Two component WIMP-FImP dark matter model with singlet fermion, scalar and pseudo scalar

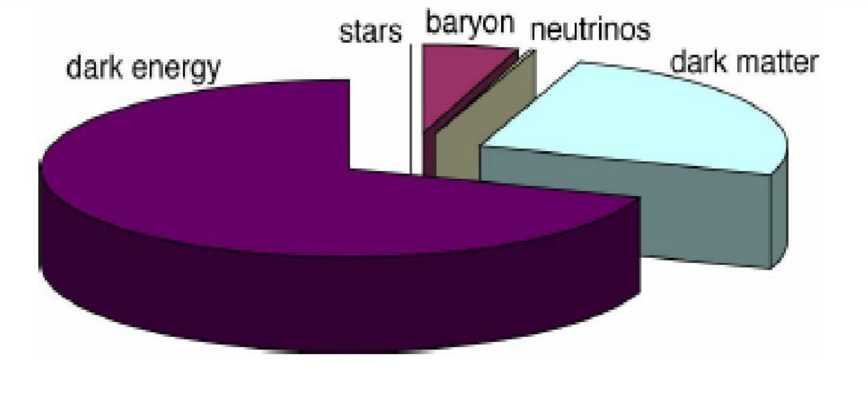
Madhurima Pandey

Astroparticle Physics and Cosmology Division
Saha Institute of Nuclear Physics
Kolkata, India

Energy Budget of the Universe

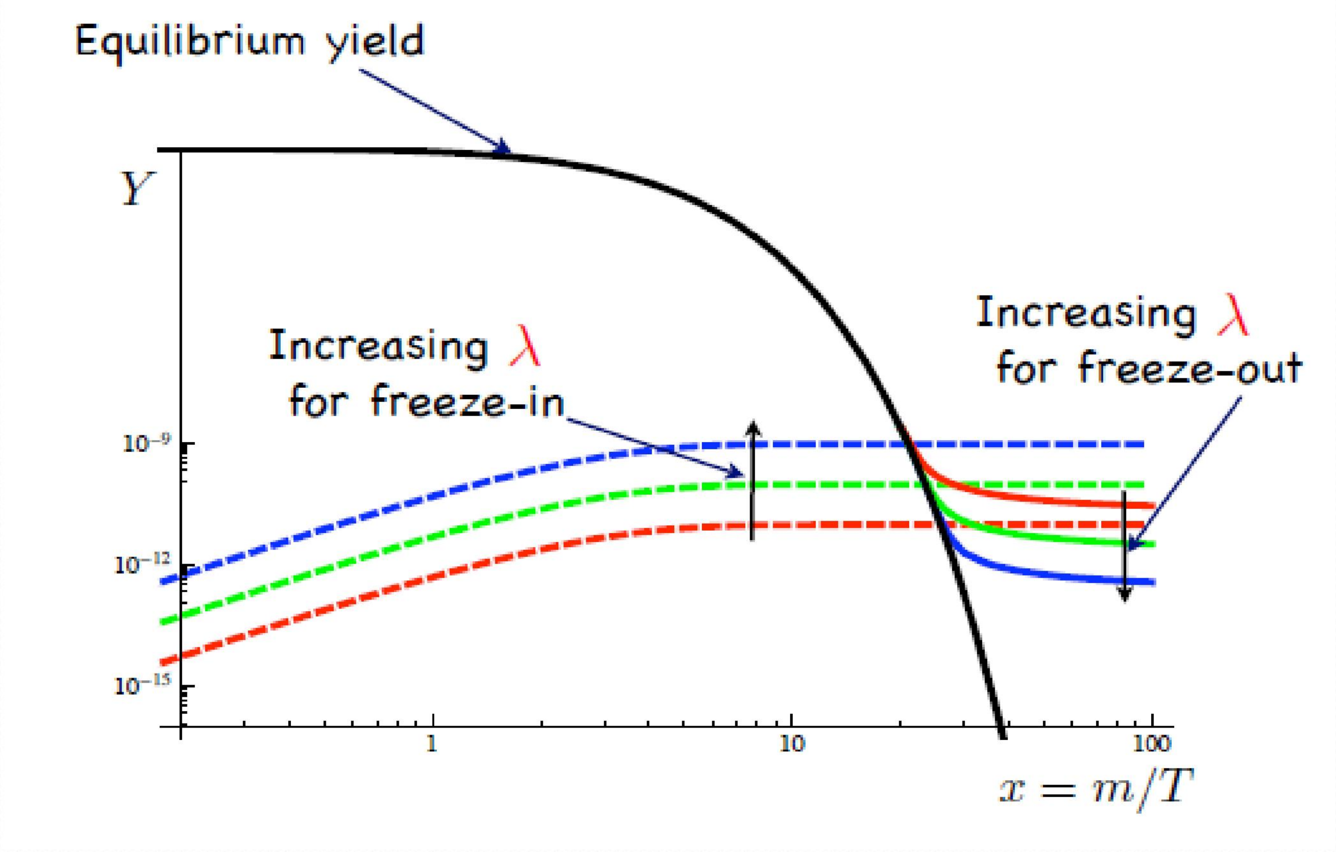
Planck Results!!

- Baryonic Matter are ~ 4.8%
- Dark Matter ~ 26.5%
- Dark Energy ~ 68.3%



DARK MATTER

- Thermal or non-thermal.
- A popular candidate is WIMP (Weakly Interacting Massive Particle).
- But WIMP may not be the only candidate.
- Challenged by null results by quite a few direct detection experiments.
- Some possible indirect signatures like DM self interaction signatures etc. may not be addressed by WIMP.
- FIMP (Feebly Interacting Massive Particle) dark matter is non-thermal in nature but produced from a particle which is in thermal equilibrium.



arXiv:0911.1120 [hep-ph]

Some possible indirect signatures

- 1-3 GeV gamma ray excess reported by Fermi-Lat from the direction of Galactic Centre (GC).

- 3.55 keV X-ray line from Perseus, Andromeda etc. and 74 other galaxy clusters observed by Newtown X-ray observatory and Chandra Telescope.

- Observational evidence for DM self-interaction in Abell and other galaxy clusters.

THE MODEL (WIMP-FImP model)

Two component DM model $\Rightarrow$ a fermion and a scalar.

The Model :- SM+ χ + S + Φ.

- χ - Dirac Fermion, S - scalar, Φ - a pseudo scalar
- χ -singlet under SM gauge group, global $U(1)_{DM}$ symmetry (global $U(1)_{DM}$ charge), doesn't talk to SM.
- χ interacts with Φ. via Yukawa interaction.
- Impose a discrete $\mathbb{Z}_2$ symmetry on the scalar S (singlet). $\mathbb{Z}_2$ is spontaneously broken & develops a VEV for S.
- The Lagrangian is CP invariant but CP symmetry breaks spontaneously when Φ acquires a VEV.

Two Component DM Model

Lagrangian of the model can be written as

$$\mathcal{L} \;=\; \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_{\Phi} + \mathcal{L}_{\rm int} \;, \qquad ...1)$$

$\mathcal{L}_{\rm DM}$ has two parts namely the fermionic and the scalar, which are given by,

$$\mathcal{L}_{\rm DM} \;=\; \bar{\chi}(i\gamma^{\mu}\partial_{\mu} - m)\chi + \mathcal{L}_{S} \;, \qquad .....2)$$

With

$$\mathcal{L}_{S} = \frac{1}{2}(\partial_{\mu}S)(\partial^{\mu}S) - \frac{\mu_s^2}{2}S^2 - \frac{\lambda_s}{4}S^4 \,. \qquad .....3)$$

The Lagrangian $\mathcal{L}_{\Phi}$ for the pseudo scalar boson Φ is given by

$$\mathcal{L}_{\Phi} \;=\; \frac{1}{2}(\partial_{\mu}\Phi)^2 - \frac{\mu_{\phi}^2}{2}\Phi^2 - \frac{\lambda_{\phi}}{4}\Phi^4 \,. \qquad ....4)$$

Two Component DM Model

The interaction Lagrangian is given as

$$\mathcal{L}_{\rm int} \;=\; -i\,g\,\bar{\chi}\gamma_5\chi\,\Phi - V'(H,\Phi,S)\,, \qquad .....5)$$

where scalars and pseudo scalar mutual interaction terms are denoted by $V'(H, S, \Phi)$.

$$V'(H,\,S,\,\Phi) = \lambda_{H\Phi}H^\dagger H\,\Phi^2 + \lambda_{HS}H^\dagger H\,S^2 + \lambda_{\Phi S}\Phi^2\,S^2\;. \qquad ...6)$$

Denoting v_1 , v_2 and v_3 to be the VEV acquired by physical Higgs, Φ and S respectively, we have

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 + h \end{pmatrix}\,,\;\; \Phi = v_2 + \phi\,,\;\; S = v_3 + s\,. \qquad ..7)$$

Two Component DM Model

Let us consider the scalar potential term V

$$V = \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \frac{\mu_\phi^2}{2}\Phi^2 + \frac{\lambda_\phi}{4}\Phi^4 + \frac{\mu_s^2}{2}S^2 + \frac{\lambda_s}{4}S^4 + \lambda_{H\Phi}H^\dagger H\,\Phi^2 + \lambda_{HS}H^\dagger H\,S^2 + \lambda_{\Phi S}\Phi^2 S^2 \,. \quad \ldots 8)$$

After SSB, the scalar potential Eq. 8) looks like

$$V = \frac{\mu_H^2}{2}(v_1+h)^2 + \frac{\lambda_H}{4}(v_1+h)^4 + \frac{\mu_\Phi^2}{2}(v_2+\phi)^2 + \frac{\lambda_\Phi}{4}(v_2+\phi)^4 + \frac{\mu_S}{2}(v_3+s)^2 + \frac{\lambda_S}{4}(v_3+s)^4 + \frac{\lambda_{H\Phi}}{2}(v_1+h)^2(v_2+\phi)^2 + \frac{\lambda_{HS}}{2}(v_1+h)^2(v_3+s)^2 + \lambda_{\Phi S}(v_2+\phi)^2(v_3+s)^2 \,. \quad 9)$$

Two Component DM Model

Using the minimisation condition that

$$\left(\frac{\partial V}{\partial h}\right), \left(\frac{\partial V}{\partial \phi}\right), \left(\frac{\partial V}{\partial s}\right)\Bigg|_{h=0,\,\phi=0,\,s=0} = 0\,, \qquad \ldots 10)$$

we obtain the three following conditions

$$\begin{aligned} \mu_H^2 + \lambda_H v_1^2 + \lambda_{H\Phi} v_2^2 + \lambda_{HS} v_3^2 &= 0 \\ \mu_\Phi^2 + \lambda_\Phi v_2^2 + \lambda_{H\Phi} v_1^2 + 2\lambda_{\Phi S} v_3^2 &= 0 \\ \mu_S^2 + \lambda_S v_3^2 + \lambda_{HS} v_1^2 + 2\lambda_{\Phi S} v_2^2 &= 0\,. \end{aligned} \qquad \ldots 11)$$

The mass matrix with respect to the basis h-ϕ-s is obtained as

$$\mathcal{M}^2_{\rm scalar} = 2 \begin{pmatrix} \lambda_H\, v_1^2 & \lambda_{H\Phi}\, v_1\, v_2 & \lambda_{HS}\, v_1\, v_3 \\ \lambda_{H\Phi}\, v_1\, v_2 & \lambda_\Phi\, v_2^2 & 2\lambda_{\Phi S}\, v_2\, v_3 \\ \lambda_{HS}\, v_1\, v_3 & 2\lambda_{\Phi S}\, v_2\, v_3 & \lambda_S\, v_3^2 \end{pmatrix}. \qquad \ldots .12)$$

Two Component DM Model

Diagonalising Eq. 12) by a unitary transformation we get 3 eigenvectors h_1, h_2 and h_3

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = U(\theta_{12}, \theta_{13}, \theta_{23}) \begin{pmatrix} h \\ \phi \\ s \end{pmatrix} , \quad ..13)$$

$U(\theta_{12}, \theta_{23}, \theta_{13})$ - PMNS matrix, h_1 - SM like Higgs boson, h_2 - scalar, h_3 - lighter scalar component of DM (FImP candidate).

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} h \\ \phi \\ s \end{pmatrix} ;$$

Bounds

Theoretical Bounds

In order to obtain a stable vacuum we have the following bounds on the quartic couplings

$$\begin{aligned} \lambda_H,\ \lambda_\Phi,\ \lambda_S &> 0 \\ \lambda_{H\Phi} + \sqrt{\lambda_H \lambda_\Phi} &> 0 \\ \lambda_{HS} + \sqrt{\lambda_H \lambda_S} &> 0 \\ 2\lambda_{\Phi S} + \sqrt{\lambda_\Phi \lambda_S} &> 0 \end{aligned}$$

$$\sqrt{2(\lambda_{H\Phi} + \sqrt{\lambda_H \lambda_\Phi})(\lambda_{HS} + \sqrt{\lambda_H \lambda_S})(2\lambda_{\Phi S} + \sqrt{\lambda_\Phi \lambda_S})} + \sqrt{\lambda_H \lambda_\Phi \lambda_S} + \lambda_{H\Phi}\sqrt{\lambda_S} + \lambda_{HS}\sqrt{\lambda_\Phi} + 2\lambda_{\Phi S}\sqrt{\lambda_H} > 0 \ . \qquad \text{....14)}$$

arXiv:1205.3781 [hep-ph]

Bounds (continued....)

Experimental Bounds

- PLANCK observed relic density

$$0.1172 \leq \Omega_{DM} h^2 \leq 0.1226$$

- They will be further constrained by the collider bounds.

Bounds (continued…) (from Collider Physics)

- h_1 - Higgs like scalar (mass~ 125.5 GeV), h_2 - non SM scalar (85 GeV $\leq m_2 \leq$ 110 GeV), h_3 - light DM candidate.
- h_1 satisfies the collider bounds on signal strength of SM scalar. Signal strength

$$R_1 = \frac{\sigma(pp \to h_1)}{\sigma^{\rm SM}(pp \to h)} \frac{{\rm Br}(h_1 \to xx)}{{\rm Br}^{\rm SM}(h \to xx)} \,. \quad \ldots 20)$$

$\sigma(pp \to h_1)$ & $\sigma^{\rm SM}(pp \to h)$ define the production cross-section of h_1 & SM Higgs respectively due to gluon fusion. ${\rm Br}(h_1 \to xx)$ & ${\rm Br}^{\rm SM}(h \to xx)$ are the decay branching ratios of h_1 & SM Higgs into any final state particles. h_1 satisfy the condition for SM Higgs signal strength $R_1 \geq 0.8$

Bounds (Continued...) (from Collider Physics)

for h_1, $\mathrm{Br}(h_1 \to xx) = \frac{\Gamma(h_1 \to xx)}{\Gamma_1}$ and for SM Higgs $\mathrm{Br}^{\mathrm{SM}}(h \to xx) = \frac{\Gamma(h \to xx)}{\Gamma_{SM}}$.

Eq. 20) becomes

$$R_1 = a_{11}^4 \frac{\Gamma_{SM}}{\Gamma_1} \quad ...21)$$

where , the total decay width $\Gamma_1 = a_{11}^2 \Gamma_{SM} + \Gamma_1^{inv}$ & the invisible decay width of h_1 into DM particles given as $\Gamma_1^{inv} = \Gamma_{h_1 \to \chi\bar{\chi}} + \Gamma_{h_1 \to h_3 h_3}$.

Similarly for h_2, ,

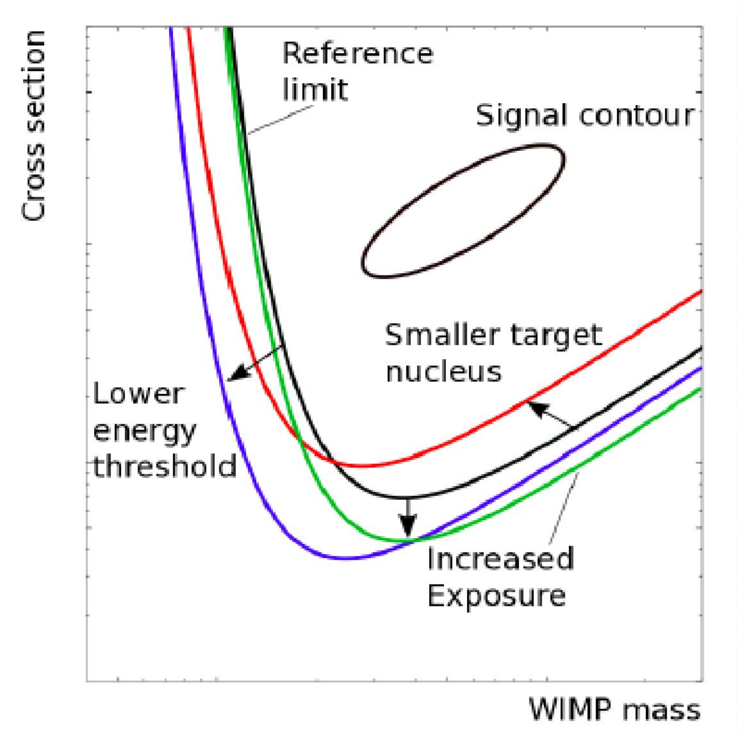
$$R_2 = a_{21}^4 \frac{\Gamma'_{SM}}{\Gamma_2} \quad ....22)$$

with $\Gamma_2 = a_{21}^2 \Gamma'_{SM} + \Gamma_2^{inv}$ & $\Gamma_2^{inv} = \Gamma_{h_2 \to \chi\bar{\chi}} + \Gamma_{h_2 \to h_3 h_3}$

The invisible decay branching ratio for the SM like Higgs is $Br_{inv}^1 = \frac{\Gamma_1^{inv}}{\Gamma_1}$. We assume Br_{inv}^1 to be small and impose $Br_{inv}^1 < 0.2$.

Bounds (continued..)

Bounds from direct detection experiments (scattering cross section vs DM mass)



We have checked the direct detection cross-section within the allowed limit by DM direct detection experiment.

Relic Density

The Boltzmann equation for χ is

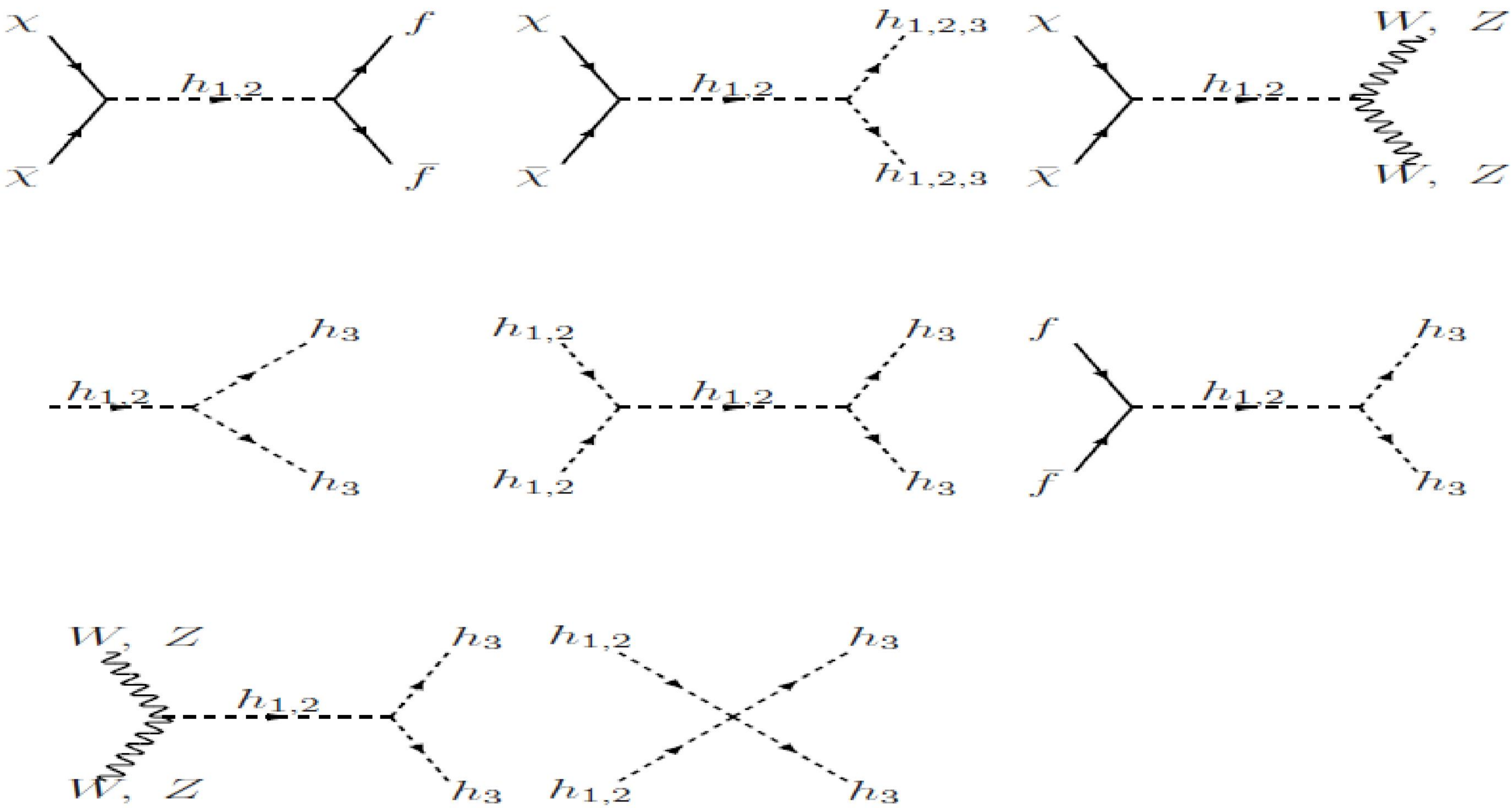
$$\frac{dY_\chi}{dz} = -\langle\sigma v\rangle_{\chi\chi\to x\bar{x}}\left(Y_\chi^2-(Y_\chi^{\rm eq})^2\right)-\langle\sigma v\rangle_{\chi\chi\to h_3h_3}\left(Y_\chi^2-\frac{(Y_\chi^{\rm eq})^2}{(Y_{h_3}^{\rm eq})^2}Y_{h_3}^2\right) . \quad .15)$$

χ -follows freeze out mechanism and becomes relic , behaves as WIMP. Initial abundance Y_{h_3} of h_3 ,the FImP component , is Y_{h_3} =0 .

$$\frac{dY_\chi}{dz} = -\langle\sigma v\rangle_{\chi\chi\to x\bar{x}}\left(Y_\chi^2-(Y_\chi^{\rm eq})^2\right)-\langle\sigma v\rangle_{\chi\chi\to h_3h_3}Y_\chi^2 , \quad ..16)$$

here h_3 follows freeze in mechanism.

Feynman Diagrams for DM



Relic Density

The Boltzmann equation for the scalar component h_3 (FImP)

$$\frac{dY_{h_3}}{dz} = -\frac{2M_{pl}z}{1.66m^2}\frac{\sqrt{g_\star(T)}}{g_s(T)}\left(\sum_i \langle\Gamma_{h_i\to h_3h_3}\rangle\left(Y_{h_3} - Y^{eq}_{h_i}\right)\right)$$
$$-\frac{4\pi^2}{45}\frac{M_{pl}m}{1.66}\frac{\sqrt{g_\star(T)}}{z^2}\left(\sum_{x=W,Z,f,h_1,h_2}\langle\sigma v_{x\bar{x}\to h_3h_3}\rangle\right.$$
$$\left.\times(Y^2_{h_3} - Y^{eq\,2}_x) - \langle\sigma v_{\bar{\chi}\chi\to h_3h_3}\rangle\left(Y^2_\chi - \frac{(Y^{eq}_\chi)^2}{(Y^{eq}_{h_3})^2}Y^2_{h_3}\right)\right) \quad .17)$$

With $Y_{h_3} = 0$

$$\frac{dY_{h_3}}{dz} = -\frac{2M_{pl}z}{1.66m^2}\frac{\sqrt{g_\star(T)}}{g_s(T)}\left(\sum_i \langle\Gamma_{h_i\to h_3h_3}\rangle\left(-Y^{eq}_{h_i}\right)\right) \quad .18)$$
$$-\frac{4\pi^2}{45}\frac{M_{pl}m}{1.66}\frac{\sqrt{g_\star(T)}}{z^2}$$
$$\times\left(\sum_{x=W,Z,f,h_1,h_2}\langle\sigma v_{x\bar{x}\to h_3h_3}\rangle\,(-Y^{eq\,2}_x)\right.$$
$$\left.-\langle\sigma v_{\bar{\chi}\chi\to h_3h_3}\rangle Y^2_\chi\right).$$

Relic Density

$Y_x = \frac{n_x}{S}$ - comoving no. density of DM candidate $x = \chi, \; h_3$,

Y_x^{eq} - equilibrium no. density , $z = m/T$ where T is the photon temperature , Planck Mass $M_{pl} = 1.22 \times 10^{22}$ GeV

$$\sqrt{g_\star(T)} = \frac{g_S(T)}{\sqrt{g_\rho(T)}} \left(1 + \frac{1}{3}\frac{d\, \ln g_S(T)}{d\, \ln T}\right)$$

,where g_S & g_ρ are the degrees of freedom corresponding to entropy & energy density of Universe.

The relic abundance of DM candidates is

$$\Omega_j h^2 = 2.755 \times 10^8 \left(\frac{m_j}{GeV}\right) Y_j(T_0), \quad j = \chi, h_3$$

In our model 2 DM components must satisfy Planck relic density Results.

$$\Omega_{DM} h^2 = \Omega_\chi h^2 + \Omega_{h_3} h^2 \; , \quad 0.1172 \le \Omega_{DM} h^2 \le 0.1226 \; .$$

....19)

DM Self Interaction

- Study of 72 colliding clusters by Harvey claim that DM self interaction cross-section $\sigma_{DM}/m < 0.47 \text{ cm}^2/\text{g}$ with 95% CL.
- Campbell have reported that a light DM (mass<0.1 GeV) produced by freeze in mechanism can provide the required amount of DM self interaction cross –section in order to explain the observations of Abell 3827 with $\sigma_{DM}/m \sim 1.5 \text{ cm}^2/\text{g}$.
- In our model the FImP DM h_3 can account for the DM self interaction cross-section.

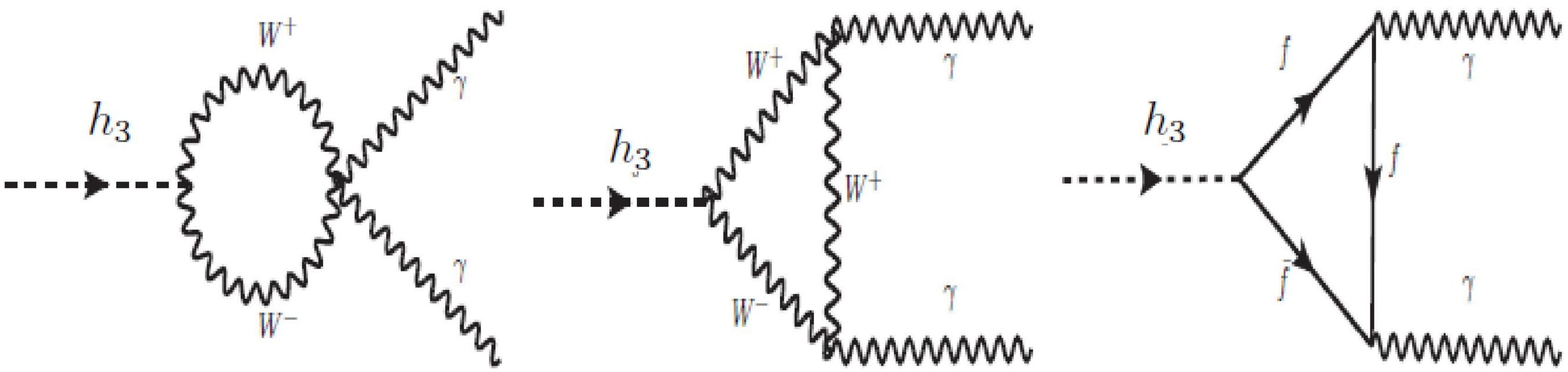
$$\frac{\sigma_{h_3}}{m_3} \simeq \frac{9\lambda_S^2}{2\pi m_3^3} \,,$$

where λ_s or λ_{3333} - the quartic coupling for h_3.

- Consider contact interaction only & neglect s-channel contributions (due to small couplings with scalars h_1 & h_2).

3.55 keV X-ray Emission

$h_3 \to \gamma\gamma$ diagrams



The decay width of h_3 into 3.55 kev X-ray is

$$\Gamma_{h_3 \to \gamma\gamma} = \left(\frac{\alpha_{\rm em}}{4\pi}\right)^2 |F|^2 \, a_{31}^2 \, \frac{G_F m_3^3}{8\sqrt{2}\pi} \,, \quad ..26)$$

- Two component dark matter (WIMP + FImP).

- 1-3 GeV γ - excess from χ (WIMP component) ($\chi\chi$ annihilation).

- 3.55 keV photon from the decay of FImP (h_3).

- Self interaction results from FImP.

Calculation and Results

By scanning over a range of model parameter space we test the viability of the two component DM model.

m_1 GeV	m_2 GeV	m_3 GeV	λ_{12}	λ_{13}	λ_{23}	R_1	Br^1_{inv}	$f_{h_3}\Gamma_{h_3\to\gamma\gamma}$ 10^{-29} s^{-1}	g
$\sim$125.5	85-110	$\sim 7.1\times10^{-6}$	10^{-4}-0.1	10^{-10}-10^{-8}	10^{-11}-10^{-9}	0.8-1.0	0-0.2	2.5-25	0.01-5.0

Table 1: Constraints and chosen region of model parameters space for the two component DM model.

We take v_1 = 246 GeV , v_2 = 500 GeV & assume two choices of v_3 = 6.5 MeV and 8.0 MeV (2.0 MeV $\leq v_3 \leq$ 10.0 MeV).

Galactic Centre(GC) Gamma ray excess and DM Self Interaction

The differential gamma ray flux obtained a region of GC for χ is

$$\frac{\mathrm{d}^2\Phi}{\mathrm{dEd}\Omega} = \frac{\langle\sigma \mathrm{v}\rangle_f}{8\pi m_\chi^2} J \frac{dN_\gamma^f}{dE_\gamma} \quad , \ldots.26)$$

where the astrophysical factor $J = \int_{\mathrm{los}} \rho^2(r(r',\theta))dr$ . ...27)

In the eq. (27) $r' = \sqrt{r_\odot^2 + r^2 - 2r_\odot r \cos\theta}$ with $r_\odot$ =8.5 kpc. The DM Distribution is spherically symmetric which follows Navarro-Frenk-White (NFW) profile

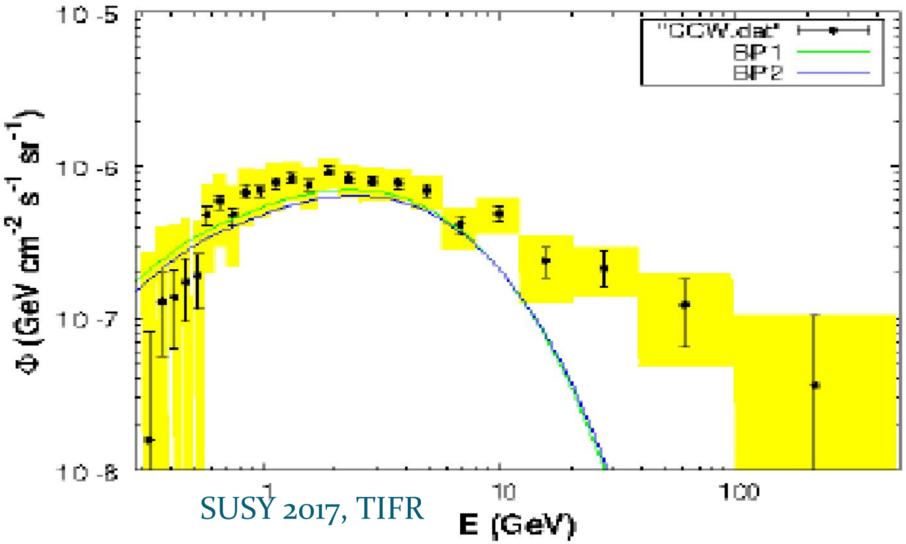
$$\rho(r) = \rho_s \frac{(r/r_s)^{-\gamma}}{(1+r/r_s)^{3-\gamma}} . \quad \ldots 28)$$

The differential gamma ray flux is calculated using the region of interest(ROI) for γ =1.2. ($r_s = 20$ kpc , $\rho_\odot = 0.4$ GeV cm^{-3})

Galactic Centre(GC) Gamma ray excess

BP1	m_1 GeV	m_2 GeV	m_χ GeV	v_3 10^{-3} GeV	g	R_1	Br^1_{inv}	f_χ	$f_\chi^2 \langle\sigma v\rangle_{b\bar{b}}$ 10^{-26} cm^3s^{-1}	r_χ	σ'^{χ}_{SI} pb
1	125.5	102.4	47.5	3.5	0.22	0.92	0.082	0.88	1.68	1.04e-06	2.09e-26
2	125.4	104.9	50.0	4.5	0.11	0.99	0.021	0.89	1.62	1.14e-06	5.81e-28

Table 3 : Benchmark points for calculation of GC gamma ray excess.



DM self interaction

BP1	m_1 GeV	m_2 GeV	m_3 keV	v_3 10^{-3} GeV	f_{h_3}	$f_{h_3}\Gamma_{h_3\to\gamma\gamma}$ 10^{-29} s^{-1}	r_{h_3}	λ_s	$f_{h_3}\frac{\sigma_{h_3}}{m_3}$ cm^2/g	$\sigma_{SI}^{h_3}$ pb
1	125.5	102.4	7.10	3.5	0.12	2.55	~ 1	2.06e-06	0.444	1.11e-23
2	125.4	104.9	7.11	4.5	0.11	2.63	~ 1	1.25e-06	0.157	9.10e-24

Table 4: Calculations of different observables for the scalar DM candidate for the same set of benchmark points given in Table 3.

From Table 4, it can be easily seen that for both the benchmark points, the light scalar DM can provide a self interaction cross-section consistent with the observed limits $\sigma/m \leq 0.47\ \mathrm{cm}^2/\mathrm{g}$ and also the decay width of h_3 is in the range $2.5\times 10^{-29}\ \mathrm{s}^{-1} \leq f_{h_3}\Gamma_{h_3\to\gamma\gamma} \leq 2.5\times 10^{-28}\ \mathrm{s}^{-1}$.

Summary and Conclusions

- We explore the viability of two component DM model with a fermionic DM χ (WIMP) and a feebly interacting light singlet scalar DM S (FImP).
- χ interacts with SM sector through a pseudo scalar Φ and as Φ acquires a non zero VEV the CP symmetry of the Lagrangian is broken spontaneously.
- The $\mathbb{Z}_2$ symmetry of S is also broken spontaneously when S is given a tiny non zero VEV.
- The global $U(1)_{\rm DM}$ symmetry of χ provides us stable dark WIMP.
- The $SU(2)_{\rm L} \times U(1)_{\rm Y}$ symmetry of SM Higgs field is also broken spontaneously.
- We have three scalars h_1 to be SM like, h_2 as non SM Higgs & h_3 is light scalar DM.
- We constrain the model parameter space by vacuum stability, unitarity, bounds from LHC results on SM scalar etc.
- We solve the coupled Boltzmann eqn. such that sum of relic densities of these DM candidates satisfy the observed Planck relic density.

Summary and Conclusions

- χ can explain the excess of GC gamma ray in the energy range 1-3 GeV, which is obtained from the analysis of Fermi-LAT.
- h_3 can account for the DM self interaction cross-section in order to explain the results from galaxy cluster collisions.
- We also test for viability of h_3 to explain the possible 3.55 keV X-ray signal .
- Both the DM candidates in the present "WIMP-FImP" framework are insensitive to direct detection experiment bounds.

THANK YOU

BACKUP SLIDES

Annihilation Cross-Section of Fermion DM candidate

$$\sigma v_{\chi\chi\to f\bar{f}} = N_c \frac{g^2}{32\pi} s \frac{m_f^2}{v_1^2}\left(1-\frac{4m_f^2}{s}\right)^{3/2} F(s,m_1,m_2)\ ,$$

$$\sigma v_{\chi\chi\to W^+W^-} = \frac{g^2}{64\pi}\left(1-\frac{4m_W^2}{s}\right)^{1/2}\left(\frac{m_W^2}{v_1}\right)^2\left(2+\frac{(s-2m_W^2)^2}{4m_W^4}\right) F(s,m_1,m_2)\ ,$$

$$\sigma v_{\chi\chi\to ZZ} = \frac{g^2}{128\pi}\left(1-\frac{4m_Z^2}{s}\right)^{1/2}\left(\frac{m_Z^2}{v_1}\right)^2\left(2+\frac{(s-2m_Z^2)^2}{4m_Z^4}\right) F(s,m_1,m_2)\ .$$

$$F(s,m_1,m_2) = \left[\frac{a_{12}^2 a_{11}^2}{(s-m_1^2)^2+m_1^2\Gamma_1^2}+\frac{a_{21}^2 a_{22}^2}{(s-m_2^2)^2+m_2^2\Gamma_2^2}\right.$$
$$\left.+a_{12}a_{11}a_{22}a_{21}\frac{2(s-m_1^2)(s-m_2^2)+2m_1m_2\Gamma_1\Gamma_2}{[(s-m_1^2)^2+m_1^2\Gamma_1^2][(s-m_2^2)^2+m_2^2\Gamma_2^2]}\right]\ .$$

Annihilation Cross-Section of Fermion DM candidate

$$\sigma v_{\chi\chi\to h_1 h_1} = \frac{g^2}{32\pi}\left(1-\frac{4m_1^2}{s}\right)^{1/2}\left[\frac{a_{12}^2\lambda_{111}^2}{(s-m_1^2)^2+m_1^2\Gamma_1^2} + \frac{a_{22}^2\lambda_{211}^2}{(s-m_2^2)^2+m_2^2\Gamma_2^2} + \frac{2a_{12}a_{22}\lambda_{111}\lambda_{211}((s-m_1^2)(s-m_2^2)+m_1m_2\Gamma_1\Gamma_2)}{[(s-m_1^2)^2+m_1^2\Gamma_1^2][(s-m_2^2)^2+m_2^2\Gamma_2^2]}\right],$$

$$\sigma v_{\chi\chi\to h_2 h_2} = \frac{g^2}{32\pi}\left(1-\frac{4m_2^2}{s}\right)^{1/2}\left[\frac{a_{12}^2\lambda_{122}^2}{(s-m_1^2)^2+m_1^2\Gamma_1^2} + \frac{a_{22}^2\lambda_{222}^2}{(s-m_2^2)^2+m_2^2\Gamma_2^2} + \frac{2a_{12}a_{22}\lambda_{122}\lambda_{222}((s-m_1^2)(s-m_2^2)+m_1m_2\Gamma_1\Gamma_2)}{[(s-m_1^2)^2+m_1^2\Gamma_1^2][(s-m_2^2)^2+m_2^2\Gamma_2^2]}\right],$$

$$\sigma v_{\chi\chi\to h_3 h_3} = \frac{g^2}{32\pi}\left(1-\frac{4m_3^2}{s}\right)^{1/2}\left[\frac{a_{12}^2\lambda_{133}^2}{(s-m_1^2)^2+m_1^2\Gamma_1^2} + \frac{a_{22}^2\lambda_{233}^2}{(s-m_2^2)^2+m_2^2\Gamma_2^2} + \frac{2a_{12}a_{22}\lambda_{133}\lambda_{233}((s-m_1^2)(s-m_2^2)+m_1m_2\Gamma_1\Gamma_2)}{[(s-m_1^2)^2+m_1^2\Gamma_1^2][(s-m_2^2)^2+m_2^2\Gamma_2^2]}\right].$$

Decay and annihilation terms for scalar DM candidate

$$\Gamma_{h_j \to h_3 h_3} = \frac{\lambda_{j33}^2}{8\pi m_j}\sqrt{1 - \frac{4m_3^2}{m_j^2}} \,, j = 1, 2 \,,$$

$$\sigma_{f\bar{f}\to h_3 h_3} = N_c \frac{1}{16\pi s}\sqrt{(s - 4m_3^2)(s - 4m_f^2)}\left(\frac{m_f}{v_1}\right)^2 F'(s, m_1, m_2) \,,$$

$$\sigma_{W^+W^-\to h_3 h_3} = \frac{1}{18\pi s}\sqrt{\frac{s - 4m_3^2}{s - 4m_W^2}}\left(\frac{m_W^2}{v_1}\right)^2\left(2 + \frac{(s - 2m_W^2)^2}{4m_W^4}\right) F'(s, m_1, m_2) \,,$$

$$\sigma_{ZZ\to h_3 h_3} = \frac{1}{18\pi s}\sqrt{\frac{s - 4m_3^2}{s - 4m_Z^2}}\left(\frac{m_Z^2}{v_1}\right)^2\left(2 + \frac{(s - 2m_Z^2)^2}{4m_Z^4}\right) F'(s, m_1, m_2) \,.$$

Decay and annihilation terms for scalar DM candidate

$$F'(s, m_1, m_2) = \left[\frac{a_{11}^2 \lambda_{133}^2}{(s - m_1^2)^2 + m_1^2 \Gamma_1^2} + \frac{a_{21}^2 \lambda_{233}^2}{(s - m_2^2)^2 + m_2^2 \Gamma_2^2} + a_{11}\lambda_{133} a_{21}\lambda_{233} \frac{2(s - m_1^2)(s - m_2^2) + 2 m_1 m_2 \Gamma_1 \Gamma_2}{[(s - m_1^2)^2 + m_1^2 \Gamma_1^2][(s - m_2^2)^2 + m_2^2 \Gamma_2^2]}\right] .$$

$$\sigma_{h_1 h_1 \to h_3 h_3} = \frac{1}{2\pi s}\sqrt{\frac{s - 4m_3^2}{s - 4m_1^2}}\left(\lambda_{1133} + 3\frac{\lambda_{111}\lambda_{133}}{(s - m_1^2)} + \frac{\lambda_{211}\lambda_{233}}{(s - m_2^2)}\right)^2 .$$

$$\sigma_{h_2 h_2 \to h_3 h_3} = \frac{1}{2\pi s}\sqrt{\frac{s - 4m_3^2}{s - 4m_2^2}}\left(\lambda_{2233} + 3\frac{\lambda_{222}\lambda_{233}}{(s - m_2^2)} + \frac{\lambda_{122}\lambda_{133}}{(s - m_1^2)}\right)^2 .$$

Invisible decay width

$$\Gamma_{h_1 \to \chi\bar{\chi}} = \frac{m_1}{8\pi} g^2 a_{21}^2 \left(1 - \frac{4m_\chi^2}{m_1^2}\right)^{1/2} ,$$

$$\Gamma_{h_2 \to \chi\bar{\chi}} = \frac{m_2}{8\pi} g^2 a_{22}^2 \left(1 - \frac{4m_\chi^2}{m_2^2}\right)^{1/2} ,$$

PMNS matrix with δ =0

$$U = \begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - s_{23}s_{13}c_{12} & c_{23}c_{12} - s_{23}s_{13}s_{12} & s_{23}c_{13} \\ s_{23}s_{12} - s_{13}c_{23}c_{12} & -s_{23}c_{12} - s_{13}s_{12}c_{23} & c_{23}c_{13} \end{pmatrix}$$

Couplings between different physical scalars obtained from the expression of potential

$$-\lambda_{111} = \lambda_H v_1 a_{11}^3 + \lambda_\Phi v_2 a_{12}^3 + \lambda_{H\Phi}(v_2 a_{11}^2 a_{12} + v_1 a_{11} a_{12}^2) + \lambda_{HS} v_1 a_{11} a_{13}^2 + 2\lambda_{\Phi S} v_2 a_{12} a_{13}^2 \,,$$

$$-\lambda_{222} = \lambda_H v_1 a_{21}^3 + \lambda_\Phi v_2 a_{22}^3 + \lambda_{H\Phi}(v_2 a_{21}^2 a_{22} + v_1 a_{21} a_{22}^2) + \lambda_{HS} v_1 a_{21} a_{23}^2 + 2\lambda_{\Phi S} v_2 a_{22} a_{23}^2 \,,$$

$$-\lambda_{122} = 3\lambda_H v_1 a_{11} a_{21}^2 + 3\lambda_\Phi v_2 a_{12} a_{22}^2 + \lambda_{H\Phi}(v_2(a_{21}^2 a_{12} + 2a_{11}a_{21}a_{22}) + v_1(a_{11}a_{22}^2 + 2a_{21}a_{12}a_{22}) + \lambda_{HS} v_1(a_{11}a_{23}^2 + 2a_{21}a_{13}a_{23}) + 2\lambda_{\Phi S} v_2(a_{12}a_{23}^2 + 2a_{22}a_{13}a_{23}) \,,$$

$$-\lambda_{211} = 3\lambda_H v_1 a_{11}^2 a_{21} + 3\lambda_\Phi v_2 a_{12}^2 a_{22} + \lambda_{H\Phi}(v_2(a_{11}^2 a_{22} + 2a_{11}a_{21}a_{12}) + v_1(a_{21}a_{12}^2 + 2a_{11}a_{12}a_{22}) + \lambda_{HS} v_1(a_{21}a_{13}^2 + 2a_{11}a_{13}a_{23}) + 2\lambda_{\Phi S} v_2(a_{22}a_{31}^2 + 2a_{12}a_{13}a_{23}) \,,$$

$$-\lambda_{133} = 3\lambda_H v_1 a_{11} a_{31}^2 + 3\lambda_\Phi v_2 a_{12} a_{32}^2 + \lambda_{H\Phi}(v_2(a_{31}^2 a_{12} + 2a_{11}a_{31}a_{32}) + v_1(a_{11}a_{32}^2 + 2a_{31}a_{12}a_{32}) + \lambda_{HS} v_1(a_{11}a_{33}^2 + 2a_{31}a_{13}a_{33}) + 2\lambda_{\Phi S} v_2(a_{12}a_{33}^2 + 2a_{32}a_{13}a_{33}) \,,$$

$$-\lambda_{233} = 3\lambda_H v_1 a_{21} a_{31}^2 + 3\lambda_\Phi v_2 a_{22} a_{32}^2 + \lambda_{H\Phi}(v_2(a_{31}^2 a_{22} + 2a_{21}a_{31}a_{32}) + v_1(a_{21}a_{32}^2 + 2a_{31}a_{22}a_{32}) + \lambda_{HS} v_1(a_{21}a_{33}^2 + 2a_{31}a_{23}a_{33}) + 2\lambda_{\Phi S} v_2(a_{22}a_{33}^2 + 2a_{32}a_{23}a_{33}) \,,$$

$$-\lambda_{1133} = \frac{3}{2}(\lambda_H a_{11}^2 a_{31}^2) + \frac{3}{2}(\lambda_\Phi a_{12}^2 a_{32}^2) + \frac{3}{2}(\lambda_S a_{13}^2 a_{33}^2) + \frac{\lambda_{H\Phi}}{2}(a_{12}^2 a_{31}^2 + a_{11}^2 a_{32}^2 + 4a_{11}a_{12}a_{31}a_{32}) + \frac{\lambda_{HS}}{2}(a_{11}^2 a_{33}^2 + a_{13}^2 a_{31}^2 + 4a_{11}a_{13}a_{31}a_{33}) + \lambda_{\Phi S}(a_{12}^2 a_{33}^2 + a_{13}^2 a_{32}^2 + 4a_{12}a_{13}a_{32}a_{33}) \,,$$

$$-\lambda_{2233} = \frac{3}{2}(\lambda_H a_{21}^2 a_{31}^2) + \frac{3}{2}(\lambda_\Phi a_{22}^2 a_{32}^2) + \frac{3}{2}(\lambda_S a_{23}^2 a_{33}^2) + \frac{\lambda_{H\Phi}}{2}(a_{22}^2 a_{31}^2 + a_{21}^2 a_{32}^2 + 4a_{21}a_{22}a_{31}a_{32}) + \frac{\lambda_{HS}}{2}(a_{21}^2 a_{33}^2 + a_{23}^2 a_{31}^2 + 4a_{21}a_{23}a_{31}a_{33}) + \lambda_{\Phi S}(a_{22}^2 a_{33}^2 + a_{23}^2 a_{32}^2 + 4a_{22}a_{23}a_{32}a_{33}) \,,$$

$$-\lambda_{3333} = \frac{1}{4}(\lambda_H a_{31}^4 + \lambda_\Phi a_{32}^4 + \lambda_S a_{33}^4) + \frac{\lambda_{H\Phi}}{2} a_{31}^2 a_{32}^2 + \frac{\lambda_{HS}}{2} a_{31}^2 a_{33}^2 + \lambda_{\Phi S} a_{32}^2 a_{33}^2 \sim \lambda_S/4 \,.$$

3.55 keV X-ray Emission

- 3.55 keV X-ray emission line from extragalactic spectrum cann't be explained by known astrophysical phenomena.
- If this signal exists then it can be explained by decay of DM candidates.
- In our work we propose light DM candidate h_3 (m_3 ~ 7.1 keV), which decay into pair of photons, to explain 3.55 keV X-ray signal.

3.55 keV X-ray Emission

Loop factor, $F = F_W(\beta_W) + \sum_f N_c Q_f^2 F_f(\beta_f)$ ...26)

Where

$$\begin{aligned} \beta_W &= \frac{4m_W^2}{m_3^2}, \quad \beta_f = \frac{4m_f^2}{m_3^2}, \\ F_W(\beta) &= 2 + 3\beta + 3\beta(2-\beta)f(\beta), \\ F_f(\beta) &= -2\beta[1 + (1-\beta)f(\beta)], \\ f(\beta) &= \arcsin^2[\beta^{-1/2}] \,. \end{aligned}$$

In order to produce the required extragalactic X-ray flux the decay width of h_3 must be in the range $2.5 \times 10^{-29}\ \mathrm{s}^{-1} \leq f_{h_3} \Gamma_{h_3 \to \gamma\gamma} \leq 2.5 \times 10^{-28}\ \mathrm{s}^{-1}$. Where $f_{h_3} = \frac{\Omega_{h_3}}{\Omega_{DM}}$ is the fractional contribution to DM relic density by h_3 component.

Direct Detection of Dark Matter

Spin independent scattering cross-section for χ is

$$\sigma_{SI}^{\chi} = \frac{g^2}{\pi} m_r^2 \left(\frac{a_{11}a_{12}}{m_1^2} + \frac{a_{22}a_{21}}{m_2^2} \right)^2 \lambda_p^2 \, v^2 \quad ,..23)$$

where $\lambda_p = \frac{m_p}{v_1} \left[\sum_q f_q + \frac{2}{9} \left(1 - \sum_q f_q \right) \right] \simeq 1.3 \times 10^{-3}$ . . ..24)

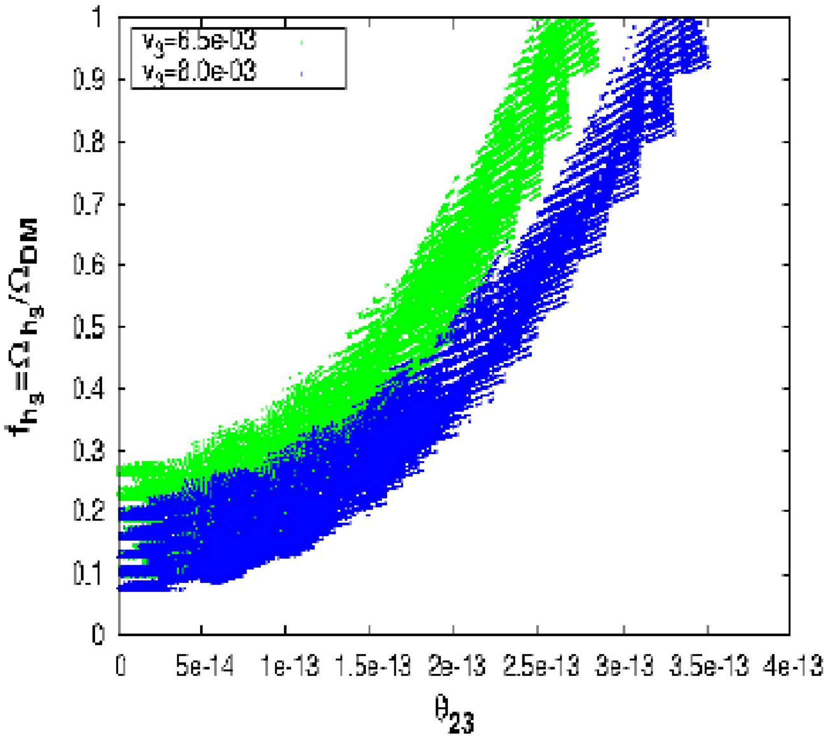
Similarly for the scalar FImP DM candidate, scattering cross-section is

$$\sigma_{SI}^{h_3} = \frac{m_r'^2}{4\pi} \frac{f^2}{v_1^2} \frac{m_p^2}{m_3^2} \left(\frac{\lambda_{133}a_{11}}{m_1^2} + \frac{\lambda_{233}a_{21}}{m_2^2} \right)^2 \quad , ...25)$$

where $m_r' = \frac{m_3 m_p}{m_3 + m_p}$ and f ~ 0.3. Since $m_3 << m_p,\ m_r' \sim m_3$ & Eq. (25) becomes

$$\sigma_{SI}^{h_3} = \frac{1}{4\pi} \frac{f^2}{v_1^2} m_p^2 \left(\frac{\lambda_{133}a_{11}}{m_1^2} + \frac{\lambda_{233}a_{21}}{m_2^2} \right)^2 .$$

Calculation and Results



Observation :-

Relic density contribution of scalar DM component increases with θ_{23} .

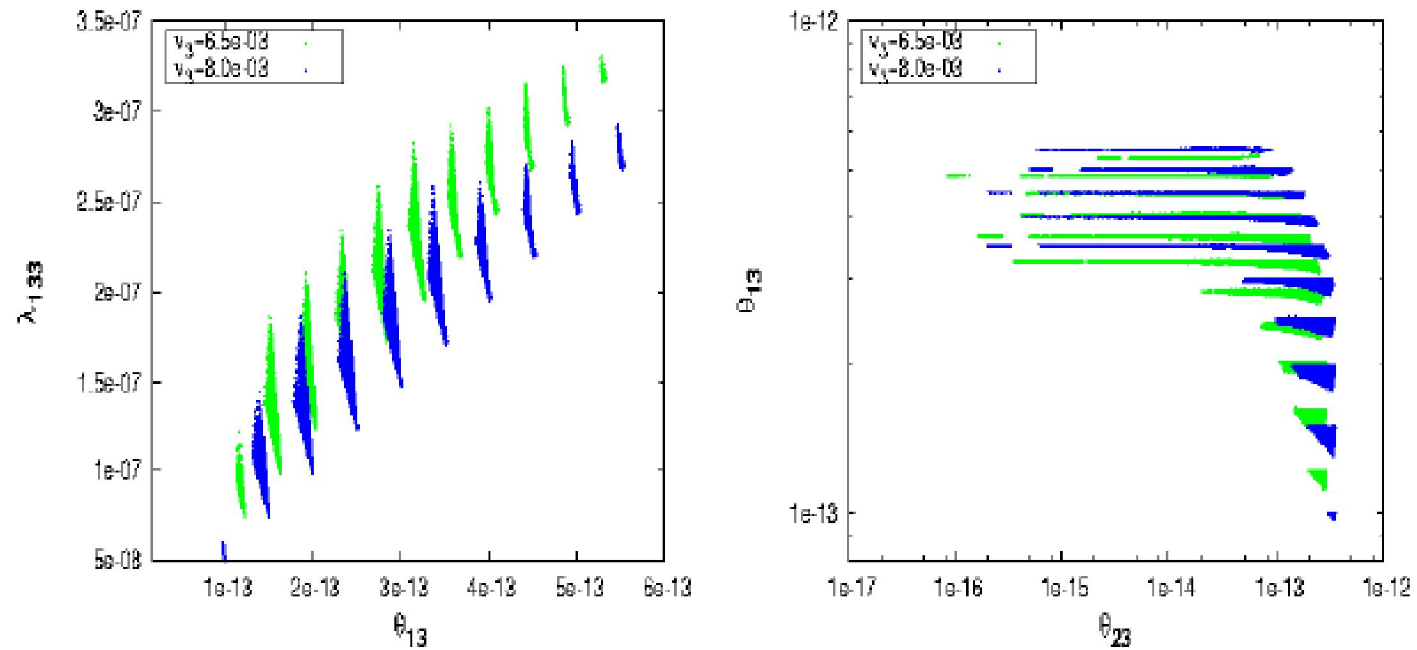
For

$$v_3 = 6.5 \times 10^{-3} \text{ GeV } \theta_{23}^{max} \sim 2.8 \times 10^{-13}$$

&

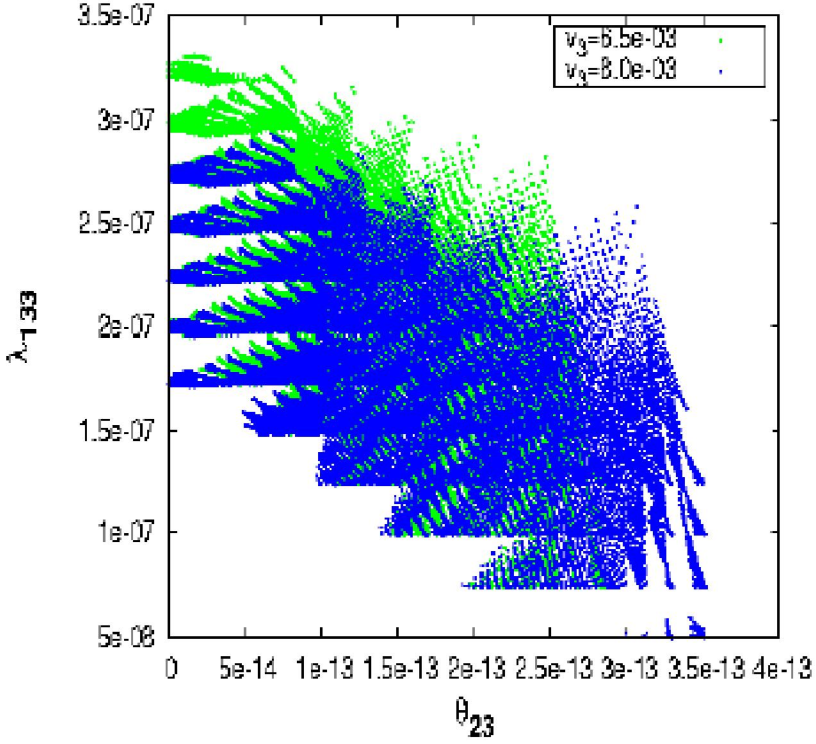
$$v_3 = 8.0 \times 10^{-3} \text{ GeV is } \theta_{23}^{max} \sim 3.5 \times 10^{-13}$$

Calculation and Results



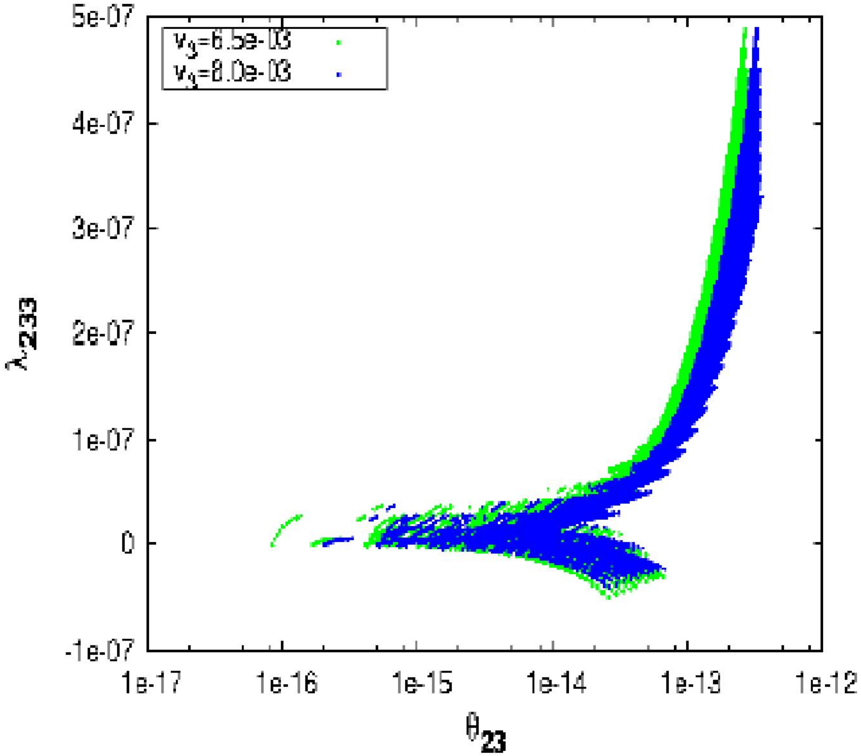
- θ_{13} varies within the range $\sim 1.0 - 6.0 \times 10^{-13}$ for both the values of $v_3 = 8.0 \times 10^{-3}$ GeV & $v_3 = 6.5 \times 10^{-3}$ GeV respectively. λ_{133} is proportional to the value of θ_{13} .
- For smaller values of $\theta_{23} \sim 10^{-16} - 10^{-14}$, θ_{13} maintains a value in the range $\sim 3 \times 10^{-13} - 6 \times 10^{-13}$.

Calculation and Results



For both the values of v_3 the maximum allowed range of λ_{133} is $0.5 \times 10^{-8} - 3.5 \times 10^{-7}$.

Calculation and Results



For both the values of v_3 the maximum allowed range of λ_{233} is ~ 5×10^{-7}

.

3.55 keV X-ray Emission

- 3.55 keV X-ray emission line from extragalactic spectrum cann't be explained by known astrophysical phenomena.
- If this signal exists then it can be explained by decay of DM candidates.

- In our work we propose light DM candidate h_3 (m_3 ~ 7.1 keV), which decay into pair of photons, to explain 3.55 keV X-ray signal.

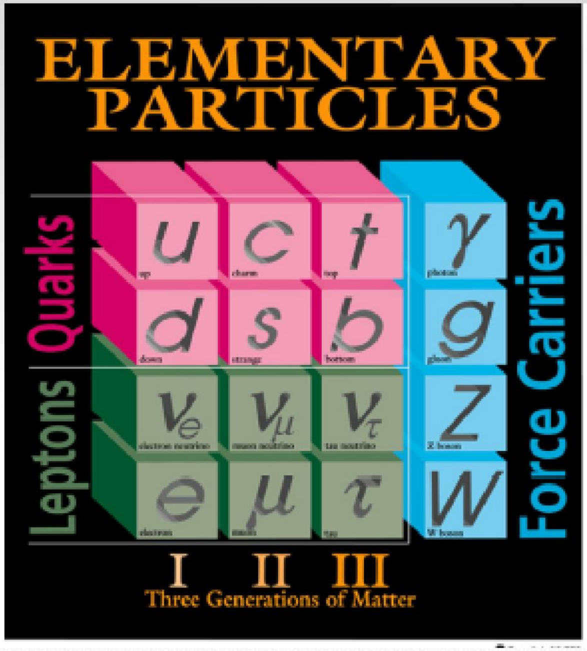
What is Dark Matter(DM)?

- An Unknown, non-luminous matter with almost no interactions with other particles except gravity.
- Contains more than 80% of the matter content of the universe.
- All pervading across the galaxies, clusters, super-clusters.

General Properties of Dark Matter

- Should be neutral
- Gravitationally interacting
- Stable
- Very weak interaction with other Standard Model particles

Weakly Interacting Massive Particle (WIMP) is a popular candidate of DM.



Particle Nature of Dark Matter

- The particle nature of dark matter is not known.
- No SM particle (Neutrinos? But contribution of active neutrinos are negligible).
- One has to look for particles in theories

    1. extension of SM.

    2. Beyond SM.
- BSM- SUSY (Neutralino), Extra dimension etc. (Kaluza-Klein dark matter).
- Our focus is on simple extension of SM.

Classification of DM

From Thermal History

- Thermal :- Initially in thermal and chemical equilibrium. Decouples and goes out of equilibrium as relic.
- Non-thermal :- Never in thermal equilibrium. Produced from out of equilibrium decay of a particle.
- Feebly Interacting Massive Particle (FIMP) :- Never in thermal equilibrium but produced from a particle which is in thermal equilibrium.
- Can be other types such as SIMP or self interacting massive particles.