Dark Energy and Standard Model States

Dark Energy – Dark Matter Interaction

Dark Energy Interaction with Gauge Fields and Neutrinos

Dark Energy and the Higgs Portal

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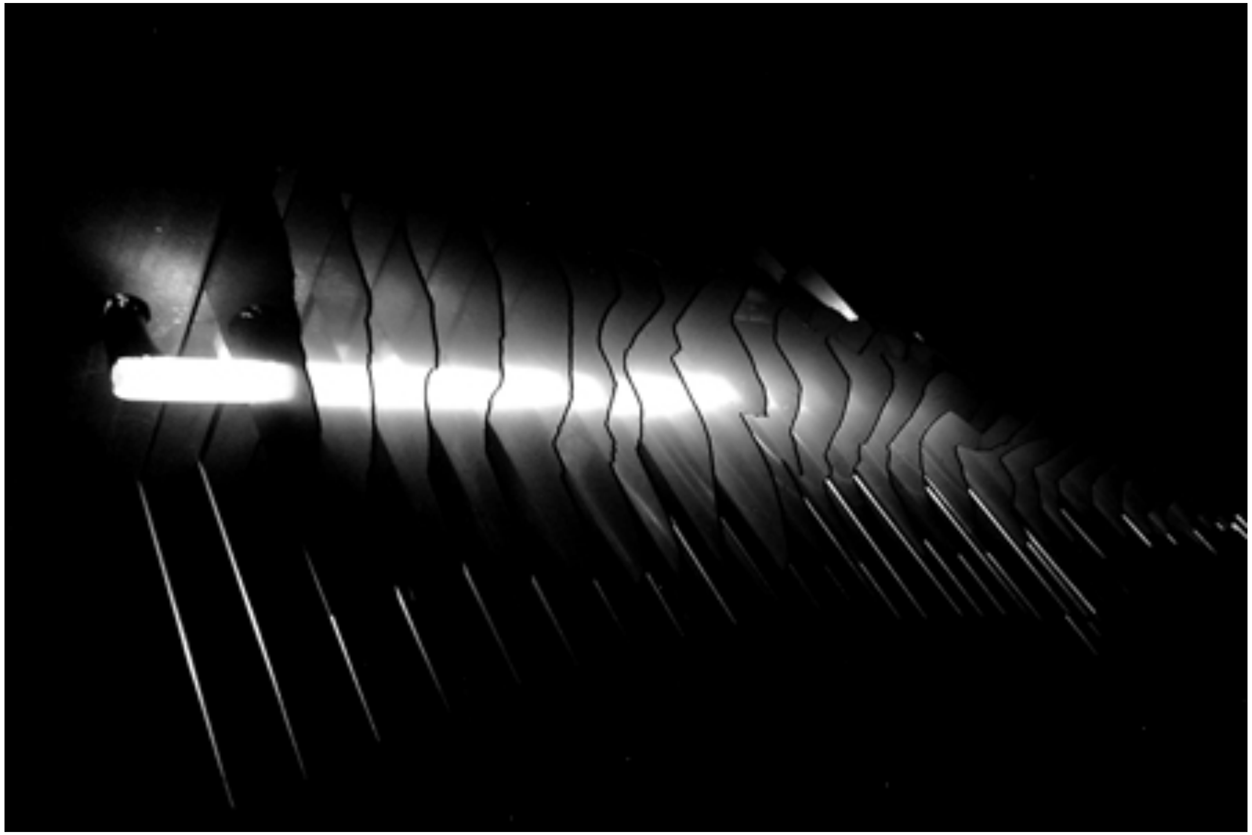
From Quantum to Cosmos III:
Fundamental Physics Research in Space
6-10 July 2008, Warrenton, Virginia, USA

√Art + Cinema = Dark Energy



Ken McMullen

Centro Cultural de Cascais

27 June – 31 August

Cosmological Tests of General Relativity

- **Outstanding challenges (GR + Quantum Field Theory)**
  - Singularity Problem
  - Cosmological Constant Problem
  - Underlying particle physics theory for Inflation

- **Theory provides in the context of the homogeneous and isotropic Big Bang model to successfully describe**
  - Nucleosynthesis ($N_\nu < 4$, $\Omega_B h^2 = 0.023 \pm 0.001$)
  - Cosmic Microwave Background Radiation
  - Large Scale Structure
  - Gravitational lensing
  - …

- **Missing links:**
  - Dark Matter
  - Dark Energy

Dark Energy

- **Evidence:**

  Dimming of type Ia Supernovae with *z > 0.35*

  Accelerated expansion (negative deceleration parameter): $q_0 \equiv -\frac{\ddot{a}a}{\dot{a}^2} \leq -0.47$

  [Perlmutter et al. 1998; Riess et al. 1998, …]

- **Homogeneous and isotropic expanding geometry**

  Driven by the vacuum energy density Ω_Λ and matter density Ω_M

  Equation of state: $p = \omega\rho \qquad \omega \leq 1$

- **Friedmann and Raychaudhuri equations imply:** $q_0 = \frac{1}{2}(3\omega + 1)\Omega_m - \Omega_\Lambda$

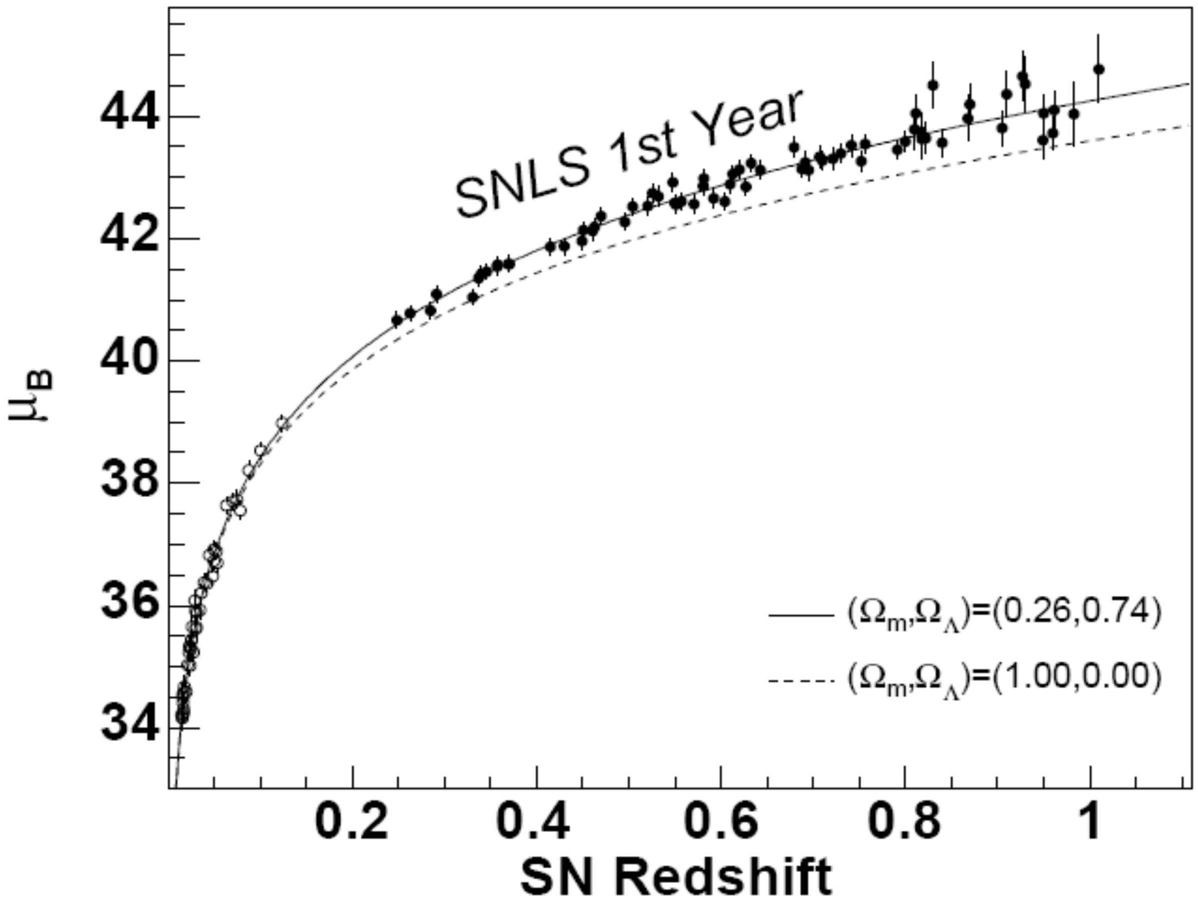
  $q_0 < 0$ suggests an invisible smooth energy distribution

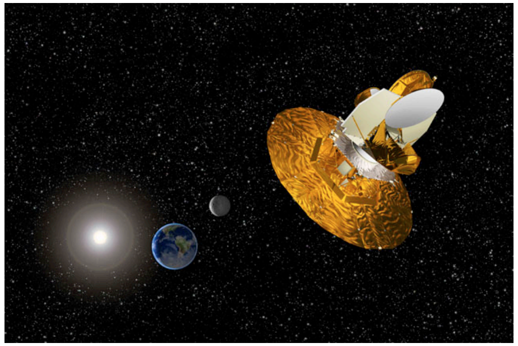
- **Candidates:**

  Cosmological constant, quintessence, more complex equations of state, etc.

Supernova Legacy Survey (SNLS)

[Astier et al., astro-ph/0510447]





WMAP 5 Year Results

E. Komatsu et al., 0803.0547 [astro-ph]

SUMMARY OF THE COSMOLOGICAL PARAMETERS OF ΛCDM MODEL AND THE CORRESPONDING 68% INTERVALS

Class	Parameter	*WMAP* 5-year ML[a]	*WMAP*+BAO+SN ML	*WMAP* 5-year Mean[b]	*WMAP*+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.268	2.263	2.273 ± 0.062	2.265 ± 0.059
	$\Omega_c h^2$	0.1081	0.1136	0.1099 ± 0.0062	0.1143 ± 0.0034
	Ω_Λ	0.751	0.724	0.742 ± 0.030	0.721 ± 0.015
	n_s	0.961	0.961	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$
	τ	0.089	0.080	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_\mathcal{R}(k_0{}^e)$	2.41×10^{-9}	2.42×10^{-9}	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.457^{+0.092}_{-0.093}) \times 10^{-9}$
Derived	σ_8	0.787	0.811	0.796 ± 0.036	0.817 ± 0.026
	H_0	72.4 km/s/Mpc	70.3 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.1 ± 1.3 km/s/Mpc
	Ω_b	0.0432	0.0458	0.0441 ± 0.0030	0.0462 ± 0.0015
	Ω_c	0.206	0.230	0.214 ± 0.027	0.233 ± 0.013
	$\Omega_m h^2$	0.1308	0.1363	0.1326 ± 0.0063	0.1369 ± 0.0037
	$z_{\rm reion}{}^f$	11.2	10.5	11.0 ± 1.4	10.8 ± 1.4
	$t_0{}^g$	13.69 Gyr	13.72 Gyr	13.69 ± 0.13 Gyr	13.73 ± 0.12 Gyr

Summary of the 95% confidence limits on deviations from the simple (flat, Gaussian, adiabatic, power-law) ΛCDM model

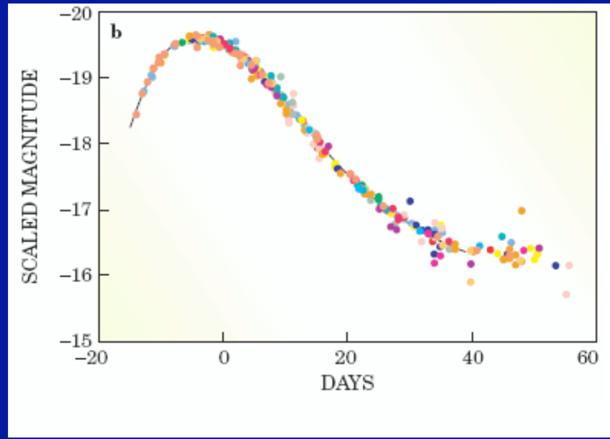
Section	Name	Type	*WMAP* 5-year	*WMAP*+BAO+SN
§ 3.2	Gravitational Wave[a]	No Running Ind.	$r < 0.43$[b]	$r < 0.20$
§ 3.1.3	Running Index	No Grav. Wave	$-0.090 < dn_s/d\ln k < 0.019$[c]	$-0.0728 < dn_s/d\ln k < 0.0087$
§ 3.4	Curvature[d]		$-0.063 < \Omega_k < 0.017$[e]	$-0.0175 < \Omega_k < 0.0085$[f]
	Curvature Radius[g]	Positive Curv.	$R_{\rm curv} > 12\ h^{-1}{\rm Gpc}$	$R_{\rm curv} > 23\ h^{-1}{\rm Gpc}$
		Negative Curv.	$R_{\rm curv} > 23\ h^{-1}{\rm Gpc}$	$R_{\rm curv} > 33\ h^{-1}{\rm Gpc}$
§ 3.5	Gaussianity	Local	$-9 < f_{NL}^{\rm local} < 111$[h]	N/A
		Equilateral	$-151 < f_{NL}^{\rm equil} < 253$[i]	N/A
§ 3.6	Adiabaticity	Axion	$\alpha_0 < 0.16$[j]	$\alpha_0 < 0.067$[k]
		Curvaton	$\alpha_{-1} < 0.011$[l]	$\alpha_{-1} < 0.0037$[m]
§ 4	Parity Violation	Chern-Simons[n]	$-5.9^\circ < \Delta\alpha < 2.4^\circ$	N/A
§ 5	Dark Energy	Constant w[o]	$-1.37 < 1+w < 0.32$[p]	$-0.11 < 1+w < 0.14$
		Evolving $w(z)$[q]	N/A	$-0.38 < 1+w_0 < 0.14$[r]
§ 6.1	Neutrino Mass[s]		$\sum m_\nu < 1.3$ eV[t]	$\sum m_\nu < 0.61$ eV[u]
§ 6.2	Neutrino Species		$N_{\rm eff} > 2.3$[v]	$N_{\rm eff} = 4.4 \pm 1.5$[w] (68%)

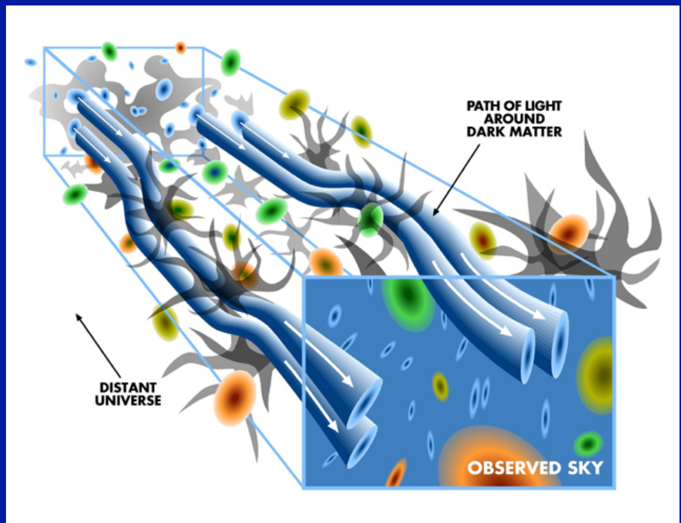
[a] In the form of the tensor-to-scalar ratio, r, at $k = 0.002\ {\rm Mpc}^{-1}$
[b] Dunkley et al. (2008)
[c] Dunkley et al. (2008)
[d] (Constant) dark energy equation of state allowed to vary ($w \neq -1$)
[e] With the HST prior, $H_0 = 72 \pm 8$ km/s/Mpc. For $w = -1$, $-0.052 < \Omega_k < 0.013$ (95% CL)
[f] For $w = -1$, $-0.0181 < \Omega_k < 0.0071$ (95% CL)
[g] $R_{\rm curv} = (c/H_0)/\sqrt{|\Omega_k|} = 3/\sqrt{|\Omega_k|}\ h^{-1}{\rm Gpc}$
[h] Cleaned V+W map with $l_{\rm max} = 500$ and the *KQ75* mask, after the point source correction
[i] Cleaned V+W map with $l_{\rm max} = 700$ and the *KQ75* mask, after the point source correction
[j] Dunkley et al. (2008)
[k] In terms of the adiabaticity deviation parameter, $\delta_{adi}^{(c,\gamma)} = \sqrt{\alpha}/3$ (Eq. [39]), the axion-like dark matter and photons are found to obey the adiabatic relation (Eq. [36]) to 8.6%.
[l] Dunkley et al. (2008)
[m] In terms of the adiabaticity deviation parameter, $\delta_{adi}^{(c,\gamma)} = \sqrt{\alpha}/3$ (Eq. [39]), the curvaton-like dark matter and photons are found to obey the adiabatic relation (Eq. [36]) to 2.0%.
[n] For an interaction of the form given by $(\phi/M)F_{\alpha\beta}\tilde{F}^{\alpha\beta}$, the polarization rotation angle is $\Delta\alpha = M^{-1}\int \frac{dt}{a}\dot{\phi}$
[o] For spatially curved universes ($\Omega_k \neq 0$)
[p] With the HST prior, $H_0 = 72 \pm 8$ km/s/Mpc
[q] For a flat universe ($\Omega_k = 0$)
[r] $w_0 \equiv w(z = 0)$
[s] $\sum m_\nu = 94(\Omega_\nu h^2)$ eV
[t] Dunkley et al. (2008)
[u] For $w = -1$. For $w \neq -1$, $\sum m_\nu < 0.66$ eV (95% CL)
[v] Dunkley et al. (2008)
[w] With the HST prior, $H_0 = 72 \pm 8$ km/s/Mpc. The 95% limit is $1.9 < N_{\rm eff} < 7.8$

Large Dark Energy Surveys

SNAP, DUNE…

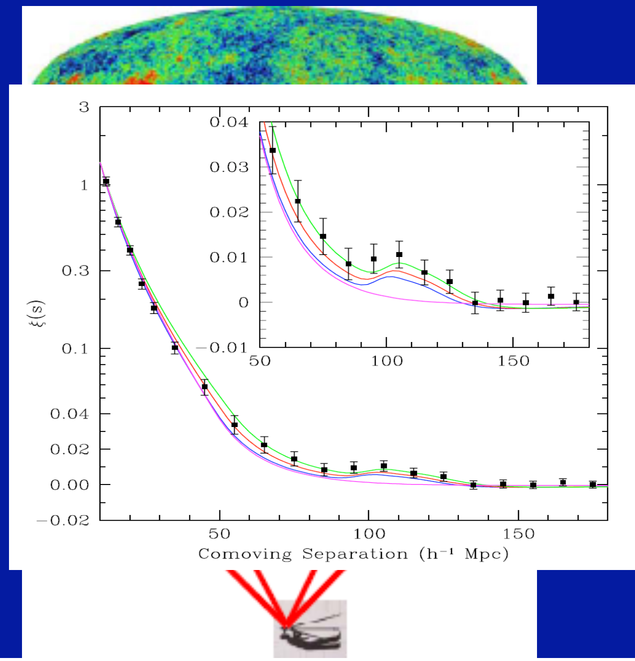
Supernovae **Standard Candles**
Luminosity Distance



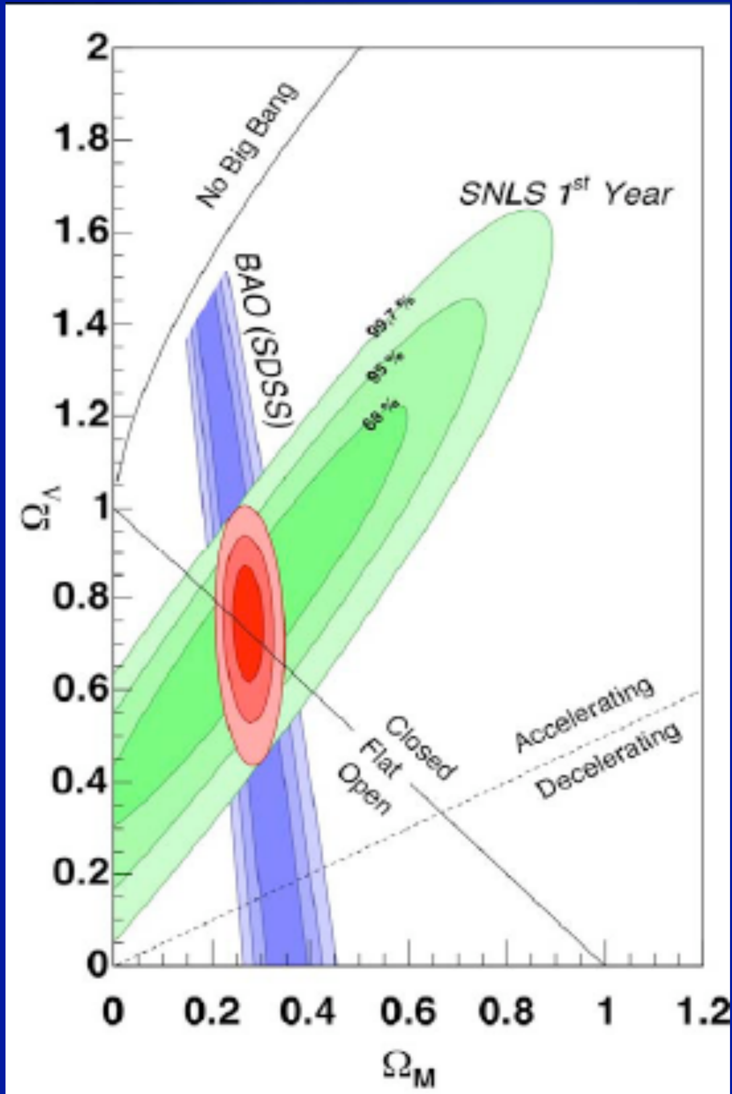


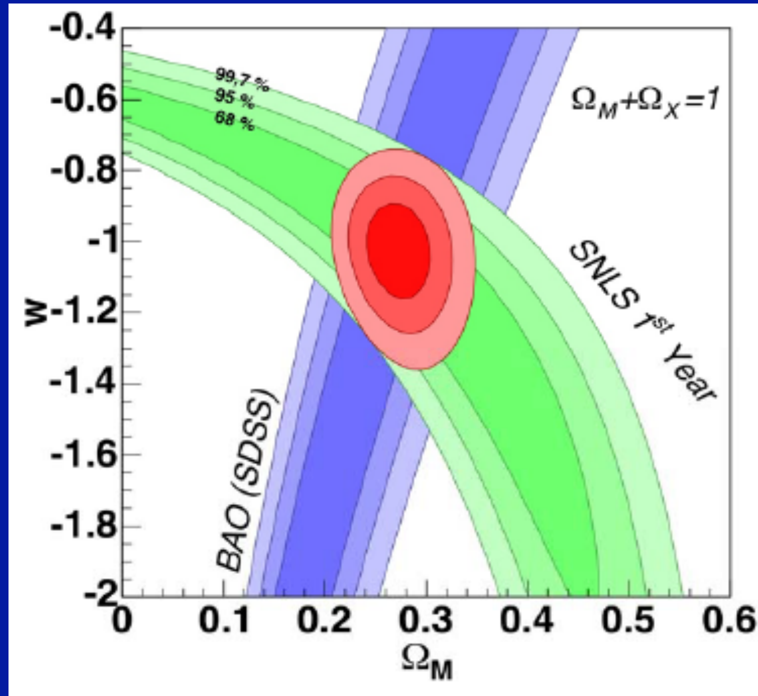
Cosmic Shear **Evolution of DM perts.**

Baryon Acoustic Oscillations
Standard ruler
Angular diameter distance



SNLS - SDSS





[Riess et al. 2004]

$$\omega = -1.02^{+0.13}_{-0.19}$$

[Astier et al. 2005]

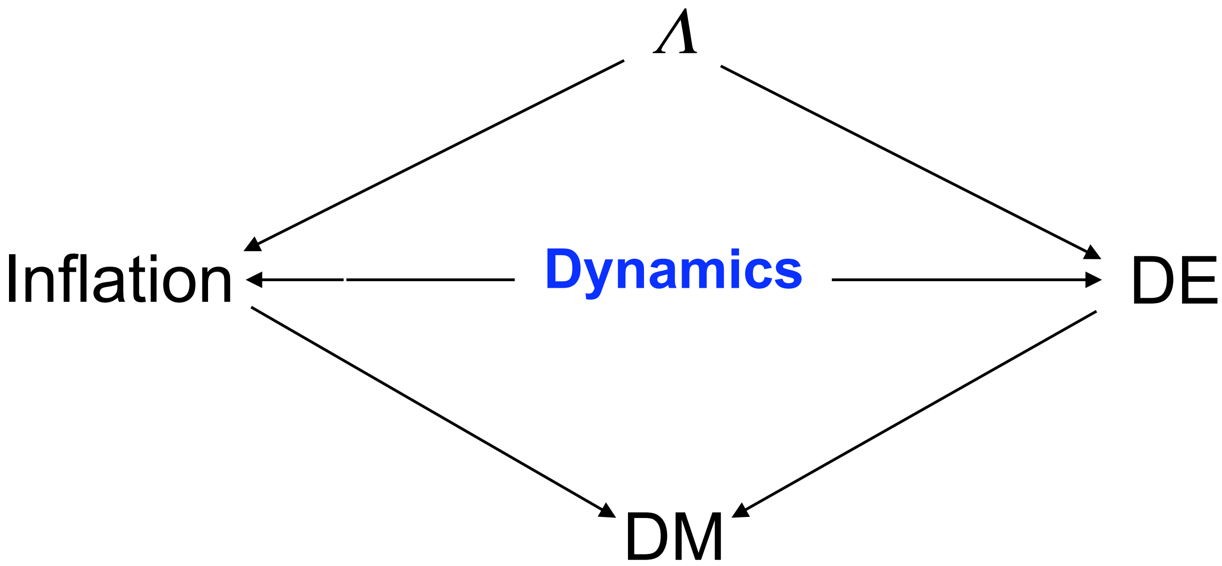
$$\omega = -1.023 \pm 0.090(stat) \pm 0.054(syst)$$

$$\Omega_m = 0.271 \pm 0.021(stat) \pm 0.007(syst)$$

Dark Energy -- Dark Matter

"Quintessential Inflation"

[Peebles, Vilenkin 99; Dimopoulos, Valle 02; Rosenfeld, Frieman 05, O.B., Duvvuri 06, …]



Dark Energy – Dark Matter interaction

[Amendola 2000, ..., O.B., Gil Pedro, Le Delliou 2007]

Dark Energy – Dark Matter Unification

[Kamenschik, Moschella, Pasquier 2001]

[Bilic, Tupper, Viollier 2002; Bento, O.B., Sen 2002]

[O.B., Rosenfeld 2007]

Dark Matter

- **Evidence:**

  Flatness of the rotation curve of galaxies
  Large scale structure
  Gravitational lensing
  N-body simulations and comparison with observations
  Merging galaxy cluster 1E 0657-56
  Massive Clusters Collision Cl 0024+17
  Dark core of the cluster A520

- **Cold Dark Matter (CDM) Model**

  Weakly interacting non-relativistic massive particle at decoupling

- **Candidates:**

  Neutralinos (SUSY WIMPS - LHC), axions, scalar fields, self-interacting scalar particles (adamastores), *etc.*

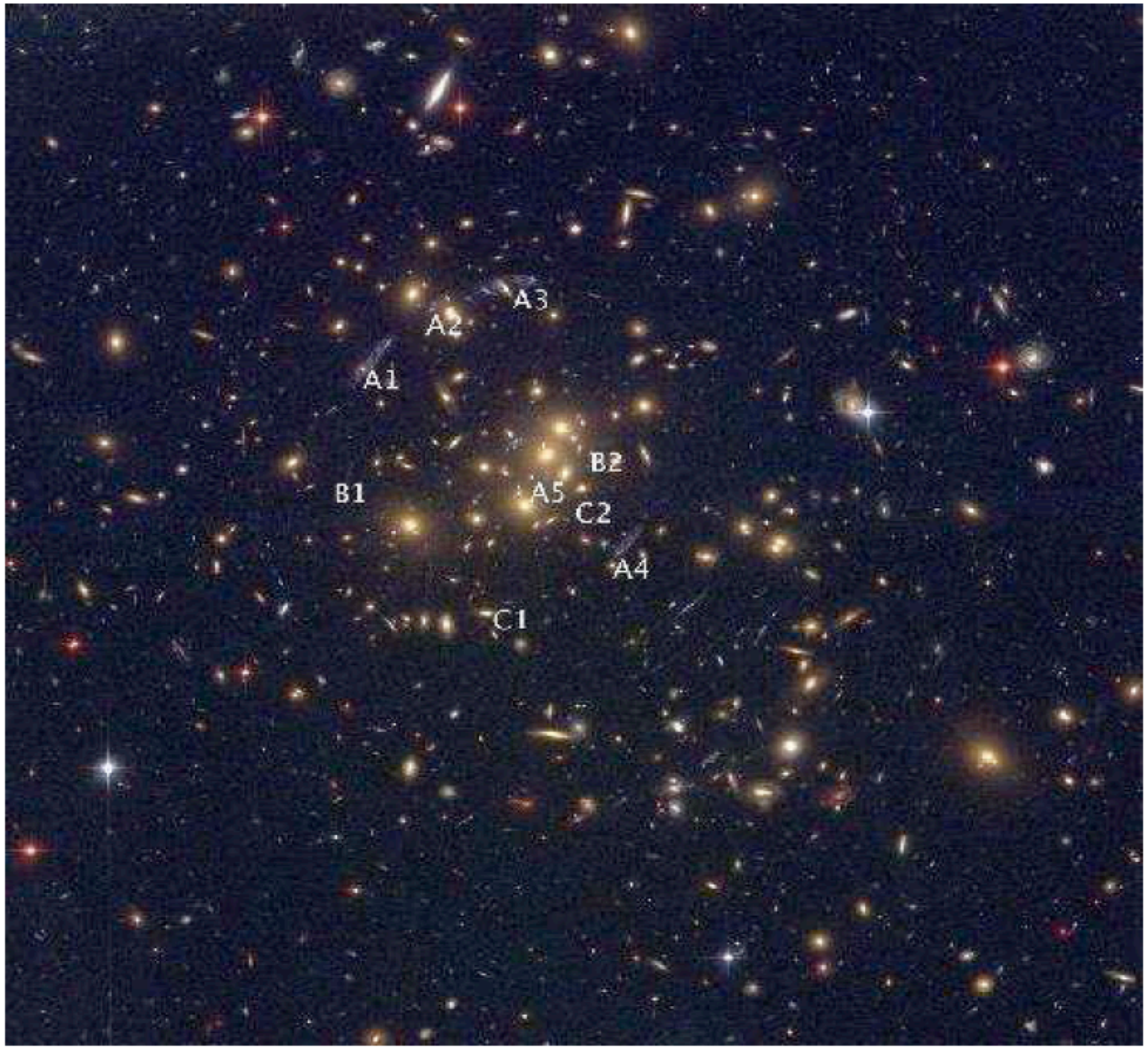
Merging Galaxy Cluster 1E 0657-56

[Clowe et al., astro-ph/0608407]

"Bullet" Cluster

Massive Clusters Collision Cl 0024+17

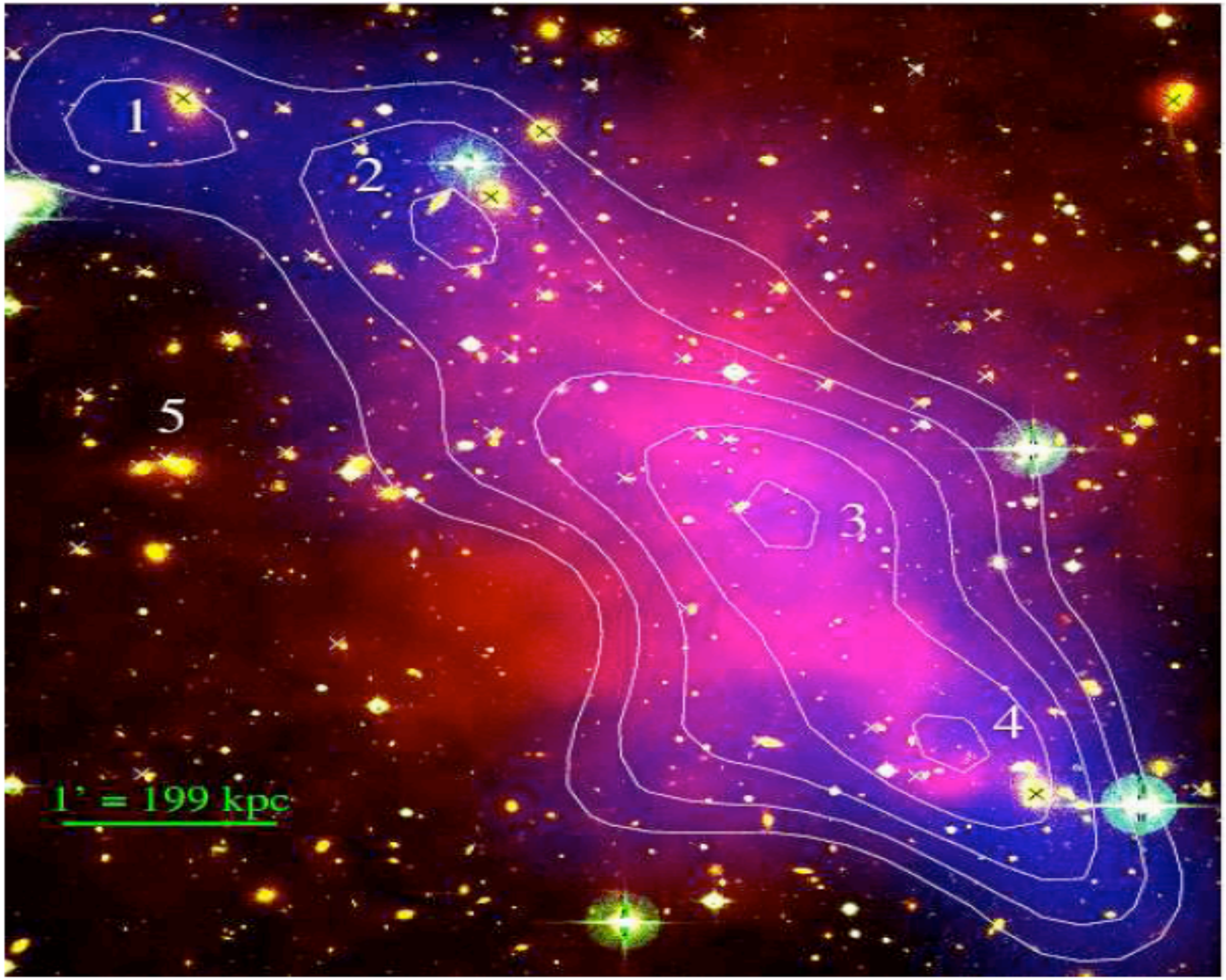
[Jee et al., astro-ph/0705.2171]



Ring-like dark matter structure

Dark core of the Abell 520

[Mahdavi et al., 0706.3048(astro-ph)]



Collisional dark matter ?

Generalized Chaplygin gas model

- **Unified model for Dark Energy and Dark Matter**

Generalized d-brane

$$\mathcal{L} = -A^{\frac{1}{1+\alpha}} \left(1 - (g^{\mu\nu}\Theta_{,\mu}\Theta_{,\nu})^{\frac{\alpha+1}{2\alpha}}\right)^{\frac{\alpha}{\alpha+1}}$$

$\alpha = 1$: d-brane

→

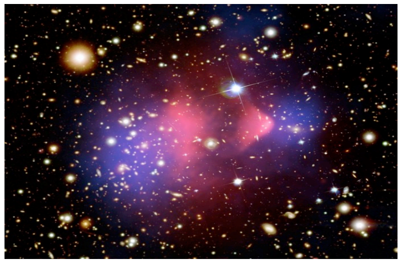
Generalized Chaplygin gas

$$p = -\frac{A}{\rho^{\alpha}}$$

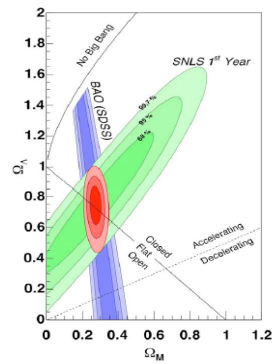
$\alpha = 1$: Chaplygin gas

↓

Dust	→	Stiff matter	→	De Sitter
$p \ll \rho$		$p = \alpha\rho$		$p = -\rho$
Dust		$\alpha = 1$: stiff matter		De Sitter



[Bento, O.B., Sen 2002]



Generalized Chaplygin Gas Model

- CMBR [Bento, O. B., Sen 2003, 2004; Amendola et al. 2004, Barreiro, O.B., Torres 2008]
- SNe Ia [O. B., Sen, Sen, Silva 2004; Bento, O.B., Santos, Sen 2005]
- Gravitational Lensing [Silva, O. B. 2003]
- Structure Formation *

  [Sandvik, Tegmark, Zaldarriaga, Waga 2004; Bento, O. B., Sen 2004; Bilic, Tupper, Viollier 2005; …]
- Gamma-ray bursts [O. B., Silva 2006]
- Cosmic topology [Bento, O. B., Rebouças, Silva 2006]
- Inflation [O.B., Duvvuri 2006]
- Coupling with electromagnetism [Bento, O.B., Torres 2007]
- Coupling with neutrinos [Bernardini, O.B. 2008]

Background tests: $\alpha \leq 0.3, \quad 0.7 \leq A_s \leq 0.99 \qquad A_s \equiv \frac{A}{\rho_{Ch0}^{1+\alpha}}$

Structure formation and BAO: $\alpha \leq 0.2$

Dark Energy – Dark Matter Interaction (I)

[O.B., Gil Pedro, Le Delliou, Phys. Lett. B654 (2007); 07053118 (astro-ph)]

- **Evolution equations:**
  ($p_{DE} = \omega_{DE}\rho_{DE}$)

$$\dot\rho_{DM} + 3H\rho_{DM} = \zeta H \rho_{DM}$$

$$\dot\rho_{DE} + 3H\rho_{DE}(1+\omega_{DE}) = -\zeta H \rho_{DM}$$

- **For** $\dfrac{\rho_{DE}}{\rho_{DM}} = \dfrac{\Omega_{DE_0}}{\Omega_{DM_0}} a^{\eta}$ **:**

$$\zeta = -\frac{(\eta + 3\omega_{DE})\Omega_{DE_0}}{\Omega_{DE_0} + \Omega_{DM_0} a^{-\eta}}$$

- **From which follows:**

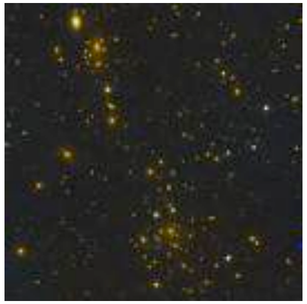
$$\begin{aligned} \rho_{DM} &= a^{-3}\rho_{DM_0} e^{\int_1^a \zeta \frac{da}{a}} \\ &= a^{-3}\rho_{DM_0}\left[\Omega_{DE_0} a^{\eta} + \Omega_{DM_0}\right]^{-\frac{(\eta+3\omega_{DE})}{\eta}} \end{aligned}$$

$$\begin{aligned} \rho_{DE} &= a^{\eta-3}\rho_{DE_0} e^{\int_1^a \zeta \frac{da}{a}} \\ &= a^{\eta-3}\rho_{DE_0}\left[\Omega_{DE_0} a^{\eta} + \Omega_{DM_0}\right]^{-\frac{(\eta+3\omega_{DE})}{\eta}} \end{aligned}$$

- **Bias parameter:**

$$b = \frac{\rho_B}{\rho_{DM}} = b_0 \left[\frac{\Omega_{DE_0} a^{\eta} + \Omega_{DM_0}}{\Omega_{DE_0} + \Omega_{DM_0}}\right]^{\frac{(\eta+3\omega_{DE})}{\eta}}$$

GCG: $\eta = 3(1+\alpha)$



Cosmic Virial Theorem and the Abell cluster **A586**

[O.B., Gil Pedro, Le Delliou, Phys. Lett. B654 (2007)]

- **Generalized Cosmic Virial Theorem (Layzer-Irvine eq.):**

$$\dot{\rho}_{DM} + H(2\rho_K + \rho_W) = -\frac{(\eta + 3\omega_{DE})H}{1 + \Omega_{DM_0}/\Omega_{DE_0} a^{-\eta}} \rho_W$$

where

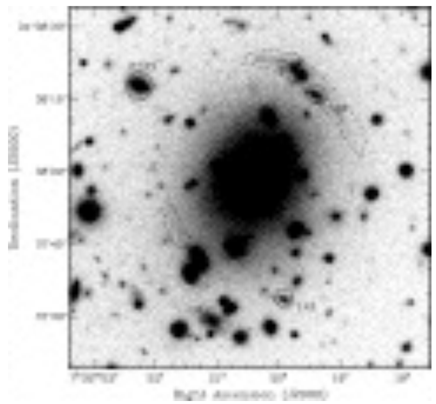
$$\rho_W \equiv M dW/dV = d(MW)/dV \propto a^{\zeta - 1}$$

$$W = -2\pi G a^2 \rho_{DM} \int dr \xi(r) r$$

($\xi(r)$ - **auto-correlation function)**

- **Abell cluster A586 – spherical and close to stationary equilibrium:**

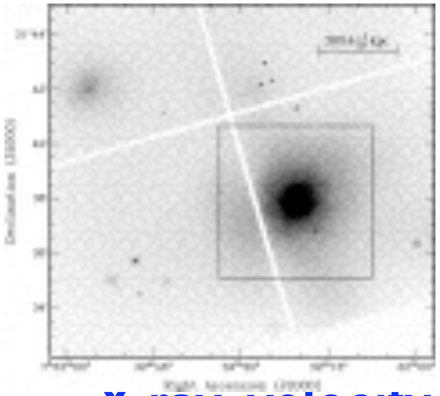
$$2\rho_K + \rho_W = \zeta \rho_W$$



- **Moreover:**

$$\rho_K = M\frac{d}{dV}K \simeq M\frac{K}{V} \simeq \frac{9}{8\pi}\frac{M_{Cluster}}{R^3_{Cluster}}\sigma_v^2$$

$$\rho_W = M\frac{d}{dV}W \simeq M\frac{W}{V} \simeq -\frac{3}{8\pi}\frac{G}{< R >}\frac{M^2_{Cluster}}{R^3_{Cluster}}$$



Estimates

[O.B., Gil Pedro, Le Delliou, Phys. Lett. B654 (2007)]

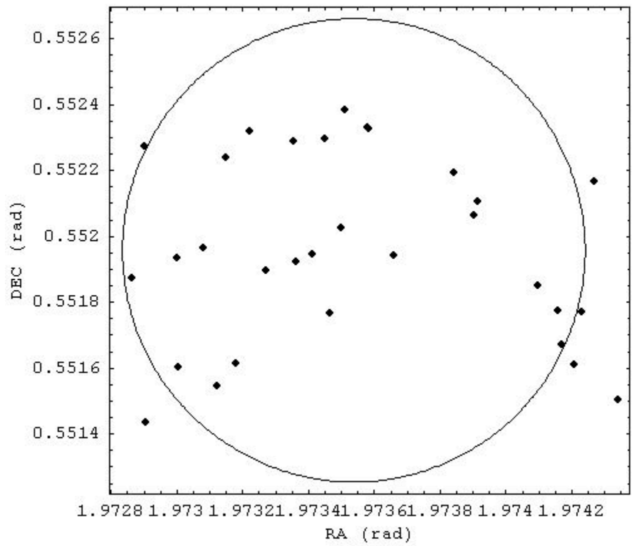
- X-ray, velocity dispersion and weak gravitational lensing (WGL):

$$M_{Cluster} = (4.3 \pm 0.7) \times 10^{14}\, M_{\odot} \qquad \sigma_v = (1243 \pm 58)\, kms^{-1}$$

[Cypriano, Neto, Sodré, Kneib 2005]

- WGL concerns a spherical region with **422 kpc** radius and **N_{Gal}=25** galaxies (within a **$570h_{70}^{-1}$ kpc** region with **31** galaxies); hence with the known coords.:

$$\left(< R >= \frac{2}{N_{gal}(N_{gal}-1)} \sum_{i=1}^{N_{gal}} \sum_{j=1}^{i} r_{ij} \right)$$



and therefore:

$$\rho_K = (2.14 \pm 0.55) \times 10^{-10} J m^{-3}$$

$$\rho_W = (-2.83 \pm 0.92) \times 10^{-10} J m^{-3}$$

- From which we get: $\dfrac{\rho_K}{\rho_W} \simeq -0.76 \pm 0.14$

Dark Energy – Dark Matter Interaction (II)

[O.B., Gil Pedro, Le Delliou, Phys. Lett. B654 (2007)]

- Interaction requires: $\eta \neq -3\omega_{DE}$
- For $\omega_{DE} = -1, \; \Omega_{DE_0} = 0.72, \; \Omega_{DM_0} = 0.24 \; , \; z = 0.1708$

$$\eta = 3.82^{+0.5}_{-0.47}$$

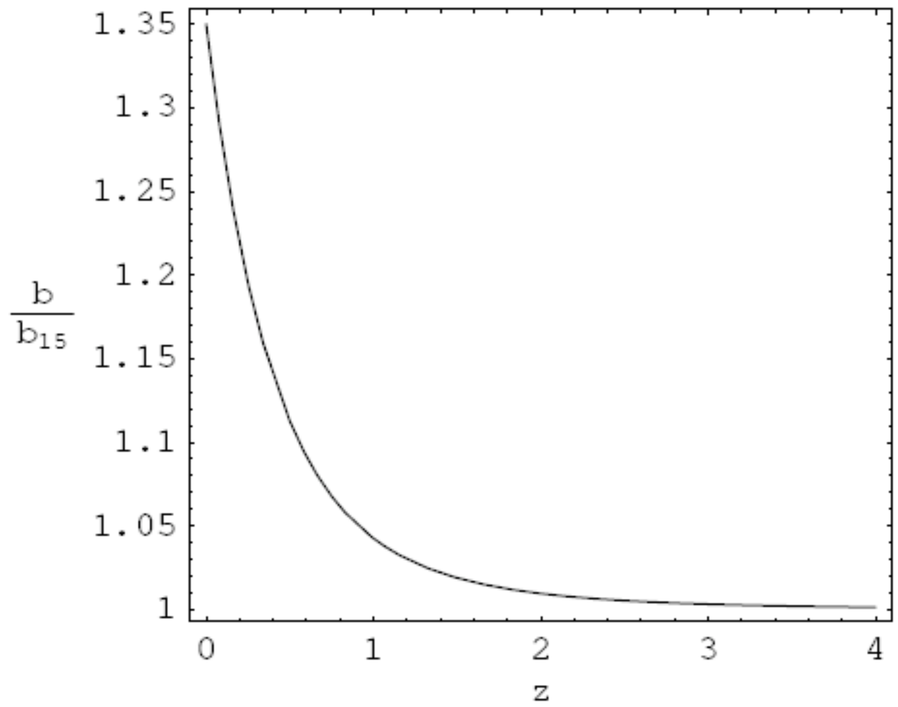
- GCG: $\alpha = 0.27^{+0.17}_{-0.16}$
- Data is consistent with interaction !
- Same methodology used for 33 relaxed galaxy clusters (optical, X-ray, gravitational lensing) suggests evidence for the interaction of DE and DM

[Abdalla, Abramo, Sodré, Wang, arXiv: 0710.1198(astro-ph)]

Dark Energy – Dark Matter Interaction and the Equivalence Principle (EP)

[O.B., Gil Pedro, Le Delliou, Phys. Lett. B654 (2007)]

- **Bias parameter evolution indicates a possible violation of the EP**



Dark energy-gauge field interaction: variation of the fine structure "constant"

$$S = \int d^4x\sqrt{-g}\;\left[-\frac{1}{2}R + \mathcal{L}_b + \mathcal{L}_Q + \mathcal{L}_{em}\right]$$

$$\mathcal{L}_Q = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi + \frac{1}{2}\partial^\mu\psi\partial_\mu\psi - V(\phi,\psi)$$

$$V(\phi,\psi) = e^{-\lambda\phi}P(\phi,\psi)$$

$$\begin{aligned} P(\phi,\psi) \;=\; & A \;+(\phi-\phi_*)^2 + B\;(\psi-\psi_*)^2 \\ & + C\;\phi(\psi-\psi_*)^2 + D\;\psi(\phi-\phi_*)^2 \end{aligned}$$

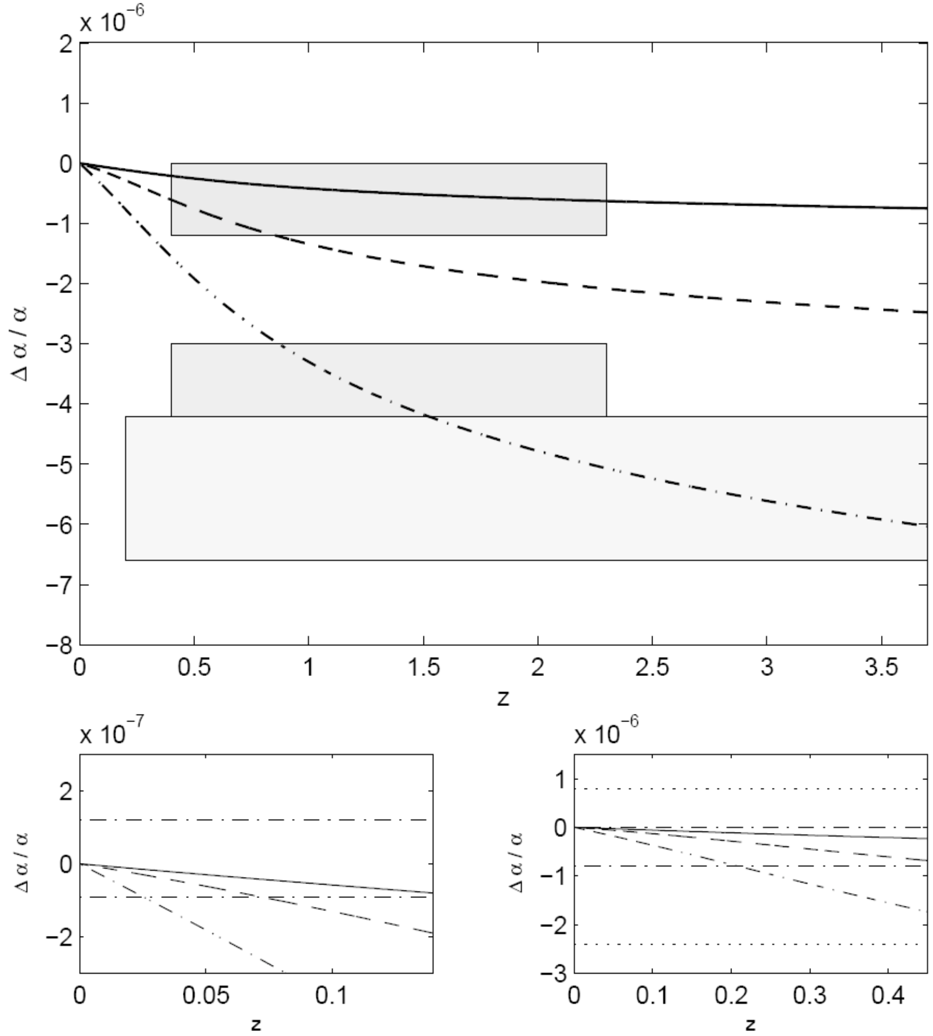
$$\mathcal{L}_{em} = -\frac{1}{4}B_F(\phi,\psi)F_{\mu\nu}F^{\mu\nu}$$

$$B_F(\phi,\psi) = 1 - \zeta_1(\phi-\phi_0) - \zeta_2(\psi-\psi_0)$$

[Olive, Pospelov 2002; Gardner 2003; …]

[O.B., Lehnert, Potting, Ribeiro 2004; Bento, O.B., Santos 2004, Bento, O.B., Torres 2007]

Oklo



Meteorites

FIG. 4: Evolution of α for a transient acceleration model with $= 2\times10^{-6}$ and $\zeta_2 = 8\times10^{-5}$ (full line), $\zeta_1 = 5.3\times10^{-6}$ and $\zeta_2 = 3\times10^{-5}$ (dashed line), $\zeta_1 = 1.4\times10^{-5}$ and $\zeta_2 = 7\times10^{-4}$ (dash-dotted line). Line and box conventions are those of

[Bento, O.B., Santos 2004]

Dark Energy – Neutrino Interaction: mass varying neutrinos

[Bernardini, O.B., Phys. Lett. B662 (2008); Phys. Rev. D77 (2008)]

- Consider the coupling to the GCG scalar field for a single neutrino flavour:

$$\mathcal{L} = m_{LR}\bar{\nu}_L\nu_R + M(\phi)\bar{\nu}_R\nu_R + h.c.$$

- GCG relevant eqs.:

$$\rho_\phi = \rho_0\left[A_s + \frac{(1-A_s)}{a^{3(1+\alpha)}}\right]^{1/(1+\alpha)}$$

$$\dot{\phi}^2(a) = \frac{\rho_0(1-A_s)}{a^{3(\alpha+1)}}\left[A_s + \frac{(1-A_s)}{a^{3(1+\alpha)}}\right]^{-\alpha/(1+\alpha)},$$

and assuming a flat evolving universe described by the Friedmann equation $H^2 = \rho_\phi$ H in units of H_0 and ρ_ϕ in units of $\rho_{\rm Crit} = 3H_0^2/8\pi G$), one obtains

$$\phi(a) = -\frac{1}{2\beta}\ln\left[\frac{\sqrt{1-A_s(1-a^{2\beta})}-\sqrt{1-A_s}}{\sqrt{1-A_s(1-a^{2\beta})}+\sqrt{1-A_s}}\right],$$

$$V(\phi) = \frac{1}{2}A_s^{\frac{1}{1+\alpha}}\rho_0\left\{\left[\cosh(\beta\phi)\right]^{\frac{2}{\alpha+1}} + \left[\cosh(\beta\phi)\right]^{-\frac{2\alpha}{\alpha+1}}\right\}.$$

Taking the time-derivative of

$$\rho_\nu = \frac{1}{a^4}\int q^2 dq\, d\Omega \epsilon f_0(q),$$

$$\dot{\rho}_\nu + 3H\left(\rho_\nu + p_\nu\right) = \frac{d\ln m_\nu}{d\phi}\dot{\phi}\left(\rho_\nu - 3p_\nu\right).$$

We describe the Dark Energy sector using a scalar field with potential $V_\phi(\phi)$. From the energy-momentum tensor for we obtain the energy and the pressure of the scalar field ϕ

$$\rho_\phi(a) = \frac{1}{2a^2}\dot{\phi}^2 + V_\phi(\phi),$$
$$P_\phi(a) = \frac{1}{2a^2}\dot{\phi}^2 - V_\phi(\phi).$$

Defining $w = P_{\rm DE}/\rho_{\rm DE}$ to be the equation of state of the coupled dark energy fluid, where $P_{\rm DE} = P_\nu + P_\phi$ denotes its pressure and $\rho_{\rm DE} = \rho_\nu + \rho_\phi$ its energy density, and the requirement of energy conservation gives,

$$\dot{\rho}_{DE} + 3H\rho_{DE}(1+w) = 0.$$

Taking into account the energy conservation of the coupled MaVaN - DE system, we find that the evolution of the scalar field is described by the modified Klein-Gordon equation,

$$\ddot{\phi} + 2H\dot{\phi} + a^2\frac{dV_\phi}{d\phi} = -a^2\frac{d\ln m_\nu}{d\phi}\left(\rho_\nu - 3p_\nu\right)$$

$- 3P_\nu)$

This equation contains an extra source term with respect to the uncoupled case, which accounts for the energy exchange between the neutrinos and the scalar field.

$m_\nu \gg T_\nu$

In the non-relativistic limit $m_\nu \gg T_\nu$ ...

MaVaN models can potentially become unstable for the following reason: the attractive force mediated by the scalar field (which can be much stronger than gravity) acts as a driving force for the instabilities. But as long as the neutrinos are still relativistic, the evolution of the density perturbations will be dominated by pressure which inhibits their growth, as the strength of the coupling is suppressed when $\rho_\nu = 3P_\nu$.

$m_\nu \gg T_\nu$ → $$\rho_\nu \simeq m_\nu n_\nu, \quad P_\nu \simeq 0,$$ → $$V = \rho_\nu + V_\phi = m_\nu n_\nu + V_\phi.$$

Assuming the curvature scale of the potential and thus the mass of the scalar field m_ϕ to be much larger than the expansion rate of the Universe,

$$V'' = \rho_\nu \left(\beta' + \beta^2\right) + V''_\phi \equiv m^2_\phi \gg H^2,$$ → $$\ddot{\phi} + 2\cancel{\mathcal{H}}\dot{\phi} + a^2 \frac{dV}{d\phi} = 0,$$

→ the adiabatic solution to the equation of motion of the scalar field

Quintessence Potentials!

In order to specify good candidate potentials $V_\phi(\phi)$ for a viable MaVaN model of dark energy, we must demand that the equation of state parameter w of the coupled scalar-neutrino fluid today roughly satisfies $w \sim -1$ as suggested by observations [66]. By noting that for constant w at late times,

$$\rho_{\rm DE} \sim V \propto a^{-3(1+w)}$$

and by requiring energy conservation $\dot{\rho}_{DE} + 3H\rho_{DE}(1+w) = 0$, one arrives at

$$1 + w = -\frac{1}{3}\frac{\partial \log V}{\partial \log a}.$$

it has been used that $V' = 0$

In the non-relativistic limit $m_\nu \gg T_\nu$ this is equivalent to

$$1 + w = -\frac{a}{3V}\left(m_\nu \frac{\partial n_\nu}{\partial a} + n_\nu \frac{\partial m_\nu}{\partial a} + \frac{V'_\phi}{a'}\right) = -\frac{m_\nu V'_\phi}{m'_\nu V},$$

$n \propto a^{-3}$

for an equation of state close to $w \sim -1$ today one can conclude that either the scalar potential V_ϕ has to be fairly flat or the dependence of the neutrino mass on the scalar field has to be very steep.

Good candidate potentials grow as small fractional powers or logarithms of the neutrino mass!

It is apparently consistent ! But ...

$$\frac{dV(\phi)}{d\phi} = -\frac{dm_\nu}{d\phi}\frac{\partial \rho_\nu}{\partial m_\nu}.$$

Equation of State

$$p_\phi = -\rho_\phi$$

$$\rho_\Lambda = V$$

In fact, once one assumes that $p_\phi = -\rho_\phi$, the neutrino mass evolution and the form of the potential become automatically entangled by the stationary condition. Thus, it should be realized that the stationary constraint Eq. (8) is quite dependent on the potential of the scalar field.

Perturbative Approach – Our proposal

We depart from na equation of motion for an unperturbed scalar field

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV(\phi)}{d\phi} = 0,$$

and we assume that the effect of the coupling of the neutrino fluid to the scalar field fluid is quantified by a linear perturbation

$\epsilon\phi$ $(|\epsilon| << 1)$ such that

$$\phi \rightarrow \varphi \simeq (1+\epsilon)\phi.$$

It then follows the novel equation for the energy conservation

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{dV(\varphi)}{d\varphi} = -\frac{dm_\nu}{d\varphi}\frac{\partial \rho_\nu}{\partial m_\nu}.$$

The explicit dependence of φ on ϕ is easy to quantify. Indeed, after a simple manipulation one finds

$$\begin{aligned}\frac{dV(\varphi)}{d\varphi} &\simeq (1+\epsilon)^{-1}\frac{dV(\varphi)}{d\phi} \\ &\simeq (1+\epsilon)^{-1}\frac{d}{d\phi}\left[V(\phi)+(\epsilon\phi)\frac{dV(\phi)}{d\phi}\right] \\ &\simeq \frac{dV(\phi)}{d\phi}+(\epsilon\phi)\frac{d^2V(\phi)}{d\phi^2}.\end{aligned}$$

The substitution of the Eqs. (10) and (12) into the Eq. (11) and use of Eq. (9), lead to

$$\epsilon\left[\phi\frac{d^2V(\phi)}{d\phi^2}-\frac{dV(\phi)}{d\phi}\right]\simeq\frac{dm_\nu}{d\varphi}\frac{\partial\rho_\nu}{\partial m_\nu}\simeq\frac{dm_\nu}{d\phi}n_\nu(a) \tag{13}$$

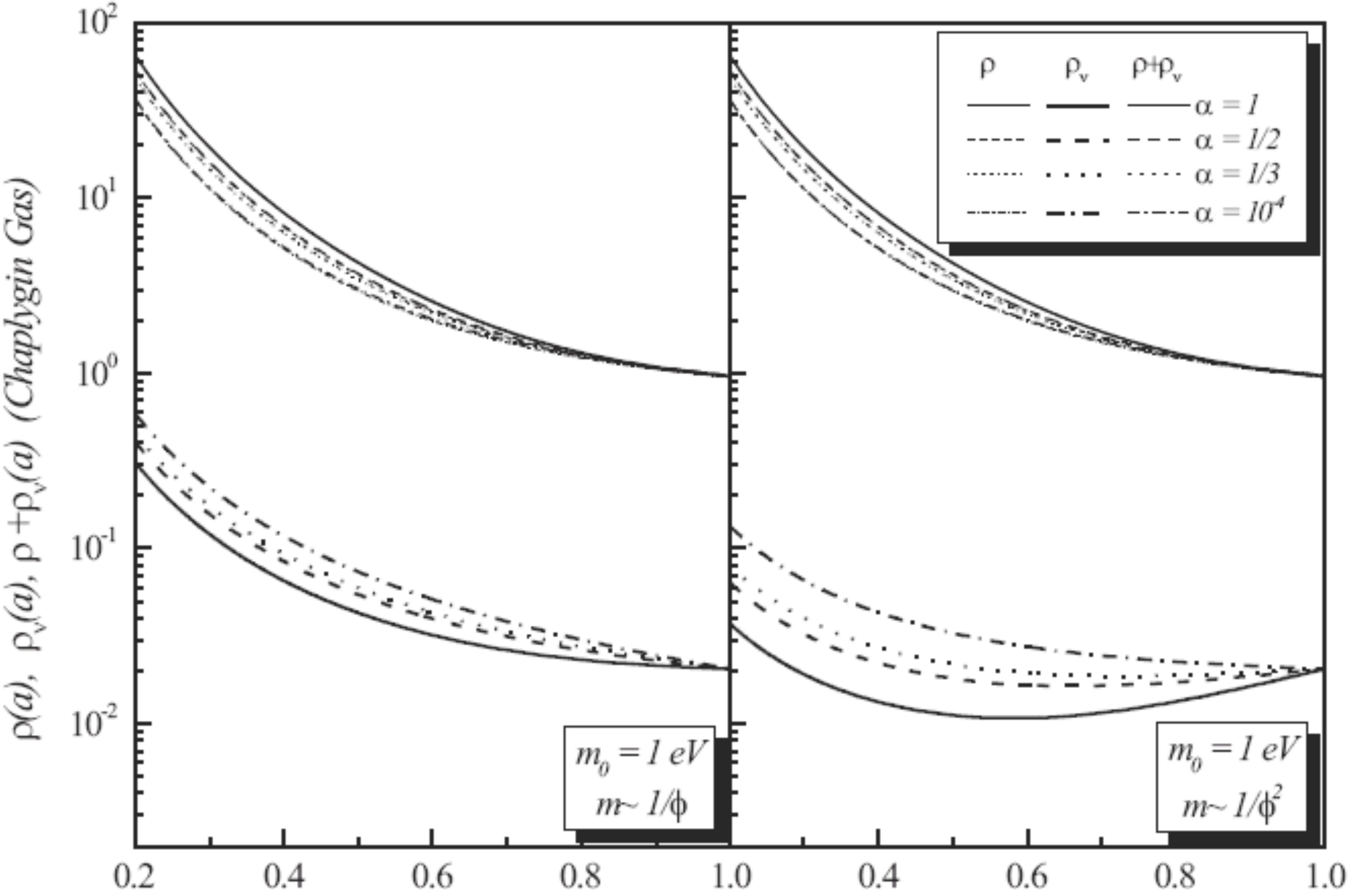
where the perturbative character of the neutrino mass term is assumed when we set the last approximation in the above equation. Finally, we can obtain for the value of the coefficient of the perturbation

$$\epsilon\simeq\frac{-\frac{dm_\nu}{d\phi}\frac{\partial\rho_\nu}{\partial m_\nu}}{\left[\phi^2\frac{d}{d\phi}\left(\frac{1}{\phi}\frac{dV(\phi)}{d\phi}\right)\right]},$$

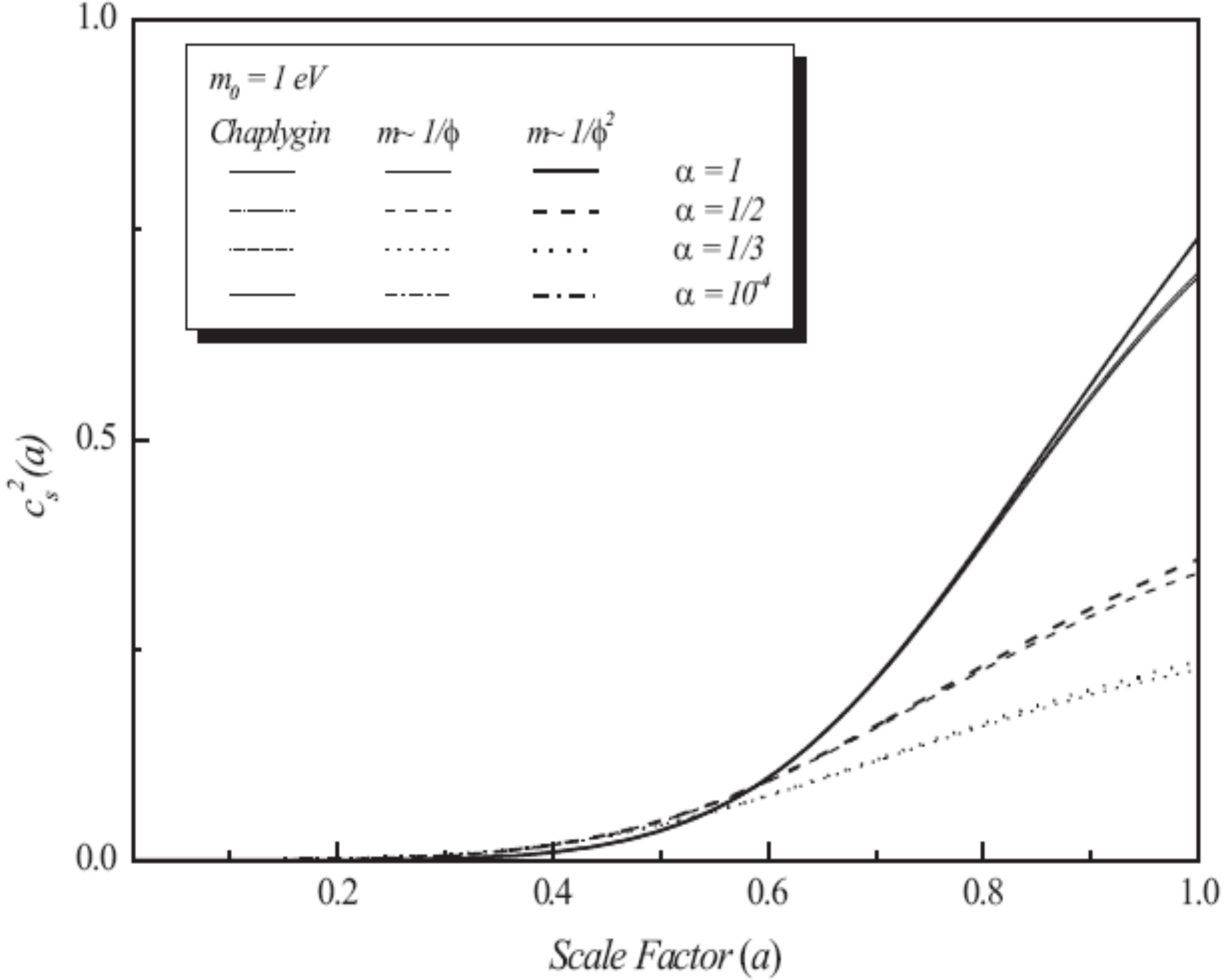
$$\rho_{UF}=\frac{1}{2}\dot{\phi}^2+V_{\rm Eff},$$

$V_{\rm Eff}$ in terms of $\frac{dV_{\rm Eff}}{d\phi}=\frac{dV(\phi)}{d\phi}+\frac{dm_\nu}{d\phi}\frac{\partial\rho_\nu}{\partial m_\nu}$

Solutions



ρ(a), ρ_v(a), ρ+ρ_v(a) (Chaplygin Gas)
ρ
ρ_v
ρ+ρ_v
α = 1
α = 1/2
α = 1/3
α = 10^-4
m_0 = 1 eV
m~ 1/φ
m_0 = 1 eV
m~ 1/φ^2
10^2
10^1
10^0
10^-1
10^-2
0.2
0.4
0.6
0.8
1.0
0.4
0.6
0.8
1.0



$m_0 = 1$ eV
Chaplygin
m~ 1/ϕ
m~ 1/ϕ²
α = 1
α = 1/2
α = 1/3
α = 10⁻⁴
1.0
0.5
0.0
0.2
0.4
0.6
0.8
1.0
$c_s^2(a)$
Scale Factor (a)

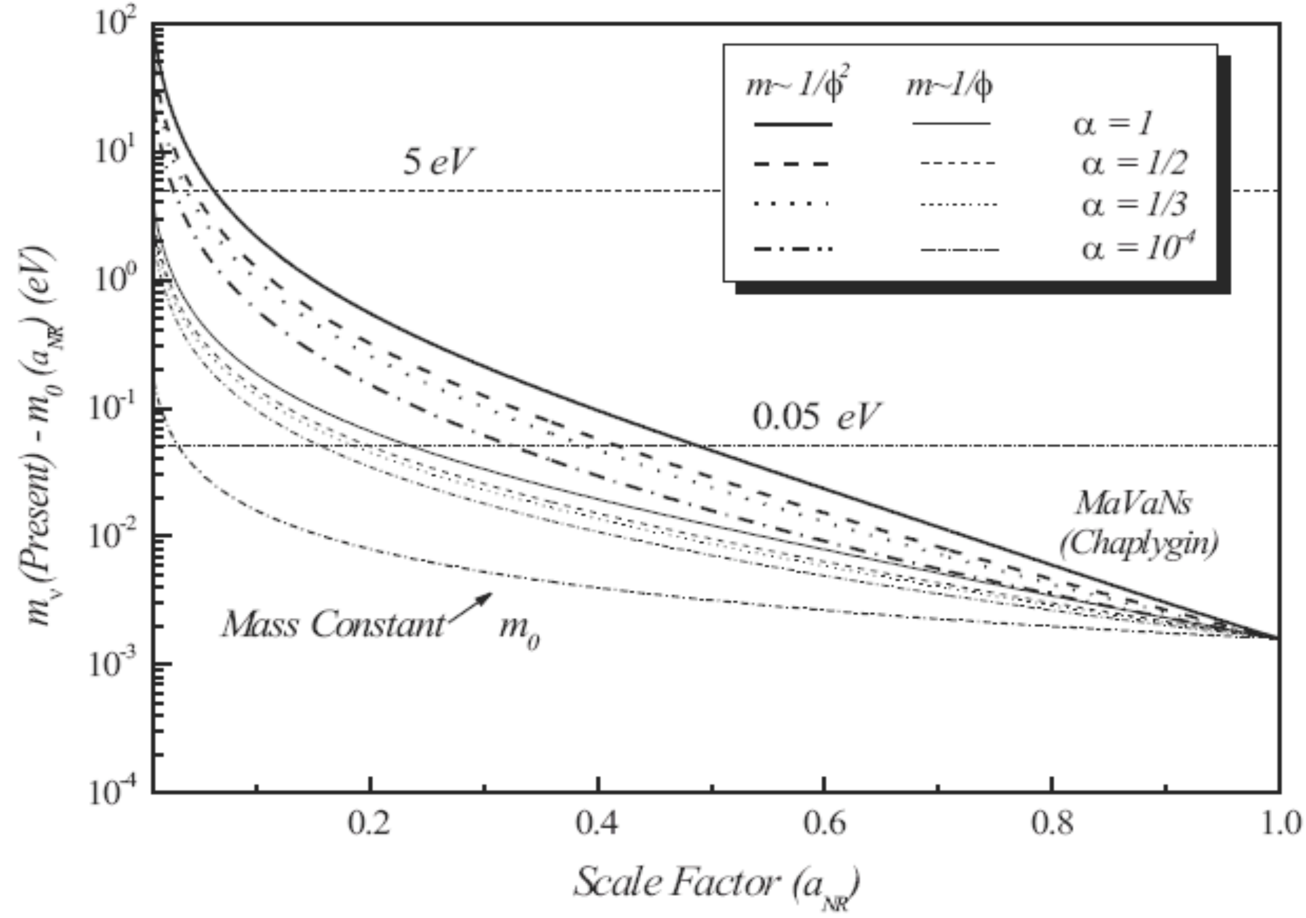


FIG. 7: Present-day values of the neutrino mass m_0 and the corresponding values of a_{NR} for which the transition between the NR and UR regimes takes place in a GCG phenomenological scenario with $A_s = 0.7$ and $\alpha = 1, 1/2, 1/3, 10^{-4}$. The choice of the model for mass generation plays a relevant role in determining the starting point a_{NR} of the coupling effectiveness. This is a section of graphs of Fig. 3 for $A_s = 0.7$.

Dark Energy and the Higgs Portal (I)

[O.B., Rosenfeld, arXiv:0708.1784 [hep-ph]]

- Higgs Portal: mixing of a singlet with the Higgs boson →

  Invisible decay of the Higgs into two singlet bosons

  [Binoth, van der Bij 1997, ...; Schabinger, Wells 2005; Patt, Wilczek 2006]

- Self-interacting dark matter coupled with the Higgs

  [Bento, O.B., Rosenfeld, Teodoro 2000; Bento, O.B., Rosenfeld 2001]

- A singlet complex scalar field:

$$V(\Phi, H) = -m_H^2|H|^2 - m_\Phi^2|\Phi|^2 + \lambda|H|^4 + \rho|\Phi|^4 + \eta|H|^2|\Phi|^2$$

$$\langle |H|^2 \rangle = v^2/2 \qquad \langle |\Phi|^2 \rangle = \xi^2/2$$

$$h = H - v/\sqrt{2} \qquad \phi = \Phi - \xi/\sqrt{2}$$

- Mixing angle with a light scalar induces long range Yukawa type interactions:

$$\tan\omega = \frac{\eta v \xi}{(\rho\xi^2 - \lambda v^2) + \sqrt{(\rho\xi^2 - \lambda v^2)^2 + \eta^2 v^2 \xi^2}}$$

Dark Energy and the Higgs Portal (II)

[O.B., Rosenfeld, arXiv:0708.1784 [hep-ph]]

- A non-relativistic particle in a gravitational field: $a = a_{gr} + a_\phi$

$$a_{gr} = \frac{M_E}{M_{Pl}^2 r^2} \qquad a_\phi = \frac{\omega^2}{M r^2}[g_N^2 N_N^E N_N^t + g_N g_e (N_N^E N_e^t + N_e^E N_N^t) + g_e^2 N_e^E N_e^t]$$

- Test bodies with distinct composition will experience different accelerations:

$$\varepsilon = 2\frac{|a_1 - a_2|}{|a_1 + a_2|}$$

$$\varepsilon = \frac{M_{Pl}}{\bar{m}}\omega^2 g_N g_e \Delta f_p \qquad \Delta f_p = \frac{N_p^{(1)}}{N_p^{(1)} + N_n^{(1)}} - \frac{N_p^{(2)}}{N_p^{(2)} + N_n^{(2)}}$$

- From the observational limit: $\varepsilon < \mathcal{O}(10^{-13})$ → $\omega < \mathcal{O}(10^{-20})$

[Dvali, Zaldarriaga 2002]

Dark Energy and the Higgs Portal (III)

[O.B., Rosenfeld, arXiv:0708.1784 [hep-ph]]

- Coupling of the Higgs with quintessence ?

$$V(\Phi, H) = U(\Phi) + \lambda \left(|H|^2 - \frac{v^2}{2} \right)^2 + \lambda_1 \Phi^2 (|H| - v/\sqrt{2})^2$$

$U(\Phi)$ - quitessence potential

Viable only if $\lambda_1 = \mathcal{O}(v^2/M_{Pl}^2)$!

Higgs portal is virtually closed for DE …

Conclusions

• Experiments in space to observe SNe (SNe “factories”), gamma-ray bursts, gravitational lensing, cosmic shear, etc, should be vigorously pursued in order to characterize the properties of DE and DM

• DE interaction with other fields might open new obervational windows:

- DE-DM interaction seems to imply deviation from the virial equilibrium of the A586 cluster

- DE interaction to the electromagnetic field imply the variation of the fine structure “constant”

- Interaction of DE to neutrinos in the context of the Chaplygin gas model is free from difficulties associated with the so-called stationary condition and can be made consistent with all phenomenological constraints

- Interaction of DE to the Higgs is unlikely to be experimentally accessible at accelerators