EXT

293

pt. 1

Cours/Lecture Series

1993 – 1994 ACADEMIC TRAINING PROGRAMME

LECTURE SERIES

SPEAKER	:	M. SPIRO / CERN-PPE
TITLE	:	Particle Astrophysics
TIME	:	14, 15, 16, 17 & 18 February from 11.00 to 12.00hrs
PLACE	:	Auditorium

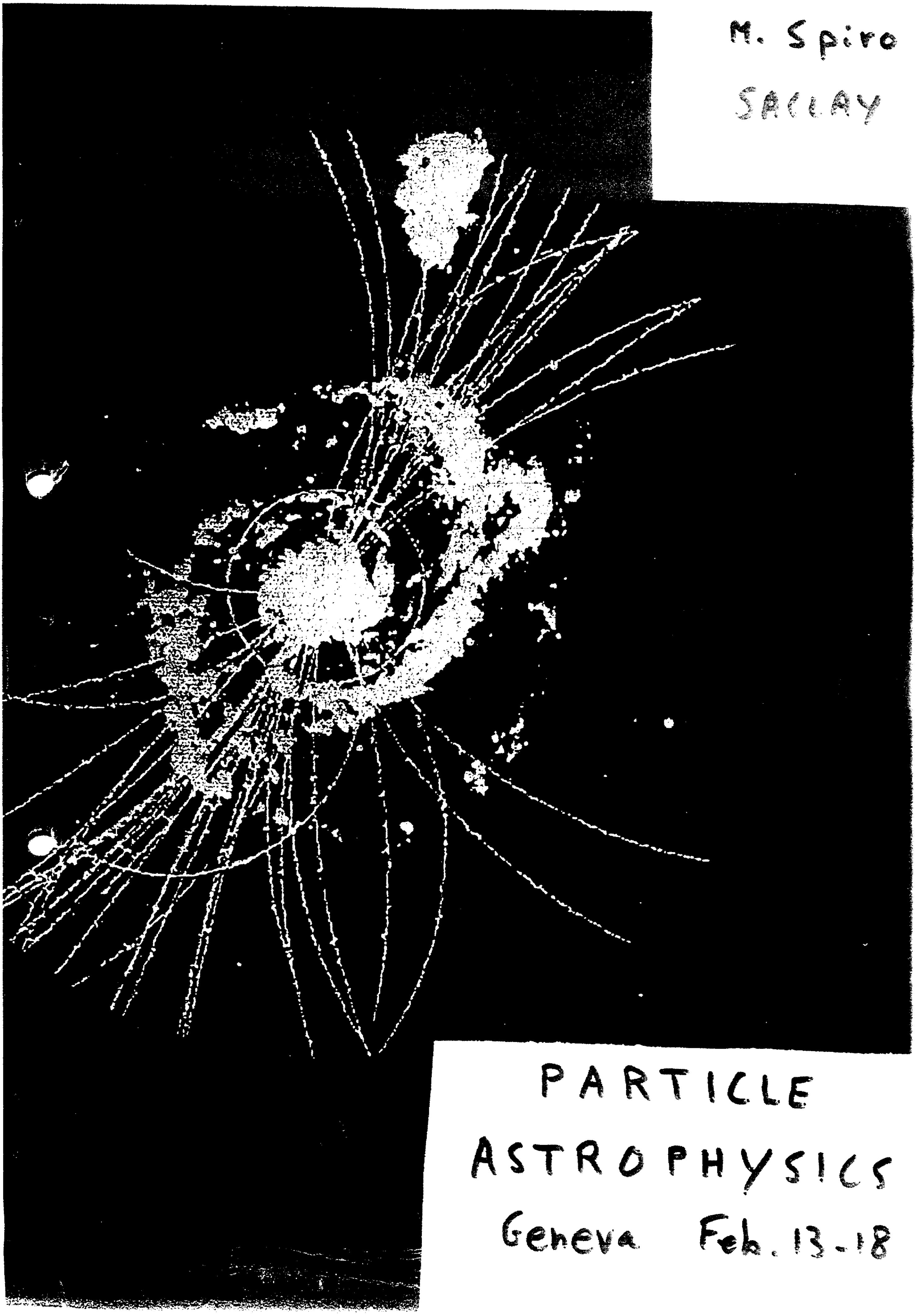
ABSTRACT

These lectures will present subjects which are at the inferface between particle physics, astrophysics and cosmology. Topics to be discussed include high energy cosmic ray, neutrino astrophysics and dark matter.

Div. DG/CP
Distr. int. & ext.

201698

M. Spiro
SACLAY



PARTICLE
ASTROPHYSICS
Geneva Feb. 13-18

$\boxed{\text{1. COSMOLOGY}}$

Ω, Ω_{bar}, Ω_{gal}, Ω_{dark}

$\boxed{\text{2. BARYONIC DARK MATTER}}$

MACHO, GAS, DUST ...

$\boxed{\text{3. WIMPs}}$

DIRECT DETECTION

INDIRECT DETECTION

$\left\{\begin{array}{l}\gamma\text{-RAY ASTRONOMY} \\ \nu\text{-ASTRONOMY}\end{array}\right.$

$\boxed{\text{4. NEUTRINOS}}$

ATMOSPHERIC

SOLAR

.....

COSMOLOGY (BASICS OF)
(BEST OF ?)

1. FRAMEWORK

2. Ω (VARIOUS DETERMINATION)

3. $\Omega_{BARYONIC}$

4. THE NEEDS FOR DARK MATTER
   - GALAXY FORMATION
   - GALACTIC HALOS

5. OVERVIEW

CURVED SPACE

(homogeneous, isotropic)

2D SPHERE

CIRCLE OF RADIUS d ON A SPHERE

$$C = 2\pi R \ \sigma \qquad \left(\sigma = \frac{r}{R}\right)$$

SCALE FACTOR (LENGTH) — R

COMOVING COORDINATE $(0 \leq \sigma \leq 1)$ — σ

$$\Delta s^2 = R^2(t)\left[\frac{\Delta\sigma^2}{1-\sigma^2} + \sigma^2 \Delta\varphi^2\right]$$

$$d(t) = R(t) \int_0^\sigma \frac{d\sigma}{\sqrt{1-\sigma^2}} \qquad \text{if } \Delta\varphi = 0$$

$$v(t) = \underbrace{\frac{\dot{R}(t)}{R(t)}}_{H(t)} \ d(t)$$

3 D (relativistic)

Friedmann - Robertson - Walker (FRW)

$$\Delta s^2 = c^2 \Delta t^2 - R^2(t) \left\{ \frac{\Delta \sigma^2}{1 - k\sigma^2} + \sigma^2 \Delta \theta^2 + \sigma^2 \sin^2\theta \, \Delta \varphi^2 \right.$$

$k = 0$ flat

$k = -1$ hyperbolic

$k = 1$ spheric

$H(t) = \frac{\dot{R}}{R}$ Hubble

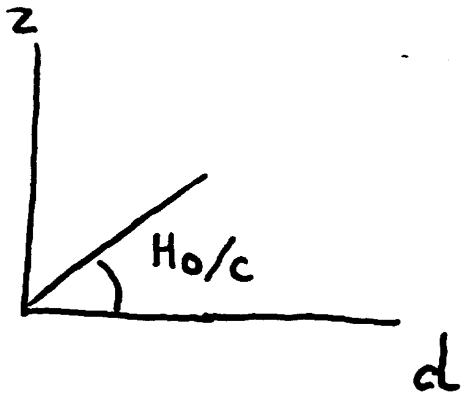
$q(t) = -\frac{\ddot{R} R}{\dot{R}^2}$ Deceleration

$$S = 4\pi R^2 \sigma^2$$

$\Delta s = 0$ for light rays

$$z = \frac{\lambda_0 - \lambda_e}{\lambda_e} = \frac{R(t_0)}{R(t_e)} - 1$$

REDSHIFT



$$H_0 = h \times 100 \text{ km / Mpc / s}$$

TODAY

$0.4 < h < 1$

EINSTEIN-FRIEDMANN EQUATIONS

$$\left(\frac{\dot R}{R}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{R^2} + \frac{\Lambda}{3}$$

$$d(\rho c^2 R^3) = -P\,d(R^3)$$

energy density

$$\left(\rho = \frac{\varepsilon}{c^2}\right)$$

"mass" density

$$\Omega = \frac{8\pi G\rho}{3H^2} = \frac{\rho}{\rho_c} \qquad \rho_c = \frac{3H^2}{8\pi G}$$

$$\lambda = \frac{\Lambda}{3H^2}, \qquad \alpha = \frac{kc^2}{R^2H^2}$$

$$\underset{\text{CURVATURE}}{\alpha} = \underset{\text{DENSITY}}{\Omega} + \underset{\text{VACUUM}}{\lambda} - 1 \qquad q = \Omega\left(1 + \frac{3P}{\rho c^2}\right)/2$$

INFLATION PREDICTS

α VERY VERY SMALL

$\sim k = 0$

RADIATION ERA $(R \to 0)$ $\Rightarrow$ YESTERDAY

$(z > 10^4 \text{ if } \Omega_0 = 1)$

$$P = \frac{\rho c^2}{3} \Rightarrow \rho \propto R^{-4} \propto T^4$$

$$H \propto \frac{1}{R^2} \propto \frac{1}{t}$$

$$R \propto \sqrt{t} \quad , \quad d_H(t) = 2ct$$

$$(T \propto R^{-1})$$

MATTER ERA $\Rightarrow$ TODAY

$$P = 0 \Downarrow \rho \propto R^{-3} \qquad H \propto \frac{1}{R^{3/2}} \propto \frac{1}{t} \qquad q = \Omega/2$$

$$R \propto t^{2/3} \quad , \quad d_H(t) = 3ct$$

$$(T_{relic} \propto R^{-1})$$

IF $\Lambda = 0$ $\quad \Omega = 1 + kc^2 \, t^{2-2\alpha}$

$$\alpha = \begin{cases} \frac{1}{2} & \text{R.E} \\ 2/3 & \text{M.E.} \end{cases}$$

VISIBLE STARS $\quad$ AGE + EXPANSION

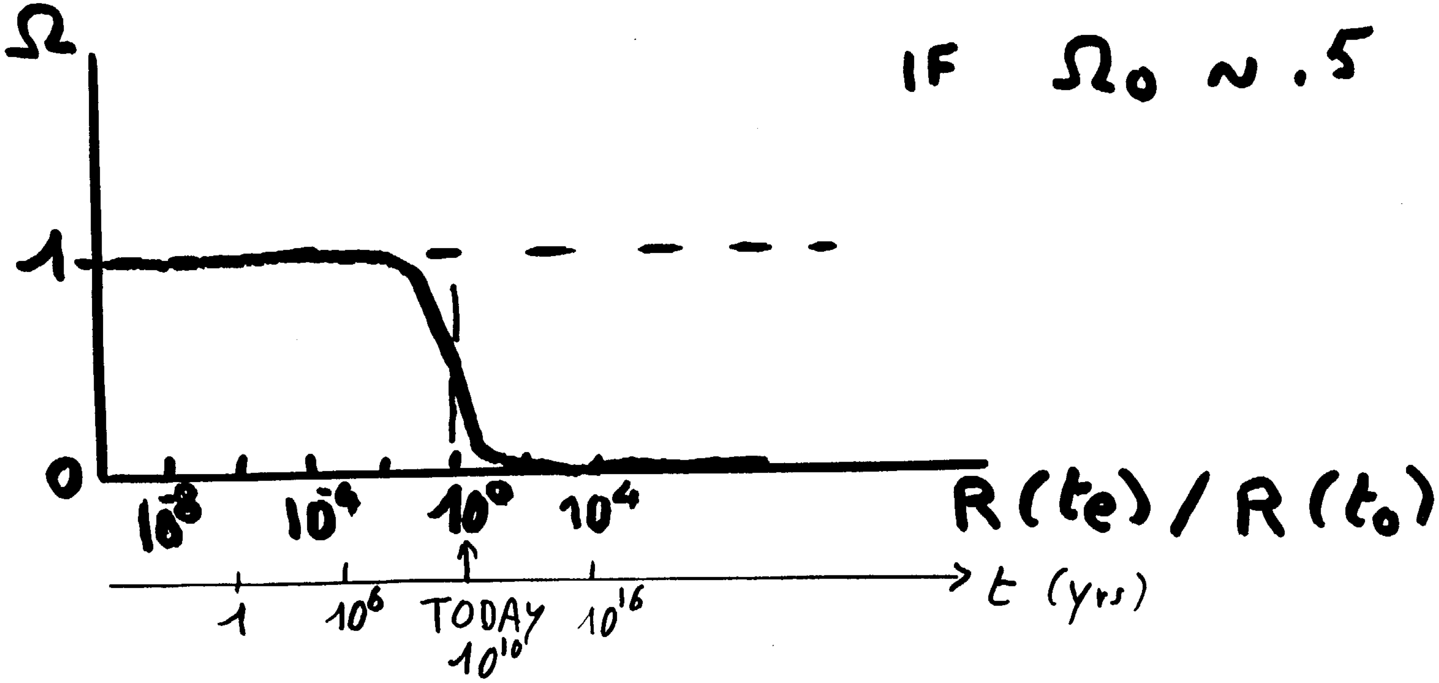
$$10^{-3} < \Omega_0 < 2 \quad \text{TODAY}$$

$$\Downarrow$$

$$.999999..9 < \Omega_{GUT} < 1.00....01$$

$$1+z = R(t_o)/R(t_e)$$

IF $\Omega_0 \sim .5$



VACUUM ERA $\Rightarrow$ TOMORROW?

$P = -\rho c^2$

$$H^2 = \frac{\Lambda}{3} = cst$$

VAC. ENERGY: $\rho_{VAC} = \dfrac{\Lambda c^2}{8\pi G}$

$$R \propto e^{Ht}$$

$\Rightarrow \dfrac{kc^2}{R^2}$ VERY SMALL

STANDARD SCENARIO

(T > GUT $\longrightarrow$ REL. ERA ??

T = GUT INFLATION (VACUUM) $\Rightarrow \begin{cases} \Omega = 1 \\ \Lambda = 0 \end{cases}$?

GUT $\longrightarrow z = 10^4$ RELATIVISTIC ERA $\Omega = 1$

few eV

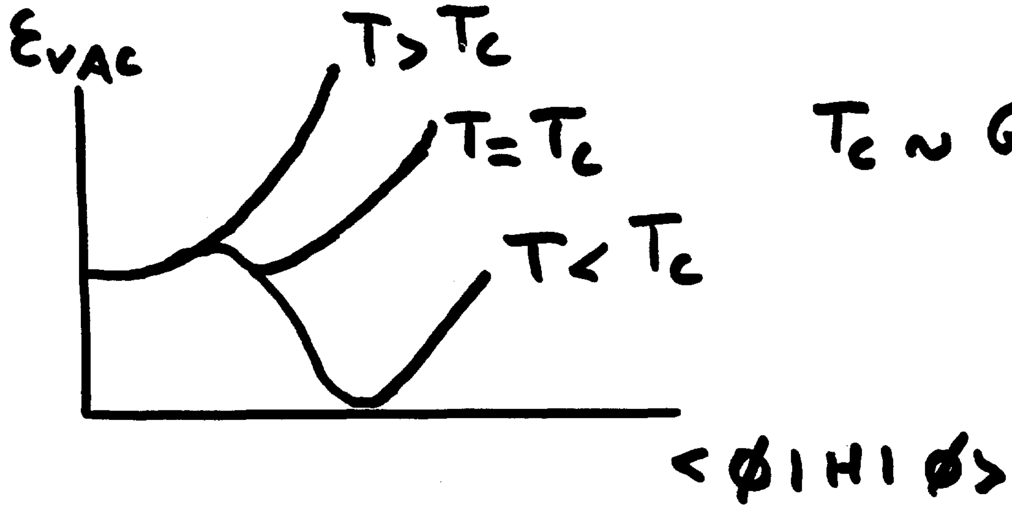
$z \searrow$ MATTER ERA

$z = 10^3$ $e^- + p \rightarrow H + \gamma$

NOW $\uparrow$ 2.7 K

Ω_0, q_0, Ω_{bar}, Ω_{GAL}? ?

INFLATION

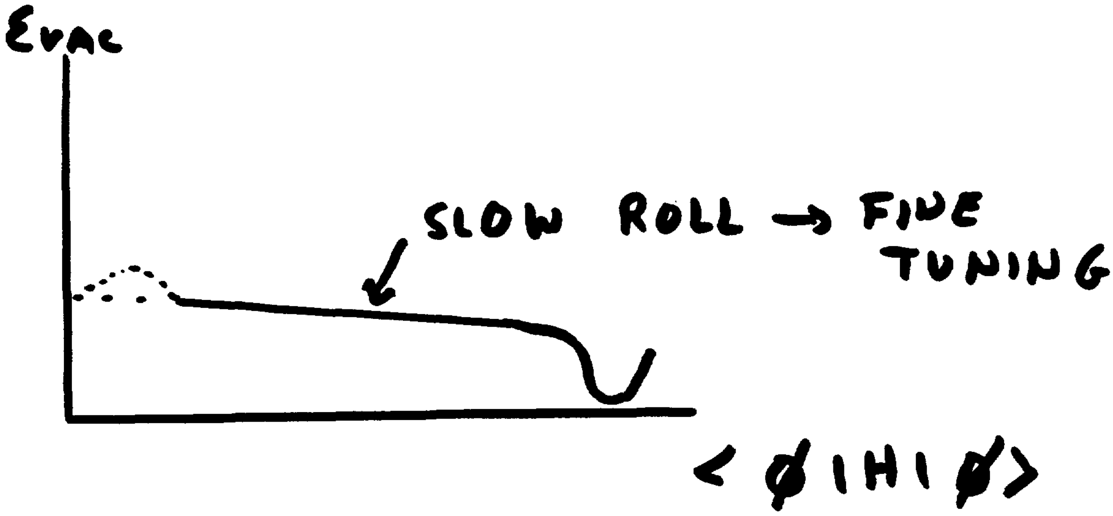


$T_c \sim$ GUT

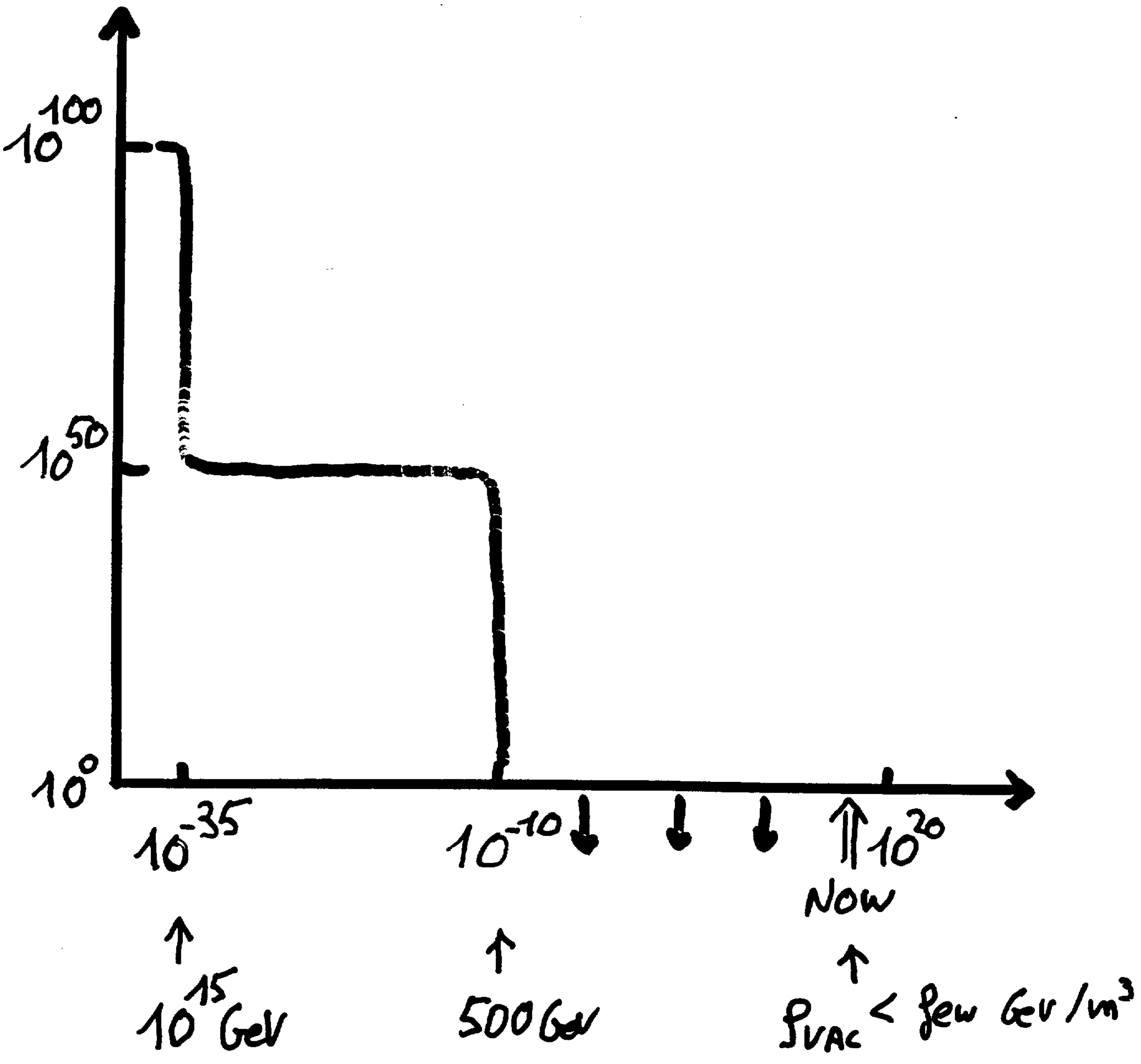
$T > T_{GUT}$ REL. ERA

$T = T_{GUT}$ VACUUM ERA $\rightarrow$ INFL.
REHEATING $\varepsilon_{VAC} \searrow 0$

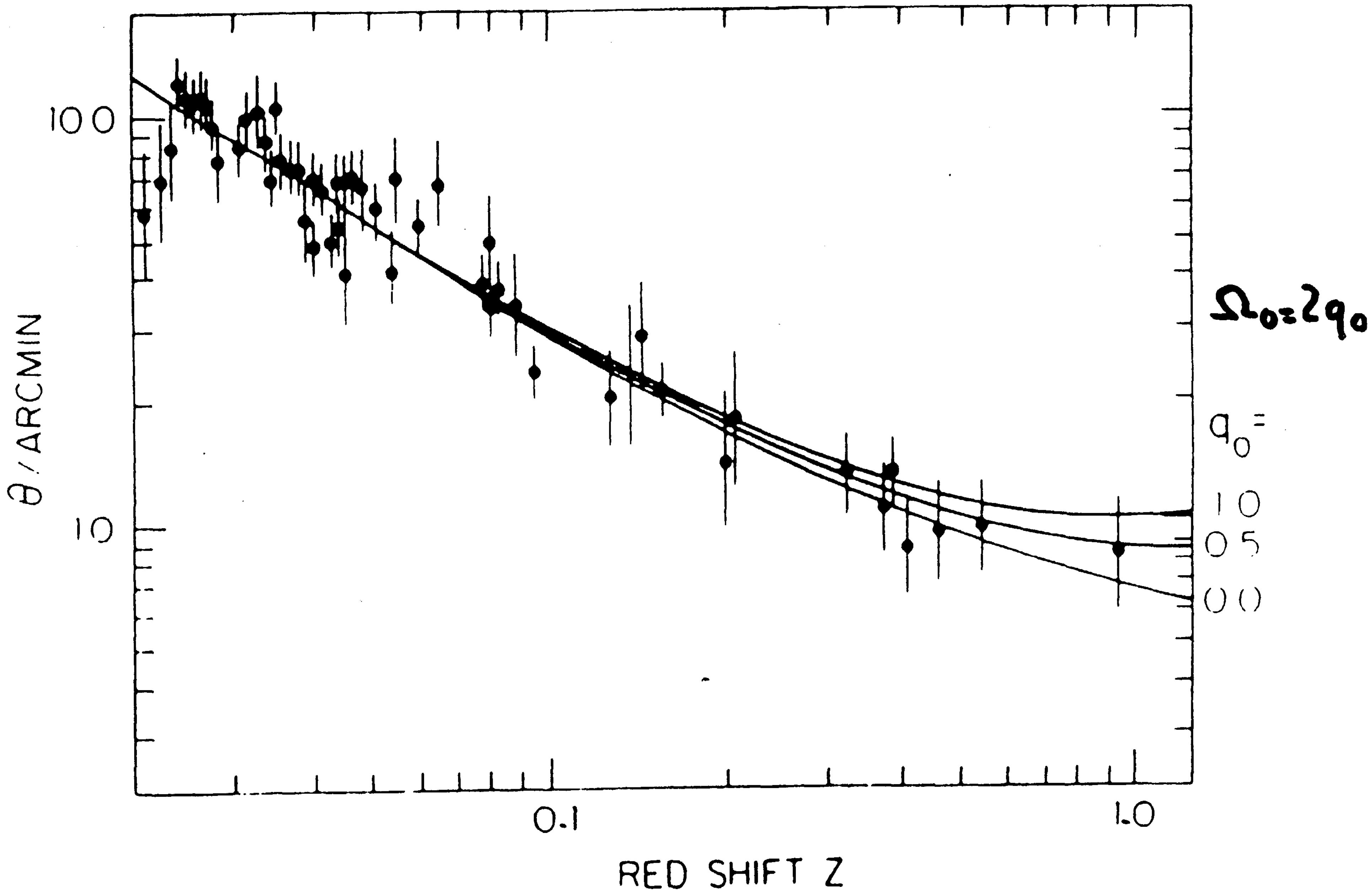
$T < T_{GUT}$ REL. ERA
MATTER ERA



COSMOLOGICAL CONSTANT
VACUUM ENERGY

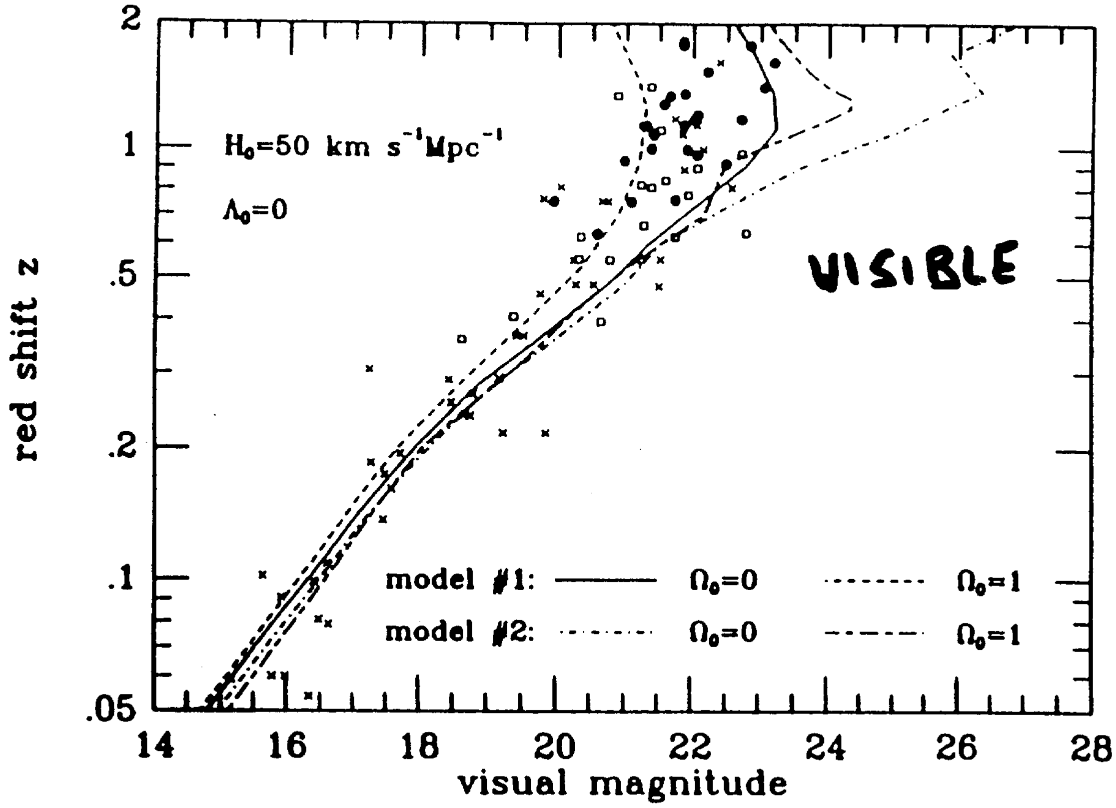


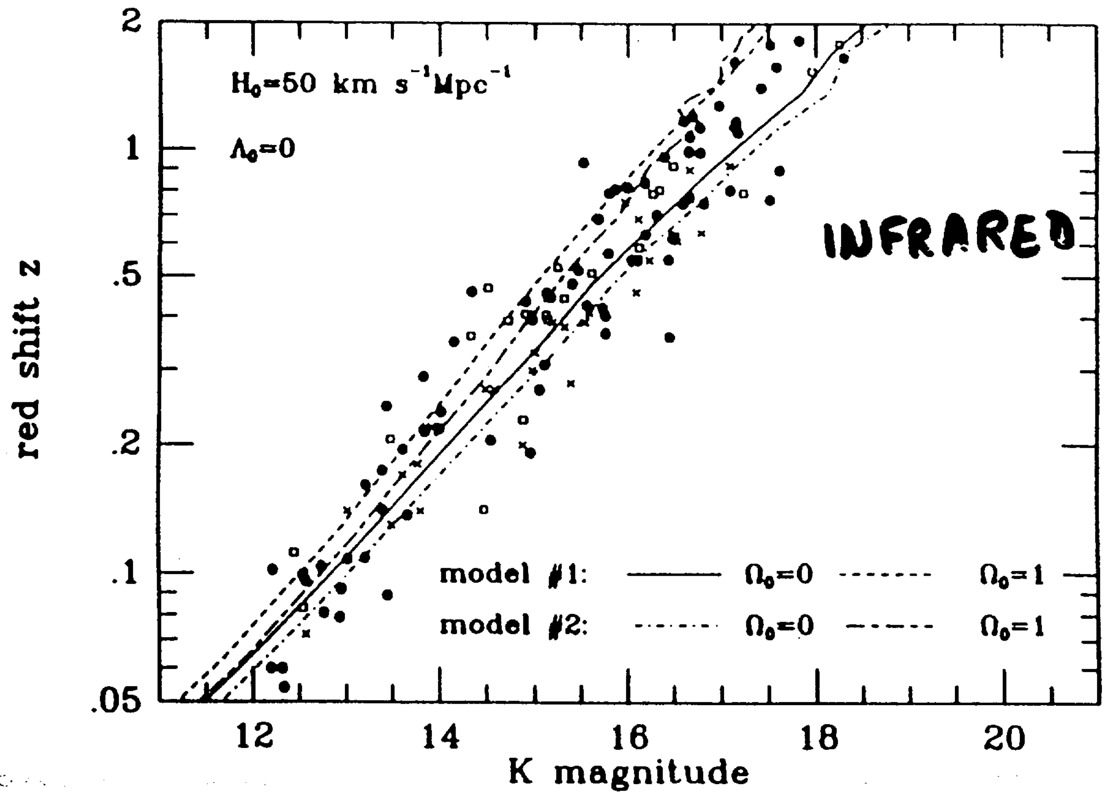
STANDARD RODS



STANDARD CANDLES

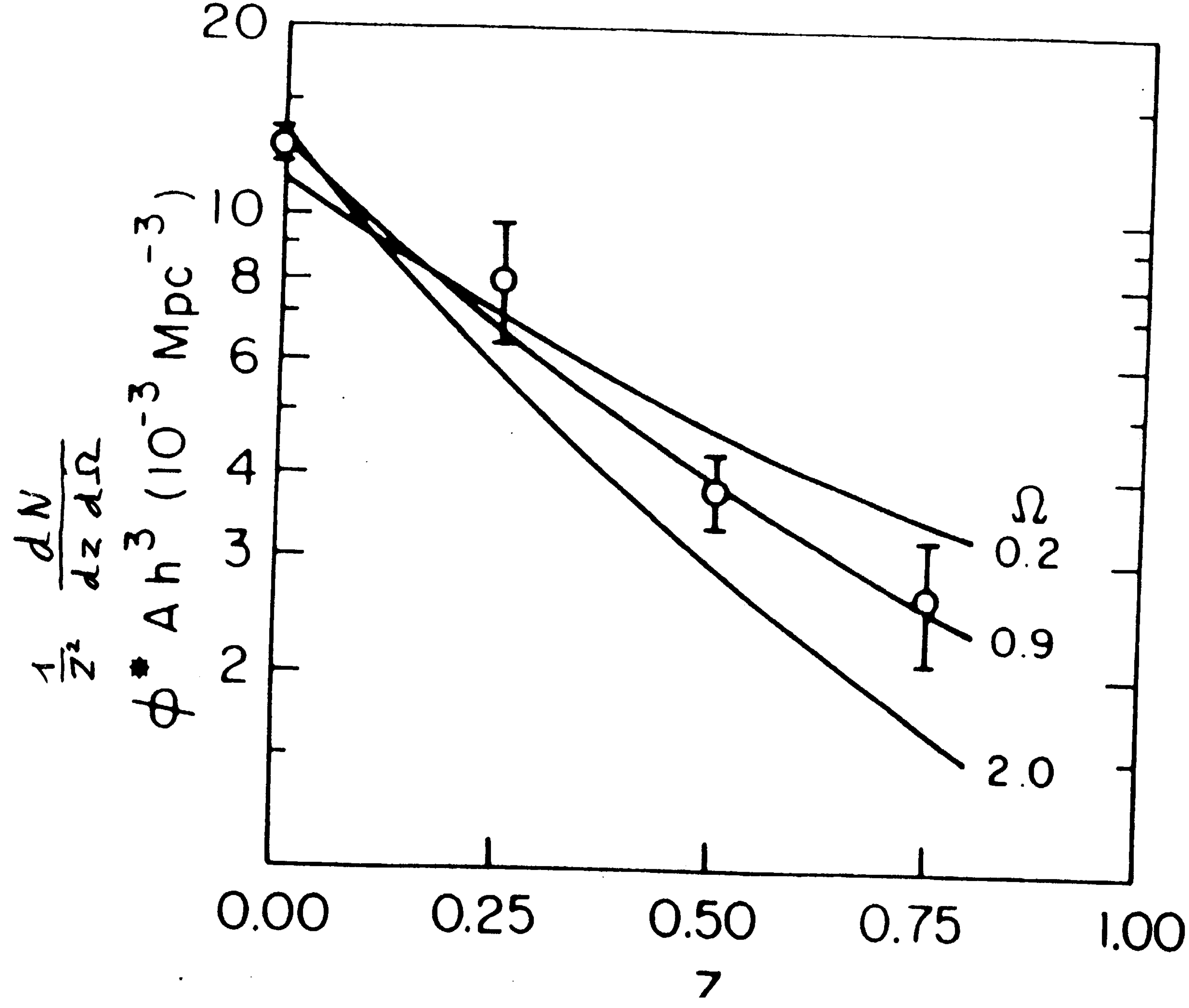
BRIGHTEST GALAXIES





(SNIa MORE PROMISING)

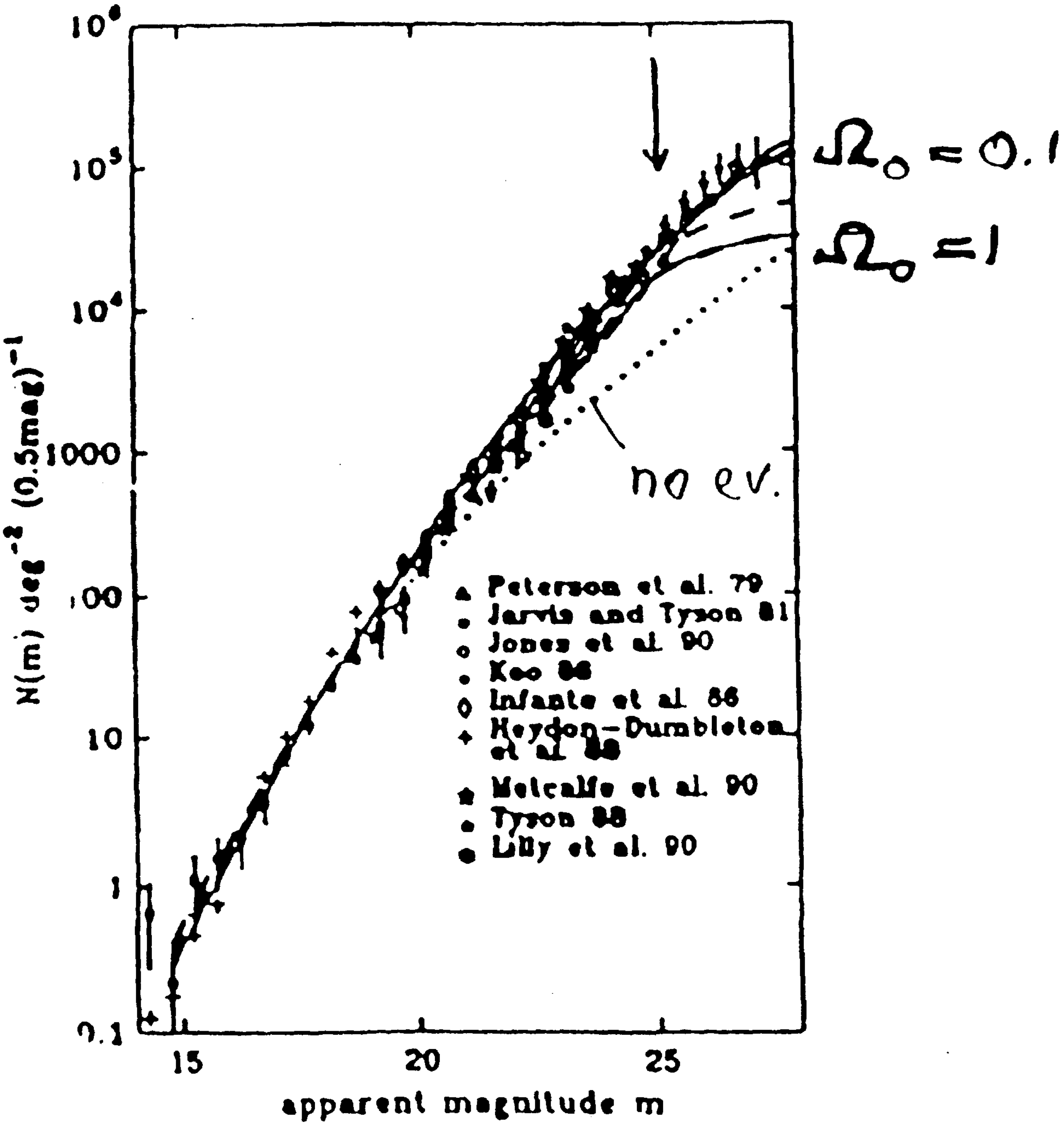
GALAXY COUNTS



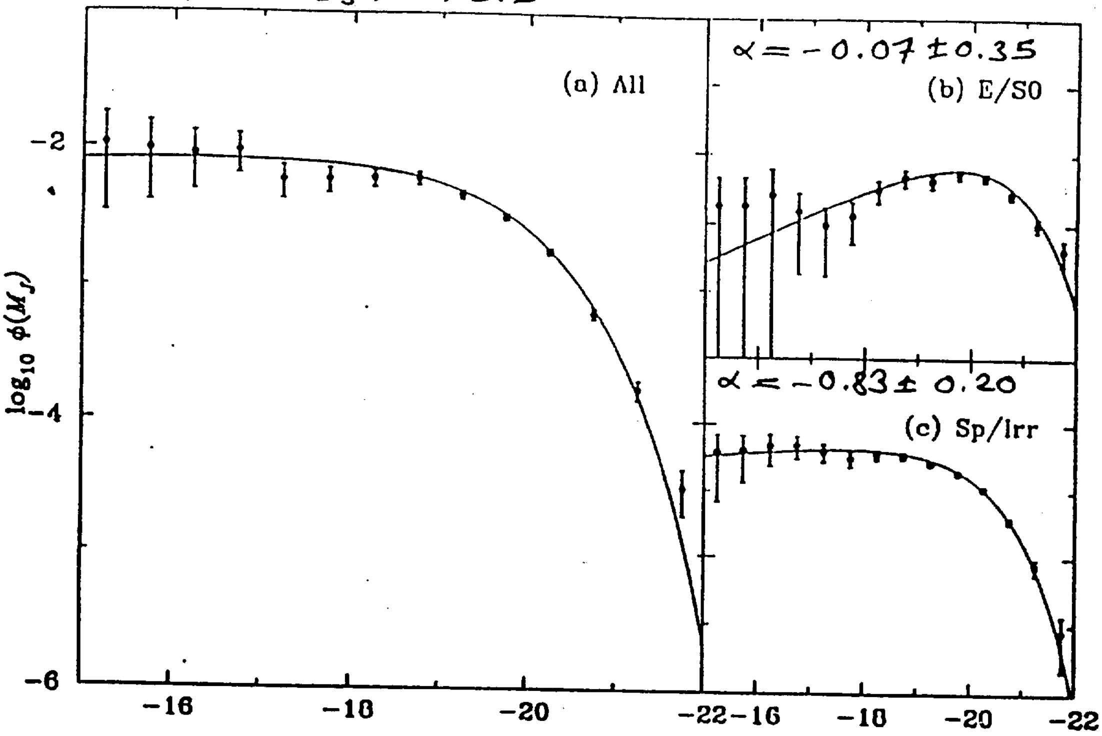
EXTINCTION (2)

effect of Ω_0

faint galaxy counts in B_J



$M^*_{B_J} = -21.2$ ($H_0 = 50\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$)
$\alpha = -0.95 \pm 0.15$
$-16.5 > M_{B_J} > -23.5$



échantillon $b_J \leq 17$ de 1420 galaxies tirées du survey APM

Loveday, Peterson, Efstathiou & Maddox

Ω_0 ?

THERMO. AND EXPANSION

$X\ ,\ \bar{X}$ $\quad m$

1 $T \gg m$ $\quad \gamma\gamma \rightleftarrows X\bar{X} \rightleftarrows i\bar{i}$

$n_B = g_B\, c/2\, T^3 \quad \left(n_F = g_F \frac{3}{8} n_\gamma \right)$

$\rho_B = g_B\, a/2\, T^4 \quad \left(\rho_F = \frac{7}{16} g_F \rho_\gamma \right)$

$T \searrow$

FREEZE OUT
WHEN

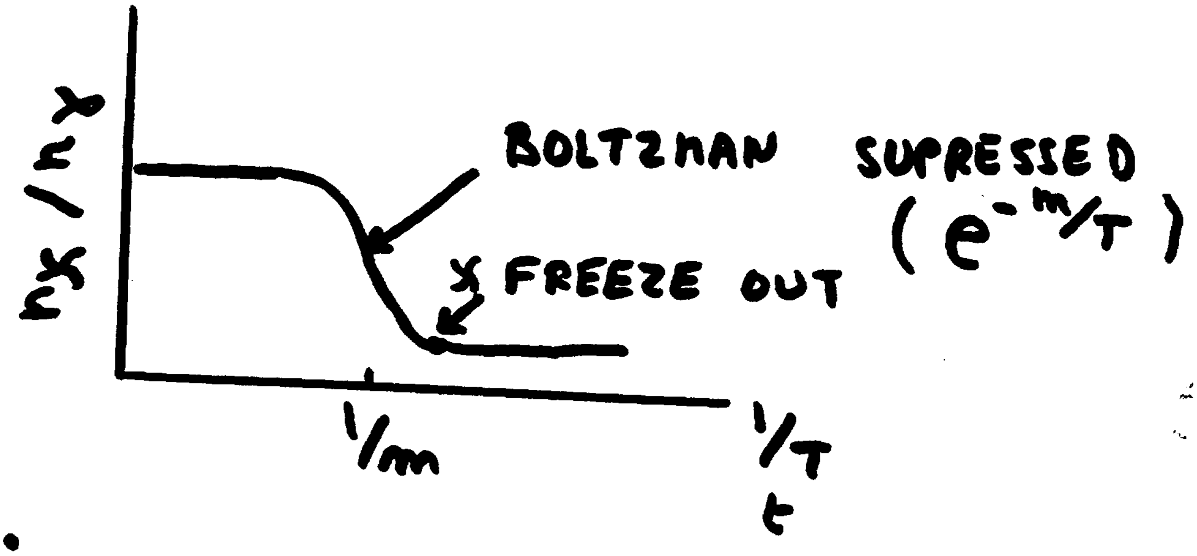
$$\bar{t}_{\text{INTERACTION}} > t_{\text{EXPANSION}}$$

$$\frac{1}{n_X \langle \sigma_{an.} v \rangle} > \frac{1}{H}$$

② COLD FREEZE OUT ($X = \chi$)

NEUTRALINO
WIMP

$$e^+e^- \rightleftarrows \gamma\gamma \rightleftarrows \nu\bar{\nu} \rightleftarrows \chi\chi$$



$$\dot{n}_\chi = -3H n_\chi - \langle \sigma v \rangle [n_\chi - n_\chi^{EQ}]$$

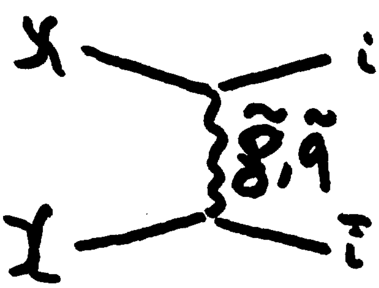
EXPANSION ANNIHILATION

X = WIMP

$$\Omega_\chi h^2 = \frac{3}{\langle \sigma v \rangle / 10^{-27} cm^3 s^{-1}}$$

AT FREEZE OUT

$\Omega_\chi = 1$ $v \sim 10^{10}$ cm s^{-1} $\Rightarrow$ WEAK SCALE



$\Rightarrow m_{\tilde{g},\tilde{q}} \sim$ W. SCALE is massless, a temperature much less than the photon temperature, $T_\psi \simeq (3.91/g_{*S})^{1/3}T$. For the latter reason, such a relic is often referred to as a *warm relic*. Examples of possible warm relics include a light gravitino, or a light photino (here, "light" means mass less than about a keV).

• *Cold Relics:* Now consider the more difficult case where freeze out occurs when the species is non-relativistic ($x_f \gtrsim 3$), and Y_{EQ} is decreasing exponentially with x. In this case the precise details of freeze out are important.

It is useful to parameterize the temperature dependence of the annihilation cross section. On general theoretical grounds the annihilation cross section should have the velocity dependence $\sigma_A|v| \propto v^p$, where $p = 0$ corresponds to s-wave annihilation, $p = 2$ to p-wave annihilation, etc. Since $\langle v\rangle \sim T^{1/2}$, $\langle\sigma_A|v|\rangle \propto T^n$, $n = 0$ for s-wave annihilation, $n = 1$ for p-wave annihilation, etc. Therefore we parameterize $\langle\sigma_A|v|\rangle$ as

$$\langle\sigma_A|v|\rangle \equiv \sigma_0(T/m)^n = \sigma_0 x^{-n} \quad (\textit{for } x \gtrsim 3). \tag{5.36}$$

With this parameterization, the Boltzmann equation for the abundance of ψ's becomes,

$$dY/dx = -\lambda x^{-n-2}(Y^2 - Y_{EQ}^2), \tag{5.37}$$

where

$$\begin{aligned} \lambda &= \left[\frac{x\langle\sigma_A|v|\rangle s}{H(m)}\right]_{x=1} = 0.264(g_{*S}/g_*^{1/2})m_{Pl}\, m\, \sigma_0, \\ Y_{EQ} &= 0.145(g/g_{*S})x^{3/2}e^{-x}. \end{aligned} \tag{5.38}$$

As we will now describe, this differential equation can be solved approximately to very good accuracy (better than 5%). To begin, consider the differential equation for $\Delta \equiv Y - Y_{EQ}$, the departure from equilibrium,

$$\Delta' = -Y_{EQ}' - \lambda x^{-n-2}\Delta(2Y_{EQ} + \Delta), \tag{5.39}$$

where prime denotes d/dx. At early times ($1 < x \ll x_f$), Y tracks Y_{EQ} very closely, and both Δ and $|\Delta'|$ are small, so that an approximate solution is obtained by setting $\Delta' = 0$:

$$\begin{aligned} \Delta &\simeq -\lambda^{-1}x^{n+2}Y_{EQ}'/(2Y_{EQ} + \Delta) \\ &\simeq x^{n+2}/2\lambda. \end{aligned} \tag{5.40}$$

At late times ($x \gg x_f$), Y tracks Y_{EQ} very poorly: $\Delta \simeq Y \gg Y_{EQ}$, and the terms involving Y_{EQ}' and Y_{EQ} can be safely neglected, so that

$$\Delta' = -\lambda x^{-n-2}\Delta^2. \tag{5.41}$$

Upon integration of (5.41) from $x = x_f$ to $x = \infty$, we obtain

$$Y_\infty = \Delta_\infty = \frac{n+1}{\lambda}x_f^{n+1}. \tag{5.42}$$

Now we must determine x_f. Recall $x = x_f$ is the time when Y ceases to track Y_{EQ}, or equivalently, when Δ becomes of order Y_{EQ}. Defining x_f by the criterion: $\Delta(x_f) = cY_{EQ}(x_f)$, c = numerical constant of order unity, the early time solution of (5.41) becomes $\Delta(x_f) \simeq x_f^{n+2}/\lambda(2+c)$, and the freeze-out criterion gives

$$x_f \cong \ln[(2+c)\lambda ac] - \left(n + \frac{1}{2}\right)\ln\{\ln[(2+c)\lambda ac]\} \tag{5.43}$$

where $a = 0.145(g/g_{*S})$. Note that x_f depends only logarithmically upon the numerical criterion for freeze out, i.e., the value of c, as does the final abundance. The results of a numerical integration of the Boltzmann equation are shown in Fig. 5.1.

Choosing $c(c+2) = n+1$ gives the best fit to the numerical results for the final abundance Y_∞ (to better than 5% for any $x_f \gtrsim 3$). With this choice

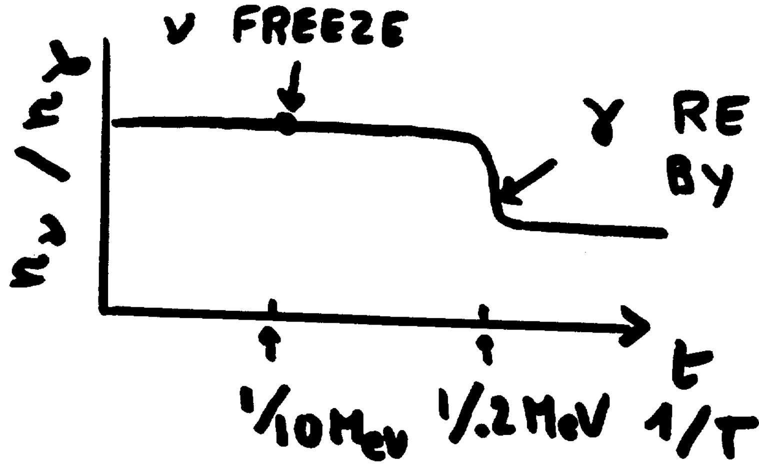
$$\begin{aligned} x_f &= \ln[0.038(n+1)(g/g_*^{1/2})m_{Pl}\, m\, \sigma_0] \\ &\quad - \left(n + \frac{1}{2}\right)\ln\left\{\ln\left[0.038(n+1)(g/g_*^{1/2})m_{Pl}\, m\, \sigma_0\right]\right\} \end{aligned} \tag{5.44}$$

$$Y_\infty = \frac{3.79(n+1)x_f^{n+1}}{(g_{*S}/g_*^{1/2})m_{Pl}\, m\, \sigma_0}. \tag{5.45}$$

We mention in passing that one could have obtained a very similar result to (5.45) by estimating x_f by the freeze-out criterion $\Gamma(x_f) \simeq H(x_f)$, and setting $Y_\infty = Y(x_f)$. The formulae for x_f and Y_∞ obtained this way differ very little; for x_f, the coefficient of the lnln term is $(-n+1/2)$ rather than $(-n-1/2)$, and for Y_∞, a factor of 5 instead of 3.79$(n+1)$.

③ HOT FREEZE OUT ($X = \nu$)

$$e^+ e^- \rightleftarrows \gamma\gamma \rightleftarrows \nu\bar{\nu}$$



$$\frac{n_{\nu_i}}{n_\gamma} = \frac{\frac{3}{4}\ (\text{FERMION})}{\underbrace{(1 + 2 \times 7/8)}_{\text{REHEATING}}} = 3/11$$

$$\Downarrow \quad 2.7\,\text{K} = 400\,\gamma / \text{cm}^3 \quad (\Omega_\gamma h^2 = 4\ 10^{-5}$$

$$110\ \nu_i / \text{cm}^3$$

$$\Omega_{\nu_i \bar{\nu}_i} h^2 = \frac{m_\nu}{100\,\text{eV}}$$

$$\Omega = 1 \Rightarrow \quad 20\,\text{eV} < \sum_i m_{\nu_i} < 100\,\text{eV}$$

PRIMORDIAL NUCLEOSYNTHESIS

$$\Downarrow$$

$$\Omega_b$$

$$\eta = \frac{n_B}{s} \qquad s = n_\nu + n_\gamma$$

$T > 10$ MeV $\qquad e^+e^- \rightleftarrows \nu\bar{\nu} \rightleftarrows \gamma\gamma$

$T_f(\nu\bar{\nu}) \sim 10$ MeV

$$\downarrow \begin{array}{ll} (1) & n + e^+ \rightleftarrows p + \bar{\nu}_e \\ (2) & p + e^- \rightleftarrows n + \nu_e \end{array} \qquad \frac{n}{p} = e^{-\frac{1.3\,\mathrm{MeV}}{T}}$$

$T_f(1,2) \sim 0.75$ MeV $\quad (t = 1\,s)$

$$\downarrow \qquad \frac{n}{p} = e^{-1.3\,\mathrm{MeV}/T_f(1,2)}$$

and $\quad n$ decay

$T_{nucl} \sim 0.1$ MeV $\quad (t = 100\,s)$

$$\downarrow$$

$$3'$$

$[n][p] = [D][\gamma > 2\,\mathrm{MeV}] \qquad n + p \to D\gamma \qquad$ no more n decay

$$\downarrow$$

nucleosynthesis

$20'$

$p\ (n,\gamma)\ d$ $\quad [p + n \to \gamma + d]$

$d\ (d,n)\ ^3He$

$d\ (d,\gamma)\ ^4He$

$d\ (d,p)\ ^3H$

$^3H\ (d,n)\ ^4He$

$^3He\ (d,p)\ ^4He$

$^4He\ (d,\gamma)\ ^6Li$

$^4He\ (^3H,\gamma)\ ^7Li$

$^4He\ (^3He,\gamma)\ ^7Be$

$^7Li\ (p\ ^4He)\ ^4He$

$^7Be\ (n\ p)\ ^7Li$

$^7Be\ e^-\ \nu)\ ^7Li$

$^7Be\ (p,\gamma)\ ^8B$

$\hookrightarrow {}^8Be \to {}^4He\ {}^4He$

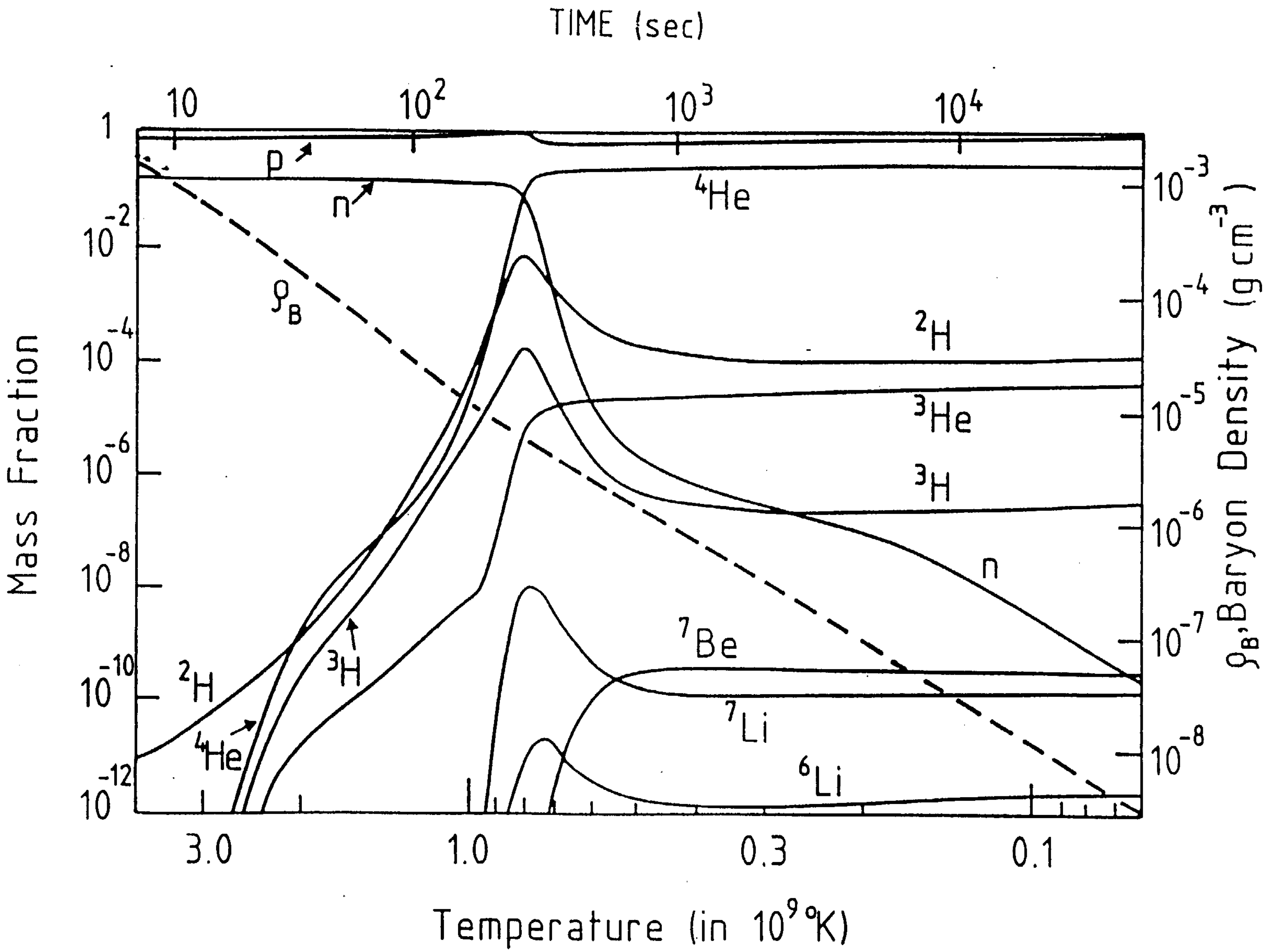

TIME (sec)
10
10²
10³
10⁴
1
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁰
10⁻¹²
Mass Fraction
p
n
⁴He
ρ_B
²H
³He
³H
n
⁷Be
⁷Li
⁶Li
²H
⁴He
³H
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
ρ_B, Baryon Density (g cm⁻³)
3.0
1.0
0.3
0.1
Temperature (in 10⁹ °K)

Fig 8

$$10^{-5} < \frac{D}{H} < 2\ 10^{-4}$$

(recently $\sim 10^{-4}$ I.G. medium)

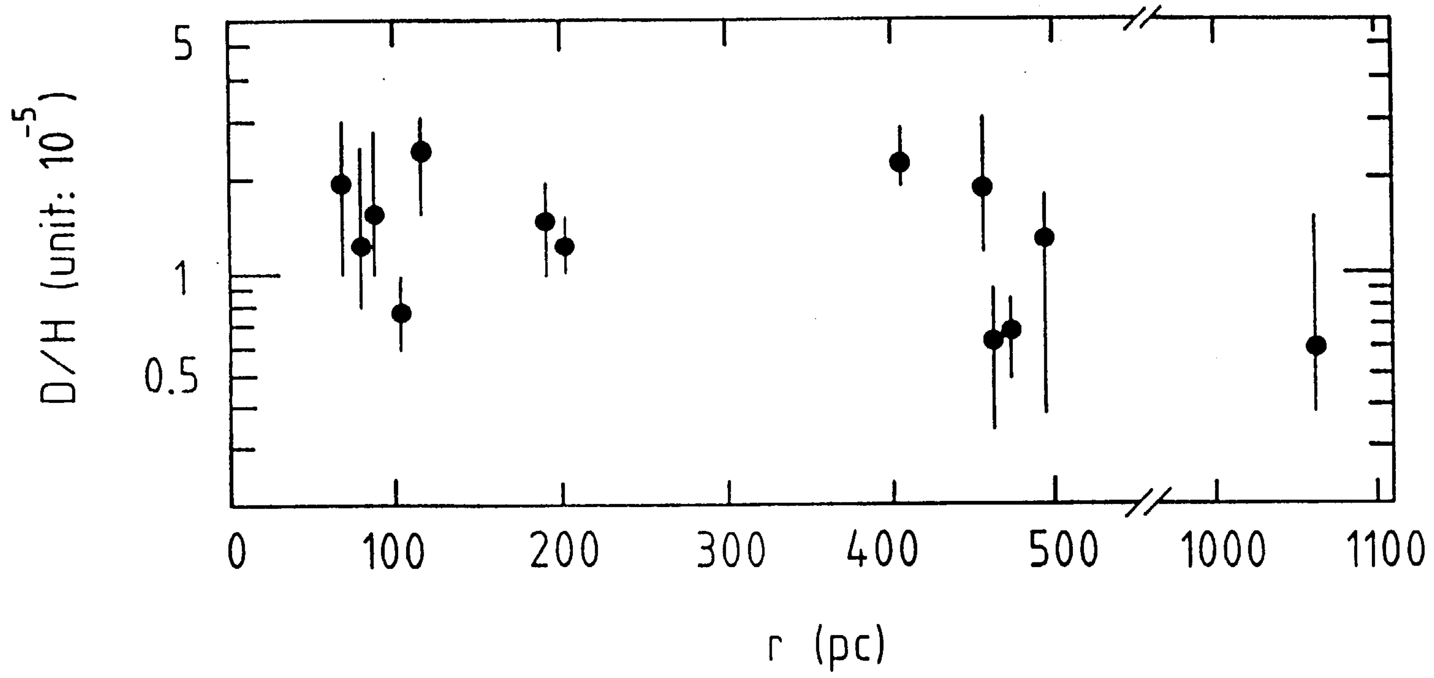


Fig 10

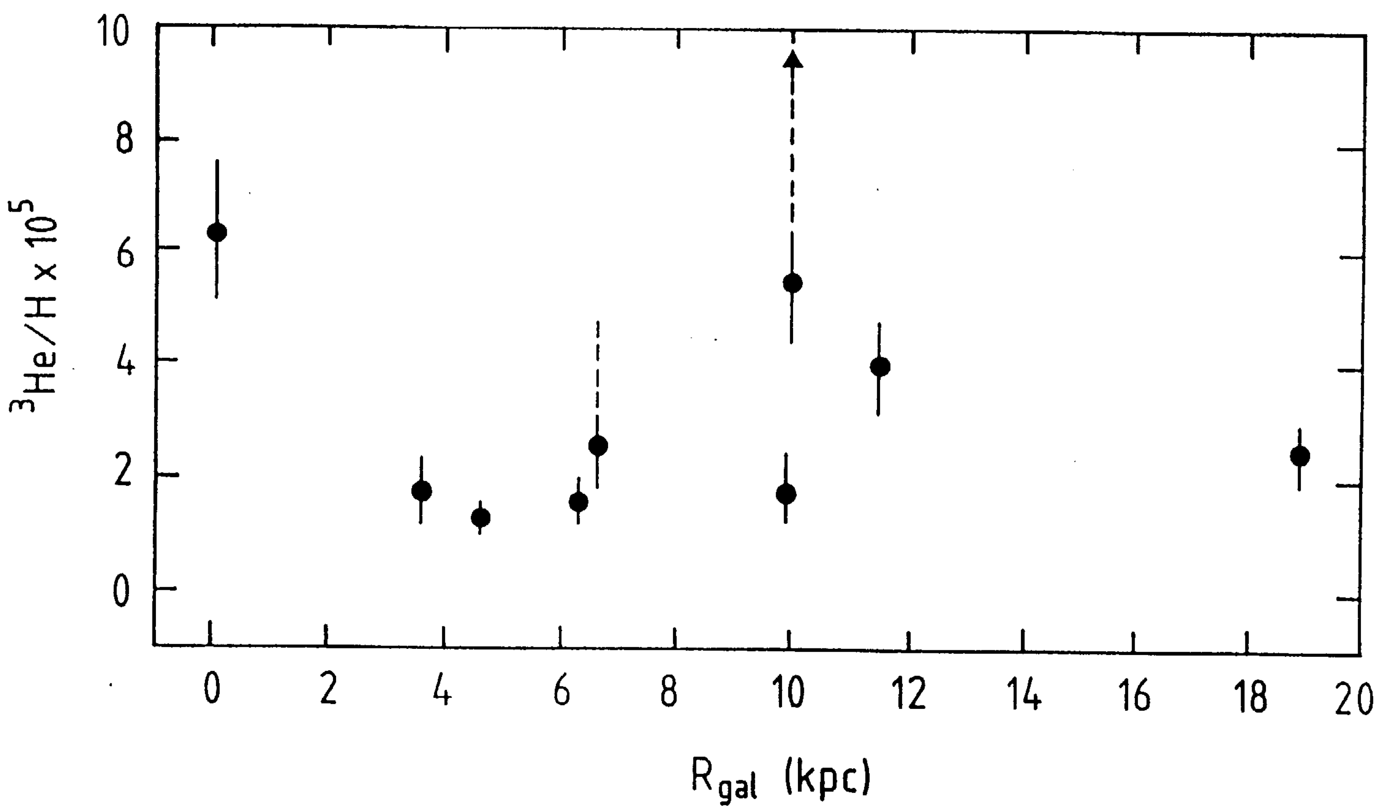
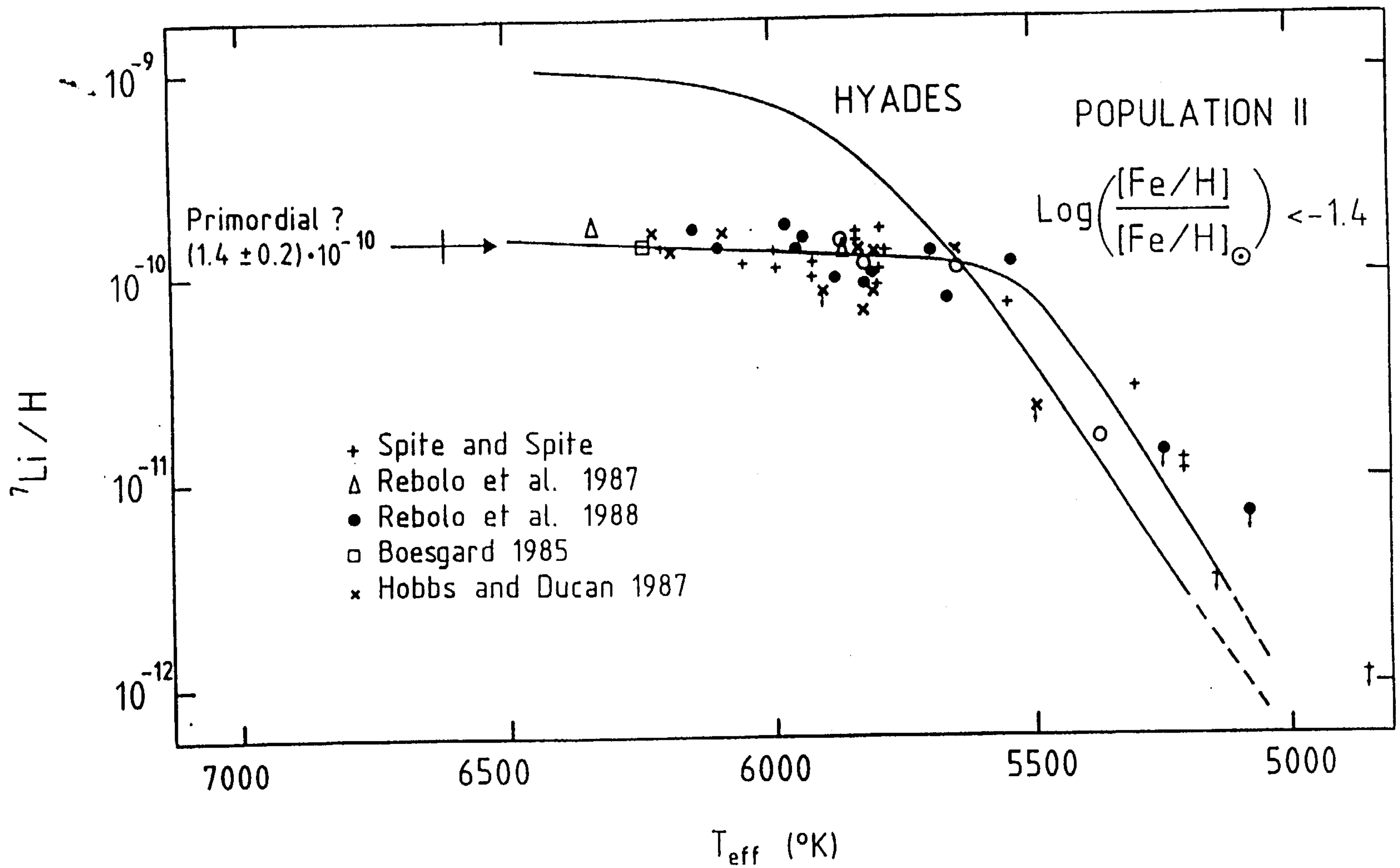
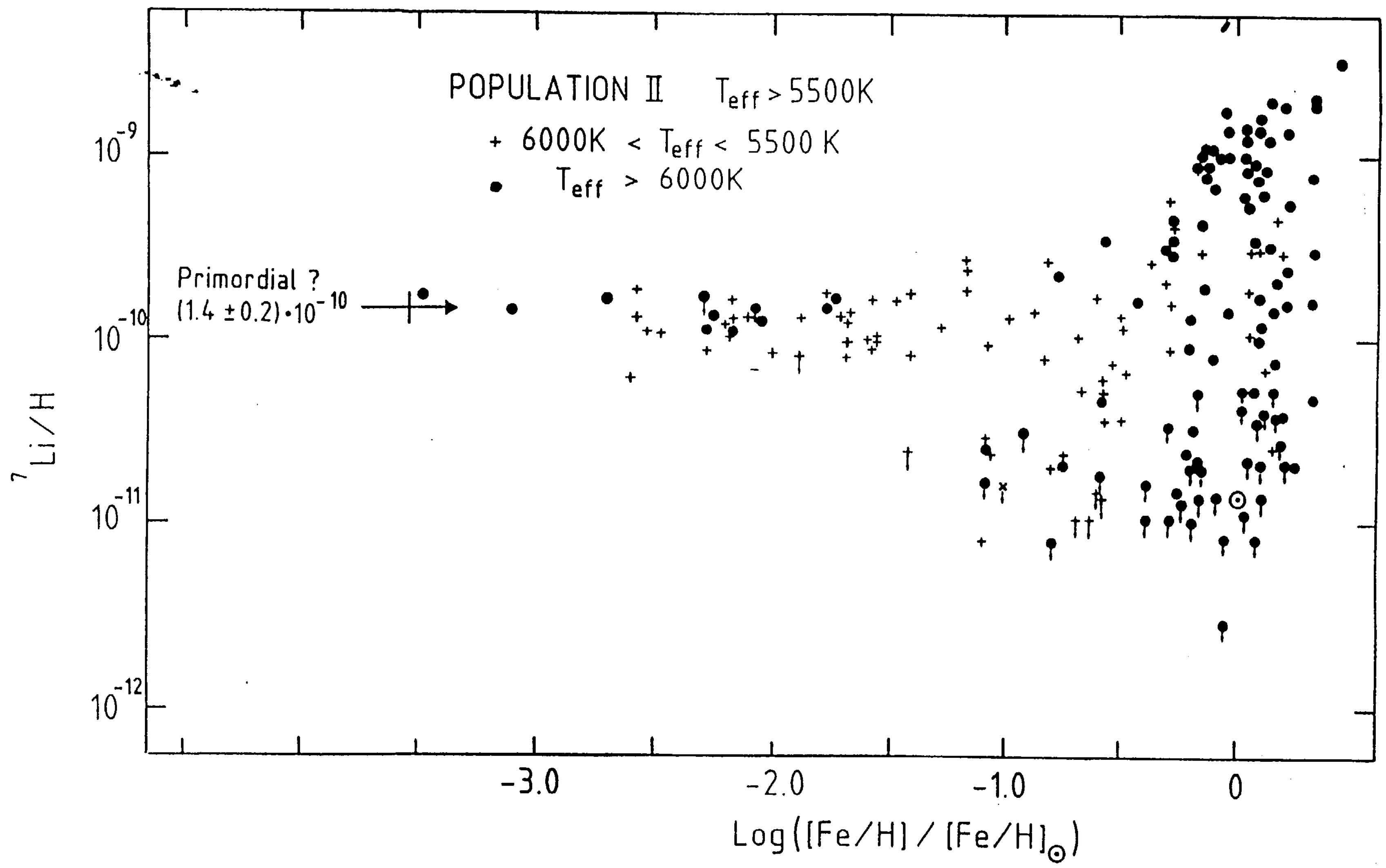


Fig. 11


HYADES
POPULATION II
Log([Fe/H]/[Fe/H]⊙) <-1.4
Primordial ?
(1.4 ± 0.2)·10^-10
+ Spite and Spite
Δ Rebolo et al. 1987
● Rebolo et al. 1988
□ Boesgard 1985
× Hobbs and Ducan 1987
7Li / H
10^-9
10^-10
10^-11
10^-12
7000
6500
6000
5500
5000
Teff (°K)

12a

5



POPULATION II $T_{eff} > 5500K$
+ $6000K < T_{eff} < 5500K$
• $T_{eff} > 6000K$
Primordial ?
$(1.4 \pm 0.2) \cdot 10^{-10}$
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$^{7}Li/H$
-3.0
-2.0
-1.0
0
$Log([Fe/H]/[Fe/H]_{\odot})$

12b

26

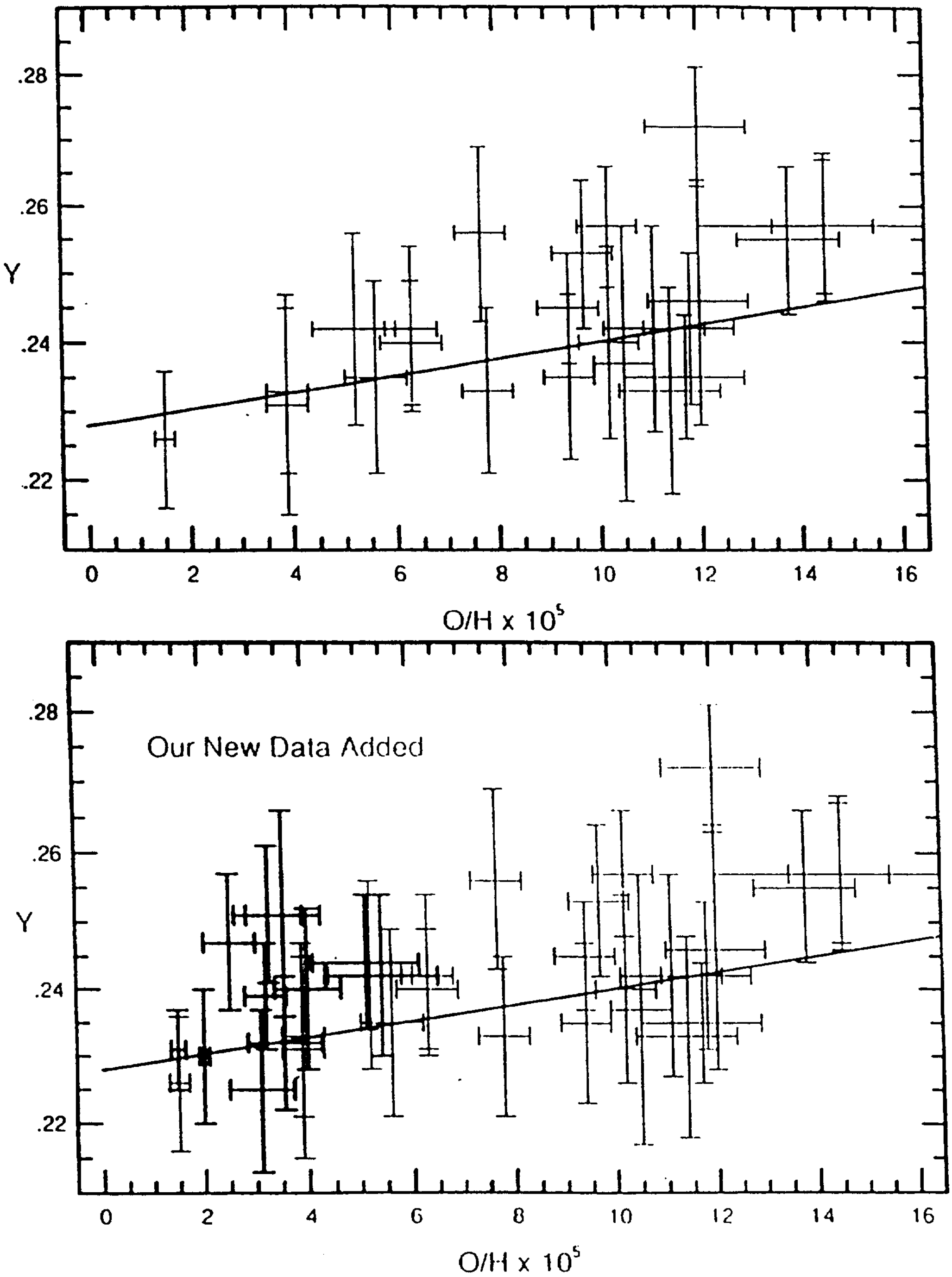
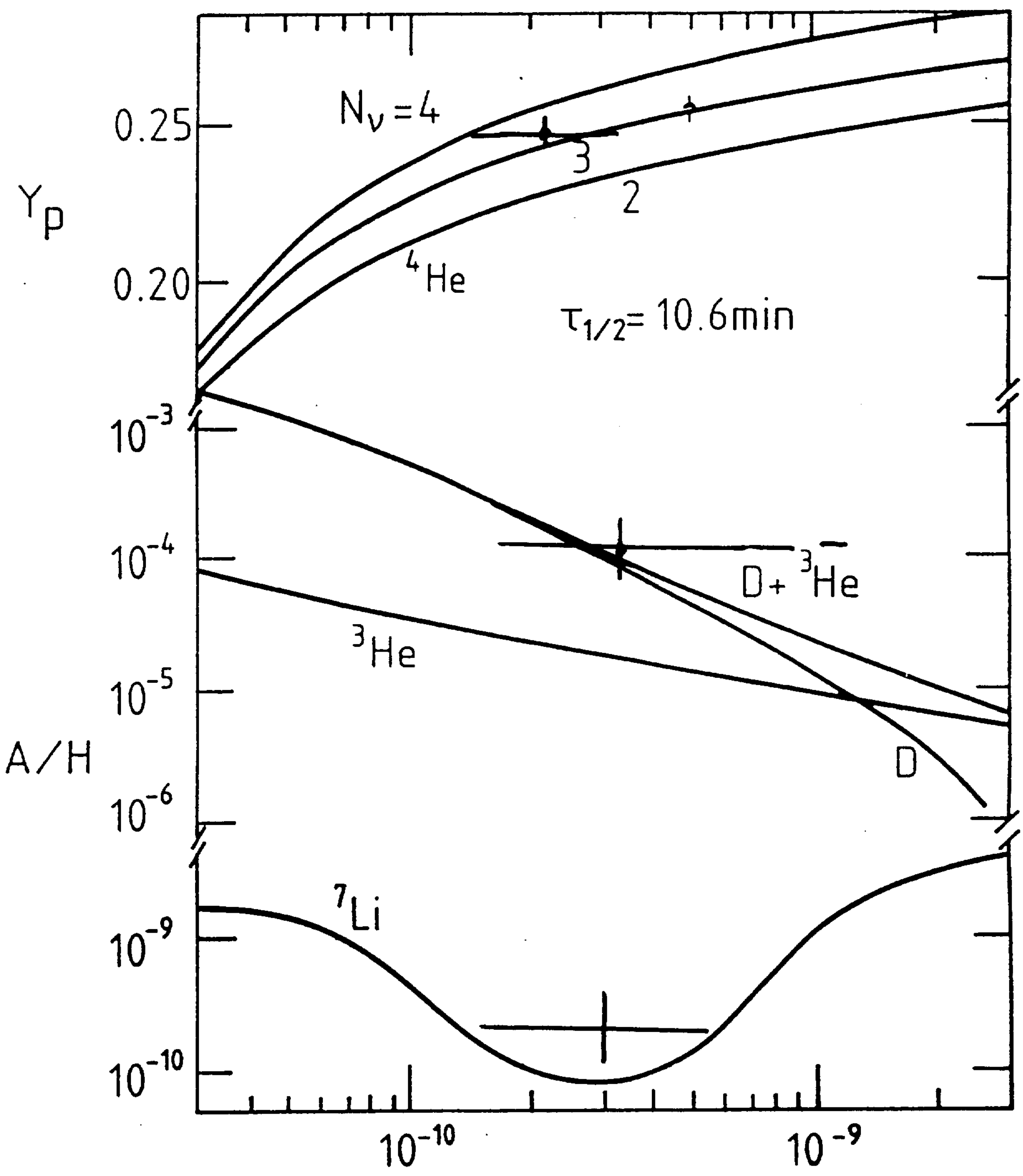


Figure 2

$$\frac{He}{H} = .24 \pm .005$$



$\eta = n_B / n_\gamma$

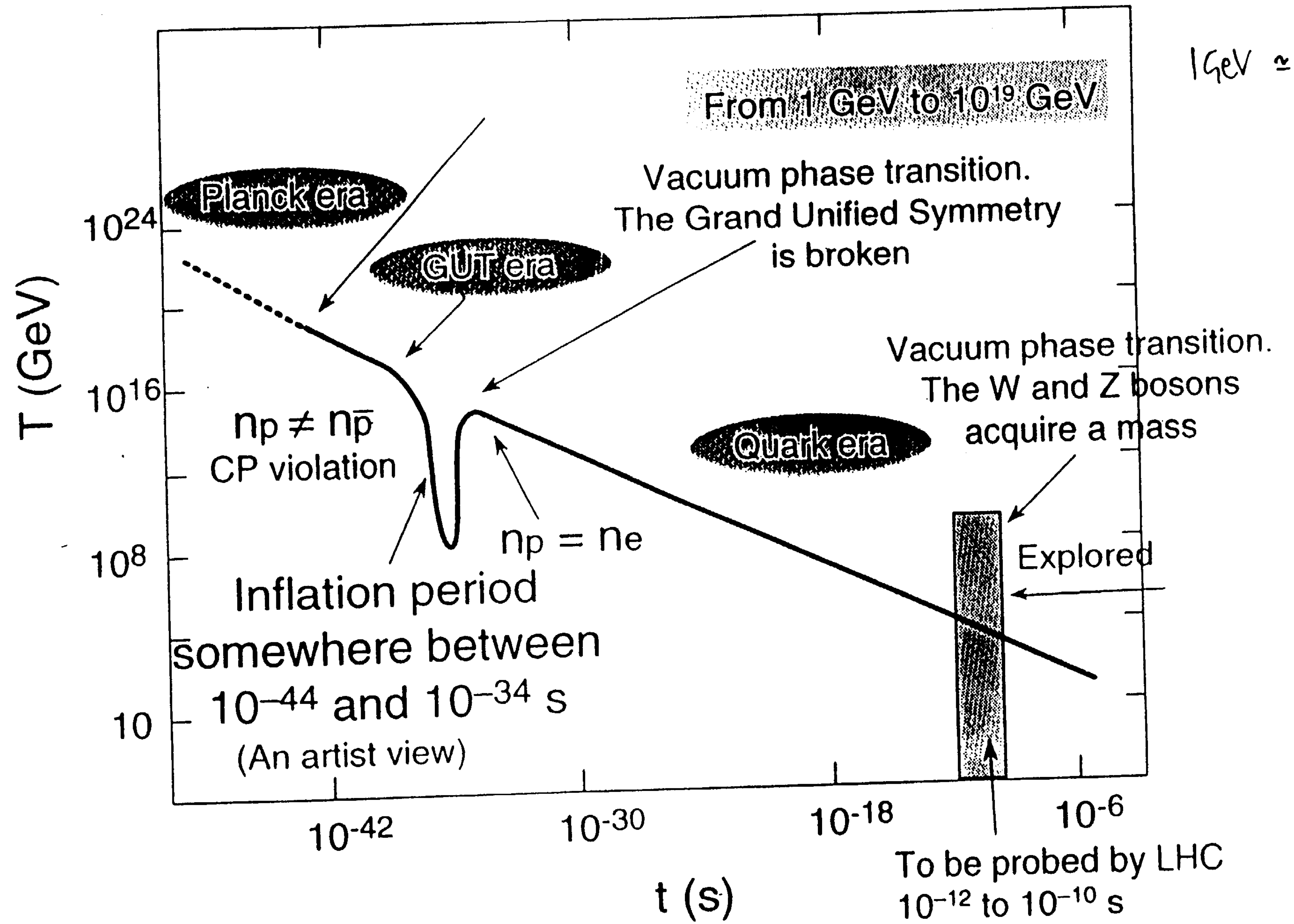
$\eta = 3\ 10^{-10}$ $\quad 1.5 < \eta < 6.10^{-10}$

$10^{-2} < \Omega_b h^2 < 4.\ 10^{-2}$

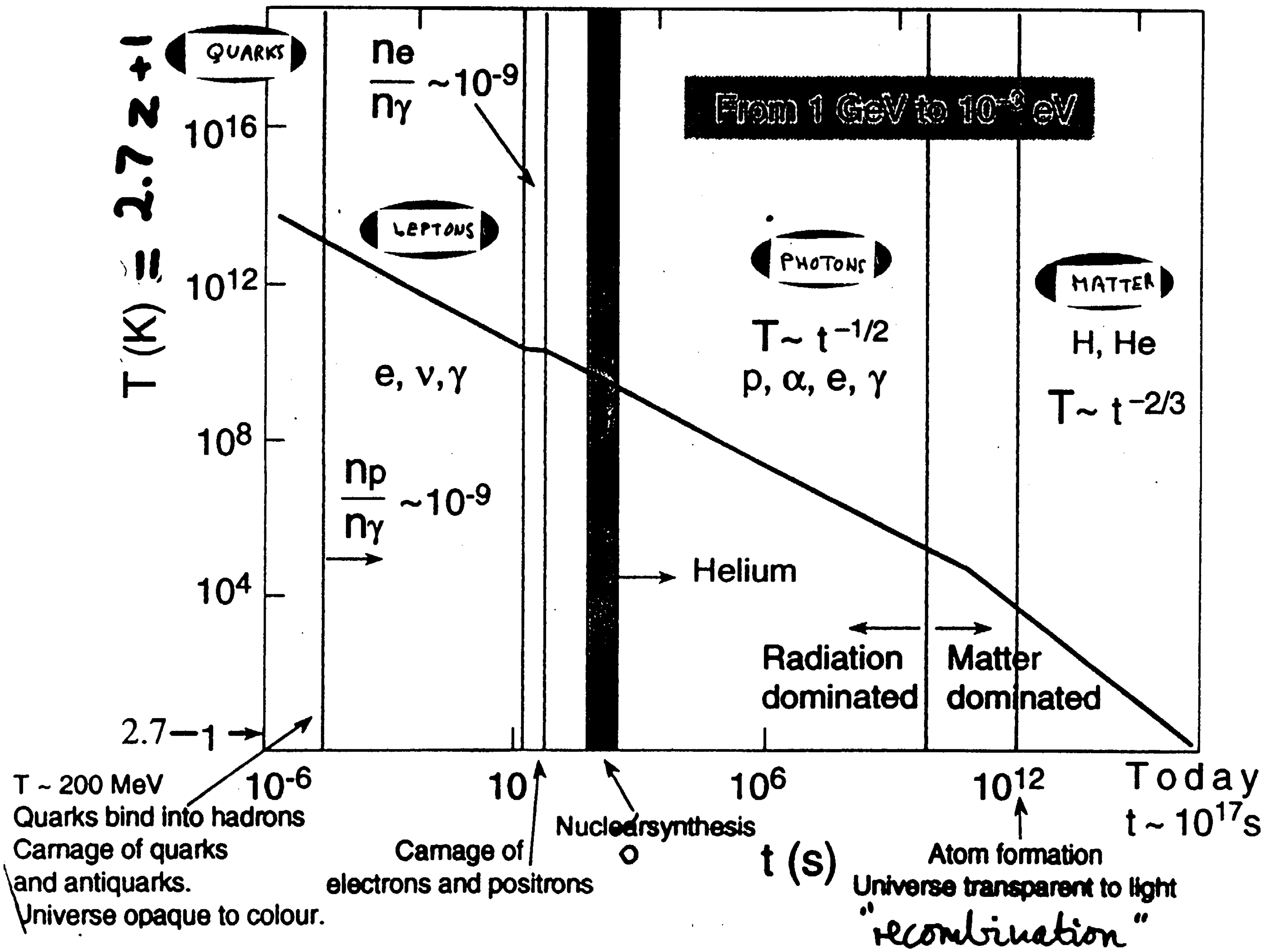
$10^{-2} < \Omega_b < 10^{-1}$

TEMPERATURE OF THE UNIVERSE AS A FUNCTION OF TIME

1GeV ≃ 10^{13} °K



TEMPERATURE OF THE UNIVERSE AS A FUNCTION OF TIME



GALAXY FORMATION

THE STANDARD LORE

GAL. FORMATION $\frac{\delta\rho}{\rho} \sim 1$
(z ~ 2)

BACK IN TIME $\delta\rho/\rho \sim \frac{1}{z} \sim \frac{2.7K}{T}$

MATTER ERA
γ DEC.

IF ONLY BARYONS

$z = 10^3$ $\gamma\, H \rightleftarrows e^- p$

$\Uparrow$

$$\frac{\delta T}{T} \propto \frac{1}{4}\,\frac{\delta\rho}{\rho} \propto 2.5\ 10^{-4}$$

AT GALACTIC SCALE ($< 1^\circ$)

NOT SEEN

t

FLUCTUATIONS GROW
WHEN MATTER ERA
+ DECOUPLED FROM γ

IF WIMPs $\Omega_W = 1$

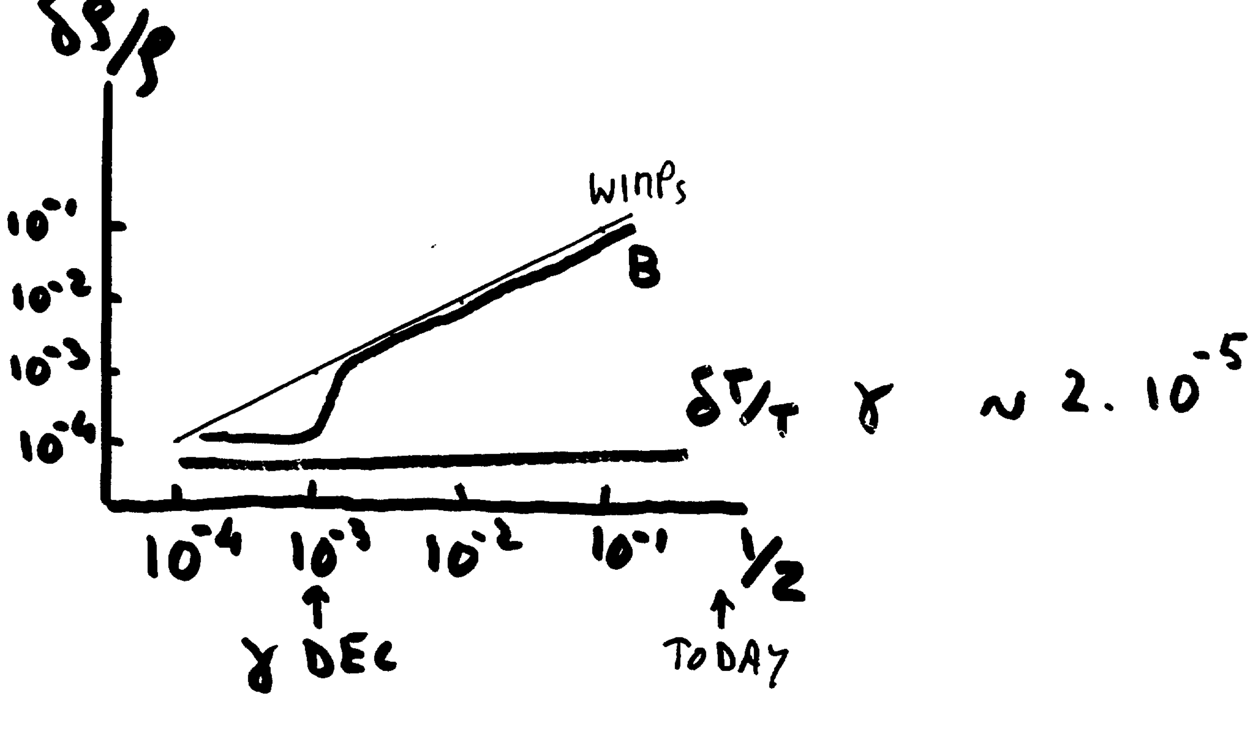
- MATTER (WIMPs) ERA $z = 10^4$
- WIMPs DECOUPLED $\frac{\delta T}{T} = \frac{1}{4}\frac{\delta\rho}{\rho} = 2.5\ 10^{-?}$

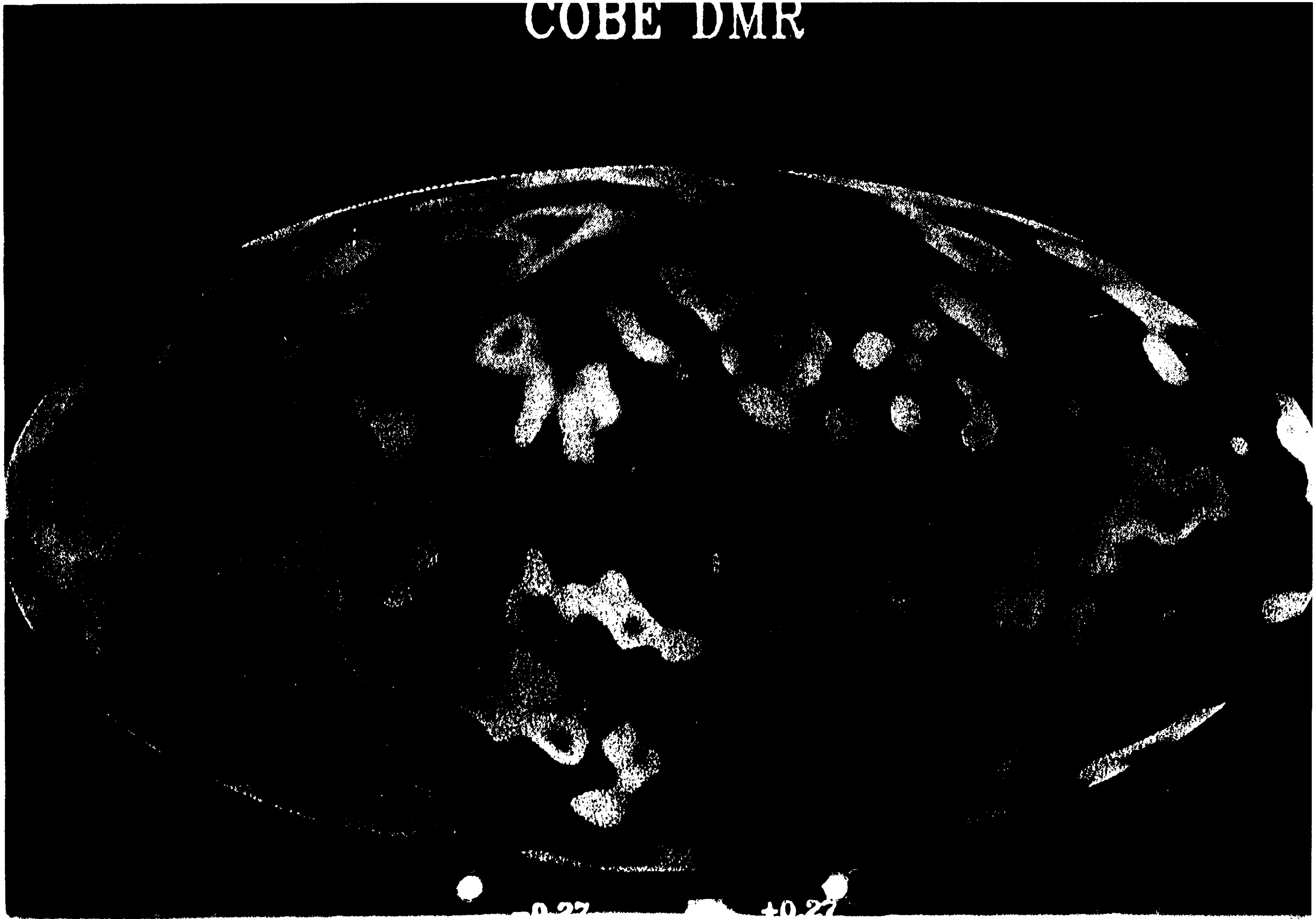
- BARYONS TRAPPED BY γ

- AT $z = 10^3$ $\quad \frac{\delta T}{T} = 2.5\ 10^{-5} = \frac{\delta n_B}{n_B}$

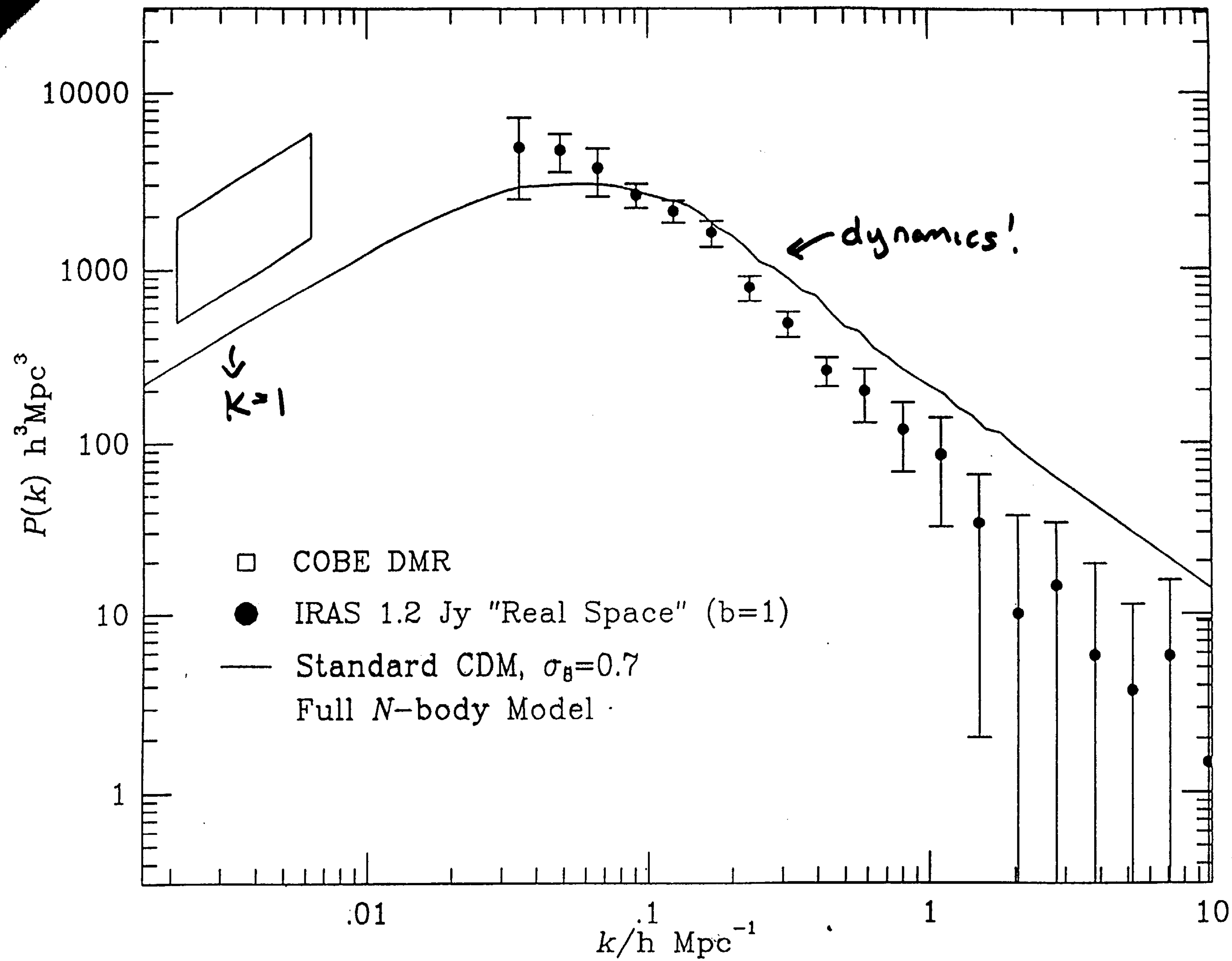
$$\frac{\delta \rho_W}{\rho_W} = 10^{-3}$$

- $z < 10^3$ $\quad \frac{\delta \rho_W}{\rho_W} = \frac{\delta n_B}{n_B}$

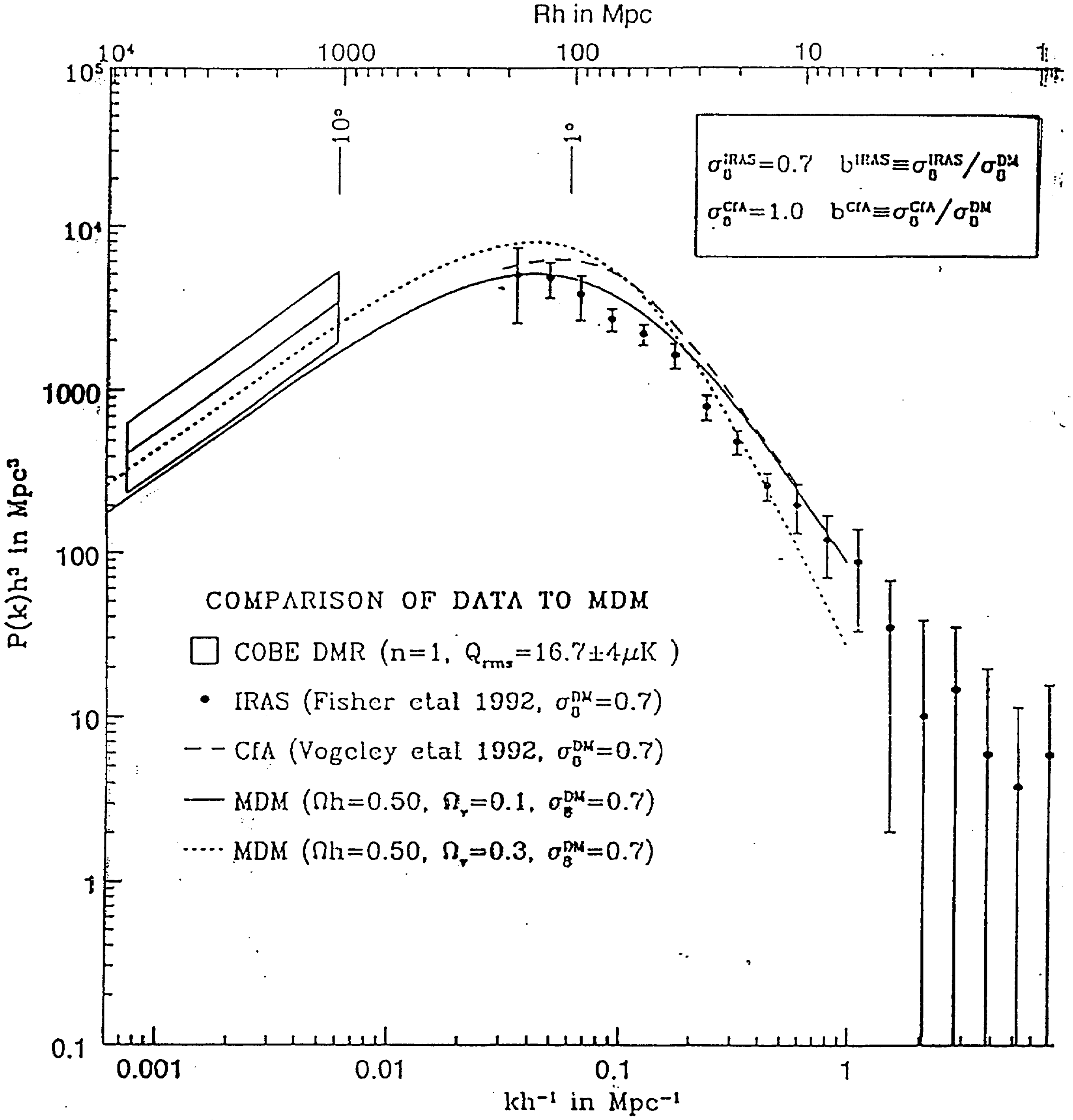



COBE DMR

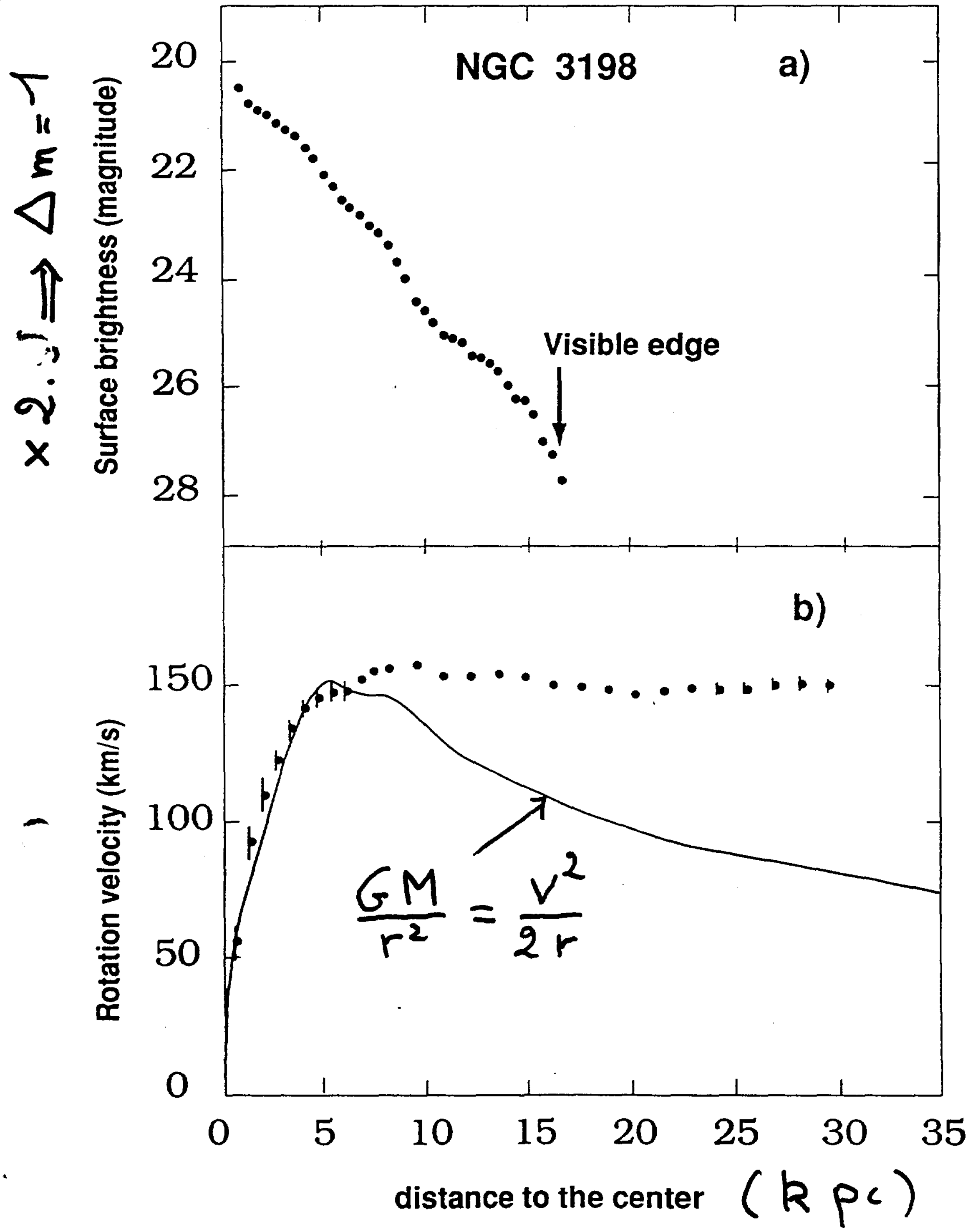
• 5304 IRAS Galaxies.



CDM


Rh in Mpc
10⁴
1000
100
10
1
10°
1°
$\sigma_8^{IRAS}=0.7$ $b^{IRAS}\equiv\sigma_8^{IRAS}/\sigma_8^{DM}$
$\sigma_8^{CfA}=1.0$ $b^{CfA}\equiv\sigma_8^{CfA}/\sigma_8^{DM}$
10^5
10^4
1000
100
10
1
0.1
P(k)h³ in Mpc³
COMPARISON OF DATA TO MDM
COBE DMR (n=1, $Q_{rms}=16.7\pm4\mu K$)
IRAS (Fisher etal 1992, $\sigma_8^{DM}=0.7$)
CfA (Vogeley etal 1992, $\sigma_8^{DM}=0.7$)
MDM ($\Omega h=0.50$, $\Omega_\nu=0.1$, $\sigma_8^{DM}=0.7$)
MDM ($\Omega h=0.50$, $\Omega_\nu=0.3$, $\sigma_8^{DM}=0.7$)
0.001
0.01
0.1
1
kh⁻¹ in Mpc⁻¹

THE STANDARD ROTATION CURVE OF SPIRAL GALAXIES



GENERAL CONCLUSION

$M_{HALO} \geqslant 10\ M_{vis}$

KEPLER: $\frac{m_* v_*^2}{r} = G \frac{m_* M_G}{r^2}$

$v_{exp} \propto \frac{1}{\sqrt{r}}$

5 S_c Galaxies

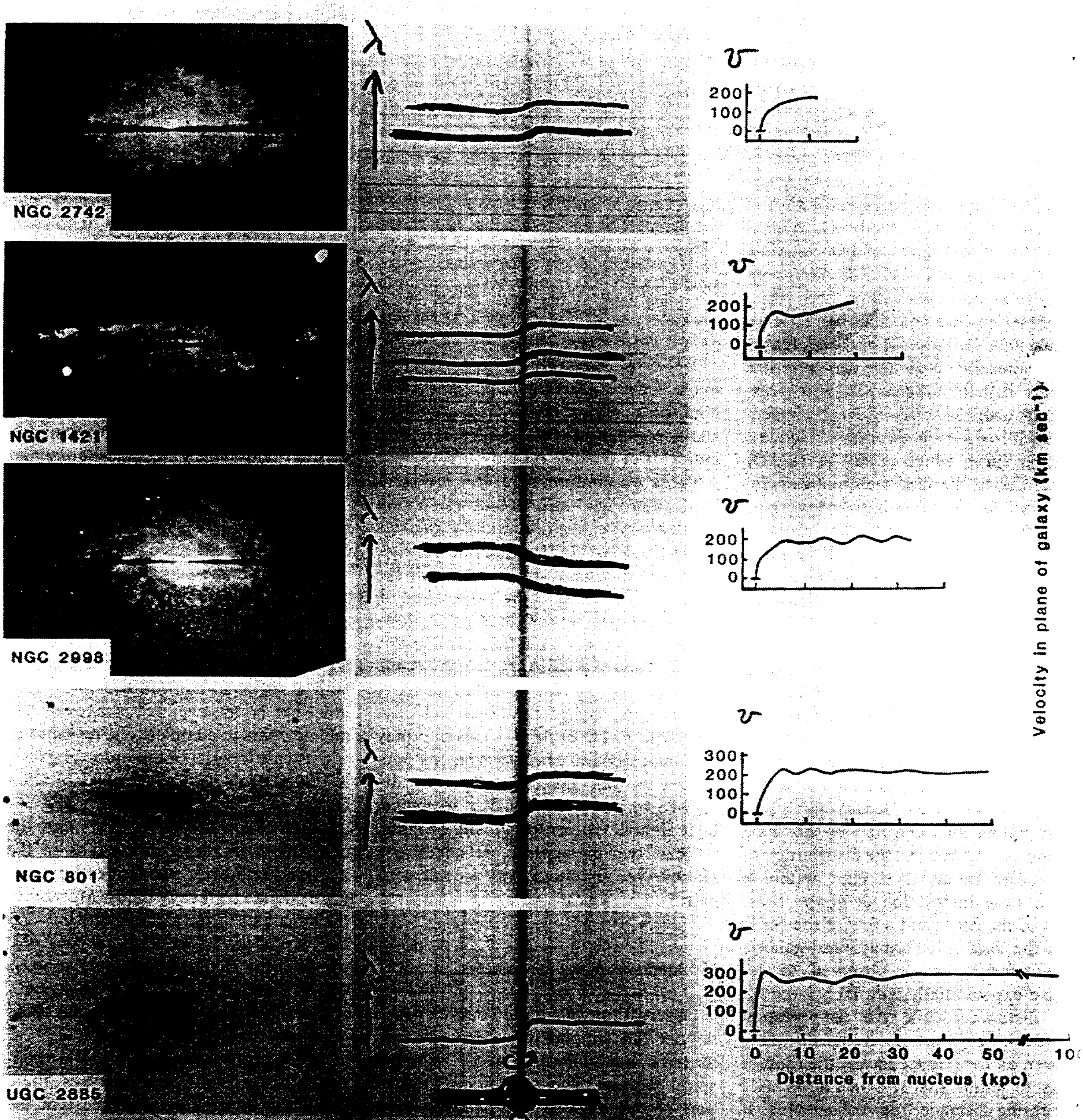
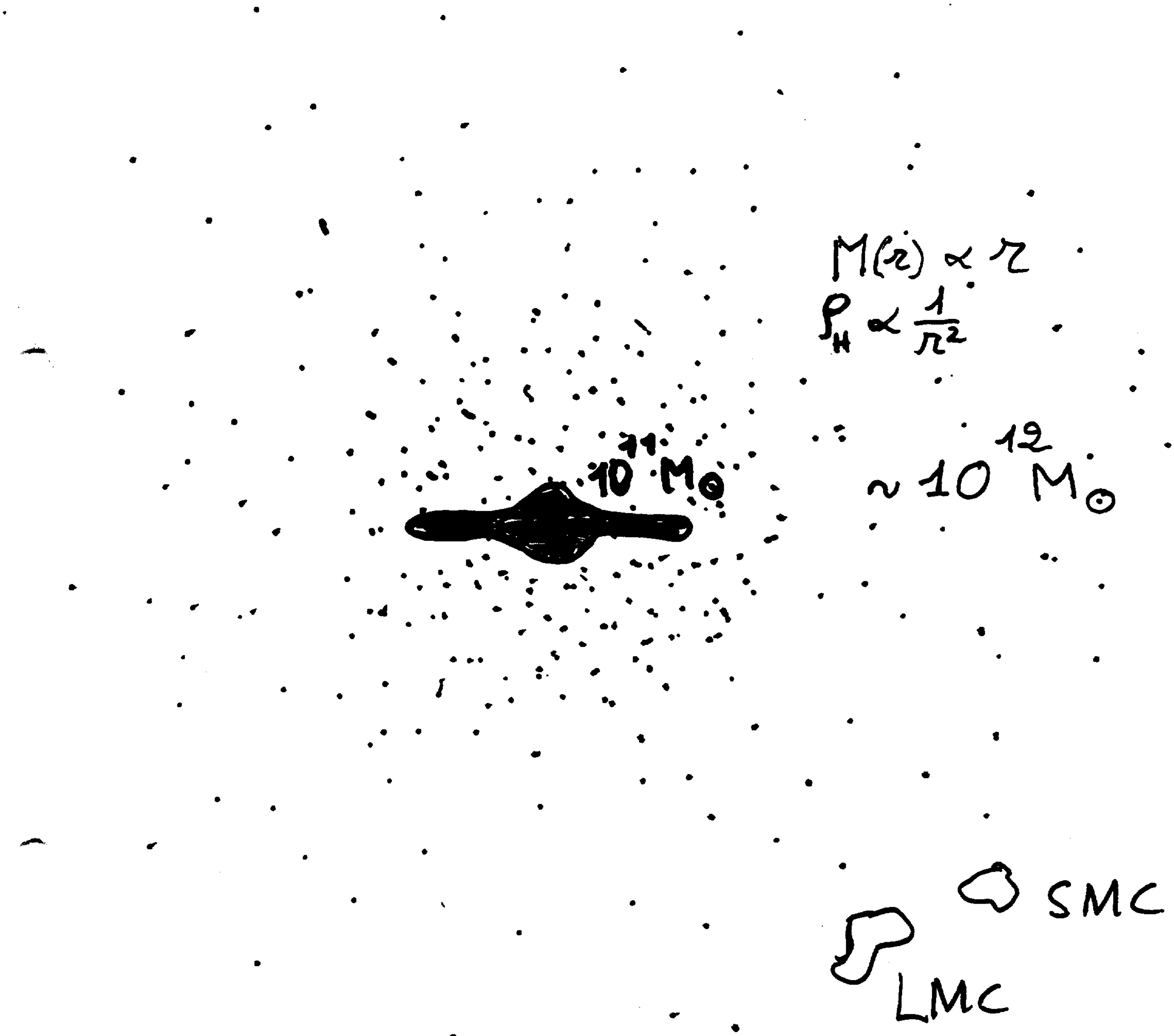


Fig. 1. Spectra and rotation curves for five Sc galaxies, arranged according to increasing luminosity. Photographs for NGC 2742, 1421, and 2998 are copies of the television screen which displays the image reflected off the spectrograph slit jaws. The dark line crossing the galaxy is the spectrograph slit. NGC 801 and UGC 2885 are reproduced from plates taken at the prime focus of the 4-m telescope at Kitt Peak National Observatory by B. Carney. The corresponding spectra are arranged with wavelength increasing from the bottom to the top. The strongest step-shaped line in each spectrum is from hydrogen in the galaxy, and is flanked by weaker lines of forbidden ionized nitrogen. The strong vertical line in each spectrum is the continuum emission from stars in the nucleus. The undistorted horizontal lines are emission from the earth's atmosphere, principally OH. The curves at the right show the rotational velocities as a function of nuclear distance, measured from the emission lines in the spectra.

The Galaxy
(GALACTIC HALOS)



$\rho_{Halo} \sim 0{,}3\ \mathrm{GeV}/\mathrm{cm}^3$. (at Earth) $\sim .01\ M_\odot/pc^3$

$V_{stars} \sim V_{\substack{Halo \\ Objects}} \sim V_{LMC} \sim 200\ \frac{km}{sec}$

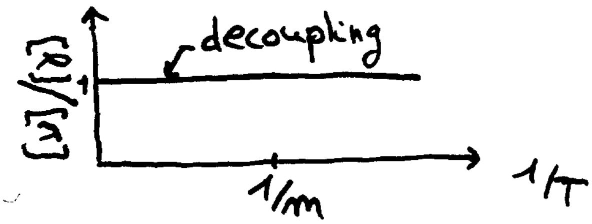
$\sim 10^{-3} c$

TERMINOLOGY

LIGHT NEUTRINOS =

$10 \div 30$ eV ν_e or ν_μ or ν_τ

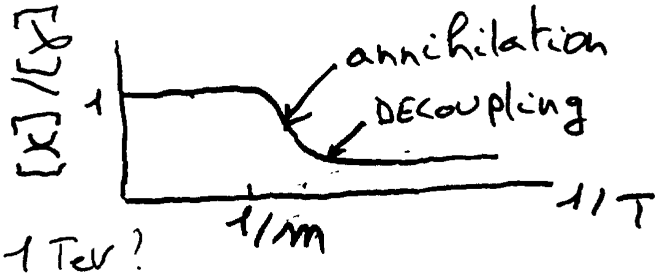
HOT DARK MATTER : DECOUPLE WHEN RELATIVISTIC



WIMP = WEAKLY INTERACTING MASSIVE PARTICLES

COLD DARK MATTER , DECOUPLE WHEN NON RELATIVISTIC

ν_H, $\tilde{\nu}$, $\tilde{\gamma}$, LSP χ



? 10 GeV < m < 1 TeV ?

MACHO =

MASSIVE ASTROPHYSICAL COMPACT (HALO) OBJECTS

BARYONIC DARK MATTER

BLACK HOLES, NEUTRON STARS, SMALL "SUNS" or ABORTED STARS or BROWN DWARFS

M. SPIRO
Saclay

MACHO

MASSIVE
- ASTROPHYSICAL
COMPACT
HALO
OBJECT

- JUPITER LIKE ? $10^{-7} \div 10^{-2} M_\odot$
- BROWN DWARVES $10^{-2} M_\odot$
- FAINT STARS $0.1 \rightarrow 0.3 M_\odot$
- STAR REMNANTS $\geqslant .5 M_\odot$ (white dwarves, n stars, black holes)

- MOST LIKELY : $H + {}^4He$

$10^{-7} M_\odot \longrightarrow$ few $10^{-1} M_\odot$

EVAPORATION

$10^{-2} M_\odot$
JEANS MASS

VISIBLE STARS

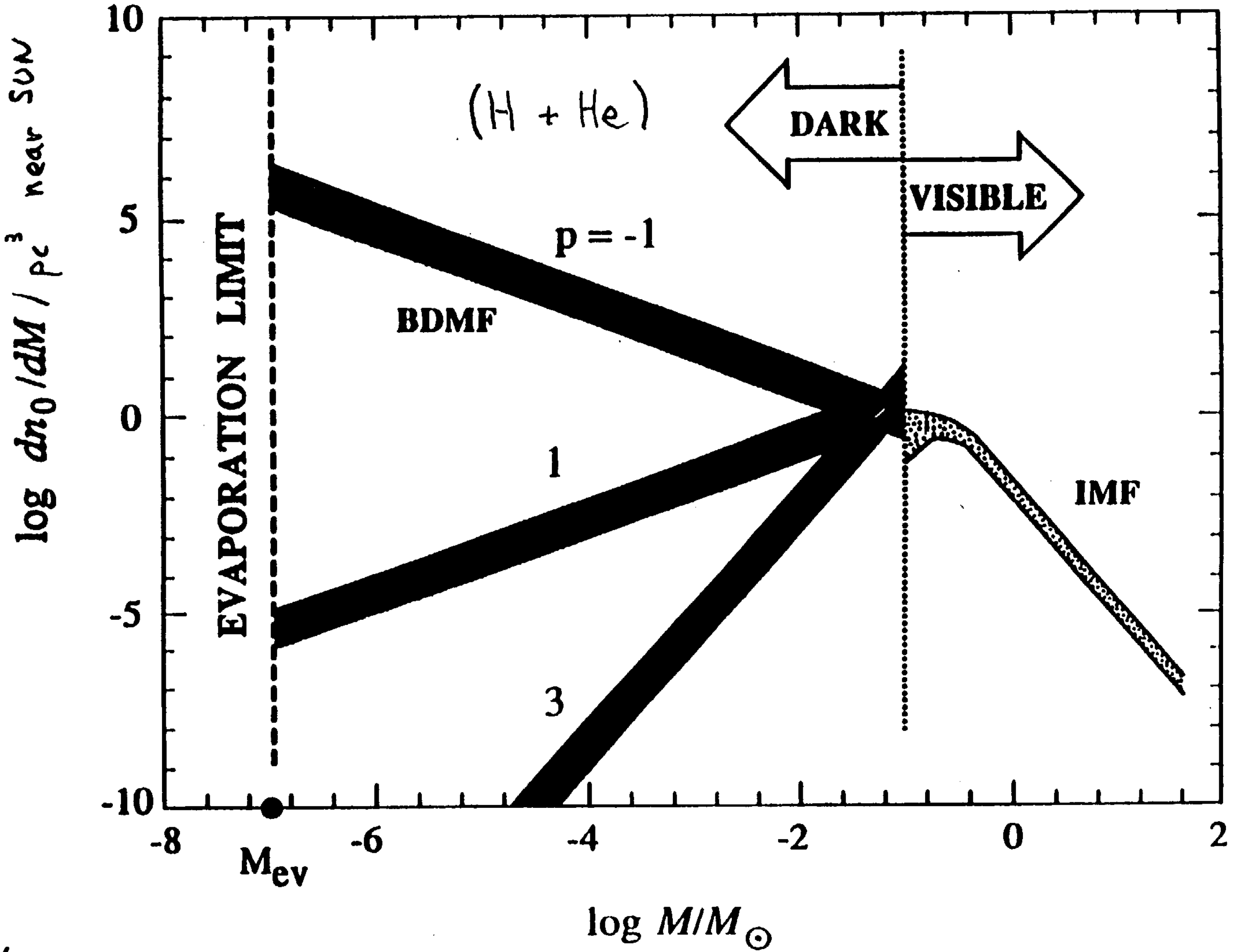


Fig. 3b

de Rújula,
Jetzer,
Massó

2a

MACHO's

Scenario: Early generation of low mass stars $M < 0.3 M_\odot$.
Remaining gas collapses to form observable disk.

$M < 0{,}07\, M_\odot \Rightarrow$ hydrogen not burned

"Good" Things:

1. No New Particles
2. Ω_{baryon} (from nucleosynthesis)
   $\sim \Omega^{\text{halo}}_{\text{galaxy}}$ (from rotation curves)
   $\sim \boxed{0.1}$

"Bad" Things:

1. Don't help galaxy formation (like WIMP's)
2. Formation of MACHO's "difficult"

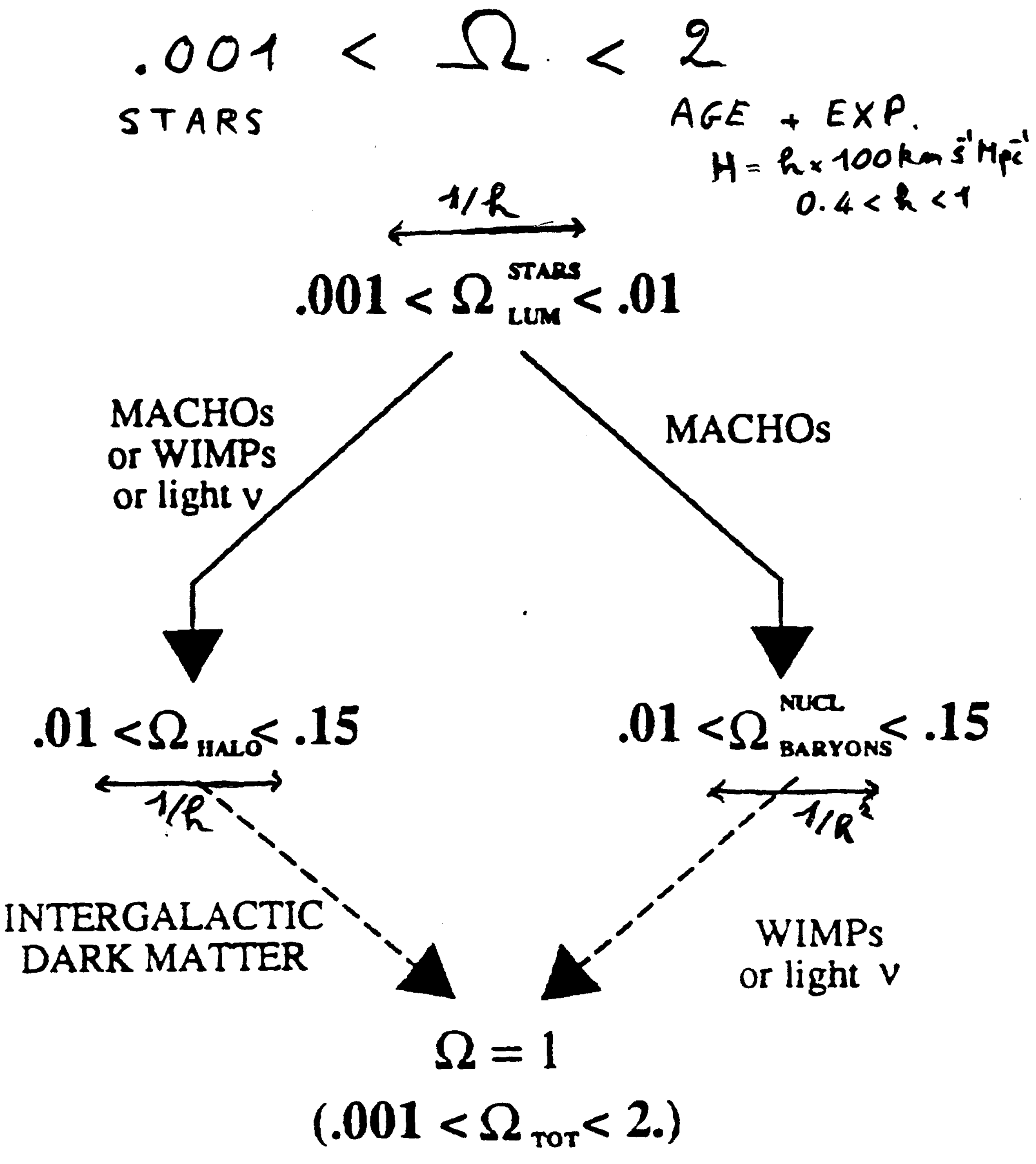
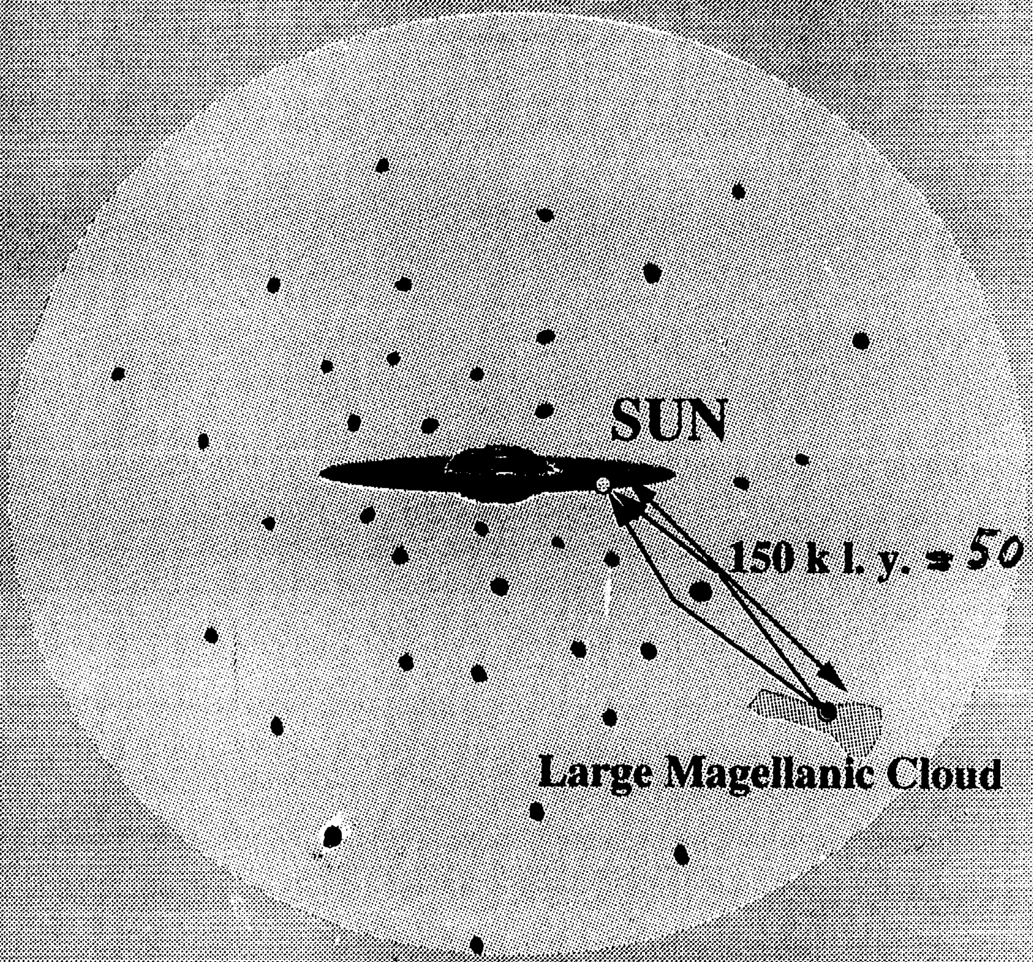


Fig.1 Present status of Ω determinations

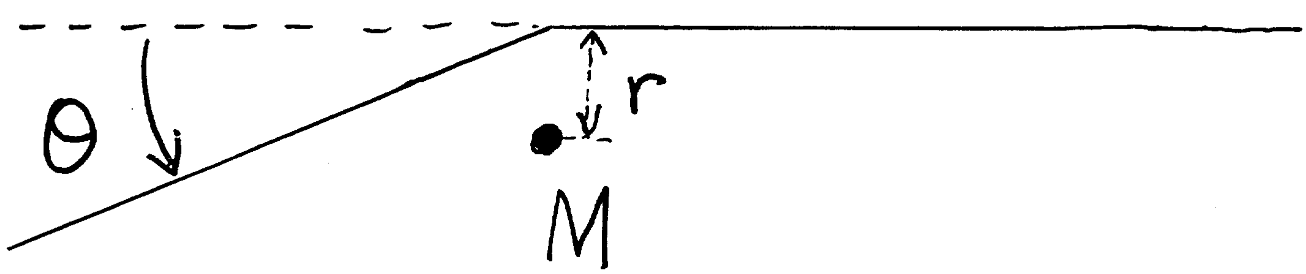
Paczynski, Ap. J., 1986, 1

EROS
Saclay,
Orsay,
Paris,
Marseille
(CHILE) (ESO)

MACHO
Livermore,
Berkeley,
Santa Barbara,
San Diego,
Mount Stromlo
(AUSTRALIA)



Gravitational Bending of Light Rays

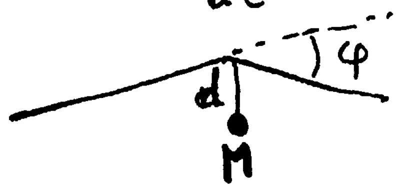


r = impact parameter

M = Mass of deflector

$$\theta = \frac{4MG}{rc^2} \quad \text{(Einstein)}$$

$$\varphi = 4\,\frac{GM}{dc^2}$$



EINSTEIN RING RADIUS $R_E^2 = \frac{4GMD}{c^2}\,x(1-x)$

$$u = \frac{d}{R_E} \qquad R_E = 10^9\sqrt{\frac{M}{M_\odot}}\ \mathrm{km}$$

$$A(t) = \frac{u(t)^2 + 2}{u(t)\left[u(t)^2 + 4\right]^{1/2}}$$

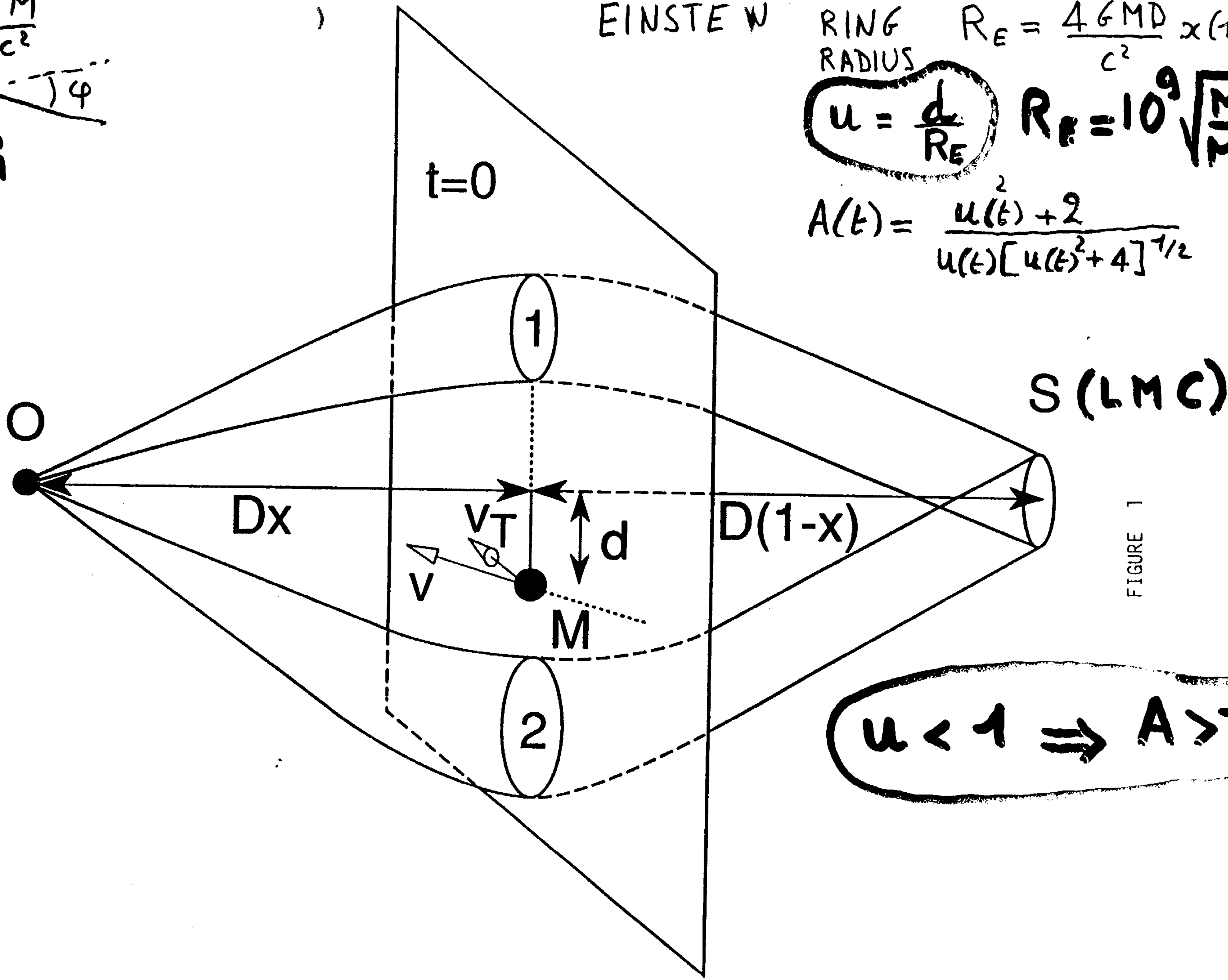
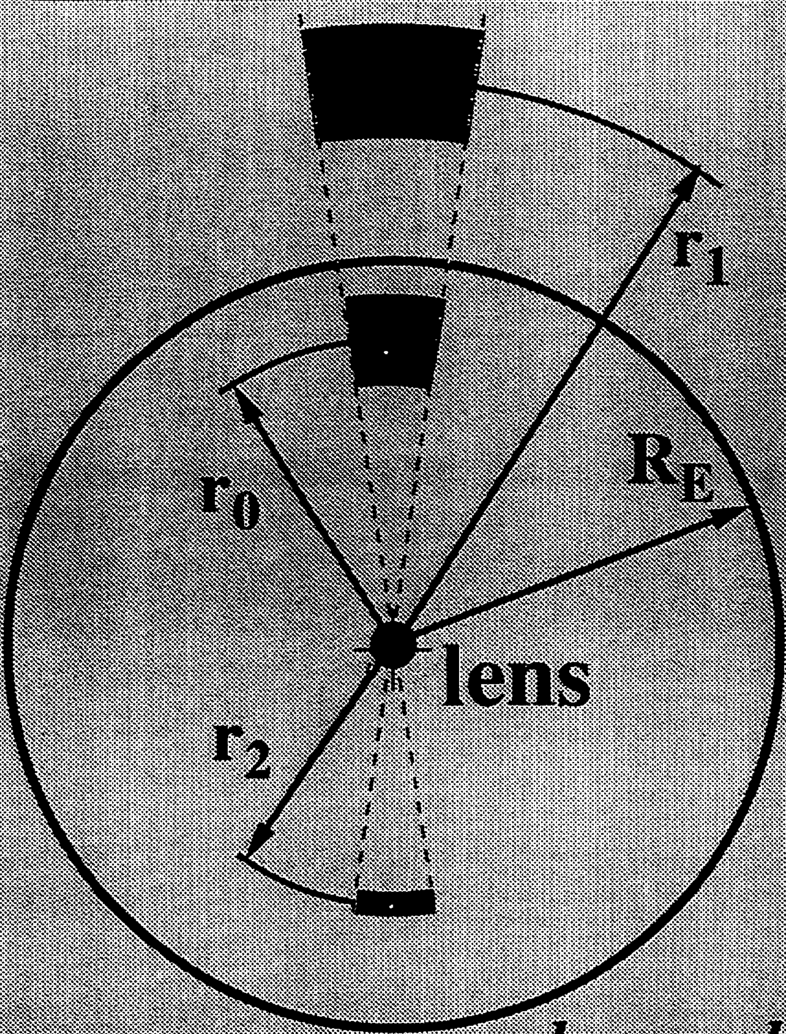


FIGURE 1

$$u < 1 \Rightarrow A > 1.3$$

Amplification



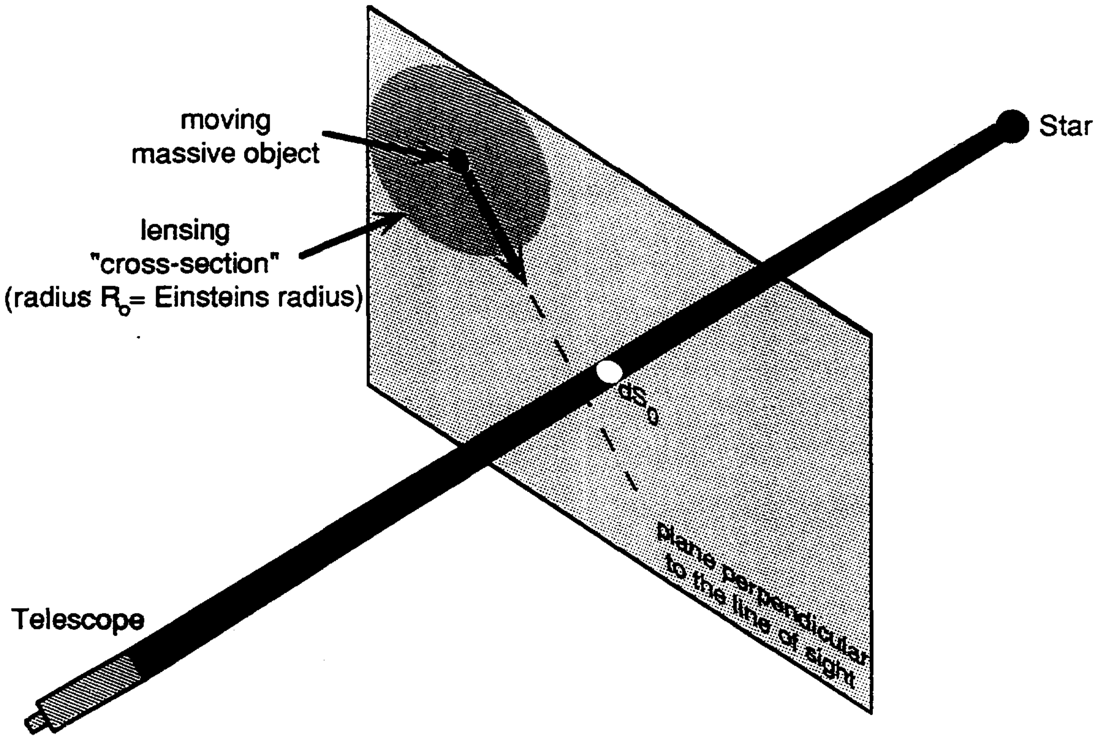
$$\text{amplification : } A = \frac{r_1\, dr_1 - r_2\, dr_2}{r_0\, dr_0}$$

Einstein ring

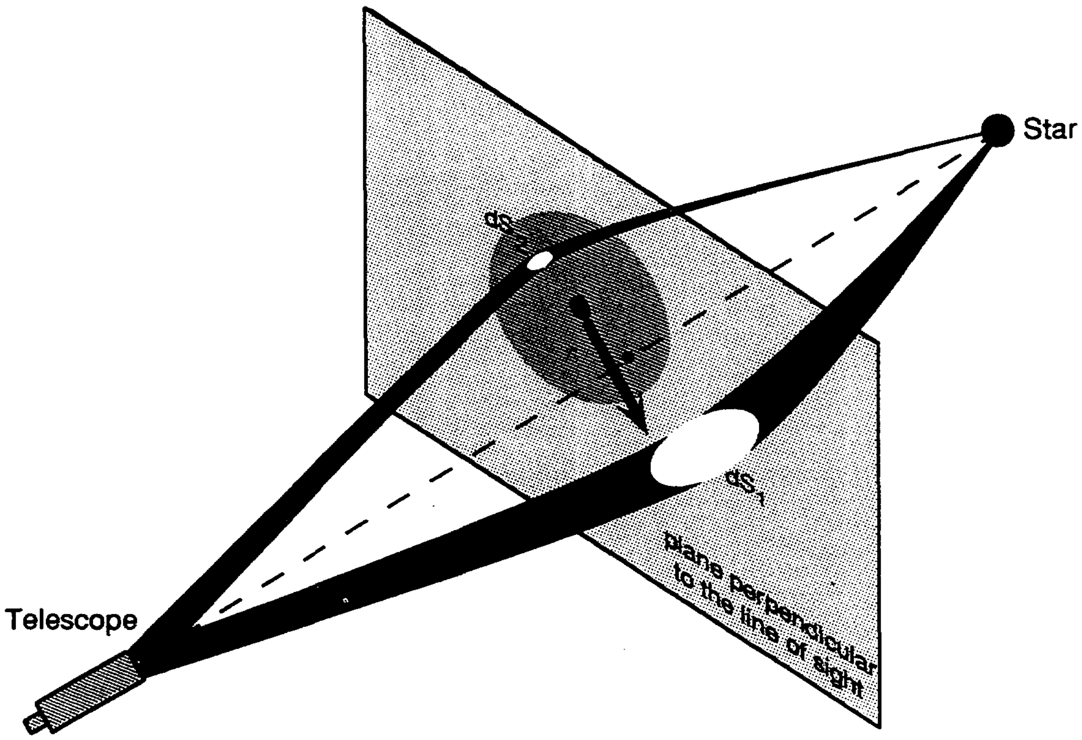
2 star images

star (undeflected)

GRAVITATIONNAL LENSING EFFECT



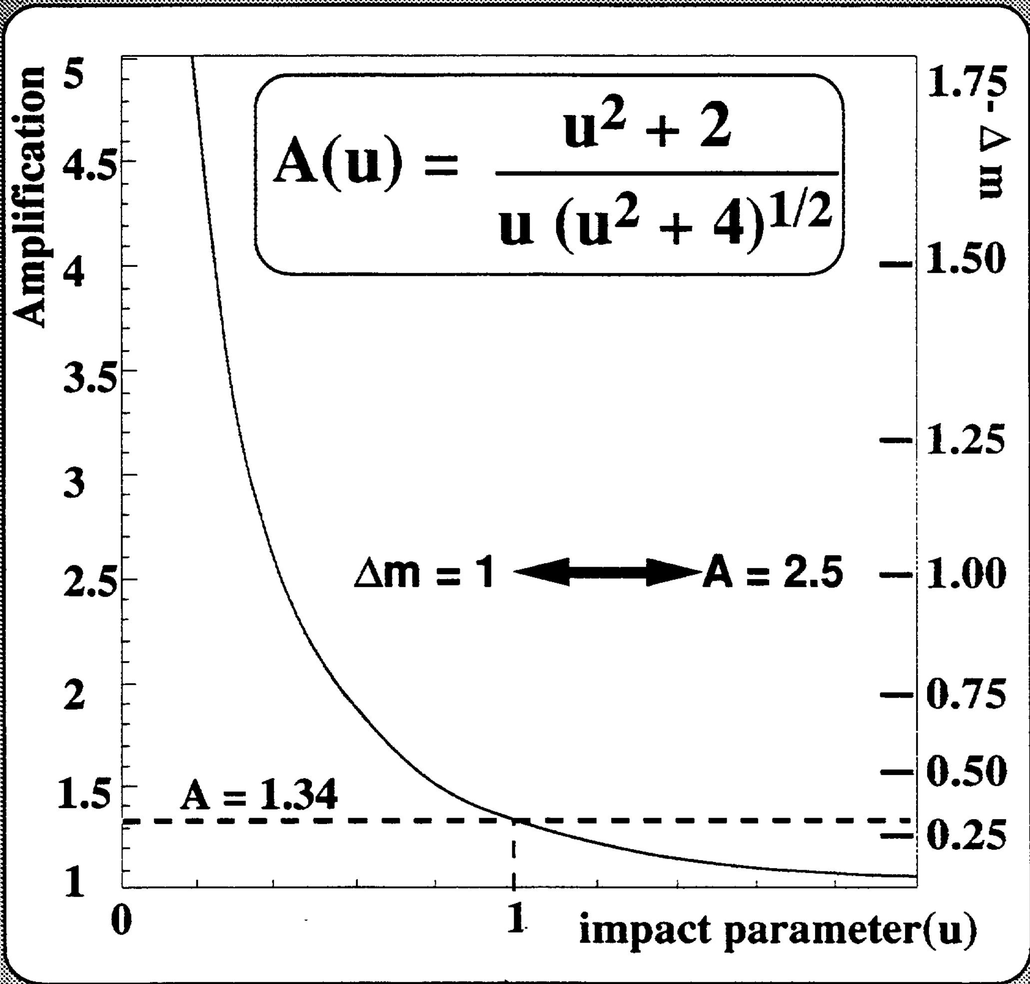
massive object far from the line of sight



massive object close to the line of sight

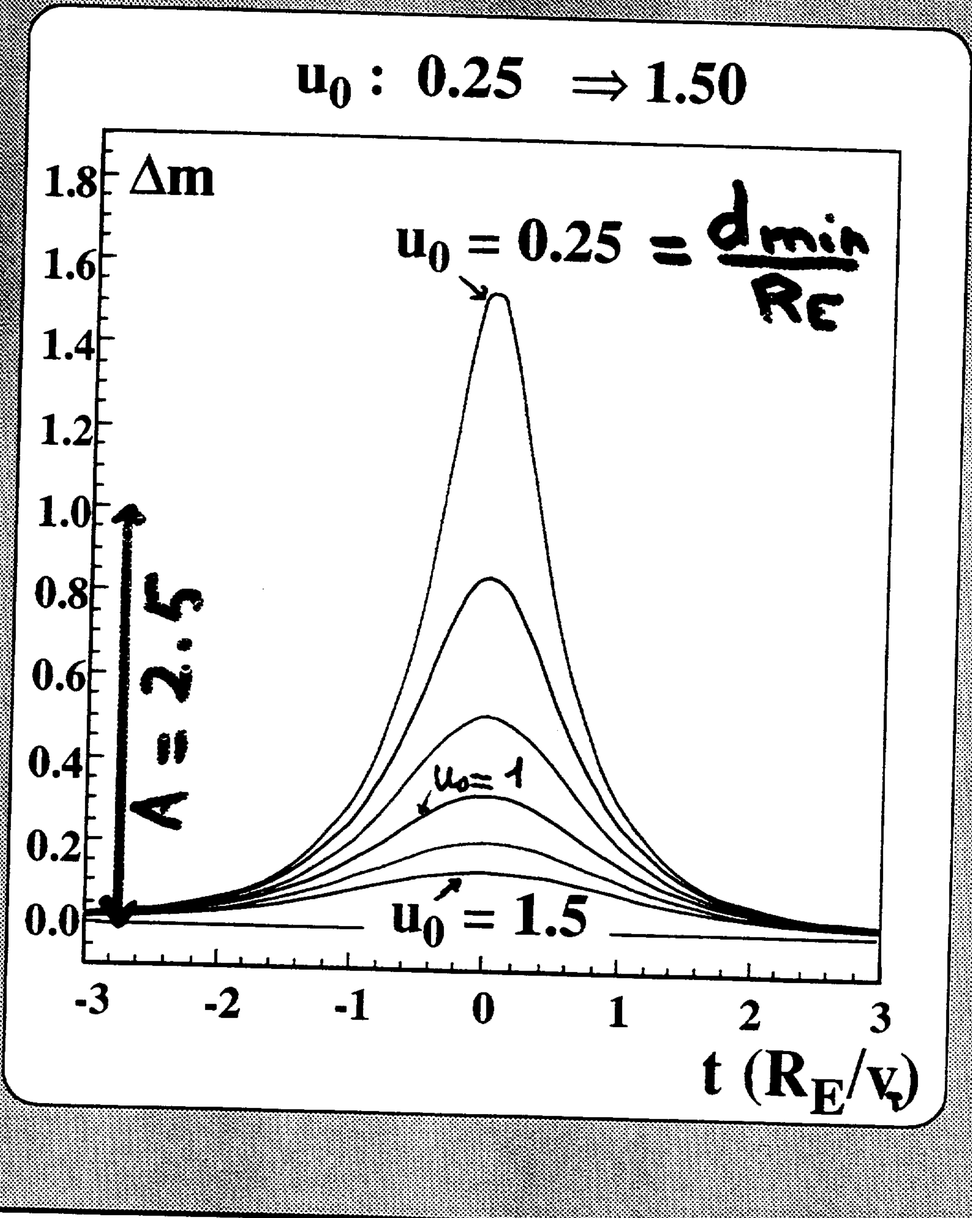
Amplification

$$u = \frac{d}{R_E}$$



Light curves

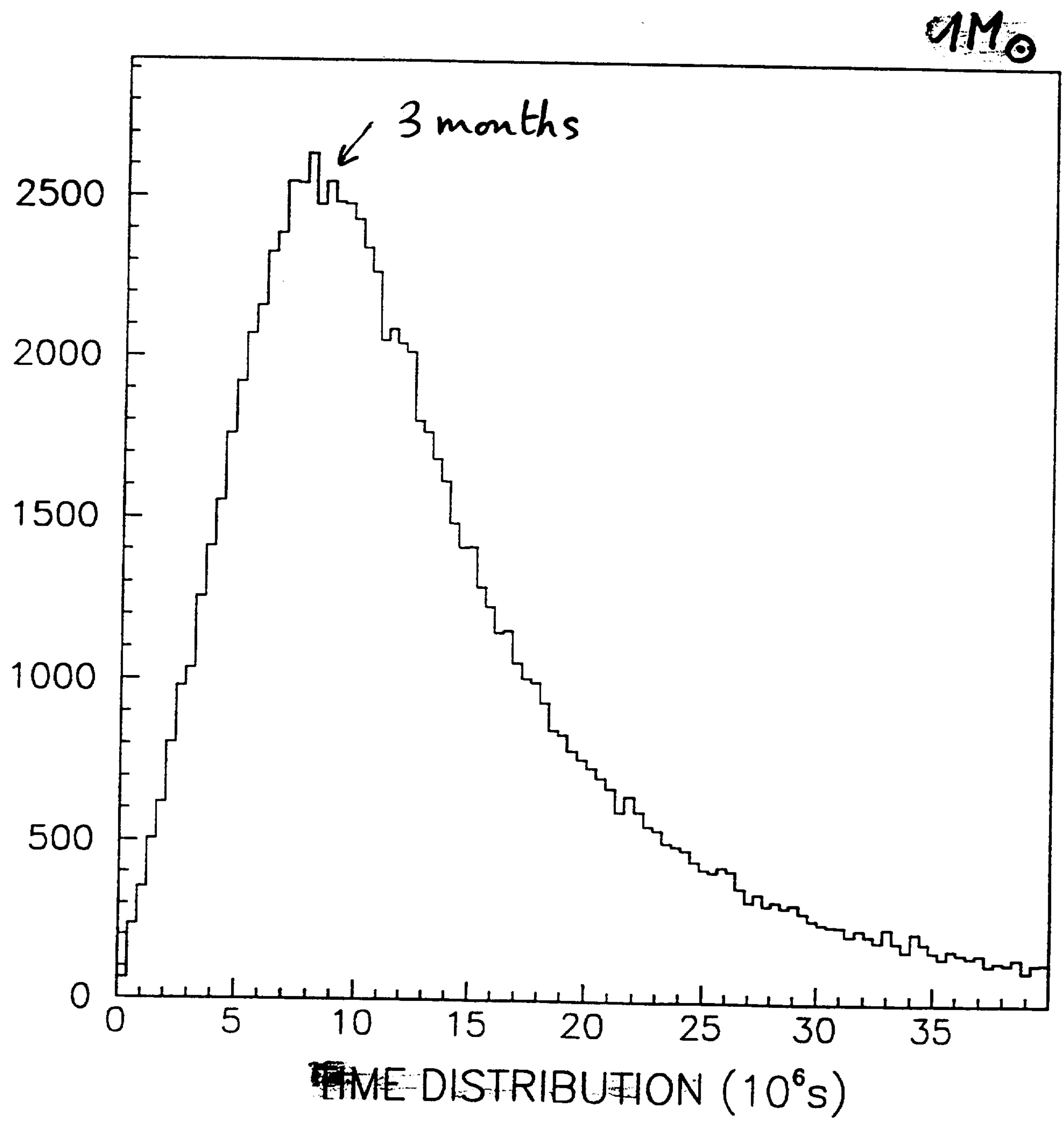
$T = 70 \sqrt{\frac{M}{M_\odot}}$ DAYS



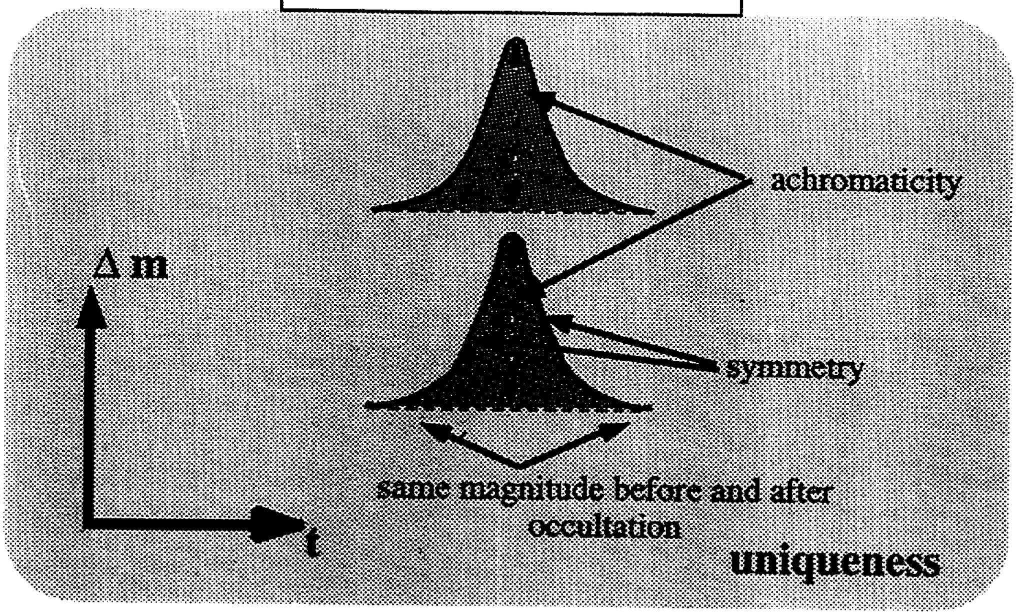
(19)

Probability distribution of "characteristic time" τ;
(For an "isothermal" halo model, with objects of $1 M_\odot$)

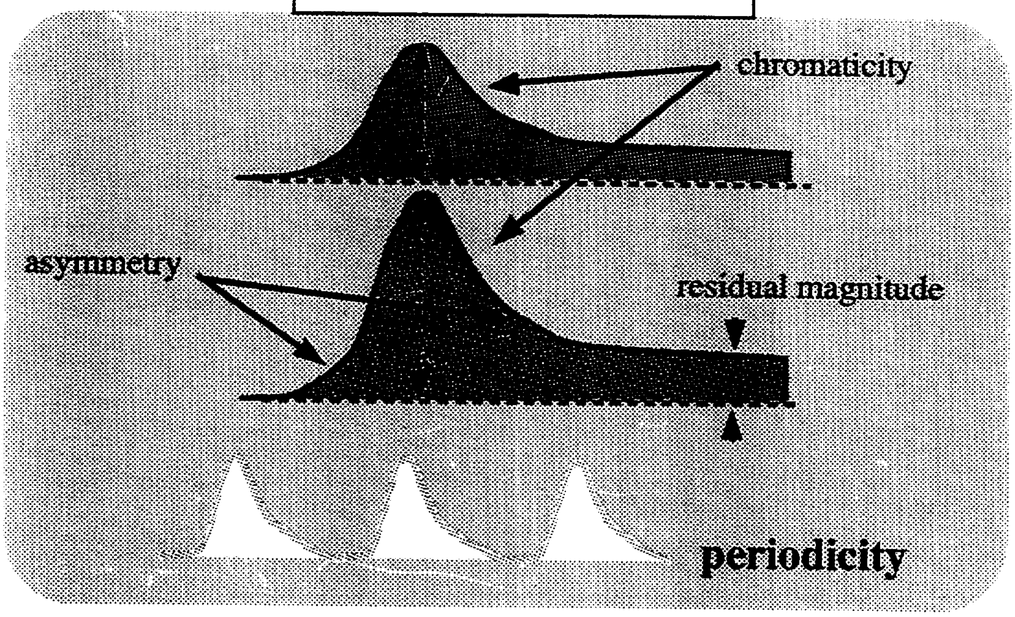
For other masses, abscissa scales as $(M/M_\odot)^{1/2}$



MICROLENSING

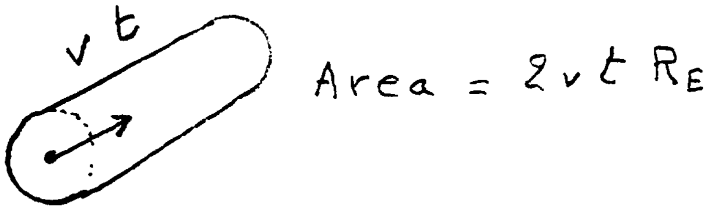


VARIABLE STARS

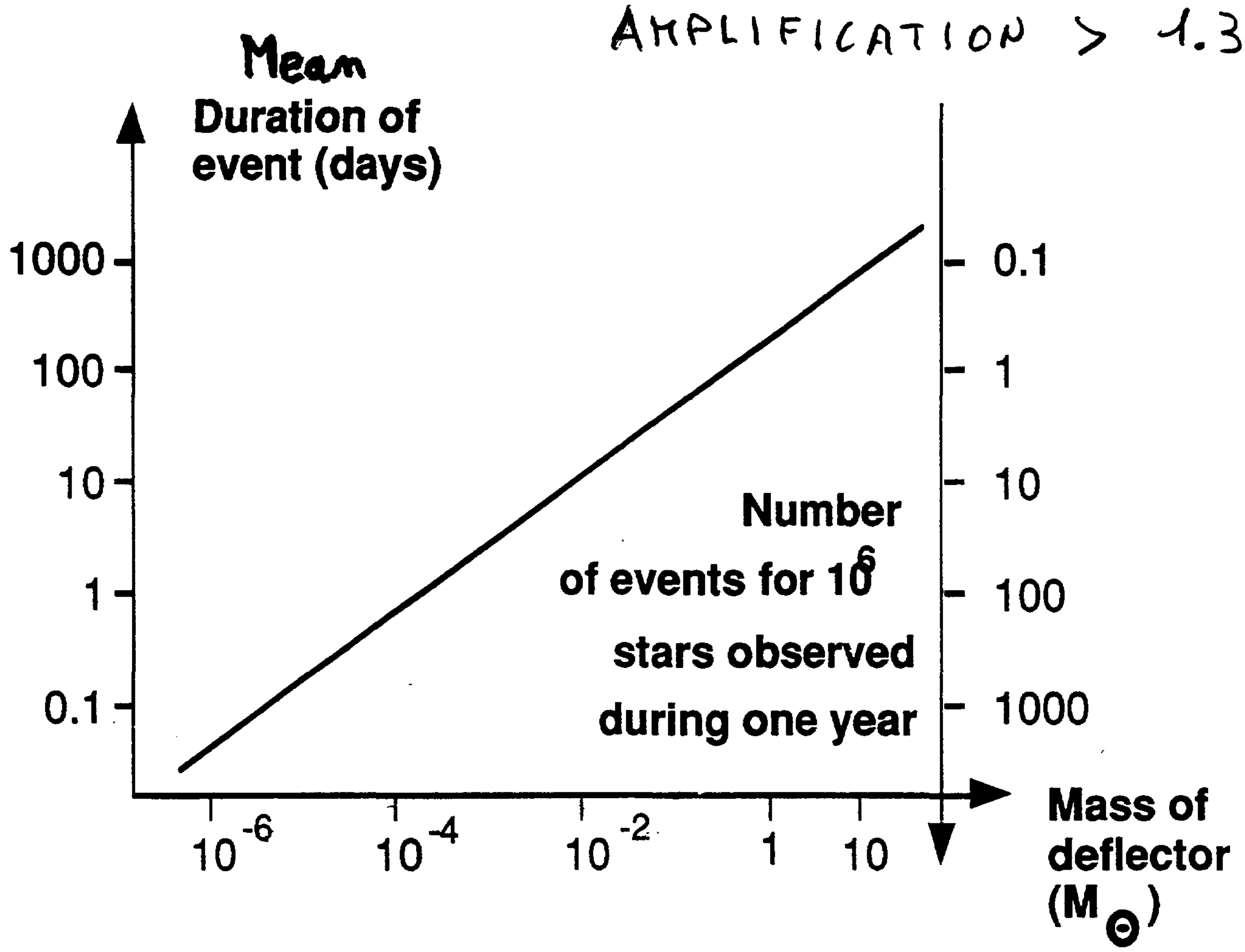


+ COLOUR vs MAGNITUDE DIAGRAM

Duration vs Mass of Deflector



AMPLIFICATION > 1.3



For stars in the LMC, and all deflectors having the same mass and the same velocity

EROS

(Expérience de Recherche d'Objets Sombres)

E. AUBOURG, P. BAREYRE, S. BRÉHIN, M. GROS, M. LACHIEZE-REY,
B. LAURENT, E. LESQUOY, C. MAGNEVILLE, A. MILSZTAJN,
L. MOSCOSO, F. QUEINNEC, J. RICH, M. SPIRO , L. VIGROUX,
S. ZYLBERAJCH

DAPNIA, CE Saclay,91191 Gif-sur-Yvette, France

R. ANSARI, F. CAVALIER, M. MONIEZ

Laboratoire de l'Accélérateur Linéaire
Centre d'Orsay, 91405 Orsay Cedex, France

J.-P. BEAULIEU, R. FERLET, PH. GRISON, A. VIDAL-MADJAR

Institut.d'Astrophysique de Paris,
98 bis boulevard Arago, 75014 Paris, France

J. GUIBERT, F. TAJAHMADY

Observatoire de Paris,
61 avenue de l'Observatoire, 75014 Paris, France

E. MAURICE, L. PREVOT
Observatoire de Marseille,
2 place Le Verrier, 13248 Marseille Cedex 04, France

C. GRY
Laboratoire d'Astronomie Spatiale de Marseille,
Traverse du Siphon, Les Trois Lacs,
13120 Marseille, France

O. MOREAU

Institut d'Astrophysique de Liège
Avenue de Cointe, 5, B -4000 Liège, Belgium

ESO, LA SILLA, CHILE

Schmidt Photo Program

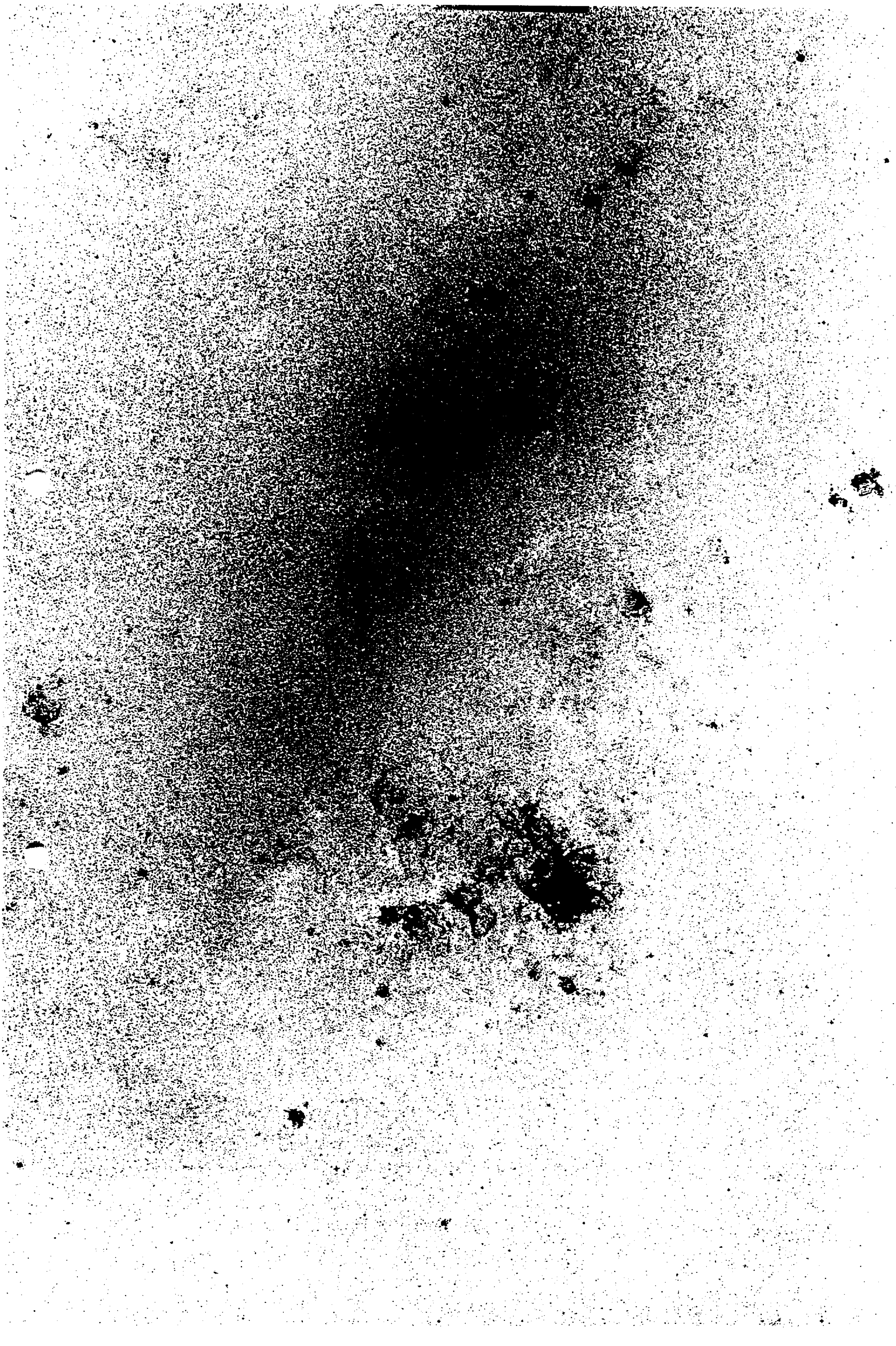
{ 1 m diameter telescope

- ESO · La Silla, Chile
- $5^\circ \times 5^\circ$ (30 cm × 30 cm)
- 1 hour poses ($\lesssim 2$ / night)
- $\sim 5\, 10^6$ ☆'s
- $\langle \sigma \rangle \sim 15\%$
- number of plates ($\frac{1}{2}$ red, $\frac{1}{2}$ blue)

50	1990–91	October–March
200	91–92	
50	92–93	
⋮		

- Sensitive to $10^{-4} M_\odot < M < M_\odot$

  $1 \text{ day} < \langle \tau \rangle < 100 \text{ days}$

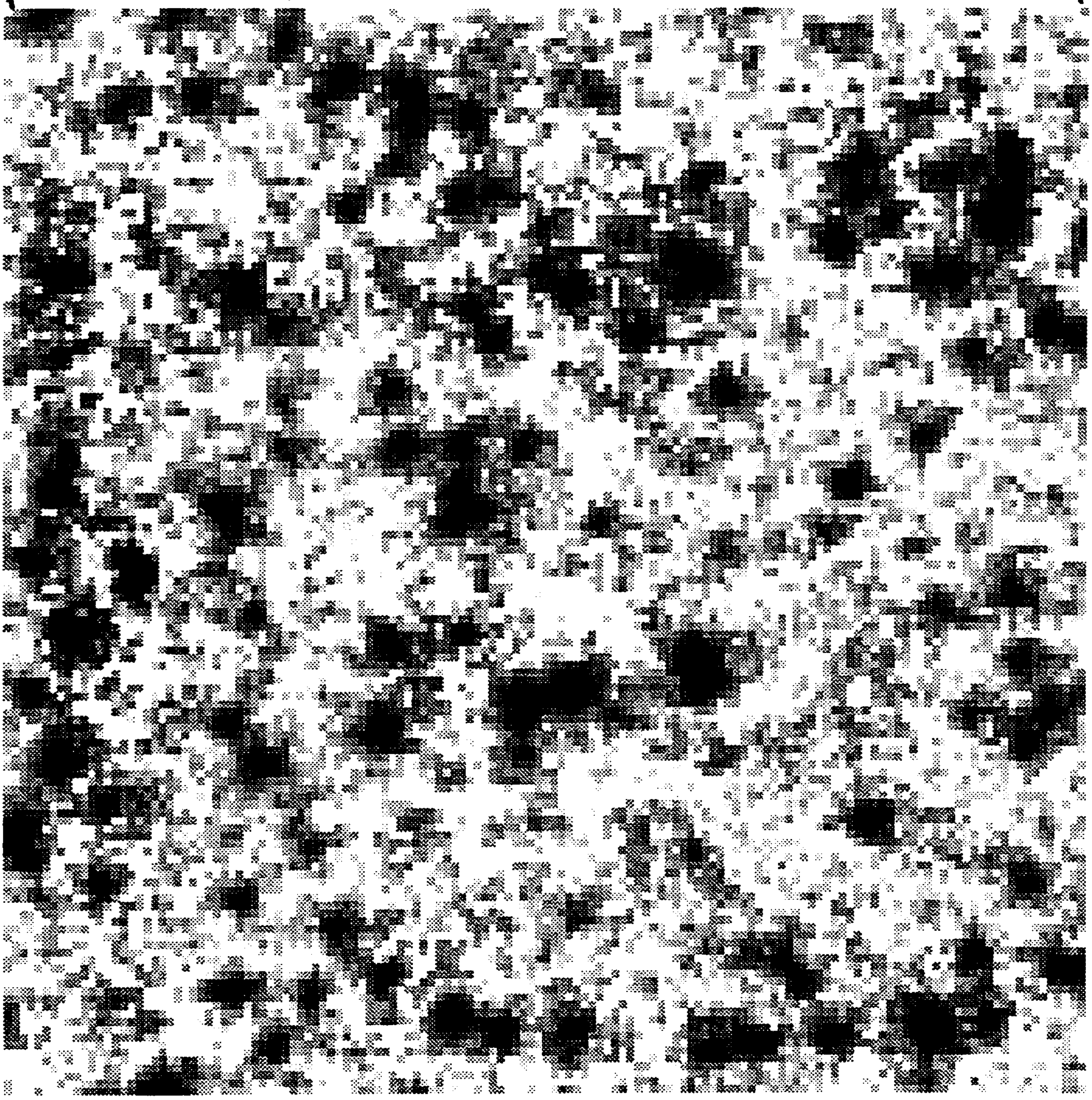


Schmidt Plate $= 5\ 10^6$ stars

30 cm × 30cm $\sim 5^\circ \times 5^\circ$

$10\mu \times 10\mu$ pxel

$\longleftarrow$ 1,5 mm $\sim$ 1.6 arcmin $\frac{1}{4 \times 10^4} \longrightarrow$



Digitization of Plate Transparency
at Paris Observatory 1,5 Gigabyte/plate

CCD Program

- 40 cm reflector
- $0{,}4^\circ \times 1^\circ$ = 16 579×400 pixel CCD's ($20\ cm^2$)
- 10 minute poses
- $1{,}5 \times 10^5$ ★'s
- $\langle \sigma \rangle \sim 8\%$
- Number of poses

2500	Dec '91	March '92
5500	August '92	March '93
8000 ?	93	94

- Sensitive to $10^{-7} M_\odot < M < 10^{-4} M_\odot$
  10^{-2} day $< \langle \tau \rangle <$ 1 day

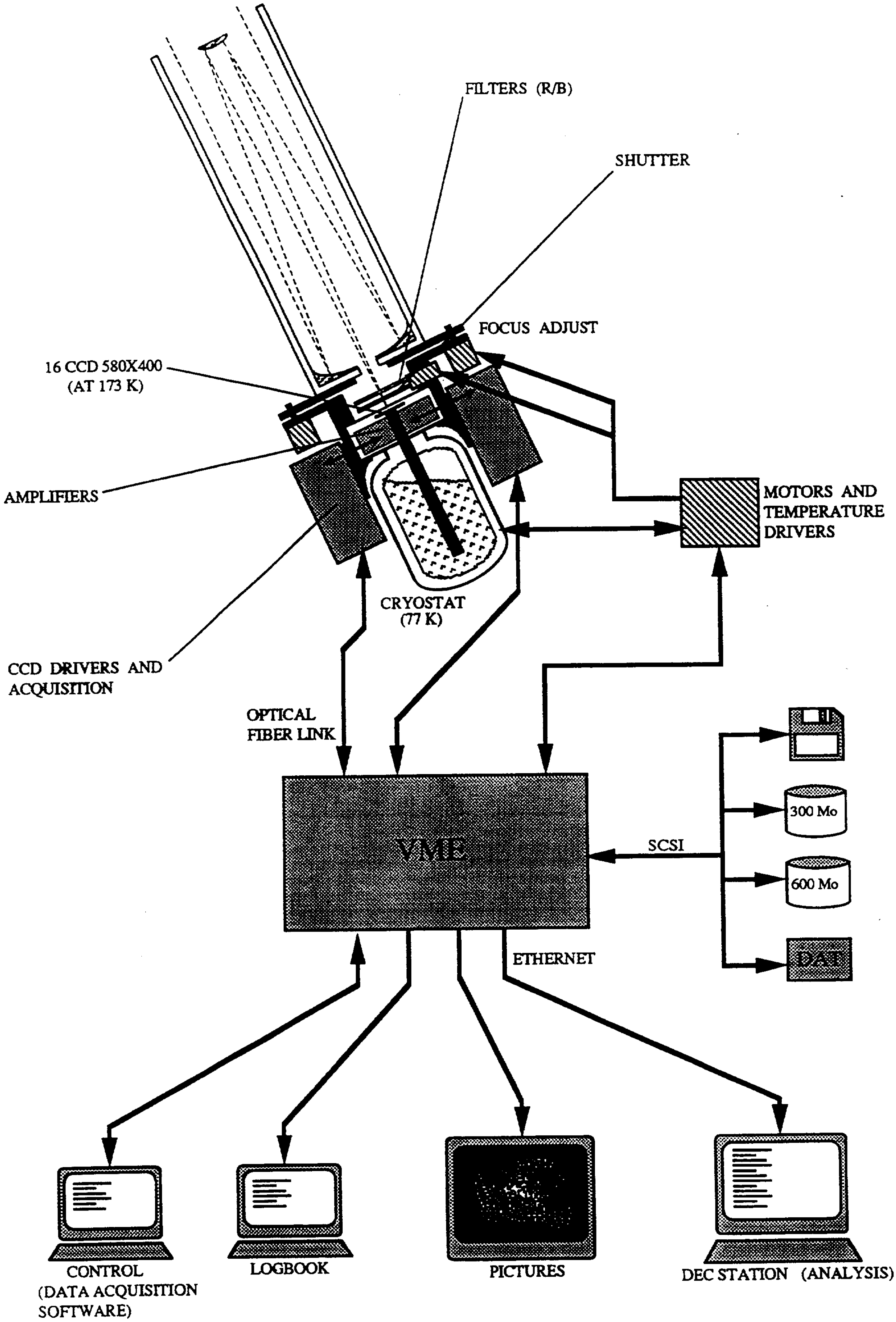

FILTERS (R/B)
SHUTTER
FOCUS ADJUST
16 CCD 580X400
(AT 173 K)
AMPLIFIERS
MOTORS AND
TEMPERATURE
DRIVERS
CRYOSTAT
(77 K)
CCD DRIVERS AND
ACQUISITION
OPTICAL
FIBER LINK
VME
SCSI
300 Mo
600 Mo
DAT
ETHERNET
CONTROL
(DATA ACQUISITION
SOFTWARE)
LOGBOOK
PICTURES
DEC STATION (ANALYSIS)

FIG. 1