Dark Energy and the AWE* Hypothesis

Jean-Michel Alimi & André Füzfa

Laboratoire Univers and Theories, Observatoire de Paris

GRECO-IAP

12 Février 2007

Phys. Rev. D 73, 023520 (2006), gr-qc/0511090, Phys. Rev. Lett. 97, 061301 (2006), astro-ph/0604517, SF2A 2006, MG11, FQTC Warrenton 2006, Phys Rev D 2007, to be submitted…

** Abnormally Weighting Energy*

One of the most Chalenging problems in Physics

- ***Several cosmological observations demonstrated that the expansion of the universe is accelerating***

- ***What is causing this acceleration ?***

- ***How can we learn more about this acceleration, the Dark Energy it implies, and the questions it raises ?***

Outline

- **Observational Evidences of Dark Energy**
- **Nature of Dark Energy: Theoretical Interpretations:**
  - **Why the dark energy cannot be simply a cosmological constant ?**
  - **Quintessence…?**
  - **« Iceberg description »**
- **The AWE hypothesis *!***
- **A First Candidat for the Abnormally Weighting Component**
  - **A new Born-Infeld gauge interaction**
  - **A natural transient mechanism which accounts for the Hubble diagram**
  - **A time variation of G while accounting naturally for the present tests on GR**
- **A new candidat: toward an unification of DM and DE problem**
  - **A natural « dual GR » at cosmological scales**
  - **Why the concordance model appears correct ?**
  - **A natural phantom dark energy**
  - **AWE dark matter as a time-dependent inertial mass**
- **Conclusion and Perspectives**

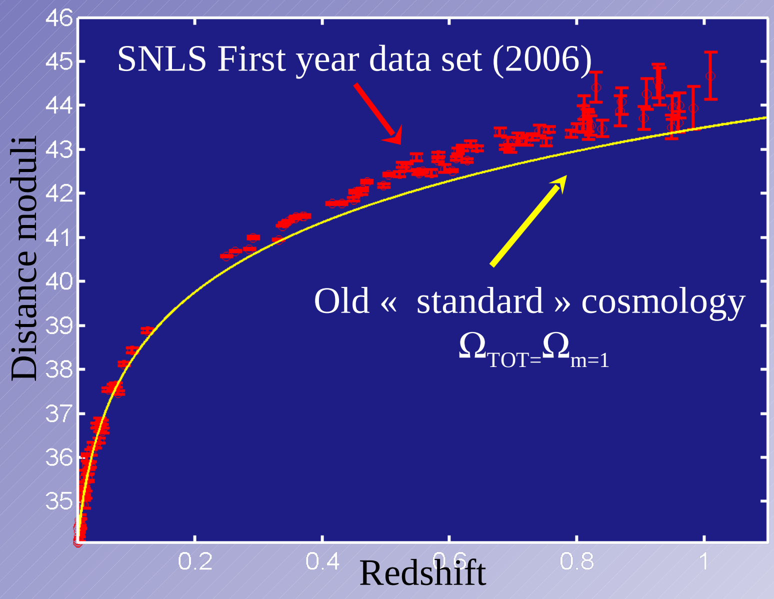
Observational Evidences of Dark Energy (1/3)

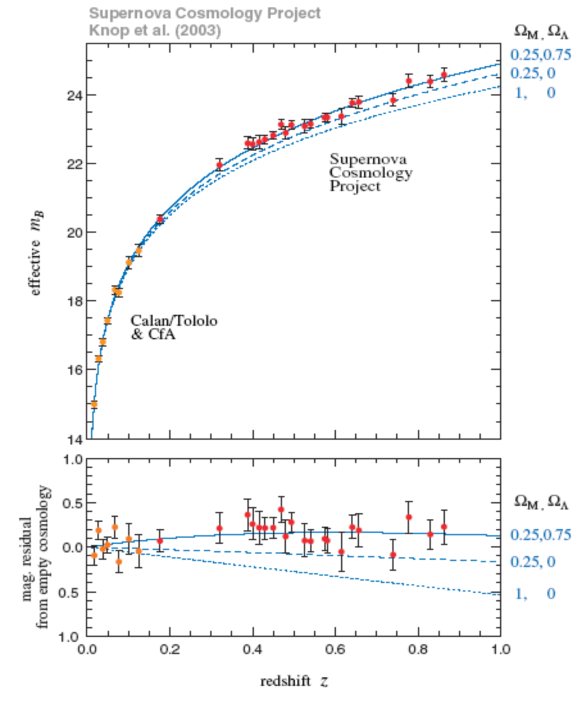
Supernovae type Ia

- Standard candles
- Their intrinsic luminosity is know, their apparent luminosity can be precisely measured*
- The ratio of the two can provide the luminosity-distance (d_L) of the supernova, the red shift z can be measured independently from spectroscopy
- Finally, one can obtain d_L (z) or equivalently the magnitude(z) and draw a Hubble diagram

- Type Ia Supernovae appear fainter than expected:

Cosmic expansion has recently accelerated or (and?) *Supernovae are not standard candles at that time*



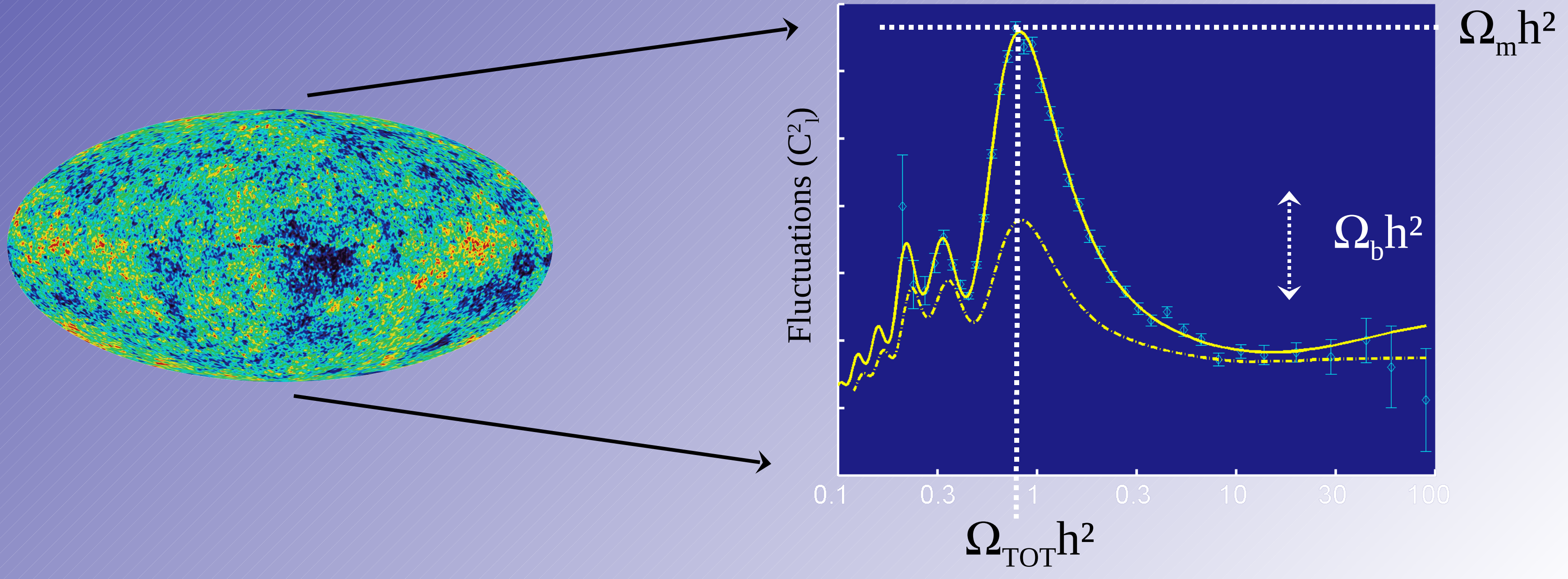


* P.S. Corasaniti 2006

Observational Evidences of Dark Energy (2/3)

Evidence from Cosmic Microwave Background Radiation (CMB)

- CMB is an almost isotropic relic radiation of T=2.725±0.002 K
- CMB is a strong pillar of the Big Bang cosmology
- It is a powerful tool to use in order to constrain several cosmological parameters

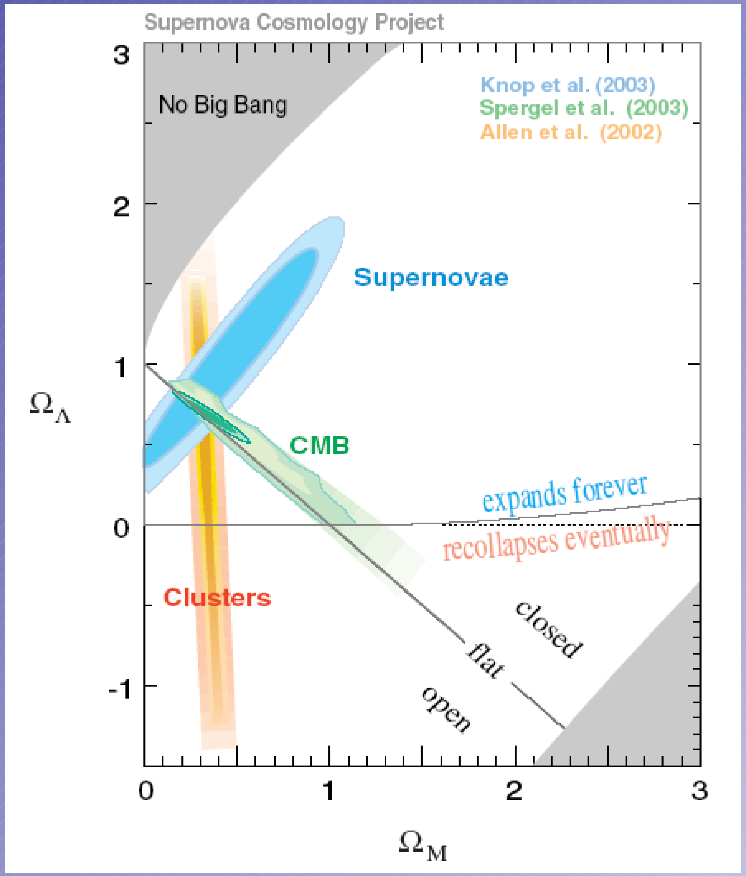


Observational Evidences of Dark Energy (3/3)

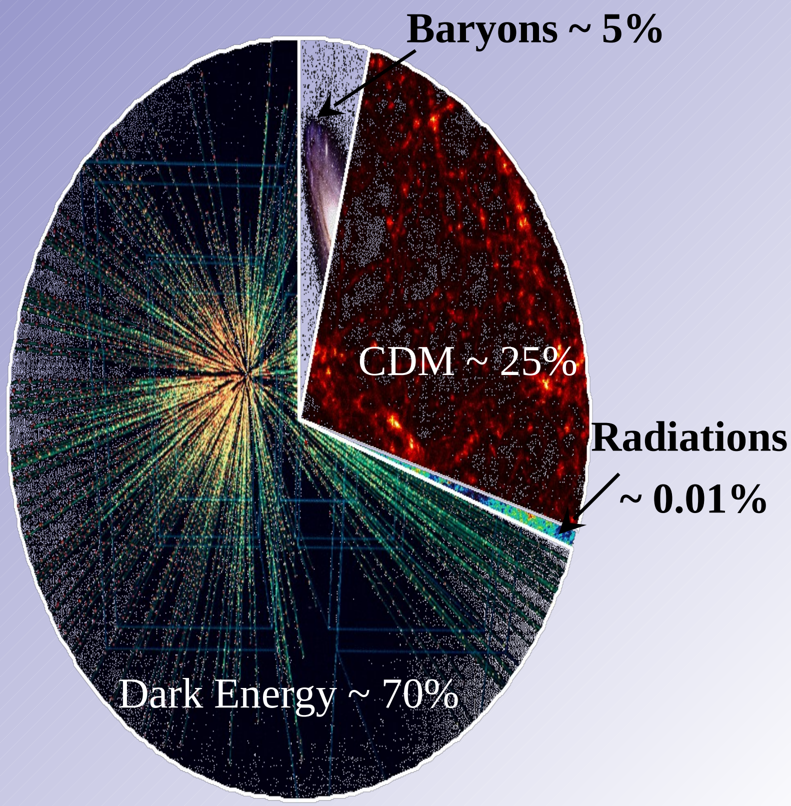
Evidence from LSS…BAO, WL…

- Counting clusters of galaxies can infer the matter energy density in the universe, Ω_{Matter} found is usually around ~0.3

Cosmic complementarity



The Concordance Model ΛCDM



Nature of Dark Energy ? (1/5)

Cosmological Paradigme

- **Covariance Principle**
- **Equivalence Principle**

$\Big\}$ **GR** $$G_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu}$$

- **(Strong) Cosmological Principle*:** Dynamics of the Univers is given only by a(t)

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G\rho}{3}$$
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

New energy-component (ρ) + to LM and DM:
Violation of the strong energy condition

$$\ddot{a} > 0 \text{ if } p < -\frac{\rho}{3}$$

Extensions to GR:
Geometrical Interpretation

- **Standard Model and theoretical extensions**

Extensions to GR can be interpreted as
an extra energy-component in a « quasi » Friedmann model ?

*Reinterpreting dark energy through backreaction: the minimally coupled **morphon field**,
J. Larena, T. Buchert, AJM: CQG. 23, 6379 (2006), gr-qc/0606020, astro-ph/0609315, astro-ph/0612774

Nature of Dark Energy: A Cosmological Constant ? (2/5)

- Λ has been historically introduced by Einstein himself in 1917 as a Mach principle-inspired term

- This Solution does not require to give up neither GR not the cosmological principle and furthermore allows to account for dark energy effects with only one additional parameters

- However, what is the nature of Λ ?
  - $P_\Lambda = -\rho_\Lambda$
  - Homogeneous DE, no direct interactions with matter, consequently only modify cosmic expansion
  - It is usually interpreted as the stress-energy term associated to the vacuum state which has non-vanishing energy due to quantum fluctuations

$$\rho_\Lambda = 8\pi G \langle T_{00} \rangle_{vac} \propto \int_0^\infty \sqrt{k^2 + m^2}\, k^2 dk = ? \quad \begin{cases} \infty\,? \\ 10^{76}\ Gev^4\ (\text{Regularized at the Planck scale})? \\ 10^{-3}\ Gev^4\ (\text{Regularized at the QCD scale})? \\ ? \end{cases}$$

$$\rho_\Lambda^{obs} \approx \rho_{c,0} \approx 10^{-47}\, GeV^4$$

Not a true problem:

Additive Integration-Constant in Einstein equations / Vacuum Energy

Nature of Dark Energy: A Cosmological Constant ? (3/5)

Coïncidence Problem !

- ρ_Λ^{obs} is very different to any other energy scale in the standard model, why Λ is so small ? (is it really constant?)

    - We live in a very particular epoch in the history of the Universe: the time when the cosmological constant starts dominating the energy content of the Universe.

- One can therefore expect that the final solution to this problem might well be quite different from the simple and may be rather naive cosmological constant*

- One could prefer suggesting a **cosmological mechanism** to justify the observed value of the cosmological constant.

    - Quintessence constitutes such an alternative explanation of DE (varying Λ)

***** Padmanabhan 2005.

Nature of DE: Quintessence and others extensions (4/5)

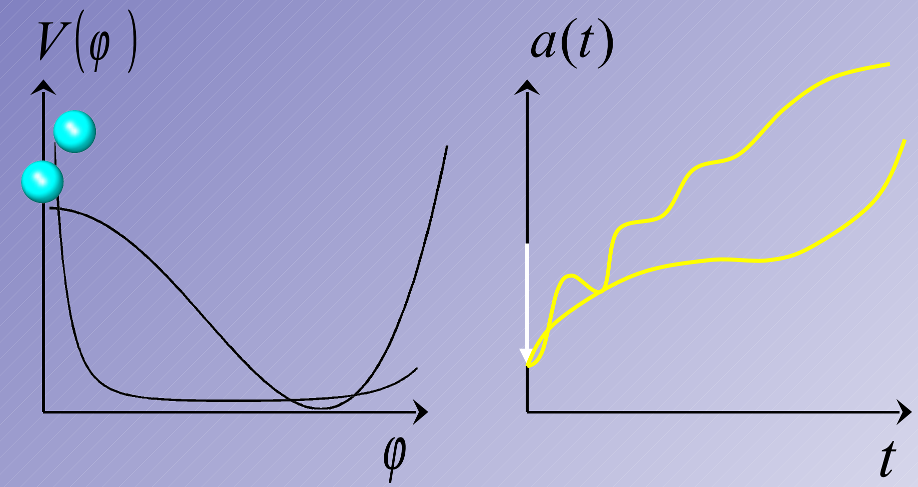
Quintessence[1]

- Dynamical DE, ρ_Q varies with time

$$\rho_Q = \frac{\dot{\varphi}^2}{2} + V(\varphi),\ p_Q = \frac{\dot{\varphi}^2}{2} - V(\varphi)$$

$$V(\phi) = V_0 f(\phi)$$

- Inhomogeneous DE : $\exists\ \delta\phi(k,t) \neq 0$ (CMB)



DE as a Violation of the strong energy condition

$$\boxed{\ddot{a} > 0 \text{ if } p_Q < -\frac{\rho_Q}{3} \ (\dot{\phi}^2 << V(\phi))}$$

- Possible direct interactions with matter: DE-DM couplings, DE-Baryons couplings[2]

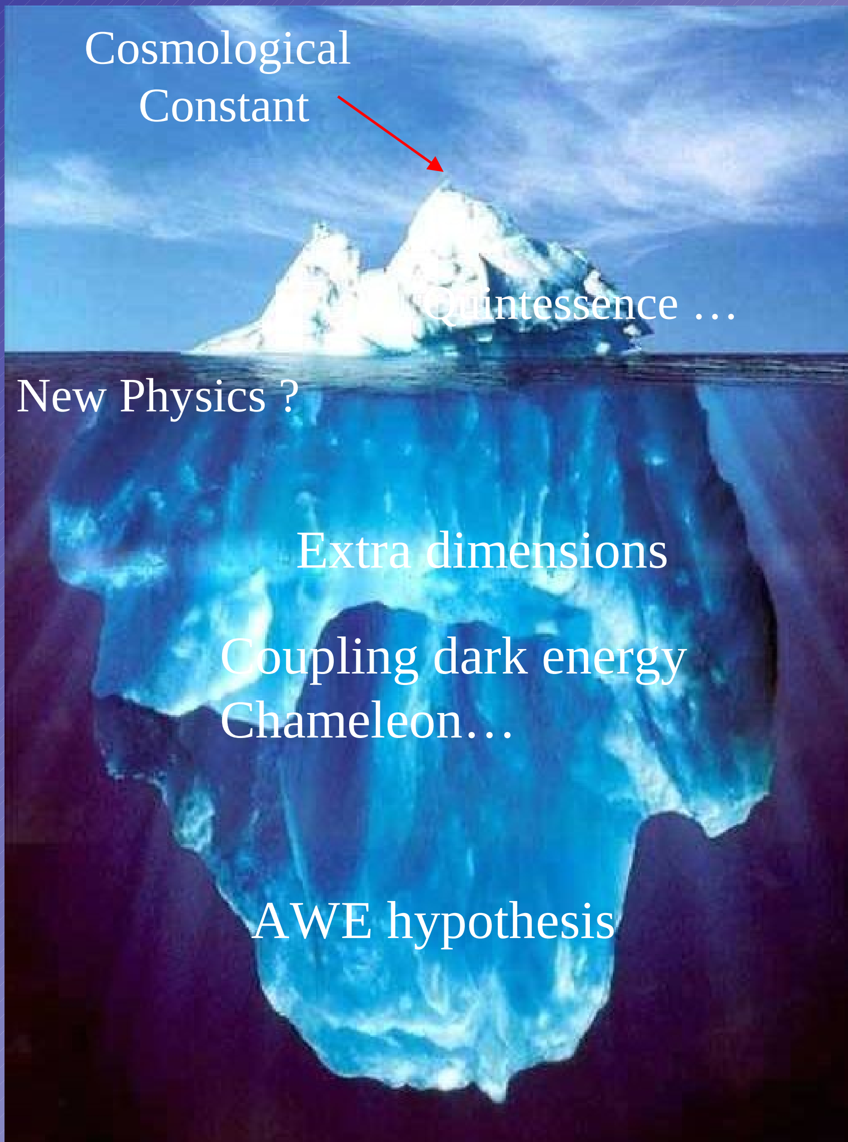
Violation of the (universal) equivalence principle!

[1] Ratra & Peebles 1988, Steinhardt et al. 1999…

[2] Amendola 2004, Khoury & Weltman 2004, Brax et al 2004, Das, Corasaniti & Khoury 2006, …

Nature of Dark Energy in Perspective? (5/5)

The Dark Cosmology Iceberg



- The simple cosmological constant can be seen as the top of the iceberg of a deeper intriguing theory of gravitation

$$S_{Einstein} = \frac{1}{2\kappa}\int d^4x\sqrt{-g}\{R+\Lambda\}$$

- In the framework of Quintessence, Λ corresponds to the limiting case where the scalar field freezes in a non-vanishing energy state.

$$S_{grav} = \frac{1}{2\kappa}\int d^4x\sqrt{-g}\{R-2\partial_{\mu}\varphi\,\partial^{\mu}\varphi+\mathrm{V}(\varphi)\}$$ (SEP+WEP)

- Quintessence itself can be seen as the limiting case of Tensor-scalr gravity with negligible violation of Strong Equivalence Principle (SEP)

$$S = S_{grav}[g_{\mu\nu},\varphi]+S_{matter}[\psi_m, A_{matter}^2(\varphi)g_{\mu\nu}]$$ (NO SEP, WEP)

- Finally, there is a generalization of the non-minimal couplings that embed the previous TST: the case where the non-minimal couplings are not universal.

$$S = S_{grav}[g_{\mu\nu},\varphi]+\sum_{matter\ i} S_i[\psi_i, A_i^2(\varphi)g_{\mu\nu}]$$ (NO SEP, NO WEP)

This will constitutes the starting point of the Abnormally Weighting Energy (AWE) Hypothesis.

The AWE Hypothesis: (1/4)
Cosmology without Equivalence Principle

Tensor-scalar theories of gravitation* (universal coupling => NO SEP, WEP)

- Dicke-Jordan Frame (Observational Frame)

$$S = \frac{1}{2}\int d^4x\sqrt{-\tilde{g}}\left\{\Phi R - \frac{\omega(\Phi)}{\Phi}\tilde{g}^{\mu\nu}\partial_\mu\Phi\,\partial_\nu\Phi\right\} + S_M\left[\Psi_M, \tilde{g}_{\mu\nu}\right]$$

- Einstein Frame $\tilde{g}_{\mu\nu} = A_M^2(\varphi)\, g^*_{\mu\nu}$

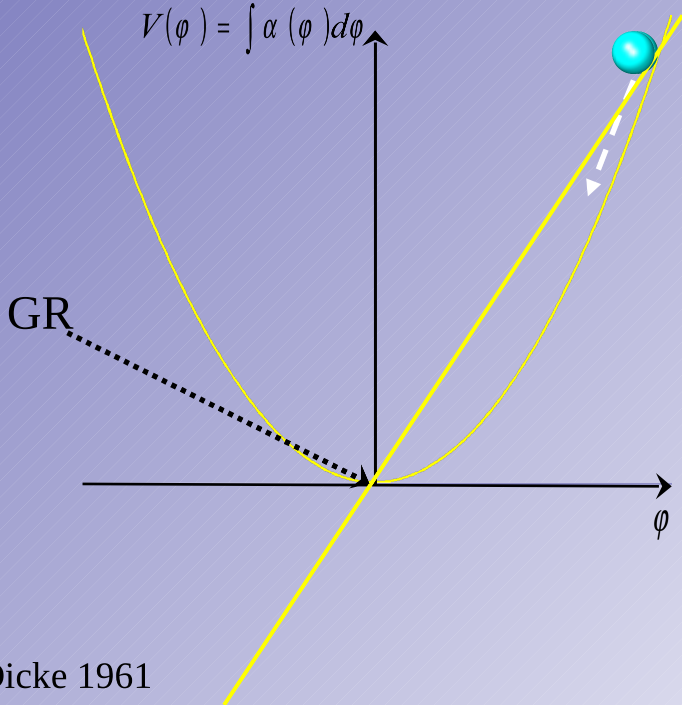
$$S = \frac{1}{2\kappa}\int d^4x\sqrt{-g^*}\left\{R - 2\partial_\mu\varphi\,\partial^\mu\varphi\right\} + S_M\left[\psi_M, A_M^2(\varphi)\, g^*_{\mu\nu}\right]$$

- Cosmological dynamics $\left(\frac{2}{3-\varphi'^2}\right)\varphi'' + \left(1-\frac{p}{\rho}\right)\varphi' + \left(1-3\frac{p}{\rho}\right)\alpha_M(\varphi) = 0$

with $' \equiv \frac{d}{d\lambda}$

where $\lambda \propto \log(a)$

and $\alpha_M(\varphi) = \frac{d\log A_M(\varphi)}{d\varphi}$



Post-Newtonian Constraints

$$|\gamma - 1| = 2\frac{\alpha_0^2}{(1+\alpha_0^2)} < 2\times 10^{-5}$$

$$|\beta - 1| = \left|\frac{d\alpha}{d\varphi}\right|_0 \left|\frac{\alpha_0^2}{2(1+\alpha_0^2)}\right| < 6\times 10^{-4}$$

$$\left|\frac{\dot{G}}{G}\right| < 6\times 10^{-12}\, yr^{-1}$$

*Jordan 1949, Fierz 1956, Brans & Dicke 1961

The AWE Hypothesis: The equivalence principle (2/4)

- All kinds of energies couple in the same way to gravitation
  - Strong equivalence principle (**SEP**): gravitational binding energy
  - Weak equivalence principle (**WEP**): non-gravitational energies

- Effective theories of gravitation:
  - Tensor Scalar gravity, low-energy limit of string theory*

$$S_{grav} = \frac{1}{2\kappa}\int d^4x\sqrt{-g}\left\{R - 2\partial_\mu\varphi\,\partial^\mu\varphi\right\}$$

$$S_{matter} = S_{gauge}\left[\psi_{gauge}, A_{gauge}^2(\varphi)g_{\mu\nu}\right] + S_{fermions}\left[\psi_{fermions}, A_{fermions}^2(\varphi)g_{\mu\nu}\right] + \ldots$$

Ψ_i: matter field, $A_i(\varphi)$ coupling functions, φ « dilaton »,

Effective metric felt by energy *i* (« observable » frame for *i*) $\tilde{g}_{\mu\nu} = A_i^2(\varphi)g_{\mu\nu}$

Gravitation: spin 2 ($g_{\mu\nu}$)+ spin 0 (φ) : NO SEP !

Non-universal coupling (A_{gauge}(φ) ≠$A_{fermions}$(φ), etc.) : NO WEP ⇒ NO SEP !

* Damour & Polyakov 1994

The Awe Hypothesis: a DE Abnormally Weighting ? (3/4)

(In Einstein Frame) Energy content of the Universe is divided in 3 parts

- A gravitational sector described by pure spin 2 (graviton) and spin 0 (dilaton) degrees of freedom and a matter sector containing :
- The **ordinary matter** (baryons, photons, ...), ruled by the equivalence principle, defines the observable frame

$$\tilde{g}_{\mu\nu} = A_M^{\,2}(\varphi)\, g_{\mu\nu}$$

- AWE sector violating the weak equivalence principle

$$A_M(\varphi) \neq A_{AWE}(\varphi) \qquad \tilde{a}(\tilde{t}) = A_m(\varphi)\, a(t)\ ,\ \tilde{H}(\tilde{t}) = \frac{1}{\tilde{a}} \frac{d\tilde{a}}{d\tilde{t}}\ ,\ \tilde{q}(\tilde{t}) = \frac{\ddot{\tilde{a}}\tilde{a}}{\dot{\tilde{a}}^2}$$

$$\boxed{\begin{aligned} S = \frac{1}{2\kappa}\int d^4x\sqrt{-g^*}\left\{R - 2\partial_\mu\varphi\,\partial^\mu\varphi\right\} + S_M\left[\psi_M, A_M^{\,2}(\varphi)\, g^*_{\mu\nu}\right] \\ + S_{AWE}\left[\psi_{AWE}, A_{AWE}^{\,2}(\varphi)\, g^*_{\mu\nu}\right] \end{aligned}}$$

The Action of the AWE Hypothesis generalizes the models DM-DE couplings Das, Corasaniti, Khoury 2006: $A_{AWE}(\varphi) \equiv A_{DM}(\varphi) = e^{\beta\varphi}\ ,\ A_M(\varphi) = 1$
Chameleon, Khoury, Weltman, Brax,Davis, van de Bruck 2004: $A_{AWE}(\varphi) = e^{\beta_{AWE}\varphi}\ ,\ A_M(\varphi) = e^{\beta_M\varphi}$
However the AWE Hypothesis consider the scalar field is massless

The Awe Hypothesis: a DE Abnormally Weighting ? (4/4)

- AWE introduces a **competition** in cosmological dynamics

$$\ddot{\varphi} + 3H^*\dot{\varphi} + \underbrace{\frac{\kappa}{2}\frac{d\log A_{AWE}}{d\varphi}\left(\rho^*_{AWE} - 3p^*_{AWE}\right)}_{\text{Repulsion from GR}} + \underbrace{\frac{\kappa}{2}\frac{d\log A_M}{d\varphi}\rho^*_M}_{\text{Attraction toward GR}} = 0$$

- **Impacts on cosmology and Precision tests of GR today:**
  - Early universe (CMB, BBN)
    - OK if DE is a late process
  - Luminosity curves of SNe Ia
    - Modification of luminous distance and $\mathbf{G_{eff}}$
  - Post-Newtonian Constraints!
    - The DE process should be **TRANSIENT**
  - Observed Universality of free fall
    - Too few DE on small scales

A First Candidat for the Abnormally Weighting Component (1/7)

$$S = \frac{1}{2\kappa}\int d^4x\sqrt{-g^*}\left\{R - 2\partial_\mu\varphi\,\partial^\mu\varphi\right\} + S_M\left[\psi_M, A_M^2(\varphi)g^*_{\mu\nu}\right] + S_{BI}\left[A_\mu, A_{BI}^2(\varphi)g^*_{\mu\nu}\right]$$

- Ideal candidate : **new Born-Infeld gauge interaction:**
  (renormalisation of point-like singularities, string theory, …)
- The non-abelian gauge interaction is described by the Born-Infeld Lagrangian upon the field strength tensor (ε_c is the Born-Infeld critical energy, $\varepsilon_c \to \infty$, YM)

$$\mathcal{L}_{BI} = \varepsilon_c^4\left(\sqrt{1 + \frac{1}{2\varepsilon_c^4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{16\varepsilon_c^8}\left(\tilde{F}^{\mu\nu}F_{\mu\nu}\right)^2} - 1\right) = \varepsilon_c(R - 1)$$

- Cosmologies with large scale massless homogeneous and isotropic gauge fields with gauge group SU(2) and ruled by usual YM dynamics have been studied for a long time[1].
  - The Einstein Born-Infeld cosmology with non-abelian gauge fields deriving from gauge group SU(2) has been studied thoroughly by Dyadichev et al[2] for flat, closed and open spacetimes.
  - A remarkable fact about non-abelian gauge fields is that they admit non-trivial homogeneous and isotropic configurations at the oppositie of their abelian U(1) counterparts[2].
  - A Scalar field $\sigma(t)$

$$R = \sqrt{1 - \frac{3A_{BI}^{-4}(\varphi)}{\varepsilon_c}\left(\frac{\dot\sigma^2}{a^2N^2} - \frac{\sigma^4}{a^4}\right) - \frac{9A_{BI}^{-8}(\varphi)}{\varepsilon_c^2a^6N^2}\dot\sigma^2\sigma^4}$$

[1] Henneaux 1982, Gal'tsov & Volkov 1991, Füzfa 2003…

[2] Dyadychev , Gal'tsov, Zorin & Zotov 2002

A First Candidat for the Abnormally Weighting Component (2/7)

Born Infeld Gauge Dynamics*

$$R=\sqrt{1-\frac{3A_{BI}^{-4}(\varphi)}{\varepsilon_c}\left(\frac{\dot\sigma^2}{a^2N^2}-\frac{\sigma^4}{a^4}\right)-\frac{9A_{BI}^{-8}(\varphi)}{\varepsilon_c^{2}a^6N^2}\dot\sigma^2\sigma^4}=\sqrt{1-\Gamma}\sqrt{1+\Delta}$$

$$\Gamma=\frac{3\dot\sigma^2A_{BI}^{-4}(\varphi)}{\varepsilon_c a^2N^2},\ \Delta=\frac{3\sigma^4A_{BI}^{-4}(\varphi)}{\varepsilon_c a^4},\ P=\sqrt{\frac{1+\Delta}{1-\Gamma}}$$

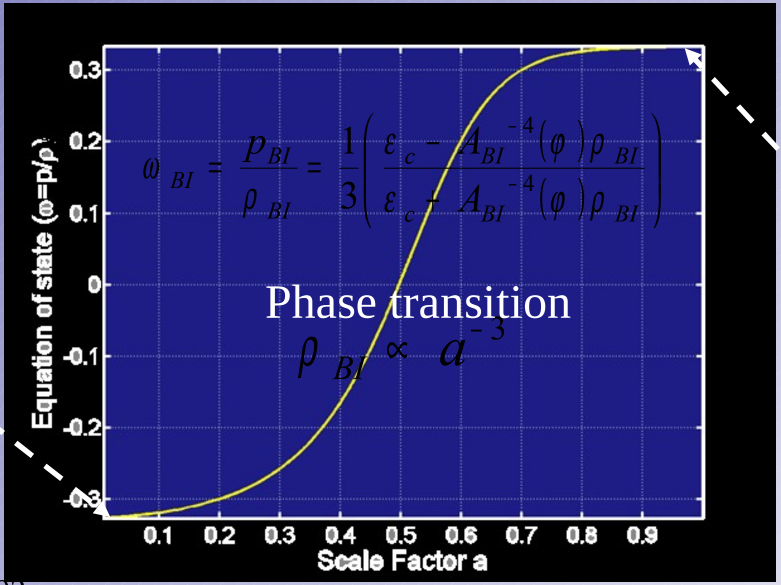
$$\rho_{BI}=\varepsilon_c A_{BI}^{4}(\varphi)(P-1)=\varepsilon_c A_{BI}^{4}(\varphi)\left(\sqrt{1+C/A_{BI}^{4}(\varphi)a^4}-1\right)$$

$$p_{BI}=\varepsilon_c A_{BI}^{4}(\varphi)\left(3-P-2P^{-1}\right)$$

High-energy limit:
(**Nambu-Goto string gas**)

$$\rho_{BI}>>\varepsilon_c^{4},\ \rho_{BI}\propto a^{-2},$$

$$\omega_{BI}\to -1/3$$



$$\omega_{BI}=\frac{p_{BI}}{\rho_{BI}}=\frac{1}{3}\left(\frac{\varepsilon_c-A_{BI}^{-4}(\varphi)\rho_{BI}}{\varepsilon_c+A_{BI}^{-4}(\varphi)\rho_{BI}}\right)$$

Phase transition

$$\rho_{BI}\propto a^{-3}$$

$$\rho_{BI}<<\varepsilon_c^{4},\ \rho_{BI}\propto a^{-4},$$

$$\omega_{BI\to}\ 1/3$$

Low-energy limit:
Yang-Mills dynamics
(**radiation**)

*Dyadychev , Gal’tsov, Zorin & Zotov 2002

A First Candidat for the Abnormally Weighting Component (3/7)

- **Einstein Born-Infeld Dilaton Cosmology (No acceleration)**

$$\left(\frac{\dot a}{a}\right)^2 = \frac{\dot\varphi^2}{3} + \frac{8\pi G_*}{3}\left(\rho_{*M} + \rho_{*BI}\right)$$

$$\frac{\ddot a}{a} = \frac{-2}{3}\dot\varphi^2 - \frac{4\pi G_*}{3}\left[\left(\rho_{*M} + 3p_{*M}\right) + \left(\rho_{*BI} + 3p_{*BI}\right)\right]$$

$$\ddot\varphi + 3\frac{\dot a}{a}\dot\varphi + \underbrace{4\pi G_* \alpha_M(\varphi)\left(\rho_{*M} - 3p_{*M}\right)}_{\text{Attraction toward GR}} + \underbrace{4\pi G_* \alpha_{BI}(\varphi)\left(\rho_{*BI} - 3p_{*BI}\right)}_{\text{Repulsion from GR}} = 0$$

- **Observational Frame**

$$\tilde g_{\mu\nu} = A_M^2(\varphi) g^*_{\mu\nu}$$

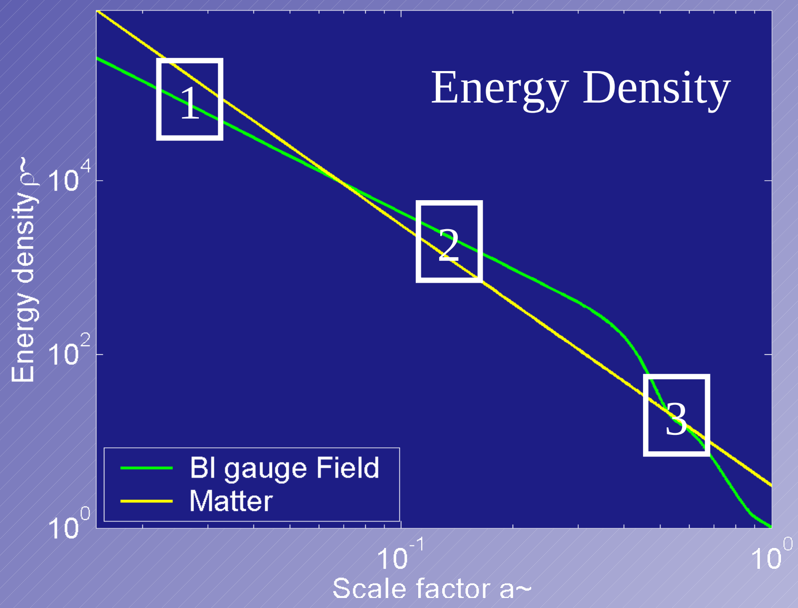
$$\tilde T^{\mu}{}_{\nu}{}^{M} = A_M^{-4}(\varphi) T^*{}_{\nu}{}^{\mu M}, \quad \tilde T^{\mu}{}_{\nu}{}^{AWE} = A_M^{-4}(\varphi) T^*{}_{\nu}{}^{\mu AWE}$$

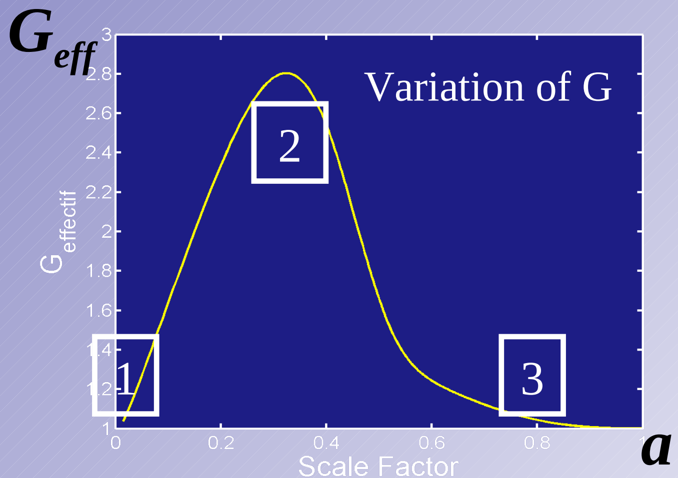
$$\frac{1}{\tilde a}\frac{d^2\tilde a}{d\tilde t^2} = -\frac{4\pi\tilde G_c}{3}\left(\tilde\rho_M + \left(\tilde\rho_{BI} + 3\tilde p_{BI}\right)\right)\times\left(1 - \frac{2\varphi'}{3-\varphi'^2}\left(\varphi'\left(\frac{d\alpha_M}{d\varphi} - \frac{2}{3}\right) - 2\alpha_M\right)\right)$$
$$- 4\pi\tilde G_c \alpha_M\left(\alpha_M\tilde\rho_M + \alpha_{BI}\left(\tilde\rho_{BI} + 3\tilde p_{BI}\right)\right)$$

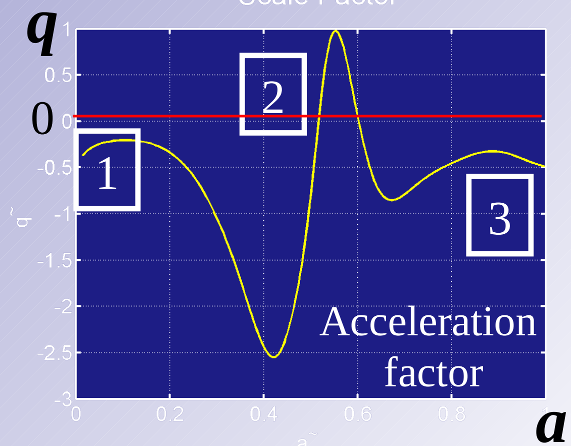
Acceleration occurs in the observational frame, for instance,
if $\alpha_{BI}<0$ and $\rho_{BI}+3p_{BI}>>\rho_M$ $\quad \rho_{BI} \propto a^{-3}$

A First Candidat for the Abnormally Weighting Component (4/7)

- **Illustration of the mechanism**
  1. Matter-dominated era : attraction toward GR
  2. Born-Infeld gauge field domination: repulsion from GR
  3. Phase transition of the BI gauge interaction into radiation and attraction toward GR







A First Candidat for the Abnormally Weighting Component (5/7)

Born-Infeld Gauge Interaction

- **Type Ia supernovae Hubble diagram (Astier et al 2006) without violating SEC**
  - By both a variation of G and an acceleration effect

$$\mu(\tilde{z}) = m - M_0 = 5\log_{10} d_L(\tilde{z}) + \frac{15}{4}\log_{10}\frac{G_{eff}(\tilde{z})}{G_0}$$

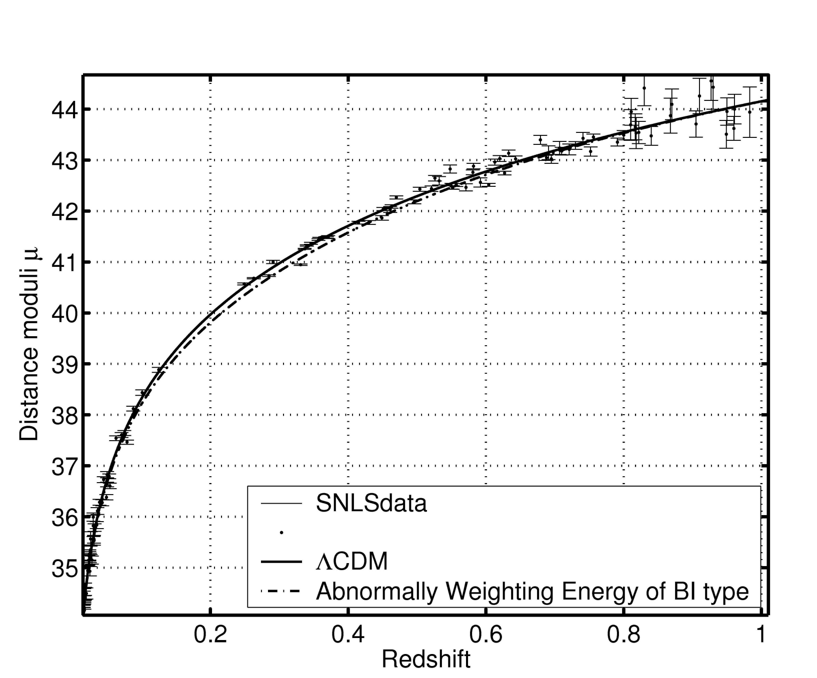
$$G_{eff} = G_0 A^2{}_M(\varphi)\left(1 + \alpha_M^2(\varphi)\right)$$

$$\alpha_M(\varphi) = k_M\varphi \Rightarrow A_M(\varphi) = e^{k_M\frac{\varphi^2}{2}}$$

$$\alpha_{BI} = k_{BI} \Rightarrow A_{BI}(\varphi) = e^{k_{BI}\varphi}$$

$$\text{avec } k_M k_{BI} < 0$$

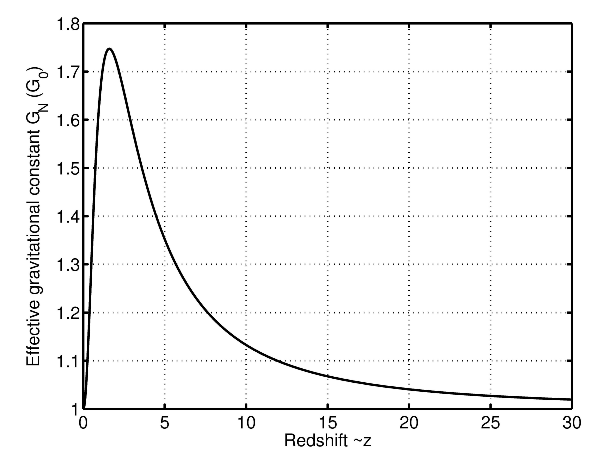
ΛCDM : χ^2/dof=1.03
BI: χ^2/dof=1.09

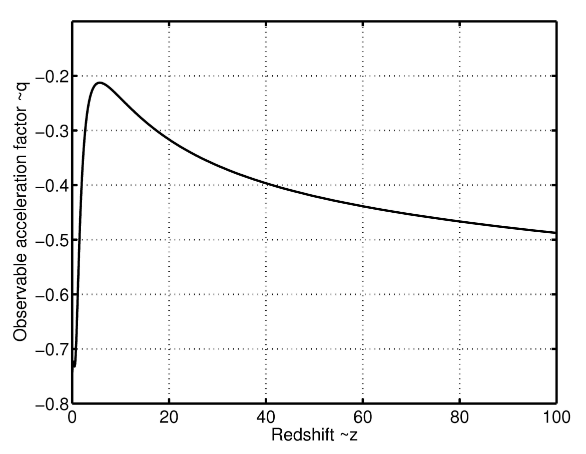


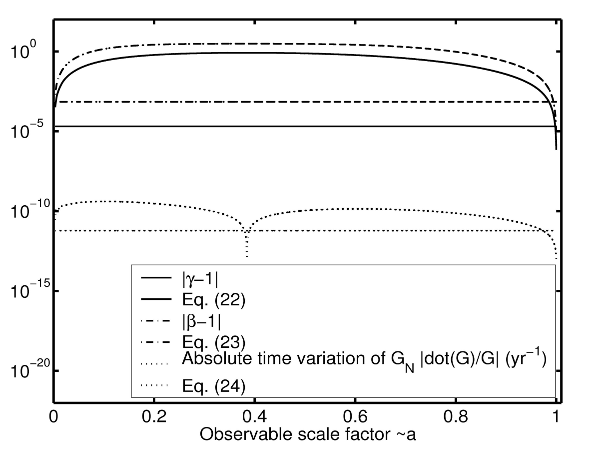
* Gaztanaga et al 2001, Riazuelo & Uzan 2002

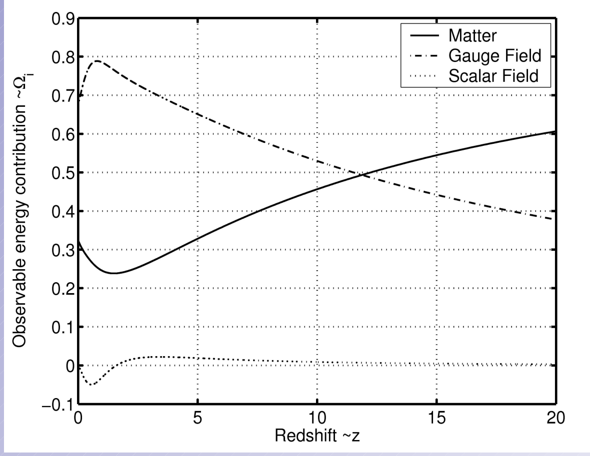
A First Candidat for the Abnormally Weighting Component (6/7)

Born-Infeld Gauge Interaction









Constraints on General Relativity OK!

The repulsing action of AW dark energy is not active today because of its radiative nature! (BI feature)

Preliminary Conclusions. (7/7)

- **Usual view of dark energy:**
  - Acceleration produced by a violation of the strong energy condition (**$p<-\rho/3$**)
  - DE (extremely) weakly coupled to matter : very low variation of constants
- **The AWE picture**
  - DE can now be strongly coupled without contradiction with tests on fundamental constants
  - Acceleration is produced while moving to the observable frame
- **BI gauge interaction acting as AWE**
  - Deviation from GR during BI domination then return to GR through attraction mechanism
  - Adequacy with **Hubble diagrams** (cosmic acceleration and variation of G), **constraints on GR** and **physics in the radiative era**
  - Natural features for a realistic AWE
  - Alternative to the condition **$p<-\rho/3$** for **DE (test of the necessity of SEC)**

A New Candidate: Toward an unification to DM and DE (1/10)

Einstein Frame

$$S = \frac{1}{2\kappa}\int d^4x\sqrt{-g*}\left\{R - 2\partial_\mu\varphi\,\partial^\mu\varphi\right\} + S_M\left[\psi_M, A_M^{\;2}(\varphi)g*_{\mu\nu}\right] + S_{AWE}\left[\psi_{AWE}, A_{AWE}^{\;2}(\varphi)g*_{\mu\nu}\right]$$

FLRW

$$H_*^{\;2} = \left(\frac{\dot a_*}{a_*}\right)^2 + \frac{\dot\varphi^2}{3} + \frac{8\pi G_*}{3}\left(\rho_{*M} + \rho_{*AWE}\right), \quad \frac{\ddot a_*}{a_*} = -\frac{2}{3}\dot\varphi^2 - \frac{8\pi G_*}{6}\left(\rho_{*M} + \cancel{3p_{*M}} + \rho_{*AWE} + \cancel{3p_{*AWE}}\right)$$

$$\ddot\varphi + 3\frac{\dot a_*}{a_*}\dot\varphi + 4\pi G_*\alpha_M(\varphi)\left(\rho_{*M} - \cancel{3p_{*M}}\right) + 4\pi G_*\alpha_{AWE}(\varphi)\left(\rho_{*AWE} - \cancel{3p_{*AWE}}\right) = 0$$

Let us consider that the AWE sector is
a pressureless fluid and focus on the matter-dominated era of the universe

Conservation equations !

$$\boxed{\begin{gathered}\nabla*_\mu T*^{\mu,M,AWE}_\nu = \alpha_{M,AWE} T*^{\mu,M,AWE}_\nu \partial_\nu\varphi \\ \dot\rho^*_{M,AWE} + 3\frac{\dot a_*}{a_*}\rho^*_{M,AWE} = \alpha_{M,AWE}(\varphi)\dot\varphi\rho*_{M,AWE} \\ \rho*_{M,AWE} = A_{M,AWE}(\varphi)\frac{C_{M,AWE}}{a*^3}\end{gathered}}$$

Toward an unification to DM and DE (2/10)

The previous two fluids systeme can be rewritten as one field system

$$\rho^*_T = \rho^*_M + \rho^*_{AWE} = \frac{\mathrm{A}(\varphi) C_M}{a^{*3}}, \mathrm{A}(\varphi) = A_M(\varphi) + \frac{A_{AWE}(\varphi)}{R_i}, R_i = C_M / C_{AWE}$$

We deduce

$$\frac{2}{3-\varphi'^2}\varphi'' + \varphi' + \aleph(\varphi) = 0$$

$$\aleph(\varphi) = \frac{d(Log(\mathrm{A}(\varphi)))}{d\varphi} = \alpha_M(\varphi) + \frac{\alpha_{AWE}(\varphi) - \alpha_M(\varphi)}{1 + R_i \frac{A_M(\varphi)}{A_{AWE}(\varphi)}}$$

where

$$R_i \frac{A_M(\varphi)}{A_{AWE}(\varphi)} = \frac{\rho^*_M}{\rho^*_{AWE}}$$

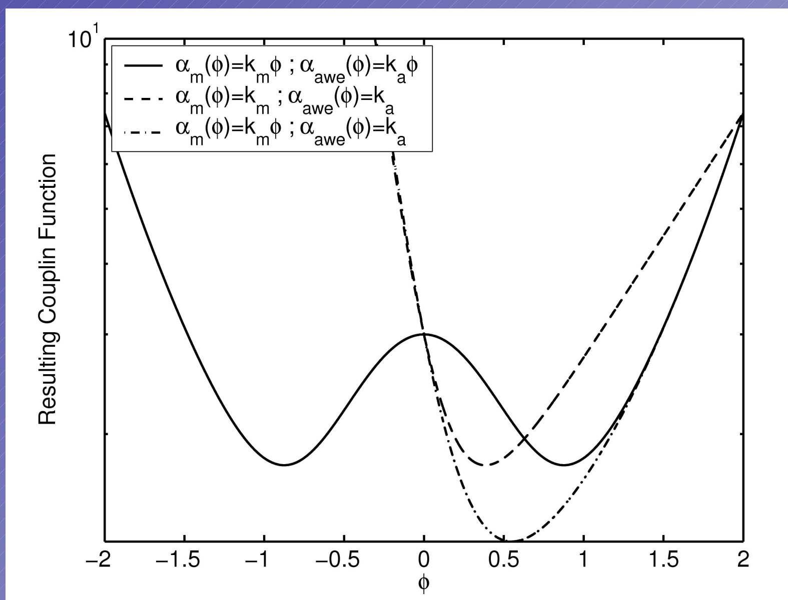
- TST in matter-dominated era are easily retrived if $\alpha_M(\varphi) = \alpha_{AWE}(\varphi) = \aleph(\varphi)$, which corresponds to no violation of the WEP and/or if $\rho^*_M >> \rho^*_{AWE}$

- The present TST exibits a sophisticated convergence mechanism even in the case of very simple constitutive coupling functions

$$\aleph(\varphi_\infty) = 0, \alpha_M(\varphi_\infty) R_i \frac{A_M(\varphi_\infty)}{A_{AWE}(\varphi_\infty)} + \alpha_{AWE}(\varphi_\infty) = 0$$

Toward an unification to DM and DE (3/10)

- For any set of constitutive coulings functions, $A_M(\varphi)$, $A_{AWE}(\varphi)$, the resulting couling function **A** has at least one extremum and there exists a finite value of the effective gravitational coupling constant $\widetilde{G}_c(\varphi)$ which is different from GR.



$$A(\varphi) = e^{\frac{k_A \varphi^2}{2}} + \frac{C_{AWE}}{C_M} e^{\frac{k_M \varphi^2}{2}}, \ with \ k_A k_M < 0$$

$$a(\varphi) = Log(A(\varphi))$$

$$\alpha(\varphi) = \frac{da(\varphi)}{d\varphi}$$

- The attracting value φ_∞ depends on the ratio of usual matter over abnormally weighting dust and is intermediate between the value of φ for which $A_M(\varphi)$ extremum (when $\rho^*_M >> \rho_{AWE}^*$) and the value of φ for which $A_{AWE}(\varphi)$ is extremum (when $\rho_M^* << \rho_{AWE}^*$).

Toward an unification to DM and DE (4/10)

Astrophysical Discussion

- The violation of the WEP strongly depends on the ratio of usual matter energy density over AWE.
  - As both usual matter and AWE clusters, this violation is different with the scale considered.

  - Furthermore, the AWE is assumed to be dark and its gravitational collapse will be therefore quite different due to the abscence of the dissipative processes that allows usual matter like baryons to cluster so much compared to DM at low scales.

  - The domination of usual matter over AWE DM at small scales, which is a consequence of the different physical processes to which baryons are submitted will tend to make the WEP well verified at small scales.

    - The usual convergence mechanism toward GR with G_* as an asymptotic value of the gravitational coupling constant is acting on scales where AWE DM is sub-dominant, i.e. at low scales.
    - We therefore conjecture that GR is verified on the very small (sub-galactic) scales at which the solar system or binary pulsar system constraints on GR have been established.

    - We then interprete the Hubble diagram of far-away supernovae only in terms of cosmic acceleration without corrections due to the variation of the gravitational constant for compact, gravitationally bound objects.
    - The precise omputation of the deviations from GR with the scale would require a complexe study of the structure formation in this AWE model.

Toward an unification to DM and DE (5/10)

Cosmological Description

- **Observational Frame**

$$\tilde{g}_{\mu\nu} = A_M^2(\varphi)g^*_{\mu\nu}\ , \tilde{G}_c = A_M^2(\varphi)G^*$$

$$\tilde{T}^{\mu}{}_{\nu}{}^{M} = A_M^{-4}(\varphi)T^*{}^{\mu}_{\nu}{}^{M}\ , \tilde{T}^{\mu}{}_{\nu}{}^{AWE} = A_M^{-4}(\varphi)T^*{}^{\mu}_{\nu}{}^{AWE}$$

- **A (quasi) Friedman description**

$$\tilde{H} = \frac{\dot{\tilde{a}}}{\tilde{a}} = A_M^{-1}(\varphi)H^*(1+\alpha_M(\varphi)\varphi')$$

$$\tilde{H}^2 = \frac{8\pi\tilde{G}_c}{3}(\tilde{\rho}_M + \tilde{\rho}_{AWE})\times\left(1+\frac{\varphi'^2(1+3\alpha_M^2)+6\alpha_M\varphi'}{3-\varphi'^2}\right)$$

$$\tilde{\Omega}_{M,AWE} = \frac{8\pi\tilde{G}_c\tilde{\rho}_{M,AWE}}{3\tilde{H}^2}$$

$$\tilde{\Omega}_{\varphi} = (\tilde{\Omega}_M + \tilde{\Omega}_{AWE})\frac{\varphi'^2(1+3\alpha_M^2)+6\alpha_M\varphi'}{3-\varphi'^2}$$

- **Accelating Universe in the AWE Hypothesis**

$$\frac{1}{\tilde{a}}\frac{d^2\tilde{a}}{d\tilde{t}^2} = -\frac{4\pi\tilde{G}_c}{3}(\tilde{\rho}_M + \tilde{\rho}_{AWE})\times\left(1-\frac{2\varphi'}{3-\varphi'^2}\left(\varphi'\left(\frac{d\alpha_M}{d\varphi}-\frac{2}{3}\right)-2\alpha_M\right)\right) - 4\pi\tilde{G}_c\alpha_M(\alpha_M\tilde{\rho}_M + \alpha_{AWE}\tilde{\rho}_{AWE})$$

Acceleration occurs in the observational frame, for instance, if $\alpha_{AWE}<0$ and $\rho_{AWE}>>\rho_M$

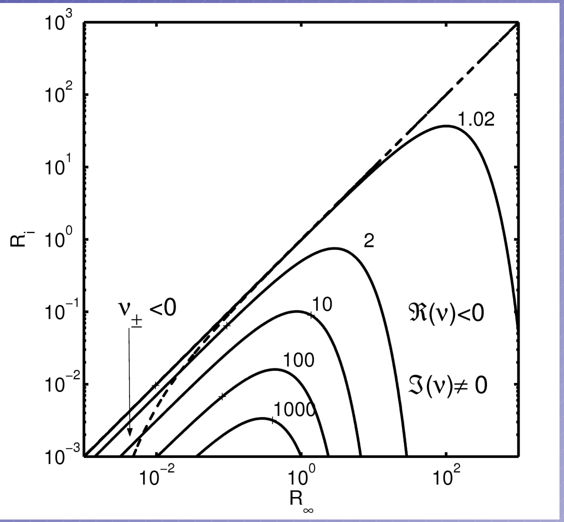
Toward an unification to DM and DE (6/10)

Cosmological Description

- **A specific model**

$$\alpha_M(\varphi) = k_M \varphi \;, \alpha_{AWE}(\varphi) = k_{AWE}\varphi$$

$$with\; k_M k_{AWE} < 0$$



$$\frac{\rho_M{}^*}{\rho_M{}^*} = \frac{C_M}{C_{AWE}} \frac{A_M(\varphi)}{A_{AWE}(\varphi)} = R_i \frac{A_M(\varphi)}{A_{AWE}(\varphi)}$$

$$R_i \frac{A_M(\varphi_\infty)}{A_{AWE}(\varphi_\infty)} = R_\infty$$

$$\varphi_\infty = \left(\frac{2}{k_M(1+R_\infty)} \log\left(\frac{R_\infty}{R_i}\right)\right)^{1/2}$$

- **3 Free Parameters**

$$R_i \;, R_\infty \;, \tilde{\Omega}_M(\tilde{z}=0)$$

$$R_i \;, R_\infty \;, k_{\mathrm{M}}$$

$$k_M \;, k_{\mathrm{AWE}} \;, R_i$$

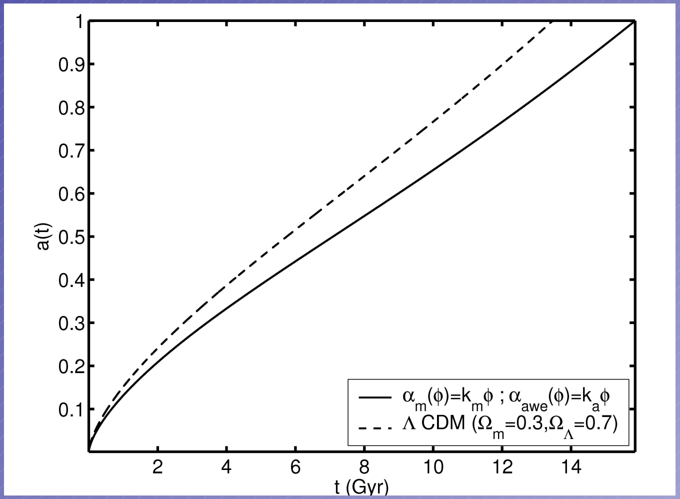
…

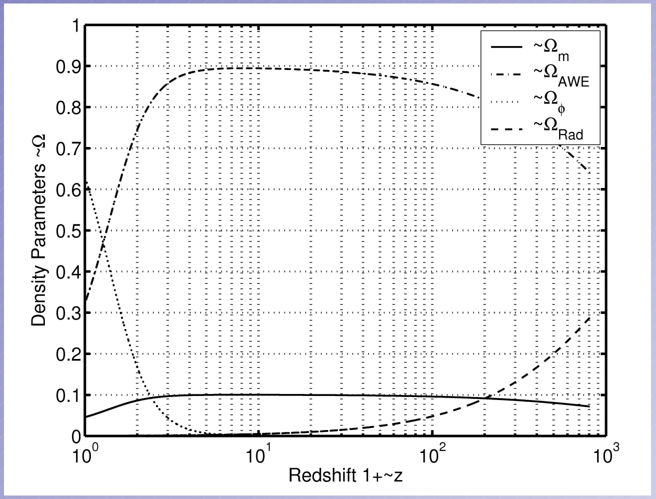
$$\boxed{\mu(\tilde{z}) = m - M = 5\log_{10} d_L(\tilde{z})}$$

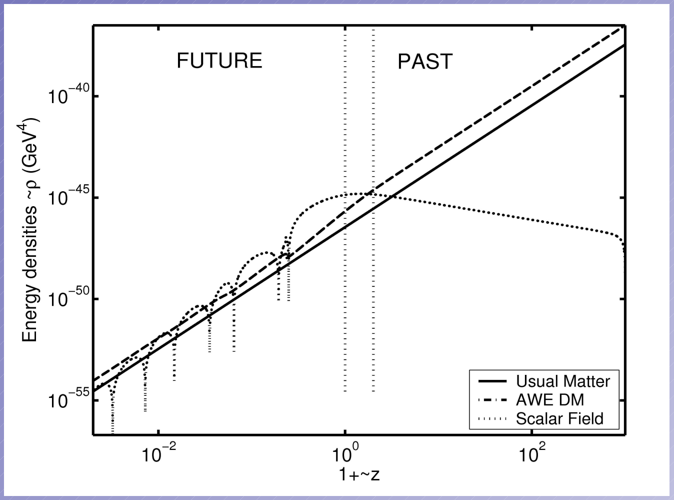
Toward an unification to DM and DE (7/10)

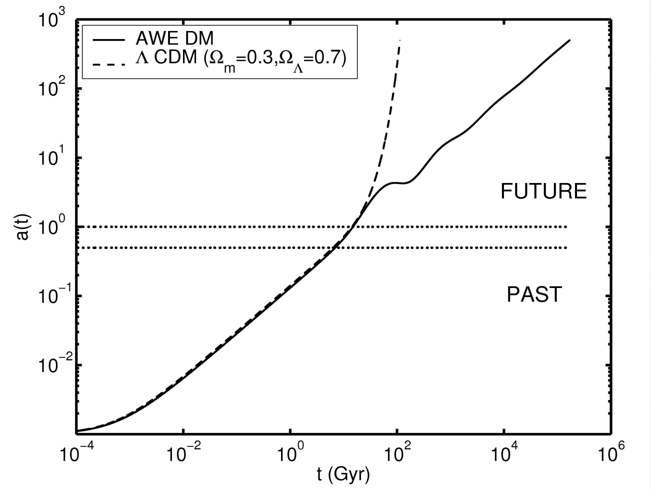
Why the concordance model appears correct ?

- **Type Ia supernovae Hubble diagram (Astier et al 2006)**
  - $R_i=0.11$, $R_\infty=0.31$, $\Omega_M{}^0=0.04$, $\Omega_{AWE}{}^0=0.26$, $t_0(\mathrm{Gyr})=15{,}9$, $\chi^2/\mathrm{dof}=1.03$





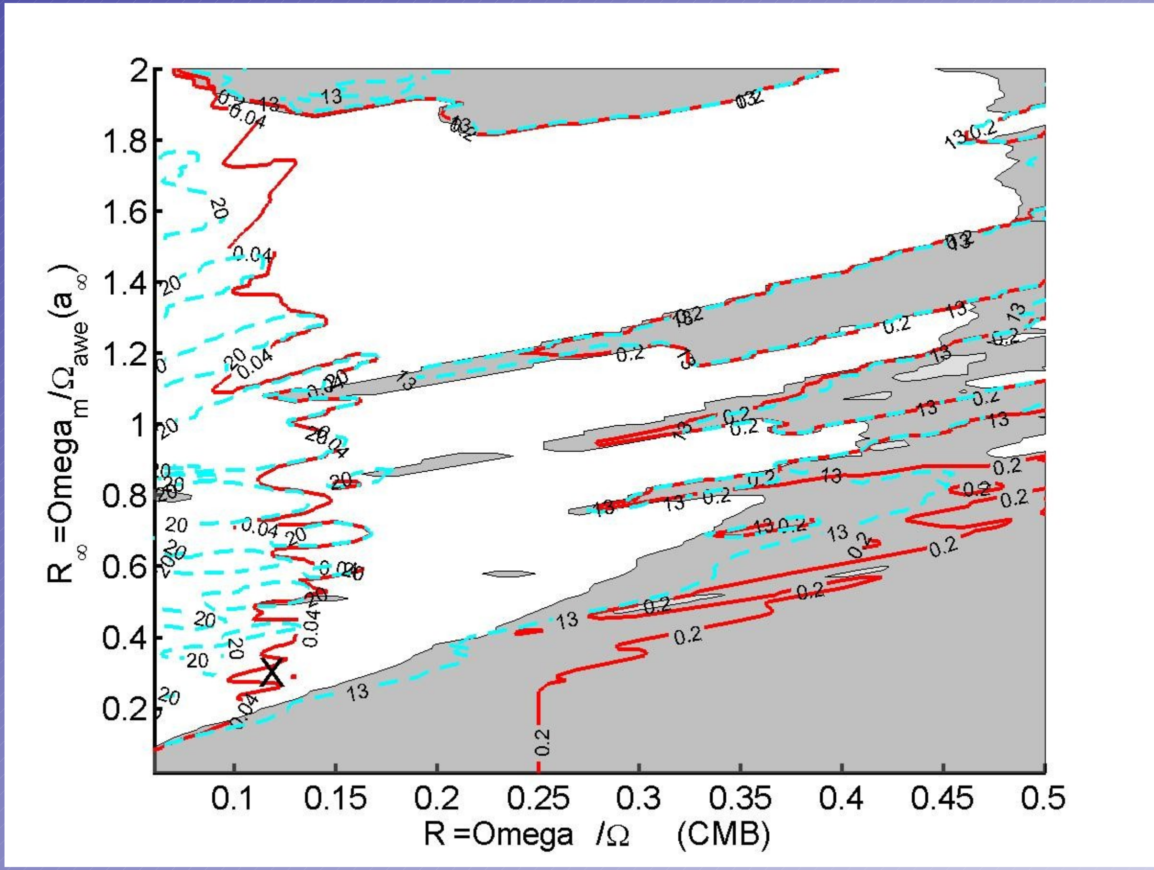




Toward an unification to DM and DE (8/10)

Why the concordance model appears correct ?

- **Type Ia supernovae Hubble diagram (Astier et al 2006)**
  - ***Preliminary results***



>95%

t_0> 13 Gyr

Ω_M^0< 0.2

Usual Matter ≡ Baryon

AWE ≡ DM

⇒

φ ≡ DE

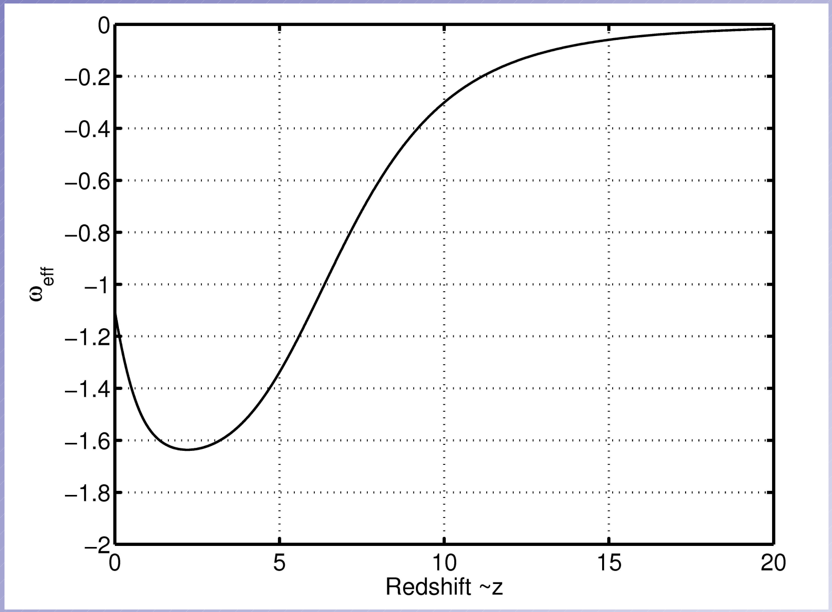
Toward an unification to DM and DE (9/10)

A natural Phantom Dark Energy

- **An accelerating Universe in the AWE hypothesis**

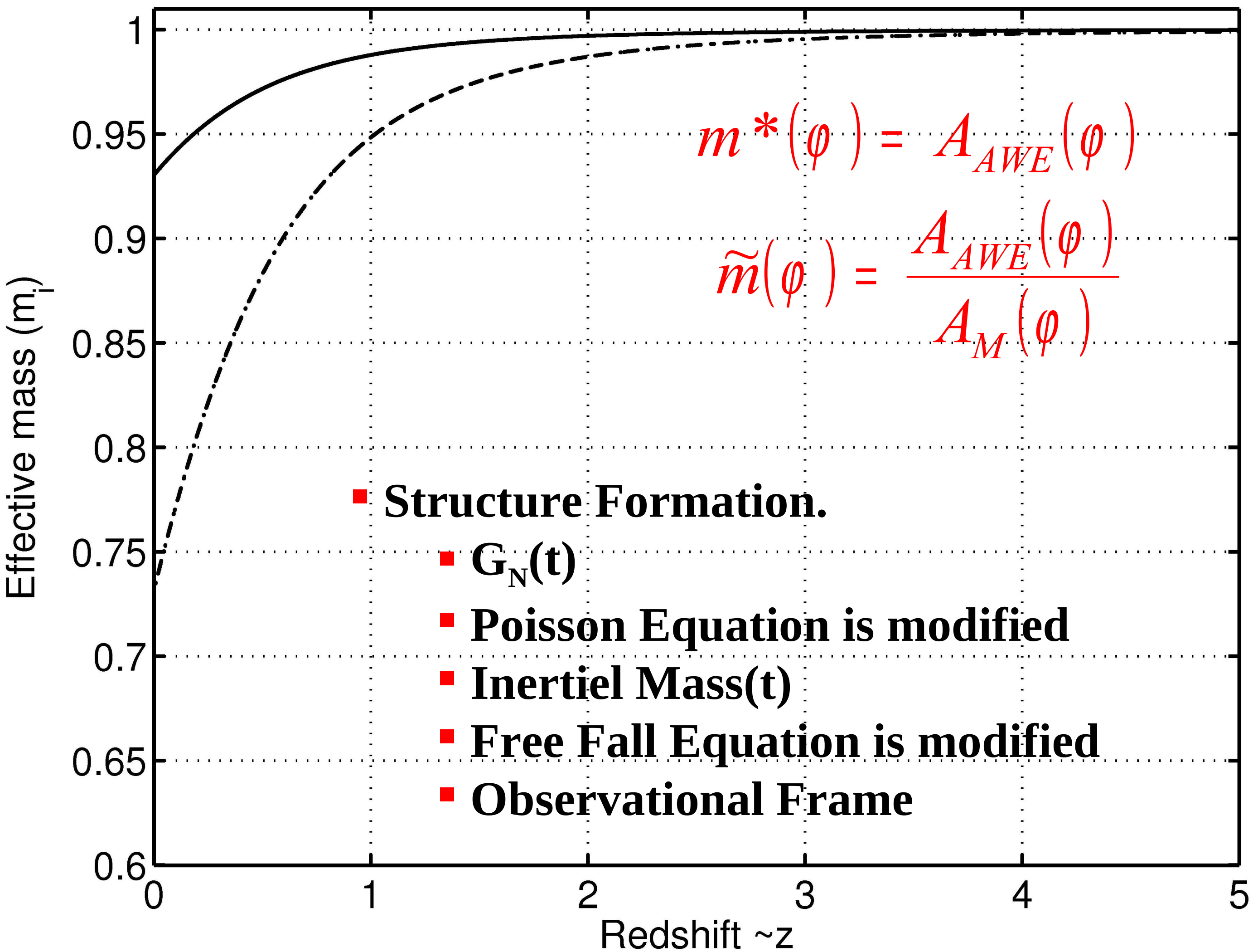
$$\tilde{H}^2 = \frac{8\pi \tilde{G}_c}{3}\left(\tilde{\rho}_T + \tilde{\rho}_{DE}\right)$$

$$\frac{1}{\tilde{a}}\frac{d^2\tilde{a}}{d\tilde{t}^2} = -\frac{4\pi \tilde{G}_c}{3}\tilde{\rho}_T - \frac{4\pi \tilde{G}_c}{3}\tilde{\rho}_{DE}\left(1 + 3\omega_{eff}\right)$$



AWE Dark MAtter as a time-dependent inertial mass (10/10)

Implications on Structure Formation



$$m^*(\varphi) = A_{AWE}(\varphi)$$

$$\tilde{m}(\varphi) = \frac{A_{AWE}(\varphi)}{A_M(\varphi)}$$

- **Structure Formation.**
  - **$G_N(t)$**
  - **Poisson Equation is modified**
  - **Inertiel Mass(t)**
  - **Free Fall Equation is modified**
  - **Observational Frame**

Conclusions and Perspectives.

- **Usual view of dark energy:**
  - Acceleration produced by a violation of the strong energy condition ($p<-\rho/3$)
  - DE (extremely) weakly coupled to matter : very low variation of constants

- **The AWE picture :**
  - DE can now be strongly coupled without contradiction with tests on fundamental constants
  - Acceleration is produced while moving to the observable frame without violation of the SEC $p<-\rho/3$ for **DE**

- **Anomalous DM acting as AWE:**
  - **A natural « dual GR » at cosmological scales**
  - **Why the concordance model appears correct, with a natural phantom dark energy**
  - **AWE dark matter as a time-dependent inertial mass**

- **Perspectives:**
  - **Post-recombination effect on CMB**
  - **Effects on structure formation ($G_N(z)$, Poisson Eq., Inertiel Mass, Free Fall, Frame)**
  - **Tests of the violation of the universality of free fall on cosmological scales**
  - **Search for similar mechanisms for inflation**
  - **(Gravitational) Topological defects**
  - **…**