Massive hadronic candidates to dark matter

Marco Merafina

Physics Department
University of Rome “La Sapienza”

(in collaboration with Kaonnis Group - LNF Frascati)

The Galaxy rotation curve

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

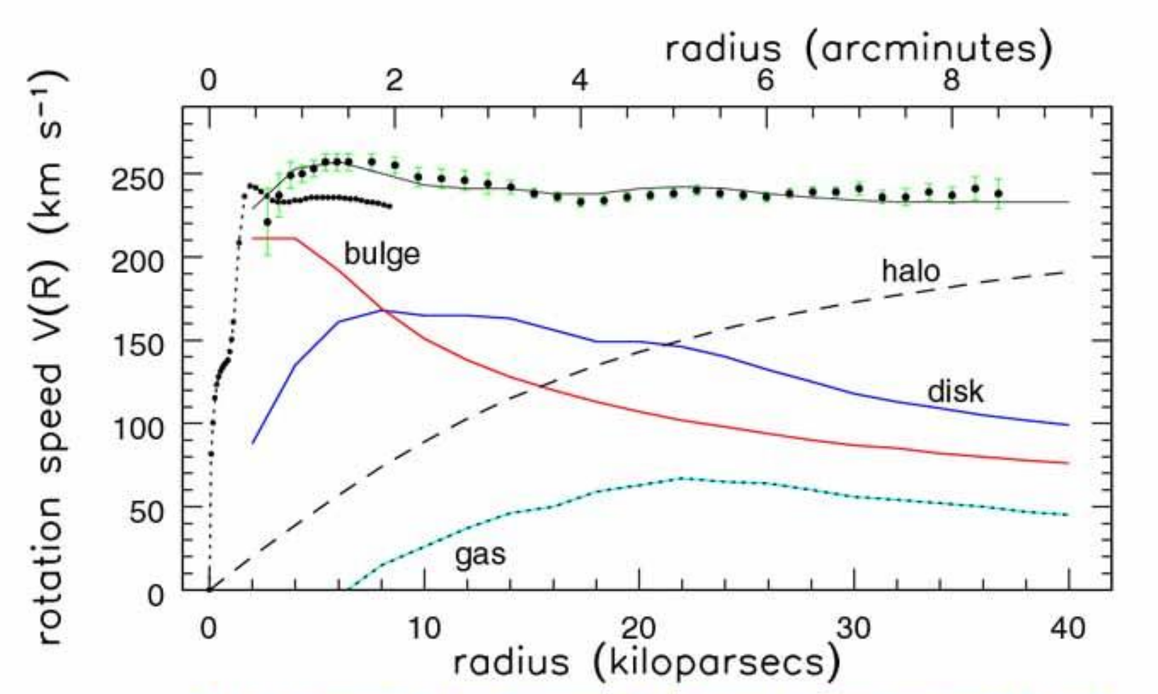


Fig 5.20 (Begeman, Sofue) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

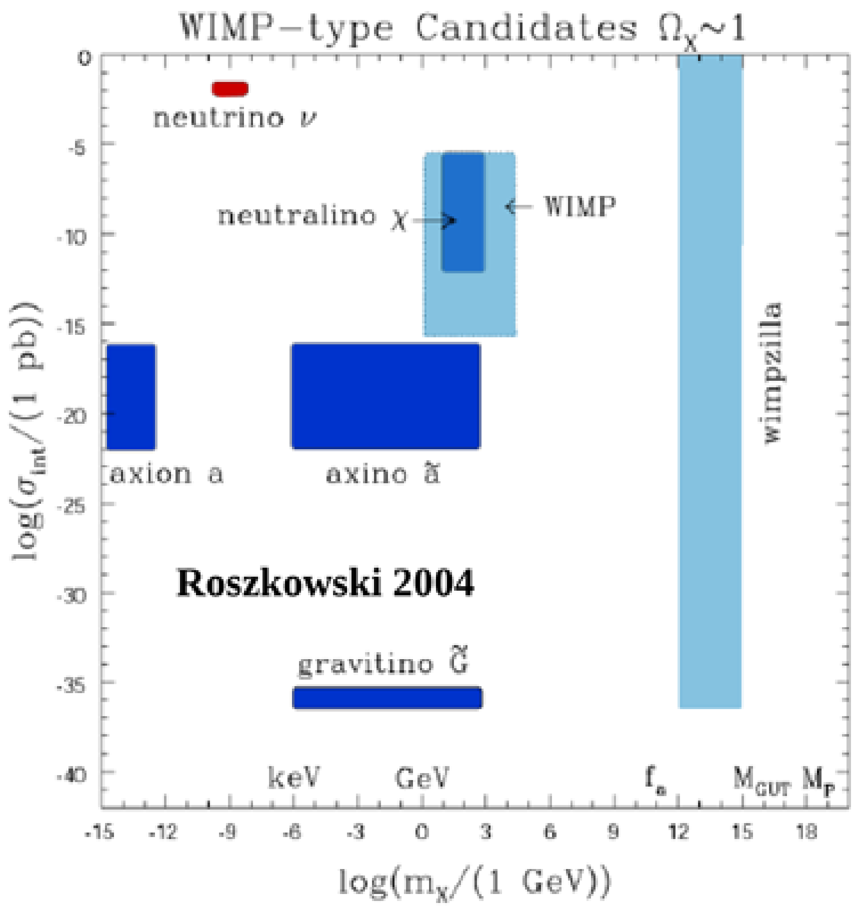
$$M_{halo} \approx 10\, M_{gal}$$

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

two big questions
what particle ?
what mass ?

Possible DM candidates

- A review of the DM candidates zoo (particles only)...



A wide range of possibilities and hypotheses

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

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

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

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

Neutrino hypothesis

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

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

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

critical density

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

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?)

A model independent mass individuation

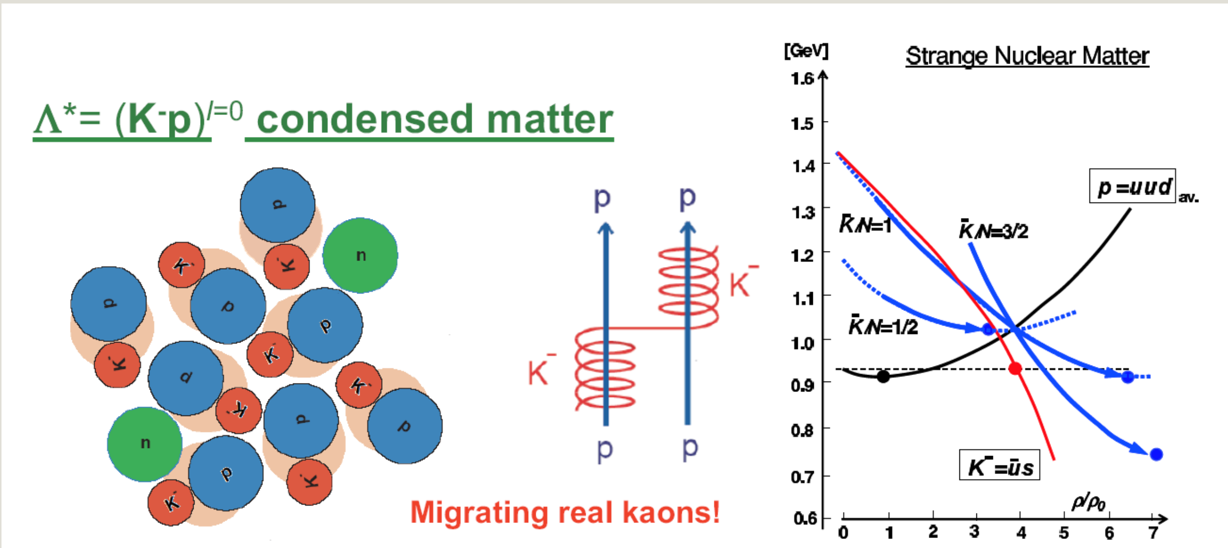
- **The possible individuation of the mass range for a dark matter particle must be not strictly connected with the choice of model that produce it.**
- **We consider the Akaishi-Yamazaki model as an example that we know to be controversial from the stabilty point of view [see Hrtánková et. al., Phys. Lett. B (2018), 785, 90].**
- **Nevertheless it has the quality to produce the correct range of masses relevant in cosmology, desumed by observations and necessary for galactic halos models of dark matter.**
- **Alternative hadron mass hypotheses concerning models of stable particles in the same range can be equally useful in order to obtain the results here presented, and the cosmological demand of mass particles in the range 10÷30 GeV remains necessary in explaining theoretical models and observations.**

THEN consider the AY model as an example

not crucial for the cosmological conclusions.

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:

$N m_{\Lambda^*} \equiv m^* \sim$ GeV

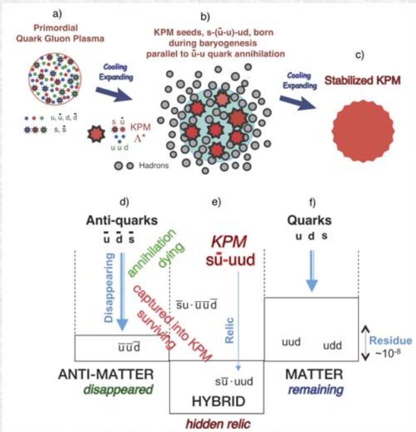
Neutron stars: $\overline{K}^0 n \rightarrow K^- p\,?\quad N << N_n\,?$ **Hyperon stars (cores) ?**

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 ?

Extension from neutron stars to cosmology

Possible cosmological origin of Λ^* conglomerates

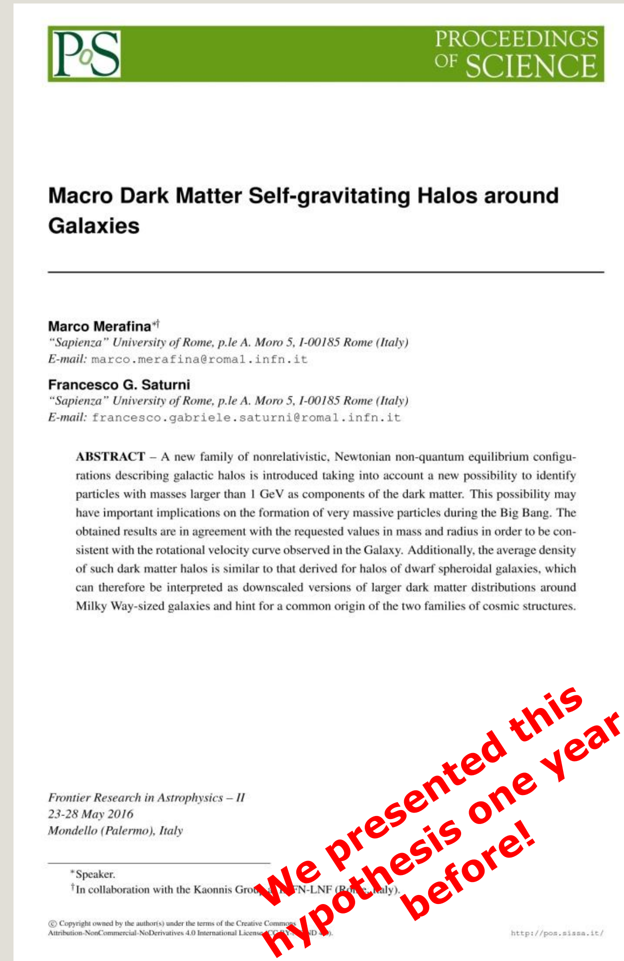


- before the hadronization stage, in the quark-gluon plasma period, when temperature reaches 100 MeV (order of the Λ^* lifetime) the qq annihilation cross section is of the order of the

su + uud → Λ^* cross section

Λ^*s could have been produced on large scale, surviving in conglomerates thanks to the big binding energy.

Strange dark matter as brick for the formation of galactic halos (halos composed by conglomerates)


PoS PROCEEDINGS OF SCIENCE

Macro Dark Matter Self-gravitating Halos around Galaxies

Marco Merafina[*†]
"Sapienza" University of Rome, p.le A. Moro 5, I-00185 Rome (Italy)
E-mail: marco.merafina@roma1.infn.it

Francesco G. Saturni
"Sapienza" University of Rome, p.le A. Moro 5, I-00185 Rome (Italy)
E-mail: francesco.gabriele.saturni@roma1.infn.it

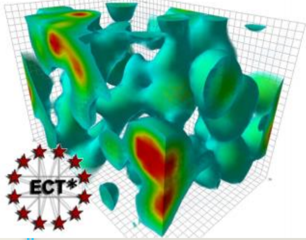
ABSTRACT – A new family of nonrelativistic, Newtonian non-quantum equilibrium configurations describing galactic halos is introduced taking into account a new possibility to identify particles with masses larger than 1 GeV as components of the dark matter. This possibility may have important implications on the formation of very massive particles during the Big Bang. The obtained results are in agreement with the requested values in mass and radius in order to be consistent with the rotational velocity curve observed in the Galaxy. Additionally, the average density of such dark matter halos is similar to that derived for halos of dwarf spheroidal galaxies, which can therefore be interpreted as downscaled versions of larger dark matter distributions around Milky Way-sized galaxies and hint for a common origin of the two families of cosmic structures.

Frontier Research in Astrophysics – II
23-28 May 2016
Mondello (Palermo), Italy

*Speaker.
†In collaboration with the Kaonnis Group, INFN-LNF (Rome, Italy).

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0). http://pos.sissa.it/

We presented this hypothesis one year before!



Stability of the conglomerates

Λ* formation today: 90% $\bar{K}$N (resonance); 10% Σπ (particle)

Big bang: only the particle Σπ is formed at very high density

A POSSIBLE SCENARIO

- Formation of Λ*

- Formation of conglomerates → strong interactions

- Negative energy interaction → effective mass of Λ* decreases from 1405 MeV to 932.5 MeV

- Every allowed decay channels are closed

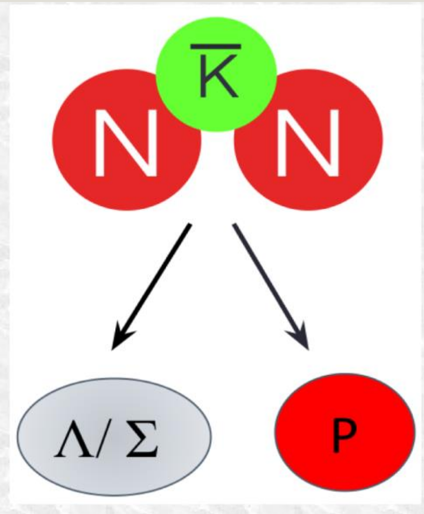
- Conglomerates become stable

<u>Problem</u>: if cooling rate and decrease of density of Universe is faster than stabilization rate of conglomerates, the process is not implemented.

Collisions among conglomerates → kinetic energy gives the energy for reaching a new instability → decay in standard model couples → gamma rays

We must search in high density regions where the collisions are probable

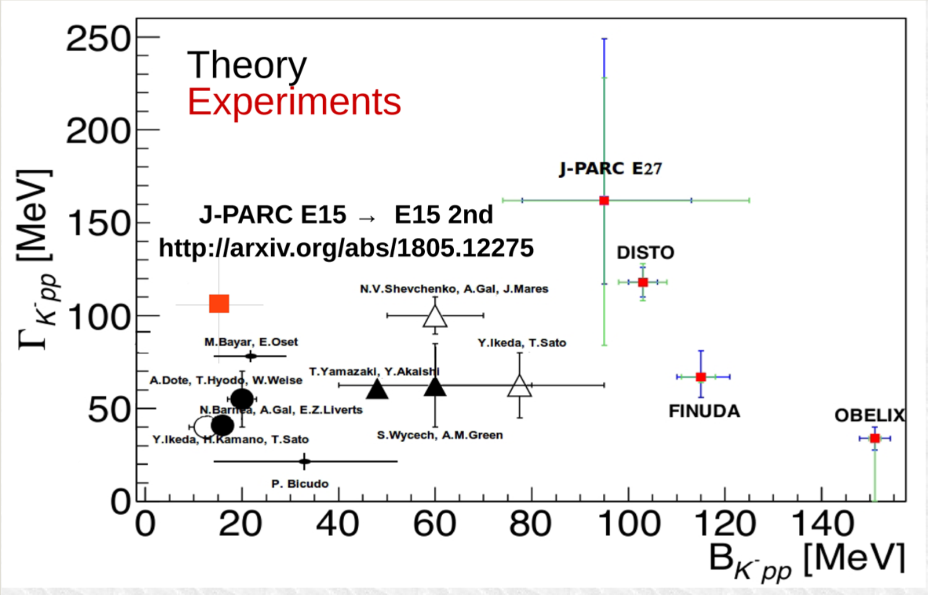
The question of the stability



Strongly attractive KN interaction in isospin I=0

K^- nucleon/multi-nucleons bound states predicted (Wycech, 1986; Akaishi & Yamazaki, 2002)

Experimentally investigated in K^- nuclei reactions
BUT
experiments and theory present a *very controversial* situation

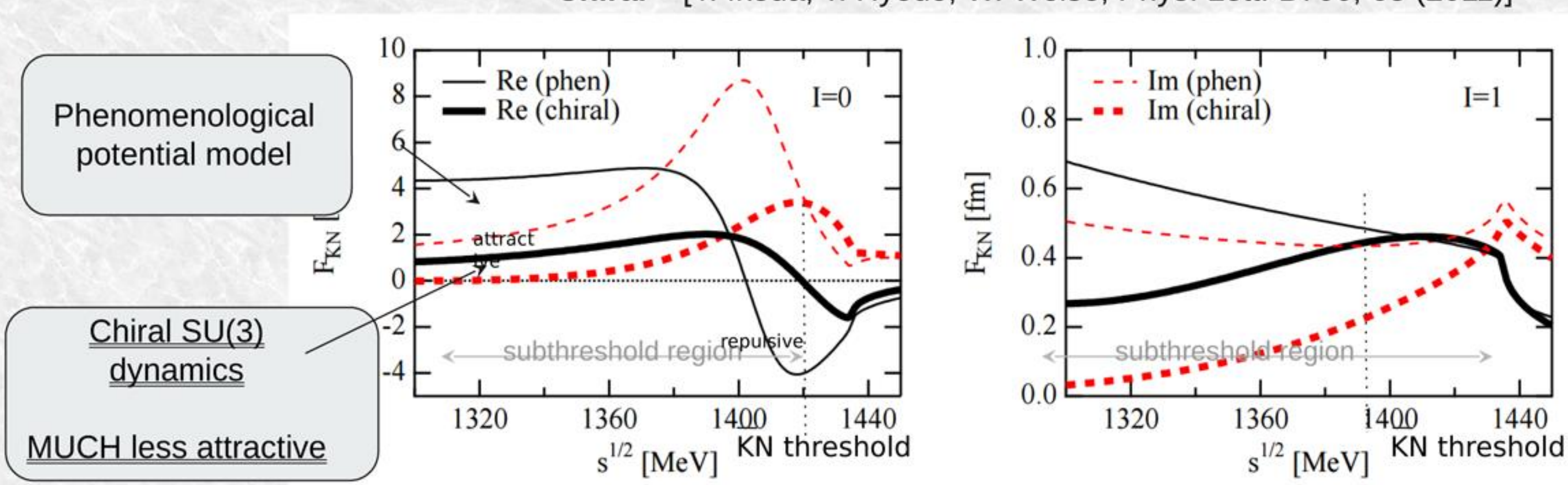


Kaon condensation realized in clusters of $\Lambda^* \equiv K^- p = (s\bar{u}) \otimes (uud)$, bricks

Under the hypotheses:

- K^- p is identified with the Λ^* hyperon resonance
- K^- p interaction is strongly attractive → B_{K^-} = 27MeV

Re Im
Phen. [Y. Akaishi, T. Yamazaki, Phys. Rev. C65, 044005 (2002)]
Chiral [Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B706, 63 (2011)]



Lower limit of conglomerate mass

Akaishi & Yamazaki Phys Lett B 774 (2017) 522

- the Λ^* - Λ^* interaction is calculated employing the Heitler- London covalent bonding, analog to H^0- H^0 interaction, but in this case the migrating particle is not e^- but K^-. Due to the bosonic nature of the K^- their wave function is symmetric:

$$\Phi(\vec{r}_1, \vec{r}_2) = N(D)[\phi_a(\vec{r}_1)\phi_b(\vec{r}_2) + \phi_b(\vec{r}_1)\phi_a(\vec{r}_2)],$$

where the two protons sit on sites a and b, which are separated by a distance of D. Then, the exchange interaction is obtained as

$$\Delta U(D) \equiv U(D) - U(\infty) \approx 4|N(D)|^2 \times$$
$$[\langle\phi_a|V_{K-p}|\phi_b\rangle\langle\phi_b|\phi_a\rangle + \langle\phi_b|V_{K-p}|\phi_a\rangle\langle\phi_a|\phi_b\rangle],$$

- consequently the bonding is always additively constructed

DECAY IS DEFINITELY SUPPRESSED FOR N≥8 AND

conglomerates become stable with respect to strong and weak interactions

Conglomerate mass: $m^* \equiv m[(\Lambda^*)_N]c^2 \approx N \cdot 1405_{[\mathrm{MeV}]} + \frac{N(N\text{-}1)}{2}\langle \Delta U \rangle_{av}$

$\langle \Delta U \rangle_{av} = -135\,\mathrm{MeV}$ ⇨ **for $N \geq 8$: $m^* \geq 7.46\,\mathrm{GeV}$**

Mass and spin

Calculation of g=2s+1 → spin ?

<u>free Λ* particles</u>

- Spin composition (angular momentum rule)
- Multiplicity of possible values

<u>bound system (our case)</u>

- Minimum energy spin configuration
- Strong interaction term depending on spin (not known)

→ *g is unknown (not yet investigated)*

we express conglomerate mass m* in terms of $m \cdot g^{1/4}$

> if g>1, minimum mass may be larger than 7.46 GeV

Stability: final considerations

Alternative hypothesis: larger value at N=10 (Akaishi & Yamazaki) based on experimental data (DISTO and E27)

Theoretical value for binding energy:
27 MeV for K^-p state and 52 MeV for K^-pp state

DISTO and E27 experiments: binding energy fixed at 100 MeV
> not reliable data (Fabbietti, DISTO; Iwasaki, E27)

First and unique reliable measurements (E15):
binging energy at 47 MeV for K^-pp state

Lower limit N=8 determines the asbolute stability for conglomerates

$m^* \geq 7.46$ GeV

Stability: alternative conclusions ?

We can refuse the conclusion concerning the AY model because could produce no stable particles

BUT

The demand of masses m ≥ 8 GeV remains valid and necessary from the cosmological point of view, in spite of the conclusions of J. Hrtánková, N. Barnea, E. Friedman, A. Gal, J. Mareš, M. Schäfer Phys. Lett. B (2018), 785, 90.

The internal structure of particle is not relevant from the gravitational point of view, the mass range, instead, is crucial for morphology.

<u>The hunt for the right particle for dark matter halos remains open</u>

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*~10GeV.

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

Gravitational equilibrium

For a mass m*=10 GeV we have

$$\rho_{cr} = \frac{m^{*4} c^3}{3\pi^2 \hbar^3} = 7.8 \cdot 10^{19}\,\text{g/cm}^3 >> <\rho>; \quad \frac{GM}{Rc^2} = 4.8 \cdot 10^{-7} << 1$$

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:

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

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 $\sigma^2 = \dfrac{2kT}{m}$

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

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

dimensionless quantities depend on W_0 and θ_R

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

where

$$z = \frac{\varepsilon}{kT}; \quad f(\varepsilon) \Rightarrow \frac{g}{h^3} g_s(z, W, \theta_R);$$

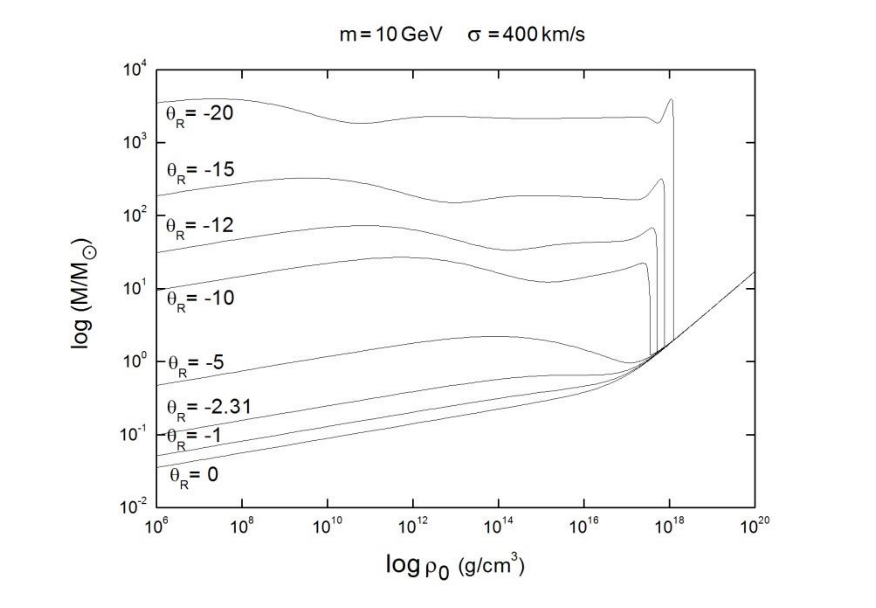
$$g_s(z, W, \theta_R) = \begin{cases} \dfrac{1 - e^{z-W}}{e^{z-W-\theta_R} + 1} & \text{for } z \le W \\ 0 & \text{for } z > W \end{cases}$$

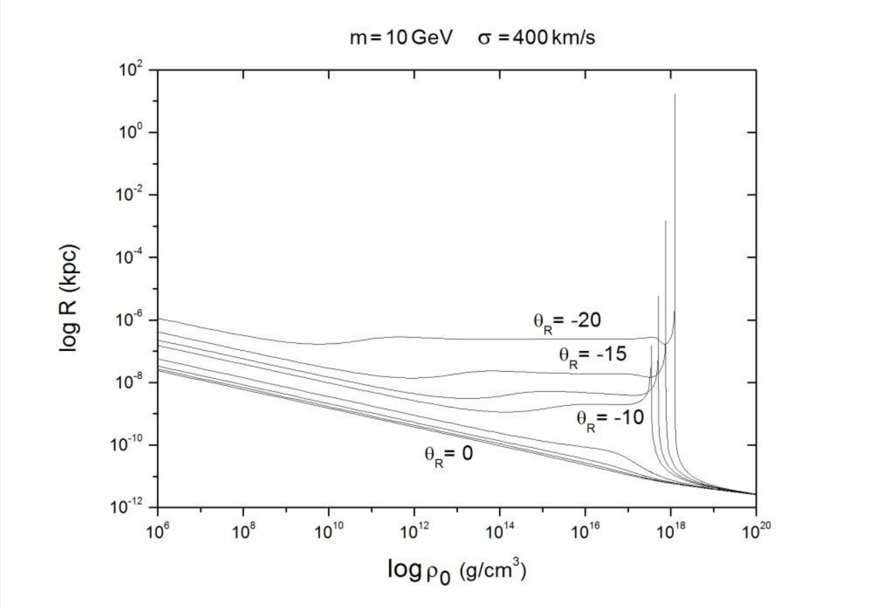
with $\theta = \dfrac{\mu}{kT}$ and $\theta_R = \theta - W \le 0$ (MM & Alberti, 2014)

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=10GeV and σ=400km/s





Non quantum (classical) statistics ?

The mass m*=10GeV 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 $-\theta_R \gg 1$ $f(\varepsilon) \rightarrow \frac{g}{h^3} e^{\mu/kT}\left(e^{-\varepsilon/kT} - e^{-\varepsilon_c/kT}\right)$ for $\varepsilon \leq \varepsilon_c$

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 $z \leq W$

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*=10GeV), 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

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

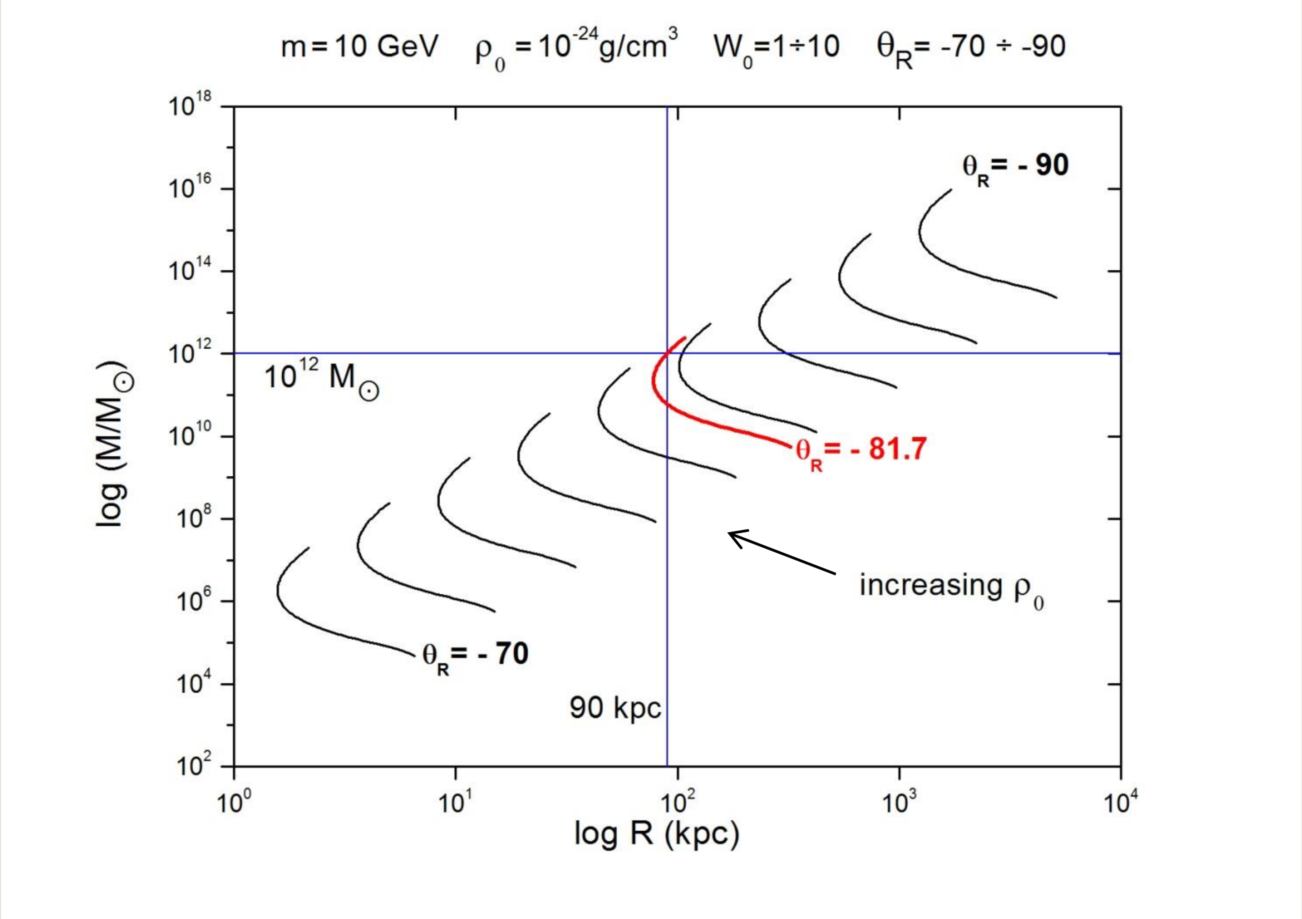
the expressions of M and R become

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

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.

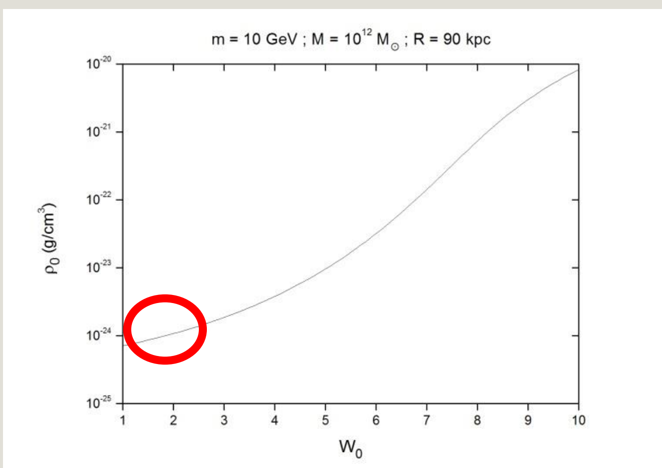
It is possible to make a tuning by varying the central density ρ_0 and the parameter θ_R in order to match the requested values in M and R, also at different values of W_0

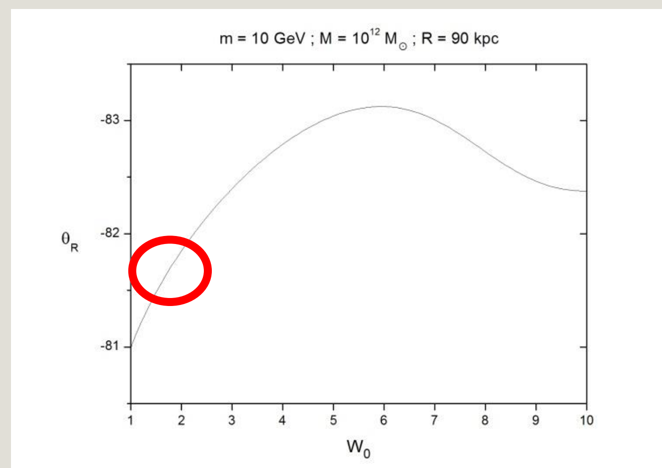
Changing parameters

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

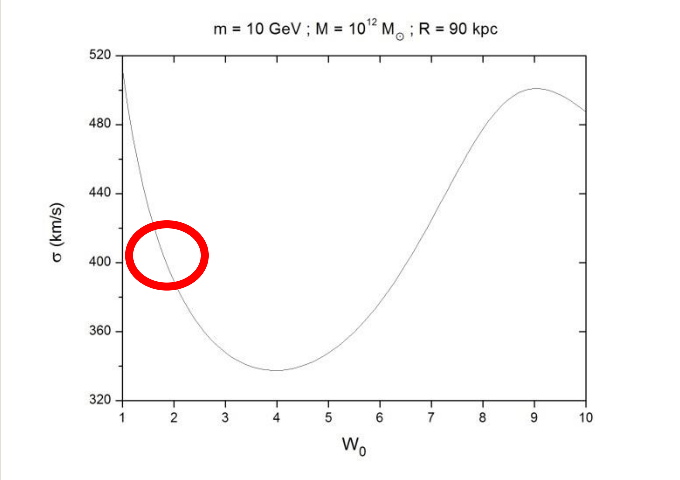
$$\rho_0 = \frac{\hat{R}^3 \hat{\rho}_0}{\hat{M}} \frac{M}{R^3}; \qquad \theta_R = \frac{1}{2} \ln\left(\frac{\hat{M}\,\hat{R}^3}{M\,R^3} \right) + \ln\left(\frac{h^3}{g\,m^4 G^{3/2}} \right)$$

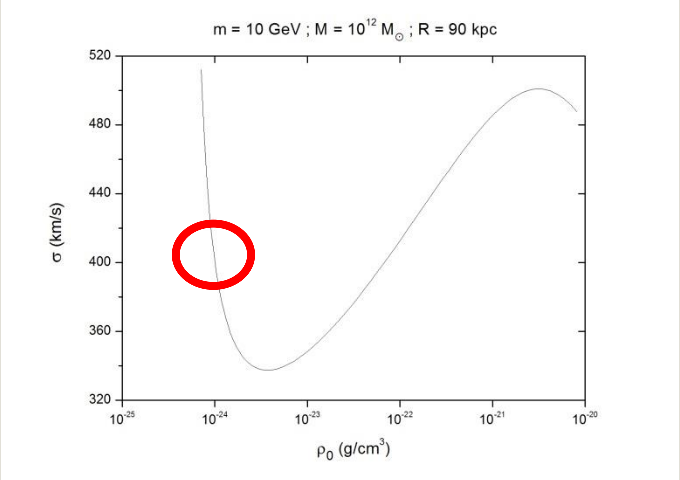
and, consequently, $$\sigma = \left(\frac{1}{\hat{\rho}_0} \frac{h^3}{g\,m^4 e^{\theta_R}} \right)^{1/3} \rho_0^{1/3}$$

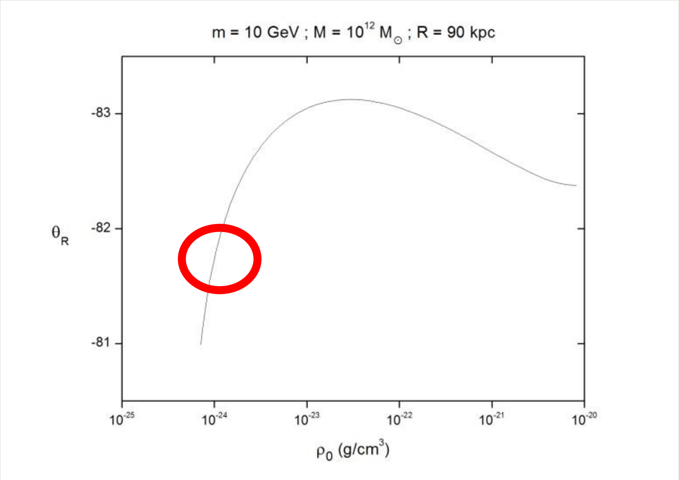


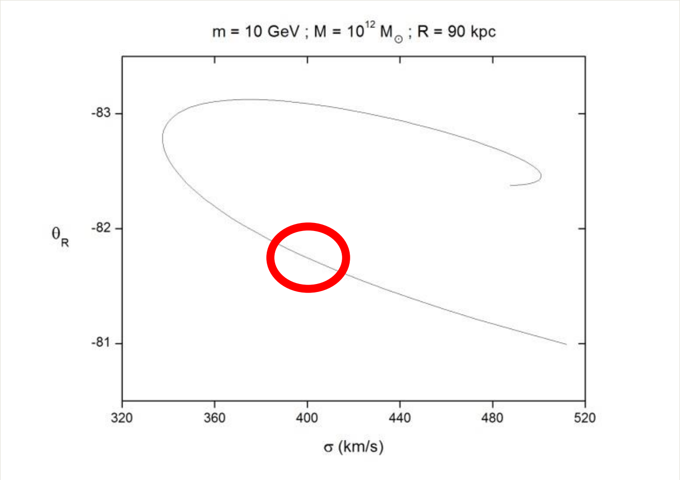


Other quantities









Results

For m*=10GeV and $\rho_0=10^{-24}$ g/cm^3 we get

$$\theta_R=-81.7\,;\; W_0=1.8\,;\; M=9.98\cdot 10^{11}\,\mathrm{M}_\odot\,;\quad R=89.41\,\mathrm{kpc}$$

$$\bar{\rho}=\frac{3\mathrm{M}}{4\pi \mathrm{R}^3}=2.26\cdot 10^{-26}\,\mathrm{g/cm}^3\,;\quad \sigma=405\,\mathrm{km/s}$$

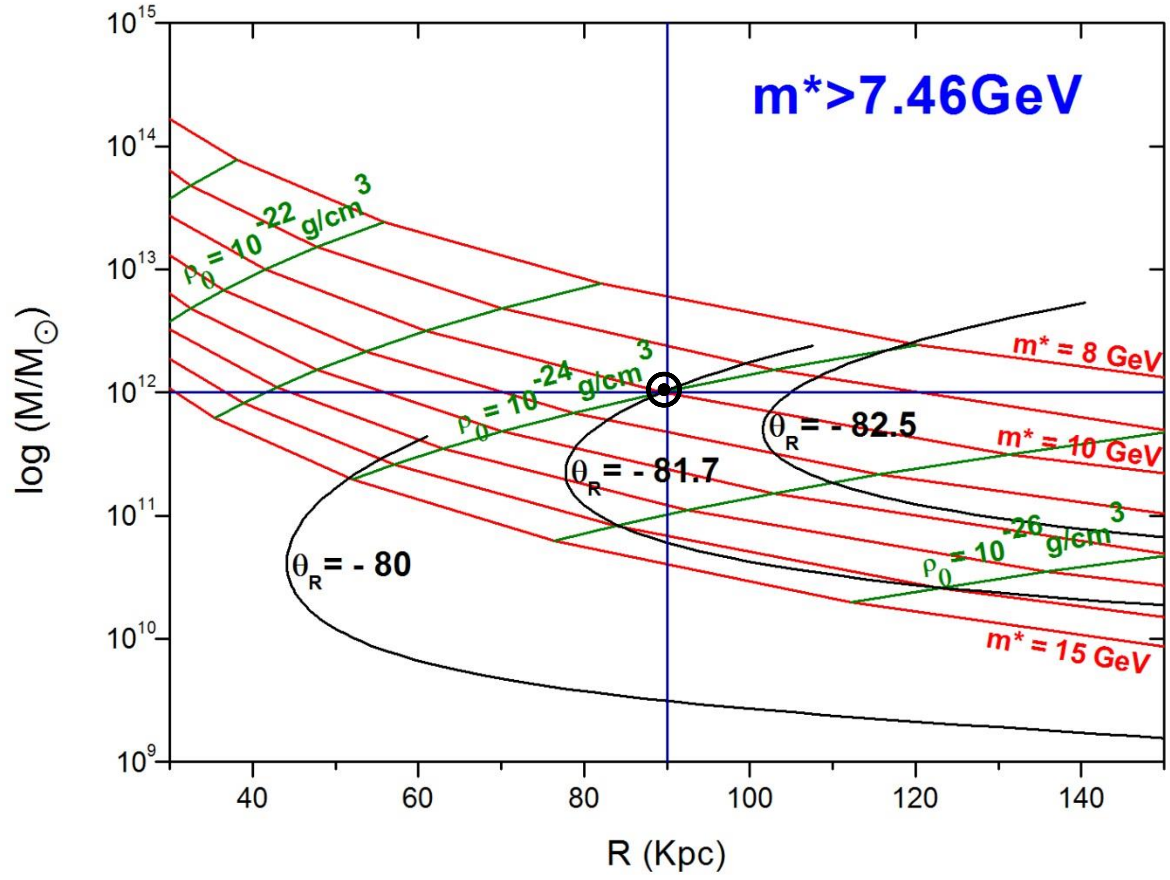
The obtained values are very satisfying !

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

$$M=9.98\cdot 10^{11}\left(\frac{\rho_0}{10^{-24}\,\mathrm{g/cm}^3}\right)^{1/2}\left(\frac{m^*}{10\,\mathrm{GeV}}\right)^{-4}\mathrm{M}_\odot$$

$$R=89.41\left(\frac{\rho_0}{10^{-24}\,\mathrm{g/cm}^3}\right)^{-1/6}\left(\frac{m^*}{10\,\mathrm{GeV}}\right)^{-4/3}\mathrm{kpc}$$

Strange dark matter halos



Dwarf Spheroidal (dSph) Galaxies

- dSph galaxies are the most interesting objects for indirect detection of self-interacting dark matter.

- Very high estimates of M/L ratios make these objects the most dark-matter dominated sources.

- Gamma-ray fluxes expected by the presence of such particles.

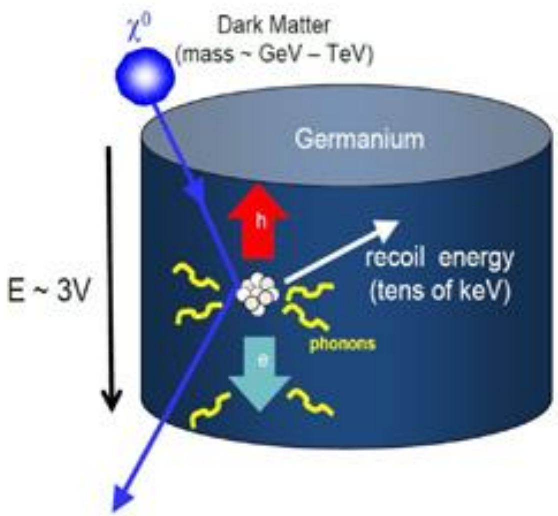
- In spite of the very difficult detection due to the faintness of such sources (and possible presence of background), there are some compelling observations of gamma-ray fluxes originating from dSph galaxies.

- Among the dSph galaxies located in the neighbors of Milky Way, it is necessary to take into account those producing a gamma-ray signal consistent with dark matter annihilation/ decay.

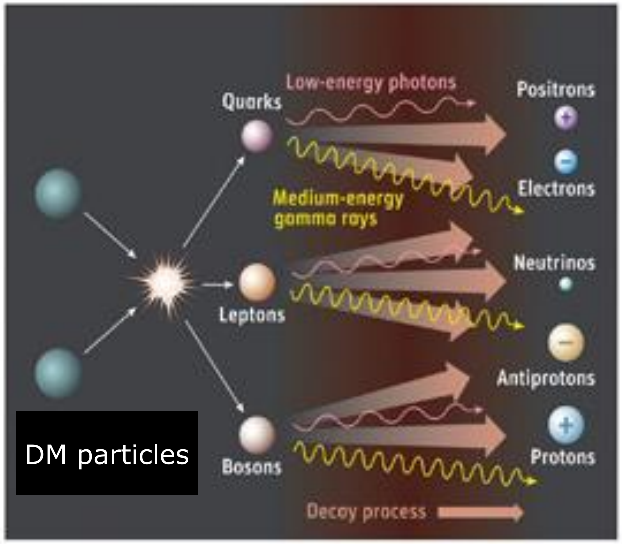
DM detection

- Since DM cross section for interaction with baryonic matter is extremely small, events of dark-baryonic matter interaction (*direct detection*) are very rare!
- *Indirect detection* looks instead for production of gamma rays from DM self-interaction (annihilation or decay), so it can be attempted with gamma detectors.

DIRECT DET.



INDIRECT DET.

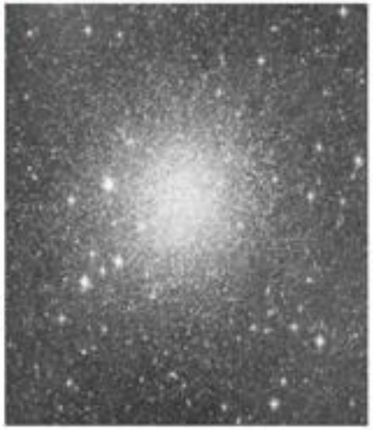


Observative targets

- Main targets of observation:

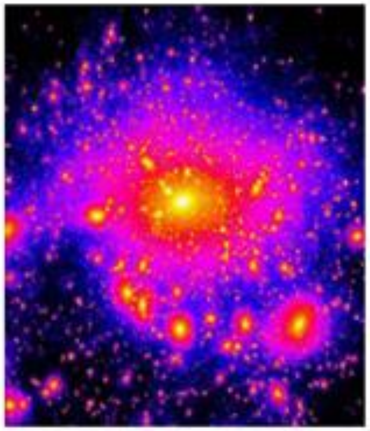
Milky Way center & MW "ridge" (very close, but risk of high bkg due to Galactic Sources + central BH)

Dwarf spheroidal galaxies (high *M/L* and almost no bkg, but small halos under current angular resolution)



Galaxy clusters (high DM content, but far and maybe contaminated by bkg due to hot ICM & AGN activity)

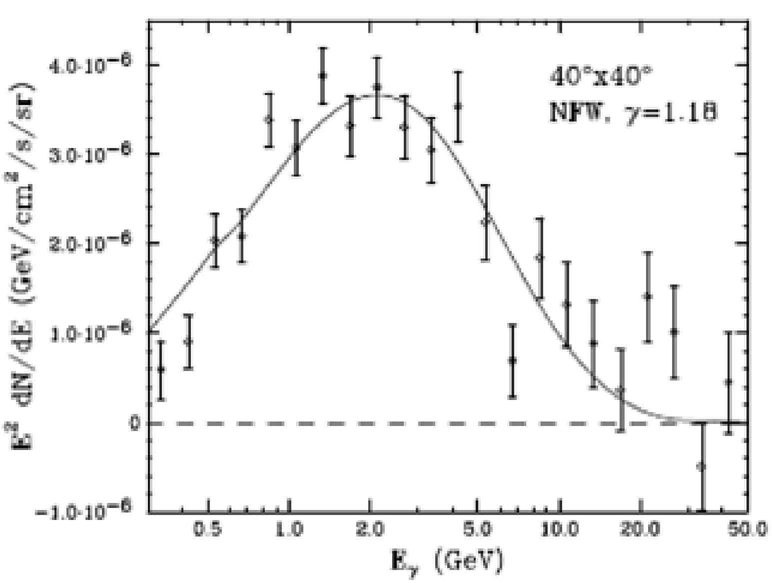
Dark clumps (conceptually dSphs withot stars, but same issues + their existence only theoretical so far)



Observational data

- Some recent clues from *Fermi* data (still controversial)...

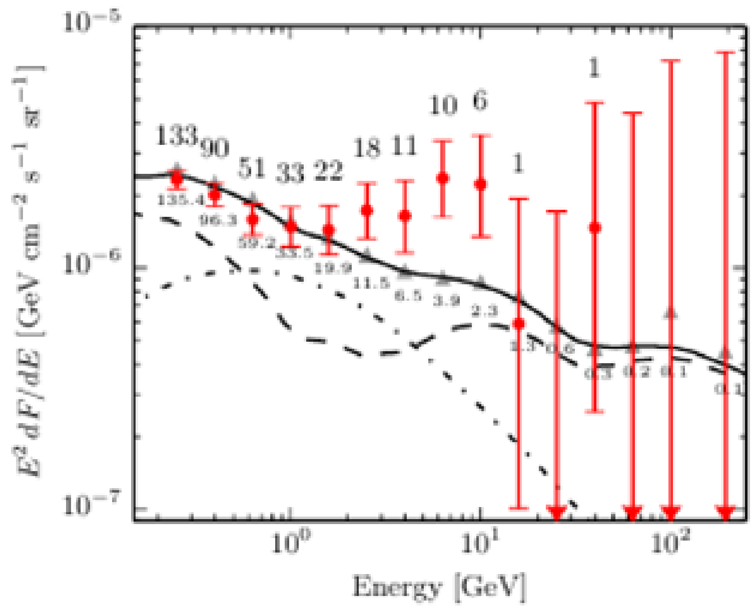
MILKY WAY CENTER (Daylan+ 2014)



m_χ = 43.0 GeV

$\langle\sigma v\rangle$ = 2.25e-26 cm³/s

dSph Ret II (Geringer-Sameth+ 2015)



m_χ = 25 GeV

$J\langle\sigma v\rangle$ ~ 1e-6 GeV²/cm²/s

Spheroidal Galaxies

DM halos of elliptical galaxies well reproduced by simulations with strange DM

$\Rightarrow$ **Can strange DM reproduce smaller halos too?**

Let's make a quick estimate:

Projected DM density for annihilation processes in point-like sources (astrophysical factor J)

$$J(\Delta\Omega) = \int_{\Delta\Omega} \mathrm{d}\Omega \int_{l} \rho^2(l,\Omega)\,\mathrm{d}l \quad \Rightarrow \quad J_{pls} = \int_{l} \rho^2(l)\,\mathrm{d}l = \left\langle \rho^2 \right\rangle D$$

Assuming point-like sources …

Inverting formula for ρ and using estimated $J \sim 4\cdot 10^{19}$ GeV^2 /cm^5 for Ret II dSph, with $\langle \sigma v \rangle = 3\cdot 10^{19}$ cm^3/s (Geringer-Sameth+ 2015) and D=30 kpc (distance) we obtain similar results

$$\rho_{rms} = \sqrt{\frac{J_{pls}}{D}} \approx 3.7 \cdot 10^{-26}\ \mathrm{g/cm}^3$$

Signals from different conglomerates

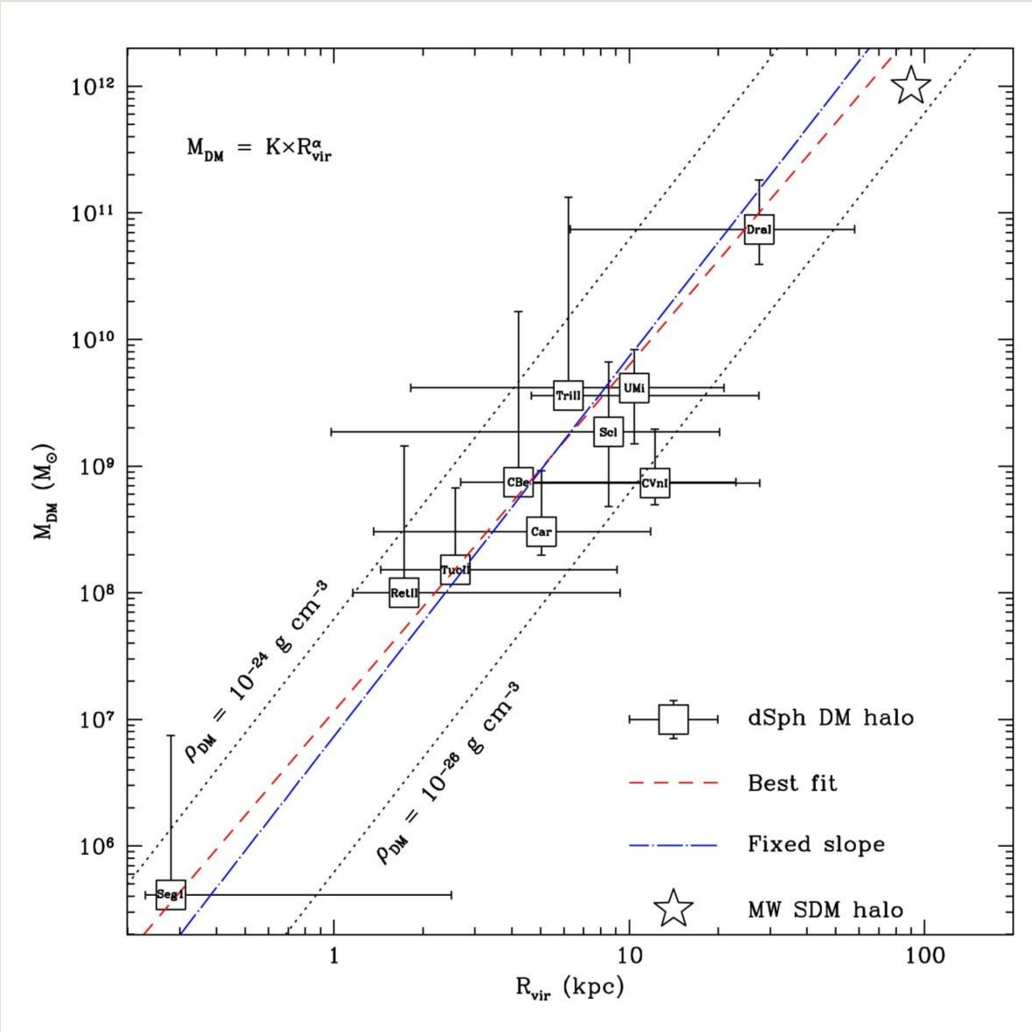
- **The considered example shows that the particles originating the gamma-ray fluxes have m_{DM} ~ 25 GeV (Reticulum II).**

- **A similar signal excess originated in dSph Tucana III (recently discovered by the survey DES Y2) and associated to annihilation in the channel $\tau^+\tau^-$ for a particle of mass m_{DM} ~ 15 GeV has been also detected.**

- **Therefore, all these signals confirm the possibility of a common cosmological origin for the formation of Λ* clusters, which could be an important component of the dark matter in the galactic structures of Universe.**

- **However, the way of formation and the stability of the Λ* clusters remain still uncertain as well as the actual mass of such DM particles.**

Halo densities



$\rho_{MWhalo} \sim \rho_{dSph}$

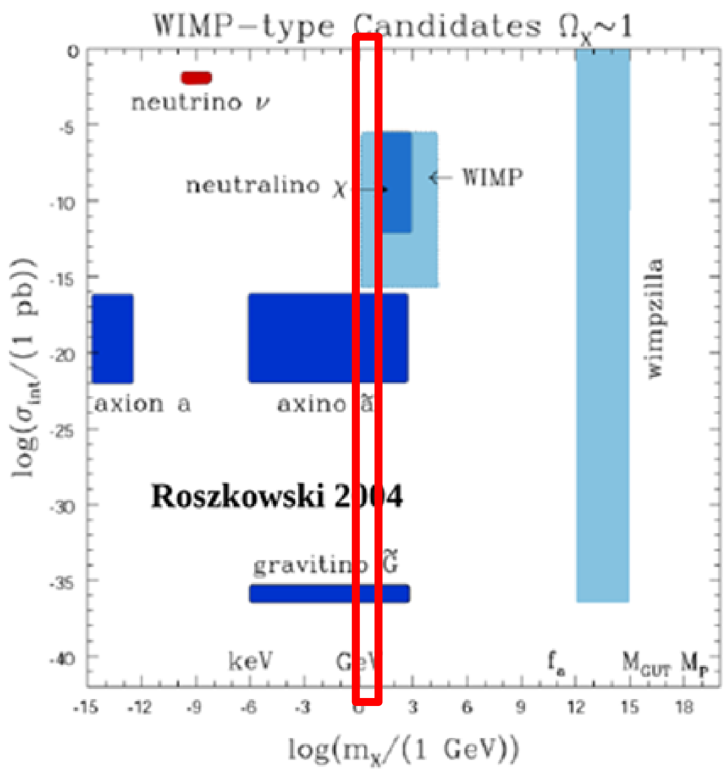
AMAZING COINCIDENCE OF RESULTS

suggesting cosmological hypothesis on DM component distribution in halos

Increasing data on dSphs in coherence with the hypothesis of strange dark matter

A model independent result

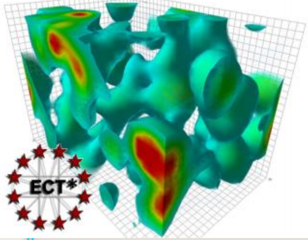
- A review of the DM candidates zoo (particles only)...



Only the mass range is important

<u>EUCLID mission</u>

data from more than 400 dwarf galaxies in order to confirm these conclusions



Conclusions

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

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

- Numerical calculations also show that such particles can reproduce both halos of elliptical galaxies (large scales) and dSphs (small scales).

- Galactic halos are completely Newtonian (only Poisson equation is needed), non relativistic (velocity dispersion σ~400km/s) and do not follow quantum statistics (θ_R~-80).

- The existence of stable Λ* clusters or particles with equivalent masses, if confirmed, may have strong implications in the standard big bang model.

- Gamma rays produced by DM self-interaction are the future observing channel to probe DM.

Thank you