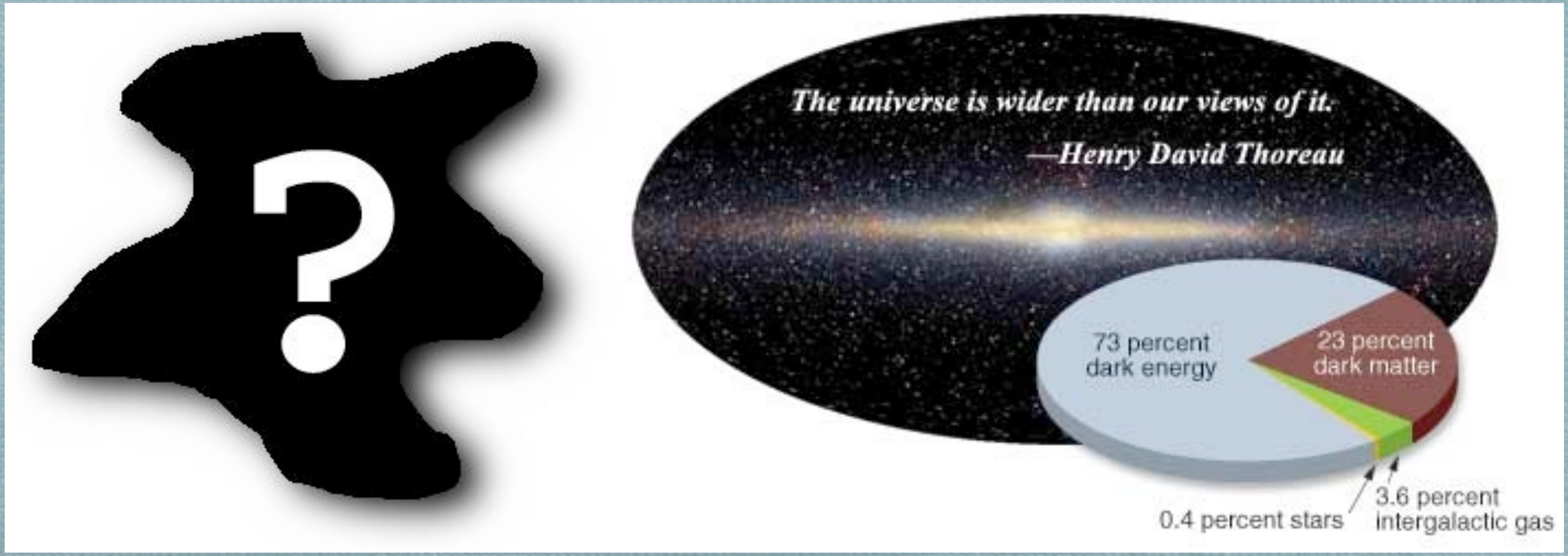


SCALAR FIELD AS A CANDIDATE FOR DARK MATTER

Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional.

Cinvestav

Abril Suárez

15th September 2013

SCALARS 2013
12-16 September 2013
Warsaw, Poland

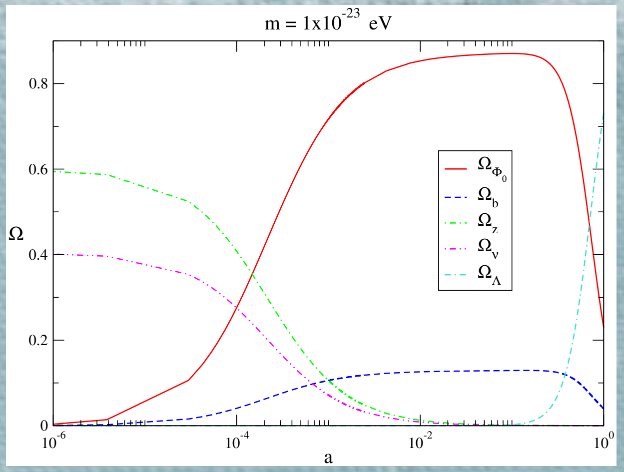
INTRODUCTION

- Standard model of cosmology ΛCDM predicts 24% of the total content of the Universe is DM.
- Even though observations seem to support it, the nature of DM remains unknown.
- Despite all its achivements there are some aspects of the model that require further considerations.

* Anomalies in the mass power spectrum obtained by the SDSS and the one obtained with ΛCDM. Excess clustering at large scales. Shaun et al., Phys. Rev. Lett., 106 (2011) [arXiv:1012.2272].

* Difficulties to explain observations at galactic scales, central densities of dark halos in LSB (cusp profiles).

* Excess of satellite galaxies predicted by N-body simulations (500) not yet observed. Moore et al. (1999), Clowe (2006), Penny et al. (2009).



INTRODUCTION

- Inconsistencies with an otherwise successful model are often the key to a new and deeper understanding.

- Explore alternatives to the paradigm of structure formation.

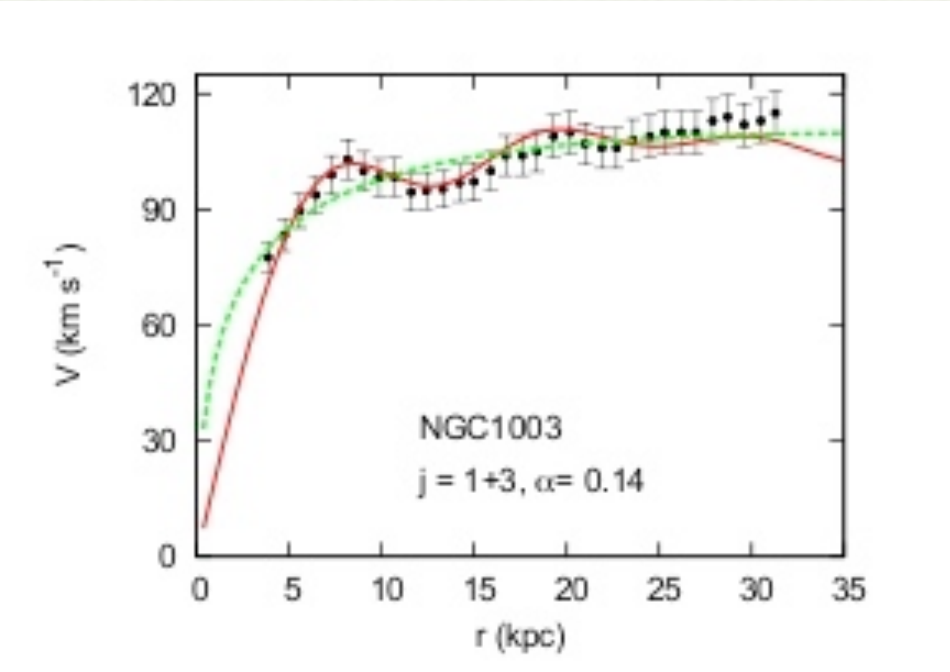
- This model supposes that DM is a real SF Φ minimally coupled to gravity, described by a scalar potential $V(\Phi)$ and that only interacts gravitationally with the rest of the matter.

* SFDM (spin-0 fundamental interaction) can lead to the formation of BEC's in the way of cosmic structure. Matos & Ureña-López, Phys. Rev. D 63 (2001) [astro-ph/0006024], Harko, Phys. Rev. D 83 (2011) [arXiv: 1105.5189]

* Can reproduce the cosmological evolution of the Universe. Matos, Vázquez-González & Magaña, Mon. Not. Roy. Astron. Soc. 393 (2009) 1359 [astro-ph/0806.0683]

INTRODUCTION

* SFDM halos can fit very well rotation curves of LSB galaxies and central density profiles can be reproduced. Robles & Matos, Mon. Not. Roy. Astron. Soc. 422 (2012) 282 [arXiv:1201.3032].



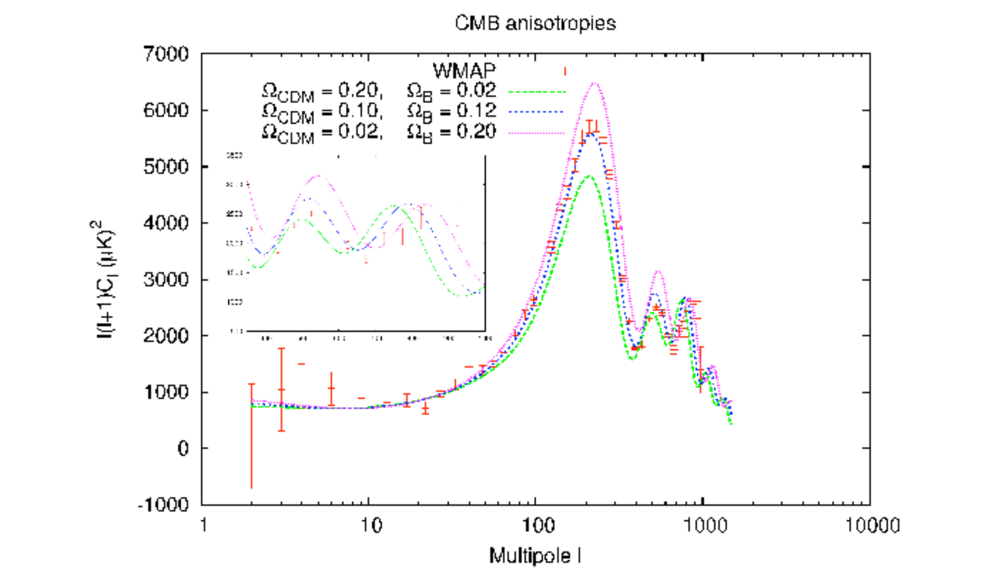


FIG. 4.— CMB power spectrums for different contents of ULBDM and CDM. For the three curves shown $\alpha \sim 10^{-27}$.

* Consistent with acoustic peaks of the CMB radiation. Rodríguez-Montoya et al., Astrophys. J. 721 (2010) [arXiv:0908.0054].

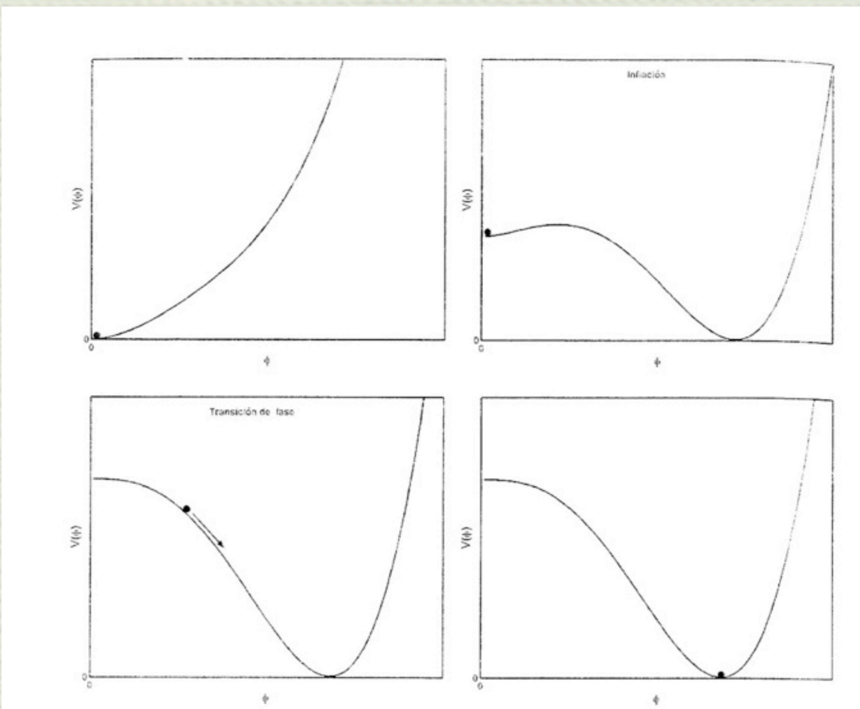
PHASE TRANSITION

- In a very early stage of the Universe the SF was in local thermal equilibrium with its surroundings. The SF is considered in a thermal bath of temperature T.
- At sometime the SF decoupled from the rest of the matter and started a lonely journey with its temperature T going down with the expansion of the Universe.
- To study the cosmological dynamics of the SF we consider the case of a single real SF with a self-interacting doble-well potential $V(\Phi, T)$ with temperature corrections. $c = \hbar = k_B = 1$

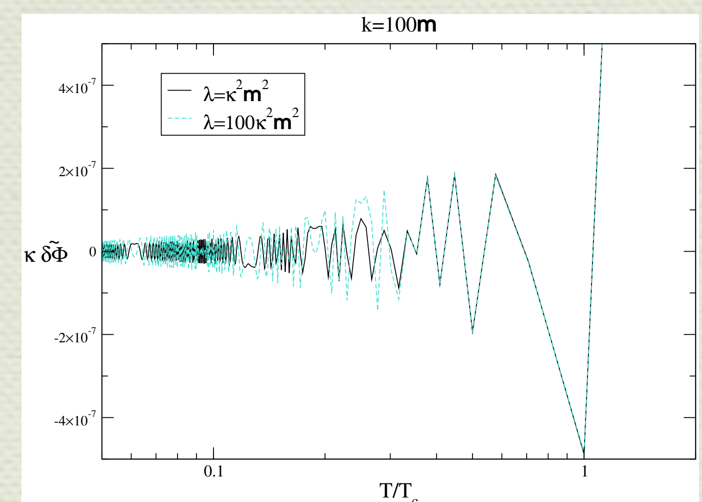
$$V(\Phi) = -\frac{1}{2}\mathbf{m}^2\Phi^2 + \frac{\lambda}{4}\Phi^4 + \frac{\lambda}{8}T^2\Phi^2 - \frac{\pi}{90}T^4 + \frac{\mathbf{m}^4}{4\lambda}$$

- We investigate the symmetry breaking and possible phase transition of this SF in the early Universe.

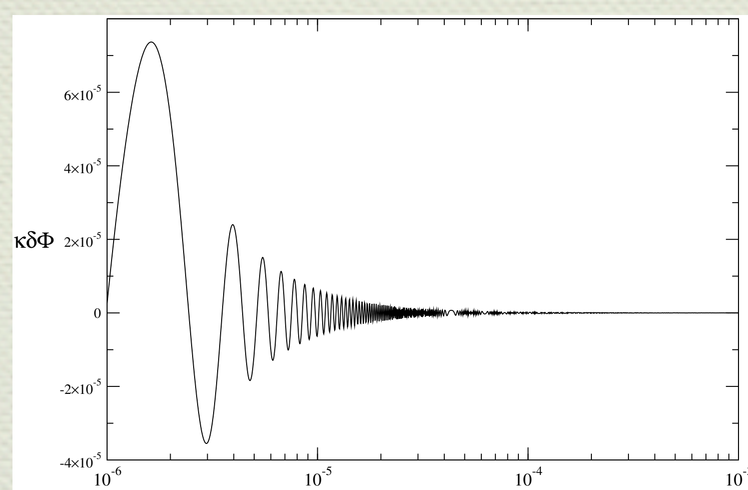
PHASE TRANSITION



- As the SF passes through T_c, there are local thermal fluctuations that will drive it from the unstable maximum towards one or the other of the minima. After the SF passes throught the breaking of symmetry (phase transition) it is stabilized and begins to oscillate around its minimum.



$$0 = (-m^2 + \lambda\tilde{\Phi}^2 + \frac{\lambda}{4}T^2)\tilde{\Phi}$$



$$T_c^2 = \frac{4\mathbf{m}^2}{\lambda}$$

$$\Phi = \pm\frac{1}{2}(T_c^2 - T^2)^{1/2}$$

PHASE TRANSITION

- At points near $T/T_c = 1$ there is a sudden change on the value of the SF, possibly associated with the symmetry breaking phase transition.
- After $T < T_c$ the SF searches for its minima stabilizes and oscillates around it.
- 3 regimes of how SF behaves in the potential

$$V(\Phi) = -\frac{1}{2}\mathbf{m}^2\Phi^2 + \frac{\lambda}{4}\Phi^4 + \frac{\lambda}{8}T^2\Phi^2 - \frac{\pi}{90}T^4 + \frac{\mathbf{m}^4}{4\lambda} \qquad T >> T_c$$

$$V(\Phi) = \frac{1}{2}m^2\Phi^2 + \frac{\lambda}{4}\Phi^4 \qquad T \sim T_c$$

$$V(\Phi) = \frac{1}{2}m^2\Phi^2 \qquad T << T_c$$

PHASE TRANSITION

- For interacting fields we are able to have large mass halos as long as the coupling constant is small. In this case, if we want our SFDM to form structures as big as 10^{12}Mo with a SF mass around m≤1ev

$$\sqrt{\lambda} \sim \frac{M}{0.06} \frac{m^2}{m_{pl}^3} \sim 1.043 \times 10^{-7}$$

- We have for the symmetry breaking temperature

$$T_c \sim \frac{2m}{\sqrt{\lambda}} \sim MeV$$

- Critical temperature corresponds to an epoch way before radiation dominated era, but low enough to allow the SF to decouple from the rest of the matter. Following this result it might turn out possible to have well formed massive halos since neutrino decoupling.

BEHAVIOUR OF SFDM

- Perturbed line element

$$ds^2 = a(\eta)^2[-(1+2\psi)d\eta^2 + 2B_{,i}\,d\eta dx^i + [(1-2\phi)\delta_{ij} + 2E_{,ij}\,]dx^i dx^j],$$

- Perturbed Einstein equations

$$\delta G^\mu_\nu = 8\pi G \delta T^\mu_\nu$$

$$\begin{aligned} -8\pi G\delta\rho_\Phi &= 6H(\dot\phi + H\phi) - \frac{2}{a^2}\nabla^2\phi, \\ 8\pi G\dot\Phi_0\delta\Phi_{,i} &= 2(\dot\phi + H\phi)_{,i}\,, \\ 8\pi G\delta p_\Phi &= 2[\ddot\phi + 3H\dot\phi + (2\dot H + H^2)\phi], \end{aligned}$$

- System of equations

$$\ddot\phi + 6H\dot\phi - \frac{\nabla^2}{a^2}\phi + (2\dot H + 4H^2)\phi + 8\pi G V_{,\Phi}\,\delta\Phi = 0$$

$$\delta\ddot\Phi + 3H\delta\dot\Phi - \frac{1}{a^2}\nabla^2\delta\Phi + V_{,\Phi\Phi}\,\delta\Phi + 2V_{,\Phi}\,\phi - 4\dot\Phi_0\dot\phi = 0.$$

BEHAVIOUR OF SFDM

- Fourier space

$$\ddot{\phi}_k + 6H\dot{\phi}_k + \left(\frac{k^2}{a^2} + 2\dot{H} + 4H^2\right)\phi_k + 8\pi G V_{,\Phi}\,\delta\Phi_k = 0.$$

$$\delta\ddot{\Phi}_k + 3H\delta\dot{\Phi}_k + \left(\frac{k^2}{a^2} + V_{,\Phi\Phi}\right)\delta\Phi_k + 2\phi V_{,\Phi} - 4\dot{\phi}\dot{\Phi}_0 = 0.$$

- Equation for the density contrast

$$\dot{\delta} + 3H\left(\left\langle\frac{\delta P_\Phi}{\delta\rho_\Phi}\right\rangle - \langle\omega_{\Phi_0}\rangle\right)\delta = 3\dot{\phi}\,\langle F_\Phi\rangle - \langle G_\phi\rangle\,.$$

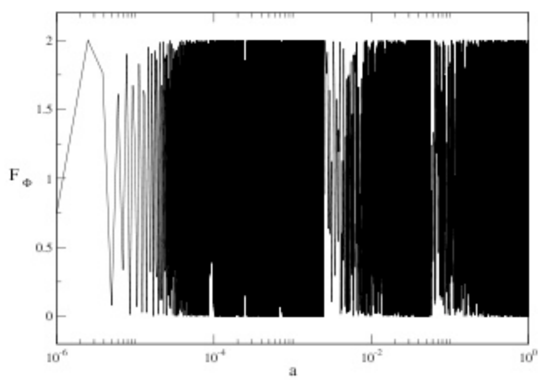


Figure 8. Evolution of $\langle F_\Phi \rangle$ term involved on the right-hand side of equation (4.21).

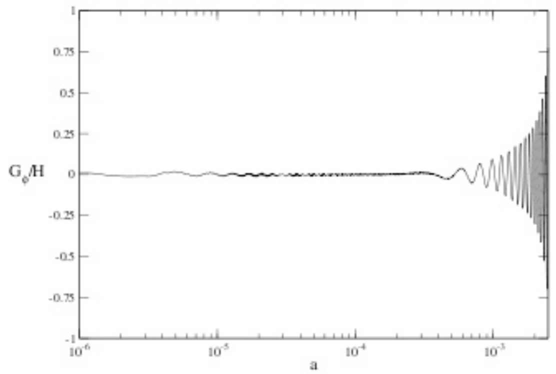


Figure 9. Evolution of $\langle G_\phi \rangle$ term involved on the right-hand side of equation (4.21).

BEHAVIOUR OF SFDM

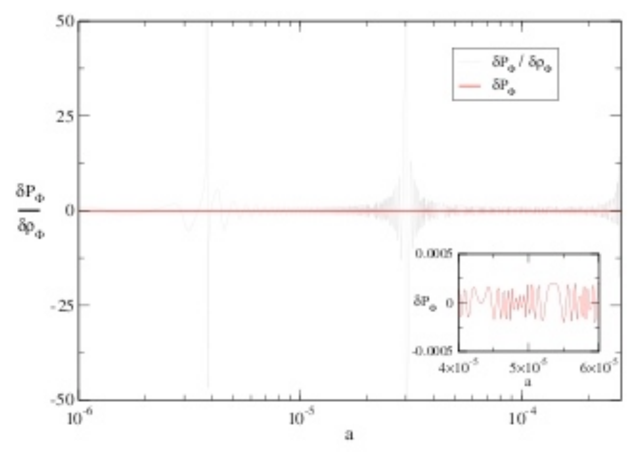


Figure 10. Evolution of $\delta P_\Phi/\delta\rho_\Phi$ term involved on the left-hand side of equation (4.21). The inset shows the evolution of δP_Φ in a short interval of a.

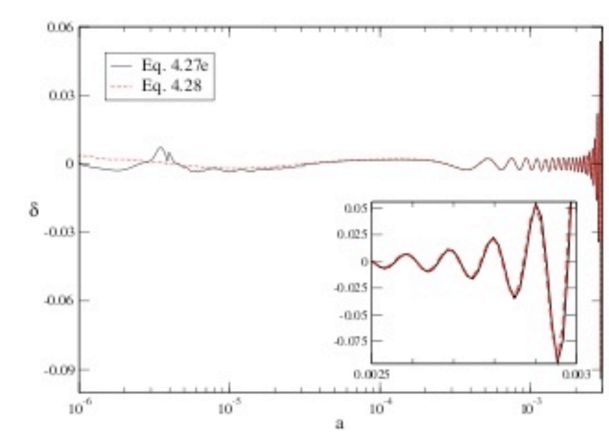


Figure 13. Evolution of the density contrast δ for a perturbation with wavelength $\lambda_k \sim$ 2Mpc calculated with the diferential equation 4.27e and the algebraical expression 4.28. The inset shows the oscillations of the density constrast when $a > 10^{-3}$.

Results might give some insight on the relation between of the SF due to the phase transition with the growth of perturbations related to the formation of structure in the Universe.

HYDRODYNAMICAL APPROACH

- Dynamics of SF is governed by KG equation

$$\Box\Phi + V,_\Phi - 2\frac{m^2}{\hbar^2}\Phi\phi = 0$$

- Analysis analogous to Ginzburg-Landau for BEC's

$$\Phi = \frac{1}{\sqrt{2\kappa}}(\Psi e^{-imt/\hbar} + \Psi^* e^{imt/\hbar})$$

- For KG's equation we have

$$i\hbar(\dot{\Psi} + \frac{3}{2}H\Psi) + \frac{\hbar^2}{2m}\Box\Psi + \frac{3\lambda}{2m}|\Psi|^2\Psi - m\phi\Psi + \frac{\lambda}{8m}k_B^2 T^2\Psi = 0$$

from the mathematical pointof view, non-linear Schrödinger equation. In the case T=H=0 and non-relativistic limit, Gross-Pitaevskii equation for BEC's

- Madelung's representation

$$\Psi = \sqrt{\rho}e^{iS} \qquad |\Psi|^2 = \Psi\Psi^* = \rho$$

HYDRODYNAMICAL APPROACH

- Equations of motion

$$\dot{\rho} + 3H\rho(1 - \frac{\hbar}{m}\dot{S}) + \frac{1}{a}\nabla\cdot(\rho\vec{v}) - \frac{\hbar}{m}(\rho\dot{S})^{\cdot}$$

$$\rho\dot{v} + \frac{\rho}{a}(\vec{v}\cdot\nabla)\vec{v} = \rho\vec{F}_{\phi} - \nabla p + \rho\vec{F}_{Q} + \nabla\sigma$$

$$\vec{v} \equiv \frac{\hbar}{ma}\nabla S$$

- Linear regime

$$\rho + 3H\rho + \frac{1}{a}\nabla\cdot(\rho\vec{v}) = 0$$

$$\rho\dot{\vec{v}} + \frac{\rho}{a}(\vec{v}\cdot\nabla)\vec{v} = \rho\vec{F}_{\phi} - \nabla p + \rho\vec{F}_{Q} + \nabla\sigma$$

$$\nabla\sigma = -H\rho\vec{v} + \frac{\lambda}{4ma}\rho T\nabla T - \eta\left[\frac{1}{a^2}\nabla(\nabla\cdot\vec{v}) + \frac{1}{a^2}\nabla[\nabla(ln\rho)\cdot\vec{v}]\right]$$

- SF as a hydrodynamical fluid (is not) inside a Universe in expansion.

- Fluid in equilibrium

$$\frac{\partial\rho_0}{\partial t} + 3H\rho_0 = 0 \qquad \rho_0 = \frac{\rho_{0i}}{a^3}$$

- System out of equilibrium

$$\frac{\partial\delta\rho}{\partial t} + 3H\delta\rho + \rho_0\nabla\cdot\delta\vec{v} = 0,$$

$$\frac{\partial\delta\vec{v}}{\partial t} + H\delta\vec{v} - \frac{\hbar^2}{2m^2}\nabla\left(\frac{1}{2}\nabla^2\frac{\delta\rho}{\rho_0}\right) + w\nabla\delta\rho + \nabla\delta\phi = 0,$$

$$\nabla^2\delta\phi = 4\pi G\delta\rho.$$

HYDRODYNAMICAL APPROACH

- Finally

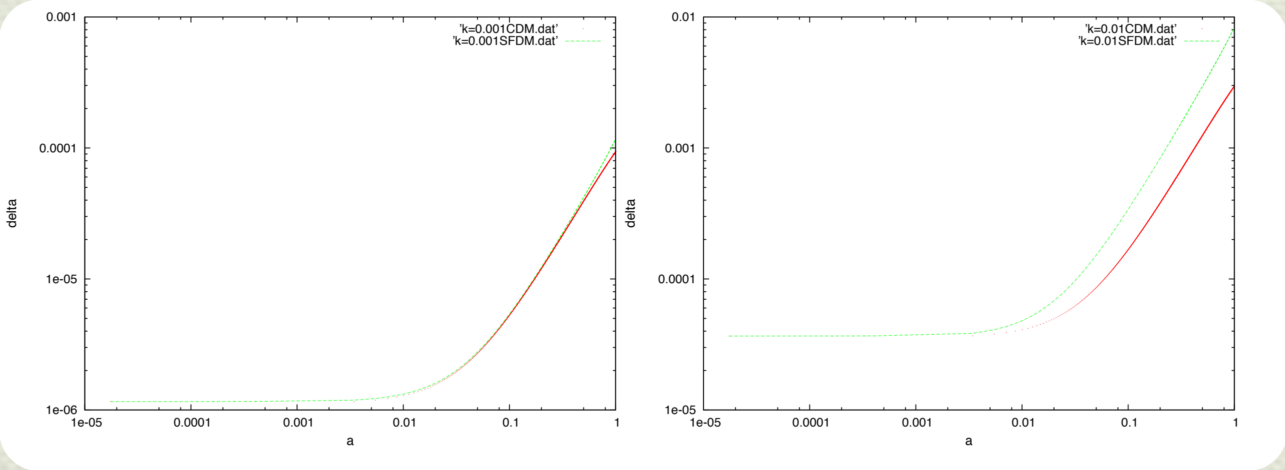
$$\frac{d^2\delta}{dt^2} + 2H\frac{d\delta}{dt} + \left[(v_q^2 + w\rho_0)\frac{k^2}{a^2} - 4\pi G\rho_0\right]\delta = 0.$$

- Conclusions

  * We discuss the thermal evolution and possible 'condensation' of SFDM particles at finite cosmological temperature.

  * When \lambda=T=0 results are consistent with those of CDM.

  * $\lambda \neq 0$ The results are quite diffeferent.



THANK YOU!!

* *Suárez A. and Matos T., Mon. Not. Roy. Astron. Soc., 416 (2011) 87.*

* *T. Matos and A. Suárez, EPL, 96 (2011) 56005.*

* *Magaña J., Matos T., Suárez A. et al., JCAP, 10 (2012) 003.*

* *Suárez A. and Matos T., submitted to Class. Quant. Grav. (2013).*