NEW SCENARIOS OF COMPOSITE DARK MATTER

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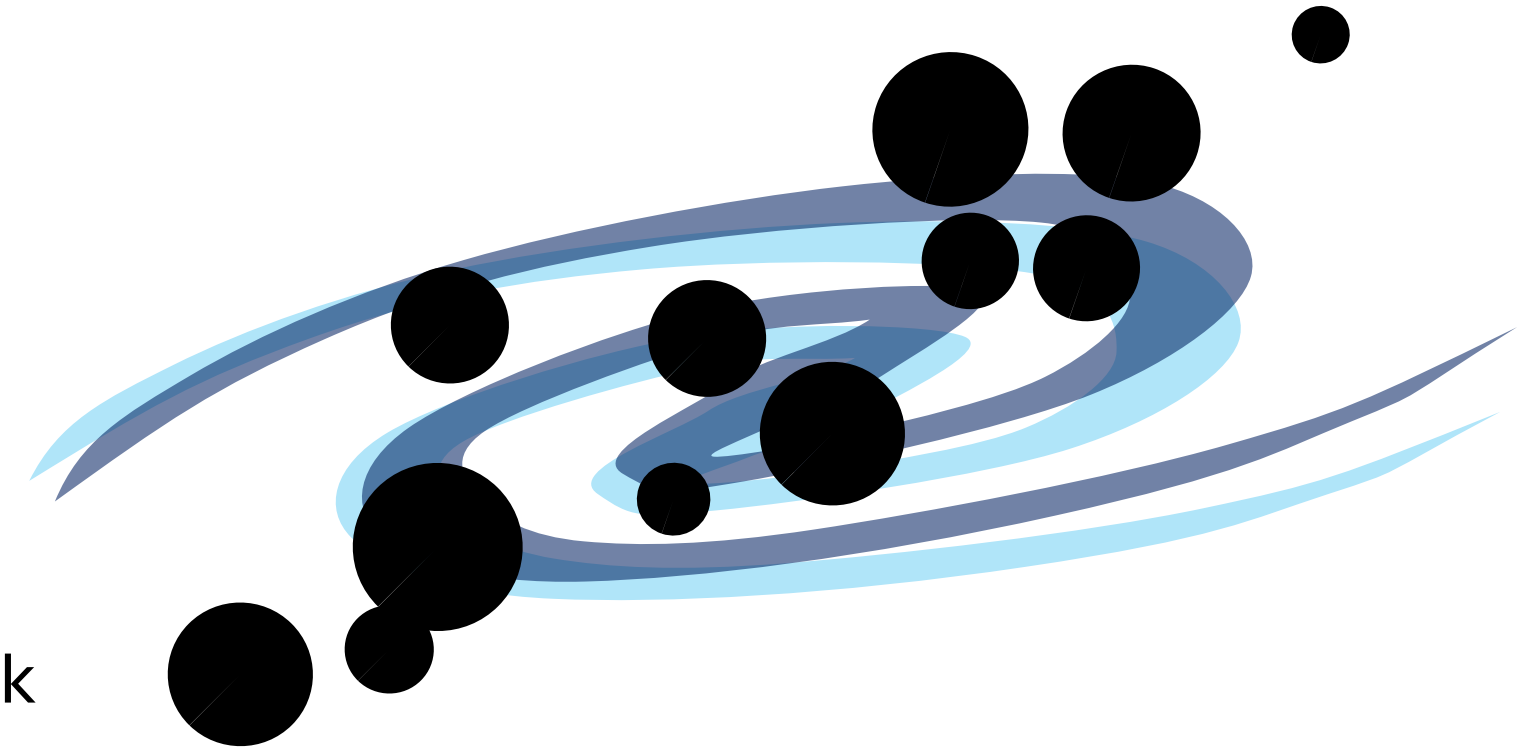
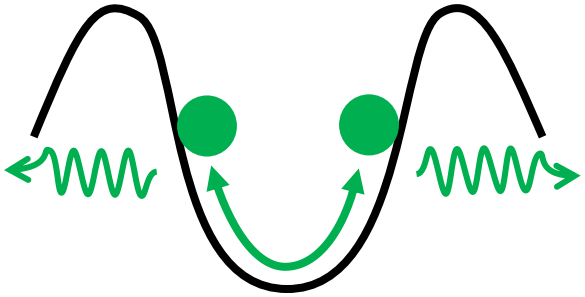


Aug. 23, 2025
DM & Neutrino Focus Week
TDLI, Shanghai

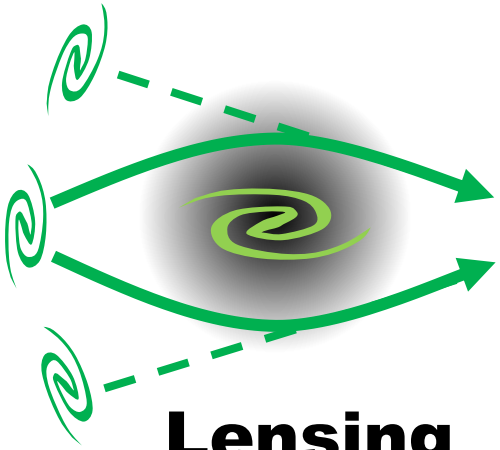
25xx.abcde H-C. Cheng, X. Jiang, LFL, E. Salvioni



CMB Power Spectra

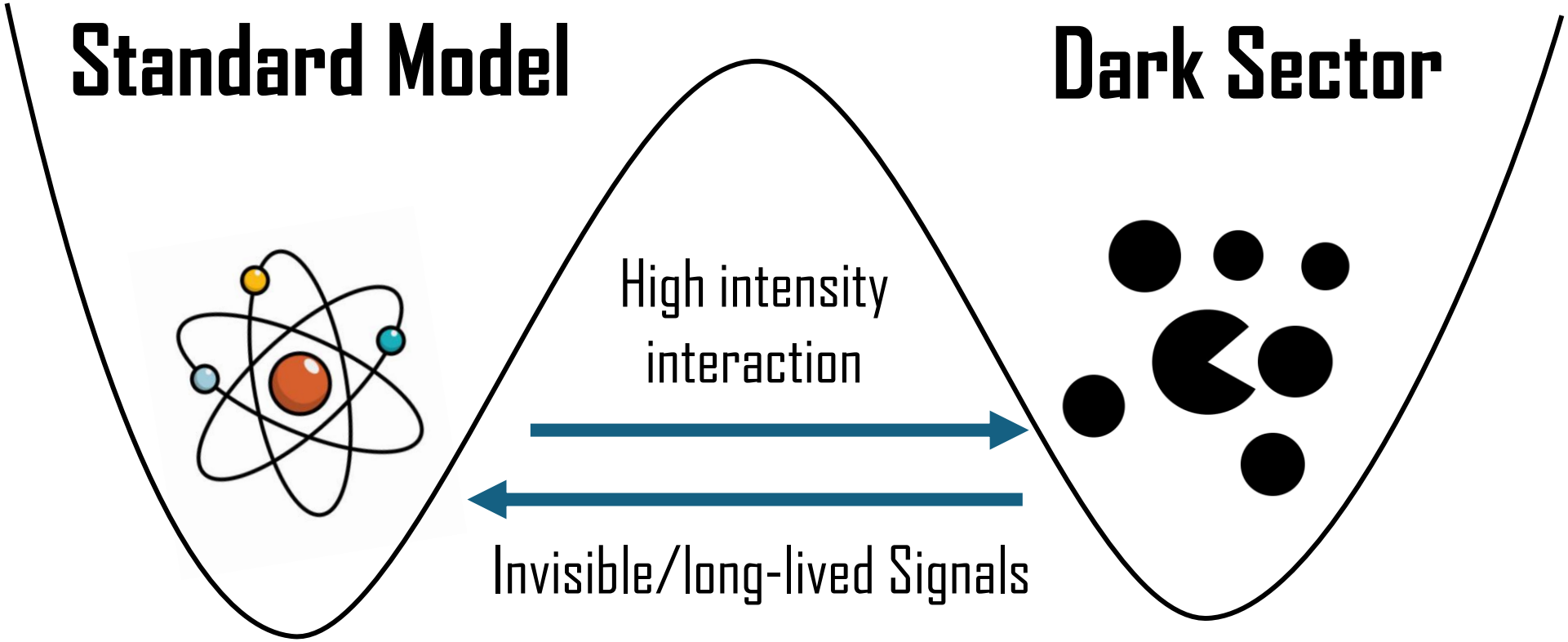
Large Scale Structure

Galaxy Formation



Lensing

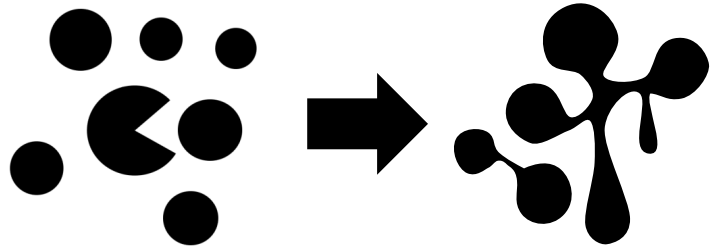
Portal to the Dark Sector



$\epsilon \mathcal{O}_{\mathrm{SM}} J_{\mathrm{Dark}}$ **Relevant portal:** small couplings to keep hidden

$\frac{1}{\Lambda^n} \mathcal{O}_{\mathrm{SM}} J_{\mathrm{Dark}}$ **Irrelevant portal:** Hidden behind EFT

DM being Composite



- Often found in UV theories (e.g. GUT, neutral naturalness)

Z. Chacko, H.S. Goh, and R. Harnik, 0506256; G. Burdman, Z. Chacko, H.S. Goh and R. Harnik, 0609152; H-C. Cheng, LFL, E. Salvioni, and C. Verhaaren, 1803.03561 ……

- Phenomenology friendly (e.g. phase transition, long-lived particles)

P. Schwaller, D. Stolarski, A. Weiler, 1502.05409;
CMS, 1810.10069; S. Knapen, J. Shelton, D. Xu, 2103.01238;
S. Born, R. Karur, S. Knapen, J. Shelton, 2303.04167; J. Carrosco, J. Zirita, 2307.04847 ……

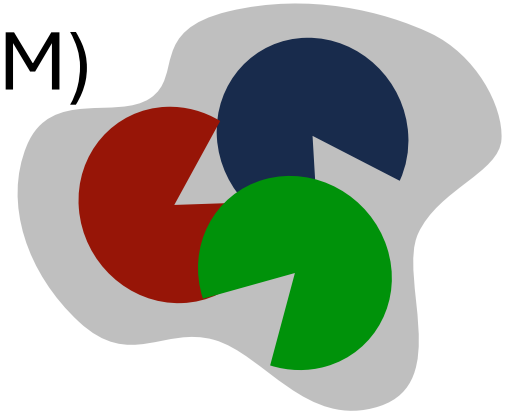
- More DM mechanism

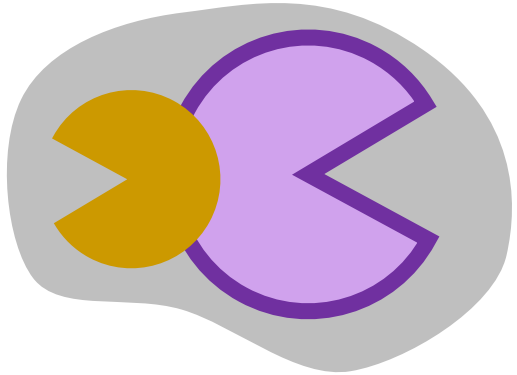
Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky, J. Wacker, 1411. 3727;
A. Katz, E. Salvioni, and B. Shakya, 2006.15148;
LFL, Y. Tsai, 1901.0993; E. Bernreuther, F. Kahlhoefer, M. Kramer and P. Tunney, 1907.04346; LFL, S.Lu, In prep……

- May resolve some cosmological issues

Composite DM Candidates

- Dark baryons (asymmetric DM)





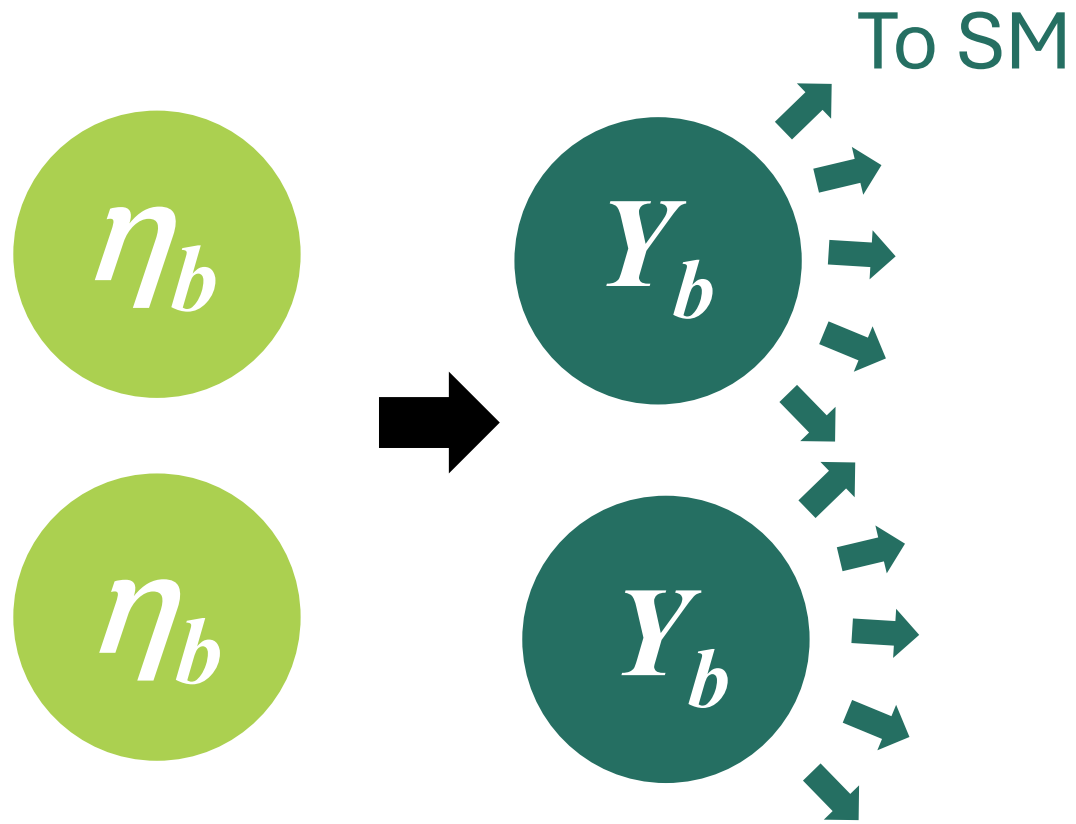
- Dark R-hadrons

- Stable dark mesons

Forbidden Composite DM

The lightest dark sector particle, the DM

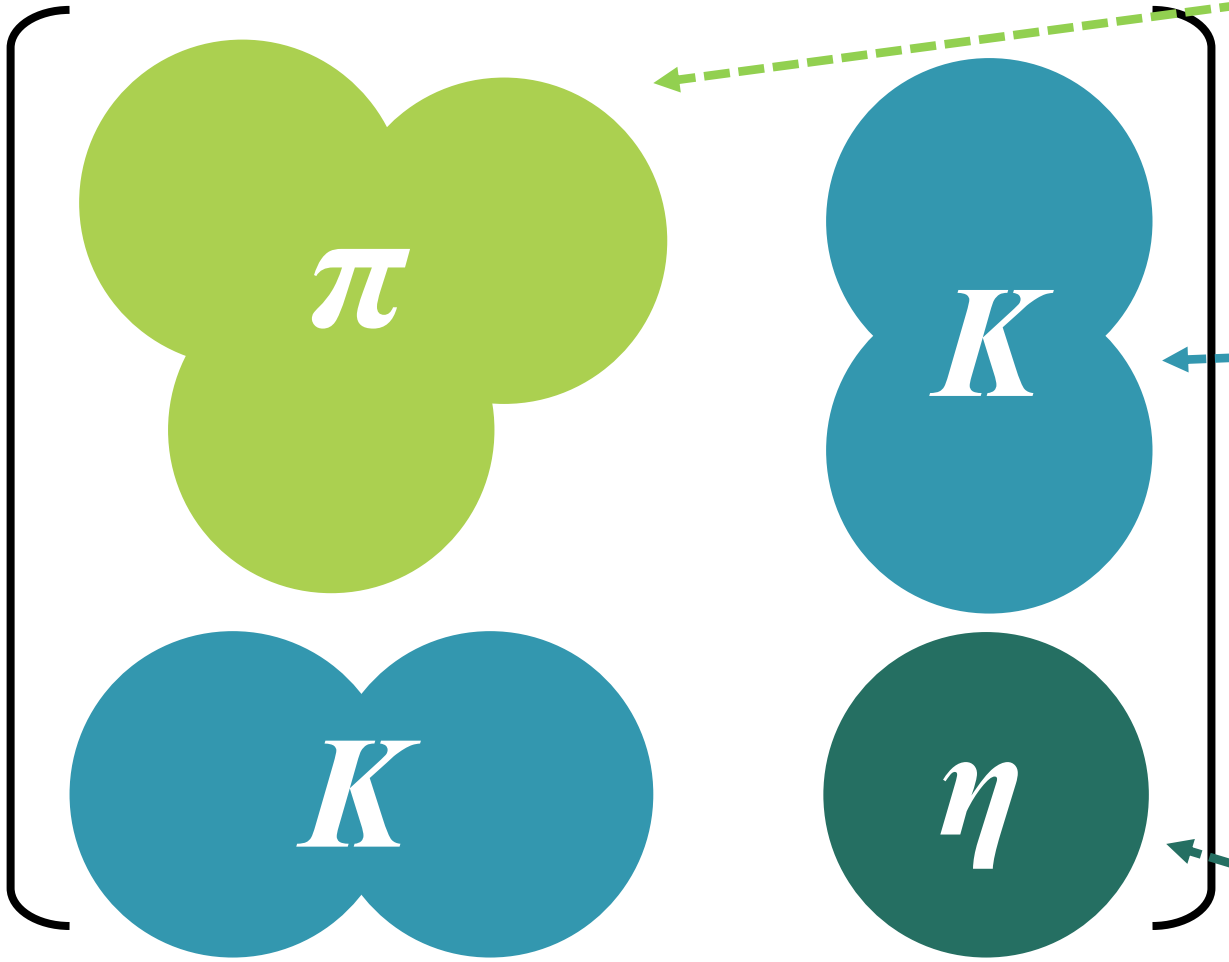
The "excited state", heavier and interacting with the SM



Only energetic particle can go through the mass gap, exponential sensitivity

R.T. D'Agnolo and J.T. Ruderman, 1505.07107; LFL, Y. Tsai, 1901.0993; E. Bernreuther, F. Kahlhoefer, M. Kramer and P. Tunney, 1907.04346……

Back in the SM



"Stable" due to SU(2) isospin symmetry

"Stable" due to strange number conservation

No protection, unstable

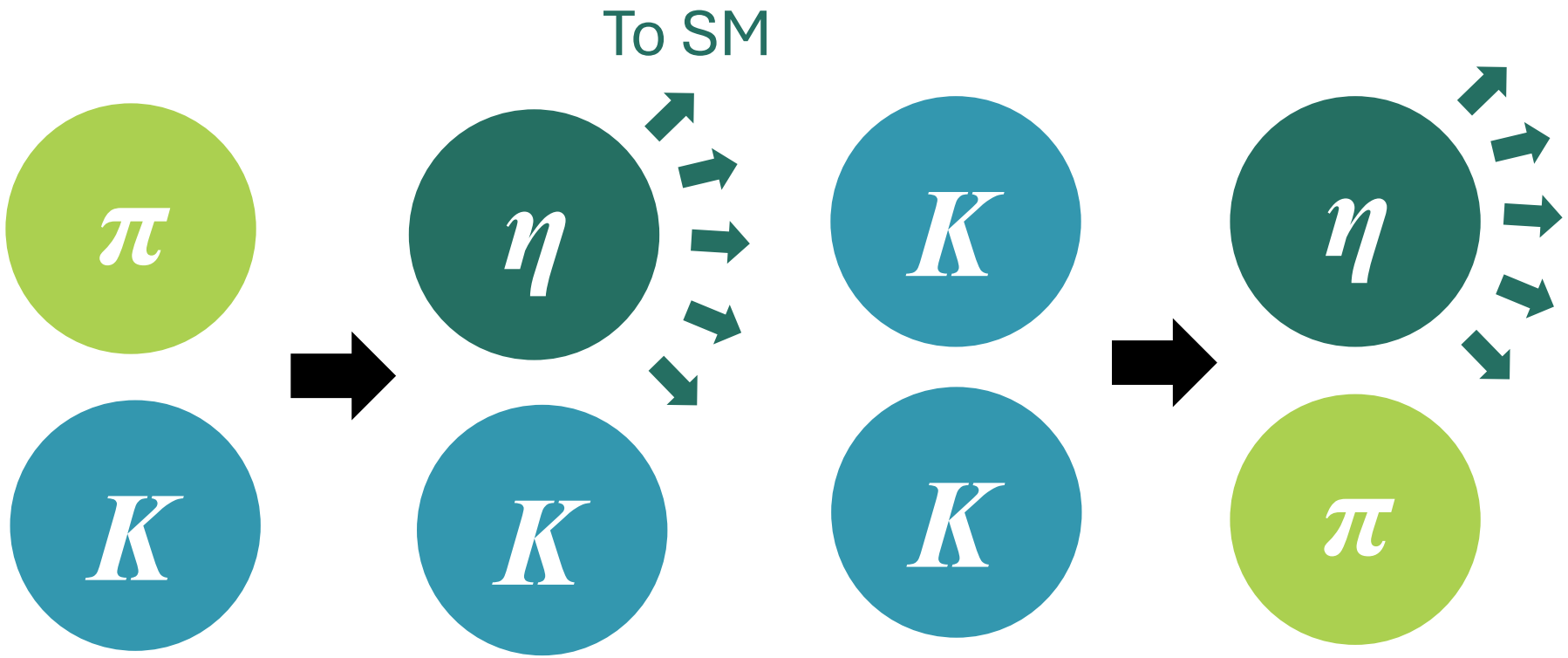
Thermal Mechanisms

η The messenger: heavy meson that decays, contact with the SM

π The DM meson, non-interacting

K The intermediate, exists in many models

Important Alternative Processes



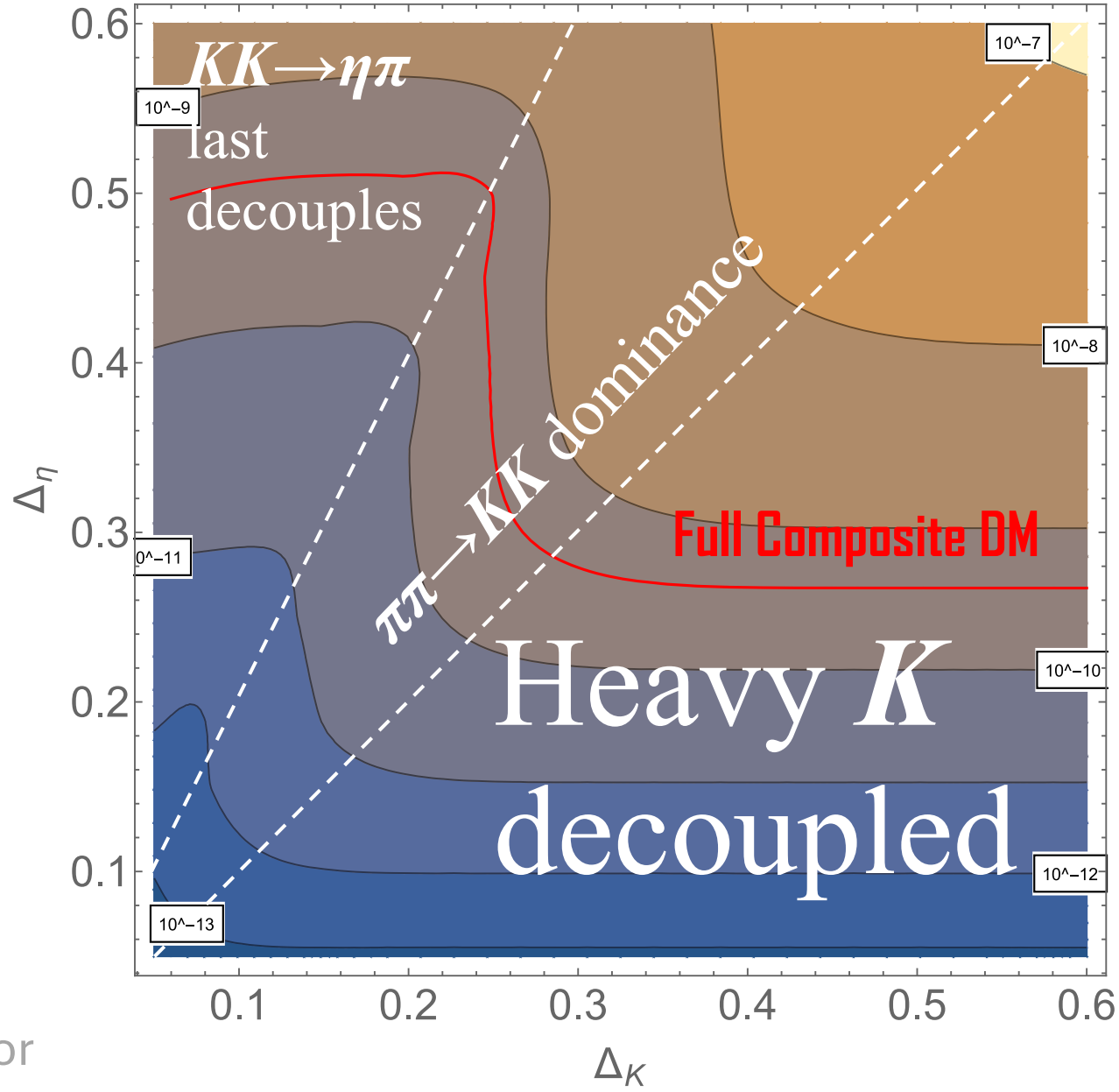
K assisted conversion, low Boltzmann suppression

K annihilation, gives indirect detection signals

GeV DM Test Run

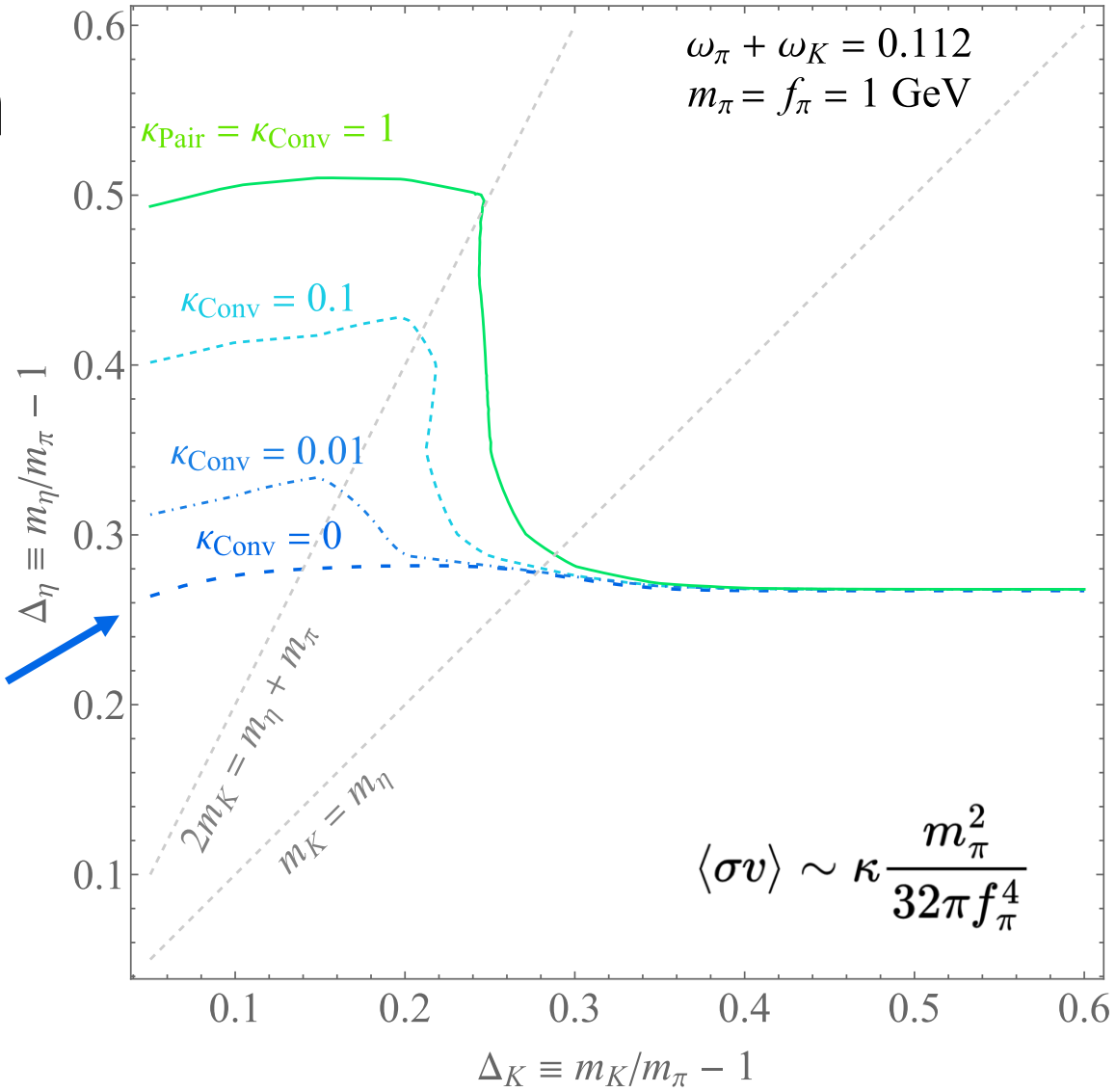
At least three DM phases recognized

* Assuming all processes having similar cross sections, not necessarily true for realistic models

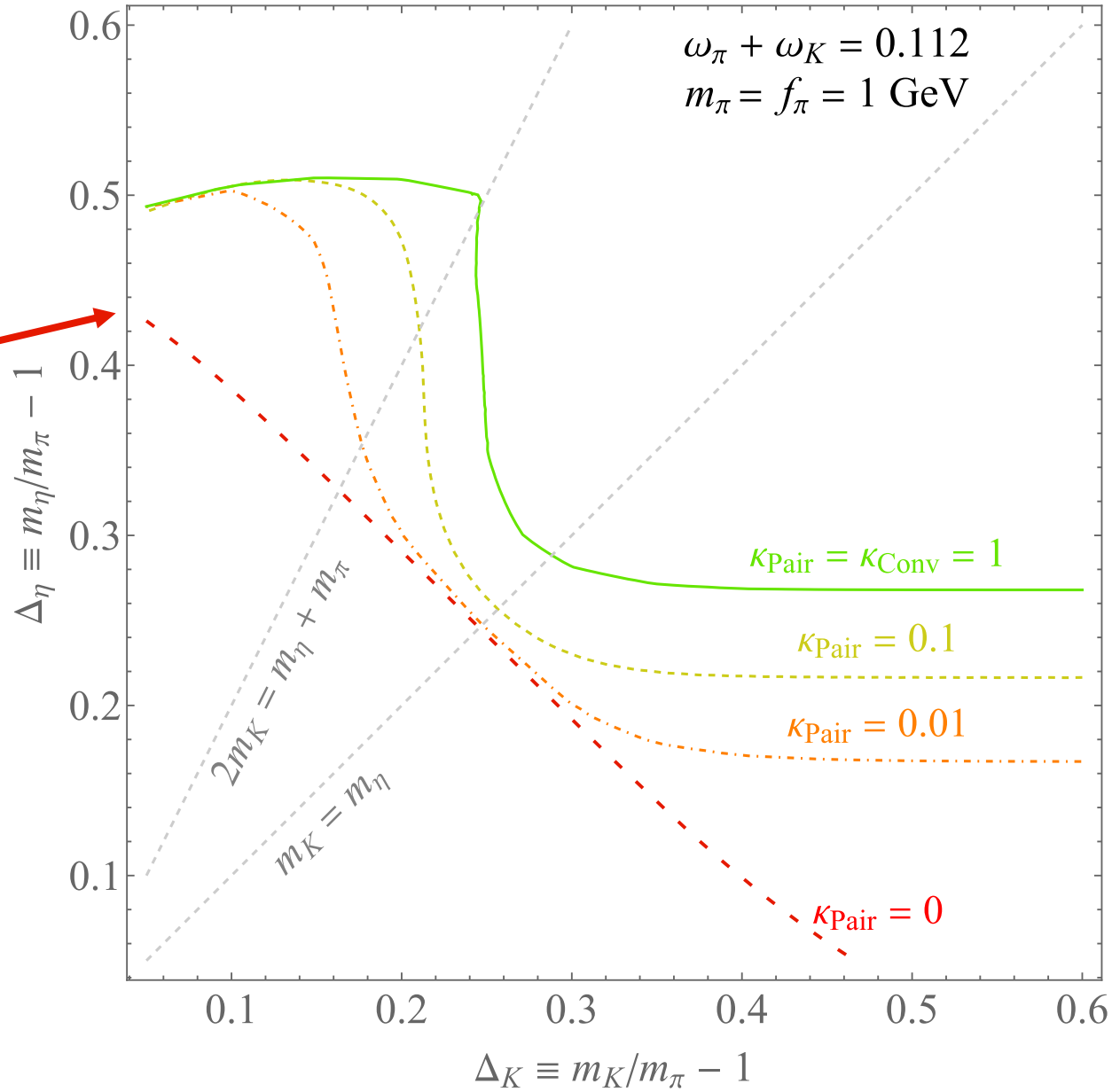


Examining Conversion Rates:

No conversion limit, K as secondary DM



Full $\pi K \to \eta K$ dominance

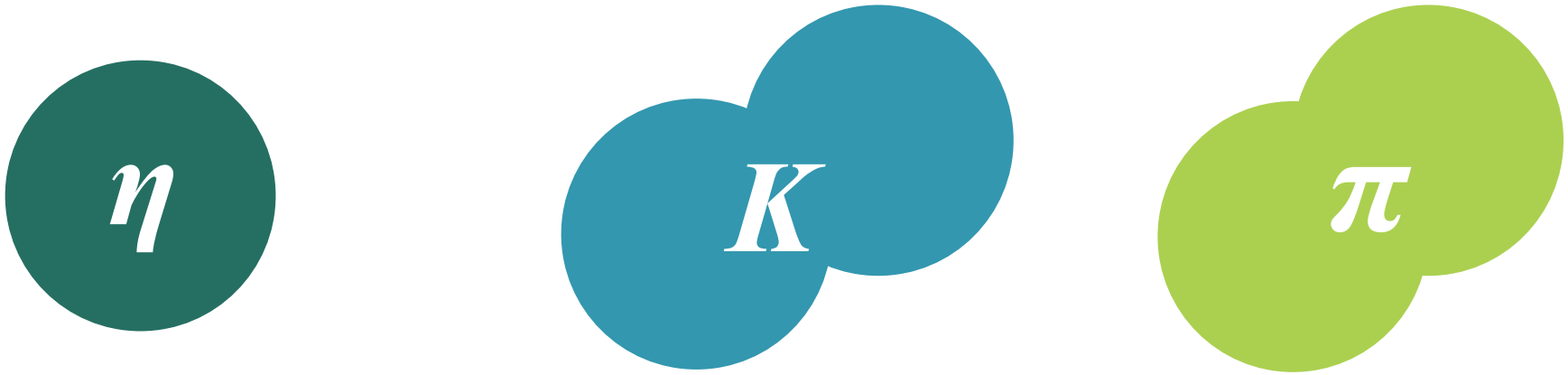


The Model

Gauge group: $SO(N_c) \quad N_c \geq 4$

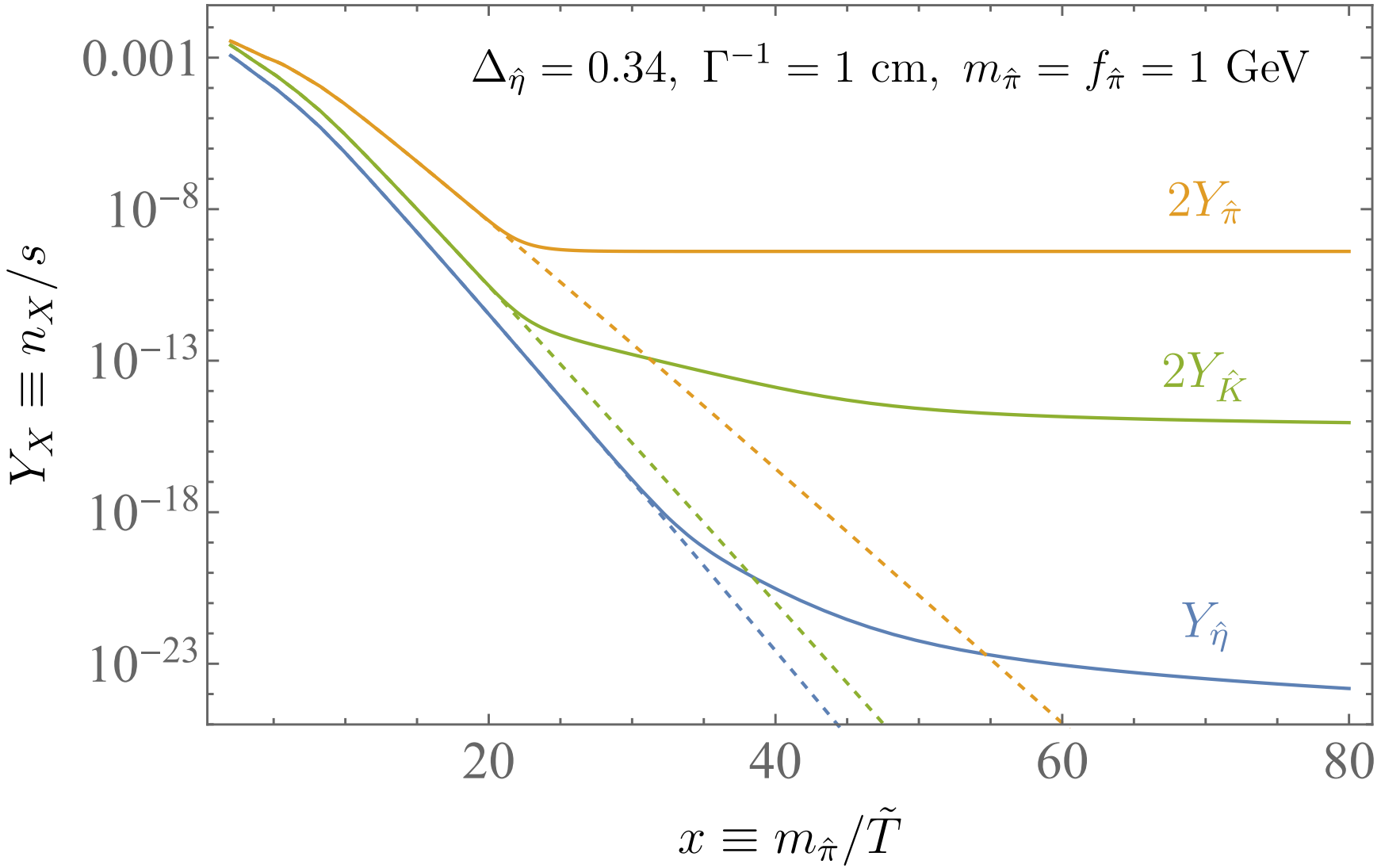
$SU(3)/SO(3) \Longrightarrow$ 5 Goldstone bosons

Two π, two K and one η

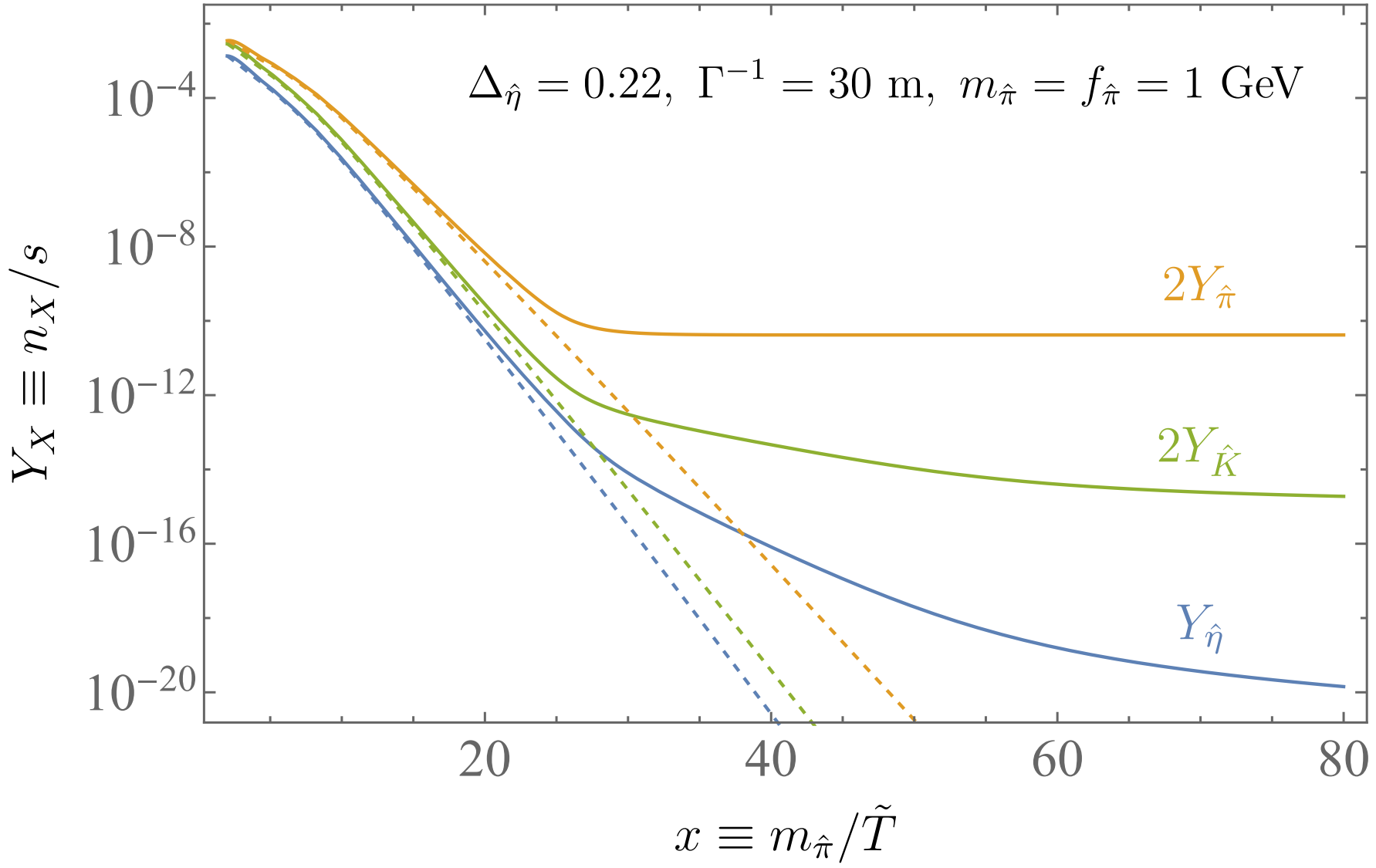


$m_\eta = (1+\Delta_\eta)\, m_\pi >$ $m_K = (1+\Delta_K)\, m_\pi >$ m_π

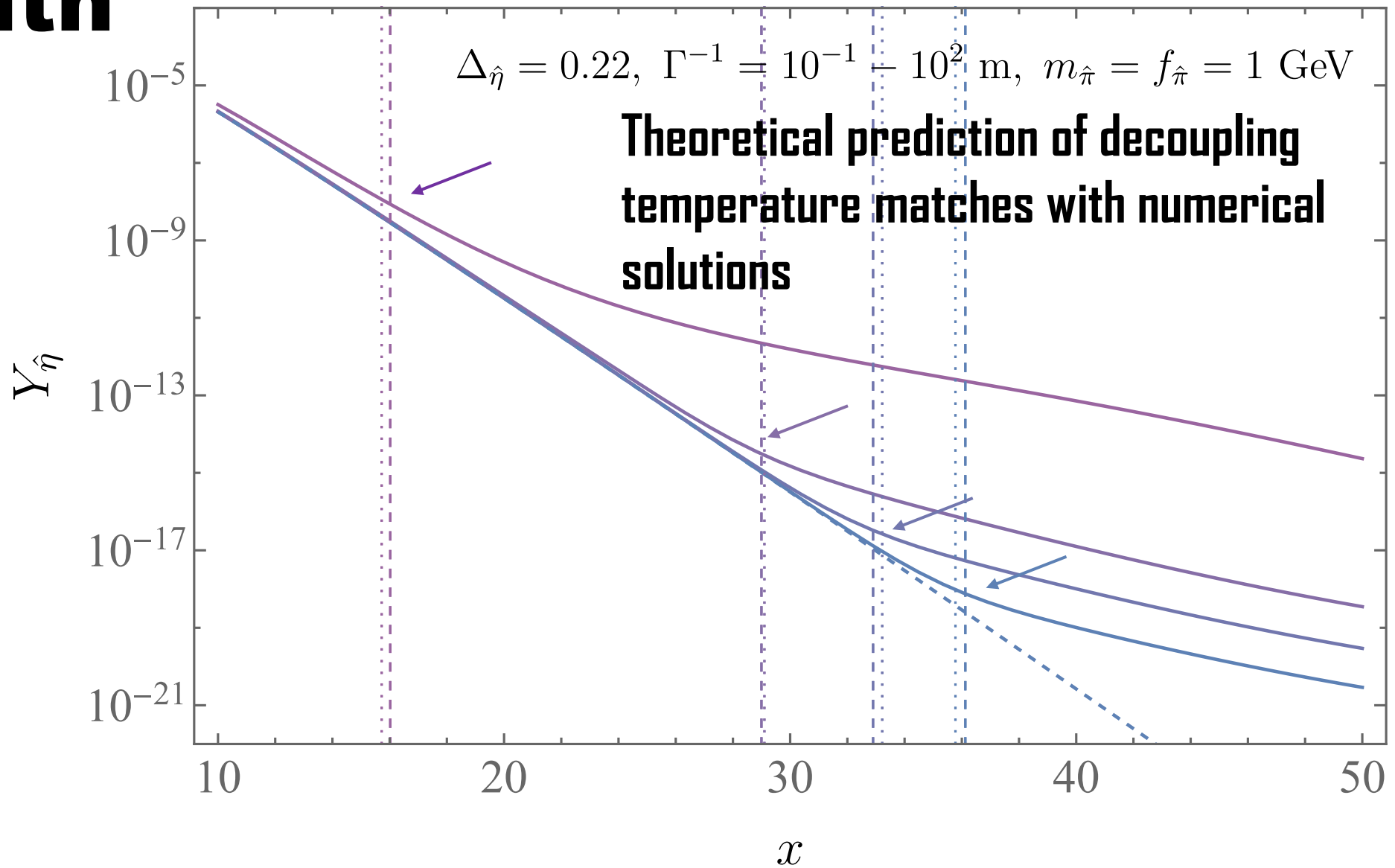
Large Decay Width Limit:
Freezeout Controlled by Conversion

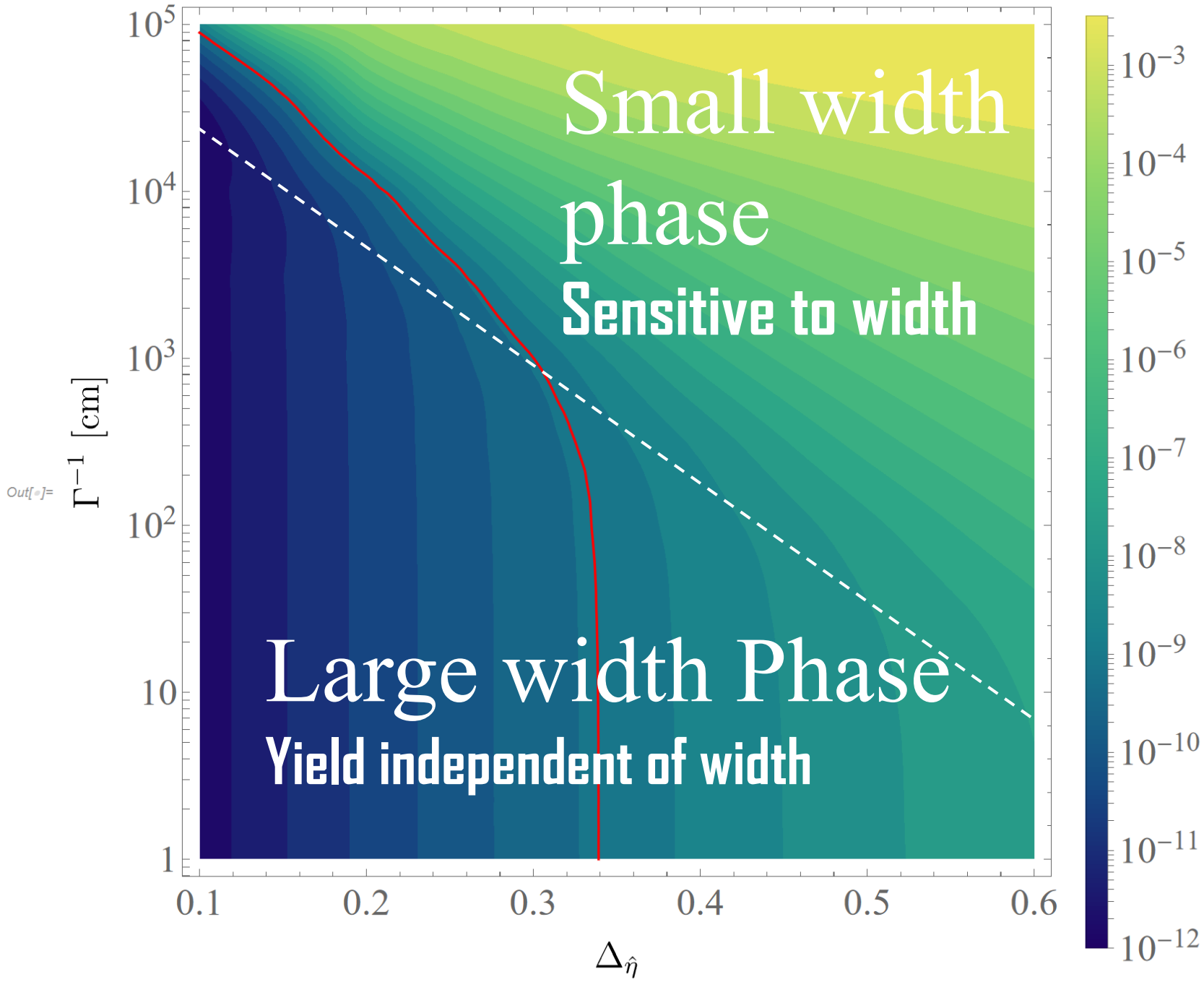


Small Decay Width Limit:
Freezeout Controlled by the Decay

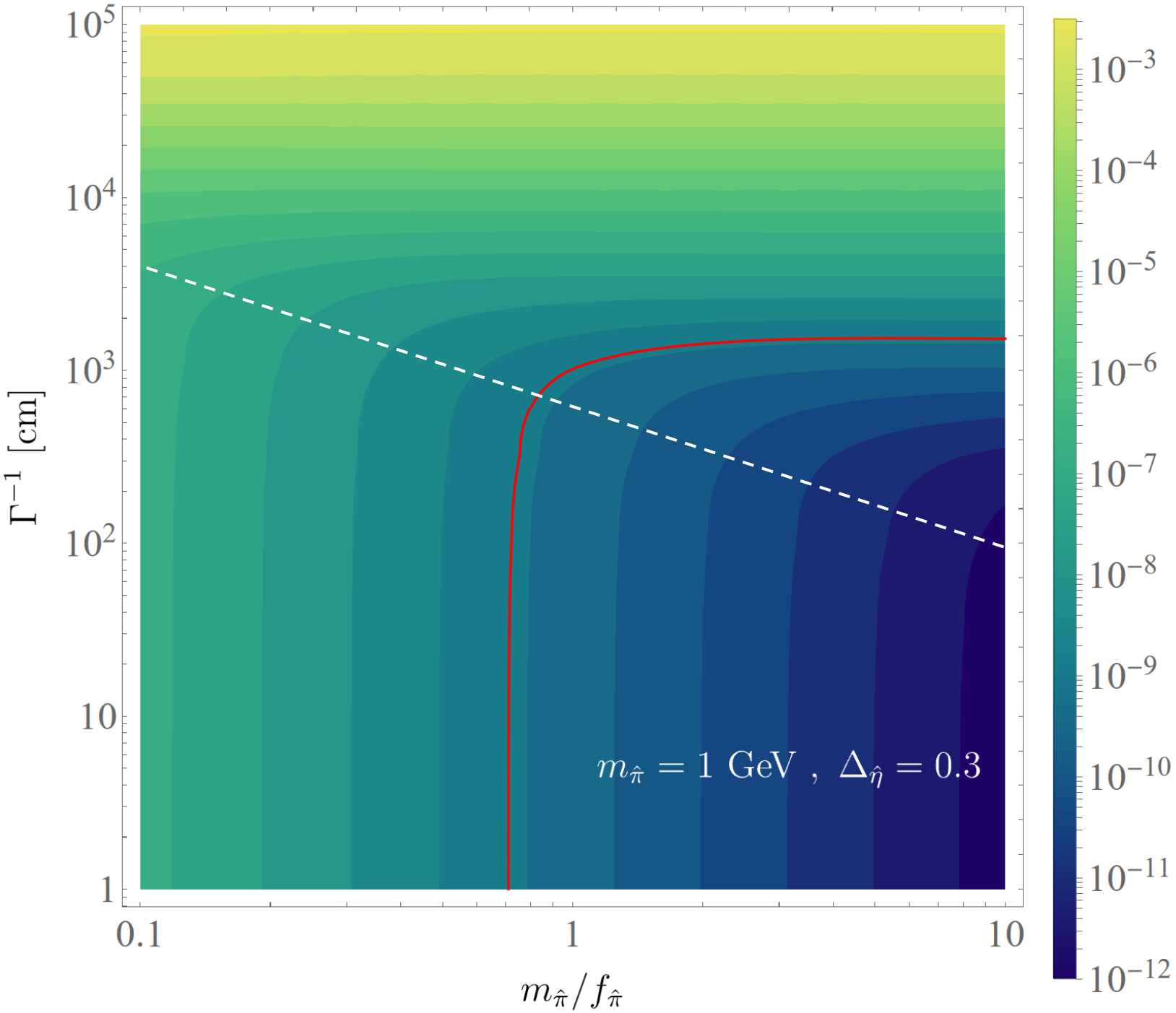


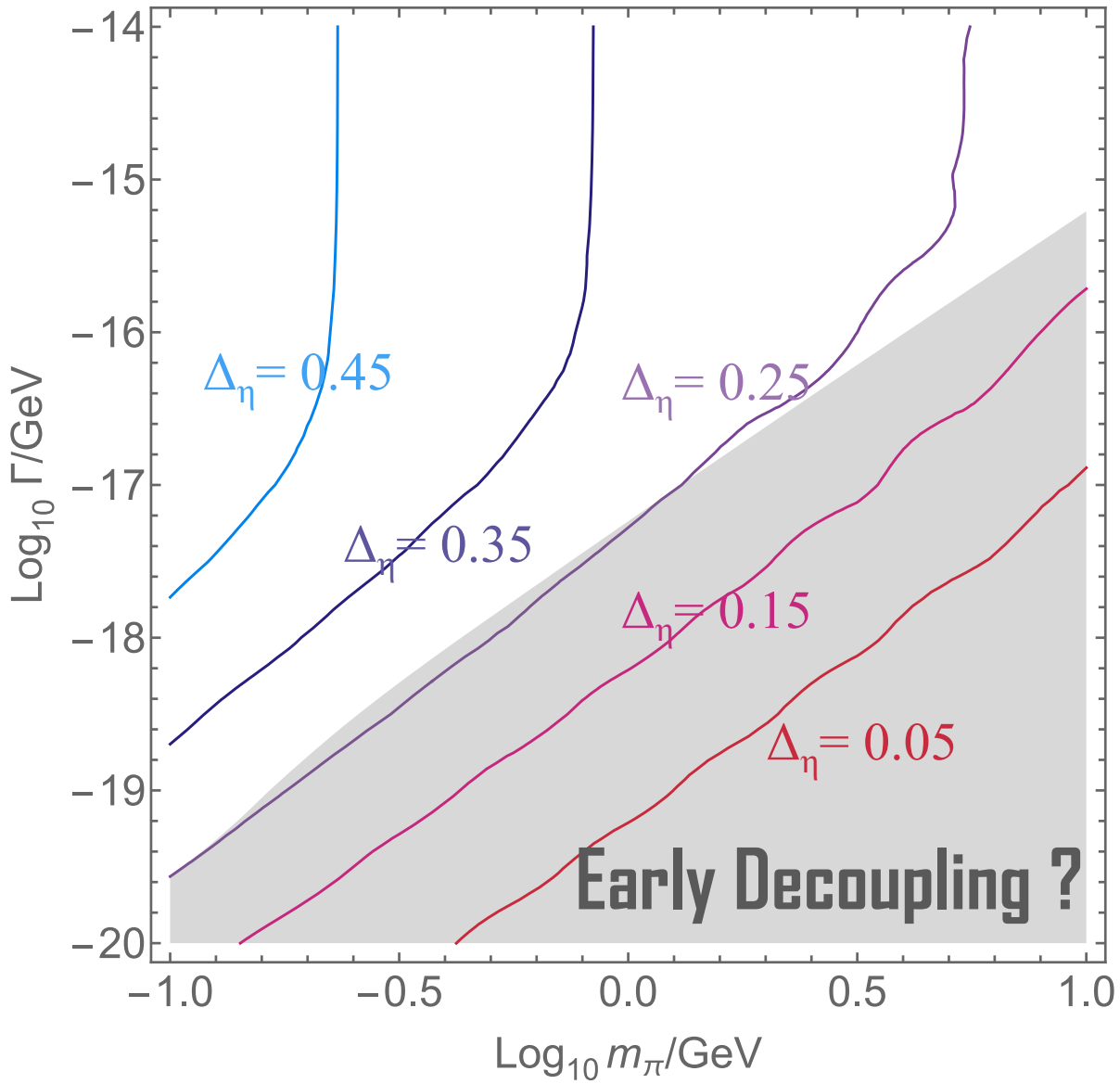
Transition Beteween Different Decay Width




Small width phase
Sensitive to width
Large width Phase
Yield independent of width
Γ^{-1} [cm]
$\Delta_{\hat{\eta}}$
10^5
10^4
10^3
10^2
10
1
0.1
0.2
0.3
0.4
0.5
0.6
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}

Out[ ]=

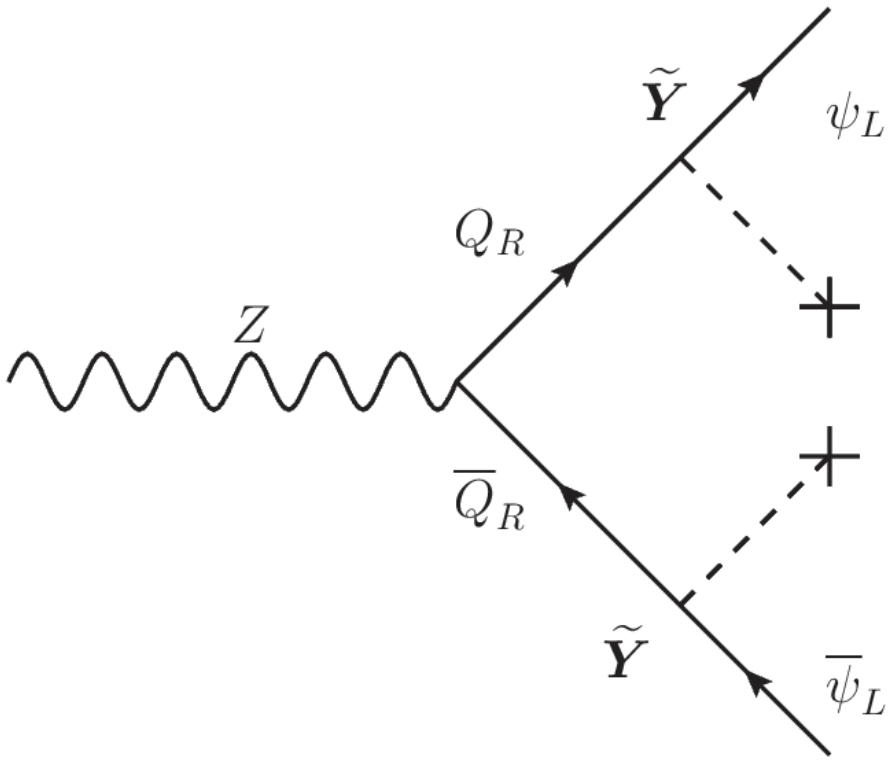

10^5
10^4
10^3
10^2
10
1
Γ^{-1} [cm]
0.1
1
10
$m_{\hat{\pi}}/f_{\hat{\pi}}$
$m_{\hat{\pi}} = 1$ GeV , $\Delta_{\hat{\eta}} = 0.3$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}


−14
−15
−16
−17
−18
−19
−20
Log10 Γ/GeV
−1.0
−0.5
0.0
0.5
1.0
Log10 mπ/GeV
Δη= 0.45
Δη= 0.35
Δη= 0.25
Δη= 0.15
Δη= 0.05
Early Decoupling ?

The EW Portal Back to SM

$$-\mathcal{L}_{\rm UV} \supset Q_i^{cT}(M_Q)_{ij}\epsilon Q_j + Q_i^T H Y_{ij}\epsilon\psi_j + Q_i^{cT}\widetilde{H}\widetilde{Y}_{ij}\epsilon\psi_j + \text{h.c.}$$

$$\begin{aligned}\mathcal{L}_{\rm EFT}^{Q+Q^c} =& \frac{1}{2}\left[\left(\frac{|y_1|^2}{M_{Q_1}^2}-\frac{|\tilde{y}_1|^2}{M_{Q_1}^2}\right)(\psi_1^\dagger\bar{\sigma}^\mu\psi_1+\psi_2^\dagger\bar{\sigma}^\mu\psi_2)+\left(\frac{|y_3|^2}{M_{Q_3}^2}-\frac{|\tilde{y}_3|^2}{M_{Q_3}^2}\right)\psi_3^\dagger\bar{\sigma}^\mu\psi_3\right](iH^\dagger D_\mu H+\text{h.c.})\\ &-\left[\frac{y_1\tilde{y}_1}{M_{Q_1}}|H|^2(\psi_1^T\epsilon\psi+\psi_2^T\epsilon\psi_2)+\frac{y_3\tilde{y}_3}{M_{Q_3}}|H|^2(\psi_3^T\epsilon\psi_3)+\text{h.c.}\right] \qquad (4.3)\\ &+|H|^2\left\{\left(\frac{|y_1|^2}{M_{Q_1}^2}+\frac{|\tilde{y}_1|^2}{M_{Q_1}^2}\right)(\psi_1^\dagger i\not{D}\psi_1+\psi_2^\dagger i\not{D}\psi_2)+\frac{|\tilde{y}_3|^2}{M_{Q_3}^2}\psi_3^\dagger i\not{D}\psi_3+\text{h.c.}\right\},\end{aligned}$$



Mass < 1 GeV : decay to $\mu\mu$

Mass > 1 GeV: hadronic decays

$$\Gamma_{\hat{\eta}} \sim \frac{y^4 f_{\hat{\pi}}^2 m_{\hat{\eta}} m_\mu^2}{M_Q^4} \ll \text{GeV}$$

2408.13304 H-C. Cheng, X. Jiang, LFL

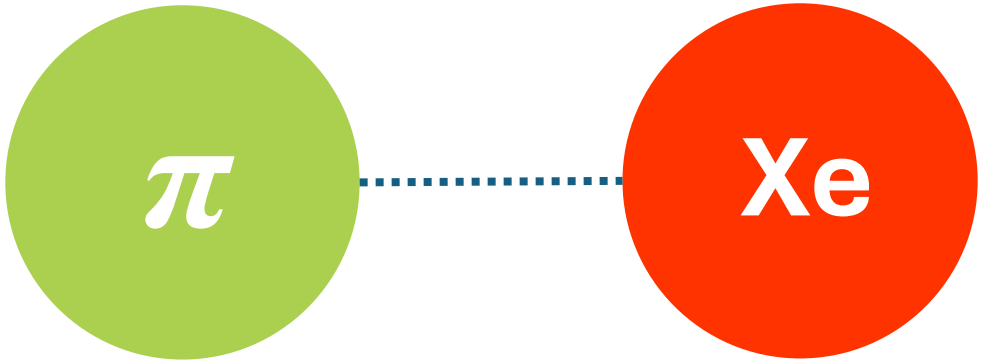
2401.08785 H-C. Cheng, X. Jiang, LFL, E. Salvioni

2110.10691 H-C. Cheng, LFL, E. Salvioni

Direct Detection Prospects

The leading Z exchange between DM and SM are forbidden by the same symmetry that stabilizes the DM, the remaining Higgs exchange:

$$\mathcal{L} \supset 4B \frac{y_1 \tilde{y}_1}{M_{Q_1}} \pi_+ \pi_- |H|^2 \,,$$



Nucleon scattering Xsec:

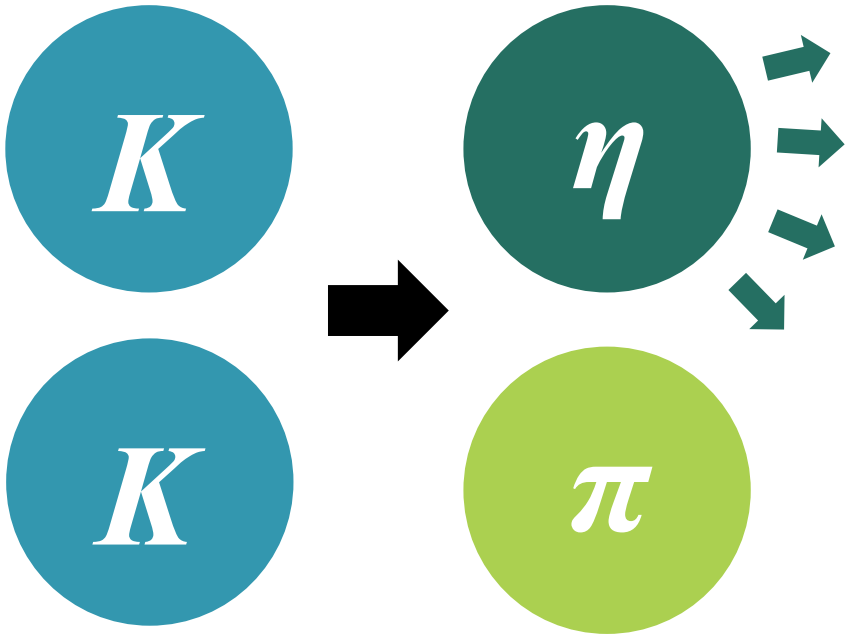
$$\simeq 2.5 \times 10^{-45}\,\mathrm{cm}^2\, b^2 \left(\frac{m_N}{m_\pi + m_N}\right)^2 \left(\frac{f}{\mathrm{GeV}}\right)^2 \left(\frac{y_1 \tilde{y}_1}{10^{-2}}\right)^2 \left(\frac{\mathrm{TeV}}{M_{Q_1}}\right)^2$$

When m > 8 GeV , could be above the neutrino fog

Indirect Detection Prospects

- As forbidden dark matter, usually free from indirect detection

- The remaining secondary Kaon DM can annihilate to SM, strongly depending on how many K remain



The most stringent CMB spectral distortion limit constraints the highly degenerate case ($\Delta < 1\%$)

Phenomenology Prospects

- Emerging jets

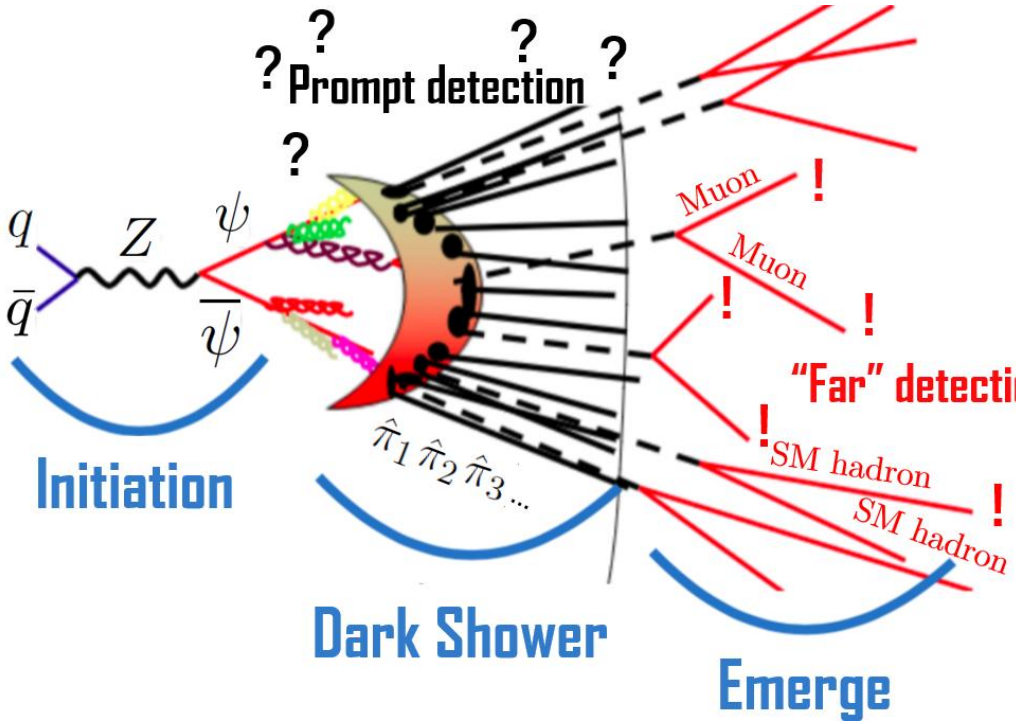
  P. Schwaller, D. Stolarski and A. Weiler, 1502.05409

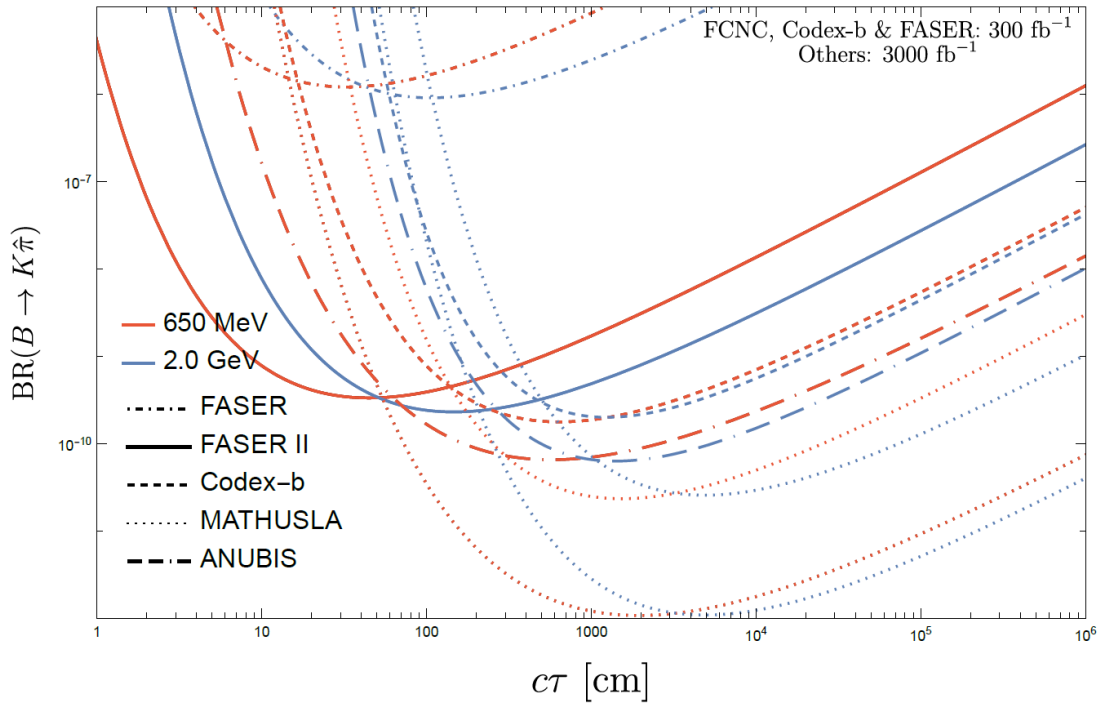
- Semi-visible jets

  T. Cohen, M. Lisanti and H. K. Lou, 1503. 00009

- Individual leptonic vertexes

  LHCb, 2007.03923; CMS, 2112.13769





- SM meson decays such as B/K FCNC decays
- EW precision tests

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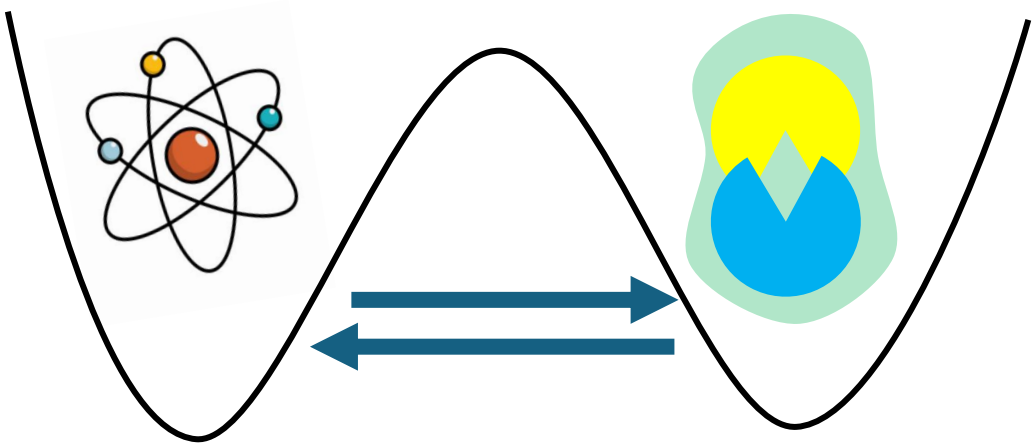
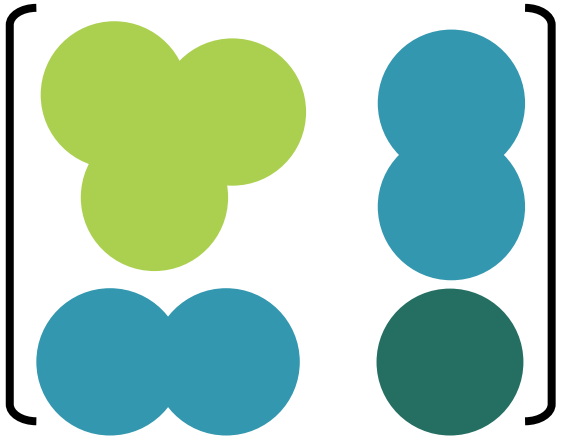
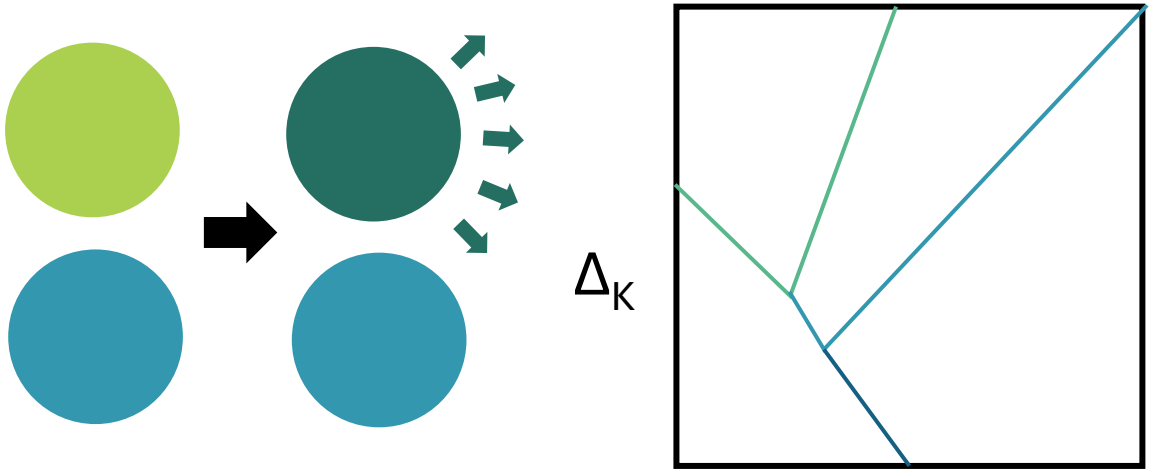
THANK YOU



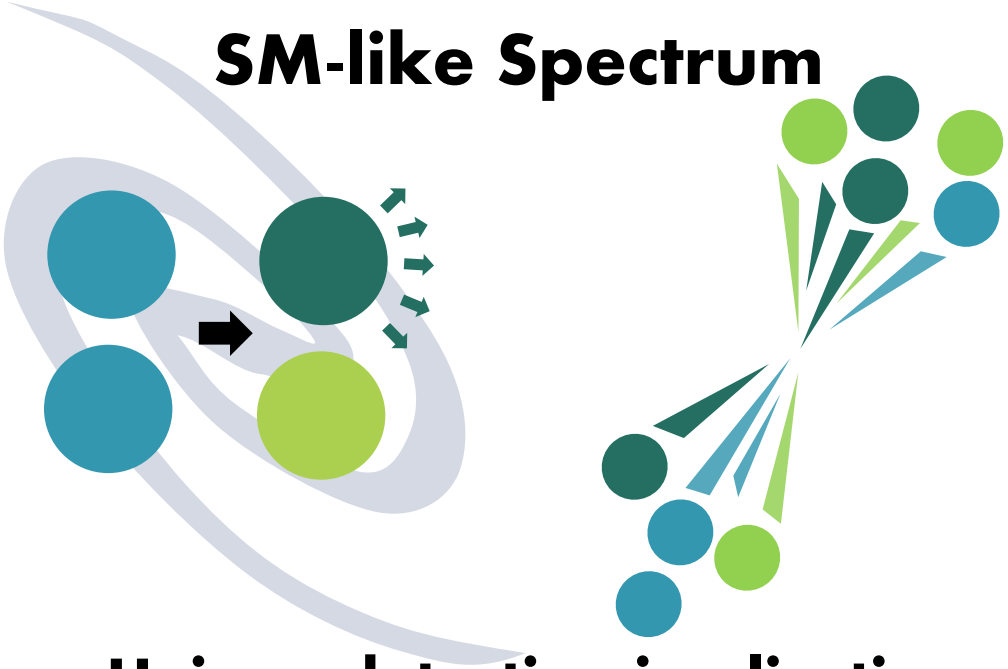
Composite DM with Portal



SM-like Spectrum



Many New Dynamics



Unique detection implications