Dark Goo: Bulk viscosity as an alternative to dark energy

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Outline

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Motivation and Objectives

- Experimental: Results from SNIa, CMB peaks, BAO, LSS

  $\rightarrow$ Universe accelerates now
  $\rightarrow$ Universe is made of 70% of a dark "something"

- Theoretical: Many models/mechanisms on the market (cosmological constant, quintessence, etc)

  $\rightarrow$ None seems satisfactory
  $\rightarrow$ Either suffer from severe fine tuning problems, lead to instabilities, are ruled out or are waiting further analysis

- Bottom line: Door is opened for new models to explain the acceleration
- Objective: Focus on a model that includes bulk viscosity

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Bulk Viscosity and Expansion

- Hydrodynamics is a theory of "fluid cells" (effective theory)
- Bulk viscosity characterizes deviations from local equilibrium $\rightarrow$ Modifies the energy-momentum tensor
- Effect of bulk viscosity on a FRW expansion[1]

$$\dot{\rho} = -\frac{3\dot{a}}{a}(\rho + p_{\text{eff}})$$

where $p_{\text{eff}} = p - 3\zeta\frac{\dot{a}}{a}$ and $\zeta > 0$ is the bulk viscosity

- Remarks:
  - Shift between EOS and measured pressures
  - Gives a negative contribution to the pressure $\rightarrow$ May act as dark energy
  - ζ must be computed from a more fundamental theory

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The "Dark Goo" Model (1)

- Need some microscopic physics to "personify" ζ
- SM particles cannot produce any ζ in the late universe
  $\rightarrow$ Need to add a new energy component to the universe
- The model:
  - Add self-interacting scalar particles with Lagrangian:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_0^2\phi^2 - \frac{\lambda}{4!}\phi^4$$

  - Assumptions:
    - Scalar and SM particles are in thermal equilibrium in the early universe, and decouple from each other afterward
    - Hydrodynamics is valid until the present time
    - Weak coupling (technical necessity)
  - Free parameters: λ, m_0, $\epsilon \equiv T_s/T_\gamma$
  - Remark: Very different from quintessence or (generalized) Chaplygin gas models[2]

[2] Fabris et al. (2006), Colistete et al. (2007), Li and Barrow (2009), Velten and Schwarz (2011)

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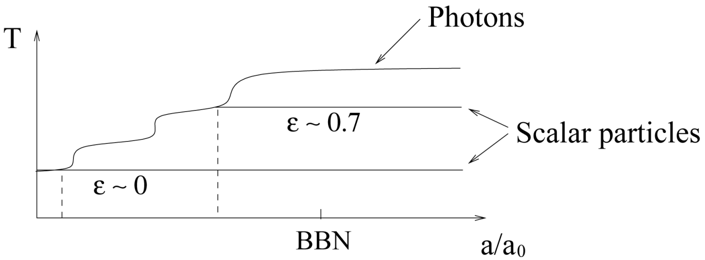
The "Dark Goo" Model (2)



- ϵ controls the scalar-photon decoupling time
- Decoupling before BBN $\rightarrow \epsilon < 0.7$
- Scalars add relativistic degrees of freedom (N_{eff})
  $\rightarrow$ Might affect the physics of the CMB

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The "Dark Goo" Model (3)

- Pressure and density for the scalar component are:

$$p_s = \frac{m_0^2 T_s^2}{2\pi^2} K_2\left(\frac{m_0}{T_s}\right) + O(\lambda T_s^4)$$

$$\rho_s = \frac{m_0^2 T_s}{2\pi^2}\left[T_s K_2\left(\frac{m_0}{T_s}\right) - \frac{m_0}{2}\left(K_1\left(\frac{m_0}{T_s}\right) + K_3\left(\frac{m_0}{T_s}\right)\right)\right]$$

- Bulk viscosity for the scalar component is[3]:

$$\zeta = \left(\frac{\tilde{m}^4}{\lambda^4 m_{\rm th}}\right)\left(\frac{m_{\rm th}}{T_s}\right)^{\kappa_3} e^{\kappa_1} e^{\kappa_2 m_{\rm th}/T_s}$$

where $m_{\rm th}^2 = m_0^2 + \lambda T_s^2/24$ and $\tilde{m}^2 = m_0^2 - \beta(\lambda) T_s^2/48$

- Physics of bulk viscosity:
  - Proportional to the mean free time
  - Proportional to breaking of conformal invariance

[3] Jeon (1995)

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Validity of the Hydrodynamic Approximation

- For the concept of bulk viscosity to make sense, hydrodynamics must be valid
- The assumptions of hydrodynamics are:
  - Local equilibrium:

$$\frac{\Gamma_s}{H} > 1 \rightarrow \frac{m_0 \lambda^4 e^{-3m_0/T_s}}{H} > 1$$

  - Small inhomogeneities and gravitational instabilities:
    $\rightarrow$ Results show that linear perturbations are well behaved
  - No cavitation:

$$p_{b\,\mathrm{max}} > \rho_{\mathrm{DE}} \rightarrow \lambda^{3/2} m_0^3 T_s > \left(\frac{3}{16\pi}\right)^{1/2} \rho_{\mathrm{DE}}$$

where $p_{b\,\mathrm{max}}$ is the tensile strength of the scalar fluid

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Commercial Break

- New public code (written by J. Lesgourgues) that computes cosmological perturbations and CMB physics:

C	*osmic*
L	*inear*
A	*nisotropy*
S	*olving*
S	*ystem*

- All numerical results presented here are obtained using this code, sligthtly modified to take into account bulk viscous effects
- Website: http://lesgourg.web.cern.ch/lesgourg/class.html
- Go get it, it's FREE![4]

[4] Limited time offer. Available while supplies last. Not responsible for misuse of the code. Do physics responsibly.

- Parameters used in CLASS:

$$(\underbrace{\epsilon, \lambda, m_0}_{\text{Scalar sector}}, \underbrace{\Omega_b, h, A_s, n_s, \tau}_{\text{CDM sector}})$$

where	Ω_b :	Baryon density fraction
	h :	Reduced Hubble parameter
	A_s :	Primordial spectrum amplitude
	n_s :	Primordial spectrum tilt
	τ :	Reionization optical depth

- More convenient to use:

$$(\epsilon, \lambda, \Omega_m, \Omega_b, h, A_s, n_s, \tau)$$

where $\Omega_b + \Omega_{\text{CDM}} + \Omega_s = 1$, $\Omega_m \equiv 1 - \Omega_s$ and Ω_s is the scalar density fraction

- Remark: m_0 can be viewed as a function of $(\epsilon, \lambda, \Omega_m, h)$

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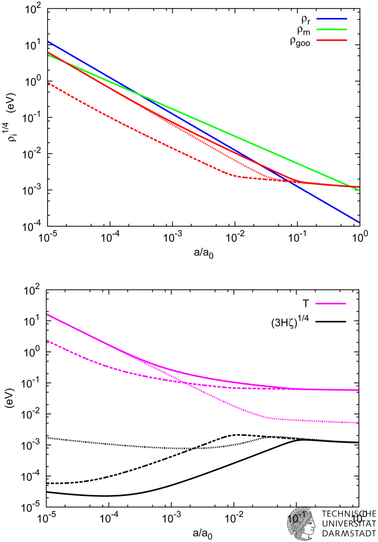
- Integrate the Friedmann equations (including bulk viscosity)
- Parameters $(\epsilon, \lambda, \Omega_m, \Omega_b, h)$:
  - Full: $(0.7, 0.25, 0.28, 0.05, 0.72)$
  - Dashed: $(0.1, 0.25, 0.28, 0.05, 0.72)$
  - Dotted: $(0.7, 10^{-4}, 0.28, 0.05, 0.72)$

(correspond to $m_0 = 1.0$, 1.0, 0.027 eV)

- Evolution of densities:
  - $T_s \gg m_0$: $\rho_s \propto a^{-4}$, $3H\zeta \ll \rho_s$
  - $T_s \sim m_0$: $\rho_s \propto a^{-3}$
  - $T_s \ll m_0$: $3H\zeta \sim \rho_s$
- Remarks:
  - Tend to a fixed point with $p_{\rm eff} = -|w|\rho_s$
  - Fixed point not reached immediately



Results for the Background Evolution (2)

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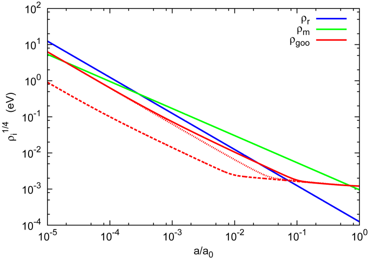
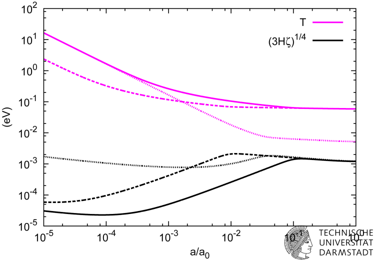
- Varying ϵ:
  - $\epsilon \searrow \Rightarrow T_s \searrow$
    $\Rightarrow$ DE domination happens sooner
  - ϵ has effects only at high T
    $\rightarrow$ Increases relativistic d.o.f.

- Vayring λ (and thus m_0):
  - $\lambda \searrow \Rightarrow m_0 \searrow$
    $\Rightarrow$ DE domination happens later
  - $\lambda \nearrow \Rightarrow$ Matter-like period $\nearrow$
    $\rightarrow$ Unified model of DM an DE?





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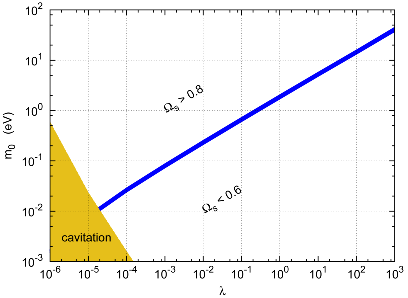

- m_0 can be viewed as a function of $(\epsilon, \lambda, \Omega_m, h)$
- Can check that m_0 is independent of ϵ
- Explore parameter space: $(\Omega_m \in [0.2, 0.4]$, $h \in [0.65, 0.75])$ (thin blue band)
- Results with hydro constraints:
  $\lambda > 2 \times 10^{-5}$ and $m_0 > 0.01$ eV
  $\lambda \in [2 \times 10^{-5}, 1]$ and $m_0 \in [0.01, 2]$ eV

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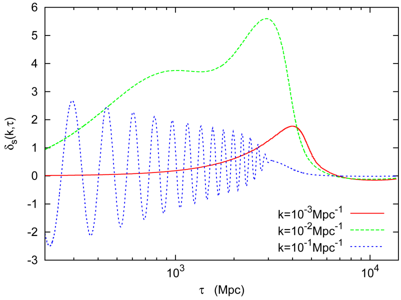
Results for Perturbations (1)



- Density perturbations for 3 modes with $(\epsilon, \lambda) = (0.7, 0.25)$
- All modes are damped out at $\tau \approx 3000$ Mpc
  $\rightarrow$ Equations are stable
- Dark Goo model is similar to any model with negligible perturbations at late times (e.g. wCDM)

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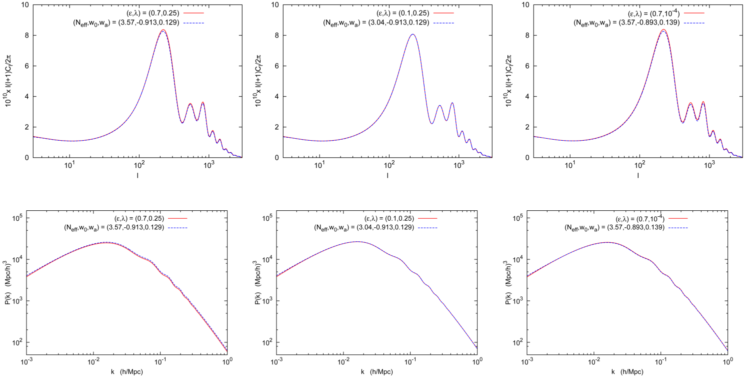
Results for Perturbations (2)



- Rad. domination: Extra scalar d.o.f. evolve differently than decoupled neutrinos (i.e. no anisotropic stress tensor)
- Expect larger oscillation amplitudes $\rightarrow$ Higher CMB peaks
- For large $\epsilon = 0.7$: Dark Goo peaks $>$ wCDM peaks
- For small $\epsilon = 0.1$: No significant difference

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Summary of Results

- Effective neutrino number (at early times):

$$N_{\rm eff} = 3.04 + 2.2\epsilon^4$$

  Model can account for any value in the range $3.04 < N_{\rm eff} < 3.62$ (or $0 < \epsilon < 0.7$)

- Equation of state parameter:

$$w_0 = -0.9085 + 0.21(\Omega_m - 0.3) + 3\lambda^{-0.4}10^{-4}$$

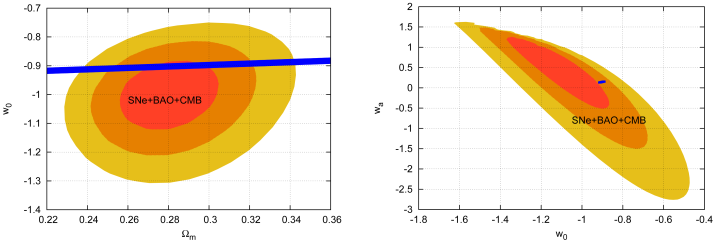
- Time dependence of the dark energy component:

$$w_a = 0.129 + 0.02(\Omega_m - 0.3) + \lambda^{-0.5}10^{-4}$$

  where the wCDM parametrization used is[5] $w(a) = w_0 + w_a(1 - a/a_0)$

[5] Chevallier and Polarski (2000), Linder (2002)

Compatibility with Observations



- Left panel: Vary $h \in [0.714, 0.724]$, $\lambda \in [2 \times 10^{-5}, 1]$
- Right panel: Vary h, λ in same range, $\Omega_m \in [0.245, 0.306]$
- Bottom line:
  - Dark Goo model compatible with current data
  - Dark Goo model predicts $(w_0, w_a) \sim (-0.9, 0.13)$

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Conclusion

- Features of the Dark Goo model:
  - First principles computation of bulk viscosity
  - Discussion in terms of physical properties of particles
  - Model is falsifiable (parameter space bounded)
  - Less fine tuning (compared to quintessence, for example)
- Future work:
  - More rigorous study of hydro assumptions (cavitation in particular)
  - Extend the model to include Dark Matter?

But really, what is Dark Goo?

Example of a Dark Goo filled universe...

THANK YOU!!!