

DARK QCD FROM COLLIDERS TO COSMOLOGY

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60th Rencontres de Moriond
Electroweak Interactions & unified theories

La Thuile

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A QCD like dark sector

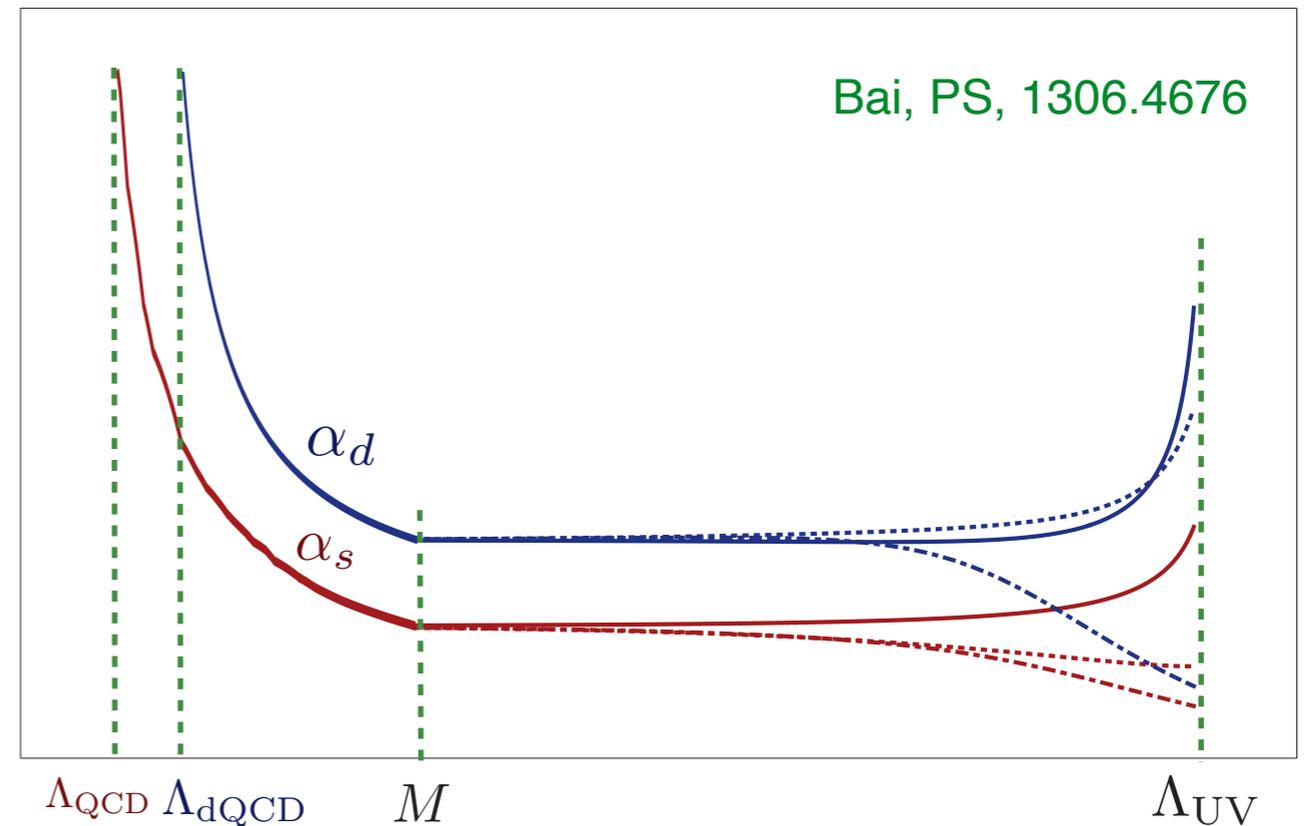
Known mechanism to generate a small mass scale

Can connect DM and proton mass via RGE running:

$$\rho_{\text{DM}} \approx \rho_{\text{matter}}$$

Motivates a specific scenario!

- ▶ Bi-fundamental, t-channel mediator
- ▶ Dark QCD with $SU(N_d = 3)$ and $n_f = 7$ dark quarks



Smoking gun signature: emerging jets

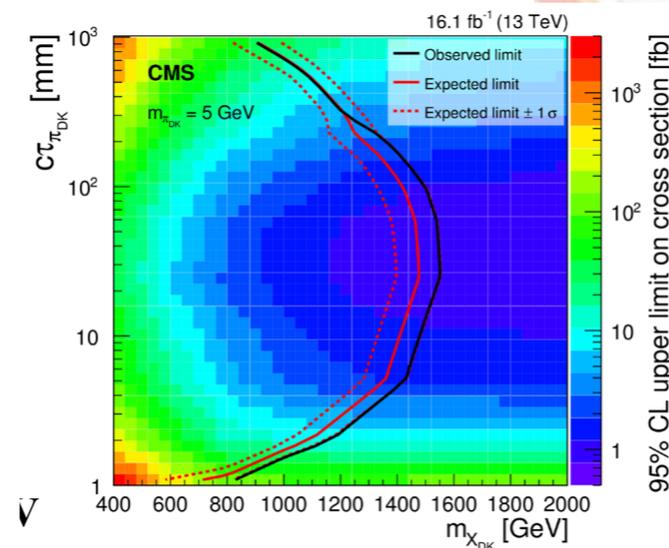
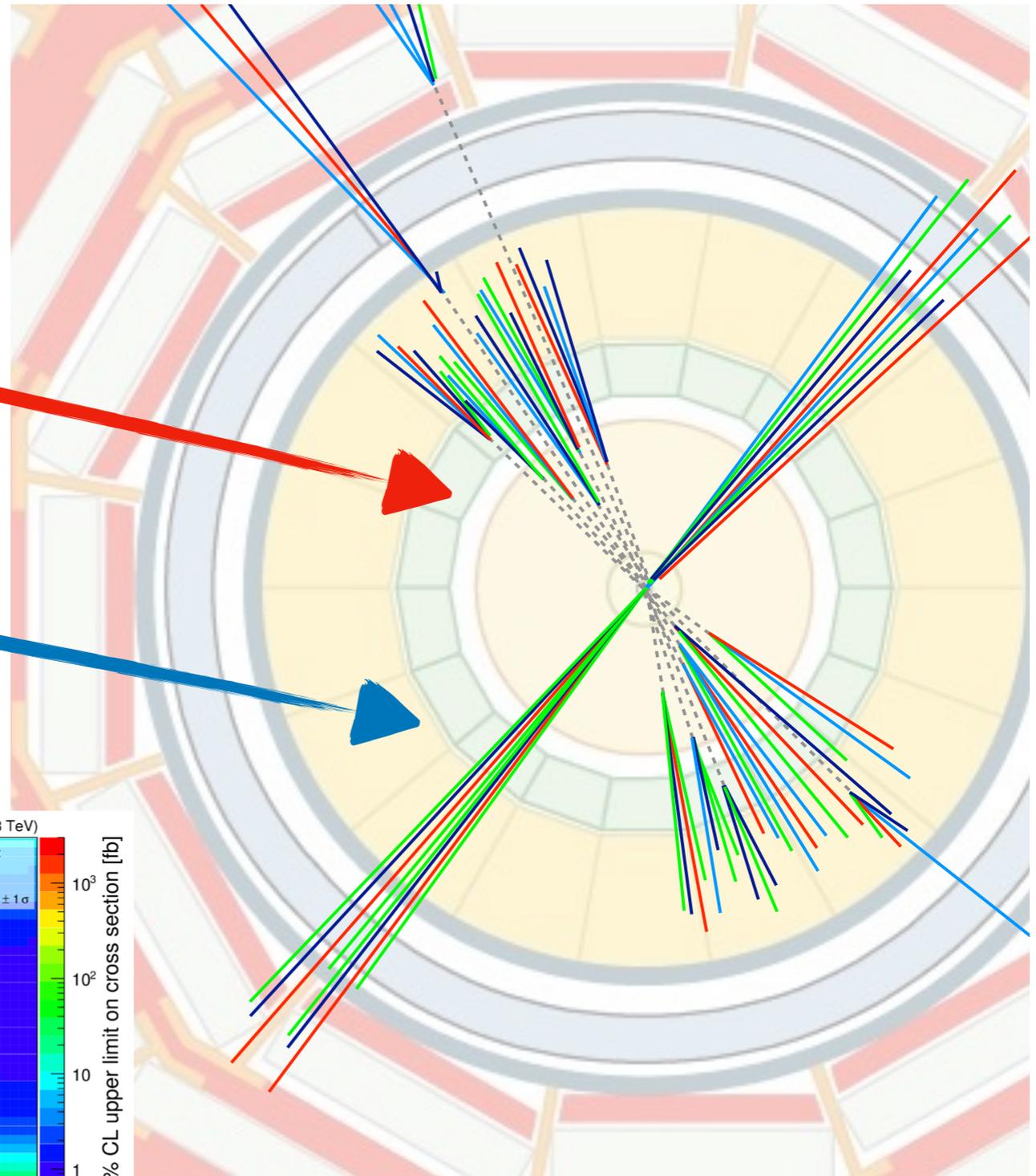
Jets composed of dark pions π_D , emerge in detector with displaced vertices

Prompt SM jets

Now an established signature!

CMS-EXO-18-001
 JHEP 02 (2019) 179

...



Are there other
motivated scenarios?

Dark flavour symmetries

Carmona, Elahi, Scherb, PS, 2411.15073

Dark QCD with n_f dark quarks Q_α

$$\mathcal{L}_D = -\frac{1}{4}(G_D^{\mu\nu,a})^2 + \bar{Q}_\alpha i \not{D} Q_\alpha - m_{Q,\alpha\beta} \bar{Q}_\alpha Q_\beta$$

Global $SU(n_f) \times SU(n_f)$ symmetry in dark sector

Broken to $SU(n_f)_V$ after confinement

Assume $SU(n_f)_V$ exact in dark sector, only broken by interactions with SM (dark MFV)

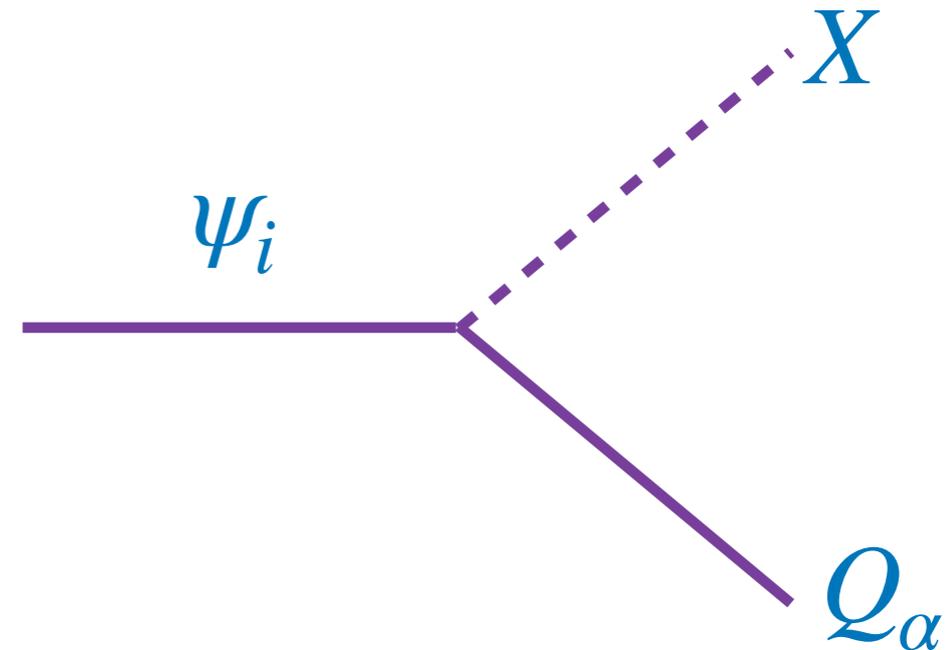
$$\Rightarrow m_{Q,\alpha\beta} = m_Q \delta_{\alpha\beta}$$

Stable dark pions π_{DM}

Carmona, Elahi, Scherb, PS, 2411.15073

T-channel mediator:

$$\mathcal{L}_{\text{portal}} = -\kappa_{\alpha i} \bar{\psi}_i Q_{\alpha} X + \text{h.c.}$$



SM quark $\psi_i = u_i, d_i, q_i$

For $n_f \geq 4$, some dark quarks decouple from SM:

$$\kappa = V D U$$

Unitary $n_f \times n_f$ Diagonal Unitary 3×3

V absorbed by $SU(n_f)_V$ rotation!

$$\Rightarrow \kappa = \begin{pmatrix} \cdot & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & 0 \end{pmatrix}$$

Sneaky Dark Matter

Carmona, Elahi, Scherb, PS, 2411.15073

π_{DM} (6 states, stable), $\pi_{transient}$ (9 states, decaying)

Rapid interactions¹ $\pi_{DM}\pi_{DM} \leftrightarrow \pi_{tran}\pi_{tran}$

$$\langle\sigma v\rangle \approx \frac{m_{DM}^2}{f_D^4} v$$

See also

Dror et al, 1607.03110

Kopp et al, 1609.02147

With $\pi_{tran} \rightarrow$ SM decays in equilibrium

- Relic abundance independent of mediator

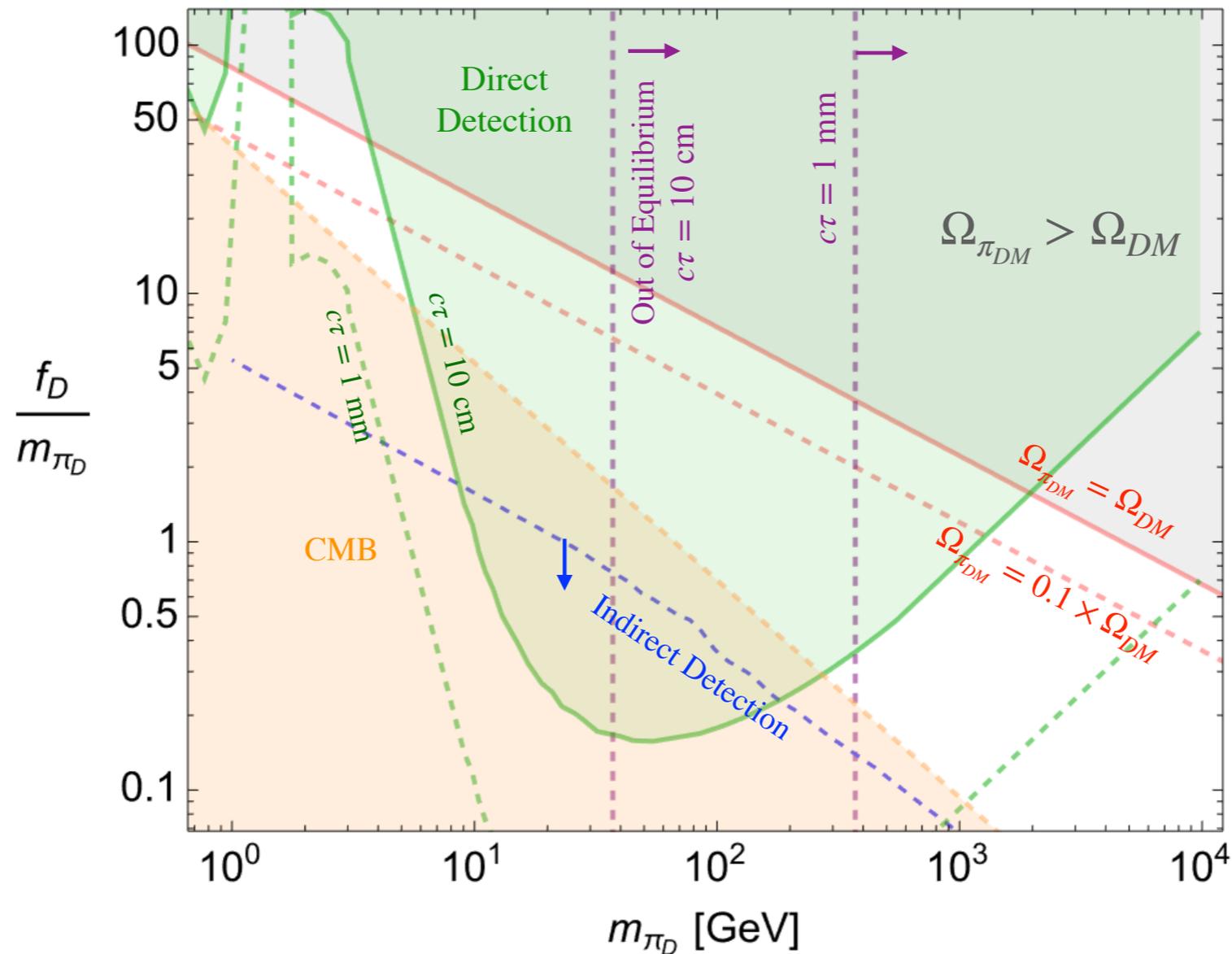
Velocity dependence suppresses indirect detection (sneaky!)

Direct detection rate is related to **lifetime of π_{tran}**

$$\sigma_{SI} \sim \frac{\kappa^4}{m_X^4}$$

¹Note: 3 \rightarrow 2 negligible

DM phenomenology (down quark case)



Nice motivation to explore cm - m lifetimes 😊

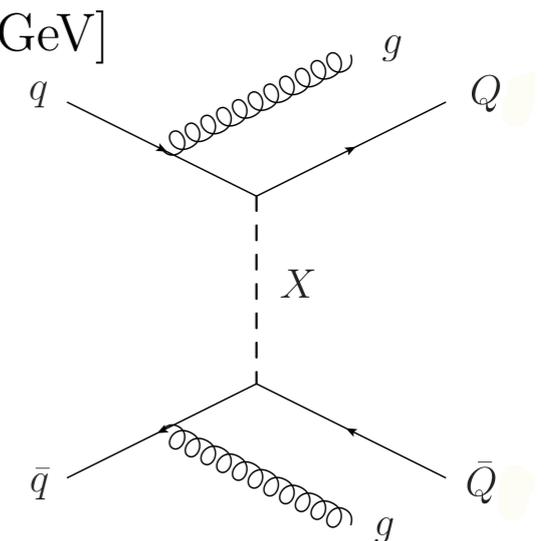
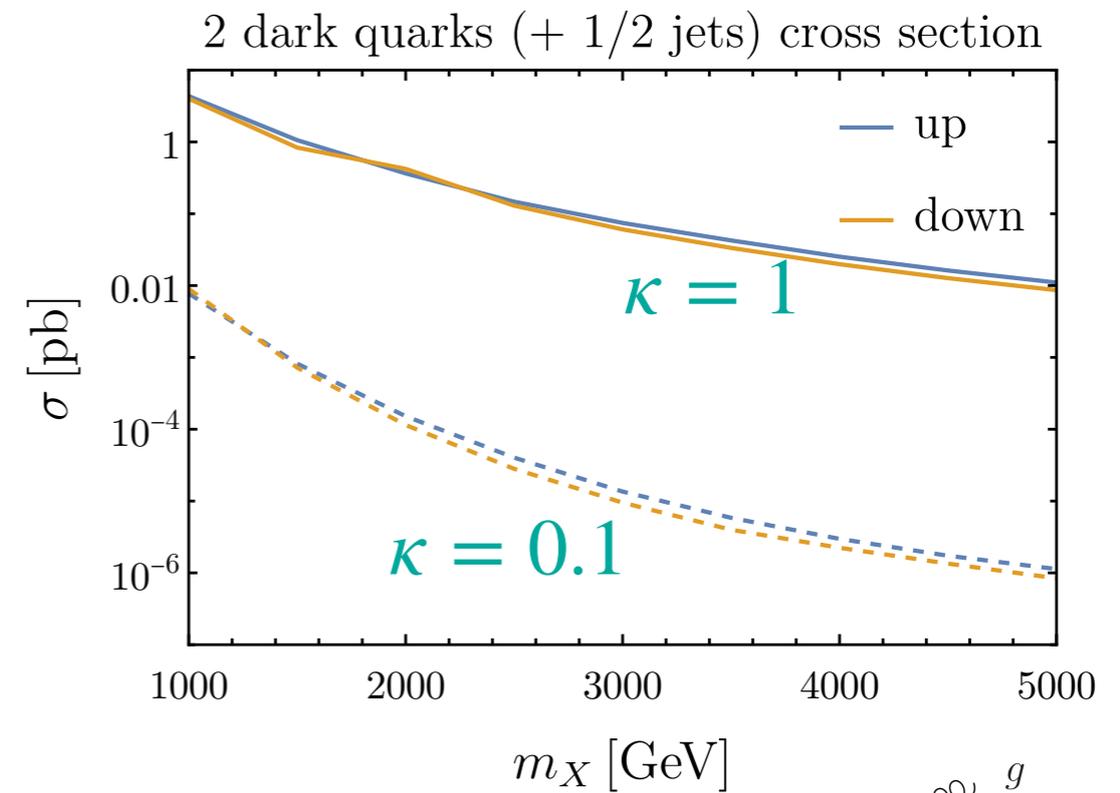
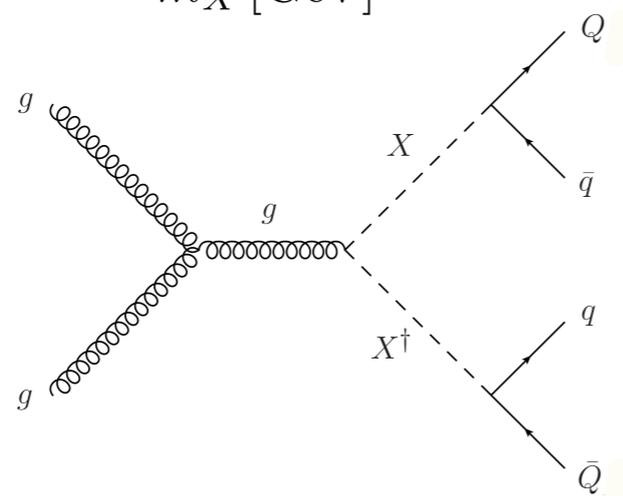
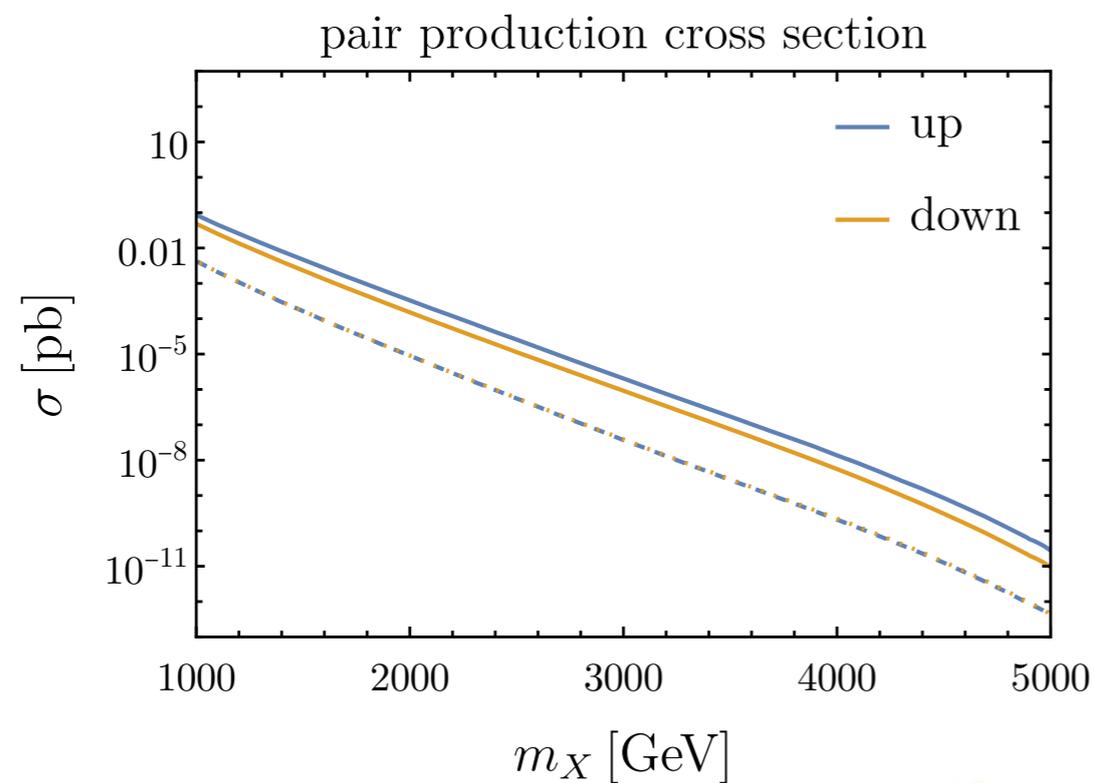
Dark showers from sneaky dark matter



LHC signals

Carmona, Elahi, Scherb, PS, 2411.15073

Pair production of X , or direct production of dark quarks



What is in the shower?

Carmona, Elahi, Scherb, PS, 2411.15073

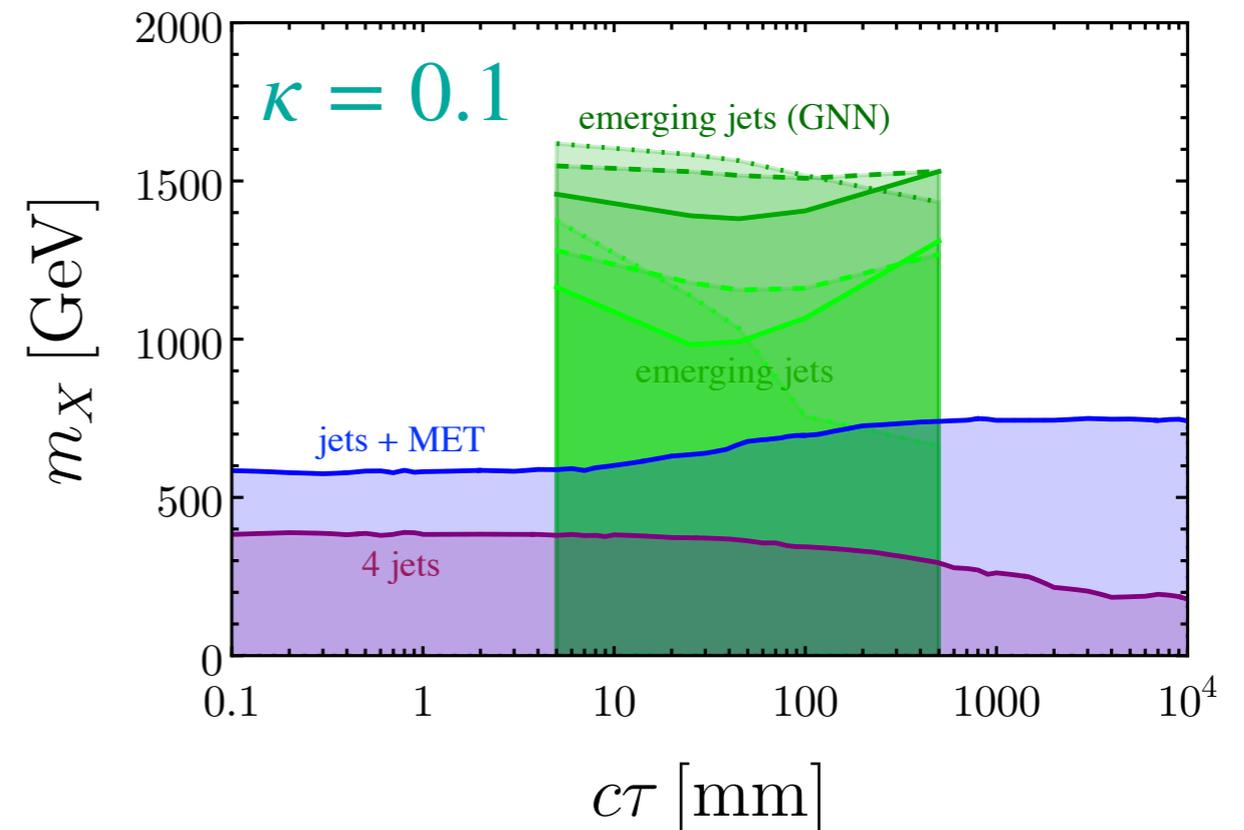
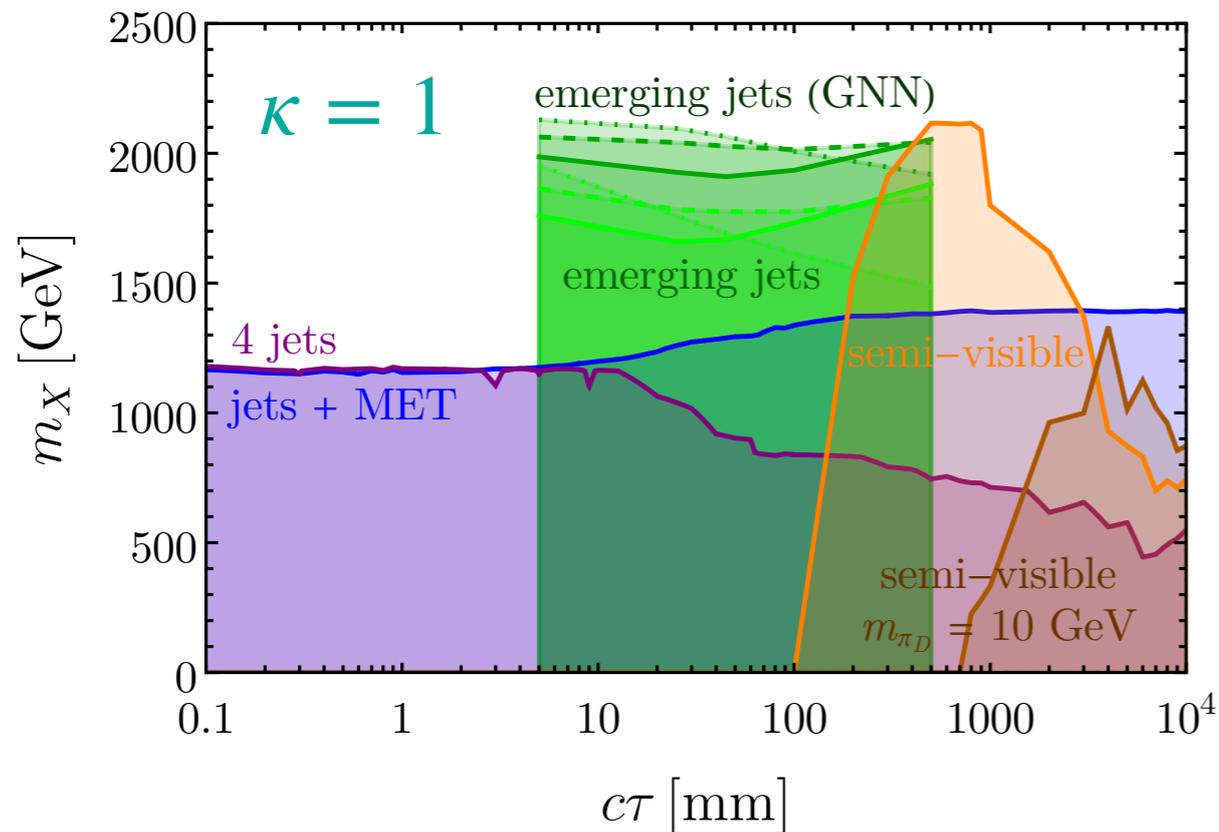
X only couples to Q_{1-3}

In dark shower and dark hadronization: Equal probability to form $Q_\alpha \bar{Q}_\alpha$ pairs for $\alpha = 1 - 4$ (or n_f)

The dark shower now contains dark matter, with a fraction determined by n_f ($\approx 1/3$ for $n_f = 4$)

Missing energy aligned with the emerging jets!

Existing limits (down quark coupling)



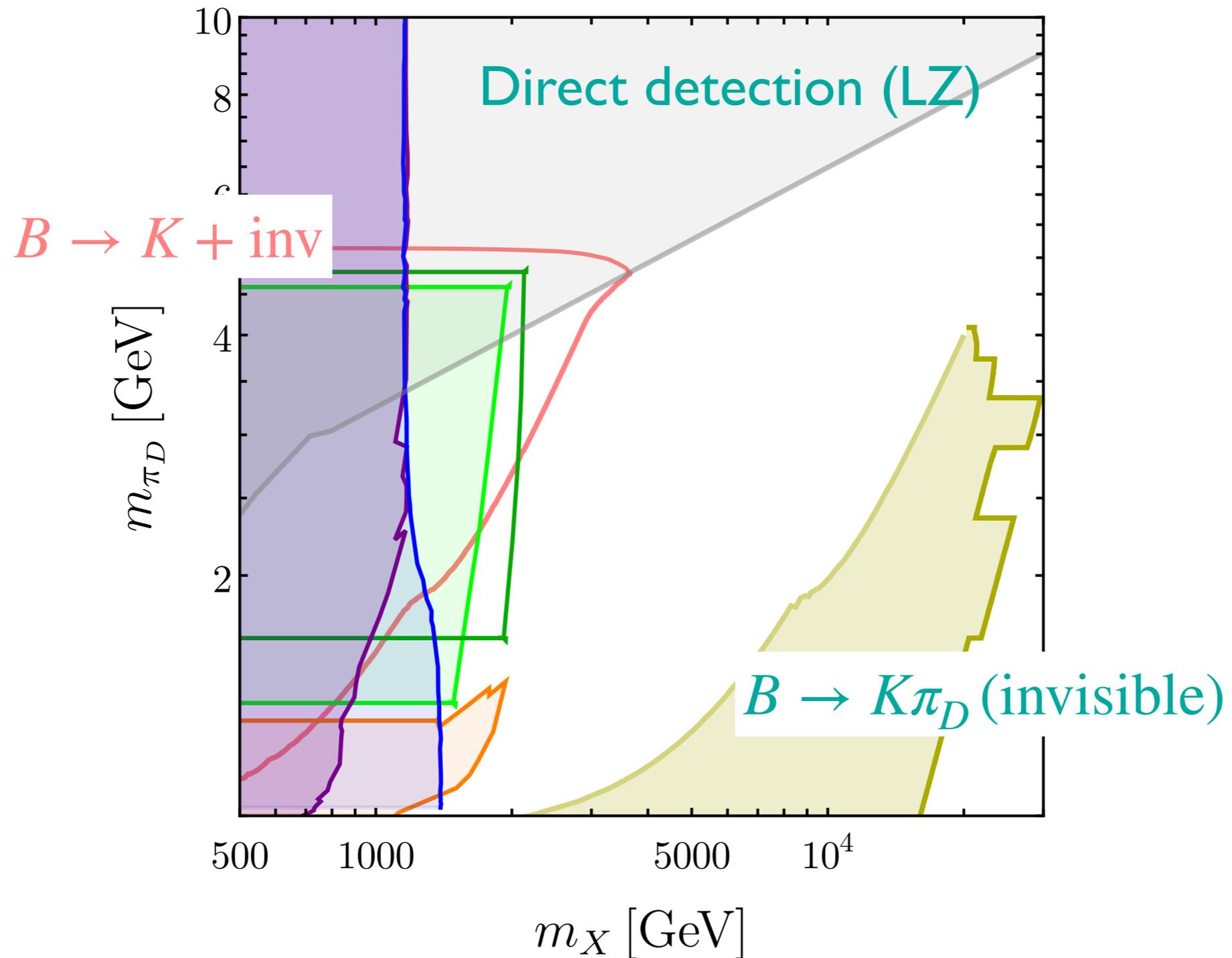
Provides novel benchmark model for semi-visible jets searches (with working UFO for event generation)

in preparation w/ D. Kar, S. Sinha

Motivates new searches for semi-visible emerging jets

see also Carrasco et al, 2511.02918

DM vs. Colliders vs. Flavour ($\kappa = 1$)



One more cosmology connection

For $n_f = 0$ or $n_f \geq 3$, the dark QCD confinement PT is first order

- ▶ Observable GWs?
- ▶ Strong coupling...

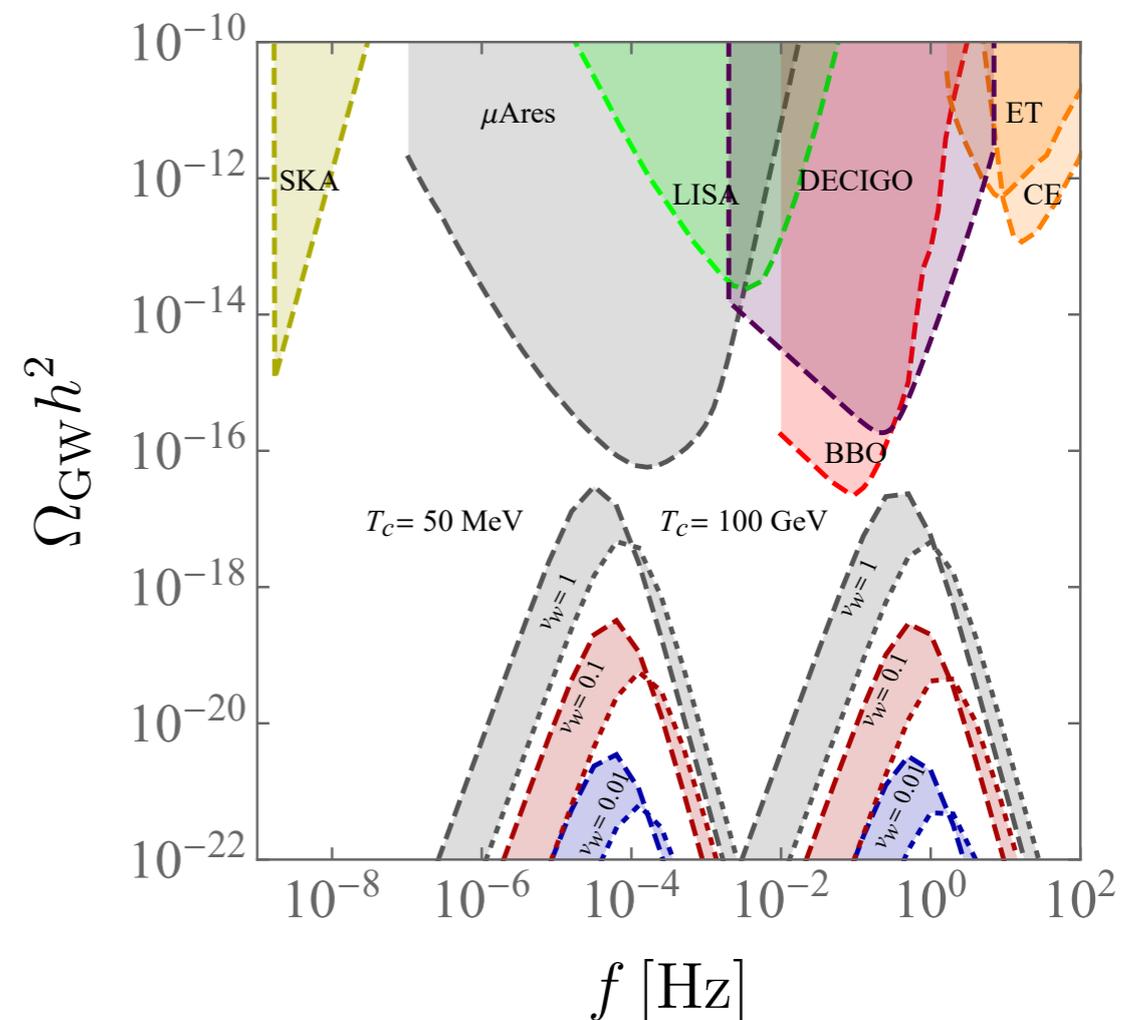
Studied PT with holographic QCD

Morgante, Ramberg, PS, 2210.11821

- ▶ Different from RS, no supercooling, there is a minimal temperature
- ▶ Fast transition, GW signal suppressed
- ▶ Potentially PBH production, density perturbations

Large N_c behaviour, surface tension, & more details:

Morgante, Ramberg, PS, to appear



Summary

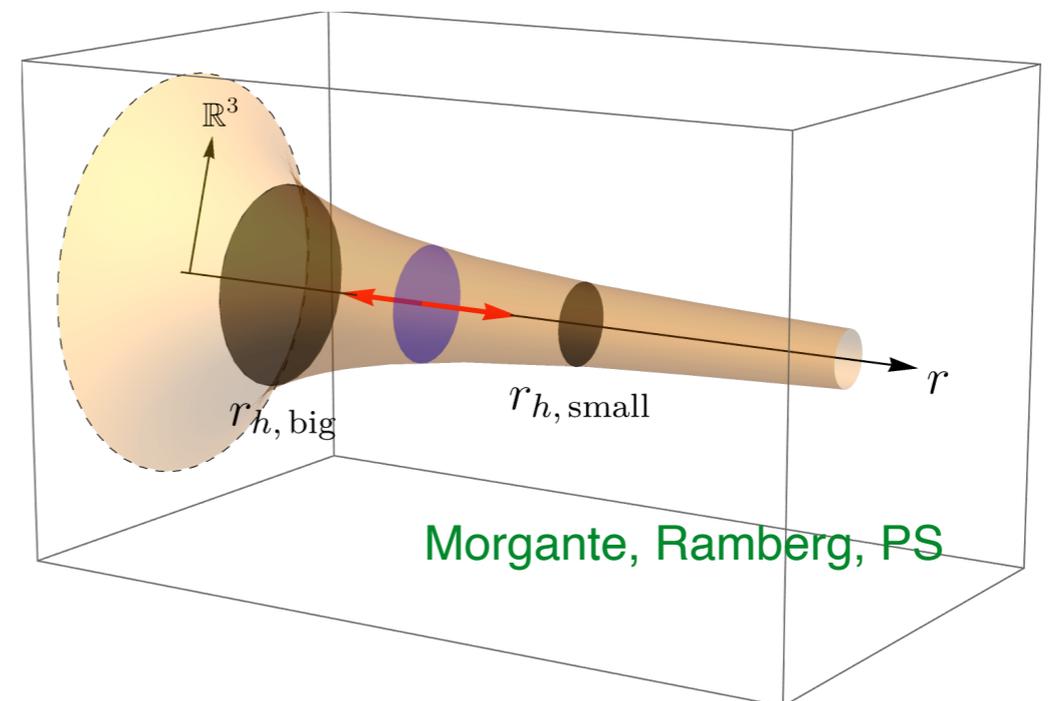
Confining dark sectors are well motivated scenarios for dark matter

Rich phenomenology, motivates new collider searches

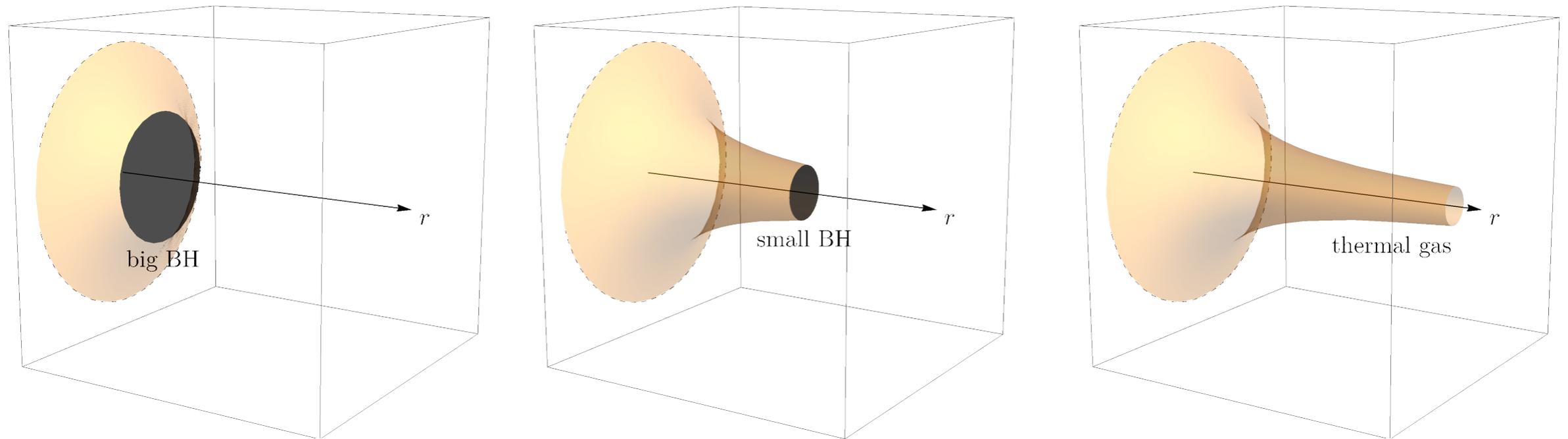
- ▶ Leave no stone unturned
- ▶ And who knows, maybe it IS the correct theory of the dark sector!

Astro/Cosmo connection

- ▶ Direct detection complementary to collider searches
- ▶ First order PT in dark sector, can be studied using holography!



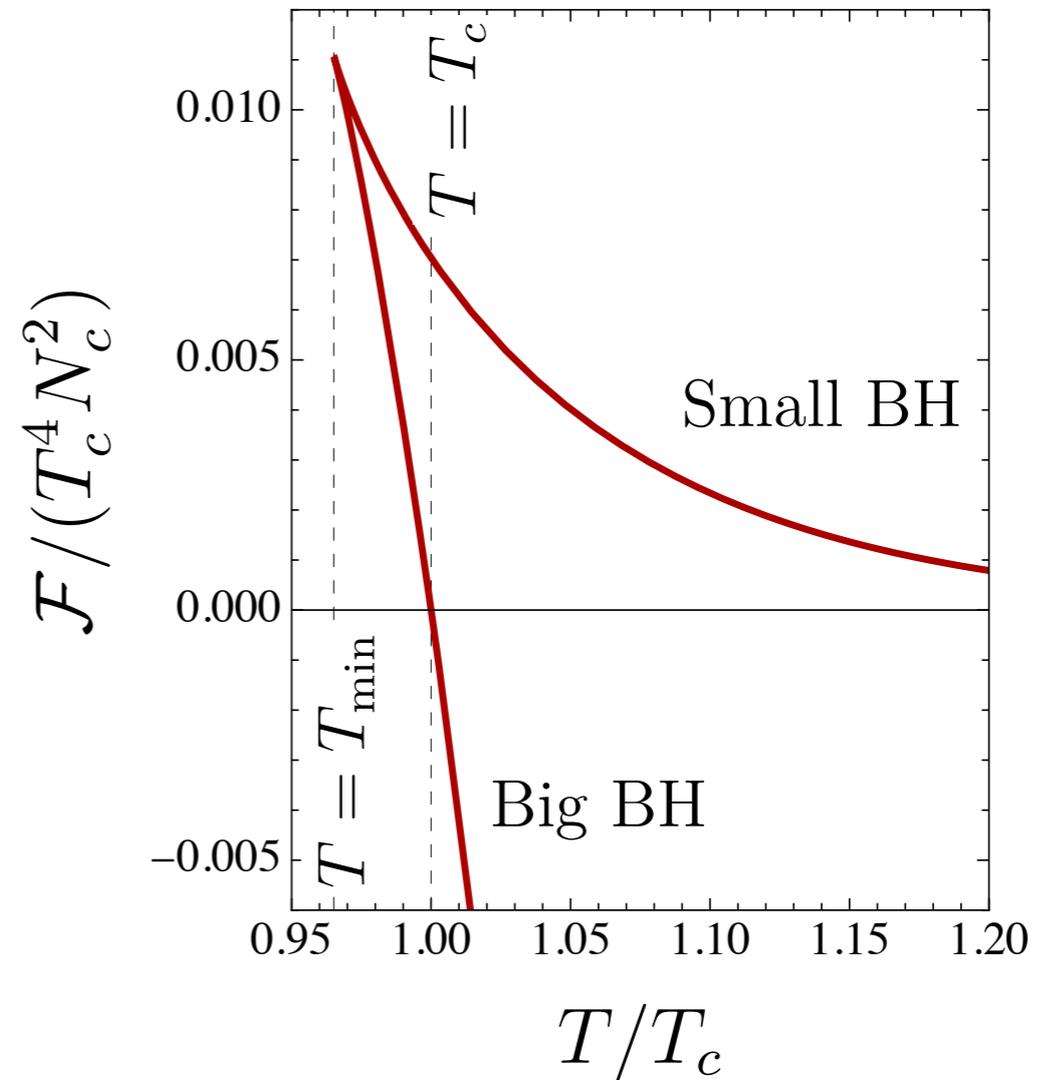
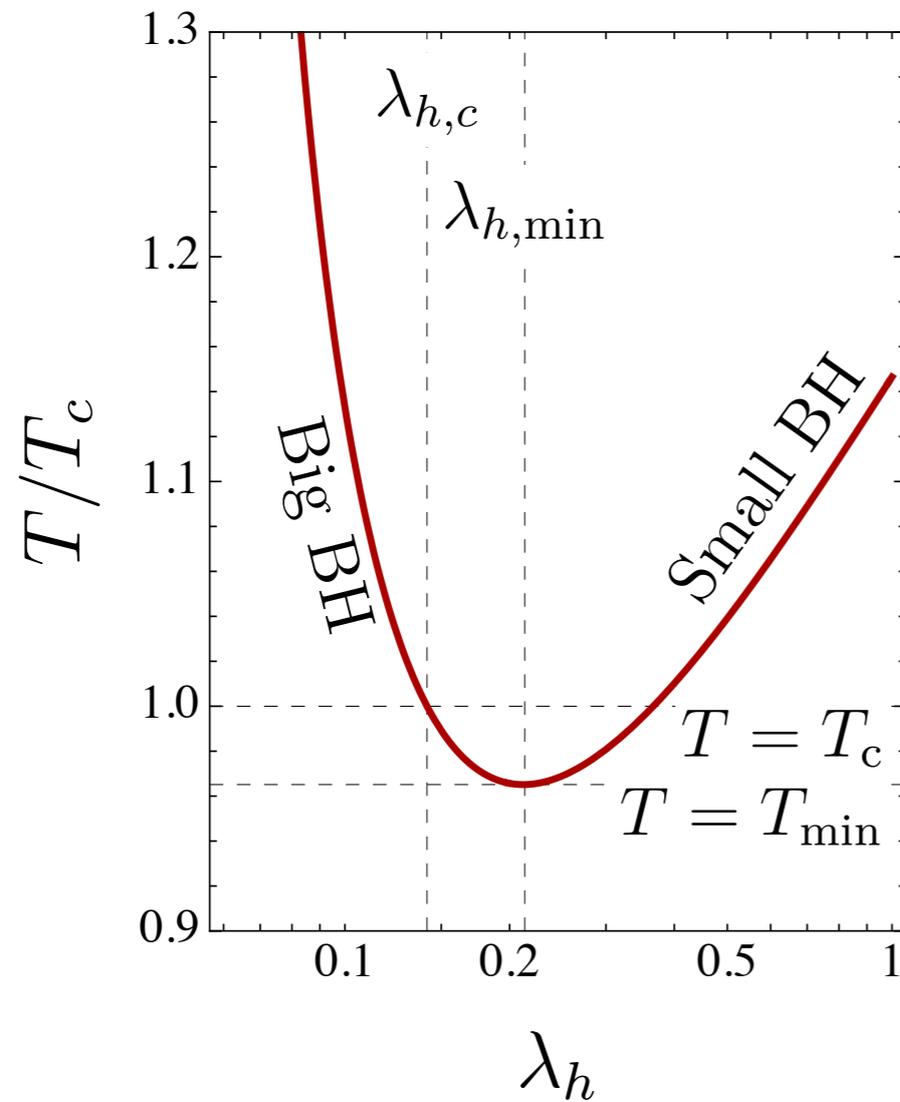
The phase transition in ihQCD



Three solutions

- ▶ Big BH: Deconfined phase
- ▶ Small BH: Unstable, saddle point
- ▶ Thermal gas: Confined phase

The phase transition in ihQCD II



At $T = T_c$, deconfined phase becomes meta-stable

The phase transition in ihQCD III

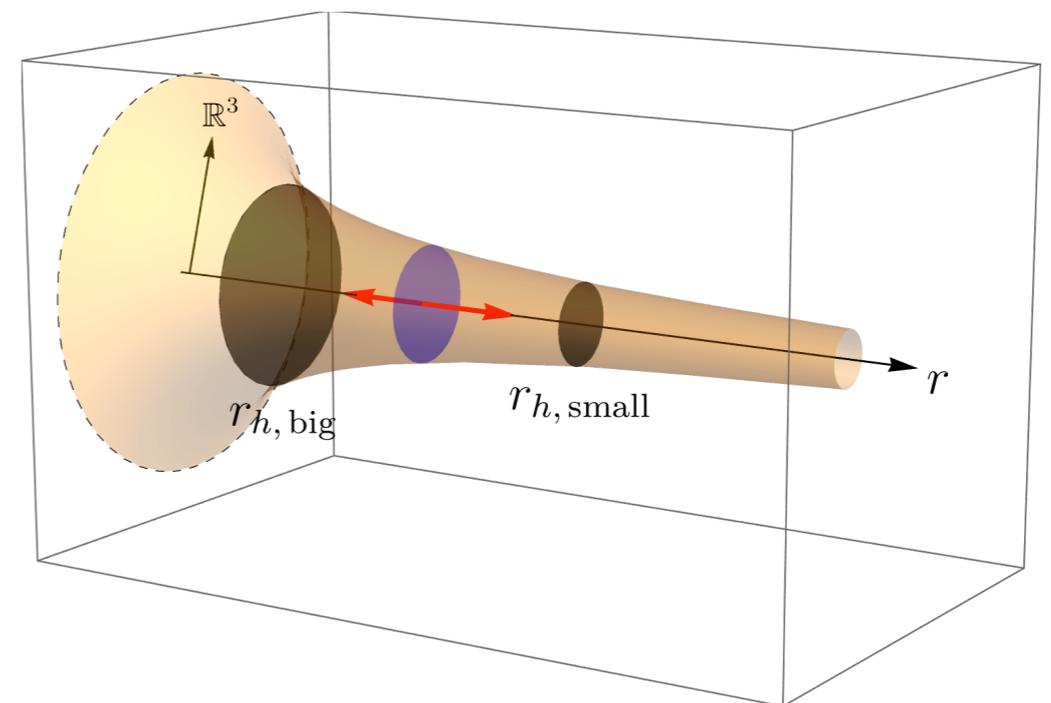
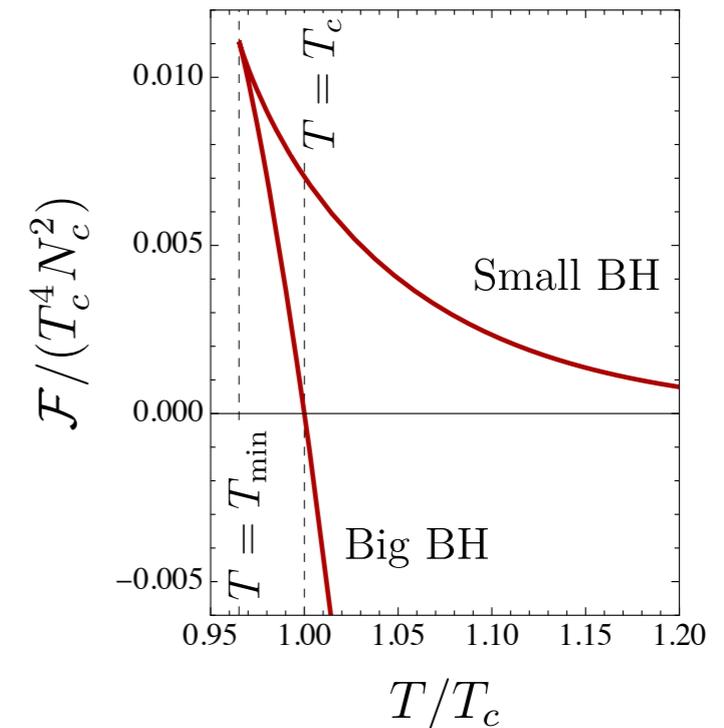
Hawking Page transition, with small BH acting as instanton

To compute bounce action, need effective action (or free energy) along the full path

Interpolate between big and small BH solutions

- ▶ Do some hard work...
- ▶ Win :)

Morgante, Ramberg, PS, 2210.11821



Effective potential and bounce action

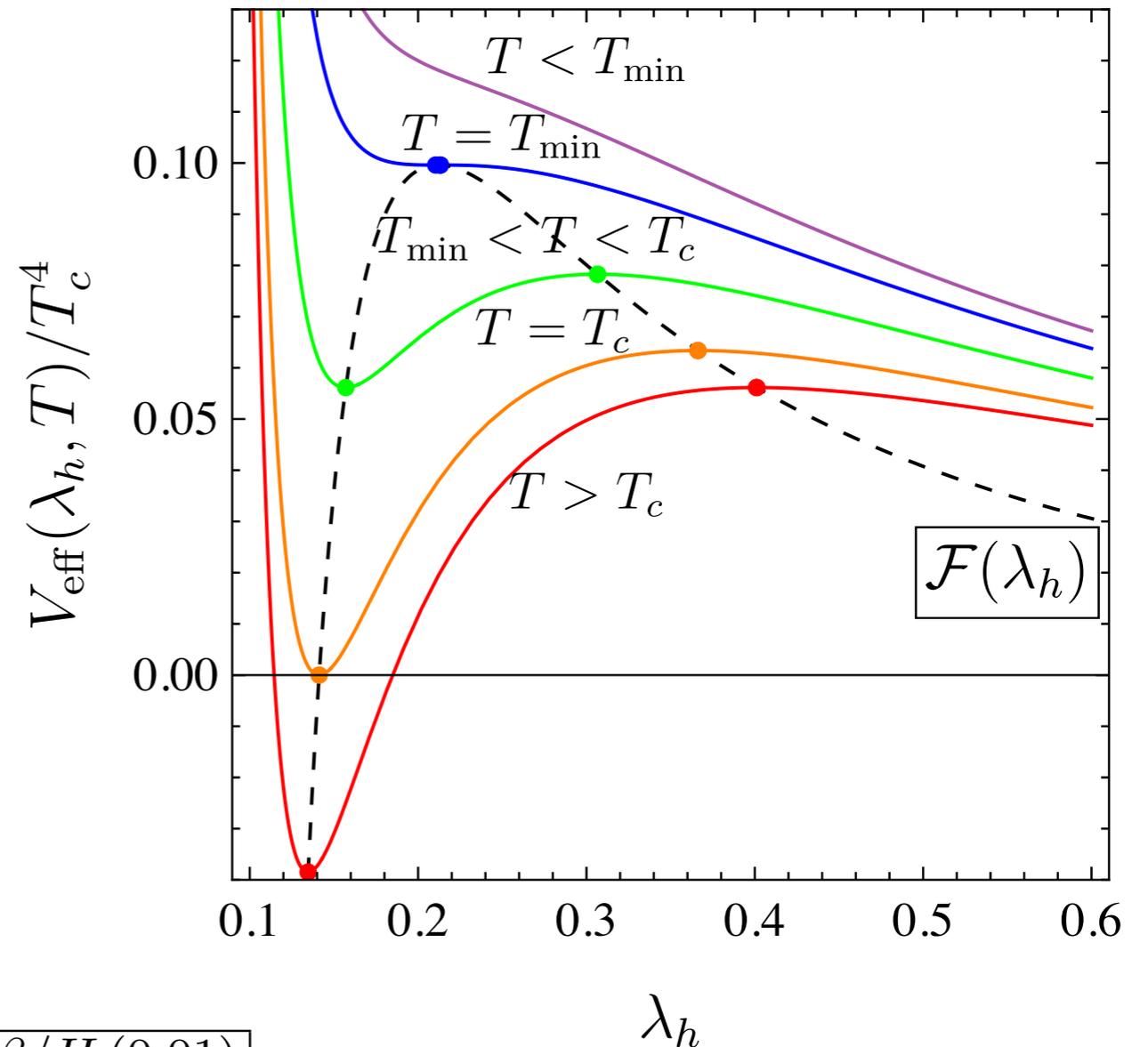
Bounce action

$$S_{\text{eff}} = \frac{4\pi}{T} \int d\rho \rho^2 \left[c \frac{N_c^2}{16\pi^2} (\partial_r \lambda_h(r))^2 + V_{\text{eff}}(\lambda_h(r)) \right]$$

Tunneling decay rate

$$\Gamma = T^4 \left(\frac{S_B}{2\pi} \right)^{3/2} e^{-S_B}$$

Allows us to compute
 α and β



	α	$\beta/H (v_w = 1)$	$\beta/H (0.1)$	$\beta/H (0.01)$
$T_c = 50 \text{ MeV}$	0.343	9.0×10^4	8.6×10^4	8.2×10^4
100 GeV	0.343	6.8×10^4	6.4×10^4	6.1×10^4

Morgante, Ramberg, PS, 2210.11821

ALPs (or dark pions) from top

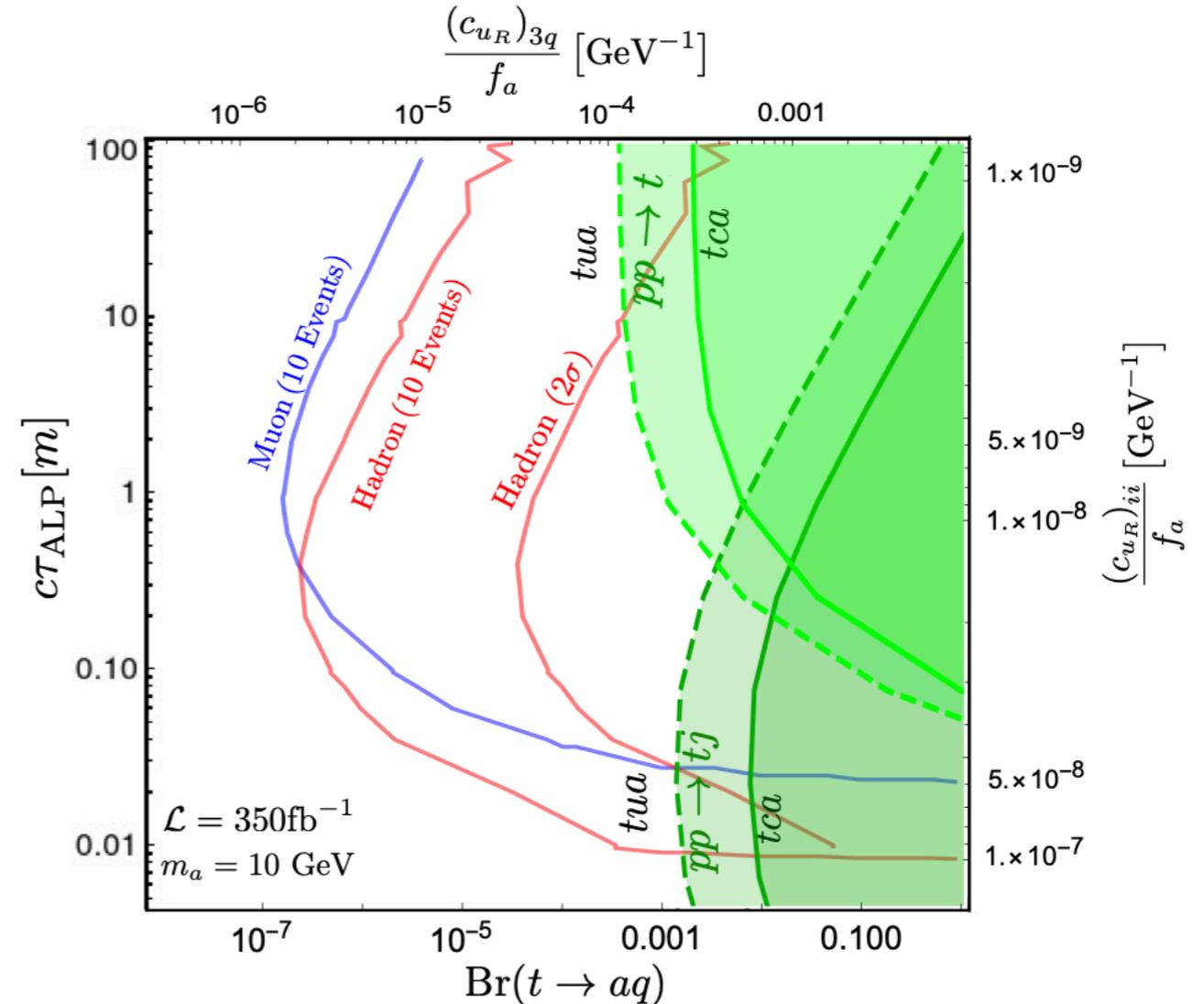
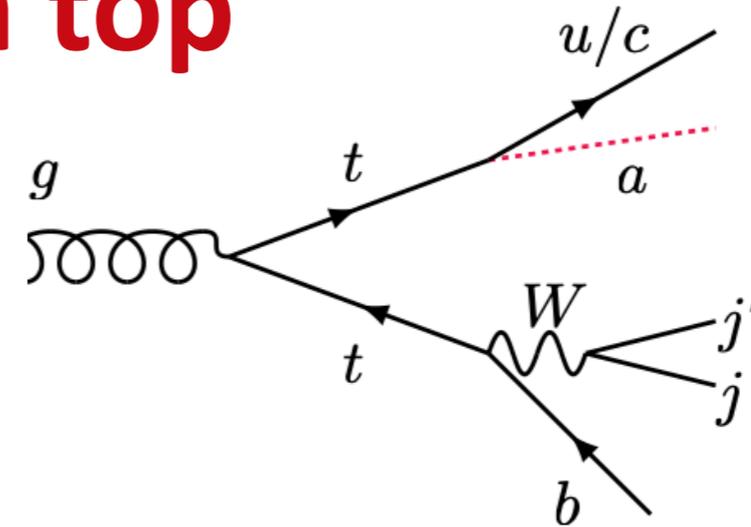
Carmona, Elahi, Scherb, PS, 2202.09371

Motivated by t-channel dark sectors with up-type couplings

ALP or dark pion decays with macroscopic lifetime

Regular top decay as trigger

ToDo: Emerging jets from top decays :)



Stable dark pions π_{DM}

Symmetry argument: κ breaks $SU(n_f)_V$ to

$$SU(n_f)_V \rightarrow SU(n_f - 3) \times U(1) = G_{DM}$$

$n_f^2 - 1$ dark pions, some of which transform non-trivially under $G_{DM} \rightarrow$ stable

Focus on $n_f = 4$! Dark pions $\pi_{\alpha\beta} \sim Q_\alpha \bar{Q}_\beta$ are stable if $\alpha \in 1,2,3$ and $\beta = 4$, or vice versa

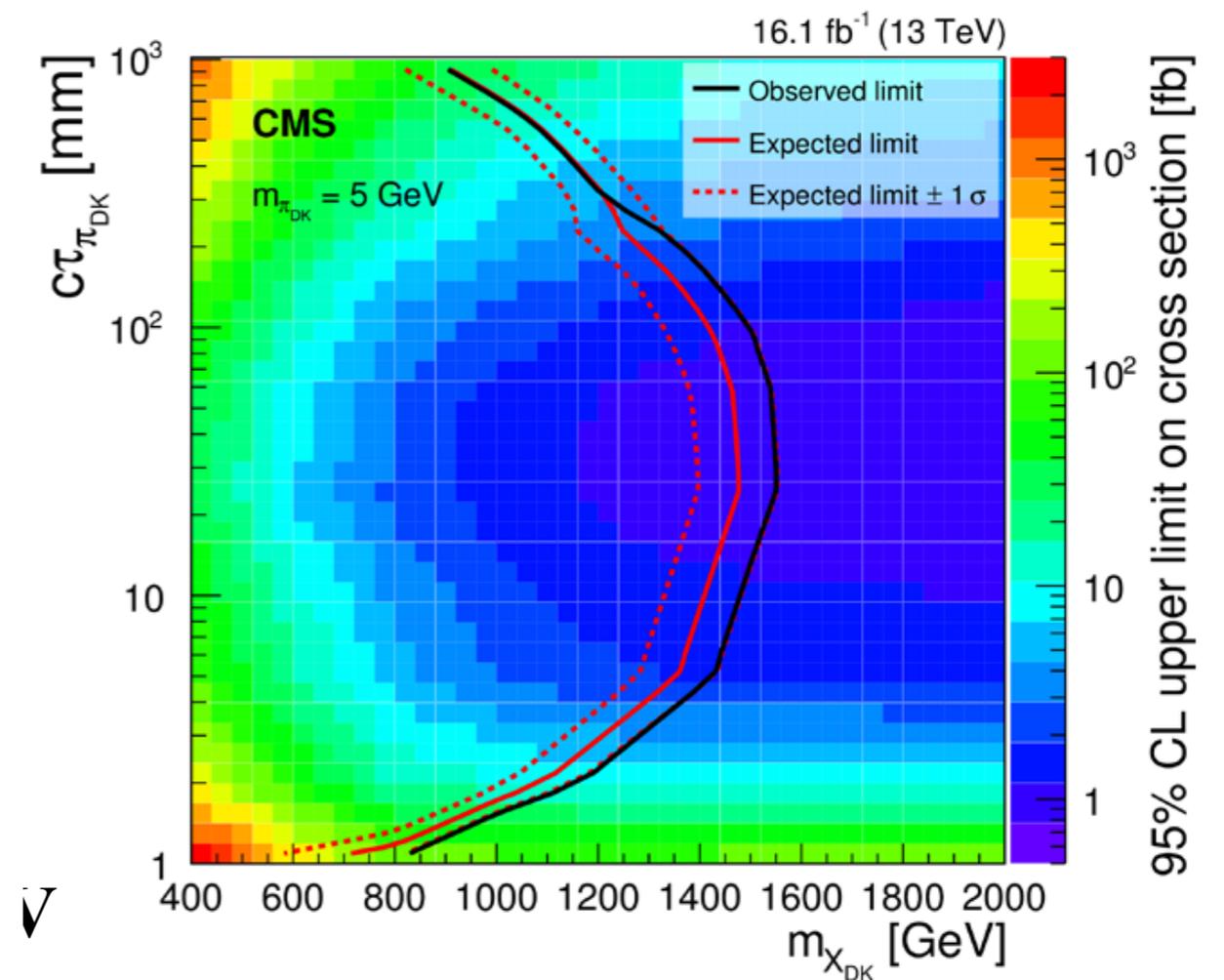
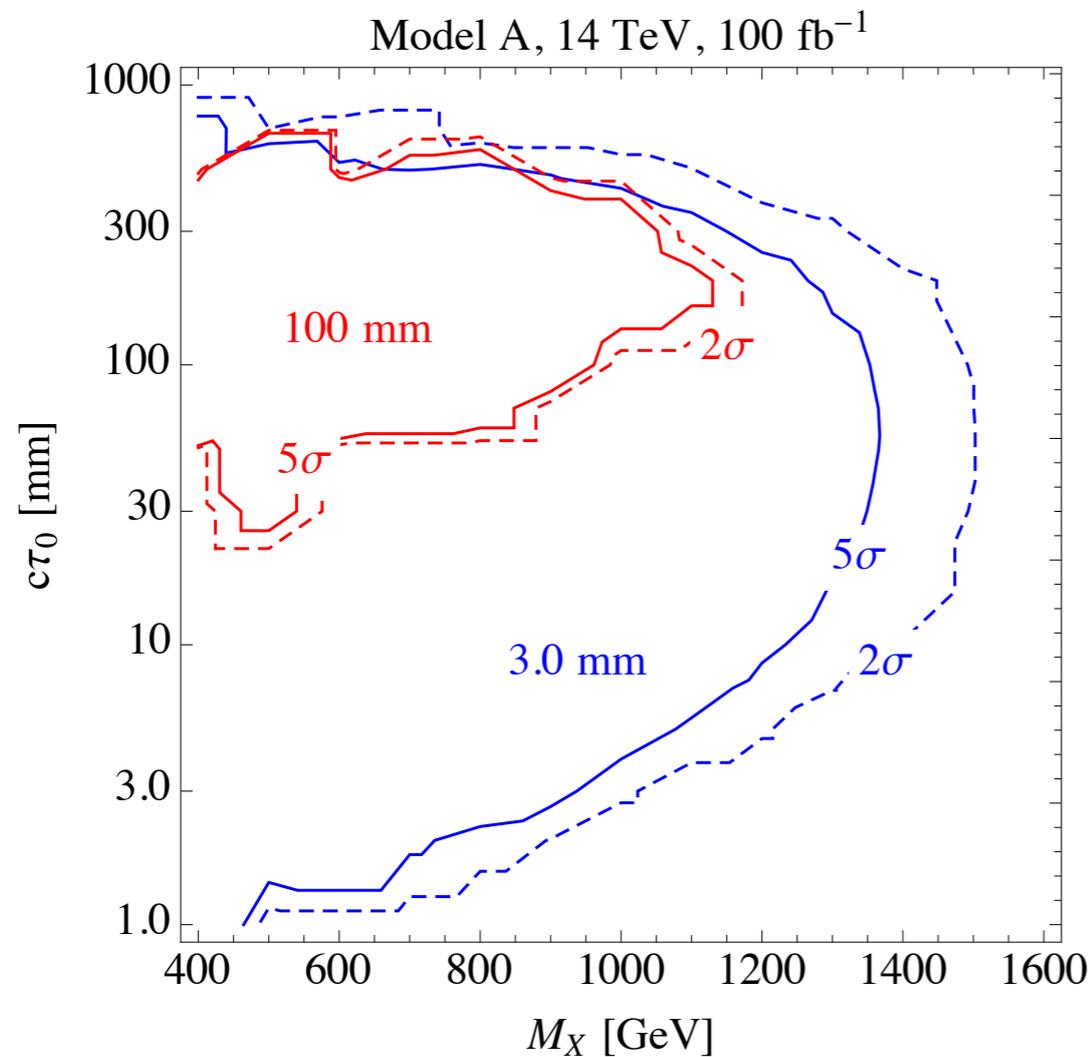
π_{DM} (6 states, stable), π_{tran} (9 states, decaying)

First search only 3 years later

PS, Stolarksi, Weiler, 2015

CMS 2018!

CMS-EXO-18-001
JHEP 02 (2019) 179



Now part of an active dark showers programme