Dark matter in galactic halos

Marco Merafina

Physics Department
University of Rome "La Sapienza"

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

SPICE: Strange hadrons as a Precision tool for strongly InteraCting systEms

THEIA Workshop 2024 - ECT*

Trento, 13 – 17 May 2024

STRONG 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

Introduction

This presentation is the result of a collaboration with Francesco Saturni (ASI - Italian Space Agency), Catalina Curceanu and some ex-members of the Kaonnis Group in Frascati: Raffaele Del Grande and Kristian Piscicchia.

Such collaboration resulted in the publication of an article in Phys Rev. D about the hypothesis of the presence of strangeness in the particles composing the dark matter in galactic halos.

The work here presented depicts its natural continuation and development.

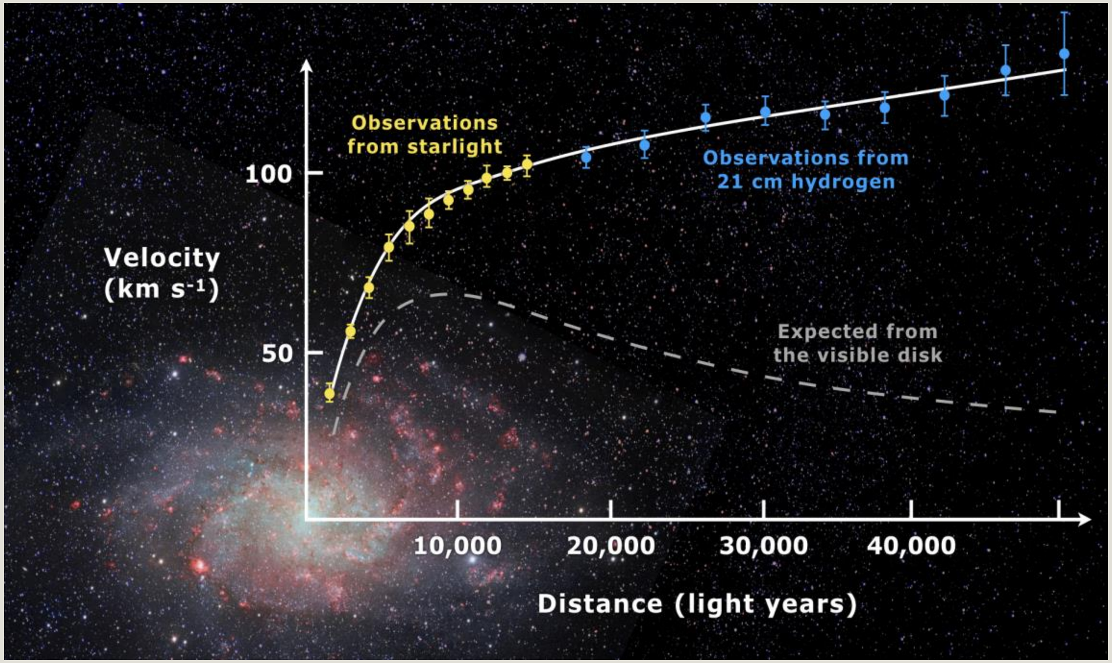
Evidences of Dark Matter (DM)

Studies of motion of Galactic Clusters (Zwicky, 1933):
first clues of the existence of dark matter in Coma cluster

OTHER EVIDENCES

- **Rotational curves in spiral galaxies (non-Keplerian behavior)**
- **Dwarf Spheroidal Galaxies (very high mass-luminosity ratio)**
- **Galaxy Clusters (missing mass to reach self-gravity, total mass calculated by using virial theorem - Zwicky, 1933 -)**
- **Gravitational Lensing (DM necessary for light deflection)**

Evidences of Dark Matter (DM):
Rotation Curve in spiral galaxies



Rotation curve of spiral galaxy M33 (Triangulum)

By 1970 about thirty spiral galaxy rotation curves and masses had been published, all based on the assumption that the unobserved region was *Keplerian*. The situation changed around 1970, as improved sensitivity in both optical and 21-cm observations permitted rotation curves to be extended to larger radii.

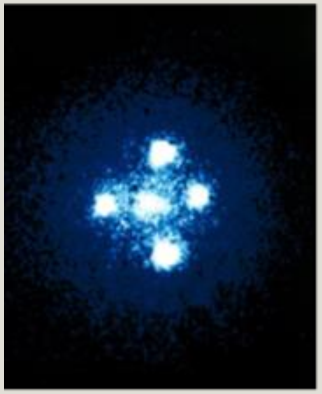
Actually, there are at least 70 galaxies whose rotation curves confirm this trend.

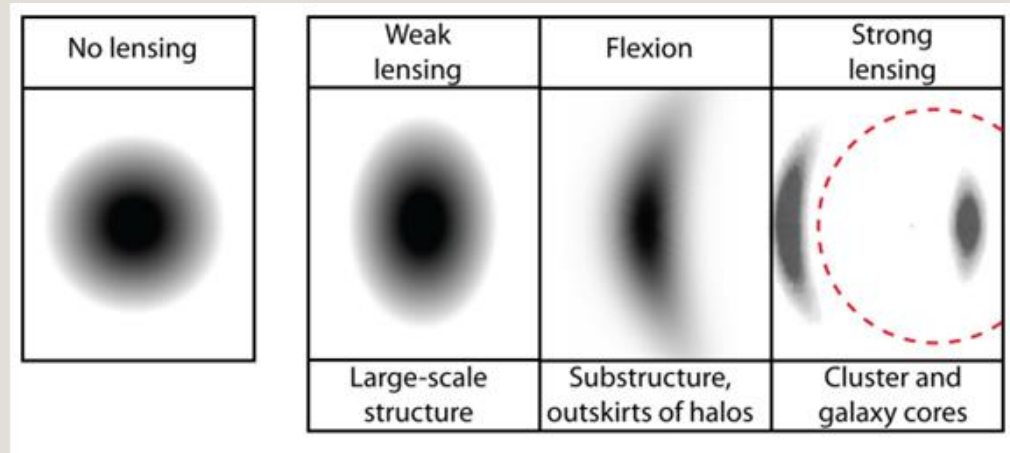
Evidences of Dark Matter (DM):
M/L Ratio in dwarf spheroidal galaxies

dSphs	*Distance* (kpc)	*VirialRadius* (kpc)	*M/L Ratio*
Boötes I	65	5-15	30
Coma Berenices	42	4-8	250
Draco I	75	4	40
Grus II	53	< 0.3	330
Reticulum II	32	2-3	470
Sculptor	84	3-4	10
Segue I	23	< 0.4	760
Sextans	84	8-10	60
Sagittarius I	31	< 1.5	10
Sagittarius II	67	3-8	20
Triangulum II	30	0.4-0.5	3600
Willman I	38	~ 1	270

Some spheroidal dwarf galaxies of the Milky Way that are good candidates to look for traces of dark matter.

Evidences of Dark Matter (DM):
Gravitational Lensing





The General Theory of Relativity explains gravity as the result of the deformation (or curvature) of the structure of space-time by mass-energy. This deformation results in the phenomenon of _gravitational lensing_: in a curved space-time, light propagates along curved trajectories.

The distortion of the images of background objects due to the gravitational mass of a cluster can be used to infer the shape of the potential well and thus the mass of the cluster. The magnitude of this effect is such that it requires a quantity of matter between source and observer that is not compatible with the observed light component → DM.

The Galaxy rotation curve

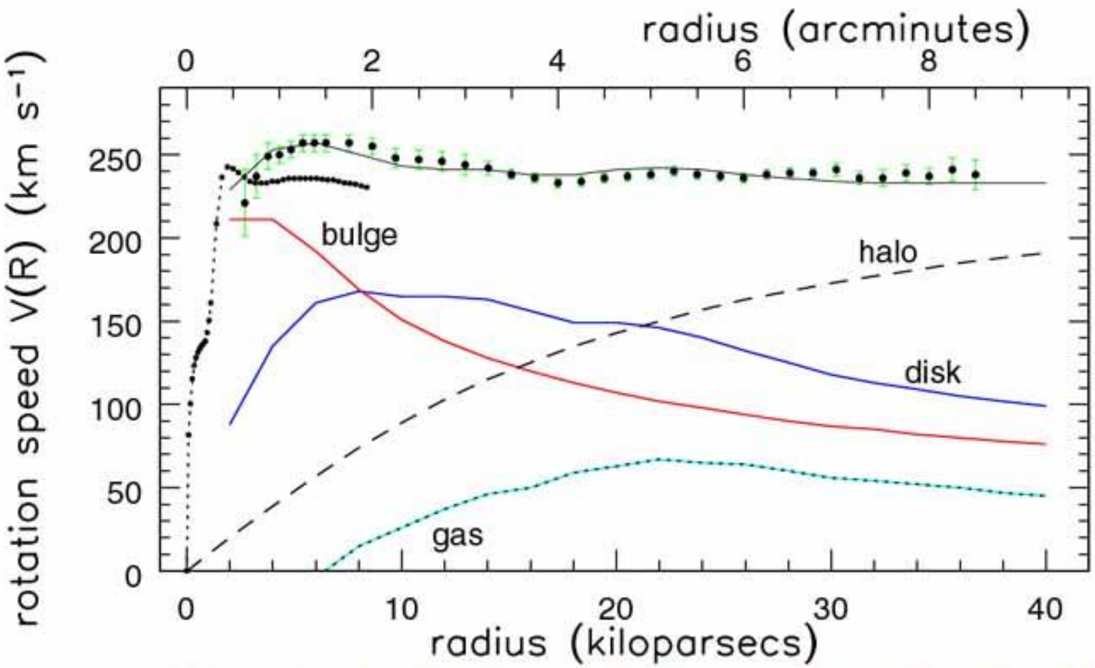


Fig 5.20 (Begeman, Sofue) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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

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

two big questions

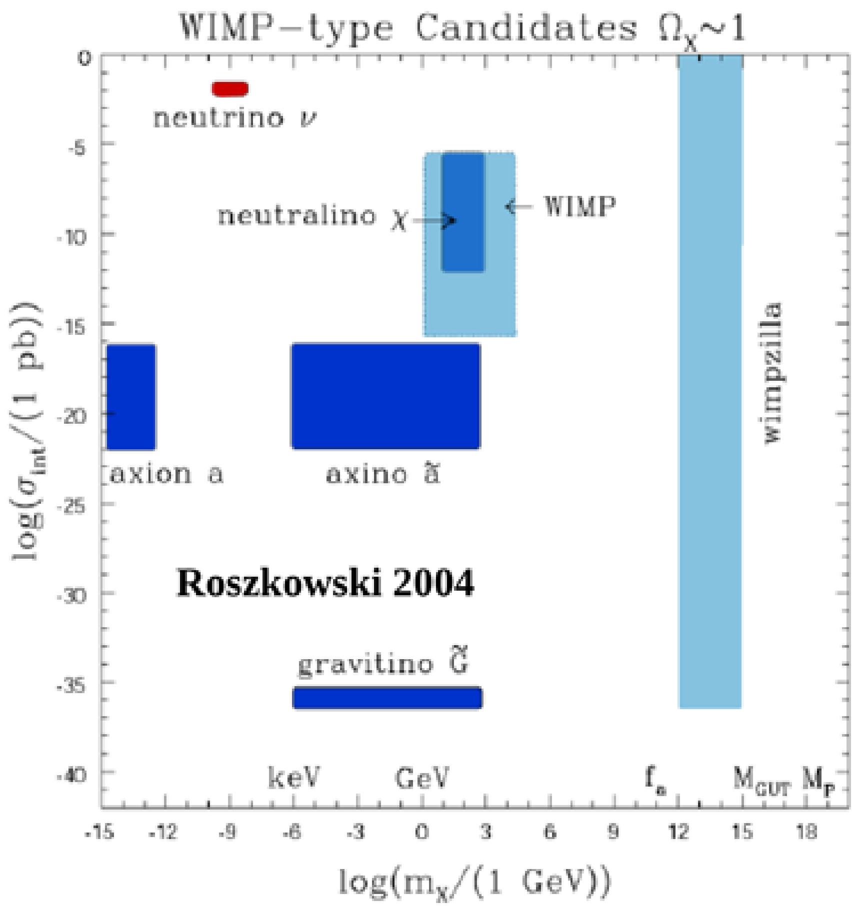
what particle ?

what mass ?

Our Galaxy: R = 10 kpc ; M = $3 \cdot 10^{11}\, M_{\odot}$

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

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

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

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

Neutrino hypothesis: 10 eV

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

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

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

critical density

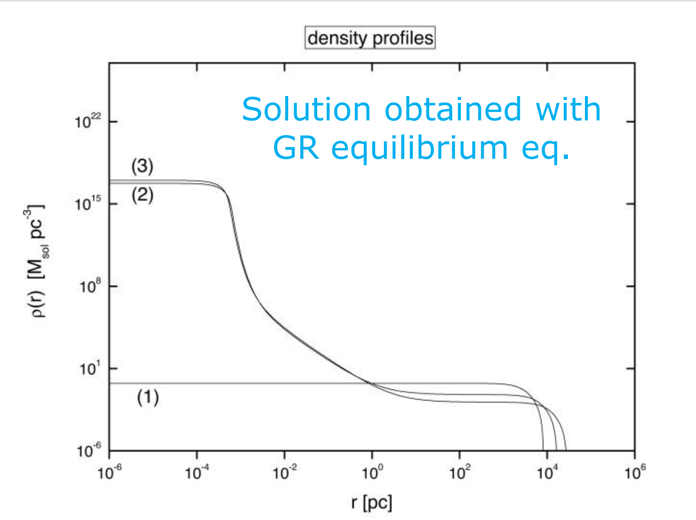
$$\rho_{cr} = \frac{m_\nu^4 c^3}{3\pi^2 \hbar^3} = 7.8 \cdot 10^{-17}\,\mathrm{g/cm^3} >> \rho_0$$

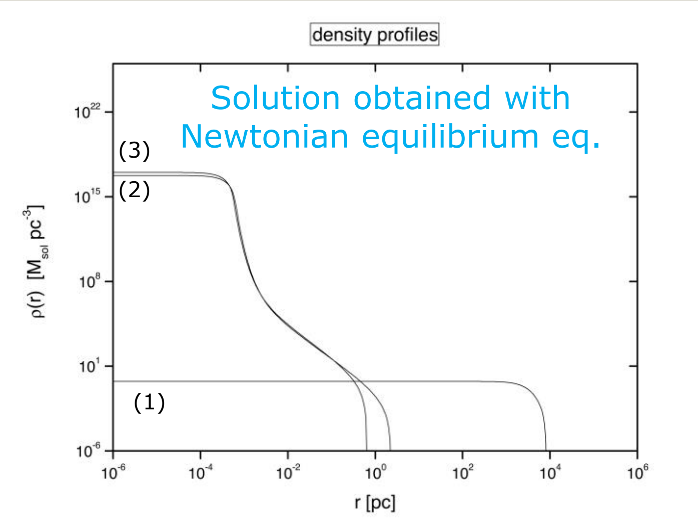
General Relativity? NO

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

neutrino dark matter halos are nonrelativistic and also Newtonian

Intermediate masses: 48 keV density profiles





Semidegenerate DM halos

Arguelles et al. MNRAS 502, 4227 (2021)

- GR framework (but $\beta = kT/mc^2 \sim 10^{-5}$!)
- Particle mass: m=48 keV (Fermions)
- Degeneracy parameter: $\theta_R = -24$ (?)

(1) β = 2.63 · 10^{-5}; W_0 = 0.03 (Stable)

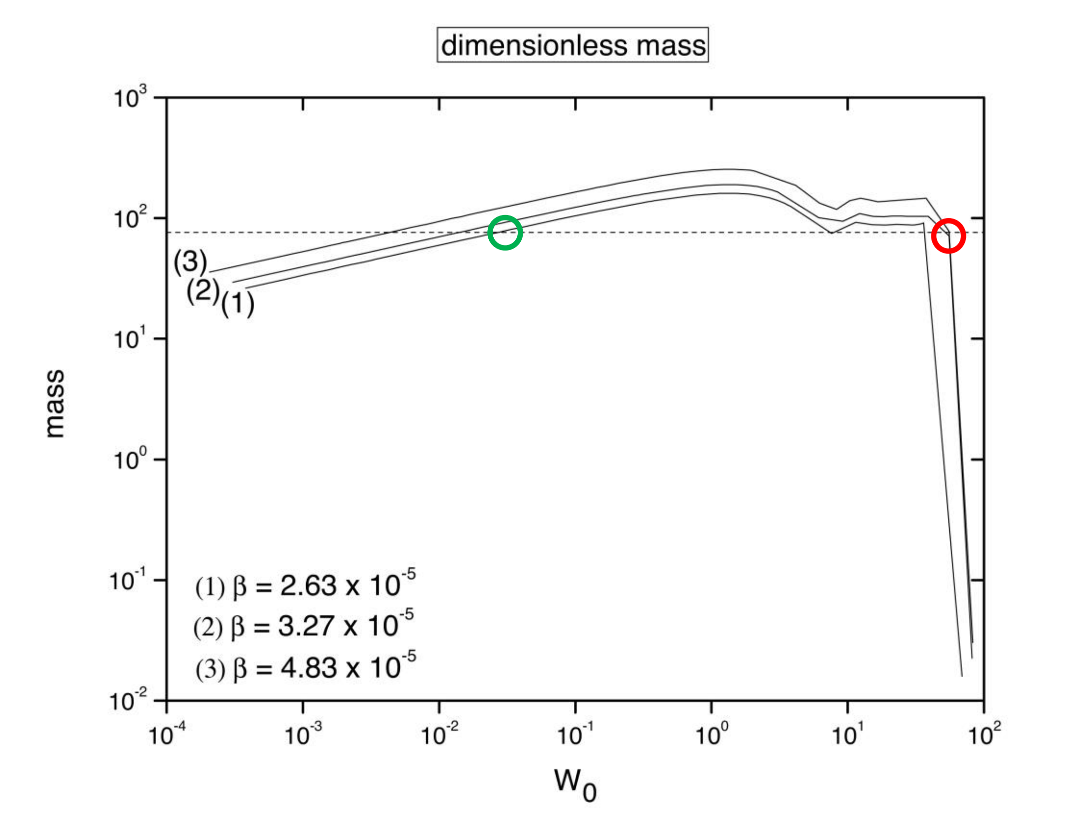
(2) β = 3.27 · 10^{-5}; W_0 = 55.52 (Unstable)

(3) β = 4.83 · 10^{-5}; W_0 = 55.54 (Stable)

Calculations in Newtonian regime using the corresponding values of σ

Why this discrepance?

Intermediate masses: 48 keV dinamical stability



Dimensionless total mass: M=N=76.25

↓

configuration (1) in the region of stability

configurations (2) and (3) in phase transition region are <u>DINAMICALLY UNSTABLE</u>

<u>Mass and Radius can drastically change due to minimal perturbation in density</u> → **discrepance in the density profile (previous slide).**

Second possibility: Axions (bosons)

Hypothesis proposed by Wilczek in late 70's, may be part of cold DM (Ayala et al., 2016)

Axions are considered as possible elementary particles produced in the early Universe and they were introduced to explain the non-violation of the *CP* symmetry in the strong interaction, product of the parity operators *P* and charge conjugation *C* (*Gelmini*, 2014).

Axions are emitted from stars in a variety of processes:

- *Compton*-like scattering
- Axionic *Bremmsstrahlung* emission
- *Primakoff* effect

Range of masses: 10^{-6} eV ≤ m ≤ 10^{-2} eV

Third possibility/hypothesis: SMPs?

- SMPs as alternative candidates 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 possible 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?

→ Λ*(1405) as a possible candidate for dark matter (also in neutron stars?)

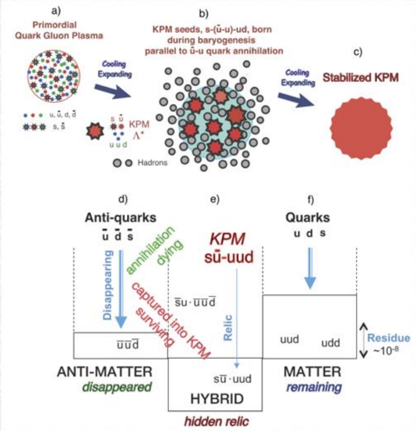
A model independent mass individuation

- **The individuation of the mass range for dark matter particles is not strictly connected with the choice of model representing them.**
- **We may consider the Akaishi-Yamazaki model (first used for neutron stars) *but it is not necessary for our purpose: we* know also that presents some problems from the stability point of view [see Hrtánková et. al., Phys. Lett. B (2018), 785, 90].**
- **Nevertheless it has the quality to indicate 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 different models of particles in the same range can be equally useful and the cosmological demand of mass particles in the range 10÷30 GeV remains necessary in developing theoretical models in agreement with the observations.**

Strangeness in galactic halos?

Extension from neutron stars to cosmology

Possible cosmological origin of Λ^* conglomerates



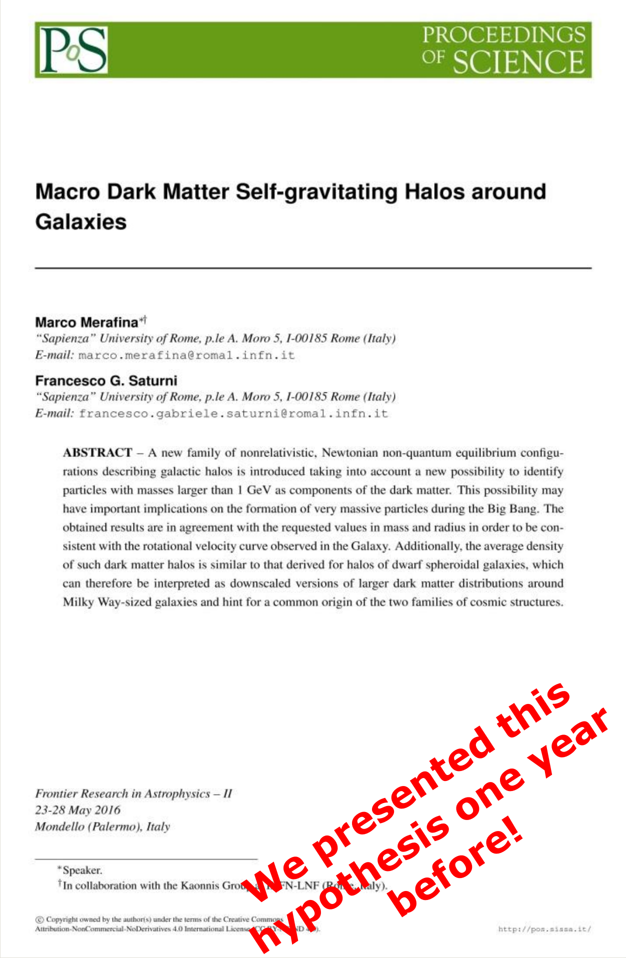
- before the hadronization stage, in the quark-gluon plasma period, when temperature reaches 100 MeV (order of the Λ^* lifetime) the qq annihilation cross section is of the order of the

  su + uud → Λ^* cross section

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

Akaishi & Yamazaki Phys Lett B 774 (2017) 522

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 at INFN-LNF (Rome, Italy).

http://pos.sissa.it/

We presented this hypothesis one year before!

Stability (?) of the conglomerates

<u>The AY Model considers conglomerates of Λ* particles</u>

The problem of the stability

In order to increase the possibility of obtaining structurally stable strange particles in conglomerate configuration, it is necessary to have a <u>high number</u> of components (Λ* particles).

Collisions among conglomerates, however, increase the instability and the possibility of decay:

→ kinetic energy gives the energy for reaching a new instability
→ decay and production of couples of gamma rays

THEN

We must search in high density regions (at the center of the galactic halo) where the collisions are more probable

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 $N \geq 8$: $m^* \geq 7.46\,\mathrm{GeV}$**

recent considerations made lesser the value of ΔU: this means that the minimum N increases

Mass and spin

Calculation of g=2s+1 → spin ?

free Λ* particles

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

bound system (our case)

- **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 becomes larger than 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 different conclusions about stability of conglomerates

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

THEREFORE

<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 particle is not relevant**.

- We consider a halo composed by massive particles of mass m* interacting only gravitationally.

- 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 $R \sim 100$kpc: the mean density $<\rho>$ is of the order of 10^{-26} g/cm^3 .

Gravitational equilibrium

For a mass m*=10 GeV we have

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

ALSO

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:

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

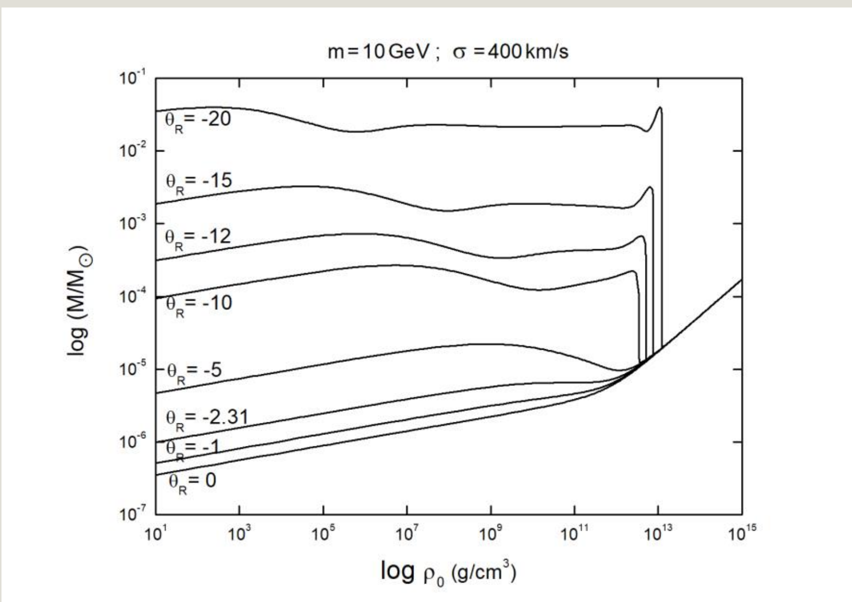
Poisson equation for gravitational equilibrium:

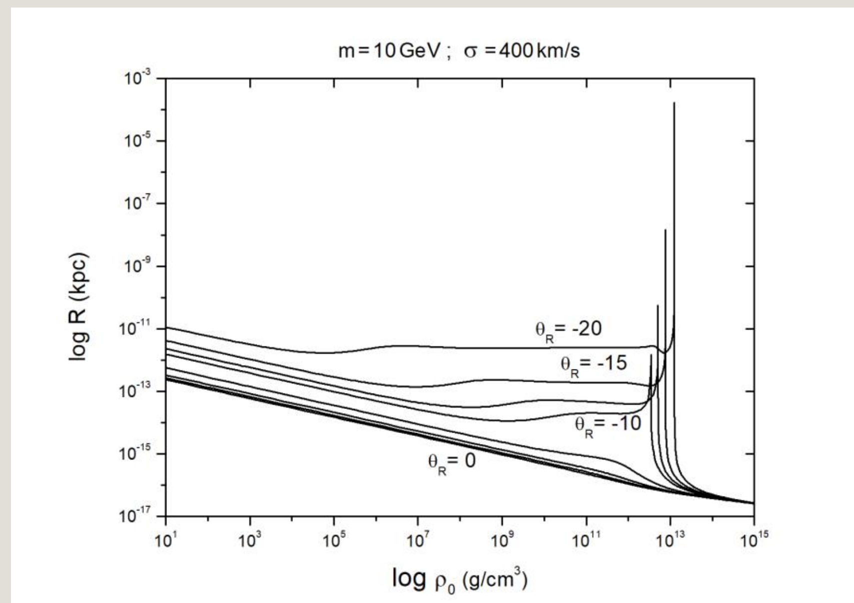
$$\frac{1}{r^2} \frac{\mathrm{d}}{\mathrm{d}r}\left(r^2 \frac{\mathrm{d}\phi}{\mathrm{d}r} \right) = 4\pi G \rho \qquad \text{with} \qquad \phi'(0) = 0; \;\; \phi(0) = \phi_0$$

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

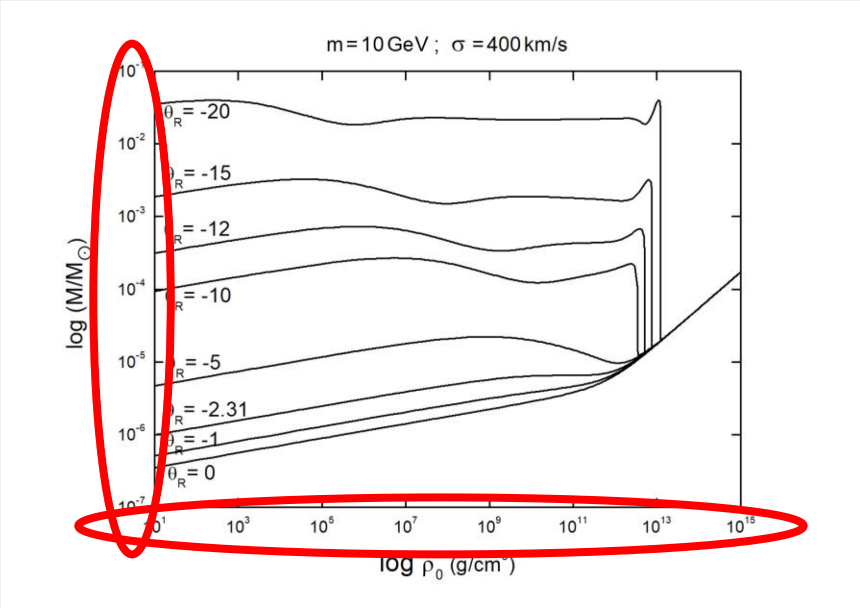


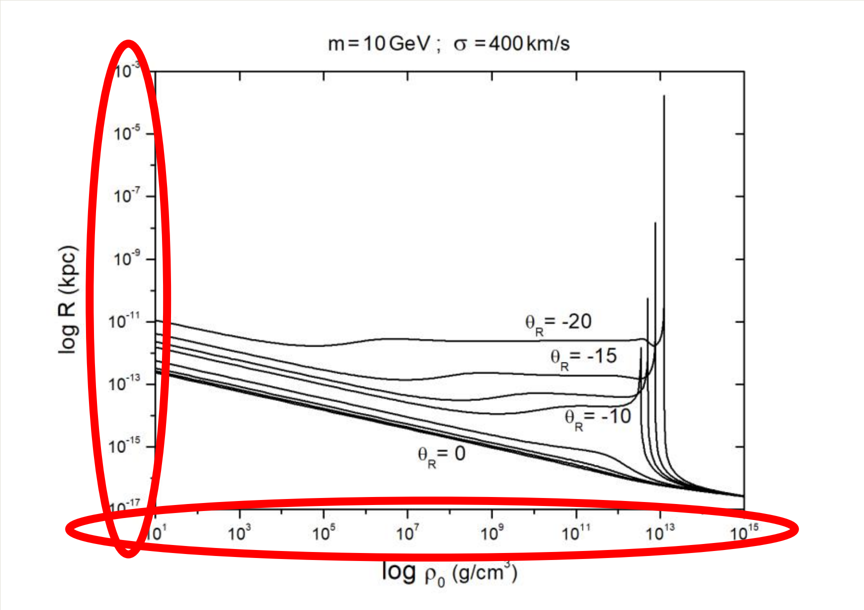


Equilibrium configurations

- 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

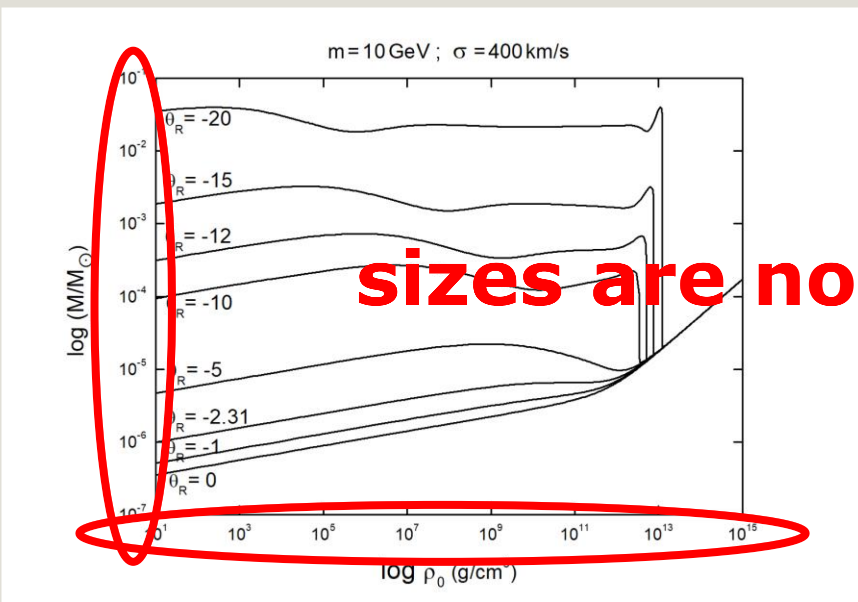




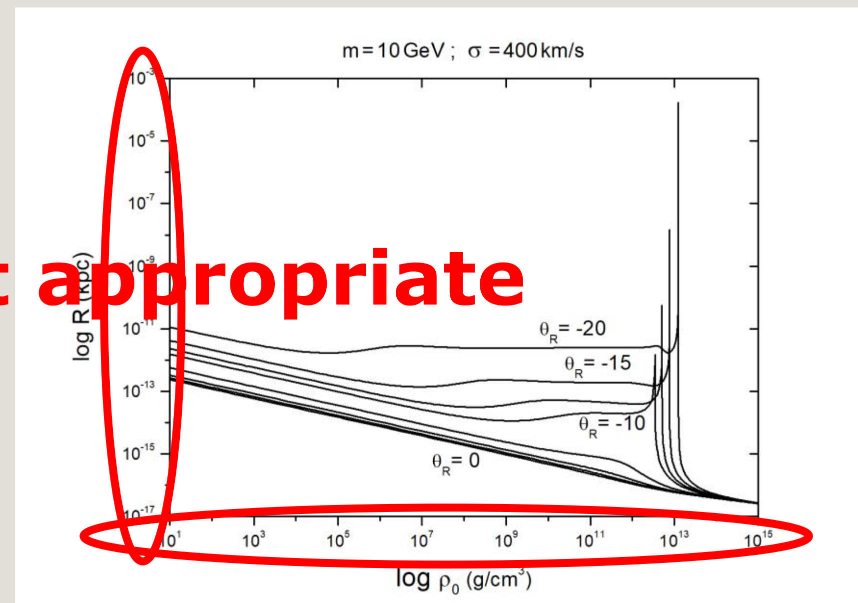
Equilibrium configurations

- 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



sizes are not appropriate



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

<u>Semidegenerate regime is not appropriate</u> to describe 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 $-\theta_R \gg 1$ $\quad f(\varepsilon) \rightarrow \frac{g}{h^3} e^{\mu/kT}\left(e^{-\varepsilon/kT} - e^{-\varepsilon_c/kT}\right) \quad \text{for } \varepsilon \le \varepsilon_c$

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

Equilibrium in classical regime

THEN

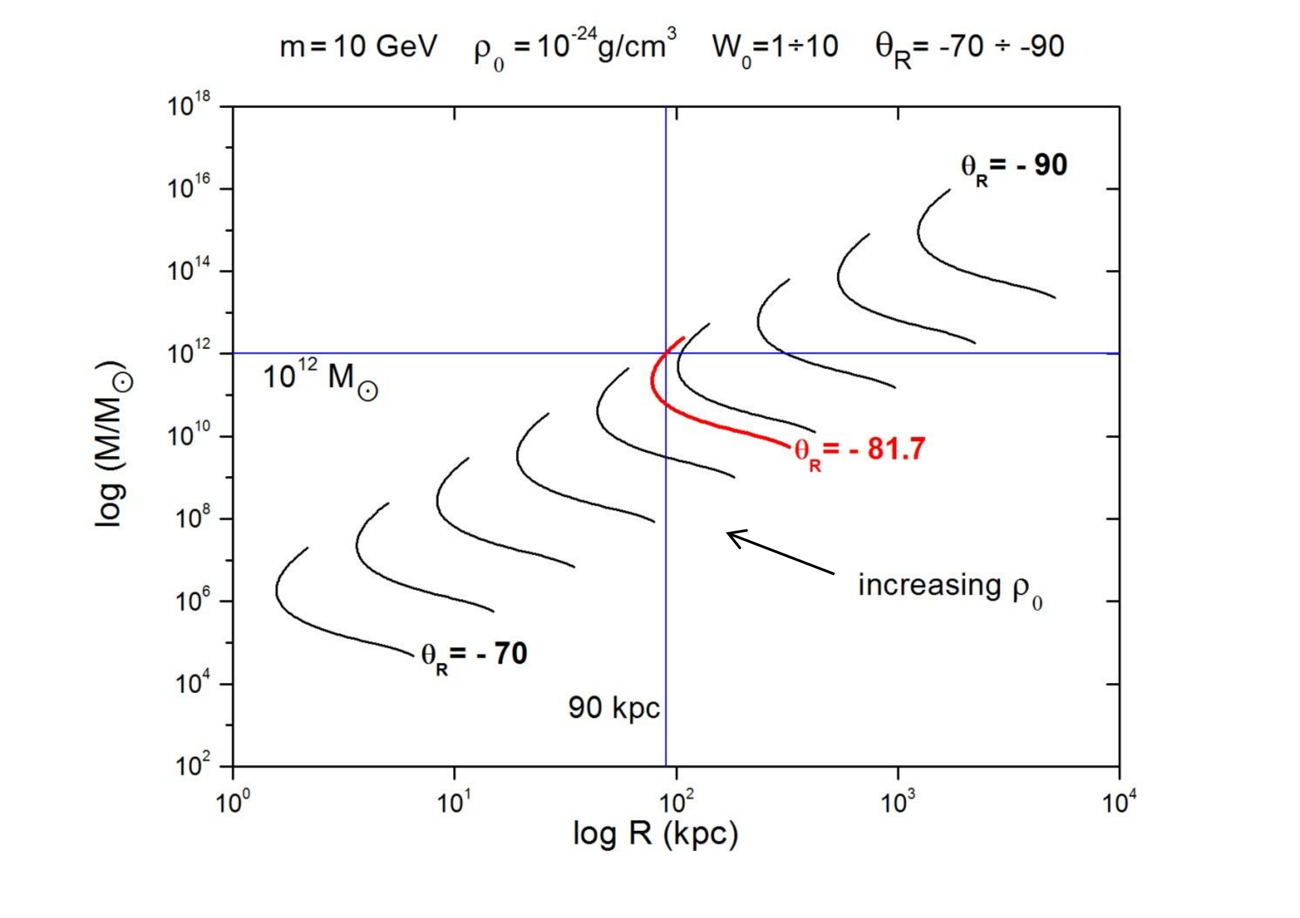
dark matter halos are nonrelativistic, Newtonian and do not follow quantum statistics

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 $M \sim 10^{12} M_\odot$ and R~100kpc.

We will consider only a specific range of the dimensionless central gravitational potential W_0

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

Summary of the results

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

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

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

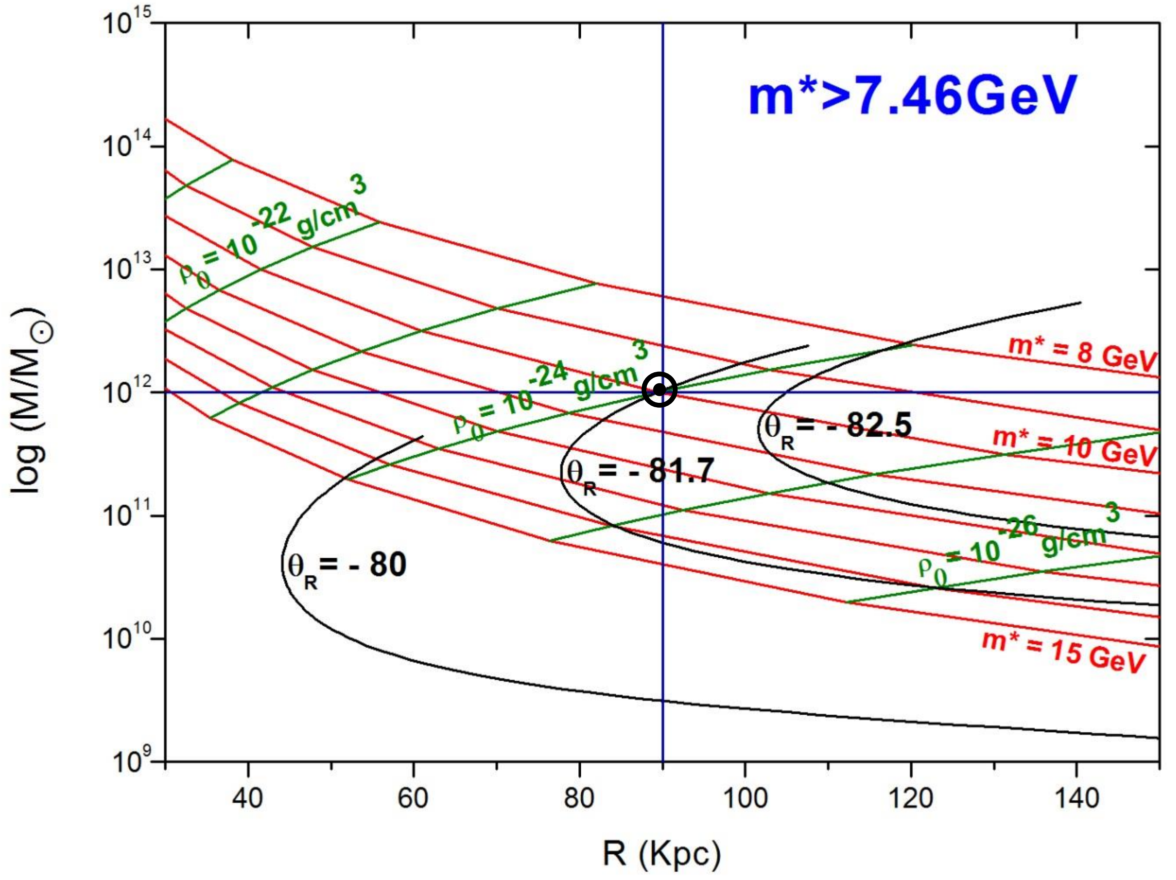
The obtained values are very satisfying !

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

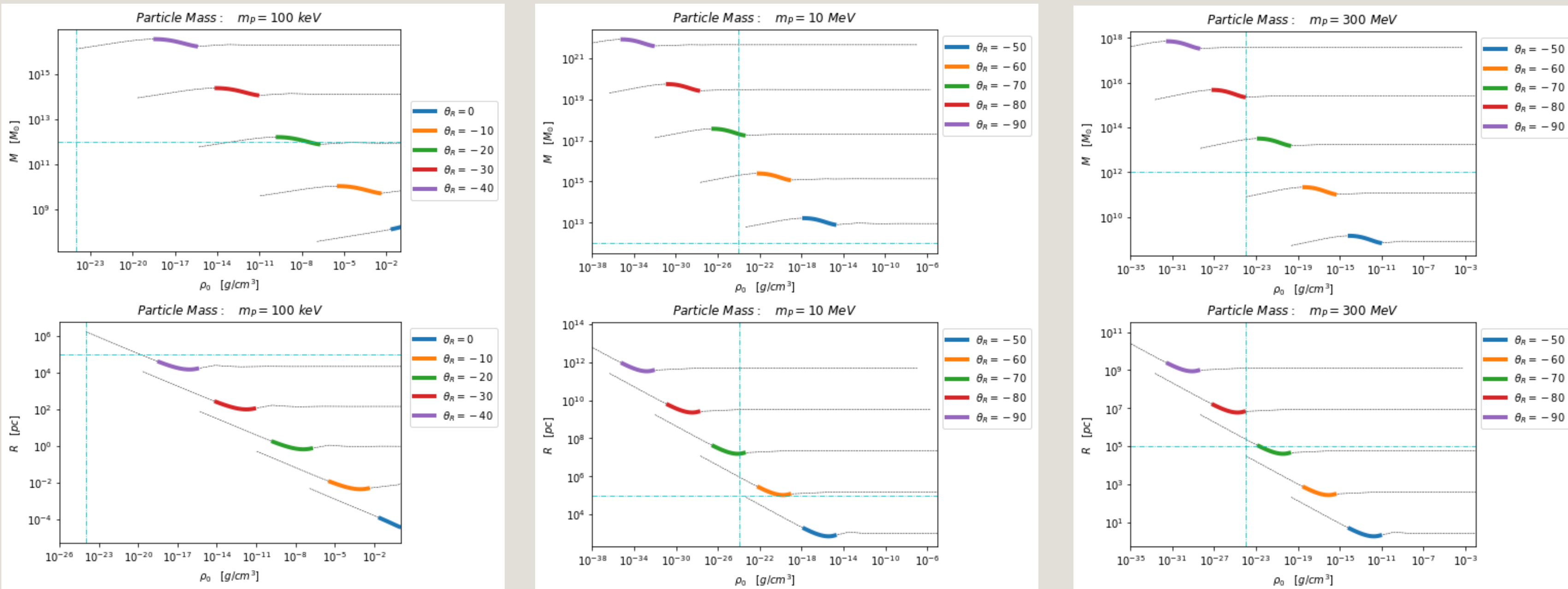
$$M = 9.98\cdot 10^{11}\left(\frac{\rho_0}{10^{-24}\,\mathrm{g/cm}^3}\right)^{1/2}\left(\frac{m^*}{10\,\mathrm{GeV}}\right)^{-4}\mathrm{M}_\odot$$

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

Tuning the parameters



Spanning different particle masses 100keV÷300MeV



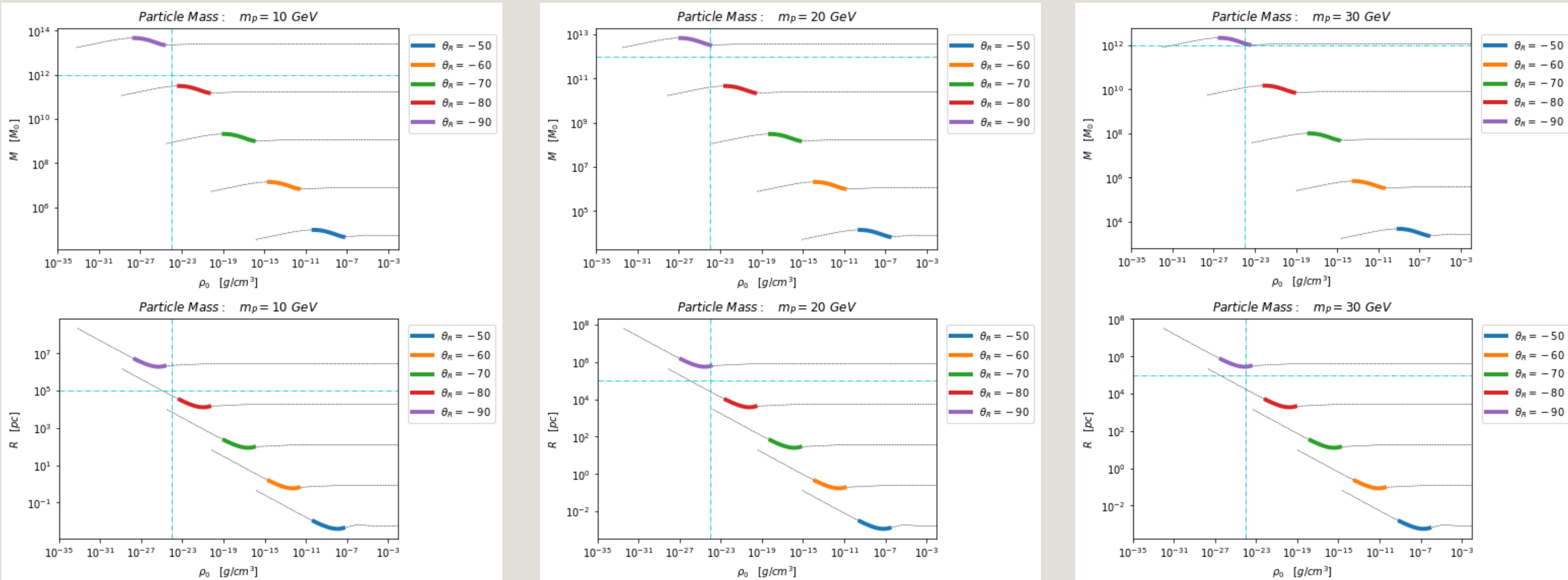
Blue dash lines correspond to $M=10^{12}M_\odot$, R=100kpc and $\rho_0=10^{-24}$ g/cm^3
Range of colored intervals (for different values of θ_R): W_0 = 4÷7

→ we are far from phase transition to degenerate configurations;

→all the equilibrium configurations are dynamically stable (Newtonian regime)

→ morphological parameters (M, R and ρ_0) do not satisfy the required values.

Spanning different particle masses 10GeV÷30GeV



Blue dash lines correspond to $M=10^{12}M_\odot$, R=100kpc and $\rho_0=10^{-24}$ g/cm^3
Range of colored intervals (for different values of θ_R): W_0 = 4÷7

→ we are far from phase transition to degenerate configurations;
→all the equilibrium configurations are dynamically stable (Newtonian regime)
→morphological parameters (M, R and ρ_0) satisfy the required values (for θ_R~-80).

Only in the range 8÷30 Gev we obtain consistent results with the observations.

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.

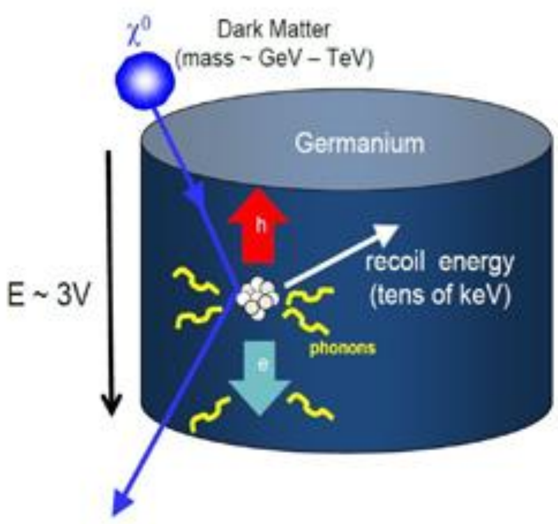
• In spite of the very difficult detection due to the faintness of such sources (and possible presence of background), there are some compelling observations of gamma-ray fluxes originating from dSph galaxies.

• 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.

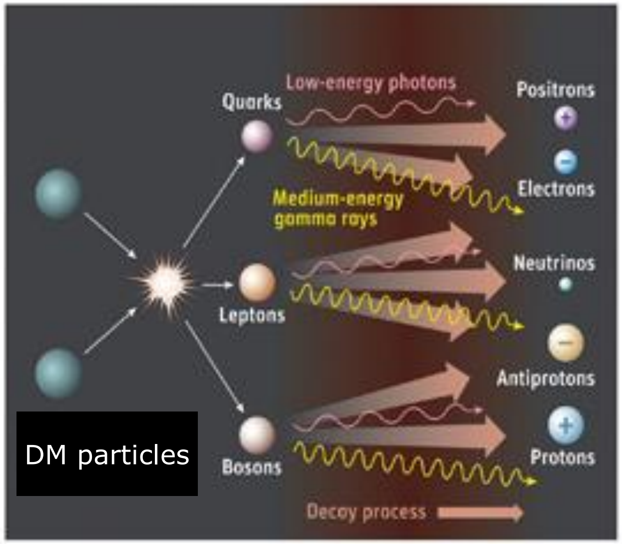
DM detection

- 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.

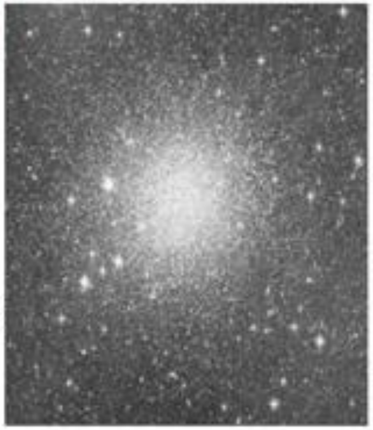


Observative targets

- Main targets of observation:

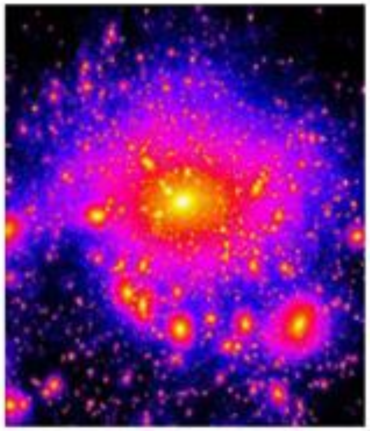
Milky Way center & MW "ridge" (very close, but risk of high bkg due to Galactic Sources + central BH)

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)



Signals from different dSphs

- 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 10 GeV particle clusters, which could be an important component of the dark matter in the galactic structures of the Universe.

Spheroidal Galaxies

DM halos of elliptical galaxies well reproduced by simulations

$\Rightarrow$ **Can 10 GeV particle DM reproduce smaller halos too?**

Let's make a quick estimate:

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

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

Assuming point-like sources …

Inverting formula for ρ and using estimated J~4·10^{19} GeV^2 /cm^5 for Ret II dSph, with <σv>=3·10^{19} cm^3/s (Geringer-Sameth+ 2015) and D=30 kpc (distance) we obtain similar results

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

Kinematic properties

- The analysis of the kinematic properties of a sample of dwarf spheroidal galaxies (dSphs) has been performed with the CLUMPY software to extract the parameters of the best-fit dark matter (DM) density profile of each source.
- The analyzed dSphs have been chosen in the framework of a key science project (KSP) for the Cherenkov Telescope Array (CTA) Consortium:

	Distance (kpc)	Virial radius (kpc)	M/L ratio
Boötes I	65	5 — 15	30
Coma Berenices	42	4 — 8	250
Draco I	75	4	40
Grus II	53	<0.3	330
Reticulum II	32	2 — 3	470
Sculptor	84	3 — 4	10
Segue 1	23	<0.4	760
Sextans	84	8 — 10	60
Sagittarius I	31	<1.5	10
Sagittarius II	67	3 — 8	20
Triangulum II	30	0.4 — 0.5	3600
Willman 1	38	~1	270

- Since the luminosity density profile is required as a CLUMPY parametric input to use it as a proxy of the baryonic mass distribution inside the dSph halo, the average luminosity density properties of a typical dSph may be derived from these parameters.

dSph luminosity (Zhao-Hernquist profile)

Parametric form of the dSph luminosity density profile: Zhao-Hernquist (ZH, 5 free pars).

$$\rho^*(r) = \frac{\rho_s^*}{\left(\frac{r}{r_s^*}\right)^{\gamma}\left[1+\left(\frac{r}{r_s^*}\right)^{\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}}$$

	Scale density ($L_\odot/kpc^3$)	Scale radius (kpc)	Profile index 1	Profile index 2	Profile index 3
Boötes I	1.1e5	0.46	1.1	7.7	0.0
Coma Berenices	1.1e5	0.07	1.1	5.4	0.0
Draco I	4.5e5	0.15	6.8	3.8	0.0
Grus II	1.6e5	0.17	1.3	7.6	0.0
Reticulum II	2.0e5	0.04	3.5	4.7	1.1
Sculptor	2.3e6	0.21	3.2	4.0	0.0
Segue 1	1.2e5	0.07	1.1	9.2	0.2
Sextans	5.6e4	0.49	2.7	4.0	0.6
Sagittarius I	2.8e4	1.87	1.1	4.9	0.0
Sagittarius II	4.3e6	0.04	3.5	5.7	0.1
Triangulum II	7.3e5	0.03	1.2	5.3	0.0
Willman 1	4.4e5	0.03	1.2	5.9	0.0

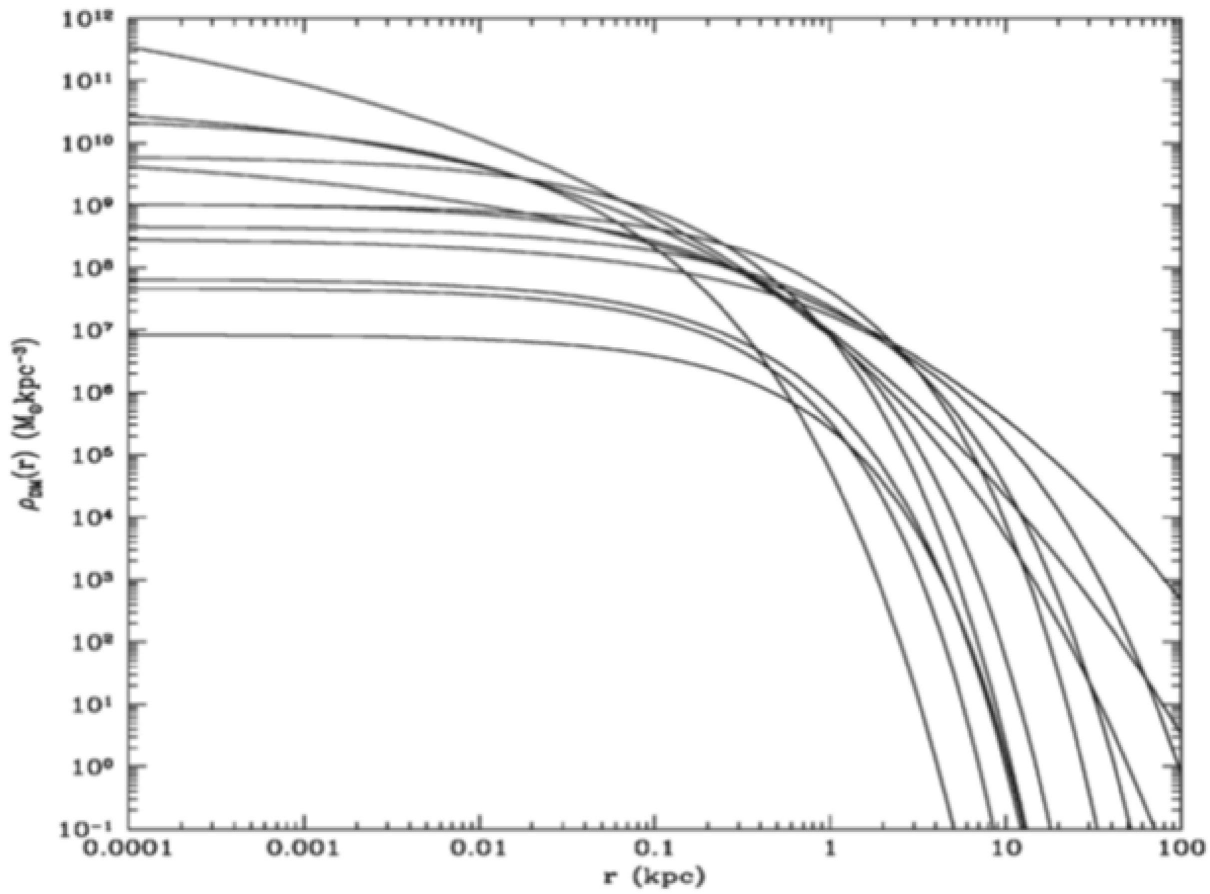
dSph DM density (Einasto profile)

Parametric form of the dSph DM density profile: Einasto (3 free pars).

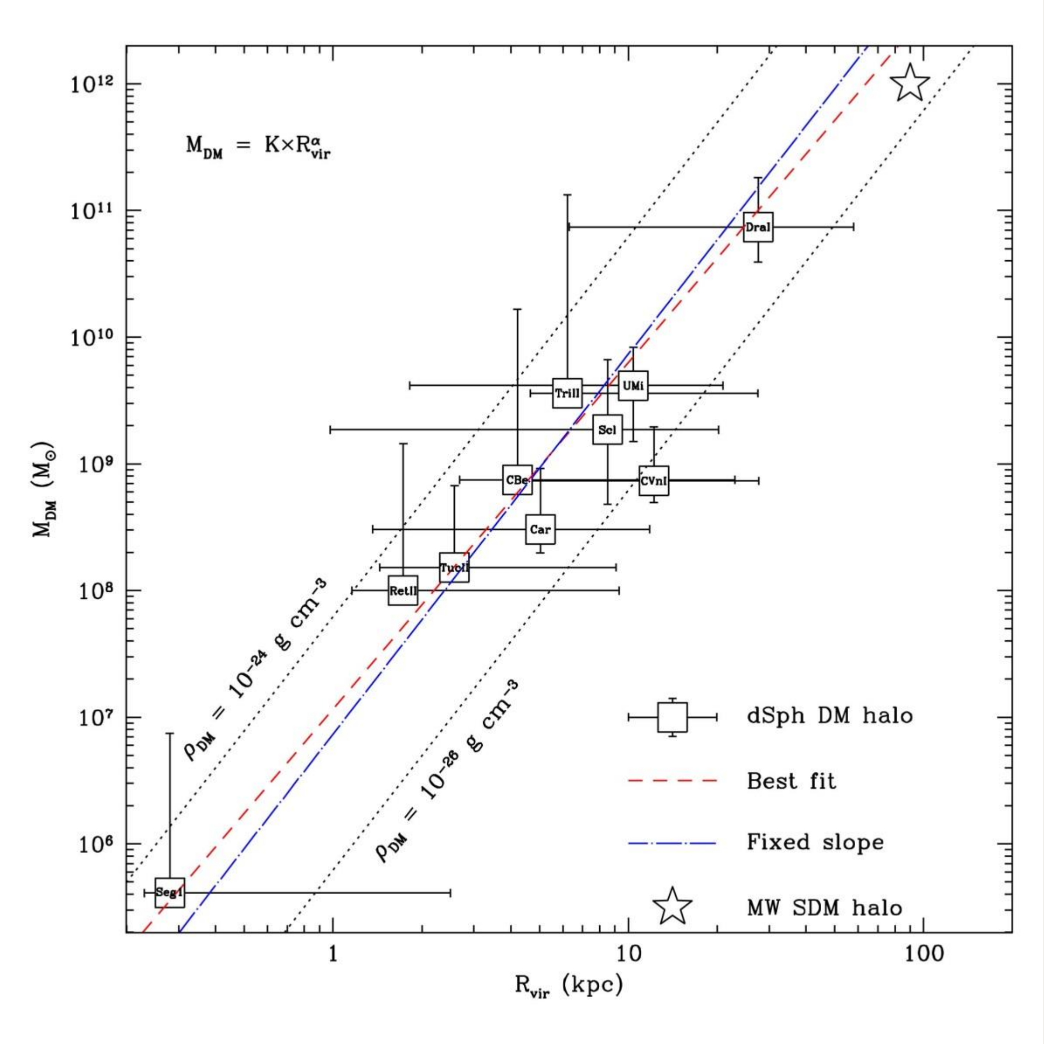
$$\rho_{\rm DM}(r) = \rho_s e^{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]}$$

	Scale density ($M_\odot$/kpc^3)	Scale radius (kpc)	Profile index
Boötes I	9.2e6	1.7	0.51
Coma Berenices	2.9e7	1.2	0.56
Draco I	3.0e7	0.6	0.16
Grus II	3.9e5	0.8	0.65
Reticulum II	2.6e7	0.6	0.54
Sculptor	2.9e7	0.6	0.26
Segue 1	2.2e6	0.6	0.59
Sextans	2.6e6	3.4	0.42
Sagittarius I	1.1e6	6.1	0.22
Sagittarius II	1.3e8	0.4	0.51
Triangulum II	2.2e6	0.5	0.65
Willman 1	2.6e8	0.1	0.43

dSph DM density profiles



Halo densities



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

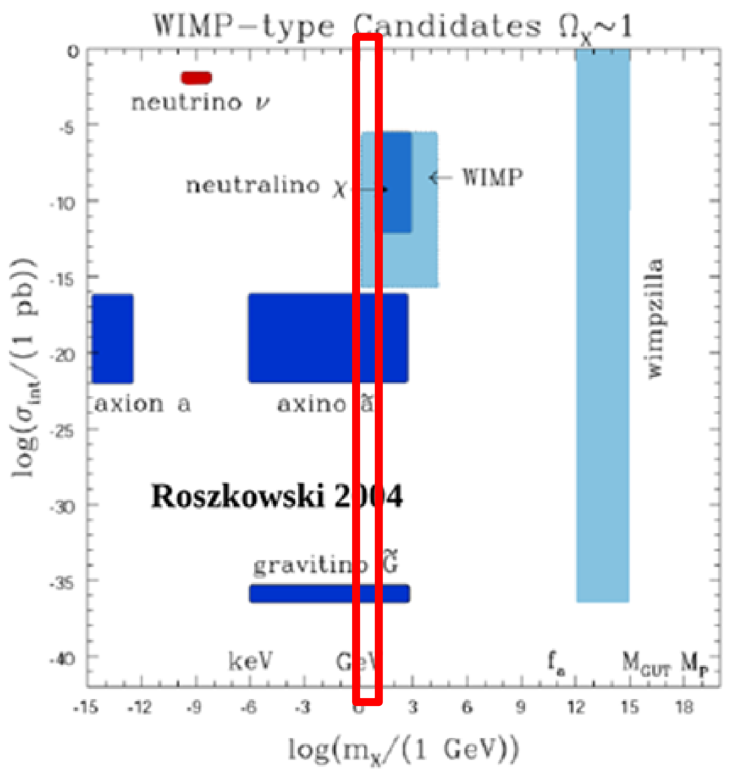
AMAZING COINCIDENCE OF RESULTS

suggesting cosmological hypothesis on DM component distribution in halos

Increasing data on dSphs in coherence with the hypothesis of 10 GeV particle 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 component (m*~GeV) deriving from dark matter.

- **10 GeV particle galactic halos reproduce the same rotation velocity curve in spiral galaxies, in alternative to WIMP-composed halos.**

- Detailed analysis of numerical equilibrium solutions over a range 100keV≤m*≤30GeV show that particles with masses 8÷30GeV can well reproduce both halos of elliptical galaxies (large scales) and dSphs (small scales). Parameters in agreement with observations.

- 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 particles with m*~GeV, 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

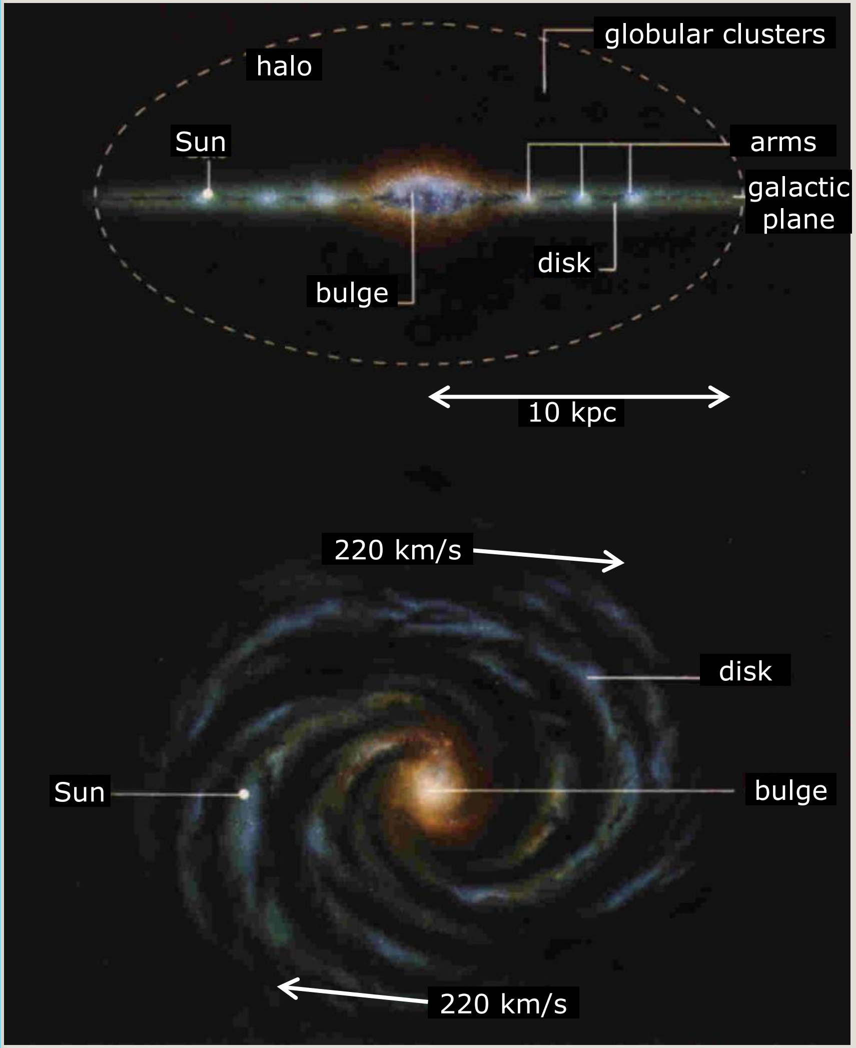
Main References

- Merafina M., Saturni F. “Macro dark matter selgravitating halos around galaxies” Proceeding of the Conference “Frontier Research in Astrophysics II” Proceedings of Science, POS (FRAPWS2016) 017, Mondello (2016)

- Merafina M. “Massive hadronic candidates to dark matter” Proceeding of the Conference “XIII Multifrequency Behaviour of High Energy Cosmic Sources Workshop” Proceedings of Science – POS (MULTIF2019) 011, Mondello (2019)

- Merafina M., Saturni F.G., Curceanu C., Del Grande R., Piscicchia K. “Self-gravitating strange dark matter halos around galaxies” Physical Review D, 102, 083015 (2020)

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

⇩

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

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

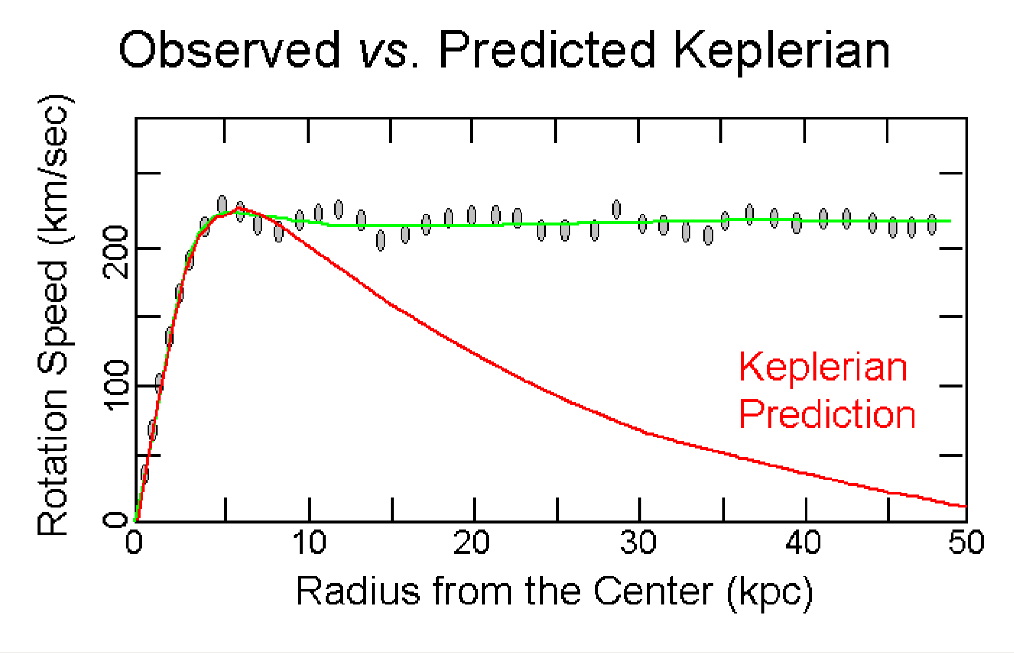
The rotation curve

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



Why this particular choice?

Arguelles et al. MNRAS 502, 4227 (2021)

The choice of particle mass: 48 keV

The choice of degeneracy parameter: $\theta_0 - W_0 = \theta_R = -24$

The choice of dimensionless total number/mass: N=M=76.25

The choice of the three different values of $\beta \sim 10^{-5}$

The claim of particular parameters by *Arguelles et al.* for a semidegenerate model, used to «provide good fits to the Milky Way rotation curve, extending it to other structures from dwarfs to ellipticals to galaxy clusters, pointing out the relevant case of m=48 keV», seems do not consider that:

- the equilibrium configuration is part of a large family of solutions;
- the characteristics of halos suggest a non-quantum and non-relativistic solution, confirmed by the values of θ_R and β (Merafina et al. 2020);
- the choice of the values of particle mass and total mass **cannot** depend on a single fit.

Intermediate masses: 48 keV caloric curve

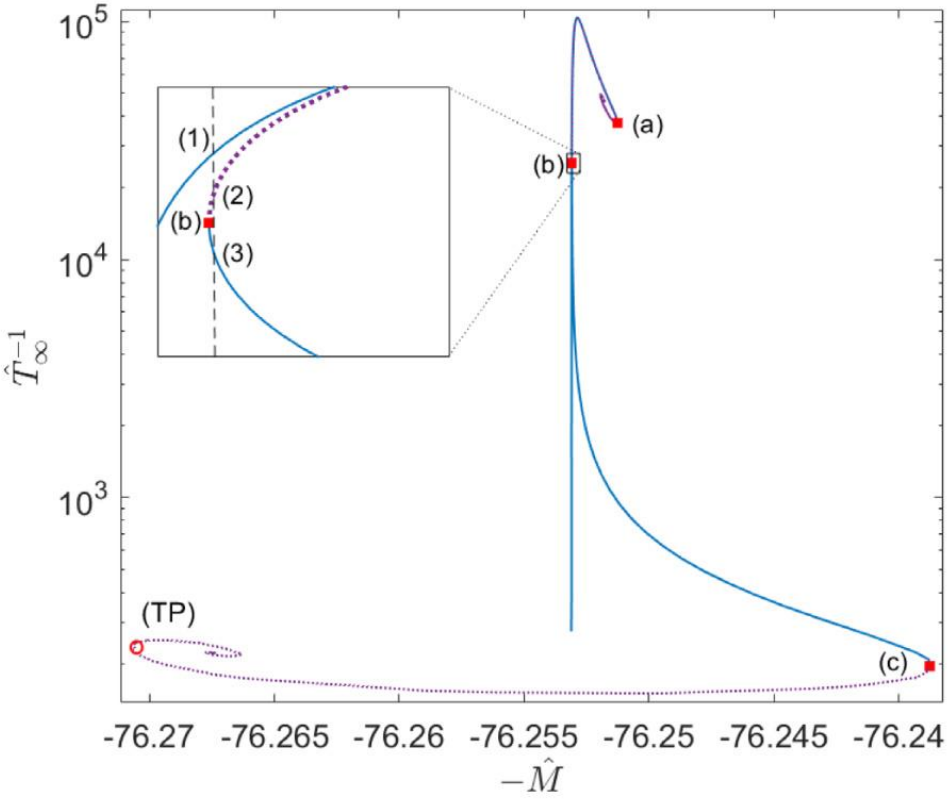


Figure from Arguelles et al. (2021)

Thermodynamic instabilities according to Katz criterion

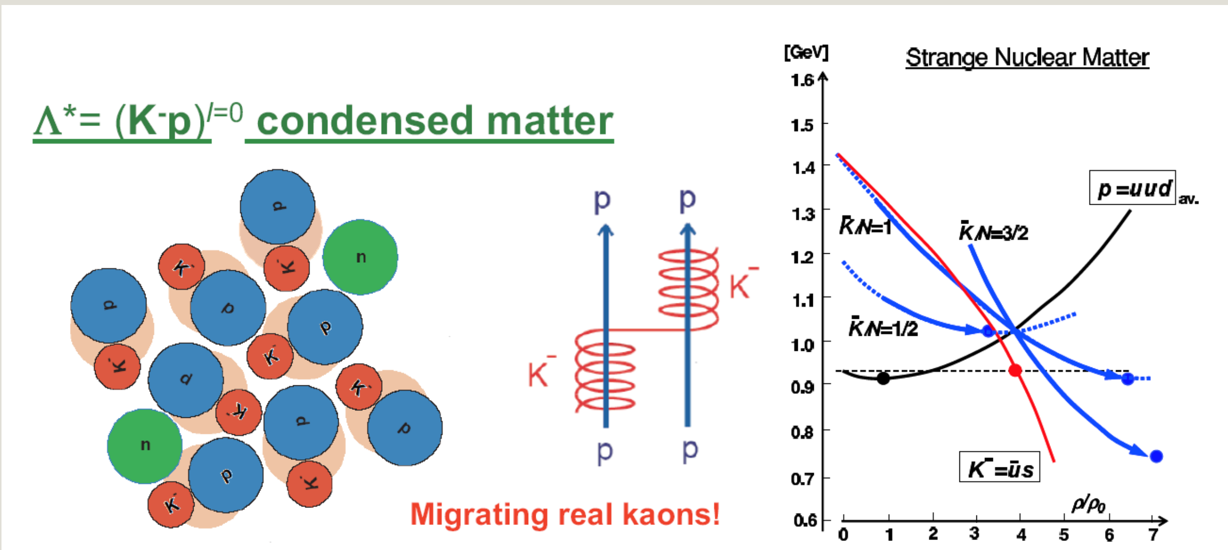
The authors consider gravothermal catastrophe for Fermionic DM halos !!

NON SENSE !

More, in the introduction of their paper, listing several contributions of different authors in literature sentenced: « … though lacking a thermodynamic stability analysis (with the exception of Chavanis in 2015).»

Strange dark matter ?

Neutron stars and … dark matter ?



Akaishi & Yamazaki, 2015 (for neutron stars)

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

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

strong decay, single Λ* is unstable

Λ* clusters:

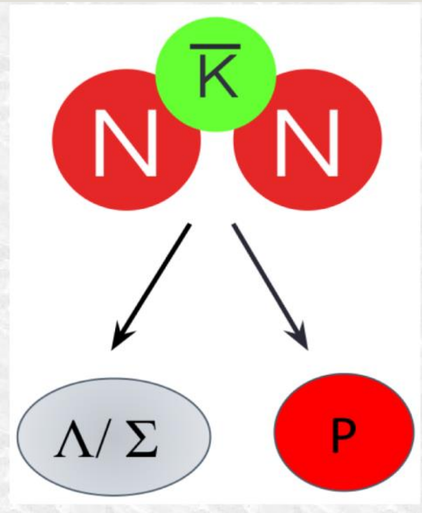
$Nm_{\Lambda^*} \equiv m^* \sim$ GeV

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

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

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

The question of the stability

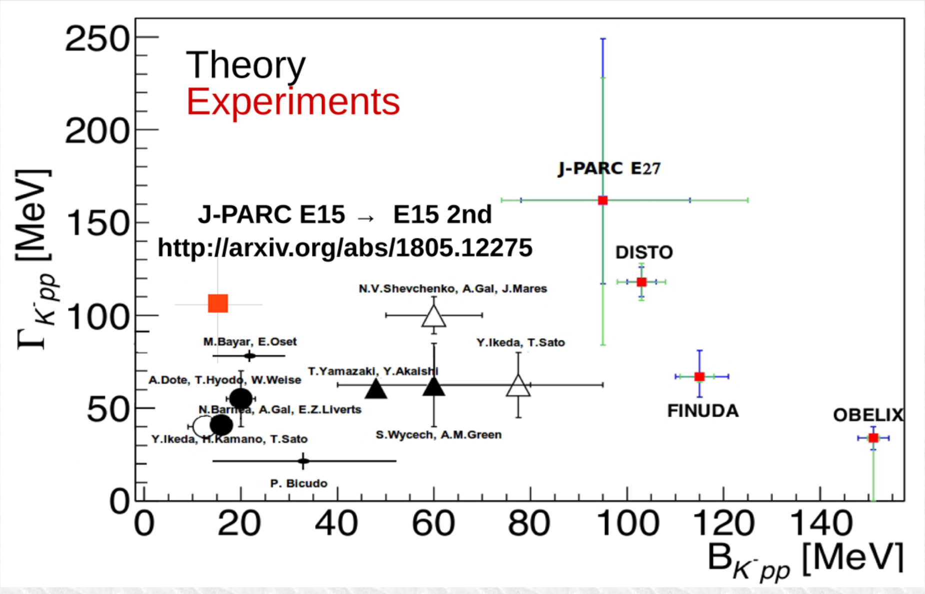


Strongly attractive KN interaction in isospin I=0

⇩

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



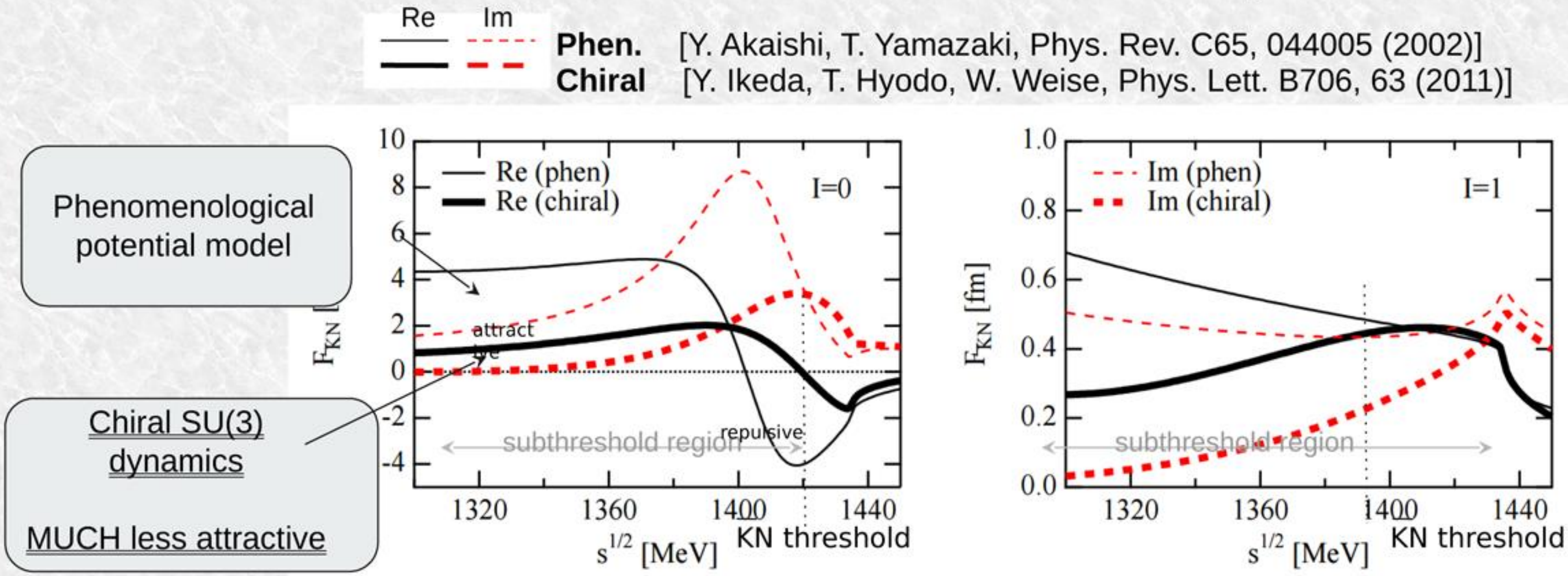
Ansatz on hadron system stabilized by s quarks

Akaishi & Yamazaki Phys Lett B 774 (2017) 522

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



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 absolute stability for conglomerates

$m^* \geq 7.46$ GeV

Dimensionless quantities

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

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

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

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

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

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

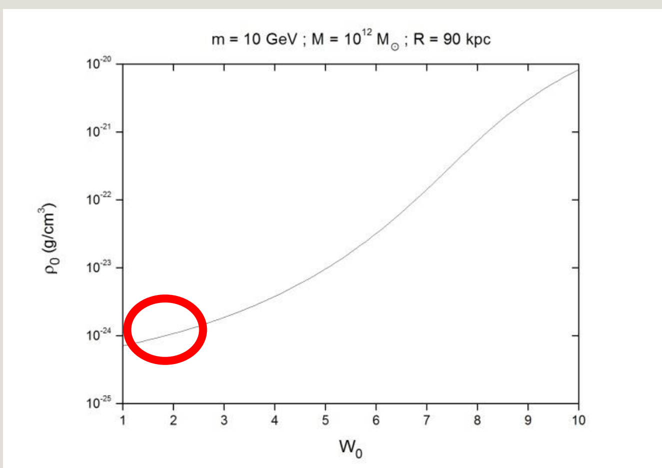
with $\theta = \frac{\mu}{kT}$ and $\theta_R = \theta - W \le 0$ (MM & Alberti, 2014)

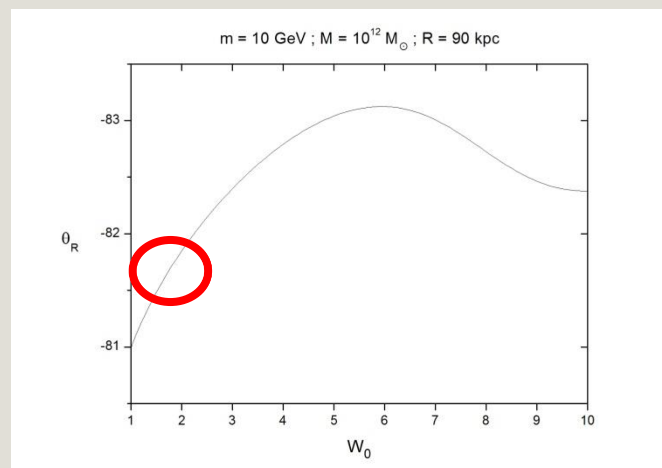
Changing parameters

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

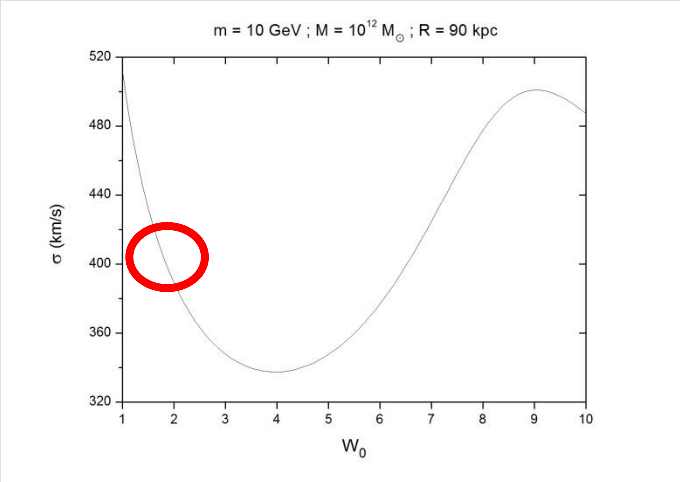
$$\rho_0 = \frac{\hat{R}^3 \hat{\rho}_0}{\hat{M}} \frac{M}{R^3}; \qquad \theta_R = \frac{1}{2} \ln\left(\frac{\hat{M}\,\hat{R}^3}{M\,R^3} \right) + \ln\left(\frac{h^3}{g\, m^4 G^{3/2}} \right)$$

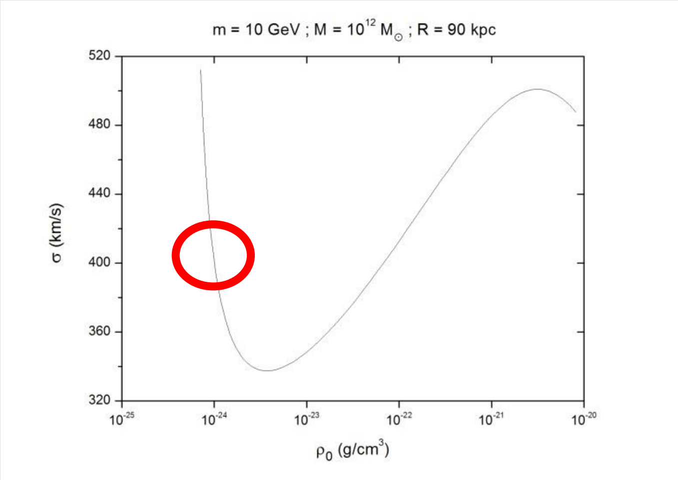
and, consequently, $$\sigma = \left(\frac{1}{\hat{\rho}_0} \frac{h^3}{g\, m^4 e^{\theta_R}} \right)^{1/3} \rho_0^{1/3}$$

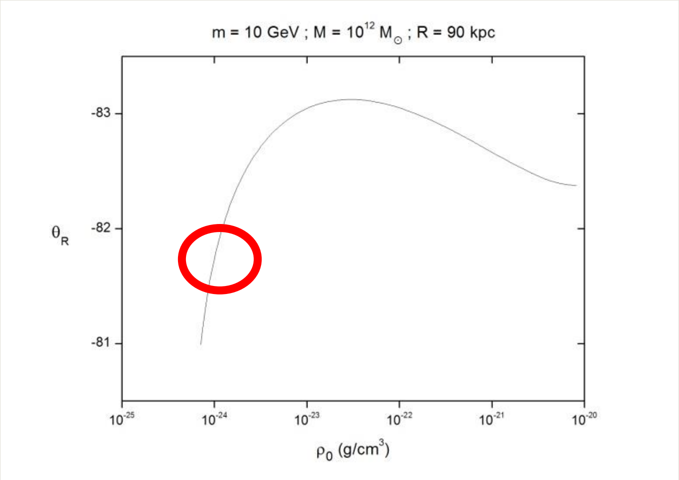


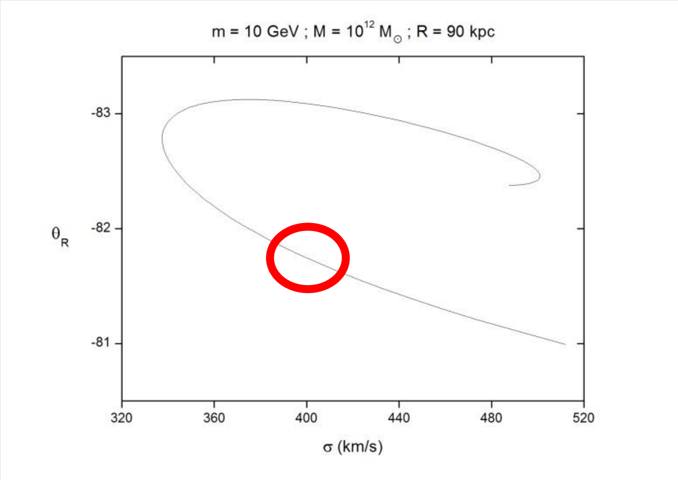


Other quantities





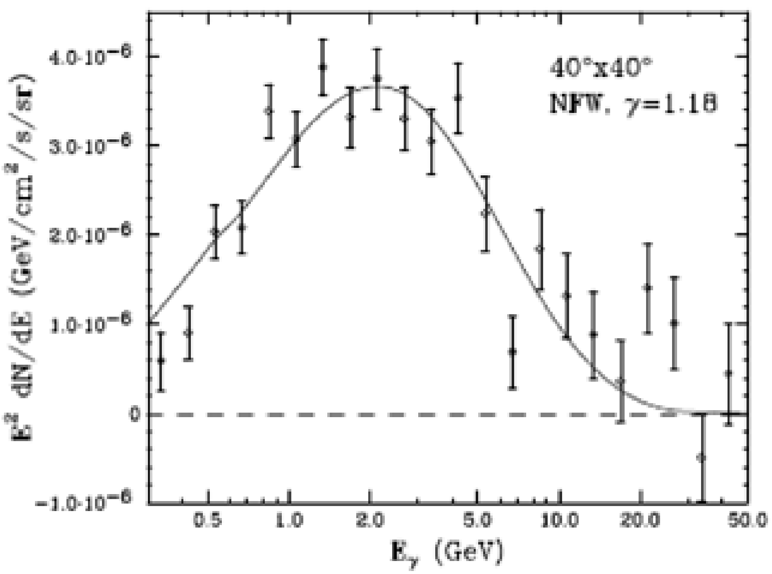




Observational data

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

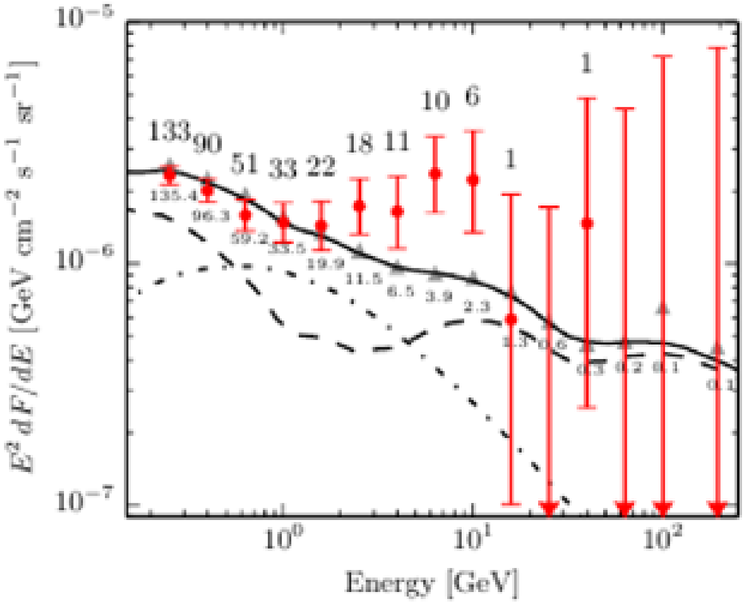
MILKY WAY CENTER (Daylan+ 2014)



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

Zhao-Hernquist density profile

- Parametric form of the dSph luminosity density profile: Zhao-Hernquist (ZH, 5 free pars).