Composite dark matter
From cosmology to colliders

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; PRD 2023)
- C. Arina, L. Mantani, H. Mies, L. Panizzi and J. Salko (PLB 2021)
- C. Arina, J. Heisig, M. Kramer, L. Mantani and L. Panizzi (230M.NNNNN, 230M.NNNNN)

Top LHC France 2023 (IPHC Strasbourg)

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Composite dark matter and how to search for it

DM natural in models featuring a strong dynamics

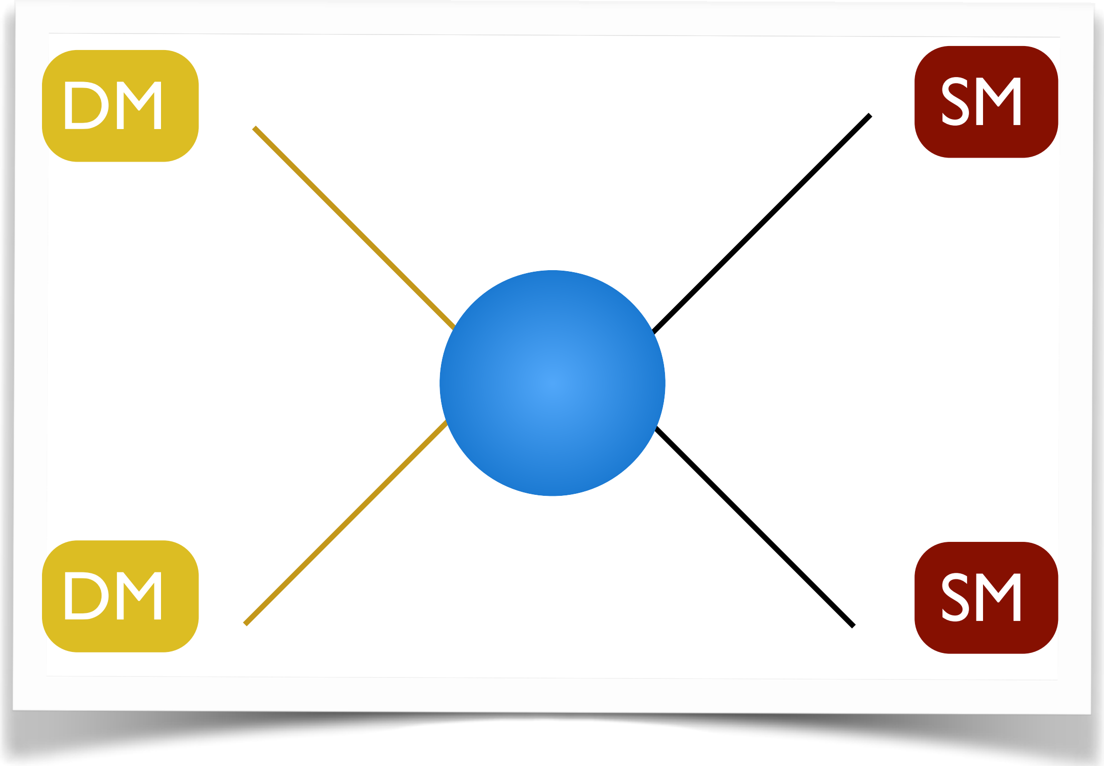
- Composite constructions
  - ★ Large spectrum of new states ➙ stable neutral scalars ubiquitous
  - ★ Remaining parity
- Dark matter ≡ composite resonance ➙ our assumption
  - ★ Non-derivative couplings to other fields
- Partial compositeness: special role of the top quark

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



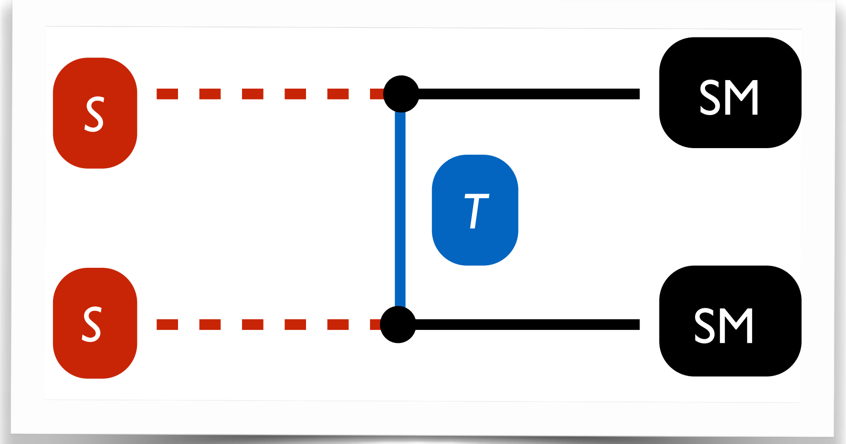
A simplified model for composite DM

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)

Model properties

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



- Lagrangian

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

★ 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 $\tilde{y}_t$

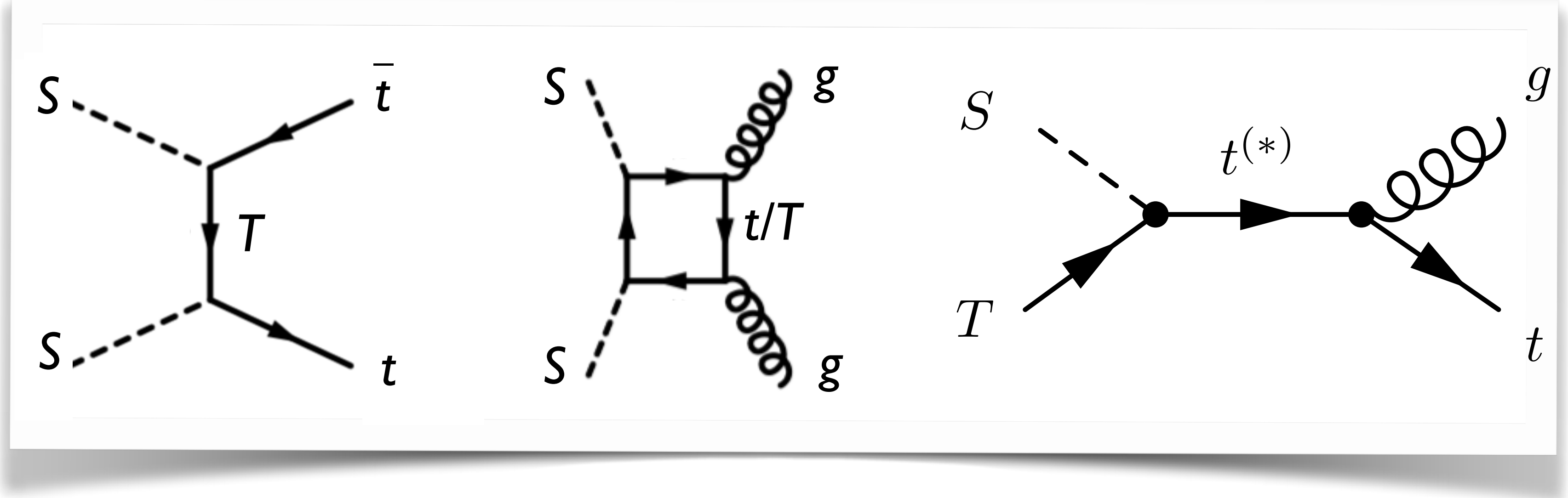
Is this viable?
➙ DM relic abundance

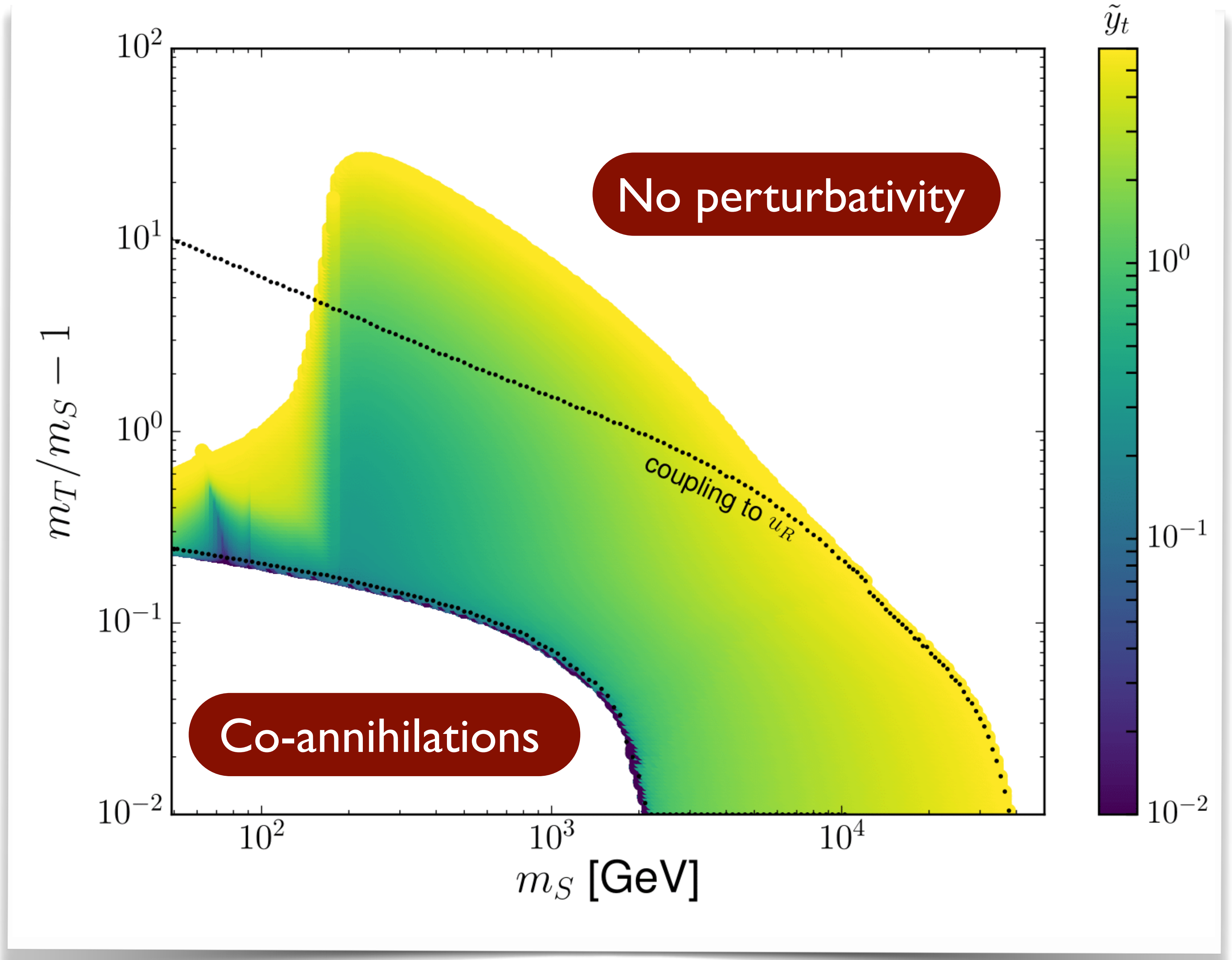
Relic abundance: generalities

[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





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)
  - ➙ perturbativity ensured (max value)

Large viable parameter space region from the relic standpoint

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

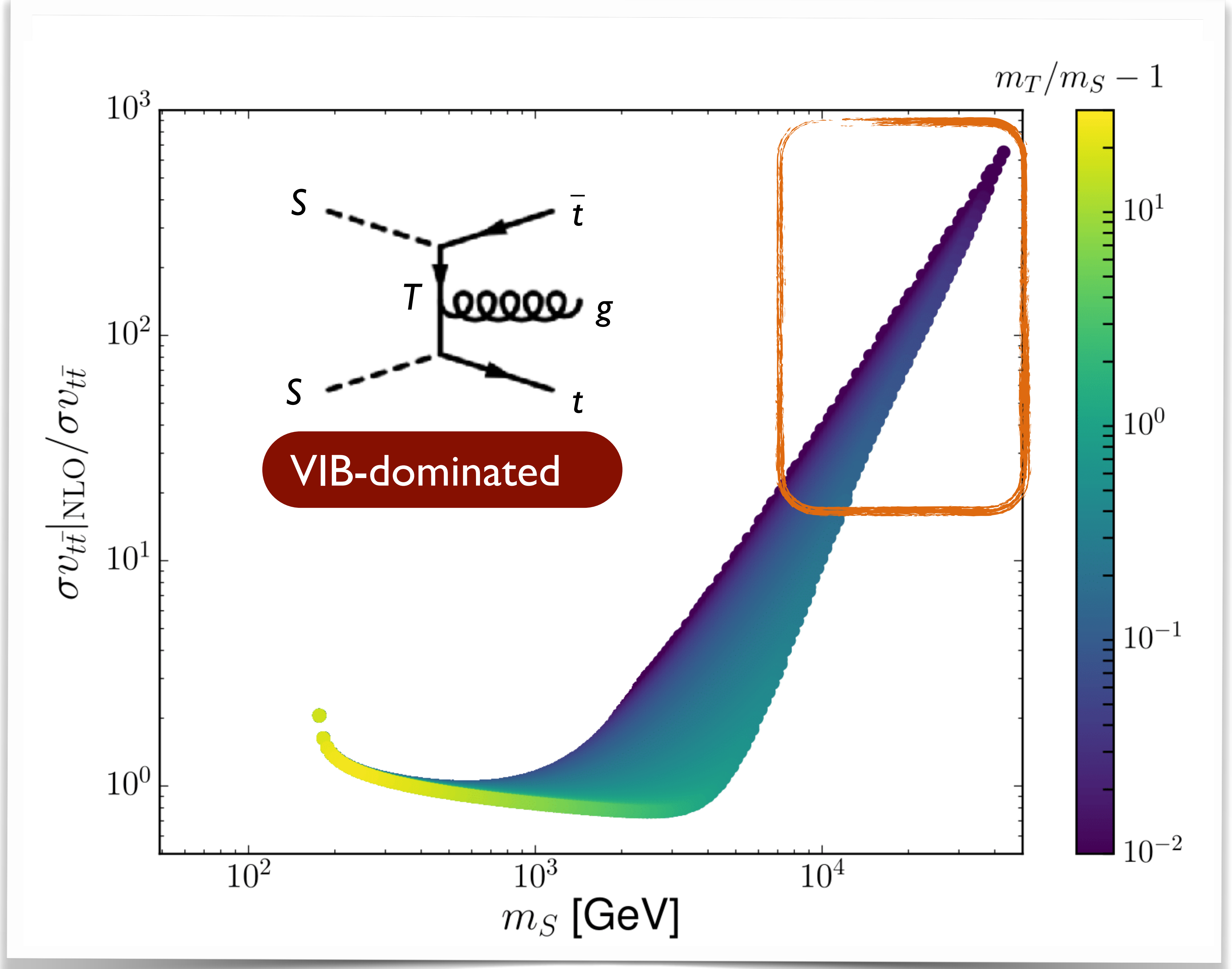
Very heavy DM regime (m_S > 5 TeV)

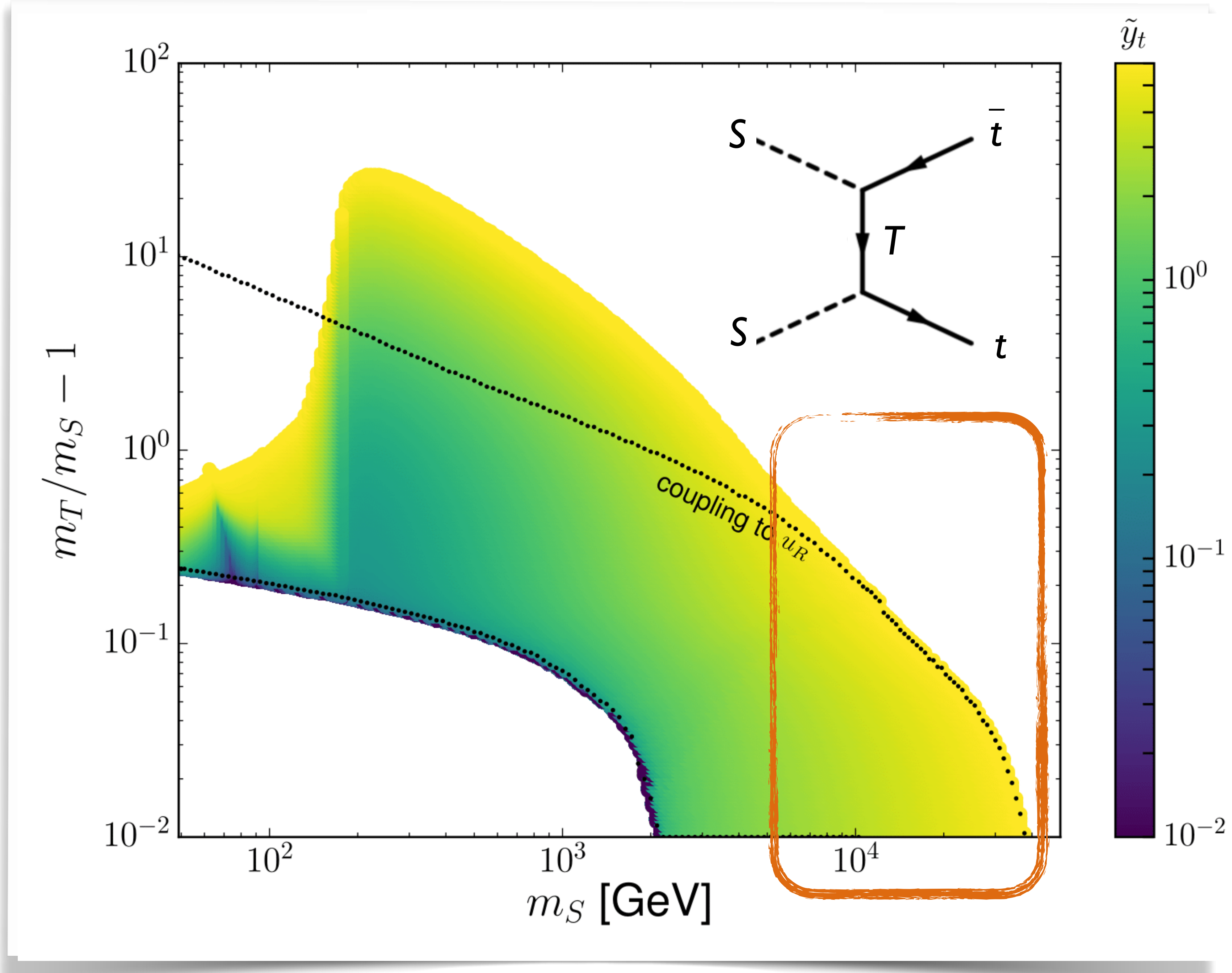
- Dominating annihilations into tops

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

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

★ Velocity-independent (v ~ 1)





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

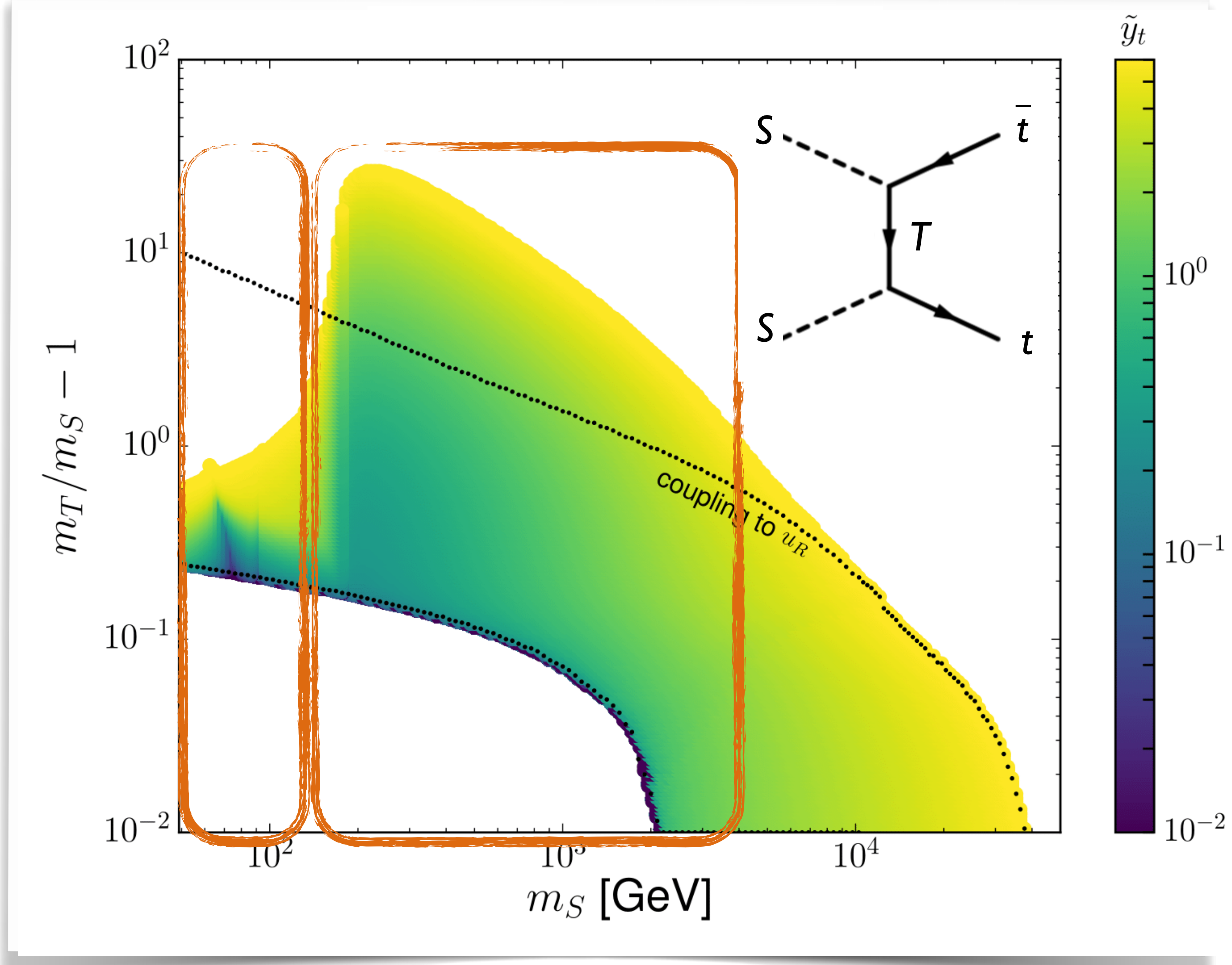
- Dominating annihilations into tops

$$(\sigma v)_{\rm NLO} \approx (\sigma v)_{\rm LO}\left[1+\frac{\alpha_s C_F}{\pi}\left(\frac{\pi^2}{2\beta_0}-1\right)\right]$$

  ★ Explicit velocity dependence
    ➙ Not viable close to threshold

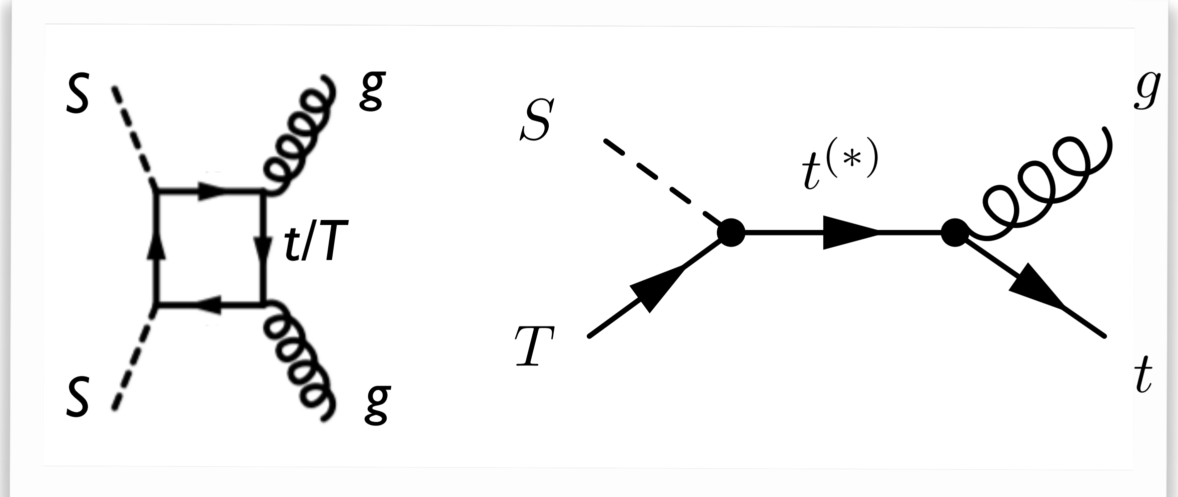
- Top mass effects important
  ★ Opens up a new region (≠ light quarks)
    ➙ annihilations into quarks negligible

- NLO effects mild (K ~ 1)

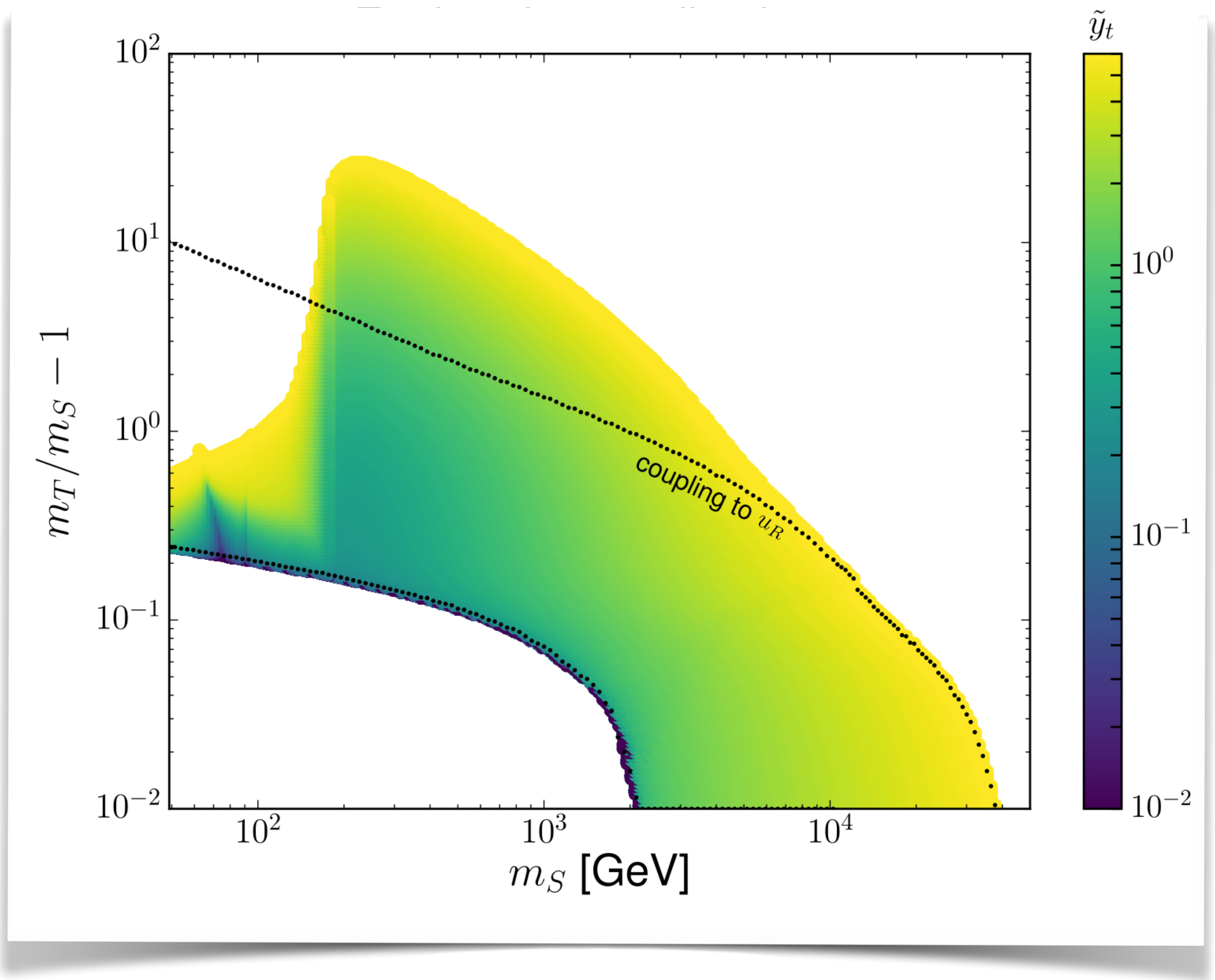


DM regime in which $m_S < m_t$

- 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 ~ 75 GeV)



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



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

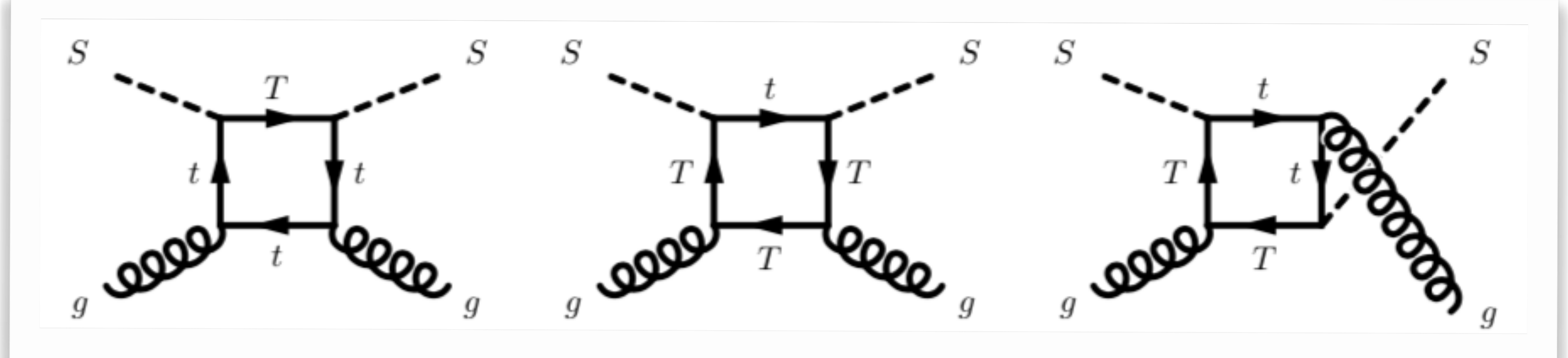
Two free parameters left (the masses)

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

Direct detection: light dark matter

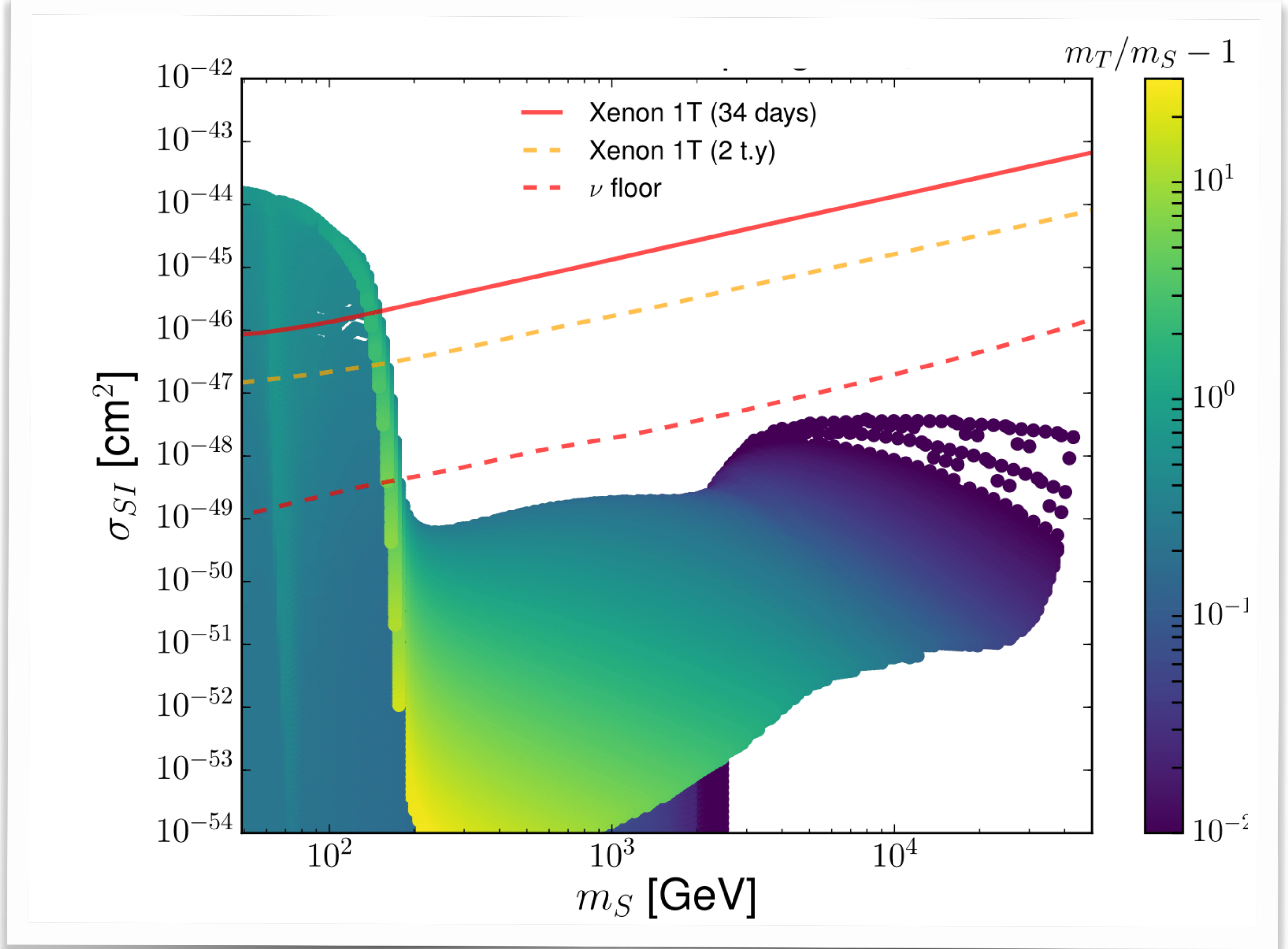
[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD'18)]

Direct detection in a nutshell



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

- Effective field theory approach
  - ⋆ StT couplings ➙ g-DM coupling ➙ nucleon-DM couplings
  - ⋆ Form factors
- Direct detection constraints on the simplified model



Mild constraints expected from DM direct detection

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

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

No constraints on heavy DM

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

Indirect detection: annihilations in tops/gluons

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

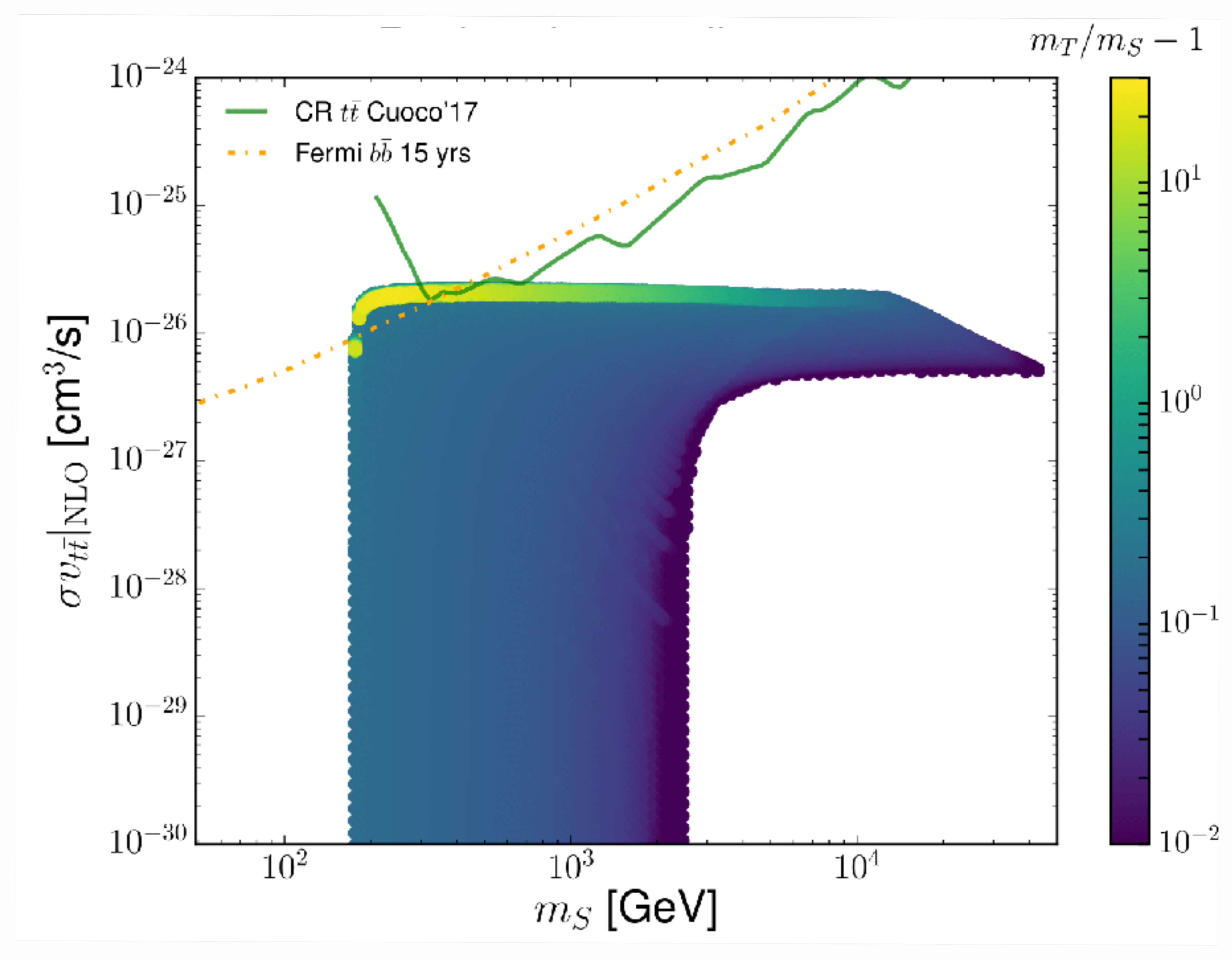
Secondary photon flux from DM annihilations

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

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

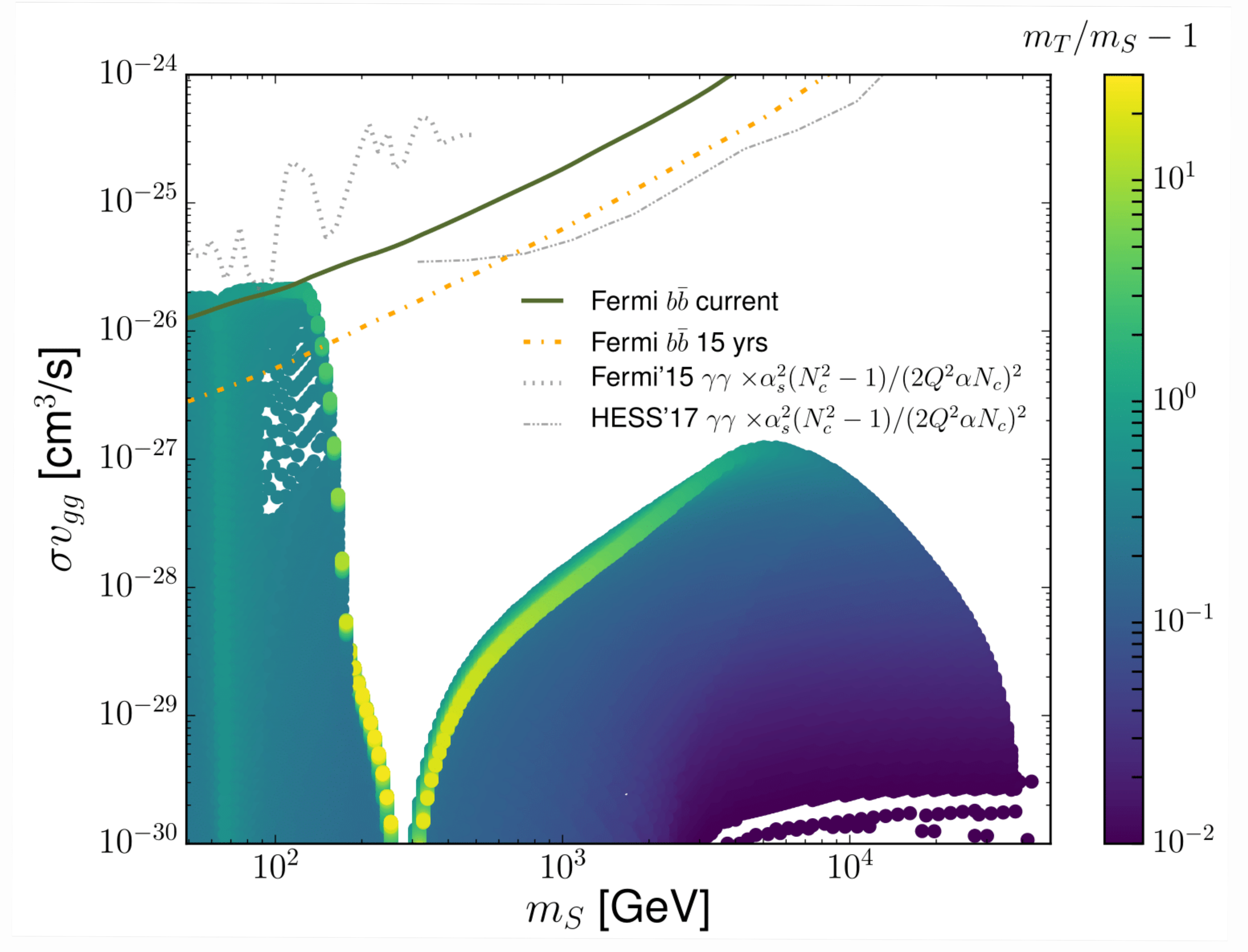
with $N_\gamma^X \equiv$ nr of γ from an X state

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



Constraints

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



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:

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

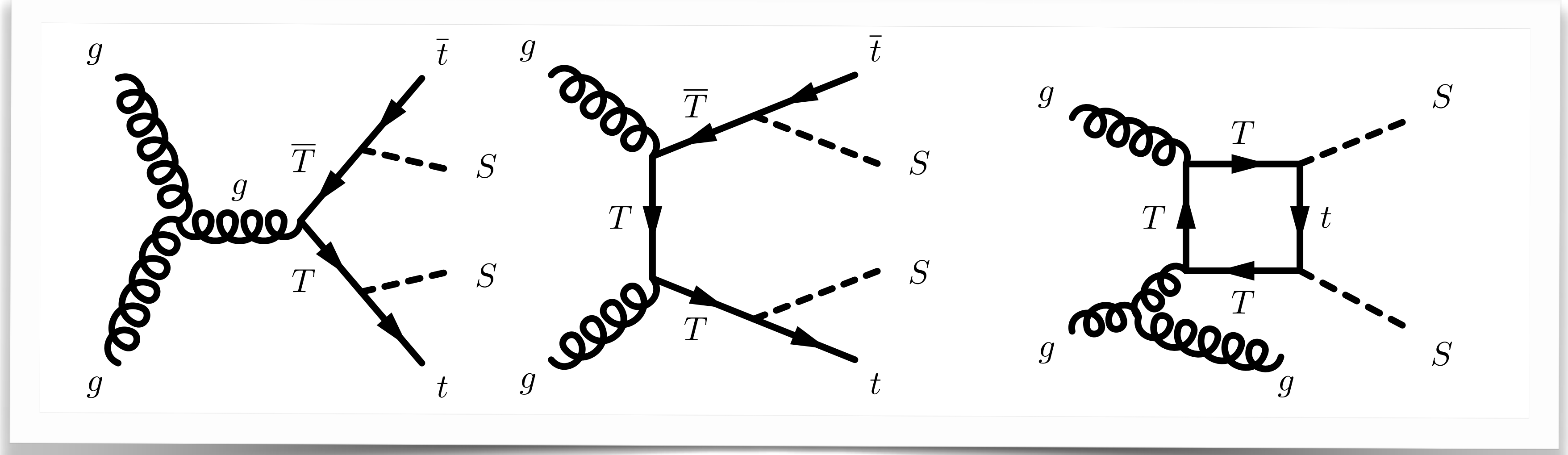
Mild constraints
Indirect detection not so relevant

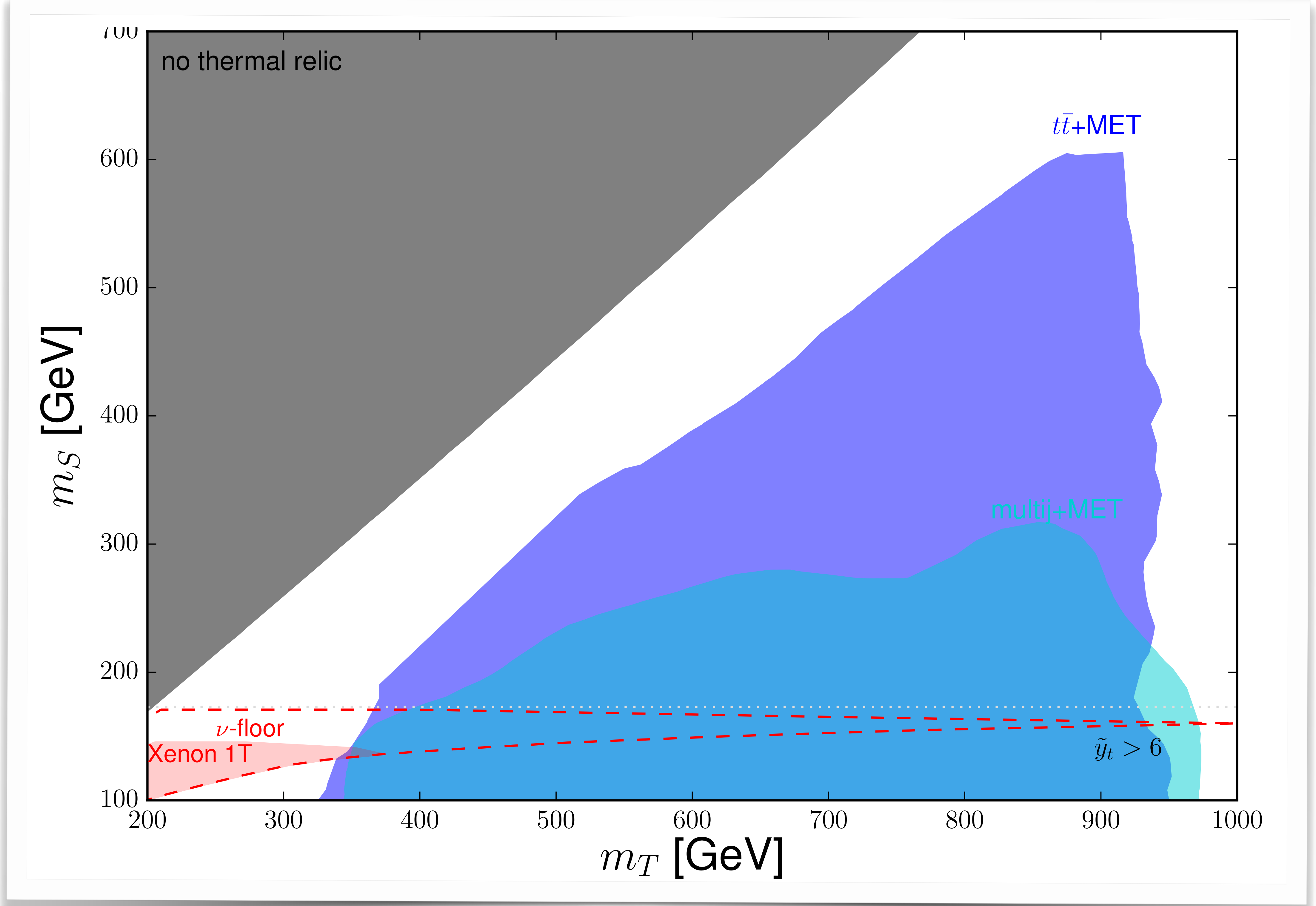
Dark matter searches at colliders

[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]





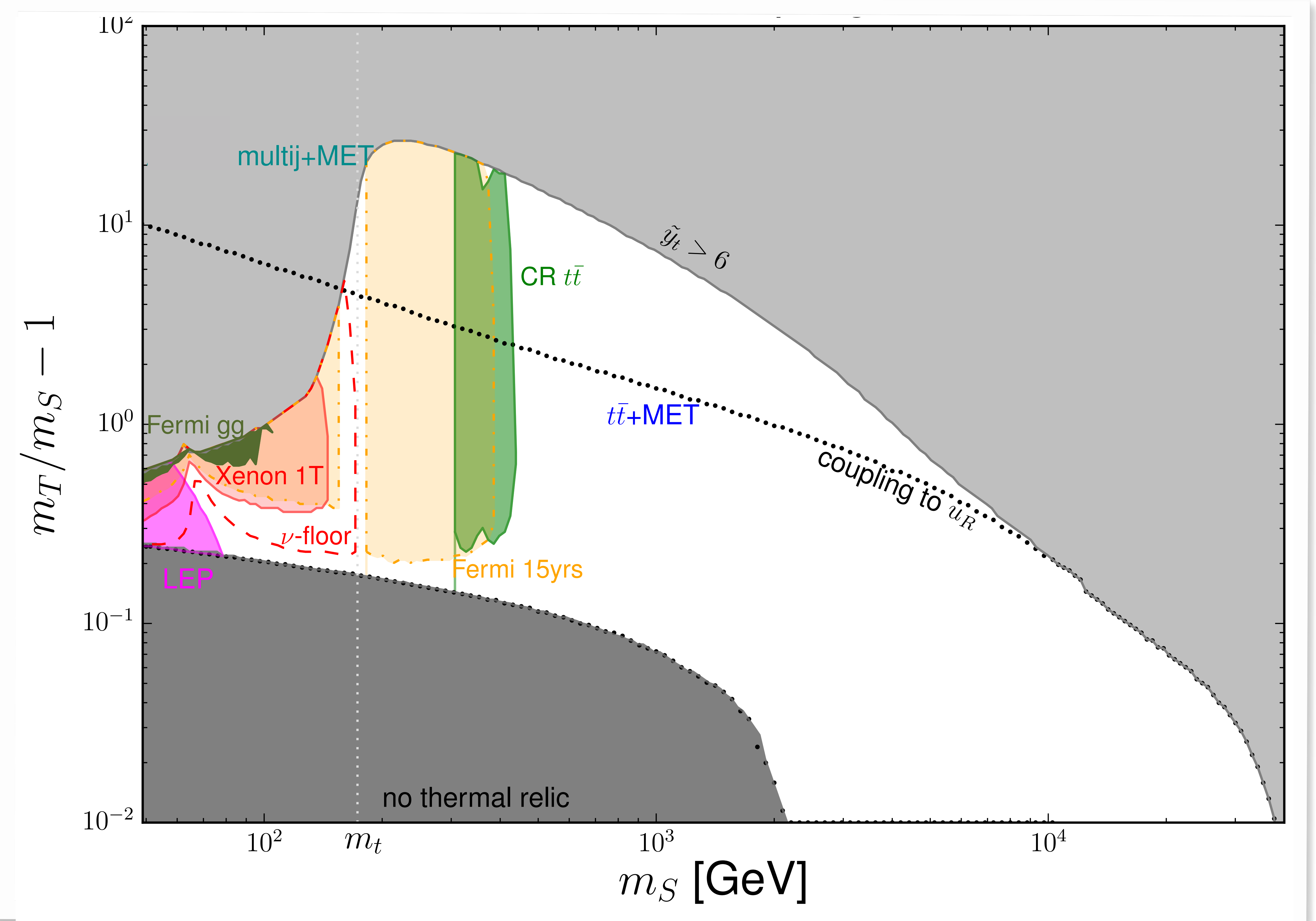
DM pair production

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

Bounds from multi-jet+MET and tt̄+MET

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

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



DM indirect detection: limited sensitivity

- Limited light DM regions

Present and future colliders

- Still limited
- Sole probes to tackle the unconstrained regions

Lagrangian

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

★ Vector-like mediator *T*
★ Scalar dark matter *S*

Correct relic density achievable

- Fixes the Yukawa $\tilde{y}_t$
- Dark grey: no thermal relic
- Light grey: loss of perturbativity
- Annihilation into gg below the m_t threshold

Poor sensitivity to DM direct detection

- DM direct detection constraints
  ★ Loop-induced process
  ★ Most parameter space below the ν floor
  ★ Exception: below the top threshold
  ★ Low expectation for the future

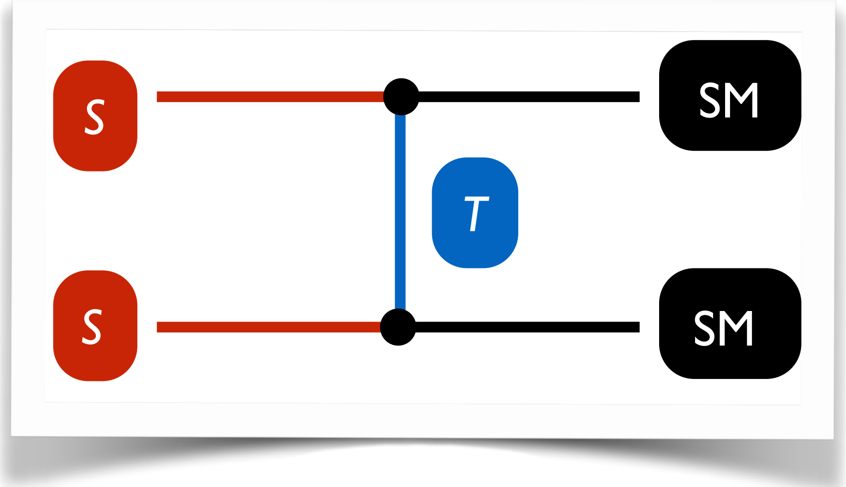
Next-to-simplified models - Contact terms

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

Simplified composite DM model

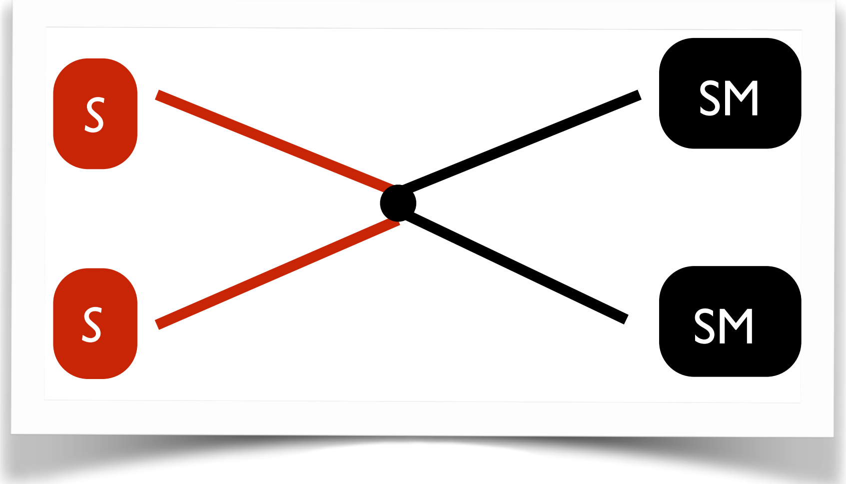
- Lagrangian

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



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

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



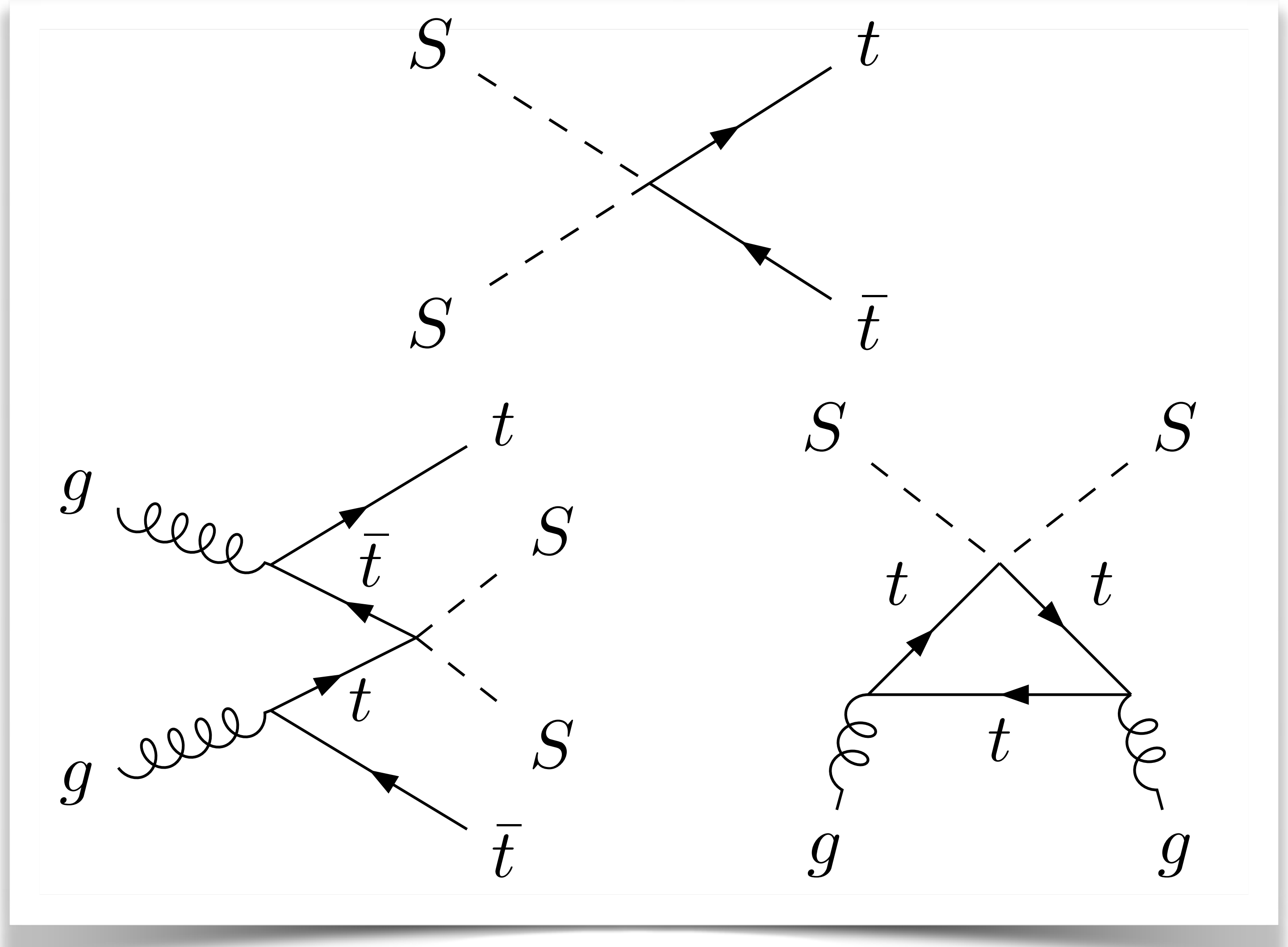
[Bellazzini, Csaki, Hubisz, Serra & Terning (JHEP'12)]

Simplified and minimal models important…

- Lack of potentially important non-minimal features…

Impact of the new contact terms

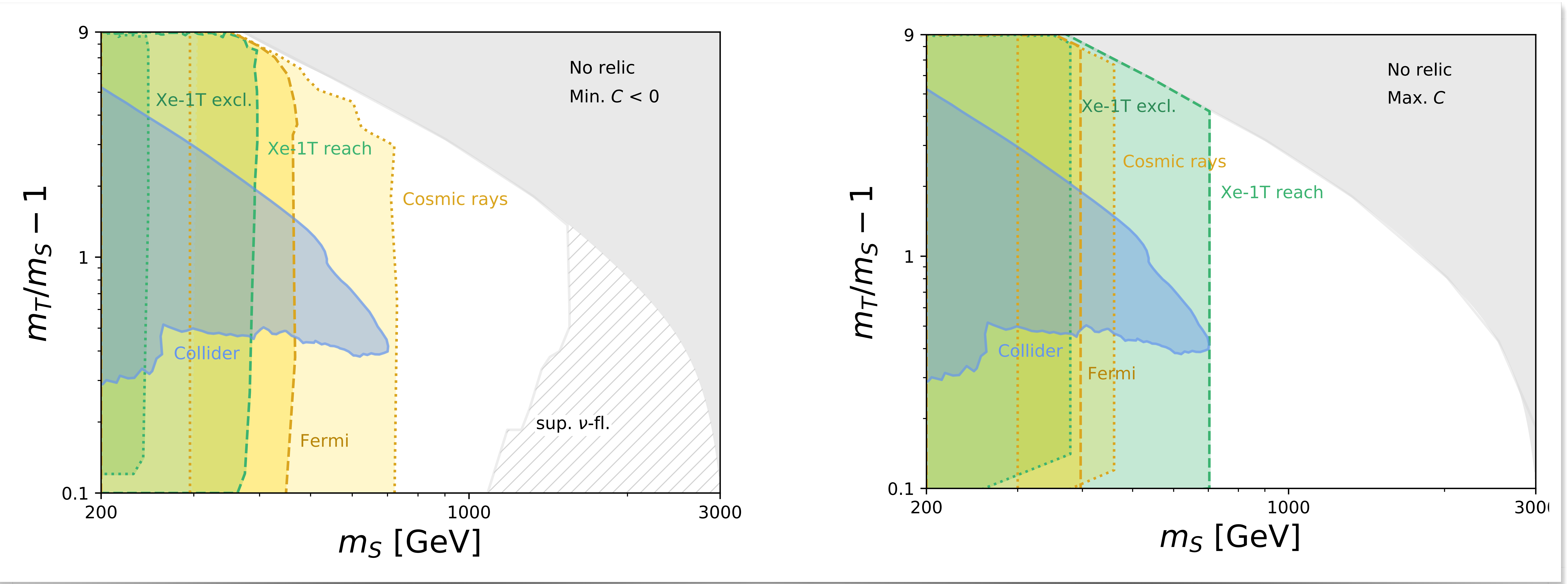
- Correct relic density with smaller Yukawa couplings
  ➞ Potentiel impact on DM indirect detection
- Possibly larger DM-nucleon scattering cross section
  ➞ Larger impact of the DM direct detection experiments
- Collider bounds ➞ no impact of $C \neq 0$
  [competition with resonant channels]



Consequences of non-minimality on DM ID and DD

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

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

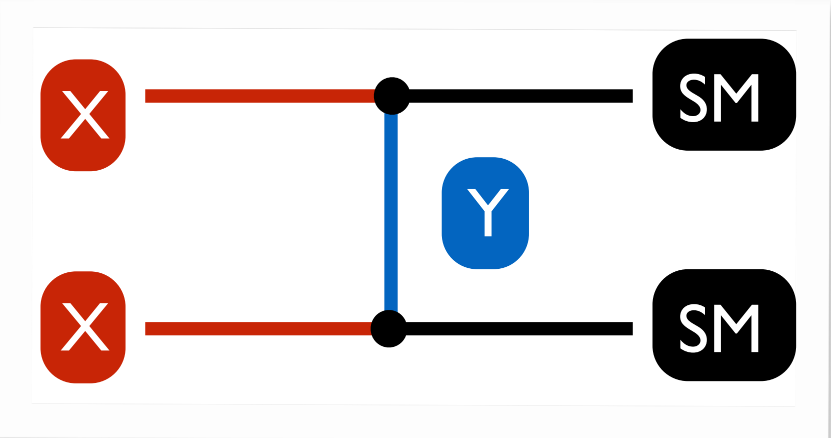


- DM-ID: modification of the γ spectrum
  - ➙ Negative C: very strong bounds (interferences)
  - ➙ Large and positive C: bounds similar to C=0
- DM-DD: much larger annihilation cross section
  - ➙ Can access scenarios with $m_S > m_t$
  - ➙ Negative C: milder bounds
  - ➙ Large and positive C: stronger bounds

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 $SU(2)_L x U(1)_Y$ 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	ψ_Q, ψ_u, ψ_d	1/2
S	0	no		
$\tilde{\chi}$	1/2	yes	$\varphi_Q, \varphi_u, \varphi_d$	0
χ	1/2	no		
$\tilde{V}_\mu$	1	yes	ψ_Q, ψ_u, ψ_d	1/2
V_μ	1	no		

Representative of many DM model with parity-odd mediators

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

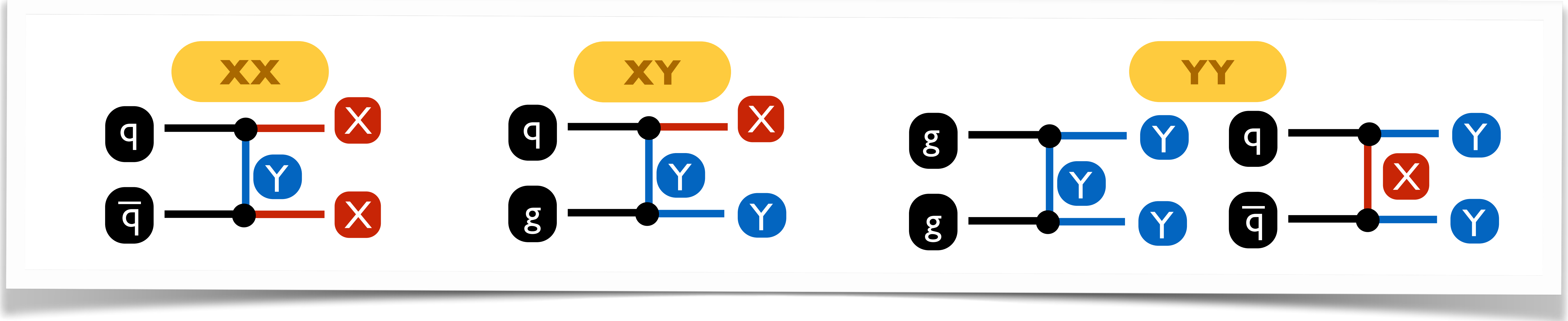
- Simple scenarios investigated by ATLAS and CMS
- Benchmarks for numerous searches
- Collider-cosmology complementarity ➙ unexpected LHC phenomenology

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

DM @ colliders: the signal…

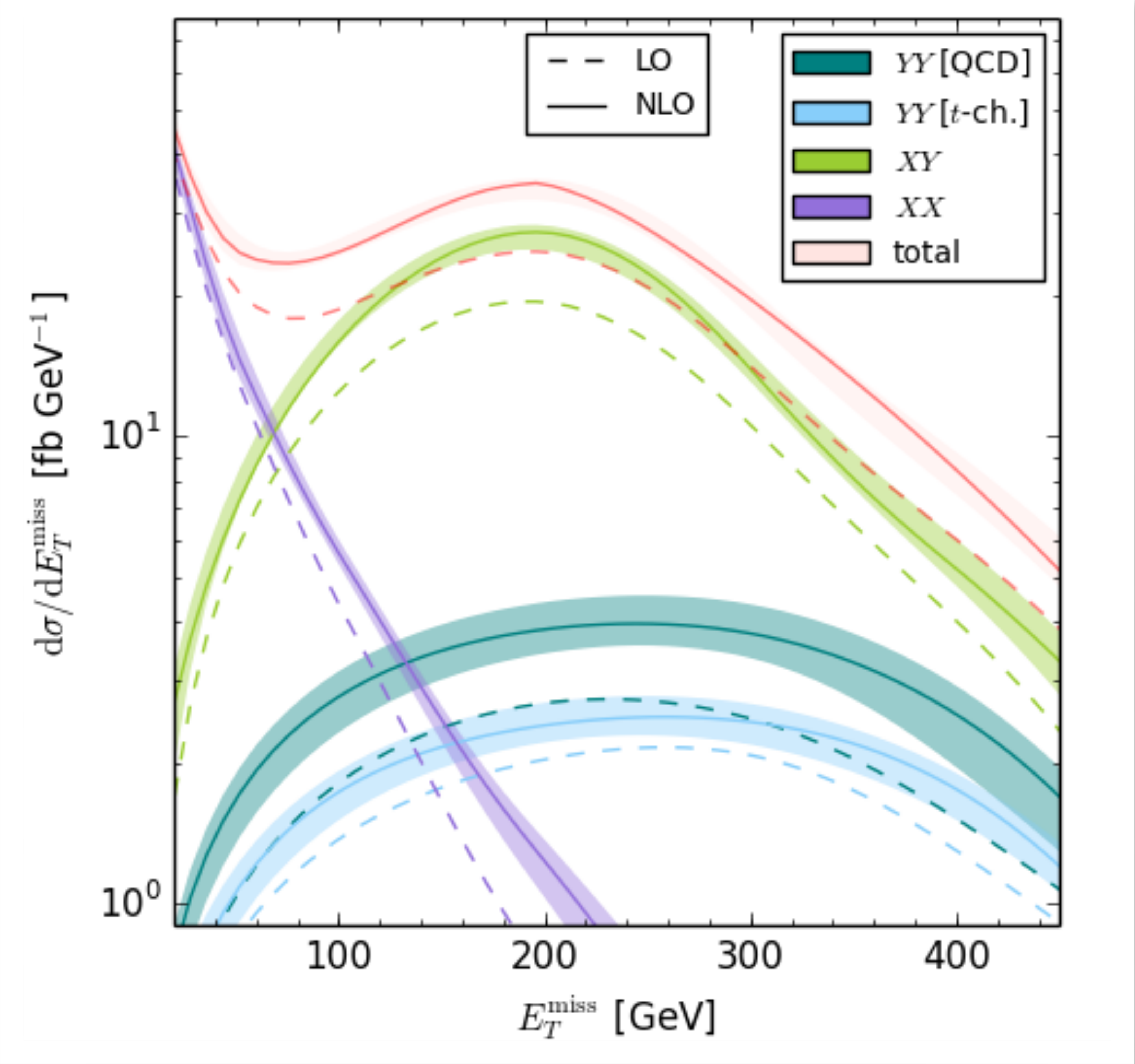
[Arina, BF & Mantani (EPJC'20)]

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



- Typical signal included in LHC simulations
  - ⋆ DM pair production (+ 1 jet)
  - ⋆ Mediator QCD pair-production (with mediator decays into DM+jet)
- Some contributions ignored
  - ⋆ DM/mediator associated production (with mediator decays into DM+jet)
  - ⋆ *t*-channel mediator pair production and interference

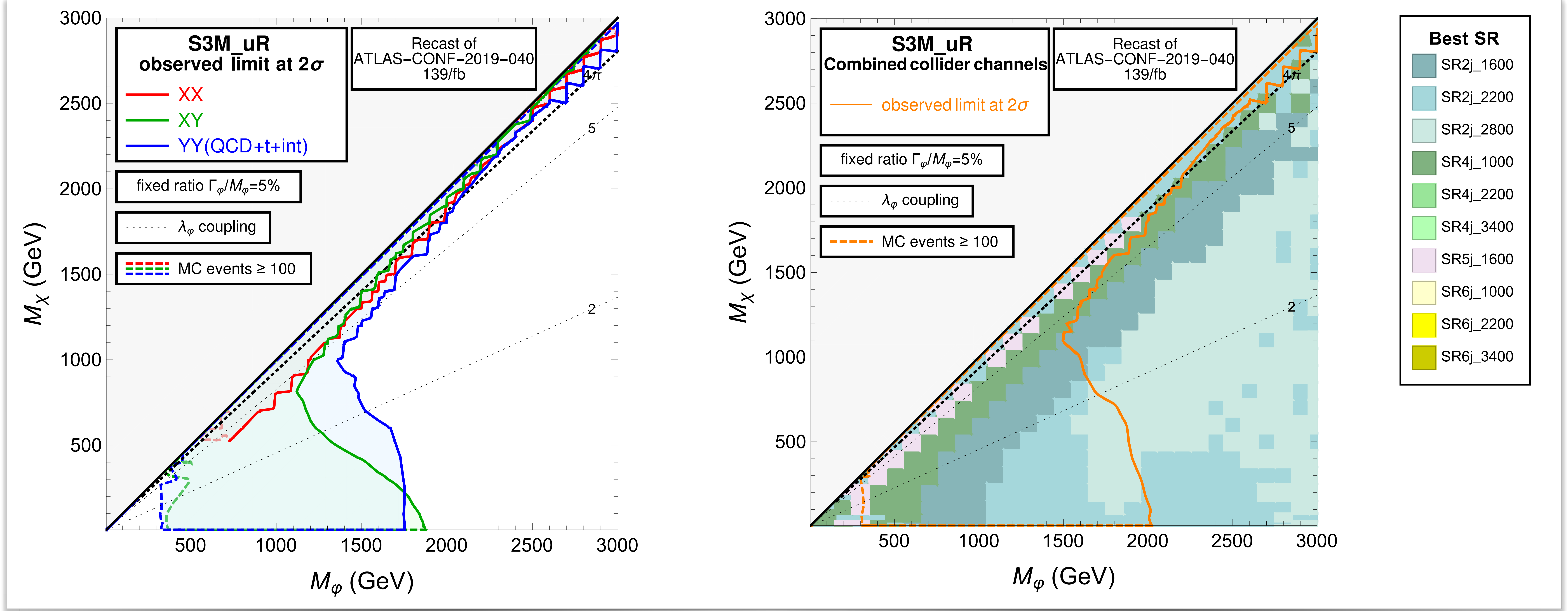
Not justified



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

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

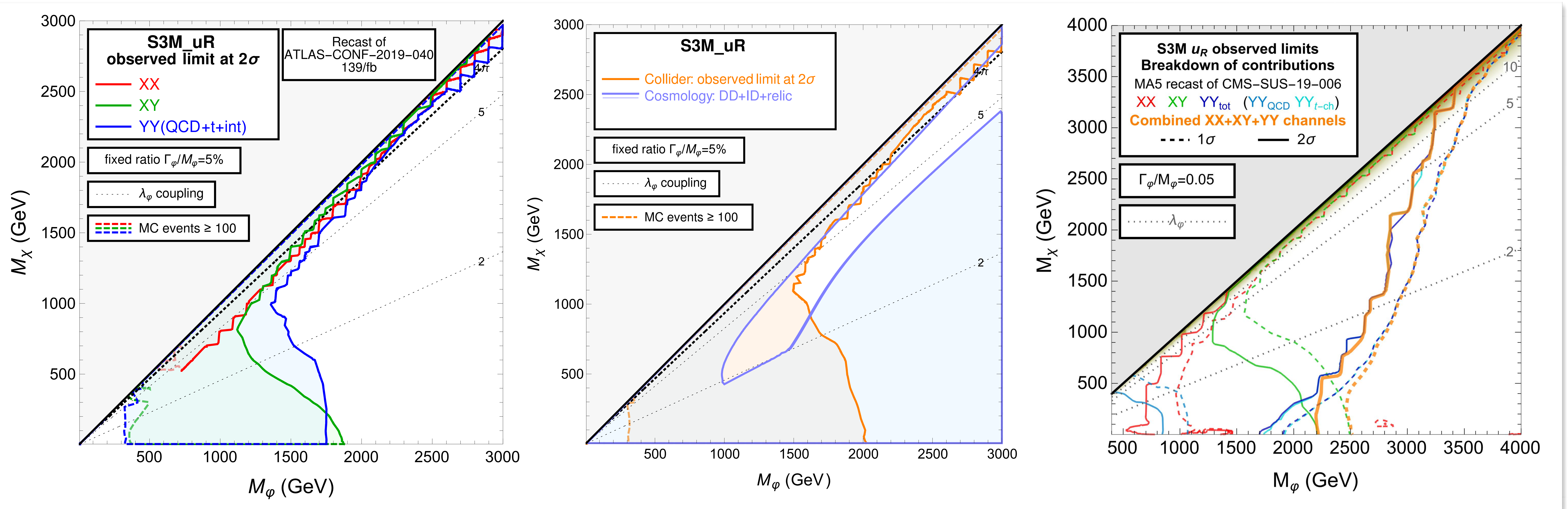
Dissecting the collider signal (Majorana DM and scalar mediator)



- All channels contribute (larger rates)
  - ⋆ XX ~ λ^4
  - ⋆ XY ~ λ^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 (to appear)]



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

- Better constraints on XY
- Slightly better constraints on XX

Mediator pair production very different

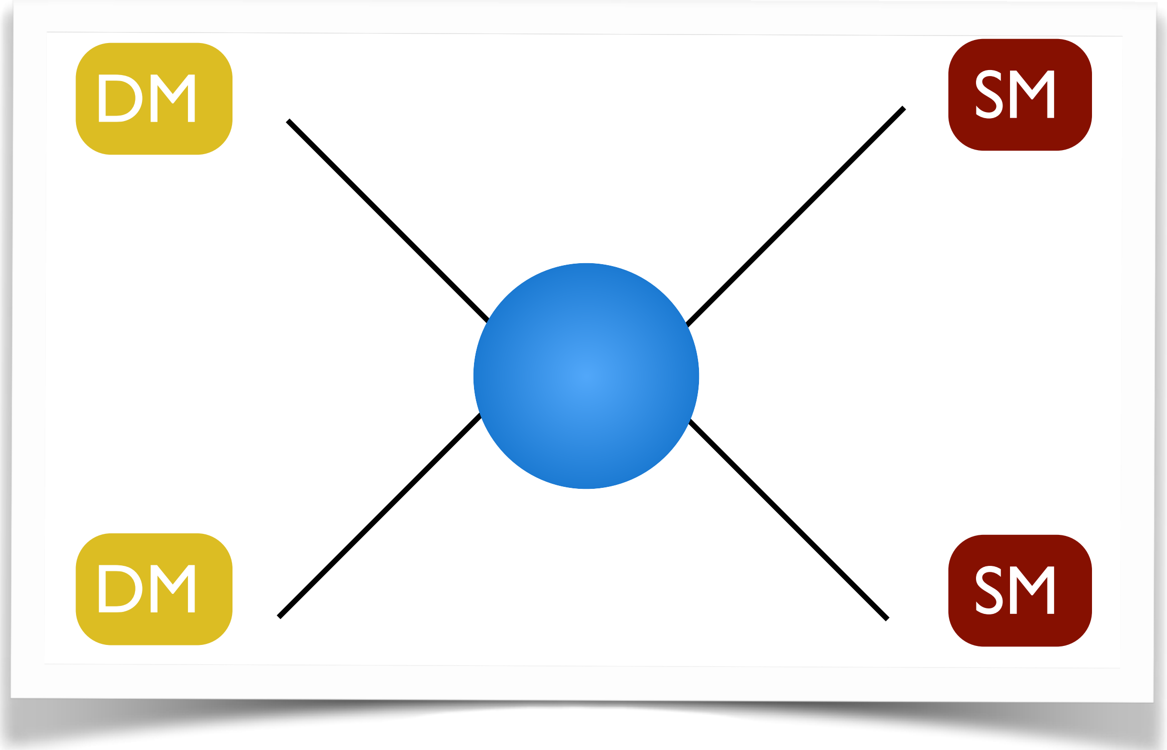
- *t*-channel DM exchanges dominate
- $p\,p \to YY$ very large (more than $p\,p \to YY^*$)
  ➞ new channel included (enhanced by valence quarks)
  ➞ significant improvements of the bounds

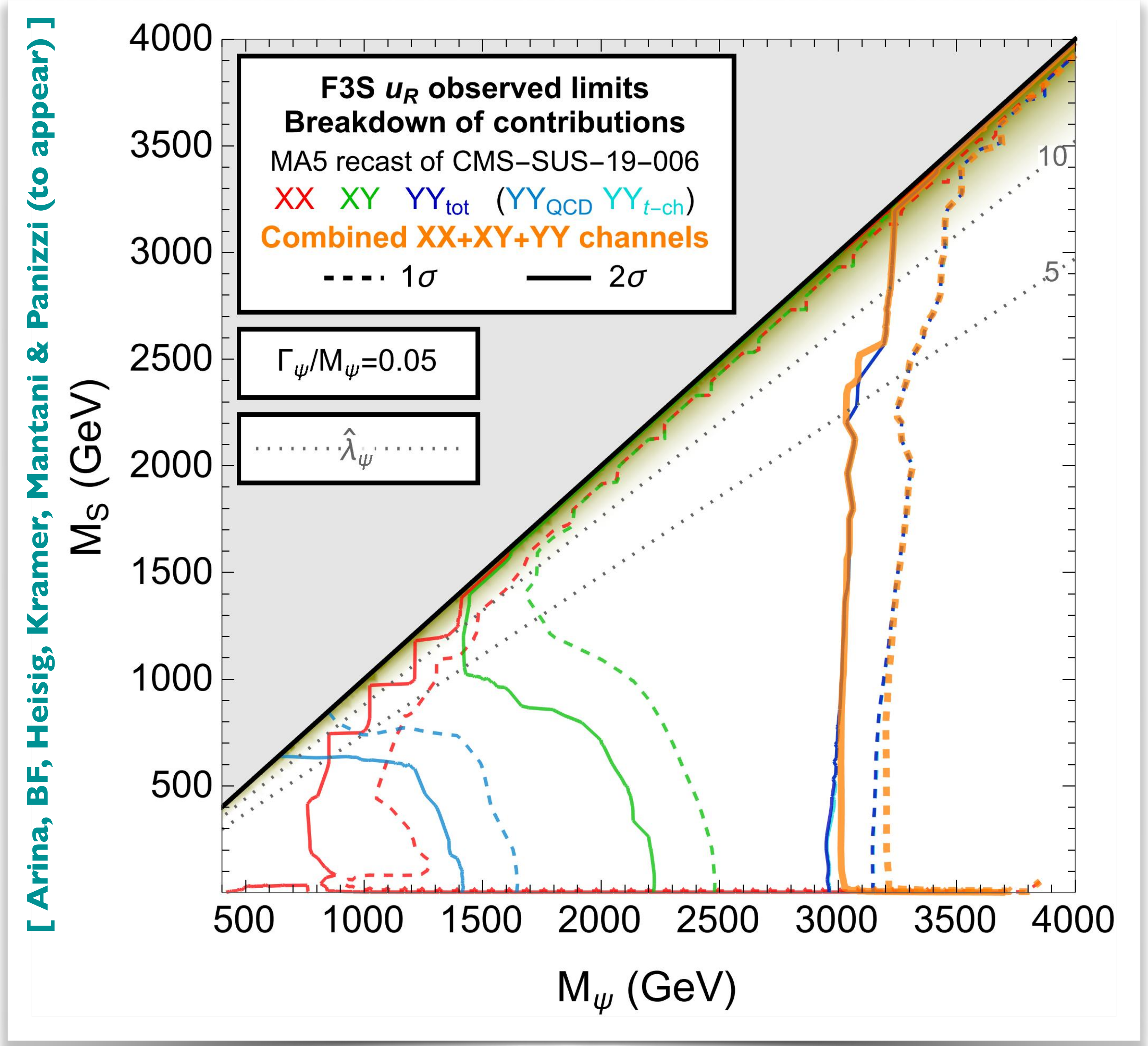
Collider simulations to be rethought!

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





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