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 $T \sim 10\,\text{keV}$. We can use this together with an assumption of hydrostatic equilibrium, which yields a relation in the form

$$k_B T \approx (1.3 \div 1.8)\text{keV}\left(\frac{M_r}{10^{14}\,\text{M}_\odot}\right)\left(\frac{1\,\text{Mpc}}{r}\right), \tag{1.3}$$

to estimate the mass.

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. ASKED

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, and also dark matter may:

1. not exist;
2. not be detectable, meaning that it only interacts gravitationally, or it has very suppressed non-gravitational interactions;
3. interact with the upper atmosphere and therefore never 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 (meaning that its interaction cross-section is at most at the weak scale);

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 abundance of dark matter, as measured with the density rescaled by the entropy $Y = n/s$, at infinity (so, now) reads

$$Y_\infty = \sqrt{\frac{45G}{\pi g_*}} \frac{1}{T_F} \frac{1}{\langle \sigma_{\text{ann}} v \rangle}\,, \tag{1.4}$$

where g_* is the effective number of degrees of freedom computed at freezeout, G is Newton's gravitational constant, T_F is the temperature at freezout, while σ_{ann} is the cross-section for the annihilation of these DM particles.

The resulting abundance, as measured with $\Omega_X = \rho_X/\rho_c$ (where $\rho_c = 3H^2/(8\pi G)$ is the critical density for the universe), is

$$\Omega_X \propto \frac{1}{|\sigma v|} \sim \frac{m_X^2}{g_X^4}\,. \tag{1.5}$$

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 $\sim 100\,\text{GeV}$.

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 2021-11-11

The name "axion" comes from a brand of detergent.

$$\mathscr{L}_{\text{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_q \bar{q}\left(i\gamma_\mu D^\mu - \mathcal{M}_q\right) q + \underbrace{\frac{\theta g^2}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}}_{\text{CP - violating}} . \tag{1.6}$$

This term would give an electric dipole moment to the neutron

$$|d_n| = \frac{e m_u m_d}{(m_u + m_d) m_n^2} \bar{\theta} , \tag{1.7}$$

where $\bar{\theta} = \theta + \arg\det \mathcal{M}$, $\mathcal{M}$ being the quark mass matrix.

The CP-violating term is allowed in the QCD Lagrangian, but we do not experimentally observe it: $\bar{\theta} < 5 \times 10^{-11}$ [CEM21] (see also Kolb and Turner [KT94]).

The neutron dipole moment is bounded at a 90 % CL by $|d_n| < 1.8 \times 10^{-26}\,\text{cm}\ e$ [Gro+20] (as opposed to the older value $|d_n| < 2.9 \times 10^{-26}\,\text{cm}\ e$ quoted in the lecture). Using the PDG values for the quark masses [Gro+20]: $m_u \approx 2.16\,\text{MeV}$, $m_d \approx 4.67\,\text{MeV}$, and the neutron mass $m_n \approx 939.57\,\text{MeV}$, we get

$$\frac{m_u m_d}{(m_u + m_d) m_n^2} \approx 1.67\,\text{MeV}^{-1} \approx 3.30 \times 10^{-17}\,\text{cm} . \tag{1.8}$$

Computing this value does lead to the correct result: it is off by an order of magnitude. Chadha-Day, Ellis, and Marsh [CEM21] report $|d_n| = 3.6 \times 10^{-16} \bar{\theta} e\text{cm}$, while this computation yields 3.3×10^{-17}!
Computing the ratio between the two, using the formula given in the slides, yields $\bar{\theta} \leq 5 \times 10^{-10}$.

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.

We can look at it from different angles:

1. efficient annihilation: $\chi\chi \to qq$, so indirect detection (in the sky);
2. efficient scattering: $\chi q \to \chi q$ (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 easily miss DM even if they do produce it.

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. In detectors such as ATLAS or CMS, neutrinos are indirectly measured by the missing energy.

> The relative uncertainty in the energy measurement of calorimeters is typically proportional to $1/\sqrt{E}$, therefore the accuracy is reported as $\sigma(E)/E = x\%/\sqrt{E/\mathrm{GeV}}$, often shortened to $\sigma(E)/E = x\%/\sqrt{E}$.

Conservation of energy does not really apply, since the quarks are moving around inside the protons before the collision, 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.[2]

Indirect DM searches involve DM particles annihilating into SM particles somewhere in the universe, which we can then detect. This is a good idea in principle, but many candidates have their own issues. Photons point to the source, but they lose energy in the ISM if they scatter, and we have a large background of them from astrophysical sources. Protons and positrons are deviated by magnetic fields therefore we cannot assign them a direction, and we don't accurately know their background level. Neutrinos have a very small cross-section, and while they do point back to the source their directions are hard to determine; also, there is a large neutrino background.

The inverse problem problem It is easy for new data to be modelled as a detection of DM, since we know very little about DM, even if it is actually just background.

2.1 Direct WIMP-like DM searches

The idea is to detect the dark matter particle "bumping into" something we can see, which is typically a nucleus.

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

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

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

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 $\sim 100\,\mathrm{events/kg/s}$, or about a billion times more.

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

We need to shield the detector from all possible backgrounds.

[2] One can find many of these plots at https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV.

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.

Monday
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Using pure germanium spectrometers allows one to not have a radioactive detector.

The bigger the detector, the more radioactivity one has to worry about.

We see a PMT sample's spectrum from the XENON collaboration.

We can have radiogenic or cosmogenic activation of the detector. Even if we go under the mountain, some cosmic ray flux remains, which can produce neutrons by spallation (this is cosmogenic). We can also have radiogenic activation: if there is a radioisotope left in our detector it can produce some new neutrons and α particles.

The typical lifetime of a detector is mostly spent trying to minimize its radioactivity.

We also have RPRs, radon progeny recoils: radon has a decay chain producing both α and β particles. Radon is in the air, and the polonium it produces gets stuck to the detector.

If the α decay happens at the edge of the detector, the polonium can escape it, leaving only the α particle inside it, which mimicks a DM signal.

The way to avoid this problem is *fiducialization*: using only signals coming from far away from the wall of the detector (in a "fiducial region"). In order to do this, we need 3D localization of each event.

Another evil background is that given by neutrinos from the Sun. These typically come from the pp chain:

$$\mathrm{p} + \mathrm{p} \to {}^2\mathrm{H} + e^+ + \nu_e \tag{2.2}$$

$$\mathrm{p} + e^- + \mathrm{p} \to {}^2\mathrm{H} + \nu_e\,, \tag{2.3}$$

and more.

Neutrino interactions will look just like the ones we are looking for, and there is no way to shield from them. We also have a diffuse SN neutrino background, as well as atmospheric neutrinos.

Experiments are currently getting close to the sensitivity at which this becomes an irreducible background. This is called the **neutrino floor**.

At GeV to TeV WIMP masses, the main contributions are neutrinos from Boron or Beryllium.

One can look at the differences between the spectrum of energy from these neutrinos, but we need a lot of statistics for this.

Another approach is to look at the directionality: fortunately, Cygnus (from which we expect DM to be coming) never overlaps with the direction of the Sun.

The event rate per unit energy reads

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = N_N \frac{\rho_0}{m_W} \int [v_{\min} < |\vec{v}| < v_{\max}]\, \mathrm{d}\vec{v}\, f(\vec{v}) v \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}\,, \tag{2.4}$$

where ρ_0 is the local DM density, while m_W is its mass; $\vec{v}$ is the velocity of the DM, and we can compute

$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}}, \tag{2.5}$$

where μ_N is the reduced mass of the interaction. This is the minimum velocity needed to produce a recoil with energy $\geq E_R$.

The local DM density and its velocity distribution come from astrophysics. We expect the DM halo to extend much further than the galactic disk.

Exclusion limits are traditionally computed setting $\rho_0 = 0.3\,\mathrm{GeV/cm^3}$, which is roughly the mean of our estimates, which are however rather uncertain, ranging from 0.2 to 0.56.

On average the halo is stationary, not corotating with the galactic center. Its velocity distribution is typically modelled as a Maxwellian, with $\sigma \sim \sqrt{3/2} v_e$, where v_e is the escape velocity for the galaxy.

We must also account for the motion of the Sun around the galaxy (which is written in terms of a "local standard of rest"), and the Earth's motion around the Sun.

We have knowledge of large-scale DM distribution, but it could be non-smooth on the milliparsec scale! The Gaia survey suggested the presence of *streams*...

The DM-nucleus cross-section $\mathrm{d}\sigma/\mathrm{d}E_R$ is not known. The order of magnitude of the momentum transfer can be used to estimate it, through $\lambda \sim \hbar/p \gtrsim r_0 A^{1/3}$.

In an effective field theory approach, we can write a Lagrangian like

$$\mathscr{L}_{\text{eff}} = \frac{1}{\Lambda^2} (\widetilde{\chi} \Gamma_{\text{dark}} \chi) \left(\widetilde{\psi} \Gamma_{\text{vis}} \psi \right). \tag{2.6}$$

We will have scalar-scalar, vector-vector interactions which are spin-independent, and enhanced by a factor A^2...

With these assumptions, we can write an expression like

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} \sim \frac{2 m_N A^2 (f^p)^2}{\pi v^2} F^2(E_R) \tag{2.7}$$

$$F^2(E_R) = \left(\frac{3 j_R q R_S}{q R_1} \right)^2 \exp\left(-q^2 s^2 \right) \tag{2.8}$$

for the spin-independent contribution.

The spin-dependent contribution is proportional to $J(J+1)$, which is nonzero only if there is an unpaired nucleon.

The important parameter is A^2 for the spin-dependent interaction.

The final term is the kinematic one. The scattering is very much nonrelativistic, since $m_W \sim 10\,\mathrm{GeV} \div 1\,\mathrm{TeV}$; the typical velocity of such a nucleus is $v \sim 220\,\mathrm{km/s} \sim c/1400$.

The recoil energy is therefore

$$E_R = \frac{p^2}{2 m_N} = \dots . \tag{2.9}$$

The kinematics of the process means that heavier nuclei cross-sections are suppressed with respect to lighter ones as the energy rises, even though the curves are higher overall because of the A^2 enhancement.

This law would be a strong confirmation that what we are looking at is indeed a DM signal.

The signal is a decaying exponential; but the background is also a decaying exponential. This poses a large problem for identification.

A more robust signature would be the temporal dependence of the rate: our velocity with respect to the center of the galaxy is modulated as we go around the Sun. This will yield a law like

$$\frac{\mathrm{d}R}{\mathrm{d}E} = S_0(E) + S_m(E)\cos\left(\frac{2\pi(t-t_0)}{T}\right). \tag{2.10}$$

DAMA claimed to have seen this kind of signal, but there might be another explanation.

The rotation around the Earth's axis also changes the apparent direction of Cygnus.

We can write a distribution depending on the direction of nuclear recoil:

$$\frac{\mathrm{d}R}{\mathrm{d}E\,\mathrm{d}\cos\gamma}. \tag{2.11}$$

This directional asymmetry is a tool to have a true, positive identification of dark matter.

If we measure the event rate, we can give a plausible region of m_W and $\mathrm{d}\sigma/\mathrm{d}E_R$.

In order to go to low DM mass we need light nuclei and a low threshold, in order to go to high DN mass we need heavy nuclei and large exposure (integration time).

We can also use the material response to a signal to figure out what it is: we can detect *charge* (ionization), *light* (scintillation) and *heat* (phonons).

DM will scatter only once, neutrinos as well. Neutrons might scatter more than once, which allows one to throw them out.

The distribution of energy between the three channels is a possible path for event discrimination.

A nuclear recoil will mostly produce heat, while an electron will mostly yield ionization. The ratio between the visible energies is known as the Quenching Factor:

$$\mathrm{QF} = \frac{E_{\mathrm{visible}}(\mathrm{keV}ee)}{E_{\mathrm{visible}}(\mathrm{keV}r)}. \tag{2.12}$$

Experiments can be then classified in terms of the three detection channels.

2.1.1 Scintillation-based detectors

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DM experiments are classified by which signals they are sensitive to. We start with experiments able to detect light: scintillating crystals and liquid noble-gas detectors.

The idea is that the energy lost as $\mathrm{d}E/\mathrm{d}x$ is converted into visible light, which is then detected with photo sensors (such as photomultipliers). The human eye was also historically used.

Is the claim "the human eye is sensitive to a single photon" true?

We hope that our detector is efficient in the conversion of excitation energy to fluorescent radiation, that it is transparent enough to the emitted light (the Stokes shift is the one between the absorption peak and the emission peak, we'd like this to be large).

The decay time should also be short, so that we have a short response time.

Photo multipliers The photomultiplier includes a photo cathode, where light releases an electron through the photoelectric effect; this electron is then accelerated towards a dynode and moves forward to generate secondary emission on successive dynodes.

The quantum efficiency is not very large: typically on the order of 10 % to 30 %.

Silicon photomultipliers are arrays of avalanche photodiodes in Geiger-Muller regime: they include a p-n junction, which has a depletion region. In this depletion region charges are free and subjected to an electric field, therefore it can be used as a radiation detector.

PMTs can be quite large, while SiPMs are typically small — 1 cm of diameter is already on the large side.

A comparison of PMTs and SiPMs follows.

Include this from the slides.

SiPMs are quite noisy if they are not cooled.

We measure the quantity

$$\mathrm{PDE} = \mathrm{FF} \times \mathrm{QE} \times \mathrm{AP}\,, \tag{2.13}$$

the product of the Filling Factor, the Quantum Efficiency and the Avalanche Probability.

Scintillators There is *quenching*: highly ionizing particles create defects in the atoms or molecules in the medium, thus resulting in quenching.

The emitted light per unit length reads

$$\frac{\mathrm{d}L}{\mathrm{d}x} = \frac{S\,\mathrm{d}E/\mathrm{d}x}{1 + kB\,\mathrm{d}E/\mathrm{d}x}\,, \tag{2.14}$$

where k is the quenched fraction, while B is called the Birks constant. This is called Birks' law.

In certain scintillators we have a two-exponential decay:

$$N(t) = A\exp\left(-\frac{t}{\tau_f}\right) + B\exp\left(-\frac{t}{\tau_s}\right). \tag{2.15}$$

In principle we can do particle identification through *pulse shape analysis*, figuring out A and B in the aforementioned formula.

For DM searches, we typically use either liquefied noble gases or inorganic crystals. Liquefied noble gases have a high yield, a fast response. We can do pulse shape discrimination with them.

However, the light they emit is typically UV. We need ways to shift their wavelengths to detectable ones.

They are very sensitive to impurities, even at the order of 10^{-6}. The best ones (like Xenon) emit several tens of photons per keV.

Electron recoils have sparse ionization, ion recoils have dense ones. The response to highly ionizing particles, such as alphas, is different from the one to minimum ionizing particles such as electrons: they can also be discriminated through PSD, since they excite triplet and singlet states in different proportions.

We compare α particles to electrons — these are the things we can reliably make in a lab setting, ideally we would like to measure the recoils of heavy nuclei, but it's very hard to make these with reproducible, low energies.

Still, the idea is that the response to these αs is roughly similar to that from nuclei.

The difference between triplet and singlet decays is the difference between fluorescence and phosphorescence.

What one can do is then just integrate the starting part of the signal and the end part: this ratio approximates the ratio of the exponential fit components, and allows for the discrimination of nuclear to electron recoils.

These detectors are typically spherical, in order to have 4π coverage. Examples are XMASS at Kamioka, and DEAP-3600 at SNOLAB.

This is the DEAP-CLEAN family. As the mass scale of these detectors grows above the ton, experimental efforts tend to merge.

We look at DEAP-3600. In order to have a fiducial region, we go from 3.6×10^3 kg to 10^3 kg.

The argon used is radioactive! Contaminated with ^{39}Ar. Thanks to pulse shape, they can suppress electron recoils by a factor 10^{10}.

What is the wavelength shifter made of?

The prompt fraction of the light is used as a discriminator. Nuclear recoils have a larger F_{prompt}, of the order of 70 %, while electron recoils have something like 30 %.

Typical efficiency values selected for nuclear recoils is of the order of 50 %.

Fiducialization is the process of reconstructing the direction the signal was coming from. It can be time-based (measuring the arrival delays), or charge-based (measuring the signal amount).

Surface background, such as radon and polonium decays, also populate the signal region for F_{prompt}, however there are other methods.

The effect of the sphere's neck is also relevant, and modelled by current detectors.

The number of photoelectrons detected can be directly mapped to the number of keV in the recoil.

They didn't find dark matter, sadly.

2.1.2 Charge + light: double-phase detectors

The scheme for the ionization of the noble gas is the same, but now we also look at the electron which is ejected when the xenon is ionized. The light signal in the slow and fast

channels is called S1, while the electron is called S2.

The ratio of S1 to S2 allows for further discrimination.

The light and charge contributions to the total energy are anti-correlated: if we add them together we reduce the fluctuation in energy by a lot.

We get energy resolutions of the order of $\sigma/E \sim 2\,\%$.

These detectors are typically shaped like cylinders, as opposed to spheres. It's very difficult to make a uniform, radial $\vec{E}$-field in a sphere.

Even in a cylinder geometry, a "field cage" is used, which prevents the field lines from exiting the cylinder. Instead of a single big voltage, we get a ladder of small voltages.

The first signal, S1, is detected early and after a certain time the charge drifts and allows us to measure the stronger S2 signal.

Electric charge does electroluminsescence and is detected by the same PMTs which detected S1.

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