The Dark Side and its Nature

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The density quest in the 90’s

\( q_0 \sim 0 \) \quad \Omega_m = 0.2-0.3 \quad \text{or} \quad \Omega_m \sim 1 \quad \text{?}

0CDM \quad \text{vs} \quad \text{SCDM}

Supported by apparent slow evolution

Inflationary models can make it acceptable without fine tuning

Supported by CMB (COBE) data

Generic inflationary prediction

SN Ia as standard candles gave an unexpected reply

\( q_0 \sim -0.6-0.7 \) \quad \Omega_m = 0.2-0.3 \quad \& \quad \Omega_\Omega \sim 1

the gap is covered by Dark Energy

**SN1a**

Cosmic expansion is accelerated

**SNLS:** Astier et al (2005) *A&A*

Only acceptable model with sound historical records

**LCDM**

\[ d_L H/c \approx z + z^2 (1-q)/2 + \ldots \]

\[ q = \Omega_m / 2 - \Omega_\Lambda \]

\[ \Omega_m = 0.26 \]

\[ \Omega_{de} = 0.74 \]
- DE, what is that?
- Don’t worry, it’s just cosmological constant

The cosmic pie

- Fire, fire!
- Don’t worry, it’s just incandescent plasma

baryons
~ 4%

CDM
~ 20%
Table 5: ΛCDM Model: Joint Likelihoods

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\Omega_m h^2$</th>
<th>$\Omega_m$</th>
<th>$h$</th>
</tr>
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<tbody>
<tr>
<td>WMAP Only</td>
<td>0.1259±0.0049</td>
<td>0.1213±0.0038</td>
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</tr>
<tr>
<td>WMAP + 2dFGRS</td>
<td>0.1262±0.0049</td>
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WMAP2+ parameter values

WMAP2+ contours on the $w$-$\Omega_m$ plane
The most immediate candidate: VACUUM ENERGY however ..... as \( \rho_o \approx (10 \, T_o)^4 \) and \( \rho_{vac,EW} \approx T_{EW}^4 \)

\[ 10 \, T_o : T_{EW} \sim 1 : 10^{14} \]
\[ \rho_{\Lambda} : \rho_{EW} \sim 1 : 10^{56} \]

But, recall that \( T_{EW} : T_{GUT} \sim 1 : 10^{14} \)

A recent and still unfinished phase transition ? perhaps concerning the neutrino sector ....

Frieman et al, 1995 P.R.L. 75
Weiss, 1987 P.L. B 42
Amendola & Barbieri CERN-PH-TH/2005-163
Matter-DE constrnts

pressure/density ratio

\( \Omega_M \)

\( \Omega_\Lambda \)
**Otherwise**

DE is a scalar field

\[
\rho = \dot{\phi}^2 / 2 + V(\phi) \\
p = \dot{\phi}^2 / 2 - V(\phi) \\
w = p / \rho \sim -1
\]

if \( V(\phi) \gg \dot{\phi}^2 \), potential energy >> kinetic energy

This depends on the choice of \( V(\phi) \) & of “initial conditions” on \( \phi' \) and \( \phi'' \)

**dDE: Wetterich, 1988, N.P.B302**

**Ratra&Peebles, 1988, P.R.D37**

**dDE apparently eliminates fine-tuning**

\[
V(\phi) = \Lambda^{\alpha+4} / \phi^\alpha \quad \text{RP potential}
\]

\[
V(\phi) = (\Lambda^{\alpha+4} / \phi^\alpha) \exp[4\pi(\phi / m_P)^2] \quad \text{SUGRA potent.}
\]

Tracking potentials preferred, so getting rid of I.C. dependence

Scale \( \Lambda \) in the energy range of EW transition or SUSY break

fine tuning hidden in

why we use “field” representation

instead of \( N \) (number of particles) representation

\( N \) is diagonal \( \rightarrow \) \( w \) positive

Brax&Martin, 1999, P.L.B468

and 2001, P.R.D62

+Riazuelo, 2000, P.R.D61
The coincidence problem

DE emerges, as significant cosmic component, just at the eve of our epoch

A possible way out: DE & DM coupled

Say it otherwise:
The Dark Substance has a complex eq of state: partially it clusters (DM) partially it doesn’t (DE)

... and we try to approach phaenomenologically such substance using DM-DE coupl.
\[ ds^2 = a^2(\tau)(-d\tau^2 + dx_i dx^i), \quad (i = 1, \ldots, 3) \]

\[ \dot{\phi} + 2\frac{\dot{a}}{a}\phi + a^2 \frac{\partial V}{\partial \phi} = \frac{4}{m_p^2} \sqrt{\frac{\pi}{3}} \beta a^2 \rho_c \]

\[ \dot{\rho}_c + 3(\dot{a}/a)\rho_c = -\frac{4}{m_p^2} \sqrt{\frac{\pi}{3}} \beta \rho_c \dot{\phi} \]


\[ \rho_{c,b} = \frac{k \cdot v_{c,b}}{\mathcal{H}} , \quad \mathcal{H} = \dot{a}/a , \quad k: \text{wavenumber} \]

\[ \dot{\delta}_c'' = -\delta_c'(1 + \frac{\mathcal{H}'}{\mathcal{H}} - 2\beta X) + \frac{3}{2} (1 + \frac{4}{3} \beta^2) \Omega_c \delta_c + \frac{3}{2} \Omega_b \delta_b \]

\[ \delta_b'' = -\delta_b'(1 + \frac{\mathcal{H}'}{\mathcal{H}} + \frac{3}{2} (\Omega_c \delta_c + \Omega_b \delta_b) \]

\[ \delta_c' = -\delta_c(1 + \frac{\mathcal{H}'}{\mathcal{H}} - 2\beta X) - \frac{3}{2} (1 + \frac{4}{3} \beta^2) \Omega_c \delta_c - \frac{3}{2} \Omega_b \delta_b , \]

\[ \delta_b' = -\delta_b(1 + \frac{\mathcal{H}'}{\mathcal{H}}) - \frac{3}{2} (\Omega_c \delta_c + \Omega_b \delta_b) . \]

Energy flow from DM to DE

conformal time

Coupling intensity set by \( \beta \) value

\( \text{eqs. for fluctuation evolution} \)

\( + \text{usual ones for baryon \& radiative components} \)
**An alternative view** (Kolb, Riotto, Matarrese, ... 2005; see also Buckert 1980, Ellis 1990 ...)

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \]

**standard**  
\( \eta_{\mu\nu} \) defined by \( a(\tau) \) & \( \kappa \) coming from ass.  
state eqs. (\( p = w \rho \)); \( h_{\mu\nu} \) initially linear,  
then developing non-linearities

**new**  
\( h_{\mu\nu} \) initially linear  
when extreme non-linearities developed  
backg. state eqn modified

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**From LCDM to dDE & cDE**

- **2 problems:** fine tuning, coincidence
- **1 & ½ problems:** fine tuning eased; coincidence remains
- **fine tuning & coincidence:** both eased
Coupling compatible with data?

e.g., baryons could not be coupled to DE, this would cause unacceptable changes in their effective gravity

**CMB data**

<table>
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<tr>
<th>Model</th>
<th>$\chi^2$</th>
<th>Probability</th>
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<tr>
<td>$\Lambda$CDM</td>
<td>1.066</td>
<td>4.7 %</td>
</tr>
<tr>
<td>dDE</td>
<td>1.064</td>
<td>5.0 %</td>
</tr>
<tr>
<td>$\beta$-coupling</td>
<td>1.066</td>
<td>4.7 %</td>
</tr>
<tr>
<td>$\phi^{-1}$-coupl.</td>
<td>1.074</td>
<td>2.9 %</td>
</tr>
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anisotropy spectrum  T-E correlation spectrum  E-mode spectrum

Seeking limits on $\beta$
Cosmological parameters for cDE with $\beta$-coupling

\[ \lambda = \log(\Lambda/\text{GeV}) \]

notice that this extra degree of freedom is almost unexploited

At 1 sigma, $\beta < 0.2$
but, at 2-sigma’s, little restrictions

$\beta < \sim 0.2$
Structure formation
PS formalism
Improved by

Starting point: spherical top-hat fluctuation growth

Fluct. radius ($R_{flu}$) expands and recontracts while the scale factor $a(t)$ drives cosmic exp.

non-linear density contrast growing more fastly than linear fluctuation

allows to find which linear $\delta_c$ would have fluctuations virializing today

$\delta_c \sim 1.68$

$\Delta \sim 180$

SCDM

virialization

RP ($\lambda=6$)
The PS expression

\[ n(M)MdM \cong \rho_m \left[ P(\delta_c, M) - P(\delta_c, M + dM) \right] \]

\[ P(\delta) = (2\pi)^{-1/2} \int_{\delta_c/\sigma_M}^{\infty} dx e^{-x^2/2} \]

\[ \frac{dP}{dM}(> \delta_c, M) = \frac{\delta_c}{\sigma_M^2} \frac{d\sigma_M}{dM} e^{-\frac{1}{2}(\delta_c/\sigma_M)^2} \]

\[ n(>M) = \frac{\rho_m}{M} \int_{M}^{\infty} dM \frac{\delta_c}{\sigma_M^2} \frac{d\sigma_M}{dM} e^{-\frac{1}{2}(\delta_c/\sigma_M)^2} \]

PS is a fair fit to simulations. ST takes partially into account non-sphericity in real fluct. growth, and provides even better fits.

**ST vs simulations**

**ST**: dashed blue line

**error bars**: poisson noise

PS formulation for cDE

Based on a newtonian description of DM-DE interactions

(i) DM particle masses to vary:
\[ M_c(\tau) = M_c(\tau_i) \exp[-C(\phi - \phi_i)]. \]

(ii) Gravitational constant between DM particles: \( G^* = \gamma G \)
\[ C = \sqrt{16\pi G/3 \, \beta} , \quad \gamma = 1 + 4\beta^2/3 \]

(Maccio’ et al., 2004, P.R.D 69)

The \( \Phi \)-field carries a long-range interaction which appears as a correction to newtonian gravity, but only for DM-DM interactions. B-DM interactions untouched.

Valid well below horizon & for negligible radiative comp.
Effective DM gravity is stronger

DM shells evolve more rapidly

A sampling of spherical shells (~1000 used)
Shell radii (bar & DM)

Models of this paper
Mainini & Bonometto, PRD 2006

Our model’s parameters
\( \Omega_m = 0.25 \)
\( \Omega_b = 0.042 \)
\( h = 0.73 \)

WMAP1

physical

comoving
Profile evolution, in bar. & DM until virialization

How small can be $\beta$, to yield appreciable shifts?
Baryon fraction leaking DM bulk

fraction increases with $\beta$ almost independent from $\Lambda$

RP fraction greater
Linear amplitudes (SUGRA)
to be used in PS or ST expressions

$\beta$ dependence at $z=0$

2 different values for $\delta_c$

Fluct. ampl $\rightarrow$ DM virial.

Fluct. ampl $\rightarrow$
baryon virial.

$z$ dependence for model’s $\beta$
$M_{\text{vir}}$ & $R_{\text{vir}}$ vary because of coupling

to be used to find halos in simul.
**PS mass functions at z=0**

**N vs redshift in comoving volumes**

**signal of coupling at z=0, expected if** $\beta \sim 0.2$
halo # evolution
compared with 0CDM

plots
M=5.6*10^{14}
h^{-1} M_{sun}
# of expected halos in fixed $\Delta z$ and solid angle

- Normalized to LCDM
- $10^{14} \, M_\odot$
- $4 \times 10^{14} \, M_\odot$

- dDE evolves more slowly than LCDM
- Coupling can invert dDE displacement
Halos are however baryon impoverished
Baryons in galaxy clusters

grey band: WMAP1 data interval

low redshift

high redshift

black dots: intracluster gas emitting X-rays
diamonds: total baryon budget

The baryonic cake, in galactic clusters

Which evidence of the warm component?

Filaments emitting:
- Soft x-rays: Kaastra et al., 2003, A&A397

To my knowledge, NO more recent data

But plenty of hydro simulations trying to show that:
- Warm phase forms
- Baryons expelled by early SNe

hoping to make it consistent with 0
cDM simulation
\( \Omega_m = 0.3 \)
\( \Omega_b = 0.026 \)
\( H = 70 \text{ km/s/Mpc} \)

SUGRA potential
\( \Lambda = 100 \text{ GeV} \)
\( \beta = 0.16 \)

ART program modified
Box: 90 Mpc
64^3 part./8 ref. lev.

Maccio', Casarini, Mainini, B. (in prep)
Former simulation performed in 2004 with RP potential

Maccio’, Quercellini, Mainini, Amendola, B., 2004, P.R.D69

Principal findings: limits on coupling
In RP models the \( \phi \) field is always increasing
Corrections to DM gravity stronger in the past \( \Rightarrow \) highly concentrated halos

Only for \( \beta < 0.2 \) concentration acceptable

NO test on baryon depletion made on it

\[
V(\phi) = \Lambda^{4+\alpha} / \phi^\alpha
\]

Main difficulty with ART implementation: agreement between finite step length and continuous M and G variat.

An easy solution for monotonic field variation

With SUGRA potential, \( \phi \) increase stopped by exp factor; with selected parameters, the recent \( \phi \) behavior almost flat

Halo concentration no longer a problem
Box contains 153 halos in mass interval:
2.3e13 M_\odot (100 part) -
2.5e14 M_\odot (1089 part)

8 halos magnified
8 levels in mass
5 levels in force
Mass function

Same $\sigma_8$ for coupled SUGRA and LCDM

369 halos in LCDM
470 halos in cDE

>30 particle halos

Mild disagreement with PS ST fits better
Halo profile for DM and baryons, NFW fits

Different concentrations for DM & bar.

$r_c(DM) = 0.137 \, h^{-1}\text{Mpc}$
$r_c(bar) = 0.178 \, h^{-1}\text{Mpc}$

$M_{halo} = 2.44 \times 10^{14} \, h^{-1}\text{M}_\odot$
$R_{halo} = 1.21 \, h^{-1}\text{Mpc}$
baryon depletion

Blue line is the background abundance

All halos
Error bars are poisson noise

Sets of 15 halos
Error bars are 1-σ standard deviation

Only halos with >100 particles

average depletion ~17 %

(all halos with >31 particles)

A trend in baryon depletion?

Where are the missing galaxy satellites?

2 solution: missing satellites did not form
missing satellites are there, but invisible...


DARK SATELLITES

see also Moore et al, 1999, ApJL 524


\[ \frac{dN}{dV}\text{sat} = 3 \times 10^4 V^{3.75} \]

\[ n(\text{sat}) \text{ (Mpc/h}^3\text{)} = \text{dDE, # of satellites predicted the same as for LCDM} \]

CONCLUSIONS

DM+LAMBDA models are an excellent ‘caloric’ description of the Dark Substance, but...

N-body simulations of cDE cosmologies yield promising results with fairly acceptable coupling strengths

In the sensitive areas a number of data require different dynamics for DM & baryons; here we considered baryon depletion in clusters

Similar patterns to be explored whenever hydrodynamics does not provide bar-DM segregation mechanism acting early enough In turn, this can provide rich information on DM-DE relations

already
β ~ 0.05 yields fair effects

β ∼ 0.05 yields fair effects