Macro dark matter selfgravitating halos around galaxies

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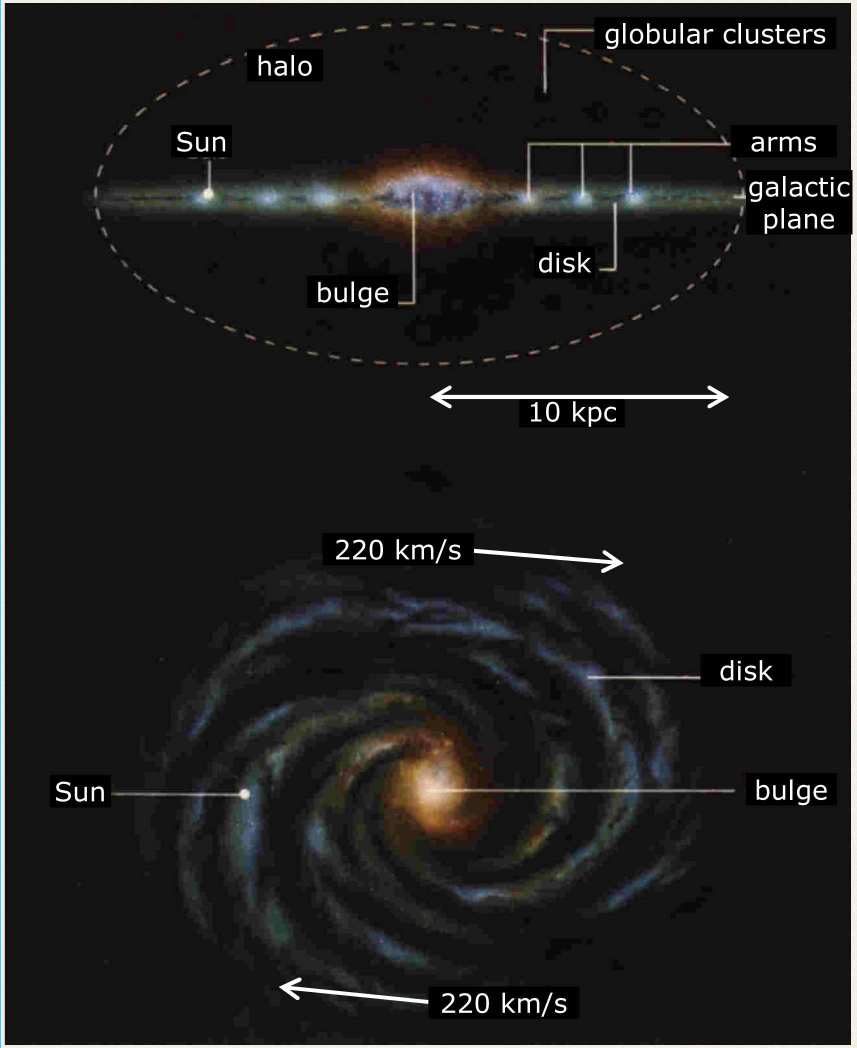
Quest for visible and invisible strange stuff in the Universe
LNF - Frascati, 27 Nov 2015

The Milky Way



radial velocity

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

simplified model with mass concentrated in the bulge

- bulge: uniform density ρ

- disk: negligible density

⇩

$$M(r) = \frac{4}{3}\pi \rho r^3 \quad \text{for } r \le R_b$$

$$M(r) = M \quad \text{for } r > R_b$$

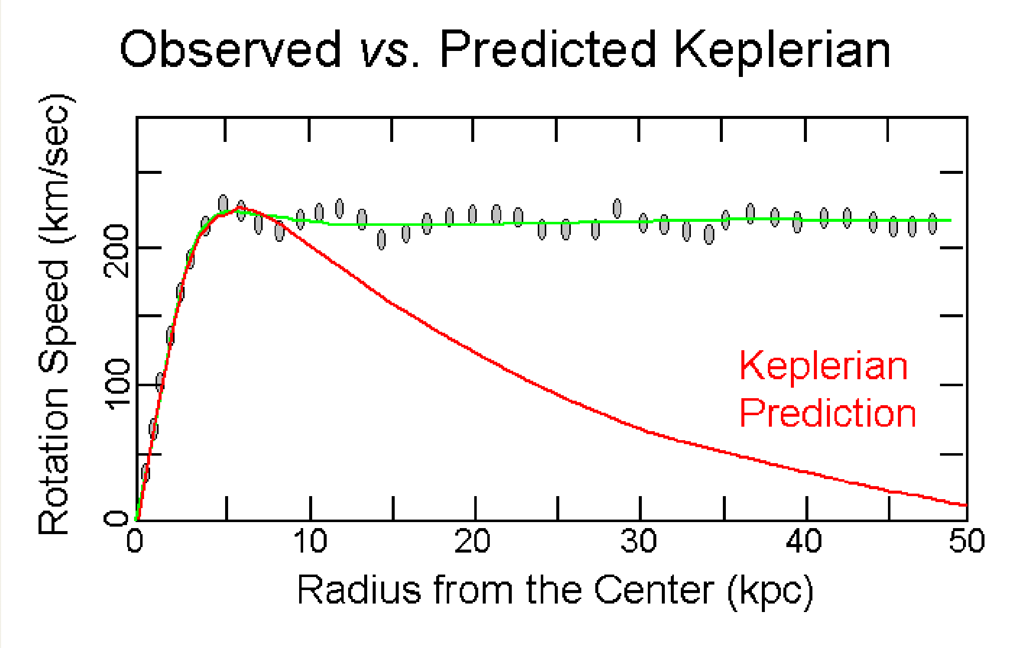
The rotation curve

rotation velocity

Bulge: $v(r) = 2\left(\frac{\pi}{3} G\rho\right)^{1/2} r \quad \text{for } r \le R_b$ (rigidly rotating body)

Disk: $v(r) = \sqrt{\frac{GM}{r}} \quad \text{for } r > R_b$ (Keplerian velocity)

theoretical predictions
in contrast
with observational data



Dark matter halo

The existence of dark matter halo can explain the rotation speed of the Galaxy (Zwicky, 1933)

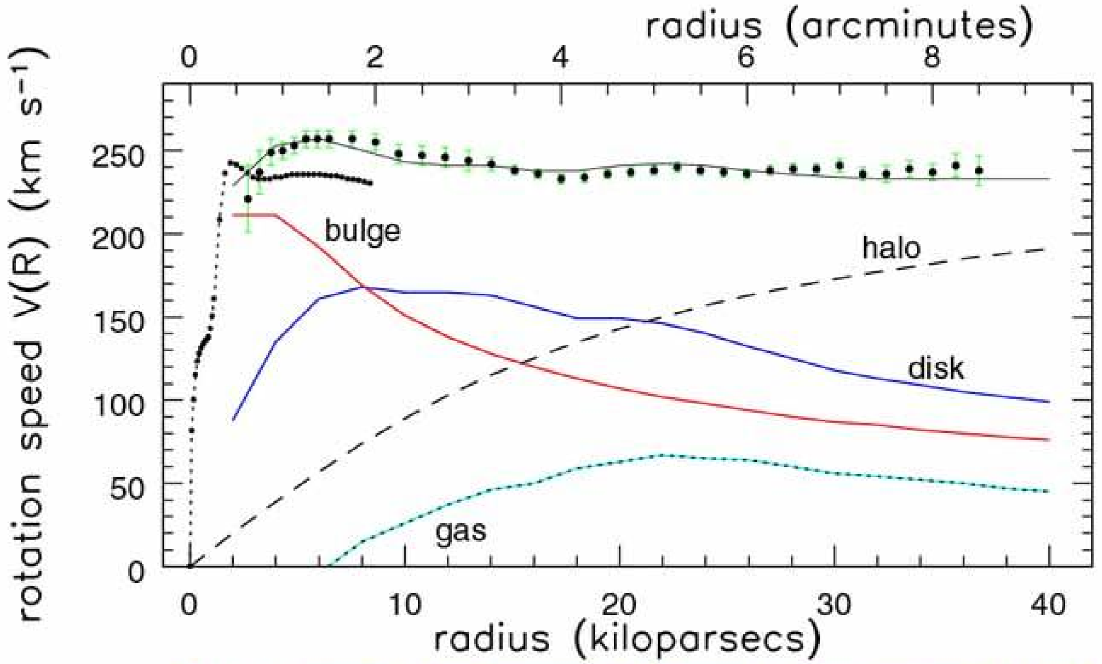


Fig 5.20 (Begeman, Sofue) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

$$M_{halo} \approx 10\, M_{gal}$$

$$R_{halo} \approx 10\, R_{gal}$$

two big questions
what particle ?
what mass ?

First possibility: WIMPs

A VERY SIMPLE CASE

degenerate gas of particles constituting the galactic halo

- polytropic model with n=3/2 -

$$M = \frac{3}{2}\left(\frac{\pi}{2}\right)^{3/2}(2.71406)\frac{\hbar^3}{G^{3/2}m^4}\rho_0^{1/2}$$

$$R = \frac{(9\pi)^{1/6}}{2\sqrt{2}}(3.65375)\frac{\hbar}{G^{1/2}m^{4/3}}\rho_0^{-1/6}$$

a possible hypothesis due to importance of β decay in stellar equilibrium

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$p + e^- \rightarrow n + \nu_e$$

⇒ **massive neutrino** ⇒ $m = m_\nu \approx 10 \text{ eV}$

Neutrino hypothesis

with $M_{halo} \approx 10\, M_{gal} \quad R_{halo} \approx 10\, R_{gal}$

$$\Rightarrow \quad \rho_0 \approx 10^{-25}\ \mathrm{g/cm^3}$$

$$\Rightarrow \quad R \cong 90 \left(\frac{M}{10^{12} M_\odot} \right)^{-1/3} \mathrm{kpc}$$

critical density

$$\rho_{cr} = \frac{m_\nu^4 c^3}{3\pi^2 \hbar^3} = 7.8 \cdot 10^{-17}\,\mathrm{g/cm^3} >> \rho_0$$

General Relativity? NO

$$\frac{GM}{Rc^2} = 4.8 \cdot 10^{-7} << 1$$

neutrino dark matter halos are nonrelativistic and also Newtonian

Second possibility/hypothesis: SMPs?

- SMPs as alternative candidates to WIMPs for dark matter

- very massive particles (m ~ GeV), low number density

→ low effective interaction rate in spite of a not small cross section (dark matter in big bang standard model ?)

- massive particle lifetime sufficiently large ? stability ?

→ big bang relics, background ?

- the role of strangeness

→ quark configuration with the same (approximate) number of u, d, s

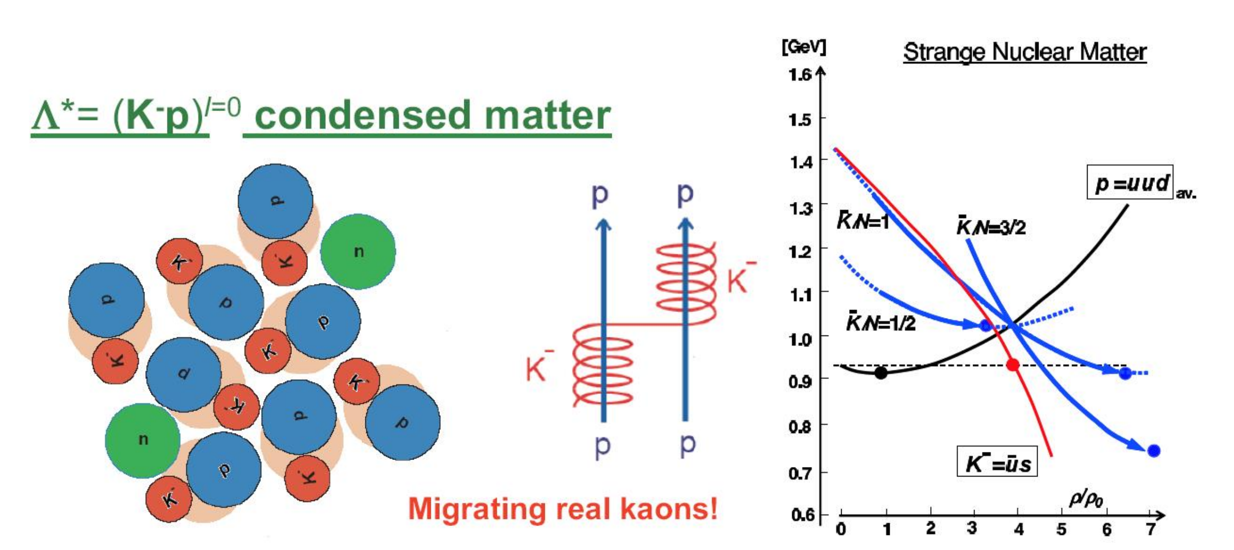
→ chemical potential due to Pauli exclusion principle favourable to stable configurations (strange quark matter conglomerates)

- quark matter configuration

→ $\Lambda^*(1405)$ as a possible candidate for dark matter (also in neutron stars?)

Strange dark matter

Neutron stars and … dark matter ?



Akaishi & Yamazaki, 2015 (for neutron stars)

one possibilty among different $\overline{K}N$ states:

$\Lambda^*(1405) \equiv K^- p$

strong decay, single Λ* is unstable

Λ* clusters:

$Nm_{\Lambda^*} \equiv m^* \sim$ GeV

Neutron stars: $\overline{K}^0 n \rightarrow K^- p\,?\quad N << N_n\,?$ **Hyperon stars (cores) ?**

Dark matter: $\Lambda^*(1405) \equiv K^- p \;\; N \leq 10$ may be stable ? **m* ~ 5÷10GeV**

Ultra-dense kaonic nuclear states as partial constituent of dark matter ?

Statistics: semidegenerate gas?

- For calculating selfgravitating equilibrium configurations of dark matter halos, the internal structure of the single Λ* cluster is not relevant. Nevertheless we could expect $\rho > 10^{15}$ g/cm^3 in the internal structure of the Λ* cluster.

- We consider Λ* cluster like a massive particle of mass m* only gravitationally interacting with the other Λ* clusters composing the halo.

- The existence of stable Λ* clusters is an ***open question***, nevertheless we may explore the possibility of having halos composed by strange dark matter.

- The first possibility is to consider a ***semidegenerate gas*** of particles with mass m*=5÷10GeV.

- We search for halos with masses $M \sim 10^{12} M_{\odot}$ and R~100kpc, then the mean density $\langle\rho\rangle$ is of the order of 10^{-26} g/cm^3 .

Gravitational equilibrium

For a mass m*=5GeV we have

$$\rho_{cr} = \frac{m^{*4} c^3}{3\pi^2\hbar^3} = 4.9\cdot 10^{18}\,\mathrm{g/cm^3} >> <\rho>; \qquad \frac{GM}{Rc^2} = 4.8\cdot 10^{-7} << 1$$

ALSO

strange dark matter halos are nonrelativistic and Newtonian

Semidegenerate Fermi distribution function with cutoff in energy:

$$\begin{cases} f(\varepsilon) = \dfrac{g}{h^3}\dfrac{1-e^{(\varepsilon-\varepsilon_c)/kT}}{e^{(\varepsilon-\mu)/kT}+1} & \text{for } \varepsilon \le \varepsilon_c \\ f(\varepsilon) = 0 & \text{for } \varepsilon > \varepsilon_c \end{cases}$$

cutoff:

$$\varepsilon_c = m(\phi_R - \phi)$$

mass density:

$$\rho = m\int f\,\mathrm{d}^3q$$

Poisson equation for gravitational equilibrium:

$$\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\frac{\mathrm{d}\phi}{\mathrm{d}r}\right) = 4\pi G\rho \qquad \text{with} \qquad \phi'(0)=0;\ \phi(0)=\phi_0$$

Dimensionless quantities

by imposing $r = \eta x$ with $\eta = \left(\dfrac{g m^4 \sigma G}{h^3} \right)^{-1/2}$ and $\sigma^2 = \dfrac{2kT}{m}$

$$\Rightarrow \quad \frac{1}{x^2}\frac{\mathrm{d}}{\mathrm{d}x}\left(x^2 \frac{\mathrm{d}W}{\mathrm{d}x} \right) = -8\,\pi\,\hat{\rho} \qquad \text{with} \quad W'(0) = 0; \quad W(0) = W_0$$

$$R = \eta \hat{R}; \quad M = \frac{\sigma^2 \eta}{G}\hat{M}; \quad \rho_0 = \frac{\sigma^2}{G\eta^2}\hat{\rho}_0; \quad W = \frac{\varepsilon_c}{kT}; \quad g = 2s+1$$

dimensionless quantities depend on W_0 and θ_R

$$\Rightarrow \quad \hat{\rho} = 2\pi \int_0^W g_s(z, W, \theta_R)\, z^{1/2} \mathrm{d}z; \quad \hat{M} = 4\pi \int_0^{\hat{R}} \hat{\rho}\, x^2 \mathrm{d}x = -\frac{1}{2}\left(x^2 \frac{\mathrm{d}W}{\mathrm{d}x} \right)_{x=\hat{R}}$$

where

$$z = \frac{\varepsilon}{kT}; \quad f(\varepsilon) \Rightarrow \frac{g}{h^3} g_s(z, W, \theta_R); \qquad g_s(z, W, \theta_R) = \begin{cases} \dfrac{1 - e^{z-W}}{e^{z-W-\theta_R} + 1} & \text{for } z \le W \\ 0 & \text{for } z > W \end{cases}$$

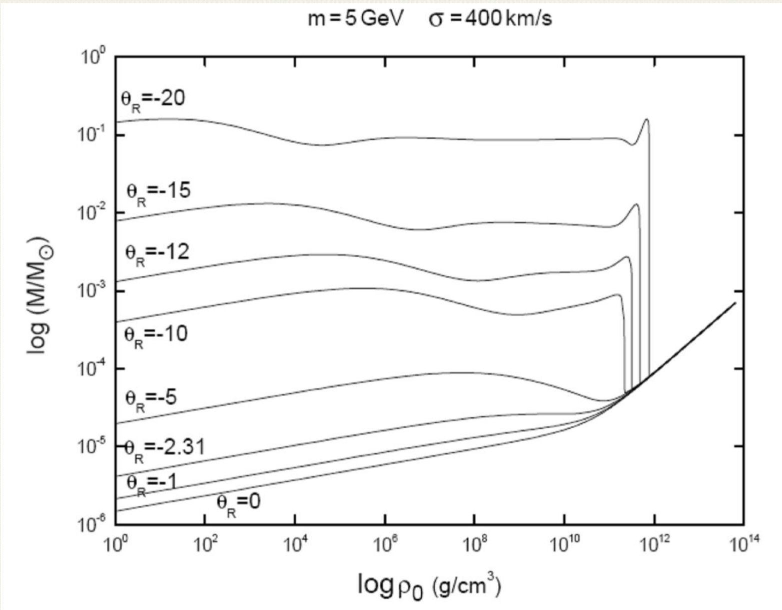
with $\theta = \dfrac{\mu}{kT}$ and $\theta_R = \theta - W \le 0$ (MM & Alberti, 2014)

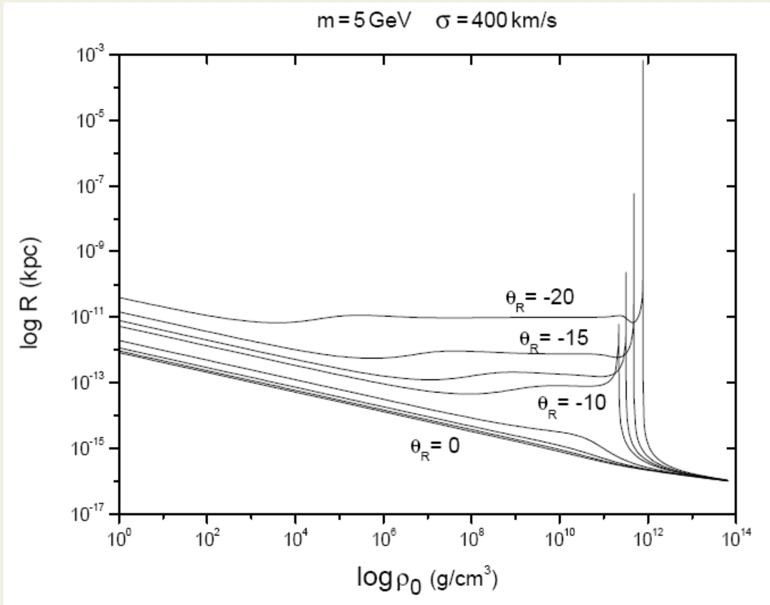
Equilibrium configurations

- By integrating the Poisson equation, we obtain different equilibrium configurations at different values of W_0 and θ_R.

- The solutions also depend on m (mass of the particle) and σ (surface velocity dispersion) through scaling laws.

- The results are summarized in M vs ρ_0 and R vs ρ_0 diagrams for m=5GeV and σ=400km/s.





Statistics: classical ?

The mass m*=5GeV doesn't allow to obtain the expected values of central density, mass and radius for a galactic halo

In fact we have: $\rho_0 \sim \sigma^3\ m^4$; $M \sim \sigma^{3/2}\ m^{-2}$; $R \sim \sigma^{-1/2}\ m^{-2}$
The densities are too large, masses and radii too small

Semidegenerate regime is not appropriate to describe strange dark matter halos: we need θ_R values much more negative, typical for a classical regime

Boltzmann (King) distribution function with cutoff in energy

On the other hand, for $-\theta_R \gg 1$ $f(\varepsilon) \to \frac{g}{h^3} e^{\mu/kT}\left(e^{-\varepsilon/kT} - e^{-\varepsilon_c/kT}\right)$ for $\varepsilon \le \varepsilon_c$

and $g_s(z,W,\theta_R) \Rightarrow e^{\theta_R} g_K(z,W)$ with $g_K(z,W) = \left(e^{W-z} - 1\right)$ for $z \le W$

Equilibrium in classical regime

THEN

strange dark matter halos are nonrelativistic, Newtonian and do not follow quantum statistics

In order to obtain halos with appropriate densities, masses and radii, we calculate equilibrium configurations at fixed central density ($\rho_0=10^{-24}$ g/cm^3) and particle mass (m*=5GeV), while increasing the value of $-\theta_R$ until to reach $M\sim10^{12}M_\odot$ and R~100kpc.

Using the expression of surface velocity dispersion σ in function of ρ_0

$$\sigma = \left(\frac{1}{\hat{\rho}_0} \frac{h^3}{g\, m^4 e^{\theta_R}} \right)^{1/3} \rho_0^{1/3} ,$$

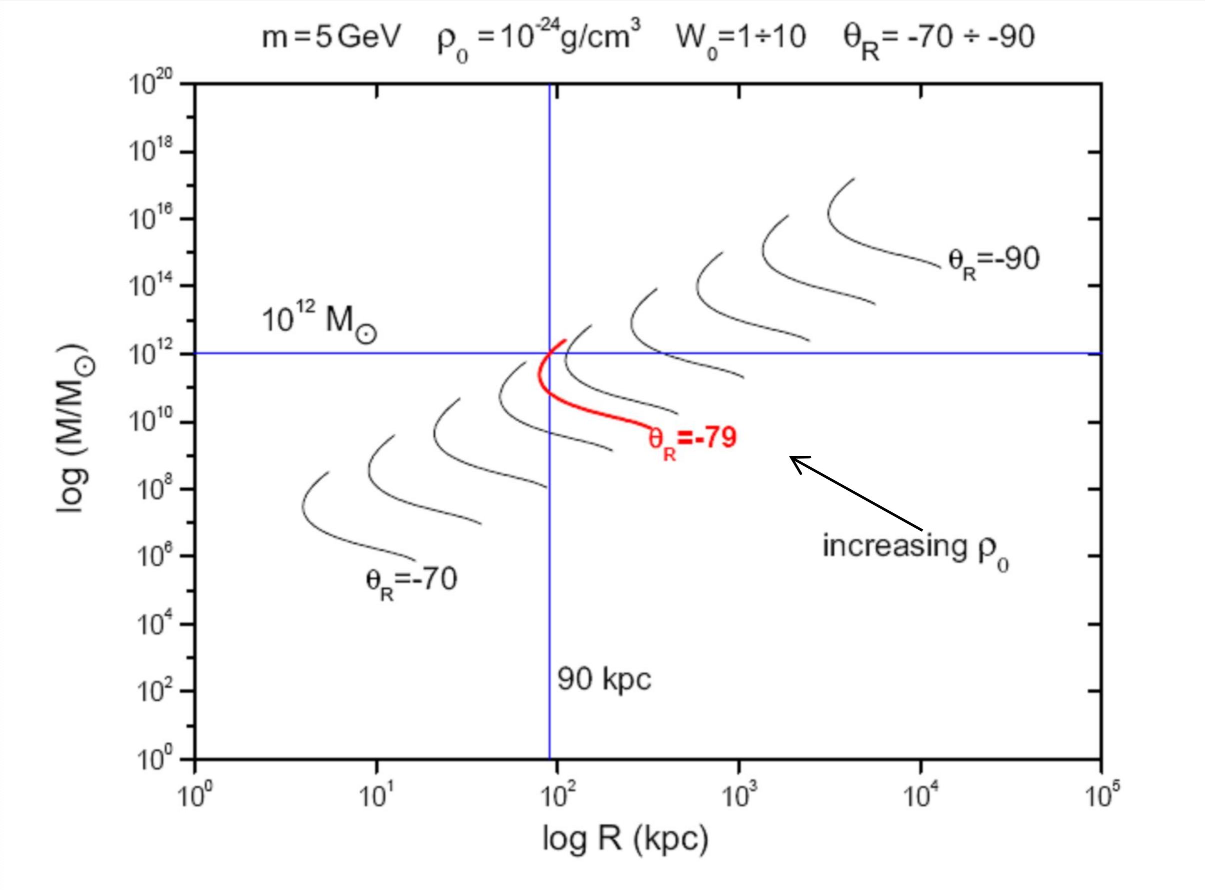
the expressions of M and R become

$$M = \frac{\hat{M}}{\hat{\rho}_0^{1/2}} \frac{h^3}{g\, m^4 e^{\theta_R} G^{3/2}} \rho_0^{1/2} ; \qquad R = \hat{R}\, \hat{\rho}_0^{1/6} \frac{h}{g^{1/3}\, m^{4/3} e^{\theta_R/3} G^{1/2}} \rho_0^{-1/6}$$

now dimensionless quantities depend on W_0 only

Individuating the value of θ_R

We calculated solutions in the range W_0=1÷10 (for globular clusters the most significant values are between 4 and 8; for galactic halos we expect even less)



In this regime, the dependence on θ_R become a scaling law.

It is possible to make a tuning by varying the central density ρ_0 and the parameter θ_R in order to match the requested values in M and R, also at different values of W_0

Results

For m*=5GeV and $\rho_0 = 10^{-24}$ g/cm³ we get

$$\theta_R = -79 ; \quad W_0 = 1.9 ; \quad M = 9.78 \cdot 10^{11} \, \mathrm{M}_\odot ; \quad R = 90.17 \, \mathrm{kpc}$$

$$\bar{\rho} = \frac{3\,\mathrm{M}}{4\pi \mathrm{R}^3} = 2.16 \cdot 10^{-26} \, \mathrm{g/cm}^3 ; \quad \sigma = 391 \, \mathrm{km/s}$$

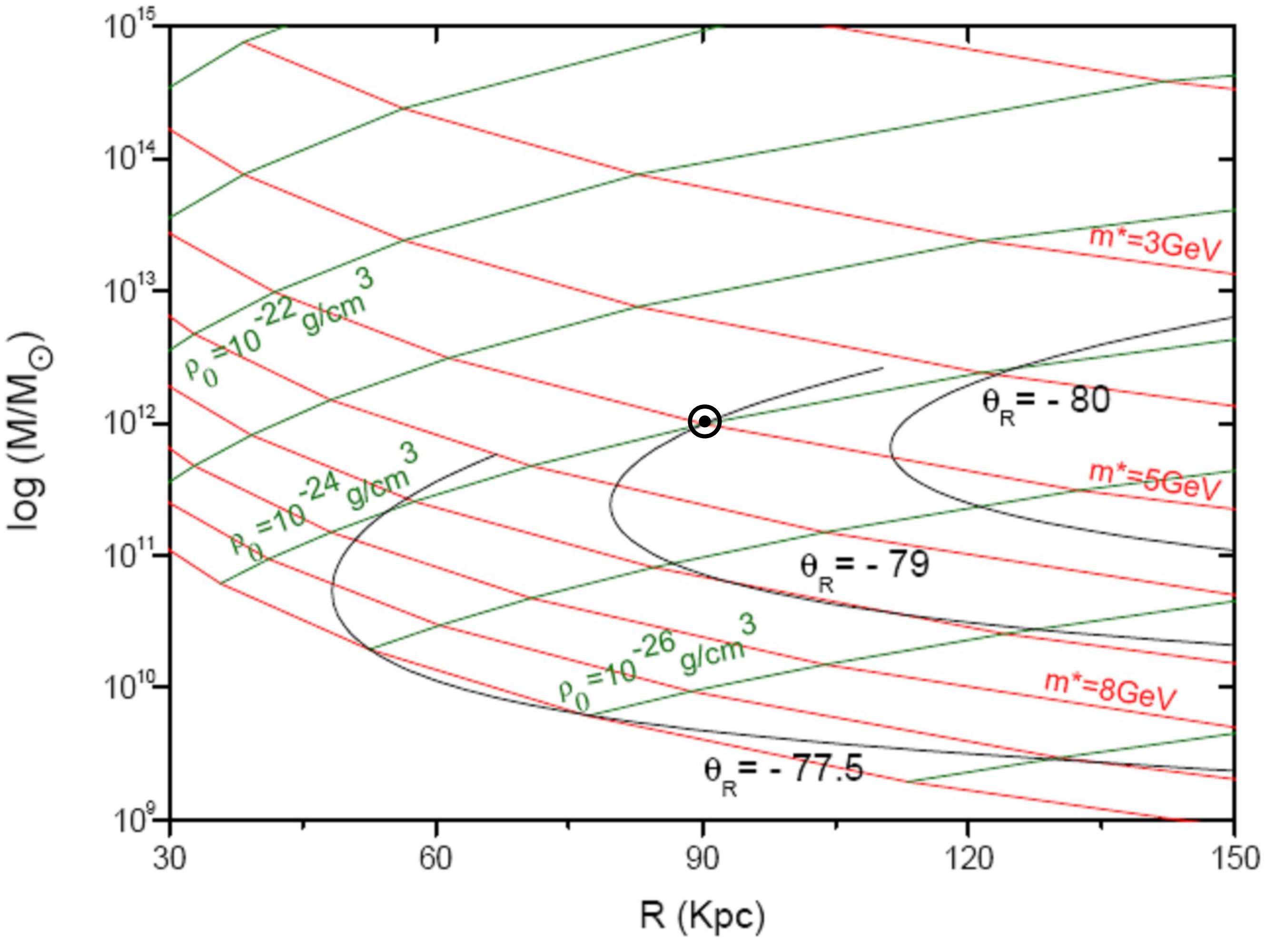
The obtained values are very satisfying !

The other solutions are obtained by scaling laws involving the total mass M and the radius R

$$M = 9.78 \cdot 10^{11} \left(\frac{\rho_0}{10^{-24} \, \mathrm{g/cm}^3} \right)^{1/2} \left(\frac{m^*}{5 \, \mathrm{GeV}} \right)^{-4} \mathrm{M}_\odot$$

$$R = 90.17 \left(\frac{\rho_0}{10^{-24} \, \mathrm{g/cm}^3} \right)^{-1/6} \left(\frac{m^*}{5 \, \mathrm{GeV}} \right)^{-4/3} \mathrm{kpc}$$

Strange dark matter halos

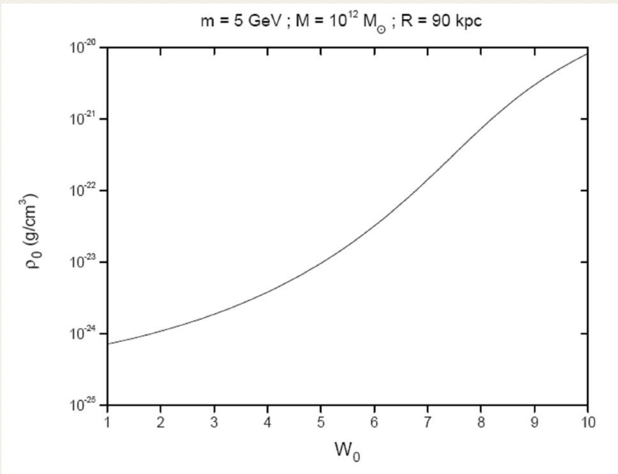


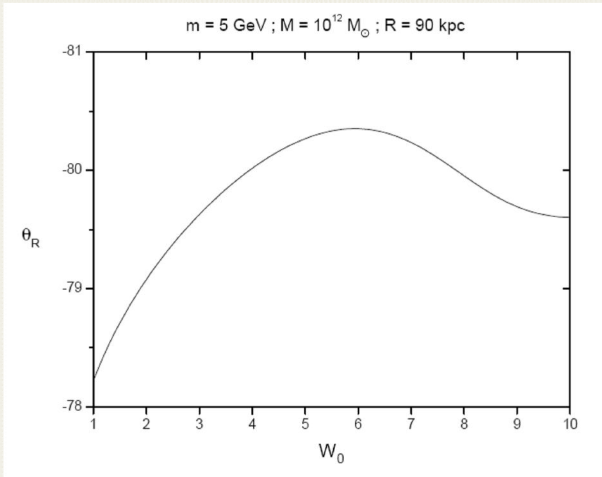
Changing parameters

We can fix m, M and R and study the behavior of the other parameters at different values of W_0

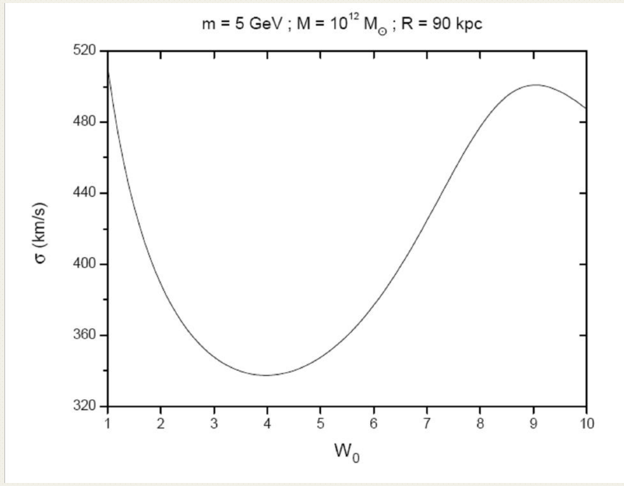
$$\rho_0 = \frac{\hat{R}^3 \hat{\rho}_0}{\hat{M}} \frac{M}{R^3}; \quad \theta_R = \frac{1}{2} \ln\left(\frac{\hat{M}\,\hat{R}^3}{M\,R^3} \right) + \ln\left(\frac{h^3}{g\,m^4 G^{3/2}} \right)$$

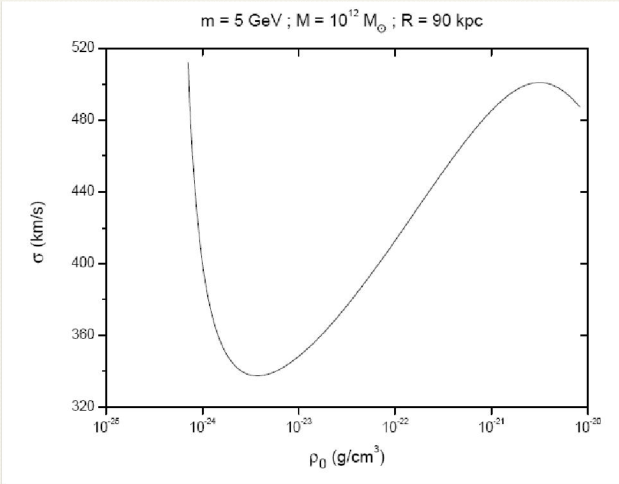
and, consequently, $$\sigma = \left(\frac{1}{\hat{\rho}_0} \frac{h^3}{g\,m^4 e^{\theta_R}} \right)^{1/3} \rho_0^{1/3}$$

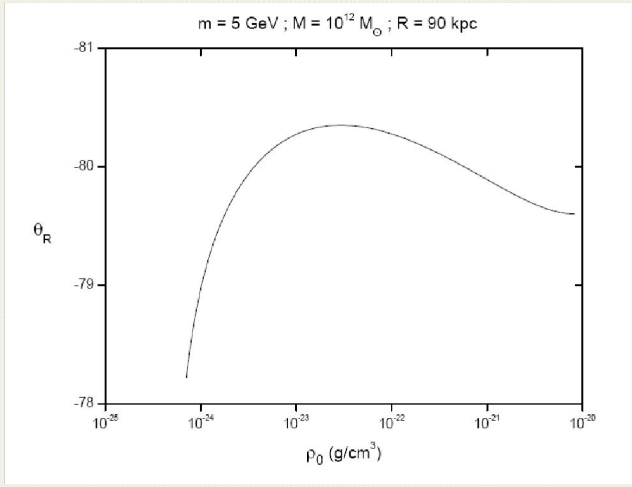


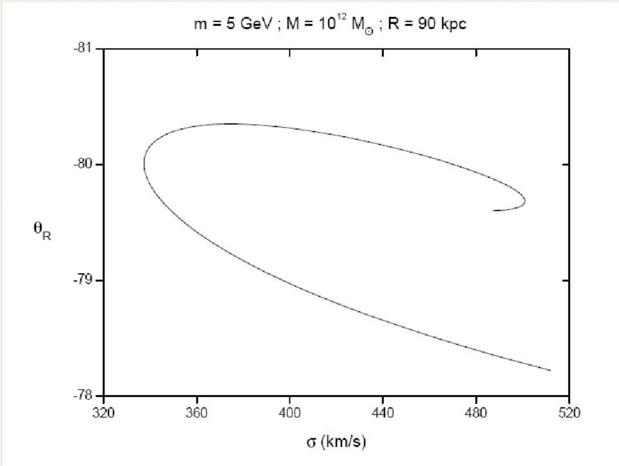


Other diagrams









Conclusions

- We obtained the relevant parameters for constructing equilibrium configurations of selfgravitating halos composed by macro component ($m^* \sim$GeV) deriving from strange dark matter.

- If Λ^* clusters are stable, galactic halos reproducing the same rotation velocity curve in galaxies are possible, in alternative to WIMP-composed halos.

- The halos have a mass $M \sim 10^{12} M_{\odot}$ and a radius $R \sim 90$kpc in complete accordance with the expected values.

- Galactic halos are completely Newtonian (only Poisson equation is needed), non relativistic (velocity dispersion $\sigma \sim 400$km/s) and do not follow quantum statistics ($\theta_R \sim -80$).

- The existence of stable Λ^* clusters, if confirmed, may have strong implications in the standard big bang model.

- The possibility to consider the presence of gravitational field of the galaxy together with visible mass luminosity data can give more stringent constraints to values of the particle mass and W_0. Finally, a dynamical stability analysis of halos will be considered.

Thank you