Toward a unified description of Dark Matter and Dark Energy?

The Abnormally Weighting Energy (AWE) Hypothesis

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Outline

1. Observational Evidence in Favour of Dark Energy

3. An Iceberg of Physical Theories Behind Dark Energy

5. Beyond Einstein with Dark Energy: the AWE Hypothesis

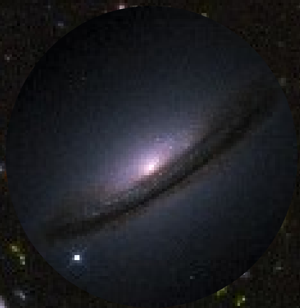
7. Dark Energy as the Anomalous Gravity of Dark Matter

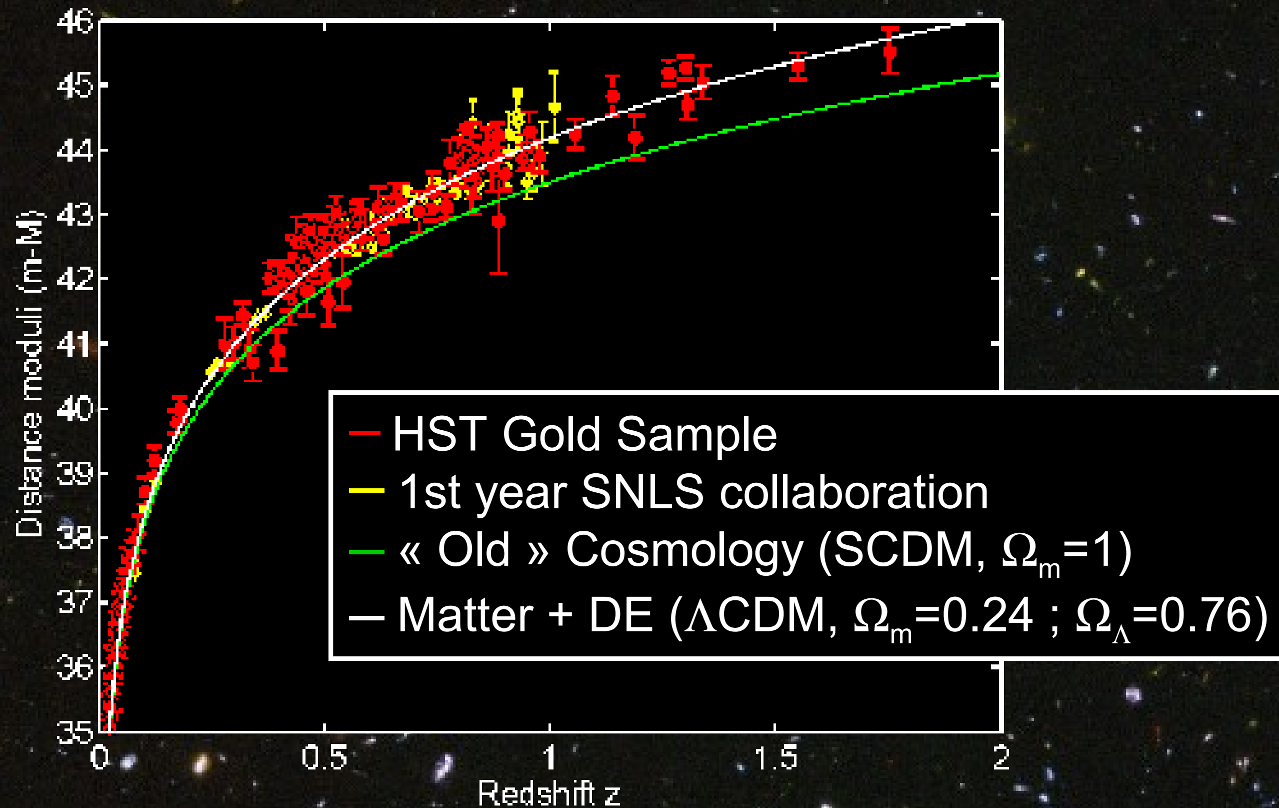
✦A. Füzfa, J.-M. Alimi, to appear in Phys. Rev. D (June 2007)
✦A. Füzfa, J.-M. Alimi, Phys. Rev. Lett. 97, 061301 (2006)
✦A. Füzfa, J.-M. Alimi, Phys. Rev. D73 (2006) 023520
✦J.-M. Alimi, A. Füzfa, Proceedings of the Workshop « From Quantum to Cosmos », Washington, USA, 2006
✦A. Füzfa, J.-M. Alimi, astro-ph/0609099
✦A. Füzfa, J.-M. Alimi, gr-qc/0702085

1. Observational evidence in favour of Dark Energy

Far-away supernovae

★ Hubble Diagram of type Ia supernovae





✦Riess et al., ApJ, 607, 665 (2004)

✦P. Astier et al., A&A 447 (2006)

★ Supernovae appear fainter than expected:

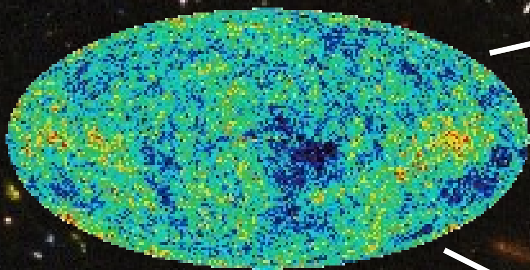
→ Cosmic expansion has recently accelerated

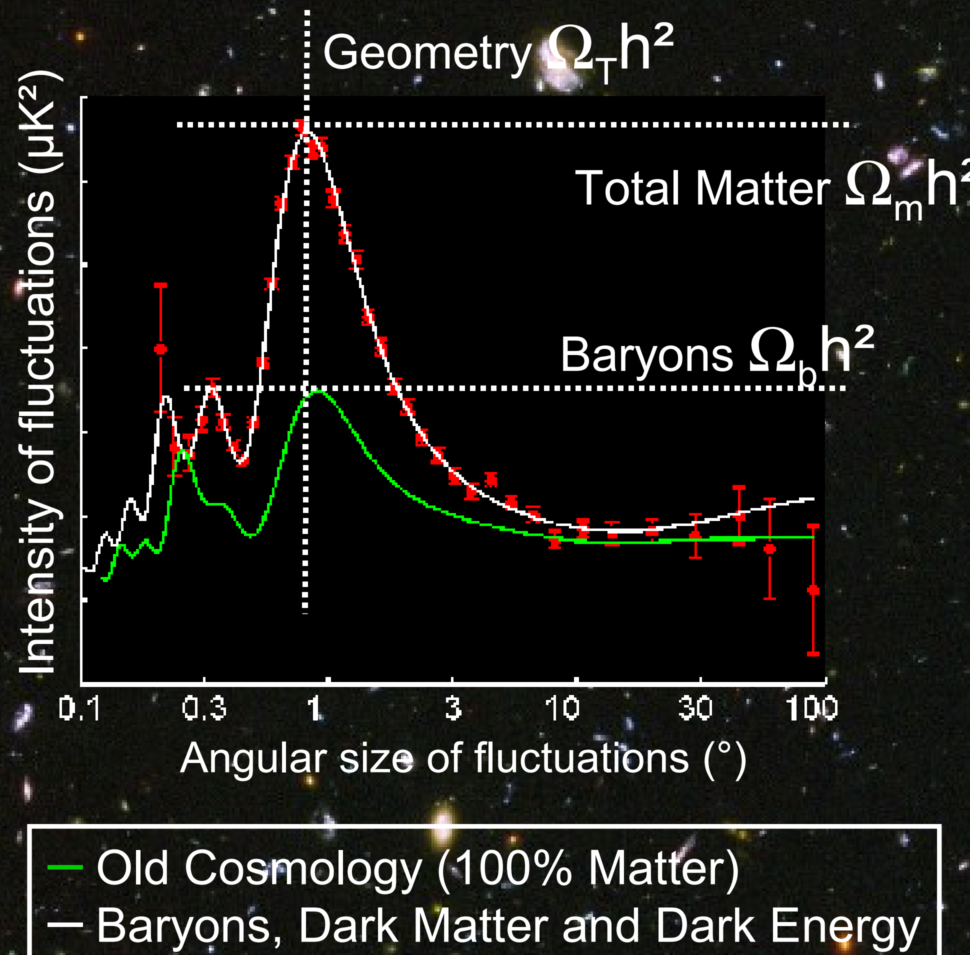
or (and?)

→ Supernovae are not standard candles

Cosmic Microwave Background

★ Angular Fluctuations of Cosmic Microwave Background (CMB):





Geometry:
Flat Universe (Ω_T~1)

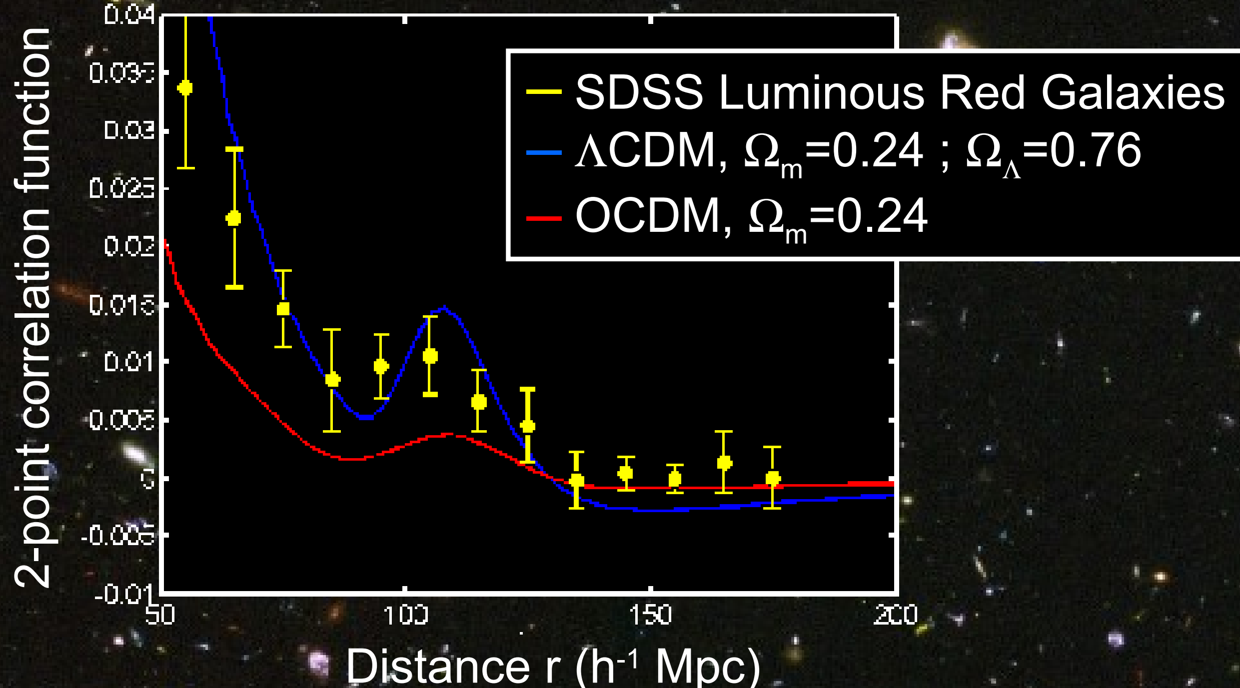
Present Energy Content:
→ Matter : ~24%
→ Baryons: ~4%

=> Dark Matter : ~ 20 %
=> Missing DE: ~76%!

✦D.N. Spergel, et al., 2003, ApJ S, 148, 175
✦D.N. Spergel et al., ApJ, in press, astro-ph/0603451

Large-scale Structures

★ Baryon Acoustic Oscillation:



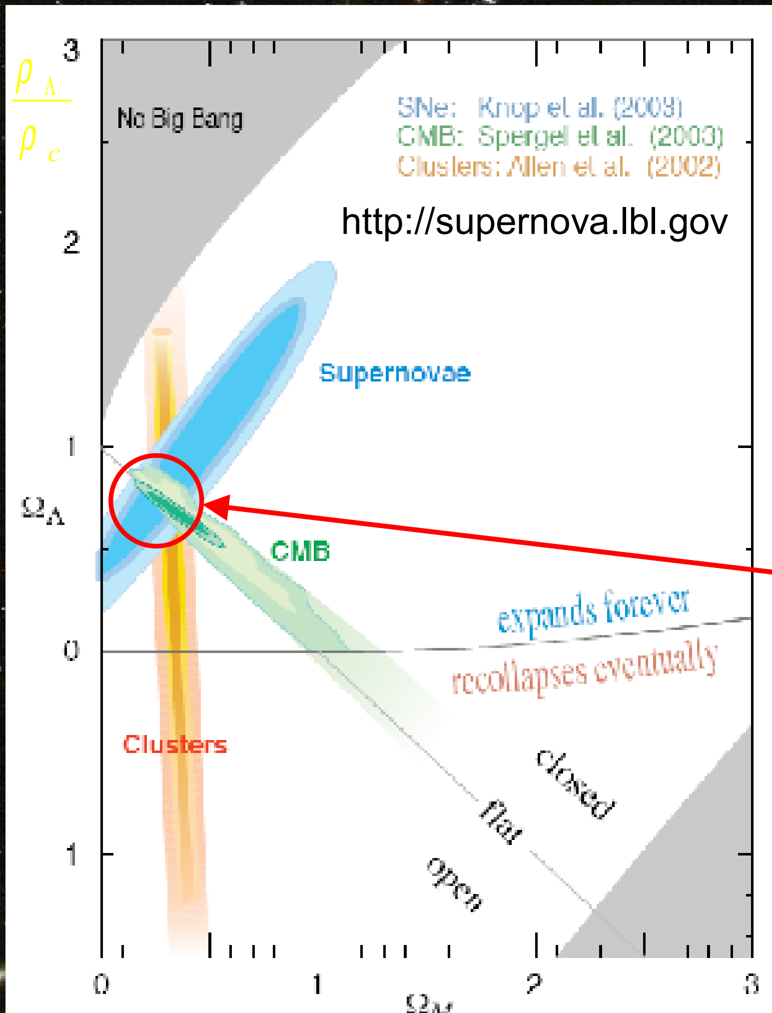
★ Large-Scale distribution of galaxies (Power Spectrum)

2dFGRS : $0.65<\Omega_\Lambda<0.85$ at 95% C.L.

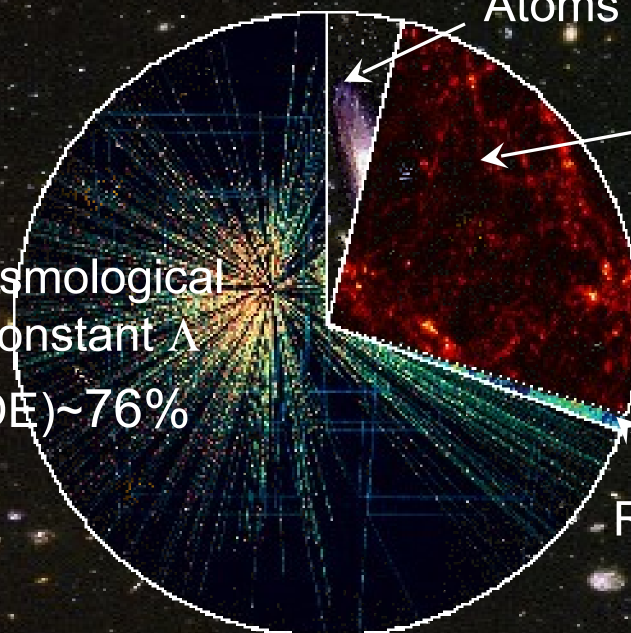
SDSS: Ω_m=0.24±0.02 at 95% C.L.

✦D. Eisenstein et al., ApJ, 633, 560 (2005)
✦G. Efstathiou et al., M.N.R.A.S. 330 (2002)
✦M. Tegmark et al., Phys. Rev.D 69 103501 (2004)
✦M. Tegmark et al., Phys. Rev.D 74 123507 (2006)

The Concordance Model of Cosmology



Energy Content of the Universe Today (>95% C.L.)



<u>ΛCDM</u>

Age of the Universe :
~ 14 billion years
Geometry : flat

The AWE-full problems of ΛCDM

★ **Nature of Dark Matter (DM) <u>AND</u> Dark Energy (DE)**

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

→ Physical relation between DM and DE?

★ **Negative Pressures of DE**

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

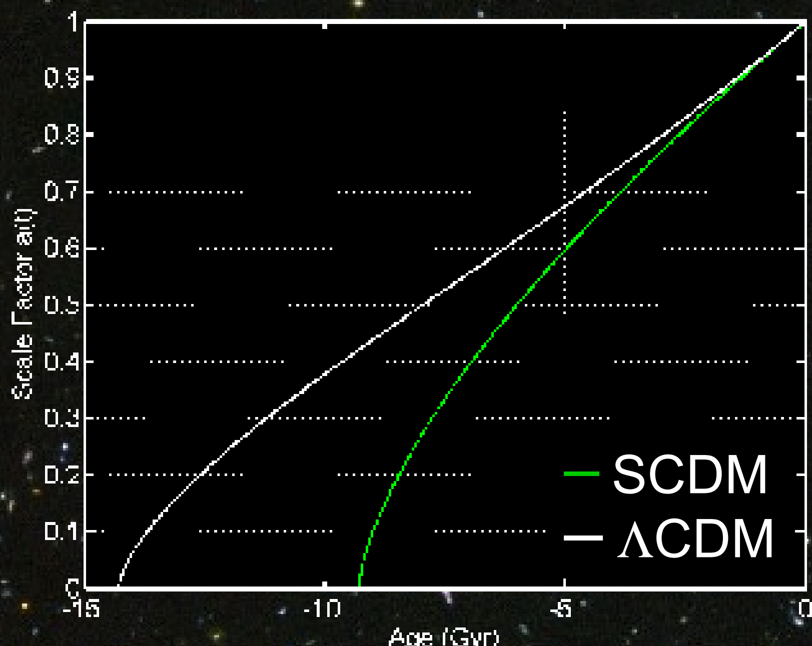
Violation of the Strong Energy Condition (SEC)

★ **Coincidence Problem**

→ Why DE appeared so recently?

→ Why these abundances?

→ Which low-energy physics behind DE?



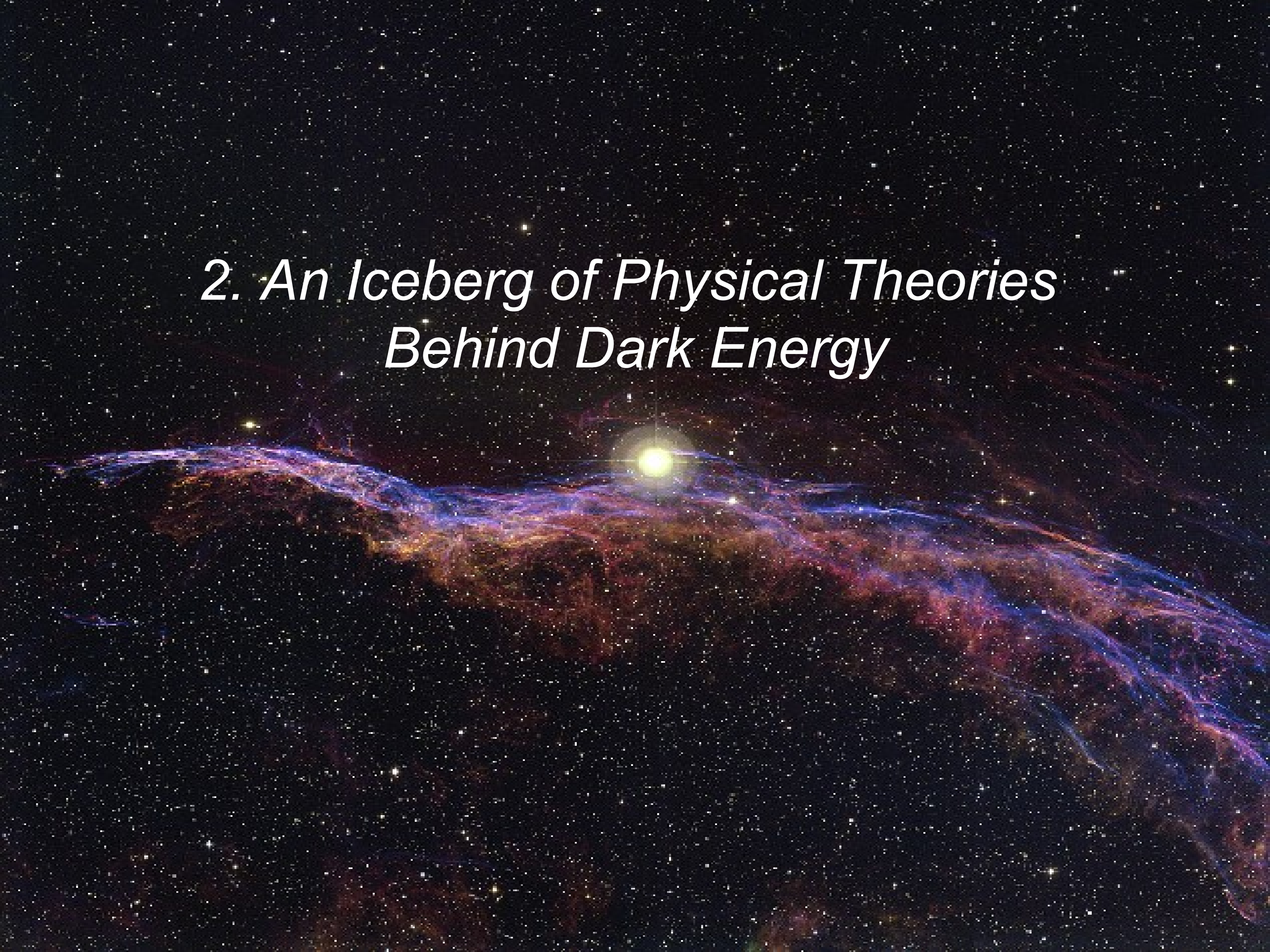
★ **Fate of the Universe**

→ Eternal cosmic acceleration

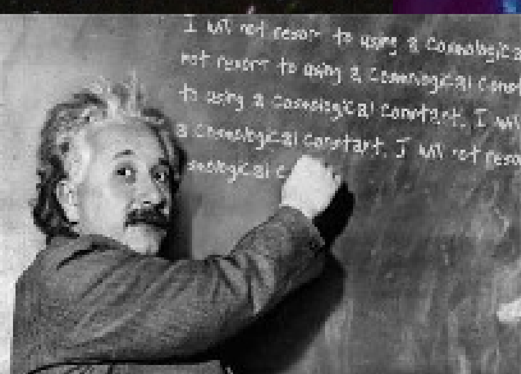
→ de Sitter asymptotic state

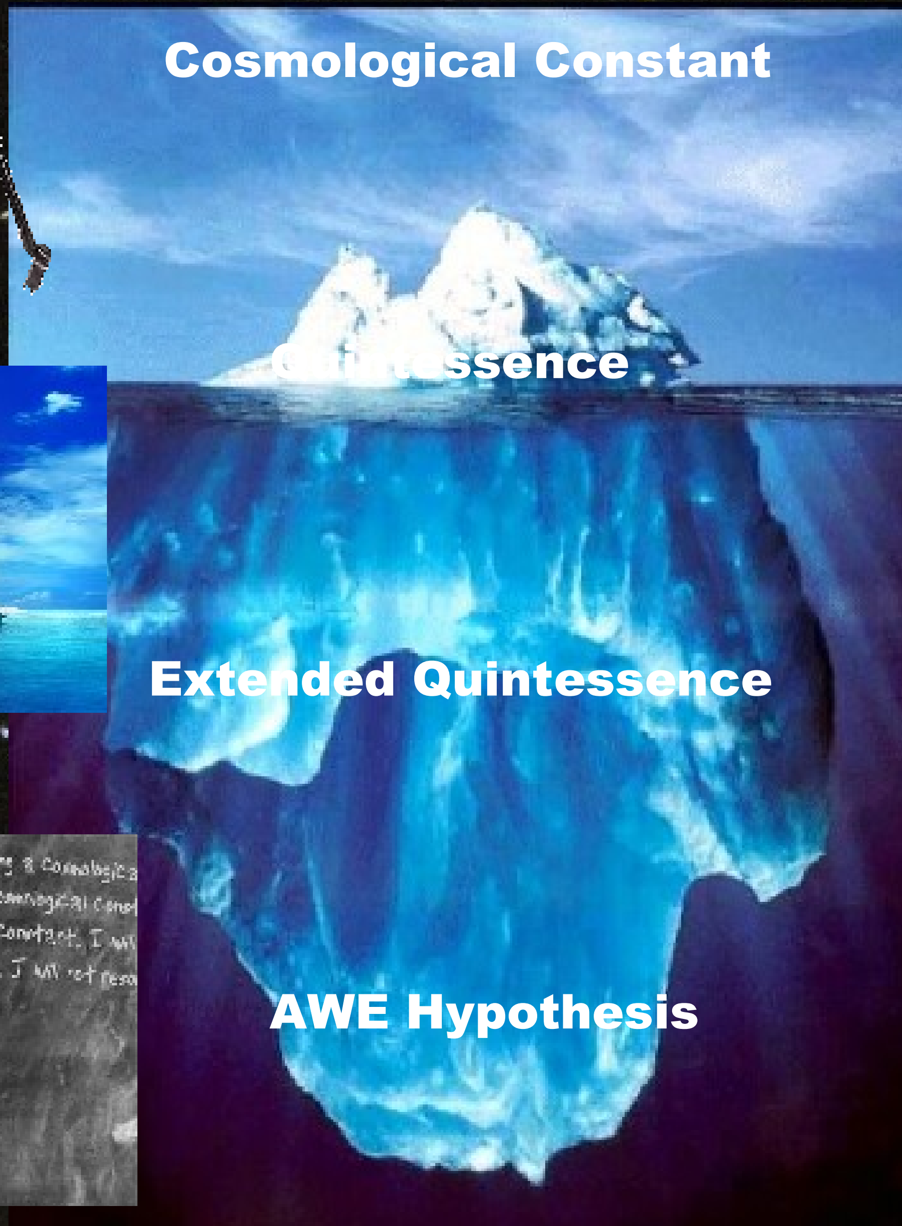
(asymmetrical non-trivial vacuum)

2. An Iceberg of Physical Theories Behind Dark Energy



The Dark Cosmology Iceberg





Vacuum properties

Exotic Fluid
of negative pressure

New gravitational field

Non-universality
of gravitation

What lies behind the Λ?

Gravitation $g_{\mu\nu}$

Λ

Minimal Coupling

ΛCDM

Invisible Sector **Visible Sector**

Frozen Vacuum Energy: **cosmological constant** Λ

Dark Matter

Baryons Photons

No Direct long-ranged Interactions

A Dynamical Cosmological Constant?

⇨New degrees of freedom!

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

→ Quintessence: Matter and DE conserved separately, only gravitational interaction

→ Modified Gravity: Matter interacting with DE (non-minimal coupling)

Fundamentals of General Relativity

- The Equivalence Principles (EPs):
  - ➔ Weak EP: gravitation is mediated by one universal metric $g_{\mu\nu}$
  - ⇨ In free fall, laws of physics are those of special relativity
  - ➔ Strong EP: non-linear dynamics of gravitation ($g_{\mu\nu}$ is the only one gravitational field)
  - ⇨ Generalised Principle of Relativity:

  « *Laws of physics are independent on the general motion of the observer* »
- Einstein-Hilbert gravitation:

Matter energy-momentum

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi}{m_{Pl}^2} T_{\mu\nu}$$

Derivatives of $g_{\mu\nu}$

$$T_{\mu\nu} = 0 \Rightarrow \begin{cases} g_{\mu\nu} = \eta_{\mu\nu} \\ \text{or} \\ g_{\mu\nu} = 0 \end{cases}$$

Vacuum: special relativity (Minkowski) or no space-time

- Conservation of Length-Duration (Bianchi) and Energy-Momentum

$$\nabla_\mu \left(R^\mu_\nu - \frac{1}{2} R \delta^\mu_\nu \right) = \nabla_\mu T^\mu_\nu = 0$$

The Mach Principle and the Cosmological Constant

- Mach's Principle:
  - → Inertia and acceleration are relative and defined with respect to the whole Universe $T_{\mu\nu} = 0 \Rightarrow g_{\mu\nu} = 0$ No matter ⇨ no space-time
- Einstein's Modification of General Relativity (GR) for Mach's Principle:

Field Equations

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} \boxed{- \Lambda g_{\mu\nu}} = \frac{8\pi}{m_{Pl}^2} T_{\mu\nu}$$

Geometry-Energy Conservation

$$\nabla_\mu \left(R^\mu_\nu - \frac{1}{2} R \delta^\mu_\nu \boxed{- \Lambda \delta^\mu_\nu} \right) = 0$$

If $\Lambda \neq 0$, either Mach's Principle $T_{\mu\nu}=0$ ⇨ $g_{\mu\nu}=0$ or de Sitter solution!

- Λ does not save Mach's Principle:
  - → always a non-trivial solution for vacuum ($T_{\mu\nu}=0$) ($\Lambda \neq 0$ ⇨ de Sitter ; $\Lambda=0$ ⇨ Minkowski)
  - → Unstable implementation of Mach's Principle ($\Lambda \neq \Lambda(x^\mu)$)
  - → If $\Lambda \neq 0$, Newton's theory is wrong!
  - → de Sitter ($\Lambda \neq 0$) non-trivial vacuum has no residual Poincaré symmetries*
- Which vacuum for gravitation?
  - → Trivial ($g_{\mu\nu}=0$) or non-trivial (Minkowski $\Lambda=0$, de Sitter $\Lambda \neq 0$, Schwarzschild, Kerr, etc.)
  - → quantum gravity question!

*S. Weinberg, Rev. Mod. Phys. 61, 1 (1989)

The Unbearable Lightness of Vacuum

- ★ Einstein introduced Λ to reconcile Mach Principle with general relativity
- ★ Weight of vacuum energy? ⇨ quantum gravity and quantum field theory!

$$\rho_\Lambda^{th} \approx \int_0^M \left(k^2 - m^2\right)^{1/2} d^3k = \begin{cases} \left(10^{28} eV\right)^4 = 10^{76} GeV^4 (Planck) \\ \left(10^{25} eV\right)^4 = 10^{64} GeV^4 (GUT) \\ \left(10^{12} eV\right)^4 = 10^{12} GeV^4 (SUSY) \\ \left(10^{7} eV\right)^4 = 10^{-6} GeV^4 (QCD) \end{cases}$$

- ★ Λ provides cosmic acceleration:

$$\rho_\Lambda^{obs} \approx \rho_{c,0} = \frac{3H_0^2 m_{Pl}^2}{8\pi} \approx \left(10^{-3} eV\right)^4 = 10^{-47} GeV^4$$

⇨ Why is the cosmological constant so small?

Fine-tuning problem!

⇨ Why is vacuum energy of the order of a **present** cosmological property?

Coincidence problem!

- ★ Solution: Λ prevents defining energies absolutely ($T_{\mu\nu}$ gauge freedom)

$$T_{\mu\nu} \to T_{\mu\nu} - \rho_{vac} g_{\mu\nu} \to T_{\mu\nu}(vac) = 0 \Rightarrow g_{\mu\nu} = \eta_{\mu\nu}$$

What lies behind the Λ?

★ Quintessence, k-essence:

Gravitation $g_{\mu\nu}$

Minimal Coupling

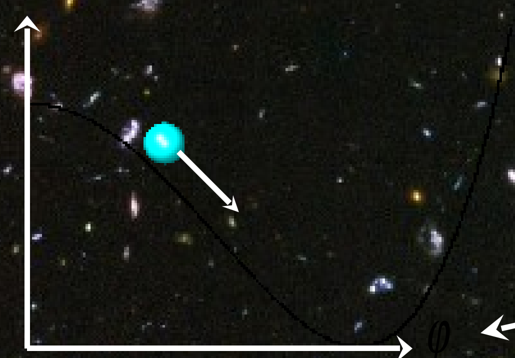
$$\Lambda$$

Invisible Sector ⟷ **Visible Sector**

Varying Dark Energy φ ⟷ Dark Matter

Baryons ⟷ Photons

(Effective) Potential $V(\varphi)$



DE dof

Cosmic acceleration if violation of SEC ($p<-\rho/3$)

Ex.: Slow-roll $\frac{\dot{\varphi}^2}{2} \ll V(\varphi)$

✦ C. Wetterich, Nucl. Phys. B 302, 668 (1988)

✦ B. Ratra & P.J.E. Peebles, Phys. Rev. D37 (1988) 3406

✦ C. Armendariz-Picon et al., Phys. Rev. D 63, 103510 (2001)

✦ E.J. Copeland, et al., Int.J.Mod.Phys. D15 (2006) 1753-1936

What lies behind the Λ? Interacting DE!

Dark Energy φ coupling non-minimally

Gravitation $g_{\mu\nu}$

φ $\quad \Lambda \quad$ φ

Invisible Sector $\longleftrightarrow\!\!\!\!\!\!\!\times$ **Visible Sector**

SEP violation:

$$G^{obs} \approx A^2(\varphi)$$

Cosmic acceleration through deviation from GR

$$a^{obs} \approx A(\varphi) a_*$$

Violation of the Strong Equivalence Principle (tensor-scalar gravitation):

- → Varying fundamental constants (G_N, α, etc.) : Standard Candles?
- → Adequacy with constraints on SEP?

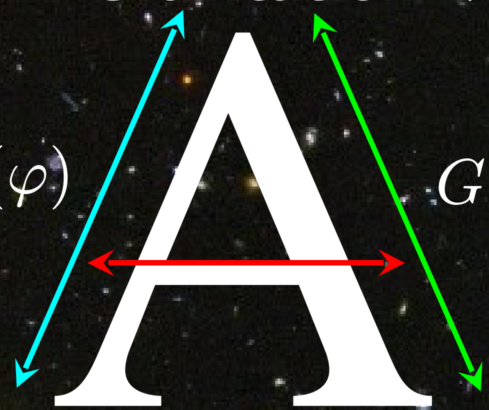
✦P. Jordan, Nature 164, 637 (1949)
✦M. Fierz, Helv. Phys. Acta 29, 128 (1956)
✦C. Brans and R. H. Dicke, Phys. Rev. 124, 925 (1961)

What lies behind the Λ? Interacting DE!

Gravitation $g_{\mu\nu}$

High-Energy Physics, Quantum Gravity, etc. → $G_{awe}(\varphi)$

High-Energy Physics, Quantum Gravity, etc. → $G_m(\varphi)$



Abnormally Weighting Invisible Sector

$m_{awe}(\varphi)$

Normally Weighting Visible Sector

$G_m(\varphi)$

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

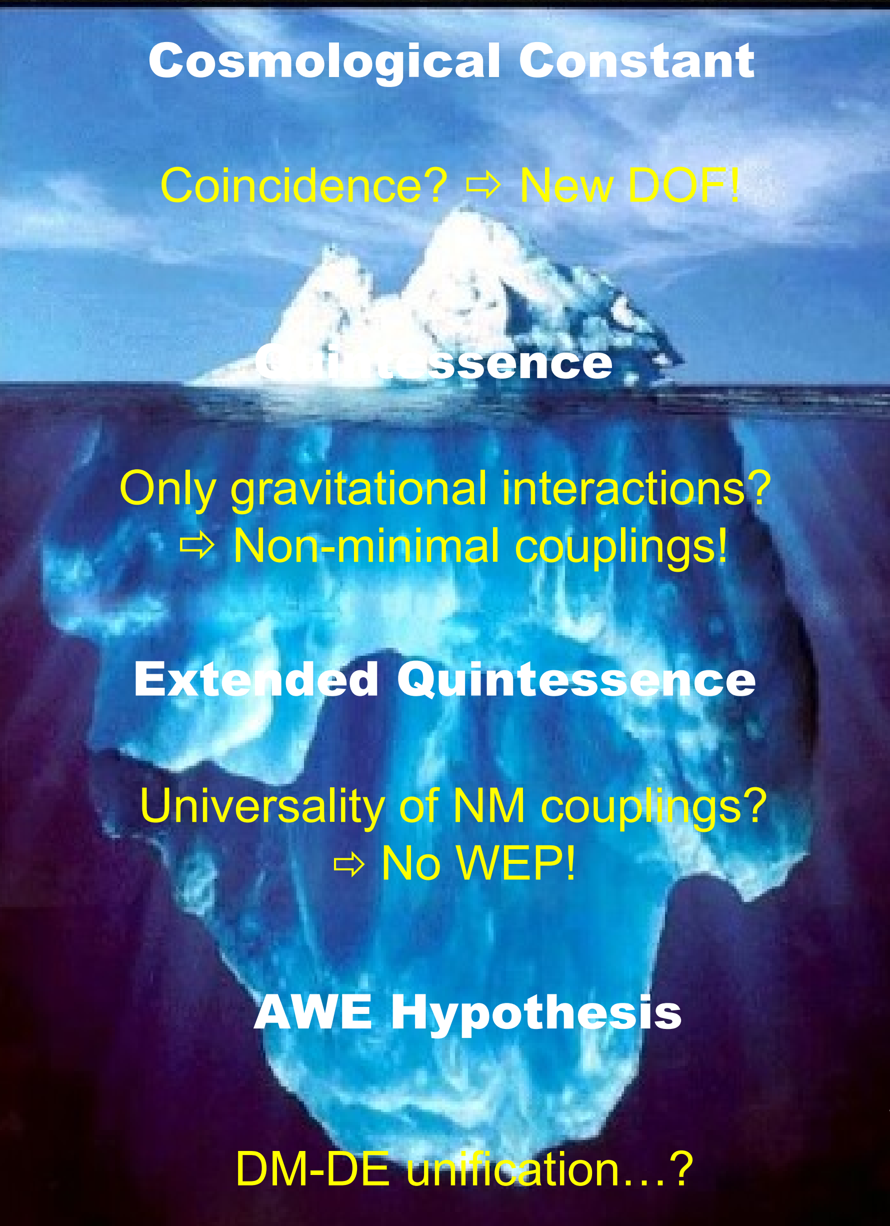
No WEP ⇨ no SEP

↓

Transient deviation from GR ⇨ cosmic acceleration

$$a^{obs} \approx A_m(\varphi) a_*$$

The Dark Cosmology Iceberg



★ DE frozen in a false vacuum

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

★ DE with minimal coupling : **SEP**!

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

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

★ Scalar-tensor gravity (WEP but no SEP)

$$\Big\downarrow\ A_m(\varphi) \neq 1$$

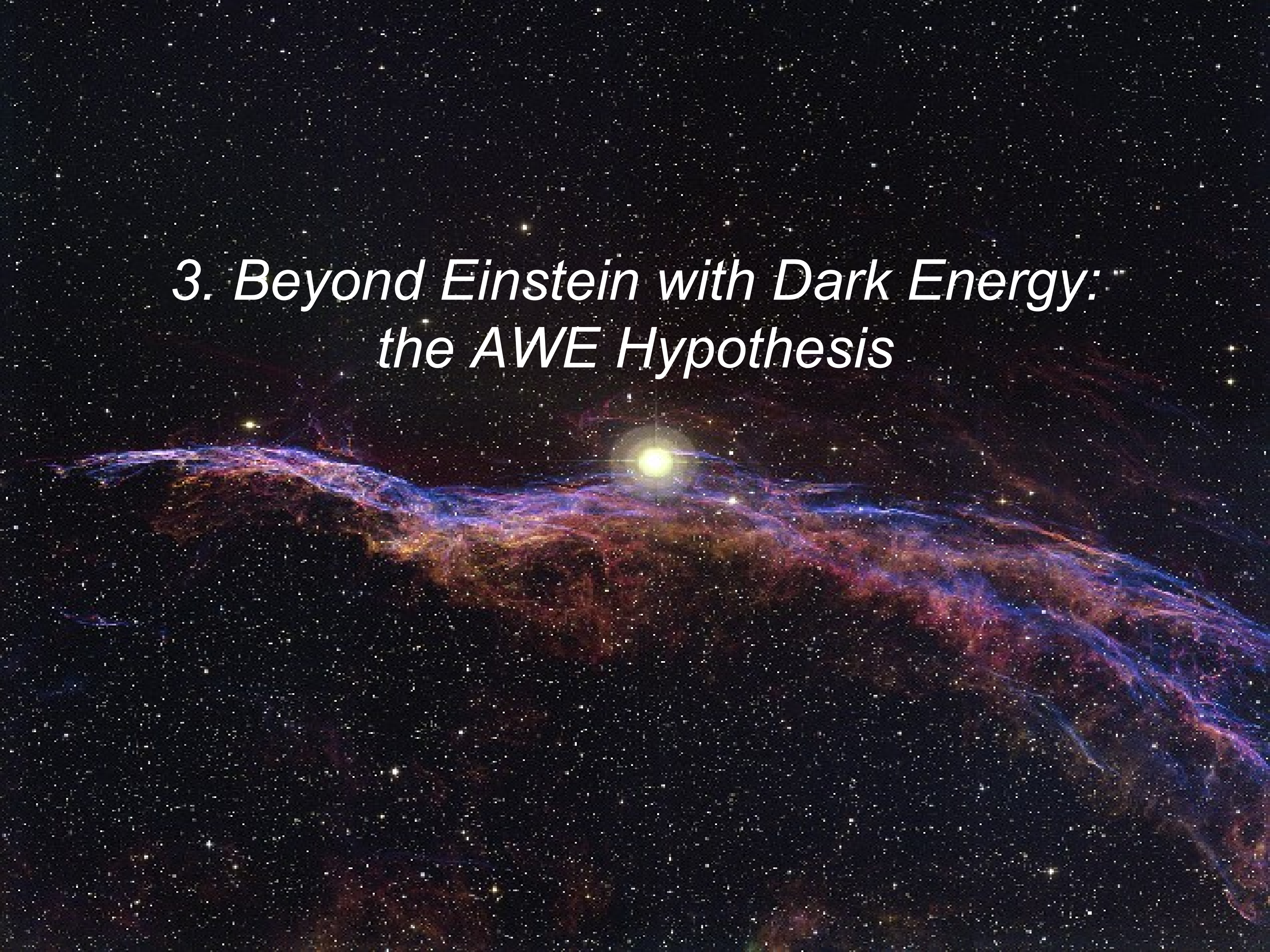
$$S_{grav}[\Lambda = 0] + S_{DE} + S_{mat}\left[\psi_m, A_m^2(\varphi)g^*_{\mu\nu}\right]$$

$$\Big\downarrow\ A_m \neq A_{awe}$$

★ Gravitation without WEP

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

3. *Beyond Einstein with Dark Energy: the AWE Hypothesis*

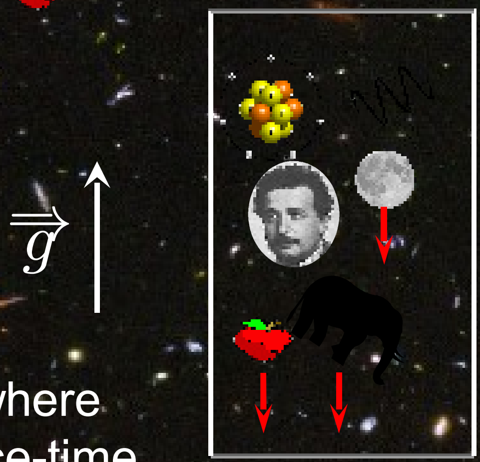


Einstein and the Equivalence Principles

Universality of gravitation

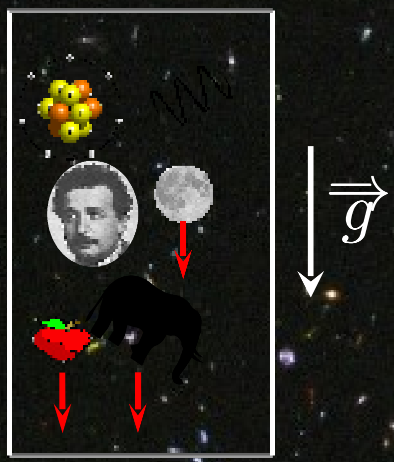
Weak Equivalence Principle WEP (Einstein Equivalence Principle) $\longrightarrow \exists g_{\mu\nu}$

Strong Equivalence Principle SEP $\longrightarrow$ Dynamics of $g_{\mu\nu}$



Anywhere in space-time, far from matter

$\Longleftrightarrow$



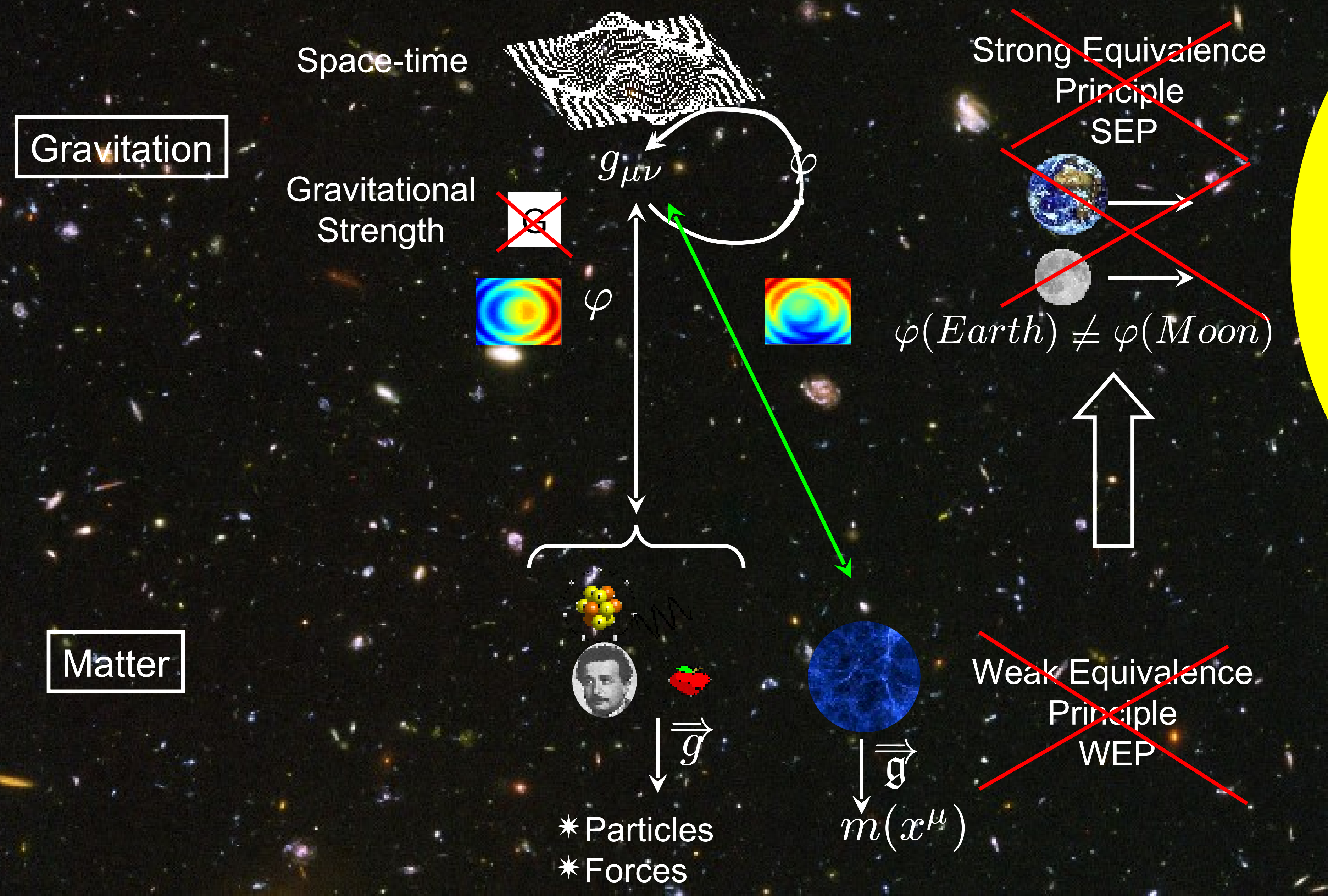
Earth

There is no way to discriminate locally between acceleration and gravitation ~~with non-gravitational experiments~~

…even with gravitational experiments!

Generalised principle of relativity

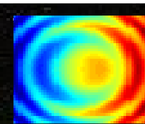
Gravitation without Equivalence Principles



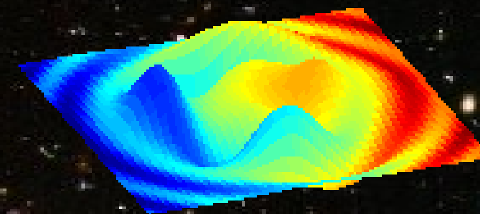
Scalar-tensor theories of gravitation

Einstein Frame
Separated DOF

$\tilde{g}_{\mu\nu} = A_m(\varphi) g^*_{\mu\nu}$ →



Observable Frame
Mixed DOF



→Bare Space-time $g^*_{\mu\nu}$

→Running coupling φ

$\tilde{g}_{\mu\nu}$=Effective metric felt by matter, suited by the scalar field

Mach Principle $\begin{cases} G = G_* = ct \\ m_*(\varphi) \end{cases}$ → Dirac Hypothesis $\begin{cases} \tilde{G} = G_* A_m^2(\varphi) \\ m^{obs} = ct \end{cases}$ ← WEP

★ Gravitation:

→ spin 2 ($g_{\mu\nu}$)+ spin 0 (φ) : NO Strong Equivalence Principle (SEP) !

→ Universal coupling function $A_m(\varphi)$: Weak Equivalence Principle (WEP)

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

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

$A_m(\varphi)$: metric screening

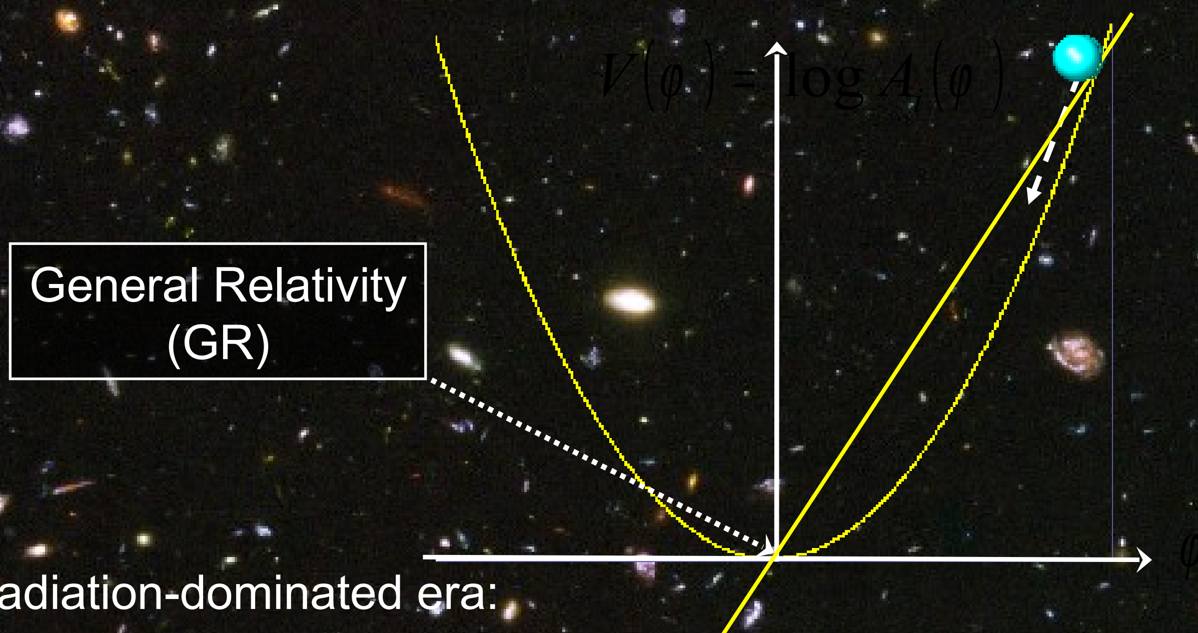
φ: scalar gravitation (dilaton)

Ψ_m: matter field

Cosmology without SEP

- Dynamics of the running coupling φ in Einstein frame:

$$\ddot{\varphi} + 3\frac{\dot{a}_*}{a_*}\dot{\varphi} + \frac{\kappa_*}{2}\alpha_m(\varphi)\left(\rho^*_m - 3p^*_m\right) = 0 \qquad \alpha_m(\varphi) = \frac{d\log A_m(\varphi)}{d\varphi} \qquad \dot{(\bullet)} = \frac{d(\bullet)}{dt_*}$$



$$\gamma - 1 < 10^{-5}$$

$$\beta - 1 < 10^{-4}$$

$$\left|\frac{\dot{G}}{G}\right| < 10^{-13} yr^{-1}$$

- Radiation-dominated era:
  - → decoupling and damping by cosmic expansion
  - → Step-by-step convergence around phase transitions of relativistic particles (kT~mc²)
- Matter-dominated era: attraction mechanism toward GR
- Adequacy with SEP constraints:
  - → GR reached globally today
  - → Scale-dependent SEP violation?

✦A. Serna et al., C.Q.G. 19 (2002) 857-874
✦T. Damour & K. Nordtvedt, PRD48 (1993)
✦J.D. Barrow, PRD 47 (1993)

The AWE Hypothesis

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

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

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

★ Energy content of the Universe :

→ The **ordinary matter** (baryons, photons, ...), ruled by the weak equivalence principle, defines the observable frame ⟹ $\tilde{g}_{\mu\nu} = A_m^2(\varphi) g^*_{\mu\nu}$

→ Abnormally Weighting Energy (AWE) sector violating the weak equivalence principle ⟹ $A_{matter}(\varphi) \neq A_{awe}(\varphi)$

★ Observable frame:

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

$$S_{awe}\left[\psi_{awe}, \left(\frac{A_{awe}}{A_m}\right)^2 \tilde{g}_{\mu\nu}\right] \Longrightarrow \int \tilde{m}_{awe}(\Phi)\, d\tilde{s}$$

*T. Damour, D. Polyakov, Nucl.Phys. B423 (1994) 532-558.

AWE Hypothesis as a Mach-Dirac Principle

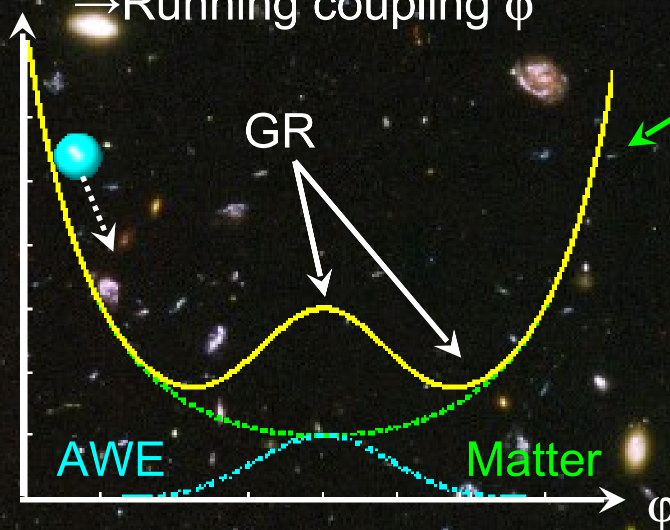
$$\bar{g}_{\mu\nu} = A^2_{awe}(\varphi) g^*_{\mu\nu}$$

→Bare Space-time $g^*_{\mu\nu}$

→Running coupling φ

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

$$\bar{G} = G_* A^2_{awe}(\varphi)$$



$$\boxed{\tilde{m}_{awe}(x^\mu) \leftrightarrow \tilde{G}_m(x^\mu)}$$

Mach ↔ Dirac

Mach-Dirac Principle!
(observable frame)

$$\begin{cases} \tilde{m}_{awe} \approx \left(\dfrac{A_{awe}}{A_m}\right) \\ \tilde{G}_m = G_* A^2_m(\varphi) \\ \tilde{m}_m = ct \end{cases}$$

- « Minimal » WEP violation: one space-time but two couplings G_{awe} and G_m
- AWE competition with matter : SEP violation! (no WEP ⇨ no SEP)

Cosmology without WEP: the AWE competition

★ AWE competes with Matter in the convergence mechanism toward GR

$$\ddot{\varphi} + 3\frac{\dot{a}_*}{a_*}\dot{\varphi} + \frac{\kappa_*}{2}\alpha_m(\varphi)\left(\rho^*_m - 3p^*_m\right) + \frac{\kappa_*}{2}\alpha_{awe}(\varphi)\left(\rho^*_{awe} - 3p^*_{awe}\right) = 0$$

★ Radiative dominated era:

→ BBN and CMB constraints on WEP violation?

⇨ AWE should be sub-dominant or decoupled at z↑↑ ⇨ only possible SEP violation

★ Local validity of GR?

A) Valid on cosmological scales today

AWE Born-Infeld Interaction

($p_{awe}^* \neq 0$)

Cosmic acceleration
and local past variation of G

✦A. Füzfa, J.-M. Alimi, PRL 97, 061301 (2006)
✦A. Füzfa, J.-M. Alimi, PRD73 (2006) 023520

B) Scale-dependent SEP violation

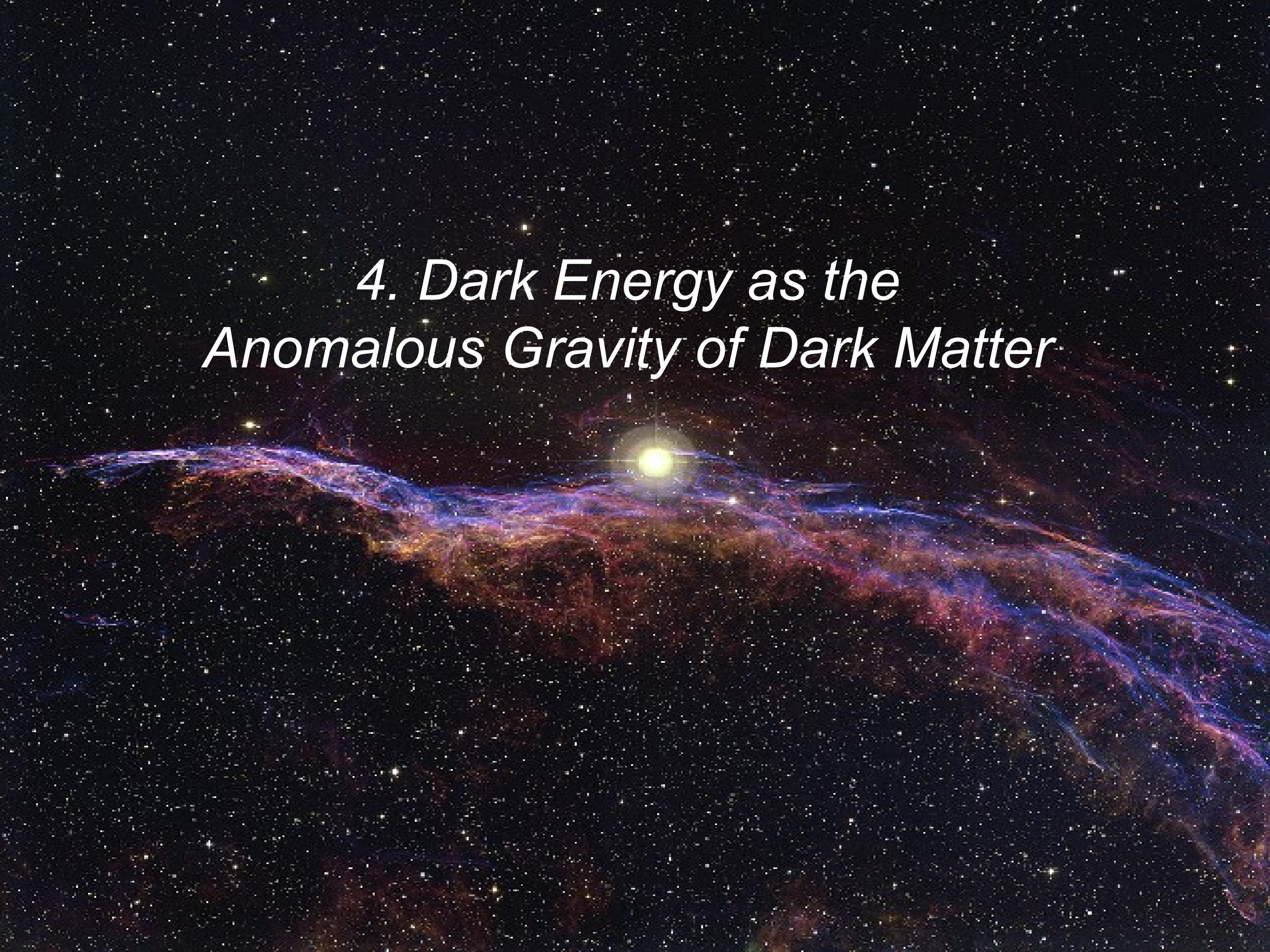
AWE Dark Matter

($p_{awe}^* = 0$)

Cosmic acceleration
DM-DE unification

✦A. Füzfa, J.-M. Alimi, to appear in PRD (2007), astro-ph/0702478

4. Dark Energy as the Anomalous Gravity of Dark Matter



The AWE Dark Matter

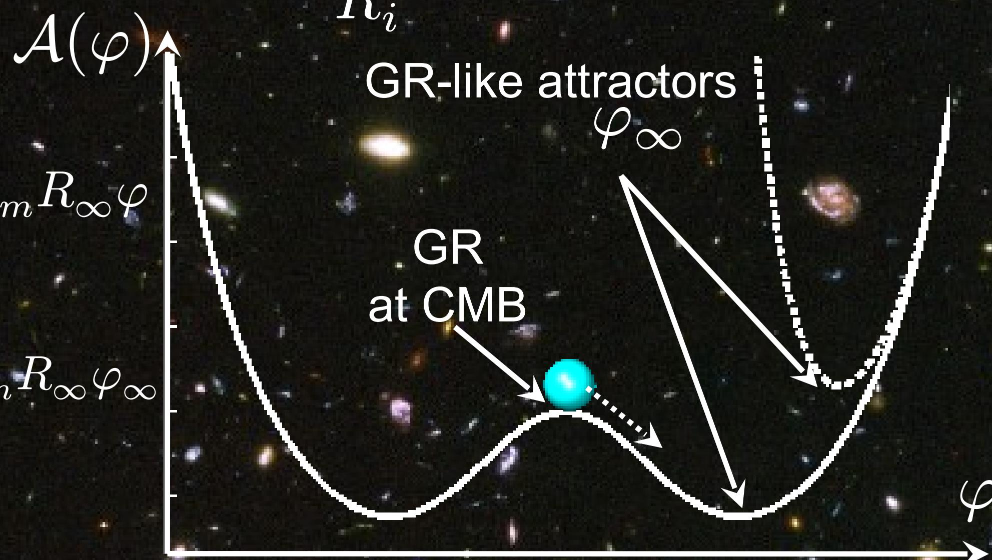
- A pressureless matter for AWE ⇨ simplified dynamics

$$\frac{2\varphi''}{3-\varphi'^2}+\varphi+\frac{d\log\mathcal{A}(\varphi)}{d\varphi}=0 \qquad (\bullet)' = a_*\frac{d(\bullet)}{da_*}$$

$$\mathcal{A}(\varphi)=A_m(\varphi)+\frac{A_{awe}(\varphi)}{R_i} \qquad R_i=\frac{\rho_m}{\rho_{awe}}\Big|_{a_*\to a_i}$$

$$\left\{\begin{array}{l}\alpha_m(\varphi)=k_m\varphi\\ \alpha_{awe}(\varphi)=-k_m R_\infty\varphi\end{array}\right.$$

$$\left\{\begin{array}{l}\alpha_m(\varphi)=k_m\varphi\\ \alpha_{awe}(\varphi)=-k_m R_\infty\varphi_\infty\end{array}\right.$$



$$R_\infty=\frac{\rho_m}{\rho_{awe}}\Big|_{a_*\to\infty}$$

- Attraction mechanism is conserved but becomes density-dependent!

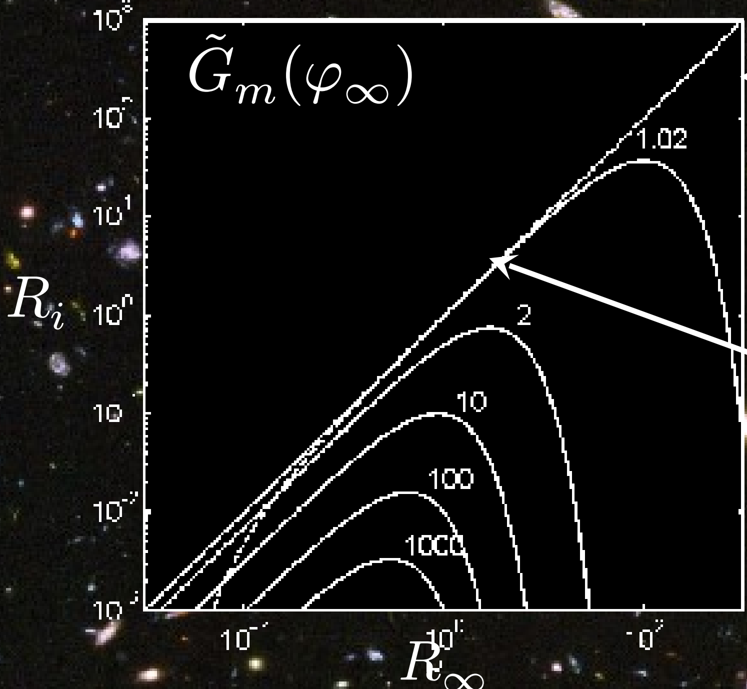
$$\varphi_\infty\equiv\alpha_m(\varphi_\infty)\frac{\rho_m}{\rho_{awe}}(\varphi_\infty)+\alpha_{awe}(\varphi_\infty)=0$$

$\boxed{\text{Chameleon Effect!}}$

✦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

AWE makes Equivalence Principle scale-dependent!

- Attracting values of $\tilde{G}_m(\varphi)$



GR:
$\rho_m/\rho_{awe} \to \infty$
AWE is
sub-dominant

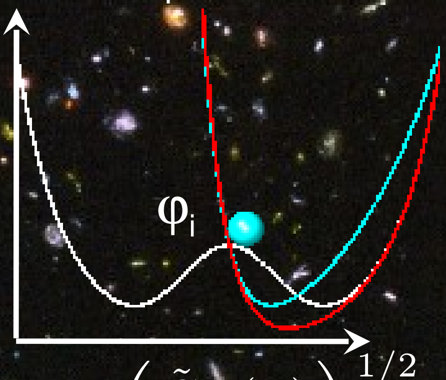
GR: $R_i = R_\infty$
AWE is normally
weighting
WEP!

$$\begin{cases} \alpha_m(\varphi) = k_m \varphi \\ \alpha_{awe}(\varphi) = -k_m R_\infty \varphi \end{cases}$$

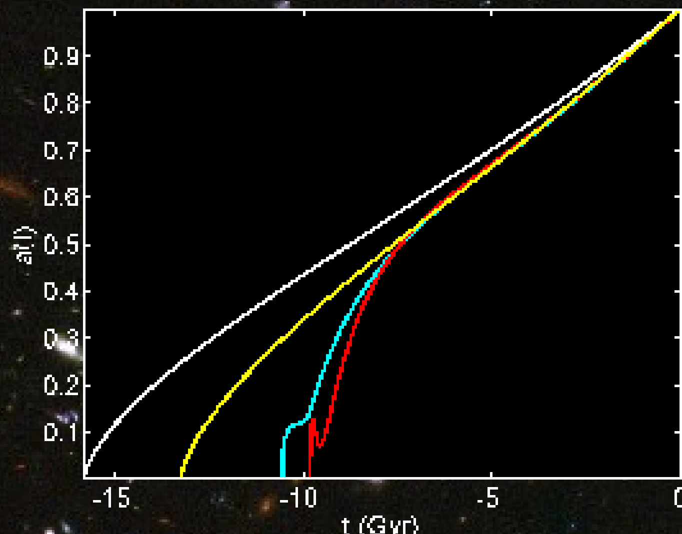
- WEP and consequently SEP violations depends on AWE concentration
- AWE and matter collapse differently
  - → EP violation is scale-dependent!
  - → AWE is dark⇨ matter is dominant on small scales but not on cosmological ones
  - ⇨ Explanation for the local validity of GR (WEP⇨ SEP)
  - ⇨ SNe Ia: Cosmic acceleration and not local variation of G_N

AWE Dark Matter and cosmic acceleration

- Large-scale cosmological dynamics
  - → Free parameters: R_i and coupling strengths k_m, k_{awe}
  - → φ starts frozen at CMB near GR values



$$\tilde{a} = \left(\frac{\tilde{G}_m(\varphi)}{G_*}\right)^{1/2} a_*$$



Best Fit Models from SNLS data*

AWE DM : (3DOF)

— χ^2/dof= 1.04

(Ω_{awe}=0.26, Ω_m=0.04)

— χ^2/dof= 1.05

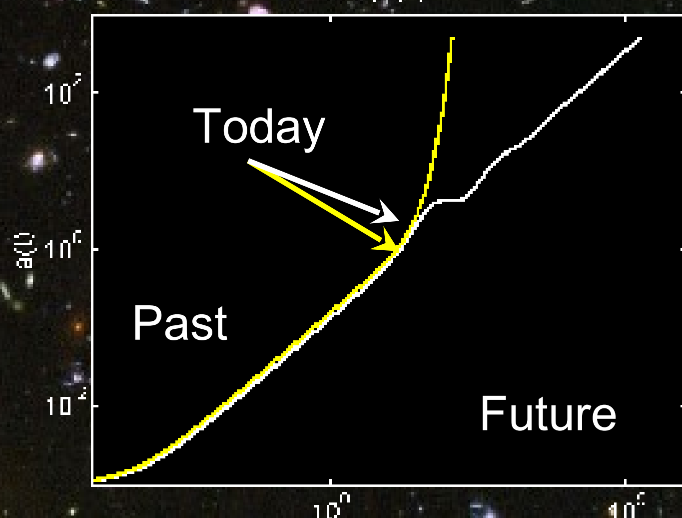
— χ^2/dof= 1.04

ΛCDM (Ω_Λ=0.7 ; 1DOF)

— χ^2/dof= 1.03

*P. Astier et al., A&A 447 (2006)

Fate of the Universe

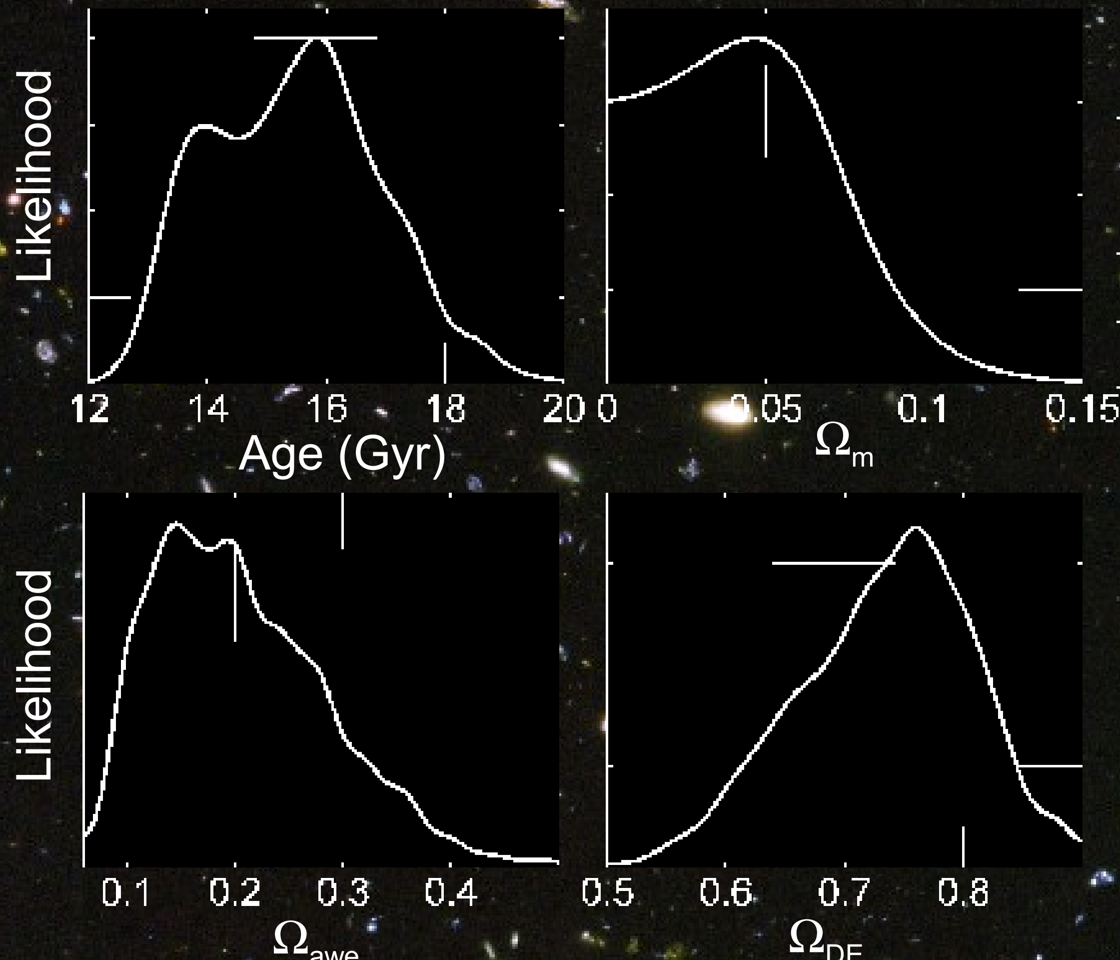


AWE DM :
→ matter-dominated Einstein-de Sitter Universe when GR is retrieved

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

Could AWE be Cold Dark Matter?

★ Likelihood analysis of SNe Ia Hubble diagram* (preliminary results)



AWE Predictions

→ t_0~16Gyr (>13Gyr at 95%C.L.)

→ Ω_m~0.05 (<0.15 at 95%C.L.)

→ Ω_{awe}~ 0.2

→ Ω_{DE}~ 0.75

AWE ⇨ CDM

Matter ⇨baryons

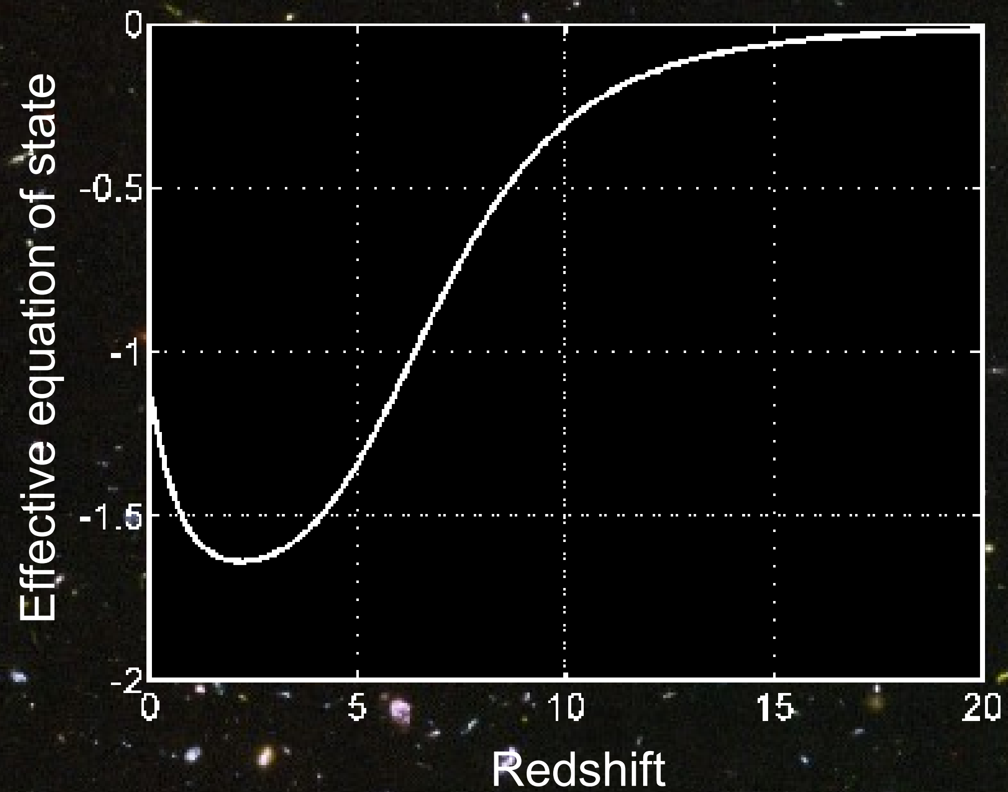
$\tilde{G}_m(\varphi)$ ⇨ DE

★ Independent predictions similar to that of CMB !

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

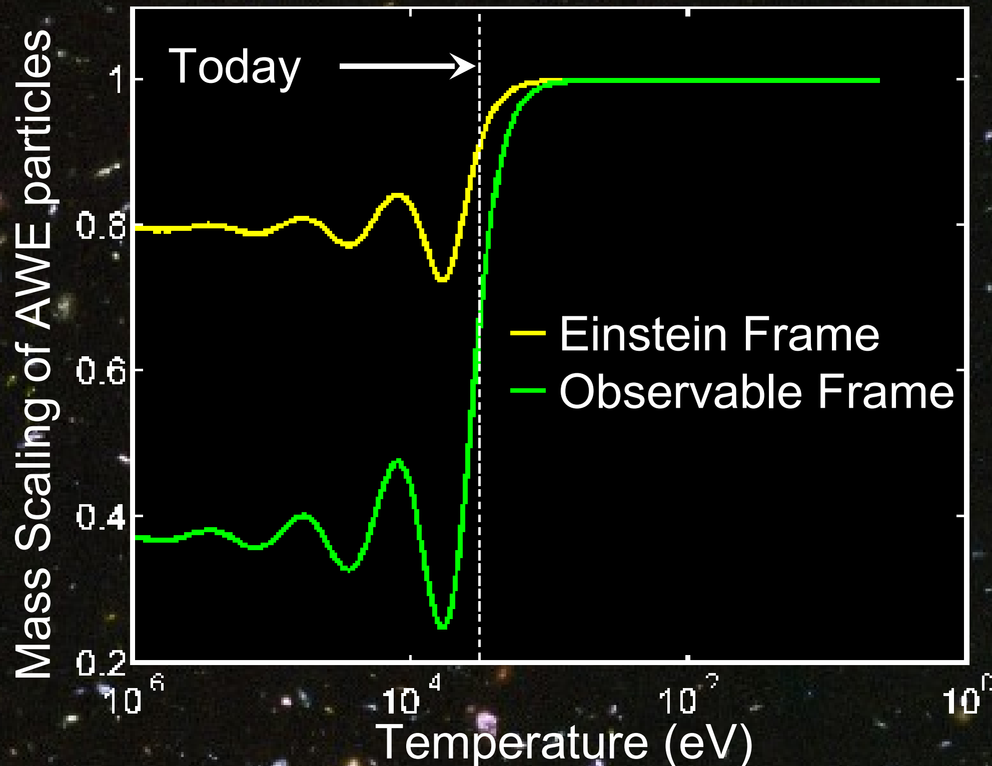
✶Data from P. Astier et al., A&A 447 (2006)

AWE DM as a pressureless « phantom » DE



- Negative pressures are obtained in the Observable Frame due to WEP violation
- AWE DM provides stronger cosmic expansion than ΛCDM and increases the age of the Universe by a few billion years

Mach-Dirac Principle and High-Energy Physics



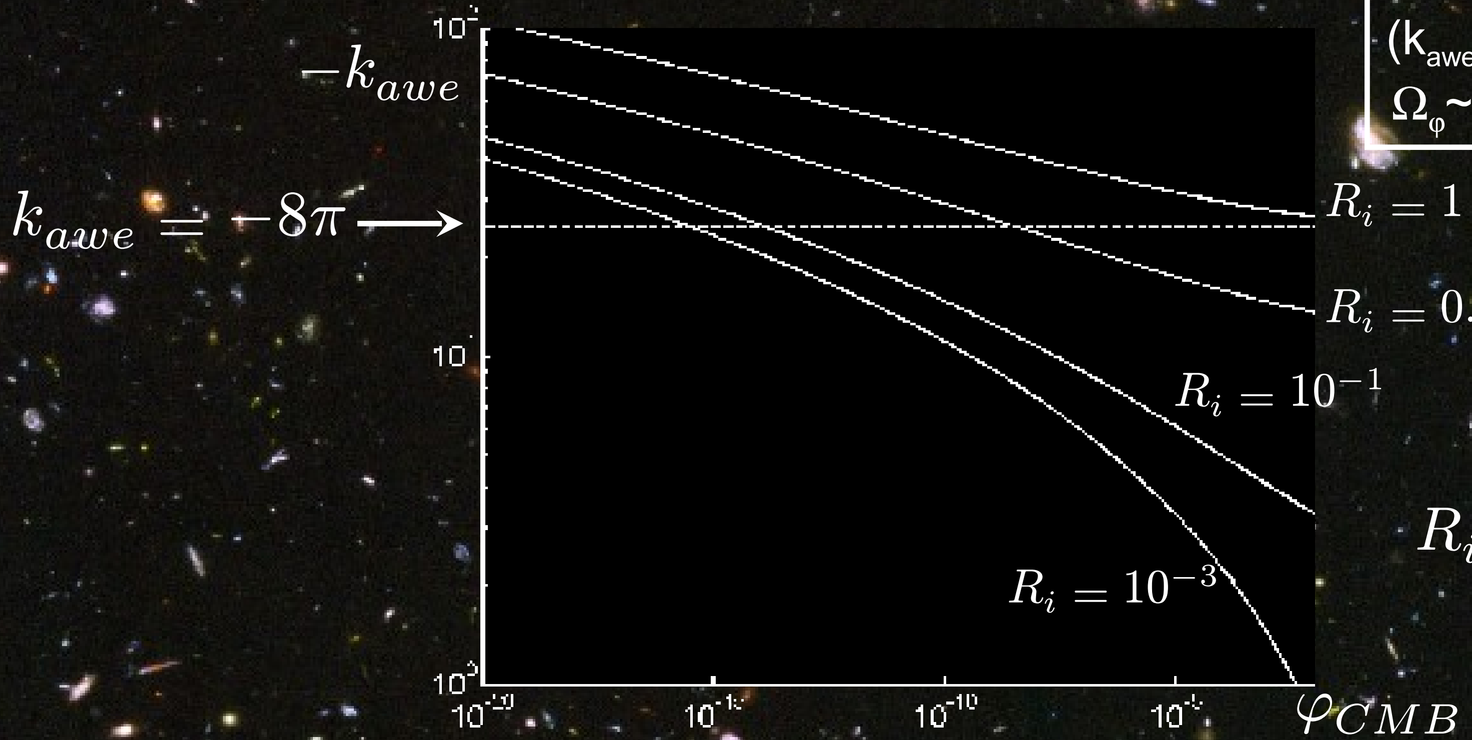
$$m^*_{awe} = A_{awe}(\varphi)$$

$$\frac{\tilde{m}_{awe}}{m^*_{awe}} = \left(\frac{\tilde{G}_m}{G_*}\right)^{-1/2}$$

- A mass scaling of ~30% accounts for cosmic acceleration
- Which candidate for AWE particles from HEP?
  - → Mass variation around T~10^{-3} eV?
  - → Mass varying neutrinos?
  - → Induced variation of G_m?
- Numerous impacts on large-scale structure formation!

✦A. Ringwald & L. Schrempp, JCAP 0610 (2006)
✦A. W. Brookfield et al., PRD 73, 083515 (2006)
✦R. Fardon et al., JCAP, 0410 (2004)

AWE DM and cosmic coincidence



(k_{awe}, φ_{CMB}) for which $\Omega_\varphi \sim \Omega_{awe} + \Omega_m$ at $z_c = 1$

$$R_i = \frac{\rho_m}{\rho_{awe}}\Big|_{CMB}$$

- Coupling constants k_m, k_{awe} of order unity $(|k_{awe}|, k_m) \approx \kappa G_*$
  - → ensure late cosmic coincidence
  - → Coincidence arise for a wide range of initial conditions at CMB
  - → Duration of transient cosmic acceleration compatible with data
- Improvement of the coincidence/fine-tuning problem of ΛCDM by natural assumptions on couplings

The AWEsome properties of Dark Matter

- **Nature of DE? ⇨ Anomalous gravity of DM ($m_{DM}(\varphi)$)**
  - → Cosmic acceleration from a Mach-Dirac Principle
  - → Adequacy to SNe Ia data with different parametrizations
  - → Independent determination of Ω_{baryon} and Ω_{DM} from supernovae alone!
  - → Explanation to why concordance cosmology appears correct
  - → Scale-dependent violation of Equivalence Principle

- **No need for negative pressures**
  - → Ghost equation of state ($p/\rho<-1$) from a frame effect
  - → Larger age of the Universe than in quintessence, ΛCDM

- **Coincidence Problem**
  - → WEP violation yields a competition between different non-minimal couplings
  - → Couplings to scalar mode φ of the same amplitude of those to the tensorial $g_{\mu\nu}$
  - → Variation of DM mass around $T\sim10^{-3}$ eV

- **Fate of the Universe**
  - → Transient cosmic acceleration
  - → Einstein-de Sitter asymptotic state

The AWE Hypothesis

Reducing Dark Energy to
a new property of Dark Matter:

The Anomalous Gravity

Thank you for your attention!

The AWEsome perspectives for Large-Scale Structures

Weak-lensing

→ Photons do not feel φ directly
→ Light deflection:

$$\Delta\theta = \frac{4\tilde{G}_m \tilde{m}_{awe}}{(1+\alpha_m^2(\varphi))bc^2}$$

DM/baryons virialisation

→ test of the universality of free fall on cosmological scales!
→Structure formation

$$\tilde{m}_{awe}(\varphi)$$

$$\tilde{G}_m(\varphi)$$

DM free-fall

$$\ddot{x}^\mu + \Gamma^\mu_{\nu\sigma}\dot{x}^\nu\dot{x}^\sigma + \frac{\partial \log(\tilde{m}_{awe})}{\partial x^\mu} = 0$$

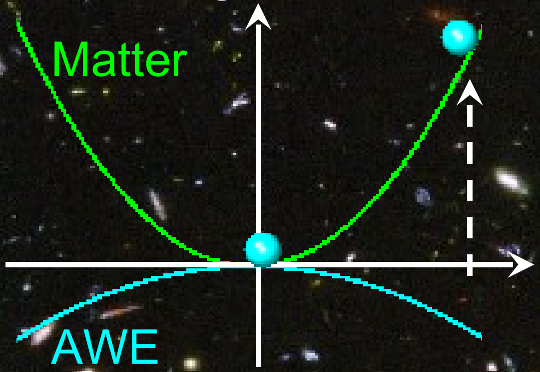
Scale-dependent EP

→ DM/baryons clusterization ⇨ $\varphi(x^\mu)$
→ Modified Newton Dynamics in ρ_m/ρ_{awe}

$$\Box\varphi + \frac{\kappa_*}{2}\alpha_m(\varphi)T^*_m + \frac{\kappa_*}{2}\alpha_{awe}(\varphi)T^*_{awe} = 0$$

Some other AWEsome perspectives

- Physics in the radiative era and beyond:
  - → Influence of WEP violation on convergence mechanism
  - → Initial conditions at the beginning of matter-dominated era
  - → Post-recombination effect on CMB
- Breathing Inflation



- If AWE particles are heavier than matter ones:
  - → AWE becomes non-relativistic : early kicks downwards and breath of acceleration
  - → Matter becomes non-relativistic: convergence mechanism
- Convergence before BBN? Tuning? Reheating? Perturbations?
- Large-scales structures:
  - → Test of the universality of free fall on cosmic scales
- Impacts on small scales physics:
  - → Amount of AWE DM on small-scales?
  - → Fifth force constraints, universality of free fall, deviation from GR
  - → Effective mass of φ

Born-Infeld (BI) Gauge Dynamics

★ Motivations to go beyond Yang-Mills dynamics:

→ Renormalisation of point-like singularities

→ Brane-induced gauge interactions and open string theory

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

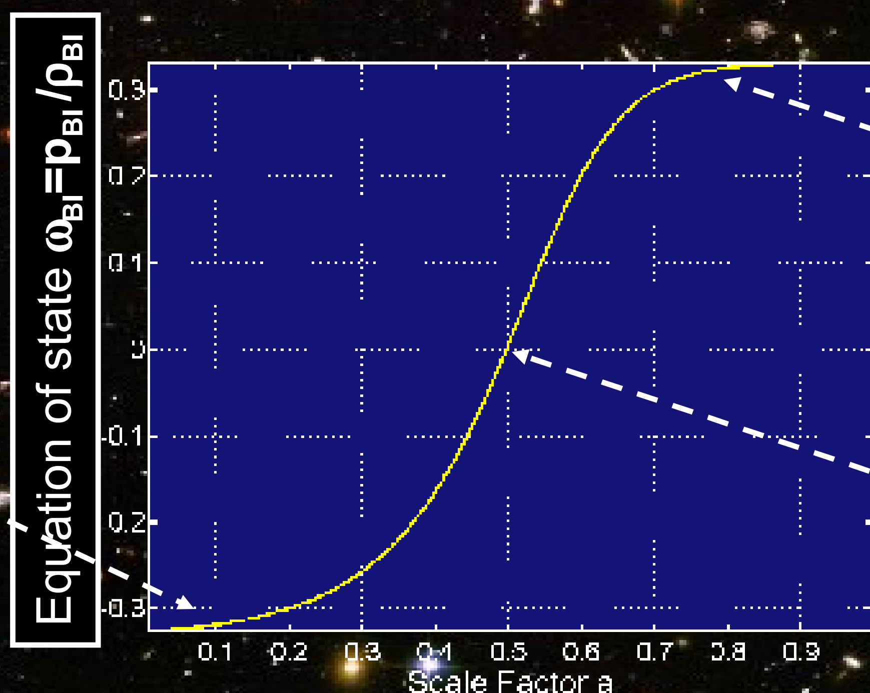
★ BI gauge interaction in cosmology (V.V. Dyadichev et al., Phys. Rev. D 65 084007)

$\rho_{BI} >> \varepsilon_c^4$

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

$\rho_{BI} \propto a^{-2}$

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



$\rho_{BI} << \varepsilon_c^4$

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

$\rho_{BI} \propto a^{-4}$

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

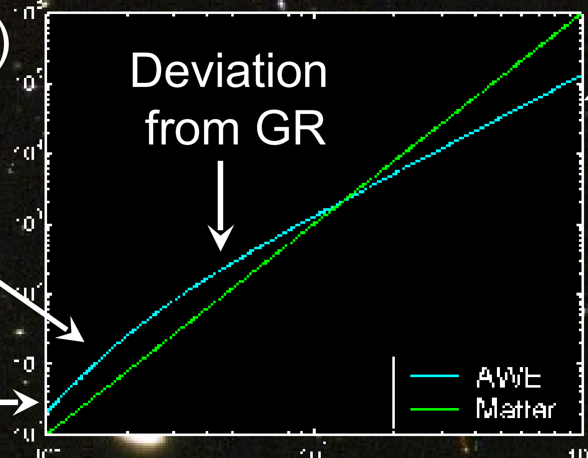
$\rho_{BI} \approx \varepsilon_c^4$

Phase transition

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

AWE Born-Infeld Interaction

- Cosmology with Born-Infeld gauge interaction[1]

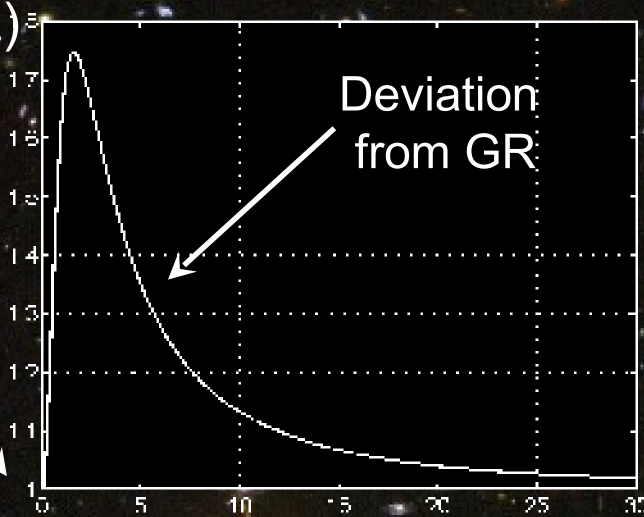


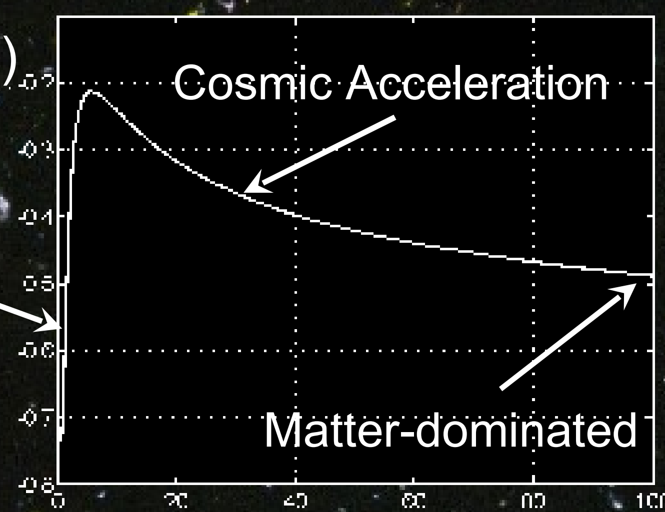
1) V.V. Dyadichev et al., PRD65 084007 (2002)
2) E. Gaztanaga et al., PRD 65 023506 (2001); A. Riazuelo, J.-P. Uzan, PRD 66 023525 (2002)

- Variation of G and Sne Ia Hubble diagram[2]:

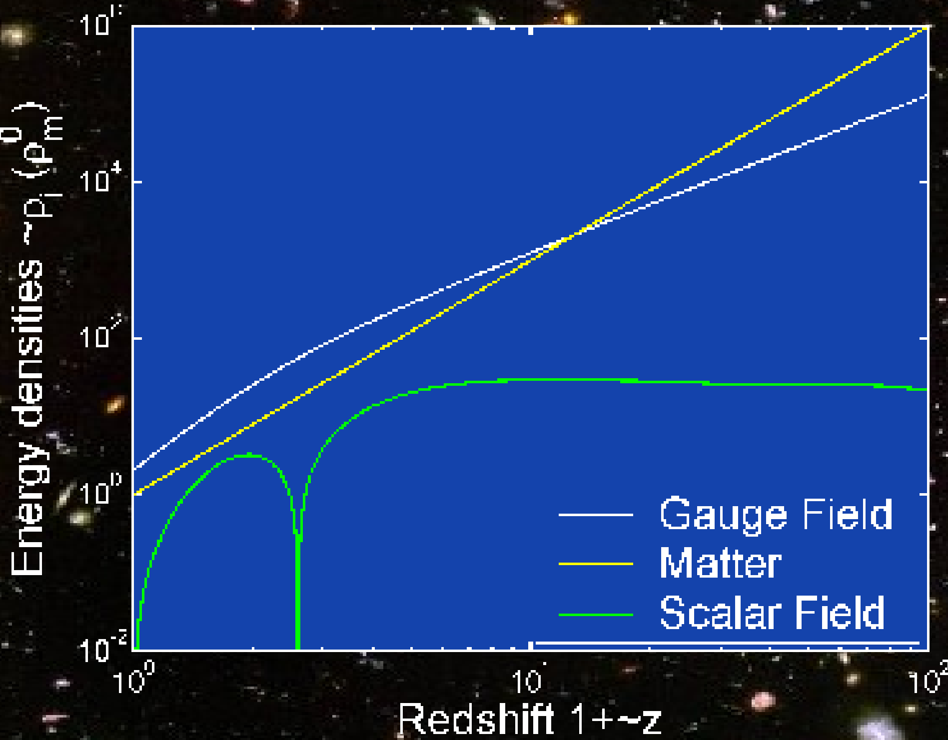
$$m - M = 25 + 5\log\left(d_L[Mpc]\right) + \frac{15}{4}\log\left(\frac{G_N(z)}{G_N(z=0)}\right)$$

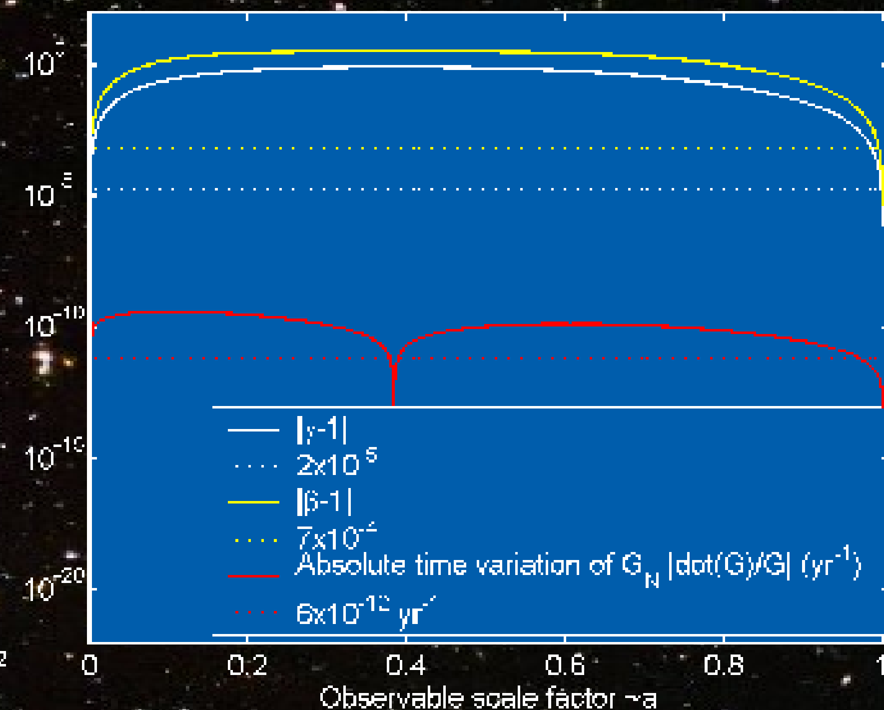
$$G_N = G_* A_m^2 (1 + \alpha_m^2)$$





AWE Born-Infeld Interaction





AWE (dark) Energy-dominated Universe today (CMB, LSS)

Constraints on General Relativity today OK!

A. Füzfa, J.-M. Alimi,
Phys. Rev. Lett. 97, 061301 (2006)

AWE Born-Infeld Interaction

★ Advantages of the Born-Infeld equation of state:

→ Late process: $p_{BI}=-\rho_{BI}/3<p_{matter}\sim 0$

→ Transient mechanism : phase transition to positive pressures $p_{BI}=\rho_{BI}/3$

→ Does not violate the strong energy condition $p<-\rho/3$!

→ Late decoupling to the scalar field ($p_{BI}=\rho_{BI}/3$) : $\Omega_{BI}>\Omega_m$ and PPN OK!

⇨ Natural features for a realistic AWE

⇨ Alternative to the condition $p<-\rho/3$ for DE (test of the necessity of SEC)

★ Does the AWE mechanism work also for simpler equation of state? For different set of coupling functions?

★ Do we need the requirement of global convergence? (scale-dependent SEP)

★ Another natural candidate for AWE?

$\boxed{\text{AWE Dark Matter}}$