Scalar Field Dark Matter in Clusters of Galaxies

[arXiv:1609.08644]

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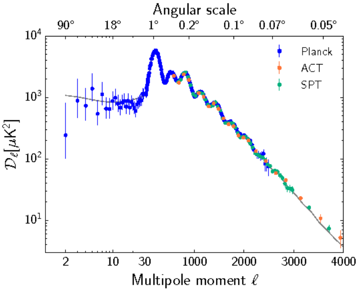
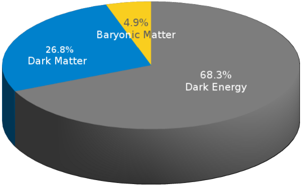
Introduction



- From the last results of the *Planck* mission, the total matter–energy content of the universe is:
  -Baryonic matter: $\sim$ 5%
  -Dark Matter: $\sim$ 27%
  -Dark Energy or a positive Λ: $\sim$ 68%.



- The standard ΛCDM model is the current paradigm to explain several observations: Cosmic Microwave Background Radiation, Mass Power Spectrum, Large Scale Structure of the Universe, Gravitational Lensing, etc.

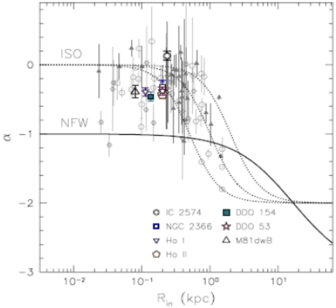
However, CDM presents some difficulties at galactic scales:

- The “core/cusp problem”: From N-body simulations, CDM forms halos with the universal Navarro-Frenk-White (NFW) density profile (Navarro et al. 1996):

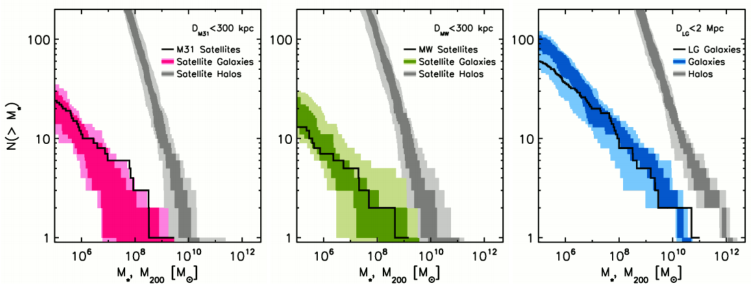
$$\rho_{\rm NFW}(r) = \frac{\rho_s}{(r/R_s)(1 + r/R_s)^2},$$

ρ_s is related to the density of the universe when the halo collapsed and R_s is a characteristic radius. For $r \ll 1$, $\rho_{\rm NFW} \to \infty$ (“cuspy”).

- Observations in dwarfs (dSph) and low surface brightness (LSB) galaxies show a core-like behavior: $\rho \sim r^{-0.2}$ (de Blok et al. 2001, Walker 2013, McGaugh et al. 2016).



- “Missing satellites problem”: CDM simulations predicts a large population of satellite halos around a Milky Way-like galaxy than observed (Sawala et al. 2015):



- “Too-big-to-fail problem”: For the MW, M31 and galaxies outside the Local Group, there are multiple subhalos expected from CDM simulations which have no visible counterpart. These massive halos should be massive enough to cool hydrogen, form stars and host a galaxy.

Solutions to the discrepancies:

- To include the physics of baryonic matter in the simulations (APOSTLE, FIRE): feedback from supernovae, star formation rate, stellar winds, active galactic nuclei, etc.
- Alternatives to CDM, instead to look for complicated and diverse baryonic processes:
  - **Warm dark matter** (WDM) (Zavala et al. 2009, Navarro et al. 2010)
  - **Self-interacting dark matter** (SIDM) (Spergel & Steinhardt 2000)
  - **Scalar field dark matter** (SFDM) (Baldeschi et al. 1983)
  - On the other side: **Modifications to gravity**

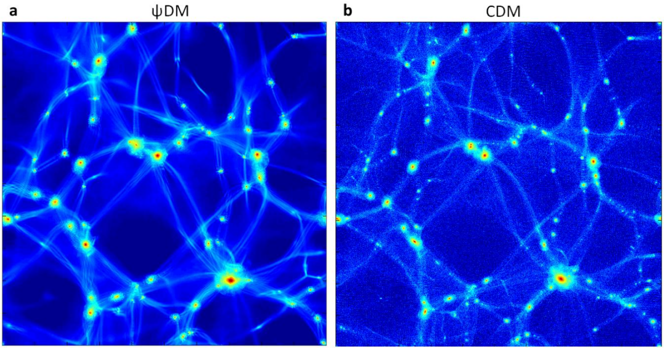
Scalar field dark matter (SFDM)

- Particle physics motivation: Scalar Field associated to spin-0 particles described by the Klein-Gordon equation.
- A widely used potential to describe dark matter includes the mass and self-interaction terms:

$$V(\phi) = \frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda^2\phi^4.$$

- A SF of typical mass $m_\phi \sim 10^{-22}\mathrm{eV}$ and $\lambda > 0$ is assumed to form a Bose-Einstein condensate (BEC), which after recombination behaves cosmologically as CDM.
- The gravitationally bound solutions are interpreted as the galaxy halos, with critical masses $M_{\mathrm{halo}} \sim 10^{12} M_\odot$.
- The SFDM model has many variants:
  1) BEC-DM: $\lambda \gg 1$ (Thomas-Fermi limit)
  2) Wave (ψDM), Fuzzy (FDM) or Ultra-light Axion (ULA) DM: $\lambda = 0$
  3) Multistate SFDM (finite-temperature corrections)

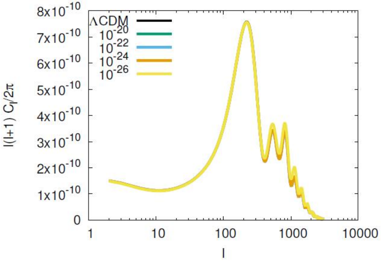
SFDM at cosmological scales

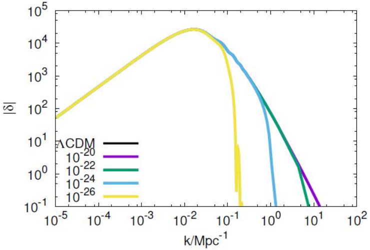


(Schive et al. 2014)

- SFDM systems with $M > 10^{12} M_\odot$ were formed by hierarchy → Same CDM predictions for large scale structure formation, but SFDM halos were formed very early in the universe.

- SFDM behaves like dust → Same CDM predictions for CMB and MPS, but SFDM has a cut-off in the MPS, predicting less small scale structure than CDM (e.g. Matos & Ureña 2000; Ureña-López & González-Morales 2015):





- SFDM profiles are naturally core by Heisenberg uncertainty principle.
- Possible detection: CASPEr-Wind (Cosmic Axion Spin Precession Experiment-DM Wind) might have the sensitivity to detect it (Kim & Marsh arXiv:1510.01701); indirectly by pulsar timing observations (Khmelnitsky & Rubakov arXiv:1309.5888).

1) BEC dark matter (Böhmer & Harko 2007)

- Fully BEC system at $T = 0$, with the self-interactions dominating over the mass term (Thomas-Fermi limit):

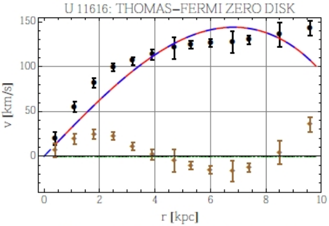
$$\rho_{\mathrm{BEC}}(r) = \rho_0 \frac{\sin(Kr)}{Kr}; \; K = \pi/\hat{R},$$

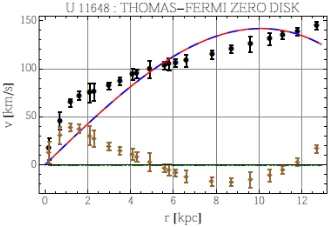
ρ_0 the central density, and the halo radius where $\rho(\hat{R}) = 0$:

$$\hat{R} = \pi\sqrt{\frac{\hbar^2 b}{G m_\phi^3}},$$

where $m_\phi \approx 10^{-6}$ eV is the boson mass, b its scattering length ($\lambda = 4\pi\hbar^2 b/m_\phi$).

- Considering the ground state only, it's not possible to fit the RC of disk galaxies (m_ϕ and b are different for each galaxy):





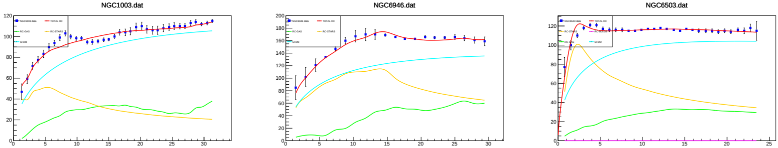
2) Fuzzy (FDM), Wave (ψDM) or Ultra-light Axion (ULA) DM

- SF with negligible self-interaction $\lambda = 0$ and $T = 0$ (Hu et al. 2000; Schive et al. 2014; Hlozek et al. 2015).
- From their cosmological simulation, Schive et al. (2014) found the empirical density profile (soliton+NFW):

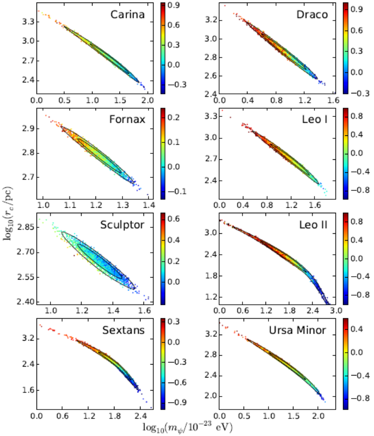
$$\rho_{\psi\mathrm{DM}}(r) = \begin{cases} \rho_{\mathrm{soliton}}(r) = \dfrac{\rho_c}{[1+0.091(r/r_c)^2]^8}, & \text{if } r \leq r_\epsilon \\ \rho_{\mathrm{NFW}}(r) = \dfrac{\rho_s}{(r/r_s)(1+r/r_s)^2}, & \text{if } r > r_\epsilon \end{cases}$$

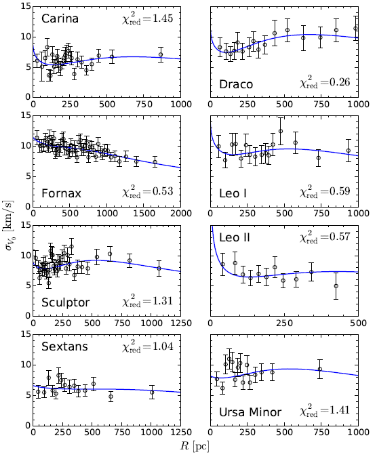
where $\rho_c := 1.9(m_\psi/10^{-23}\mathrm{eV})^{-2}(r_c/\mathrm{kpc})^{-4}$ and r_ϵ is the transition radius.

- For rotation curves of disk galaxies:



- Results from dwarf spheroidal galaxies (Schive et al. 2016):





$$m_\psi = 1.18^{+0.28}_{-0.24} \times 10^{-22}\mathrm{eV}(2\sigma)(2007)$$

$$m_\psi = 1.79^{+0.35}_{-0.35} \times 10^{-22}\mathrm{eV}(2\sigma)(2009)$$

3) Finite-temperature multistate SFDM (Robles & Matos 2013)

- Motivated by the symmetries restored at high T, they included temperature corrections to one loop in perturbations at the very early universe ($\lambda \neq 0$, $T \neq 0$) (Kolb & Turner 1994):

$$V(\phi) = -\frac{m^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 + \frac{\lambda}{8}T^2\phi^2 - \sigma T^4.$$

- Initially, the SF perturbations from inflation interact with the radiation and matter. As T decreases, a SSB occurs at T_c and the fluctuation can start growing and form halos, decoupling from the rest of the universe.
- Solving the perturbed EKG eqs. in a FLRW background:

$$\rho_\phi(r) = \rho_0 \frac{\sin^2(kr)}{(kr)^2},$$

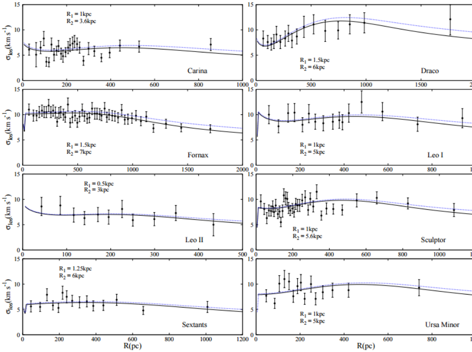
where the radius defined as $\rho(R) = 0$ fixes $k_j R = j\pi$, for $j = 1, 2, 3, ...$ the ground and excited states.

- Hyphotesis: The whole galaxy and galaxy cluster halos allow linearly combined excited states:

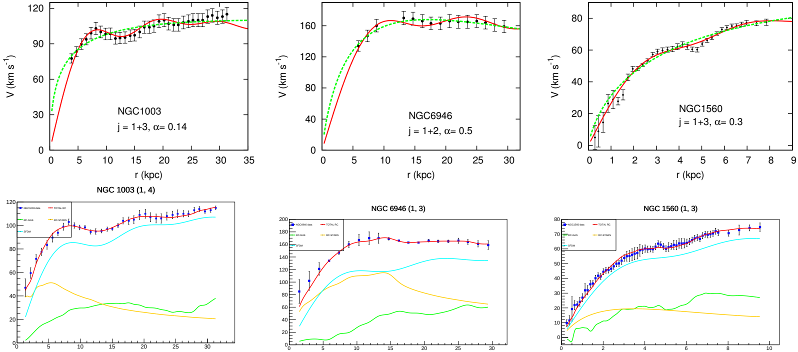
$$\rho_{\rm SFDM}(r) = \sum_j \rho_0^j \frac{\sin^2(j\pi r/R)}{(j\pi r/R)^2}.$$

- Problem to constrain (m_ϕ, λ): ρ_ϕ is degenerated (it depends on T_c, $T_{\rm form}$).

- However, the model fits well the dSph galaxies (Robles et al. 2013):



- Also the high-resolution rotation curves of disk galaxies:

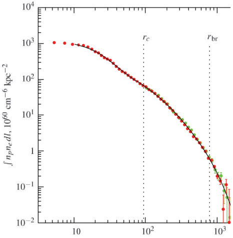


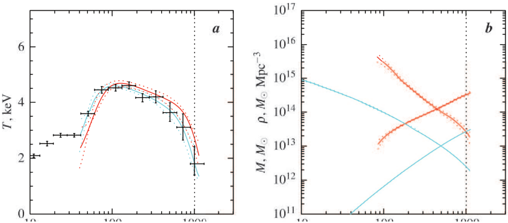
- This is an indication that the realistic SFDM halos might include temperature-corrected multistate solutions.

Fit with observations of galaxy clusters

- 13 Chandra X-ray galaxy clusters (Vikhlinin et al. 2006). Observables: gas density $\rho_{\mathrm{g}}(r)$ and gas temperature $T(r)$.
- We assume a merging scenario of multistate haloes, showing up an effective multistate density and compare to the NFW profile.
- The dynamical mass of the system is:

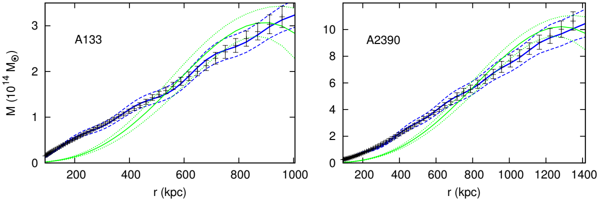
$$M_{\mathrm{dyn}} = M_{\mathrm{gas}}(r) + M_{\mathrm{stars}}(r) + M_{\mathrm{DM}}(r) = \frac{k_{\mathrm{B}} T(r)}{\mu m_p G} r \left[\frac{\mathrm{d} \ln \rho_{\mathrm{g}}(r)}{\mathrm{d} \ln r} + \frac{\mathrm{d} \ln T(r)}{\mathrm{d} \ln r} \right] .$$



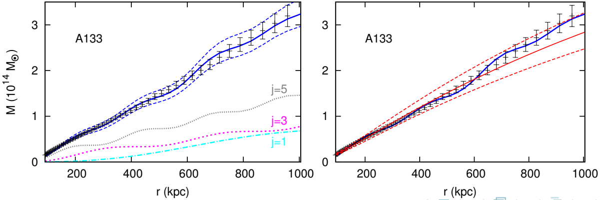


Results I

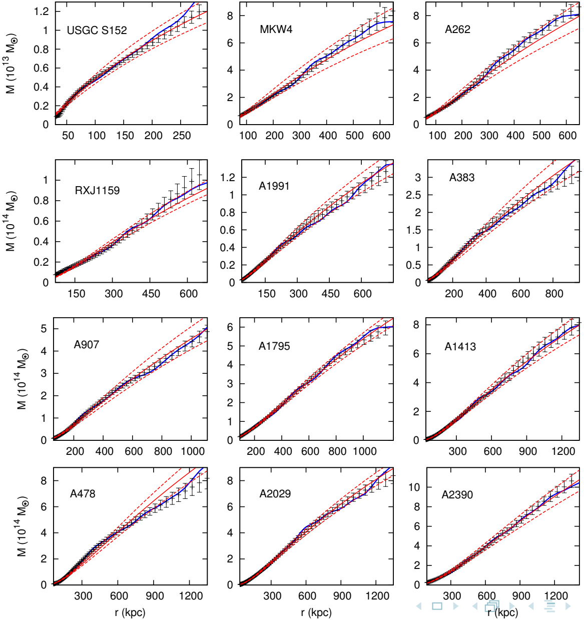
- MCMC method to fit the free parameters.
- Comparison of multistate SFDM with BEC-DM:



- Comparison of multistate SFDM with the NFW profile:

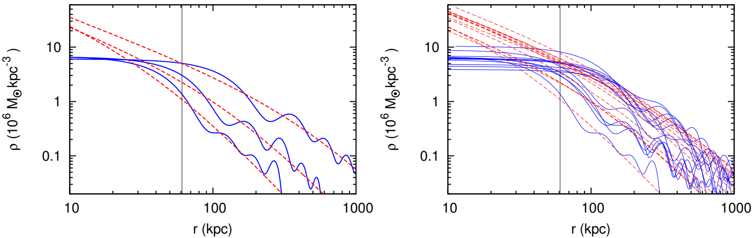


Results II



USGC S152
MKW4
A262
RXJ1159
A1991
A383
A907
A1795
A1413
A478
A2029
A2390
M (10^{13} M$_\odot$)
M (10^{14} M$_\odot$)
r (kpc)

- Density profiles:



- The multistate SFDM model is consistent with the Wave DM simulations, whose empirical density profile is:

$$\rho_{\psi\mathrm{DM}}(r) = \begin{cases} \rho_{\mathrm{soliton}}(r) = \frac{\rho_c}{[1+0.091(r/r_c)^2]^8}, & \text{if } r \leq r_\epsilon \\ \rho_{\mathrm{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}, & \text{if } r > r_\epsilon \end{cases}$$

Conclusions I

- The SFDM model is a good alternative to CDM at galactic and galaxy cluster scales, addresing the “core/cusp”, “missing satellites” and “Too-big-to-fail” problems. At cosmological scales it behaves as CDM.
- Other applications: boson stars, supermassive black holes.
- The BEC-DM model ($\lambda \gg 1$, Thomas-Fermi limit) only reproduces the small galaxies observations, but fails for big galaxies and galaxy clusters.
- The finite-temperature multistate SFDM solution is a theoretical-motivated model, and alternative to the *ad hoc* empirical Soliton+NFW profile, indicating that a realistic galaxy halo must be a multistate SF configuration at finite temperature.

¡Muchas gracias por su atención!