NEUTRINO TELESCOPE
VENICE '99

DARK MATTER WITH A COSMOLOGICAL CONSTANT ?

A. MASIERO

SISSA - TRIESTE

'98
- $\Omega_{MATTER} < 1$
- $\Omega_0 \sim 1$
- $\Omega_\Lambda > 0$

IMPACT ON PARTICLE PHYSICS

THE DM PROBLEM

$\Omega = \rho/\rho_c$ $\quad$ $\rho_c = \frac{3H^2}{8\pi G_N} \simeq 10^{-29}\, g/cm^3$; $\quad$ $H = h\ 100$ Km/s Mpc

$0.4 < h < 0.9$

↳ '98 $h = 0.65 \pm 0.15$

* $\boxed{\Omega \geq 0.1}$ galactic rotation curves

* $\boxed{\Omega \gtrsim 0.2 - 0.3}$ clusters and superclusters

* $\boxed{\Omega_{LUMINOUS} < 0.01}$ total luminous mass density

* $0.01 \leq \Omega_{baryons} h^2 \leq 0.015$ $\quad$ from nucleosynthesis

⇓

$\boxed{0.01 < \Omega_{baryons} < 0.1}$

↙ $\exists$ baryonic DM (Machos ...) $\quad$ ↘ $\exists$ <u>NON</u>-BARYONIC DM

* $\boxed{\Omega = 1}$ favoured by { INFLATION / "NATURALNESS" arguments

* $\boxed{\Omega h^2 \leq 1}$ ($\tau_{univ} > 10^{10}$ yrs.)

Ω_{Baryon}

BBN: D, ^{3}He, ^{4}He, ^{7}Li

↓

$$0.007 < \Omega_B h^2 < 0.024$$

(Copi et al. '95)

D best "baryometer"

↳ density $\propto \rho_B^{-1.7}$

D/H { ~ 10^{-5} low-D; ~ 3×10^{-4} high-D }

in (1998) Burles and Tytler

$$D/H = (3.4 \pm 0.3) \cdot 10^{-5}$$

↓

$$* \; \Omega_B h^2 = 0.02 \pm 0.002 \; *$$

→ independent determination from CBR (height of 1st peak) consistent with Burles and Tytler

Ω_{Matter}

total density of matter from baryon fraction in rich clusters → "fair sample" of matter in the Universe (density perturb. of size ~ 10 Mpc)

$$\rho_B^{cluster} : \rho_M^{cluster} = \rho_B^{Univ} : \rho_M^{Univ}$$

↓

$$\Omega_M = \Omega_B / f_B$$

↳ ρ_B/ρ_M in clust[ers]

↓ from motion of galaxies + virial th. or grav. lensing

↓ B in intracluste[r] gas → measure x-ray flux from gas

$$\Omega_M = (0.3 \pm 0.05) h^{-1/2}$$

Mohr et al (98)
Carlstrom (99)

↓

$$* \; \Omega_M = 0.4 \pm 0.1 \; *$$

consistent with other (more disputable) methods

WHAT IS THE DM MADE OF ?

Ω →
- Ω_{MATTER} at least 0.3
- Ω_{Λ} Λ cosm. const.

$\Omega_\gamma h^2 = 2.48 \times 10^{-5}$ with $m_\nu = 0$ $\Omega_\nu = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \Omega_\gamma$

SM : relics γ, ν, baryons $\Omega_{SM} < 0.1$

$\Omega_B < 0.1$

⇓

NON-BARYONIC DM

CALLS FOR **NEW** PHYSICS BEYOND SM

DM RELIC PARTICLES

- THERMAL
  - **HOT**
    $m \ll T_{decoupl}$
    relativistic at time structure formation [illegible]
  - **COLD**
    $m \gg T_{decoupl.}$
    non relativistic when galaxies start forming
- NON-THERMAL (ex. axions)

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⇓

NON-BARYONIC DM

CALLS FOR <u>NEW</u> <u>PHYSICS</u>

BEYOND SM

DM RELIC PARTICLES

- THERMAL
  - **HOT**: $m \ll T_{decoupl}$ relativistic at time structure formation starts
  - **COLD**: $m \gg T_{decoupl.}$ non relativistic when galaxies start forming
- NON-THERMAL (ex. axions)

$$\Omega_0 = \Omega_M + \Omega_\Lambda$$

Ω_0 ↓ BEST DETERMINATION FROM ANISOTROPY OF **CBR**

Ω_M ↓ 0.4 ± 0.1 (baryon fraction method)

Ω_Λ ?

at last scattering Baryons coupled to γ: B fall into DM potential wells → γ pressure acts as a restoring force → gravity-driven acoustic oscillations

↳ Fourier modes with $k \sim \ell \frac{H_0}{2}$

➡ SERIES OF ACOUSTIC PEAKS STARTING AT $\ell \sim 200$

POSITION OF THE FIRST PEAK $\ell \simeq \frac{200}{\sqrt{\Omega_0}}$

⬇

CBR → $\Omega_0 = 1 \pm 0.2$?

Lineweaver '98

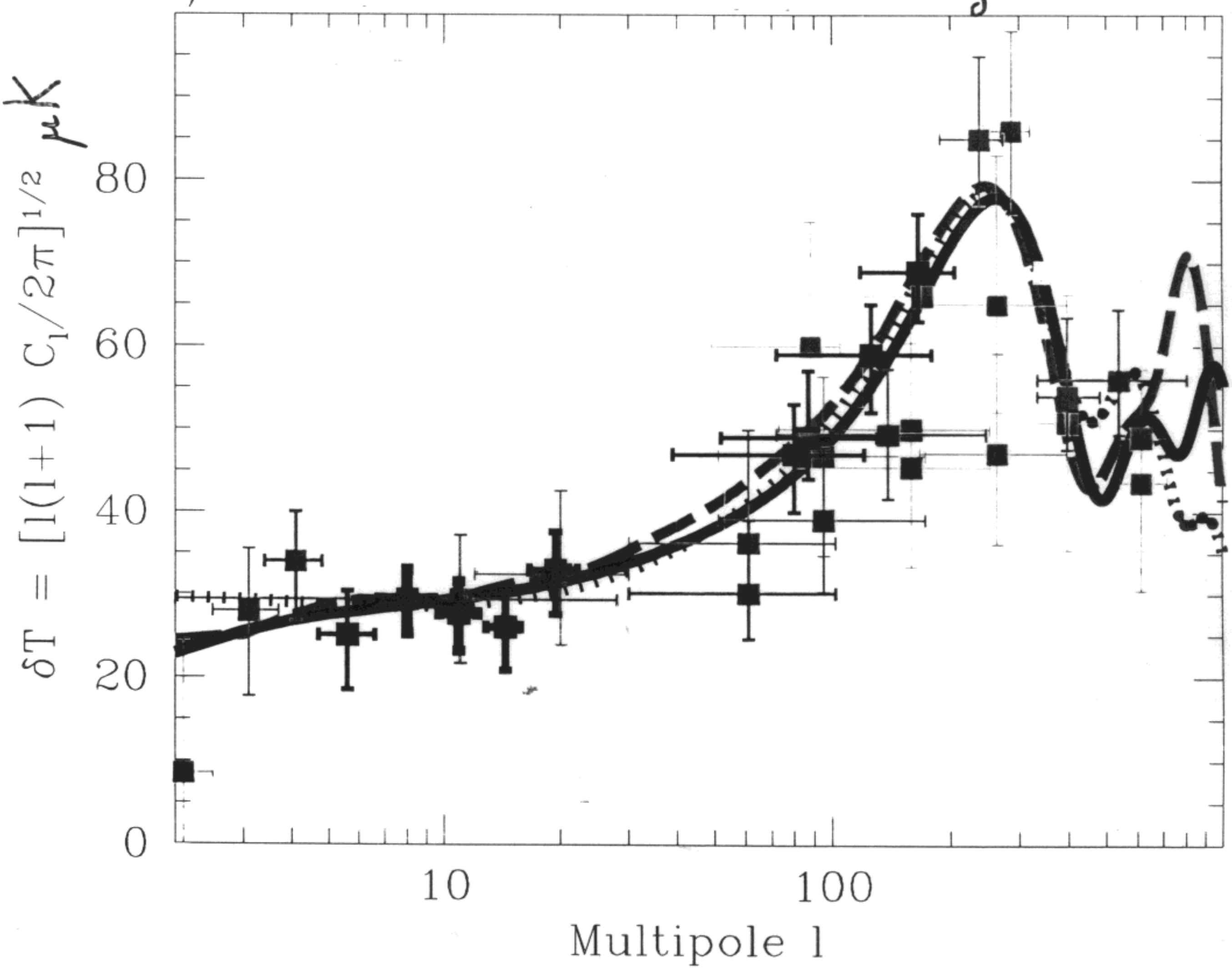
position of the 1st peak is insensitive to the composition of Ω_M and Ω_Λ, only to their sum

COBE MOST PRECISE COVERS MULTIPOLE $\ell \sim 2-20$

OTHER MEASUREMENTS FROM BALLOON-BORNE, ANTARCTICA-BASED, GROUND-BASED EXPTS.

USING LOW-FREQUENCY ($f < 100$ GHz) and HIGH-FREQUENCY ($f > 100$ GHz)

Tegmark '98



SATELLITES { MAP (NASA) late 2000
PLANCK (ESA) 2007 }

resolution ~ 30 times better than COBE (~0.1°)

map entire CBR sky

Tegmark astro-ph/9809201
from CMB data

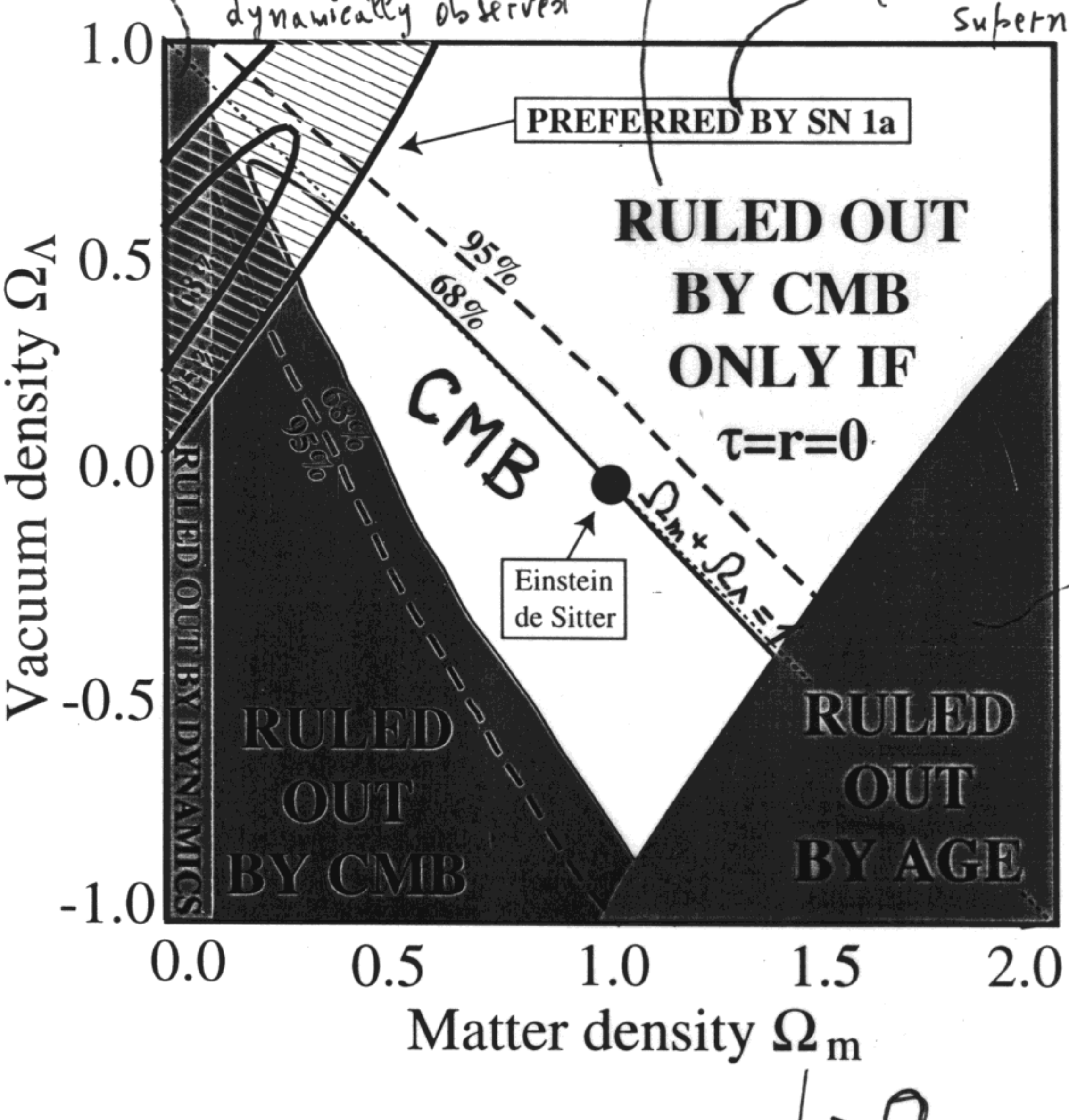
Lineweaver '98 + QMAP

τ optical depth from reionisation

$r \rightarrow$ gravity-wave (tensor) fluctuations

$\Omega_m < 0.1$ inconsistent with amount of matter dynamically observed

from White '98 (combined data of the two supernova teams)



$H_0 t_0 > 0.6$ as a lower limit

$\hookrightarrow \Omega_m = \Omega_{CDM} + \Omega_B$

FROM OBSERVATIONS

$\Omega_M \sim 0.4$

$\Omega_0 = \Omega_M + \Omega_\Lambda \simeq 1$

$\exists$ of DARK, EXOTIC FORM OF ENERGY SMOOTHLY DISTRIBUTED (UNCLUSTERED)

$\Downarrow$

$$\Omega_\Lambda \neq 0 \quad \text{with} \quad \Omega_\Lambda \sim 0.6$$

$\Downarrow$

IS IT POSSIBLE TO TEST IT ?

$\Rightarrow$ main signature :

ACCELERATING (instead of de-accelerating) UNIVERSE

try to measure q_0

$$R^2_{curv} = \frac{H_0^{-2}}{\Omega_0 - 1} \quad ; \quad q_0 \equiv -\frac{(\ddot{R}/R)_0}{H_0^2} = \frac{1}{2}\Omega_0 + \frac{3}{2}\Omega_i w$$

$p_i = w_i \rho_i$ ($w_i = 0$ baryons ; $w_i = 1/3$ rad ; $w_i = -1$ cosm. cons

Ω_Λ

TO AVOID INTERFERING WITH STRUCTURE FORMATION

(UNIVERSE MUST HAVE BEEN MATTER-DOMINATED FROM THE EPOCH OF MATTER-RADIATION EQUALITY UNTIL VERY RECENTLY) $\Rightarrow$ Λ form of energy must be less important in the past than it is today

eq. of state: $p_\Lambda = w_\Lambda \rho_\Lambda \Rightarrow \rho_\Lambda \propto R^{-n}$

$$n = 3(1 + w_\Lambda)$$

to be less important in the past $\Rightarrow n < 3$, i.e. $w_\Lambda < 0$

ex.: cosmological const. $w_\Lambda = -1$

bonus: $H_0 t_0 \uparrow$ with $w \downarrow$ $\Rightarrow$ older Univ. for a given h_0 (no "age crisis")

$$q_0 = \frac{1}{2}\Omega_M - \Omega_\Lambda \sim -0.4$$

(from obs. values of Ω_M and Ω_Λ)

$\Downarrow$

EVIDENCE FOR THIS "SMOKING GUN" FROM SNe Ia

MEASURING q_0

Expansion of the Universe is just a conformal scaling up of all distances:

$$v = H_0 d \quad \text{(Hubble Law)}$$

⇒ if the distances and velocities to distant galaxies were all measured at the present then they would obey $v = H_0 d$

but we see distant galaxies at an earlier time

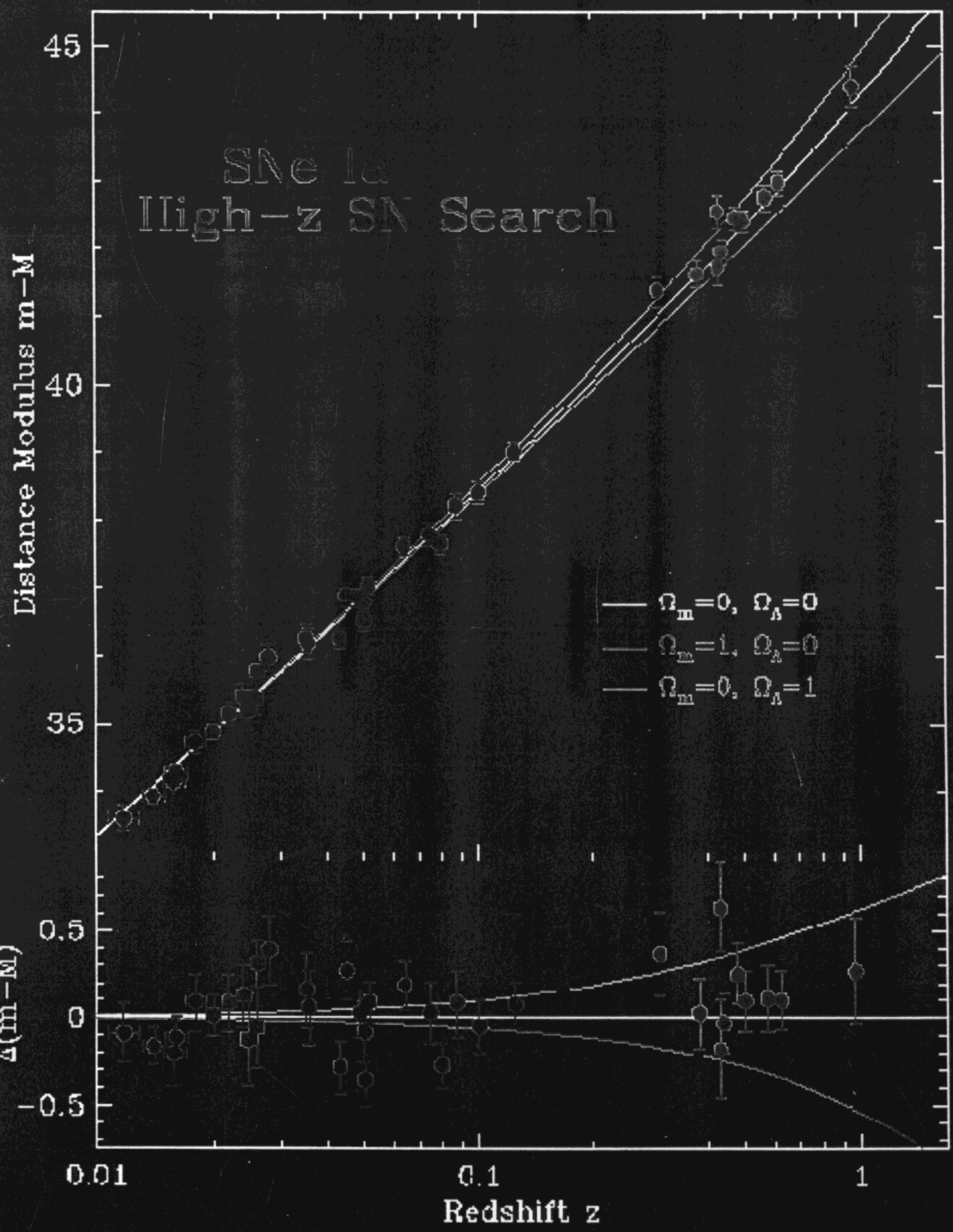
and so
- ⇒ if the expansion is SLOWING their velocity should be ABOVE the Hubble-law prediction
- ⇒ if the expansion is SPEEDING UP their velocity should fall BELOW the Hubble-law prediction

↓

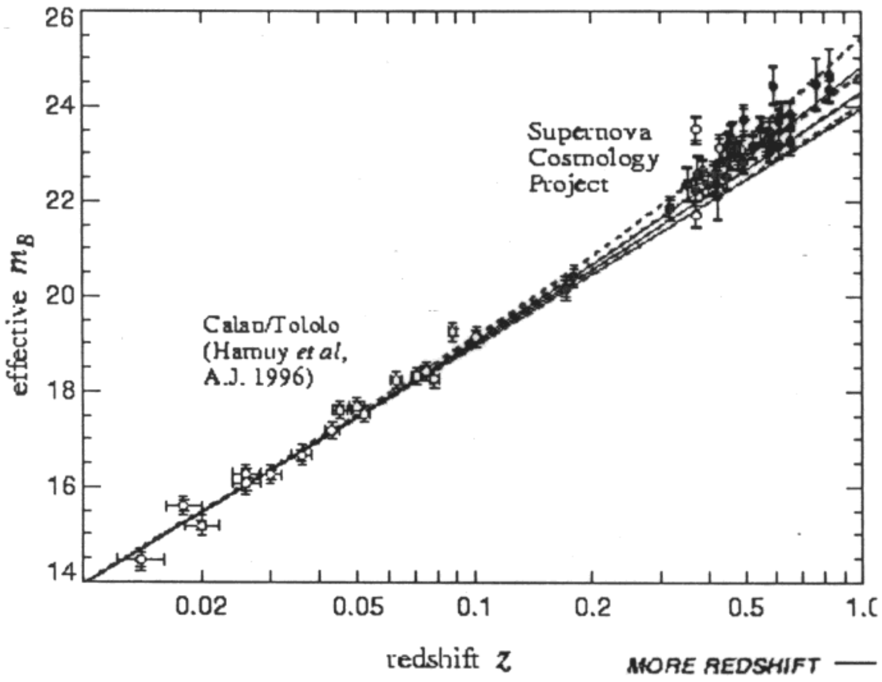
magnitude-redshift Hubble diagram for ~ 50 SNe Ia out to z of nearly 1

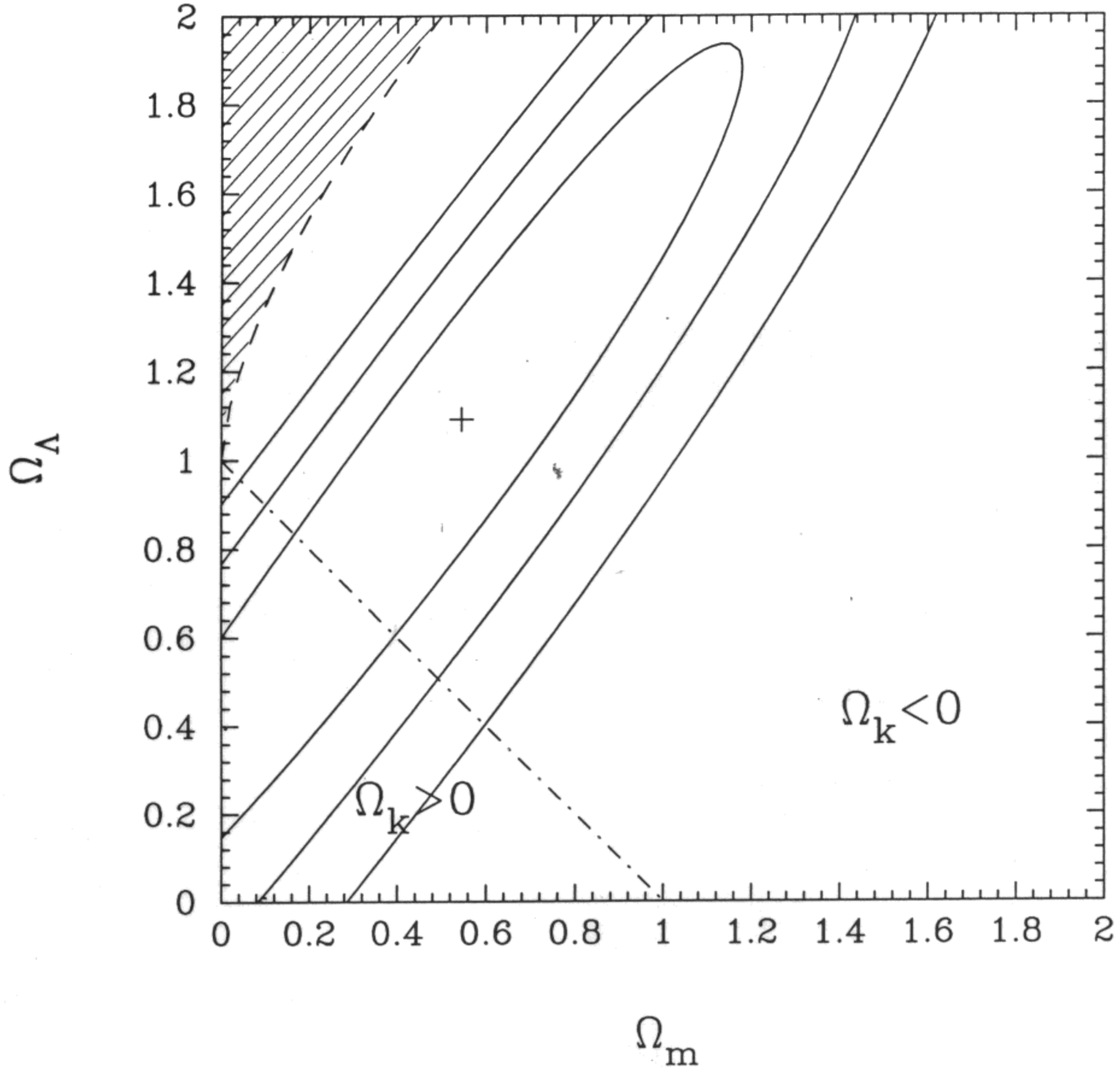
this is what was found by the

two groups
- SUPERNOVA COSMOLOGY PROJECT
- HIGH-Z SUPERNOVA SEARCH

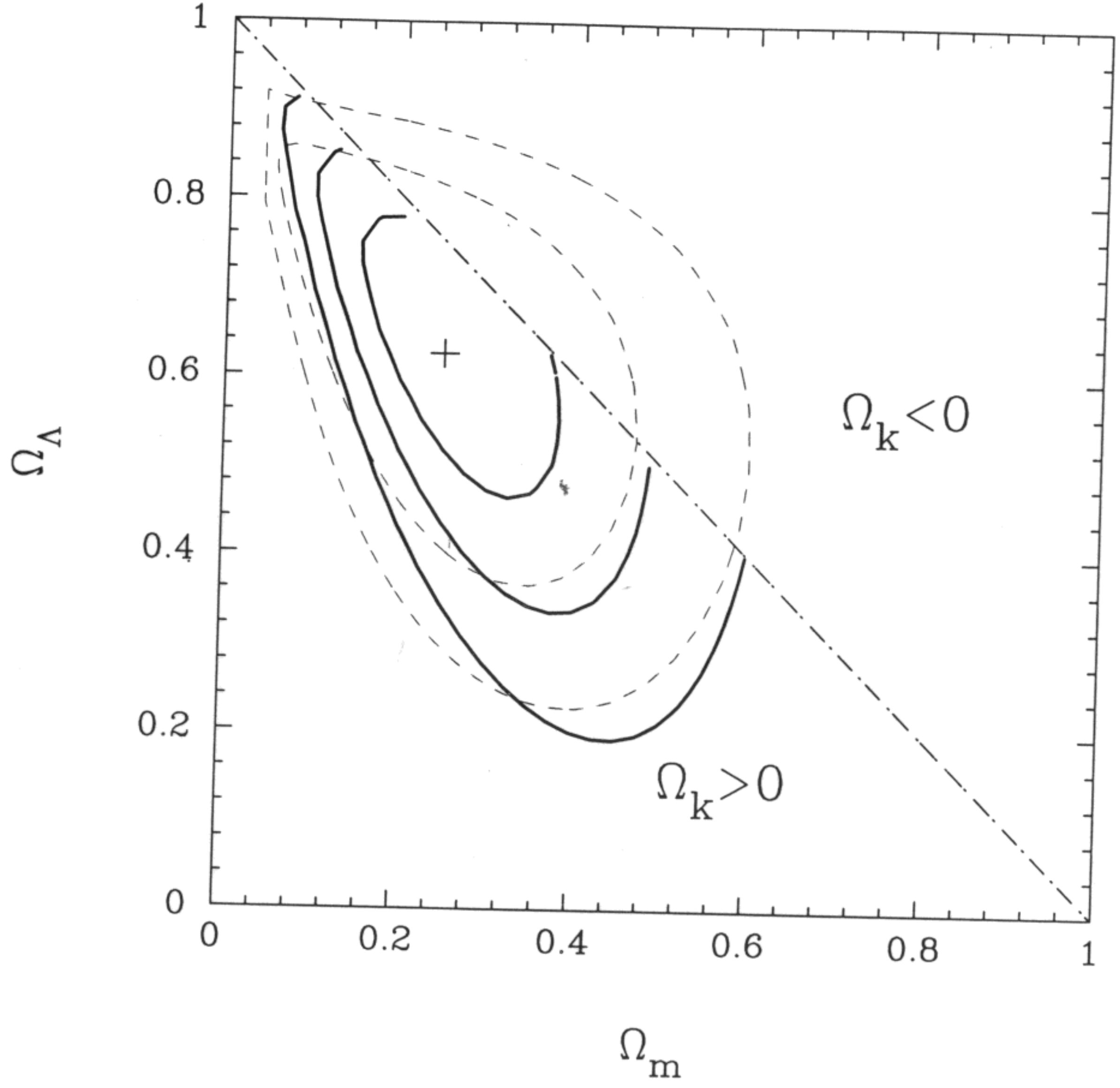


SNe Ia
High-z SN Search
45
40
35
Distance Modulus m-M
$\Omega_m=0,\ \Omega_\Lambda=0$
$\Omega_m=1,\ \Omega_\Lambda=0$
$\Omega_m=0,\ \Omega_\Lambda=1$
0.5
0
-0.5
Δ(m-M)
0.01
0.1
1
Redshift z


Supernova
Cosmology
Project
Calan/Tololo
(Hamuy et al,
A.J. 1996)
effective m_B
26
24
22
20
18
16
14
0.02
0.05
0.1
0.2
0.5
1.0
redshift z
MORE REDSHIFT



Ω_Λ
Ω_m
$\Omega_k>0$
$\Omega_k<0$
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2



1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
Ω_Λ
Ω_m
Ω_k<0
Ω_k>0

Now STAT. ERRORS $<$ possible SYST. ERRORS

QUESTION: HOW RELIABLE IS IT TO TAKE SNe Ia AS ONE-PARAMETER STANDARD CANDLES ?

SNe Ia from nuclear detonation of Chandrasekhar mass white dwarfs: ONE PARAMETER IS THE RATE OF DECLINE OF THE LIGHT CURVE (the brigther ones decline more slowsly – Phillips relation $\Rightarrow$ empirical eviden that there is a relationship peak brightness $\leftrightarrow$ rate of decline)

QUESTION: DISTANT SAMPLE OF SNe Ia SIMILAR TO THE NEARBY SAMPLE ?

several tests say yes: for instance the distribution of decline rates and dispersion about the Phillips relationship

TURNER astro-ph/9811454

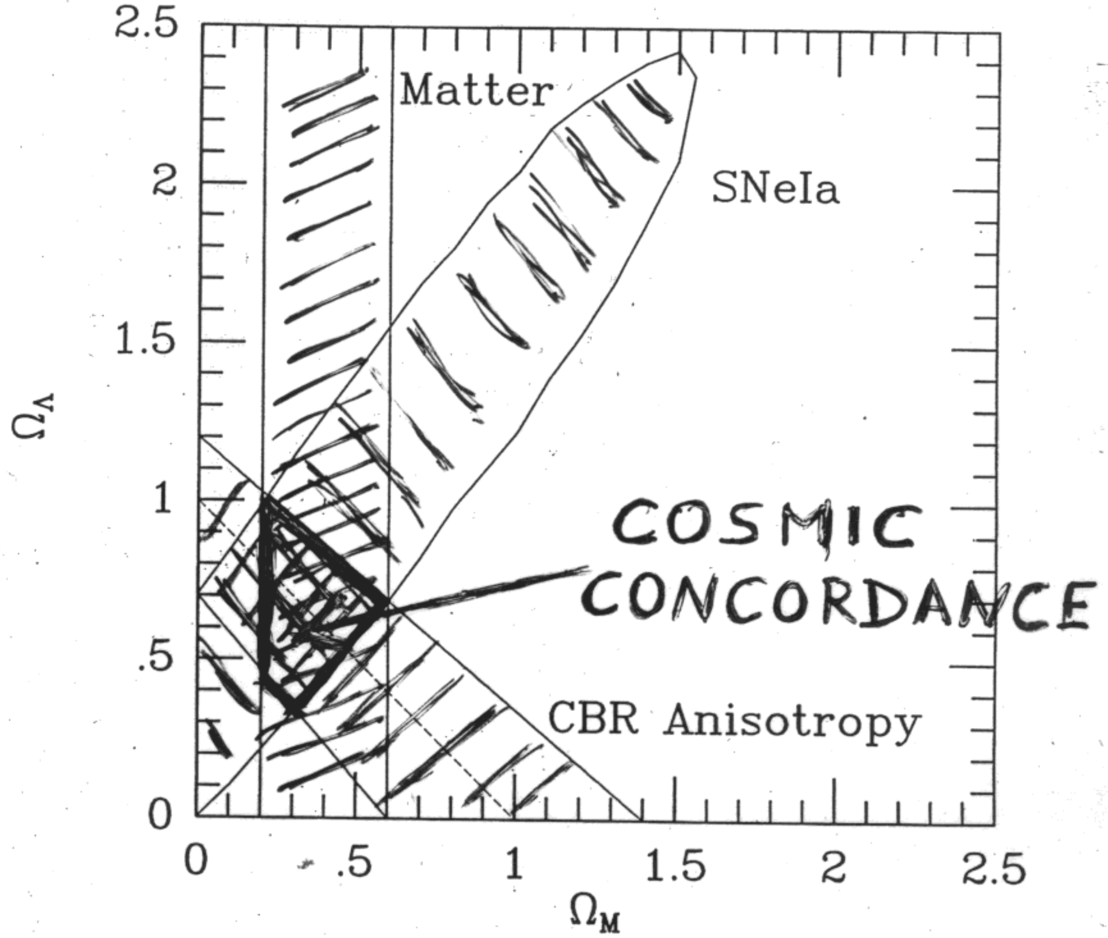


Figure 6. Constraints to Ω_M and Ω_Λ from CBR anisotropy, SNeIa, and measurements of clustered matter. Lines of constant Ω_0 are diagonal, with a flat Universe shown by the broken line. The concordance region is shown in bold: $\Omega_M \sim 1/3$, $\Omega_\Lambda \sim 2/3$, and $\Omega_0 \sim 1$. (Particle physicists who rotate the figure by 90° will recognize the similarity to the convergence of the gauge coupling constants.)

CONCORDANCE REGION

$$\Omega_M \simeq \frac{1}{3} \quad \Omega_\Lambda \simeq \frac{2}{3}$$

STRUCTURE FORMATION

DM

AMOUNT AND NATURE OF THE MATERIAL IN THE UNIVERSE

$\Omega_i = \rho_i / \rho_{crit}$

COLD, HOT, WARM

SEED OF DENSITY FLUCTUATIONS

INITIAL SPECTRUM OF ρ FLUCTUATIONS

⇓

INFLATION OR TOPOLOGICAL DEFECT

→ SCALE INVAR. FLUCTUATION SPECTRUM

⇓

EVOLUTION UNDER GRAVITY

→ EXP. INPUT: COBE, GALAXY DISTRIBUTIONS, PECULIAR VELOC.

→ TH. INPUT: GROWTH OF $\delta\rho/\rho$ (dependence on the nature of DM)

THE STANDARD COLD DARK MATTER (CDM) MODEL

$\Omega = 1$; $\Omega_{CDM} \sim 90-95\%$

$\Omega_B \sim 5-10\%$; $\Omega_{\gamma,\nu} < 1\%$

seed fluctuations are generated during inflation and with a scale-invariant spectrum

$\lambda_{EQ} \simeq 30\,(\Omega h^2)^{-1}$ Mpc

PROBLEM: with the normalization fixed at COBE data

⇒ THE STANDARD CDM MODEL PREDICTS MORE POWER AT SMALL SCALES THAN OBSERVED (see fig.)

(λ_{EQ} relatively small)

BEYOND STANDARD CDM

- CHANGE THE DM CONTENT

- ADDITION OF A HOT COMPONENT (e.g. neutrino(s) of few eV's) → **MIXED DM**

$$\Omega_{CDM} \sim 70\text{-}80\% \quad \Omega_{HDM} \sim 20\text{-}30\%$$

(Shafi-Stecker '84; Bonometto-Valdarnini '85; Achilli et al.'85; Taylor-Rowan-Robinson '92; Holtzman-Primack '92; Yu-Starobinski '95)

- REPLACEMENT OF COLD DM with WARM DM (Colombi, Dodelson, Widrow '96; Borgani, A.M., Yamaguchi '96; Kawasaki, Sugiyama, Yanagida '97; Pierpaoli, Borgani, A.M., Yamaguchi '9

- CDM + VOLATILE COMPONENT ($\lambda_{EQ} \rightarrow$) (Kim and Kim; Bonometto, Pierpaoli)

- CHANGE THE FRIEDMAN BACKGROUND

- $\Omega_{0\,matter} < 1$, either with or without a cosmological constant term $\Omega_\Lambda = 1 - \Omega_{0\,matter}$

- by decreasing the Hubble parameter to $h \simeq 0.3$

- MODIFY THE NATURE OF THE PRIMORDIAL FLUCT.

- by changing the spectrum shape $P(k) \propto K^n$ $n < 1$
- by resorting to non-Gaussian fluctuations: string, textures, ...

- SHIFT OF THE EQUIVALENCE SCALE

$\Rightarrow$ DELAY THE MOMENT MATTER STARTS DOMINATING OVER RADIATION

(reason: during radiation domination superhorizon fluctuations can grow, while subhorizon ones cannot $\Rightarrow$ if we delay matter domination, i.e. we increase the horizon length at equivalence λ_{eq}, the small (subhorizon) modes are kept "frozen" by a sort of "radiation pressure"

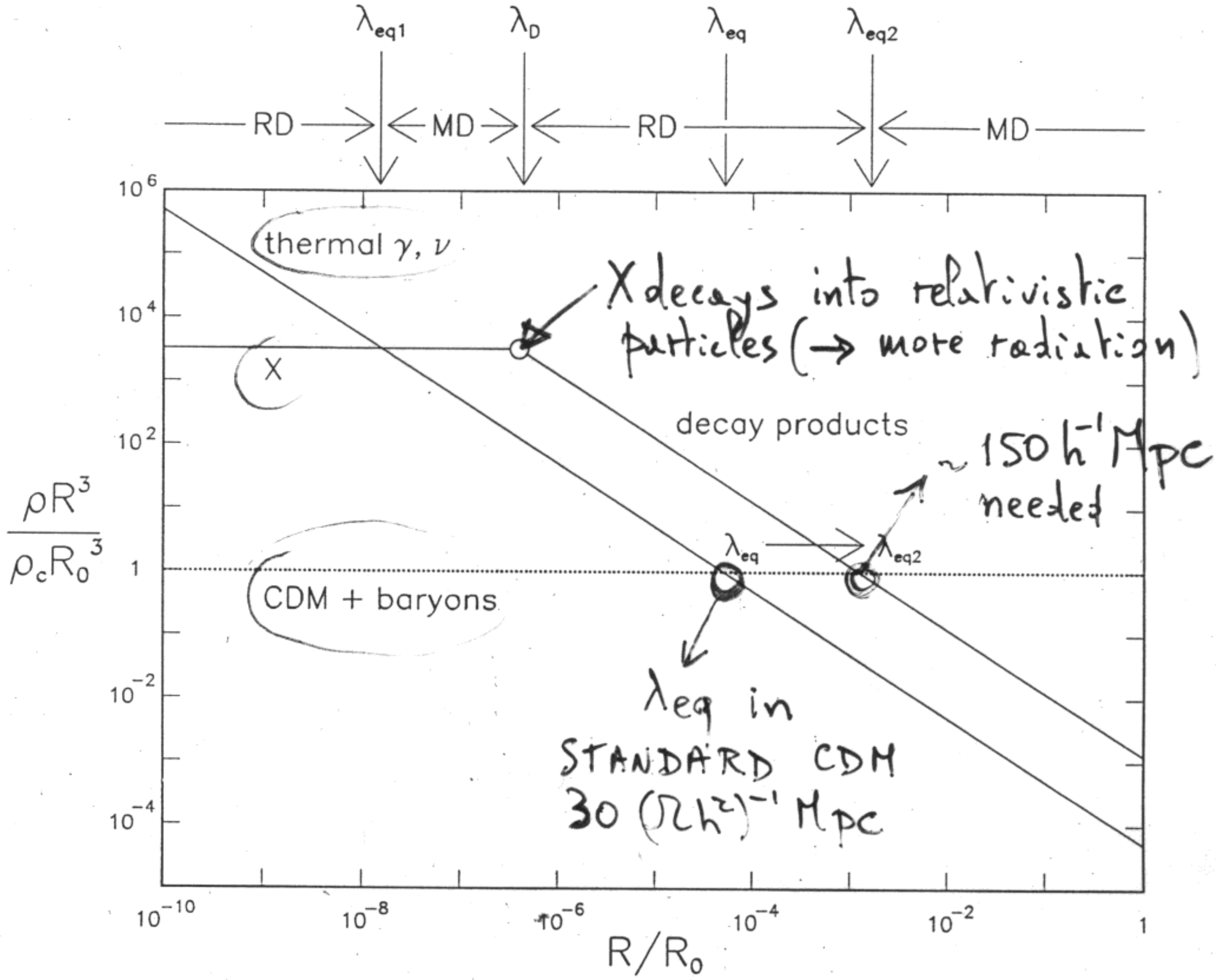
$$\lambda_{eq}^{\text{STANDARD CDH}} \simeq 30\,(\Omega h^2)^{-1}\ \text{Mpc} \qquad (\Omega \to 1)$$

$\Downarrow$ need   Bond, Efstathiou

$$\lambda_{eq} \simeq 150\, h^{-1}\ \text{Mpc}$$

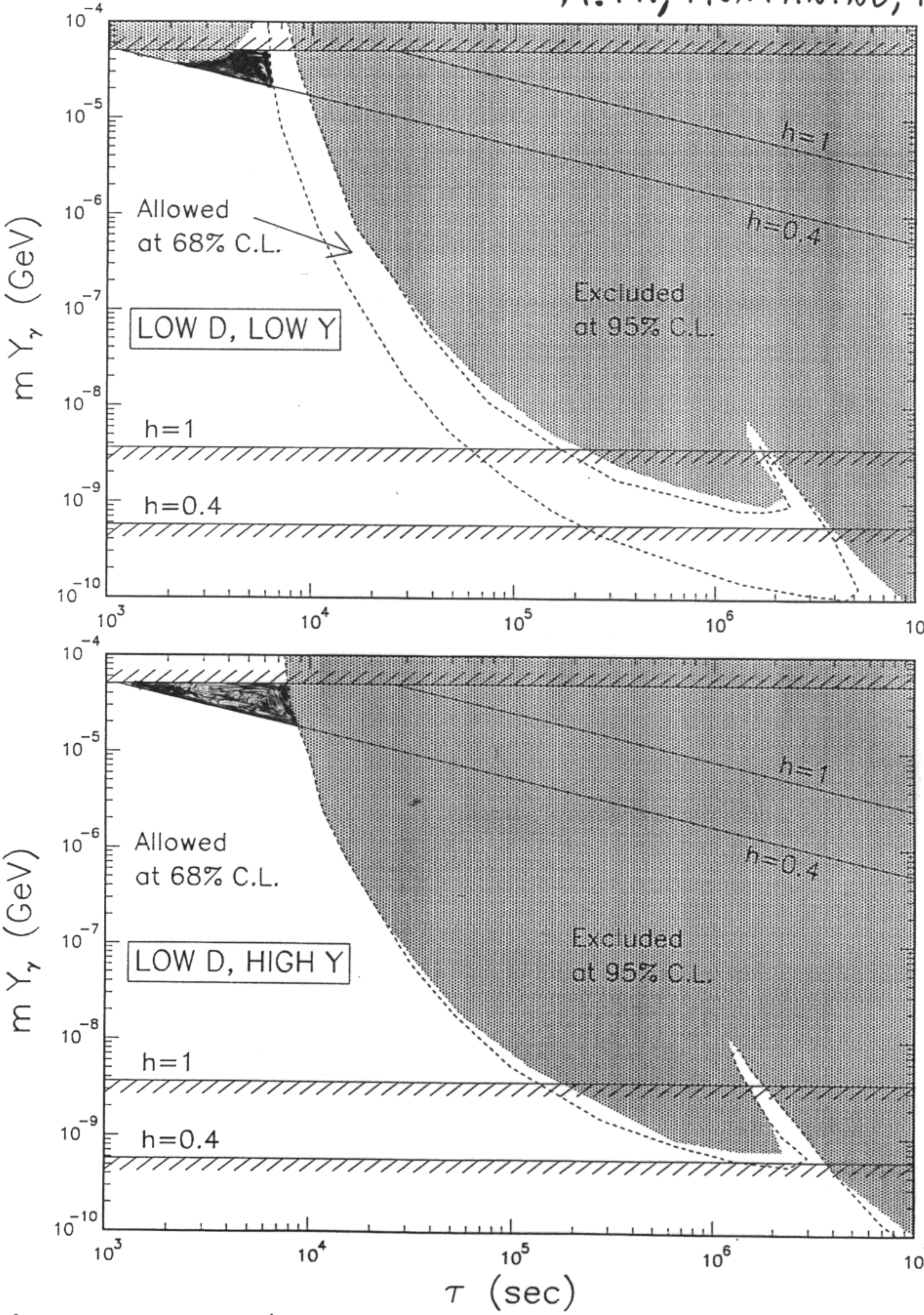
Delay of matter domination may be accomplished by UNSTABLE MATTER DECAYING INTO RELATIV. PART. (Radiation)   KIM & KIM

KIM & KIM NP B433 (1995)



SEVERE ASTROPH. AND COSM. CONSTRAINTS ON RADIATIVE DECAYS

A. M., MONTANINO, PELOSO



⇒ other possibility : decays without γ or charged part. in the decay products (ex : $\nu \to \nu' +$ majoron)

BEST "THERMAL" CDM CANDIDATES ⇒ **WIMPS**

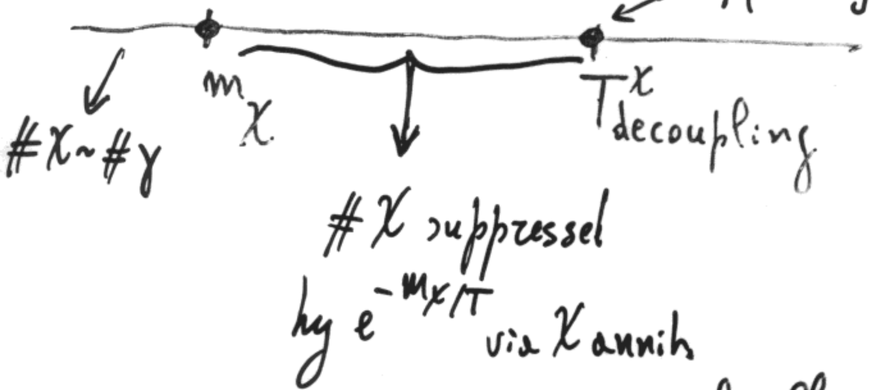
(weakly interacting part.)

↓ particles at one time in thermal equilibrium

(best "non-thermal" CDM candidates : axions, superheavy relic part.)

Chung, Kolb, Riotto ; Ellis, Nanopoulos et al.

typically $T_{decoupl.} \sim \left(\frac{1}{20 \div 30}\right) m_\chi$



↖ $\#\chi$ does not change any more

$\rho_\chi = m_\chi n_\chi$

↳ $\propto \frac{1}{\sigma_{annih}(\chi\chi \to ...}$

Goldberg ; Ellis, Hagelin, Nanopoulos, Olive, Srednicki ; Roszkowski

$$\frac{n_\chi}{\boxed{T_0^3}} \sim \frac{n_\chi(T_{decoupl.})}{T^3_{decoupl}}$$

$T_{decoupl.}$ determined by : $n_\chi(T_{dec}) < \sigma_{ann}(\chi\chi)\, v_\chi > \sim \frac{T^2_{decoupl}}{M_{Planck}}$

Ω_χ depends on particle physics (σ_{annih}) + T_0 + M_{Planck}

$$\Omega_\chi h^2 \simeq \frac{10^{-3}}{\underbrace{<\sigma_{annih}(\chi\chi)\, v_\chi>}_{\sim\, \alpha^2/M_\chi^2} \; \text{TeV}^2}$$

⟶ TeV from $\sqrt{T_0 \cdot M_{Planck}}$

$\Rightarrow \Omega_\chi h^2 < 1 \Rightarrow m_\chi < 1\,\text{TeV}$ $m_\chi \sim 10^2 - 10^3\,\text{GeV}$ $\Omega_\chi h^2 \sim 10^{-2} - 10$!!!

WIMP CANDIDATES

* HEAVY NEUTRINOS of few GeV's $\Omega_\nu h_0^2 \sim 3 \left(\frac{GeV}{m_\nu}\right)$

but $Z \to \nu \bar{\nu}$ if this heavy neutrino couples to Z with the usual $Z-\nu-\nu$ coupling

$\Rightarrow m_{\nu_{heavy}} > m_Z/2$ very low Ω $\left(\Omega_0 h_0^2 \lesssim 10^{-3}\right)$

if the $SU(2)$ doublet heavy ν mixes with some "sterile" $SU(2) \times U(1)$ singlet $\Rightarrow$ reduction of $Z-\nu_{heavy}$ coupling but cumbersome schemes

* **Best WIMP: LIGHTEST SUSY PARTICLE IN SUSY SCHEMES WHERE A DISCRE SYMM. R-PARITY DISCRIMINATE ORDINARY FROM SUPER- PARTICLES**

ν as HDM

- consider $m_\nu < 1$ MeV and ν stable
  $\downarrow$ it decouples when still relativistic

if $m_\nu < 1e^{-4}$ eV $\rightarrow$ ν still relativistic today

if $m_\nu > 1e^{-4}$ eV $\rightarrow$ $\rho_\nu = m_\nu n_\nu$

- n_ν determined by $T^\nu_{decoupling}$
  $\rightarrow$ weak interactions

$T^\nu_{dec} > m_e \Rightarrow$ relic ν slightly colder than relic γ

$\rightarrow n_\nu = \frac{3}{22} g_\nu n_\gamma$ $\quad \left(g_\nu = \begin{cases} 2 & \text{Major} \\ 4 & \text{Dirac} \end{cases}\right)$

$\downarrow$

$$\Omega_\nu \equiv \frac{\rho_\nu}{\rho_c} = \underline{\underline{0.01}} \times m_\nu(\text{eV})\, h_0^{-2} \left(\frac{g_\nu}{2}\right)\left(\frac{T_0}{2.7}\right)^3$$

$0.4 < h_0 < 0.9$ $\qquad$ $0.01 \rightarrow \Omega_{LUM} \lesssim 0.01$

LIGHT ν AS DM

$$\Omega_\nu h^2 \sim \frac{m_\nu}{30\,eV}$$

→ few eV ν fine to obtain $\Omega_{DM} \sim 0.1-1$

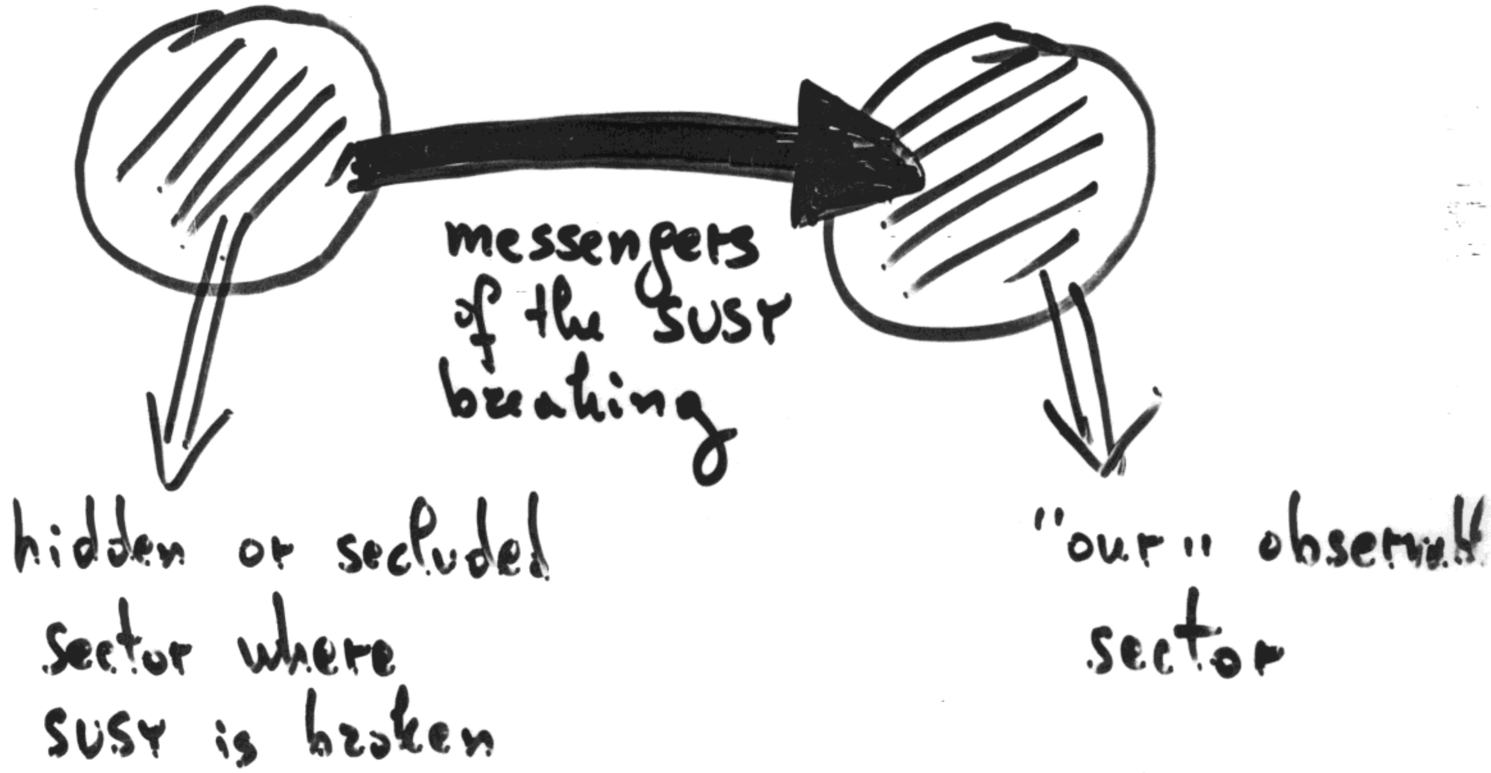
PROBLEMS: a) impossible for ν to form the dark haloes of dwarf galaxies (phase space dens. of ν limited by Fermi statistics)

b) light ν are HOT: still relativistic when galaxy formation could have begun (causal horizon contained about 1 galactic mass) ⇒ hot DM has a large free-streaming length which tends to smear out primordial density perturbations until ν slow down enough

⇒ first superlarge structures form → too few old galaxies

→ cosmic strings as "seeds" of perturbations ?

SUSY BREAKING



"TRADITIONAL" N=1 SUPERGRAVITY MODELS

hidden sector where local SUSY is broken AT A VERY HIGH SCALE $M_S \sim 10^{11}$ GeV → gravitational messengers $1/M_P^n$ suppression

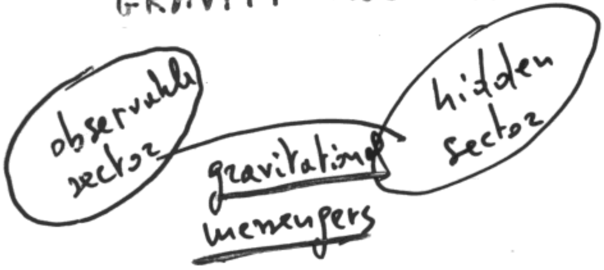
"NEW" MODELS WITH SUSY BROKEN AT LOW SCALE $M_S \sim 10^5 - 10^6$ GeV → gauge messengers Dine, Nelson, Shirman, Nir – Dvali, Giudice, Ra...

$$m_{3/2} = \frac{M_S^2}{M} <$$

- $10^2 - 10^3$ GeV SUGRA
- $10^{2} - 10^{3}$ eV GAUGE-MEDIATED SUSY BREAKI...

LARGE SCALE SUSY BREAKING

GRAVITY MEDIATED SUSY$\not{}$



$$\Lambda_{SUSY} \sim 10^{11}\ GeV$$

↑

$$M_{SUSY} \sim \frac{\Lambda^2_{SUSY}}{M_P}$$

$$m_{3/2} \sim \frac{\Lambda^2_{SUSY}}{M_P}$$

$$M_{SUSY} \sim m_{3/2} \sim O(1\,TeV)$$

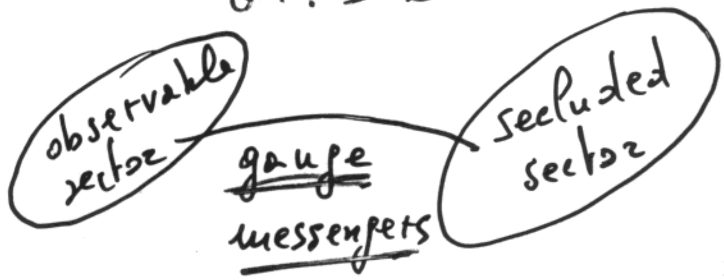
LSP → lightest neutralino

$m > 20\ GeV$

CDM possibility of having $\Omega_{\chi^0} \sim 0.1-1$

LOW SCALE SUSY BREAKING

GMSB



$$\Lambda_{SUSY} \sim 10^{6}\ GeV$$

↑

$$m_{3/2} \sim \frac{\Lambda^2_{SUSY}}{M_P} \sim 10^2 - 10^3\ eV$$

$$M_{SUSY} \sim 100\ GeV$$

$\psi_{3/2}$ gravitino is LSP

WARM DM

$$\tilde{\chi}^0 \to \psi_{3/2} + \gamma$$

↓

γ in the final state

LIGHT GRAVITINO : WARM DM CANDIDATE

WARM → for a gravitino in the (0.1 − 1) KeV range
the free-streaming mass scale ~ galaxy mass scale

- just replacing CDM with WDM does **not** work
(suppression of fluctuation only at the galaxy mass scale
but power spectrum unaffected on the cluster mass scales
where standard CDM fails)

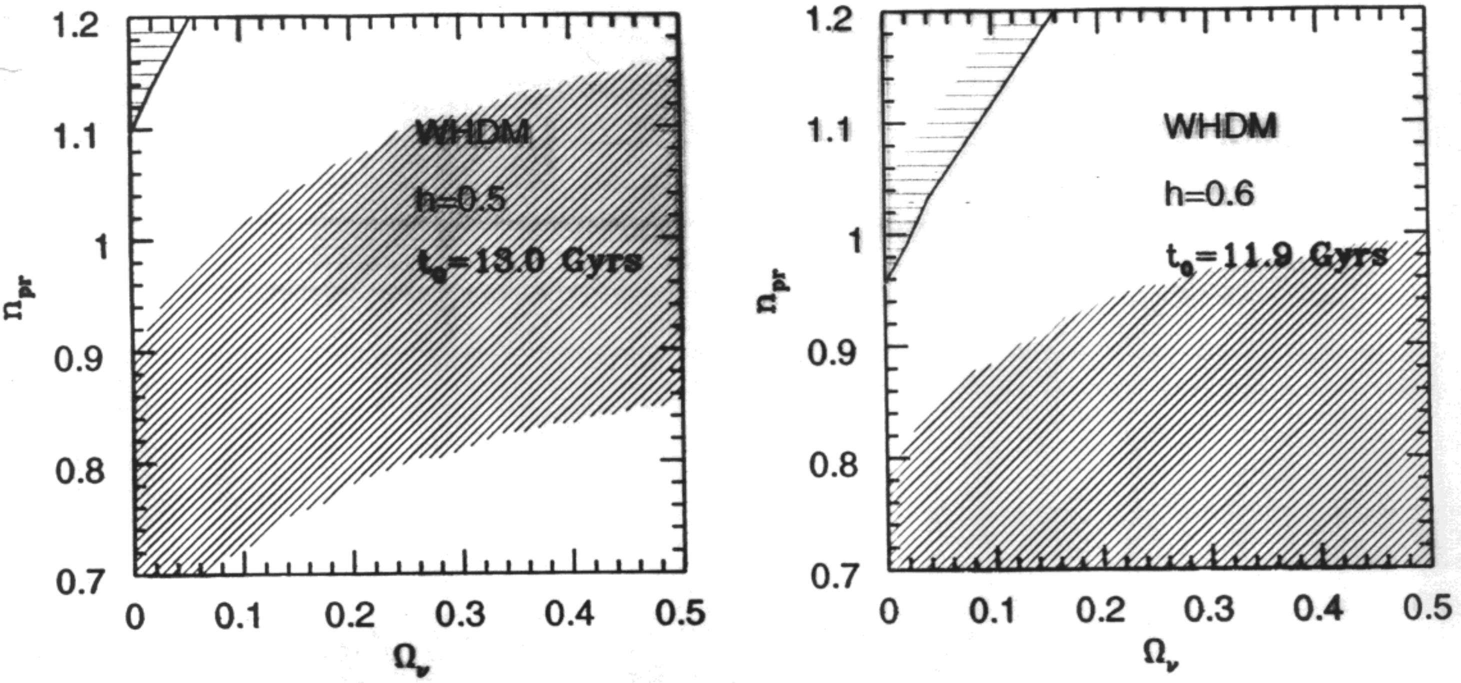
- given the success of suitable MIXED DM and LOW-DENSITY
CDM models in accounting for { low-level density fluc. $\sim 10\, h^{-1}$ Mpc ; enough power at $1 h^{-1}$ Mpc (form galaxy early enough epoch) }

⇒ **test light gravitino with { hot component ↩ ; low-density $\Omega_0 < 1$ }**

OBSERVATIONAL CONSTRAINTS { HIGH-REDSHIFT OBJECTS ; CLUSTER ABUNDANCE }

WARM + HOT DM $\Omega_0 = 1$

$(g_* = 150)$ E. PIERPAOLI, S. BORGANI, A.M., M. YAMAGUCHI



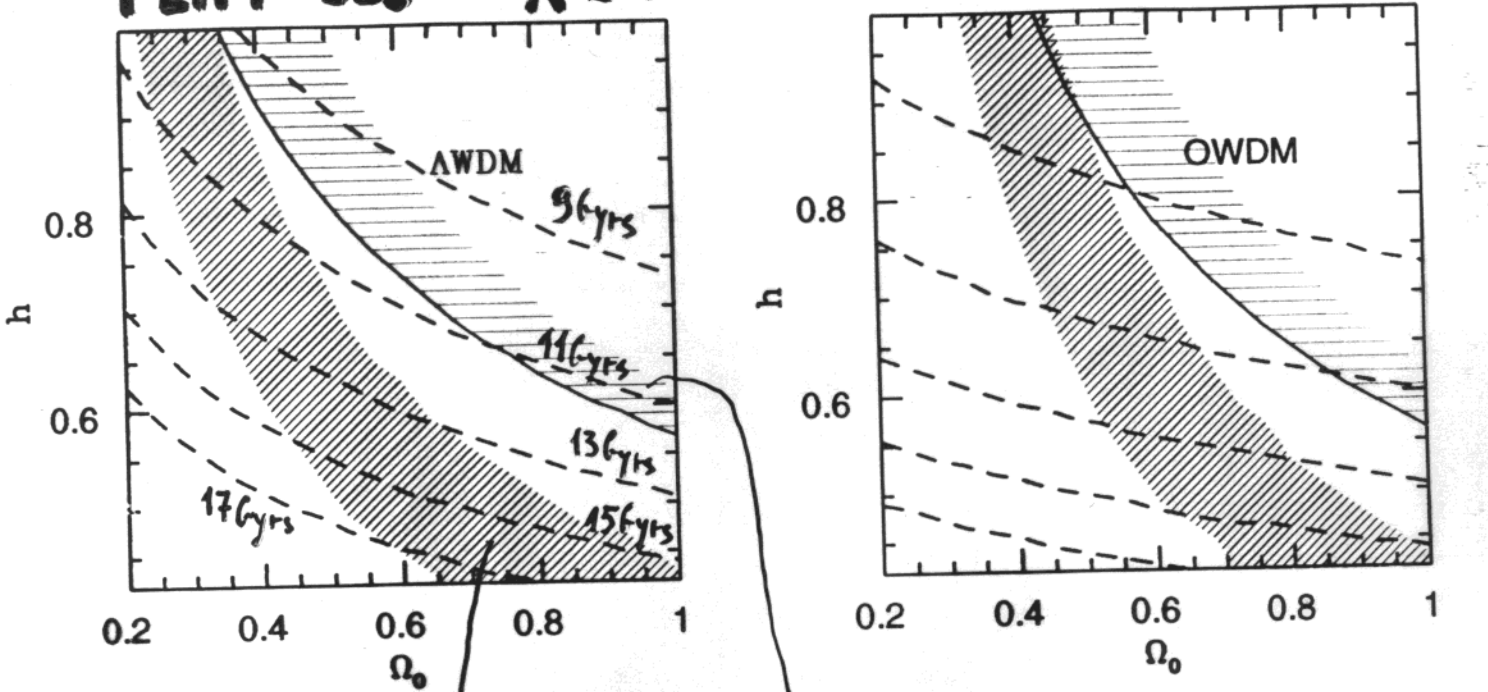
COMBINED FREE STREAMING OF ν and $\psi_{3/2}$ $\Rightarrow$ STRONG SUPPRESSION OF FLUCTUATIONS AT $\sim 1\,h^{-1}$ Mpc $\Rightarrow$ DIFFICULT TO FORM $z \sim 4$ PROTOGALACTIC OBJECTS (while matching low-z cluster abundance)

LIGHT GRAVITINOS WITH $\Omega_{0\,matter} < 1$

$n=1$ ($n \neq 1$ does not improve the situation)

E. PIERPAOLI, S. BORGANI, A.M., M. YAMAGUCHI

FLAT $\Omega_0 + \Omega_\Lambda = 1$ **OPEN $\Omega_0 < 1$ $\Omega_\Lambda = 0$**



$g_* = 150$

HIGH-REDSHIFT OBJECTS CONSTRAINT **

CLUSTER ABUNDANCE *

* using the relation between σ_8 (r.m.s. fluctuation value within a sphere of $8h^{-1}$ Mpc radius) and Ω_0 from Viana and Liddle 96

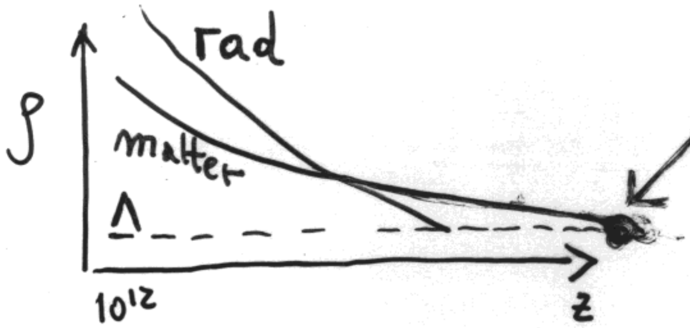
** constraint from the abundance of neutral hydrogen contained within damped Ly-α system (DLAS) → value of Ω_{HI} at $z \sim 4.25$ from Storrie-Lombardi et al. '95

$\Omega_\Lambda \neq 0$

only a nightmare for a particle physicist?

i) FIRST CANDIDATE: COSMOLOGICAL CONSTANT

$p = -\rho$ $\quad w = -1$ $\quad (p = w\rho)$



why Λ so small*?

why today?

* en. of the vacuum $\sim (0.003\,\text{eV})^4$

ii) SECOND POSSIBILITY:

DYNAMICAL TIME-DEPENDENT AND SPATIALLY INHOM. COMPONENT WITH $p = w\rho$ $\hookrightarrow -1 < w < 0$

present data seem to favor $w \sim -0.6$ or so

HOW TO MAKE VACUUM ENERGY DYNAMICAL ?

Simplest case: EVOLVING SCALAR FIELD which has not reached its state of minimum energy

→ the energy of the true vacuum is zero but not all fields have evolved to their state of minimum energy: field classically unstable rolling towards its lowest energy state

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi) \quad ; \quad p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

eq. of motion: $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$

$$w = \left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right) / \left(\frac{1}{2}\dot{\phi}^2 - V(\phi)\right)$$

↳ can take any value from +1 to −1

w can vary with time

Bronstein 1933 "decaying cosmological constant"

Freese et al 87 ; Ozer+Taha 87 ; Ratra-Peebles 88 ; Frieman et al 95 ; Coble et al. 96 ; Turner-White 97 and →

R. Caldwell, Dave and Steinhardt PRL '98

↳ name for this rolling scalar:

QUINTESSENCE

Candidates: pseudo-Goldstone bosons
Frieman, Hill, Stebbins, Waga

scalar fields with a scalar potential decreasing to zero for infinite field values Caldwell et al; Turner and White; Spergel and Pen; Zlatev, Wang, Steinhardt

↓

IDEA: such a behaviour occurs naturally in models of DYNAMICAL SUSY BREAKIN[G]

Scalar potential of SUSY models has many flat directions (directions in field space where the potential vanishes) after dynamical susy breaking ⇒ degeneracy of flat directions is lifted by flat directions restored at infinite values of the scalar fields!

⇒ potential smoothly decreasing to zero at infinity

GLOBAL SUSY ⇒ VANISHING GROUND STATE ENERGY

(hope for solution of the cosm. const. problem Zumino)

$V(\phi) \to 0$ at infinity

(in some case $\phi \to 1/g$ → coupl. const. associated with the dynamics responsible for SUSY breaking

$\phi \to \infty$ $g \to 0$ → restoration of SUSY $V=0$)

ex: dilaton ϕ not appearing in V

$\phi F^{\mu\nu} F_{\mu\nu}$ → G gauge symm.

when G interaction strong $\Lambda = M_P \, e^{-\phi/2b_0}$

$\Rightarrow \langle\bar\lambda\lambda\rangle = \Lambda^3 = M_P^3 \, e^{-3\phi/2b_0}$

$V \to e^{-\phi/b_0}$

w_ϕ starts at 1 then w_ϕ decreases to $w_B = 0$ for $\phi \to \infty$

w positive!

2^{nd} example:

SUSY QCD $\quad SU(N_c) \quad N_f < N_c$ flavors

chiral multiplets

$Q^i \quad i = 1, \ldots, N_f \qquad \bar{Q}^i$

fundam. of $SU(N_c)$ $\qquad$ antifundam. of $SU(N_c)$

$$T_i = Q_i \cdot \bar{Q}_i \qquad W = (N_c - N_f)\left(\frac{\Lambda^{3N_c - N_f}}{\det T}\right)^{\frac{1}{N_c - N_f}}$$

Taylor, Veneziano, Yankielowicz
Affleck, Dine, Seiberg

if $Q_i = Q$ for $i = 1, \ldots, N_f$

$$\Rightarrow V(Q) = \frac{\Lambda^{\frac{2(3N_c - N_f)}{N_c - N_f}}}{Q^{\frac{2(N_c + N_f)}{N_c - N_f}}} \cdot N_f$$

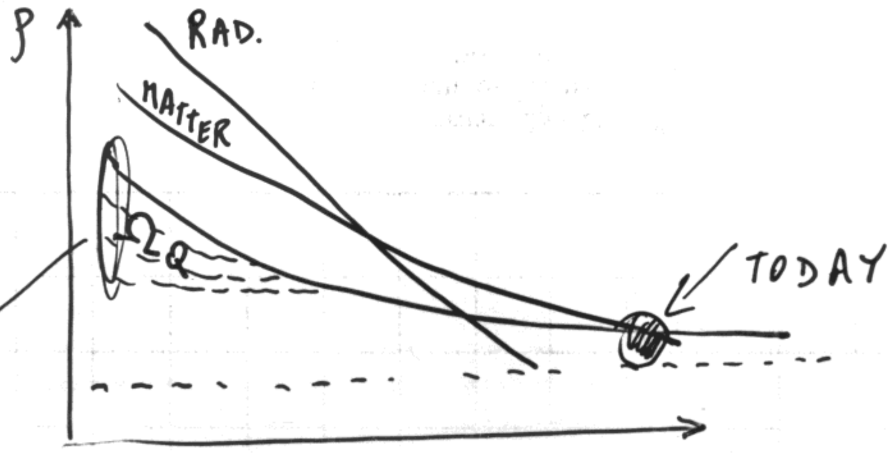
Binetruy

$\hookrightarrow V(\phi) \sim \phi^{-n}$ inverse power potential

$$w_Q = -1 + \frac{\alpha(1 + w_B)}{2 + \alpha} \qquad \alpha = 2\,\frac{N_c + N_f}{N_c - N_f}$$

$\hookrightarrow$ w_Q between $-1/2$ and 0 $\quad (w_B = 0)$

(it might be not "negative" enough
data favor $w \lesssim -0.6$)



IF ATTRACTOR SOLUTION

$\Rightarrow$ Q TRACKER FIELD

changing initial conditions
(by orders of magnitude)
the field Q is alway "attracted"
to the "right" track leading
to $\Omega_M \sim \Omega_Q$ today

"partial" solution to the
why today problem
still smallness of Λ is an open problem

WHAT HAPPENS IF NOT ALL Q_i are EQUAL, i.e.

SUSY QCD with several Q_i

for instance Q_1 and Q_2 A.M., PIETRONI, ROSATI

main features:

* THERE EXIST AN ATTRACTOR SOLUTION for Q_1 and Q_2 (both tracker fields)

* INTERPLAY OF Q_1 and Q_2 STARTING WITH DIFFERENT INITIAL CONDITIONS

→ DIFFERENT ρ_Q and w_Q behaviour

possible to have $w_Q < 0.5$

EFFECTS OF INTERACTIONS OF Q_i WITH ORDINARY FIELDS ⇒ POSSIBLE $\beta H^2 Q^2$ terms

β limited by bounds on long range interactions of light scalar Q

Cosmic Concordance and Quintessence

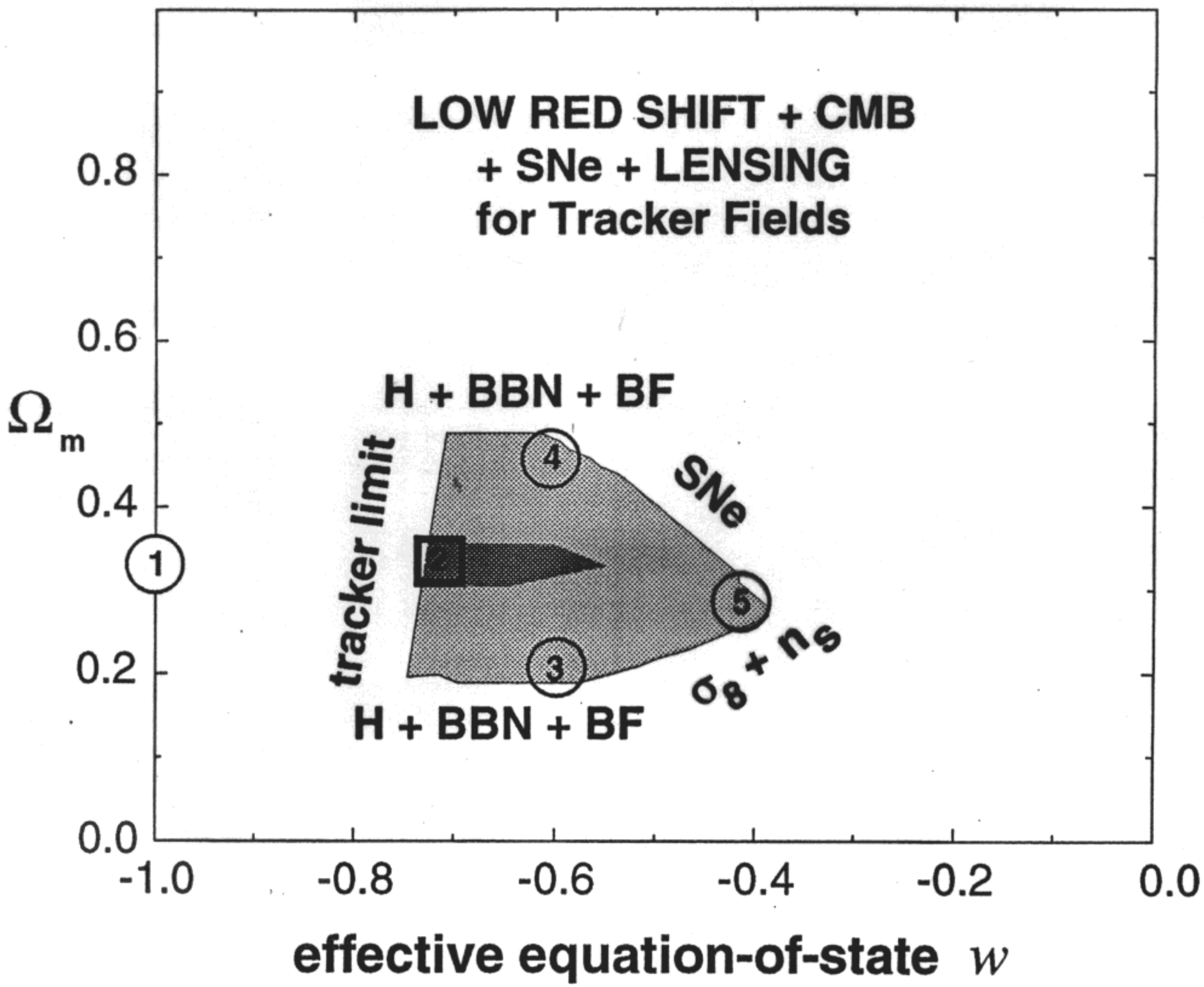
Wang, Caldwell, Ostriker, Steinhardt -- astro-ph/9901388

Quintessence Parameters:

Ω_m, w, h, n_s, Ω_b

CONSTRAINTS

- low red shift
  - cluster abundance
  - BBN, baryon fraction
  - H, age, velocities
- intermediate red shift
  - SNe, lensing, ly-a,
  - cluster evolution
- high red shift
  - COBE norm, tilt
  - small angle CMB



CONCLUSIONS

- Ω_B , Ω_{MATTER} ⇒ data confirm the need for NON-BARYONIC DM
  ⇒ new physics beyond the elw. SM

- $\Omega_{0\,TOTAL} \sim 1$ from CBR

- $\Omega_\Lambda \neq 0$ from SNe Ia

- STILL NEED FOR CDM (axions, WIMPS → relic SUSY particles)

- $\Omega_\Lambda \neq 0$ accounted for by rolling scalar fields that have not reached their minimum yet ⇒ TRACKER SOLUTIONS IN THE SUSY QCD AND DILATON CASES
  ↳ $w < 0$