Dark QCD

From Colliders to Cosmology

Pedro Schwaller
DESY

Anticipating 13 TeV
GGI, Florence
16.10.15

Based on
Bai, PS, 1306.4676
PS, Stolarski, Weiler, 1502.05409
PS, 1504.07263

Dark QCD (aka Hidden Valley)

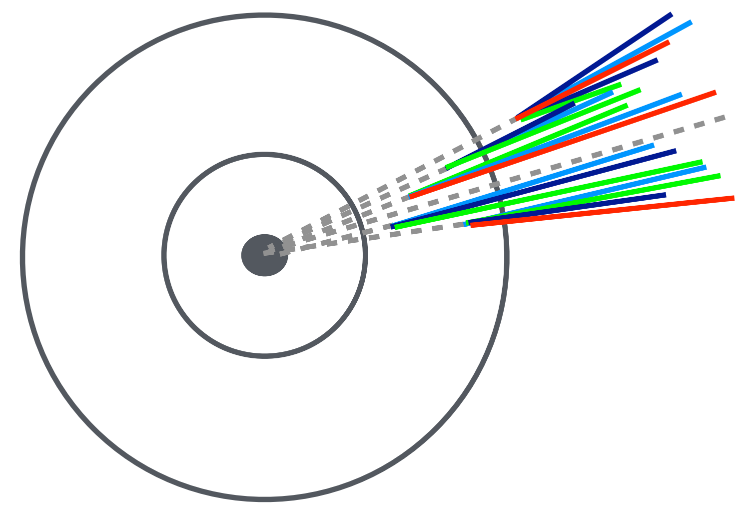
- $SU(N_d)$ dark sector
  - Confinement scale Λ_d
  - n_f light dark quarks (no SM charges)
- Talks featuring dark *SU(N)*
  - Katz — Baryogenesis
  - Hochberg, Kuflik, Schmaltz — Dark Matter
  - Graham, Harnik — Naturalness
  - Strassler — Phenomenology

Dark QCD - DM

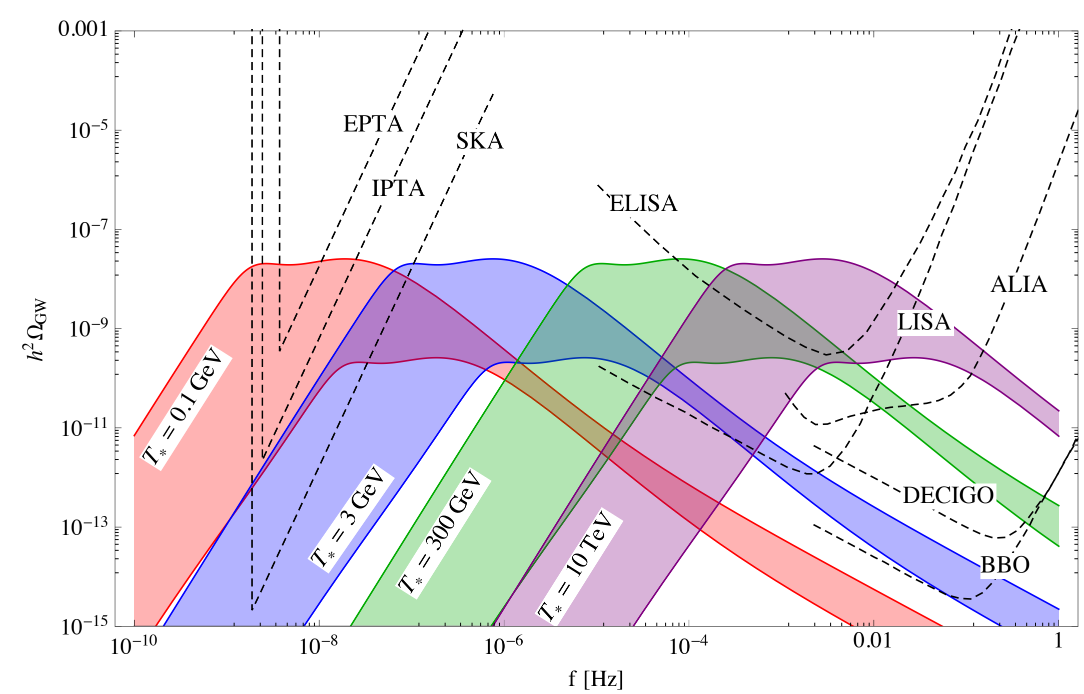
- New mechanisms for relic density, extend mass range:
  - Asymmetric DM - GeV-TeV scale
  - Strong Annihilation - 100 TeV scale
  - SIMP - MeV scale
- Advantages of Composite
  - DM mass scale and stability
  - Fast annihilation for ADM
  - Self-interactions for structure formation (?)

Today

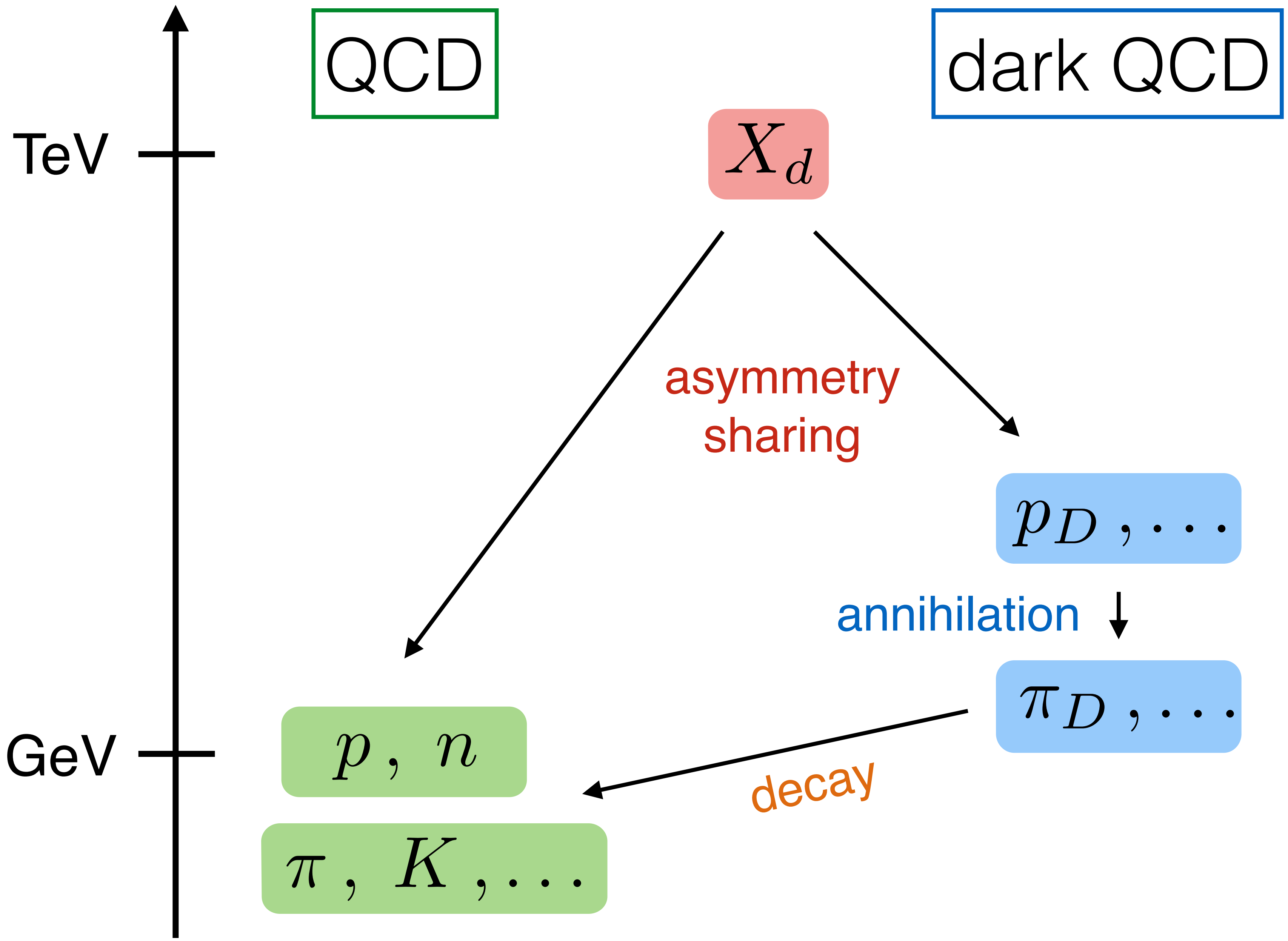
- Emerging Jets from a GeV scale dark sector



- Gravitational Wave signals from hidden sector phase transitions



Dark QCD



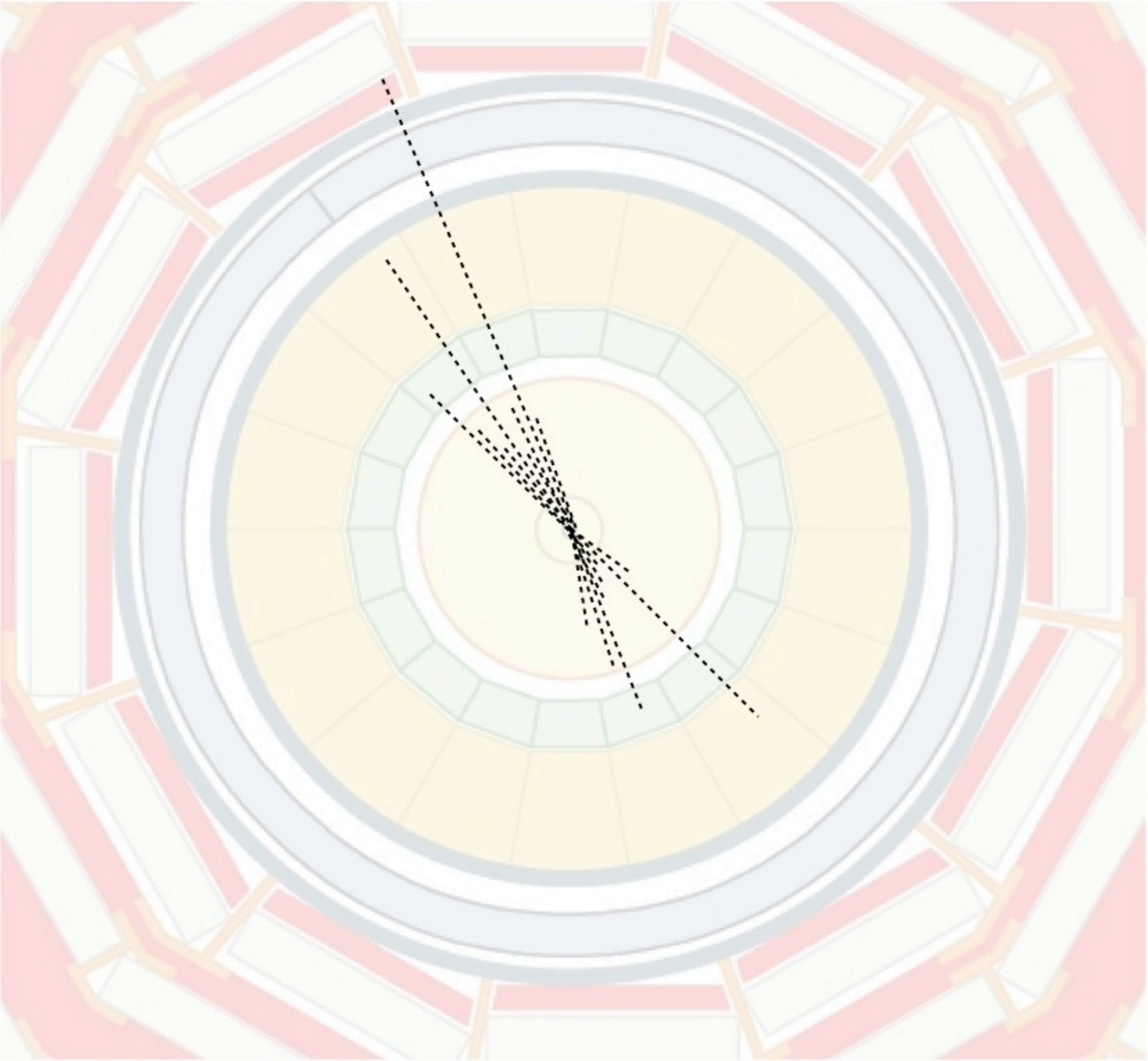
- SU(N) dark sector with neutral "dark quarks"
- Confinement scale $\Lambda_{\rm darkQCD}$
- DM is composite "dark proton"
- "Dark pions" unstable, long lived

Emerging Jets at the LHC

- Dark meson jets from dark parton shower

- Macroscopic lifetime for

$m_{\pi_d} \sim \text{few GeV}$

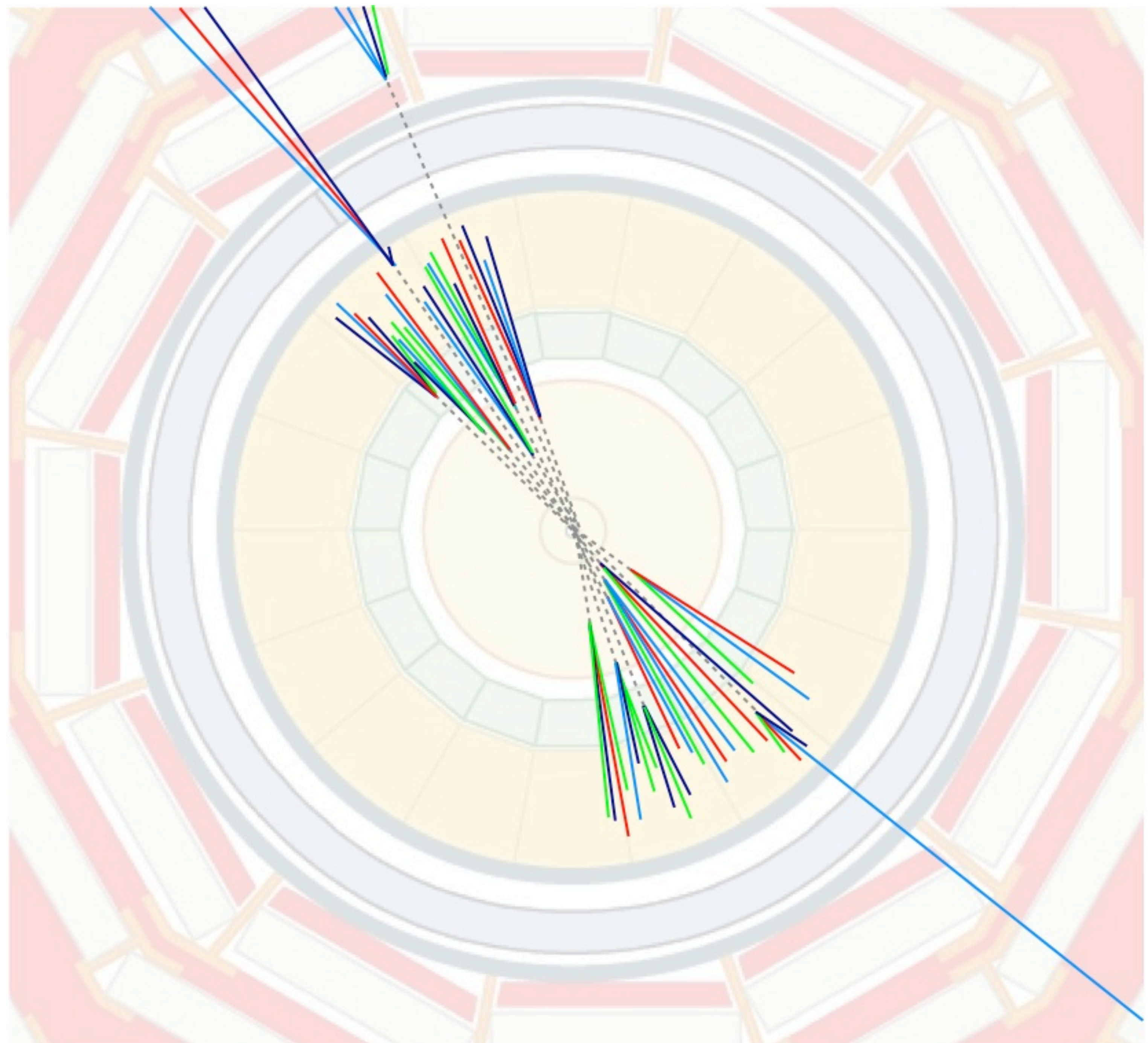


Emerging Jets at the LHC

- Decay back to SM quarks
- Jets emerge at distance

$c\tau$

- Several displaced vertices inside a jet "cone"

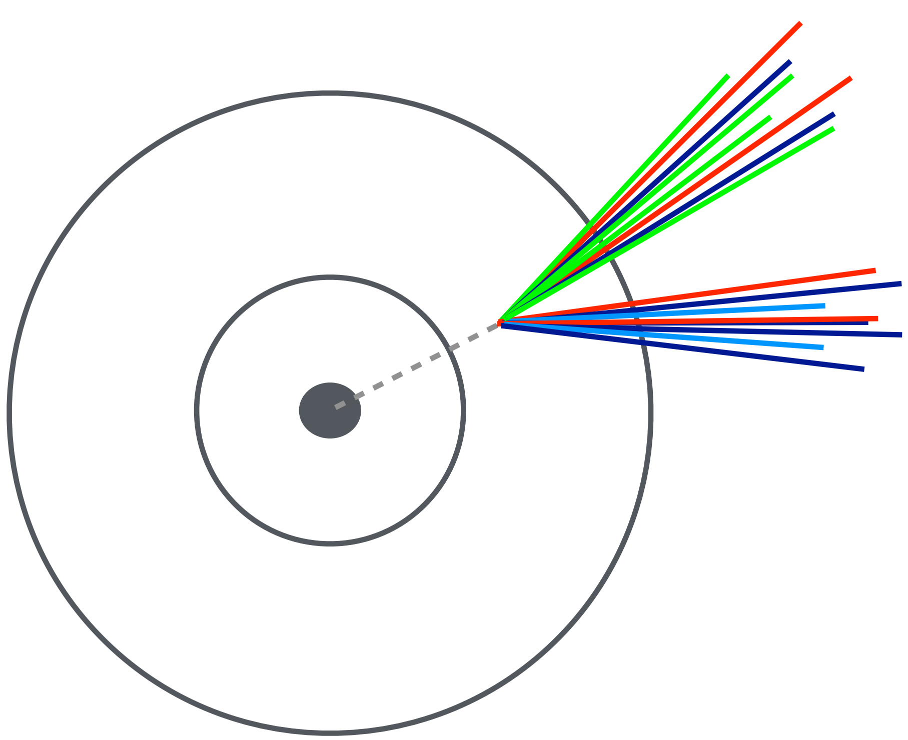


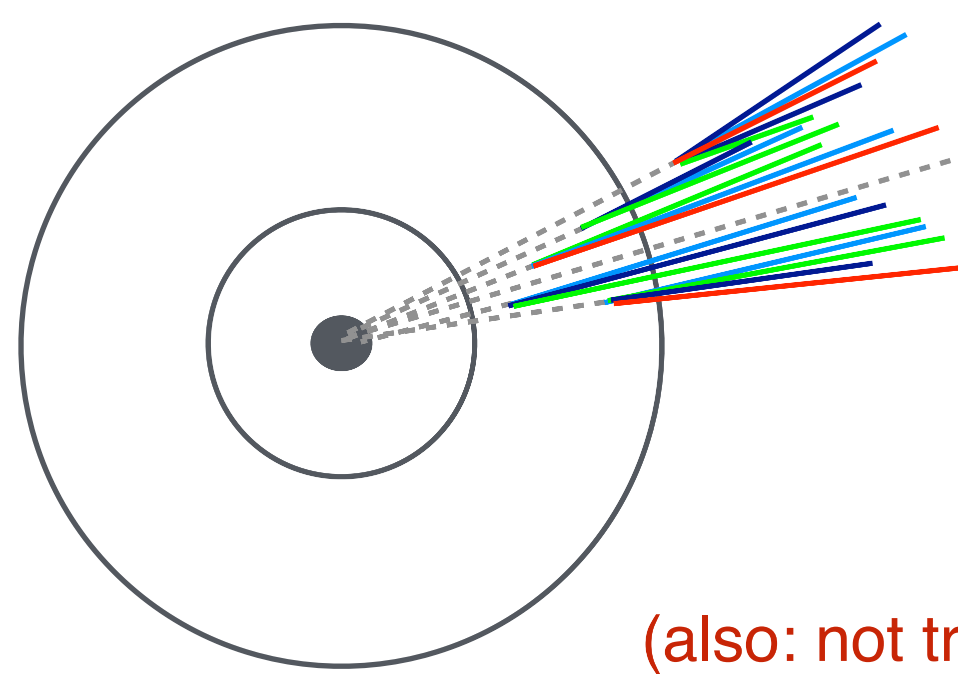
Should we have seen this already?

- ATLAS (arXiv:1409.0746)
- CMS (arxiv:1411.6530)
- LHCb (arxiv:1412.3021)

Main differences:

- Lower mass
- Lower track multiplicities from individual vertices
- Multiple displaced vertices in same cone

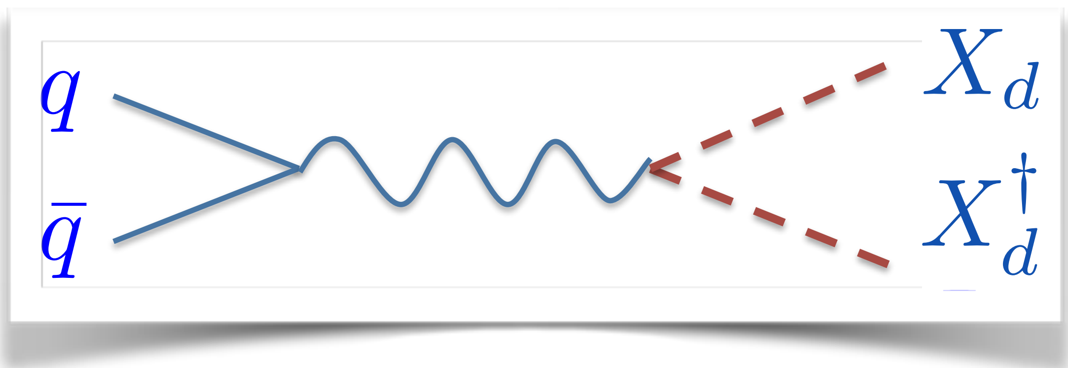




(also: not trackless!)

Benchmark/Strategy

- Pair production of mediator:



  - Two QCD jets
  - Two Emerging Jets

- 4-jet trigger (calo!)

$p_T > 200$ GeV $\quad H_T > 1$ TeV

Benchmark/Strategy

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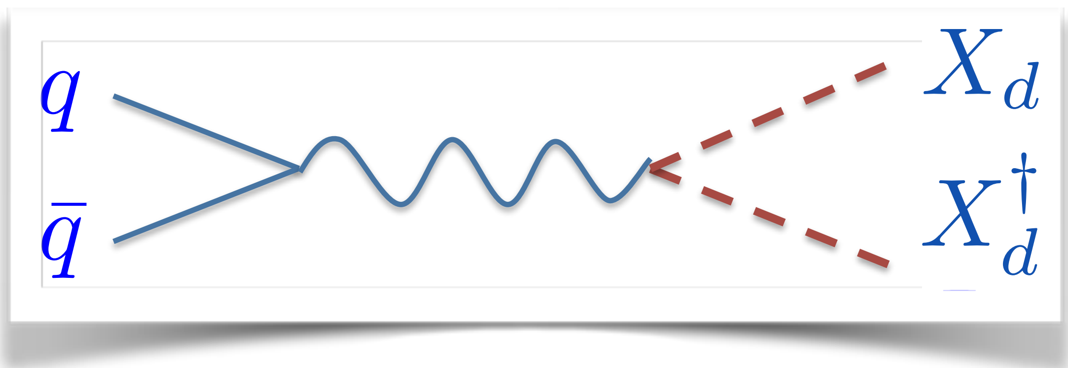

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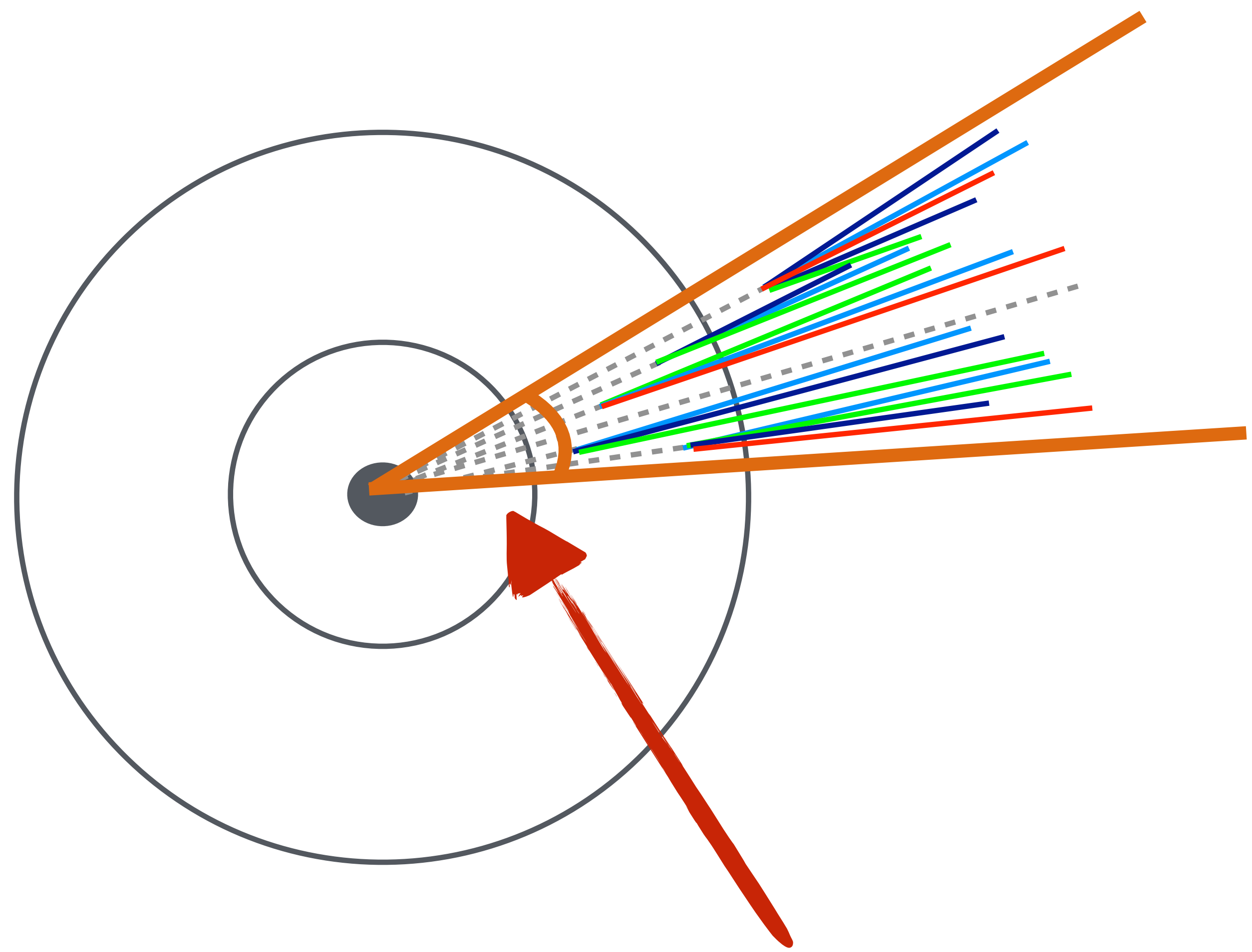

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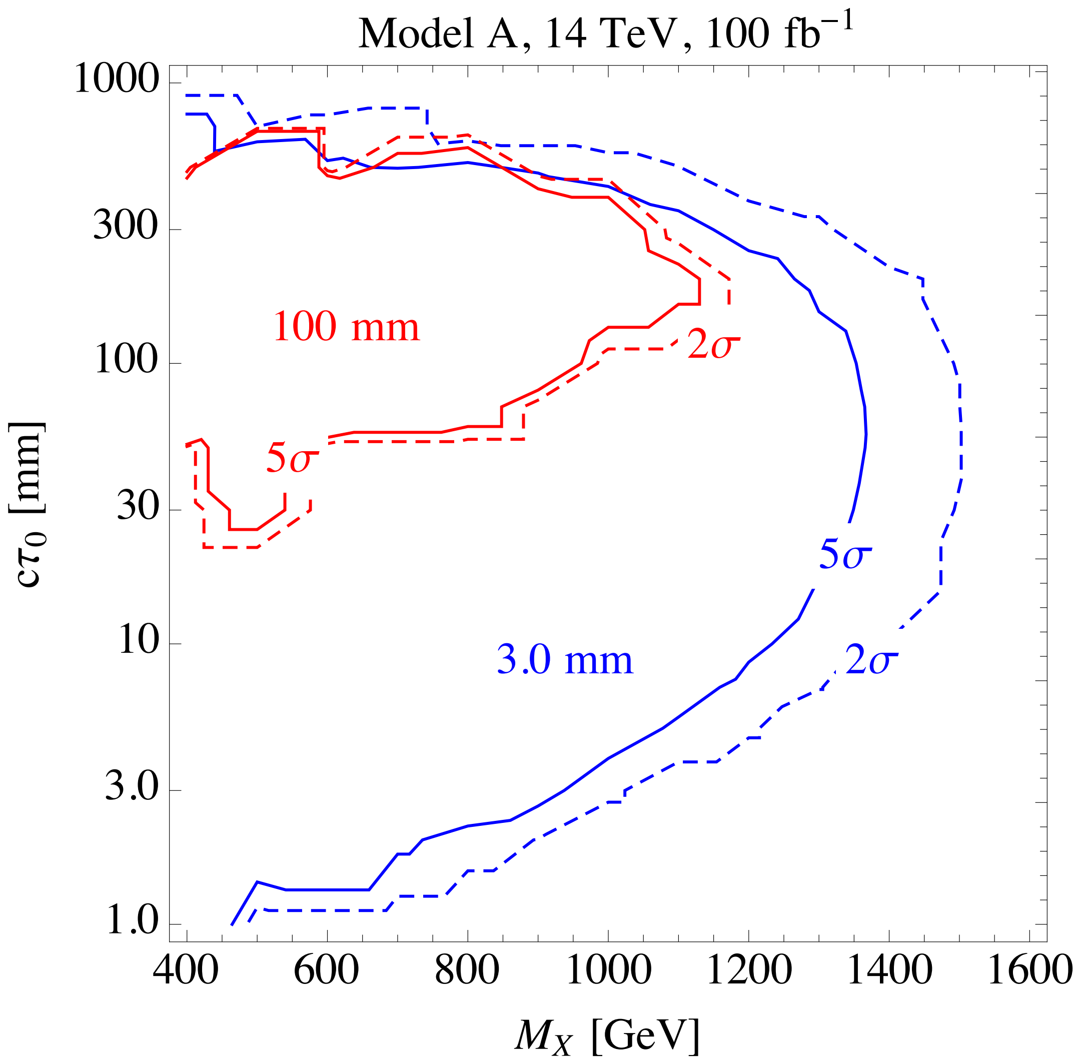
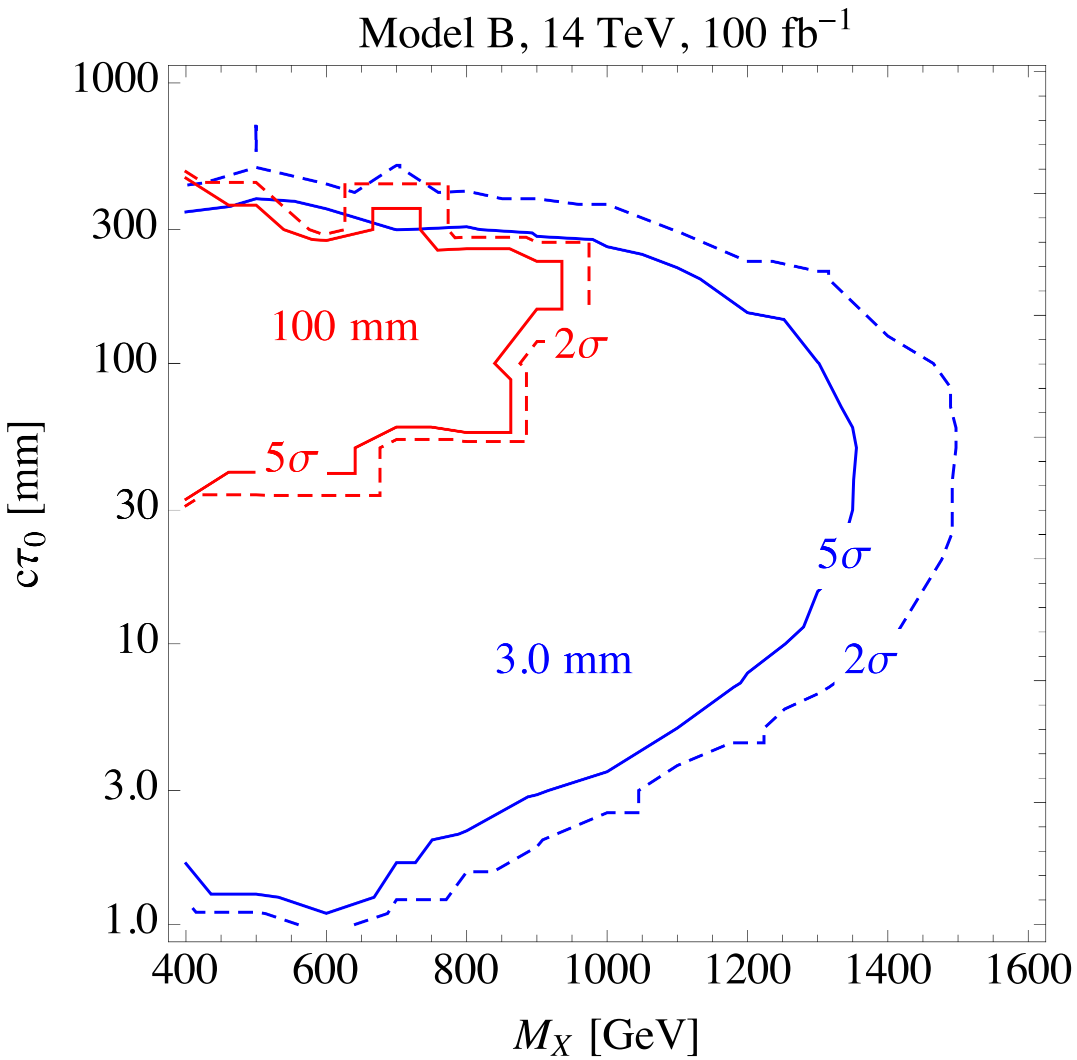
$p_T > 200$ GeV $\quad H_T > 1$ TeV

Reach ATLAS/CMS





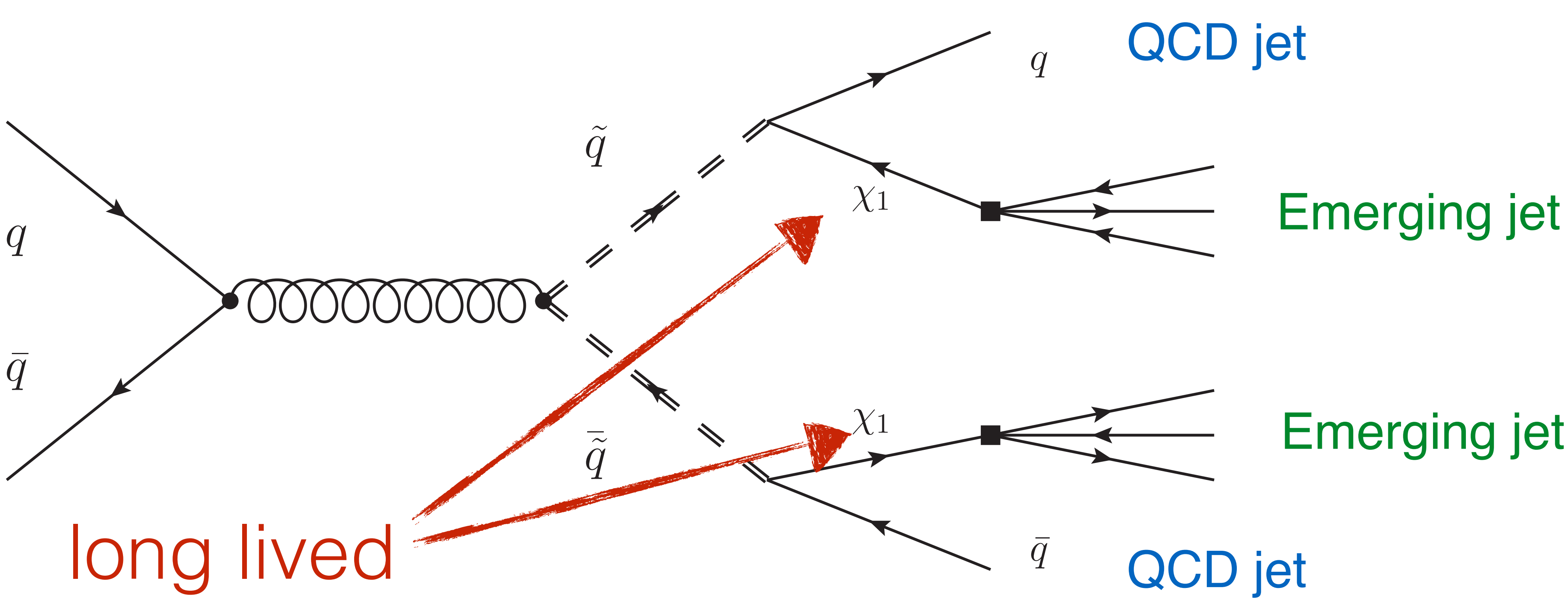
- Optimistic scenario (no non-collisional BGs)
- More realistic studies under way at CMS (ATLAS soon?)

Other New Physics

Y. Gershtein
C. Csaki
Thursday

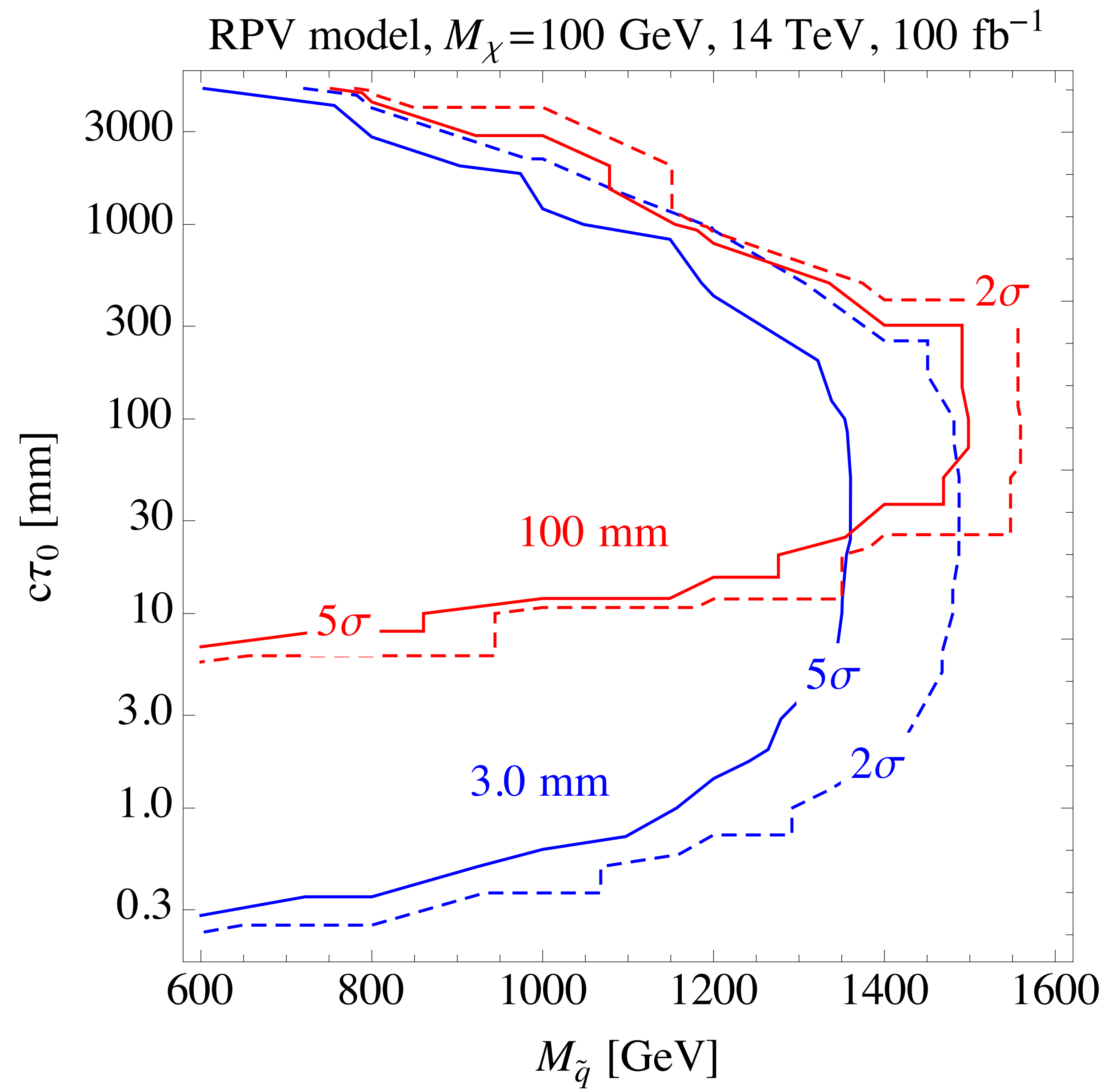
- RPV SUSY $\mathcal{W}_{\text{RPV}} \supset \frac{1}{2}\lambda''_{ijk}U_iD_jD_k$

- One of the last “natural” MSSM scenarios



RPV SUSY sensitivity

- Competitive with displaced vertex searches
- Less model dependent
- “Natural SUSY” scenario with top jets to be done

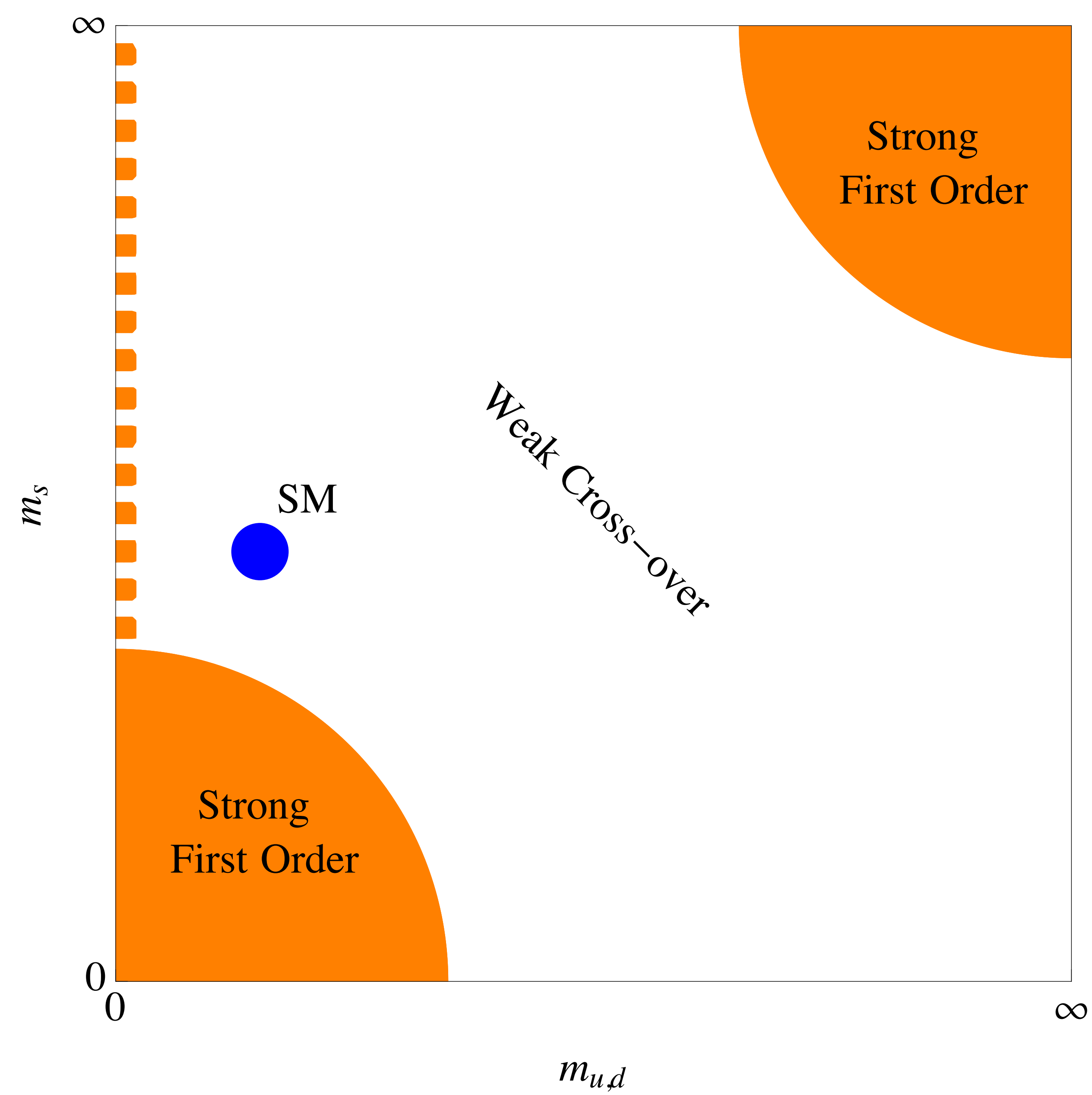


Other scenarios

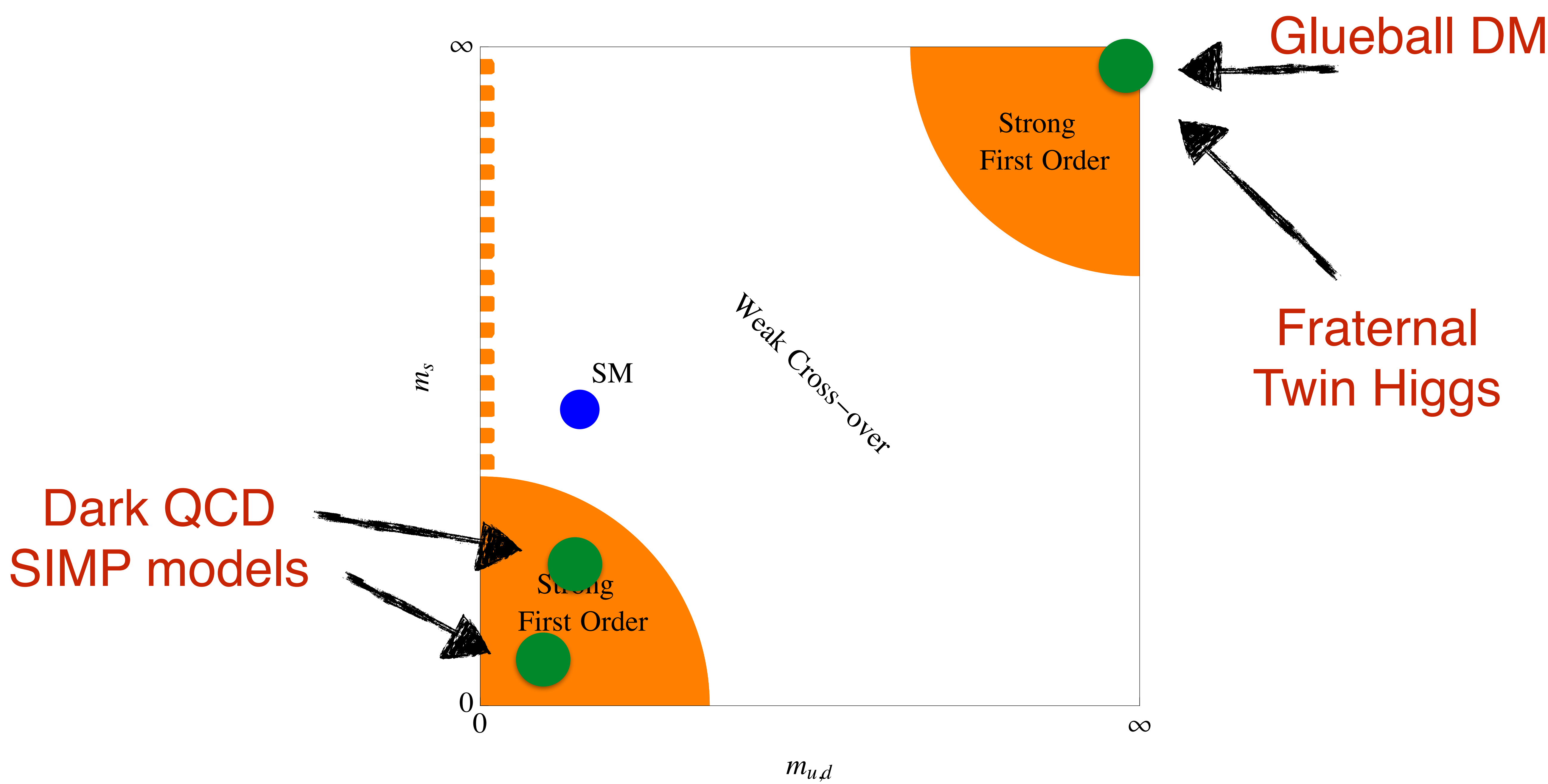
- Dark pions prompt/stable - jets with MET
  - Cohen, Lisanti, Lou, 1503.00009
- Some prompt, some displaced dark pions
  - b-taggers
  - Simplified model (split Higgs portal) study underway with Kang, Mccullough, Scanlon
- Heavy mediator - search for individual dark pions
  - LHCb, SHiP

The Dark Phase Transition

QCD Phase Diagram



Phase Diagram II



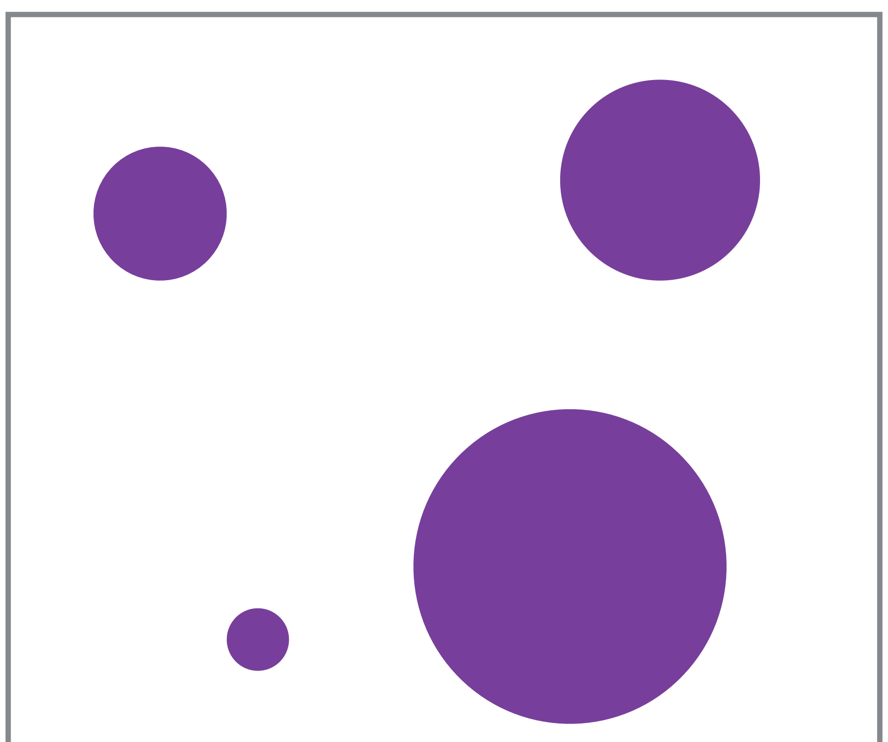
SU(N) - PT

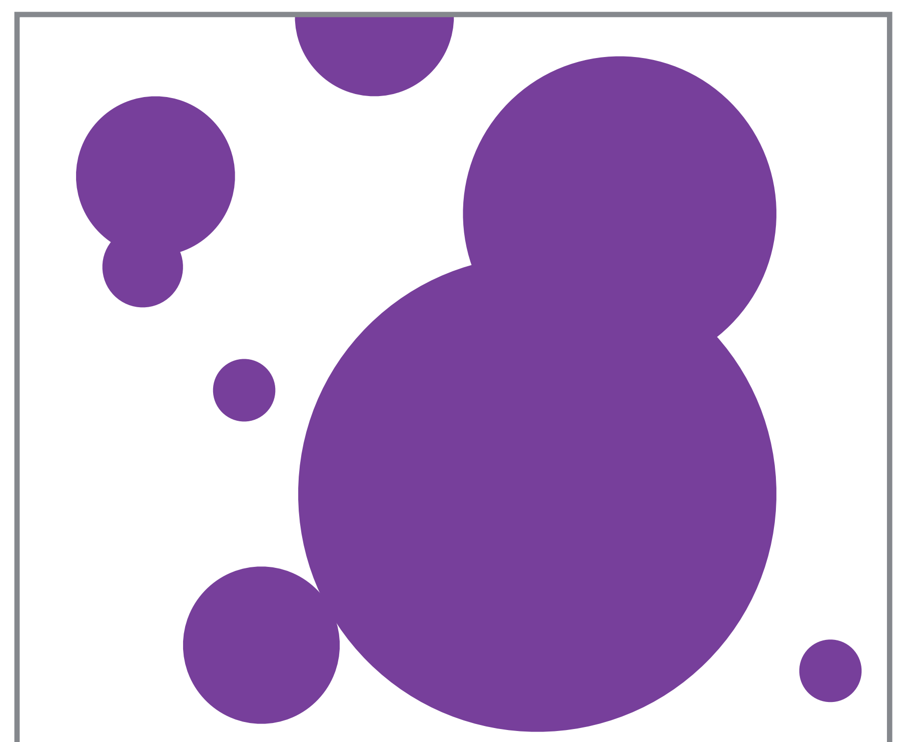
- Consider $SU(N_d)$ with n_f massless flavours
- PT is first order for
  - $N_d \geq 3 \ , \quad n_f = 0$ — Svetitsky, Yaffe, 1982; M. Panero, 2009
  - $N_d \geq 3 \ , \quad 3 \leq n_f < 4N_d$ — Pisarski, Wilczek, 1983
- Not for:
  - $n_f = 1$ (no global symmetry, no PT)
  - $n_f = 2$ (not yet known)

GW Signal

First order PT ➞ Bubbles nucleate, expand

Bubble collisions ➞ Gravitational Waves





Peak Frequency

- Redshift:

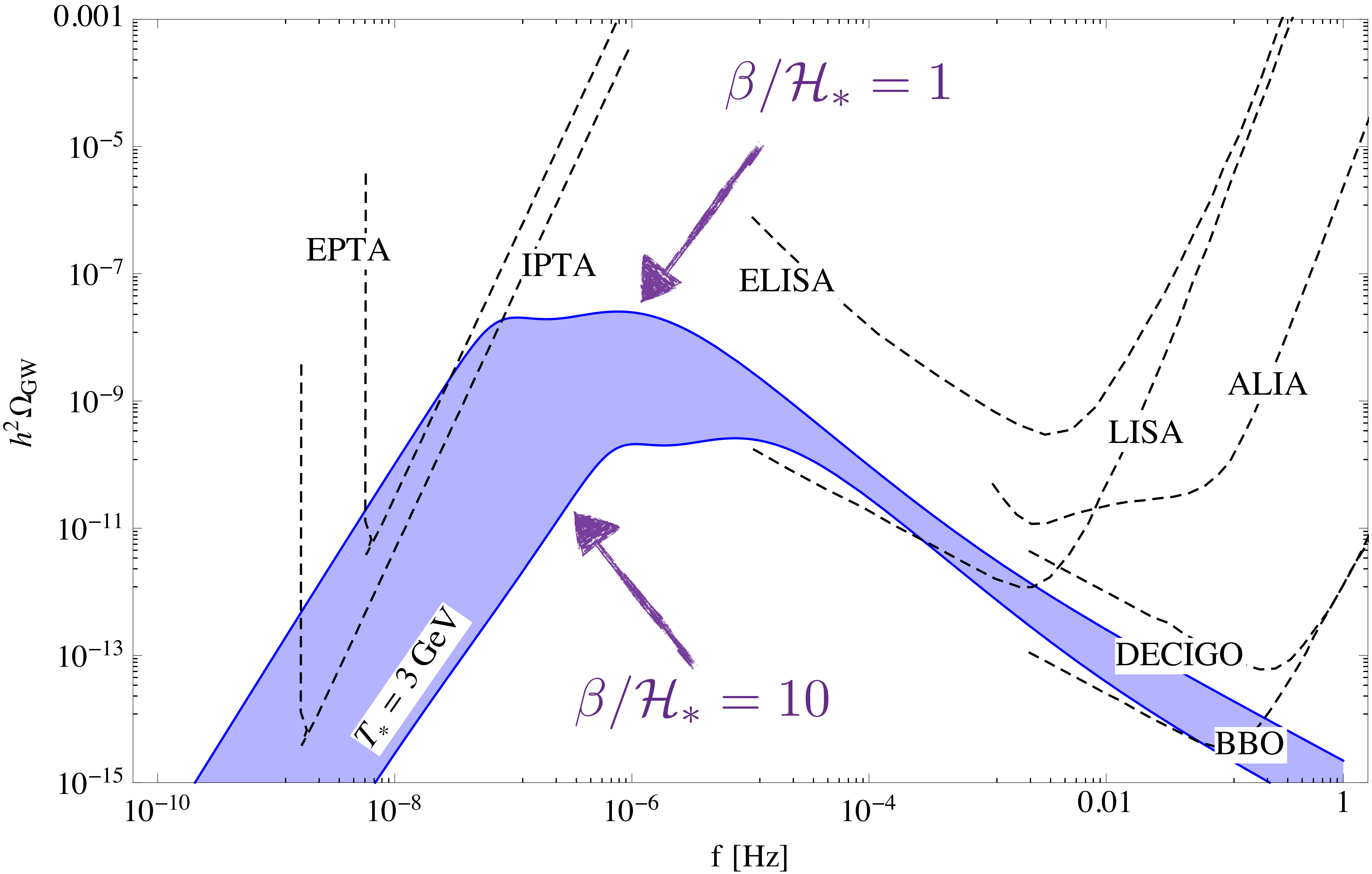
$$f = \frac{a_*}{a_0} H_* \frac{f_*}{H_*} = 1.59 \times 10^{-7}\ \mathrm{Hz} \times \left(\frac{g_*}{80}\right)^{\frac{1}{6}} \times \left(\frac{T_*}{1\ \mathrm{GeV}}\right) \times \frac{f_*}{H_*}$$

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

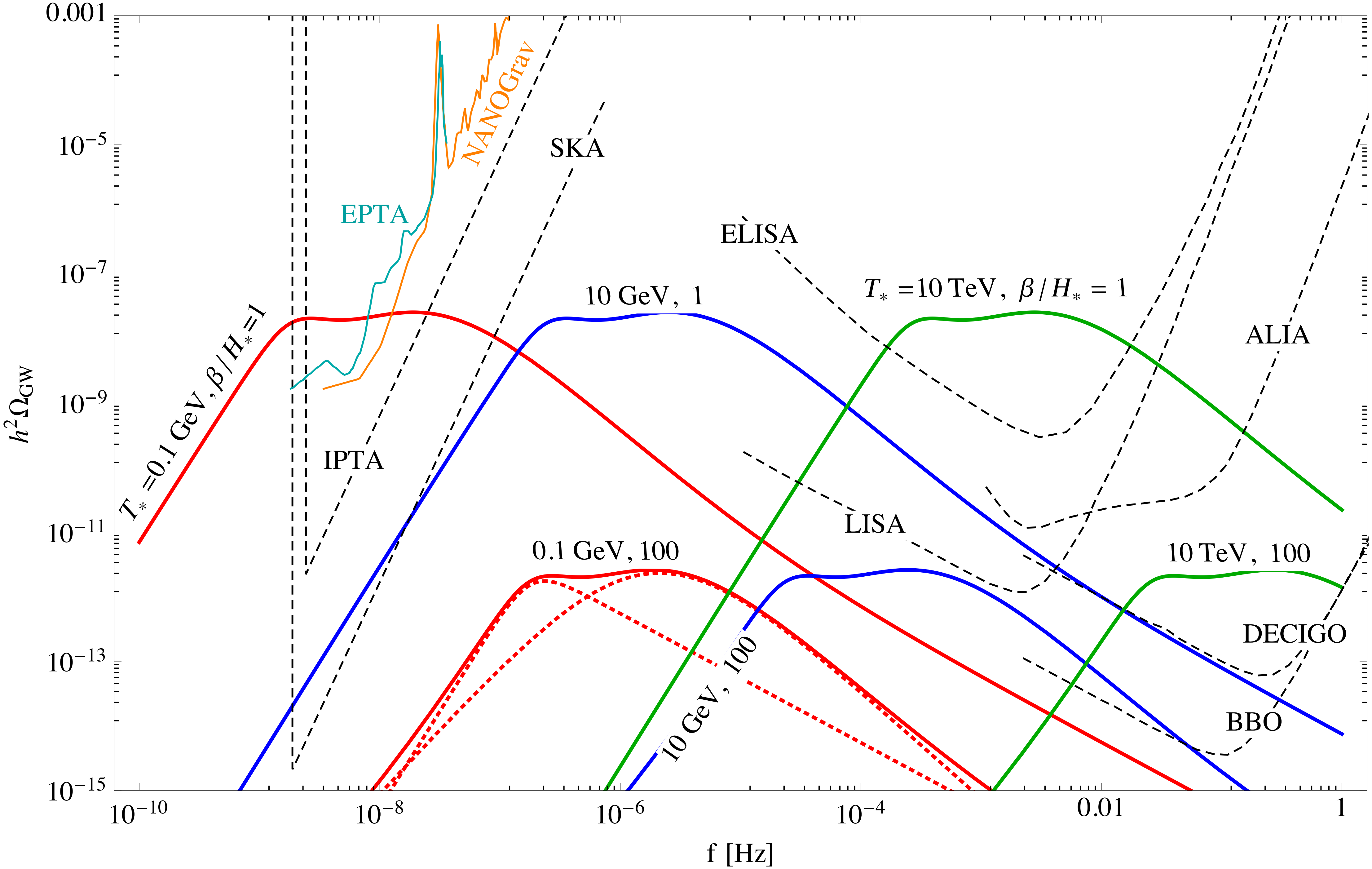

0.001
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
$h^2\Omega_{GW}$
10^{-10}
10^{-8}
10^{-6}
10^{-4}
0.01
1
f [Hz]
EPTA
IPTA
ELISA
LISA
ALIA
DECIGO
BBO
$T_* = 3$ GeV
$\beta/\mathcal{H}_* = 1$
$\beta/\mathcal{H}_* = 10$

SIMP

Composite ADM Twin Higgs

Composite WIMP-y

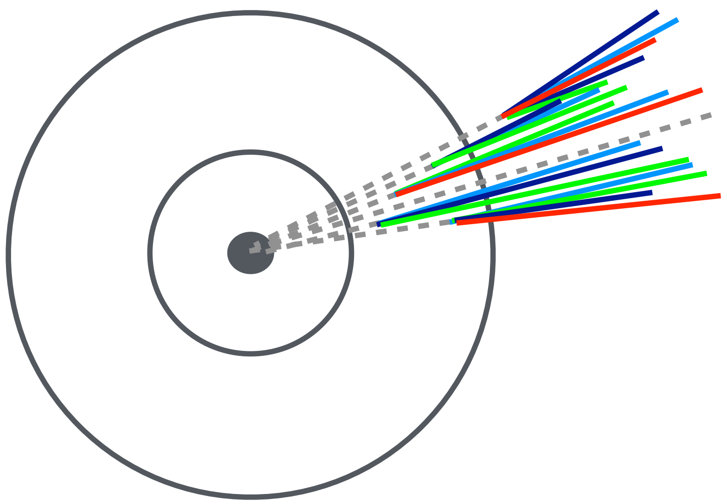
DM Unitarity



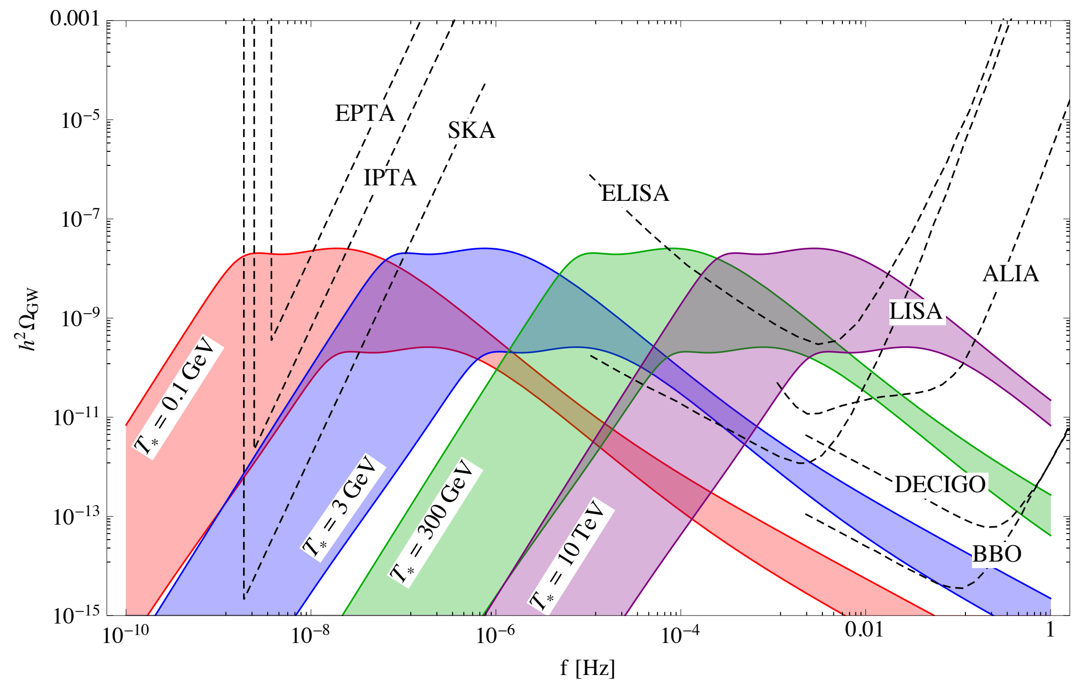
Summary

- QCD like dark sectors motivated in many models

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



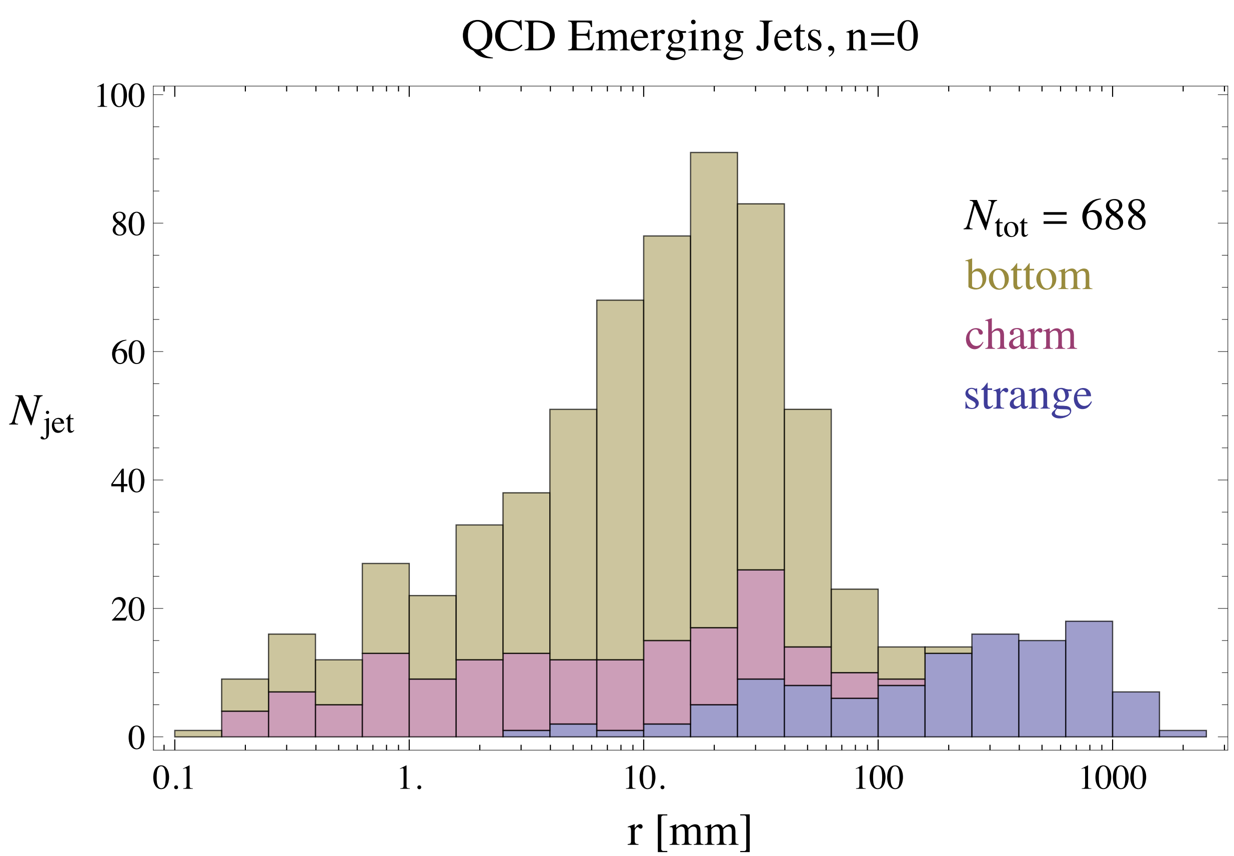
- Gravitational waves are independent probe of dark sector phase transition

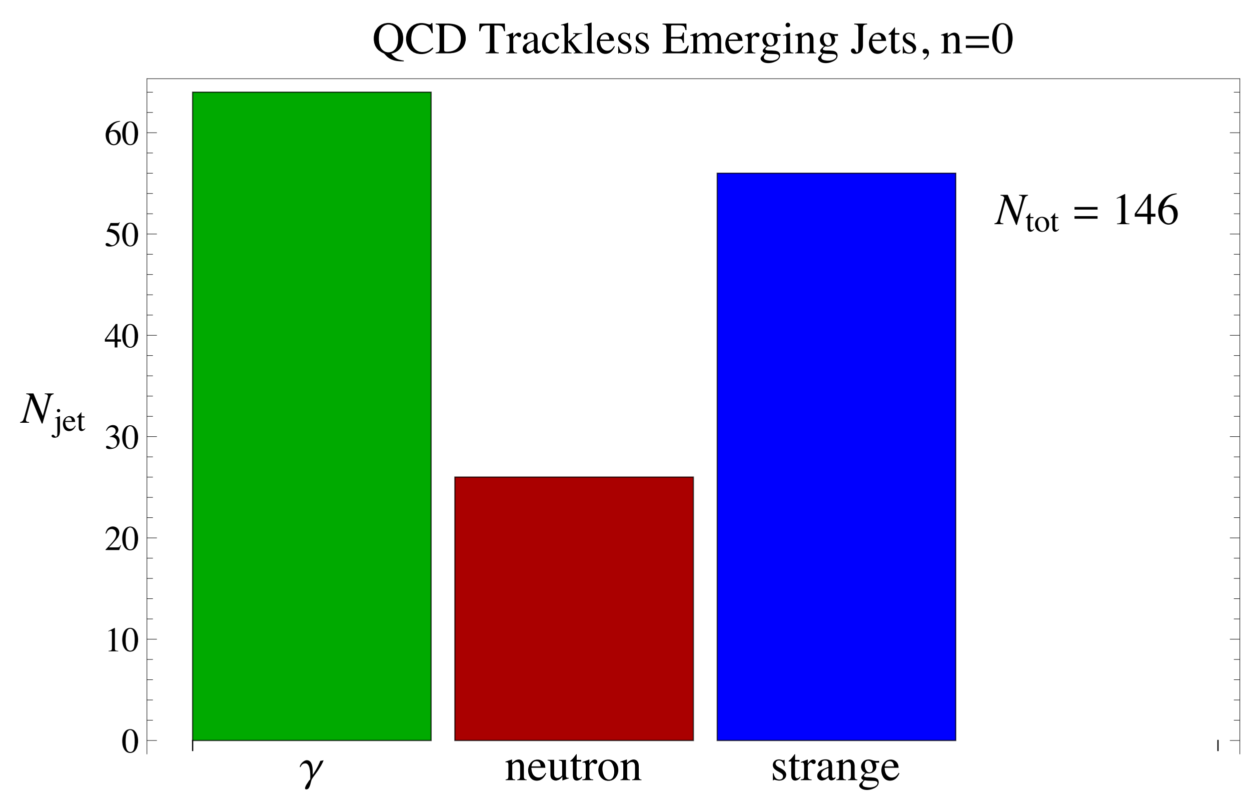


Extra slides :)

Composition of QCD backgrounds

- QCD jets with $p_{T,j} > 200\ \mathrm{GeV}$



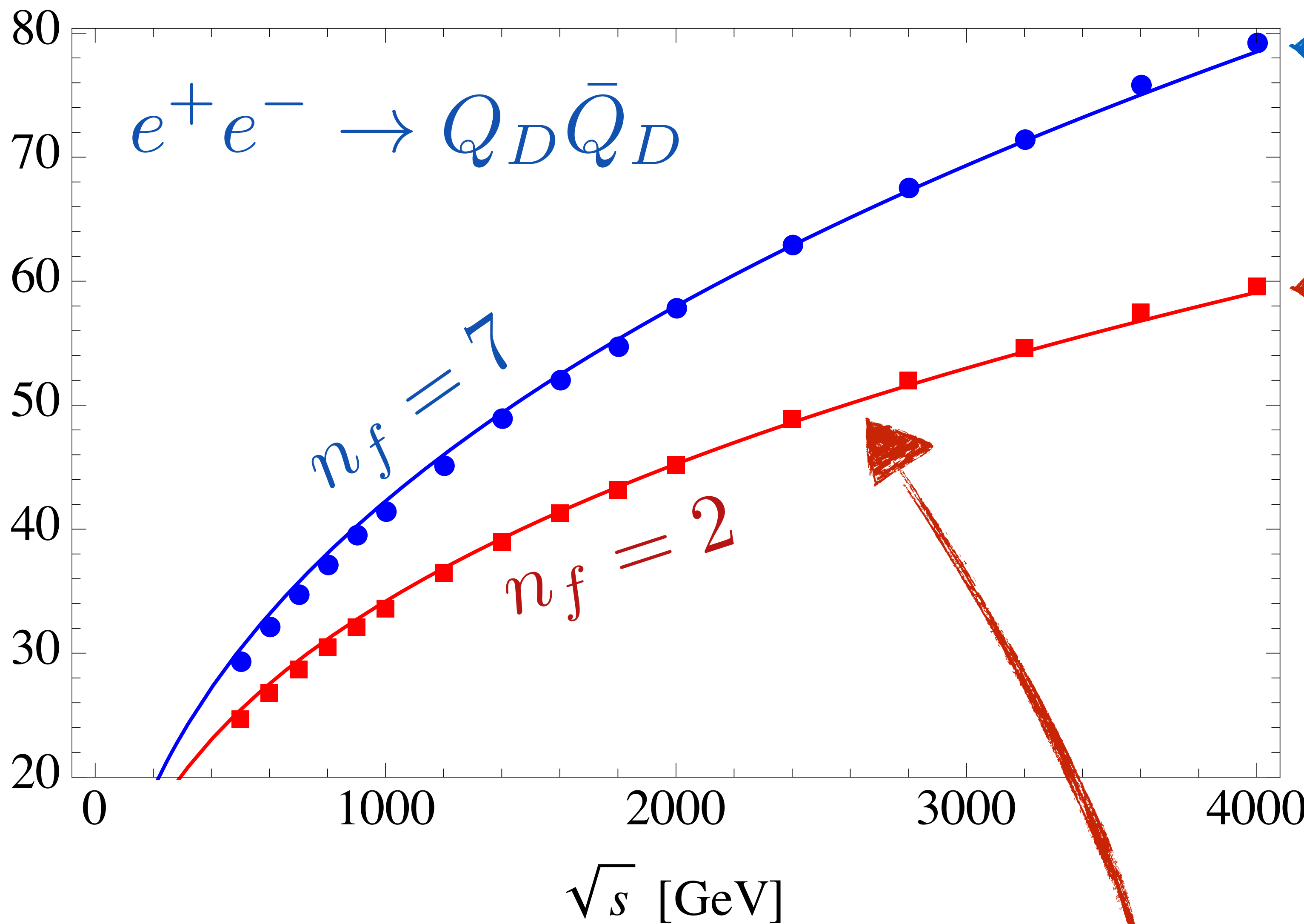


Track(s) appears at distance *r*
Flavour of long lived state

Purely trackless jets
identity of hardest particle

Dark Shower

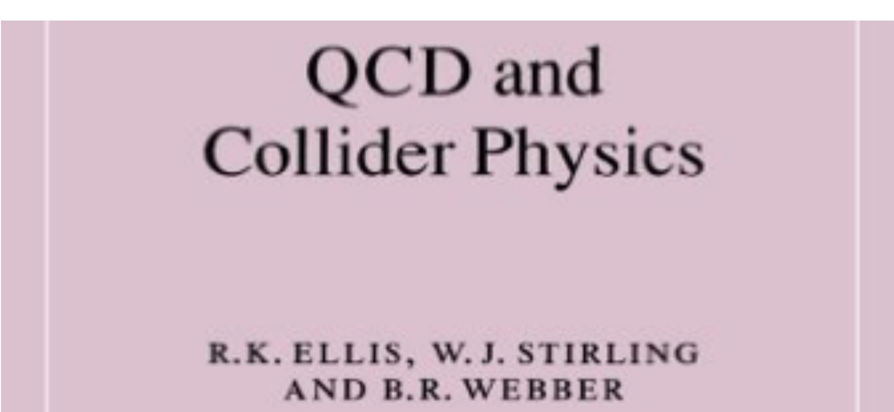
dark meson multi-plicities



Pythia 8

Carloni, Sjostrand, 2010 + modifications

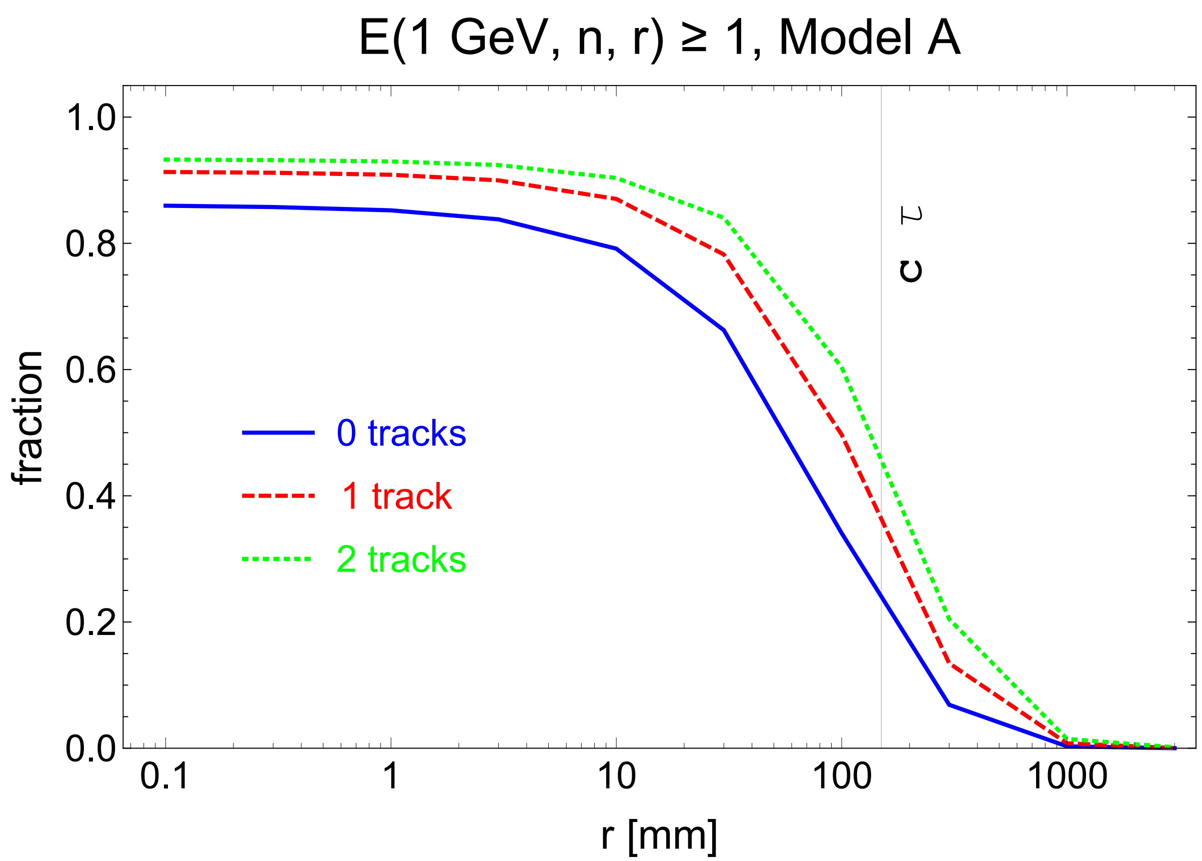
github.com/pedroschwaller/EmergingJets



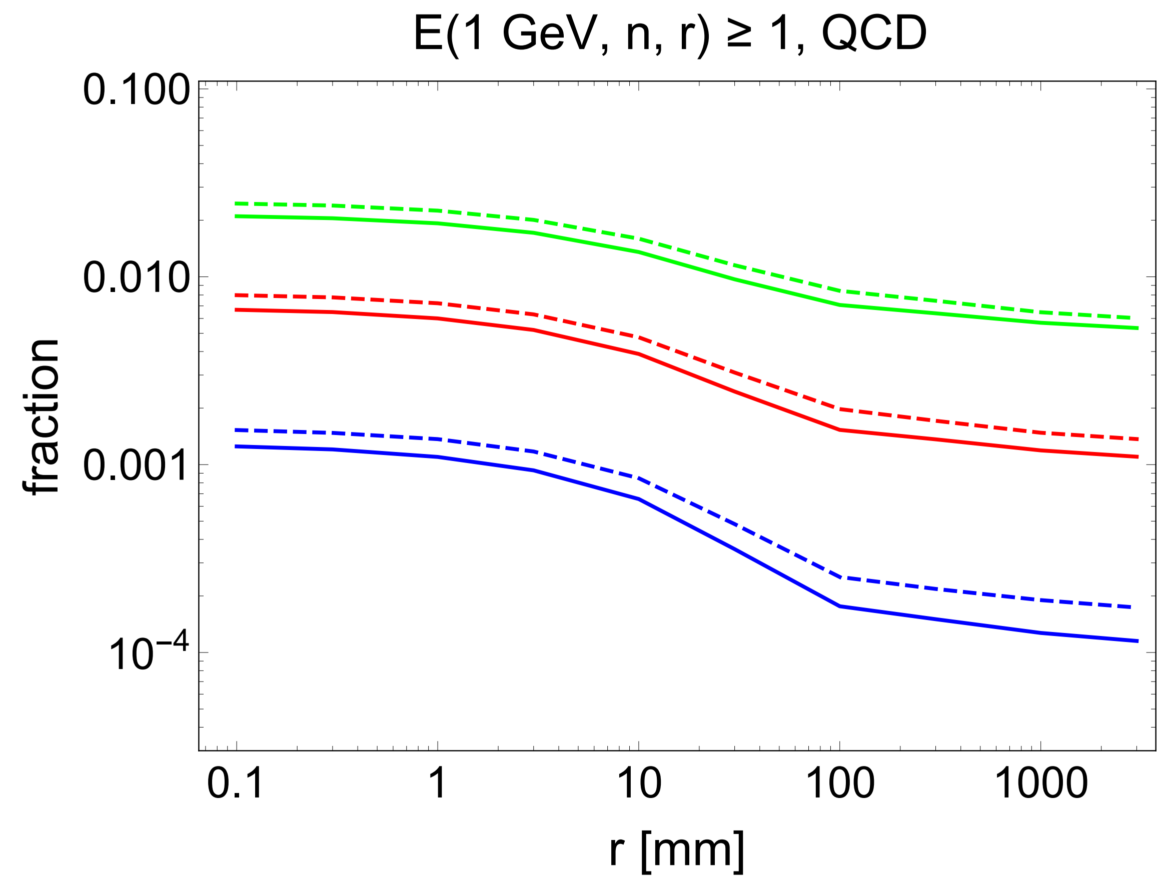
$$\langle N(\hat{s})\rangle \propto \exp\left(\frac{1}{b_1}\sqrt{\frac{6}{\pi\alpha_s(\hat{s})}} + \left(\frac{1}{4} + \frac{5n_f}{54\pi b_1}\right)\log\alpha_s(\hat{s})\right)$$

Cut Efficiencies

Signal



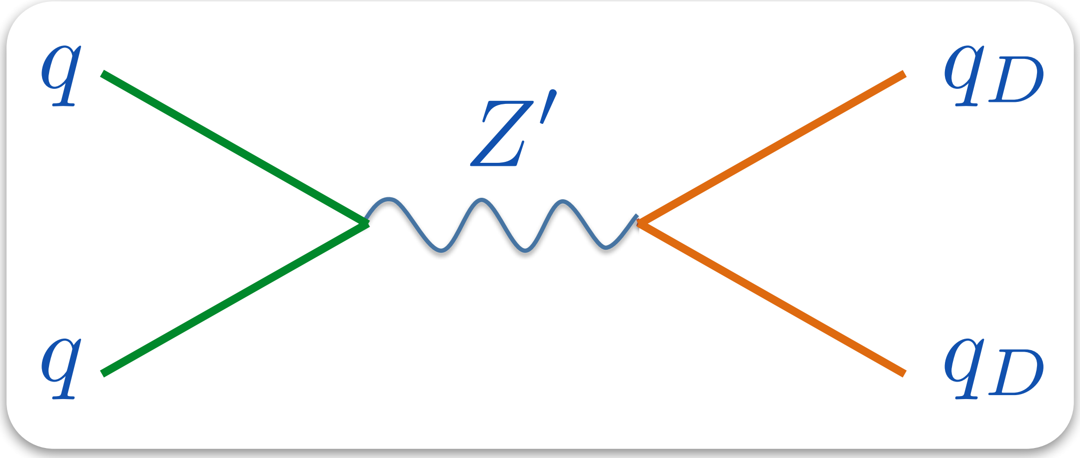
Background

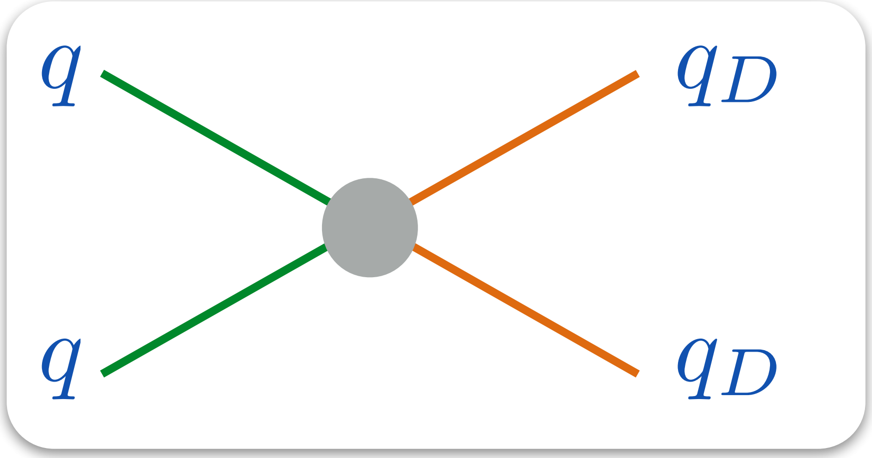


- Factor 100-1000 improved S/B **per jet**, compared to ordinary 4-jet search

LHCb, SHIP, low energy

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

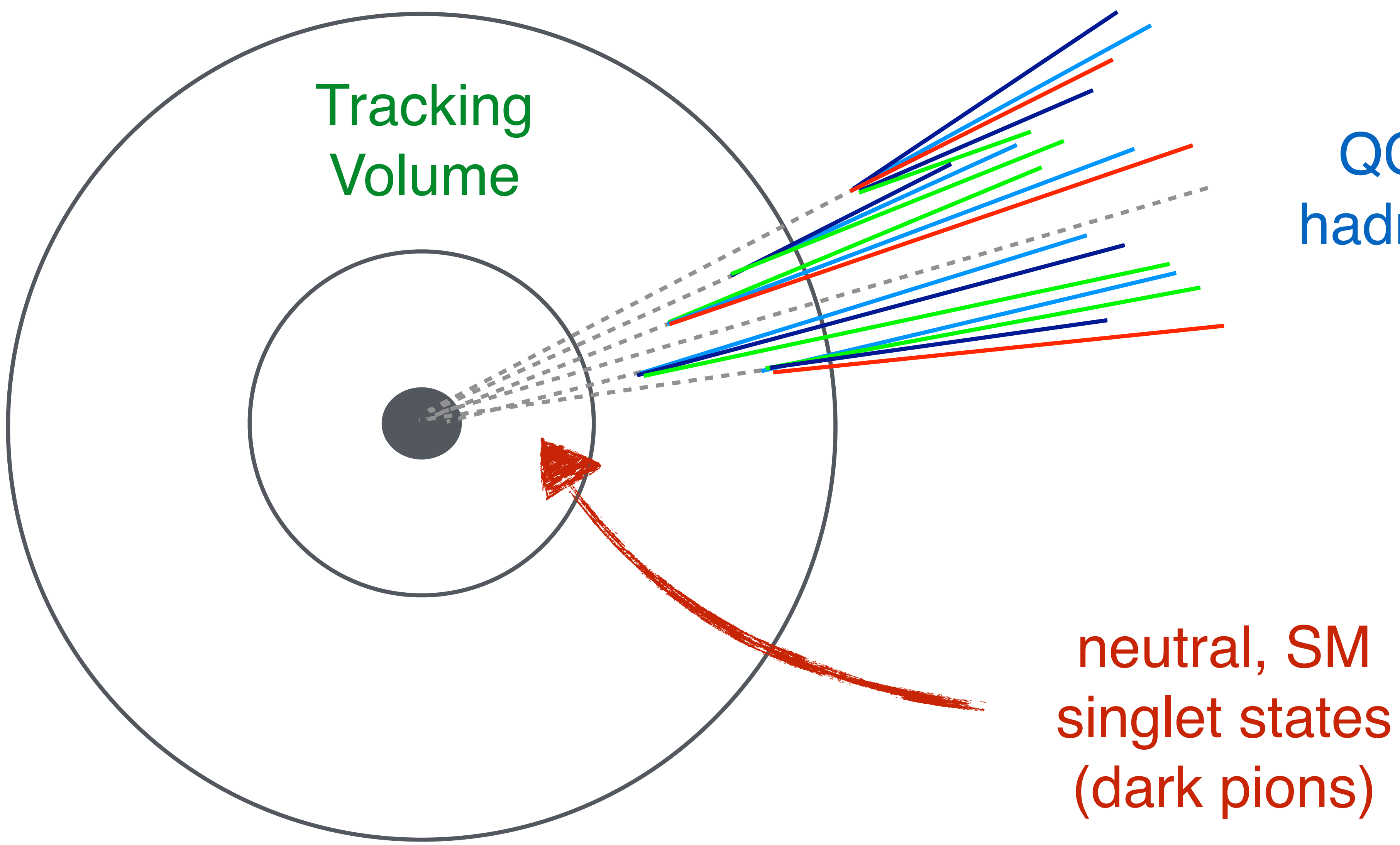




- Reconstruct individual dark pions, differentiate using lifetime, mass, decay products

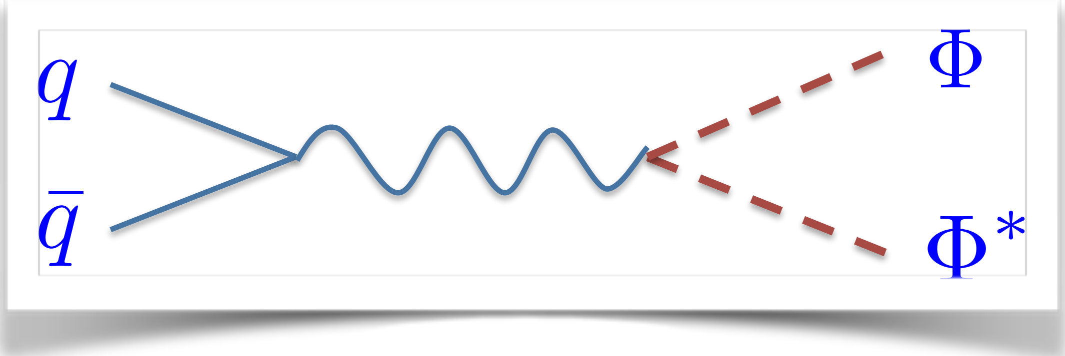
- Depends on flavour structure → in progress

What is an Emerging Jet?



Model

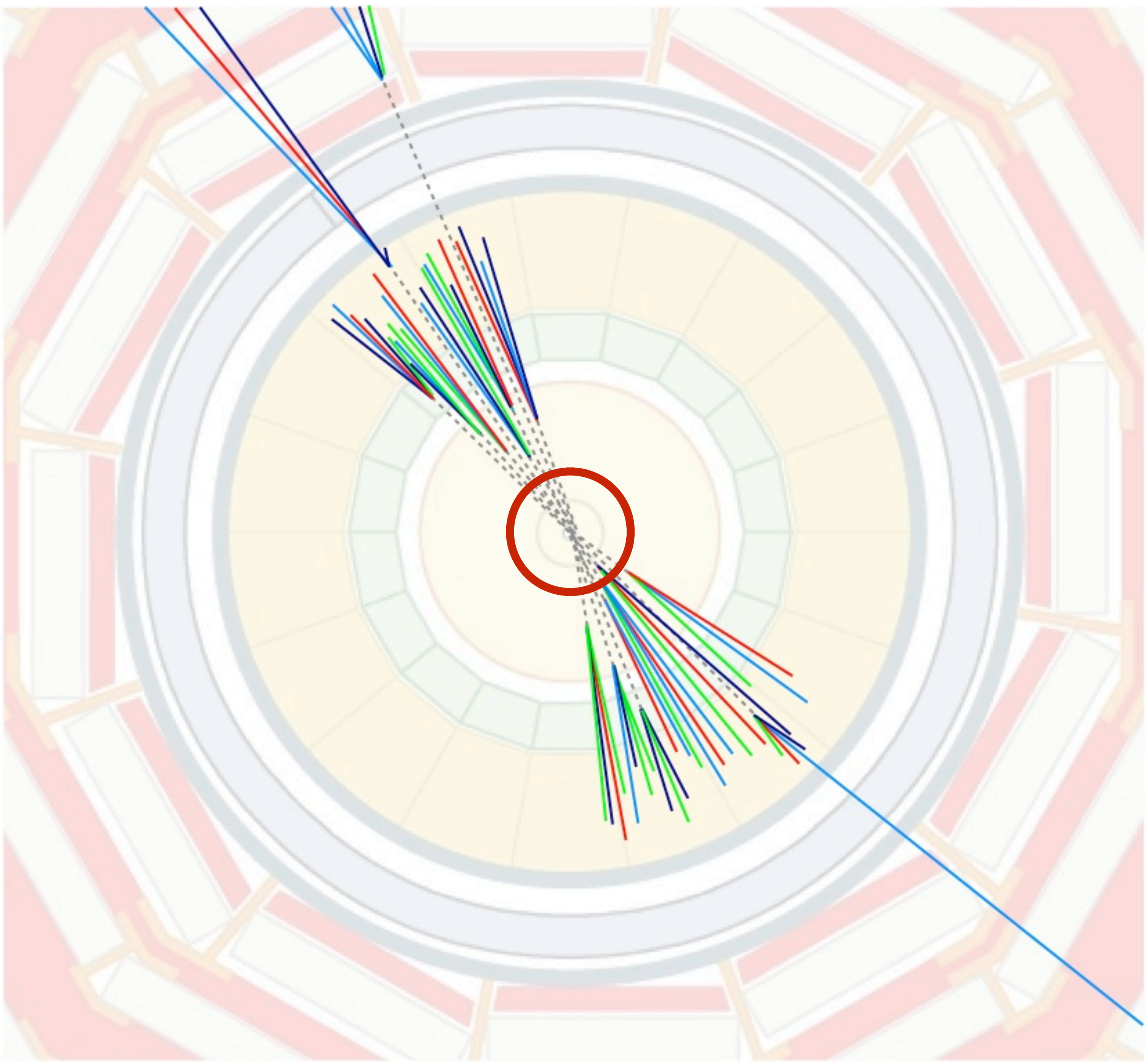
- Mediators:
  - Bifundamental scalar Φ $\mathcal{L} \supset \kappa \Phi \bar{Q}_D d_R$
  - or Z' (Hidden Valleys!) $\mathcal{L} \supset g' \bar{Q}_D \gamma^\mu Q_D Z'_\mu$ + couplings to SM
- Pair production of heavy bi-fundamental fields:



- Decay to quark - dark quark pairs: Two QCD jets, two Emerging Jets

Emerging Jets at the LHC

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



Benchmark Signal/Strategy

- Pair production of 1 TeV bi-fundamental scalars
- Trigger on 4 HCAL jets $p_T > 200$ GeV
- Require one or two “emerging jets:”
  Jets with at most 0/1/2 tracks originating from a distance $r < r_{\text{cut}}$
- Two scenarios:

	Model **A**	Model **B**
Λ_d	10 GeV	4 GeV
m_V	20 GeV	8 GeV
m_{π_d}	5 GeV	2 GeV
$c\,\tau_{\pi_d}$	150 mm	5 mm

S/B

	Model **A**	Model **B**	QCD 4-jet	
Tree level	14.6	14.6	410,000	fb
≥ 4 jets, $\lvert\eta\rvert < 2.5$ $p_T(\text{jet}) > 200$ GeV $H_T > 1000$ GeV	4.9	8.4	48,000	fb
$E(1\,\text{GeV}, 0, 3\,\text{mm}) \geq 1$	4.1	4.1	45	fb
$E(1\,\text{GeV}, 0, 3\,\text{mm}) \geq 2$	1.8	0.8	~ 0.08	fb
$E(1\,\text{GeV}, 0, 100\,\text{mm}) \geq 1$	1.7	$\lesssim 0.01$	8.5	fb
$E(1\,\text{GeV}, 0, 100\,\text{mm}) \geq 2$	0.2	$\lesssim 0.01$	$\lesssim 0.02$	fb

- Can still add paired di-jet cuts
- Will also catch some displaced vertex & SIMP signals, possibly photon jets

Shapes

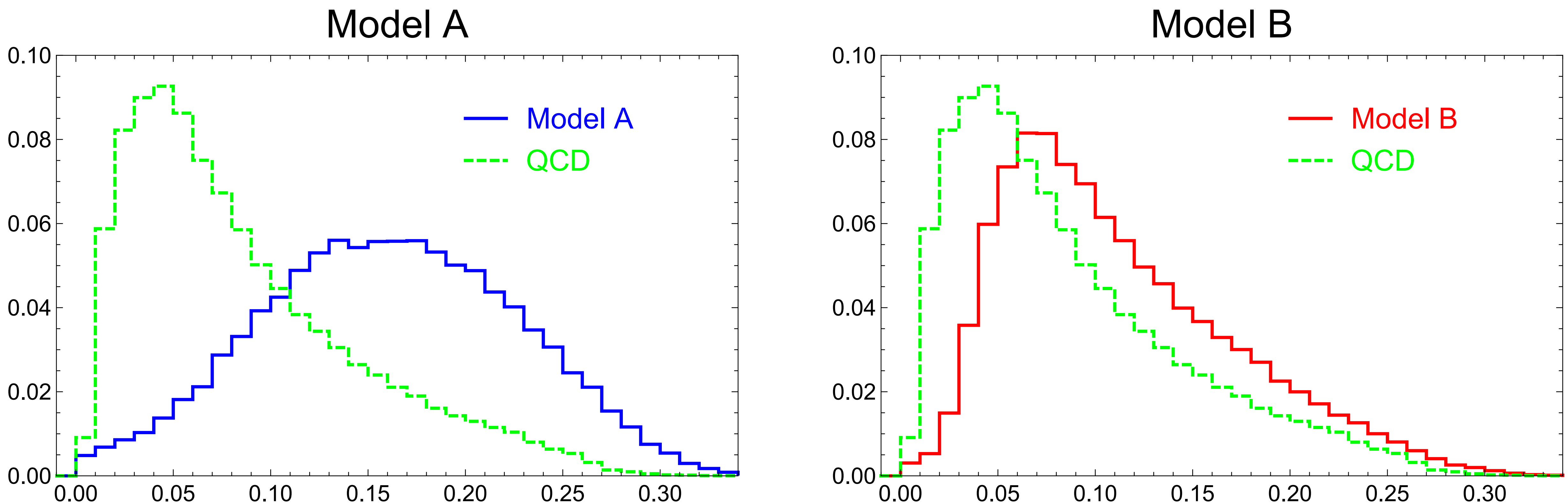
&

Substructure?

Jet Shape(s)

- Girth

$$\frac{1}{p_T^{\text{jet}}} \sum_i p_T^i \, \Delta R_i$$



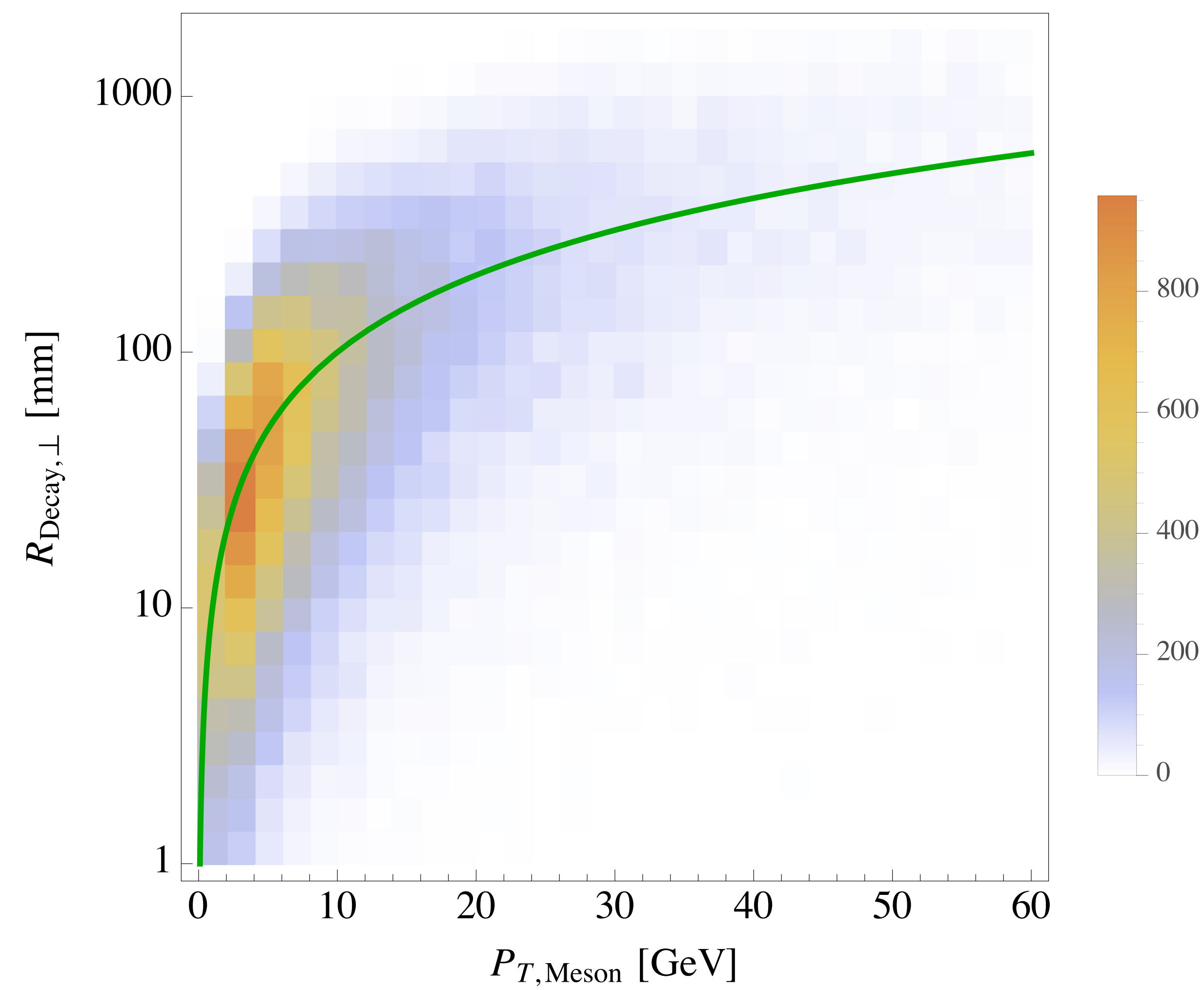
- Model discrimination (?)

- Subtleties: Might loose hardest dark meson, etc…

What if cτ ≪ mm ?

- No displaced tracks. Can we still discriminate QCD and dark QCD jets?

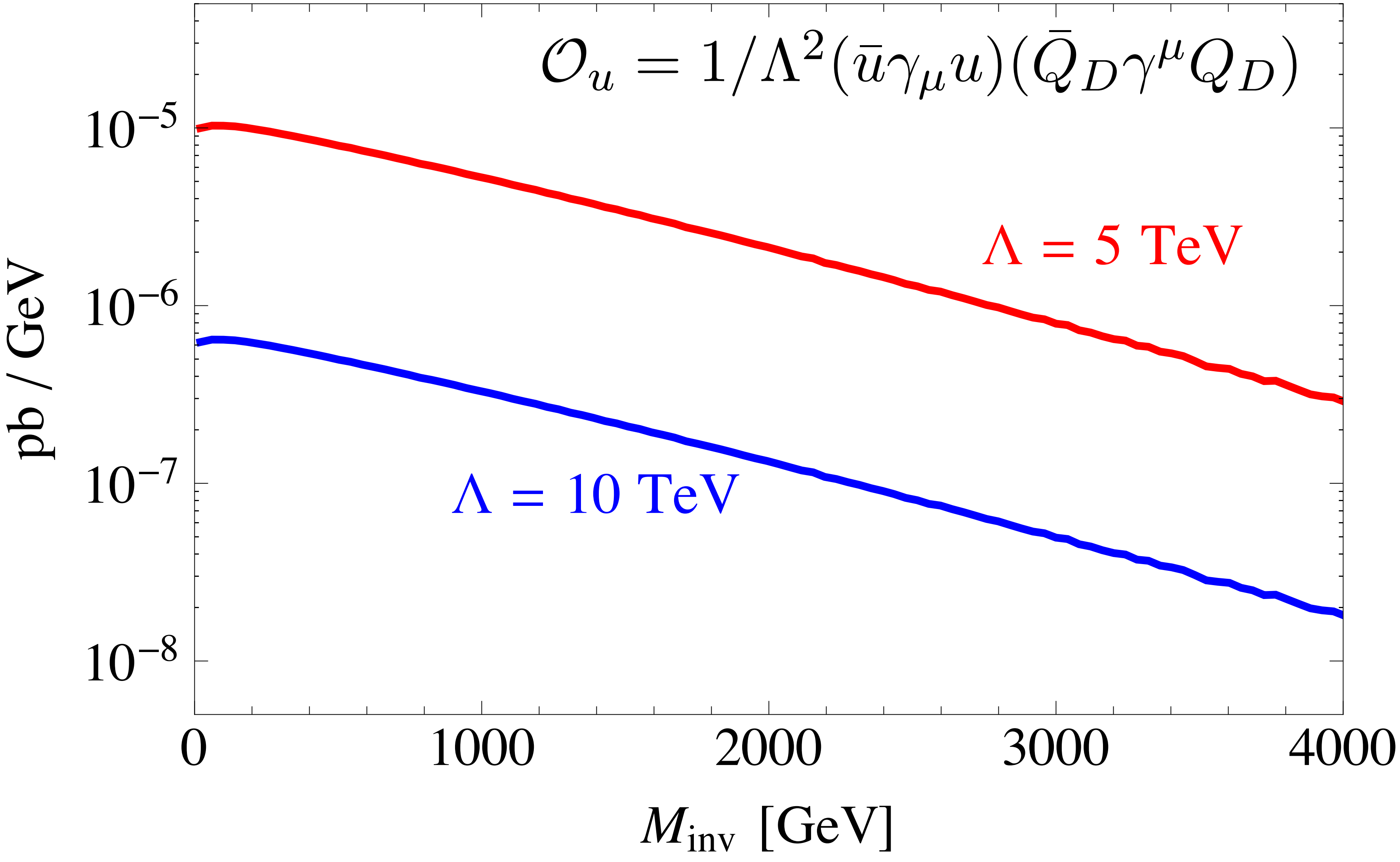
- Sub-jets from individual dark pion decays



Probably discussed 8 years ago in context of Hidden Valleys

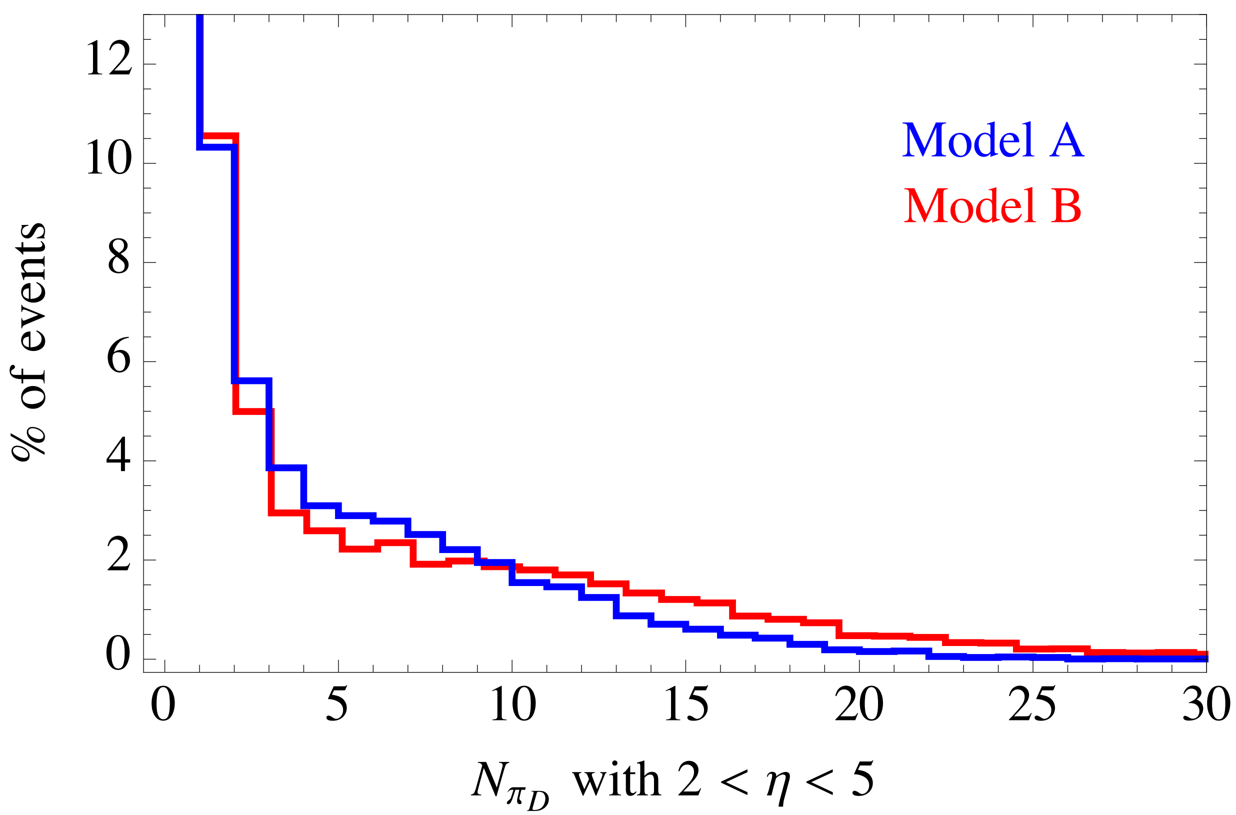
Much better tools now available!!!

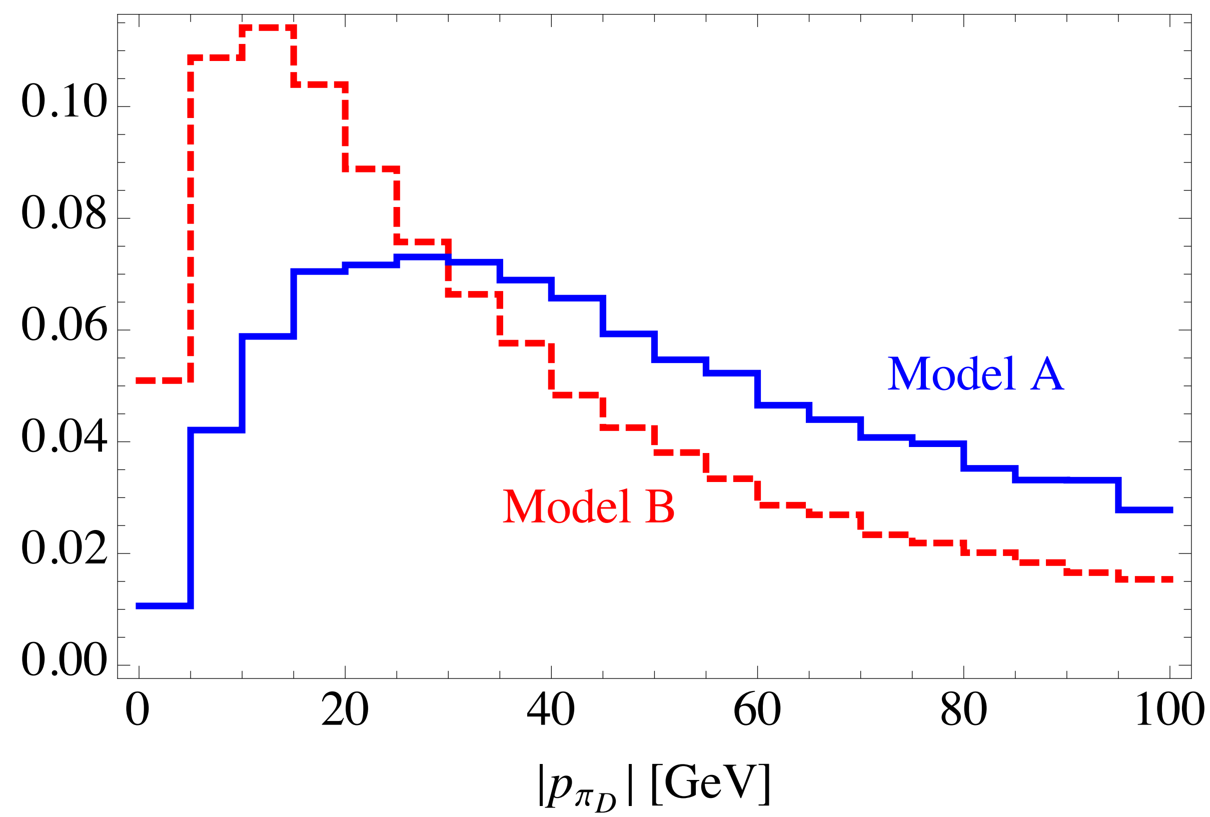
Off-shell production



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

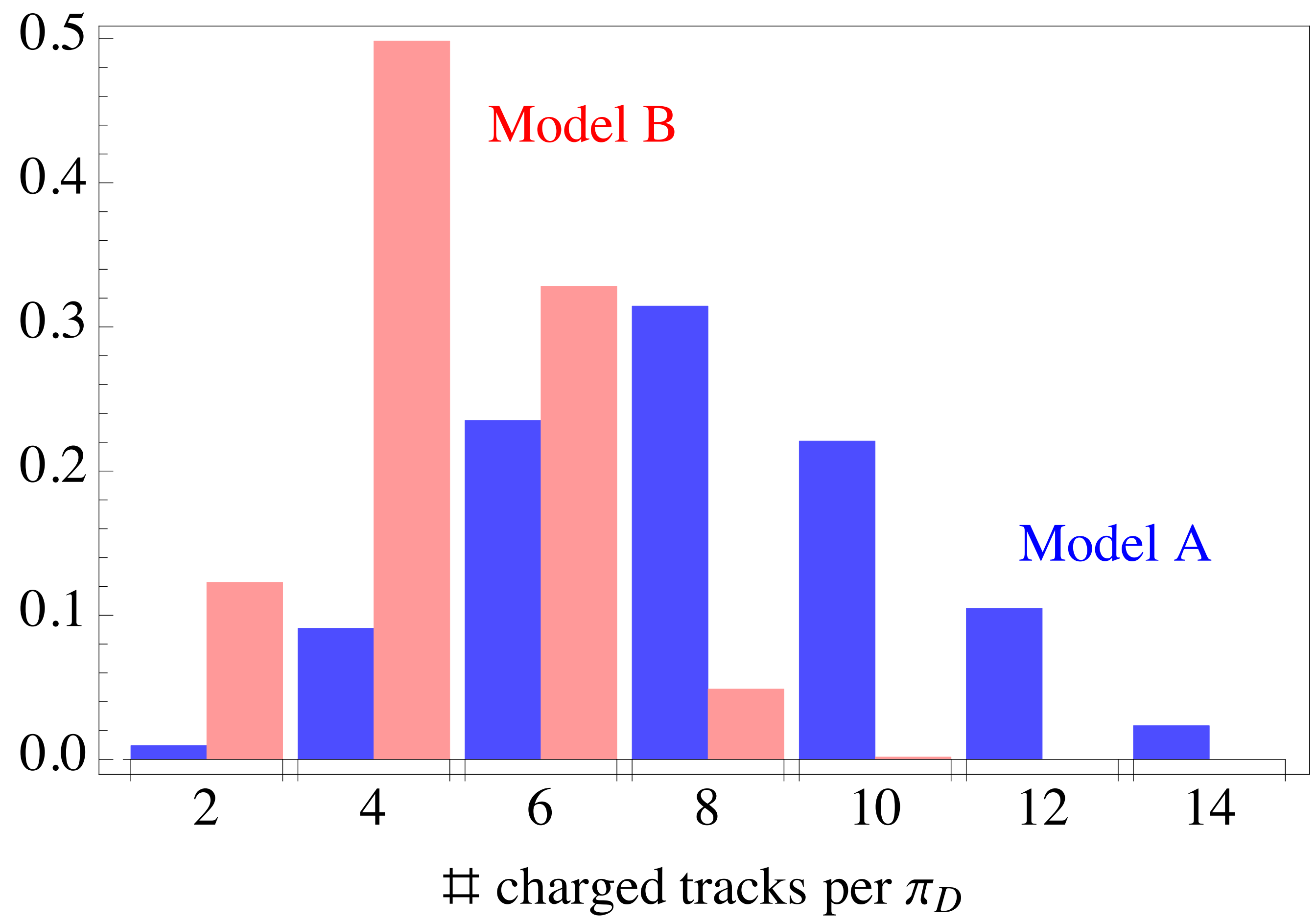
Forward region





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

Decay characteristics



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

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 $\sigma = 8\ \mathrm{fb}$, corresponds to $\Lambda \approx 5\ \mathrm{TeV}$

Shape

- From Bubble collisions and turbulence

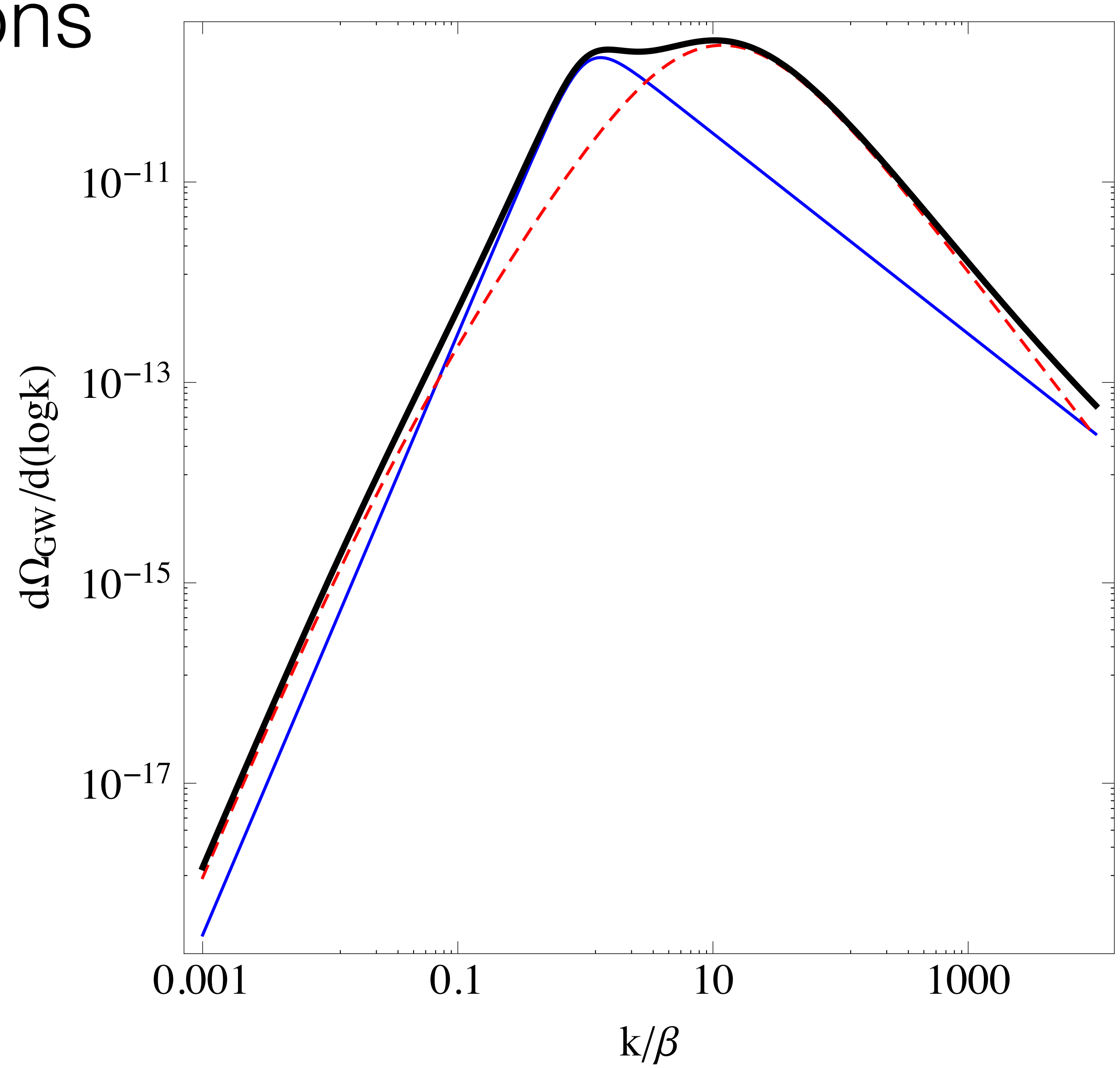
$$\frac{d\Omega^{(B)}_{\rm GW}h^2}{d\log k} \simeq \frac{2}{3\pi}h^2\Omega_{r0}\left(\frac{\mathcal{H}_*}{\beta}\right)^2\Omega^2_{S*}v^3\frac{(k/\beta)^3}{1+(k/\beta)^4}\,,$$

$$\frac{d\Omega^{(MHD)}_{\rm GW}h^2}{d\log k} \simeq \frac{8}{\pi^6}h^2\Omega_{r0}\left(\frac{\mathcal{H}_*}{\beta}\right)\Omega^{3/2}_{S*}v^4\,\frac{(k/\beta)^3}{(1+4k/\mathcal{H}_*)\,(1+(v/\pi^2)(k/\beta))^{11/3}}$$

Caprini, Durrer, Siemens, 2010
Huber, Konstandin, Servant, …

- k conformal wave number

$$\beta \sim (1-100)\mathcal{H}_*$$



Sound waves not included yet!

Hindmarsh, Huber, Rummukainen, Weir, 2013, 2015