Simplified t-channel dark matter models and LLPs

Dipan Sengupta

University of New South Wales, Sydney

With C.P-Yuan, B. Yan, K. Mohan, Tim Tait, Matthias Becker, Emanuele Copello and Julia Harz + LHC-t-channel Dark Matter Working Group

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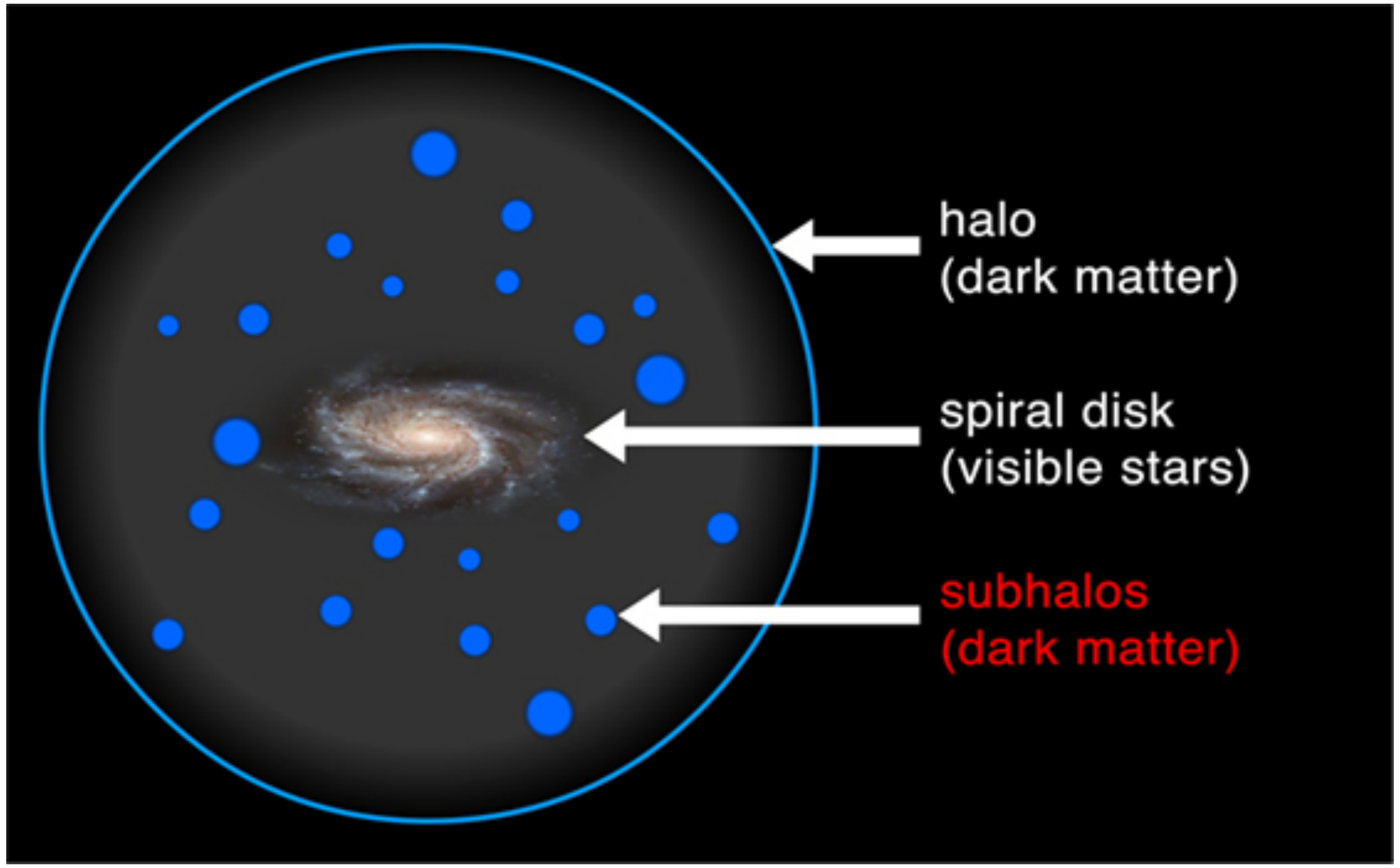
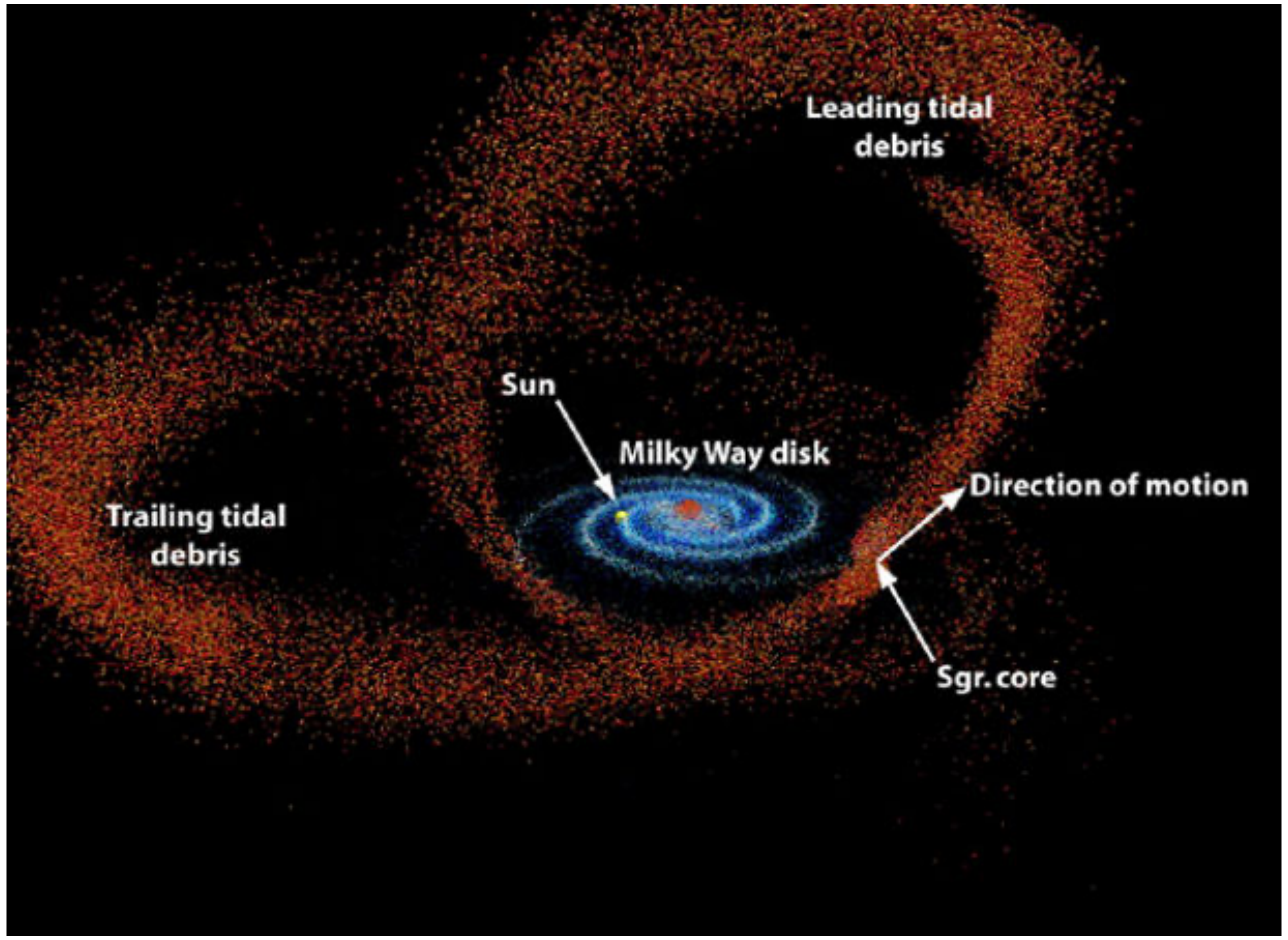
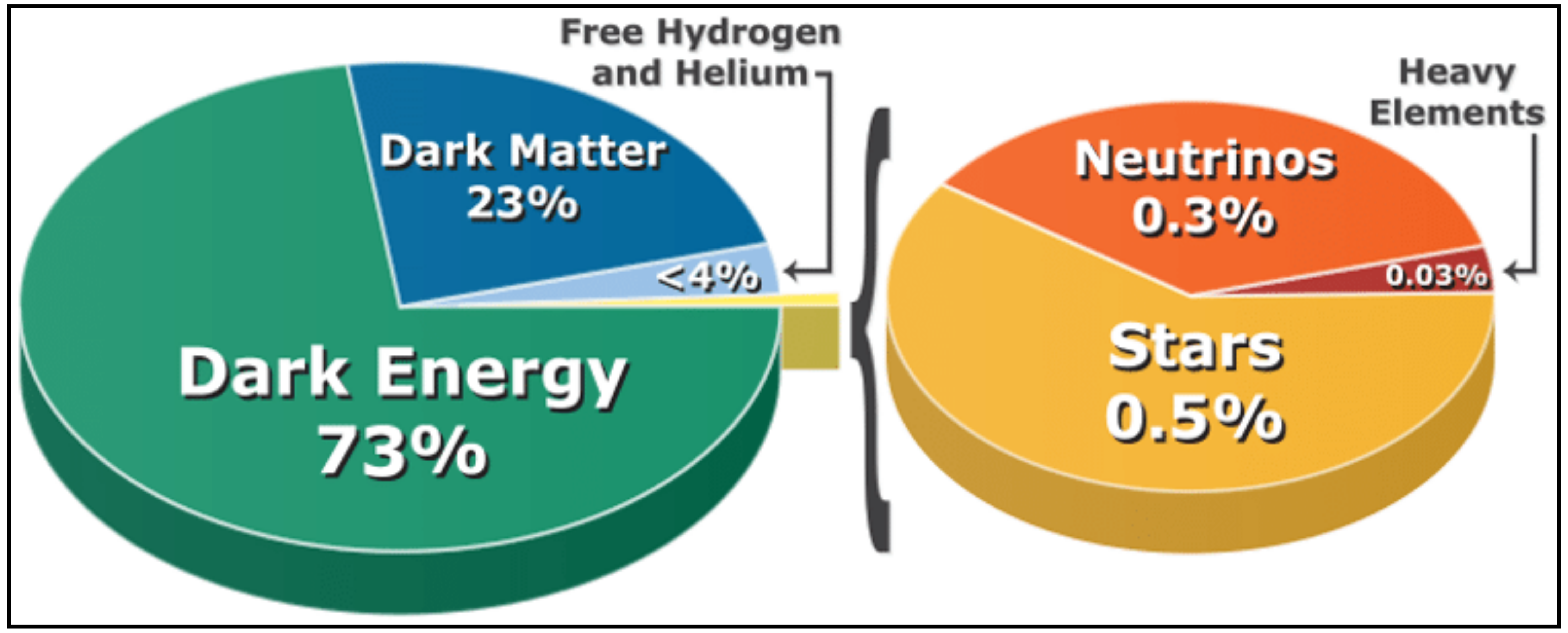
Properties and the Particle Physics of Dark Matter



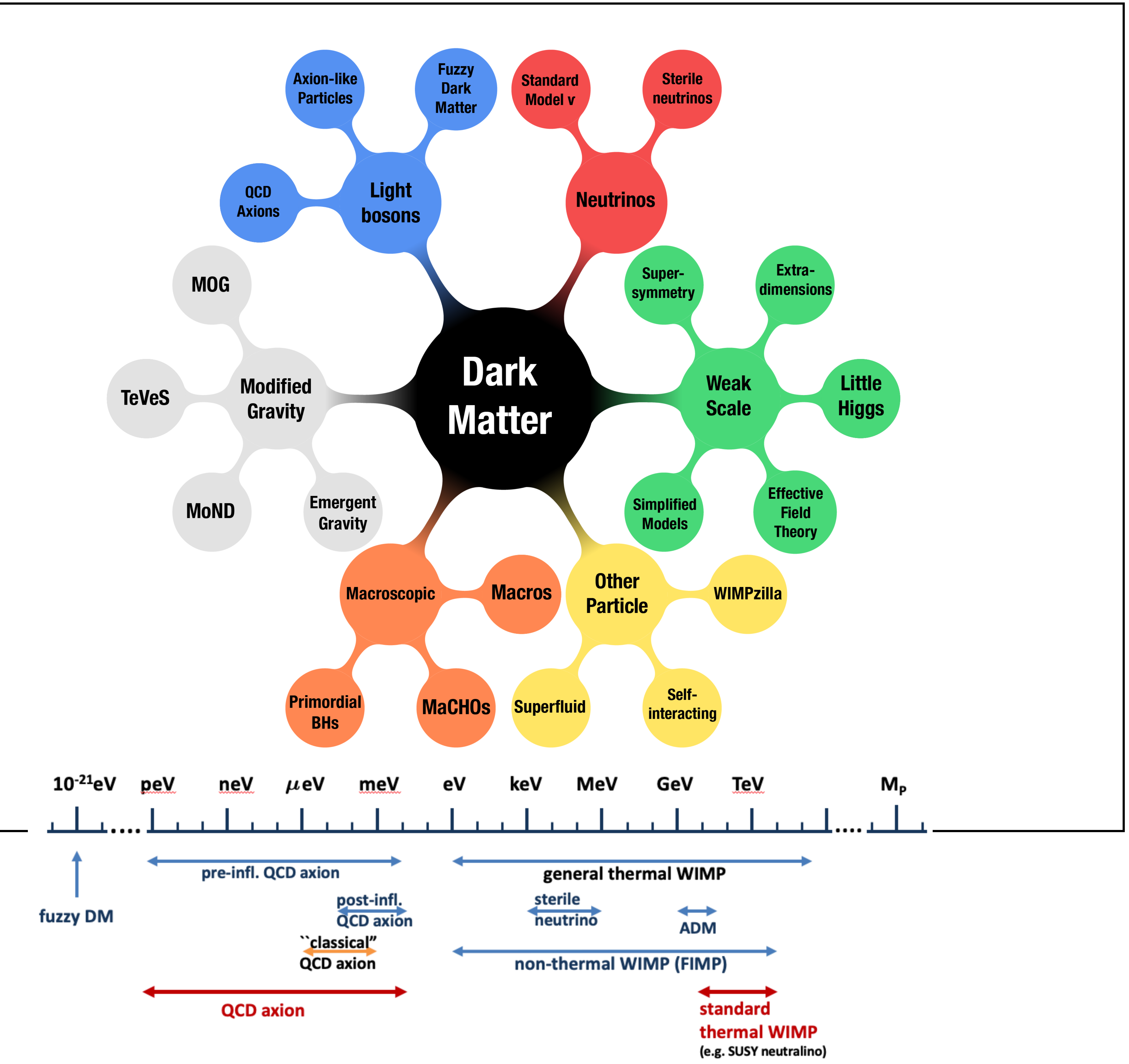


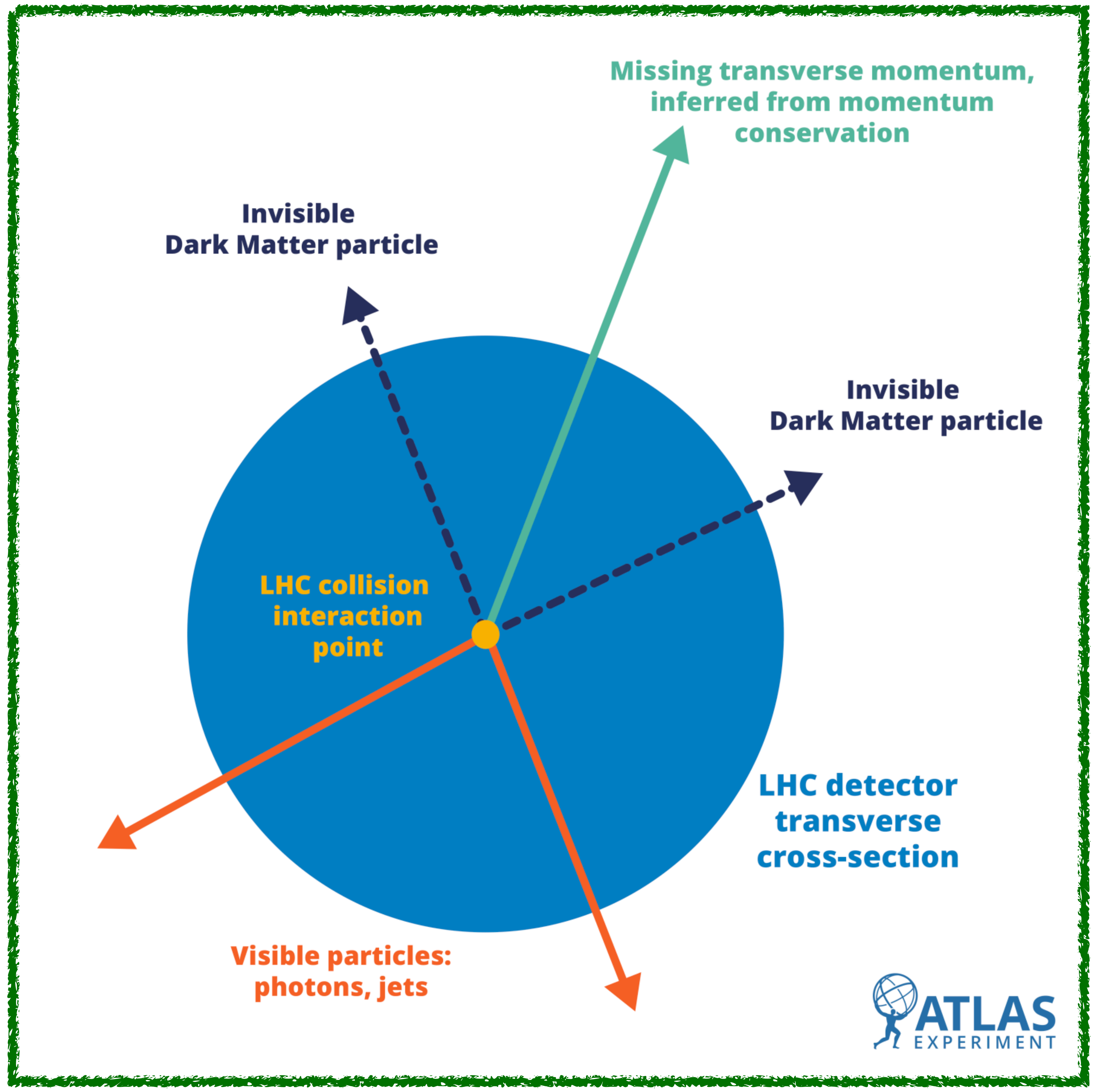
- Cold and Neutral: Non relativistic today.
- Preserves the success of Big Bang Nucleosynthesis (Formation of Atoms and Nuclei in the early Universe)
- "Almost" **Dark** with respect to other forces of nature.
- Collisionless within the DM sector at large scales.
- Stable, on Cosmological time scales.
- Forms halos in the galaxy

Dark Matter belongs in Astronomy/Cosmology .
Why should we care about colliders ?



Dark Matter at Colliders



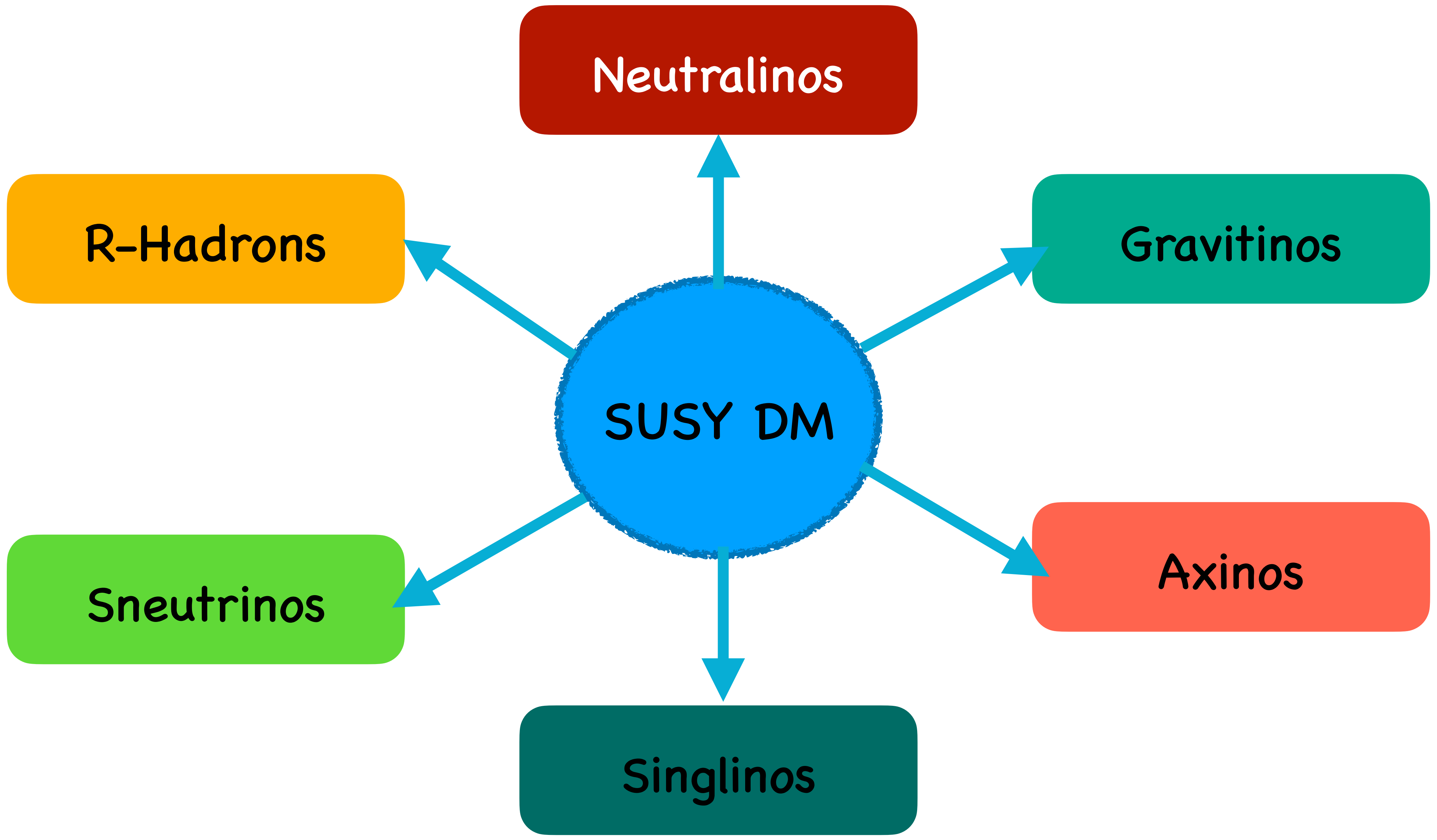


Comment : Even in the event of a missing energy signature, we can't be sure it is dark matter

Full Models vs EFTs

Full Models vs EFTs

Supersymmetry as an Example



Full Models vs EFTs

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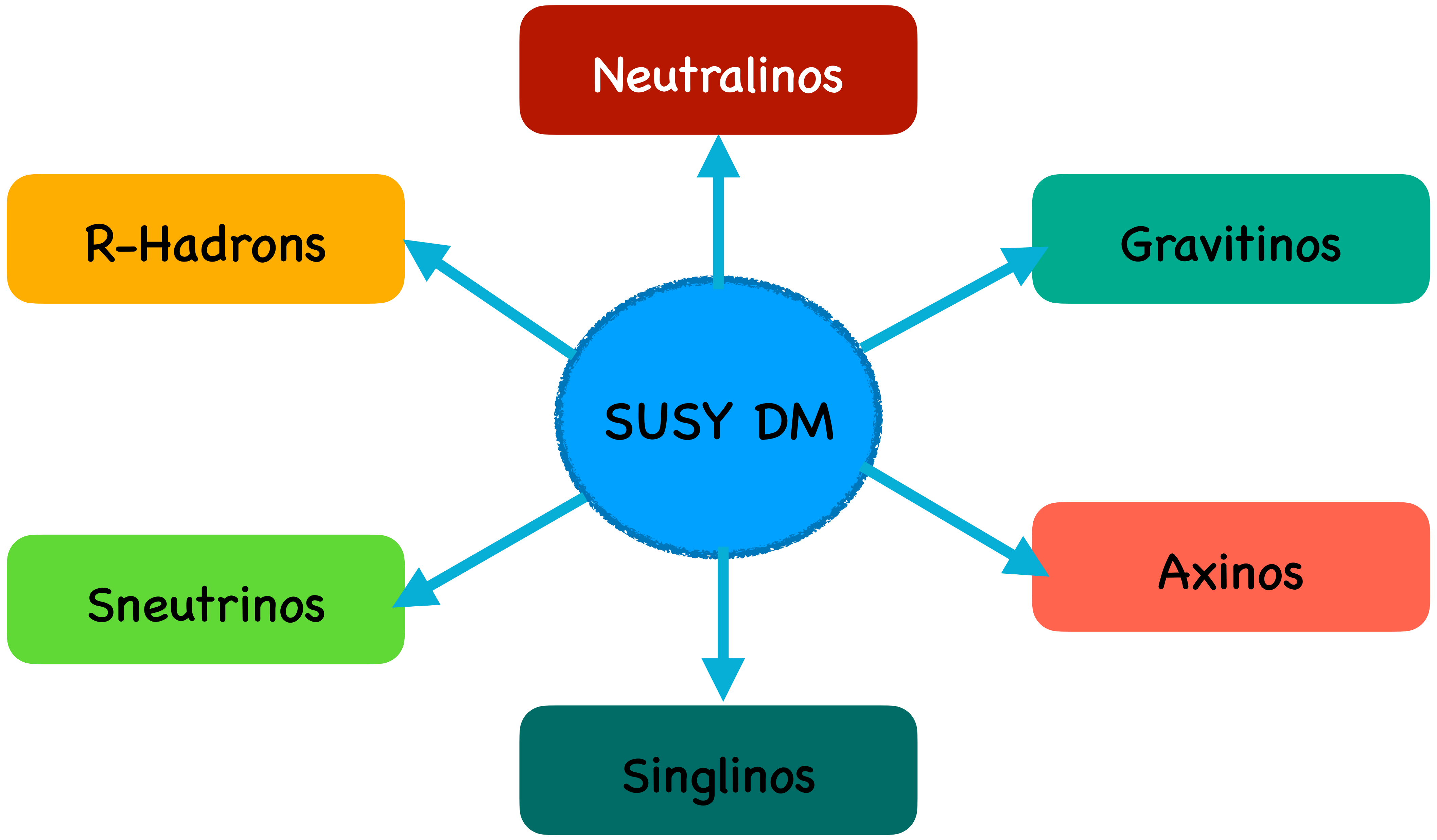


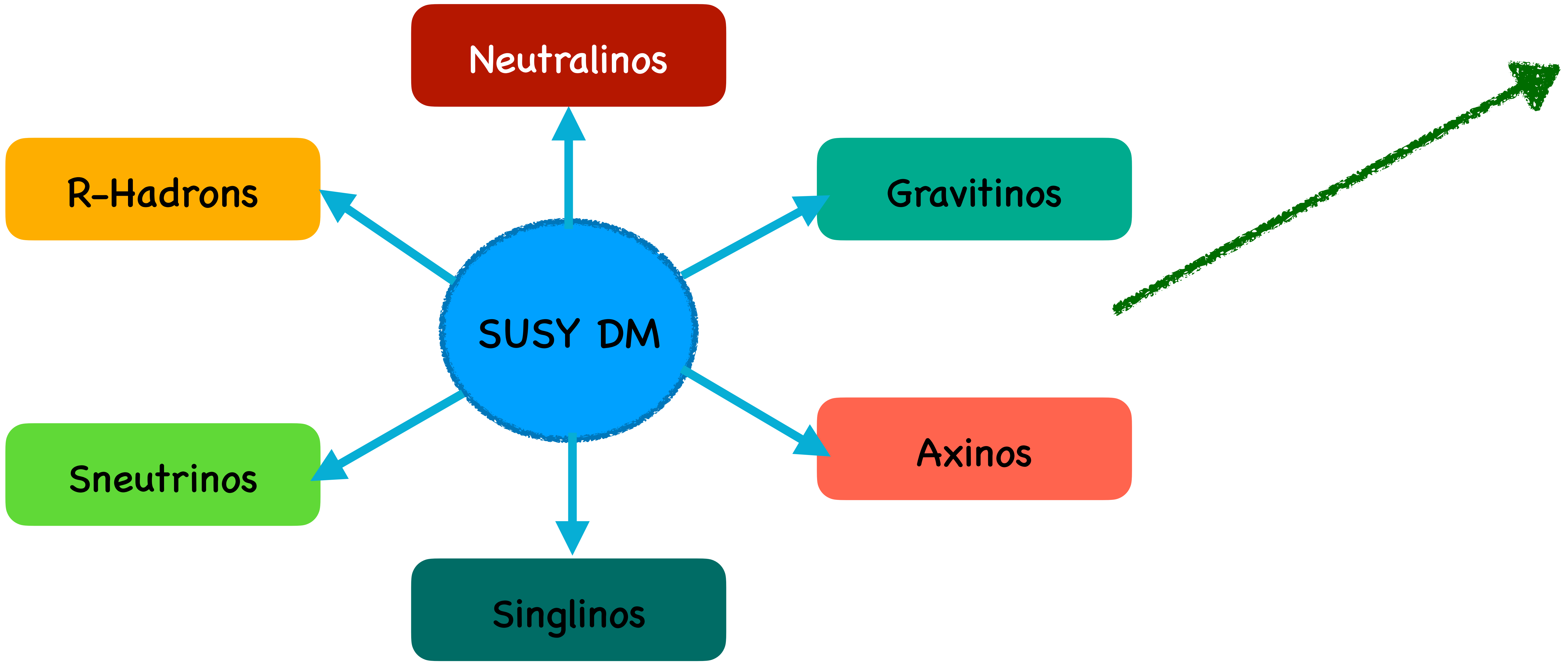
A few mediators with specific DM couplings generates the relic density and direct detection rates.

For heavy mediators, can integrate the mediator out

And classify the DM by spin

Full Models vs EFTs

Supersymmetry as an Example



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Full Models vs EFTs

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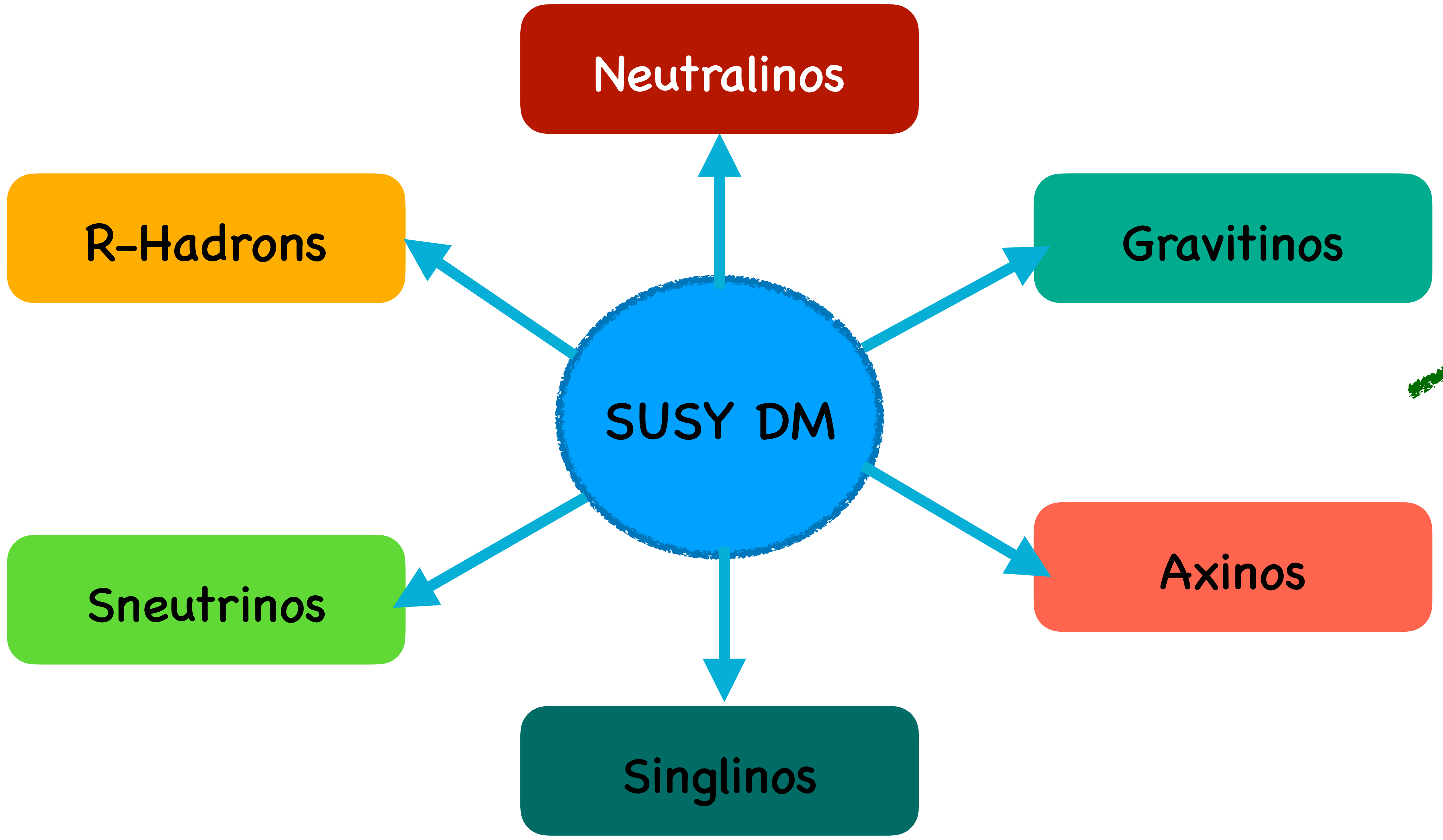

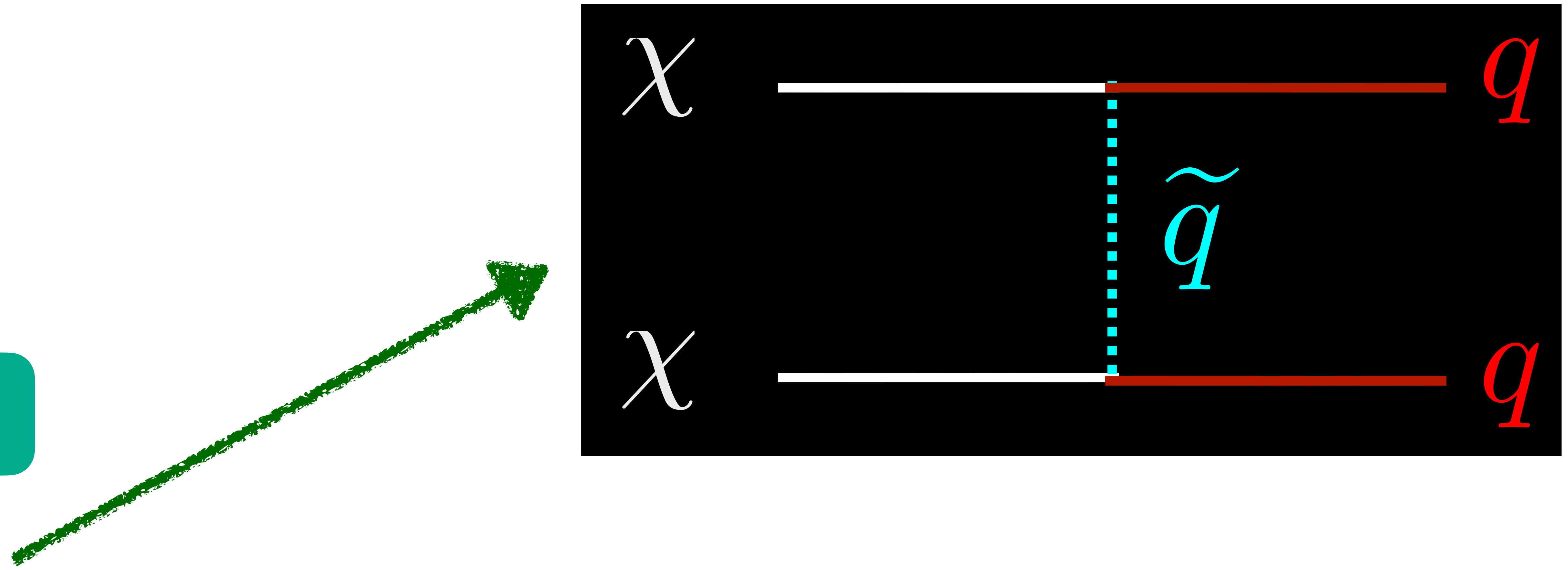

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Full Models vs EFTs

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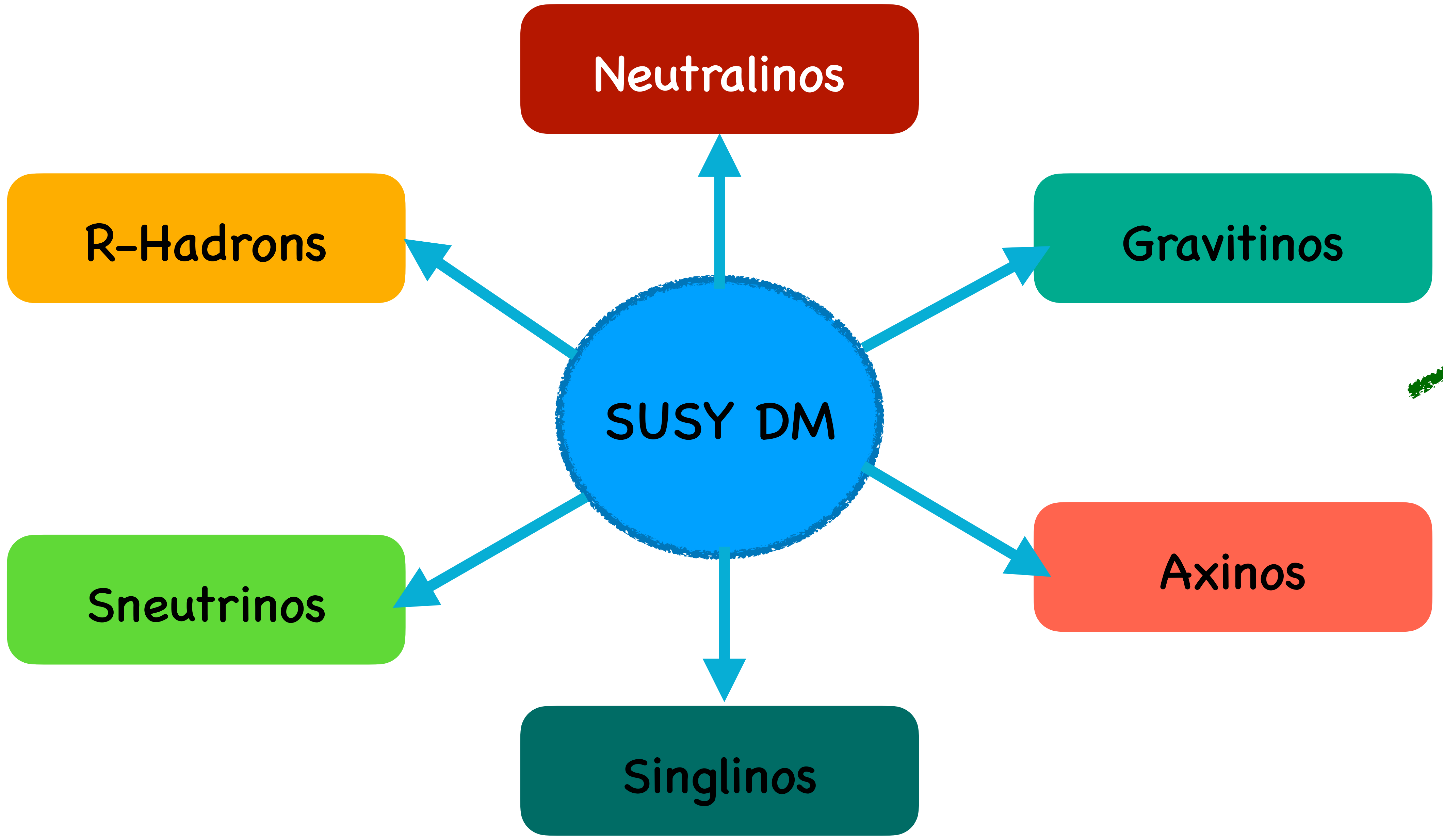

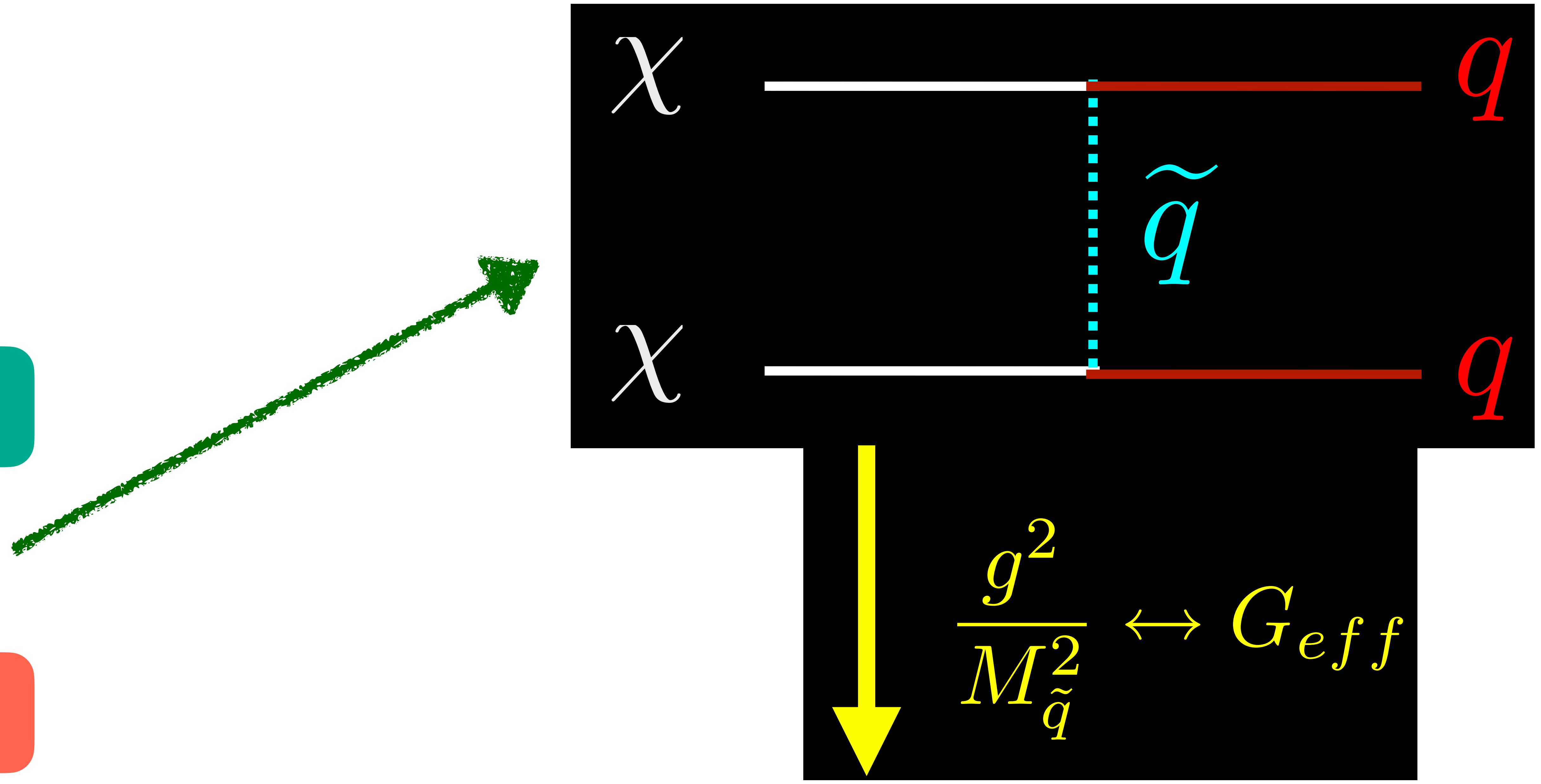

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Full Models vs EFTs

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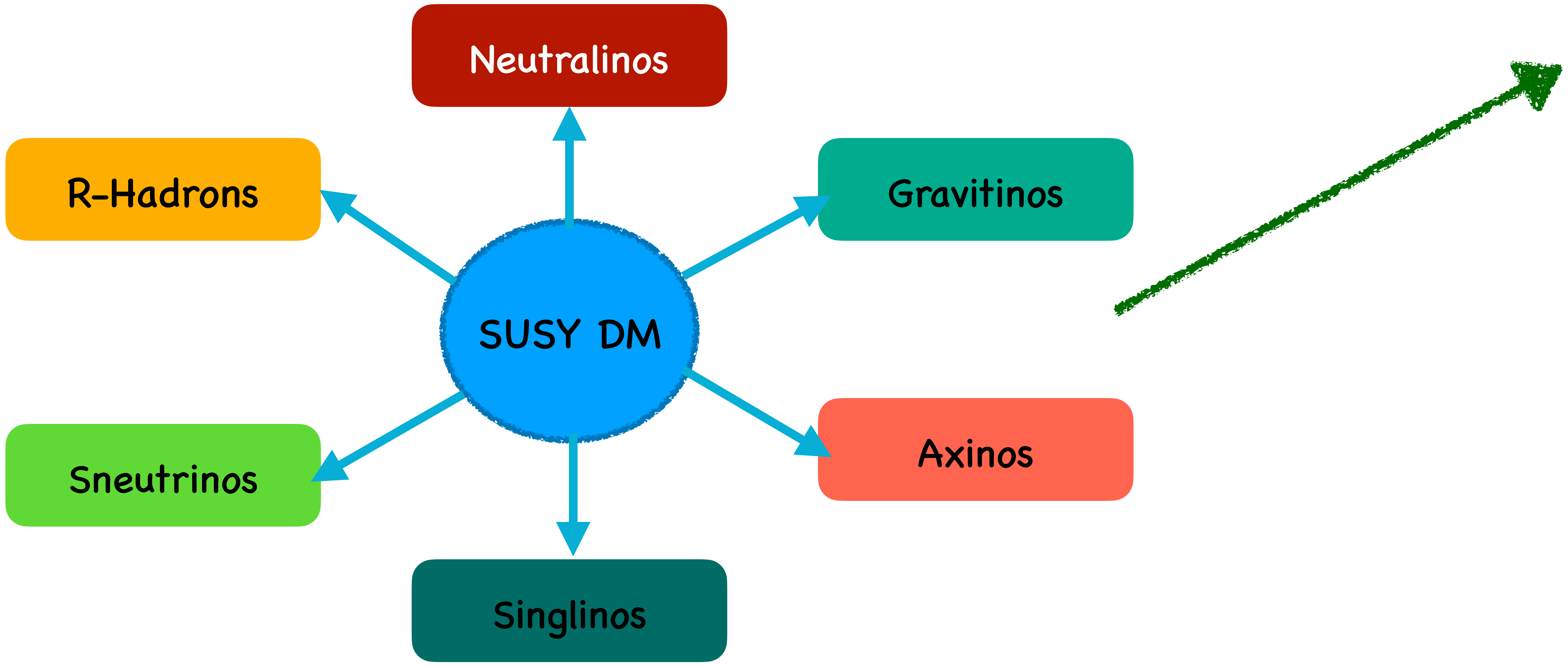

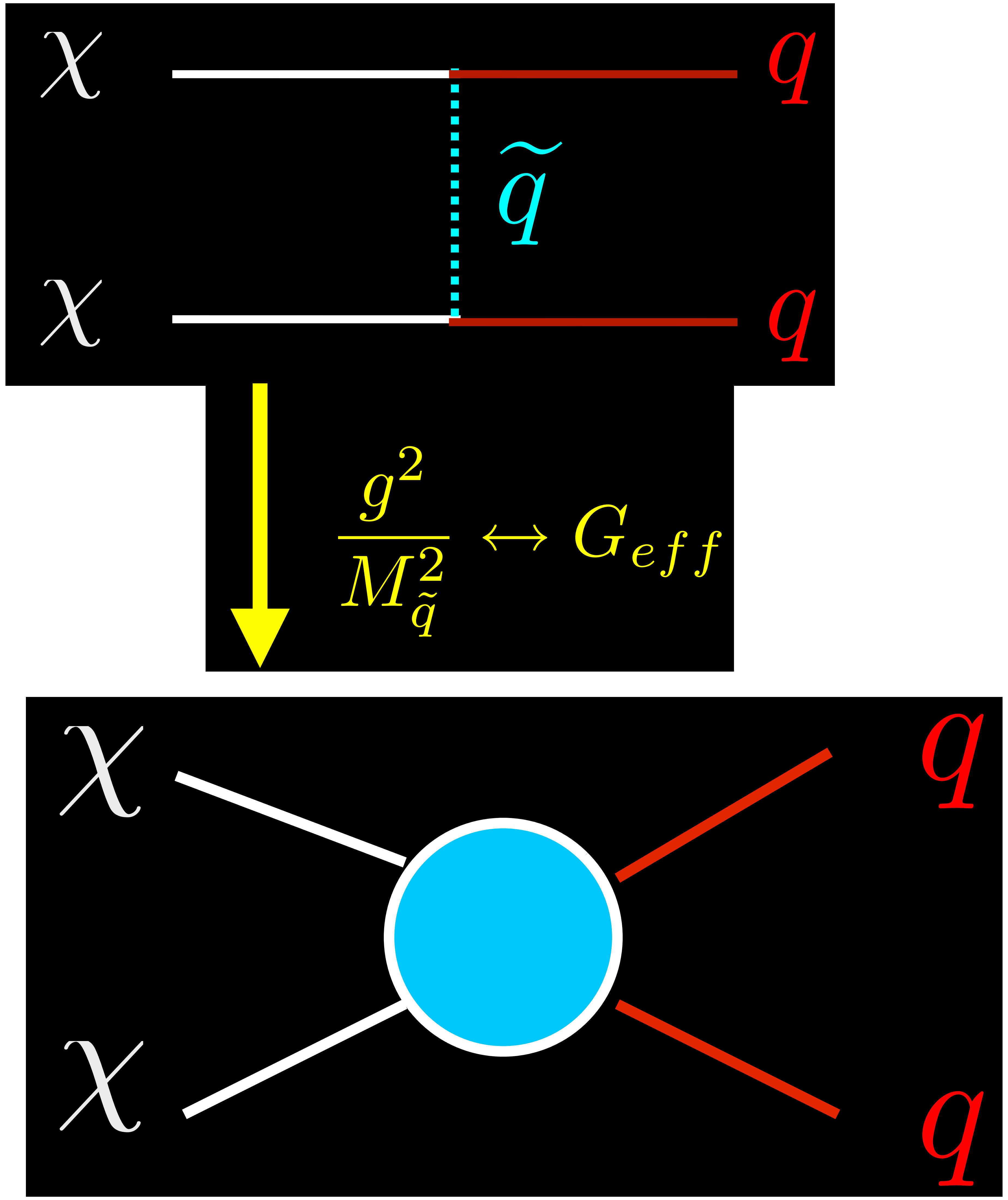

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For heavy mediators, can integrate the mediator out

And classify the DM by spin

Full Models vs EFTs

Majorana Dark Matter: 10 operators with an

EFT strength M

Full Models vs EFTs

Majorana Dark Matter: 10 operators with an EFT strength M

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
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M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
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M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
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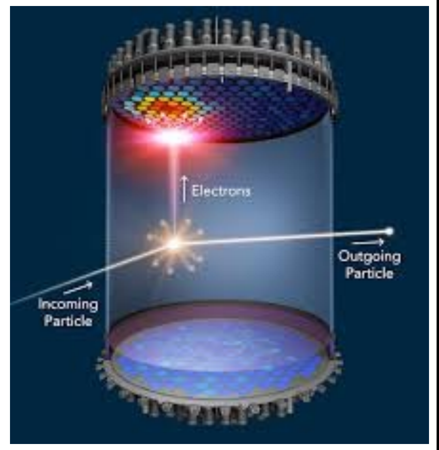
Full Models vs EFTs

Majorana Dark Matter: 10 operators with an EFT strength M

SI Elastic Scattering



Source: KIPAC

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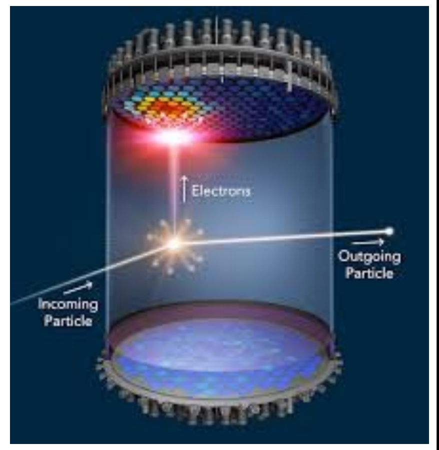

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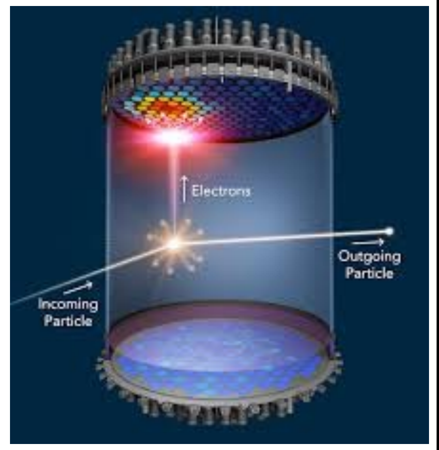
Full Models vs EFTs

Majorana Dark Matter: 10 operators with an EFT strength M

- SI Elastic Scattering
- SD Elastic Scattering
- Annihilation in the galactic halo



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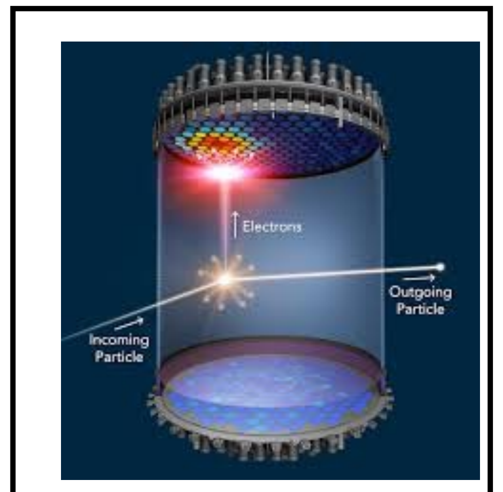
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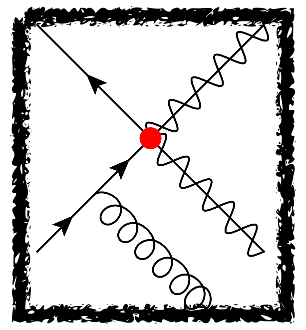

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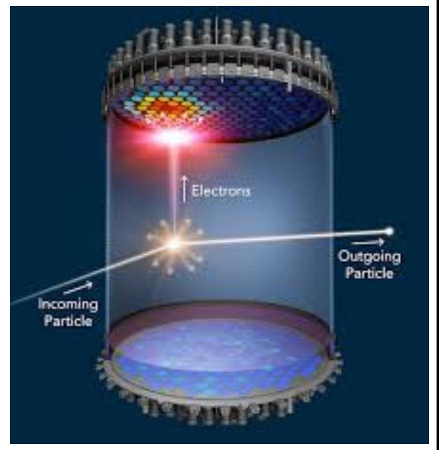
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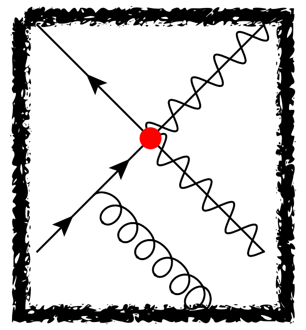

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$$G_\chi\,[\bar{\chi}\Gamma^\chi\chi]\,G^2$$

$$\sum_q G_\chi\,[\bar{q}\Gamma^q q]\,[\bar{\chi}\Gamma^\chi\chi]$$

Other operators may be rewritten in this form by using Fierz transformations.

Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB

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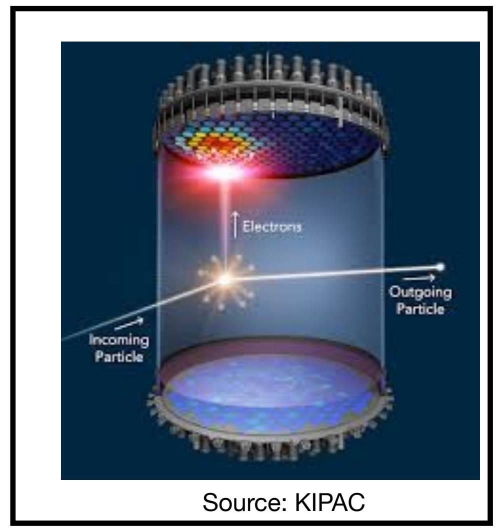

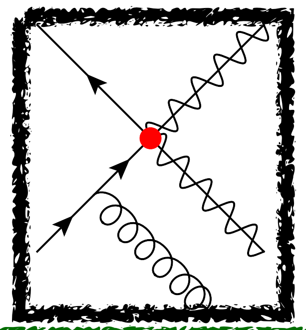

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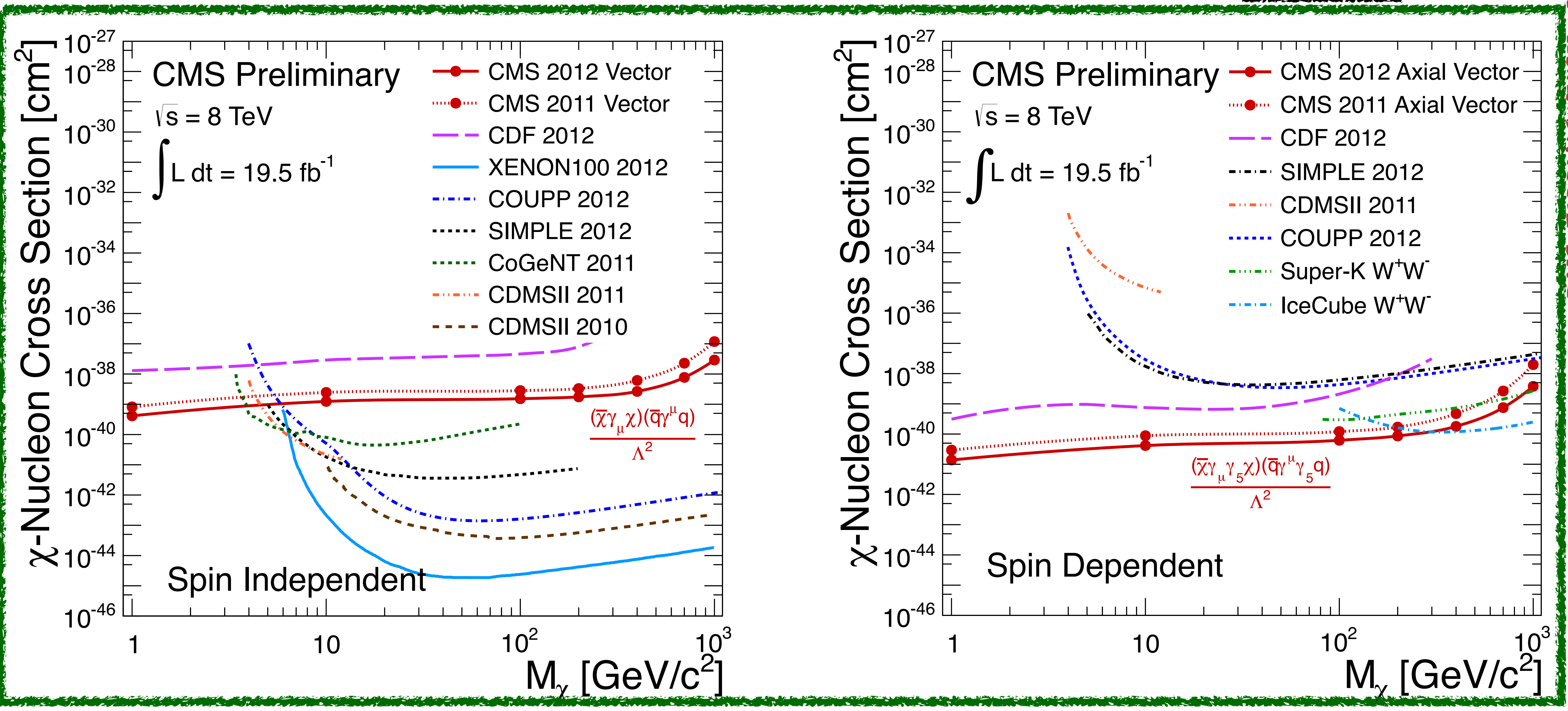

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EFTs vs Simplified Models

$$\mathcal{L}_{\text{DM-EFT}} = \sum_{f=u,d,s,c,b,t,e,\mu,\tau} \left(\frac{C_1^f}{\Lambda^2} \bar{f} f \, \bar{\chi} \chi + \frac{C_2^f}{\Lambda^2} \bar{f} \gamma_5 f \, \bar{\chi} \gamma_5 \chi \, + \cdots \right)$$

$$\left\{ m_\chi \,,\; C_n^f / \Lambda^2 \right\}$$

Justified for $q^2 \ll \Lambda^2$

The breakdown of EFT is "**time-dependent**", since energies probed by LHC depend on PDFs, therefore hard to be absolutely quantitative

EFTs vs Simplified Models

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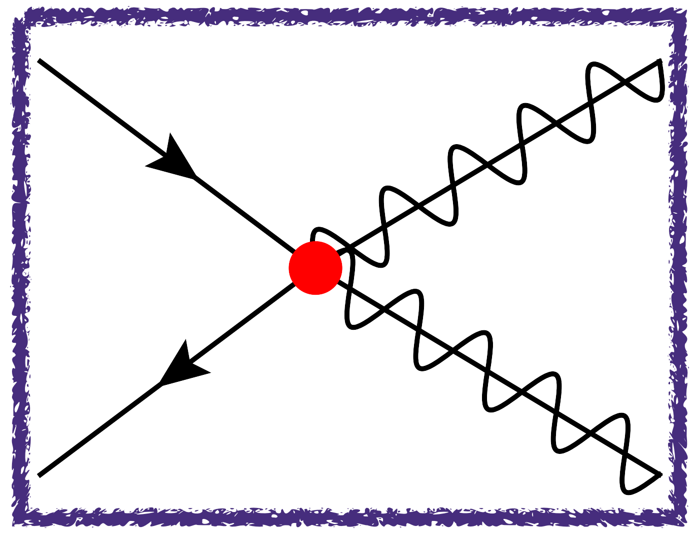

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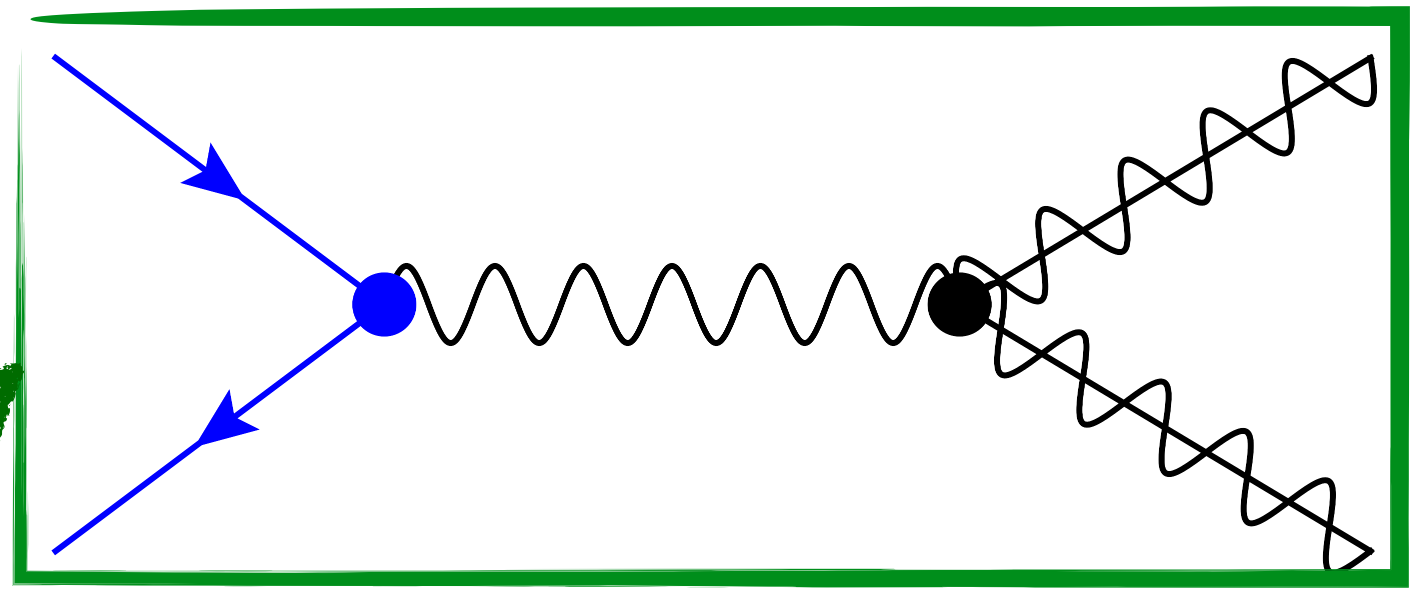
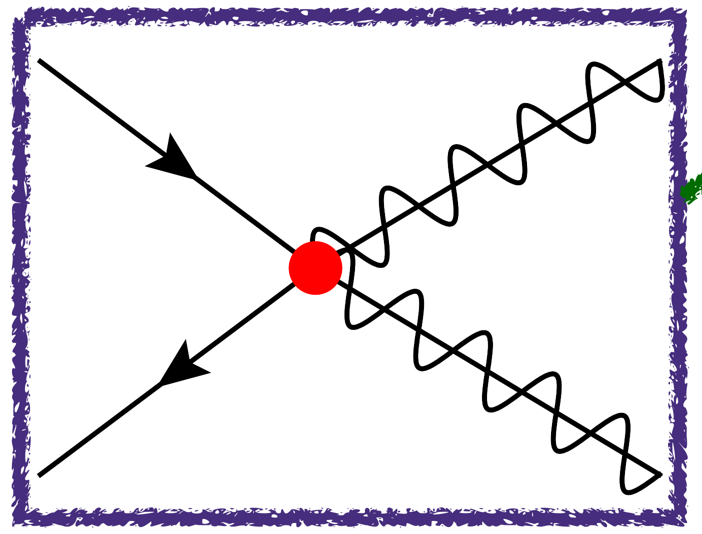


S-channel mediators : Masses can be

Larger or smaller than the DM



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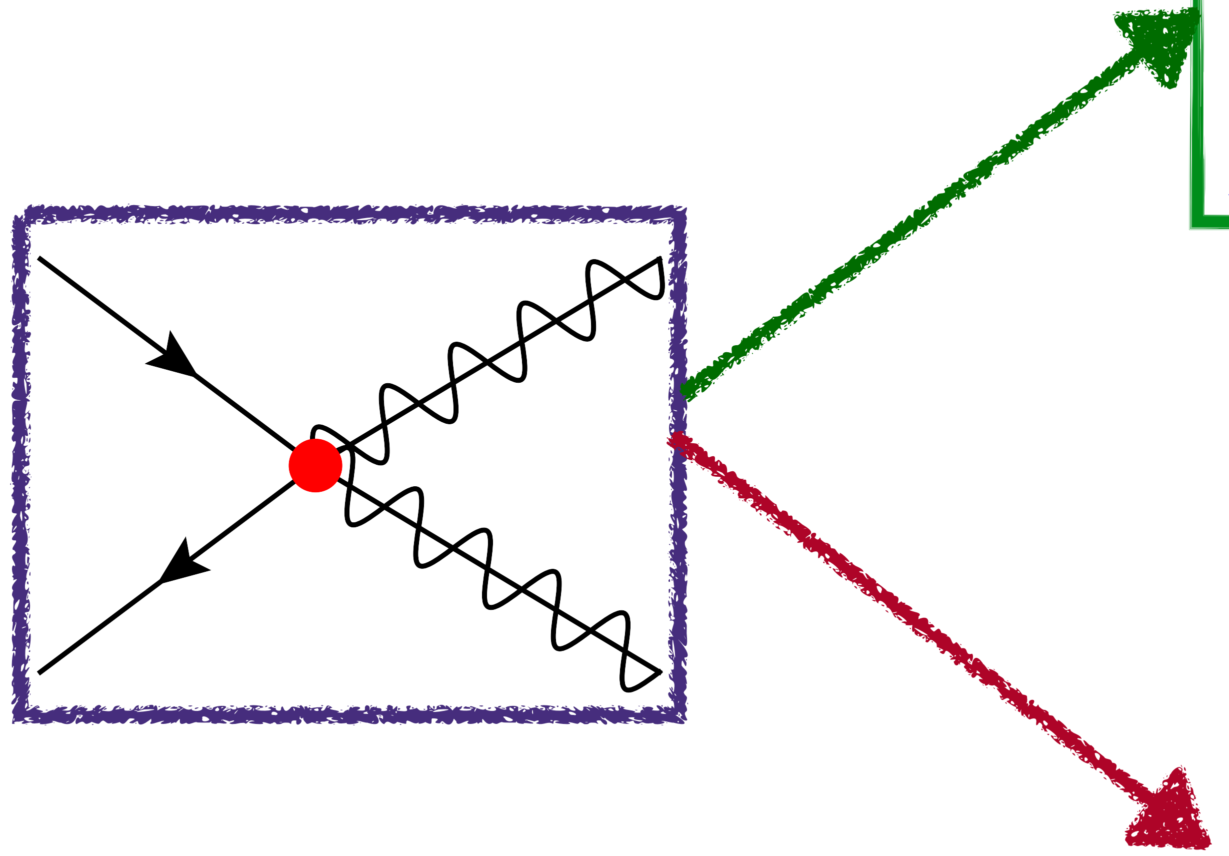

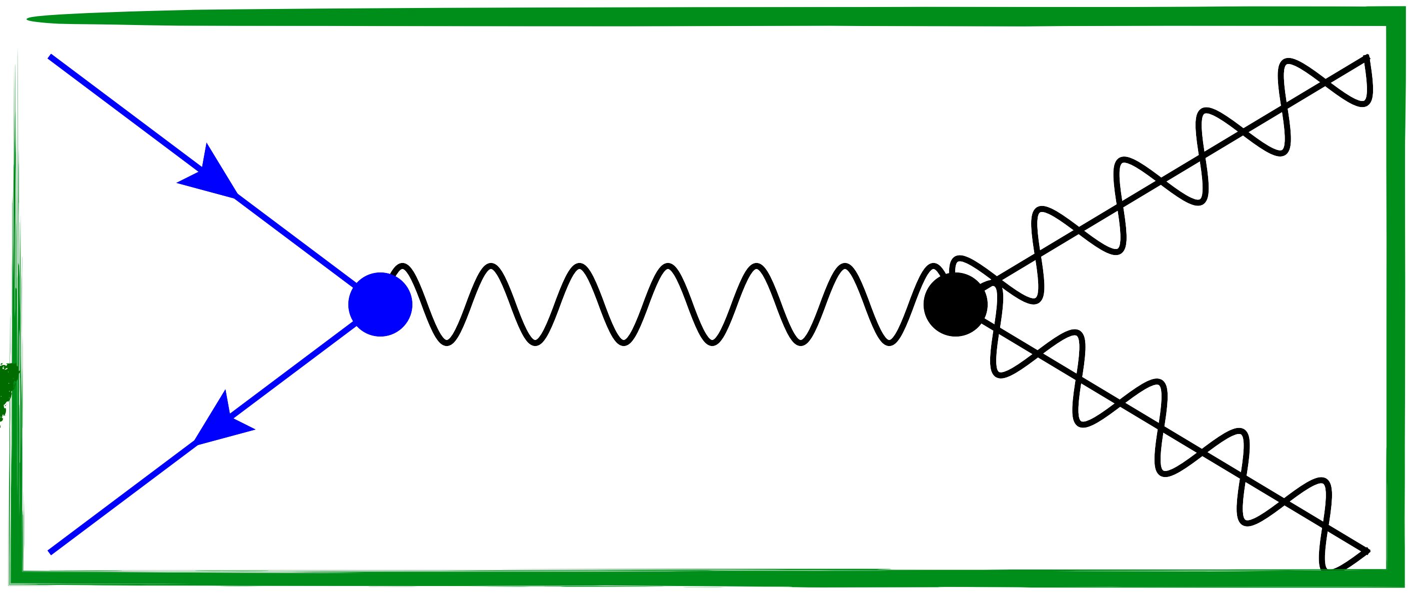

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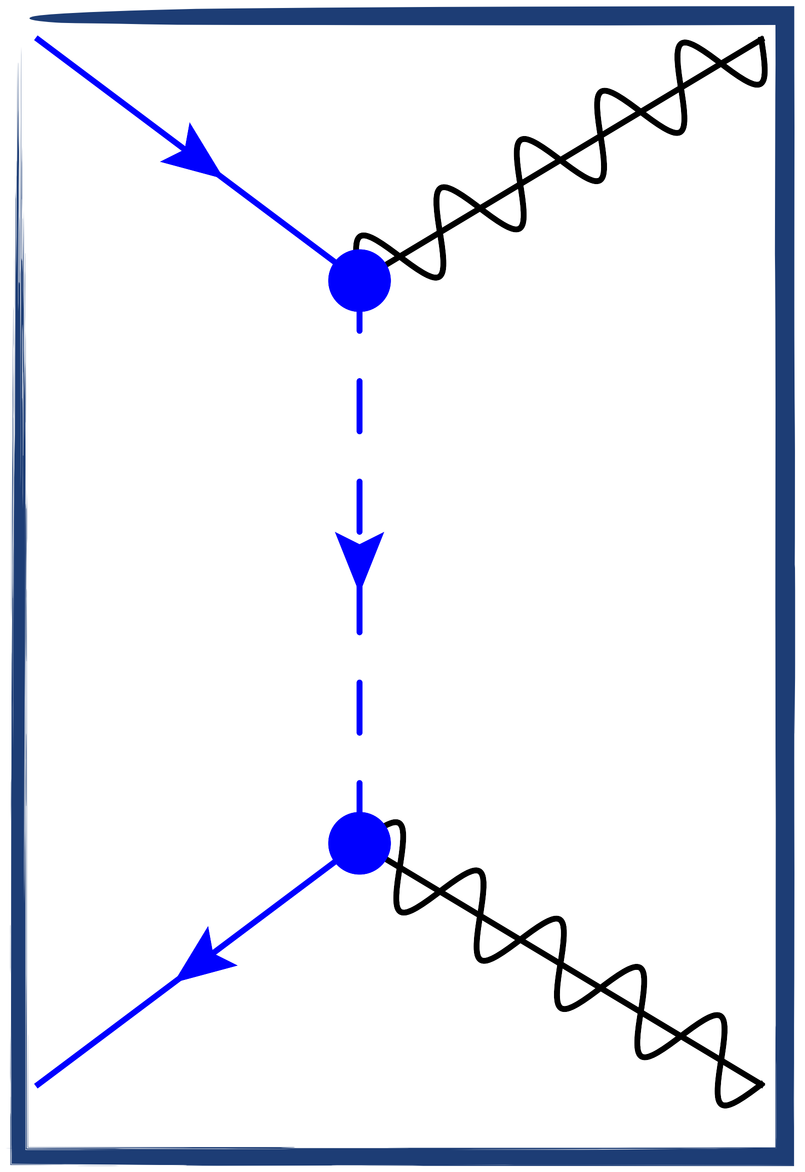
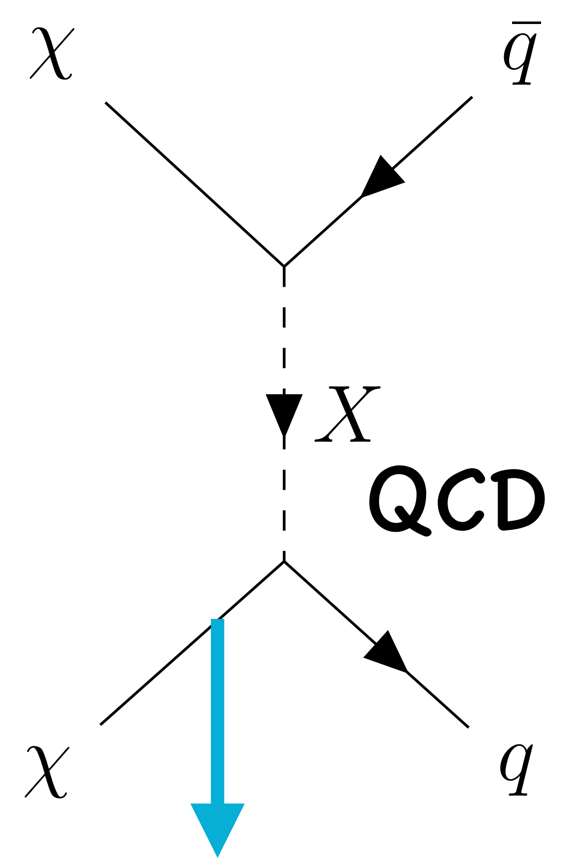


t-channel mediators : Masses are always larger than the DM (otherwise DM will decay)

t- channel Simplified Models

A Majorana Fermion Dark Matter (Neutralino) interacting with Scalar Colored Scalar Mediators (Squarks)



QCD Colored Mediators

Dark Matter particle:
A Majorana Fermion

X= $\tilde{u} = \{\tilde{u}, \tilde{d}, \tilde{s}\}$ $\tilde{d} = \{\tilde{d}, \tilde{s}, \tilde{b}\}$ $\tilde{q} = \{\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}, \tilde{t}\}$

$(SU(3), SU(2))_Y$	$(3,1)_{2/3}$	$(3,1)_{-1/3}$	$(3,2)_{-1/6}$

$$\mathcal{L} \supset \sum_i (D_\mu X_i)^\dagger (D^\mu X_i) + \sum_{i,j} \left(g_{\mathrm{DM},ij} X_i^\dagger \bar{\chi} P_R q_j + g^*_{\mathrm{DM},ij} X_i \bar{q}_j P_L \chi \right)$$

$$\mathcal{L}_{u_R} = \sum_u \left[(D_\mu \tilde{u})^* (D^\mu \tilde{u}) - M^2_{\tilde{u}} \; \tilde{u}^* \tilde{u} + g_{DM} \; \tilde{u}^* \; \bar{\chi} P_R u + g^*_{DM} \; \tilde{u} \; \bar{u} P_L \chi \right]$$

$$\mathcal{L}_{d_R} = \sum_d \left[(D_\mu \tilde{d})^* (D^\mu \tilde{d}) - M^2_{\tilde{d}} \; \tilde{d}^* \tilde{d} + g_{DM} \; \tilde{d}^* \; \bar{\chi} P_R d + g^*_{DM} \; \tilde{d} \; \bar{d} P_L \chi \right]$$

$$\mathcal{L}_{q_L} = \sum_{\tilde{q}} \left[(D_\mu \tilde{q})^* (D^\mu \tilde{q}) - M^2_{\tilde{q}} \; \tilde{q}^* \tilde{q} + g_{DM} \; \tilde{q}^* \; \bar{\chi} P_L q + g^*_{DM} \; \tilde{q} \; \bar{q} P_R \chi) \right]$$

t- channel Simplified Models

Relic Density/velocity averaged cross-section

$$\langle \sigma v \rangle \simeq N_c^f g_{DM}^4 \left[\frac{m_f^2 \sqrt{1 - \frac{m_f^2}{m_\chi^2}}}{64\pi (m_{\tilde{q}}^2 + m_\chi^2 - m_f^2)^2} + \beta^2 \left\{ \frac{m_\chi^2 \sqrt{m_\chi^4 + m_{\tilde{q}}^4}}{32\pi (m_\chi^2 + m_{\tilde{q}}^2)^4} + \mathcal{O}(m_f^2) \right\} \right]$$

Velocity independent part (s wave)   Velocity dependent part (p wave)

t- channel Simplified Models

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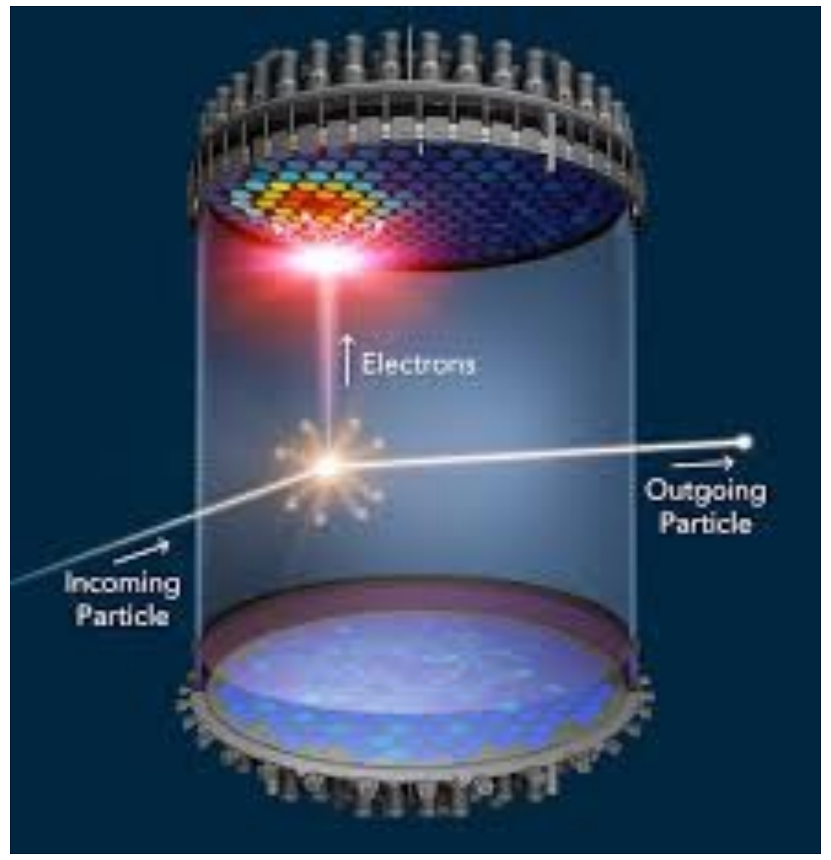
Velocity independent part (s wave)　　Velocity dependent part (p wave)

Spin-Independent : Coherent interaction with the whole Atomic Nucleus

Spin-Dependent : For Axial Vector coupling, couples to the spin of the Nucleus



Source: KIPAC

t- channel Simplified Models

Relic Density/velocity averaged cross-section

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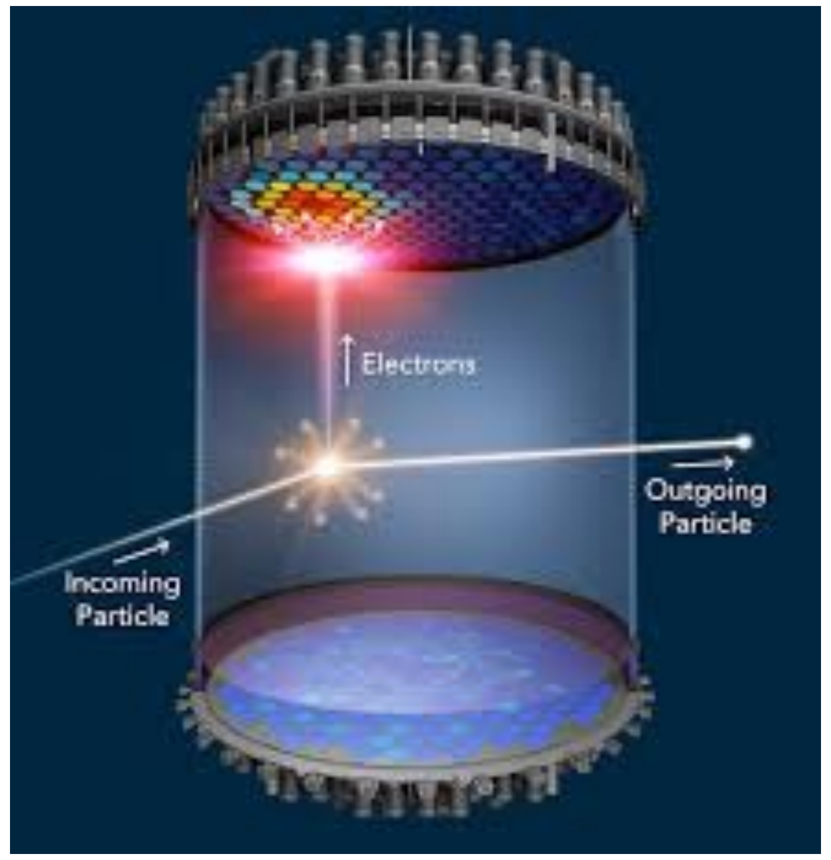

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- Given a DM model, we need to calculate the spin-independent and spin-dependent cross sections at the quark level and match it at the nucleon level using form factors
- Spin-Indepedent limits at tree level more constraining than the spin-dependent part

t- channel Simplified Models

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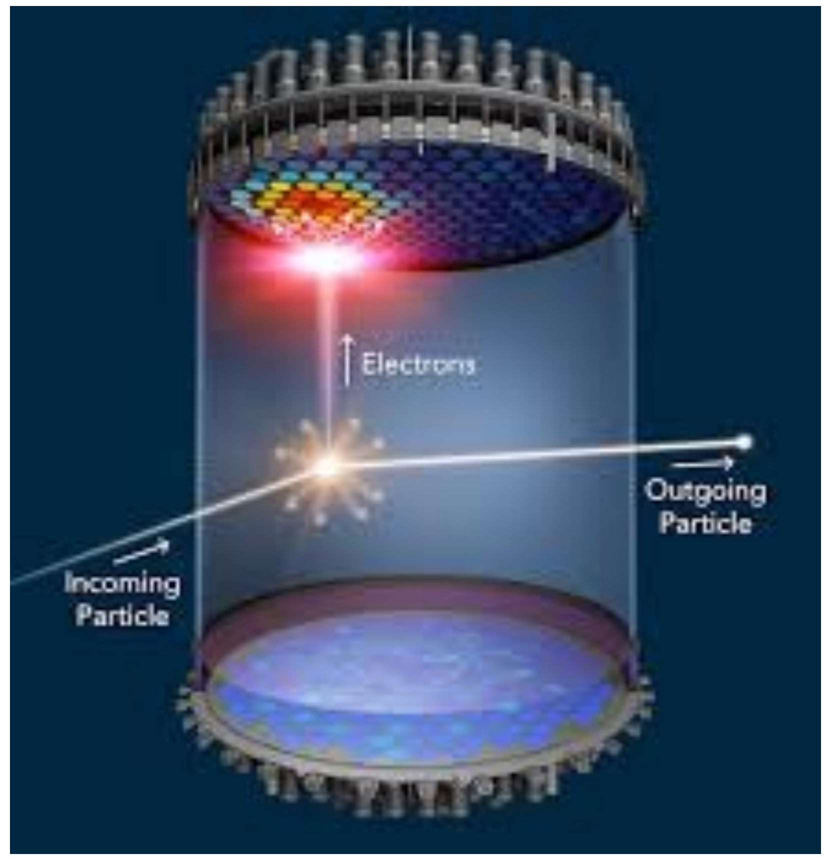

Source: KIPAC

$$\mathcal{M} = (-ig_{DM})^2 (\bar{\chi} P_R u) \frac{i}{p^2 - M_{\tilde{u}}^2} (\bar{u} P_L \chi) \approx \frac{i g_{DM}^2}{M_{\tilde{u}}^2 - m_\chi^2} \frac{1}{8} [(\bar{\chi}\gamma^\mu \chi)(\bar{u}\gamma_\mu u) - (\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{u}\gamma_\mu\gamma_5 u)]$$

SI = 0 for Majorana fermion

at tree level, Vector Bilinear vanishes

$$\sigma_p = \frac{4}{\pi} \left(\frac{M_\chi m_p}{M_\chi + m_p} \right)^2 |\langle \mathcal{M}_{DD} \rangle_{NR}|^2$$

t- channel Simplified Models

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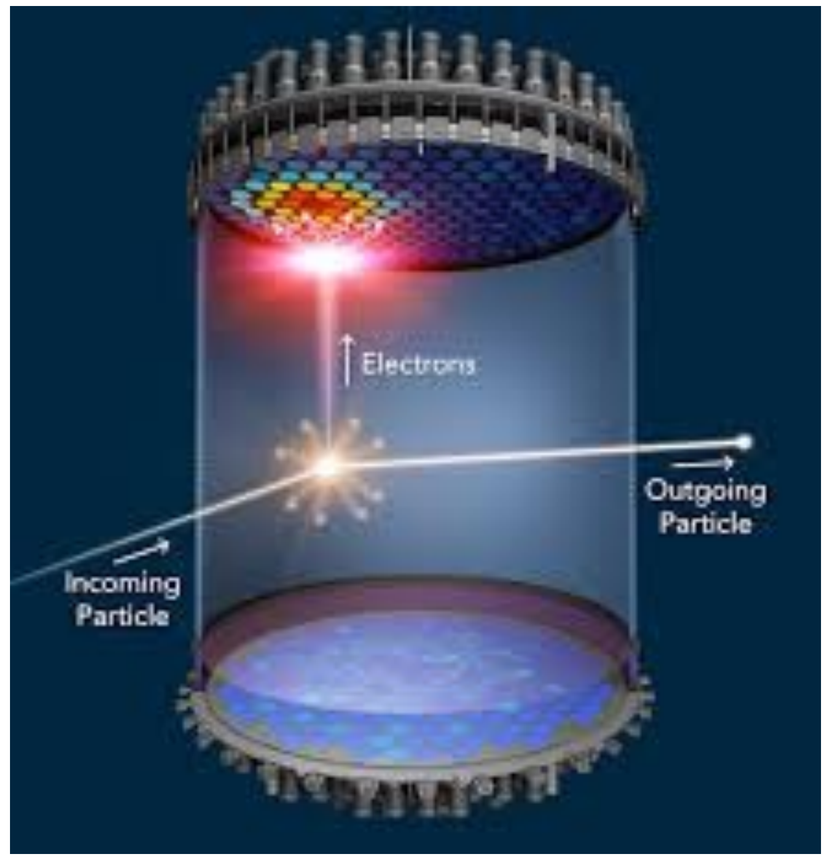

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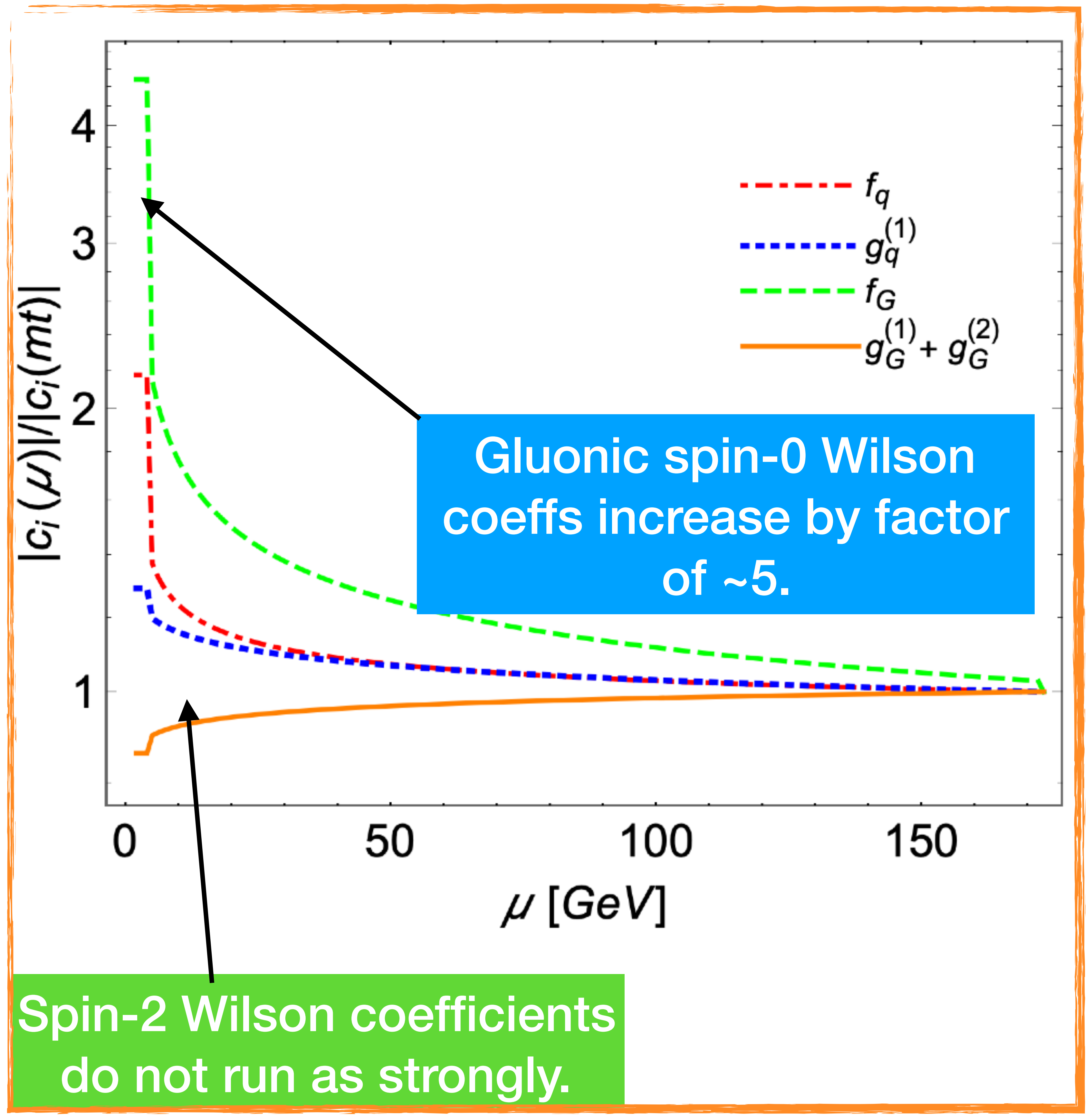
Is the spin-independent 1-loop more sensitive than the tree level spin-dependent direct detection limit?

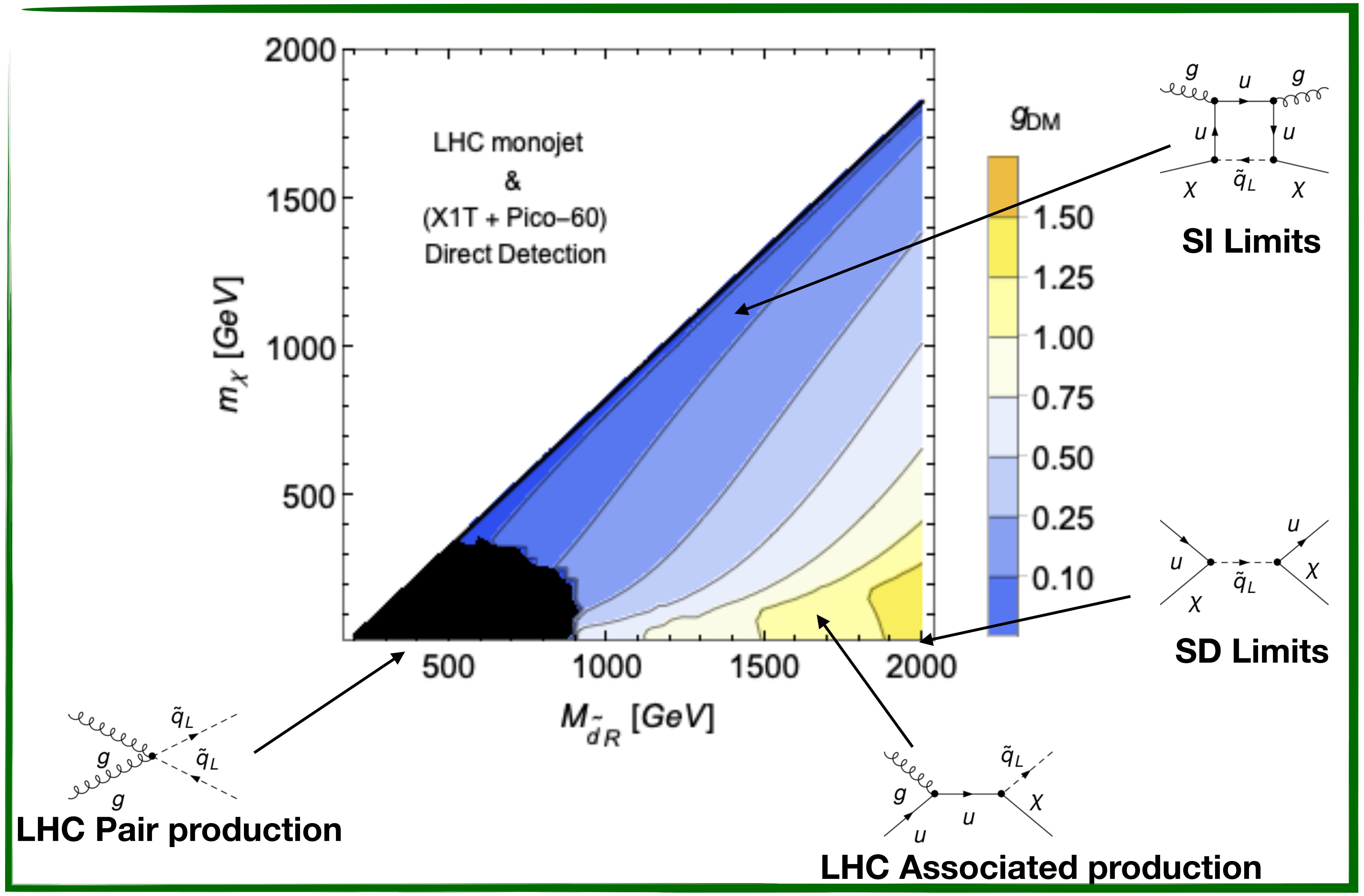
t- channel Simplified Models

We also need a Renormalization Group Evolution

At what scale do we define coupling and masses?

If at nuclear scale, to compare to LHC we should run up, for the reverse, run down.





Factor 4 enhancement in cross-section

See K. Mohan, **DS**, T. Tait, B.Yan, C.P Yuan. JHEP 05 (2019) 115 for details

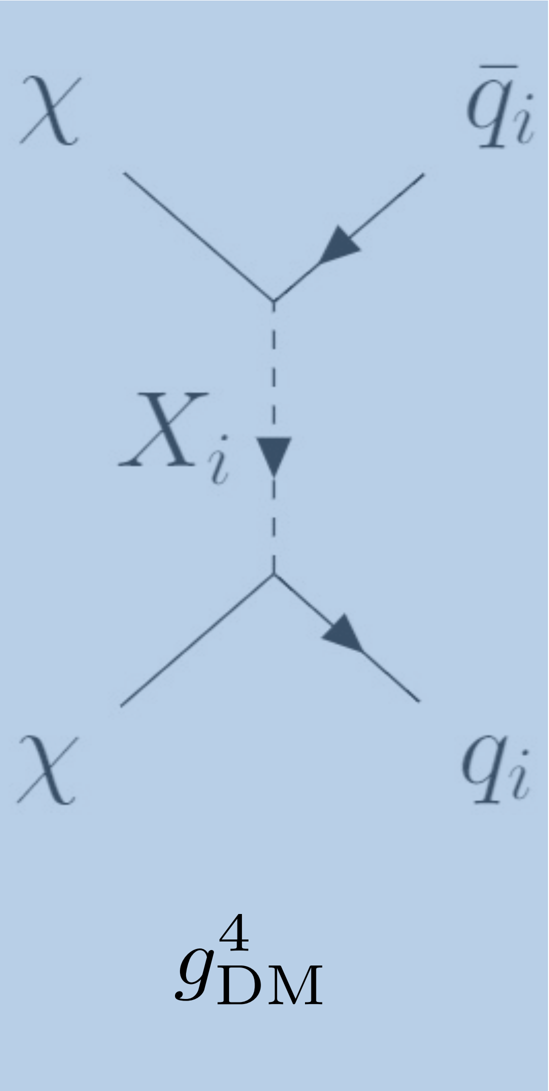
Take home message

Precision Calculations can significantly improve constraints on the coupling (DM interaction)

Coannihilations, Radiative and Non-Perturbative Effects in Relic Density Calculation

Let's go deeper into the same model,
think of small mass gap between DM and mediator

$$\delta \equiv \frac{m_X - m_\chi}{m_\chi} \equiv \frac{\Delta m}{m_\chi}, \quad \Delta m \equiv m_X - m_\chi$$



Large mass gap,
only relevant process

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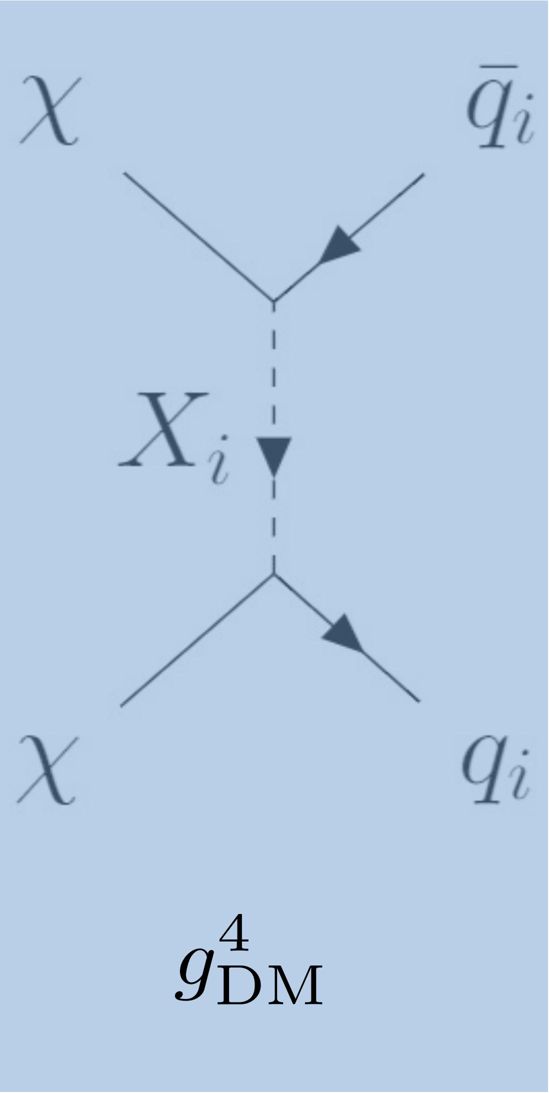

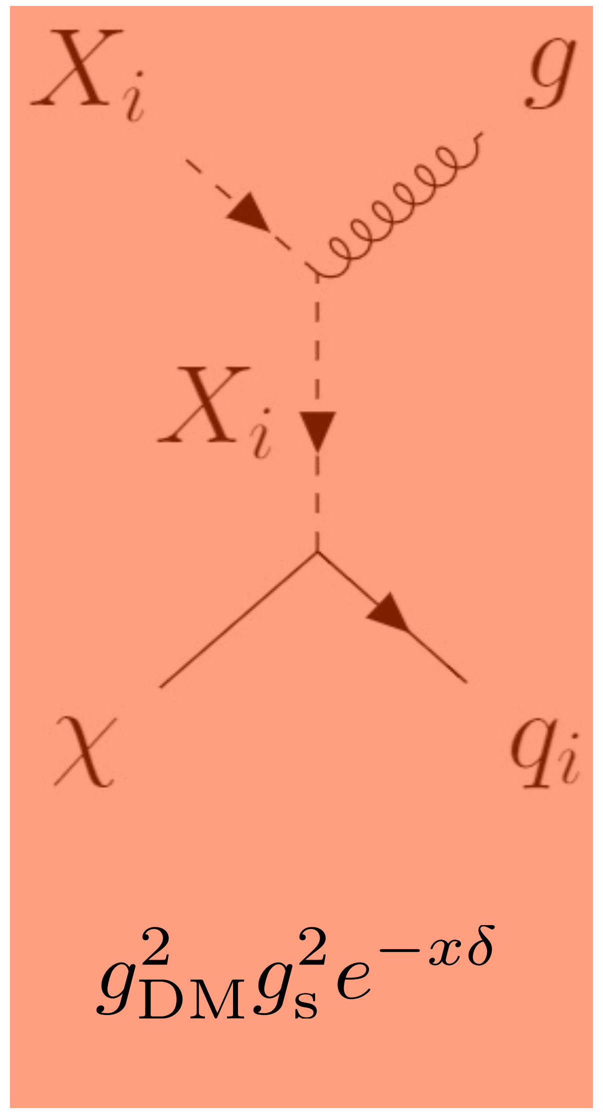

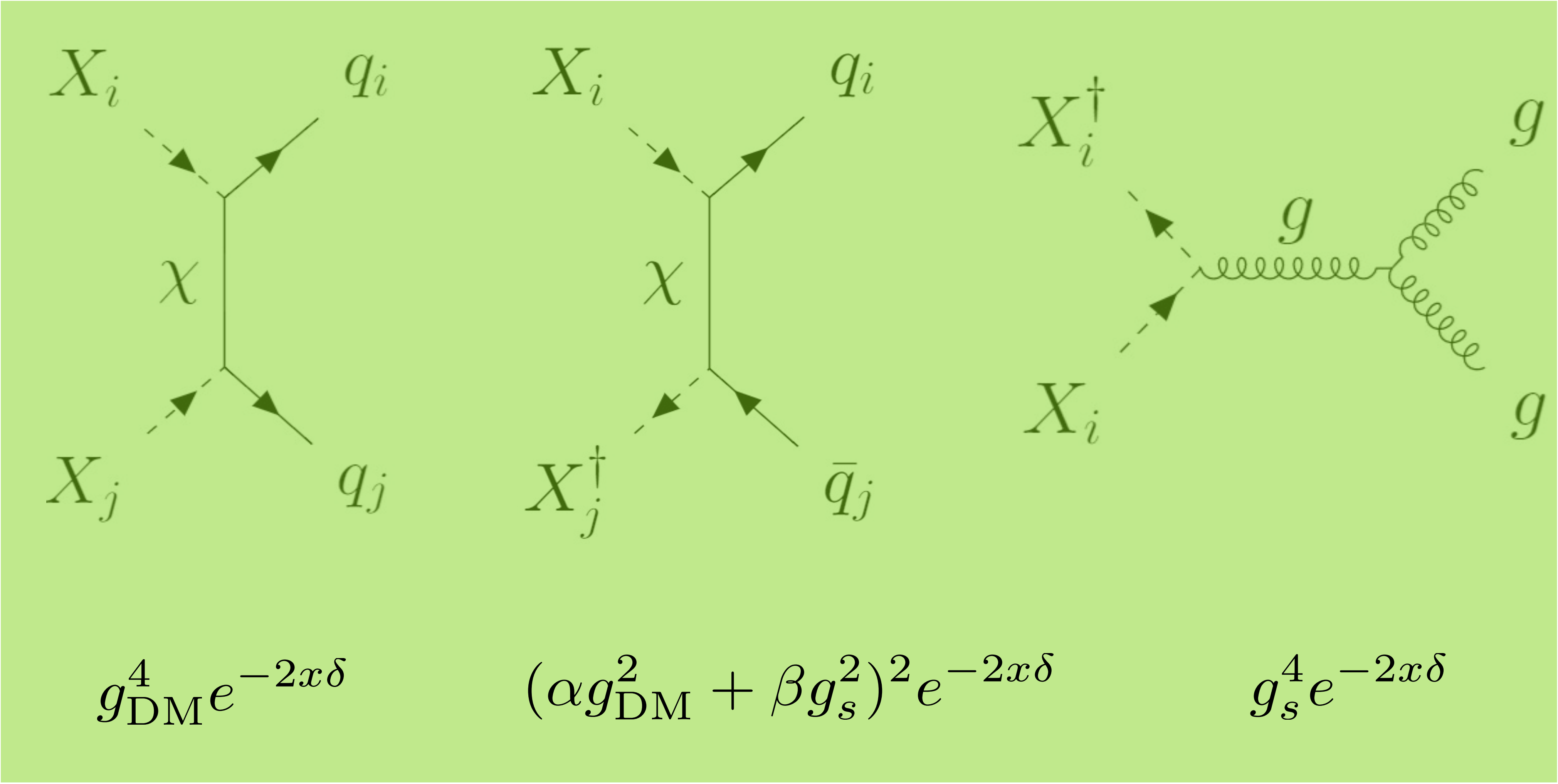

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Coannihilating channels in Boltzmann equations

Large mass gap,
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Small mass gap, additional coannihilation channels become relevant

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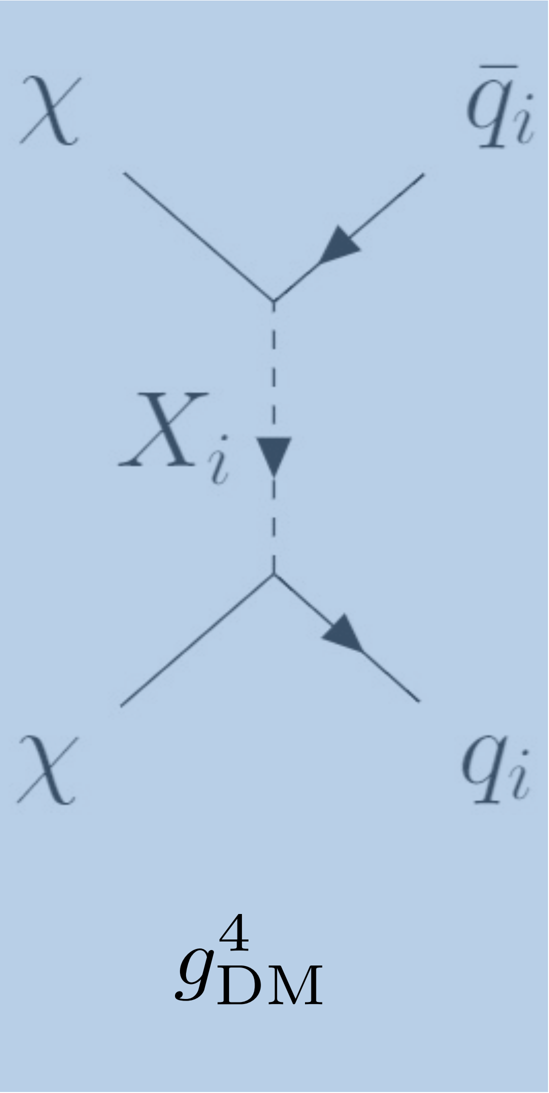

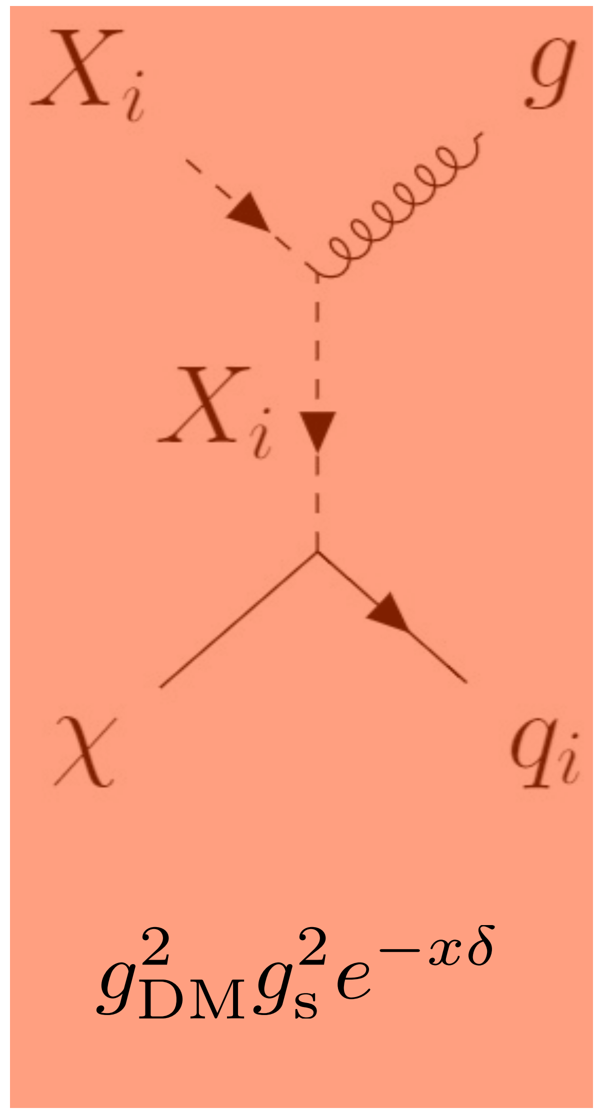

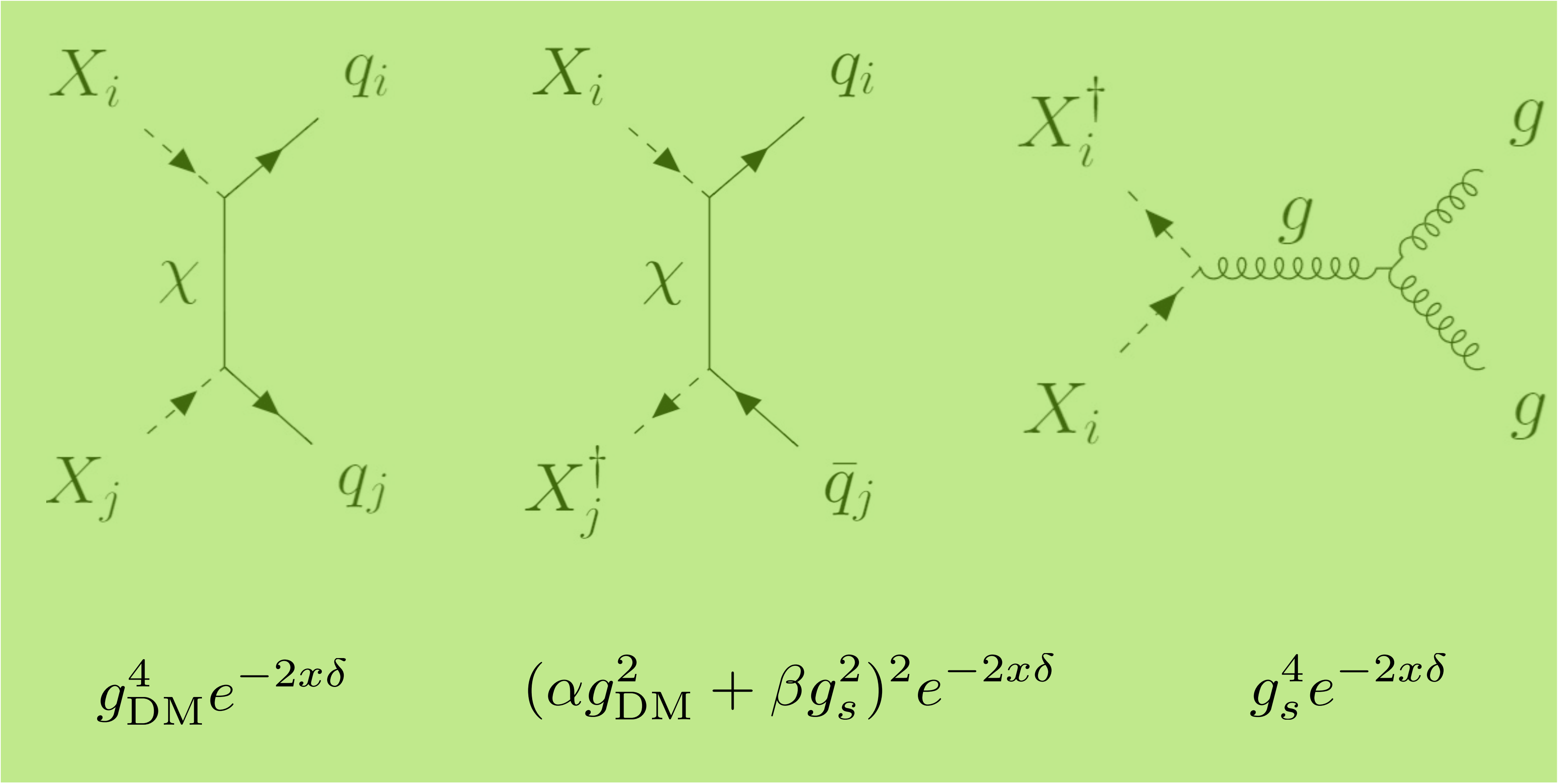

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Coannihilating channels in Boltzmann equations

Large mass gap, only relevant process

Small mass gap, additional coannihilation channels become relevant

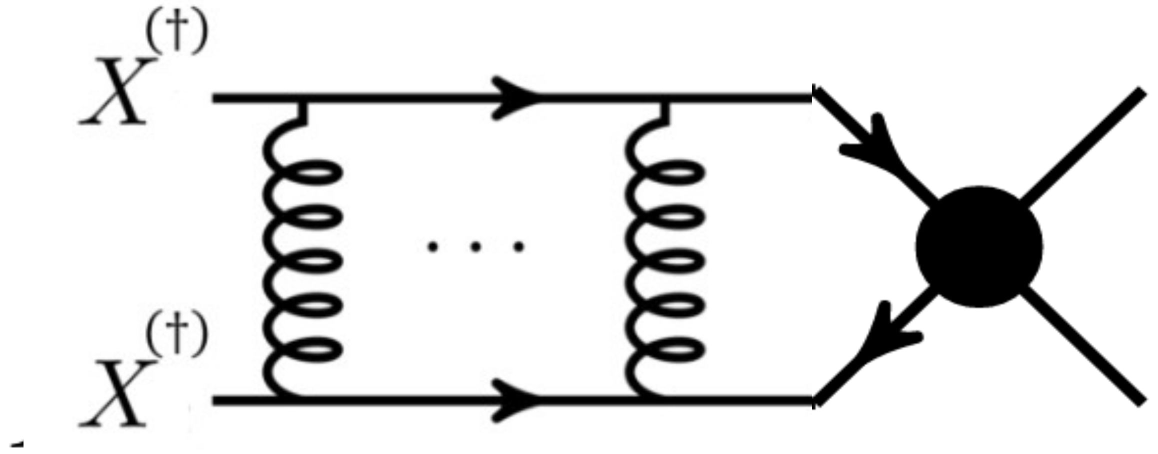
Assumptions:

- Coannihilating particle will later decay into DM $n = \sum_{i=1}^{N} n_i$
- Coannihilating particle in thermal equilibrium with DM particle $\Gamma(X + SM \longleftrightarrow \chi + SM) >> H$

Two further novel effects can affect the velocity averaged cross section

Sommerfeld Enhancement and Bound State Formation in relic abundance

Sommerfeld Enhancement



$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$

$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \mathbf{6}$

- Relevant for $\alpha \sim v_{\rm rel}$
- Exchange of n gluons lead to $\left(\frac{\alpha}{v_{\rm rel}}\right)^n \sim 1$, which requires resummation

Non-relativistic enhancement of cross section due to an attractive potential

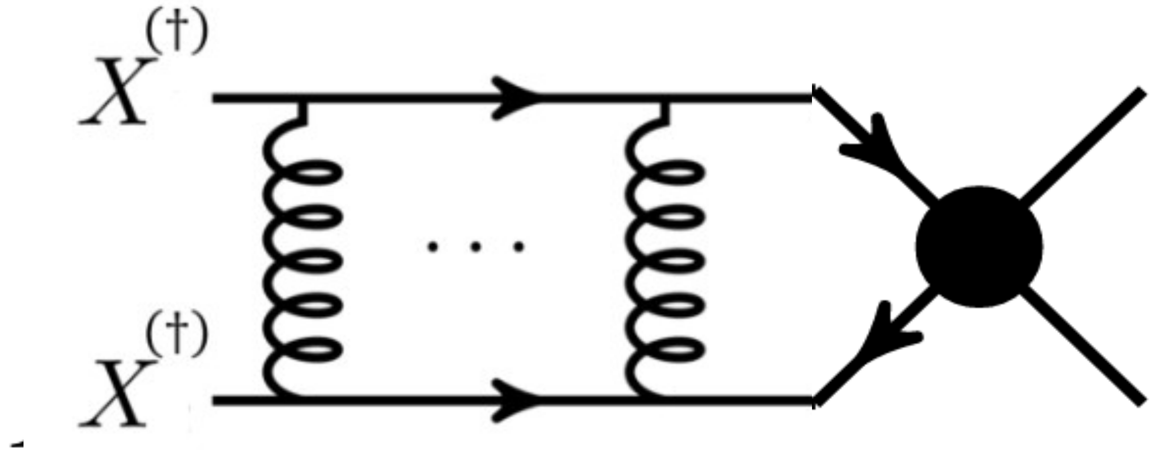
$$V(r)_{\mathbf{3}\otimes\bar{\mathbf{3}}} = \begin{cases} -\frac{4}{3}\frac{\alpha_s^S}{r} & [\mathbf{1}] \quad \textbf{attractive} \\ +\frac{1}{6}\frac{\alpha_s^S}{r} & [\mathbf{8}] \quad \textbf{repulsive} \end{cases}$$

$$\sigma_{\rm SE} = S_0\left(\frac{\alpha_s^S C_{[\hat{\mathbf{R}}]}}{v_{\rm rel}}\right)\sigma_0$$

Enhancement for attractive potential

Sommerfeld Enhancement and Bound State Formation in relic abundance

Sommerfeld Enhancement



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Bound State Formation

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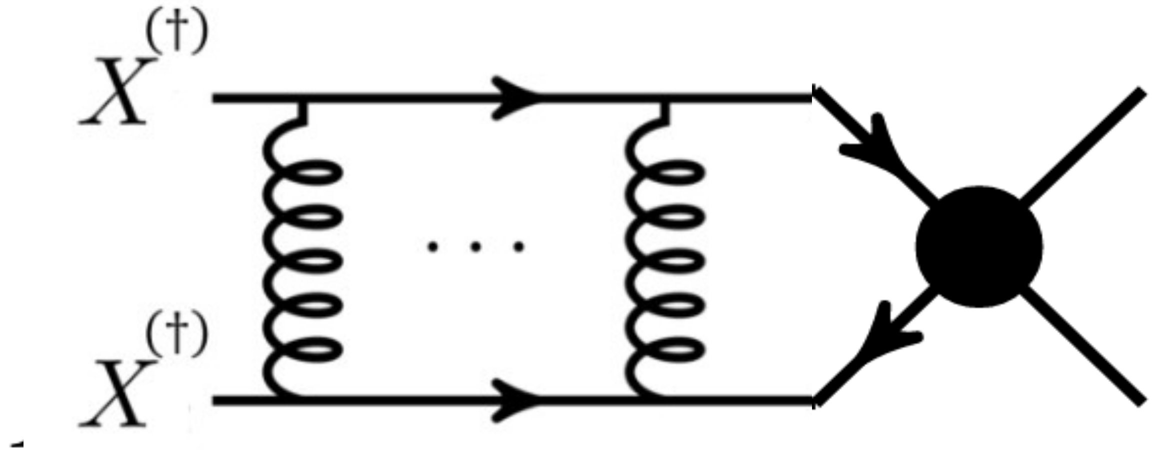

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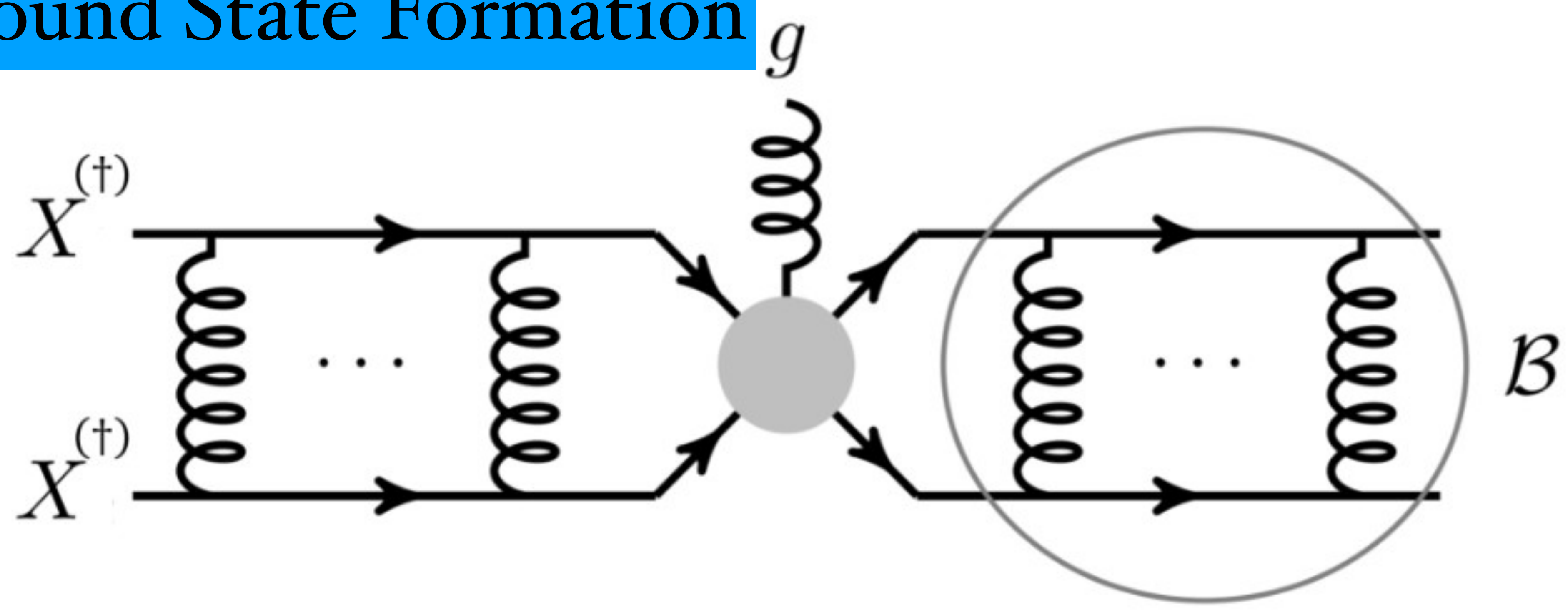
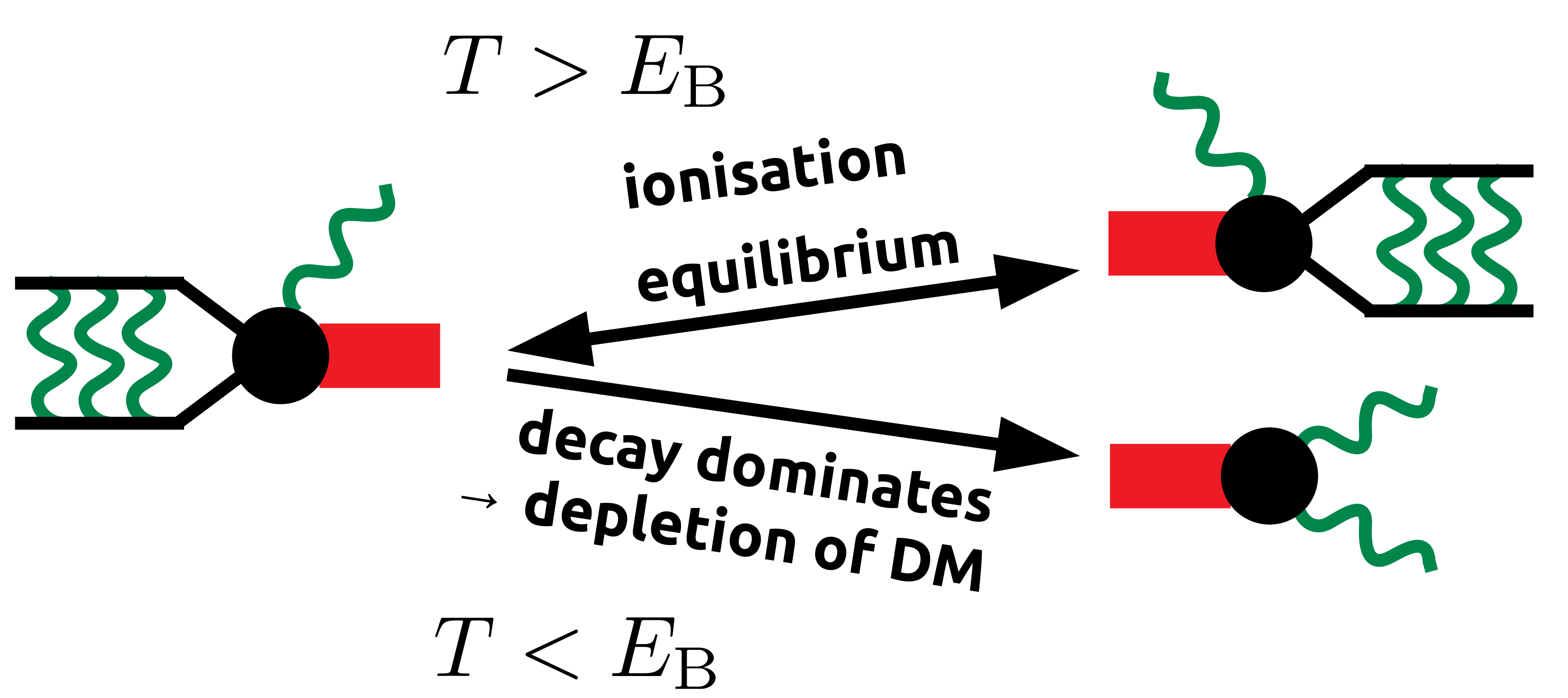




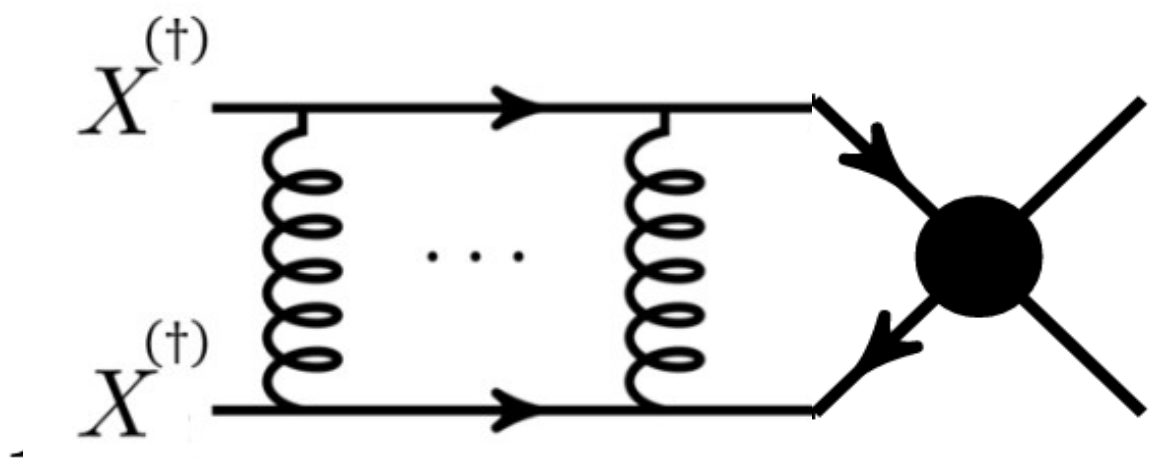
bound state formation

bound state ionisation

bound state decay

Sommerfeld Enhancement and Bound State Formation in relic abundance

Sommerfeld Enhancement



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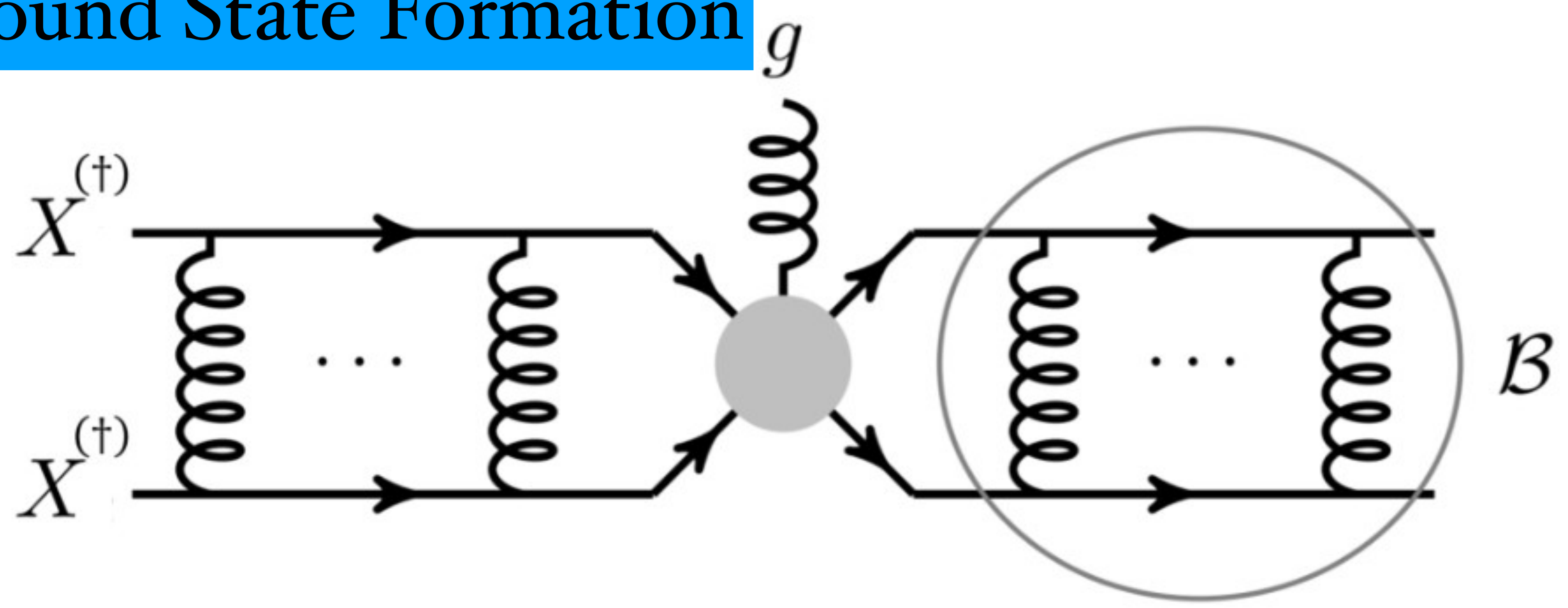

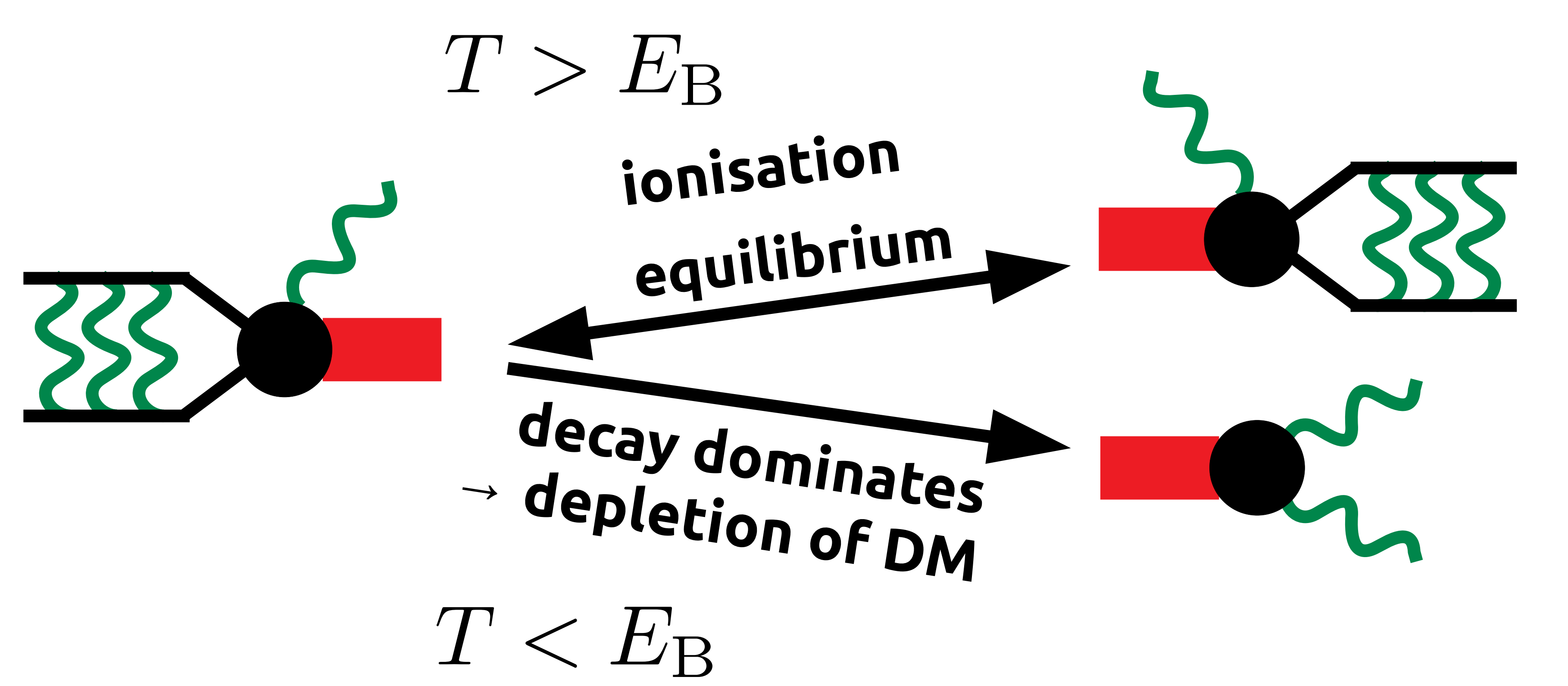

bound state formation

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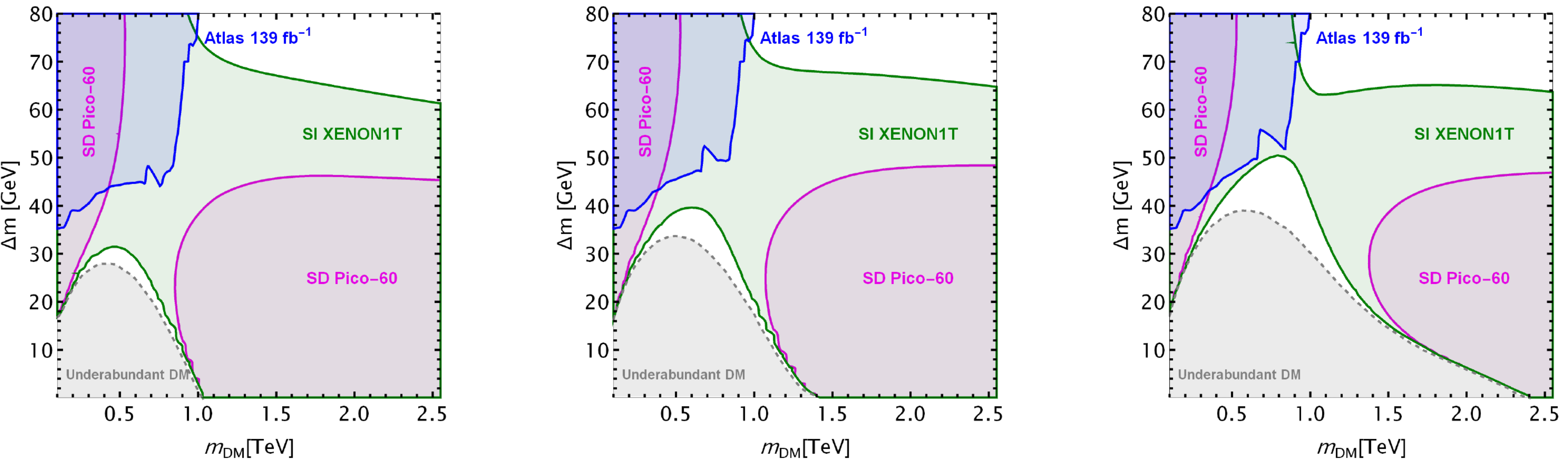
M. Becker, E. Copello, J. Harz K. Mohan, **DS**. JHEP08(2022) 145 Also see J. Harz, K. Petraki JHEP2018, Klasen, Harz, Wiggering,Sassi PRD2023

Impact of Sommerfeld Enhancement and bound states

perturbative only **+ Sommerfeld effect** **+ bound states**



- DD and LHC searches set upper bound on g_{DM}
- Requirement of non-overproduction sets lower bound on g_{DM}

1. The model tightly constrained by Direct Detection,
2. Model parameters then relaxed by SE + BSF.

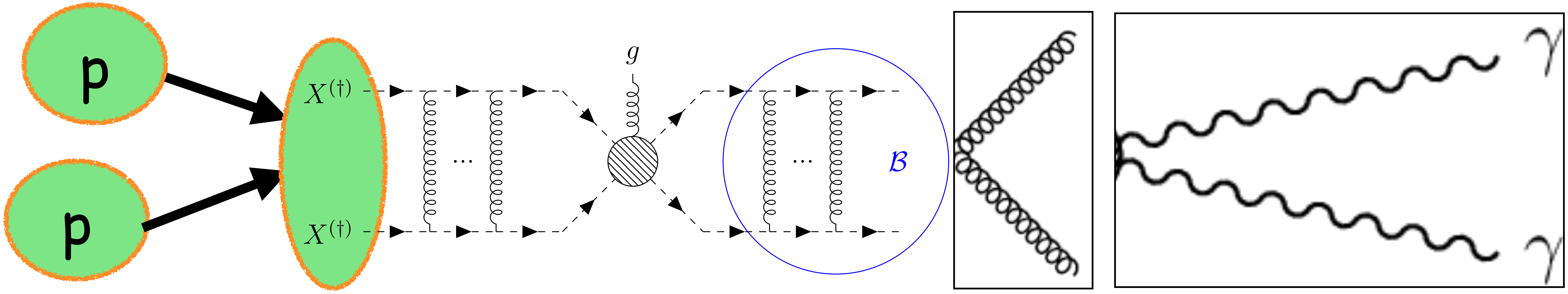
→ **Correction on g_{DM} due to SE and BSF lead to altered exclusion limits**

→ **opens up parameter space that was previously thought to be excluded**

The package is now implemented in MicrOmegas Dark Matter Tool

M. Becker, E. Copello, J. Harz K. Mohan, DS. JHEP08(2022) 145

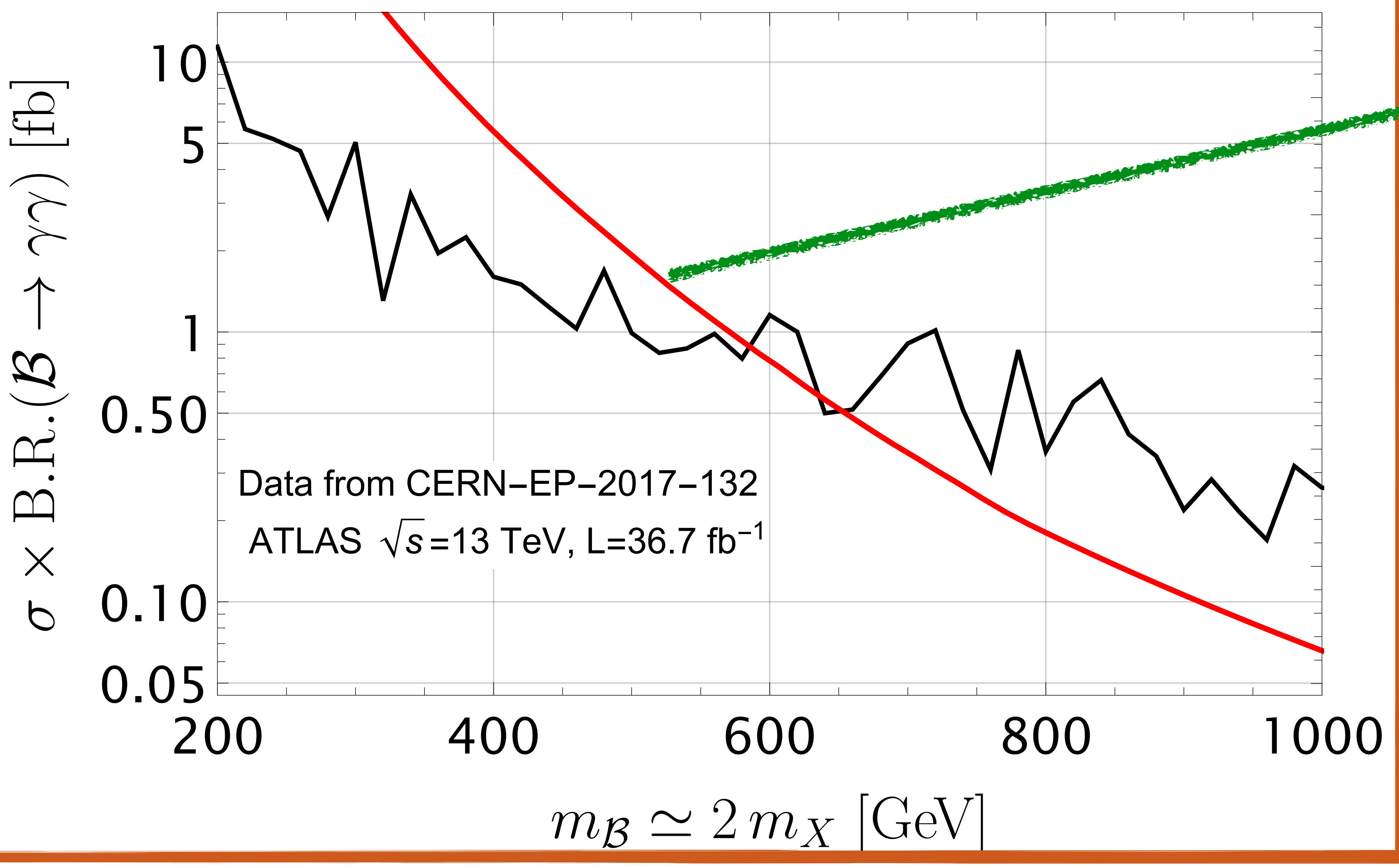
t- channel Simplified Models : Bound State Production/decay at LHC



$$\sigma\left(pp \to \mathcal{B}(XX^\dagger)\right) = \frac{\pi^2}{8m_{\mathcal{B}}^3}\Gamma\left(\mathcal{B}(XX^\dagger)\right)$$

$$\Gamma(\eta_{\tilde{t}} \to gg) \simeq \frac{4}{3}\alpha_s^2\frac{|R(0)|^2}{m_{\eta_{\tilde{t}}}^2}$$

$$\Gamma(\eta_{\tilde{t}} \to \gamma\gamma) = \frac{32}{27}\alpha^2|R(0)|^2/m_{\eta_{\tilde{t}}}^2$$



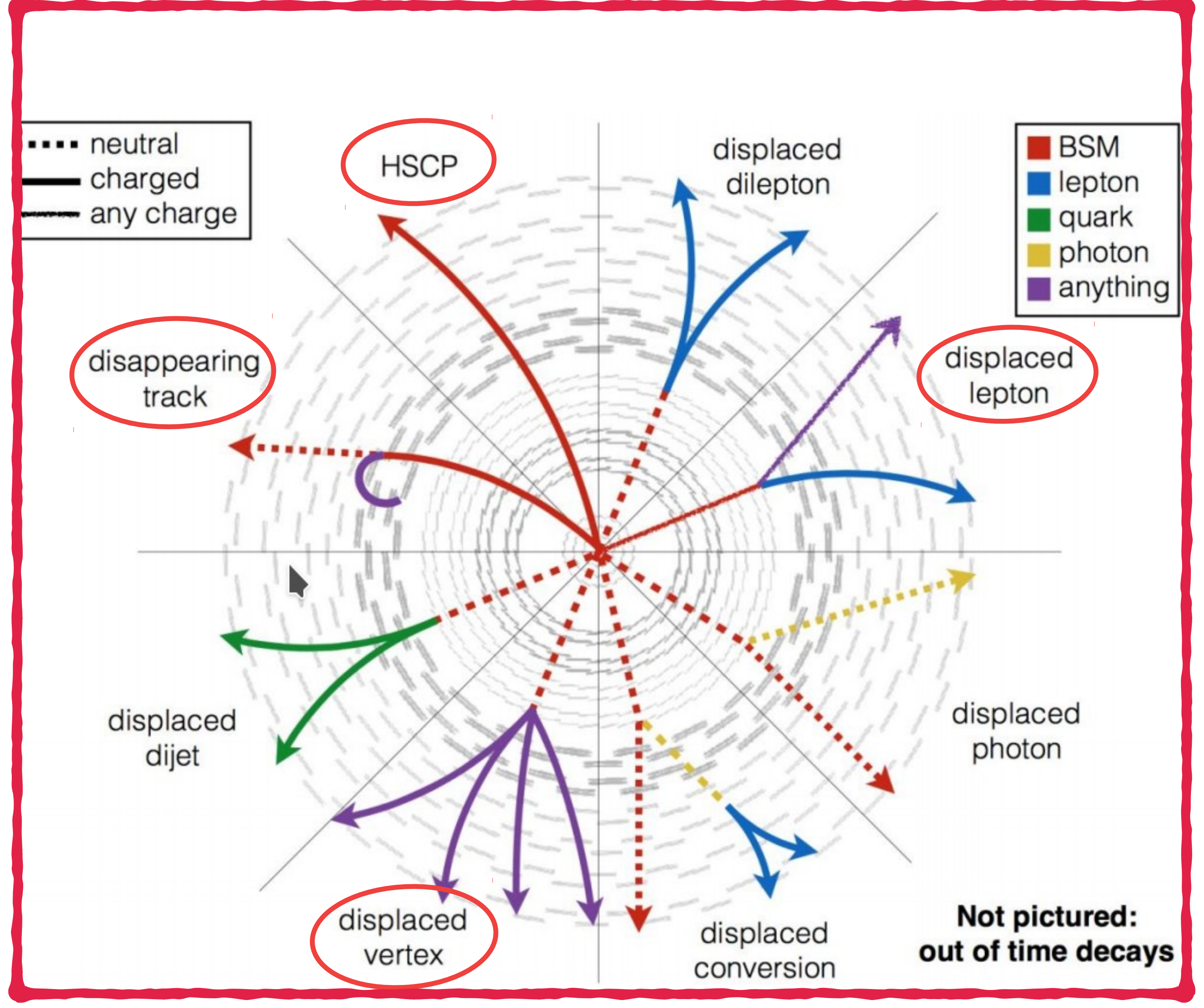
Theoretical Prediction for the uR model

For large stoponium masses,
could lead to emerging/displaced photons

$$100 \text{ GeV} \lesssim m_X \lesssim 290 \text{ GeV}$$

t- channel Simplified Models : HSCP searches

- **Heavy**: Implies slow particles, β < 1.0
- **Stable**: Lives long enough so it can reach tracker and/or muon detectors or even get past them.
- **Charged**: Can be detected by the muon detectors.



★ The massive colored mediator X travels the detector producing an ionizing track

★ If it decays outside the detector, time of flight measured using hits in muon chamber is large.

dE/dx: Ionization energy lost.

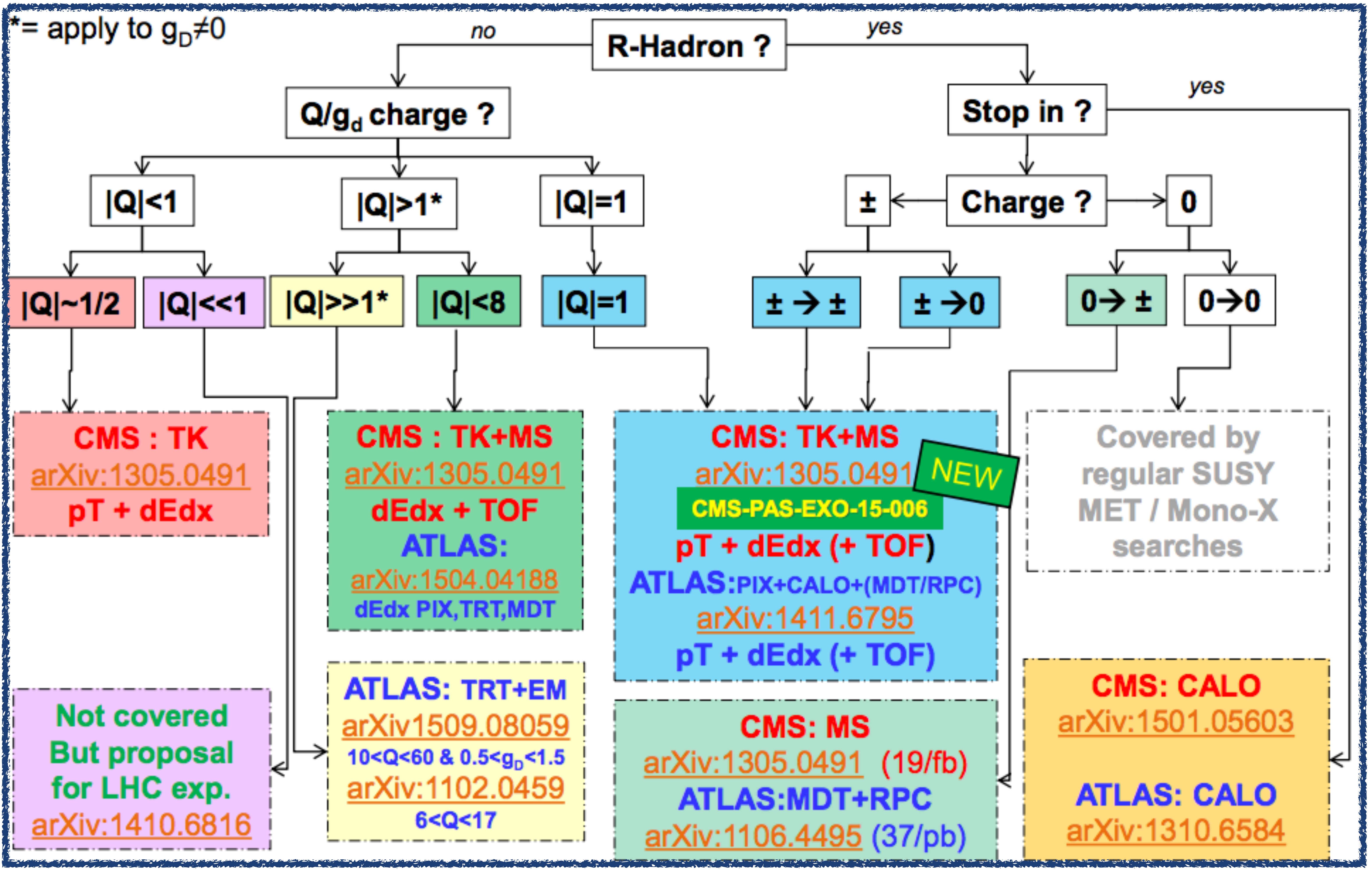
$$\frac{dE}{dx} \approx Q^2 \left[\frac{A}{\beta^2} + B\right] \text{ for } \beta << 1$$

TOF: Time of flight

$$\frac{1}{\beta} = 1 + \frac{c\delta_t}{L}$$

Fraction of charged hadrons depend on hadronization model: typically use a cloud hadronization model. (Mackperang, Rizza: hep-ph/0612161, Kraan, hep-ex/0404001

t- channel Simplified Models : HSCP searches



Searches for Heavy Stable Charged Particles at the LHC Past, Present and Future, Loïc Quertenmont. 12 February 2015

Typicaly Tracker+TOF analysis is more constraining, requires HSCP decays outside the detector

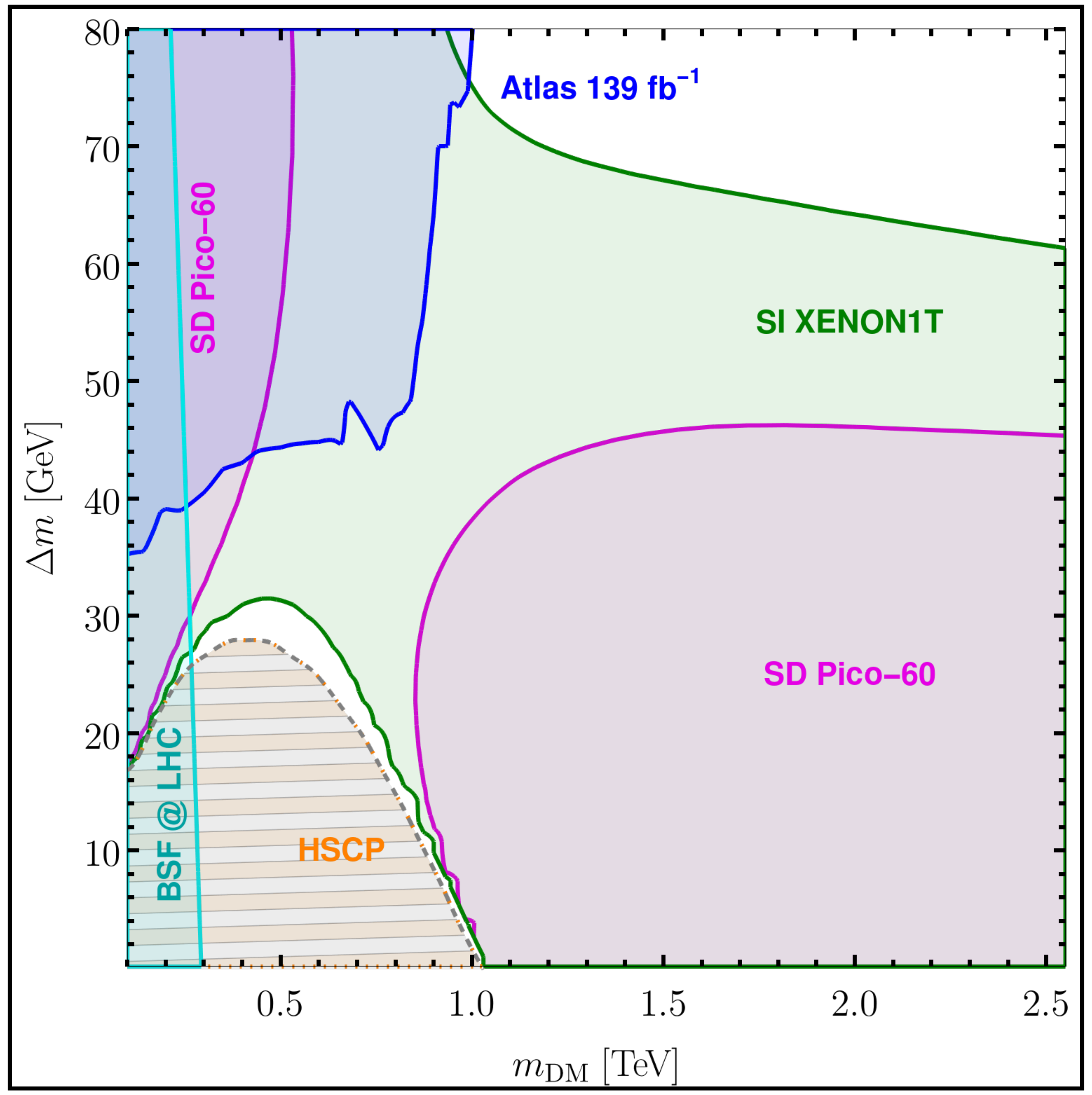
$$\sigma_{\rm eff} = \sigma \times f_{\rm LLP}(L, \tau)$$

Fraction of LLPs that decay inside the detector (tracker only) or outiside The detector (tracker +TOF) :
Computed using trigger and selection efficiencies (CMS: EPJC 75 (325))

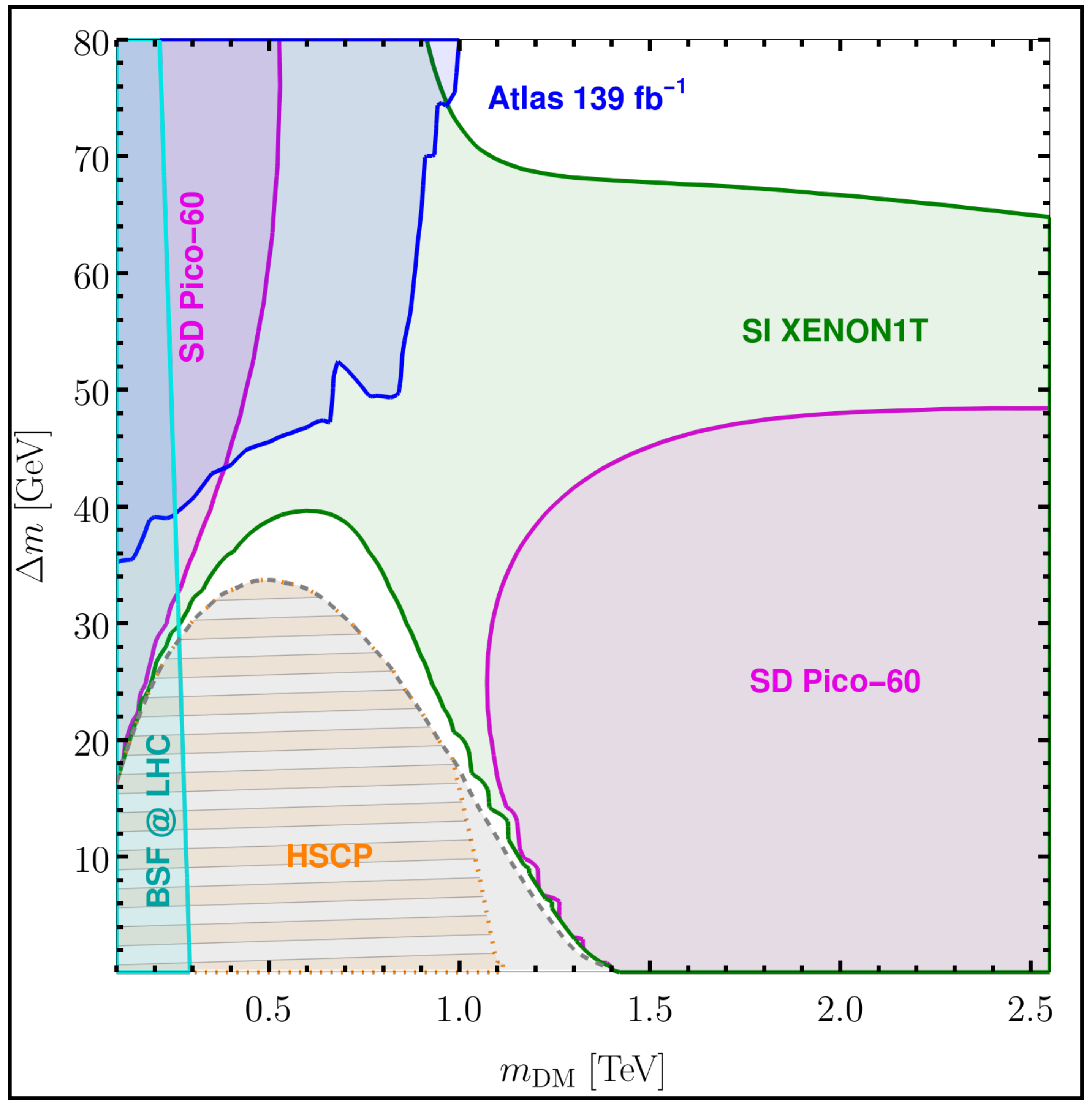
Use two CMS analysis for reinterpretation using cross-section upper limits

1. CMS : Search for LLP in pp collisions : JHEP 07 (2013) 122
2. CMS : Search for heavy stable charged particles CMS-PAS-EXO-16-036

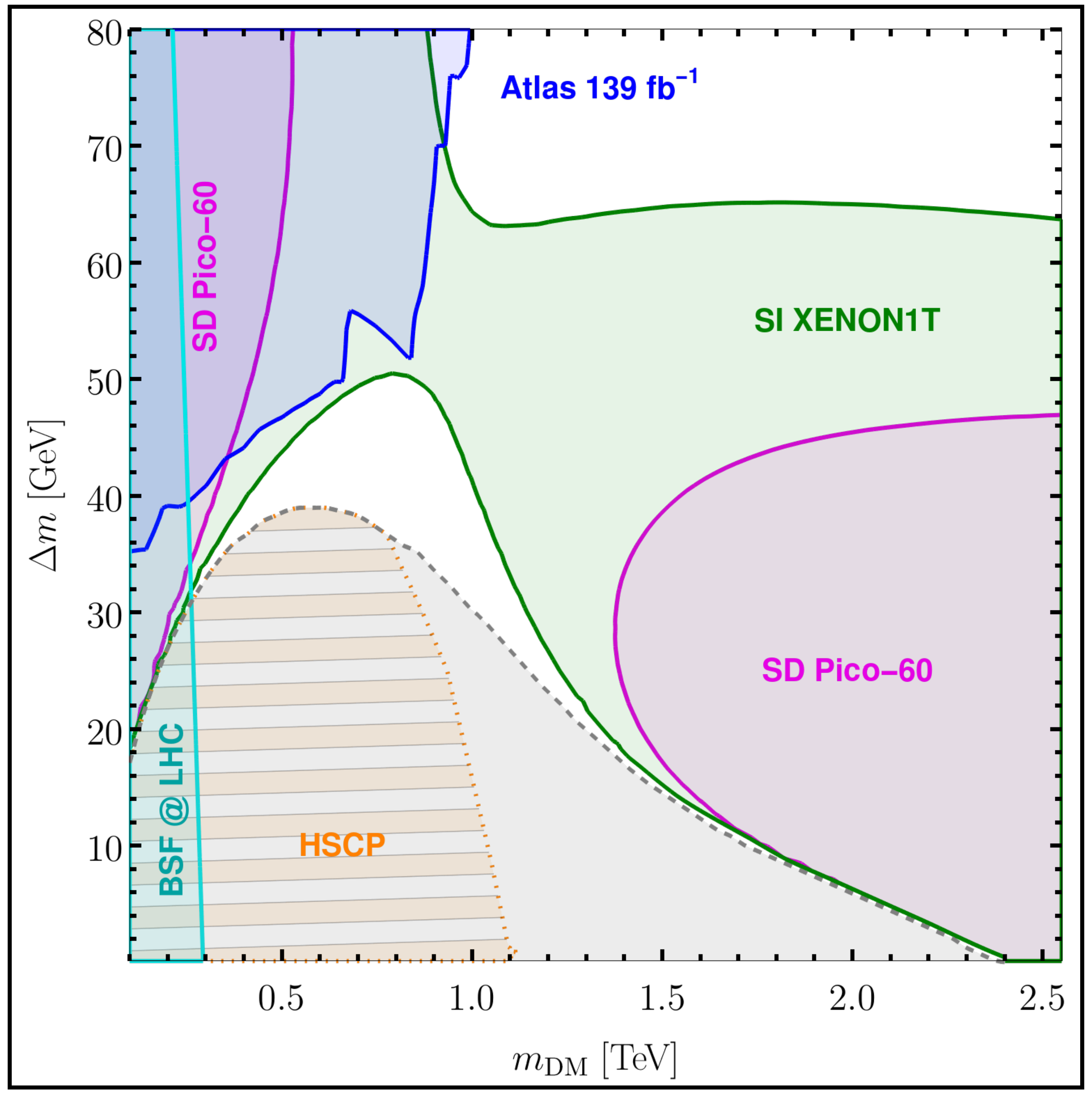
t- channel Simplified Models : Combined limits



Perturbative Annihilations

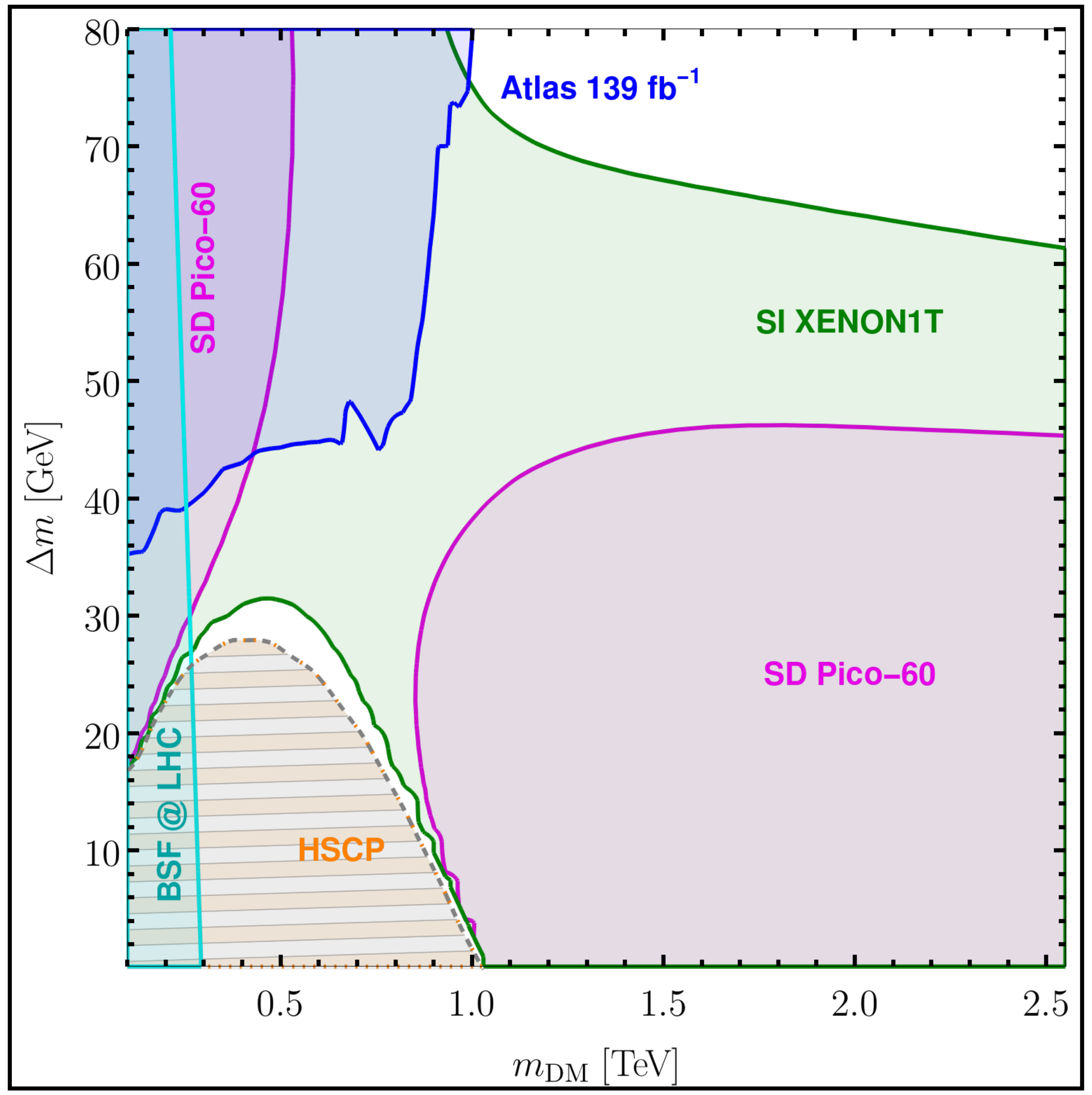


Sommerfeld



Sommerfeld+BSF

t- channel Simplified Models : Combined limits



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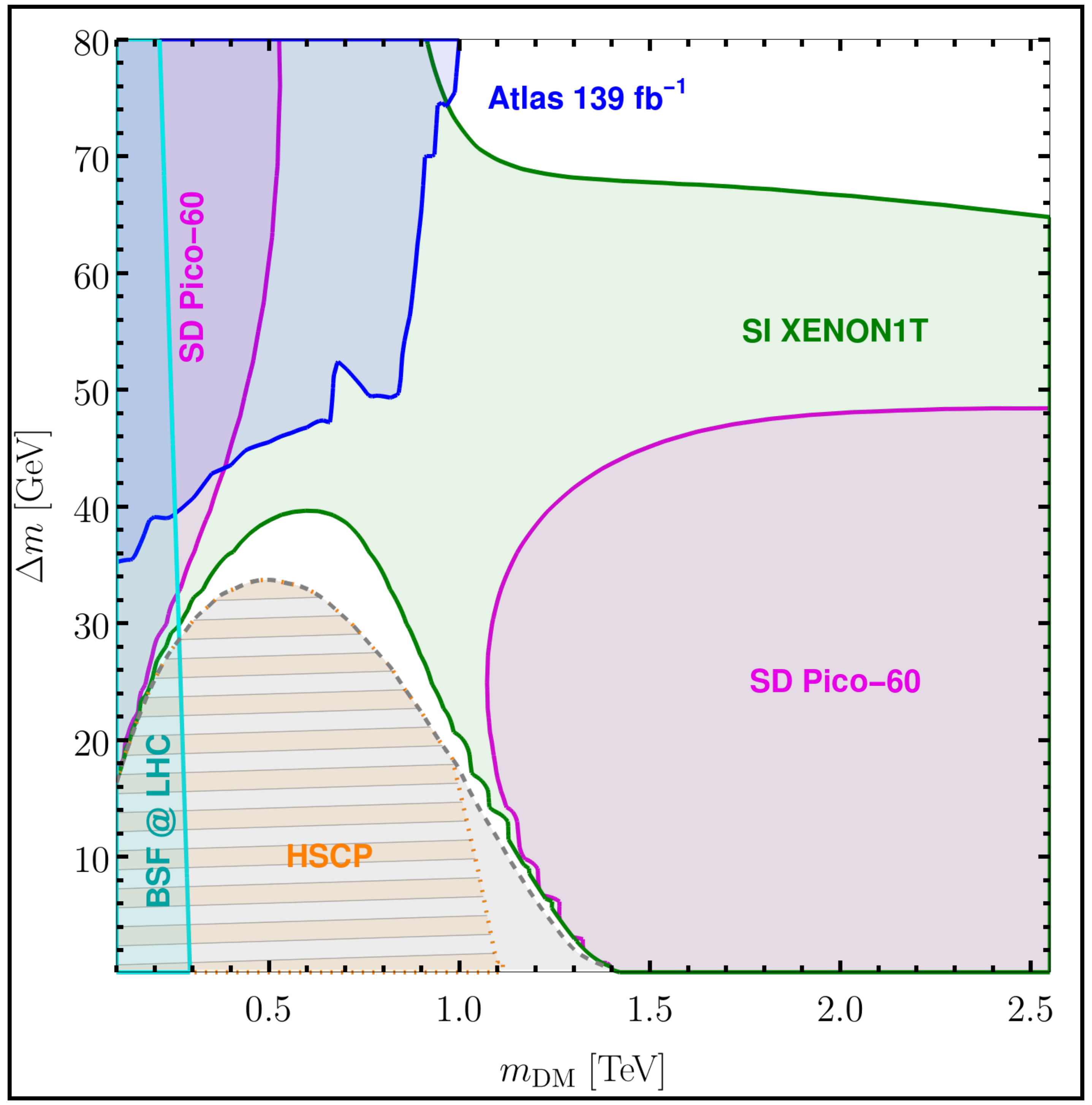

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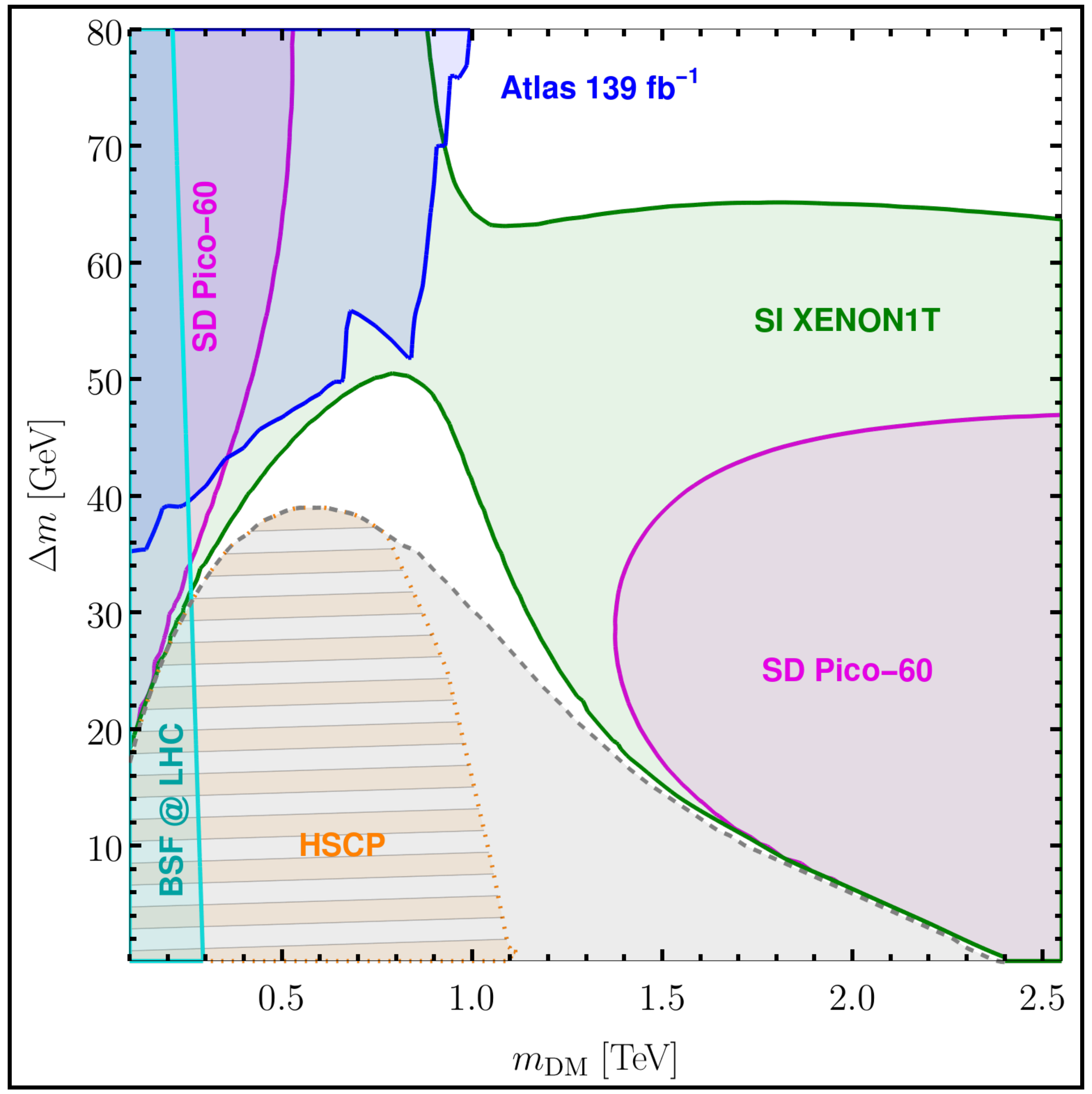

Sommerfeld+BSF

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t- channel Simplified Models : Future projection

Perturbative Annihilations

Sommerfeld

Sommerfeld+BSF

t- channel Simplified Models : Future projection

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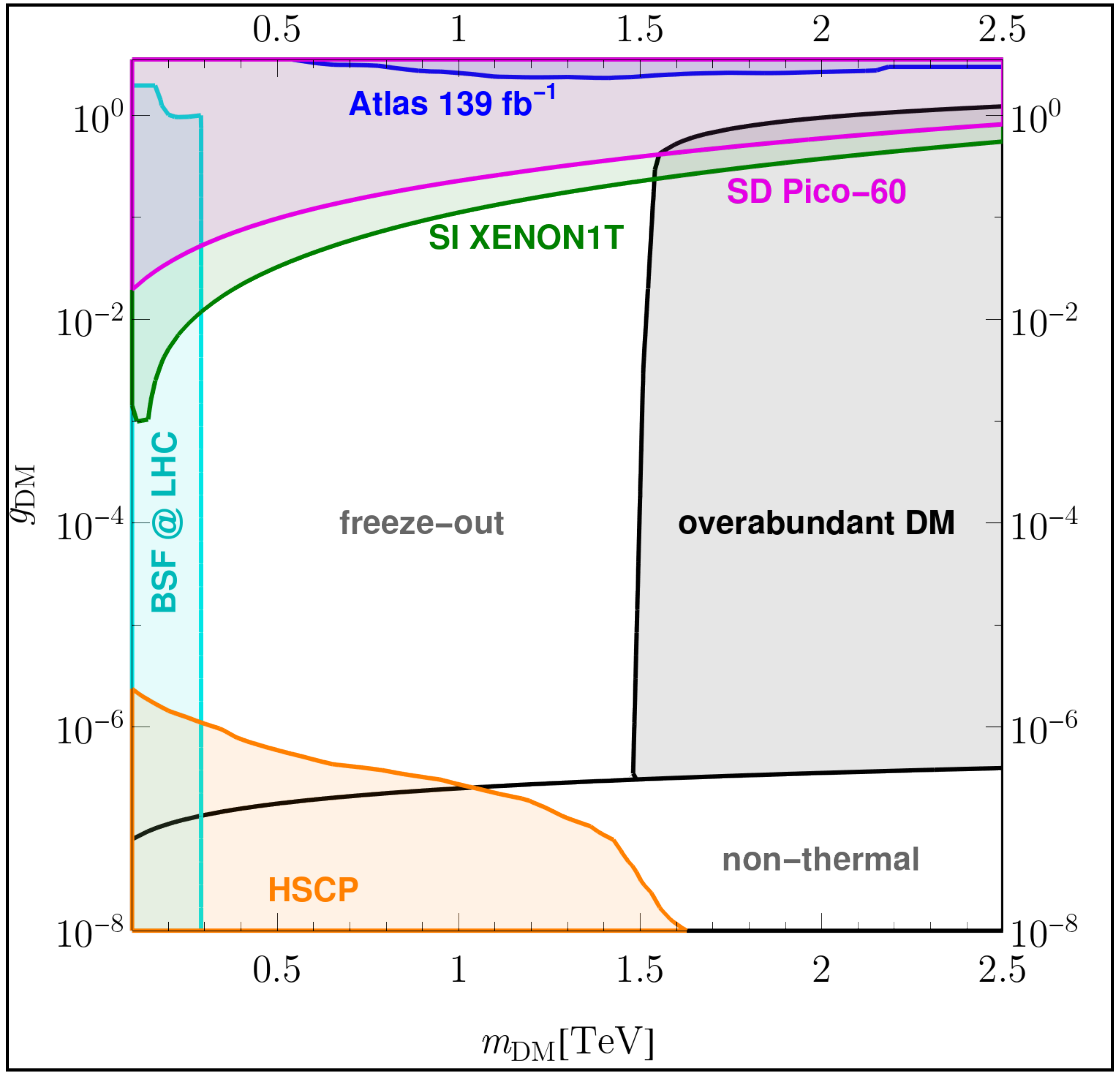
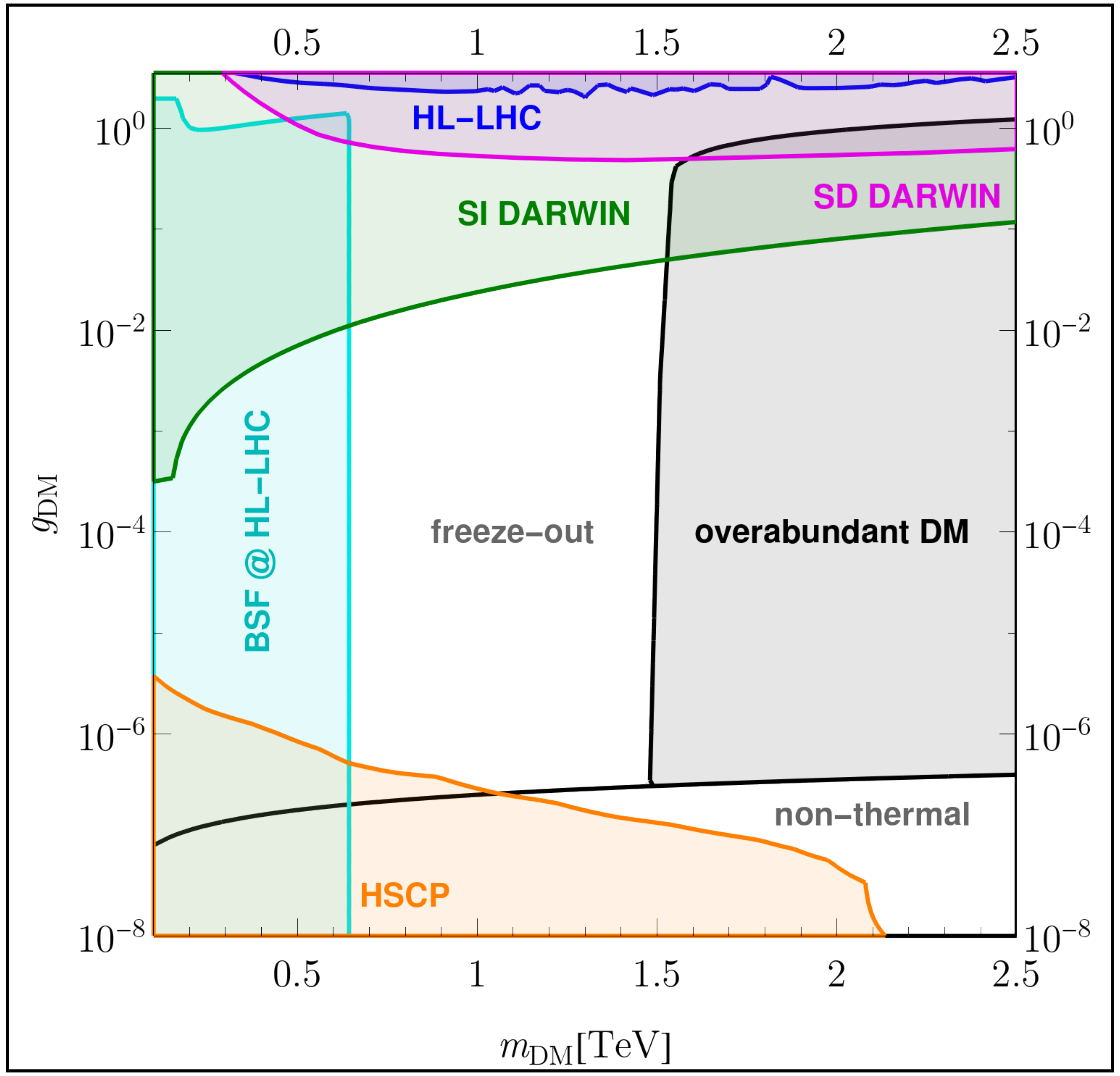
Sommerfeld+BSF

. Becker, E. Copello, J. Harz K. Mohan, DS. JHEP08(2022) 145

t- channel Simplified Models : Current and future projections





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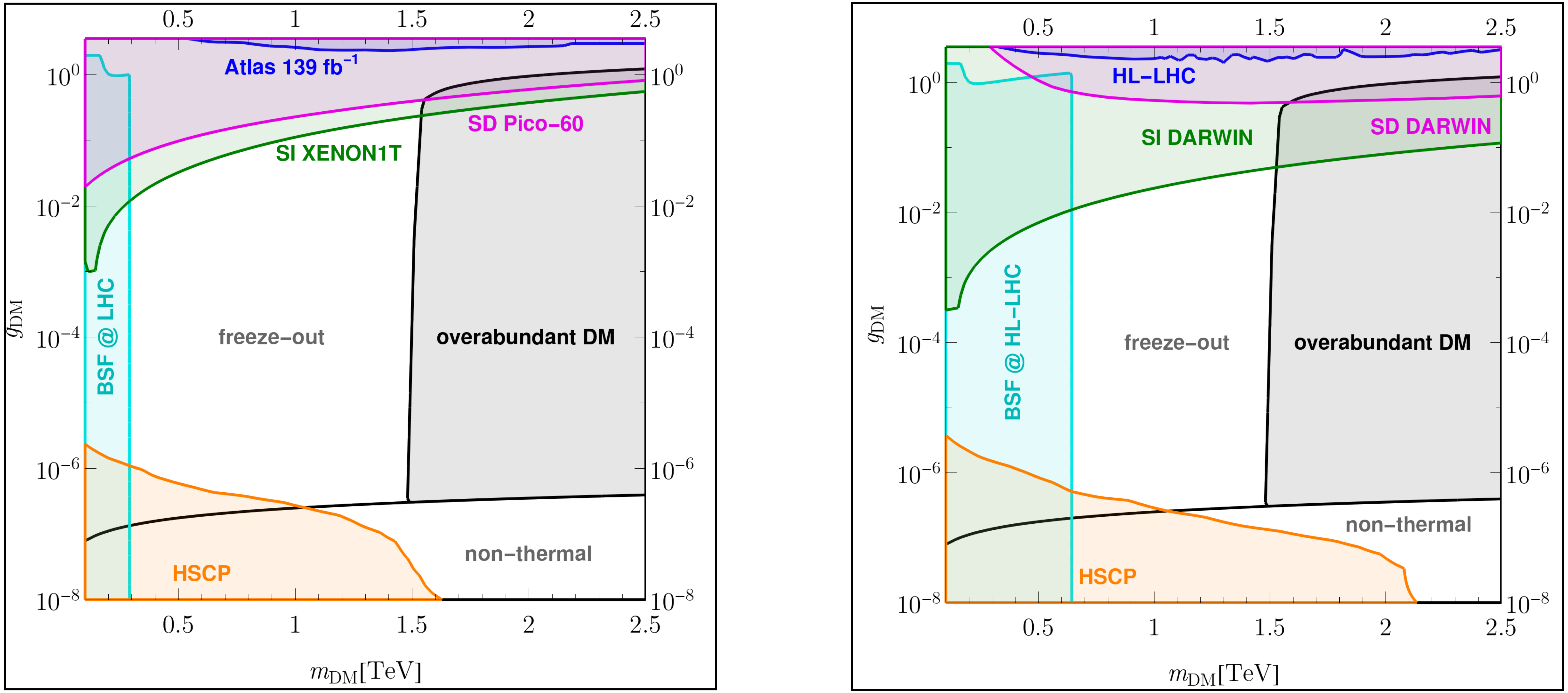


M. Becker, E. Copello, J. Harz K. Mohan, DS. JHEP08(2022) 145

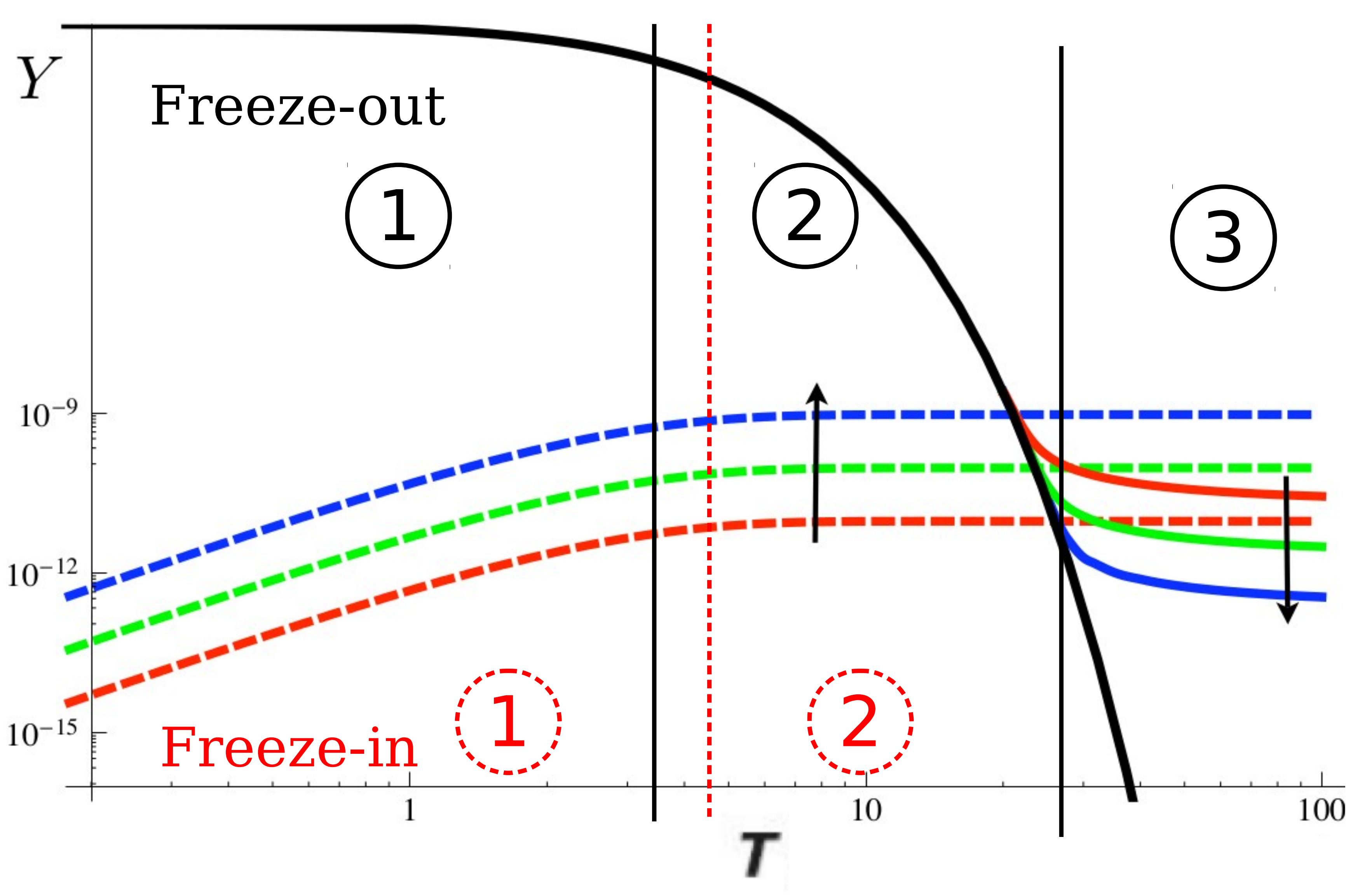
Alternative Mechanisms of Dark Matter Production

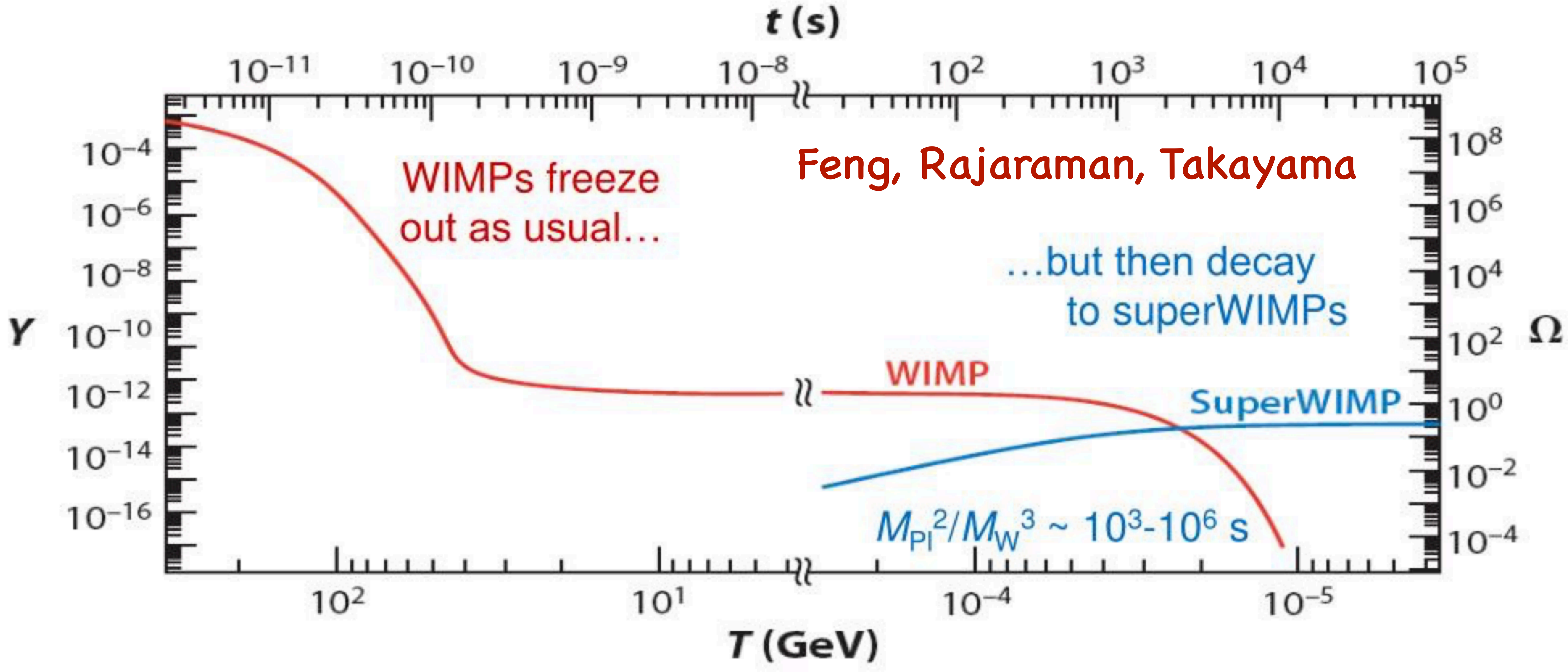
(Non-) Thermal mechanisms

Freeze-In

Super WIMPS

Tweaked from arXiv:0911.1120





Both set ups characterised by extremely weakly interacting particles

Cosmological Probes of SuperWIMP Dark Matter

What if Neutralinos are not the Lightest SUSY particle, but next to lightest?

- In Supergravity inspired Supersymmetry scenarios, the gravitino can be the lightest particle, and very very weakly coupled to the neutralino, leading to a long lived neutralino (decaying to a gravitino + a Photon).
- The neutralino (a WIMP) can Freeze-out, and long afterwards decay to gravitino (**SuperWIMP**).
- Being extremely long lived it will escape the detector without a trace (No prompt searches).
- However it will leave definite signatures in Cosmology due to energy dump as photon.

The gravitino mass is a free parameter related to the SUSY breaking scale F   Feng, Rajaraman, Takayama hep-ph/0306204

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$$m_{\tilde{G}} \simeq \langle F \rangle / m_{\rm pl}$$

Extremely long lived

$$L = c\tau \simeq 2.8 \times 10^{22} \left(\frac{\rm GeV}{m_{\chi_1^0}}\right)^3 \frac{(1-2\epsilon_{SM})}{\epsilon_{SM}^3(1+3(1-2\epsilon_{SM}))} m$$

$$\epsilon_{\rm SM} \equiv \frac{E_\gamma}{m_{\chi_1^0}} = \frac{m_{\chi_1^0}^2 - m_{\tilde{G}}^2}{2m_{\chi_1^0}^2}$$

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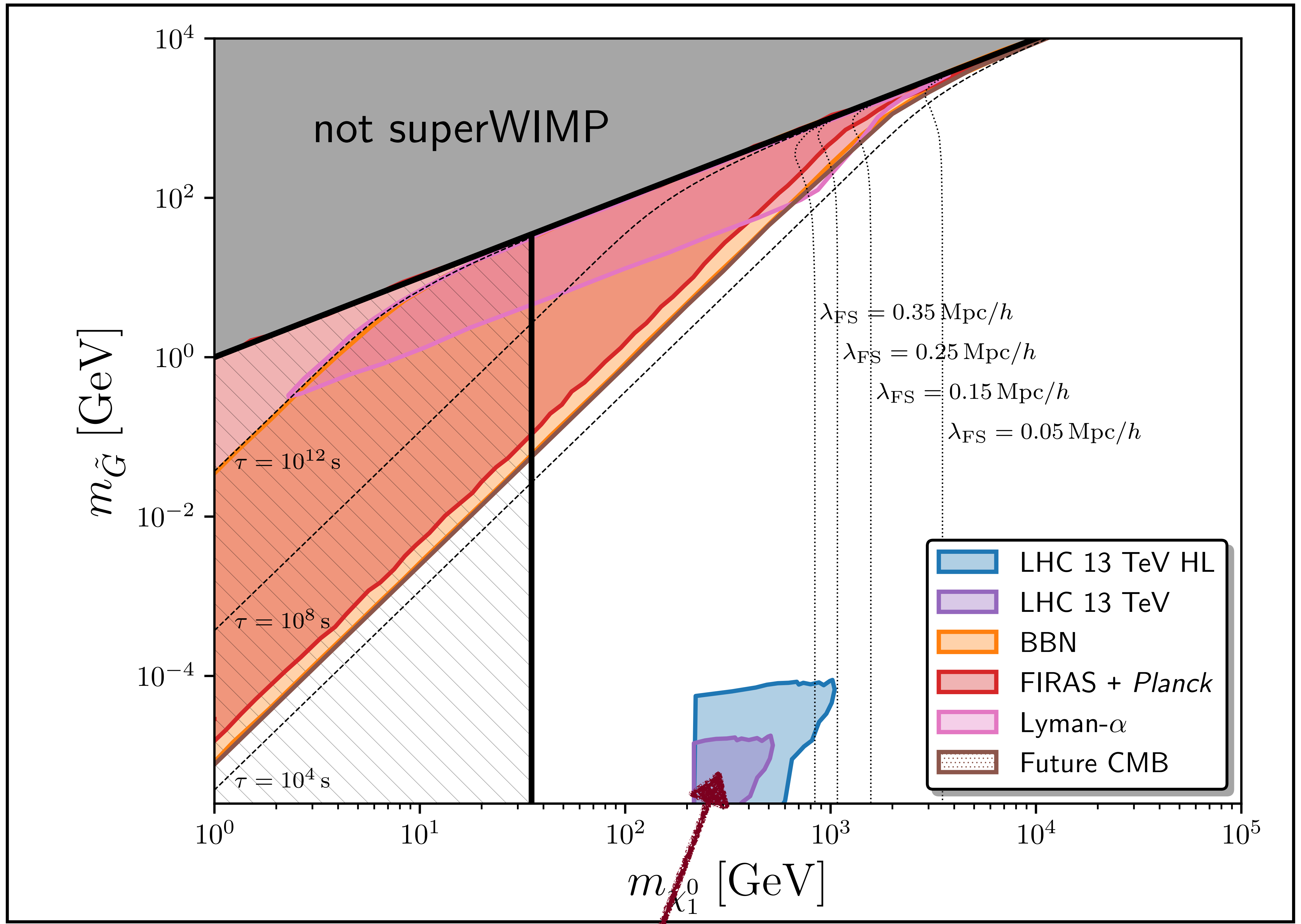
1. **Big Bang Nucleosynthesis**: Injected photons/energy can photodissociate nuclei and change primordial element abundances

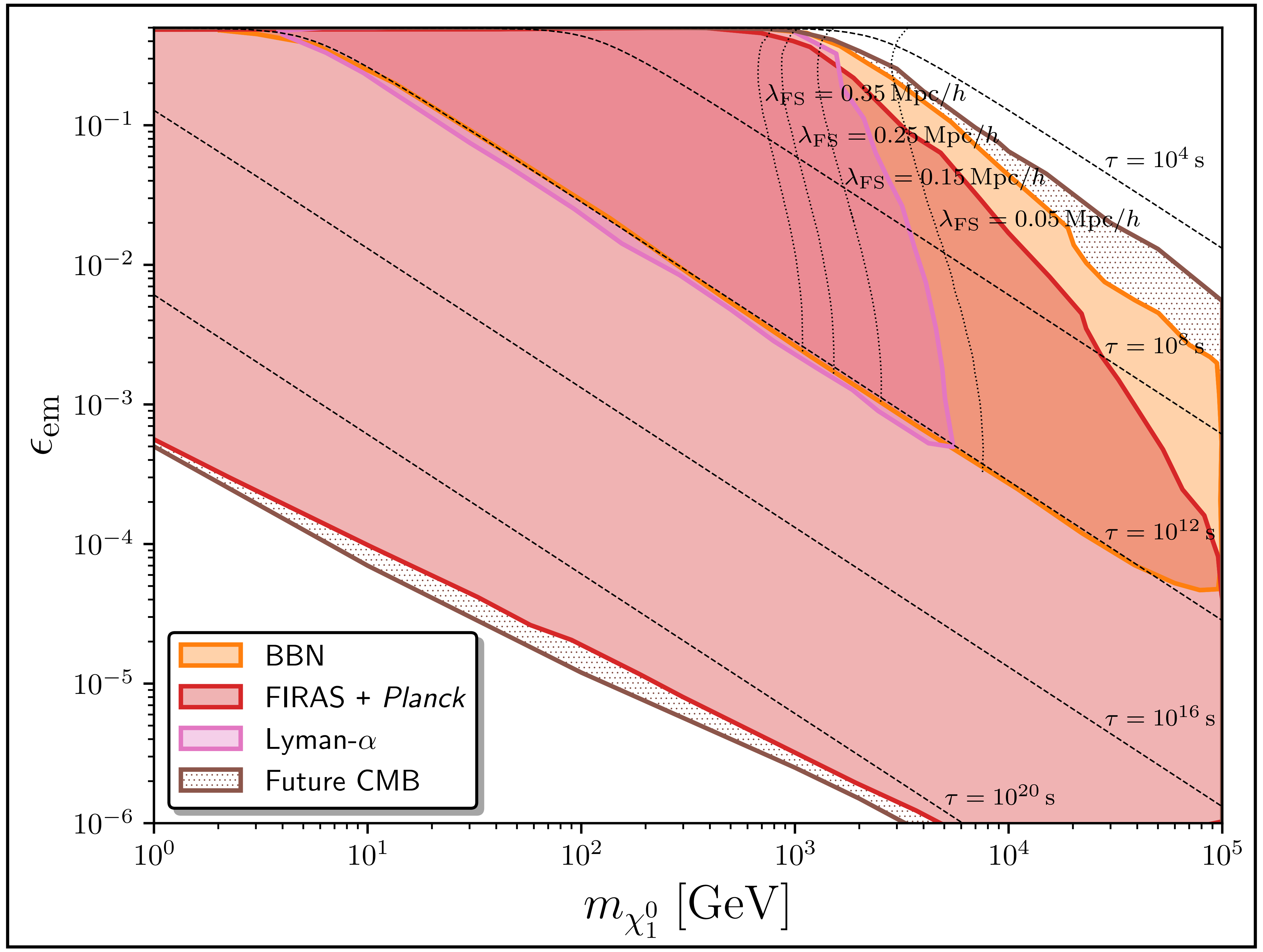
2. **CMB Spectral Distortion**: If the lifetime is about 10^6-10^{13} s can distort the CMB blackbody energy spectrum

3. **CMB Anisotropies**: Temperature and polarization anistotropies due to changes in accoustic peaks of CMB angular spectra

4. **Constraints from Lyman-alpha forest**: A relativistic component of the SuperWIMP leads to a non-zero velocity dispersion, hence a large free streaming scale and suppression of small scale fluctuations

t- channel Simplified Models : Constraints on gravitino Superwimps





LLP searches reinterpreted from displaced photon searches

1. ATLAS: PRD90 11(2014) 11205
2. CMS: Phys. Rev. D 100, 112003 (2019)

M. Deshpande, J. Hamman, DS, M. White, A.G Williams, YY Wong 2309.05709 , EPJC XXX

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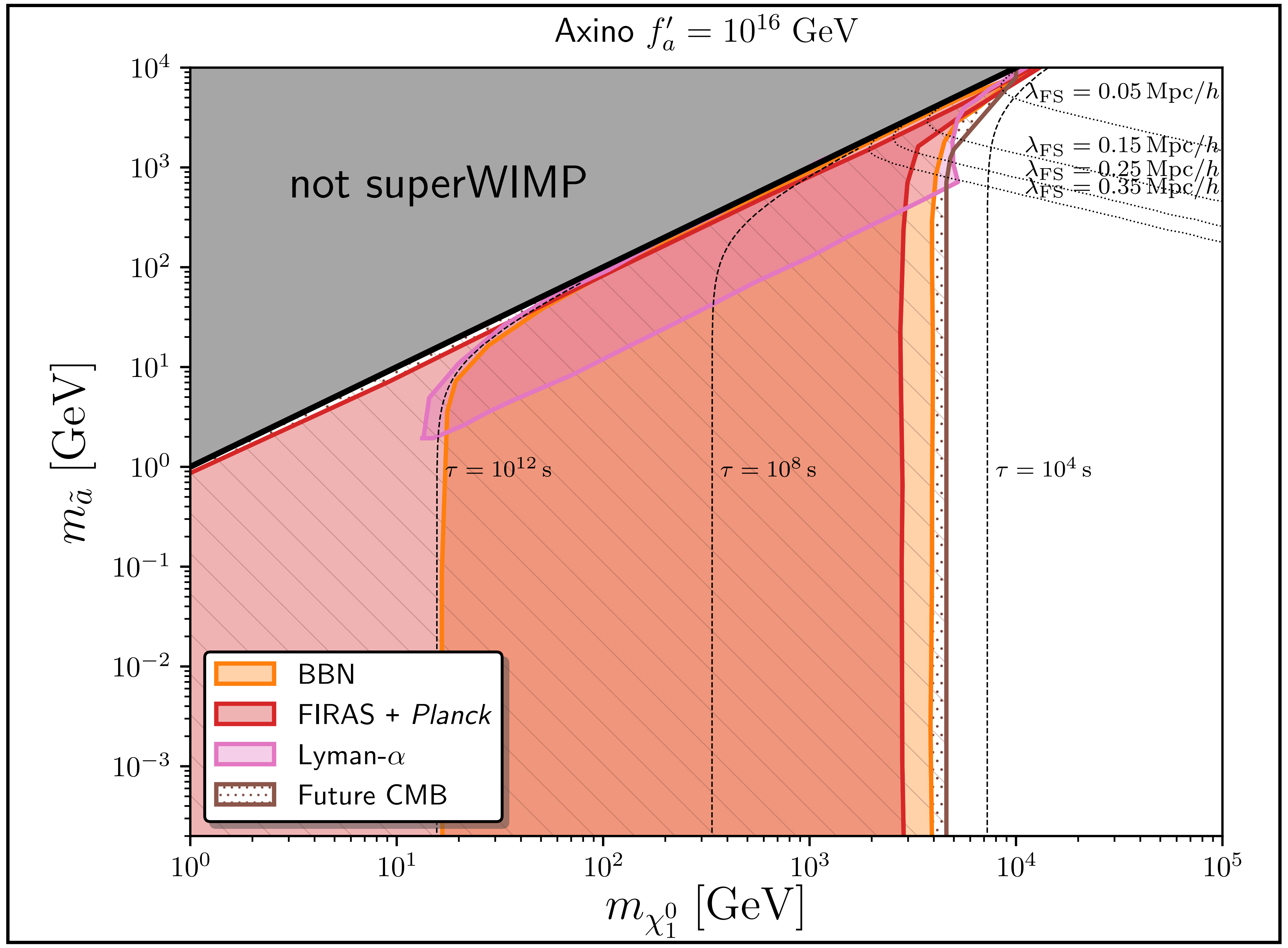

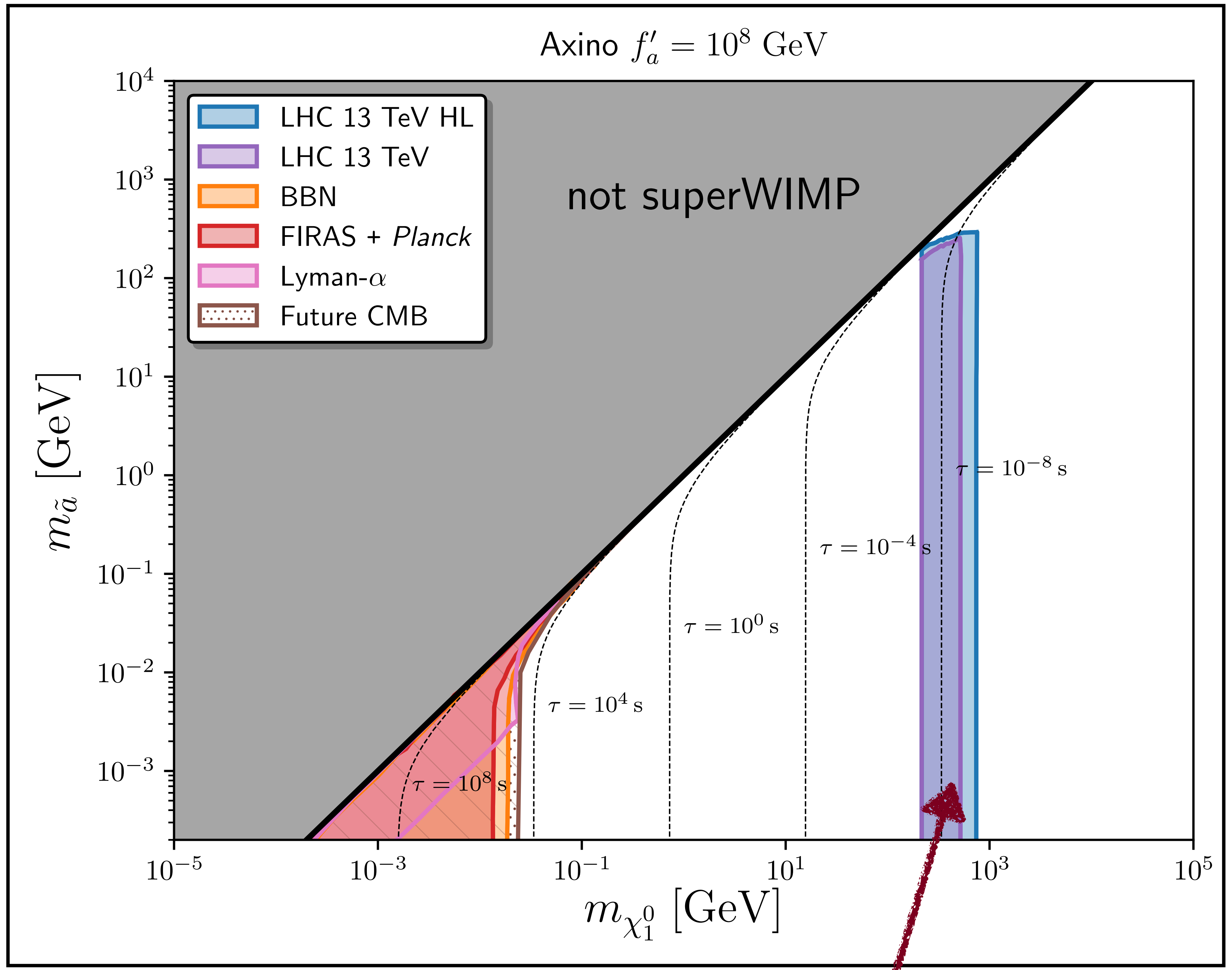

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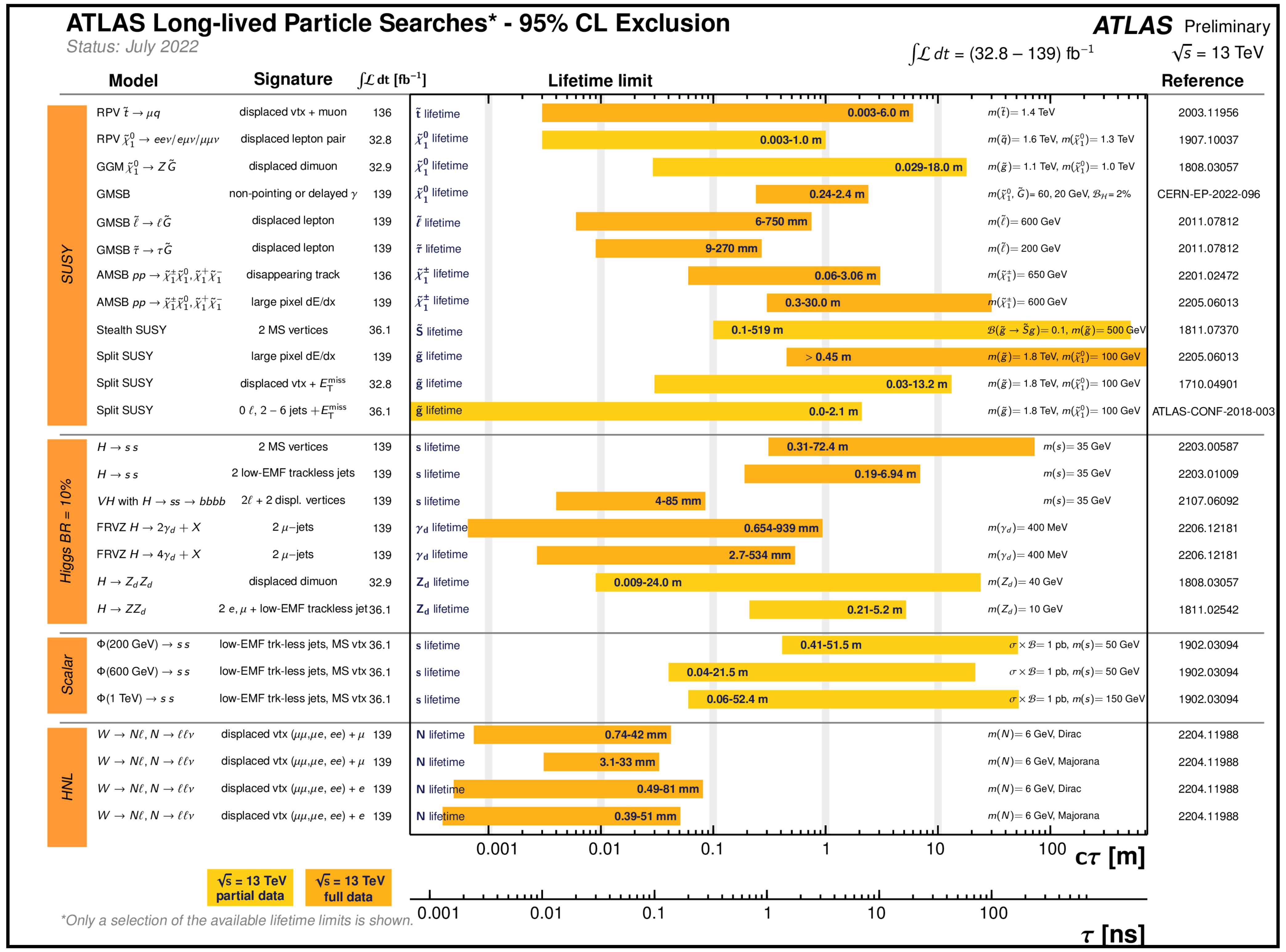
t- channel Simplified Models : Recommendations and benchmarks

Dark Matter via t-channel Production
Cosmology section

A Preprint

LHC Dark Matter Working Group

Contents



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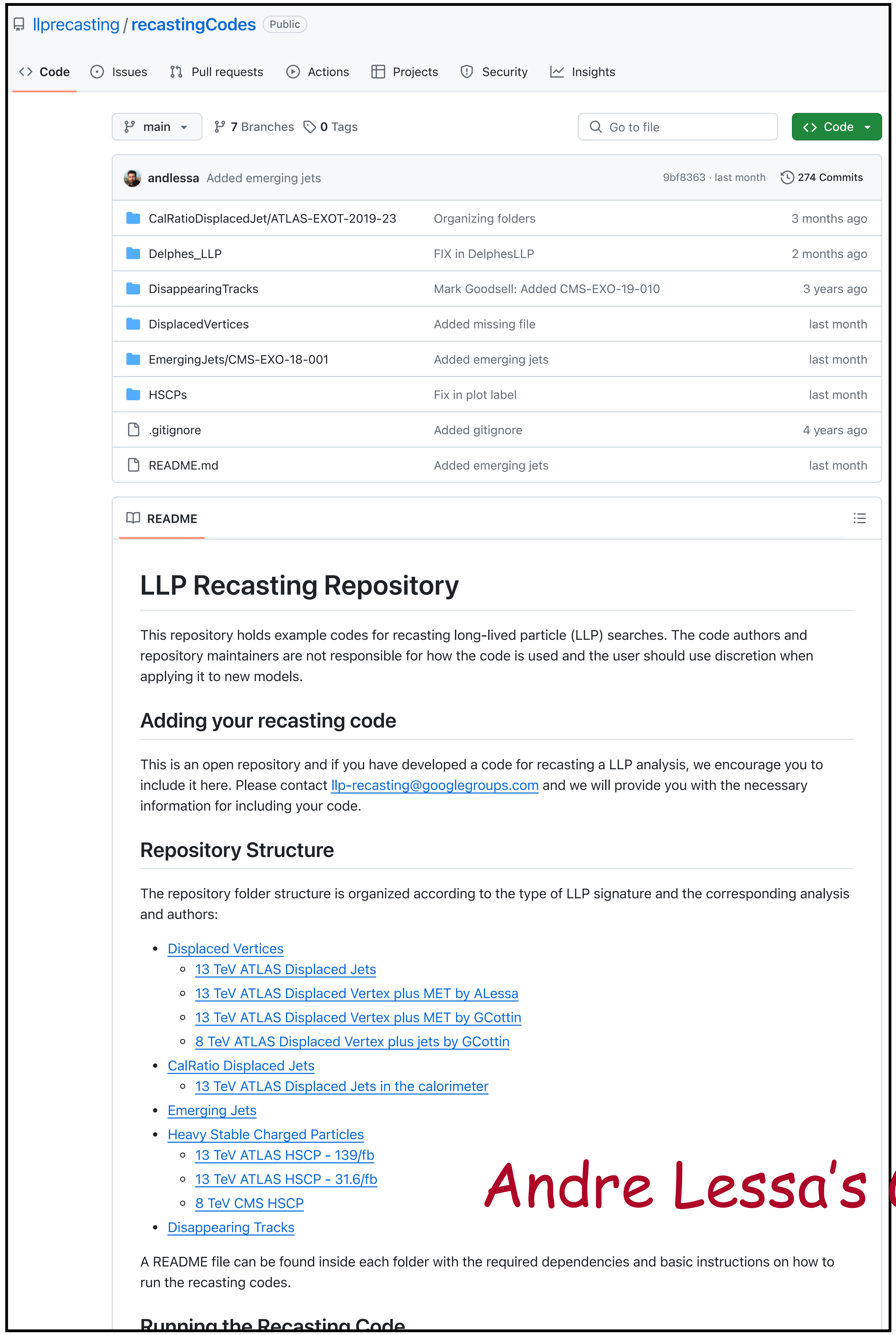


llprecasting / recastingCodes Public

Code Issues Pull requests Actions Projects Security Insights

main 7 Branches 0 Tags Go to file Code

andlessa Added emerging jets 9bf8363 · last month 274 Commits

CalRatioDisplacedJet/ATLAS-EXOT-2019-23	Organizing folders	3 months ago
Delphes_LLP	FIX in DelphesLLP	2 months ago
DisappearingTracks	Mark Goodsell: Added CMS-EXO-19-010	3 years ago
DisplacedVertices	Added missing file	last month
EmergingJets/CMS-EXO-18-001	Added emerging jets	last month
HSCPs	Fix in plot label	last month
.gitignore	Added gitignore	4 years ago
README.md	Added emerging jets	last month

README

LLP Recasting Repository

This repository holds example codes for recasting long-lived particle (LLP) searches. The code authors and repository maintainers are not responsible for how the code is used and the user should use discretion when applying it to new models.

Adding your recasting code

This is an open repository and if you have developed a code for recasting a LLP analysis, we encourage you to include it here. Please contact llp-recasting@googlegroups.com and we will provide you with the necessary information for including your code.

Repository Structure

The repository folder structure is organized according to the type of LLP signature and the corresponding analysis and authors:

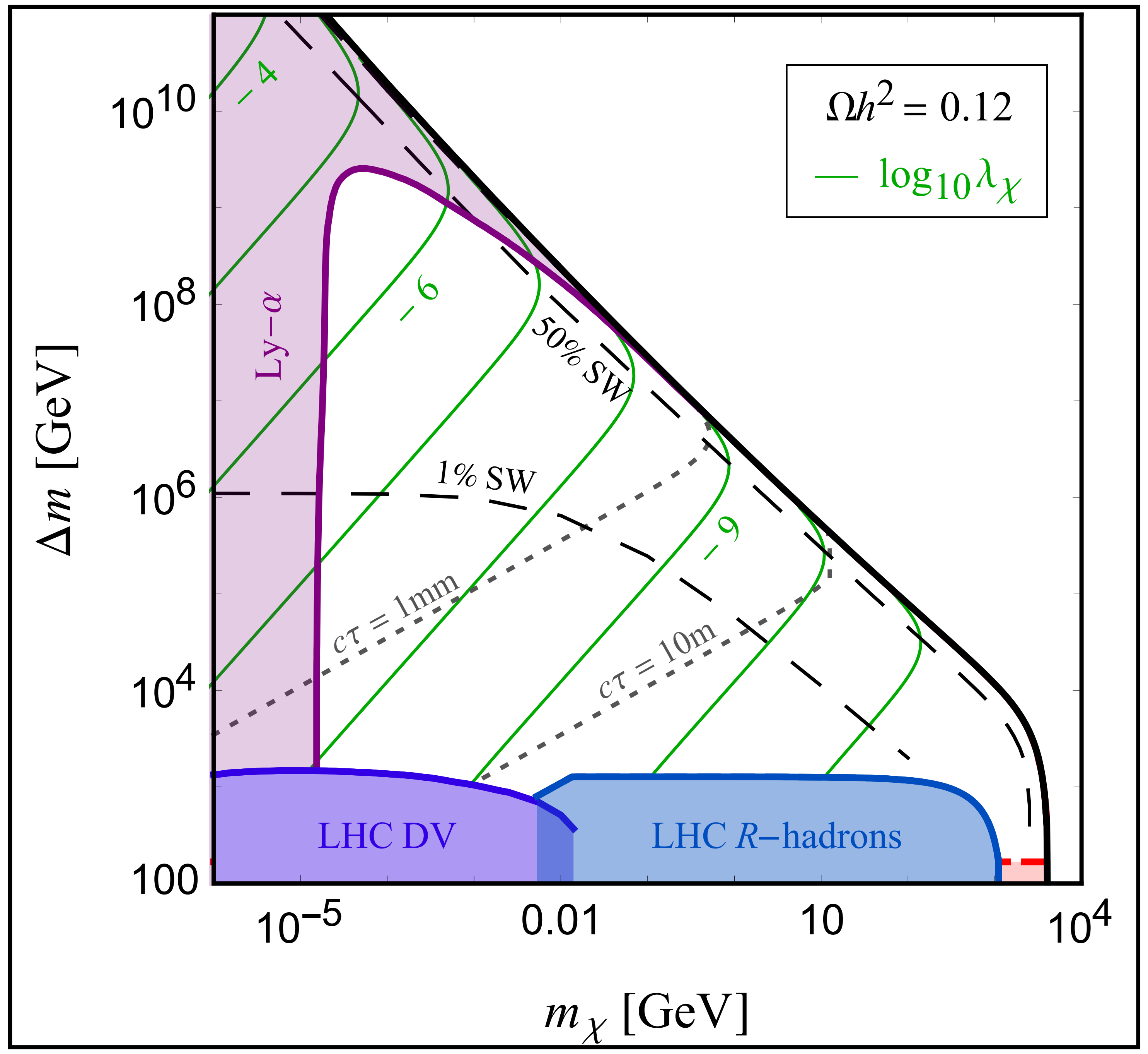
- Displaced Vertices
  - 13 TeV ATLAS Displaced Jets
  - 13 TeV ATLAS Displaced Vertex plus MET by ALessa
  - 13 TeV ATLAS Displaced Vertex plus MET by GCottin
  - 8 TeV ATLAS Displaced Vertex plus jets by GCottin
- CalRatio Displaced Jets
  - 13 TeV ATLAS Displaced Jets in the calorimeter
- Emerging Jets
- Heavy Stable Charged Particles
  - 13 TeV ATLAS HSCP - 139/fb
  - 13 TeV ATLAS HSCP - 31.6/fb
  - 8 TeV CMS HSCP
- Disappearing Tracks

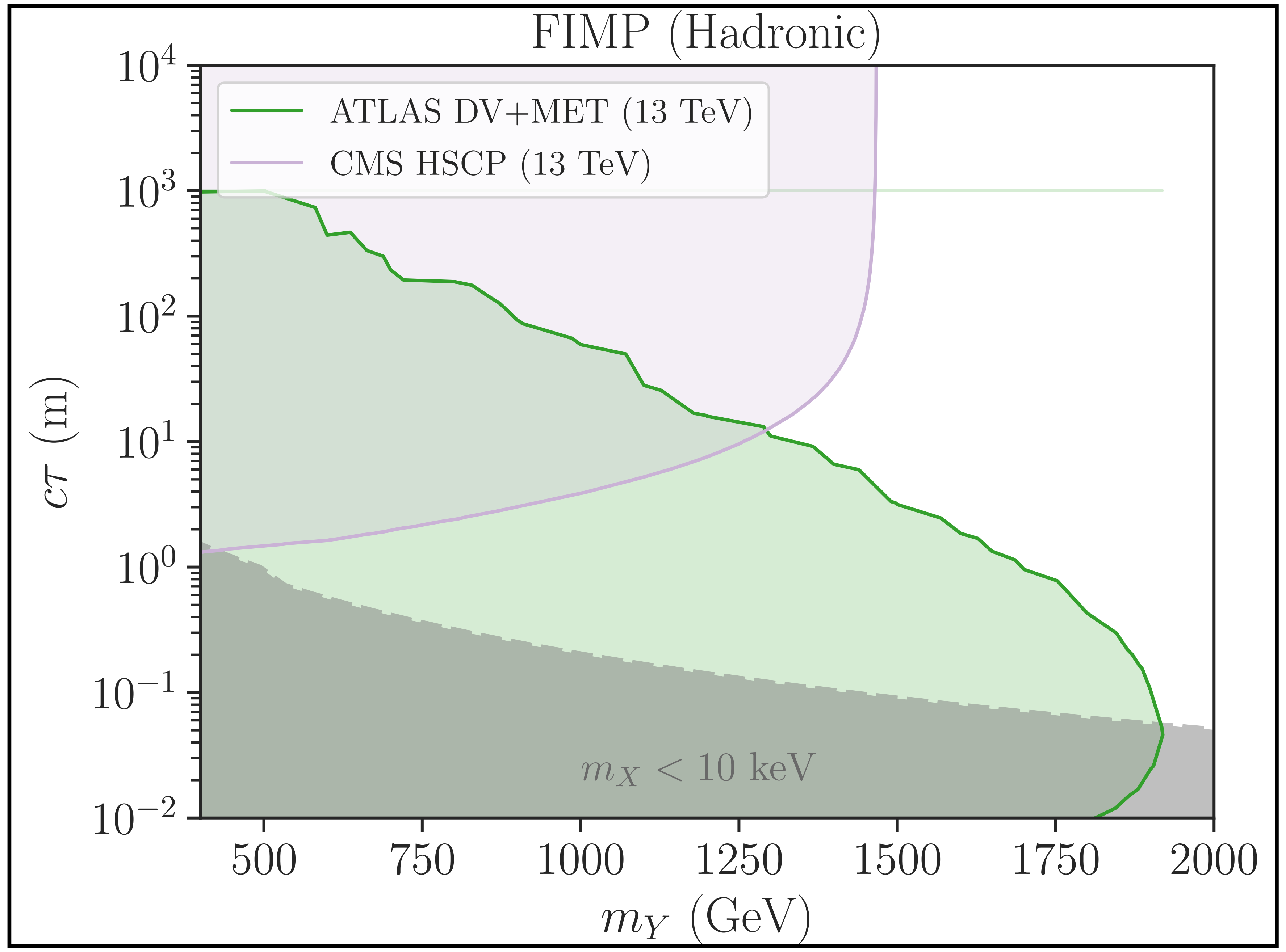
A README file can be found inside each folder with the required dependencies and basic instructions on how to run the recasting codes.

Running the Recasting Code

We need more recast codes implemented, for which

We need help and resources from our experimental collleagues





Andre Lessa's Github repo

Conclusions

- Simplified models provide a robust pathway to analyze theoretical and experimental Constraints that map to constraints on full-models.
- t-channel DM models provide a rich phenomenology, with complementary constraints from a variety of signatures
- LLP searches form a crucial component in closing the gap between freeze-out and non-thermal mechanisms of dark matter in t-channel.
- Needed: Experiment-theory collaborations, more recast/reinterpretation codes