Emerging jets - with flavour

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Selected topics in high energy physics
Brda, Slovenia
October 13, 2017

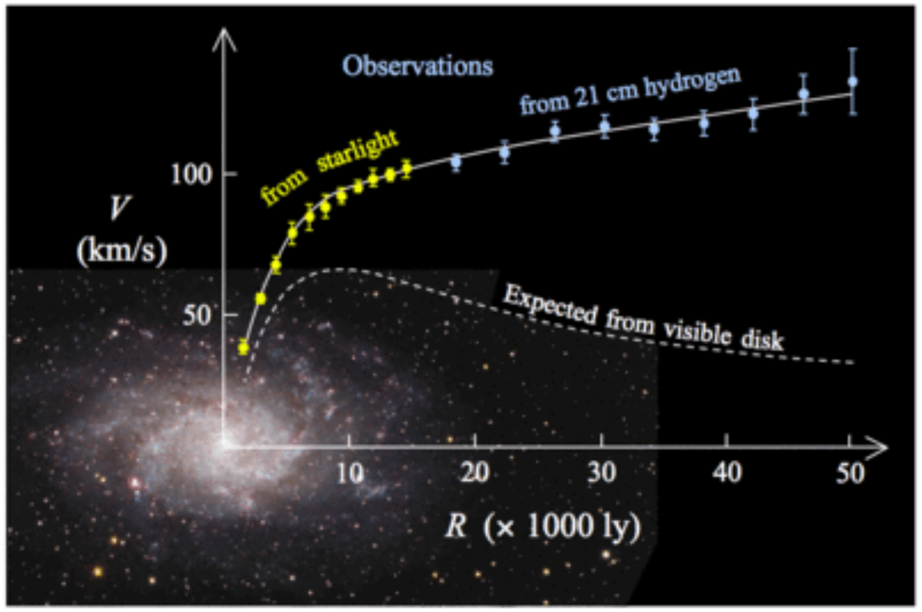
Based on: Bai, PS, 1306.4676; PS, Stolarski, Weiler, 1502.05409; S. Renner, PS, in progress

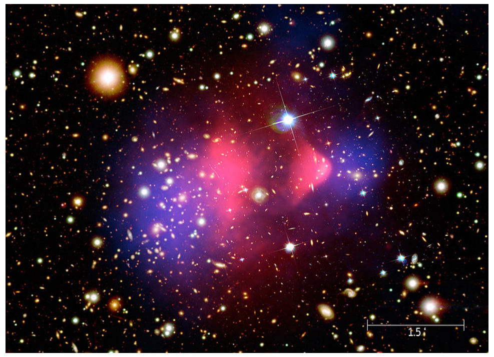
Outline

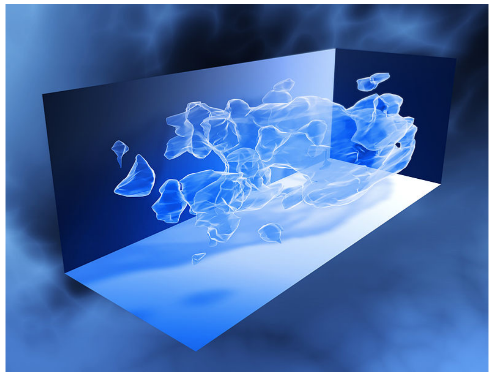
- Dark Matter: Motivation to go beyond WIMPs
- QCD Like Dark Sectors
- Emerging Jets at the LHC
- The flavour portal and consequences

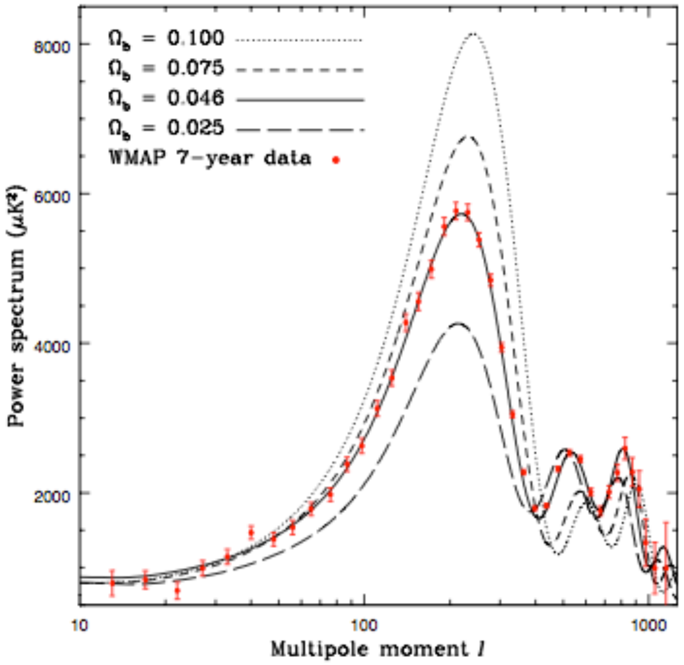
Dark Matter

- Astrophysical observations and simulations







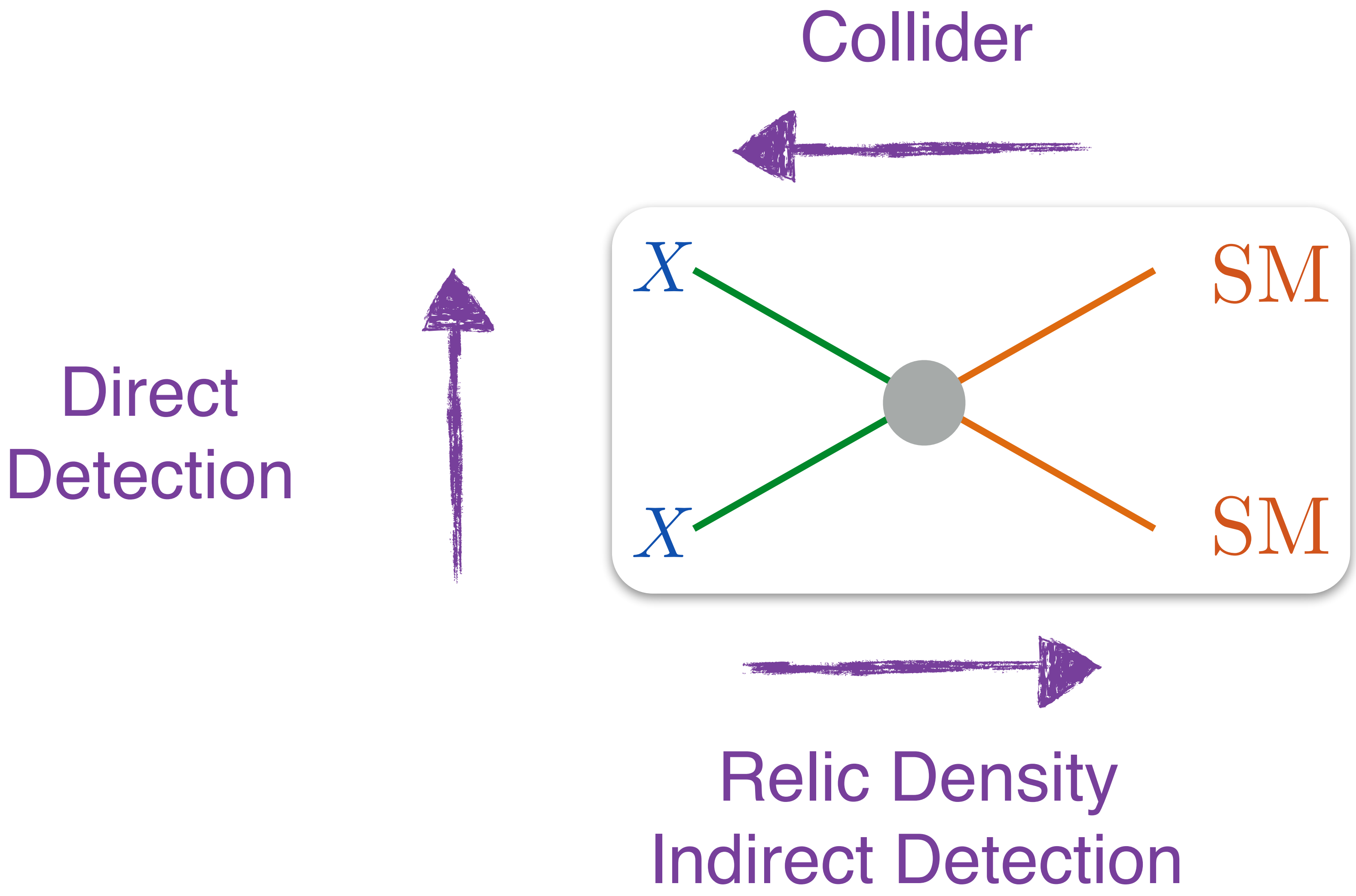


- Nature & interactions with visible matter unknown

What is the Dark Matter?

Standard candidate: WIMP

- Stable, neutral, weakly interacting particle X



Collider

Direct
Detection

Relic Density
Indirect Detection

WIMP miracle:

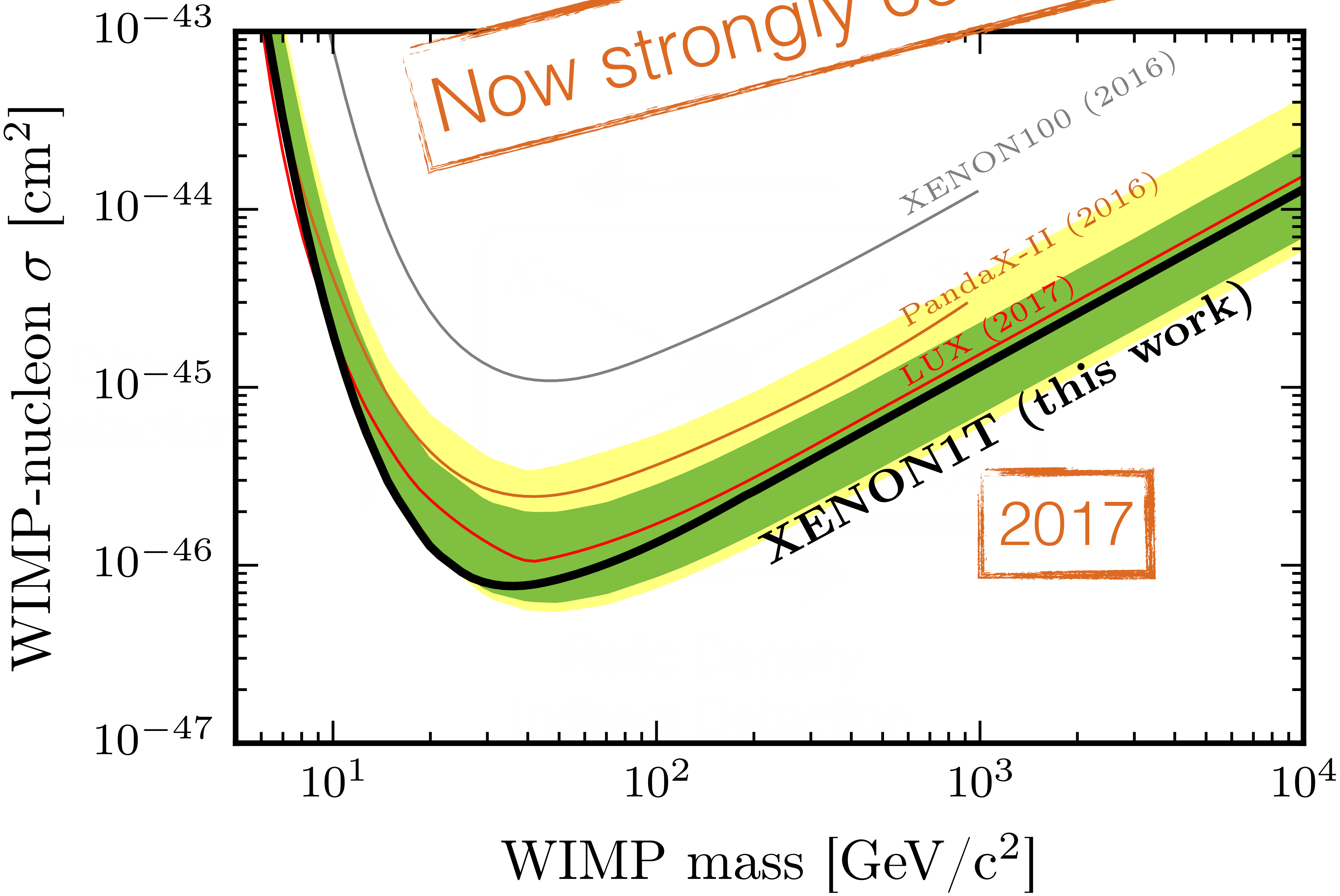
$$\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle}$$

$$\Longrightarrow$$

$$M_X \approx \mathrm{TeV} \left(\frac{g^2}{0.3} \right)$$

Standard candidate: WIMP

Now strongly constrained!

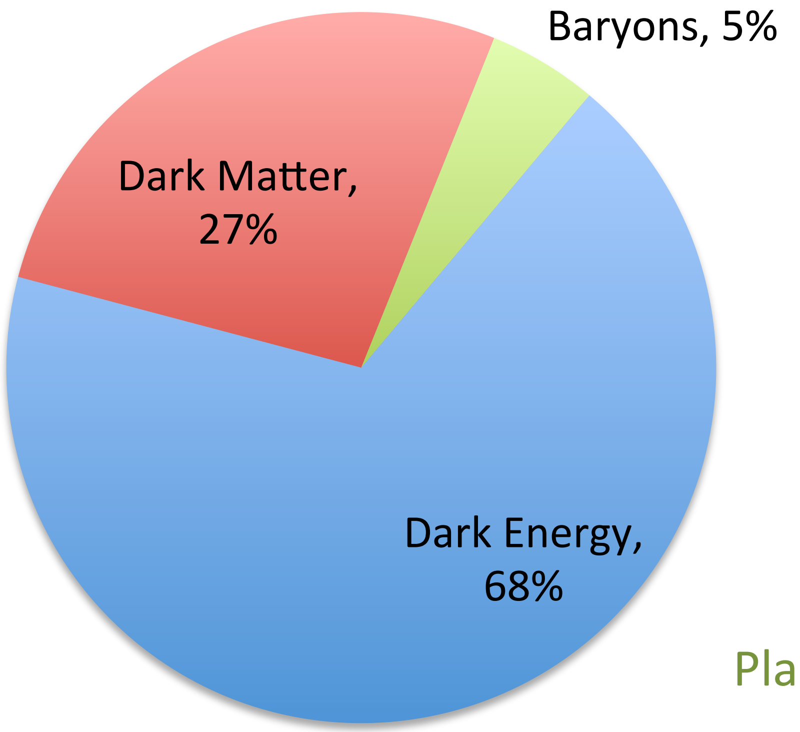


2017

Consider alternatives

A hint from nature?

Composition of energy density of the universe today!



Planck 2013, XVI

$$\rho_{\mathrm{DM}} \approx 5 \times \rho_B$$

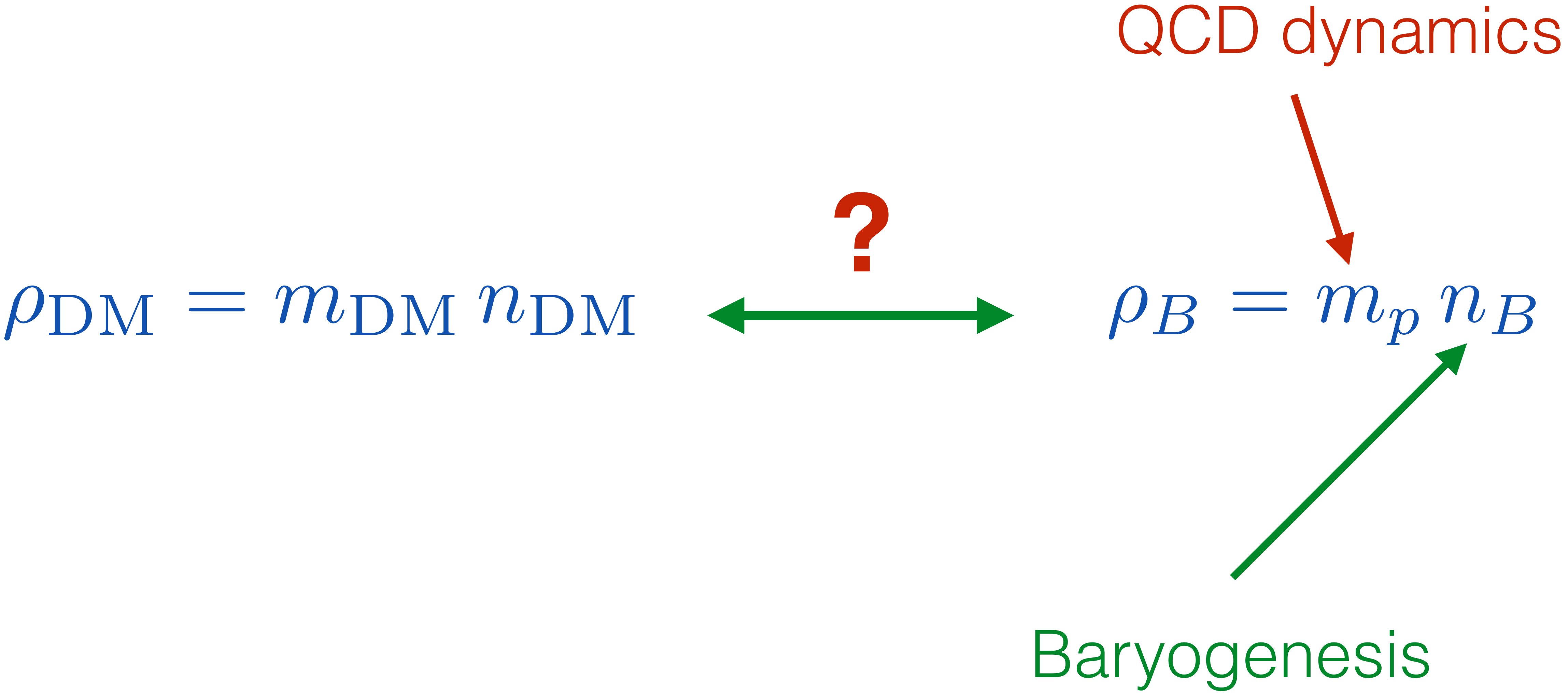
A hint from nature?

$$\rho_{\mathrm{DM}} \approx 5 \times \rho_B$$

$$\rho_{\mathrm{DM}} = m_{\mathrm{DM}}\, n_{\mathrm{DM}} \quad \xleftrightarrow{\quad ? \quad} \quad \rho_B = m_p\, n_B$$

A hint from nature?

$$\rho_{\rm DM} \approx 5 \times \rho_B$$



QCD dynamics

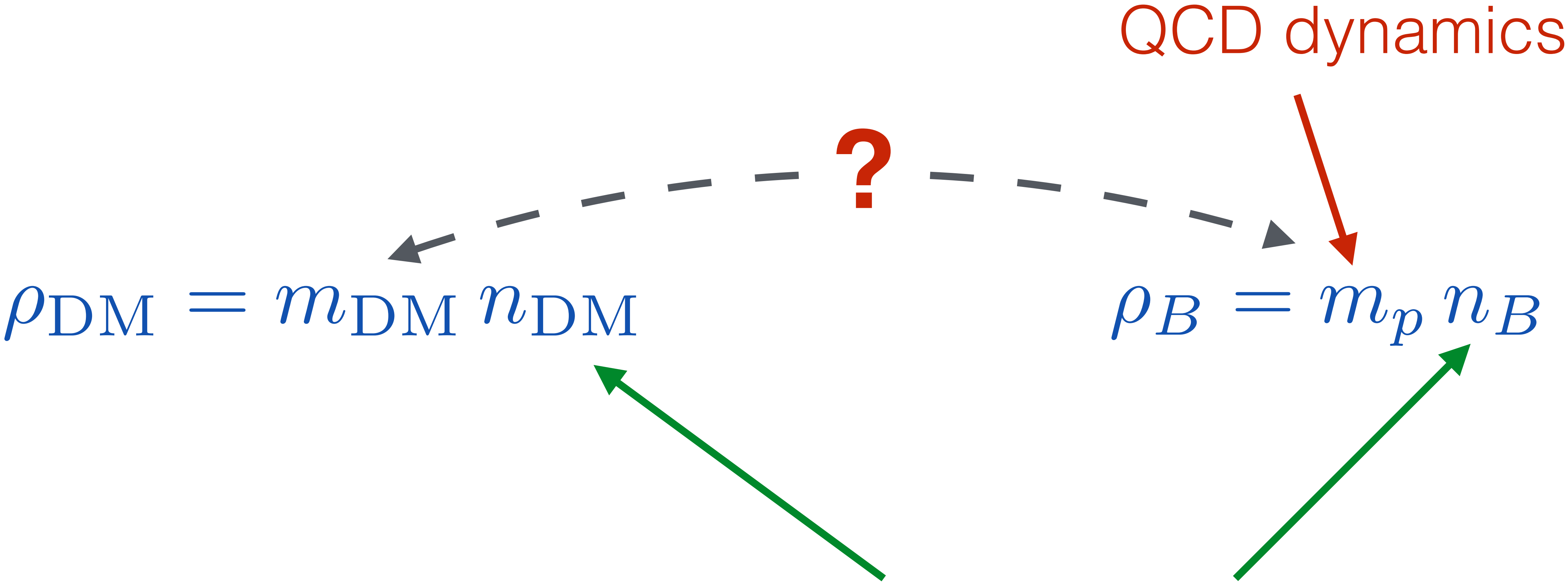
?

$$\rho_{\rm DM} = m_{\rm DM}\, n_{\rm DM} \longleftrightarrow \rho_B = m_p\, n_B$$

Baryogenesis

Asymmetric DM

$$\rho_{\rm DM} \approx 5 \times \rho_B$$



QCD dynamics

?

$$\rho_{\rm DM} = m_{\rm DM}\, n_{\rm DM}$$

$$\rho_B = m_p\, n_B$$

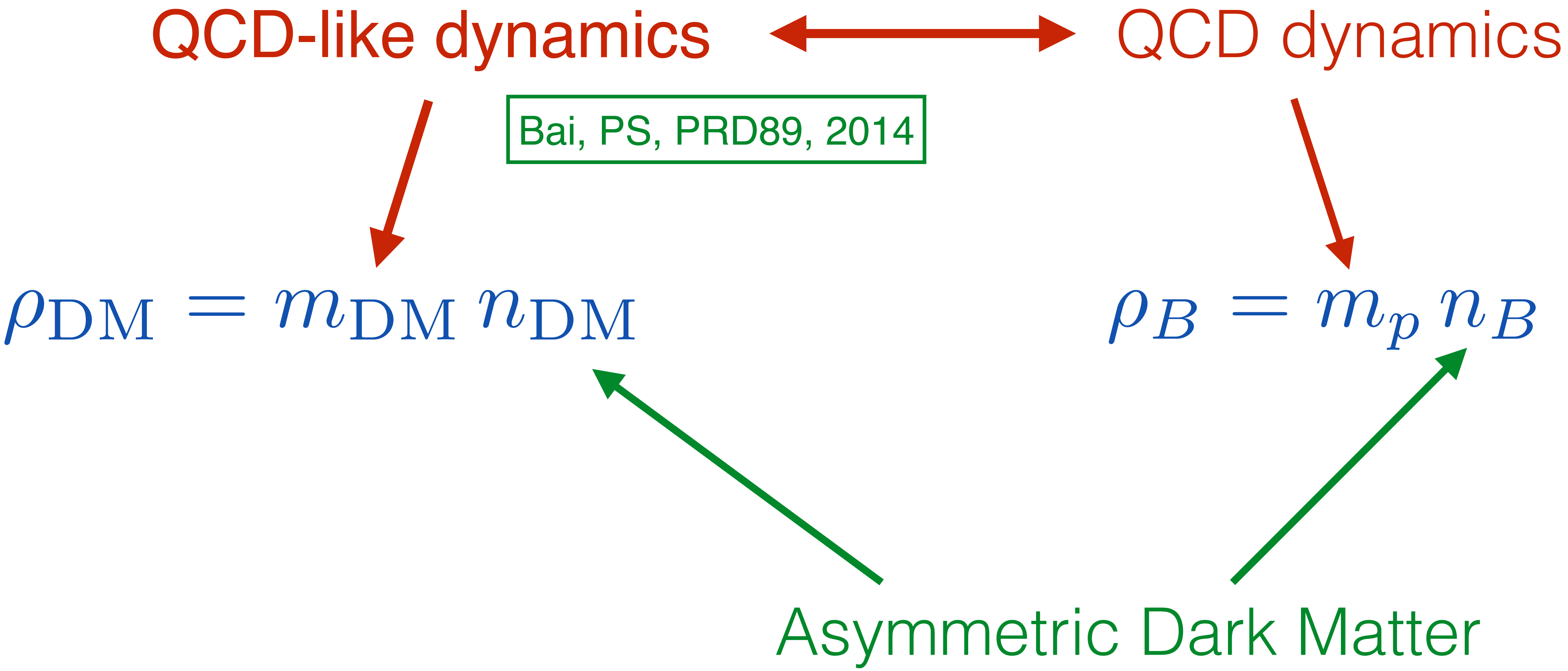
Asymmetric Dark Matter

e.g. Nussinov; Barr; Barr, Chivukula, Farhi; Gudnason, Kouvaris, Sannino; Kitano, Low; Luty, Kaplan, Zurek; Buckley, Randall; Davoudiasl, Morrissey, Sigurdson, Tulin; Shelton, Zurek; Falkowski, Rudermann, Volanski; N. Rius et al; S. Davidson et al; Servant, Tulin; …

Reviews: Petraki, Volkas, 2013; Zurek 2013;

Dark QCD

$$\rho_{\mathrm{DM}} \approx 5 \times \rho_B$$



QCD-like dynamics

QCD dynamics

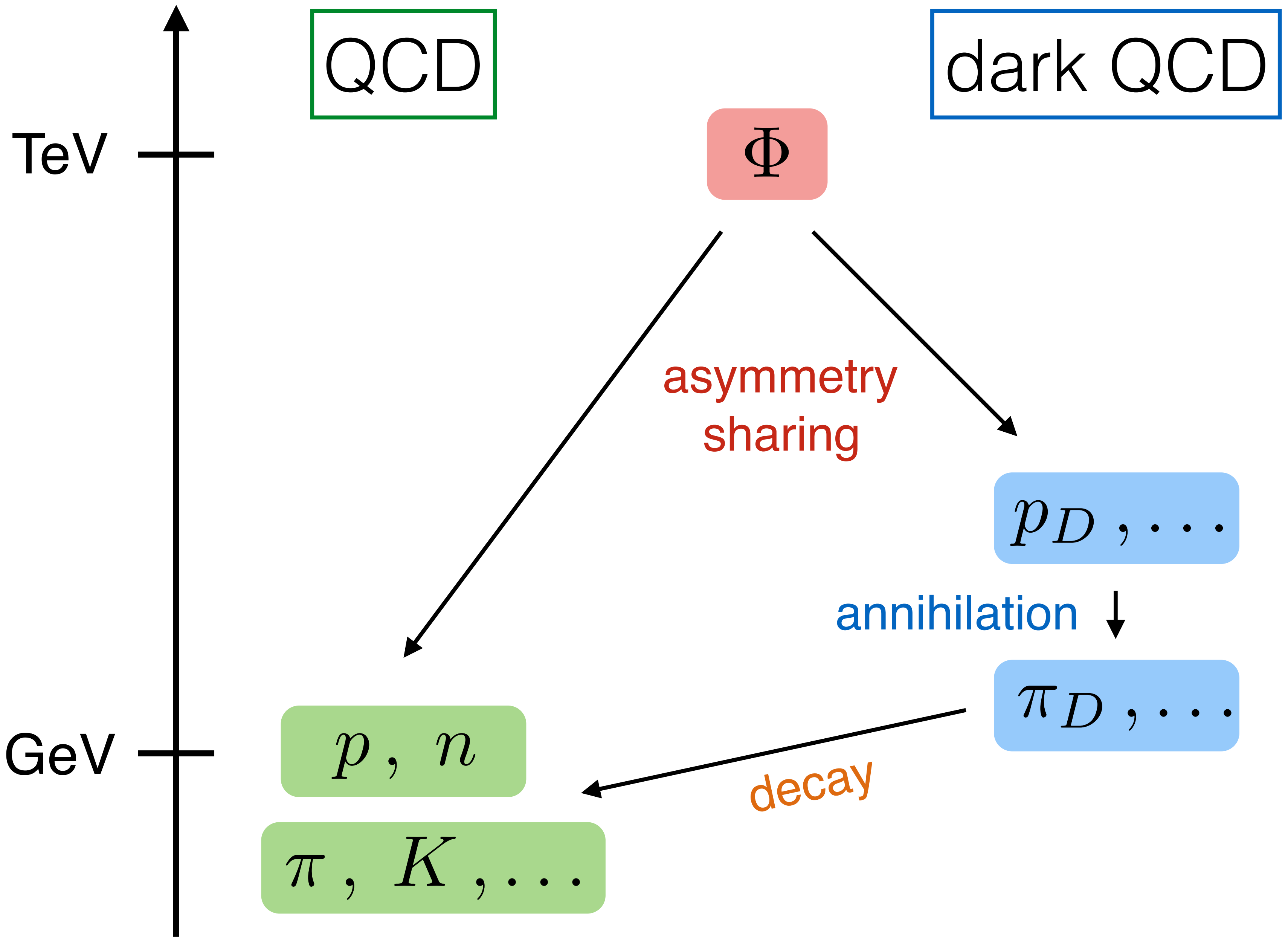
Bai, PS, PRD89, 2014

$$\rho_{\mathrm{DM}} = m_{\mathrm{DM}}\, n_{\mathrm{DM}}$$

$$\rho_B = m_p\, n_B$$

Asymmetric Dark Matter

Dark QCD



- SU(N) dark sector with neutral **"dark quarks"**
- Confinement scale

$$\Lambda_{\mathrm{darkQCD}}$$

- DM is composite **"dark proton"**
- "Dark pions" unstable, long lived

Today: Focus on
Phenomenology

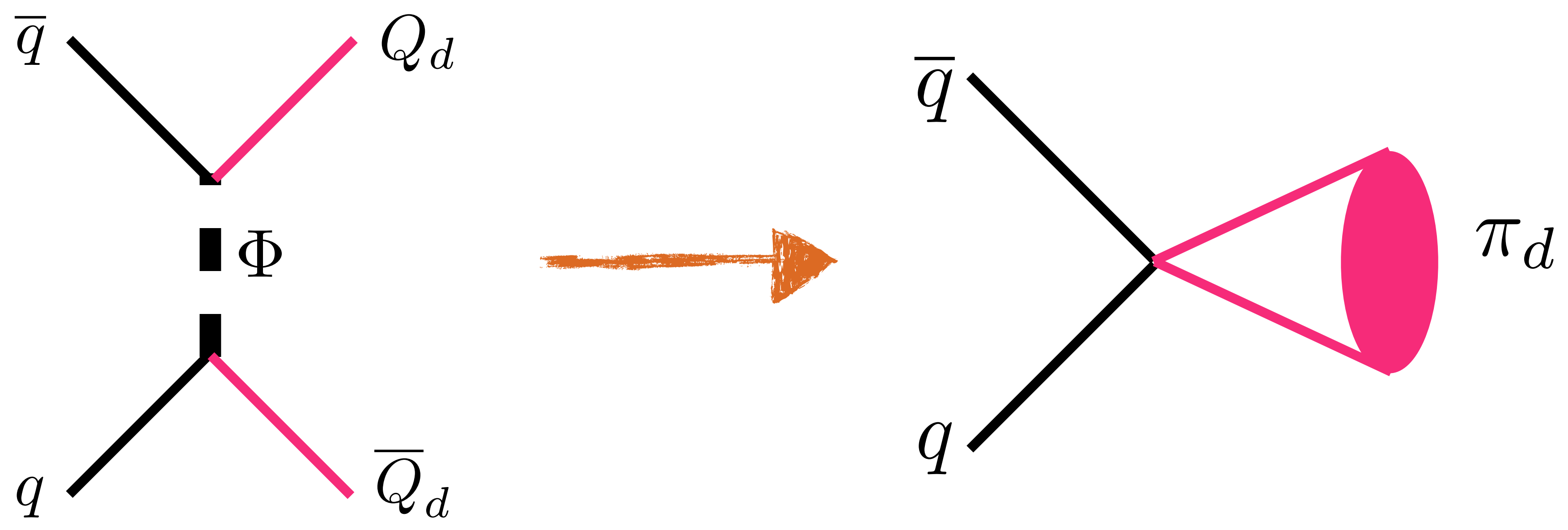
Particle content

- Dark “protons” p_d with conserved DM number
- Dark pions π_d and other composite states
  - Not protected by symmetries, $\pi_d \to \mathrm{SM}$ allowed
- Mediators:
  - Bifundamental scalar Φ $\mathcal{L} \supset \kappa \Phi \bar{Q}_D d_R$
  - or Z' (Hidden Valleys!) $\mathcal{L} \supset g' \bar{Q}_D \gamma^\mu Q_D Z'_\mu$

$+$ couplings to SM

Dark Pion Lifetime

- Integrate out mediator, match to dark pion current



- Decay to SM jets (pions)

$$\Gamma(\pi_d \to \bar{d}d) \approx \frac{f_{\pi_d}^2 m_{\mathrm{d}}^2}{32\pi M_{X_d}^4} m_{\pi_d}$$

Dark Pion Lifetime

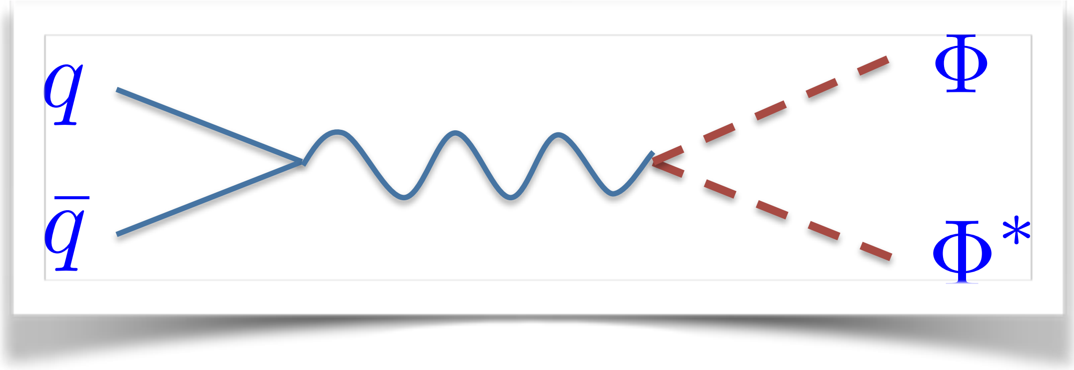
$$\Gamma(\pi_d \to \bar{d}d) \approx \frac{f_{\pi_d}^2 m_{\mathrm{d}}^2}{32\pi M_{X_d}^4} m_{\pi_d}$$

$$c\tau \approx 5\,\mathrm{cm} \times \left(\frac{1\ \mathrm{GeV}}{f_{\pi_d}}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\mathrm{d}}}\right)^2 \left(\frac{1\ \mathrm{GeV}}{m_{\pi_d}}\right) \left(\frac{M_{X_d}}{1\ \mathrm{TeV}}\right)^4$$

Decay in LHC detectors!

Collider Signature

- Pair production of heavy bi-fundamental fields:

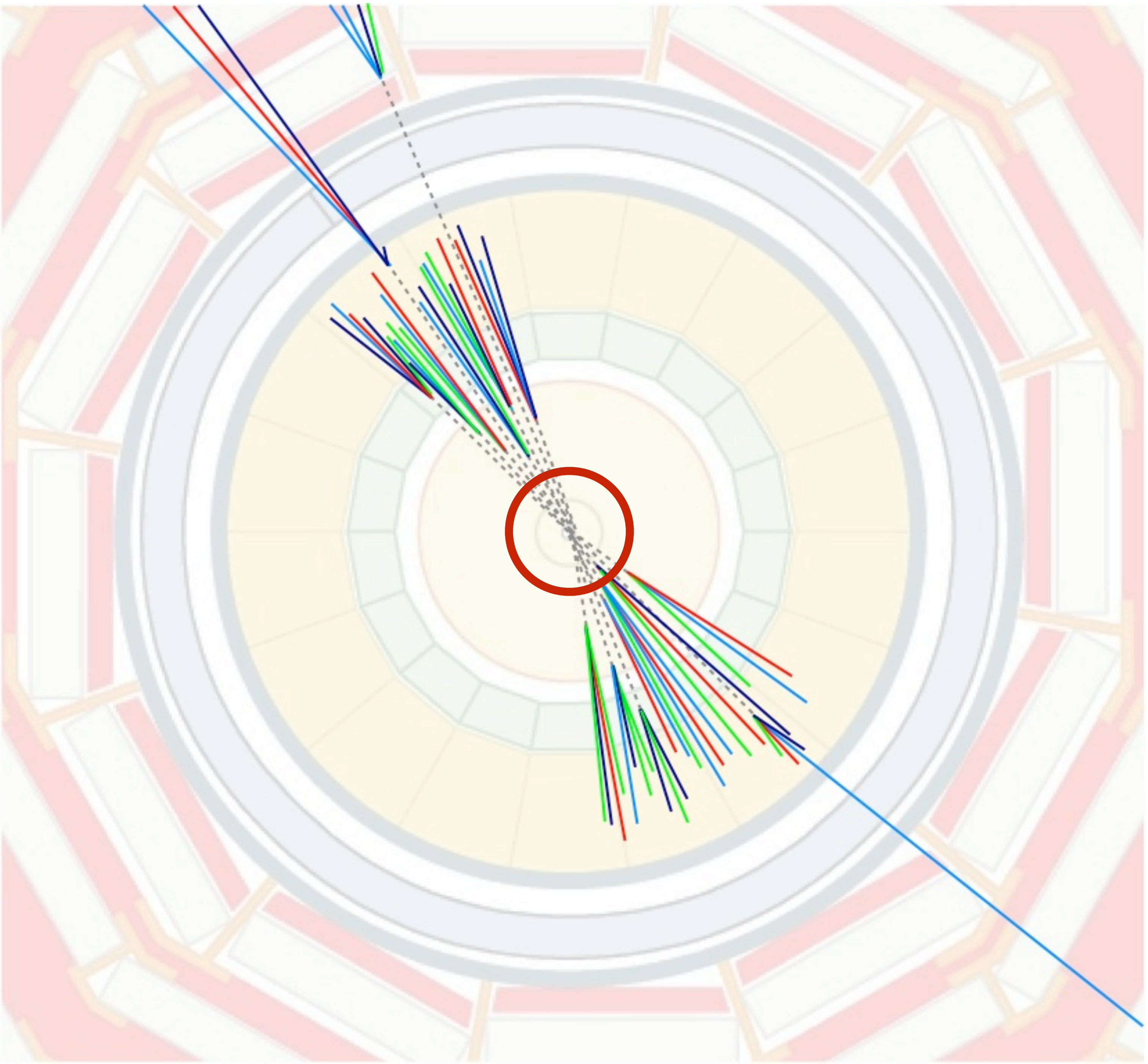


- Decay to quark - dark quark pairs
  - two QCD-jets
  - two “Emerging Jets”:
    dark quarks shower and hadronize in dark sector
    decay back to SM jets with displaced vertices

Also “Hidden Valley” signature
Strassler, Zurek, 2007; …
related: SIMP dark matter
Bai, Rajaraman, 2011

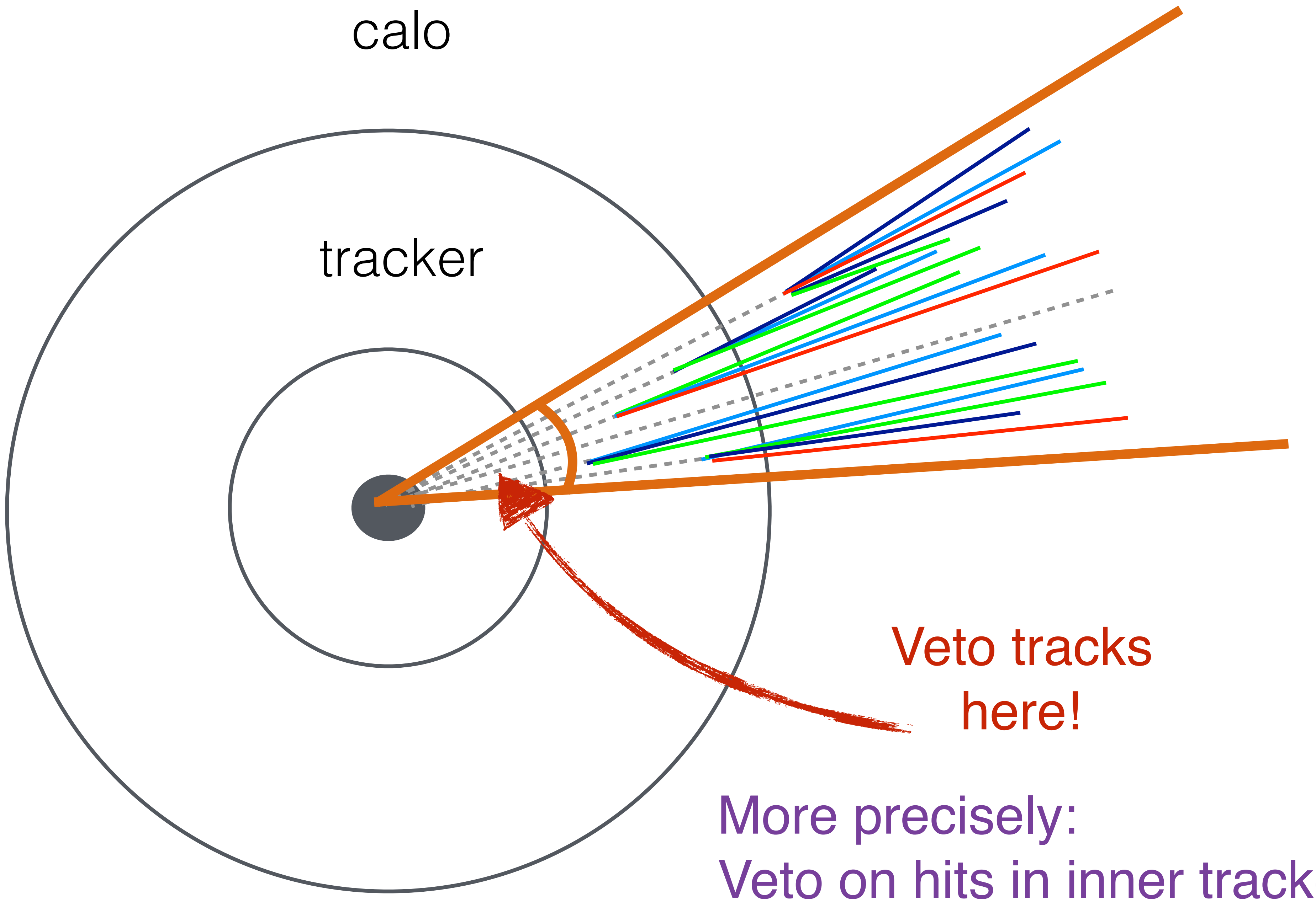
Emerging Jets at the LHC

- Characteristic:
  - few/no tracks in inner tracker
- New "emerging" jet signature
- Universal for large class of composite DM models!



PS, Stolarski, Weiler, 2015

Strategy

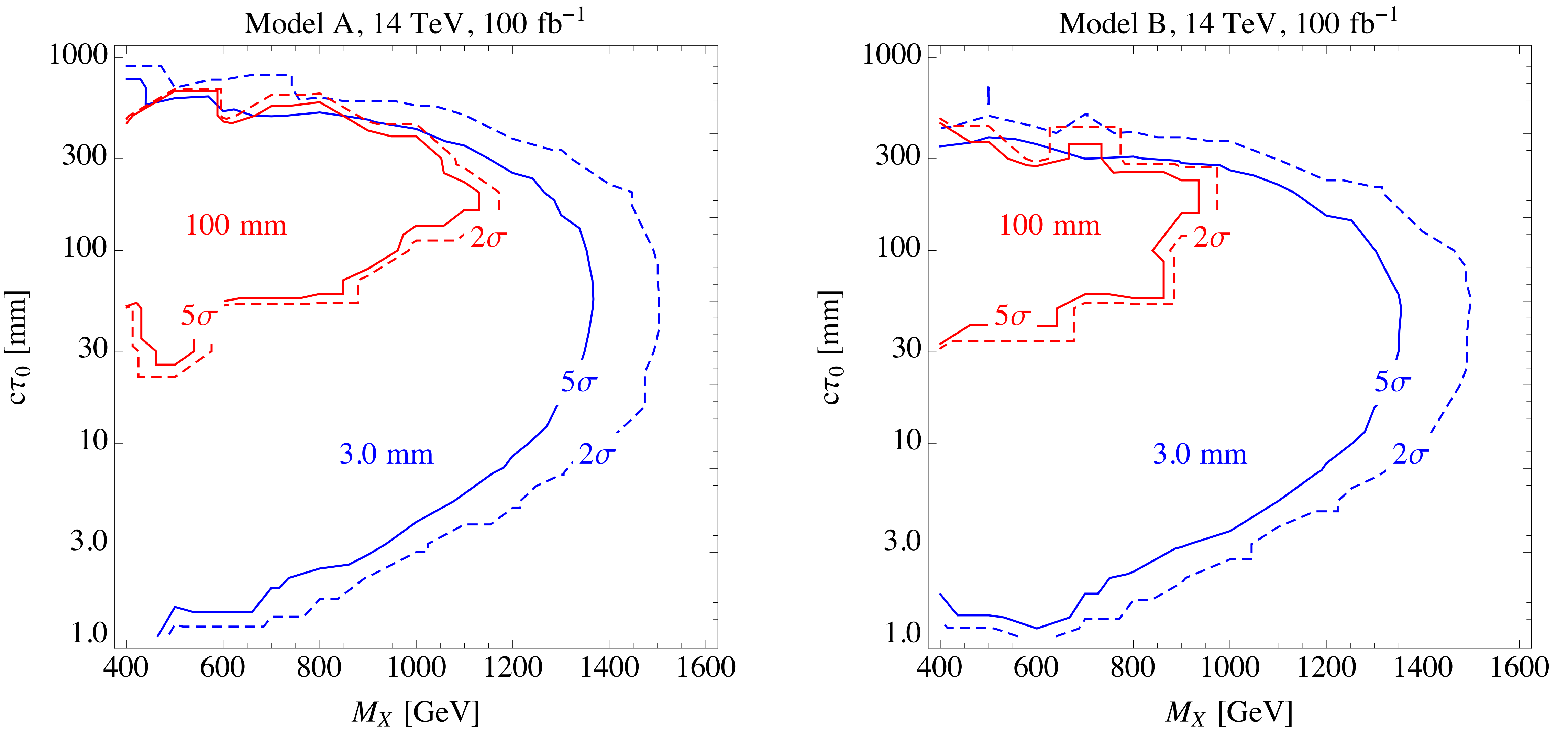


Veto tracks here!

More precisely:
Veto on hits in inner tracker or on reconstructed vertices with $L_{xy} < r$

PS, Stolarski, Weiler, 2015

Reach ATLAS/CMS



- Optimistic scenario (no non-collisional BGs)
- Also sensitive to some RPV SUSY models etc

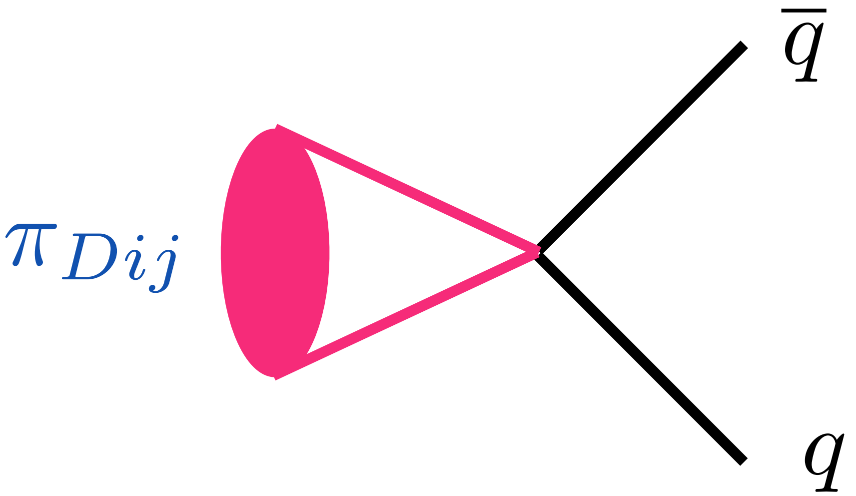
PS, Stolarski, Weiler, 2015

Adding flavour

- So far, assumed universal lifetime for dark pions
- Actually

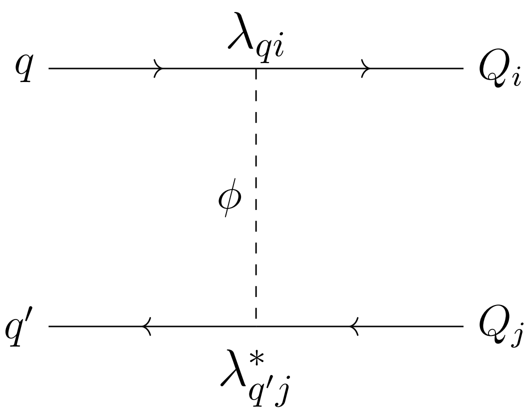
$$\lambda \bar{d}_R Q_L \Phi = \lambda_{ij} \bar{d}_{Ri} Q_{Lj} \Phi$$

- Not all pions are equal:



$$\propto \sum_{q,q'} |\lambda_{qi} \lambda^*_{q'j}|^2$$

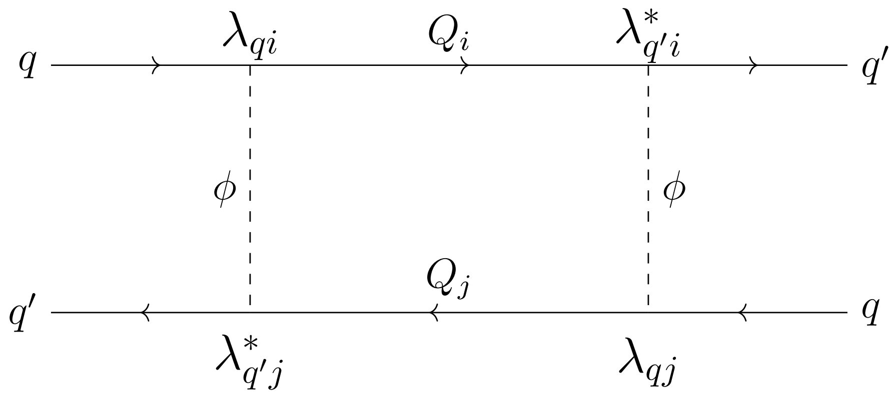
Flavour matters



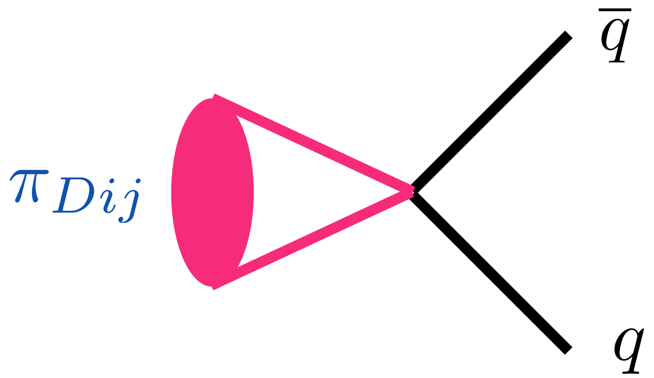
ΔF = 1

ΔF = 2

constraints



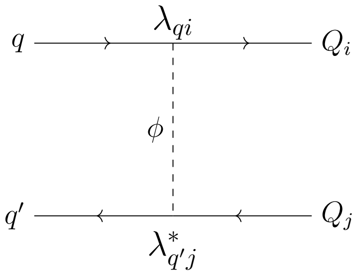
$$\lambda_{ij}\bar{d}_{Ri}Q_{Lj}\Phi$$



dark pion properties

fixed target experiments

NA62



SHiP

Search for Hidden Particles

Flavour constraints

- Parameterise

Parameterisation from
Agrawal, Blanke,
Gemmler, 2014

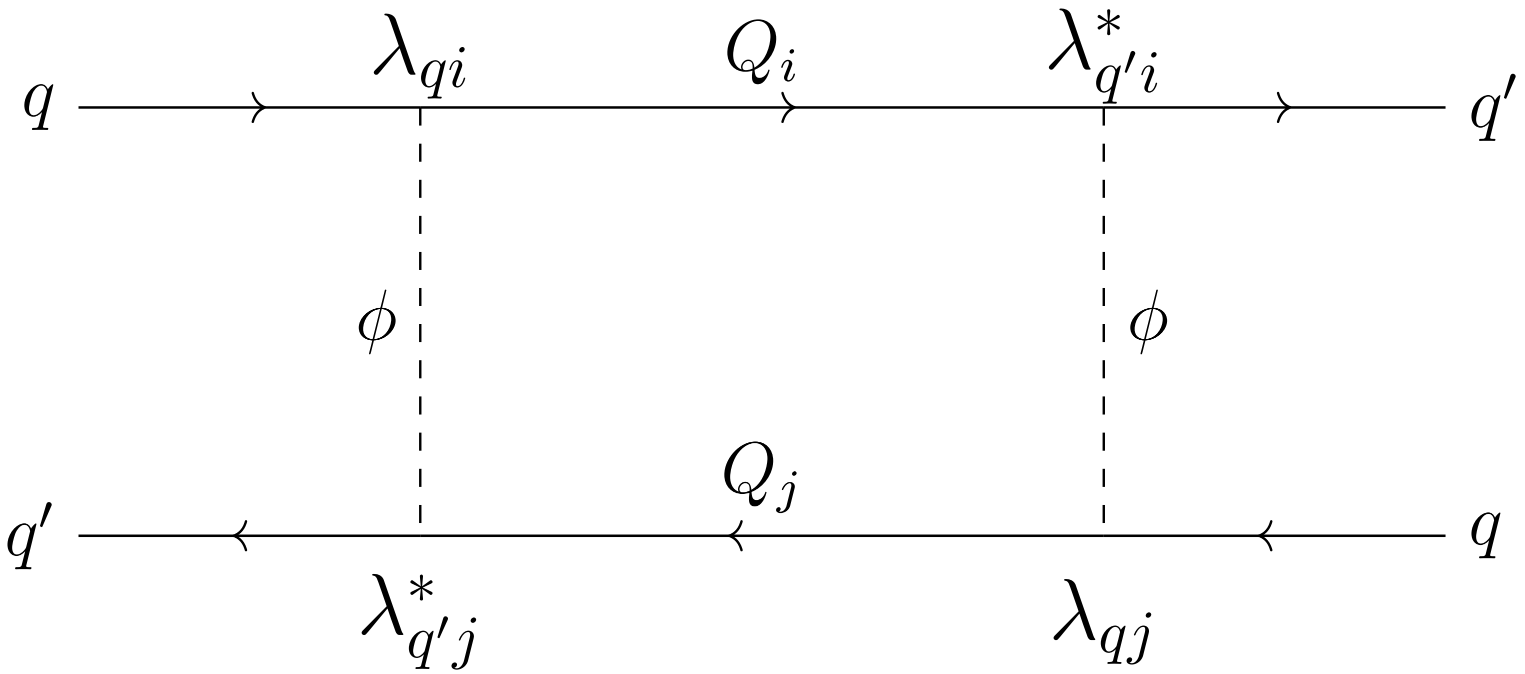
unitary

$$\lambda = UDV$$

diagonal

- For degenerate dark quark masses, can absorb V
- If $D \propto \mathbb{1}$, SM flavour symmetry unbroken
- Write $D = \Big(\lambda_0 \cdot \mathbb{1} + \mathrm{diag}(\lambda_1, \lambda_2, -(\lambda_1 + \lambda_2))\Big)$

ΔF=2



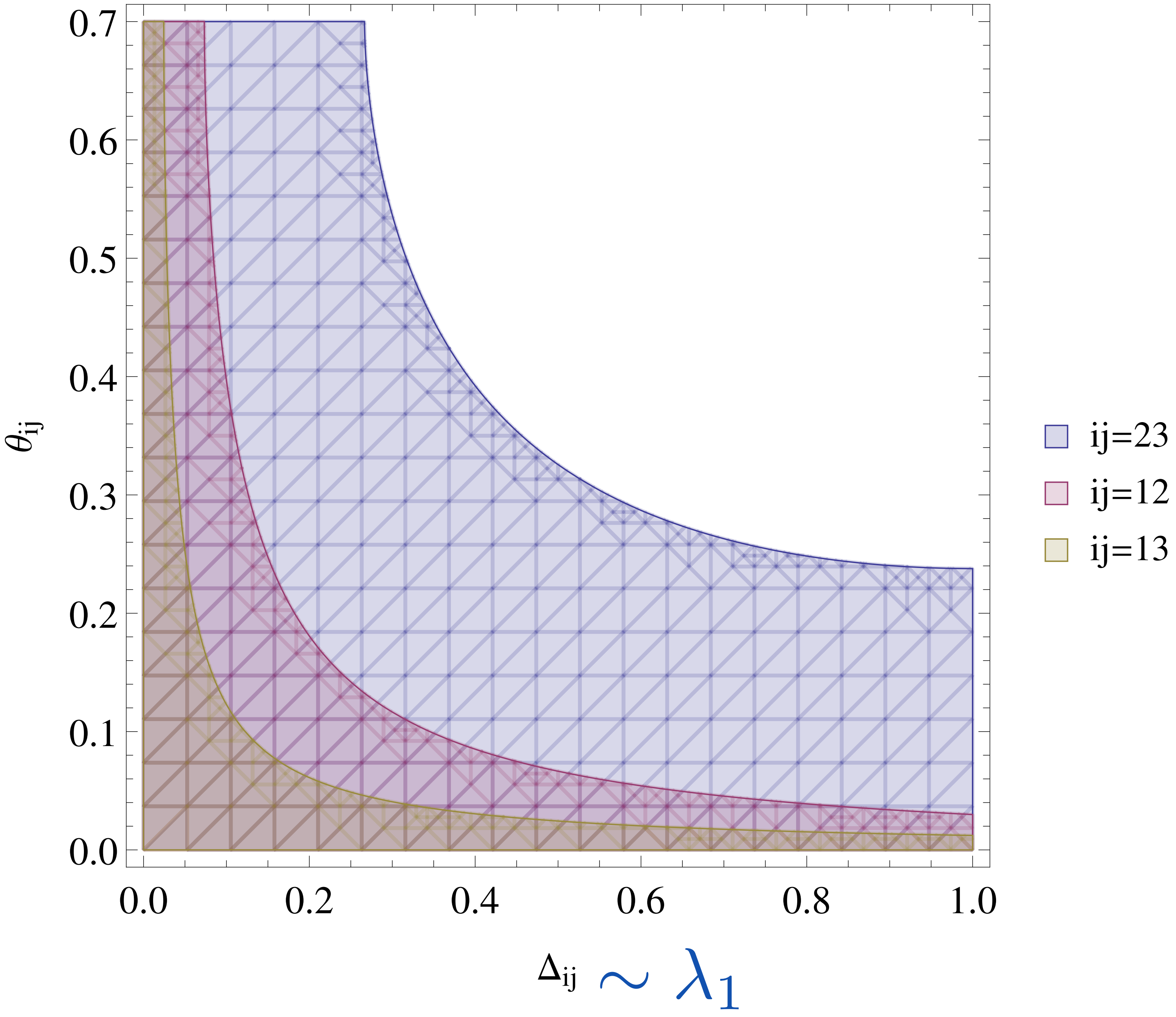
- Absent in $D = \lambda_0 \cdot \mathbb{1}$ limit!

$$\left(\sum_{i=1}^{3} \lambda_{qi} \lambda^*_{q'i} \right)^2 = \left([UD(UD)^\dagger]_{qq'} \right)^2 = \lambda_0^4 \left([UU^\dagger]_{qq'} \right)^2 = 0$$

ΔF=2

- Otherwise bounds on mixing matrix

$$U = U_{12} U_{13} U_{23}$$

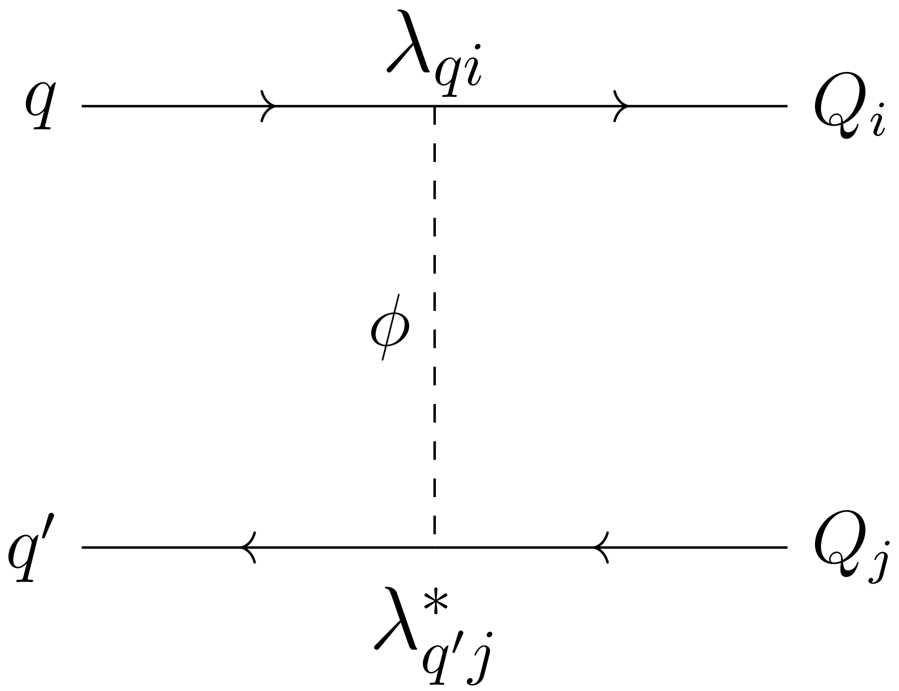


ΔF=1

- Allows rare decays

$B \to (K, \pi) + \text{invisible}$

$K \to \pi + \text{invisible}$



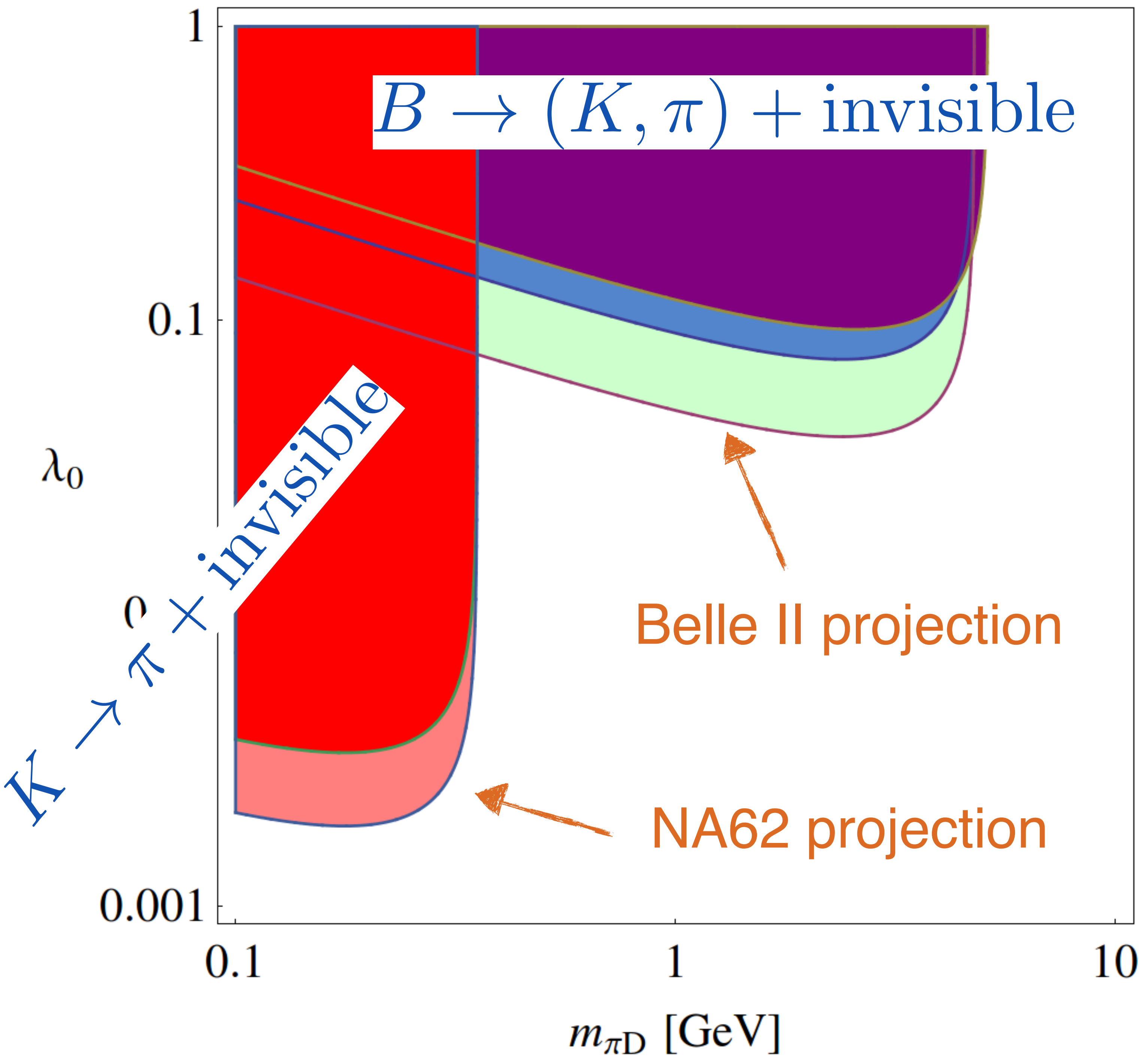
- Strongest close to thresholds: $K \to \pi\,\pi_D$ wins over $K \to \pi\, Q\bar{Q}$

- Don’t vanish in flavour symmetric limit!

great resource:
Kamenik, Smith, 2011

ΔF=1

- Best bound on couplings for very light dark pions



Emerging jets revisited

- Range of dark pion lifetimes

Scenario	Flavour composition	$c\tau_0\lambda_0^4\ /mm$ $(m_{\pi_D} = f_{\pi_D} = 2\text{GeV})$	$c\tau_0\lambda_0^4\ /mm$ $(m_{\pi_D} = f_{\pi_D} = 15\text{GeV})$
Aligned	Diagonal	88.6	1.08×10^{-4}
	$\bar{Q}_1 Q_2$	88.6	0.210
	$\bar{Q}_1 Q_3$	Long-lived	1.08×10^{-4}
	$\bar{Q}_2 Q_3$	Long-lived	1.08×10^{-4}
$\sin\theta_{12} = 0.1$, $\Delta_{12} = 0.5$	Diagonal	86.5	1.72×10^{-3}
	$\bar{Q}_1 Q_2$	40.0	9.48×10^{-2}
	$\bar{Q}_1 Q_3$	Long-lived	1.92×10^{-4}
	$\bar{Q}_2 Q_3$	Long-lived	4.25×10^{-4}
$\sin\theta_{13} = 0.05$, $\Delta_{13} = 0.5$	Diagonal	88.6	3.37×10^{-4}
	$\bar{Q}_1 Q_2$	56.9	2.29×10^{-2}
	$\bar{Q}_1 Q_3$	5.7×10^{6}	1.23×10^{-4}
	$\bar{Q}_2 Q_3$	2.27×10^{5}	1.91×10^{-4}

Emerging jets revisited

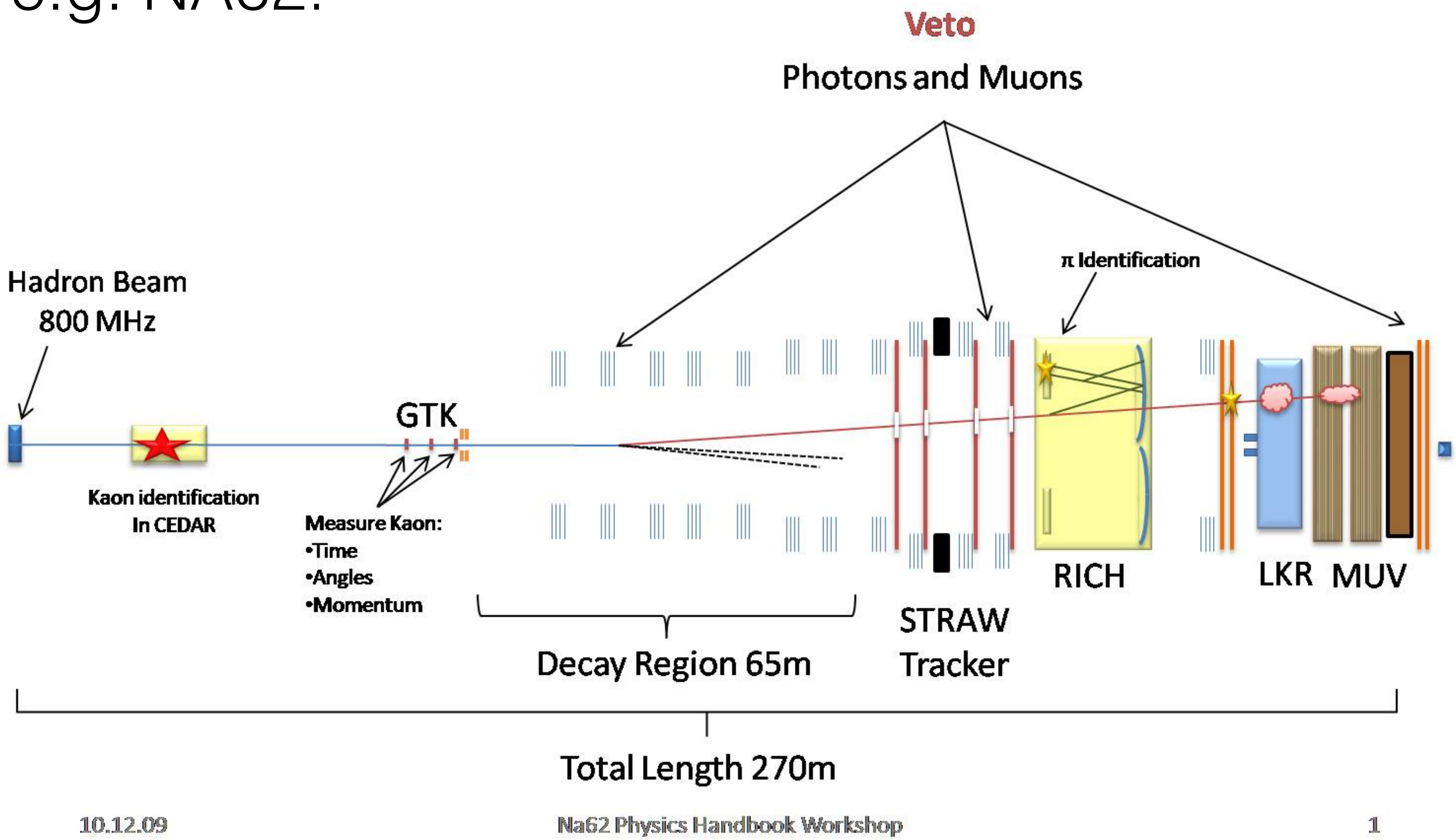
- “Visible” jet fraction as function of distance modified

- New flavour compositions
    - e.g. prompt decays to B’s, displaced decays to light flavours

- Sometimes detector stable mesons
    - Comparison with Z’ mediator: Ratio of unstable to stable pions only depends on n_f

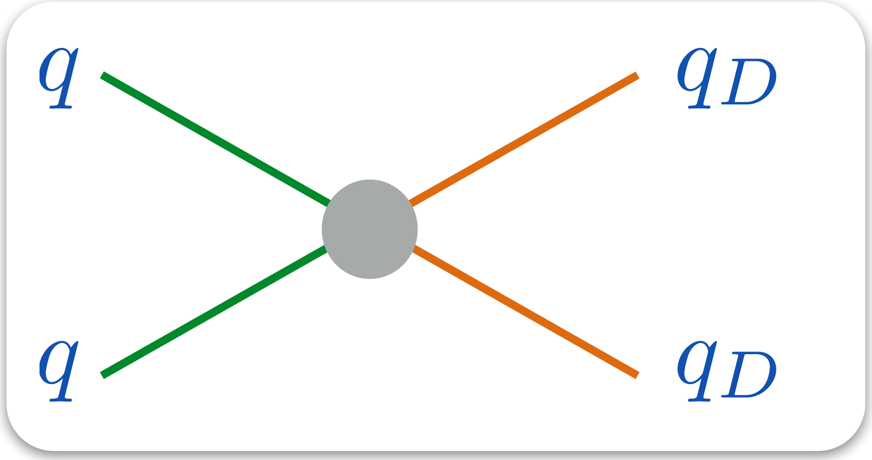
Fixed target

- e.g. NA62:



Fixed target

- Initially negative, direct production rate too low



- But, produce 10^{11} B-mesons, countless Kaons
- Up to 10^{6} dark pions if bound on rare decays is saturated!
    - Very promising, work in progress

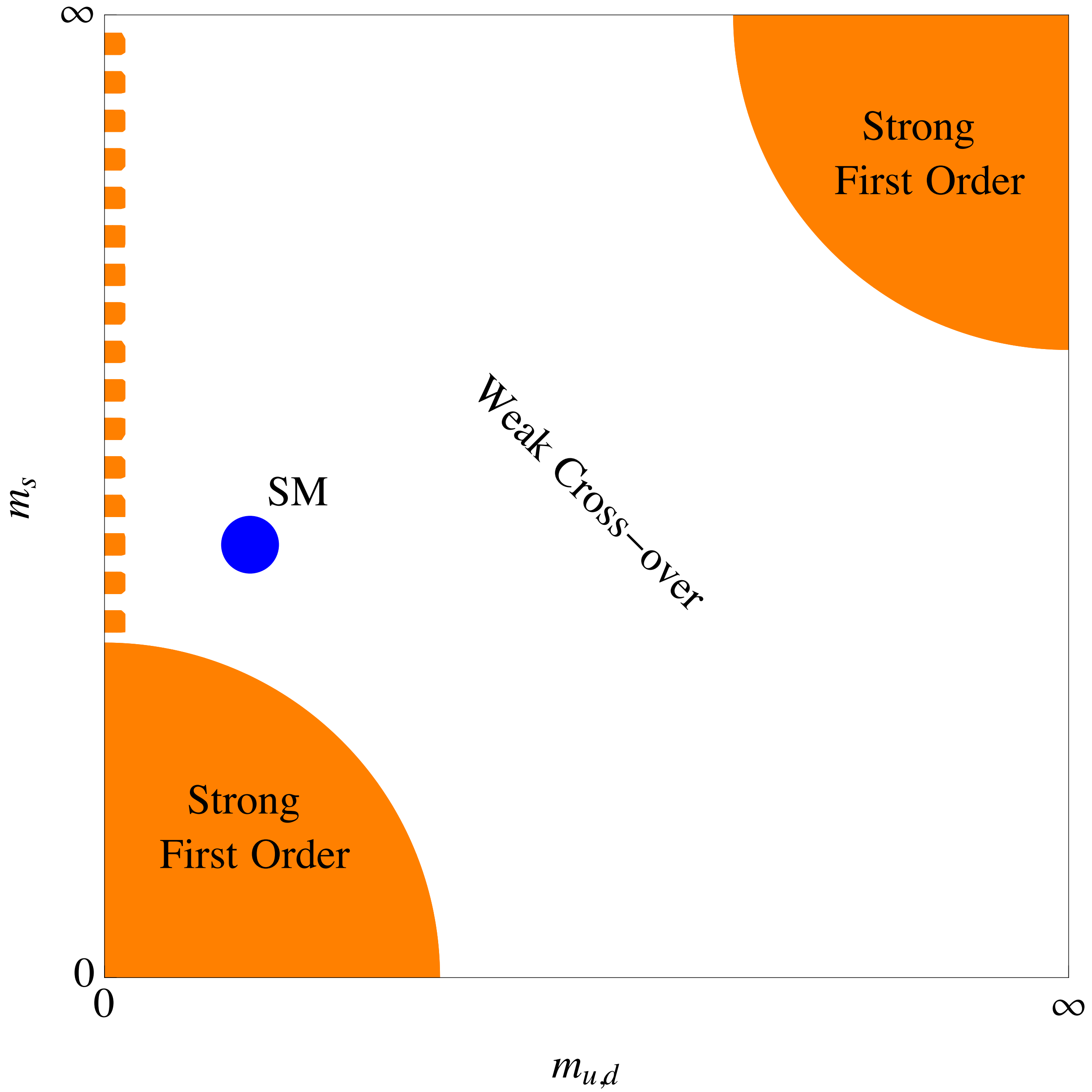
Summary

- “Dark QCD” motivated in many BSM scenarios, in particular: DM and Naturalness
- Emerging jets are smoking gun, good prospects for ATLAS/CMS
    - Test TeV scale mediators without MET or Leptons
- Flavour adds new dimension to emerging jets phenomenology
- Interesting opportunity for fixed target experiments

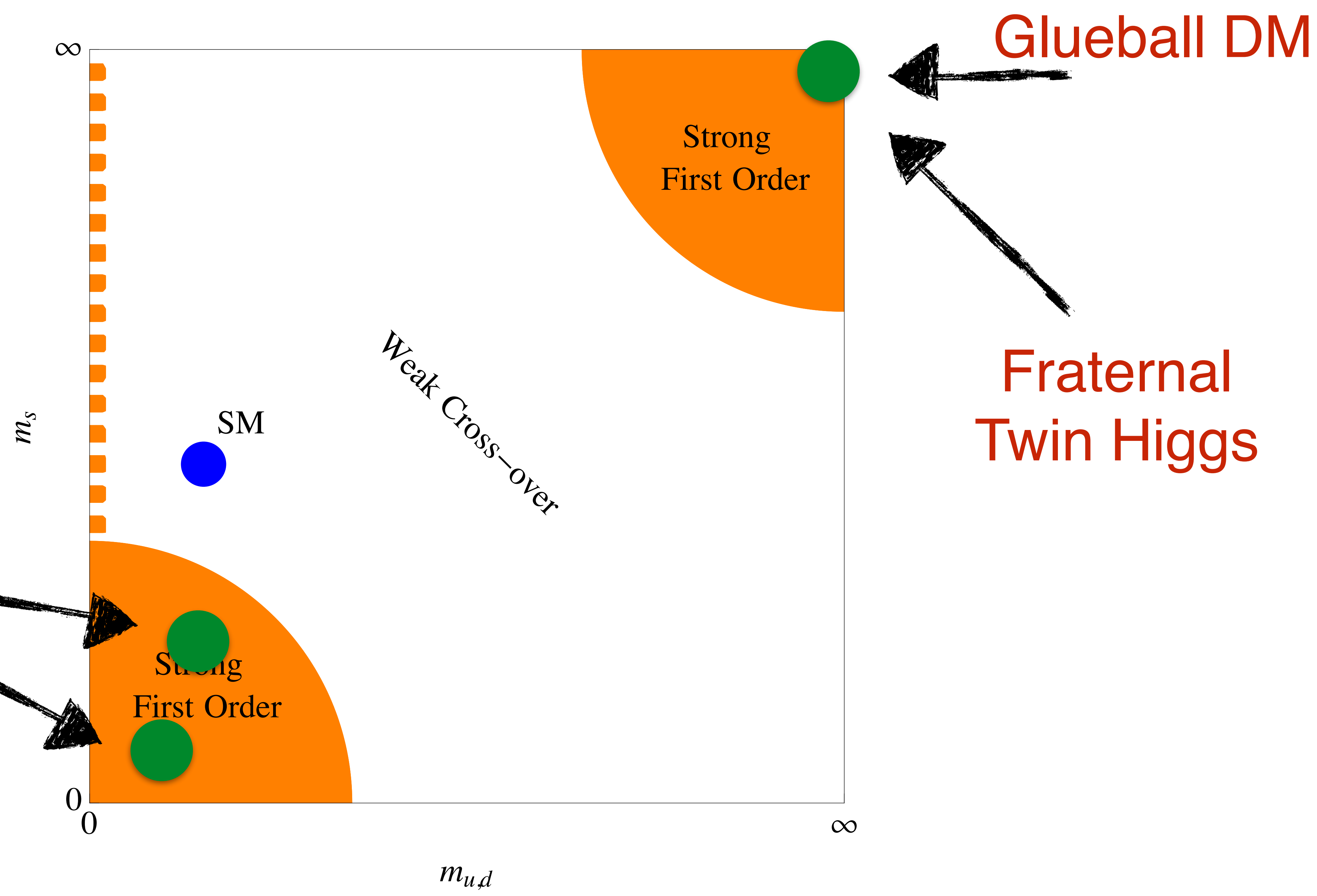
Thank You

The Dark Phase Transition

QCD Phase Diagram



Phase Diagram II



Glueball DM

Fraternal
Twin Higgs

Dark QCD
SIMP models

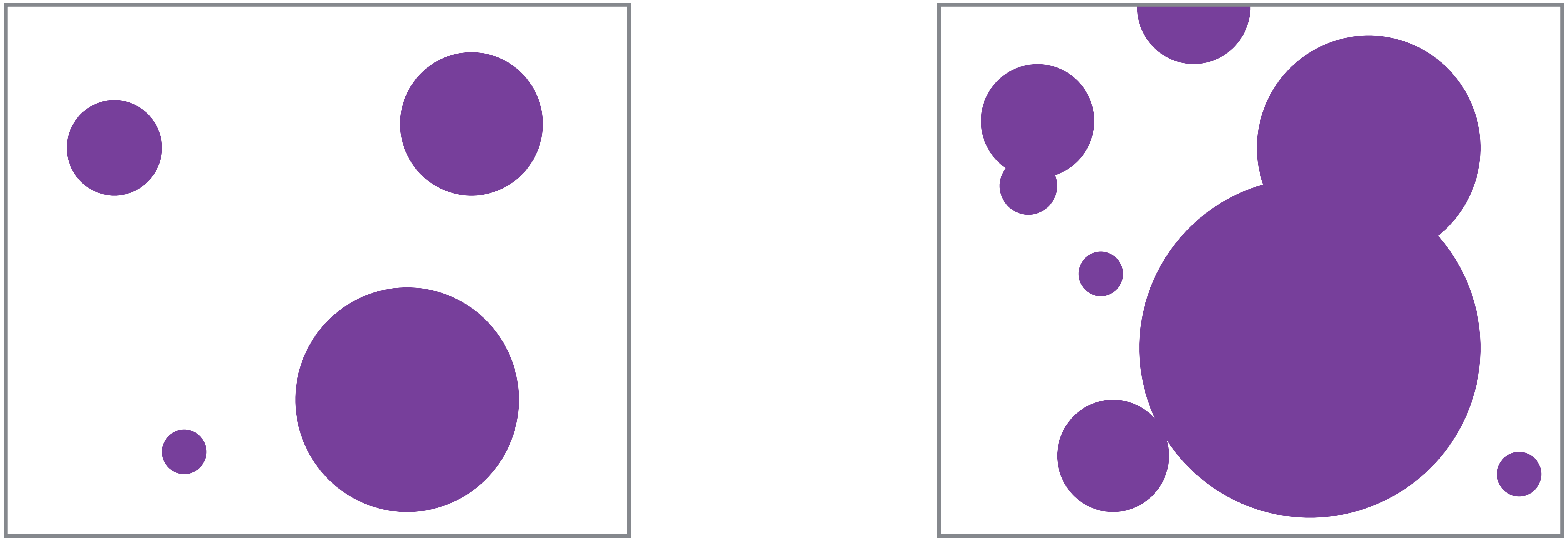
SU(N) - PT

- Consider $SU(N_d)$ with n_f massless flavours
- PT is first order for
  - $N_d \geq 3 \ , \quad n_f = 0$ Svetitsky, Yaffe, 1982 M. Panero, 2009
  - $N_d \geq 3 \ , \quad 3 \leq n_f < 4N_d$ Pisarski, Wilczek, 1983
- Not for:
  - $n_f = 1$ (no global symmetry, no PT)
  - $n_f = 2$ (not yet known)

GW Signal

First order PT → Bubbles nucleate, expand

Bubble collisions → Gravitational Waves



Peak Frequency

- Redshift:

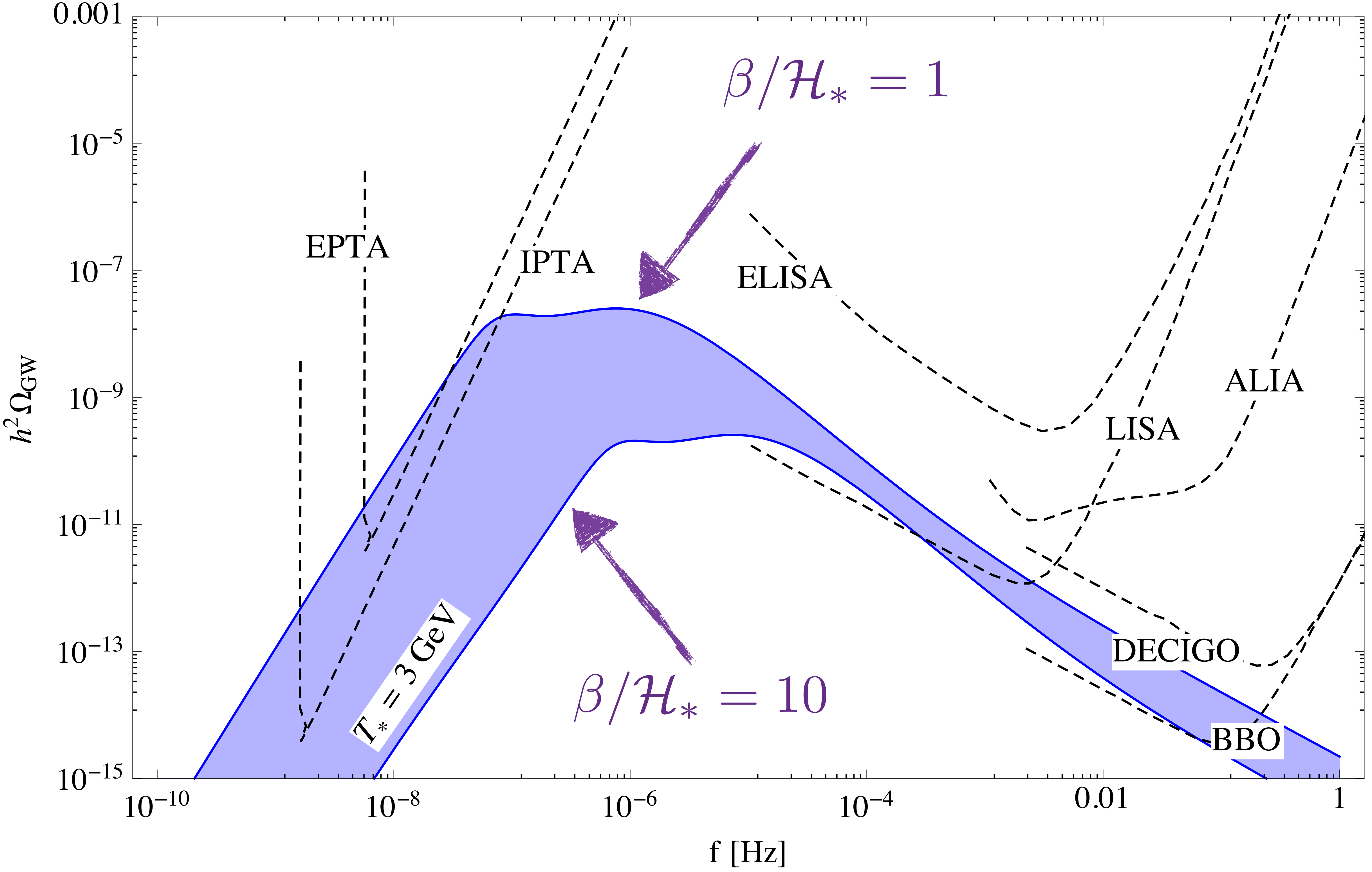
$$f = \frac{a_*}{a_0} H_* \frac{f_*}{H_*} = 1.59 \times 10^{-7}\ \mathrm{Hz} \times \left(\frac{g_*}{80}\right)^{\frac{1}{6}} \times \left(\frac{T_*}{1\ \mathrm{GeV}}\right) \times \frac{f_*}{H_*}$$

DM mass

- Peak regions: $k/\beta \approx (1 - 10)$

$$f^{(B)}_{\mathrm{peak}} = 3.33 \times 10^{-8}\ \mathrm{Hz} \times \left(\frac{g_*}{80}\right)^{\frac{1}{6}} \left(\frac{T_*}{1\ \mathrm{GeV}}\right) \left(\frac{\beta}{\mathcal{H}_*}\right)$$

T* ~ Few GeV



$\beta/\mathcal{H}_* = 1$

$\beta/\mathcal{H}_* = 10$

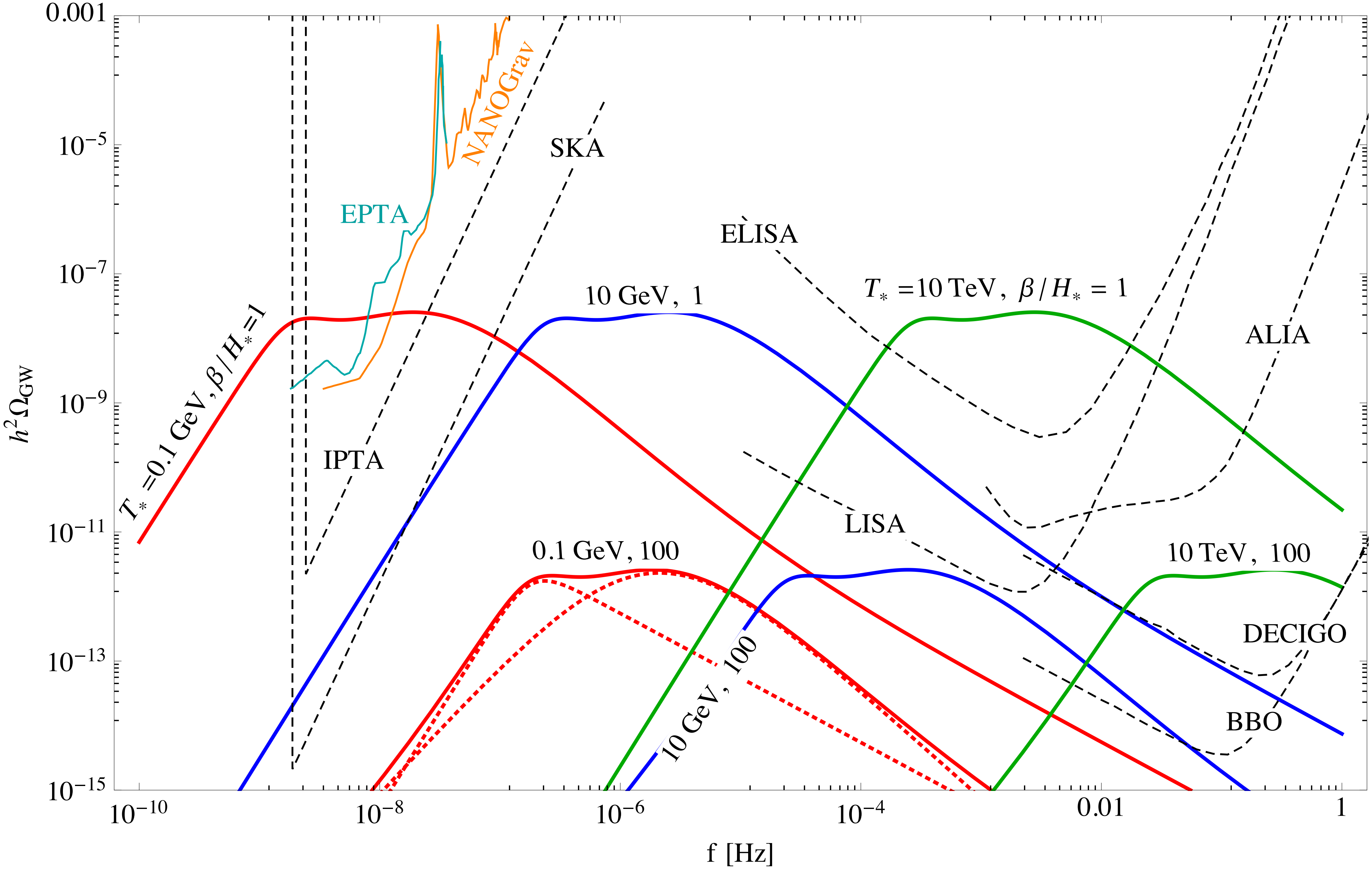
PS, PRL115, 2015

SIMP

Composite ADM
Twin Higgs

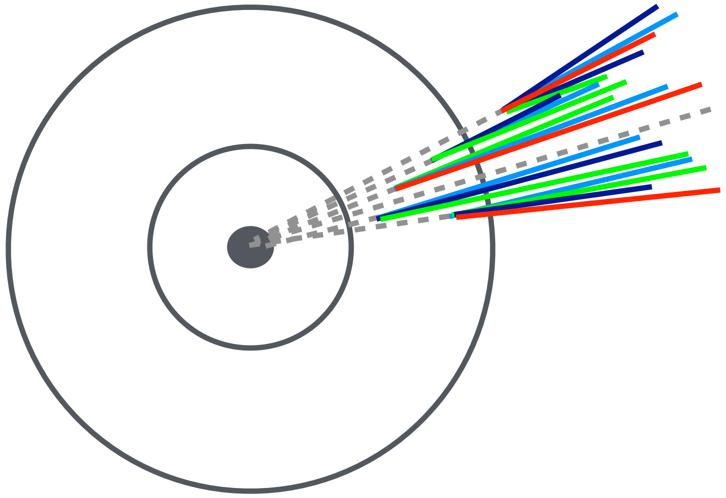
Composite
WIMP-y

DM
Unitarity



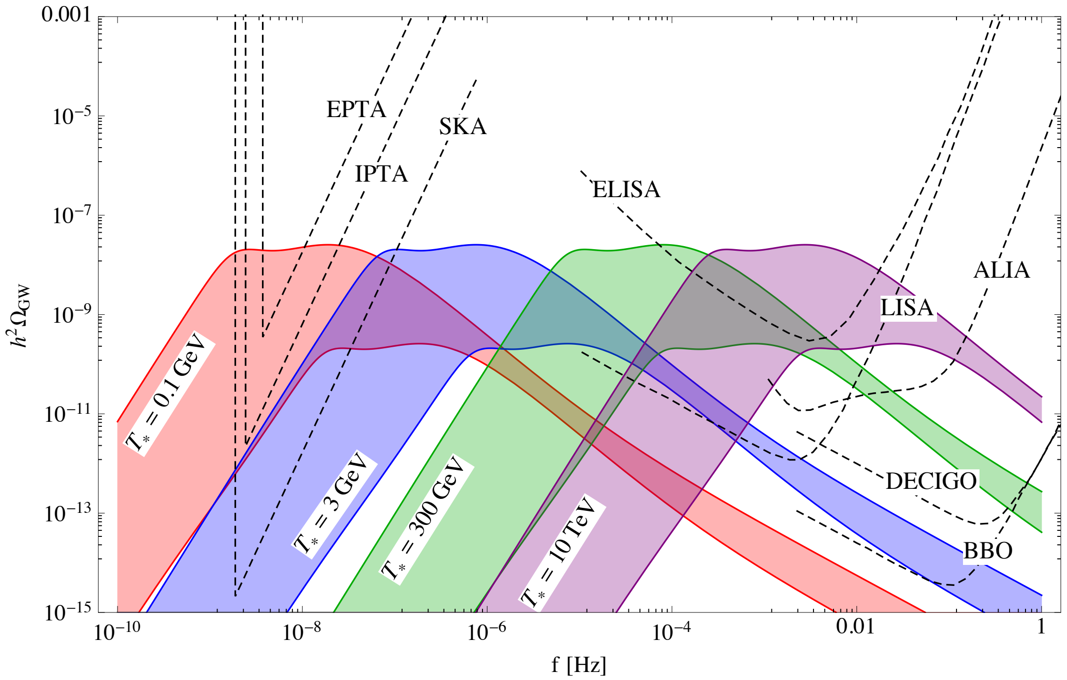
Summary

- QCD like dark sectors motivated in many models



- Emerging jets are "smoking gun", good prospects for ATLAS/CMS

- Gravitational waves are independent probe of dark sector phase transition



Supplemental Material

Check dark shower w/ meson multiplicity

e.g. Ellis, Stirling, Webber

$$\langle N(\hat{s})\rangle \propto \exp\left(\frac{1}{b_1}\sqrt{\frac{6}{\pi\alpha_s(\hat{s})}} + \left(\frac{1}{4} + \frac{5n_f}{54\pi b_1}\right)\log\alpha_s(\hat{s})\right)$$

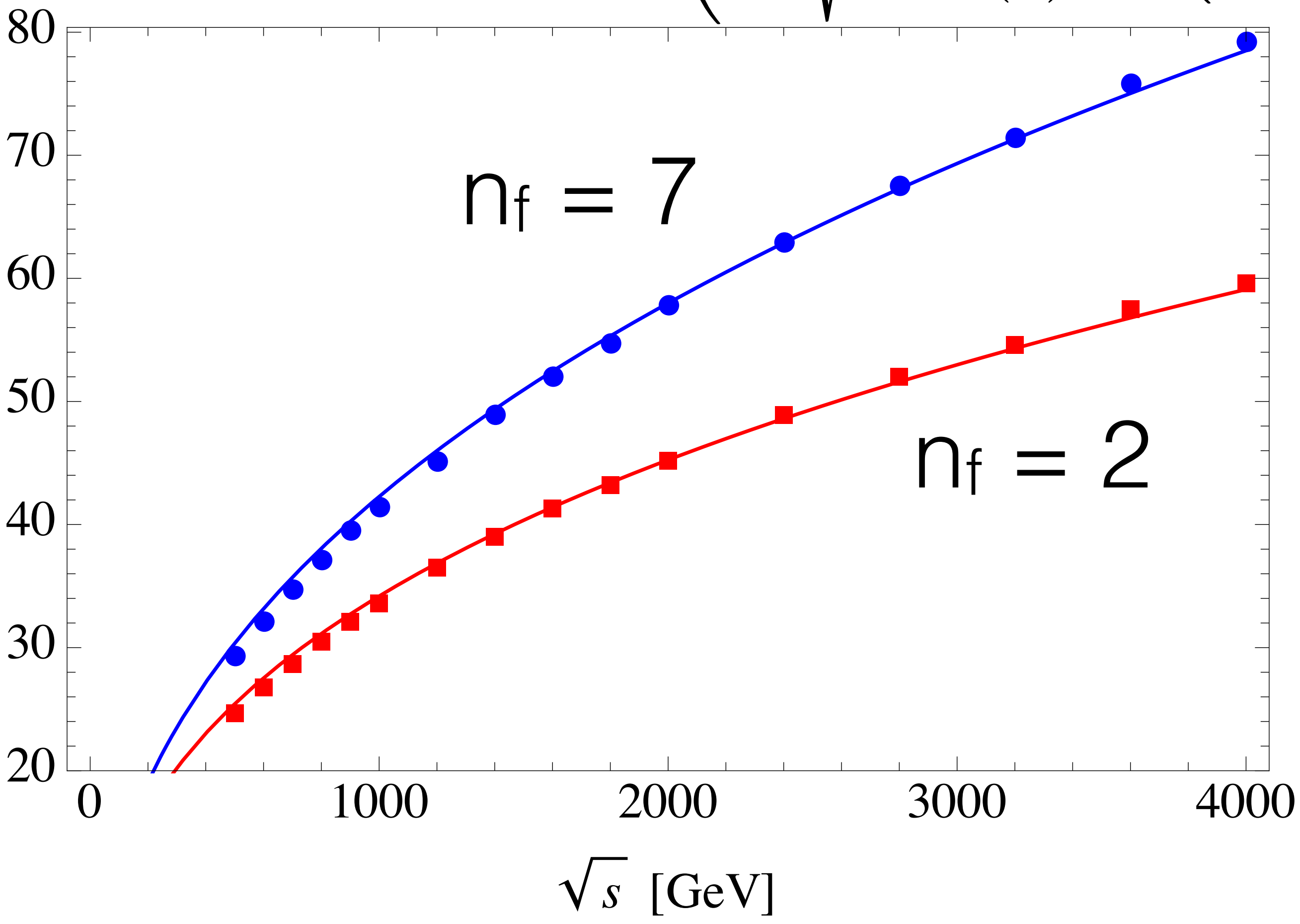
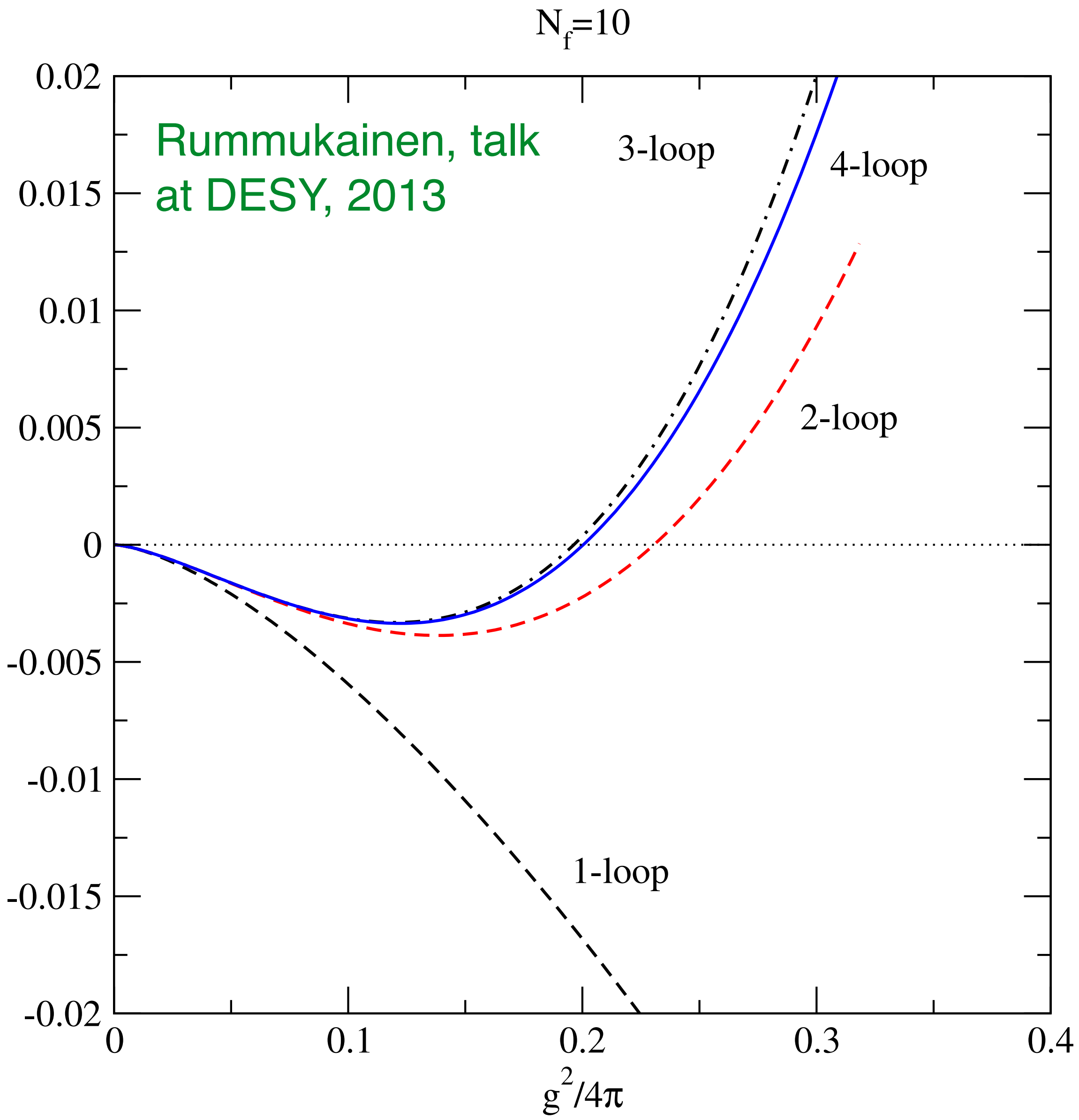


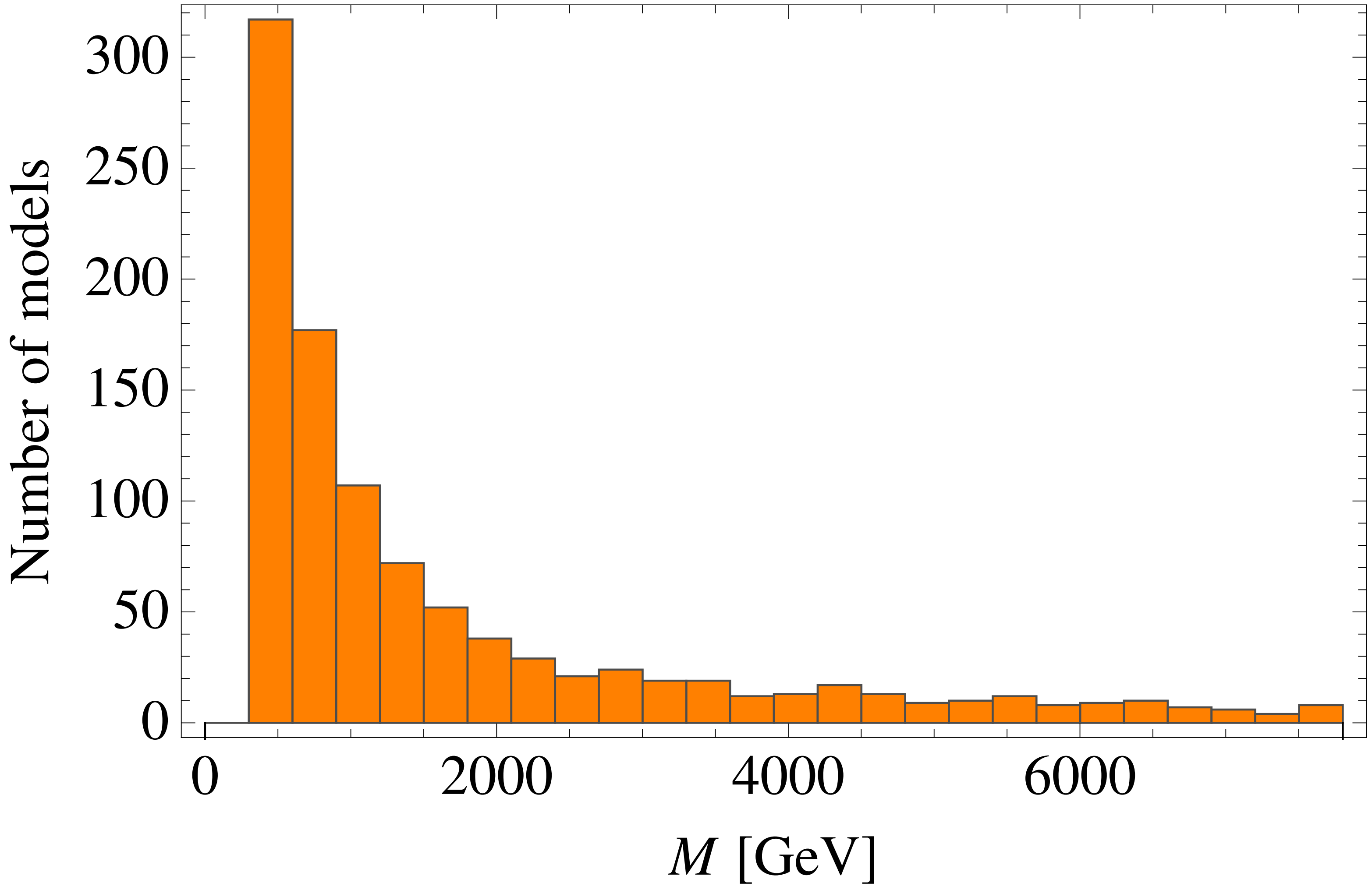
Figure 11: Average dark meson multiplicity in $e^+e^- \to Z'^* \to \bar{Q}_d Q_d$ as a function of the centre-of-mass energy $\sqrt{s}$. We compare the output of the modified PYTHIA implementation for $n_f = 7$ (blue circles) and $n_f = 2$ (red squares) to the theory prediction Eqn. (15), where we only float the normalisation. The dark QCD scale and dark meson spectrum corresponds to benchmark model B.

Validity of two loop FP



- SU(2) with 10 fundamental fermions
- 1-4 loop beta functions
- two loop estimate for fixed point is reliable in weak coupling regime

Model distribution



- Models with DM mass close to proton mass

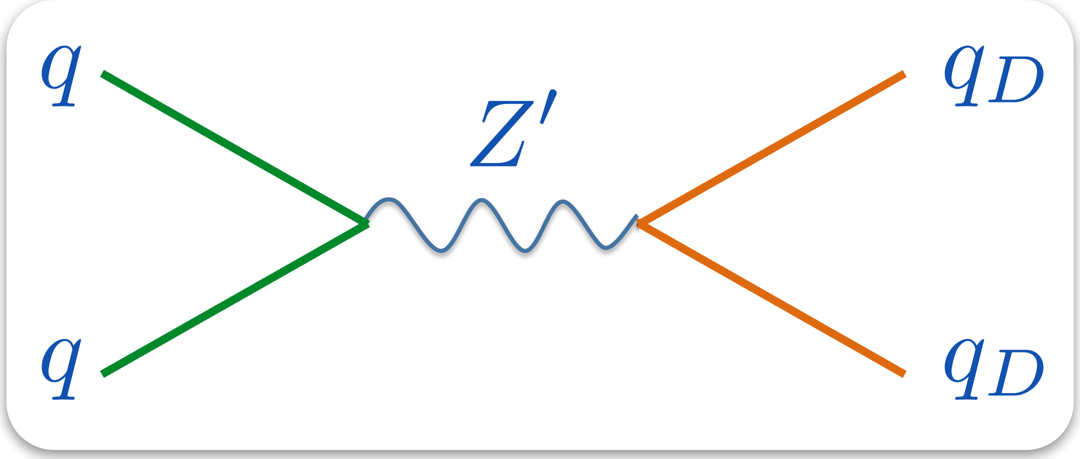
Open Questions/Outlook

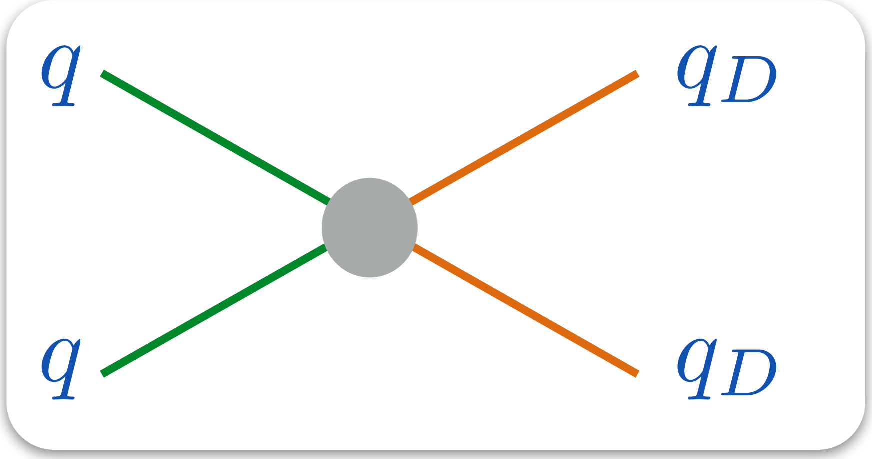
- Flavour
- Dark matter bound state formation (dark BBN)
- Different mediators (triggers!)
- Alternative dark pion searches (heavy flavour decays, direct production LHCb, SHIP)
- Model building

PS, Stolarski, Weiler, in progress

LHCb opportunities

- Z' mediator is difficult to trigger at ATLAS/CMS
  Same if dominant production is off-shell



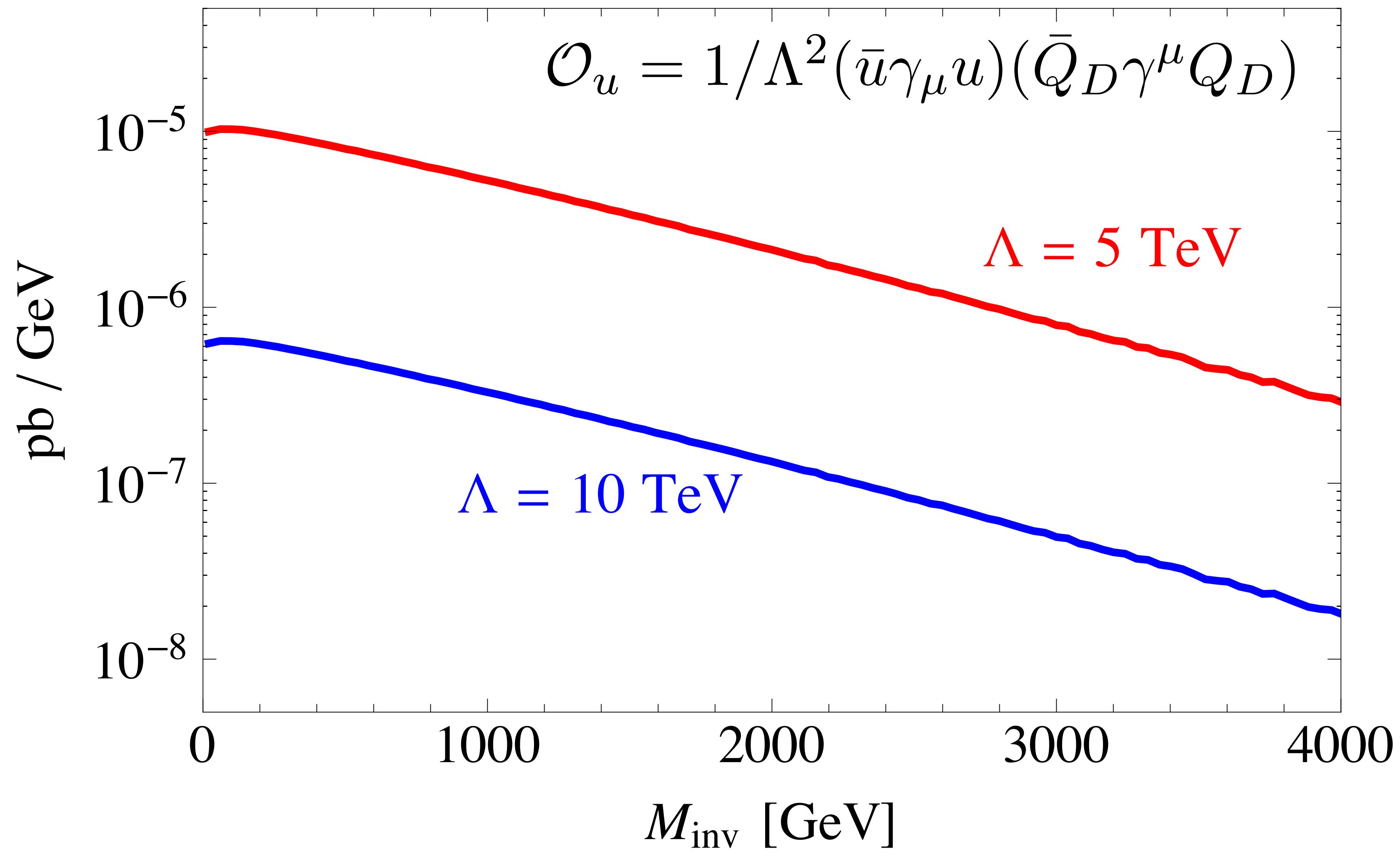


- Reconstruct individual dark pions, differentiate using lifetime, mass, decay products

- Emerging jets without (hard) trigger requirements?

PS, Stolarski, Weiler, in progress

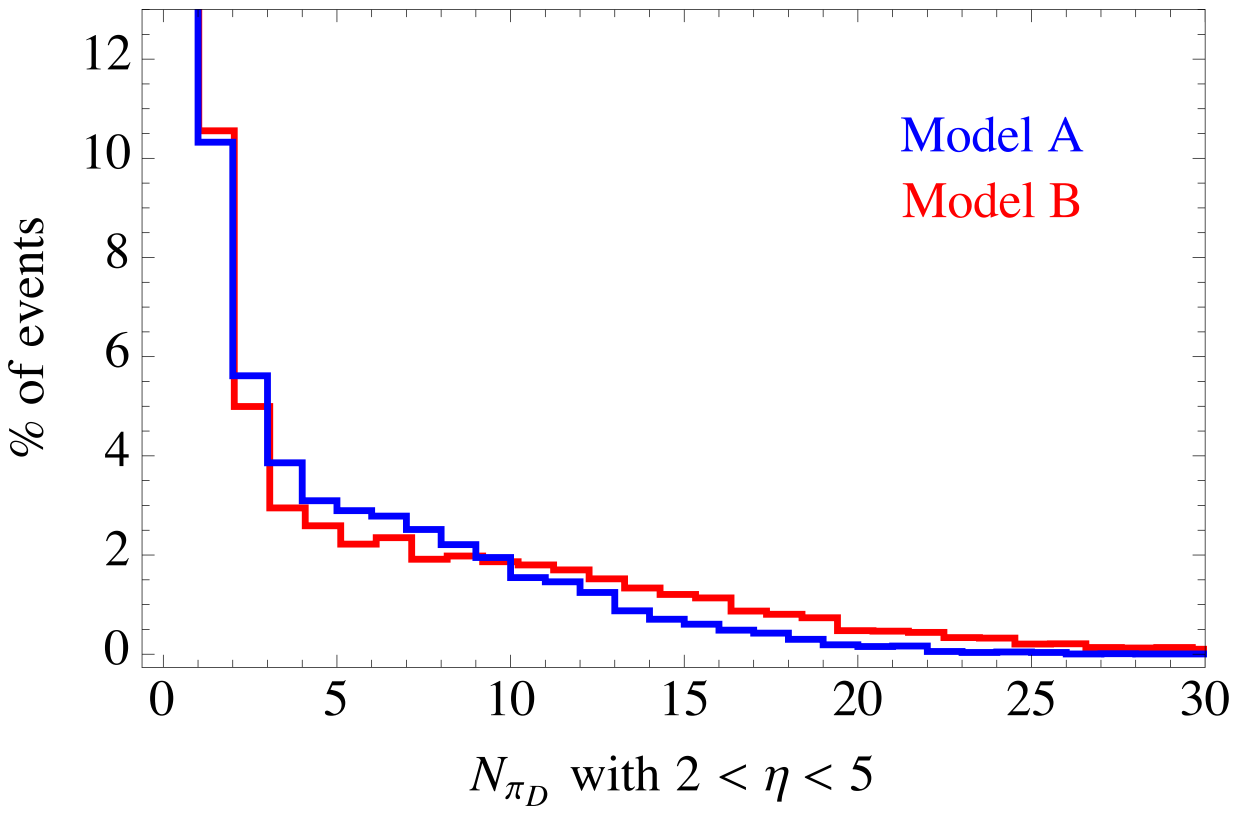
Off-shell production

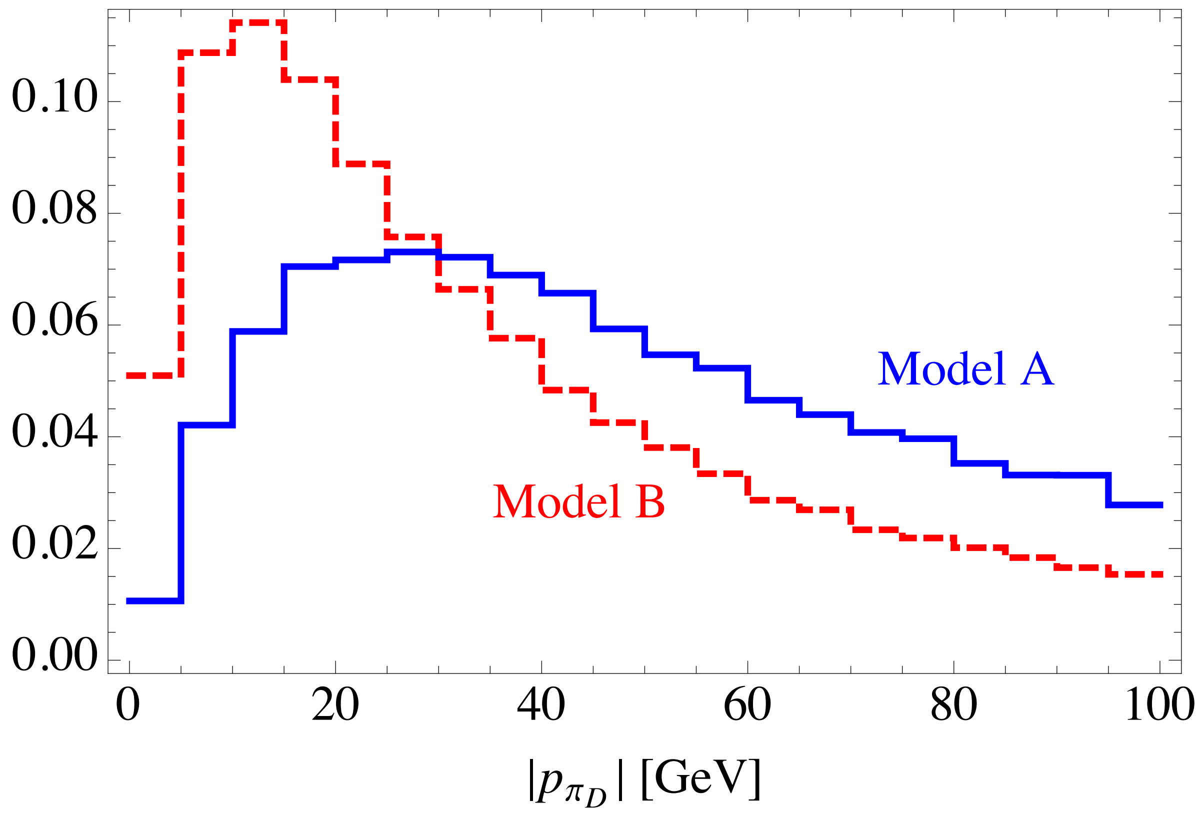


- Total rate: $\sigma(pp \to \bar{Q}_D Q_D) \approx 8.2 \text{ pb} \times \left(\frac{\text{TeV}}{\Lambda}\right)^4 \times N_d \times N_F$

PS, Stolarski, Weiler, in progress

Forward region

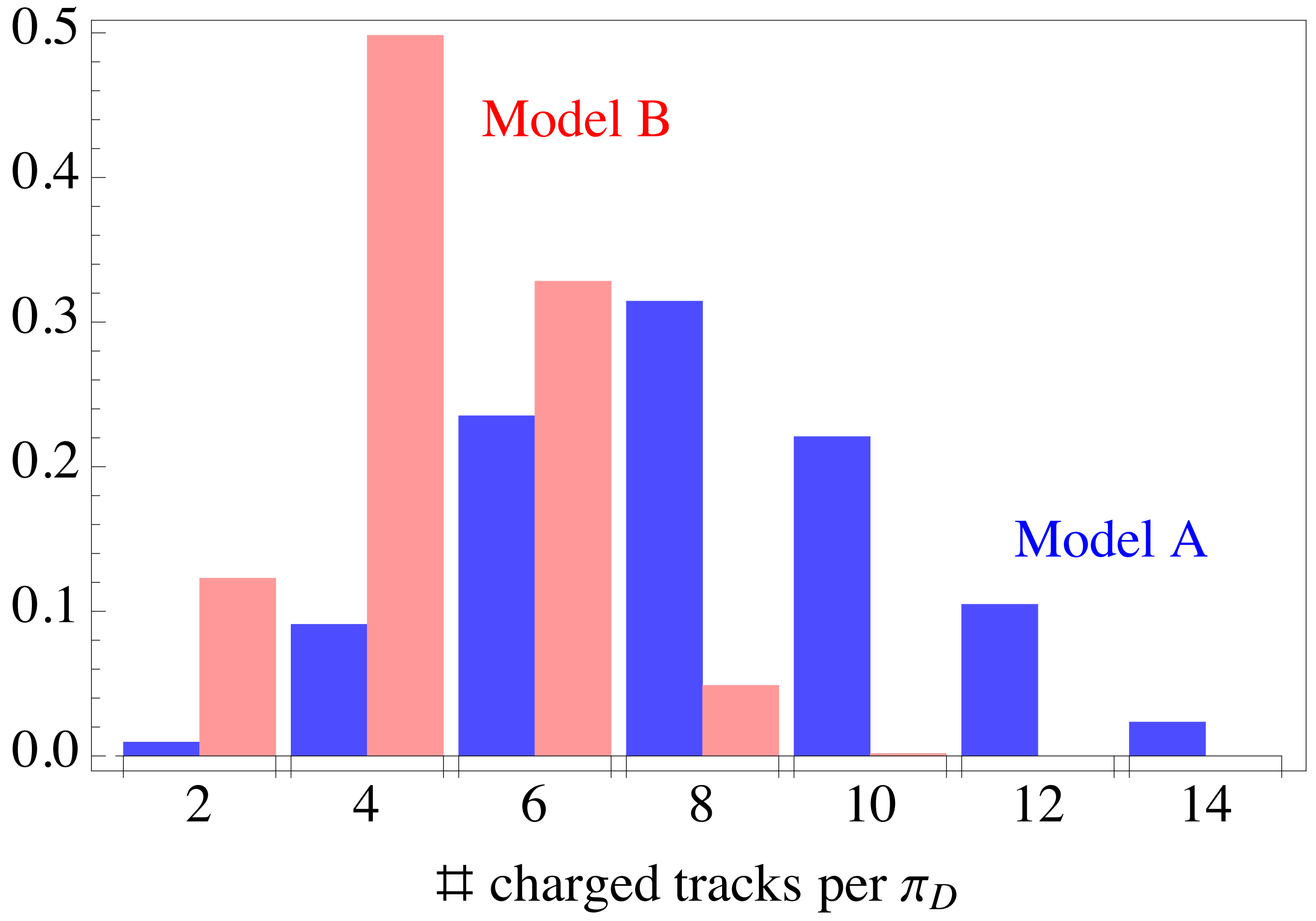




- Fraction of all signal events with N dark pions in $2 < \eta < 5$
- Momentum (not pT) distribution of dark pions in $2 < \eta < 5$

PS, Stolarski, Weiler, in progress

Decay characteristics



- Number of charged tracks from dark pion decays
- Also depend on flavour structure - some more work!

PS, Stolarski, Weiler, in progress

Very very (very) rough estimate

- 20 inverse fb

- Assume that events with 3 or more reconstructed dark pions are significantly different from QCD (i.e. no background)

- 10% reconstruction efficiency

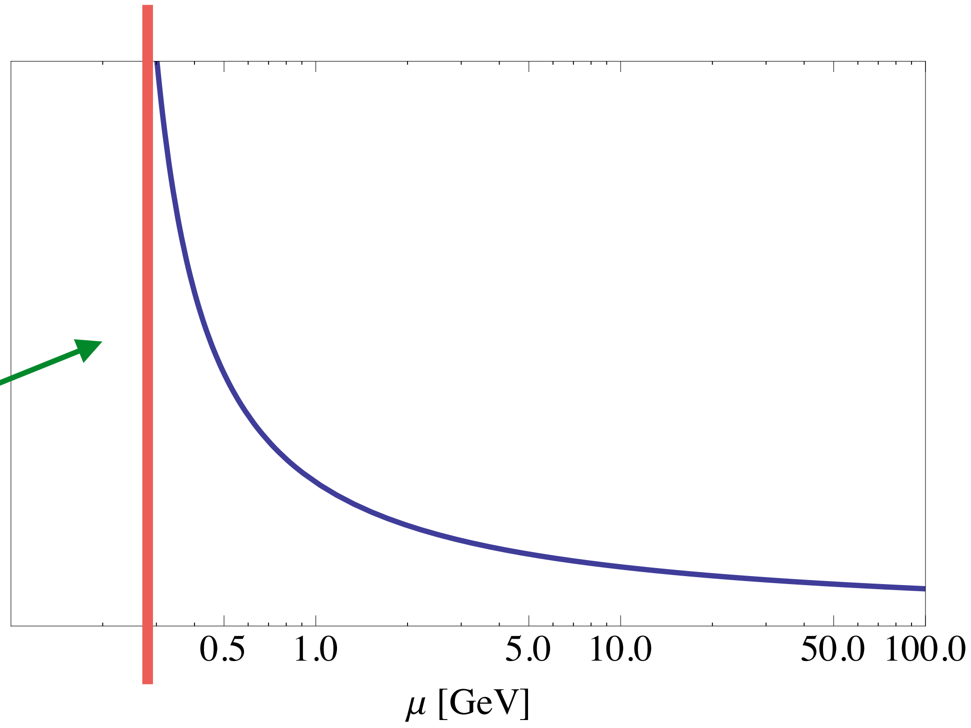
➡ Sensitivity to $\sigma = 8 \text{ fb}$, corresponds to $\Lambda \approx 5 \text{ TeV}$

Composite DM

- QCD running coupling

$$\frac{d}{d(\log \mu)} g_s = \beta(g_s)$$

- QCD scale Λ_{QCD} is mass scale of QCD bound states (e.g. proton)



- Introduce new $SU(N_d)$ “dark QCD”, dark quarks Q_D

- Dark Matter is dark baryon with mass ~ $\Lambda_{\mathrm{darkQCD}}$

Relating the scales

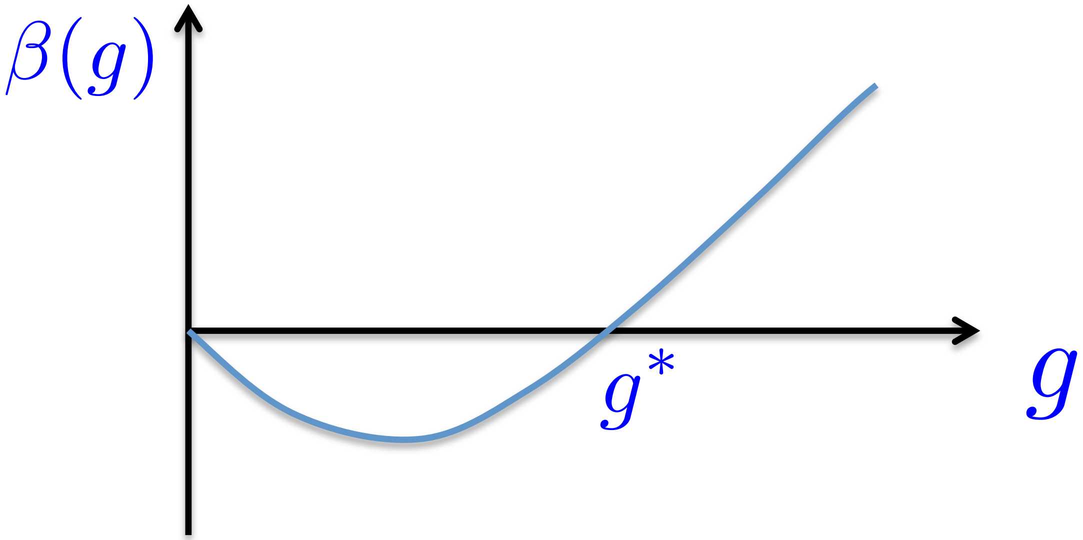
- Option 1: Mirror world
  α_s and α_d related at high (GUT) scale through parity symmetry, identical running below
  - need small breaking
  - cosmology nontrivial ($N_{\rm eff}$, structure formation)
- Here:
  Relate α_s and α_d dynamically at an intermediate scale $M \sim \rm TeV$
  - Obtain $\Lambda_{\rm darkQCD} \sim \Lambda_{\rm QCD}$ “naturally”

Relating the scales II

- Infrared Fixed Points:

$$\frac{dg}{dt} = \beta(g) = 0$$

for $g = g^*$



- Perturbative solutions can exist for specific particle content (i.e. choices of N_F)

- Bi-fundamentals of $SU(3)_{\text{QCD}} \times SU(3)_{\text{darkQCD}}$ relate the fixed point solutions at the two loop level

Two loop β-function

number of quarks

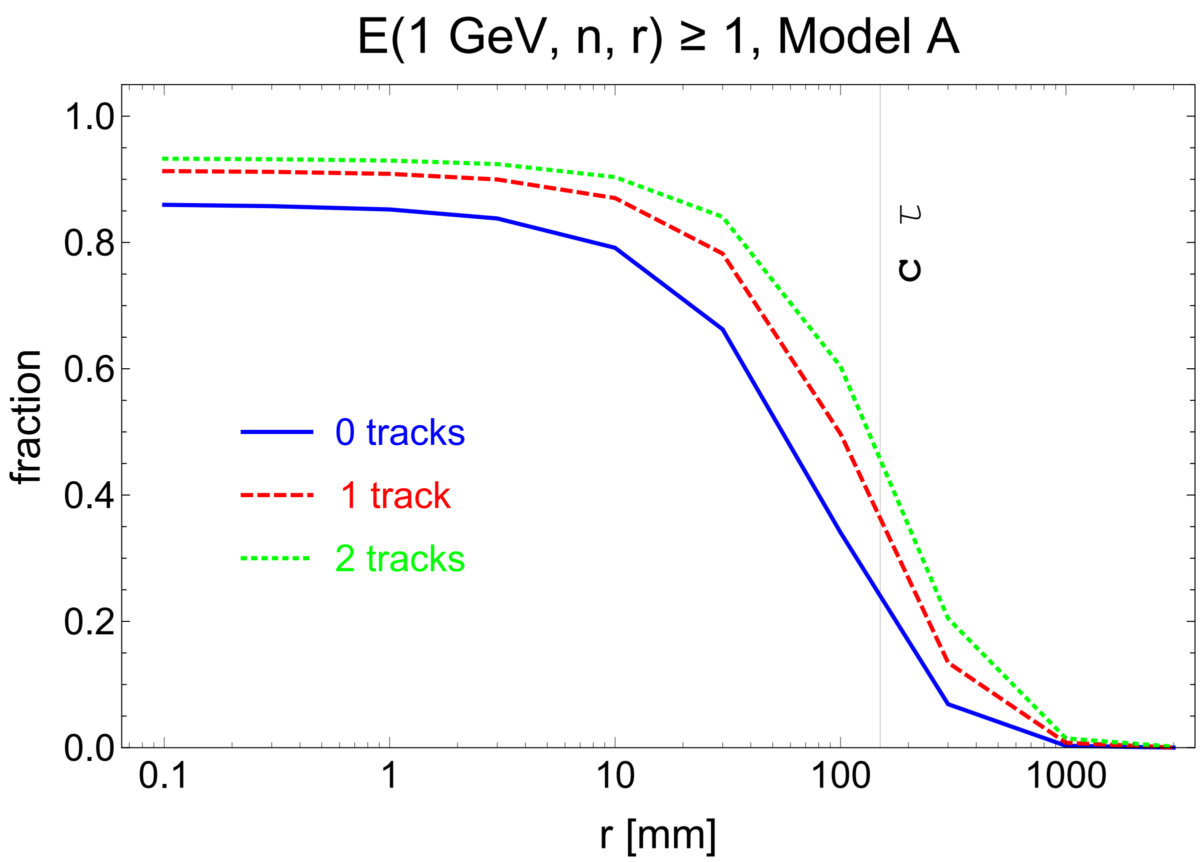
$$\begin{aligned}\beta_c(g_c, g_d) = {} & \frac{g_c^3}{16\pi^2}\left[\frac{4}{3}T(R_f)(n_{fc} + N_d\, n_{fj}) - \frac{11}{3}C_2(G_c)\right] && \text{1-Loop} \\ & + \frac{g_c^5}{(16\pi^2)^2}\left[\left(\frac{20}{3}C_2(G_c) + 4C_2(R_f)\right)T(R_f)(n_{fc} + N_d\, n_{fj}) - \frac{34}{3}C_2^2(G_c)\right] && \text{2-Loop single} \\ & + \frac{g_c^3 g_d^2}{(16\pi^2)^2}\left[4C_2(R_f)T(R_f)N_d\, n_{fj}\right] && \text{2-Loop mixed}\end{aligned}$$

number of bi-fundamentals

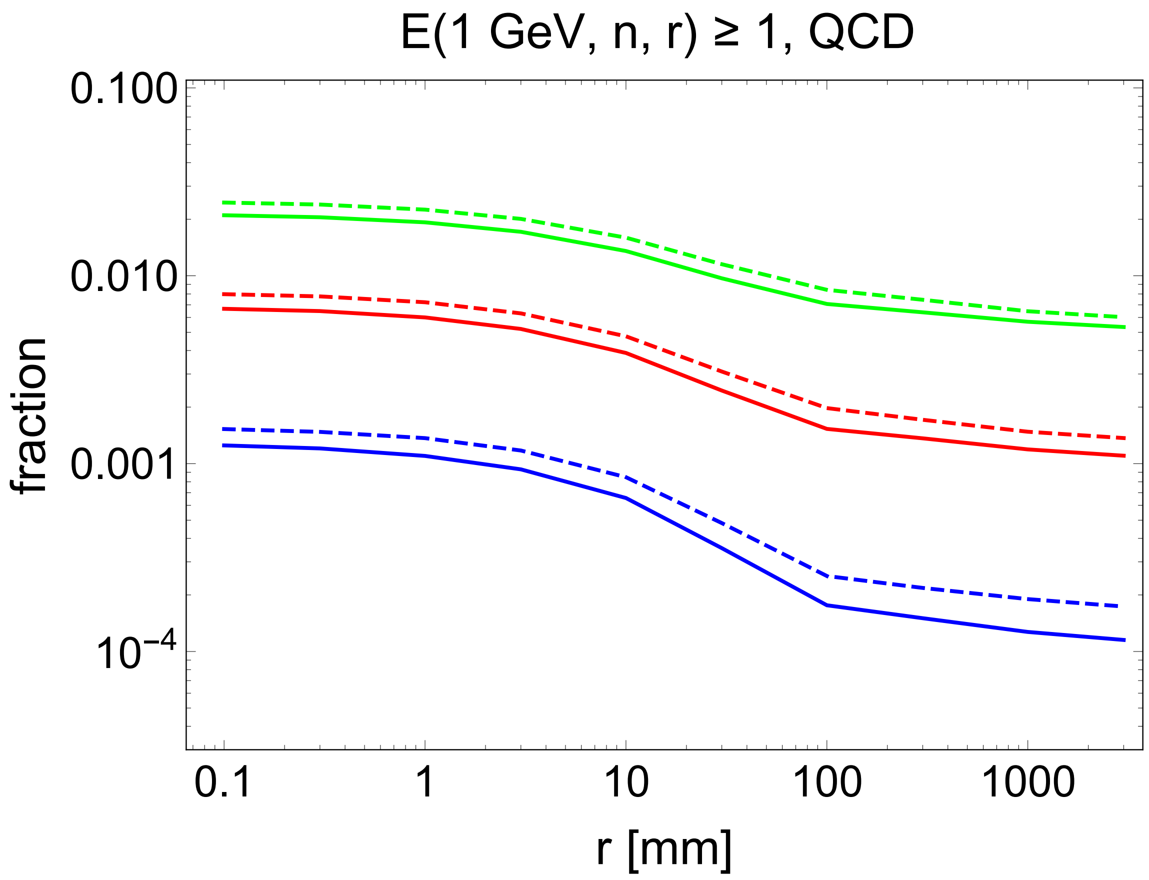
- Solve $\beta_c = \beta_d = 0$ with $\frac{g_{c,d}^2}{4\pi} \ll 1$
- Obtain fixed point couplings α_c^* , α_d^*

Cut Efficiencies

Signal


E(1 GeV, n, r) ≥ 1, Model A

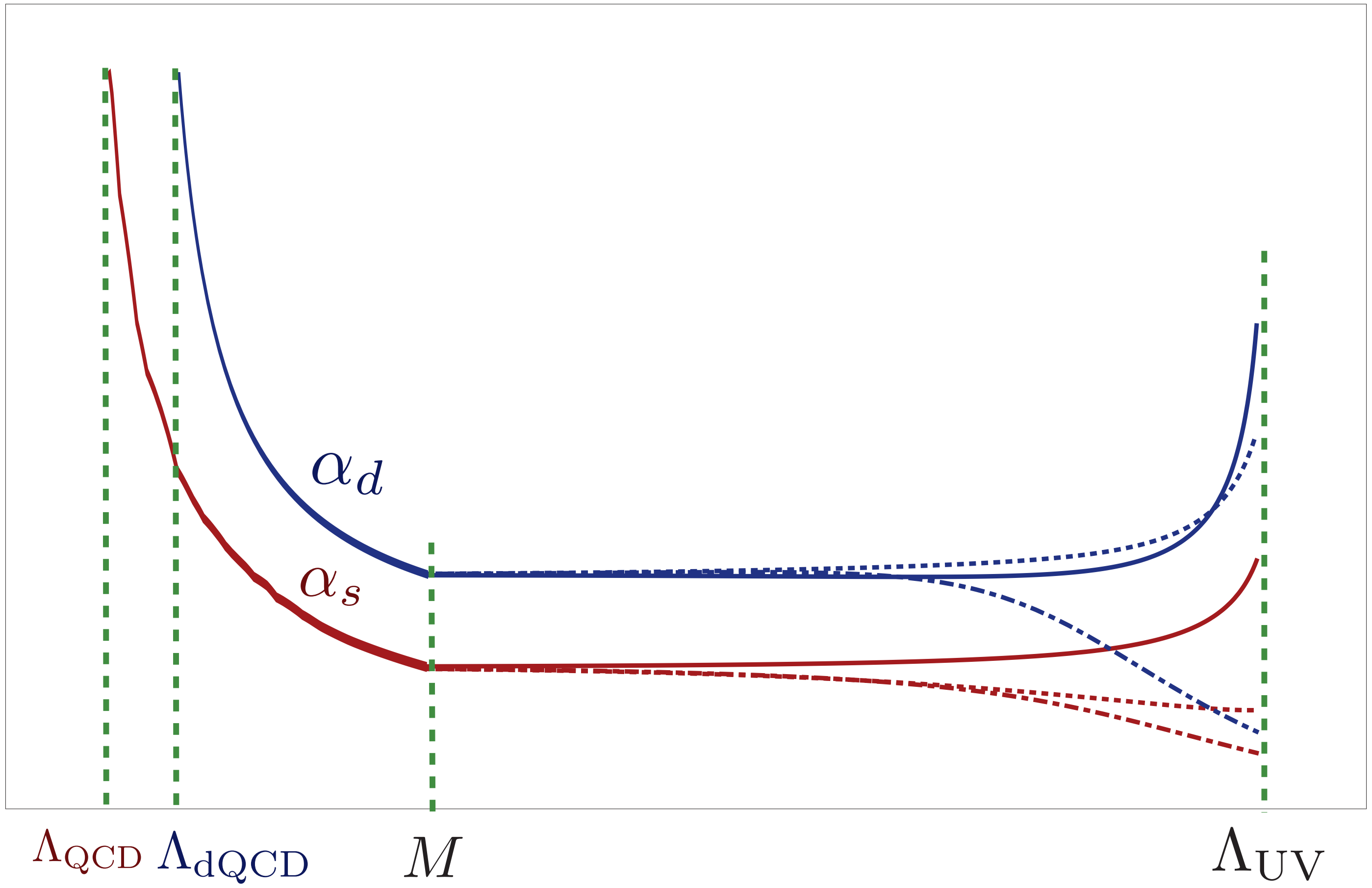
Background


E(1 GeV, n, r) ≥ 1, QCD

- Factor 100-1000 improved S/B **per jet**, compared to ordinary 4-jet search

Side note: Relating the scales

Bai, PS, PRD89, 2014



- Bi-fundamental fields decouple at scale M

$$\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm dark}} \approx e^{\frac{2\pi}{b_c \alpha_c^*}\left(1 - \frac{b_c \alpha_c^*}{b_d \alpha_d^*}\right)}$$

Asymmetry

- Produce asymmetry in bi-fundamentals from heavy particle decay (à la Leptogenesis)
- Decay to quarks and dark quarks (color conservation) → equal B and D
- Including sphalerons: $\frac{|n_D|}{n_B} = \frac{79}{56} \approx \frac{7}{5}$
- Example:

$$\boxed{\frac{\rho_{DM}}{\rho_B} = \frac{7}{5}\,\frac{3.5\text{ GeV}}{0.94\text{ GeV}} \approx 5}$$

"naturally"

Features

- Relic density fine, without direct detection trouble
- Symmetric component annihilation:
  - $p_D \bar{p}_D \to \pi_D \pi_D$ very efficient
  - $\pi_D \to SM$ transfers entropy back to SM
- DM self interaction mediated by dark pions, might help with structure formation issues

Generic properties of “dark QCD” models worth studying their phenomenology!