FIP

A model of light pseudo scalar Dark matter

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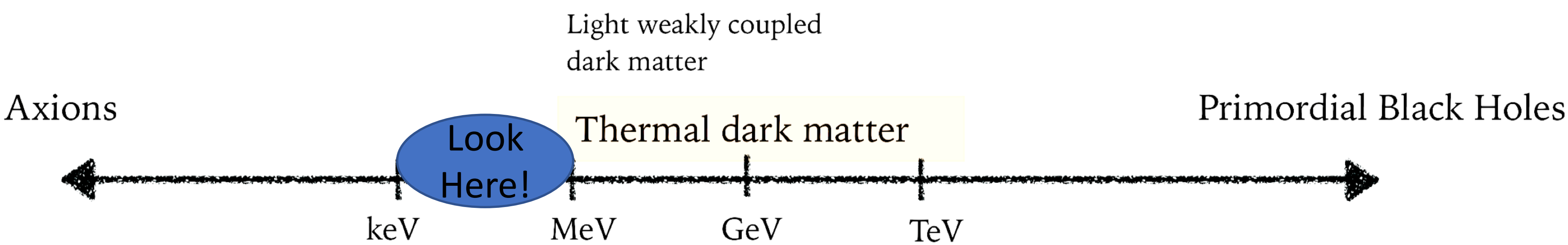
standard *WIMP* Freeze out scenario

- Most studied BSM DM scenario: WiMP → EW +weak coupling SM
- Produced thermally early Universe, thermal equilibrium with SM up to certain temp → decouples from thermal bath@ T_f, interaction rate drops below expansion rate of Universe (*H)* → $\Omega h^2 \simeq 0.12$
- Observed abundance is set almost exclusively by annihilation crosssec, largely insensitive to unknown details of early Universe and to mass



- Null results at direct detection ⇒ Strong constraints WIMP paradigm
- Alternate possibilities: FIP, Axion, ALPs etc.

Dark matter Freeze out vs in

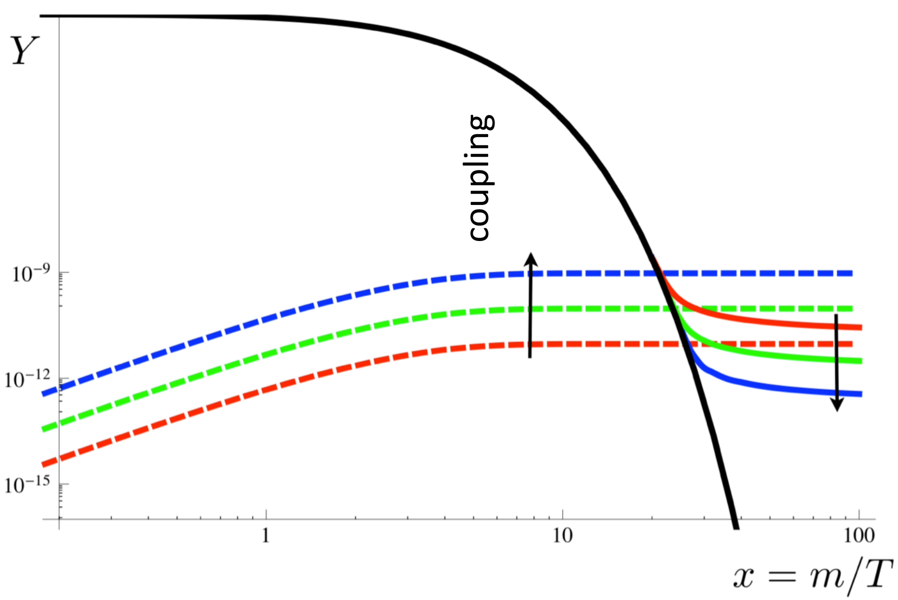


Fig 1: *Evolution with temperature of DM abundance for conventional freeze-out and freeze-in mechanism*.

- Freeze-in as *opposite process* to freeze-out: as T drops below the mass of the relevant particle, DM is either heading away from (freeze- out) or towards (freeze-in) thermal equilibrium
- Freeze-in: DM interacts extremely weakly with SM particles, negligible initial abundance and never attain thermal equilibrium (Feebly Interacting Particle)

Theory Framework

- **EWν_R** model contains non-sterile RH $\nu's$ with Majorana masses ~EW
- Dirac mass term comes from a complex singlet scalar ϕ_S, imaginary part of this singlet is a pseudo-NG (PNG) boson A_S^0 (light DM)
- When a global symmetry is spontaneously broken A_S^0 acquires mass from explicit breaking term in scalar potential
- EW SSB scale of global symmetry & sub-MeV explicit breaking scale for A_S^0 makes this PNG boson naturally light DM candidate

Majorana

$$\mathcal{L}_M = g_M \left(l_R^{M,T} \sigma_2\right)\left(i\, \tau_2\, \tilde{\chi}\right) l_R^M + h.c.$$

$$\tilde{\chi}\ (3, \frac{Y}{2} = 1)$$

$$M_R = g_M v_M;\ <\chi^0>= v_M \sim \Lambda_{EW}$$

$$\tilde{\chi} = \begin{pmatrix} \frac{1}{\sqrt{2}}\chi^+ & \chi^{++} \\ \chi^0 & -\frac{1}{\sqrt{2}}\chi^+ \end{pmatrix}$$

Dirac

$$\mathcal{L}_S = g_{Sl} \bar{l}_L \phi_S l_R^M + h.c.$$

$$\phi_S\ (1, \frac{Y}{2} = 0)$$

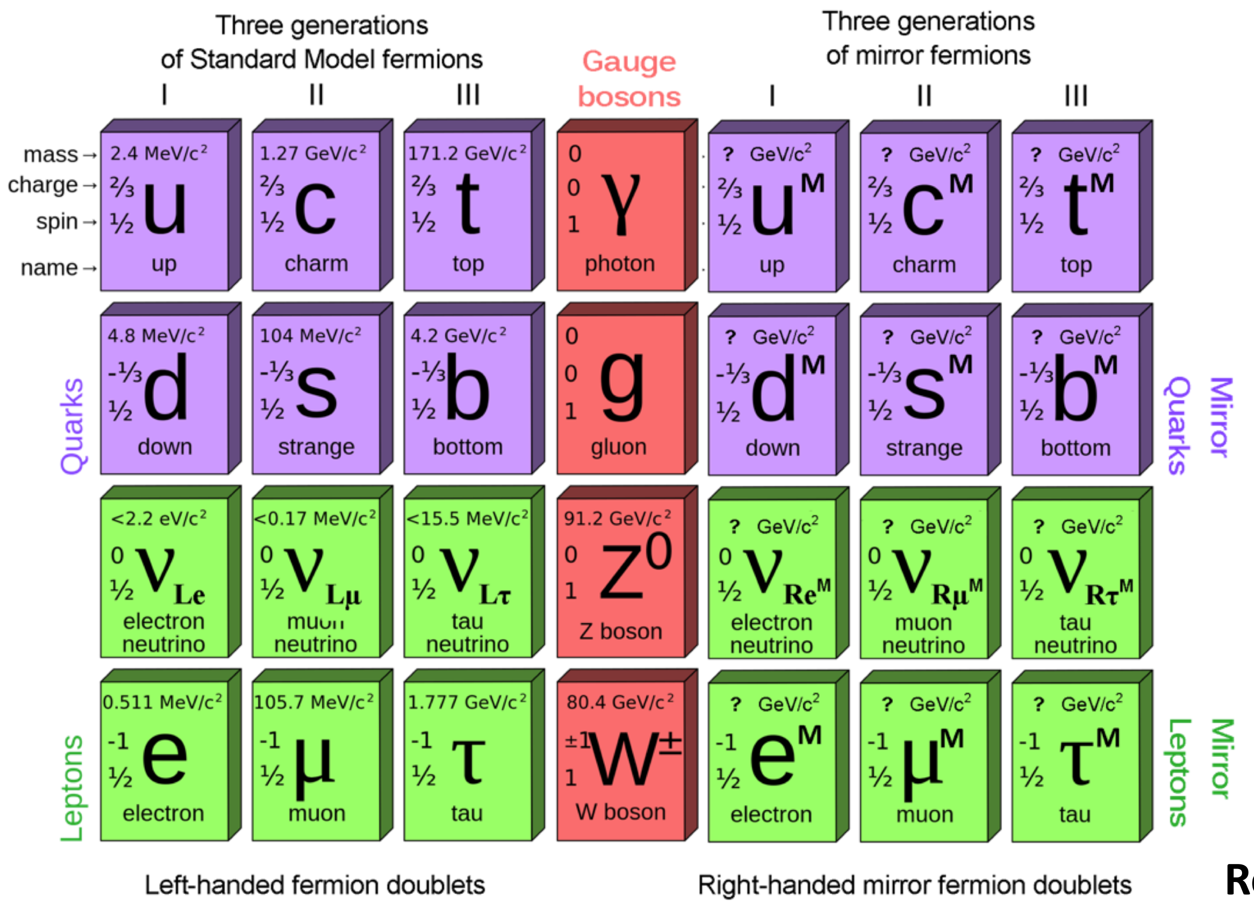
$$m_\nu^D = g_{Sl} v_S \quad \text{where} \quad <\phi_S>= v_S$$

$$m_\nu \leq 1eV \quad \Rightarrow \quad v_S \sim 10^{5-6} eV \text{ with } g_{Sl} \sim \mathcal{O}(1)$$

$$\text{or} \quad v_S \sim \Lambda_{EW} \text{ with } g_{Sl} \sim \mathcal{O}(10^{-6})$$

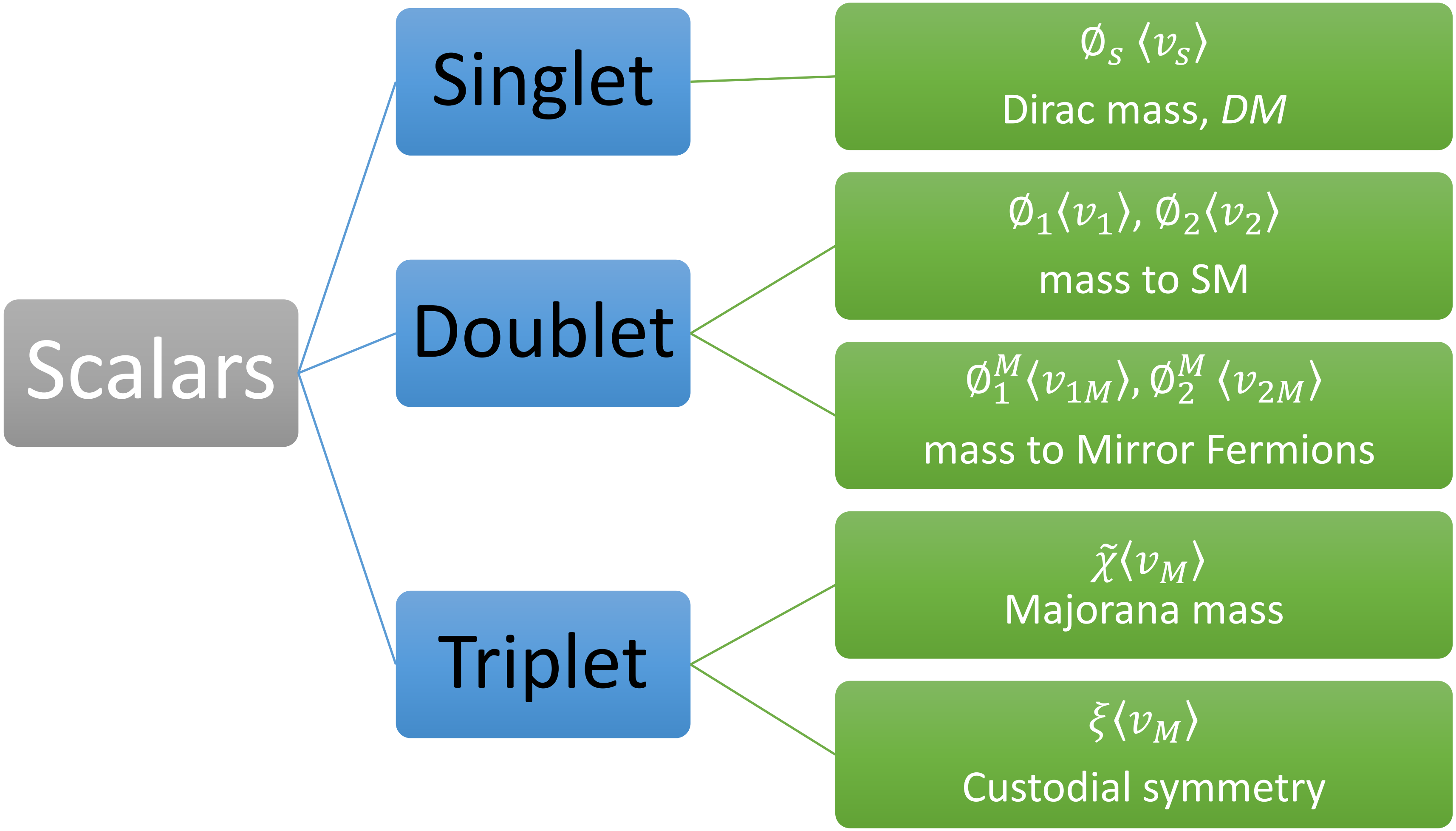
Particle content: EW$\boldsymbol{\nu_R}$ model

SM+ mirror fermions+ extended scalar sector (*DM*)



Refs: Chakdar, Ghosh, Hoang, Hung, Nandi
Phys.Rev.D 95 (2017) 1, 015014,
Phys.Rev.D 93 (2016) 3, 035007

Complete *Scalar* Sector



Scalar sector parameters

- Complex part of singlet scalar A_s^0 does not mix with other scalars
- Mass of complex singlet scalar

$$M_{A_s^0}^2 = 8\,\lambda_{5c}(v_1 + v_2)\,(v_{1M} + v_{2M})$$

- $\sqrt{(v_1^2 + v_{1M}^2 + v_2^2 + v_{2M}^2 + 8v_M^2)}$ = 246 GeV
- After Spontaneous EW symmetry breaking → SU(2)$_D$ singlet mass eigenstates denoted by $\widetilde{H_s}$, $\widetilde{H}$, $\widetilde{H}'$, $\widetilde{H}''$, $\widetilde{H}'''$, $\widetilde{H}''''$
- $\widetilde{H_s}$ → lightest, singlet DM, next heavier ones are $\widetilde{H}'$, $\widetilde{H}''$, $\widetilde{H}'''$, with heaviest state $\widetilde{H}''''$ and $\widetilde{H}$ being the 125 GeV Higgs
- The decay rate of $\widetilde{H}$ into two lightest CP-even scalars $\widetilde{H_s}$ (A_s^0) can contribute to the Higgs invisible decay width depending on mixing, i.e., the value of the quartic coupling λ_{4a} and vevs
- Singlet scalar $v_s \sim 10^4$ GeV, $y_{sl} \sim 10^{-8}$ chosen → ν mass ~ $0.1\ eV$

BP's and $\mu's$: Scalar mass spectrum

	Benchmark Points																							
	VEV of the scalar fields (GeV)						Scalar quartic couplings λ's									Masses of the scalar fields (GeV)								
	v_1	v_2	v_{1M}	v_{2M}	v_M	v_s	λ_{1a}	λ_{1b}	λ_{2a}	λ_{2b}	λ_3	λ_4	λ_5	λ_8	λ_s	$M_{\widetilde{H}''''}$	$M_{\widetilde{H}'''}$	$M_{\widetilde{H}''}$	$M_{\widetilde{H}'}$	$M_{\widetilde{H}}$	$M_{\widetilde{H}_s}$	m_5	$m_{3,H^\pm,H_3^0}$	$m_{3,\text{All others}}$
BP-1 52.04% Φ_1, 47.95% Φ_2	140	145	43.5	43.5	45	10^4	0.09	0.1	9.0	9.0	9.0	2.9	9.0	9.0	10^{-14}	1126.12	607.15	369.85	352.90	124.16	0.0028	1279.4	738.66	972.59
BP-2 51.52% Φ_1, 48.47% Φ_2	138	142	51.07	51.07	45	10^4	0.1	0.1	9.0	9.0	9.0	2.9	9.0	9.0	10^{-14}	1130.13	610.94	433.36	402.58	125.18	0.0028	1279.4	738.66	972.34
BP-3 51.52% Φ_1, 48.47% Φ_2	152	145	42.99	42.99	40	10^4	0.001	0.1	9.0	9.0	9.0	0.5	9.0	9.0	10^{-14}	622.02	454.13	364.76	337.63	125.82	0.0.0028	1279.4	738.66	987.95
BP-4 53.69% Φ_1, 46.31% Φ_2	130	135	68.19	68.19	45	10^4	0.116	0.1	9.0	9.0	9.0	2.9	9.0	9.0	10^{-14}	1142.13	624.92	534.13	463.67	125.23	0.0028	1279.4	738.66	972.34
BP-5 52.03% Φ_1, 47.97% Φ_2	130	140	62.95	62.95	45	10^4	0.11	0.11	9.0	9.0	9.0	2.9	9.0	9.0	10^{-14}	1150.57	635.59	578.61	481.12	124.23	0.0028	1279.4	738.66	972.34

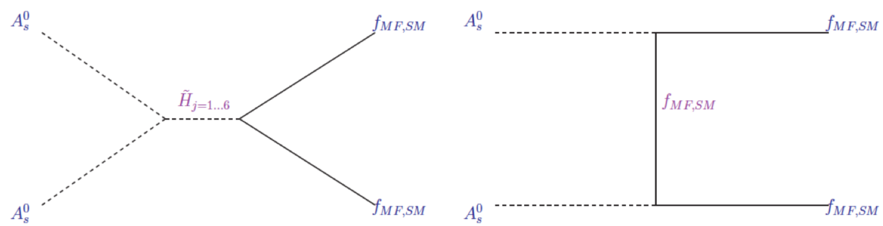
TABLE I: BPs obtained fitting for constraints with m_H at 125 GeV in conjunction with other heavier scalars

Signal Strength	Benchmark Points and Signal strength of SM like Higgs				
	$\mu_{b\bar{b}}$	$\mu_{\tau\bar{\tau}}$	μ_{WW}	μ_{ZZ}	$\mu_{\gamma\gamma}$
$\mu_{\text{Best-Fit}}$	$2.51^{+2.43}_{-2.01}$	$1.05^{+0.53}_{-0.47}$	$1.35^{+0.35}_{-0.21}$	$1.22^{+0.23}_{-0.21}$	$1.16^{+0.21}_{-0.18}$
$\mu_{\text{BP}-1}$	1.70	1.91	1.214	1.211	1.19
$\mu_{\text{BP}-2}$	1.81	2.03	1.239	1.236	1.25
$\mu_{\text{BP}-3}$	1.42	1.59	1.114	1.111	1.10
$\mu_{\text{BP}-4}$	1.85	2.06	1.03	1.029	1.23
$\mu_{\text{BP}-5}$	2.06	2.30	1.16	1.15	1.22

TABLE II: 125 GeV Higgs signal strengths corresponding to the BP's shown in Table I

Why *NOT* Freeze out?

- For viable sub-MeV *DM,* corresponding quartic coupling $\lambda_{5c} < 10^{-12}$
- Allowed annihilation channels are: $A_s^0\, A_s^0 \rightarrow \widetilde{H}'_{All} \rightarrow \bar{\nu}_l \nu_l$ / $l\bar{l}$



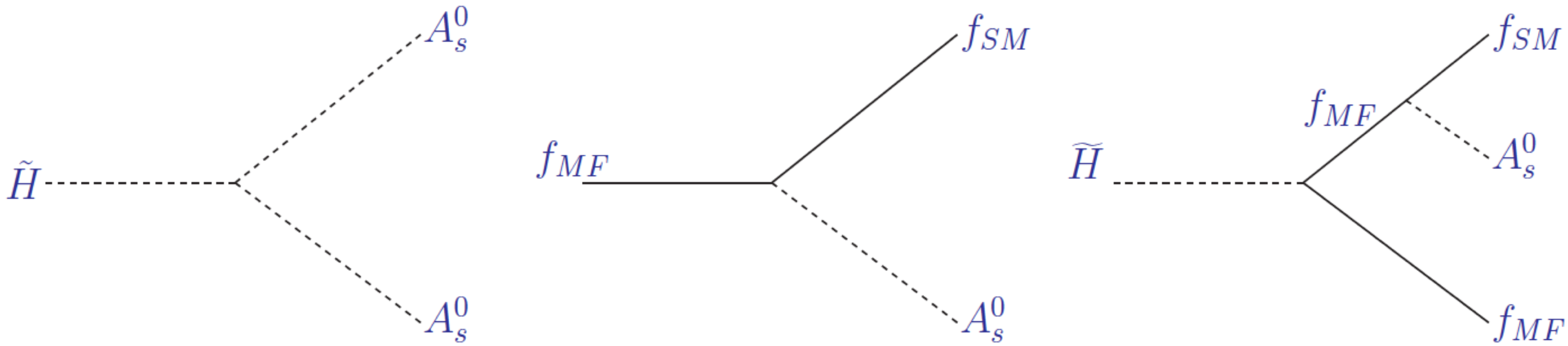
- Large Higgs portal couplings produce relic density at right ballpark through freeze-out mechanism, but violates direct detection limits
- DM unable to remain in thermal bath at MeV due to BBN, forcing it to decouple from thermal bath at some higher temperature
- For such relativistic decoupling, the relic density can be calculated by

$$\Omega h^2 = 7.83 \times 10^4 \left(\frac{g_i}{g_{*s}(T_{dec})}\left(\frac{M_{DM}}{MeV}\right)\right)$$

- Turns out to be Overabundant by a few orders of magnitude!

Freeze in relic density

- DM is produced from annihilations of SM particles: a + b → χ + χ or decay of heavier particle in equilibrium with thermal bath: Y→ χ + χ
- In this model, *FIP* DM is produced dominantly from **the decay of the mirror fermions and heavy Higgs** (scattering processes negligible)



- Boltzmann equation: $\frac{dn}{dt} + 3Hn = -\sum_i S\,(X_{Heavy,i} \rightarrow A_S^0 A_S^0, A_S^0 f_{SM})$ & corresponding relic density:

$$\Omega h^2 = \frac{h^2}{3H_0^2\, M_{Pl}^2} M_{A_S^0} \sum_i \frac{g_{XHeavy,i}\, \Gamma(X_{Heavy,i} \rightarrow A_S^0 A_S^0, A_S^0 f_{SM})}{M_{XHeavy,i}^2}$$

Freeze in relic density

- Decay of heavy Higgs into DM & decay of mirror fermion to SM + DM,

$$\Gamma\left(\widetilde{H}_i \to A_S^0\, A_S^0\right) = \frac{y^2_{\widetilde{H}_i\, A_S^0 A_S^0}}{32\,\pi M_{\widetilde{H}_i}}\left(1 - \frac{M^2_{A_S^0}}{M^2_{\widetilde{H}_i}}\right)^{1/2},\ \Gamma\left(f_{MF} \to f_{SM} A_S^0\right) = \frac{M_{f_{MF}}}{8\pi}\, y^2_{f_{MF} f_{SM} A_S^0}$$

- Decay of heavy scalars and Mirror fermions can be controlled by λ_{5c}, $\lambda_{4a}, \lambda_s, y_{sl}$ and VEVs with $M_{A_S^0}$ mainly depending on λ_{5c} and VEVs

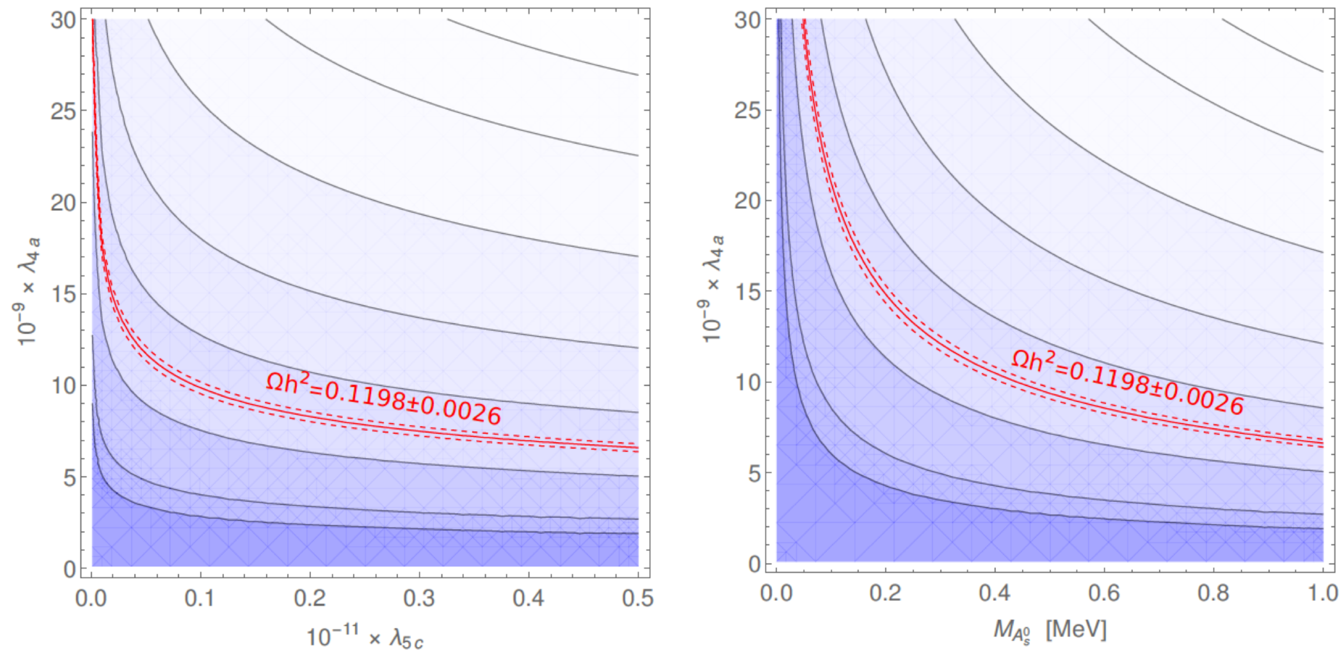
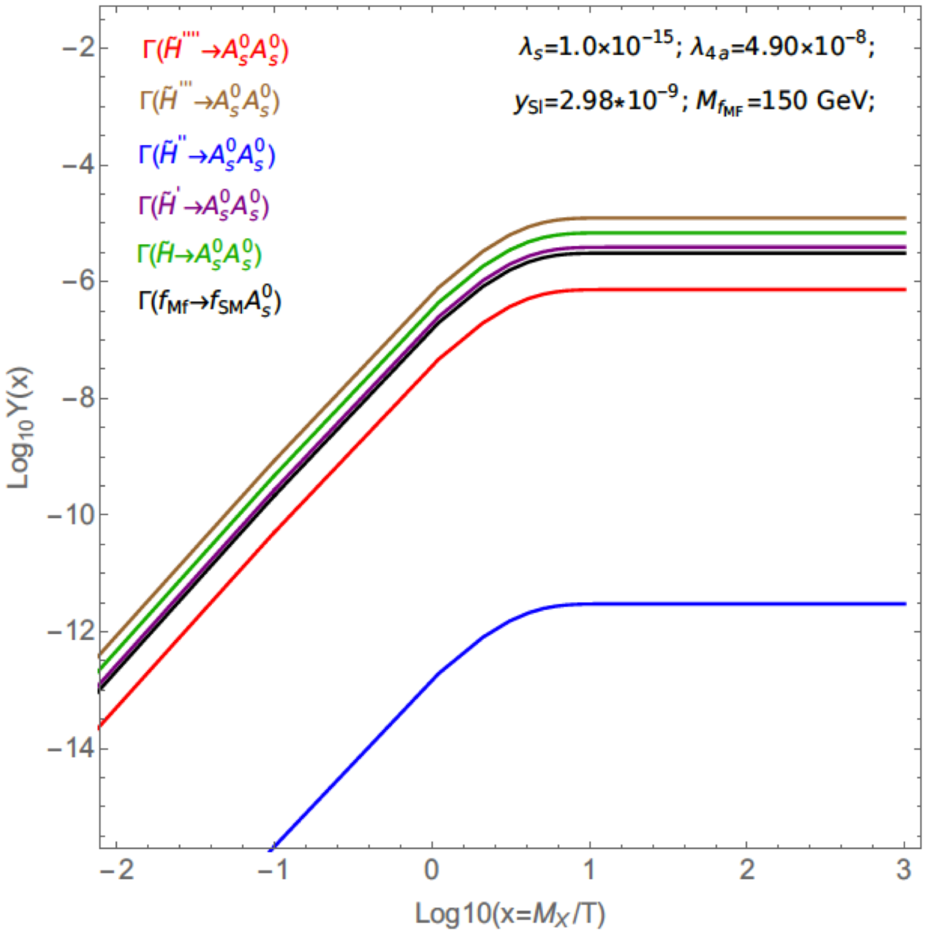


Fig: Variation of the parameters $\lambda_{5c}$and λ_{4a} and dark matter mass $M_{A_S^0}$ against λ_{4a} variation

Evolution of *FIP* DM with T

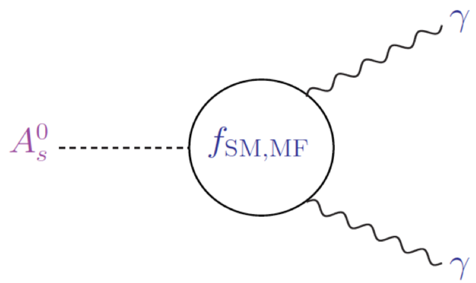


Freeze-in effect: initially density of DM being zero and increasing during the cooling of Universe and after a certain temperature DM density becoming constant.

Fig: The variation of Yield $Y(x)$ against x for contributions coming from heavy Higgs and Mirror fermion decay ($M_{A_S^0}$ = 10 keV)

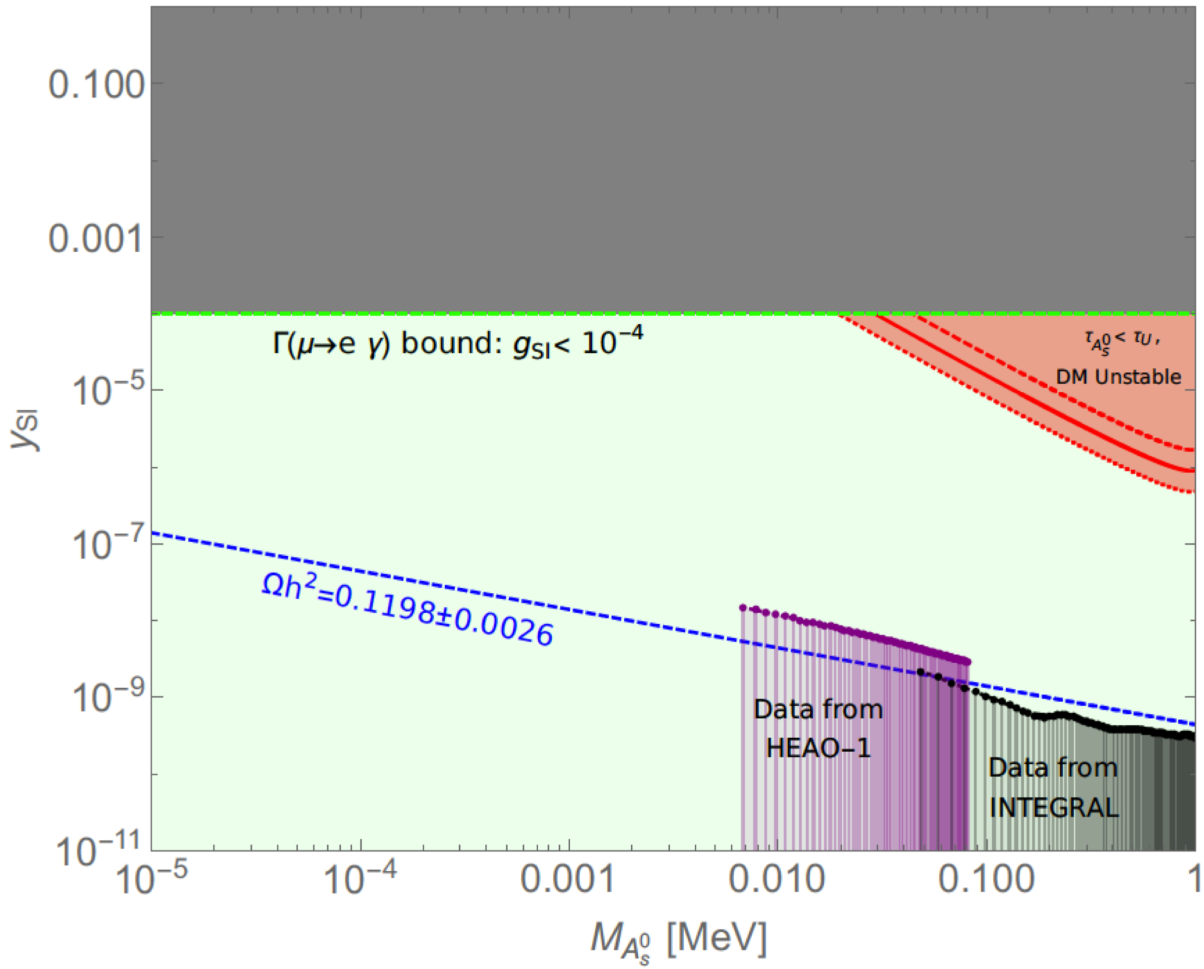
Bounds and Searches

- $A_s^0 \to ff$ not possible at tree level, $A_s^0 \to \gamma\gamma$ via charged particles



- Lifetime of the decay (dominated by e): $\tau_{A_s^0} = \dfrac{6.582\times10^{-25}}{\Gamma_{tot}(A_s^0 \to\gamma\gamma)GeV}\,sec$
- DM can remain stable for $y_{sl} \sim$ O(10^{-2}) for keV mass scale and $y_{sl} \sim$ O(10^{-5}) for MeV scales respectively ($y_{sl} < 10^{-4}$ from rare decays)
- **Indirect detection**: weak scale DM (100 MeV) constrained by FERMI-LAT ($\tau_{A_s^0} > 10^{26}$s); HEAO-1 and INTEGRAL able to put stringent constraints on parameter space preferring DM lifetime $\tau > 10^{29}$s
- **Direct detection**: due to feeble interactions hard to get the signature of DM from the direct-detection experiments through nucleon-dark matter scattering ($\sigma \sim 10^{-61}$cm^2)

Exclusion region

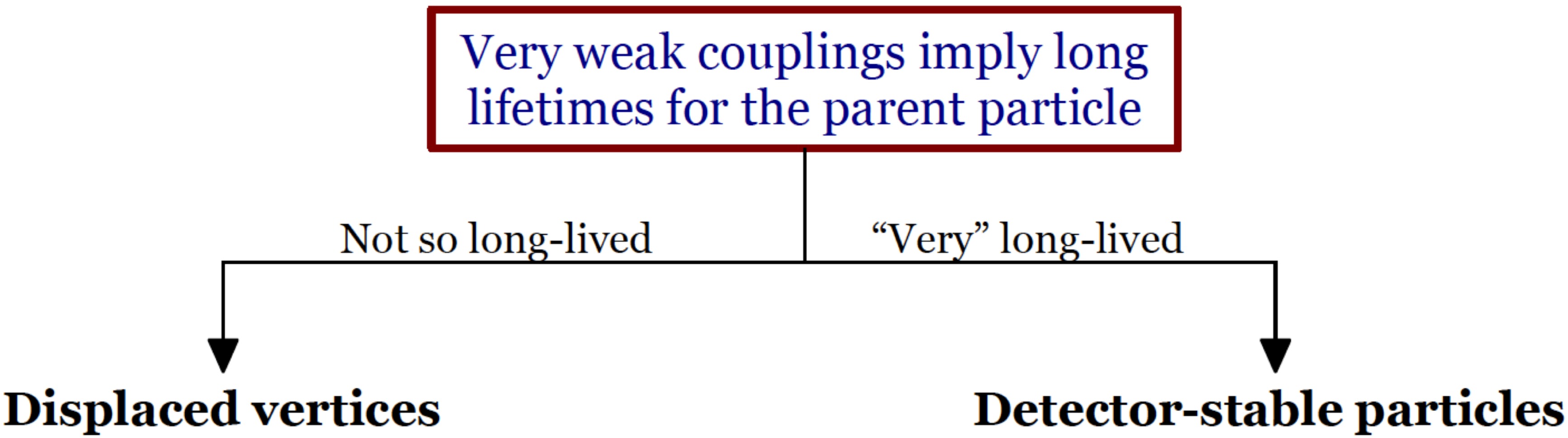


- Blue dashed line relic density Ωh^2 = 0.1198 $\pm$ 0:0026.
- DM is stable in the region below the red-line, $\tau_{A_S^0} > \tau_U$ (3 red lines correspond to g_u^M = 1; $\sqrt{4\pi}$ and 4π).
- Grey region is excluded from $\mu \to$ e γ and μ2e implying $g_{sl} < 10^{-4}$.
- Indirect detection bounds are shown preferring lifetime $\tau > 10^{29}$s

Fig: y_{sl} vs $M_{A_S^0}$ exclusion plot showing the relic density constraints

Freeze in in Colliders

- Can be searched in Colliders using charged track forming due to the decay of mirror fermions into SM fermion and DM.



- Requires new experiments like MATHUSLA: construction of detector on surface above ATLAS/CMS (surface$\sim$ 40000 m^2, $\sim$ height 25m)
- Large luminosity + energy to get significant event MATHUSLA100/200 detector for this scenario(prod cross-section of mother particle < O(10^{-10}) fb.)

Outlook

- Investigated prospect of a light (sub-MeV) scalar as a *FIP DM*
- Freeze in: DM interacts very weakly with SM & never attain thermal equilibrium
- DM sector gets populated through decay (or annihilation) of SM until the number density of SM species becomes Boltzmann-suppressed
- Mechanism needs feeble interactions →naturally suppressed coupling
- Successfully identified exclusion region for sub-MeV *FIP*, consistent with rare decay constraints, relic density and direct/indirect searches
- Tricky to search through direct detections, indirect detections have some handle, large energy & luminosity needed for MATHUSLA

Thank You!