Multimessenger astroparticle physics

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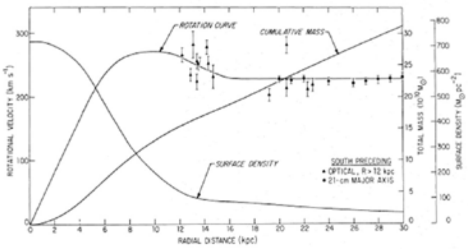
Lecture 3
The budget of energy and matter in the Universe; dark matter.

How can (V)HE photons be produced?

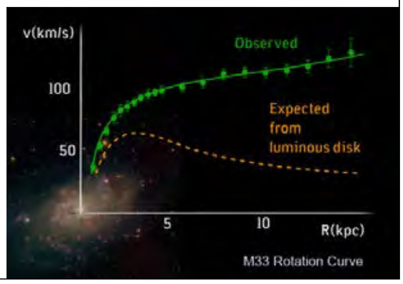
1. Interaction of accelerated charged particles with radiation and matter fields
   – The particle is accelerated via the Fermi 1st order mechanism (collective shocks with a preferred direction)
   – It undergoes purely leptonic mechanisms (electrons), or hadronic collisions (protons) with subsequent π^0 decays
2. Top-down mechanisms
   – The decay or the annihilation of a heavy particle produce unavoidably photons, either direcly or in a q-qbar chain
   – Are there reservoirs of "TeV" particles around? Unlikely unless there are new particles…

(2) Top-down: are there new (heavy) particles which can produce HE photons?

- Rotation curves of spiral galaxies



  - flat at large radii: if light traced mass we would expect them to be Keplerian at large radii, $v \propto r^{-1/2}$, because the light is concentrated in the central bulge
    - and disc light falls off exponentially
    - Zwicky had already noted in 1933 that the velocities of galaxies in the Coma cluster were too high to be consistent with a bound system
    - Observed for many galaxies, including the Milky Way



A way out

To assume that in and around the Galaxies there is

Dark Matter

subject to gravitational interaction but no electromagnetic interaction

$$M(r) \propto r \Rightarrow v_{rot} = \sqrt{\frac{GM(r)}{r}} = const.$$

- Must be "cold", i.e., non-relativistic (it is trapped by the gravitational field)
- The hypothsis is not odd: remember that the existence of Neptune was suggested on the basis of the irregular motions of Uranus
- How much DM do we need? results to be 5 times more than luminous matter (astrophysics, evolution of the Universe)

The Hubble constant and the energy density of the Universe determine the fate of the Universe

Velocity of recession

$$v = HR$$

Escape velocity

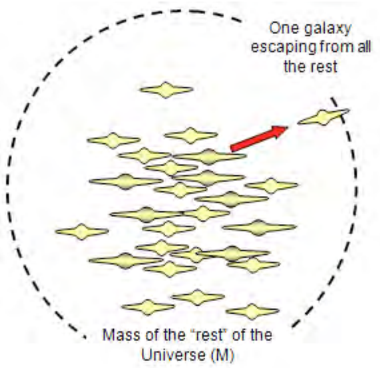
$$v_{esc} = \sqrt{\frac{2GM}{R}} = \sqrt{\frac{2G}{R}\cdot\frac{4}{3}\pi R^3\cdot\rho} = R\sqrt{\frac{8\pi G}{3}\cdot\rho}$$

Universe will recollapse if

$$v < v_{esc} \Rightarrow H < \sqrt{\frac{8\pi G}{3}\rho}$$

i.e., if

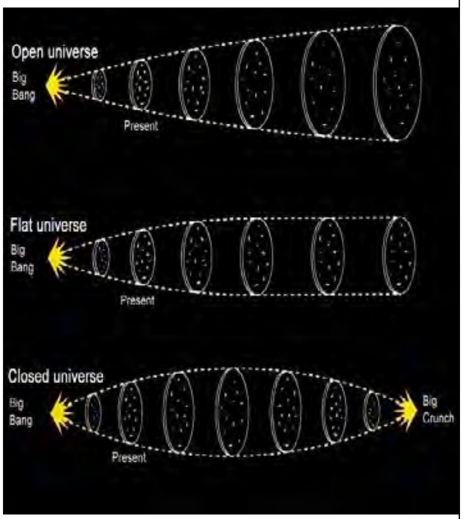
$$\rho > \rho_{crit} = \frac{3H^2}{8\pi G}$$



- Take H = 70 km s^{-1} Mpc^{-1} then:
  Critical density = $3H^2/8\pi G$ ~ 9.22×10^{-27} kg m^{-3}
  The mass of a proton is ~ 1.66×10^{-27} kg => ~6 protons per cubic meter in average

Travel into the future

- Define a "normalized density" $\Omega = \rho/\rho_{crit}$
- $\Omega < 1$: the Universe will expand forever
- $\Omega > 1$: the Universe will eventually recollapse due to the action of Gravity



What is the matter density of the Universe?

- A simple technique to measure is just to count galaxies!

Look into a dark spot with the HST for a long time, extrapolate to the full space, add some dust and some black holes…

$\Omega_B \sim \Omega_M \sim 0.05 << 1$

- You can also use some cosmological models to confirm & increase the accuracy
- And how much Dark Matter? From the motions in the Galaxies, and astrophysics

$\Omega_{CDM} \sim 0.26$

The ΛCDM model

$$H^2 - \frac{8}{3}\pi G\rho = -\frac{k}{R^2}$$

- The key CDM parameters are:

H_0 = (67.3 ± 1.2) km/s Mpc^{-1}

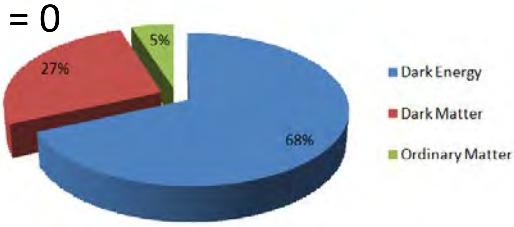
Ω_M, the matter density ~ Ω_B = 0.050 ± 0.002

Ω_{CDM}, the DM density = 0.265 ± 0.011

… (radiation, anisotropies)

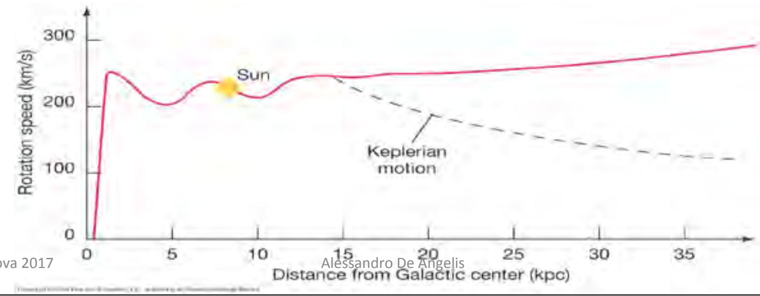
We are convinced that k = 0

$\Omega_M + \Omega_{CDM} + \Omega_r + \Omega_\Lambda = 1$



But the density of DM is much larger nearby

- 1.5 proton masses (~1.5 GeV) per cubic meter of dark matter in the Universe, so what?
- Well, there is a lot more near us…
- From the study of the rotation curve of the Milky Way, close to the solar system the density is 10^5 times larger than average: 4 10^5 proton masses/m^3
- The Earth moves in such a sea of dark matter. What is it?



What we know about Dark Matter

- Impossible to avoid if you believe that gravity is universal
  - Electrically neutral (dark, not observed in direct searches)
  - Non-baryonic (BBN, astrophysics)
  - Cold (astrophysics, structure formation)
  - "Weakly" interacting (bullet cluster, non-observation in direct searches)
  - If "weak"~ Weak at production => (very small m) or m > 45 GeV (LEP) – Both ranges have important consequences in observational astrophysics
  - Ω_{CDM} = 0.265 ± 0.011 (WMAP, Planck) ~ 5 Ω_B
- No Standard Model candidate
  - neutrinos are too light, and they are "hot" (relativistic at decoupling)
    - hot dark matter does not reproduce observed large-scale structure

➔Physics beyond the standard model

- WIMPs are particularly good candidates
  - well-motivated from particle physics [SUSY]
  - thermal production "automatically" leads to the right relic abundance

WIMPs

- WIMPs must have been in thermal equilibrium in the early Universe, when the temperature T exceeded by far the mass of the particle, $k_B T >> m_\chi$.
- The equilibrium abundance was maintained by annihilation of the WIMP with its anti-WIMP χbar into lighter particles (χ χbar → f fbar) and vice versa (f fbar → χ χbar). If the WIMP is a gauge boson as the photon, or a Majorana particle, χ = χbar.
- When at a given time t* the Universe cooled to a temperature such that $k_B T << m_\chi$, the interaction length becomes larger than the radius of the Universe (or the rate Γ for the annihilation falls below the Universe expansion rate): decoupling

$$\lambda = 1/H \Rightarrow H(t^*) = \Gamma = \langle \sigma_\chi v \rangle n_\chi \quad [\mathrm{cm}^2][\mathrm{cm/s}][\mathrm{cm}^{-3}]$$

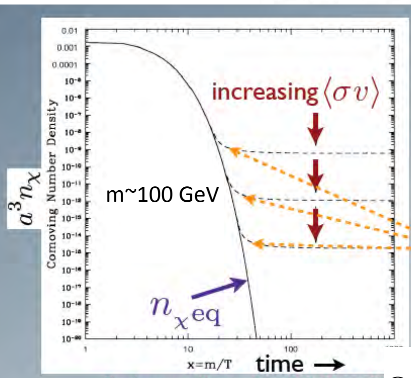


Fig.: Jungman, Kamionkowski & Griest, PR

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2 \right)$$

$\langle \sigma v \rangle$: $\chi\chi \to$ SM SM (thermal average)

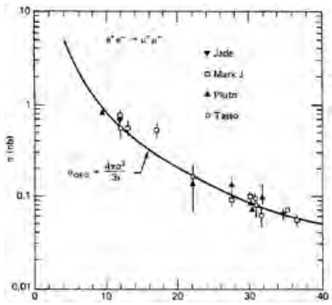
"Freeze-out" when annihilation rate falls behind expansion rate ($\to a^3 n_\chi \sim$ const.)

$$\Omega_\chi \approx \frac{3 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{<\sigma v>} \approx 0.1\ ;\ k_B T \sim \frac{m_\chi c^2}{20} \Rightarrow v \sim \frac{c}{4}$$

$$\Omega_\chi \approx \frac{3 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{<\sigma v>} \approx 0.1 \Rightarrow <\sigma v> \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

The WIMP "miracle"

- For electroweak interactions (see μμ production in ee collisions),



$$\sigma_W v \sim \frac{86.8\ \mathrm{nb}}{(E/\mathrm{GeV})^2} \frac{c}{4} \sim \frac{86.8 \times 10^{-33}\ \mathrm{cm}^2}{(E/\mathrm{GeV})^2} 3 \times 10^9 \frac{\mathrm{cm}}{\mathrm{s}} \sim \frac{3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{(E/100\ \mathrm{GeV})^2}$$

=> Weak coupling gives for free the right density at m_χ~100 GeV

In general at any time in a matter-dominated Universe (another miracle, Scherrer & Turner 1986)

Ω_χ approximately proportional to m_χ^2/M^2 for $\Omega_\chi < 1$

Beyond the Minimal SM of Particle Physics

- The SM of PP has been incredibly successful. It looks however an ad-hoc model, and the SU(3)⊗ SU(2)⊗ U(1) looks like a low-energy symmetry which is part of a bigger picture.
  - The SM looks a bit too complicated to be thought as the fundamental theory:
    - There are many particles, suggesting some higher symmetries (between families, between quarks and leptons, between fermions and bosons) grouping them in supermultiplets
      - Compositeness?
    - There are many free parameters
  - It does not describe gravity, which is the interaction driving the evolution of the Universe at large scale
  - It does not include dark matter
  - Interactions don't unify at high energy
  - The fundamental constants have values consistent with conditions for life as we know; this requires a fine tuning.
- Is there any physics beyond the SM we would need anyway and can provide "for free" DM candidates?

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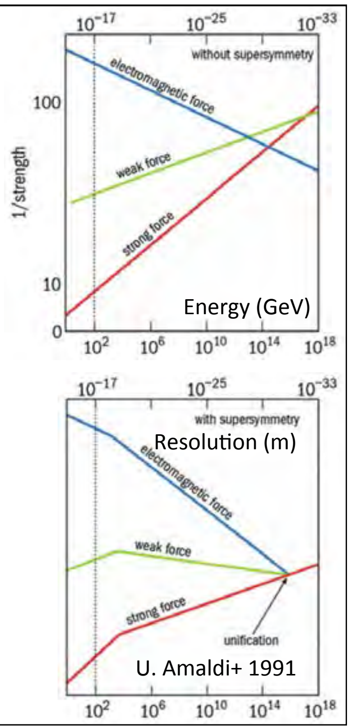
SUSY and the neutralino

- The most popular among non-minimal GUTs in particle physics is SUperSYmmetry.
- SUSY involves a symmetry between fermions and bosons: a SUSY transformation changes a boson into a fermion and vice-versa (each fermion has a superpartner which is a boson and vice-versa)
- To each particle a quantum number can be associated (R=1 for "our" particles and R=-1 for their partners). If SUSY is not violated or if it is mildly violated, R-parity is conserved, and the LSP is stable
- SUSY provides "for free" unification of forces at a scale elow the Planck scale, provided

  25 GeV < m_{LSP} < 25 TeV (90% C.L.)
- The LSP is likely one of the neutralinos χ (a Majorana fermion!)
  - Warning: there are many "SUSYs"



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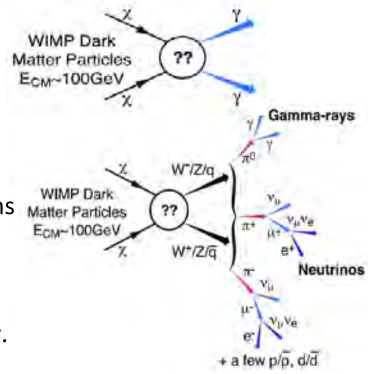
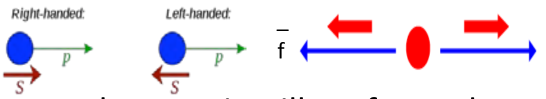
How do WIMPs produce photons?

- The energy “blob” from χχ annihilation might decay:
  - Directly into 2γ, or into Zγ if kinematically allowed. Clear experimental signature (photon line), but not very likely (requires one loop). In SUSY, the BR depends on what is the lightest neutralino composition.
  - Into a generic f-fbar pair, then generating a hadronic cascade with π^0 decaying into photons in the final state. Remind that flavors are left-handed and anti-flavors are right-handed with amplitude $[1+|p|/(E+m_f)]/2 \sim v/c$, and in this case for an s-wave you need to “force” one of the decay products to have the “wrong” elicity.

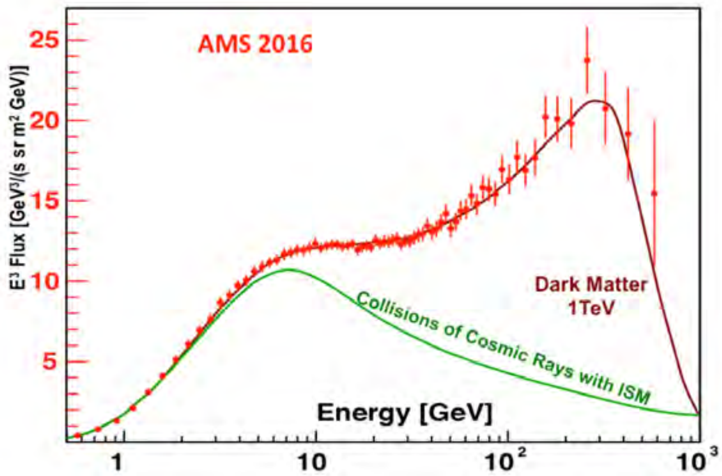




$$M_{fi} \propto \frac{1}{2}\left(1-\frac{|p|}{E+m_f}\right)=\frac{m_f}{2m_\chi+m_f}$$

=> The χχ pair will prefer to decay into the heaviest available pair – i.e., if 20 GeV < m_χ < 80 GeV, into b-bbar

WIMPs produce antimatter, too…



WISPs and other DM candidates

- WIMPs in the form of SUSY LSP are not the only possible "cold" DM candidates theoretically motivated:
  - WISPs, or weakly interacting slim particles.
    - Axions. Hypothetical light pseudoscalar postulated to explain the strong CP problem (CP should not be a symmetry of the QCD Lagrangian; however, CP appears to be conserved in QCD). A SSB at a very-high-energy scale, giving rise to an associated boson called the axion, might explain it. Being pseudoscalar (like the π^0), the axion can decay into two photons.

$$g_{a\gamma\gamma} \approx \frac{1}{M} \; ; \; \frac{m_a}{1 \text{ eV}} \sim \frac{1}{\text{M}/(6 \text{ x } 10^6 \text{ GeV})}$$

Some other consequences for cosmological photon propagation (see later in these lectures).

    - ALPs. An extension of axions, relaxing the above relation between mass and coupling.
    - Sterile Neutrinos. A neutrino which does not interact via weak interactions. Constraints form cosmology make it unlikely that they can be the main component of DM; sterile neutrinos with masses of ~ keV and above could be, with some difficulty, accommodated in the present theories.
    - Matter in parallel branes; Shadow or Mirror matter. Some theories postulate the presence of matter in parallel branes, interacting with our world only via gravity or a super-weak interaction. In theories popular in the 1960s, a "mirror matter" was postulated to form astronomical mirror objects; the cosmology in the mirror sector could be different from ours, possibly explaining the formation of dark halos. This mirror-matter cosmology has been claimed to explain a wide range of phenomena.
  - Other possible candidates:
    - Superheavy Particles. Particles above the GZK cutoff (WIMPzillas) and other gravitational monsters could have been produced in the early Universe; their presence could result in excess of CR at UHE.
- And don't forget modifications of the theory of gravitation…

Summary of Lecture 3

- If our understanding of gravity is correct, unknown ``dark'' particles populate the Universe with a density 5 times larger than ordinary matter. Their presence should manifest itself in a flux of cosmic gamma-rays (and an excess of neutrinos and anti-matter), or in any case affect the flux of cosmic gamma-rays.

Exercises

1. *Virialized systems.* A cluster of galaxies, called Abell 2715 (at a redshift z ~ 0.114), contains about 200 galaxies, each the mass of the Milky Way. The average distance of the galaxies from the center of the cluster is 1 Mpc. If Abell 2715 is a virialized system, what is the approximate average velocity of the galaxies with respect to the center? The Milky Way has a mass of about $2\ 10^{42}$ kg.
2. *M/L.* At r = 10^5 light-years from the center of a galaxy the measurement yields v_{meas} = 225 km/s while the expected velocity calculated from the luminous mass is of v_{calc} = 15 km/s. Calculate the visible and the true galaxy mass, and the ratio M/L between the total and the luminous masses. How high is the average dark matter mass density?
3. *The WIMP annihilation prefers the production of heavy fermions.* Demonstrate that, in the reaction χχ ➔ f fbar,

$$\frac{1}{2}\left(1-\frac{|p|}{E+m_f}\right)=\frac{m_f}{2m_\chi+m_f}$$

and use the above relation to compute, for a WIMP of mass of 30 GeV, the ratios of the branching fractions into τ+τ- and into b-bbar