The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR.1663- 21

SUMMER SCHOOL ON PARTICLE PHYSICS

13 - 24 June 2005

Dark Matter, Dark Energy and New Physics beyond the Standard Model

A. MASIERO
Dipartimento di Fisica "G. Galilei"
Università degli Studi di Padova
Via F. Marzolo, 8
35131 Padova
ITALY

ICTP SUMMER SCHOOL
ON
PARTICLE PHYSICS
13-24 June 2005

DM, DE

and

NEW PHYSICS BEYOND THE SM

Antonio Masiero

Univ. and INFN, PADOVA

OBSERVATIONAL HINTS FOR NEW PHYSICS BEYOND THE SM

- HIGH ENERGY — A^b_{FB} ~ 3σ

  FLAVOR PHYS. — $b \to s q \bar{q}$: average of S-penguin decays ~ 3.5σ

  RARE PHYS — $(g-2)_\mu$ ~ 2.6σ (using e^+e^-)

- ν PHYSICS: MASSES and MIXINGS

  $\to \frac{LLHH}{M}$ ↗ first access to a new mass scale $M > M_W$ (?)

- "CLASHES" between

PARTICLE PHYSICS SM	COSMOLOGY SM
G-W-S SM	BIG BANG SM

GRAND UNIFICATION

PREDICTION OF $\alpha_s(M_Z)$

Given the precision on $\sin^2\theta_W$

$\Rightarrow$
- use $\sin^2\theta_W(M_Z)$ and $\alpha_{em}(M_Z)$ as INPUT
- determine M_X, α_{GU}, $\alpha_s(M_Z)$

Hall, Nomura

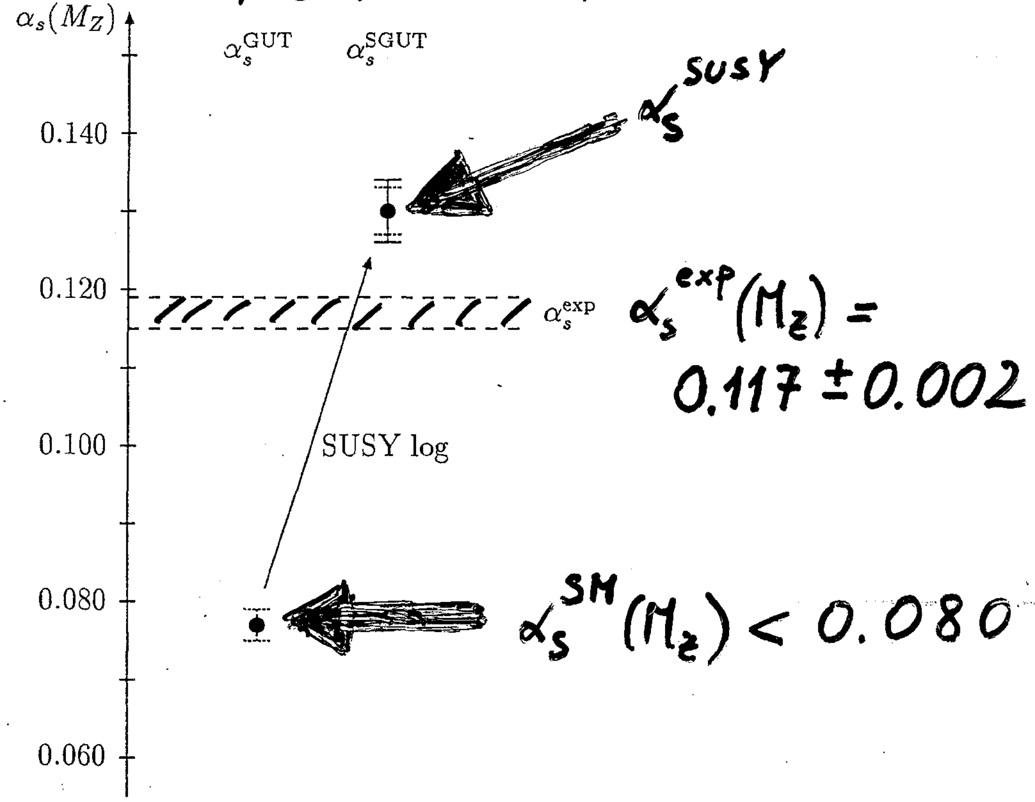


Figure 1: The predictions for $\alpha_s(M_Z)$ in non-supersymmetric grand unification, α_s^{GUT}, and supersymmetric grand unification, α_s^{SGUT}. The solid error bar represents the threshold corrections from the superpartner spectrum. Dotted error bars represent threshold corrections from the unified scale corresponding to a heavy $\mathbf{5}+\bar{\mathbf{5}}$ representation with unit logarithmic mass splitting between doublets and triplets.

$$\alpha_s(M_Z) = \frac{\alpha_{em}(M_Z)}{(1+8x)\sin^2\theta_W(M_Z) - 3x} \qquad x \equiv \frac{1}{5}\left(\frac{b_2-b_3}{b_1-b_2}\right)$$

MICRO — MACRO

PARTICLE PHYSICS — COSMOLOGY

GWS STANDARD MODEL — HOT BIG BANG STANDARD MODEL

↘ ↙

HAPPY MARRIAGE

ex. : NUCLEOSYNTHESIS

BUT ALSO POINTS OF FRICTION

- ** — COSMIC MATTER-ANTIMATTER ASYMMETRY
- * — INFLATION
- *** — DARK MATTER + DARK ENERGY

↓

"OBSERVATIONAL" EVIDENCE FOR NEW PHYSICS BEYOND THE (PARTICLE PHYSICS) STANDARD MODEL

ΛCDM after WMAP

$$\Omega_{MATTER} h^2 = 0.135^{+0.008}_{-0.009}$$

$$\Omega_{BARYON} h^2 = 0.0224 \pm 0.0009$$

$$\Omega_{CDM} h^2 = 0.1126^{+0.0161}_{-0.0181}$$

consistent with what inferred from earlier observations, but significantly more precise

before : $0.1 < \Omega_{CDM} h^2 < 0.3$

now (after WMAP results) : $0.094 < \Omega_{CDM} h^2 < 0.129$

Large Scale Structure: the Sloan Digital Sky Survey

New determination of the power spectrum at small scales from Ly α data [astro-ph/0405013,07377]

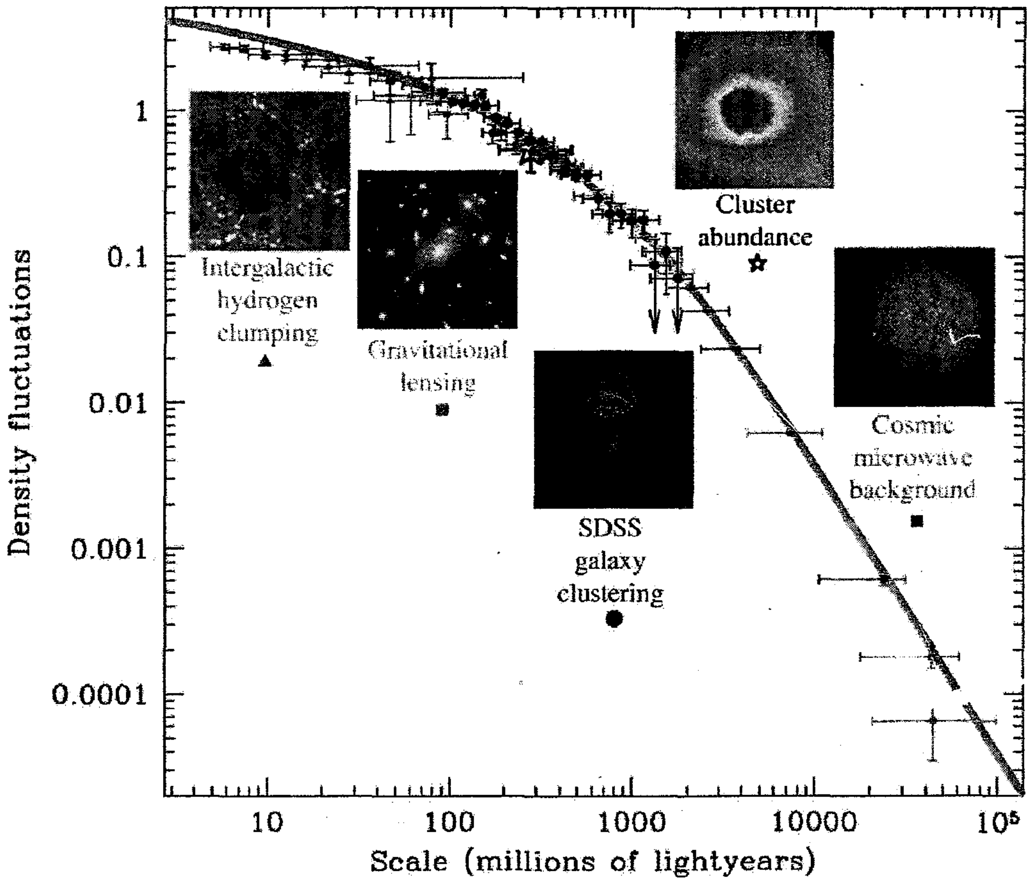


Figure by M. Tegmark

→ better control of systematics

→ longer lever arm in scale

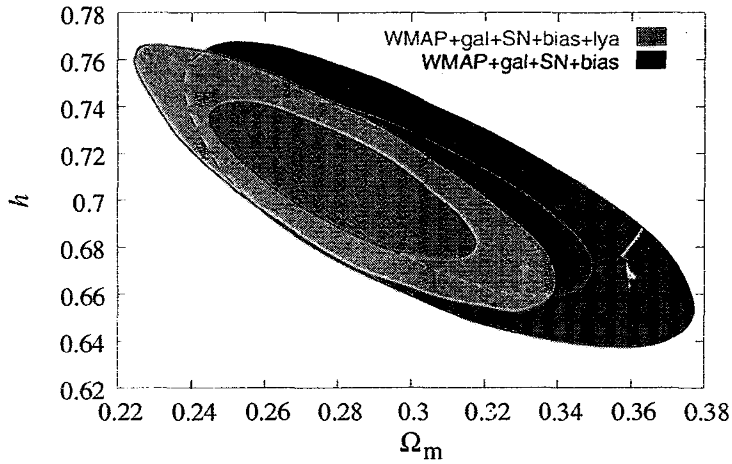
⇓

NEW determination of the cosmological parameters from WMAP data, SDSS galaxy clustering, bias and Lyman α data, SN Ia data.

New analysis by Seljak *et al* [astro-ph/0407372]

What has changed ???

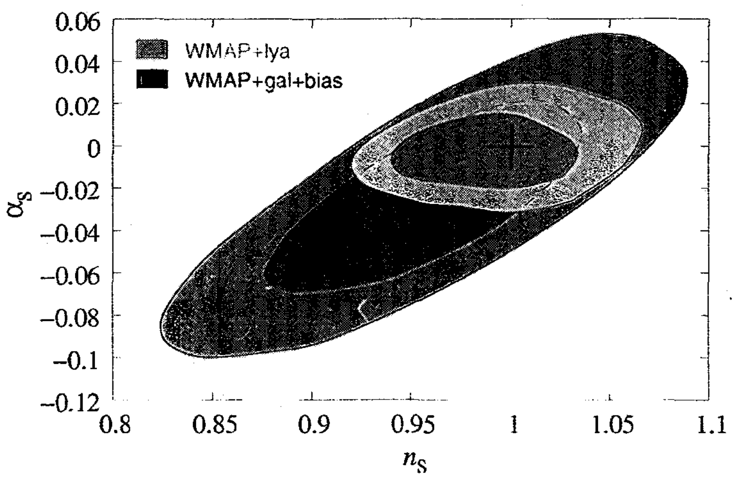
- Improved accuracy on all parameters, e.g.



- More stringent bound on neutrino masses

$$\sum m_\nu \leq 0.66 \text{ eV } (3\nu) \quad \text{or } m_\nu \leq 0.79 \text{ eV } (3+1\nu)$$

- Spectral index $n_s = 0.977^{+0.025}_{0.021}$ and
  $\alpha_s = n_s' = \quad 0.003 \pm 0.010$: NO RUNNING !



Also bound on the tensors as $r \leq 0.45$ at 1σ.

WHAT IS THE DM MADE OF ?

Ω → Ω_{MATTER} at least 0.2
→ 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 $\Omega_{SM} < 0.1$
$\Omega_B \lesssim 0.1$

(MACHOS only small part of galactic halo)

⬇

NON-BARYONIC DM

CALLS FOR NEW PHYSICS

BEYOND SM

DM RELIC PARTICLES

THERMAL — NON-THERMAL (ex. axions) → STRONG CP PROBLEM

THERMAL → HOT, COLD

HOT

ex.: $m_{\nu} \sim 10\ eV$
$T^{\nu}_{decoupl} \sim MeV$

$m \ll T_{decoupl}$
relativistic at time structure formation ...

COLD

ex: $m_{\chi^0} \sim 100\ GeV$
$T^{\chi^0}_{decoupl} \sim 10\ GeV$

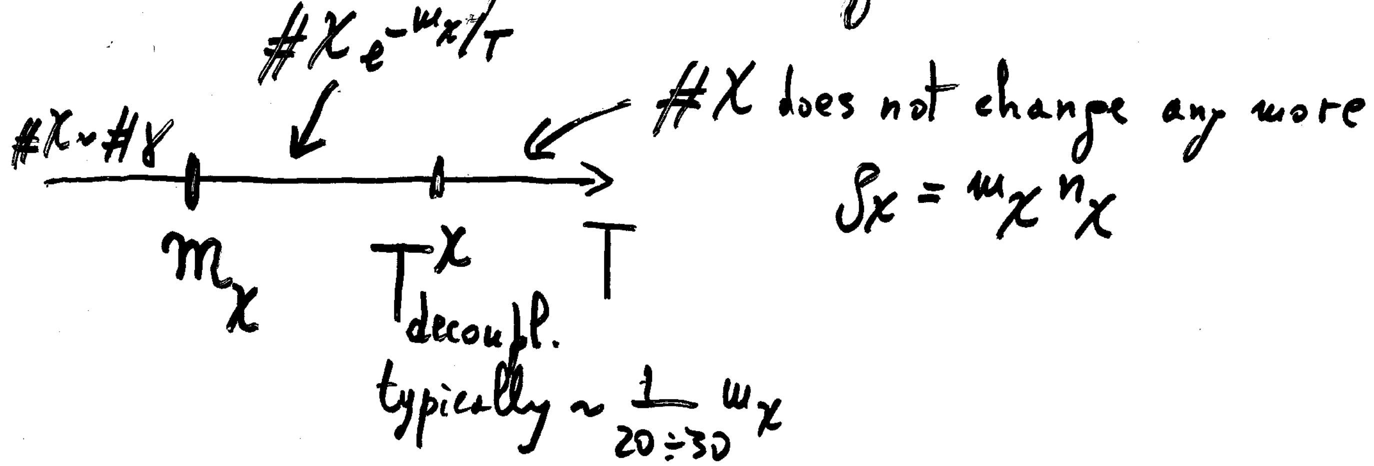
$m \gg T_{decoupl.}$
non relativistic when galaxies start forming

BEST "THERMAL" CDM CANDIDATES

$\Downarrow$

WIMPS

Weakly Interacting Particles



Ω_χ depends on particle physics ($\sigma^\chi_{annih.}$) and "cosmological" quantities (H, T_0, ...)

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

$\text{TeV}^2 \longrightarrow$ from $\sqrt{T^0}\, M_{Planck}$

$\Omega_\chi h^2$ in the range $10^{-2} - 10$ to be cosmologically interesting (for DM)

$m_\chi \sim 10^2 - 10^3$ GeV (weak interaction) $\Rightarrow \Omega_\chi h^2 \sim 10^{-2} - 10$!!

NON-BARYONIC DARK MATTER

HOT $\Rightarrow$ LIGHT NEUTRINOS

COLD $\Rightarrow$ AXIONS

WIMPs

$\Downarrow$

LSP

SUPERHEAVY DM

LIGHTEST K-K

⋮

BEST WIMP CANDIDATE :

LSP

L → LIGHTEST, S → SUSY, P → PARTICLE

SUSY EXTENSION OF THE SM

⇒ MOTIVATION FOR "LOW ENERGY" SUSY : STABILIZATION OF HIGGS MASS AT ~ M_W

SUPPORT : UNIFICATION OF ELW + STRONG GAUGE COUPL.

PROBLEM : PROTON FAST DECAY

REMEDY : IMPOSING (ADDITIONAL) DISCRETE SYMMETRY (R PARITY)

BONUS : LSP STABLE
↳ WIMP CANDIDATE

LINKING $\Lambda_{\text{NEW PHYSICS}}$ TO THE ELECTROWEAK BREAKING

$$M_Z = \Lambda_{\text{New Physics}} \times f(\text{phys. param.})$$

MSSM

$$M_Z^2 \sim (90\ \text{GeV})^2 \left(\frac{\langle m_{\tilde{t}} \rangle}{250\ \text{GeV}}\right)^2 \log\left(\frac{\Lambda}{\langle m_{\tilde{t}} \rangle}\right) + \dots$$

if no fine-tuning with ...

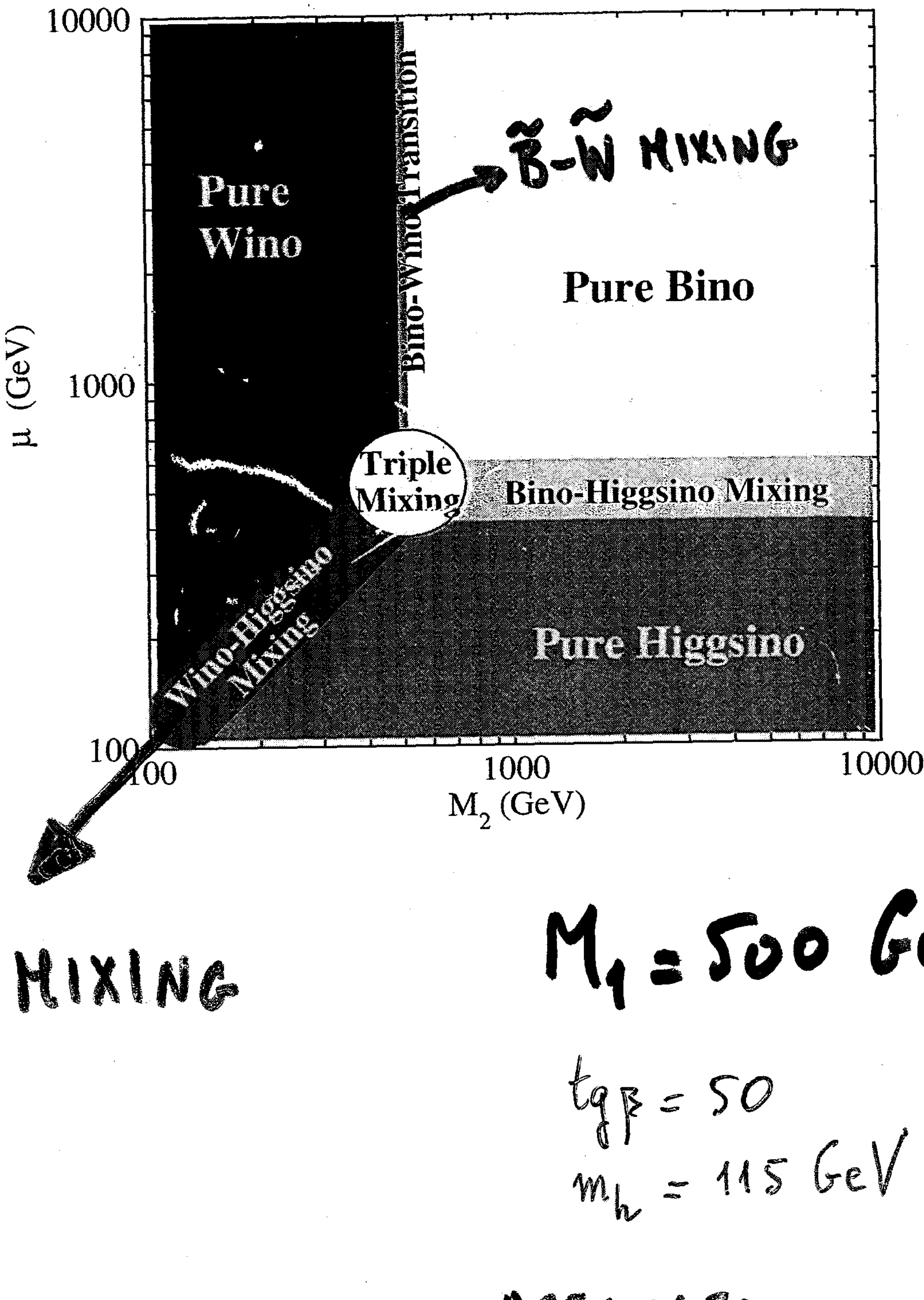
$\Rightarrow$ $\langle m_{\tilde{t}} \rangle$ upper bounded

but NEED for large $\langle m_{\tilde{t}} \rangle$ to enhance rad. corr. to m_{Higgs}

$\rightarrow$ if $m_{\text{Higgs}} \sim 120$ GeV still need a few percent tuning between the first term and ... in M_Z^2

NEUTRALINO COMPOSITION

A.M., PROFUMO, ULLIO



$M_1 = 500$ GeV

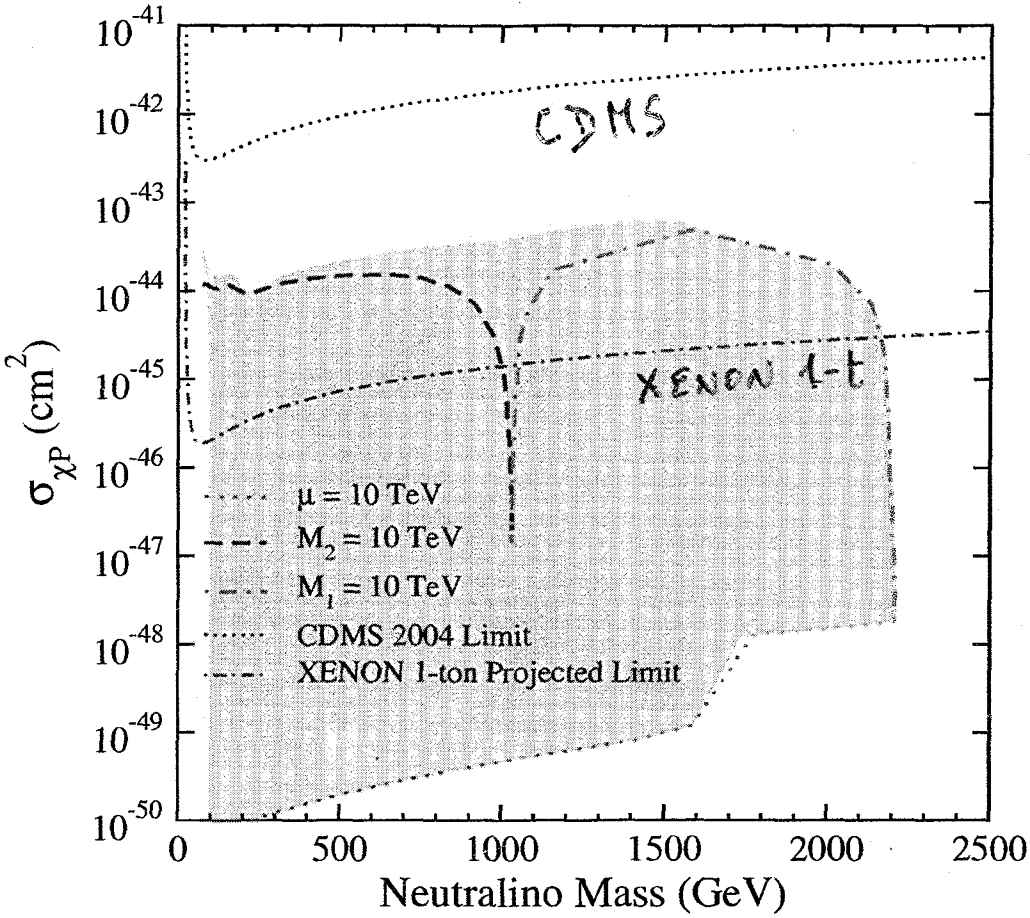
$tg\beta = 50$

$m_h = 115$ GeV

NO GUT RELATION ASSUMED

M_1, M_2, μ ARE CONSIDERED AS INDEPENDENT PARAMETERS

SCANNING FOR M_1, M_2, μ up to 10 TeV !

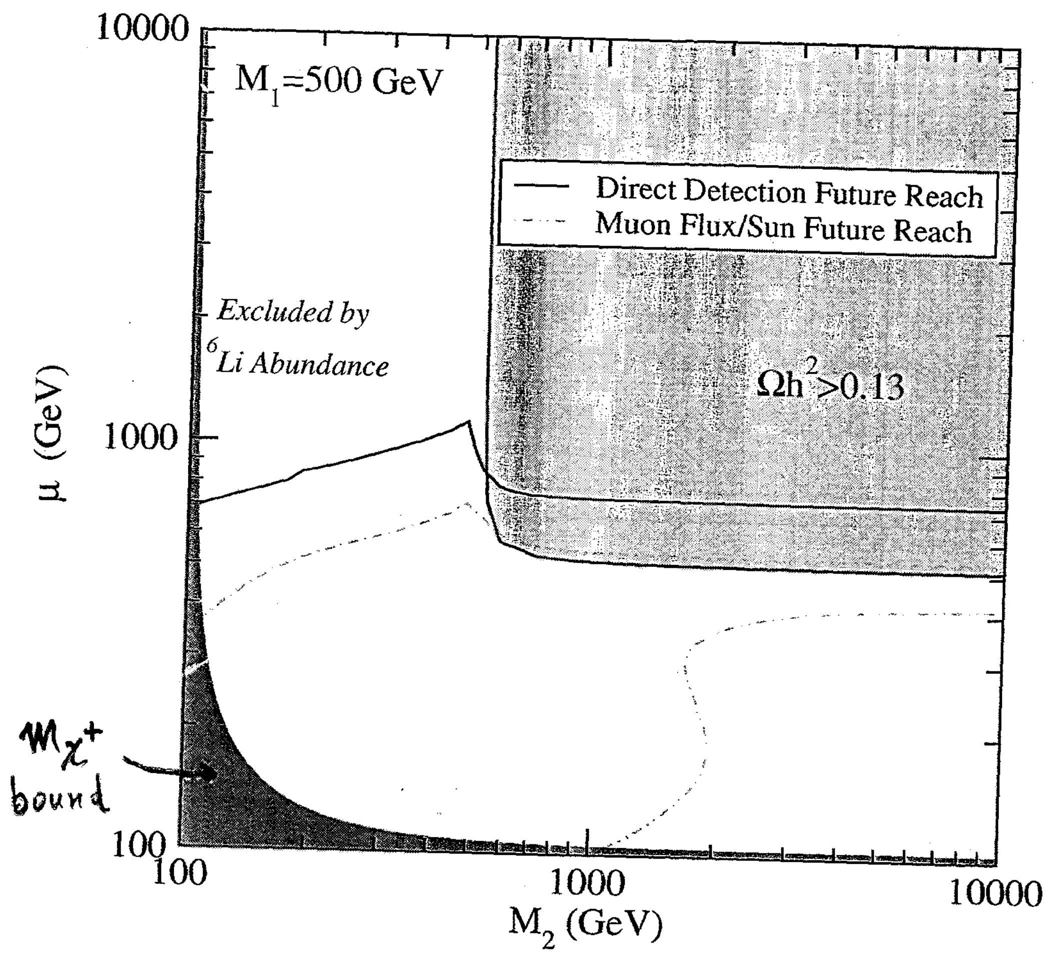


A.M., PROFUMO, ULLIO

SUSY EXTENSION WITH HEAVY S-FERMIONS, H, A

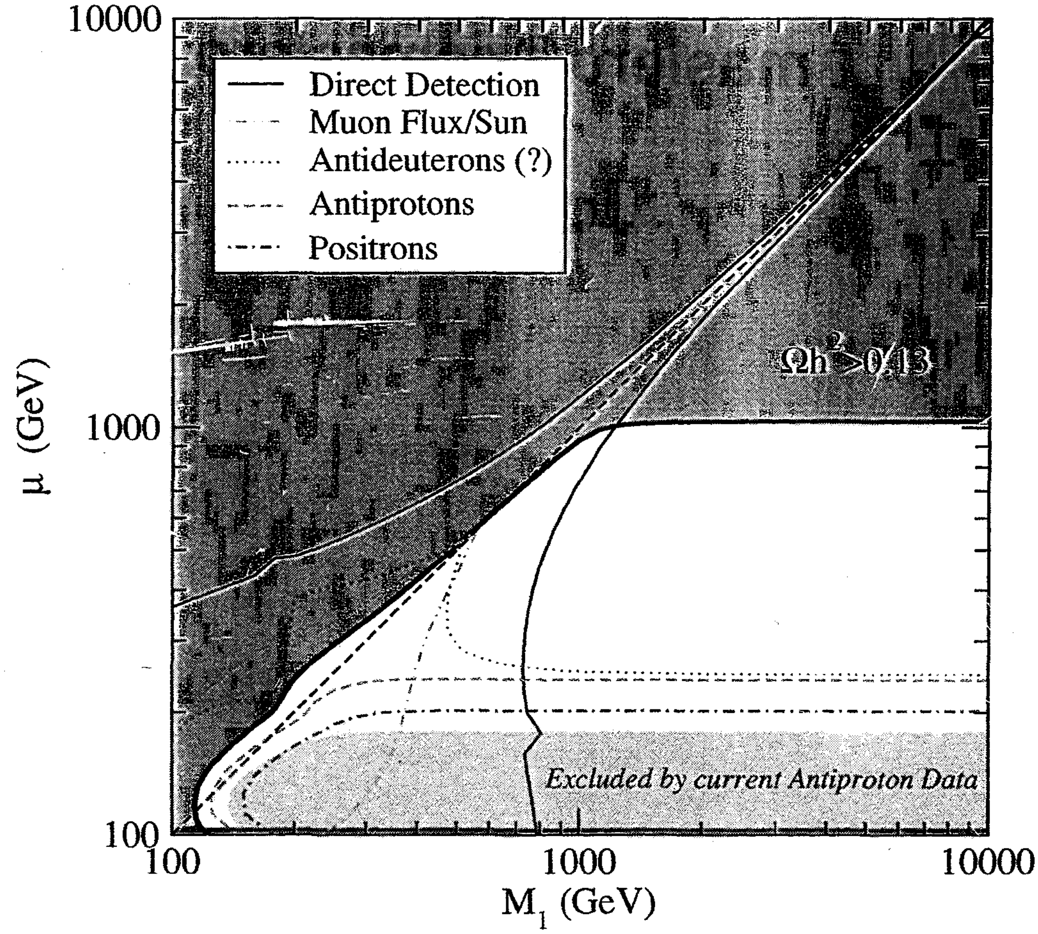
NO M_1, M_2, M_3 RELATIONS

A.M., PROFUMO, ULLIO



THE REACH IN FUTURE FACILITIES IN THE DIRECT DETECTION —— AND μ-flux from the Sun —·—·—· CHANNELS ON THE (M_2, μ) PLANE AT $M_1 = 500$ GeV

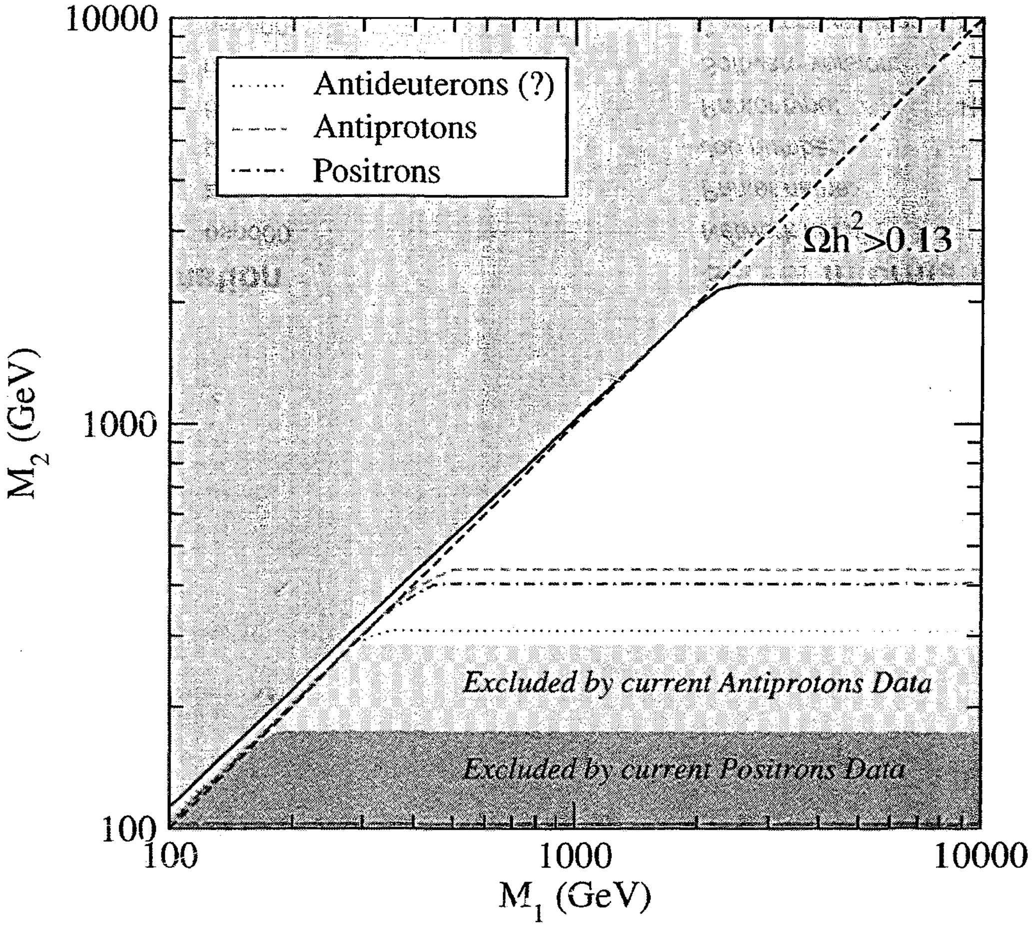
A.M., Profumo, Ullio



FUTURE EXCLUSION LIMITS ON THE (M_1, μ) plane at $M_2 = 10$ TeV

Cored Burkert profile assumed

A.M., PROFUMO, ULLIO



FUTURE EXCLUSION LIMITS ON THE (M_1, M_2) plane at [redacted] $\mu = 10$ TeV

CORED BURKERT PROFILE IS ASSUMED

THE DE PUZZLE

- MISINTERPRETATION OF THE DATA ?

1) SNe data   2) CMB $\Omega_T = 1$ 3) measures of ρ_{DM}

↓

two variables : Ω_{DM}, Ω_{DE} 3 indep. meas.

⇒ **cosmic concordance** for an ACCELERATING UNIVERSE

" The lengths to which it seems necessary to go in order to avoid concluding that the Universe is accelerating is a strong argument in favor of the concordance model "   S. CARROLL

- **BREAKDOWN OF GENERAL RELATIVITY** ?

→ possibility that gravitation might deviate from conventional GR on scales corresponding to the radius of the entire Universe

Ex. : gravity can be FOUR-DIMENSIONAL below a certain (very large) length scale, but HIGHER-DIMEN at larger distances → universe acceleration at late times

Dvali, Gabadadze, Porrati
Arkani-Hamed, Dimopoulos, Dvali, Gabada
Deffayet, Dvali, Gabadadze
Dvali, Gruzinov, Zaldarriaga
Lue, Starkman

or 4-dim. modification of GR :

ex. $S = \int d^4x \sqrt{|g|}\, R \longrightarrow S = \int d^4x \sqrt{|g|} \left(R - \frac{\mu^4}{R} \right)$

Carroll, Duvvuri, Trodden, Turner

"The difficulty in finding a simple extension of GR that does away with the cosmological constant provides yet more support for the standard scenario (ΛCDM)

CARROLL

● ACCELERATION ONLY IN OUR "LOCAL" RIPPLE ? Kolb, Matarrese, Notari, Riotto

IF : UNIV. IS HOMOGENEOUS, ISOTROPIC AND **ACCELERATING**

IF : GENERAL RELATIVITY HOLDS

⇓

NEED FOR SOME SORT OF DARK ENERGY SOURCE

⇓

SMOOTHLY-DISTRIBUTED, PERSISTENT ENERGY DENSITY DOMINATING THE UNIVERSE ENERGY DENSITY

← **UNCLUSTERISED**

DARK ENERGY : COSMOLOGICAL CONSTANT

or

DYNAMICAL DARK ENERGY ?

VACUUM ENERGY

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G_N T_{\mu\nu} + \lambda g_{\mu\nu}$$

$$[\lambda] = L^{-2}$$

if the vacuum energy is non-zero:

$$\langle T_{\mu\nu} \rangle = - \langle \rho \rangle g_{\mu\nu}$$

$$\Rightarrow R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G_N T_{\mu\nu} + \underbrace{8\pi G_N \langle \rho \rangle}_{\lambda_{eff} \equiv \frac{\Lambda^4}{M_P^2}} g_{\mu\nu}$$

$$\frac{1}{|\lambda_{eff}|^{1/2}} = \frac{M_P}{\Lambda^2} \gtrsim \frac{1}{H_0} = 10^{60} \ell_P \Rightarrow \Lambda \lesssim 10^{-30} M_P$$

$$\ell_P = \sqrt{8\pi G_N} \sim 10^{-32}\,\text{cm}$$

$$\rightarrow M_P = \sqrt{\frac{1}{8\pi G_N}} \sim 10^{18}\,\text{GeV}$$

$$H^2 = \frac{\dot{a}^2}{a^2} = \frac{8\pi G_N}{3} \rho_{TOT} \Longrightarrow \dot{a}^2 \propto a^2 \rho$$

acceleration ($\ddot{a}$ increasing) in an expanding universe $\Rightarrow$ if ρ falls off more slowly than a^{-2}

$\rho_{MATTER} \propto a^{-3}$, $\rho_{RADIATION} \propto a^{-4}$

- COSM. CONST. - CONST. VACUUM ENERGY
- SMOOTHLY-DISTRIBUTED SOURCES OF DARK ENERGY VARYING SLOWLY WITH TIME

↓

POSSIBILITY OF FINDING A

DYNAMICAL SOLUTION TO THE COINCIDENCE PROBLEM

→ "DE TRACKING SOME MATTER COMPONENT + RECENT TAKEOVER BY DE (for a wide range of param. of the theor

HOW TO MAKE VACUUM ENERGY DYNAMICAL ?

SIMPLEST CASE : EVOLVING SCALAR FIELD which has not reached its state of minimum energy

Ex. the energy of the true vacuum is zero, but not all fields have evolved to their state of minimum energy $\Rightarrow$ field classically unstable rolling towards its lowest energy state

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad P = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

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

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

⬇ can take any value from +1 to −1

can vary with time

Bronstein (1933) "decaying cosmological constant"

Freese et al. '87; Ozer-Taha '87; Ratra-Peebles '88;

Frieman et al. ; Turner, White '97 ;
R. Caldwell, Dave, Steinhardt '98

↳ QUINTESSENCE scalar field

Candidates: pseudo-Goldstone bosons, axions, scalar fields with a potential decreasing to zero for infinite values of the field

ex: $V(\phi) = e^{1/\phi}$

$V(\phi) = \frac{1}{\phi^n}$

↓ such a behaviour occurs naturally in models of dynamical SUSY breaking

BINETRUY ;
A.M., Pietroni, Rosati

⇒ possibility of "tracking" behaviour that makes the current energy density largely independent of the initial conditions   Zlatev, Wang, Steinhardt

but: no solution to the coincidence problem
⇒ when the scalar field begins to dominate is still set by tuning parameters of the theory

DM $\Longleftrightarrow$ DE

DO THEY "KNOW" EACH OTHER ?

- DIRECT INTERACTION ϕ (quintessence) WITH DM

⚠ DANGER :
ϕ very LIGHT
$m_\phi \sim H_0^{-1} \sim 10^{-33}\,eV$

$\Rightarrow$ threat of violation of the equivalence principle, constancy of the fundamental "constants", ...

- INFLUENCE of ϕ ON THE NATURE AND THE ABUNDANCE OF CDM

$\rightarrow$ modifications of the standard picture of WIMPS FREEZE-OUT

↳ CDM CANDIDATES

KINATION

DOMINATION BY THE KINETIC ENERGY OF THE QUINTESSENCE FIELD ϕ AT EPOCHS BEFORE BBN, IN PARTICULAR AT THE TIME WIMPS FREEZE OUT → SALATI

JOYCE ; JOYCE, PROKOPEC ; FERREIRA, JOYCE

$$\rho_\phi \equiv T^0_{\ 0} = \frac{\dot{\phi}^2}{2} + V(\phi)$$

↳ assumption : for some time $\dot{\phi}^2/2$ dominates

$\rho_\phi = \dot{\phi}/2 \propto a^{-6}$ $\quad \rho_{rad} \propto T^4 \sim a^{-4}$

↳ when WIMPS decouple

$$\eta_\phi = \frac{\rho_\phi}{\rho_\gamma} \qquad \text{def: } \eta^0_\phi = \frac{\rho^0_\phi}{\rho^0_\gamma} = \frac{\rho_\phi}{\rho_\gamma}\Big|_{T_{BBN}}$$

⇒ the expansion rate H of the Universe increases by a factor $\sqrt{\eta_\phi}\ T/T_{BBN}$ with respect to conventional radiation dominated cosmology

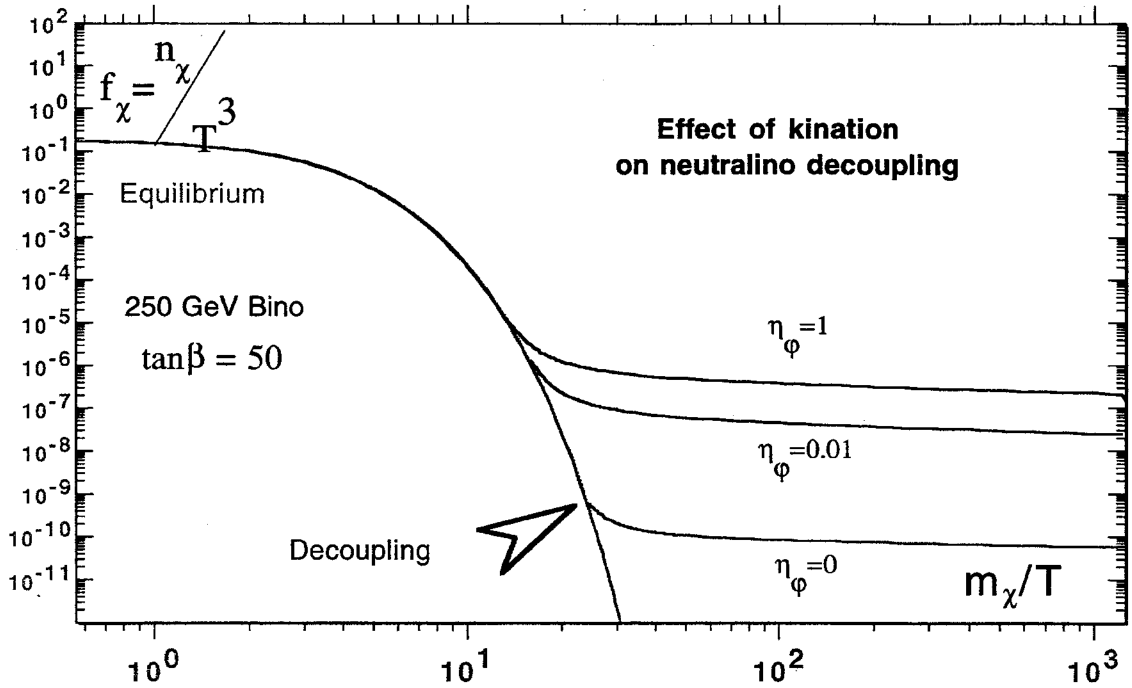


FIG. 1. Neutralino codensity as a function of the mass–to–temperature ratio $y = m_\chi/T$ for three different values of the kination parameter. For $\eta_\Phi = 0$, we recover the standard radiation dominated cosmology whereas for $\eta_\Phi = 0.01$ and $\eta_\Phi = 1$, the expansion rate H is significantly increased. This leads to an earlier decoupling and to a much larger asymptotic value for the neutralino codensity.

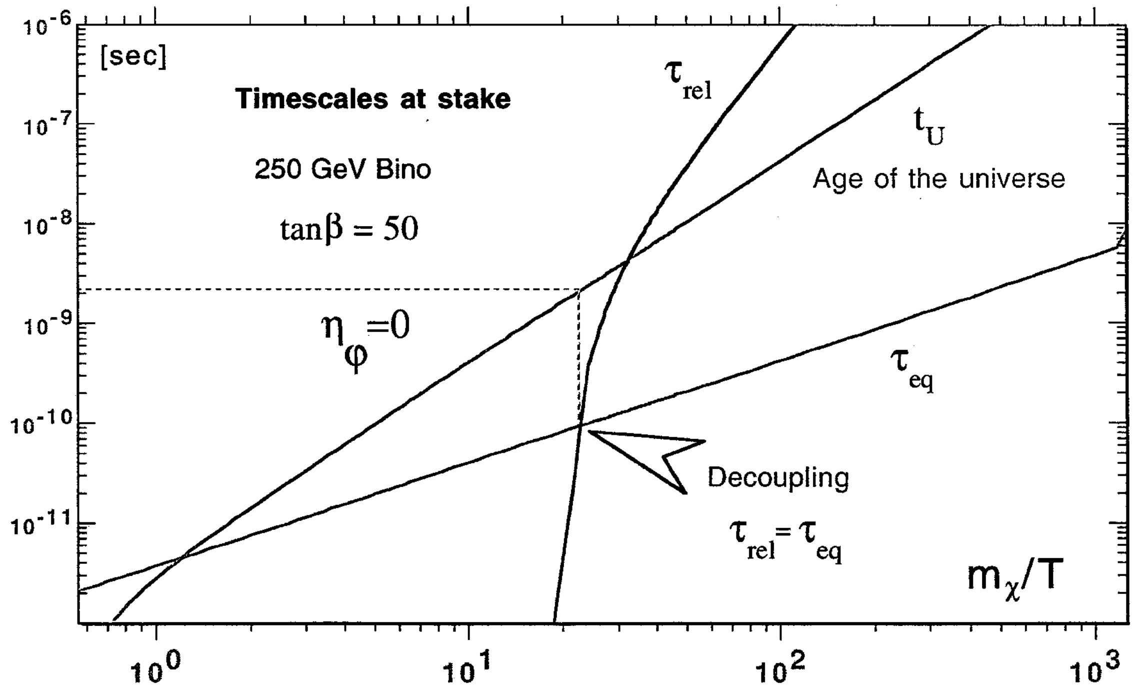


FIG. 2. The age of the universe t_U as well as the typical time scales τ_{rel} and τ_{eq} are featured as a function of the mass–to–temperature ratio $y = m_\chi/T$. The freeze-out occurs at $y_F = 22.7$ when τ_{rel} overcomes τ_{eq}. The standard radiation dominated cosmology is assumed here with $\eta_\Phi = 0$ so that t_U evolves like y^2.

"HARMLESS" QUINTESSENCE

NO EQUIVALENCE PRINCIPLE

VARYING COUPLINGS ... PROBLEMS

SCALAR-TENSOR (ST) GRAVITY THEORY

⇒ MATTER HAS A PURELY METRIC COUPLING WITH GRAVITY

JORDAN ; FIERZ ; BRANS-DICKE

DOUBLE ATTRACTOR IN ST GRAVITY WITH QUINTESSENCE

BARTOLO-PIETRONI

large class of ST Gravities have an attractor mechanism towards General Relativity (GR)

⇒ expansion of the Universe during matter domination tends to drive the scalar fields towards a state where the theory becomes indistinguishable from GR

2 attraction mechanisms:
- → TRACKER SOLUTION → accelerated Univ
- → Towards GR → ultra light scalars safe

$$S_{\text{ST theories of gravity}} = S_{grav} + S_{matter}$$

Damour, Nordtvedt;
Damour, Polyakov;
Santiago, Kalligas, Wagoner
Damour, Pichon

$$S_{grav} = \frac{1}{16\pi}\int d^4x \sqrt{-\tilde{g}}\left[\phi^2 \tilde{R} + 4\omega(\phi)\,\tilde{g}^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi - 4\tilde{V}(\phi)\right]$$

$$S_{matter} = S_{matter}\left[\psi_m, \tilde{g}_{\mu\nu}\right]$$

ψ_m coupled only to the metric tensor not to ϕ

$\tilde{R}$ = Ricci scalar constructed from the physical metric $\tilde{g}_{\mu\nu}$

each ST model identified by $\begin{cases} \omega(\phi) \\ \tilde{V}(\phi) \end{cases}$

Jordan-Fierz-Brans-Dicke: $\omega(\phi) = \omega$ const., $\tilde{V}(\phi) = 0$

$$\tilde{T}^{\mu\nu} = \frac{2}{\sqrt{-\tilde{g}}}\frac{\delta S_m}{\delta \tilde{g}_{\mu\nu}}$$

is conserved, masses and NON-GRAVIT. couplings are time independent, non-grav. physics laws take usual form

$\tilde{g}_{\mu\nu}, \phi$ "physical" → Jordan variables but eqs. of motion are cumbersome in Jordan frame as they mix spin-2 and spin-0

Einstein frame
$$\begin{cases} \tilde{g}_{\mu\nu} \equiv A^2(\varphi)\, g_{\mu\nu} \\ \phi^2 \equiv A^{-2}(\varphi)\, G_*^{-1} \\ \tilde{V}(\phi) \equiv A^{-4}(\varphi)\, V(\varphi) \end{cases}$$

$$\alpha(\varphi) \equiv \frac{d}{d\varphi} \log A(\varphi)$$

taking $\alpha^2(\varphi) = \dfrac{1}{2\omega(\phi)+3}$

$$S_{grav}^{\text{"Einstein frame"}} = \frac{1}{16\pi G_*} \int d^4x \sqrt{-g} \left[R - 2g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi - 2V(\varphi) \right]$$

but now S_{matter} contains also the scalar field

$$S_{matter}^{\text{Einstein frame}} \left[\psi_m , A^2(\varphi)\, g_{\mu\nu} \right]$$

↙

masses and non-grav. coupl. const. are field-dependent ; G_* time-independent and field eqs. have a simple form

$$
\begin{cases}
R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{T^{\phi}_{\mu\nu}}{M_*^2} + \frac{T_{\mu\nu}}{M_*^2} \\
\partial^2 \phi + \frac{1}{M_*^2} \frac{\partial V}{\partial \phi} = - \frac{1}{M_*^2} \frac{\alpha(\phi)}{\sqrt{2}} T
\end{cases}
$$

$$T \equiv g^{\mu\nu} T_{\mu\nu}$$

$T_{\mu\nu} \equiv \frac{2}{\sqrt{-g}} \frac{\delta S_m}{\delta g^{\mu\nu}}$ matter-energy momentum tensor in the **Einstein frame**

$$T^{\phi}_{\mu\nu} = M_*^2 \partial_\mu \phi \, \partial_\nu \phi - g_{\mu\nu} \left[M_*^2 \frac{g^{\rho\sigma}}{2} \partial_\rho \phi \, \partial_\sigma \phi - V(\phi) \right]$$

when $\alpha(\phi) \to 0$ **ST → GR**

➜ MODIFICATION OF THE HUBBLE PARAMETER $\tilde{H} \equiv \frac{d}{d\tilde{\tau}} \log \tilde{a}$

$d\tilde{\tau} = A(\phi)\, d\tau \qquad \tilde{a} = A(\phi)\, a$

DAMOUR-PICHON

$$\tilde{H}^2 = \frac{H^2}{A^2(\phi)} \left[1 + \alpha(\phi)\, \phi' \right]^2$$

$H \equiv \frac{d}{d\tau} \log a \, ; \; \tilde{H} \equiv \frac{d}{d\tilde{\tau}} \log \tilde{a}$

$\phi' = \frac{d\phi}{d\ldots} \qquad r \equiv \log a / \ldots$

IMPLEMENTATION OF THE DOUBLE ATTRACTOR MECHANISM

$$V(\phi) = \frac{\Lambda^4}{\phi^\delta}$$

$\delta > 0 \Rightarrow$ "TRACKER" SOLUTIONS (attractors in field space)

$\alpha(\phi)$ run-away behavior with positive slope

Ex.: $A(\phi) = 1 + B e^{-\beta\phi}$

$$\Downarrow$$

$$\alpha(\phi) = \frac{\beta B e^{-\beta\phi}}{1 + B e^{-\beta\phi}}$$

$\phi \to \infty \quad \alpha(\phi) \to 0$

ST $\to$ GR

Phenomenological Bounds from

Nucleosynthesis — CMB — GR tests

- Bound on $A(\phi)$ from BBN

$$\tilde{H}^2_{BBN} \simeq A^2(\phi)\,\frac{1}{3M_*^2}\,\tilde{\rho}\Big|_{BBN}$$

$$\frac{\Delta \tilde{H}^2}{\tilde{H}^2}\Big|_{BBN} \equiv \frac{\tilde{H}^2 - \tilde{H}^2_{GR}}{\tilde{H}^2_{GR}}\Big|_{BBN} = \frac{A^2(\phi_{BBN}) - A^2(\phi_0)}{A^2(\phi_0)}$$

$$\Rightarrow \frac{A(\phi_{BBN})}{A(\phi_0)} < 1.08$$

(using the bound $\Delta N_\nu < 1$ for BBN)

GENERAL RELATIVITY TESTS

At the post-newtonian level → deviations from GR may be parametrized in terms of an effective field-dependent newtonian constant

$$G = G(\phi) \equiv G_* A(\phi)^2 \left(1 + \alpha^2(\phi)\right)$$

+2 dimensionless parameters γ_{PN} β_{PN}

$$\gamma_{PN} - 1 = -2 \frac{\alpha^2}{1+\alpha^2} \; ; \quad \beta_{PN} - 1 = \frac{k \alpha^2}{(1+\alpha^2)^2}$$

$$k \equiv \partial\alpha / \partial\phi$$

RECENT SEVERE BOUND ON $\gamma_{PN} - 1$ FROM CASSINI MISSION

$$\gamma_{PN} - 1 = (2.1 \pm 2.3) \times 10^{-5}$$

→ β large

→ B very small → $\alpha \to 0$ ST → GR

BOUND FROM THE CMB POWER SPECTRUM

main change w.r.t. theory of DE based on GR is due to a difference in the expansion rate affecting the angular scale of anisotropies

Riazuelo, Uzan; Chen, Kamionkowski; Perrotta, Baccigalupi, Matarrese

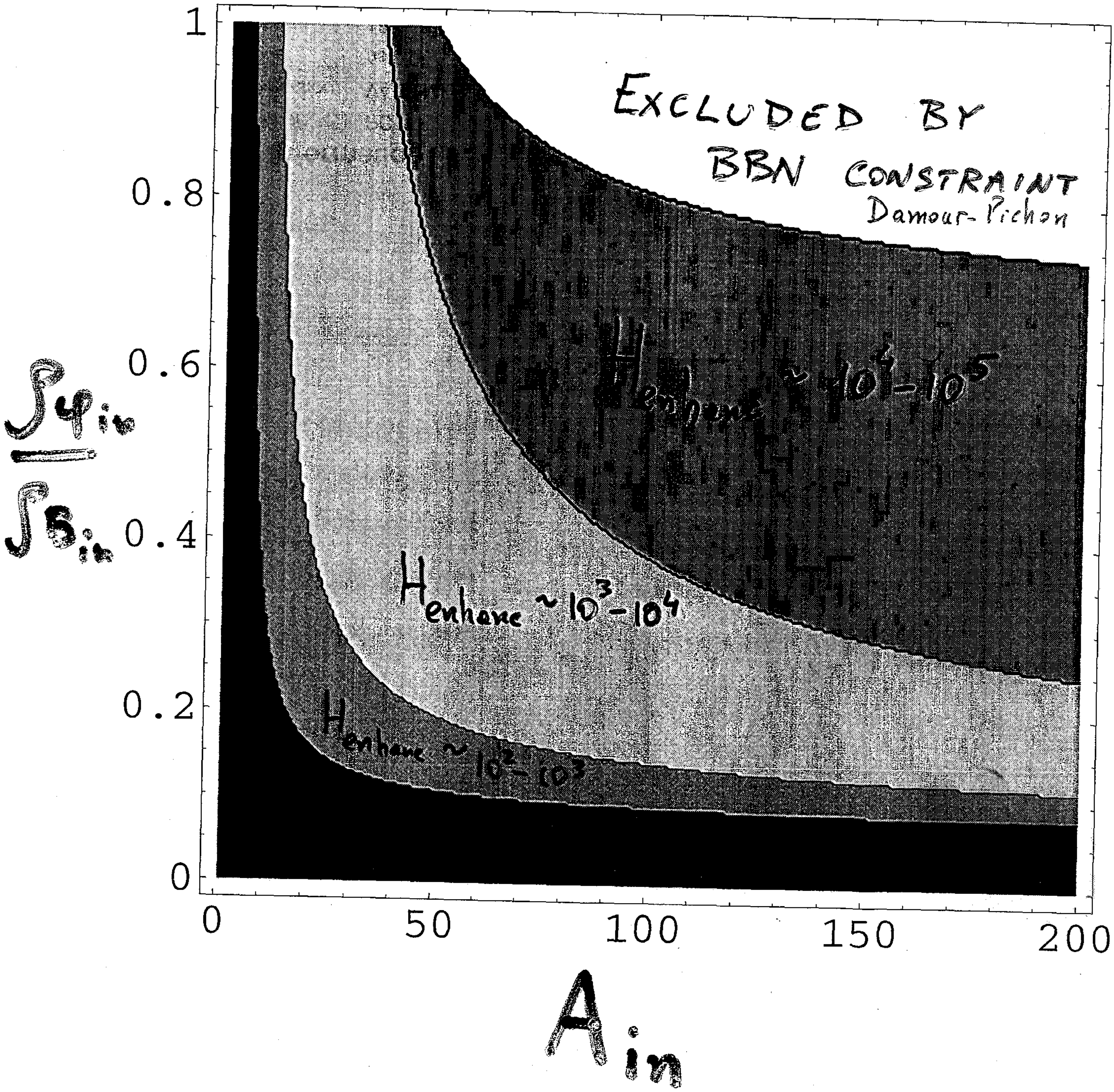
$$\frac{\Delta \ell_{peak}}{\ell_{peak}} \simeq \frac{4}{3} \frac{A(\tilde{a}_{dec}) - 1}{A(\tilde{a}_{dec})}$$

$\Longrightarrow$ once the BBN bound on A has been imposed $\rightarrow$ $A(\tilde{a}_{dec})$ is so close to 1 that shifts in the peak multiples are smaller than the exp. error

CMB spectrum does NOT provide significant bounds on the scenario we study here

ENHANCEMENT OF H at $T \sim 10$ GeV in ST theories of Gravity $\lesssim T^{x}_{freeze\text{-}out}$

$\beta = 6$

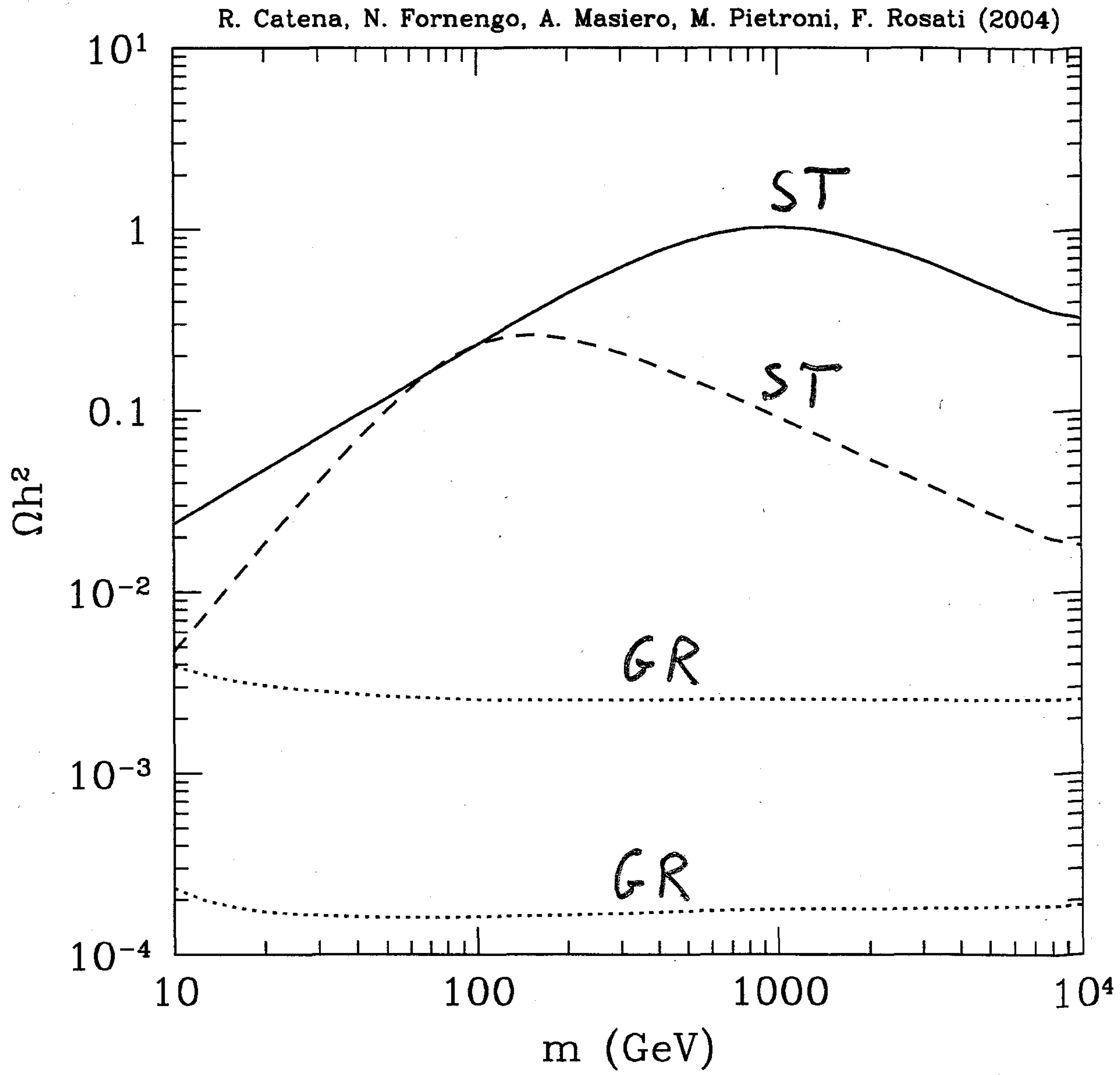


FORNENGO, CATENA, A.M., PIETRONI, ROSATI

EXAMPLE: χ relic abundance in the cases

$\langle \sigma_{ann} v \rangle \equiv a = 10^{-7}$ GeV ———

$\langle \sigma_{ann} v \rangle \equiv \frac{b}{x} = 10^{-4}$ GeV$/x$ - - - - -



$\Longrightarrow \Omega^{\chi}_{CDM} h^2 \big|_{GR}$ too small $< 10^{-2}$

jumps up to $\Omega^{\chi}_{CDM} h^2 \big|_{ST} \sim 0.1$ in ST

SHARING THE UNIVERSE ENERGY BUDGET

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

FLAT UNIV $\rightarrow k = 0$ $\qquad \rho = \rho_c = \frac{3H^2}{8\pi G} = 1.88 \cdot 10^{-29} h^2 \, g\,cm^{-3}$

$\Omega_i \equiv \rho_i / \rho_c$ $\qquad = (2.73 \pm 0.36) \times 10^{-11} eV^4$

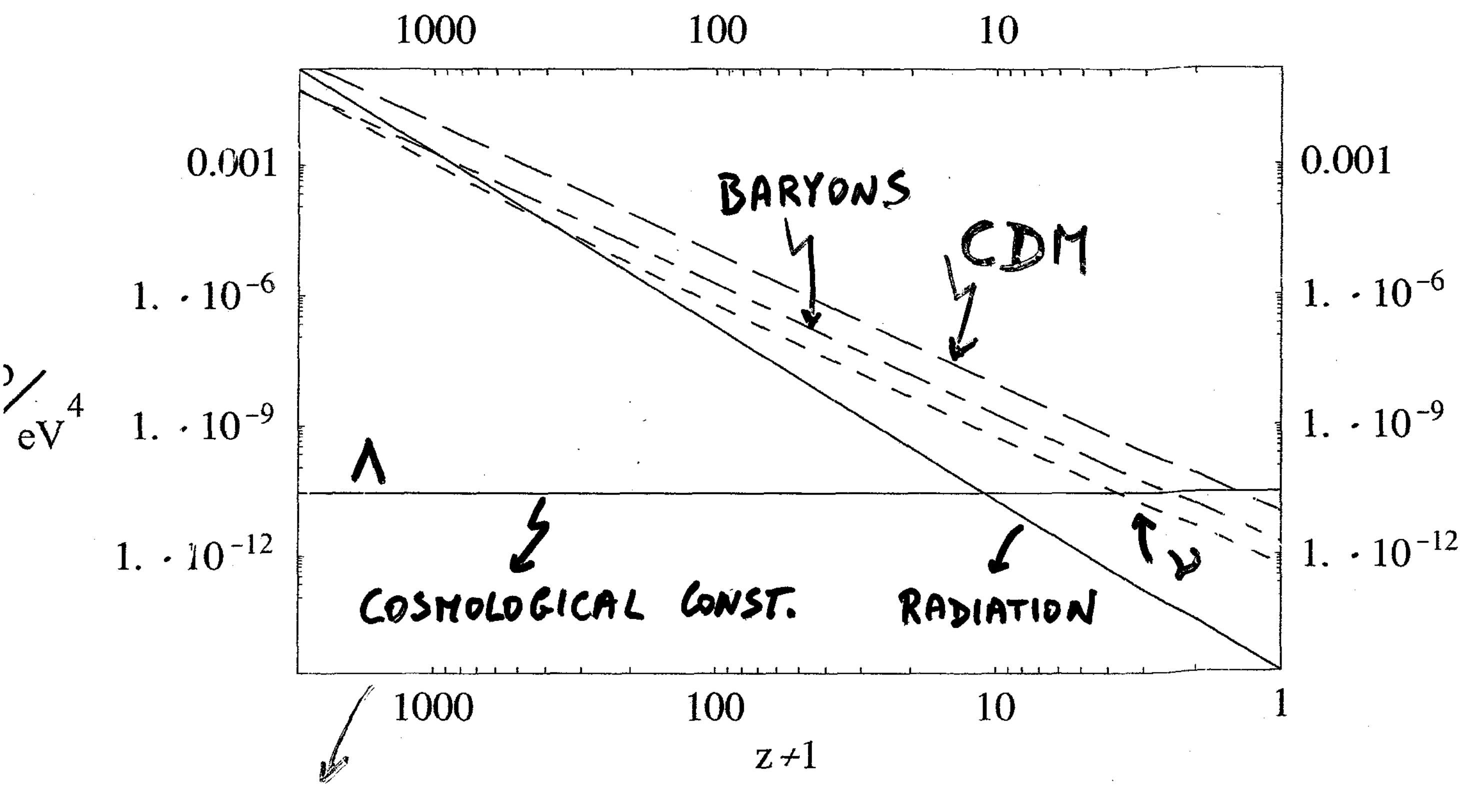
5 SHARE HOLDERS :

BARYONS, PHOTONS, NEUTRINOS + DARK MATTER + DARK ENERGY

- $\Omega^\circ_\gamma \sim 5 \times 10^{-5}$
- $\Omega^\circ_B \sim 5 \times 10^{-2}$
- $7 \times 10^{-4} < \Omega_\nu < 2 \times 10^{-2}$
- $\Omega_{DM} \sim 0.3$
- $\Omega_{DE} \sim 0.7$

COSMOLOGICAL ENERGY DENSITIES AS A FUNCTION OF REDSHIFT IN THE ΛCDM MODEL

FARDON, NELSON, WEINER



$z \simeq 1100$ from CMB → DM dominance

$$\frac{\rho_\Lambda}{\rho_{DM}} \sim \frac{1}{3\times 10^8} \quad \text{at recombination}$$

$$\frac{\rho_\Lambda}{\rho_{DM}} \sim 2 \div 3 \quad \text{today}$$

Domande:

1) ρ_{DE} tracking ρ_B

DE ⟷ TRACKING

- DM ?
- BARYONS ?
- RADIATION ?
- NEUTRINOS

$$\rho_{DARK} = \rho_{\nu} + \rho_{DE}$$

ρ_{DE} ↓ ex: quintessence

FARDON, NELSON, WEINER

FNW PROPOSAL

$\rho_{\nu}^{0} \sim \rho_{\Lambda}^{0}$ within a factor of 10^3

is NOT a coincidence ⇒ but a relationship holding over a large portion of the history of the Universe

m_ν ?

$m_\nu \propto \frac{1}{n_\nu}$ + effect of ν clustering

when ν becomes non-relativ.

PECCEI $\Rightarrow$ ν's cluster, i.e. gravity pulls some ν into existing DM halos

ex: $m_\nu = 0.6\,\text{eV}\big|_{\text{at } z=1}$ $\quad z = \frac{T}{T_0} - 1 \quad T_{z=1} = 2T_0$

ν clustering produces an overdensity of ~ 30 in the local group

$$m_\nu^0\Big|_{\text{in our vicinity}} \sim 0.6 \times 2^3 \times \frac{1}{30} \sim 0.15\,\text{eV}$$

$$m_\nu^0\Big|_{\text{outside gravit. bound systems}} \sim 0.6 \times 2^3 \sim 5\,\text{eV}$$

$\hookrightarrow w \gtrsim -0.8$

in the non-relativistic limit $\Rightarrow \rho_\nu = m_\nu n_\nu$

$$V(m_\nu(\phi)) = m_\nu(\phi)\, n_\nu + V_0(m_\nu(\phi))$$

V_0: SCALAR POTENTIAL

FNW, Kaplan, Nelson, Weiner

$m_\nu(\phi)\, n_\nu$: THERMAL BACKGROUND NEUTRINOS ACT AS A SOURCE DRIVING $m_\nu \downarrow$

Assume $V_0(m_\nu(\phi))$ is MINIMIZED FOR LARGE $m_\nu \uparrow$

$\Rightarrow$ COMPETITION BETWEEN $m_\nu n_\nu$ and V_0

$\rightarrow$ minimum at an intermediate value of m_ν

Universe expansion $\Rightarrow$ ν density $\downarrow$ $\Rightarrow$ source term $\downarrow$ $\Rightarrow$ m_ν is driven to larger values

Assume: ρ_{DARK}, i.e. $V(m_\nu)$ is **STATIONARY** w.r.t. variations in m_ν:

$$V'(m_\nu) = n_\nu + V_0'(m_\nu) = 0$$

+ conservation of energy: $\dot{\rho} = -3H(\rho + p)$

$w \equiv \frac{p_{dark}}{\rho_{dark}}$

$$w + 1 = \frac{\Omega_\nu}{\Omega_\nu + \Omega_\phi} = \frac{m_\nu n_\nu}{m_\nu n_\nu + V_0(m_\nu)} \Rightarrow m_\nu \sim \frac{1}{n_\nu}$$

CONCLUSIONS

- STRONG EVIDENCE FOR NON-BARYONIC DM ⇒ EVIDENCE FOR NEW PHYSICS BSM

- WIMPs ⇒ LSP → SUSY } DIRECT - INDIRECT DM SEARCHES / LHC } COMPLEM. IN SUSY SEARCH

- $\Omega_{DE} \sim 2/3 \qquad \Omega_{DM} \sim 1/3$

  - WHAT IS DE? COSM. CONST., DYNAMICAL QUANTITY (ex. SCALAR QUINTESSENCE)

    ...

  - $\Omega_{DE} \sim 2\, \Omega_{DM} \big|_{TODAY}$ WHY TODAY PROBLEM

    ARE DE - DM SOURCES "CORRELATED"?

    DE - DM INTERACTION?

    DE presence can largely influence DM even though no direct DE-DM interaction exists → ex. scalar-tensor theories of gravity

OUTLOOK

THEORY
Superstrings, Brane theories

RARE PHYSICS
FCNC, $\not{CP}$, $g-2$

NEW PHYSICS AT THE TEV SCALE

HIGH ENERGY PHYSICS

LHC
ILC
ν PHYSICS

ASTROPARTICLE PHYSICS

- CMB: WMAP, PLANCK
- γ: GLAST, AGILE, MAGI
- ANTIM: PAMELA, AMS
- ν: ANTARES, NEMO, AMANDA, ICECUBE...
- DIRECT DM SEARCHES