Jožef Stefan Institute

# Peeping into dark matter scenarios - From Freeze out to Freeze in

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# Why

Beyond Standard Model?

#  reasons why

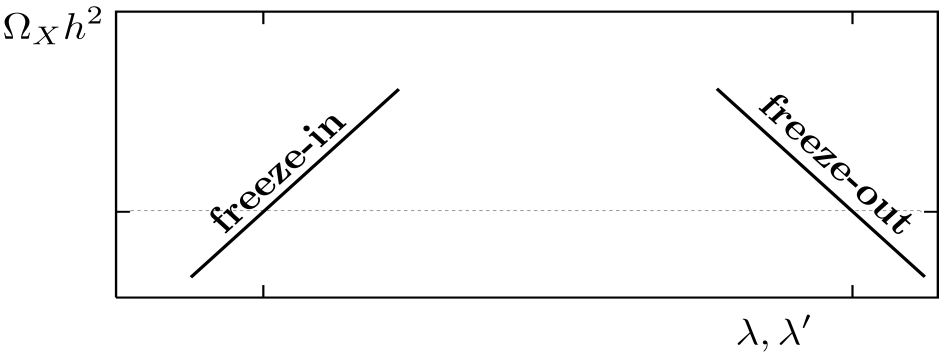
- Neutrino mass
- **Dark matter**(!)
- Fermion mass hierarchy

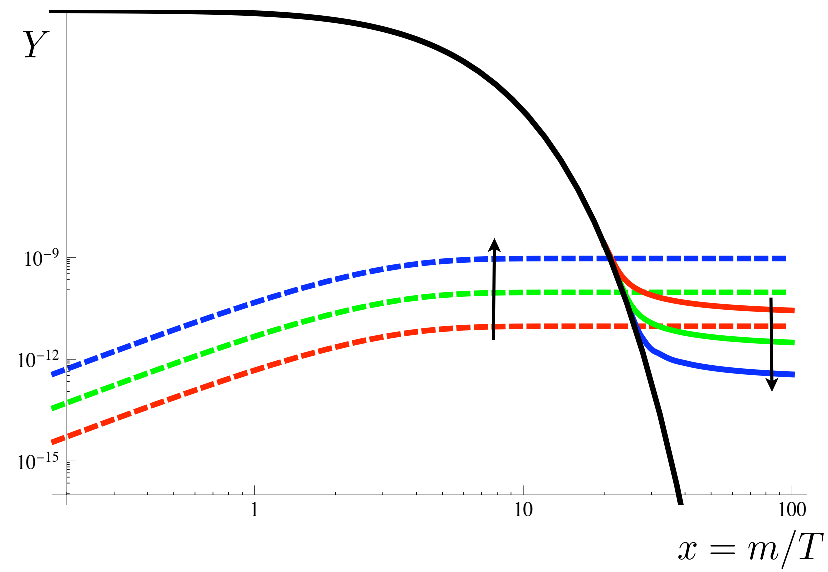
and many more….

# Quick Recap: Dark Matter

- Dark Matter is a non-luminous, non-baryonic form of matter which provides roughly 26% energy density of the universe.
- Observational evidences only strengthen its existence.
- However the nature of DM is still unknown.
- Though dark matter has yet only been seen by gravitational interaction, particle nature of DM is an intriguing possibility.
- We would be exploring that possibility through out the talk.
- Among the production mechanism of dark matter, Freeze out is the most popular one, then comes Freeze in.

# Freeze-out and Freeze-in in nutshell



# Exploring freeze out in Vector Dark Matter context

- Relatively less explored due to necessity of gauge extensions

- Can give spin independent cross-section still allowed from the LZ constraints.

# Idea of Vector Dark Matter

- A gauge boson breaking a local $U(1)_X$ symmetry.
- One extra $U(1)_X$ charged scalar is needed to break this symmetry spontaneously.
- Stabilized by a dark charge conjugation symmetry

$$Z_2^{(a)}: \quad Z_\mu' \rightarrow -Z_\mu', \quad S \rightarrow S^*,$$
$$Z_2^{(b)}: \quad Z_\mu' \rightarrow -Z_\mu', \quad S \rightarrow -S^*$$

## VDM in context of Type II Seesaw

- An extra $SU(2)_L$ triplet which generates neutrino mass via Type II Seesaw mechanism.
- This extra degrees of freedom can help in initial thermalisation of the dark matter as well as increase the relic satisfied parameter space.

2402.01317, Phys. Rev. D 109, 115020

## VDM in two-Higgs doublet model

- An extra $SU(2)_L$ doublet is present which can have lighter masses (80 GeV onwards).
- This light scalar can contribute to correct relic density for a DM mass range (40-60)GeV where Direct Detection bounds are very strong.

2505.17211

# How do they look

$$\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^\dagger \\ \frac{1}{\sqrt{2}}(\rho_2 + v_2 + i\eta_2) \end{pmatrix},$$

$$\begin{aligned} V(\Phi,\Delta,S) &= \mu_\Phi^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 + M_\Delta^2 \mathrm{Tr}[\Delta^\dagger\Delta] + \lambda_1(\Phi^\dagger\Phi)\mathrm{Tr}[\Delta^\dagger\Delta] \\ &+ \lambda_2(\mathrm{Tr}[\Delta^\dagger\Delta])^2 + \lambda_3\mathrm{Tr}[(\Delta^\dagger\Delta)^2] + \lambda_4(\Phi^\dagger\Delta\Delta^\dagger\Phi) + [\mu\,\Phi^{\mathrm{T}} i\sigma_2\Delta^\dagger\Phi + \text{ h.c.}] \\ &+ \mu_s^2(S^\dagger S) + \lambda_s(S^\dagger S)^2 + \lambda_{s\phi}(S^\dagger S)(\Phi^\dagger\Phi) + \lambda_{S\Delta}(S^\dagger S)\mathrm{Tr}[\Delta^\dagger\Delta]. \end{aligned}$$

$$\begin{aligned} V(\Phi_1,\Phi_2,S) &= m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) + m_{33}^2(S^*S) - [m_{12}^2(\Phi_1^\dagger\Phi_2) + \text{h.c.}] + \lambda_1(\Phi_1^\dagger\Phi_1)^2 \\ &+ \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_S(S^*S)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+ \lambda_{S1}(\Phi_1^\dagger\Phi_1)(S^*S) + \lambda_{S2}(\Phi_2^\dagger\Phi_2)(S^*S) + \Big\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 \\ &+ [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2) + \lambda_8(S^*S)] \times (\Phi_1^\dagger\Phi_2) + \text{h.c.}\Big\} \end{aligned}$$

## VDM in context of Type II Seesaw

### Experimental Constraints

- ρ parameter constraint
- Experimental limits on singly and doubly charged scalar masses
- Collider constraints on the neutral scalar masses and mixing
- Constraint from Lepton Flavor Violation
- Constraint from oblique parameters
- Higgs Invisible decay constraint
- Constraints from $h \to \gamma\gamma$ and $h \to Z\gamma$

### Theoretical constraints

- Vacuum stability conditions
- Unitarity conditions

## VDM in two-Higgs doublet model

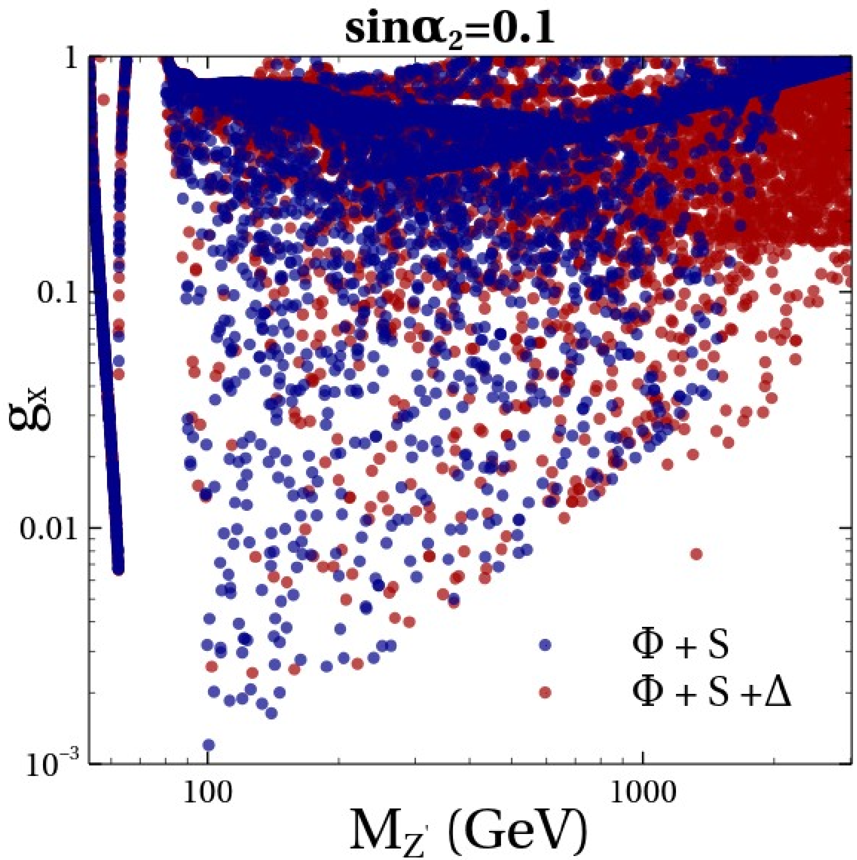
### Experimental Constraints

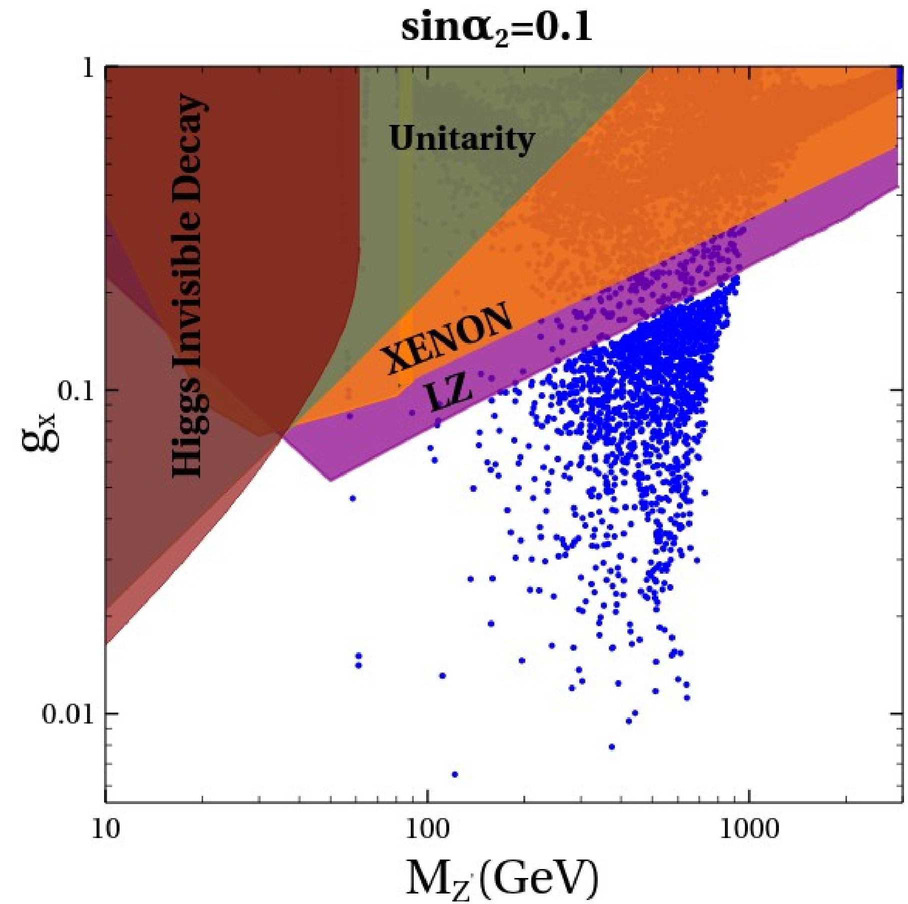
- Constraints from flavor physics
- Constraints from Higgs Boson searches
- Constraint from oblique parameters

### Theoretical constraints

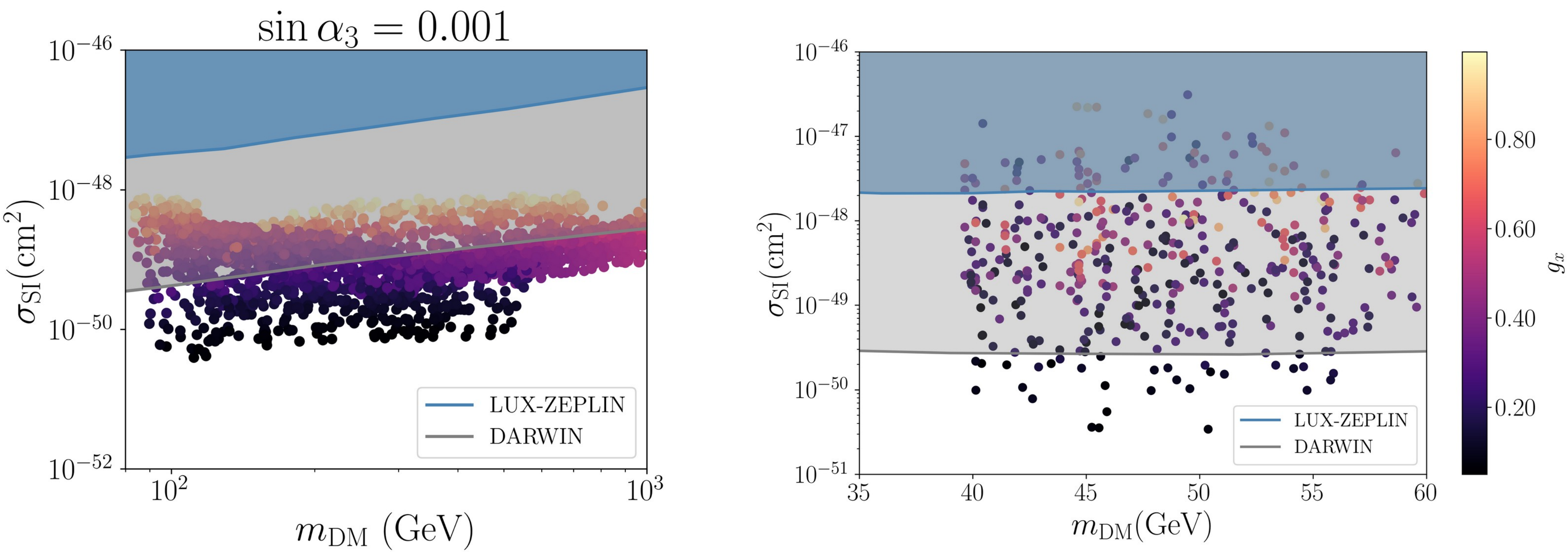
- Vacuum stability conditions
- Unitarity conditions

# VDM in context of Type II Seesaw

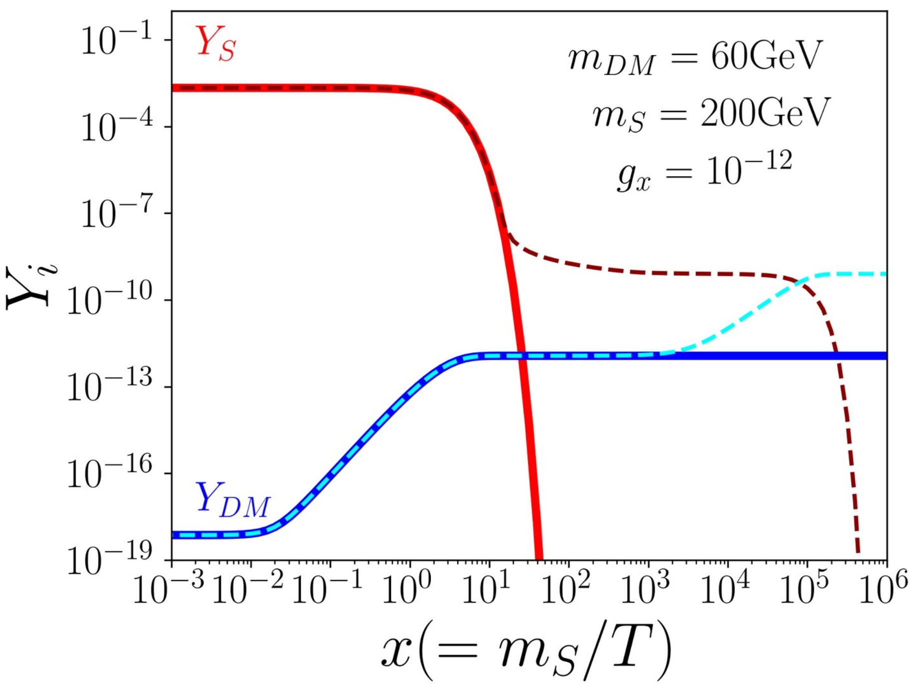


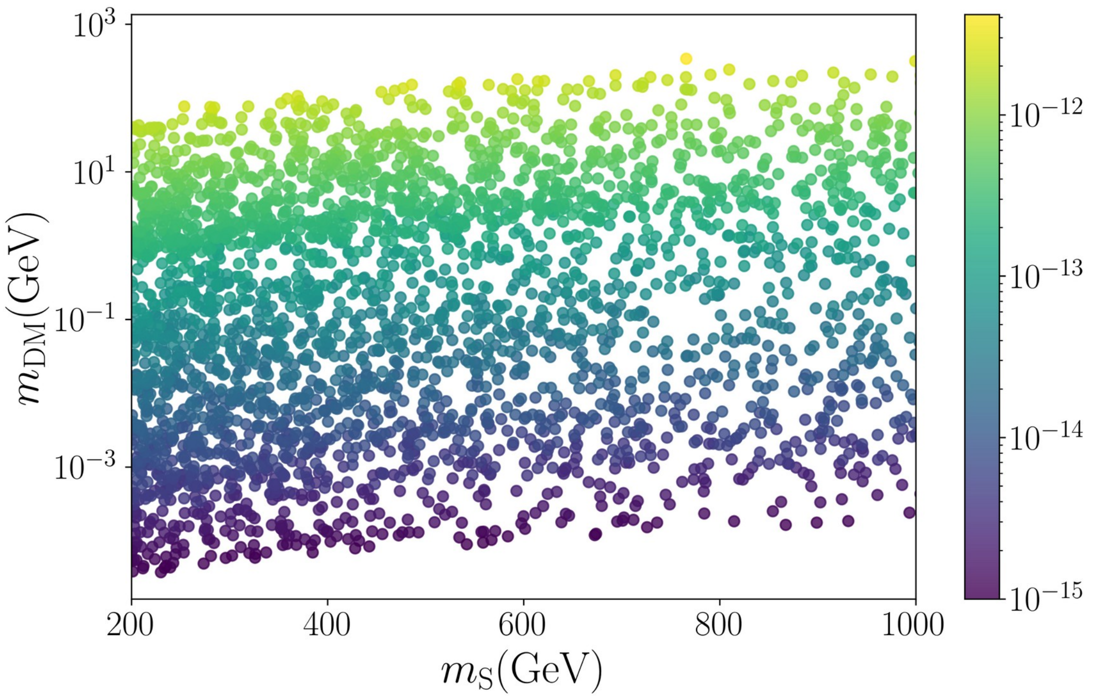



# VDM in two-Higgs doublet model



# Freeze-in aspect



# Is there a problem?

- The nature of freeze-in coupling
- Motivating the smallness of freeze-in coupling is an issue.
- Can we motivate this kind of coupling from symmetry perspective?

# Model Set up

- Symmetry:

$$SM \otimes U(1)_{FN}$$

- Global abelian symmetry

- Particle content:
- S, flavon, a singlet complex scalar
- $\chi$, a majorana fermion

# The problem and the solution

- The problem
  - The wide range of fermion masses in the Standard Model

| | | |
|---|---|---|
| $m_u$ = 2.3 ± 0.7MeV | $m_c$ = 1275 ± 25MeV | $m_t$ = 173210 ± 510MeV |
| $m_d$ = 4.8 ± 0.5MeV | $m_s$ = 95 ± 5MeV | $m_b$ = 4180 ± 30MeV |
| $m_e$ = 0.51MeV | $m_\mu$ = 105.658 ± 38MeV | $m_\tau$ = 1776.84 ± 17MeV |

One of the solution

- Frogatt Nielson Mechanism

# FN mechanism in a nut-shell

- Yukawa term in SM

$$Y^{ij} \bar{Q}_i H d_j$$

- In FN framework

$$y^{ij} \left(\frac{S}{\Lambda}\right)^{n_{ij}} \bar{Q}_i H d_j$$

Therefore

$$Y^{ij} = y^{ij} \epsilon^{n^{ij}}$$

where

$$\epsilon = \frac{v_S}{\sqrt{2}\Lambda} \approx 0.225$$

# Flavon scenario

- The relation to be respected to conserve $U(1)_{FN}$ symmetry is

$$n^d_{ij} = a_{Q_i} - a_H - a_{d_j}, \qquad n^u_{ij} = a_{Q_i} + a_H - a_{u_j}.$$

- The charge assignment of the fermions here are

$$\begin{pmatrix} a_{Q_1} & a_{Q_2} & a_{Q_3} \\ a_{u_1} & a_{u_2} & a_{u_3} \\ a_{d_1} & a_{d_2} & a_{d_3} \\ a_{L_1} & a_{L_2} & a_{L_3} \\ a_{e_1} & a_{e_2} & a_{e_3} \end{pmatrix} = \begin{pmatrix} 4 & 2 & 0 \\ 4 & 2 & 0 \\ 4 & 3 & 3 \\ 4 & 3 & 3 \\ 4 & 2 & 0 \end{pmatrix}$$

# DM Phenomenology

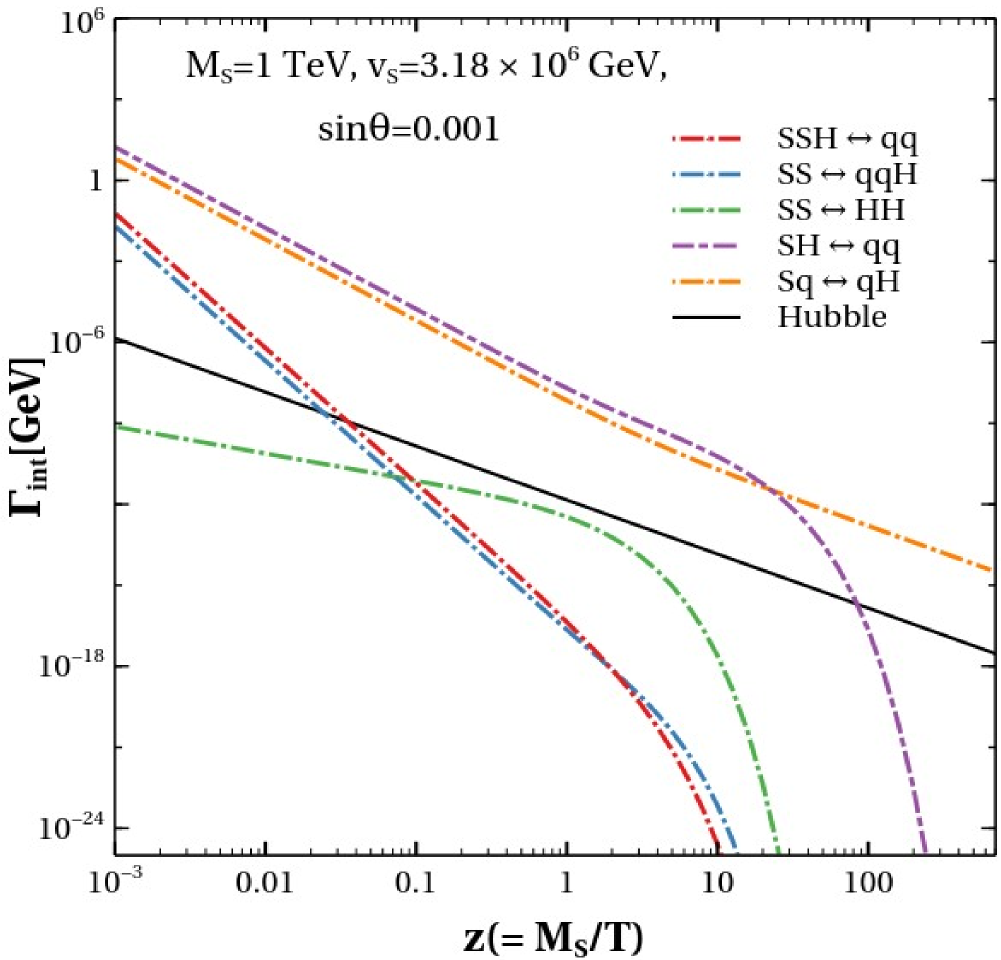
- We want a minimal model for dark matter and we chose a Majorana fermion as our candidate.
- The dark sector Lagrangian looks like

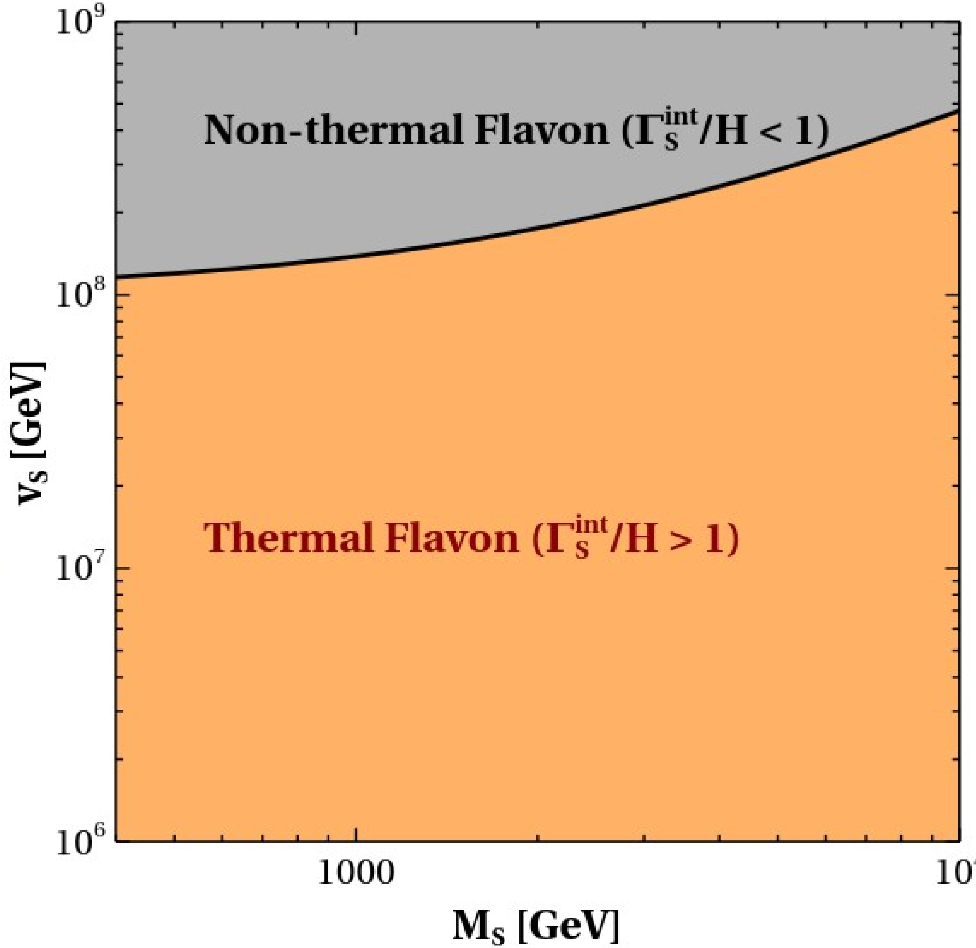
$$L_{DM} = \frac{1}{2}\bar{\chi}(i\gamma^{\mu}\partial_{\mu})\chi - y_{\chi}\left(\frac{S}{\Lambda}\right)^{2n-1} S\overline{\chi^{c}}\chi + h.c$$

where n is the $U(1)_{FN}$ charge of DM.

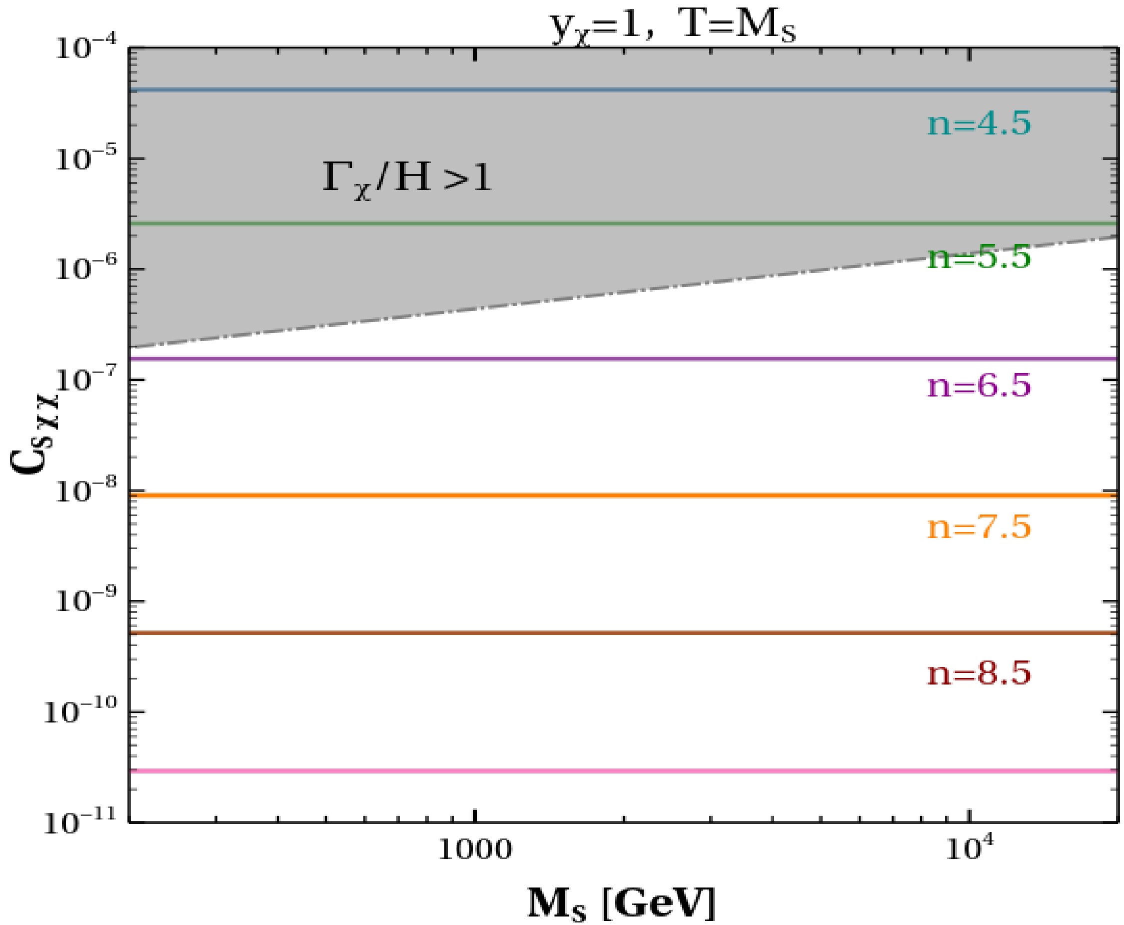
- For n being half integer, the dark matter is stable.
- For n being a little high, it can create freeze in coupling naturally.

# Thermalisation of S



# Condition for non-thermal DM



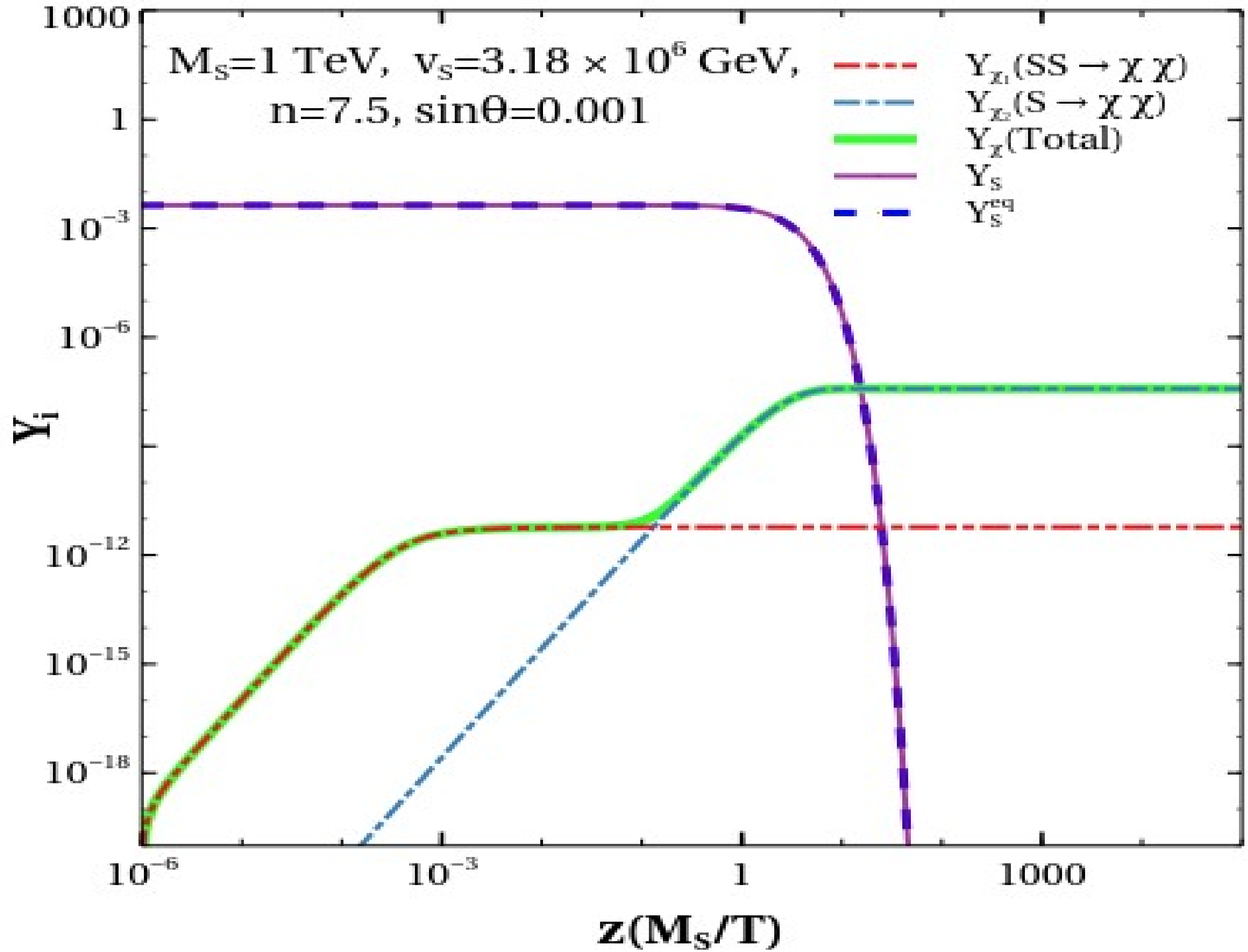
# Boltzmann equation

$$\frac{dY_\chi}{dz} = \frac{\langle \Gamma(S \rightarrow \chi\chi) \rangle}{H\, z} Y_s(z) + \frac{4\pi^2}{45} \frac{M_{Pl} M_S}{1.66} \frac{\sqrt{g(z)}}{z^2} \langle \sigma v_{SS \rightarrow \chi\chi} \rangle Y_S^2(z)$$

$$\frac{dY_S}{dz} = -\frac{\langle \Gamma(S \rightarrow \chi\chi) \rangle}{H\, z} Y_s(z) - \frac{4\pi^2}{45} \frac{M_{Pl} M_S}{1.66} \frac{\sqrt{g(z)}}{z^2} \langle \sigma v_{SS \rightarrow \chi\chi} \rangle Y_S^2(z)$$

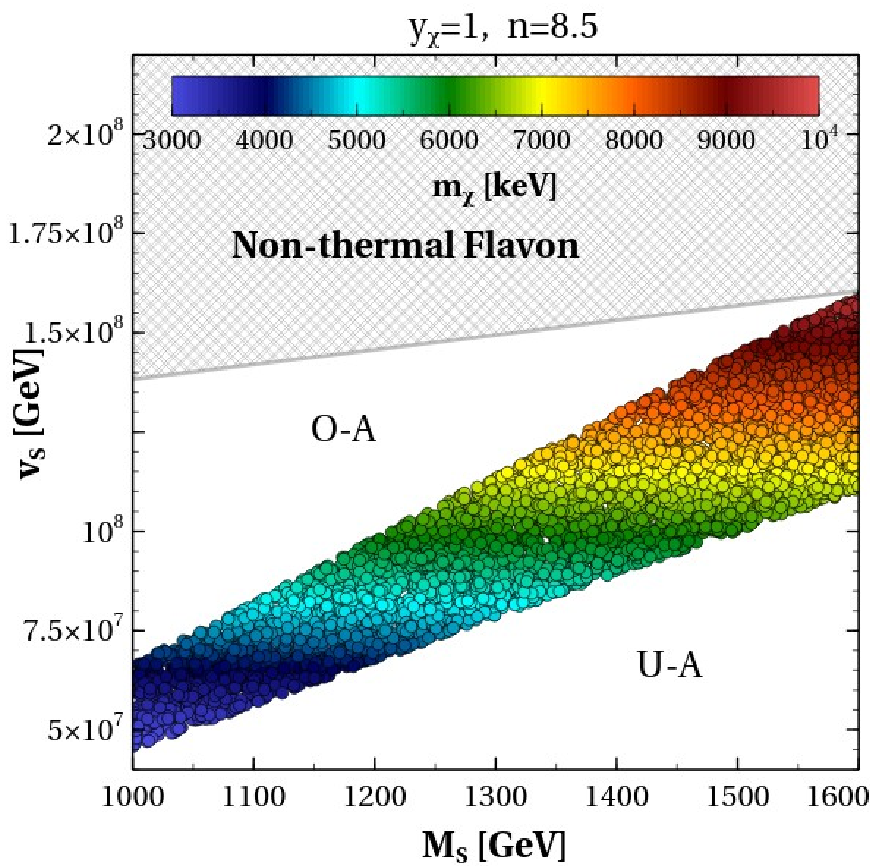
$$+\, other\ terms$$

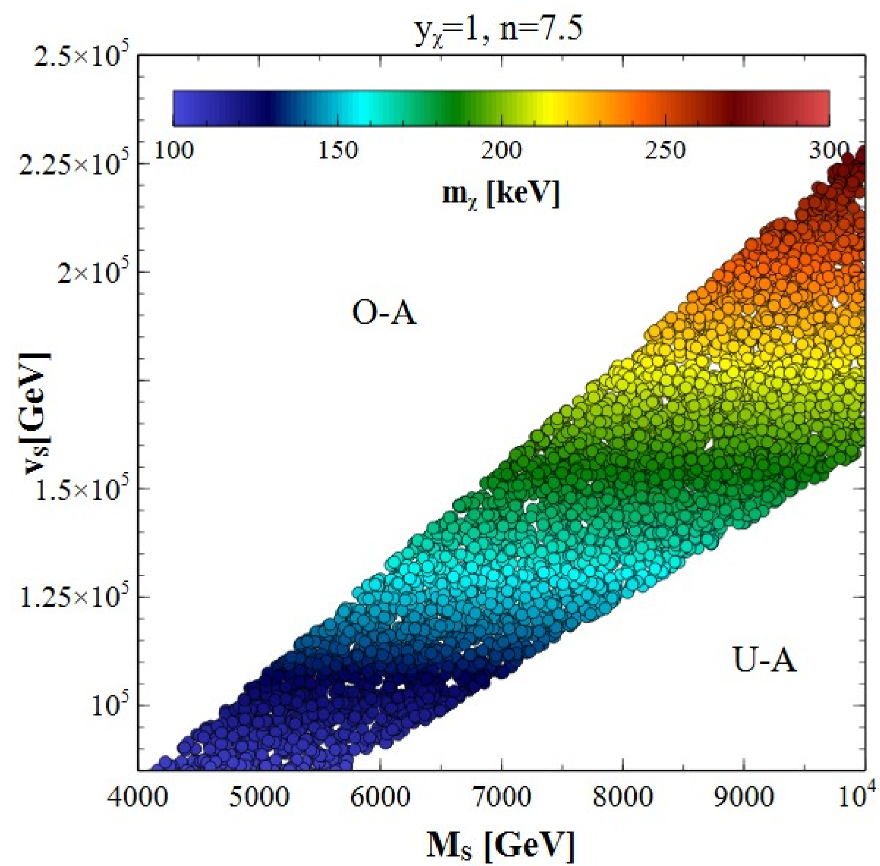
# How it looks



$M_S$=1 TeV, $v_S$=3.18 × $10^6$ GeV,
n=7.5, sinθ=0.001
$Y_{\chi_1}(SS \to \chi\chi)$
$Y_{\chi_2}(S \to \chi\chi)$
$Y_\chi$(Total)
$Y_S$
$Y_S^{eq}$
1000
1
$10^{-3}$
$10^{-6}$
$10^{-12}$
$10^{-15}$
$10^{-18}$
$Y_i$
$10^{-6}$
$10^{-3}$
1
1000
$z(M_S/T)$

# DM abundance



# Based on

- Vector Dark Matter in a $U(1)_X$ extended 2HDM,

  e-Print: 2505.17211

  in collaboration with Juhi Dutta (Oklahoma U. and IMSc, Chennai ), Dilip Kumar Ghosh (IACS, Kolkata), Santosh Kumar Rai (Harish-Chandra Res. Inst.)

- Vector dark matter with Higgs portal in type II seesaw framework

  Published in: Phys.Rev.D 109 (2024) 11, 11, e-Print: 2402.01317

  in collaboration with Tapoja Jha(IACS, Kolkata and Oulu U.), Dibyendu Nanda(Korea Inst. Advanced Study, Seoul and Bhubaneswar, Inst. Phys.)

- FIMP dark matter from flavon portals

  Published in: JHEP 07 (2023) 143, e-Print: 2305.03167

  in collaboration with K.S. Babu( Oklahoma State U.), Shreyashi Chakdar(Holy Cross Coll.), Dilip Kumar Ghosh (IACS, Kolkata), Purusottam Ghosh (IACS, Kolkata)

# Summary

- In this journey, we have discussed different dark matter scenarios, ranging from keV to GeV, with different production mechanism with different particle type namely vector gauge boson and fermion.

*Thank You*