Observational constraints on Dark Matter models

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Abstract

In this short course, which complements the lecture on Dark Matter alternatives, I provide concrete examples of how Dark Matter (DM) models can be tested, whether for generic DM properties, or specific scenarios. First, I review searches for WIMPs, one of the most well-studied DM candidates. I also showcase some constraints on DM models that predict a modification of the cosmological matter power spectrum at high k. To this end, I focus primarily on bounds derived from the Lyman-α forest observations, which I will present in a brief overview beforehand.

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1 Introduction

As students in this School have learned, a wide variety of observations clearly demonstrate the existence of a so-called "Dark Matter" (DM) fluid in the Universe. DM drives the dynamics of large, gravitationally bound systems such as galaxies and clusters of galaxies. DM also drives the formation of large-scale structures, and is essential to understanding the properties of Baryon Acoustic Oscillation peaks, which are measured with great precision from CMB temperature anisotropies. However, all that we know about the physical nature of DM is that, from a phenomenological point of view, it behaves like a non-relativistic, collisionless fluid that obeys to the laws of gravitation on cosmological scales.

The known elementary particles that comprise our Standard Model of particle physics cannot reproduce the DM phenomenology; therefore, a large number of "exotic" models have been developed over the past 30 to 40 years to explain the nature of DM. Many of these models are extensions of the Standard Model, but other ideas include modified gravity. On the observational or experimental side, the long-term hunt for DM [1] may be somewhat artificially divided into two approaches:

- Use astrophysical or cosmological observations to constrain the general properties of the DM "fluid": eg. to what extent is it collisionless or non-relativistic? Can we measure its sound speed and mass?

- Conduct dedicated observations or experiments to test specific Dark Matter models that appear promising, eg. direct searches for WIMPs or axions.

In this short course, I won't attempt to present or classify all of these observational or experimental tests – a virtually impossible task. Instead, I focus on two examples of DM searches. In Sect. 2, I provide an overview of searches for a prominent class of DM candidates, the WIMPs, and I describe the so-called direct and indirect detection strategies. In Sect. 4, I present constraints on a wide range of DM models that predict some modification of the small-scale matter power spectrum with respect to the Cold Dark Matter (CDM) paradigm. There are several observational probes of this small-scale power. I will focus on one of them: the Lyman-α (Lyα) forest. Since the Lyα forest has not been discussed in detail during this School, I will first devote Section 3 to introducing the basics of the Lyα forest as a cosmological probe.

1.1 A first example: constraining the mass of DM from dwarf galaxies

As an introductory example, let's examine how observations of dwarf galaxies alone can constrain the mass of DM based on fundamental physical principles. DM candidates are sometimes classified according to their mass. Phenomenologists have proposed candidates over an extraordinarily wide range of masses, from 10^{-22} eV to around 100 solar masses. This range can actually be determined by very simple considerations. Dwarf galaxies are very good laboratories for studying Dark Matter, because their dynamics is Dark Matter dominated and we observe many of them in the Milky Way's neighborhood. They have sub-kpc size R, and typical velocity dispersion $v \sim 10-50$ km/s.

- If the mass of the DM particle, $m_{\rm DM}$, is extremely low, then its quantum wavelength $\lambda = h/mv$ will eventually be larger than the size of the halo associated with those galaxies. This argument implies a lower bound $m_{\rm DM} \gtrsim 10^{-22}$ eV.

- In addition to the uncertainty principle, if DM is made of fermions, then it must obey the Pauli exclusion principle. This means that the total number of DM particles in the dwarf's halo, $N = M/m_{\rm DM}$ where $M \sim Rv^2/G$ is the halo mass, should be smaller than $V_{\rm phase}/\hbar^3$ where $V_{\rm phase}$ is the total phase-space volume occupied by the halo. This implies the Gunn-Tremaine bound $m_{\rm DM} \gtrsim 200$ eV [2]. This simple bound rules out the possibility of Standard Model's neutrinos being DM.

- On the other end of the mass range, if DM is massive enough, it will impart granularity to the dwarf's DM halo. Tidal forces are then expected to disrupt the galaxy on a short dynamical timescale. The related upper bound is $m_{\rm DM} \lesssim 10-100\, M_{\odot}$.

2 The search for WIMPs

From the 1990s to the 2010s, the WIMP scenario was arguably the most explored DM scenario. Weakly Interacting Massive Particles arise in many extensions of the Standard Model that assume new physics at the scale of electroweak phenomena, eg. supersymmetry [3] or models with extra dimensions. The order of magnitude of the WIMP mass is in the 10 GeV – 1 TeV range, and it interacts with Standard Model particles through "weak" couplings, ie. the exchange of massive particles such as the Z or Higgs bosons, or other supersymmetric particles. WIMPs are thermal cosmological relics: they were in thermal equilibrium in the primordial plasma before decoupling. Their comoving density after decoupling can be computed: for a range of parameters, it roughly matches the measured dark matter density. This "WIMP miracle" is a clear appeal. Even more appealing is its testability; we have opportunities to detect the coupling of WIMPs to ordinary matter in different ways.

2.1 Collider searches

At particle colliders, like the LHC at CERN, WIMPs may be produced if the center-of-mass energy of the collisions is large enough relative to the WIMP mass. The most common signature is that WIMPs escape detection due to their very small interaction cross-section. However, there is a measurable missing energy when examining the interaction products. Many searches for WIMP signatures have been carried out over the years, but they have only yielded null results thus far.

2.2 Direct detection

The direct detection method was first considered in the 1980s [4]. Assuming the Milky Way halo is composed of WIMPs, we expect a flux of WIMPs to pass through the Earth at a mean velocity $v \sim 250$ km/s, and interact with any material on Earth. The energy deposited during each interaction, in the form of a nuclear recoil, is in the $1-100$ keV range depending on the WIMP mass. The interaction rate depends on the local DM density in our MW halo, ρ_0, on the velocity distribution of WIMPs and on its scattering cross-section with nuclei, σ_0. For a large range of WIMP models, the resulting rate is very low (eg. around one interaction per day in a ton of material). This rate is much larger than the usual background from natural radioactivity. Therefore, a large range of experimental detection strategies have been devised in order to overcome this background and identify interactions specifically produced by WIMPs. Despite their diversity, these strategies rely on two main pillars:

- Shielding WIMP detectors against radioactive backgrounds. The detectors are encased in a set of shields to minimize radioactivity in their vicinity (eg. radio-pure lead shields against gamma radioactivity). The detectors are operated in deep underground laboratories, in tunnels or in mines, where cosmic-ray induced radioactivity is reduced. The detectors and their related instrumentation and cables are made from radio-pure material.

- While most radioactivity (beta particles and gamma rays) interacts with electrons, WIMPs mostly interact with nuclei because they are heavy. Therefore, specific detector technologies, often with dual measurement capacity, were developed to discriminate between electronic and nuclear recoils within their volume.

An impressive number of WIMP direct detection experiments have been conducted. Here, I will briefly describe one technique: dual-phase xenon time projection chambers (TPCs). These detectors consist of a large vessel filled with ultra-pure liquid xenon, instrumented with a set of photomultipliers (PMTs, sensitive to fast UV flashes), on the top and bottom of the vessel. Liquid Xenon is a scintillating material; therefore, any interaction produces a brief flash of light called "S1". Second, free electrons are usually produced during an interaction. In this setup, a large vertical electrostatic field is applied to the xenon vessel so that the electrons drift toward the top. There, they reach a small location where the xenon is in a gaseous state. When they jump into the gas phase, they produce a second "S2" flash of light. This flash can be easily identified because it is recorded by the PMTs after the "S1" flash. Nuclear recoils, particularly those from WIMPs, naturally produce fewer free electrons than electron recoils from gamma rays. Therefore, the S2/S1 ratio is used to discriminate against these interactions, providing a nearly background-free measurement.

To date, the most sensitive direct WIMP search has been conducted by the LUX-ZEPLIN experiment [5]. Their detector contains several tons of liquid xenon and recorded PMT signals continuously for 280 live days. Many interactions were observed during data collection, but after cleaning the data, the residual distribution of signal amplitudes in the (S1, S2) plane was consistent with that expected from residual radioactivity. By fixing the local DM density and velocity distributions to reference values, the team derived upper bounds on the WIMP-nucleon cross-section, as a function of WIMP mass. These bounds exclude a wide range of WIMP models.

2.3 Indirect detection

In the most common models, WIMPs annihilate each other into lighter particles of the Standard Model. This process dictates the relic comoving WIMP density in the primordial plasma, therefore at the origin of the "WIMP miracle". At late times in cosmic history, DM is concentrated in dense halos so we expect these annihilation processes to occur again. This will produce secondary high-energy particles, such as protons, anti-protons, neutrinos and gamma rays. Depending on their intensity, the flux of these secondary particles may be detectable. The predicted flux from a given astrophysical object depends on the WIMP annihilation cross-section, and on the integral of the squared WIMP density along the line of sight to this object, called the J-factor: $J = \int_{\mathrm{los}} ds\, \rho^2(s)$. It also depends on the precise WIMP physics model.

Due to the variety of potential astrophysical objects to observe (our MW's galactic center, dwarf galaxies, clusters of galaxies, and even the Sun in certain scenarios), as well as possible decay channels, numerous searches were conducted using our arsenal of high-energy astrophysics experiments, including cosmic ray detectors (eg. AMS), neutrino detectors (eg. IceCube), and gamma-ray detectors (eg. HESS, Fermi). Here, we will focus here on one of the most sensitive searches, the results of which are presented in [6]. This search used gamma-ray data from the Fermi's full-sky observations.

The astrophysical targets are dwarf galaxies. As explained in Sect. 1.1, these are DM-dominated objects with a quite well-measured J-factor. Furthermore, since these objects have low stellar densities, the gamma-ray background emitted by standard objects in dwarf galaxies, eg. pulsar wind nebulae or supernovae, is low. In fact, it has not yet been firmly detected. The upper bound derived from Fermi data on the gamma-ray fluxes from each dwarf can be translated into a bound on the annihilation cross-section, assuming a given WIMP mass and decay channel, as well as taking into account observational uncertainties on the J-factors. Remarkably, for WIMP masses below ~ 100 GeV, the annihilation cross-sections needed to achieve the thermal "WIMP miracle" are clearly disfavored.

2.4 Summary

After a few decades of intense searches, no convincing WIMP signal was found, from colliders to space [1]. However, this doesn't mean that WIMPs are excluded as DM candidates, since a significant fraction of the WIMP parameter space has not yet been explored, especially in the high-mass range $\sim$ TeV.

WIMP searches continue today, but there is also a growing effort to detect another class of DM candidates called axions, which are particularly well-motivated. Like WIMPs, searches for DM axions involve a combination of dedicated terrestrial experiments and indirect astrophysical searches.

3 Basics of Lyman-α forest in cosmology

The Lyman-α (Lyα) forest is a powerful probe of several DM models, as we will see in Sect. 4. Here we provide a summary of the Lyα forest as a cosmological probe. This section is completely independent from the rest of the lecture notes.

3.1 Lyman-α forest signal and data

The Lyα forest is a set of features observed in the spectra of distant sources. It is produced by the resonant Lyman-α absorption by neutral hydrogen in the intergalactic medium (IGM) [7]. The absorption occurs at a wavelength of 1215 Å, but is redshifted to a wavelength that depends on the location of the IGM "clouds" along the line of sight of the source. It falls in the optical wavelength range for IGM absorbers at $z \sim 2-5$.

The Lyα absorption signal is $F(\lambda) = e^{-\tau(z)}$, where τ is the IGM's optical depth at redshift z. τ scales with the neutral hydrogen density $n_{\rm HI}$, which depends on two main factors. First, $n_{\rm HI}$ depends on the ionization fraction in the IGM, which is dictated by photodissociation and recombination processes. For the IGM at $z \sim 2-4$, this fraction is about 10^{-5}. Second, $n_{\rm HI}$ is proportional to the matter density fluctuations. In the dilute IGM with mild density fluctuations (cosmic voids and filaments), the optical depth is of the order of unity, $\tau \sim 1$, for $z \sim 2-4$. Therefore, the transmission $F(\lambda)$ is sensitive to those mild fluctuations, making the Lyα forest an excellent tracer of matter fluctuations over a range of cosmological scales. At higher redshifts, the IGM is less ionized and τ is much larger than one on average. The residual transmitted flux is a leftover from the late reionization process. Conversely, at low redshifts, we have $\tau \ll 1$, and only a few absorption features are visible, tracing the dense environments around galaxies.

The background sources typically used to measure the Lyα forest are high-redshift quasars, due to their luminosity and strong continuum emission. There are two categories of spectroscopic Lyα observations in the range $z \sim 2-4$:

- The largest statistical samples come from massive cosmological spectroscopic surveys; DESI is currently their flagship. The latest DESI sample, DR2, includes 820,000 Lyα spectra from quasars with $z > 2.1$. With such a large sample size, density correlations in the IGM are measured up to very large scales. The BAO feature can be measured at

[1] There have been indications from several experiments or observations, but none were considered robust enough or reproducible to convince the community: extraordinary claims require extraordinary evidence.

$z_{\rm eff} = 2.33$ with 0.7 % precision [8], which is comparable to the precision of BAO measurements at lower redshifts from galaxy positions.

- Smaller Lyα samples are also available from dedicated observations with large telescopes. These samples contain only a few hundred spectra (eg. the KODIAQ sample obtained with Keck/HIRES currently has around 300 spectra). However, these are high-signal-to-noise measurements obtained with a high spectroscopic resolution, capable of resolving the Lyα forest down to sub-Mpc scales.

3.2 The Lyman-α 3D power spectrum

Remarkably, modern cosmology provides a way to predict the Lyα forest signal with good precision using an almost ab-initio approach. Within a given cosmological model, hydrodynamical simulations, such as GADGET or NYX [9], compute the dark matter density using N-body methods, and the properties of the dilute IGM, such as density, temperature and ionization state, using either Eulerian (grid) or Lagrangian (SPH) methods. These simulations require some explicitly tuned inputs to model gas properties, particularly the heating rate induced by radiation. However, as long as one is interested in the dilute IGM, it is unnecessary to explicitly simulate galaxy formation, which requires subgrid modellng. From these hydro simulation outputs, it is relatively easy to compute the Lyα forest absorption signal by tracing lines-of-sight through the snapshots.

We define the associated fluctuations of the 3D absorption field, $F(\mathbf{r})$, as follows: $\delta_F = F/\bar{F}{-}1$. This 3D cosmic field traces matter in redshift space similarly to the galaxy density or 21cm emission field. The most important summary statistic on large scales is its three-dimensional power spectrum, which is the Fourier transform of its autocorrelation function $\xi(\mathbf{r}) = \langle \delta_F((x)\delta_F(\mathrm{x{+}r}) \rangle$. As with all biased tracers of the large-scale structure, we can expand the 3D power spectrum:

$$P_{\rm 3D}(k,\mu) = b^2(1+\beta\mu^2)^2 P_{\rm lin}(k)\, F_{\rm NL}(k,\mu) \tag{1}$$

In this expression, b and β are the linear biases of the Lyα forest (with β being associated with redshift-space distortions), $P_{\rm lin}$ is the linear matter power spectrum, and $F_{\rm NL}$ represents small-scale corrections to the linear bias expansion. The wavenumber amplitude is k, and μ is the cosine of its direction with respect to the line of sight. Hydrodynamical simulations provide predictions for the bias terms, as well as for $F_{\rm NL}(k,\mu)$. On small scales, the power spectrum is affected not only by nonlinear gravitational growth but also by the broadening of the Lyα absorption lines due to nonlinear velocity dispersions and thermal broadening. On scales of about ~ 100 kpc, $P_{\rm 3D}$ is cut off by the Jeans smoothing of the gas.

3.3 The Lyman-α 1D power spectrum

On small scales, measurements of transverse correlations in the Lyα forest are limited by the line-of-sight separations between background quasars. These separations are typically above 10 Mpc in large surveys like DESI. Conversely, longitudinal correlations can be measured from a single line of sight down to sub-Mpc scales, as they are only limited by the thermal broadening of the absorption lines. Thus, a preferred tool is the Lyα 1D power spectrum, which is measured by correlating Lyα samples within individual spectra. The 1D power spectrum can be directly predicted from the 3D power spectrum:

$$P_{\rm 1D}(k_{\parallel}) = \int \frac{d^2k_{\perp}}{(2\pi)^2} P_{\rm 3D}(k_{\parallel},k_{\perp}) \tag{2}$$

It follows from this relation that there is a quite direct connection between $P_{\rm 1D}$ and the linear matter power spectrum, even up to wavenumbers $k \sim 1$ Mpc. $P_{\rm 1D}$ measurements, which have reached a remarkable near-percent-level precision, were then used in conjunction with predictions from hydrodynamical simulations, in order to constrain P_{lin} at large k values, which cannot be reached with CMB measurements. The slope of P_{lin} at $k \sim 1$ Mpc, for example, provides interesting constraints on the sum of neutrino masses, or the running of the primordial power spectrum. In some analysis, these were found to be in tension with a scale-invariant primordial power spectrum [10].

More generally, any cosmological model that predicts a deviation in the linear matter power spectrum from a power law at Mpc scales can be constrained by these Lyα measurements.

4 Dark Matter constraints with the Lyman-α forest

In several DM models, the specific microphysical properties of DM generate a modification of the matter power spectrum at small scales and early times. This can be tested, using various observations. As demonstrated in the previous section, the Lyα forest is one such example, which I will focus on. Other probes include weak and strong lensing, high-redshift galaxy counts, the properties and statistics of dwarf galaxies, or 21cm emission. Here, I present three examples of very different DM models, all of which are constrained by Lyα forest observations.

4.1 Warm Dark Matter

Warm Dark Matter (WDM) is a generic class of DM characterized by mildly relativistic velocities at the time of equality. The large, unimpeded displacements of DM particles erase gravitational structures on scales smaller than their free-streaming horizon.

One well-motivated WDM model is the keV-scale sterile neutrino. There is room in the Standard Model for massive, right-handed counterparts of the known active neutrinos. There is a window in the sterile neutrino mass and mixing parameter space, for which the right amount of these particles is produced by resonant production in the primordial plasma. They would also pass all other constraints, particularly the Gunn-Tremaine bound presented in Sect. 1.1. The mass range is $\sim 1-50$ keV. For this range of masses, calculations show that the sterile neutrinos are expected to free-stream at early cosmic times. The exact value of the free-streaming scale at equality, λ_{FS}, is model-dependent.

Free-streaming of DM produces a cutoff in the linear matter power spectrum at high k and can therefore be constrained with P_{1D}. Recent results [11] have found constraints of the order of $\lambda_{\text{FS}} \leq 70$ kpc. The corresponding model-dependent bound on the mass of resonantly produced sterile neutrinos is around ~ 10 keV, which partially closes the window on this scenario.

4.2 Fuzzy Dark Matter

Fuzzy Dark Matter (FDM) is a scenario presented in Sect. 1.1, in which the mass of DM is extremely low, down to $\sim 10^{-22}$ eV. On cosmological scales, the quantum effect associated with the large de Broglie wavelength of FDM smooths density perturbations on small scales. The quantum pressure is the source of a scale-dependent effective speed of sound in the FDM fluid. Consequently, the linear matter power spectrum is damped for scales smaller than the related Jeans scale at the time of equality.

From a phenomenological point of view, FDM is therefore quite similar to WDM, and it is actually possible to translate bounds on the WDM free-streaming into FDM mass bounds [12]. Existing Lyα forest data excludes FDM masses up to $\sim 10^{-21}$ eV.

4.3 Massive Primordial Black Holes

This scenario was also presented in Sect. 1.1. If DM consists of very massive point-like objects, such as primordial black holes (PBHs), the number density $n_{\rm PBH}$ becomes so low that the fluid's "granularity" affects even cosmological scales. Statistically, this granularity results in additional shot noise in the matter power spectrum, which can be expressed as follows:

$$P(k) = P_{\rm CDM}(k) + \frac{1}{n_{\rm PBH}} \tag{3}$$

Since $P_{\rm CDM}$ is a sharply decreasing function of k, this means that the matter power spectrum is strongly enhanced above a certain wavenumber. Once again, the small-scale Lyα1D power spectrum would be affected. Although calculations show that $P_{\rm 1D}$ is not the most constraining probe for this scenario, it still excludes PBH masses above $\sim 100\,M_\odot$.

5 Conclusion

These lecture notes only offer a glimpse into the large, vibrant efforts investigating the nature of Dark Matter. Needless to say, many of these efforts were not mentioned in the notes. The diversity of approaches reflects the variety of alternatives that can be considered to solve this mystery. While no definitive detection has yet been made, each experiment or observation narrows the possibilities, hopefully guiding us closer to understanding this elusive component of our Universe.

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