Slow-roll suppression of adiabatic instabilities in coupled scalar field-dark matter models

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Non-Minimally Coupled Scalar Fields

where are they from?

Particle Physics

• Coupled scalar and hierarchy problem (Wetterich '87; Ellis et al. '89)

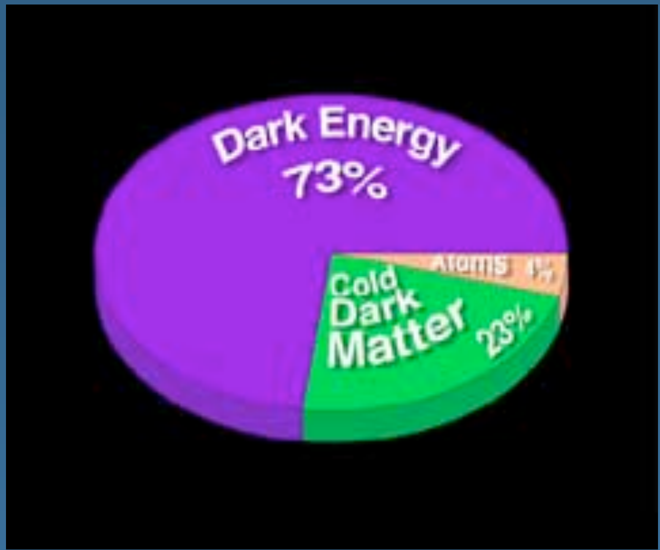
String Theory

• Coupled scalars in the low energy from compactification of extra-dimensions

• Dilaton couples to all matter fields $\Rightarrow$ EP violation

• Several mechanisms can reconcile EP violation with local tests of GR: e.g. non-universality of the couplings (Damour et al. '90, Casas et al. '92); string-loops corrections to dilaton coupling and GR attractor (Damour et al. '93, '94)

The Dark Energy Problem



Dark Energy: $\Omega_{DE} = 0.73 \pm 0.03$

- DE = Cosmological Constant Λ

- Λ = vacuum energy $\Rightarrow$ Fine Tunning

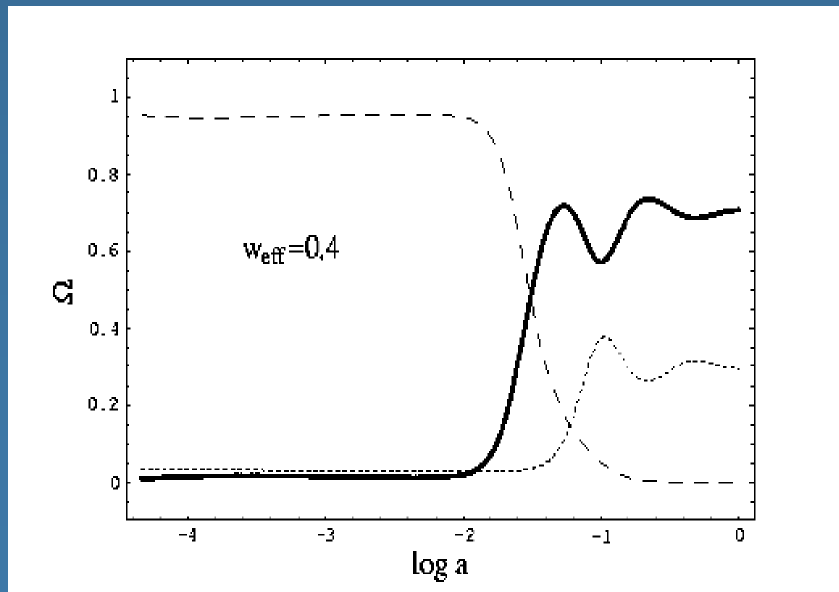
- Λ and Structure Formation $\Rightarrow$ Cosmic Coincidence (?)

- DE = Non-Minally Coupled Scalar Field with Exponential Potential

 - Late time accelerating attractor solution $\Rightarrow$ IC dependence erased

 - Along the attractor Matter to Dark Energy density ratio is constant

(Amendola '99)



Dark Sector Interaction Model Building

φ-DM:

• Non-minimally coupled scalar + exponential potential + DM-coupling

- Runaway Dilaton (Gasperini et al. '02)

- Moduli Fields and Brane World Scenario (Brax et al. '03)

Mass Varying Neutrinos:

• Non-minimally coupled scalar to Neutrinos (Fardon et al. 2004)

Chameleon Model:

• Non-minimally coupled scalar + inverse power law + universal-coupling

- local density dependent $m_\varphi \Rightarrow$ EP test satisfied (Khoury & Weltman '04)

- gravity constraints $\Rightarrow M<10^{-3}$ eV $\Rightarrow$ dark energy = chameleon + adiabatic evolution (Brax et al. '04)

What the action looks like?

$$S = \int d^4x \sqrt{-g} \left\{ \frac{M_{\rm Pl}^2}{2} \mathcal{R} - \frac{1}{2}(\partial\phi)^2 - V(\phi) \right\} - \int d^4x \mathcal{L}_{\rm m}(\psi_{\rm m}^{(i)}, g_{\mu\nu}^{(i)})$$

and if you do not like working with the action,
assume two interacting fluids in FRW with given eos, such that
$T_{Tot}^{\mu\nu}$ is conserved, eq. of motion follows:

$$\rho'_X = -3H\rho_X(1+w_X) - aQ$$
$$\rho'_Y = -3H\rho_Y(1+w_Y) + aQ$$

…and Q is some function parameterizing the type of interaction

Are These Still Viable Models?

Linear Perturbations: instabilities found

- in some realizations of coupled scalar field with exponential potential (Koivisto '05; Kaplinghat & Rajamaran '06) and in specific MaVaN models (Afshordi et al. '05)
- in scenarios with adiabatic background evolution (Bean et al. '08)

$$\frac{1}{c_a^2} = -1 - \frac{\alpha+1}{\beta}\frac{M_{Pl}}{\varphi}$$

negative!!

- in more generic fluid-description instabilities found for couple dark energy models with constant w ~ -1 (Valiviita et al. '08)

$$\psi = A_\psi (k\tau)^{n_\psi}$$

$$n_\psi = n_\pm = \frac{-(1+2w_x) \pm \sqrt{3w_x^2 - 2}}{1+w_x}$$

see also Wang et al. '08

What is the relation between the background scalar field evolution and the onset of the instabilities? Are instabilities really generic and dangerous?

A non-minimally coupled Model

- Ingredients: $f(\phi/M_{Pl})\bar{\psi}\psi$ with $f(\phi) = e^{\beta\phi/M_{pL}}$ and $V(\phi)$: $\Gamma \equiv \frac{V_{,\phi\phi}V}{V_{,\phi}^2} > 1$

- $T^{tot}_{\mu\nu}$ conservations

$$\begin{aligned} T^{\mu(DM)}_{\nu;\mu} &= \beta\phi_{;\nu}T^{\gamma(DM)}_{\gamma}, \\ T^{\mu(\phi)}_{\nu;\mu} &= -\beta\phi_{;\nu}T^{\gamma(DM)}_{\gamma} \end{aligned}$$

$\Rightarrow$

- Equation of motions

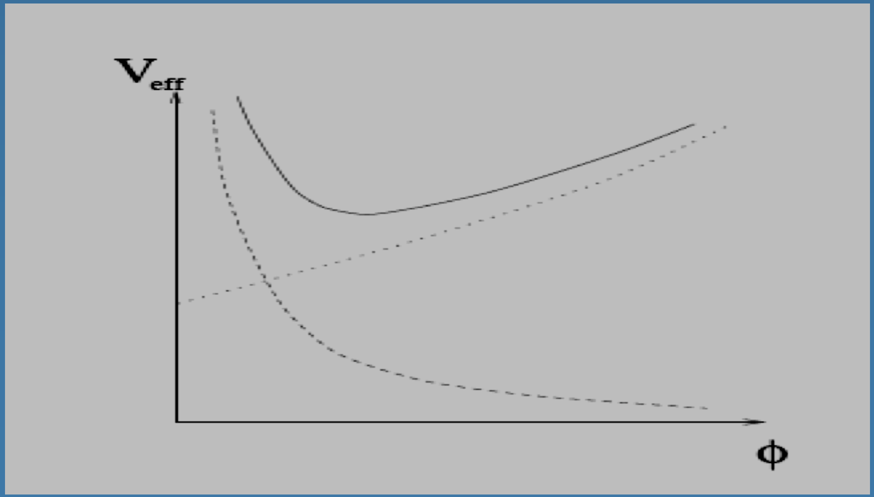
$$\begin{aligned} \dot{\rho}_{DM} + 3H\rho_{DM} &= \beta\dot{\phi}\rho_{DM} \\ \ddot{\phi} + 3H\dot{\phi} + V_{,\phi} &= -\beta\rho_{DM} \end{aligned}$$

- DM density evolution

$$\rho_{DM} = \frac{\rho^{(0)}_{DM}}{a^3}e^{\beta(\phi-\phi_0)}$$

- Scalar Effective Potential

$$V_{\text{eff}}(\phi) = V(\phi) + \frac{\rho^{(0)}_{DM}}{a^3}e^{\beta(\phi-\phi_0)}$$



Adiabatic Regime

- Minimum of the potential:

$$V_{,\phi} = -\beta \frac{\rho_{DM}^{(0)}}{a^3} e^{\beta(\phi-\phi_0)}$$

which gives

$$\left(\frac{\phi_0}{\phi_{\min}}\right)^{\alpha+1} = \frac{1}{a^3} e^{\beta(\phi_{\min}-\phi_0)}$$

- 'Adiabatic' Attractor Solution: $m_\phi > H$

$$m^2 = \frac{\rho_{DM}^{(0)}}{a^3}\left(\frac{\beta}{M_{Pl}}\right)^2 \frac{f}{f_0}\left[1 + \frac{\Gamma}{V}\frac{\rho_{DM}^{(0)}}{a^3}\frac{1}{f_0}\right]$$

$\Longrightarrow$ e.g. today

$$\frac{m_0^2}{H_0^2} > 3\Omega_{DM}^{(0)}\left(\frac{\beta}{M_{Pl}}\right)^2\left[1 + \frac{\Gamma}{f_0}\frac{\Omega_\phi^{(0)}}{\Omega_{DM}^{(0)}}\right]$$

It can be shown to be the case at all times

- Slow-Roll Evolution: $(d\phi_{min}/dt)^2/2 << V_{eff}(\phi_{min})$

$$\dot{V}_{eff}^{,\phi} = 0 \quad \Longrightarrow \quad \dot{\phi} = \frac{3H}{m^2}\frac{\rho_{\rm DM}^{(0)}}{a^3}\frac{f_{,\phi}}{f_0} = -\frac{3H}{m^2}V_{,\phi} \quad \Longrightarrow \quad \frac{\dot{\phi}^2}{2V} = \frac{9H^2}{2m^4}\frac{V_{,\phi}^2}{V} < \frac{9H^2}{2m^2}\frac{1}{\Gamma}$$

(Brax et al. '04; Das et al. '06)

A Specific Example

- Inverse Power-Law Potential:

$$V(\phi) = \frac{M^{4+\alpha}}{\phi^\alpha},$$

- Attractor and Slow-Roll Condition:

- $\alpha \lesssim O(1)$

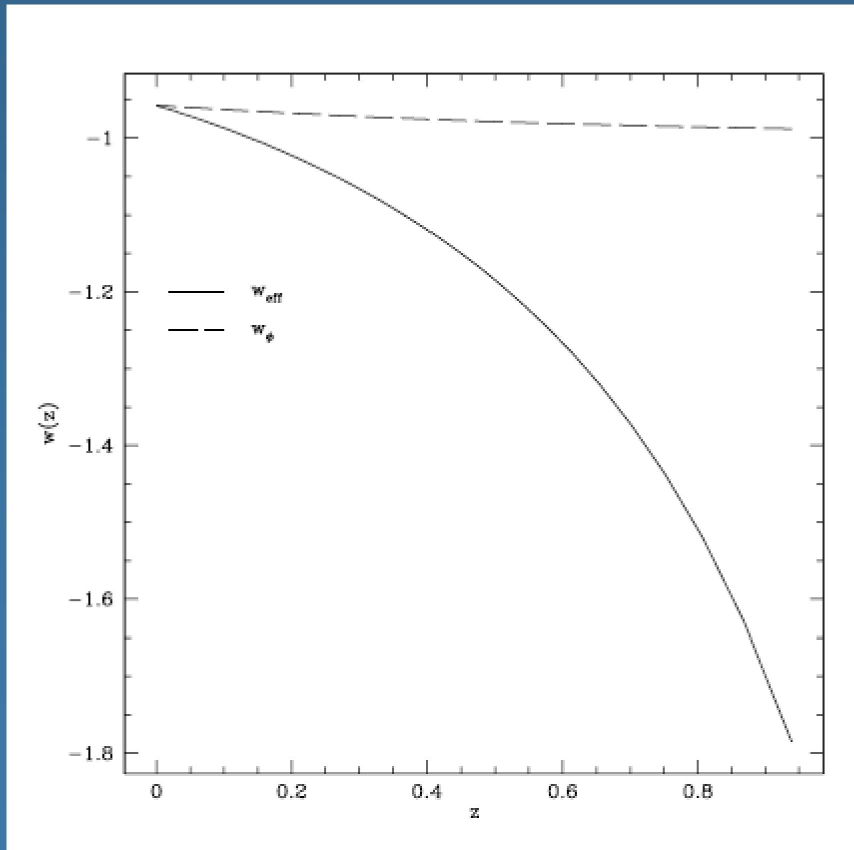
- $\beta \gtrsim O(1)$

- Mimicking Phantom:

$$w_{\rm eff} = \frac{w_\phi}{1-x}$$

$$x \equiv -\frac{\rho^{(0)}_{\rm DM}}{a^3 \rho_\phi}\left[\frac{f(\phi/M_{\rm Pl})}{f(\phi_0/M_{\rm Pl})} - 1\right] \geq 0$$

- $\alpha = 0.2$, $\beta = 1$ $\Longrightarrow$ $\bar{w}_{\rm eff} \approx -1.1$



Linear Perturbations

- Einstein Equation about linearly perturbed FRW:

$$\begin{aligned}
\dot{\delta}_{DM} &= -\left(\frac{\theta_{DM}}{a} + \frac{\dot{h}}{2}\right) + \beta\delta\dot{\phi}, \\
\dot{\theta}_{DM} &= -H\theta_{DM} + \beta\left(\frac{k^2}{a}\delta\phi - \dot{\phi}\theta_{DM}\right), \\
\delta\ddot{\phi} &+ 3H\delta\dot{\phi} + \left(\frac{k^2}{a^2} + V_{,\phi\phi}\right)\delta\phi + \frac{1}{2}\dot{h}\dot{\phi} = \\
&= -\beta\rho_{DM}\delta_{DM},
\end{aligned}$$

$$\dot{h} = \frac{2k^2\eta}{a^2 H} - \frac{8\pi G}{H}\left[\delta\rho_\phi + \rho_{DM}\delta_{DM}\right]$$

$$\dot{\eta} = \frac{4\pi G}{k^2} a\left[\rho_{DM}\theta_{DM} + ak^2\dot{\phi}\delta\phi\right]$$

Unified Fluid Description

- Total Energy momentum is conserved

$$\dot{\rho}_T = -3H(1+w_T)\rho_T,$$

- The unified fluid is non-barotropic:

$$\begin{aligned} \dot{\delta}_T &= -3H(c_{sT}^2 - w_T)\delta_T + \\ &- (1+w_T)\left\{\left[\frac{k^2}{a^2H^2} + 9(c_{sT}^2 - c_{aT}^2)\right]\frac{aH^2}{k^2}\theta_T + \frac{\dot{h}}{2}\right\}, \end{aligned} \quad (16)$$

$$\dot{\theta}_T = -H(1-3c_{sT}^2)\theta_T + \frac{c_{sT}^2 k^2}{a(1+w_T)}\delta_T, \quad (17)$$

- Adiabatic Sound Speed

$$c_{aT}^2 = \dot{p}_T/\dot{\rho}_T$$

- Non-Adiabatic Sound Speed

$$c_{sT}^2 = \delta p_T/\delta \rho_T$$

Slow-Roll Suppression of Adiabatic Instabilities

- Sound speeds in terms of individual components:

$$c_{aT}^2 = \frac{3H\dot{\phi}^2 + \dot{\phi}[2V_{,\phi} + \beta\rho_{DM}]}{3H\dot{\phi}^2 + 3H\rho_{DM}}, \qquad (18)$$

$$c_{sT}^2 = \frac{\dot{\phi}\delta\dot{\phi} - V_{,\phi}\delta\phi}{\dot{\phi}\delta\dot{\phi} + V_{,\phi}\delta\phi + \rho_{DM}\delta_{DM}}. \qquad (19)$$

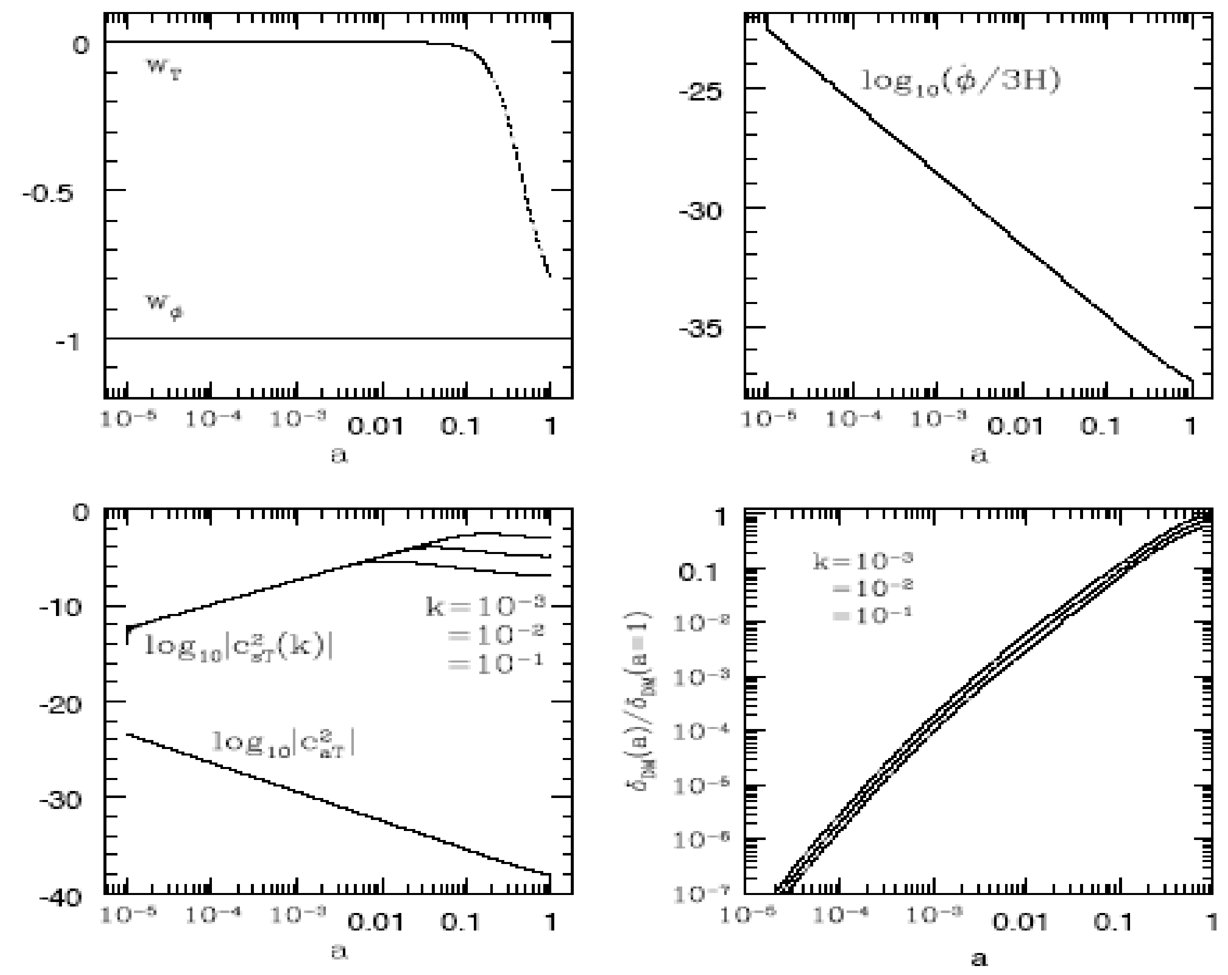
- Along the adiabatic solution:

$c_{aT}^2 = -\beta\frac{\dot{\phi}}{3H},$ < 0 but $3H\dot{\phi} \approx 0$ $\Rightarrow$ $c_{aT}^2 \approx 0^-$

$c_{sT}^2 = -\frac{1}{1 - \frac{1}{\beta}\frac{\delta_{DM}}{\delta\phi}}$ if $\delta\phi < \delta_{DM}$ $\Rightarrow$ $c_{sT}^2 \approx \beta\frac{\delta\phi}{\delta_{DM}} \cong 0$

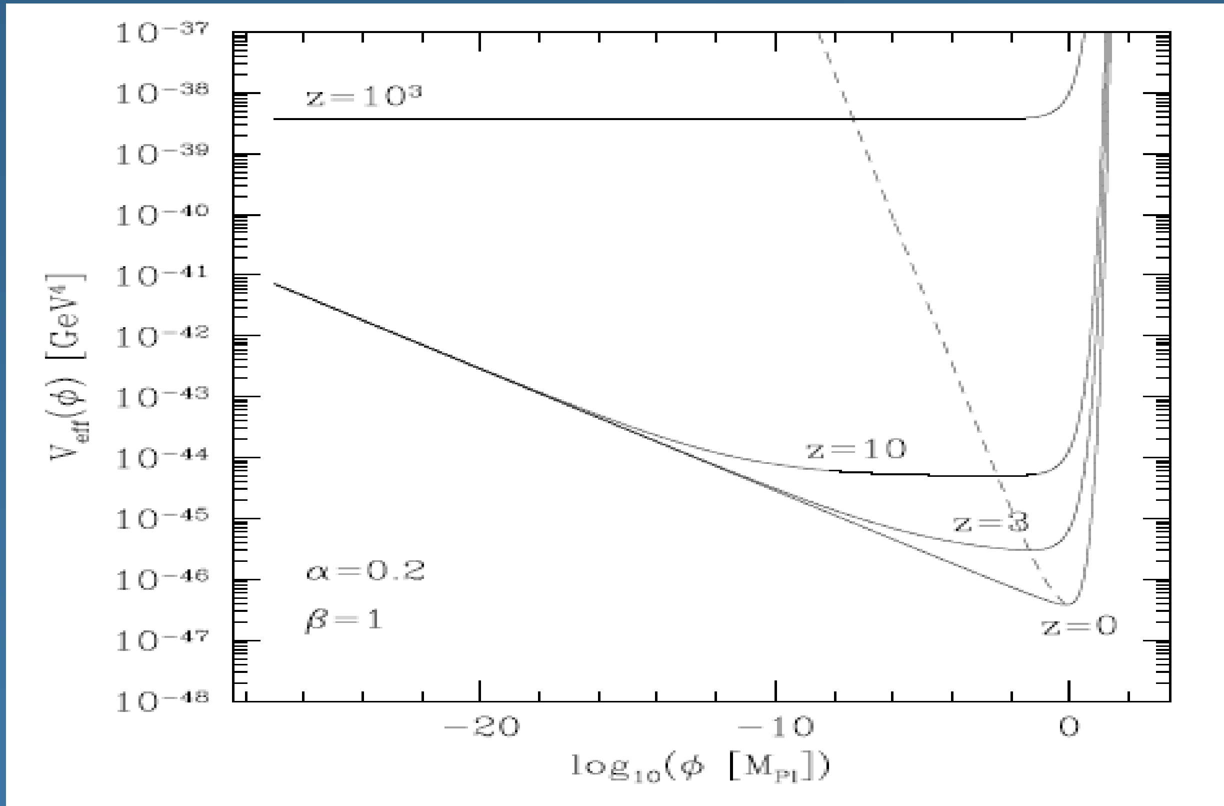
Corasaniti '08

Numerical Results



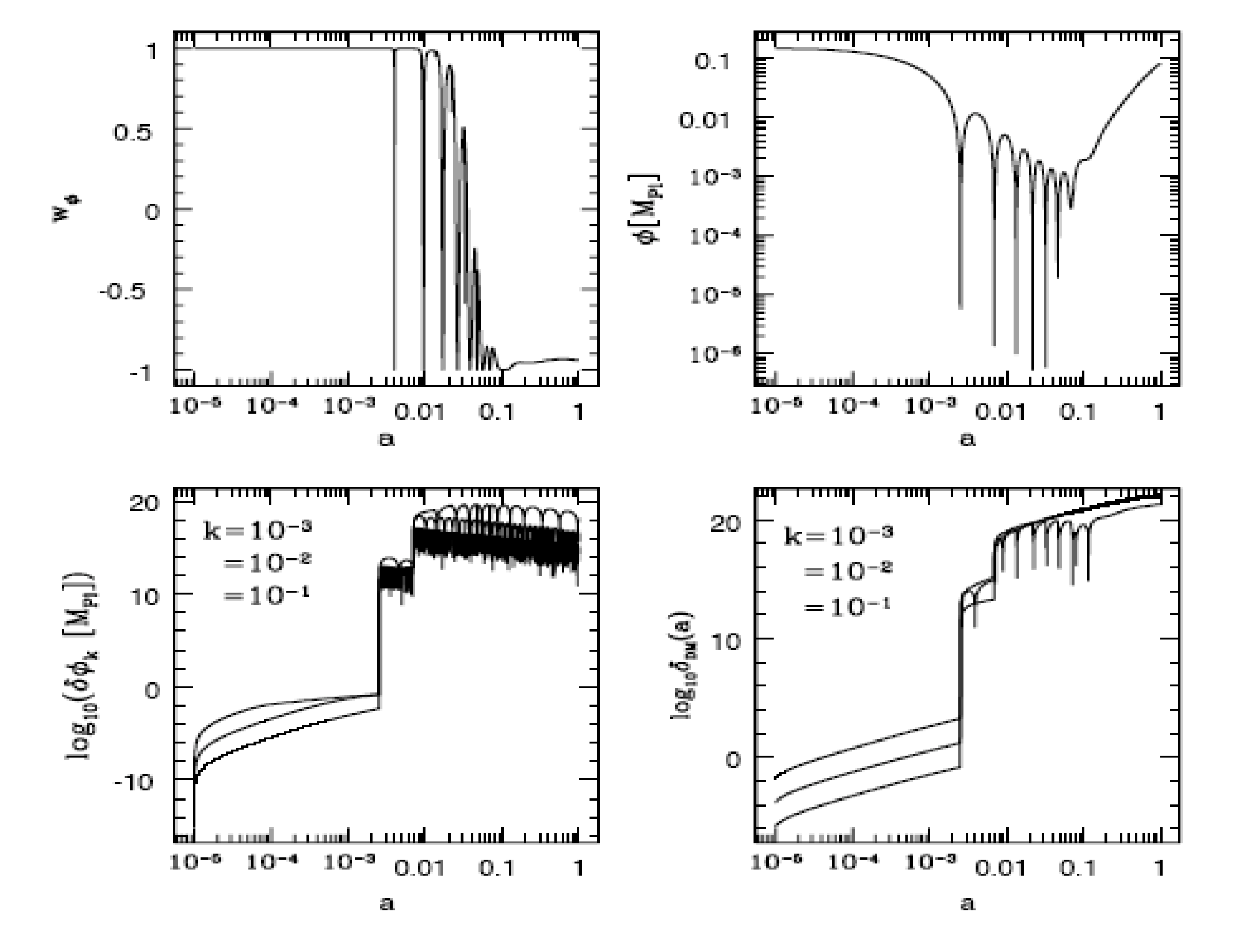
Non-Adiabatic Regime

- Initial Large Field Values: $\phi_i > \phi_i^{MIN}$



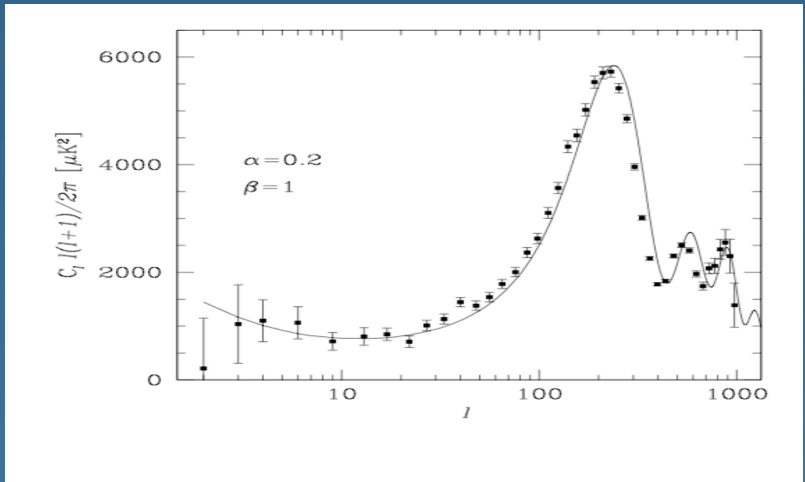
- Oscillating Scalar Field:
  - $\delta\phi$ instability like in inflationary reheating (Tsujikawa '99)

Large Field Oscillations and Resonance



Phenomenology

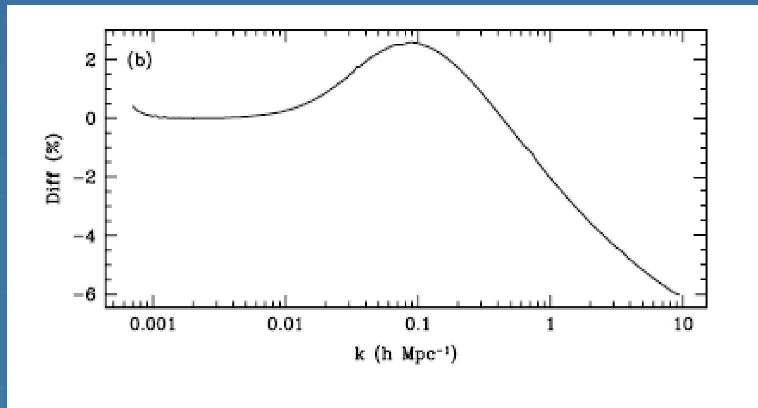
- Full CMB calculation and data model comparison



- Structure Formation at k > 0.1

$$\delta'' + aH\delta' = \frac{3}{2}a^2H^2\left[1+\frac{2\beta^2}{1+a^2V_{,\phi\phi}/k^2}\right]\delta$$

$$\lambda \equiv V_{,\phi\phi}^{-1/2} = \sqrt{\frac{\phi^{\alpha+2}}{\alpha(\alpha+1)M^4}} \Rightarrow \lambda_0 \approx 0.7H_0^{-1}$$



- Non-linear regime

- Voids phenomenon (Farrar & Peebles '04)
- Missing satellite problem

Cosmological Constraints

MCMC Likelihood Analysis:

β =1 (gravitational coupling)

- (Ω_{DM}, $\Omega_b h^2$, H_0, n_s, τ, log[α], A_s, b)

- WMAP5+UNION SNIa+SDSS

Ω_{DM}=0.22 +/- 0.07

$\Omega_b h^2$=0.022 +/- 0.002

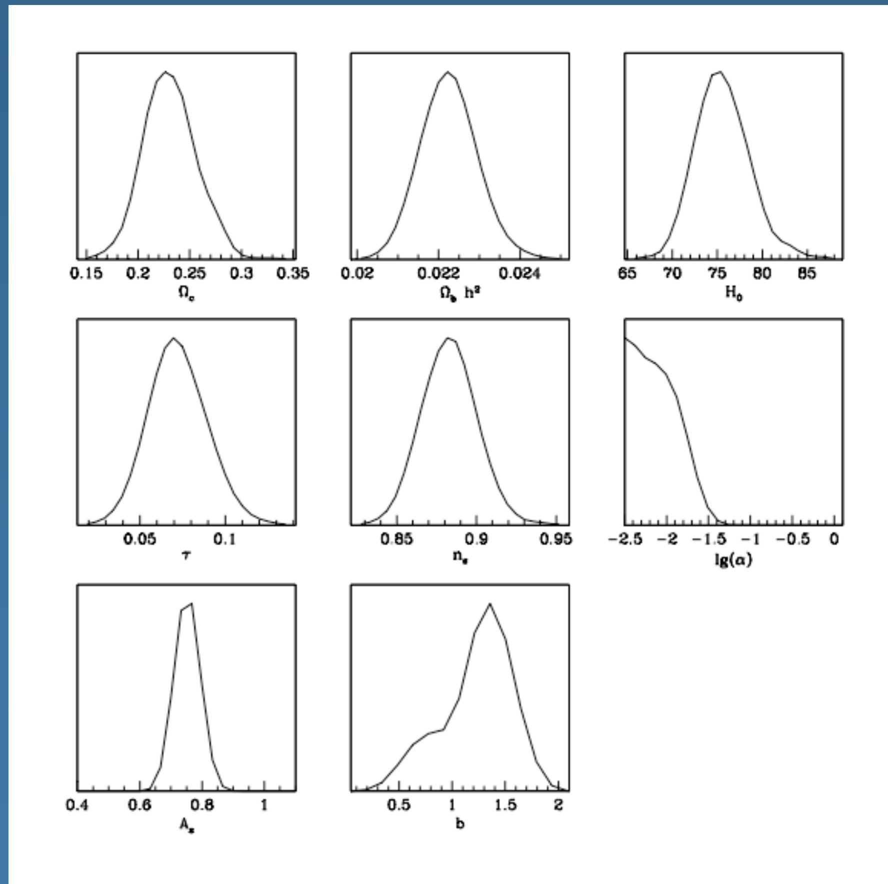
H_0=75 +/- 8 Km/s/ Mpc^{-1}

n_s= 0.89 +/- 0.03

log[α]<-1.5 (α<0.032)

$A_s(k_p$=0.02)=0.74 +/- 0.07

b = 1.45 $+^{2.35}/-_{0.98}$



Conclusions

- Non-Minimally coupled Scalar Field-Matter Scenario can still provide viable cosmological models

- In models with coupling O(1) the slow-roll dynamics of the field along the adiabatic solution suppress the rise of instabilities of the perturbations

- Instabilities can arise only in extremely strongly coupled cases or non-adiabatic background field solutions
- Compatible fits to homogeneous and linear cosmological data

- Yukawa-correction to the DM newtonian potential on cosmological scales, imprint on the DM clustering and halo formation. N-Body simulations needed

- LOTS OF WORK STILL TO BE DONE!