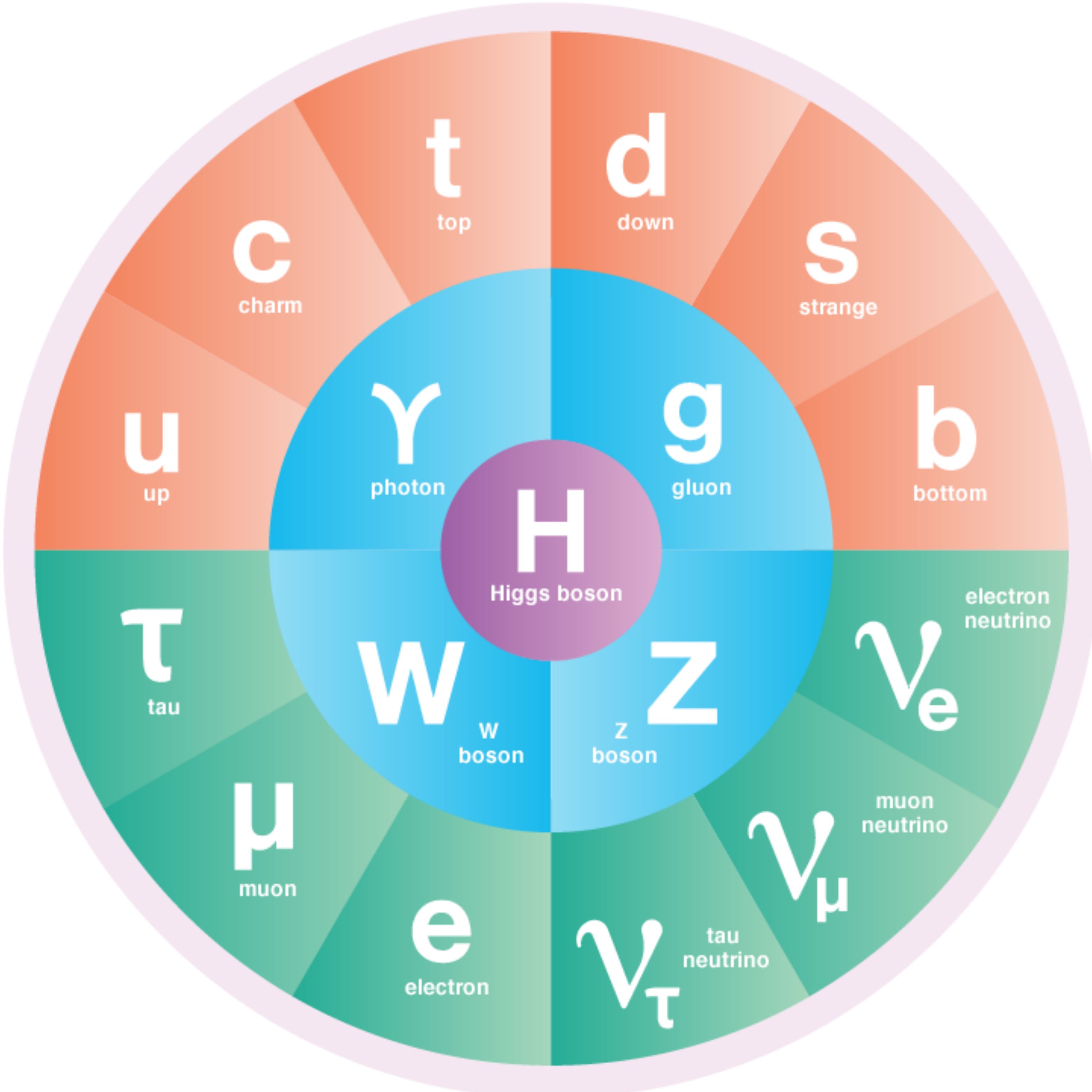
SILAFAE XV

Cinvestav

Exploring Bicomponent Dark Matter and Neutrino Mass Generation in a Standard Model Extension

MARIO LAMPREA, NOV 5TH 2024



The Standard Model

QUARKS

LEPTONS

BOSONS

HIGGS BOSON

Symmetry mag.

MARIO LAMPREA, NOV 5TH 2024

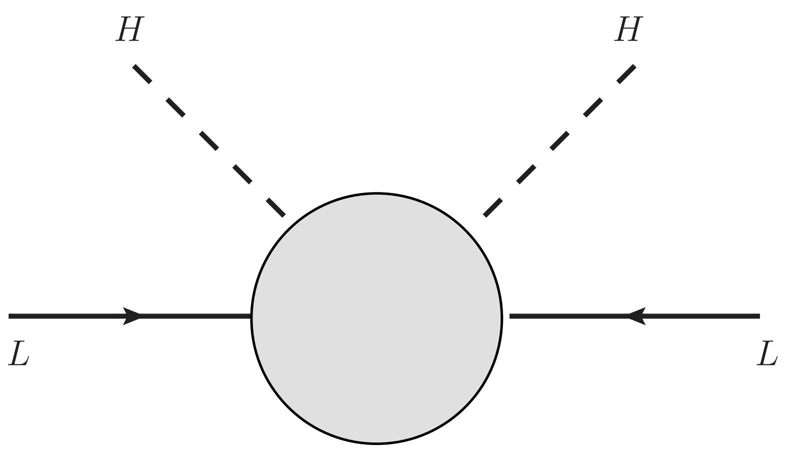
Neutrino masses

Neutrino oscillations are evidence for their **non-negligible masses** (δm^2, Δm^2).

Neutrino masses could be added to SM as a Higgs interaction (**cannot explain** their low scale $\mathcal{O}(m_\nu) \sim$ eV).

Mass generation in the case of **LH Majorana** neutrinos through the effective dim-5 Weinberg operator ($|\Delta L| = 2$).

$$\mathcal{O}^{(5)} = \frac{g}{\Lambda}\left(\bar{L}^c \otimes H \otimes H \otimes L\right)$$



$$m_{\nu_e} \sim \mathcal{O}\left(1 \text{ eV}\right)$$

$$g \sim \mathcal{O}(1)$$

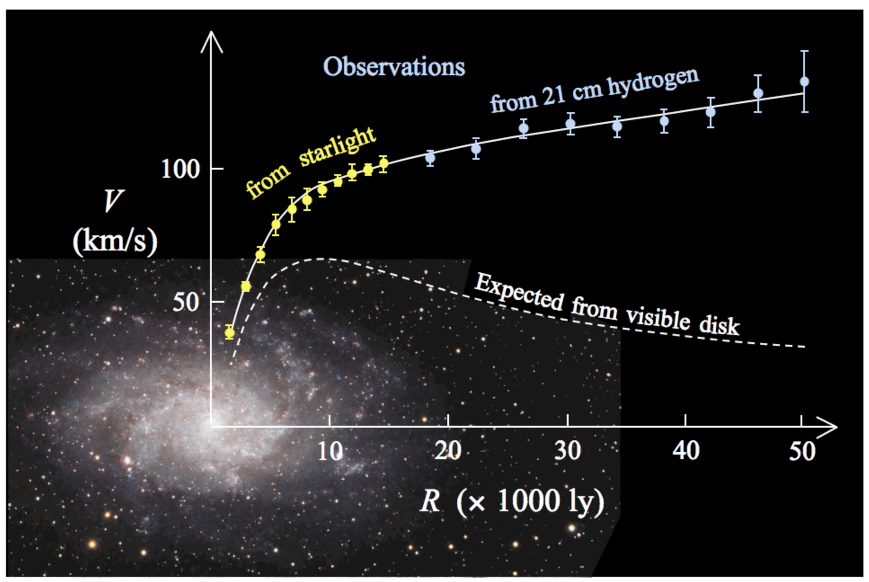
$$\Lambda \sim \mathcal{O}(10^{13} - 10^{15}) \text{ GeV}$$

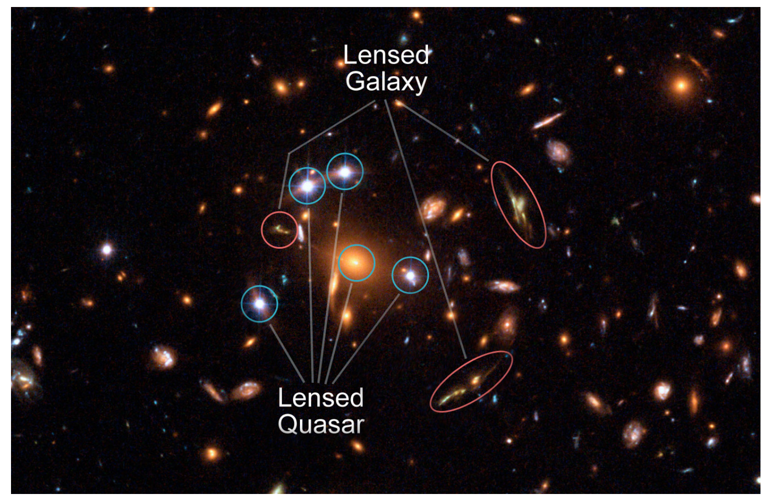
Completion of this op. at **tree level** via exchange of heavy mediators (e.g. high scale seesaw type-I, -II & -III).

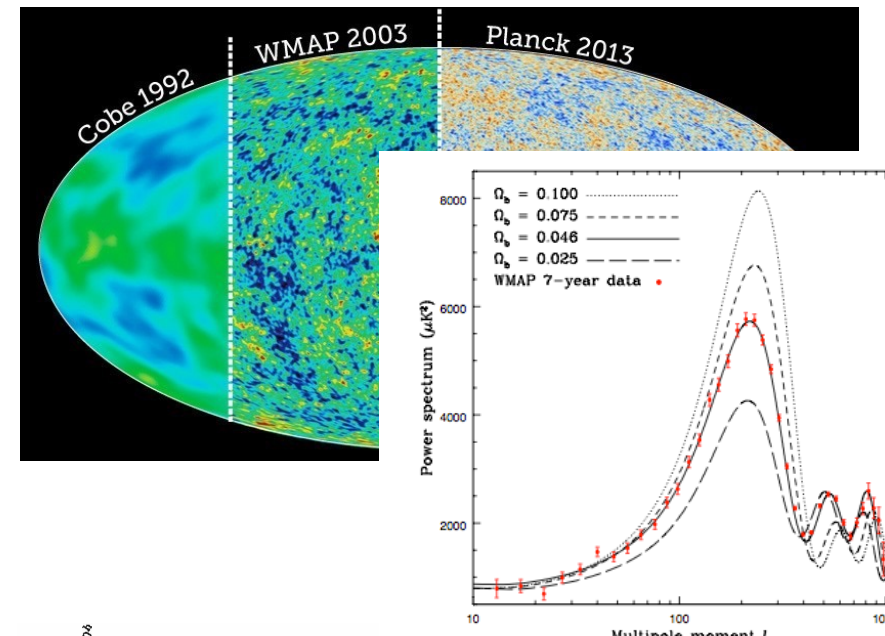
S. Weinberg, 80

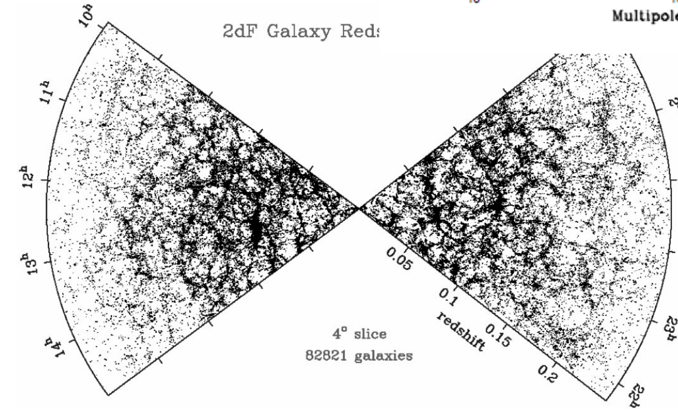
Dark Matter

Dark matter **existence** inferred from **gravitational** effects on visible matter at several scales (galactic, galactic cluster, cosmological).









One possible explanation: **particle(s) DM** (stable or long-lived) **thermaly** produced.

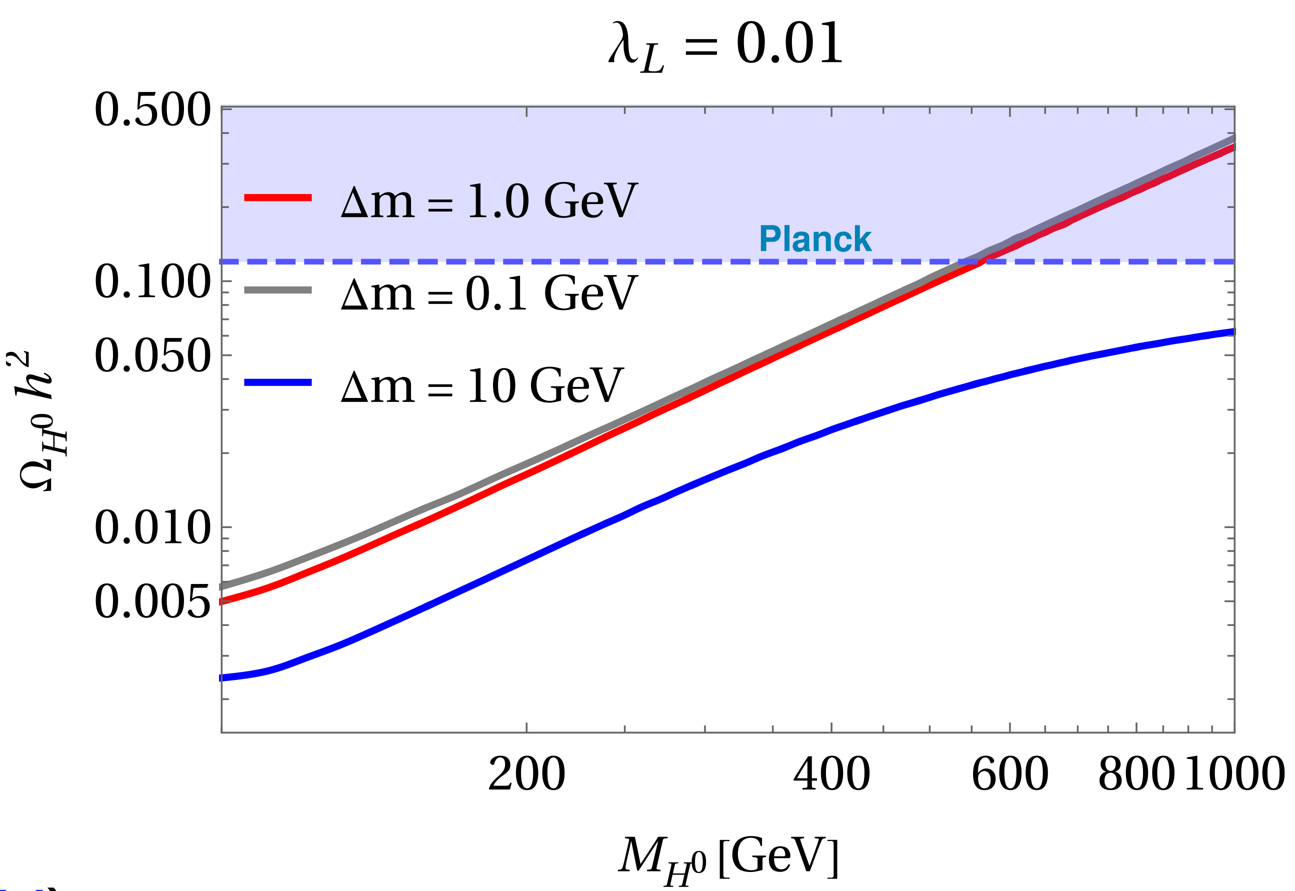
Inert Doublet Model -IDM-

N. G. Deshpabde & E. Ma (78)

- SM symmerty extension: SM $\otimes$ $\mathbb{Z}_2$.
- Scalar complex SU(2)$_L$ doublet

  ($Y = 1/2$): $\Phi_2 = \begin{pmatrix} H^+ \\ \frac{H^0 + iA^0}{\sqrt{2}} \end{pmatrix}$.

- Adds 5 new parameters:
  M_{H_0}, M_A, $M_{H^\pm}$, μ_2^2, λ_L.
- **Desert region** ($M_W < M_{H0} < 550$ GeV) relic density under-abundant.



Inert Triplet Model -ITM-

- SM symetry extension: SM $\otimes\ \mathbb{Z}_2$.
- Scalar complex SU(2)$_L$ triplet ($Y = 0,\ 2$)

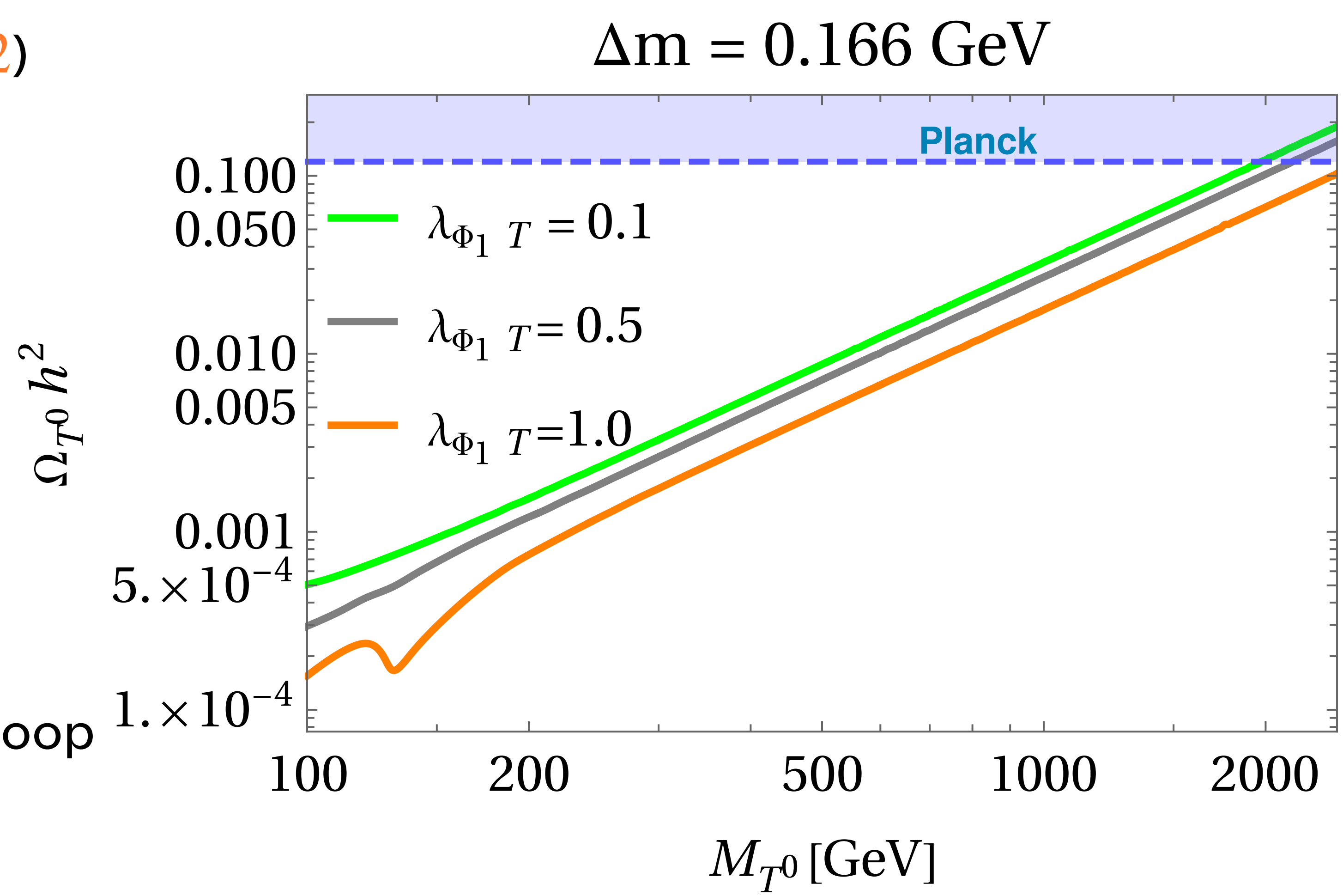
$$T = \begin{pmatrix} \frac{T^0}{\sqrt{2}} & -T^+ \\ -T^- & -\frac{T^0}{\sqrt{2}} \end{pmatrix}.$$

- Adds 3 new parameters: $M_{T^0}, \lambda_2, \lambda_3$.
- $M_{T_0}, M_{T^\pm}$ degeneracy is removed by 1-loop radiative correction:

$$\Delta m_T = m_{T^\pm} - m_{T^0} = 166\ \text{MeV}\,.$$

- Desert region ($M_{T_0} < 1970\,\text{GeV}$) relic density under-abundant.

Takeshi Araki, C. Q. Geng, and Keiko I. Nagao



A bi-component model

S. Merala, R. Gaitan, **J. M. L.** (2306.09617)

- SM symmetry extension: SM $\otimes\ \mathbb{Z}_2 \otimes \mathbb{Z}_2'$.

Particle	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$	$\mathbb{Z}_2'$
Φ_1	$\mathbf{2}$	$1/2$	$+$	$+$
Φ_2	$\mathbf{2}$	$1/2$	-	$+$
Δ	$\mathbf{3}$	1	$+$	$+$
T	$\mathbf{3}$	0	$+$	-

- Complex scalar SU(2)$_L$ doublet (Y=1/2)

$$\Phi_2 = \begin{pmatrix} H^+ \\ \dfrac{H^0 + iA^0}{\sqrt{2}} \end{pmatrix}$$

- Real scalar SU(2)$_L$ triplet

(Y=0) $$T = \begin{pmatrix} \dfrac{T^0}{\sqrt{2}} & -T^+ \\ -T^- & -\dfrac{T^0}{\sqrt{2}} \end{pmatrix}$$

- Real scalar SU(2)$_L$ triplet (Y=1)

$$\Delta = \begin{pmatrix} \dfrac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ v_\Delta + \Delta^0 & -\dfrac{\Delta^+}{\sqrt{2}} \end{pmatrix}.$$

A bi-component model

S. Merala, R. Gaitan, **J. M. L.** (2306.09617)

- SM symmetry extension: SM $\otimes \mathbb{Z}_2 \otimes \mathbb{Z}_2'$.
- Complex scalar SU(2)$_L$ doublet (Y=1/2)

$$\Phi_2 = \begin{pmatrix} H^+ \\ \frac{H^0 + iA^0}{\sqrt{2}} \end{pmatrix}$$

- Real scalar SU(2)$_L$ triplet

(Y=0) $$T = \begin{pmatrix} \frac{T^0}{\sqrt{2}} & -T^+ \\ -T^- & -\frac{T^0}{\sqrt{2}} \end{pmatrix}$$

Particle	Q_{EM}	$U(1)_Y$	$SU(2)_L$	$SU(3)_C$	$\mathbb{Z}_2$	$\mathbb{Z}_2'$
h	0	1/2	**2**	1	+	+
$H^\pm$	±1	1/2	**2**	1	-	+
H^0	0	1/2	**2**	1	-	+
A^0	0	1/2	**2**	1	-	+
$T^\pm$	±1	0	**3**	1	+	-
T^0	0	0	**3**	1	+	-
$\Delta^{\pm\pm}$	±2	1	**3**	1	+	+
$\Delta^\pm$	±1	1	**3**	1	+	+
Δ^0	0	1	**3**	1	+	+

Table 2: Quantum numbers of the physical scalars after EWSB.

- Real scalar SU(2)$_L$ triplet (Y=1)

$$\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ v_\Delta + \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}.$$

Model mass spectra

SM Higgs

Neglect mixing

$\mathcal{O}(v_\Delta) \sim 1\text{eV}$

$$\boxed{m_h^2 = 2\lambda_1 v^2,}$$

$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2 + \lambda_{\Phi_2\Delta} v_\Delta^2,$$

$$m_{H^0}^2 = \mu_2^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 + \lambda_5\right) v^2 + \mu_{\Phi_2\Delta} v_\Delta + \lambda_{\Phi_2\Delta} v_\Delta^2,$$

$$m_{A^0}^2 = \mu_2^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 - \lambda_5\right) v^2 - \mu_{\Phi_2\Delta} v_\Delta + \lambda_{\Phi_2\Delta} v_\Delta^2,$$

ID

$$\boxed{m_{T^\pm,T^0}^2 = \mu_T^2 + \frac{1}{2}\lambda_{\Phi_1 T} v^2,}$$

IT

$$m_{\Delta^{\pm\pm}}^2 = -\frac{1}{2}\kappa_{\Phi_1\Delta}\frac{v^2}{v_\Delta},$$

$$m_{\Delta^\pm,\Delta^0}^2 = -\frac{1}{4}\kappa_{\Phi_1\Delta}\frac{v^2}{v_\Delta},$$

ActiveTriplet

Relevant parameters for DM pheno:

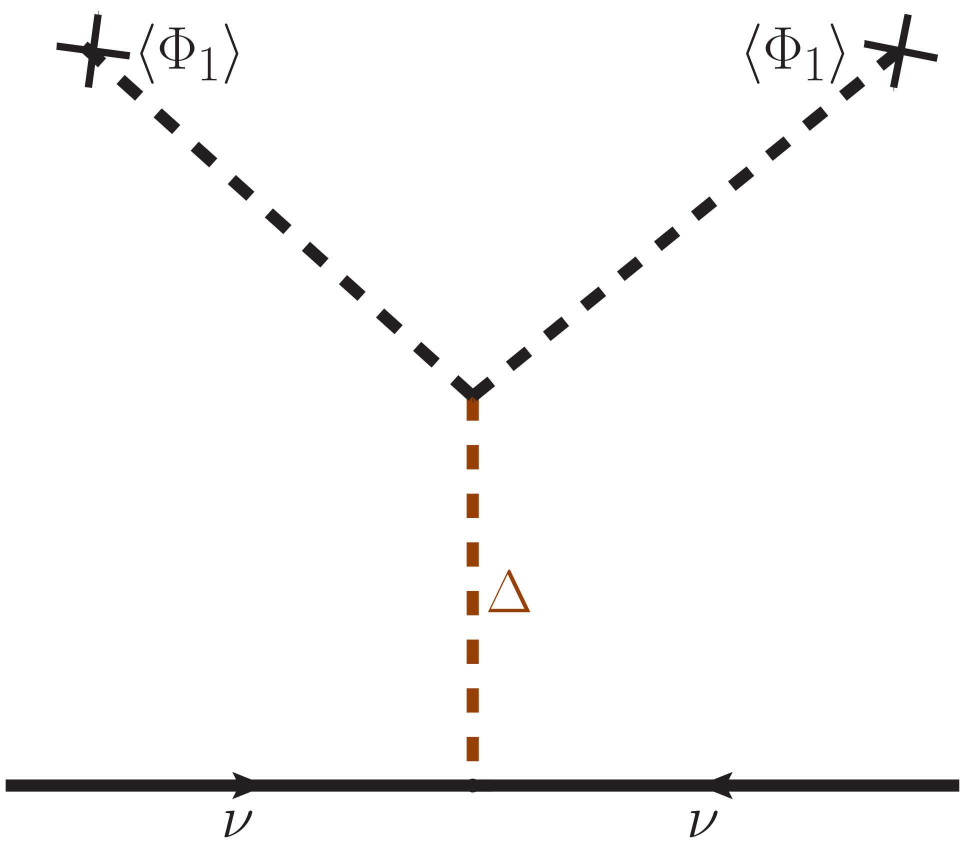
5 masses ($m_{H^0}, m_{H^\pm}, m_{A^0}, m_{T^0}, m_{T^\pm}$),

3 quartic couplings $(\lambda_L, \lambda_{\Phi_1 T}, \lambda_{\Phi_2 T})$.

Neutrino masses

- LH Majorana neutrino masses are generated via **type-II seesaw**.

$$\mathcal{L}_Y = Y_\Delta^{\alpha\beta} L_\alpha^T \, C \, i\tau_2 \, \Delta \, L_\beta + h.c.$$



- The **VEV** of the **triplet** is related to the **VEV of Higgs** through:

$$v_\Delta \simeq \kappa_{\Phi_1\Delta} v^2 / 2M_\Delta^2.$$

- We can **adjust the Yukawa coupling** matrix Y_Δ to produce the light neutrino masses (NO)

$$m_\nu^{II} = U^* m_\nu^d U^\dagger$$

$$Y_\Delta = 10^{-3} \times \begin{pmatrix} 1.361 + 0.560i & -0.646 - 1.956i & -3.208 - 1.742i \\ -0.646 - 1.956i & 15.221 - 0.214i & 10.697 + 0.008i \\ -3.208 - 1.742i & 10.697 + 0.008i & 12.300 + 0.185i \end{pmatrix}$$

Model Constraints

- We have performed a parameter scan over the space:

$$\lambda_{\Phi_1\Delta} = \lambda_{\Phi_2\Delta}, \lambda_\Delta = 0.01, \lambda_T = 0.1,$$
$$m_{\Delta^0} = 1000 \text{ GeV}, m_{\Delta^{\pm\pm}} - m_{\Delta^\pm} = m_{\Delta^\pm} - m_{\Delta^0} = 10 \text{ GeV}, \kappa_{\Phi_1\Delta} = \kappa_{\Phi_2\Delta} \simeq 10^{-5}$$

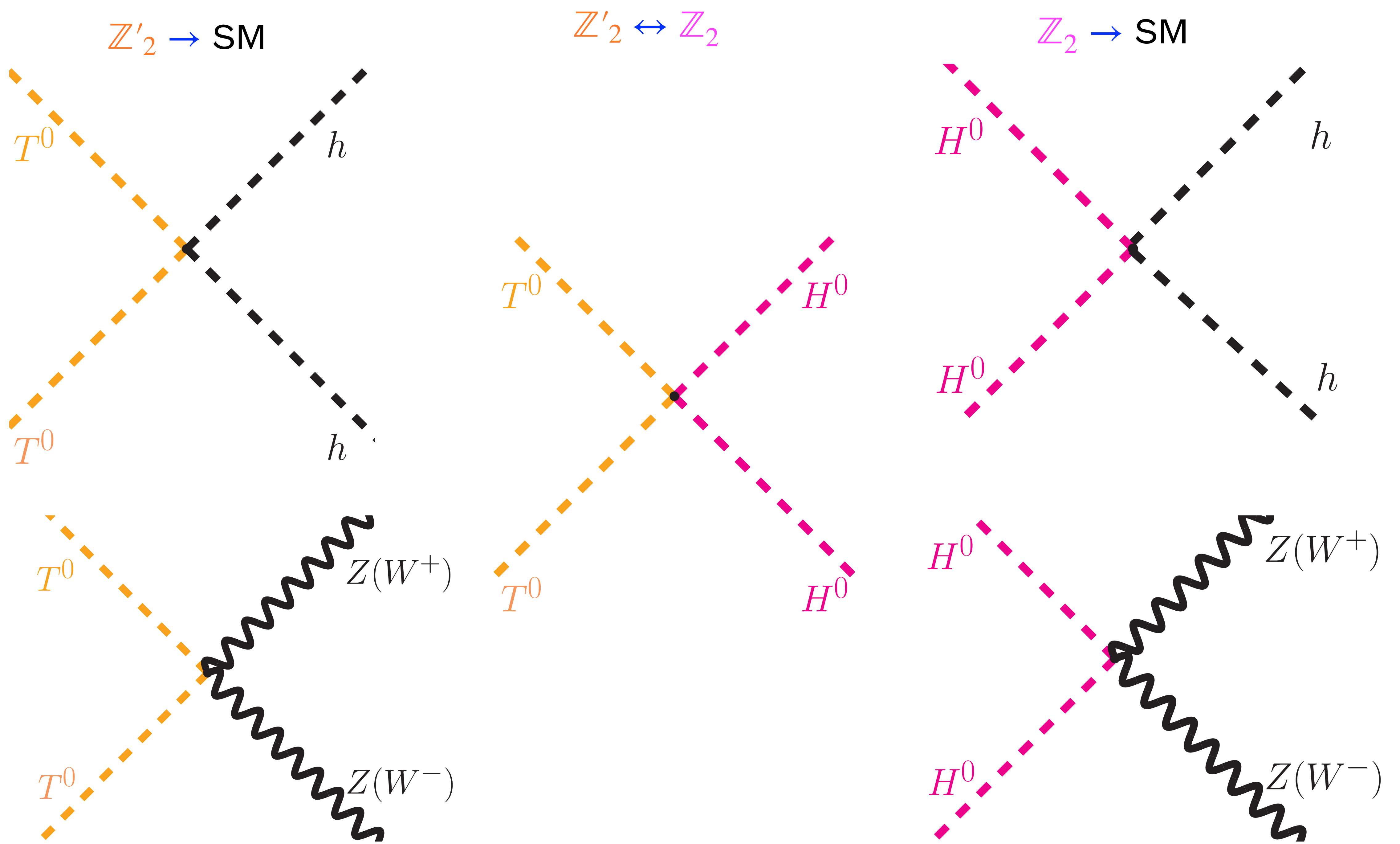
- We take into account the following constraints:
  - DM abundance (Planck 18) $$\Omega_{DM}h^2 = 0.1200 \pm 0.0010.$$
  - Constriction from colliders (LEP, LHC)

$$m_{H^0} > 80 \text{ GeV}, \qquad m_{A^0} > 100 \text{ GeV} \qquad \text{and} \;\; \Delta m = m_{A^0} - m_{H^0} < 8 \text{ GeV}.$$
$$m_{H^\pm} \gtrsim 70 - 90 \text{ GeV}.$$
$$m_{\Delta^{\pm\pm}} > 820 \text{ GeV and } m_{\Delta^\pm} > 350 \text{ GeV}.$$

  - Theoretical constraints
    - Positivity and stability of the scalar potential, Unitarity, Perturbativity, EW Parameters (S, T, U).

DM Abundance

M a i n c h a n n e l s

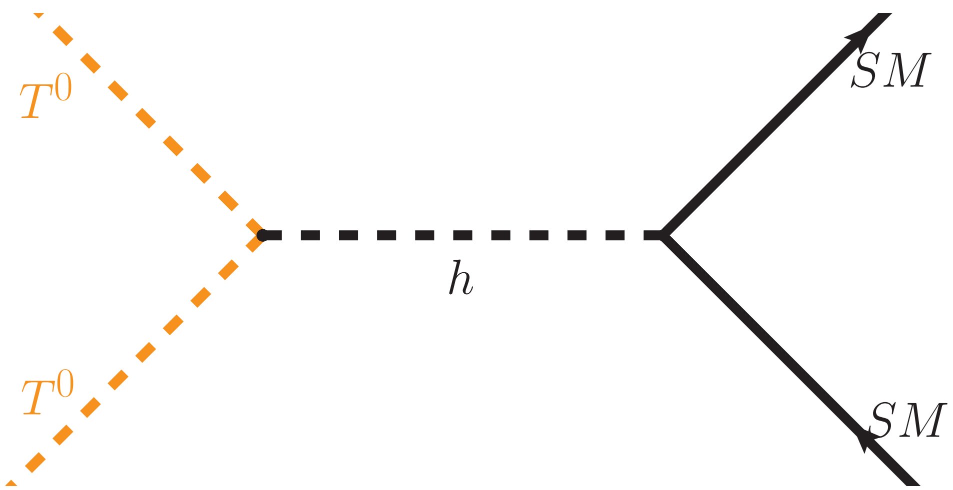


DM Abundance

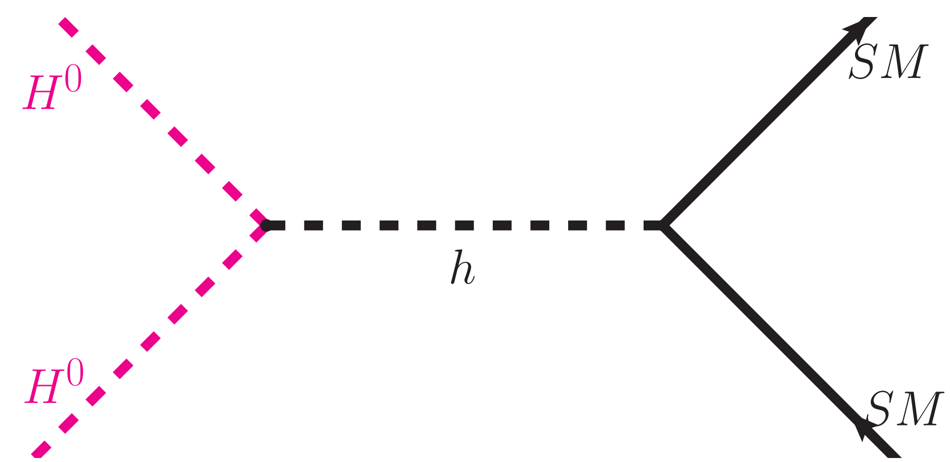
H
i
g
g
s

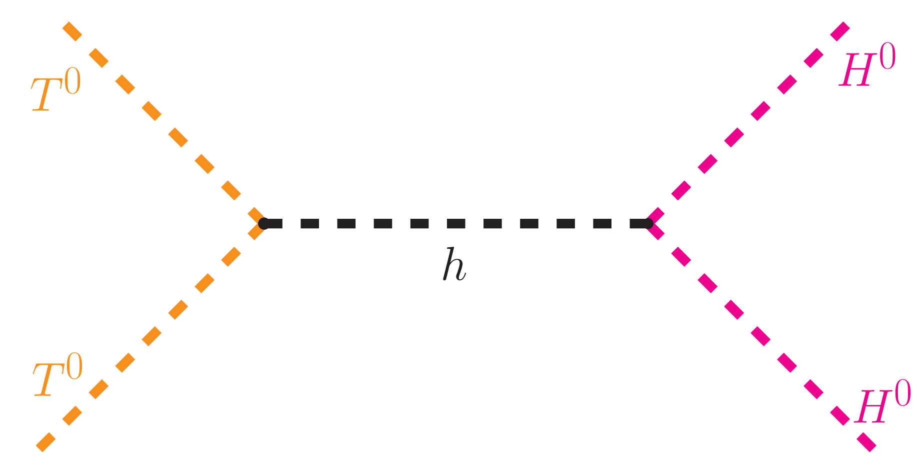
r
e
s
o
n
a
c
e
s

$\mathbb{Z}'_2 \rightarrow$ SM



$\mathbb{Z}_2 \rightarrow$ SM



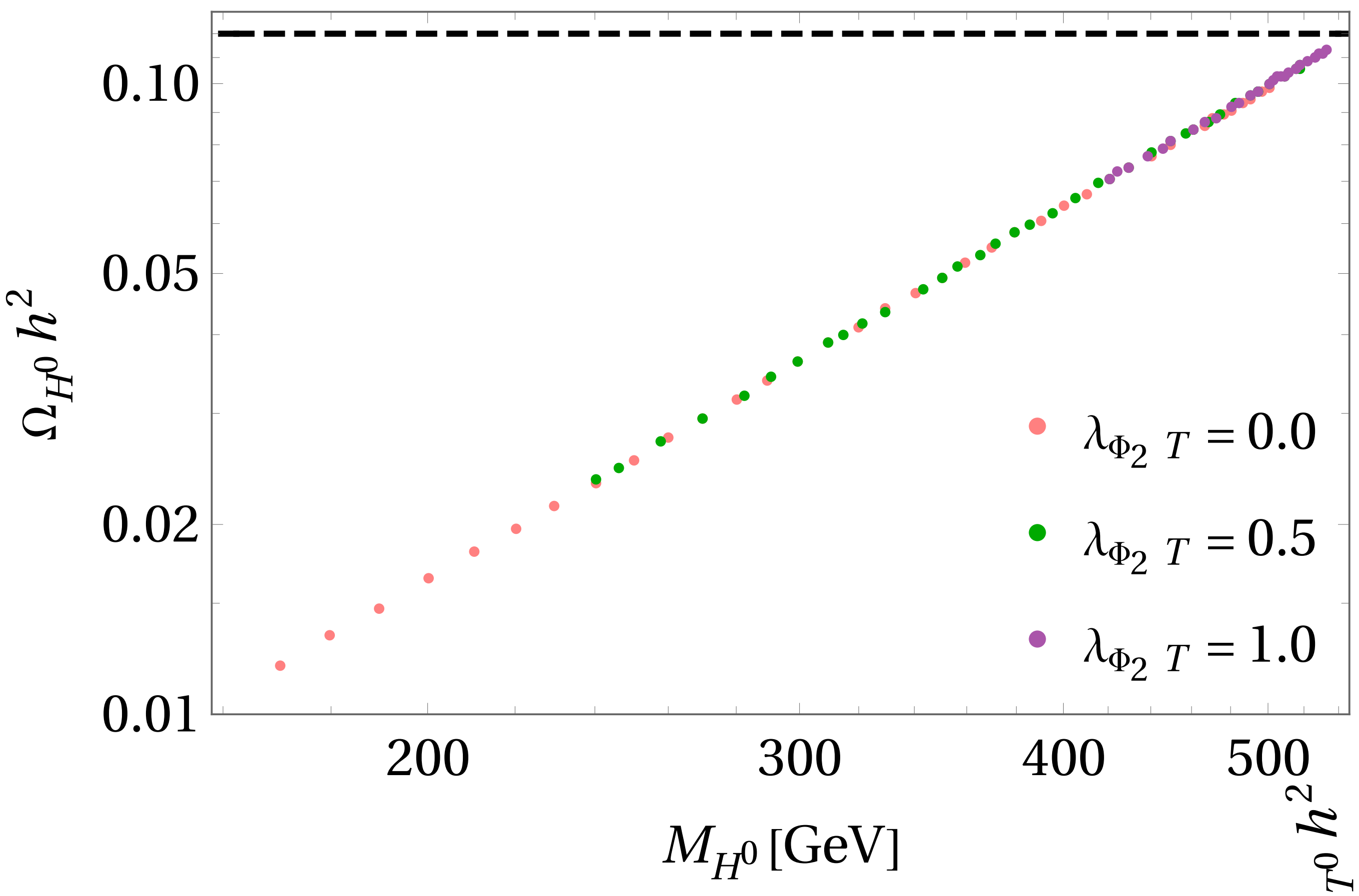


$\mathbb{Z}'_2 \leftrightarrow \mathbb{Z}_2$

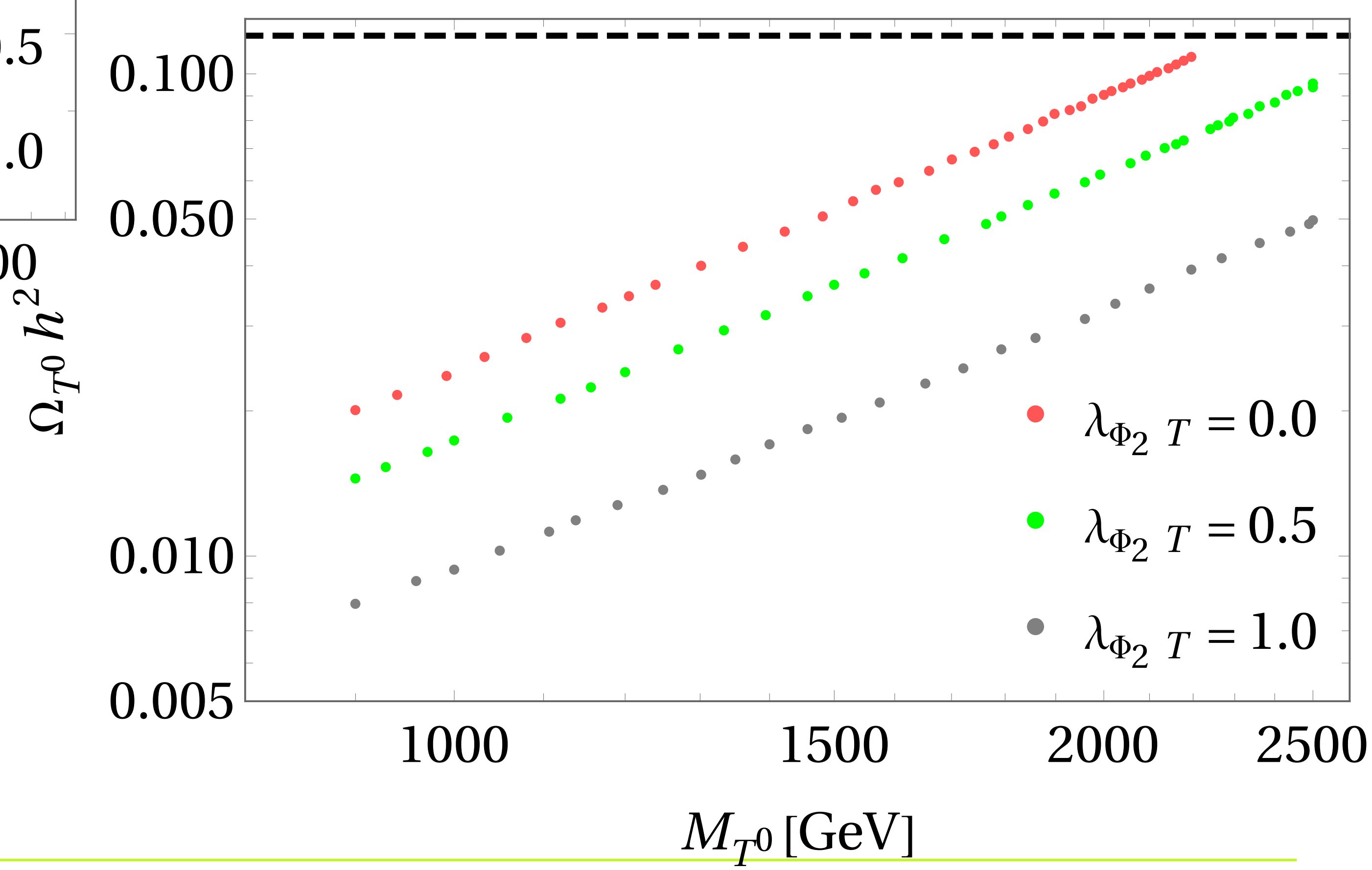
DM Abundance

$$\Omega_{\text{Tot}}h^2 = \Omega_{T^0}h^2 + \Omega_{H^0}h^2$$

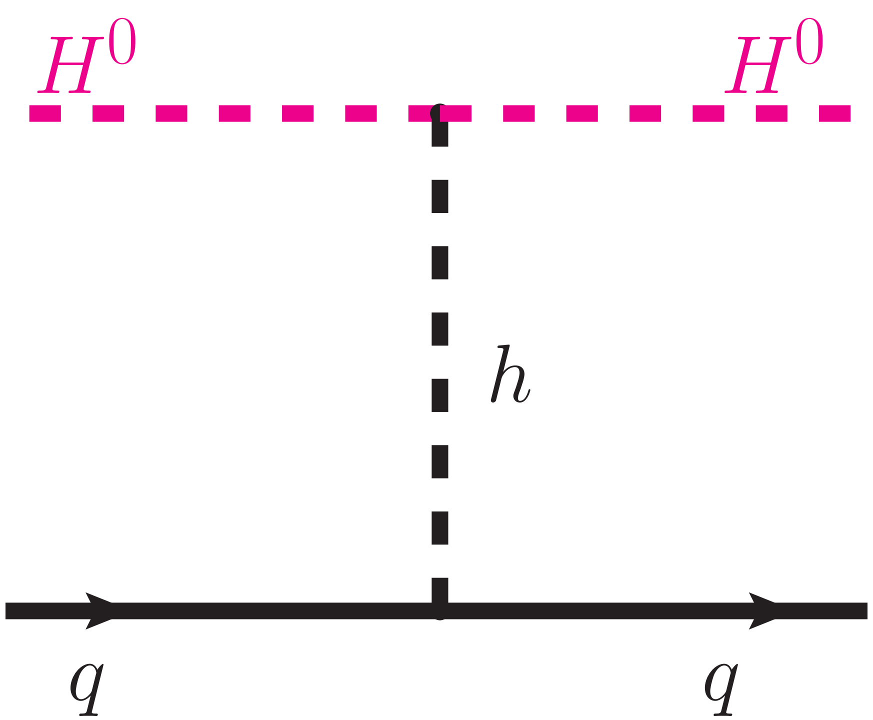
Δm = 1GeV, $\lambda_{\Phi_1\ T}$ = 0.1, λ_L=0.01

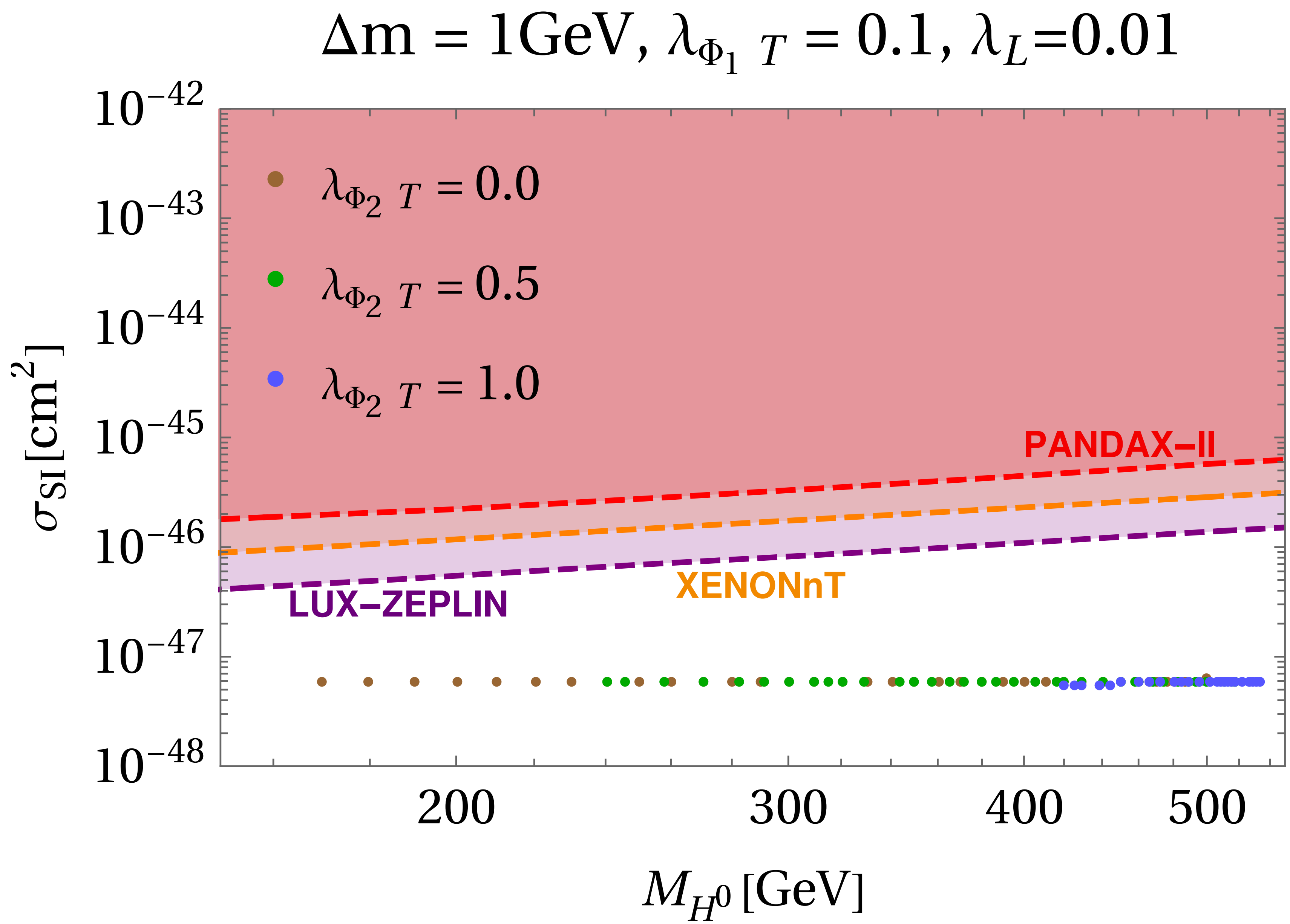


Δm = 1GeV, $\lambda_{\Phi_1\ T}$ = 0.1, λ_L=0.01

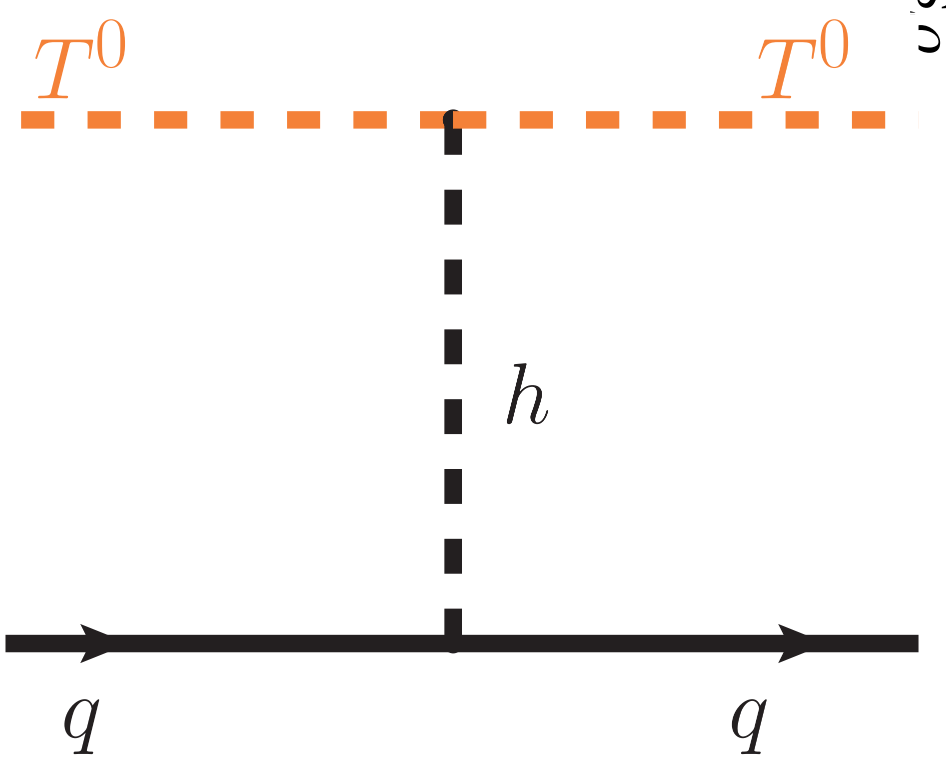


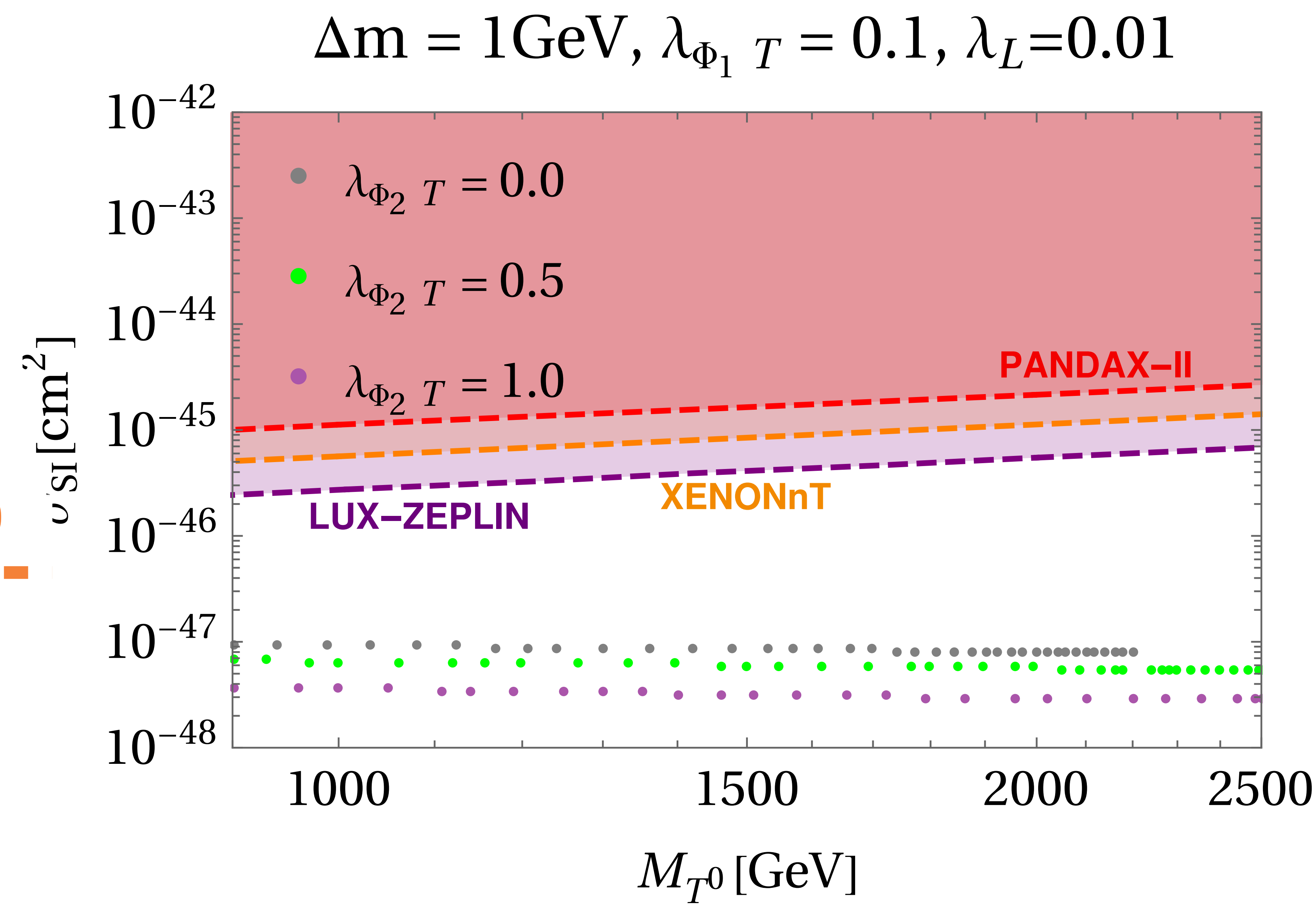
DM Direct Detection



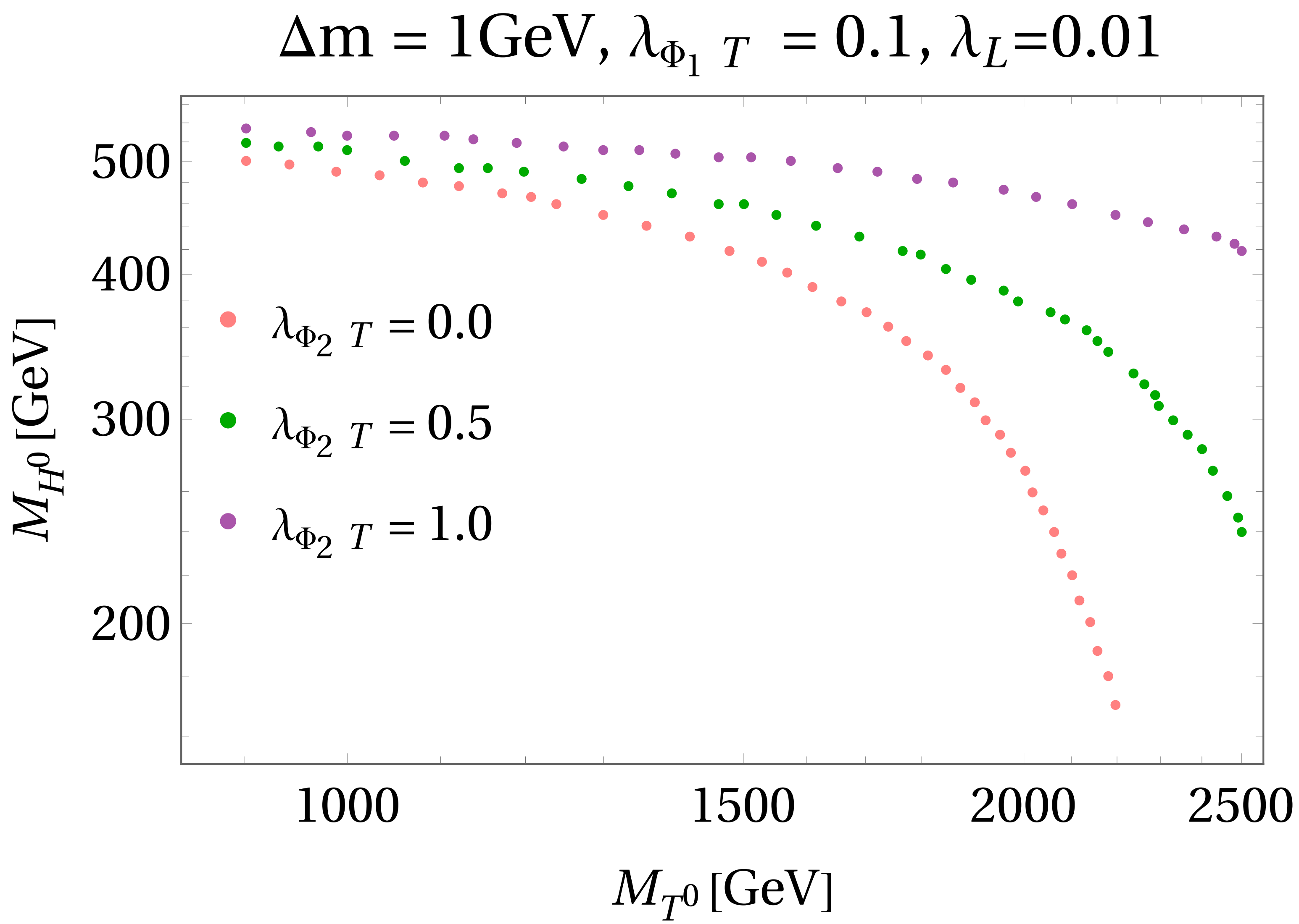


DM Direct Detection





Benchmarks



Δm = 1GeV, $\lambda_{\Phi_1\ T}$ = 0.1, λ_L=0.01
500
400
300
200
1000
1500
2000
2500
M_{H^0} [GeV]
M_{T^0} [GeV]
$\lambda_{\Phi_2\ T} = 0.0$
$\lambda_{\Phi_2\ T} = 0.5$
$\lambda_{\Phi_2\ T} = 1.0$

Concluding Remarks

We investigate a SM extesion, introducing a complex **inert** $SU(2)_L$ **doublet**, an **inert** $SU(2)_L$ **triplet** with Y=0, and an **active** $SU(2)_L$ **triplet** with Y=1.

DM candidates arise from two dark sectors ($\mathbb{Z}_2 \times \mathbb{Z}_2'$), allowing for a two-component dark matter that **addresses desert regions** within the **IDM** and **ITM**.

The model can accommodate the generation of light **neutrino masses** through the **seesaw type-II** mechanism.

The results are **consitent** with the **upper bounds** for the **SI cross-section** DM-nucleon interaction (PANDAX-II, XENONnT, and LUX-ZEPLIN) and within their f**orthcoming experimental sensitivities**.

There is a **potential** for **matter-antimatter asymmetry** generation via **leptogenesis**, involving **CP-violating decays** of the **active** scalar **triplet** into leptons.

Thanks!

Backup Slides

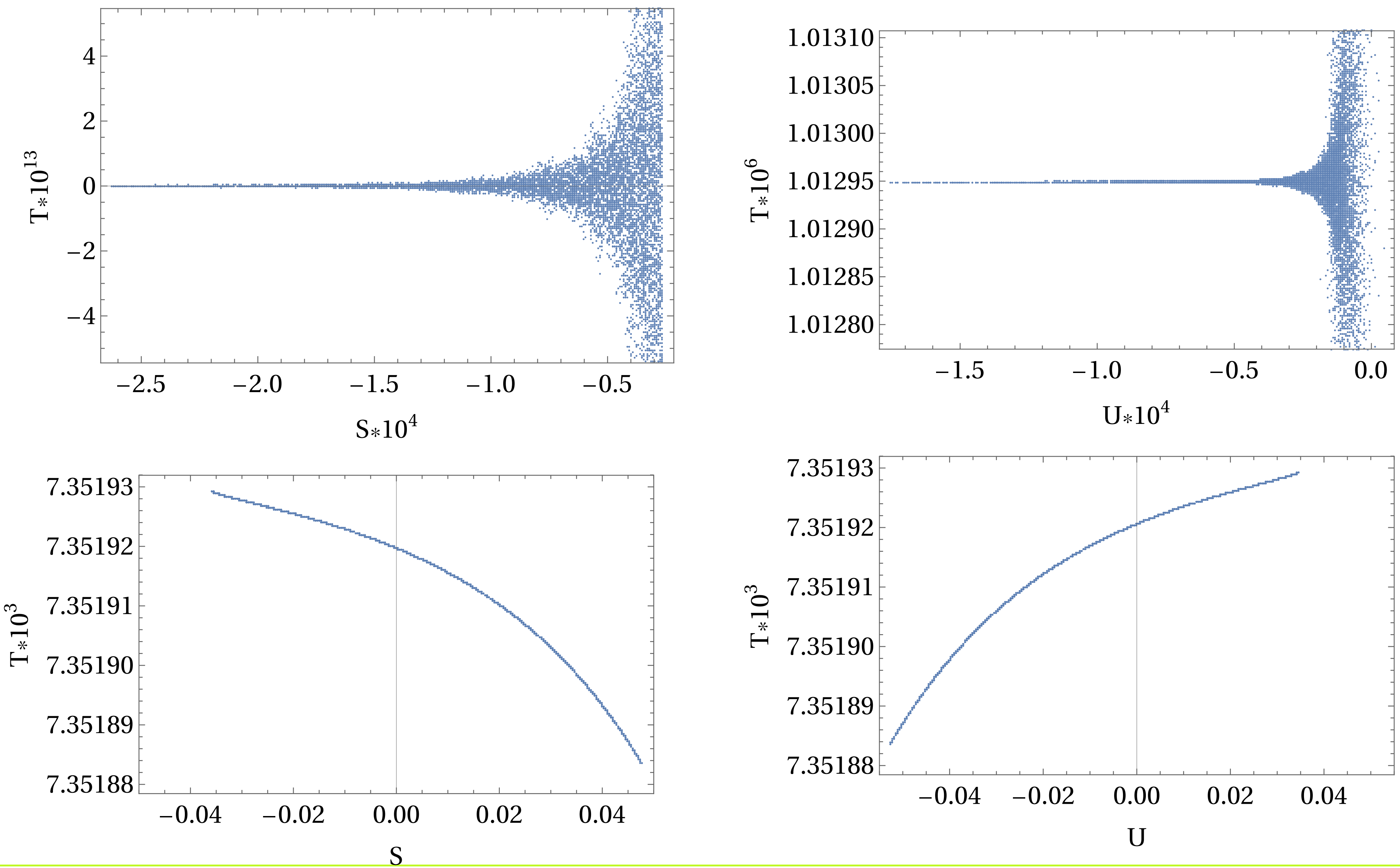
EW Constraints

M. E. Peskin, T Takeushi (1992)

PDG (2022)

$$\Delta S = -0.02 \pm 0.10,$$
$$\Delta T = 0.03 \pm 0.12,$$
$$\Delta U = 0.01 \pm 0.11.$$

$$\Delta X = \Delta X_{ID} + \Delta X_{IT} + \Delta X_{AT}, \quad X = S, T, U$$



Benchmarks

M_{H^0}	M_{T^0}	$\lambda_{\Phi_2 T}$	$\Omega_{H^0} h^2$	$\Omega_{T^0} h^2$	$\Omega_{\text{Tot}} h^2$	$\sigma_{SI}^{H^0} [pb]$	$\sigma_{SI}^{T^0} [pb]$
170	2200	0.0	1.20×10^{-2}	1.08×10^{-1}	0.120	5.892×10^{-11}	8.901×10^{-12}
240	2500	0.5	2.35×10^{-2}	9.51×10^{-2}	0.119	2.939×10^{-11}	6.830×10^{-12}
518	900	0.5	1.07×10^{-1}	1.44×10^{-2}	0.121	6.852×10^{-12}	5.693×10^{-11}
430	2440	1.0	7.39×10^{-2}	4.74×10^{-2}	0.121	9.202×10^{-12}	7.182×10^{-12}
506	1460	1.0	1.02×10^{-1}	1.83×10^{-2}	0.120	6.909×10^{-12}	2.083×10^{-11}