# Composite dark matter
# Simplified and non-minimal models and overlooked channels


## Benjamin Fuks


**Based on works with:**

- S. Colucci, F. Giacchino, L. Lopez Honorez, M.H.G. Tytgat and J.Vandecasteele (PRD 2018)
- C. Arina and L. Mantani (EPJC 2020)
- A.S. Cornell, A. Deandrea, T. Flacke and L. Mason (JHEP 2021; 2209.13093)
- C. Arina, L. Mantani, H. Mies, L. Panizzi and J. Salko (PLB 2021)
- C. Arina, J. Heisig, M. Kramer, L. Mantani, L. Panizzi and J. Salko (230M.NNNNN, 230M.NNNNN)

**Workshop on Higgs and Cosmology Connection (Yonsei University)**

**12-16 December 2022**

# Composite dark matter and how to search for it

DM natural in models featuring a strong dynamics

- Composite constructions
  - ⋆ Large spectrum of new states ➝ stable neutral scalars ubiquitous
  - ⋆ Remaining parity
- Dark matter ≡ pNGBs [ Cacciapaglia, Cai, Deandrea & Kushwaha (JHEP'19) ]
  - ⋆ Derivative couplings to other fields
- Dark matter ≡ composite resonance ➝ our assumption
  - ⋆ Non-derivative couplings to other fields
- Partial compositeness: special role of the top quark

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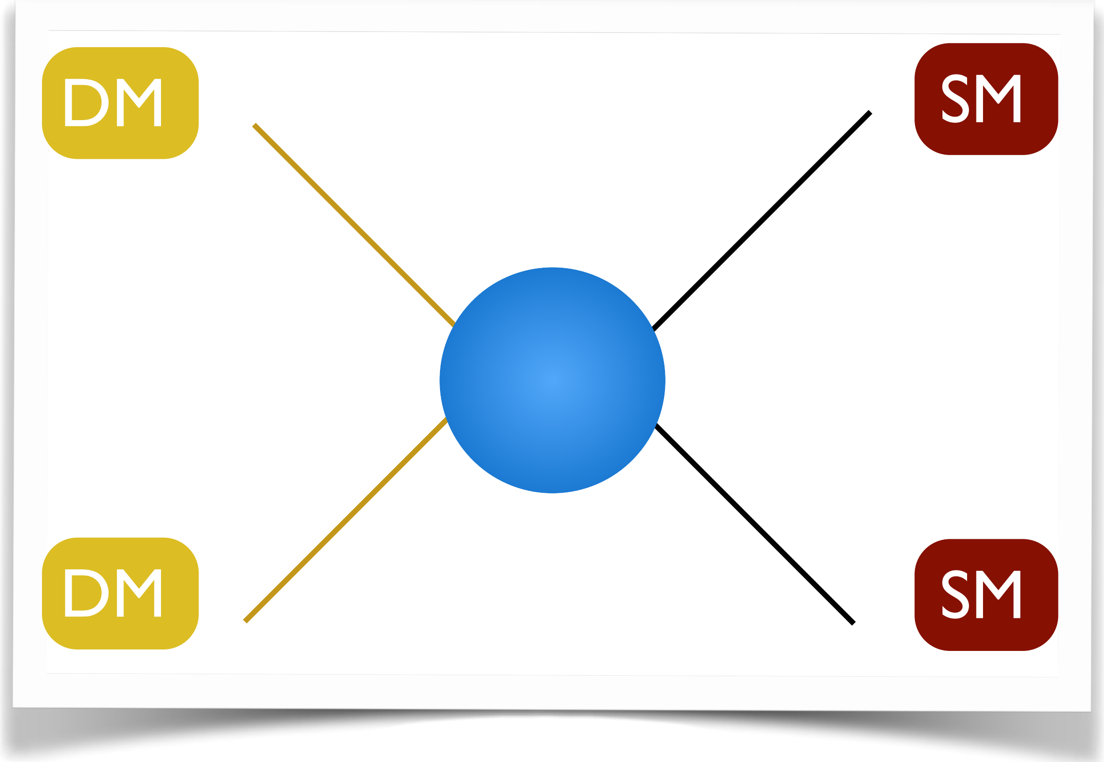
- Partial compositeness: special role of the top quark

## DM searched for directly, indirectly and at colliders

- Huge experimental effort → strategy to constrain models




## Complementary between colliders and cosmology

- Dark matter direct/indirect detection constraints
- Direct production at (hadron) colliders

# Outline

1. Collider/cosmology constraints on a simplified model for composite dark matter
2. Non-minimality and its phenomenological consequences
3. First generation couplings, LHC searches and overlooked channels
4. Summary

# A simplified model for composite DM

## A simplified model for composite dark matter

- Scalar DM (*S*) interacting with the SM (top quark)
  - ★ Need for a vector-like fermionic mediator (*T*)
  - ★ Lack of non-minimal features (multiple mediators, multi-component DM, *etc.*)
    - ➙ Potential impact of non-minimality (see later)

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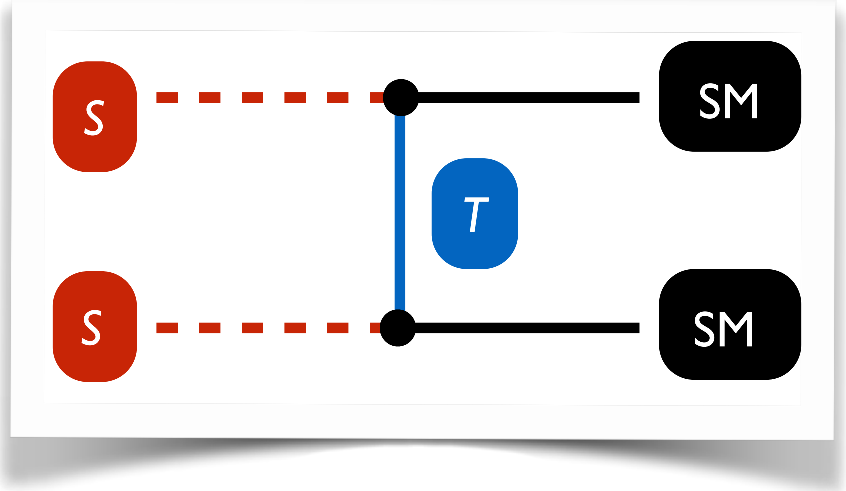
## Model properties

- $S$ stable
  - ★ Odd under some $\mathbb{Z}_2$ discrete symmetry
  - ★ SM states even
- $T$ interactions with DM and quarks/gluons (top mass motivation)
  - ★ $\mathbb{Z}_2$-odd: $t$-channel models
    - ➙ colour triplet and electrically charged



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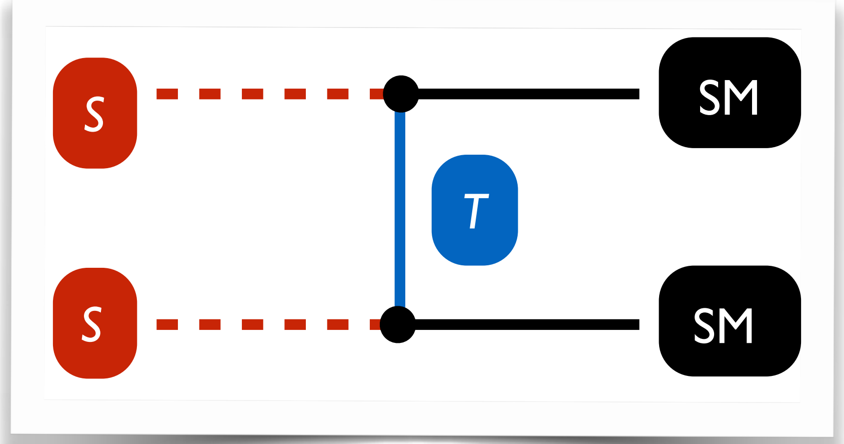


$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \Big[\tilde{y}_t\, S\, \bar{T} P_R t + {\rm h.c.}\Big]$$

★ SU(2) singlet vector-like mediator *T*
★ EW singlet scalar dark matter *S*

- Simplest simplified model for DM
  - ★ 2 masses: $m_S$, $m_T/m_S-1$; 1 Yukawa coupling $\tilde{y}_t$

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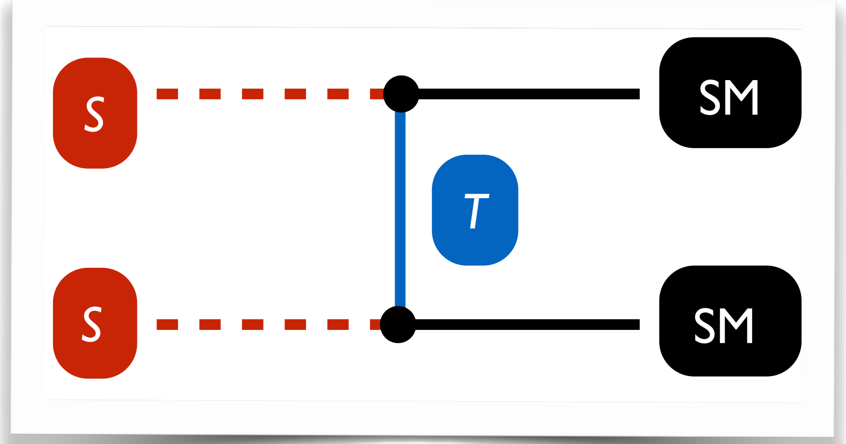


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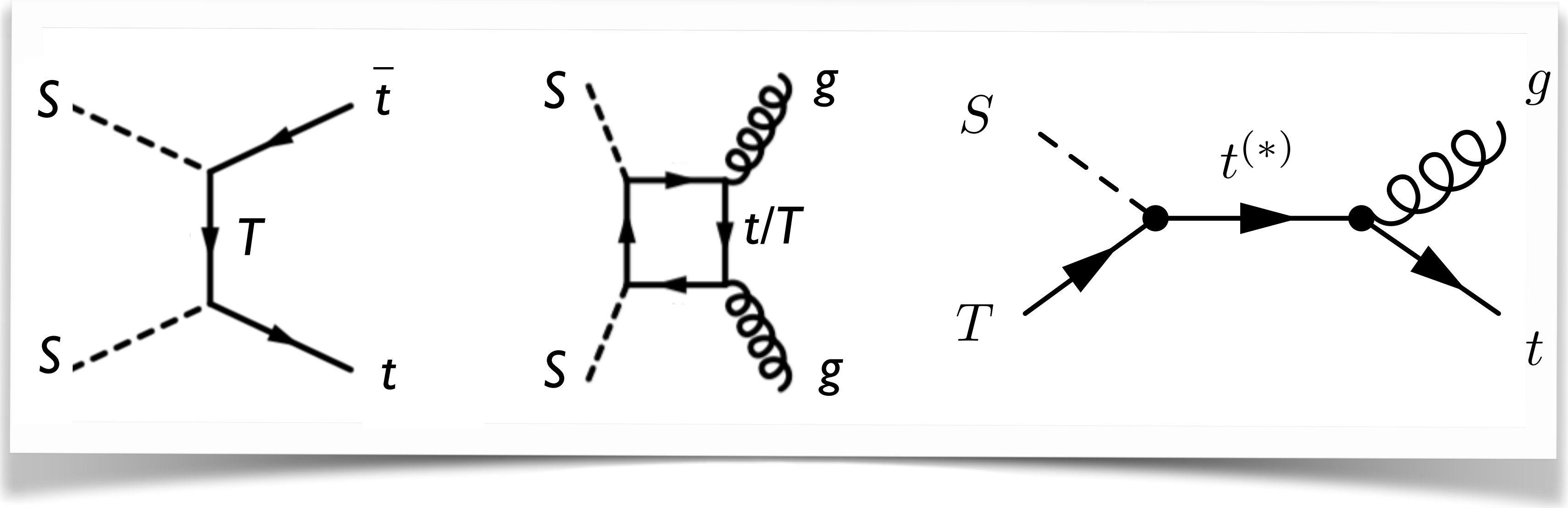
Is this viable?
➙ DM relic abundance

# Relic abundance: generalities

[ Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD'18) ]

## DM annihilation to SM (and *vice versa*)

- Several competing DM annihilation channels
  - ★ In (possibly virtual) tops
  - ★ Into gluons (loop-induced)
- Co-annihilations possibly important
  - ★ $ST \to t$
  - ★ Resonant for light new physics



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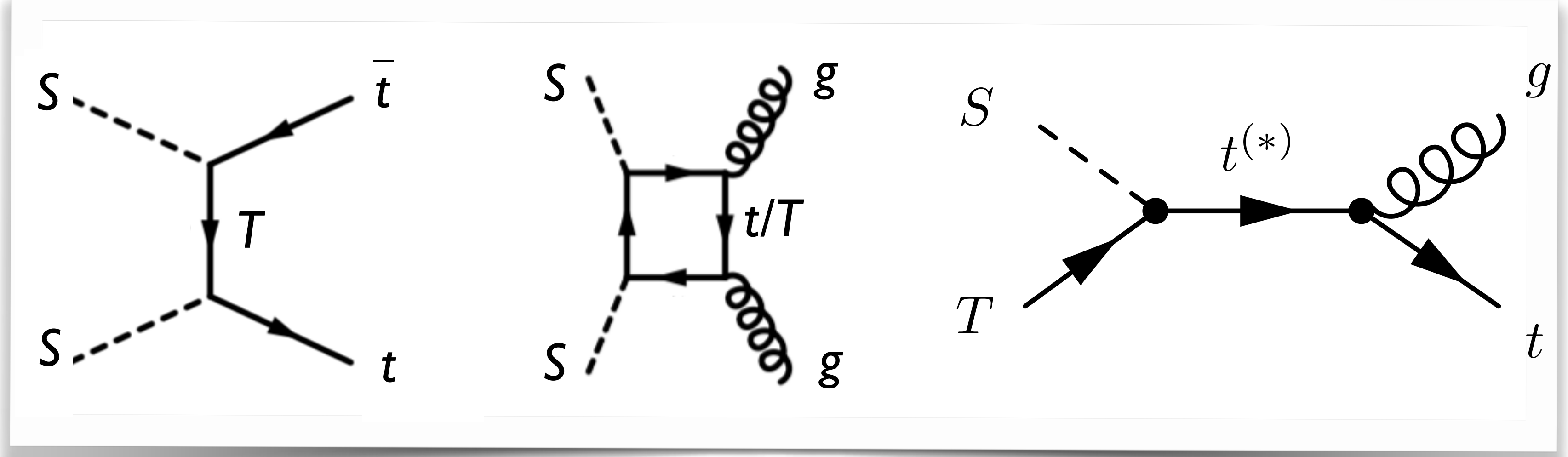


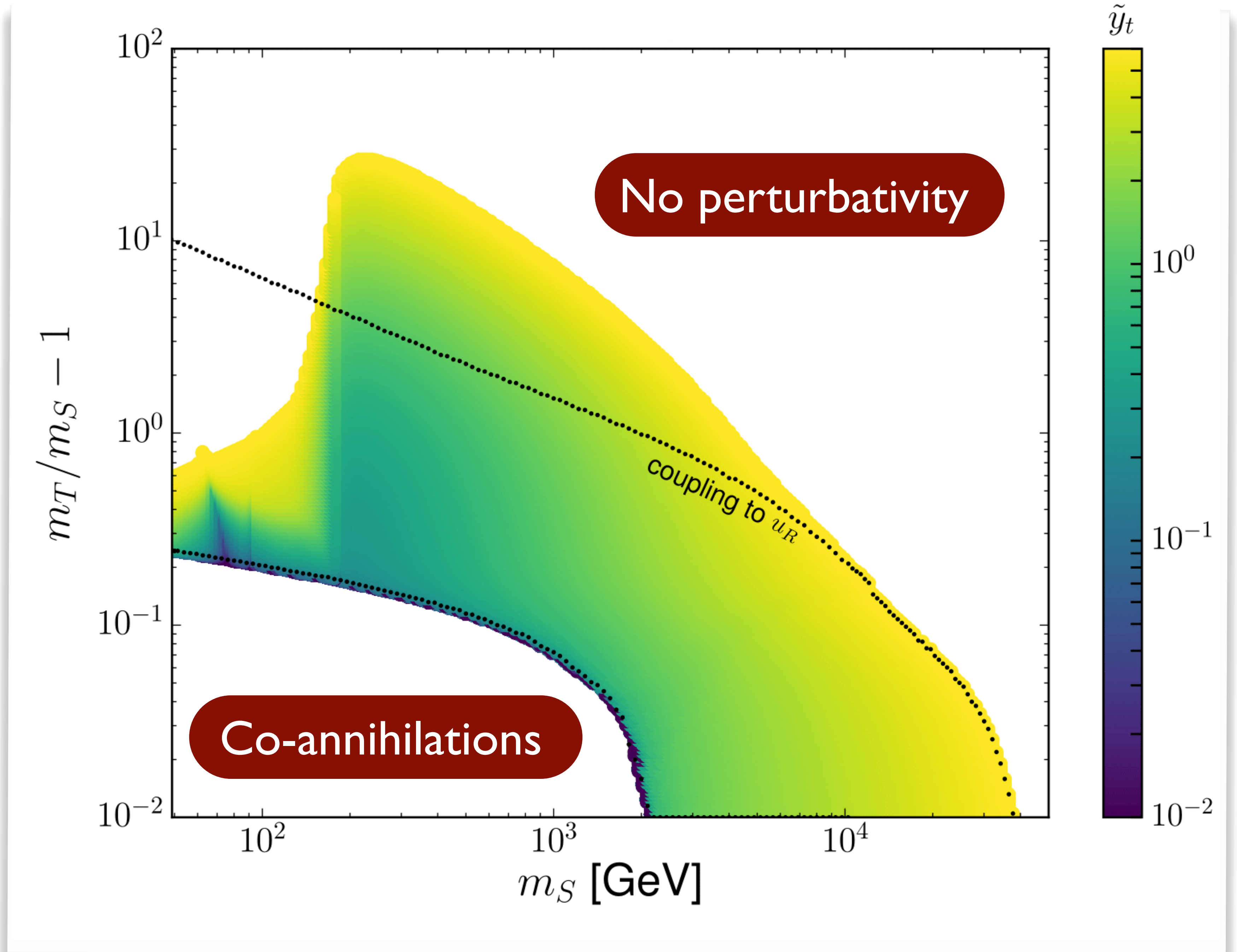


## Scan of the 3D parameter space (2 masses + 1 Yukawa)

- NLO QCD corrections included in the predictions
- Coloured point ≡ viable scenario
  - ➞ $\tilde{y}_t$ value such that:

$$\Omega_{\rm DM} h^2 = 0.12$$ [ Planck Collaboration (AA`20) ]

$$\tilde{y}_t \in [10^{-3}, 6]$$

  - ➞ correct co-annihilation treatment (min value)
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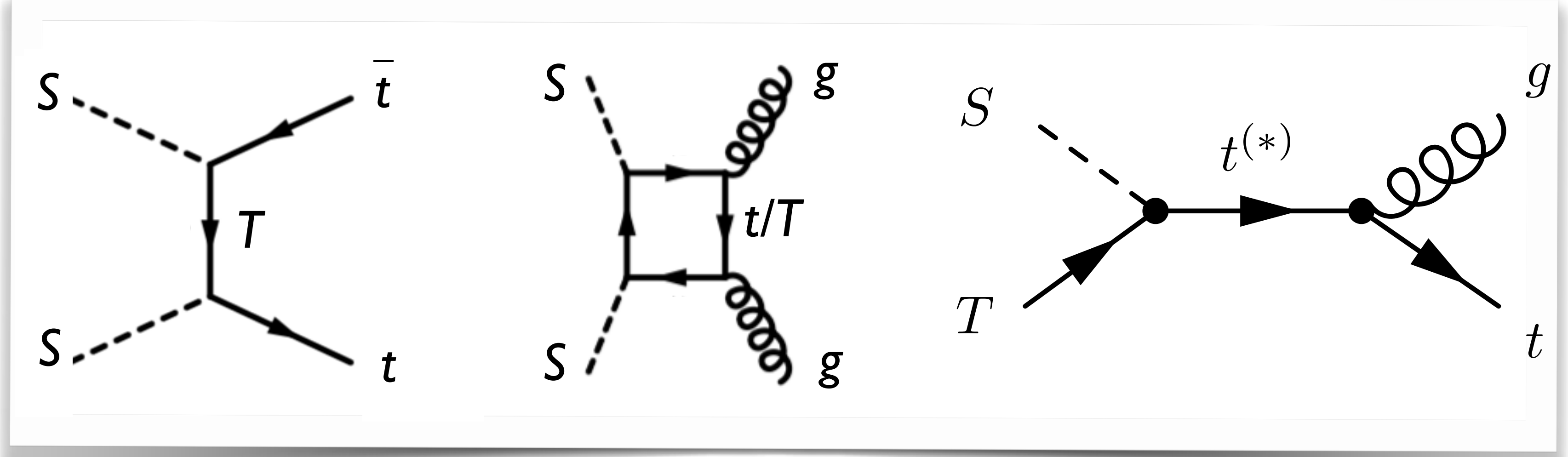


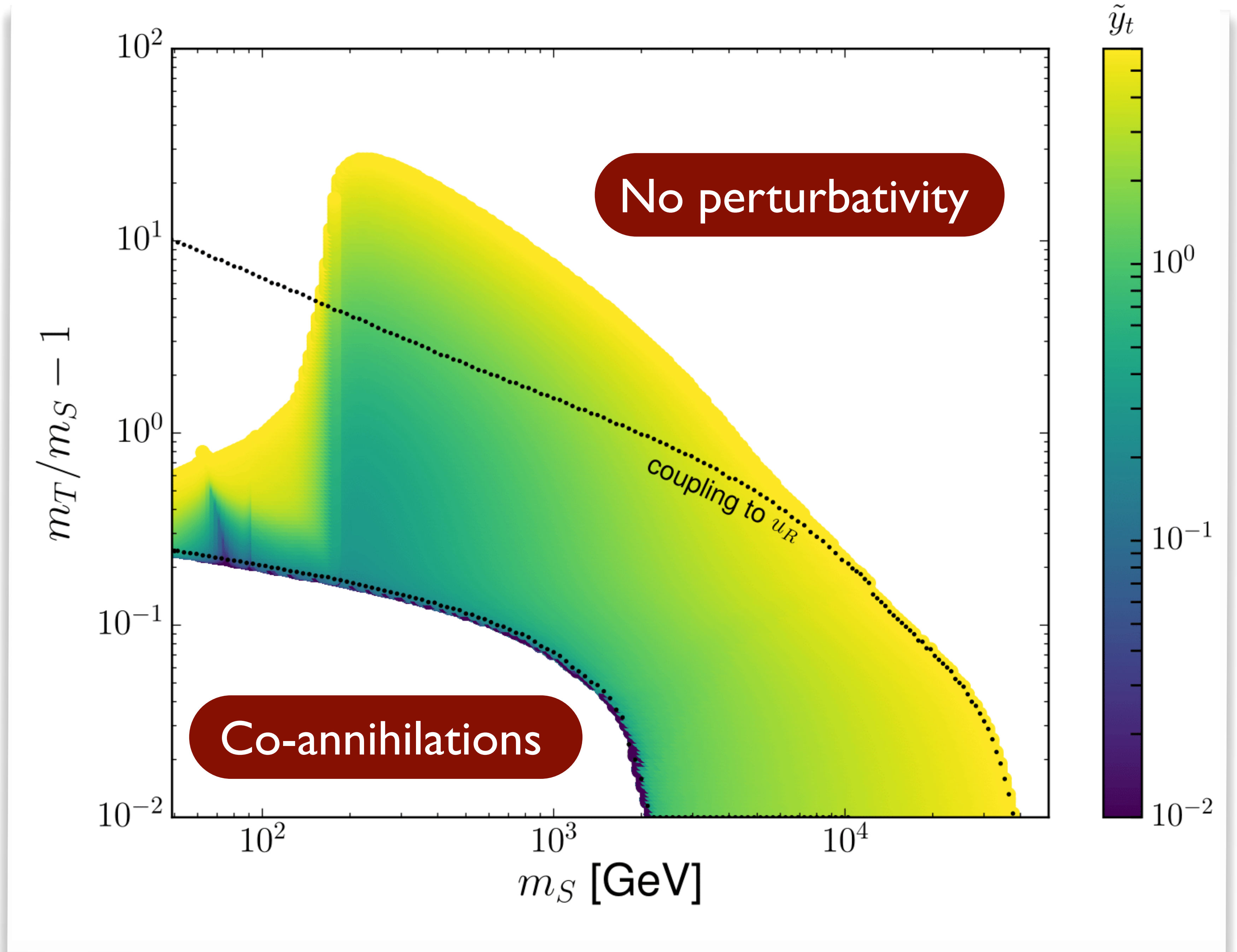


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Large viable parameter space region from the relic standpoint

# Relic abundance – Multi-TeV DM

[ Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD'18) ]

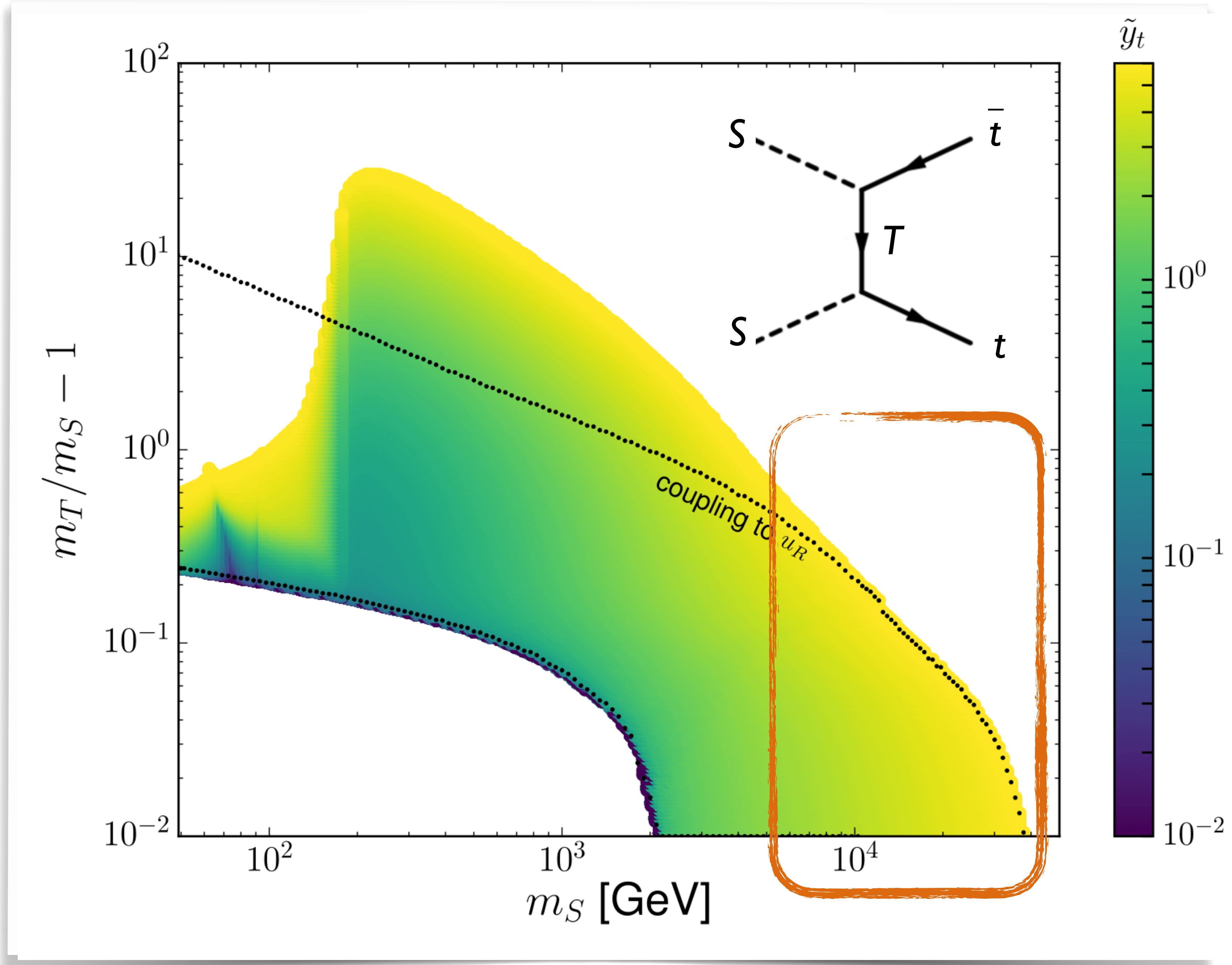
## Very heavy DM regime ($m_S$ > 5 TeV)

- Dominating annihilations into tops

$$(\sigma v)_{\rm NLO} \approx (\sigma v)_{\rm LO} \left[1 + \frac{\alpha_s C_F}{\pi}\left(\frac{9}{4} - \frac{3}{2}\log\frac{M_S^2}{m_t^2}\right)\right]$$

★ Top-mass effects negligible (*cf.* black curve)

★ Velocity-independent ($v$ ~ 1)



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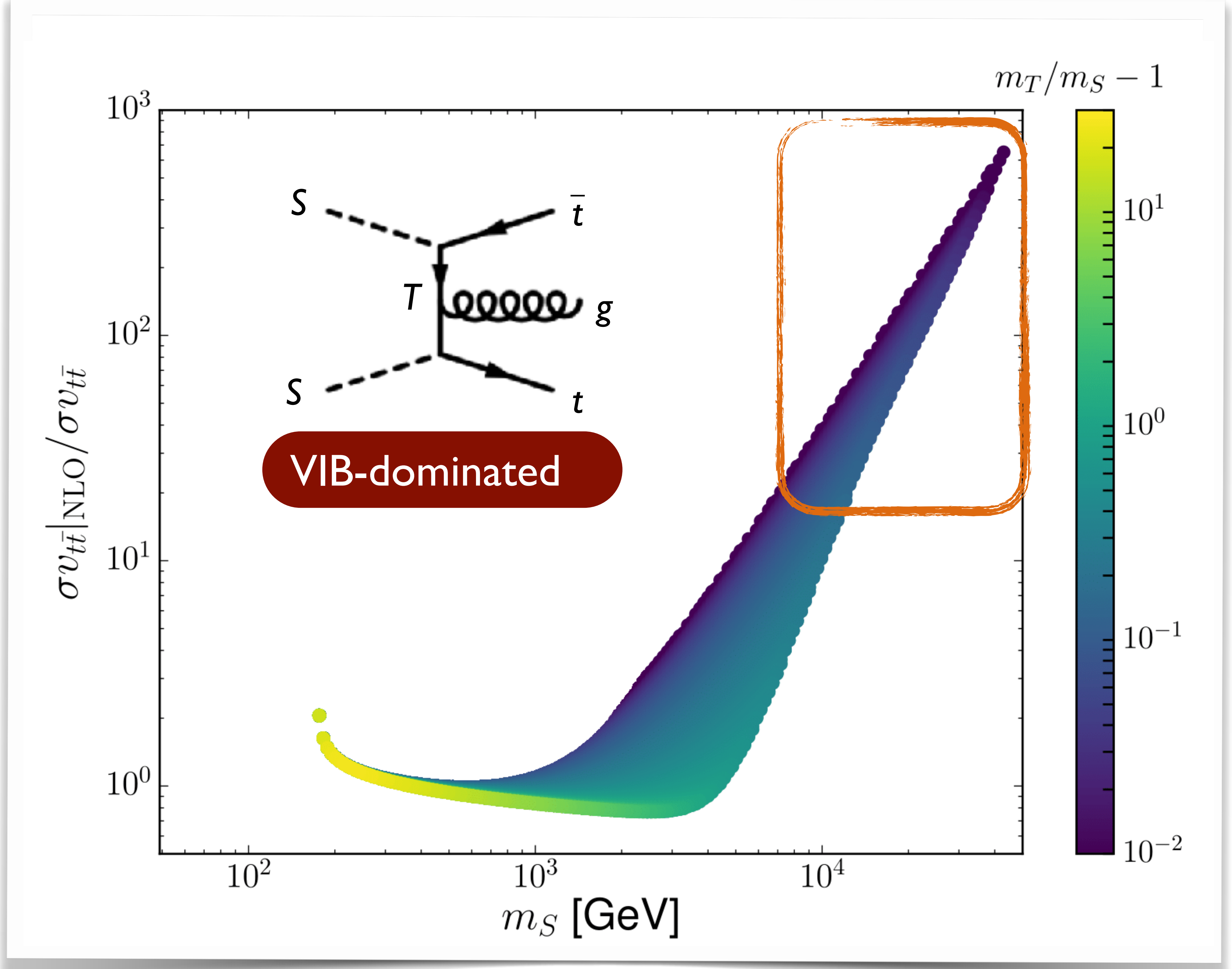


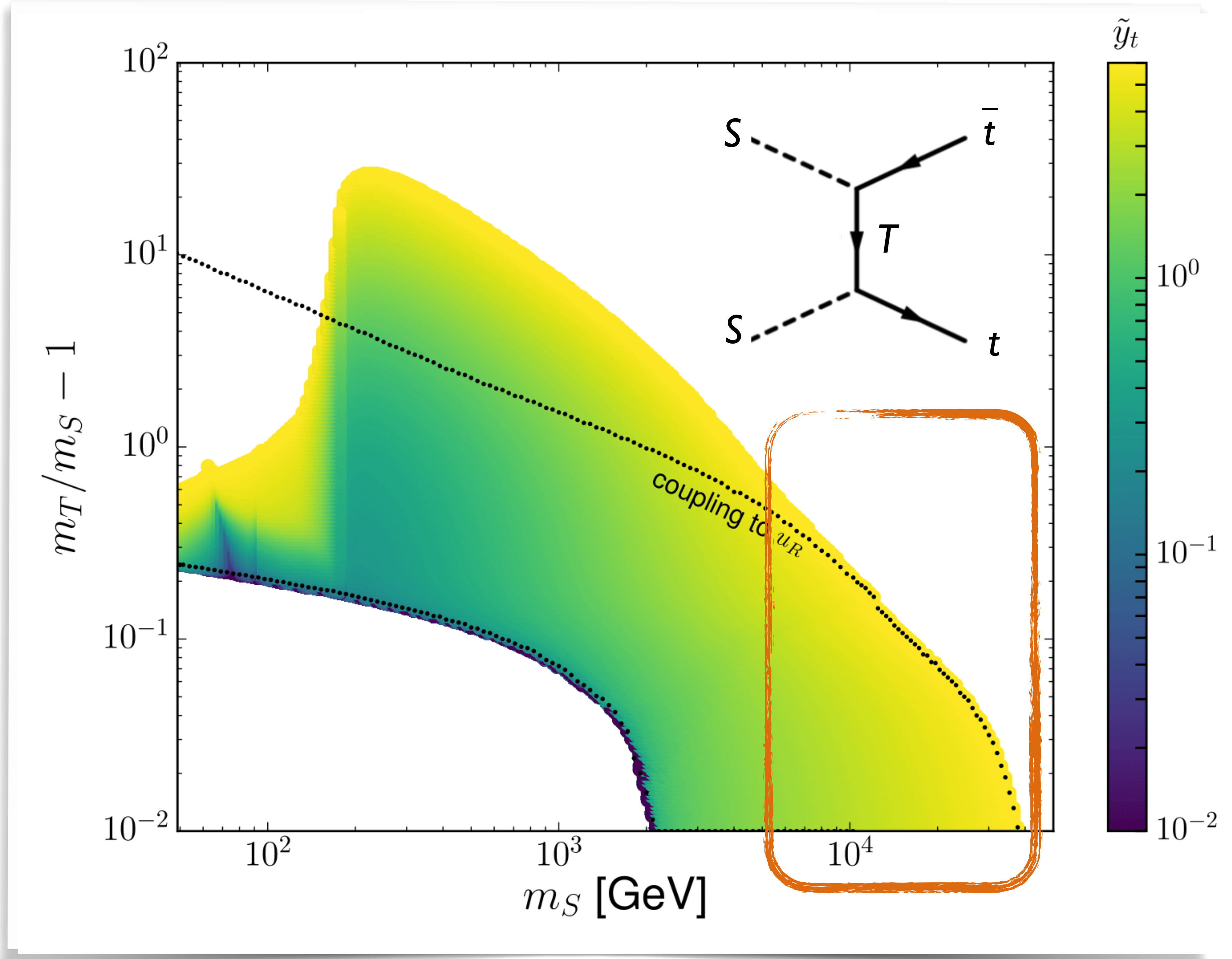


## NLO QCD impact (for $m_S$ > 5 TeV)

- Huge QCD *K*-factors!
- Virtual internal bremsstrahlung (VIB) [ $\propto$ $(m_T/m_S)^{-4}$ ]

# Relic abundance – Other scenarios ($m_S$ < 5 TeV)

[ Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD'18) ]

DM regime in which $m_t < m_S <$ 5 TeV

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★ Explicit velocity dependence
➙ Not viable close to threshold

- Top mass effects important

★ Opens up a new region (≠ light quarks)
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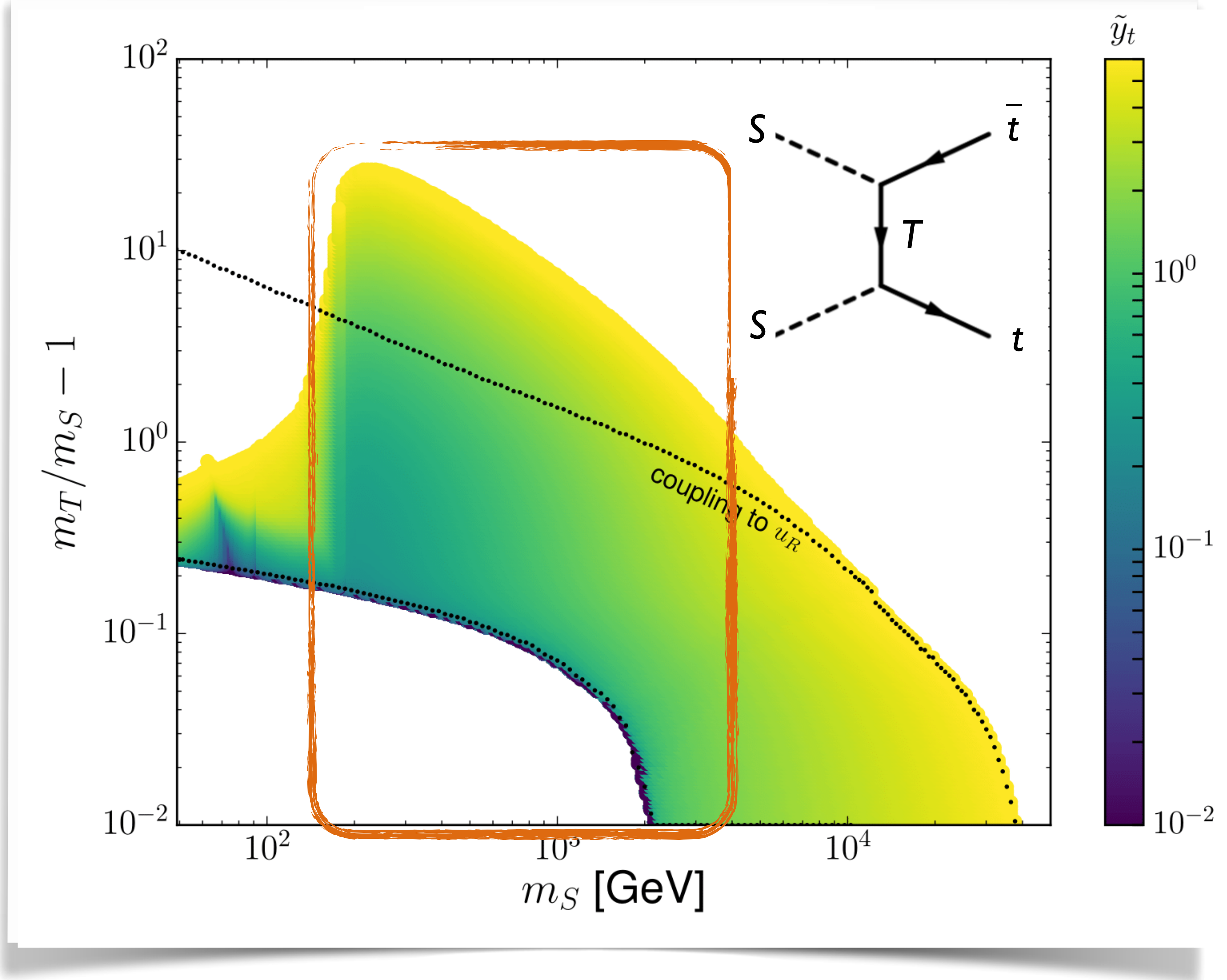

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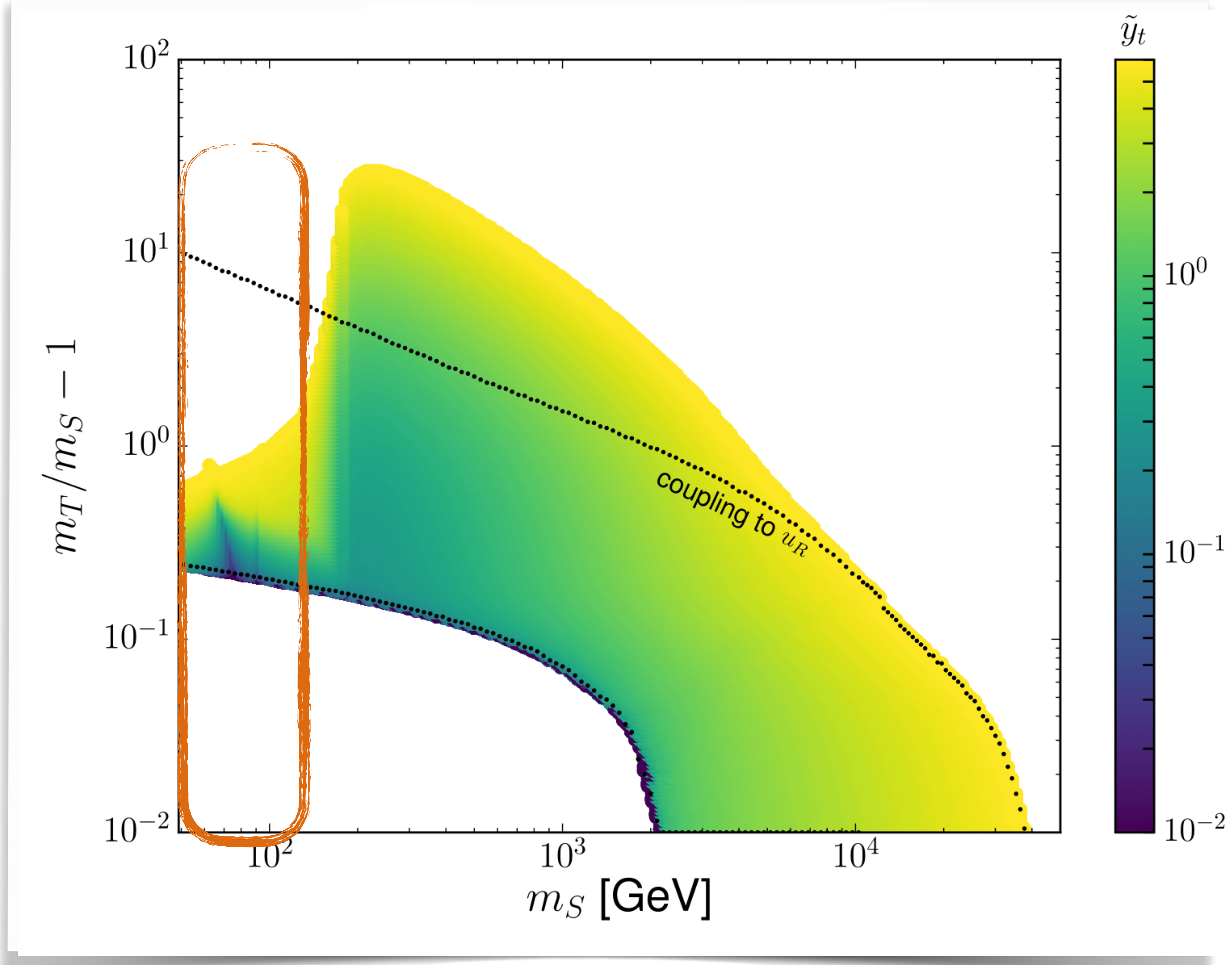
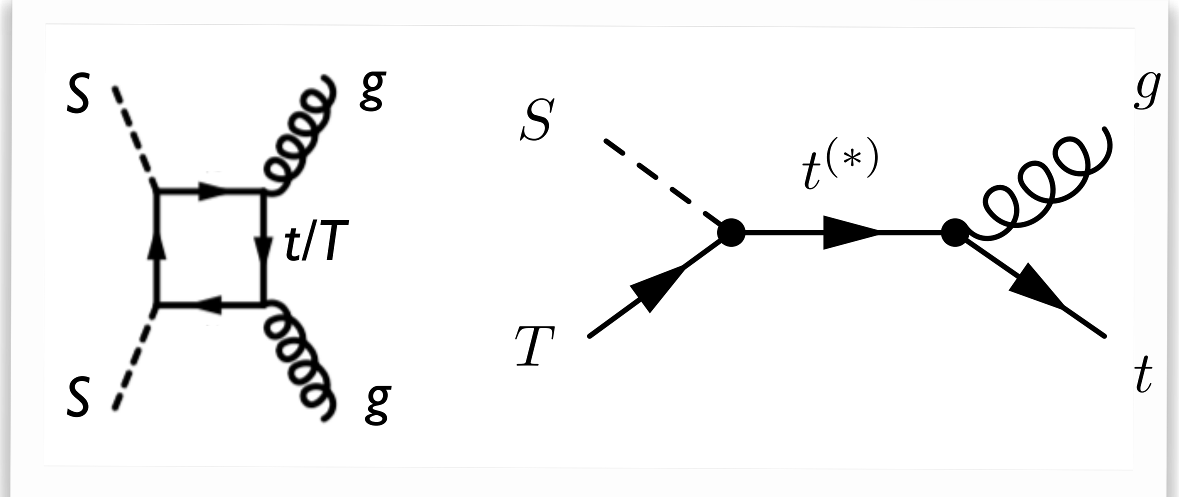



## DM regime in which $m_S < m_t$

- Annihilations in tops closed
  ➙ 3-body annihilations (into $tWb$) if $m_S > (m_t + m_W)/2$
  ➙ Loop-induced $SS \to gg$ annihilations for $m_S < (m_t + m_W)/2$
- Co-annihilations crucial near $m_T + m_S \sim m_t$
  ➙ resonant enhancement ($m_S \sim 75$ GeV)



# Relic abundance: summary

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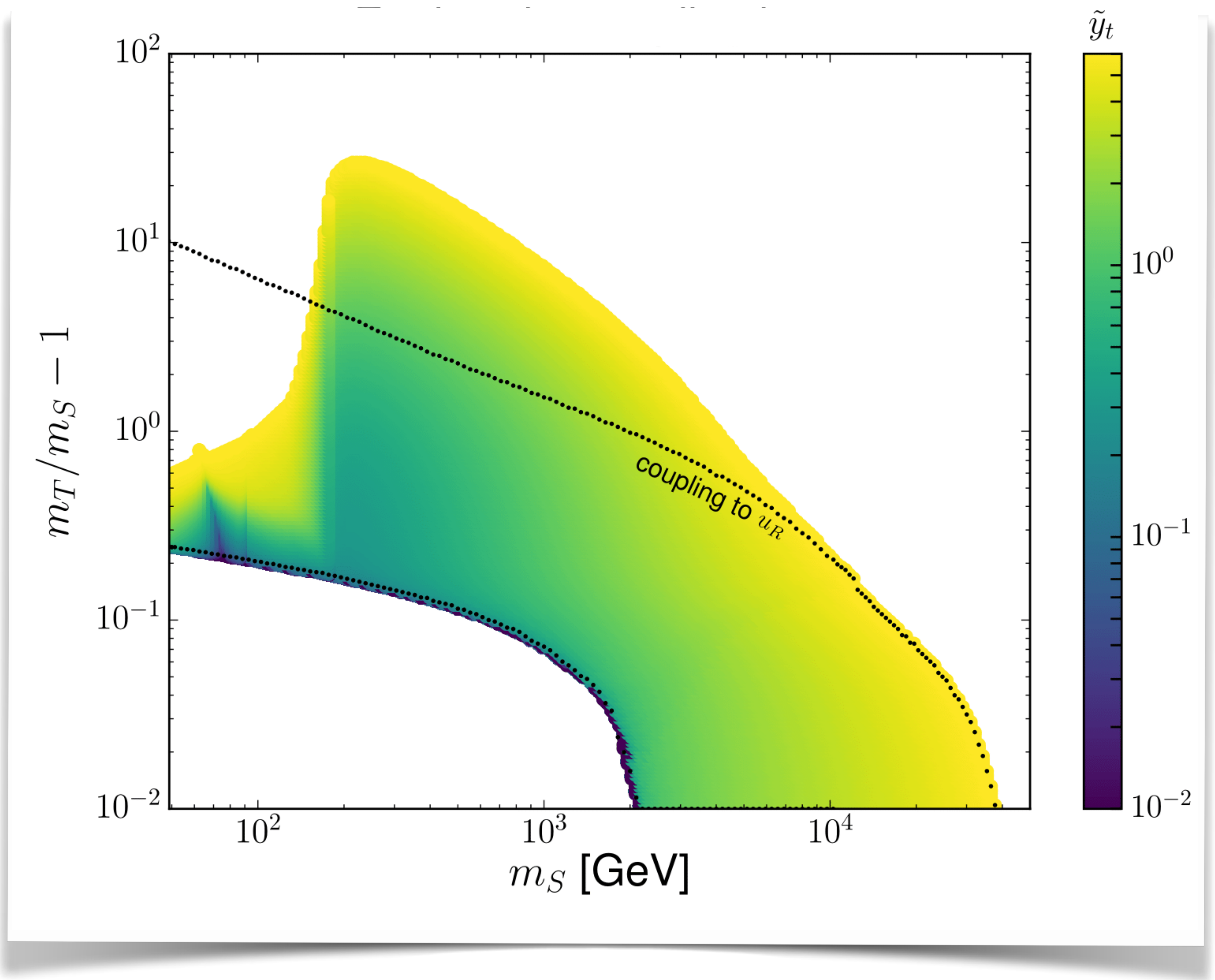



Large variety of acceptable scenarios

- Not all mass combinations allowed
  (because of bounds on the Yukawa coupling)
  ➙ Dark matter masses from 50 to 40000 GeV
- The Yukawa couplings ➙ matching with Planck data

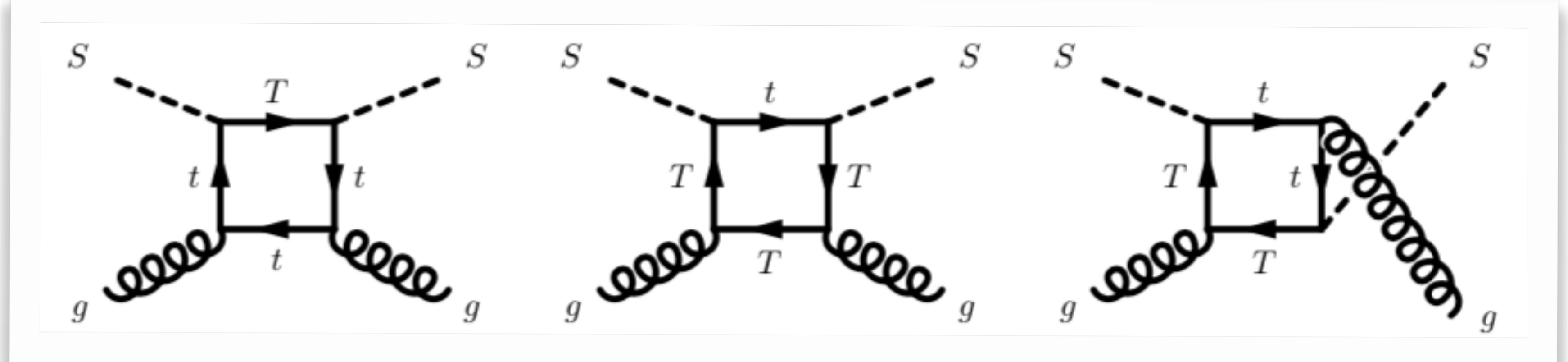
Two free parameters left (the masses)

- What can we learn from DM direct/indirect detection?

# Direct detection: light dark matter

[ Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD'18) ]

## Direct detection in a nutshell




- Effective field theory approach
  - ★$T$ is integrated out
  - ★Full calculation if $T$ is light

$$\langle N| \frac{\alpha_s}{\pi} G_{\mu\nu} G^{\mu\nu} |N\rangle$$

- $StT$ couplings ➙ $g$-DM coupling ➙ nucleon-DM couplings
  - ★Including form factors
- Direct detection constraints on the simplified model

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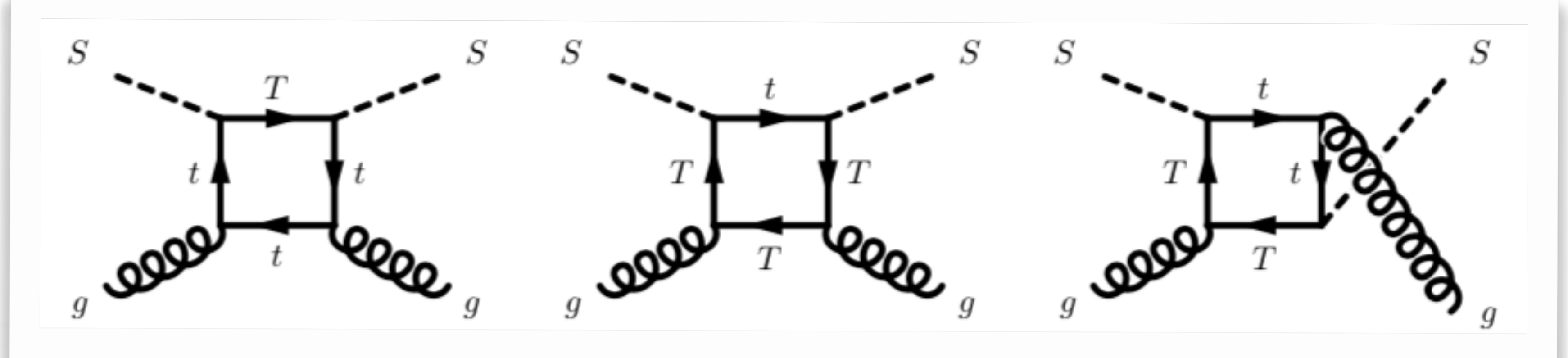


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## Mild constraints expected from DM direct detection

- Loop-suppressed process (DM-gluon scattering)
- Small scattering cross section

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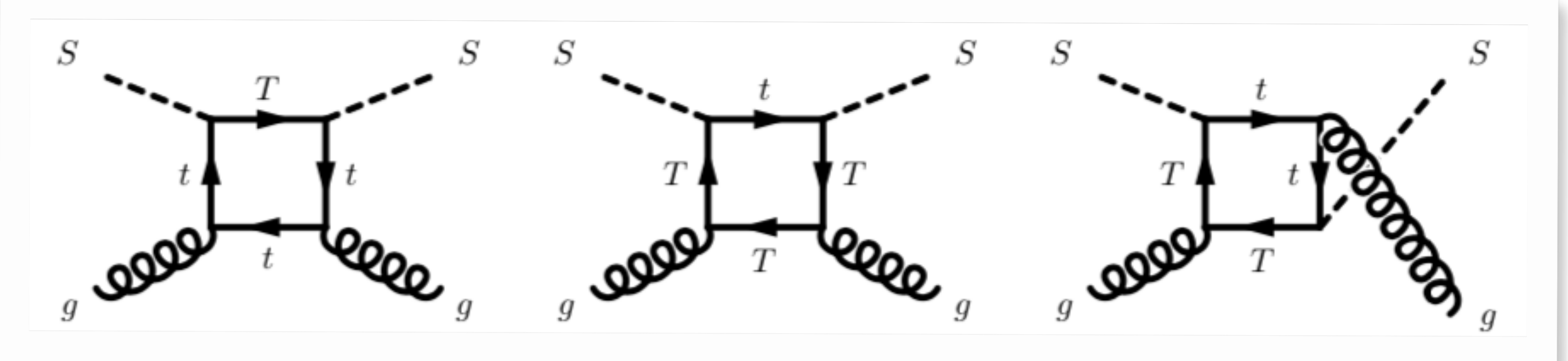

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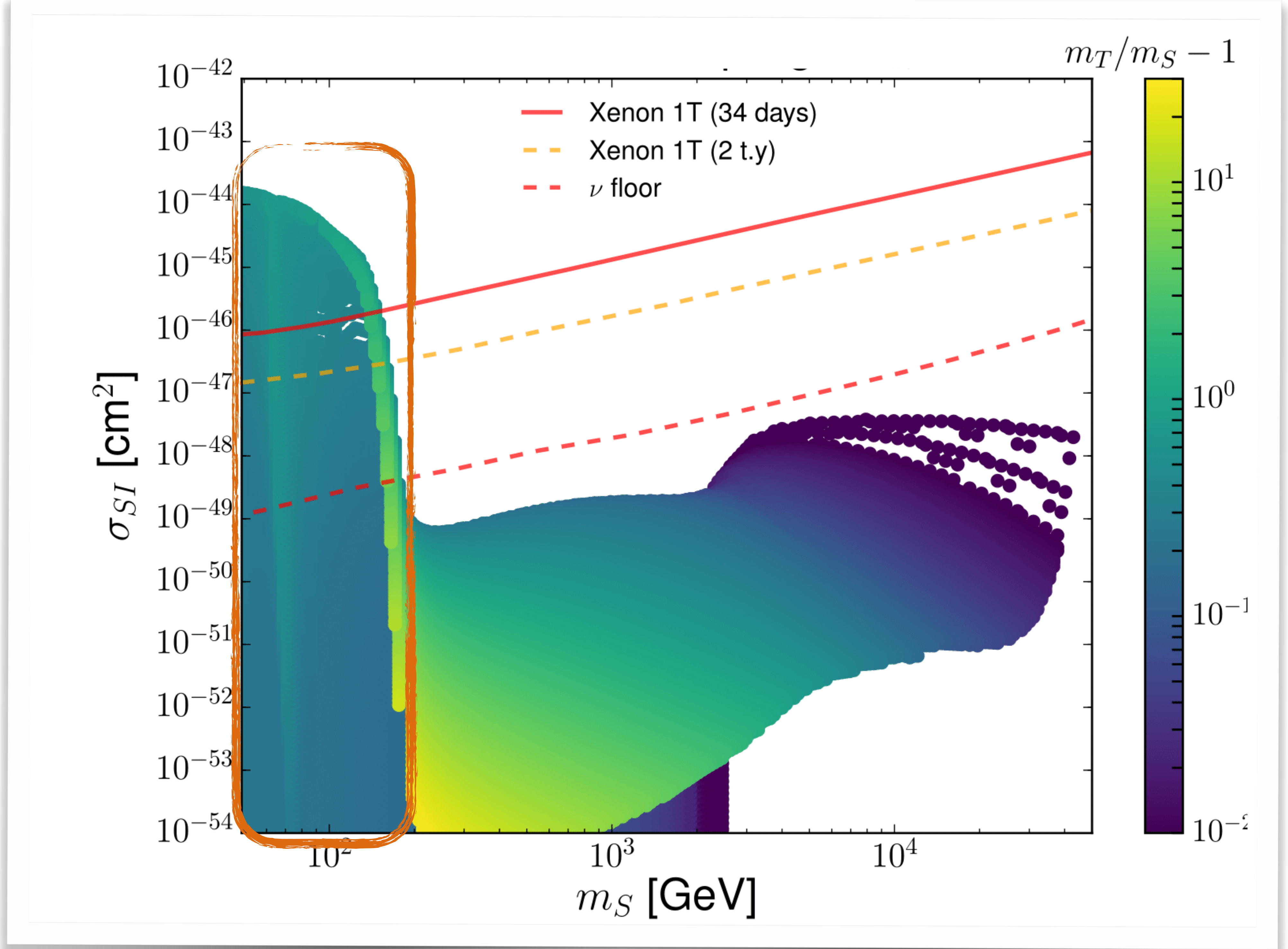


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## Some constraints on light DM

- $SS \to gg$ relevant for the relic density
  ➙ especially for $m_S < (m_t + m_W)/2$
- Yellow band at ~ 75 GeV
  ➙ $ST \to t$ resonant co-annihilation regime

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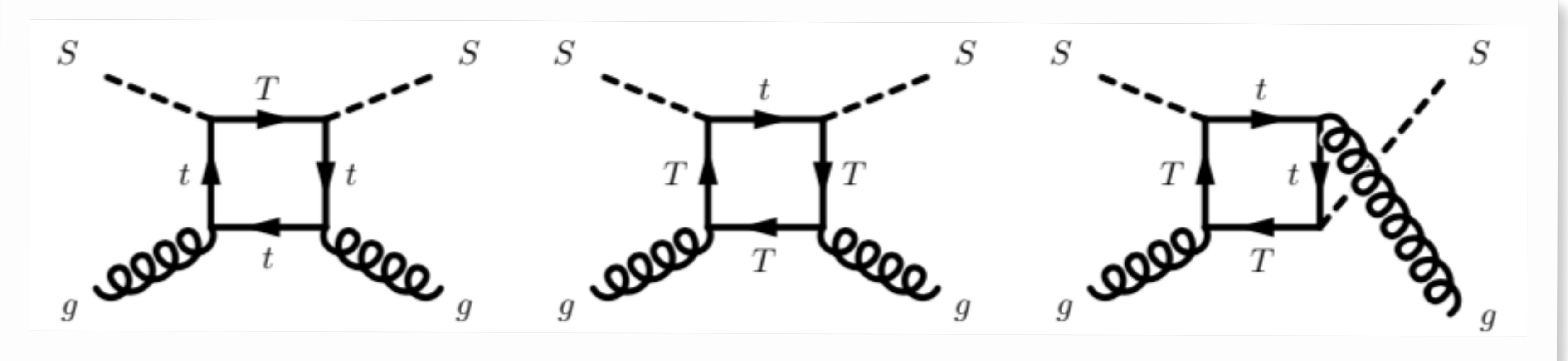

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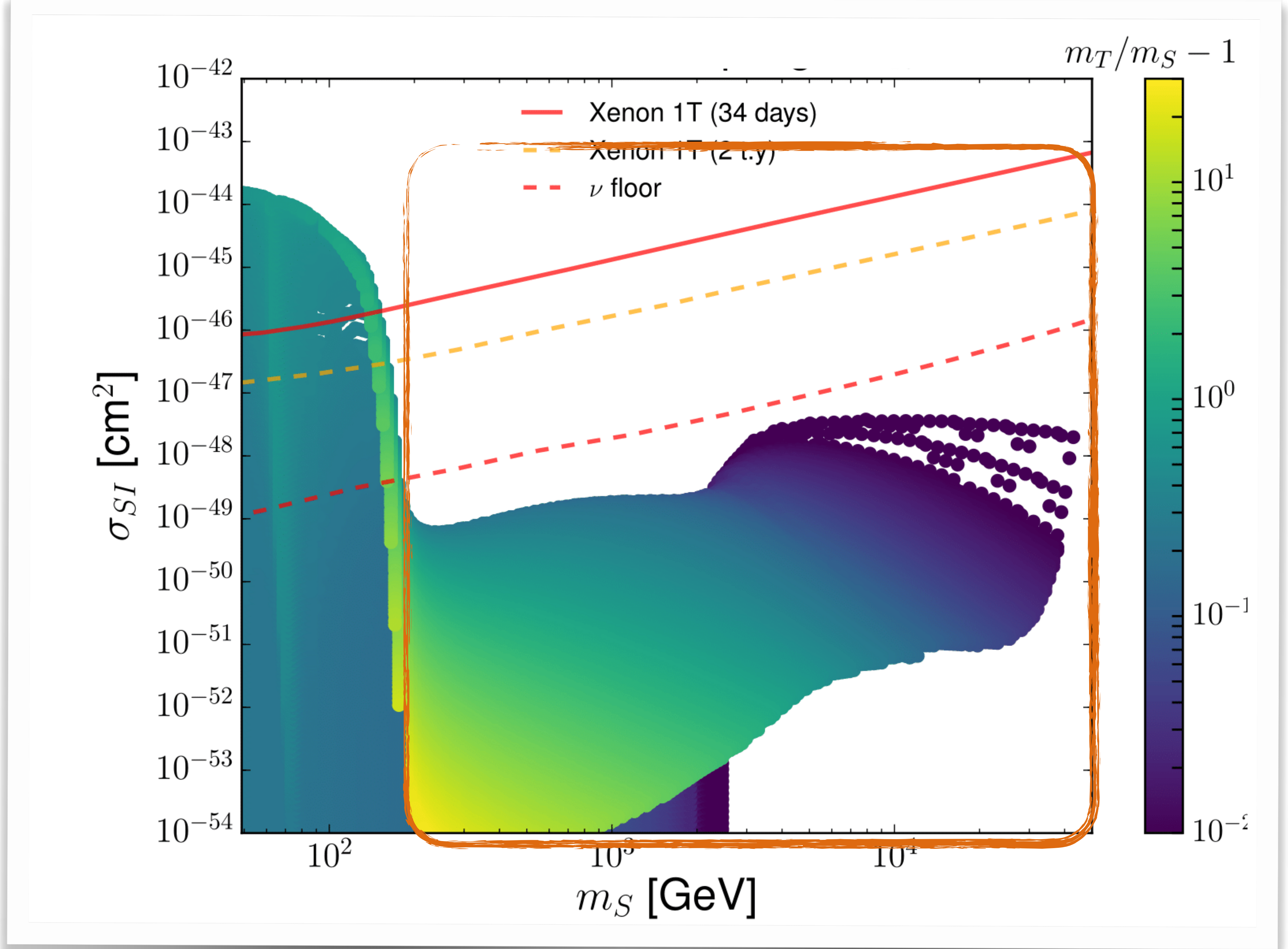


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## No constraints on heavy DM

- $SS \to gg$ negligible
- Large suppression (masses, Yukawa)
  - ➙ Most parameter space below the $\nu$ floor

# Indirect detection: annihilations in tops/gluons

[ Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD'18) ]

## Secondary photon flux from DM annihilations

- Derivation of associated gamma ray continuum from $b\bar{b}$

$$\sigma v_{gg,t\bar{t}} = \sigma v_{b\bar{b}} \frac{N_\gamma^{b\bar{b}}}{N_\gamma^{gg,t\bar{t}}}$$

with $N_\gamma^X \equiv$ nr of $\boldsymbol{\gamma}$ from an $X$ state

[ Bringmann, Huang, Ibarra, Vogl &Weniger (JCAP`12) ]

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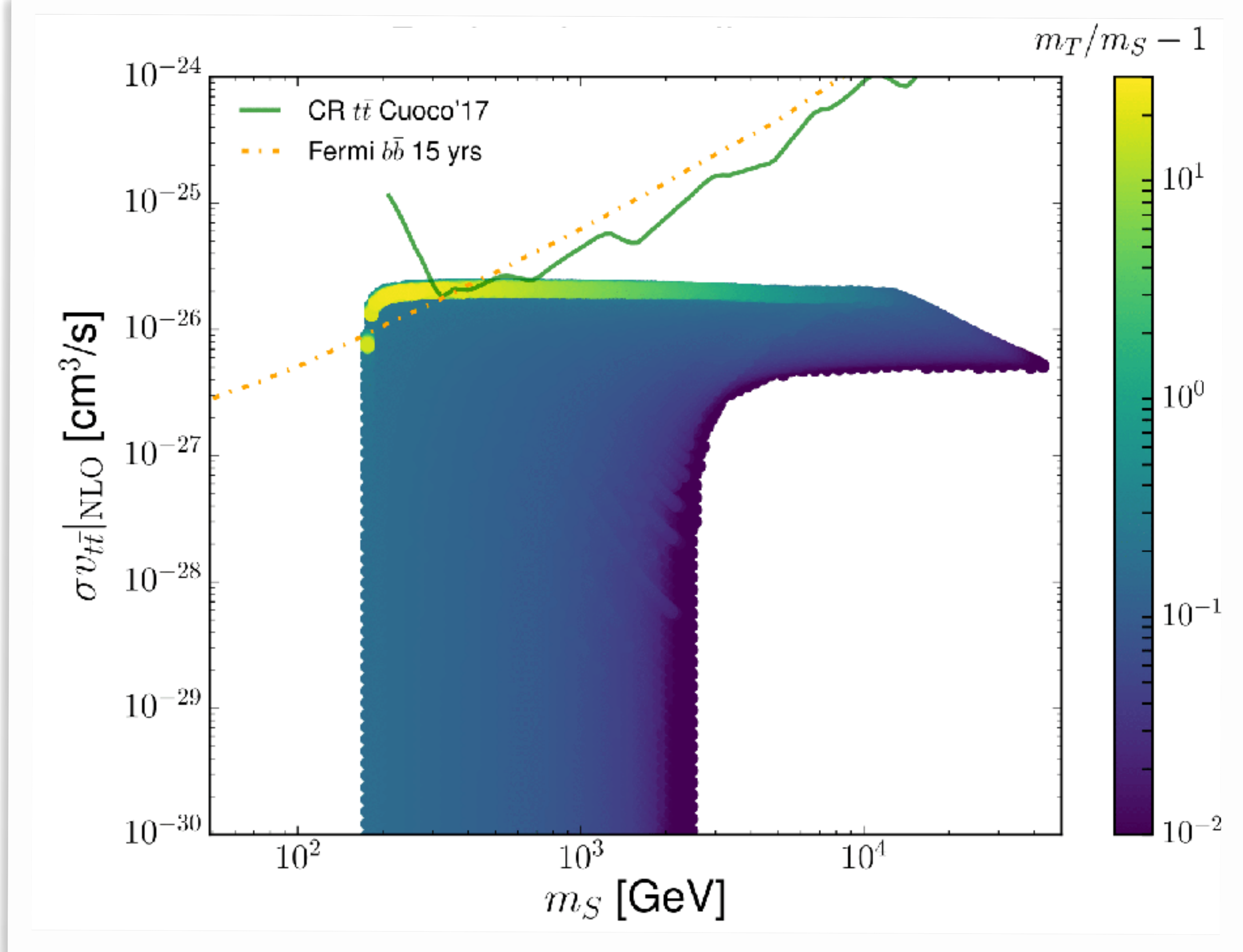
## Constraints

- Mild constraints from Fermi projections (dwarfs)
- Mild constraints from AMS antiprotons



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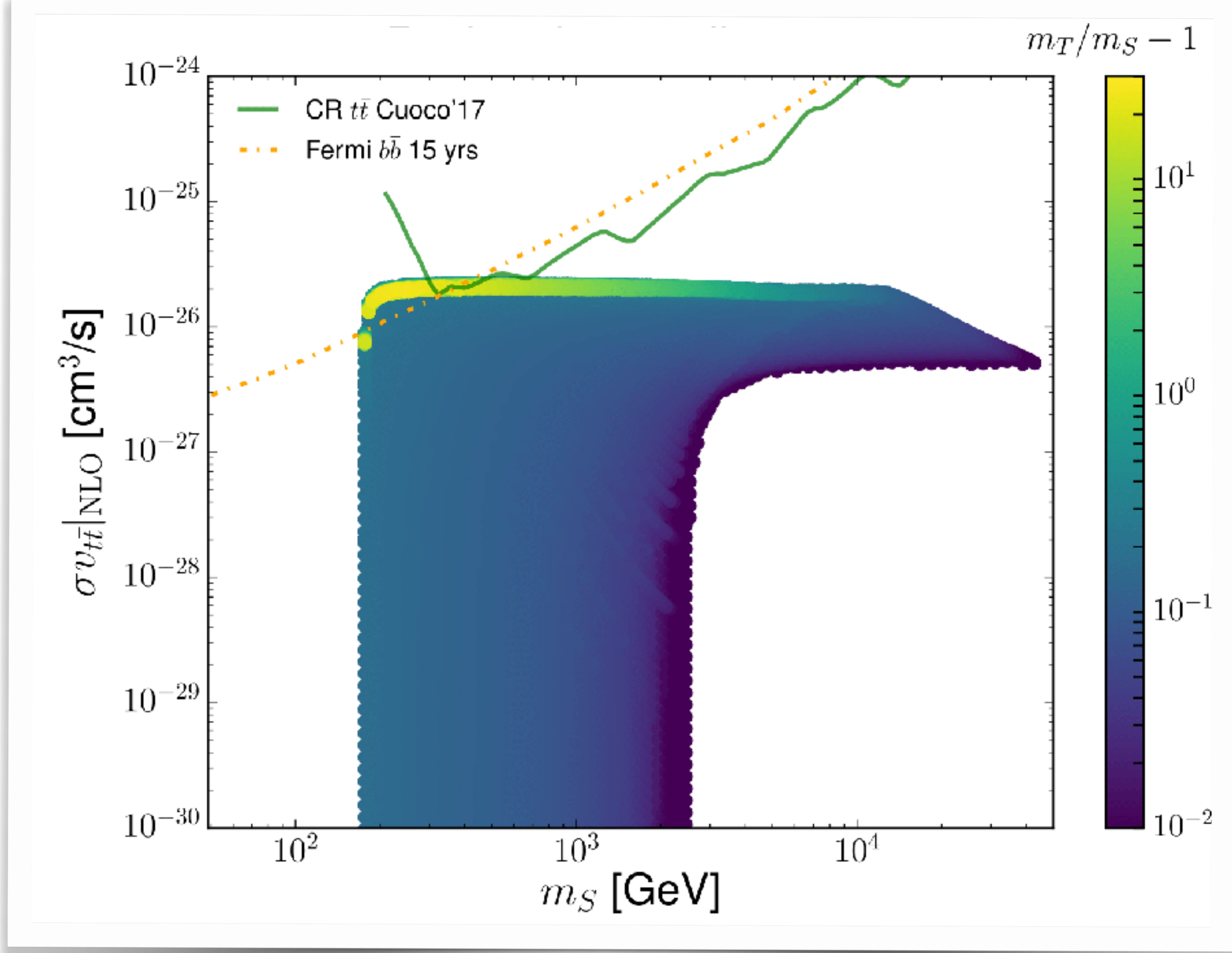


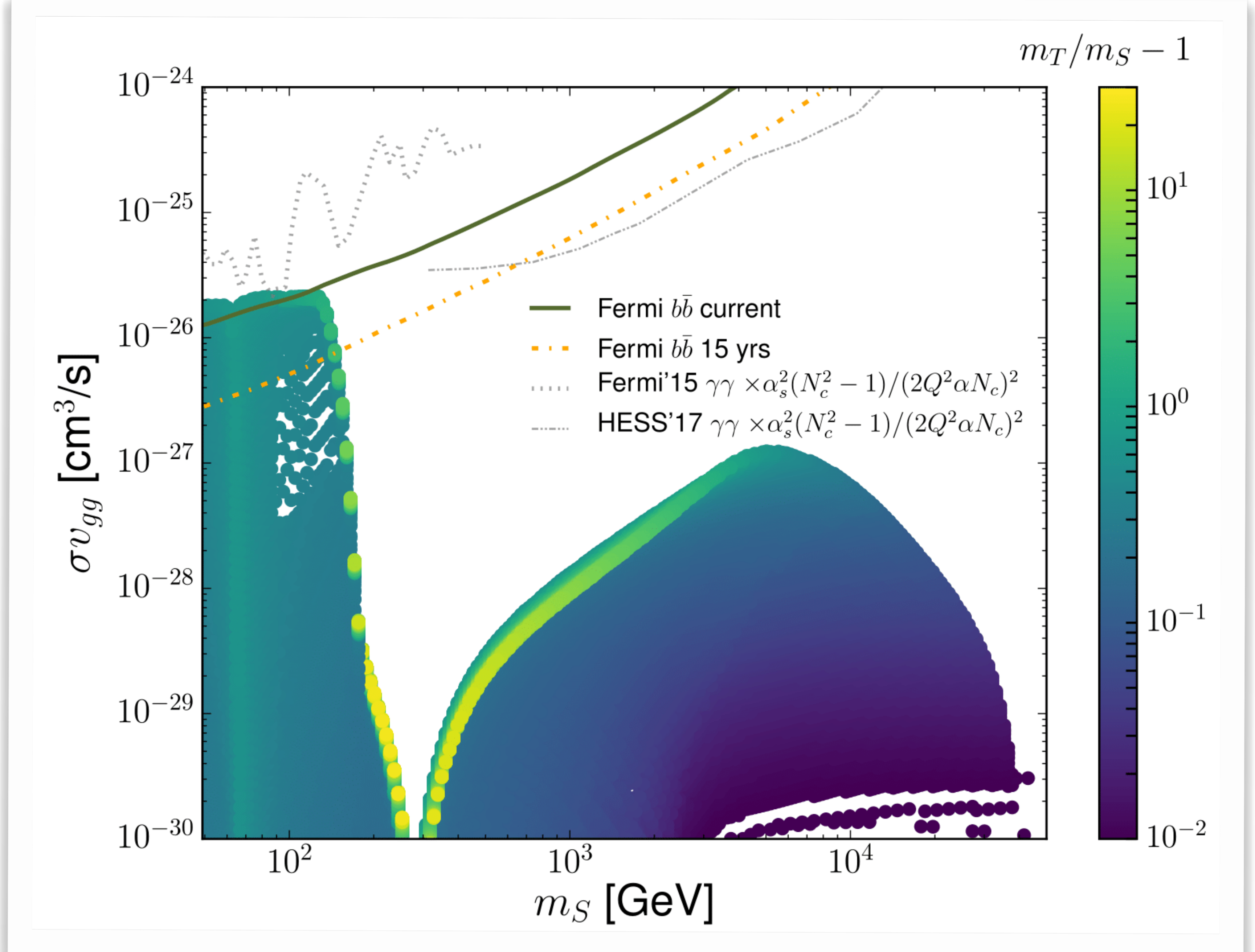


## Direct annihilations into photons

- Where the gg channel dominates:

$$\frac{\sigma v_{\gamma\gamma}}{\sigma v_{gg}} = \frac{4Q^4\alpha^2 N_c^2}{\alpha_S^2\,(N_c^2-1)} \approx 4.3\cdot 10^{-3}$$

- Where VIB dominates:

$$\frac{\sigma v_{t\bar{t}\gamma}}{\sigma v_{t\bar{t}g}} = \frac{2N_c Q^2\alpha}{(N_c^2-1)\alpha_s} \approx 2.3\cdot 10^{-2}$$

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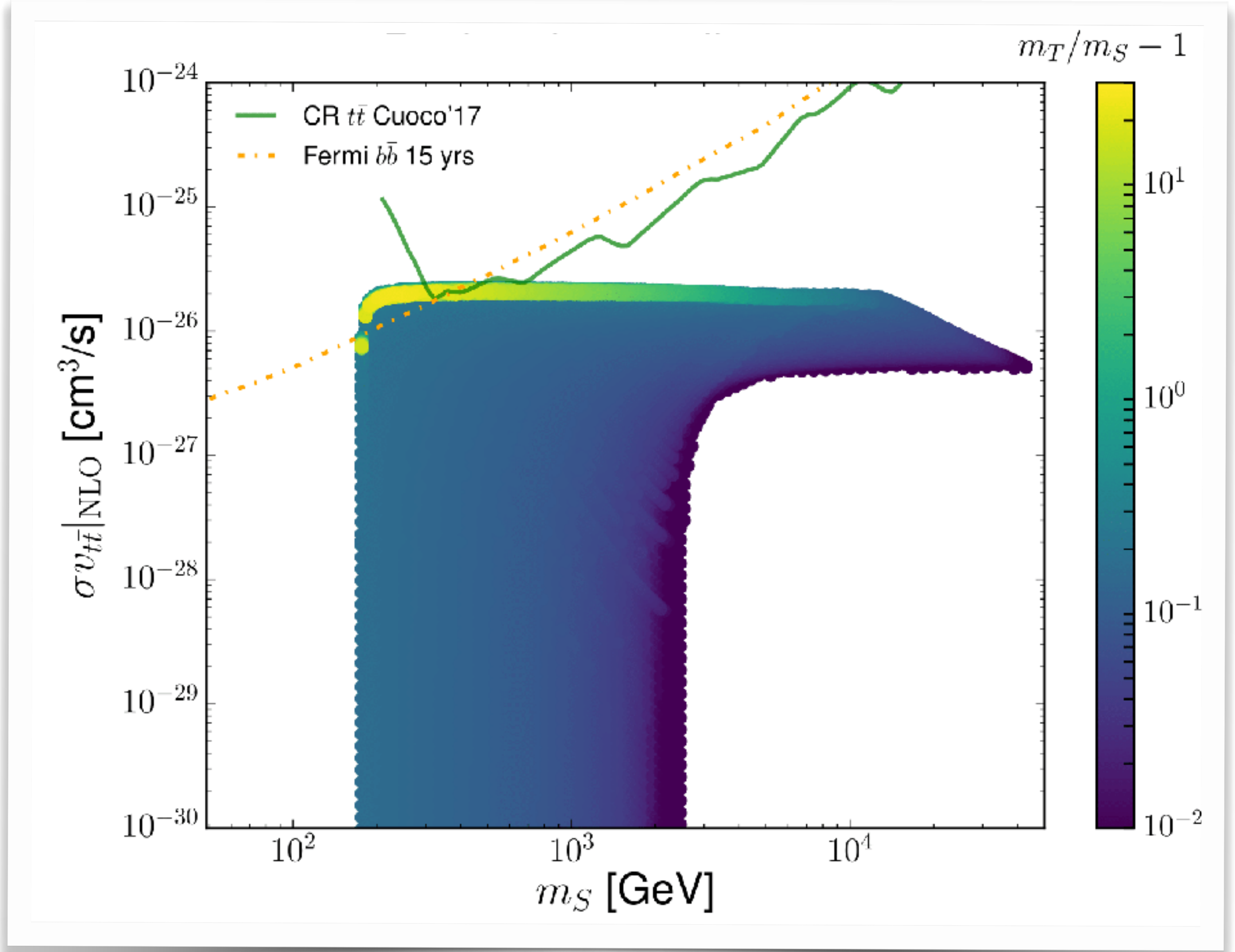


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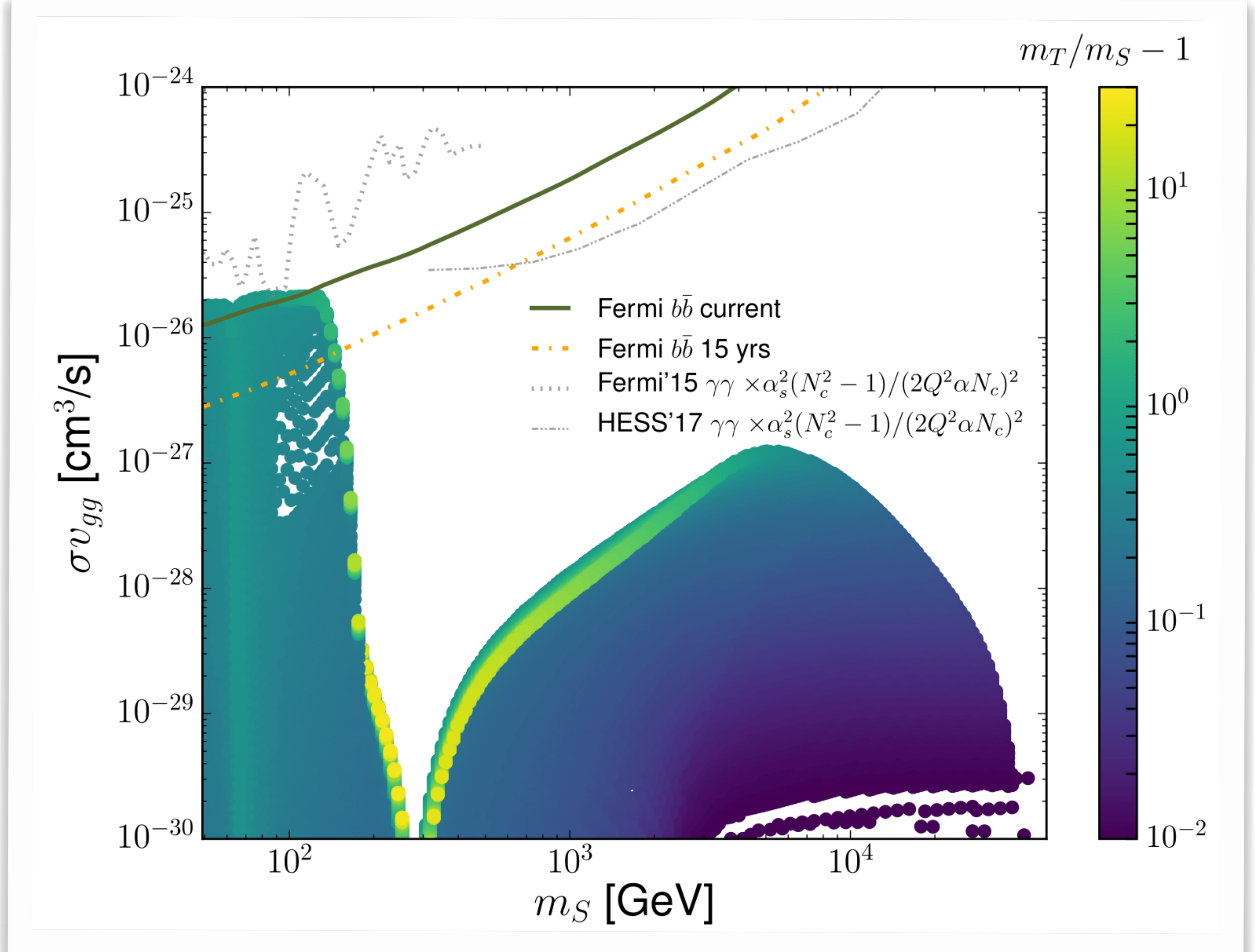


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$$\frac{\sigma v_{t\bar{t}\gamma}}{\sigma v_{t\bar{t}g}} = \frac{2N_c Q^2 \alpha}{(N_c^2-1)\alpha_s} \approx 2.3 \cdot 10^{-2}$$

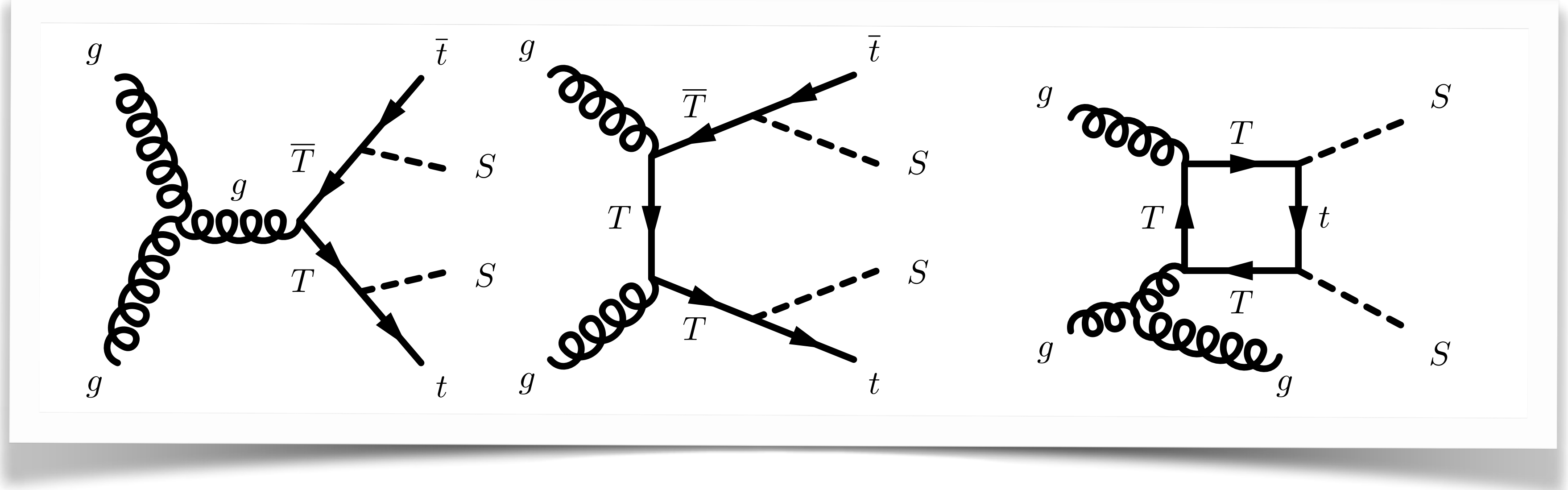
Mild constraints
Indirect detection not so relevant

# Dark matter searches at colliders

[ Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD'18) ]

Two classes of new physics processes at colliders

- Loop-induced DM pair production
- Mediator pair production (with mediator decays into DM + top) [at NLO]



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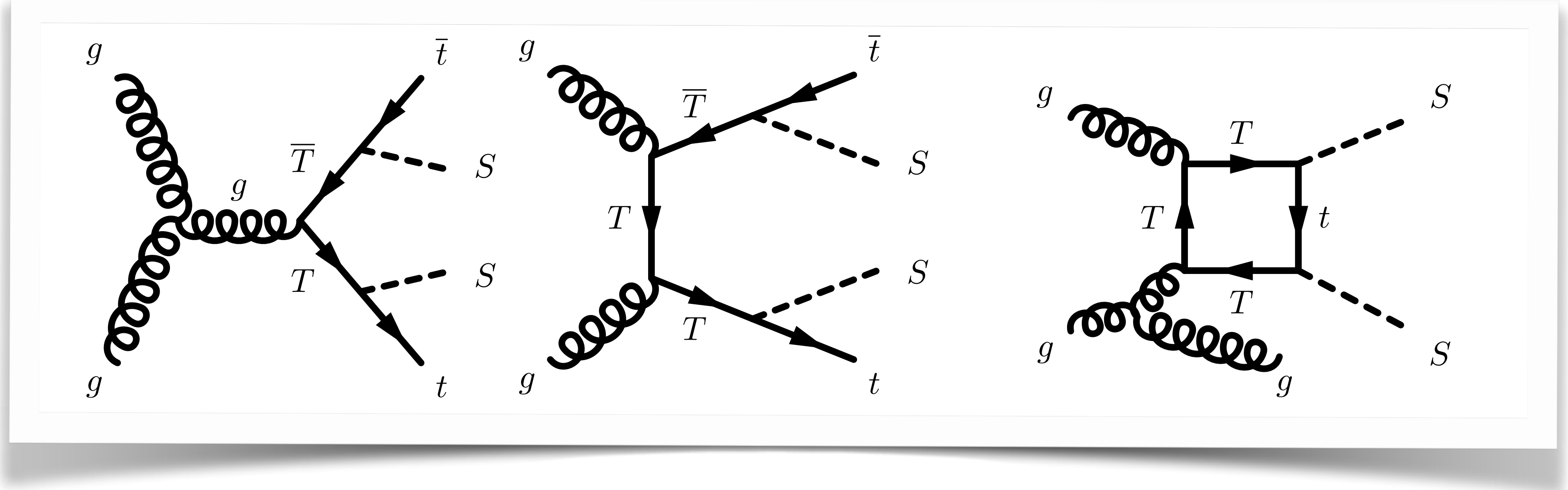


## DM pair production

- Negligible ($SS \to gg$ small for heavy DM)

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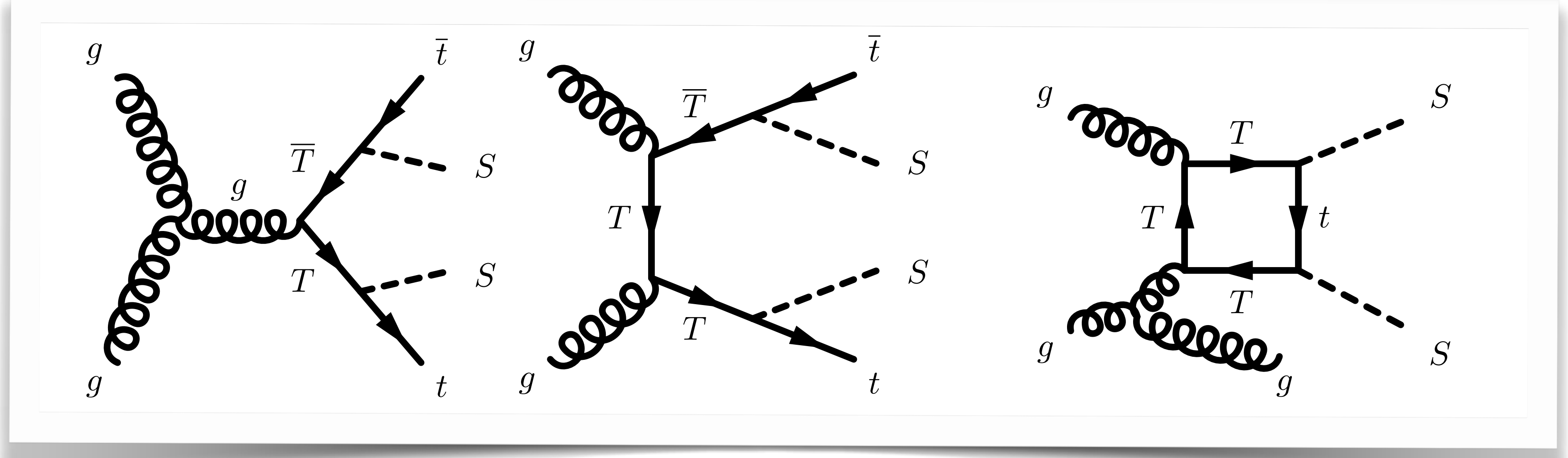


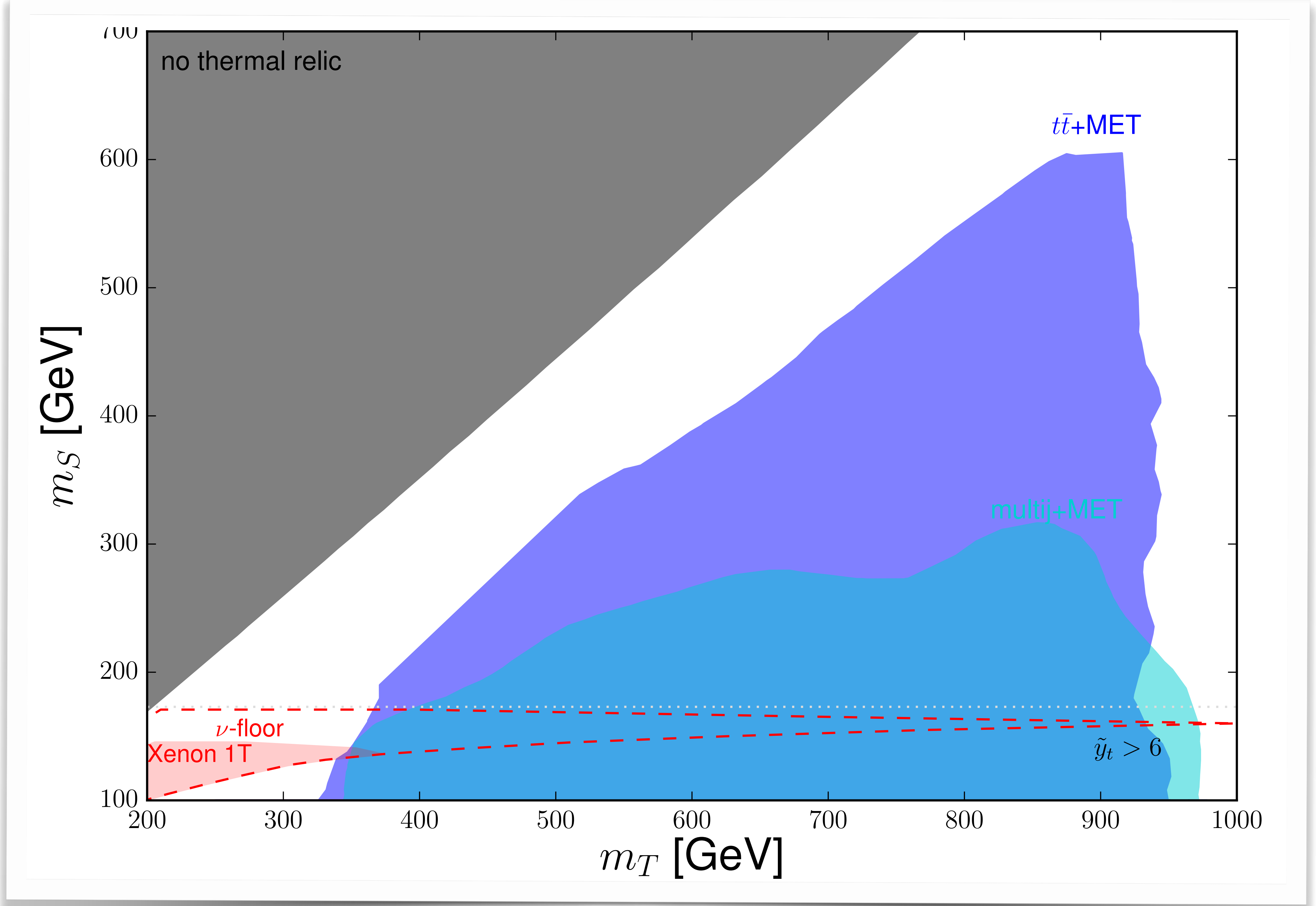


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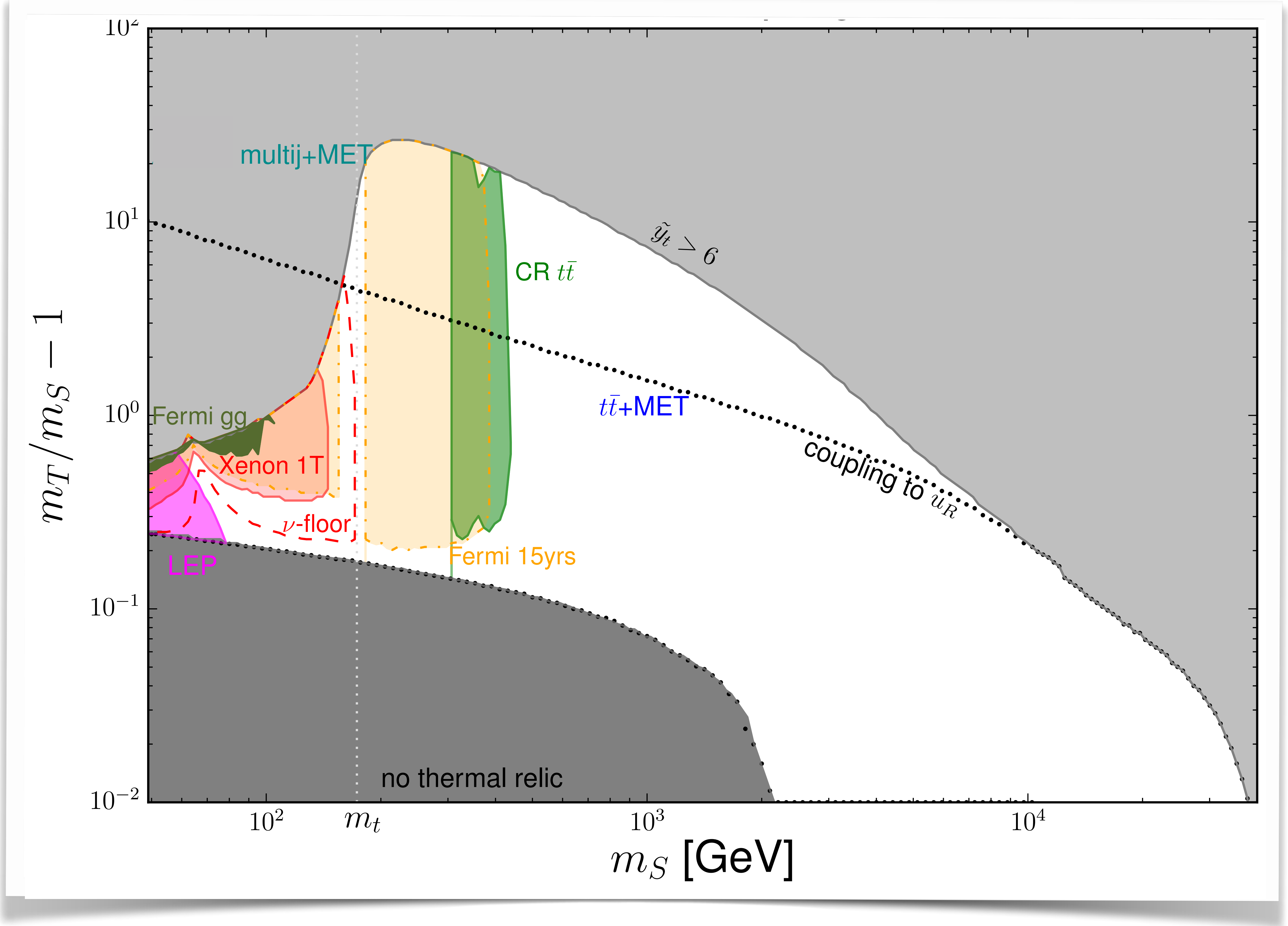
## Bounds from multi-jet+MET and $t\bar{t}$+MET

- Loop-induced DM pair production
- Multi-jet constraints: generic, while specific to $t\bar{t}SS$
  ➞ mild bounds (mono-et like topology)
- $t\bar{t}$+MET constraints: well adapted to the $t\bar{t}SS$ final state
  ➞ best constraints (and chance of discovery)

# Collider-cosmology complementarily at work

[ Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD'18) ]




## Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \Big[\tilde{y}_t\, S\, \bar{T} P_R t + {\rm h.c.}\Big]$$

- ★ Vector-like mediator $T$
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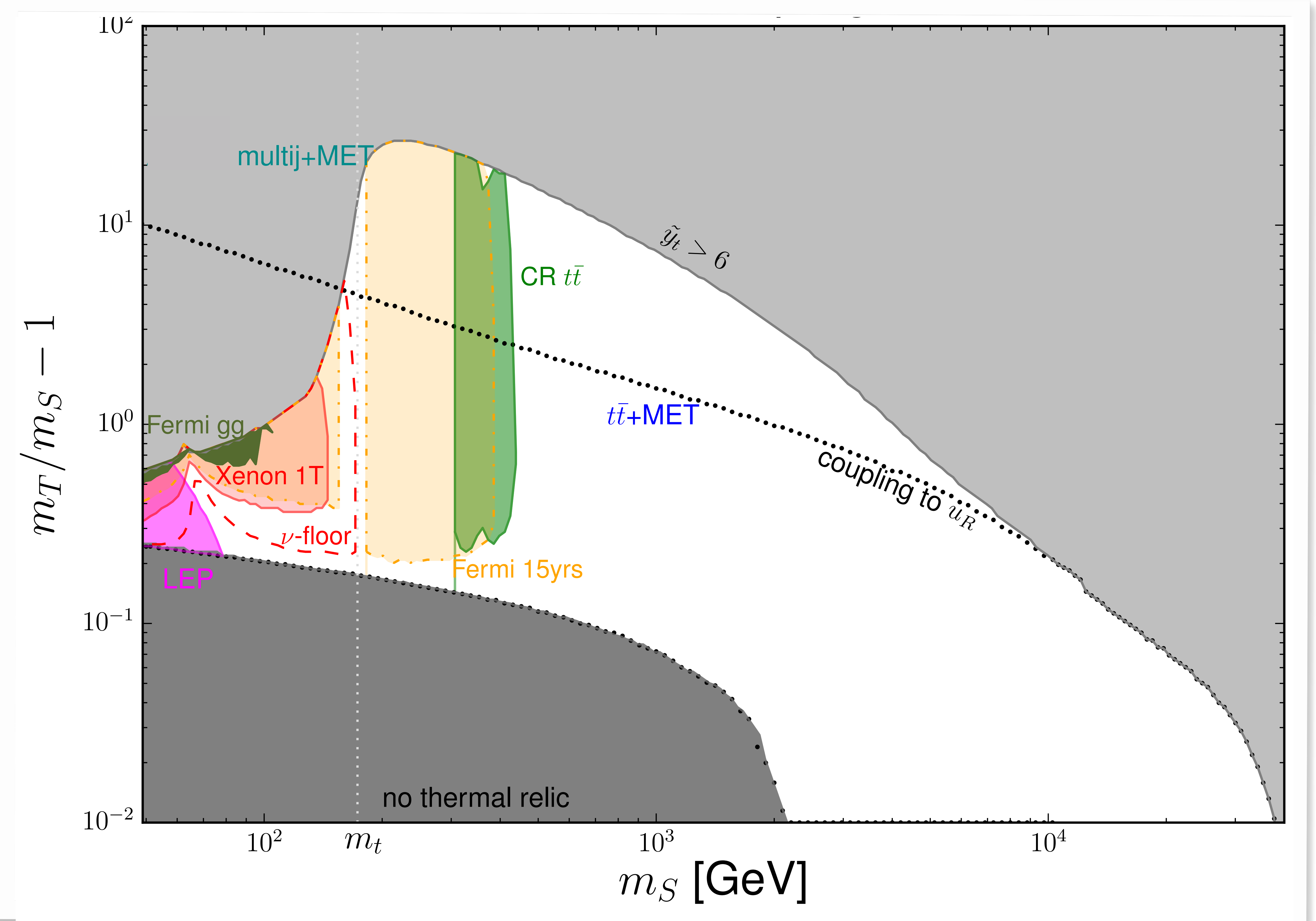


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- Fixes the Yukawa $\tilde{y}_t$
- Dark grey: no thermal relic
- Light grey: loss of perturbativity
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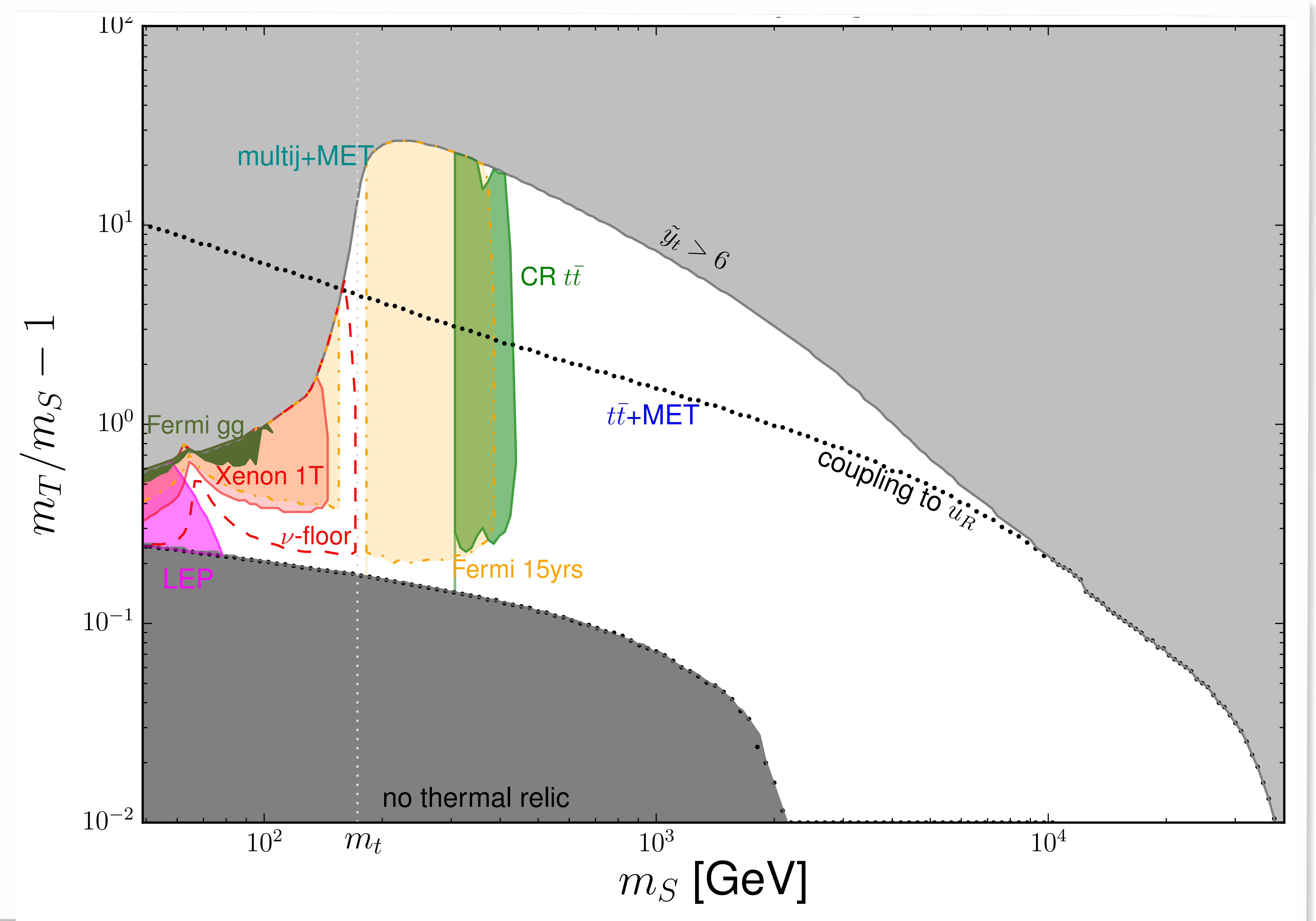


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- DM direct detection constraints
  - ★ Loop-induced process
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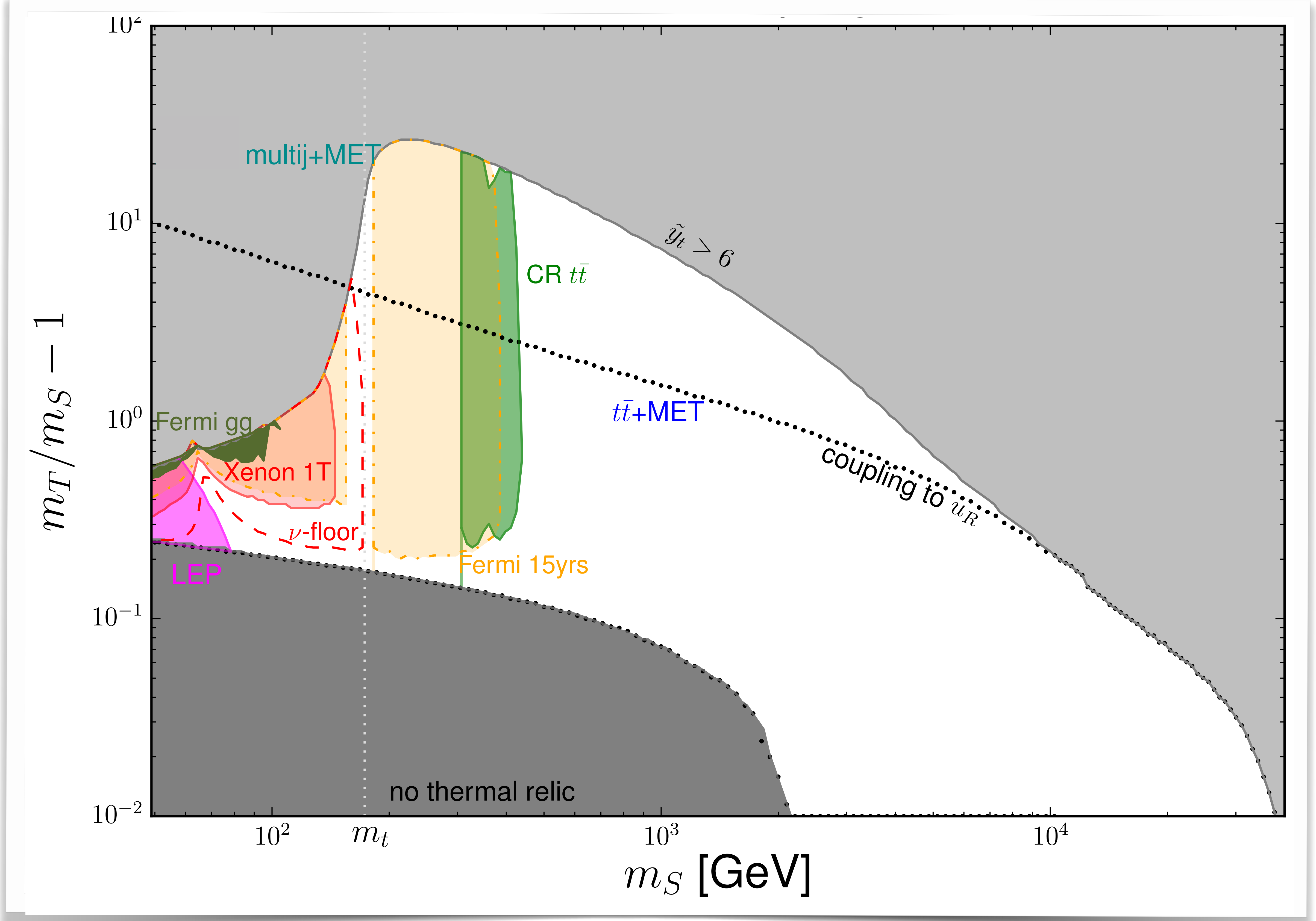


## DM indirect detection: limited sensitivity

- Limited light DM regions

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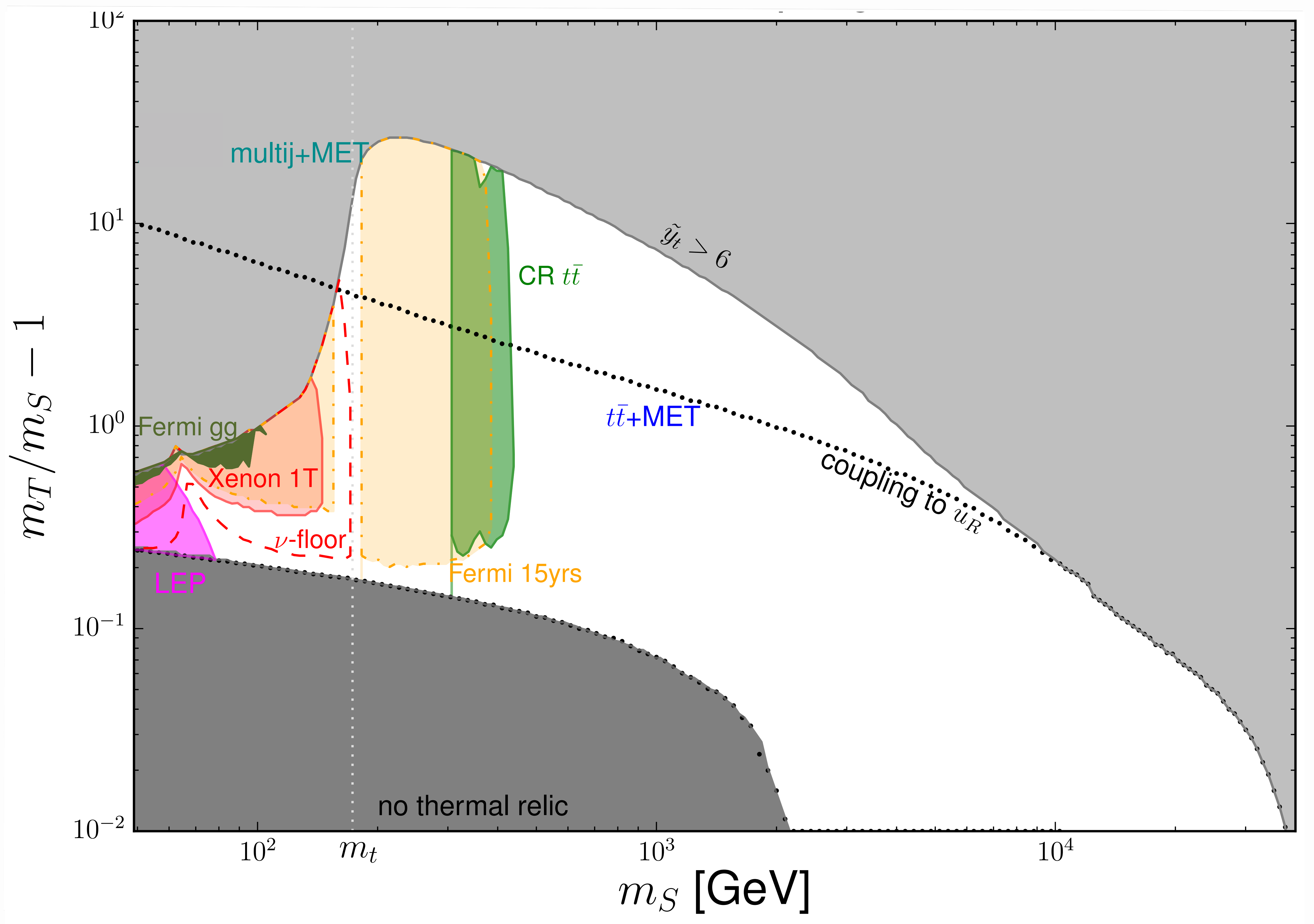


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## Present and future colliders

- Still limited
- Sole probes to tackle the unconstrained regions

# Next-to-simplified models - Contact terms

[ Cornell, Deandrea, Flacke, BF & Mason (JHEP'21) ]

## Simplified composite DM model

- Lagrangian

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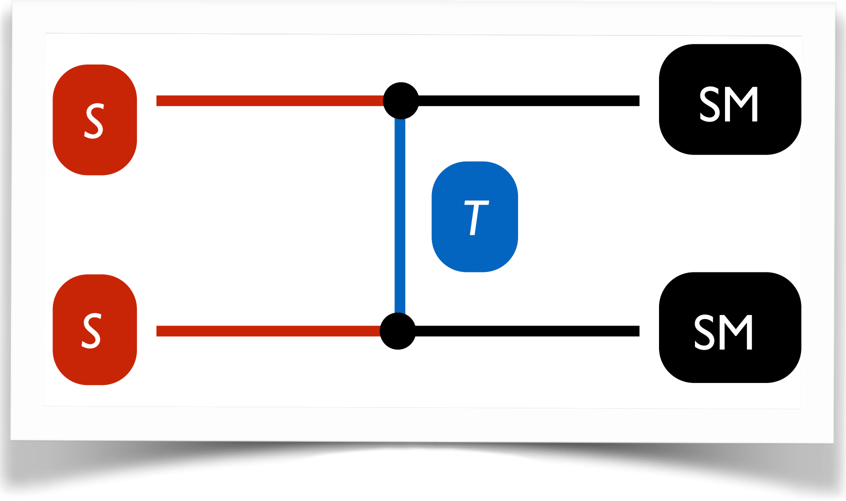
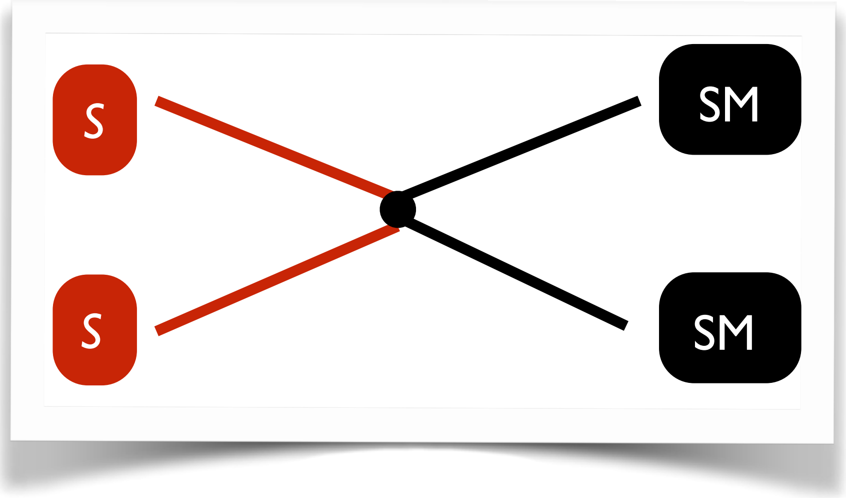



- Strong dynamics ➞other lower-energy consequences
  ★ Additional non-decoupling dimension-five interactions
  ➞ *SStt* contact term

$$\mathcal{L}' = \mathcal{L} + \frac{C}{\Lambda} S S t \bar{t}$$




[ Bellazzini, Csaki, Hubisz, Serra & Terning (JHEP'12) ]

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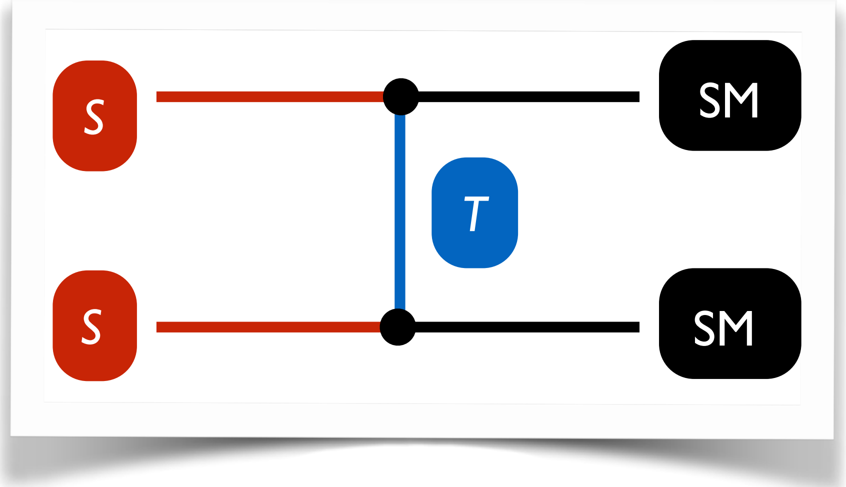


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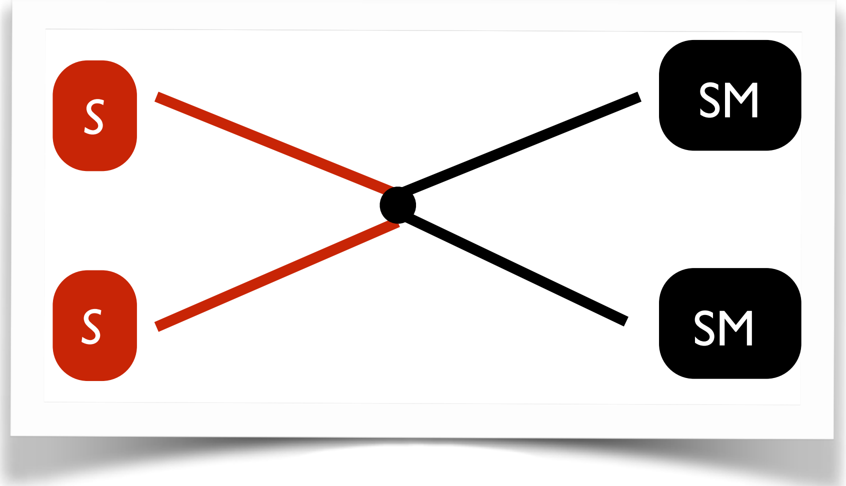


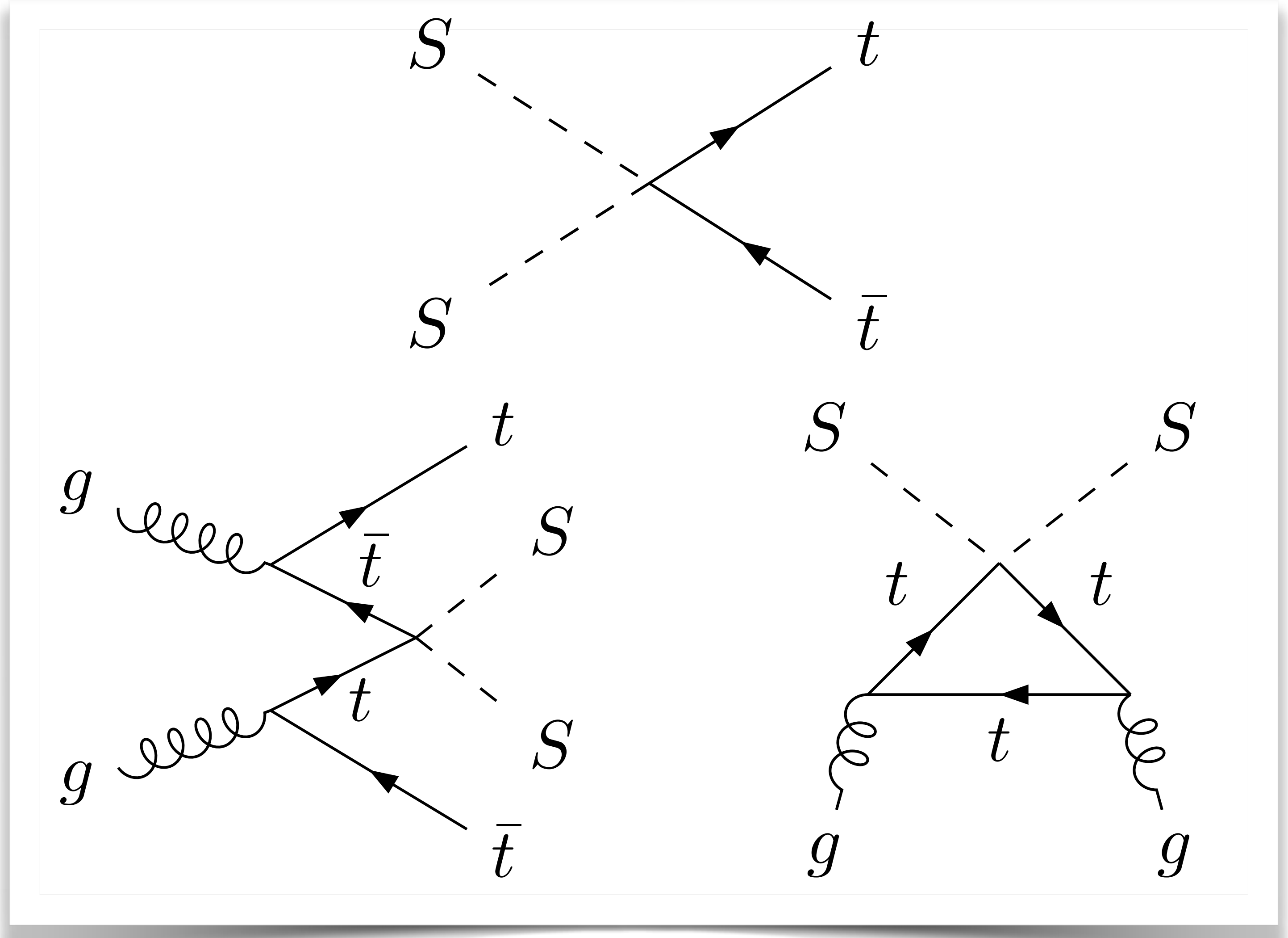

[ Bellazzini, Csaki, Hubisz, Serra & Terning (JHEP'12) ]

## Simplified and minimal models important…

- Lack of potentially important non-minimal features…

## Impact of the new contact terms

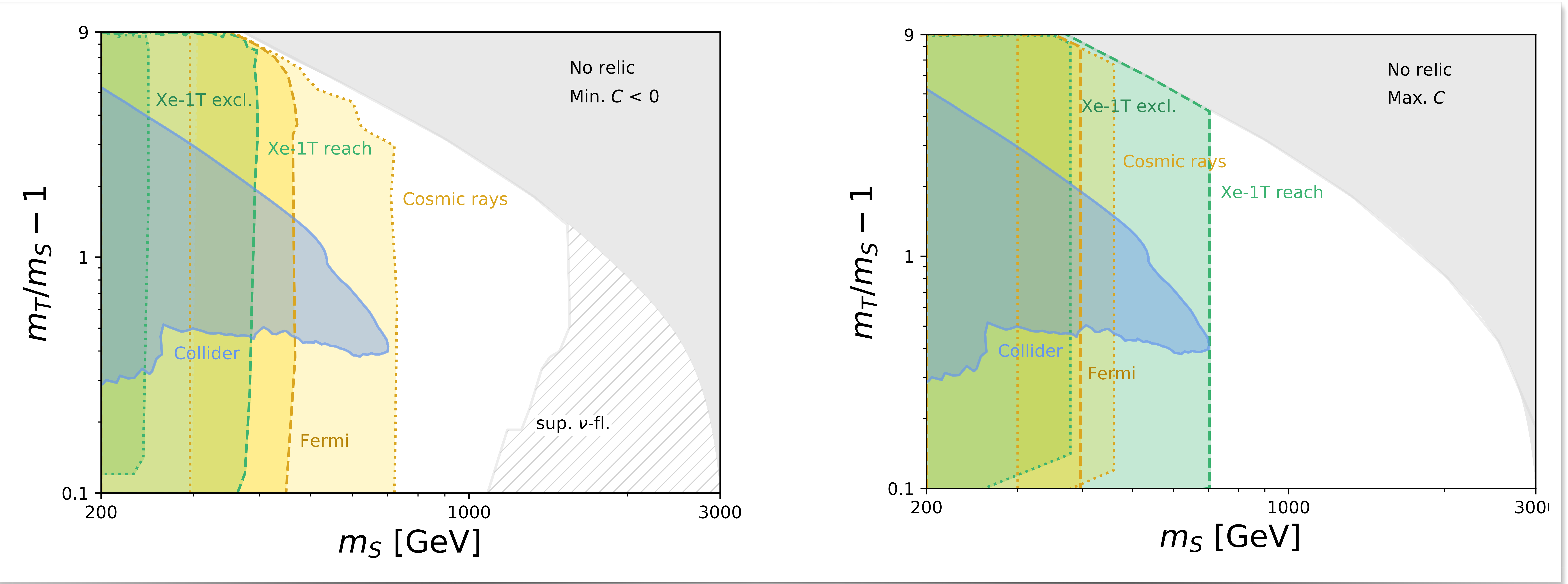
- Correct relic density with smaller Yukawa couplings
  ➝ Potentiel impact on DM indirect detection
- Possibly larger DM-nucleon scattering cross section
  ➝ Larger impact of the DM direct detection experiments
- Collider bounds ➝ no impact of $C \neq 0$
  [competition with resonant channels]



# Consequences of non-minimality on DM ID and DD

[ Cornell, Deandrea, Flacke, BF & Mason (JHEP'21) ]

## 2 setups: max($C$) and min($C$)



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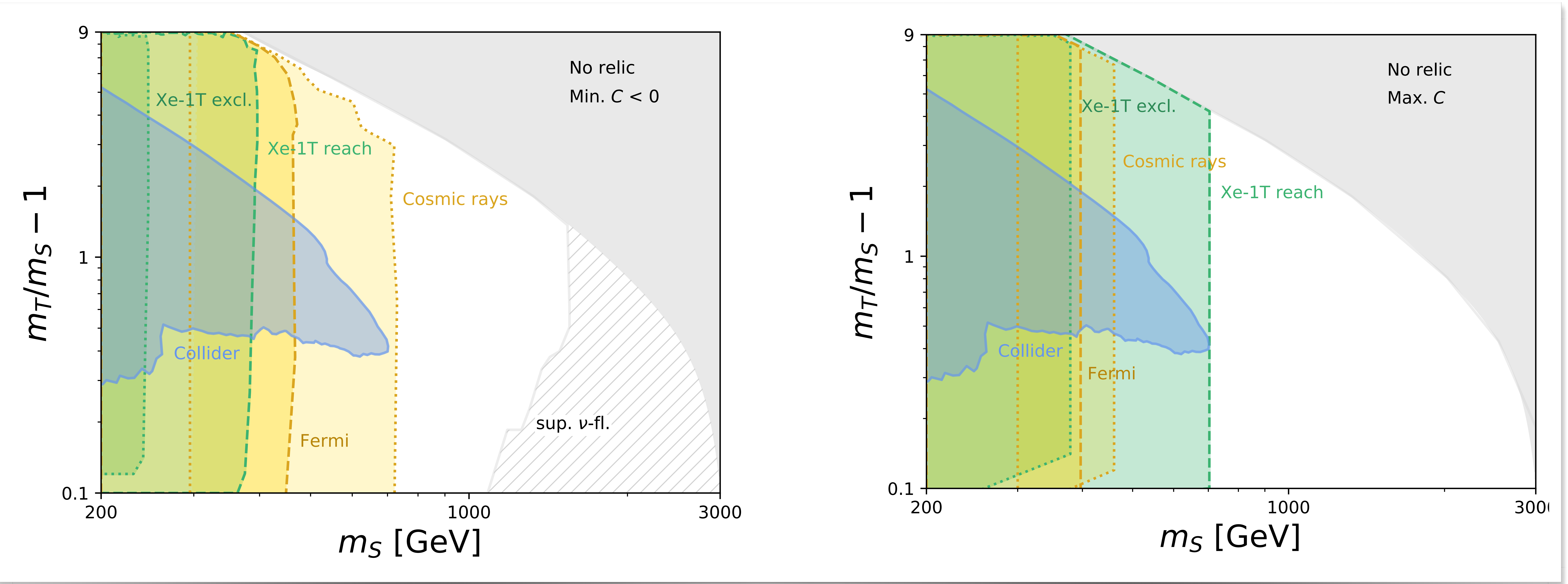


- DM-ID: modification of the $\gamma$ spectrum
  - ➞ Negative $C$: very strong bounds (interferences)
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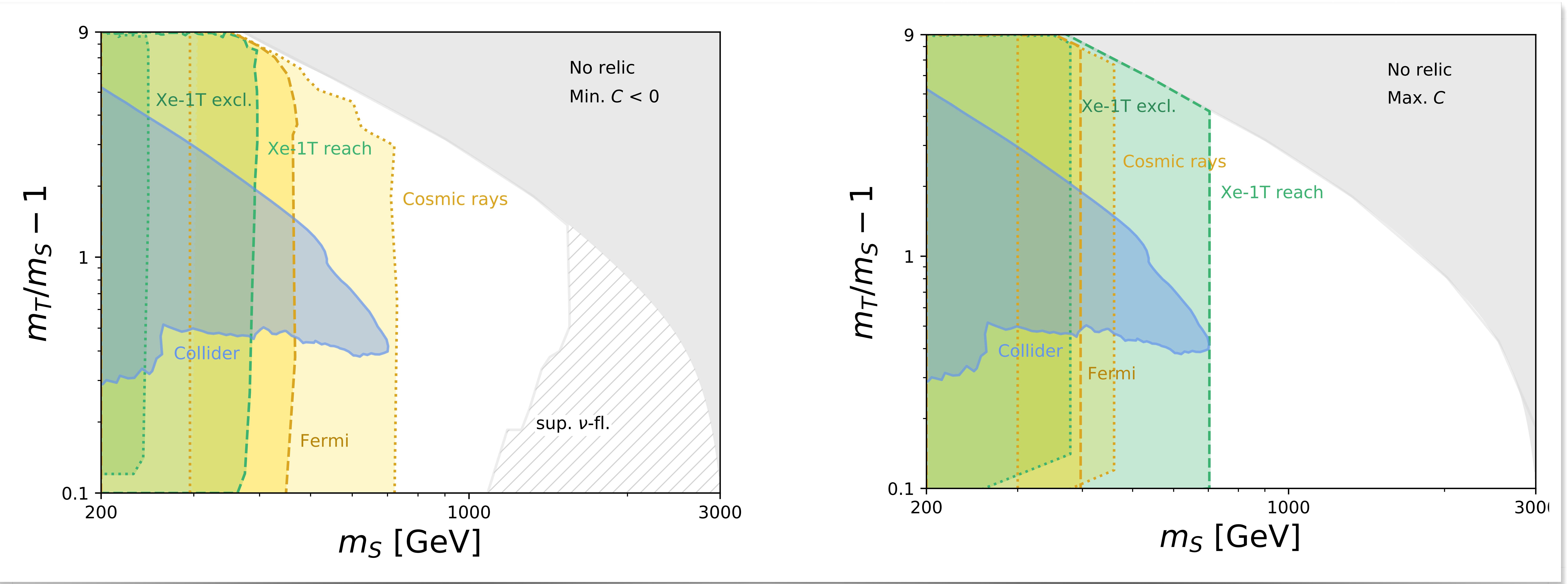


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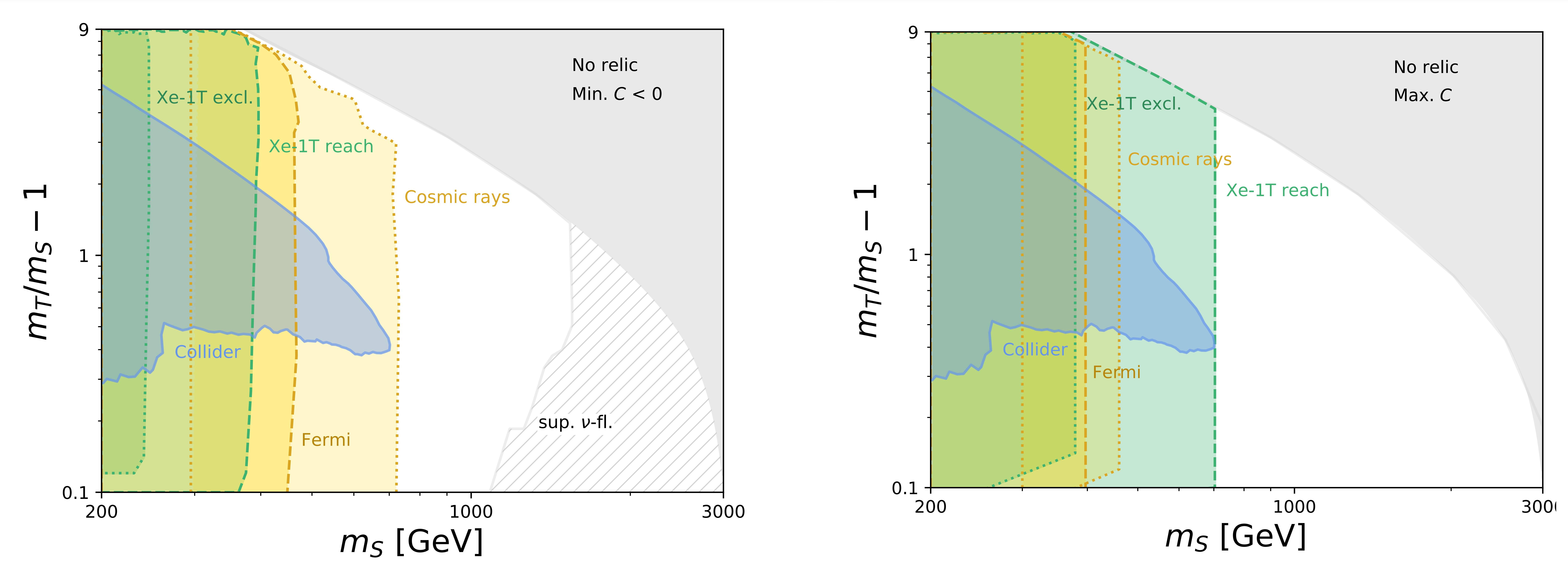


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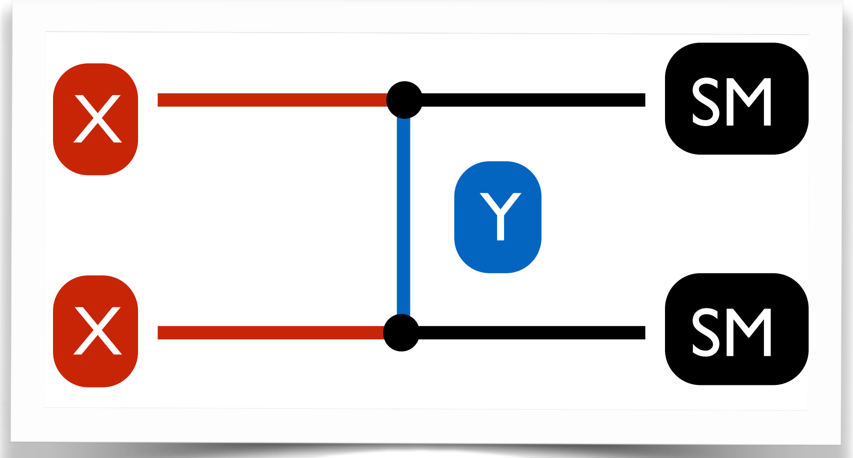
**Complementarity of the two classes of probes**

# Generalisation of the model

A generic *t*-channel DM model ≡ perfect playground for DM at colliders




- 2 spins: $J_X$, $J_Y$
- 13 masses:
  - ★ 1 DM mass: $m_X$
  - ★ 12 mediator masses (SM = $u_L$, $d_L$, $u_R$, $d_R$)
- 9 couplings (with $SU(2)_L \times U(1)_Y$ invariance)
  - ★ 3 vectors in flavour space
  - ★ SM = $Q_L$, $u_R$, $d_R$

| X (DM) | Spin | Self-conj. | Y (med.) | Spin |
|---|---|---|---|---|
| $\tilde{S}$ | 0 | yes | $\psi_Q, \psi_u, \psi_d$ | 1/2 |
| $S$ | 0 | no | | |
| $\tilde{\chi}$ | 1/2 | yes | $\varphi_Q, \varphi_u, \varphi_d$ | 0 |
| $\chi$ | 1/2 | no | | |
| $\tilde{V}_\mu$ | 1 | yes | $\psi_Q, \psi_u, \psi_d$ | 1/2 |
| $V_\mu$ | 1 | no | | |

Representative of many DM model with parity-odd mediators

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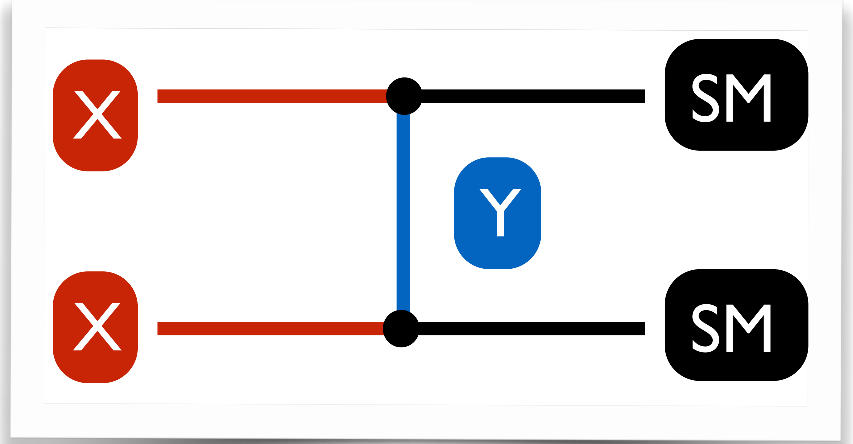


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Representative of many DM model with parity-odd mediators

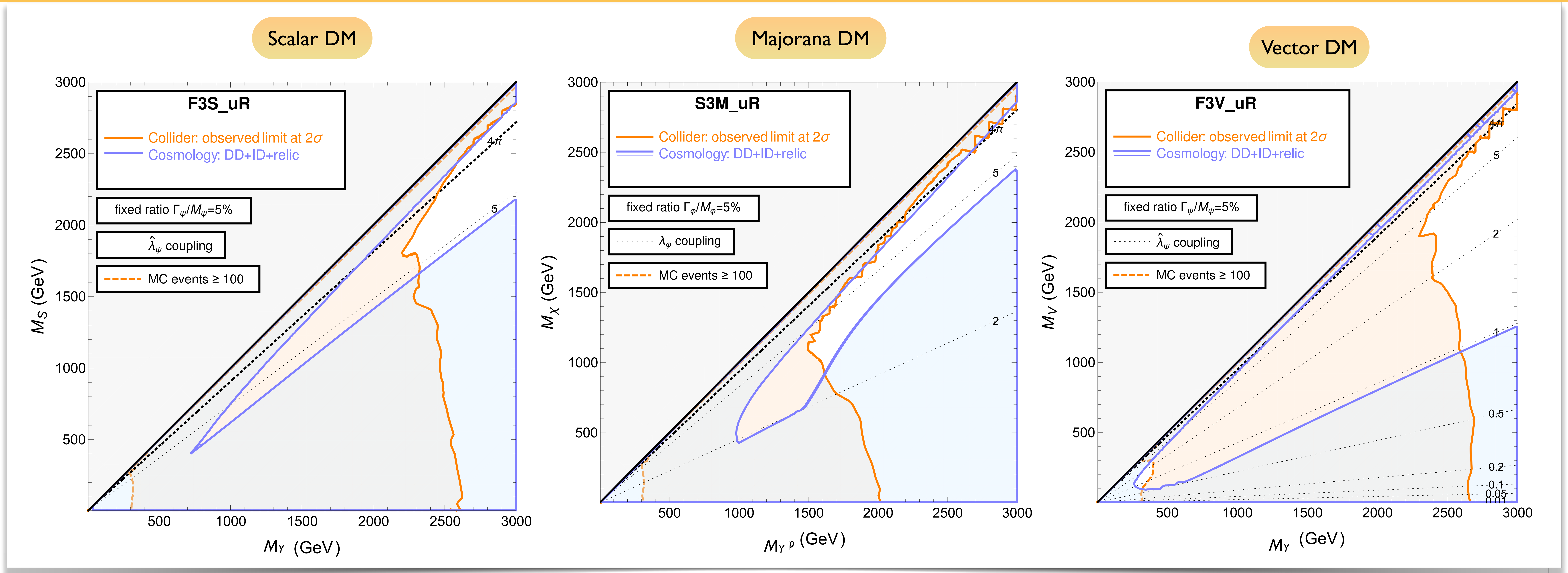
## Toy model: DM coupling to right-handed up quarks only

- Simple scenarios investigated by ATLAS and CMS
- Benchmarks for numerous searches
- Collider-cosmology complementarity ➙ unexpected LHC phenomenology

$$\mathcal{L}_{\texttt{X\_uR}}(X) = \left[\lambda_\varphi \bar{X} u_1 \varphi^\dagger_{u_1} + \text{h.c.}\right]$$

# Strongly coupled $t$-channel DM

[ Arina, BF, Mantani, Mies, Panizzi & Salko (PLB'21) ]




## Colliders and cosmology complementary

- A narrow mediator ➝ strongly-coupled DM from cosmology
- Lighter options further restricted by multi-jet+MET collider constraints (ATLAS-CONF-2019-040)

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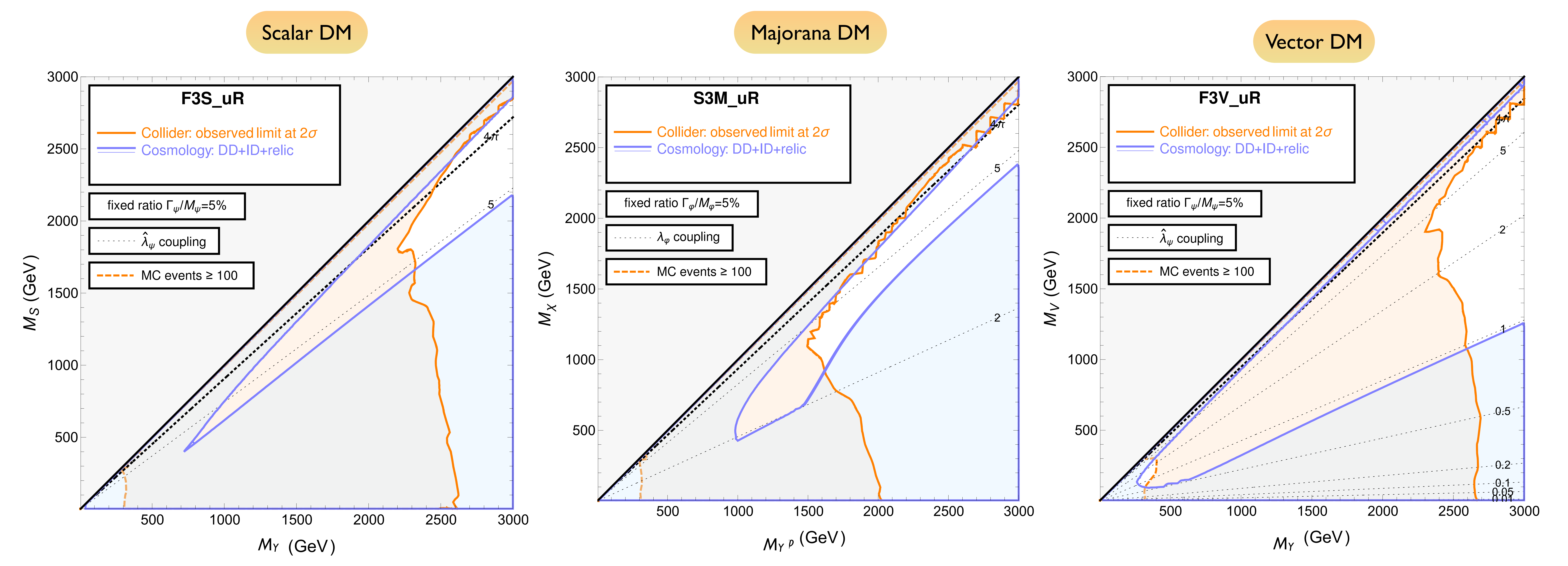


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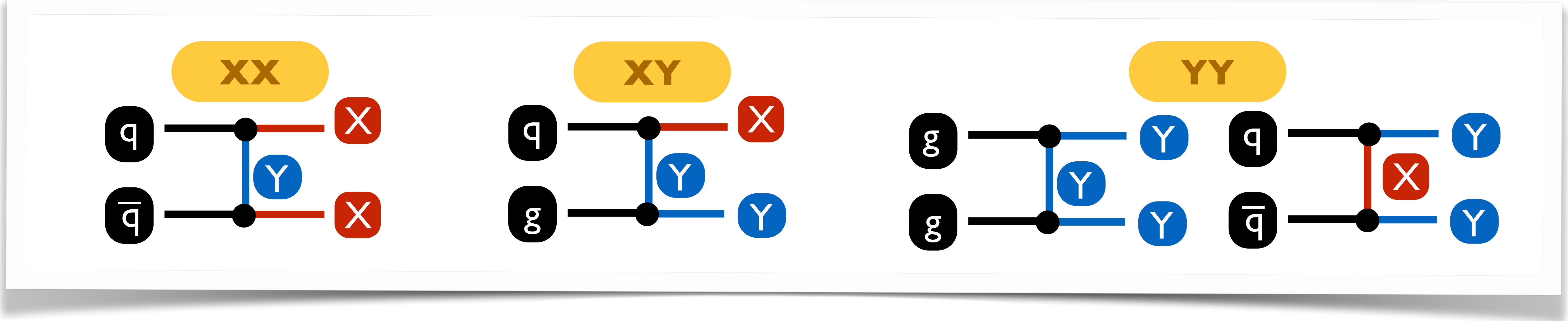
Estimation of the collider bounds from multi-jet + MET production?

# DM @ colliders: the signal…

[ Arina, BF & Mantani (EPJC'20) ]

3 classes of processes ➙ jets from radiation or *Y*-decays



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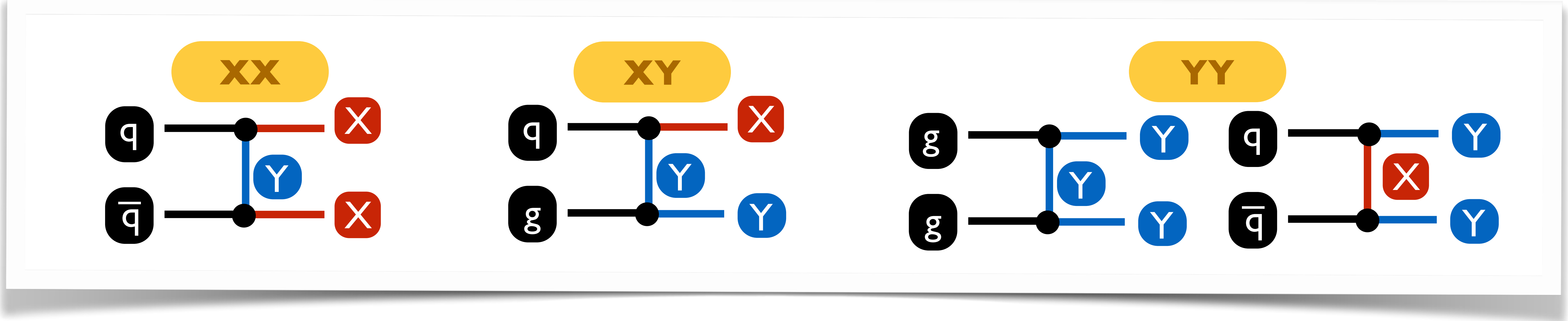


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  - ★ DM pair production ( + 1 jet)
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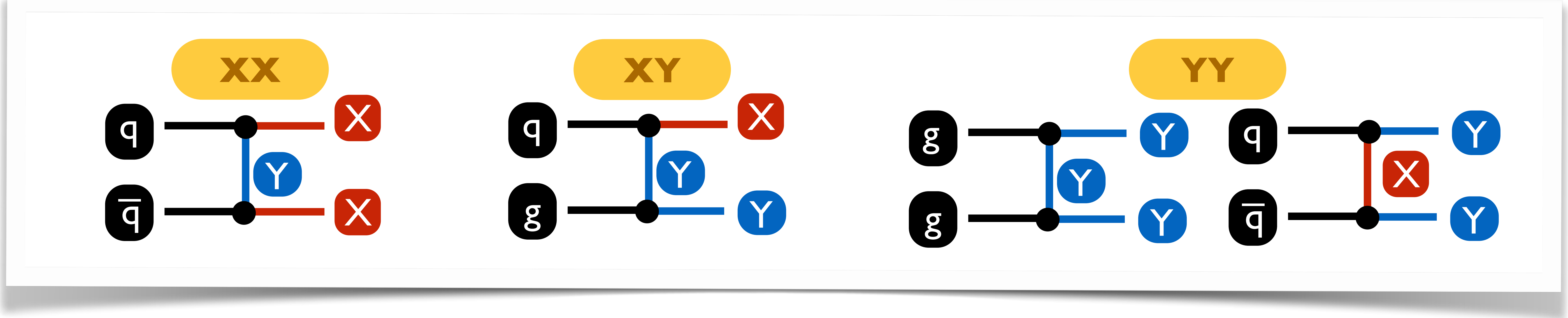


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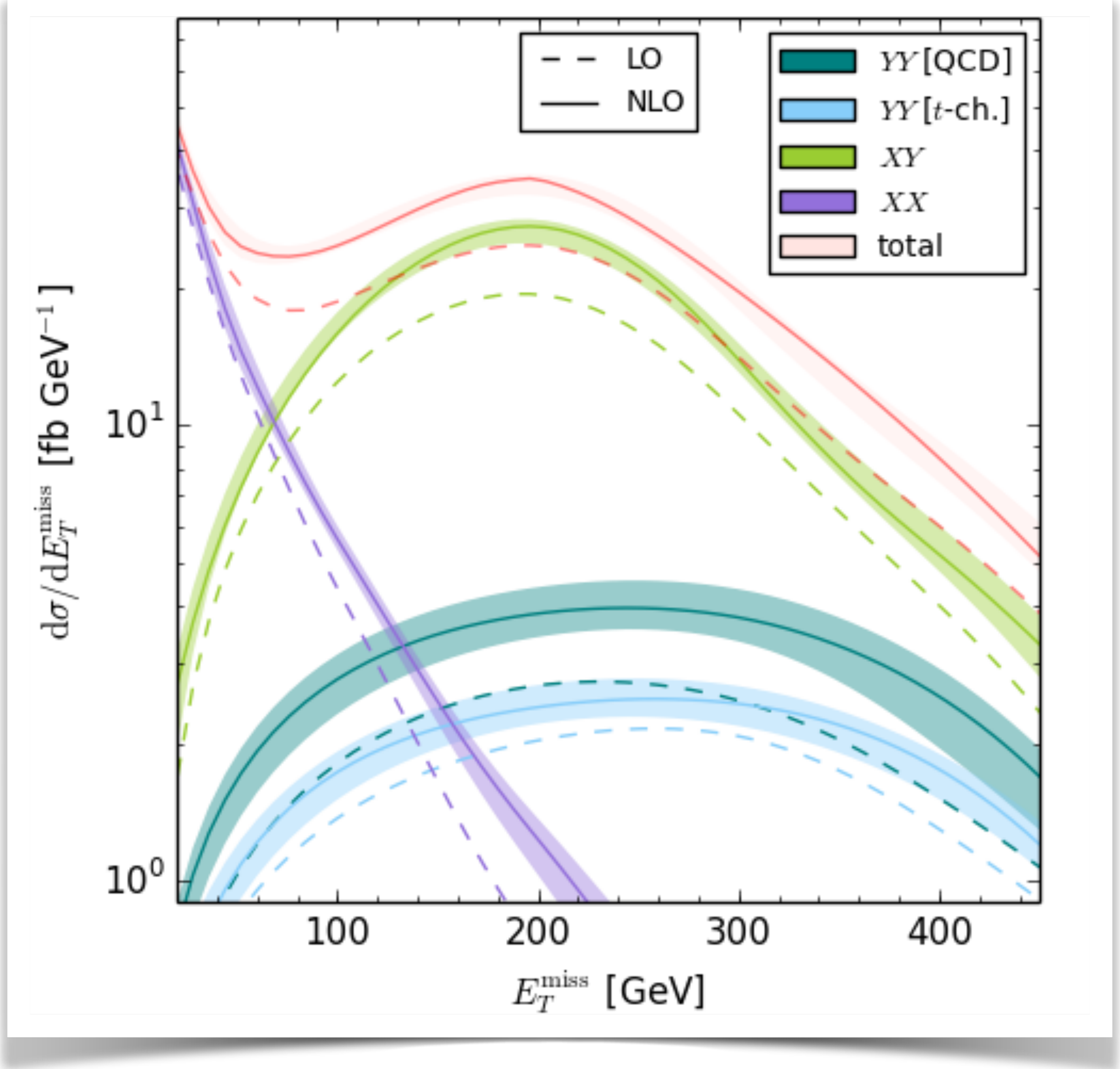
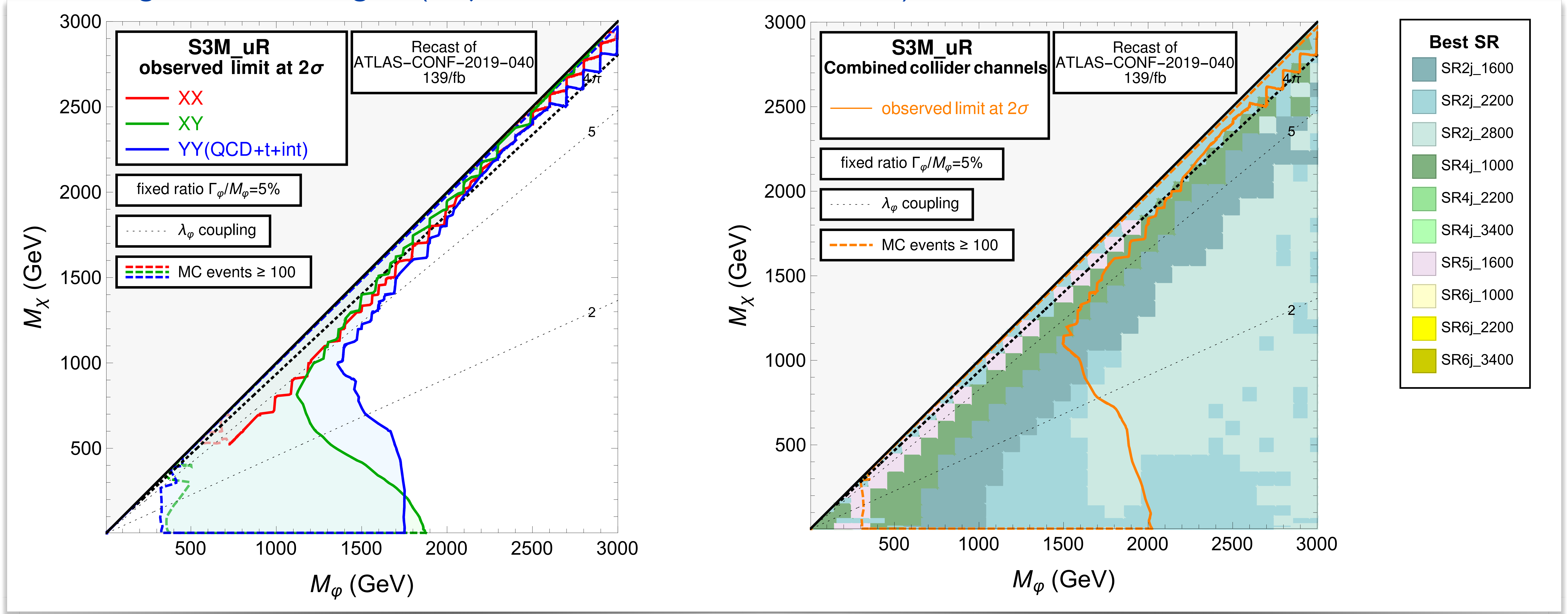
Not justified



# DM @ colliders: the *full* signal for a SUSY-like scenario

[ Arina, BF, Mantani, Mies, Panizzi & Salko (PLB'21) ]

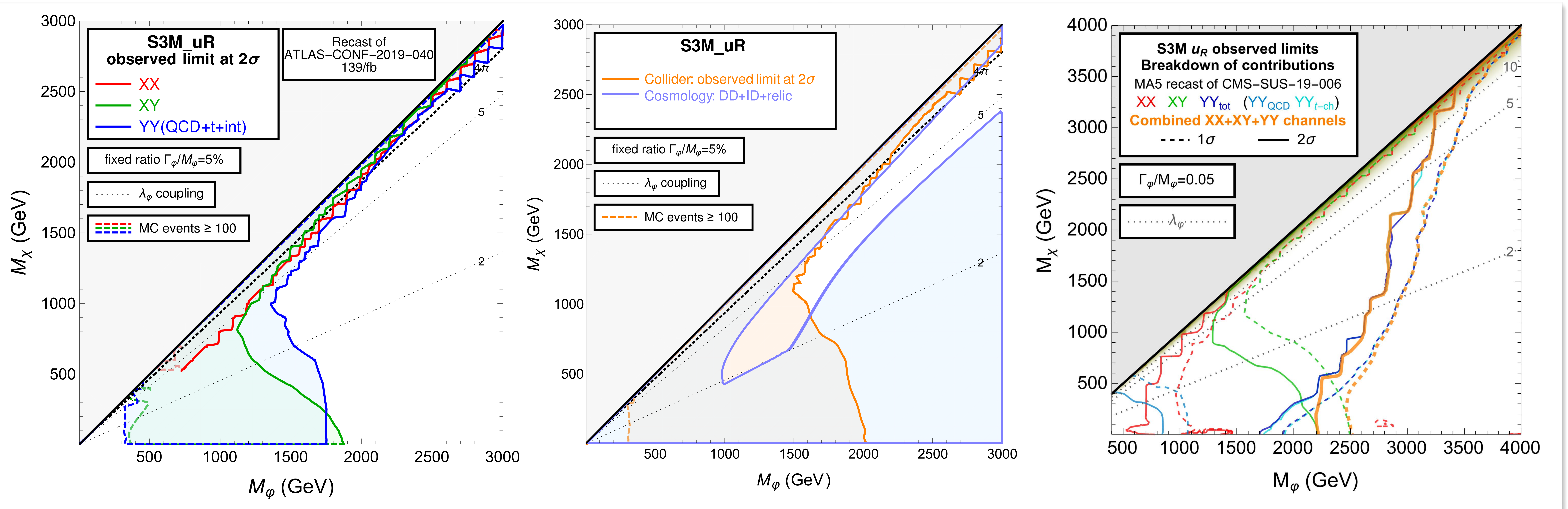
## Dissecting the collider signal (Majorana DM and scalar mediator)




- All channels contribute (larger rates)
  - ★ XX ~ $\lambda^4$
  - ★ XY ~ $\lambda^2$
  - ★ YY ~ $\lambda^4 + \lambda^2 + \lambda^0$
- ATLAS-CONF-2019-040 targets different topologies
  - ★ XX: small number of softer jets
  - ★ XY: medium number of mostly softer jets
  - ★ YY: larger number of hard jets

# The story is not over…

[ Arina, BF, Heisig, Kramer, Mantani, Panizzi & Salko (to appear) ]



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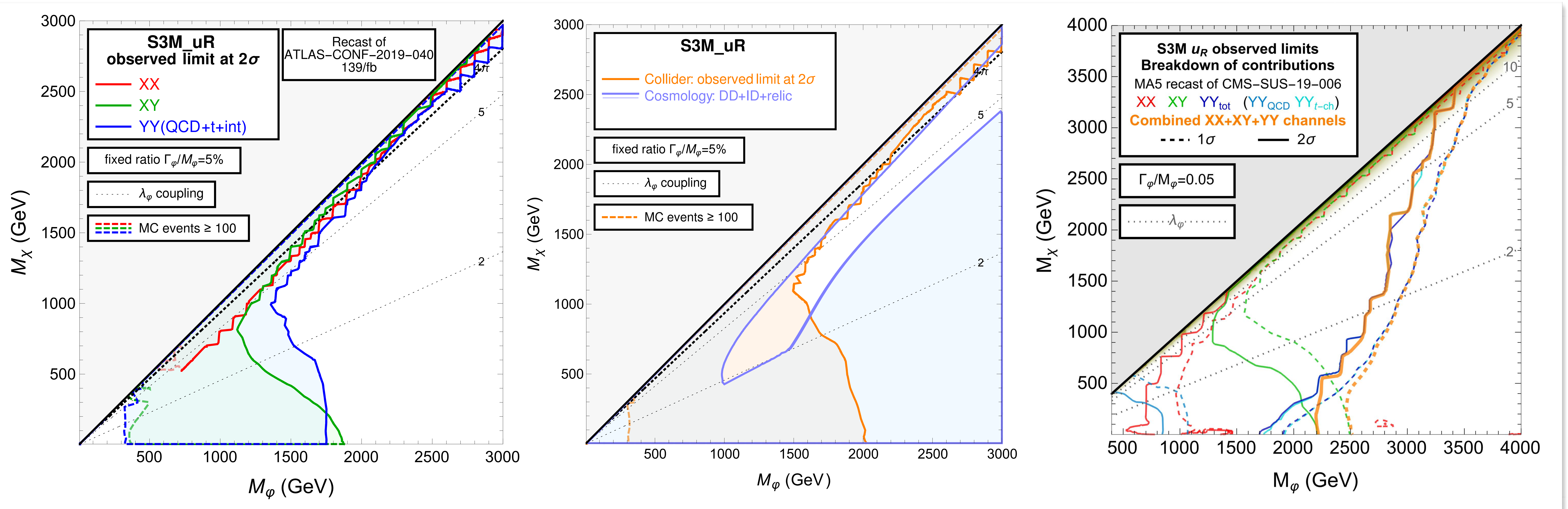


A more inclusive search: CMS-SUS-19-006

- Better constraints on XY
- Slightly better constraints on XX

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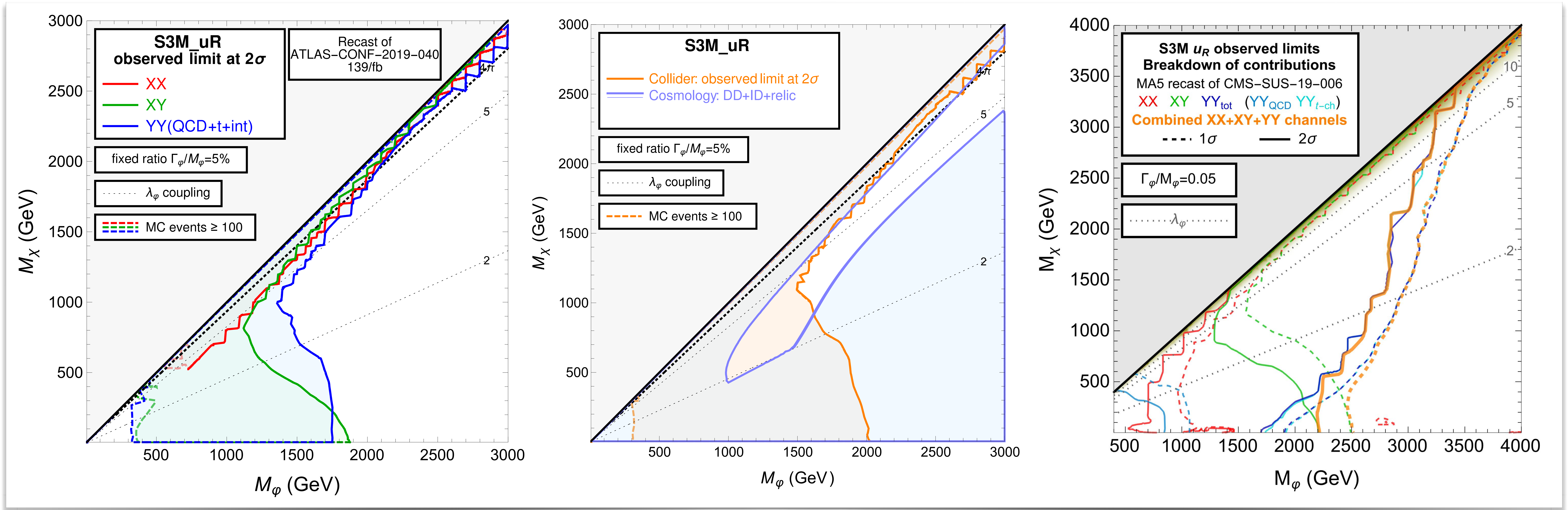


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- *t*-channel DM exchanges dominate
- $p\,p \to YY$ very large (more than $p\,p \to YY^*$)
  ➙ new channel included (enhanced by valence quarks)
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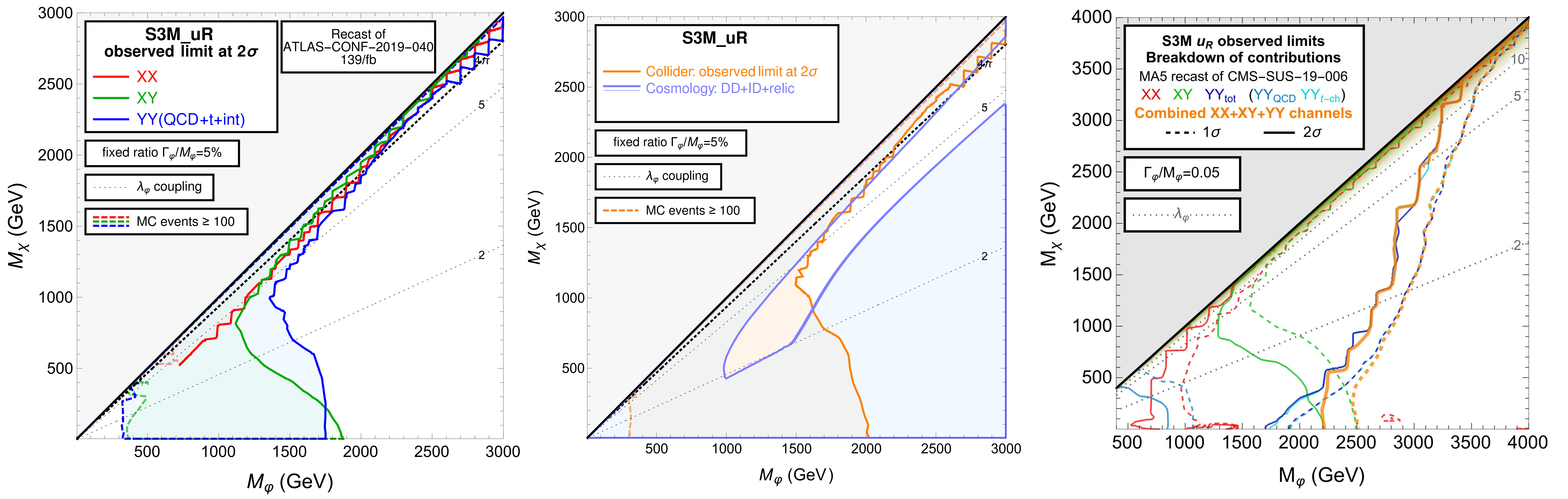


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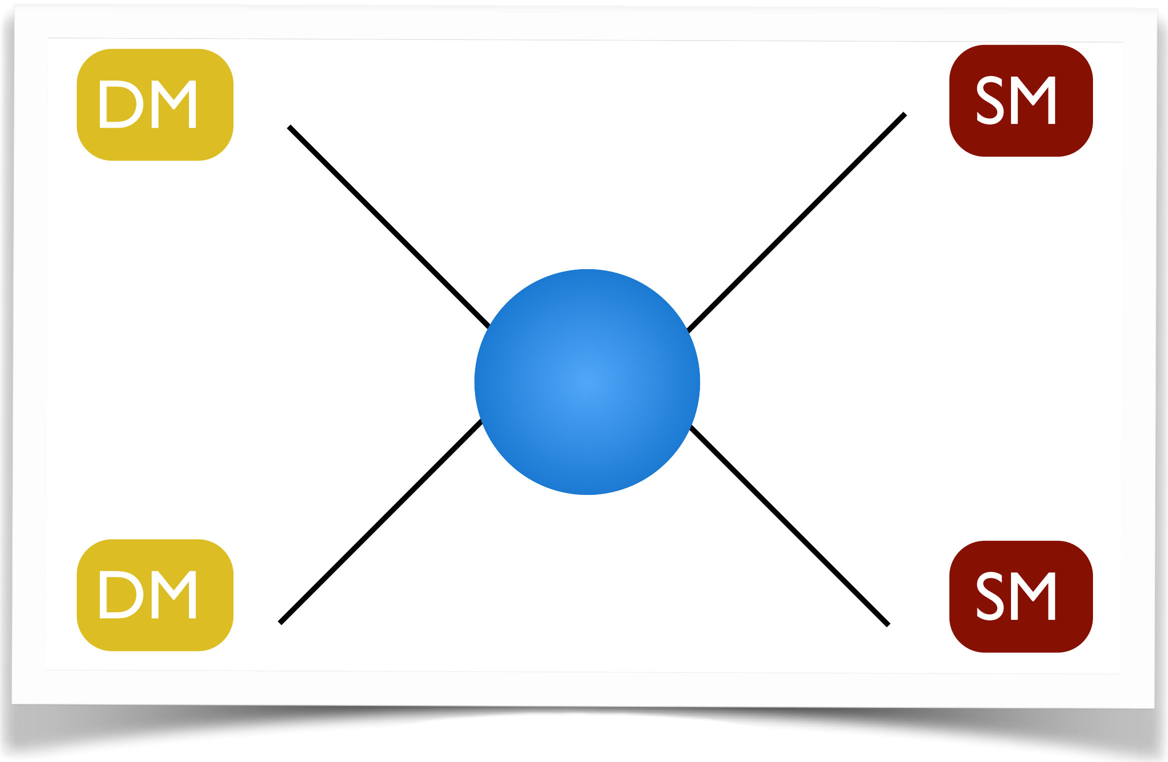
Collider simulations to be rethought!

# Summary

Dark matter very appealing to explain cosmological data

- Can be probed complementarily
  - ★ Direct/indirect detection
  - ★ Collider searches
- We explored a simplified setup inspired by strong dynamics
- Non-minimality may change the picture
- We generalise it to generic *t*-channel DM models



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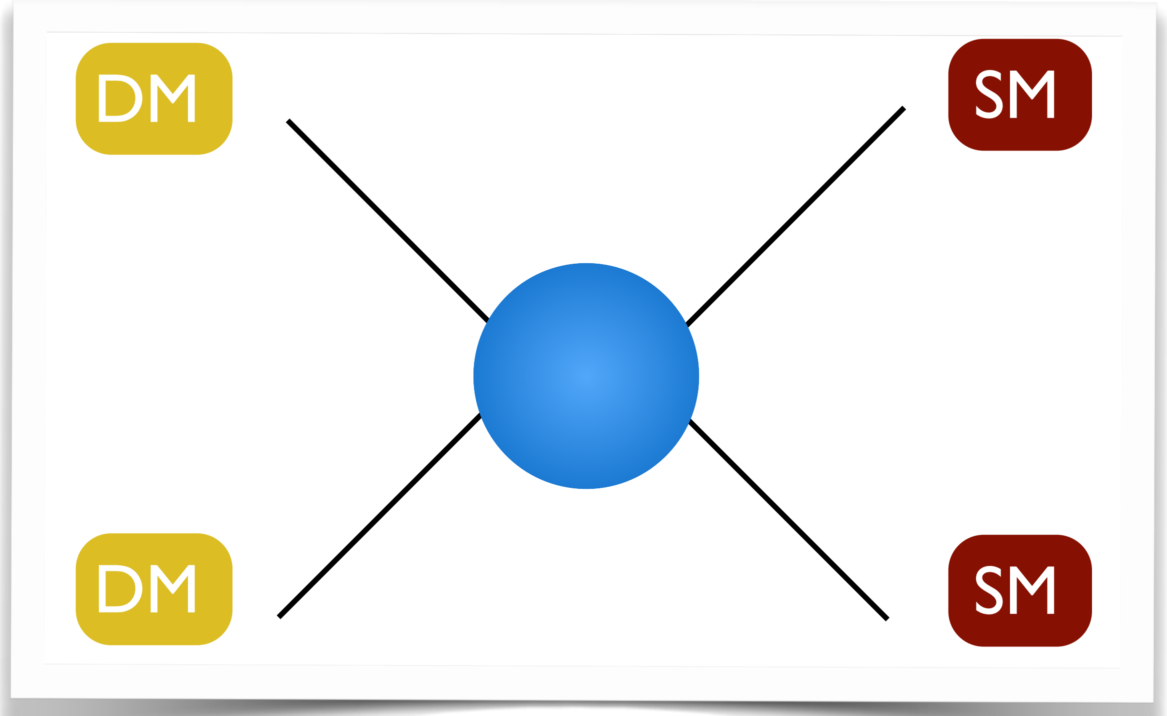
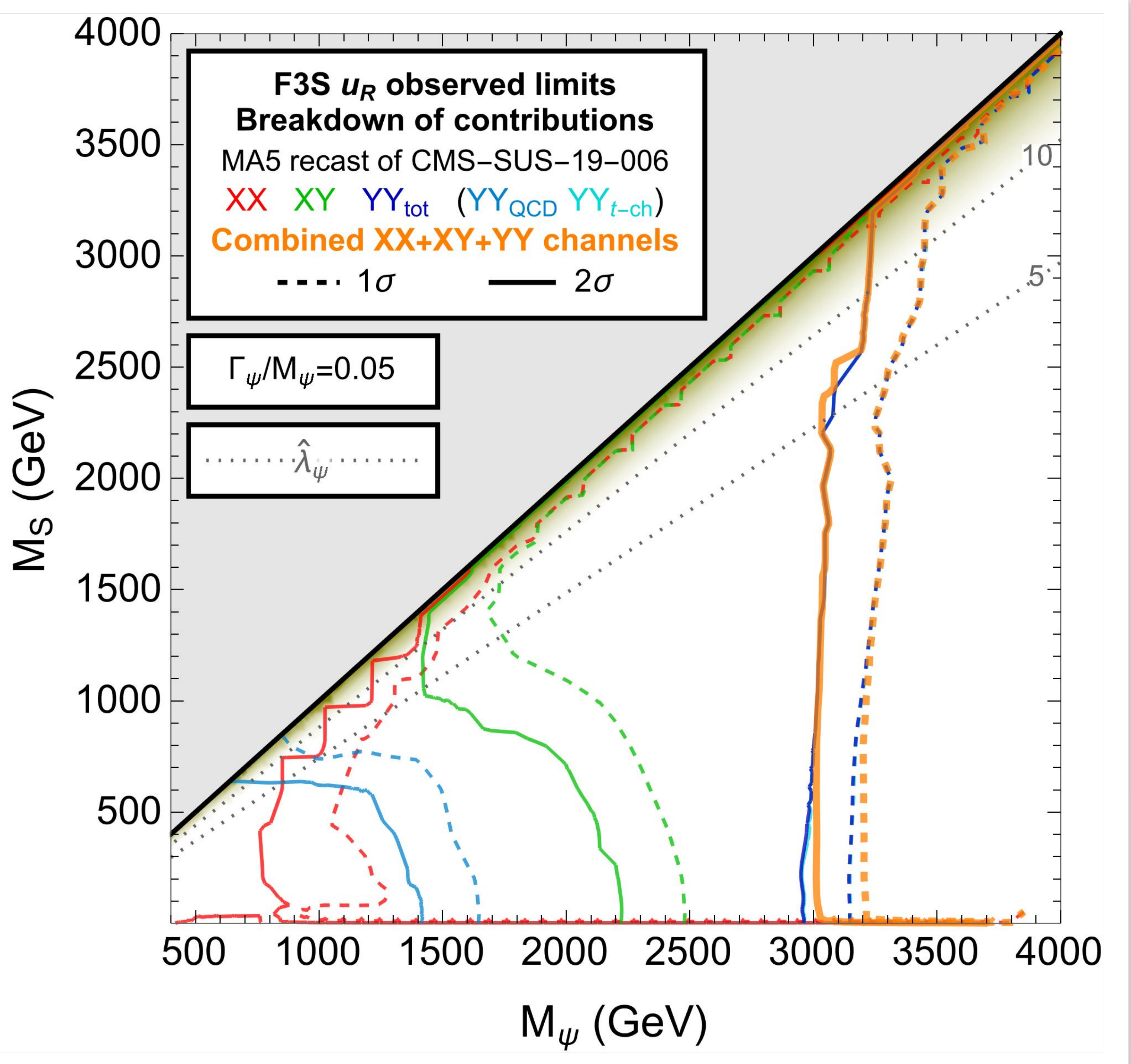
- Non-minimality may change the picture
- We generalise it to generic *t*-channel DM models




[ Arina, BF, Heisig, Kramer, Mantani, Panizzi & Salko (to appear) ]

## Robust predictions crucial for a discovery

- NLO corrections
- Signal modelling, in particular at colliders

## A last plot…

- Couplings on VLQs coupling to $u_R$ and DM
  - → 3 TeV VLQs are excluded! [regardless of the DM mass]
  - → Naive VLQ signal: bounds smaller than 1.5 TeV

Results to be presented to ATLAS and CMS on Jan 12th