Heavy Quark Flavored Scalar Dark Matter

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based on arXiv: 1606.00072 and 1709.00697

Scalars 2017
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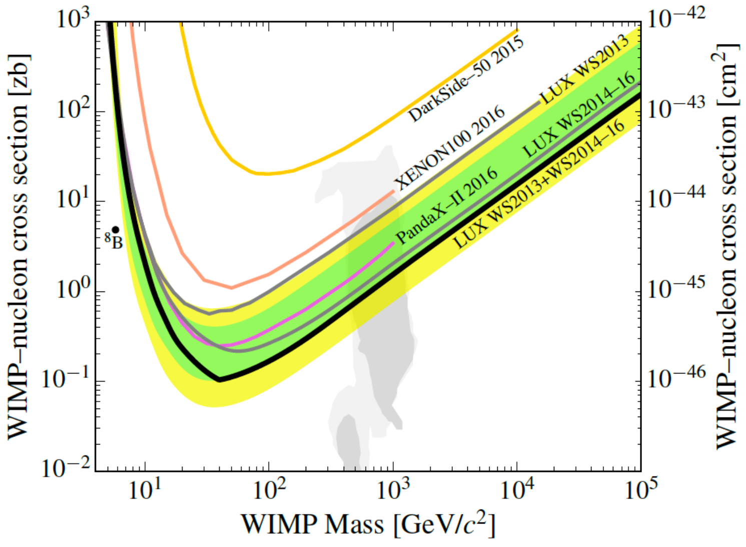
Outline

- Motivation: Why heavy quark flavored DM?
- Model description
- Properties:
  - Direct detection, RGE effects
  - Indirect detection
  - Thermal relic abundance
  - Top FCNC
  - Collider Signals
- Summary

Why Flavored DM?

[LUX, 1608.07648]

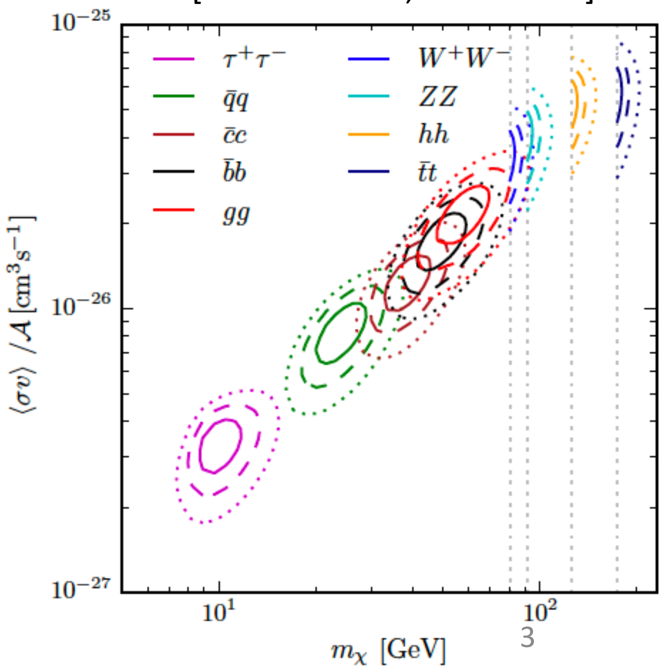


- No confirmed DD signal yet
  - small/vanishing ***direct*** coupling of DM to u/d quarks

- Favored channels when fitting astro- anomalies
  - $b\bar{b}, \tau\tau$ are favored, up to astro- uncertainties

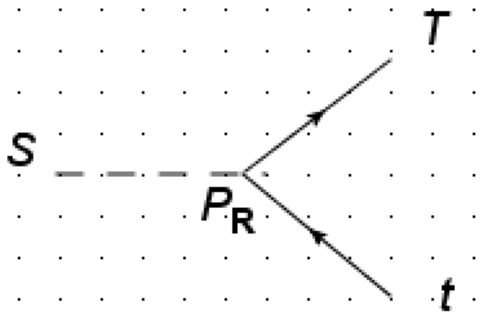
[see Hooper et al]

[F. Calore et al, 1411.4647]



- Theoretical model building [see Agrawal, Kilic et al]
  - flavor symmetry in dark sector, MFV…

Top-flavored DM



- DM: real scalar S
  - SM singlet, couple only to t_R
- Vector-like (VL) fermion T
  - (T, t_R) same quantum number
  - no chiral anomaly
- Z_2 parity to stabilize DM: S, T are odd
  - no mass mixing $(S, H), (T, t)$
  - $Br\left(T \to St^{(*)}\right) = 100\%$
  - LHC searches for VL (T, B) do not apply

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_S + \mathcal{L}_T + \mathcal{L}_Y$$

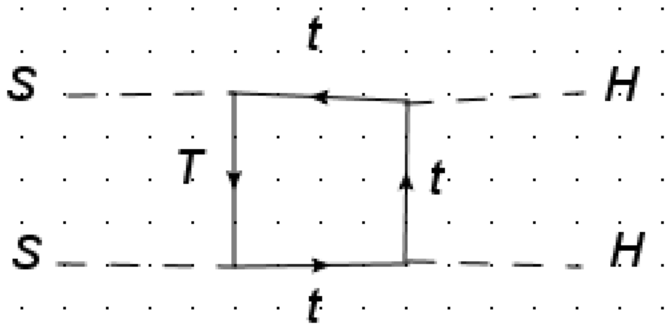
$$\mathcal{L}_Y = -(y_{ST} S \bar{T} t_R + h.c.)$$

$$\mathcal{L}_S = \frac{1}{2}\left(\partial_\mu S\right)^2 - \frac{1}{2} m_S^2 S^2$$

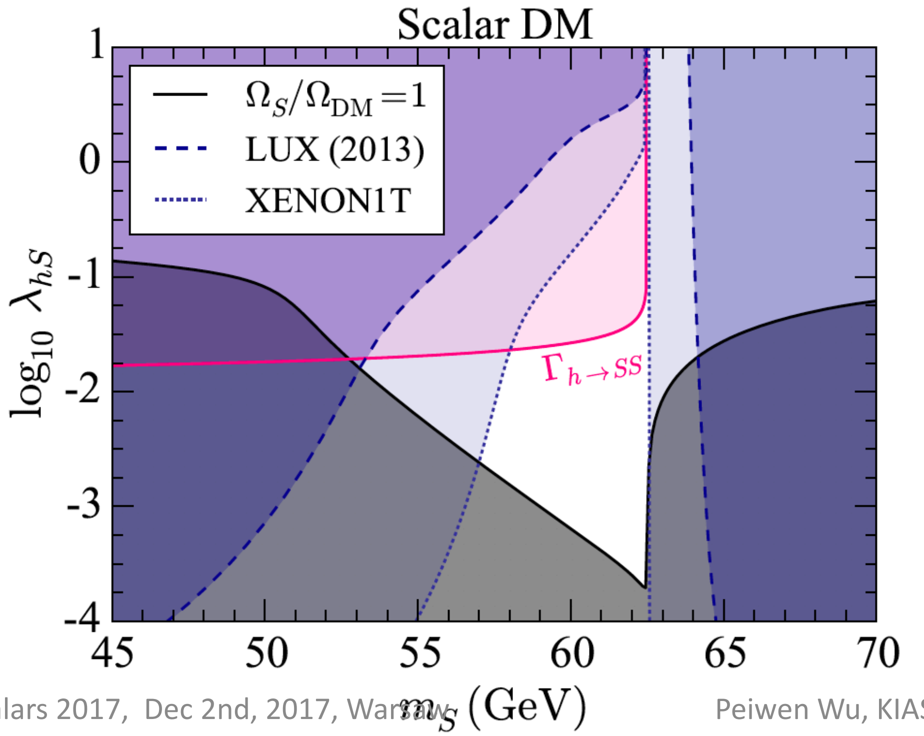
$$\mathcal{L}_T = \bar{T}(i\not{D} - m_T)T$$

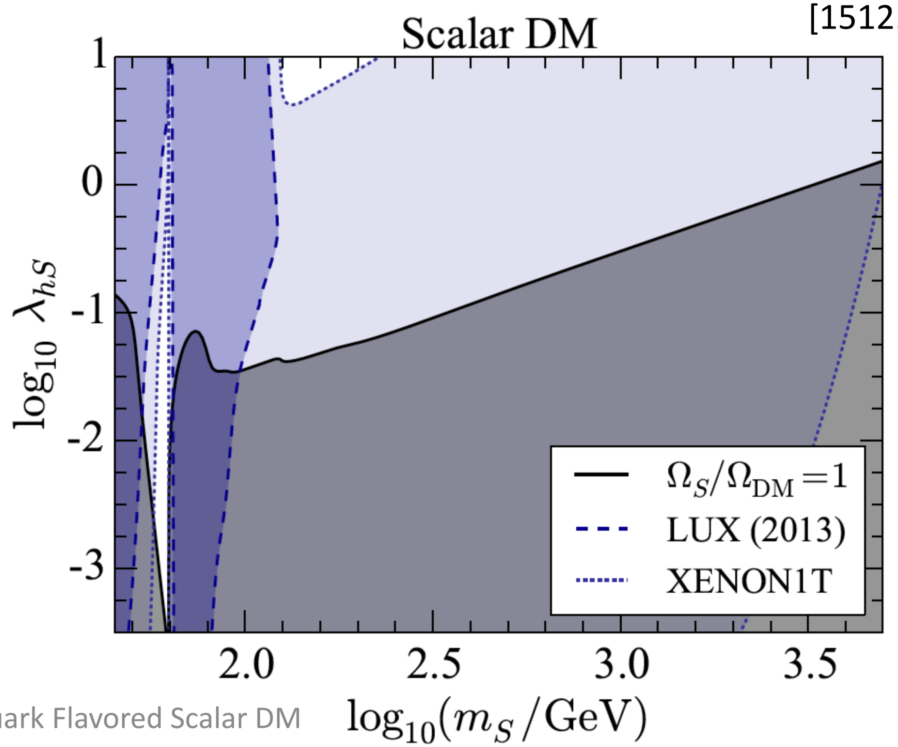
Higgs portal set to be negligible

- generated via tree/loop
- strongly constrained by current experiments
- We set $\lambda_{SH}^{ren.}(\mu_{EFT} = m_Z) = 0$ in this work

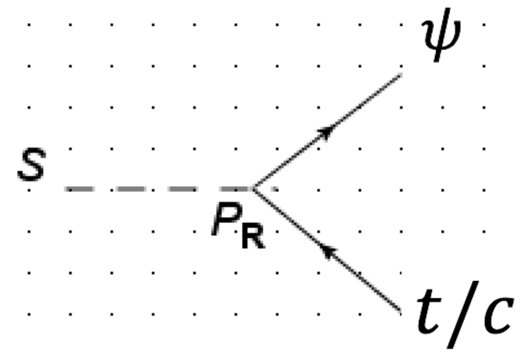


[1512.06458, Beniwal *et al*]





Top + Charm Flavored



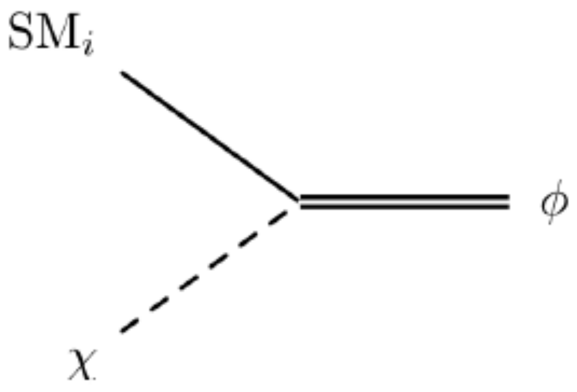
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_S + \mathcal{L}_\psi + \mathcal{L}_Y$$

$$\mathcal{L}_Y = -(y_3 S\bar{\psi}t_R + y_2 S\bar{\psi}c_R + h.c.)$$

$$\mathcal{L}_S = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2$$

$$\mathcal{L}_\psi = \bar{\psi}(i\not{D} - m_\psi)\psi$$

Realization in M(inimal) F(lavor) V(iolation)



[arXiv: 1109.3516 Can Kilic *et al*]

- U_R-flavored DM: $\mathcal{L} \supset U^i [\lambda]_i{}^j (DM)_j (med.)$
- expansion of $\lambda_i{}^j, m_{DM}$ in terms of SM Yukawa Y
- $U(3)_{DM} = U(3)_U$
  - $[\lambda]_i{}^j = (\alpha_U \cdot 1 + \beta_U\, Y_u^+ Y_u\,)_i{}^j,\quad [m_{DM}]_i{}^j = (m_{0,U} \cdot 1 + \Delta m_U\, Y_u^+ Y_u\,)_i{}^j$
- $U(3)_{DM} = U(3)_D$
  - $[\lambda]_i{}^j = \beta_D\,(Y_d^+ Y_u\,)_i{}^j,\quad [m_{DM}]_i{}^j = (m_{0,D} \cdot 1 + \Delta m_D\, Y_d^+ Y_u\,)_i{}^j$
- $U(3)_{DM} = U(3)_Q$
  - $[\lambda]_i{}^j = \beta_Q\,(Y_u)_i{}^j,\quad [m_{DM}]_i{}^j = (m_{0,Q} \cdot 1 + \Delta m_{Qu}\, Y_u Y_u^+ + \Delta m_{Qd}\, Y_d Y_d^+)_i{}^j$

Direct Detection : EFT

[Hisano et al, 1502.02244]

- $\mu_{EFT} \sim m_Z$ $\quad \mathcal{L}_{\text{eff}} = \sum_{p=q,g} C_S^p \mathcal{O}_S^p,$ $\quad \mathcal{O}_S^q \equiv \phi^2 m_q \bar{q} q\ ,\quad \mathcal{O}_S^g \equiv \frac{\alpha_s}{\pi} \phi^2 G^{A\mu\nu} G^A_{\mu\nu}$
- RGE

$$C_{\rm S}^q(\mu) = C_{\rm S}^q(\mu_0) - 4C_{\rm S}^G(\mu_0)\frac{\alpha_s^2(\mu_0)}{\beta(\alpha_s(\mu_0))}(\gamma_m(\mu) - \gamma_m(\mu_0))\ ,$$

$$C_{\rm S}^G(\mu) = \frac{\beta(\alpha_s(\mu))}{\alpha_s^2(\mu)}\frac{\alpha_s^2(\mu_0)}{\beta(\alpha_s(\mu_0))}C_{\rm S}^G(\mu_0)\ .$$

- Quark thresholds

$$C_{\rm S}^q(\mu_b)|_{N_f=4} = C_{\rm S}^q(\mu_b)|_{N_f=5}\ ,$$

$$C_{\rm S}^G(\mu_b)|_{N_f=4} = -\frac{1}{12}\left[1 + \frac{11}{4\pi}\alpha_s(\mu_b)\right] C_{\rm S}^b(\mu_b)|_{N_f=5} + C_{\rm S}^G(\mu_b)|_{N_f=5}$$

- $\mu_{QCD} \sim 1$ GeV

$$\mathcal{L}_{\rm SI}^{(N)} = f_N \phi^2 \overline{N} N\ ,\quad \sigma = \frac{1}{\pi}\left(\frac{M_T}{M + M_T}\right)^2 |n_p f_p + n_n f_n|^2$$

Direct Detection : EFT

[Hisano et al, 1502.02244]

top: integrated -> $\phi^2 G^2$
charm: active d.o.f
no contribution to $\phi^2 G^2$?

- $\mu_{EFT} \sim m_Z$

$$\mathcal{L}_{\rm eff} = \sum_{p=q,g} C_S^p \mathcal{O}_S^p, \quad \mathcal{O}_S^q \equiv \phi^2 m_q \bar{q} q \ , \quad \mathcal{O}_S^g \equiv \frac{\alpha_s}{\pi} \phi^2 G^{A\mu\nu} G^A_{\mu\nu}$$

- RGE

$$C_{\rm S}^q(\mu) = C_{\rm S}^q(\mu_0) - 4C_{\rm S}^G(\mu_0)\frac{\alpha_s^2(\mu_0)}{\beta(\alpha_s(\mu_0))}(\gamma_m(\mu) - \gamma_m(\mu_0)) \ ,$$

$$C_{\rm S}^G(\mu) = \frac{\beta(\alpha_s(\mu))}{\alpha_s^2(\mu)} \frac{\alpha_s^2(\mu_0)}{\beta(\alpha_s(\mu_0))} C_{\rm S}^G(\mu_0) \ .$$

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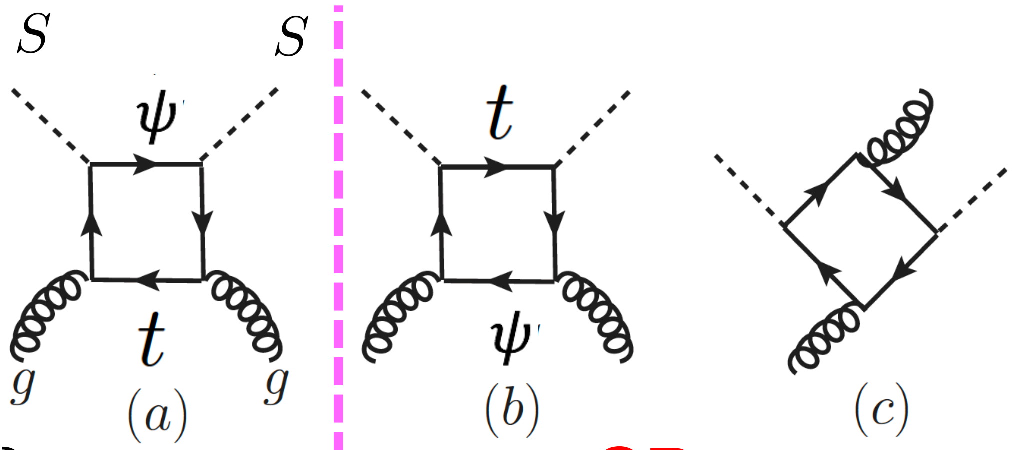
$$\mathcal{L}_{\rm SI}^{(N)} = f_N \phi^2 \overline{N} N \ , \quad \sigma = \frac{1}{\pi}\left(\frac{M_T}{M+M_T}\right)^2 |n_p f_p + n_n f_n|^2$$

Loop momentum: SD & LD



LD~m_t SD~m_ψ

- SD: $q \sim m_{mediator}$ LD: $q \sim m_{Q=\{c,b,t\}}$
- top, fully integrated out, generates $\{O_S^g\}$
- charm, active *d.o.f*, generates $\{O_S^g, O_S^c\}$

LD~$m_t > m_Z$ SD SD ~m_ψ

$$C_S^g|_t = \left(\frac{1}{4}\frac{y_3^2}{2}\right)\left(f_+^{(a)} + f_+^{(b)} + f_+^{(c)}\right)(m_S; m_t, m_\psi)$$

SD SD

$$C_S^g|_c = \left(\frac{1}{4}\frac{y_2^2}{2}\right)\left(f_+^{(b)} + f_+^{(c)}\right)(m_S; m_c, m_\psi)$$

LD~$m_c < m_Z$

$$C_S^c = \Big(-12\Big)\left(\frac{1}{4}\frac{y_2^2}{2}\right) f_+^{(a)}(m_S; m_c, m_\psi).$$

$$-\frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\mu\nu} \to m_Q \bar{Q} Q$$

$$f_Q = (-12) f_G \Big|_Q^{LD}$$

RGE

top loop -> $\{O_S^g\}$
charm loop -> $\{O_S^g, O_S^c\}$

- $\mu_{EFT} \sim m_Z$
  - top, fully integrated out, generates $\{O_S^g\}$
  - charm, active *d.o.f*, generates $\{O_S^g, O_S^c\}$
- RGE evolution: $\{O_S^g, O_S^c\}$ are different

$$C_S^q(\mu) = C_S^q(\mu_0) - 4C_S^G(\mu_0)\frac{\alpha_s^2(\mu_0)}{\beta(\alpha_s(\mu_0))}(\gamma_m(\mu) - \gamma_m(\mu_0)) \, ,$$

$$C_S^G(\mu) = \frac{\beta(\alpha_s(\mu))}{\alpha_s^2(\mu)}\frac{\alpha_s^2(\mu_0)}{\beta(\alpha_s(\mu_0))}C_S^G(\mu_0) \, .$$

- reaching charm threshold, O_S^c is absorbed into O_S^g

$\mu \sim m_Z$

$\mu \sim m_c$

Direct Detection: RGE effects

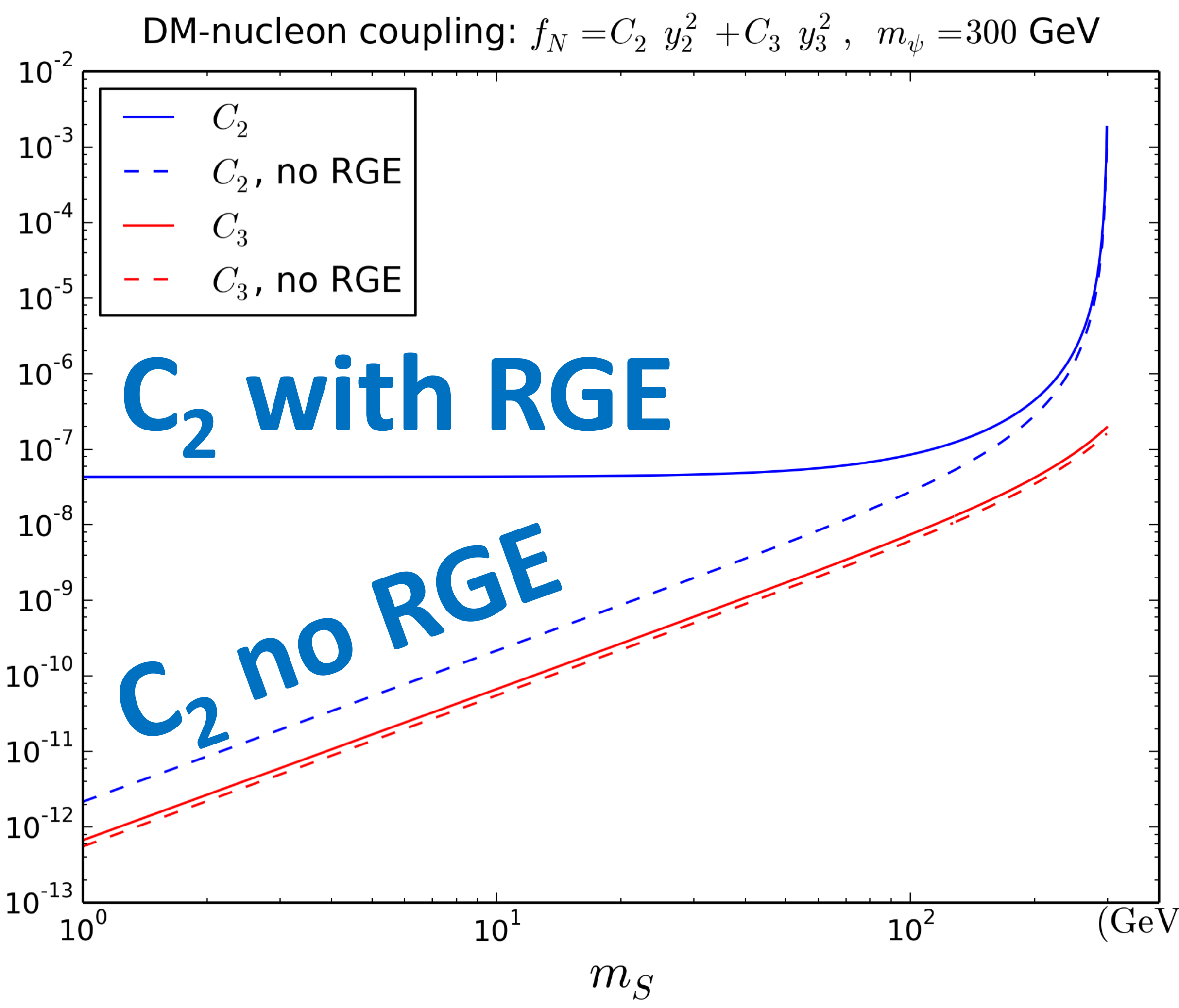
$$\mathcal{L}_{SI}^{(N)} = f_N S^2 \overline{N} N \ , \ f_N = C_2 \, y_2^2 + C_3 \, y_3^2$$

f_N : DM-nucleon coupling @ 1 GeV

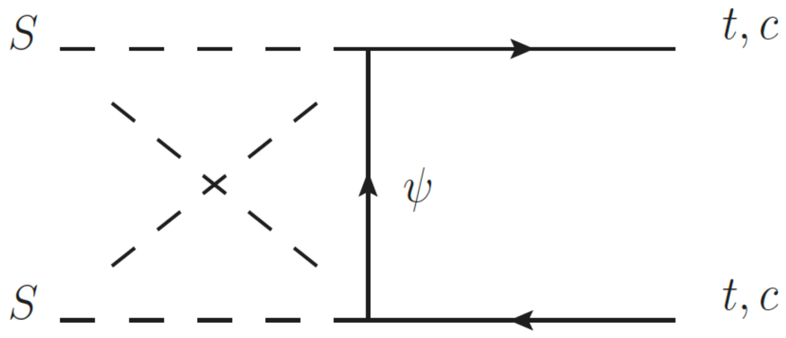
when $m_S \rightarrow 0$

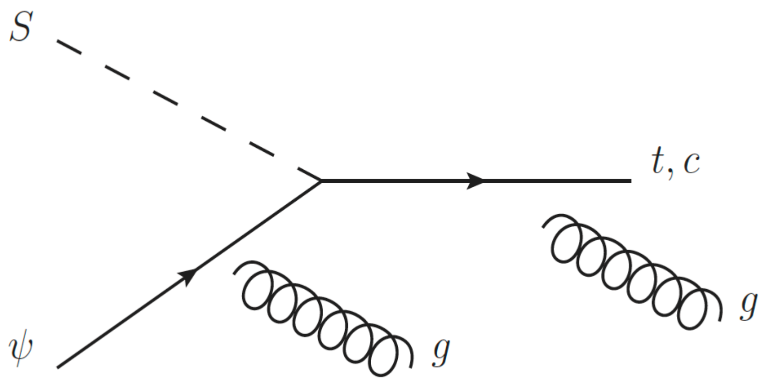
- w/o RGE, $C_{2,3} \propto \frac{m_S^2}{m_\psi^2} \rightarrow 0$
- **w/** RGE, $C_2 \rightarrow$ **constant**, $C_3 \rightarrow 0$

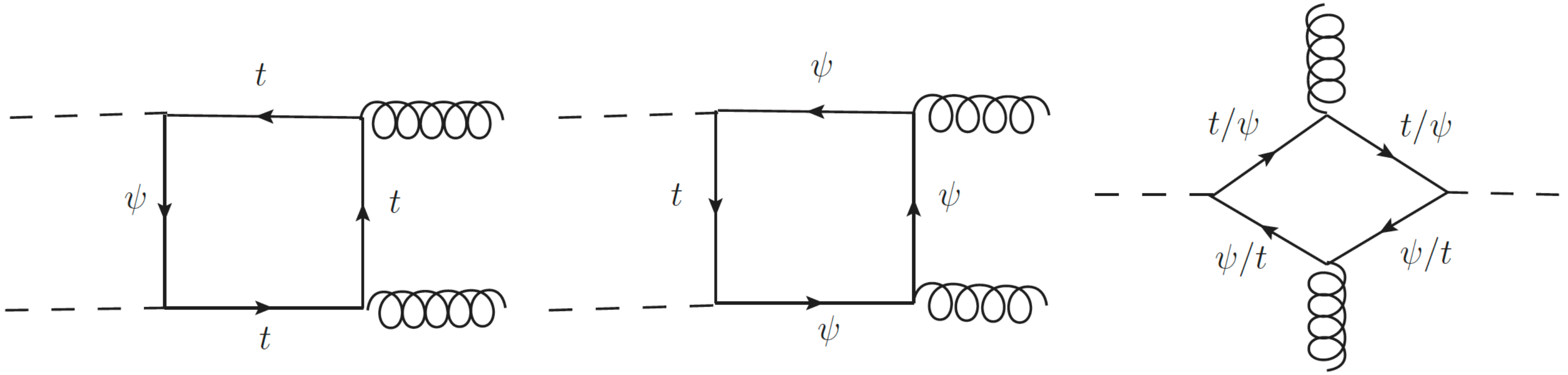
- $C_2 \gg C_3$, charm contribution dominates



Thermal Relic / Indirect Detection



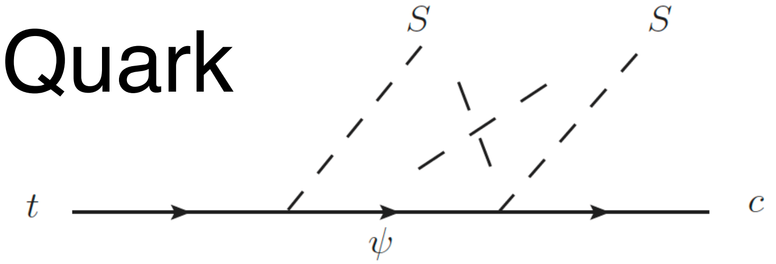


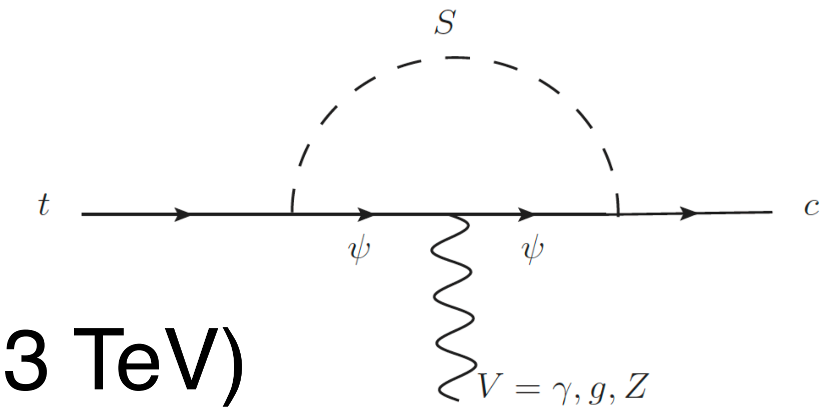


(a) (b) (c)

[arXiv: 1502.02244, J. Hisano *et al*]

- FCNC of Top Quark





- Collider search (ATLAS 36 fb^{-1} @ 13 TeV)
  $pp \to \psi\bar{\psi} \to t\bar{t}/c\bar{c} + MET$

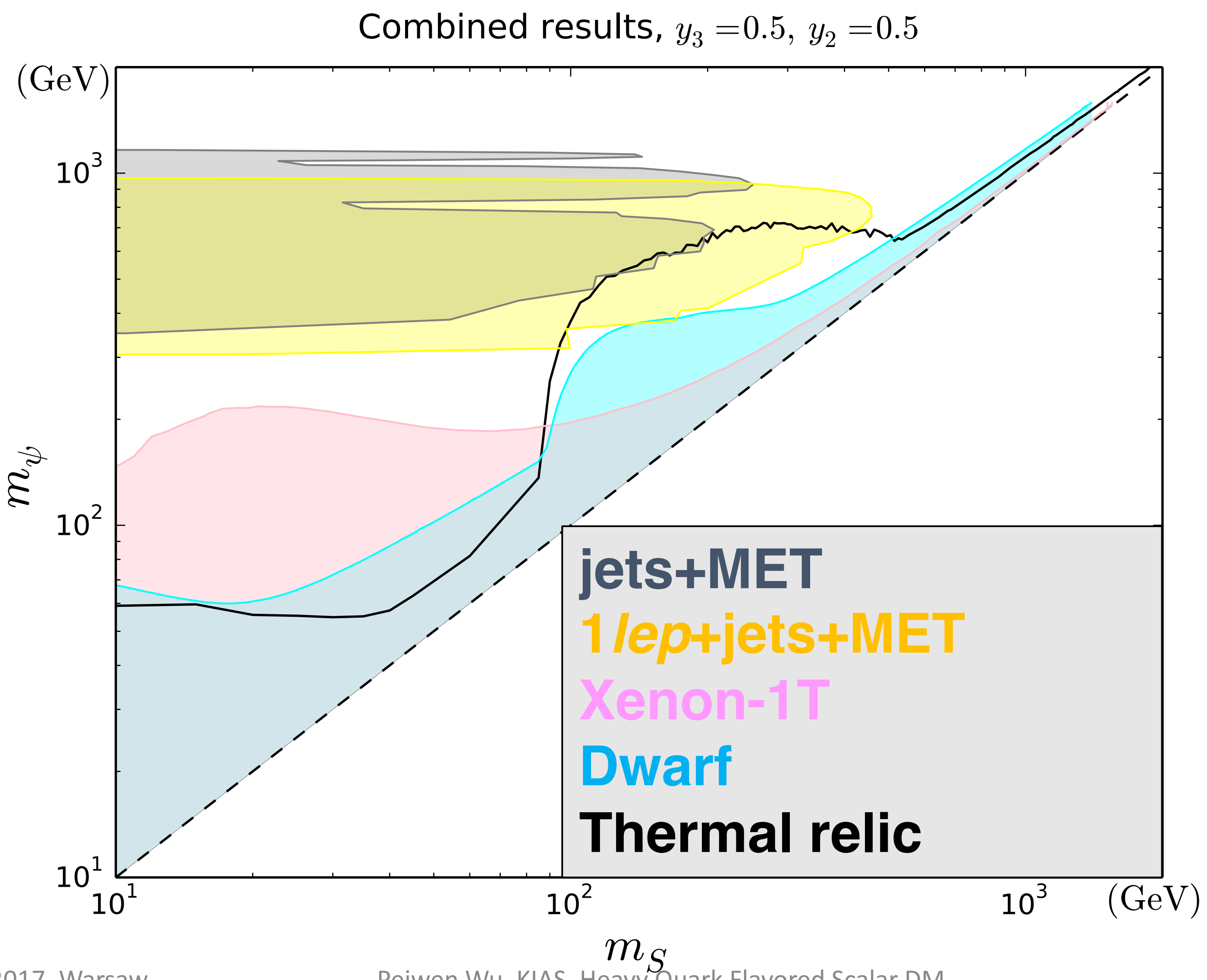
$$\sigma\left(pp \to \psi\overline{\psi} \to \not{E}_T + t\bar{t}\right) = \sigma\left(pp \to \psi\overline{\psi}\right) Br^2(\psi \to St)$$

$$\sigma\left(pp \to \psi\overline{\psi} \to \not{E}_T + jj\right) = \sigma\left(pp \to \psi\overline{\psi}\right) Br^2(\psi \to Sc)$$

Combined results

$y_3 = 0.5$

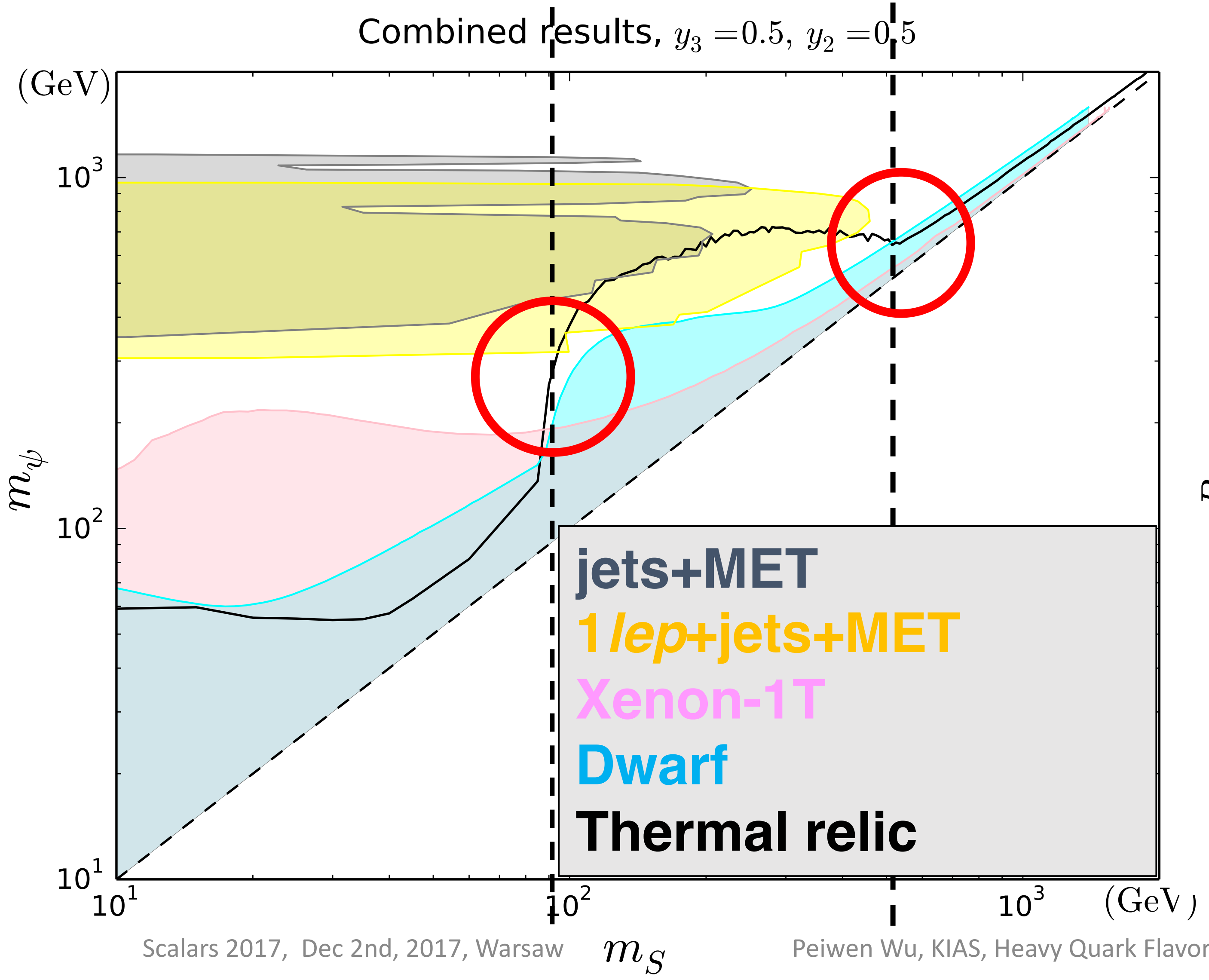
$\mathbf{y_2 = 0.5}$



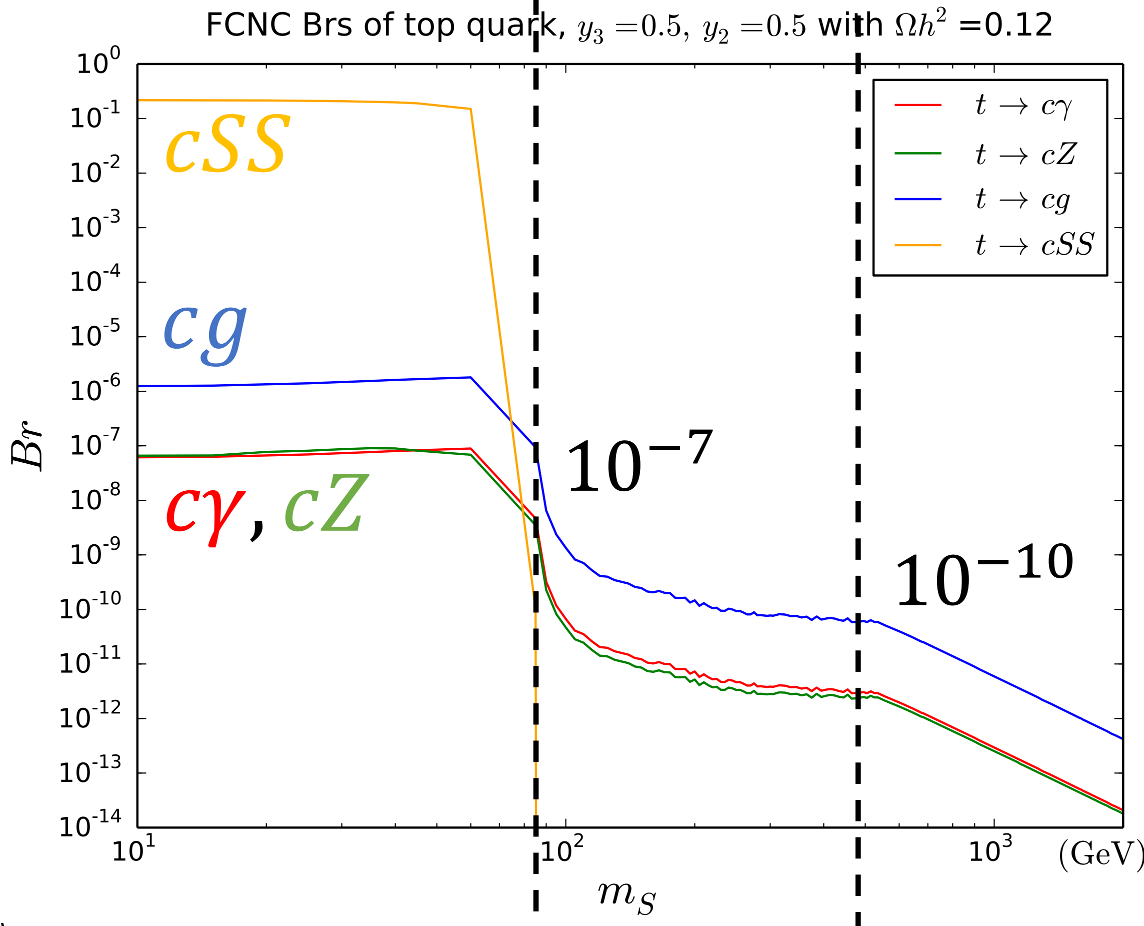
$y_3 = 0.5$

$y_2 = 0.5$

$m_S \sim \frac{m_t}{2}$ $m_S \sim 500$ GeV



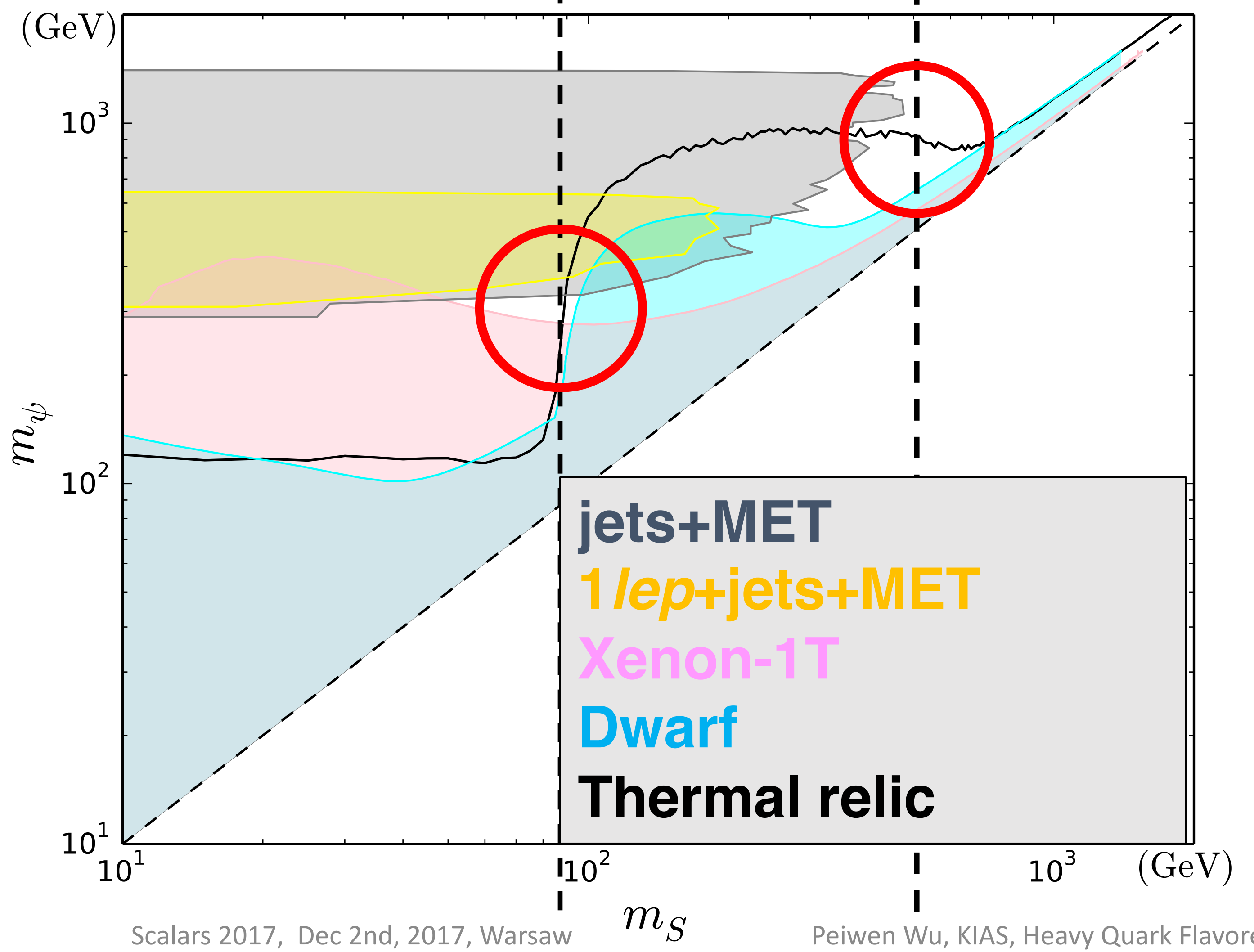
$m_S \sim \frac{m_t}{2}$ $m_S \sim 500$ GeV



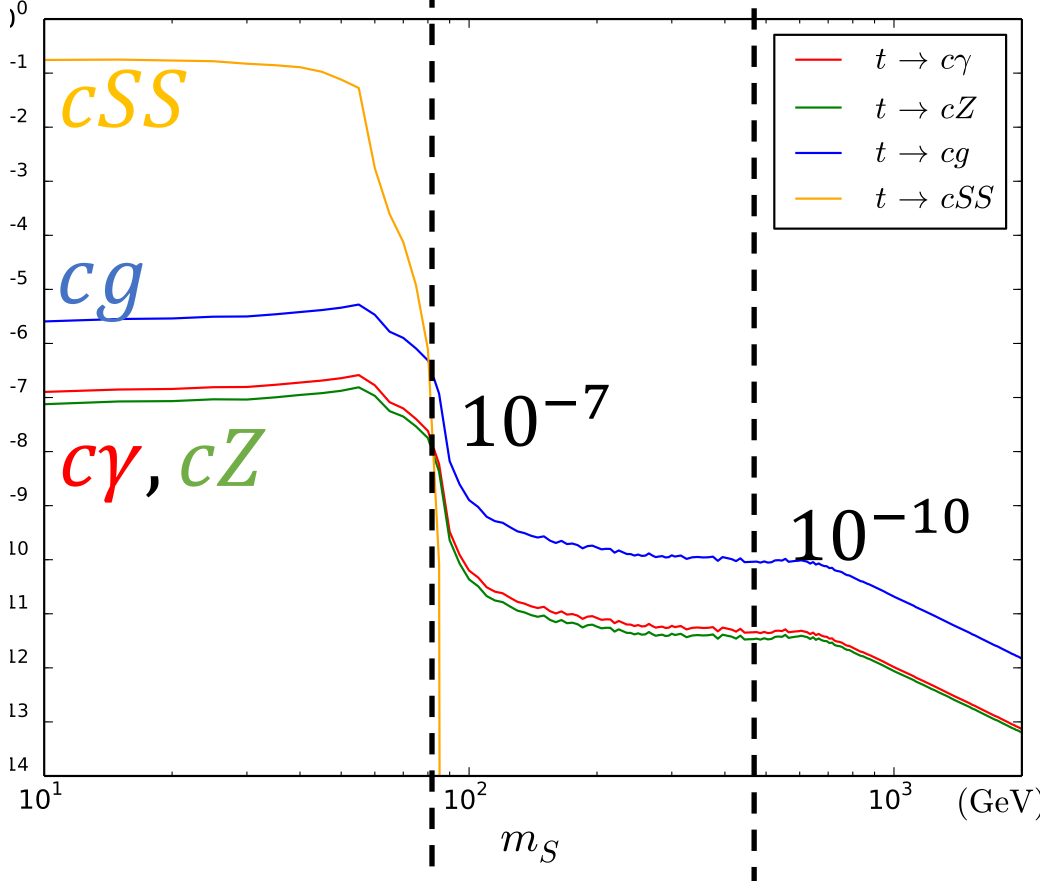
$y_3 = 0.5$

$y_2 = 1.0$

$m_S \sim \frac{m_t}{2}$ $m_S \sim 500$ GeV



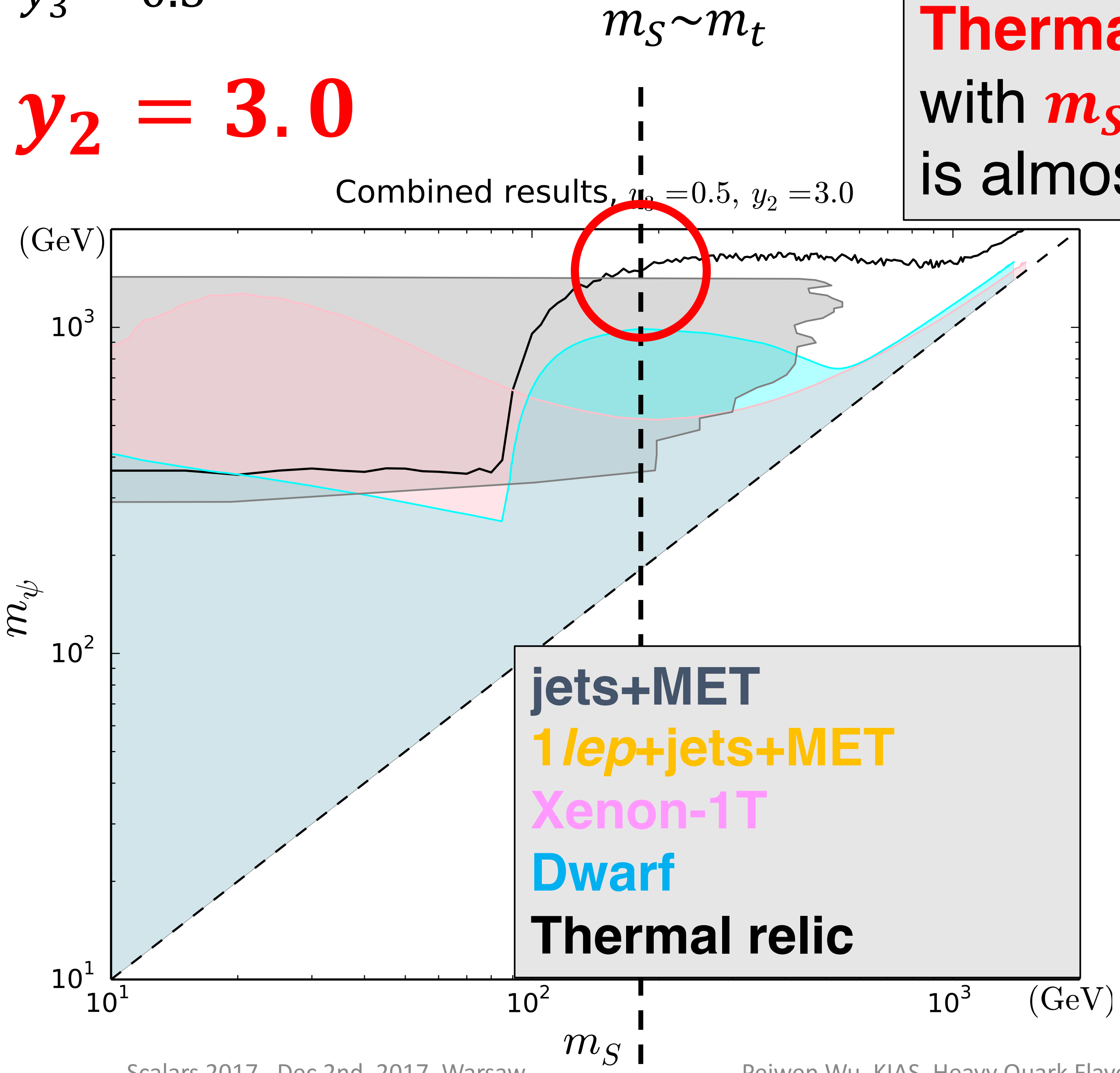
$m_S \sim \frac{m_t}{2}$ $m_S \sim 500$ GeV

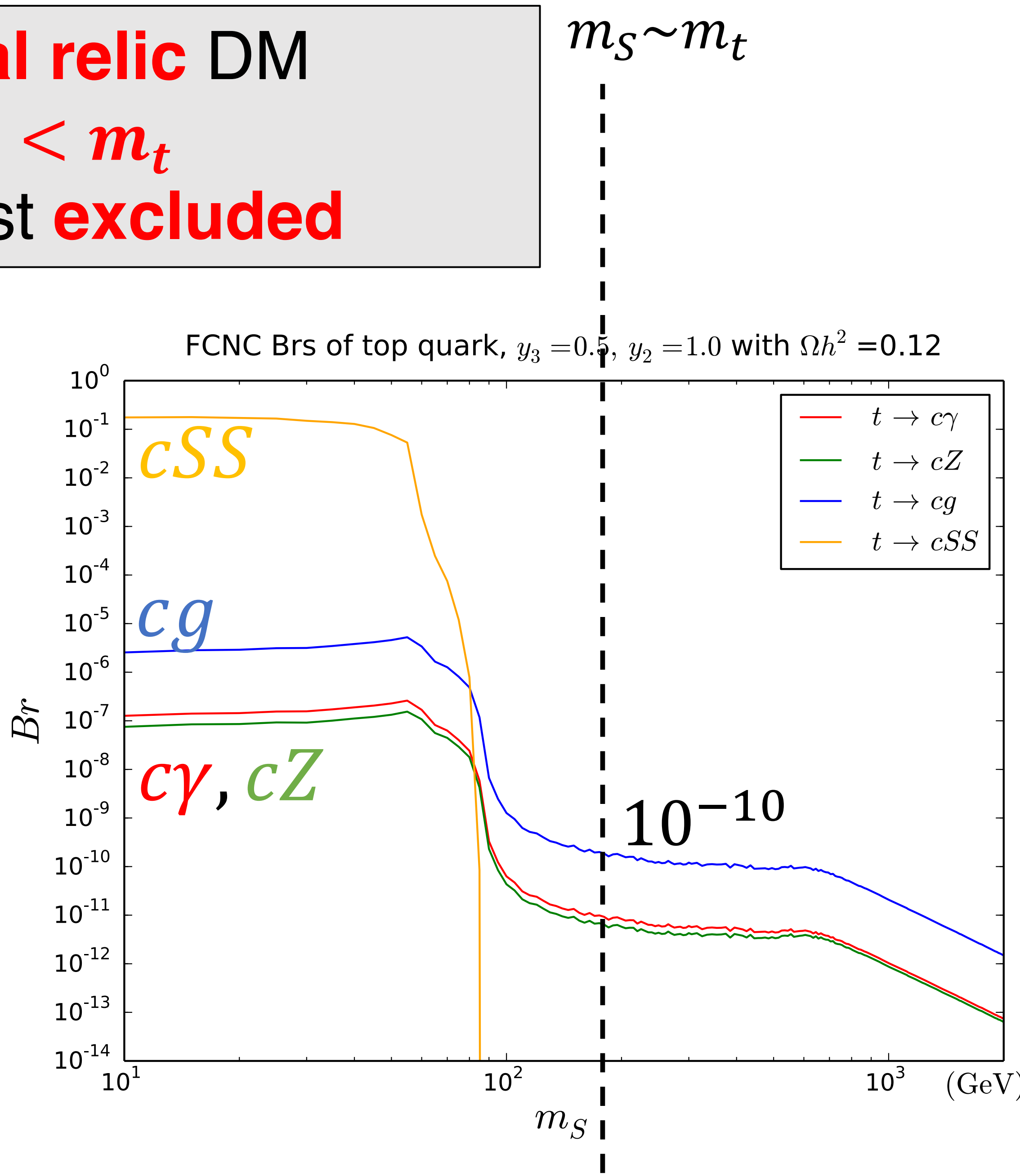


$y_3 = 0.5$

$y_2 = 3.0$

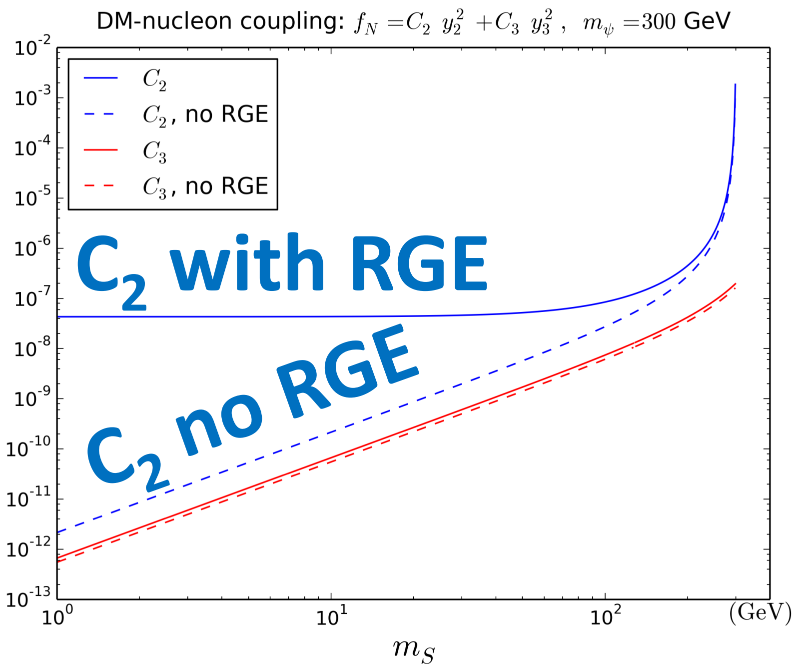
Thermal relic DM
with $m_S < m_t$
is almost **excluded**





Summary

- No confirmed DD signal yet, DM may couple **dominantly** to **heavy quarks**
- We considered a ***real scalar DM*** coupling dominantly to right handed ***top*** and ***charm*** quark, via a colored ***fermion mediator***.



- ***RGE*** are ***important*** in ***DM-nucleon scattering***.

When $y_2, y_3 \sim O(1)$:

- **Thermal relic** DM with $m_S < m_t$ is **almost excluded**
- Top FCNC **Brs <** $\mathbf{10^{-7}}$, still allowed in current bounds
- Future data would further test this model.

DA(ark) M(atter) P(article) E(xplorer) e^+e^- peak @ 1.4 TeV

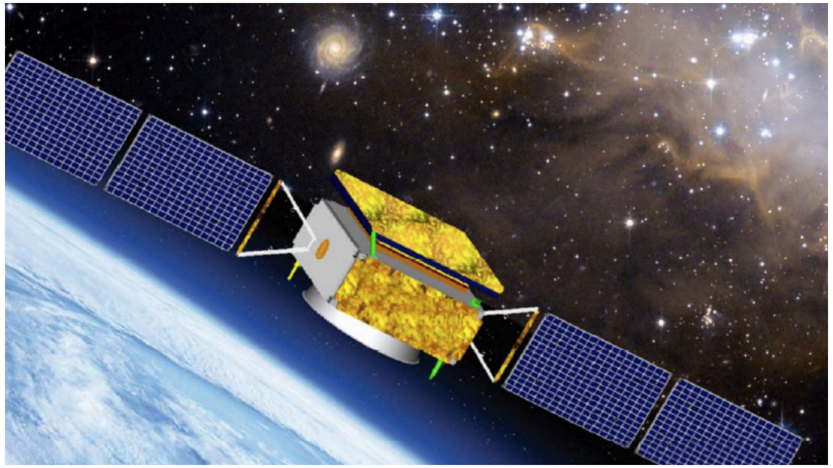
LETTER

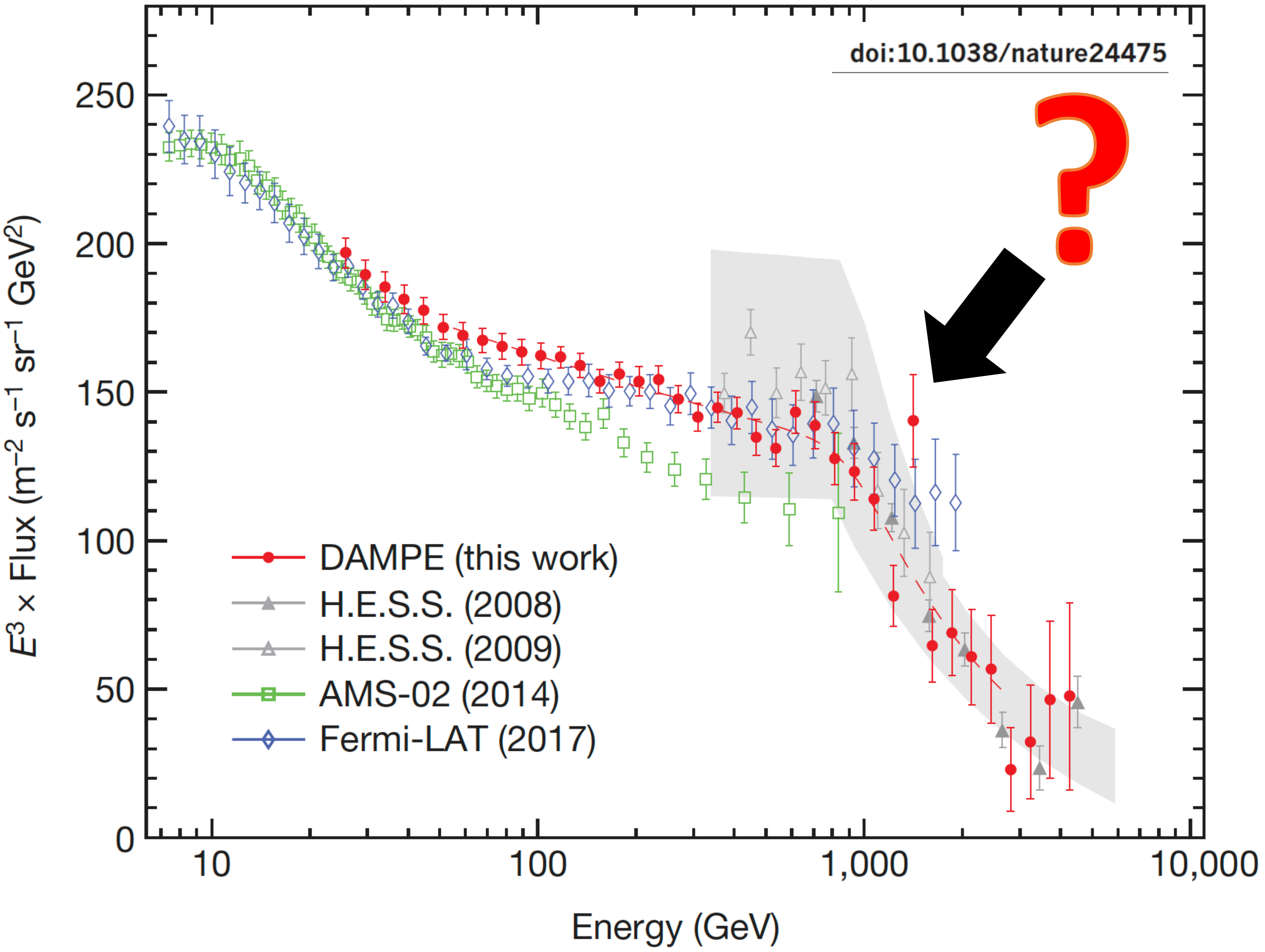
nature.com

doi:10.1038/nature24475

Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons

DAMPE Collaboration*




doi:10.1038/nature24475
?
$E^3 \times$ Flux (m^{-2} s^{-1} sr^{-1} GeV^2)
250
200
150
100
50
0
10
100
1,000
10,000
Energy (GeV)
DAMPE (this work)
H.E.S.S. (2008)
H.E.S.S. (2009)
AMS-02 (2014)
Fermi-LAT (2017)

Sca

DM fitting with $\sigma v \sim 3 \times 10^{-26} cm^3/s$

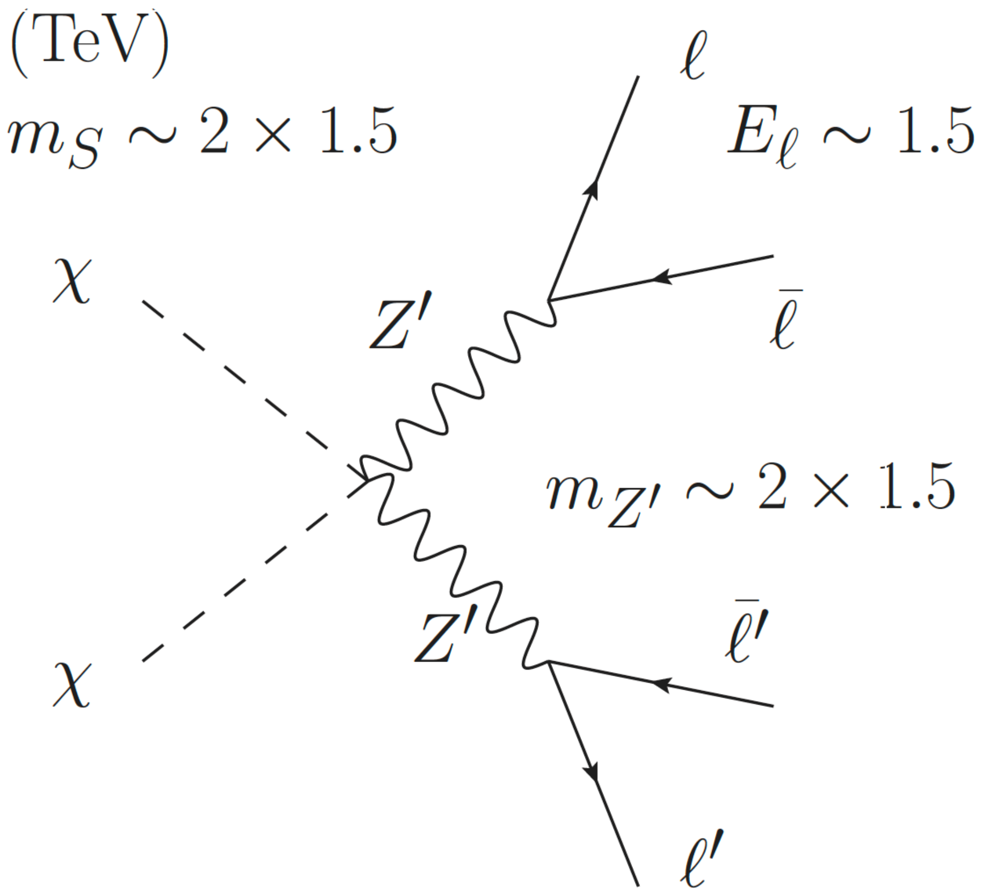
Q. Yuan et al, 1711.10989

channel	1.0 kpc			0.3 kpc			0.1 kpc		
	m_χ/TeV	$M_{\rm sub}/M_\odot$	$\mathcal{L}/\mathrm{GeV^2cm^{-3}}$	m_χ/TeV	$M_{\rm sub}/M_\odot$	$\mathcal{L}/\mathrm{GeV^2cm^{-3}}$	m_χ/TeV	$M_{\rm sub}/M_\odot$	$\mathcal{L}/\mathrm{GeV^2cm^{-3}}$
e^+e^-	2.2	3.8×10^9	1.0×10^{67}	1.5	8.0×10^7	3.8×10^{65}	1.5	5.0×10^6	3.5×10^{64}
$e\mu\tau$	2.2	1.0×10^{10}	2.3×10^{67}	1.5	2.6×10^8	1.0×10^{66}	1.5	1.9×10^7	1.1×10^{65}

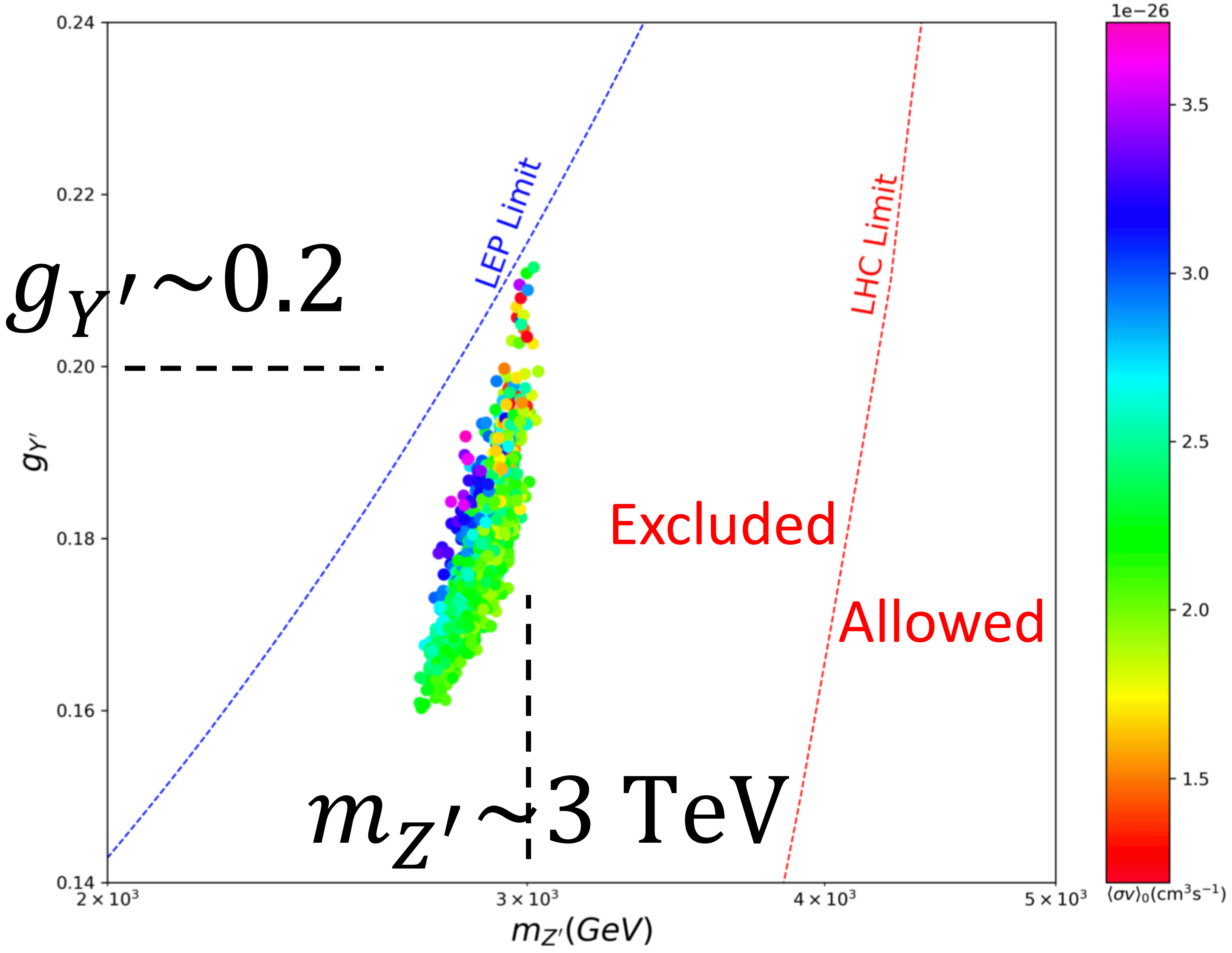
Scalar DM with $G_{SM} \times U(1)_{Y'}$

Name	Spin	Gen.	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{Y'}$
H	0	1	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	0
Q	1/2	3	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$\frac{1}{3}$
d_R^*	1/2	3	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	$-\frac{1}{3}$
u_R^*	1/2	3	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$-\frac{1}{3}$
L_1	1/2	1	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	3
$L_{\{2,3\}}$	1/2	2	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-3
$\ell_{R,1}^*$	1/2	1	$\mathbf{1}$	$\mathbf{1}$	1	-3
$\ell_{R,\{2,3\}}^*$	1/2	2	$\mathbf{1}$	$\mathbf{1}$	1	3
$\nu_{R,1}^*$	1/2	1	$\mathbf{1}$	$\mathbf{1}$	0	-3
$\nu_{R,\{2,3\}}^*$	1/2	2	$\mathbf{1}$	$\mathbf{1}$	0	3
ϕ_s	0	1	$\mathbf{1}$	$\mathbf{1}$	0	6
ϕ_χ	0	1	$\mathbf{1}$	$\mathbf{1}$	0	6

Cao, Feng, Guo, Shang, Wang, Wu, 1711.11452

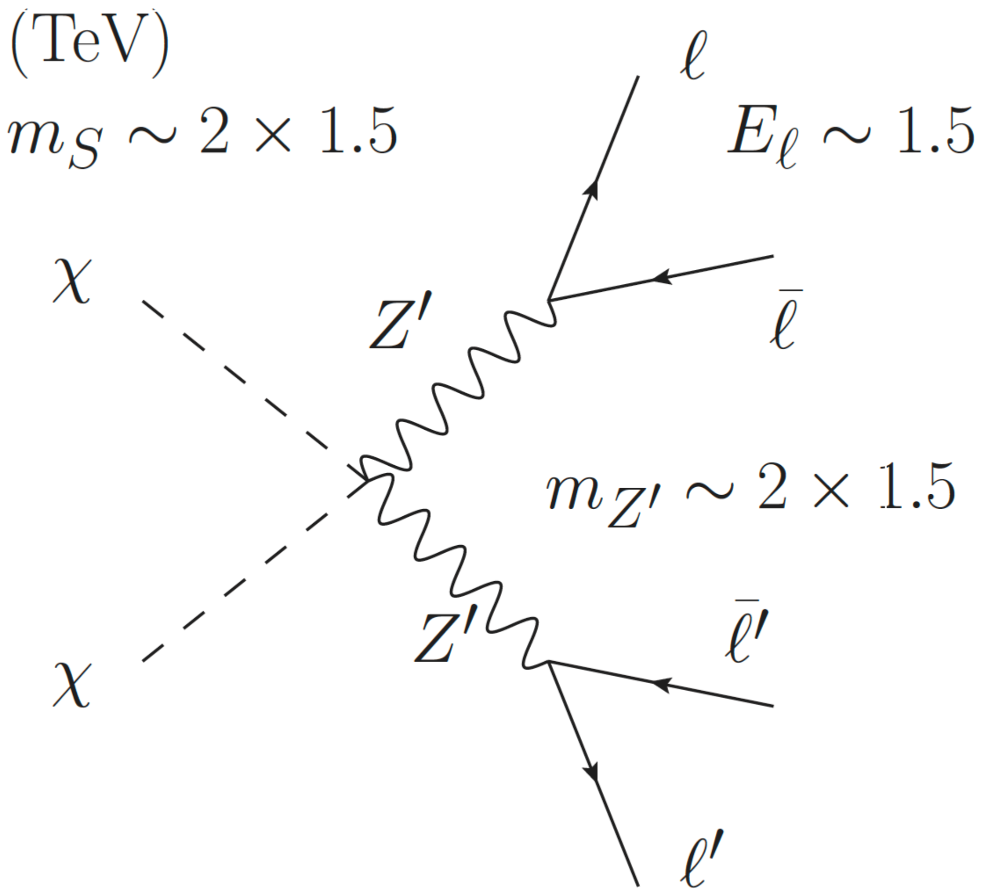


Scalar DM with $G_{SM} \times U(1)_{Y'}$

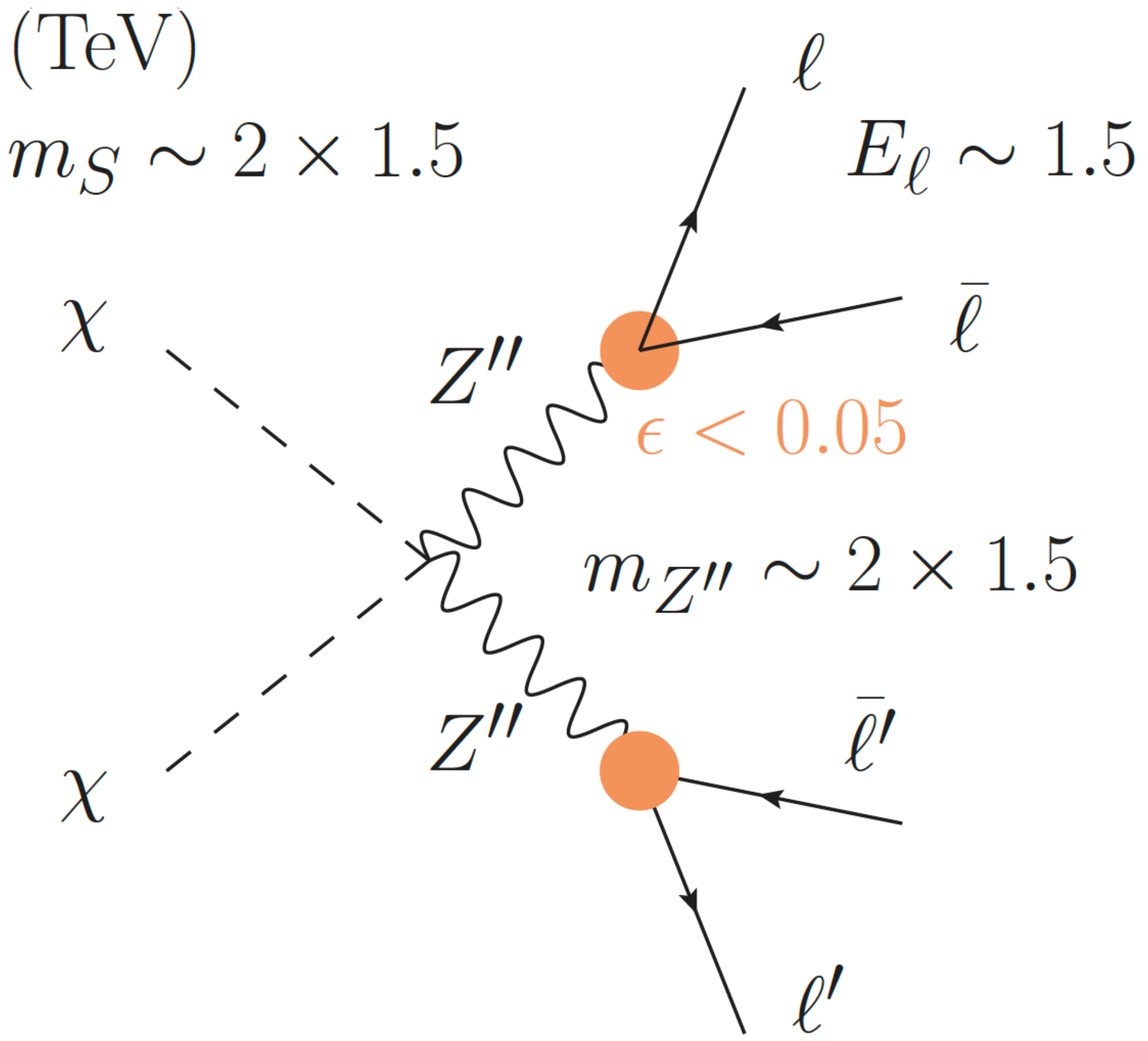


Excluded by LHC Z' search

Cao, Feng, Guo, Shang, Wang, Wu, 1711.11452



Scalar DM with $G_{SM} \times \boxed{U(1)_{Y'} \times U(1)_{Y''}}$

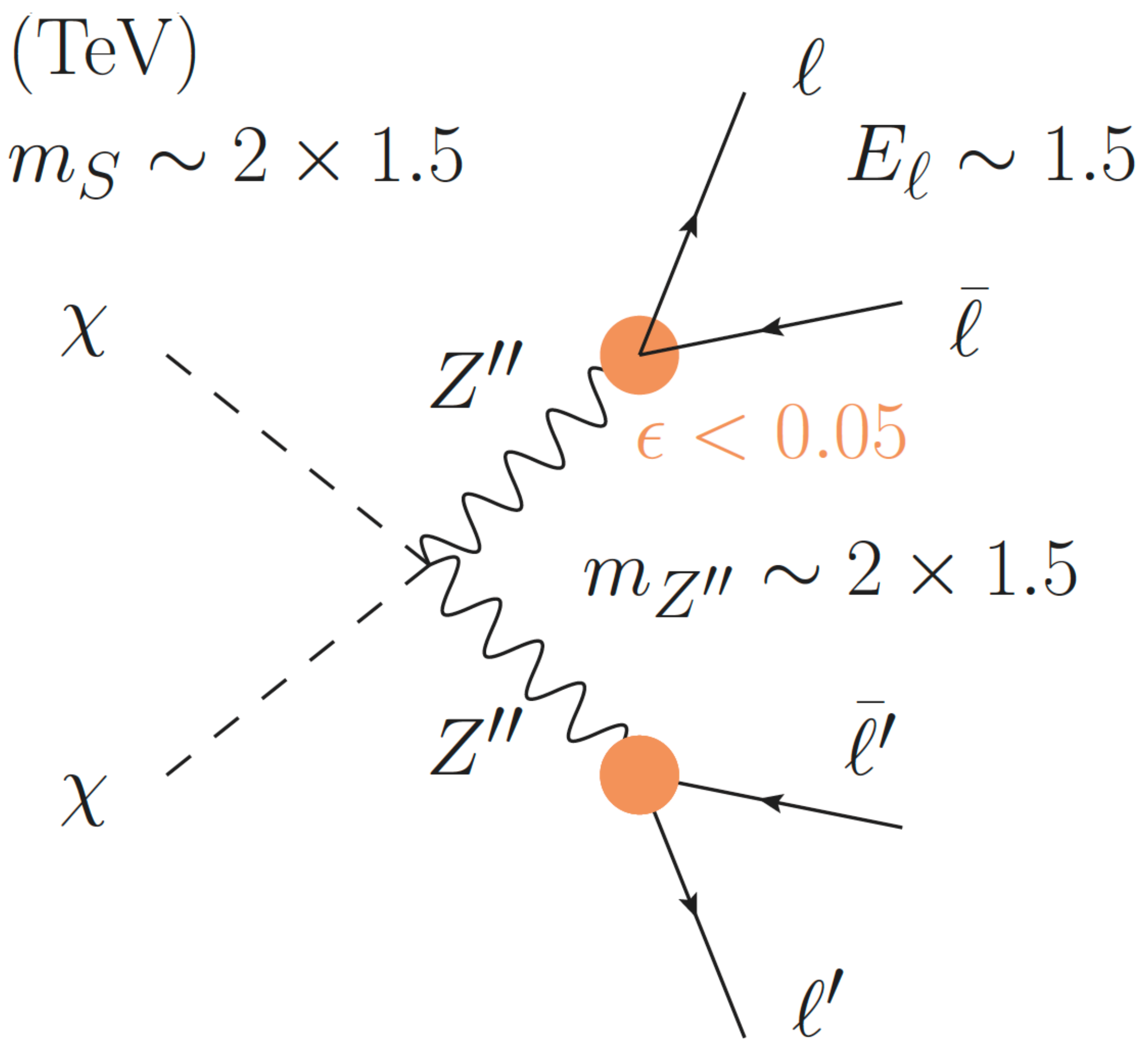


[Cao, Feng, Guo, Shang, Wang, Wu, 1711.11452]()

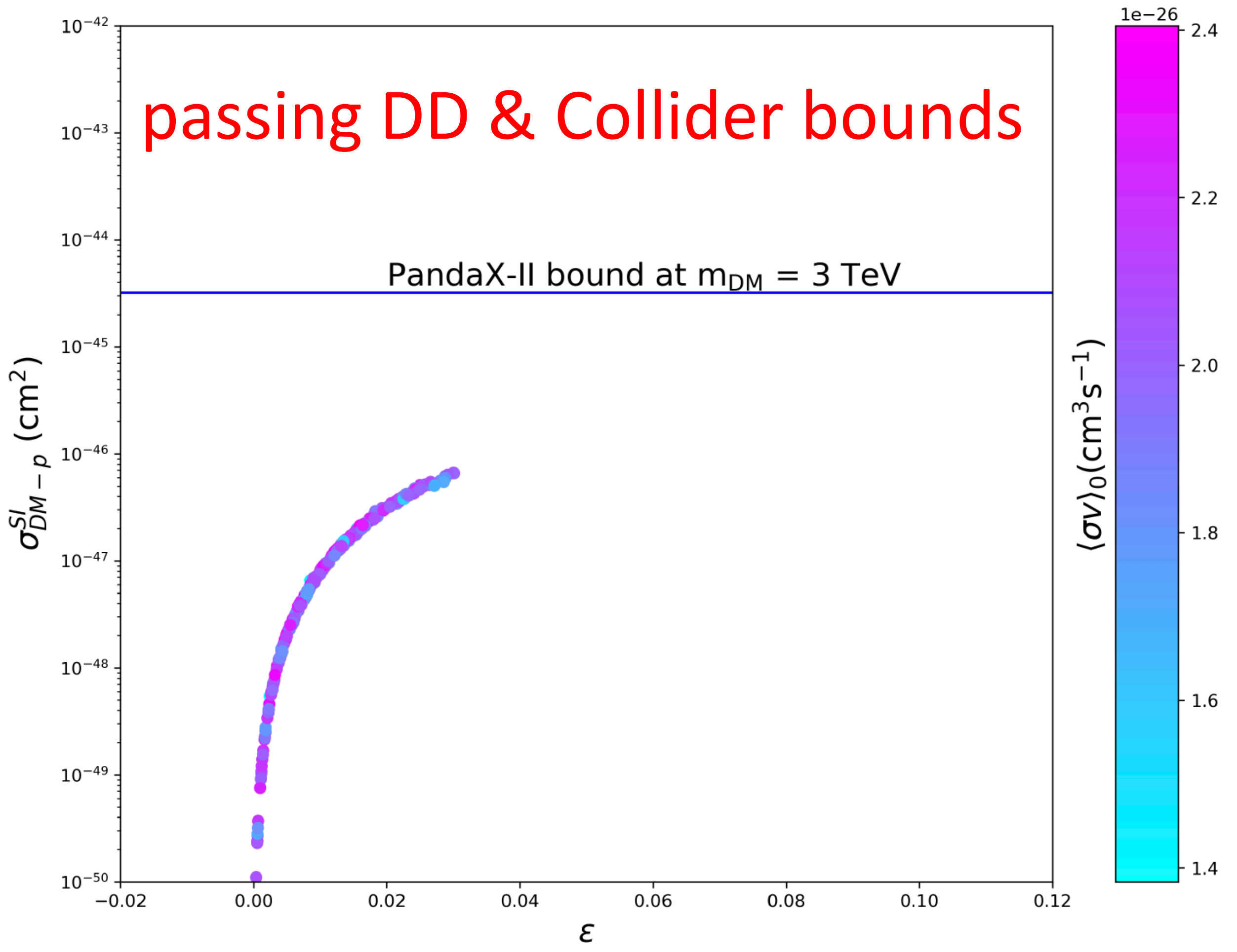
$$\mathcal{L} \supset -\frac{1}{4}|F'_{\mu\nu}|^2 - \frac{1}{4}|F''_{\mu\nu}|^2 - \frac{\epsilon}{2}F'^{\mu\nu}F''_{\mu\nu}$$

$$\Big(\chi - [g_{Y''}Y''] - \boxed{Z''\Big) - [\epsilon] - \Big(Z'} - [g_{Y'}Y'] - \mathrm{SM}\Big)$$

Scalar DM with $G_{SM} \times \boxed{U(1)_{Y'} \times U(1)_{Y''}}$

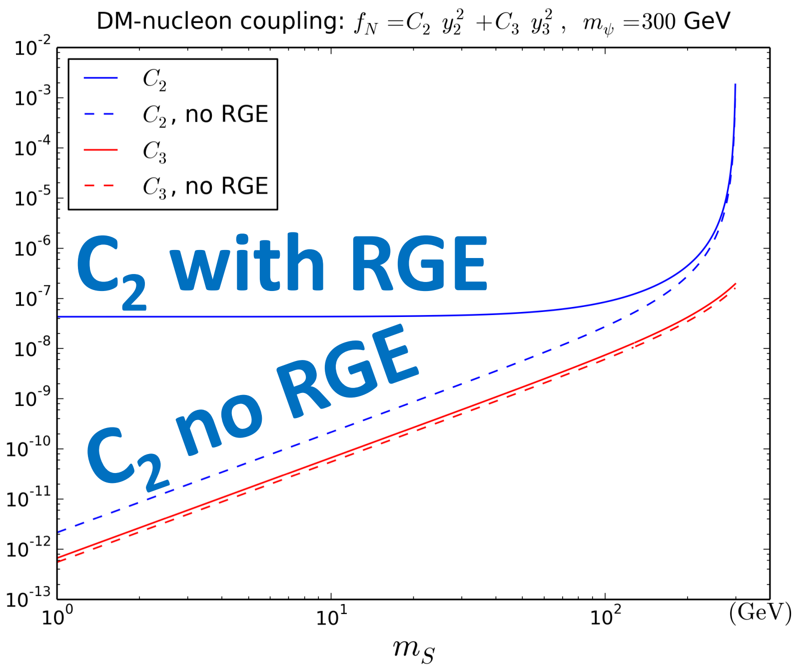


Cao, Feng, Guo, Shang, Wang, Wu, 1711.11452



Summary

- No confirmed DD signal yet, DM may couple **dominantly** to **heavy quarks**
- We considered a ***real scalar DM*** coupling dominantly to right handed ***top*** and ***charm*** quark, via a colored ***fermion mediator***.



- ***RGE*** are ***important*** in ***DM-nucleon scattering***.

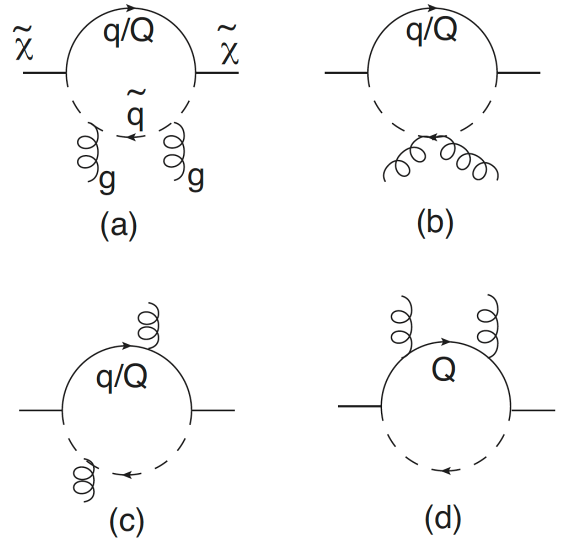
When $y_2, y_3 \sim O(1)$:

- **Thermal relic** DM with $m_S < m_t$ is **almost excluded**
- Top FCNC **Brs <** 10^{-7}, still allowed in current bounds
- Future data would further test this model.

Thank you for your attention

Back up slides

SUSY case $\mathcal{O}_S^g \equiv \frac{\alpha_s}{\pi}\overline{\widetilde{\chi}^0}\widetilde{\chi}^0 G^A_{\mu\nu}G^{A\mu\nu}$



$$\mathcal{L} = \bar{q}(a_q + b_q\gamma_5)\tilde{\chi}\tilde{q} + \text{h.c.}$$

$$f_G = \sum_{q=\text{all}} f_G^{\text{SD}}|_q + \sum_{Q=c,b,t} f_G^{\text{LD}}|_Q$$

$$f_G^{\text{SD}}|_q = \frac{\alpha_s}{4\pi}\left(\frac{a_q^2+b_q^2}{4}M f_+^s + \frac{a_q^2-b_q^2}{4}m_q f_-^s\right)$$

$$f_G^{\text{LD}}|_q = \frac{\alpha_s}{4\pi}\left(\frac{a_q^2+b_q^2}{4}M f_+^l + \frac{a_q^2-b_q^2}{4}m_q f_-^l\right)$$

$$\begin{aligned} f_+^s &= m_{\tilde{q}}^2\,(\boxed{B_0^{(1,4)}} + B_1^{(1,4)})\,, \\ f_-^s &= m_{\tilde{q}}^2\,B_0^{(1,4)}\,, \\ f_+^l &= m_q^2\,(\boxed{B_0^{(4,1)}} + B_1^{(4,1)})\,, \\ f_-^l &= B_0^{(3,1)} + m_q^2\,B_0^{(4,1)}\,, \end{aligned}$$

$$\int \frac{d^4q}{i\pi^2}\frac{1}{((p+q)^2 - m_q^2)^n(q^2-m_{\tilde{q}}^2)^m} \equiv B_0^{\boxed{(n,m)}},$$

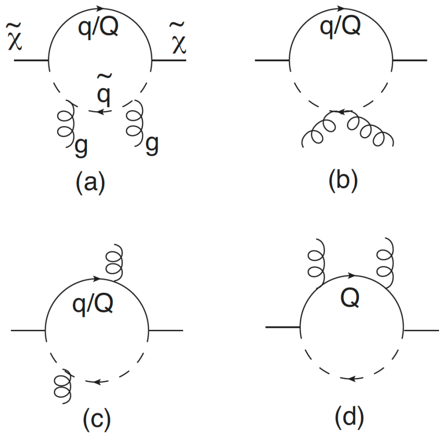
$$\int \frac{d^4q}{i\pi^2}\frac{q_\mu}{((p+q)^2 - m_q^2)^n(q^2-m_{\tilde{q}}^2)^m} \equiv p_\mu B_1^{(n,m)}$$

SD is characterized by $q_{loop} \sim m_{\tilde{q}}$

LD is characterized by $q_{loop} \sim m_q$

higher energy $\Rightarrow$ shorter distance

Perturbative QCD requires $q_{loop} > \Lambda_{QCD}$



- SD ($p \sim m_{\tilde{q}}$) is integrated out into f_G, since $m_{\tilde{q}} \sim \mu_{EFT} \sim m_Z$

$$f_G = \sum_{\boxed{q=\text{all}}} \boxed{f_G^{\text{SD}}}|_q + \sum_{\boxed{Q=c,b,t}} \boxed{f_G^{\text{LD}}}|_Q$$

- LD ($q_{loop} \sim m_q$) of $q = \{u, d, s\}$
  - ***non-perturbative*** QCD, must ***NOT*** be included in f_G
  - belongs to quark mass fractions in nucleons $f_{Tq} = \langle N|m_q \bar{q} q|N\rangle / m_N$
- LD ($q_{loop} \sim m_Q$) of $Q = \{c, b, t\}$
  - if $m_Q > \mu_{EFT}$, integrated out into f_G
  - if $m_Q < \mu_{EFT}$, Q is **active *d.o.f*,**

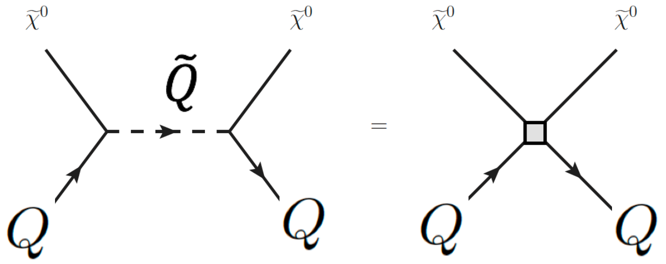
LD of Heavy Quark in DM-Gluon $f_G^{LD}|_Q$ is used to calculate DM-Heavy Quark coupling f_Q

LD of Heavy Quark in DM-Gluon $f_G^{LD}|_Q$
is used to calculate
DM-Heavy Quark coupling f_Q

f_Q Pole removal

- Tree-level matching of f_Q contains pole at $m_{\tilde{Q}} = m_\chi + m_Q$

[Gondolo et al, 1307.4481]



$$f_Q = -\frac{1}{4m_q}\frac{a_q^2 - b_q^2}{m_{\tilde{q}}^2 - (m_\chi + m_q)^2} + \frac{m_\chi}{8}\frac{a_q^2 + b_q^2}{[m_{\tilde{q}}^2 - (m_\chi + m_q)^2]^2}$$

LD of Heavy Quark in DM-Gluon $f_G^{LD}|_Q$
is used to calculate
DM-Heavy Quark coupling $\boldsymbol{f_Q}$

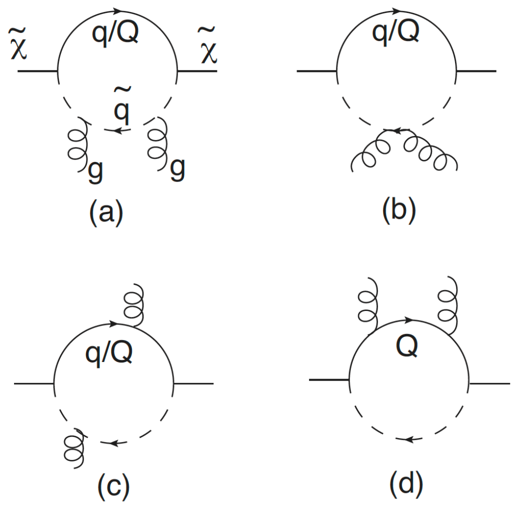
$\boldsymbol{f_Q}$ Pole removal

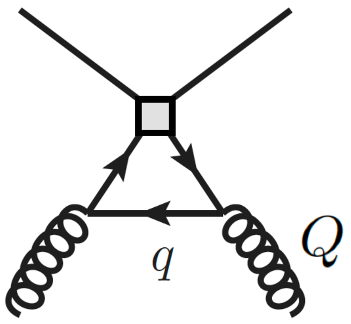
[Gondolo et al, 1307.4481]

- One can use **LD** in f_G(loop calculation) to obtain f_Q, which is regular at $m_{\tilde{Q}} = m_\chi + m_Q$.

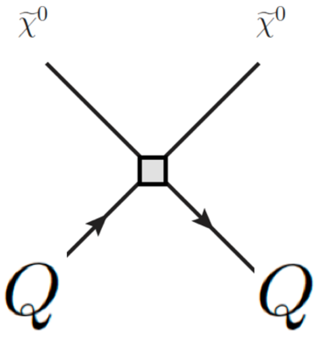
$$\mathcal{O}_S^g \equiv \frac{\alpha_s}{\pi}\overline{\tilde{\chi}^0}\tilde{\chi}^0 G^A_{\mu\nu}G^{A\mu\nu} \Rightarrow \boxed{-\frac{\alpha_s}{12\pi}G^a_{\mu\nu}G^{a\mu\nu} \to m_Q\bar{Q}Q} \Rightarrow \mathcal{L}_Q^{\text{eff}} = f_Q m_Q \bar{\tilde{\chi}}\tilde{\chi}\bar{Q}Q$$

$$f_Q = (-12) f_G\Big|_Q^{LD}$$





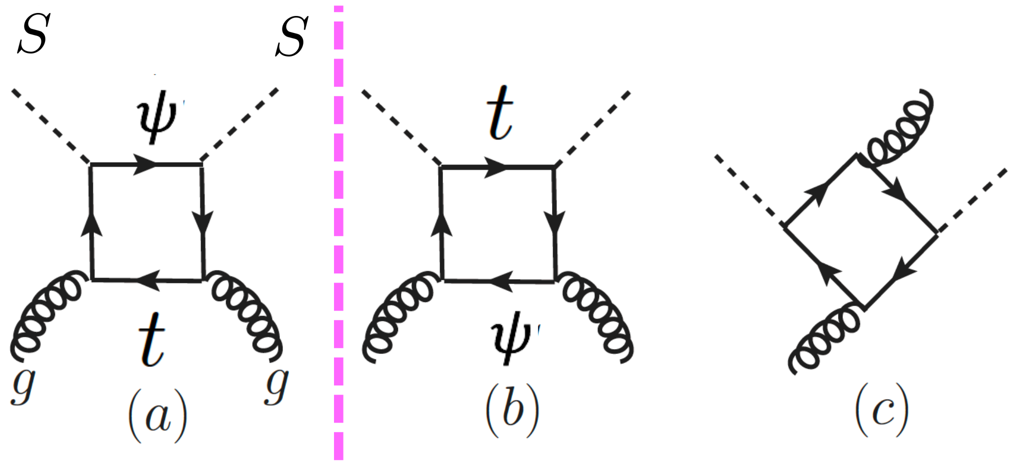
[Shifman et al, 1978]



Scalar DM case

[Hisano et al, 1502.02244]

- Taking top loop as an example



LD~m_t SD~m_ψ

$$\mathcal{L} = S\overline{\psi}(a_Q + b_Q\gamma^5)Q + h.c.$$

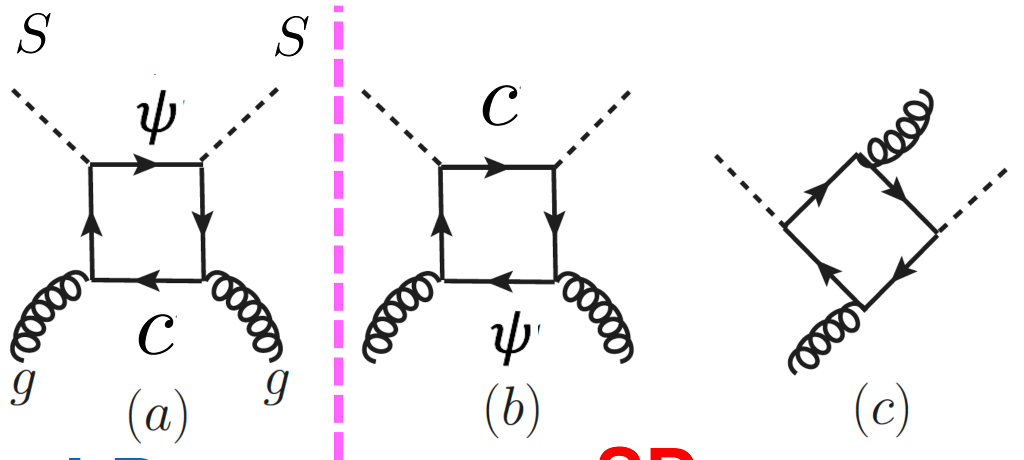
$a_Q = b_Q = \frac{y_3}{2}$ in our model for top quark

$$C_S^g|_t = \frac{1}{4}\sum_{\boxed{i=a,b,c}}\left[(a_Q^2 + b_Q^2)f_+^{(i)}(m_S; m_Q, m_\psi) + (a_Q^2 - b_Q^2)f_-^{(i)}(m_S; m_Q, m_\psi)\right]$$

summation over {a,b,c} diagrams.

a: LD~m_t **b,c: SD~m_ψ**

Charm threshold matching



LD~m_c

SD~m_ψ

top loop -> $\{O_S^g\}$

charm loop -> $\{O_S^g, O_S^c\}$

- Without RGE:

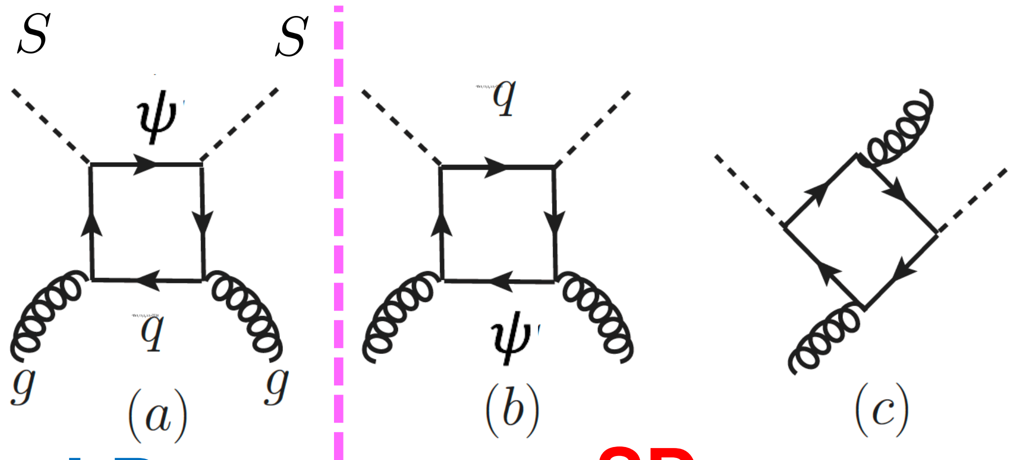
$$C_S^g(\mu_c)|_{N_f=3} = \left(\frac{1}{4}\frac{y_2^2}{2}\right)\left(f_+^{(a)} + f_+^{(b)} + f_+^{(c)}\right)(m_S; m_c, m_\psi)$$

  - ***same*** coefficients in front of f^{a} and $f^{\{b,c\}}$
  - LD/SD splitting of charm loop at $\mu_{EFT} \sim m_Z$ is recovered.

- With RGE:
  - running $\alpha_s(\mu), \beta(\alpha_s), \gamma_m(\alpha_s)$
  - ***different*** coefficients in front of f^{a} and $f^{\{b,c\}}$
  - LD/SD splitting at $\mu_{EFT} \sim m_Z$ is not fully recovered at $\mu_c \sim m_c$

residual terms appear

Loop function behavior



LD~m_c

SD~m_ψ

$$\left(f_+^{(a)} + f_+^{(b)} + f_+^{(c)}\right)(m_S; m_c, m_\psi)$$

- When $m_c \ll m_S, m_\psi$, i.e. $m_S \sim O(10)$ GeV

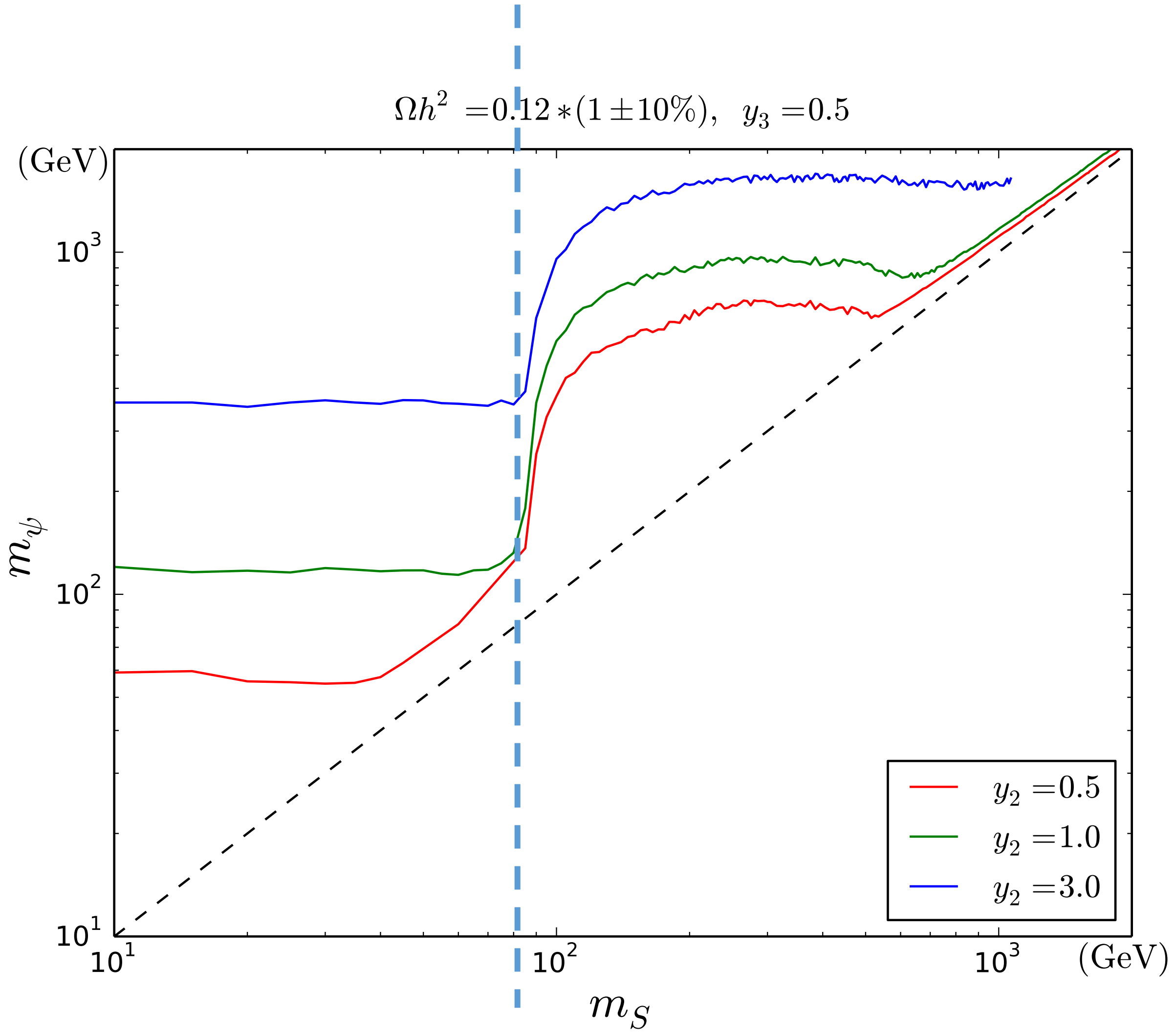
top loop -> $\{O_S^g\}$

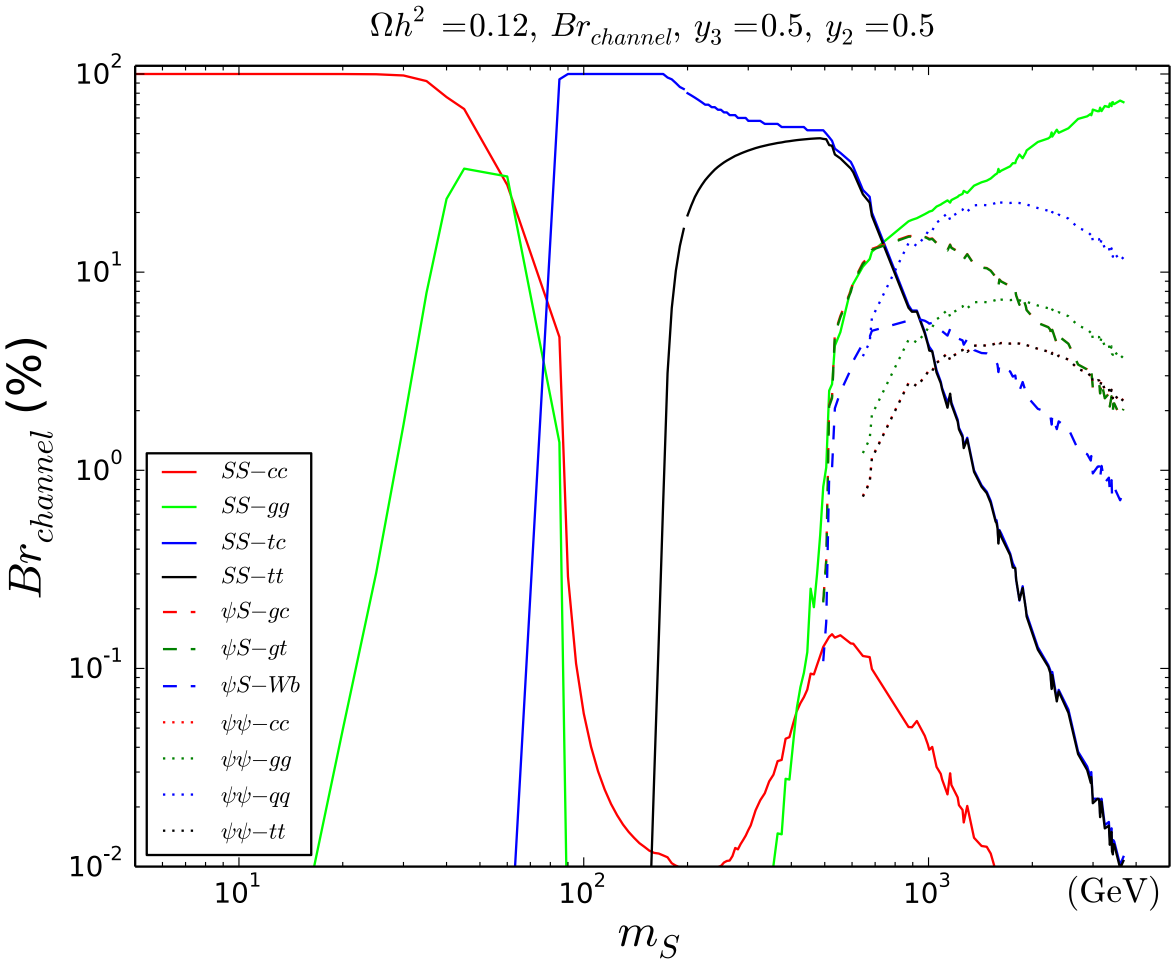
charm loop -> $\{O_S^g, O_S^c\}$

$$f_+^{(a)} \simeq -\frac{2m_\psi^2 - m_S^2}{6(m_\psi^2 - m_S^2)^2}, \qquad f_+^{(b)} \simeq -\frac{1}{6(m_\psi^2 - m_S^2)}, \qquad f_+^{(c)} \simeq \frac{1}{2(m_\psi^2 - m_S^2)},$$

$$f_+^{(a)} + f_+^{(b)} + f_+^{(c)} \simeq -\frac{\boxed{m_S^2}}{2(m_\psi^2 - m_S^2)^2},$$

Thermal Relic: $y_3 = 0.5,\ y_2 = \{0.5,\ 1,\ 3\}$





Scalar DM with $G_{SM} \times U(1)_{Y'} \boxed{\times U(1)_{Y''}}$

Cao, Feng, Guo, Shang, Wang, Wu, 1711.11452

Name	Spin	Gen.	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{Y'}$	$U(1)_{Y''}$
H	0	1	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	0	0
Q	1/2	3	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$\frac{1}{3}$	0
d_R^*	1/2	3	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	$-\frac{1}{3}$	0
u_R^*	1/2	3	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0
L_1	1/2	1	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	3	0
$L_{\{2,3\}}$	1/2	2	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-3	0
$\ell_{R,1}^*$	1/2	1	$\mathbf{1}$	$\mathbf{1}$	1	-3	0
$\ell_{R,\{2,3\}}^*$	1/2	2	$\mathbf{1}$	$\mathbf{1}$	1	3	0
$\nu_{R,1}^*$	1/2	1	$\mathbf{1}$	$\mathbf{1}$	0	-3	0
$\nu_{R,\{2,3\}}^*$	1/2	2	$\mathbf{1}$	$\mathbf{1}$	0	3	0
ϕ_s	0	1	$\mathbf{1}$	$\mathbf{1}$	0	6	0
ϕ_χ	0	1	$\mathbf{1}$	$\mathbf{1}$	0	0	Y''_{ϕ_χ}
ϕ_d	0	1	$\mathbf{1}$	$\mathbf{1}$	0	0	Y''_{χ_d}