DM after LHC

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Bulk of matter in the universe is dark: about 70% of Dark Energy (DE), unknown substance creating accelerated expansion (antigravity); 25% of Dark Matter (DM), unknown invisible form of matter with normal gravitational action; 5% of usual known matter, protons, neutrons, electrons. Still directly observed is not more than half of it.

Cosmological matter content:

$\Omega_j = \rho_j/\rho_c$, where $\rho_c = 3H^2 m_{Pl}^2/8\pi = 1.88{\cdot}10^{-29}$ g/cm^3 $= 10.5 h_{100}^2$ keV/cm^3.

Before Planck and **after Planck**:

$H = 71 \pm 2.5$, $\quad H = 67.3 \pm 1.2$;
$\Omega_B = 4.5\%$, $\quad \Omega_B = 4.9\%$;
$\Omega_{DM} = 22.7\%$, $\quad \Omega_{DM} = 26.8\%$;
$\Omega_{DE} = 72.8\%$, $\quad \Omega_{DE} = 68.3\%$.

Tension between low H-value by Planck and direct measurements. New physics, e.g. light dark matter, or systematics? UGS 3789 recalibrated now down to $H = 68.9 \pm 7.1$ km/sec/Mps.

Observation of DM.

1. Flat rotational curves: $v(r)$ outside shining galaxies. Expected $v(r) \sim 1/\sqrt{r}$, observed $v(r) \to const$ up to 10 galactic radii.

2. Gravitational lensing.

3. Equilibrium of hot gas in rich galactic clusters demand 5 times more matter than it is observed.

4. Cluster evolution, $N_{cluster}(z)$.

5. Combined analysis of CMB and LSS (in particular, BAO=baryon acoustic oscillations). Distribution of visible matter has a peak at wave length corresponding to δT-maximum $\theta \approx 1^o$, i.e. to the half-wavelength 80 Mpc. Circles in the sky with radius of about 160 Mpc are expected and observed!

All different independent pieces of data agree, giving $\Omega_{DM} + \Omega_B \approx 0.3$.

Without DM life would not exist now. **Because of low $\delta T/T$ of CMB, density fluctuations at hydrogen recombination at $T \approx 3000$ K, i.e. $z \approx 10^3$, are also small, $\delta\rho/\rho \sim 10^{-4}$. Without DM $\delta\rho/\rho$ could start rising only after recombination and rose at most as the cosmological scale factor, so today $\delta\rho/\rho < 0.1$. Stars and planets could not be created by now.**
Could MOND (or any other modification) explain all the pieces of data?

Astronomical classification of DM by free streaming (FS) length:

1. If $M_{FS} > M_{gal} \sim 10^{12} M_{\odot}$ - hot dark matter (HDM). HDM dominated universe is excluded.

Example: neutrino, $m \lesssim$ eV.

2. If $m \sim$ keV, then $M_{FS} \sim M_{gal}$ - warm dark matter (WDM).

Example: sterile neutrino, if exists, or pseudogoldstone boson.

3. Cold dark matter (CDM):

$M_{FS} < M_{gal}$, plethora of candidates.

Forms of CDM:

Two types: MACHOs or WIMPs; the latter include FIMPs (feebly interacting massive particles) - never in thermal equilibrium.

1. LSP, m $\sim 10^2 - 10^3$ GeV. Not yet detected.
2. Heavy leptons, m ~ 2 GeV. 4th generation? Why long-lived?
3. Ultraheavy, quasi-stable particles, m $\sim 10^{13}$ GeV, should decay fast due to gravitational effects. Gauge symmetry (new long range forces) helps?

4. Axions, $m \sim 10^{-5}$ eV. Why CDM?
5. PBH, $M \geq 10^{16}$ g.
6. Mirror matter, "normal masses", strongly interacting and dissipating.
7. Non-topological solitons, Q-balls.
8. QCD nuggets.
9. Asymmetric DM, possibly related to baryon asymmetry.
10. None of the above.

Standard Cosmological Model:
ΛCDM, i.e. DE+CDM.

Cosmological density of CDM, thermally equilibrium and charge symmetric, according to Zeldovich (1964) or Lee-Weinberg (1977) equation:

$$\frac{n_X}{n_\gamma} \approx \frac{(m_X/T_f)}{\langle \sigma_{ann} v \rangle m_{Pl} m_X},$$

where $m_X/T_f \approx \ln\left(\langle \sigma_{ann} v \rangle m_{Pl} m_X\right)$.
For LSP: $\sigma_{ann} v \sim \alpha^2/m_X^2$ **and**

$$\Omega_X \sim (m_X/TeV)^2 .$$

Non-observation of LSP at LHC jeopardizes very natural SUSY DM.

"Heavier" SUSY WIMPs would lead to a younger universe at $T_\gamma = 2.7$ K. Is it possible to allow LSP DM with $m_{LSP} \gg$ TeV? A modification of the Standard Cosmological Model would be necessary, e.g. heavy particle production by PBH evaporation at the early stage of PBH dominance or particle production by oscillating curvature in modified gravity.
FIMPs decaying to SUSY WIMPs.
Fine-tuning is always needed.

SuperWIMPs: axino, gravitino (may be rather light), Majorana fermions with $s = \frac{1}{2}, \frac{3}{2}$.
FIMPs are e.g. RH sneutrinos or some scalar modulus. They are motivated by symmetry, e.g. SUSY+PQ for axinos and SUGRA for gravitinos, not just to solve the DM problem.

Problems with CDM.

1. Missing satellites: CDM predicts an order of magnitude more galactic satellites than observed.
2. Destruction of galactic disk: Even if the number of the satellites is reduced by star formation winds, many smaller tightly bound DM systems would survive and destroy galactic disk by gravitational heating.

3. Central cusps: expected singularity in galactic centers, $\rho_{DM} \sim r^{-\kappa}$, $\kappa = 1 - 2$, while flat profiles are observed.

4. Excessive angular momentum: CDM predicts much smaller galactic angular momentum than observed.

Possible solutions:

1. Insufficient accuracy of numerical simulation or neglected physical effects, e.g. role of baryons
2. Dissipative and self-interacting DM (e.g. mirror). Possibly does not help.
3. WDM, or better, a mixture of WDM and CDM.

Problems of cusps is possibly solved by the baryon heating of DM,
A. Pontzen, F. Governato, "Cold dark matter heats up", arXiv:1402.1764;
a review submitted to Nature on 1 Oct 2013. Accepted version scheduled for publication on 13 Feb 2014.

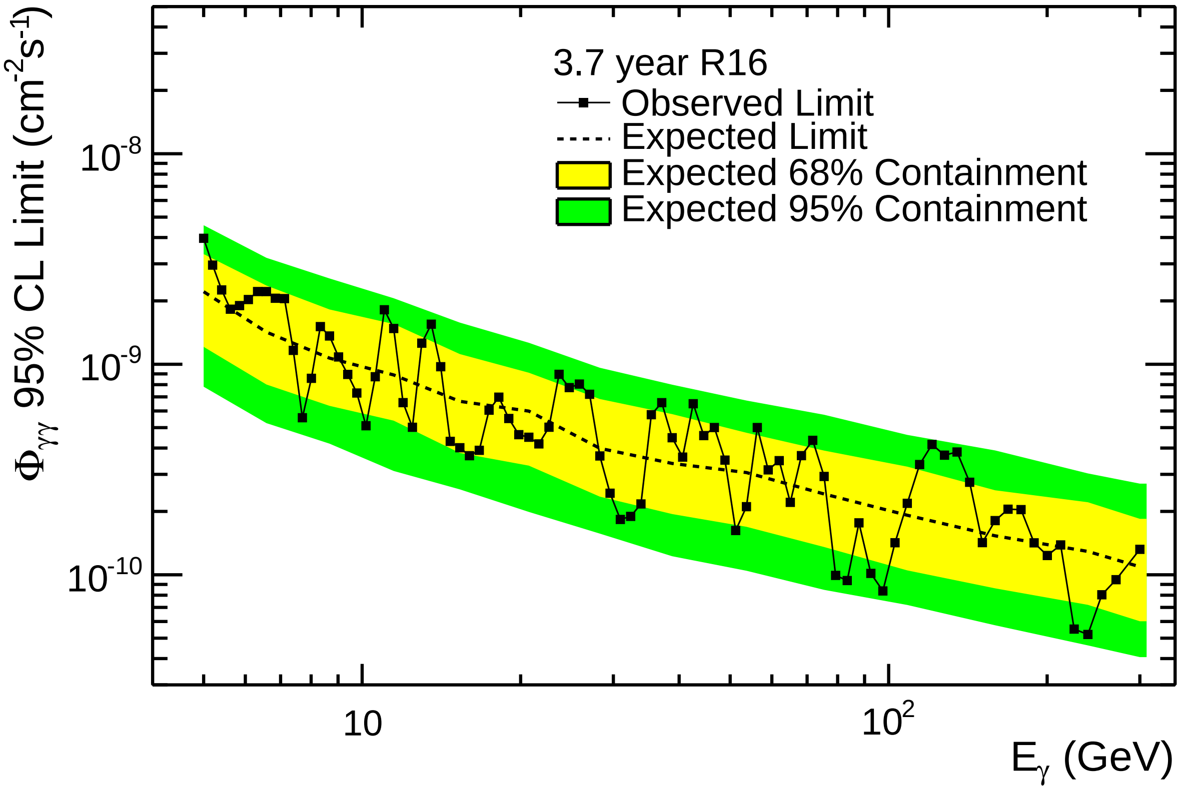
Search of DM through cosmic rays.

Decay or annihilation signals from high DM density regions: Milky Way center, other galaxies, clumps of DM, etc... FERMI-LAT (Large Area Telescope) collaboration observes an excess of 3.2 sigma (local) and 1.5 σ (global) from 5 to 300 GeV, [1305.5597].

Statistical fluctuations?

130 GeV feature disappeared?

Our most significant fit occurred at 133 GeV ... and had a local significance of 3.3 standard deviations ... We discuss potential systematic effects in this search, and examine the feature at 133 GeV in detail. We find.. the reduction in significance of the line-like feature near 130 GeV relative to significances reported in other works. ...the feature is narrower than the LAT energy resolution at the level of 2 to 3 standard deviations, which somewhat disfavors the interpretation of the 133 GeV feature as a real WIMP signal.

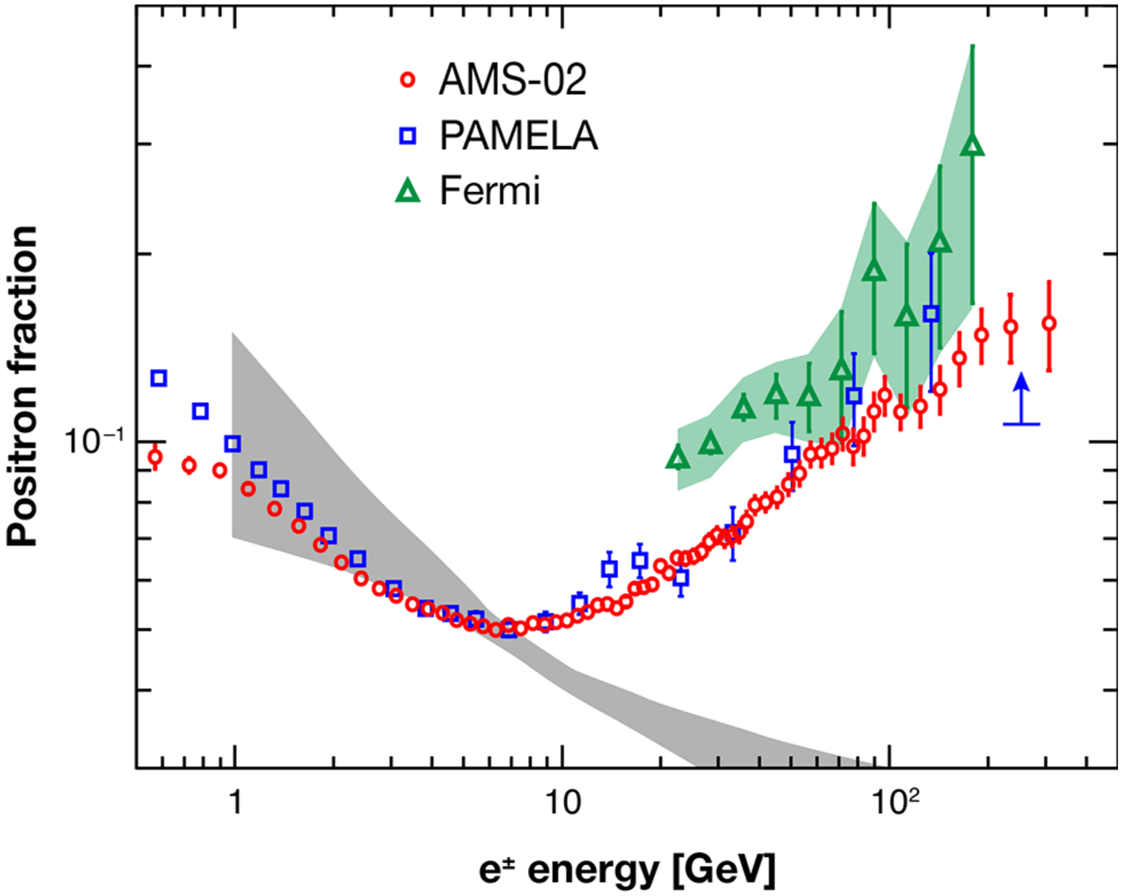

3.7 year R16
Observed Limit
Expected Limit
Expected 68% Containment
Expected 95% Containment
$\Phi_{\gamma\gamma}$ 95% CL Limit (cm^{-2}s^{-1})
10^{-8}
10^{-9}
10^{-10}
10
10^2
E_γ (GeV)

Mysterious excess of high energy positrons, discovered by PAMELA and confirmed and extended up to 350 GeV by Fermi and AMS-02. No excess of antiprotons is observed.

Pulsar or lepto-philic DM?

No convincing explanation is yet found.

One more mystery: 0.511 meV from the Galactic center. Positrons from the decay or annihilation of light dark matter?



Plot: M. Aguilar *et al*. [1]; Grey region, see Ref. [4]

Figure 1: The positron fraction in high-energy cosmic rays. The new measurement from the AMS extends over a wider energy range and has much lower uncertainty than the earlier measurements from the PAMELA and Fermi-LAT satellites (or older balloon experiments). The AMS measurement confirms an excess in the high-energy positron fraction, above what is expected from positrons produced in cosmic-ray interactions. (The grey band indicates the expected range in the positron fraction, which is based on calculations in Ref. [4].)

WIMP annihilation would shift the epoch of recombination due to influx of energy into primordial plasma and make imprints on CMB.

WMAP puts some constraints, but the sensitivity to the cross sections needed by PAMELA can be reached by Planck.

Recent positive(?) data: An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster, A. Boyarsky et al, 1402.4119. New weak line at $E \sim 3.5$ keV from the data by the XMM-Newton X-ray observatory (X-ray Multi-Mirror Mission). A possible hint to radiative decaay of sterile neutrino - WDM(?).

Two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Although the line is weak, it has a clear tendency to become stronger towards the centers of the objects; it is stronger for the Perseus cluster than for the Andromeda galaxy and is absent in the spectrum of a very deep "blank sky" dataset. Although for individual objects it is hard to exclude the possibility that the feature is due to an instrumental effect or an atomic line of anomalous brightness, it is consistent with the behavior of a line originating from the decay of dark matter particles. Future detections or non-detections of this line in multiple astrophysical targets may help to reveal its nature.

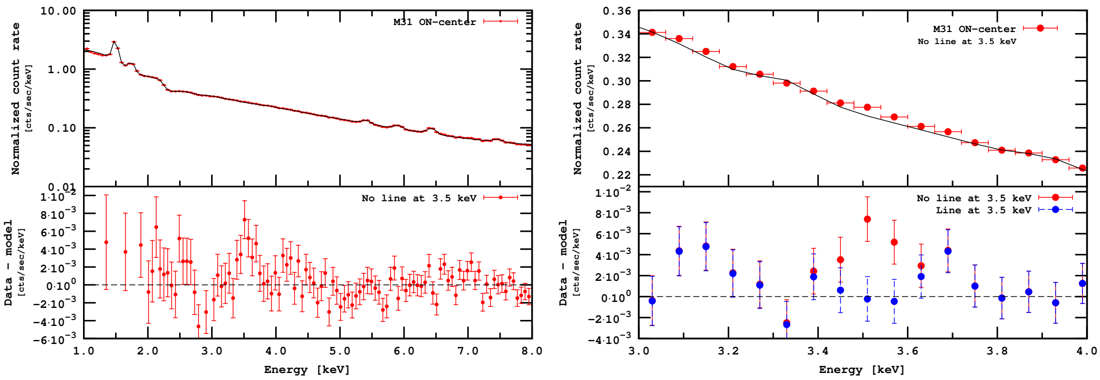


Figure 1: *Left:* Folded count rate (top) and residuals (bottom) for the MOS spectrum of the central region of M31. Statistical Y-errorbars on the top plot are smaller than the point size. The line around 3.5 keV is *not added*, hence the group of positive residuals. *Right*: zoom onto the line region.

DIRECT DETECTION.

Elastic scattering of WIMP on nuclei. The recoil energy is in the keV range:

$$\Delta E = \frac{4 m_{DM}\, m_N\, E_{DM}^{(kin)}}{(m_{DM} + m_N)^2},$$

where

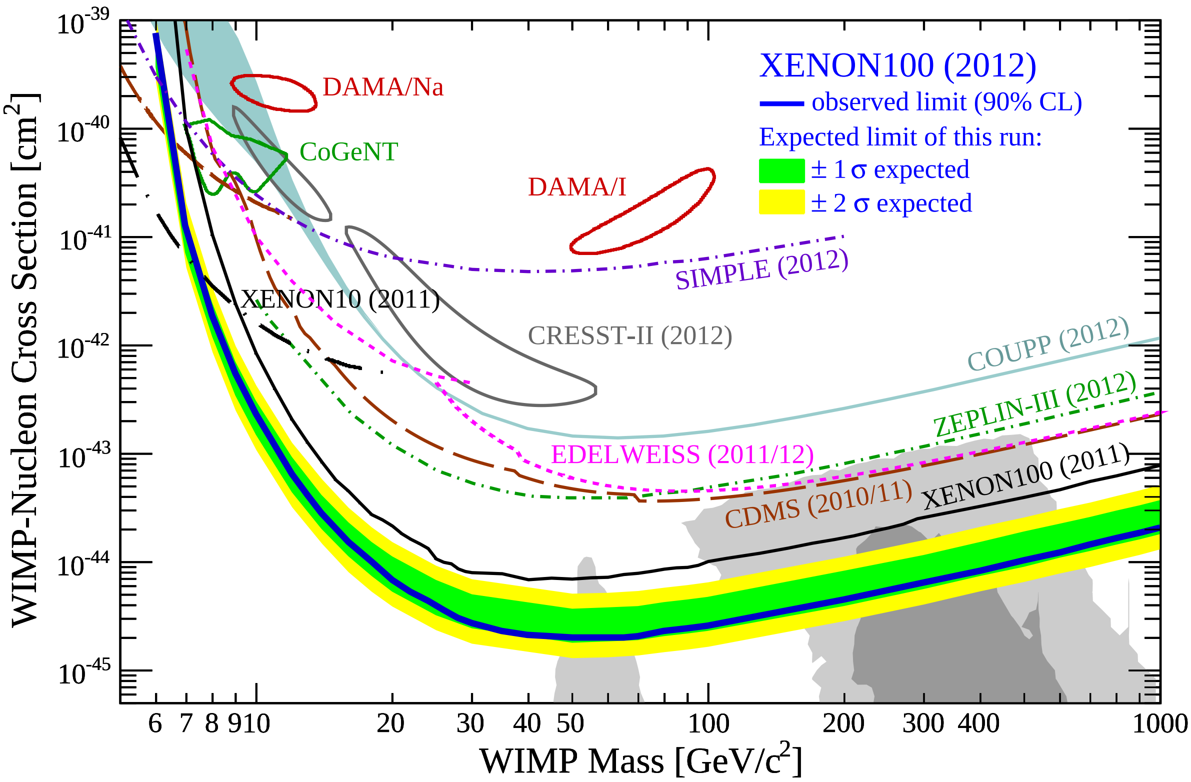
$$E_{DM}^{(kin)} = \frac{1}{2} m_{DM} V^2 \sim 50\, keV\, \frac{m_{DM}}{100\, GeV}.$$

Indications of direct detection.

DAMA/LIBRA: annual modulation 9σ.

Cogent: excess+annual modulation;
CRESST: 67 events with 38 background,
CDMS: 2 events with 0.8 background,
no annual modulation.

However, the region is excluded by XENON100 and LUX = Large Underground Xenon detector, 375 kg; lowest threshold. No events reported.



XENON100 (2012)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
CoGeNT
DAMA/I
SIMPLE (2012)
XENON10 (2011)
CRESST-II (2012)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011/12)
CDMS (2010/11)
XENON100 (2011)
WIMP-Nucleon Cross Section [cm²]
WIMP Mass [GeV/c²]

DM production at accelerators.

No signal of direct production of DM particles at colliders is yet(?) observed.

Missing energy: disappears without trace. No conclusion.

Observation by bremsstrahlung of photons or gluons from partons interacting with DM particles?

Long-lived heavy particles, observation by displaced vertices.

D. Kazakov (large overlap but different spirit) and N. Krasnikov talks today.

CONCLUSION.

Evasive Dark matter (invisible indeed). **CDM made of (quasi)stable heavy elementary particles is most natural but no detector yet confirmed that.**

What remains? or "WHAT NEXT?" **CDM: axions, PBHs...**

Warm dark matter: sterile neutrinos, ...

Exotics: "everything which is not forbidden is allowed" and even "something which is forbidden may be allowed", e.g. condensed neutrinos making HDM+CDM or something even more crazy.