ELEMENTARY PARTICLE PHYSICS
Current Topics in Particle Physics
Laurea Magistrale in Fisica,
curriculum Fisica Nucleare e Subnucleare
Lecture 10

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Preliminaries

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Bibliography

♠ Bibliography

- K.A. Olive et al. (Particle Data Group), *The Review of Particle Physics*, Chin. Phys. C, 38, 090001 (2014)(PDG) update 2015, http://pdg.lbl.gov/
- F. Halzen and A. Martin, *Quarks and Leptons: An introductory course in Modern Particle Physics* , Wiley and Sons, USA(1984).

♠ Other basic bibliography:

- A.Das and T.Ferbel, *Introduction to Nuclear Particle Physics* World Scientific,Singapore, $2^{\rm nd}$ Edition(2009)(DF).
- D. Griffiths, *Introduction to Elementary Particles* Wiley-VCH,Weinheim, 2^{nd} Edition(2008),(DG)
- B.Povh *et al.*, *Particles and Nuclei* Springer Verlag, DE, $2^{\rm nd}$ Edition(2004).(BP)
- D.H. Perkins,*Introduction to High Energy Physics* Cambridge University Press, UK, $2^{\rm nd}$ Edition(2000).
- Y.Kirsh & Y. Ne'eman, *The Particle Hunters*

♠ Particle Detectors bibliography:

- William R. Leo *Techniques for Nuclear and Particle Physics Experiments*,
  Springer Verlag (1994)(LEO)
- C. Grupen, B. Shawartz *Particle Detectors*,
  Cambridge University Press (2008)(CS)
- *The Particle Detector Brief Book*,(BB)
  http://physics.web.cern.ch/Physics/ParticleDetector/Briefbook/

Specific bibliography is given in each lecture

Lecture Contents - 1 part

1. Introduction. Lep Legacy
2. Proton Structure
3. Hard interactions of quarks and gluons: Introduction to LHC Physics
4. Collider phenomenolgy
5. The machine LHC
6. Inelastic cros section *pp*
7. W and Z Physics at LHC
8. Top Physics: Inclusive and Differential cross section $t\bar{t}$ W, $t\bar{t}$ Z
9. Top Physics: quark top mass, single top production
10. Dark matter
    - Indirect searches
    - Direct searches

Specific Bibliography

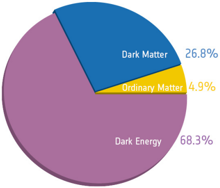
♠ Bibliography of this Lecture

- O. Lahav and A.R. Liddle *The Cosmological parameters* The Review of Particle Physics (2017) C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update. (PDG-Rev-Cosmo) rpp2016-rev-cosmological
- M. Drees and G. Gerbier *Dark Matter* The Review of Particle Physics (2017) C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update. (PDG-Rev-dark) rpp2016-rev-dark-matter
- Katherine Freese *Status of dark matter in the universe*,Proceedings of 14th Marcel Grossman Meeting, MG14, University of Rome "La Sapienza", Rome, July 2015,arXiv:1701.01840

Contents

Composition of Universe

A standard model of cosmology is emerging in which the Universe consists of [1]:



From analysis of the Planck mission's cosmic microwave background data:

- 5% ordinary baryonic matter,
- ∼ 26% dark matter,
- ∼ 69% dark energy.

The baryonic content is well-known, both from element abundances produced in primordial nucleosynthesis roughly 100 seconds after the Big Bang, and from measurements of anisotropies in the cosmic microwave background (CMB). The evidence for the existence of dark matter is overwhelming, and comes from a wide variety of astrophysical measurements.

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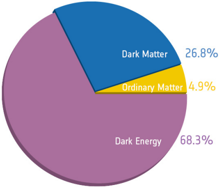
[1] Planck Collaboration, P. A. R. Ade et al., *Planck 2015 results. XIII. Cosmological parameters*, arXiv:1502.01589, Astron. Astrophys. 594, A13 (2016).

Composition of Universe

[2]:



- **Total matter**(dynamics):

$$\rho_{\mathrm{m}} \simeq 3 \times 10^{-27} \frac{\mathrm{kg}}{\mathrm{m}^3}$$

- **Baryons**(measurements, baryogenesis):

$$\rho_{\mathrm{b}} \simeq 4.5 \times 10^{-28} \frac{\mathrm{kg}}{\mathrm{m}^3}$$

- **Visible matter**(stars, gas and dust):

$$\rho_{\mathrm{lum}} \simeq 9 \times 10^{-29} \frac{\mathrm{kg}}{\mathrm{m}^3}$$

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[2] Planck Collaboration, P. A. R. Ade et al., *Planck 2015 results. XIII. Cosmological parameters*, arXiv:1502.01589, Astron. Astrophys. 594, A13 (2016).

Composition of Universe

$$\rho_{\mathrm{dark}} = \frac{\rho_{\mathrm{m}} - \rho_{\mathrm{b}}}{\rho_{\mathrm{m}}} \Longrightarrow (int)(100 * \frac{3 \times 10^{-27} - 4.5 \times 10^{-28}}{3 \times 10^{-27}}) = 85\%$$

$$\boxed{\text{The dark matter constitues 85\% of Universe matter}}$$

If one takes stock of the observed components, one finds the following:

- The **total density of matter**, deduced from the gravitational potential measured from the movement of stars in galaxies, is of the order of some $10^{-27} \frac{\mathrm{kg}}{\mathrm{m}^3}$.
- The **total density of baryons**, visible or invisible, both measured and deduced from the well established baryogenesis process, is smaller by about a factor of 10.
- **Visible matter**, shining light, concentrated in stars, gas and dust is again less dense by a factor of 5.
- Most of the matter is thus neither visible nor baryonic. It is called **Dark Matter**.

Lecture outline

In this lecture, we will discuss one of the two mysterious components of the Universe: the **Dark Matter**. The second one Dark energy isn' t in purpose of this course. In particularly we will discuss:

- How dark matter is detected by its gravitational effects;
- How we try to identify its quanta, the particles that make up dark matter .

Contents

The Beginnings of the Dark Matter Problem and Rotation Curves

- The first evidence of what later was named dark matter was provided by a Swiss astrophysicist Fritz Zwicky in 1933.
- Zwicky noticed that galaxies in the Coma Cluster were moving too rapidly to be explained by the stellar material in the cluster.
- He used also a method for estimating the matter density of the Universe is the *mass-to-light ratio technique.* The average ratio of the observed mass to light of the largest possible system is used multiplied by the total luminosity density of the Universe to obtain the total mass density.
- The relative velocities of galaxies in galaxy clusters were much larger than the escape velocity due to the mass of the cluster, if that mass was estimated from the amount of light emitted by the galaxies in the cluster.
- This suggested that there should actually be much more mass in the galaxy clusters than the luminous stars we can see.

The Beginnings of the Dark Matter Problem and Rotation Curves

- For nearly four decades the *missing mass problem* was ignored, until Vera Rubin in the late 1960s and early 1970s measured velocity curves of edge-on spiral galaxies to an theretofore unprecedented accuracy.
- she demonstrated that most stars in spiral galaxies orbit the center at roughly the same speed, no matter their distance to galatic center,
- suggesting that mass densities of the galaxies were uniform well beyond the location of most of the stars.
- This was consistent with the spiral galaxies being embedded in a much larger halo of invisible mass (*dark matter halo*).

Mass-to light ratios

Mass-to light ratios

Astronomical observations of individual galaxies provide us with the **radial luminosity distribution I(R)**and the **velocities of stars** orbiting the center of the galaxy **v(R)**. From the luminosity distribution, the density of the luminous matter $\boldsymbol{\rho_l(r)}$:

$$\boldsymbol{\rho_l(r)} \;=\; -\frac{1}{\pi}\int_r^{\infty}\frac{dI}{dR}\frac{dR}{\sqrt{R^2 \;-\; r^2}}$$

R = the projected radius (as seen in the plane of the sky), r = the spatial (deprojected) radius.

From this spherical approximation to the density distribution of the galaxy, the predicted rotation curves due to this luminous matter alone can be computed as follows.

Rotation Curves

Rotation curves of galaxies. According to Kepler's third law, the velocity of a body orbiting a central mass is related to its distance as:

$$\begin{aligned} \frac{mv_l^2}{r} &= G\frac{mM(r)}{r^2} \Longrightarrow \boldsymbol{v_l} = \sqrt{\frac{GM(r)}{r}} \\ \boldsymbol{M(r)} &= 4\pi\int_0^r \rho_l(r)r^2\mathrm{d}r \end{aligned}$$

$\boldsymbol{M(r)}$= the galaxy mass enclosed within the sphere of radius r,$\boldsymbol{v_l(r)}$is represented by the sum of the contributions of gas and stars.

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

Figure : NASA/ESA Hubble Space Telescope image shows galaxy NGC 6503. The galaxy, which lies about 18 million light-years

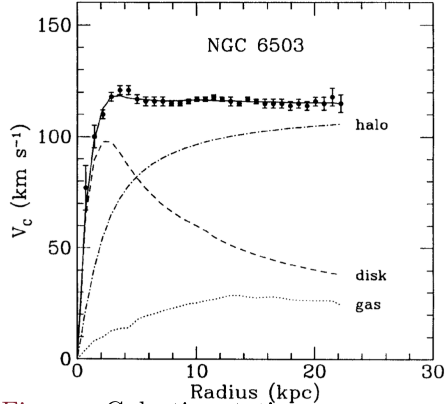


Figure : Galactic rotation curve for NGC 6503 showing disk and gas contribution plus the dark matter halo contribution needed to match the data

Conclusions

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

- **Rotation curves of galaxies are flat**. The velocities of objects (stars or gas) orbiting the centers of galaxies, rather than decreasing as a function of the distance from the galactic centers as had been expected, remain constant out to very large radii.
- The simplest explanation is that galaxies contain far more mass than can be explained by the bright stellar objects residing in galactic disks. This mass provides the force to speed up the orbits.To explain the data, galaxies must have enormous **dark halos** made of unknown **dark matter**. Indeed, large part of the mass of galaxies consists of dark matter.

Summary

Galaxies rotation curve

- Among the most compelling evidence for the existence of dark matter is the observation of the **rotational velocity** v of stars around their galaxy, as a function of their distance R from the center of the galaxy. According to Kepler's third law, this velocity is determined by the total mass $M(R)$ included within the orbit.
- If $M(R)$ became nearly constant outside R_{vis}, the visible boundary of the galaxy, there would be a decrease in the rotational velocity with the **square root of distance** from then on.
- Observation indicates, on the contrary, that $v(R)$ remains more or less **constant at large** R. This means that there is an **invisible mass halo** that extends far beyond the optical limit.
- Its **density** decreases with the square of the distance

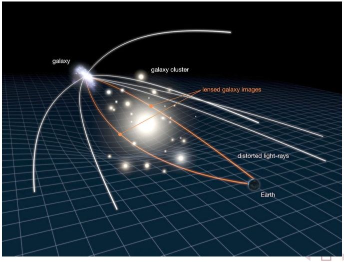
Gravitational lensing . Direct consequence of General Relativity: **trajectory of a photon is affected by the curvature of spacetime induced by the presence of a massive object (lens)**.

- **Gravitational lensing** is a formidable tool to measure the total mass of large astronomical structures, even when this mass does not emit light.
- The principle is based on the fact that light rays follow **straight lines in space-timeme distorted by the gravity of objects**. In this manner the gravity of the object in the foreground causes **multiple deformed images** of the object in the background.
- Measuring the **deformation of the image** of a galaxy behind a cluster, for example, we can calculate the **mass of the cluster in the foreground**.

- *Strong* light rays leaving a source in different directions are focused on the same spot (the observer here on Earth) by the intervening galaxy or cluster of galaxies. It produces multiple distorted images of the source from which the mass and shape of the lens can be inferred.
- *Weak* small distortions in the shapes of background galaxies can be created via weak lensing by foreground galaxy clusters. Statistical averaging of these small distortions yields mass estimates of the cluster.

Gravitational lensing

- Normal lenses bend light rays that pass through them (refraction), in order to focus the light somewhere (such as in your eye) .
- Gravitational lensing works in an analogous way: **the mass bends light**.The gravitational field of a massive object will extend far into space, and cause light rays passing close to that object (and thus through its gravitational field) to be bent and refocused somewhere else. The **more massive the object**, the stronger its gravitational field and hence the **greater the bending of light rays**. Just like using denser materials to make optical lenses results in a greater amount of refraction.

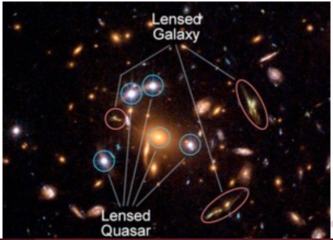


Gravitational strong lensing

- Between the Earth and the galaxies observed by astronomers is a mysterious entity called dark matter. Dark matter is invisible, but it does have mass, considerable part of the mass of the Universe.
- **Light rays** coming towards us from distant galaxies will pass through the gravitational field of dark matter and hence will be **bent by the lensing effect**.
- Abell 2218 cluster. The **real galaxies** are not this shape. .They are usually elliptical or spiral shaped. They **distorted because of lensing**.

Gravitational strong lensing

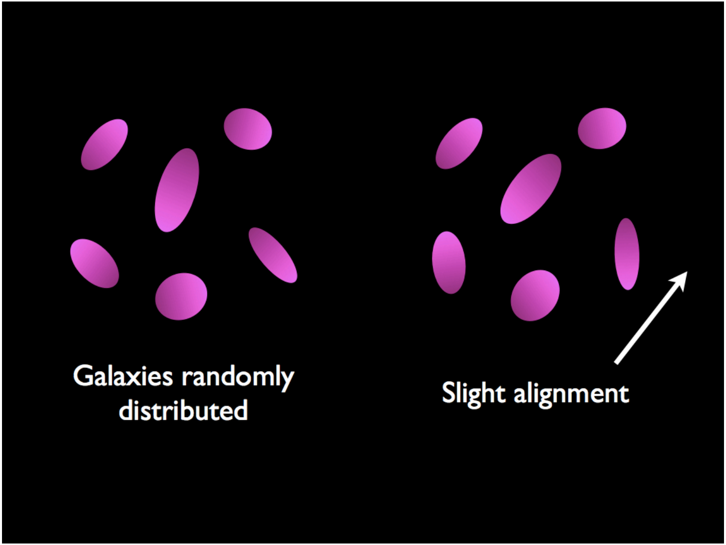
- Another effect that can occur due to lensing is the formation of **multiple images of the same galaxy**. This occurs because light rays from a distant galaxy that would otherwise diverge may be focused together by lensing.
- From the point of view of an observer on the Earth, it looks as if two very similar light rays have travelled along straight lines from different parts of the sky. Orange lines in the figure above. **More than one image of the same galaxy in different places**.
- The lensing effect is strong enough to be seen by the human eye on an astronomical image.



Gravitational weak lensing

- Most galaxies are lensed such that their shapes are altered by only 1%. Modification on image too small to be seen with our own eyes.
- Average lensing effect on a set of galaxies.
- Assumption firstly, that all galaxies are roughly elliptical in overall shape, and secondly that they are orientated randomly on the sky
- In the presence of a lensing effect, the galaxies lign themselves together slightly and their images are stretched in the same direction.
- Any deviation from a random distribution of galaxy shape orientations is a direct measure of the lensing signal

Gravitational weak lensing



Gravitational lensing

Lensing has also been used to help verify the existence of dark matter itself. The image below is known as the Bullet Cluster, and it has been observed in both optical (visible) light and in X-ray.

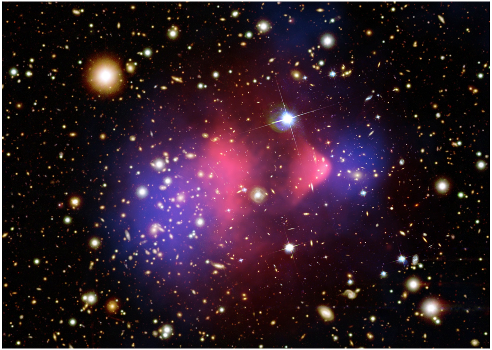


Figure : NASA Chandra X-Ray Observatory:1E 0657-56

Gravitational lensing

Another convincing indication is obtained by observing the components of the so-called **Bullet Cluster**. It consists of two colliding galaxy clusters.

- Using **gravitational lensing** and **X-ray imaging**, we can visualize the behavior of different forms of matter after a galaxy cluster collision.
- The pink part of this image is reconstructed from data of the satellite **Chandra**, observing the intensity of X-rays emitted by the cluster. This corresponds to the **luminous material density**, which shows the deformation, deceleration by friction, and the coalescence which is expected after such a **collision for ordinary matter**. Interact with each other through both **gravity and electrostatic forces**, slowing and shocking one another.

Gravitational lensing

- The blue part , on the contrary, is the **mass density** reconstructed through **gravitational lensing**.The distribution shows that the majority of the mass of the two clusters passed through the collision **without much interaction only** interact **through gravity**. It is therefore in advance with respect to the luminous mass.
- We conclude from all this evidence that **Dark Matter** accounts for about 85% of the mass of galaxies and their clusters,but this percentage can vary a lot. A recently discovered galaxy, named Dragonfly 44, is even suspected to contain 99.9% of dark matter.

Summary

Gravitational lensing

- Gravitational lensing consists in the light bending by masses.
- *Strong lensing* light rays leaving a source in different directions are focused on the same spot, producing multiple distorted images of the source → mass.
- *Weak lensing* small distortions in the shapes of background galaxies → statistical averaging mass.
- Using **gravitational lensing** and **X-ray imaging** $\Longrightarrow$ the baryonic X-ray gas particles (the *normal* matter)interacting with each other through both gravity and electrostatic forces, is slow. The dark matter particles, only interact through gravity and can pass through, without elettrostatic interactions. This means that the X-ray gas (visible matter)lags behind the dark matter, but lensing tells us that most of the mass lies further out.

Existence of Dark Matter

- It is therefore beyond doubt that **Dark Matter exists** and contributes to the confinement of matter in galaxies (and probably also to their formation). The gravitational behavior of this substance is the same as that of the luminous matter, so this is indeed a form of matter, but an unconventional one, in that it **shines no light, does not reflect nor absorb it**
- If it consists of **particles** , their properties must be the following:
  - They must be **stable on cosmological time scale**(otherwise they would have decayed by now).
  - They must be **electrically neutral**, else they would radiate light.
  - They should have evolved at **non-relativistic velocity** at the epoch of matter-radiation equilibrium. We therefore speak of **cold** dark matter.
  - They must **interact weakly** among themselves and with normal matter, otherwise the products of their reactions would be abundant.
  - Their **density** must be compatible with the **missing mass balance**.

Cosmological parameters and dark matter

The currently most accurate, if somewhat indirect, determination of Ω_{DM} comes from global fits of cosmological parameters to a variety of observations. For example, using measurements of the anisotropy of the cosmic microwave background (CMB) and of the spatial distribution of galaxies[3]. The Friedmann equations are a set of equations in physical cosmology that govern the expansion of space in homogeneous and isotropic models of the universe within the context of general relativity:

$$\sum_i \Omega_i \ + \ \Omega_\Lambda - 1 \ = \frac{k}{R^2 H^2}$$

density parameters Ω_i for the various matter species($\Omega_b$baryons, $\Omega_\gamma$photons, Ω_ν neutrinos,Ω_{DM} cold dark matter) and Ω_Λ for the cosmological constant. Hubble constant, h, (the present-day Hubble parameter being written $H_0 \ \equiv \ 100h \ kms^{-1}Mpc^{-1}$)

$\underline{\Omega_{\mathrm{tot}} \ = \ \sum_i \Omega_i \ + \ \Omega_\Lambda \ = \ 1.0002} \pm 0.0026$(from Planck Coll.)

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[3] PDG-Rev-Cosmo

when $\Omega_{\text{tot}} > 1$, k = +1 and the Universe is closed, when $\Omega_{\text{tot}} > 1$, k = -1 and the Universe is open, when $\Omega_{\text{tot}} = 1$, k = 0, and the Universe is spatially flat. From these data:

Table : Cosmological parameters

Parameter	symbol	value
Baryon density parameters	$\Omega_b h^2$	0.02226 ± 0.00023
Cold dark matter	Ω_{DM}	0.1186 ± 0.0020
Hubble constant	h	0.678 ± 0.009
Cosmological constant	Ω_Λ	0.692 ± 0.012

density parameter: Ω_b barion,Ω_{DM} dark matter,

Age universe from CMB data 13.80 ± 0.004 Gyr .

Candidate for Dark Matter

- Dark matter candidates include primordial black holes, axions, sterile neutrinos, and weakly **interacting massive particles (WIMPs)**.
- Weakly interacting massive particles (WIMPs) χ are particles with **mass** roughly between **10 GeV and a few TeV**, and with **cross sections** of approximately **weak strength**.
- These particles, if present in thermal abundance in the early universe, annihilate with one another so that a predictable number of them remain today.The relic density of these particles comes out to be the right value:

$$\Omega_\chi h^2 \; = \; (3 \times 10^{-27} cm^3/s)/ < \sigma v >_{\text{ann}}$$

Here h is the Hubble constant in units of 100 km/s/Mpc, and the annihilation cross section $< \sigma v >_{\text{ann}}$ of weak interaction strength automatically gives the correct abundance of these particles today.

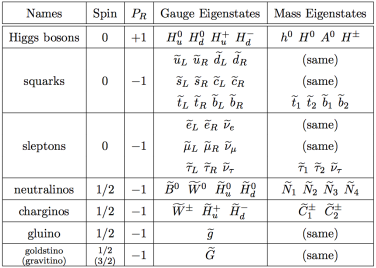
Candidate for Dark Matter: WIMP

Reason why WIMPs are taken so seriously as dark matter candidates:

1. **Annihilation cross section** $< \sigma v >_{\text{ann}}$ of **weak interaction** strength automatically gives the **correct abundance of these particles today**.
2. WIMP candidates automatically exist in models that have been proposed to resolve problems in theoretical particle physics.

SUSY theory

In the Minimal Supersymmetric Standard Model(MSSM), there are



Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \widetilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

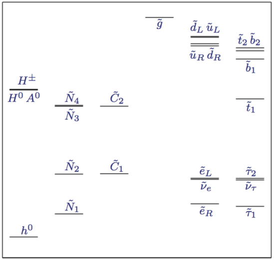


Figure : MSSM. neutralino $\tilde{N}_i = \chi_i^0$, chargino $\tilde{C}_i^\pm = \chi_i^\pm$

Figure : mSUGRA masses. Five parameter model.

The LightestSupersymmetric-Particle(LSP) is χ_1^0

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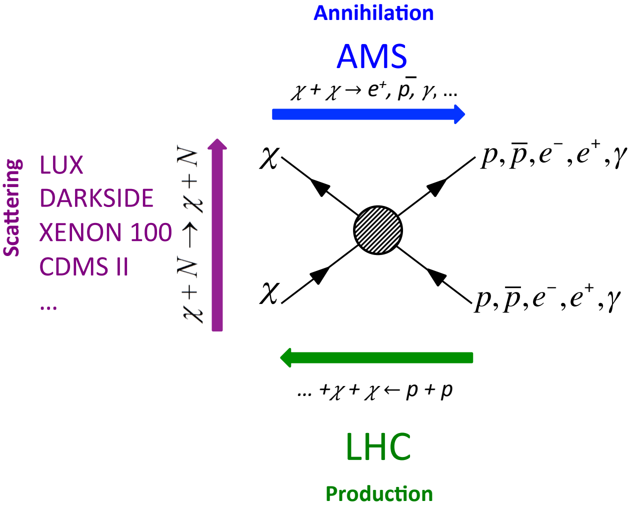
[4] S. Martin, *A Supersummetry Primer*,arXiv:hep-ph/9709356v7

Contents

Existence of Dark Matter:Research Methods

Three independent methods to search for Dark Matter



Annihilation

AMS

$\chi + \chi \rightarrow e^+, \bar{p}, \gamma, \ldots$

Scattering

LUX
DARKSIDE
XENON 100
CDMS II
...

$\chi + N \rightarrow \chi + N$

χ

χ

$p, \bar{p}, e^-, e^+, \gamma$

$p, \bar{p}, e^-, e^+, \gamma$

$\ldots + \chi + \chi \leftarrow p + p$

LHC

Production

Existence of Dark Matter:Research Methods

The main **research methods**, which attempt to identify the generic Dark Matter particle χ, are the following:

- The search for **self-annihilation** products of dark matter particles, which are their own antiparticles. Annihilation should give pairs of ordinary particles and antiparticles. This could result in a detectable signal in the energy spectra of otherwise secondary and rare cosmic rays, like positrons, antiprotons etc. This is the line of research with AMS...
- Search for **interactions** of dark matter with ordinary matter, where one looks for the recoil of a heavy nucleus. Because of the low rates and tiny recoils, this is done with cryogenic liquid noble gas detectors. his is the line of research with XENON, LUX, Darkside...
- Search for χ production at high energy colliders like the LHC, according to the profile we just showed. You will find examples of this on the CERN web site. So far this research has not identified signals, but the line is vigorously pursued by ATLAS and CMS.

Alpha Magnetic Spectrometer

AMS

Alpha Magnetic Spectrometer

5m x 4m x 3m
7.5 tons

GF ≈ 0.5 m^2sr

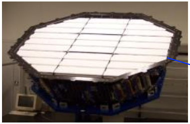
Alpha Magnetic Spectrometer

- The **cosmic ray spectrometer AMS**, installed on the International Space Station ISS for several years. searches for products of auto-annihilation between dark matter particles.
- AMS is installed in May 2011 and it is taking data since 6 years without interruption.
- The spectrometer identifies cosmic ray particles and measure their energy. It is sensitive to energies between a fraction of a GeV and several TeV. It has so far collected over **100 billion particles**, the largest sample of cosmic rays analyzed since their discovery more than 100 years ago.

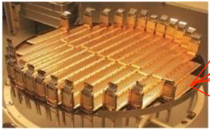
Alpha Magnetic Spectrometer

AMS: A TeV precision, multipurpose, magnetic spectrometer

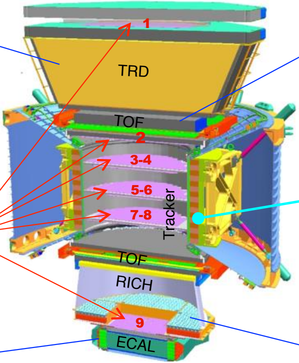
Transition Radiation Detector (TRD)
Identify e^+, e^-



Silicon Tracker
Z, P or R=P/Z



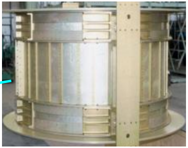
Electromagnetic Calorimeter (ECAL)
E of e^+, e^-



Z and P, E or R are measured independently by Tracker, ECAL, TOF and RICH

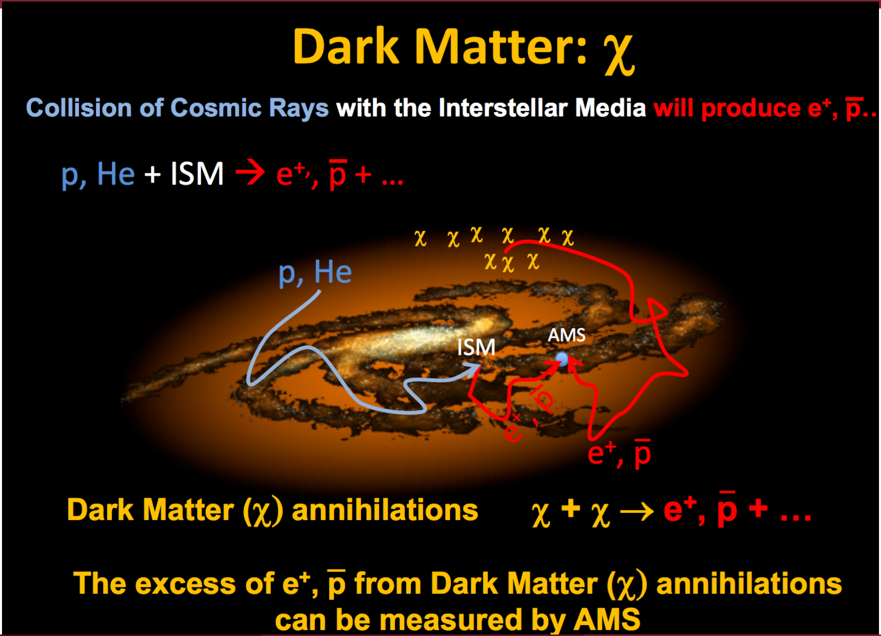
Time of Flight (TOF)
Z, E

Magnet
±Z



Ring Imaging Cherenkov (RICH)
Z, E

Dark matter interactions



Dark Matter: χ

Collision of Cosmic Rays with the Interstellar Media will produce e^+, $\bar{p}$..

p, He + ISM → e^+, $\bar{p}$ + ...

Dark Matter (χ) annihilations $\chi + \chi \rightarrow e^+, \bar{p} + \ldots$

The excess of e^+, $\bar{p}$ from Dark Matter (χ) annihilations can be measured by AMS

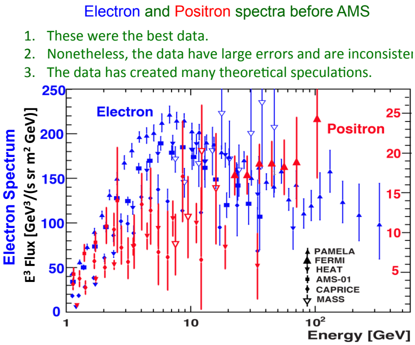
Dark matter interactions: fluxes

- A result that could be relevant for dark matter detection is the fact that beyond a few tens of GeV, the **fluxes of cosmic positrons and electrons** deviate from their normal form. This is particularly noticeable for **positrons**, antiparticles which are **rare** compared to electrons.
- This clearly indicates that there is a **new source** of electrons and positrons, with a characteristic energy of several hundred GeV. The question is whether this is a diffuse source, such as the annihilation of Dark Matter, or a localized source such as one or more pulsars close to Earth.
- These two hypothesis can be differentiated by the detection of anisotropies in the arrival direction of high energy cosmic ray electrons and positrons. A higher level of anisotropy is expected from localized near-by sources.

Electron and positron Fluxes

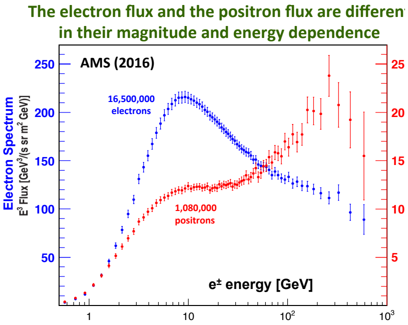
Before AMS

After AMS



Electron and Positron spectra before AMS

1. These were the best data.
2. Nonetheless, the data have large errors and are inconsisten
3. The data has created many theoretical speculations.

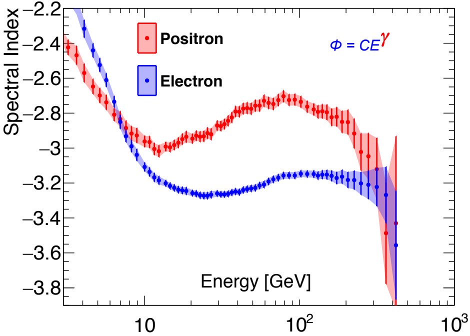


The electron flux and the positron flux are differen
in their magnitude and energy dependence

Electron and positron spectrum

Traditionally, the spectrum of cosmic rays is characterized by a single power law function $\Phi = CE^{\gamma}$ where γ is the spectral index and E is the energy.

Before AMS, γ was assumed to be **constant** for the electron and positron spectra.

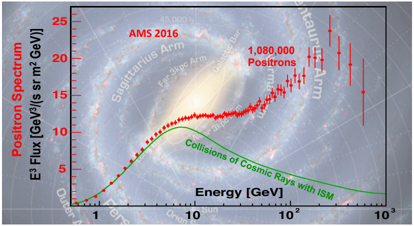


The electron and positron spectral indices are not constant.

They are different in their magnitude and energy dependence

Dark matter from positron spectrum

- Collision of Cosmic Rays with the Interstellar Media produce e^+ .... and this is indeed true at low energies.
- Annihliation of Dark Matter produce additional e^+, which are characterized by sharp drop off at the mass of dark matter.



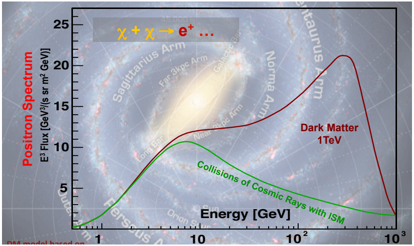
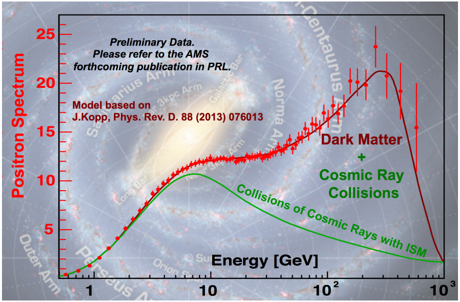


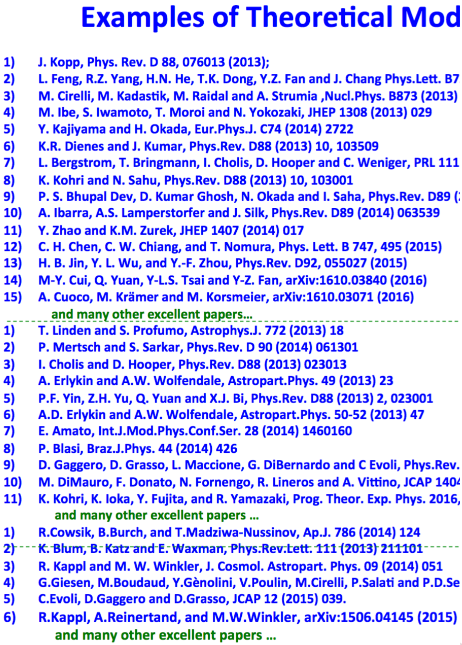
Figure : DM model based on J. Kopp, Phys. Rev. D 88 (2013) 076013

Electron and positron spectrum



The AMS positron spectrum

- Unexpectly, starting **from ∼ 8 GeV**, the AMS e^+ data show an **excess**above ordinary **Cosmic Ray** collisions.
- Something different with respect conventional model of e^+ productions by collisions of CR hadrons with interstellar matter (ISM). DM model based on J. Kopp, Phys. Rev. D 88 (2013) 076013



Examples of Theoretical Mod

1) J. Kopp, Phys. Rev. D 88, 076013 (2013);
2) L. Feng, R.Z. Yang, H.N. He, T.K. Dong, Y.Z. Fan and J. Chang Phys.Lett. B7
3) M. Cirelli, M. Kadastik, M. Raidal and A. Strumia ,Nucl.Phys. B873 (2013)
4) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
5) Y. Kajiyama and H. Okada, Eur.Phys.J. C74 (2014) 2722
6) K.R. Dienes and J. Kumar, Phys.Rev. D88 (2013) 10, 103509
7) L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper and C. Weniger, PRL 111
8) K. Kohri and N. Sahu, Phys.Rev. D88 (2013) 10, 103001
9) P. S. Bhupal Dev, D. Kumar Ghosh, N. Okada and I. Saha, Phys.Rev. D89 (
10) A. Ibarra, A.S. Lamperstorfer and J. Silk, Phys.Rev. D89 (2014) 063539
11) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017
12) C. H. Chen, C. W. Chiang, and T. Nomura, Phys. Lett. B 747, 495 (2015)
13) H. B. Jin, Y. L. Wu, and Y.-F. Zhou, Phys.Rev. D92, 055027 (2015)
14) M-Y. Cui, Q. Yuan, Y-L.S. Tsai and Y-Z. Fan, arXiv:1610.03840 (2016)
15) A. Cuoco, M. Krämer and M. Korsmeier, arXiv:1610.03071 (2016)

and many other excellent papers…

1) T. Linden and S. Profumo, Astrophys.J. 772 (2013) 18
2) P. Mertsch and S. Sarkar, Phys.Rev. D 90 (2014) 061301
3) I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013
4) A. Erlykin and A.W. Wolfendale, Astropart.Phys. 49 (2013) 23
5) P.F. Yin, Z.H. Yu, Q. Yuan and X.J. Bi, Phys.Rev. D88 (2013) 2, 023001
6) A.D. Erlykin and A.W. Wolfendale, Astropart.Phys. 50-52 (2013) 47
7) E. Amato, Int.J.Mod.Phys.Conf.Ser. 28 (2014) 1460160
8) P. Blasi, Braz.J.Phys. 44 (2014) 426
9) D. Gaggero, D. Grasso, L. Maccione, G. DiBernardo and C Evoli, Phys.Rev.
10) M. DiMauro, F. Donato, N. Fornengo, R. Lineros and A. Vittino, JCAP 140
11) K. Kohri, K. Ioka, Y. Fujita, and R. Yamazaki, Prog. Theor. Exp. Phys. 2016,

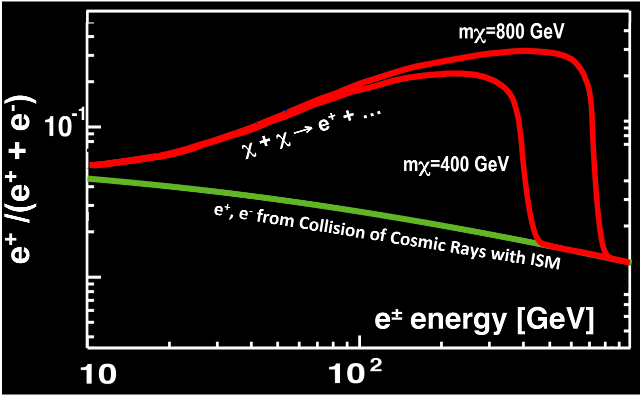
and many other excellent papers …

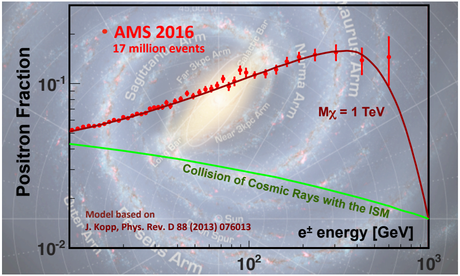
1) R.Cowsik, B.Burch, and T.Madziwa-Nussinov, Ap.J. 786 (2014) 124
2) K. Blum, B. Katz and E. Waxman, Phys.Rev.Lett. 111 (2013) 211101
3) R. Kappl and M. W. Winkler, J. Cosmol. Astropart. Phys. 09 (2014) 051
4) G.Giesen, M.Boudaud, Y.Gènolini, V.Poulin, M.Cirelli, P.Salati and P.D.Se
5) C.Evoli, D.Gaggero and D.Grasso, JCAP 12 (2015) 039.
6) R.Kappl, A.Reinertand, and M.W.Winkler, arXiv:1506.04145 (2015)

and many other excellent papers …

Dark matter from positron fraction

- The excess of positron can be also measured as **positron fraction** $\frac{e^+}{e^+ + e^-}$.
- This is an alternative method to search for signature of Dark Matter(positron spectrum and positron fraction have different errors)





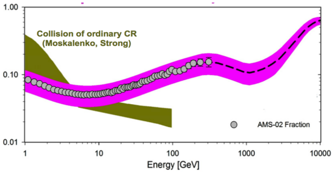
- Comparison of the positron fraction measurement with Dark matter model. DM model based on J. Kopp, Phys. Rev. D 88 (2013) 076013

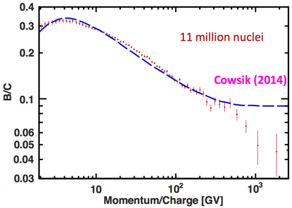
Positron Fraction Measurements

Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements:

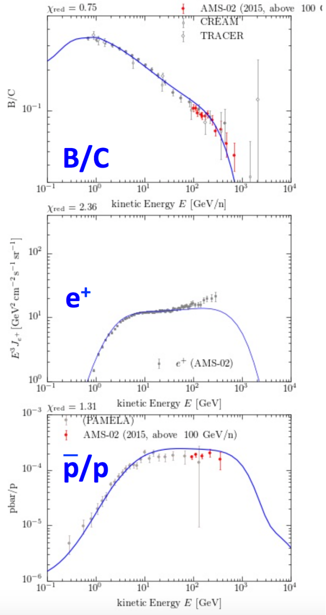
- **Modified Propagation of Cosmic Rays**
- Supernova Remnants
- Pulsars

R. Cowsik et al., Ap. J. 786 (2014) 124, (pink band) explaining that the AMS positron fraction (gray circles) above 10 GV is due to **propagation effects**. However, this requires a specific energy **dependence of B/C ratio**that is **not verified**.





Supernovae remnants



Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements

- Modified Propagation of Cosmic Rays
- **Supernova Remnants**
- Pulsars

From Subir Sarkar: AMS Days@CERN, April 2015

It sounds difficult to explain

Pulsars

Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements.

- Modified Propagation of Cosmic Rays
- Supernova Remnants
- **Pulsars**

Let's look to anti-proton.
The AMS **Antiproton-to-Proton ratio**

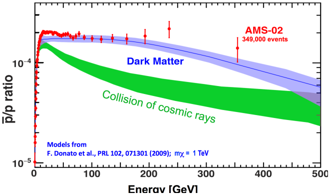
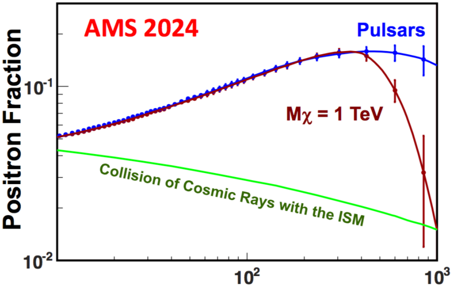


Figure : Propagation of cosmic rays

The AMS results on **antiprotons**also are in **good agreement with Dark Matter Models**

AMS on future

The AMS **Antiproton-to-Proton ratio**



- The **excess of antiprotons**observed by AMS **cannot come from pulsars**.
- By 2024, AMS will distinguish Dark Matter from pulsar with future data.

The Collaboration thus is actively fencing in Dark Matter from all sides with experimental searches. I hope to still see the Dark Matter particle