united nations
educational, scientific
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international atomic
energy agency

the
abdus salam
international centre for theoretical physics

SMR.1317 - 8

SUMMER SCHOOL ON PARTICLE PHYSICS

18 June - 6 July 2001

ASPECTS OF ASTROPARTICLE PHYSICS

Lectures IV & V

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Minneapolis, MN 55455, USA

Please note: These are preliminary notes intended for internal distribution only.

LECTURE II

Historical Perspective

Intimate connection with CMB

Alpher
Herman
Gamow

Conditions for BBN:

Require $T > 100$ keV $\Rightarrow t < 200$ s

$\sigma v(p + n \rightarrow D + \gamma) \approx 5 \times 10^{-20}\ cm^3/s$

$$\Rightarrow n_B \sim 1/\sigma v t \sim 10^{17}\ cm^{-3}$$

Today:

$$n_{Bo} \sim 10^{-7}\ cm^{-3}$$

and

$$n_B \sim R^{-3} \sim T^3$$

Predicts the CMB temperature

$$T_o = (n_{Bo} / n_B)^{1/3}\, T_{BBN} \sim 10\ K$$

BBN Theory

Conditions in the Early Universe:

$$T \gtrsim 1 \text{ MeV}$$

$$\rho = \frac{\pi^2}{30}(2 + \frac{7}{2} + \frac{7}{4}N_\nu)T^4$$

$$\eta = n_B/n_\gamma \sim 10^{-10}$$

β-Equilibrium maintained by weak interactions

Freeze-out at ~ 1 MeV determined by the competition of expansion rate $H \sim T^2/M_p$ and the weak interaction rate $\Gamma \sim G_F^2 T^5$

$$\begin{aligned} n + e^+ &\leftrightarrow p + \bar{\nu}_e \\ n + \nu_e &\leftrightarrow p + e^- \\ n &\leftrightarrow p + e^- + \bar{\nu}_e \end{aligned}$$

At freezeout n/p fixed modulo free neutron decay, $(n/p) \simeq 1/6 \to 1/7$

Nucleosynthesis Delayed (Deuterium Bottleneck)

$p + n \rightarrow \mathbf{D} + \gamma$ $\qquad\qquad \Gamma_p \sim n_B \sigma$

$p + n \leftarrow \mathbf{D} + \gamma$ $\qquad\qquad \Gamma_d \sim n_\gamma \sigma e^{-E_B/T}$

Nucleosynthesis begins when $\Gamma_p \sim \Gamma_d$

$\frac{n_\gamma}{n_B} e^{-E_B/T} \sim 1$ $\qquad$ @ $T \sim 0.1$ **MeV**

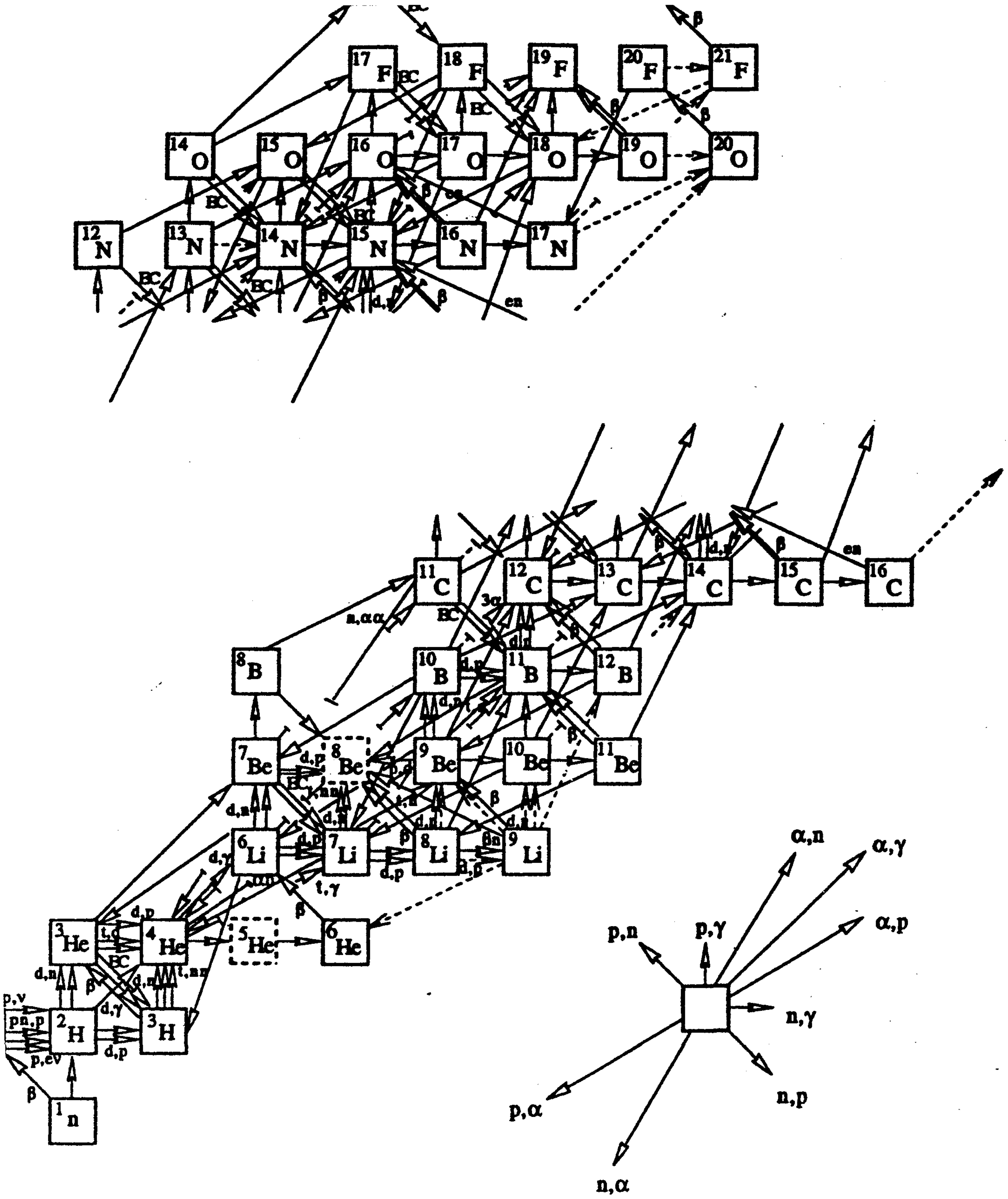
All neutrons $\rightarrow$ ^{4}He

with mass fraction

$$Y_p = \frac{2(n/p)}{1 + (n/p)} \simeq 25\%$$

Remainder:

D, ^{3}He $\sim$ 10^{3} and ^{7}Li $\sim$ 10^{10} by number

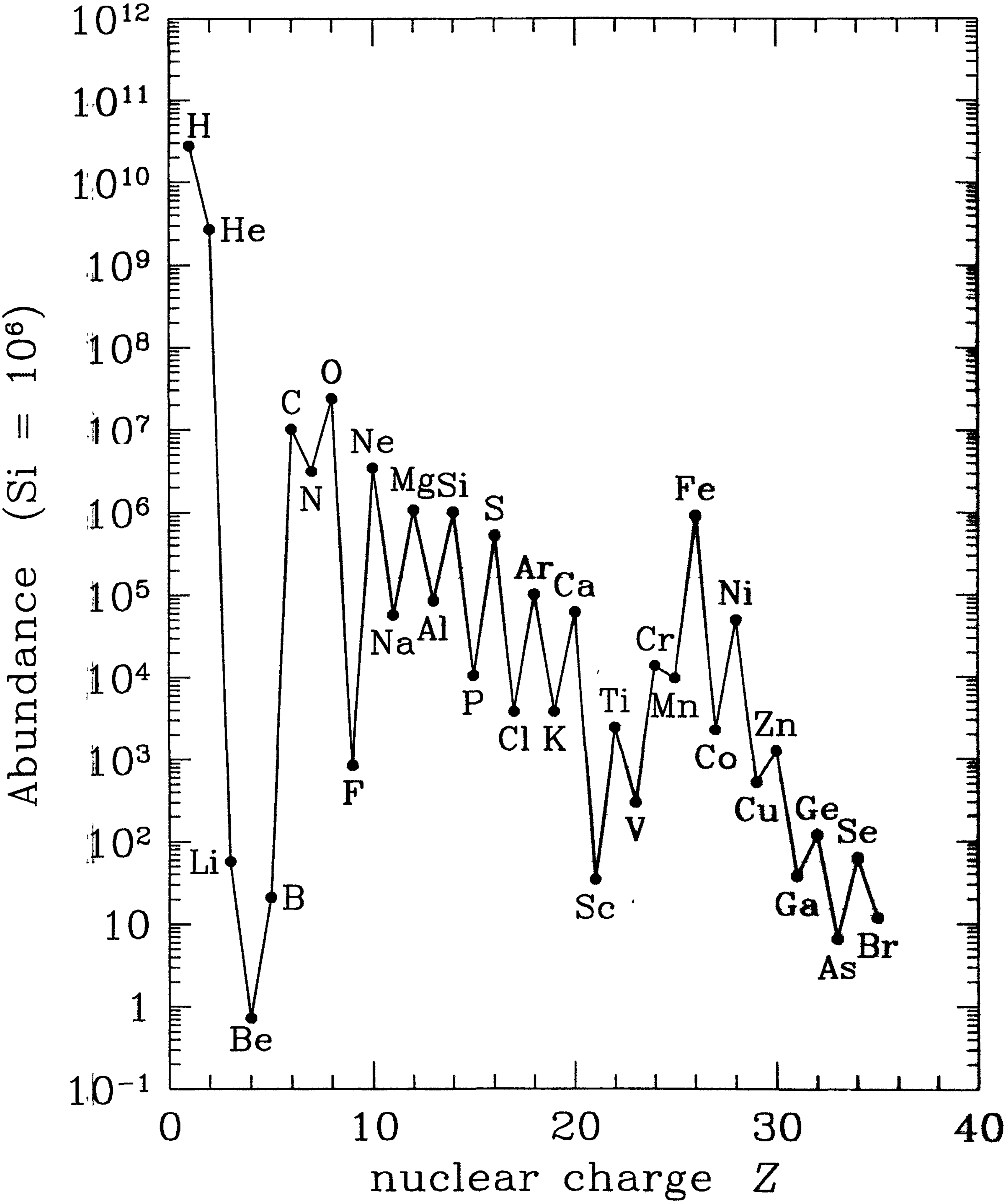


^{8}Li, ^{8}B lifetimes < 1 s

Fig. 1

29

KAO
Thomas Schramm



Abundance (Si = 10^6)
nuclear charge Z
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
0
10
20
30
40
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br

Decline:

BBN could <u>not</u> explain the abundances (or patterns) of ***all*** the elements.

⇒ growth of stellar nucleosynthesis

But,

Questions persisted:

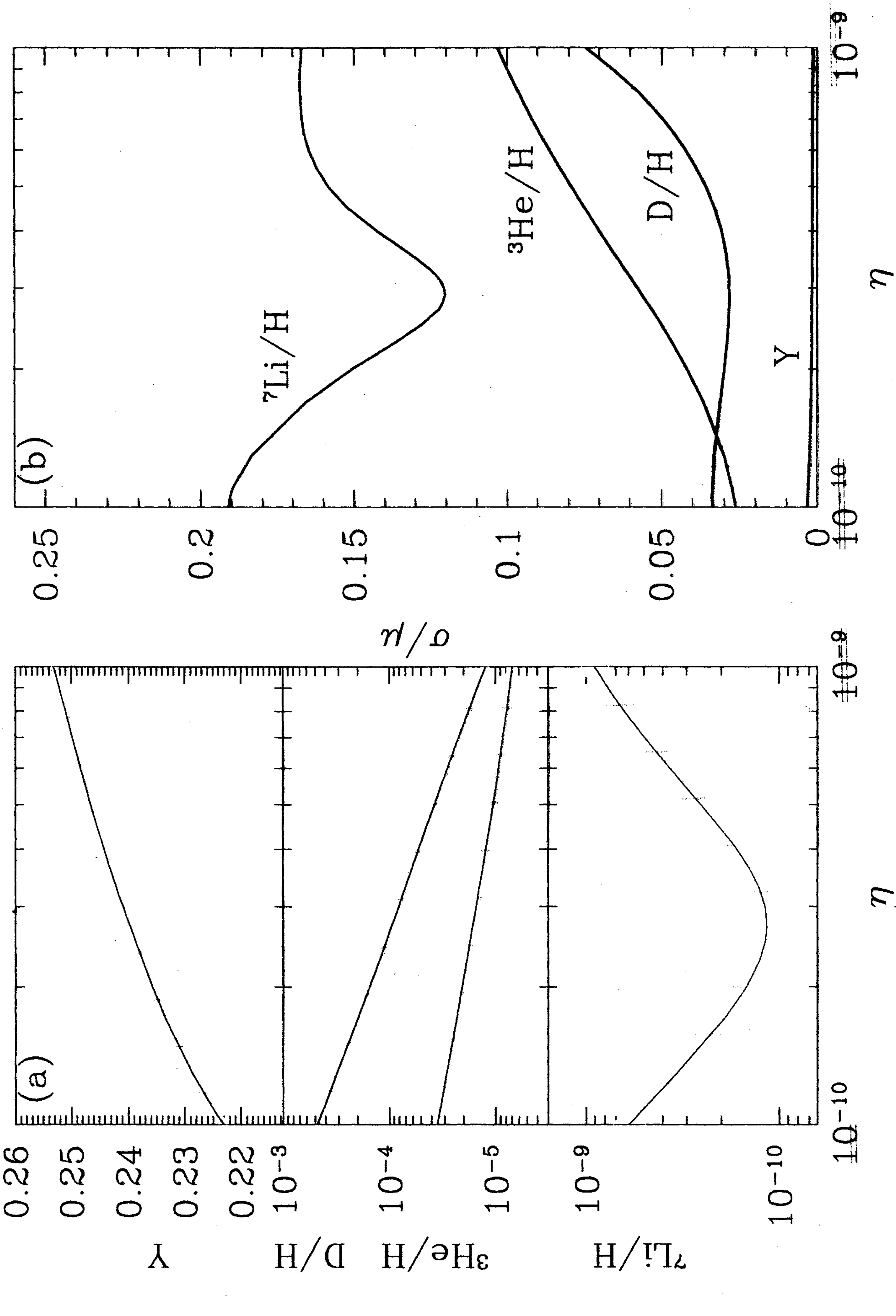
25% (by mass) of ^4He ?

D?

Resurgence:

BBN could successfully account for the abundance of

D, ^3He, ^4He, ^7Li.



(a)
(b)
Y
D/H
3He/H
7Li/H
η
σ/μ
0.26
0.25
0.24
0.23
0.22
10−3
10−4
10−5
10−9
10−10
0
0.05
0.1
0.15
0.2
0.25

Measured in low metallicity extragalactic HII regions

Pagel etal
Skillman etal
Izatov/Thuan

$$Y_P = Y(O/H \rightarrow 0)$$

n_e (SII) consistent with

$$Y_P = 0.238 \pm 0.002 \pm 0.005$$

statistical (large N) systematic

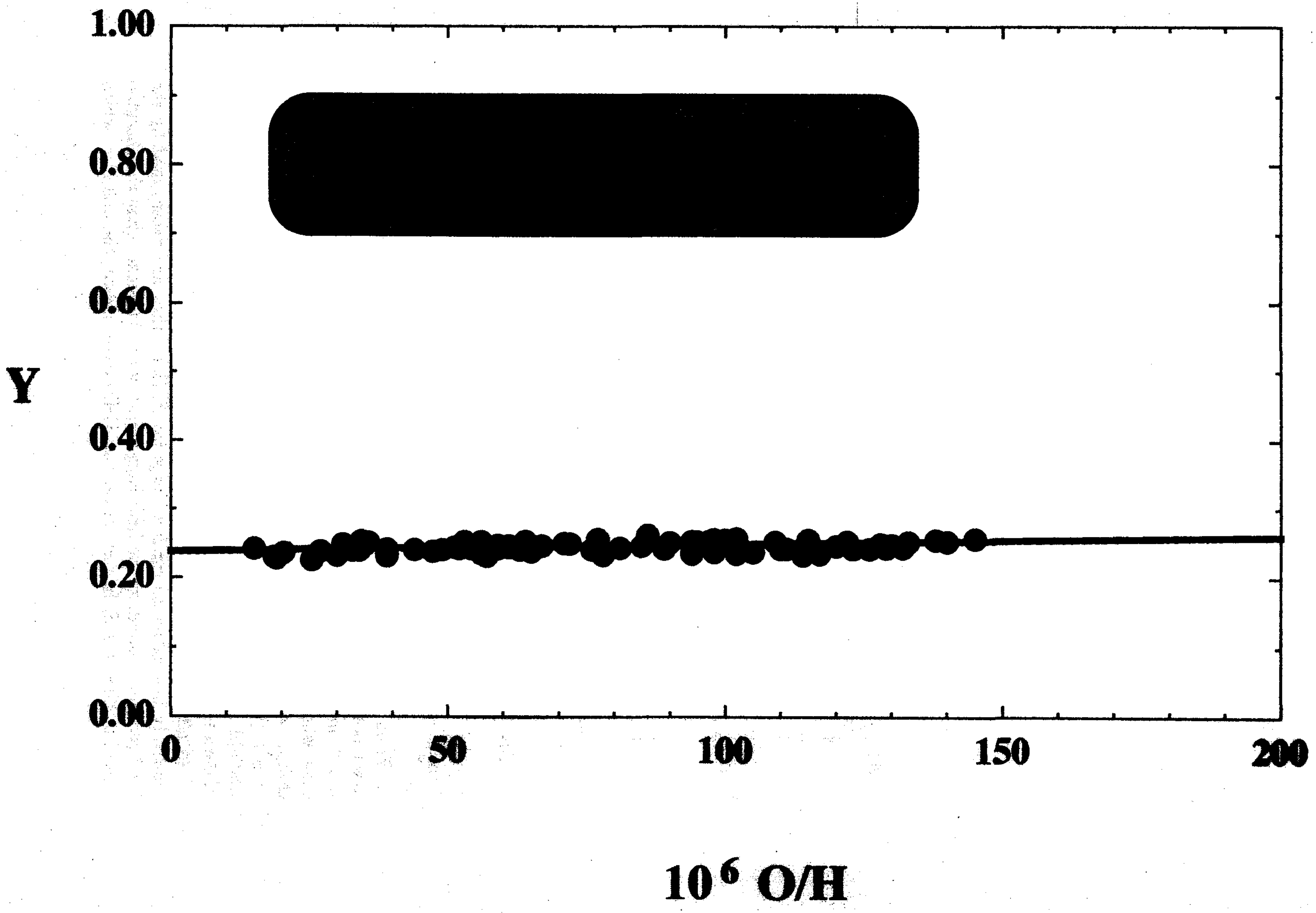
KAO
Skillman
Steigman

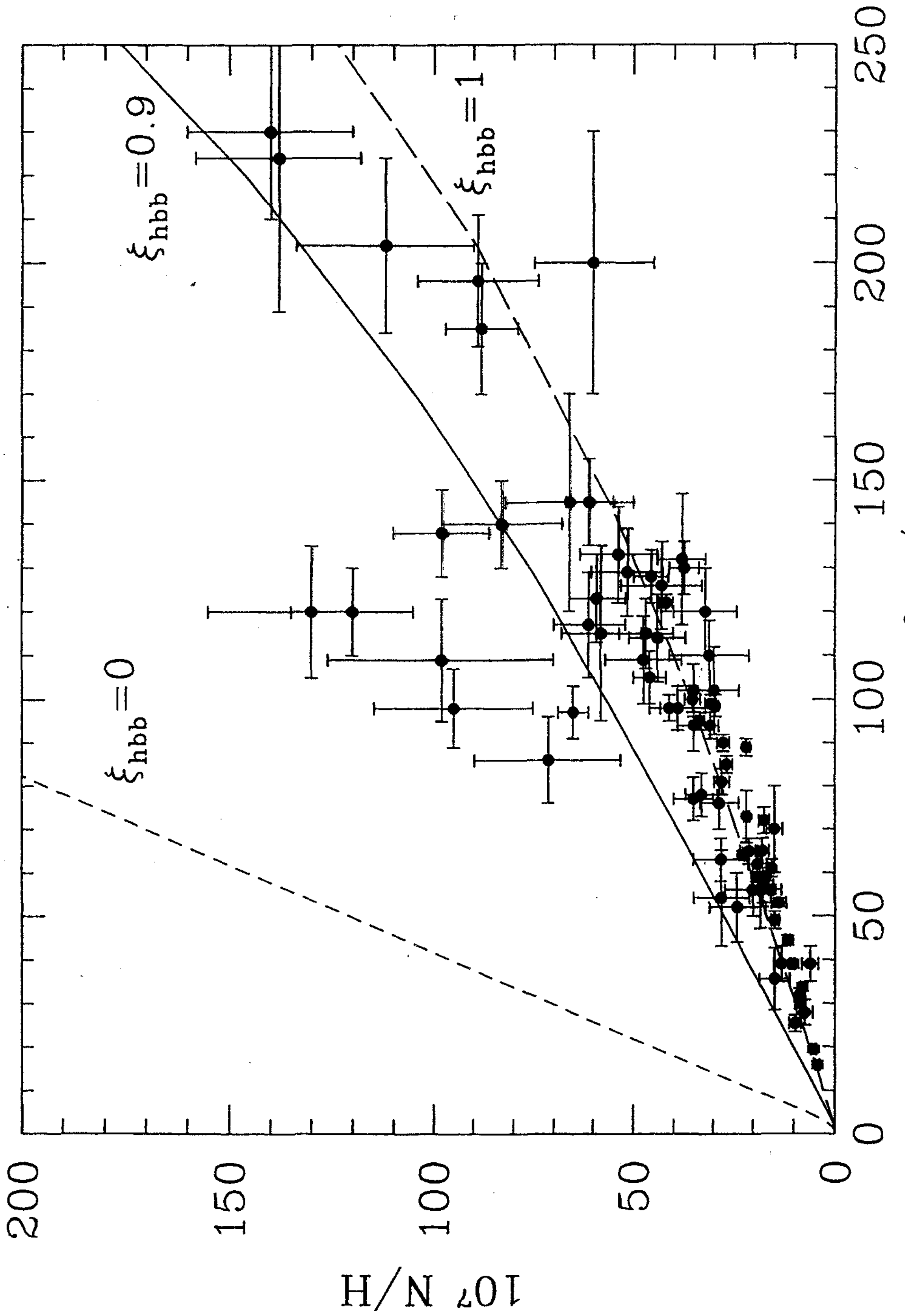
Fields/KAO

n_e self-consistent

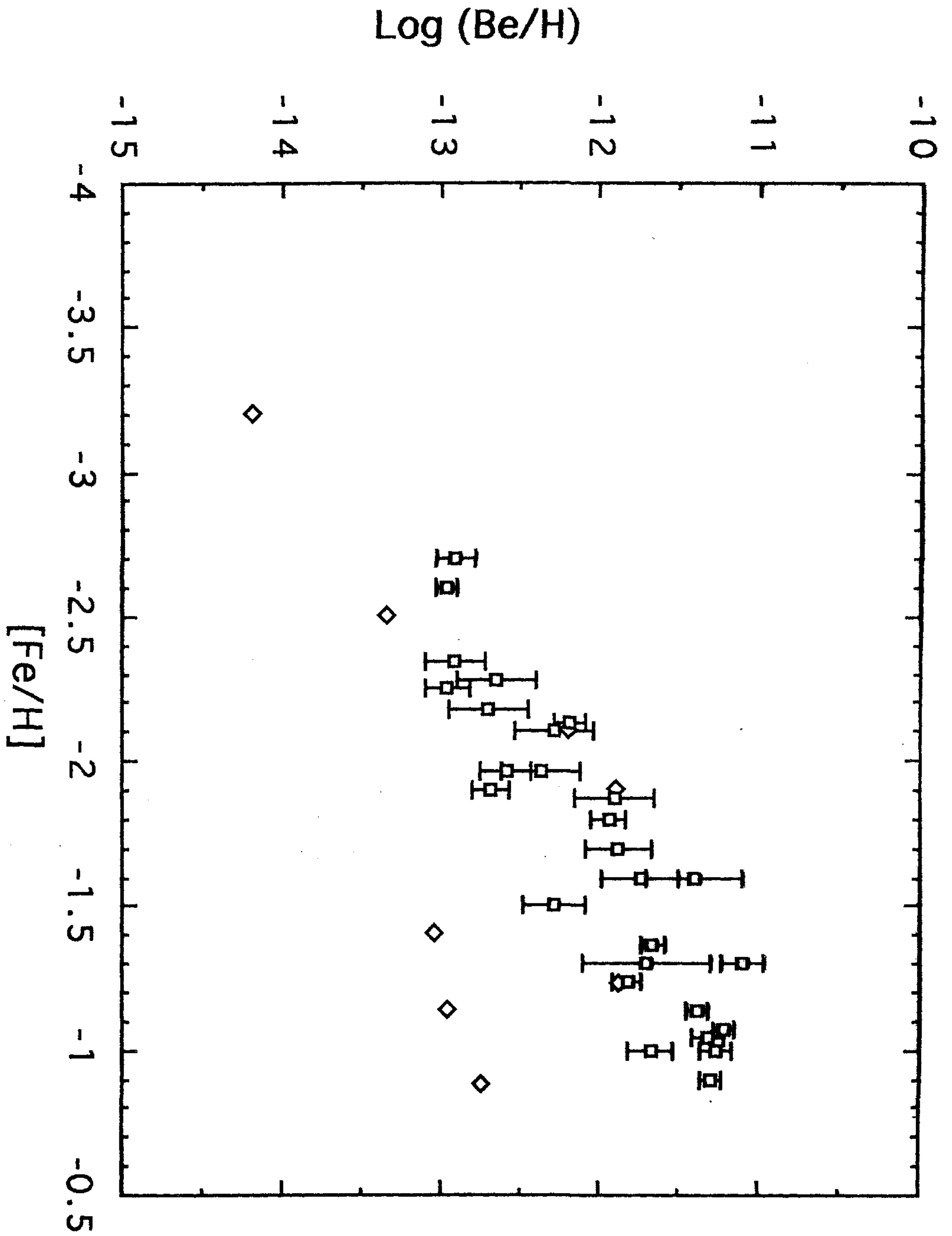
$$Y_P = 0.244 \pm 0.002 \pm 0.005$$

Izatov/Thuan

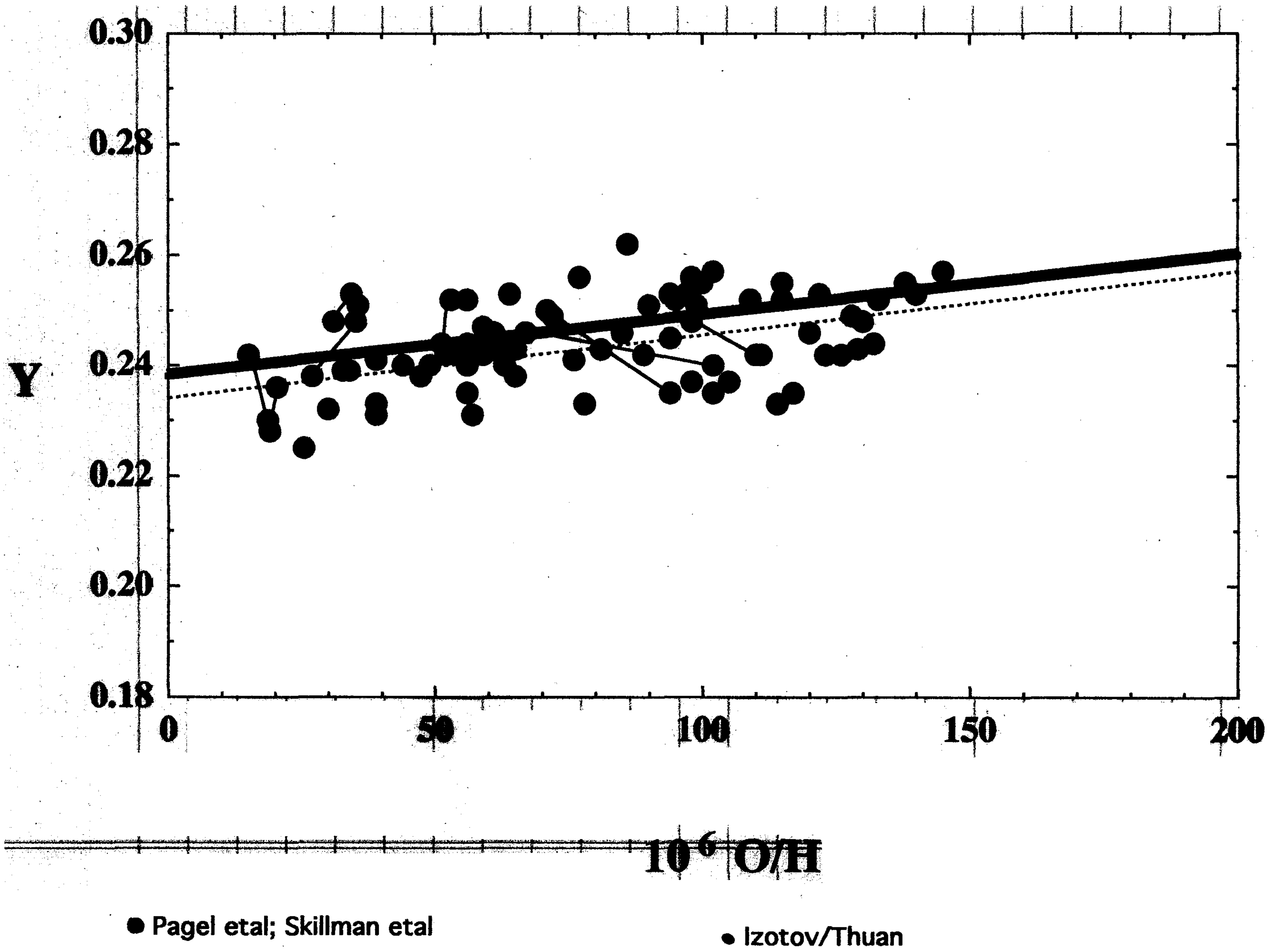

1.00
0.80
0.60
0.40
0.20
0.00
Y
[redacted]
0
50
100
150
200
10 6 O/H



10^6 O/H
10^7 N/H
$\xi_{hbb}=0$
$\xi_{hbb}=0.9$
$\xi_{hbb}=1$
0
50
100
150
200
250



Log (Be/H)
-15
-14
-13
-12
-11
-10
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
[Fe/H]


0.30
0.28
0.26
0.24
0.22
0.20
0.18
Y
0
50
100
150
200
10^6 O/H
Pagel etal; Skillman etal
Izotov/Thuan

[redacted]

Measured in low metallicity halo stars (over 100) together with Fe/H

Plateau Value

[redacted]

Spite/Spite
Thorburn
Bonifacio/
Molaro
[redacted] etal.

statistical (large N)

Questions:

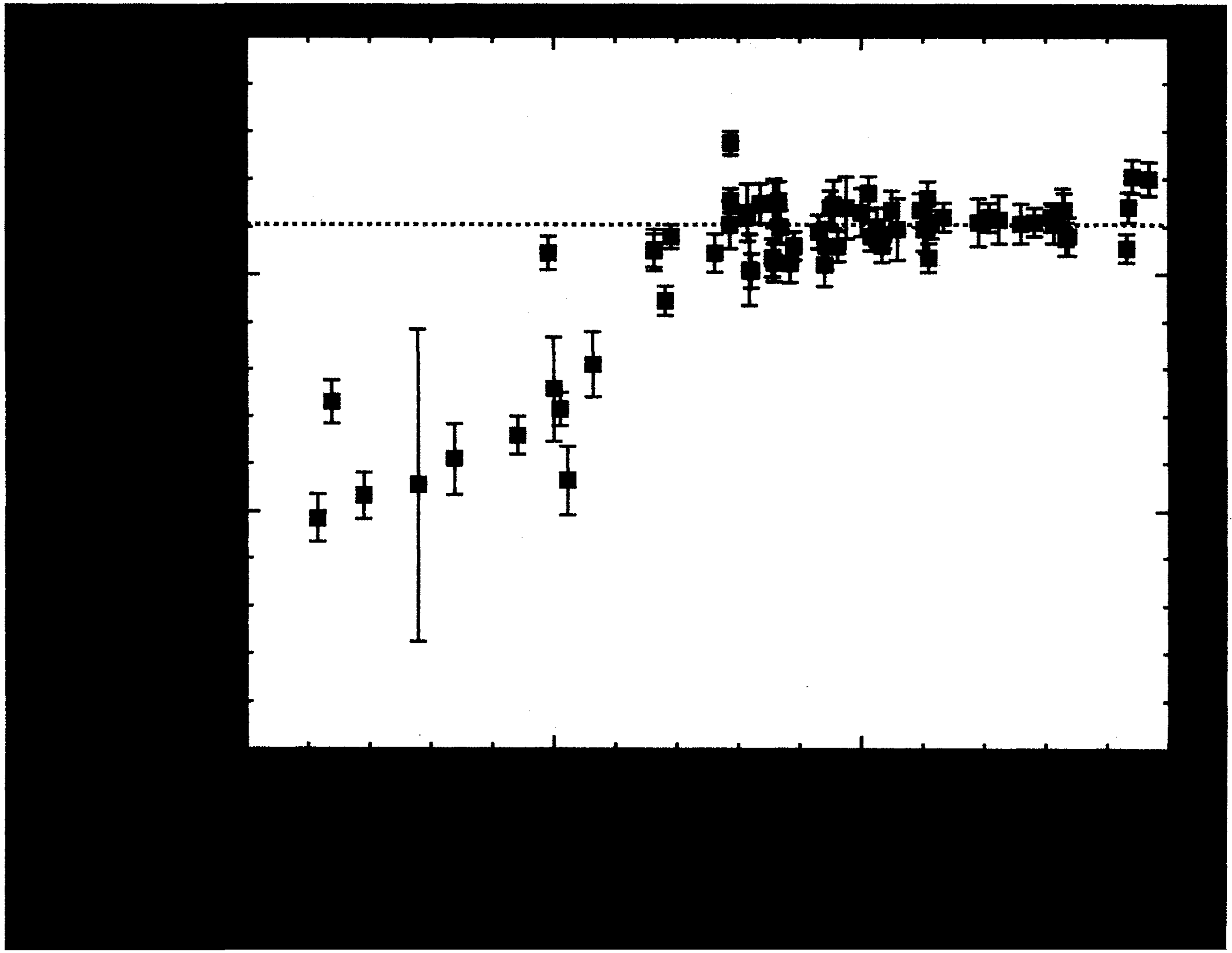
Production by Galactic Cosmic Rays

(20-30%?)

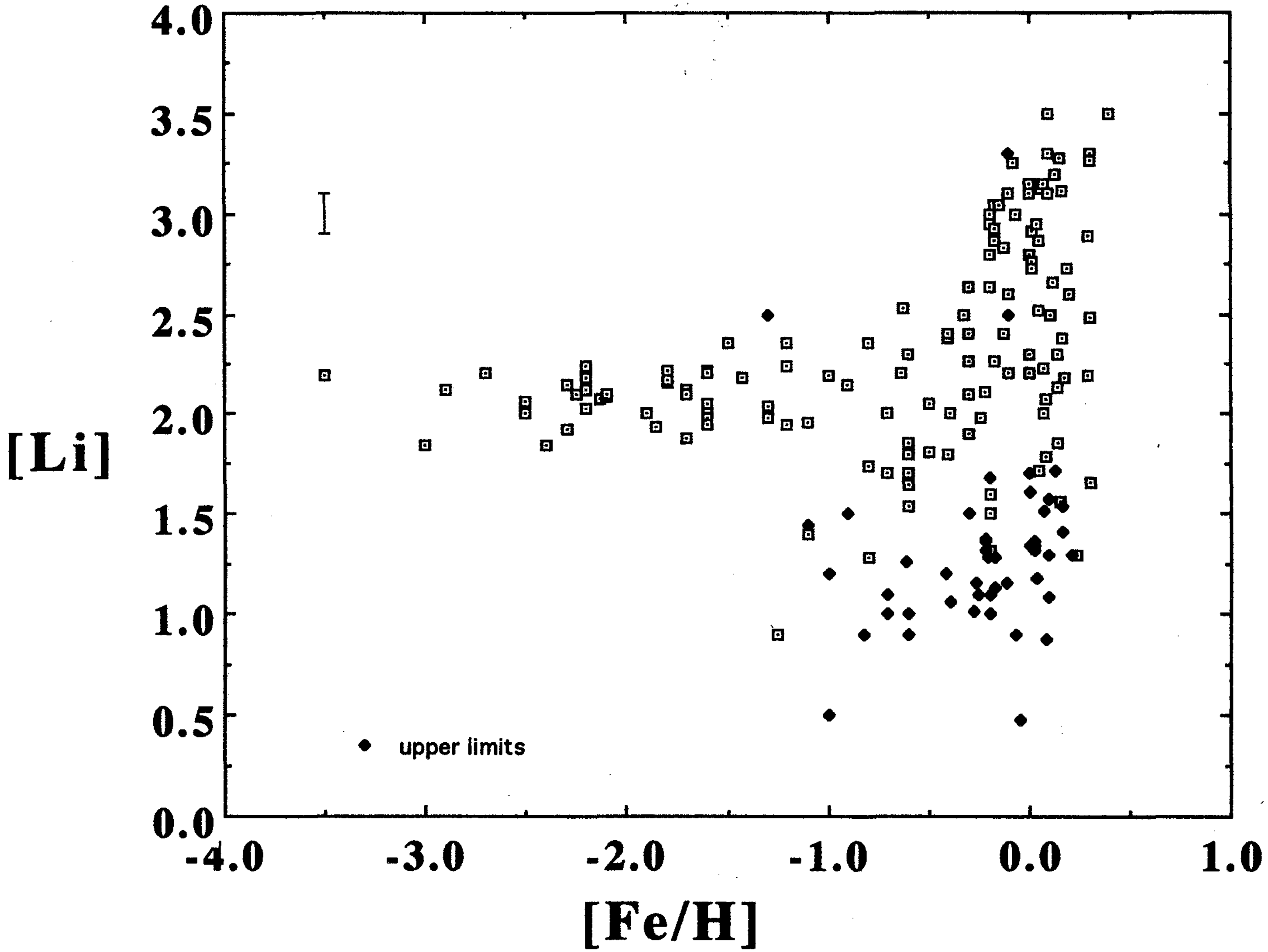
Stellar Depletion

(factor of 2?)

[Li] = 2.21 ± 0.02



from Bonifacio & Molaro


4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
[Li]
upper limits
-4.0
-3.0
-2.0
-1.0
0.0
1.0
[Fe/H]

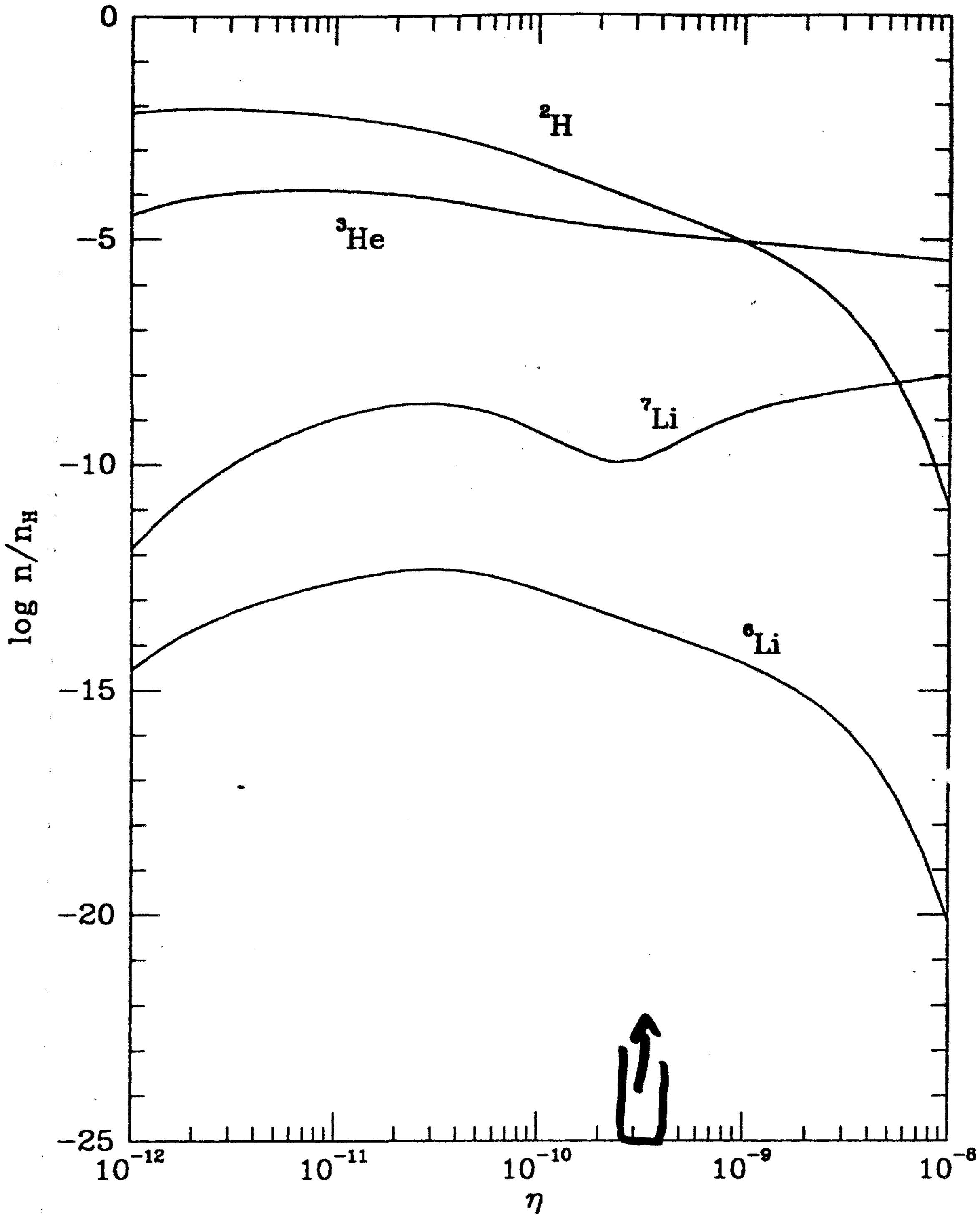
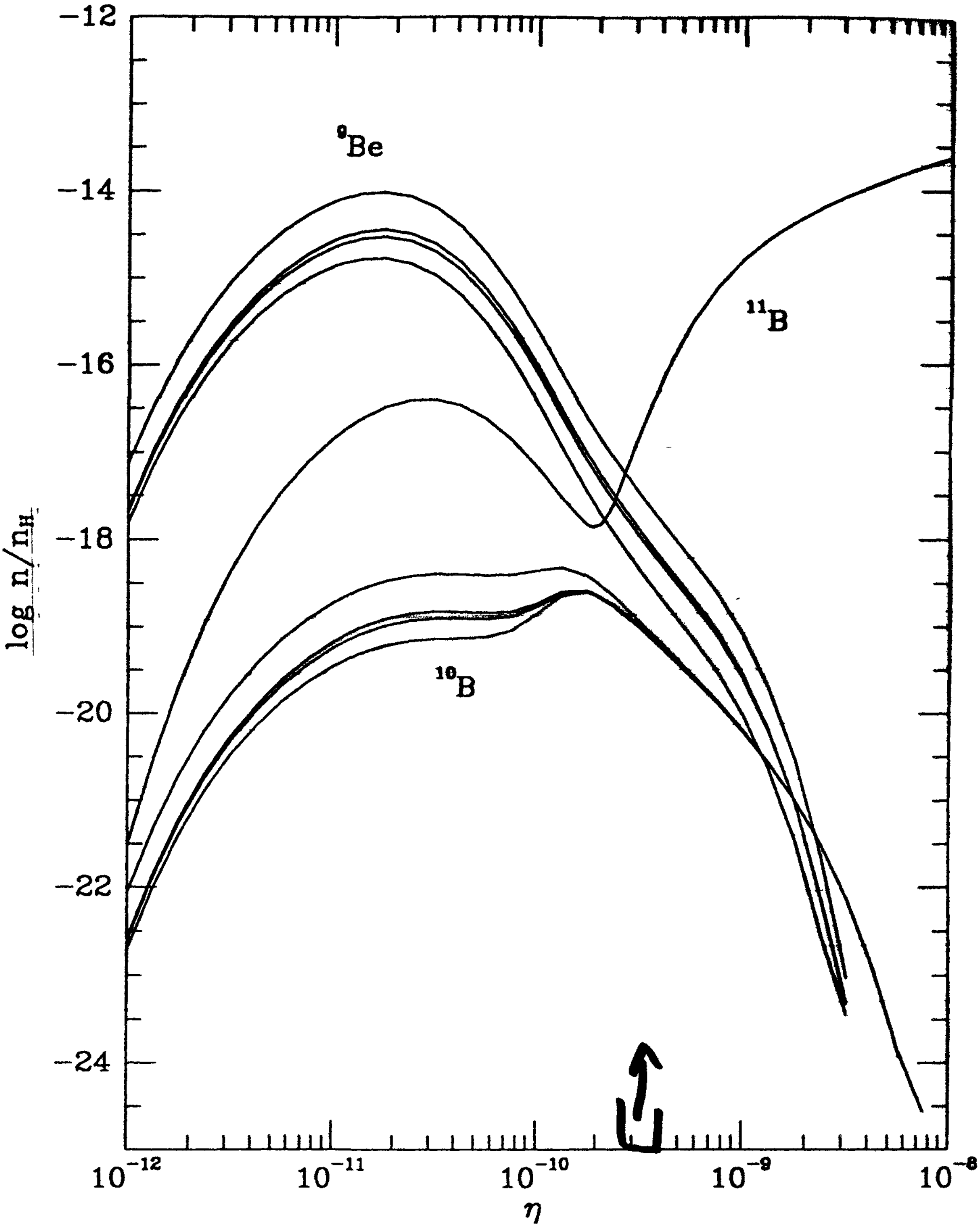


Fig. 3b

Thomas, Schramm ...



-12
-14
-16
-18
-20
-22
-24
^{9}Be
^{11}B
^{10}B
log n/n$_H$
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
η

Fig. 3c

TSWF

^{6}LiBeB

For η_{10} in the range 1.5 - 4.5

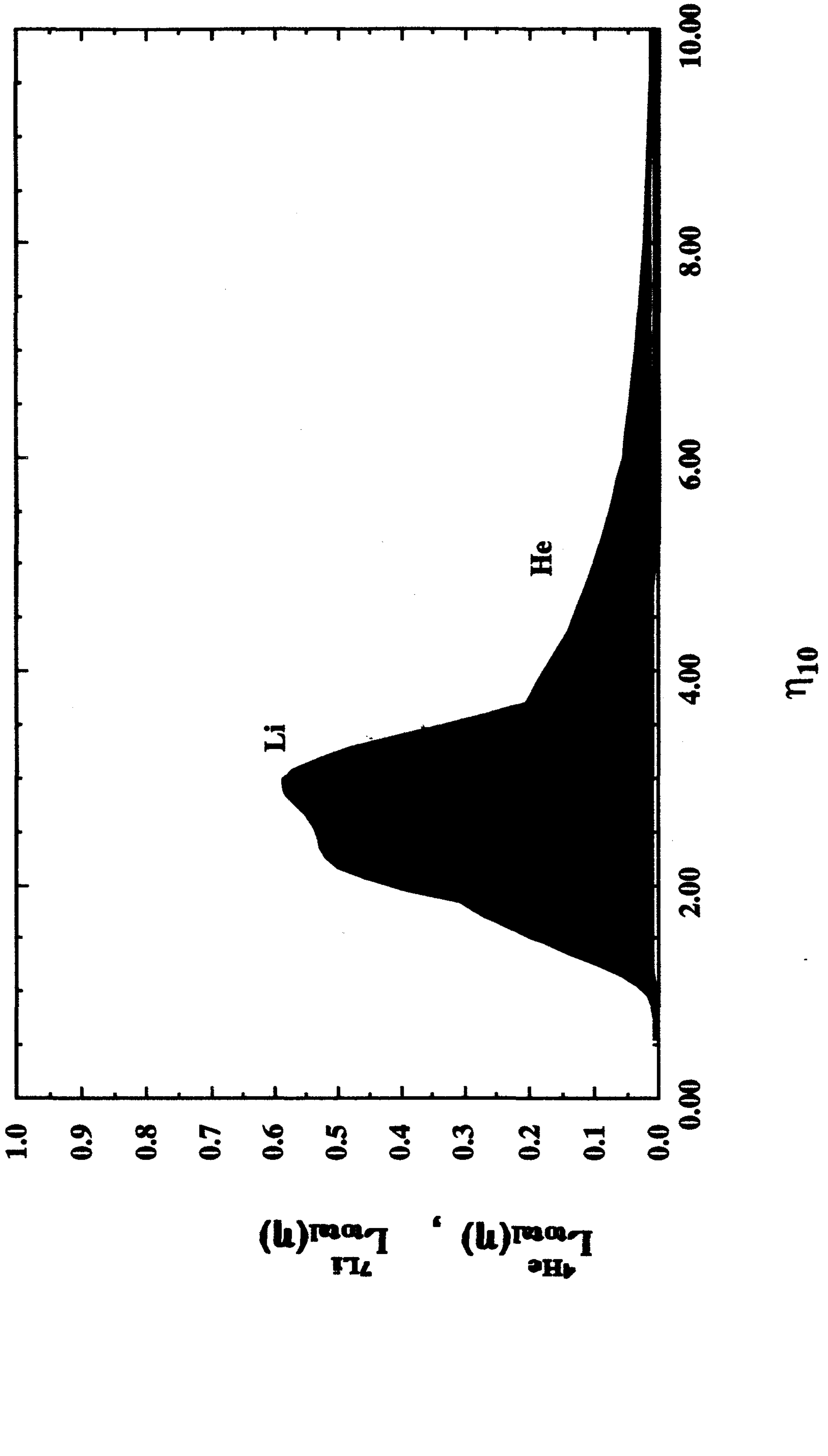
$$^{6}\mathrm{Li/H} = 2 - 9 \times 10^{-14}$$
$$^{9}\mathrm{Be/H} = .04 - 2 \times 10^{-17}$$
$$^{10}\mathrm{B/H} = .5 - 3 \times 10^{-19}$$
$$^{11}\mathrm{B/H} = .02 - 1 \times 10^{-16}$$

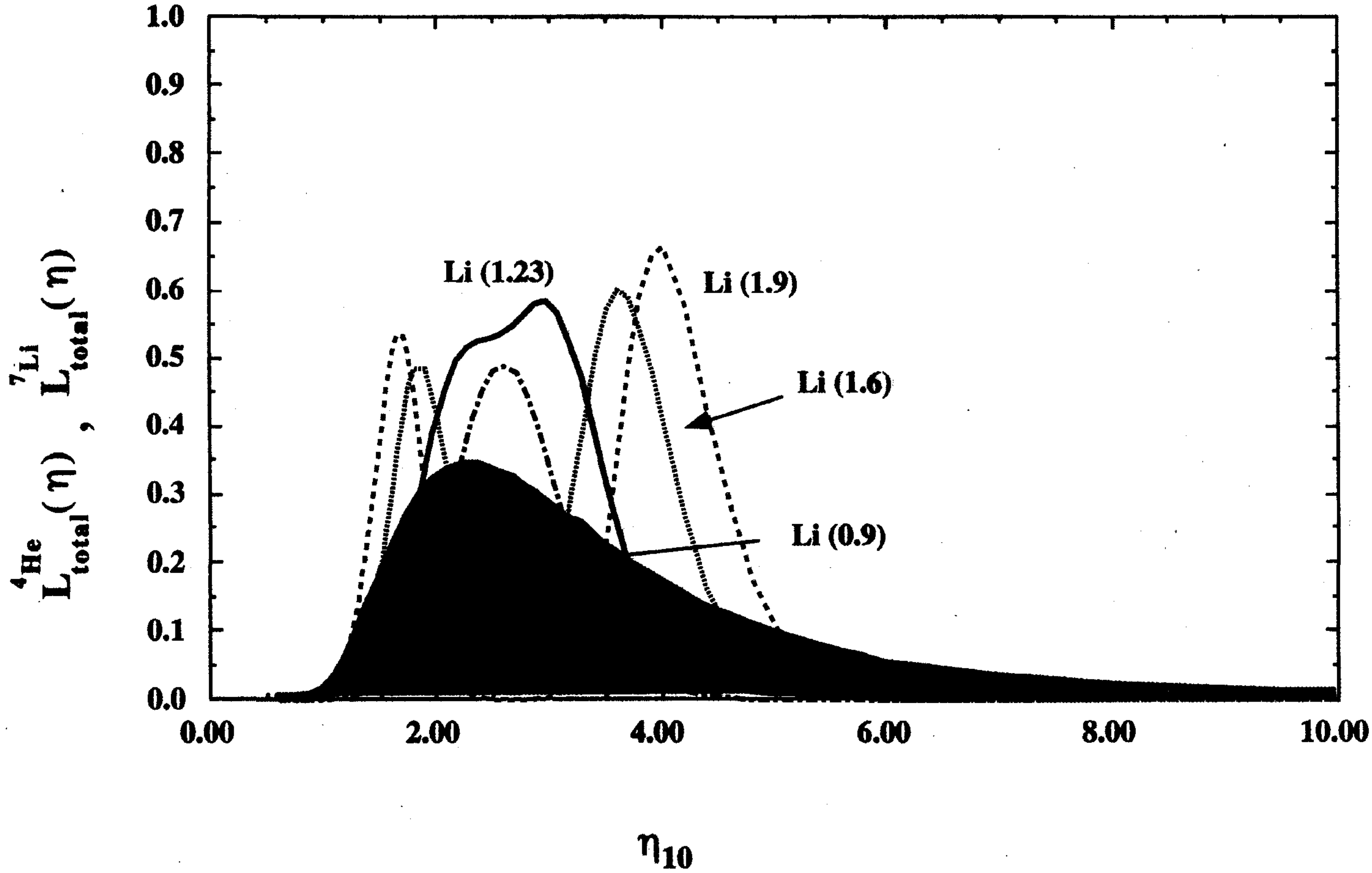
Far Below the observed values in Pop II stars

$$^{6}\mathrm{Li/H} \approx \text{few} \times 10^{-12}$$
$$^{9}\mathrm{Be/H} \sim 1 - 10 \times 10^{-13}$$
$$\mathrm{B/H} \sim 1 - 10 \times 10^{-12}$$

These are not BBN produced.

GCR Nucleosynthesis


Li
He
η10
0.00
2.00
4.00
6.00
8.00
10.00
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
4He Ltotal(η) , 7Li Ltotal(η)



Ryan
Beers
Olive
Fields

Net change from fits

$\Delta[Li] = -.11^{+.07}_{-.09} \Rightarrow [Li] = 2.09^{+.19}_{-.13}$

Results

With $^7Li = 1.23 \times 10^{-10}$

($Y_p = 0.238$)

Best value for η:

$$\eta_{10} \approx 2.4$$

$$1.7 < \eta_{10} < 4.7 \quad (95\% \text{ CL})$$

for Ω_B:

$$\Omega_B h^2 \approx 0.009$$

$$0.006 < \Omega_B h^2 < 0.017 \quad (95\% \text{ CL})$$

With $^4He = 0.244$:

shift up in η_{10} by

about 0.1 - 0.2

All observed D is primordial!

Reeves
Audouze
Fowler
Schramm

Observations:

- ISM (today)

$$D/H = 1.6 \pm 0.1 \times 10^{-5}$$

Linsky etal
Ferlet

with possibly significant dispersion

- (Inferred) Meteoritic (solar)

$$D/H = 2.6 \pm 0.6 \times 10^{-5}$$

Geiss
Gautier/Morel
Niemann etal

also HD from Jupiter

But These are not *PRIMODIAL* values

- requires Galactic chemical evolution

Primordial Measurements from Quasar Absorption Systems ?

Moderate to High redshift systems

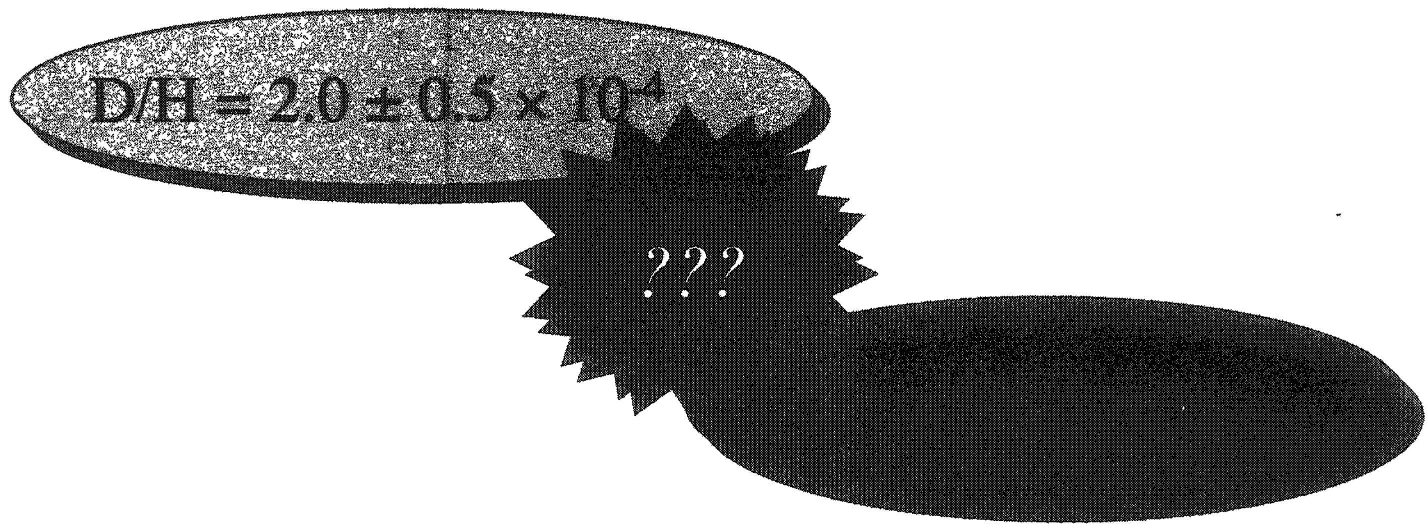
$z = 0.7 - 3.5$

- High Values

  vs.

- Low Values

Carswell etal
Songaila etal
Tytler etal
Burles/Tytler
Webb etal
Tytler etal



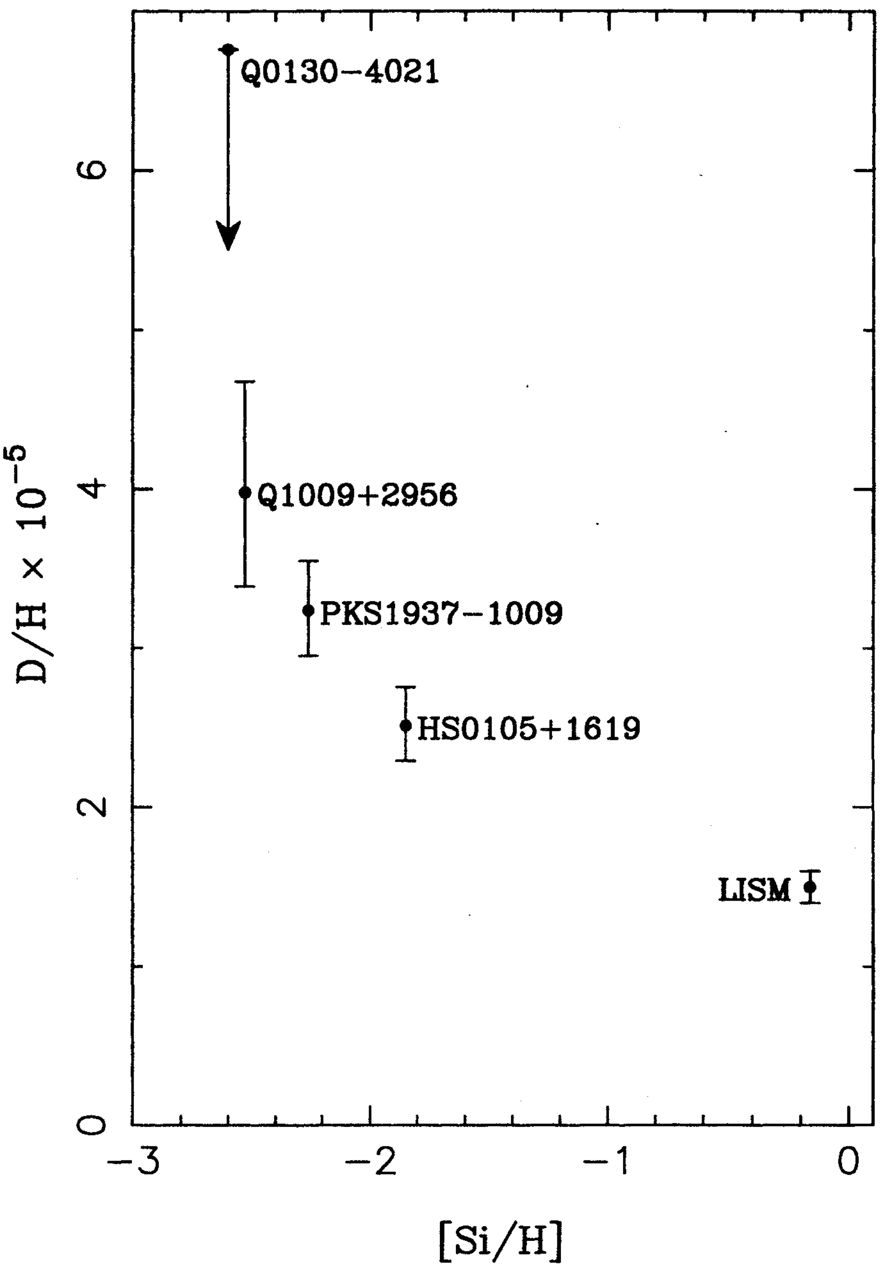
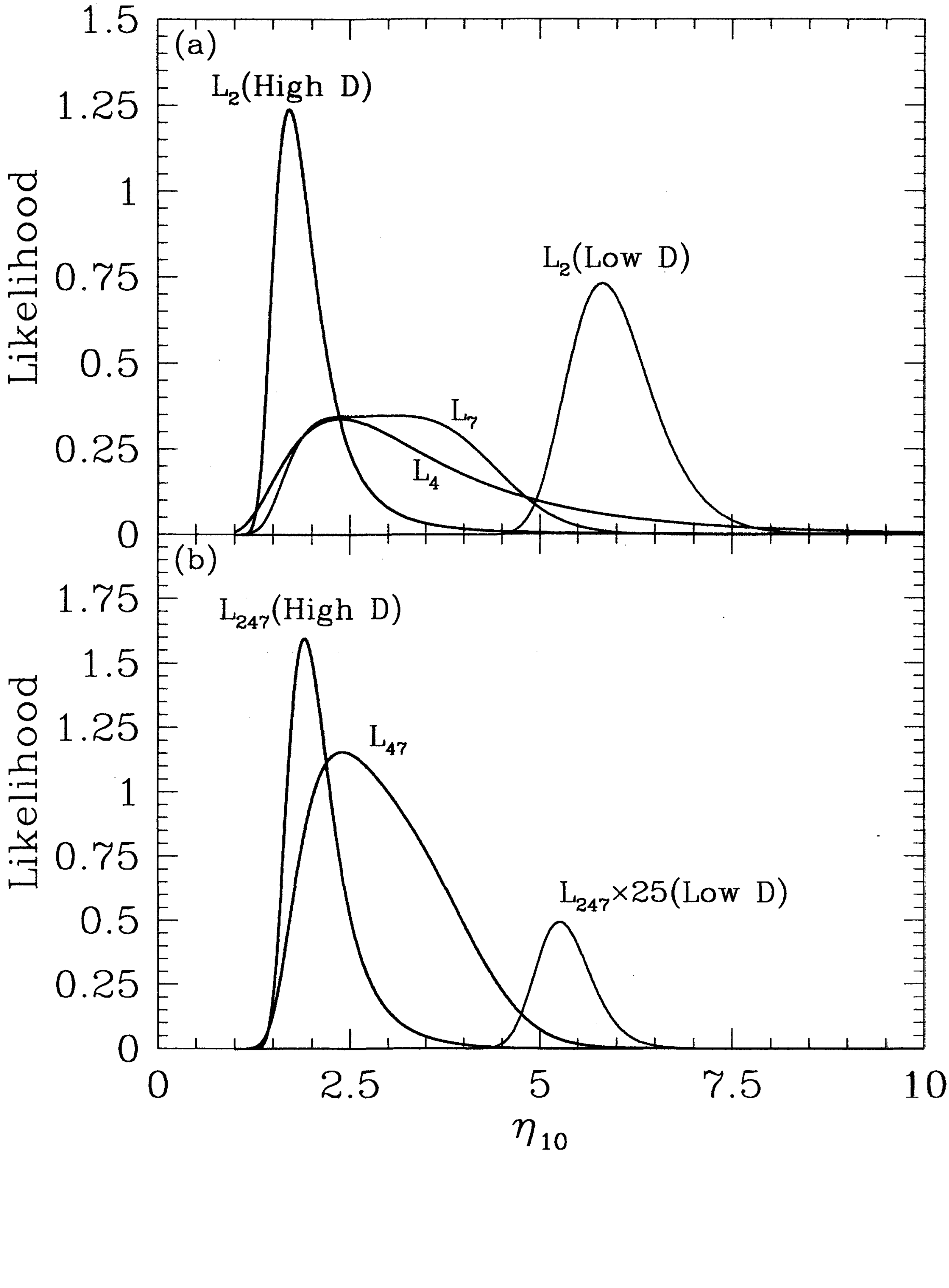
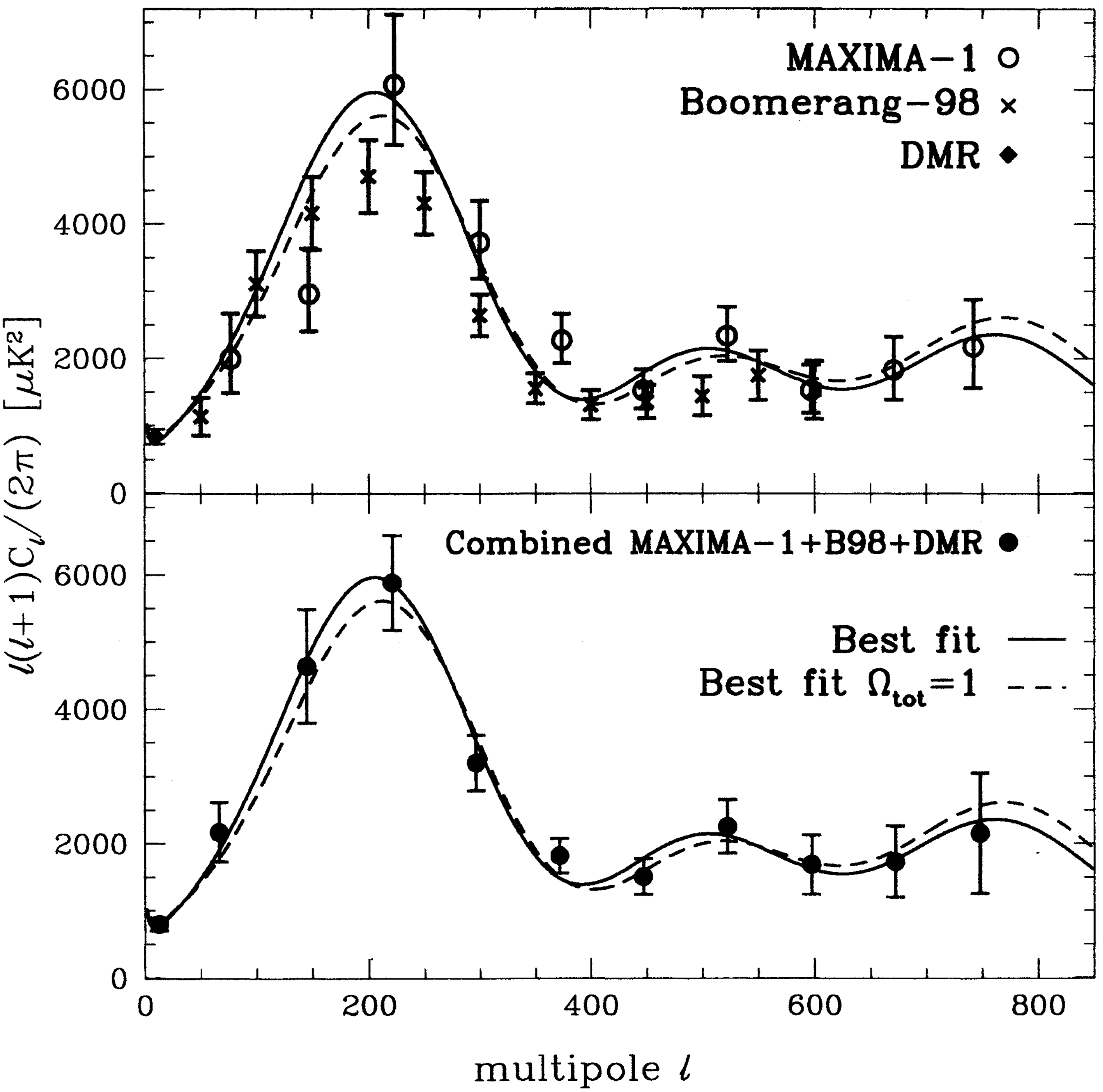
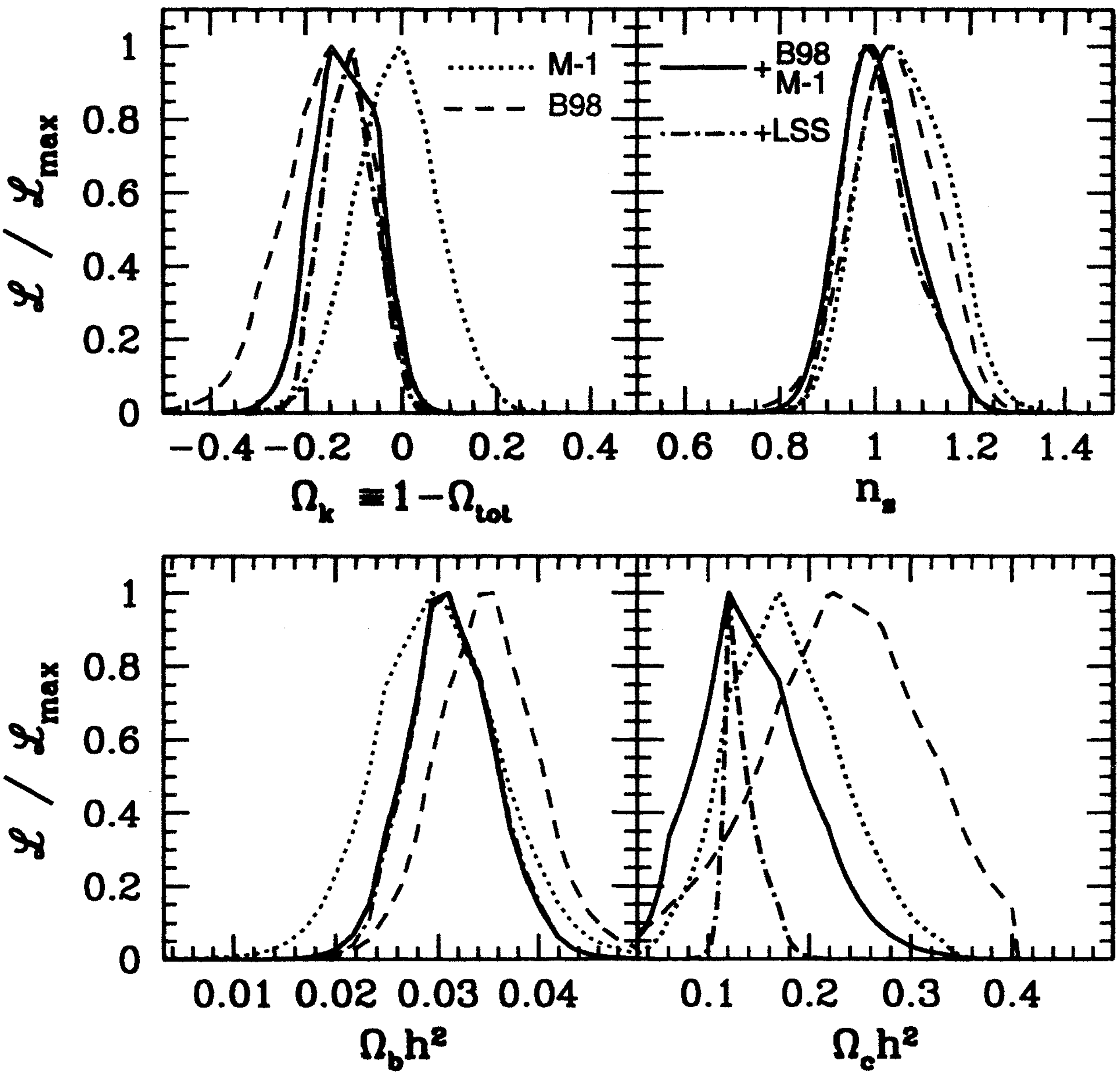


Fig. 12.— The relationship between D/H measurements and metal abundances, as gauged by silicon. Standard chemical evolution models predict little change in D/H until the [Si/H] > -1, at which time a significant fraction of the gas has come from inside stars, where the D has been destroyed. The values of [Si/H] for PKS 1937–1009 and Q1009+2956 represent the mean value, weighted by the total H column density in each component: -2.26 and -2.53 respectively. The D/H value for the local interstellar medium (LISM) is from Linsky (1998), and the LISM [Si/H] is from Savage & Sembach (1996).

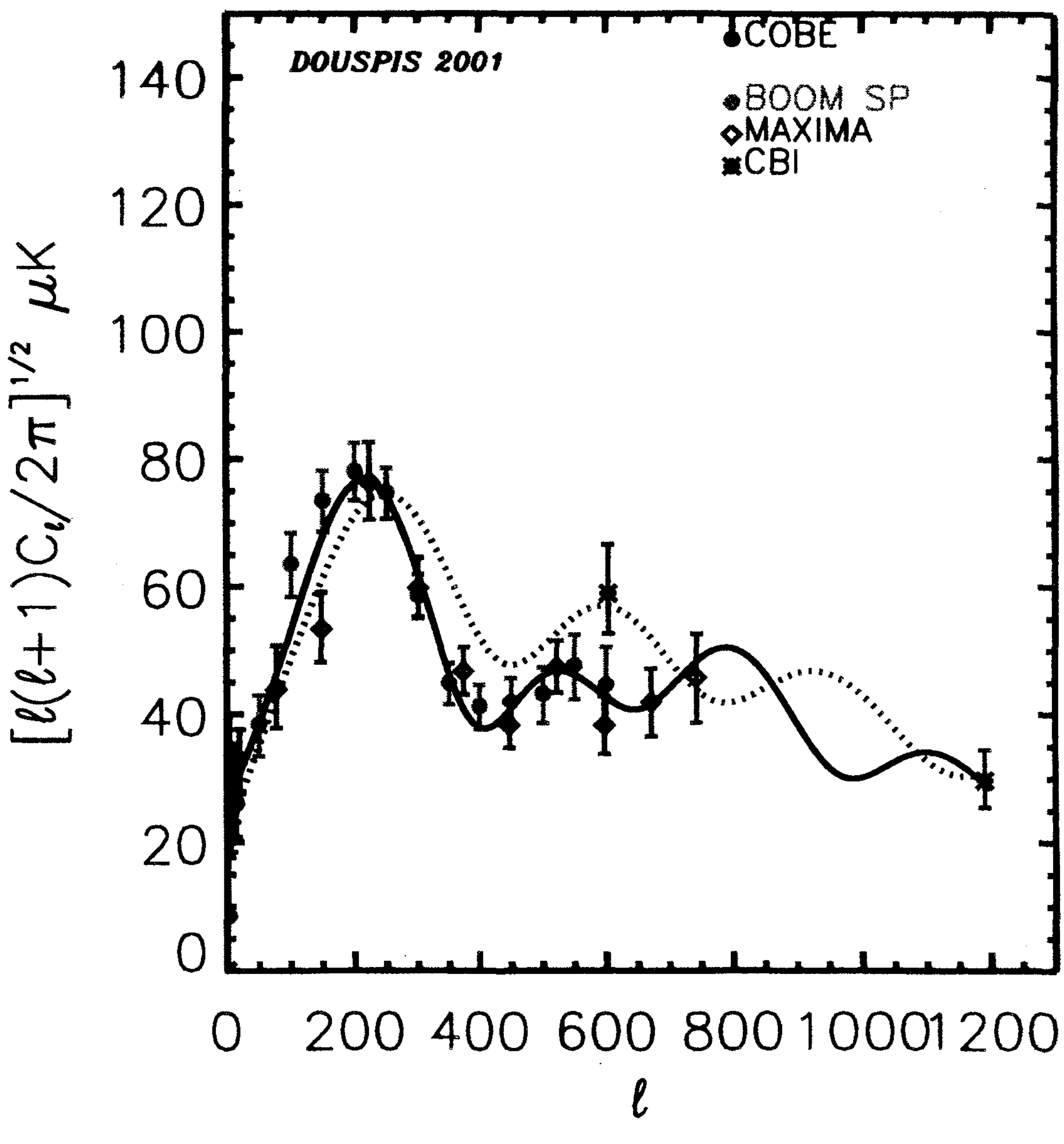

(a)
L2(High D)
L2(Low D)
L7
L4
(b)
L247(High D)
L47
L247×25(Low D)
Likelihood
1.5
1.25
1
0.75
0.5
0.25
0
1.75
η10
2.5
5
7.5
10



MAXIMA−1
Boomerang−98
DMR
Combined MAXIMA−1+B98+DMR
Best fit
Best fit Ω_{tot}=1
$\ell(\ell+1)C_\ell/(2\pi)$ [μK^2]
multipole ℓ
0
2000
4000
6000
0
200
400
600
800



M-1
B98
+B98 M-1
+LSS
$\mathcal{L}$ / $\mathcal{L}_{max}$
$\Omega_k \equiv 1-\Omega_{tot}$
n_s
$\Omega_b h^2$
$\Omega_c h^2$


DOUSPIS 2001
COBE
BOOM SP
MAXIMA
CBI
140
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
ℓ
$[\ell(\ell+1)C_\ell/2\pi]^{1/2}\ \mu K$

Constraints

- Success of BBN is delicate
- Fine Balance between

    Interaction Rates

    Expansion Rate
- Constraints on :
- Particle Types
- Particle Interactions
- Particle Masses
- Fundamental Parameters

Limits on "N_ν"

Expansion rate^2:

$$H^2 \propto \rho \propto (N_{SM} + \tfrac{7}{4}\Delta N_\nu)$$

$$N_{SM} = 2 + \frac{7}{2} + \frac{21}{4} \qquad (N_\nu = 3)$$

γ → 2, $e^\pm$ → $\frac{7}{2}$, ν's → $\frac{21}{4}$

$\Delta N_\nu = 1$ — fermion

$\Delta N_\nu = 4/7$ — boson

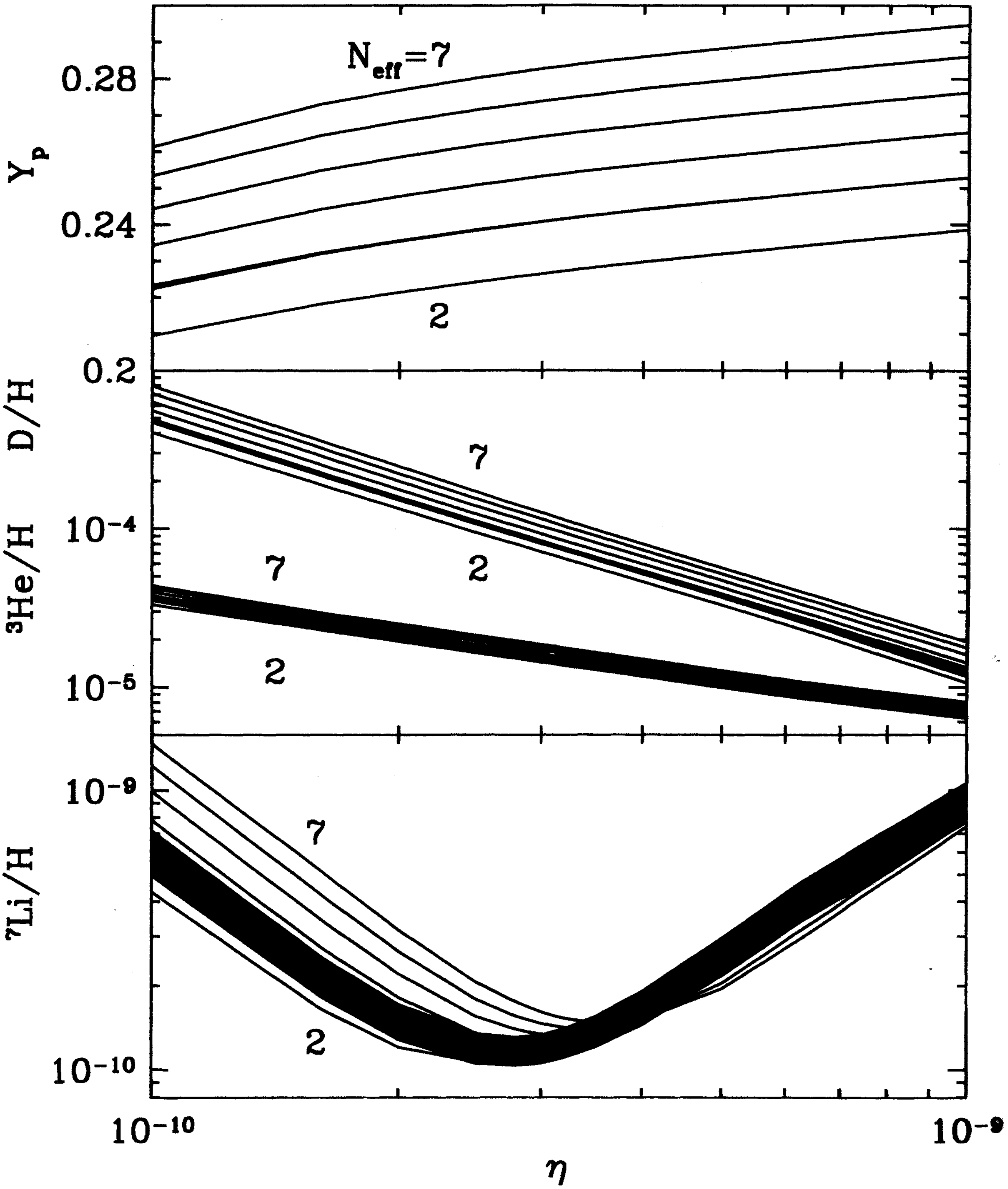
Affects $H(T_f) = \Gamma(T_f)$

Affects (n/p) and Y_p

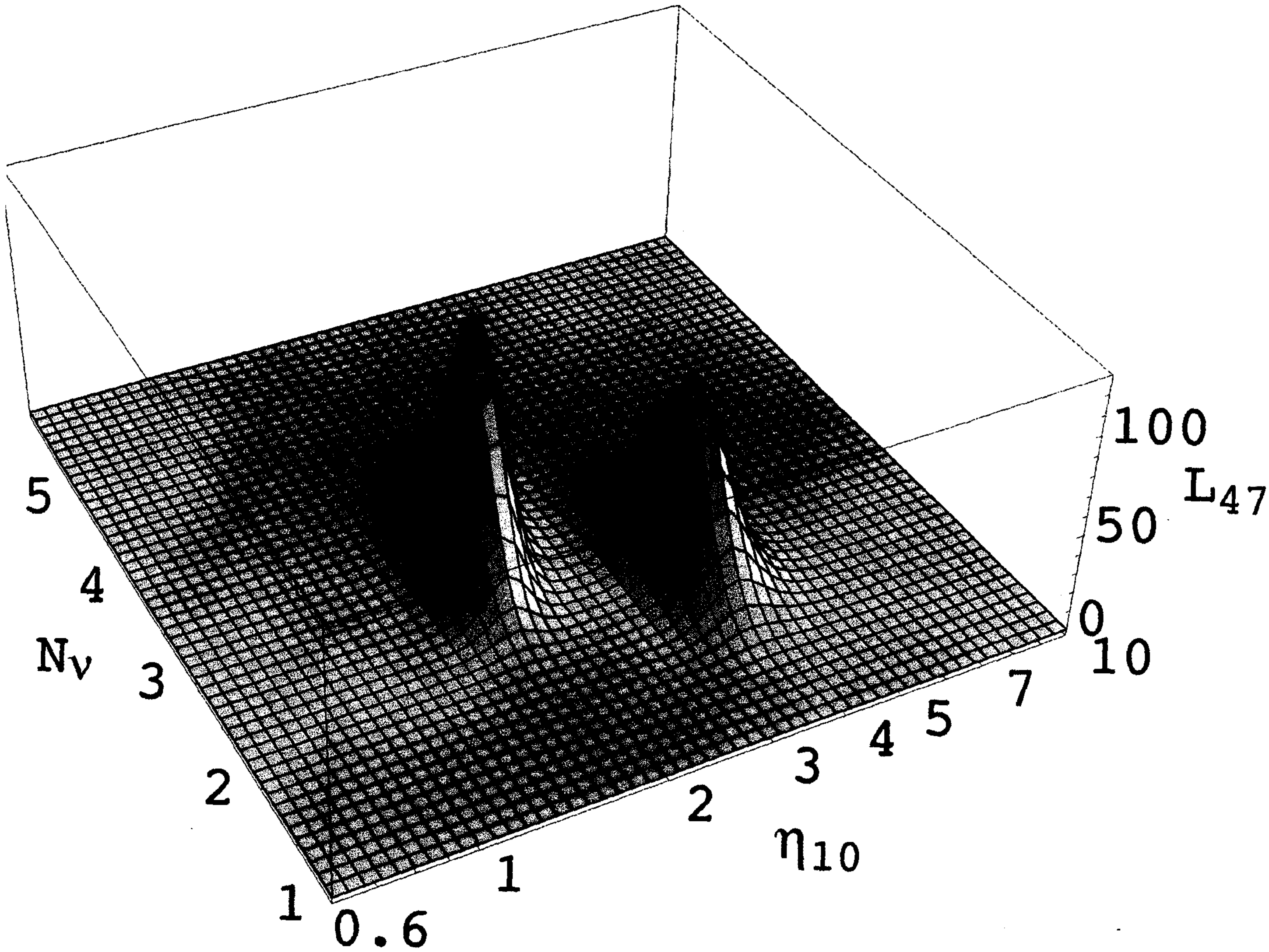
Establish $\mathcal{L}(\eta, N_\nu)$

Sensitivity to N_ν

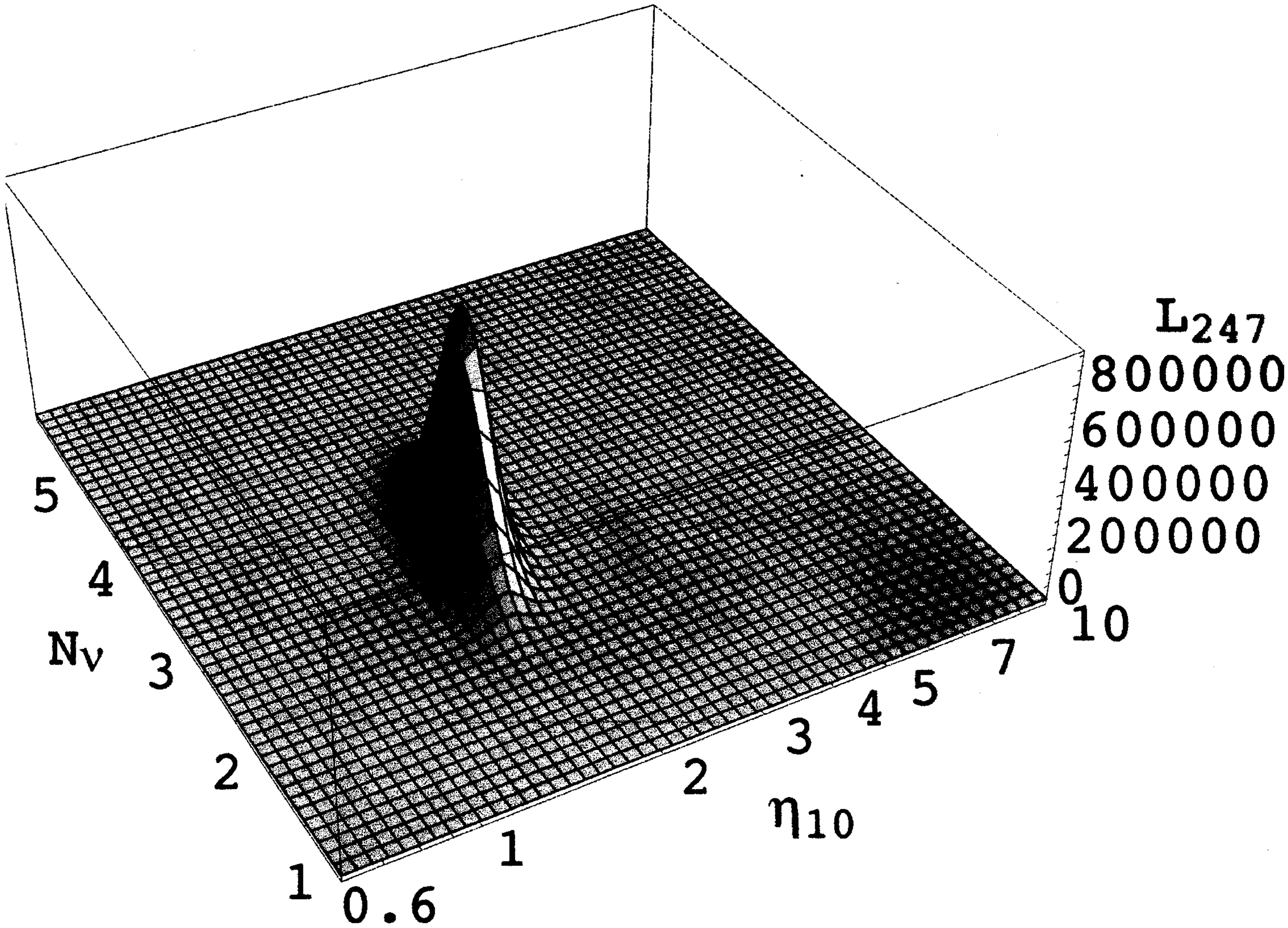
of light-element abundances



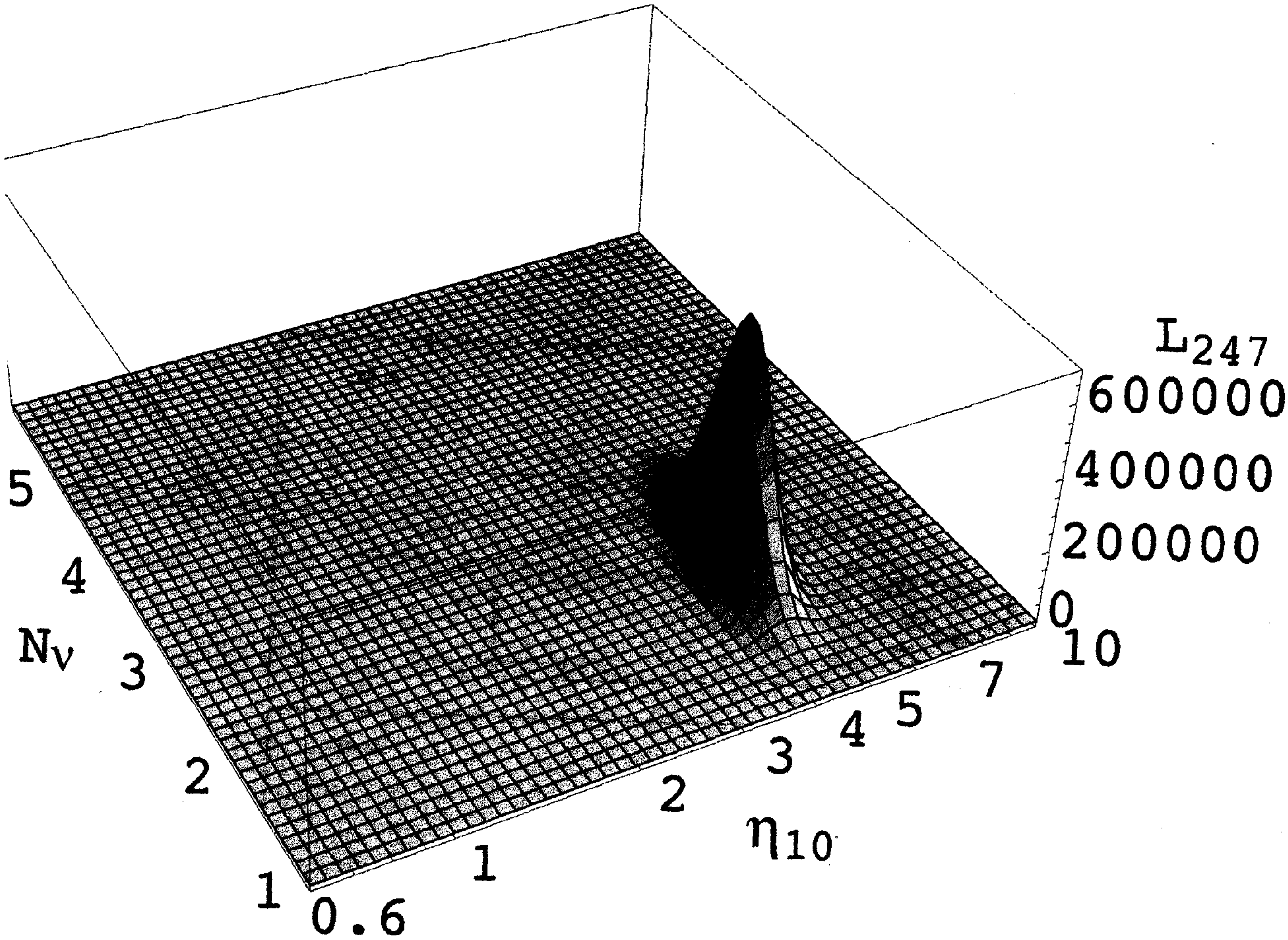
(Cyburt + Fields + Olive: 2001



KAC
thomas



KAC
Thomas



KAO
Thomas

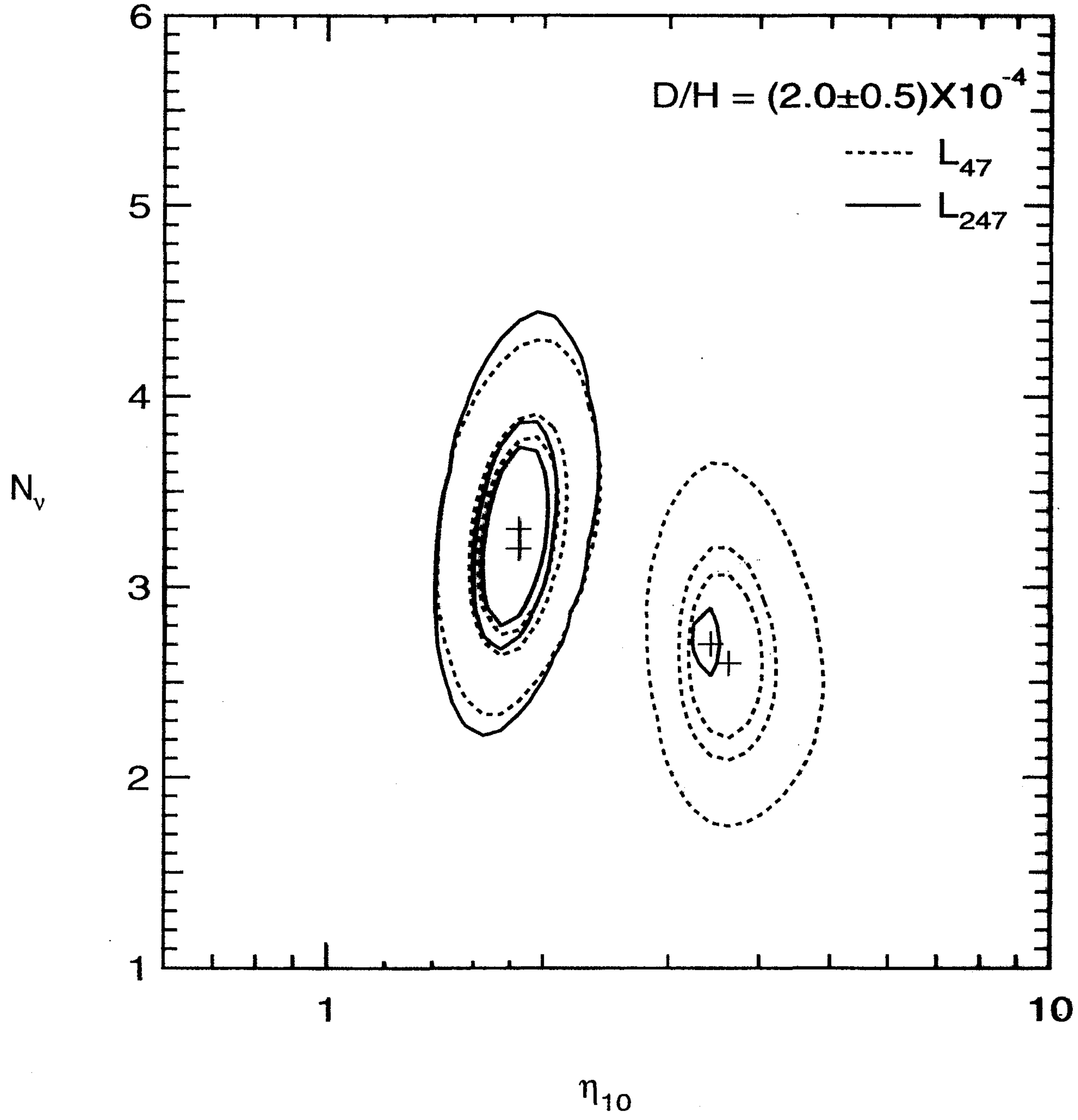


Figure 2: (a) Contour plot for D/H= $(2.0 \pm 0.5) \times 10^{-4}$

KAC
Thomas

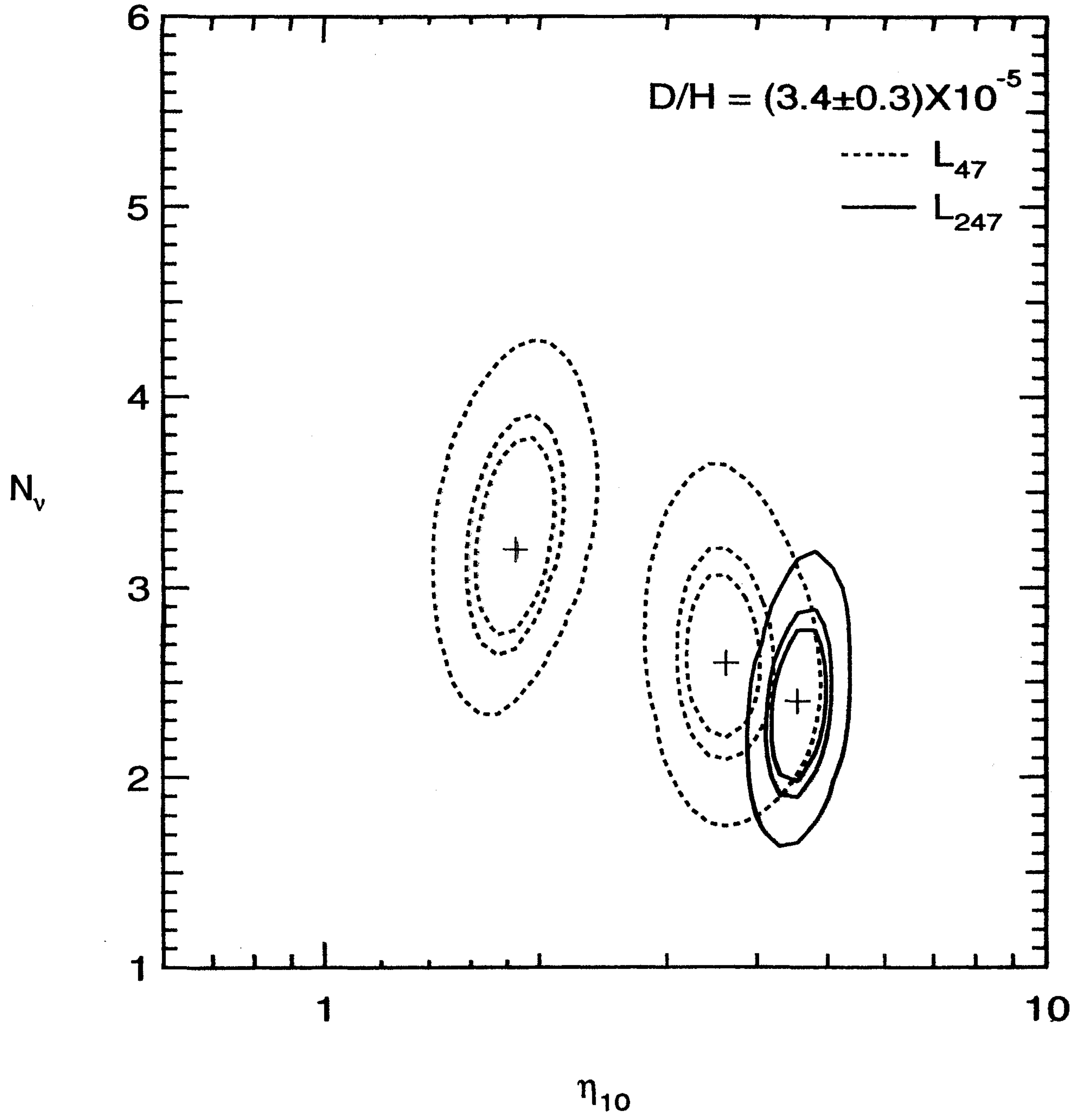
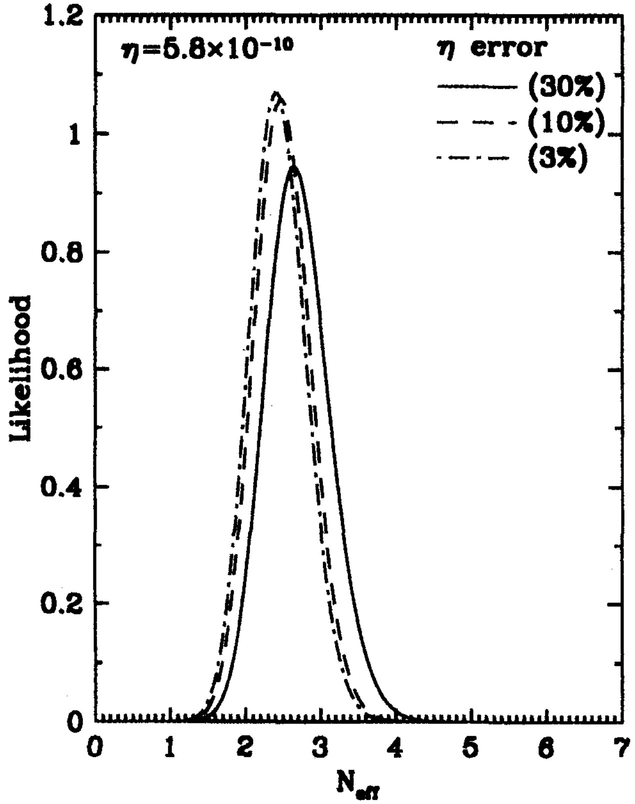


Figure 2: (b) Contour plot for D/H= $(3.4 \pm 0.3) \times 10^{-5}$

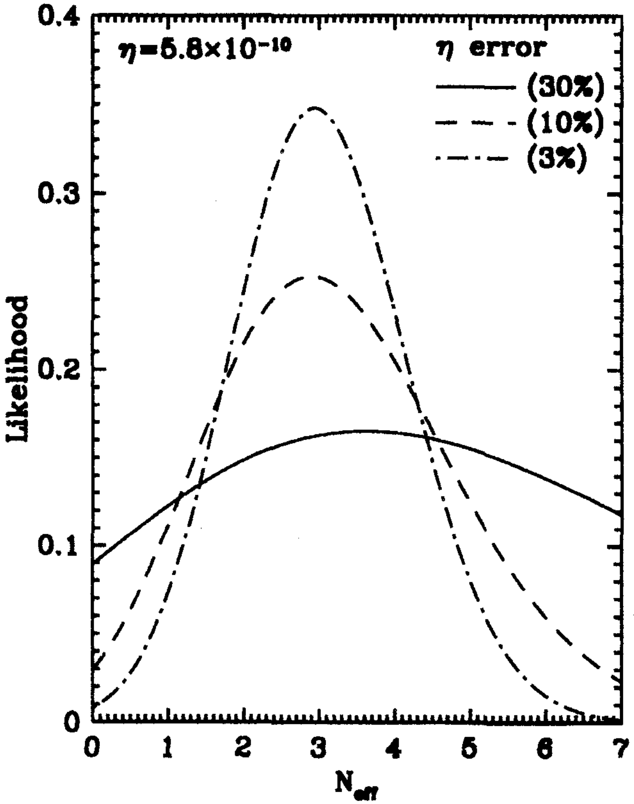
1540
Thomas

CMB Constraints on N_ν

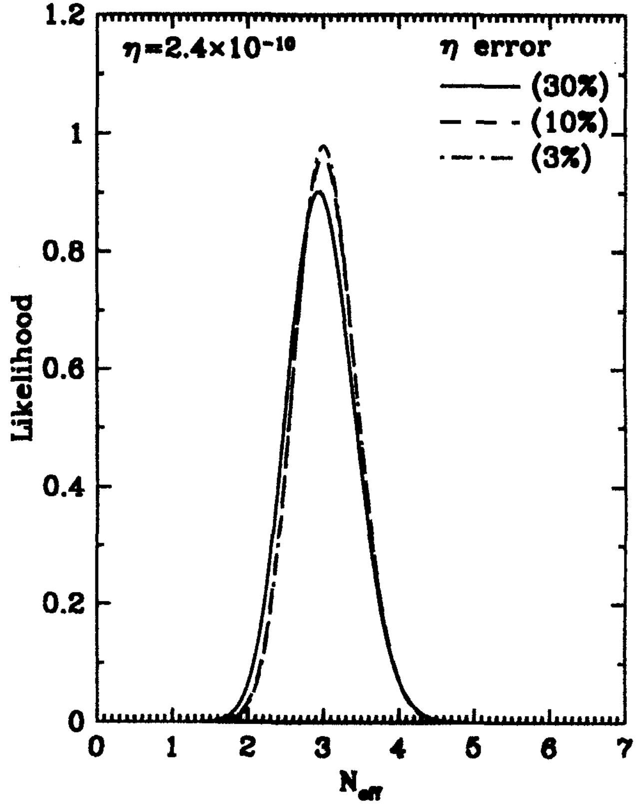
CMB + ^4He + $^7Li/H$



CMB + D/H



assuming higher D/H



Cyburt, Fields, Olive

Implications for Dark Matter

» From D/H, $\Omega_B < 0.1$

$\Rightarrow$ Non Baryonic Dark Matter in the Universe.

» On the scale of binaries and small groups, $\Omega > 0.05$

$\Rightarrow$ from ^{4}He and ^{7}Li – $\Omega_B h^2 \approx 0.007$

$\Omega_B \approx 0.03 \quad (h \sim 1/2)$

Some Galactic Non-Baryonic Dark Matter needed.

» Supported by high D/H

» Low D/H measurements

$\Rightarrow \quad \Omega_B h^2 \approx 0.007$ and possibly $\Omega_B \approx 0.1$

No Non-Baryonic Dark Matter needed in Galaxies.

Summary

The Success of BBN rests on a fine competition between interactions and the expansion of the Universe

$\Rightarrow$ it does not favor departures from the standard model

Success evidenced by ^{4}He and ^{7}Li

$\Rightarrow$ possibly D in the near future

Strong Implications for

Galactic Chemical Evolution — ^{3}He
Dark Matter
Limits on Particle Properties

LECTURE V

Dark Matter

Observations	Theory

Observations

- Galactic Rotation Curves
  $M \propto r$
- Hot Gas in Ellipticals and Clusters
- Gravitational Lensing
- Large Scale Velocity fields
- SN Ia

Theory

- Inflation
  $\Omega_{total} = 1$
- Growth of Density Fluctuations
- Big Bang Nucleosynthesis
  $\Omega_B < 0.09$

Galactic Rotation Curves

Observe: $v(r)$

Expect: $\frac{GM^2}{r^2} = \frac{KMv^2}{r}$

or $M(< r) = \frac{Kv^2r}{G}$

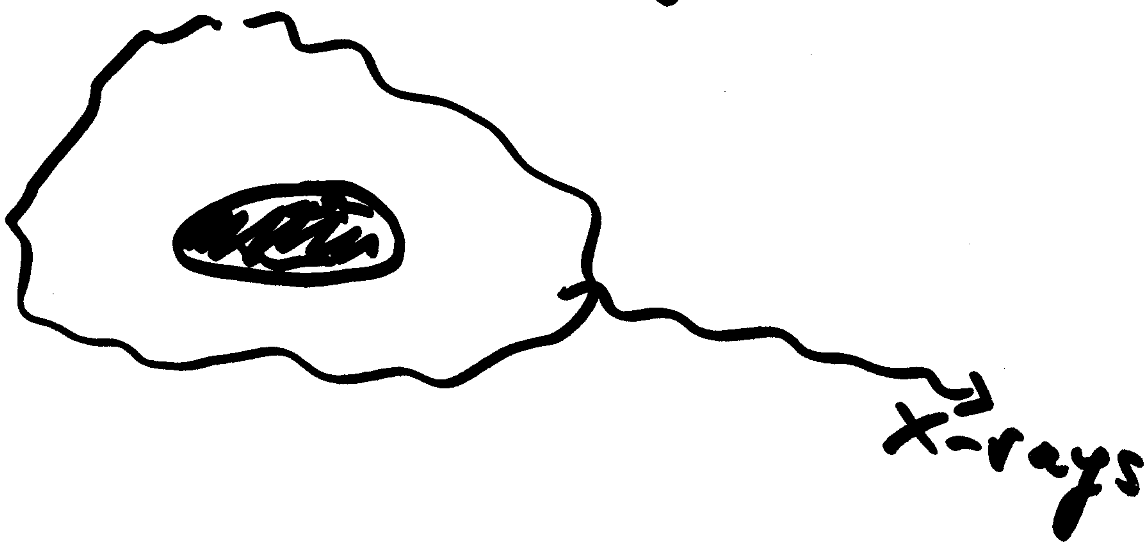
if M **is constant** $v^2 \sim 1/r$

if v **is constant** $M \sim r$

$\Rightarrow$ Existence of Dark Matter

Hot X-Ray Gas

X-ray emitting gas is seen to surround elliptical galaxies

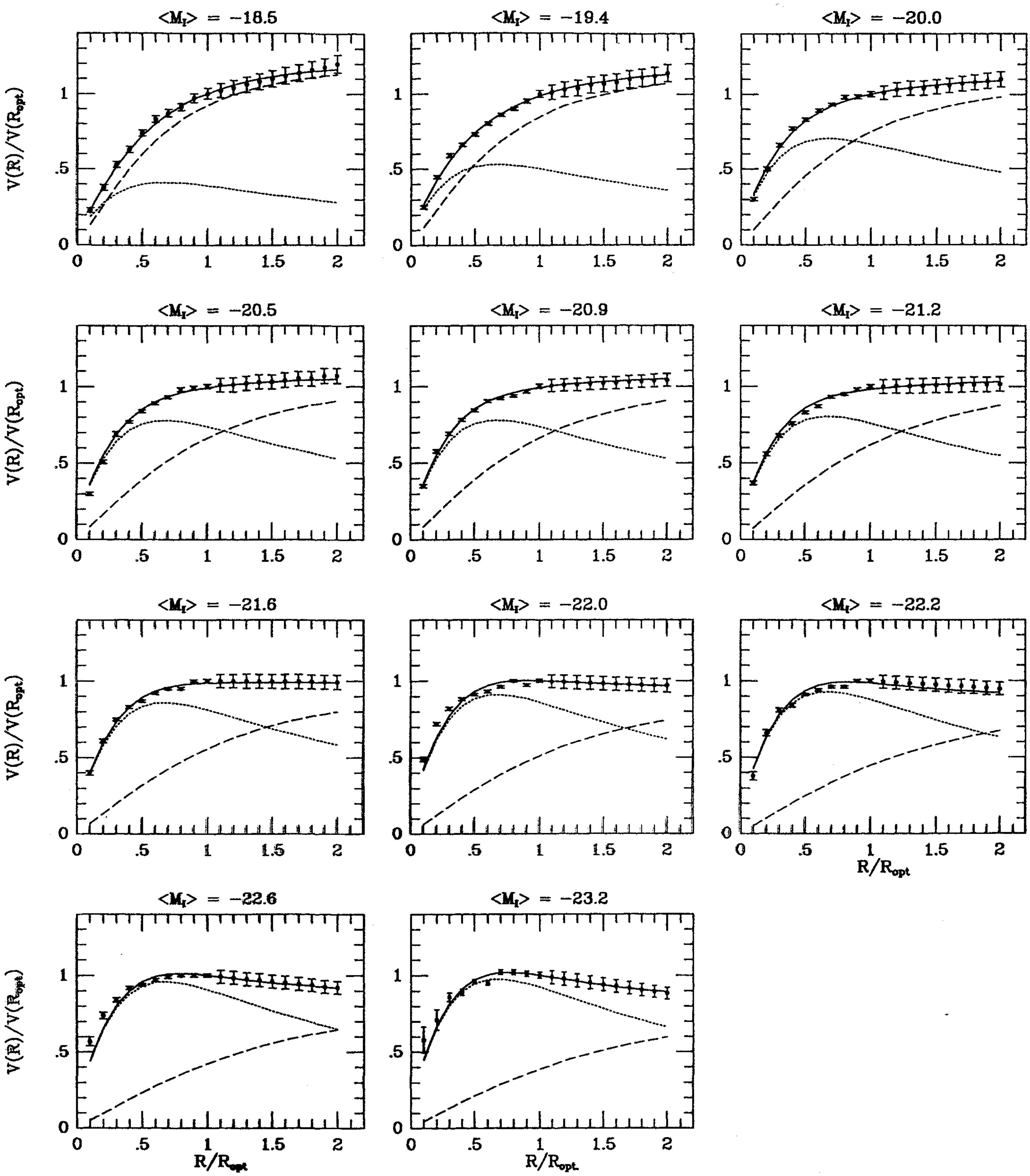


X-ray gas is hot and "wants" to escape
⇒ must be <u>bound</u> ⇒ $M_{Total} > 10^{13} M_{\odot}$

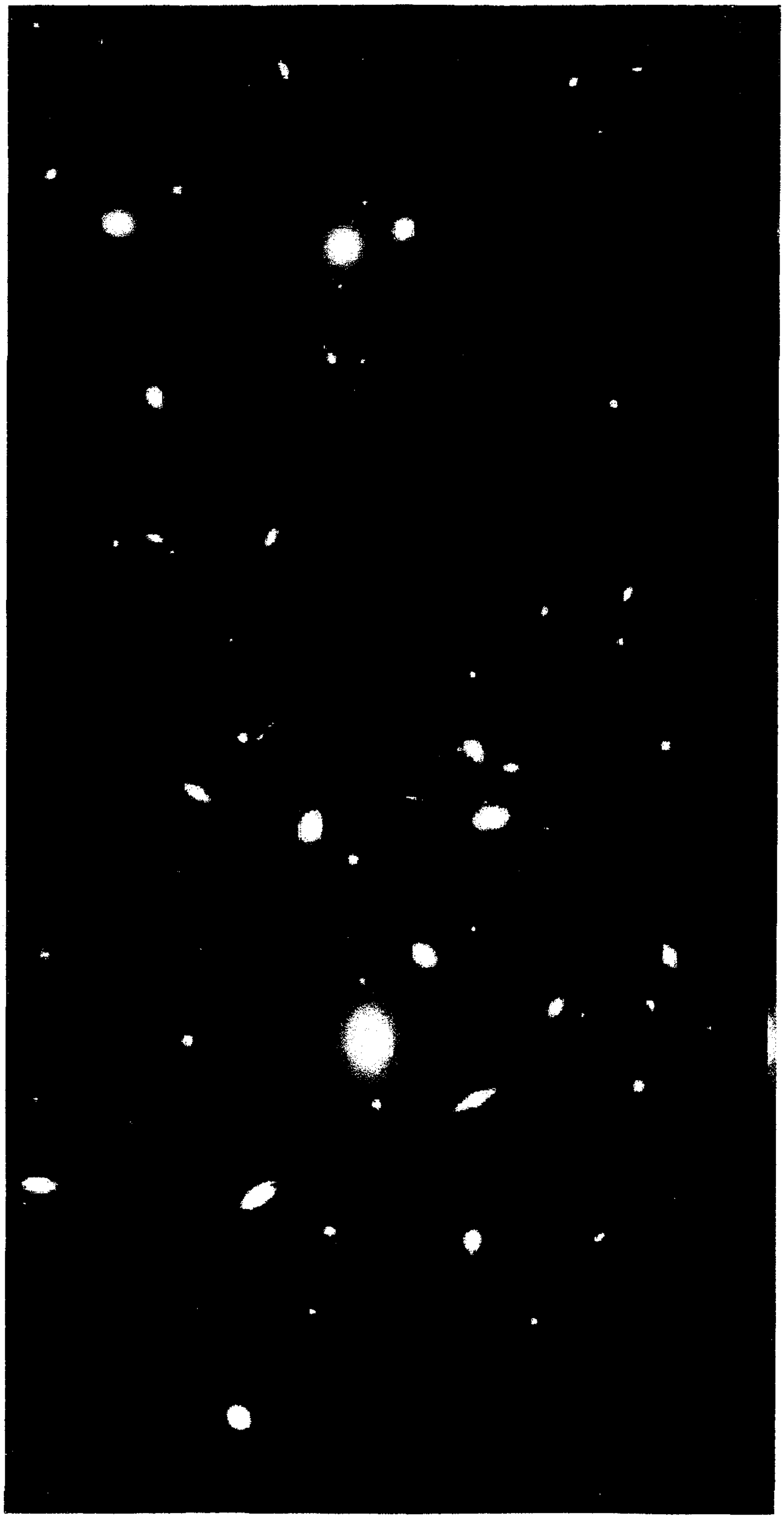
But, $M_{Ell} \lesssim 1\% \, M_T$

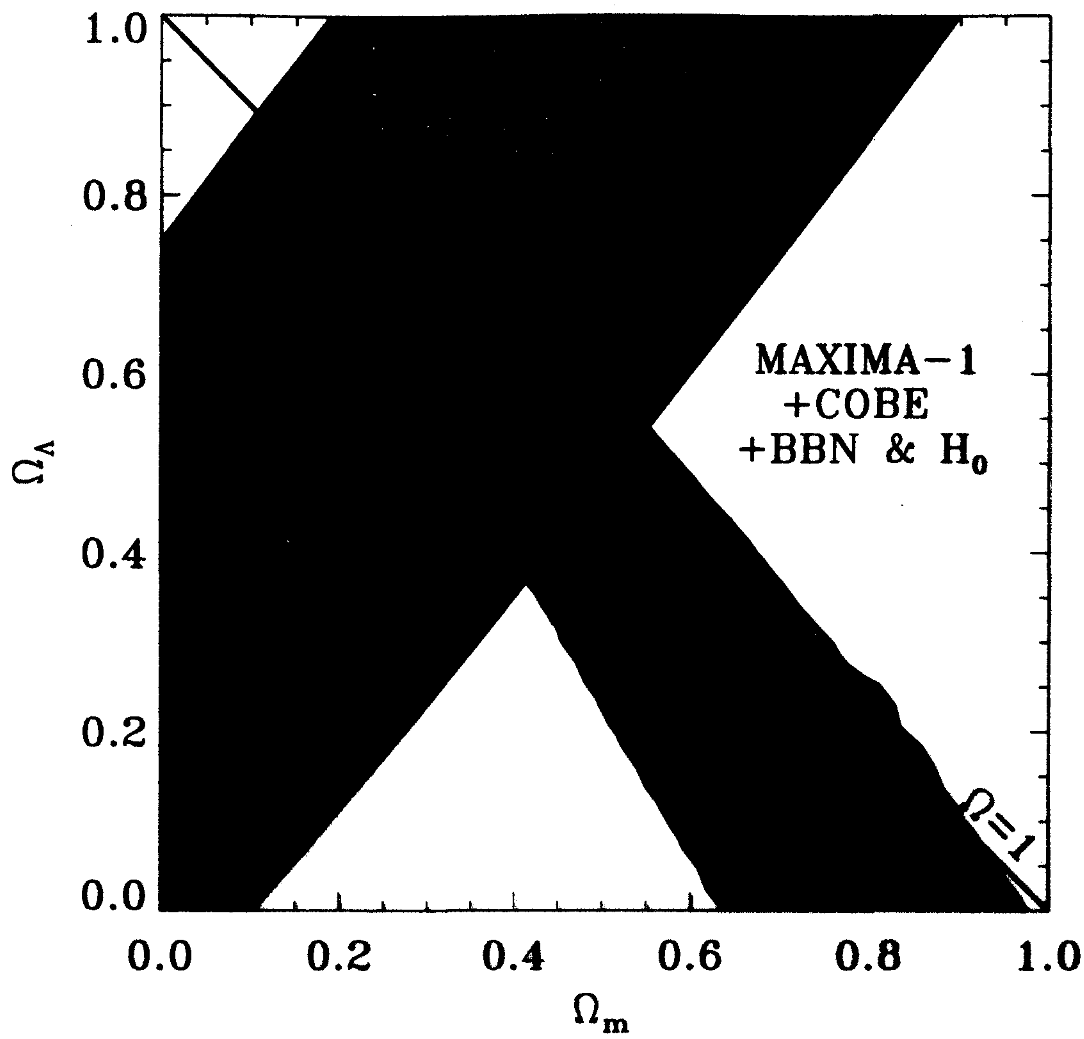
$M_{Gas} \lesssim 5\% \, M_T$

Also seen for Clusters



From
Persic
Salucci
Stel





1.0
0.8
0.6
0.4
0.2
0.0
Ω_Λ
MAXIMA−1
+COBE
+BBN & H_0
Ω=1
0.0
0.2
0.4
0.6
0.8
1.0
Ω_m

Balbi et al

Inflation

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} \qquad \Lambda = 0$$

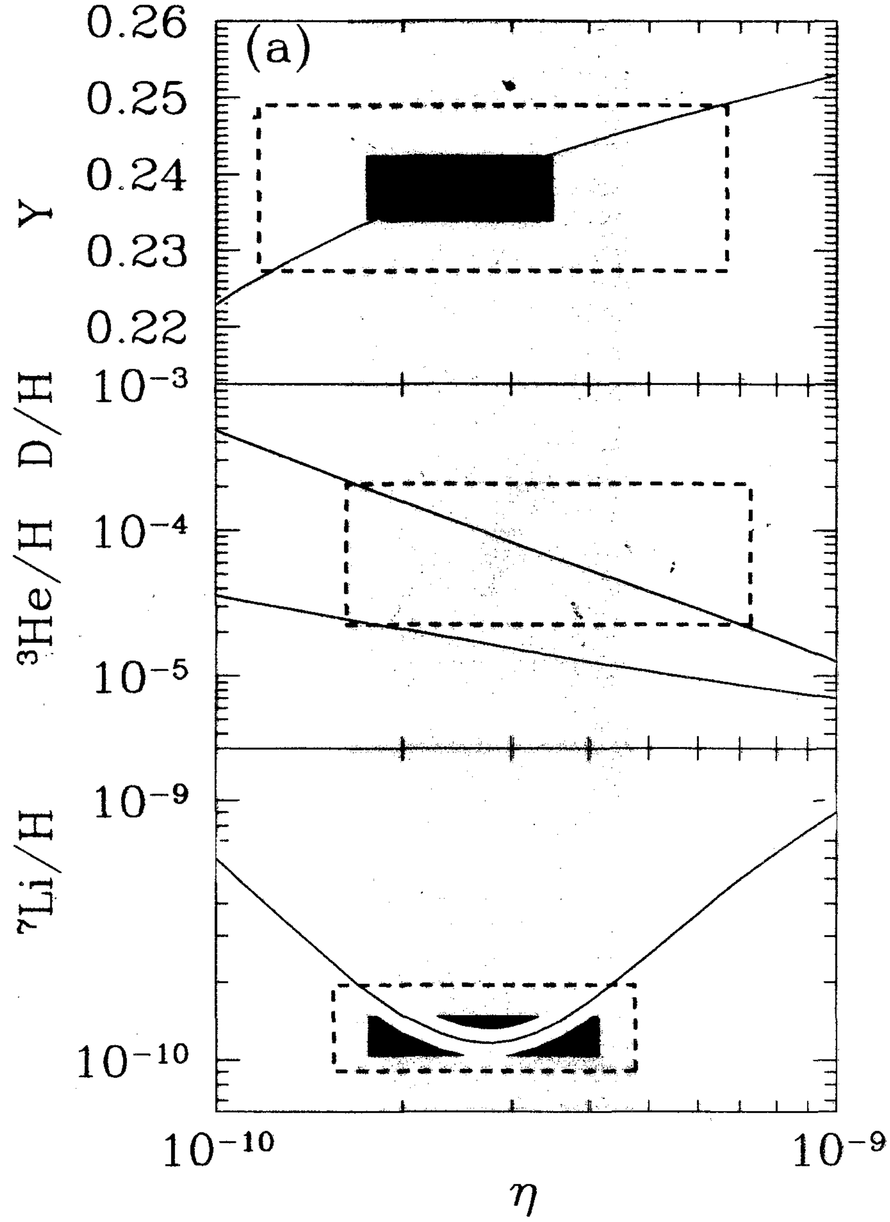
$$\Omega \lesseqgtr 1 \ ? \qquad \Rightarrow \qquad \frac{k}{a^2} < \frac{8\pi G\rho}{3}$$

$$\hat{k} \equiv \frac{k}{a^2T^2} < \frac{8\pi G\rho}{3T_0^2} < O(10^{-58})$$

Before Inflation	$a = a_i,\ T = T_i,\ a \sim T^{-1}$
During Inflation	$a \sim T^{-1} \sim e^{Ht}$
After Inflation	$a_f \gg a_i,\ T = T_R < T_i$

$$\hat{k} = (\Omega - 1)H^2/T^2 \to 0$$

$$\Rightarrow \Omega \to 1$$



$\eta_{10} = 274\,\Omega_B h^2$

Growth of Density Fluctuations

Density perturbation $\delta\rho = \rho_1$

$$\frac{\partial^2 \rho_1}{\partial t^2} + v_s^2 \nabla^2 \rho_1 + 4\pi G \rho \rho_1 = 0$$

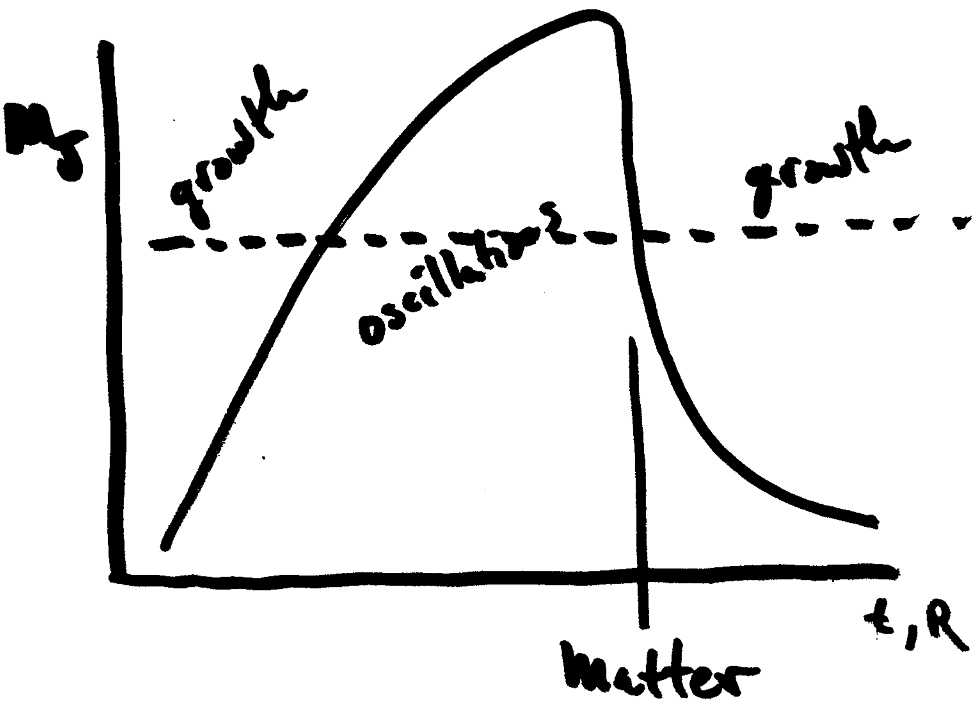
$$\rho_1 \sim e^{i(k \cdot x - \omega t)} \qquad \omega^2 = k^2 v_s^2 - 4\pi G \rho$$

$$k_J = \left(\frac{4\pi G \rho}{v_s^2}\right)^{1/2}$$

Growth for $k > k_J$

Jean's Mass $\propto \left(\frac{2\pi}{k_J}\right)^3 \frac{4\pi\rho}{3}$ Growth for $M > M_J$

Depends on Equation of State



How Much Dark Matter

Upper limit to Ωh^2

age of the Universe

(t > 12 Gyr)

allows one to set an upper limit

$\Omega h^2 < 0.3$

Lower limit to Ωh^2

Structure formation requires at least $\Omega h^2 > 0.1$ in dark matter

But this is not a strict constraint on SUSY dark matter

Values of Ωh^2

$\Omega \equiv \rho/\rho_c \quad \rho_c = 1.88 \times 10^{-29}$ g cm^{-3} h^2

$$\Omega = \Omega_\chi + \Omega_B + \Omega_\nu + \Omega_\Lambda$$

Ω_B determined from nucleosynthesis

$$\Omega_B h^2 = 0.006 - 0.016 \text{ He, Li}$$

$$\Omega_B h^2 = 0.015 - 0.020 \text{ with Low D}$$

Ω_ν determined from neutrino masses

$$\Omega_\nu h^2 = (\Sigma_\nu (g_\nu/2) m_\nu)/94 \text{ eV}$$

Ω_Λ determined from supernovae?

$$\Omega_\Lambda \sim 0.65$$

Upper limit to Ωh^2 from age of the Universe

$$\Omega h^2 \leq 0.3$$

Net Result $\Omega_\chi = 0.1 - 0.3$

Candidates

Normal Baryonic Matter

Clusters

Neutrinos - at least they exist

Neutrino masses?

Light ν's Heavy ν's

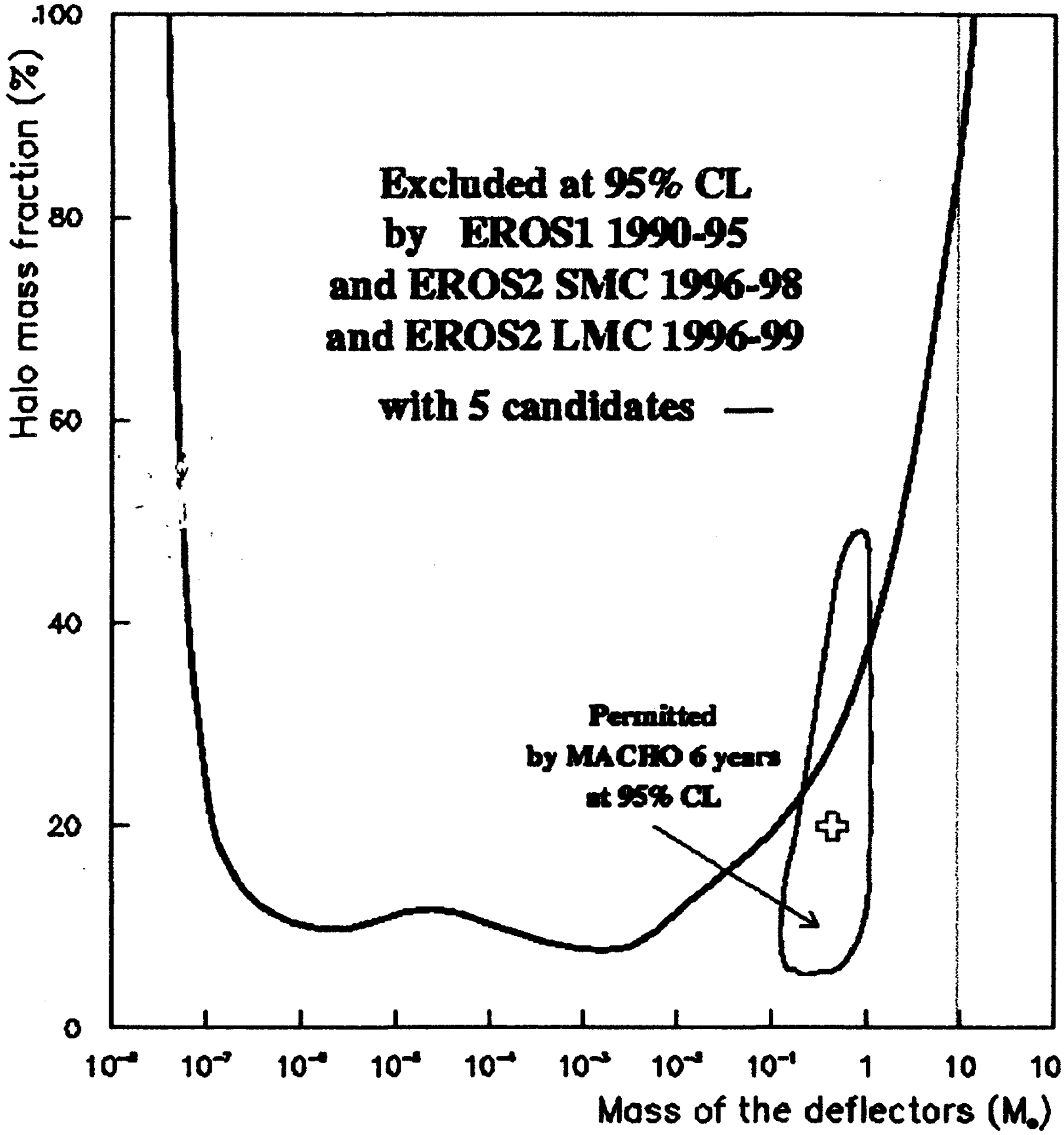
$\Rightarrow$ Supersymmetry

a new stable particle

Axions

Combined limit LMC/SMC
EROS 1990-99

Spherical standard halo : $M = 4\ 10^{11}\ M_\odot$ within 50 kpc



1996/98 Limit confirmed and improved

Standard Halo fully comprised of MACHOs excluded à 95% C.L. for $M_{LENS} < 10\ M_\odot$

Baryonic Dark Matter

- Hydrogen

  a) Snow Balls

  b) Cold Gas

  c) Hot Gas

- Low Mass Stars/Jupiters

  Machos

- Remnants: White Dwarfs or Neutron Stars

  Machos

- Black Holes

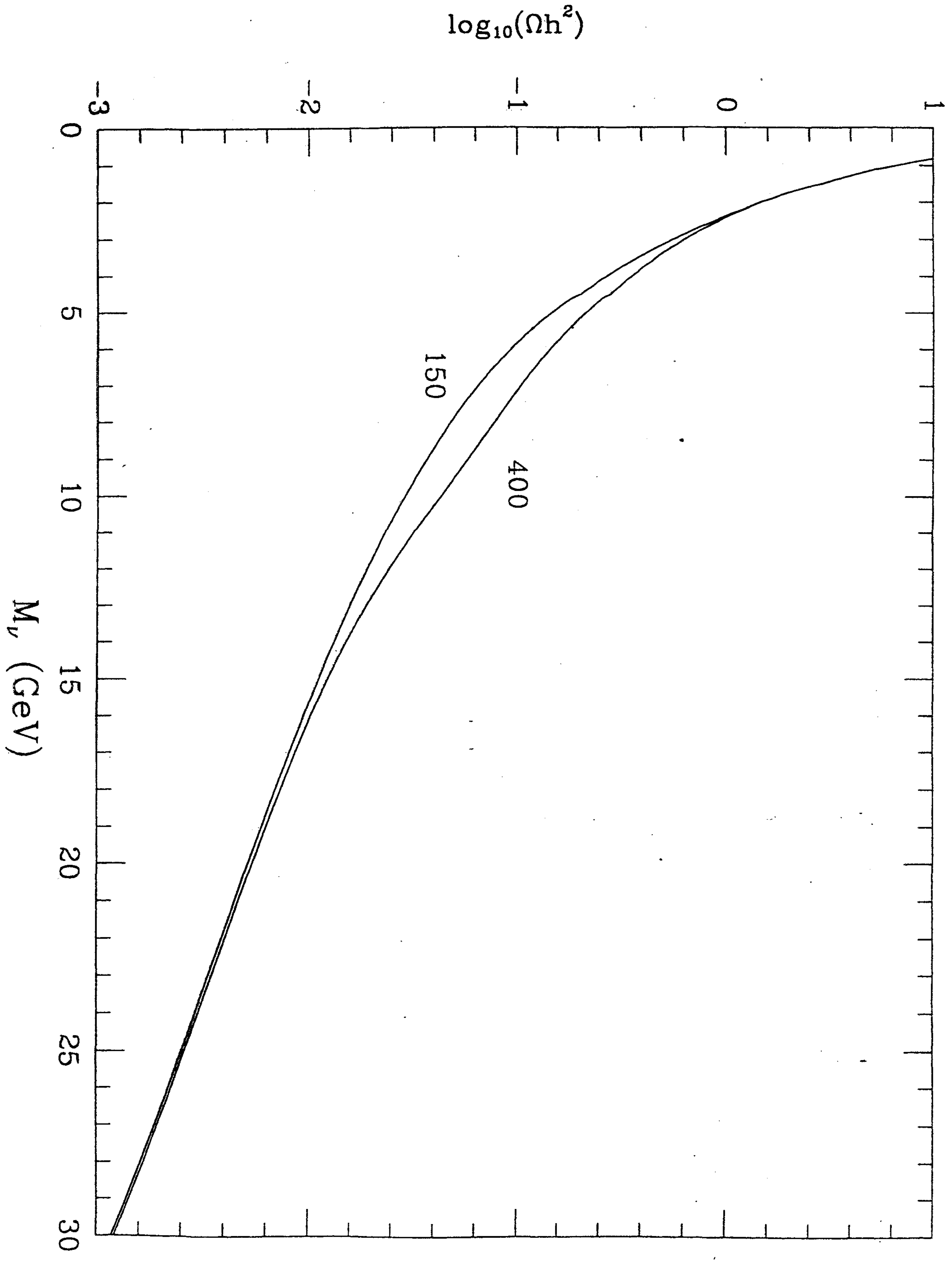


Fig.(7)

What is the MSSM

1) Add minimal number of new particles: Partners for all SM particles + 1 extra Higgs EW doublet.

2) Add minimal number of new interactions: Impose R-parity to eliminate many UNWANTED interactions.

$$R = (-1)^{3B+L+2S}$$

All New particles have R = -1

E.g.:

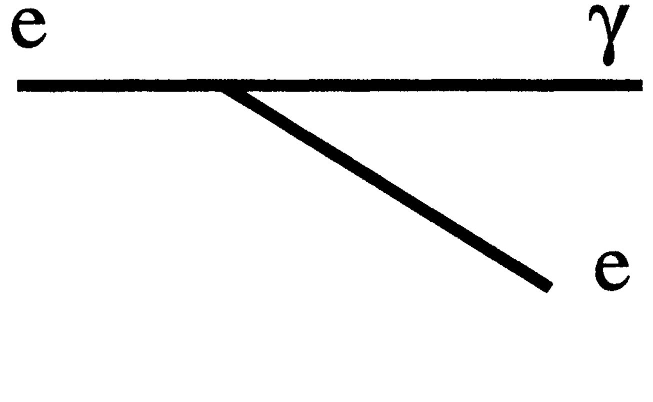
$\tilde{\gamma}$: S=1/2; B=L=0; $R=(-1)^1 = -1$

$\tilde{e}$: S=0; B=0; L= -1; $R=(-1)^{-1} = -1$

$\tilde{u}$: S=0; B=1/3; L=0; $R=(-1)^1 = -1$

R-Parity Conservation ⇒

The Lightest Supersymmetric Particle (LSP) is stable



Particle Content of the MSSM

Gauge

γ		B		$\tilde{B}$	neutralinos
Z	or	W^3	$\Longrightarrow$	$\tilde{W}^3$	
$W^\pm$		W^1		$\tilde{W}^\pm$	charginos

Higgs

H_1	$\Longrightarrow$	$\tilde{H}_{1,2}$	neutralinos
H_2		$\tilde{H}^\pm$	charginos

Matter

q	$\Longrightarrow$	$\tilde{q}_{L,R}$	squarks
l		$\tilde{l}_{L,R}$	sleptons

MSSM vs CMSSM

nUHM vs UHM

Parameters:

M_2, m_0, μ, m_A

$m_1, m_2 \neq m_0$

and are fixed by EWSB.

μ and m_A are independent

Plots: M_2, μ

Parameters:

$m_{1/2}$, m_0, sgn(μ)

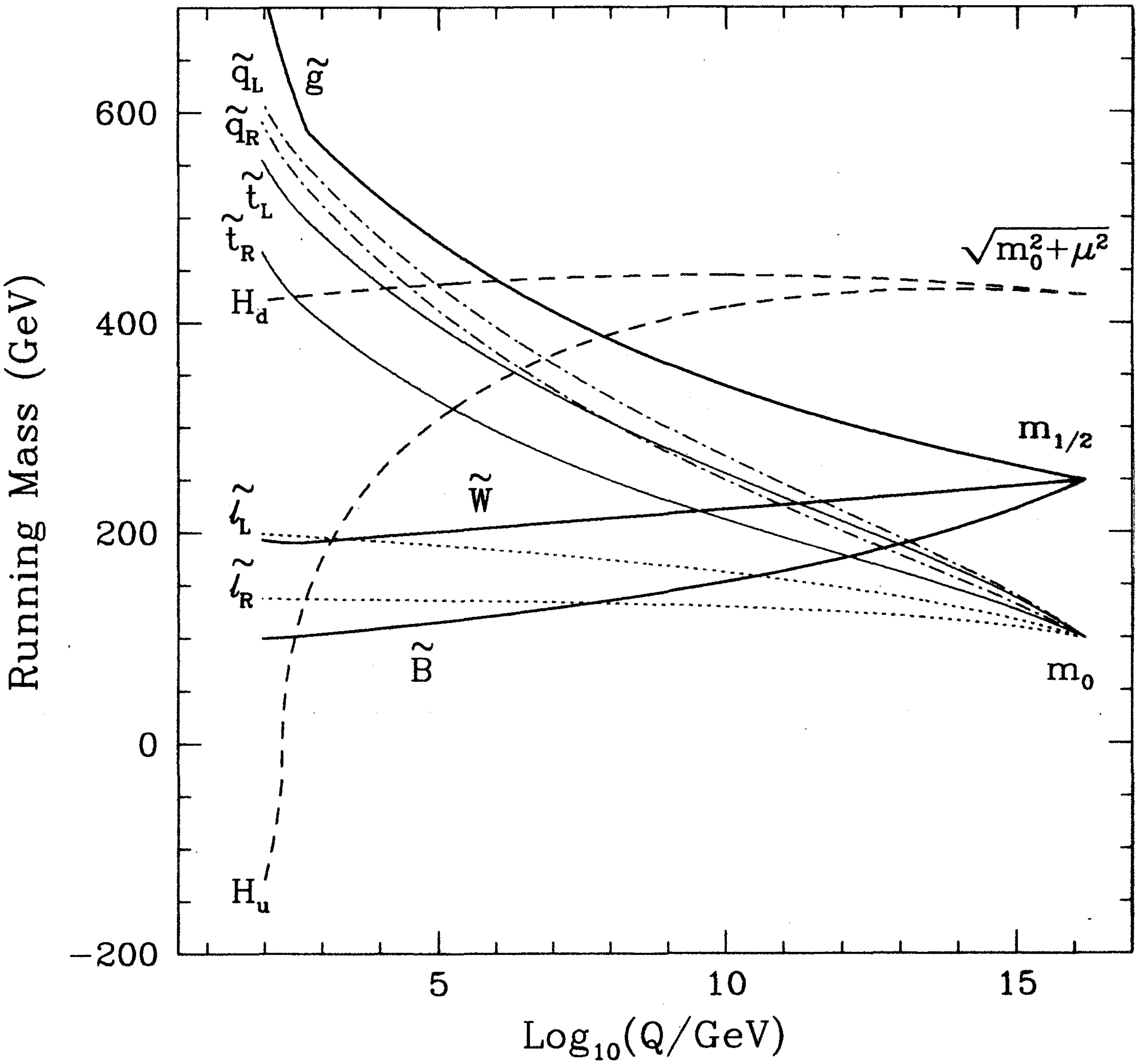
$m_1, m_2 = m_0$

μ and m_A are fixed by EWSB

Plots: $m_{1/2}$, m_0

At unification, $M_1 = M_2 = M_3 = M_{1/2}$

Common Parameters: $\tan\beta$, A


Running Mass (GeV)
600
400
200
0
−200
5
10
15
Log10(Q/GeV)
$\tilde{g}$
$\tilde{q}_L$
$\tilde{q}_R$
$\tilde{t}_L$
$\tilde{t}_R$
H_d
$\sqrt{m_0^2+\mu^2}$
$m_{1/2}$
$\tilde{W}$
$\tilde{l}_L$
$\tilde{l}_R$
$\tilde{B}$
m_0
H_u

T. Falk

SUSY Dark Matter

MSSM and R-Parity ⇒

Stable DM candidate

1) Neutralinos

$$\tilde{\chi}_i = \alpha_i \tilde{B} + \beta_i \tilde{W} + \gamma_i \tilde{H}_1 + \delta_i \tilde{H}_2$$

2) Sneutrinos

Excluded

(unless add L-violating terms)

3) Other:

Axinos, Gravitinos, etc

Neutralinos

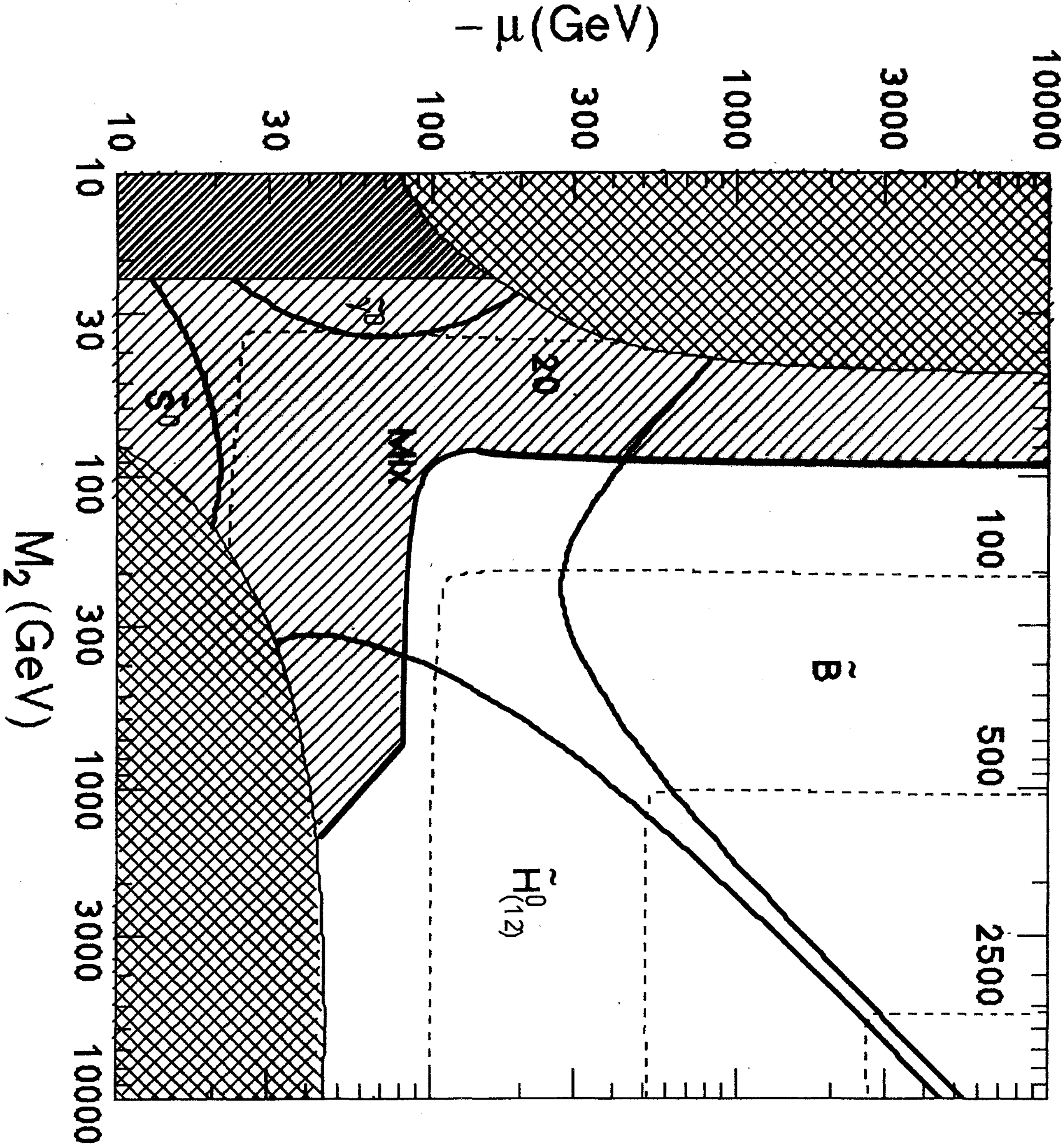
mass matrix

$$(\tilde{B}, \tilde{W}^3, \tilde{H}_1^0, \tilde{H}_2^0) \begin{pmatrix} M_1 & 0 & \frac{-g_1 v_1}{\sqrt{2}} & \frac{g_1 v_2}{\sqrt{2}} \\ 0 & M_2 & \frac{g_2 v_1}{\sqrt{2}} & \frac{-g_2 v_2}{\sqrt{2}} \\ \frac{-g_1 v_1}{\sqrt{2}} & \frac{g_2 v_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g_1 v_2}{\sqrt{2}} & \frac{-g_2 v_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

Depends on $M_{1/2}$, μ, **and** $\tan\beta$

Assume $M_1 = M_2 = M_3 = M_{1/2}$ **@ GUT Scale**

Also, Relic Density Depends on m_o, m_A


− μ (GeV)
10000
3000
1000
300
100
30
10
10
30
100
300
1000
3000
10000
M2 (GeV)
100
500
2500
Mix
20
B̃
H̃0(12)

The Relic Density

At high temperatures $T >> m_\chi$;

χ's in equilibrium $\Gamma > H$

$$n_\chi \sim n_\gamma$$

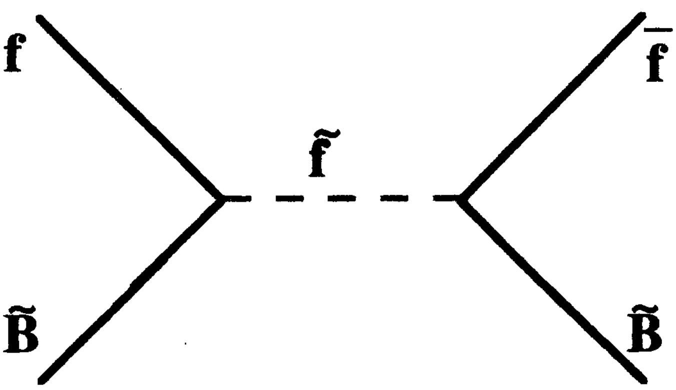
$\Gamma \sim n\sigma v \sim T^3\sigma v$; $HM_p \sim \sqrt{\rho} \sim T^2$

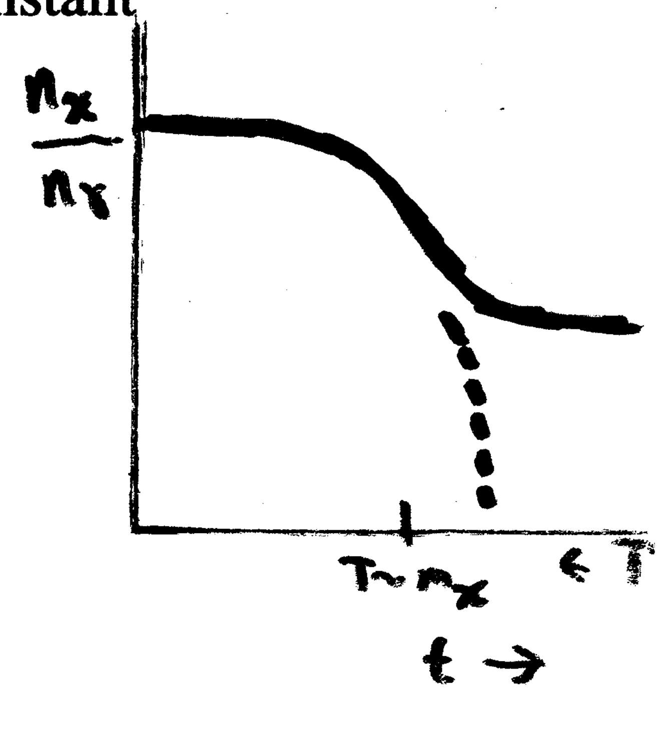
As $T < m_\chi$; annihilations drop n_χ

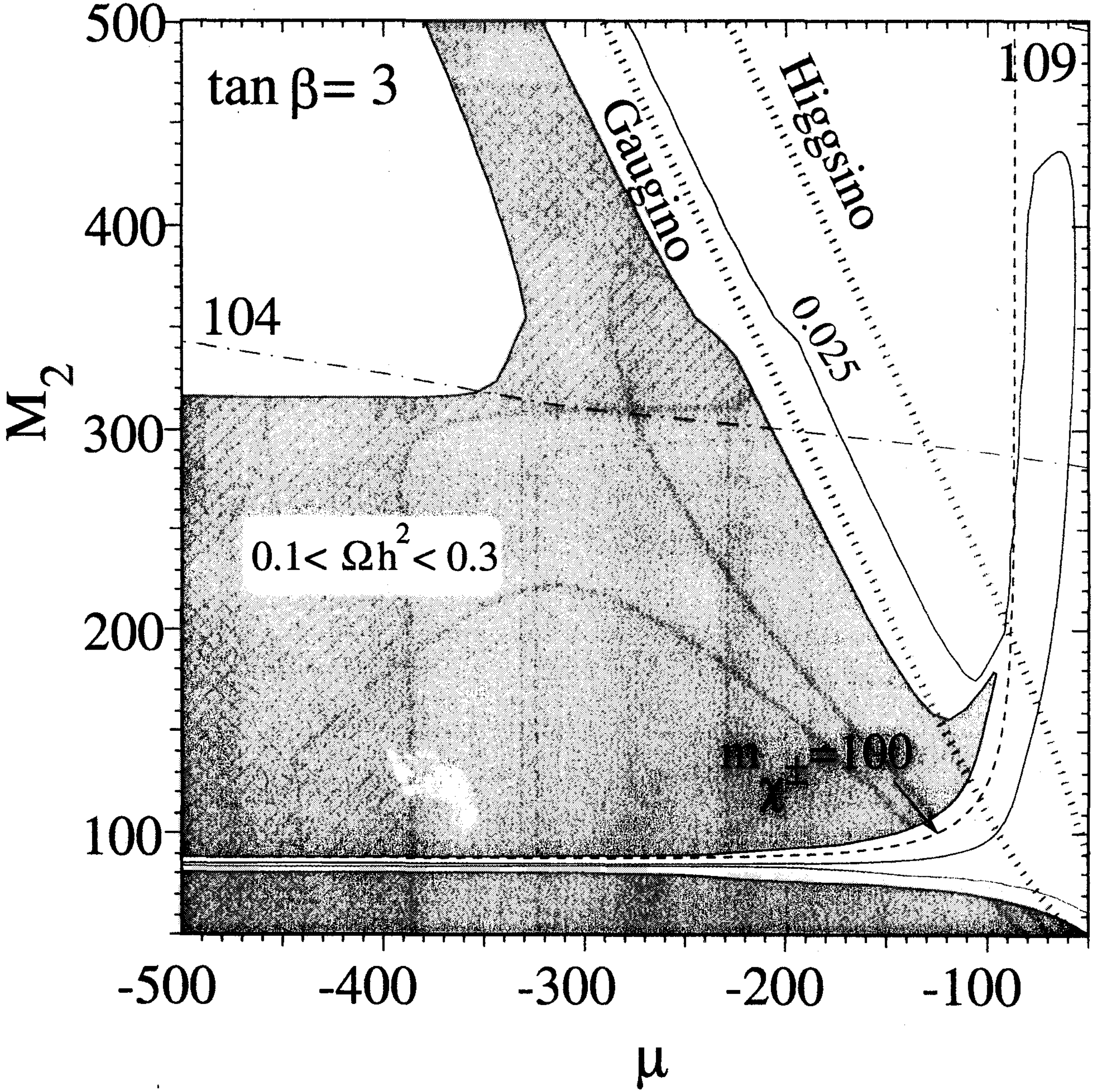
$$n_\chi \sim e^{-m_\chi/T}\, n_\gamma$$

Until freeze-out, $\Gamma < H$

$$n_\chi/n_\gamma \sim \text{constant}$$

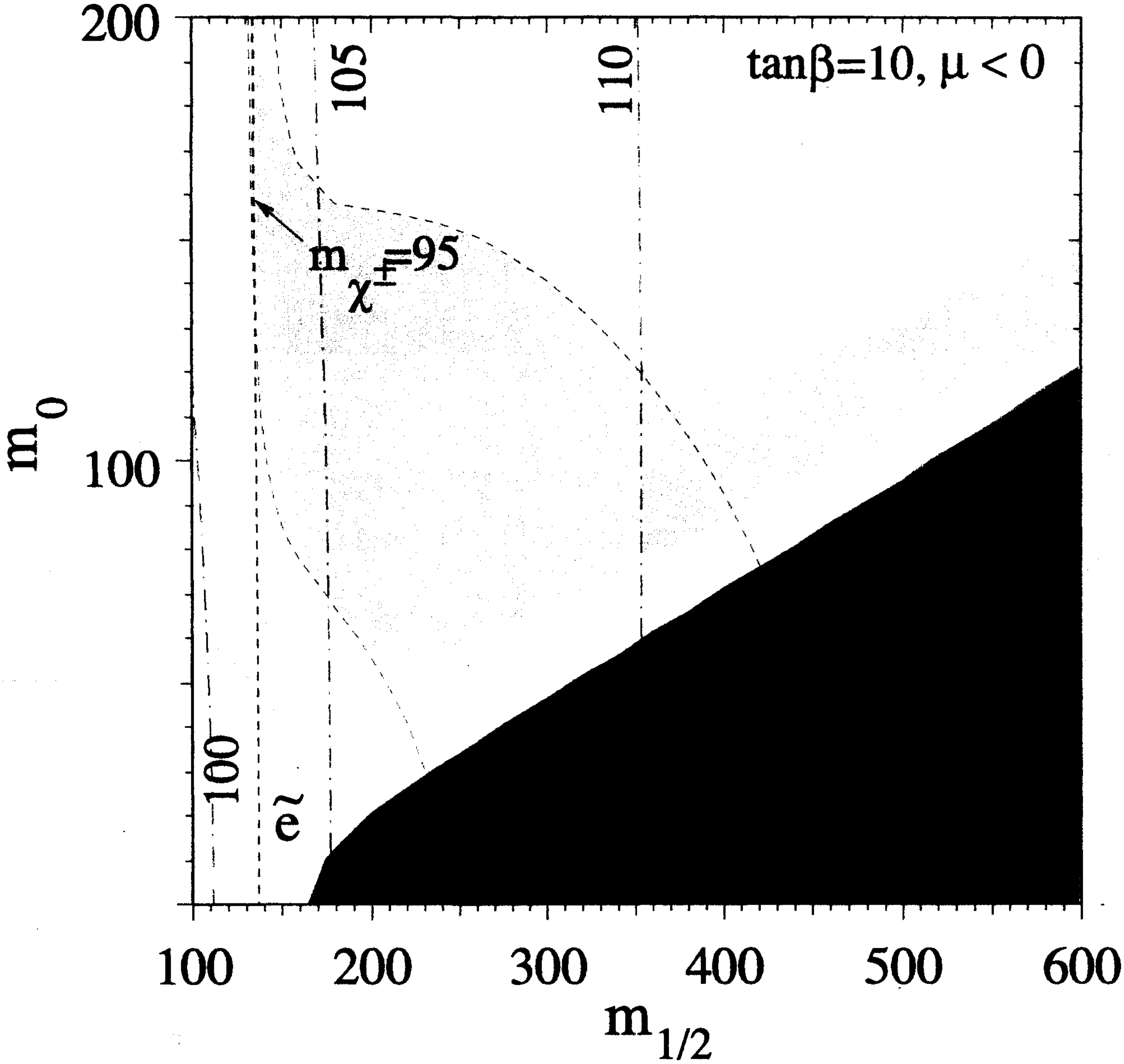






Ellis, Falk, Ganis, Olive (EFGO)

$m_0 = 100$ GeV, $m_A = 1$ TeV


200
100
100
200
300
400
500
600
m_0
$m_{1/2}$
tanβ=10, μ < 0
105
110
100
$m_{\chi^\pm}$=95
ẽ

Co-annihilation

Often, the LSP is nearly degenerate with another SUSY sparticle.

Greist + Seckel

χ, χ', $\chi^{\pm}$ nearly degenerate when $M_2 >> \mu$

Mizuta + Yamaguchi

Enhanced annihilation

$\Rightarrow$ lower Ωh^2

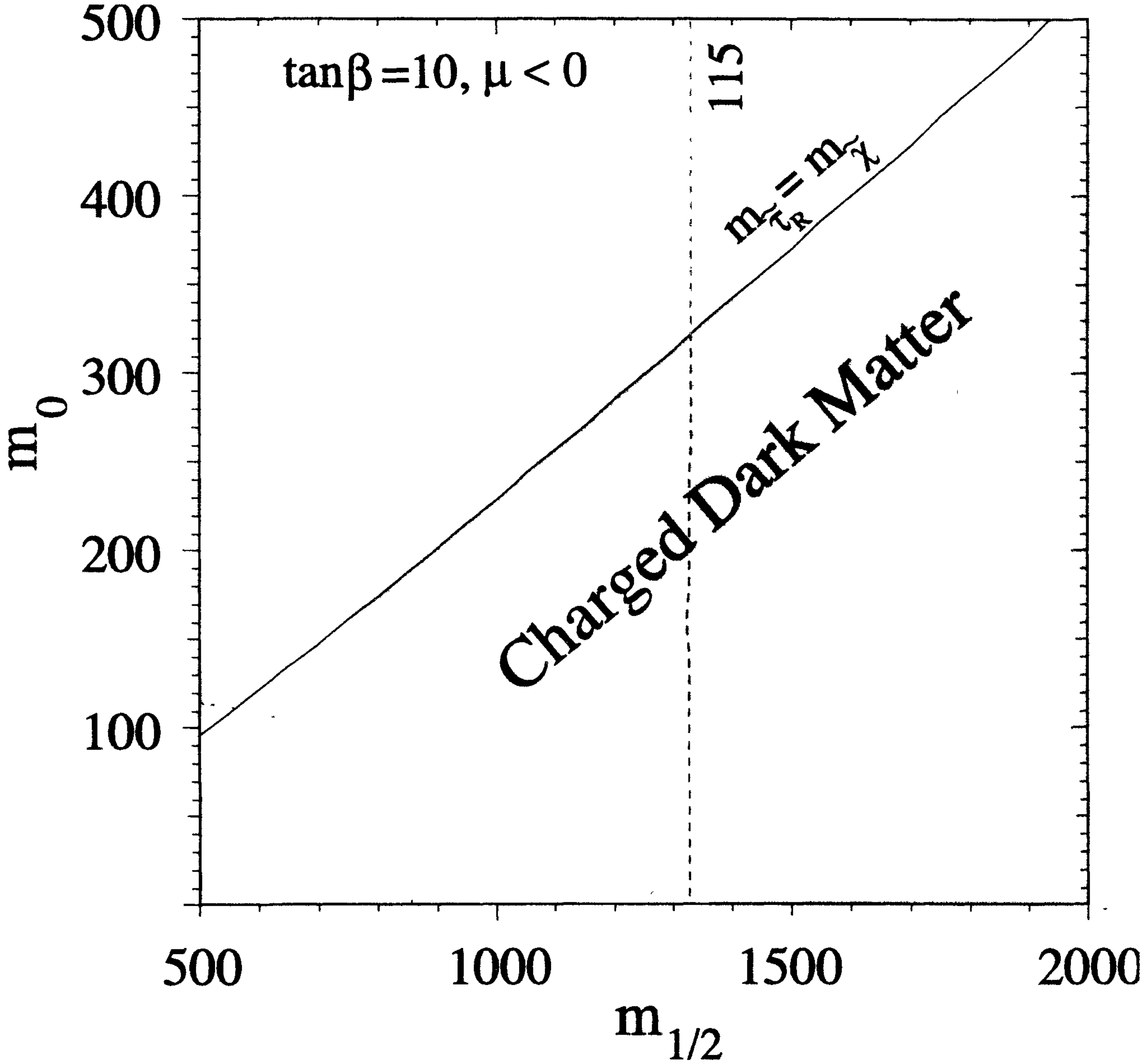
Higgsino dark matter all but excluded [illegible]

Also, in CMSSM, $\chi - \tilde{\tau}$ or $\chi - \tilde{t}$

Ellis Falk Olive Srednicki

Boehm Djouadi Drees

greatly affects upper limits to LSP.



tanβ =10, μ < 0
115
$m_{\tilde{\tau}_R} = m_{\tilde{\chi}}$
Charged Dark Matter
500
400
300
200
100
m_0
500
1000
1500
2000
$m_{1/2}$

Constraints

- Chargino mass limit

$$M_{\chi^{\pm}} \geq 104 \text{ GeV}$$

Constrains (M_2 and μ)/ $m_{1/2}$

- Higgs mass limit

$$M_H \geq 113 \text{ GeV}$$

Constrains (m_A, M_2, A)/ $m_{1/2}$

particularly at low tan β

- b to s γ

Constrains (m_A)/ $m_{1/2}$ at high tan β and $\mu < 0$

- Also sfermion mass limits from LEP and CDF

$$m_{\tilde{f}} \geq 98 \text{ GeV (roughly)}$$

χ is the LSP

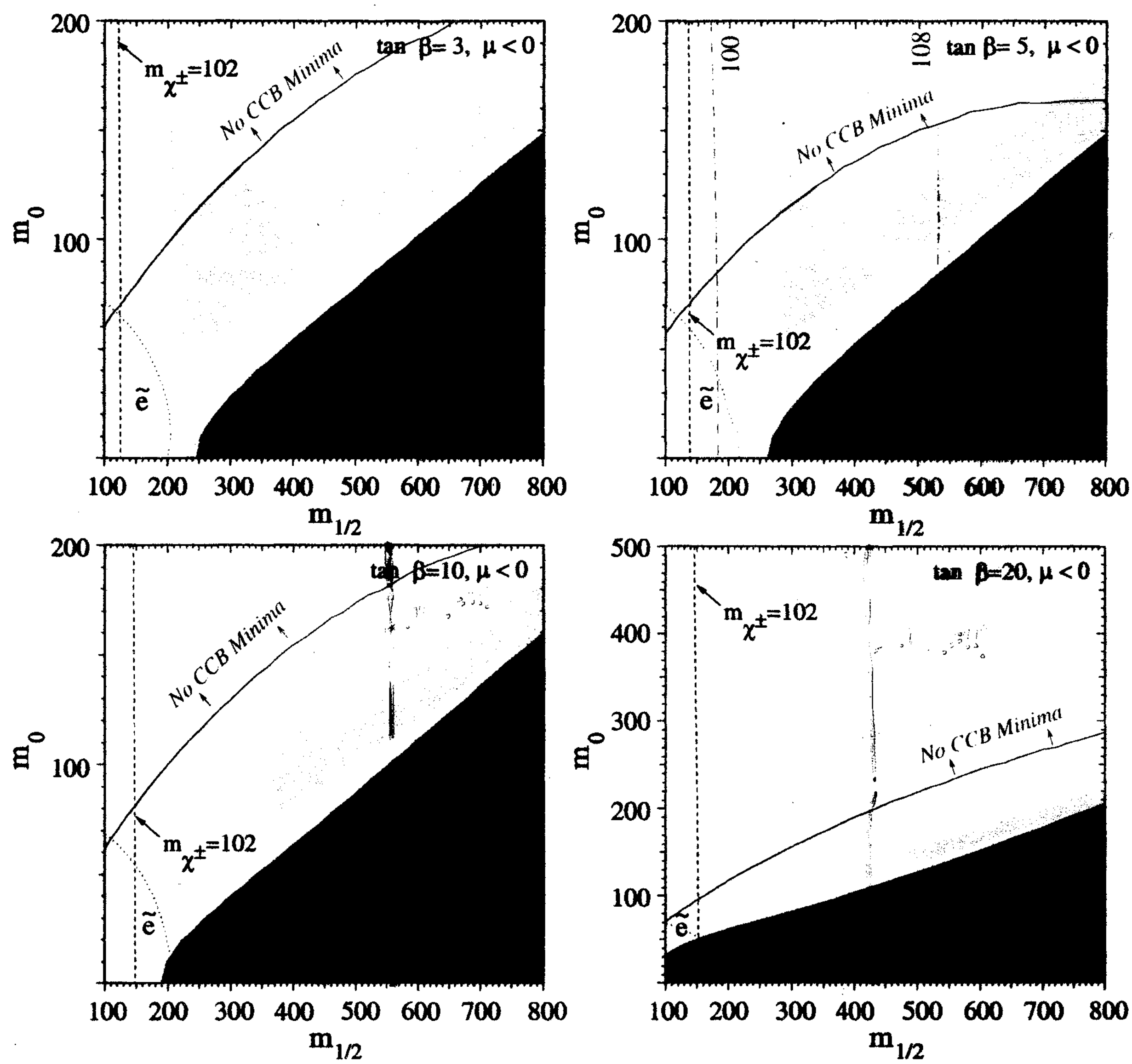


Figure 8: *The $m_{1/2}, m_0$ plane for $\mu < 0$, $A = -m_{1/2}$ so as to minimize the impact of the CCB constraint (indicated by a solid line) and* $\tan\beta$ = *(a) 3, (b) 5, (c) 10 and (d) 20. The region excluded by our $b \to s\gamma$ analysis has light shading. The region allowed by the cosmological constraint* $0.1 \leq \Omega_\chi h^2 \leq 0.3$, *after including coannihilations, has medium shading. Dotted lines delineate the announced LEP constraint on the $\tilde{e}$ mass and the disallowed region where $m_{\tilde{\tau}_1} < m_\chi$ has dark shading. The contour $m_{\chi^\pm}$ = 102 GeV is shown as a near-vertical dashed line in each panel. Also shown as dot-dashed lines are relevant Higgs mass contours.*

EPW

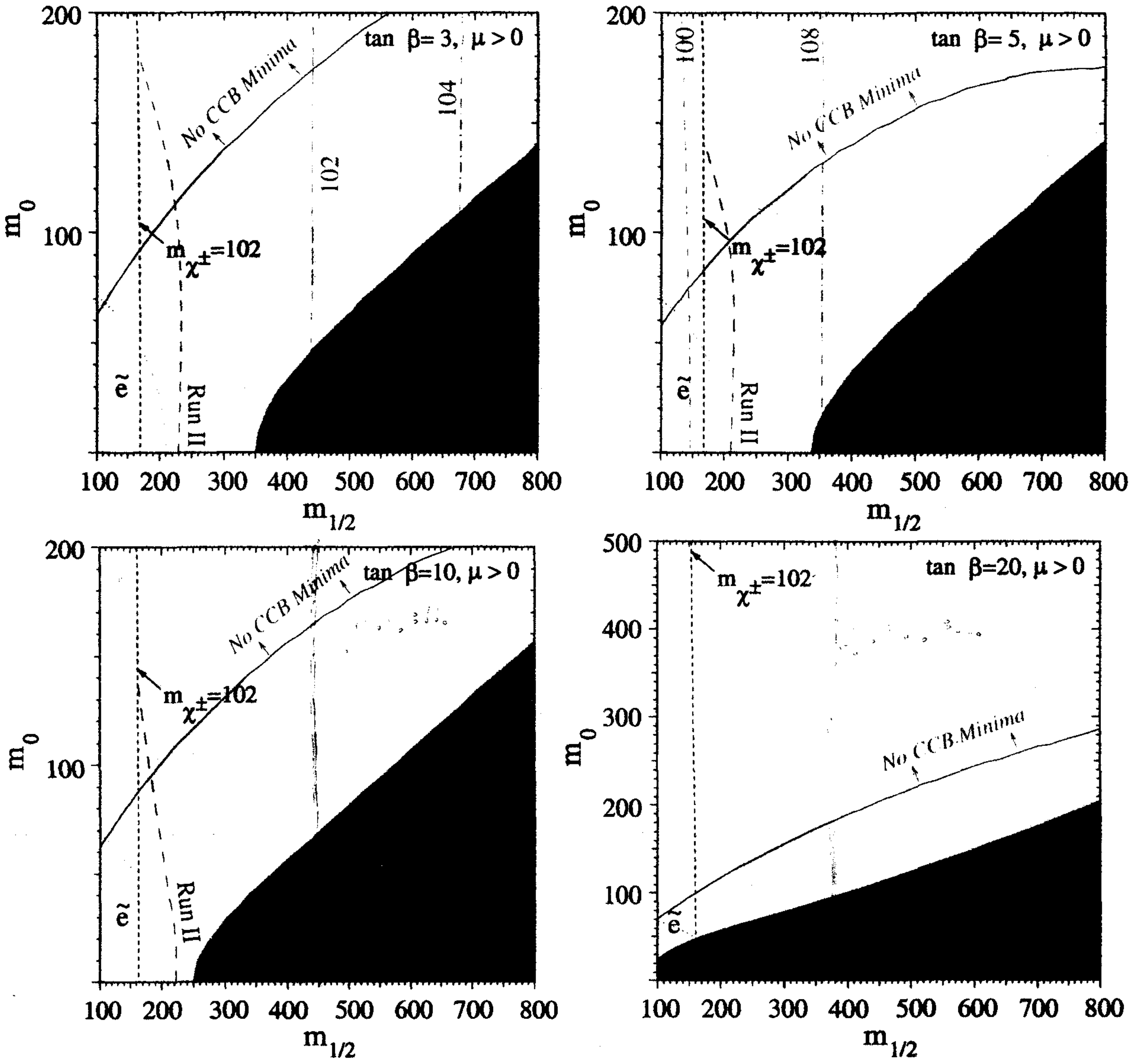


Figure 9: *The* $m_{1/2}, m_0$ *plane for* $\mu > 0$, $A = -m_{1/2}$ *and* $\tan\beta =$ *(a) 3, (b) 5, (c) 10 and (d) 20. The significances of the curves and shadings are the same as in Fig. 8. The light-shaded region in panel (d) is excluded by the* $b \to s\gamma$ *constraint. The long dashed curves in panels (a), (b) and (c) represent the anticipated limits from trilepton searches at Run II of the Tevatron [2].*

F=60

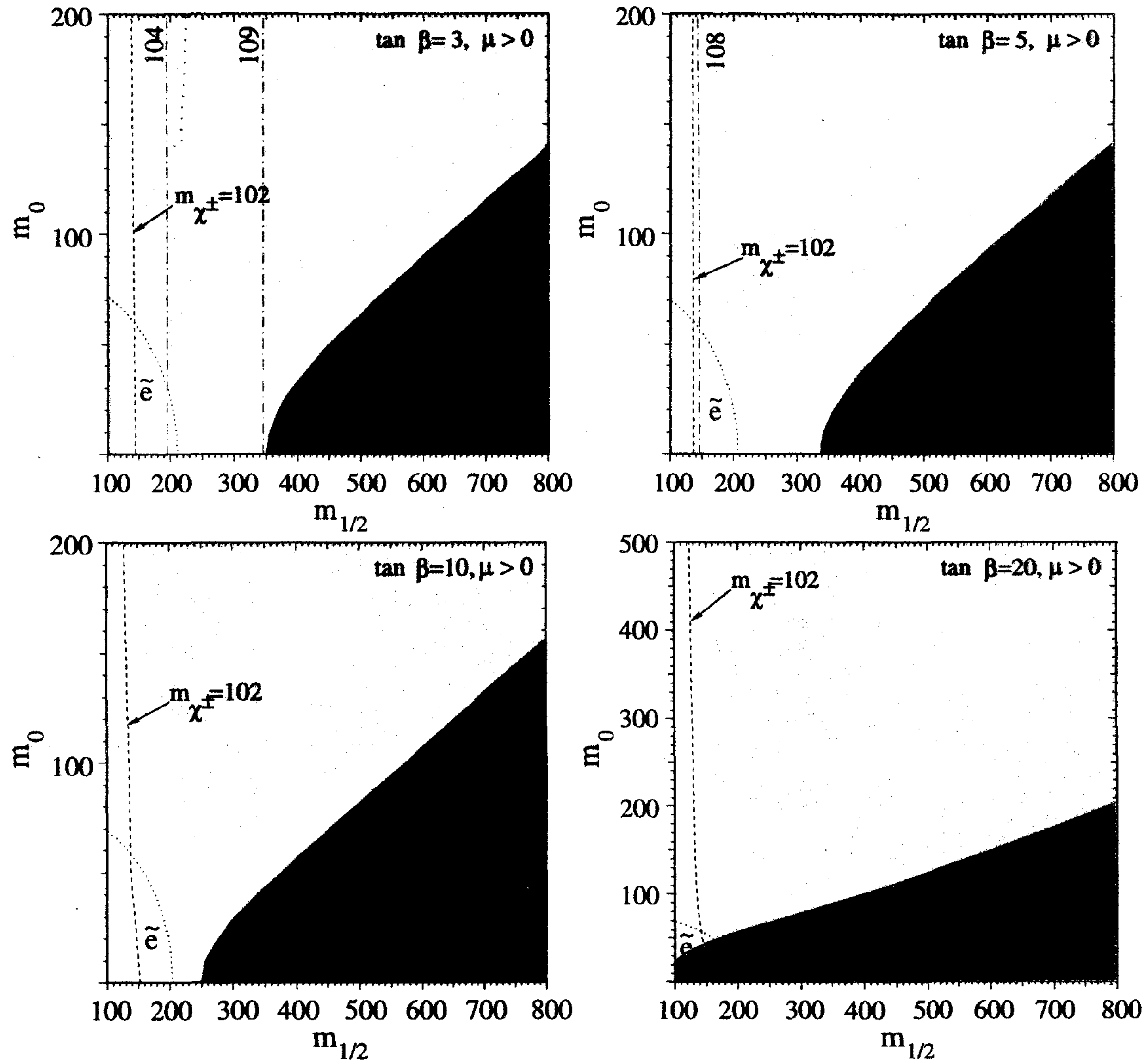


Figure 13: *The $m_{1/2}, m_0$ plane for $\mu > 0$ in the nUHM case, for* $\tan\beta =$ *(a) 3, (b) 5, (c) 10 and (d) 20. The significances of the curves and shadings are the same as in Fig. 12. The dotted extension of the $m_h = 104$ GeV contour corresponds to the shift in the Higgs contour when the cosmological limit on the relic density is imposed (visible only in (a)).*

The CMSSM at large tan β

- Increased sensitivity to bottom quark mass - radiative corrections
- Rapid annihilation through s-channel A and H exchange

  due to:

  – $m_{A,H}$ decreases as tan β increases

  – and $2m_\chi \sim m_{A,H}$ for a wide range in $m_{1/2}$

  – b quark coupling enhanced by tan β

Ellis, Falk, Ganis, Olive, Srednicki

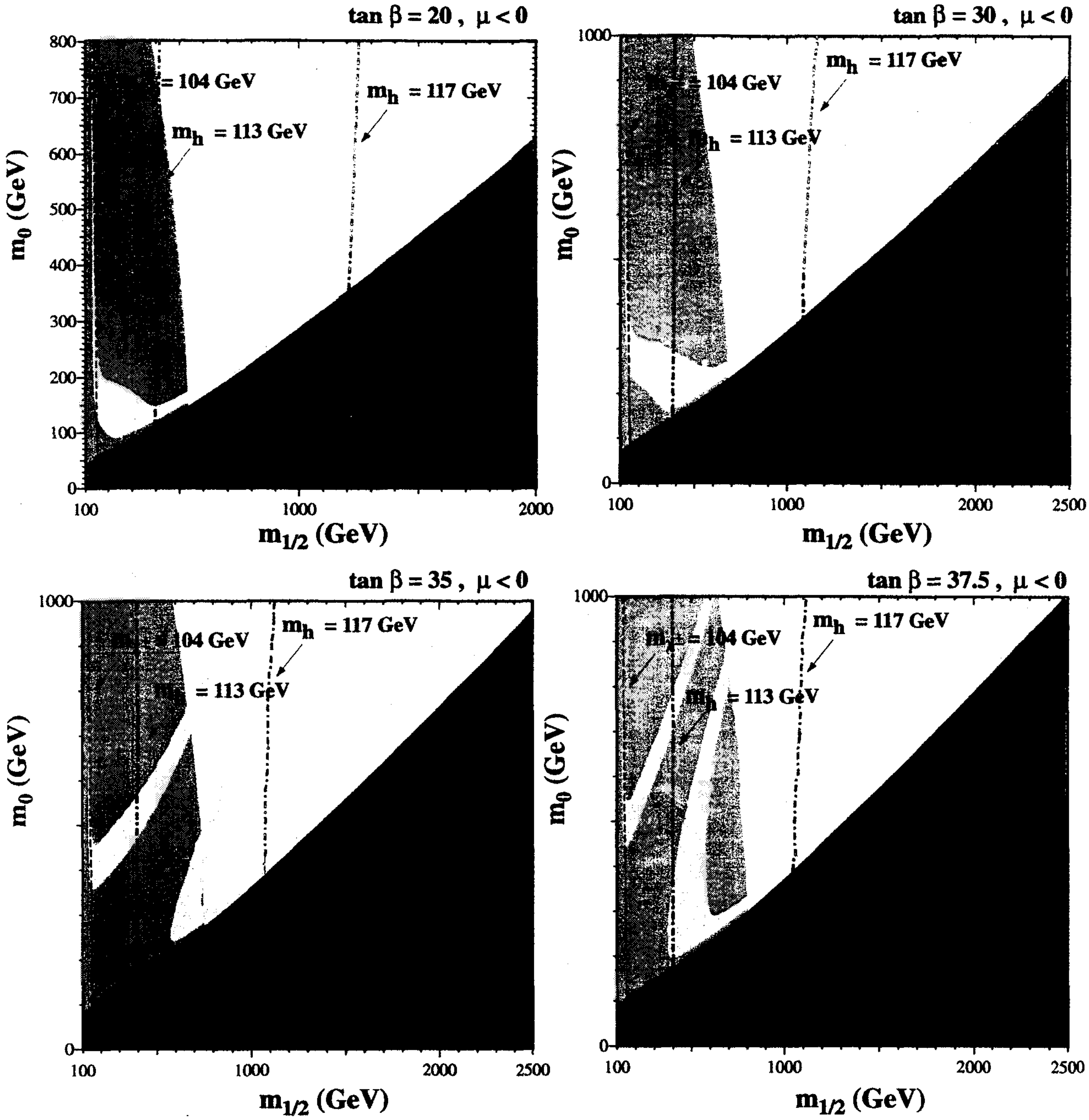


Figure 1: *The* $(m_{1/2}, m_0)$ *planes for* $\mu < 0$ *and* $\tan\beta =$ *(a) 20, (b) 30, (c) 35 and (d) 37.5, found assuming* $A_0 = 0, m_t = 175$ *GeV and* $m_b(m_b)^{\overline{MS}}_{SM} = 4.25$ *GeV. In this case, we find no large allowed region for* $\tan\beta \geq 40$*. The near-vertical are the contours* $m_{\chi^\pm} = 104$ *GeV (dashed),* $m_h = 113, 117$ *GeV (dot-dashed). The medium (dark green) shaded regions are excluded by* $b \to s\gamma$*. The light (light green) shaded areas are the cosmologically preferred regions with* $0.1 \leq \Omega_\chi h^2 \leq 0.3$*. Away from the pole, above (below) these light-shaded areas, the relic density* $\Omega_\chi h^2 > 0.3 (< 0.1)$*. In the dark (red) shaded regions, the LSP is the charged* $\tilde{\tau}_1$*, so this region is excluded. The diagonal channel of low relic densities visible for* $\tan\beta \geq 30$*, flanked on both sides by cosmologically preferred regions, is due to direct-channel annihilation via the* A, H *poles.*

Constraints at large tan β

- At large tan b, only significant region with cosmological dark matter is due to A,H pole annihilation regions.

- Upper limit to m_χ even further relaxed:
  - Previous limit of $m\chi < 600$

    now becomes $m\chi < 750$ for $\mu < 0$

    and $m\chi < 900$ GeV for $\mu > 0$

- No guarantees for LHC ☹

Have future accelerators been saved by g-2?

Ellis,

Nanopoulos, KO

- Results from Recent BNL E821

$$\delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM}$$
$$= 43 \pm 16 \times 10^{-10}$$

(does not really take into account theoretical uncertainties)

- Strong correlations between

  a_μ and μ

  $\mu > 0$ strongly favored.

  $\tan\beta \gtrsim 8$

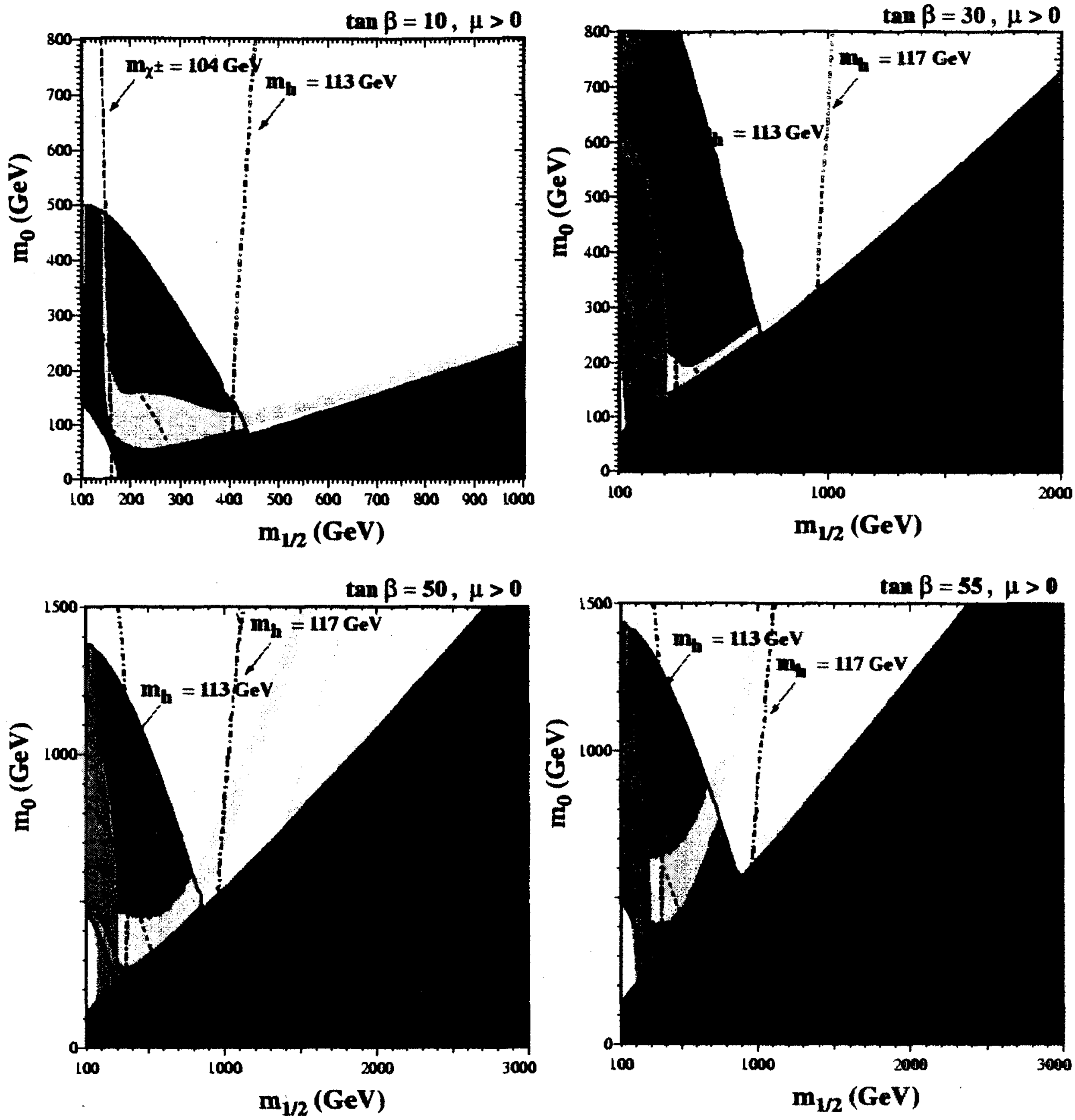


Figure 1: *The* $(m_{1/2}, m_0)$ *planes for* $\mu > 0$ *and* $\tan\beta =$ *(a) 10, (b) 30, (c) 50 and (d) 55, found assuming* $A_0 = 0, m_t = 175$ *GeV and* $m_b(m_b)^{\overline{MS}}_{SM} = 4.25$ *GeV. The near-vertical (red) dot-dashed lines are the contours* $m_h = 113, 117$ *GeV, and the near-vertical (black) dashed line in panel (a) is the contour* $m_{\chi^\pm} = 104$ *GeV. The medium (dark green) shaded regions are excluded by* $b \to s\gamma$*. The light (turquoise) shaded areas are the cosmologically preferred regions with* $0.1 \le \Omega_\chi h^2 \le 0.3$*. In the dark (brick red) shaded regions, the LSP is the charged* $\tilde{\tau}_1$*, so this region is excluded. The regions allowed by the E821 measurement of* a_μ *at the 2-σ level are shaded (pink) and bounded by solid black lines, with dashed lines indicating the 1-σ ranges.*

Direct Detection

Eastic scattering cross sections
for χ p

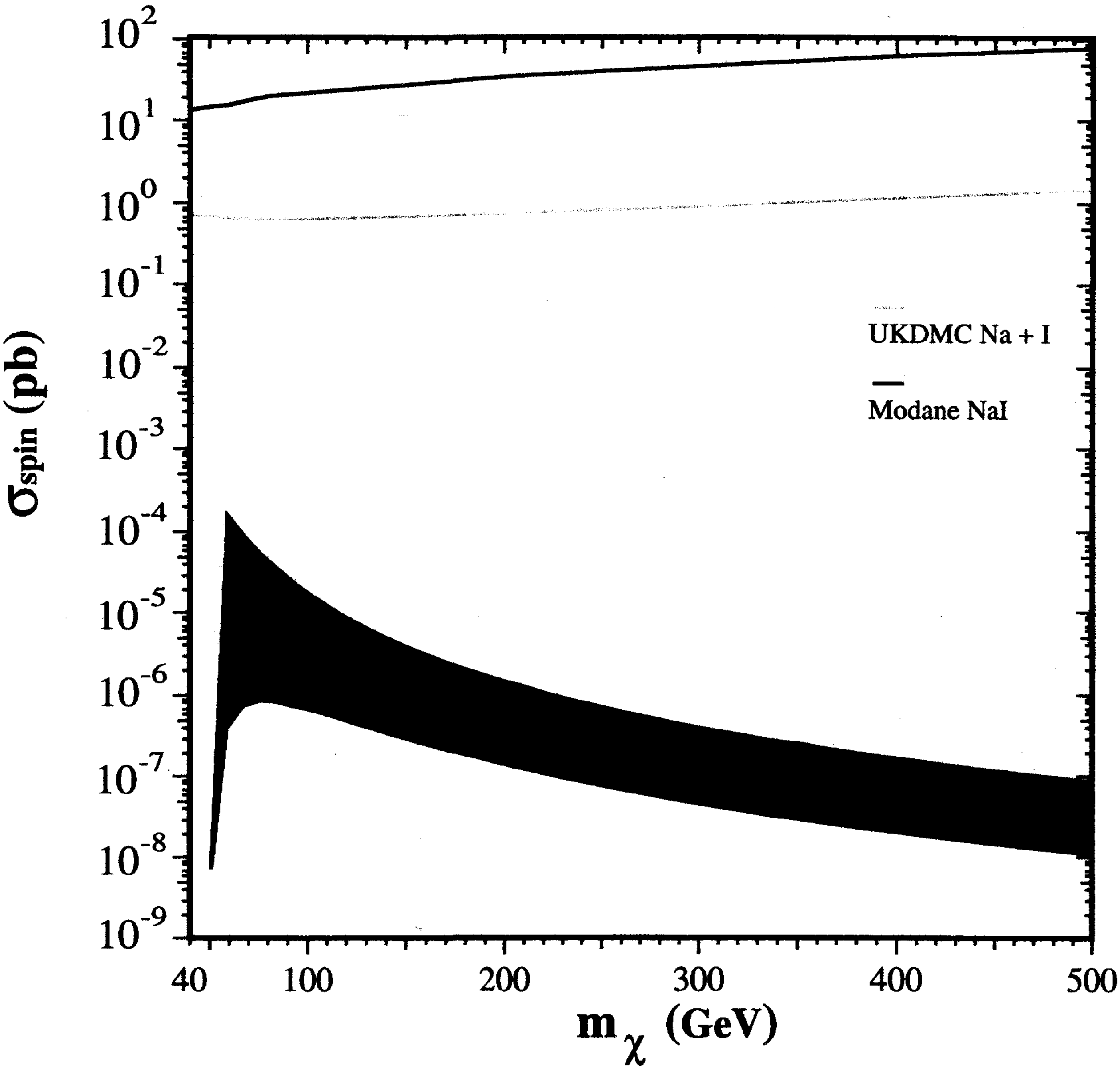
Use only parameters which satify
accelerator bounds and
relic denisty

Results: low cross sections

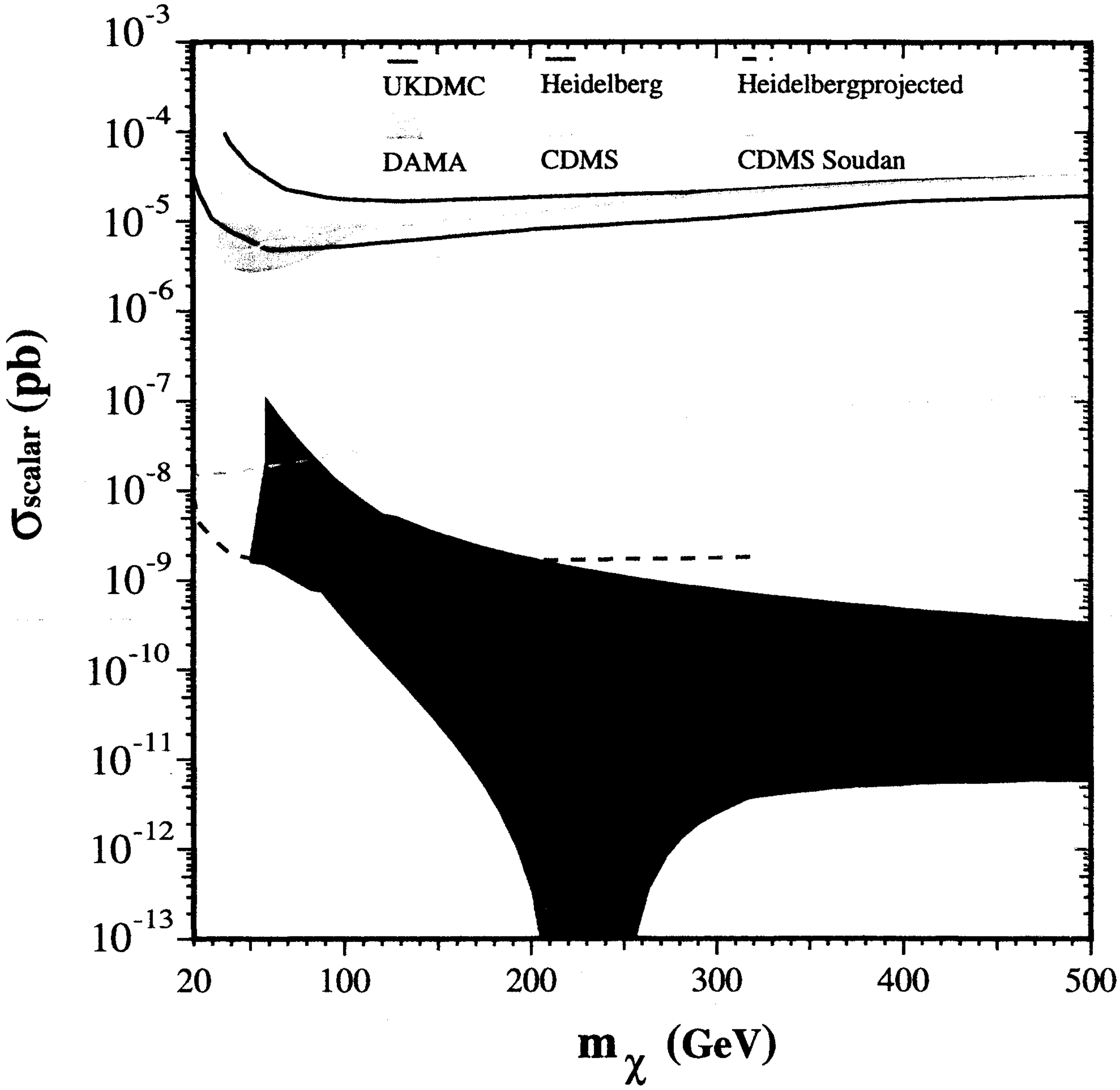
$< 10^{-3}$ pb spin

$< 10^{-7}$ pb scalar

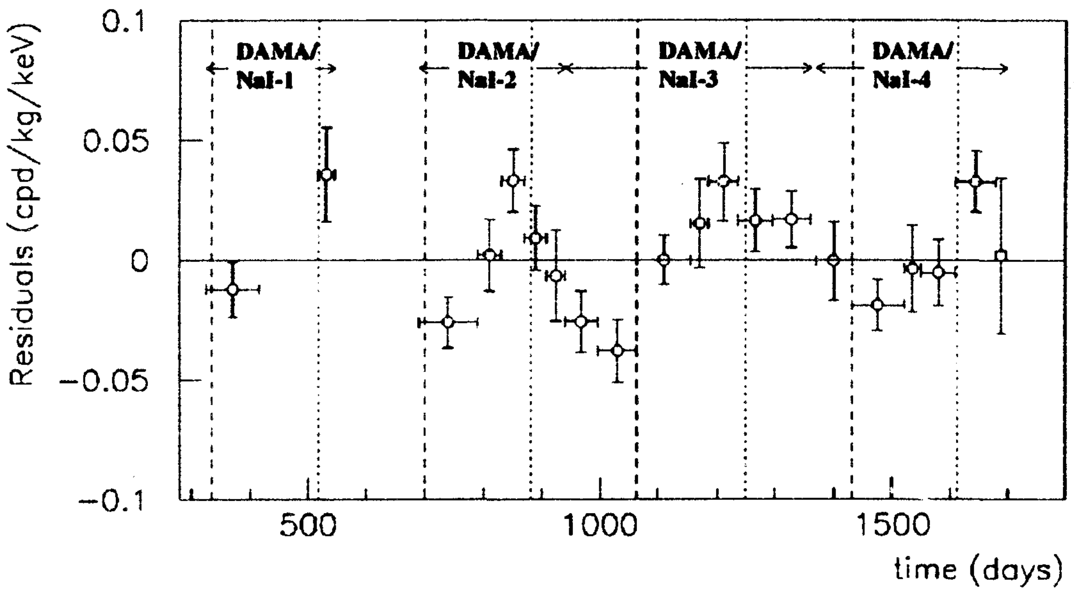
MSSM allows higher cross sections at higher m_χ



10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
σspin (pb)
UKDMC Na + I
Modane NaI
40
100
200
300
400
500
mχ (GeV)


UKDMC
Heidelberg
Heidelbergprojected
DAMA
CDMS
CDMS Soudan
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
σ_{scalar} (pb)
20
100
200
300
400
500
m_χ (GeV)

DAMA modulation plot



- **Live time of detector < total time**

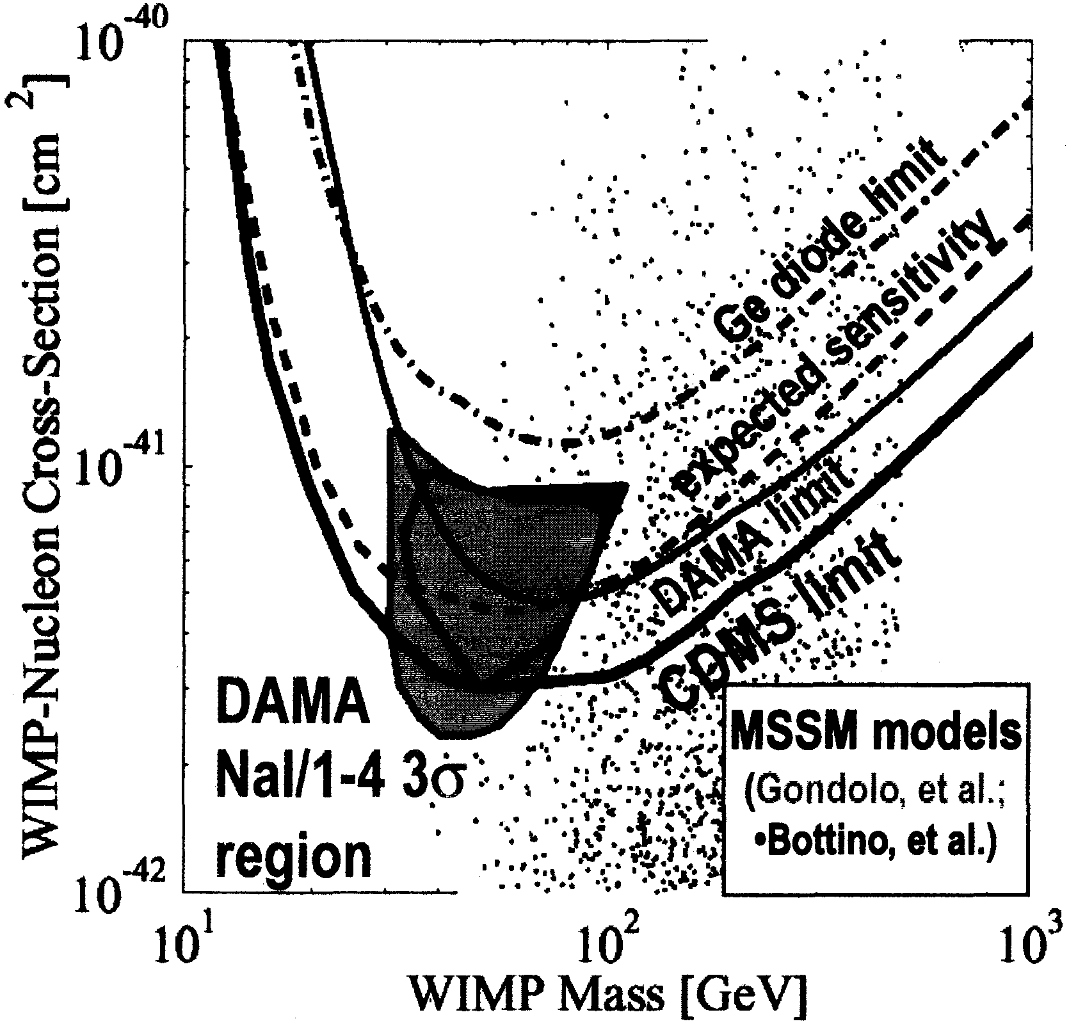
- Mass of detector = 9 * 9.7 = 87,3 kg
- NaI-3 08/97=>09/98 — 410 days tot time
 Statistics = 22 455 kg.d <=>257 days live
- NaI-4 10/98=>08/99 — 300 days tot time
 Statistics = 16 020 kg.d <=>183 days live

=> Acq/total = 62 %

- There are holes in the data taking not shown in the graph

- How was defined the varying binning of the data points ?

New CDMS Upper Limits



- CDMS excludes new parameter space and some MSSM models
- Because we see more multiples than expected (4 vs. 1), limits are 50% better than expected CDMS sensitivity (dashes)
- Bottom of DAMA NaI/1-2 2σ (~87%) region excluded at 89% CL
- Bottom of DAMA NaI/1-4 3σ (~99%) region excluded at 75% CL

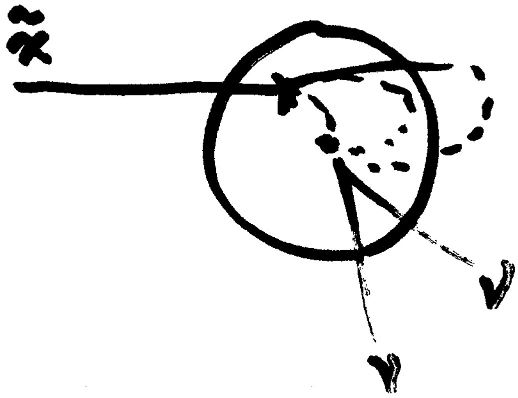
See http://dmtools.berkeley.edu/

Indirect Detection

| High Energy ν's from the Sun + Earth

Silk, KAO Srednicki

Krauss Srednicki Wilczek Freese



) e^+, $\bar{p}$, γ from the Galactic Halo

Silk Srednicki

$$\chi\chi \to X$$

above cosmic-ray, gamma ray background

FIGURES

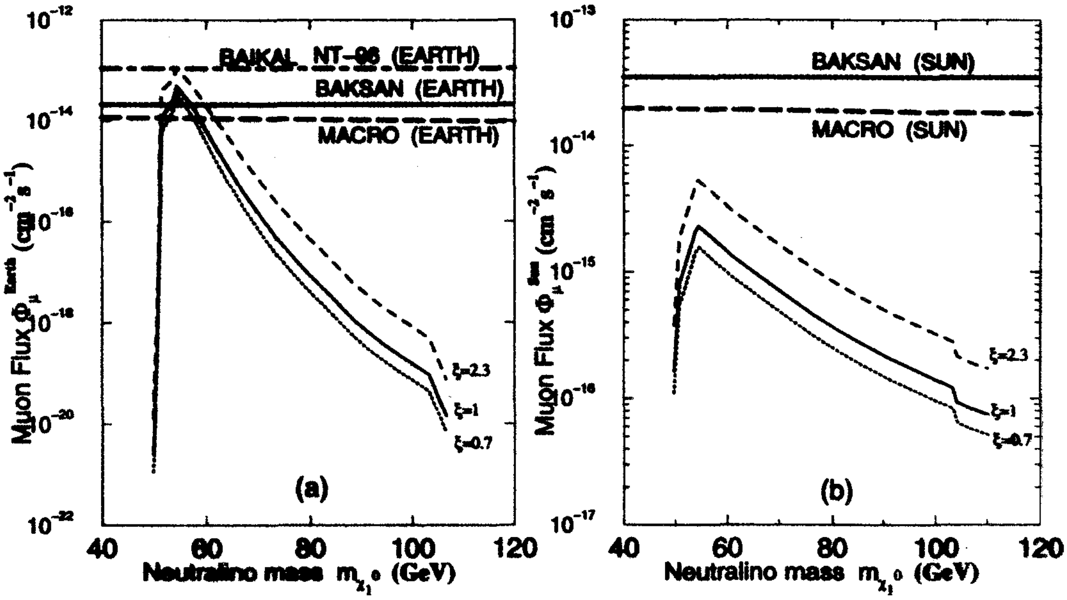


Fig. 1. (a): Plot of the maximum out-going muon flux for the Earth in mSUGRA as a function of the neutralino mass for three different values of the local wimp density corresponding to $\xi = 0.7, 1, 2.3$, and $\mu > 0$ (Our μ sign convention is as in Ref.[19]). The horizontal lines show limits from experiment; (b) Same as (a) except for the Sun.

Corsetti + Nath