Astroparticle Physics

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Abstract

These are the current notes for Astroparticle Physics. They are being updated continually.

Contents

Chapter 1

Course Summary

This course is the MMathPhys Astroparticle course. It consists of 16 lectures in total, and will cover a variety of topics in astroparticle physics.

General Comments

Astroparticle physics is a subject that straddles particle physics, astrophysics and Beyond-the-Standard-Model Physics. It also involves the highest energy particles anywhere in the universe. It is therefore an appealing subject to a physicist as it involves the intersection of many different areas of physics at some of the most extreme conditions of the universe. Unlike certain topics in mathematical physics, it also does not simply build up as a set of ideas starting from certain axioms. Most of the subject cannot be 'deduced' - it depends on the history of the universe and the specific properties of many astrophysical systems. The more physics you know, the better!

Books

The course does not follow any single book. Broadly, the course aims to straddle approaches to the subject which are based on high-energy astrophysics and approaches which are based on Beyond-the-Standard-Model physics. Below are some examples of texts:

1. Raffelt(Stars as Laboratories for Fundamental Physics) - a nice physical book, with a strong sense of the physics of how to search for new physics using astrophysical objects (especially stars)

2. Grupen (Introduction to Astroparticle Physics) - a decent undergaduate-level overview of the subject. Plenty of hand-drawn cartoons by the author, some of which are more tacky than others.

Errata

Please send any corrections to joseph.conlon@physics.ox.ac.uk.

Chapter 2

Introduction: The Universe Observed

2.1 Particles and Forces

We know of *four* fundamental forces. These are

- Electromagnetism
- The weak force
- The strong force
- Gravity

(One could also include the scalar force mediated by the Higgs boson, but this would be mildly pedantic for this course)

Particles can interact under some or all of these forces. All particles interact under the gravitational force - it is the only truly universal force. For all of the other forces, there are particles which are neutral under that force.

The *strong force* confines at short distances ($\sim 10^{-15}$m). Particles which interact directly under the strong force (e.g. quarks or gluons) bound into composite colour-neutral objects (e.g. pions, protons, or neutrons). 'Bare' strong-charged objects do not exist. The resulting composite particles do not directly feel the strong force at distances $r \gtrsim 10^{-15}$m.

The *weak force* is suppressed by the Fermi constant G_F, which originates from W or Z boson exchange. As these are heavy particles $M \sim 10^2$GeV, the weak force is extremely suppressed at low energies. As a result, particles which *only* interact via the weak force (for example, neutrinos) see matter as almost transparent and pass through the Earth without difficulty - indeed, neutrinos are emitted from the cores of type II supernovae during their final moments and give us a probe of the physics of the collapsing core.

The *electromagnetic force* is *long-range.* Charged particles are deflected by the magnetic fields ($B \sim 1\mu G \sim 10^{-10} T$ inside the Milky Way) that permeate the Universe and travel on helical spirals about the direction of the magnetic field. Note that as photons are not themselves charged under electromagnetism (this is in contrast to e.g. the weak force, where the W and Z bosons are themselves charged under the weak force) they can travel long distances through the universe without deflection or interaction. A well-known example is the Cosmic Microwave Background which has propagated freely since the surface of last scattering at $t \sim 380,000$years.

The *lifetimes*, *interactions* and *propagation distances* of all particles - central for their role in the Universe - depend crucially on the forces they are charged under.

2.2 The Universe

The backdrop for all astroparticle physics is the universe at the various stages of its existence. Here we review the various stages in the history of the universe - or at least, the stages as we currently believe them to be.

1. Initial conditions - we state these to say that we know rather little about them. There are no current observational probes of this era. This is an era of quantum gravity - perhaps string theory? But whereof we do not know, thereof we should be silent.

2. Inflation - inflation is the best candidate theory for the simultaneous origin of both the large-scale homogeneity in the universe and also the small-scale inhomogeneities (characterised by the primordial density fluctuations $\frac{\delta\rho}{\rho} \sim 10^{-5}$). We do not **know** that inflation occurred, but it is certainly the best theory we have for the very early universe.

   During inflation, the universe was dominated by the energy density of a slowly rolling scalar field - to a good approximation, it was just vacuum energy. This leads to a rapidly accelerating expansion in which the universe grew in linear radius by a factor of approximately e^{60}. During this epoch, the vacuum energy density was large - we do not know exactly how large, but typical models may give $V \sim (10^{15}\text{GeV})^4$.

   The period of inflation homogeneised the universe while also - through the quantum vacuum fluctuations of a scalar field - generating density perturbations. At the end of inflation, the energy was transferred to quanta of the scalar field (i.e. inflaton particles). These then decayed to 're'-heat the universe and initiate the Hot Big Bang.

3. The Hot Big Bang consists of the stage of the universe where the energy density is dominantly in relativistic thermalised Standard Model degrees of freedom. This epoch is radiation dominated. We do not know the temperature at which it starts (this could reach up to 10^{12}GeV) but this epoch must have started by a temperature of $T \sim 10$MeV in order to give rise to Big Bang Nucleosynthesis.

4. The final epoch is the current one, which is dominated by a mixture of dark matter and dark energy. The universe cooled down and expanded. In this expansion, radiation redshifts as $\rho_\gamma \sim a(t)^{-4}$ while matter redshifts as $\rho_{DM} \sim a(t)^{-3}$ and so over time the radiation fraction of the universe becomes minimal. Dark energy is associated to the vacuum energy of spacetime itself. For reasons that are deeply mysterious, observations imply this is small but non-zero, having a value of approximately $\Lambda \sim (10^{-3}\text{eV})^4$. This is a similar scale to the apparent mass of the lightest neutrinos, but no connection is known.

   The energy density of the universe today is 70% dark energy, 25% dark matter and 5% Standard Model matter (principally baryons). The early thermalised radiation persists as the cosmic microwave background at a temperature $T = 2.73$K. The universe is also permeated by *magnetic fields*. These take characteristic scales $B \sim 10^{-10}$T inside galaxies or galaxy clusters and $B \lesssim 10^{-13}$T in deep intergalactic space.

   On large scales, the universe is both *homogeneous* and *isotropic*. It looks (statistically) the same in all directions - the Northern sky shows the same physics as the Southern sky. It also appears to have the same physical properties wherever we would be - i.e. physics ten billion light years away would be the same as on Earth, and if we observed the universe from there we would see the same distributions and types of galaxies, etc.

Chapter 3

Cosmic Rays

As a discipline, astroparticle physics is roughly one century old - in terms of the conscious search for particles, as particles, from astrophysical sources. Of course, it is true that the observation of photons from astrophysical source goes back to prehistory - but they were not known to be photons until the 20th century.

This original history of astroparticle physics is closely associated to the observation of *cosmic rays.*

Cosmic rays are particles incident on the Earth from space. They can be observed either from ground or also, more recently, from space through satellites. We can classify them into two types,

- *Primary* cosmic rays
- *Secondary* cosmic rays

Primary cosmic rays are directly incident from astrophysical sources. An example would be a GeV photon produced in the vicinity of an Active Galactic Nucleus (AGN) that has travelled straight to us. *Secondary* cosmic rays are cosmic rays that are produced, not by the astrophysical source itself, but by secondary scattering events. An obvious example here would be a pion produced in the upper atmosphere when a primary cosmic ray proton interacts with more-or-less stationary protons, e.g

$$p + p \to p + p + \pi^+ + \pi^-$$

The definition of secondary cosmic ray may slightly depend on what object we are studying. If we are interested in the physics of AGNs, particles produced in a scattering event in the Interstellar Medium (ISM) on the way to Earth may be regarded as secondaries; if we are interested in the spectrum of all-source particles arriving at Earth, then such particles count as primaries.

Primary cosmic rays can be either *charged* or *uncharged.* The charged cosmic rays consist of

- approx. 85% protons
- approx. 12%α particles
- approx. 3% heavier elements
- small amounts of e^-, e^+

The distribution of heavier elements broadly tracks the distribution (often referred to as *chemical composition* in the astrophysics literature) of elements found in the Sun. However there are excesses in both the low-Z elements, such as Lithium, Beryllium and Boron, and also in the elements just below Iron (so atomic numbers $Z = 20 \to 25$).

The way to understand both features is through *spallation* or *fragmentation* of heavier elements. Spallation is when a nucleus is hit by an energetic particle and some of the protons or neutrons are knocked off. For the low-Z cases, these arise from spallation or fragmentation of the highly abundant nuclei Carbon $Z = 6$ and Oxygen $Z = 8$. For the cases of $Z = 20 \to 25$, these arise from spallation of Iron, which is highly abundant as it is produced as the endpoint of fusion in massive stars just before they form type II supernovae.

Primary charged cosmic rays cover a very large range of energies that extend up to $10^{20}\text{eV} = 10^{11}\text{GeV}$ - and note that this is a factor of 10^7 larger than the beam energies at the LHC. Charged cosmic rays are affected by magnetic fields - as charged particles, their directions of motion are altered by any magnetic field present. For lower energy cosmic rays, the solar and earth magnetic field give a significant effect (the solar wind alters the direction of the B-field lines near the Earth) and this gives a pronounced East/West anisotropy in the arrival direction of charged cosmic rays.

The incoming spectrum of primary cosmic rays can be described (roughly) as a power-law. Note that similar power-laws are found in most astrophysical energy sources. The short one-line form of this spectrum is

$$\frac{dN}{dE} \propto E^{-\gamma}$$

with $\gamma \sim 3$. extending up to energies $E \sim 10^{19}\text{eV}$, although this is an oversimplification and there are several threshold energies. For the very highest energies, the arrival flux of such primary rays can be naturally expressed in the wonderful units of $\text{km}^{-2}\,\text{century}^{-1}$.

The charged cosmic ray spectrum can be broadly classed into three regions

- $E \lesssim 10^{15}\text{eV}$ - in this range cosmic rays can be produced within supernovae. Cosmic rays of these energies are expected to have originated from within the Milky Way galaxy. The index is $\gamma \sim 2.7$.

- $E \sim 10^{15}$eV - this is the 'knee' in the spectrum. This marks a transition where the index changes.
- $10^{15}\text{eV} \lesssim E \lesssim 10^{19}$eV - in this range cosmic rays are expected to arise from extra-galactic sources, as such cosmic rays cannot be confined within the galaxy.
- $E \sim 10^{19}$eV - the 'ankle' where the spectrum broadly flattens
- $E \gtrsim 6 \times 10^{19}$eV - the 'toe', a sharp cutoff in the spectrum.

This spectrum is plotted in the FIGURE TO COME.

The origin of the highest energy cosmic rays is not known. This does not mean that they represent some entirely exotic mystery, where we expect to have to invoke new physics, quantum gravity or violations of Lorentz invariance to explain them. It means that we cannot, for certain, trace them back to their extragalactic sources. The most obvious candidate are AGNs (Active Galactic Nuclei), the enormously energetic regions in the vicinity of large supermassive black holes at the centre of galaxies. However, we do not know this for certain, and it is possible that there is a more exotic explanation.

It is relatively easy to understand why the highest energy cosmic rays must necessarily have an extragalactic source and cannot be confined by the Mily Way magnetic field. To do so, recall that the gyro-radius of a particle in a magnetic field is

$$r = \frac{p}{qB}. \tag{3.1}$$

If we put $q = 1$ as applicable for a proton, we have

$$\frac{r}{\text{meter}} = 3.3 \times 10^{10}\text{m} \left(\frac{E}{\text{GeV}}\right) \left(\frac{10^{-10}\text{T}}{B}\right) \tag{3.2}$$

As a quick estimate, we require a gyroradius of $\lesssim 100$ light-years. This is motivated by the vertical height of the Milky Way disk - if the gyroradius is significantly larger than the vertical scale height of the Milky Way, then particles will fail to be confined and will escape into intergalactic space. Taking $B = 10^{-10}$T as a typical value of galactic magnetic fields, we require

$$E \lesssim 3 \times 10^{8}\text{GeV} \tag{3.3}$$

for a proton to be confined by the Milky Way magnetic field. This result will be an over-estimate as we have taken a single gyroradius rather than considering the long-term evolution of particles; more refined estimates lead to $E \lesssim 10^{6}$GeV.

One interesting case concerns a cosmic ray proton of energy E incident on a photon of energy E_γ. An exercise in undergraduate relativity gives a center of mass energy

$$s = m_p \left(1 + \frac{4EE_\gamma}{m_p^2}\right)^{\frac{1}{2}} \tag{3.4}$$

where m_p is the mass of the proton. The striking fact is that for photon energies $E \sim 10^{-3}$eV (typical for photons of the cosmic microwave background) and a cosmic ray energy $E \sim 6 \times 10^{19}$eV, we have

$$s \simeq m_p + m_\pi,$$

and so we are above threshold for photo-pion production!

$$\gamma + p \to \pi^0 + p$$

The significance of this is that it implies that protons with energies above 6×10^{19}eV lose energy to photo-pion production through interactions with the CMB.

This is the famous GZK cutoff, which predicts an (apparently observed) cutoff in the energies of the highest energy cosmic rays. The GZK cutoff is believed to account for the 'toe' in the spectrum of the highest energy cosmic rays, by showing that the highest energy protons cannot propagate cosmological distances without losing their energy to the above photo-pion interaction with the CMB.

Many foundational research papers are hard to read, either very technical or written in a physics language that has now gone out of date. The GZK paper is, however, relatively easy to read and I encourage you to do so!

The center-of-mass energies associated to collisions of such primary cosmic rays can be rather larger. Consider the collision of an energtic cosmic ray proton of energy E with a stationary proton (i.e. Hydrogen) in the upper atmosphere. It is an easy exercise in undergraduate relativity to show that the center of mass energy is

$$s = \sqrt{2Em} \sim 1.4\text{TeV}\frac{\sqrt{E}}{10^6\text{GeV}}. \tag{3.5}$$

For an ultra-high energy cosmic ray with $E \sim 10^{10}$GeV, we therefore have $s \sim 140$TeV - an order of magnitude higher than the LHC!

Cosmic rays have always offered the prospect of higher-energy collisions than those available at terrestrial colliders. While the frequency of cosmic ray events exceeding today's colliders is so rare as not to be useful, this was not always so and historically, cosmic ray experiments were extremely important for the discovery of new particles. To see why, just imagine the potential products of high-energy pp collisions

$$p + p \to \pi^+, \pi^-, \pi^0, K, \bar{K}, \ldots$$

followed by

$$\begin{aligned} \pi^+ \;&\to\; e^+ + \bar{\nu}_e, \\ &\to\; \mu^+ + \bar{\nu}_\mu, \end{aligned} \tag{3.6}$$

and

$$\pi_0 \to \gamma.$$

Given current knowledge, we can easily see how such high-energy collisions would have resulted in many particles that were entirely unknown to the physicists of the 1920s and 1930s. Such cosmic ray experiments led to the discovery of the positron - as a particle of the same mass of the electron but giving an opposite curvature within a cloud chamber magnetic field - and also the pions and muon, the last a heavier, more penetrating identically-charged particle to the electron. Time has dulled the freshness of these particles, but it is less than a century since they were all entirely unknown.

It is instructive to compare cosmic rays and particle accelerator for their discovery potential for high energy particle physics. Today, the scales tilt in favour of the latter, but for many year they went the other way. Cosmic ray collisions

- Can extend to higher energies than particle accelerators (this is still true even today!)
- Gives more access to the rarest events at ultra high energies
- Has lower luminosity
- Has far less controlled instrumentation of the collision point.

In contrast, accelerators have

- A sharp limit on the maximal collision energy set by the accelerator technology
- The ability to generate intense beams of particle
- A far better ability to control the interaction point and surround it with instrumentation

The shift of the discovery frontier of particle physics from cosmic rays to accelerators took place during the 1950s, even though it is still the case today that the highest energy cosmic ray events are more energetic than any LHC collisions.

Today, cosmic ray physics is more a question of astrophysics - where do these energetic particles come from, and what is the mechanism by which they were accelerated? - than an attempt to discover new particles. Cosmic ray observatories utilise the fact that high-energy cosmic rays tend to produce *showers* of particles. Experimentally, this discovery goes back to the development of *coincidence detectors*, which would only take a picture of the cloud chamber when a particle was passing through. It was then discovered that there was a strong tendency towards simultaneous discharge of nearby detectors, namely that the presence of charged particles in one detector was correlated with their presence in other nearby detectors. This discovery (by Bruno Rossi in 1934 and Pierre

Auger in 1937) was the first sign of large air showers from energetic cosmic ray primaries.

XXDIAGRAM OF SHOWR XX

If you are familiar with LHC detectors (in particular electromagnetic or hadronic calorimeters) you will see that for such ultra-high energy cosmic rays, the detectors essentially treat the atmosphere as one giant calorimeter, and infer the energy of the primary particle by counting the total number of particle produced in the shower. These particles are all secondary cosmic rays produced at the end of the shower. Direct detection of the primary cosmic rays requires an above-atmospheric detector, for example on a balloon or a satellite.

3.0.1 Non-hadronic Cosmic Rays

While protons are the most common form of cosmic ray, other types are also of great interest. These include

- Electrons and positrons
- Photons
- Neutrinos

Electrons and Positrons

We now discuss these. Electrons and posistrons are *more local* than protons. The reason is fairly easy to understand. As these are lighter than protons, they lose energy faster and so 'age' quicker. Energy losses for electrons can proceed via

- Inverse Compton up-scattering

  $$e^- + \gamma \to e^- + \gamma$$

  where γ can be a photon drawn from either the CMB or the Extragalactic Background Light (EBL) - this latter is the sum of all the starlight emitted over the course of the universe.

- Synchroton emission in galactic magnetic field, generating radio waves. This latter effect is much more important for e^-/e^+ than for protons, due to the lighter mass of the former.

Energetic electrons can clearly be produced in many ways, as they are abundant in the universe. Positrons are more interesting - as they are antimatter, there are relatively few ways to produce high-energy positrons.

- Cosmic ray interactions on the interstellar medium. This can produce π^+ mesons, whose subsequent decays can produce e^+, either directly or via intermediary μ^+ decays.
- Matter-induced conversion of energetic photons produced in pulsars or supernova remnants,
$$\gamma \to e^+ + e^-$$
- Dark matter? A possible and speculative origin for high-energy positrons!

There is an 'excess' in the spectrum of high-energy positrons, as measured by the AMS experiment. This excess is most likely due to positron production from nearby pulsars.

Neutrinos

We next discuss neutrinos. These have both advantages and disadvantages from a cosmic ray perspective. The advantages are that

- They point straight at the source
- They do not interact with anything else along the way
- They can give direct probes from extreme astrophysical environments (for example, the interior of supernovae)

The disadvantages are

- They interact very weakly and so need large detectors for a small number of events
- They are very hard to detect and most pass straight through the earth.
- The relatively small number of events give much worse statistics than for other types of particle.

Photons

Photons are the oldest type of astroparticle known. They are highly abundant and so can be used to build up detailed images of the source structure. As they are uncharged, they point back directly at the source allowing them to be used for imaging (on one level, this is 'obvious', but it is worth stressing that this is because photons do not themselves feel the electromagnetic force - otherwise, they would be deflected by the intervening magnetic fields).

High energy photons can be absorbed through the process

$$\gamma + \gamma \to e^+ + e^-$$

through scattering off either the extraglactic background light or off the CMB. For energies in the range $10\text{GeV} \lesssim E \lesssim 10^5\text{GeV}$, scattering off the EBL is important, whereas for energies $E \gtrsim 10^5\text{GeV}$, scattering off the CMB is dominant.

For energies $E \lesssim 100\text{GeV}$, the mean free path of photons is greater than the size of the universe, and so photons can come from cosmological distances. The mean free path decreases with energy, and for high-energy photons with $E \gg 1\text{TeV}$ most photons are galactic and emanate from within the Milky Way.

Chapter 4

Dark Matter

The question of the nature and origin of dark matter is arguably the deepest and most interesting aspect of astroparticle physics. What do we know about dark matter? we know that it is stuff which is

- Matter - it behaves as something which is both *heavy* and *non-relativistic*, i.e. like dust.

- Dark - it does not have any known electromagntic interactions, and so we cannot *see* it.

We *weigh* dark matter through its gravitational interactions, but we cannot see it.

The first evidence for dark matter's existence was adduced by Zwicky in the 1930's. He observed the velocities of galaxies in the Coma cluster of galaxies. The velocity dispersion of the galaxies (the range of velocities present) was too large to be explained solely by the gravitational pull of the visible luminous matter alone - there had to be, he concluded, additional *dunkelmateriel* - extra dark non-luminous matter present in the galaxy cluster.

In the 1960s and 1970s further evidence for dark matter emerged, associated to the rotation curves of spiral galaxies. This involves measuring the rotation speeds of stars around the centre of a galaxy at progressively larger distances from the galaxy center. Observations - in particular associated with Vera Rubin - found that the rotation curves were too flat to be accounted for by the visible stars alone. Instead, there had to be additional dark matter also present within the galaxies.

Both arguments are arguments set in the present day, and within the local universe. They come from making observations of (relatively!) nearby astrophysical systems, and which are sensitive to the *total amount of mass* present in the system and comparing this to the *total amount of visible mass*.

Note that here that *dark energy*, the energy associated to the vacuum of space, is not relevant here (although it does gravitate). Galaxies or clusters of galaxies represent significant local over-densities of energy. Dark energy only becomes important when it is integrated over cosmological volumes.

Over the last couple of decades, cosmological arguments for dark matter, arising from the structure of the CMB, have grown ever stronger. The detailed physics of the CMB - the various acoustic peaks, their amplitude, the form of their damping - all give a precise measurement of the different elements that made up the early universe and determined both the expansion rate and the medium (the combination of baryons, dark matter and radiation) through which it propagated. For example, the acoustic peaks in the CMB reflect the interaction of radiation and baryons, and so are sensitive to the amount of baryons present - but the overall expansion rate does not distinguish between dark and baryonic matter. As CMB measurements have become ever more precise (moving through both WMAP and Planck), we can now say that the present day universe consists of three principal components (by energy density)

- Dark energy, making up 70% of the energy density
- Dark matter, making up 25% of the energy density
- Standard Model matter, making up 5% of the energy density

What is the 25%? Good question - and currently we do not know. Dark matter is *dark* and it is *matter* - and that is as much as we know. Candidates range in mass from $1M_{\odot} \sim 10^{30}$kg to around 10^{-24}eV. The top end of this range corresponds to solar mass black holes and the bottom end to something still just about heavy enough to behave as matter at the time when the CMB was formed. Note that dark matter does not have to be particles - elementary excitations of a quantum field. Even if we do restrict to particles, the upper range becomes $\sim 10^{18}$GeV $\sim M_P$, still leaving an enormous range of possible candidates (note that this range of 51 orders of magnitude is larger than the ratio between the volume of a haystack and the volume of a proton-sized needle!).

When trying to understand dark matter, and think of models of particle physics that can lead to it, there are three key questions, separate but interrelated.

1. How to produce the *phenomenology* of dark matter - specifically, something that is both dark and matter? This is, in a sense, a question of *kinematics*.
2. How to create the correct relic abundance? That is, how do the dynamics of the early universe lead to a situation where this dark matter candidates ends up today representing one quarter of the universe's energy density? This is a question of *dynamics* and of the history and interactions present in the early universe.

3. Given a model of dark matter, how can we *know that it is true*? How do we *detect* and *determine the nature* of dark matter in experiments? This is a far more nebulous question, that sits at the intersection of current technological limits, political availability of funding and theoretical creativity.

We start our thinking about dark matter models with the simplest example of the former: a massive scalar whose only interactions are via non-renormalisable terms suppressed by the Planck scale. Specifically,

$$\mathcal{L} = -\frac{1}{2}\partial_\mu \phi \partial^\mu \phi + \frac{1}{2}m^2\phi^2 \tag{4.1}$$

with

$$\mathcal{L}_{int} = \frac{\phi}{M_P} F_{\mu\nu}F^{\mu\nu}. \tag{4.2}$$

This is just a free scalar field, given a coupling to photons via the interaction term. The interaction allows for decays of the dark matter particle $\phi \to \gamma\gamma$. Naively, the photons will all have $E_\gamma = m_\phi/2$ (and this will be the case in the ϕ rest frame). However, in an actual galactic environment this line will be broadened due to the velocity dispersion of the dark matter.

((*Exercise: estimate the velocity dispersion of the line for both the Milky Way and also for a cluster of galaxies*)

On dimensional grounds, the decay lifetime of this particle will be

$$\Gamma_\phi \sim \frac{m_\phi^3}{16\pi M_P^2} \tag{4.3}$$

(the 16π arises from kinematic factors in 2-body decays). This corresponds to a lifetime

$$\tau_\phi \sim 1\text{s}\left(\frac{10\text{TeV}}{m_\phi}\right)^3 \tag{4.4}$$

From this, we can work out an *expected signal strength* and use this to bound the allowed range of masses for such a particle to exist and constitute all of dark matter. What bounds can we place? The most obvious one is that the lifetime of a viable dark matter candidate must be less than the age of the universe $\tau_\phi \lesssim 3 \times 10^{17}$s. From this we can rapidly infer that, in this model,

$$m_\phi \lesssim 10\text{MeV}$$

as heavier masses are ruled out as the particle is not stable on the lifetime of the universe.

We can then move on and constrain the regime $m_\phi \lesssim 10$MeV. In this case, decays of ϕ would produce gamma rays. We know the local dark matter density $\rho_{DM} \sim 0.3\text{GeVcm}^{-3}$, and so from this we can work out the injection rate of (more or less monochromatic) gamma rays and compare with the observed gamma ray spectrum.

The injection rate of energy is

$$I = \rho_{DM} \times m_{DM} \tag{4.5}$$

((*Exercise: for such a model, estimate (as a function of* m*) the number of photons arriving per square metre at a telescope pointed towards the Milky Way centre*)