Dark Energy as the Gravitational Feedback of Mass-Varying Dark Matter

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The AWE-full problems of concordance cosmology

★ Physical nature of Dark Matter (DM) AND Dark Energy (DE)

→ Why $\Omega_{baryons}$=0.04, Ω_{CDM}=0.2 and Ω_{Λ}=0.76? (Triple coincidence)

→ Physical relation between DM and DE?

★ Negative Pressures of DE

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3m_{Pl}^2}(\rho + 3p) \qquad \boxed{\ddot{a} > 0 \text{ if } p < -\frac{\rho}{3}}$$

Cosmological Constant Λ

$$\rho_\Lambda = -p_\Lambda = cst$$

★ Fate of the Universe

→ Eternal cosmic acceleration

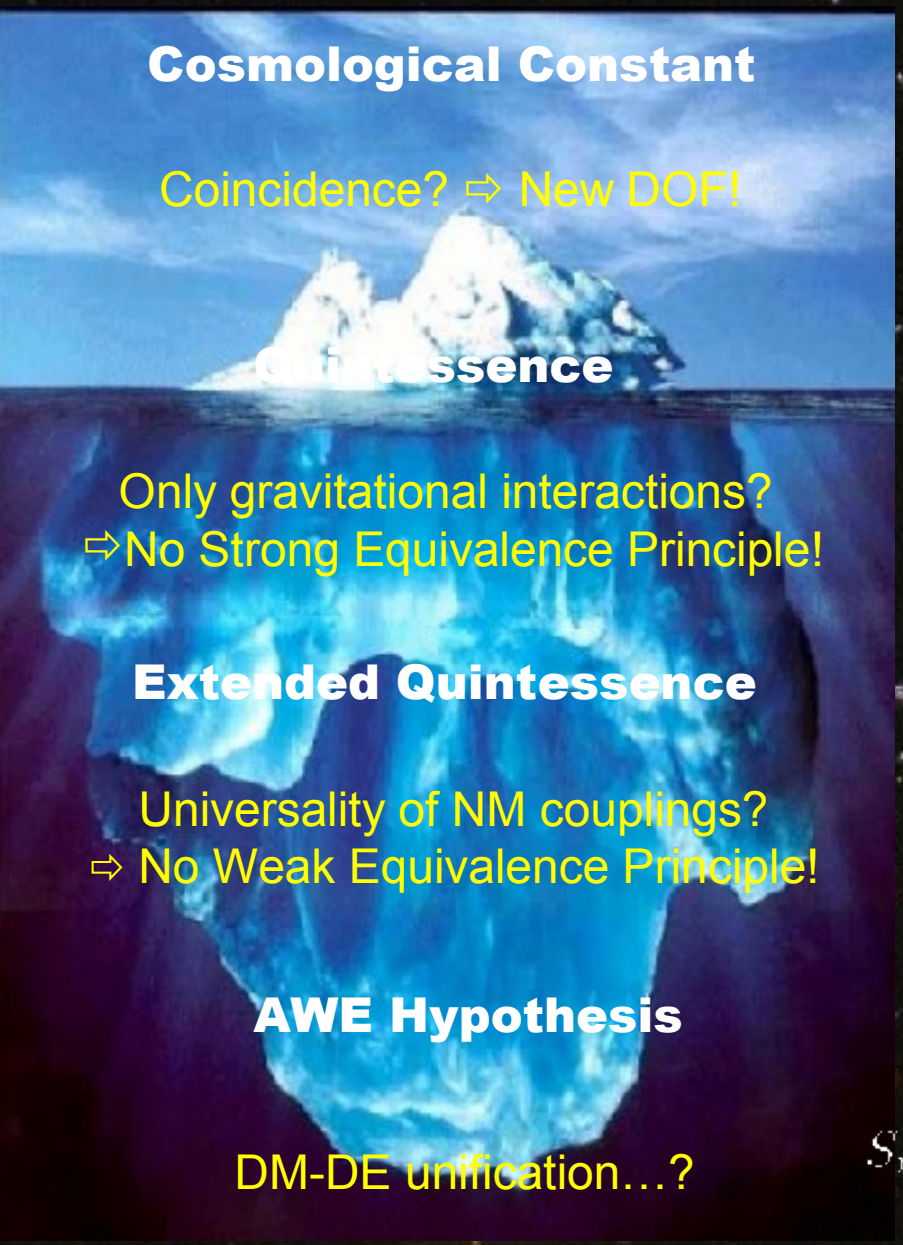
→ de Sitter asymptotic state (asymmetrical non-trivial vacuum)

★ Coincidence Problem

→ Why DE appeared so recently?

→ Which low-energy physics behind DE? (Fine-tuning of parameters)

The Dark Cosmology Iceberg



★ DE frozen in a false vacuum

$$S_{grav} = \frac{1}{2\kappa_*}\int \sqrt{-g_*}\,d^4x\,\{R^* + 2\Lambda\}$$

★ DE with minimal coupling : **SEP**!

$$S_{DE} = \frac{1}{\kappa_*}\int \sqrt{-g_*}\,d^4x\,\{\partial_\mu\varphi\partial^\mu\varphi - V(\varphi)\}$$

$$S_{mat} = S\left[\psi_m, g^*_{\mu\nu}\right]$$

★ Scalar-tensor gravity (WEP but no SEP) $\quad A_m(\varphi) \neq 1$

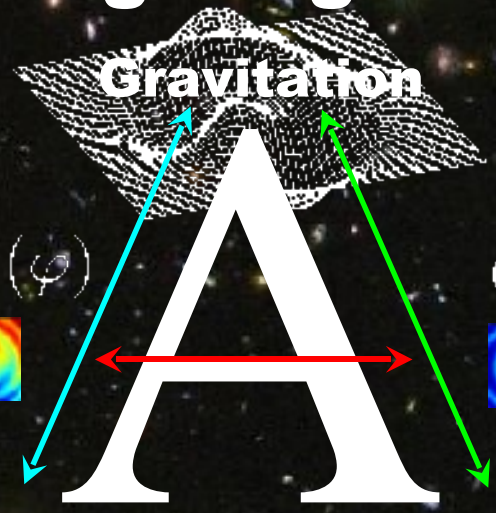
$$S_{grav}[\Lambda = 0] - S_{DE} + S_{mat}\left[\psi_m, A_m^2(\varphi) g^*_{\mu\nu}\right]$$

★ Gravitation without WEP $\quad A_m \neq A_{awe}$

$$S_m\left[\psi_m, A_m^2(\varphi) g^*_{\mu\nu}\right] - S_{awe}\left[\psi_{awe}, A_{awe}^2(\varphi) g^*_{\mu\nu}\right]$$

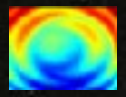
The Abnormally Weighting Energy Hypothesis

Space-time dependent
nonuniversal interactions

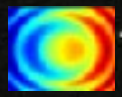


→Bare Space-time $g^*_{\mu\nu}$
→Running coupling φ

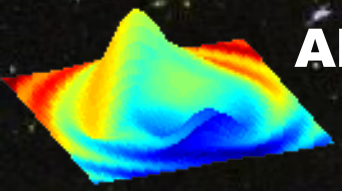
$G_{awe}(\varphi)$



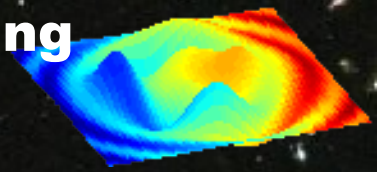
$G_m(\varphi)$



$g_{\mu\nu}$



$\tilde{g}_{\mu\nu}$



Abnormally Weighting Invisible Sector

Normally Weighting Visible Sector

$m_{awe}(\varphi)$ ⟷ $G_m(\varphi)$

AWE Mechanism:

- Competition between different non-minimal couplings
- No WEP ⇨ gravitationally bound AWE objects ≠grav. bound matter ones ⇨ no SEP
- AWE Dynamics allows to retrieve locally the Equivalence Principles

- A. Füzfa, J.-M. Alimi, PRD 75 123007 (2007)
- A. Füzfa, J.-M. Alimi, PRL 97, 061301 (2006)
- A. Füzfa, J.-M. Alimi, PRD73 (2006) 023520

The AWE Hypothesis

★ Relaxation of WEP:

→ Restricted WEP on visible matter (« normally weighting » sector)

→ one space-time but two couplings G_{awe} and G_m (« minimal » WEP violation)

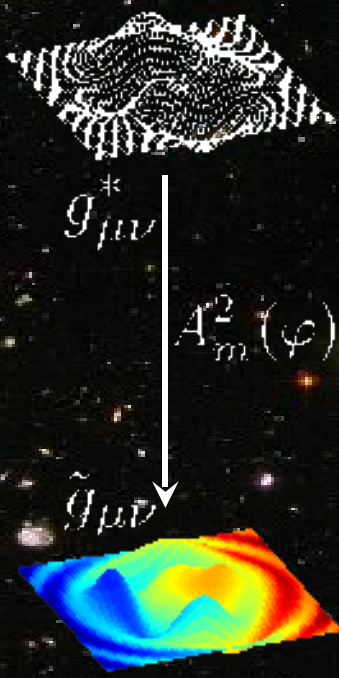
★ Einstein frame: decoupled degrees-of-freedom

→ Separated spin-2 and spin 0 dofs but free-fall not along geodesics

→ Effective theories of gravitation* (string theory, modified gravity…)

$$S_{grav} = \frac{1}{2\kappa_*}\int \sqrt{-g_*}\, d^4x \{R^* - 2g_*^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi\}$$

$$S_{source} = S_m\left[\psi_m, A_m^2(\varphi)g_{\mu\nu}^*\right] + S_{awe}\left[\psi_{awe}, A_{awe}^2(\varphi)g_{\mu\nu}^*\right]$$



★ Dicke-Jordan Observable frame: mixed degrees-of-freedom

→ (ordinary) matter follow geodesics of metric not of pure spin-2

→ Invisible sector has varying mass

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

$$S_{source} = S_m\left[\psi_m, \tilde{g}_{\mu\nu}\right] + S_{awe}\left[\psi_{awe}, M(\Phi)^2\tilde{g}_{\mu\nu}\right]$$

✦T. Damour et al. PRL 64, 123 (1990)

✦T. Damour, D. Polyakov, Nucl.Phys. B 423 (1994)

AWE as a generalization of Chameleons

★ Chameleon action in Einstein frame:

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

★ How does AWE generalize Chameleon approaches?

Mass-varying DM => No WEP => No SEP!

⇩

Mach-Dirac Mechanism

$$M_{DM} = m^*_{DM} M(\Phi) \quad \Rightarrow \quad \omega_{BD} = \omega_{BD}(M) = \omega_{BD}(\Phi)$$

$$C = \Phi^{-1}$$

DM is the source of WEP and SEP violations!

→ Scalar field stabilization of φ.: $A_m(\varphi)$ vs $A_{awe}(\varphi)$ only and not $A_{m,awe}(\varphi)$ vs $V(\varphi)$

→ No need of well-shaped potential to provide cosmic acceleration

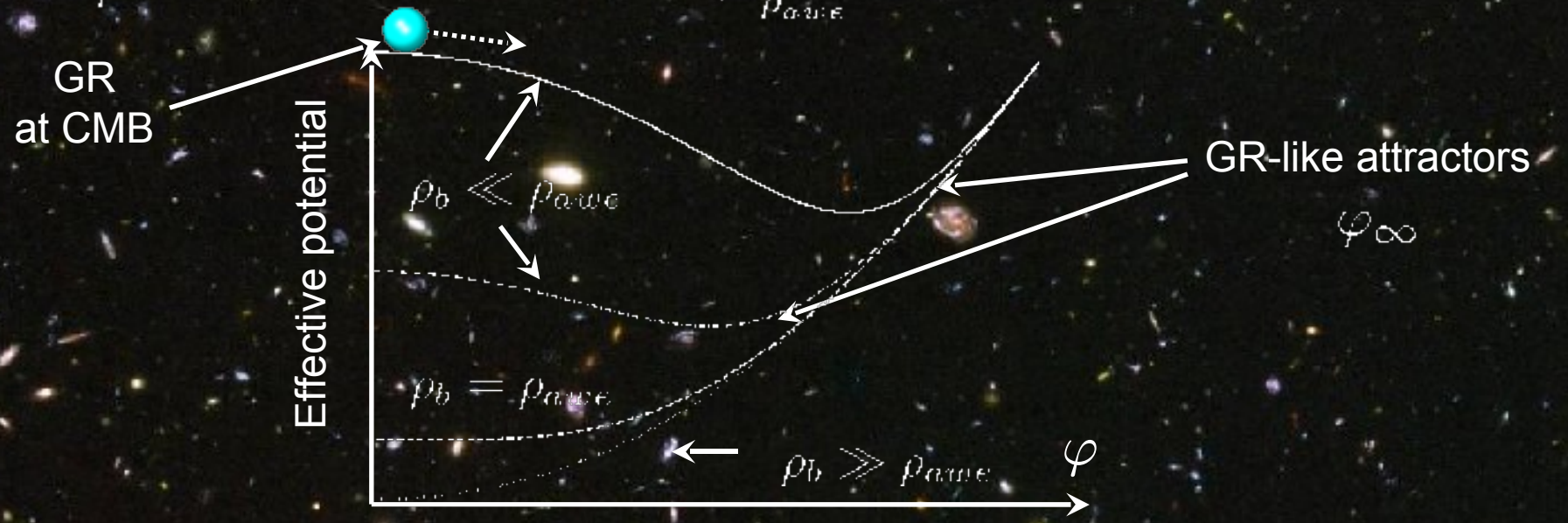
→ Definition of Observable frame : WEP violation is not observed directly

→ Non-linear nonminimal couplings $\omega_{BD}(\varphi)$: ln $A_{m,awe}(\varphi) \sim \varphi^2 + \ldots$ (local validity of GR)

The AWE Dark Matter

- Dynamics during matter-dominated era:
  - → WEP OK if universal couplings ($\alpha_m=\alpha_{awe}$) and/or $\rho_m >>> \rho_{awe}$

$$\frac{2\varphi''}{3-\varphi'^2}+\varphi'+\alpha_m(\varphi)+\frac{\alpha_{awe}(\varphi)-\alpha_m(\varphi)}{1+\frac{\rho_m}{\rho_{awe}}}=0 \qquad (\bullet)' = a\frac{d(\bullet)}{da}$$



- Attraction mechanism is conserved but becomes density-dependent!

$$\varphi_\infty \equiv \alpha_m(\varphi_\infty)\frac{\rho_m}{\rho_{awe}}(\varphi_\infty)+\alpha_{awe}(\varphi_\infty)=0$$

Chameleon Effect!

- ✦J. Khoury, A. Weltman, PRL 93, 172204 (2004), PRD 69, 044026 (2004)
- ✦P. Brax et al., Phys. Rev. D 70, 123518 (2004)
- ✦D. F. Mota & D. J. Shaw, PRL 97 151102 (2006); PRD 75, 063501 (2007)
- ✦D. F. Mota, J. D. Barrow, MNRAS 349, 291

Dark Energy as a gravitational feedback

★ Friedmann equation

$$\tilde{H}^2 = \frac{8\pi\tilde{G}_m}{3}\left(\tilde{\rho}_m + \tilde{\rho}_{awe}\right) \times \left(1 + \frac{\varphi'^2\left(1+3\alpha_m^2\right) + 6\alpha_m\varphi'}{3-\varphi'^2}\right)$$

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

★ FLRW-like but

→ DM not scaling in a^{-3} (varying mass)

→ Exotic DE tracking DM and baryons

★ Acceleration equation

$$\frac{1}{\tilde{a}}\frac{d^2\tilde{a}}{d\tilde{t}^2} = -\frac{4\pi\tilde{G}_m}{3}\left(\tilde{\rho}_m + \tilde{\rho}_{awe}\right) \times \left(1 - \frac{2\varphi'}{3-\varphi'^2}\left(\varphi'\left(\frac{d\alpha_m}{d\varphi} + \frac{2}{3}\right) - 2\alpha_m\right)\right)$$

$$-4\pi\tilde{G}_m\alpha_m\left(\alpha_m\tilde{\rho}_m + \alpha_{awe}\tilde{\rho}_{awe}\right)$$

→ EP violation terms constitute an exotic DE fluid with negative pressures

→ Ghost effective equation of state

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

✦A. Füzfa, J.-M. Alimi, PRD73 (2006) 023520

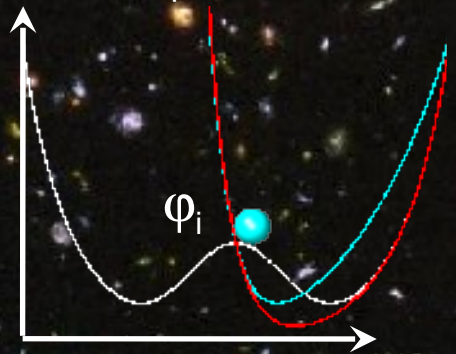
AWE Dark Matter and cosmic acceleration

★ Large-scale cosmological dynamics

→ Free parameters: R_i , R_∞,φ_R and coupling strength k_m

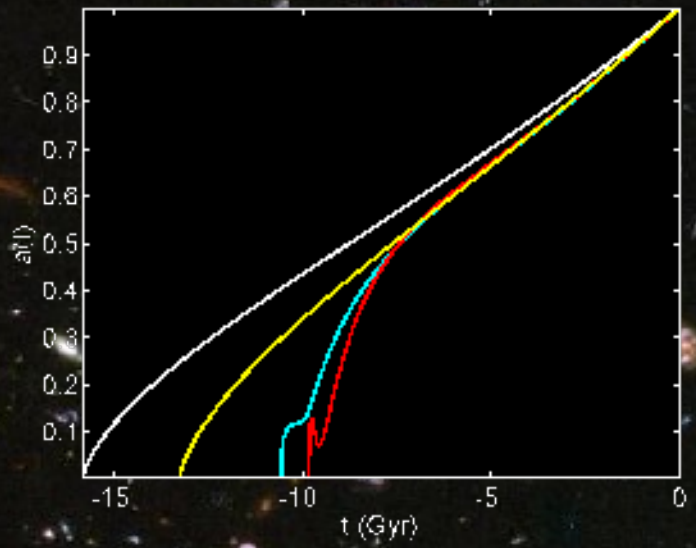
→ φ starts frozen at CMB near GR values ($\varphi(a<10^{-3})=\varphi_R$)

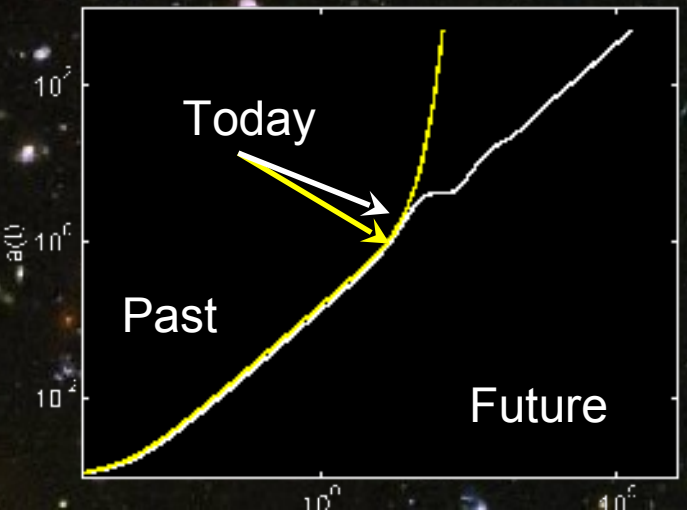
$$R_{i,\infty} = \frac{\rho_m}{\rho_{awe}}|(a_+ \to a_{CMB,\infty})$$



$$\tilde{a} = \left(\frac{\tilde{G}_m(\varphi)}{G_\infty}\right) a_+$$

Fate of the Universe





Some Models fitting SNLS data

AWE DM : (3DOF)

— χ^2/dof= 1.04 (Ω_{awe}=0.26, Ω_m=0.04)

— χ^2/dof= 1.05

— χ^2/dof= 1.04

ΛCDM (Ω_Λ=0.7 ; 1DOF)

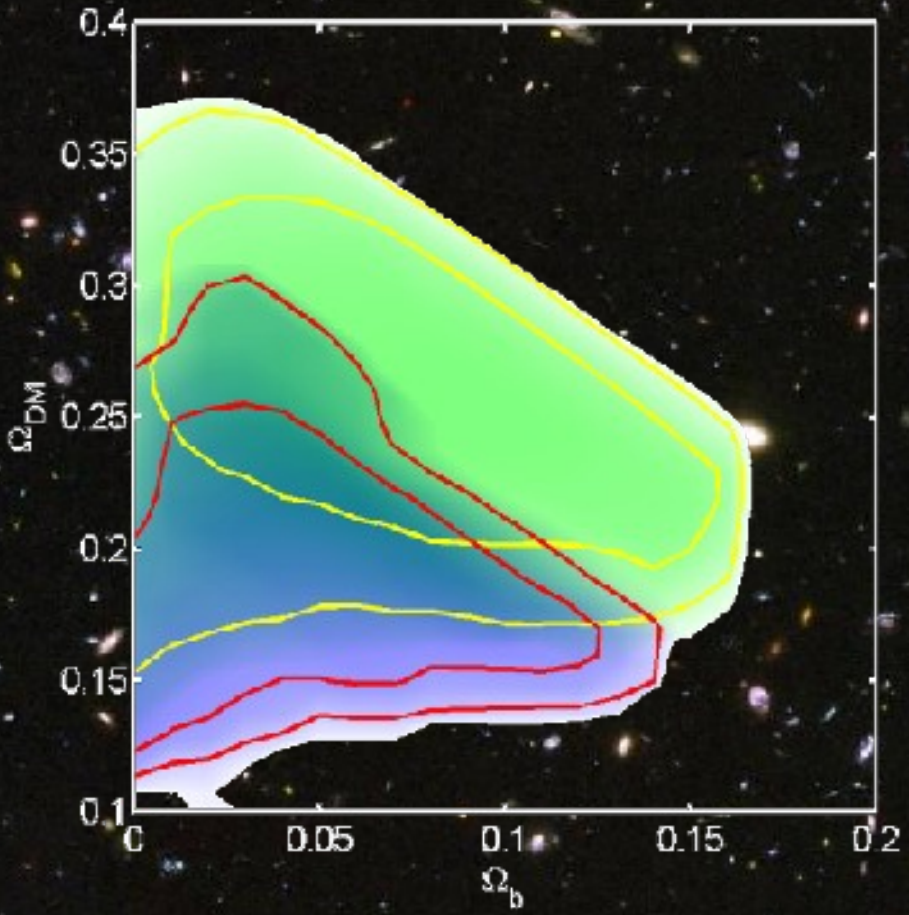
— χ^2/dof= 1.03

AWE DM :
→ matter-dominated Einstein-de Sitter Universe when GR is retrieved

ΛCDM :
→ Λ-dominated de Sitter Universe, eternal cosmic acceleration

Is Λ the anomalous weight of CDM?

★ Constraints from SNe Ia Hubble diagrams* (sample of 10^6 models)



AWE Predictions on HST (SNLS) at 95%C.L.

→ R_i=0.18+0.30 (R_i=0.17+0.31)

→ Ω_m=0.06+0.10 (Ω_m=0.04+0.09)

→ $\Omega_{awe}=0.25^{+0.09}_{-0.07}$ ($\Omega_{awe}=0.18^{+0.16}_{-0.05}$)

→ Ω_{DE}= 1-Ω_m- Ω_{awe}

→ $t_0=13.2\text{Gyr}^{+0.6}_{-0.5}$ ($t_0=14.1\text{Gyr}^{+1.0}_{-0.4}$) for h=0.7

AWE ⇨ CDM

Matter ⇨baryons

$G_m(\varphi)$ ⇨ DE

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

★ Independent predictions close to that of ΛCDM !

✶A.G. Riess et al., Astrophys. J. 607 665-687 (2004).

✶P. Astier et al., Astron. Astrophys. 447 31-48 (2006).

A keystone between microphysics and gravitation?

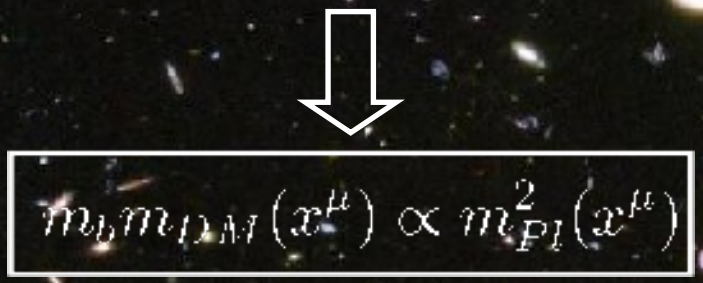
★ Relation between G and $M_{DM}(x^\mu)$?

$$\Lambda_{une}(\varphi) = \Lambda_m(\varphi)^{-R_\infty}$$

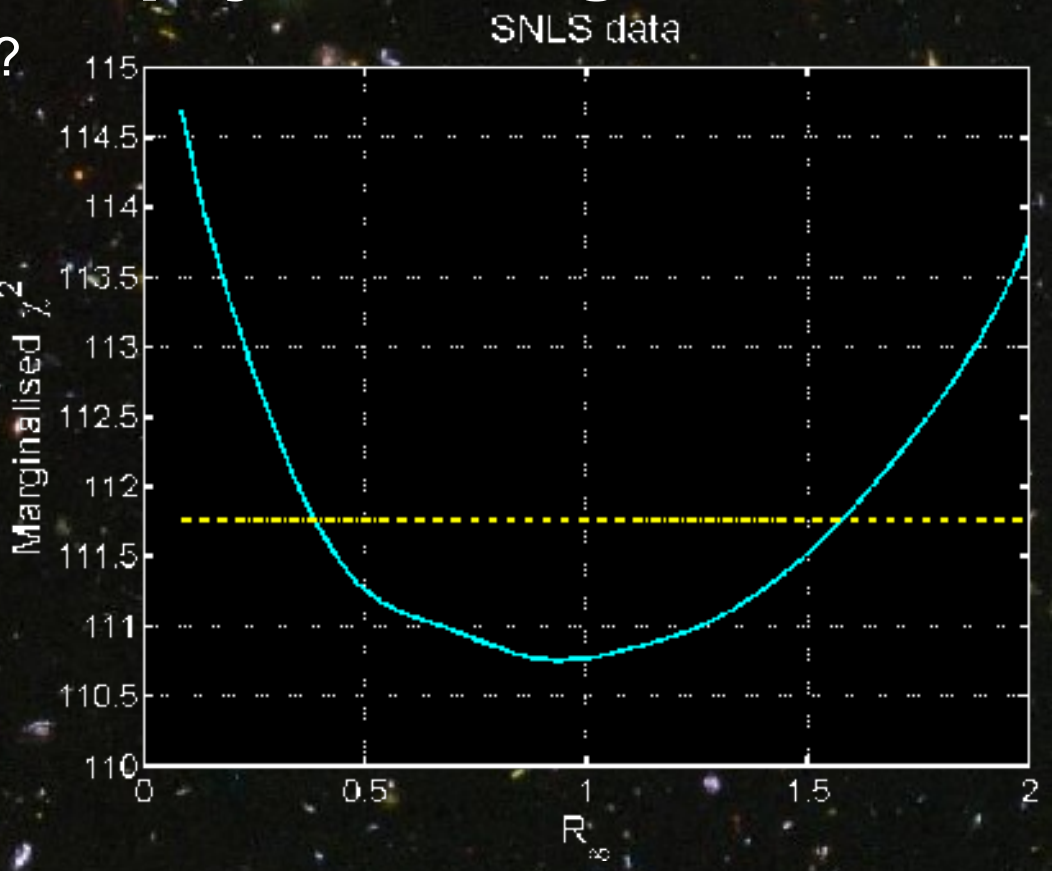
$$R_\infty = 0.94^{-0.64}_{-0.55}(SNLS)$$

$$R_\infty = 0.93^{-0.52}_{-0.53}(HST)$$

(at 68% C.L.)



$$m_b m_{DM}(x^\mu) \propto m_{Pl}^2(x^\mu)$$



$$S_{source} = S_m\left[\psi_m, \Lambda^2(\varphi) g^*_{\mu\nu}\right] + S_{une}\left[\psi_{une}, \Lambda^{-2}(\varphi) g^*_{\mu\nu}\right]$$

★ When M_{DM} vary, the product of the gravitational masses is conserved!

★ A fundamental relation between Planck and DM running scales?!

★ A glimpse at the intimate nature of gravitation?

✶J.-M. Alimi & A. Füzfa, under preparation

The AWEsome properties of Dark Matter

★ **Nature of DE? ⇨ Anomalous gravity of mass-varying DM ($m_{DM}(\varphi)$)**

- → Cosmic acceleration from a Mach-Dirac Mechanism $M_{DM} \leftrightarrow G$
- → Independent determination of Ω_{baryon} and Ω_{DM} from supernovae alone!
- → Explanation to why concordance cosmology appears correct
- → Running fundamental scales of gravitation and DM are linked! ($m_b m_{DM}/m_{Pl}^2 \sim cst$)
- → Scale-dependent violation of Equivalence Principle (chameleon effect)

★ **No need for negative pressures**

- → Ghost equation of state ($p/\rho<-1$) from a frame effect
- → Can lead to larger age of the Universe than in quintessence, ΛCDM

★ **Fate of the Universe**

- → Transient cosmic acceleration
- → GR is finally retrieved (Einstein-de Sitter asymptotic state)

★ **Coincidence Problem**

- → DE tracks DM and baryons densities, coincidence during matter-dominated era
- → Couplings to scalar mode φ of the same amplitude of those to the tensorial $g_{\mu\nu}$
- → Variation of DM mass of 30% around $T \sim 10^{-3}$ eV

What lies behind the AWE action?

$$S_{visible}\left[\psi_v, F(x^\mu) g^*_{\mu\nu}\right] + S_{invisible}\left[\psi_i, F^{-1}(x^\mu) g^*_{\mu\nu}\right]$$

Thank you for your attention!