Dark Matter EFTs at Colliders

Based on work with:

Francesco Riva and Alfredo Urbano

1607.02474

1607.02475

Why EFTs at colliders?

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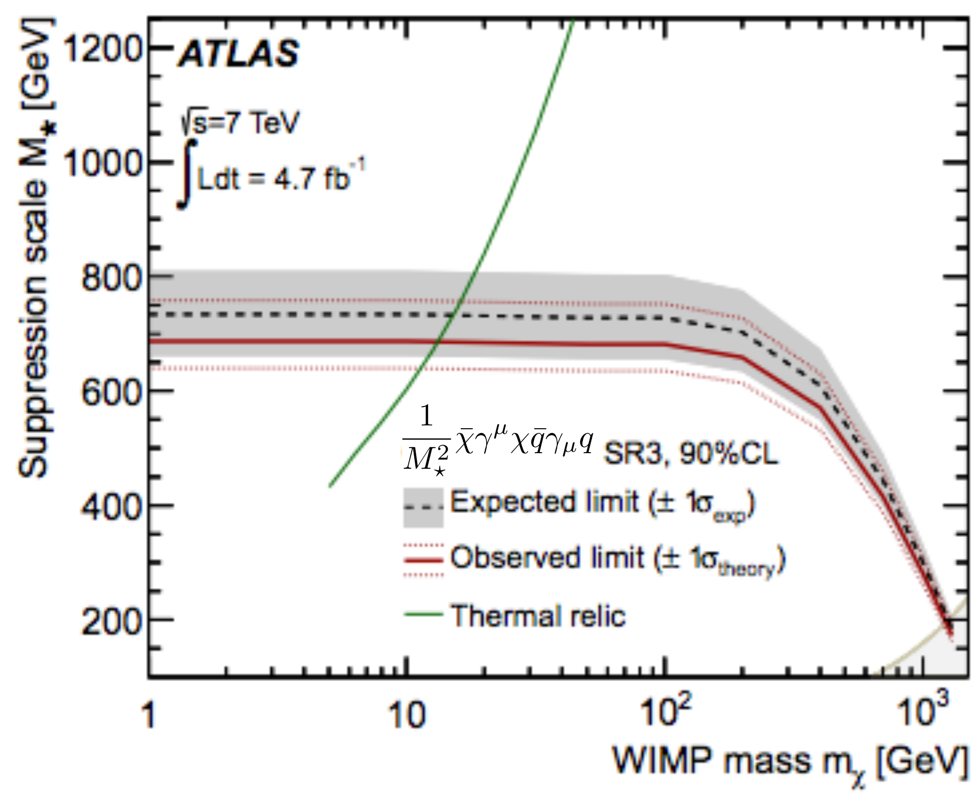

Figure from:
1210.4491

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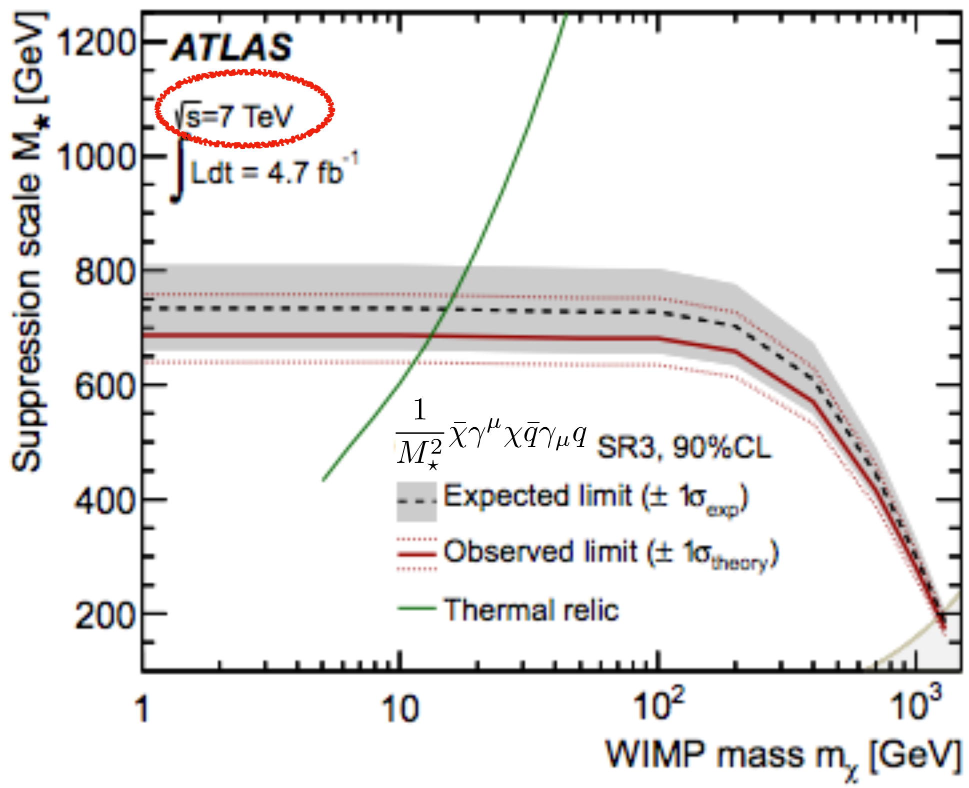

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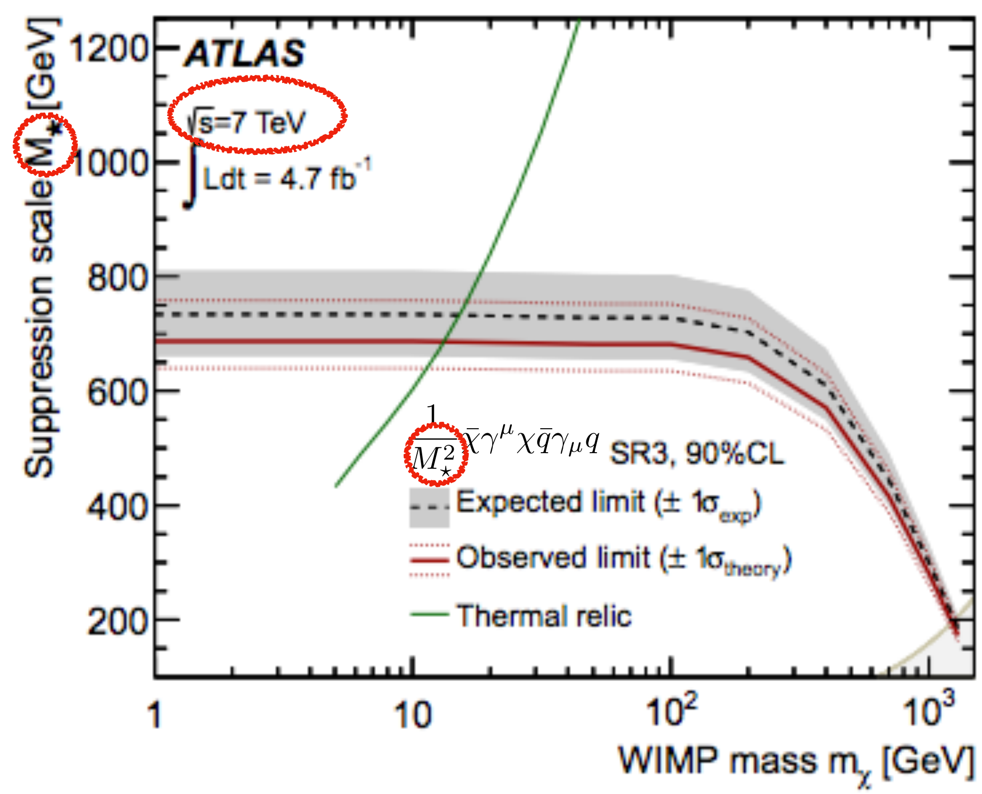
Why EFTs at colliders?

- What is $M_\star$?



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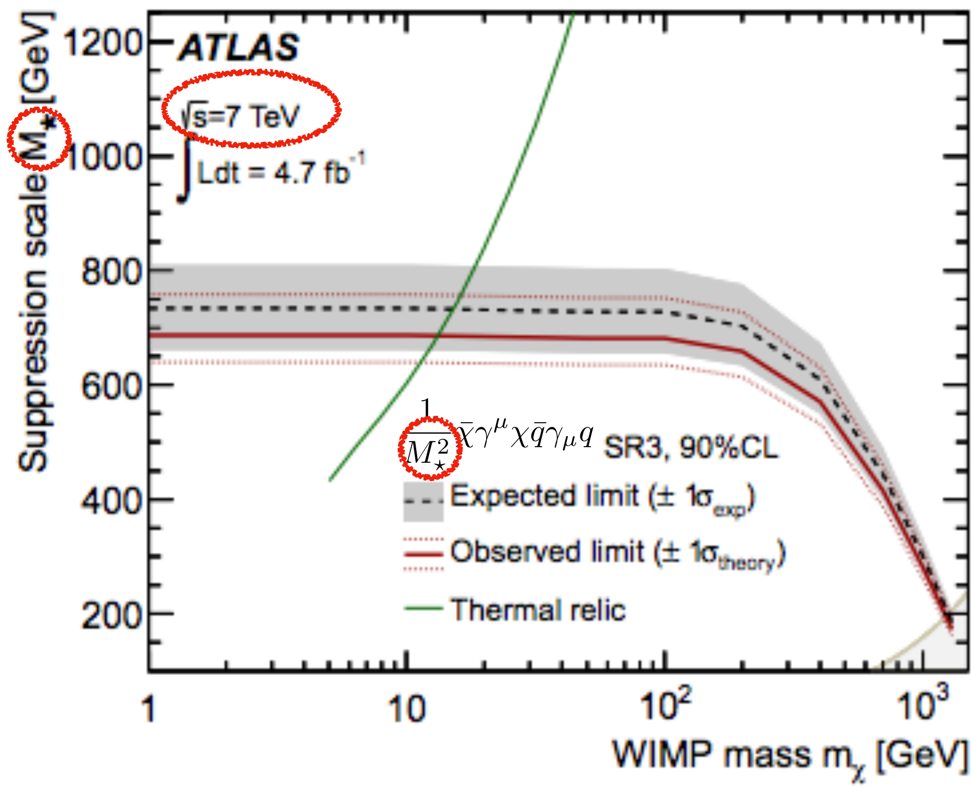

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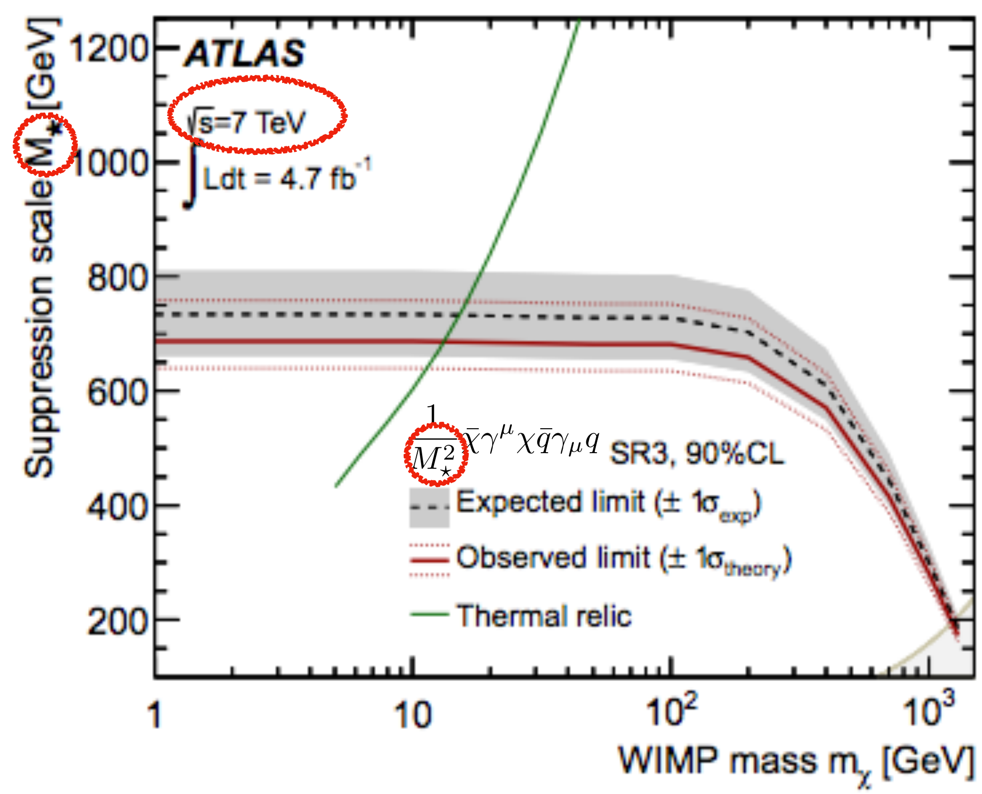

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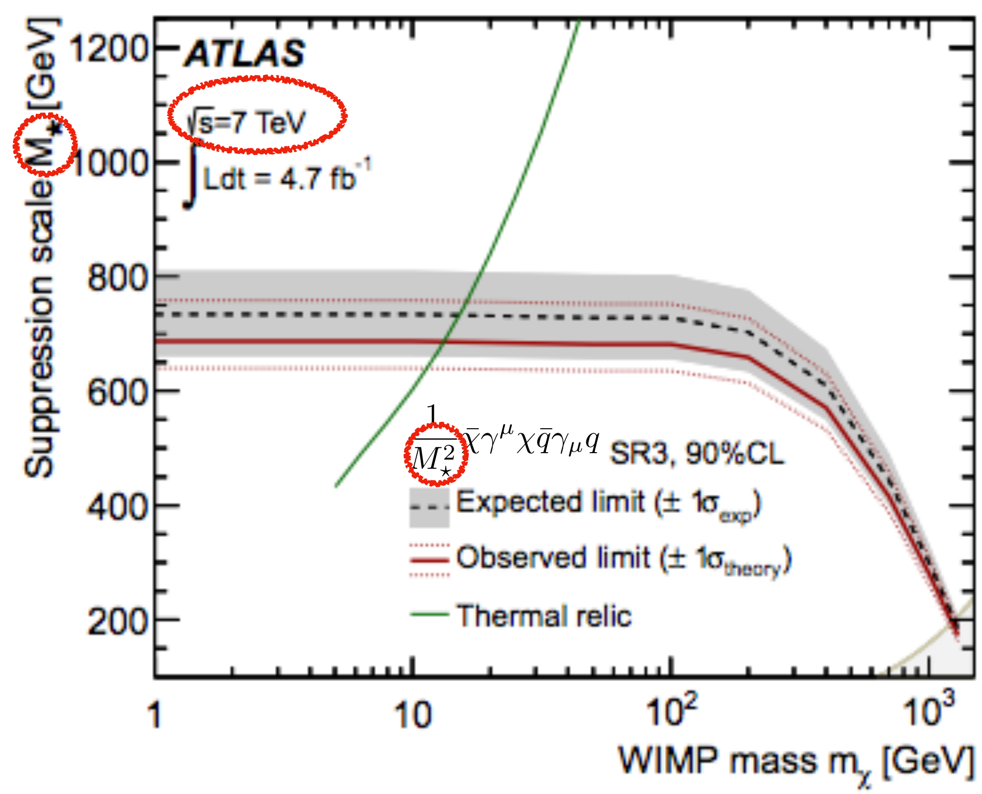

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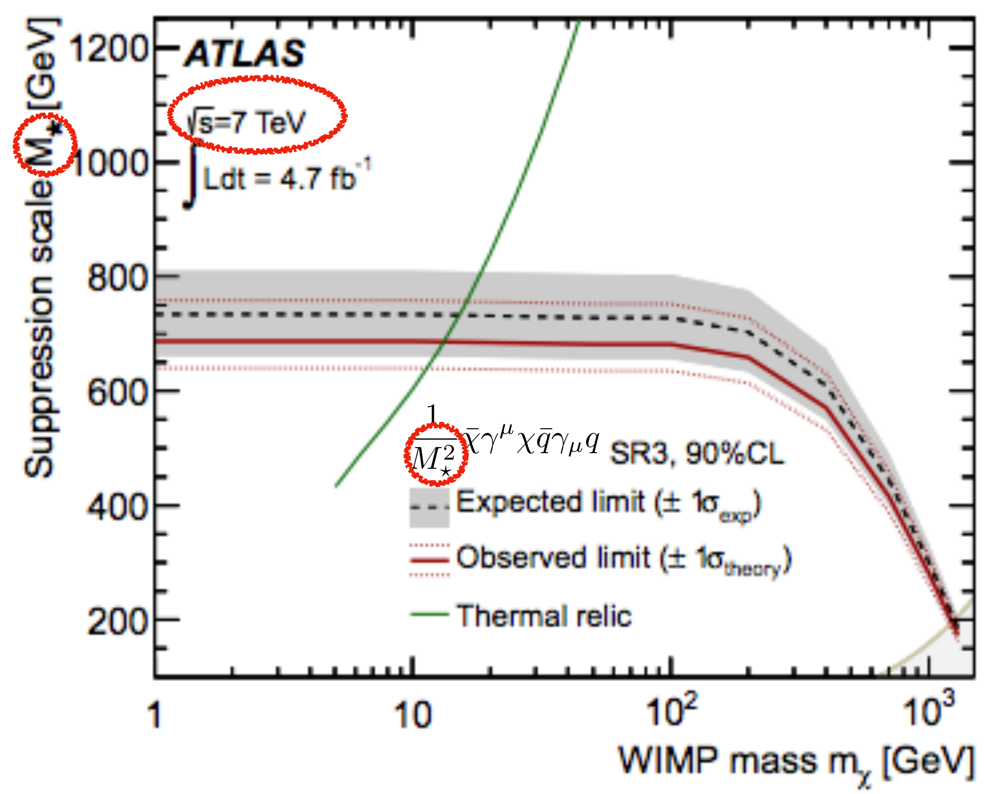

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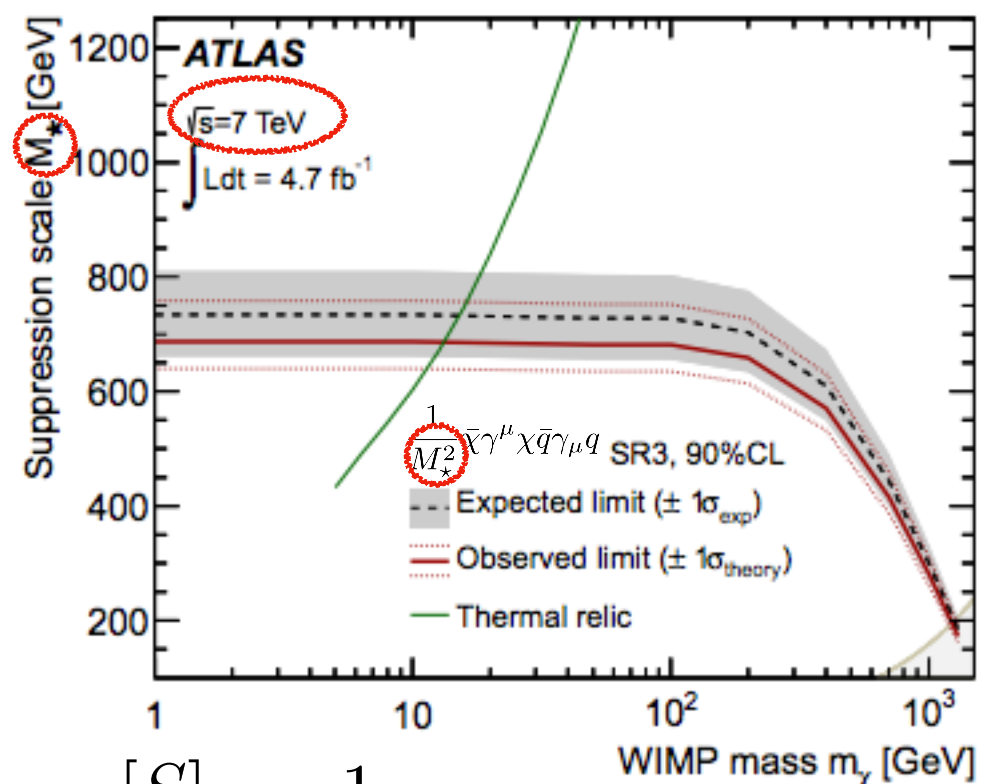

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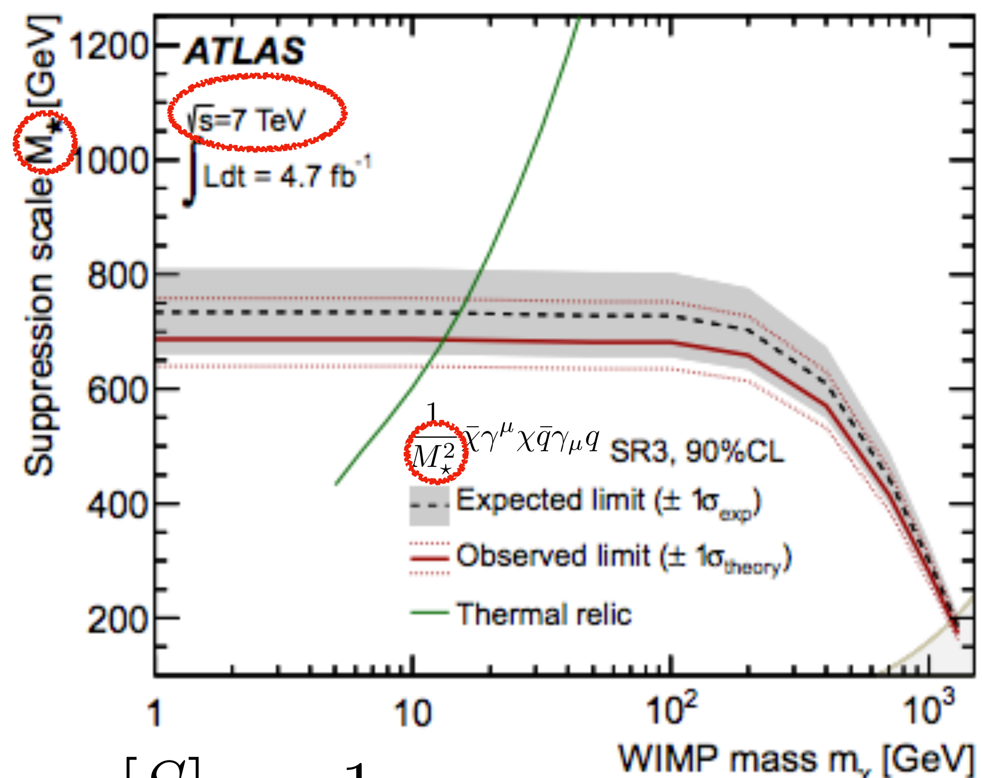

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Kinetic term

$$[\phi]_\hbar = \frac{1}{2}$$

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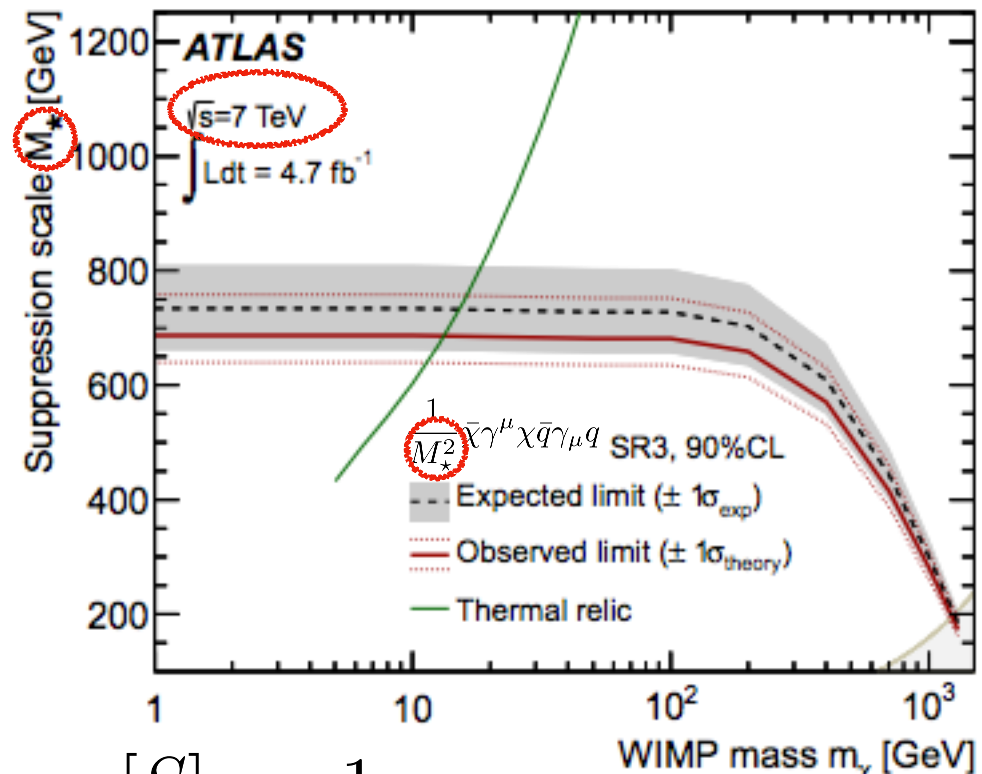

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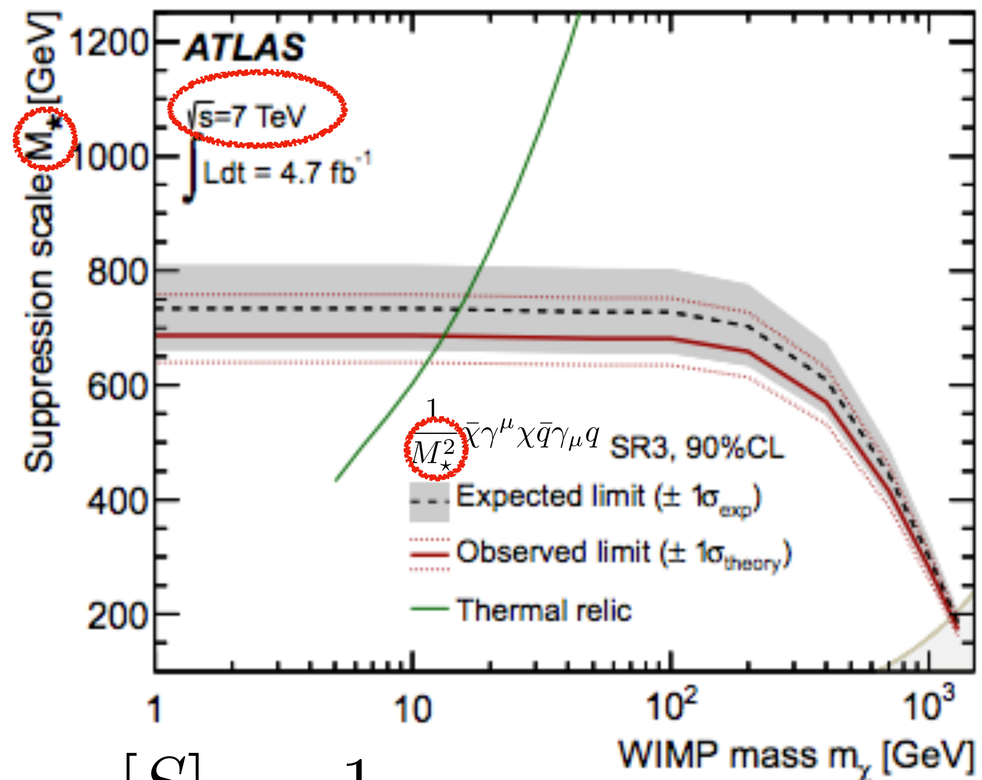

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Number of fields in operator

$$\mathcal{L}_{eff} = \sum_{i,d} c_i \frac{\mathcal{O}_i^d}{M^{d-4}} \implies c_i \sim (\text{coupling})^{n_i-2}$$

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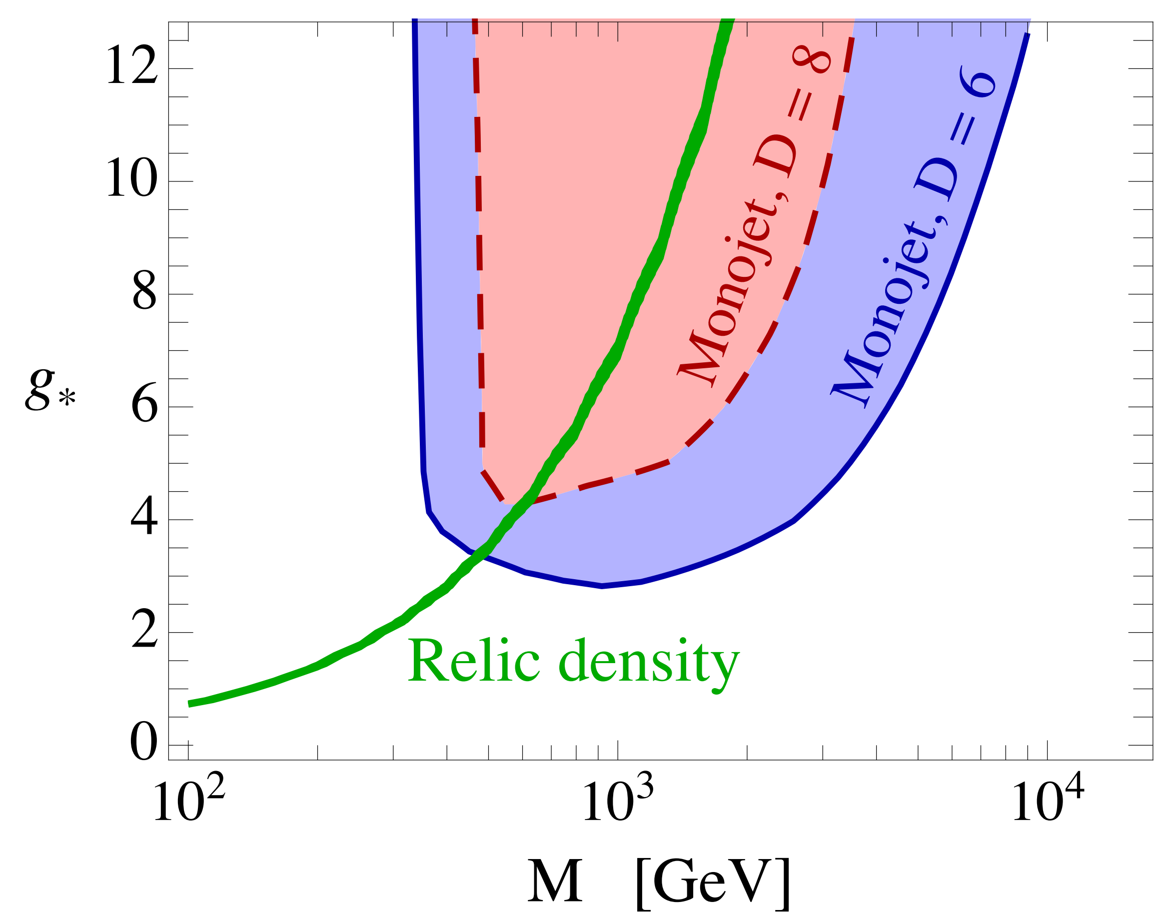

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Order on factor

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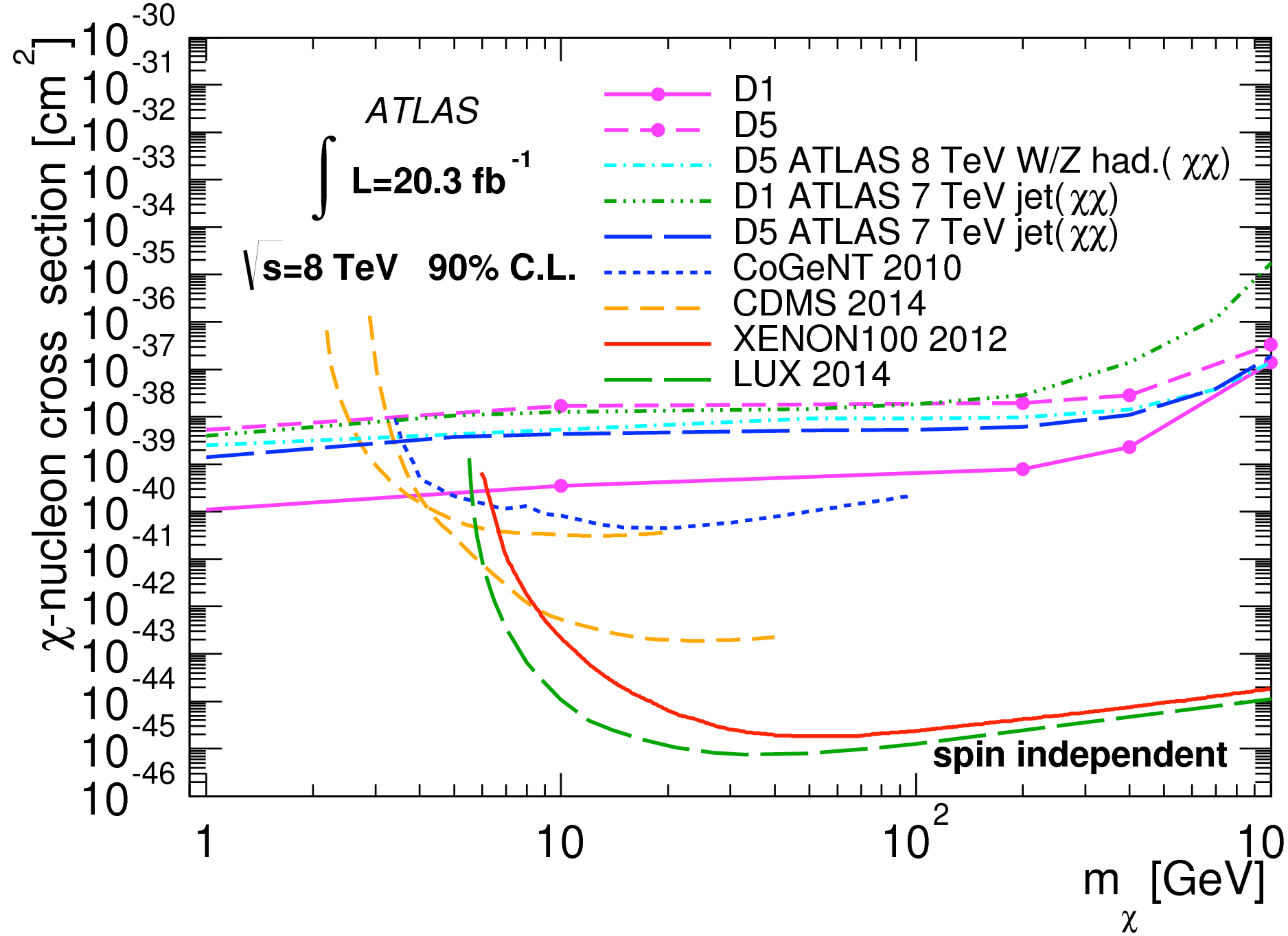

ATLAS
∫ L=20.3 fb⁻¹
√s=8 TeV 90% C.L.
D1
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spin independent
χ-nucleon cross section [cm²]
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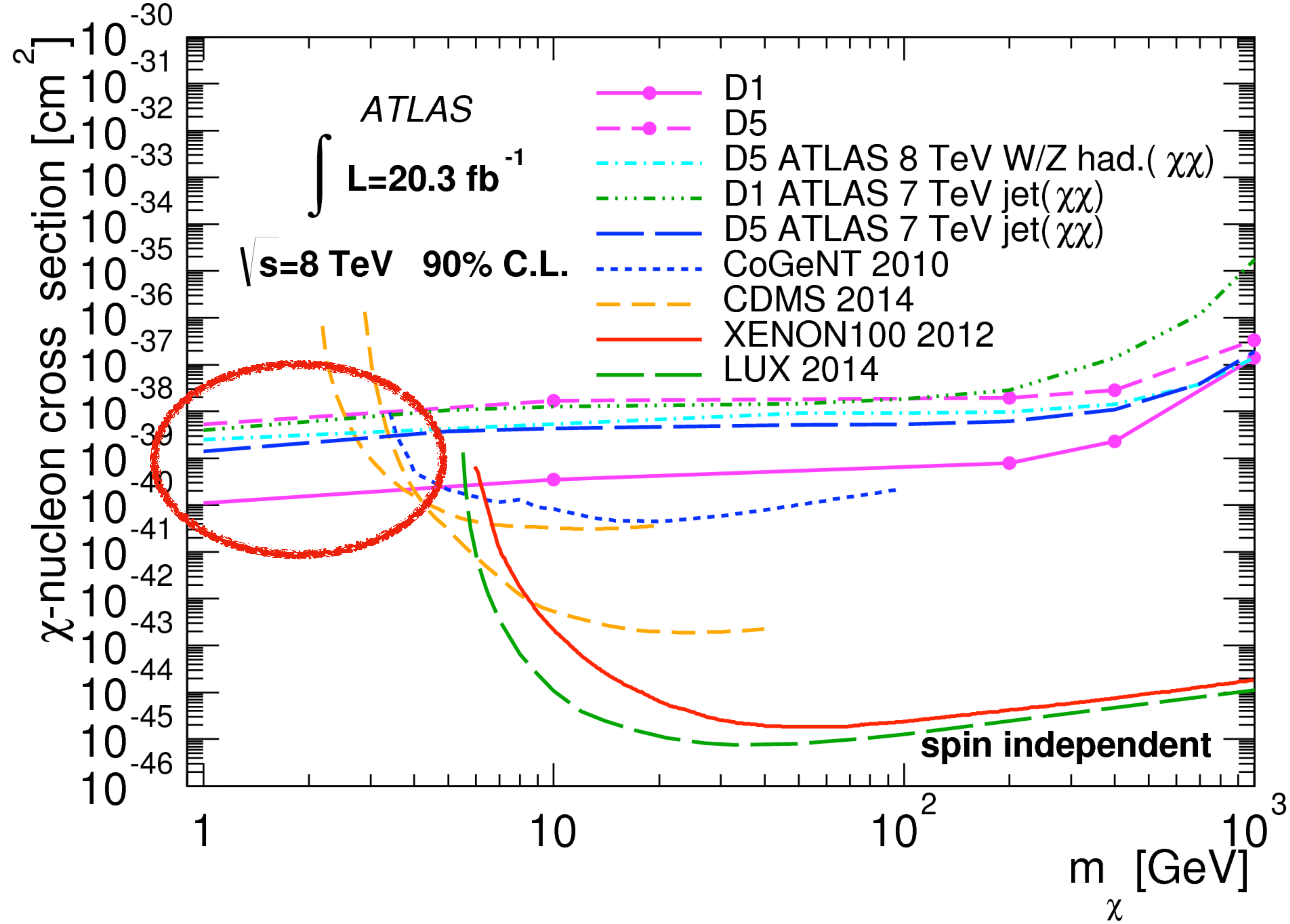

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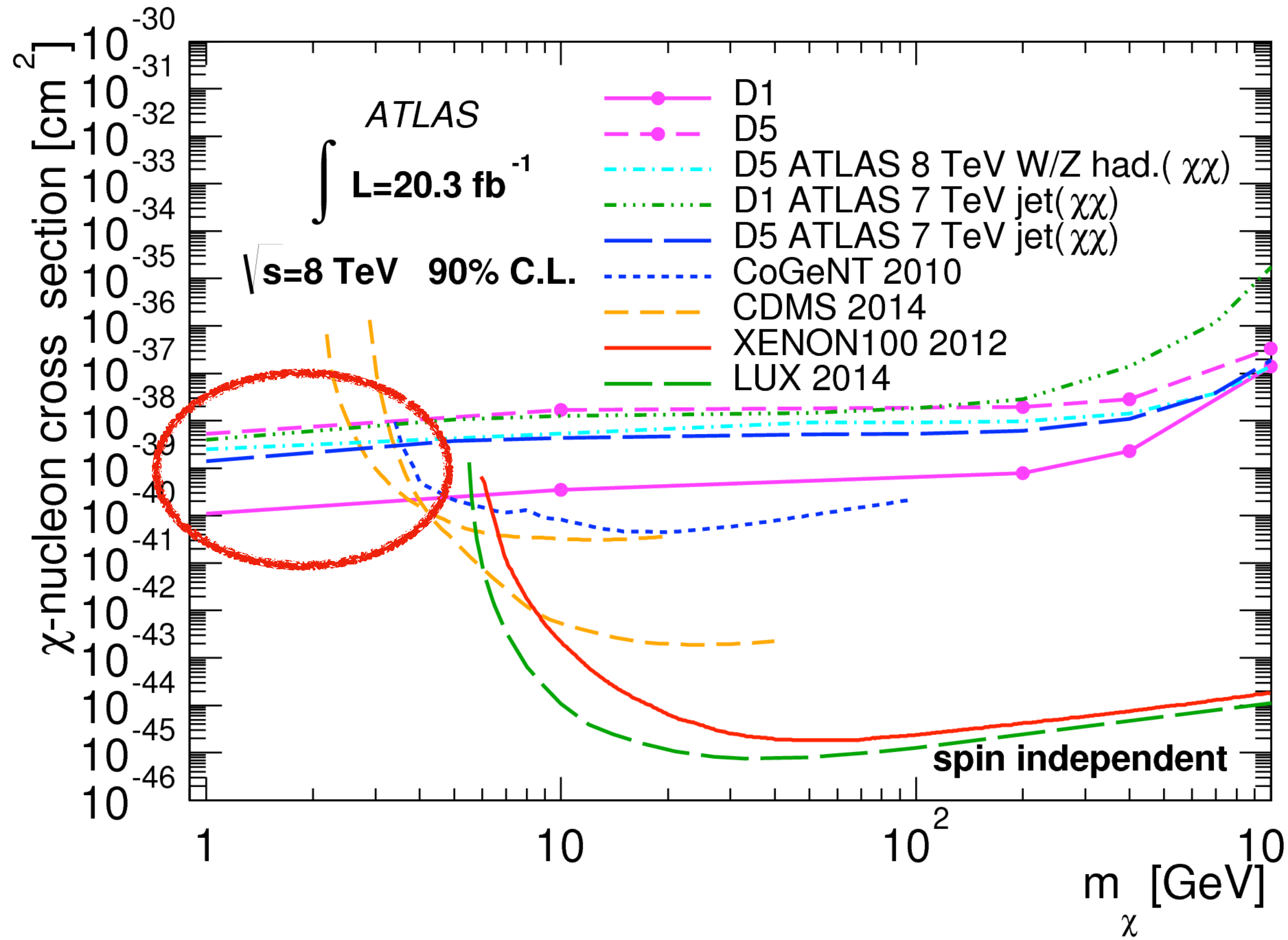

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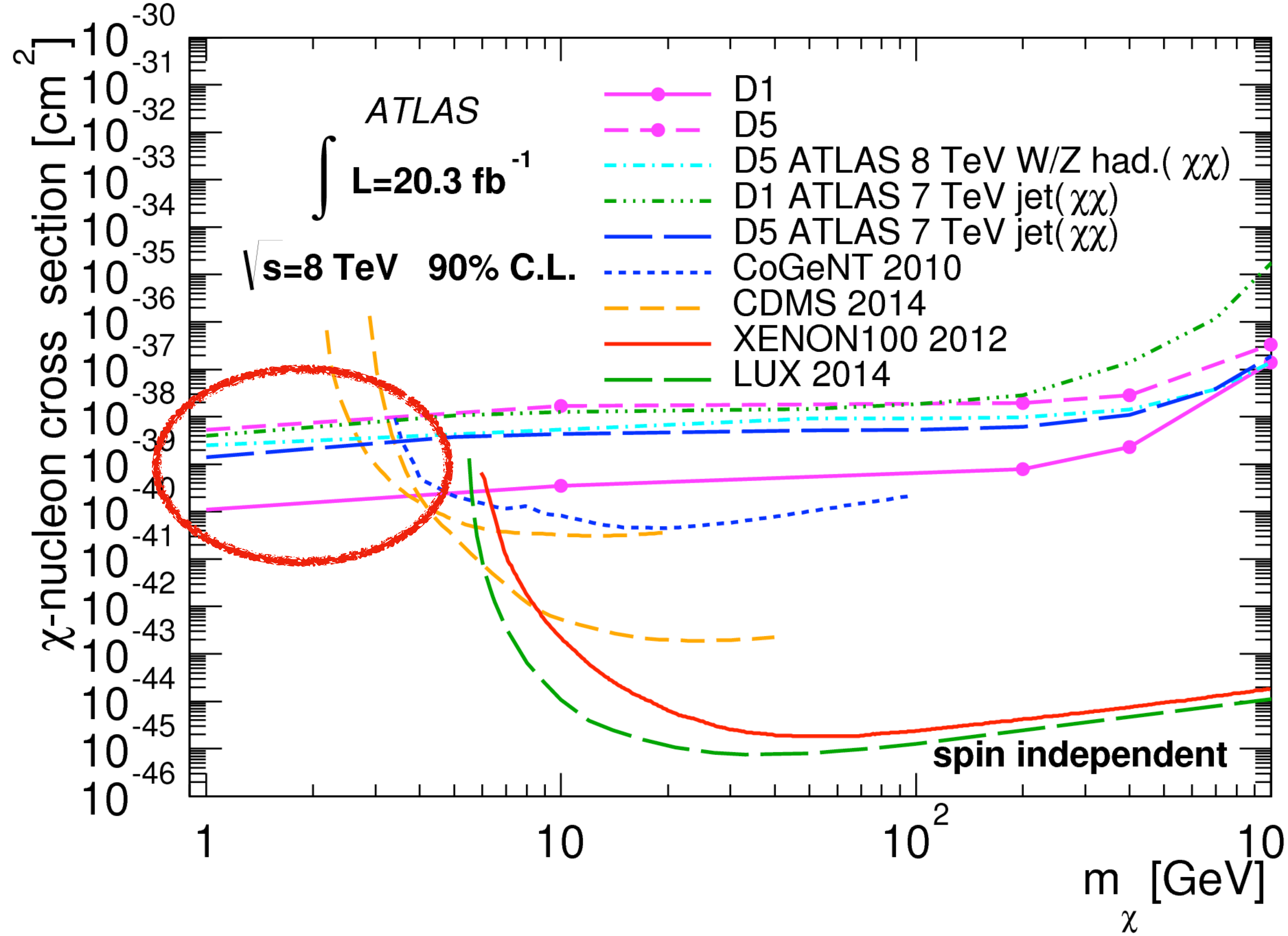

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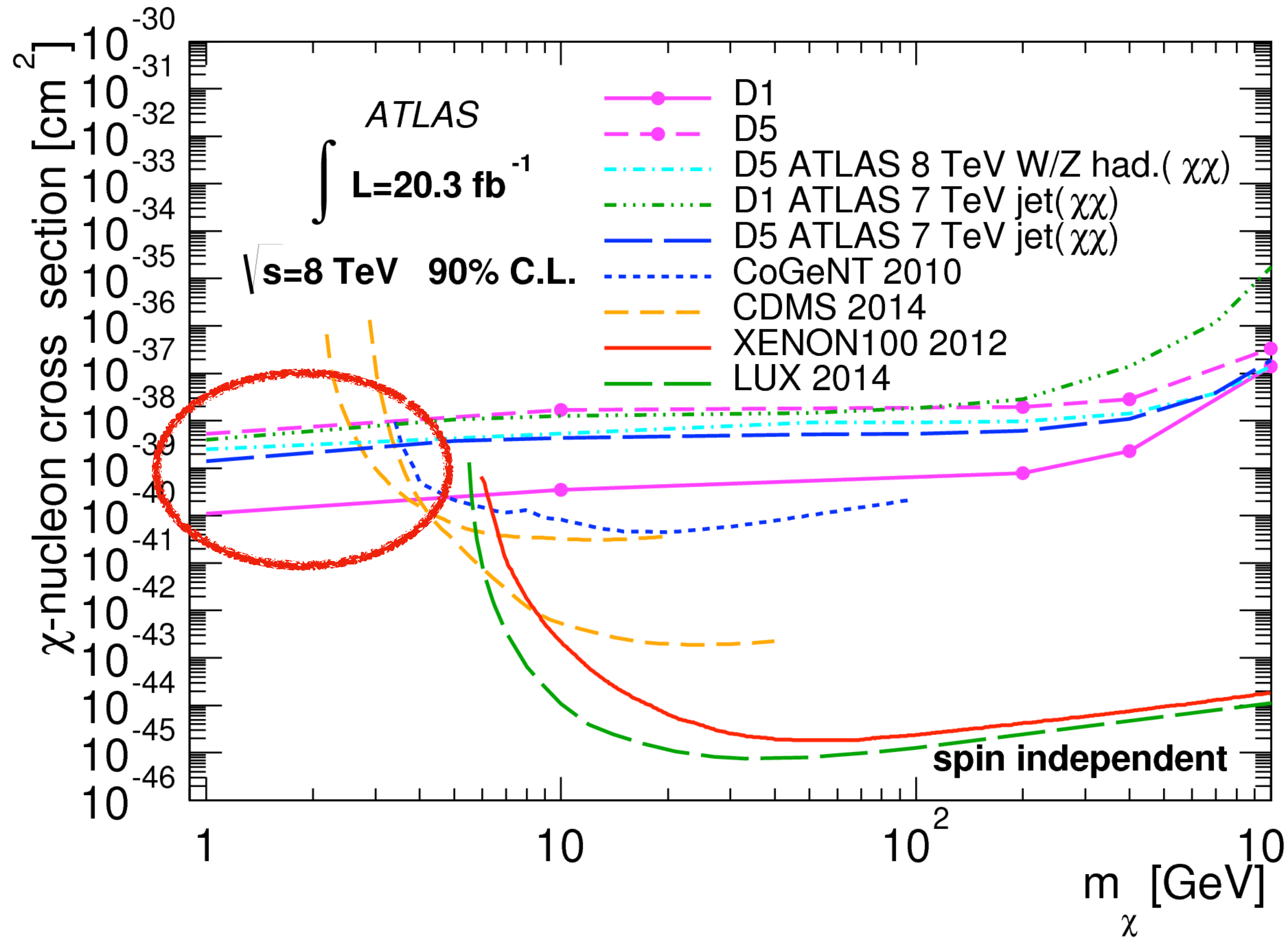

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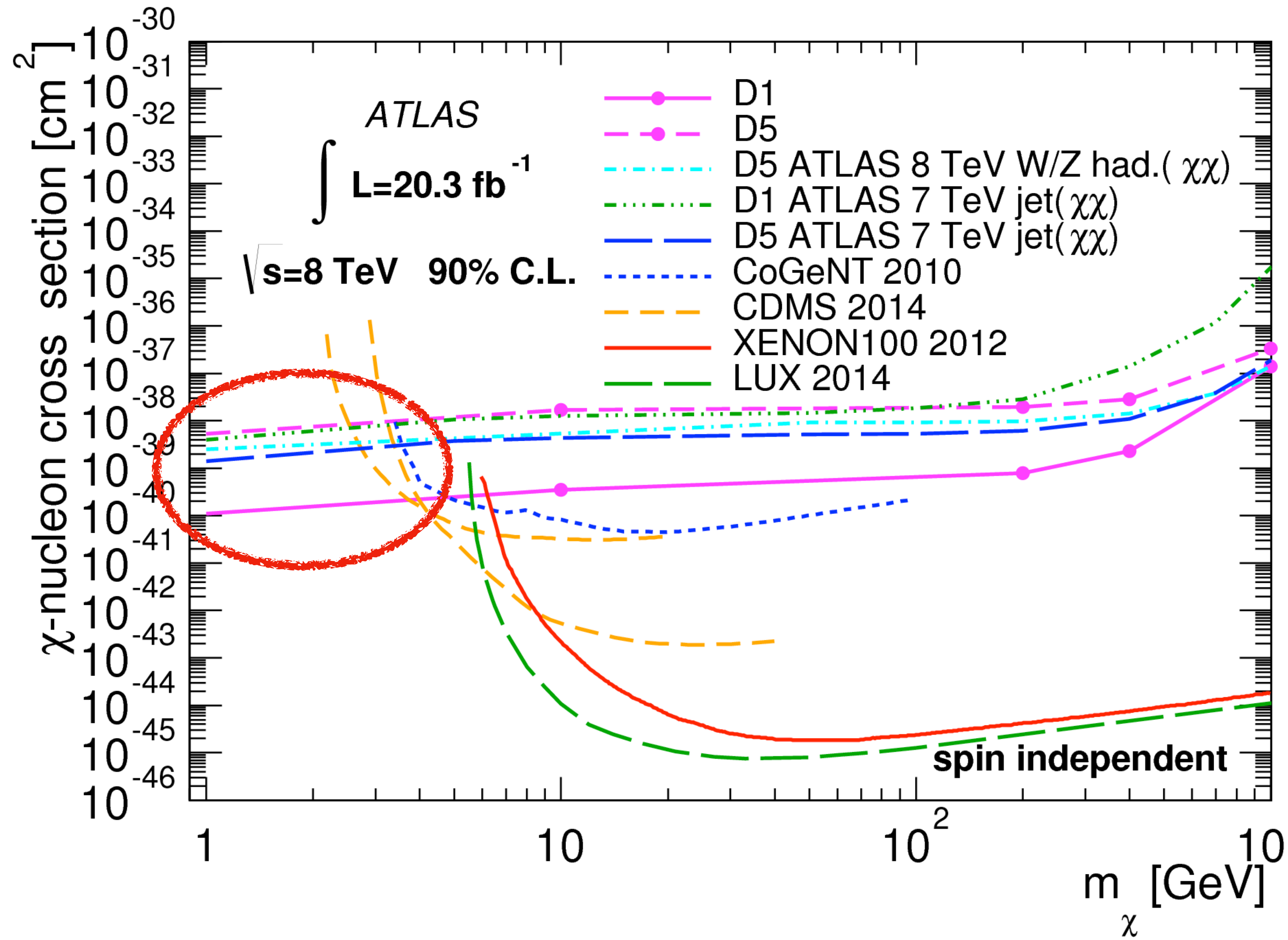

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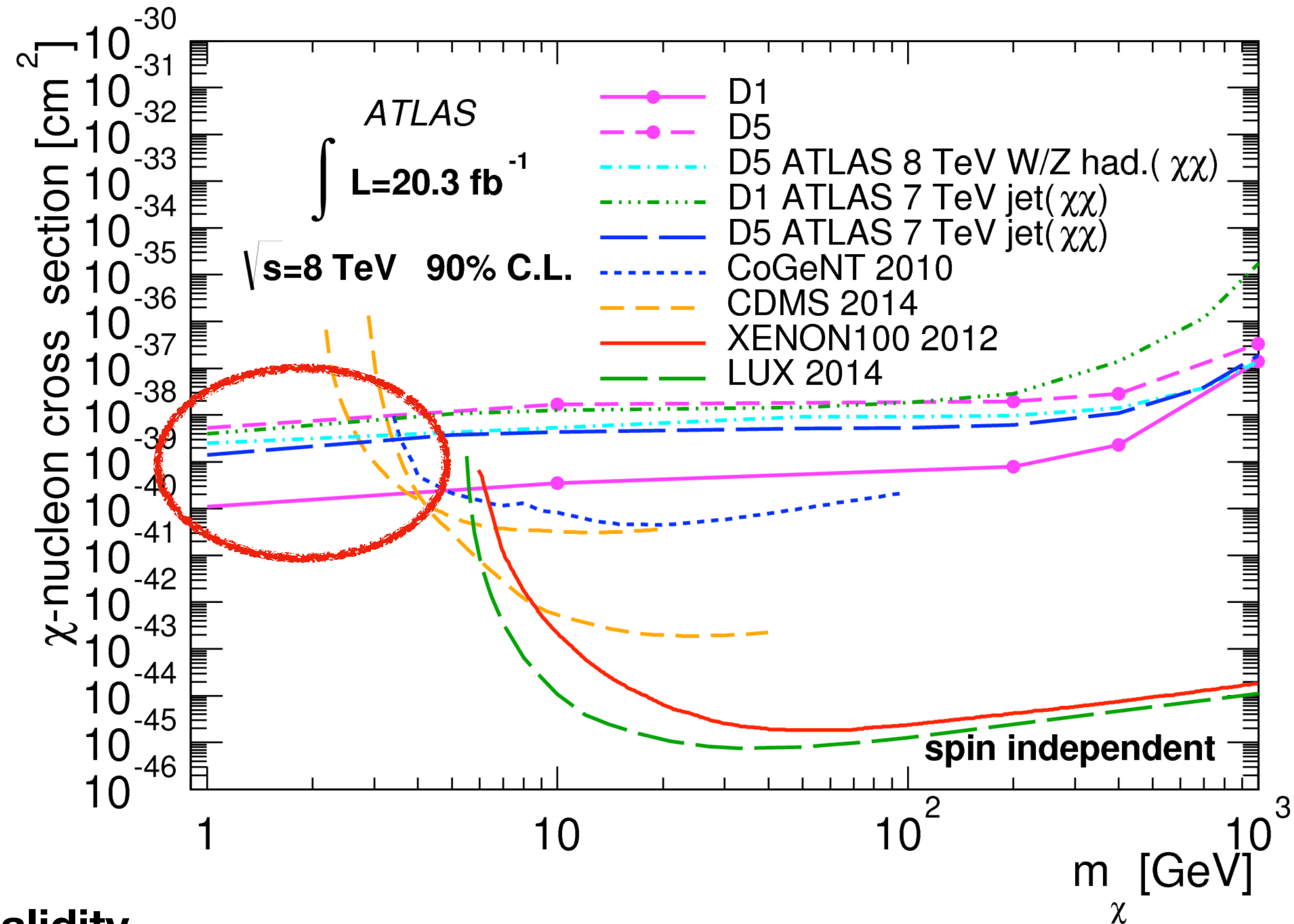
EFT validity



Our paradigm

Strongly coupled

Light dark matter

Employ non-linearly realised symmetries forbiding relevant and marginal operators

The WIMP miracle

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$$\langle \sigma v_{rel} \rangle \sim \left(\frac{\alpha_{DM}}{m_{DM}} \right)^2$$

$$\Downarrow$$

$$\Omega_{DM} h^2 \approx \frac{10^{-26} cm^3/s}{\langle \sigma v_{rel} \rangle} \approx 0.1 \left(\frac{0.01}{\alpha_{DM}} \right)^2 \left(\frac{m_{DM}}{100\text{GeV}} \right)^2$$

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e.g. *d*=6 $$\Omega_{DM} h^2 \approx 0.1 \left(\frac{4\pi}{g_*} \right)^4 \left(\frac{5\text{GeV}}{m_{DM}} \right)^2 \left(\frac{M}{3\text{TeV}} \right)^4$$

Consistent Recast

Racco, Wulzer, Zwirner
1502.04701

Discard events with $E > M$

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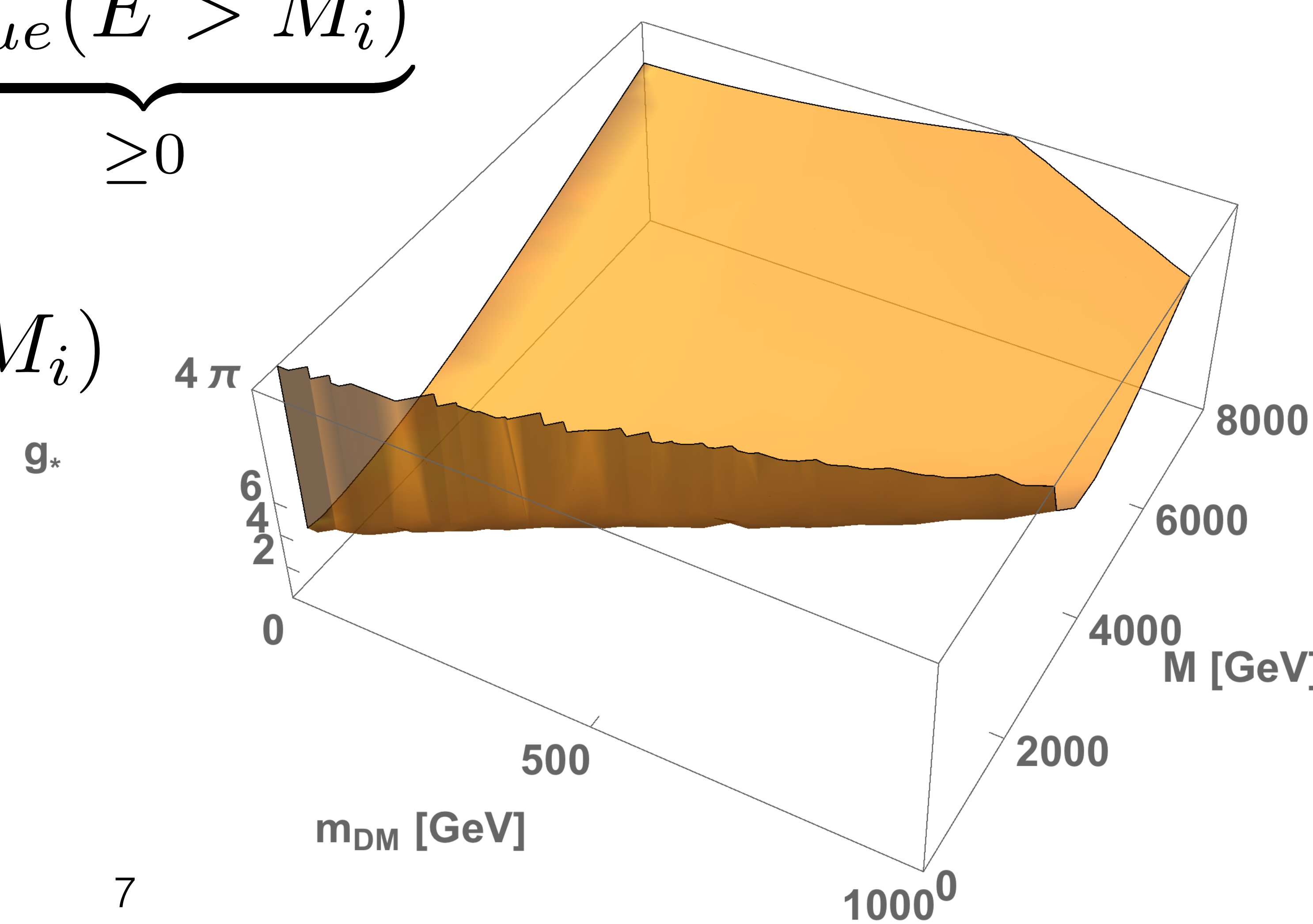

Recast of ’15 ATLAS mono-jet search

ATLAS collaboration
1502.01518

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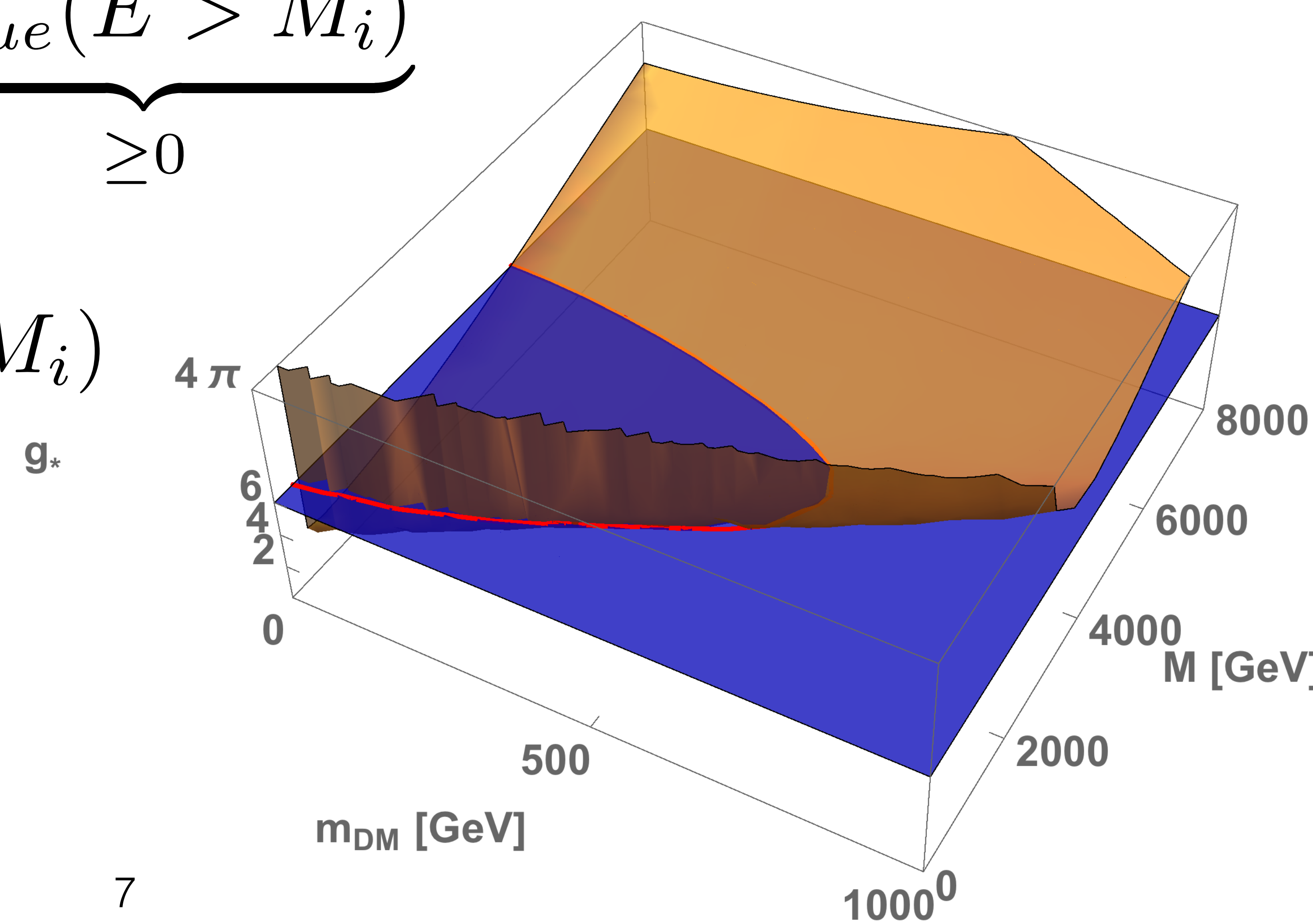

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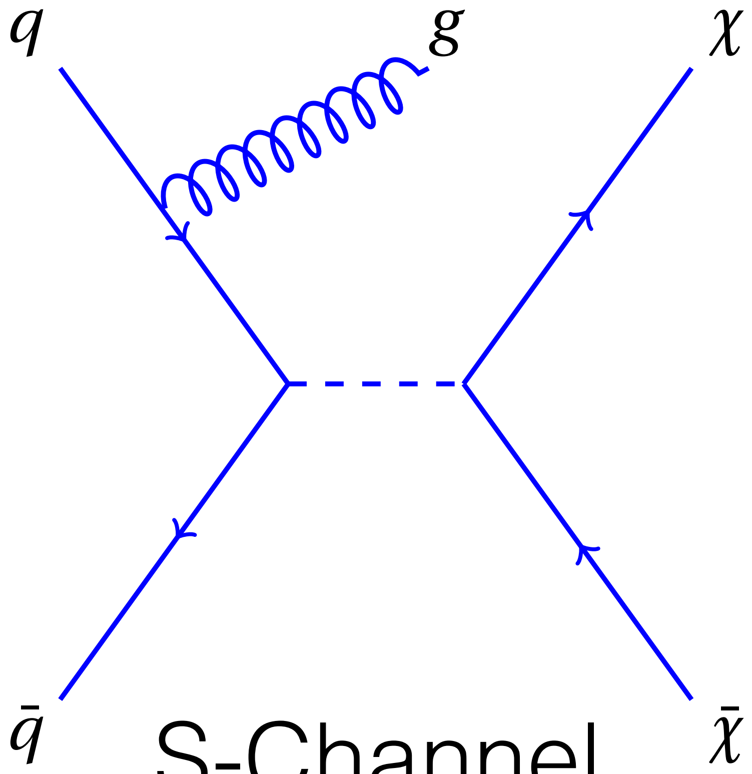
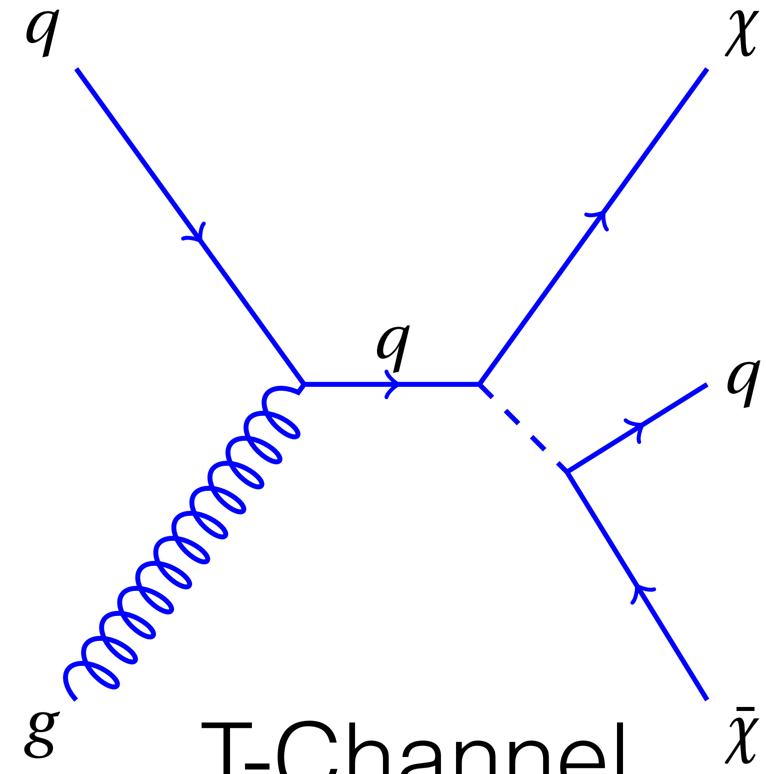
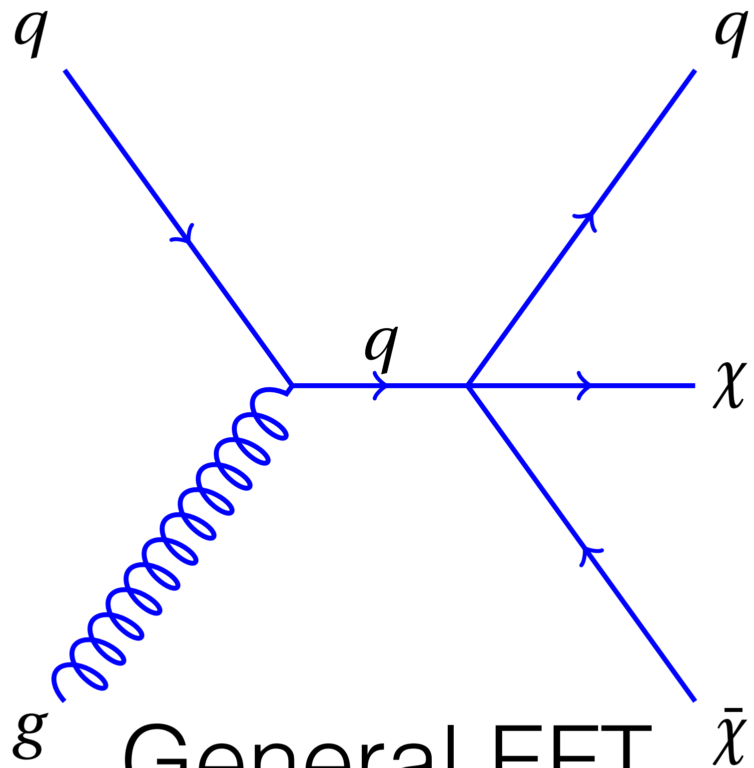
The right energy scale



S-Channel

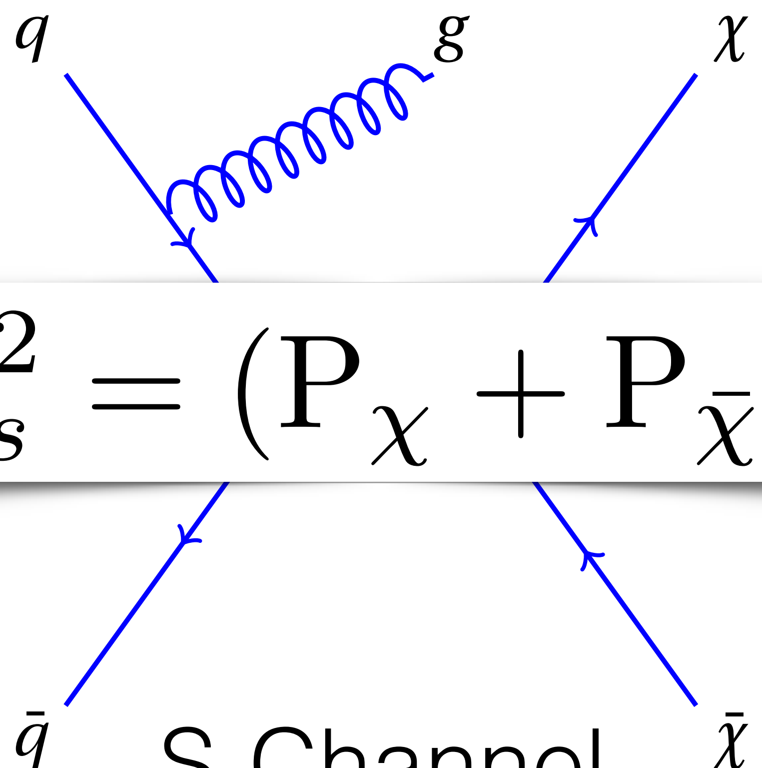


T-Channel



General EFT

The right energy scale



$$E_s^2 = (\mathrm{P}_\chi + \mathrm{P}_{\bar{\chi}})^2$$

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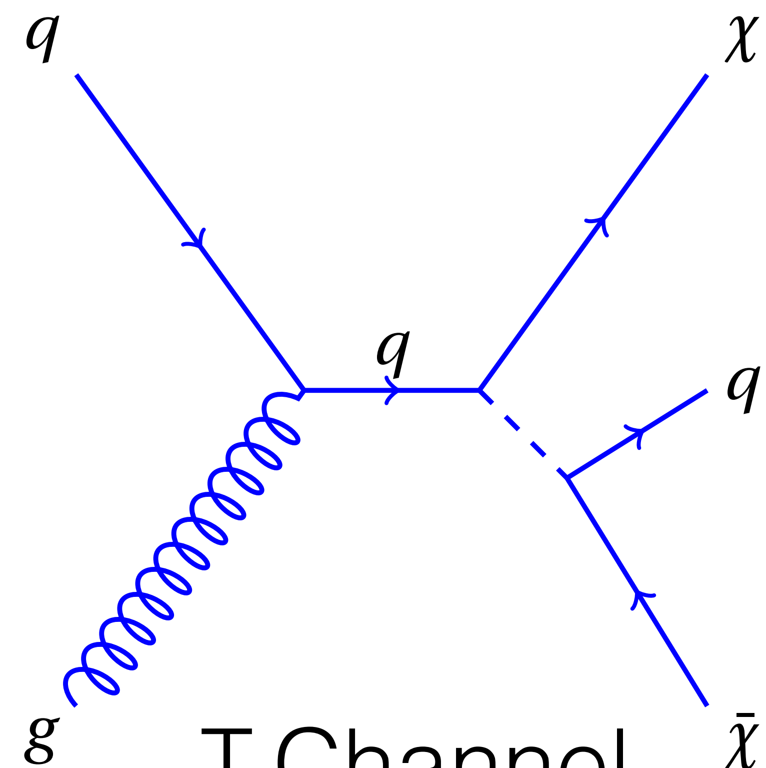

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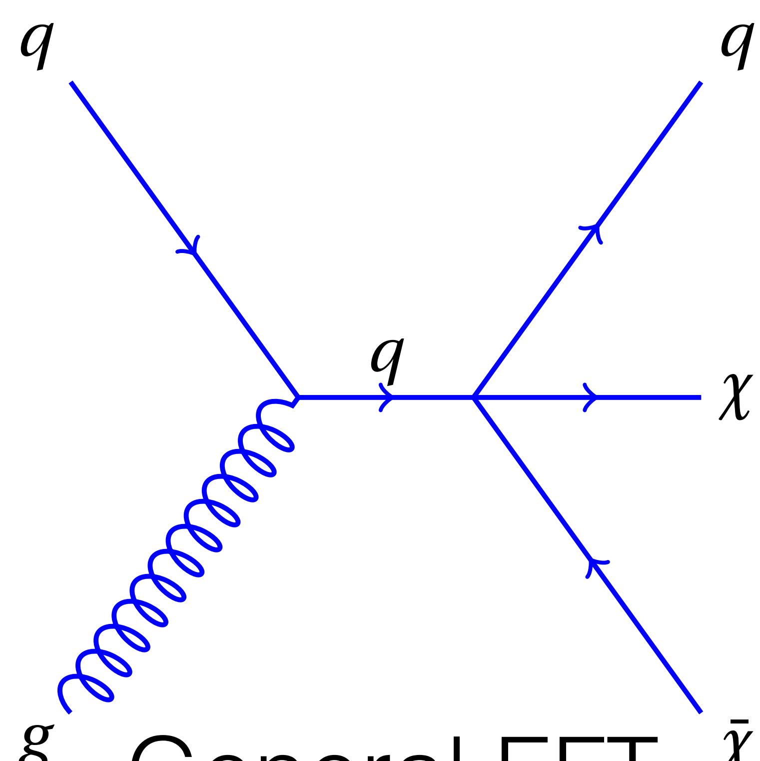

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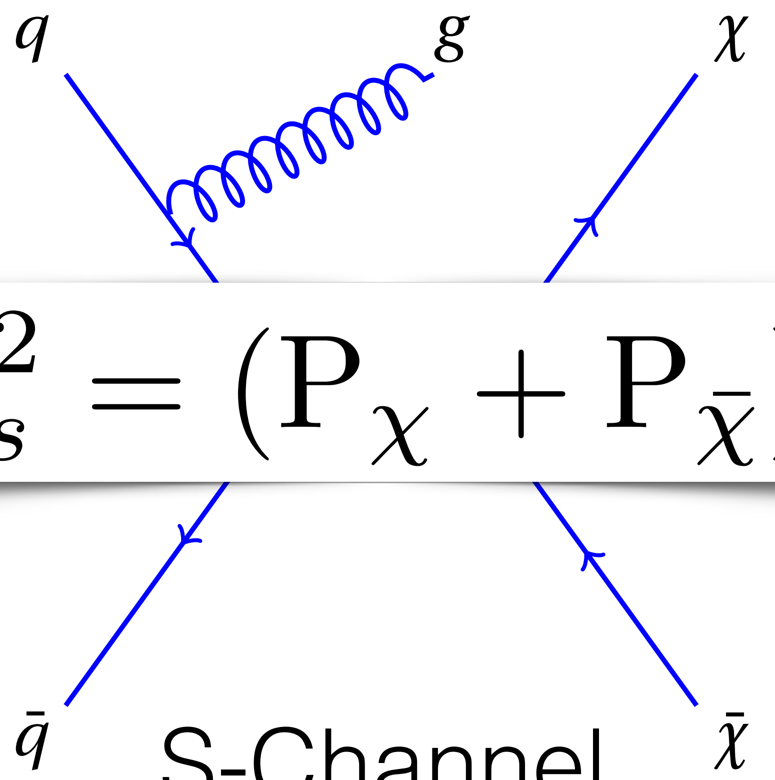

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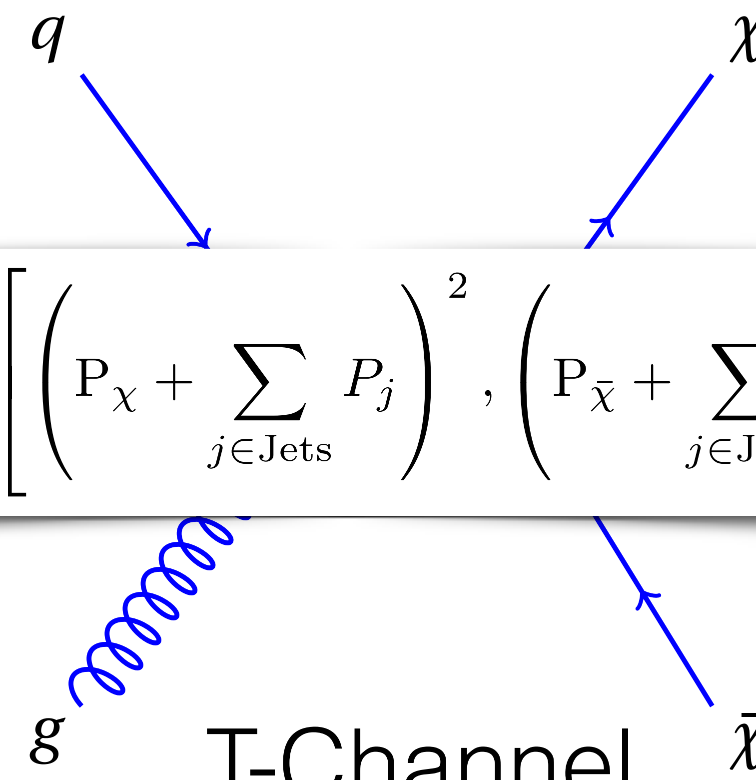
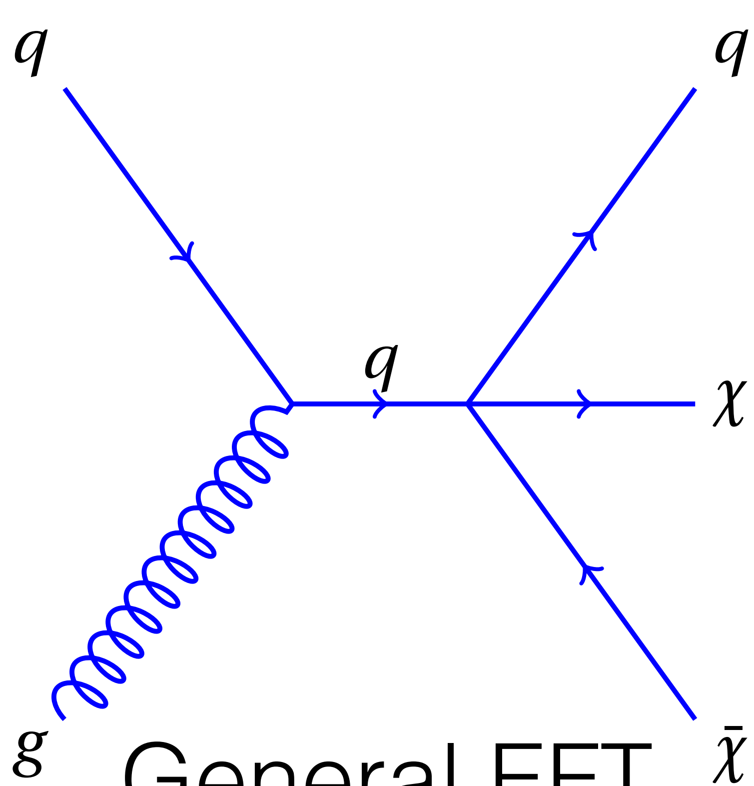


$$E_t^2 = Max\left[\left(\mathrm{P}_\chi + \sum_{j\in\mathrm{Jets}} P_j\right)^2, \left(\mathrm{P}_{\bar{\chi}} + \sum_{j\in\mathrm{Jets}} P_j\right)^2\right]$$

T-Channel



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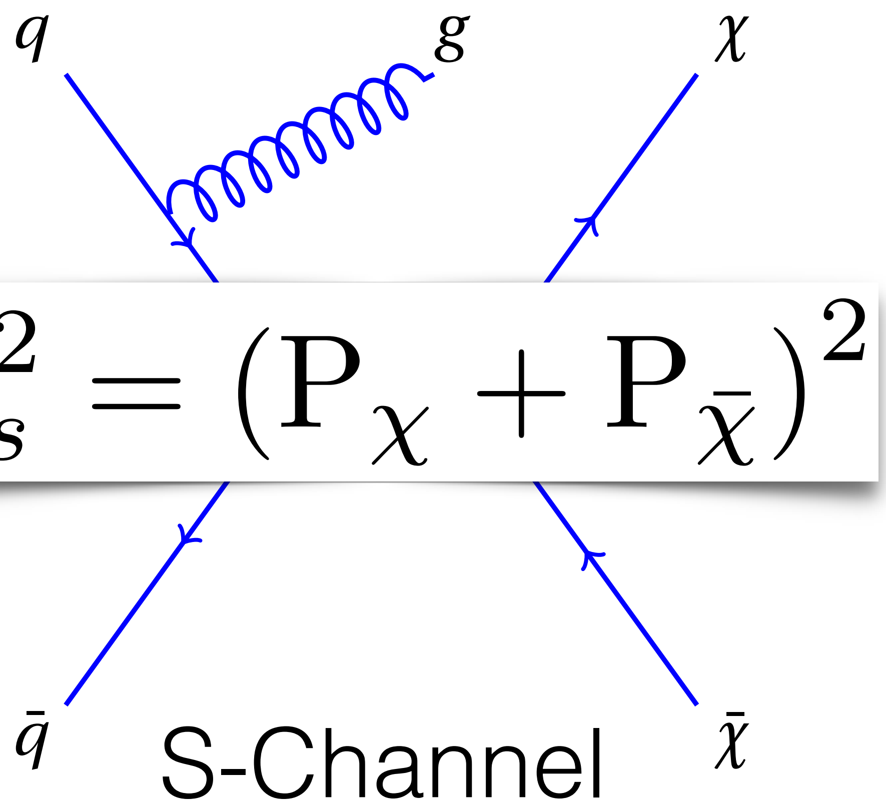

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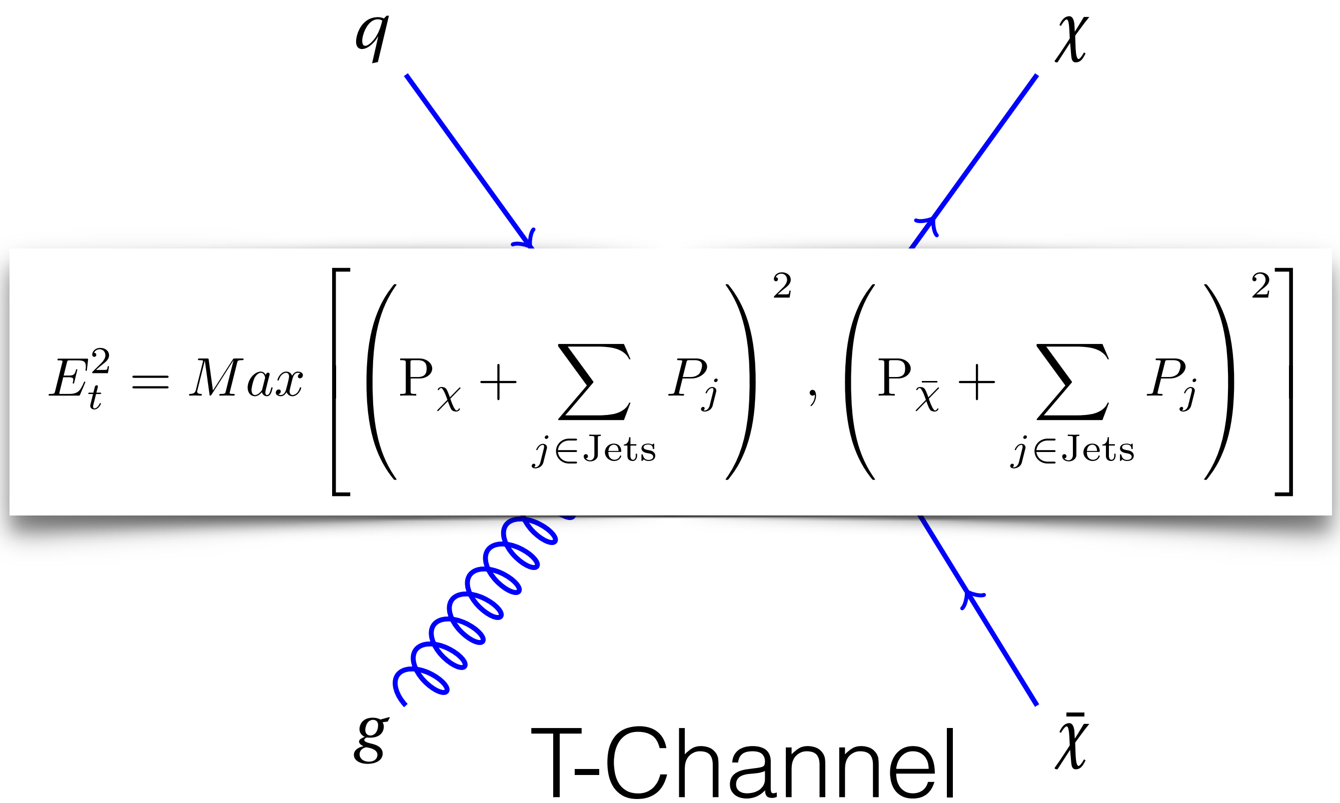

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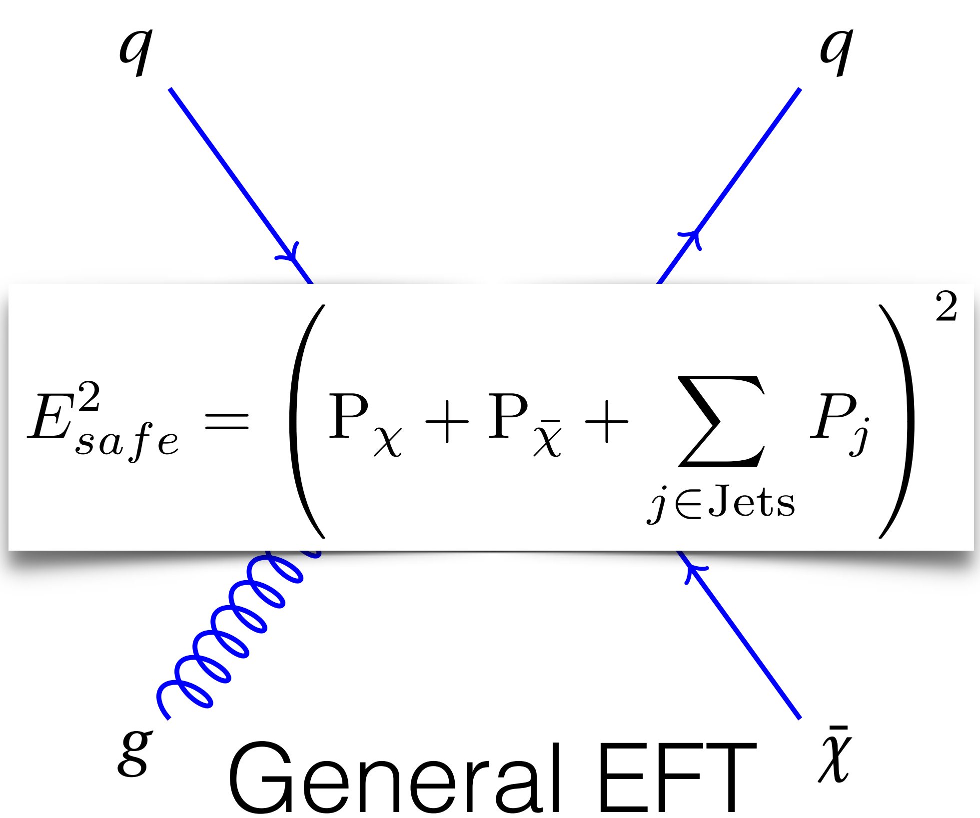
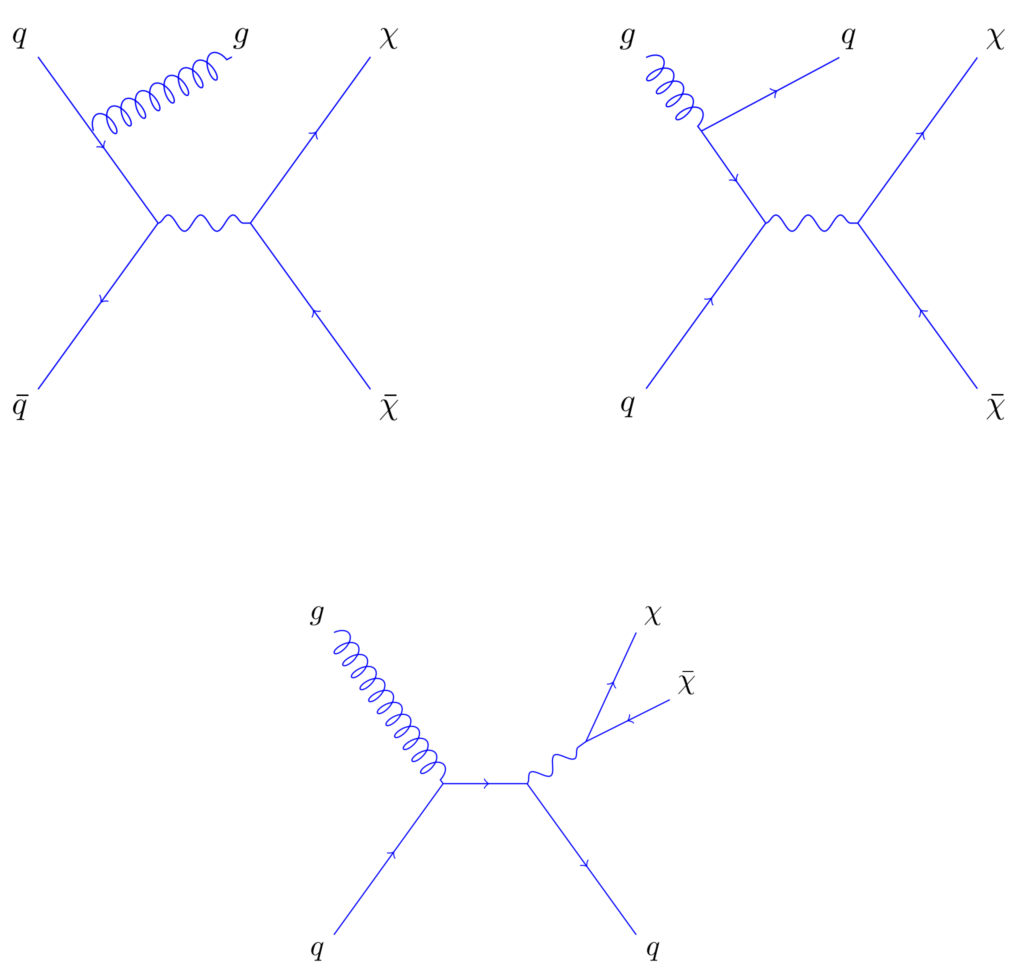


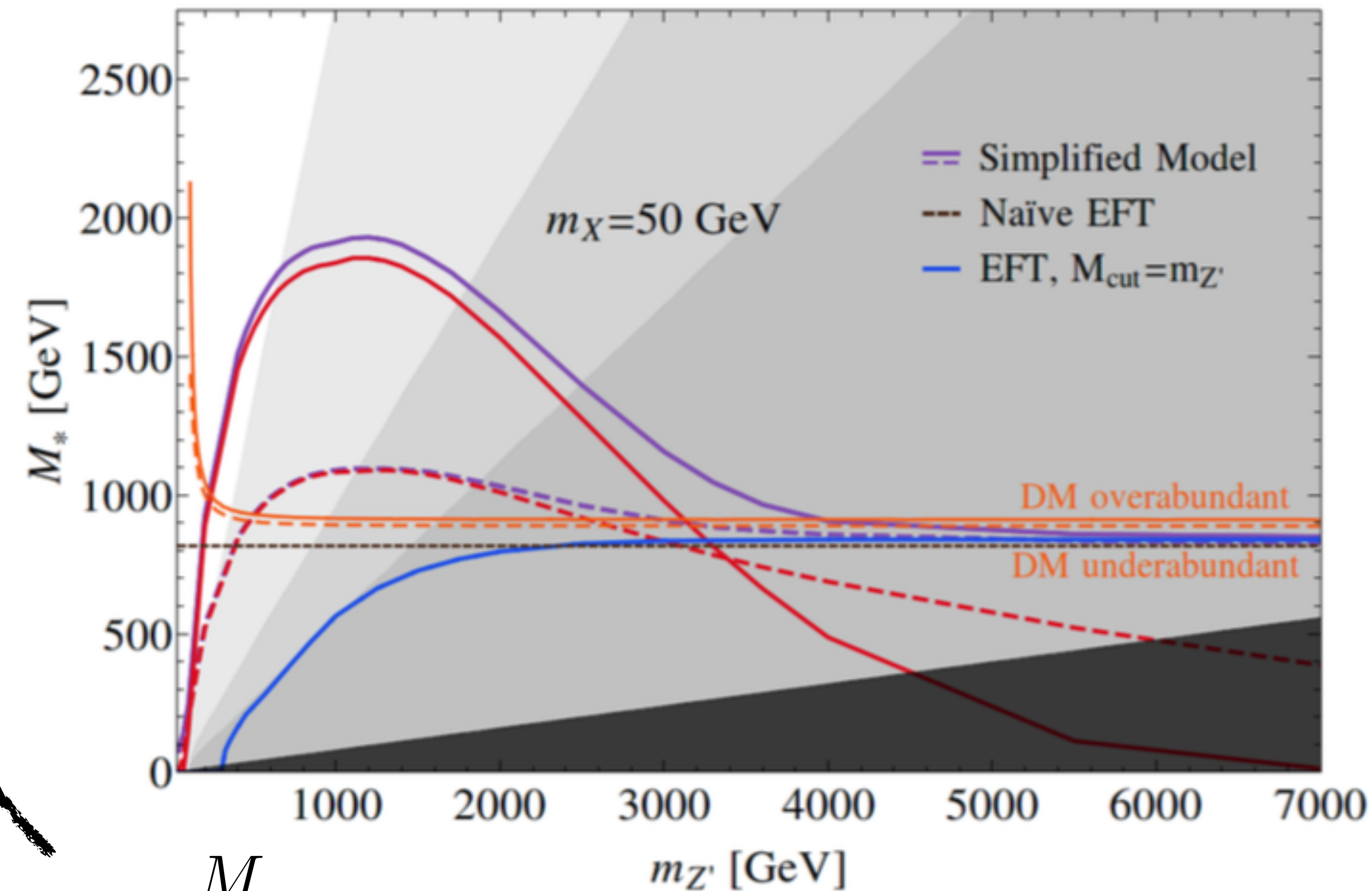
$$E_{safe}^2 = \left(\mathrm{P}_\chi + \mathrm{P}_{\bar{\chi}} + \sum_{j\in\mathrm{Jets}} P_j\right)^2$$

General EFT

Checking validity

Comparing with Z' simplified model:





$$M_\star = \frac{M}{g_\star}$$

Figure from: 1502.04701

Assumptions for EFT

- One coupling one scale
- 2 -> 2 processes only
- Only keep lowest order terms and neglect higher order ones.
- Respect all the SM (exact and approximate) symmetries
- Non-linearly realised symmetries protect small DM masses

Scalar DM

Example 1: Scalar Dark Matter ϕ

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- Naturally light scalar: pseudo Nambu-Goldstone.
- Symmetry G spontaneously breaks to subgroup H.
- Symmetry breaking pattern G/H dictates degrees of freedom and interactions.
- Write all the interactions compatible with SM symmetries (exact and approximate).
- Weight terms that break G/H symmetry by breaking factor $\left(\frac{m_\phi}{M}\right)^2$

Scalar DM

$$D = 6$$

$$\begin{aligned}
{}_6\mathcal{L}_{\rm eff}^{DM_\phi} &= c_\psi^V \frac{g_*^2}{M^2}\phi^\dagger \partial_\mu \phi\, \psi^\dagger\bar{\sigma}^\mu\psi + c_B^{dip}\frac{g_*}{M^2}\partial_\mu\phi^\dagger\partial_\nu\phi\, B^{\mu\nu} \\
&+ c_H^S \frac{g_*^2}{M^2}|\partial_\mu\phi|^2\,|H|^2 + c_H^{\not{s}}\frac{g_*^2 m_{\phi,H}^2}{M^2}|\phi|^2\,|H|^2 \\
&+ c_\psi^{\not{s}}\frac{g_*^2 y_\psi}{M^2}|\phi|^2\psi\psi H
\end{aligned}$$

$$D = 8$$

$$\begin{aligned}
{}_8\mathcal{L}_{\rm eff}^{DM} &= C_V^{\not{s}}\frac{g_*^2 m_\phi^2}{M^4}|\phi|^2 V^a_{\mu\nu}V^{a\,\mu\nu} + C_\psi^S\frac{g_*^2 y_\psi}{M^4}|\partial^\mu\phi|^2\psi\psi H \\
&+C_V^S\frac{g_*^2}{M^4}|\partial^\mu\phi|^2 V^a_{\nu\rho}V^{a\,\rho\nu} + C_H^S\frac{g_*^2}{M^4}|\partial^\mu\phi|^2|D^\nu H|^2 \\
&+C_V^T\frac{g_*^2}{M^4}\partial^\mu\phi^\dagger\partial^\nu\phi V^a_{\mu\rho}V^{a\,\rho}_{\nu} + C_H^T\frac{g_*^2}{M^4}\partial^\mu\phi^\dagger\partial^\nu\phi D_{\{\mu}H^\dagger D_{\nu\}}H \\
&+C_\psi^T\frac{g_*^2}{M^4}\partial^\mu\phi^\dagger\partial^\nu\phi\psi^\dagger\bar{\sigma}_\mu D_\nu\psi\,,
\end{aligned}$$

Weyl spinors!

Scalar DM

SU(2)/U(1), only Monojet relevant

$D = 6$

$$
{}_6\mathcal{L}_{\rm eff}^{DM_\phi} = c_\psi^V \frac{g_*^2}{M^2} \phi^\dagger \partial_\mu \phi\, \psi^\dagger \bar\sigma^\mu \psi + c_B^{dip} \frac{g_*}{M^2} \partial_\mu \phi^\dagger \partial_\nu \phi\, B^{\mu\nu}
+ c_H^S \frac{g_*^2}{M^2} |\partial_\mu \phi|^2 |H|^2 + c_H^{\not s} \frac{g_*^2 m_{\phi,H}^2}{M^2} |\phi|^2 |H|^2
+ c_\psi^{\not s} \frac{g_*^2 y_\psi}{M^2} |\phi|^2 \psi\psi H
$$

$D = 8$

$$
{}_8\mathcal{L}_{\rm eff}^{DM} = C_V^{\not s} \frac{g_*^2 m_\phi^2}{M^4} |\phi|^2 V_{\mu\nu}^a V^{a\,\mu\nu} + C_\psi^S \frac{g_*^2 y_\psi}{M^4} |\partial^\mu \phi|^2 \psi\psi H
+ C_V^S \frac{g_*^2}{M^4} |\partial^\mu \phi|^2 V_{\nu\rho}^a V^{a\,\rho\nu} + C_H^S \frac{g_*^2}{M^4} |\partial^\mu \phi|^2 |D^\nu H|^2
+ C_V^T \frac{g_*^2}{M^4} \partial^\mu \phi^\dagger \partial^\nu \phi V_{\mu\rho}^a V_\nu^{a\,\rho} + C_H^T \frac{g_*^2}{M^4} \partial^\mu \phi^\dagger \partial^\nu \phi D_{\{\mu} H^\dagger D_{\nu\}} H
+ C_\psi^T \frac{g_*^2}{M^4} \partial^\mu \phi^\dagger \partial^\nu \phi \psi^\dagger \bar\sigma_\mu D_\nu \psi\,,
$$

Weyl spinors!

Scalar DM

U(1)/Z$_2$, only Monojet relevant

$$D = 6$$

$$_6\mathcal{L}_{\rm eff}^{DM_\phi} = c_\psi^V \frac{g_*^2}{M^2}\phi^\dagger \partial_\mu \phi\, \psi^\dagger \bar{\sigma}^\mu \psi + c_B^{dip}\frac{g_*}{M^2}\partial_\mu \phi^\dagger \partial_\nu \phi\, B^{\mu\nu} + c_H^S \frac{g_*^2}{M^2}|\partial_\mu \phi|^2 |H|^2 + c_H^{\not{s}} \frac{g_*^2 m_{\phi,H}^2}{M^2}|\phi|^2 |H|^2 + c_\psi^{\not{s}} \frac{g_*^2 y_\psi}{M^2}|\phi|^2 \psi\psi H$$

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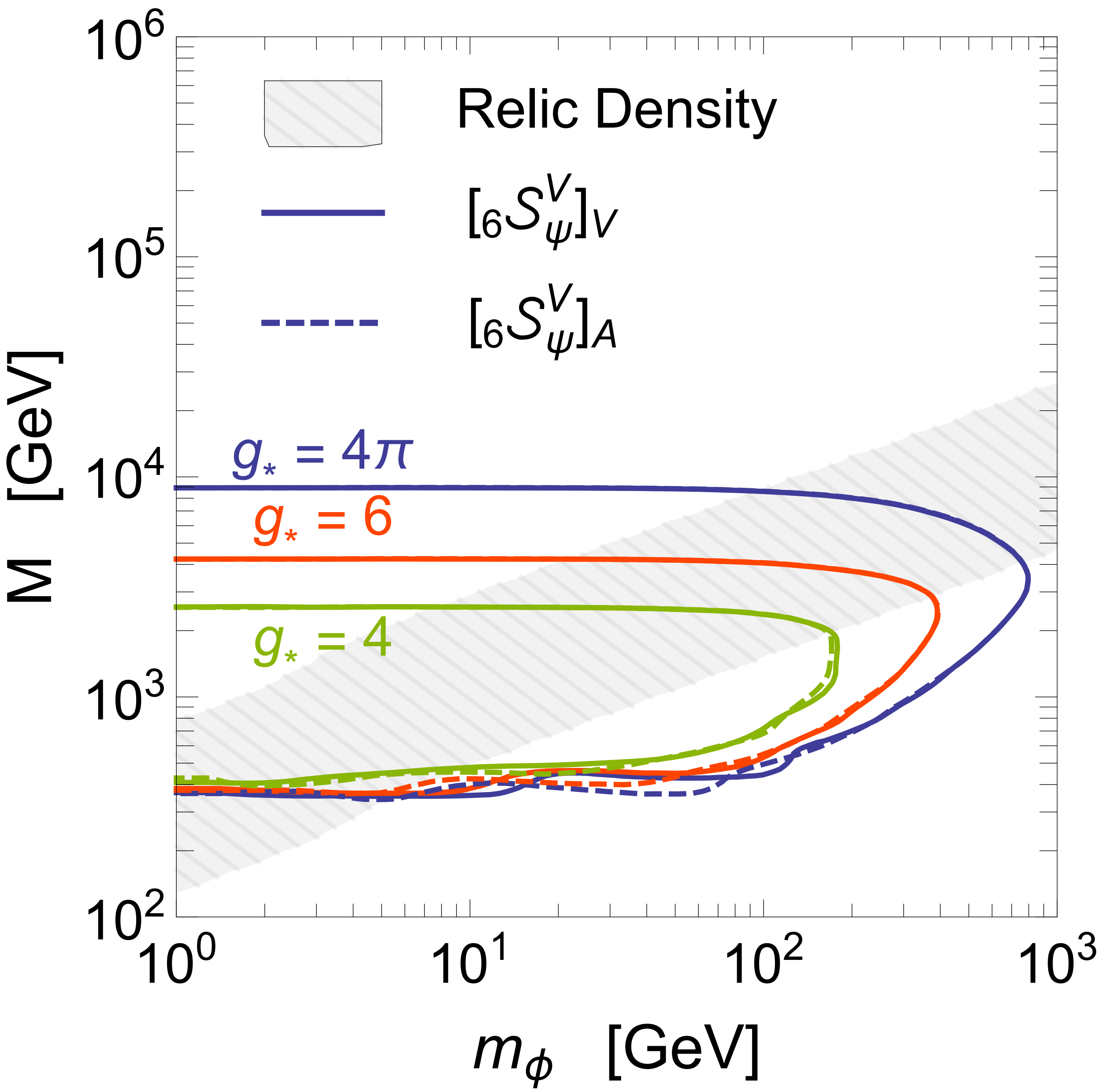
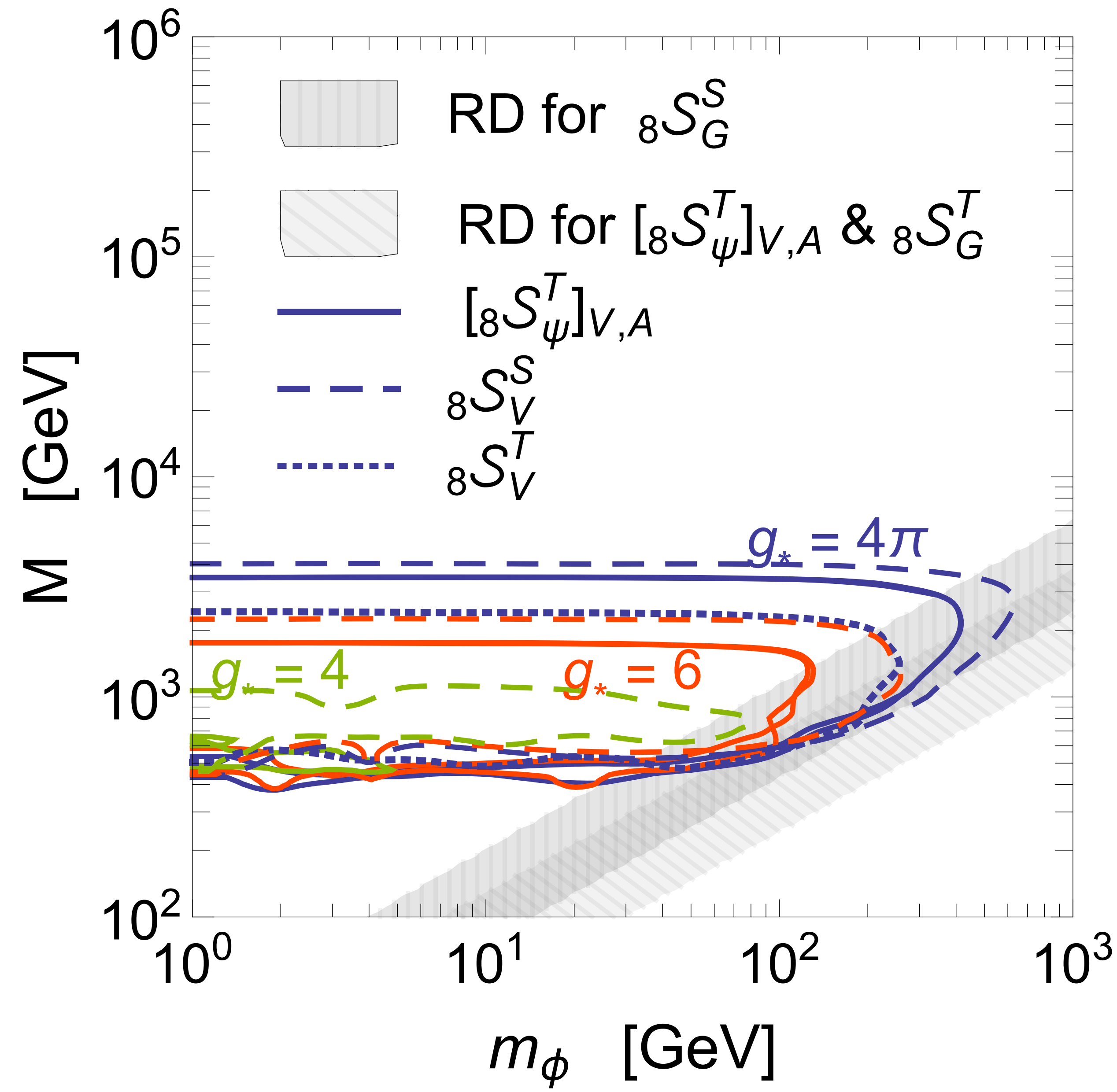
Weyl spinors!

D=6 > D=8?

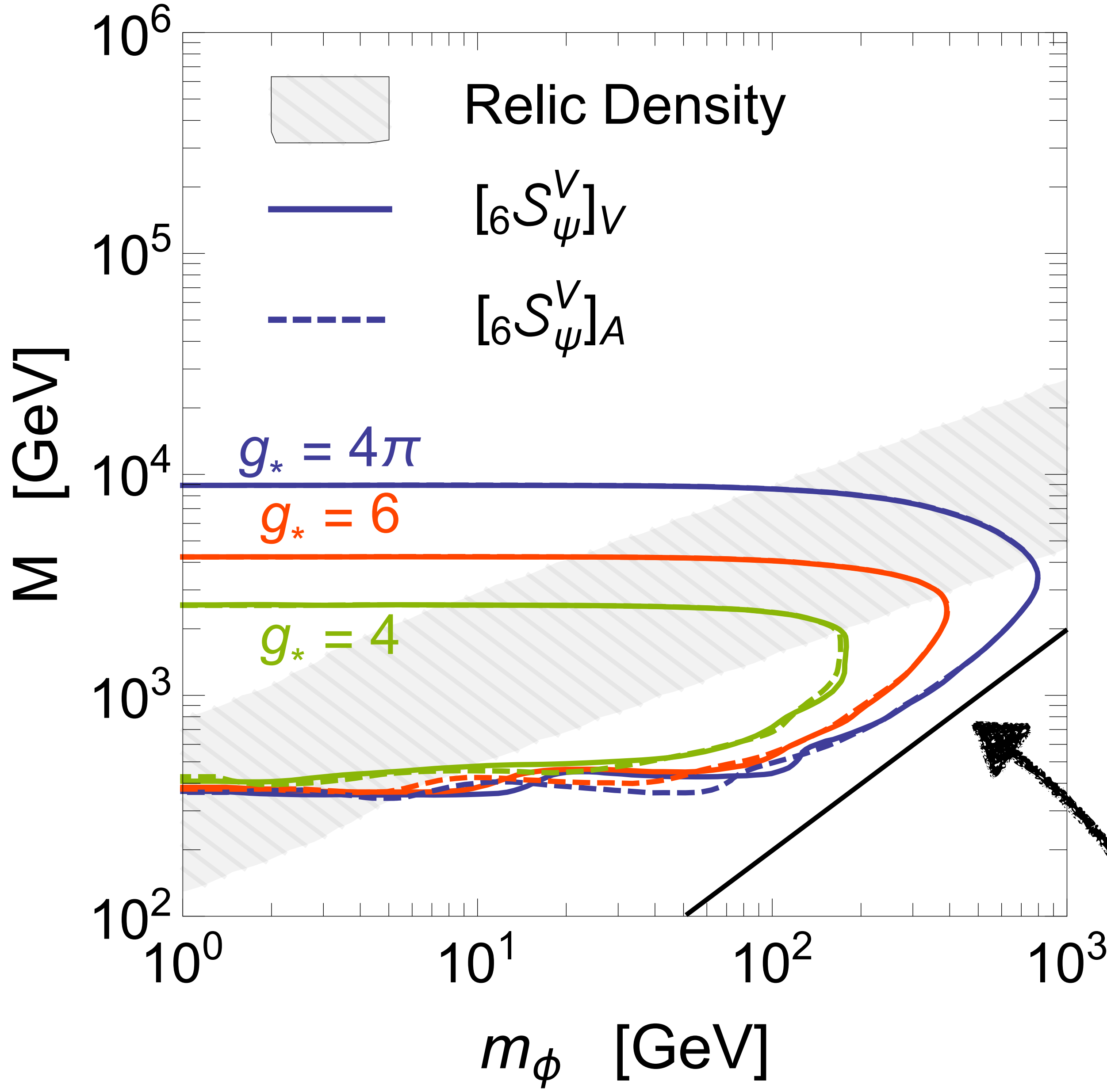

Relic Density
$[{}_6S_\psi^V]_V$
$[{}_6S_\psi^V]_A$
$g_* = 4\pi$
$g_* = 6$
$g_* = 4$
M [GeV]
m_ϕ [GeV]

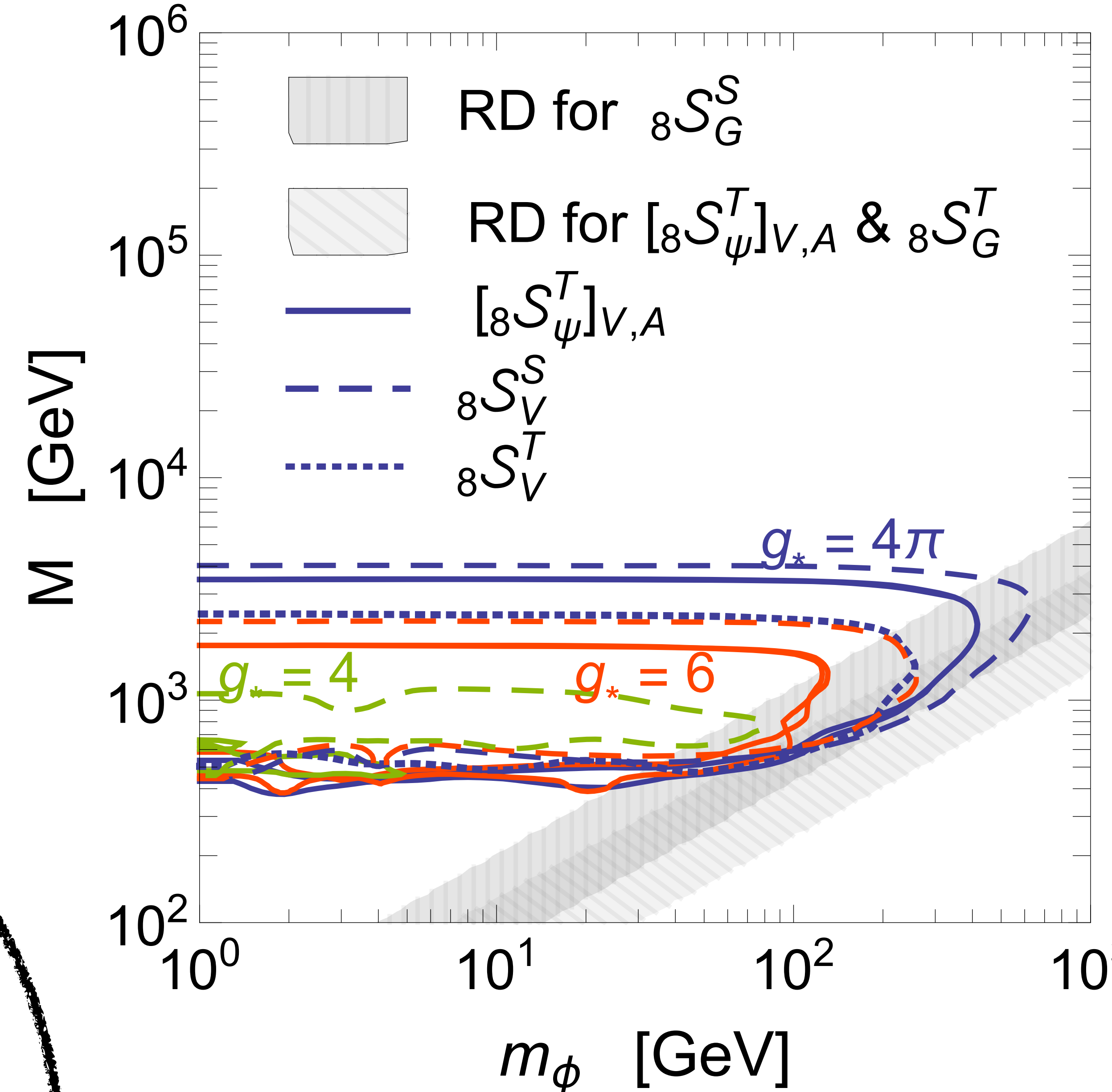
D=6


RD for ${}_8S_G^S$
RD for $[{}_8S_\psi^T]_{V,A}$ & ${}_8S_G^T$
$[{}_8S_\psi^T]_{V,A}$
${}_8S_V^S$
${}_8S_V^T$
$g_* = 4\pi$
$g_* = 4$
$g_* = 6$
M [GeV]
m_ϕ [GeV]

D=8

D=6 > D=8?



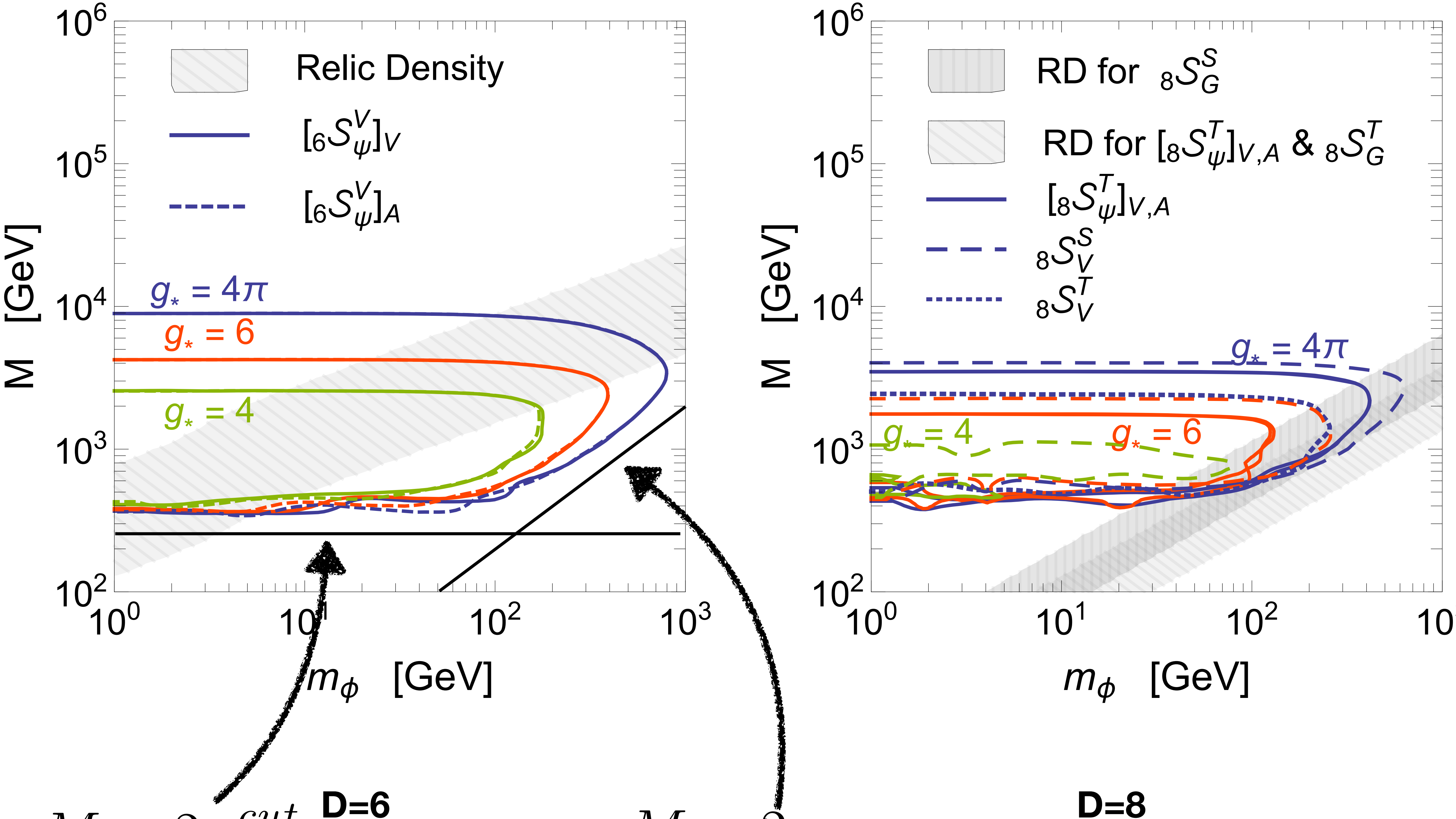


D=6

D=8

$M \sim 2m_{DM}$

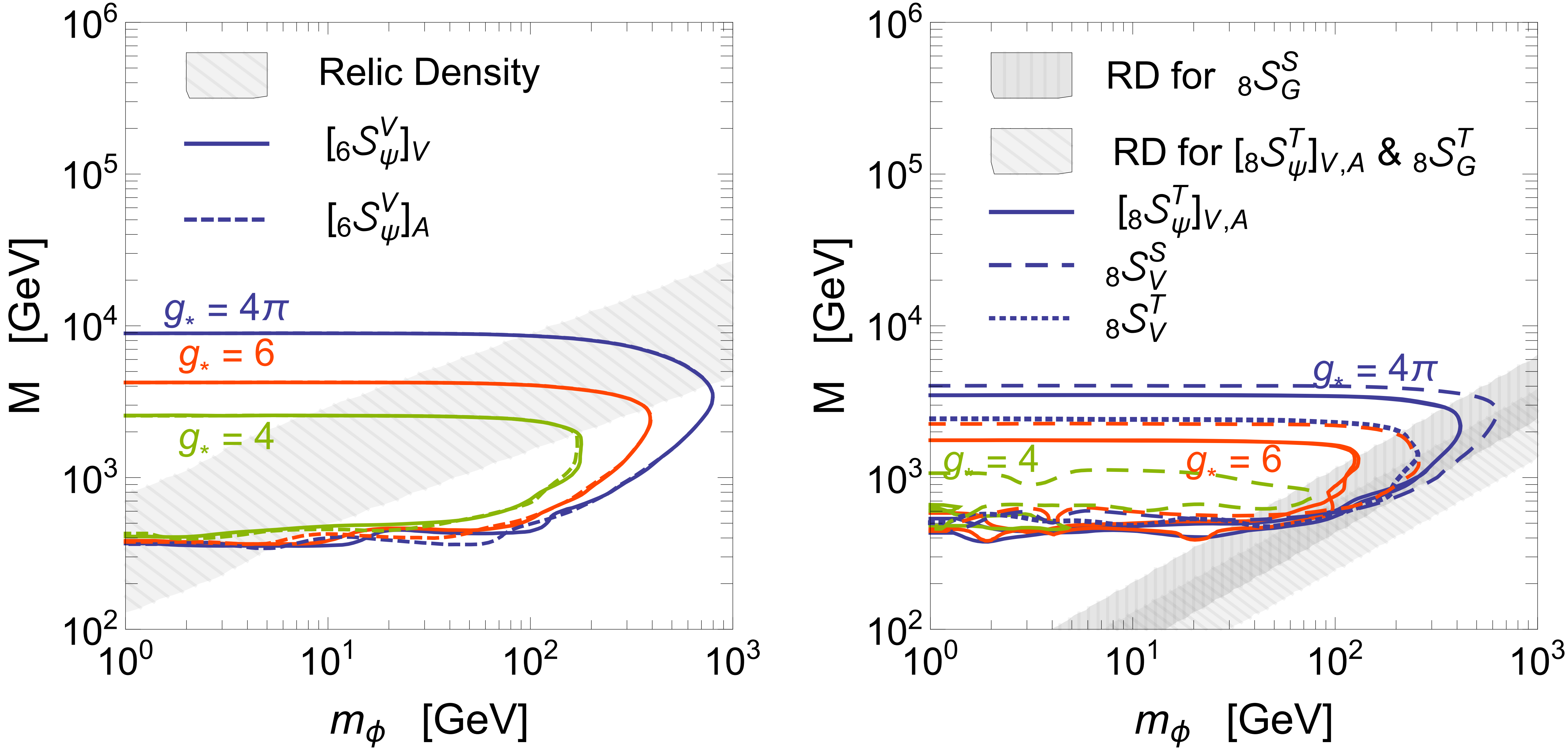
D=6 > D=8?



$M \sim 2\,p_T^{cut}$

$M \sim 2m_{DM}$

D=6 > D=8?



Relic Density
$[{}_6S^V_\psi]_V$
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$g_* = 4\pi$
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M [GeV]
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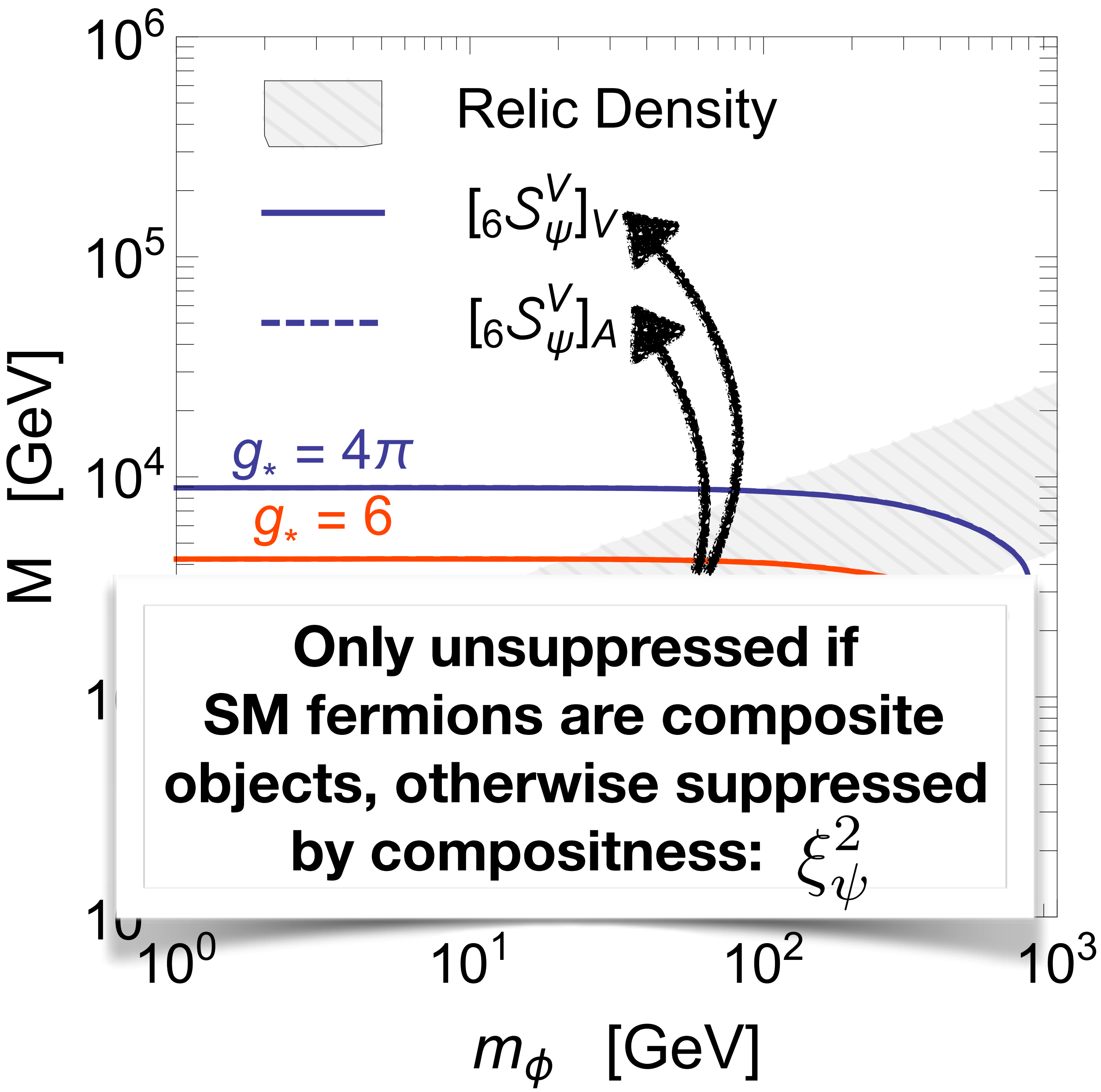
$[{}_8S^T_\psi]_{V,A}$
${}_8S^S_V$
${}_8S^T_V$

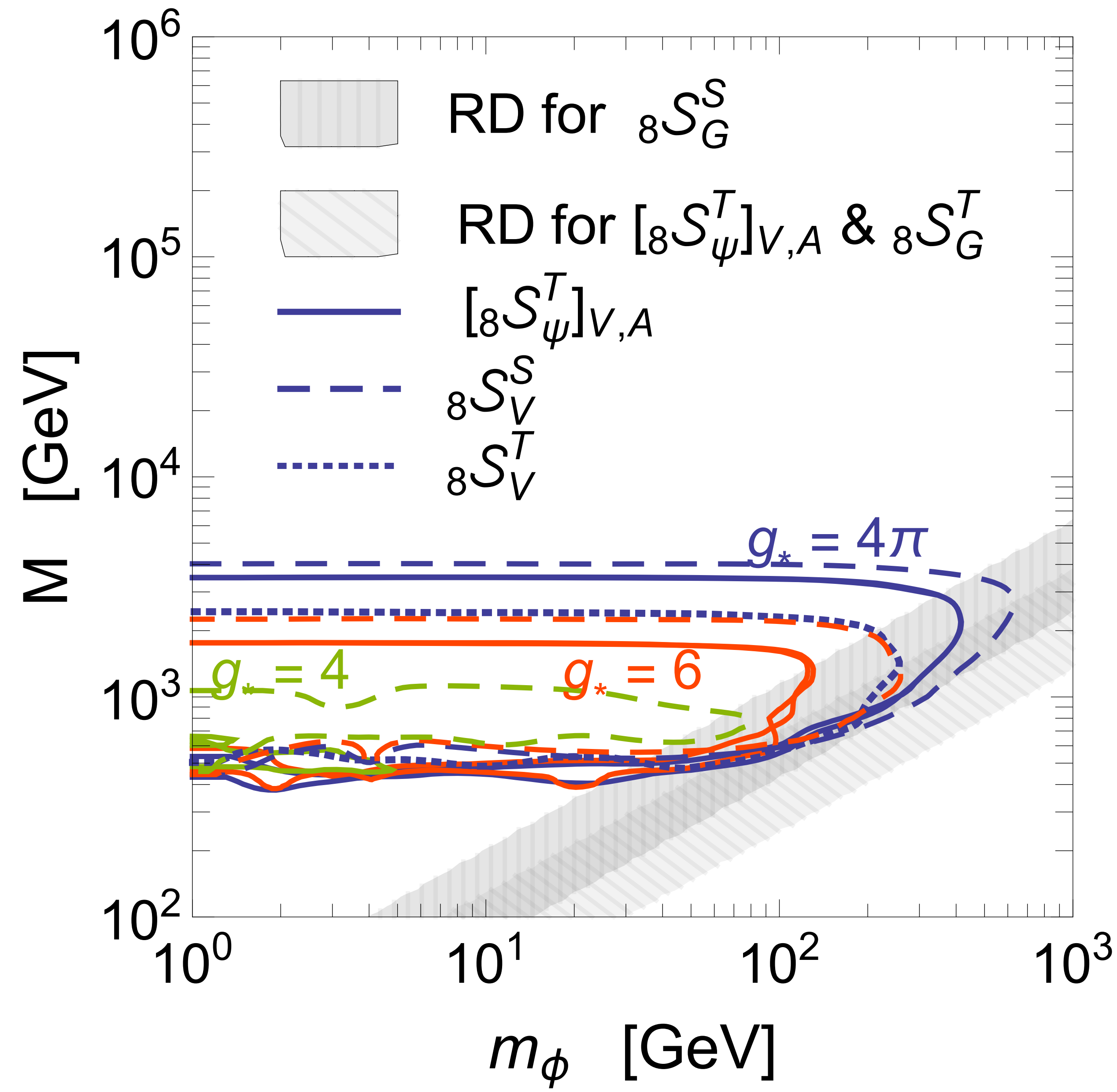
D=6 **D=8**

D=6 > D=8?



Relic Density
$[{}_6S^V_\psi]_V$
$[{}_6S^V_\psi]_A$
$g_* = 4\pi$
$g_* = 6$
Only unsuppressed if SM fermions are composite objects, otherwise suppressed by compositness: ξ_ψ^2
M [GeV]
m_ϕ [GeV]

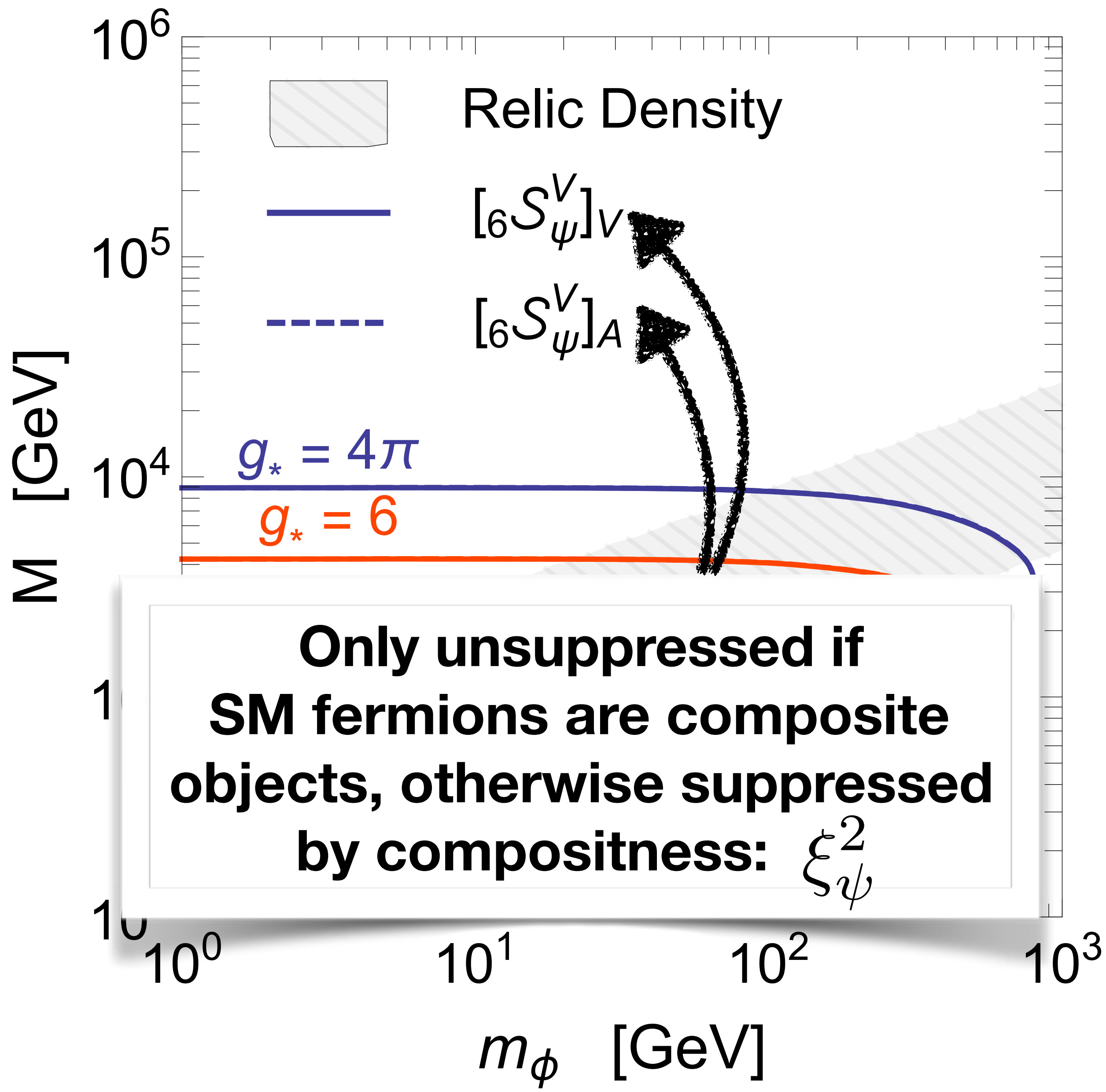
D=6



RD for ${}_8S^S_G$
RD for $[{}_8S^T_\psi]_{V,A}$ & ${}_8S^T_G$
$[{}_8S^T_\psi]_{V,A}$
${}_8S^S_V$
${}_8S^T_V$
$g_* = 4\pi$
$g_* = 6$
$g_* = 4$
M [GeV]
m_ϕ [GeV]

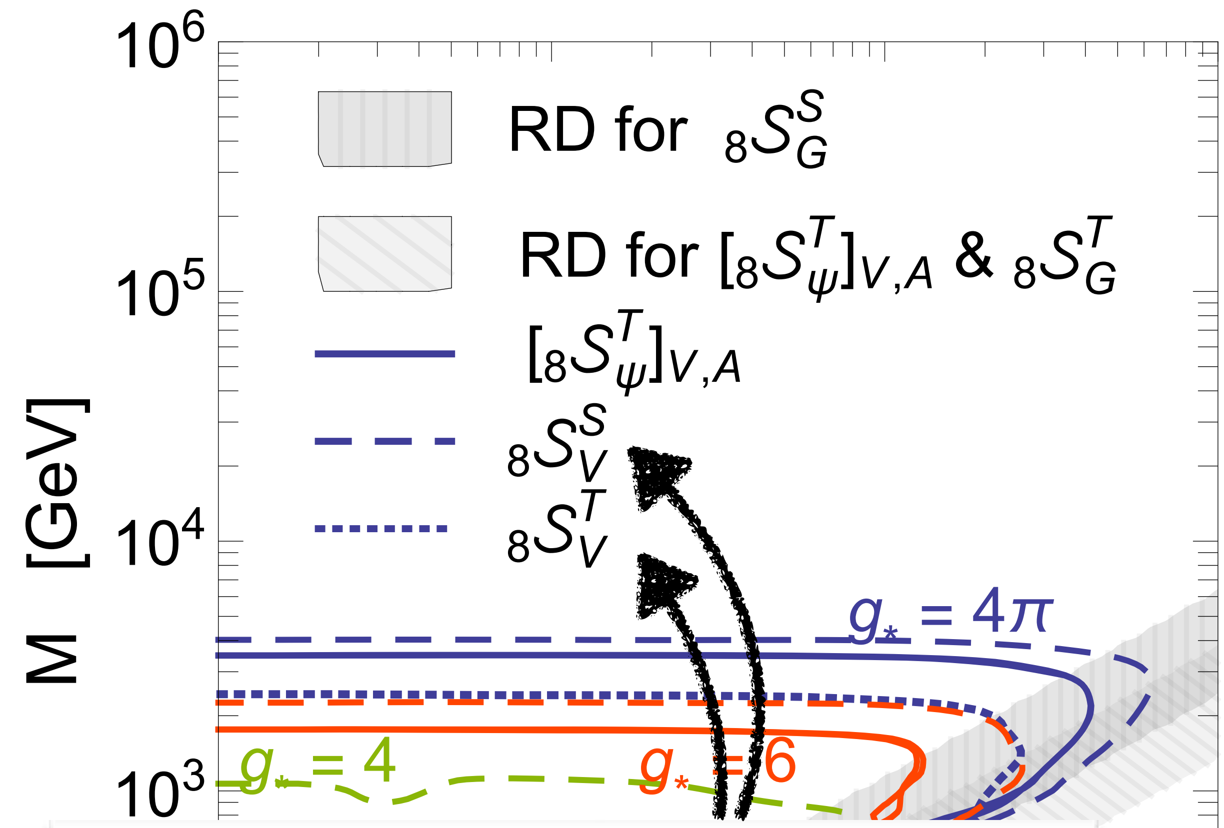
D=8

D=6 > D=8?



Only unsuppressed if SM fermions are composite objects, otherwise suppressed by compositness: ξ_ψ^2

D=6



Only unsuppressed if SM vectors are composite objects, otherwise suppressed by $\frac{g_V^2}{g_\star^2}$

See: Liu, Pomarol, Rattazzi, Riva 1603.03064

What about relict density?

$$D8 \sim \left(\frac{E}{M}\right)^4$$

$$\text{Suppressed } D6 \sim \left(\frac{m_\phi}{M}\right)^2 \left(\frac{E}{M}\right)^2$$

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At LHC energies $E \sim M \quad \Rightarrow \quad D8 \gg D6$

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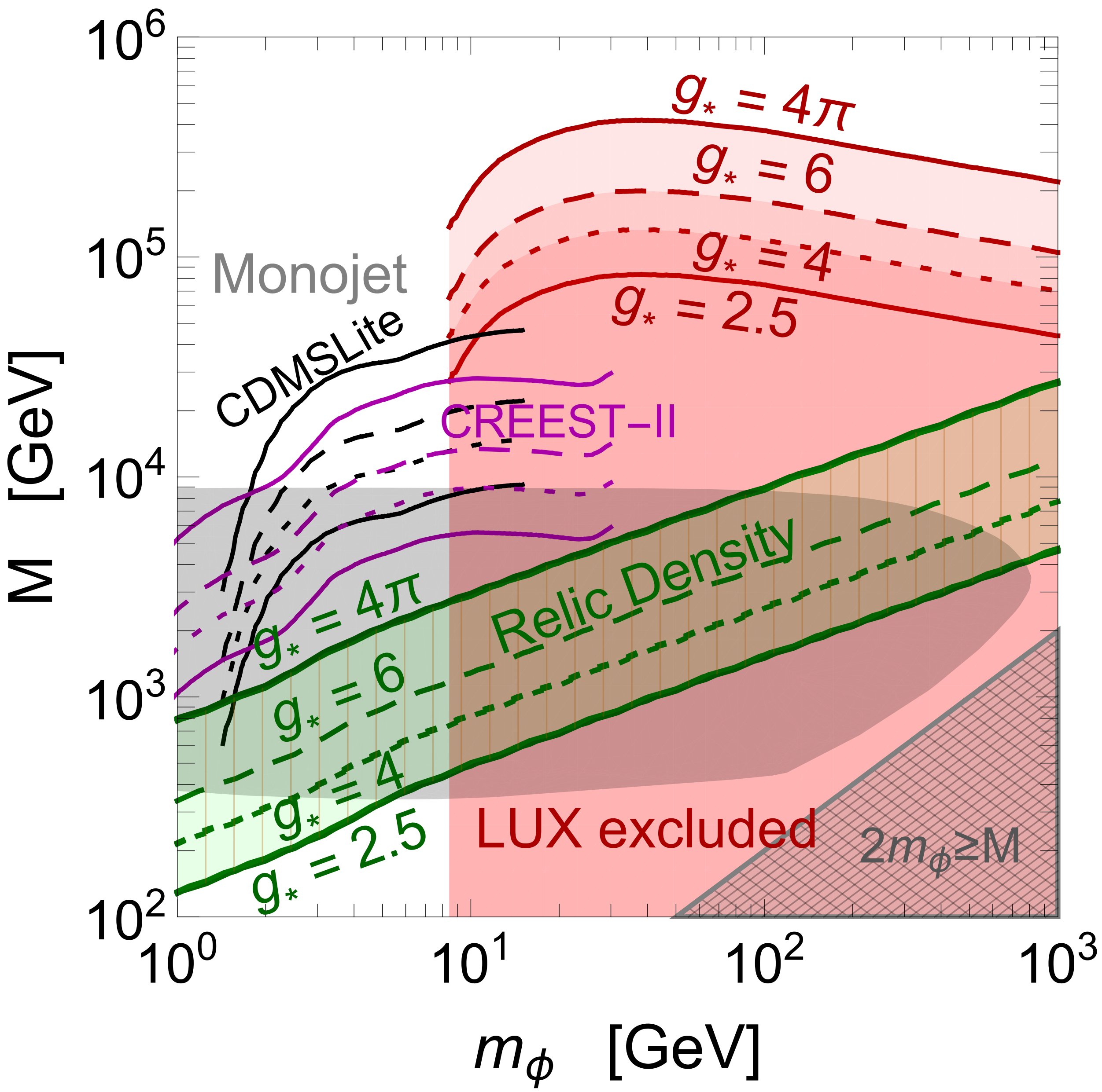
At LHC energies $E \sim M \quad \Rightarrow \quad D8 \gg D6$

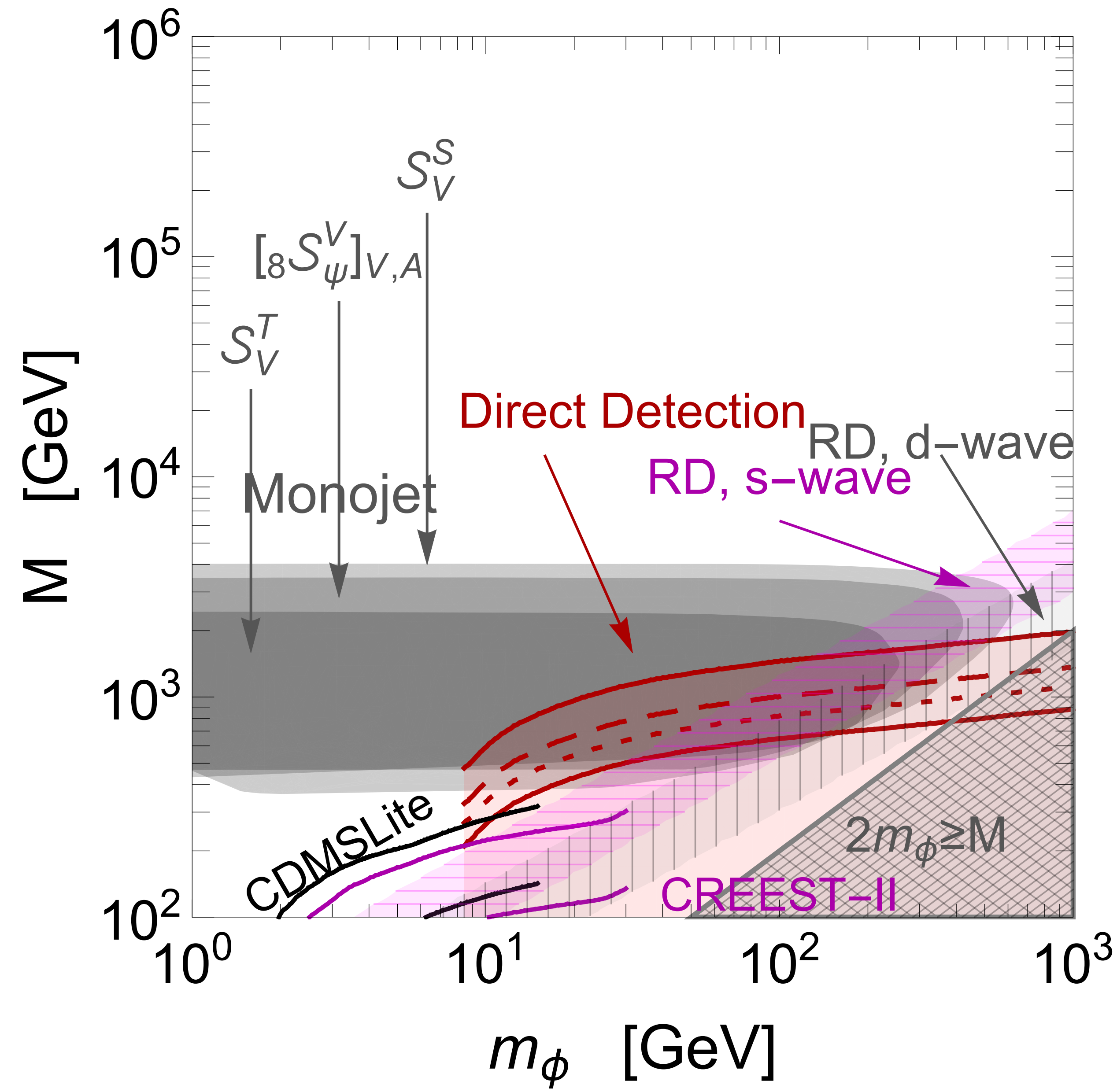
At RD & DD energies $E \sim m_\phi \quad \Rightarrow \quad D8 \sim D6$

$\Longrightarrow$ Dark Matter complementarity is (partially) lost

What about relict density?



D=6



Comparison only as indication!

D=8

Fermionic DM

Example 2: Fermionic Dark Matter χ

Fermionic DM

Example 2: Fermionic Dark Matter χ

- Naturally light fermion: Chiral-symmetry-breaking or Goldstino.

Fermionic DM

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Fermionic DM

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- Write all the interactions compatible with SM symmetries (exact and approximate).

Fermionic DM

Example 2: Fermionic Dark Matter χ

- Naturally light fermion: Chiral-symmetry-breaking or Goldstino.
- Goldstino -> Majorana; Otherwise Dirac.
- Write all the interactions compatible with SM symmetries (exact and approximate).
- Weight terms that break symmetry by $\frac{m_\chi}{M}$

Fermionic DM

$$
{}_6\mathcal{L}_{eff}^{DM} = c_\psi^V \frac{g_\star^2}{M^2} \chi^\dagger \bar{\sigma}^\mu \chi \psi^\dagger \bar{\sigma}_\mu \psi + c_H^S \frac{g_{SM}^2 m_\chi}{M^2} \chi^\dagger \chi H^\dagger H
+ c_B^{dip} \frac{g_\star m_\chi}{M^2} \chi^\dagger \sigma^{\mu\nu} \chi B_{\mu\nu}
$$

$$
\begin{aligned}
{}_8\mathcal{L}_{eff}^{DM} = & C_\psi^{\not{s}} \frac{m_\chi y_\psi g_\star^2}{M^4} \chi^\dagger \chi \psi^\dagger \psi H + C_\psi^{\not{s}\,\prime} \frac{m_\chi y_\psi g_\star^2}{M^4} \chi^\dagger \psi^\dagger \psi \chi H \\
& + C_V^{\not{s}} \frac{g_\star^2 m_\chi}{M^4} \chi^\dagger \chi V_{\mu\nu}^a V^{a\,\mu\nu} + C_V \frac{g_\star^2}{M^4} \chi^\dagger \bar{\sigma}^\mu \partial^\nu \chi V_{\mu\rho}^a V_\nu^{a\,\rho} \\
& + C_\psi \frac{g_\star^2}{M^4} \chi^\dagger \bar{\sigma}^\mu \partial^\nu \chi \psi^\dagger \bar{\sigma}_\mu D_\nu \psi + C_\psi' \frac{g_\star^2}{M^4} \chi^\dagger \bar{\sigma}^\mu \chi D^\nu \psi^\dagger \bar{\sigma}_\mu D_\nu \psi \\
& + C_H \frac{g_\star^2}{M^4} \chi^\dagger \bar{\sigma}^\mu \partial^\nu \chi D_\mu H^\dagger D_\nu H
\end{aligned}
$$

Weyl spinors!

Fermionic DM

Dirac Fermion, monojet relevant

$$
{}_6\mathcal{L}_{eff}^{DM} = c_\psi^V \frac{g_\star^2}{M^2} \chi^\dagger \bar\sigma^\mu \chi \psi^\dagger \bar\sigma_\mu \psi + c_H^S \frac{g_{SM}^2 m_\chi}{M^2} \chi^\dagger \chi H^\dagger H + c_B^{dip} \frac{g_\star m_\chi}{M^2} \chi^\dagger \sigma^{\mu\nu} \chi B_{\mu\nu}
$$

$$
\begin{aligned}
{}_8\mathcal{L}_{eff}^{DM} = & C_\psi^{\not s} \frac{m_\chi y_\psi g_\star^2}{M^4} \chi^\dagger \chi \psi^\dagger \psi H + C_\psi^{\not s\,\prime} \frac{m_\chi y_\psi g_\star^2}{M^4} \chi^\dagger \psi^\dagger \psi \chi H \\
& + C_V^{\not s} \frac{g_\star^2 m_\chi}{M^4} \chi^\dagger \chi V_{\mu\nu}^a V^{a\,\mu\nu} + C_V \frac{g_\star^2}{M^4} \chi^\dagger \bar\sigma^\mu \partial^\nu \chi V_{\mu\rho}^a V_\nu^{a\,\rho} \\
& + C_\psi \frac{g_\star^2}{M^4} \chi^\dagger \bar\sigma^\mu \partial^\nu \chi \psi^\dagger \bar\sigma_\mu D_\nu \psi + C_\psi' \frac{g_\star^2}{M^4} \chi^\dagger \bar\sigma^\mu \chi D^\nu \psi^\dagger \bar\sigma_\mu D_\nu \psi \\
& + C_H \frac{g_\star^2}{M^4} \chi^\dagger \bar\sigma^\mu \partial^\nu \chi D_\mu H^\dagger D_\nu H
\end{aligned}
$$

Weyl spinors!

Fermionic DM

Majorana (Goldstino) fermion, monojet relevant

$$
{}_6\mathcal{L}^{DM}_{eff} = c^V_\psi \frac{g_\star^2}{M^2}\chi^\dagger\bar\sigma^\mu\chi\psi^\dagger\bar\sigma_\mu\psi + c^S_H\frac{g_{SM}^2 m_\chi}{M^2}\chi^\dagger\chi H^\dagger H + c^{dip}_B\frac{g_\star m_\chi}{M^2}\chi^\dagger\sigma^{\mu\nu}\chi B_{\mu\nu}
$$

$$
\begin{aligned}
{}_8\mathcal{L}^{DM}_{eff} =& C^{\not s}_\psi \frac{m_\chi y_\psi g_\star^2}{M^4}\chi^\dagger\chi\psi^\dagger\psi H + C^{\not s\,\prime}_\psi\frac{m_\chi y_\psi g_\star^2}{M^4}\chi^\dagger\psi^\dagger\psi\chi H \\
&+ C^{\not s}_V\frac{g_\star^2 m_\chi}{M^4}\chi^\dagger\chi V^a_{\mu\nu}V^{a\,\mu\nu} + C_V\frac{g_\star^2}{M^4}\chi^\dagger\bar\sigma^\mu\partial^\nu\chi V^a_{\mu\rho}V^{a\,\rho}_\nu \\
&+ C_\psi\frac{g_\star^2}{M^4}\chi^\dagger\bar\sigma^\mu\partial^\nu\chi\psi^\dagger\bar\sigma_\mu D_\nu\psi + C'_\psi\frac{g_\star^2}{M^4}\chi^\dagger\bar\sigma^\mu\chi D^\nu\psi^\dagger\bar\sigma_\mu D_\nu\psi \\
&+ C_H\frac{g_\star^2}{M^4}\chi^\dagger\bar\sigma^\mu\partial^\nu\chi D_\mu H^\dagger D_\nu H
\end{aligned}
$$

Weyl spinors!

Fermionic DM

Majorana (Goldstino) fermion, monojet relevant

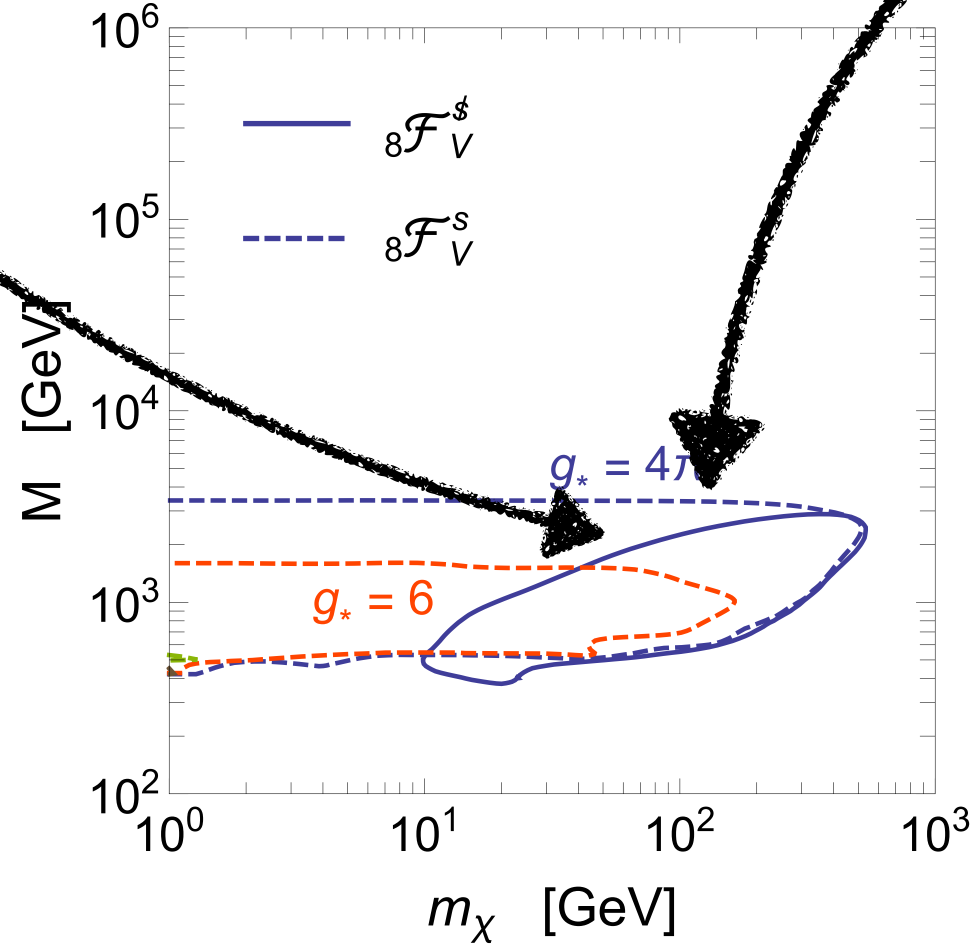
$$ {}_6\mathcal{L}_{eff}^{DM} = c_\psi^V \frac{g_\star^2}{M^2} \chi^\dagger \bar{\sigma}^\mu \chi \psi^\dagger \bar{\sigma}_\mu \psi + c_H^S \frac{g_{SM}^2 m_\chi}{M^2} \chi^\dagger \chi H^\dagger H + c_B^{dip} \frac{g_\star m_\chi}{M^2} \chi^\dagger \sigma^{\mu\nu} \chi B_{\mu\nu} $$

$$ {}_8\mathcal{L}_{eff}^{DM} = C_\psi^{\not{s}} \frac{m_\chi y_\psi g_\star^2}{M^4} \chi^\dagger \chi \psi^\dagger \psi H + C_\psi^{\not{s}\,\prime} \frac{m_\chi y_\psi g_\star^2}{M^4} \chi^\dagger \psi^\dagger \psi \chi H + C_V^{\not{s}} \frac{g_\star^2 m_\chi}{M^4} \chi^\dagger \chi V_{\mu\nu}^a V^{a\,\mu\nu} + C_V \frac{g_\star^2}{M^4} \chi^\dagger \bar{\sigma}^\mu \partial^\nu \chi V_{\mu\rho}^a V_\nu^{a\,\rho} + C_\psi \frac{g_\star^2}{M^4} \chi^\dagger \bar{\sigma}^\mu \partial^\nu \chi \psi^\dagger \bar{\sigma}_\mu D_\nu \psi + C_\psi' \frac{g_\star^2}{M^4} \chi^\dagger \bar{\sigma}^\mu \chi D^\nu \psi^\dagger \bar{\sigma}_\mu D_\nu \psi + C_H \frac{g_\star^2}{M^4} \chi^\dagger \bar{\sigma}^\mu \partial^\nu \chi D_\mu H^\dagger D_\nu H $$

Weyl spinors!

Symmetry breaking effects

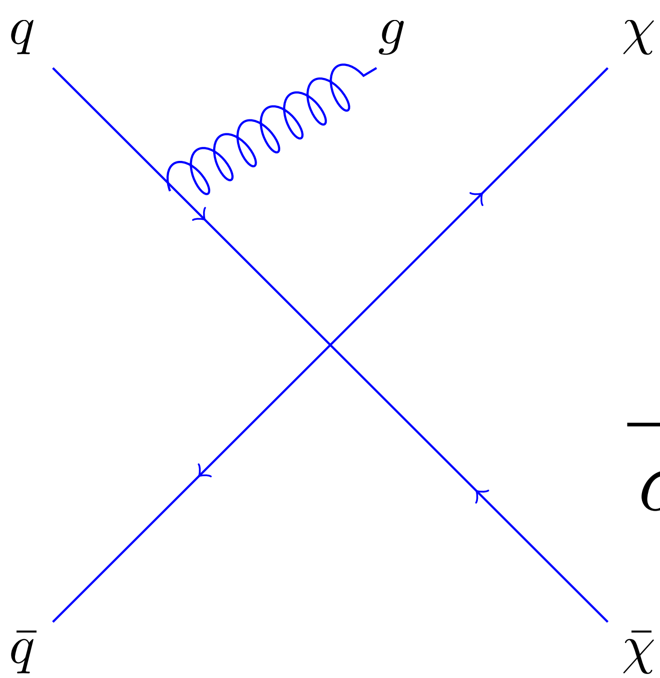
$$C_V^{\not{s}}\,\frac{g_\star^2 m_\chi}{M^4}\chi^\dagger\chi V^a_{\mu\nu}V^{a\,\mu\nu} \quad \text{vs.} \quad C_V\,\frac{g_\star^2}{M^4}\chi^\dagger\bar{\sigma}^\mu\partial^\nu\chi V^a_{\mu\rho}V_\nu^{a\,\rho}$$



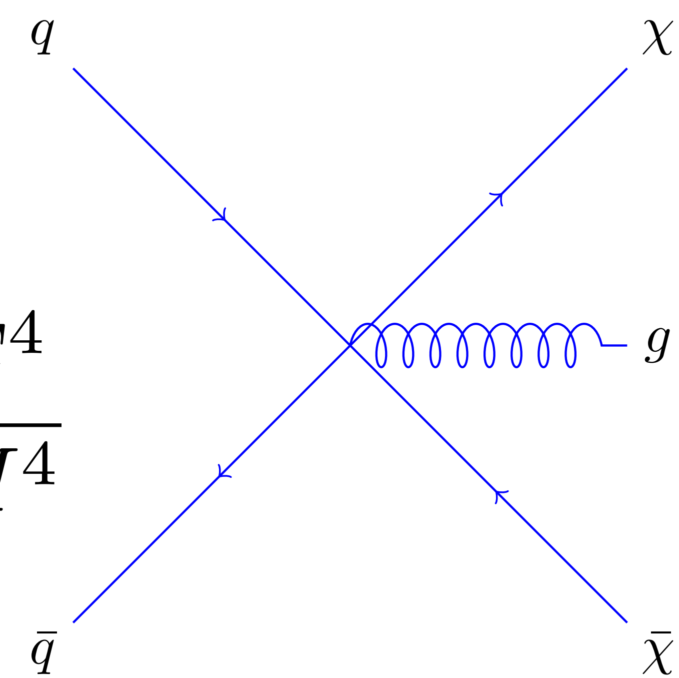
Composite Vectors

NEW! $$C_\psi^{mono}\,\frac{g_\star^3}{M^4}\,\chi^\dagger\bar{\sigma}_\mu\chi\psi^\dagger\bar{\sigma}_\nu T^a\psi V^{a\,\mu\nu}$$

$$2\to 2+\mathrm{ISR}\ \text{vs.}\ 2\to 3$$



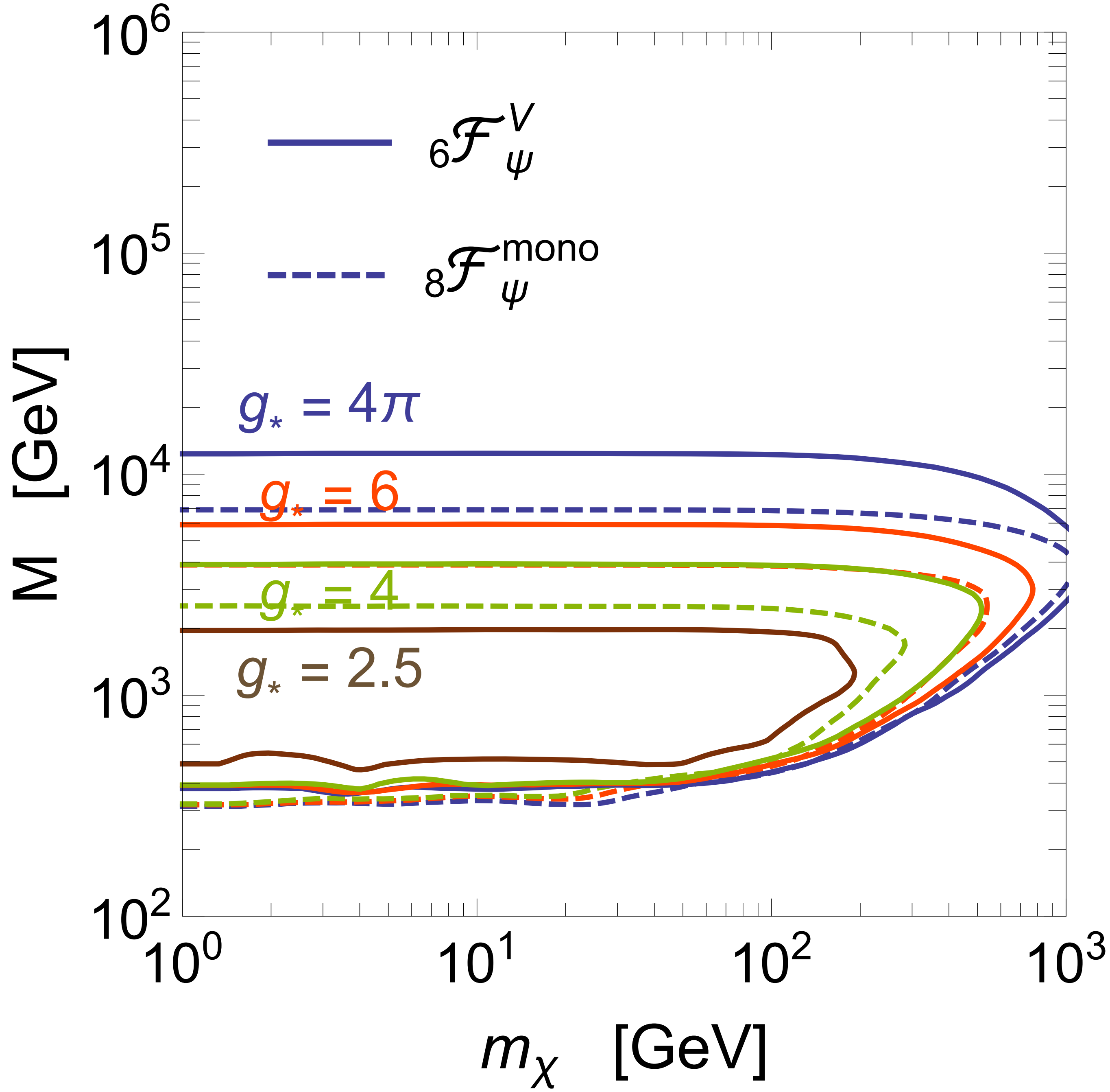
$$\frac{\sigma\big|_{6\mathcal{F}_\psi^V}}{\sigma\big|_{8\mathcal{F}_\psi^{mono}}}\sim\frac{g_s^2}{g_\star^2}\,\frac{E^4}{M^4}$$



Composite Vectors

NEW!

$$C_{\psi}^{mono}\,\frac{g_{\star}^{3}}{M^{4}}\chi^{\dagger}\bar{\sigma}_{\mu}\chi\psi^{\dagger}\bar{\sigma}_{\nu}T^{a}\psi V^{a\,\mu\nu}$$



Message

- Operators might be more suppressed than expected
- Consistent analysis of data within the framework of EFTs is possible and sometimes needed
- We can test well define hypotheses on UV physics
- Complementarity between collider searches and direct detection is sometimes lost