Synergies between Astroparticle and HEP

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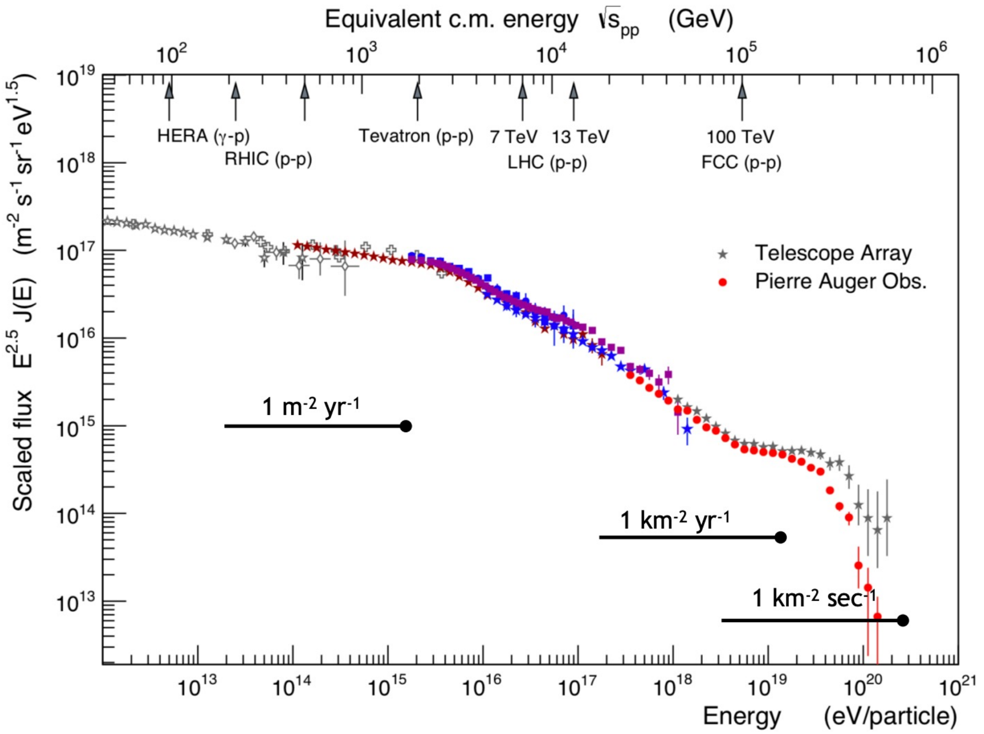
Astroparticle searches and methods

- Fields-
  - High energy, Very High energy, Ultra High energy charged particles
  - Gamma rays
  - Neutrinos
    - Solar neutrinos
    - Energetic neutrinos
  - Gravitational waves.
    - Coalescing heavy objects(BH-NS…)
    - Low frequencies (~10 Hz)
  - New physics
    - Dark Matter direct serches
    - Dark matter indirect searches (gamma, positrons etc..)

Charged particles observation

- Lower energy: element composition
  - Example: AMS RICH
- VHE and UHE searches:
  - AUGER etc…

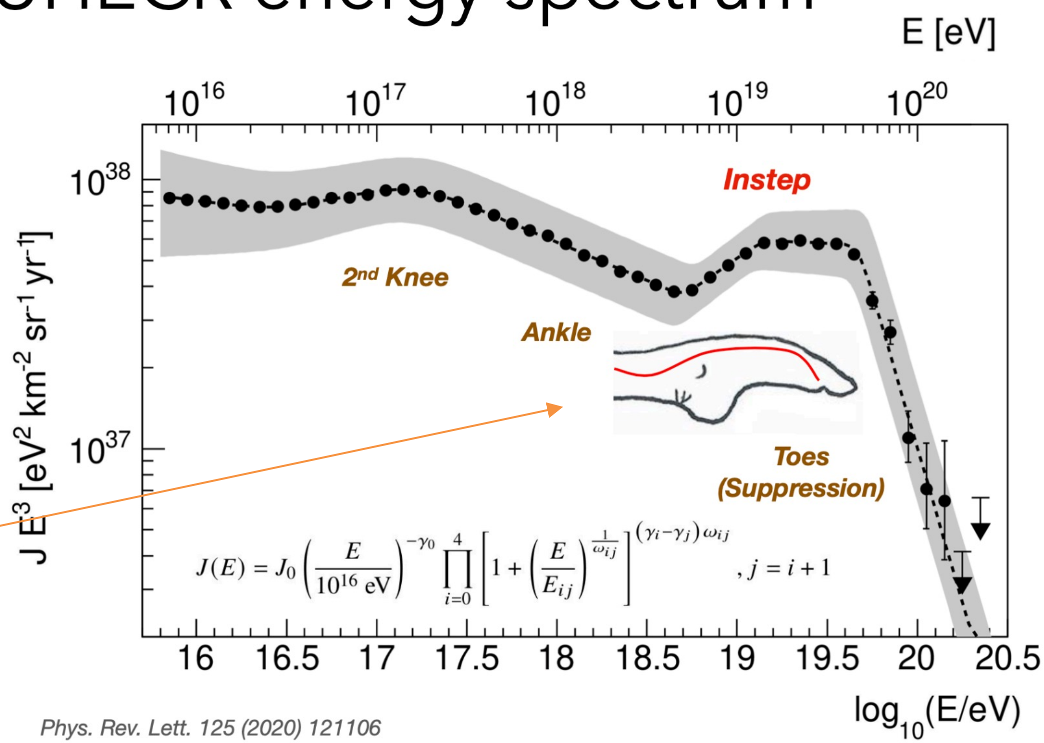
Ultra High Energy Cosmic Rays



UHECR

- Extreme energy particles as seen by AUGER up to 10^{20} eV
- Acceleration mechanism
- Structures in the spectrum
- Possible sources
  - Some directionality still present due to very large momentum of the original particle

UHECR energy spectrum



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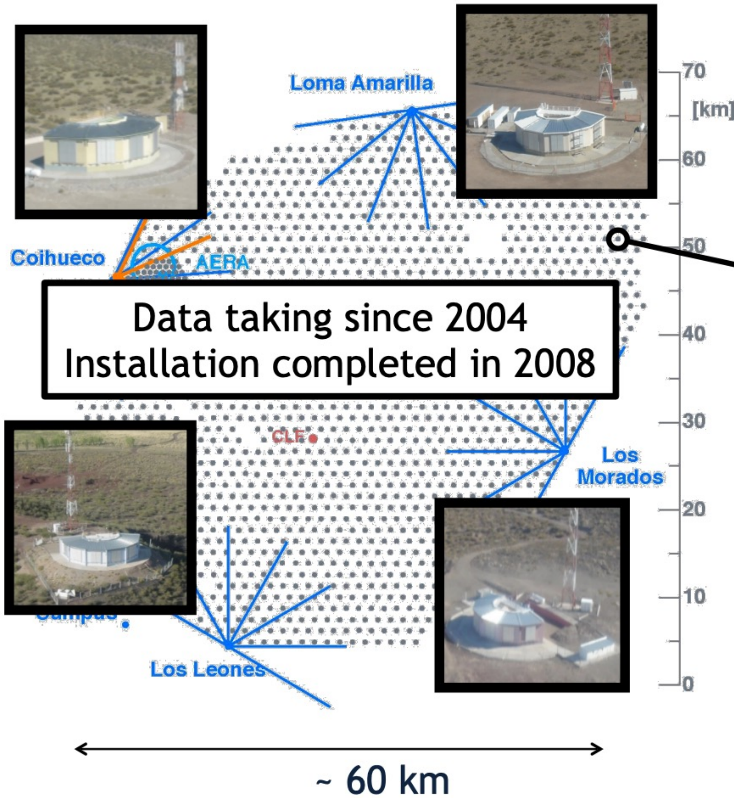
Pierre Auger Observatory



Data taking since 2004
Installation completed in 2008

- 4 Fluorescence Detectors (FD)
- 6 x 4 Fluorescence Telescopes

- 1600 Surface Detectors (SD) Stations
- SD stations spaced by 1.5 km
- Covering an area of 3000 km^2

Tecniques

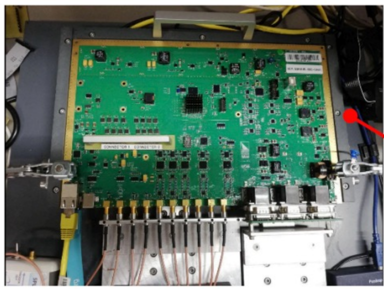
- Cherenkov pools – Scintillation light from atmosphere

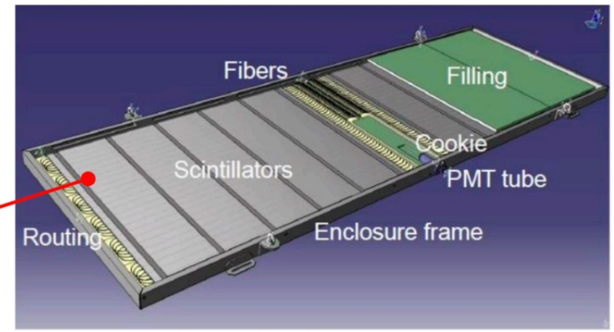
Photosensors!

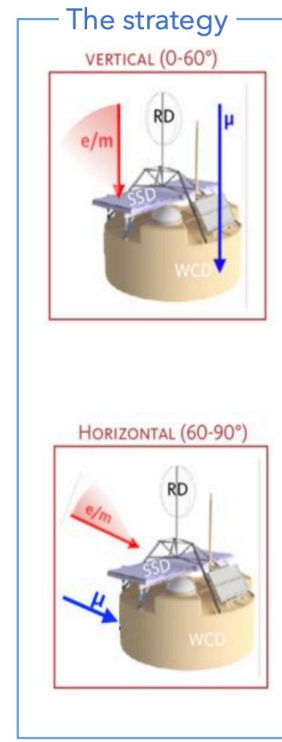
Large sensitive area -> Dear old PHOTOMULTIPLIERS

Auger Prime detectors

New electronics (UUB) and Scintillators(SSD)







High dynamic range PMTs

Radio Upgrade

Underground Muon Detector (UMD)

Auger Phase I data taking from 2004 on (from 2008 with the full array) to 2021

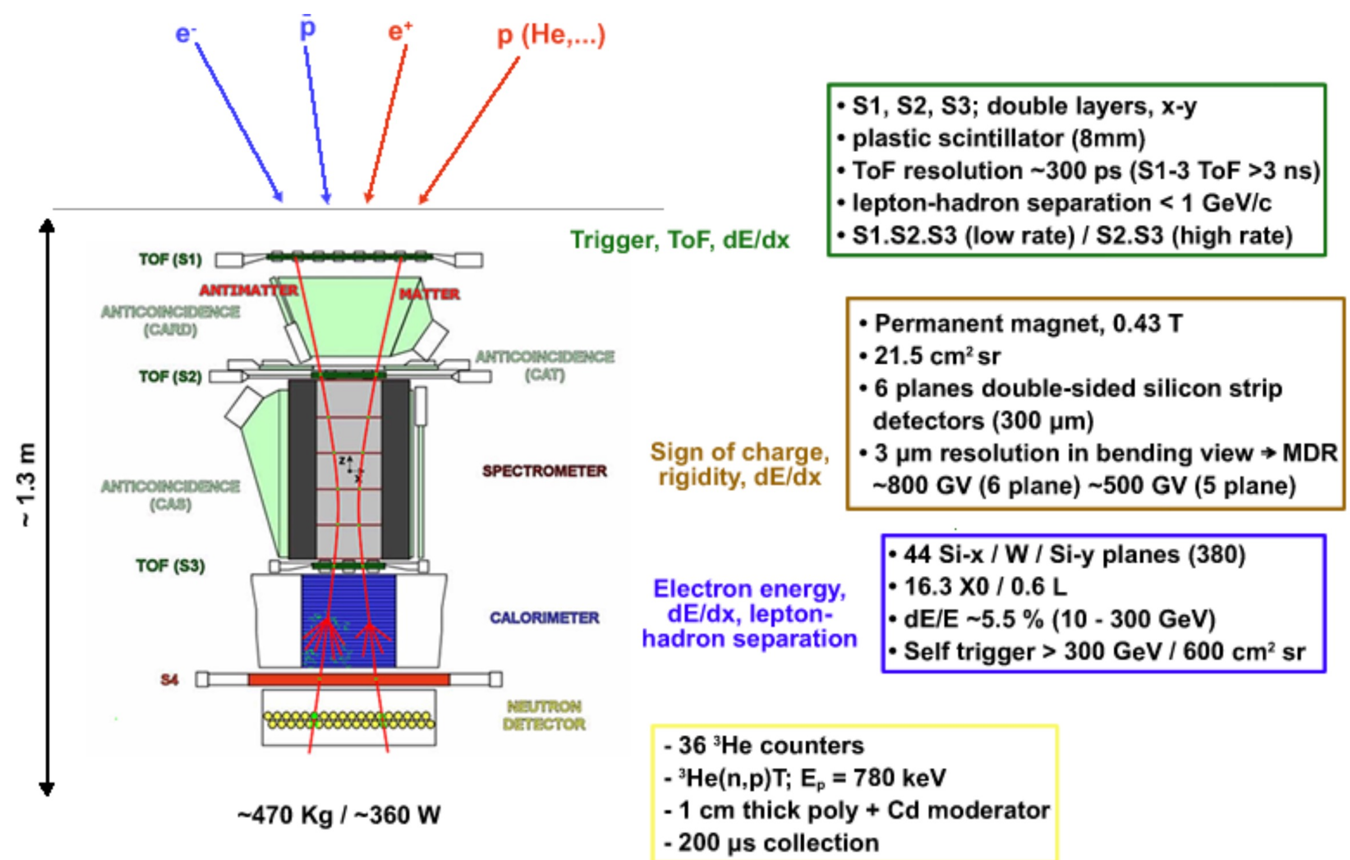
Auger Phase II data taking from 2022 to 2035

AMS/Pamela and HEP techniques

Pamela experiment was the first spectrometer launched in space.

It opened a new window in astroparticle physics using a HEP standard techinque

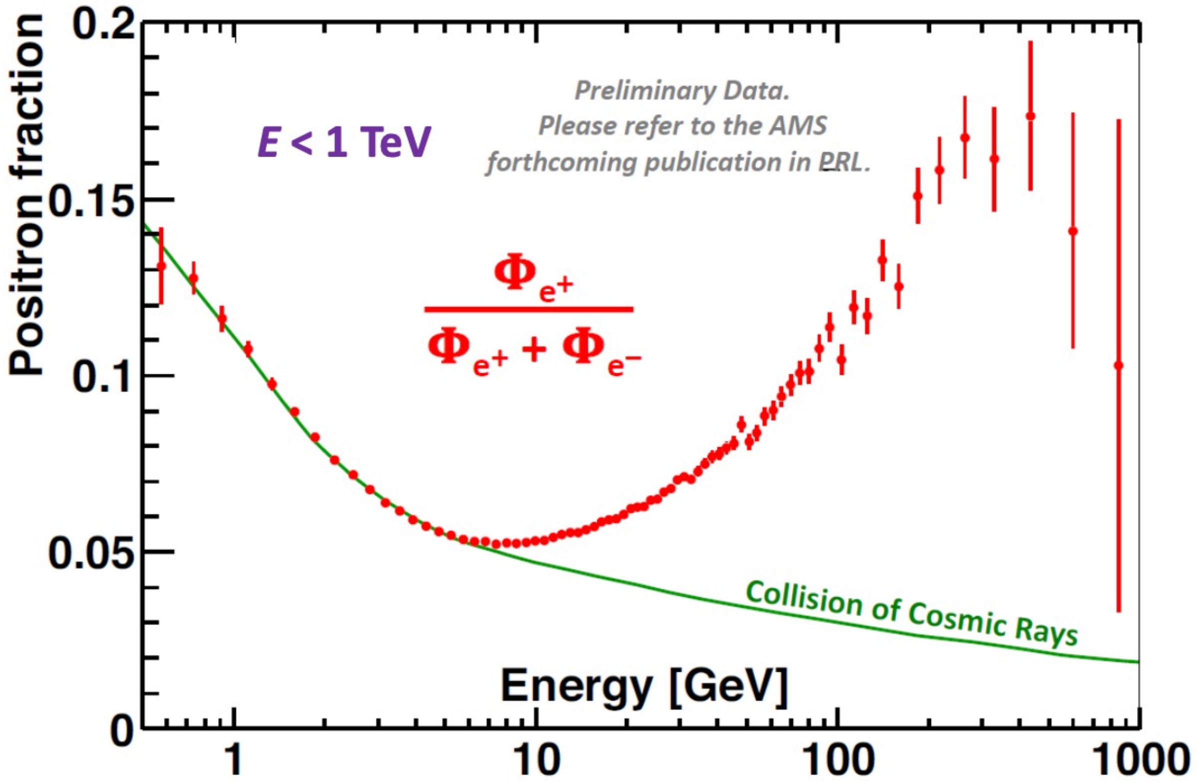
- Si Tracker in a Magnetic field
- Electromagnetic Calorimeter
- Bottom counters



Positron excess

- Early Pamela observation was confirmed by AMS-02 experiment
- AMS-02 has a larger rigidity acceptance and detection area
- Many papers on possible explanation:
  - Pulsars
  - DM annihilation
  - Molecular clouds/ UHECR secondary interaction
- NONE CONVINCING!!!

The AMS-02 positron fraction with 6.5 years of data



Gamma rays detection

- Gamma rays are together the neutrinos, the only pointing radiation toward possible sources
  - Multiwavelenght study of astronomic sources from radio-optical-xrays-gamma

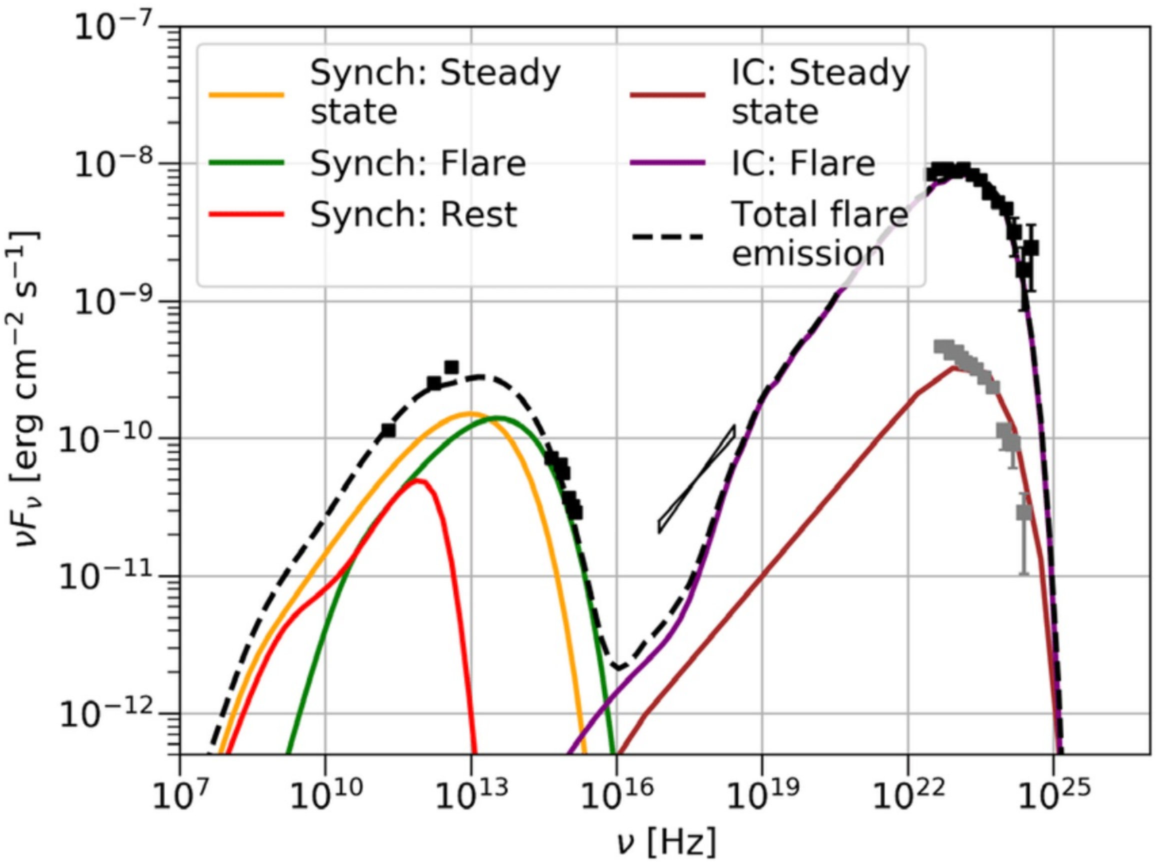
- Space
  - FERMI-LAT
    - Covering the lower part of the spectrum (MeV-100GeV)
    - Large field of view
    - Small collection area
- Ground
  - IACTs (30GeV-10/100TeV)
  - Ground sampling (EAS) (10 TeV up)

Gamma ray production

Inverse Compton gamma ray production in a Active Galactic Nuclei (AGN)

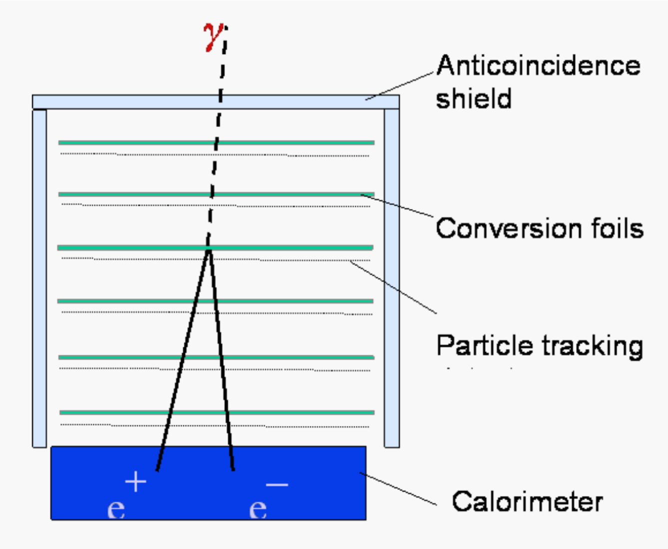
Flare and Steady state

Supernova Remnants shows similar accelerating (Fermi) and production methods

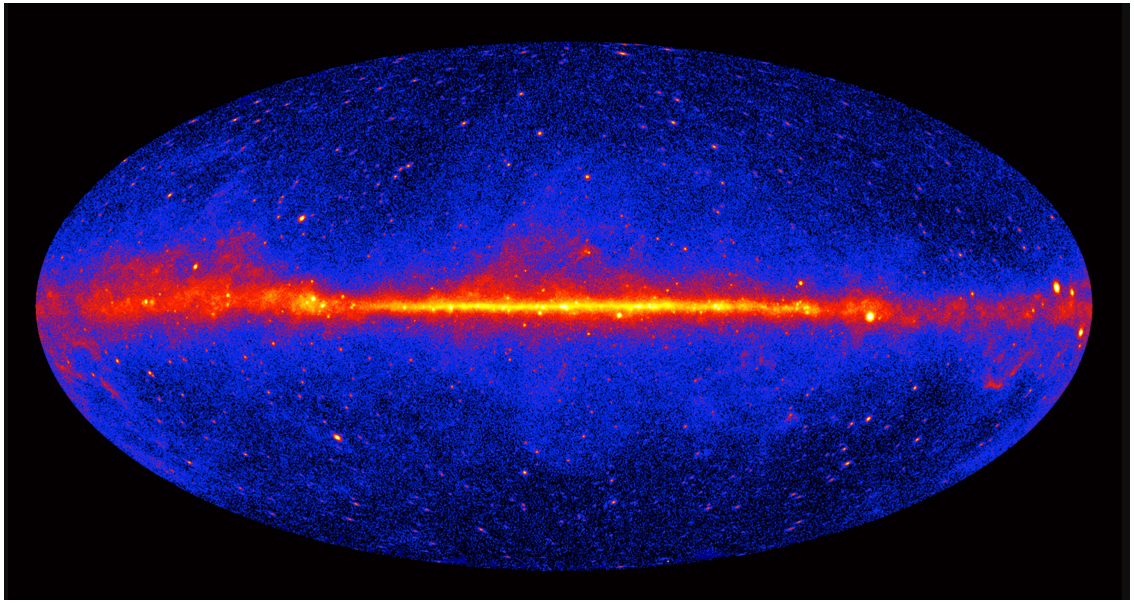


SED from our jet model, showing synchrotron and inverse-Compton emission from the flare and steady-state regions, and the synchrotron emission from the rest of the jet. Data from Ref. [56]. Black points show data taken during a flare, and gray points show steady-state emission.

FERMI-LAT



Schematic Structure of the LAT



Fermi is the medium energy Gamma ray telescope that most has changed the understanding the High Energy sky.
A silicon tracker with interlayed conversion sheets plus an electromagnetic calorimeter.

IACT

- Use of the earth atmosphere as a electromagnetic calorimeter
- Catch the energy/direction of the γ showers just looking to the Cherenkov light emitted by the charged electron/positron with a parabolic (Newtonian) telescope
  - Large background from cosmic protons and distorted muons rings
  - Need of efficient discriminating tools
    - Stereo view of the shower

CTA

Three types of telescopes with different energy range

- LST (10GeV-1 TeV)
- MST (150GeV-5TeV
- SST (5TeV-300TeV)

Two Location (North and South) for a full sky coverage.

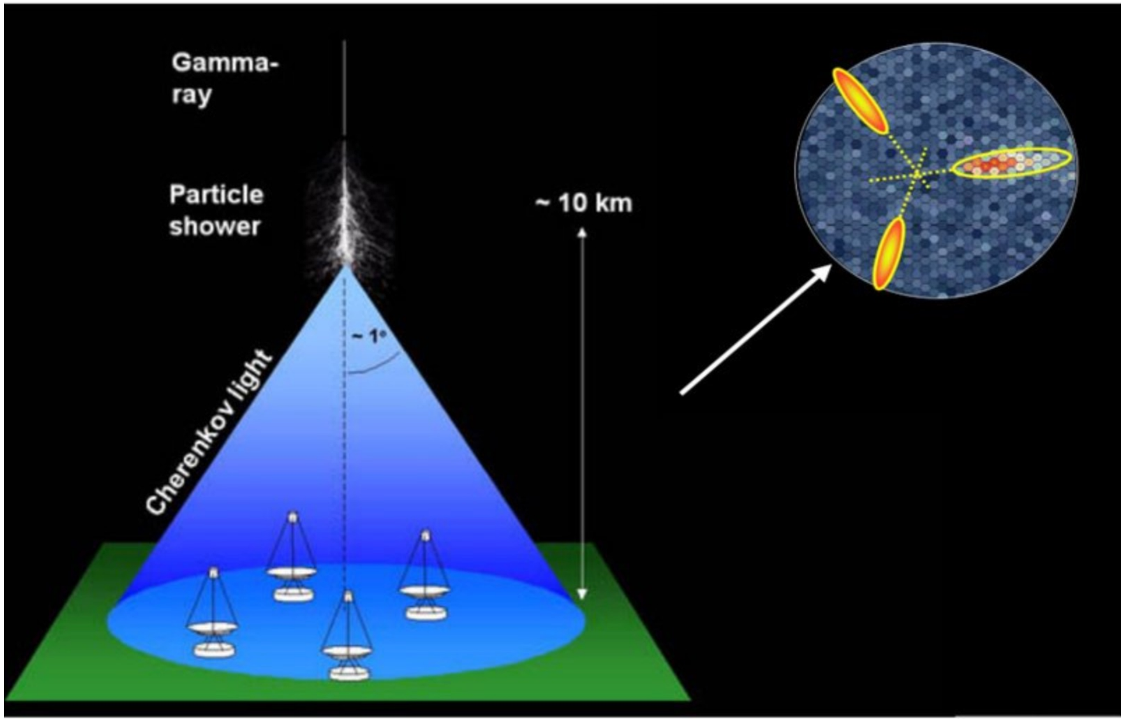
- Noth area dedicated to softer gammas (LST-MST)
- South area dedicated to harder gammas (LST?-MST-SST)

Cherenkov Telescopes techniques

Stereo view of the cherenkov light emitted by a air shower

Large pixel area photosensors -> PM

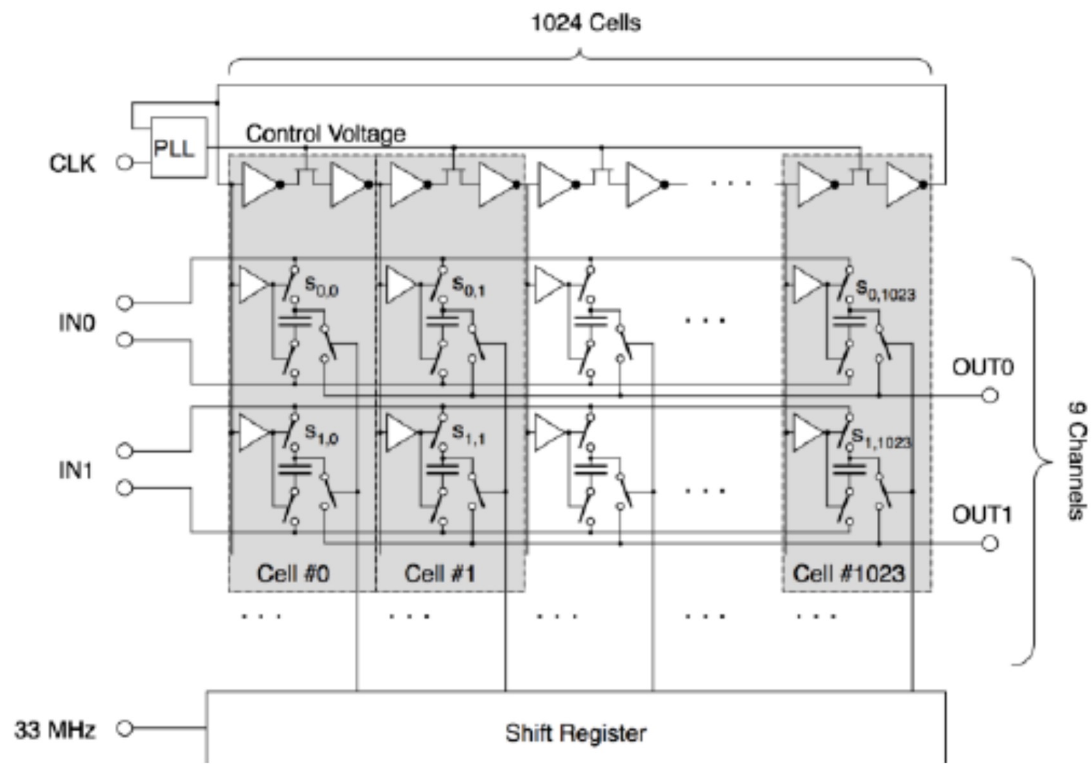
- Only MST with more than 10000 SiPm
- Shape discrimination
  - Gamma shower very compact and with a specific shape
  - Hadron shower more like a potato with side legs
- Shower image development in time
  - Fast sampling of the pixels images



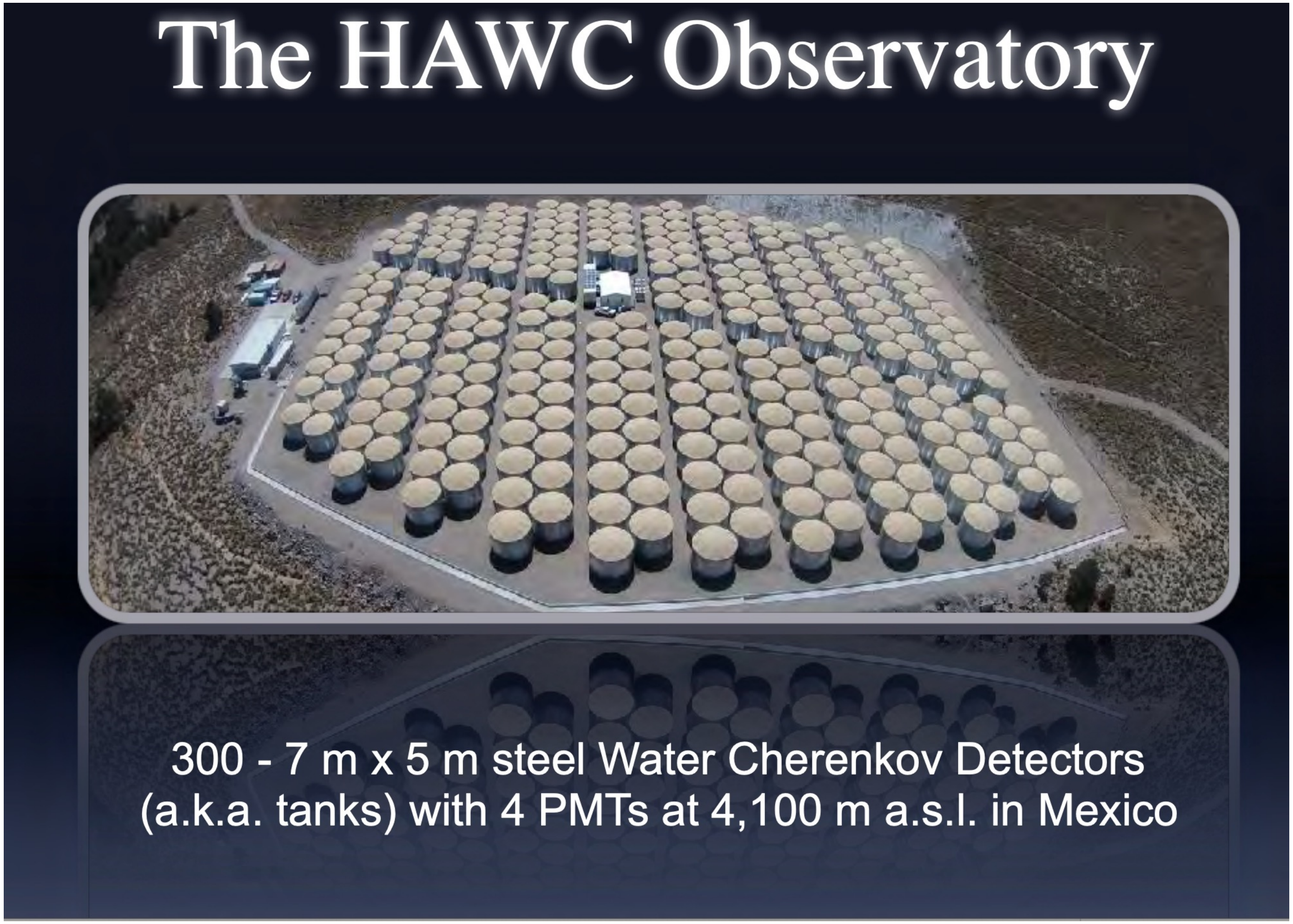
Timing information

- -Low trigger rate

- Analog sampling:
  - Ring sampler controlled by a DLL
  - Trigger stops the sampling
  - The analog charge of a section of the ring is transferred at low frequency to an external ADC
- New developments on dead time suppression with internal analog buffers.



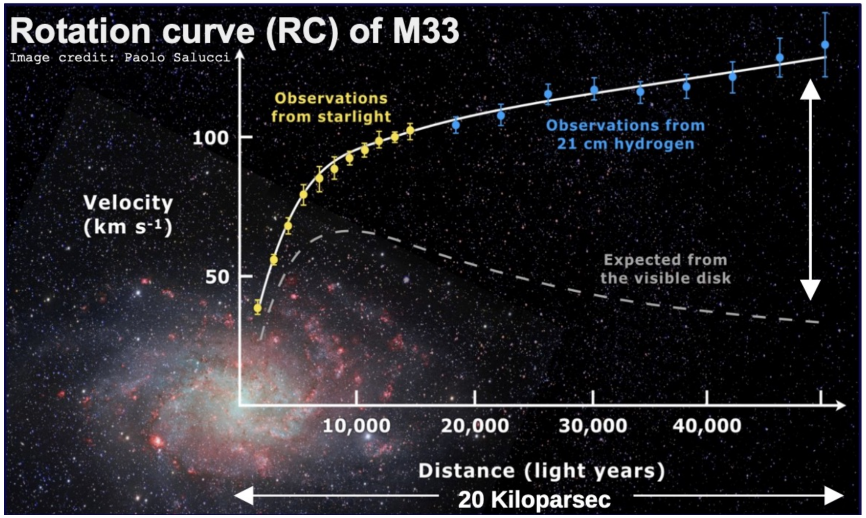
Simplified schematics of the DRS4 chip.



Photomultipliers!

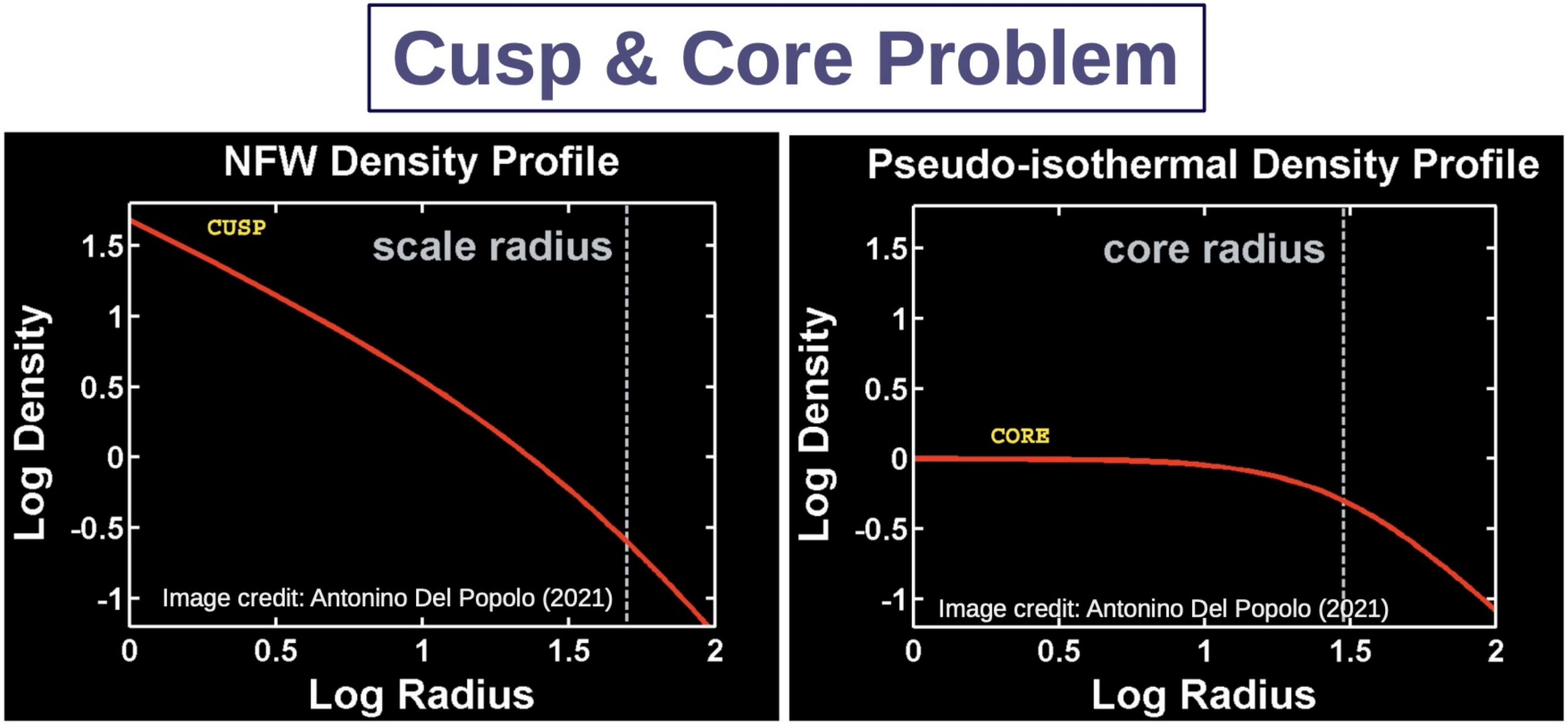
Dark Matter detection

- DM is seen only in astrophysical observations
  - Galaxies rotation curves
  - Galaxy clusters dynamics
  - Galaxy clusters microlensing
- CMB fitting
  - LCDM (Cold Dark Matter)
- Fwhat can it be?
  - Modified Gravity (MOND)
  - From FuzzyDM (ultralight Axions) to Primordial BH!



- Many models has been tested
- The most promising was the WIMP model (WIMP Miracle/SuSy)
- WIMPs are well compliant to LCDM
- WIMP searches are all negative except DAMA (no trust on it from the community)

LCDM/WIMP problems

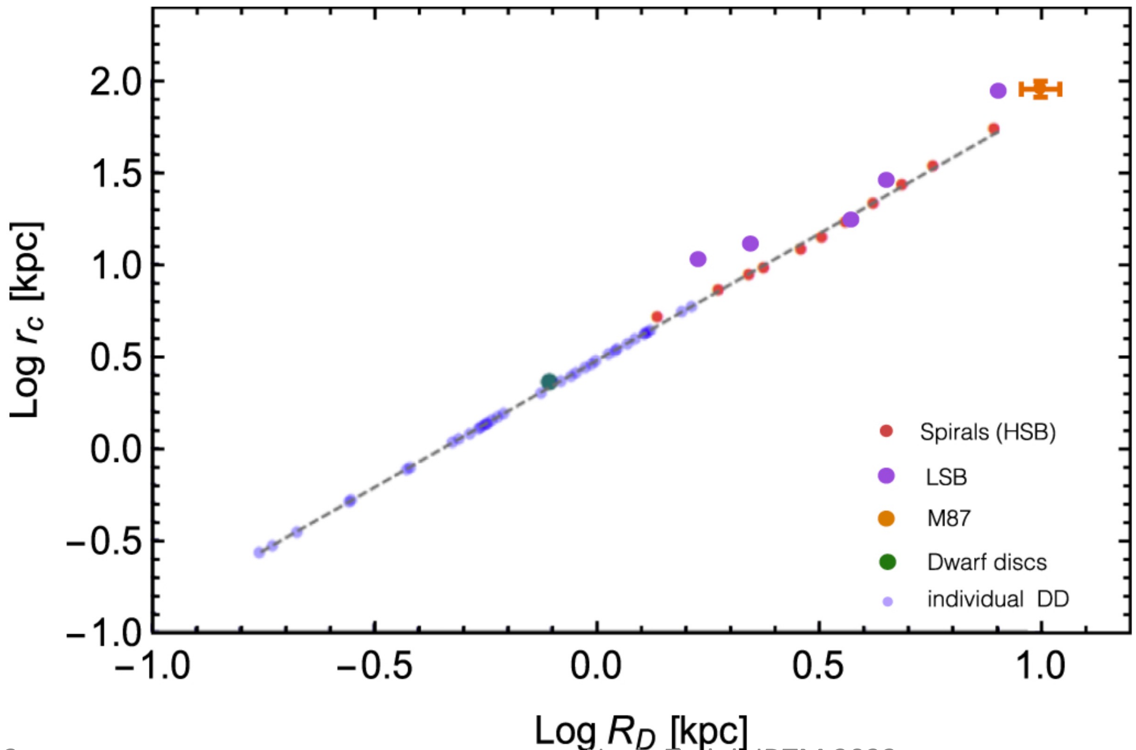


Burkert, 1995; Navarro et al., 1996b; Palunas & Williams, 2000; Salucci & Burkert, 2000a; de Blok et al., 2001; de Blok et al., 2003; Gentile et al., 2004; Simon et al., 2005; Salucci et al., 2007; Salucci 2019; Del Popolo & Le Delliou 2021,

The existence of a central flat in density part of the DM halo corresponding to the baryon dominated region (CORE) is in contrast to the CDM cusped predictions (NFW density curve)

Cores Structure

- The existence of Cores in galaxies is described in large part with an Universal Rotation Curve (URC)
- Tight correlation between core radiuses (R_D) and the disk radiuses (r_0) in all the galaxies
- Baryon feedback on CDM is failing in DM dominated Dwarf Galaxies
- Fuzzy DM forecast cores that get smaller the higher the galaxy mass
- Warm DM (m=1-3KeV) is dynamically unstable



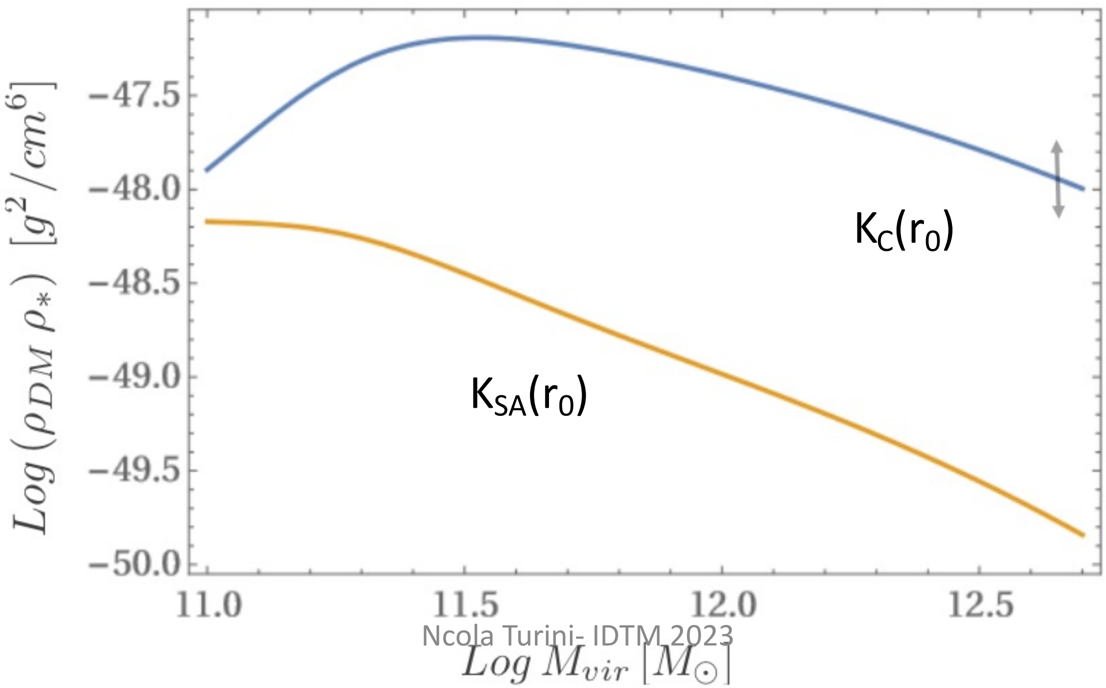
Log r_0 *vs* log R_D in normal Spirals (*red*), dwarf Spirals (*green*), Low Surface Brightness (*violet*) and the giant elliptical M87 (*orange*)

Cores Structure

- 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:

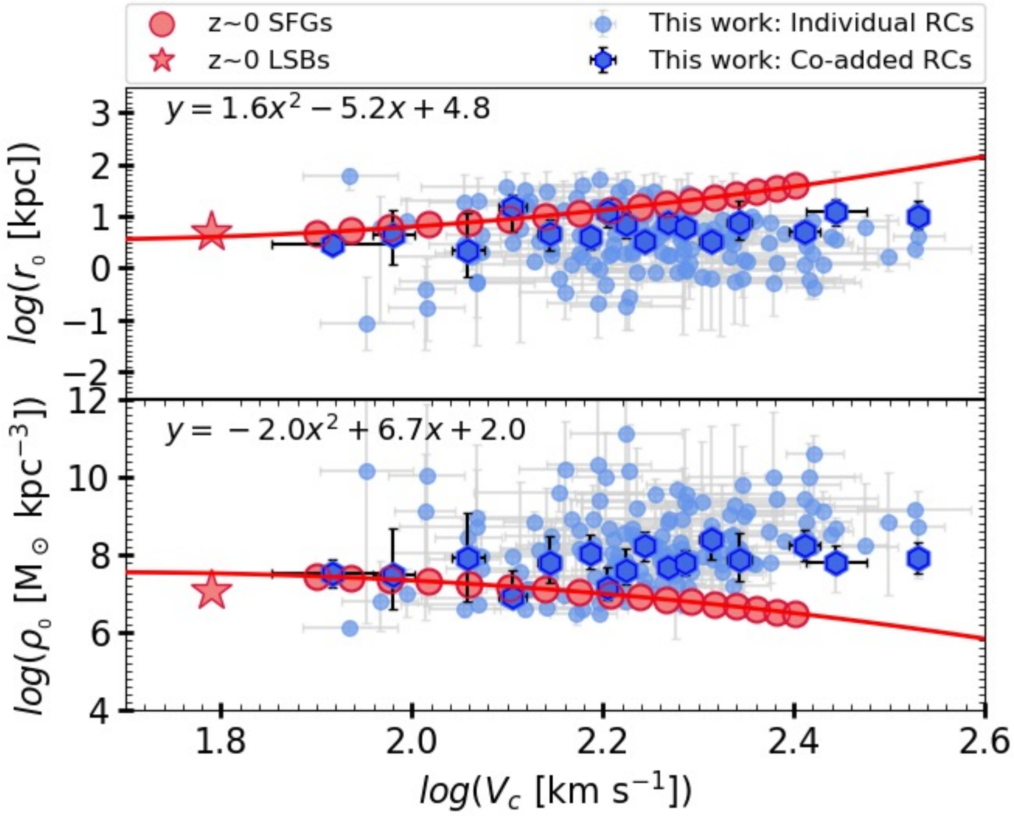
$$K_C(r_0) \simeq const = 10^{-47.5\pm0.3} g^2 cm^{-6}$$

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



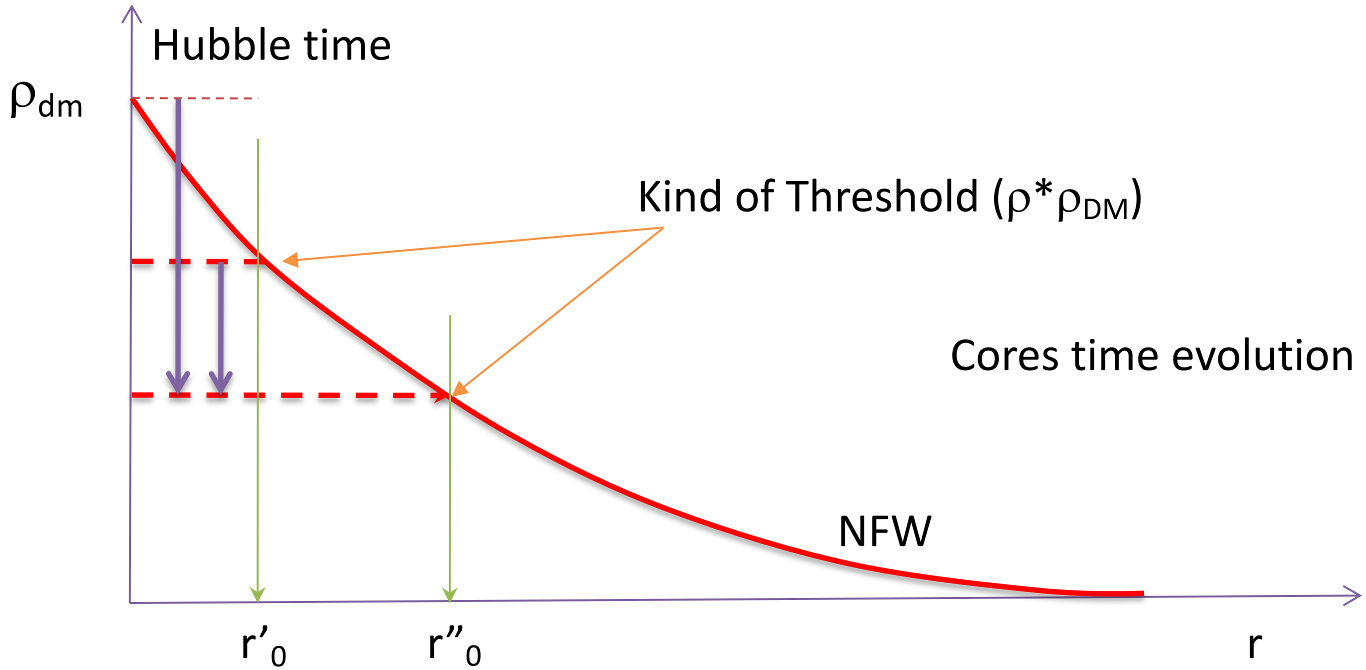
Cores evolution

- 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



Collisional DM?

- The WIMP modeling is not efficient in describing the small (galaxy) scale of the baryon-DM structure.
- Baryonic astrophysical feedback can be tuned on a certain galaxy scale but fails as soon as we change the scale
  - Dwarf Galaxies are DM dominated and show the same core structure as the larger galaxies.
- Other models are even less efficient (Fuzzy DM-Warm DM etc)
- Are there different way to constrain the DM phenomenon?

- The above observations suggest a baryonic matter that is tightly correlated with the DM

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.

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.
    - Underground experiment cannot see it since it is too slow.
    - 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

- The two communities (HEP and Astroparticle) had never been really separated since the detection techniques are basically the same
- New ideas developed in each field reverberate and resonate on the other
- A new hot topic surged in the last years, the Dark Matter phenomenon.
- The potential experimental environment has to be fully developed since the past and current experiments have given a negative result.
- The newest direct searches will reach soon the “neutrino cloud” sensitivity.
- Observations tell us that the picture could be much different from what we have up to now explored.
- A brand new series of experiments have to be conceived and developed following the latest indications from all the possible sources.