Dark Matter halos in Scalar Field Dark Matter model

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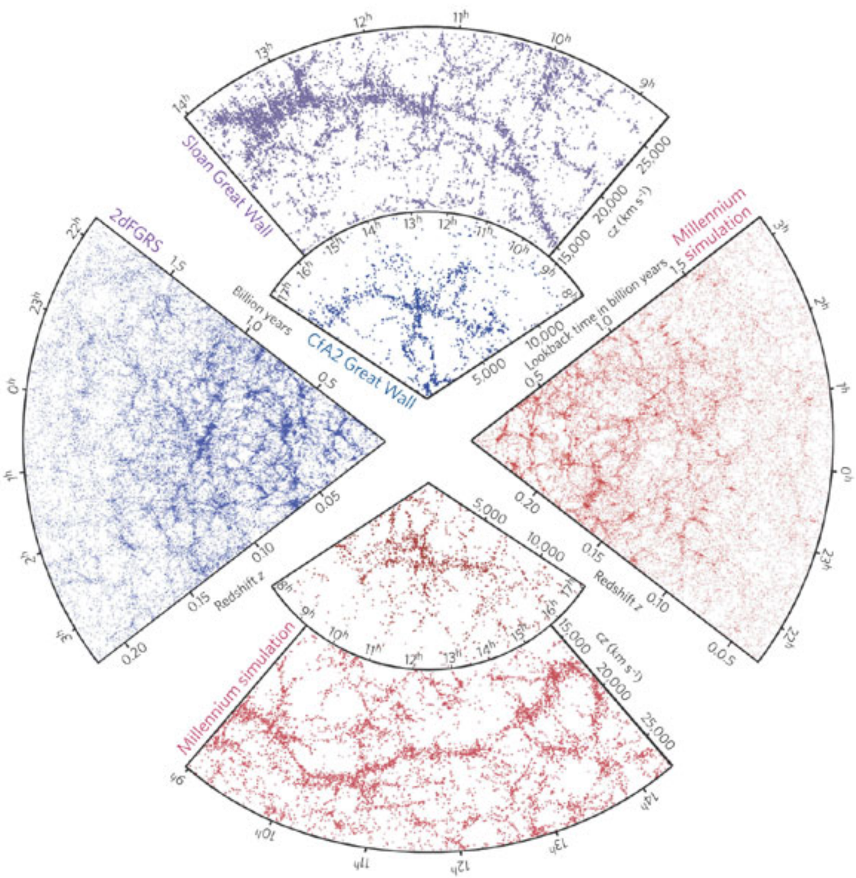
Outline:

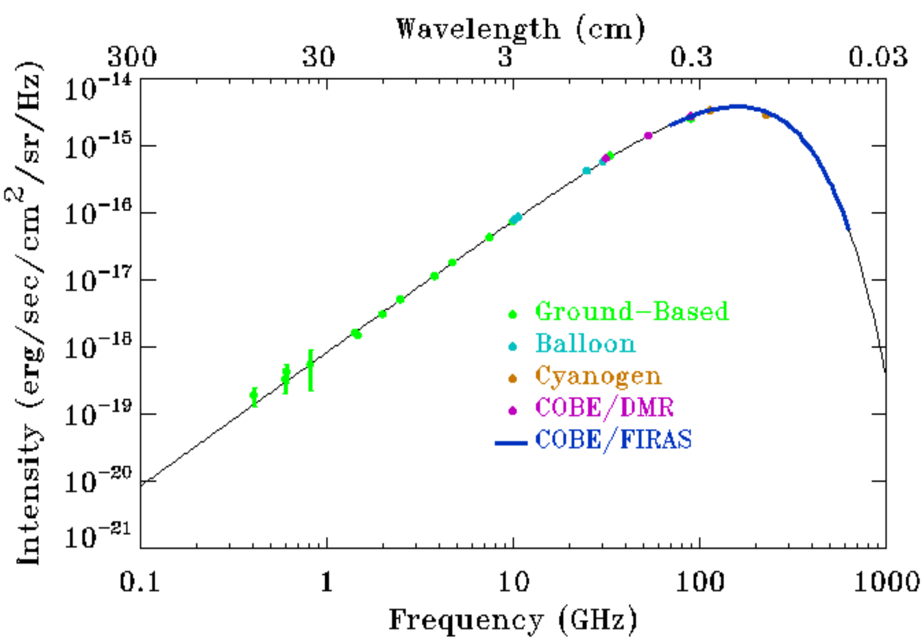
- Motivation : CDM simulations and problems
- Alternative theory: Scalar Field DM model
- SFDM Halos
- Conclusions

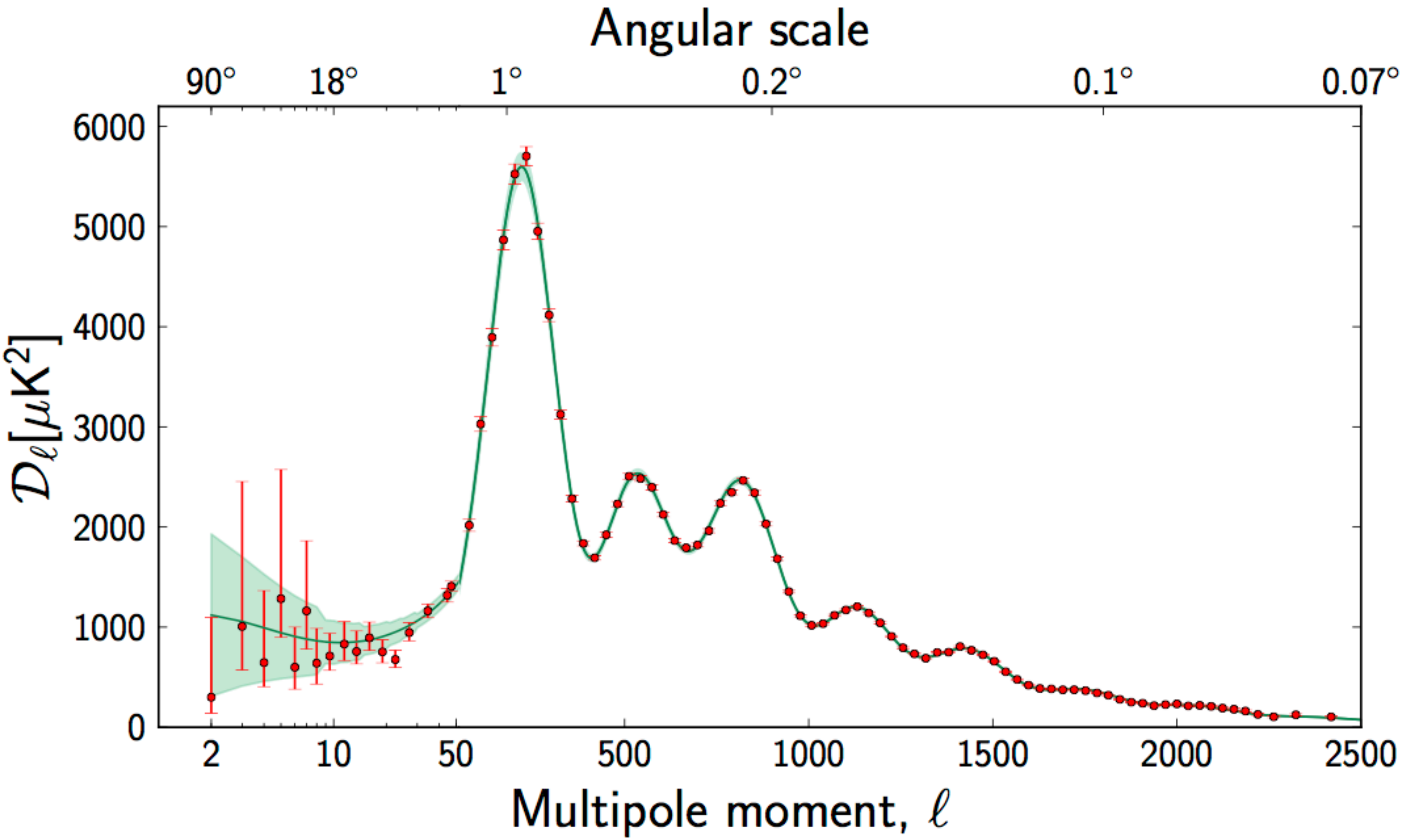
ΛCDM

Cosmological test are accurately described.



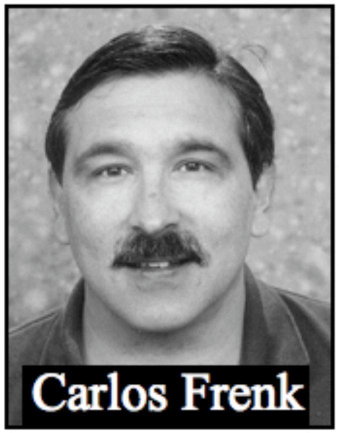
LSS,CMB, Angular Power Spectrum etc.

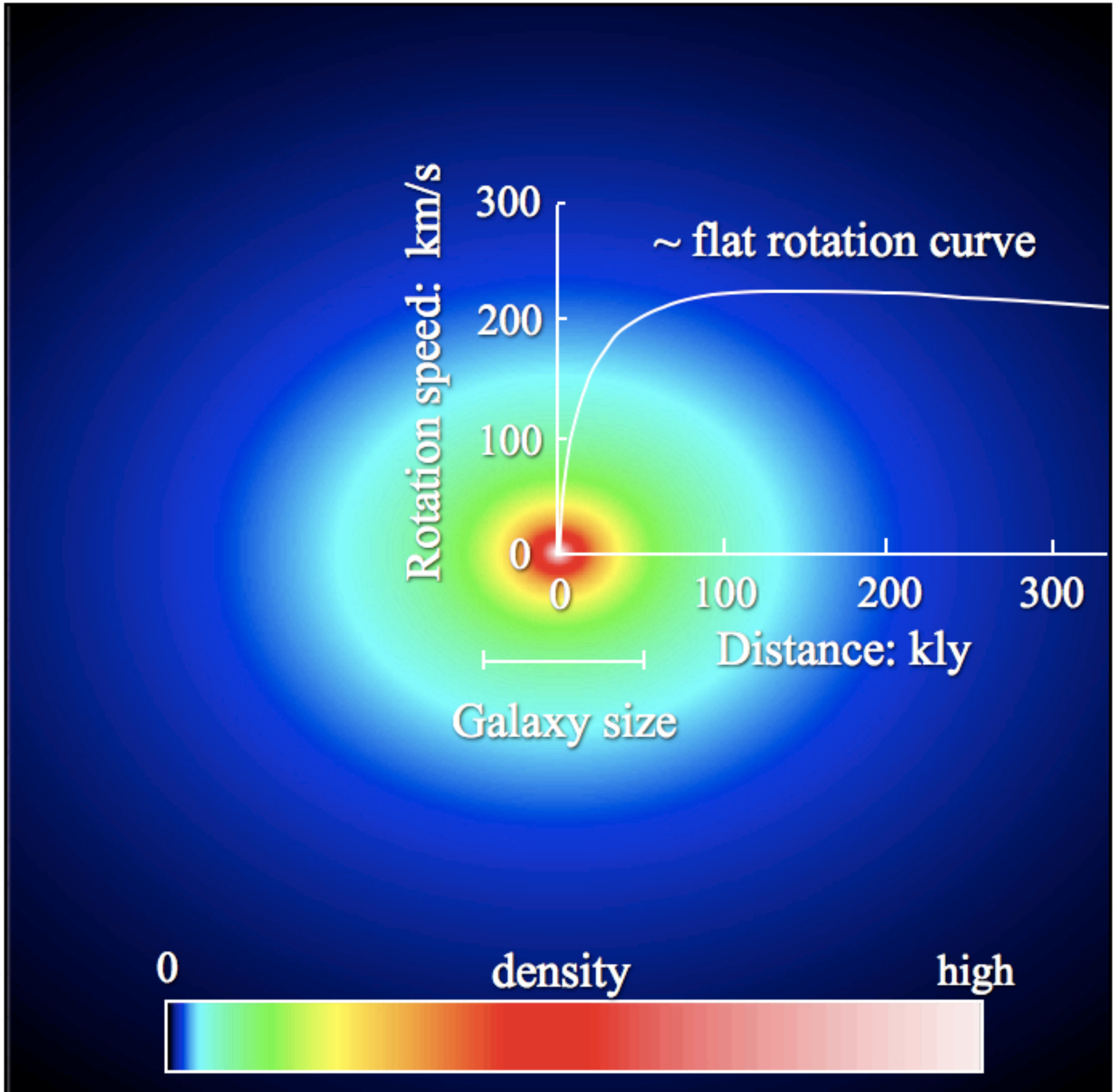




Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

The "NFW" form for dark matter halos





But, some long standing ΛCDM unsolved issues

- Nature of DM remains unknown(neutralino,WDM, axion,…)
- Three remain unsolved
- Cusp/core problem
- Missing galaxy problem
- Too big to fail problem

Garrison-Kimmel(2013),Boylan-Kolchin, Michael; Bullock, James S.; Kaplinghat, Manoj(2013)

- Cusp/core problem
- Difficulties to describe observed central densities of dark halos in LSB

(cusp profiles predicted $\rho \approx r^{-1}$).

Missing galaxy problem (abundance)

- Excess of satellite halos

predicted by N-body simulations Moore et al. (1999), Penny et al (2009).

- Too big to fail problem (distribution)
- Galaxies associated to the most massive halos in numerical simulations are not observed. Bullock, James S.; Kaplinghat, Manoj(2013)

- Alternative explanations to the current paradigm of structure formation

Galaxies are a good test to CDM

Cusp/Core problem

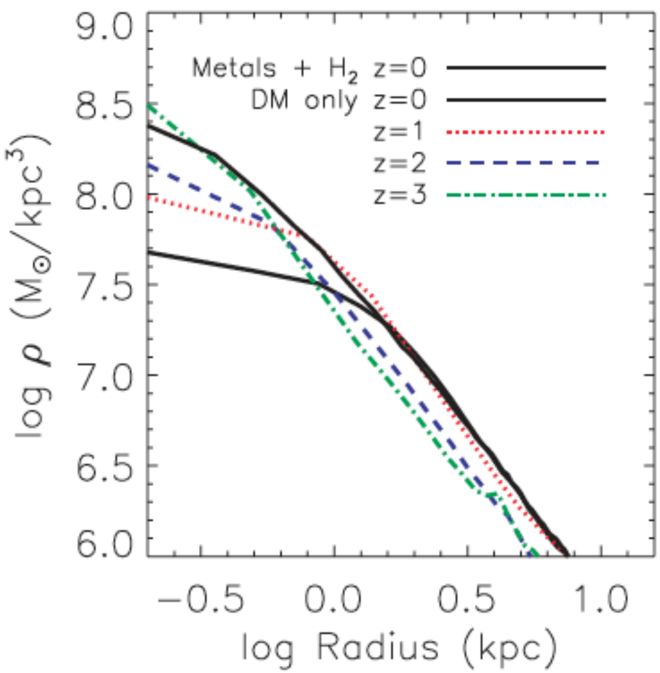


Figure 3. The DM density profile of a dwarf galaxy in our sample, at $z =$ 4, 3, 1, 0. The prolonged process of cusp flattening due to many separate outflows results in a shallow inner profile at $z = 0$. For comparison, the density profile of the same galaxy, but simulated with DM only, is shown in the black dot–dashed line. In the DM only simulation, the DM maintains its cuspy density profile at all redshifts.

Low Surface Brightness (LSB) galaxies, dwarfs and UFD

Even if SN Feedback is able to remove cusps is some galaxies. Same FB recipe **unlikely to work in LSBs and dwarf galaxies, smaller halos have higher DM concentrations**

SATELLITES IN CDM IS
Feedback the solution?

- Sawala et al.(2012) find in their simulation TWICE as many satellites of a given luminosity around a MW size CDM halo

Feedback
Tidal Interation

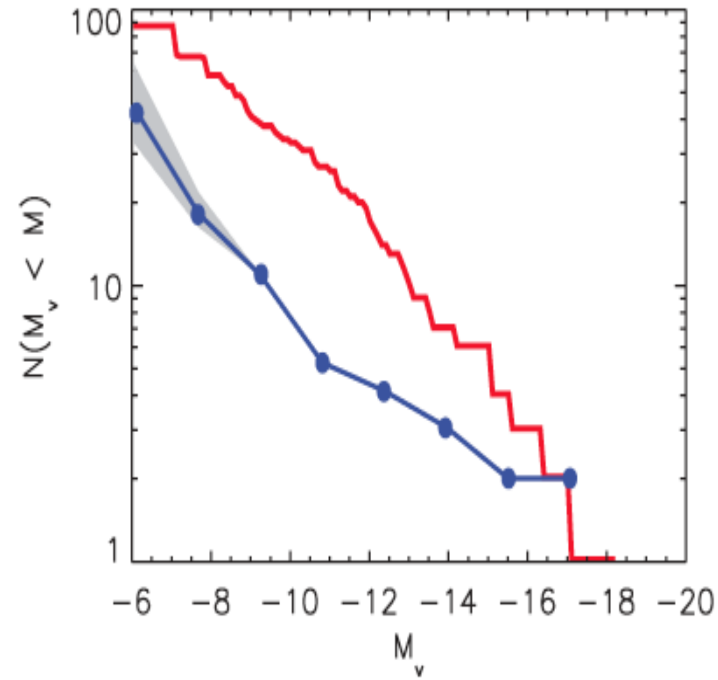


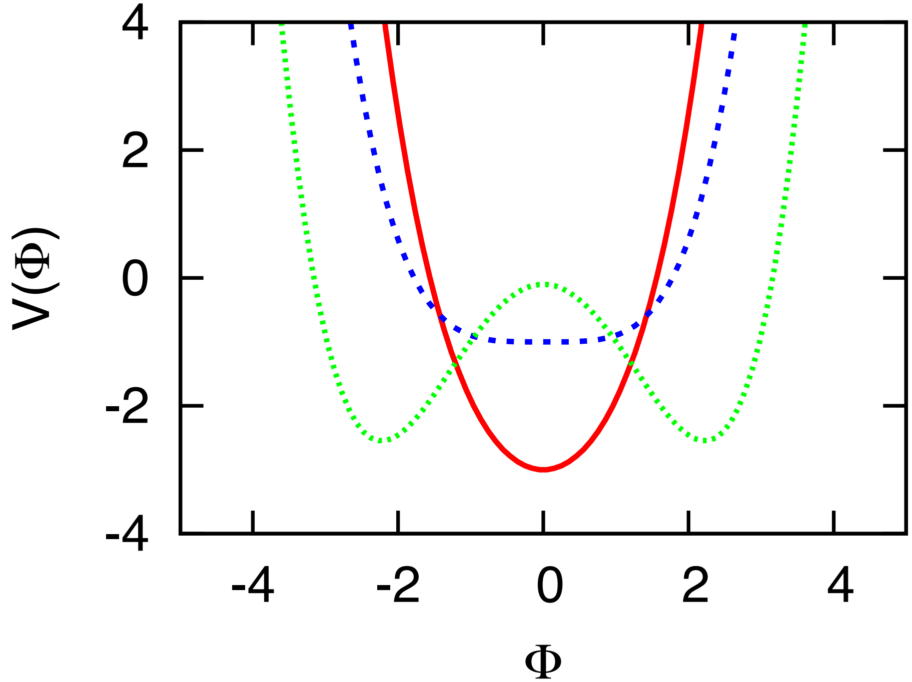
Figure 5. Cumulative satellite luminosity function, in our simulation (red), compared to observational estimates of the Milky Way by Tollerud et al. (2008) (blue), corrected for completeness, both within a radius of 417 kpc. The simulation produces approximately twice as many satellites of a given luminosity compared to the Milky Way.

- Satellite galaxies are too luminous :"wrong" FB methods?

Scalar Field Dark Matter

- This model supposes that DM is a real SF minimally coupled to gravity, described by a scalar potential and that only interacts gravitationally with the rest of the matter (Robles & Matos 2013, ApJ, 763, 19[arXiv: 1207.5858], arXiv:1302.0903)

- 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]



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

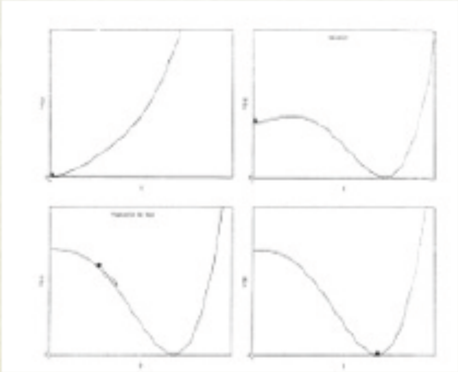
PHASE TRANSITION

- In a very early stage of the Universe, the SF was in local thermodynamical equilibrium with its surroundings. The SF is considered in a thermal bath of temperature T.

- At some time 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.

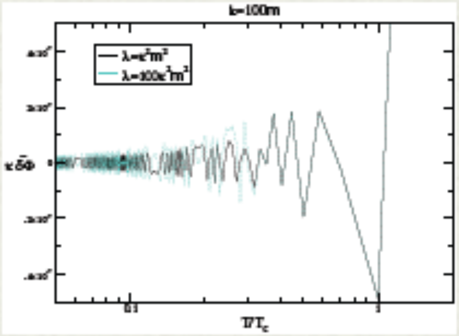
- To study the cosmological dynamics of the SF we consider the case of a single real SF with a self-interacting double-well potential $V(\Phi,T)$ extended to one-loop temperature corrections $c=\hbar=k_B=1$

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



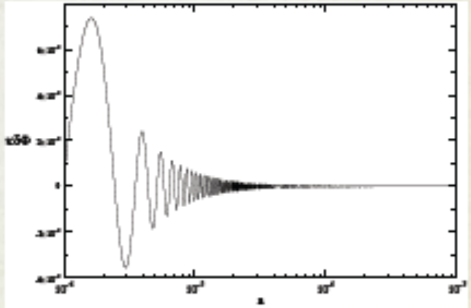
- We investigate the symmetry breaking and possibly a phase transition of this scalar field in the early Universe.

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



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

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



- 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.

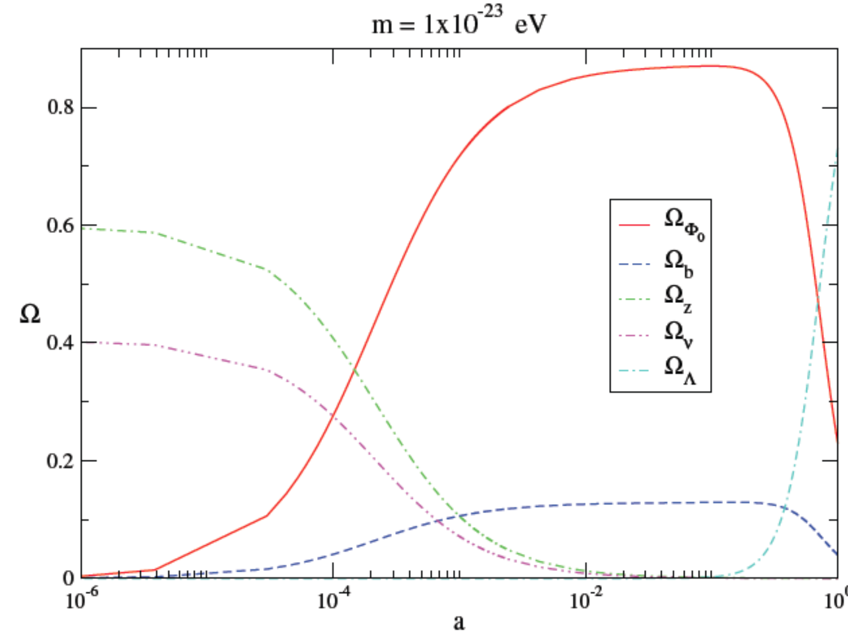
- After $T<T_c$ the SF searches for its minima stabilizes and oscillates around it.

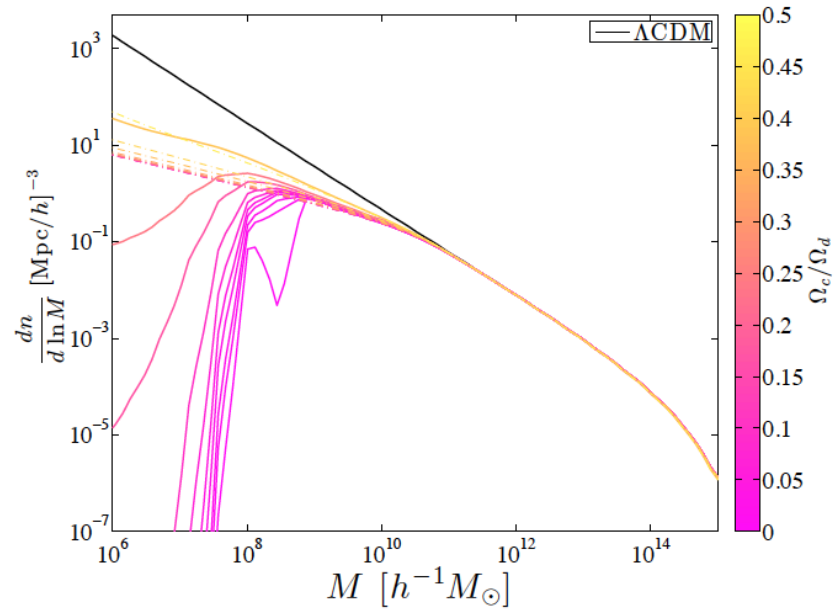
Large scale resembles CDM behavior

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

- Small mass (10^{-23}eV) natural cut off in mass power spectrum (no satellite problem) Tonatiuh Matos et al. Mon. Not. R. Astron. Soc. 393, 1359–1369 (2009),David J. E. Marsh,Joseph Silk, arXiv:1307.1705v1

- SFDM halos can fit very well rotation curves of LSB galaxies and central density profiles can be reproduced, Robles and Matos, Mon. Not. Roy. Astron. Soc. 422 (2012) 282 [arXiv: 1201.3032]
- Consistent with acoustic peaks of the CMB radiation, Rodríguez-Montoya et al., Astrophys. J.721 (2010) [arXiv: 0908.0054]





Using the Newtonian gauge

$$ds^2 = a^2 \left\{ -(1+2\psi)d\tau^2 + (1-2\phi)dx^i dx_i \right\}$$

$$d/d\eta = a(d/dt)$$

With respect to cosmological time t we have for the perturbations

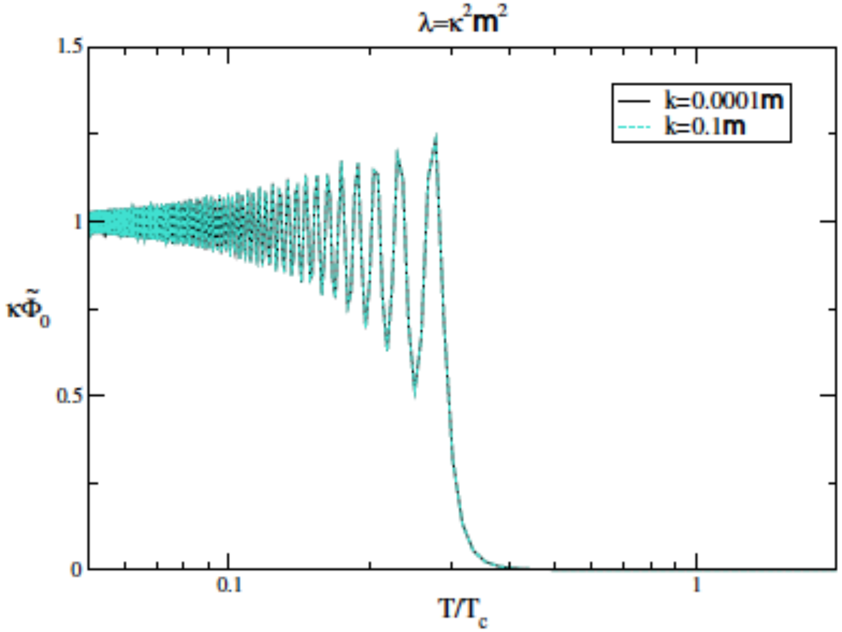
$$\begin{aligned}
\delta T^0_0 &= -\delta\rho_\Phi = -(\dot{\Phi}_0 \delta\dot{\Phi} - \dot{\Phi}_0^2 \psi + V_{,\Phi}\, \delta\Phi), \\
\delta T^0_i &= -\frac{1}{a}(\dot{\Phi}_0 \delta\Phi_{,i}\,), \\
\delta T^i_j &= \delta P_\Phi = (\dot{\Phi}_0 \delta\dot{\Phi} - \dot{\Phi}_0^2 \psi - V_{,\Phi}\, \delta\Phi)\delta^i_j.
\end{aligned}$$

$$\begin{aligned}
-8\pi G \delta\rho_\Phi &= 6H(\dot{\phi} + H\phi) - \frac{2}{a^2}\nabla^2\phi, \\
8\pi G \dot{\Phi}_0 \delta\Phi_{,i} &= 2(\dot{\phi} + H\phi)_{,i}\,, \\
8\pi G \delta P_\Phi &= 2[\ddot{\phi} + 3H\dot{\phi} + (2\dot{H} + H^2)\phi]
\end{aligned}$$

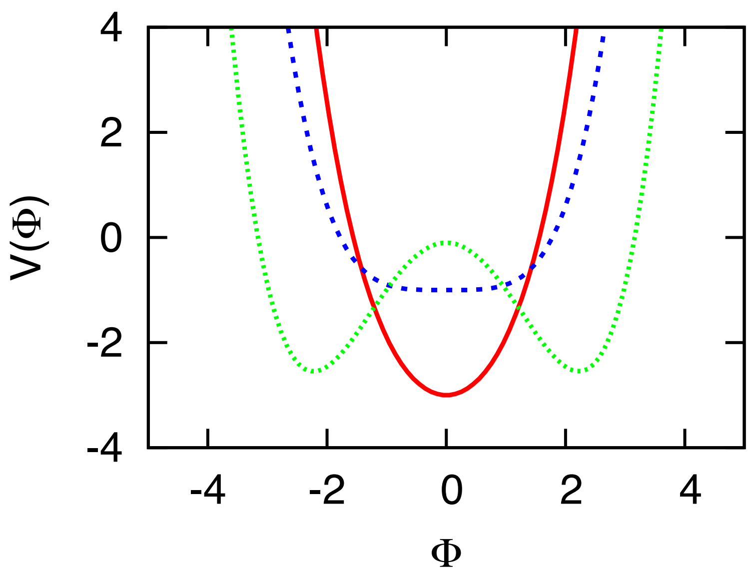
Field and gravitational potential eqs.

$$\delta\ddot{\Phi} + 3H\delta\dot{\Phi} - \frac{1}{a^2}\nabla^2\delta\Phi + V_{,\Phi\Phi}\,\delta\Phi + 2V_{,\Phi}\,\phi - 4\dot{\Phi}_0\dot{\phi} = 0.$$

$$\ddot{\phi} + 6H\dot{\phi} - \frac{1}{a^2}\nabla^2\phi + (2\dot{H} + 4H^2)\phi + 8\pi G\,V_{,\Phi}\,\delta\Phi = 0.$$



Background field



SFDM halos

Near the minimum of *V and after T<<$T_{C,}$* we can obtain an analytical equilibrium solution, relating the density with the field as usual ρ α $(\delta\Phi)^2$

A FINITE HALO IMPLIES

CORE PROFILE

$$\rho(r) = \rho_0 \frac{Sin^2(kr)}{(kr)^2}$$

$$k_j R = j\pi,$$

Rotation curve profile

SF (CORE)

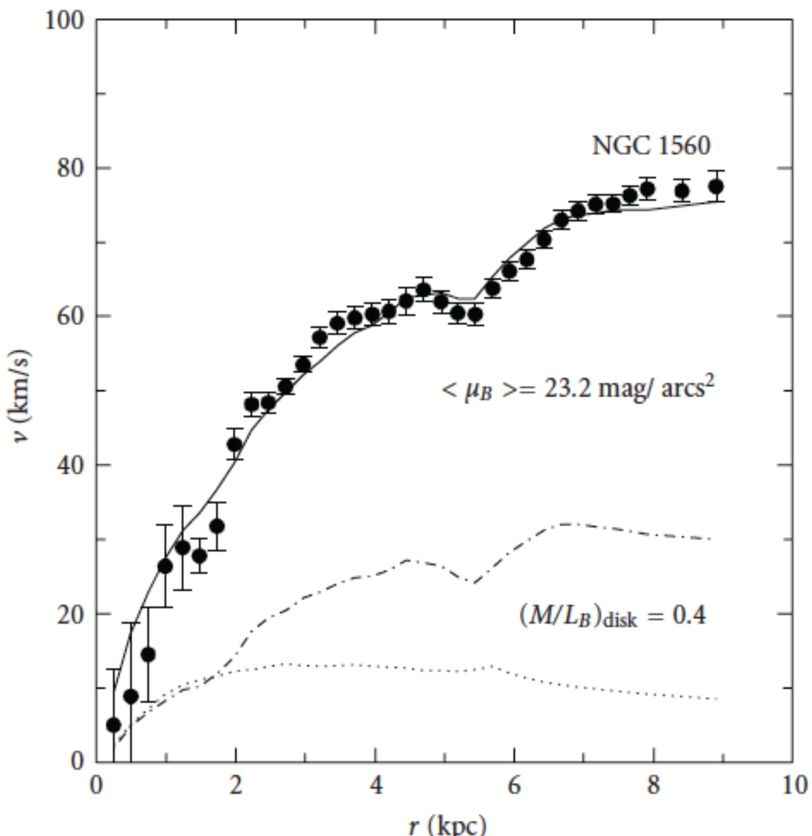
$$V_{SF}^2(r) = \frac{4\pi G\rho_0}{2k^2}\left(1 - \frac{Sin(2kr)}{2kr}\right)$$

EINASTO (CUSP)

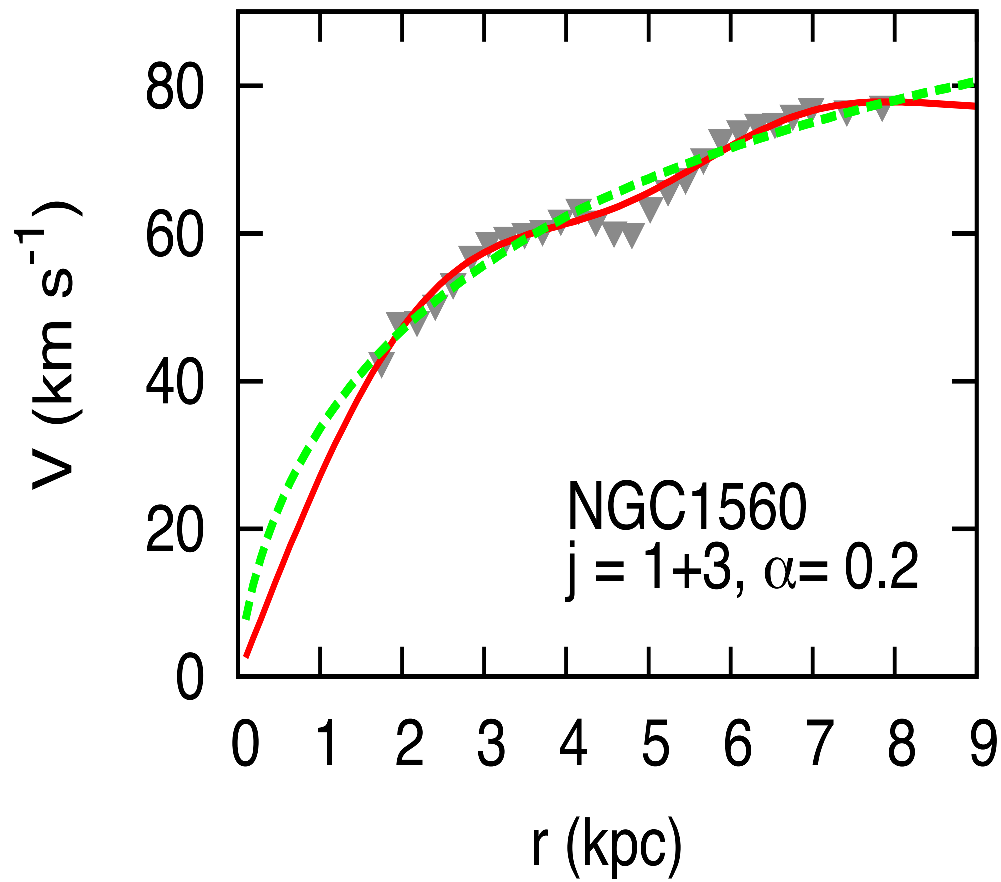
$$V_E^2(r) = 4\pi G\rho_{-2}\frac{r_{-2}^3}{r}\left(\frac{e^{2/\alpha}}{\alpha}\left(\frac{\alpha}{2}\right)^{(3/\alpha)}\int_0^{(r/r_{-2})^\alpha(2/\alpha)} e^{-t}t^{(3/\alpha)-1}\,dt\right)$$

TESTING WITH GALAXIES

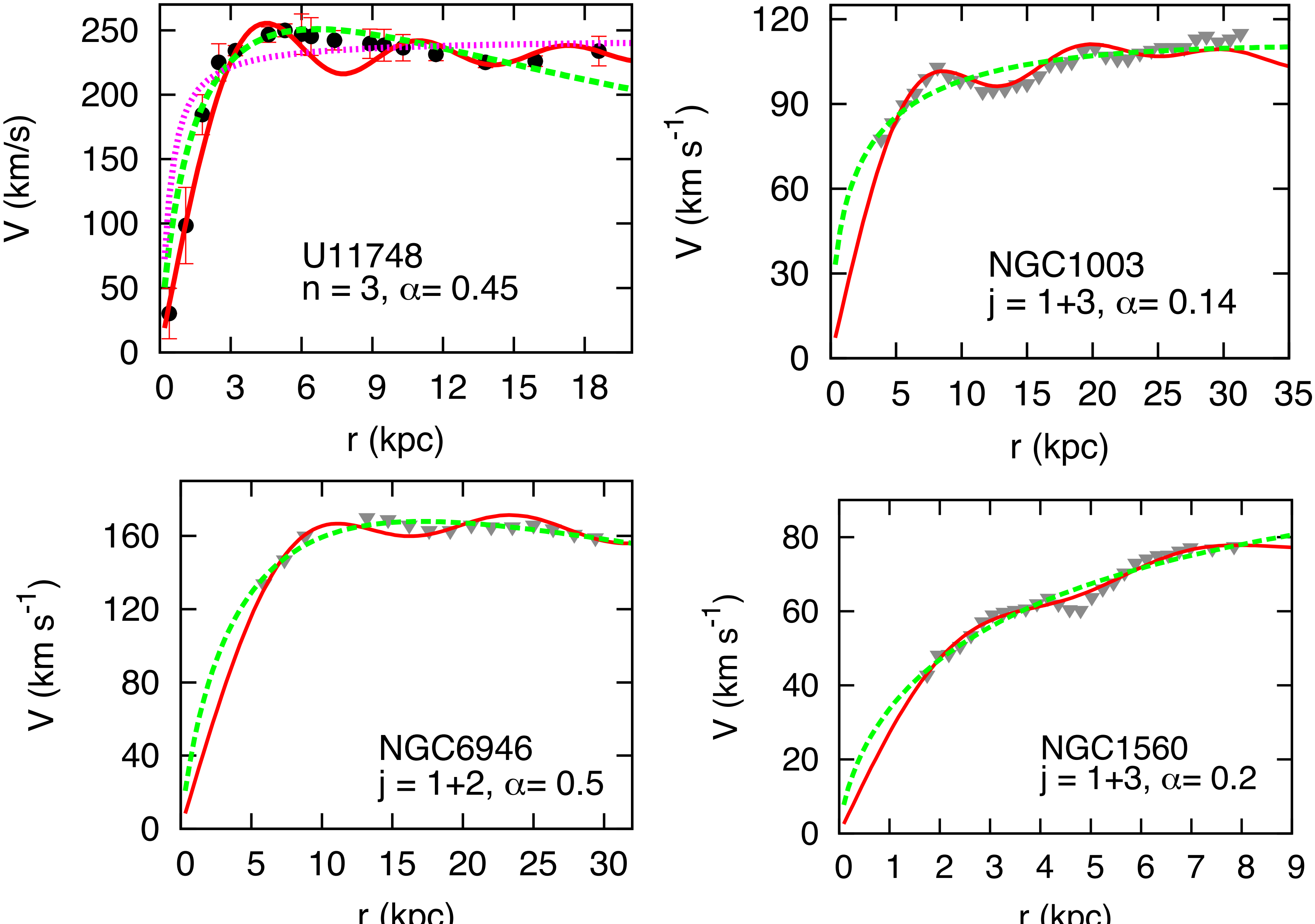
NGC 1560



MOND FIT



SFDM Fit (red), Einasto (green) Victor H. Robles, T. Matos, MNRAS 422: 282–289



V (km/s)
r (kpc)
U11748
n = 3, α= 0.45
V (km s-1)
r (kpc)
NGC1003
j = 1+3, α= 0.14
V (km s-1)
r (kpc)
NGC6946
j = 1+2, α= 0.5
V (km s-1)
r (kpc)
NGC1560
j = 1+3, α= 0.2

Conclusions

- ΛCDM is successful but probably is not the final answer, other models are possible.
- SFDM seem to be a viable candidate to DM
- Consistent with CDM at large scales but provides possible solutions to small scales
- Density profile is constant in the central region and not empirical as NFW, Einasto, Burkert, etc.
- RC fits of large and small spirals are in very good agreement with data.

Future work

- We propose baryons play a minor role in the RC of LSBs and dwarfs => ADD feedback but only what is needed.
- Distribution of satellites.