16th Marcel Grossman - 2021, DE1 Session

# *Soft Dark Energy and Soft Dark Matter*

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# Goal and Motivation

- We examine the possibility of "soft cosmology", namely small deviations from the usual framework due to the effective appearance of soft-matter properties in the Universe sectors.

- [ Emmanuel N. Saridakis, 2105.08646]
- [ Emmanuel N. Saridakis et. al, to appear in arxiv soon]

## Goal and Motivation

- Standard cosmology has been proven very efficient, qualitatively and quantitatively, in describing the Universe evolution and properties at early and late times, as well as at large and small scales.

- Cosmology has now become an accurate science, and slight disagreements and tensions between theory and observations lead to a large variety of extensions and modifications of the concordance paradigm.

## Goal and Motivation

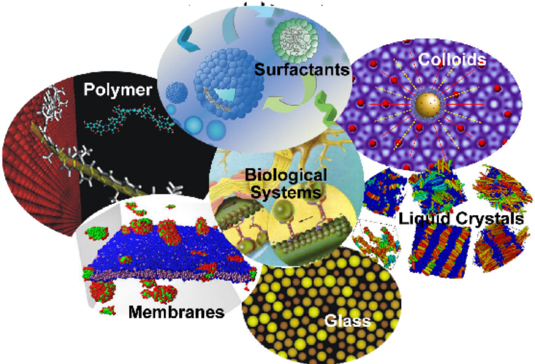
- Although in the usual ways of extensions one may add various novel fields, fluids, sectors, or alter the underlying gravitational theory [CANTATA Collaboration, 2105.12582], there is a rather strong assumption that is maintained in all of them:
- The sectors that constitute the Universe are simple, or equivalently that one can apply the physics, the hydrodynamics and thermodynamics of usual, “hard” matter.

## Soft matter

- In condensed matter physics it is well known that there is a large variety of “soft” matter forms, which are characterized by complexity, simultaneous co-existence of phases, entropy dominance, extreme sensitivity, viscoelasticity, etc.
- These properties arise effectively at intermediate scales due to scale-dependent effective interactions that are not present at the fundamental scales.

## Soft matter

- Soft matter is the one that has the properties of soft materials. Examples of soft materials are the polymers (plastic, rubber, polystyrene, lubricants etc), the colloids (paints, milk, ice-cream etc), the surfactants, granular materials, liquid crystals, gels, biological matter (proteins, RNA, DNA, viruses, etc), etc.



## Soft matter

- Although these examples of soft matter are very different from each other, they have some common properties and features that distinguish them from usual, hard, matter. Amongst others these include:

- Complexity (new qualitative properties arise at intermediate scales due to interactions that are not present at the fundamental scales).
- Co-existence of phases (they have different phase properties depending on the scale at one examines them, e.g at the same time they can be fluid at small scales and solid at large scales).
- Entropy dominance instead of energy dominance, Flexibility, Extreme sensitivity to reactions, Viscoelasticity, etc.

- We examine the possibility that the dark sectors of the universe may exhibit (intrinsically or effectively) slight soft properties, which could then lead to small corrections to the corcodance model.
- The analysis holds independently of the underlying gravitational theory, i.e it is valid both in the framework of general relativity as well as in modified gravity.

## Standard Cosmology

- Friedmann-Robertson-Walker (FRW) metric $ds^2 = dt^2 - a^2(t)\,\delta_{ij}dx^i dx^j$.
- Baryonic matter and radiation (i.e. all Standard Model particles), the dark matter sector, as well as the dark energy sector.
- Cosmological scales are suitably large in order to allow one to neglect the microphysics of the universe ingredients and describe them effectively through fluid dynamics and continuum flow. Hence, one can ignore the microscopic Lagrangians, and write their energy momentum tensors as $T^{(i)}_{\mu\nu} = (\rho_i + p_i)u_\mu u_\nu + p_i g_{\mu\nu}$,

## Standard Cosmology

- Friedmann equations

$$H^2 = \frac{\kappa^2}{3}(\rho_b + \rho_r + \rho_{dm} + \rho_{de}), \quad (1)$$

$$2\dot{H} + 3H^2 = -\kappa^2(p_b + p_r + p_{dm} + p_{de}), \quad (2)$$

- Conservation equation $\nabla^\mu T^{(tot)}_{\mu\nu} = \nabla^\mu \left[\sum_i T^{(i)}_{\mu\nu}\right] = 0$ in the case of FRW geometry and for non-interacting fluids gives rise to $\dot{\rho}_i + 3H(\rho_i + p_i) = 0$, while the extension to interacting cosmology through $\sum_i Q_i = 0$ and with $\dot{\rho}_i + 3H(\rho_i + p_i) = Q_i$.
- $p_i = w_i \rho_i$ with $w_i$ the equation-of-state parameter. ΛCDM cosmology is obtained for $\rho_{de} = -p_{de} = \Lambda/\kappa^2$, with Λ the cosmological constant.

## Standard Cosmology

- Small perturbations around the FRW background $ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1-2\Phi)\gamma_{ij}dx^i dx^j$.
-

$$\dot{\delta}_i + (1+w_i)\left(\frac{\theta_i}{a} - 3\dot{\Psi}\right) + 3H[c_{\rm eff}^{(i)2} - w_i]\delta_i = 0, \quad (3)$$

$$\dot{\theta}_i + H\left[1 - 3w_i + \frac{\dot{w}_i}{H(1+w_i)}\right]\theta_i - \frac{k^2 c_{\rm eff}^{(i)2}\delta_i}{(1+w_i)a} - \frac{k^2\Psi}{a} = 0, \quad (4)$$

  $\delta_i \equiv \delta\rho_i/\rho_i$ are the density perturbations and $\theta_i$ is the divergence of the fluid velocity. Furthermore, $c_{\rm eff}^{(i)2} \equiv \delta p_i/\delta\rho_i$ is the effective sound speed square of the $i$-th sector (it determines the amount of clustering).
- Poisson equation at sub-horizon scales $-\frac{k^2}{a^2}\Psi = \frac{3}{2}H^2\sum_i\left[\left(1+3c_{\rm eff}^{(i)2}\right)\Omega_i\delta_i\right]$.

## Soft Cosmology

- Soft Dark Energy:
  As a simple phenomenological model of soft dark energy we consider the case where dark energy has the usual EoS at large scales, namely at scales entering the Friedmann equations, but having a different value at intermediate scales, namely at scales entering the perturbation equations.
- We introduce the effective "softness parameter" $s_{de}$ of the dark energy sector. At cosmological, large scales (ls) dark energy has the usual EoS, namely $w_{de-ls}$, at intermediate scales (is) we have

$$w_{de-is} = s_{de} \cdot w_{de-ls}, \tag{5}$$

  and standard cosmology is recovered for $s_{de} = 1$. The background evolution remains unaffected

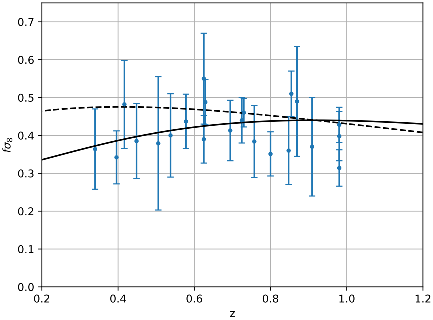
## Soft Cosmology

- Soft Dark Matter:
  We introduce the dark matter softness parameter $s_{dm}$ (standard cosmology is recovered for $s_{dm} = 1$) as:

$$w_{dm-is} + 1 = s_{dm} \cdot (w_{dm-ls} + 1), \tag{6}$$

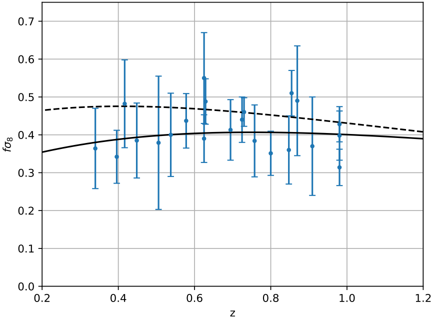
  (mind the difference in the parametrization comparing to soft dark energy, in order to handle the fact that the dark matter EoS at large scales $w_{dm-ls}$ is 0).
- Note that it can effectively arise just due to the dark-energy clustering even if dark energy is not soft.

# Soft Cosmology




The $f\sigma_8$ as a function of $z$. The dashed curve is for ΛCDM. The solid curve is for soft dark energy with $s_{de} = 1.1$, i.e. with $w_{de-ls} = -1$ and $w_{de-is} = -1.1$, and $c_{\rm eff}^{(de)} = 0.1$, while dark matter is standard (i.e. not soft) with $w_{dm} = 0$.

# Soft Cosmology

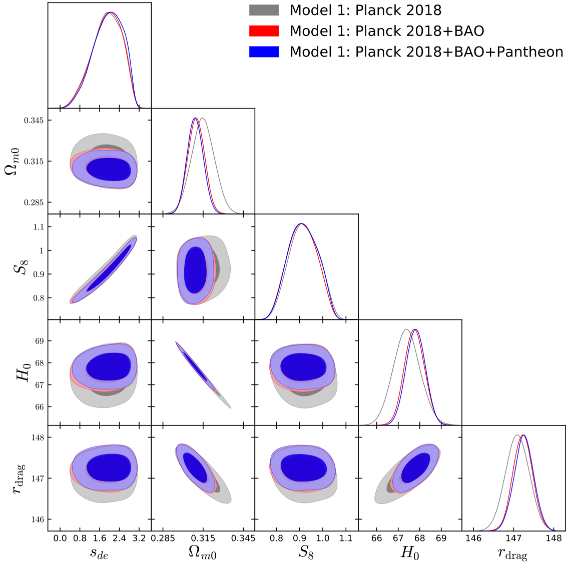



The $f\sigma_8$ as a function of $z$. The dashed curve is for ΛCDM. The solid curve is for soft dark matter with softness parameter $s_{dm} = 1.05$, i.e. for dark matter with $w_{dm-ls} = 0$ and $w_{dm-is} = 0.05$ (note that dark energy is not soft).

## Models

- Model 1: Soft DE only. With $w_{de-ls} = -1$, $w_{dm-ls} = 0$ and fixed $s_{dm} = 1$. Only $s_{de}$ is free.
- Model 2: Soft DE only. With DE following Chevallier-Polarski - Linder (CPL) parametrization, i.e with $w_{de-ls} = w_0 + w_a(1-a)$, and with $w_{dm-ls} = 0$ and fixed $s_{dm} = 1$. Only $s_{de}$ is free, and of course $w_0$, $w_a$.
- Model 3: Soft DM only. With $w_{de-ls} = -1$, fixed $s_{de} = 1$, and with $w_{dm-ls} = 0$. Only $s_{dm}$ is free.
- Model 4: Soft DM only. With DE following CPL, i.e with $w_{de-ls} = w_0 + w_a(1-a)$, fixed $s_{de} = 1$, and with $w_{dm-ls} = 0$. Only $s_{dm}$ is free.
- Model 5: Both soft DE and DM. i.e $w_{de-ls} = -1$, $w_{dm-ls} = 0$, but with both $s_{de}$ and $s_{dm}$ free parameters.
- Model 6: Both soft DE and DM. i.e $w_{de-ls} = w_0 + w_a(1-a)$, $w_{dm-ls} = 0$, but with both $s_{de}$ and $s_{dm}$ free parameters.

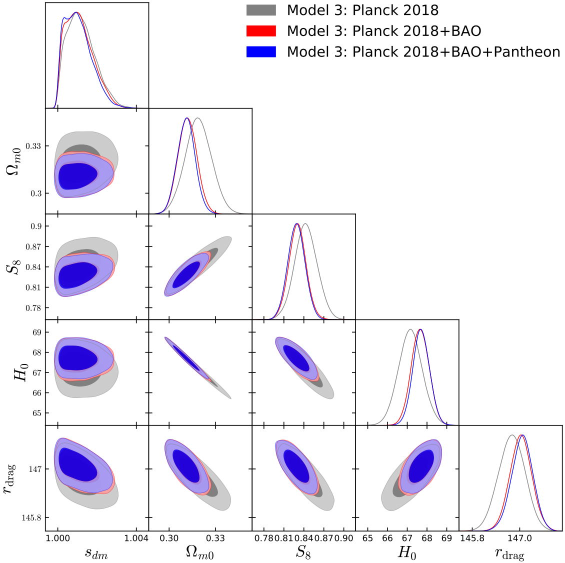
# Model 1: Soft DE only.



## Model 1: Soft DE only.

| Parameters | Planck 2018 | Planck 2018+BAO | Planck 2018+BAO+Pantheon |
|---|---|---|---|
| $w_{de-is}$ | $-1.90^{+0.51+1.06}_{-0.75-1.1}$ | $-1.90^{+0.51+1.09}_{-0.73-1.10}$ | $-1.95^{+0.51+1.04}_{-0.74-1.05}$ |
| $s_{de}$ | $1.77^{+0.71+1.12}_{-0.78-1.11}$ | $1.77^{+0.71+1.10}_{-0.78-1.14}$ | $1.86^{+0.69+1.05}_{-0.74-1.15}$ |
| $\Omega_{m0}$ | $0.315^{+0.0086+0.017}_{-0.0085-0.016}$ | $0.310^{+0.0062+0.012}_{-0.0063-0.012}$ | $0.309^{+0.0059+0.012}_{-0.0059-0.011}$ |
| $\sigma_8$ | $0.898^{+0.064+0.121}_{-0.069-0.114}$ | $0.898^{+0.064+0.115}_{-0.068-0.115}$ | $0.902^{+0.066+0.119}_{-0.070-0.114}$ |
| $H_0$ [Km/s/Mpc] | $67.40^{+0.60+1.25}_{-0.67-1.19}$ | $67.76^{+0.46+0.91}_{-0.49-0.88}$ | $67.81^{+0.44+0.86}_{-0.44-0.86}$ |
| $S_8$ | $0.920^{+0.068+0.117}_{-0.065-0.118}$ | $0.912^{+0.066+0.115}_{-0.064-0.116}$ | $0.916^{+0.069+0.121}_{-0.066-0.117}$ |
| $z_{\rm eq}$ | $3400.70^{+31.10+59.74}_{-30.67-58.92}$ | $3383.84^{+22.98+44.59}_{-23.29-44.62}$ | $3380.79^{+22.46+44.32}_{-22.38-42.96}$ |
| $r_{\rm drag}$ | $147.09^{+0.30+0.57}_{-0.29-0.57}$ | $147.23^{+0.24+0.48}_{-0.24-0.47}$ | $147.26^{+0.24+0.47}_{-0.24-0.47}$ |
| $\Omega_{m0}h^2$ | $0.1430^{+0.0013+0.0025}_{-0.0013-0.0025}$ | $0.1422^{+0.00096+0.0019}_{-0.00097-0.0019}$ | $0.1421^{+0.00094+0.0019}_{-0.00094-0.0018}$ |
| $r_{\rm drag}h$ | $99.15^{+1.07+2.12}_{-1.08-2.04}$ | $99.76^{+0.80+1.54}_{-0.80-1.52}$ | $99.86^{+0.77+1.48}_{-0.76-1.49}$ |

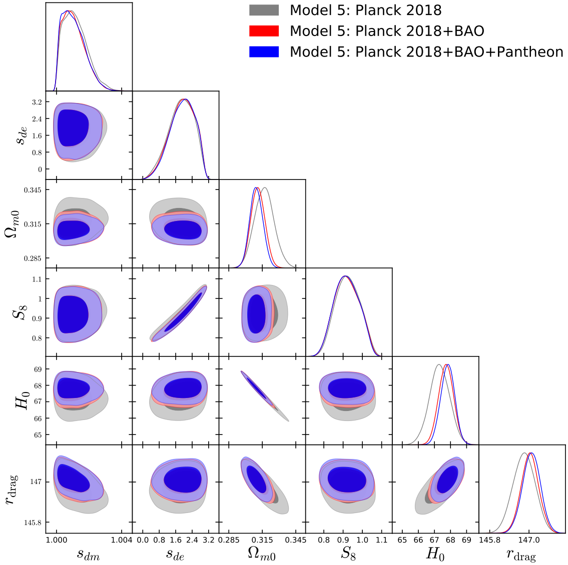
# Model 3: Soft DM only



# Model 3: Soft DM only

| Parameters | Planck 2018 | Planck 2018+BAO | Planck 2018+BAO+Pantheon |
|---|---|---|---|
| $w_{dm-is}$ | $0.0012^{+0.00051+0.0013}_{-0.00094-0.0012}$ | $0.0011^{+0.00040+0.0013}_{-0.00098-0.0011}$ | $0.0010^{+0.00033+0.0012}_{-0.00099-0.0010}$ |
| $s_{dm}$ | $1.00120^{+0.00074+0.00156}_{-0.00075-0.00111}$ | $1.00110^{+0.00072+0.00151}_{-0.00073-0.00103}$ | $1.00104^{+0.00069+0.00149}_{-0.00071-0.00099}$ |
| $\Omega_{m0}$ | $0.319^{+0.0085+0.017}_{-0.0085-0.017}$ | $0.312^{+0.0060+0.012}_{-0.0061-0.012}$ | $0.311^{+0.0056+0.011}_{-0.0058-0.011}$ |
| $\sigma_8$ | $0.818^{+0.0079+0.016}_{-0.0087-0.016}$ | $0.814^{+0.0076+0.015}_{-0.0076-0.015}$ | $0.814^{+0.0077+0.016}_{-0.0077-0.015}$ |
| $H_0$ [Km/s/Mpc] | $67.16^{+0.60+1.21}_{-0.60-1.17}$ | $67.65^{+0.45+0.87}_{-0.44-0.89}$ | $67.71^{+0.42+0.83}_{-0.41-0.82}$ |
| $S_8$ | $0.843^{+0.017+0.034}_{-0.018-0.034}$ | $0.830^{+0.013+0.026}_{-0.013-0.026}$ | $0.829^{+0.013+0.025}_{-0.013-0.025}$ |
| $z_{\rm eq}$ | $3421.37^{+31.92+62.90}_{-31.37-62.66}$ | $3395.57^{+23.22+46.42}_{-23.43-46.30}$ | $3392.24^{+22.21+45.22}_{-22.60-44.13}$ |
| $r_{\rm drag}$ | $146.80^{+0.33+0.64}_{-0.34-0.66}$ | $147.03^{+0.28+0.55}_{-0.28-0.55}$ | $147.06^{+0.27+0.52}_{-0.27-0.55}$ |
| $\Omega_{m0}h^2$ | $0.1438^{+0.0013+0.0026}_{-0.0013-0.0026}$ | $0.1427^{+0.00097+0.0019}_{-0.00098-0.0019}$ | $0.1426^{+0.00093+0.0019}_{-0.00095-0.0018}$ |
| $r_{\rm drag}h$ | $98.59^{+1.05+2.12}_{-1.05-2.05}$ | $99.47^{+0.78+1.51}_{-0.77-1.52}$ | $99.58^{+0.74+1.46}_{-0.72-1.45}$ |

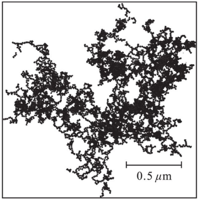
# Model 6: Both soft DE and DM.

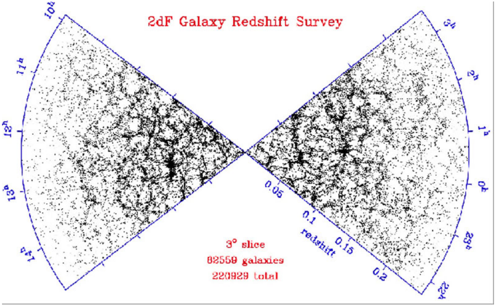


## Model 6: Both soft DE and DM.

| Parameters | Planck 2018 | Planck 2018+BAO | Planck 2018+BAO+Pantheon |
|---|---|---|---|
| $w_{dm-is}$ | $0.0012^{+0.00046+0.0013}_{-0.00098-0.0012}$ | $0.0011^{+0.00035+0.0013}_{-0.0010-0.0011}$ | $0.0011^{+0.00034+0.0013}_{-0.0010-0.0011}$ |
| $w_{de-is}$ | $-1.87^{+0.53+1.10}_{-0.76-1.13}$ | $-1.92^{+0.52+1.06}_{-0.76-1.08}$ | $-1.93^{+0.52+1.04}_{-0.73-1.07}$ |
| $s_{de}$ | $1.72^{+0.72+1.15}_{-0.69-1.09}$ | $1.76^{+0.73+1.14}_{-0.77-1.16}$ | $1.77^{+0.72+1.13}_{-0.78-1.09}$ |
| $s_{dm}$ | $1.00116^{+0.00074+0.00161}_{-0.00075-0.00109}$ | $1.00108^{+0.00072+0.00155}_{-0.00072-0.00102}$ | $1.00105^{+0.00070+0.00152}_{-0.00071-0.00099}$ |
| $\Omega_{m0}$ | $0.317^{+0.0086+0.018}_{-0.0088-0.017}$ | $0.311^{+0.0063+0.012}_{-0.0063-0.012}$ | $0.310^{+0.0056+0.012}_{-0.0062-0.011}$ |
| $\sigma_8$ | $0.900^{+0.065+0.117}_{-0.069-0.115}$ | $0.904^{+0.066+0.124}_{-0.072-0.116}$ | $0.905^{+0.064+0.122}_{-0.070-0.114}$ |
| $H_0$ [Km/s/Mpc] | $67.32^{+0.63+1.23}_{-0.61-1.24}$ | $67.73^{+0.46+0.92}_{-0.46-0.91}$ | $67.82^{+0.43+0.83}_{-0.43-0.85}$ |
| $S_8$ | $0.925^{+0.068+0.118}_{-0.066-0.118}$ | $0.920^{+0.067+0.125}_{-0.072-0.119}$ | $0.919^{+0.065+0.124}_{-0.072-0.116}$ |
| $z_{\rm eq}$ | $3413.94^{+32.21+64.78}_{-33.06-63.28}$ | $3393.38^{+23.59+47.04}_{-23.84-46.41}$ | $3388.25^{+22.04+44.42}_{-24.18-43.62}$ |
| $r_{\rm drag}$ | $146.85^{+0.34+0.65}_{-0.34-0.66}$ | $147.03^{+0.27+0.53}_{-0.27-0.53}$ | $147.08^{+0.27+0.53}_{-0.27-0.54}$ |
| $\Omega_{m0}h^2$ | $0.1435^{+0.0013+0.0027}_{-0.0014-0.0026}$ | $0.1426^{+0.00099+0.0020}_{-0.0010-0.0019}$ | $0.1424^{+0.00092+0.0019}_{-0.0010-0.0018}$ |
| $r_{\rm drag}h$ | $98.86^{+1.10+2.16}_{-1.08-2.15-2.77}$ | $99.58^{+0.80+1.58}_{-0.80-1.55}$ | $99.75^{+0.74+1.44}_{-0.76-1.46}$ |

# Soft Cosmology




The fractal dimension has been experimentally found to cover all the range from 1 to 3 according to different materials (e.g. colloids of gold nanoparticle in aqueous media give $d_f = 1.75 \pm 0.05$ for diffusion-limited kinetics [S. Lazzari, et.al., Adv. Coll. Int. Sc. 235, 1.]). On the other hand, the large scale structure and the galaxy distribution in the Universe has a fractal dimension $d_f = 1.63 \pm 0.20$ [S. Teles et.al., Phys. Lett. B 813, 136034 (2021)].

## Conclusions

- We examined the possibility of “soft cosmology”, namely small deviations from the usual framework due to the effective appearance of soft properties in the Universe sectors.
- Although the background evolution remains unaffected, even a slight softness at intermediate scales can improve the clustering behavior and alleviate e.g. the $f\sigma_8$ tension.
- Confrontation with observations seem to favour soft cosmology.
- Cuspy halo problem, Dwarf galaxy problem, etc?
- In order to incorporate complexity and estimate the scale-dependent behavior of the EoS’s from first principles we should revise and extend the cosmological perturbation theory and perform a detailed mesoscopic statistical mechanical analysis.

THANK YOU!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