Dark matter and displaced decays of Hidden Valley mesons

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1809.10152

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Amsterdam
October 23rd, 2018

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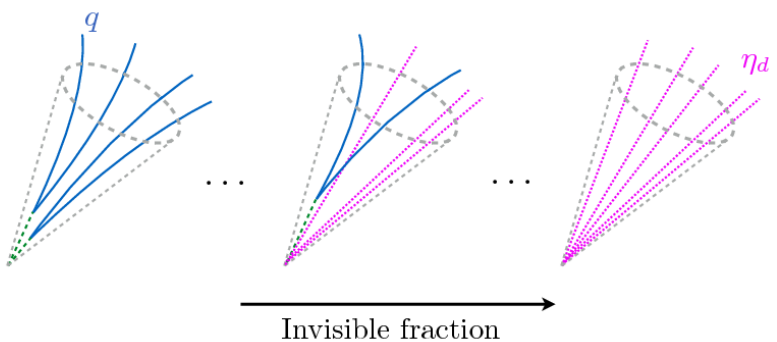
Context

- We know there is dark matter (DM) and the WIMP paradigm is under tension (direct detection, indirect detection...).
  - Looking for new ideas.
- There has been some work on DM being the light mesons of a Hidden Valley sector:
  - 1307.2647: Bhattachrya *et al*
  - 1312.3325: Cline *et al*
  - 1411.3727: Hochberg *et al*
  - ...
- These studies assumed the pseudo-Goldstone mesons are all stable.
- Nobody (carefully) considered the possibility of having both stable and unstable mesons.

Motivations

- It might be possible to avoid more naturally the bounds from direct and indirect detection.
- Simple and easy to build models
  - The SM could have been this way.
- These models can be embedded in larger models (Twin Higgs, Mirror World, Relaxion...).
- One of the motivations for semivisible jets (1503.00009: Lisanti *et al*)



1503.00009

- Could this lead to new exotic collider signatures?

Goal

Goal:

- Present an overview of the cosmological constraints on Hidden Valley models whose spectra of light particles consists of both stable and unstable dark mesons and map this to collider signatures

Four big questions:

- Can the stable dark pions serve as valid DM candidates?
- What is the mechanism for reproducing the correct DM abundance?
- What are the bounds from direct and indirect detection?
- What should we look for at colliders?

Benchmark dark sector

- Assume a dark copy of QCD with three light dark quarks n_i.
- Can define three $U(1)_i$ symmetries
- Pion matrix:

$$\Pi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi_1^u + \frac{1}{\sqrt{6}}\pi_2^u & \pi_1^s & \pi_2^s \\ \bar{\pi}_1^s & -\frac{1}{\sqrt{2}}\pi_1^u + \frac{1}{\sqrt{6}}\pi_2^u & \pi_3^s \\ \bar{\pi}_2^s & \bar{\pi}_3^s & -\sqrt{\frac{2}{3}}\pi_2^u \end{pmatrix}.$$

- The off-diagonal pions are charged under the $U(1)_i$ symmetries, but not the on-diagonal ones.

Mechanism I

General comments:

- Interactions in the early Universe can fall in different regimes.
- Assume interactions between the SM and dark sector are controlled by a parameter λ.

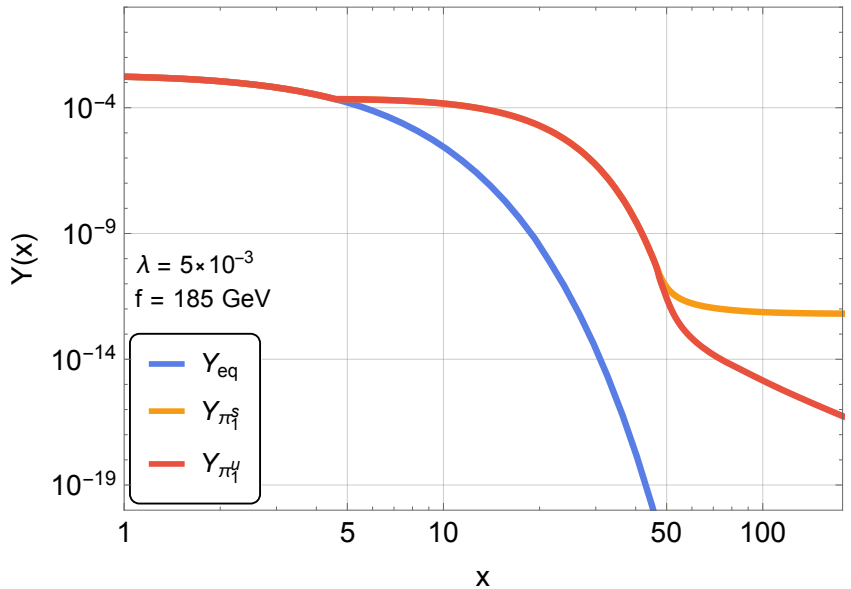
$\lambda \to 0$

- SIMP (1402.5143: Hochbert *el al*)
- ELDER (1512.04545: Kuflik *el al*)
- Already well studied

Mechanism II

λ very small

- Codecaying DM
  - 1607.03110: Dror *et al*
  - 1607:03108: Farina *et al*
  - 1607.08520: Okawa *et al*
- Two sectors decouple early.
- D density is reduced via:



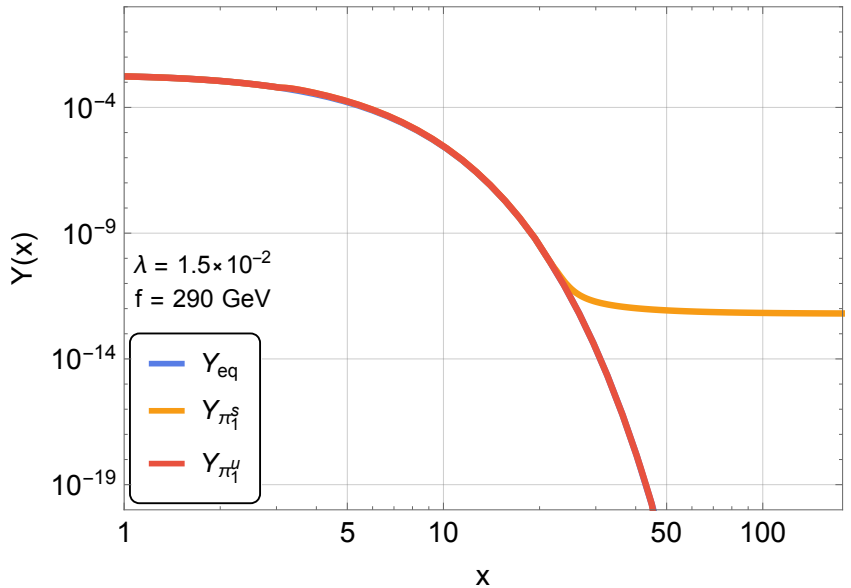
$$\pi_i^s \bar{\pi}_i^s \longrightarrow \pi_j^u \bar{\pi}_k^u$$

with π_j^u decaying and inverse decay not being efficient.

Mechanism III

λ small

- 'Coupling-independent' regime
- Unstable pions remain in thermal equilibrium until after the pions have decoupled.
- Decays and inverse decays are good for maintaining thermal equilibrium.
- Relative independence on λ



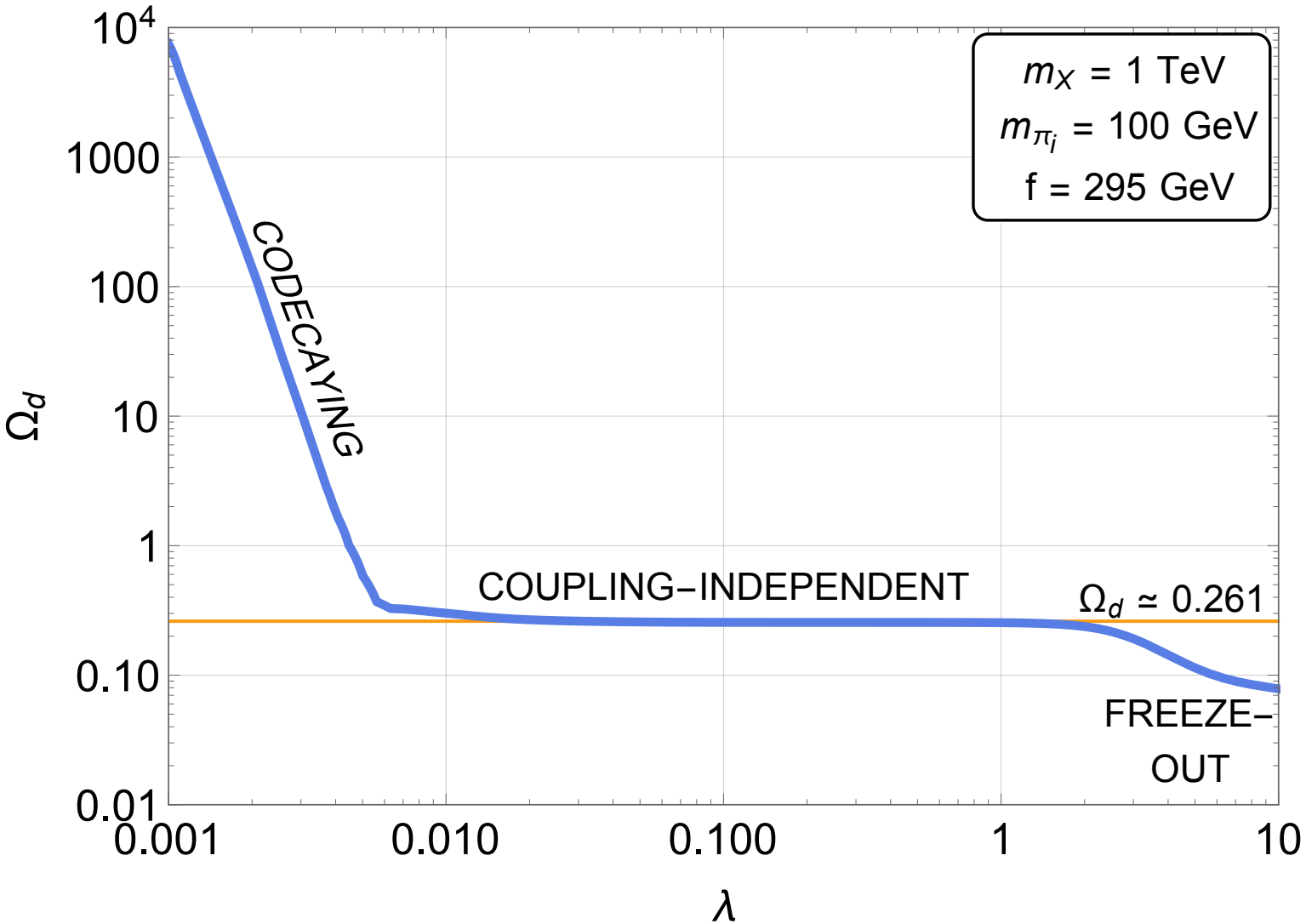
Mechanism IV

λ large

- Standard WIMP freeze-out

$$\pi_i^s \bar{\pi}_i^s \to \text{SM SM}$$

Mechanism V


m_X = 1 TeV
m_{π_i} = 100 GeV
f = 295 GeV
CODECAYING
COUPLING–INDEPENDENT
$\Omega_d \simeq 0.261$
FREEZE–
OUT
Ω_d
λ
10^4
1000
100
10
1
0.10
0.01
0.001
0.010
0.100
1
10

Contraints and other

Direct detection

- Xenon 1T (1705.06655: XENON collaboration)
- Running effects (1605.04916: D'Eramo *el al*)

Indirect detection

- Cascade decays (1511.08787: Elor *el al*)
- Constraints from:
  - CMB (1502.01589: Planck collaboration)
  - Gamma rays (1503.02632: Fermi-LAT collaboration)
  - Positrons (Phys. ReV. Lett. 113 (2014) 121102: AMS collaboration, Phys. ReV. Lett. 113 (2014) 121102: AMS collaboration)

Other effects:

- $3 \rightarrow 2$ processes
- Thermal exchange

Toy model I

$X^S_{D^c}$: Scalar mediator with D^c SM gauge number and an antifundamental of $SU(3)_D$.

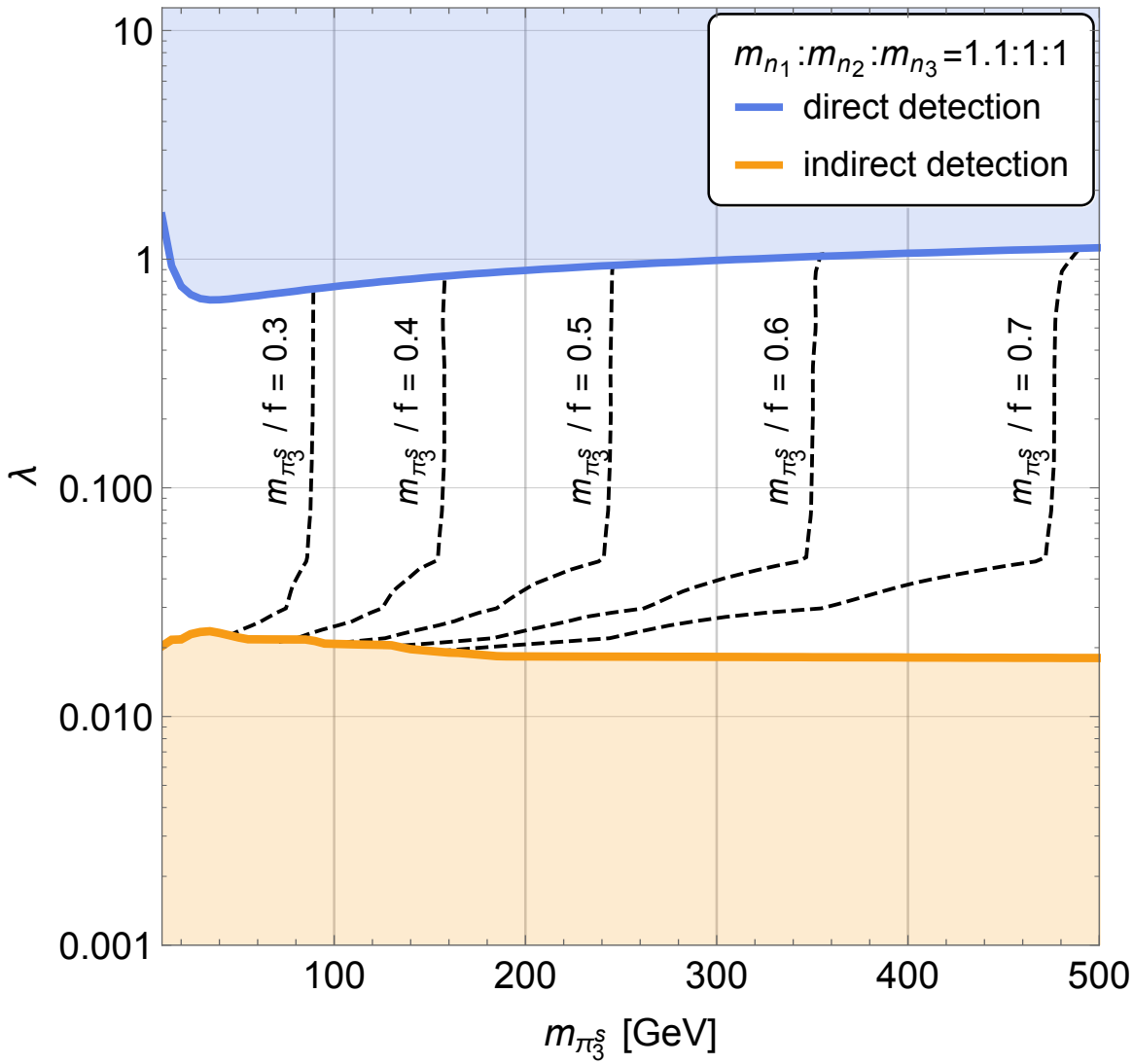
$$\lambda^S_{D^c_{ij}} (X^S_{D^c})^\dagger \bar{n}_i P_R D^c_j + \text{h.c.}$$

Assume:

$$\lambda^S_{D^c_{ij}} = \lambda \delta_{i1} \delta_{jk},$$

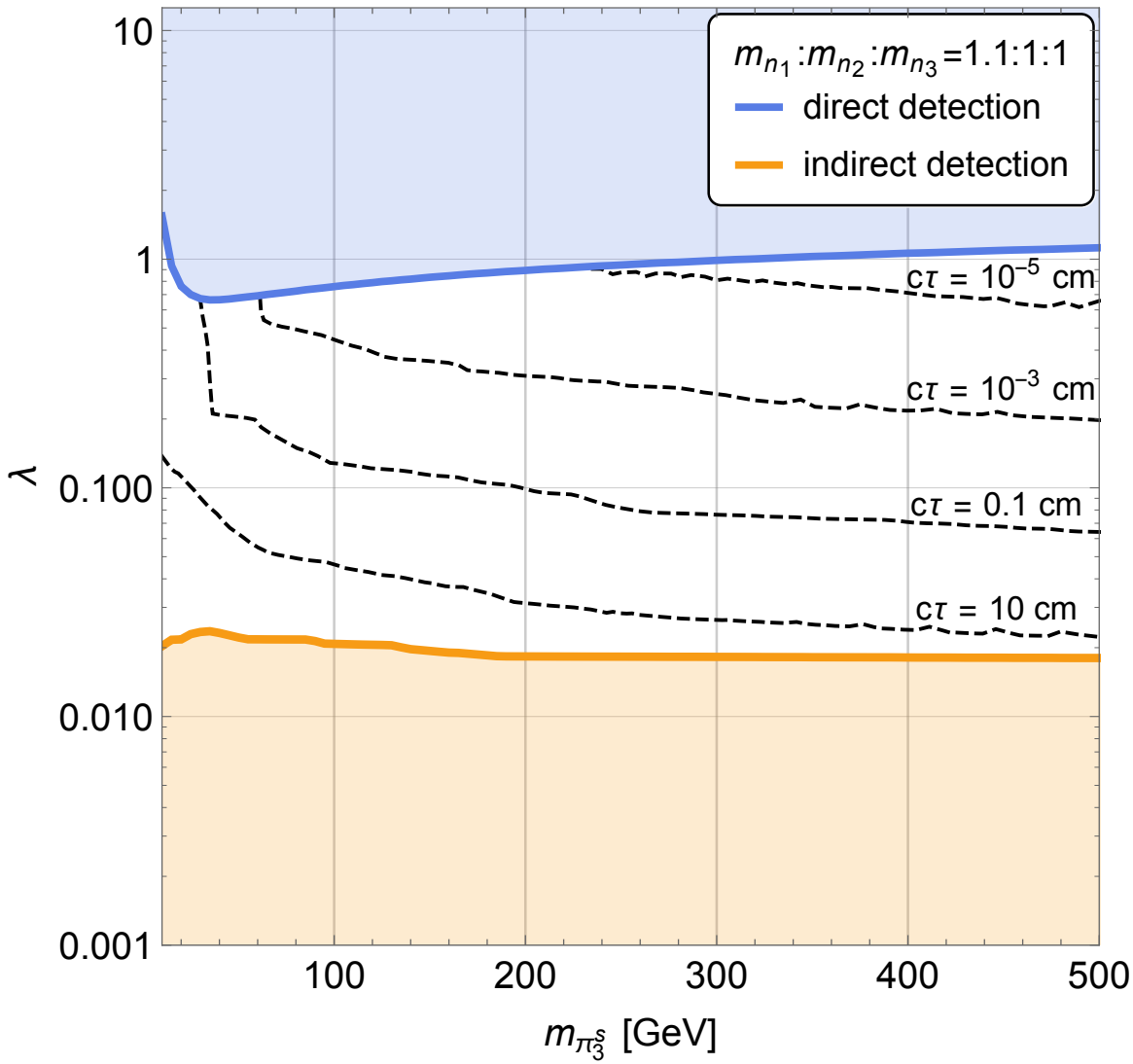
with $k \in \{1, 2, 3\}$.

Toy model II



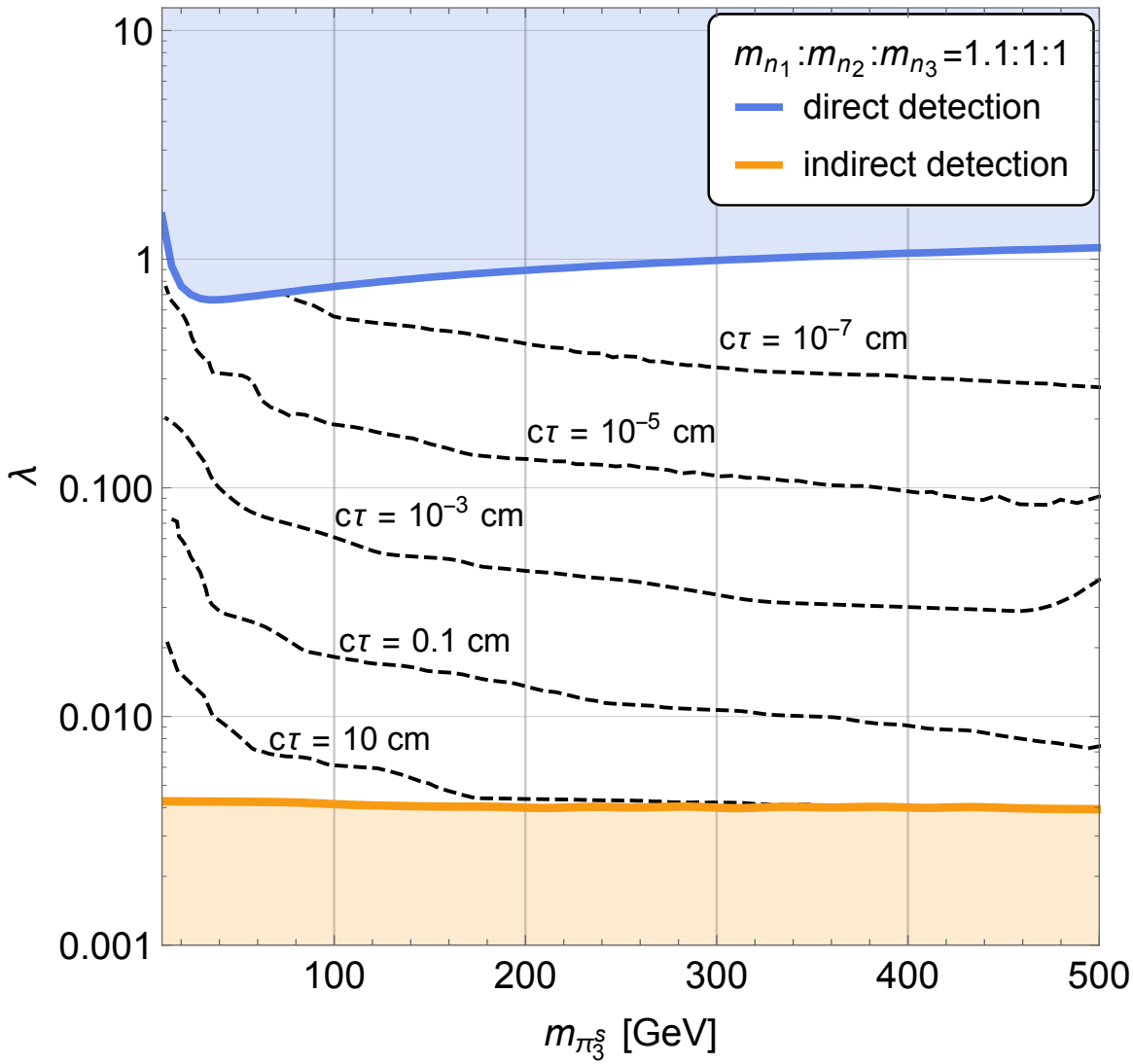
Strange

Toy model III



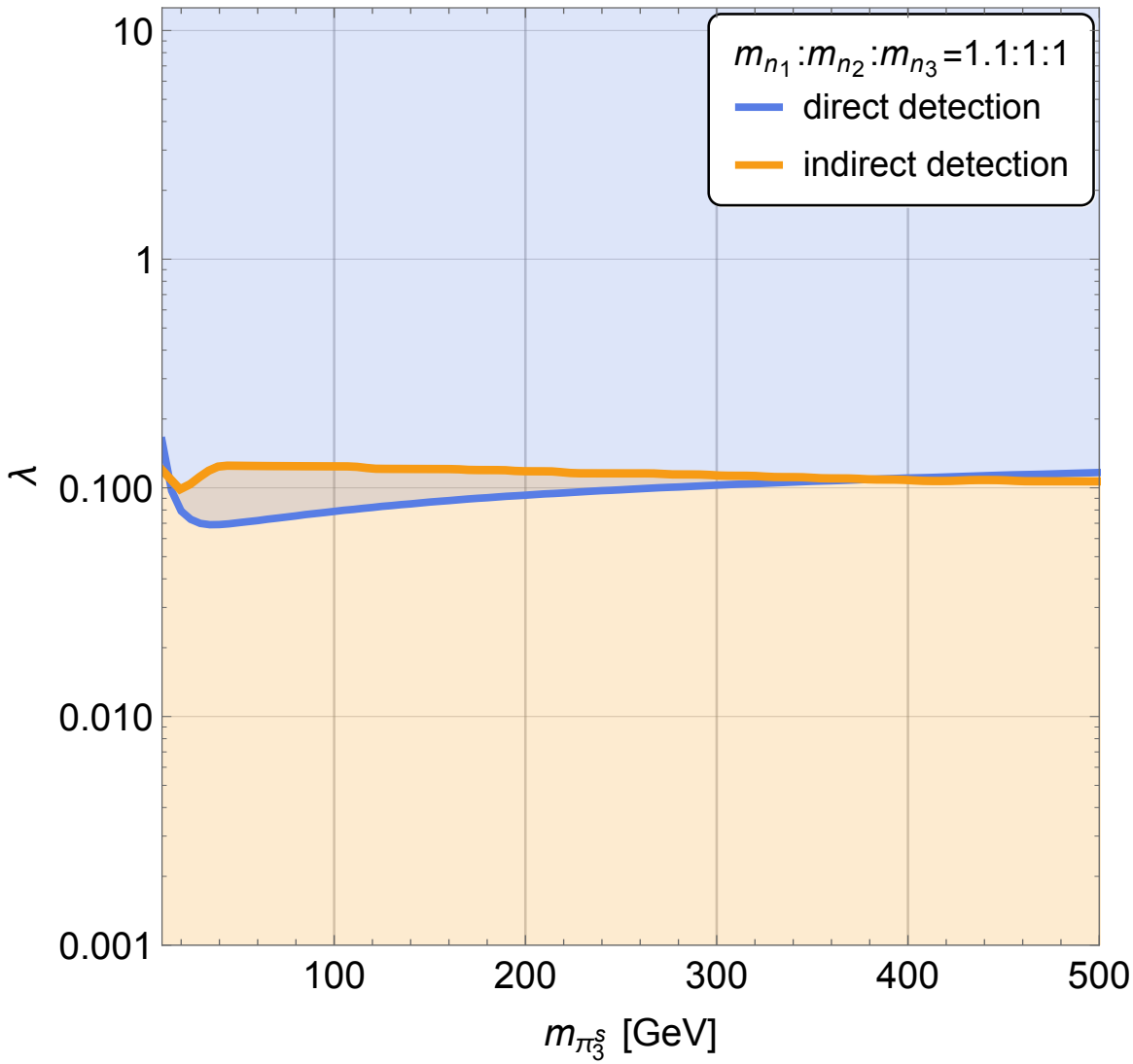
Strange

Toy model IV



Bottom

Toy model V



Down

Realistic model A I

Include multiple copies of the mediator:

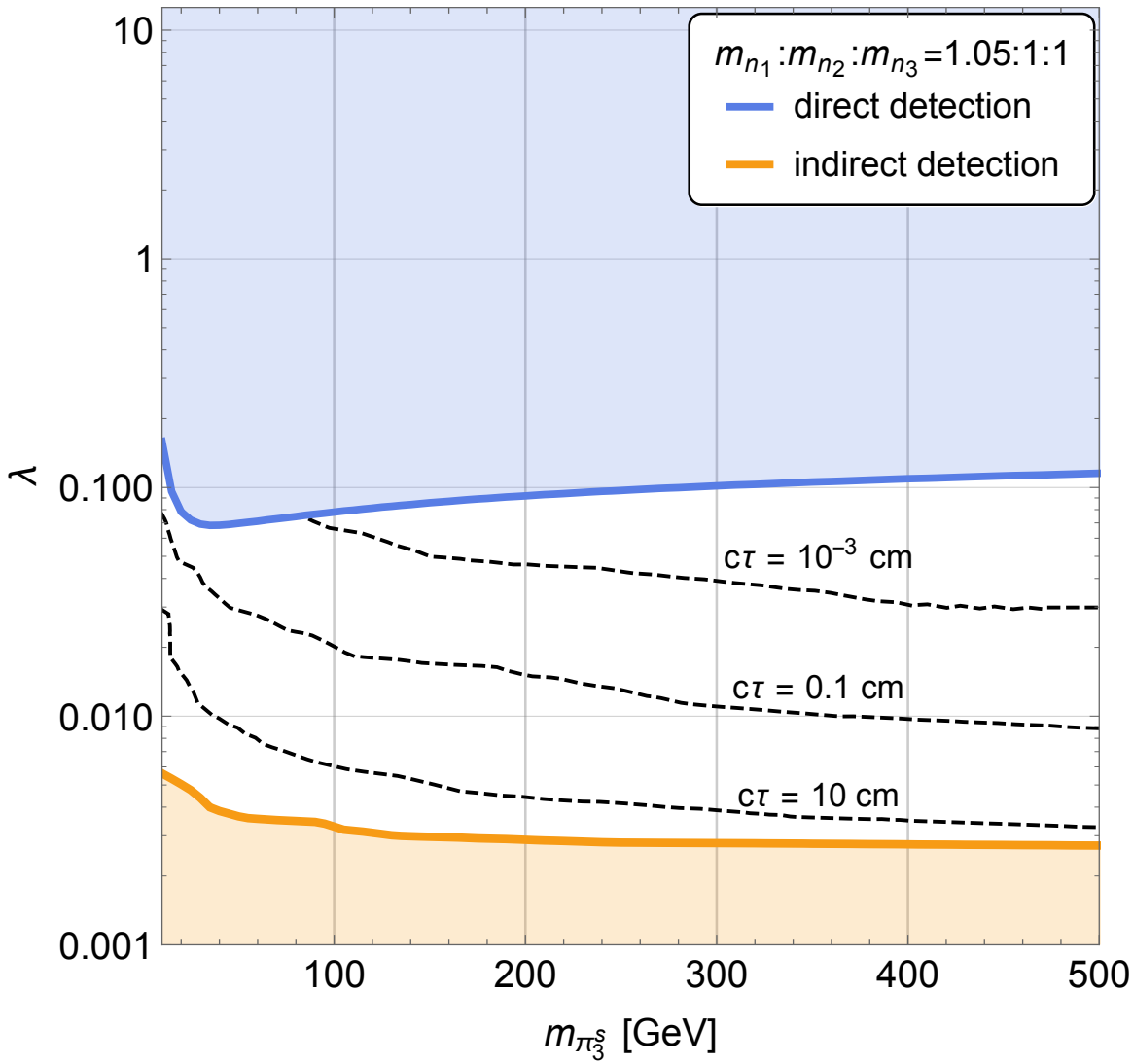
$$\lambda^{S}_{D^c_{ijk}} (X^{S}_{D^c_k})^{\dagger} \bar{n}_i P_R D^c_j + \text{h.c.}$$

with:

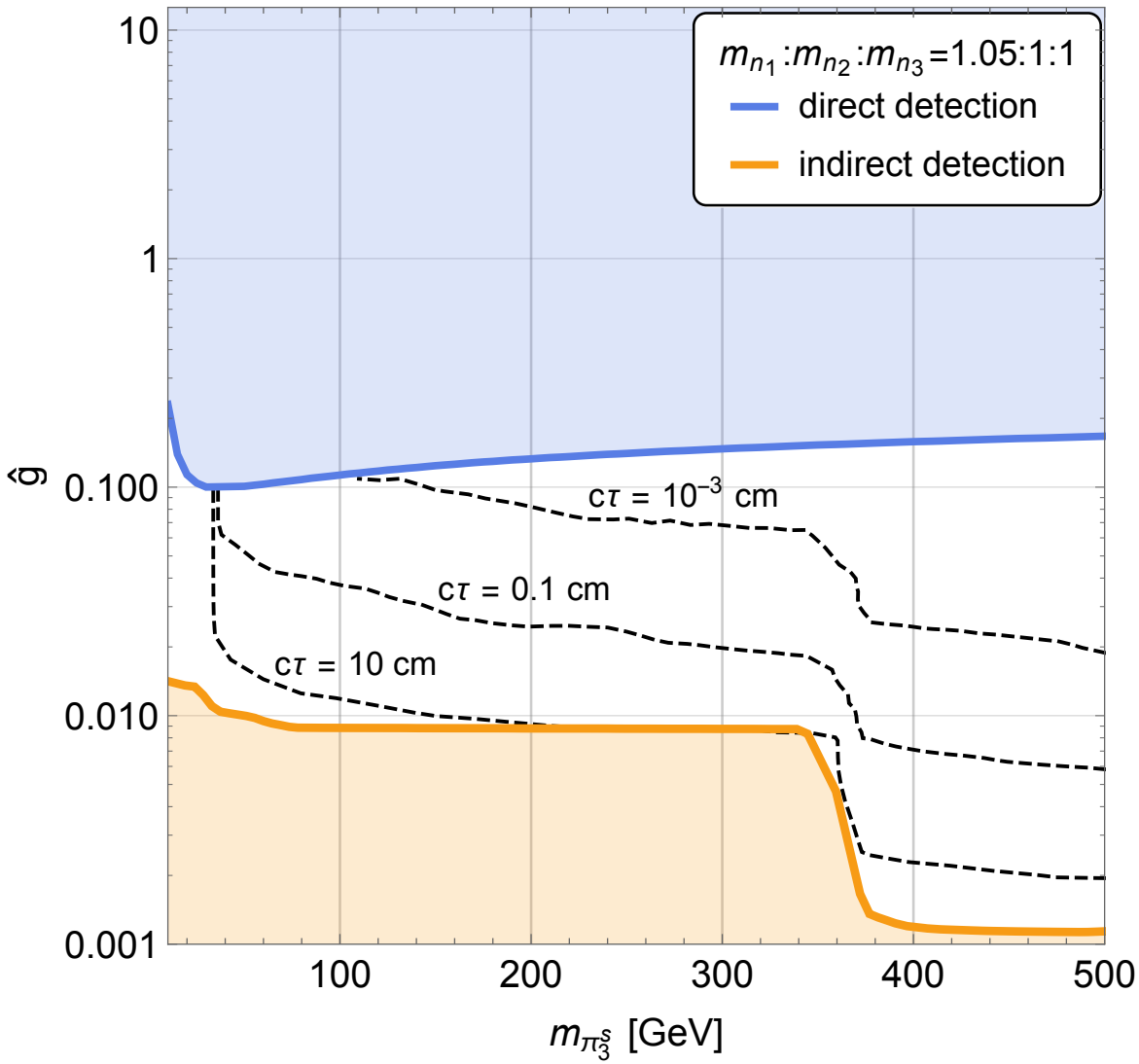
$$\lambda^{S}_{D^c_{ijk}} = \lambda \delta_{i1} \delta_{jk},$$

with $j, k \in \{1, 2, 3\}$.

Realistic model A II



Realistic model B



Sequential Z' with n_1 of charge 1

Collider signatures

Large λ

- Semivisible jets: For another talk...

Small λ

- 'Emerging semivisible' jets: Emerging jets + MET
- Lower multiplicity than normal Emerging jets
- Upper limit on the decay length of ~ 1 m
  - Good: ATLAS, CMS...
  - Less good: MATHUSALA, FASER...
- Prefers decays to heavier generations (second or third)
  - Quarks or leptons
- Additional model building could lead to other decays.
- In many of these models, you expect the emerging jets to be accompanied by other prompt objects.
  - Model A: Two jets

Conclusion

Goal:

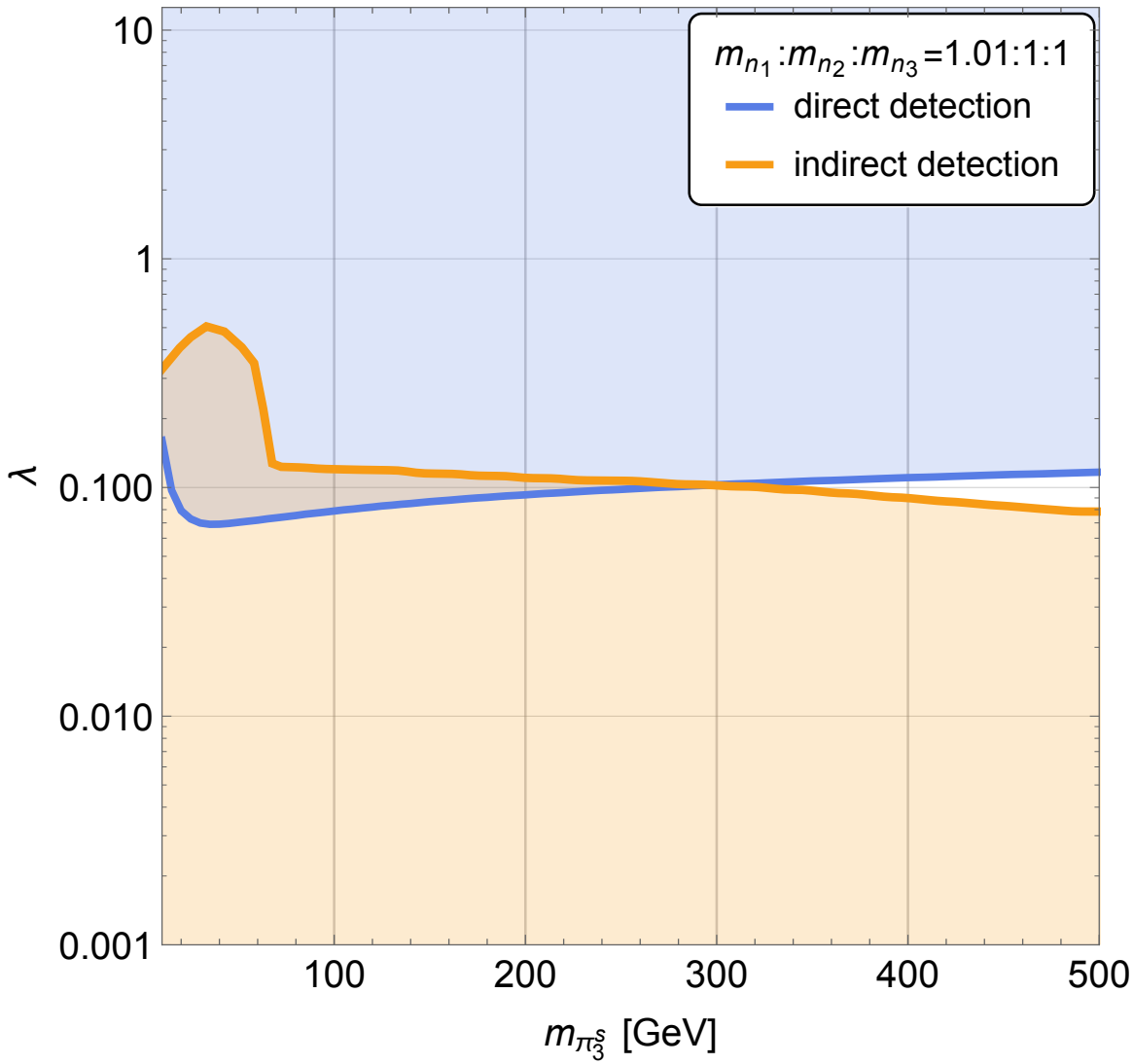
- Present an overview of the cosmological constraints on Hidden Valley models whose spectra of light particles consists of both stable and unstable dark mesons and map this to collider signatures

Take-home points:

- Well-motivated problem
- Plenty of parameter space available
- Large region of parameter space leads to displaced decays
- Exotic collider signatures

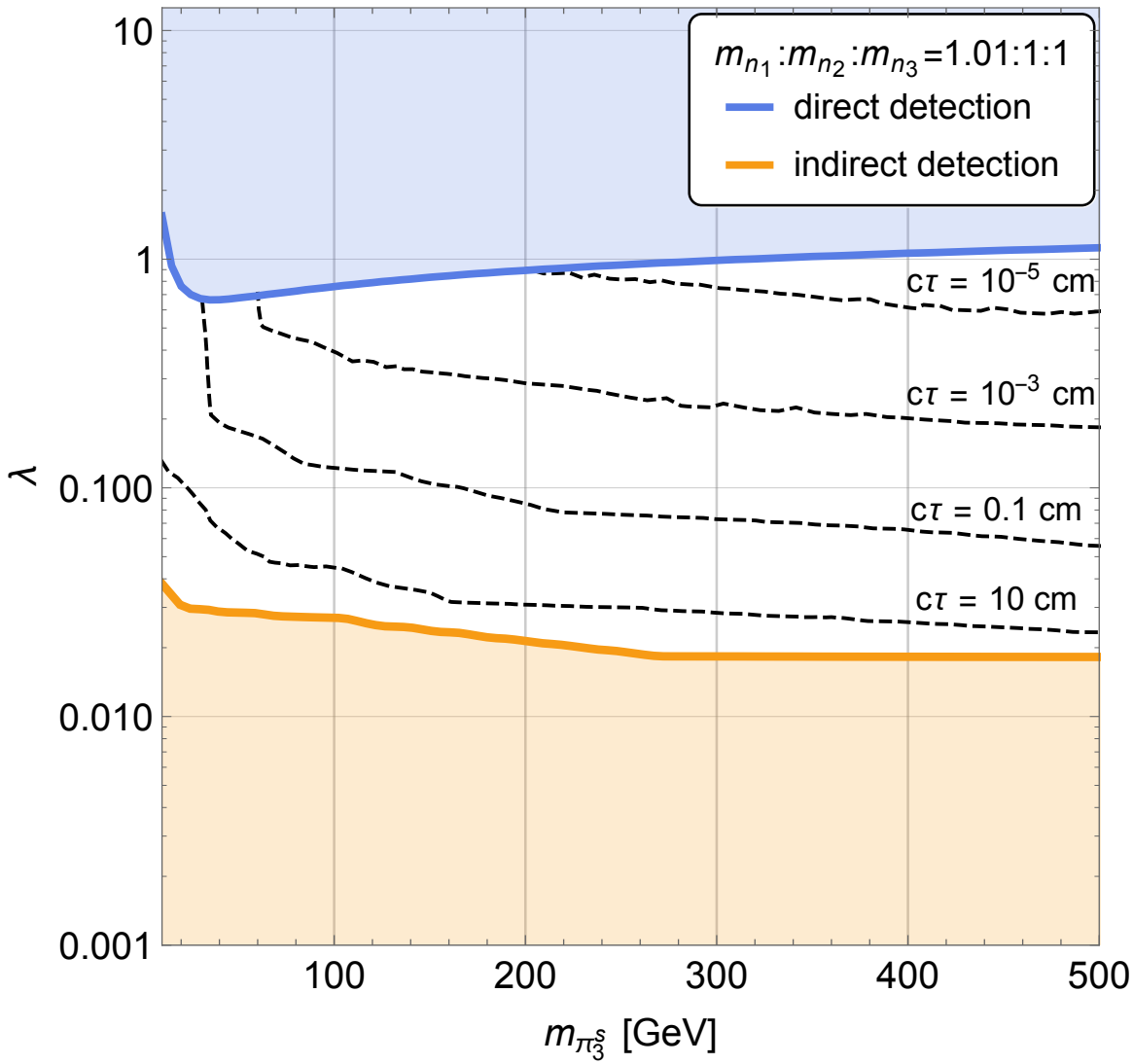
Hugues Beauchesne is grateful to the Azrieli Foundation for the award of an Azrieli Fellowship.

Down other mass



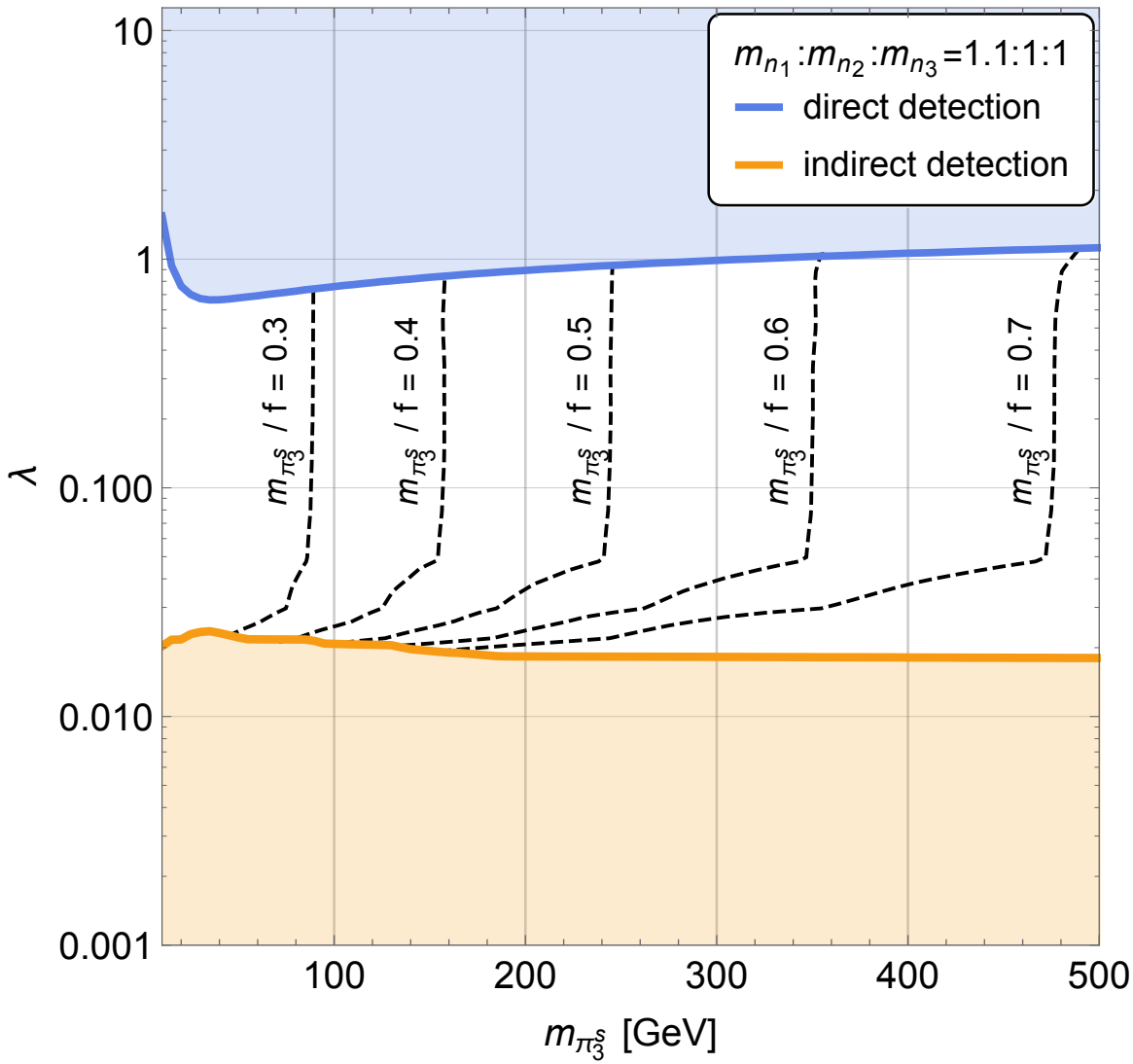
Down

Strange other mass I



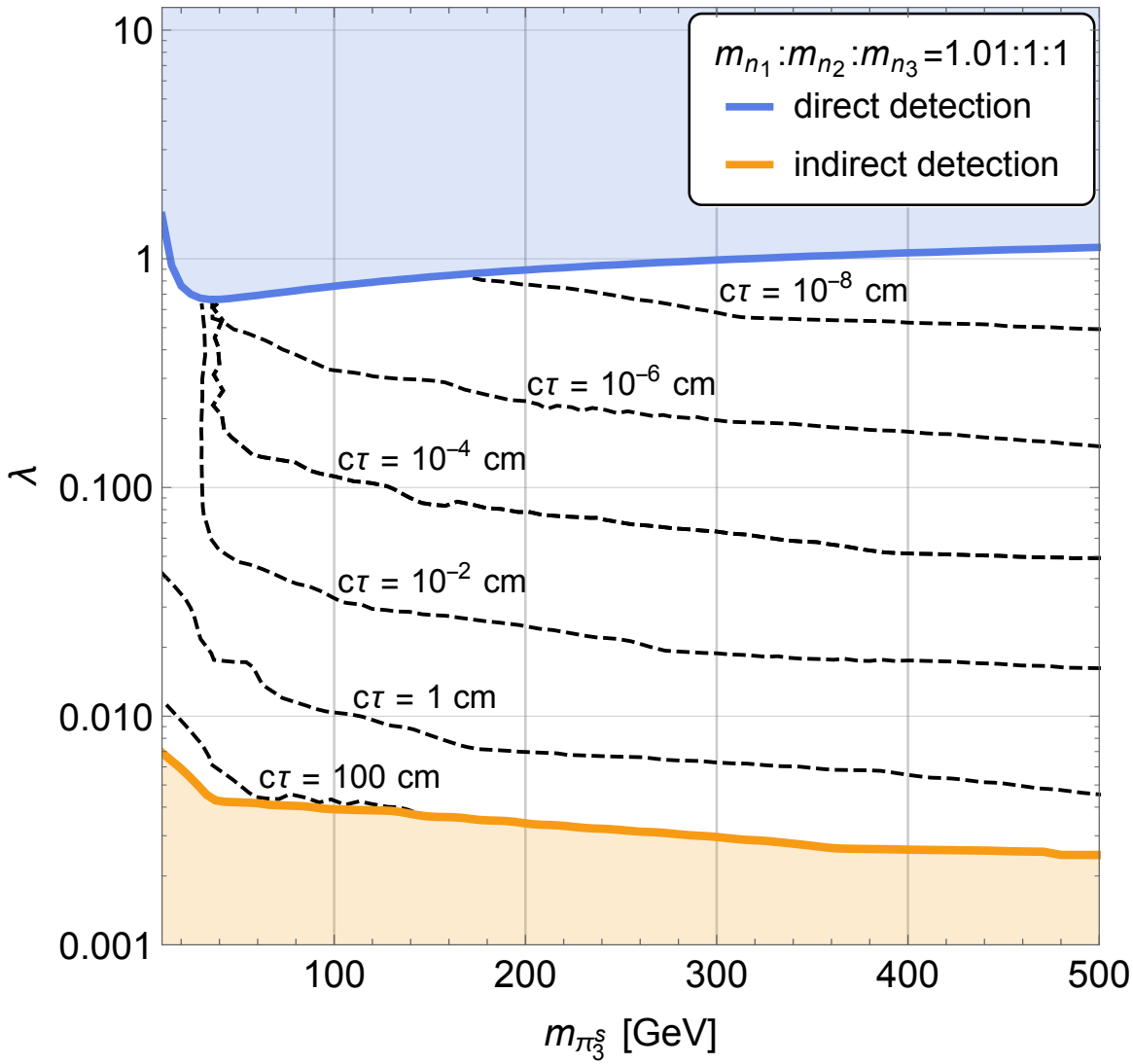
Strange

Strange other mass II



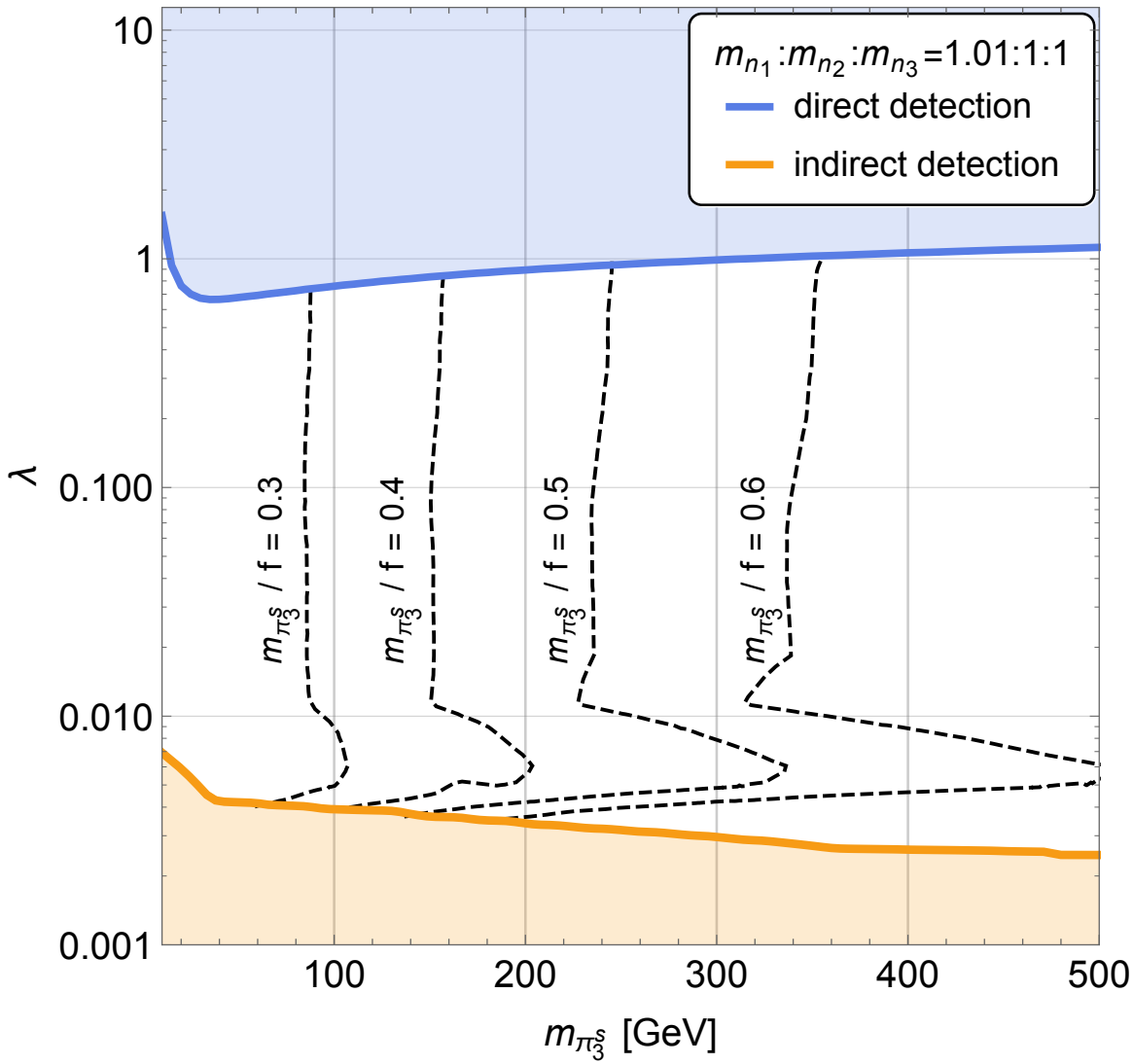
Strange

Bottom other mass I



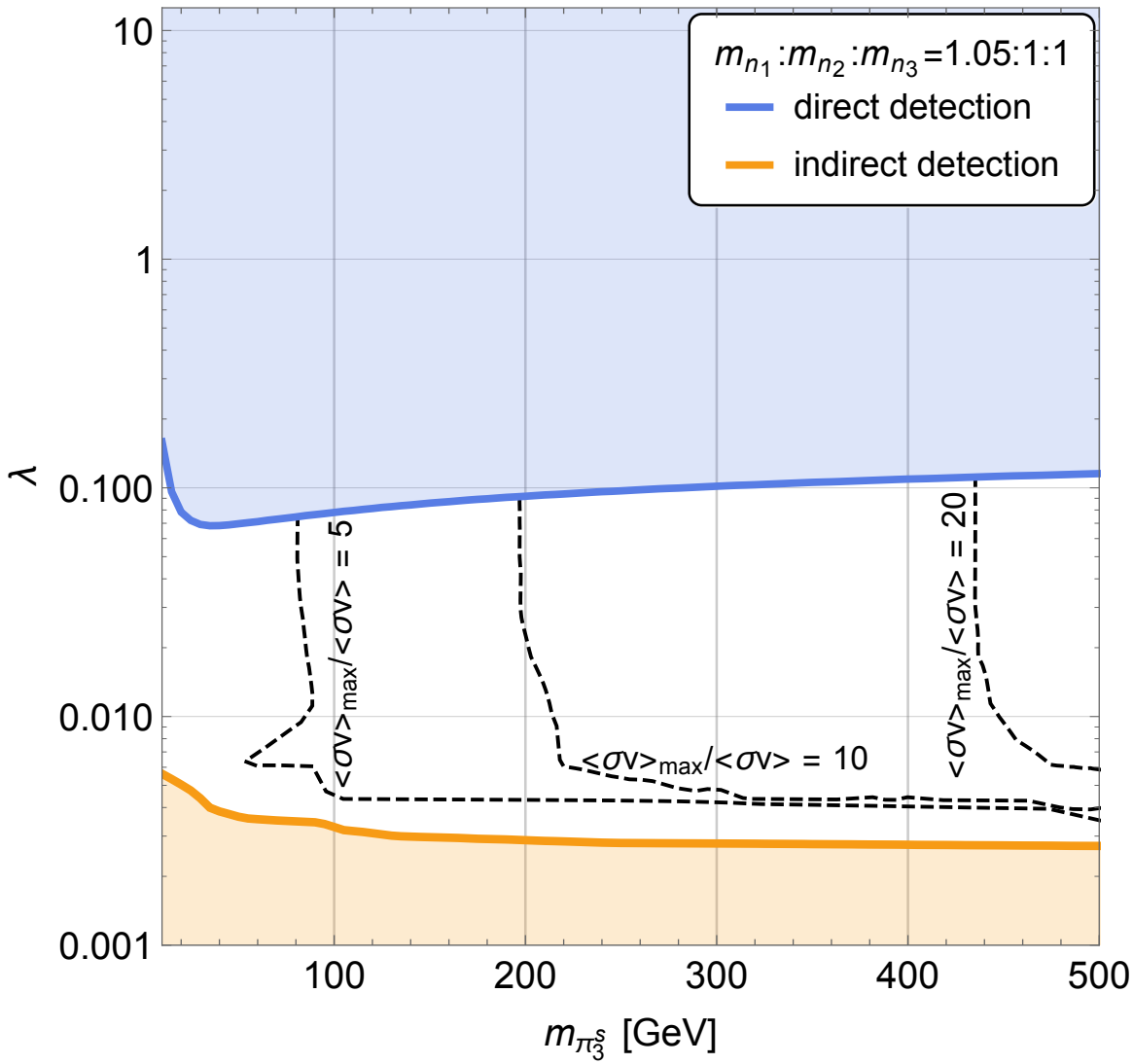
Bottom

Bottom other mass II



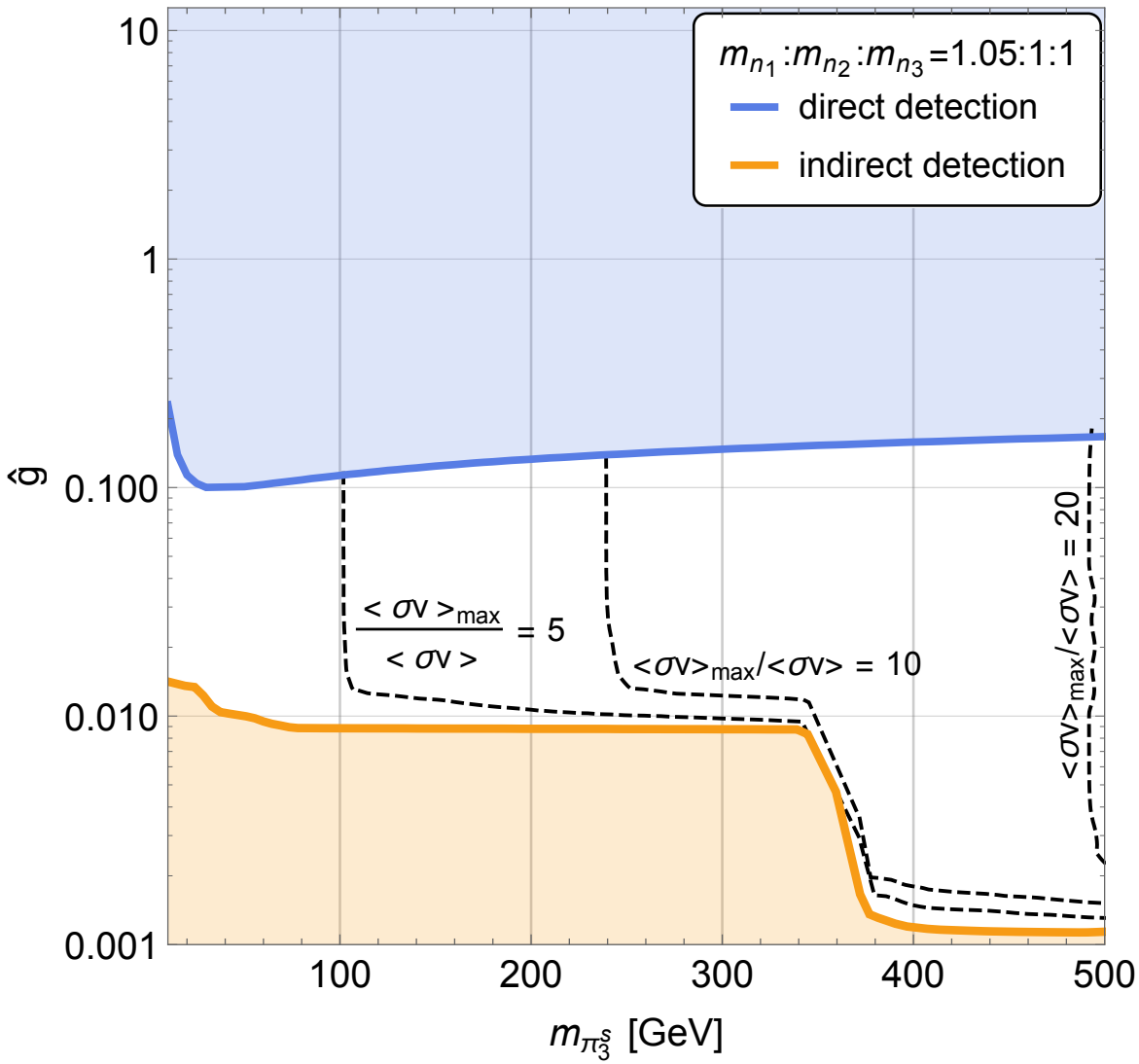
Bottom

Indirect detection improvement I



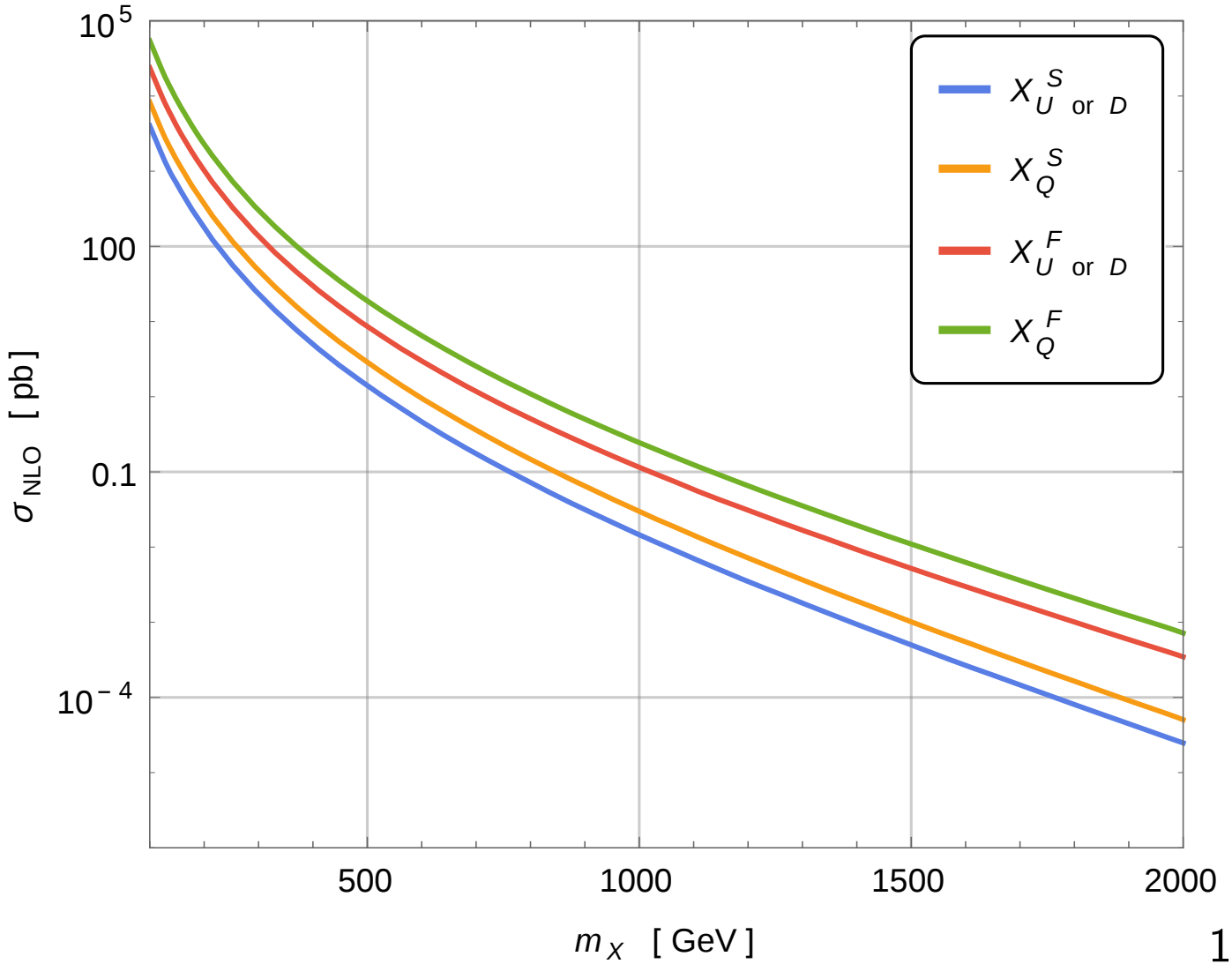
Model A

Indirect detection improvement II



Model B

Toy model cross section



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