Low Energy Experimental Astroparticle Physics

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1 Direct dark matter searches and experimental challenges

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This part of the course, "LE-EXP2" is held by Elisabetta Baracchini.

An archaic example of the search for something "dark" is given by Neptune and Vulcan.

The presence of Neptune was theorized by Le Verrier in the 1800s thanks to its influence on the orbit of Uranus. In this case, the observed anomalies were indeed caused by something "dark".

On the other hand, Le Verrier also attributed the anomalies in Mercury's orbit to a new inner solar system planet, Vulcan; however this was never observed, since the corrections were instead to be attributed to the precession induced by general-relativistic effects.

The idea behind these anecdotes is that, *a priori*, Dark Matter may very well exist, but it may also be an effect of an incomplete theory of gravity: both have happened in the past.

1.1 Evidence for dark matter

Galactic rotation curves The Keplerian velocity of test particles moving around a central mass (which is a good approximation for, say, the Solar system) looks like $v = \sqrt{GM/r}$.[1]

This is roughly what we would expect for the motion of stars at the edges of the galaxy, where little luminous mass is stored; instead of this $v \propto r^{-1/2}$ decay we observe flat rotation curves, indicating the presence of large amounts of mass even at the edges where the luminous mass fades.

This is, in a sense, the most "classic" and oldest indication of the presence of something we now call dark matter.

Galaxy clusters We can give an estimate for the mass of a galaxy cluster by measuring its *velocity dispersion* and applying the virial theorem, which can be simplified to

$$\left\langle v^2 \right\rangle \simeq GM \left\langle \frac{1}{r} \right\rangle . \tag{1.1}$$

[1] This can be easily computed, say, through the virial theorem: $2T + V = 0$, where $T = mv^2/2$ and $V = -GMm/r$.

This measurement of the mass can also be validated through other techniques: we can look at gravitational lensing, by which light is deflected by an angle

$$\Delta\phi = \frac{4GM}{bc^2} \tag{1.2}$$

to first perturbation order in GR, where b is the impact parameter.

Also, we can look at the X-ray emission by the gas in the cluster. This tells us that the average temperature is $T \sim 10\,\mathrm{keV}$.

…which we can use together with the virial theorem?

Invisible gas is not the culprit: its mass can be estimated to account for around 10 % of the total, while the observed ratio of virial mass to luminous mass is on the order of 300.

This number does not really seem to jibe with the 5 % and 25 % figures by Planck: is this a true mismatch or are we comparing things which should not be compared?

Types of gravitational lensing This is a quick aside:

1. *strong* lensing refers to the case in which a massive source deflects the light from a source behind it, which we can see as a distortion or as an Einstein ring or cross;
2. *weak* lensing refers to the combination of several minor lensing episodes in the path taken by the light from its source to us;
3. *micro* lensing refers to an episode of strong lensing in which the lens has a low mass, and there is relative motion which allows us to see a variation in the lensing. This has applications in the search for exoplanets.

Mergers of superclusters Superclusters are the largest gravitationally bound systems we observe, and we have been able to observe their mergers. Here, we can tell that the visible matter is not aligned with the gravitating matter.

Cosmic Microwave Background There are several effects impacting the multipolar decomposition of the CMB: the main ones are

1. the Sachs-Wolfe effect, in which radiation is red-shifted by coming out of an overdense region, so $-\Delta T/T \sim \Delta\rho/\rho$;
2. the Doppler effect, in which radiation is red-shifted depending on the velocity of the matter, so $-\Delta T/T \sim \Delta\rho/\rho$;
3. the Sunyaev-Zel'dovich effect, in which radiation is affected by scattering on hot electrons
4. the integrated Sachs-Wolfe effect, in which radiation goes in and out of a gravitational well, but because of the expansion of the universe it takes longer to get out than it does to get in, resulting in an overall red-shift.

We can model the dependence of the peaks in the CMB spectrum on the presence of baryonic and non-baryonic matter in the early universe, which is what allows us to get very tight constraints on these parameters.

Big Bang Nucleosynthesis BBN depends a lot on the balance between baryonic and non-baryonic matter. With it, we can look at the Universe *before* the CMB.

Hydrogen is 25 % of total matter ... ? But this does not refer to Helium.

Still, the estimated amount of baryonic matter from BBN is much lower than the total mass.

1.1.1 Modified Newtonian Dynamics

The idea is that we have never tested Newtonian gravity in a very low-acceleration regime.

MOND was developed to explain galactic rotation curves, but other phenomena are not well-explained by it. Right now, no one has made a MOND theory which can explain all the data.

These lectures will focus on DM as a *particle* which we might be able to detect.

The proposal of DM as a WIMP has been strongly questioned.

Dark Matter may:

1. not exist;
2. not be detectable — only interact gravitationally, or have very suppressed non-gravitational interaction;
3. interact with the atmosphere and therefore not reach the ground;
4. be incredibly under-dense. . .

However, the WIMP hypothesis is not completely ruled out. There is a region in the parameter space we have not explored yet.

Also, developing the instruments used to search for DM is useful for other areas of physics as well.

1.2 Dark Matter candidates

The things we know about it (if it is a particle) are, roughly:

1. it is non-baryonic;
2. it is dark (does not interact with electromagnetic radiation) and neutral;
3. it is stable, or it has a lifetime which is long compared to the age of the universe;
4. it is, at most, weakly interacting;
5. it is either cold or warm, not hot;

6. we have data about its abundance.

Are there any SM candidates? The obvious candidate is the neutrino; however given the limits we have on their mass we have put limits on their relic density ($\Omega_\nu h^2 \lesssim 0.07$).

This is just one among the many known problems with the Standard Model.

Therefore, we look for candidates beyond the standard model. There is a whole "zoo" of candidates. A convenient way to plot these is on a cross-section versus mass log-log plot.

Some interesting candidates are those which come from other fields: for example, the axion emerged as a solution for the strong CP problem.

1.3 Weakly interacting massive particles

The assumption is that there was no dark matter asymmetry in the early Universe, but two DM particle can annihilate into two SM particles.

The freeze-out mechanism is crucial for the *WIMP miracle*: The decoupling happens when we start to have $\Gamma \lesssim H$.

In the hot, early Universe we have thermal equilibrium between SM and DM particles; then the Universe started to cool, and we only had decay of DM particles into SM ones; then finally both channels decoupled.

Changing the annihilation strength changes the resulting abundance. As we increase the annihilation strength, we decrease the resulting abundance.

There is a quantitative way to discuss this with the Boltzmann equation, the resulting equation is

$$\Omega_X \propto \frac{1}{|\sigma v|} \sim \frac{m_X^2}{g_X^4}\,. \tag{1.3}$$

The "miracle" is that to get the observed density we need to have an interaction on the order of the weak scale, on the order of $\sim 100\,\mathrm{GeV}$.

The SM itself is an effective theory, and it needs new physics at the $\sim$ TeV scale. Supersymmetry provides DM candidates, as well as solving this problem.

Supersymmetric models are many, and they have many parameters.

We also have Universal Extra Dimensions theories. Here gravity propagates in $3+1+n$ dimensions, reconciling the difference between the electroweak and the Planck scale.

The compactification of these dimensions happens in "Kaluza-Klein towers". Here we also get DM candidates.

In the next lecture we will give a quick introduction to axion-like dark matter (Weakly Interacting Slim Particles), but a more complete overview will follow in the last lecture of the course. Thursday

The name "axion" comes from a brand of detergent. 2021-11-11

$$\mathscr{L}_{\mathrm{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_q \overline{q} \Big(i\gamma_\mu D^\mu - \mathcal{M}_q \Big) q + \underbrace{\frac{\theta g^2}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}}_{\text{CP - violating}}\,. \tag{1.4}$$

The CP-violating term is allowed in the QCD Lagrangian, but we do not experimentally observe it: $\bar{\theta} < 10^{-10}$.

This term would give an electric dipole moment to the neutron

$$|d_n| = \frac{e m_u m_d}{(m_u + m_d) m_n^2} \bar{\theta}, \tag{1.5}$$

What is the barred theta?

Why is this CP-violating phase so ("unnaturally") small?

The Peccei-Quinn mechanism promotes this phase to a dynamical field a, with its own kinetic term $\partial_\mu a \partial^\mu a / 2$,

If we define the dimensionless parameter $\theta = a / f_a$, this is minimized for $\theta_{\text{eff}} = \theta + \langle a \rangle / f_a$.

This field is driven to 0 under the spontaneous breaking of a new global $U(1)$ symmetry.

If we assume the SM gauge group, the mass of this axion will be on the order of the μeV.

This axion may couple to photons, or to gluons, or to fermions. The photon coupling would allow for a $a \to \gamma\gamma$ process.

2 WIMP-like DM experimental detection

What may DM couple to?

1. nuclear matter (quarks, gluons)?
2. leptons (electrons, muons, taus, neutrinos)?
3. photons, or other W, Z, h bosons?
4. other dark particles?

We don't know, so we try them all. We must do it in different contexts, both astrohysical and from particle physics.

Consider the Feynman diagram for a process $\chi\chi \leftrightarrow qq$, where q means "quark" but it could be substituted for any SM particle really. We can look at

1. efficient annihilation now: $\chi\chi \to qq$, so indirect detection (in the sky);
2. efficient scattering now: $\chi q \to \chi q$ (underground);
3. efficient production: $qq \to \chi\chi$ (in particle colliders).

In particle colliders a χ may be produced, but it would be among a huge amount of other things. There, the particle physics people also must do trigger selection, so they may lose DM.

Particle detectors measure the energy of the final state particles with calorimeters, as well as their momentum and trajectory with a tracking detector equipped with a magnetic field.

An explanation of the characteristics of ATLAS and CMS. Neutrinos are indirectly measured by the missing energy.

Why are the uncertainties reported as $\sigma(E)/E \sim x\%/\sqrt{E}$?

Conservation of energy does not really work, since the quarks are moving around inside the protons, while the conservation of transverse momentum can be used.

Search paradigms include:

1. mono-X searches, a SM particle recoiling against nothing;
2. mediator searches, a DM particle acting as a mediator, so it yields a bump in the mass spectrum of SM particle pairs;
3. Higgs portal: if DM couples to it, a Higgs can decay into DM.

Several model-dependent bounds have been given, most of which are below 1 TeV.

Indirect DM searches involve DM particles annihilating into SM particles somewhere in the universe, and these SM particles are then detected by us.

Photons: large background from astrophysical sources; protons/positrons: deviated by magnetic fields, and we don't know the background; neutrinos: too small cross-section…

The "inverse problem" problem…

The parameter space for DM searches is very large, so…

2.1 Direct DM searches

Detect the DM bumping into something we can see.

The Solar System is moving towards the Cygnus constellation. Therefore, we expect to see an apparent wind of DM in that direction.

Cygnus is *in our galaxy*, though!

Do we expect larger mean distances between particles if they are heavier?

Our signal is WIMPs bumping into nuclei, with recoil velocity $v/c \sim 7 \times 10^{-4}$, and recoil energy $E_R \sim 10\,\text{keV}$.

Our background is both electromagnetic (photons bumping into nuclei) and neutral (neutrons or neutrinos bumping into nuclei).

The expected rate is

$$R = N_N \phi_0 \sigma_{WN} = \frac{N_A}{A} \frac{\rho_0}{m_W} \langle v \rangle \sigma_{WN} \,, \tag{2.1}$$

where $\rho_0 \approx 0.3\,\text{GeV/cm}^3$ is the local DM density, the mean velocity is $\langle v \rangle \approx 220\,\text{km/s} \approx 0.75 \times 10^{-3} c$, but the cross-section is $\sigma_{WN} \lesssim 10^{-38}\,\text{cm}^2$.

Therefore, we get $R \sim 0.13$ events per kg per year.

The interaction rate is very low, while backgrounds are very high.

A single banana, on the other hand, yields $\sim 100\,\text{events/kg/s}$, or about a billion times more.

Calcare is “limestone”

Environmental natural radioactivity is a mess. At LNGS we have more γs than at Boulby in the UK, because that is a salt mine.

Why is the neutron flux reported as single data points?

We need to shield the detector from all possible backgrounds.

The chain is α easier to block then β, then γ (where we need steel plates), then finally neutrons (for which we need a water tank).

This is because hydrogen has the best kinematic match: same-mass moderators for neutrons are the best.

Roman lead! the production process makes lead radioactive, but if it was produced 2000 years ago we are fine.

Another approach is to have active shielding: have detectors which are sensitive to backgrounds around the detector, and then actively remove the background.