Universität Zürich[UZH]

Gauged flavor and dark matter

work in progress

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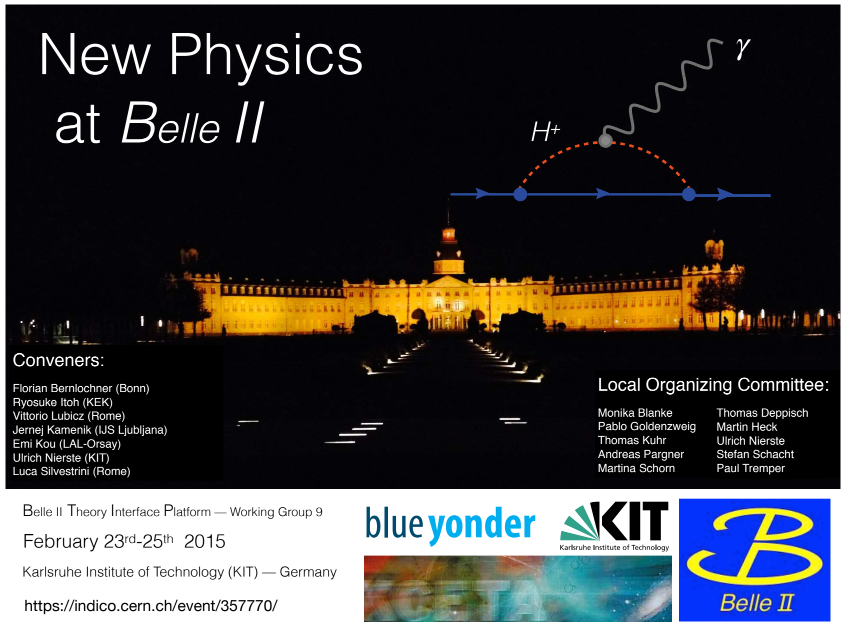
“New physics at Belle II”, 24/02/2015, KIT

Outline

- Motivation
- Stability of flavored dark matter
- Phenomenology of $SU(3)^3$ model
  - Thermal relic DM
  - Flavor constraints
  - DM direct detection
  - Cosmology constraints
  - Searches at the LHC
- Conclusions

Motivation



- Flavor transitions in a remarkable agreement with the SM predictions, so far…
- However, the origin of flavor still a mystery
- Flavor - hint of new fundamental symmetries

- Dark matter existence is an empirical evidence for physics beyond the SM
- New symmetries required to insure DM stability

Gauged flavored symmetries

Flavor symmetries

- In the limit of vanishing Yukawa interactions, SM quark sector has a **global** symmetry

$$\mathcal{G}_F^{\mathrm{SM}} \times U(1)_Y \times U(1)_B \times U(1)_{\mathrm{PQ}}$$

$$\mathcal{G}_F^{\mathrm{SM}} \equiv SU(3)_Q \times SU(3)_U \times SU(3)_D$$

- The SM quarks transform as

$$Q_L \sim (3,1,1)\,,\; U_R^c \sim (1,\bar{3},1)\,,\; D_R^c \sim (1,1,\bar{3})\,.$$

- Flavor breaking

$$\mathcal{L}_Y = \bar{Q}_L \tilde{H} y_u U_R + \bar{Q}_L H y_d D_R + \mathrm{h.c.}$$

- Flavor breaking spurions

$$Y_u \sim (\bar{3},3,1) \quad Y_d \sim (\bar{3},1,3)$$

If these are the only flavor breaking spurions in new physics (NP) sector, the theory is of minimal flavor violation (MFV) type.

- Center group

$$\mathcal{G}_F^{\mathrm{SM}} \longrightarrow \mathcal{Z}_3^{UDQ}$$

$$\{U_R, D_R, Q_L\} \to e^{i2\pi/3}\{U_R, D_R, Q_L\}$$

The origin of DM stability?!

Flavor symmetries and DM stability

- Center group $\mathcal{G}_F^{\rm SM} \longrightarrow \mathcal{Z}_3^{UDQ}$

  $\{U_R, D_R, Q_L\} \to e^{i2\pi/3}\{U_R, D_R, Q_L\}$

The origin of DM stability?!

In the SM, Z_3 can be identified as a subgroup of $U(1)_B$. This is no longer true in presence of NP. In MFV, Z_3 remains exact while $U(1)_B$ can be broken, i.e. by dimension 9 operators.

$\epsilon_{\alpha\beta\gamma}\epsilon_{ij}((u^\alpha)^T C u^\beta)((u^\gamma)^T C e)((l^i)^T C l^j)$

Consider diagonal subgroup of $\mathcal{Z}_3^{UDQ} \times \mathcal{Z}_3^c$ - SM quarks transform trivially.

- Consider representation X under G_F $\quad X \sim (n_Q^X, m_Q^X) \times (n_U^X, m_U^X) \times (n_D^X, m_D^X)$

- **Flavor triality** $\quad (n_X - m_X) \bmod 3$

  1309.4462 - Batell, Lin, Wang

$$n_X = n_Q^X + n_U^X + n_D^X$$
$$m_X = m_Q^X + m_U^X + m_D^X$$

(n,m)	$SU(3)_Q \times SU(3)_{u_R} \times SU(3)_{d_R}$
$(0,0)$	$(\mathbf{1},\mathbf{1},\mathbf{1})$
$(1,0)$	$(\mathbf{3},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{3},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{3})$
$(0,1)$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\bar{\mathbf{3}},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\bar{\mathbf{3}})$
(2,0)	$(\mathbf{6},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{6},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{6})$ $(\mathbf{3},\mathbf{3},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\mathbf{3},\mathbf{3})$
(0,2)	$(\bar{\mathbf{6}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\bar{\mathbf{6}},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\bar{\mathbf{6}})$ $(\bar{\mathbf{3}},\bar{\mathbf{3}},\mathbf{1})$, $(\bar{\mathbf{3}},\mathbf{1},\bar{\mathbf{3}})$, $(\mathbf{1},\bar{\mathbf{3}},\bar{\mathbf{3}})$
(1,1)	$(\mathbf{8},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{8},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{8})$ $(\mathbf{3},\bar{\mathbf{3}},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\bar{\mathbf{3}})$, $(\mathbf{1},\mathbf{3},\bar{\mathbf{3}})$ $(\bar{\mathbf{3}},\mathbf{3},\mathbf{1})$, $(\bar{\mathbf{3}},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\bar{\mathbf{3}},\mathbf{3})$

1105.1781 - Batell, Pradler, Spannowsky

DM candidates if color singlets

Flavored DM stability conditions

Gauge symmetry…

- G_F needs to be a good symmetry in UV
- G_F needs to be broken only by spurions with zero flavor triality.
- DM candidate is color singlet and in a nontrivial flavor representation with nonzero flavor triality.

To insure Z_3 remains unbroken. Flavor DM models can significantly deviate from MFV.

$SU(3)^3$ gauged flavor model

1009.2049 - Grinstein, Redi, Villadoro

New fermions to cancel gauge anomalies

Yukawas promoted to scalar fields

	Q_L	U_R	D_R	H	Ψ_{u_R}	Ψ_{d_R}	Ψ_{u_L}	Ψ_{d_L}	Y_u	Y_d
$SU(3)_c$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$+^1/_6$	$+^2/_3$	$-^1/_3$	$+^1/_2$	$+^2/_3$	$-^1/_3$	$+^2/_3$	$-^1/_3$	0	0
$SU(3)_{Q_L}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$
$SU(3)_{U_R}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$
$SU(3)_{D_R}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}$

1009.2049 - Grinstein, Redi, Villadoro
1112.4477 - Buras, Carlucci, Merlo, Stamou

New gauge symmetries

Scalar potential not specified in this work. See for instance:

1103.2915 - Alonso, Gavela, Merlo, Rigolin

For analysis of U(1) gauged flavor models see:

1501.07268 - Calibbi, Crivellin, Zaldivar

SU(3)^3 gauged flavor model

Universal coupling constants

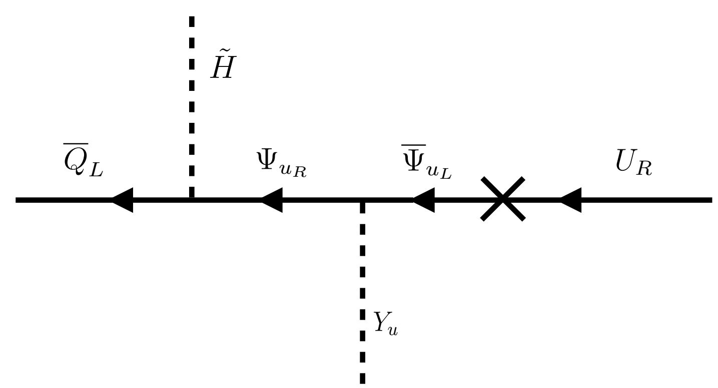
Universal mass parameter

$$\mathcal{L}_{\rm mass} \supset \lambda_u \bar{Q}_L \tilde{H} \Psi_{uR} + \lambda'_u \bar{\Psi}_{uL} Y_u \Psi_{uR} + M_u \bar{\Psi}_{uL} U_R$$
$$+ \lambda_d \bar{Q}_L H \Psi_{dR} + \lambda'_d \bar{\Psi}_{dL} Y_d \Psi_{dR} + M_d \bar{\Psi}_{dL} D_R + \text{h.c.}$$

$$\begin{pmatrix} u^i_{R,L} \\ u'^i_{R,L} \end{pmatrix} = \begin{pmatrix} c_{u_{(R,L)i}} & -s_{u_{(R,L)i}} \\ s_{u_{(R,L)i}} & c_{u_{(R,L)i}} \end{pmatrix} \begin{pmatrix} U^i_{R,L} \\ \Psi^i_{u_{R,L}} \end{pmatrix}$$

$$m_{u^i} \approx \frac{v}{\sqrt{2}} \frac{\lambda_u M_u}{\lambda'_u \langle Y_u \rangle_i}, \qquad m_{u'_i} \approx \lambda'_u \langle Y_u \rangle_i.$$

Inverted hierarchy



$$y_u \simeq \frac{\lambda_u M_u}{\lambda'_u \langle Y_u \rangle}, \; y_d \simeq \frac{\lambda_d M_d}{\lambda'_d \langle Y_d \rangle}.$$

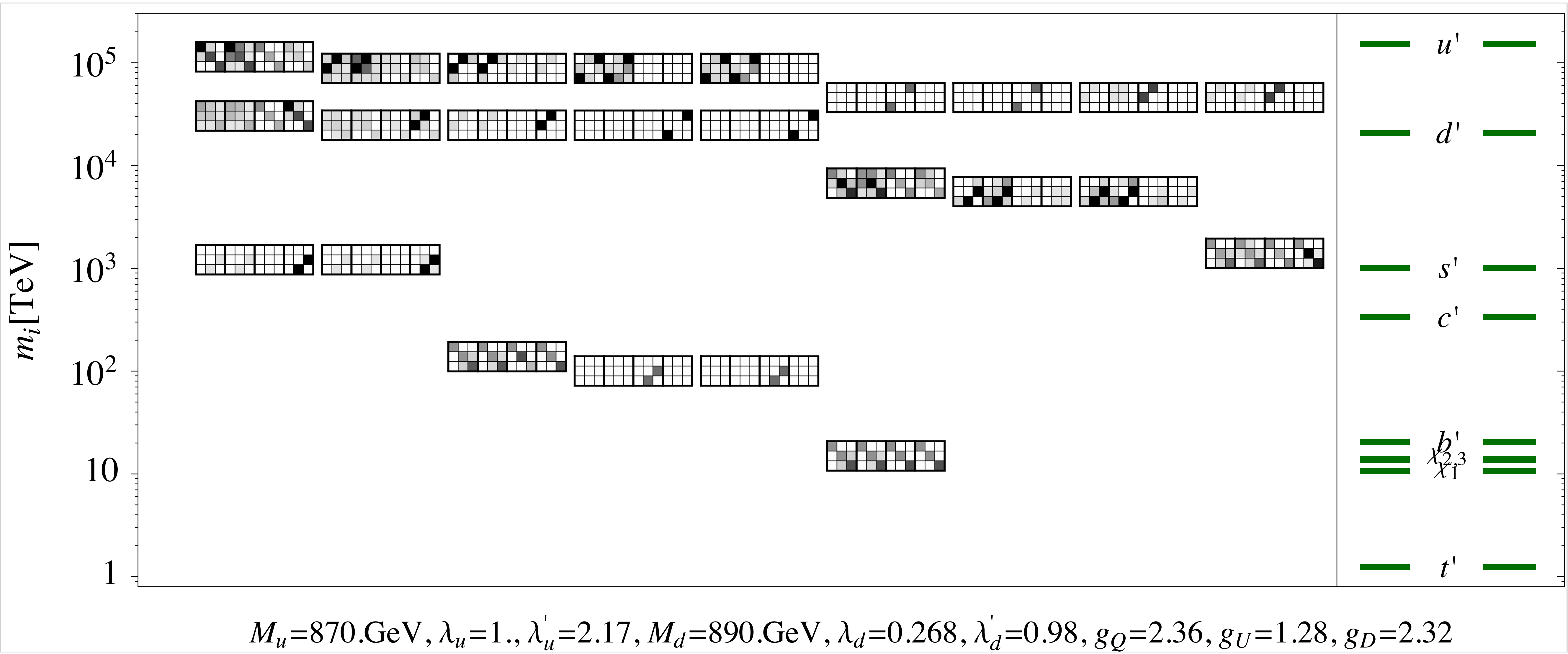
The theory is not of MFV type.

$$(\mathcal{M}^2_{AB})_{ab} = \frac{1}{4} g_A g_B \,\text{Tr}\left[\langle Y_u \rangle \{\lambda^a, \lambda^b\} \langle Y_u \rangle^\dagger\right] (\delta_{AB}\delta_{AQ} - 2\delta_{AQ}\delta_{BU} + Q \leftrightarrow U) + U, u \leftrightarrow D, d,$$

24 flavor gauge boson (FGB) mass eigenstates

SU(3)^3 gauged flavor model

Spectrum: Example



Flavor constraints

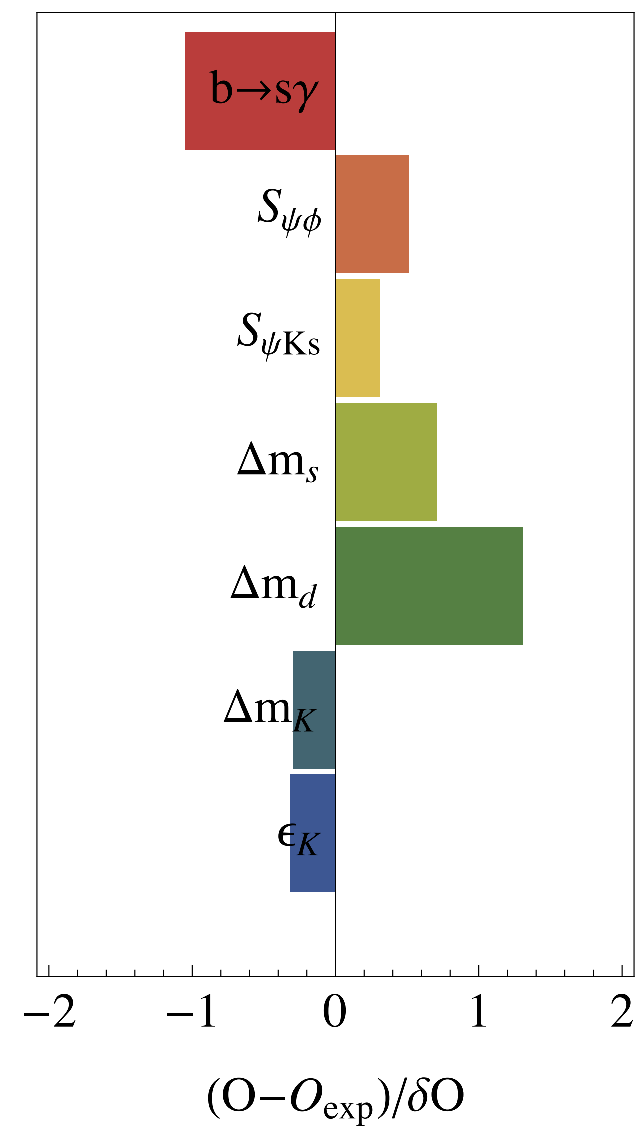
1112.4477 - Buras, Carlucci, Merlo, Stamou

- Inverted hierarchy provides mechanism of flavor protection
- Flavor violation roughly controlled by the Yukawas, suppressing transitions for the light generations

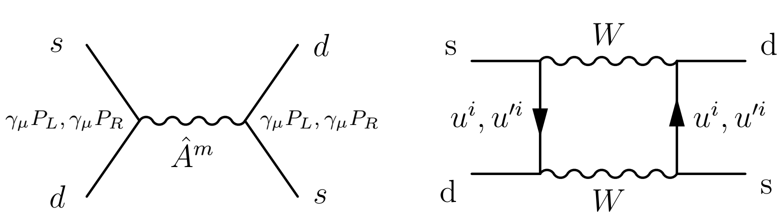
$$\sim \frac{1}{Y^2_{u,d}}(\bar{q}\gamma^\mu q)^2$$

- FCNCs at acceptable level even for NP at electroweak scale
- In the numerical scan of the parameter space we check if the present flavor constraints are satisfied following the methodology of Buras et al.

For the spectrum given in previous slide

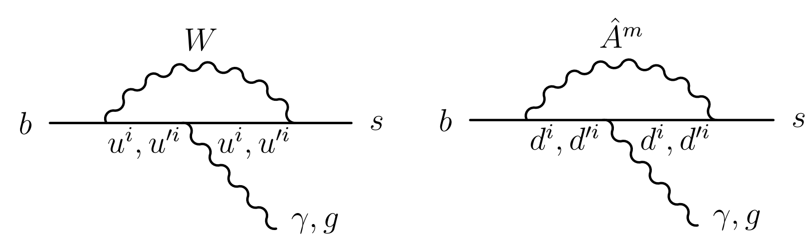


$\Delta F = 2$



tree level + box

$\bar{B} \to X_s\gamma$



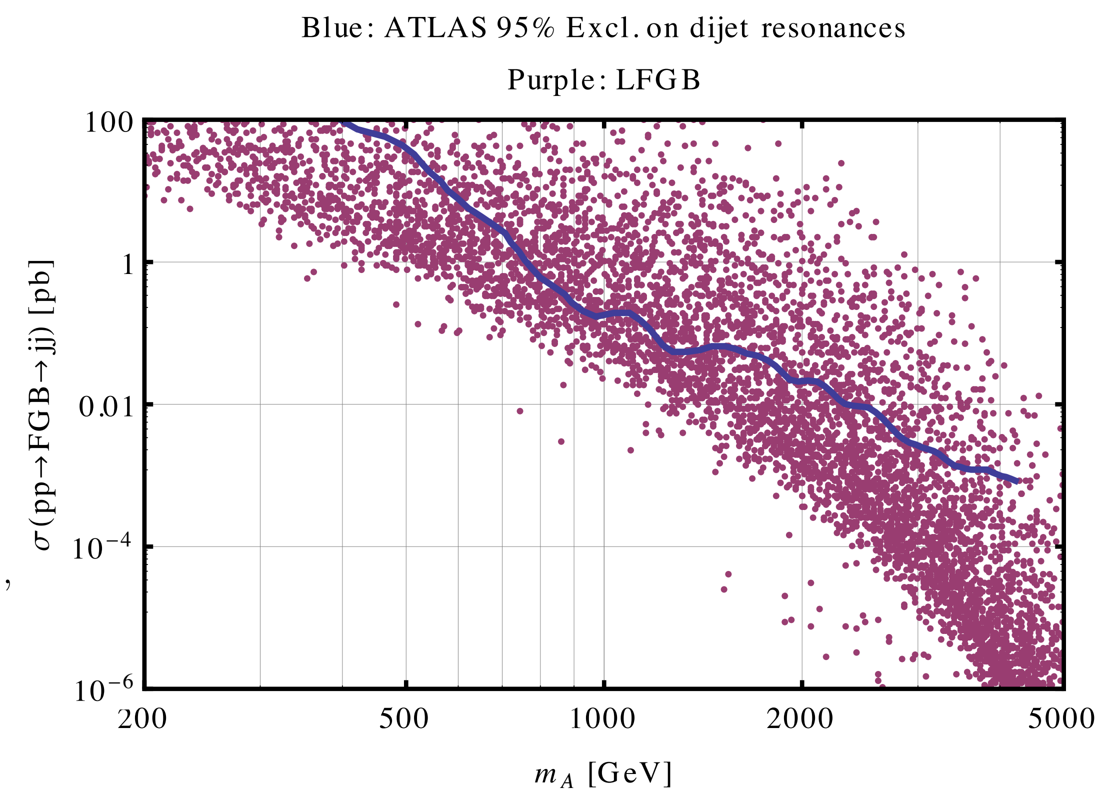
LHC searches

Di-jet resonances

- FGB can appear as a resonance in di-jet invariant mass distribution

$$\frac{d}{dz}\hat{\sigma}(i\bar{i} \to j\bar{j}) = \frac{1}{32\pi}\,\beta_f \frac{\mathscr{M}^2}{\left(\mathscr{M}^2 - m_{Am}^2\right)^2 + m_{Am}^2\Gamma_{Am}^2} \left(\left|\hat{\mathcal{G}}_V^{u,d}\right|^2_{ii,m} + \left|\hat{\mathcal{G}}_A^{u,d}\right|^2_{ii,m}\right)$$

$$\times \left[\left(\left|\hat{\mathcal{G}}_V^{u,d}\right|^2_{jj,m} + \left|\hat{\mathcal{G}}_A^{u,d}\right|^2_{jj,m}\right)\left(1 + \beta_f^2 z^2\right) + 4\left(\left|\hat{\mathcal{G}}_V^{u,d}\right|^2_{jj,m} - \left|\hat{\mathcal{G}}_A^{u,d}\right|^2_{jj,m}\right)\frac{m_j^2}{\mathscr{M}^2}\right],$$



Vector-like quarks

- The lightest exotic quarks are top and bottom partners
- CMS and ATLAS limits on vector-like quarks apply trivially after correcting for branching ratios

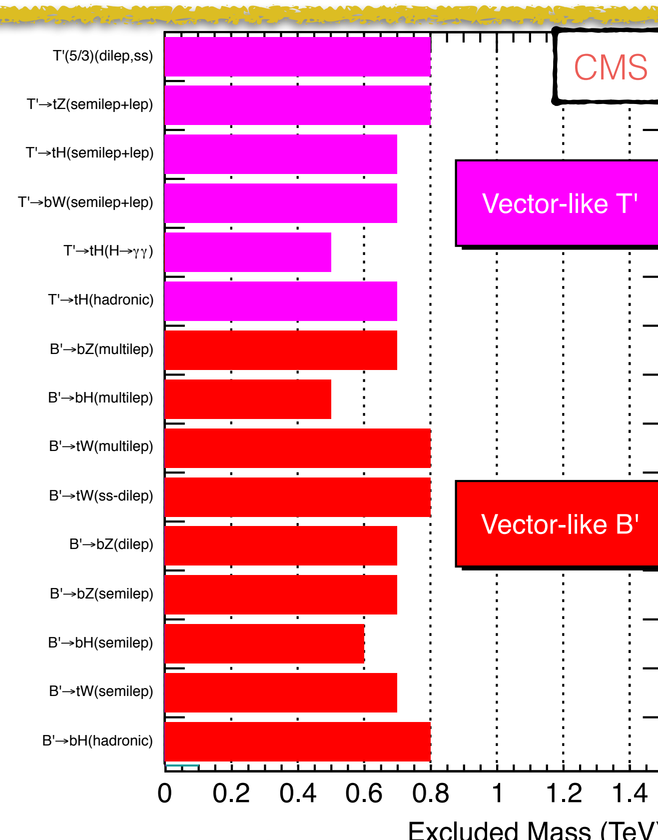
$$\Gamma(t' \to bW) = \frac{g_w^2}{64\pi}\left|s_{u_L 3} V_{33} c_{d_L 3}\right|^2 \frac{m_{t'}^3}{m_W^2}\left(1 - x_W^2\right)^2\left(1 + 2x_W^2\right)$$

$$\Gamma(t' \to tZ) = \frac{g_w^2}{128\pi}\left(c_{u_L 3} s_{u_L 3}\right)^2 \frac{m_{t'}^3}{m_W^2}\sqrt{\left[1 - (x_z + x_t)^2\right]\left[1 - (x_z - x_t)^2\right]}$$

$$\times \left\{\left(1 - x_z^2\right)\left(1 + 2x_z^2 - x_t^2\right) - x_t^2\left(1 - x_t^2\right)\right\}$$

$$\Gamma(t' \to tH) = \frac{\lambda_u^2}{64\pi} m_{t'}\sqrt{\left[1 - (x_h + x_t)^2\right]\left[1 - (x_h - x_t)^2\right]}$$

$$\times \left\{\left(s_{u_R 3}^2 s_{u_L 3}^2 + c_{u_R 3}^2 c_{u_L 3}^2\right)\left(1 + x_t^2 - x_h^2\right) - 4 s_{u_R 3}\, s_{u_L 3}\, c_{u_R 3}\, c_{u_L 3}\, x_t\right\}$$



SU(3)^3 model and DM candidate

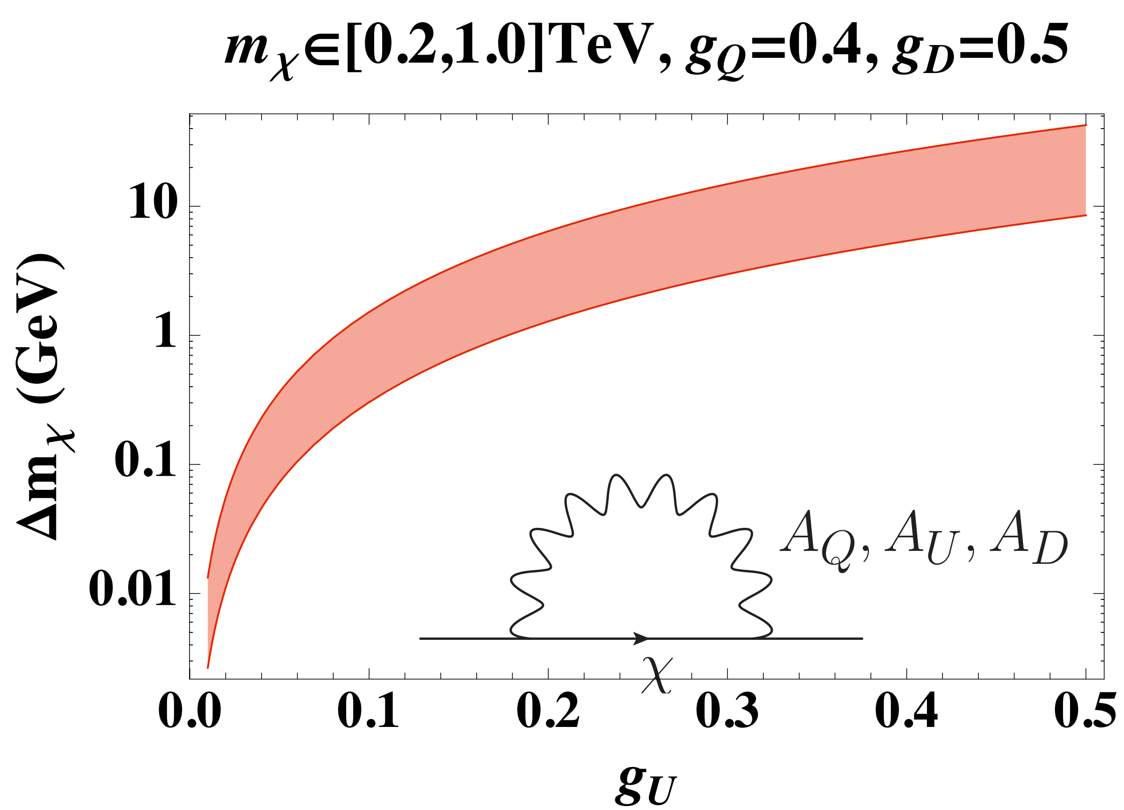
1) Dirac fermion in fundamental of SU(3)$_U$

$$\chi_L \sim (1,3,1)\,, \qquad \chi_R^c \sim (1,\bar{3},1)$$

$$\mathcal{L}_\chi \supset (\hat{g}_\chi^m)_{ij}\bar{\chi}_i\gamma^\mu\chi_j A_\mu^m + \bar{u}_{q'}\gamma^\mu\left(\left(\hat{\mathcal{G}}_R^u\right)_{q'q,m}P_R + \left(\hat{\mathcal{G}}_L^u\right)_{q'q,m}P_L\right)u_q A_\mu^m$$
$$+\,\bar{d}_{q'}\gamma^\mu\left(\left(\hat{\mathcal{G}}_R^d\right)_{q'q,m}P_R + \left(\hat{\mathcal{G}}_L^d\right)_{q'q,m}P_L\right)d_q A_\mu^m\,,$$

- Radiative DM mass splitting

$$\Delta m_\chi = -\frac{3}{4}\frac{g_U^2}{16\pi^2}m_\chi^0\left(\Xi - \frac{1}{3}\mathrm{Tr}\,\Xi\right)\,,$$
$$\Xi \;=\; \lambda^a(\log\mathcal{M}_A^2/\mu^2)^{ab}\lambda^b.$$



- Partial decay width

$$\Gamma(\chi_i\to\chi_j q\bar{q}') = \frac{3}{(2\pi)^3}\frac{\Delta m_{ij}^5}{15}\left[\left|\sum_m(\hat{g}_\chi^m)_{ji}\frac{1}{m_{A^m}^2}\left(\hat{\mathcal{G}}_L^u\right)_{q'q,m}\right|^2 + L\to R\right]$$

$SU(3)^3$ model and DM candidate

2) Complex scalar in fundamental of $SU(3)_U$

$$\phi \sim (1, 3, 1)$$

Higgs portal

$$\mathcal{L}_{\rm int}^{\rm DM} = \lambda_H (\phi^\dagger \phi)(H^\dagger H)$$

DM mass splitting at tree level

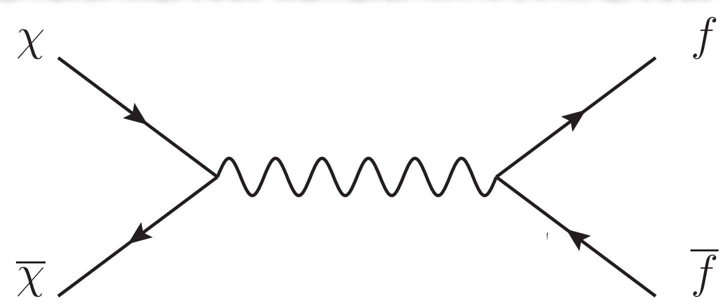
$$\mathcal{L} \supset \kappa (\phi^\dagger \lambda^a \phi) {\rm Tr}(Y_u^\dagger \lambda^a Y_u)$$

Parameter scan

- We perform an extensive scan of parameter space of the model (~30k points)
- We fix $\lambda_u = 1$ and vary $\lambda_d \in [1/(4\pi), 1]$
- In addition, we vary $\lambda'_{u,d} \in [1/(4\pi), \sqrt{4\pi}]\,,\ g_{Q,U,D} \in [1/(4\pi), \sqrt{4\pi}]\,,\ M_{u,d} \in [0.2, 20]\ \mathrm{TeV}\,.$
- To have control over the perturbative expansion we require all the FBG decay widths to be less then 1/2 FGB mass as well as radiative DM mass splittings to be less then 1/2 DM mass
- In the plots, we show only the points that can accommodate for the **observed DM relic density**
- Different colors denote consecutively applied constraints of perturbativity, direct DM searches, LHC searches, flavor and cosmology constraints

DM as a thermal relic

1) Fermionic DM



- Correct DM relic abundance requires **resonant** exchange of the lightest FGB!

$$\sigma(\chi_i\bar{\chi}_i \to \bar{u}_j u_j) \simeq \frac{(\hat{g}_\chi^{24})^2_{ii}}{4\pi} \frac{s^{1/2}\left(s+2m_{\chi_i}^2\right)}{\sqrt{s-4m_{\chi_i}^2}} \frac{\left(\hat{\mathcal{G}}_V^u\right)^2_{jj,24}+\left(\hat{\mathcal{G}}_A^u\right)^2_{jj,24}}{(s-m_{A^{24}}^2)^2+m_{A^{24}}^2\Gamma_{A^{24}}^2}$$

$$\Gamma(A^{24}\to \bar{u}_j u_j) \simeq \frac{m_A^{24}}{4\pi}\left(\left(\hat{\mathcal{G}}_V^u\right)^2_{jj,24}+\left(\hat{\mathcal{G}}_A^u\right)^2_{jj,24}\right)$$

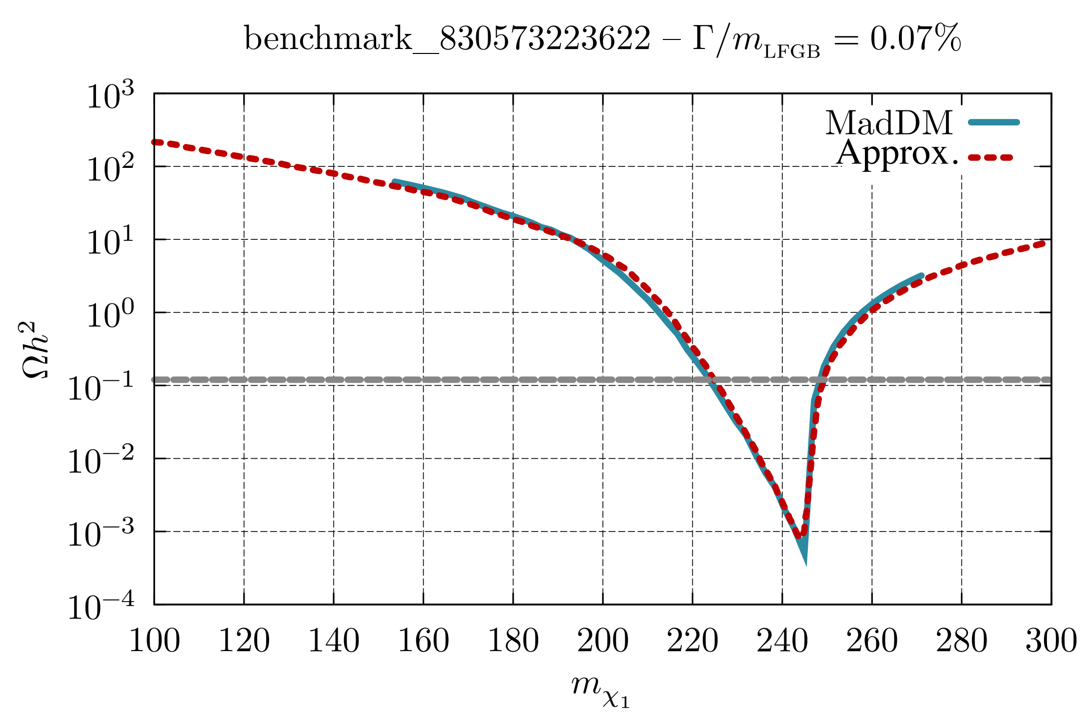
→

$$\langle \sigma v\rangle \propto \frac{1}{\langle Y\rangle^2_{A^{24}}} + \mathcal{O}(\Gamma_{A^{24}}/m_{A^{24}})$$

$$m_{A^{24}} \sim \langle Y\rangle_{A^{24}} g_{A^{24}}$$

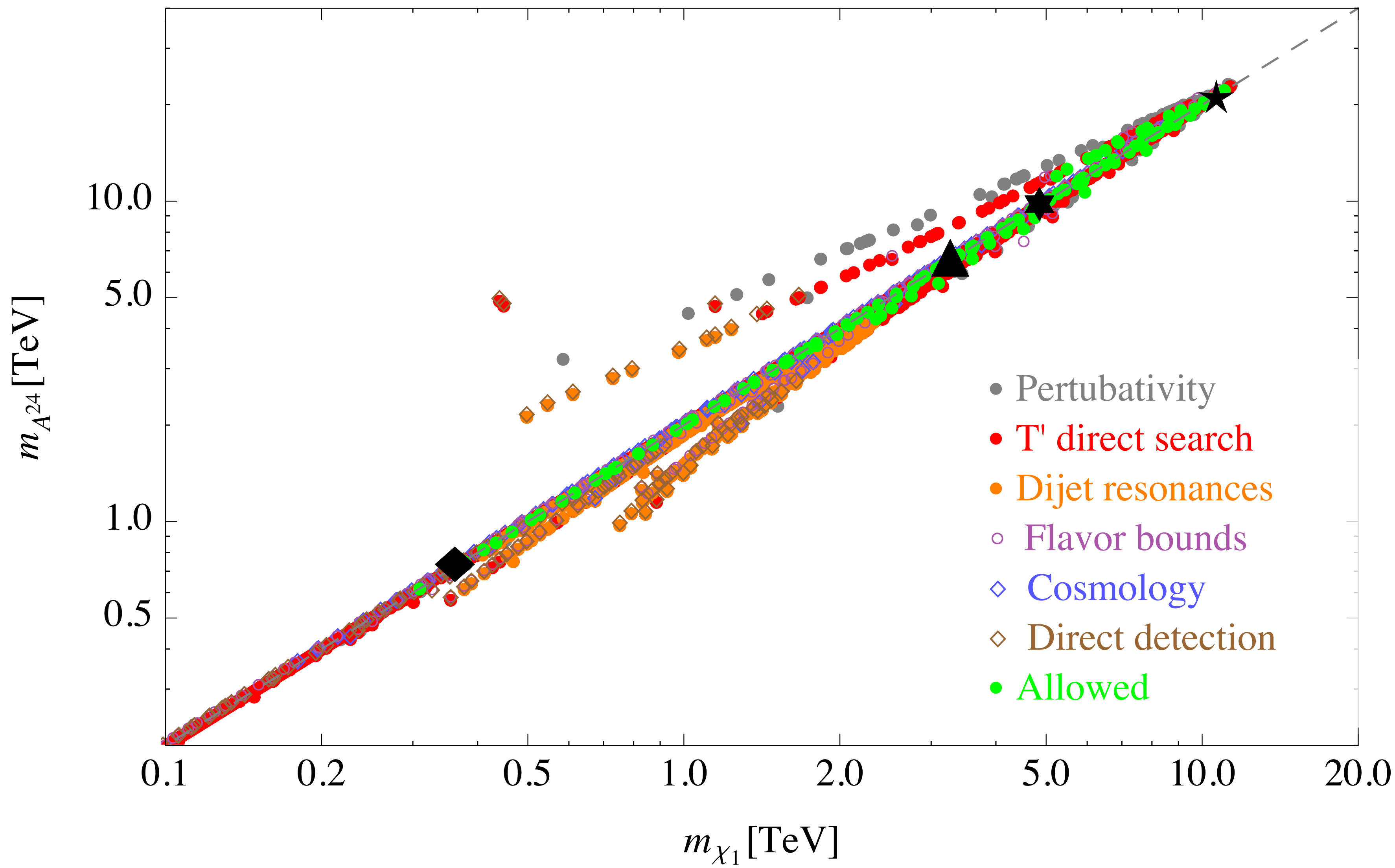
Thermal relic calculation used in the numerical scan considers only lightest FGB exchange and adopts non-relativistic and freeze-out approximations. The results are cross-checked with MadDM code for some benchmarks.

→



DM as a thermal relic

1) Fermionic DM



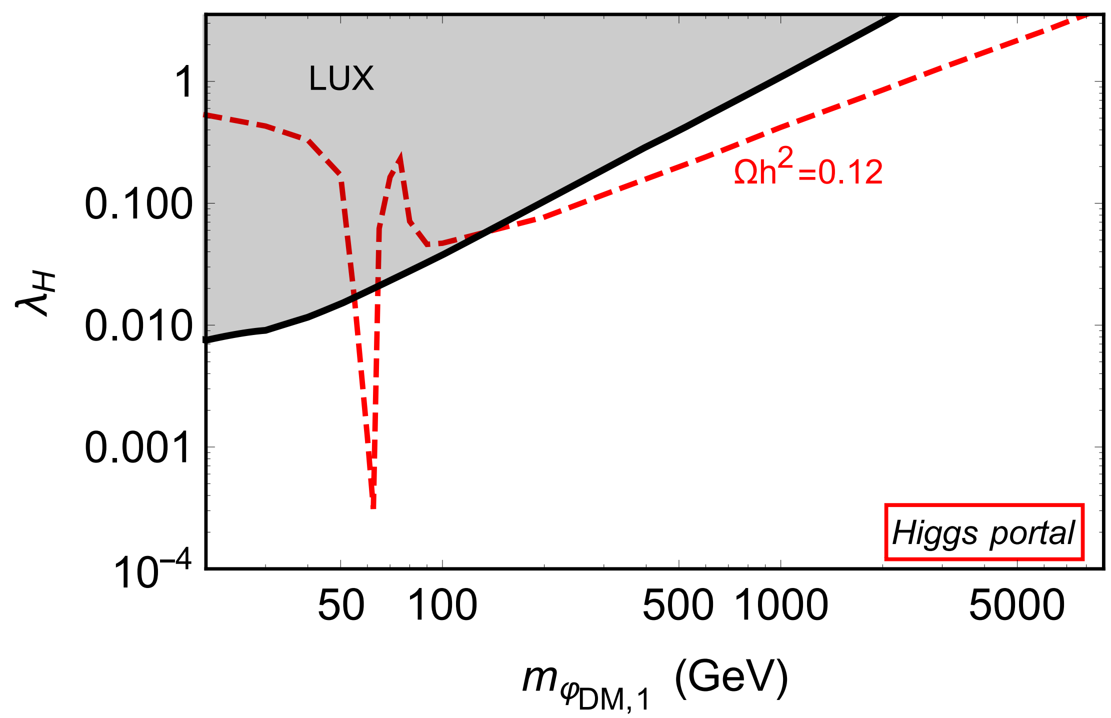
- Correct DM relic abundance requires **resonant** exchange of the lightest FGB!

DM as a thermal relic

2) Scalar DM

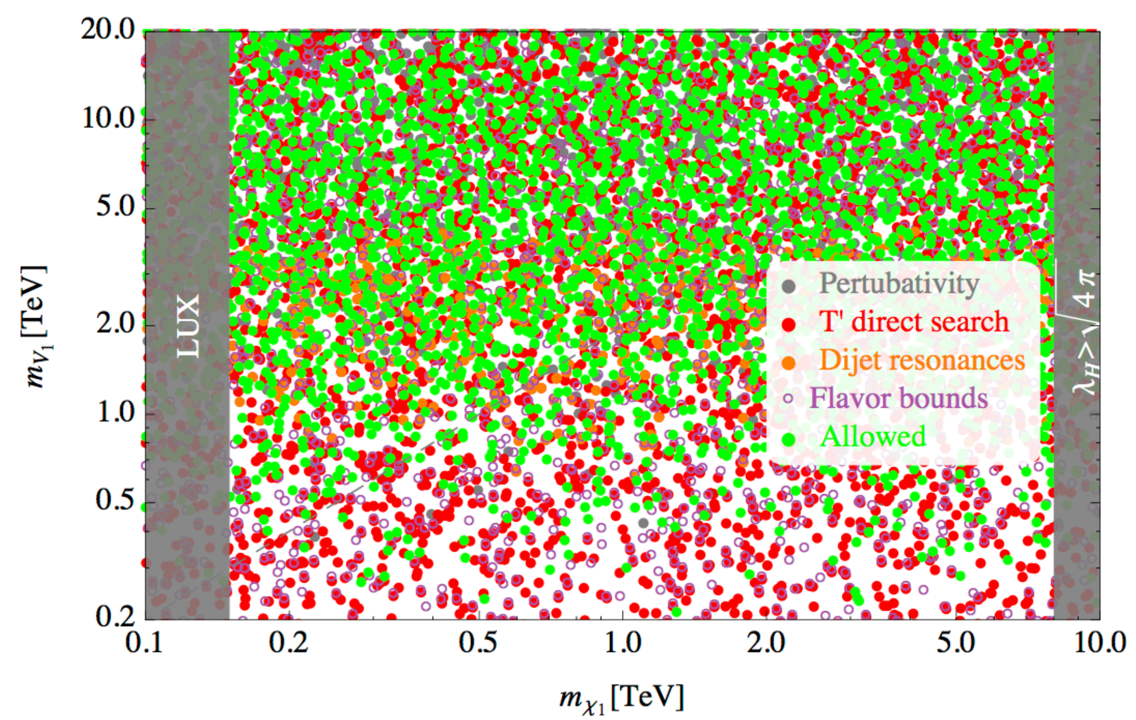
- Both, flavor and Higgs portal present.

$$\phi^\dagger_{DM}\phi_{DM} \to \bar{b}b, \bar{c}c, \tau^+\tau^-, W^+W^-, ZZ, hh$$



$$\sigma(\phi^\dagger\phi \to \bar{f}f) = \frac{\lambda_H^2 m_f^2 N_c \left(1-\frac{4m_f^2}{s}\right)^{3/2}}{8\pi\sqrt{1-\frac{4m_\phi^2}{s}}\,((m_h^2-s)^2+m_h^2\Gamma_h^2)},$$

$$\sigma(\phi^\dagger\phi \to VV) = \frac{c_V\lambda_H^2\sqrt{1-\frac{4m_V^2}{s}}(12m_V^4-4m_V^2 s+s^2)}{16\pi s\sqrt{1-\frac{4m_\phi^2}{s}}((m_h^2-s)^2+m_h^2\Gamma_h^2)},$$



- No correlation between m_{DM} and m_{LFGB}

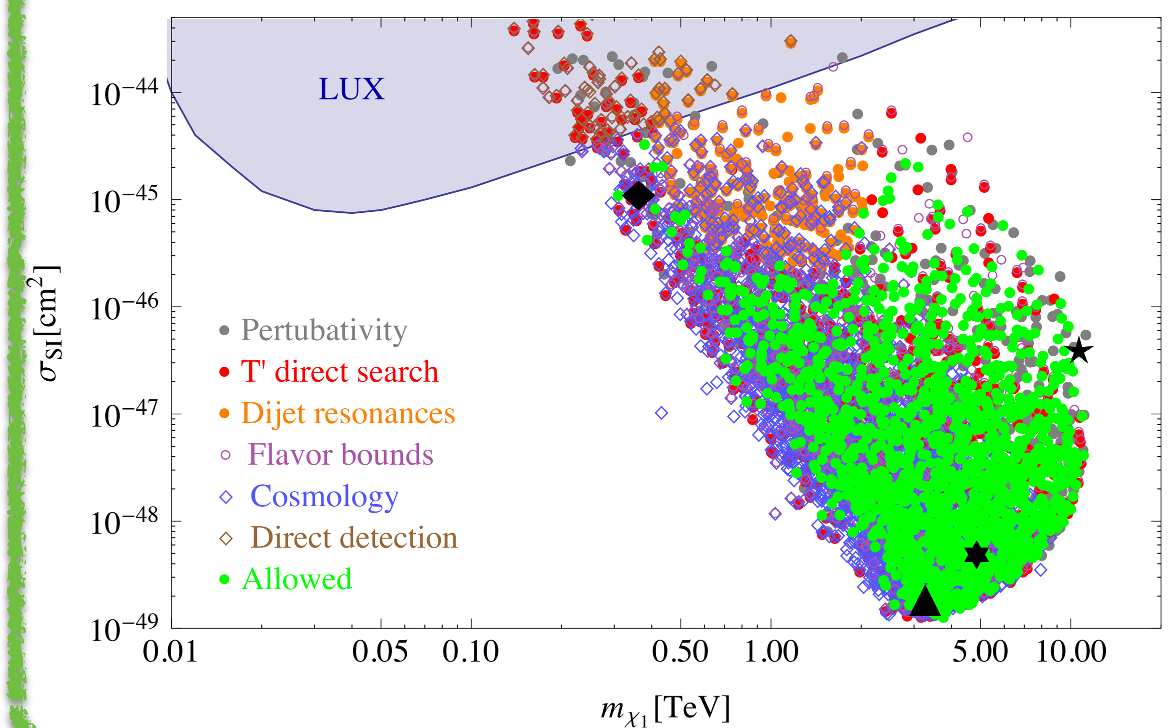
DM direct detection

1) Fermionic DM

- t-channel FBGs exchange

$$\sigma_{\chi N}^{SI} = \left[1 + \frac{Z}{A}\left(\frac{f_p}{f_n} - 1\right)\right]^2 \frac{\mu_{\chi n}^2 f_n^2}{\pi}$$

$$f_p = \sum_m (\hat{g}_\chi^m)_{11} \frac{2(\hat{\mathcal{G}}_V^u)_{11,m} + (\hat{\mathcal{G}}_V^d)_{11,m}}{m_{A^m}^2} \qquad f_n = \sum_m (\hat{g}_\chi^m)_{11} \frac{(\hat{\mathcal{G}}_V^u)_{11,m} + 2(\hat{\mathcal{G}}_V^d)_{11,m}}{m_{A^m}^2}$$

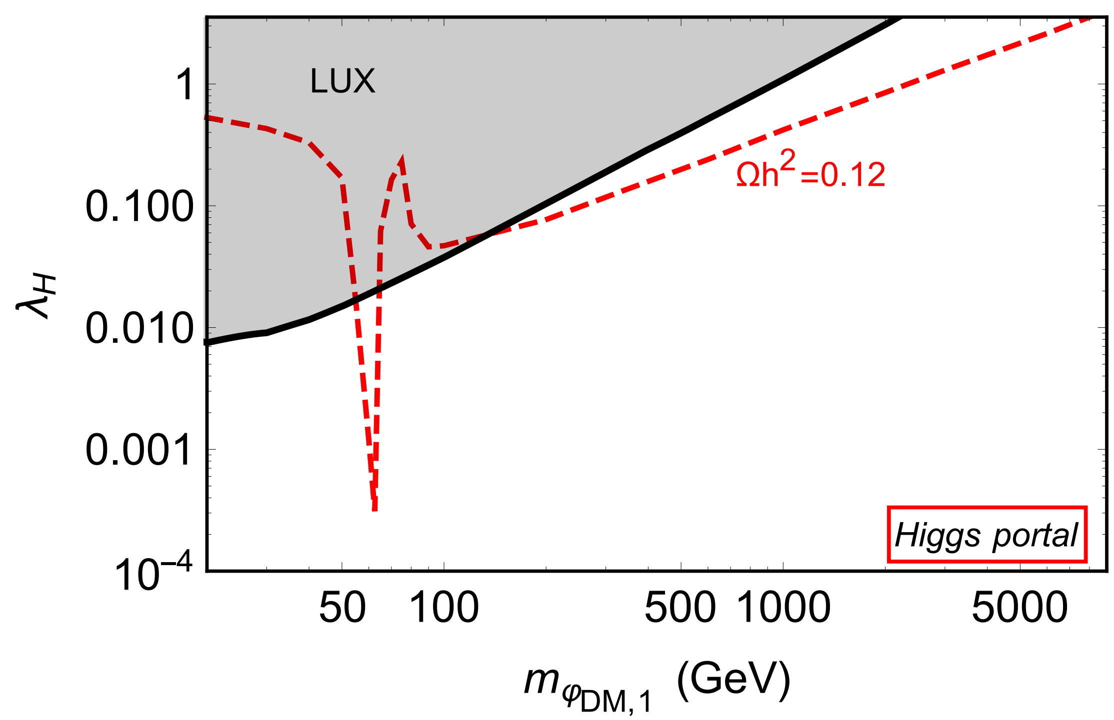


2) Scalar DM

- t-channel Higgs exchange

$$\sigma_{\chi N}^{SI} = \frac{\lambda_H^2 f_{N,h}^2}{4\pi} \left(\frac{m_{\phi_1} m_N}{m_{\phi_1} + m_N}\right)^2 \frac{m_N^2}{m_h^4 m_{\phi_1}^2}$$

$$f_{N,h} = \frac{2}{9} + \frac{7}{9}\left(\sum_q f_q^{(N)}\right)$$

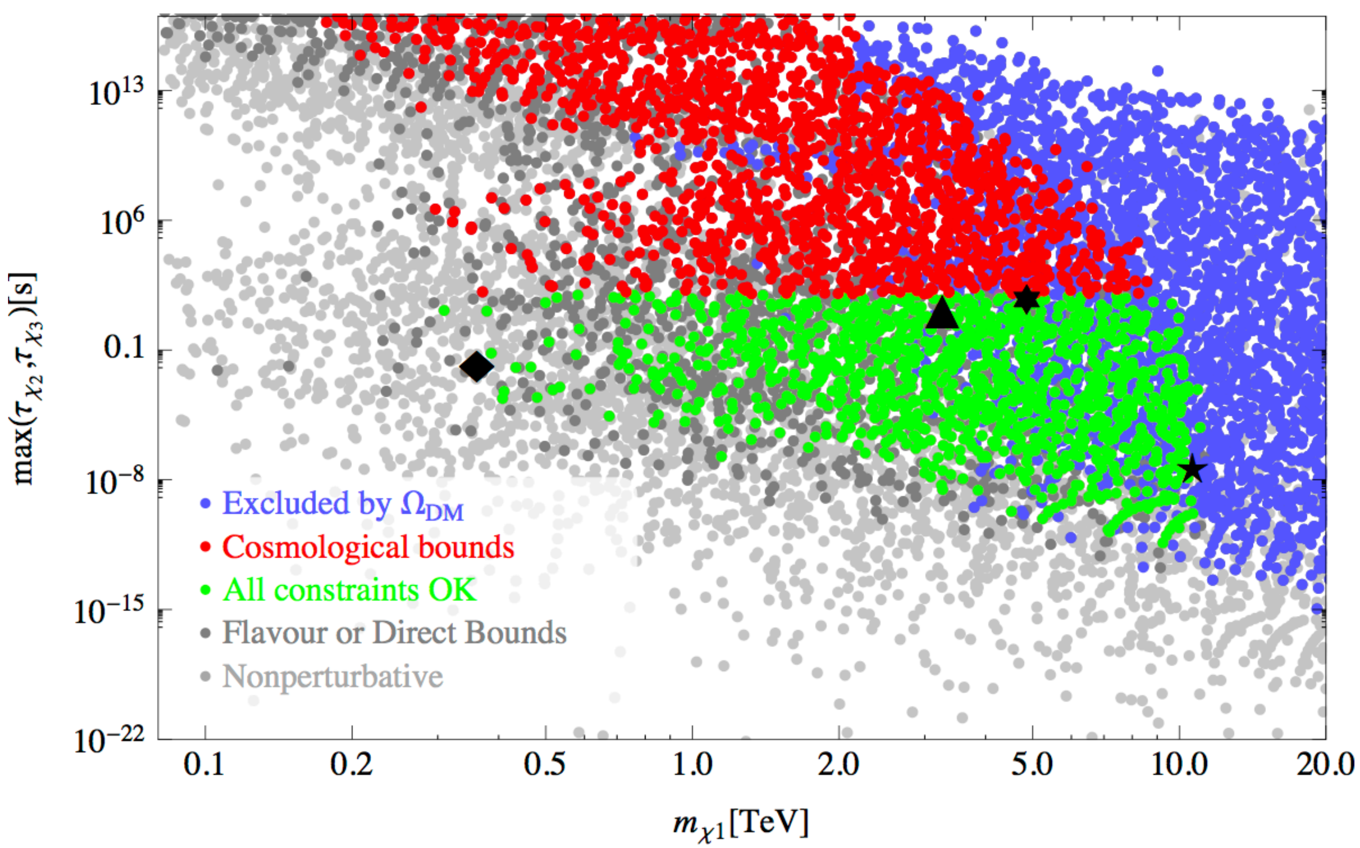


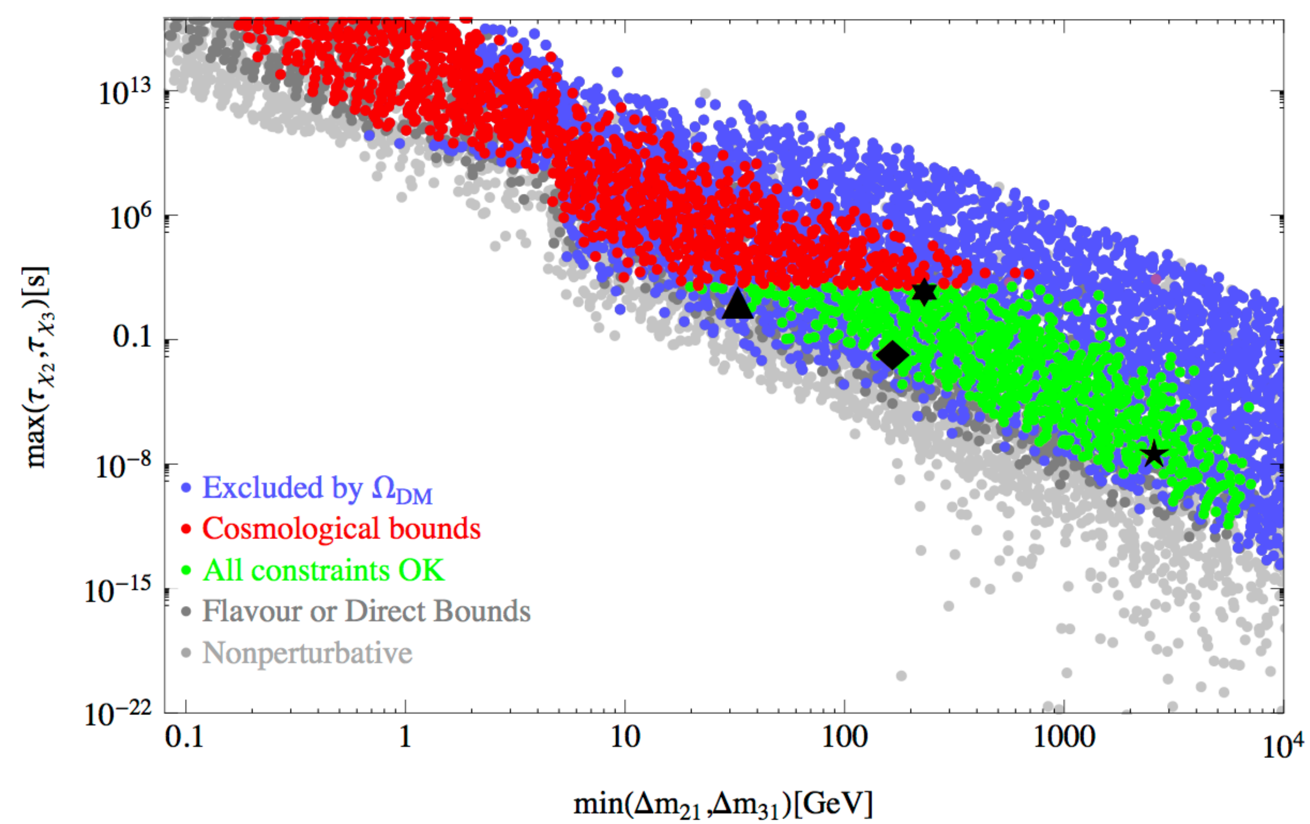
Cosmology constraints

- Heavier DM states are unstable
- Induce creation of energetic SM particles in the early universe
- This may affect the primordial generation of light nuclear elements

astro-ph/0408426 - Kawasaki, Kohri, Moroi

- Relevant parameter - decay lifetimes and mass splittings
- Fermionic multiplets more degenerate (radiative mass splittings), thus potentially long lived





Conclusions

- Maximally gauged flavor model exhibits flavor protection and therefore allows for new physics at TeV scale
- On the other hand, it provides a viable framework for thermal relic dark matter around TeV scale
- We discuss general conditions for flavored DM stability
- We present the phenomenological analysis of viable $SU(3)^3$ model
- Future LHC searches, flavor measurement and DM direct detection will probe the parameter space further