SLIDING DARK MATTDR AND PHENOMENOLOGY

HIDDEN VALLEY

Lingfeng Li

李凌风

Nanjing Normal University

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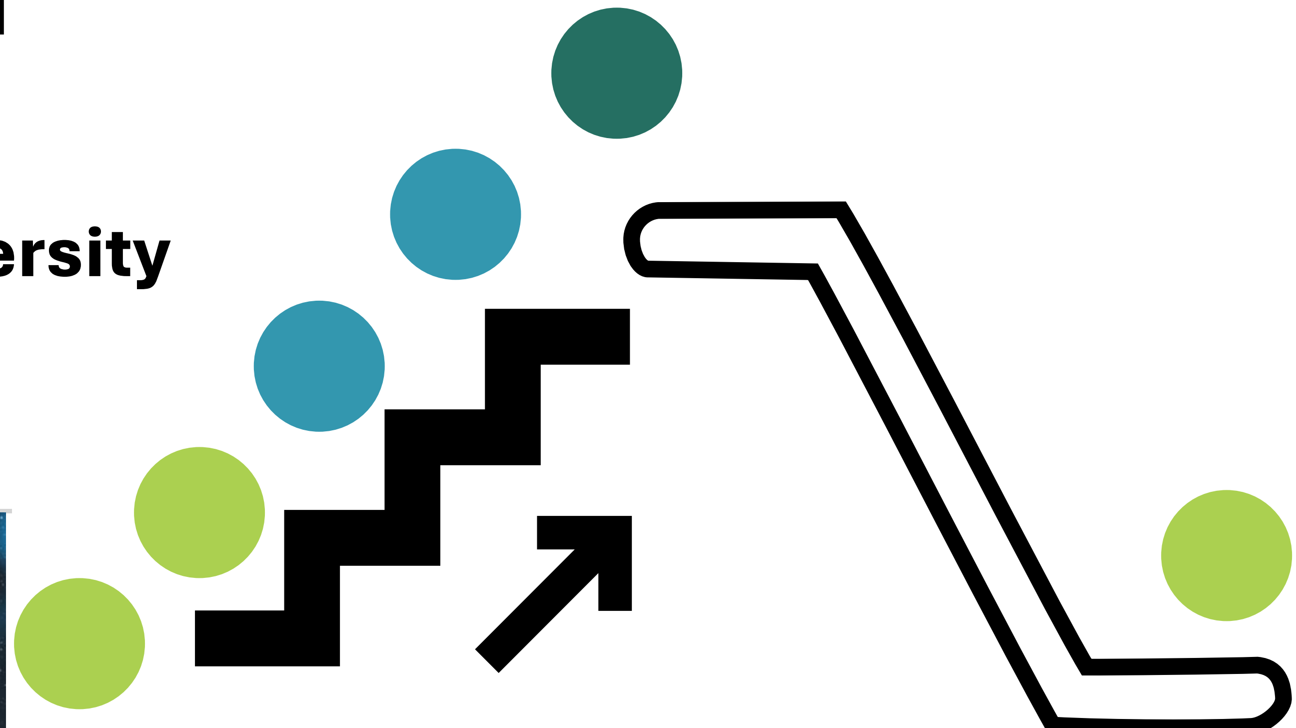


2604.06315 H-C. Cheng, X. Jiang, LFL, E. Salvioni

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

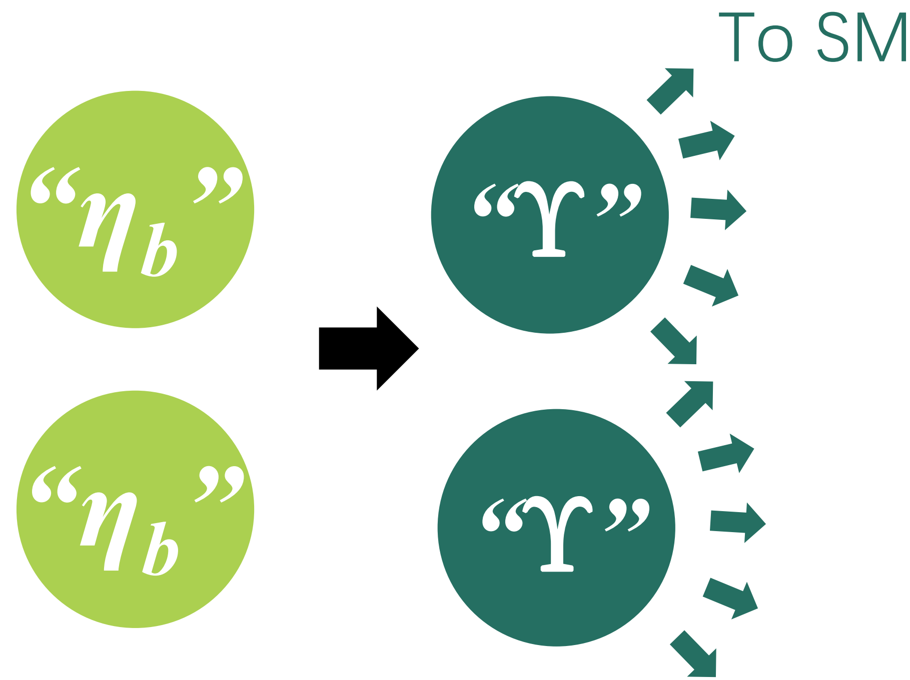
+2401.08785 H-C. Cheng, X. Jiang, LFL, E. Salvioni

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

Forbidden Composite DM

The lightest dark sector particle, the DM

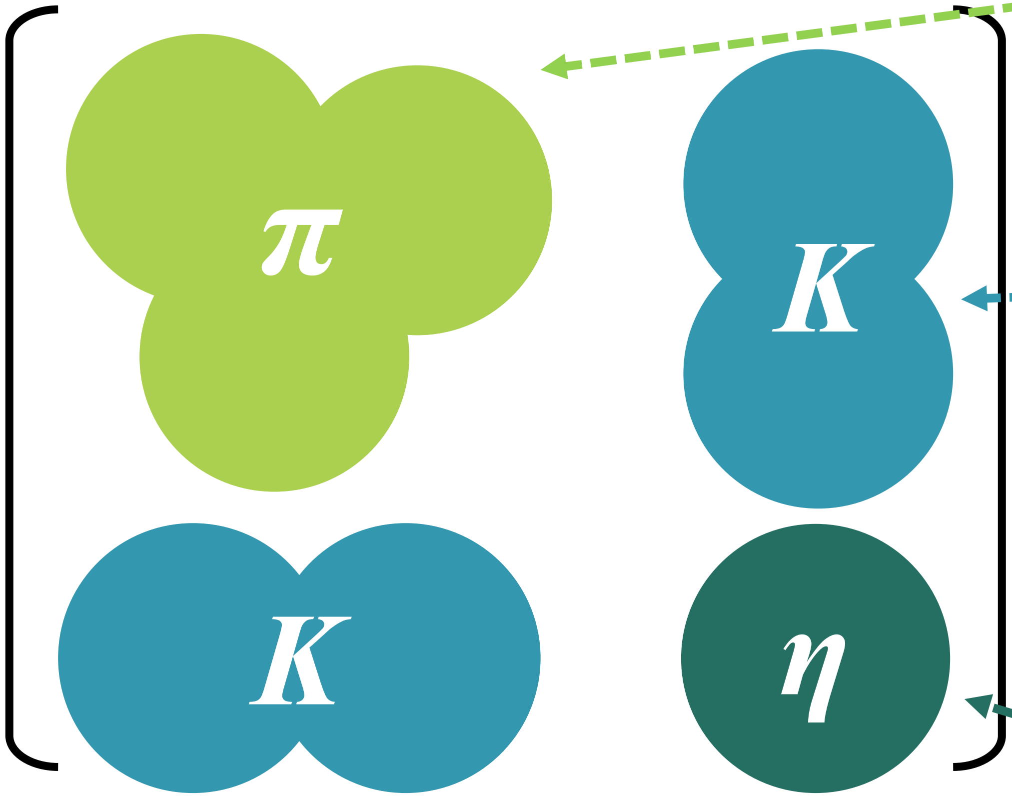
The “excited state”, heavier and interacting with the SM



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

Possible 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

Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky, J. Wacker, 1411.3727; A. Katz, E. Salvioni, and B. Shakya, 2006.15148……

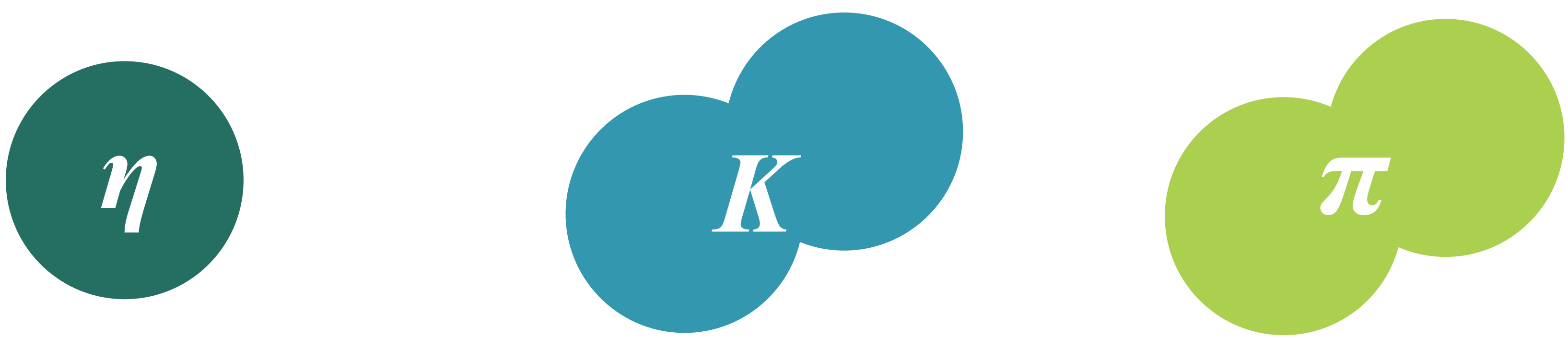
SIMP-like | Pairwise | Scattering

The (Minimal) Model

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

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

Two π, two K and one η



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

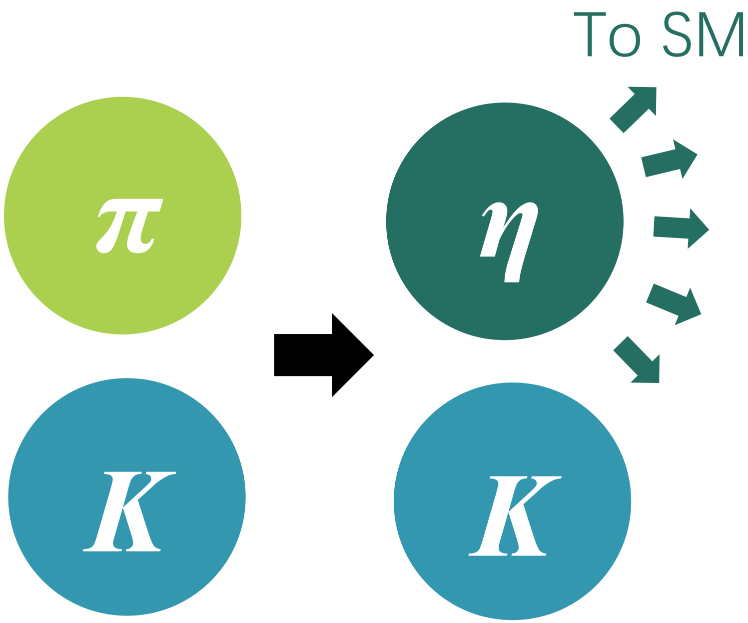
$$\hat{\eta}_0 = \hat{\pi}_8 \qquad \hat{K}_{\pm 1/2} = \frac{1}{\sqrt{2}}(\hat{\pi}_4 \mp i\hat{\pi}_6) \qquad \hat{\pi}_\pm = \frac{1}{\sqrt{2}}(\hat{\pi}_3 \mp i\hat{\pi}_1)$$

Leading ChPT Lagrangian (Low Temp)

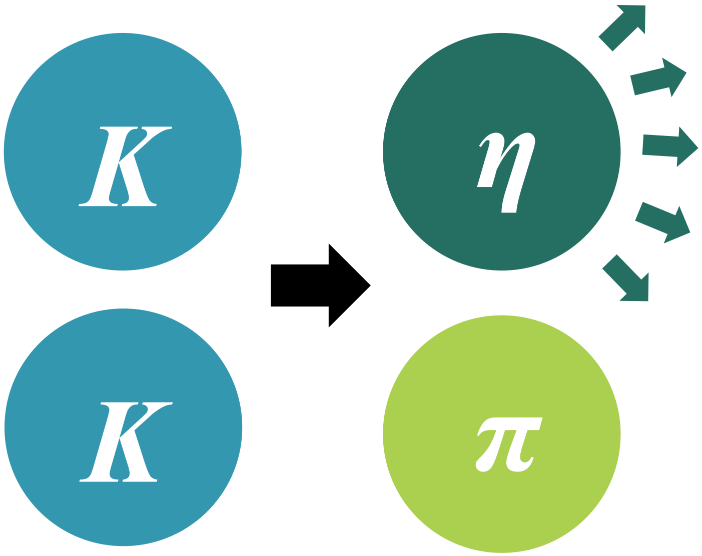
$$
\begin{aligned}
\mathcal{L}_2 \supset \frac{1}{24f^2}\Big\{ & m_{\hat\pi}^2\Big[\hat\eta_0^2 + 2\hat\pi_+\hat\pi_- + 2\hat K_{+1/2}\hat K_{-1/2}\Big]^2 + 2(m_{\hat K}^2 - m_{\hat\pi}^2)\Big[\frac{8}{9}\hat\eta_0^4 + 3\hat\eta_0^2\hat K_{+1/2}\hat K_{-1/2} \\
& - \sqrt{\frac{2}{3}}(\hat\eta_0\hat K_{+1/2}^2\hat\pi_- + \hat\eta_0\hat K_{-1/2}^2\hat\pi_+) + 2\hat K_{+1/2}^2\hat K_{-1/2}^2 + 2\hat K_{+1/2}\hat K_{-1/2}\hat\pi_+\hat\pi_-\Big]\Big\} \\
& + \frac{1}{24f^2}\Big\{4(\partial\hat\pi_+)^2\hat\pi_-^2 + 4\hat\pi_+^2(\partial\hat\pi_-)^2 - 8\partial\hat\pi_+\hat\pi_+\partial\hat\pi_-\hat\pi_- + (\partial\hat K_{+1/2})^2\hat K_{-1/2}^2 + \hat K_{+1/2}^2(\partial\hat K_{-1/2})^2 \\
& - 2\partial\hat K_{+1/2}\hat K_{+1/2}\partial\hat K_{-1/2}\hat K_{-1/2} + 8\hat K_{+1/2}\partial\hat K_{-1/2}\hat\pi_+\partial\hat\pi_- + 8\partial\hat K_{+1/2}\hat K_{-1/2}\partial\hat\pi_+\hat\pi_- \\
& - 4\hat K_{+1/2}\hat K_{-1/2}\partial\hat\pi_+\partial\hat\pi_- - 4\hat K_{+1/2}\partial\hat K_{-1/2}\partial\hat\pi_+\hat\pi_- - 4\partial\hat K_{+1/2}\hat K_{-1/2}\hat\pi_+\partial\hat\pi_- \\
& - 4\partial\hat K_{+1/2}\partial\hat K_{-1/2}\hat\pi_+\hat\pi_- - 6\hat\eta_0^2\partial\hat K_{+1/2}\partial\hat K_{-1/2} - 6(\partial\hat\eta_0)^2\hat K_{+1/2}\hat K_{-1/2} \\
& + 6\hat\eta_0\partial\hat\eta_0\partial\hat K_{+1/2}\hat K_{-1/2} + 6\hat\eta_0\partial\hat\eta_0\hat K_{+1/2}\partial\hat K_{-1/2} + 2\sqrt{6}\Big[\partial\hat\eta_0\partial\hat K_{-1/2}\hat K_{-1/2}\hat\pi_+ \\
& + \partial\hat\eta_0\partial\hat K_{+1/2}\hat K_{+1/2}\hat\pi_- - \partial\hat\eta_0\hat K_{+1/2}^2\partial\hat\pi_- - \partial\hat\eta_0\hat K_{-1/2}^2\partial\hat\pi_+ - \hat\eta_0(\partial\hat K_{-1/2})^2\hat\pi_+ \\
& - \hat\eta_0(\partial\hat K_{+1/2})^2\hat\pi_- + \hat\eta_0\partial\hat K_{-1/2}\hat K_{-1/2}\partial\hat\pi_+ + \hat\eta_0\partial\hat K_{+1/2}\hat K_{+1/2}\partial\hat\pi_-\Big]\Big\}.
\end{aligned}
\tag{A.1}
$$

Mass & 4-point interaction terms

Important Alternative Processes



K assisted conversion, low Boltzmann suppression



K annihilation, gives indirect detection signals

The key scattering terms

$$\frac{dY_{\hat\pi}}{dx} = -\frac{s(x)}{\tilde H(x)x}\Bigg[-\langle\sigma v\rangle_{\hat K\hat K\to\hat\pi\hat\pi}\left(Y_{\hat K}^2 - Y_{\hat K}^{\mathrm{eq}\,2}\frac{Y_{\hat\pi}^2}{Y_{\hat\pi}^{\mathrm{eq}\,2}}\right) - \frac{1}{2}\langle\sigma v\rangle_{\hat K\hat K\to\hat\pi\hat\eta}\left(Y_{\hat K}^2 - Y_{\hat K}^{\mathrm{eq}\,2}\frac{Y_{\hat\pi}Y_{\hat\eta}}{Y_{\hat\pi}^{\mathrm{eq}}Y_{\hat\eta}^{\mathrm{eq}}}\right)$$

$$-\langle\sigma v\rangle_{\hat K\hat\eta\to\hat K\hat\pi}\left(Y_{\hat K}Y_{\hat\eta} - Y_{\hat\eta}^{\mathrm{eq}}\frac{Y_{\hat K}Y_{\hat\pi}}{Y_{\hat\pi}^{\mathrm{eq}}}\right) - \frac{1}{2}\langle\sigma v\rangle_{\hat\eta\hat\eta\to\hat\pi\hat\pi}\left(Y_{\hat\eta}^2 - Y_{\hat\eta}^{\mathrm{eq}\,2}\frac{Y_{\hat\pi}^2}{Y_{\hat\pi}^{\mathrm{eq}\,2}}\right)\Bigg]$$

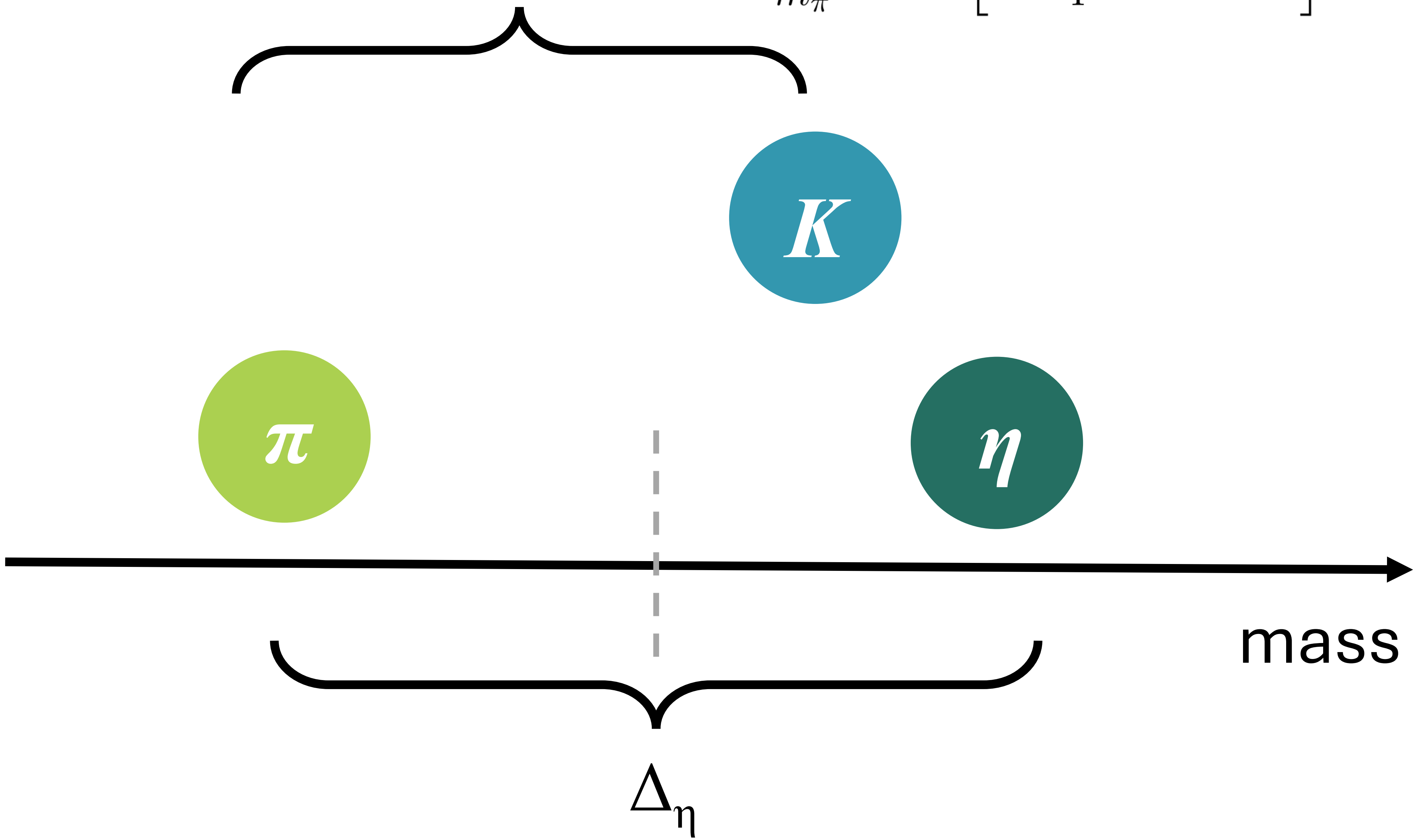
$$-\frac{s(x)^2}{\tilde H(x)x}\Bigg[2\langle\sigma v^2\rangle_{\hat K\hat\pi\hat\pi\to\hat\eta\hat K}\left(Y_{\hat K}Y_{\hat\pi}^2 - Y_{\hat\pi}^{\mathrm{eq}\,2}\frac{Y_{\hat\eta}Y_{\hat K}}{Y_{\hat\eta}^{\mathrm{eq}}}\right) + \langle\sigma v^2\rangle_{\hat\eta\hat\pi\hat\pi\to\hat K\hat K}\left(Y_{\hat\eta}Y_{\hat\pi}^2 - Y_{\hat\eta}^{\mathrm{eq}}Y_{\hat\pi}^{\mathrm{eq}\,2}\frac{Y_{\hat K}^2}{Y_{\hat K}^{\mathrm{eq}\,2}}\right)$$

$$-\langle\sigma v^2\rangle_{\hat\eta\hat K\hat K\to\hat\pi\hat\pi}\left(Y_{\hat\eta}Y_{\hat K}^2 - Y_{\hat\eta}^{\mathrm{eq}}Y_{\hat K}^{\mathrm{eq}\,2}\frac{Y_{\hat\pi}^2}{Y_{\hat\pi}^{\mathrm{eq}\,2}}\right)\Bigg], \quad (\mathrm{A.9})$$

5-pt WZW terms negligible

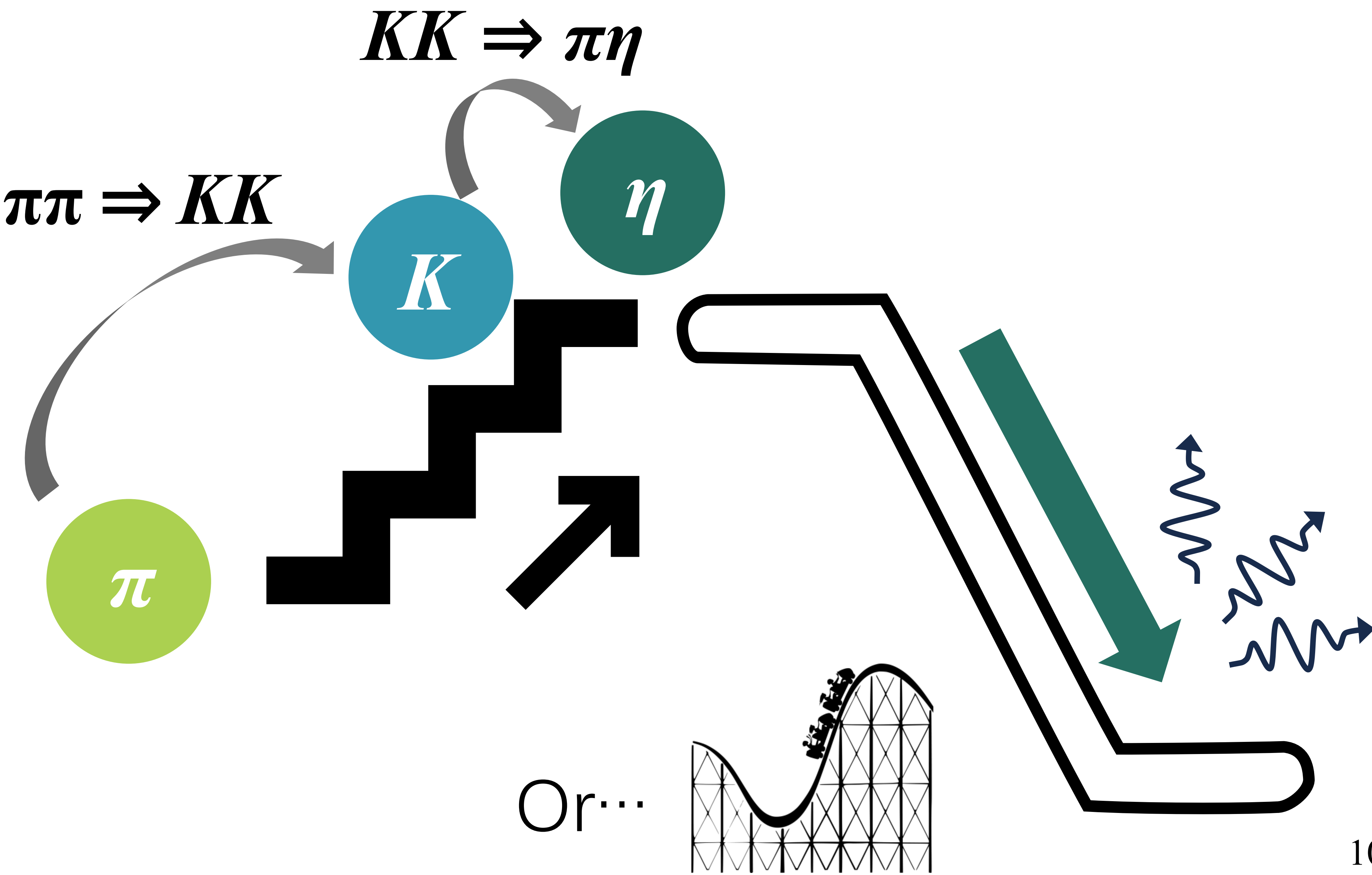
Δ_K

$$\Delta_{\hat{K}} \equiv \frac{m_{\hat{K}}}{m_{\hat{\pi}}} - 1 = \left[1 + \frac{3}{4}\Delta_{\hat{\eta}}(2 + \Delta_{\hat{\eta}})\right]^{1/2} - 1$$

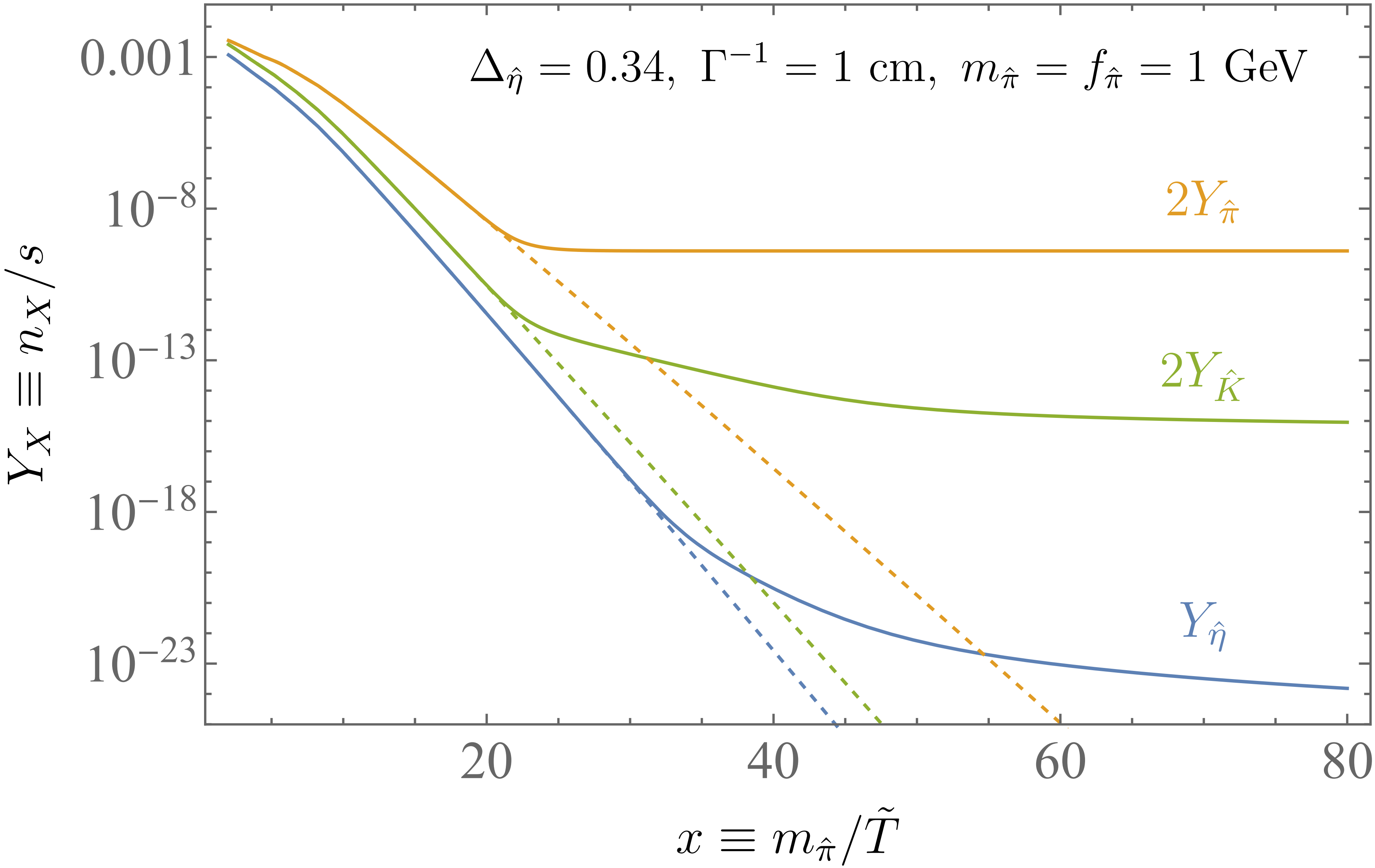


$KK \Rightarrow \pi\eta$ onshell and unsupressed

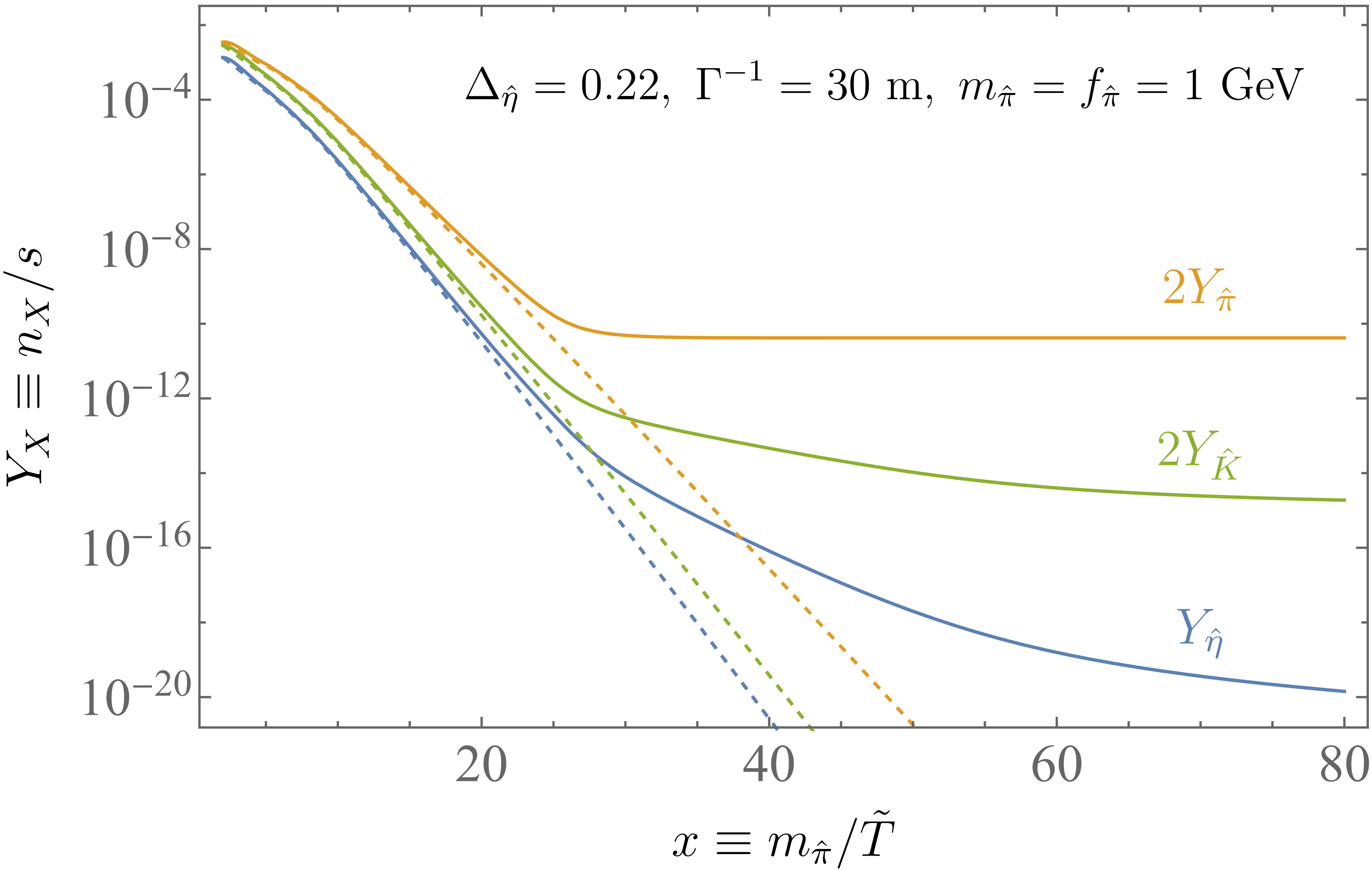
The “Sliding” Process



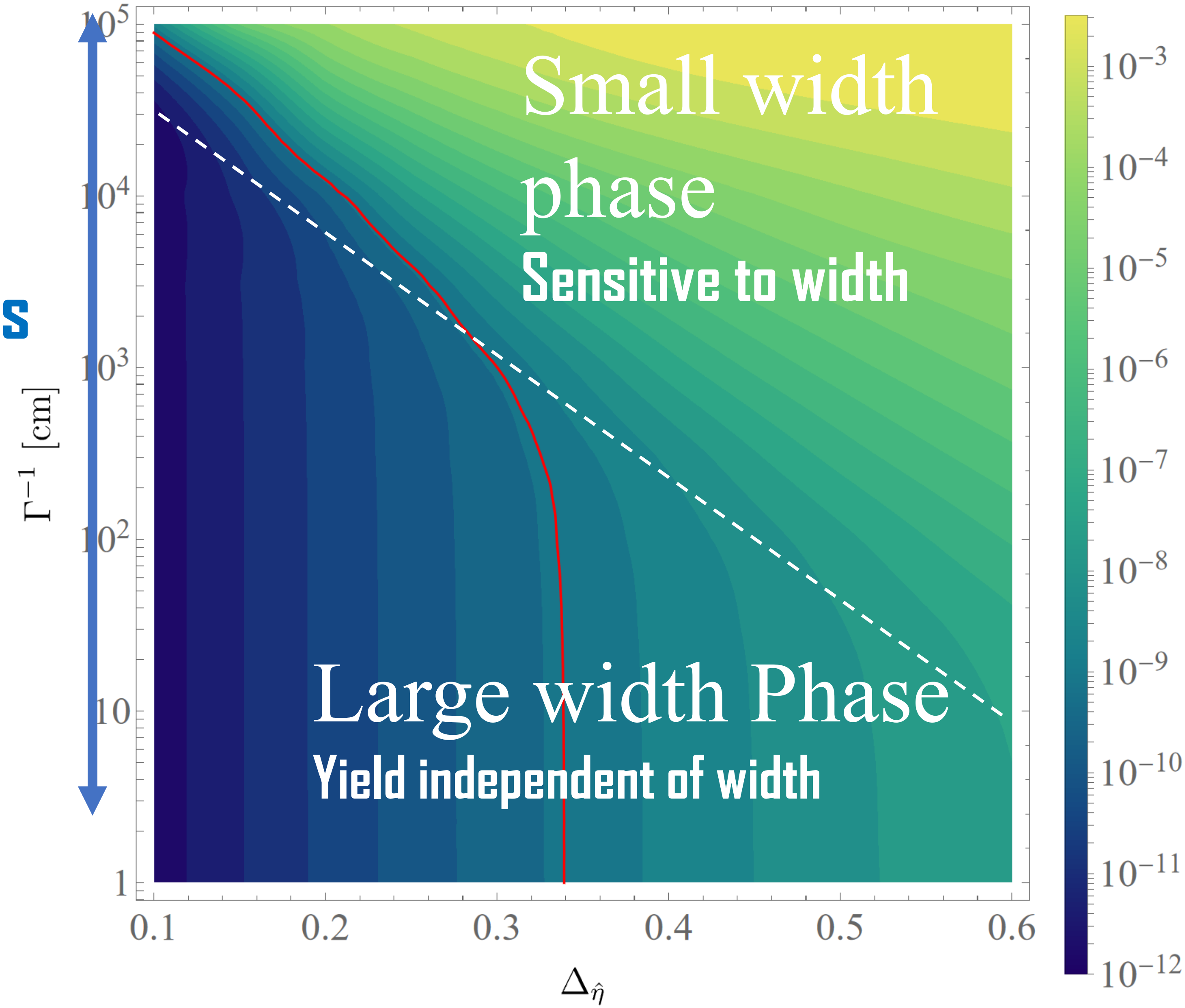
Large Decay Width Limit:
Freezeout Controlled by Conversion

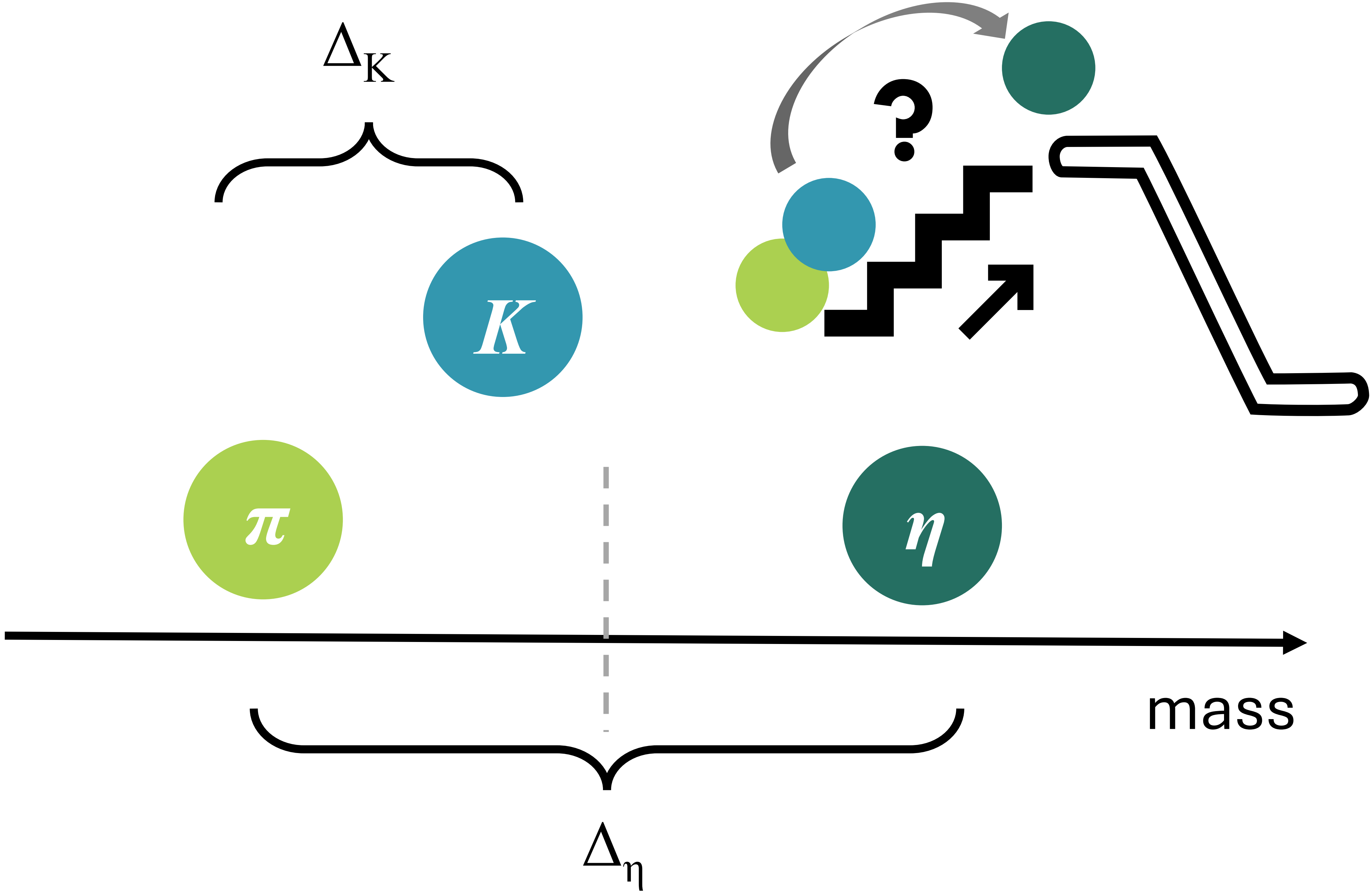


Small Decay Width Limit: Freezeout Controlled by Decay

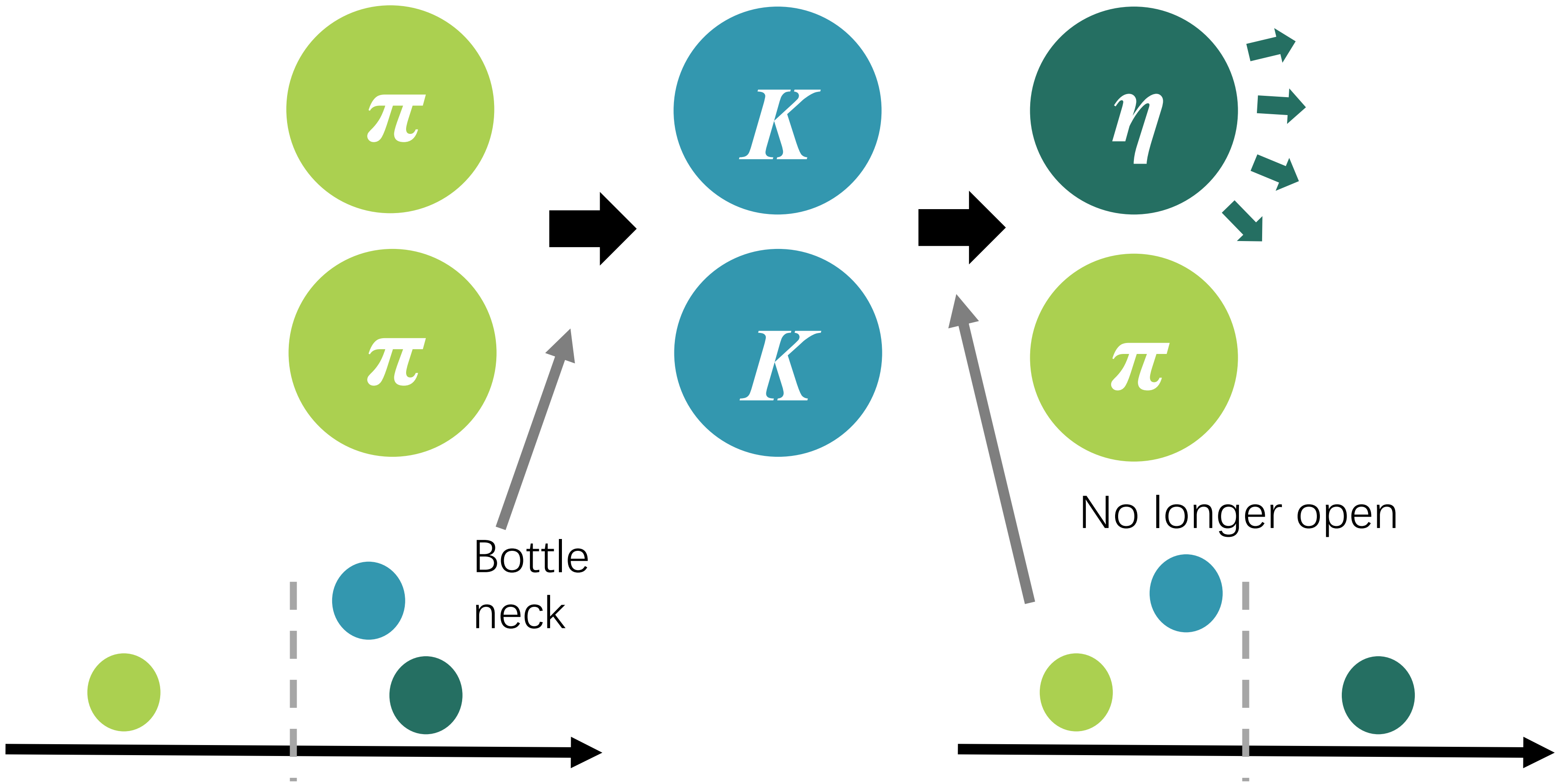


Decay at Human/Lab Length Scales

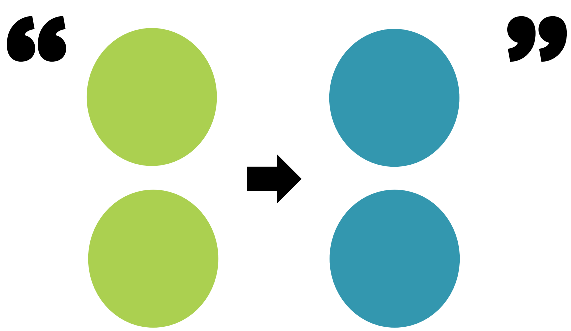




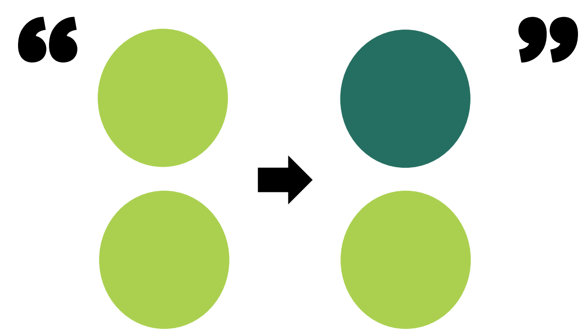
Δ_K
K
π
η
mass
Δ_η



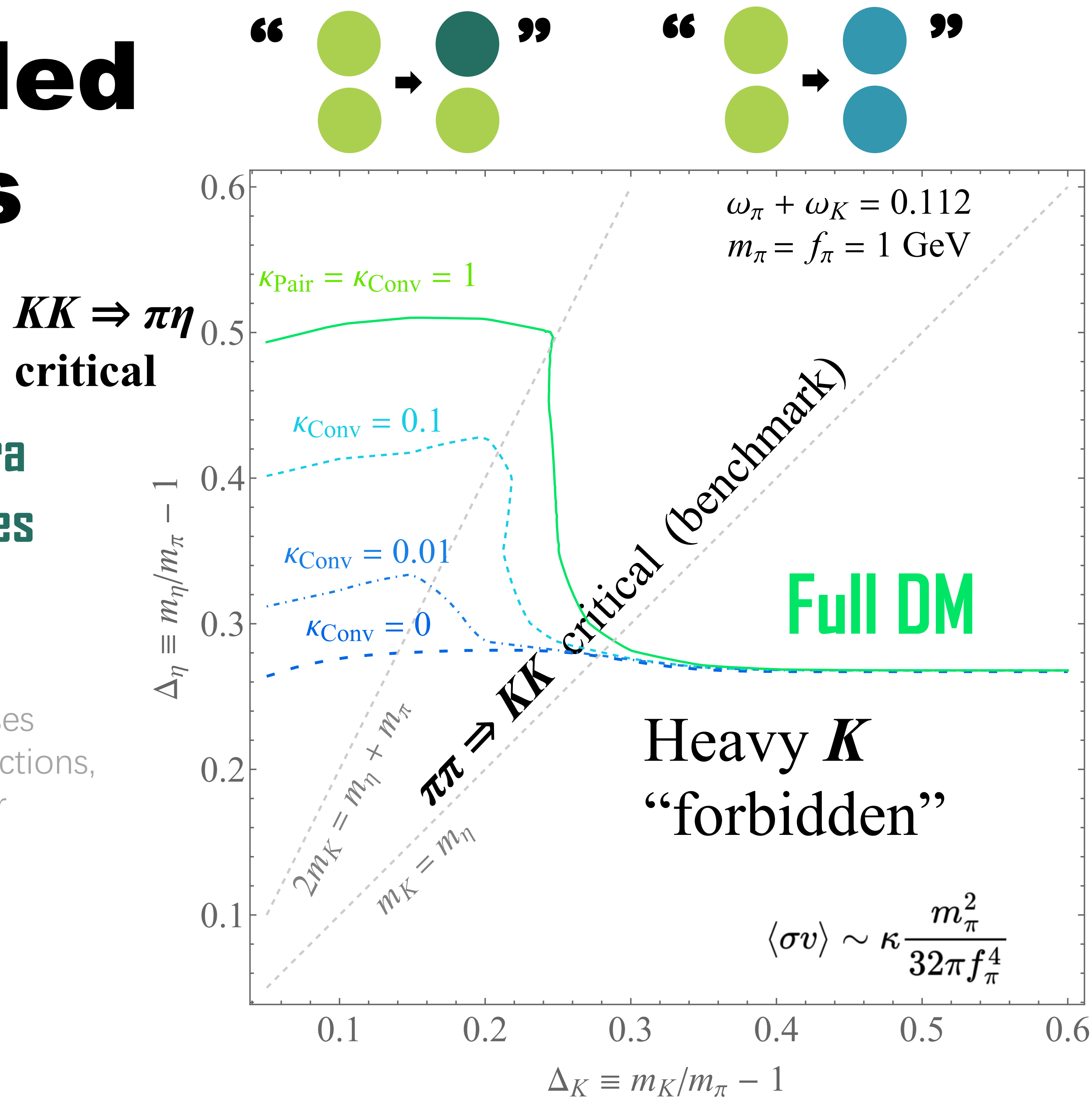
Effectively $\pi\pi \Rightarrow KK$



Effectively $\pi\pi \Rightarrow \pi\eta$

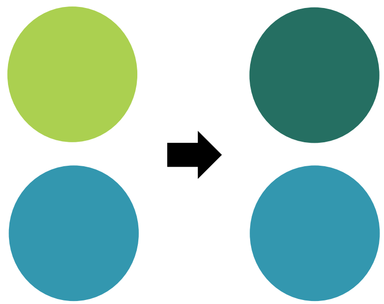


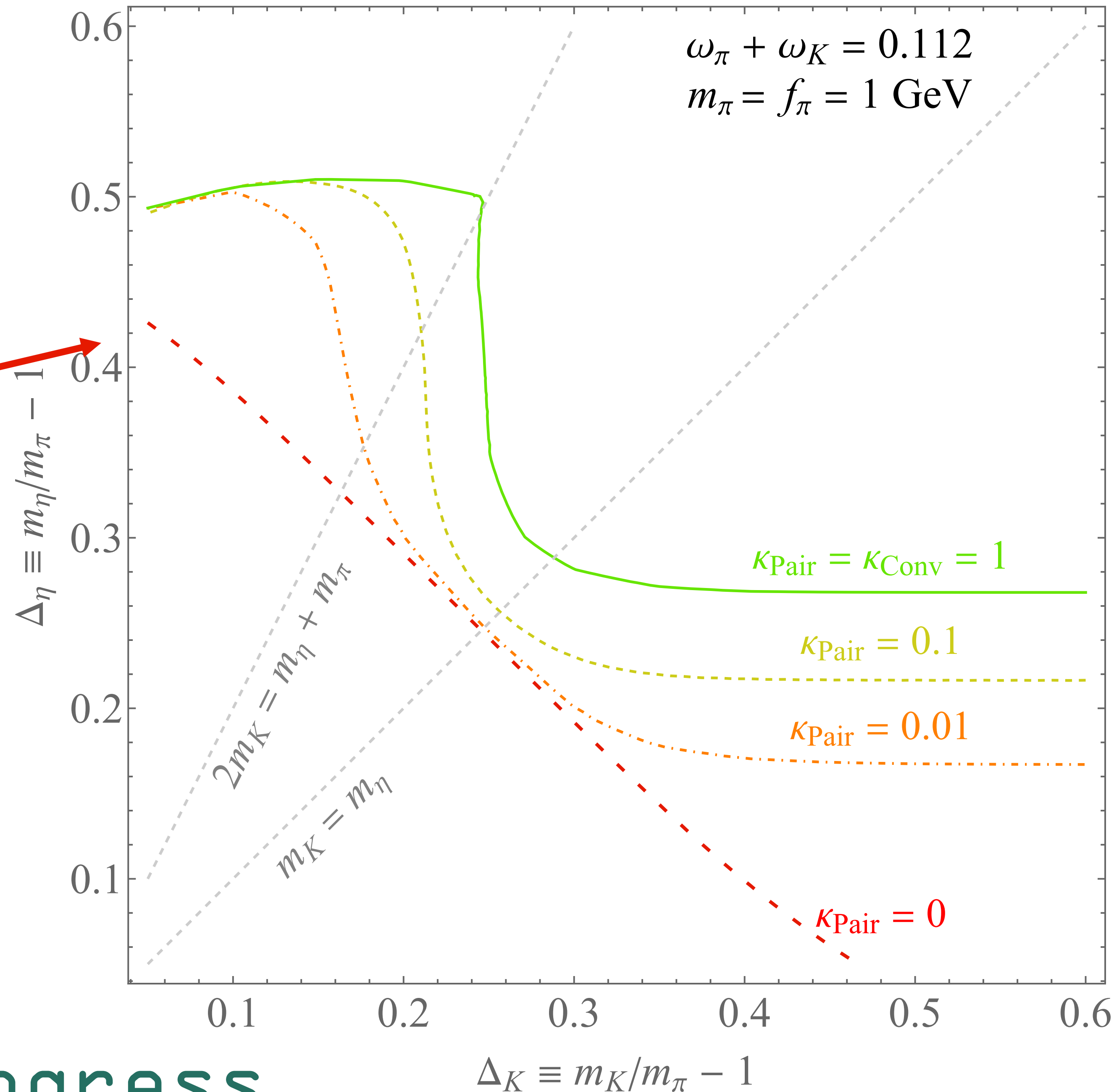
Extended Phases



At least 3 extra dynamic phases recognized

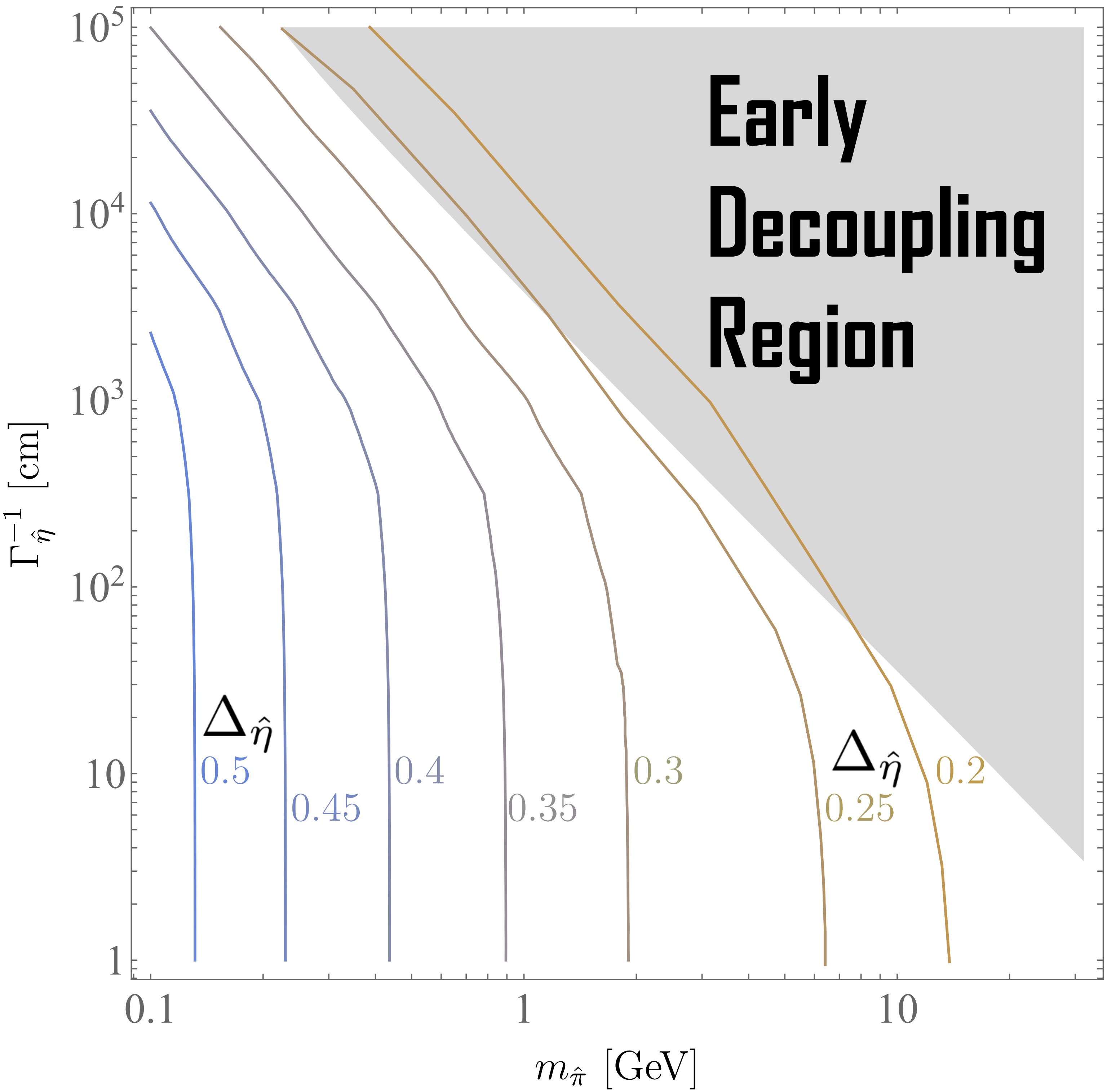
* Assuming all processes having similar cross sections, not necessarily true for realistic models





Full $\pi K \rightarrow \eta K$ dominance

Work in progress


Early Decoupling Region
$\Gamma_{\hat{\eta}}^{-1}$ [cm]
$m_{\hat{\pi}}$ [GeV]
$\Delta_{\hat{\eta}}$
0.5
0.45
0.4
0.35
0.3
$\Delta_{\hat{\eta}}$
0.25
0.2
10^5
10^4
10^3
10^2
10
1
0.1
1
10

Direct Detection Prospects

The leading Z exchange between DM and SM are forbidden by the same parity that stabilizes the DM

$$\psi_i \xrightarrow{\mathcal{C}} -(-1)^i\,\psi_i$$

$$\Rightarrow \quad \hat{\pi}_{\pm} \rightarrow \hat{\pi}_{\mp}$$

The leading vector portal scattering is forbidden:

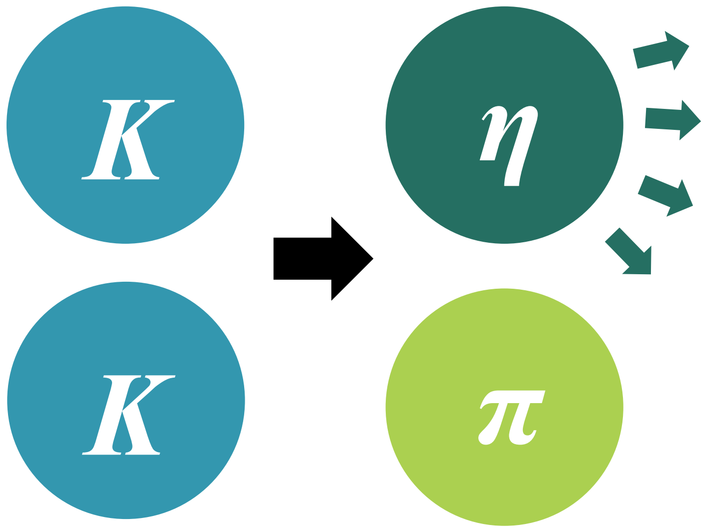
$$\cancel{i(\hat{\pi}_{+}\partial_{\mu}\hat{\pi}_{-} - \hat{\pi}_{-}\partial_{\mu}\hat{\pi}_{+})J^{\mu}_{\mathrm{SM}}}$$

Higgs/scalar portal interaction is still possible……

Indirect Detection Prospects

- As forbidden dark matter, usually free from indirect detection

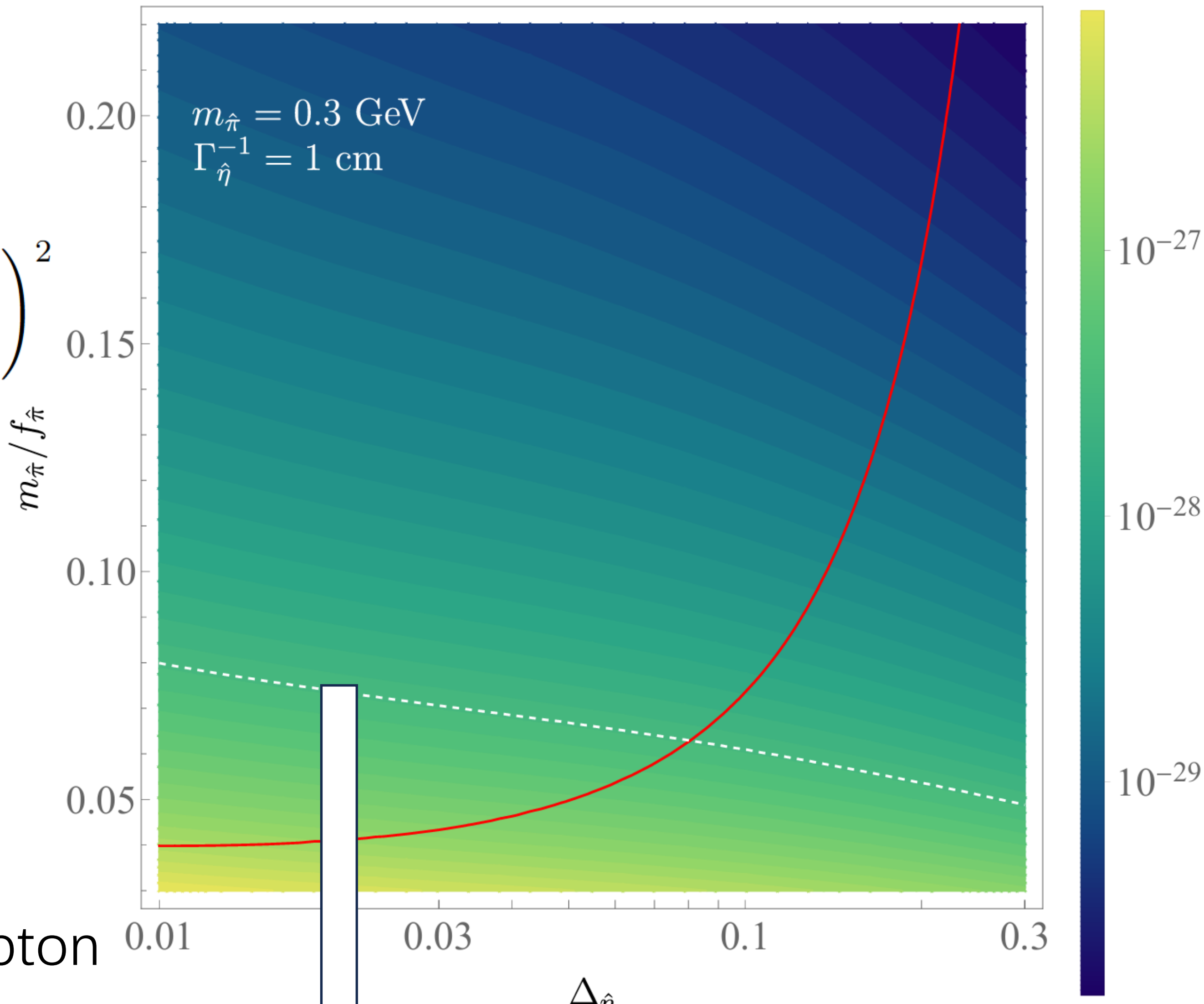
- The remaining secondary Kaon DM can annihilate to SM, strongly depending on how many K remain



The most stringent CMB spectral distortion limit constraints the highly degenerate case (Δ of a few %)

Effective Annihilation Xsec

$$\langle \sigma v \rangle_{\rm eff} \equiv \frac{\xi^2}{2} \langle \sigma v \rangle_{\hat{K}\hat{K}\to\hat{\pi}\hat{\eta}} \left(\frac{2 Y^0_{\hat{K}} m_{\hat{K}}}{Y_{\rm DM} m_{\rm DM}} \right)^2$$

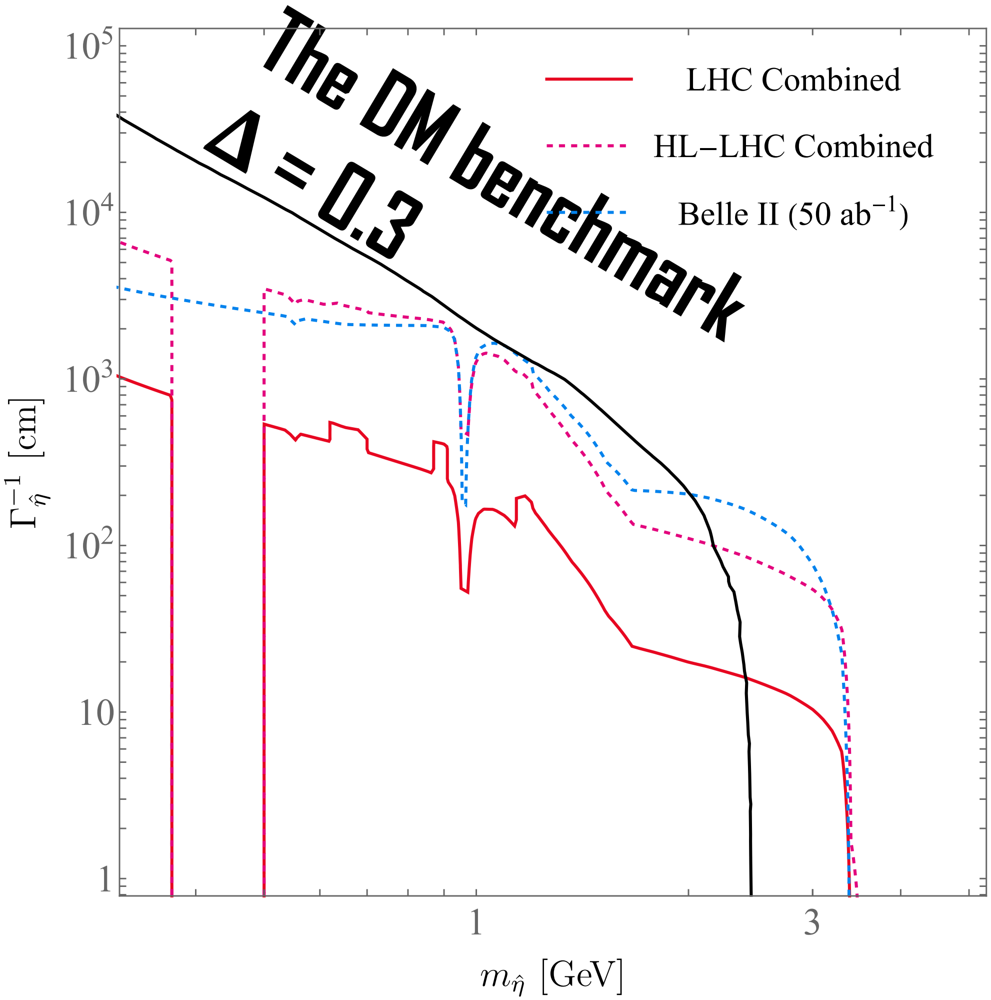


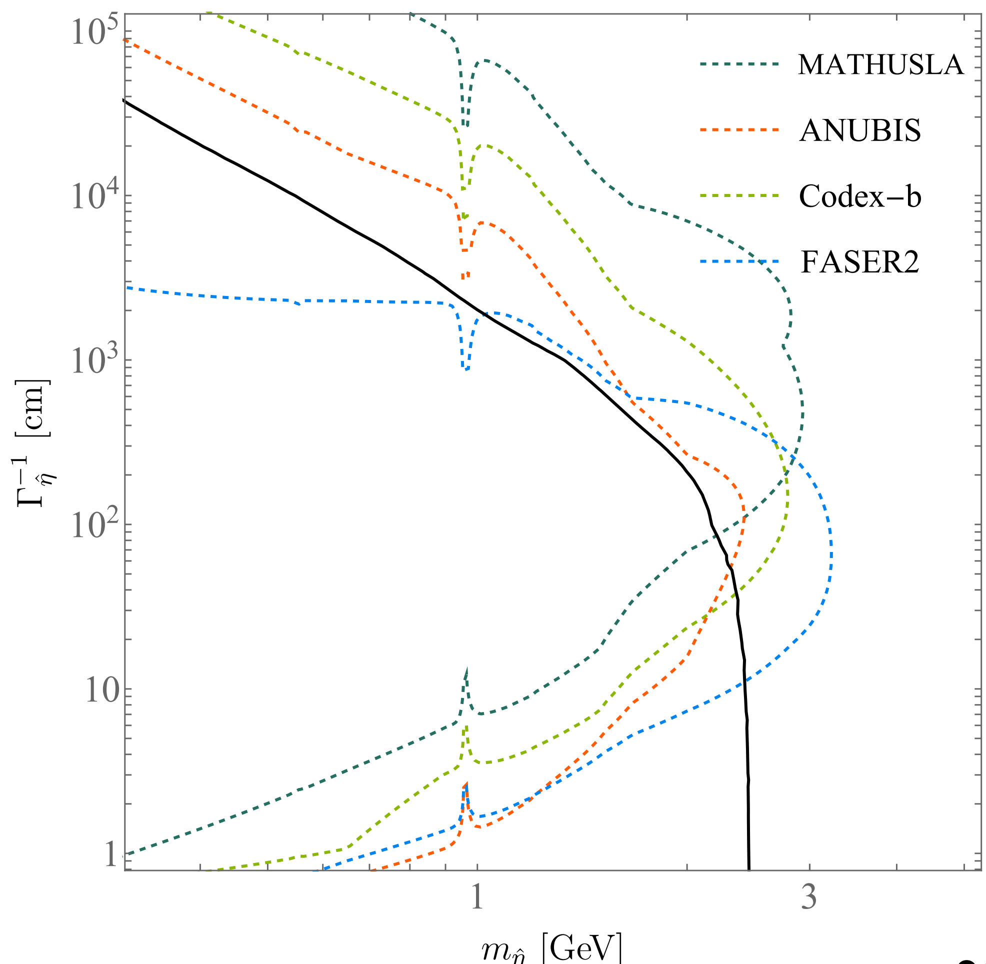
Signals include:

- ❑ Primary gamma photons
- ❑ Secondary inverse-Compton photons
- ❑ Cosmic ray
- ❑ CMB spectral distortions

Too much K annihilation

Collider Bounds When η Decays to Muons (Model Dependent)





Future Prospects?

- Freeze out ⇒ Freeze in
- Collider ⇒ Beam Dumps
- Better Direct/Indirect predictions
- ……