Can dark matter be dissipative?

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Introduction: dissipative hidden sector dark matter

The nature of dark matter (DM) is among the big unsolved problems in physics. We incorporate DM by introducing a hidden sector featuring an unbroken $U(1)'$ interaction with coupling g', mediated by a *dark photon* (γ_D), and two Dirac fermions (F_1 and F_2). The dark photon interacts via kinetic mixing with the ordinary photon. The full Lagrangian is:

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \overline{\psi}_j(iD_\mu\gamma^\mu - m_j)\psi_j - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} \,.$$

F_1 and F_2 have charges opposite in sign, with charge ratio Z'. Kinetic mixing allows dark fermions to couple to ordinary photon via a tiny ordinary electric charge, $\epsilon_{F_j}e$. Two accidental $U(1)$ symmetries imply conservation of F_1 and F_2 number. Hence, the particle content is dark, massive and stable: a good DM candidate! The unbroken $U(1)'$ interaction implies our DM is dissipative, and thus requires a heat source that can replace the energy lost to dissipative interactions. We argue that kinetic mixing induced processes in the core of supernovae can play this role, provided $\epsilon \sim 10^{-9}$. Note that $\epsilon \ll 1$ is technically natural.

The fundamental physics of our model is described by 5 parameters: masses of fermions (m_{F_1} and m_{F_2}), dark fine structure constant ($\alpha' \equiv g'^2/4\pi$), charge ratio (Z') and kinetic mixing coupling ($\epsilon \equiv \epsilon_{F_1}$). We focus on the case where $m_{F_1} \ll m_{F_2}$ and explore the model in the context of early Universe phenomenology and galactic structure.

Early Universe cosmology

In the early Universe, kinetic mixing induced processes transfer energy and entropy between the visible and dark sectors. For $m_{F_1} \gtrsim 0.1$ MeV, the dominant channel is $e\overline{e} \to F_1\overline{F}_1$, with cross-section $\sim \epsilon^2$. We study how the entropy transfer affects the evolution of $\mathcal{X} \equiv T_{\gamma_D}/T_\gamma$, with initial condition $\mathcal{X} = 0$. Numerically we find that $\mathcal{X}$ evolves to a constant:

$$\frac{T_{\gamma_D}}{T_\gamma} \simeq 0.31\sqrt{\frac{\epsilon}{10^{-9}}}\left(\frac{m_e}{\mathcal{M}}\right)^{\frac{1}{4}} \,,\; \mathcal{M} \equiv \max(m_e, m_{F_1}) \,.$$

This new physics modifies the time-temperature relation and hence the fraction of Helium synthesized during BBN. We parametrize the extra energy density as an effective number of neutrino species at Hydrogen recombination and BBN, via the quantities $\delta N_{\rm eff}$[CMB] and $\delta N_{\rm eff}$[BBN]. Recent results suggest these are bounded above by $\simeq 1$, which we use to constrain the allowed region of ϵ-m_{F_1} parameter space, obtaining the following bound:

$$\epsilon \lesssim 3.5 \times 10^{-9}\left(\frac{\mathcal{M}}{m_e}\right)^{\frac{1}{2}} \,.$$

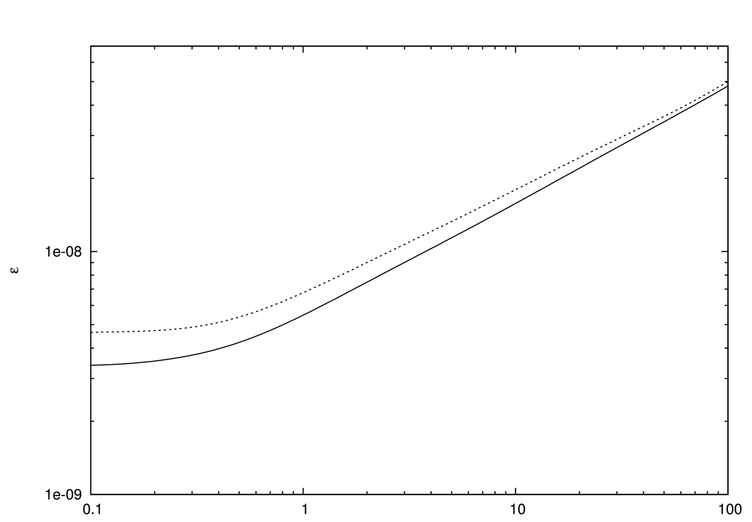

Figure 1: Exclusion limits from $\delta N_{\rm eff}$[CMB]<0.84 (above solid line) and $\delta N_{\rm eff}$[BBN]<1 (above dashed line).

Dark recombination

When the temperature of the Universe has dropped sufficiently, F_1 and F_2 particles combine into a neutral dark state, D^0, with ionization energy I'. Prior to dark recombination (DR), DM undergoes dark acoustic oscillations, suppressing power on small scales. We require DR to take place prior to matter-radiation equality, so the early growth of large-scale structure is unaffected. We solve the Saha equation for an ionization fraction $\chi \simeq 10\%$ to obtain the redshift of DR:

$$\frac{1-\chi}{\chi^2} = \mathcal{A}\xi^{-\frac{3}{2}}e^{\xi} \,, \xi \equiv \frac{I'}{T_{\gamma_D}} \,,$$

where $\mathcal{A} \simeq 3.5 \times 10^{-7}\left(\frac{10^{-9}}{\epsilon}\right)^{\frac{3}{2}}\left(\frac{\mathcal{M}}{m_e}\right)^{\frac{3}{4}}\left(\frac{\rm GeV}{m_{F_2}}\right)\left(\frac{I'}{m_{F_1}}\right)^{\frac{3}{2}}$. We obtain I' by scaling I, the binding energy of the correspective ordinary element with atomic number $Z = |Z'|$: $I' = (\frac{\alpha'}{\alpha})^2(\frac{m_{F_1}}{m_e})I$. Numerically we find that the redshift of DR depends very weakly on m_{F_2} and $|Z'|$, and obtain the following bounds:

$$\epsilon \lesssim 10^{-8}\left(\frac{\alpha'}{\alpha}\right)^4\left(\frac{m_{F_1}}{\rm MeV}\right)^2\left(\frac{\mathcal{M}}{m_e}\right)^{\frac{1}{2}} \,.$$

Galactic structure: a dynamical halo

The DM halo in spiral galaxies consists of a plasma of F_1 and F_2 particles, which loses energy through dissipative processes, such as thermal dark bremsstrahlung, at a rate $\Gamma_{\rm cool}$. We argue that kinetic mixing processes in the core of ordinary supernovae can replace this energy. Provided that $\epsilon \sim 10^{-9}$ and $m_{F_1} \lesssim 100$ MeV, these processes can convert $\sim 1/2$ of the core-collapse energy into F_1-$\overline{F}_1$ pairs and eventually dark photons. These dark photons can input energy in the halo at a rate $\Gamma_{\rm heat}$. Additionally, we require $m_{F_1} \gtrsim 0.01$ MeV, which arises from White Dwarf studies. The dynamics of the halo are governed by the Euler equations. If the system evolves to a static configuration, these reduce to two equations, dictating hydrostatic equilibrium (HE) and energy balance (EB):

$$\frac{dP(r)}{dr} = -\rho(r)g(r) \,,\quad \frac{d\Gamma_{\rm heat}}{dV} = \frac{d\Gamma_{\rm cool}}{dV} \,.$$

We first study a toy model, where all supernovae act as a point source at the galactic centre, and show that an isothermal halo ($\rho \sim 1/r^2$) provides a solution to both the HE and EB conditions. In a second more realistic model, we smear the supernova energy source over a distance scale r_D, given by the size of the galactic disk. This time the EB condition gives us a density profile $\rho \propto f(r, \cos\phi)$, where $f(r, \cos\phi) \propto 1/r^2$ for $r \gg r_D$ but is only logarithmically divergent for $r \sim r_D$. This suggests we can approximate $\rho(r)$ with a quasi-isothermal density profile, $\rho(r) \simeq \rho_0 r_0^2/(r^2 + r_0^2)$, with $r_0 \sim r_D$. This argument offers a solution to the core-cusp problem, with the core in DM halos arising from a supernovae feedback mechanism.

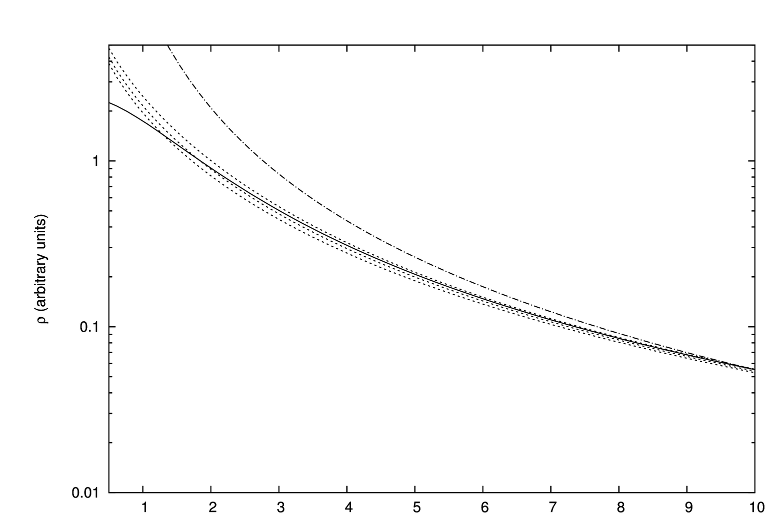

Figure 2: Comparison between radial dependence of $\rho \propto f(r, \cos\phi)$ [dotted, for varying ϕ], a cored profile [solid], and a cuspy profile [dot-dashed].

Halo scaling relations

The scaling relation $r_0 \sim r_D$ (observed to hold in spiral galaxies) was derived by imposing EB within a given galaxy. We now demand that EB hold for every spiral galaxy. We assume the halo is heated by a dark photoionization process, with cross-section σ_{DP}. The heating rate is proportional to the supernovae rate, $R_{\rm SN}$, with each supernova releasing an amount $E_{\rm SN}$ of energy, of which a fraction R_{γ_D} is converted into creation of dark photons. Cooling takes place via thermal dark bremsstrahlung, with cooling function $\Lambda(T)$. Defining $\kappa \equiv (m_{F_2} + |Z'|m_{F_1})^{-1}$:

$$\Gamma_{\rm heat} = \frac{\pi R_{\gamma_D}\sigma_{DP}\kappa\langle E_{\rm SN}\rangle}{2}\rho_0 r_0 R_{\rm SN} \,,\quad \Gamma_{\rm cool} = \pi^2\kappa^2(|Z'| - 2)\Lambda(T)\rho_0^2 r_0^3 \,.$$

Equating $\Gamma_{\rm heat}$ and $\Gamma_{\rm cool}$ we obtain the scaling relation $R_{\rm SN} \propto \Lambda(T)\rho_0 r_0^2$. For bremsstrahlung, $\Lambda(T) \propto \sqrt{T} \propto v_\infty$, where $v_\infty = \sqrt{4\pi G\rho_0 r_0^2}$ is the asymptotic rotational velocity, and hence $R_{\rm SN} \propto v_\infty^3$. Further, observational studies have related $R_{\rm SN}$ to the B-band luminosity of a galaxy, via $R_{\rm SN} \propto (L_B)^{0.73}$. It follows that:

$$L_B \propto v_\infty^4 \,.$$

The above is known as Tully-Fisher relation and is observed to hold for all spiral galaxies, although currently unexplained. We show that it arises from nontrivial energy balance dynamics, suggesting a connection between the baryonic and DM components in spiral galaxies.

It is also possible the final evolutionary stage of spiral galaxies, when these have exausted their baryonic gas, be represented by elliptical galaxies. In this case, we have shown that our model can explain a similar scaling relation that holds for ellipticals, the Faber-Jackson relation.

Consistency conditions

The viability of our model requires a few consistency conditions to hold for all spiral galaxies, regardless of size ($v_{\rm rot} \sim 50 - 300$ km/s), else there would be significant observational differences along their spectrum.

Firstly, the cooling timescale has to be less than the Hubble time. This sets an upper bound on the mass of F_2:

$$m_{F_2} \lesssim 200\left(\frac{\rm MeV}{m_{F_1}}\right)\left(\frac{\alpha'}{10^{-2}}\right)^2\left(\frac{|Z'|}{10}\right)^{\frac{3}{4}} \,{\rm GeV} \,.$$

Next, the temperature of the halo has to be sufficiently high, allowing it to be ionized and cool via bremsstrahlung. Nevertheless, the assumed heating mechanism, dark photoionization, requires the dark bound state to retain its K-shell atomic F_1 particles. Hence, the temperature must not be too high, else heating via dark photoionization cannot occur. Clearly, $|Z'| \geq 3$ is also required. These consideration allow to set an upper and a lower bound on the mass of the F_2 particle:

$$\left(\frac{|Z'|}{10}\right)\left(\frac{\alpha'}{10^{-2}}\right)^2\left(\frac{m_{F_1}}{\rm MeV}\right) \lesssim \frac{m_{F_2}}{\rm GeV} \lesssim 100\left(\frac{|Z'|}{10}\right)^3\left(\frac{\alpha'}{10^{-2}}\right)^2\left(\frac{m_{F_1}}{\rm MeV}\right)g(\alpha', Z') \,,$$

where $g(\alpha', Z') \equiv \max(\alpha'^3 Z'^4, 1)$. Requiring the upper bound to be greater than the lower bound we obtain $|Z'| \gtrsim \max[3, 4\left(\frac{m_{F_1}}{10\ {\rm MeV}}\right)^3]$.

Finally, we impose the EB condition, expressing the cooling function for bremsstrahlung explicitly. For the heating rate we can only derive an upper bound as we do not know the exact details of the spectrum of dark photons heating the halo. Exploiting the fact that $R_{\gamma_D} \propto \epsilon^2$ in $\Gamma_{\rm heat}$, we compare the two rates and, using the upper bound on m_{F_2} from the cooling timescale, we find $\epsilon \gtrsim 10^{-10}$. Finally, combining the bounds on ϵ with those on m_{F_1}, we obtain:

$$0.01\ {\rm MeV} \lesssim m_{F_1} \lesssim 100\ {\rm MeV} \,,\quad 10^{-4} \lesssim \alpha' \lesssim 10^{-1} \,.$$

Diurnal modulation signal

Cosmology and galactic structure considerations dictated that m_{F_1} be in the MeV range and m_{F_2} in the GeV-TeV range. Two types of interaction are then important for DM direct detection: F_1-electron and F_2-nuclei scattering. We focus on the latter. Due to self-interactions, F_2 particles will be accumulate inside the Earth, and can shield the halo DM wind. The maximum distance of closest approach for which a DM particle is captured determines the shielding radius of the captured DM, which we determine to be:

$$R_s \simeq 5300\left(\frac{\alpha'}{10^{-3}}\right)^{0.06}\left(\frac{m_{F_2}}{10\ {\rm GeV}}\right)^{-0.55}\left(\frac{|Z'|}{10}\right)^{0.14} \,{\rm km} \,.$$

We then study the interaction rate, which we modify by multiplying by a case function which is 0 if the distance of closest approach of the halo DM particle is less than R_s, 1 otherwise. We then calculate $\mathcal{R}$, the percentage rate suppression due to DM capture. For a detector located in the Southern hemisphere the rate suppression during a sidereal day varies between a minimum $\sim 0\%$ and a maximum $\mathcal{R}_{\rm max}$ which can be considerable, giving rise to an appreciable diurnal modulation effect. This happens because for a detector in the Southern hemisphere, the direction of the halo wind can vary from being vertically down to coming straight up through the Earth's core, and hence being shielded. For a detector located at Stawell ($\theta_l \simeq 37.1°$):

$$\mathcal{R}_{\rm max} \approx \min\left[55\left(\frac{\alpha'}{10^{-3}}\right)^{0.1}\left(\frac{m_{F_2}}{50\ {\rm GeV}}\right)^{-0.9}\left(\frac{|Z'|}{10}\right)^{0.6}\%, 100\%\right] \,.$$

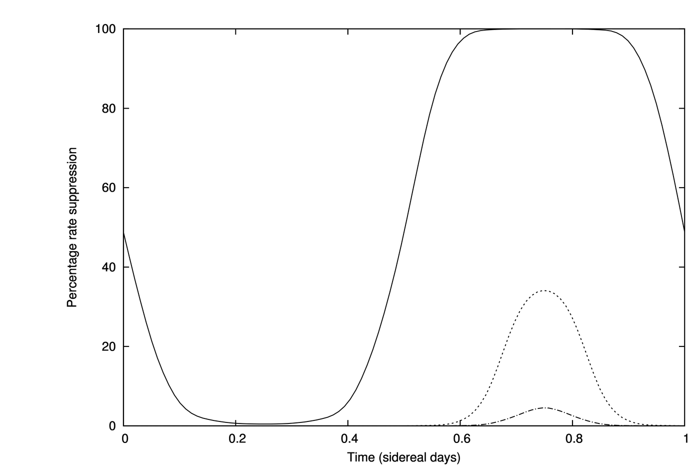

Figure 3: Percentage suppression rate for a detector located at Stawell, for $\alpha' = 10^{-2}$, $|Z'| = 10$, $m_{F_2} = 10$ GeV, 100 GeV, 1 TeV [solid, dashed, dot-dashed lines], during a sidereal day.

Conclusion

A hidden sector can be a viable way of accommodating dark matter. We have focused on a particular dissipative two-component hidden sector, and have shown that it is capable of addressing shortcomings of collisionless CDM, and explaining observed features within spiral galaxies. We have constrained the parameter space and shown that it favors a light fermion in the MeV range and a heavier one in the GeV-TeV range. Finally, we have shown that for experiments located in the Southern hemisphere, a diurnal modulation in the interaction rate is expected to be seen.

Further information and acknowledgements

For further information refer to:

R. Foot and **S. Vagnozzi**, arXiv:1409.7174 [hep-ph]

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