Dark Matter & Dark Energy from the solution of the strong-CP problem

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Mainini & Bonometto 2004 PRL 93, 121301
Topics:

A particle model yielding Dark Matter & Dark Energy and solving the strong—CP problem (Dual Axion Model)

Dynamical & Coupled Dark Energy models, fitted to WMAP data

Growth of spherical perturbations within Coupled Dark Energy model

Predictions on fluctuation growth vs data on galactic satellites

General conclusions
# of Cosmological Parameters

N(photons)/N(baryons)
Density/Critical Density
CDM Density/Baryon density

**baryogenesis**

**geometry**

SCDM: these parameters

\[ \rho_{\text{dm}} \sim \rho_b \]
A puzzle?

**LCDM cosmology**
1 extra parameter: Matter density/DE density

**Dynamical DE** (+ 1 parameter)
\[ \rho_{\text{vac}_o} \approx 10^4 T_0^4 \]
\[ \rho_{\text{vac}_{ew}} \approx T_{ew}^4 \]
\[ \rho_{\text{vac}_o} / \rho_{\text{vac}_{ew}} = \]
\[ = 10^4 (10^{-4} \text{ eV} / 10^{11} \text{ eV})^4 = 10^{-56} \]

**Coupled DE** (+2 parameter)
Underlying ideology: Should astrophysics put limits on extra parameters new physics discovered and constrained

Even better: (new) physics requires DE & DM, setting their parameters in the fair range: A MICROPHYSICAL WAY OUT FROM FINE TUNING & COINCIDENCE

**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

Problems addressed by added parameters
The Dual-Axion Model (DAM)
A microphysical solution

belongs to the family of cDE models

but same # of parameters as SCDM

1 par. less than LCDM
2 par. less than dDE models
3 par. less than standard cDE models

DM & DE from the same scalar field
(exploit better the field in PQ approach)

strong-CP problem solved

fair fit to WMAP data

+, hopefully, solution of some LSS problems
Non-perturbative effects related to the vacuum structure in QCD yield a CP-violating term in $L_{QCD}$:

$$L_\theta = \frac{\alpha_s}{2\pi} \theta G \cdot \tilde{G}$$

Gluon field tensor and its dual

$d_n \approx 5 \cdot 10^{-16} \theta_{eff} e \cdot cm < 10^{-25} e \cdot cm$

Neutron electric dipole moment

Experimental limits on electric dipole moment

$\theta < 10^{-10}$

Why $\theta$ is so small?
Peccei-Quinn solution and the axion

Peccei & Quinn 1977

PQ idea: CP-violating term suppressed by making $\theta$ a dynamical variable. Potential drives it to zero.

- Additional global $U(1)_{PQ}$ symmetry in SM.

$$\Phi = \frac{\phi}{\sqrt{2}} e^{i\theta} \quad \text{with NG potential } \quad V(|\Phi|) = \lambda [\phi^2 - F_{PQ}^2]^2$$

- $U(1)_{PQ}$ is spontaneously broken at the scale $F_{PQ}$.

- $\theta$-parameter is now the NG boson due to sym.br. : the axion.

Weinberg 1978; Wilczek 1978
- CP-violating terms generate a potential for the axion which acquires a mass $m(T)$ (chiral symmetry break).

From instantonic calculus:

$$V(\theta) = m^2 F_{PQ}^2 (1 - \cos \theta) \approx \frac{1}{2} m^2 F_{PQ}^2 \theta^2$$

$$m(T \gg \Lambda_{QCD}) = 0$$

$$m(T \ll \Lambda_{QCD}) \propto F_{PQ}^{-1}$$

- $F_{PQ}$ is a free parameter

- Cosmological and astrophysical constraints require:

$$10^{11} < F_{PQ} / \text{GeV} < 10^{12} \quad \rightarrow \quad 6 \cdot 10^{-6} < m_{T=0} / \text{eV} < 2 \cdot 10^{-5}$$
Axion cosmology

- Equation of motion ($\theta \ll 1$):
  \[ \ddot{\theta} + 2\frac{\dot{a}}{a}\dot{\theta} + a^2 m^2(T)\theta = 0 \]

- Coherent oscillations for $m(T) > 2H$

- Oscillations damped by cosmic expansion

- **Axions as Dark Matter candidate**

Averaging over cosmological time $\langle E_{\text{kin}} \rangle = \langle E_{\text{pot}} \rangle$

\[ p_\theta = \langle E_{\text{kin}} \rangle - \langle E_{\text{pot}} \rangle = 0 \]

\[ \dot{\rho}_\theta = \left( \frac{\dot{m}}{m} - 3\frac{\dot{a}}{a} \right)\rho_\theta \Rightarrow \rho \propto a^{-3}m(T) \]

\[ T \ll \Lambda_{\text{QCD}} \Rightarrow \dot{m} = 0 \Rightarrow \rho_\theta \propto a^{-3} \]

Kolb & Turner 1990
A single field to account for both DM and DE?

NG potential $\implies$ Tracker quintessence potential $V(|\Phi|)$ with a complex scalar field

$|\Phi| = \phi \sqrt{2}$ no longer constant but evolves over cosmological times

PQ model

\[
<\phi> = F_{PQ}
\]

\[
m(T << \Lambda_{QCD}) \approx F_{PQ}^{-1}
\]

Angular oscillations still axion-DM; radial slow-roll yields DE

Dual-Axion Model

\[
<\phi> \neq \text{cost}
\]

\[
m(T << \Lambda_{QCD}) \propto \phi^{-1}
\]

variations over cosmological times only
LAGRANGIAN THEORY

\[
\mathcal{L} = \sqrt{-g} \left\{ \frac{1}{2} \left[ \partial^\mu \phi \partial_\mu \phi + \phi^2 \partial^\mu \theta \partial_\mu \theta \right] - V(\phi) - m^2 (T, \phi) \phi^2 (1 - \cos \theta) \right\}
\]

AXION

\[
\dot{\rho}_\theta + 3 \frac{\dot{a}}{a} \rho_\theta = -C(\phi) \phi \rho_\theta
\]

DARK ENERGY

\[
\ddot{\phi} + 2 \frac{\dot{a}}{a} \dot{\phi} + a^2 V'(\phi) = C(\phi) \rho_\theta a^2
\]

\[
\dot{\rho}_\phi + 3 \frac{\dot{a}}{a} (\rho_\phi + p_\phi) = C(\phi) \phi \rho_\theta
\]

Amendola 2000, 2003

COUPLED DE MODEL

time dependent coupling \( C(\phi) = 1/\phi \)
Background evolution

We use SUGRA potential \( V(\phi) = \frac{\Lambda^{4+x}}{\phi^x} e^{4\pi G \phi^2} \)

\( \Phi \)

\( \Omega_{DM} \approx 10^{10} GeV \)

Note: in a model with dynamical DE (coupled or uncoupled) once \( \Omega_{DM} \) is assigned \( \Lambda \) can be arbitrarily fixed.

Here \( \Lambda \) is univocally determined
Background evolution

\[ \dot{\phi} + 2a \frac{\dot{a}}{a} \dot{\phi} + a^2 \phi V'(\phi) = \phi \dot{\theta}^2 \]

coupling term \( \phi \dot{\theta}^2 \gg a^2 V' \)

\( \phi \) settles on different tracker solution
Background evolution

After equivalence kinetic energy of DE non-negligible, although matter era
axion mass

\( \Phi \) evolution causes axion mass to depend on scale factor
Rebounce at \( z=10 \) (sugra), critical for structure formation?

Maccio' et al 2004, PRD 69, 123516
Density fluctuations: linear evolution

DM and baryons fluctuations: 2 coupled Jeans’ equations:

\[
\begin{align*}
\ddot{\delta}_{DM} + \left( \frac{\dot{a}}{a} - C(\phi)\dot{\phi} \right) \dot{\delta}_{DM} &= 4\pi \left( G^* \rho_{\text{DM}} \delta_{DM} + G \rho_b \delta_b \right) \\
\ddot{\delta}_b + \frac{\dot{a}}{a} \dot{\delta}_b &= 4\pi G \left( \rho_{\text{DM}} \delta_{DM} + \rho_b \delta_b \right)
\end{align*}
\]

modified friction term
modified dynamical term

\[
G' = G \left( 1 + \frac{4}{3} \beta^2(\phi) \right)
\]
Density fluctuations: linear evolution

Red: dual axion $C(\phi) = 1/\phi$
Blue: Coupled DE $C = \text{cost} = \langle C(\phi) \rangle$
Black: $\Lambda$CDM

Differences from LCDM:
- objects form earlier
- baryon fluctuations $<$ DM fluctuations until recently
General conclusions on DAM

- One (complex) scalar field -> both DM & DE

- Fair DM & DE proportions from one par: $\Lambda/\text{GeV} \sim \text{some } 10^{10}$

- Strong CP problem solved

- DM-DE coupling established ( $C = 1/\phi$ )

- Fair growth of matter density fluctuations

- Fine tuning & coincidence problems eased
Fit to WMAP data

Best fit parameters:

<table>
<thead>
<tr>
<th>Uncoupled SUGRA</th>
<th>SUGRA with C=cost</th>
<th>SUGRA with C=1/φ</th>
</tr>
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<tr>
<td>$x$</td>
<td>$&lt;x&gt;$</td>
<td>$\sigma_x$</td>
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<td>$\Omega_0h^2$</td>
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<td>$\Omega_{dm}h^2$</td>
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<td>$h$</td>
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<td>0.06</td>
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<td>$\tau$</td>
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<tr>
<td>$n_s$</td>
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<td>0.04</td>
</tr>
<tr>
<td>$A$</td>
<td>0.97</td>
<td>0.13</td>
</tr>
<tr>
<td>Log $\Lambda$</td>
<td>3.0</td>
<td>7.7</td>
</tr>
</tbody>
</table>

No real constraint on $\lambda$

- Main differences at low $l$
- $\chi^2_{eff}$ from 1.064 (uncoupled SUGRA) to 1.071 (C=1/φ)
- SUGRA with C=1/φ $h=0.93\pm0.05$
- Better $\chi$-square for u.c.SUGRA than for LCDM

Fit performed allowing for arbitrary $\lambda$, -> DAM $\lambda$ within 2-$\sigma$
Fit to WMAP data

Results obtained with MCMC technique
1 and 2-sigma confidence levels

notice how
\( \lambda = \log(\Lambda/\text{GeV}) \)
almost
unconstrained

Uncoupled SUGRA dDE cosmology
A similar plot for $1/\phi$ coupled cosmologies

all parameters ($\Lambda$ in particular) strongly constrained
Post–linear evolution of density fluctuation
The spherical “top-hat” collapse

Gravitational instability:

galaxies, groups, clusters from small density perturbation growth

\[ \delta = \frac{\rho - \bar{\rho}}{\bar{\rho}} \quad (\rho = \text{density field}) \]

Perturbation evolution:

linear theory until \( \delta \ll 1 \)

\[ \ddot{\delta} + 2 \frac{\dot{a}}{a} \dot{\delta} = 4\pi G \rho \delta \quad \text{(Jeans' eq.)} \]

But real objects must have \( \delta \gg 1 \)

Insight into non-linear behavior from spherical inhomogeneity growth

Also used in PS theory -> fair halo MF in sim.

fair cluster MF, other ingred. to get gal.MF
Post–linear evolution of density fluctuation: The spherical “top-hat” collapse

Top-hat over-density in SCDM:
Initially expanding with Hubble flow, then 
(i) separating from background, (ii) reaching top expansion, (iii) collapsing to 0

\[ \dot{R} = - \frac{4\pi}{3} G \bar{\rho}_m (1 + \delta_m) R \]

…as a closed FRW universe

Extra assumption: Virial equilibrium stopping (no heat release)
Assuming mass conservation ….

Virial theorem

\[ 2T + U = 2T + \frac{3}{5} G \frac{M^2}{R} = 0 \]

Energy conservation between turn-around and virialization

\[ U_{ta} = U_{vir} + T_{vir} = \frac{1}{2} U_{vir} \]

\[ R_{vir} = \frac{1}{2} R_{ta} \]

Density contrast

\[ \Delta_{vir} = \frac{\rho_m}{\rho_{cr}} \approx 178 \]
A graphical description of the evolution of a system over time, assuming collapse to occur at present time.
Post–linear evolution of density fluctuation:
The spherical “top-hat” collapse

Top-hat overdensity in $\Lambda$CDM and uncoupled DE models:
Assuming an homogeneous DE field…..

$$\ddot{R} = -\frac{4\pi}{3} G [\overline{\rho}_m (1 + \delta_m) + \overline{\rho}_{DE} (1 + 3w_{DE})] R$$

Virial radius
…again from virial theorem and energy conservation but….  

$$R_{\text{vir}} \neq \frac{1}{2} R_{\text{ta}}$$

Density contrast
no longer constant in time

Mainini, Macciò & Bonometto 2003, New Astron., 8, 173
Coupled Dark Energy (cDE)
Basic equations

Spatially flat FRW universe with:
baryons, radiation, cold DM and DE (scalar field φ with potential V(φ))

Friedmann eq. \[
\left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi}{3} G (\rho_r + \rho_b + \rho_c + \rho_{DE}) a^2
\]

Continuity equations:
Interaction DM-DE parametrized by \[ C = \sqrt{16\pi G / 3\beta} \]

\[
\dot{\rho}_{DE} + 3 \frac{\dot{a}}{a} (1 + 3 w_{DE}) \rho_{DE} = -C \rho_c \dot{\phi} \quad \text{or} \quad \dot{\phi} + 2 \frac{\dot{a}}{a} \dot{\phi} + a^2 V, \phi = C \rho_c a^2
\]

\[
\dot{\rho}_c + 3 \frac{\dot{a}}{a} \rho_c = -C \rho_c \dot{\phi} \quad \Rightarrow \quad \rho_c \propto a^{-3} e^{-C\phi}
\]

\[
\dot{\rho}_b + 3 \frac{\dot{a}}{a} \rho_b = 0
\]

\[
\dot{\rho}_r + 4 \frac{\dot{a}}{a} \rho_r = 0
\]

Usual eqs. for baryons and radiation
Coupled Dark Energy
Coupling effects: modified DM dynamics

- DM particle mass variation
  \[ \rho_c \propto a^{-3} e^{-C\phi} \Rightarrow m \propto e^{-C\phi} \]

- Violation of equivalence principle
  \[ \dot{p} = 0 \Rightarrow \ddot{x} + \frac{\dot{m}}{m} \dot{x} = 0 \]

- Newtonian interactions:
  DM-DM particles: effective gravitational constant
  \[ G^* = G\left(1 + \frac{4}{3} \beta^2\right) = G\gamma \]
  DM-baryons or baryons-baryons: ordinary gravitational constant
Coupled Dark Energy (cDE)
Coupling effects: DM-baryons bias

From linear theory:
DM and baryons density fluctuations described by 2 coupled Jeans’ equations:

\[
\ddot{\delta}_b + \frac{\dot{a}}{a} \dot{\delta}_b = 4\pi \left( G\rho_c \delta_c + G\rho_b \delta_b \right) a^2 \\
\ddot{\delta}_c + \left( \frac{\dot{a}}{a} - C\dot{\phi} \right) \dot{\delta}_c = 4\pi \left( G^* \rho_c \delta_c + G\rho_b \delta_b \right) a^2
\]

Linear bias
\[
\delta_b = b \delta_c
\]

N-body simulations indicate that the bias persists also at non-linear level
Macciò, Quercellini, Mainini, Amendola & Bonometto 2004, Phys.Rev.D 69, 123516
Spherical collapse in cDE models

Start with:

- DM and baryons *top-hat* fluctuations of identical radius $R_{TH,i}$ expanding with Hubble flow

- Fluctuation amplitudes in DM and baryons set by linear theory:

  $\delta_b = b \delta_c$

  \[ \delta_b = b \delta_c \]

then, consider

set of concentric shells with radii $R_n^c$ (DM) $R_n^b$ (baryons)

\[ R_1^{c,b} < R_2^{c,b} < \ldots < R_{TH,i} < \ldots < R_n^{c,b} \]

initial conditions:

\[ R_n^c = R_n^b \]

\[ \frac{\dot{R}_n^c}{R_n^c} = \frac{\dot{R}_n^b}{R_n^b} = \frac{\dot{a}}{a} \]
Spherical collapse in cDE models:
Time evolution of concentric shells

From $T_{\nu, \mu} = 0$, using comoving radii and

\[ b_n = R_n^b / a \quad \text{and} \quad c_n = R_n^c / a \]

\[ \dot{b}_n = -\frac{\dot{a}}{a} b_n - \frac{4\pi}{3} G\left[\rho_c \delta_c + \rho_b \delta_b\right] a^2 b_n \]

\[ \ddot{c}_n = -\left(\frac{\dot{a}}{a} - C\phi\right) \dot{c}_n - \frac{4\pi}{3} \left[ G^* \rho_c \delta_c + G \rho_b \delta_b \right] a^2 c_n \]

\[ \rho_c = \bar{\rho}_c (1 + \delta_c) \]
\[ \rho_b = \bar{\rho}_b (1 + \delta_b) \]
\[ \rho_{DE} = \bar{\rho}_{DE} \]

**Eqs. in physical coordinates**

Usual Friedmann-like equation for baryon shells

\[ \ddot{R}_n^b = -\frac{4\pi}{3} G\left[\rho_c + \rho_b + \rho_{DE} (1 + 3w_{DE})\right] R_n^b \]

Modified equation for DM shells

\[ \ddot{R}_n^c = C\phi \dot{R}_n^c - C\phi \frac{\dot{a}}{a} R_n^c - \frac{4\pi}{3} G\left[\bar{\rho}_c (1 + \gamma\delta_c) + \rho_b + \rho_{DE} (1 + 3w_{DE})\right] R_n^c \]
Spherical collapse in cDE models:
Time evolution of concentric shells

- DM fluctuation expands more slowly and reach turn-around earlier
- Baryons contraction at different times for different layers
- Baryons gradually leak out from the fluctuation bulk

As a consequence..... **baryon component deviates from a top-hat geometry**
Spherical collapse in cDE models
Density profiles

- Top-hat geometry kept for DM
- Deviation from a top-hat geometry for baryons outside $R_{TH}$
- Perturbation also in material outside the boundary of fluctuation:
  outside $R_{TH}$ baryon re-infall fastened by greater DM density
Virialization in cDE models

- Slower gravitational infall for baryons: outer layers of halo rich of baryons

- Gradual re-infall of external baryons onto DM-richer core:
  DM layers, initially outside fluctuation, infall with baryons

- DM / baryon ratio however increased

  \[
  \text{No virialization with all the materials of original fluctuation – and only them}
  \]

How to define virialization in cDE models?

1 - Only materials within top-hat considered: escaped baryon fraction neglected
2 - All materials inside original fluctuation plus intruder DM considered
   but........any intermediate choice also allowed
Virialization in cDE models

Our choice: Only materials within top-hat considered: escaped baryon fraction neglected

Virialization condition:

$$2T(R_{TH}) = R \frac{dU(R_{TH})}{dR}$$

Kinetic and potential energies:

$$T(R_{TH}) = T^c(R_{TH}) + T^b(R_{TH}) = \frac{1}{2} \int dm \dot{r}^2 + \frac{1}{2} \int dm_b \dot{r}^2$$

$$U(R_{TH}) = U^c(R_{TH}) + U^b(R_{TH}) = \int dm \left[ \Phi_c(r) + \Phi_b(r) + \Phi_{DE}(r) \right] + \int dm_b \left[ \Phi_b(r) + \Phi_c(r) + \Phi_{DE}(r) \right]$$

Potential energy made of three terms: self-interaction, mutual interaction, interaction with DE

$$\Phi_i = -\frac{4\pi}{3} G \bar{\rho}_i (1 + \delta_i) r^2 \quad i = c, b, DE \ ; \delta_{DE} = 0$$

$$\Phi_c = -\frac{4\pi}{3} G \bar{\rho}_c (1 + \gamma \delta_c) r^2 \quad \text{DM-DE energy exchange for fluctuation described by } G^* = \gamma G$$
Virialization in cDE models

Performing integrals...

\[ U^c (R_{TH}) = \int dm_c \left[ \Phi^c_c (r) + \Phi^b_b (r) + \Phi^c_{DE} (r) \right] = -\frac{3}{5} G \frac{M^c_c + \gamma \Delta M^c_c + M^b_b}{R_{TH}} - \frac{4\pi}{5} GM^c_c \rho^c_{DE} R_{TH}^2 \]

\[ U^b (R_{TH}) = \int dm_b \left[ \Phi^b_b (r) + \Phi^c_c (r) + \Phi^c_{DE} (r) \right] = -\frac{3}{5} G \frac{M^b_b + M^c_c}{R_{TH}} - \frac{4\pi}{5} GM^b_b \rho^c_{DE} R_{TH}^2 \]

\[ T^c (R_{TH}) = \frac{1}{2} \int dm_c \dot{r}^2 = \frac{3}{2} \frac{M^c_c}{5} \dot{R}^2 \]

... but different baryons layers have different growth rates

\[ \frac{\dot{r}}{r} = \frac{\dot{R}}{R} \text{ used} \]

not valid for \( T^b (R_{TH}) \)

\[ T^b (R_{TH}) = \frac{1}{2} \int dm_b \dot{r}^2 \approx \sum_n T^b_n = \sum_n \frac{1}{2} M^b_n (\dot{R}^b_n)^2 \]

for all \( R^b_n < R_{TH} \)

Final density contrast

\[ \Delta_{\nu} = \frac{\Omega^b_b - \Omega^b_\nu}{\Omega^c_c} \]

\[ \Omega^b_b = 0.25, \Omega^b_\nu = 0.05 \]

\[ \Omega^b_b = 0.21, \Omega^b_\nu = 0.04 \]
Spherical collapse in cDE models: Escaped baryon fraction

- Barion fraction $f_b$ outside $R_{TH}$ at virialization:

$$20\% \leq f_b \leq 58\% \quad \text{for} \quad 0.1 \leq \beta \leq 0.3$$

- Mild dependence on scale $\Lambda$

Preliminary result: RP potentials causes just minor quantitative shifts
Conclusions on spherical growth

_Spherical top-hat collapse model in cDE theories:_

Ambiguity of definition of halo virialization:  
hard comparing simulations or data  
with PS (or similar) predictions

But…indepdently of the way how virialization is defined:

1 - Only materials within top-hat considered: escaped baryon fraction neglected  
2 - All the materials inside the original fluctuation plus intruder DM considered  
(or any intermediate choice)

Final virialized system is richer of DM  
**EVEN MUCH RICHER ….. IF OUTER LAYERS STRIPPED**
DM-baryons segregation during spherical growth:
a fresh approach to deal with quite a few cosmological problems

*large scale:* baryon enrichment of large clusters?

*intermediate scale:* lost baryonic materials as intra-cluster light?
  (X-ray, EUV excess emission problem)

*small scale:* systems likely to loose their outer layers because of close encounters with heavier objects
  (missing satellite problem ?)
ANDROMEDA SATELLITES
Where are the missing galaxy satellites?

2 solution: missing satellites did not form
missing satellites are there, but invisible...
Bullock, Weinberg & Kravtsov 2002

PopIII stars reionize the Universe at $z \sim 8$. Gas infall in low-mass halos is suppressed after reionization.

Working only for $z(\text{reion}) \sim 8$. If reionization earlier mechanism fails (Maccio’ et al 2005).

$\tau \sim 16$ requires $z(\text{reion}) \sim 18$.

MECHANISM NEEDED TO REMOVE BARYONS FROM SMALL HALOS.
OTHER MECHANISMS TO PRODUCE DM-ENRICHED SATELLITES (early SNe to blow out gas?)

OTHER EVIDENCES OF DM-BARYON SEGREGATION ON GREATER SCALES
e.g. THE L-T CLUSTER PROBLEM

IN THIS LAST CASE
ASTROPHYSICAL SOLUTIONS PROPOSED
THEIR EFFICIENCY STILL DISPUTED

DM-DE COUPLING PROVIDES MECHANISM FOR BARYON-DM SEGREGATION

AN EVIDENCE IN FAVOR OF COUPLING WITHIN THE DARK SECTOR?
Spherical growth with $1/\phi$ coupling to be studied

Simulations of cDE cosmologies urgently required

Still many problems in the dark ......