XI Int. Workshop
on ν TELESCOPES

VARYING NEUTRINO MASS
and
DARK ENERGY

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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 $\rightarrow k = 0$

$\Omega_i \equiv \rho_i / \rho_c$

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

$$= (2.73 \pm 0.36) \times 10^{-11} e\ldots$$

5 SHARE HOLDERS :

BARYONS, PHOTONS, NEUTRINO,

+ DARK MATTER + DARK ENERGY

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

ΛCDM after WMAP

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

$$\swarrow \quad \searrow$$

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

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

$$\Uparrow$$

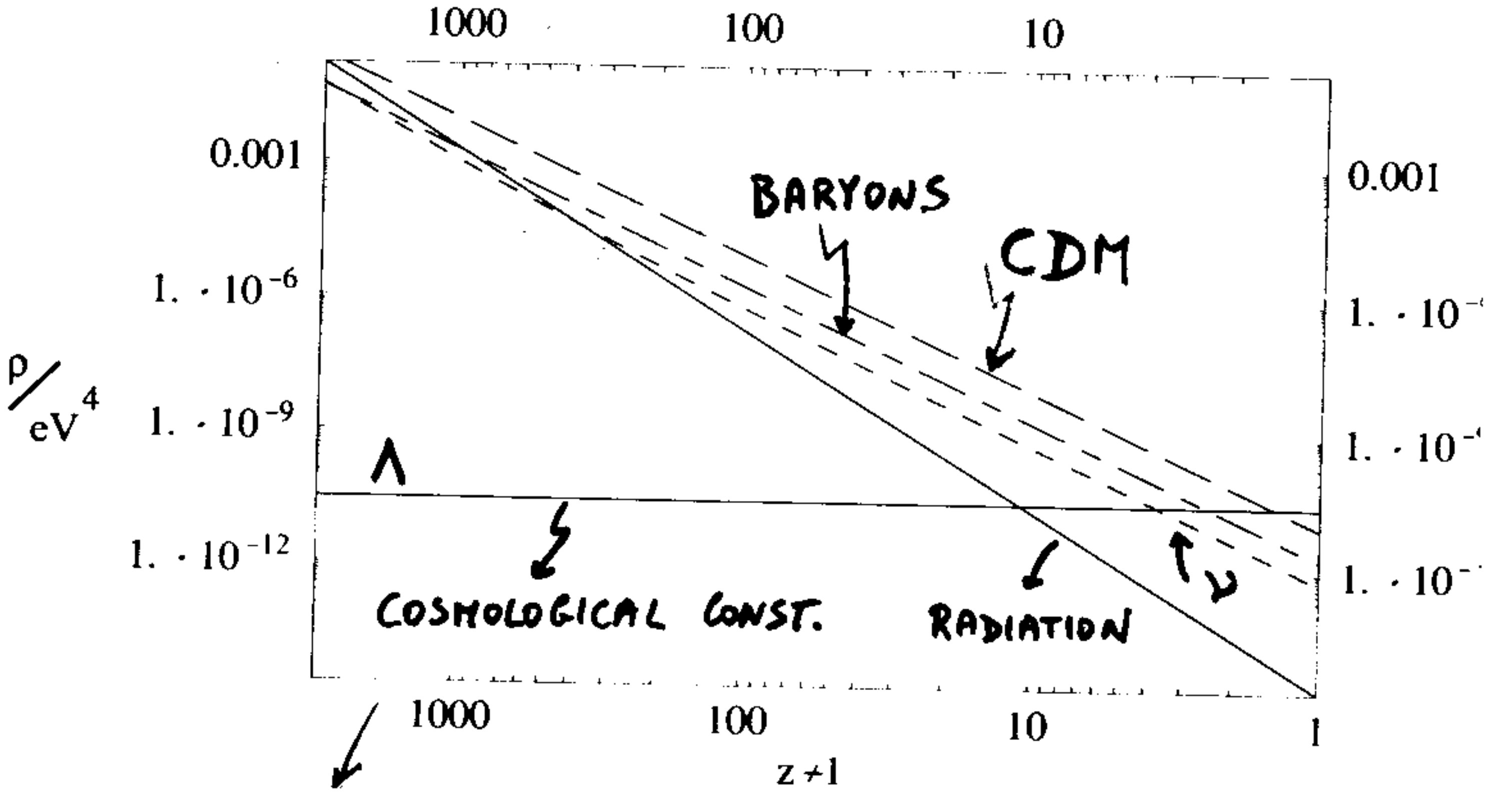
consistent with what inferred from earlier observations, but significantly more precise

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

new (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, WEINE



$z \simeq 1100$ from CMB → DM dominance

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

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

THE DE [illegible]

- **MISINTERPRETATION OF THE DATA (?)**

1) SNe data 2) CMB $\Omega_T = 1$ 3) measures of ρ

$\Downarrow$

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

$\Rightarrow$ [illegible] for an ACCELERATING UNIVERSE

" The lengths to which it seems necessary to go in orde to avoid concluding that the Universe is accelerati 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-DI[illegible] at larger distances → universe acceleration at late times

Dvali, Gabadadze, Porrati
Arkani-Hamed, Dimopoulos, Dvali, G[illegible]
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 SOUR

$\Downarrow$

UNCLUSTERED SMOOTHLY-DISTRIBUTED, PERSISTE
ENERGY DENSITY DOMINATING
THE UNIVERSE ENERGY DENSIT

DARK ENERGY : COSMOLOGICAL CONSTANT

OR

DYNAMICAL DARK ENERGY

Domande:

1) ρ_{DE} ~~Galileo~~ VACUUM ρ_B 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:

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

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

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

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

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

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

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

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

- COSM. CONST. - CONST. VACUUM ENERGY
- SMOOTHLY - DISTRIBUTED SOURCES OF DARK ENERG[Y] VARYING SLOWLY WITH TIME

POSSIBILITY OF FINDING A DYNAMICAL SOLUTION TO THE COINCIDENCE PROBLEM

→ "DE TRACKING SOME MATTE[R] COMPONENT + RECENT TAKEOVE[R] BY DE (for a wide range of param. of the theo[ry]

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

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

$\Downarrow$ 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, Rosat

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

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

DM $\Longleftrightarrow$ DE

DO THEY "KNOW" EACH OTHER ?

- DIRECT INTERACTION ϕ (quintessen
  WITH DM

  ⚠ **DANGER** :

  ϕ very LIGHT

  $m_\phi \sim H_0^{-1} \sim 10^{-33}$ e

  $\Rightarrow$ threat of violation of the equivalence princ
  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

KINATION

DOMINATION BY THE KINETIC ENER
OF THE QUINTESSENCE FIELD ϕ AT
EPOCHS BEFORE BBN, IN PARTICULAR
AT THE TIME WIMPS FREEZE OUT $\rightarrow$ SALA

JOYCE; JOYCE, PROKOPEC; FERREIRA, JOYCE

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

$\hookrightarrow$ assumption: for some time $\dot\phi^2/2$ dominates

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

$\hookrightarrow$ when WIMPS decouple

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

$\Rightarrow$ 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

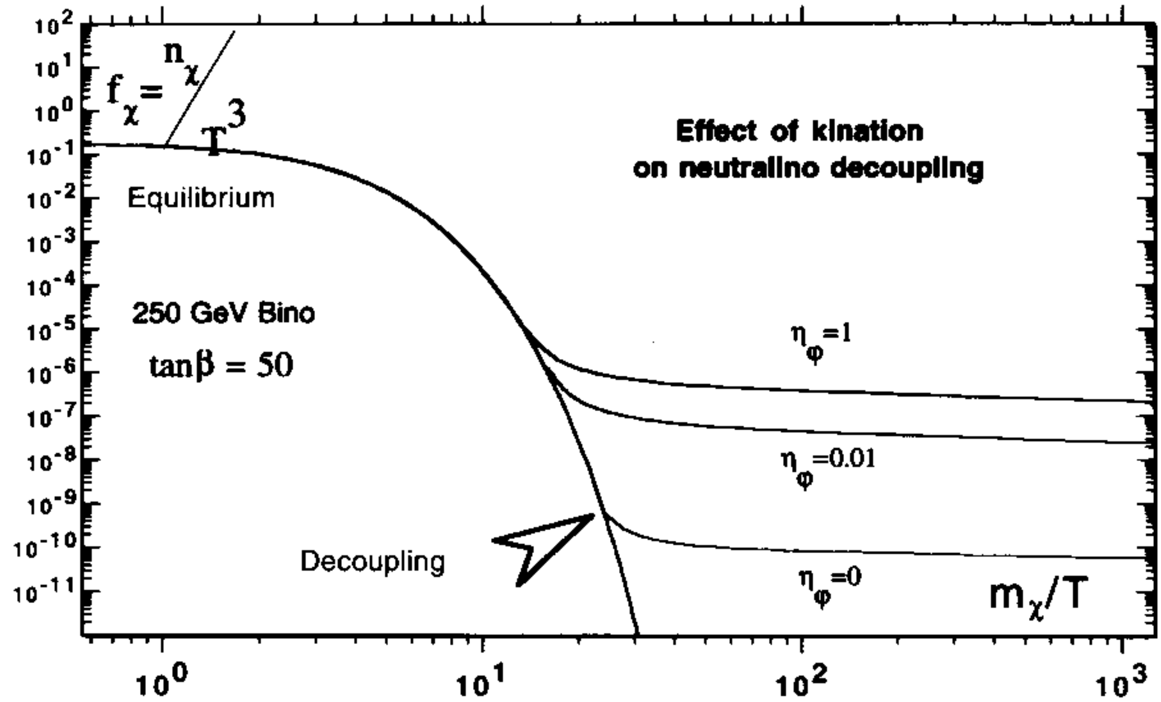


FIG. 1. Neutralino codensity as a function of the mass-to-temperature ratio $y = m_\chi/T$ for three different values of the kination parameter. For $\eta_\Phi = 0$, we recover the standard radiation dominated cosmology whereas for $\eta_\Phi = 0.01$ and $\eta_\Phi = 1$, the expansion rate H is significantly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

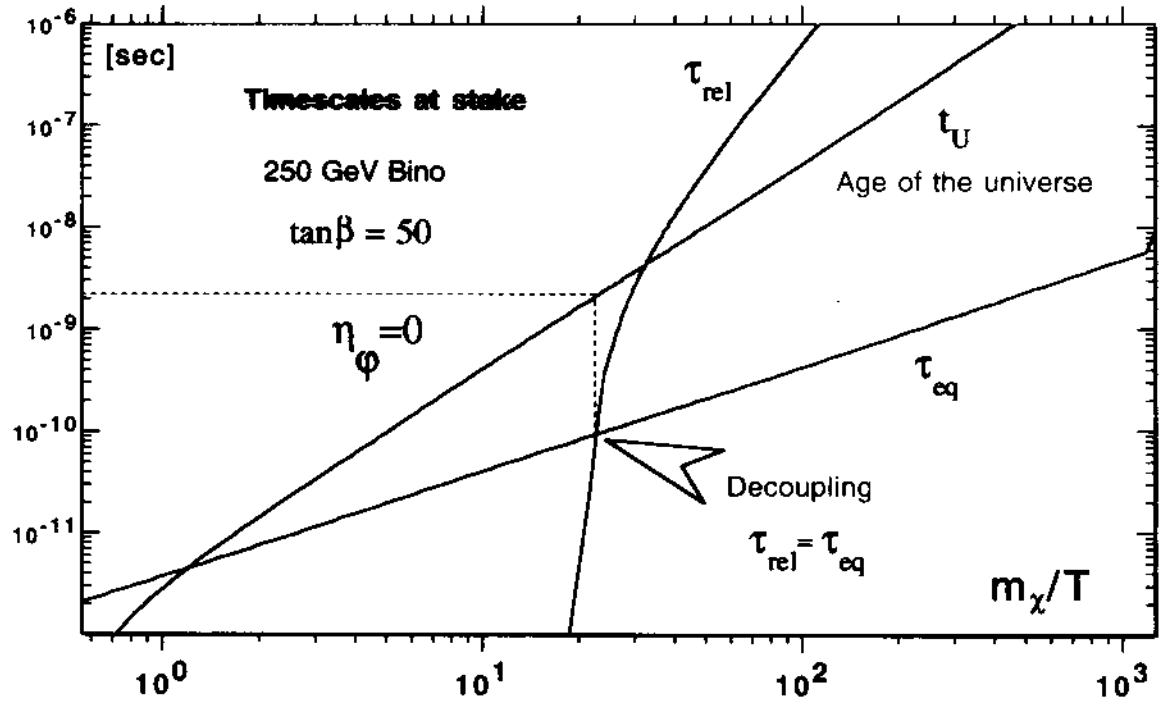


FIG. 2. The age of the universe t_U as well as the typical time scales τ_{rel} and τ_{eq} are featured as a function of the mass-to-temperature ratio $y = m_\chi/T$. The freeze-out occurs at $y_F = 22.7$ when τ_{rel} overcomes τ_{eq}. The standard radiation dominated cosmology is assumed here with $\eta_\Phi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

1 "HARMLESS" QUINTESSENCE

$\Downarrow$

NO EQUIVALENCE PRINCIPLE ... PROBLEMS
VARYING COUPLINGS

$\Downarrow$

SCALAR-TENSOR (ST)
GRAVITY THEORY

$\Rightarrow$ MATTER HAS A PURELY METRIC COUPLING WITH GRAVITY

JORDAN; FIERZ;
BRANS-DICKE

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

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

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

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

ψ_m coupled only to the metric tens
not to ϕ

$\tilde{R}$ = Ricci scalar constructed from the physical metric

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

Jordan-Fierz-Brans-Dicke $\begin{cases} \omega(\phi) = \omega \text{ const.} \\ \tilde{V}(\phi) = 0 \end{cases}$

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

$\tilde{g}_{\mu\nu}, \phi$ "physical" Jordan variables → time independent, non-gra
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 $\alpha^2(\varphi) = \dfrac{1}{2\omega(\phi)+3}$

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

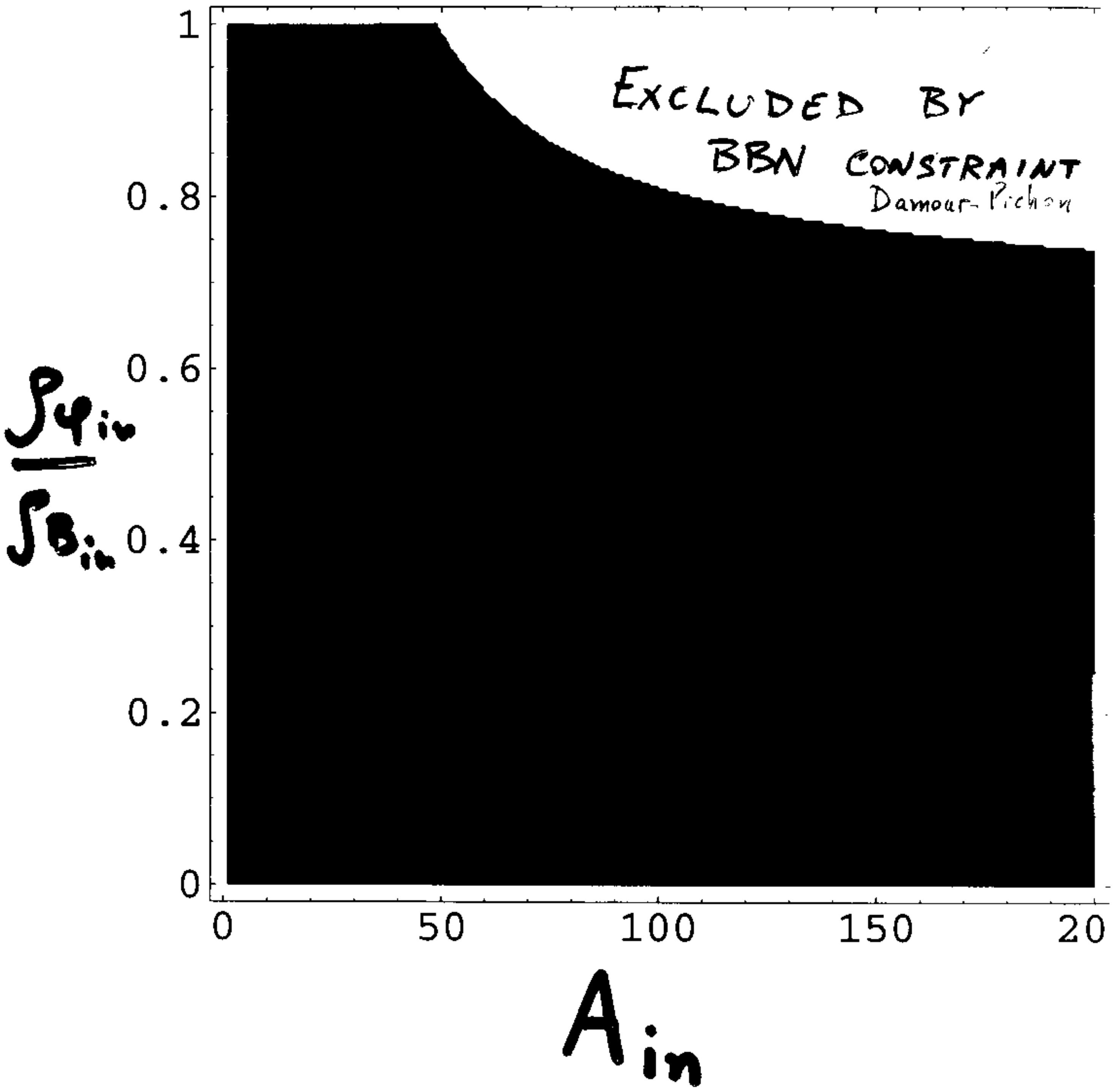
but now S_{matter} contains also the scalar field

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

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

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

$\beta = 6$



FORNENGO, CATENA, A.M., PIETRONI, ROSAT

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

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

FARDON, NELSON, WEINER ex: quintessence

FNW PROPOSAL

$\rho^\circ_\nu \sim \rho^\circ_\Lambda$ 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 in the non-relativistic limit $\Rightarrow$ $\rho_\nu = m_\nu n_\nu$

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

SCALAR POTENTI

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:

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

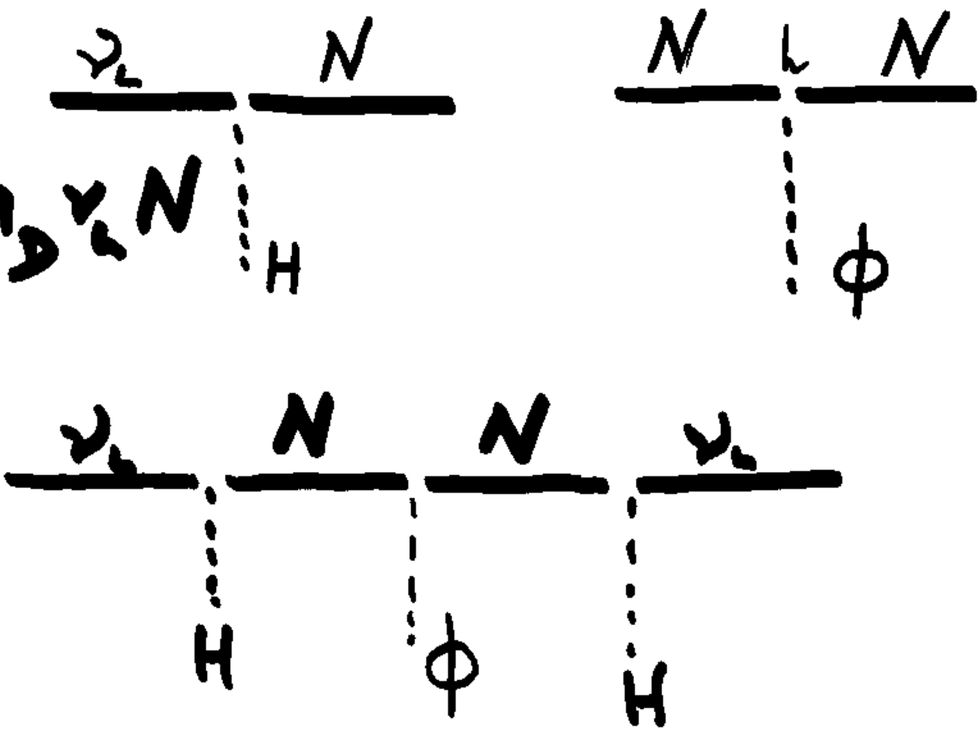
+ conservation of energy: $\dot\rho = -3H(\rho + p)$

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

m_ν as a dynamical field
function of a scalar field ϕ

$$m_\nu(\phi)$$

Ex.:



$m_D \nu_L N$

$M(\phi) NN$

$M(\phi) = h$

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

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

or ...

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

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

$$\mathcal{L} = \underbrace{\mathcal{L}_\nu}_{\bar\nu i \not{\partial} \nu} + \underbrace{\mathcal{L}_\phi}_{\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V_0(\phi)} + \underbrace{m(\phi)\bar\nu\nu}_{\text{coupl. } \nu\text{-quintessence via } \nu \text{ mass term}}$$

FNW DE MODELS ARE SPECIFIED BY THE FORM

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

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

$$\frac{dV_I}{d\phi} = \frac{d\,m(\phi)}{d\phi} n_\nu \left< \frac{m}{E} \right>$$

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

→ DE - ν DECOUPLE

NON-RELATISTIC ν:

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

ENERGY FOR EACH COMPONENT DOES NOT CONSERVE

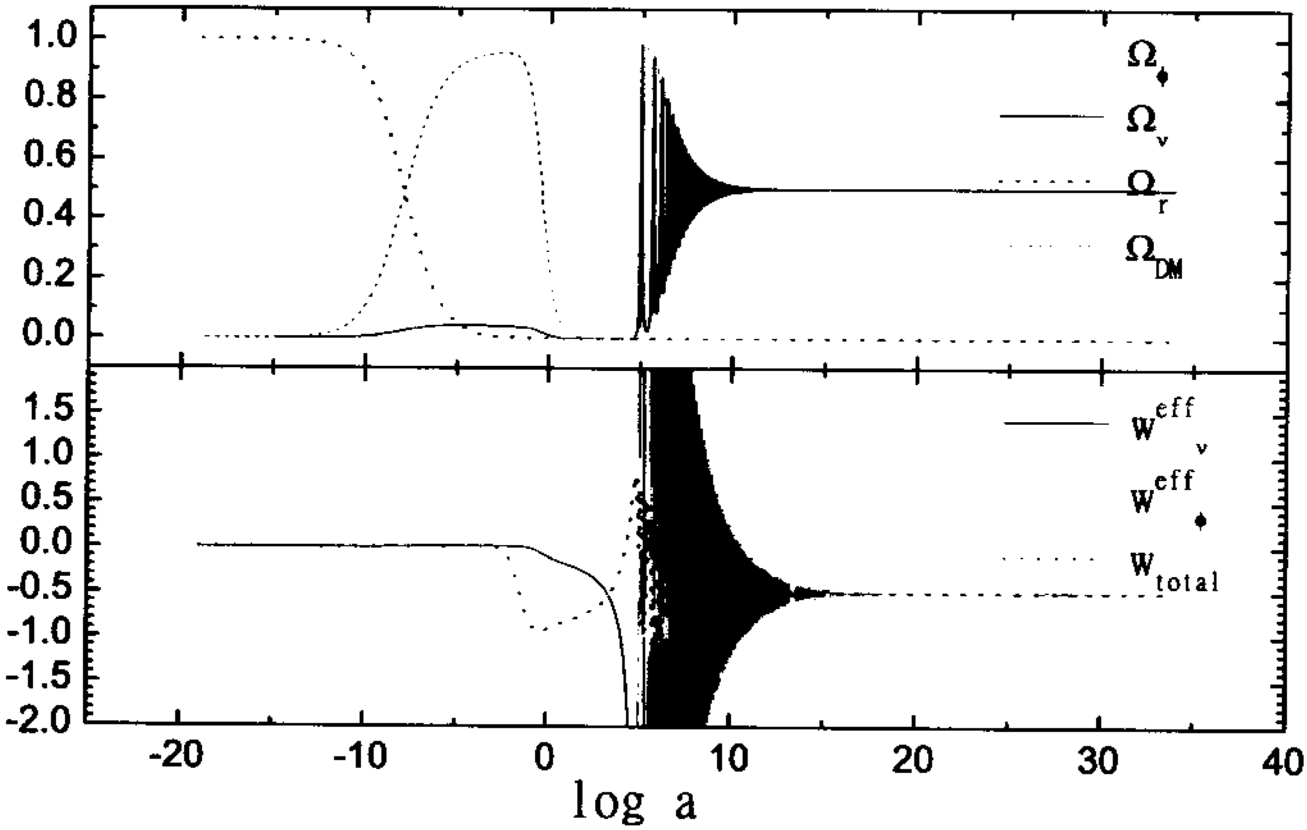
$$
\begin{cases}
\dot{\rho}_\nu + 3H\rho_\nu = n_\nu \dfrac{dm_\nu}{d\phi}\dot{\phi} \\
\dot{\rho}_\phi + 3H\rho_\phi(1+w_\phi) = -n\dfrac{dm_\nu}{d\phi}\dot{\phi}
\end{cases}
$$

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

Bi, Feng, Li, Zhang

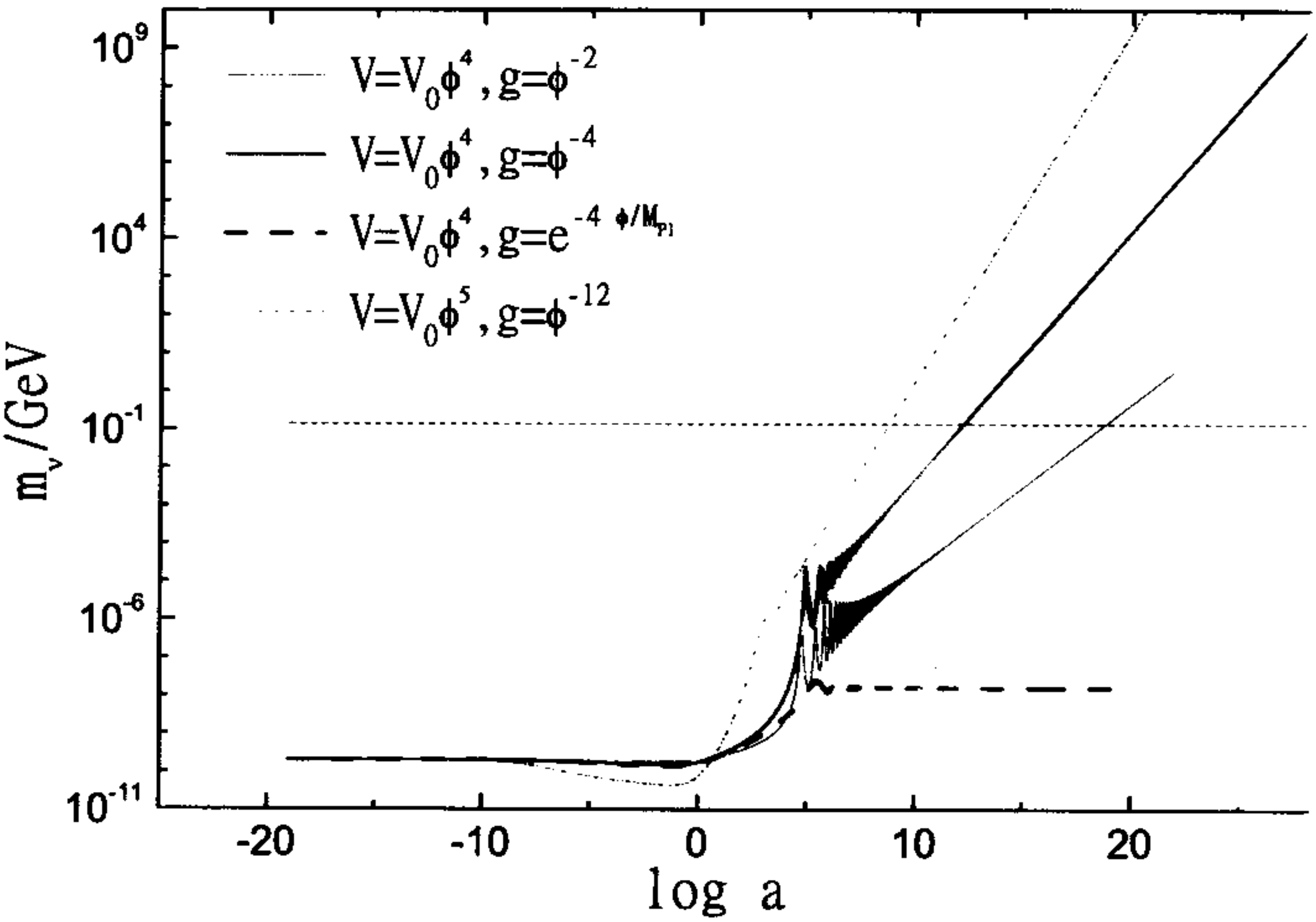
$$V_0(\phi) = A\,\phi^4$$

$$m_\nu(\phi) = \bar{m}\,\phi^{-4}$$



Bi, Bo Feng, Li, Zhang

$\nu \rightarrow e^- + \pi^+$ when $m_\nu > m_e + m$



Bi, Feng, Li, Zhang

LIMITS ON THE MASS OF ϕ

- neutrino source term for ϕ spatially constant

$\Rightarrow$ ϕ does not vary on distances $O(\nu-\nu \text{ spacing})$

$\sim O(10^{-4}\,eV) \Rightarrow m_\phi < 10^{-4}\,eV$

- adiabatic evolution of ϕ since BBN

$\Rightarrow m_\phi > H_{BBN} \sim 10^{-17}\,eV$

PROBLEM: stabilization of ϕ at its minimum

1) of the potential before BBN

2) but then $m_\nu n_\nu$ switches on:

how to guarantee the minimum at the "correct" value $V(m_\nu^0) \sim T_0^3\, m_\nu^0 \sim \rho_{DE} \sim (2\times10^{-3}\,e$

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

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

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

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

$\hookrightarrow w \simeq -0.8$

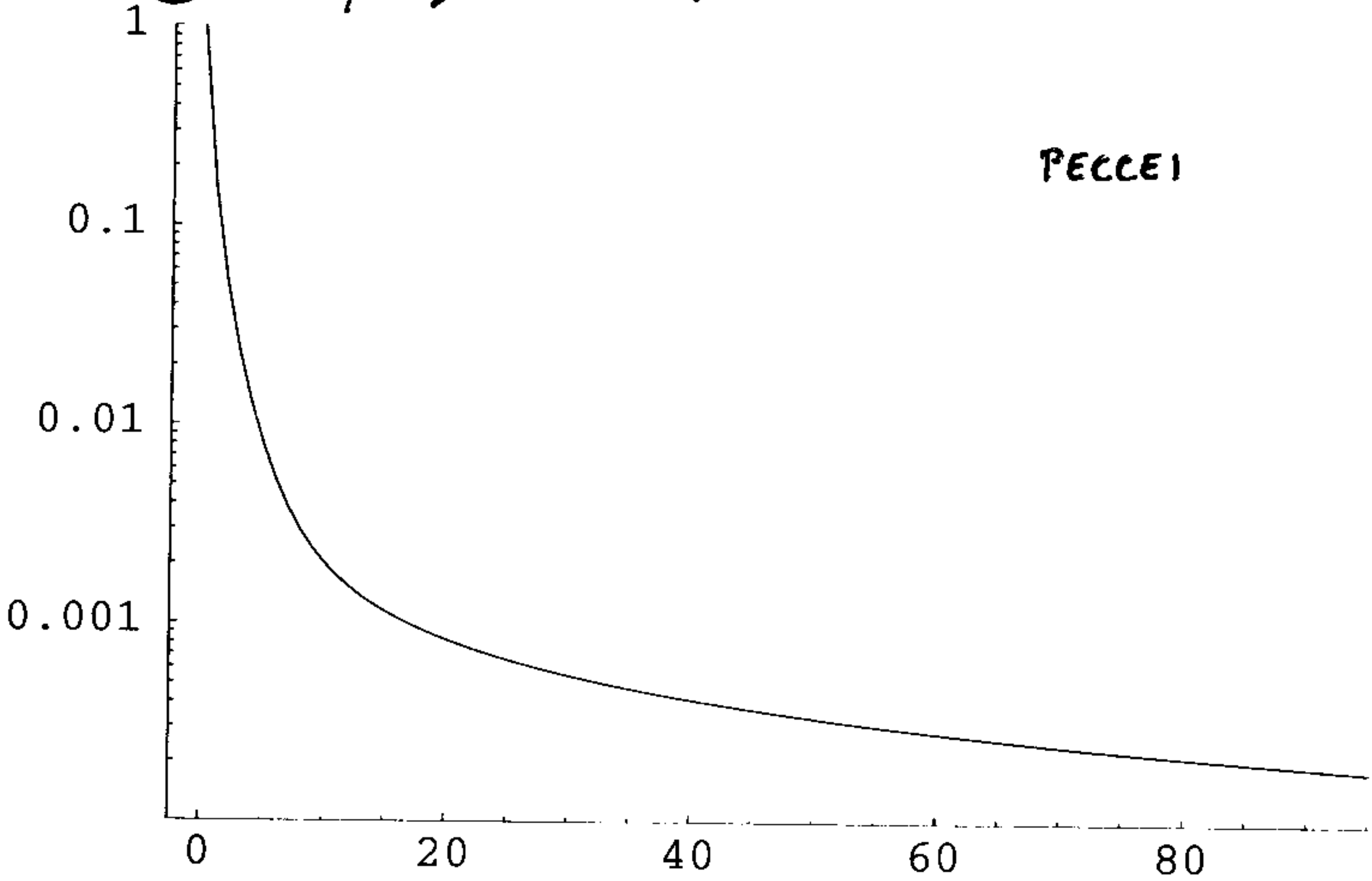
POWER-LAW POTENTIAL $V(m_\nu) \propto m_\nu^{\frac{1+w_0}{w_0}}$

$w_0 = -0.9$

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

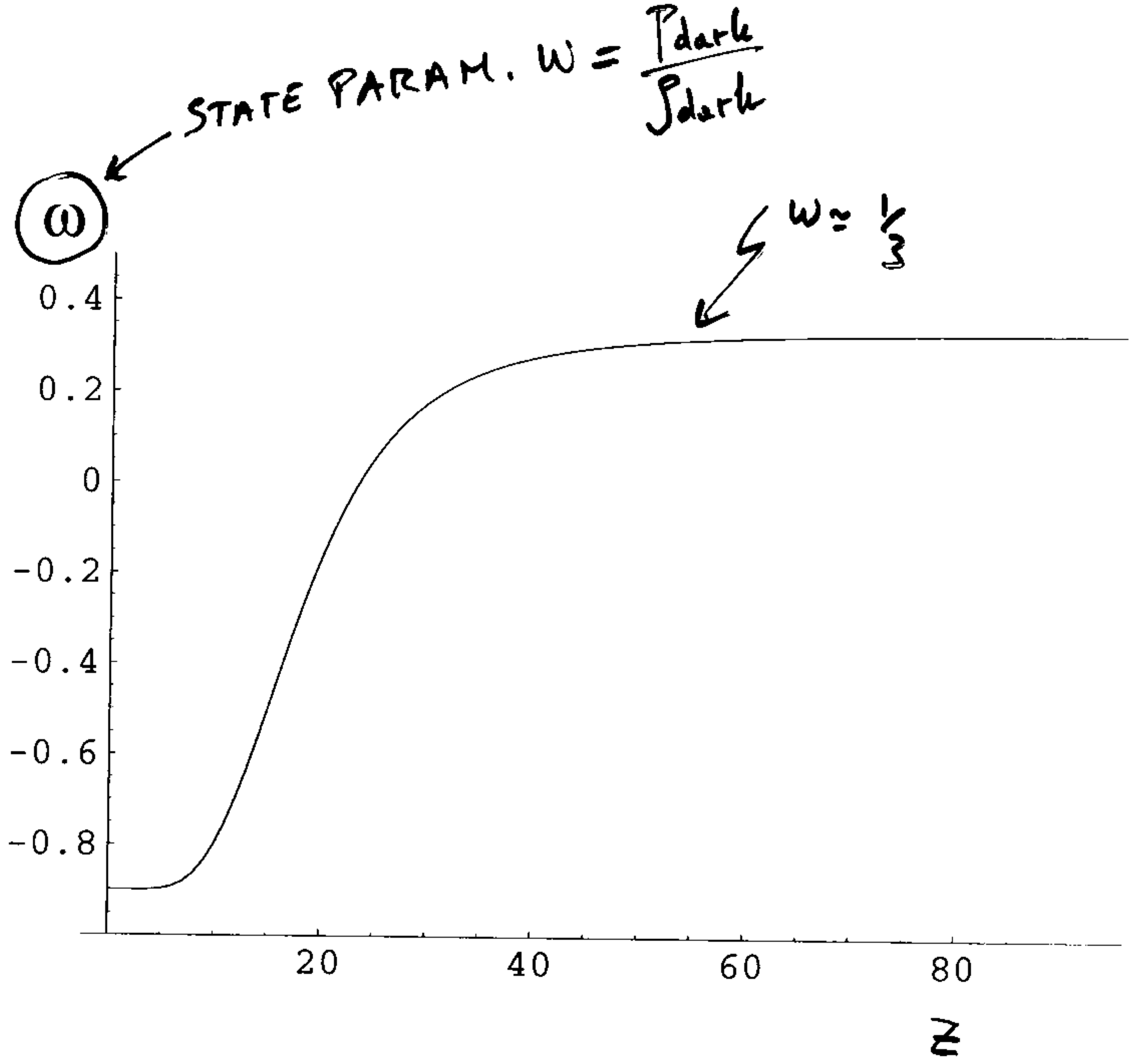
$\rho_{dark}^0 = 0.7\, \rho_c$

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



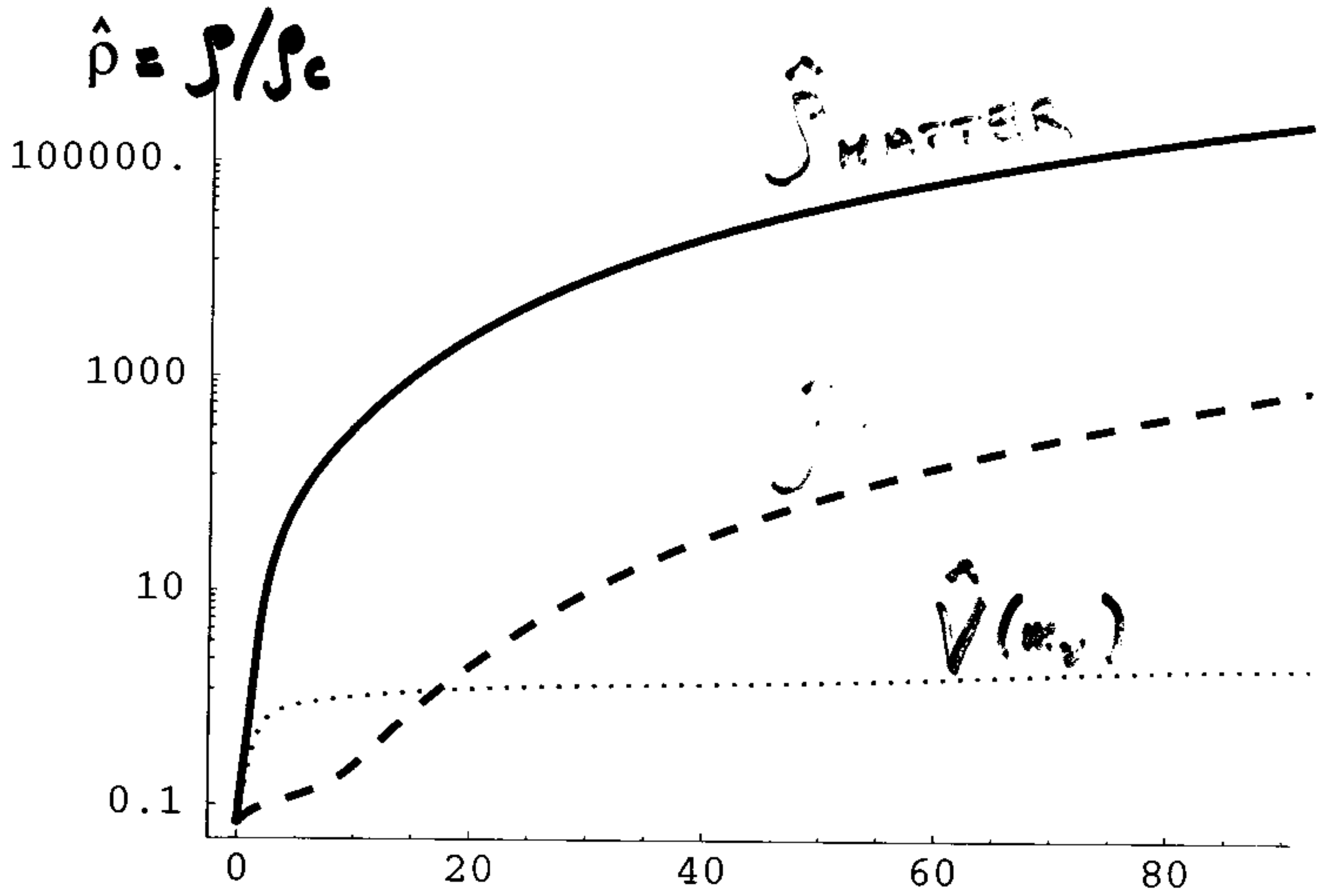
$z = \dfrac{T}{T_0} - 1$

POWER-LAW POTENTIAL



PECCEI

POWER-LAW POTENTIAL



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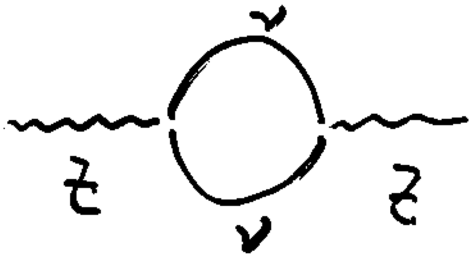
ϕ - MATTER INTERACTIONS



corrections depend on ϕ at $O\left(G_F m_\nu^2\right) \to$ 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 $\to$ further suppression of $O\left(G_F^2 m_N^2(\phi)\right)$ $\Rightarrow$ very small corrections

NON-RENORM. OPER. COUPLING DE TO MATTER

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

$$\swarrow \qquad\qquad \swarrow \qquad\qquad \swarrow$$

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

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 CONSTAN

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

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 ?

Fajar

CONCLUSIONS

1. DARK ENERGY: "DYNAMICAL" VACUUM ENERGY → MINIMUM OF THE POTENTIAL OF SOME ROLLING SCALAR FIELD → QUINTESSEN

2. COINCIDENCE PROBLEM ⟹ QUINTESSENCE TRACKS SOME MATTER COMPONENT ($\rho_B, \rho_\nu, \rho_{DM}$
$\Rightarrow V_{eff} = V_{QUINTESS.}$ + MATTER SOURCE TERMS

3. QUINTESSENCE TRACKS NEUTRINOS
$$V_{eff}(\phi) = V_0(\phi) + \rho_\nu$$
$\rho_\nu \rightarrow m_\nu(\phi)\, n_\nu$ in the NR case

4. LINK $\rho_{DE} \leftrightarrow m_\nu$
smallness of $(\rho_{DE})^{1/4}$ en. scale ⟺ smallness of m_ν

5. VARYING NEUTRINO MASS
m_ν function of ν density and baryon density

⟹ TESTABLE IMPLICATIONS ?