A new Paradigm for understanding the Dark Matter phenomenon.

Nicola Turini
University of Siena

From observation to DM modeling

- Dark Matter has been seen exclusively by astrophysics observations.
- No other experimental apparatus on Earth has seen any significant anomaly respect the Standard Model of particles predictions.
  - Recent tensions have been observed in W mass measurement by CDF (7σ from SM predictions) somehow reduced by Atlas measurement, and the muon precession dipole momentum measurement in g-2 experiment at Fermilab.
  - Although we have the feeling that new physics is there, no striking evidence is seen up to now except the Dark Matter phenomenon. (Dark Energy too…)

ΛCDM and Standard Model

While the large scale observations fit quite well the ΛCDM picture we see divergences at galaxy scale.

- From ΛCDM we have one of the most important input for DM modeling:

Relic Density

- Using only just this parameter we can fit DM particle with a mass from "almost zero" (Axions) up to billion solar masses.
- Till now the DM modeling was mostly guided by the relic density and a generic non collisional, or almost non collisional "matter", practically invisible.
- The WIMP miracle added to SuSy created an optimistic picture.
- The SuSy believers (15 years ago almost everybody) had the neutralino as the natural WIMP, and was thought that was only matter of time that LHC could see it to finely modelize the Universe.
- Unfortunately (or fortunately) it didn't happen. Now SuSy believers are just few renegades. SuSy has, if it appears, an Energy Scale that doesn't solve all the SM latent problems.

Do we have other handles to restrict our Dark Matter searches?

Reversing the way we model the Dark Matter

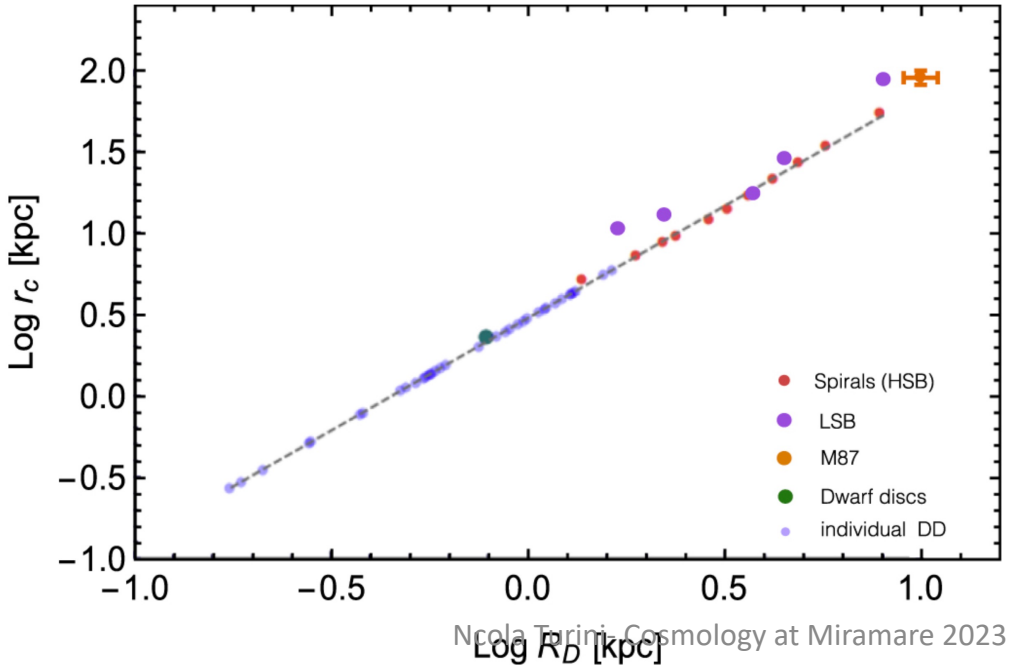
- The actual way of DM modeling is Up-Down: we make a theory with the right Relic Density and then we build astrophysics simulation or an experiment for particle physics that could find it (either direct or indirect).
  - We have a pletora of models ranging from Axions, Axion Like Particle up to the most exotic ideas, primordial black holes as DM and any possible SM Lagrangian extension with EFT is considered as a possible solution of the puzzle.

- Why instead don't we start from the indication from the only experimental source of information about the DM?
  - Check all the possible DM observations from cosmic scale up to galactic scales on all the possible type of galaxies in any evolution period.
  - Cores topology and cores evolution.
  - Cores scale correlation in different type and mass galaxies.
  - Astrophysical tensions and astro-particle observations.
- Given the large amount of data flowing in the recent years together with what we will access in the next future we can heavily constrain the possible source of the DM phenomenon.

(Particle physicists rarely talk with astrophysicists and consequently rarely the theory is checked there)

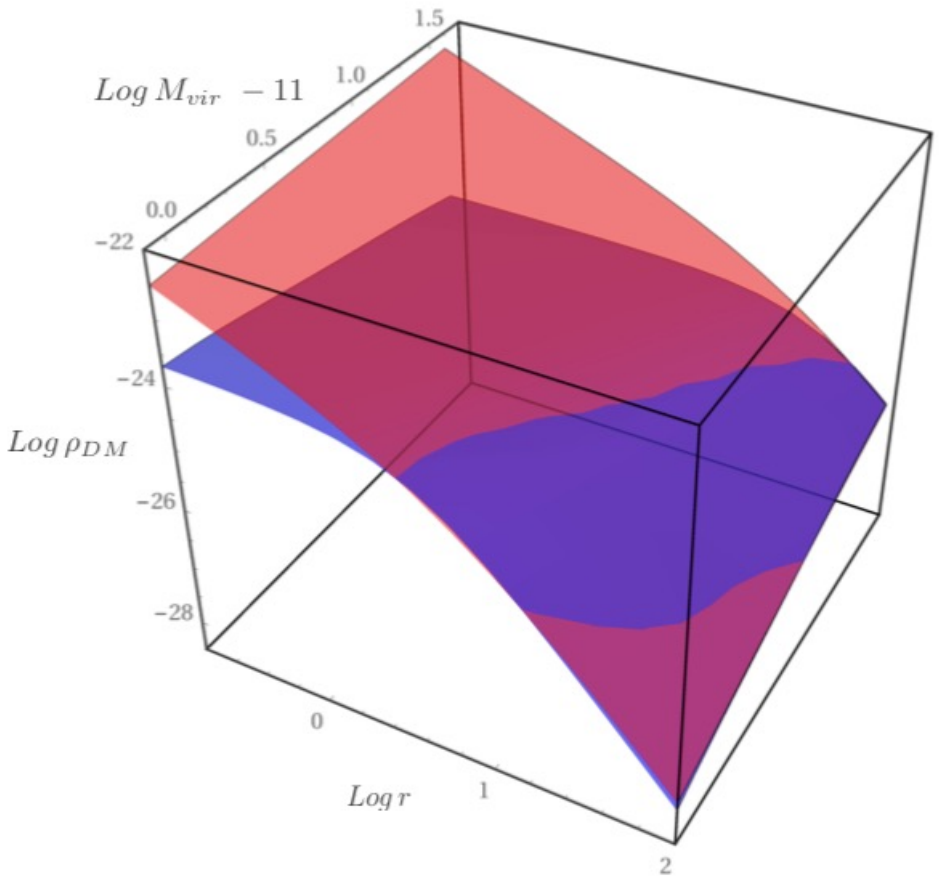
Some examples: Cores Structure

- The existence of Cores in galaxies is the most striking evidence that not all the possible invisible particle we can think of are matching the observations.
- More striking is the tight correlation between core radiuses (R_D) and the disk radiuses (r_0) in all the galaxies



Log r_0 *vs* log R_D in normal Spirals (*red*), dwarf Spirals (*green*), Low Surface Brightness (*violet*) and the giant elliptical M87 (*orange*)

Cores Structure



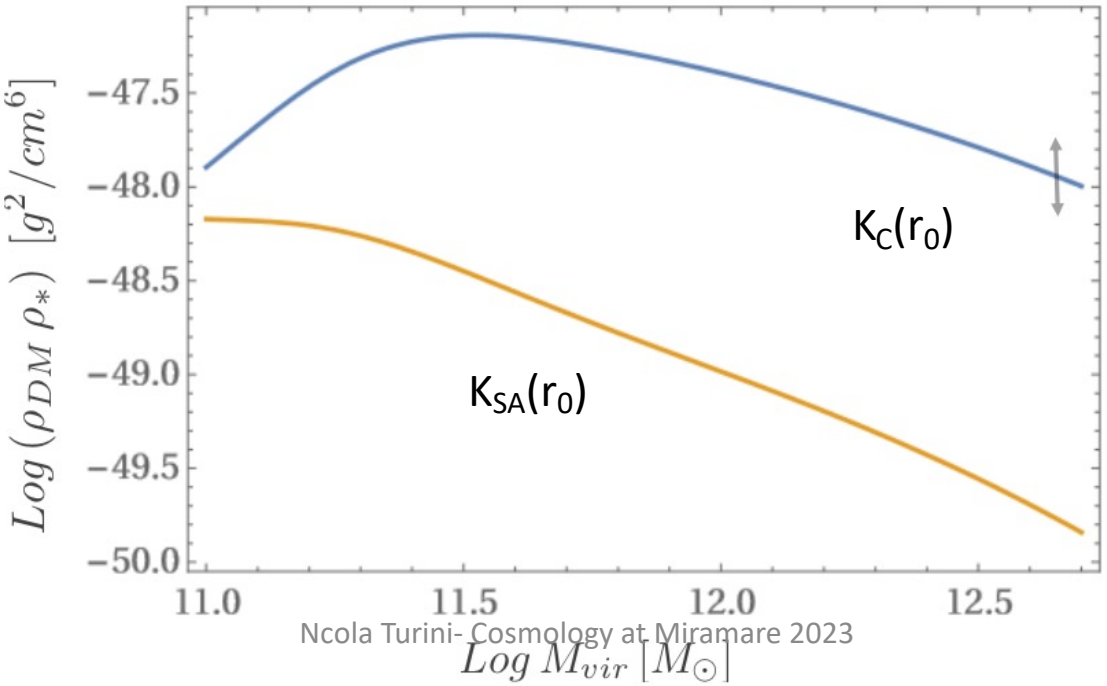
- On this respect also the existence of an Universal Rotation Curve in Spirals induces to think about a large correlation between the displacement of the luminous matter and the structure of the cores.
- The DM densities have two regions:
  - one external to r0 where the density decrease as supposed in any non collisional model
  - one internal where the things are not matching the NFW profile (red) and the density is flat.

Cores Structure

- Considering the quantity $K_C(r) \equiv \rho_{Dm}(r)\rho_*(r)$ we observe that at $r=r_0$ is almost constant for all the spirals:

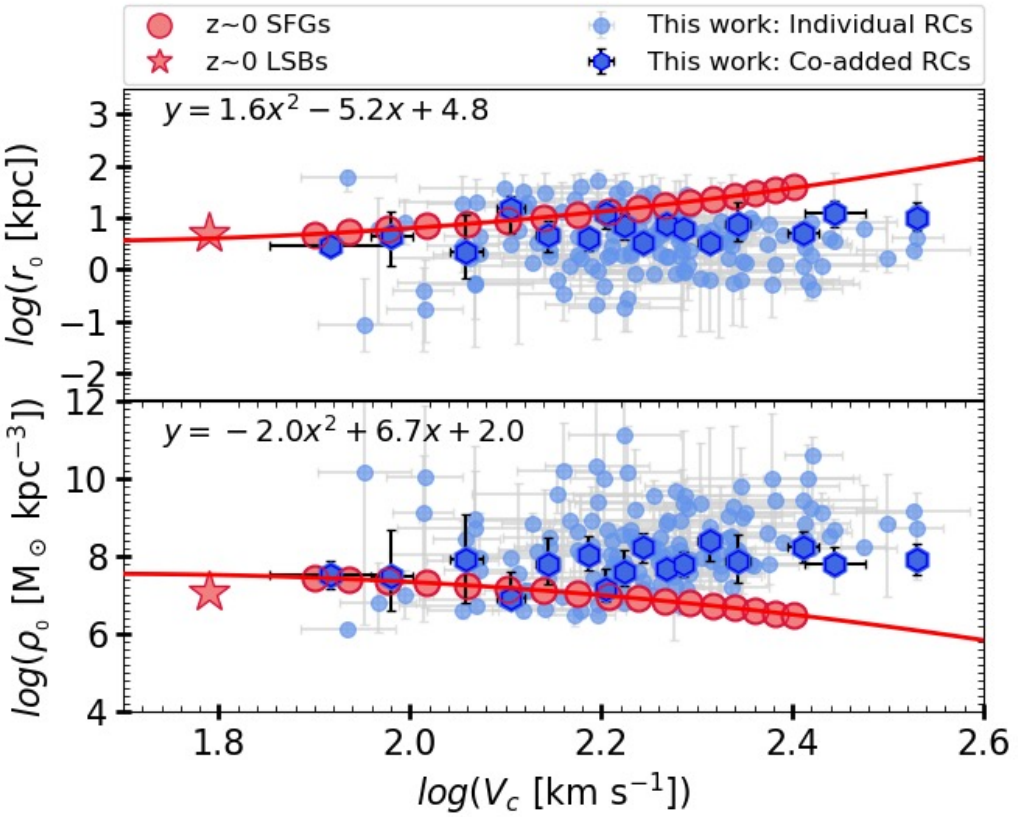
$$K_C(r_0) \simeq const = 10^{-47.5\pm0.3} g^2 cm^{-6}$$

- While this is not happening to the quantity $K_{sa}(r) \equiv \rho_{Dm}(r)\rho_{Dm}(r)$



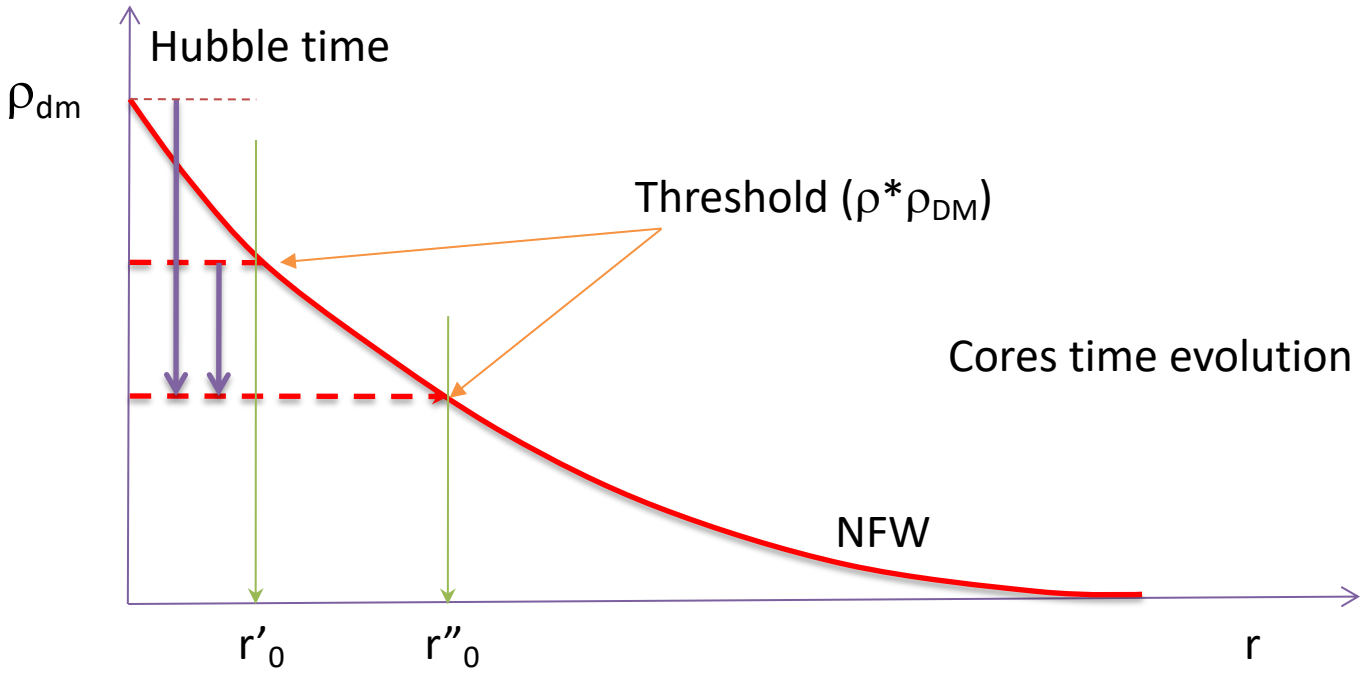
Cores evolution

- A recent work from G. Sharma and P. Salucci suggests that at larger Z the core radius is smaller than at present time



A way to explain the Cores evolution

- The simplest idea is that the inner part is “eroded” by the presence of the luminous matter over the time



DM models constraining

- The Cores structure can be used together with other observations to further constrain the possible sources of the DM.
- The tight correlation between the core structure and the visible structure in all galaxies suggest that for some reason the presence of luminous matter is responsible to the core formation.
- Thus implies, together with the secular cores evolution, if confirmed, that models implying an intrinsic core structure, such as light axions or Warm Dark Matter etc… could be ruled out.
- With similar conjectures we can in principle rule out extremely heavy DM particles or astronomical objects like MACHOS or BH.
- In particular, the large correlation between cores and visible matter are difficult to be reproduced with baryonic feedback at all scales without fine tuning.

Collisional DM

- The above discussion requires that the DM particle should in principle be heavier than some KeV.
- Moreover the quantity $K_C(r_0) \simeq const = 10^{-47.5\pm0.3} g^2 cm^{-6}$ observed in spirals suggest that some form of interaction between the two species should be envisaged.
- With a collisional DM we solve naturally many problems like scale correlation and cores evolution.

Discussion

- We can imagine three different scenarios:
  - DM that exchange momentum with hot galactic spots and warm up escaping the galactic center.
  - Heavy DM that annihilate in galactic gravitational pits, such as stars and heavy objects.
  - Direct DM and baryonic matter interaction

Scattering of DM particles

- To ensure the large scale correlations we can naturally imagine that some DM particle get a kick from the central baryonic dominated regions.
- We don't need a very large momentum exchange to make the DM to escape:

$$E_{core} = (100 - 500)\, eV\, \frac{m_P}{GeV}$$

- Unfortunately the hot spots where DM can get a kick, although numerous, stars, accretion disks etc…, they are filling a small volume meaning that we need an efficient way to exchange momentum and make the core formation appear.
- A star like the Sun can confine, and eventually kick out the DM particles, a maximum of 10^{-10} solar masses in 4 billion years. This is clearly not sufficient to enable a significant cusp depletion.
- Another way to exchange momentum from compact objects is through Slingshot. Whatever is the DM particle particle mass (below stellar mass) it is gravitationally diffused by stars or other compact objects. Still this process, happening close to the heavy obects, is not yet enough to ensure the observed core structure for the above reasons.

Annihilation of DM particles

- DM particles can be trapped inside stars or any heavy object
  - this in principle could make DM disappear from the cusp
- Unfortunately, for the above mentioned motivations, we cannot ensure that enough DM is trapped to fit the observations.
- In any case the annihilation could in principle happen in some regions where the the densities locally are enough large, giving for example origin to the positron excess seen by Pamela/AMS, but cannot be the origin of the core formation.
  - In this case if the excess is due to DM annihilation, the cut-off of the positron spectrum at high energies point to DM masses around 500/1000 GeV.

Weak interaction or else?

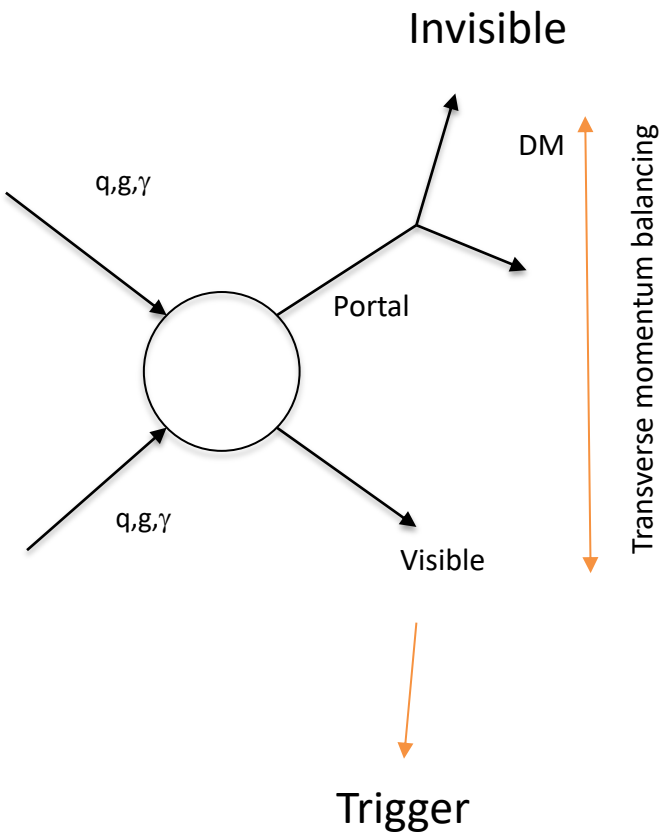
- In principle the Weak interaction has the ingredients to perform as intended. (WIMPS)
  - The annihilation cross section for a SuSy neutralino is too low while other WIMP models are close to marginal (~$10^{-40}cm^2$).
- No one can exclude a DM sector with another intrinsic short range interaction and completely neutral regard to SM forces.
- In this second case we need a “portal” from SM to DM that for heavy particles can be related to Higgs or special Vector particles.
- EFT theories provide hints on how the portal can be cooked.
- Also massive Axion Like Particles (ALPs) can be put in the game.

- All the above models give interaction cross sections between the two species that cannot account for the tight correlation we see in the galaxies.

How to search for such DM?

Accelerators

- At LHC energies in principle we can produce efficiently DM
  - The problem is that the standard searches require enough large unbalance in the kinematics.
  - From quark, gluons, gamma we access the DM sector through portals of various form (Vectors, Scalars)
  - If in the decay of the portal particle the invisible debris have not enough transverse momentum the event cannot be distinguished from the standard background, mostly from QCD (close to the decay threshold).
  - Higgs portals require typically gluon-gluon fusion, but also photon-photon collisions should be considered.
  - ALPs are naturally produced in gamma gamma interactions (not DM but can be portals).
  - If photon photon collisions are efficient enough in DM production the sensitivity can be enhanced with forward proton spectrometers like PPS (CMS) or AFP (Atlas). Here the kinematics is closed and can be seen also events close to the threshold as new scalar resonances and escaping masses in a mass spectrum.



Direct searches

- Normally for WIMP searches we consider the nuclear recoil as the standard DM tagging.
- If DM has different properties, the probability of nuclear recoil inside underground experiments can be suppressed.
- Maybe it is more efficient the search for a direct annihilation close-by given the fact that Earth is a dense object.
- Where to search? If Pamela positrons are relic from the DM annihilation it suggests that the DM could have a large mass >400 GeV. This means that an annihilation is seen as a large isotropic shower somewhere in the ground and rarely close to the surface.
- Neutrino experiments, such as Icecube, could in principle be the right place to look around-modulo the trigger!
  - If they don't trigger such kind of events we don't see them.
- Underground large area trackers could be another way searching for converging muon tracks. (estimation of the occurrence of such events to be done)

Indirect searches

- We expect that the annihilation happens mostly inside dense objects.
- Only a limited part of the debris of the annihilation process can escape into opens space.
- Given the complex decay chain we expect that the final particles ejected are electron/positrons, gamma and neutrinos
- Gamma photons can in this case have lower energy (~MeV/~GeV) and a large spectrum, being the final states of multiple decays (mostly neutral pions). We could expect a diffuse gamma flux in the galaxies from different regions.
- Same story with electrons and positrons, that diffuse inside the galactic magnetic field, but we should anyhow expect a cutoff close to the mass of the DM particle.
- The flux we expect will be extremely low (simulation and estimation needed) compatible with the Pamela excess.

Provocation: direct interaction with baryonic matter (BM)

- An interesting way to correlate the two components is just adding some friction beween the two component.
- A viscosity between DM and BM could squeeze the DM into the disk in the central regions of the halo enhancing by two orders of magnitude the local DM density.
- The DM will be compacted also in regions where winds and clouds are present enhancing the momentum transfer and/or annihilation
  - Such a particle can be seen by the actual experiments?
    - If the interaction DM-BM is strong enough the particle get immediately thermalized and if the interaction is purely elastic the momentum transfer, at least on earth, is negligible and invisible with the current experiments.
    - The original speed foreseen of such particle is one order of magnitude less (30m/s) since it is corotating with the disk components. Only a special bolometer in space can catch it directly.
    - The density is still so small that again the probability to catch it needs large volumes.
    - The eventual annihilation will happen mostly in the internal regions of the compact objects, so almost invisible.
    - Only a small part of the decay products will escape and may contribute to the Pamela/AMS positron excess.
    - Gamma ray observatories could in principle see the annhilation pattern but it would likely happens in region where other atrophysical gamma sources are present (SNR, OB stars winds shells…)
- This picture although very interesting clashes with particle physics modeling since we need to add an elastic interaction between the two sectors with cross sections of the order the nuclear cross section (~Barn) and long range.
- This is partially in contrast with the Bullet Cluster observation.

Conclusions

- Here has been presented an example on how constrains from astrophysics can be applied in any modeling of a possible DM sector.
- I don’t cover all the possible aspects and possible different explanation that are behind the DM phenomenon. The picture can be surely different and more complicated.
- I apply a kind of “Mediocrity” principle to find the easiest and natural explanation on the the large correlations observed between the DM and SM
- This is a work in progress that will be expanded in the near future to produce limits on cross sections and compatible masses of any hypothetical DM new sector and give a better guidance on future searches.