (POTIRAS   Sigad et al 98)

  GI, $\delta_g \sim b\delta$ $\chi^2 \sim 1$ $R<50$

  $\beta_{I,12} = 0.89 \pm 0.15$

- $v - v$ 3 h^{-1}Mpc   (VELMOD   Willick et al 97)

  $\beta_{I,3} = 0.5 \pm 0.1$ $\chi^2 \sim 1$ $R<30$

- $v - v$ (ITF   Davis et al 96)

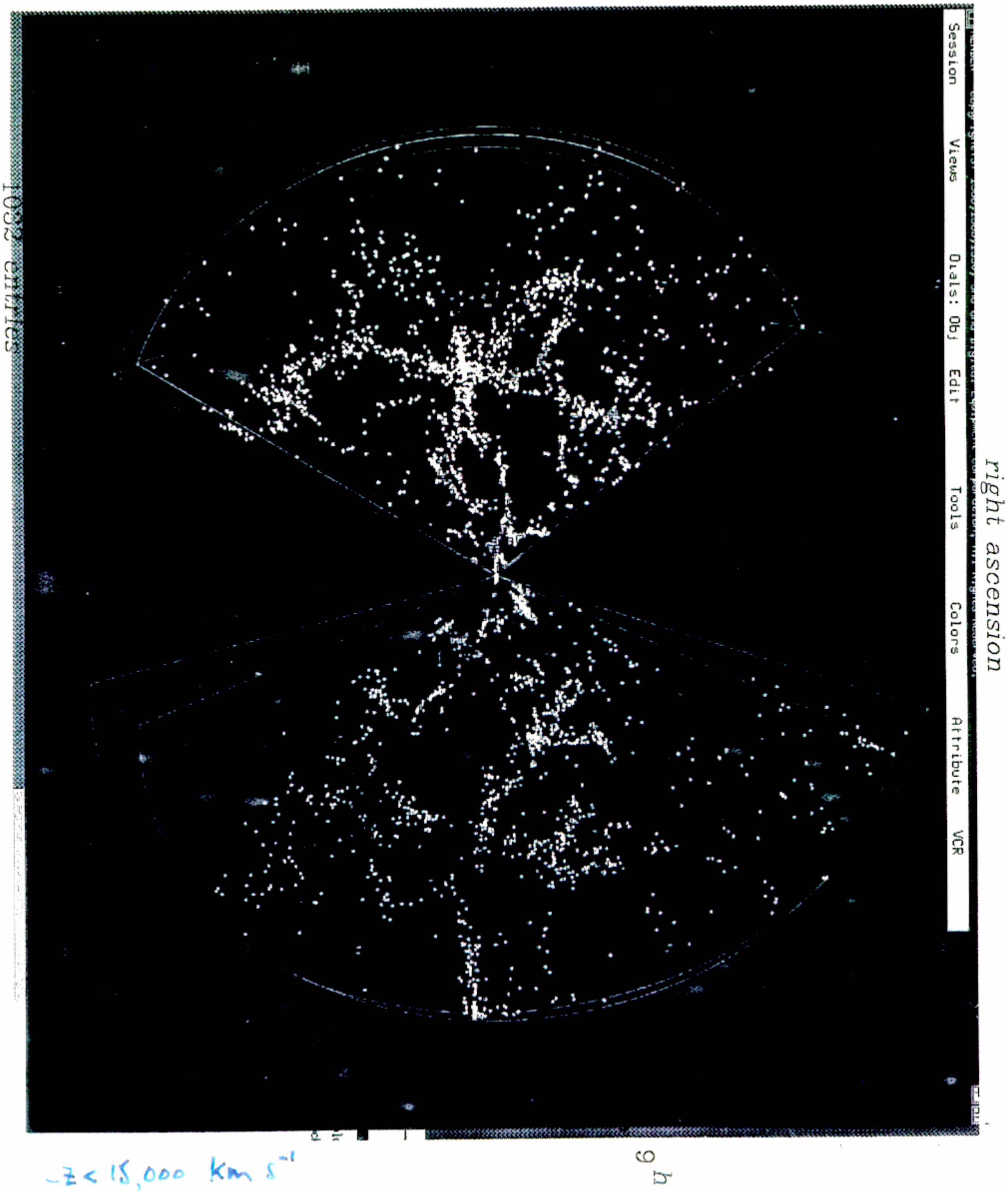
  $\beta_I \sim 0.5$ $\chi^2 > 1$ at $R>30$

- $\delta - v$ (SIMPOT   Nusser & A.D. 97)

  $\beta_{I,12} = 1.0 \pm 0.15$ $\beta_{I,6} = 0.6 \pm 0.1$

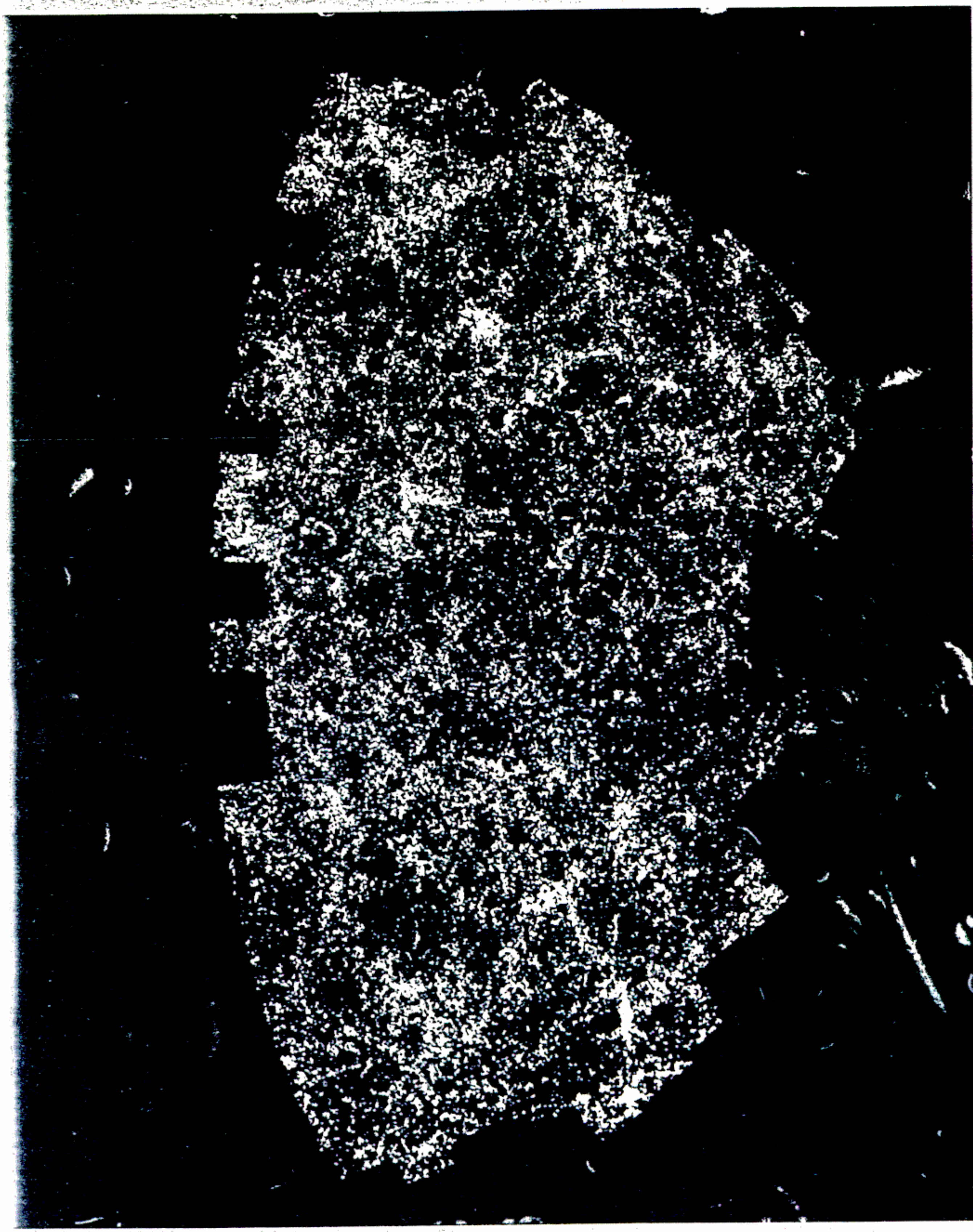
→ Non-trivial biasing:
- Scale dependent
- Non-linear
- Stochastic

The "Great Wall" (Geller, Huchra, ... da Costa 1990)

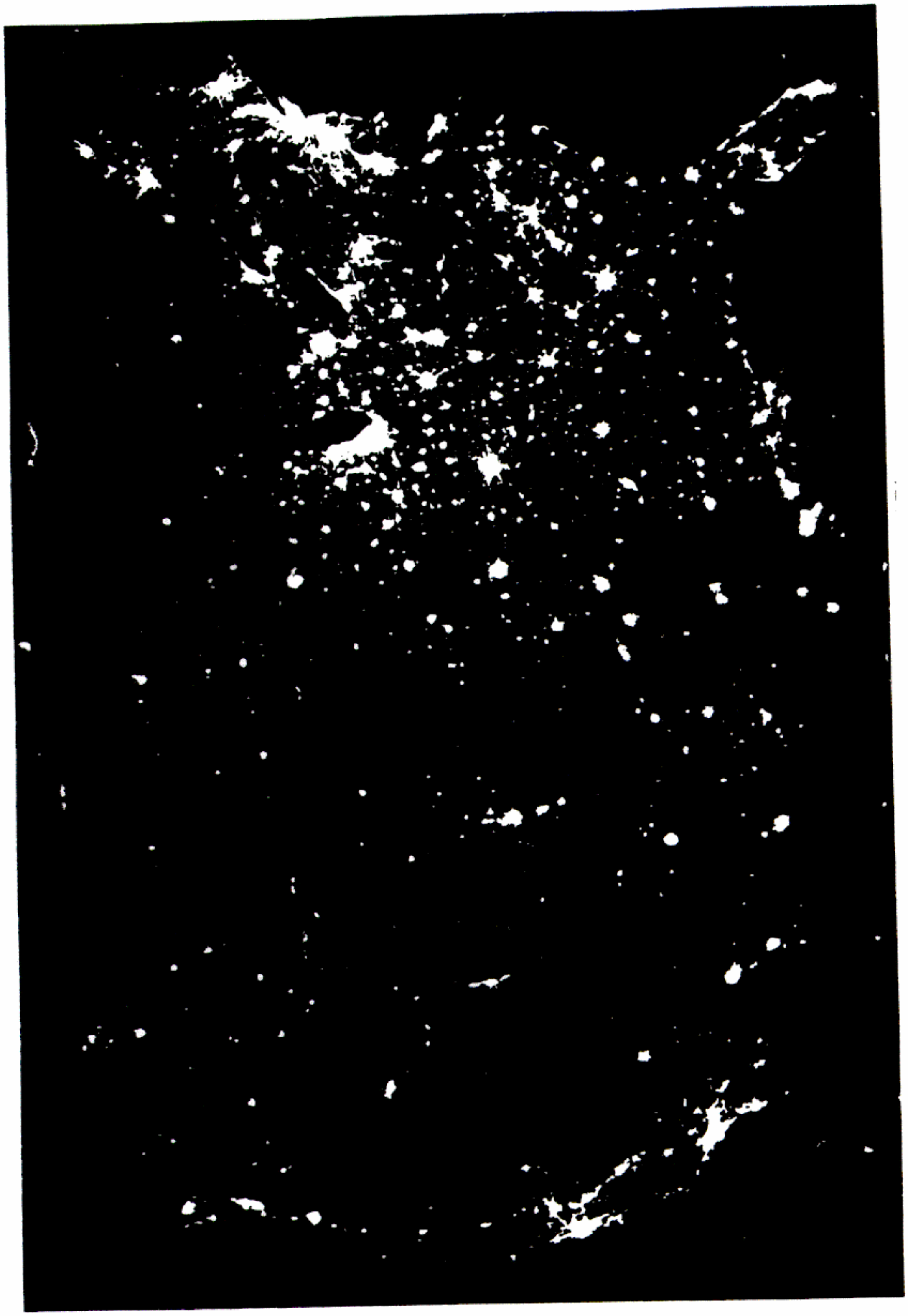


$cz < 15{,}000$ km s^{-1}

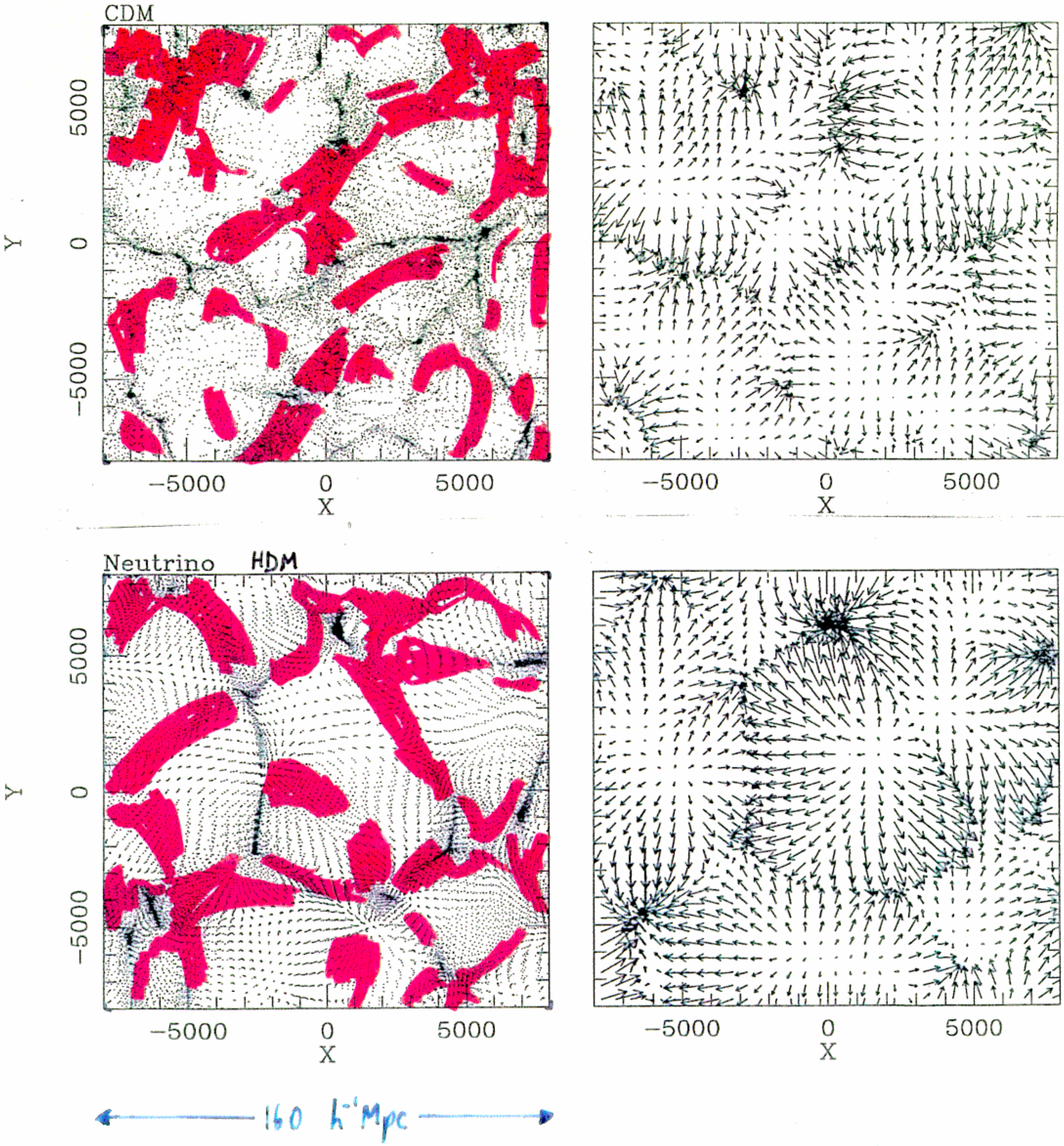
$m < 14.5$ $\quad$ $20^\circ < \delta < 40^\circ$



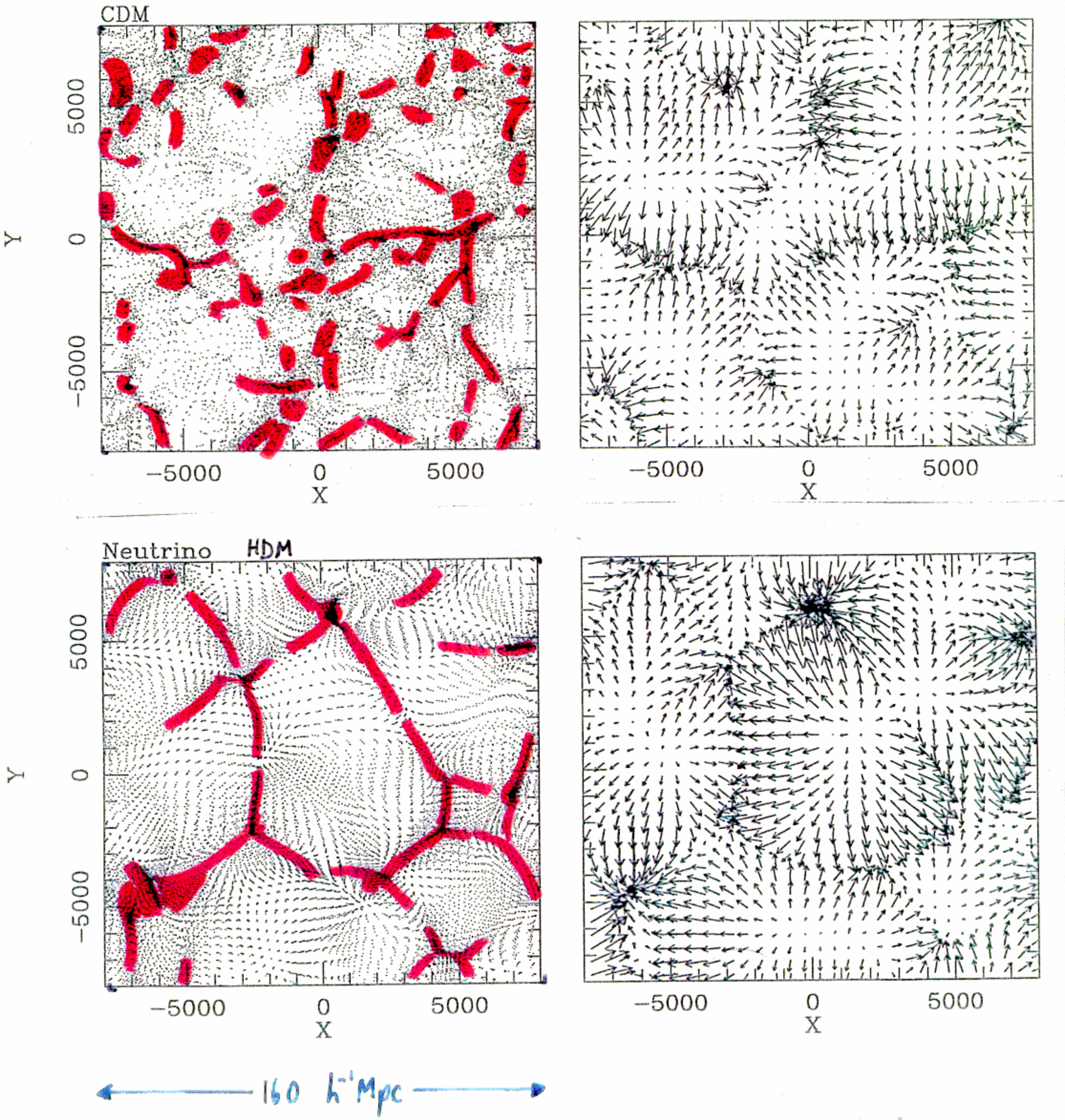
APM 2M galaxies 1.5 rad² 100 Mpc deep Maddox et al.



Anti biasing



Biasing



Results

- V_{pec} + Gaussian → $\Omega > 0.3$ $> 95\%$
- V_{pec} → $V_{50} = 375 \pm 85$, $P_{0.1}\,\Omega^{1.2} = (5 \pm 2) \times 10^{3}$

  $\sigma_8 \Omega^{0.6} = 0.8 \pm 0.2$
- $V_{pec} + n_{gal}$ → Galaxies ~trace mass

  $\beta_I \equiv \Omega^{0.6} / b_I \sim 0.5 - 1.0$ scale dependent biasing
- V_{pec} + CDM + COBE → $\Omega n^2 h_{65}^{0.6} \simeq 0.7 \pm 0.2$

  $+ \delta T \sim 1^{\circ}$ → $n \gtrsim 0.9$ $\Omega_b \sim 0.01$
- Local void SNe Ia $\delta H / H \sim +6\%$ $R < 70\ h^{-1}\mathrm{Mpc}$

  2.5σ

Cosmological Parameters

$H_0 = 65 \pm 10$	$km\ s^{-1}\ Mpc^{-1}$	SN Ia
$t_0 = 12 \pm 2$	Gyr	star clusters + Hipparcos
$\Omega_m = 0.3 - 1.0$		Flows, Global
$\Omega_\Lambda = 0.7 - 0.0$		Global
$\Omega_b = 0.05 - 0.1$		BBN + D
$\Omega_\nu < 0.3$		LSS, experiment
$n = 0.9 - 1.1$		CMB + LSS
$\sigma_8 \Omega^{0.6} = 0.5 - 0.8$		cluster abund. Flows
$\beta \equiv \Omega^{0.6}/b_I \sim 0.4 - 1.0$		Flows + IRAS

A ugly model that barely passes all current tests

- $H_0 = 65$ $t_0 = 12$

- $\Omega_{tot} = 1$ $\longrightarrow$ $\Omega_m = 0.5$ $\Omega_\Lambda = 0.5$

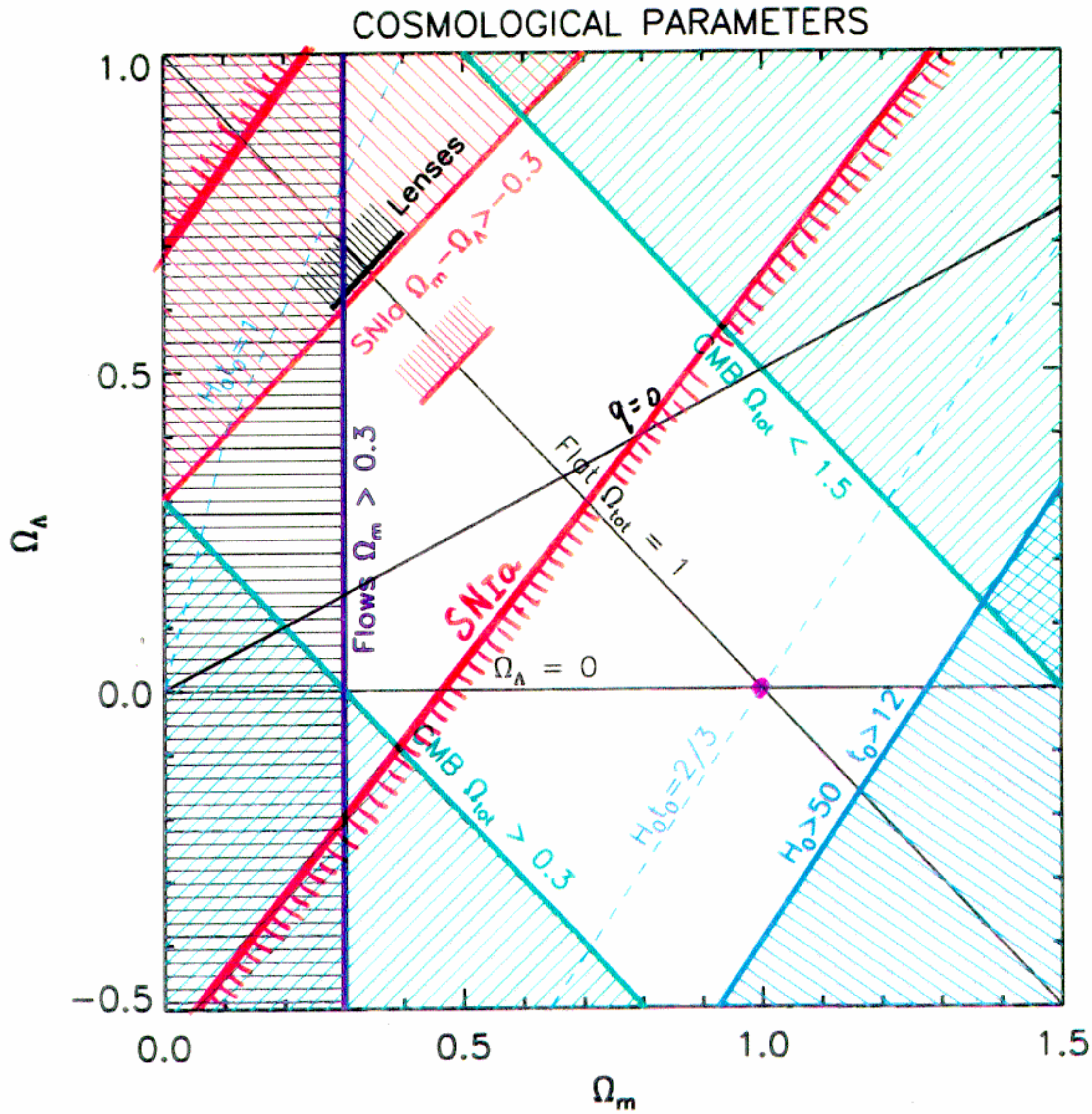
  $\downarrow$

  $\Omega_c = 0.3$

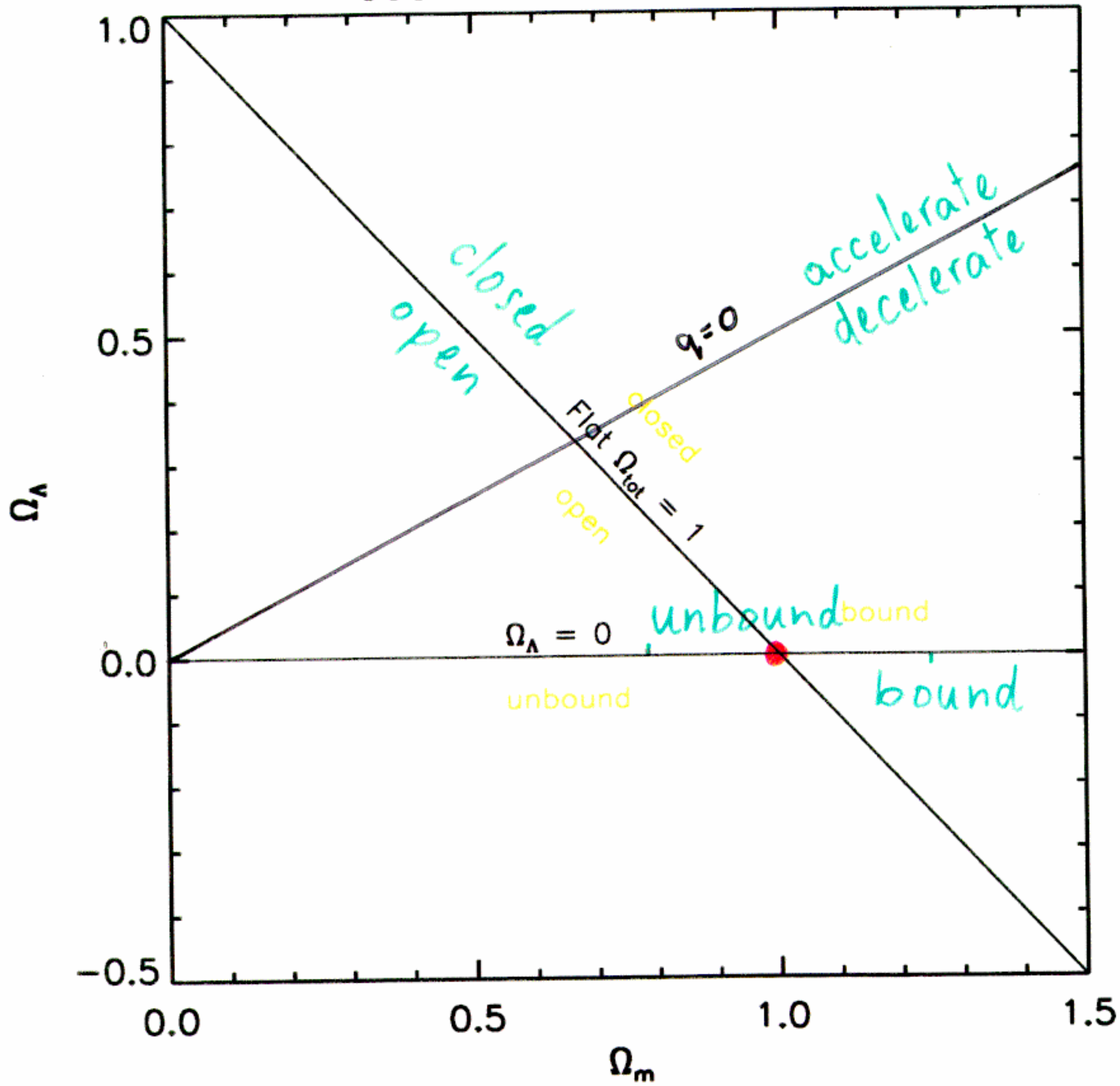
  $\Omega_\nu = 0.1$

  $\Omega_b = 0.1$

- $n = 0.95$ $\sigma_8 = 1$


COSMOLOGICAL PARAMETERS
Lenses
SNIa $\Omega_m - \Omega_\Lambda > -0.3$
$q=0$
Flat $\Omega_{tot} = 1$
CMB $\Omega_{tot} < 1.5$
Flows $\Omega_m > 0.3$
SNIa
$\Omega_\Lambda = 0$
CMB $\Omega_{tot} > 0.3$
$H_0 t_0 = 2/3$
$H_0 > 50$
$t_0 > 12$
Ω_Λ
Ω_m
1.0
0.5
0.0
−0.5
0.0
0.5
1.0
1.5

COSMOLOGICAL PARAMETERS



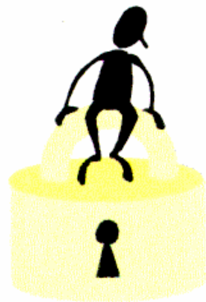
$\Omega_m = \rho_m / (3H_0^2 / 8\pi G)$ $\Omega_\Lambda = \Lambda c^2 / 3H_0^2$

$\Omega_{tot} = \Omega_m + \Omega_\Lambda$ $\Omega_m - 0.7\Omega_\Lambda \sim 5.8(1 - 1.3\ ht)$

Is the Universe

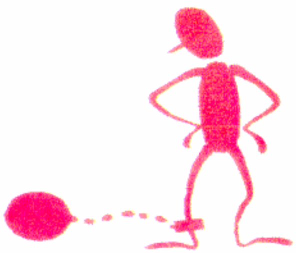
- Open ? or Closed?

$\Omega_m + \Omega_\Lambda \lessgtr 1$



- Bound or Unbound?

$\Omega_\Lambda \lessgtr 0 \qquad \Omega_m \gtrless 1$



- Decelerating or Accelerating?

$\frac{1}{2}\Omega_m - \Omega_\Lambda \gtrless 0$

Avishai Dekel