The Dark Degeneracy: The Dark Fluid and Interacting Cosmic Components

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National Nuclear Research Institute (ININ), Mexico

Cosmology at the Beach, 2012

Standard Model of Cosmology

Homogeneus and isotropic (and flat) spacetime: $\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\delta_{ij}\mathrm{d}x^i\mathrm{d}x^i$.

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_T)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G\, a}{3}(\rho_T + 3P_T)$$

where $\rho_T = \rho_\gamma + \rho_\nu + \rho_b + \rho_{dm} + \rho_{de}$, which comply with

$$\dot{\rho}_{\rm rel} + 4\mathcal{H}\rho_{\rm rel} = 0, \qquad \dot{\rho}_{\rm nonrel} + 3\mathcal{H}\rho_{\rm nonrel} = 0, \qquad \rho_{de} = \text{const.}$$

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Two main properties are relevant: clustering dark matter ($c_s^2 = 0$) and accelerating dark energy ($P_T < -1/3$).

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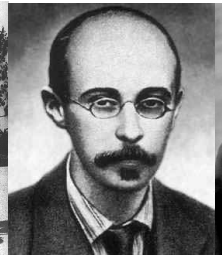

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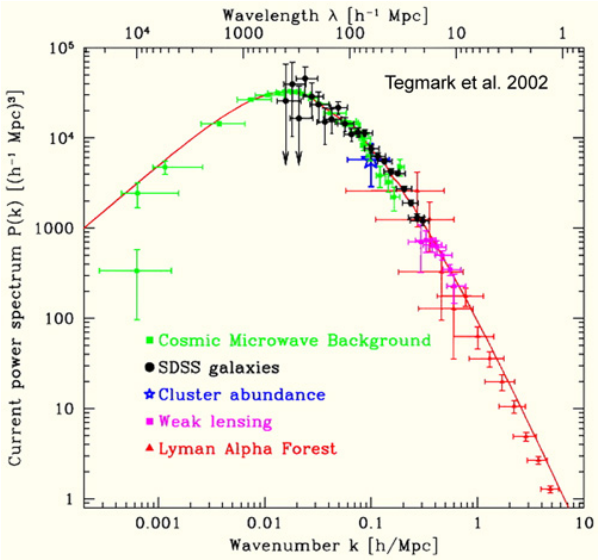

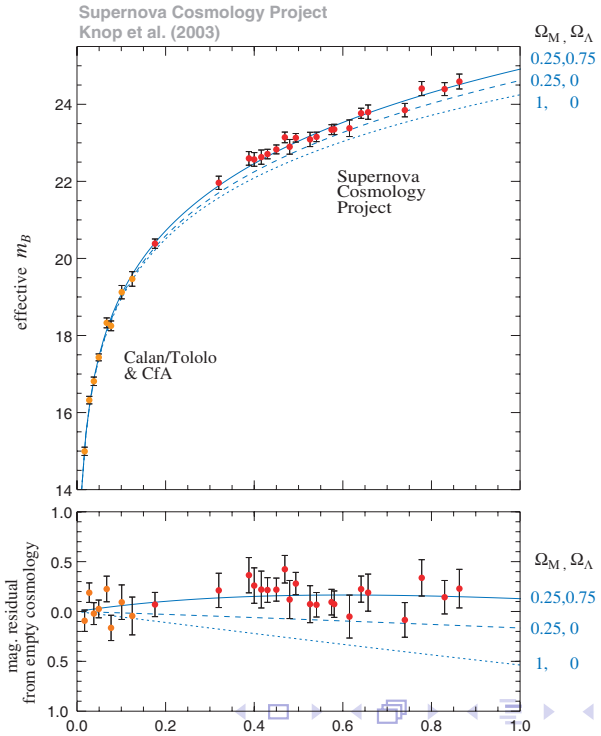

Dark fluids or dark geometry?

Dark Fluid Components

$$\frac{1}{8\pi G} G_{\mu\nu} = T^{\rm obs}_{\mu\nu} + T^{\rm dark}_{\mu\nu}$$

Any selection of the dark energy-momentum tensor is arbitrary.

Dark Geometry

$$\frac{1}{8\pi G} (G_{\mu\nu} + G^{\rm dark}_{\mu\nu}) = T^{\rm obs}_{\mu\nu}$$

Any selection of the dark Einstein tensor is arbitrary.

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A popular choice (historical reasons!):

$$T^{\rm dark}_{\mu\nu} = T^{\rm dm}_{\mu\nu} + T^{\rm de}_{\mu\nu}$$

with:

$$T^{\rm dm}_{\mu\nu} = \rho u_\mu u_\nu \qquad \text{a perfect fluid of CDM,}$$

$$T^{\rm de}_{\mu\nu} = \Lambda\, g_{\mu\nu} \qquad \text{the cosmological constant,}$$

a very successful model , but there are many possibilities.

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Alternative models to ΛCDM

- k-essence
- phantom energy
- strings's motived models: ghost condensates, UV corrections to curvature, conformal anomalies.
- Non-minimal couplings $f(\phi)R$
- dm-de interacting models
- Chameleons
- Galileons, etc, etc

...and more

- MOND
- backreaction of perturbations
- Chaplygin gas, $p = 1/\rho^{\alpha}$
- Brane worlds: RS, DPG, Gauss Bonnet
- Loop Quantum Cosmology
- Infrared corrections to curvatures: f(R)
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Dark matter from scalar field-baryonic couplings

Plethora of couplings: Conformal, trace, non-minimal...

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \frac{1}{2}\phi^{,\alpha}\phi_{,\alpha} - V(\phi)\right] + S_{int} + S_m,$$

with $\mathcal{L}_{int} = \sqrt{-g}A(\phi)T$.

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$$w_{dark} = -\frac{1}{1 + \frac{e^{\alpha(\phi)}-1}{V(\phi)}\rho_b^0 a^{-3}} \qquad \textit{(in slow roll)}$$

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2, \quad e^\alpha = 1 + \frac{1}{2}\epsilon\phi^2$$

$$C_1 = \frac{e^{\alpha(\phi)}-1}{V(\phi)}\rho\Big|_{z=0} \approx \frac{\Omega_{DM}^{(0)}}{\Omega_{DE}^{(0)}} \approx 0.3,$$

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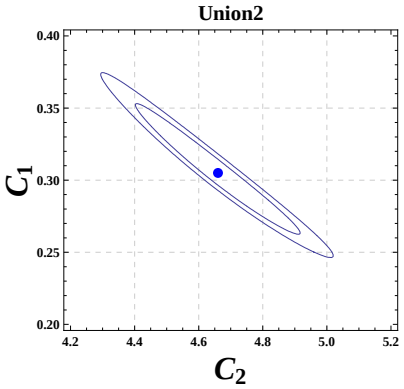

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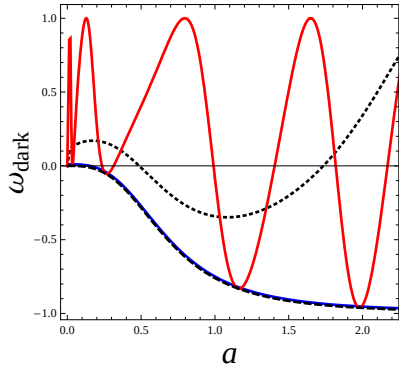
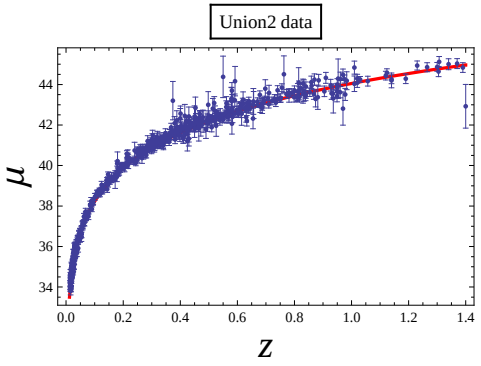
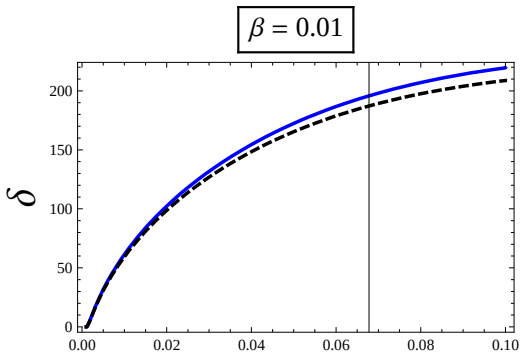
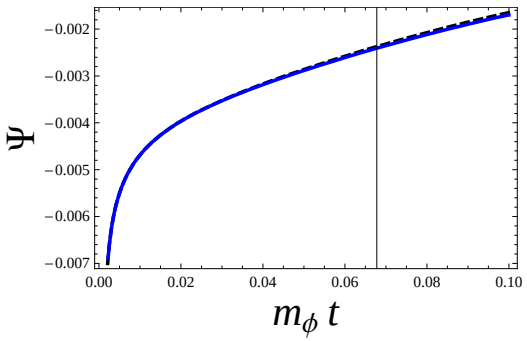
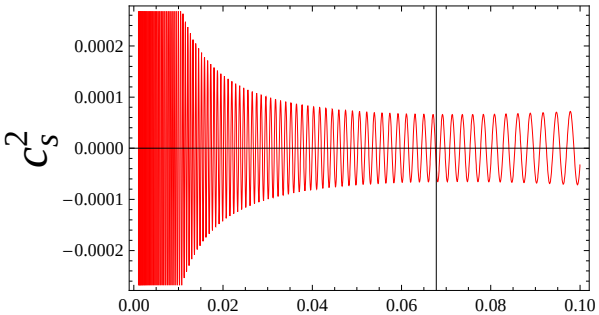




Linear Perturbations







$$c_s^2 = \frac{\dot{\phi}_0 \dot{\delta\phi} - \dot{\phi}_0^2 \Psi - m_\phi^2 \phi_0 \delta\phi}{\dot{\phi}_0 \dot{\delta\phi} - \dot{\phi}_0^2 \Psi + m_\phi^2 \phi_0 \delta\phi + \frac{1}{2}\epsilon\phi_0^2 (\delta + \frac{\epsilon\phi_0}{1+\frac{1}{2}\epsilon\phi_0^2}\delta\phi)}$$

(A. Aviles and J.L. Cervantes-Cota, 2011a)

Towards a single fluid description

The elements: locally clustering (perturbations) and globally accelerating (background).

Astrophysics

At very large scales ($>$ 100's Mpc) the Universe is homogeneous and isotropic: $\rho(t, \vec{x}) = \rho(t)$

Matter perturbations: $\delta(t, \vec{x}) = \delta\rho/\rho$

$$\delta'' + 2H\delta' + \left(c_s^2 k_{\text{phys}}^2 - 4\pi G\rho\right)\delta = 0,$$

where a prime stands for a cosmic time derivative.

Jeans length

$$l_J = c_s\sqrt{\frac{\pi}{G\rho}}$$

- $l > l_J$ *Growth*
- $l < l_J$ *No growth*

and we infer non-baryonic structure growth from dwarf galaxies to cosmological scales.

We define the Dark Fluid (d) as a barotropic fluid with $c_s^2 = 0$.

$$P_d(\rho) = w_d(\rho)\rho_d \quad \longrightarrow \quad w_d \propto \frac{1}{\rho_d} \quad \longrightarrow \quad P_d = \text{const.}$$

Astrophysical observations constrain $P_d \ll \rho_{\text{astro}}$, but no necessarily equal to zero, and this will be important to interpret the single fluid as dark energy too.

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$$\rho_d = \frac{\rho_{d0}}{1+\mathcal{K}}\left(1 + \frac{\mathcal{K}}{a^3}\right), \qquad P_d = -\frac{\rho_{d0}}{1+\mathcal{K}}$$

$$\rho_d > 0 \qquad \longrightarrow \qquad P_d < 0.$$

The single fluid behaves as dark matter and dark energy!

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The Dark Degeneracy

Equation of state parameter of the dark fluid: $w_d = -\frac{1}{1+\mathcal{K}a^{-3}}$

Equation of state parameter of the dark components in the ΛCDM model:

$$w_{dark} \equiv \frac{\sum_i w_i \rho_i}{\sum_i \rho_i} = -\frac{1}{1+\frac{\Omega_{dm}}{\Omega_\Lambda} a^{-3}}$$

Under the identifications

$$\Omega_d = \Omega_{dm} + \Omega_\Lambda, \qquad \mathcal{K} = \Omega_{dm}/\Omega_\Lambda$$

the background evolution in both models is exactly the same!

- The Dark Degeneracy (M. Kunz 2009). Any collection of fluids whose total equation of state parameter is equal to $w_{\rm dark}$ presents the degeneracy. The background evolution is the same as in the ΛCDM model.

- The fundamental reason is that we define

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Equation of state parameter of the dark components in the ΛCDM model:

$$w_{dark} \equiv \frac{\sum_i w_i \rho_i}{\sum_i \rho_i} = -\frac{1}{1+\frac{\Omega_{dm}}{\Omega_\Lambda} a^{-3}}$$

Under the identifications

$$\Omega_d = \Omega_{dm} + \Omega_\Lambda, \qquad \mathcal{K} = \Omega_{dm}/\Omega_\Lambda$$

the background evolution in both models is exactly the same!

- The Dark Degeneracy (M. Kunz 2009). Any collection of fluids whose total equation of state parameter is equal to $w_{\rm dark}$ presents the degeneracy. The background evolution is the same as in the ΛCDM model.

- The fundamental reason is that we define

$$T_{\mu\nu}^{\rm dark} = \frac{1}{8\pi G} G_{\mu\nu} - T_{\mu\nu}^{\rm obs}.$$

  Any split of the the dark energy momentum tensor is arbitrary, but the particular given properties of the single fluid are important to exactly emulate the ΛCDM model.

Beyond the background

Perturbations to the background metric in the Newtonian Conformal gauge

$$ds^2 = a^2(\tau)\big[-(1+2\Psi)d\tau^2 + (1-2\Phi)\delta_{ij}dx^i dx^j\big],$$

Perturbations to the matter fields.

$$T^0{}_0 = -\rho(1+\delta), \qquad T^i{}_0 = -(\rho+P)v^i, \qquad T^i{}_j = (P+\delta P)\delta^i{}_j + P\Pi^i{}_j.$$

For the dark fluid, $\delta P_d = c_s^2 \delta\rho_d = 0$, and being a perfect fluid $\Pi^i{}_j = 0$, the perturbed eqs. are:

$$\begin{aligned}
\dot{\delta}_d &= -(1+w_d)(\theta_d - 3\dot{\Phi}) + 3\mathcal{H}w_d\delta_d, \\
\dot{\theta}_d &= -\mathcal{H}\theta_d + k^2\Psi.
\end{aligned}$$

But these are exactly the same as the usual Cold Dark Matter equations, provided that

- $\rho_d\delta_d = \rho_{\rm dm}\delta_{\rm dm}$
- $\rho_d(1+w_d)\theta_d = \rho_{\rm dm}\theta_{\rm dm}$

The fluid equations are supplemented with the Einstein's equations:

$$\begin{aligned}
k^2\Phi &= -4\pi G a^2 \sum_i \rho_i \Delta_i, \\
k^2(\Phi - \Psi) &= 12\pi G a^2 \sum_i (\rho_i + P_i)\sigma_i\,.
\end{aligned}$$

the sum runs over all fluid contributions and $\Delta_i = \delta_i + 3\mathcal{H}(1+w_i)\frac{\theta_i}{k^2}$ the rest fluid energy density.

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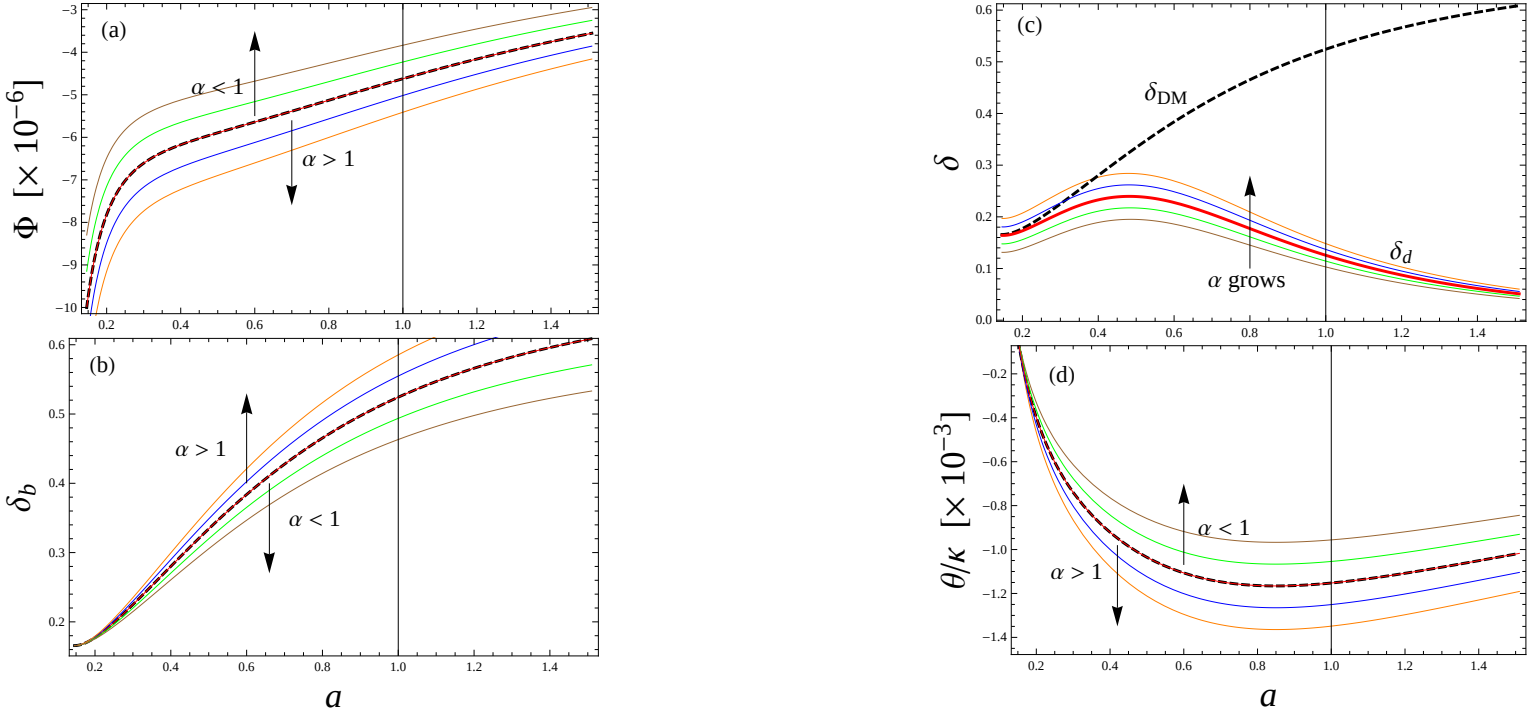

$$\rho_d \delta_d = \alpha \rho_{\rm dm} \delta_{\rm dm}, \qquad \rho_d (1 + w_d) \theta_d = \alpha \rho_{\rm dm} \theta_{\rm dm}$$

Beyond linear order...

$$T_{\mu\nu} = T^{(0)}_{\mu\nu} + T^{(1)}_{\mu\nu} + T^{(2)}_{\mu\nu} + \cdots$$

1. If $T^{\Lambda\rm CDM}_{\mu\nu} = T^{d}_{\mu\nu}$ then $T^{\Lambda\rm CDM\,(i)}_{\mu\nu} = T^{d\,(i)}_{\mu\nu}$
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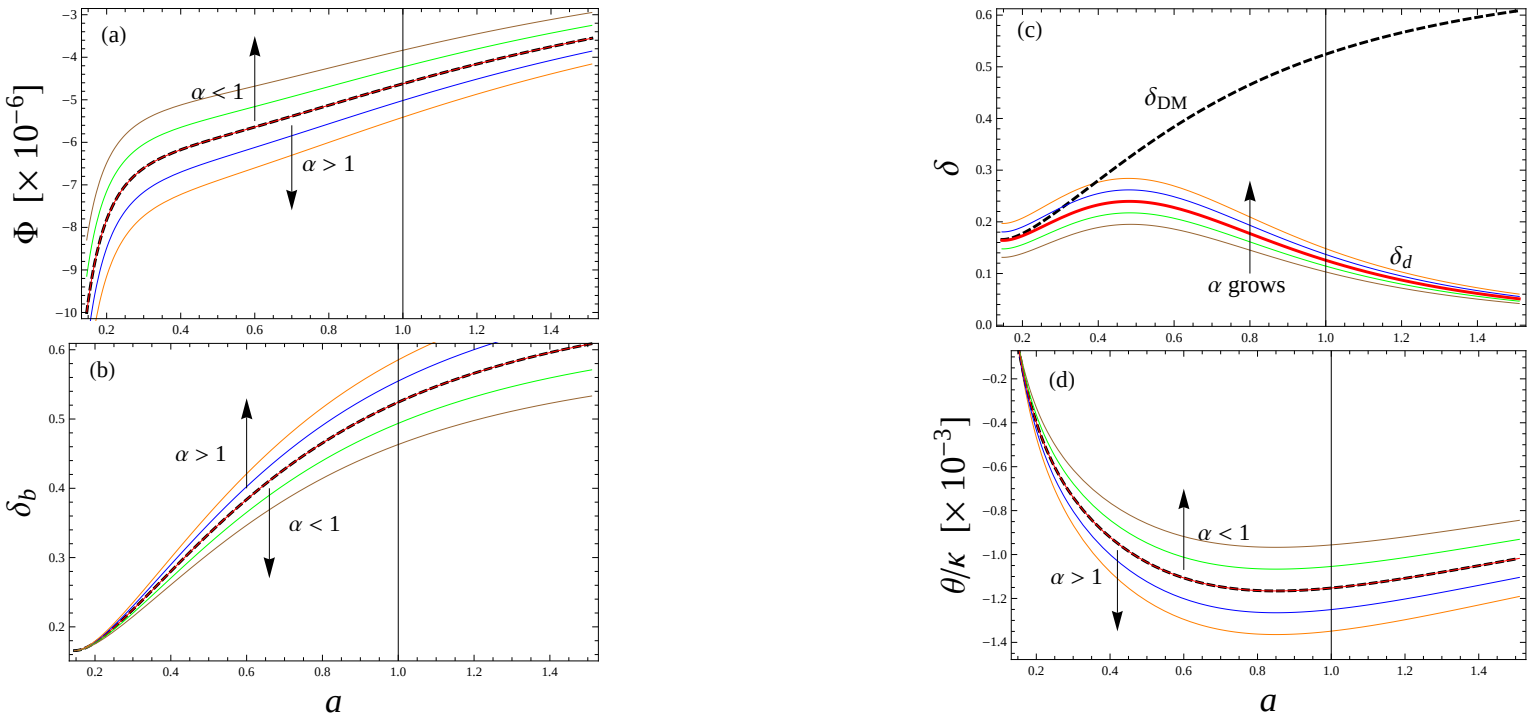
(A. Aviles and J.L. Cervantes-Cota, 2011b)



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The averaging problem

The smoothness of the Universe at large scales allows us to expand the energy-momentum tensor:

$$T^{(0)}_{\mu\nu} = \langle T_{\mu\nu} \rangle, \qquad G_{\mu\nu}(g^{(0)}) = \langle T_{\mu\nu} \rangle.$$

But this is not true in general due to the nonlinear character of gravity, it is well known that backreaction effects contribute to this last equation. (S.R. Green and R.M. Wald, 2011)

In fact, $\langle P \rangle = P(\langle \rho \rangle)$ is not necessarily true and non-linear instabilities occur (P. P. Avelino et al 2004, 2007, 2008).

However, there are two exceptions: the equation of state are $P =$ constant and $P = w\rho$, with w a constant. Ours is the former model and we are safe from this *averaging problem*.

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Multiple Interacting Cosmic Components

$$G^{\mu\nu} = 8\pi G \left(\sum_i T_i^{\mu\nu} + T_{\rm SM}^{\mu\nu} \right) \qquad \text{with} \qquad \nabla_\mu T_{\rm SM}^{\mu\nu} = 0.$$

i labels the different dark components.

$$\nabla_\mu T_i^{\mu\nu} = Q_i^\nu \qquad \longrightarrow \qquad \sum_i Q_i^\nu = 0, \qquad Q^\nu = \frac{1}{a}(q + \delta q)u^\nu + f^\nu$$

$$\dot{\rho}_i + 3\mathcal{H}(1 + w_i)\rho_i = q_i$$

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Interactions to the standard model

Couplings between cosmic components: baryons (b), photons (γ), dark fluid (d) ...

- Thomson scattering (up to quadrupole moment):

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Now we look for interactions between the dark sector and the standard model...
...to break the dark degeneracy?

- Electromagnetic inspired (Σ_I):

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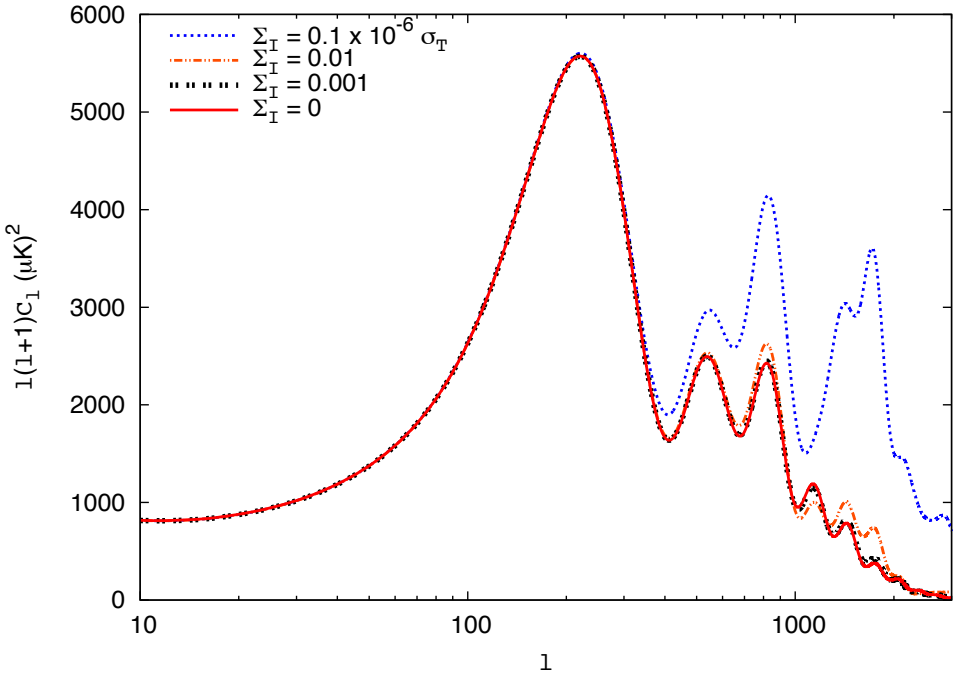
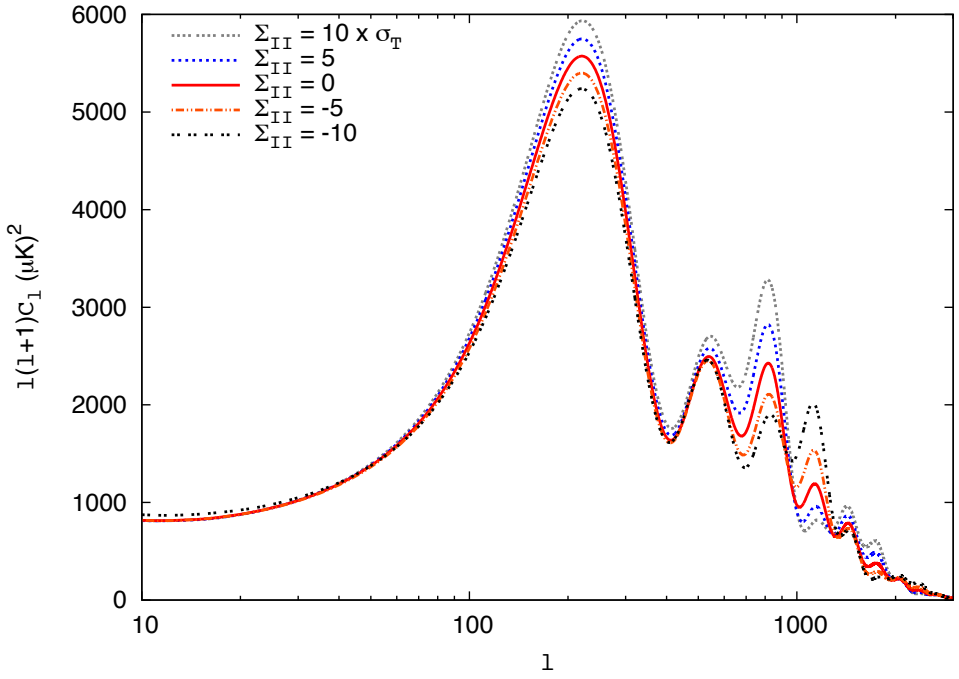
CAMB and COSMOMC

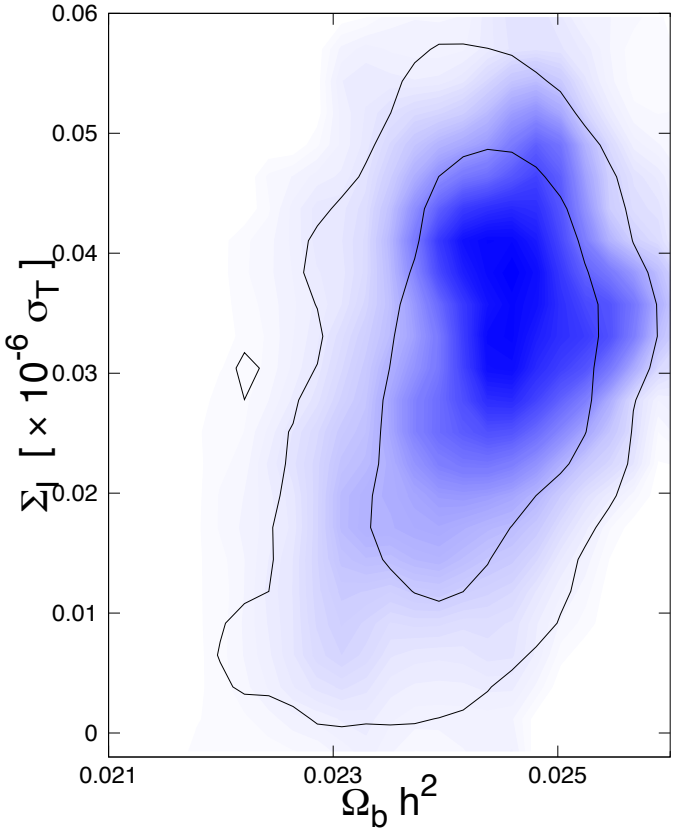




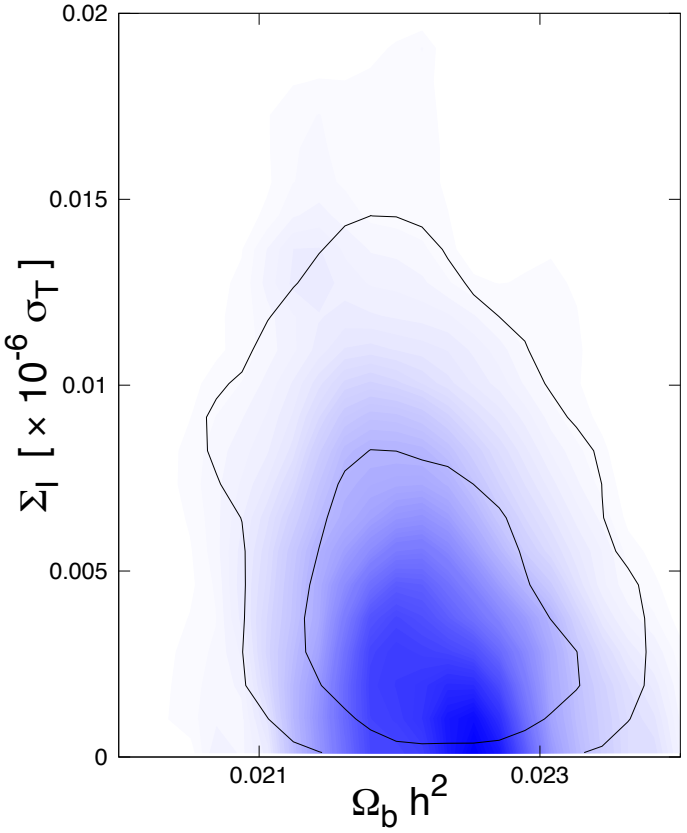
The *effective* thermalized cross section for interaction *II* is $a^2\Sigma_{II} \sim \Sigma_I$ at $z \sim 10^5$. Before this epoch interaction *I* dominates. Just before recombination, at $z \simeq 1100$, interactions *I* and *II* are smaller in strength than the Thomson interaction by about 9 and 5 orders of magnitude, respectively.

$$3.58 \times 10^{-22} < \frac{\Sigma_I}{m_d} < 8.68 \times 10^{-22} \ \frac{\mathrm{cm}^3/\mathrm{s}}{\mathrm{GeV}/c^2}.$$

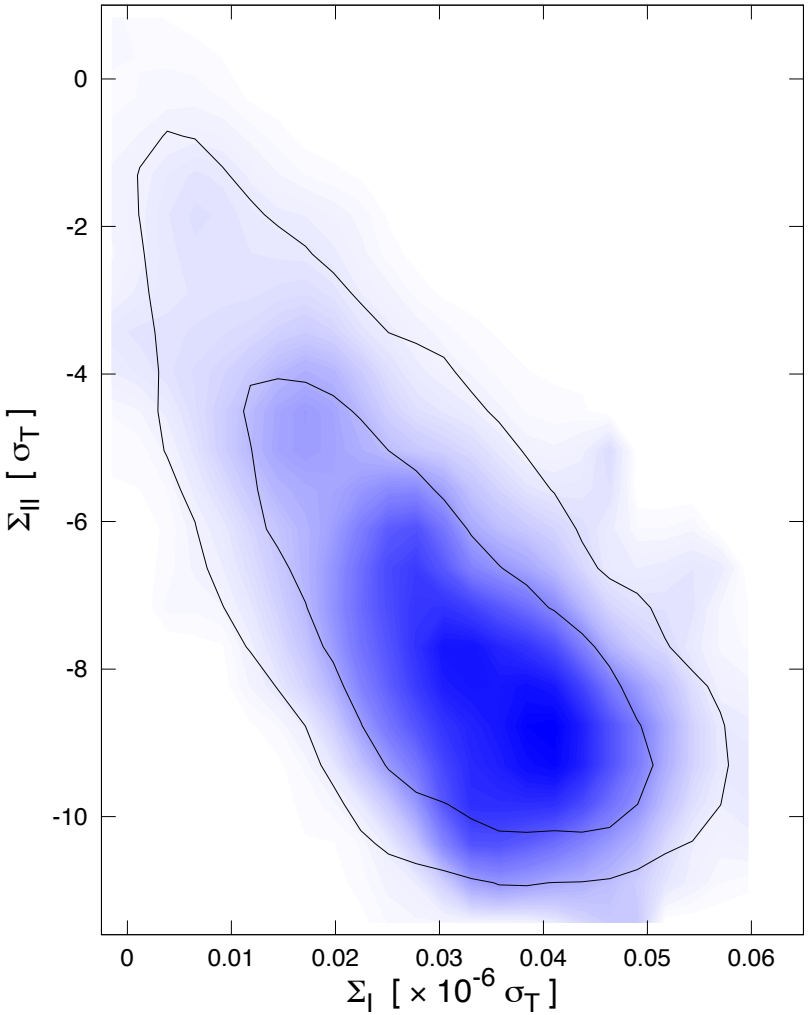
$$-1.94 \times 10^{-13} < \frac{\Sigma_{II}}{m_d} < -1.05 \times 10^{-13} \ \frac{\mathrm{cm}^3/\mathrm{s}}{\mathrm{GeV}/c^2}.$$

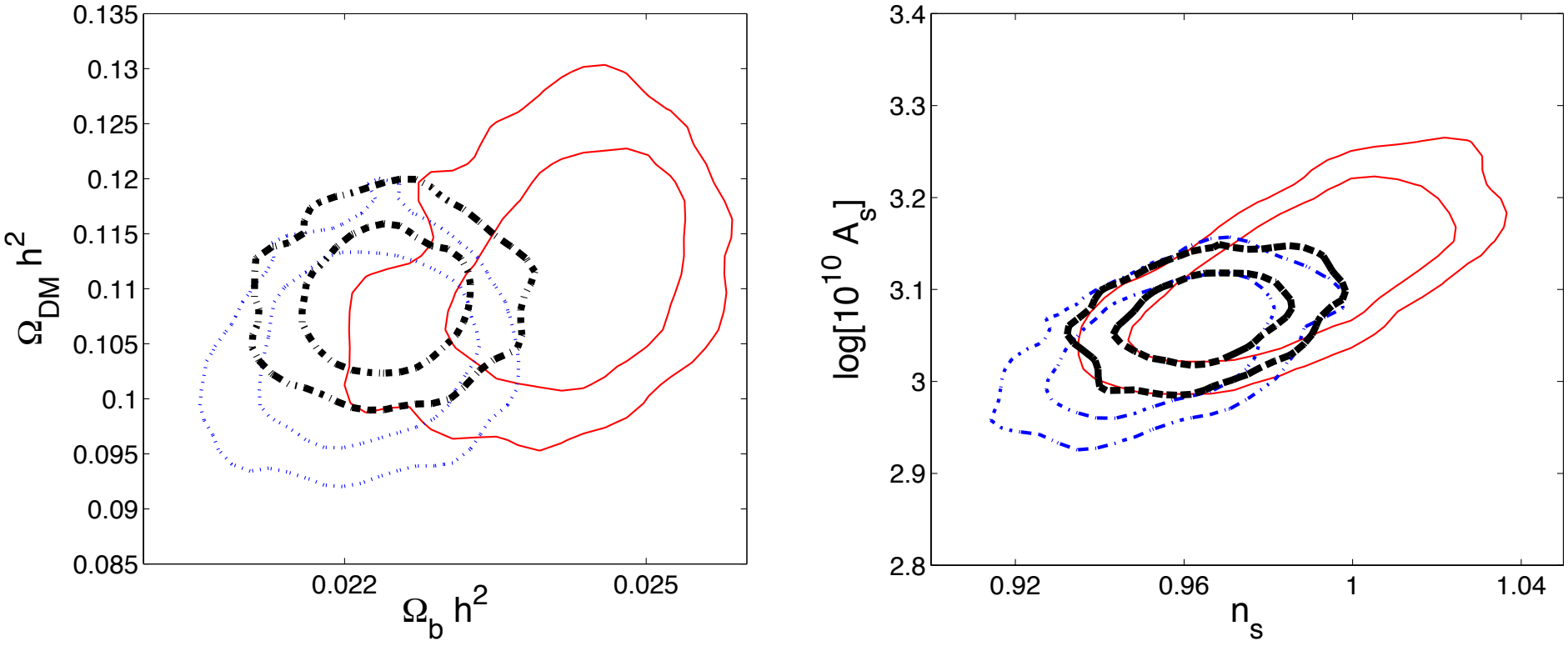


Using $\Sigma_I + \Sigma_{II}$

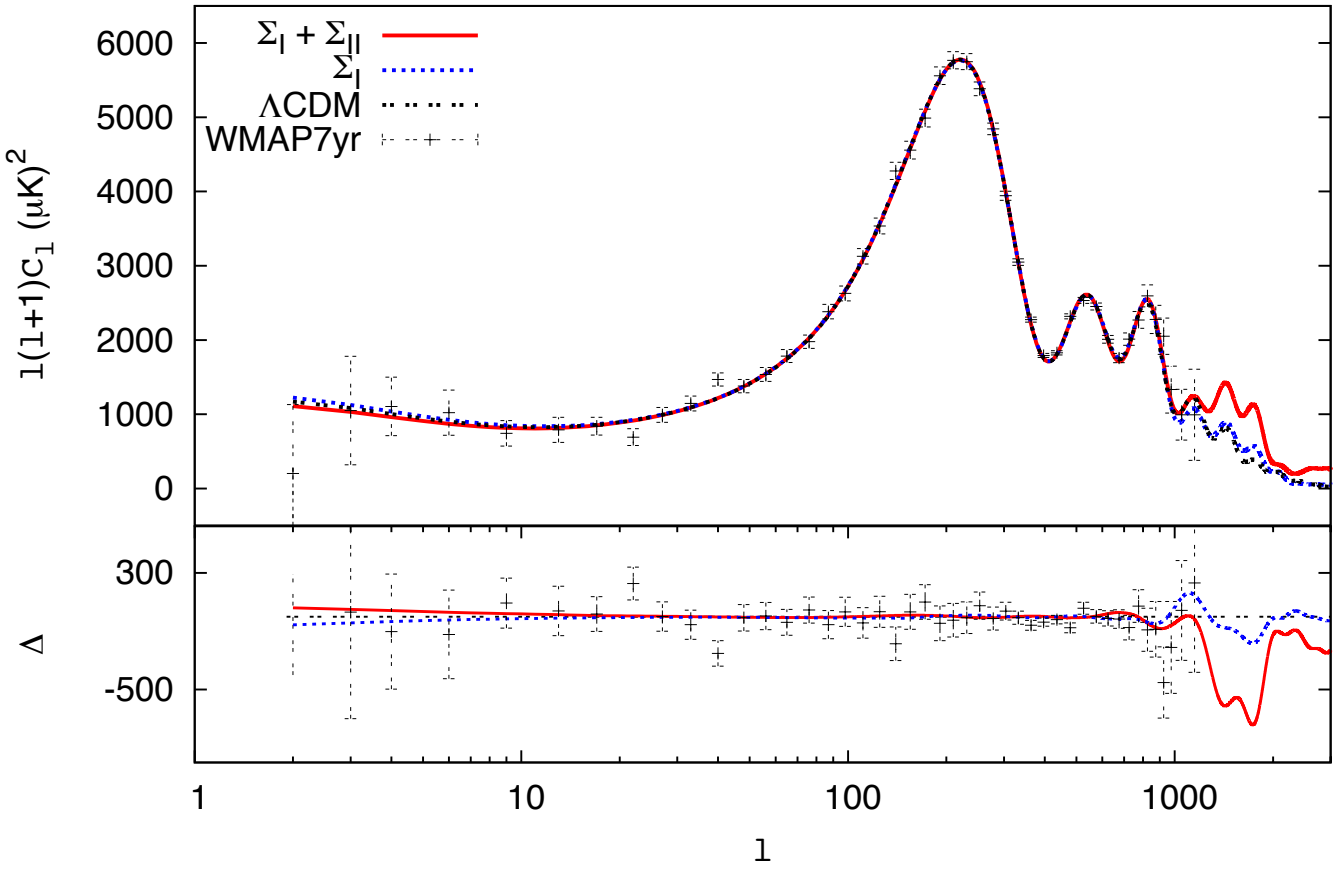


Σ_I only


0
-2
-4
-6
-8
-10
Σ_{II} [σ_T]
0
0.01
0.02
0.03
0.04
0.05
0.06
Σ_I [$\times 10^{-6}$ σ_T]



Red lines are for a model with Σ_I and $\Sigma_{//}$, blue for a model with only Σ_I, and black for ΛCDM.



CMB power spectrum for the mean estimated values stemming from CosmoMC.

Table: Summary of constraints. The upper panel contains the parameter spaces explored with MCMC for each one of the three models. The bottom panel contains derived parameters. The data used are the WMAP seven years data, Union 2 compilation and HST.

Parameter	Model $\Sigma_I + \Sigma_{II}$ [a]	Model Σ_I [a]	Model ΛCDM [a]
$10^2\Omega_b h^2$	$2.420^{+0.066}_{-0.064}$	$2.219^{+0.056}_{-0.056}$	$2.243^{+0.053}_{-0.053}$
$\Omega_c h^2$	$0.1114^{+0.0061}_{-0.0060}$	$0.1046^{+0.0047}_{-0.0049}$	$0.1089^{+0.0041}_{-0.0041}$
θ	$1.039^{+0.003}_{-0.003}$	$1.037^{+0.003}_{-0.003}$	$1.039^{+0.003}_{-0.003}$
τ	$0.08712^{+0.00565}_{-0.00721}$	$0.08646^{+0.0061}_{-0.0067}$	$0.08797^{+0.00618}_{-0.00627}$
$10^8\Sigma_I$ [b]	$2.910^{+1.169}_{-1.229}$	$0.4845^{+0.2980}_{-0.3824}$	$--$
Σ_{II} [b]	$-7.169^{+2.218}_{-1.959}$	$--$	$--$
n_s	$0.9869^{+0.0192}_{-0.0184}$	$0.9551^{+0.0135}_{-0.0137}$	$0.9651^{+0.0123}_{-0.0124}$
$\log[10^{10}A_s]$	$3.118^{+0.051}_{-0.051}$	$3.039^{+0.040}_{-0.040}$	$3.070^{+0.031}_{-0.033}$
A_{SZ} [c]	1.054 ± 0.578	0.9544 ± 0.5911	1.040 ± 0.574
Ω_d	$0.952^{+0.033}_{-0.033}$	$0.956^{+0.031}_{-0.030}$	$0.955^{+0.027}_{-0.027}$
$\mathcal{K}$	$0.296^{+0.042}_{-0.041}$	$0.270^{+0.034}_{-0.036}$	$0.291^{+0.034}_{-0.032}$
t_0	$13.64^{+0.12}_{-0.13}$ Gyr	$13.85^{+0.11}_{-0.12}$ Gyr	$13.79^{+1.16}_{-1.15}$ Gyr
Ω_Λ	$0.734^{+0.024}_{-0.024}$	$0.754^{+0.022}_{-0.021}$	$0.740^{+0.019}_{-0.020}$
H_0 [d]	$71.55^{+1.86}_{-1.91}$	$71.95^{+2.09}_{-1.96}$	$71.14^{+1.71}_{-1.85}$

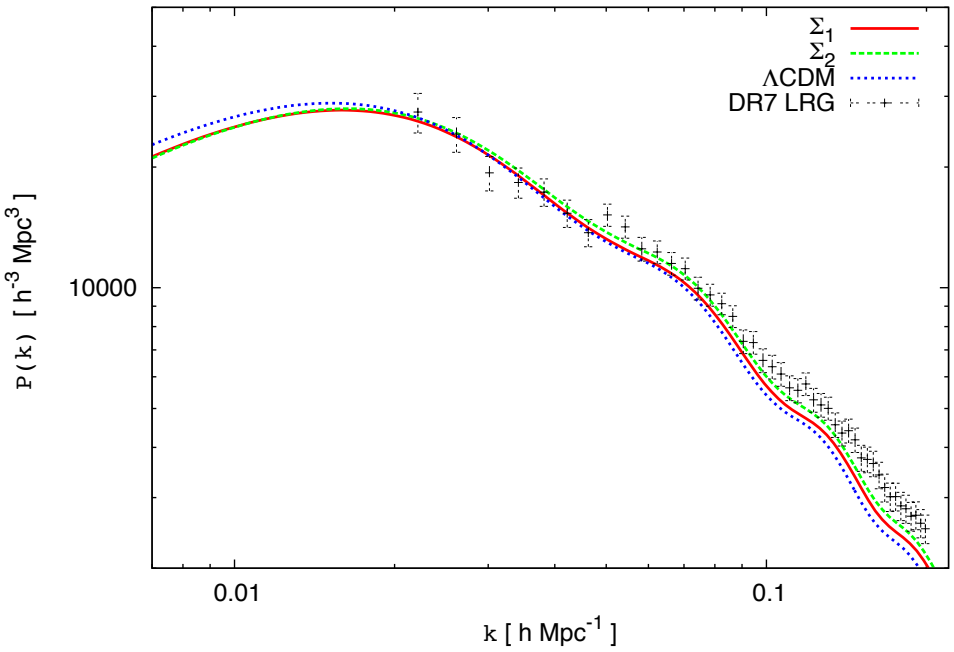
Notes.

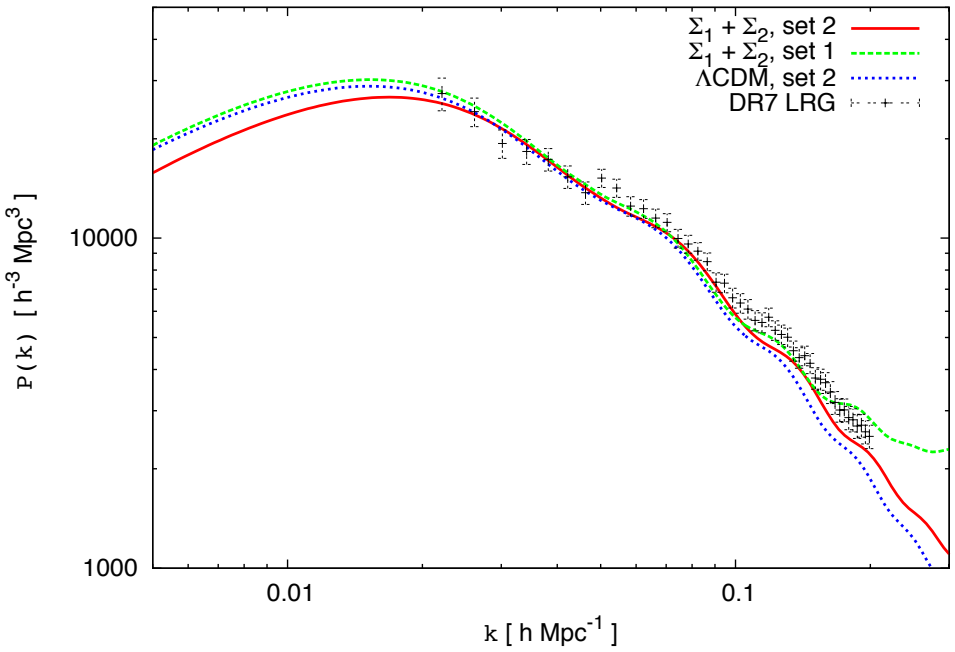
a. The mean values of the posterior distribution for each parameter. The quoted errors show the 68% confidence levels.

b. Σ_I and Σ_{II} are given in units of the Thomson scattering cross section times the speed of light, $\sigma_T = 6.65 \times 10^{-25}$ cm^2 and $c = 1$.

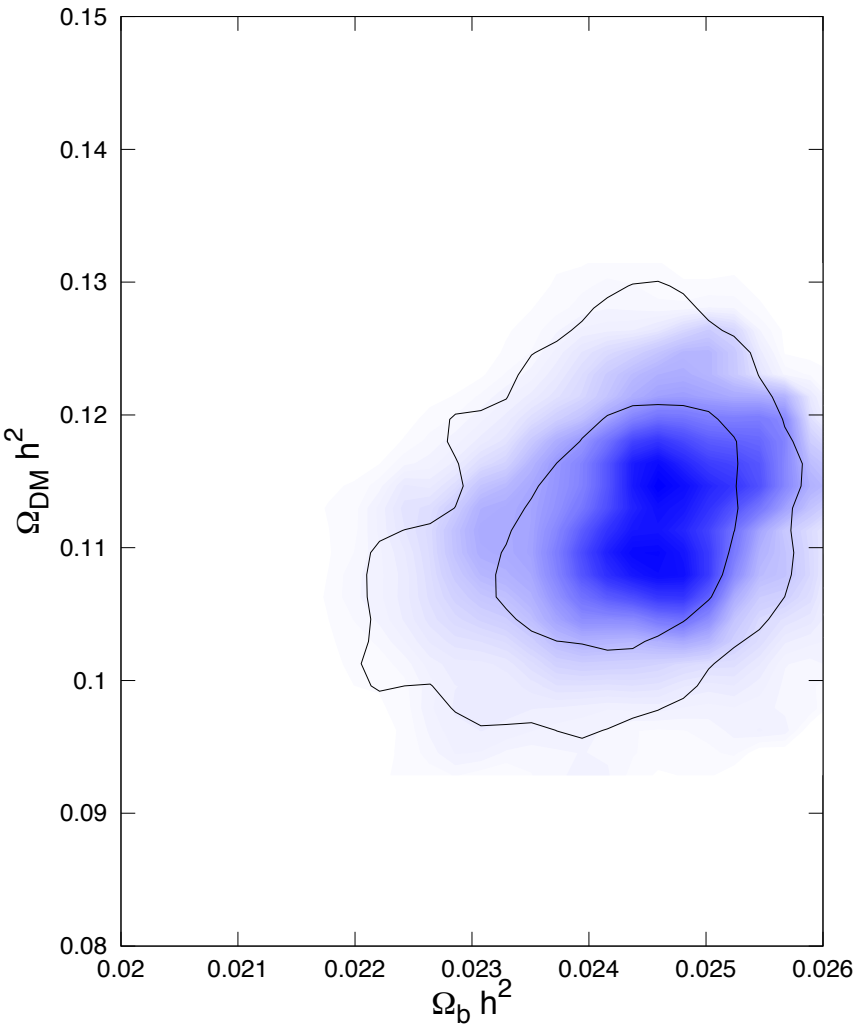
c. The quoted errors in A_{SZ} are the standard deviations of the distributions.

Matter Power spectrum

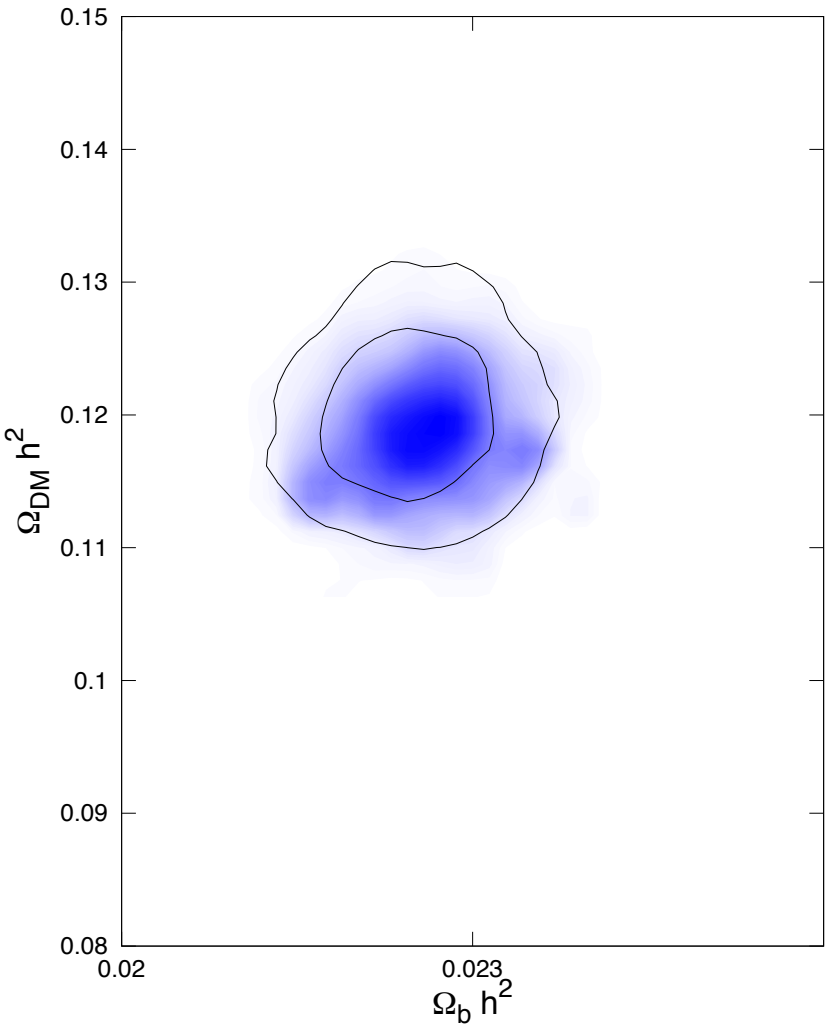




Set 1 includes WMAP7, HST, and UNION 2.
Set 2 includes WMAP7, HST, UNION 2, and SDSS DR7 LRG


0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
$\Omega_{DM}\,h^2$
0.02
0.021
0.022
0.023
0.024
0.025
0.026
$\Omega_b\,h^2$

Set 1


0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
$\Omega_{DM}\,h^2$
0.02
0.023
$\Omega_b\,h^2$

Set 2

breaking degeneracies?

But these interactions do not necessarily break the dark degeneracy. They can be understood as interactions between dark matter and baryons:

$$\begin{aligned}\dot{\delta}_{\rm dm} &= -\theta_{\rm dm} + 3\dot{\Phi} + \frac{\delta q_{\rm dm}}{\rho_{\rm dm}}, \\ \dot{\theta}_{\rm dm} &= -\mathcal{H}\theta_{\rm dm} + k^2\Psi + \frac{k^2 f_{\rm dm}}{\rho_{\rm dm}},\end{aligned}$$

with

$$\delta q_{\rm dm} = \delta q_d \qquad \text{and} \qquad f_{\rm dm} = f_d\,.$$

Summary

- Scalar field couplings to baryons can lead to the Dark Fluid. In this case the dark degeneracy is not exact, but tuning the parameters can make it as precise as desire.
- What is measured in gravitational experiments is the energy momentum tensor of the total dark sector. Any split into components (as in dark matter and dark energy) is arbitrary.
- A single fluid, with the simple definition $c_s^2 = 0$, leads to the same phenomenology as the ΛCDM model. Also, this Dark Fluid could be composed by a large zoo of particles with complicated interactions between them.
- Without non-gravitational interactions it is fundamentally impossible to elucidate the actual structure of the dark sector. Interactions to baryons could help, but not necessarily, since new degeneracies can appear.

Thanks!

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