LA THUILE
27/2 → 5/3, 2005

DARK ENERGY

and

NEW PARTICLE PHYSICS

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- DARK MATTER and DARK ENERGY

ARE THEY CORRELATED?

(DM-DE INTERACTIONS, INFLUENCE OF DE ON PRESENT DM ABUNDANCE, ρ_{DE} TRACKING ρ_{DM} or ρ_{ν} ...)

The NEW COSMOLOGY
at the beginning of the 21st century

- FLAT, CRITICAL DENSITY UNIVERSE
- EARLY PERIOD OF RAPID EXPANSION (INFLATION)
- DENSITY INHOMOGENEITIES PRODUCED FROM QUANTUM FLUCTUATIONS DURING INFLATION
- COMPOSITION: 2/3 DARK ENERGY; 1/3 DARK MATTER; 1/200 BRIGHT STARS
- MATTER CONTENT: $\Omega_{CDM} \sim 30\%$ $\Omega_B \sim 5\%$ $\Omega_\nu > 7 \cdot 10^{-4}$

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 $\rightarrow k = 0$

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

$$= (2.73 \pm 0.36) \times 10^{-11}\, eV^4$$

$\Omega_i \equiv \rho_i / \rho_c$

5 SHARE HOLDERS :

BARYONS, PHOTONS, NEUTRINOS + DARK MATTER + DARK ENERGY

- $\Omega^0_\gamma \sim 5 \times 10^{-5}$
- $\Omega^0_B \sim 5 \times 10^{-2}$
- $7 \times 10^{-4} < \Omega_\nu < 2 \times 10^{-2}$
- $\Omega_{DM} \sim 0.3$
- $\Omega_{DE} \sim 0.7$

ΛCDM after WMAP

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

$$\swarrow \quad \searrow$$

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

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

$$\Uparrow$$

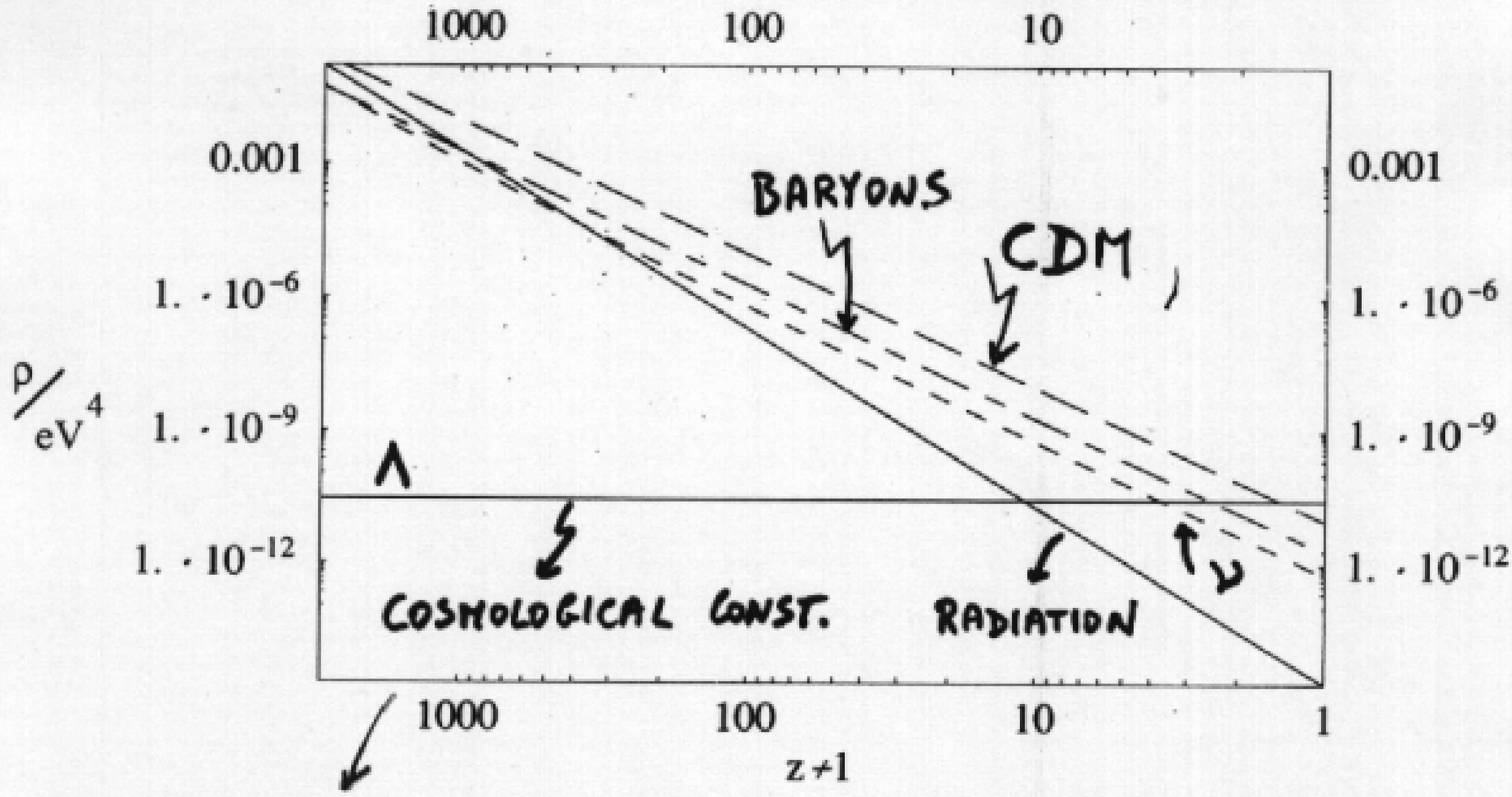
consistent with what inferred from earlier observations, but significantly more precise

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

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

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

FARDON, NELSON, WEINER



$z \simeq 1100$ from CMB $\rightarrow$ DM dominance

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

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

THE DE PUZZLE

- MISINTERPRETATION OF THE DATA ?

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

$$\underbrace{\text{1) SNe data} \quad \text{2) CMB } \Omega_T = 1 \quad \text{3) measures of } \rho_{DM}}$$

$\Downarrow$

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

$\Rightarrow$ **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 ?

$\rightarrow$ 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-DIMENS at larger distances → universe acceleration at late times

Dvali, Gabadadze, Porrati
Arkani-Hamed, Dimopoulos, Dvali, Gabadadze
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

IF : UNIV. IS HOMOGENEOUS, ISOTROPIC AND ACCELERATING

IF : GENERAL RELATIVITY HOLDS

$\Downarrow$

NEED FOR SOME SORT OF DARK ENERGY SOURCE

$\Downarrow$

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:

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

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

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

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

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

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

acceleration ($\dot{a}$ increasing) in an expanding universe $\Rightarrow$ if ρ falls off more slowsly 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 theory)

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

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

$\downarrow$

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 $\rightarrow$ 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

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

↳ when WIMPS decouple

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

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

SALATI 6

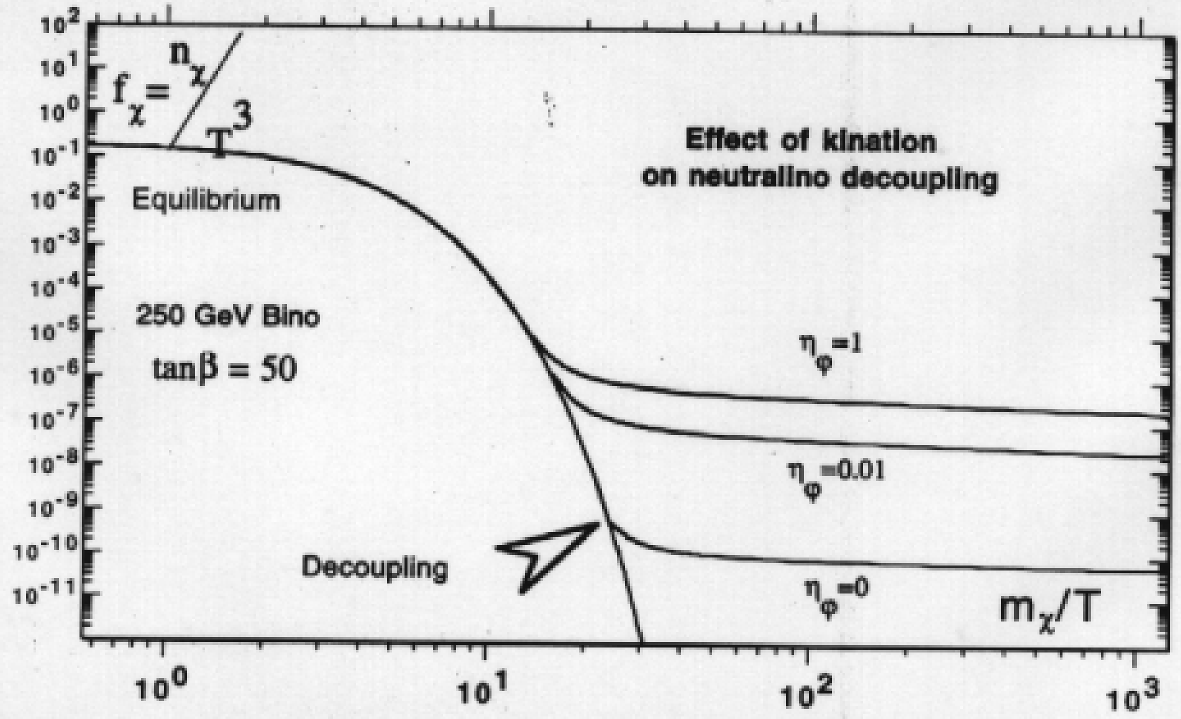


FIG. 1. Neutralino codensity as a function of the mass-to-temperature ratio $y = m_\chi/T$ for three different values of the kination parameter. For $\eta_\Phi = 0$, we recover the standard radiation dominated cosmology whereas for $\eta_\Phi = 0.01$ and $\eta_\Phi = 1$, the expansion rate H is significantly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

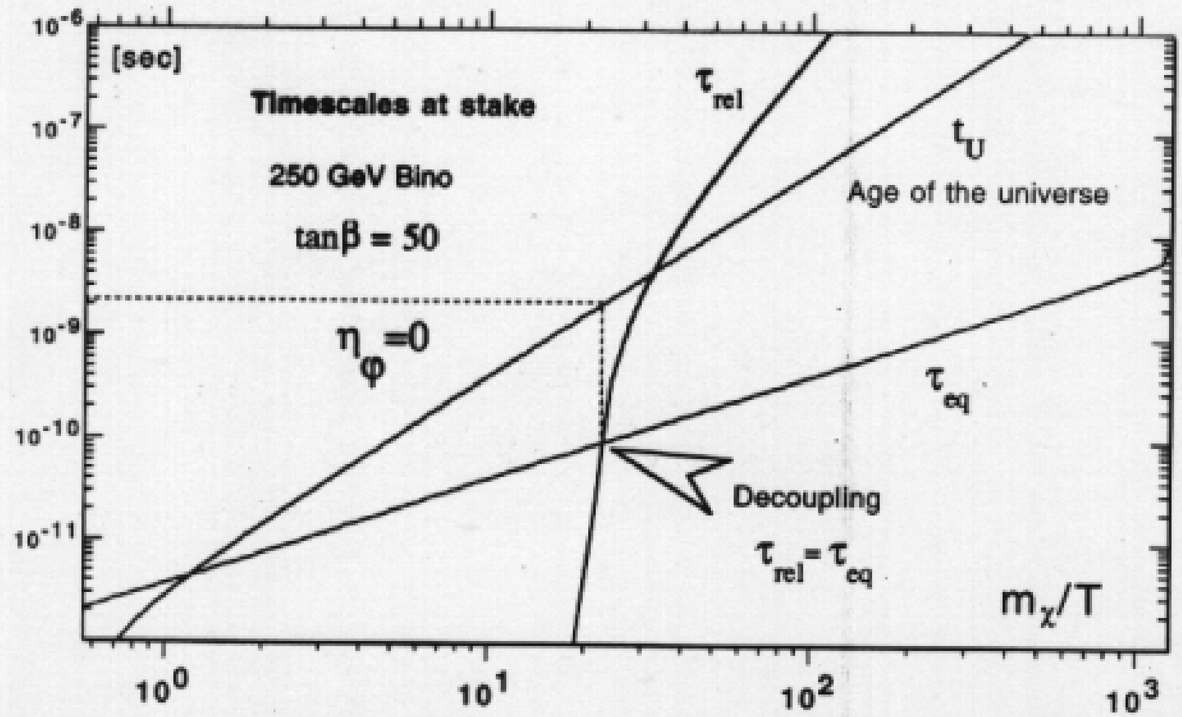


FIG. 2. The age of the universe t_U as well as the typical time scales τ_{rel} and τ_{eq} are featured as a function of the mass-to-temperature ratio $y = m_\chi/T$. The freeze-out occurs at $y_F = 22.7$ when τ_{rel} overcomes τ_{eq}. The standard radiation dominated cosmology is assumed here with $\eta_\Phi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

"HARMLESS" QUINTESSENCE

$\swarrow$

NO EQUIVALENCE PRINCIPLE
VARYING COUPLINGS ... PROBLEMS

$\Downarrow$

SCALAR-TENSOR (ST) GRAVITY THEORY

$\Rightarrow$ 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)

$\Rightarrow$ 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 $\begin{cases} \rightarrow \text{TRACKER SOLUTION} \\ \quad \rightarrow \text{accelerated Univ} \\ \rightarrow \text{Towards GR} \rightarrow \text{ultra light scalars safe} \end{cases}$

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

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 $\begin{cases} \omega(\phi) = \omega \text{ const.} \\ \tilde{V}(\phi) = 0 \end{cases}$

$\tilde{T}^{\mu\nu} = \dfrac{2}{\sqrt{-\tilde{g}}}\dfrac{\delta S_m}{\delta\tilde{g}_{\mu\nu}}$ is conserved, masses and NON-GRAVIT. couplings are

$\tilde{g}_{\mu\nu}, \phi$ "physical" $\rightarrow$ time independent, non-grav.
Jordan variables physics laws take usual form

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

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

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

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

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

$T_{\mu\nu} \equiv \dfrac{2}{\sqrt{-g}} \dfrac{\delta S_m}{\delta g^{\mu\nu}}$ 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 $\tilde{H} \equiv \dfrac{d}{d\tilde{\tau}} \log \tilde{a}$

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

DAMOUR-PICHON

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

$\phi' = \frac{d}{r}\phi \quad r \equiv \log a/a_0$

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

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

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

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

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

(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

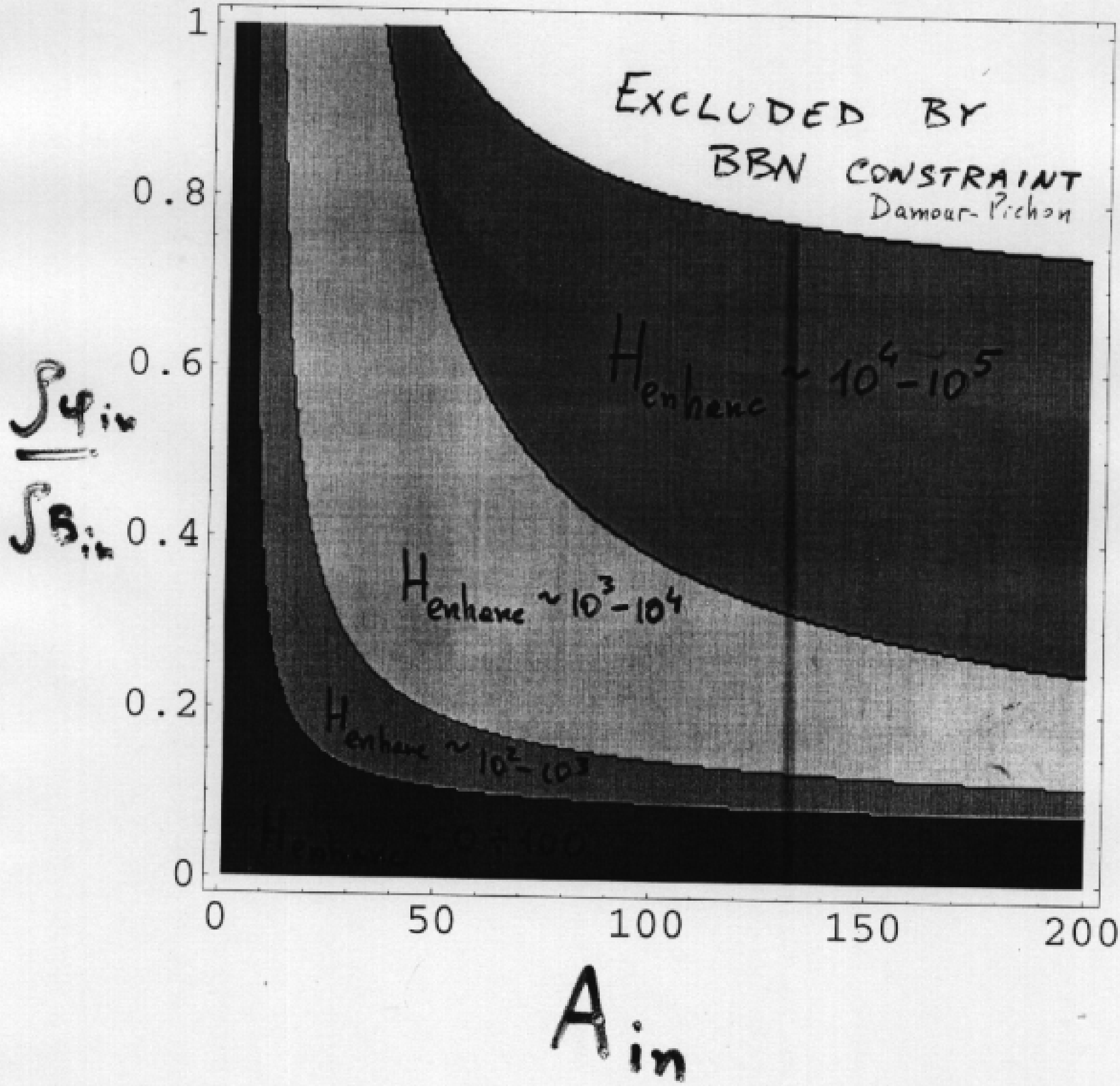
$$\frac{\Delta l_{peak}}{l_{peak}} \simeq \frac{4}{3}\,\frac{A(\tilde{a}_{dec})-1}{A(\tilde{a}_{dec})}$$

$\Longrightarrow$ 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 $\lesssim T_{freeze\text{-}out}^{x}$

$\beta = 6$



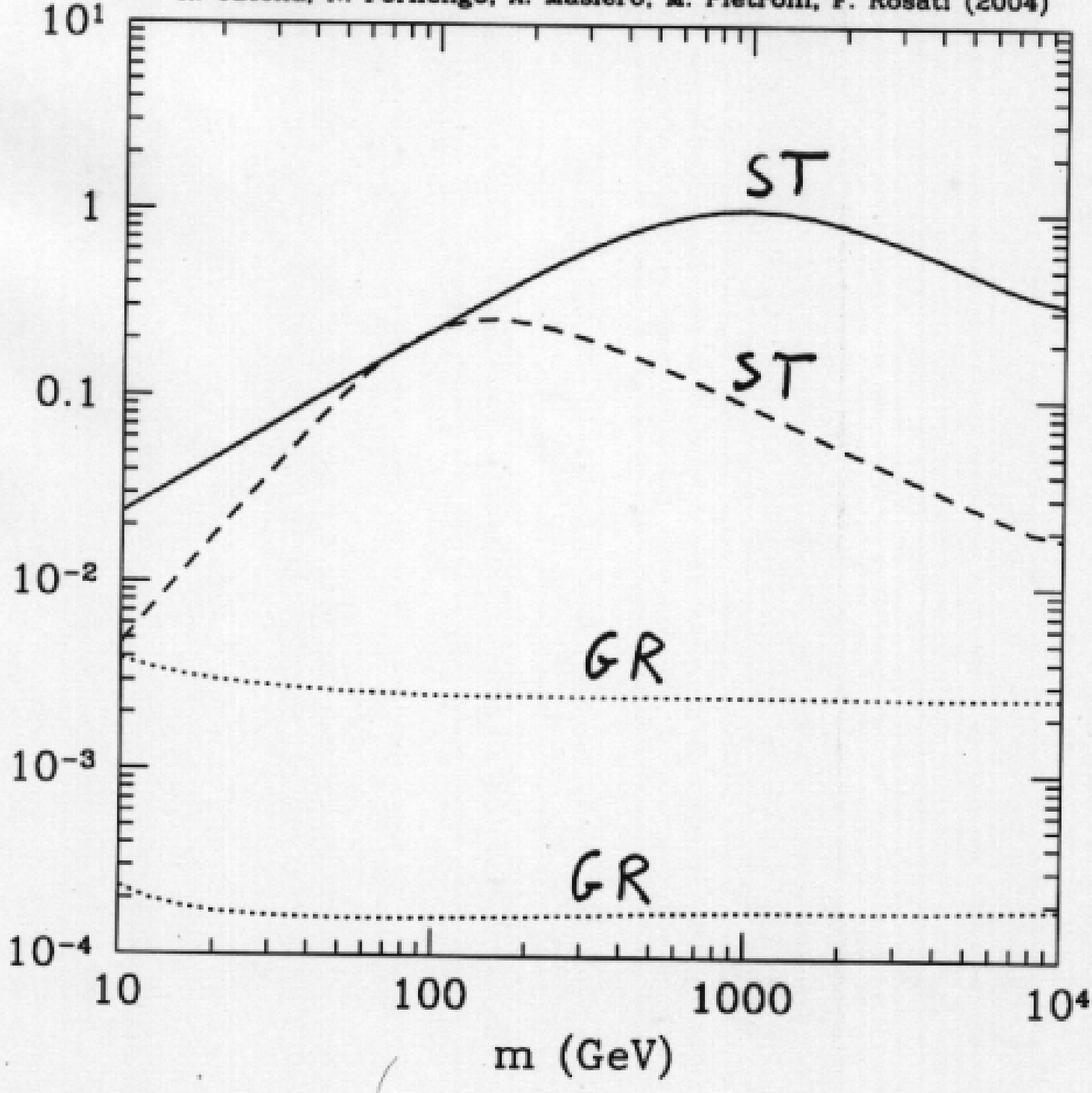
FORNENGO, CATENA, A.M., PIETRONI, ROSATI

EXAMPLE: χ relic abundance in the cases

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

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

R. Catena, N. Fornengo, A. Masiero, M. Pietroni, F. Rosati (2004)



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

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

(THERMAL) LEPTOGENESIS AND GRAVITINO PROBLEM revisited in ST THEORIES OF GRAVITY

WORK IN PROGRESS BY

CATENA, KITANO, A.M., MURAYAMA, PIETRONI

GRAVITINO PROBLEM: gravitinos produced by thermal scatterings in plasma at the REHEATING after inflation

$Y_{3/2} \equiv n_{3/2}/s$ (s entropy density)

$$Y_{3/2} \simeq 10^{-11} \left(\frac{T_R}{10^{10}\,\mathrm{GeV}} \right)$$ gravitino abundance

KAWASAKI, MOROI

$m_{3/2} \sim 10^2 - 10^3$ GeV range in supergravity

$$\tau_{3/2} \simeq \frac{M_{Pl}^2}{m_{3/2}^3} \simeq 10^5 \left(\frac{1\,\mathrm{TeV}}{m_{3/2}} \right)^3 \mathrm{sec.}$$

→ gravitino decays after BBN

→ PHOTO-DISSOCIATION OF LIGHT NUCLEI

TO AVOID CLASH WITH BBN SUCCESSFUL PREDICTIONS

$\Rightarrow$ LIMIT GRAVITINO ABUNDANCE $\Rightarrow$ HENCE

LIMIT T_R

CYBURT, ELLIS, FIELDS, OLIVE
KAWASAKI, KOHRI, MOROI

BUT LEPTOGENESIS $\longrightarrow$ $M_{\nu_R} > 10^9$ GeV

CLASH BETWEEN UPPER LIMIT ON T_R

AND LOWER LIMIT ON M_{ν_R} (?)

How ST theories of gravity can come to our rescue

if $A(\varphi) \sim 1$ at gravitino <u>production</u>

but $A(\varphi) \gg 1$ at gravitino <u>decay</u>

gravitino decays when $\underset{\propto 1/M_{Pl}^2}{\Gamma_{3/2}} = \underset{\propto 1/M_{Pl}}{H}$

$\rightarrow$ large $A(\varphi)$ $\rightarrow$ smaller effective M_{Pl} $\rightarrow$ gravitinos can decay before BBN for $A(\varphi) \sim 10^2 - 10^3$

$$DE \xleftrightarrow[\text{TRACKING}]{} \begin{cases} \text{DM} & ? \\ \text{BARYONS} & ? \\ \text{RADIATION} & ? \\ \text{NEUTRINOS} & \end{cases}$$

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

FARDON, NELSON, WEINER

ex: quintessence

FNW PROPOSAL

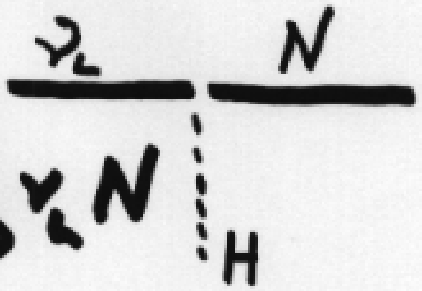
$\rho_\nu^\circ \sim \rho_\Lambda^\circ$ within a factor of 10^3

is NOT a coincidence $\Rightarrow$ but a relationship holding over a large portion of the history of the Universe

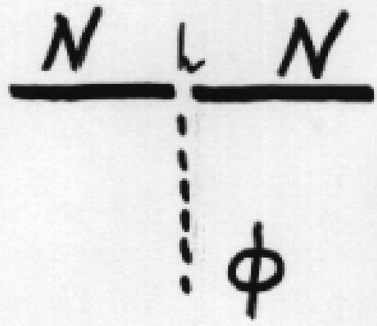
m_ν as a dynamical field
function of a scalar field ϕ

$m_\nu(\phi)$

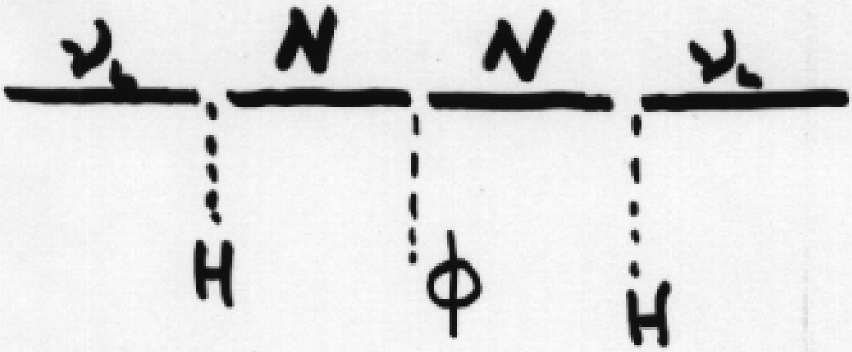
Ex.:



$m_D \nu_L N$



$\underbrace{M(\phi) NN}_{M(\phi) = h\phi}$



$$\Rightarrow \frac{m_D^2}{M(\phi)} \nu_L \nu_L$$

ex: $M(\phi) = h\phi$ or $M(\phi) = \bar{M} e^{\phi^2/f^2}$

or ...

$$\mathcal{L} = m_D \nu_L N + M(\phi) NN + h.c. + \Lambda^4 \log\left(1 + \left|\underline{M(\phi)}\right|\right)$$

$$\to \mathcal{L}_{eff} = \left(m_D^2 / M(\phi)\right) \nu_L \nu_L + h.c. + \Lambda^4 \log\left(M(\phi)/\mu\right)^4$$

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

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

SCALAR POTENTIAL

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

$w \equiv \frac{p_{dark}}{\rho_{dark}}$ $\quad w + 1 = \frac{\Omega_\nu}{\Omega_\nu + \Omega_\phi} = \frac{m_\nu n_\nu}{m_\nu n_\nu + V_0(m_\nu)} \Rightarrow m_\nu \sim \frac{1}{n_\nu}$

m_ν ?

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

when ν becomes non-relativ.
$\Rightarrow$ ν's cluster, i.e. gravity pulls
some ν into existing DM halos

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

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

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

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

$\hookrightarrow w \simeq -0.8$

$$\mathcal{L} = \mathcal{L}_\nu + \mathcal{L}_\phi + \underbrace{m(\phi)\,\bar{\nu}\nu}_{\text{coupl. } \nu\text{-quintessence via } \nu \text{ mass term}}$$

$$\mathcal{L}_\nu \rightarrow \bar{\nu}\, i \not{\partial}\, \nu \qquad \mathcal{L}_\phi \rightarrow \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V_0(\phi)$$

FNW DE MODELS ARE SPECIFIED BY THE FORM OF

$$V_0(\phi)\ ,\ m(\phi)$$

Eq. of motion of ϕ: $\ddot{\phi} + 3H\dot{\phi} + \frac{dV_0}{d\phi} + \frac{dV_I}{d\phi} = 0$

$$\frac{dV_I}{d\phi} = \frac{dm(\phi)}{d\phi}\, n_\nu \left\langle \frac{m}{E} \right\rangle$$

- RELATIVISTIC ν : $\frac{dV_I}{d\phi}$ very suppressed

  $\rightarrow$ DE - ν DECOUPLE

- NON-RELATISTIC ν :

$$V_{eff}(\phi) = V_0(\phi) + n_\nu\, m_\nu(\phi)$$

ENERGY FOR EACH COMPONENT DOES NOT CONSERVE

$$\begin{cases} \dot{\rho}_\nu + 3H\rho_\nu = n_\nu \dfrac{dm_\nu}{d\phi}\dot{\phi} \\ \dot{\rho}_\phi + 3H\rho_\phi(1+w_\phi) = -n\dfrac{dm_\nu}{d\phi}\dot{\phi} \end{cases}$$

$$\Rightarrow \begin{cases} \dot{\rho}_\nu + 3H\rho_\nu(1+w_\nu^{eff}) = 0 \\ \dot{\rho}_\phi + 3H\rho_\phi(1+w_\phi^{eff}) = 0 \end{cases}$$

Bi, Feng, Li, Zhang

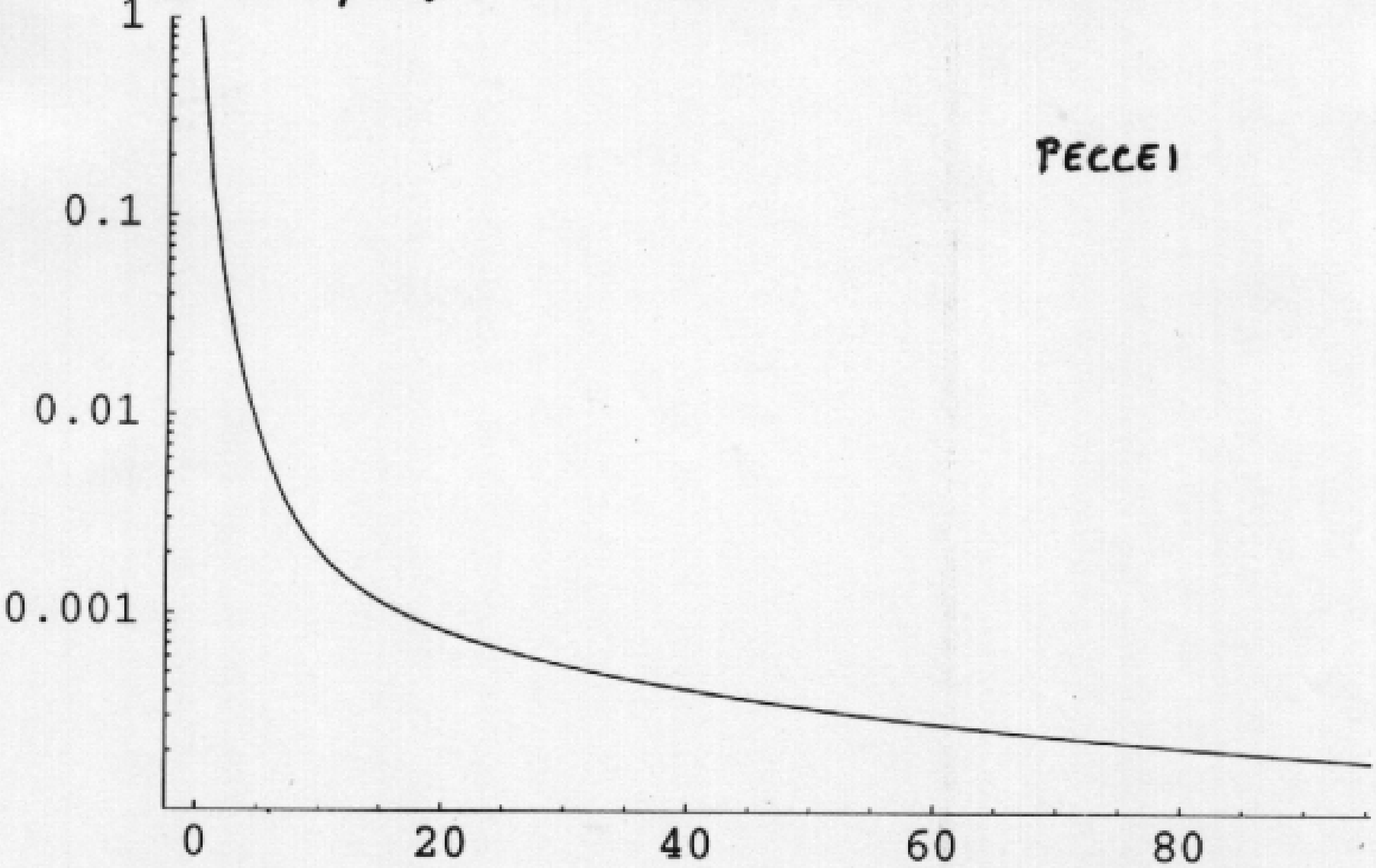
POWER-LAW POTENTIAL $V(m_\nu) \propto m_\nu^{\frac{1+w_0}{w_0}}$

$w_0 = -0.9$

$m_\nu^0 n_\nu^0 = 0.1\, \rho_{dark}^0 \qquad V(m_\nu^0) = 0.9\, \rho_{dark}^0$

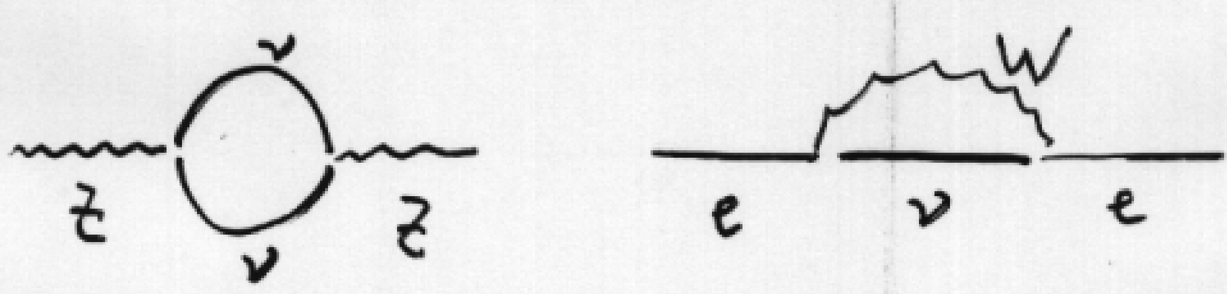
$\rho_{dark}^0 = 0.7\, \rho_c$

$m \equiv m_\nu / m_\nu^0 \qquad m_\nu^0 = 3.09$ eV



$z = \frac{T}{T_0} - 1$

ϕ - MATTER INTERACTIONS



corrections depend on ϕ at $O(G_F m_\nu^2) \rightarrow$ in matter with density of $3 g/cm^3$ effect on $V(\phi)$ comparable to that of the cosmic ν background

Kaplan - Nelson - Weiner

if N lighter than $M_W \rightarrow$ further suppression of $O(G_F^2 m_N^2(\phi)) \Rightarrow$ very small corrections

NON-RENORM. OPER. COUPLING DE TO MATTER

$$h_e \phi \bar{e} e \qquad h_p \phi p \bar{p} \qquad h_n \phi n \bar{n}$$

$$\downarrow \qquad\qquad \downarrow \qquad\qquad \downarrow$$

$$\lambda_e \frac{m_e}{M_P} \qquad \lambda_p \frac{m_p}{M_P} \qquad \lambda_n \frac{m_n}{M_P}$$

deviations from $\frac{1}{r^2}$ for gravit. inter. $\Rightarrow \lambda_{n,p} < 10^{-2}$ for $m_\phi \gtrsim 10^{-11}$ eV

Adelberger, Heckel, Nelson

tests of the equivalence principle $\Rightarrow \lambda_n \simeq \lambda_p < 10^{-2}$ for $m_\phi \gtrsim 10^{-8}$ eV

Su et al. ; Smith et al.

VARIATION OF THE FUNDAMENTAL COUPLING CONSTANTS

$$\frac{1}{e^2(\phi)} F_{\mu\nu} F^{\mu\nu}$$

possible reconciliation of the bound on the variation of α from a 2 Gyr old natural nuclear reactor on Earth with some claim of increase of α by a fraction $\sim 10^{-5}$ since redshift greater than 0.5

$\Rightarrow$ terrestrial value of α could be $\sim$ const.

but α outside our galaxy cluster could be slightly varying $\Rightarrow$ variation of α with matter density ?

FNW

CONCLUSIONS

- DYNAMICAL EXPLANATION OF DE (ex. SCALAR QUINTESSENCE) MAY ENTAIL PROFOUND CONSEQUENCES ON THE PRESENT AMOUNT AND NATURE OF DM
(ex.: SCALAR-TENSOR THEORIES OF GRAVITY → H DIFFERENT FROM H IN USUAL GR COSMOLOGY → NEW DM CANDIDATES, NEW PROSPECTS FOR LEPTOGEN. ...)

- DIRECT DE-DM, DE-BARYONS, DE-ν INTERACTIONS: DANGEREOUS
(equiv. principle, varying masses and couplings)
but POSSIBLE: ex. ρ_{DE} TRACKING $\rho_\nu \Rightarrow$ VARYING MASS NEUTRINOS