Cosmology of Hidden Sector with Higgs Portal

by

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Abstract

In this thesis, we are investigating cosmological implications of hidden sector models which involve scalar fields that do not interact with the Standard Model gauge interactions, but couple directly to the Higgs field. We particularly focus on their relic particle density as a candidate for dark matter. For the case of hidden sector without a gauge field we have improved the accuracy of the bounds on the coupling constant and give bounds on the Lagrangian parameters. Models with Abelian and non-Abelian gauge fields are also studied with relic density bounds, BBN and galactic dynamics constraints. Several discussions on phase transitions and alternative dark matter candidates are included.

Thesis Supervisor: Frank Wilczek
Title: Herman Feshbach Professor of Physics

Acknowledgments

"There is always another way to do it."

Richard Feynman

This is the quote I started my graduate school application. I now know that I have come to the right place and met the perfect advisor for seeking the other ways of seeing physics. *Frank Wilczek* along these years introduced me to many fascinating corners of physics, taught me how to explain things in many different ways and always encouraged me to get off the beaten track and explore the uncharted territories of physics. Every single time I got out of his office, I felt enlightened and motivated. He was not only a mentor, but a friend whom you can talk for hours with constant intellectual stimulation of many different subjects. Graduate school would not be as much fun without him.

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It is not an exaggeration to say that *my extended family*'s exceptional support brought me all the way here. They were always caring, kind and wise. I cannot express my gratitude enough.

Last but not least, my dear fiancée *Nalan Şenol*. She was always by my side, even when she was oceans away. She made me laugh, she made me dance, she made me play. She kept me cheerful and life pleasurable with her gentle touch. Together we have witnessed the development of communication through internet, now is the time to live together, forever.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Twentieth century physics brought our understanding of fundamental laws of nature from the discovery of electron to quantum mechanics, relativity, their fusion into quantum field theory and finally the Standard Model, a quantum field theory that apparently describes every directly observable phenomenon within our experimental abilities up to an immense level of accuracy. Since the completion of the model with the understanding of asymptotic freedom [1, 2] it has passed numerous tests. Even the unforeseen discoveries like the massive neutrinos can fit into the model with minimal changes. This way we now have confidence in our modern view of the fundamental laws of nature; any theory can be written as a quantum field theory Lagrangian of relevant degrees of freedom such that the Lagrangian includes all the renormalizable terms consistent with the postulated symmetries of the theory. This philosophy successfully found its way into as far as condensed matter theory. Also we learned that the physics of the very large and physics of the very small are intriguingly entangled. Many high energy physics theories has unavoidable consequences in the early universe yielding testable predictions for today.

On the other hand we know for sure that we haven't reached the final picture. There are problems ranging from the elusive quantum gravity to the more immediate issues like dark matter and dark energy puzzles and unification of forces, waiting to be tackled. Fortunately we are not short of ideas. Many different type of particles and extra symmetries can be used to extend Standard Model, or venues beyond quantum field theory can be explored as in the string theory. But symmetries we know so far gives us a firm standing on what is possible and what is not. In this thesis we will explore cosmological implications of a very natural extension of the Higgs sector, only unexplored territory in the Standard Model, so called the *hidden sector with Higgs portal* [3].

1.1 Electroweak symmetry breaking

Our understanding of the local symmetries of fields began with the seminal work of Yang and Mills. Their extension of the gauge symmetries of the electromagnetism into a model of local SU(2) symmetries of isospin [4], turned into the theory of weak interactions. Short range nature of weak interactions can be addressed by a massive force carrying particle, but that is not compatible with the gauge symmetries that for example protect the vanishing mass of the photon in electromagnetism. Soon it has been understood that mechanism proposed by Higgs [5] as a vacuum state with a broken symmetry, can be used to describe both electromagnetism and weak interactions in SU(2)×U(1) electroweak theory [6, 7, 8]. In electroweak theory gauge bosons interact with a complex SU(2) doublet scalar called the Higgs field. Even though the Lagrangian is symmetric under rotations in the complex plane of the Higgs field, lowest energy state is not, so the vacuum state develops a vacuum expectation value in a random direction. This is a breakthrough in our understanding of nature, because we now know that what we call as vacuum is more than void space. Fields may have non-zero values everywhere leading to observable consequences, massive gauge bosons and massive fermions that have gauge interactions as well, in this case. We see Higgs field as the source of all the bare mass of the fundamental particles.

Higgs field is one of the main pillars of Standard Model, which we have great confidence in. But so far we are unable to create and detect Higgs particles, excitations of this field (although one might argue that we have seen three quarters of the Higgs sector as the longitudinal excitations of the weak boson). There is a remarkable chance that Higgs sector is more complicated than the simplest case we have been using in the Standard Model. It may well be a composite particle as in the technicolor models, have more than one component, interact with particles that do not interact with the other particles in the Standard Model, or show extra properties that have been suggested or not in the countless number of works in the literature.

As of this writing, we are at the verge of a historical moment in science. Large Hadron Collider (LHC) at CERN will start its science runs soon, and for the first time we will be able to directly probe energies at the scale of electroweak interactions. Whether there is plain Higgs or a more exciting reality, we will be able to observe and learn. So it is timely for us theorists to think all the possibilities in the Higgs sector and may be bring clues from cosmology if possible.

1.2 Dark matter problem

One of the oldest surviving puzzles of modern theoretical physics is the dark matter problem. As early as 1930s, thanks to Zwicky's observations [9], it was evident that ordinary matter that interacts with photons cannot constitute all the matter in the galaxies. Following these early observations on galactic rotational velocity curves, decades of evidence piled up in every part of astrophysics. Star clusters, galaxies, galaxy clusters, structure formation simulations, Big Bang Nucleosynthesis calculations, gravitational lensing studies and most recently cosmic microwave background fluctuations, all consistently point out that there is significant amount of non-relativistic particles that are not in the Standard Model. We now estimate about 25% of all the energy is in the form dark matter, leaving room for 70% of even more mysterious dark energy and only 5% in ordinary matter [57, 58].

There are innumerable theoretical suggestions in the literature [10]. One of the most interesting observations is the "WIMP miracle". It is a generic result that any electromagnetically neutral particle that were in thermal equilibrium until the universe cools down to electroweak scale and has a mass at the order of electroweak scale will give about the right magnitude for the relic density for dark matter today. So particles that have only weak interactions are a natural candidate. They are generally referred as WIMPs (Weakly Interacting Massive Particles).

We will give two concrete theories that give natural dark matter candidates while addressing other important issues in high energy physics. First are the supersymmetric theories. Supersymmetry is an extension of the Lorentz symmetry that allows Lagrangians with symmetries between bosons and fermions, which never happens in the symmetries we discovered so far. It is possible to extend Standard Model by postulating a supersymmetry, most popular way is the MSSM (Minimal Supersymmetric Standard Model) [11]. It is obvious that no known particle can turn into another by a change of half spin. So if there is supersymmetry there must be extra particles for each particle in the Standard Model. Also supersymmetry cannot be exact, otherwise supersymmetric partners will have the same mass with the Standard Model counterparts and we would produce and observe them in the laboratory. There are many ways to break supersymmetry to give extra mass to supersymmetric partners. Almost all of them leave some weakly interacting particles with electroweak scale mass. Unfortunately details are tied to the details of the symmetry breaking scheme. If supersymmetry exists, we will most probably be able to see it in LHC or in ILC (International Linear Collider), the next collider currently being planned. Possibility of supersymmetry is exciting not only because it gives dark matter candidates but also an explanation for the hierarchy problem [11], make the unification scenarios more plausible [12] and extends our understanding of symmetry to the maximally possible case (up to conformal symmetry) [13].

Despite the WIMP miracle, having a particle with electroweak scale interactions is not the only way to have a dark matter candidate. One attractive theory that has a much different origin and energy scale is the theory of *axions*. Only Lagrangian term that is consistent with Standard Model symmetries, we don't observe is the CP violating "θ term" in QCD:

$$\theta F_{\mu\nu}\tilde{F}^{\mu\nu} \tag{1.1}$$

Unnaturally strong observational bounds on this term is known as the *strong CP* *problem*. Peccei and Quinn introduced a new symmetry on the θ which is promoted into a field of its own [14, 15]. Spontaneous breaking of the symmetry leaves a pseudo-Goldstone boson with a small mass. It is called the axion [16, 17]. There is a freedom in the mass of the axion and it may have energy densities comparable to what we need for dark matter.

1.3 Hidden sector and Higgs portal

Renormalizability is a strong condition on quantum field theory Lagrangians and leaves little room for changes, especially in the Standard Model. All the terms are strictly renormalizable with dimensionless coupling constants, with only one exception[1]. Negative bare mass term of the Higgs field has a coupling constant of mass dimension 2:

$$-\mu^2\phi^\dagger\phi \tag{1.2}$$

One can promote this constant to a new field and make a still renormalizable term out of this super-renormalizable one. This is what we call as the Higgs portal. This is a generic feature of scalar field theories, in the sense that unless forbidden by some unknown symmetry any two scalars will interact with each other therefore with the Higgs as well.

Even though having a Higgs portal into new types of fields, is an attractive idea, one should also make sure that new fields do not interact with Standard Model in any other way or they are very massive. Having particles that have no Standard Model charges (i.e. gauge singlets) is not a new idea [19]. They are called hidden sector in general [3, 28, 29, 30, 71, 42, 53]. Many high energy theories predict such extra sectors at low energy like the $E_8 \times E_8'$ superstring theories or intersecting D-brane theories[20, 21].

One class of popular hidden sector models is the *mirror world* models. These are theories with an exact copy of Standard Model in terms of gauge symmetry structure,

[1]One might also add a Yukawa coupling between leptons and the Higgs field $\bar{L}\tilde{H}$ [18].

sometimes interacting with the Higgs sector. Both particle physics and the cosmology of these models is extensively studied [22, 23, 24, 25, 26, 27]. Main difficulty here is to have an asymmetry between two worlds, since we do not see indications for hidden astronomical objects (stars, galaxies etc.). One way is to create much less of the mirror world particles or make them much colder at reheating.

Similar concerns undermine many hidden sector theories, as we do not know the physics at the reheating stage. Theories with Higgs portal have considerable advantages in this respect. They are concrete and give us control on the amount of particles. Also naturally giving dark matter candidates with electroweak scale mass and interactions without directly coupling with weak bosons.

In addition to that, Higgs portal opens up a new venue for direct searches both at the accelerators and astrophysical detectors. LHC will soon be online and probing Higgs sector. Anything that couples strongly with Higgs should have observable consequences. Either seen as large missing momentum, or completely hiding Higgs by invisible decays, or significantly shifting the Higgs mass we will be able to understand whether Higgs portal opens up to new world or not.

If a hidden world of particles exist, by the history of particle physics we would not expect them to be plain and of a single kind. As well as having a self potential, they might possess new gauge symmetries. New gauge symmetries are exiting because they bring plenty of non-trivial phenomena, like new phase transitions, new low energy effective theories and of course new unification schemes.

Until LHC, cosmology is the best place to understand the limits on those ideas and identify the areas of opportunity. In the following chapters we will follow both of these paths and along the way we will find scenarios that are not evident at the first place when we start writing our simple Lagrangians.

1.4 Outline

We will start our discussion in Chapter 2 with the simplest possible theory of hidden sector with Higgs portal, just a single gauge singlet scalar field with Higgs coupling.

We will comment on the effects in electroweak symmetry breaking at zero and finite temperature, calculate relic particle density and improve the bounds on the physical quantities as well as introduce bounds on Lagrangian parameters. Chapter 3 extends the discussion with an Abelian gauge field in the hidden sector. We will explore the new phenomenology and corresponding limits from Big Bang Nucleosynthesis, galactic dynamics and once again relic particle densities. More complex scenarios will also be mentioned. In Chapter 4 ramifications of non-Abelian gauge fields is considered. We will see that, their confining nature may enhance the energy density of hidden sector. And finally in Chapter 5 we will give our concluding remarks and state further avenues in research as well as opportunities in particle accelerators.

Chapter 2

Gauge Singlet Hidden Sector

In this chapter, we will be studying a scalar hidden sector particle with Higgs interactions. This is a well studied model [3, 28, 29, 30, 71, 42, 53]. We will comment on its effects in the electroweak phase transition. As the hidden scalar particle is stable it is a natural dark matter candidate even in its simplest manifestation as discussed before. We will carefully improve previous bounds and for the first time introduce bounds on the Lagrangian parameters.

2.1 The model

Simplest renormalizable extension of the Standard Model Lagrangian with an extra scalar field and its coupling to the complex Higgs doublet has the following extra terms in addition to the fermions and vector bosons of the Standard Model Lagrangian:

$$\mathscr{L} = \frac{1}{2}\partial_\mu\phi_H\partial^\mu\phi_H^\dagger + \frac{1}{2}\partial_\mu\phi_S\partial^\mu\phi_S - V_0(\phi_H,\phi_S) \tag{2.1}$$

$$V_0(\phi_H,\phi_S) = -\frac{1}{2}\mu_H^2\phi_H\phi_H^\dagger - \frac{1}{2}\mu_S^2\phi_S^2 + \frac{1}{4}\lambda_H(\phi_H\phi_H^\dagger)^2 + \frac{1}{4}\lambda_S\phi_S^4 + g(\phi_H\phi_H^\dagger)\phi_S^2 \tag{2.2}$$

Here ϕ_H is the Standard Model Higgs field doublet and ϕ_S is the hidden sector scalar field. Signature of each term is important. Signature of the λ term must be positive for potential to be bounded from below so that the vacuum is stable. On the other hand g term can be negative but it cannot get every negative value. One can find the constraint by looking at the limit at infinity on an arbitrary direction $\langle\phi_H\rangle = k\langle\phi_S\rangle$. In that case $(\frac{1}{4}\lambda_H k^4 - gk^2 + \frac{1}{4}\lambda_S) > 0$ for all k, so discriminant of the polynomial must be negative; $(g^2 - \frac{1}{4}\lambda_H\lambda_S) < 0$. This gives the condition on the magnitude of negative coupling constant g:

$$g < \frac{1}{2}\sqrt{\lambda_H\lambda_S} \tag{2.3}$$

Also we will assume all these dimensionless parameters (g, λ_H, λ_S) to be less than unity to stay in the perturbative regime of the quantum theory. We are free to choose signature for the μ terms, but in the classical field theory they need to be negative for spontaneous symmetry breaking in the corresponding term.

2.2 Classical phase transition

We can understand the vacuum structure of the Lagrangian (2.1) in classical field theory, by just studying the minimums of the potential (2.2). Obviously there are four possible states where Higgs sector and the hidden sector develop a vacuum expectation value or not. But for phenomenological purposes Higgs has to have the right magnitude of the vacuum expectation value. So we will be interested only in such states. Using the gauge freedoms of Standard Model, we can write the SU(2) doublet Higgs field in the following form, so called the unitary gauge:

$$\phi_H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_H + h \end{pmatrix} \tag{2.4}$$

Here v_H is the vacuum expectation value of the Higgs field and h is the field corresponding the physical Higgs scalar. Remaining degrees of freedom will be observed as the longitudinal components of the Standard Model weak bosons. In this gauge expectation values will be:

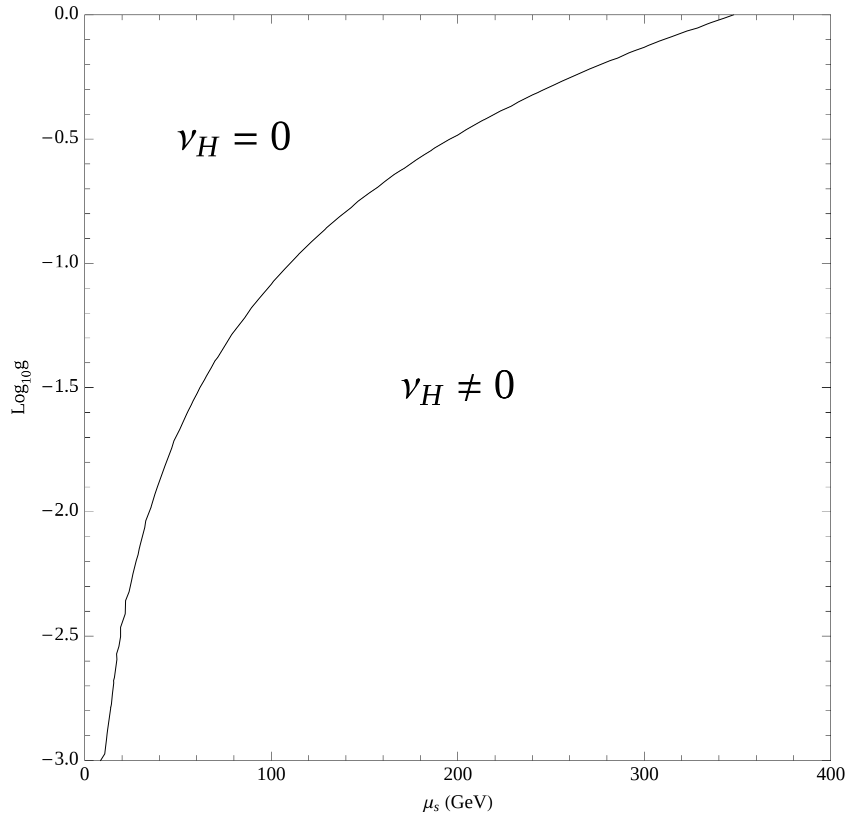

Figure 2-1: Prediction of classical field theory of phase transition for v_H =246 GeV.

$$\langle\phi_H\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_H\end{pmatrix} \tag{2.5}$$

$$\langle\phi_S\rangle = \frac{1}{\sqrt{2}}v_S \tag{2.6}$$

When we require $v_H \neq 0$ effective potential for ϕ_S becomes.

$$V_{eff}(\phi_S) = -\frac{1}{2}\mu_S^2\phi_S^2 + \frac{1}{4}\lambda_S\phi_S^4 + gv_H^2\phi_S^2 \tag{2.7}$$

Spontaneous symmetry breaking under this potential occurs when

$$gv_H^2 - \frac{1}{2}\mu_S^2 < 0 \tag{2.8}$$

with the vacuum expectation value of:

Vacuum	M_S^2
$v_S = 0$	$2gv_H^2 - \mu_S^2$
$v_S \neq 0$	$2\mu_S^2 - 4gv_H^2$

Table 2.1: Mass of the hidden scalar for different vacuum states

$$v_S = \sqrt{\frac{\mu_S^2 - 2gv_H^2}{\lambda_S}} \tag{2.9}$$

Figure 2-1 shows the phase boundary on the parameter space for v_H =246 GeV. At this vacuum state mass of the Higgs field and the hidden scalar is given by:

$$M_S^2 = 2\frac{d^2V_{eff}}{d\phi_S^2}\bigg|_{\phi_S=v_S} = -\mu_S^2 + 3\lambda_S v_S^2 + 2gv_H^2 \tag{2.10}$$

Using (2.9) we get the result shown in Table 2.1 for M_S.

By doing the same analysis on the Higgs sector, we can see that it is always possible to find μ_H and λ_H to get the right value of M_H and v_H consistent with the above values.

2.3 Radiative effects on phase transition

Classical field theory is not the end of story. One needs to check the quantum effects on the vacuum state. We will be studying the one-loop corrections to the effective potential of interacting scalar field. Such effects on spontaneous symmetry breaking was first studied by Coleman and Weinberg [34]. They showed that it is possible to have broken symmetric state through radiative corrections even if classical prediction does not say so.

One loop correction in the effective potential of a scalar field through an interaction of another one is given by [35, 43]:

$$V_1 = \frac{M^4}{64\pi^2}\left(\ln\frac{M^2}{Q^2} - \frac{3}{2}\right) \tag{2.11}$$

Here M is the mass of the interacted field. For example it is the mass of the hidden

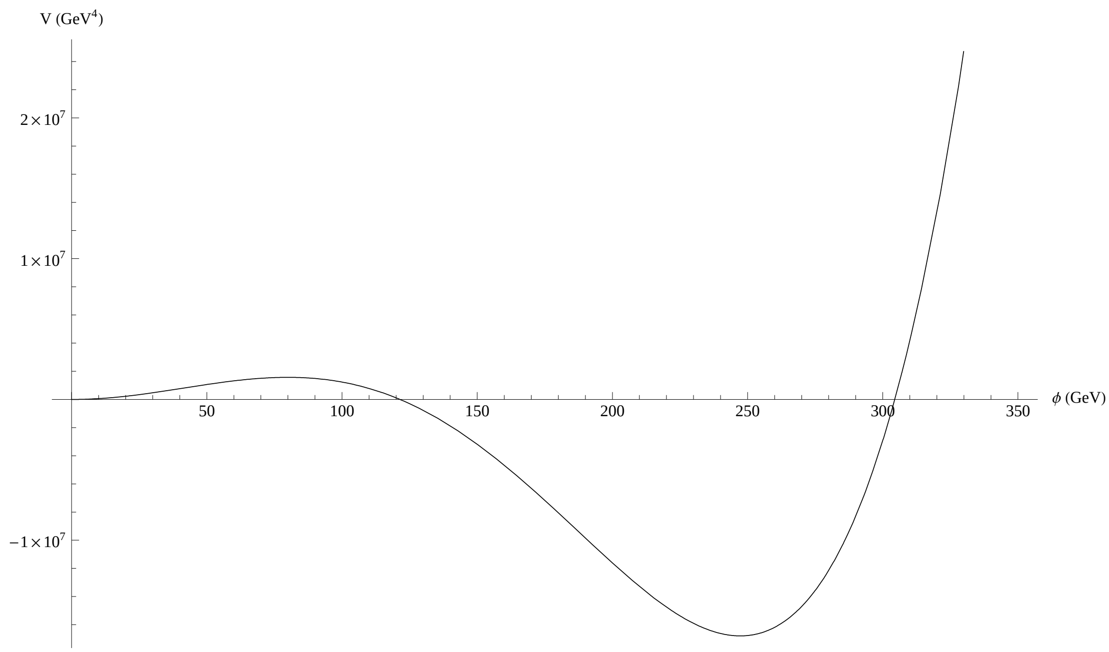

Figure 2-2: Effective potential with one-loop corrections at the renormalization scale $Q = M_{top} \approx$170 GeV, $\mu_H(Q)$=35 GeV, $\lambda_H(Q)$=-0.001 with 12 species of hidden scalars which has no self potential.

scalar if we are calculating the Higgs potential this is mass of the hidden scalar and vice versa. Q on the other hand is the renormalization scale of the quantum calculations. We set it to a phenomenologically relevant scale and in other energy scales coupling constants run to keep physical quantities (like the vacuum expectation value of Higgs) at the correct value. In the following discussion we take it to be the top quark mass $M_{top} \approx$170 GeV as all the Standard Model particles are lighter than this cut-off scale.

Electroweak symmetry breaking is a sector that we do not have any direct experimental results so far. Assuming that the Higgs field exists, we do not know what is the symmetry breaking mechanism, whether it is explicit in the fundamental Lagrangian or due to interactions with other fields. Hidden sector scalar is a possible extension of Standard Model Higgs, which might have significant effects in the symmetry breaking. Recently Espinosa *et. al.* published a study on the effects of an extra scalar which does not have its own explicit potential [43]. In that case, they showed that one loop corrections as written in (2.11) may lead to dynamical symmetry breaking of the Higgs field for reasonable values of parameters while the signature of the explicit mass term is positive, provided that there exist enough species in the hidden sector.

There are several consequences for the Higgs sector symmetry breaking. First of all in quantum formalism coupling constants run (i.e. have different values for different renormalization scales). We no longer require that λ to be positive or signature of the mass term to be negative for a stable broken vacuum state. Figure 2-2 is one such example. Note that effect of this magnitude required 12 species of hidden scalars. Two-loop corrections are naturally much smaller and do not change this picture significantly.

In our model we assumed that there is a single Higgs and single hidden scalar. In this case corrections of the order of (2.11) are negligible next to the electroweak scale coupling constants in the hidden sector potential. Hence in calculations of the relic density we will follow the classical approximation for the mass and ignore the logarithmic running of the coupling constants in the collisions at different energies.

2.4 Phase transition at finite temperature

One-loop quantum corrections not only has effects on the vacuum state at low energy limit, but also determine what is the symmetry breaking energy and what is the nature of the phase transition. This is essentially studying the quantum field theory at finite temperature. Finite temperature QFT is a well studied area and in this section we will state few relevant results.

One loop effective potential is defined to be:

$$V_{eff}(\phi_H, \phi_S) = V_0(\phi_H, \phi_S) + V_1(\phi_H, \phi_S) \tag{2.12}$$

Temperature dependent part of the one-loop potential is dominated by the following T^4 term [35]:

$$V_1^T = \frac{T^4}{2\pi^2} \int_0^\infty x^2 \ln \left[1 - e^{-\sqrt{x^2 + m^2/T^2}} \right] dx \tag{2.13}$$

for every scalar in the theory. When there is a symmetry breaking there will be

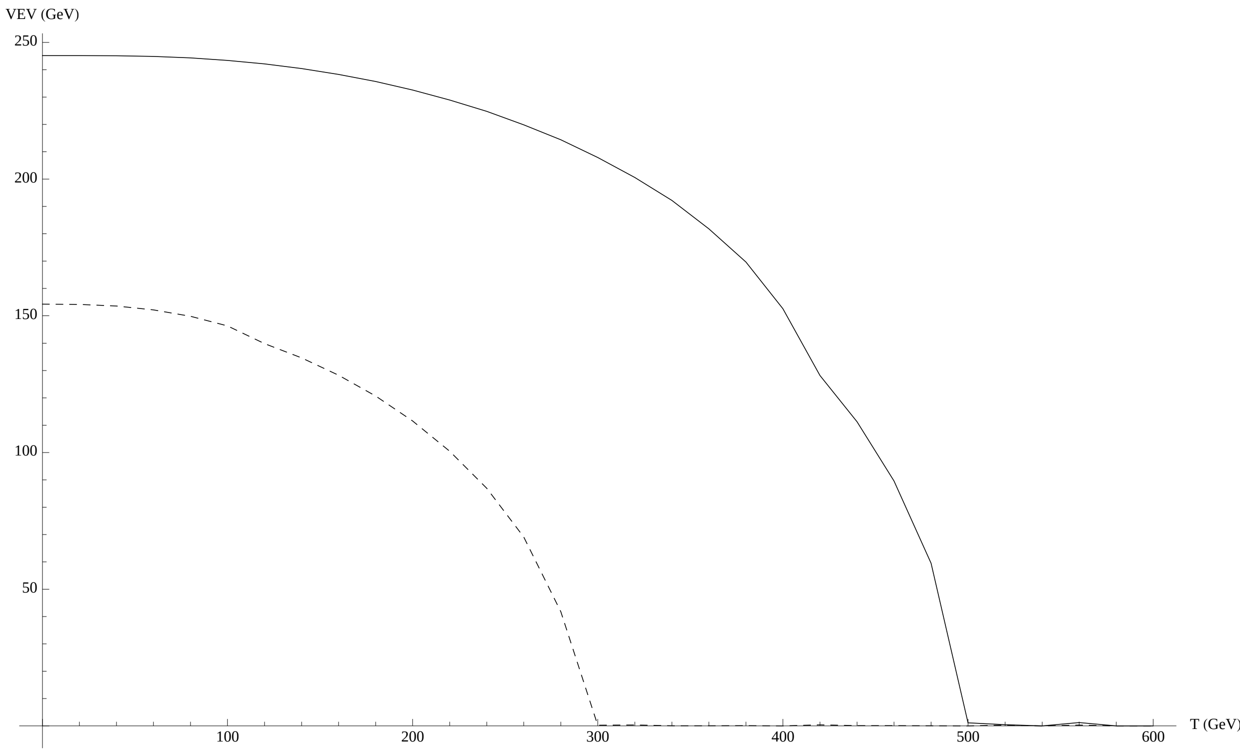

Figure 2-3: Minima of the effective potential at different temperatures. Here $\mu_H = (120/\sqrt{2})$ GeV, $\mu_S = 50$ GeV, $\lambda_H = 120^2/(2 \times 246^2)$, $\lambda_S = 0.1$ and $g = 0.001$. Solid curve is the Higgs field, dashed curve is the hidden scalar.

two states with the following shifted masses:

$$M_H^2 = -\mu_H^2 + 3\lambda_H \phi_H^2 + 2g\phi_S^2 \tag{2.14}$$

$$M_S^2 = -\mu_S^2 + 3\lambda_S \phi_S^2 + 2g\phi_H^2 \tag{2.15}$$

One can use this temperature corrected potential to calculate the field values for the minimum of the potential. One caveat is that V_1^T can be imaginary at some points. This peculiarity of perturbative approach has been carefully studied by Weinberg & Wu [36]. Basically, it is interpreted as usual for a decay rate of the state, so one needs to minimize with respect to the real part and make sure that imaginary part is small enough for a stable state.

In our model as we have seen it is easy to find some parameters such that both fields acquire a vacuum expectation value. Figure 2-3 is an example. For these particular parameters, both fields go through a second order phase transition. Note that zero temperature Higgs vacuum expectation value has the correct phenomenological value. Also in this case imaginary part of the potential is about three orders of magnitude smaller.

Order of phase transition has observable cosmological consequences. For example, first order electroweak phase transitions are associated with strong gravitational wave signals due to the corresponding bubble nucleations in the vacuum [37, 42]. Similarly various models of electroweak baryogenesis requires such thin bubble walls occurring during the first order phase transition [37, 38, 39, 40]. It is very unlikely to have such an effect for the second order transition [41]. Hence details of the hidden and Higgs sector coupling is relevant to cosmology beyond the possible dark matter candidates we will discuss in the next section.

2.5 Relic density constraints

As we have seen in the previous sections there is a significant portion of parameter space that allows vanishing vacuum expectation value in the hidden sector. When there is no vacuum expectation value, hidden sector is $\mathbb{Z}_2$ (i.e. $\phi_H \to -\phi_H$) invariant, so the hidden particle is stable. Stable particles are interesting from the cosmological perspective because they may constitute dark matter if it has enough abundance. On the other hand known bounds on the dark matter density give constraints on the model parameters. In this section we will study the cosmology of relic particles in our model.

Calculation of relic densities is a well known procedure [54, 55]. Assuming that interactions are strong enough, in the early universe all particle species will be in thermal equilibrium. Hidden sector will stay in equilibrium through the Higgs portal. As the universe cools down and dilutes hidden particles will not be able to find each other and energy transfer between the sector becomes negligible. This is called the *freeze-out*. After the freeze out Hidden sector cools separately and since the particle

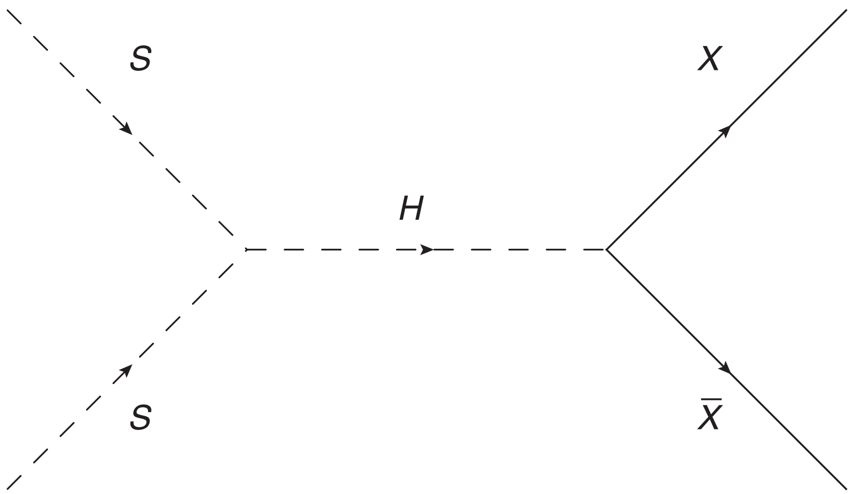

Figure 2-4: S-channel interaction that keeps hidden sector and Standard Model particles in thermal equilibrium in the early universe. Here X and $\bar{X}$ are any Standard Model particle and its anti-particle, that has 3-vertex interaction with the Higgs.

is stable, dilutes by the change of the volume of the universe. We will follow these steps in the calculation below.

In the early universe, dominant interaction that keeps two sectors at the same temperature would be by the s-channel annihilation of two hidden scalars into a virtual Higgs and through that into Standard Model pairs (see Figure 2-4). Freeze-out temperatures are typically an order of magnitude smaller than the mass of the decoupled particle. In our case mass of the hidden scalar is around the electroweak scale, so it is safe to assume that during the freeze-out Higgs is a massive single degree of freedom scalar and both particles are non-relativistic. Non-relativistic cross section of two scalars into Standard Model particles through an intermediary Higgs is given by [30]:

$$\sigma v = \frac{8g^2 v_{EW}^2}{(4M_S^2 - M_H^2)^2 + M_H^2 \Gamma_h^2} F_x \text{ with } F_x := \lim_{m_{\tilde{h}} \to 2M_S} \left(\frac{\Gamma_{\tilde{h}}}{m_{\tilde{h}}} \right) \tag{2.16}$$

where σ is the cross section, v is the relative velocity of two particles, g is the

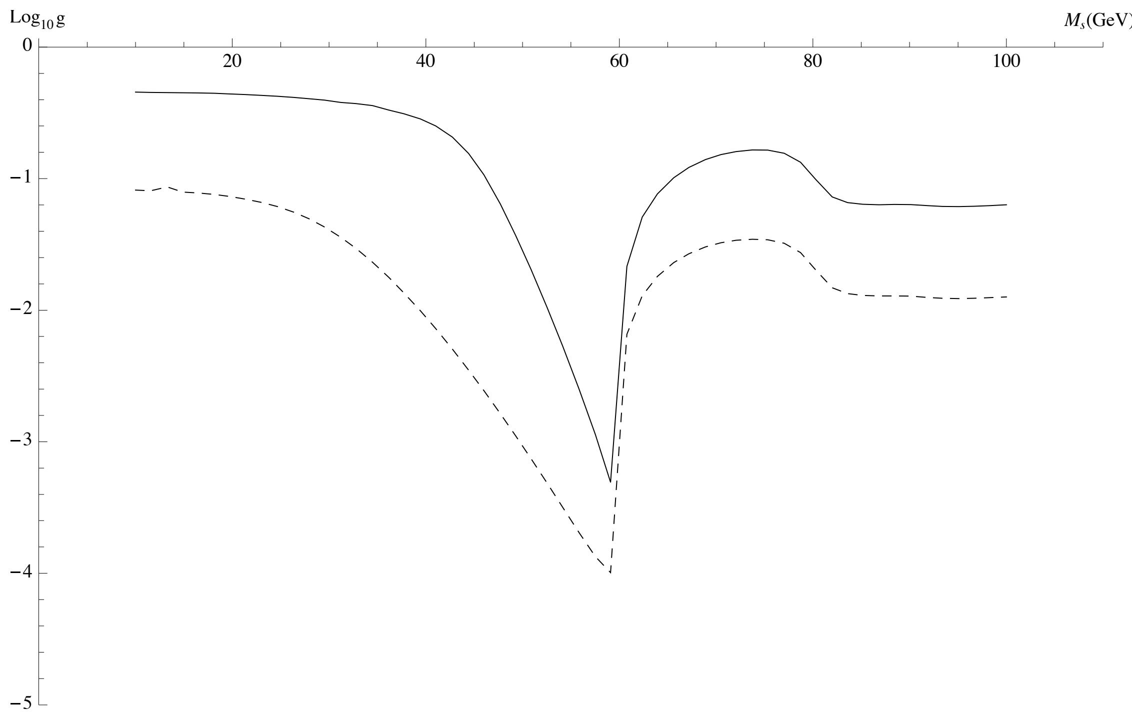

Figure 2-5: Effect of post-freeze-out annihilations on the lower bound of g for varying hidden scalar mass. Here Higgs mass is 120 GeV and upper bound on Ωh^2 is 0.3. Solid curve is our result and dashed curve is due to Burgess *et.al.*

coupling constant, v_{EW} is the vacuum expectation value of the Higgs field, M_S is the hidden scalar mass, M_H is the Higgs mass, Γ_h is the total Higgs decay rate and $\Gamma_{\tilde{h}}$ is the decay rate for a virtual Higgs with mass $m_{\tilde{h}} = 2M_S$.

Since the relative velocity is a distribution, we need to do a thermal averaging of the cross section:

$$\langle \sigma v \rangle = \frac{x^{3/2}}{2\pi^{1/2}} \int_0^\infty v^2 (\sigma v) e^{-xv^2/4} dv \tag{2.17}$$

where $x = M_S/T$ is a measure of temperature T.

Interactions effectively freeze-out at a temperature that is the solution of the equation

$$x_f = \frac{M_S}{T_f} \approx \ln \frac{0.038 m_{Pl} M_S \langle \sigma v \rangle}{g_*^{1/2} x_f^{1/2}} \tag{2.18}$$

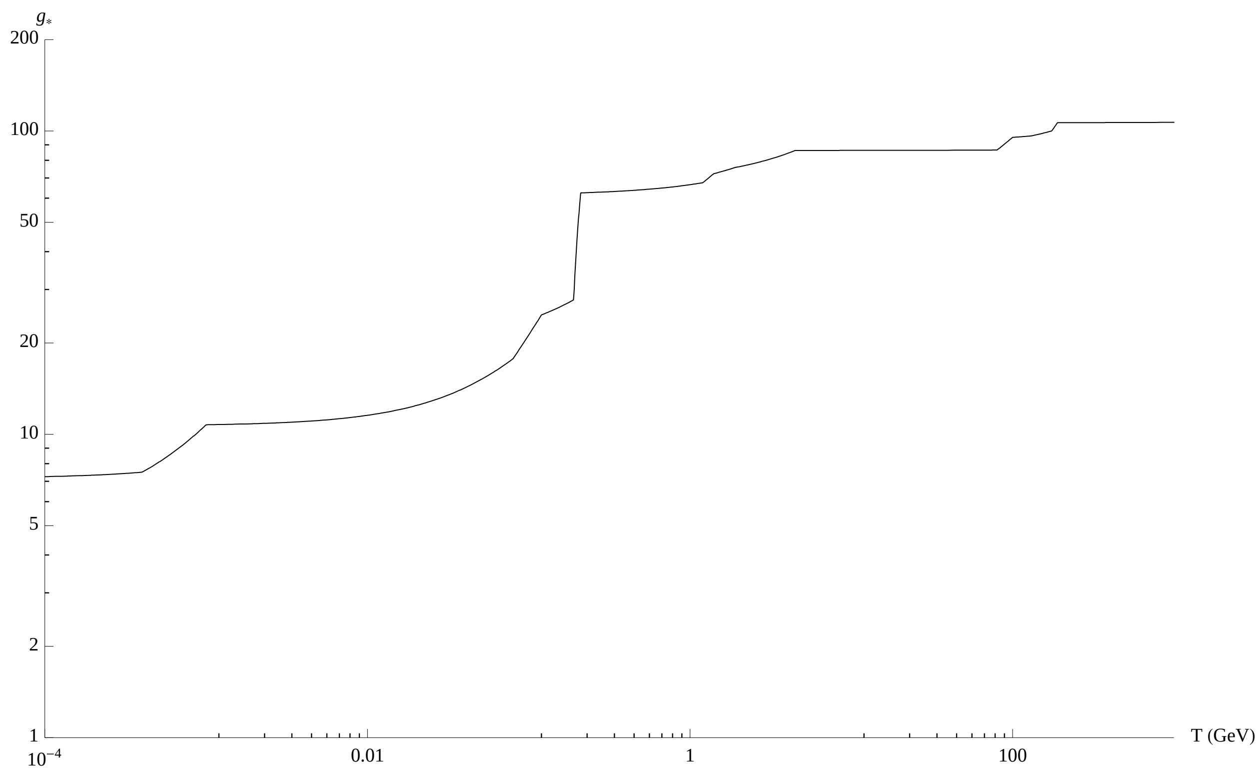

Figure 2-6: Relativistic degrees of freedom vs temperature for Standard Model. Values are extracted from PDG tables [58]. QCD phase transition temperature is taken to be 200 MeV.

where m_{Pl} is the Planck mass and g_* is the relativistic degrees of freedom at this temperature. After the freeze-out particles dilute and reach present day abundance of

$$\Omega h^2 \approx \frac{1.07 \times 10^9 \text{ GeV}^{-1}}{J g_*^{1/2} m_{Pl}} \tag{2.19}$$

where Ω is the ratio of the energy density to the critical density, h is the dimensionless Hubble parameter and J is a modified cross-section to take into account of further annihilations after freeze-out [31]

$$J = \int_{x_f}^{\infty} \frac{\langle \sigma v \rangle}{x^2} dx = \int_0^{\infty} v(\sigma v) \text{erfc}(v\sqrt{x_f}/2) dv \tag{2.20}$$

One can plot g vs the physical mass of the hidden scalar for a given Higgs mass and current relic density Ωh^2. Figure 2-5 is one such plot. For these type of plots, one

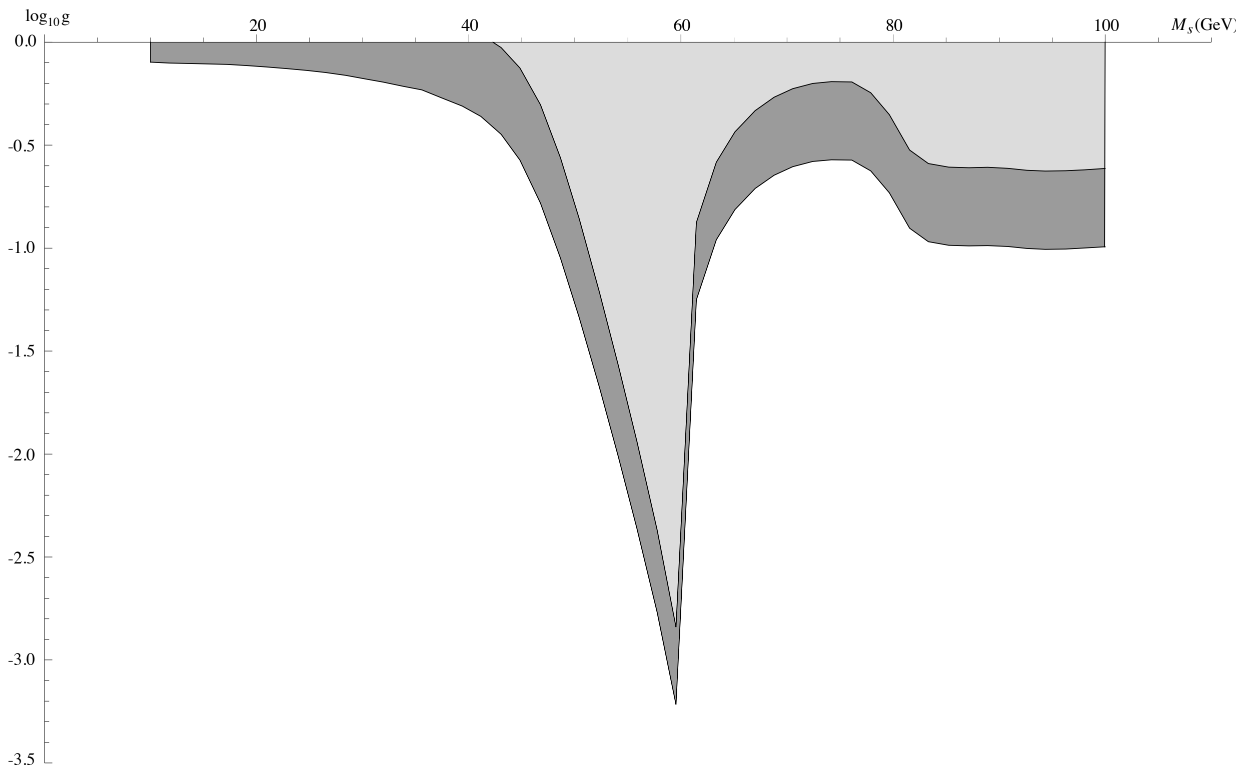

Figure 2-7: Constraints on the coupling constant g between the two sectors for various values of hidden scalar mass M_S. Shaded regions are allowed for Higgs mass of $M_H = 120$ GeV and $\Omega_{CDM}h^2 = 0.1131$. Upper contour is for 20% dark matter so dark shaded region gives significant amount of dark matter.

needs to calculate decay widths Γ_S and $\Gamma_{\tilde{h}X}$ precisely. Full decay widths include many processes in the Standard Model and do not have a simple form. Fortunately there are well developed computer software already available. We have used HDECAY [32] for numerical values of decay widths. Then we found a solution to g and x_f iterating equations (2.18) and (2.19).

In an earlier work Burgess *et.al.* performed this analysis [30]. Here we are improving the accuracy of the bounds in several ways. Most important one is the effect of post-freeze-out interactions (2.20). Previous values are calculated assuming that there is no annihilation at all after freeze-out. This essentially corresponds to taking $J = \langle\sigma v\rangle/x_f$. In Figure 2-5 we are using the parameters in this particular study. We have found that this changes the bounds by about an order of magnitude.

In recent years, thanks to unprecedented raise of precision cosmology we have

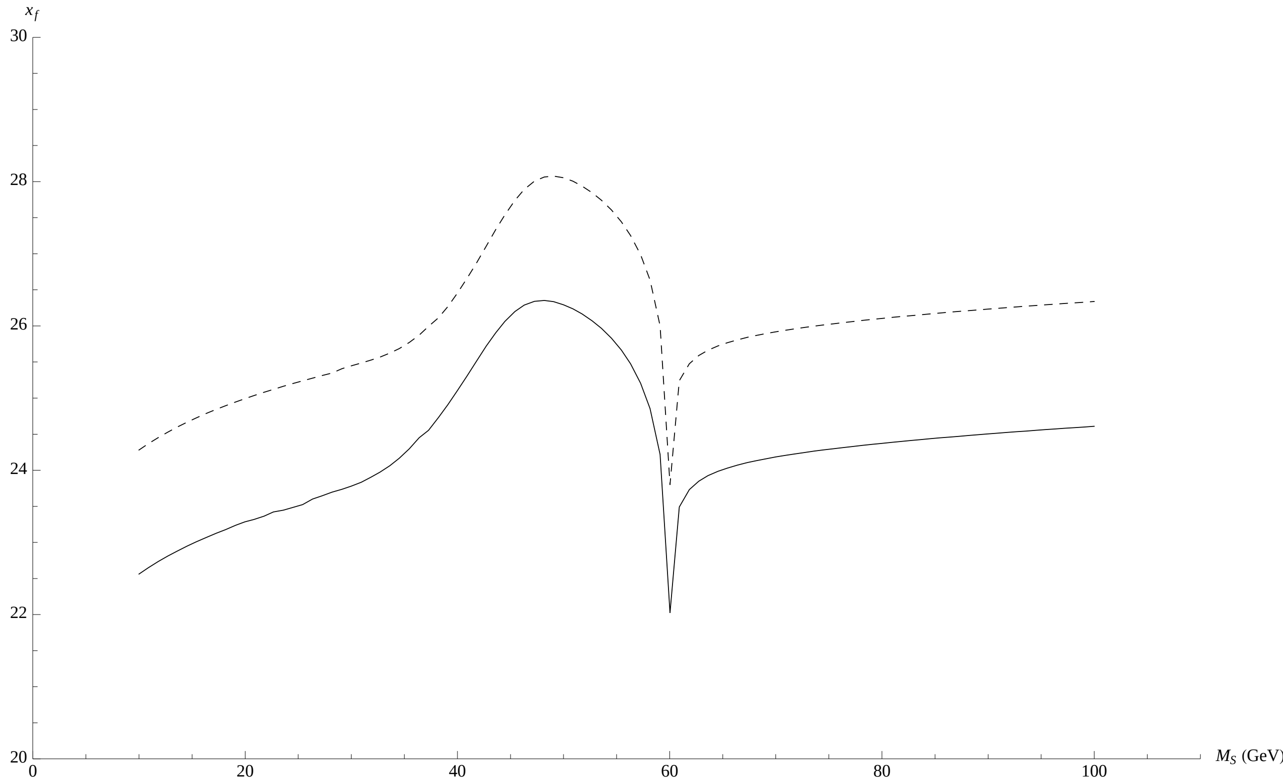

Figure 2-8: Inverse freeze-out temperature $x_f = M_S/T_f$ for different values of M_S in the cases when hidden sector is all of the current dark matter (solid line) and 20% of it (dashed line). Again $M_H = 120$ GeV.

much better accuracy in cosmological parameters compared to a decade ago. Best estimates on the cold dark matter density is $\Omega_{CDM}h^2 \approx 0.1131 \pm 0.0034$ [56, 57]. We will use this value for the rest of the calculations.

Another improvement we are offering is using temperature dependent relativistic degrees of freedom. Figure 2-6 shows the values we extracted from PDG tables [58]. These two changes has significant effect as seen on the following plots. Also we are taking Higgs mass to be M_H =120 GeV as it is the mostly likely value within the most recent collider results [59].

Final results taking all the aforementioned conditions into account, are plotted in Figure 2-7. Here the lower contour is the current constraint on g and values above are allowed. Note that in (2.19) current density is inversely proportional to cross section, so higher coupling constant gives lower current density. Upper contour is for the case when the current density is only the 20% of the cold dark matter today. So we can see the band of values in dark shade where there is significant amount of dark matter from the hidden sector. Dip around 60 GeV is due to the resonance of the intermediate Higgs boson at the twice that mass. Higher cross section around the resonance makes lower values of the coupling constants possible.

Figure 2-8 is the values of the inverse freeze-out temperature for the above scenario, again for 100% and 20% of the dark matter. Values of x_f in the range of 20-30 is very typical for electroweak scale dark matter candidates. We can still see the effect of Higgs resonance.

In Figure 2-9 we are offering a new type of analysis, namely the constraints on the Lagrangian parameter μ_S instead of the mass M_S. This is done in the same way Figure 2-7 but using Table 2.1. Note that this result is independent of the value of λ_S, it only changes the vacuum expectation value when there is one. Also there is a large region where considerable amount of dark matter is produced.

2.6 Unstable relic particles

We have seen that for large part of the parameter space we investigated, relic particles are unstable. On the other hand unstable particles still may have cosmological effects. They may either have lifetimes comparable to universe, or live long enough to survive until nucleosynthesis era ($\sim$ 300 sec.). In the latter case either by bringing extra mass density or photodisassociation and photoproduction of light elements unstable particles may have observable consequences [44, 45].

One can estimate the lifetime, corresponding to an interaction of the hidden scalar to its background field through a virtual Higgs into Standard Model particles. There are two one vertex Feynman diagrams as shown in Figure 2-10. For the first one, decay rate will include square of the vertex factor with two Higgs propagators, two virtual Higgs decay rates as calculated by HDECAY times the phase space factor with mass dimension three as can be seen from the dimensional analysis:

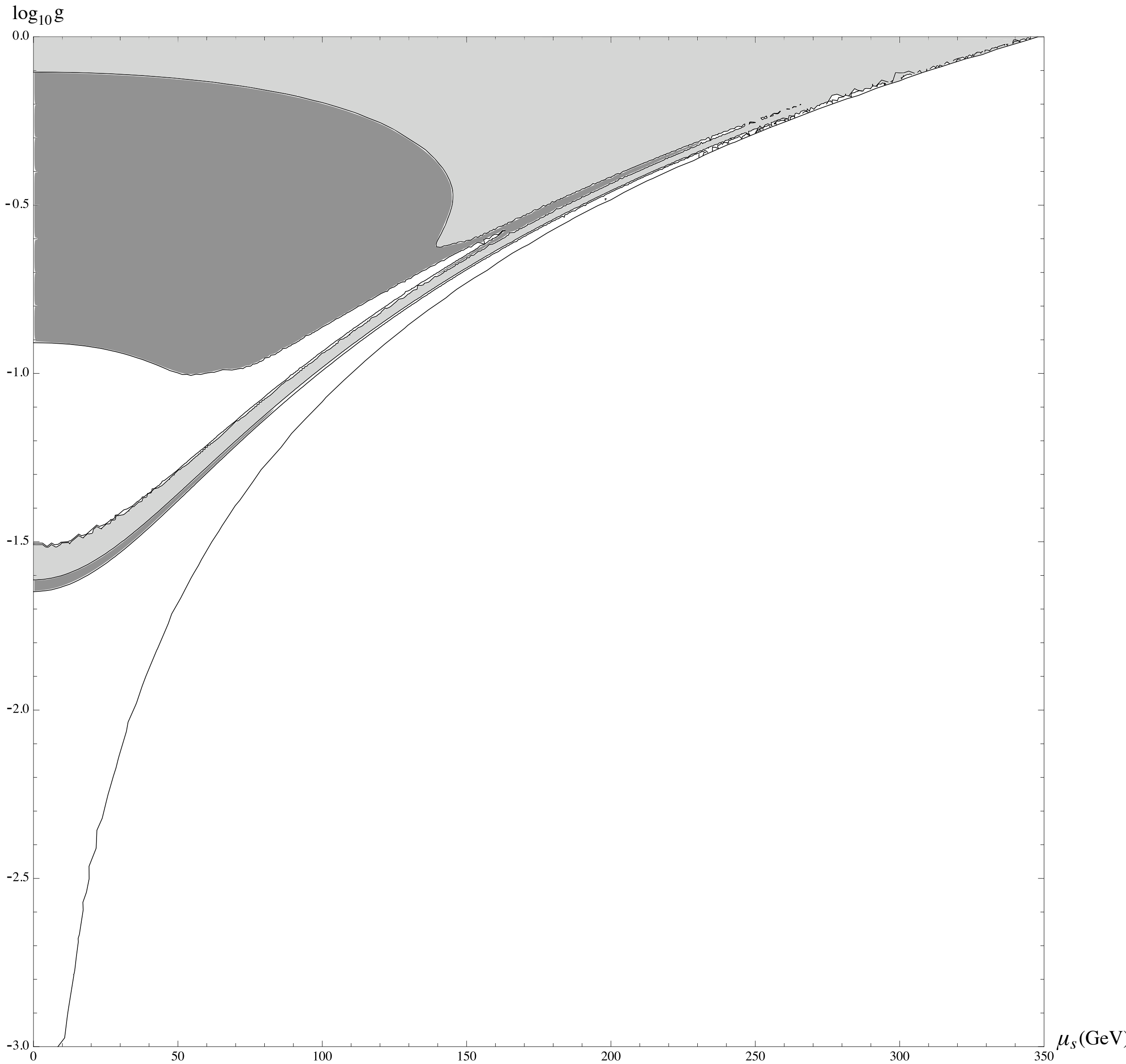

Figure 2-9: Constraints on the Lagrangian parameters from the relic densities. Shaded region is the allowed parameters. Dark shade indicates relic density greater than 20% of current cold dark matter density. Lower right region under the large arc is the non-zero vacuum expectation value, so no stable relic particle.

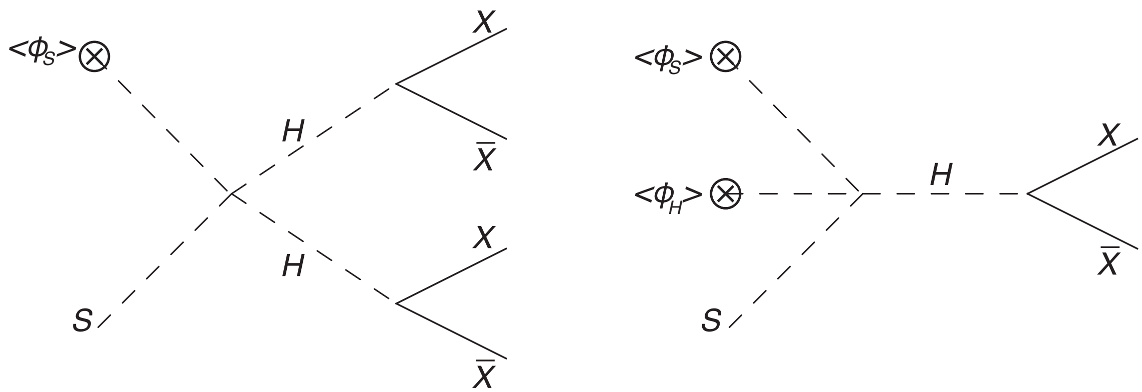

Figure 2-10: Feynman diagrams of two decay processes of S into Standard Model particles, in the case of spontaneously broken hidden sector. Cross nodes denote interactions with the background field.

$$\Gamma_{S\to 4X} \propto \left(\frac{v_S g}{M_H^4}\right)^2 \Gamma_{\tilde{h}}^2\left(M_S/2\right) M_S^3 \tag{2.21}$$

Similarly in the second case we get:

$$\Gamma_{S\to 2X} \propto \left(\frac{v_S v_H g}{M_H^2}\right)^2 \Gamma_{\tilde{h}}\left(M_S\right) \tag{2.22}$$

Half-life of the particle will be proportional to

$$T_{1/2} = \frac{1}{\sum \Gamma} \tag{2.23}$$

For some typical values in the parameter range we investigated that will maximize the lifetime ($M_S = 10$ GeV, $M_H = 120$ GeV, $v_S = 10$ GeV, $g = 0.0001$) second rate dominates the decay by many orders of magnitude, as it is not suppressed by a second virtual Higgs and its decay rate. These values yield to a life-time at the order of 10^{-11} seconds. These values do not leave room for observable BBN effects and safely rule out any cosmologically stable relic (i.e. a dark matter candidate) for spontaneously broken hidden sector. Finally we should note that in the case of spontaneous symmetry breaking in both sectors results in mixing of the mass states [3], but corrections due to this are at the order of unity so would not change our order of magnitude estimates.

2.7 Scholium

In this chapter, we have introduced our basic hidden sector model. We have studied its phase transitions and commented on the ramifications on electroweak phase transition. Relic density constraints of the coupling constant is improved and shown to be even more restrictive than previously thought. If hidden sector exists, it must be strongly coupled to Higgs unless the hidden scalar is around the half of the Higgs mass. In which case bounds are less restrictive but it is not a viable dark matter candidate anymore. So heavier (towards 100 GeV) hidden particles are preferred for dark matter scenarios. We have also for the first time introduced the limits on the bare Lagrangian parameters. There is a considerably large region that is viable for substantial amount of dark matter. Though most of the parameter space gives a vacuum expectation value to the hidden scalar and make it unstable. They are generally so short lived that there are not even bounds from nucleosynthesis.

Chapter 3

Hidden Sector with Abelian Gauge Field

As it is the simplest of the Lie groups many unified theories predict extra copies of U(1) gauge interactions at low energies. Such interactions are interesting in astrophysical and cosmological settings due to their long range nature.

In this chapter we will add a U(1) gauge field coupled only to the hidden scalar. This will add new decoupling scale and a more complex phenomenology. BBN constraints on the new relativistic degrees of freedom will be investigated. Next we will look at the constraints on the long range interactions within dark matter from measurements and simulations of halo properties. Relic density scenarios will be more detailed than the previous case. Finally we will qualitatively comment on various extensions in the phenomenology in the form of hidden atoms and massive hidden photons.

3.1 The model

We can extend our model to a complex hidden scalar and a U(1) gauge field B_μ. New Lagrangian would be:

$$\mathscr{L} = \frac{1}{2} D_\mu \phi_S^* D^\mu \phi_S - \frac{1}{4} G_{\mu\nu} G^{\mu\nu} - V_0(\phi_H, \phi_S) \tag{3.1}$$

with the usual definitions:

$$D_\mu = \partial_\mu + ie_S B_\mu \quad (3.2)$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad (3.3)$$

Here e_S is the charge of the hidden scalar that also defines the fine structure constant for the hidden sector.

$$\alpha_S = \frac{e_S^2}{4\pi} \quad (3.4)$$

We are omitting the gauge invariant term for the kinetic coupling between the Standard Model photon the hidden photon $G_{\mu\nu}F^{\mu\nu}$. Such fields are generally referred as *paraphotons* [46, 47]. Although their phenomenology is interesting, it is already studied elsewhere and has strict bounds on the coupling constant [48, 49, 50]. So we will assume all such effects are negligible if exist at all.

In addition to the large literature of paraphotons there is a current interest in hidden sector models with gauge symmetries similar to what we are discussing here. A series of work is done on their accelerator signatures [82, 51, 52]. Cosmological implications are also studied for generic hidden sectors with no interaction with Standard Model and interaction through weak bosons [53]. Our analysis in the following sections on the Higgs portal will complement this recent work.

3.2 Phenomenology

Phenomenology of the Abelian gauge field is considerably richer than the case in the previous chapter. At the classical level neither the freeze-out temperature calculated at (2.18), nor the symmetry breaking structure shown in Figure 2-1 is changed apart from some numerical factors that will be discussed below. But existence of the gauge boson may alter the relic density, change the distribution through long-range interactions, add new relativistic degrees of freedom etc. Also symmetry breaking in the

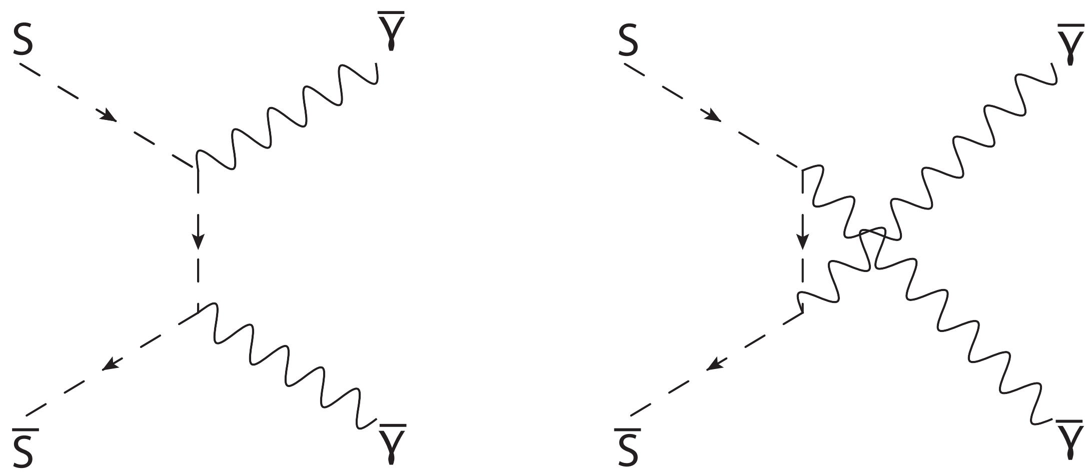

Figure 3-1: Feynman diagrams of t-channel and u-channel reactions that keep hidden scalars and hidden photons in equilibrium.

hidden sector now has a new implication as it gives mass to the gauge boson. In the following few sections we will analyze the unbroken case and later in Section 3.6 we will comment on the broken one.

Even though the existence of the gauge boson doesn't alter significantly when the freeze-out happens or what the hidden particle abundance is at the freeze-out it may still change the relic density today. Because there is now a second freeze-out when the hidden photons effectively decouple from the hidden scalars. Let us indicate this new decoupling temperature scale with T_d as opposed to T_f the temperature when the Higgs portal becomes negligible. As we have stated T_f is the solution of (2.18), but this time there is a factor of 2 due to the fact that complex scalar has 2 degrees of freedom and a 1/4 factor due to the fact that there are now two oppositely charged species that need to find each other for an interaction.

$$x_f = \frac{M_S}{T_f} = \ln \frac{0.038 \times 2 m_{Pl} M_S (1/4) \langle \sigma v \rangle_{Higgs}}{g_*^{1/2} x_f^{1/2}} \tag{3.5}$$

We will now calculate T_d. Hidden scalars and hidden photons are kept at equilib-

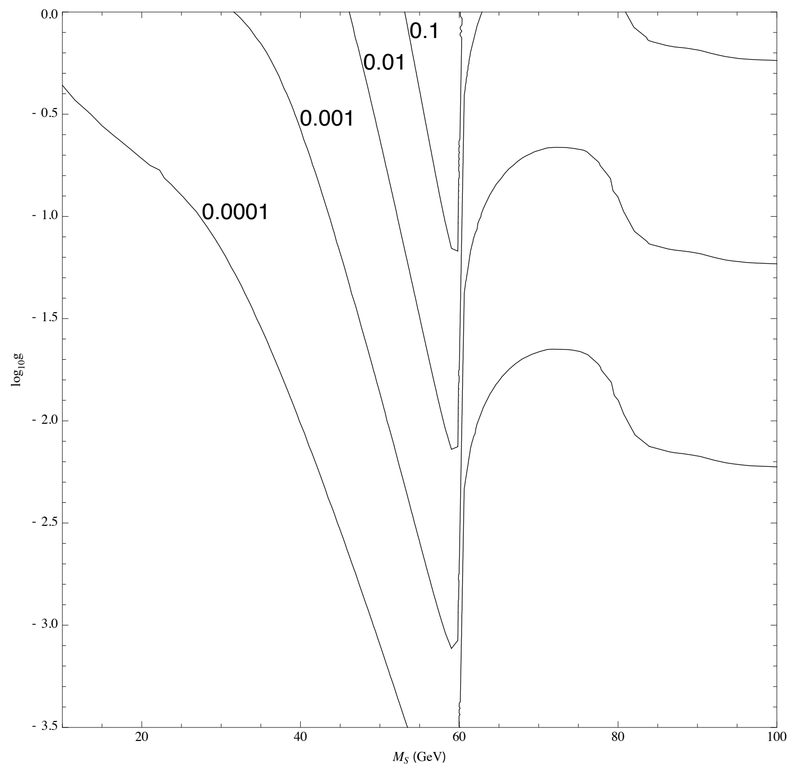

Figure 3-2: Boundaries in g vs M_S parameter space that separates regions where order of decoupling with Higgs sector and with the hidden Abelian boson changes, for different values of α_S as indicated on the curves. Above each curve $T_f < T_d$

rium through the reactions shown in Figure 3-1. Cross section into the photons has a simple form from these diagrams which bring two coupling constants and a scalar propagator. Thermally averaged cross section is independent of the relative velocity at the first order:

$$\langle \sigma v \rangle_{Photon} \approx \frac{4\pi^2 \alpha_S^2}{M_S^2} \tag{3.6}$$

Similar to (3.5) we get

$$x_d = \frac{M_S}{T_d} = \ln \frac{0.038 \times 2 m_{Pl} M_S \langle \sigma v \rangle_{Photon}}{g_*^{1/2} x_f^{1/2}} \tag{3.7}$$

We have computed and compared x_f and x_d, Figure 3-2 and Figure 3-3 illustrates the results. In Figure 3-2 we show the g vs. M_S plane and the boundaries where the order of T_f and T_d changes, for different values of α_S. Above each curve α_S is not

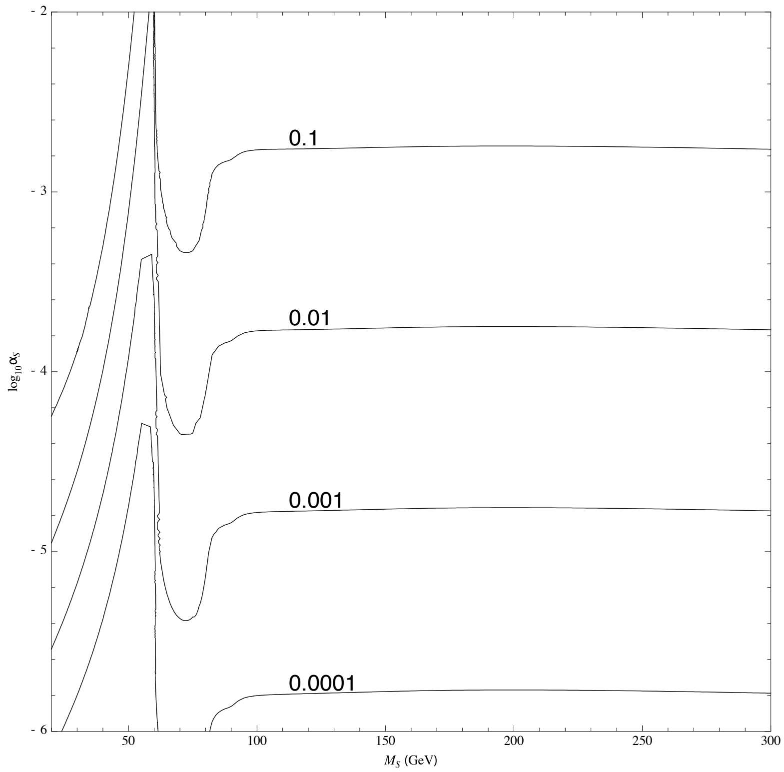

Figure 3-3: Boundaries in α_S vs M_S parameter space that separates regions where order of decoupling with Higgs sector and with the hidden Abelian boson changes, for different values of g as indicated on the curves. Above each curve $T_f > T_d$

strong enough so hidden photons decouple before the Higgs sector, hence $T_d > T_f$. We have chosen the range for easy comparison to Figure 2-7. In Figure 3-2 we did the same thing for α_S vs M_S and varying g. This time above each curve $T_d < T_f$. Range of parameters are chosen for the relevance to the interaction constraints that will be discussed in Section 3.4.

As we now understand the qualitative behavior, in the next three sections we will look at various cosmological constraints. Here our analysis closely follows that of Ackerman *et. al.* [53] and we will demonstrate the differences due to Higgs portal.

3.3 Big Bang Nucleosynthesis constraints

As we introduced a new gauge field in addition to the various Standard Model fields, there will be new relativistic degrees of freedom which will effect the expansion rate at the radiation dominated era. Number densities of nuclei created at the Big Bang Nucleosynthesis (BBN) are very sensitive to expansion rate and give us strict constraints on such degrees of freedom.

First we need to define a relativistic degree of freedom. There are two useful definitions [54]. One for the energy density:

$$g_* = \sum_{i=bosons} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{i=fermions} g_i \left(\frac{T_i}{T}\right)^4 \tag{3.8}$$

that gives the energy density of relativistic particles

$$\rho_R = \frac{\pi^2}{30} g_* T^4 \tag{3.9}$$

One for the entropy density

$$g_{*S} = \sum_{i=bosons} g_i \left(\frac{T_i}{T}\right)^3 + \frac{7}{8} \sum_{i=fermions} g_i \left(\frac{T_i}{T}\right)^3 \tag{3.10}$$

that gives the entropy density of relativistic particles

$$s = \frac{2\pi^2}{45} g_{*S} T^3 \tag{3.11}$$

For all the above equations g_i and T_i are degrees of freedom and temperature of the ith species respectively. Whereas T is always the photon temperature. For Standard Model, difference between g_* and g_{*S} is negligible for temperatures higher than $\sim$1 MeV. Figure 2-6 is a plot of g_* values used in this study for different temperatures. Some particularly important ones are; high energy limit (all Standard Model particles) of 106.75, low energy limit (only photon and neutrinos) of 7.25 and the value at BBN (photon, neutrinos and electron) of 10.75.

Most strict limits on the number of relativistic DOF come from recent analysis combining He_4 abundance and ratio of Deuterium to Hydrogen as well as the total baryon density derived from WMAP measurements [45, 58]. It is customarily given in number of extra light neutrino species $\delta N_\nu = N_\nu - 3$. Assuming that it is positive, 95% confidence level observational bounds are:

$$\delta N_\nu < 1.44 \tag{3.12}$$

Corresponding constraint on the relativistic degrees of freedom is

$$\delta g_* = \frac{7}{8} \times 2 \times \delta N_\nu < 2.52 \tag{3.13}$$

So it is not possible to increase g_* beyond this limit. If we have an extra relativistic particle that is not in thermal equilibrium with Standard Model at all times (like our gauge boson), this limit is even looser. Because in general hidden sector will be colder than the Standard Model sector which is heated by the annihilated species. We will have an extra factor of (T^4_{hidden}/T^4_{SM}). In conclusion an extra photon that decoupled energies higher than BBN scale is well within the current observational bounds.

3.4 Galactic dynamics constraints

One major issue when we add an Abelian gauge field is that there will be long range interactions. If the particles constitute significant amount of dark matter in the universe, long range interactions will have observable consequences on the dark matter distribution particularly inside the galaxies. In the past, dark matter interactions due to Standard Model electromagnetism or other long range forces has been studied [47, 65, 66, 67, 68, 69, 70, 71]. Most important bounds are due to ellipticity study of dark matter halo cores [60], structure formation simulations [61, 62] and recent bullet cluster observations [63, 64]. Even though the last one is a more direct confirmation of particle dark matter hypothesis, limits from the former ones are more restrictive. In the most physical sense, these observations show that change in the momentum of dark matter particles is less than a fraction of their initial momentum in duration of the entire age of the universe.

We can study the collisions in two separate limits, hard collisions (where the potential energy is comparable or larger than the kinetic energy) and so called the soft collision (where kinetic energy dominates potential energy). It turns out that soft

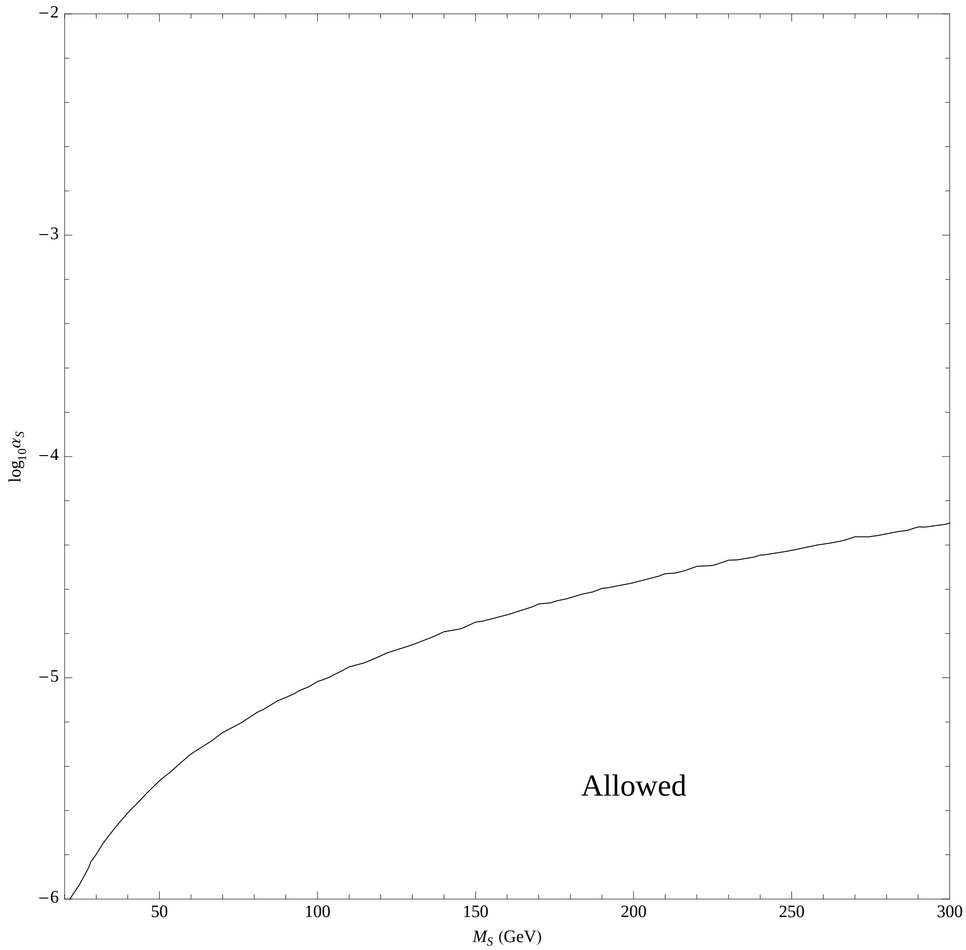

Figure 3-4: Bounds on the fine structure constant of the hidden sector for different values of M_S. Region below the curve is allowed. Compare this with Figure 3-3.

collision bounds are tighter, so we will reproduce the calculations for soft collisions in this section [53].

At an impact parameter of b, non-relativistic particles with velocity v exchange momentum of magnitude

$$\delta v = \frac{8\pi\alpha_S}{M_S b v} \tag{3.14}$$

Throughout the galaxy there are particles at every impact parameter up to the size of the galaxy. Number of particles within the range of db around impact parameter b is

$$\delta n = 2\pi b \frac{N}{\pi R^2} db \tag{3.15}$$

where R is the radius of the galaxy, N is the number of hidden sector particles in the galaxy. Assuming that significant amount of the mass in the galaxy is in the hidden sector. N is at the order of mass of the galaxy divided by the mass of the scalar:

$$N \approx \frac{M_{\text{Gal}}}{M_S} = 10^{67} \left(\frac{M_S}{\text{GeV}} \right)^{-1} \tag{3.16}$$

Change in the square velocity in one rotation of the particle around the galaxy is proportional to $\delta v^2 = (\delta v)^2 \delta n$ which gives:

$$\delta v^2 = \frac{2(8\pi\alpha_S)^2 N}{M_S^2 v^2 R^2} b^{-1} db \tag{3.17}$$

We need to integrate this from the hard scattering limit b_{hard} to R. b_{hard} is the distance where the potential energy is equal to kinetic energy.

$$b_{hard} = \frac{8\pi\alpha_S}{v^2 M_S} \tag{3.18}$$

Final result for the total change in velocity per revolution is

$$\Delta v^2 = \int_{b_{hard}}^{R} \delta v^2 = \frac{2(8\pi\alpha_S)^2 N}{M_S^2 v^2 R^2} \ln(R/b_{hard}) \tag{3.19}$$

Number of revolutions required to get significant amount of change in velocity is $\Delta v^2/v^2$. Assuming the galaxy rotation period is about $\sim 2 \times 10^8$ years (as in Milky Way) we need about 50 revolutions to get the order of age of the universe ($\sim 10^{10}$ years). Estimating the velocity v in terms of the other quantities

$$v = \sqrt{\frac{G M_{\text{Gal}}}{R}} = \sqrt{\frac{G N M_S}{R}} \tag{3.20}$$

gives the soft collision bounds on the interactions:

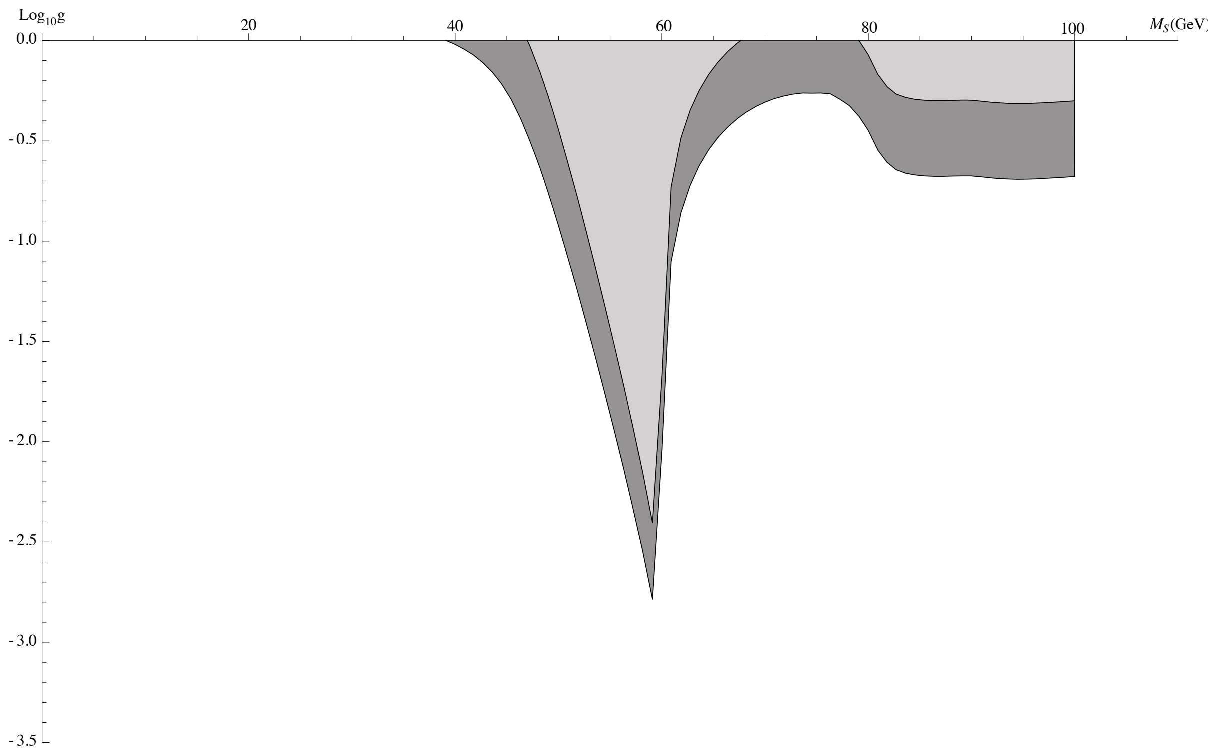

Figure 3-5: Constraints on the coupling constant g between the two sectors for various values mass M_S of the complex hidden scalar. Shaded regions are allowed for Higgs mass of $M_H = 120$ GeV and $\Omega_{CDM}h^2 = 0.1131$. Upper contour is for 20% dark matter so dark shaded region gives significant amount of dark matter. Compare it with Figure 2-7.

$$\frac{G^2 M_S^4 N}{2(8\pi\alpha_S)^2}\left[\ln\left(\frac{GNM_S^2}{8\pi\alpha_S}\right)\right]^{-1} \gtrsim 50 \tag{3.21}$$

Figure 3-4 shows the corresponding bound on the hidden fine structure constant for varying hidden scalar mass. By comparing Figure 3-4 and Figure 3-3 we can see that there is a region where allowed fine structure constant has both orderings of T_f and T_d at low values of g. We will discuss the implications on the relic densities in the next section.

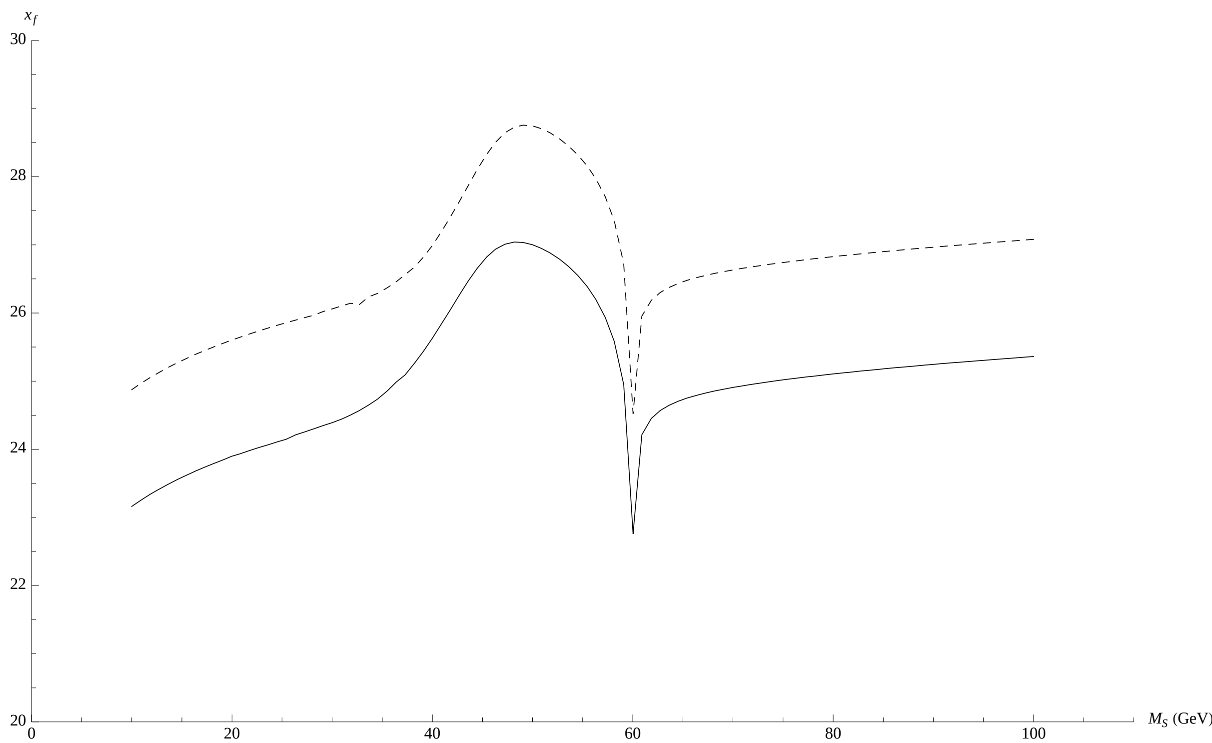

Figure 3-6: Inverse freeze-out temperature $x_f = M_S/T_f$ for different values of M_S in the cases when hidden sector is all of the current dark matter (solid line) and 20% of it (dashed line) and there is an Abelian gauge boson. Again $M_H = 120$ GeV. Compare it with Figure 2-8.

3.5 Relic density constraints

We can repeat the calculations in Section 2.5 for the Abelian gauge field case. As we have discussed in Section 3.2 main differences are some extra factors in due to the doubling of the degrees of freedom and effective change in cross section due to two different particle species (positively and negatively charged).

Figure 3-5 is the Abelian version of Figure 2-7. Dark shaded region is where there is significant amount of dark matter, light shaded region is allowed but produce less than 20% of the dark matter and white region is ruled out as it yields too much relic density. We immediately see that mass values below 40 GeV is completely ruled out and coupling constants below 10^{-2} are very unlikely for a complex hidden scalar.

Similarly Figure 3-6 is the Abelian version of Figure 2-8. As expected from the form of (2.18) and (3.5) they are only shifted by a small amount so still within the generic range.

These calculations are done under the assumption that Higgs freeze-out happens after the hidden photon decoupling ($T_f < T_d$). If we didn't have any further constraints on α_S it would be possible to have strong enough gauge interactions which would keep hidden scalar in thermal equilibrium with relativistic particles down to lower temperatures ($T_f > T_d$) hence leaving less relic particles. One might think that some forbidden parts in Figure 3-5 where the energy density is too much, possibly turned out to be allowed by annihilations into hidden photons.

To have deeper understanding we need to compare Figure 3-3 and Figure 3-4. Figure 3-7 combines the curves from both graphs. We can see that allowed regions in Figure 3-5 is well above 10^{-2} which is plotted in Figure 3-7. For all the values allowed by the galactic dynamics T_f is smaller than T_d, so calculated boundaries in Figure 3-5 are safe. At the lower end of the diagram ($g < 10^{-3}$) there will be an overlap and possibility of lowering the relic density. However having T_d smaller than T_f is essentially the same case with having no Higgs portal. That case has been studied and shown that it never gives low enough relic densities [53]. Hence Figure 3-5 captures all the possibilities.

3.6 Other scenarios

Phenomenology of hidden Abelian gauge theory is even richer than the cases we presented. Here we will introduce two more scenarios qualitatively, namely the hidden atoms and massive hidden photons.

Electromagnetism is responsible for many rich phenomena in our world. It is what holds the atoms together and form chemical reactions. In the model we have been studying positively and negatively charged hidden scalars may form bound states, but they would be unstable just like the positronium in Standard Model. Half-life will be:

$$t_{1/2} \approx \frac{1}{M_S \alpha_S^5} \tag{3.22}$$

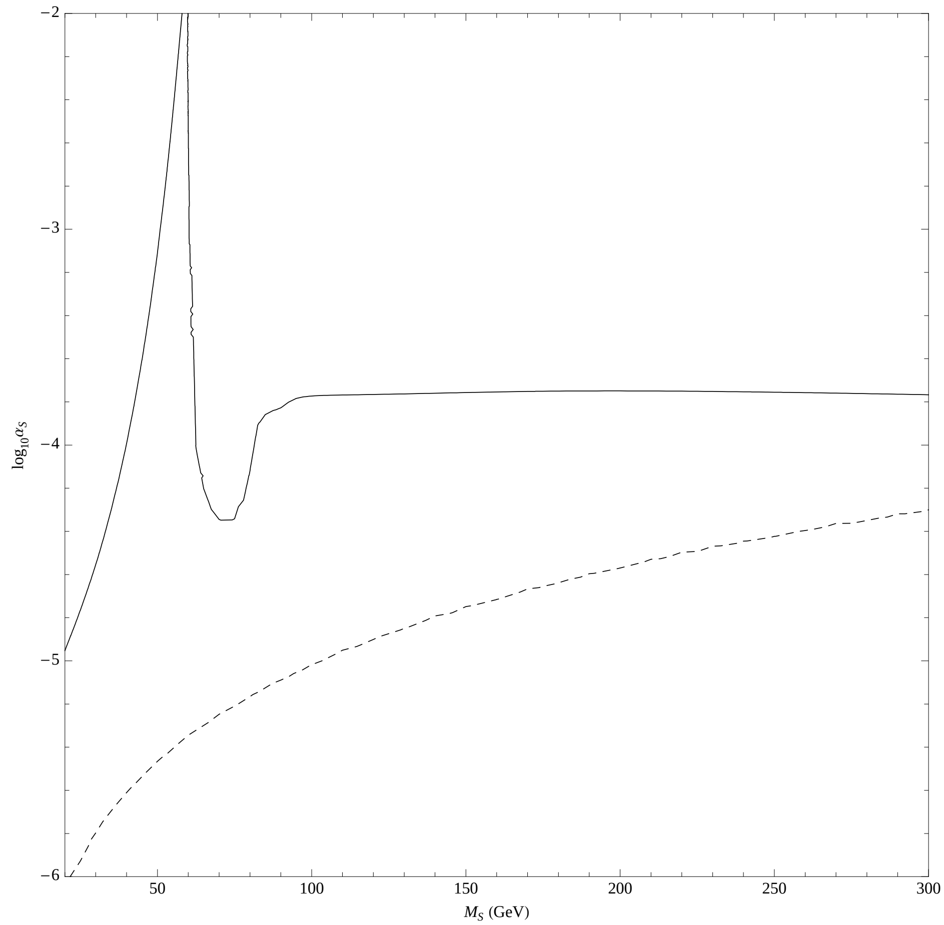

Figure 3-7: Comparison of Figure 3-3 and Figure 3-4. Region under the dashed curve is allowed from the galactic dynamics. Below the solid curve that covers all the allowed region, $T_f < T_d$. Solid curve is for $g = 10^{-2}$.

which doesn't give cosmologically relevant times. But if we have multiple species of hidden particles, such that they only interact via U(1) interaction, then they will form stable bound states we may call as atoms. This has basically two implications. First, atoms will be neutral under long range forces so soft scattering limits would not apply. On the other hand hard scattering limits are only about one order of magnitude less restrictive in terms of the fine structure constant. Second, photon may decouple before the interactions freeze-out with individual particles, if the atoms form. This is what happened in the early universe in electromagnetism and known as the "last scattering surface". Atoms will form temperatures at the order of binding energy of the atoms approximately

$$T \approx M_S \alpha^2 \tag{3.23}$$

This may be larger than T_d so hidden photons may decouple even earlier. These two conditions do not significantly change our conclusions in the previous section other than adding extra species. If both particles are interacting with the Higgs this will enhance the binding energy of the atoms but will not give any extra decay modes.

Another possibility is the case of spontaneous symmetry breaking. As we have discussed in Section 2.2 there is a large part of the parameter space where hidden scalar develops a vacuum expectation value. If there is also a gauge field, it will acquire a mass via Higgs mechanism. Independent of the details of how and when the hidden photons decouple, we can always find a vacuum expectation value that gives a desired value for the hidden photon mass. Even the existence of the Higgs portal is not essential. But the massive hidden photon will share the same fate with the hidden scalar in the case of a broken symmetry. In general, it will decay into Standard Model particles through the Higgs and consequently is subject to similar bounds. One notable difference is the existence of the fine structure constant. Decay rates will be suppressed by extra factors of this coupling constant. Nevertheless, complete freedom in choosing the mass and lack of interactions, prevent us further investigation before any observational evidence for the hidden sector. One particularly relevant model is the case of a hidden photon that interacts the Standard Model through kinetic mixing, instead of a Higgs portal. It is recently been studied by Redondo and Postma [72].

3.7 Scholium

We have found that U(1) gauge theories are not restricted by the BBN constraints. Since the hidden sector will in general be at a lower temperature at BBN era, even tens of extra relativistic extra particles can be accommodated. On the other hand long range interactions are substantially constraint inside the galaxies thanks to recent precision measurements with gravitational lensing. This brings us to a scenario where Higgs portal is dominant interaction and hidden photons decouple at an early stage.

Preferred values the hidden scalar mass is about 100 GeV with strong Higgs coupling (around unity) and low fine structure constant ($< 10^{-5}$). Mass values below 40 GeV are forbidden, whereas they were possible in the real (single degree of freedom) scalar field. Most important result of this chapter is that Higgs portal makes hidden sector with Abelian interaction possible, which was forbidden otherwise [53].

Chapter 4

Hidden Sector with Non-Abelian Gauge Field

Gauge theories are not limited to U(1). In Stadard Model, QCD brings large array of new phenomena, confinement, asymptotic freedom, quark-gluon plasma, chiral symmetry breaking etc. In this chapter we would like to add a QCD like interaction to the hidden sector and see the consequences particularly of confinement. Such interactions will be short range by their nature, so won't be limited by the large scale structure observations.

4.1 The Model

We are interested in the confining properties of non-Abelian gauge theories. Even though it is possible to have confinement in smaller group SU(2) (as in the Farhi-Abbott model [73]) we will choose the more familiar SU(3) for our explicit representation. However our results are generic to any confining interaction.

Just like in the Abelian case, new Lagrangian have the following extra terms:

$$\mathscr{L} = \frac{1}{2} D_\mu \phi_S^* D^\mu \phi_S - \frac{1}{4} H_{\mu\nu} H^{\mu\nu} - V_0(\phi_H, \phi_S) \tag{4.1}$$

but this time definitions will be:

$$
\begin{aligned}
D_\mu &= \partial_\mu + ik\tau^a C^a_\mu && (4.2)\\
H_{\mu\nu} &= \tau^a(\partial_\mu C^a_\nu - \partial_\nu C^a_\mu - k\varepsilon^{abc} C^b_\mu C^c_\nu) && (4.3)
\end{aligned}
$$

Here C^a_μ are the components of the gauge field, k is the coupling constant of the interaction, τ^a are the generators of the Lie algebra and finally ε^{abc} are the structure constants of the algebra:

$$\left[\tau^a, \tau^b\right] = \varepsilon^{abc}\tau^c \tag{4.4}$$

4.2 Phenomenology

We know that SU(3) gauge fields go thorough a phase transition from a quark-gluon plasma into mesons and hadrons, as the universe cools down. Detailed calculations of when and how the phase transition happens and what are the masses of the final bound states in Standard Model, are a rapidly developing field of current research. But certainly they are functions of the coupling constant and the masses of the scalar fields which might be called as hidden quarks in this case.

In many cases, existence of highly massive quarks, that have color charge and dominate the energy density of the universe, will change the phenomenology dramatically from the Standard Model. First of all, existence of a phase transition is not guaranteed. It may not be energetically favorable to change the vacuum state and to have effectively infinitely massive quarks. Also we cannot predict the final states and the number densities. Flux tubes connecting the spatially separated particles may break and we might get more hadrons than the initial number of quarks estimate. For an arbitrary non-Abelian sector hadrons may decay into mesons so the final density of the hadrons will be less. In the rest of the section we will be interested in the simplest case, where symmetry breaking exists, final hadron number is one third of the initial quark number and the hadrons are stable.

Phenomenology of this scenario can be explored in terms of two basic physical quantities; critical temperature of the color confinement T_c and the mass of the final stable particle M_Λ. We expect these composite particles to be either mesons (2 quarks) or hadrons (3 quarks). Just like the hidden atoms we discussed in the previous chapter, for mesons to be stable we need more than one species of hidden quarks so that quark and the anti-quark do not annihilate. On the other hand hadrons will be stable even with one species of quarks. Also T_c and M_Λ to be at the same order of magnitude.

One important condition that determines the low energy physics is the ordering of T_c and the Higgs portal freeze-out temperature T_f. If $T_f < T_c$ hadrons formed during the Higgs interaction era, so the effective mass term of the calculations in Section 2.5 will be M_Λ and all the calculations will follow essentially the same way. So if $T_f < T_c$, once more Figure 2-7 will give the desired bounds (but now g in the horizontal axis is the effective coupling constant of the hadrons). One exceptional case we would like comment on, is the stable mesons of two quark species. If some symmetry ensures that the Higgs coupling constants of these two species exactly cancel each other ($g_1 = -g_2$) than meson might turn to neutral against Higgs and fall out of equilibrium at T_c rather than the calculated value before.

For the case of $T_f > T_c$, we will turn our attention into the hidden quark masses. In general hadron masses are more than the quark masses. Since the quarks has number density as we have calculated in the free case, after the color confinement, energy density will be boosted by a factor of $M_\Lambda/3M_S$. We can repeat our relic density calculations by lowering the required $\Omega^2 h$ by this factor. Figure 4-1 shows these bounds for three different hadron masses 300, 600 and 900 GeV (solid lines from bottom to top respectively) compared to the noninteracting case (dashed line). For comparison, in Standard Model QCD phase transition happens around 100-300 MeV but the lightest hadron, proton has mass of 938 MeV with practically massless quarks. So it is conceivable that for small (less than T_f) T_c one can get such massive hadrons.

Up to this point we have assumed scalar masses around the electroweak scale, as it is the relevant case for the dark matter problem. One might naively think that

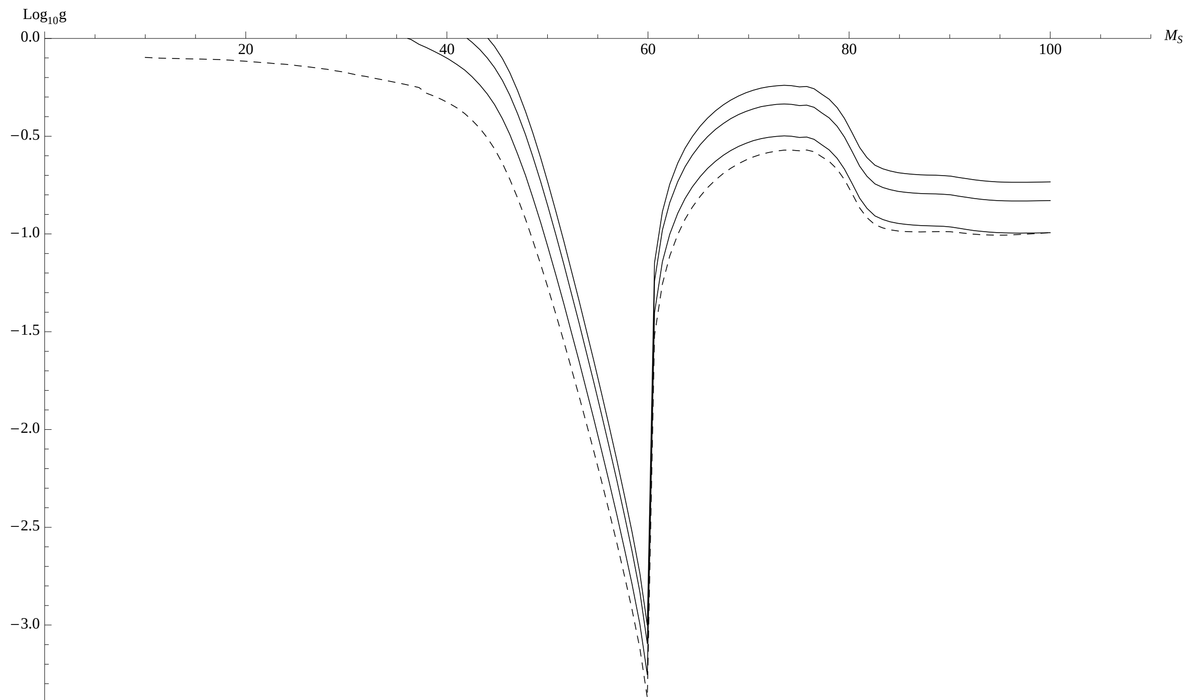

Figure 4-1: Relic density constraints for scalars forming hadrons. Dashed line is the reproduction of the noninteracting case in Figure 2-7. Solid lines from bottom to top shows the bounds for hadron masses 300, 600 and 900 GeV.

thanks to the boosting due to color confinement, we can explore much lower scalar masses. But very light particles will be relativistic so the cross section (2.16) will not be accurate and relic abundances will only depend on the freeze-out temperature T_f. As any other hot relic their number density will be comparable to photon density. Masses of such particles are subject to Cowsik-McClelland bound [74], even if they acquire mass afterwards. This bound is a function of the freeze-out temperature as the number of relativistic degrees of freedom change with the temperature. Higher the freeze-out temperature is, lower the particle density today. But even for particles decoupling beyond all Standard Model particles (T_f >300 GeV) limit is about a keV [54]. Hence we can easily rule out particles decoupling at relativistic energies and acquire mass later by color confinement.

4.3 Scholium

In this chapter we gave a glimpse of the rich phenomenology of hidden sectors with non-Abelian interactions. Under some non-trivial assumptions the scenario is tractable and similar to the cases in the previous chapters. Once again particle masses and phase transition temperatures are the main parameters that define the phenomenology.

We have just argued that $T_f < T_c$ case doesn't bring new bounds, it just makes the quark mass irrelevant for the favor of the hadron mass. When $T_f > T_c$ we stated that hidden quark must still be heavy enough to be non-relativistic at the freeze-out. In that case freeze-out calculations stay intact but the energy density is boosted after the confinement. Surprisingly as we see in Figure 4-1, bounds on the coupling constant do not change significantly (though one should keep in mind that this is a logarithmic plot so the upper part covers most of the linear span). Just like in the Abelian case large scalar masses are preferred, masses below 40 GeV is forbidden. Around Higgs resonance energy density is very low so a very large interval of g is allowed but do not give enough dark matter. As in the other cases strong interaction with the Higgs is required.

Besides our generic discussion on the hidden sector with Higgs portal, there are other recent works in the literature that explores hidden sectors with non-Abelian gauge interactions. There has been studies, inspired by the technicolor theories, on chiral symmetry breaking of a fermionic hidden sector and its effects on the electroweak symmetry breaking [75, 76]. Also massive non-Abelian gauge boson as dark matter candidates themselves was studied [77].

Chapter 5

Conclusion and Outlook

In the last three chapters we have covered many cosmological aspects of the Higgs portal into a hidden sector of scalar particles. We can summarize our results as follows. In terms of relic density constraints, coupling between the two sectors needs to be strong for a stable relic, as lower couplings lead early decoupling and higher number densities. Higher values of the hidden scalar mass is preferred, on the other hand there is a large region around the Higgs resonance that is allowed but does not give enough energy density for a conceivable dark matter candidate. These are generic conclusions with or without a gauge interaction. In the case of gauge interaction we showed that hidden scalar masses below about 40 GeV is forbidden as long as we assume coupling constants below unity. If we look into the parameters in the self interaction of the hidden scalars, quartic coupling is irrelevant in most of the discussion unless we want to know when the phase transition happens or what is the magnitude of the vacuum expectation value in the broken symmetry case. On the other hand the quadratic constant (or the bare mass term) determines the vacuum state and the stability of the particle. As seen in Figure 2-9, there is substantial region the parameter space that gives large amount of dark matter. Broken symmetry and unstable particle is on the other hand compatible with the BBN theory but not further constrained by that.

Relic density constraints are not the only place to learn about the hidden sector. We have seen that for gauge symmetries, there are interaction constraints that limit long range forces to a great degree. Previously it was shown that completely separated hidden sector with U(1) gauge interactions is forbidden. We found that having a Higgs portal remedy the problems and be able to coexist with a weak long range interaction. This scenario is also valid under BBN constraints.

For the non-Abelian interaction there is a rich phenomenology waiting to be explored. We have shown that in the simplest case where confinement begins before the decoupling, bounds cited for the first case is still valid but the relevant mass is now the hadron mass instead of the quark mass. For late confinement bounds are dependent on both masses but insensitive to the hadron masses in the logarithmic scale, so very heavy ($\sim$ 1 TeV) hadrons can still be viable dark matter candidates as long as quarks are heavy as well ($\sim$ 0.1 TeV) and the Higgs coupling is strong ($\sim$ 0.5).

Over the last few years, various groups studied the implications of such theories in collider physics [78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88]. General consensus is that there is a large possibility of domination of Higgs boson decay into hidden sector if it exists. Under these conditions it is not obvious to spot the Higgs signal as expected, but not impossible, especially at ILC.

Another opportunity is the emerging field of gravitational waves. If we succeed in detecting gravitational waves in the near future, we can see signatures from various phase transitions in the early universe, including the hidden sectors even if they are completely separated from the Standard Model [42, 37].

As of this writing, there are many exciting developments in dark matter searches and various clues from different direct search efforts are being delivered. PAMELA experiment reported excess positrons in high energy cosmic rays, ATIC experiment had similar conclusions at a different energy range. WMAP signals from the galactic core indicate some unknown emission that is consistent with various dark matter annihilation processes. Finally EGRET detects extra gamma-rays again from the galactic center. Whether these experimental clues stand up to the test time is yet to be seen. But there are already complex hidden sector models trying to address all of these signals at once [89, 90]. There exist other attempts to explain especially the

PAMELA signal from different versions of hidden sectors [91, 92, 93, 94].

Just like any theoretical possibility there are numerous ways to extend our research. As we have seen accelerator and direct search possibilities are very fruitful. We would like to suggest that phase transition in various hidden sector models is not completely understood. This is not only essential in our understanding of the future collider experiments but also precision cosmology of the expansion history, cosmic microwave fluctuations and gravitational wave background. As we have discussed, coupling with the Higgs is a generic feature of any extra scalar field unless forbidden by some exotic symmetry principle. There are already various proposals of scalar fields in cosmology, most notably the inflaton and the quintessence. Combining the knowledge of these two areas will further our understanding.

We are confident that our technology is reaching the level of probing long standing questions of fundamental physics the nature of electroweak interaction and the dark matter problem. We hope that our analysis in this thesis will lead the experimental efforts in the right direction and open new possibilities for knowing whether or not such world of particles exist in nature. The author is optimistic, excited, curious and happy to live in this era of discovery.

“Whereof one cannot speak, thereof one must be silent.”

Ludwig Wittgenstein

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