



Dark Energy and Dark Matter from Gravitational Symmetry Breaking

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Why Dark Matter-Dark Energy interactions?

★ Theoretical problems of the cosmological constant Λ

→ Fine-tuning & coincidence, independent nature of DM & DE, origin of negative pressures,...

★ A cosmological mechanism for DE?

→ Dynamical DE \Rightarrow new degrees of freedom

$$\nabla_\mu [T^\mu_\nu(m) + T^\mu_\nu(DE)] = 0$$

Separately conserved: QUINTESSENCE
(only gravitational interaction)

Conserved together: COUPLED DE

Violation of the
equivalence principles !

$$\nabla_\mu T^\mu_\nu(m) \neq 0$$

★ New interactions: toward a unified physics of the dark sector?

→ Same physical nature for DM & DE ; new insights on coincidence and nature of DE

★ Famous examples:

→ Extended quintessence (Perrotta, et al., PRD 61 2000, Riazuelo & Uzan, PRD 66 2002)

→ Coupled DM-DE (Amendola, PRD 62 2000, Farrar & Peebles, ApJ 604 2004)

→ Mass-Varying Neutrinos (MaVaNs), growing neutrinos
(Fardon, Nelson, Weiner, JCAP0410 2004 ; Peccei, PRD 71 2005 ; Wetterich, Phys.Lett.B 655
2007 ; Amendola, Baldi, Wetterich PRD78 2008, etc.)

Gravitation without equivalence principles

Einstein Equivalence Principle (EEP):
non-gravitational binding energies

Equivalence principles :
Universality of gravitation

Strong Equivalence Principle (SEP):
any type of binding energies
 $SEP \Leftrightarrow EEP$

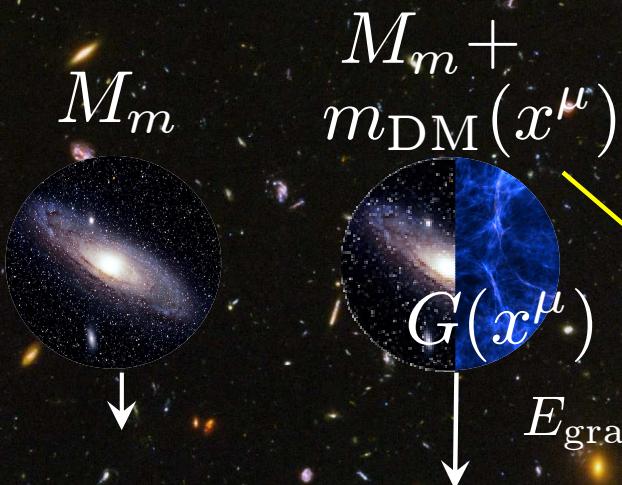
EEP violation:
Coupled DM-DE
MaVaNs, chameleons, etc.

SEP violation:
Extended quintessence
Brans-Dicke tensor-scalar theories

AWE Hypothesis

No EEP \Rightarrow no SEP

$m(x^\mu) \Rightarrow G(x^\mu)$



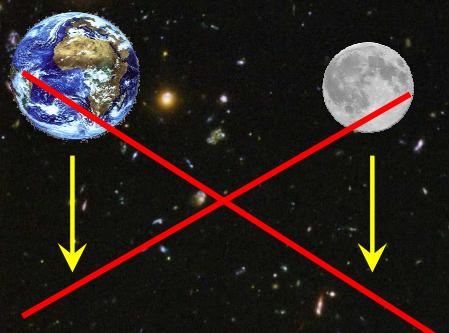
Non-universality
of free fall

DM-induced SEP violation!

Gravitational binding energy:

$$E_{\text{grav}}(x^\mu) = G \int_V \frac{M_{\text{int}}(x^\mu) dm_{sh}(x^\mu)}{r}$$

$$\varphi(\text{Earth}) \neq \varphi(\text{Moon})$$



The anomalous weight of Dark Matter

★ Interactions in the dark sector:

→ Variation of DM mass

→ **violation of the Equivalence PrincipleS (EEP and SEP)**

⇒ No EEP : non-universality of free fall (DM vs ordinary matter)

⇒ **No EEP ⇒ no SEP : variation of gravitational strength G**

→ **DM-induced modifications of gravity !!**

⇒ **Negative pressures are no more required for producing cosmic acceleration**

★ **The AWE Hypothesis: a relaxed equivalence principle**

$$S_{grav} = \frac{1}{2} \int \sqrt{-\tilde{g}} d^4\tilde{x} \left\{ \Phi \tilde{R} - \frac{\omega_B D(\Phi)}{\Phi} \tilde{g}^{\mu\nu} \partial_\mu \Phi \partial_\nu \Phi \right\}$$
$$S_{source} = S_m [\psi_m, \tilde{g}_{\mu\nu}] + S_{awe} [\psi_{awe}, M^2(\Phi) \tilde{g}_{\mu\nu}]$$

SEP violation
(varying G)

EEP relaxation
(mass-variation of dark sector)

See Jean-Michel Alimi's talk

AWE also means

« Abnormally Weighting Energy »

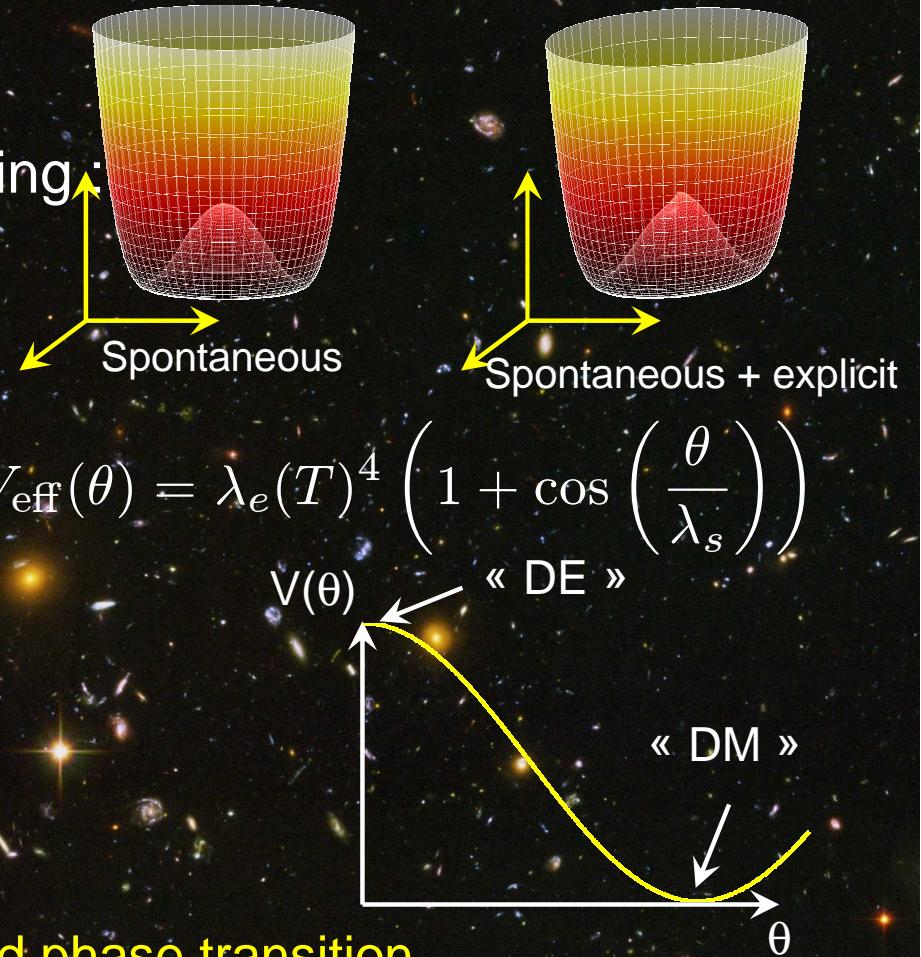
- ★ T. Damour, et al. PRL 64, 123 (1990)
- ★ J.-M. Alimi, A. Füzfa, JCAP 0809 (2008)
- ★ A. Füzfa, J.-M. Alimi, PRD 75 123007 (2007)
- ★ A. Füzfa, J.-M. Alimi, PRL 97, 061301 (2006)

A famous example of mass-varying DM : the axion

- ★ Global U(1) symmetry (eg.: Peccei-Quinn, B-L, etc.) and new complex scalar

$$\Psi = \sigma e^{i\theta/\lambda_s}$$
- ★ Spontaneous and explicit symmetry breaking
 - ψ acquires a vev λ_s
 - θ acquires a mass : the axion
- ★ Cosmological implications
 - pNGB quintessence model :

$$\Rightarrow \lambda_s \sim m_{Pl}; \lambda_e \sim m_v$$
 - Late-forming dark matter
- ★ Axion-like DM has a varying mass
 - violation of the equivalence principle around phase transition
 - Why not a gravitational mechanism for vev stabilisation?



- ★ J. Frieman et al., PRL 75 (1995)
- ★ L. Amendola, R. Barbieri, PLB (2006)
- ★ R. Mainini, S. Bonometto, PRL 93 (2004)

- ★ A. Arbey, PRD 74 (2006)
- ★ S. Das, N. Weiner, astro-ph/0611353
- ★ Kolb, Turner, 1992
- ★ Copeland, Sami, Tsujikawa, IJMP D (2006)

A mechanism for gravitational symmetry breaking

- ★ Alternative to SSB : Ψ runs cosmologically...and rules the EPs

→ Ψ has non-minimal couplings to gravity

→ Ψ does not couple in the same way to ordinary and dark matter

→ AWE Hypothesis : $\langle \Psi \rangle$ is now **stabilised by a gravitational mechanism**

- ## ★ After explicit symmetry breaking:

$$V_{\text{eff}} = \lambda_e^4 \left(\frac{\sigma}{\lambda_g} \right)^4 \left(1 + \cos \left(\frac{\theta}{\lambda_g} \right) \right)$$

$$S_{\text{grav}} = \frac{1}{2\kappa} \int \sqrt{-g} d^4x \left\{ \Phi R - \frac{\omega(\Phi)}{\Phi} \partial_\mu \Phi \partial^\mu \Phi \right\}$$

$$+ S_m [\psi_m, g_{\mu\nu}] + S_\theta [\theta, M^2(\Phi)g_{\mu\nu}]$$

with $M \equiv \frac{\sigma}{\lambda_g}$

- ## ★ Cosmological implications

→ Dark Matter : the axion (pNGB) θ

→ Dark Energy : σ stabilization during accelerated expansion

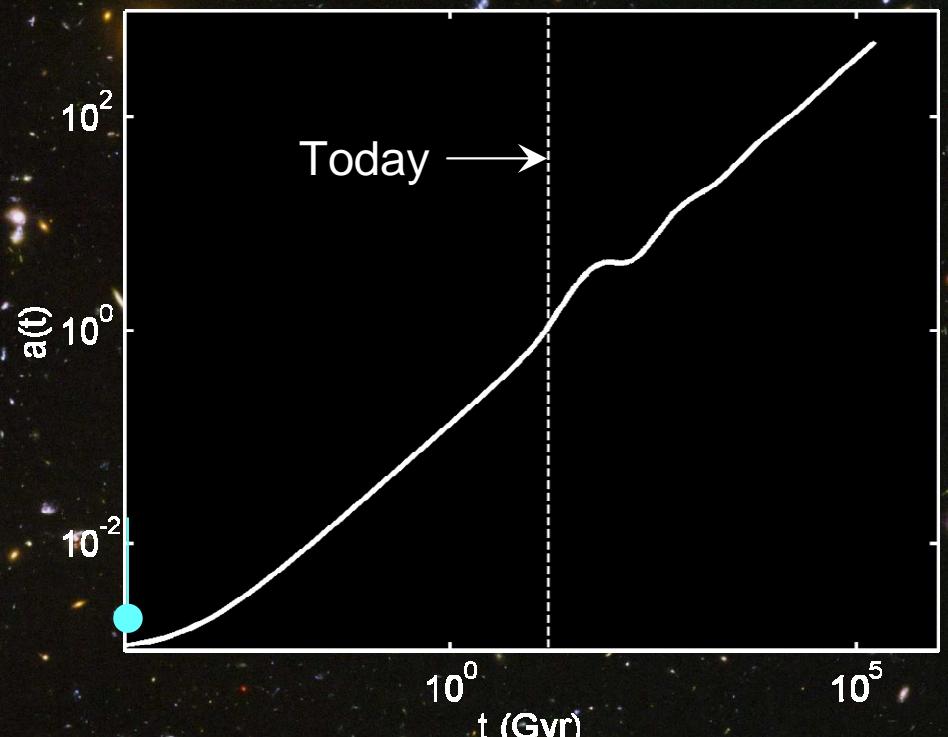
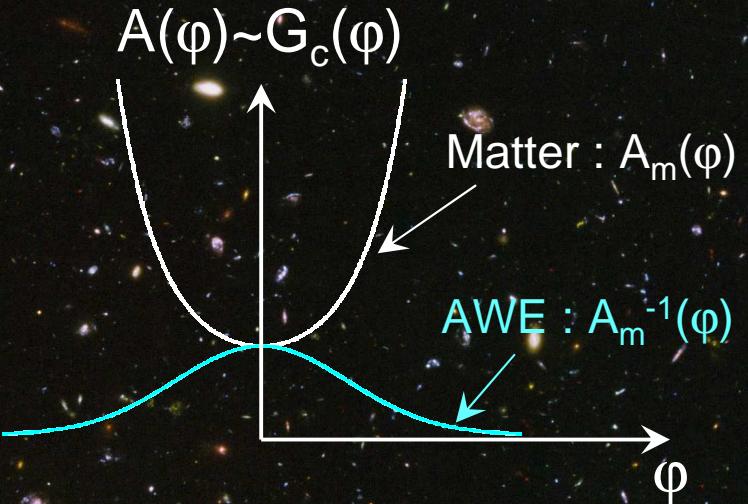
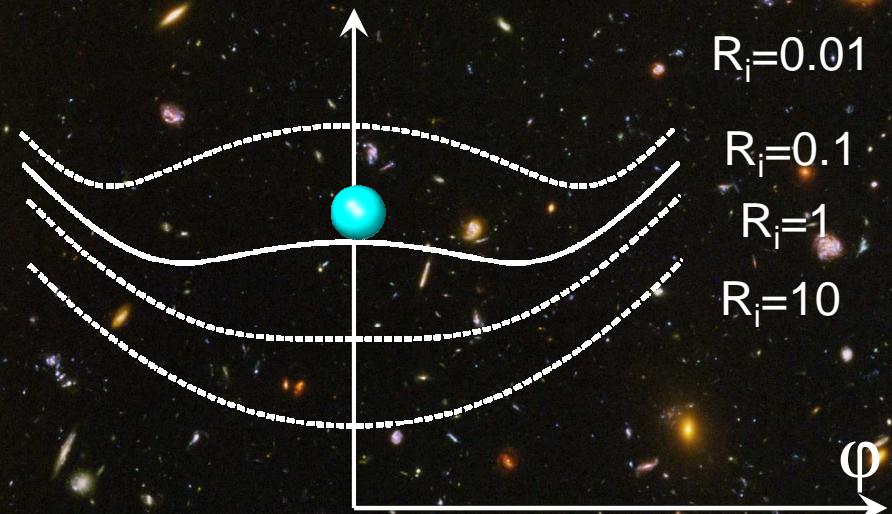
Scalar field stabilization in the AWE hypothesis

- ★ Decoupled Klein-Gordon equation in Einstein frame $\Phi = A_m^{-2}(\varphi)$ $M(\Phi) = \frac{A_{\text{awe}}(\varphi)}{A_m(\varphi)}$

$$\frac{2\varphi''}{3 - \varphi'^2} + \varphi' + \frac{d \ln \mathcal{A}(\varphi)}{d\varphi} = 0$$

$$(\bullet)' = \frac{d(\bullet)}{d \ln a_*} \quad R_i = \rho_m / \rho_{\text{awe}}|_{\varphi=\varphi_{\text{GR}}}$$

$$\mathcal{A}(\varphi) = A_m(\varphi) + \frac{A_{\text{awe}}(\varphi)}{R_i}$$



★ J.-M. Alimi, A. Füzfa, JCAP 0809 (2008)

★ A. Füzfa, J.-M. Alimi, PRD 75 123007 (2007)

Why does cosmic expansion accelerate?*

* According to the AWE Hypothesis

- ★ Observable acceleration factor:

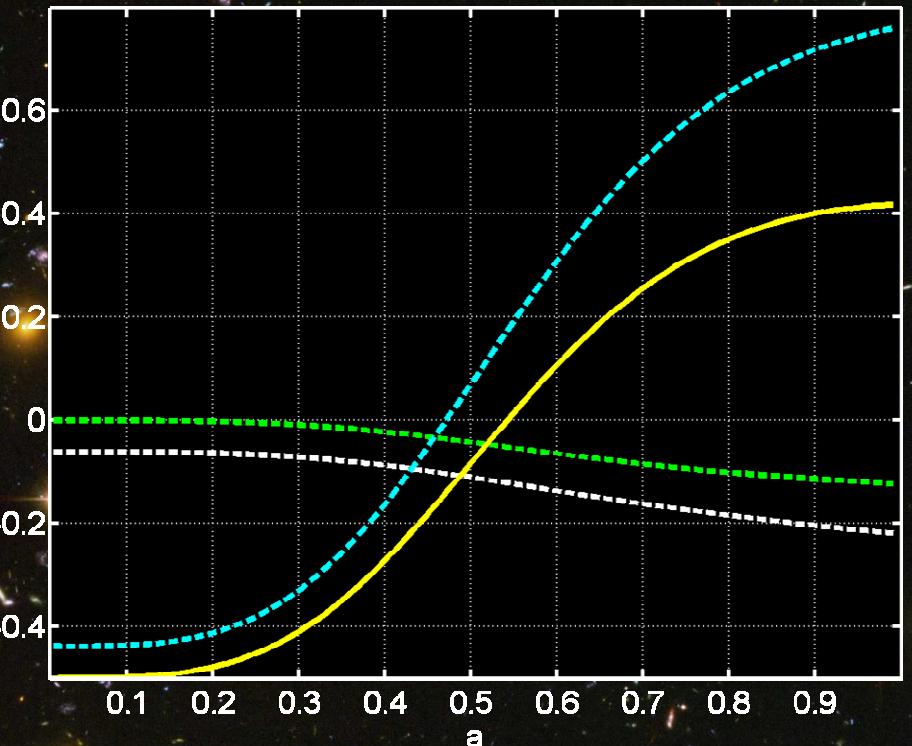
$$q = \frac{\varphi'^2 \left(3 \frac{d\alpha_m}{d\varphi} - 2 \right) - 6\alpha_m \varphi'}{3 (1 + \alpha_m \varphi')^2}$$

$$-\frac{4\pi G A_m^2(\varphi)}{3} (1 + 3\alpha_m^2) \rho_m$$

$$-\frac{4\pi G A_m^2(\varphi)}{3} (1 + 3\alpha_m \alpha_{awe}) \rho_{awe}$$

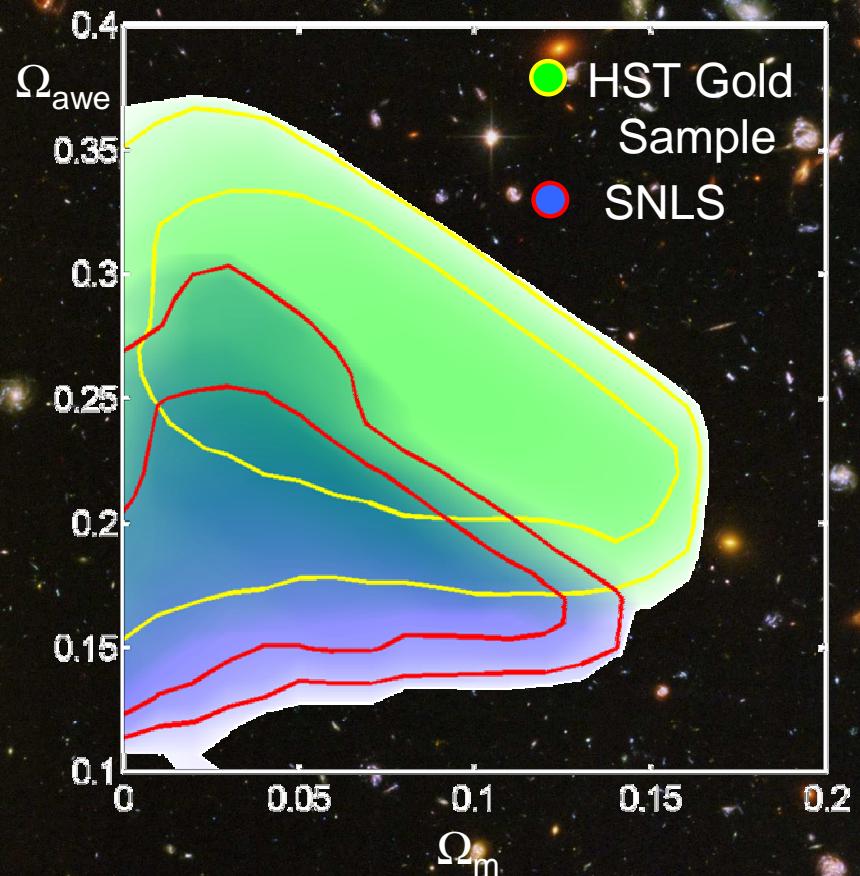


Best fit on SNLS data set
($\chi^2/\text{dof(AWE)}=1.06$, $\chi^2/\text{dof}(\Lambda\text{CDM})=1.05$)



- ★ The scalar fifth force induced by DM produces the cosmic acceleration!

Predictions on cosmological parameters



Combined HST & SNLS data sets

$$\chi^2/\text{dof}(\text{AWE})=1.12, \chi^2/\text{dof}(\Lambda\text{CDM})=1.11$$

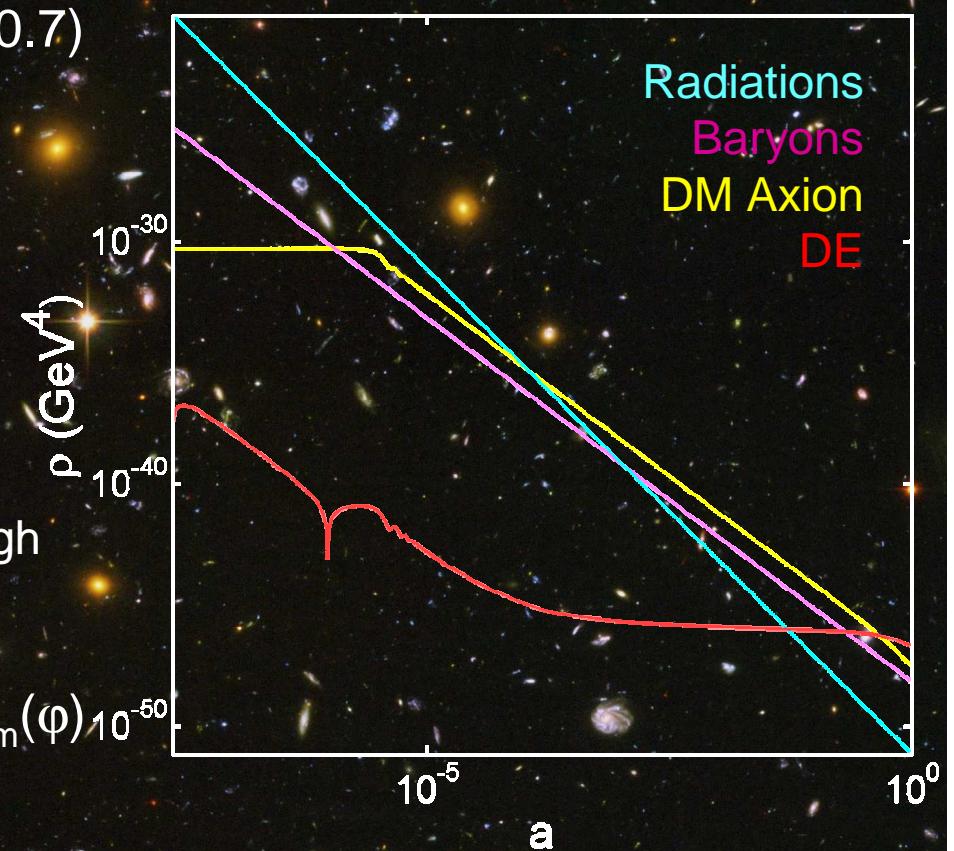
$$\begin{aligned}\rightarrow R_i &= 0.13^{+0.23}_{-0.08} \\ \rightarrow \Omega_m &= 0.05^{+0.06}_{-0.03} \\ \rightarrow \Omega_{\text{awe}} &= 0.24^{+0.03}_{-0.04} \\ \rightarrow \Omega_\varphi &= 0.71^{+0.04}_{-0.06} \\ \rightarrow t_0 &= 13.85 \text{Gyr}^{+0.19}_{-0.38} \\ (\text{for } h=0.7) &\end{aligned}$$

Matter \Rightarrow baryons
AWE \Rightarrow CDM
 φ dynamics \Rightarrow DE

- Measurement of baryons and DM distribution from SNe Ia alone!

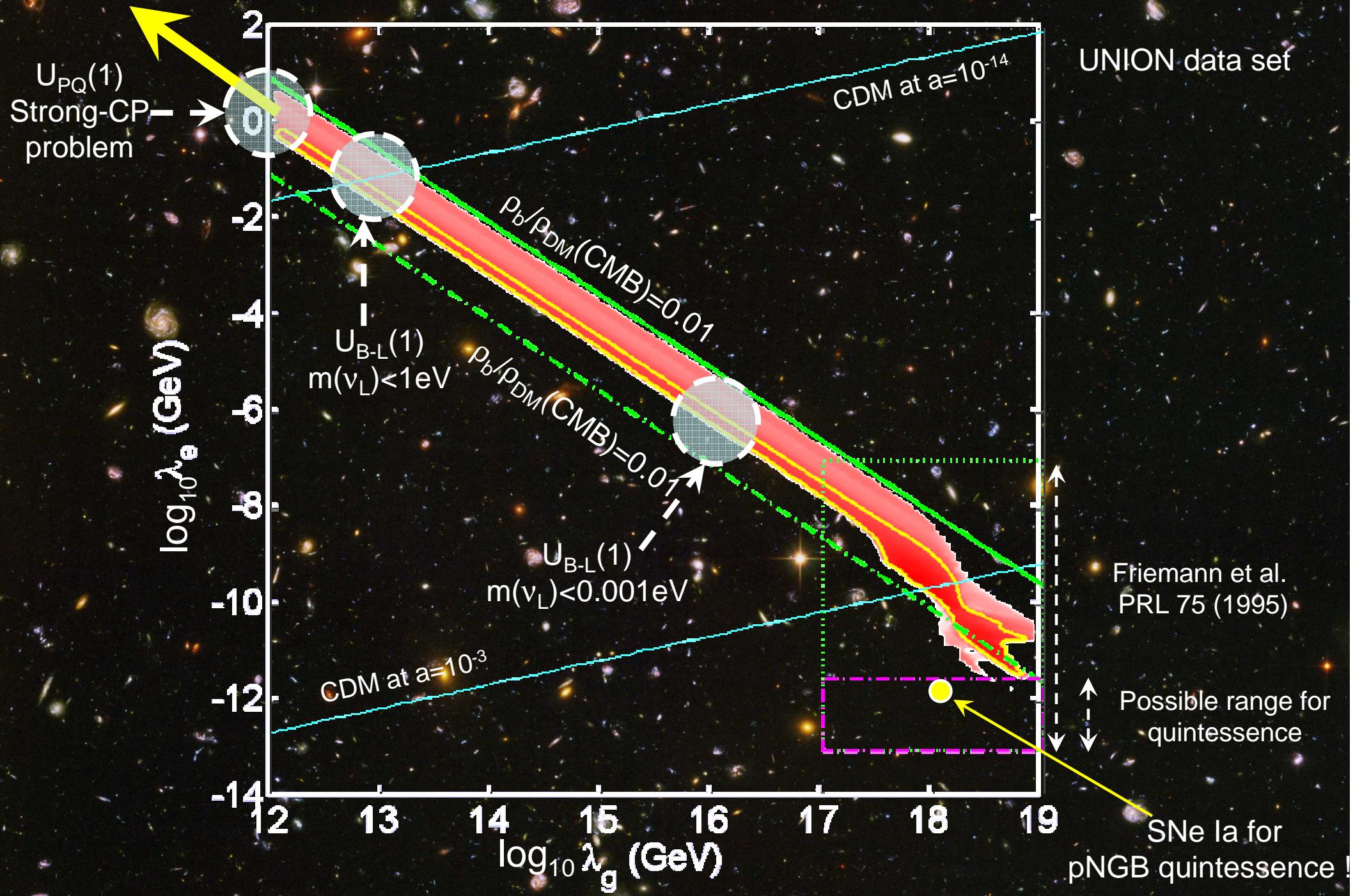
- Consistent with CMB & BBN constraints (though obtained in the Λ CDM framework)

- Results robust against reparametrization of $A_m(\varphi)$ (mexican hat shape)



a

Predictions on energy scales



Application to neutrino mass generation

- ★ ν oscillations: ν mass eigenstates \neq ν flavour eigenstates (interactions)
 - ⇒ Lepton number is a global broken symmetry
 - ⇒ Physical ingredients:
 - A new scalar particle Ψ charged under $U_{B-L}(1)$ couples to right neutrinos ν_R

$\mathcal{L}_{\nu_R} \approx \Psi \bar{\nu}_R^c \nu_R$ Yukawa coupling \Rightarrow Majorana mass term

→ No direct couplings of Ψ to Standard Model particles ($L_\psi = -2$)

$\rightarrow v_B$ couples directly to v_L (Dirac mass) $\mathcal{L}_{\nu_L} \approx m_D \bar{\nu}_B \nu_L$

$\rightarrow v$ mixing : Seesaw mechanism $m_{\nu_L} \approx \bar{m_D^2}/m_{\nu_R}$ $m_{\nu_B} \approx <\Psi>$

- ★ Lightness of ν_L requires a huge vacuum expectation value for ψ (large m_{ν_R})
 - Usually: spontaneous symmetry breaking of $U_{B-L}(1)$ (at Planck scale)
 - Here: gravitational symmetry breaking (stabilisation with non-minimal couplings)

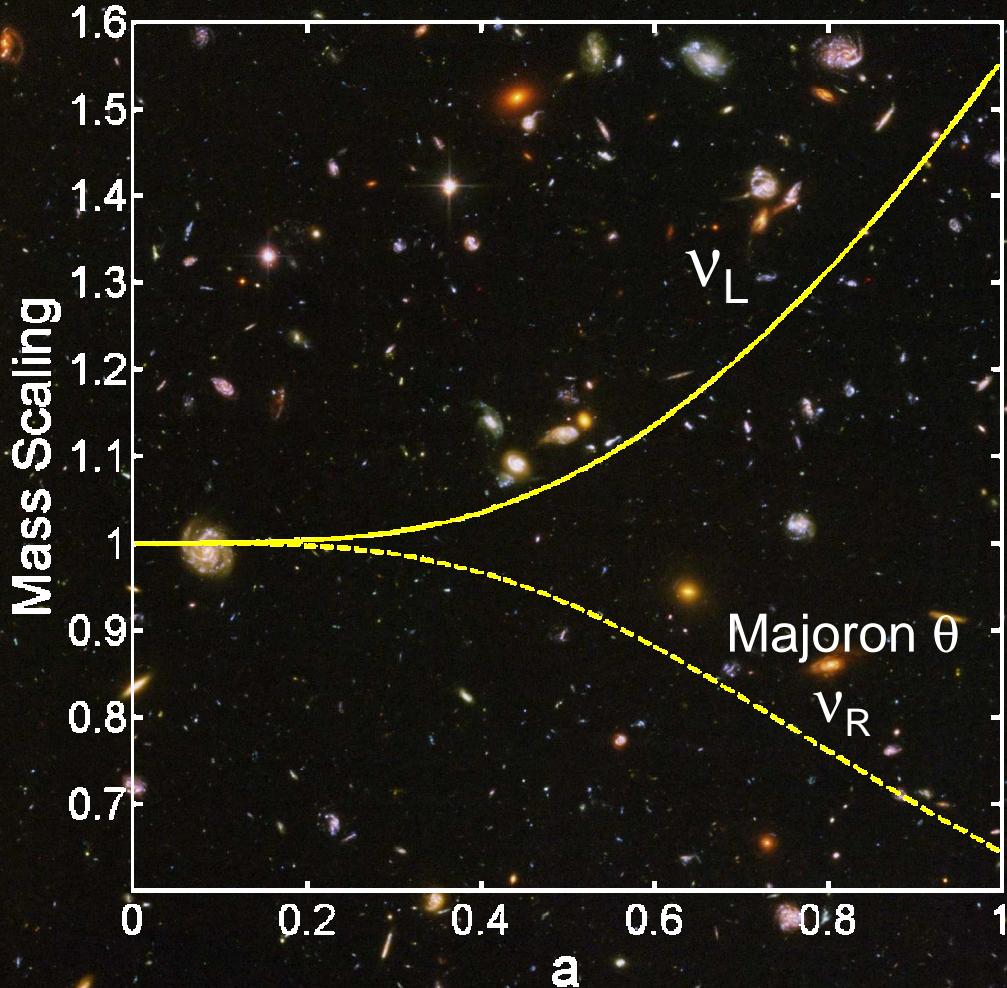
$$S_m [\psi_m, g_{\mu\nu}] + S_\theta [\theta, m_\theta(|\Psi|)g_{\mu\nu}] + \int m_{\nu_R}(|\Psi|) ds + \int m_{\nu_L}(|\Psi|) ds$$

SM physics is B-L invariant:
 No dependence on Ψ

Majoron



Variation of neutrino masses



Example:

$$\lambda_e \sim 10^{-5} \text{ GeV}$$

$$\lambda_g \sim 10^{15} \text{ GeV}$$

« Bare » masses:

$$m_\theta = \lambda_e^2 / \lambda_g \sim 10^{-5} \text{ GeV}$$

$$m_R \sim \lambda_g$$

$$m_L = (v_{EW})^2 / m_R \sim 0.01 \text{ eV}$$

- ★ A mass scaling of ~30% of Majoron accounts for cosmic acceleration
- ★ Numerous impacts on large-scale structure formation! (CDM↔HDM)
- ★ The mass scaling is density-dependent => DM-induced modified gravity

Summary

★ The AWE hypothesis:

- DM is abnormally weighting: DM-induced modification of gravity
- Completes usual coupled DM-DE models with only varying m_{DM}
- Effective theory of gravitation of relaxed equivalence principle

★ Proposal : gravitation and symmetry breaking

- Particle masses changes during phase transition : violation of equivalence principle
- Gravitational symmetry breaking : stabilisation thanks to non-minimal couplings

★ Predictions

- Cosmology : cosmic acceleration, coincidence, Ω_{baryon} & Ω_{DM} from SNe Ia alone
- **EP violation & gravitational dynamics on large-scales**
- **Particle physics constraints on mass variation**
- ...

Thank you for your attention!



AWE and Cosmic coincidence

- ★ Effective DE follows pressureless matter: coincidence after CMB epoch!

$$\tilde{\rho}_{DE} = \tilde{\rho}_m (1 + R_i^{-1}) \left\{ 3 \frac{A_m^i{}^2 + R_i (1 + \alpha_m \varphi^0)^2}{1 + R_i} - 1 \right\}$$

$$R_i = \rho_m / \rho_{\text{awe}}(\text{CMB})$$

- ★ Coincidence when $\rho_{DE} \sim \rho_m (1 + R_i^{-1})$:

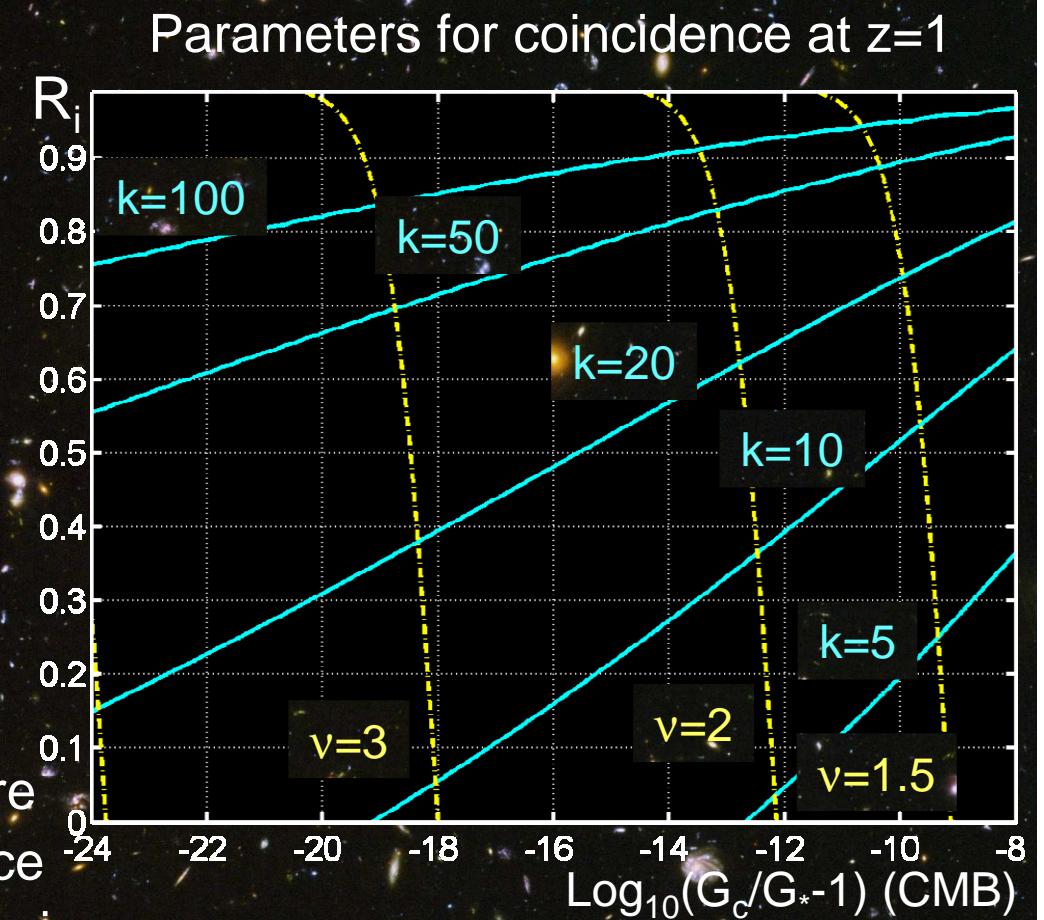
$$a_c \approx a_{\text{CMB}} \left(\frac{\sqrt{2} - 1}{k\nu \varphi_{\text{CMB}}^2} \right)^{1/(2\nu)}$$

- ★ Coincidence depends on:

→ $R_i (< 1)$: initial mixing parameter
 → $R_\infty (\sim 1)$: ratio of coupling strengths
 → $k (\sim 1)$: scalar coupling strength
 → $\varphi_{\text{CMB}} (\sim 0)$: initial departure from GR

- ★ Coincidence occurs naturally:

→ scalar coupling $k \approx$ tensor coupling
 → Not too large departure from GR before CMB ($\varphi_{\text{CMB}} < 10^{-4}$): OK with convergence mechanism of usual tensor-scalar theories



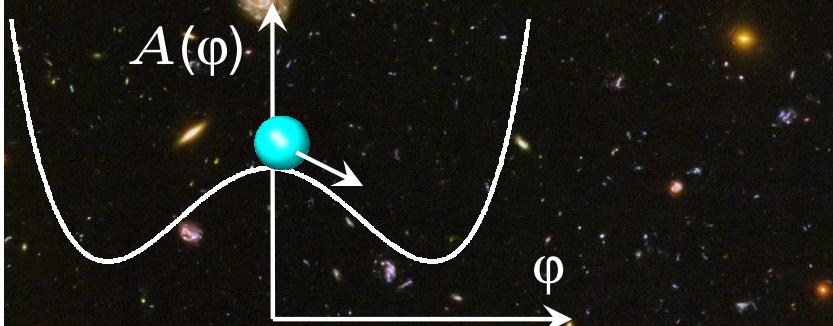
AWE mimics a fictive exotic fluid

- ★ Friedmann equation in the observable frame

$$\tilde{H}^2 = \frac{8\pi G_{\text{x}} A_m^2}{3} (\tilde{\rho}_m + \tilde{\rho}_{\text{awe}}) \frac{3(1 + \alpha_m \varphi^0)^2}{3 - \varphi'^2} = \frac{8\pi G_{\text{x}} A_m^2}{3} (\tilde{\rho}_m (1 + R_i^{i-1}) + \rho_{DE})$$

$$\tilde{\rho}_{DE} = \tilde{\rho}_m (1 + R_i^{i-1}) \left\{ 3 \frac{A_m^{i-2} + R_i}{1 + R_i} \frac{(1 + \alpha_m \varphi^0)^2}{3 - \varphi'^2} - 1 \right\}$$

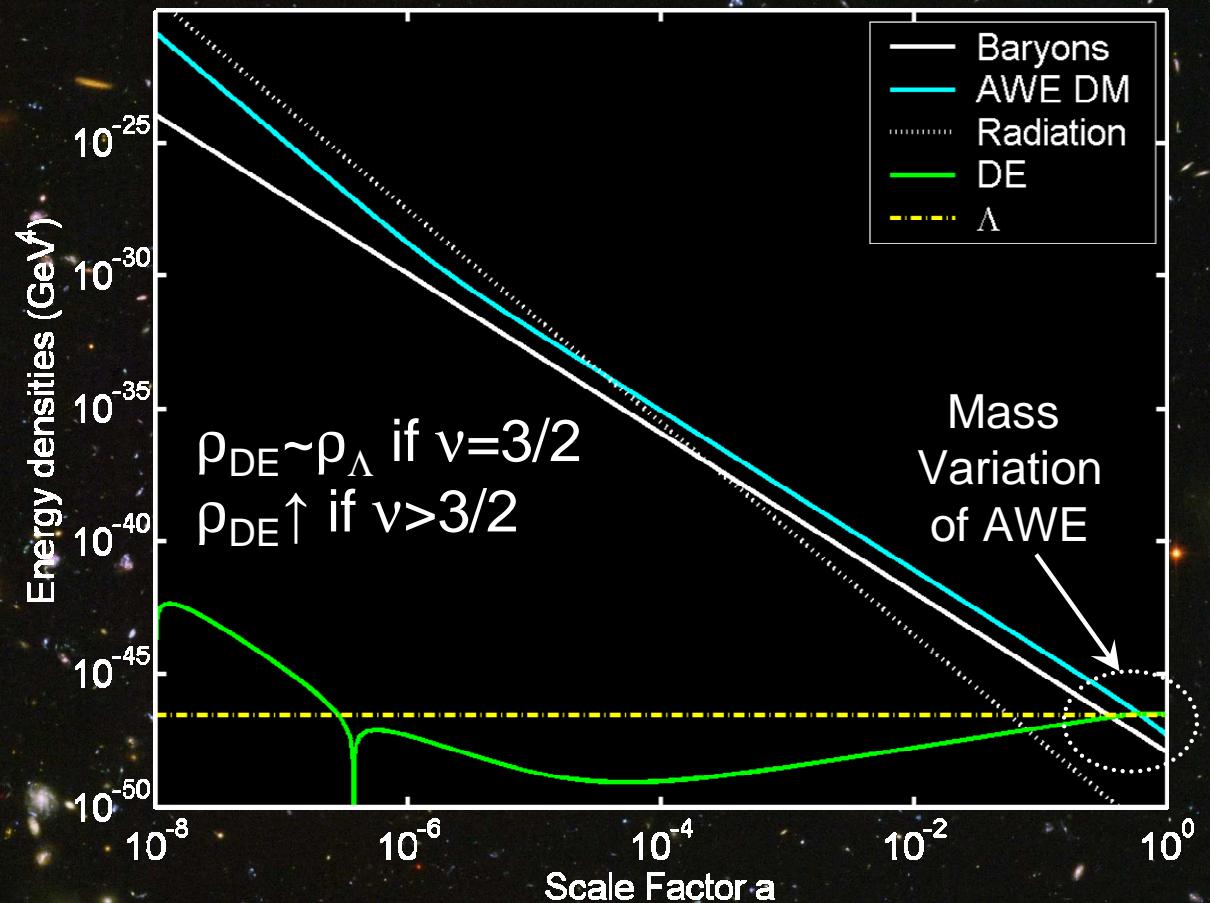
- ★ Early cosmological evolution:



$$\varphi(a) \approx \varphi_{\text{CMB}} \left(\frac{\tilde{a}}{a_{\text{CMB}}} \right)^\nu$$

$$\nu = \frac{3}{4} \left(-1 + \sqrt{1 - \frac{8}{3} k \frac{R_i - R_1}{1 + R_i}} \right)$$

$$\tilde{\rho}_{DE} \approx k\nu \varphi_{\text{CMB}}^2 \tilde{\rho}_m \left(\frac{\tilde{a}}{a_{\text{CMB}}} \right)^{2\nu}$$

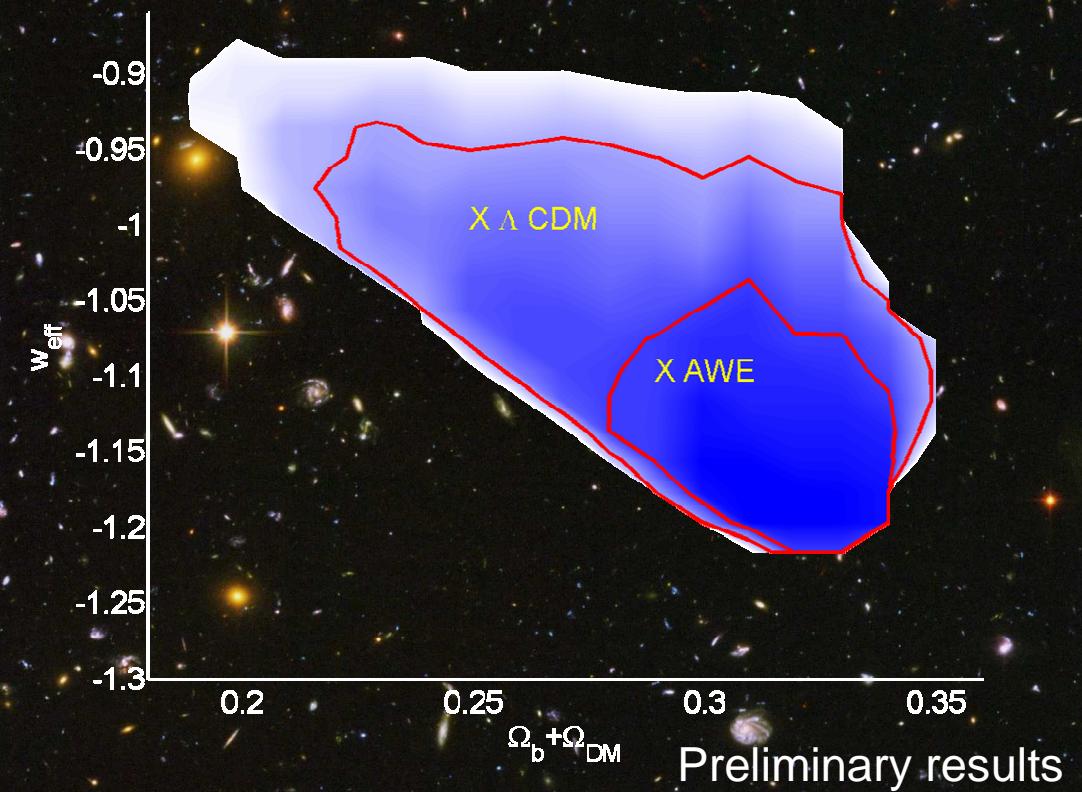
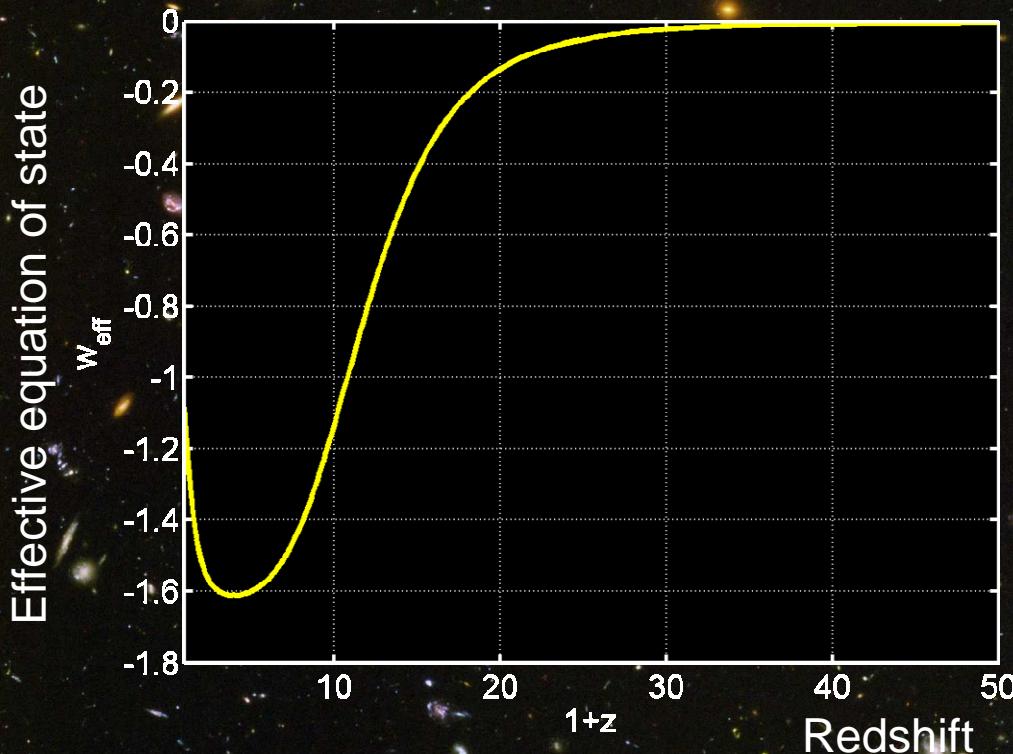


Cosmic acceleration without negative pressures

- Effective equation of state for the fictive exotic fluid of DE:

$$\frac{1}{\tilde{a}} \frac{d^2 \tilde{a}}{d\tilde{t}^2} = -\frac{4\pi G_{\alpha} A_m^2}{3} \left\{ \tilde{\rho}_m \left(1 + R_i^{i-1} \right) + \tilde{\rho}_{DE} \left(1 + 3\omega_{\text{eff}} \right) \right\}$$

- WEP violation ($\alpha_m \neq \alpha_{\text{awe}}$) mimics negative pressures
- AWE provides stronger cosmic expansion than Λ CDM ($w_{\text{eff}} < -1$, « ghost »)



Preliminary results

AWE completes Chameleons Fields

★ AWE action:

$$S_{AWE} = \frac{1}{2\kappa_{\alpha}} \int \sqrt{-g_{\alpha}} d^4x \{ R^{\alpha} - 2g_{\alpha}^{\mu\nu} \partial_{\mu}\varphi \partial_{\nu}\varphi \} + \sum_i S_i [\psi_i, A_i^2(\varphi) g_{\mu\nu}^{\alpha}]$$

★ Chameleon action :

$$S_{cham} = \int \sqrt{-g_*} d^4x \left\{ \frac{1}{2\kappa} R - \partial_{\mu}\varphi \partial^{\mu}\varphi - V(\varphi) \right\} + \sum_i S_i [\psi_i, e^{\beta_i \varphi} g_{\mu\nu}]$$

★ Chameleon approaches do not make the most of nonminimal couplings:

★ AWE

- Opposite scalar coupling strengths
- Scalar field stabilization :
 $A_m(\varphi)$ vs $A_{awe}(\varphi)$ only
- Cosmic acceleration is achieved without requiring to a potential
- Non-linear nonminimal couplings
 $\ln A_{m,awe}(\varphi) \sim \varphi^2 + \dots$ (local validity of GR)

★ Chameleons

- Universal nonminimal couplings \Rightarrow
WEP is OK!
- Scalar field stabilization :
 $\exp(\beta\varphi)$ vs $V(\varphi)$
- Cosmic acceleration:
a well-shaped potential is put
- Linear nonminimal couplings
 $A(\varphi) = \exp(\beta\varphi)$ are used although strongly constrained