Flavored Dark Matter

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Based on:

- 1105.1781 - BB, J. Pradler, M. Spannowsky
- 1309.4462 - BB, T. Lin, L. T. Wang
- 1404.1373 - P. Agrawal, BB, D. Hooper, T. Lin

Outline

- Motivation - Minimal Flavor Violation
- Flavor Triality and Dark Matter Stability
- Flavored Dark Matter and R-parity violation
- Gamma rays from Flavored Dark Matter

Generic phenomenological problems in BSM

- B, L violation
- Flavor, CP violation
- Electroweak precision

Impose symmetries to forbid dangerous terms!

Discrete Symmetry (e.g., R-parity)

- B, L violation
- Flavor, CP violation
- Electroweak precision

Side effect: lightest odd particle stable

Dark Matter candidate!

New physics flavor problem

- Prejudice for new physics at TeV scale
- NP cannot have generic flavor structure
- e.g. Kaon mixing:

SM: $$\mathcal{H}^{SM}_{\Delta F=2} = \frac{G_F^2}{4\pi^2}(V_{ts}V_{td}^*)^2 m_W^2 S(m_t/m_W)\,(\bar{s}_L\gamma^\mu d_L)^2$$

NP: $$\mathcal{H}^{NP}_{\Delta F=2} = \frac{c_{sd}}{\Lambda^2}\,(\bar{s}_L\gamma^\mu d_L)^2$$

$$c_{sd} \sim \mathcal{O}(1) \quad \Rightarrow \quad \Lambda \gtrsim 10^4\ \mathrm{TeV}$$

Minimal Flavor Violation

Flavor symmetry broken only by SM Yukawas

- B, L violation
- Flavor, CP violation ✗
- Electroweak precision

Can MFV provide a DM candidate?

MFV in a nutshell

Chivukula, Georgi, '87;
Hall, Randall, '90;
Buras et al. , '00;
D'Ambrosio et al. '02

$$-\mathcal{L} \supset \bar{Q}\, Y_d\, d_R\, H + \bar{Q}\, Y_u\, u_R\, H^\dagger + \bar{L}\, Y_e\, e_R\, H + \text{h.c.}$$

In the limit $Y_{u,d,e} \to 0$ the SM exhibits large $U(3)^5$ global flavor symmetry:

$$G_F = SU(3)_Q \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$$

MFV Hypothesis:

In the presence of new physics, the SM Yukawas are the only source of flavor breaking

⇒ Built-in protection against large FCNCs

Implementing MFV:

- Promote Yukawas to spurion fields

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

- Write flavor-symmetric Lagrangian

e.g.

$$\mathcal{L} = \frac{c_{ijkl}}{\Lambda^2} (\bar{Q}_i \gamma^\mu Q_j)(\bar{Q}_k \gamma^\mu Q_l) + \ldots$$

$$\begin{aligned} c^1_{ijk\ell} &= c^1_1 \mathbf{1}_{ij} \mathbf{1}_{k\ell} + c^1_2 \mathbf{1}_{i\ell} \mathbf{1}_{kj} + c^1_3 (Y_u Y_u^\dagger)_{ij} \mathbf{1}_{k\ell} \\ &+ c^1_4 \mathbf{1}_{ij} (Y_u Y_u^\dagger)_{k\ell} + c^1_5 (Y_u Y_u^\dagger)_{i\ell} \mathbf{1}_{kj} \\ &+ c^{1*}_5 \mathbf{1}_{i\ell} (Y_u Y_u^\dagger)_{kj} + \ldots, \end{aligned}$$

Flavor Triality and Dark Matter Stability

[BB, Pradler, Spannowsky ’11]
[BB, Lin, Wang ’13]

Dark matter stability from MFV

Consider the following element of $SU(3)_c \times SU(3)_Q \times SU(3)_u \times SU(3)_d$:

$$U = (\omega^2)_c \times (\omega)_Q \times (\omega)_u \times (\omega)_d$$

with $\omega \equiv e^{2\pi i/3}$

	$SU(3)_c$	$SU(3)_Q$	$SU(3)_u$	$SU(3)_d$
Q	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$
$\bar{u}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{1}$
$\bar{d}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{1}$
Y_u	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{3}$	$\mathbf{1}$
Y_d	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{3}$
G	$\mathbf{8}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$

How do fields transform under U ?

e.g.,

$$Q \rightarrow (\omega^2)_c(\omega)_Q\, Q = \omega^3 Q = Q$$

Dark matter stability from MFV

Consider the following element of $SU(3)_c \times SU(3)_Q \times SU(3)_u \times SU(3)_d$:

$$U = (\omega^2)_c \times (\omega)_Q \times (\omega)_u \times (\omega)_d$$

with $\omega \equiv e^{2\pi i/3}$

	$SU(3)_c$	$SU(3)_Q$	$SU(3)_u$	$SU(3)_d$
Q	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$
$\bar{u}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{1}$
$\bar{d}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{1}$
Y_u	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{3}$	$\mathbf{1}$
Y_d	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{3}$
G	$\mathbf{8}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$

The quark fields, gluon field, and Yukawa spurions transform trivially!

$$Q \to (\omega^2)_c(\omega)_Q\, Q = \omega^3 Q = Q$$

$$\bar{u} \to (\omega^{-2})_c(\omega^{-1})_u\, \bar{u} = \omega^{-3}\bar{u} = \bar{u}$$

$$\bar{d} \to (\omega^{-2})_c(\omega^{-1})_d\, \bar{d} = \omega^{-3}\bar{d} = \bar{d}$$

$$Y_u \to (\omega^{-1})_Q(\omega^1)_u\, Y_u = \omega^0\, Y_u = Y_u$$

$$Y_d \to (\omega^{-1})_Q(\omega^1)_d\, Y_d = \omega^0\, Y_d = Y_d$$

$$G \to (\omega^{-1+1})_c\, G = G$$

Give Dark Matter Flavor!

Consider a dark matter candidate in a color singlet, general flavor representation

$$U = (\omega^2)_c \times (\omega)_Q \times (\omega)_u \times (\omega)_d$$

with $\omega \equiv e^{2\pi i/3}$

$$\chi \sim (n_Q, m_Q)_Q \times (n_u, m_u)_u \times (n_d, m_d)_d$$

Under *U*, χ transforms as

$$\chi = (\omega^{n_Q - m_Q})_Q (\omega^{n_u - m_u})_u (\omega^{n_d - m_d})_d \chi \equiv \omega^{n-m} \chi$$

where $n \equiv n_Q + n_u + n_d$, $m \equiv m_Q + m_u + m_d$

This transformation is nontrivial if

$$(n - m) \bmod 3 \neq 0$$

Flavor Triality

Given Minimal Flavor Violation, we have found a new Z_3 symmetry

$$U = (\omega^2)_c \times (\omega)_Q \times (\omega)_u \times (\omega)_d$$

$$\text{with } \omega \equiv e^{2\pi i/3}$$

The Standard Model fields and Yukawas are not charged under flavor triality

Dark matter carries non-vanishing charge provided $(n - m) \bmod 3 \neq 0$

If this condition holds then χ is stable!

Note that this statement is true at the non-renormalizable level

Lowest Dimensional Flavor Representations:

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

Many possible models of flavored dark matter!

Flavored Dark Matter and R-Parity Violation

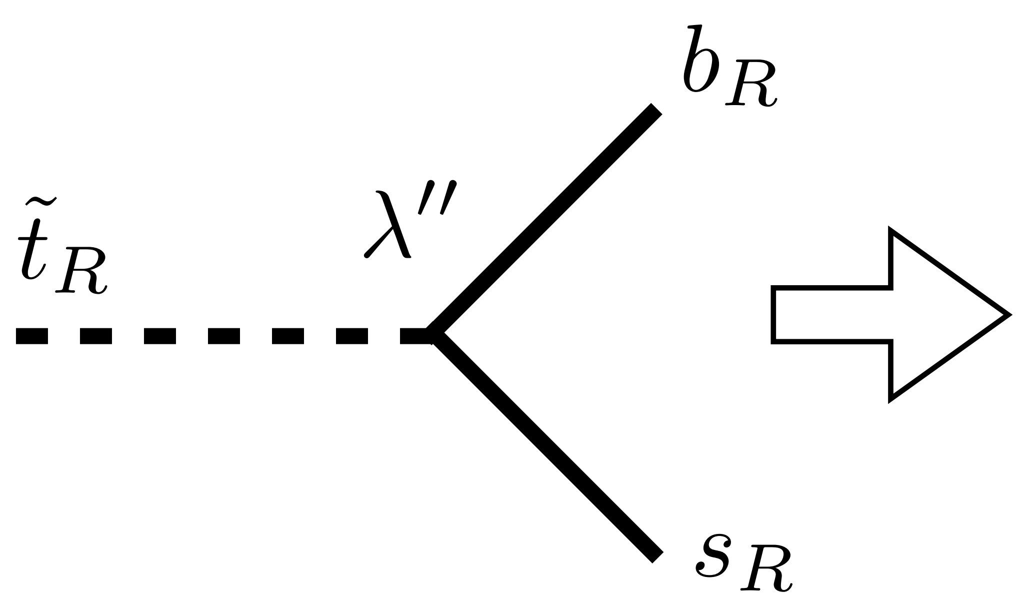
[BB, Lin, Wang '13]

R-Parity Violation provides one of the few mechanisms to hide SUSY

$$W = \lambda L L \bar{e} + \lambda' L Q \bar{d} + \lambda'' \bar{u} \bar{d} \bar{d} + \mu' L H_u$$

RPV allows superpartners to decay back to the SM, dramatically reducing the amount of MET.

e.g. UDD operator leads to interactions such as

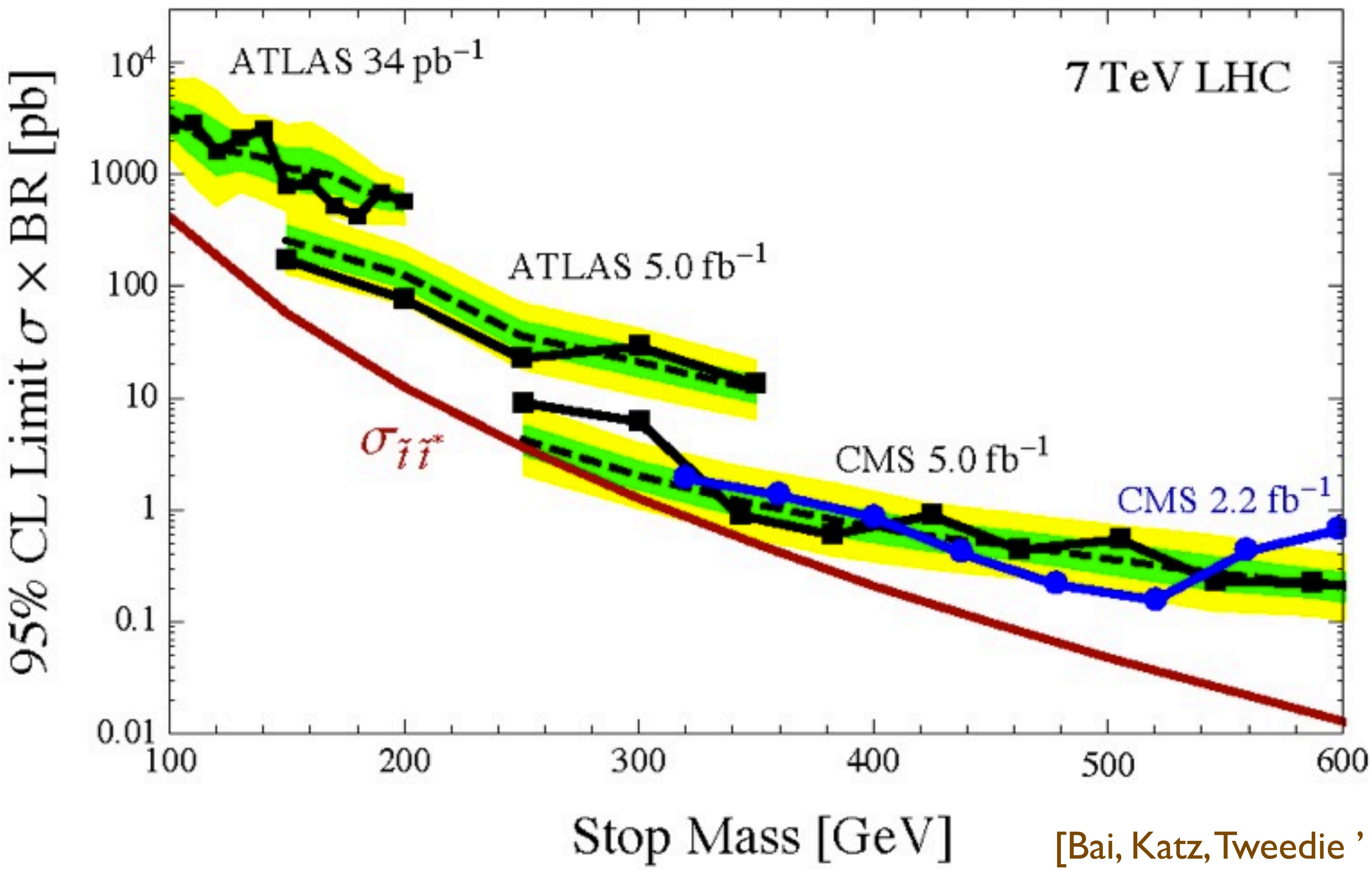


stop decay

$$\tilde{t} \to jj$$

Limits are generally weaker than R-Parity conserving SUSY

Limits on Stop LSP decaying via UDD



[Bai, Katz, Tweedie '13]

Stop can be as light as 100 GeV

But, RPV is a step backwards in two ways:

1. No symmetry understanding of why proton is stable

2. Give up on dark matter and WIMP miracle

Minimal Flavor Violation
can address both of these issues!

MFV SUSY

[Nikolidakis, Smith]
[Csaki, Grossman, Heidenreich]

Basic idea: replace R-parity with MFV

⇨ Most RPV couplings are forbidden!

$$W = \lambda LL\bar{e} + \lambda' LQ\bar{d} + \lambda'' \bar{u}\bar{d}\bar{d} + \mu' LH_u$$

UDD is only term allowed, and it is suppressed by Yukawas and CKM:

$$\lambda'' \sim y^{(u)} y^{(d)} y^{(d)} \, V_{\mathrm{CKM}}$$

This suppresses proton decay to an adequate level

But, still no Dark Matter...

Supersymmetric Flavored Dark Matter

[BB, Lin, Wang '13]

Dark matter chiral superfield X - choose flavor representation + SM quantum numbers (should contain EM neutral component)

The dark matter will be the lightest flavor and can be either the scalar or fermion component

With only dark matter, no renormalizable interactions with SM exist

- Either work in EFT, or introduce mediators Y

$$W = \hat{M}_X \, X \, \overline{X} + \hat{M}_Y \, Y \, \overline{Y} + \hat{\lambda} \, X \, Y \, \Phi_{\rm SM}$$

Dark Matter

Mediator

SM matter field

Example: Top Flavored Dark Matter

Field content
$$X_i \supset (\eta_i, \chi_i) \sim (\mathbf{1}, \mathbf{1}, 0)_{\rm SM} \times (\mathbf{1}, \mathbf{3}, \mathbf{1})_{G_q}\,,$$
$$Y \supset \; (\phi,\, \psi) \; \sim (\mathbf{3}, \mathbf{1}, \tfrac{2}{3})_{\rm SM} \times (\mathbf{1}, \mathbf{1}, \mathbf{1})_{G_q}\,,$$

Superpotential
$$W = \hat{M}_X \, X_i \, \overline{X}^i + \hat{M}_Y \, Y \, \overline{Y} + \hat{\lambda} \, X_i \, Y \, \bar{u}^i .$$

We will take the dark matter candidate to be the top-flavored fermion χ_t

Flavor splittings arise from the Kähler potential as discussed previously

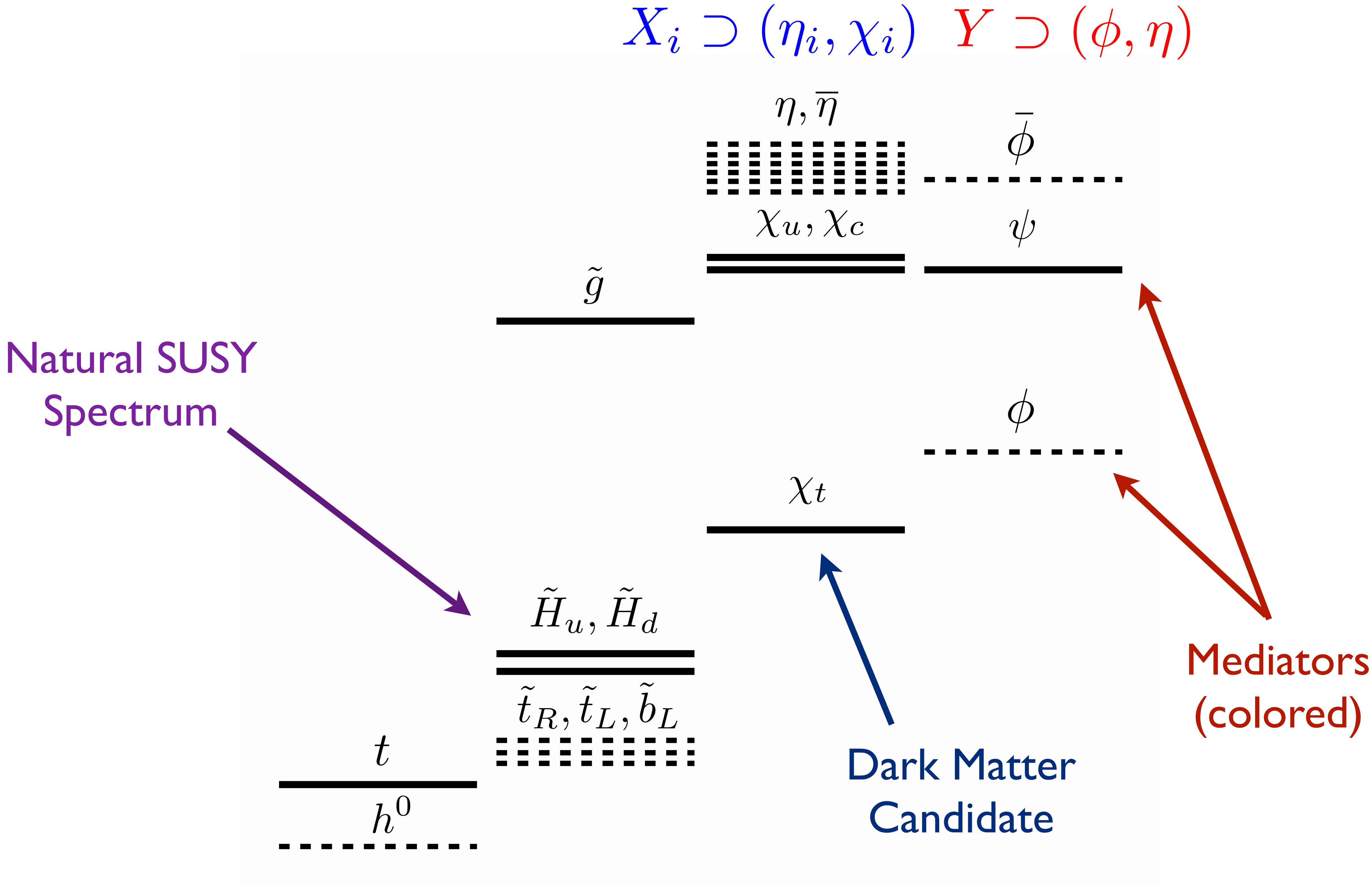
$$\mathcal{M}_\chi = \bar{Z}_X \left(\hat{M}_X + \frac{F}{M} \hat{\mu}_X \right) Z_X \quad \approx {\rm diag} \left(m, m, \frac{m + (F/M)\mu_1 y_t^2}{\sqrt{(1 + k y_t^2)(1 + \bar{k} y_t^2)}} \right),$$

Additional soft scalar mass terms split scalar and fermion components

Interactions of dark matter, mediator, and top, stop:

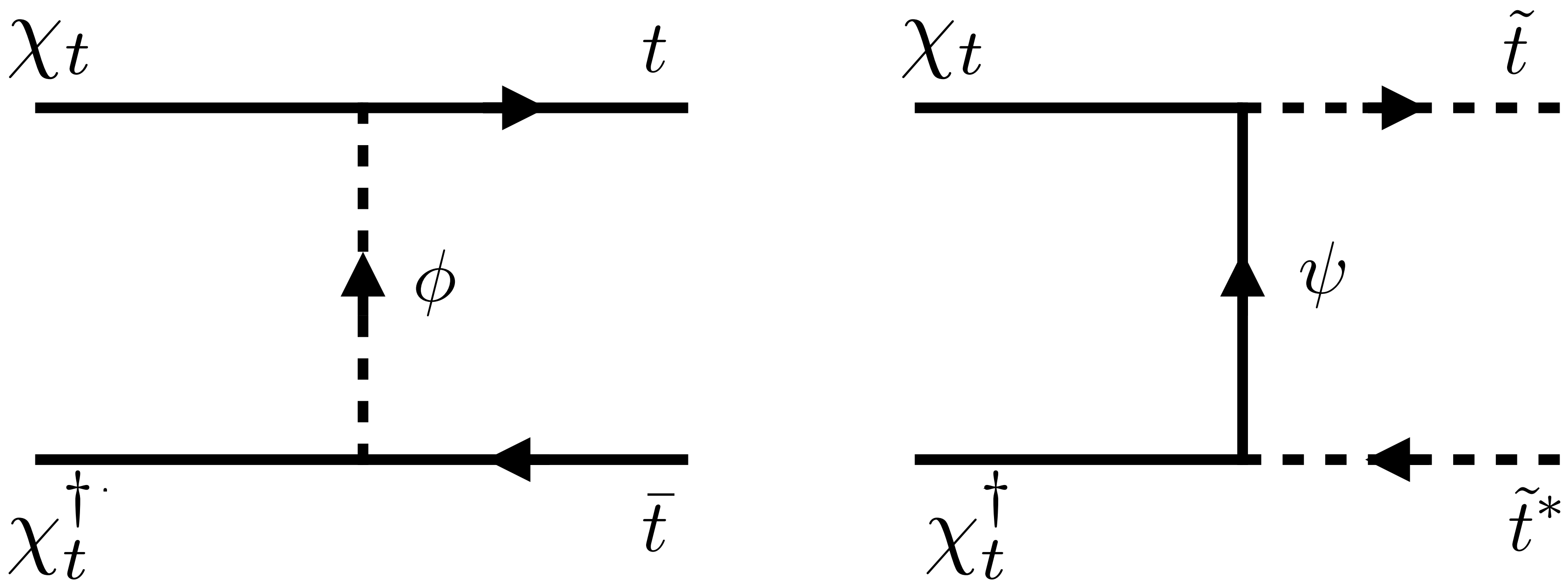
$$-\,\mathcal{L} \supset \lambda_t \, \bar{t}_R \, \chi_t \, \phi + \lambda_t \, \tilde{t}^*_R \, \chi_t \, \psi + {\rm h.c.},$$

Possible spectrum



Cosmology

The top FDM χ_t will dominantly annihilate to tops and stops



For simplicity - assume $m_\psi \gg m_\phi$ so that $t\bar{t}$ dominates

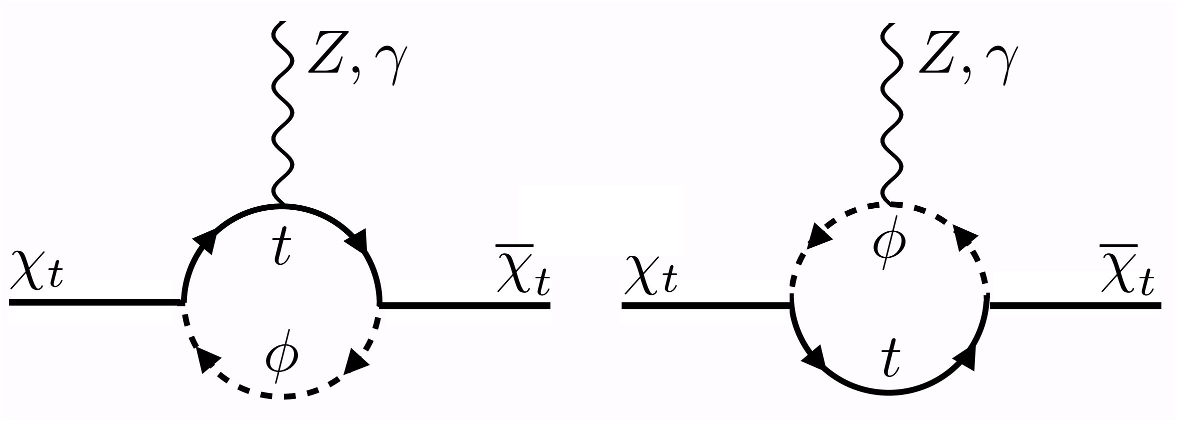
$$\langle \sigma v \rangle_{t\bar{t}} = \frac{N_c \lambda_t^4 m_{\chi_t}^2}{32\pi (m_{\chi_t}^2 + m_\phi^2 - m_t^2)^2} \left(1 - \frac{m_t^2}{m_{\chi_t}^2}\right)^{1/2}$$

$$\approx 1 \text{ pb} \times \lambda_t^2 \left(\frac{m_\chi}{300\text{GeV}}\right)^2 \left(\frac{1\text{TeV}}{m_\phi}\right)^4$$

Direct Detection

The dominant spin-independent interaction comes from loop induced Z-boson exchange

[See also Kumar, Tulin '13]



$$\mathcal{L} \supset g_Z \, Z_\mu \, \overline{\chi}_t \, \gamma^\mu \, P_L \, \chi_t$$

$$g_Z \simeq -\frac{g}{c_w} \frac{\lambda_t^2 N_c}{16\pi^2} \left(\frac{m_t}{m_\phi}\right)^2 \left(1 + \log\left[\frac{m_t^2}{m_\phi^2}\right]\right)$$

Effective WIMP - nucleon SI cross section:

$$\sigma_n \simeq \frac{G_F^2}{2} \left(\frac{\lambda_t^2 N_c}{16\pi^2}\right)^2 \left(\frac{m_t}{m_\phi}\right)^4 \frac{\mu_n^2}{\pi} \left(\frac{A-Z}{A}\right)^2$$

$$\approx 10^{-45}\,\mathrm{cm}^2 \times \lambda_t^4 \left(\frac{\mathrm{TeV}}{m_\phi}\right)^4$$

Being probed now by LUX!

LHC signals of Top FDM

$$W = \lambda \, X_i \, Y \, \bar{u}^i$$

Dark Matter (3 flavors) → X_i

Mediator (colored) → Y

up-type quark (3 flavors) → $\bar{u}^i$

- The mediator Y is colored, so can be directly produced at LHC
- The lightest flavor of X is stable and the Dark Matter
  - This leads to missing energy
- Generic signature is jets + MET

Generic signature of FDM is jets + MET

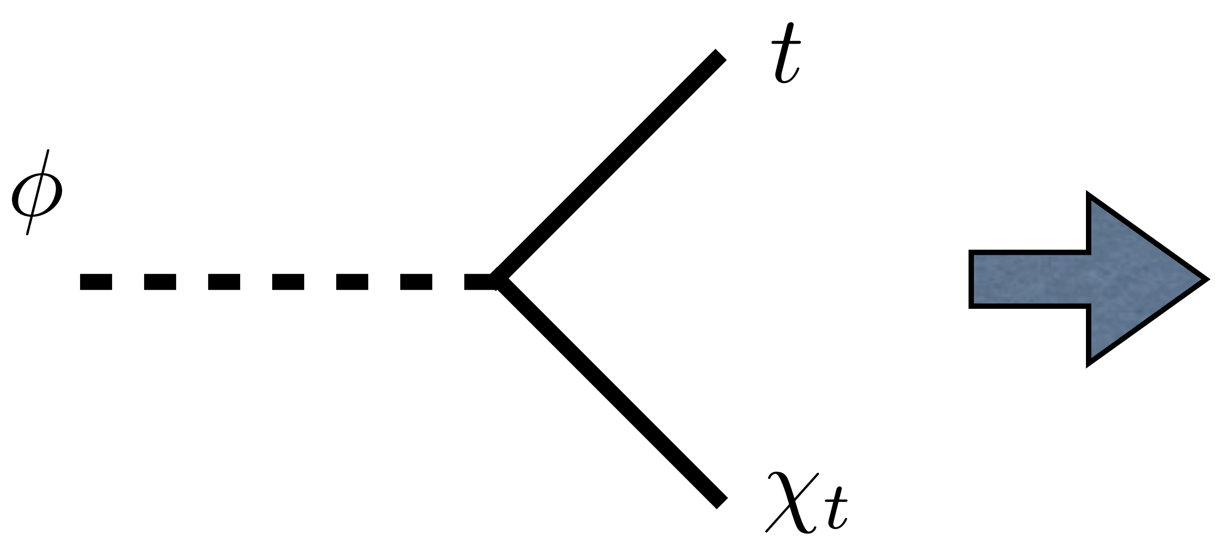
But isn't this why we gave up on R-parity in the first place?

The point is that the mass scale of flavored dark matter is not as strongly tied to naturalness of the MSSM!

- For the top FDM, there is a contribution to the Higgs potential and thus the tuning at two loop - similar to gluino
- Bounds on colored mediators ϕ, ψ are much weaker than gluino
- Suggests that the FDM sector should not be too heavy
- In other models, e.g., bottom FDM, the connection to naturalness would be even weaker

Scalar Mediator : $\phi \subset Y$ "Fake Stop"

$\phi \sim (3, 1, 2/3)$ same quantum numbers as stop



ϕ decay

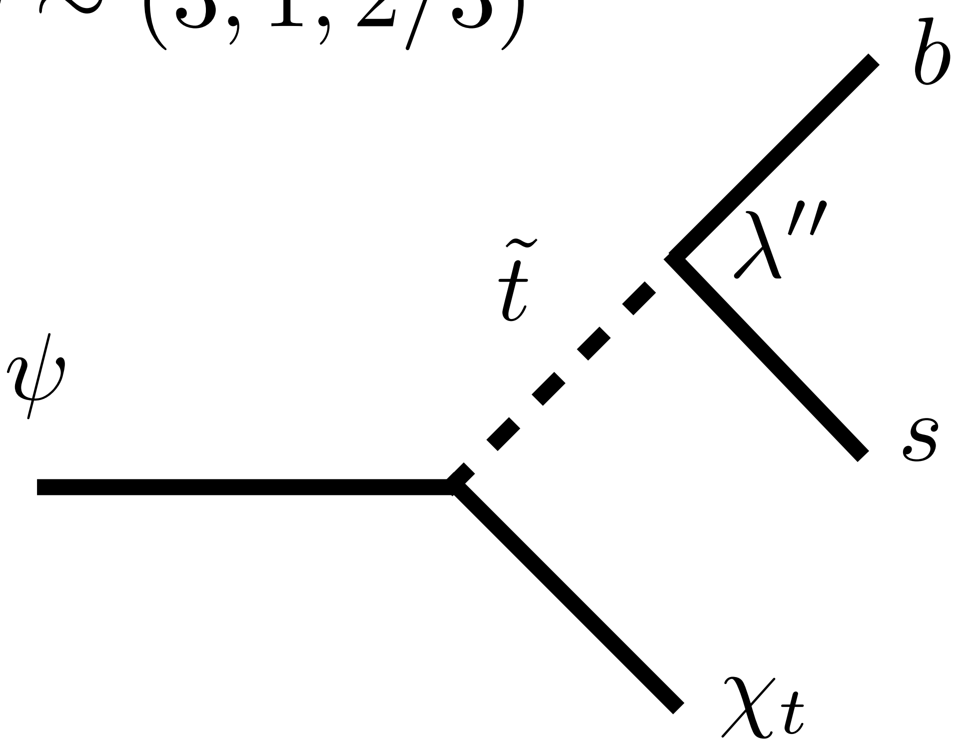
$\phi \to t\bar{\chi}_t$

Looks just like the canonical R-parity conserving stop!

- ϕ pair production leads to ttbar + MET, with the same rate as stops, so we should be able to directly apply existing stop searches
- Can directly apply existing stop searches to this mode
- Conceivable that we could discover a heavy "fake stop" in ttbar +MET as well as the "true stop" paired dijet resonance searches

Fermionic mediator: $\psi \subset Y$

$\psi \sim (3, 1, 2/3)$

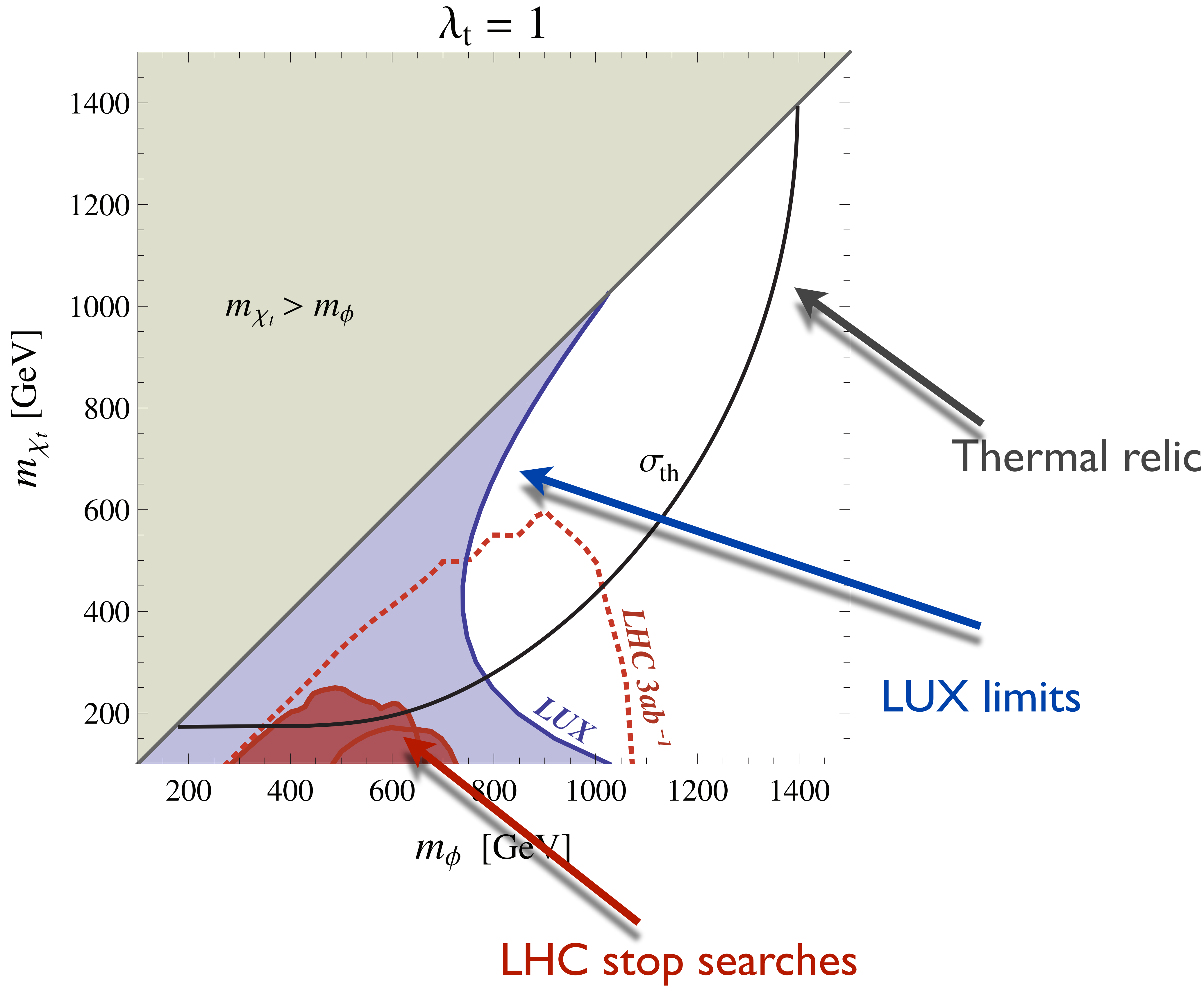


ψ decay

$$\psi \to \tilde{t}\chi_t \to jj + \not{E}_T$$

Similar to gluino

- ψ pair production leads to 4 jets + MET - similar signature to canonical gluino, but with a much lower rate since ψ is a color triplet, whereas the gluino is an octet



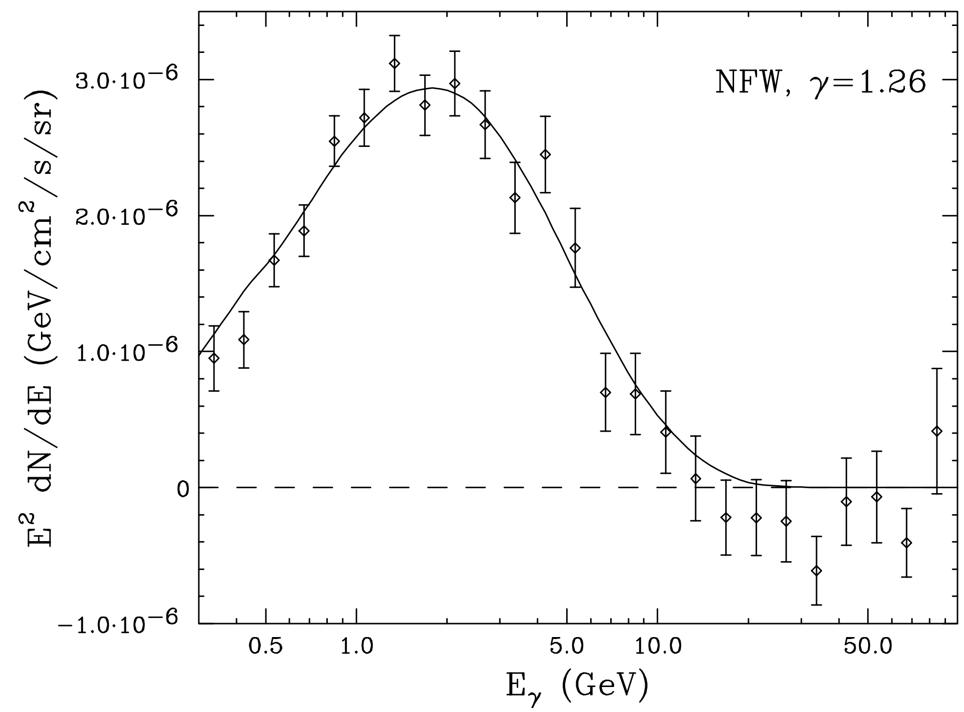
λt = 1
1400
1200
1000
800
600
400
200
200
400
600
800
1000
1200
1400
mχt [GeV]
mϕ [GeV]
mχt > mϕ
σth
LUX
LHC 3ab⁻¹
Thermal relic
LUX limits
LHC stop searches

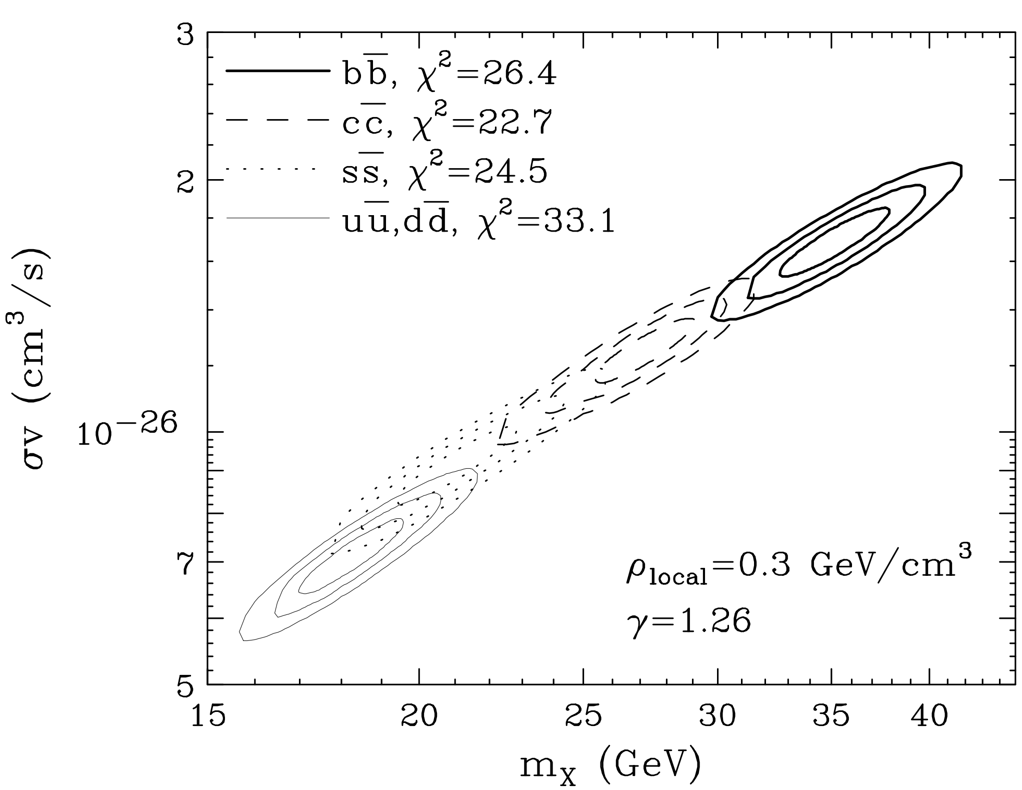
Flavored Dark Matter and the Galactic Center Gamma-Ray Excess

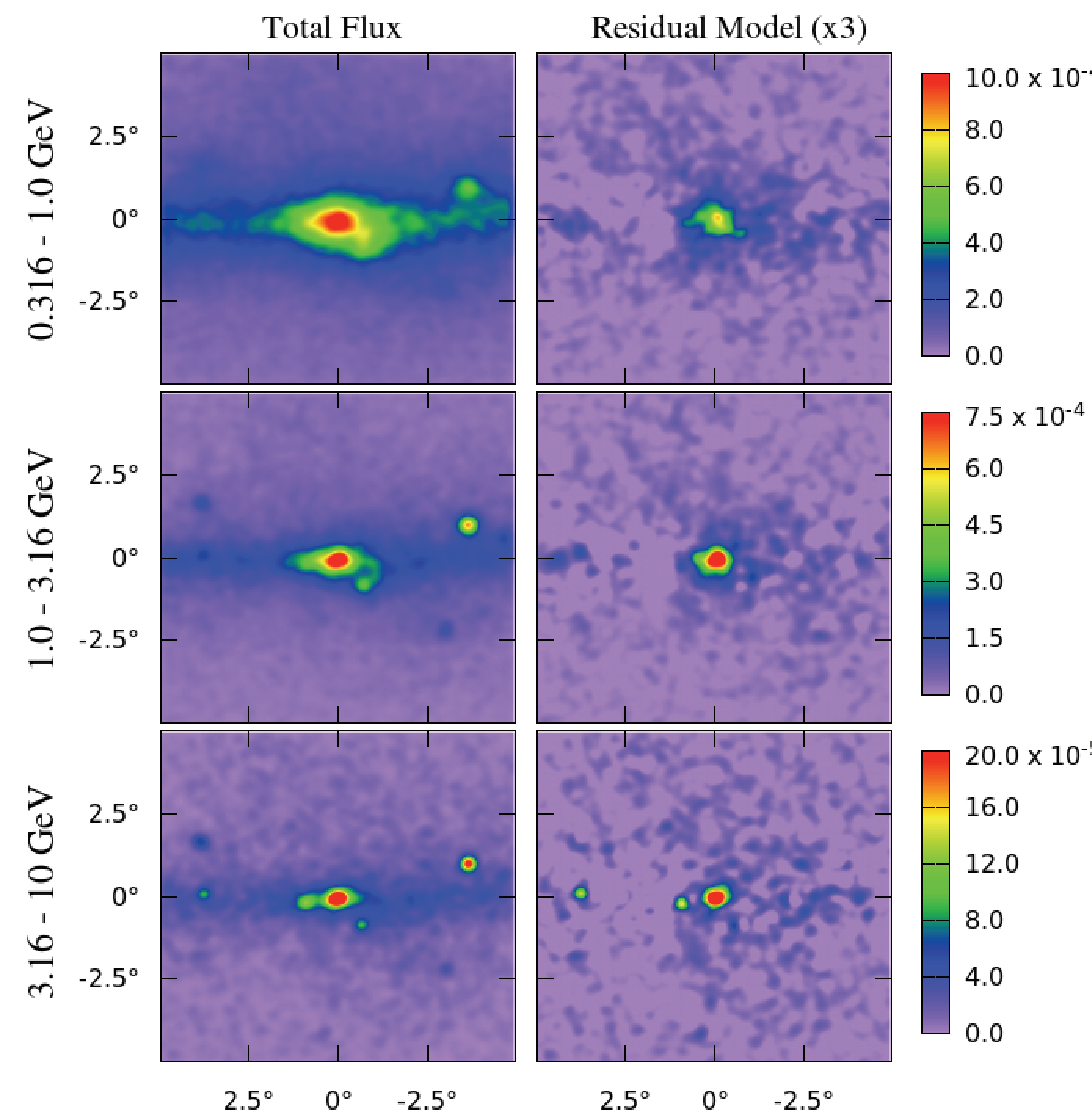
[P. Agrawal, BB, D. Hooper, T. Lin '14]

Gamma Rays from the Galactic Center

Goodenough, Hooper '09
Hooper, Goodenough '10
Hooper, Linden '11
Abazajian, Kaplinghat '12
Hooper, Slatyer '13
Gordon, Macias '13
Huang, Urbano, Xue '13
Abazajian et al, '14
Daylan et al, '14







from Daylan et al, '14

Bottom flavored dark matter

$$\mathcal{L} = [m_\chi]_{ij}\,\chi_i\,\chi_j^c + \lambda_{ij}\,\chi_i\,d_j^c\,\phi + \text{h.c.}$$

Take the dark matter candidate to be the bottom-flavored χ_b

Two possible options:

1) χ is a triplet under $SU(3)_d$

$$\lambda = \lambda_0 \mathbf{1} + \beta y_d^\dagger y_d + \ldots$$

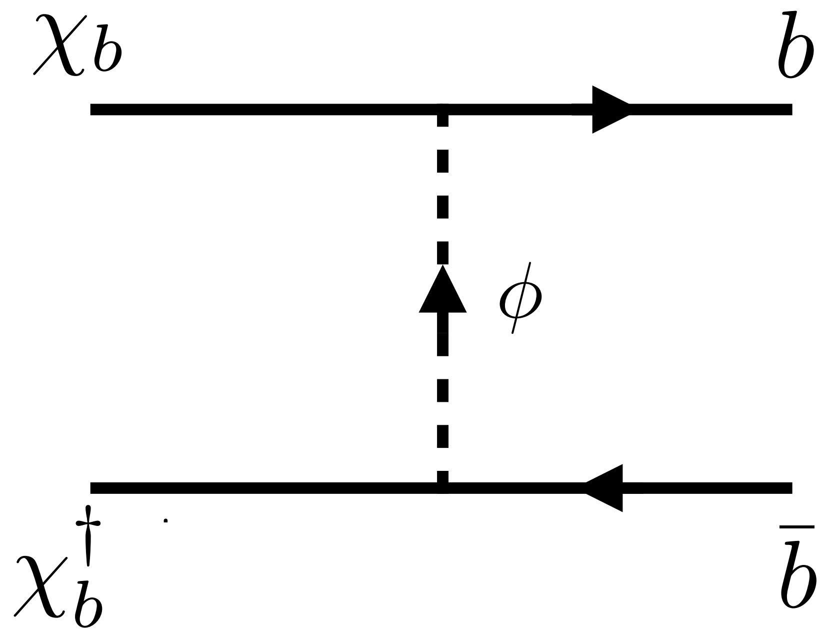
→ Sizable couplings to all dark flavors

2) χ is a triplet under $SU(3)_Q$

$$\lambda = \lambda_0 y_d + \ldots$$

→ hierarchical couplings
χ_b has largest coupling

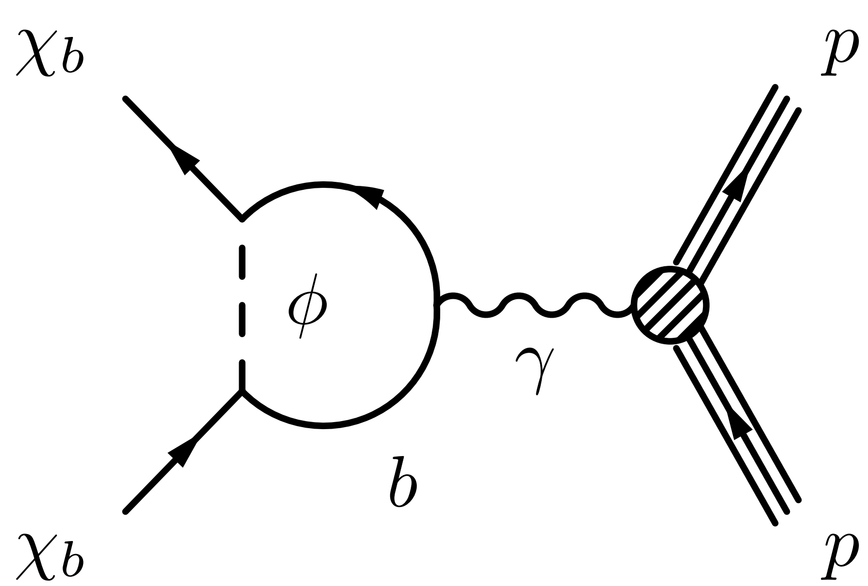
Annihilation to bottom quarks



$$\sigma v = \frac{3\lambda_b^4 m_{\chi_b}^2 \sqrt{1 - m_b^2/m_{\chi_b}^2}}{32\pi(m_{\chi_b}^2 + m_\phi^2)^2} \times [1 + O(v^2)]$$

$$\approx 4.4 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s} \left(\frac{\lambda_b}{2.16}\right)^4 \left(\frac{m_{\chi_b}}{40\,\mathrm{GeV}}\right)^2 \left(\frac{725\,\mathrm{GeV}}{m_\phi}\right)^4$$

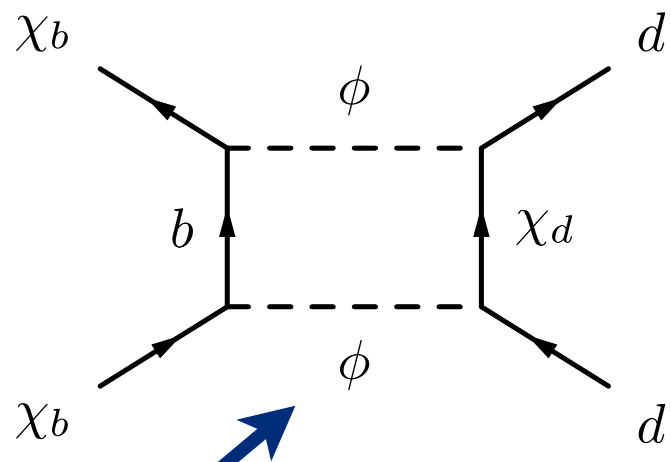
Direct Detection

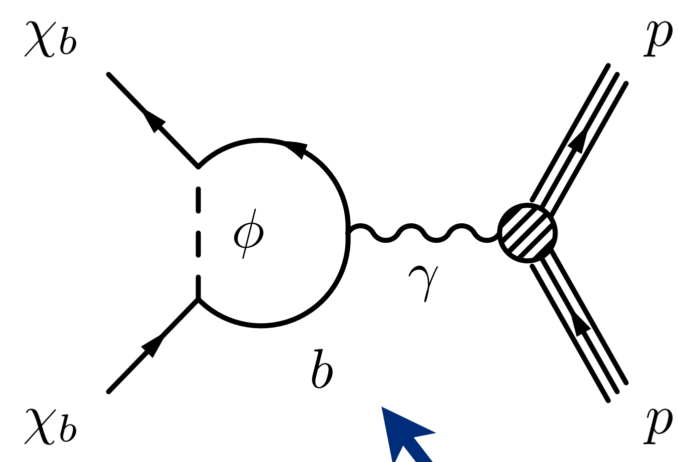


$$\sigma_n \approx 1.1 \times 10^{-45}\,\mathrm{cm}^2 \times \left(\frac{\lambda_b}{2.16}\right)^4 \left(\frac{725\,\mathrm{GeV}}{m_\phi}\right)^4 .$$

Being probed now by LUX!

Direct Detection

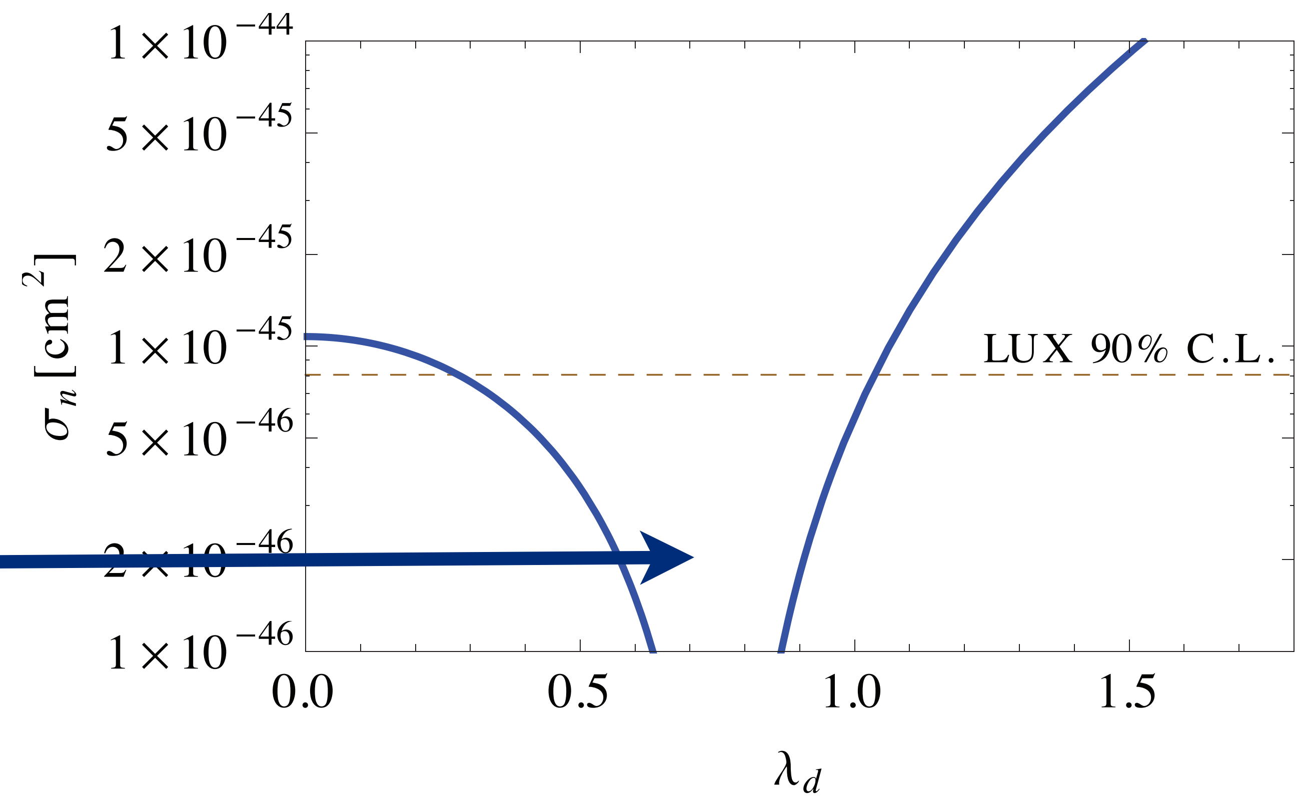




Important if $\chi \sim \mathbf{3}_d$

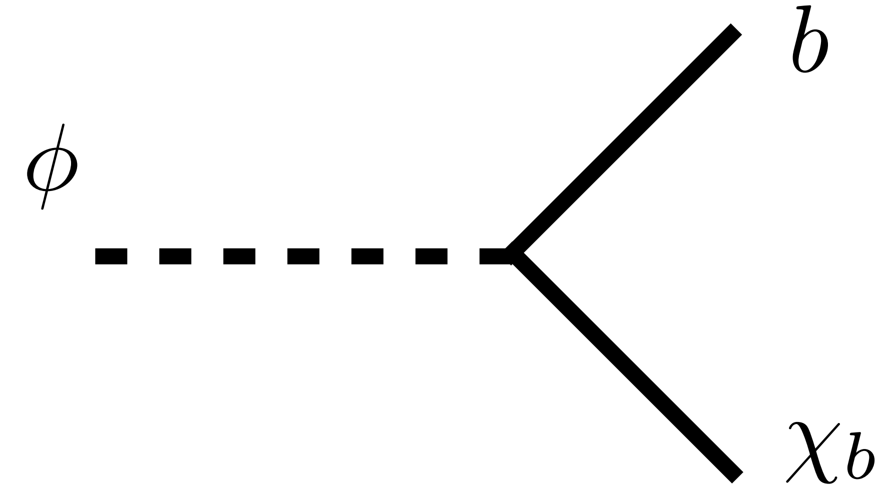
Always important

Destructive interference



LHC signatures

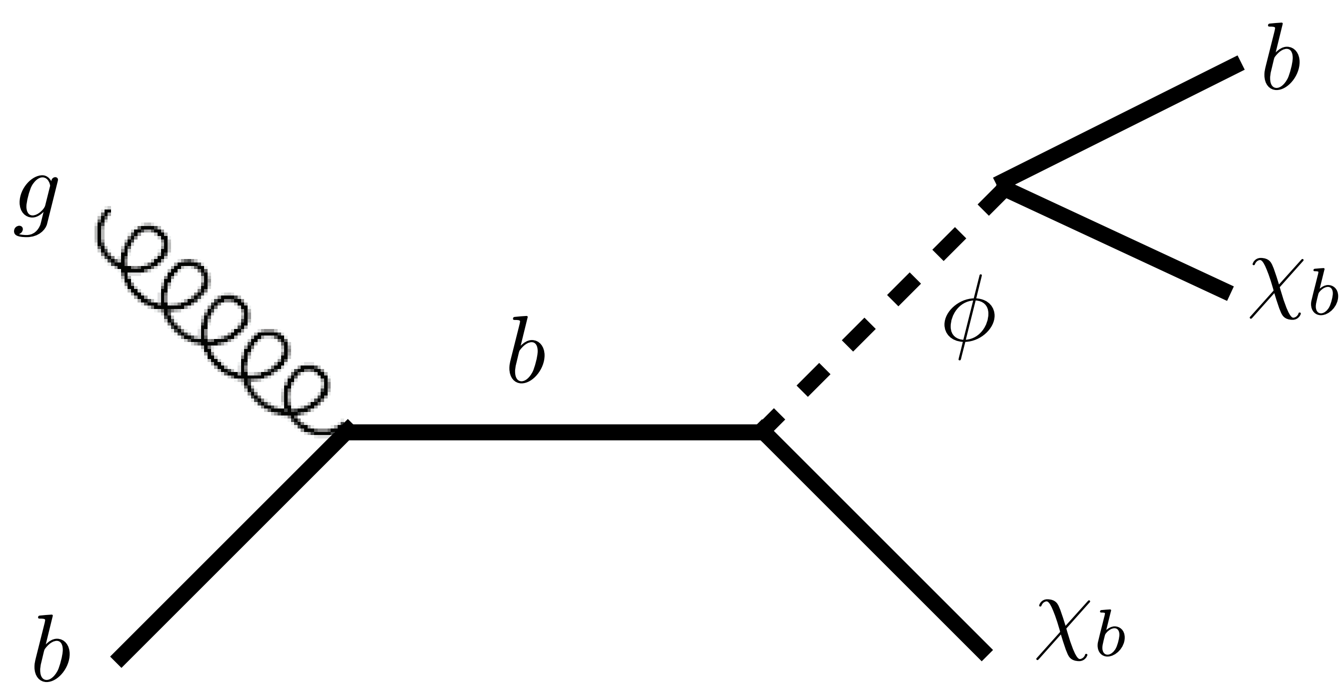
- Scalar mediator ϕ is similar to "sbottom" in SUSY

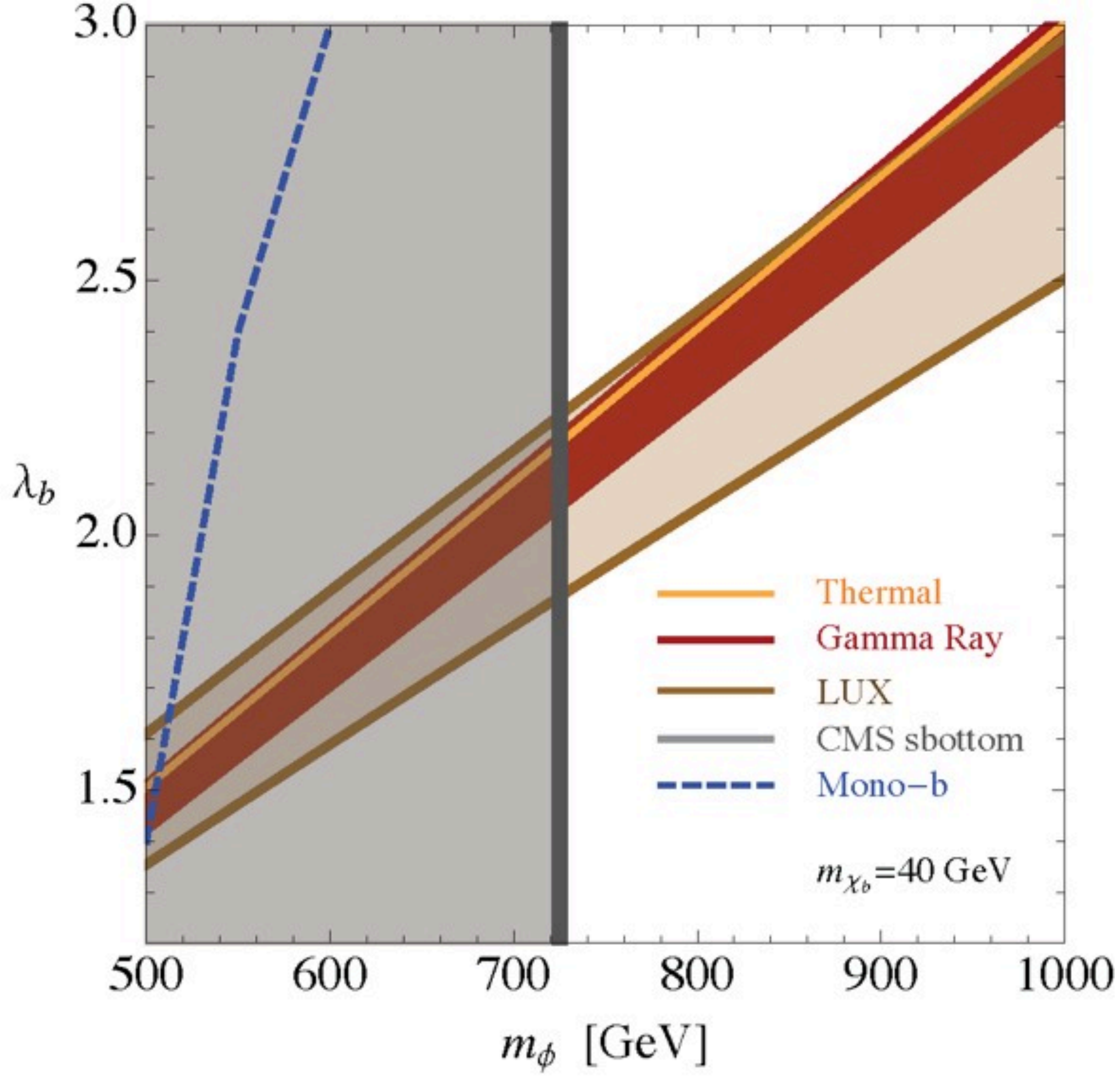


- CMS sbottom limit: $m_\phi > 725\,\mathrm{GeV}$

[CMS-SUS13018]

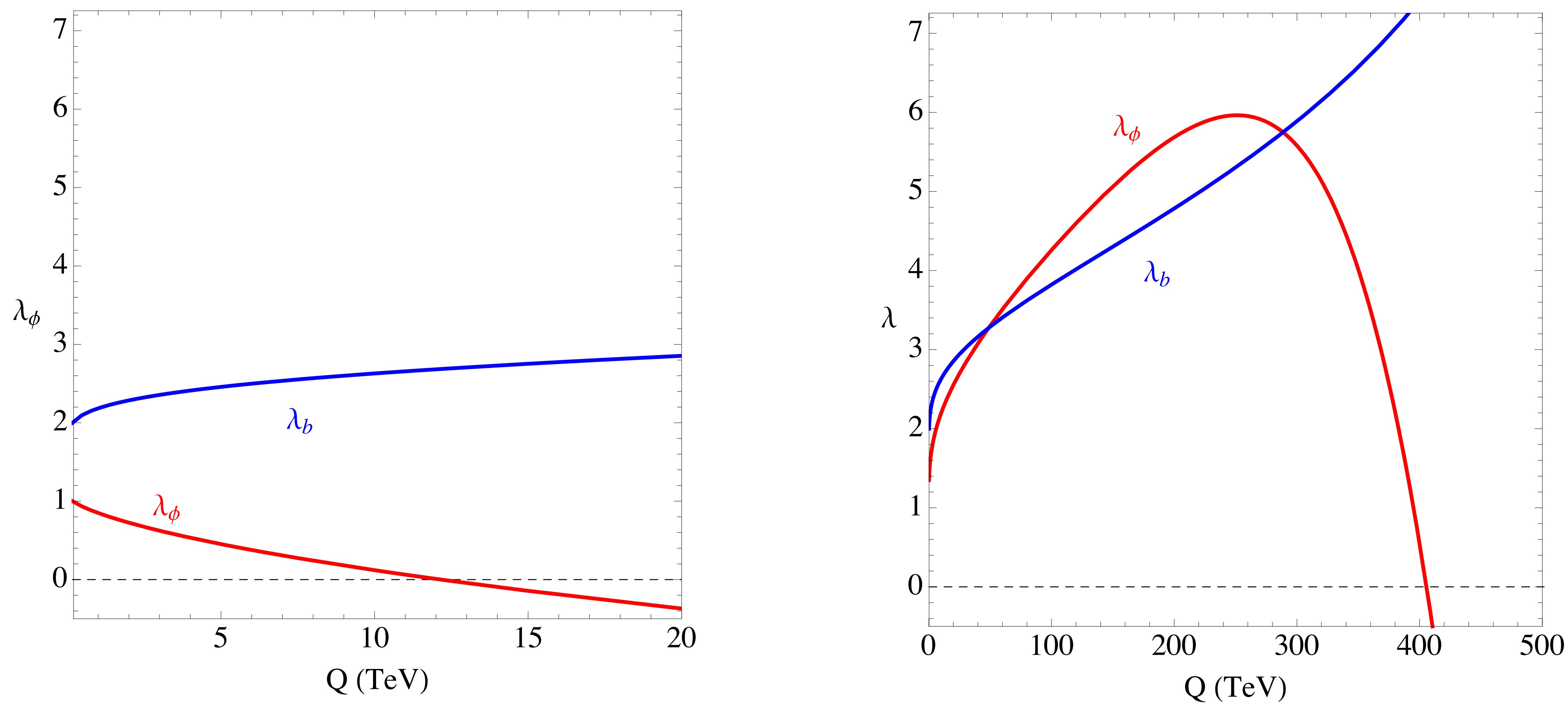
- There is also a mono-b signature - can be used to distinguish from SUSY





3.0
2.5
2.0
1.5
λ_b
500
600
700
800
900
1000
m_ϕ [GeV]
Thermal
Gamma Ray
LUX
CMS sbottom
Mono−b
m_{χ_b}=40 GeV

Vacuum Stability



- Large Yukawa coupling tends to drive scalar quartic negative
- Theory needs UV completion below ~ O(100 TeV) , e.g., SUSY FDM
- LHC will test entire range of perturbative couplings

Outlook

- Flavor symmetries and MFV provide a rationale for Dark Matter
- Dark matter stability is ensured by Flavor Triality
- Rich phenomenology & cosmology
- Many Flavored Dark Matter models are possible; a systematic investigation should be carried out.