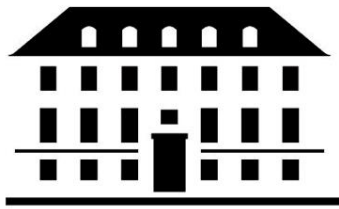
Composite Dark Matter and the LHC

William Shepherd



The Niels Bohr International Academy

Drawing heavily on:
Bai, Schwaller 1306.4676
Schwaller, Stolarski, Weiler 1502.05409
Cohen, Lisanti, Lou 1503.00009
Kaplinghat, Tulin, Yu 1508.03339

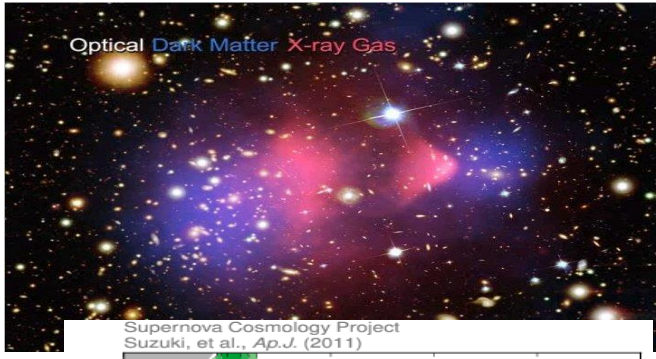
Dark QCD
From Colliders to Cosmology

Pedro Schwaller
DESY

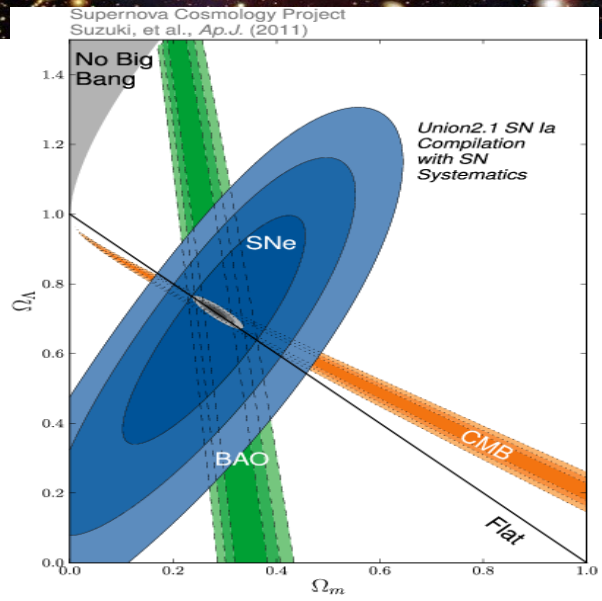
Theory Seminar
BCTP, Universität Bonn
18.01.2016

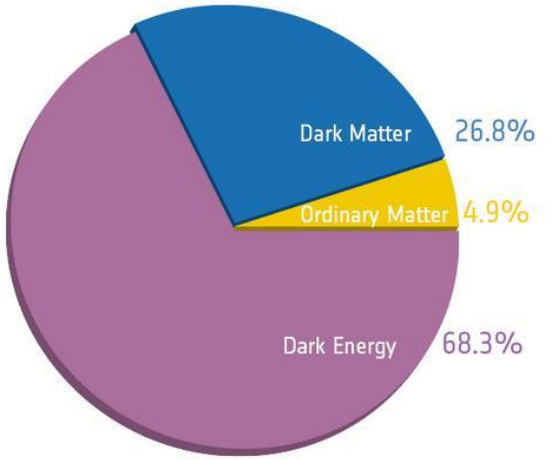
Based on
Bai, PS, 1306.4676
PS, Stolarski, Weiler, 1502.05409
PS, 1504.07263

Dark Matter



- The evidence for dark matter is myriad and well-known.
- This evidence is one of the only truly experimental signs that we must have physics beyond the Standard Model.
- Cosmological observations tell us how much dark matter is needed to match observations.
- From the particle physics perspective, we're left asking what dark matter is and how it fits into a microscopic understanding of nature.

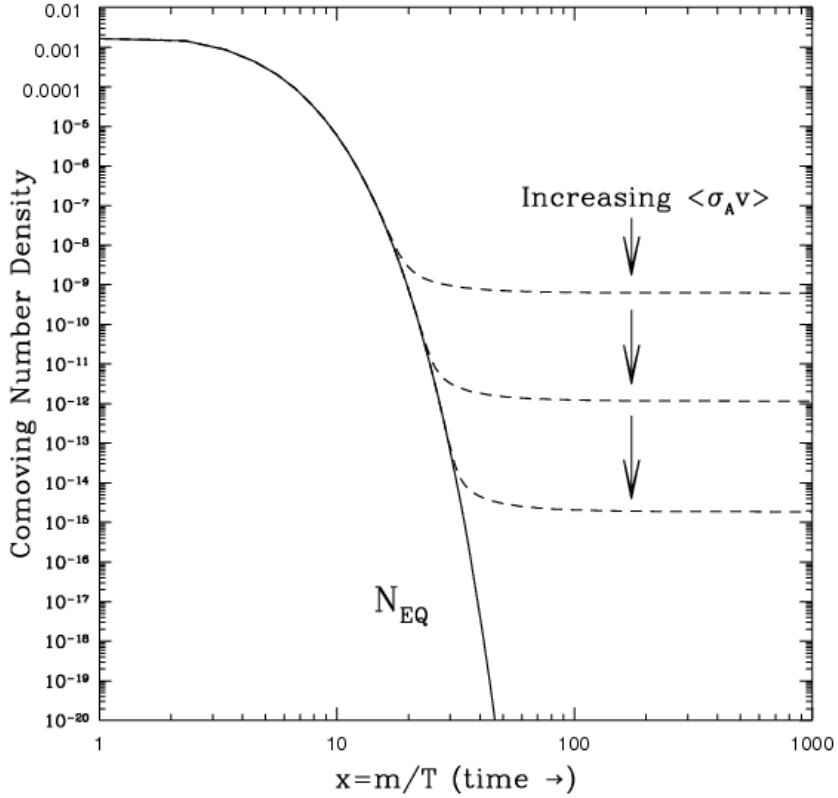




WIMP Miracle

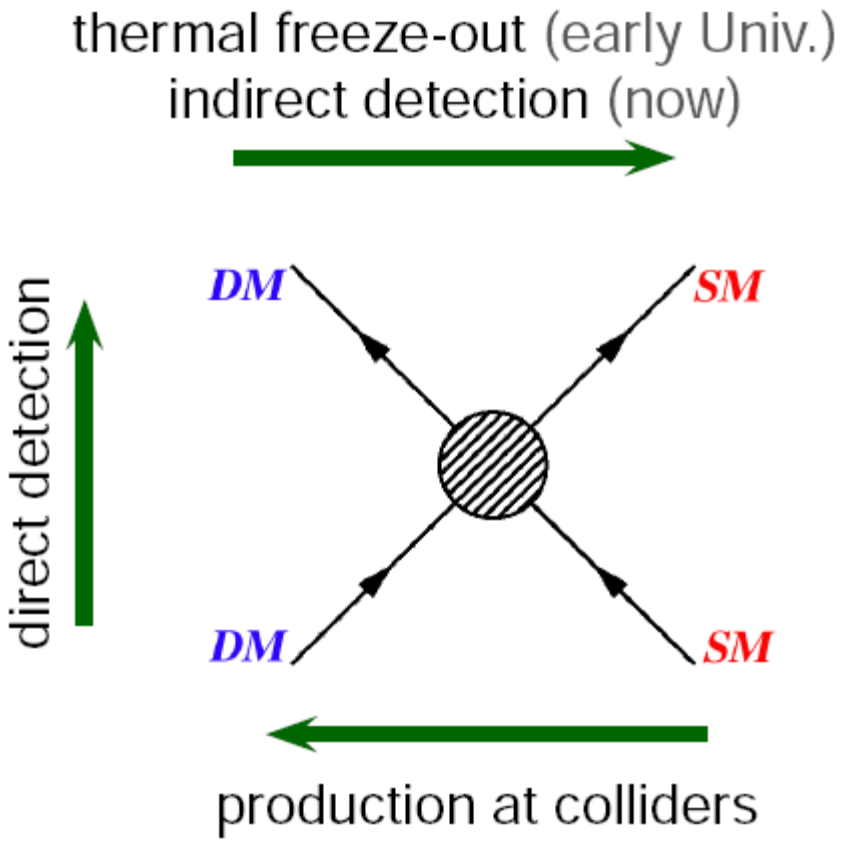
- If DM was in thermal equilibrium, then its current density is easily calculable.
- To match measurements,

$$\frac{M_\chi}{\alpha} \sim \sqrt{T_{eq} M_{Pl}} \sim \frac{2.3 \text{ TeV}}{0.03}$$



Crossing Symmetry Bedtime Story

- We may not understand the detailed dynamics of DM interactions, but we can think of them as some interaction, and look for it in different ways.
- Everything should be weak-scale, since we like the thermal WIMP.



MANY caveats; see Profumo, WS, Tait 1307.6277

WIMPy Issues

- Relic density constraint fixes strength of DM - SM interaction
- Often in conflict with experimental data:
  - Higgs portal DM: $m_{\mathrm{DM}} \leq \frac{m_H}{2}$ excluded
  - LUX et al: Strong bounds on interaction with quarks, Annihilation through Z-boson ruled out
  - Tension with indirect detection (s-wave)

Worth considering other ways of getting the right relic density

Further WIMPy Issues

- Issues in CDM simulations at ~galactic scales
  - Cusp-Core
  - Missing Satellites
  - Too Big to Fail
- Could be resolved by strong self-scattering DM
- Could be baryon effects

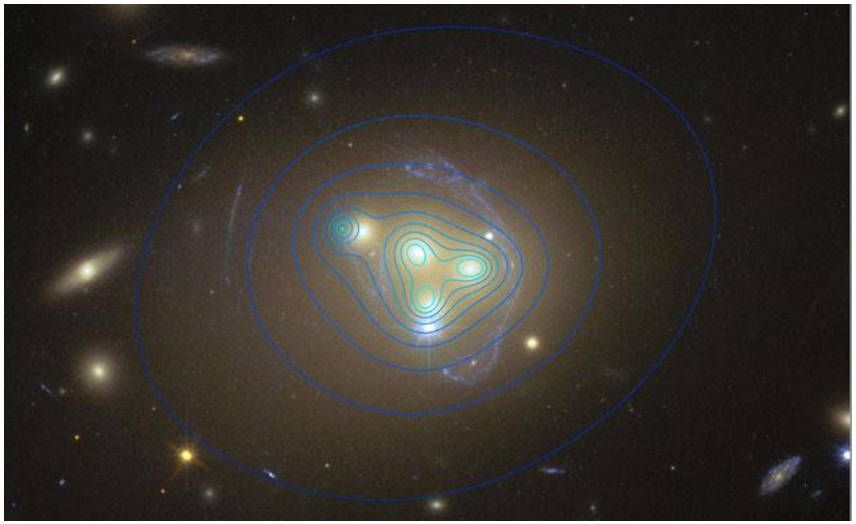
see e.g. Tulin, Yu, Zurek, 2013
Boddy, Feng, Kaplinghat, Tait, 2013

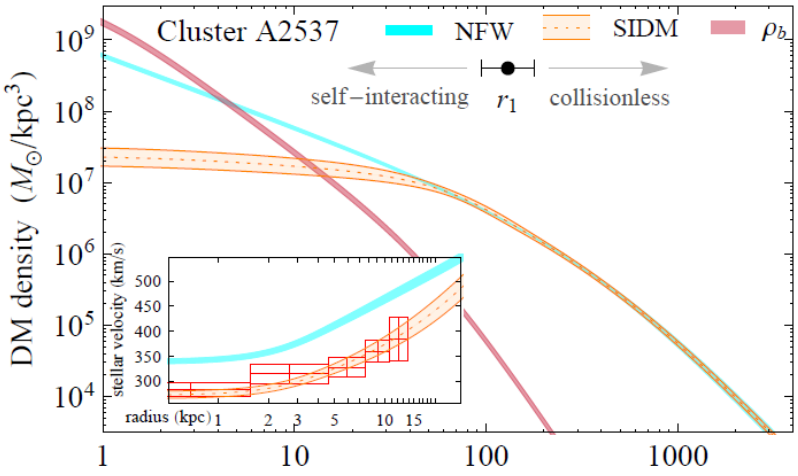
- (Some) could be late kinetic decoupling
- Could be observational issues

e.g. Bringmann et al 1603.04884
Cornell, Profumo, WS 1305.4676

SIDM Explanation

- DM Scatterings can explain e.g. the drag effect in Abell cluster
- Also will give some pressure-type effect
  - Keeps cusp structure from developing in halo center





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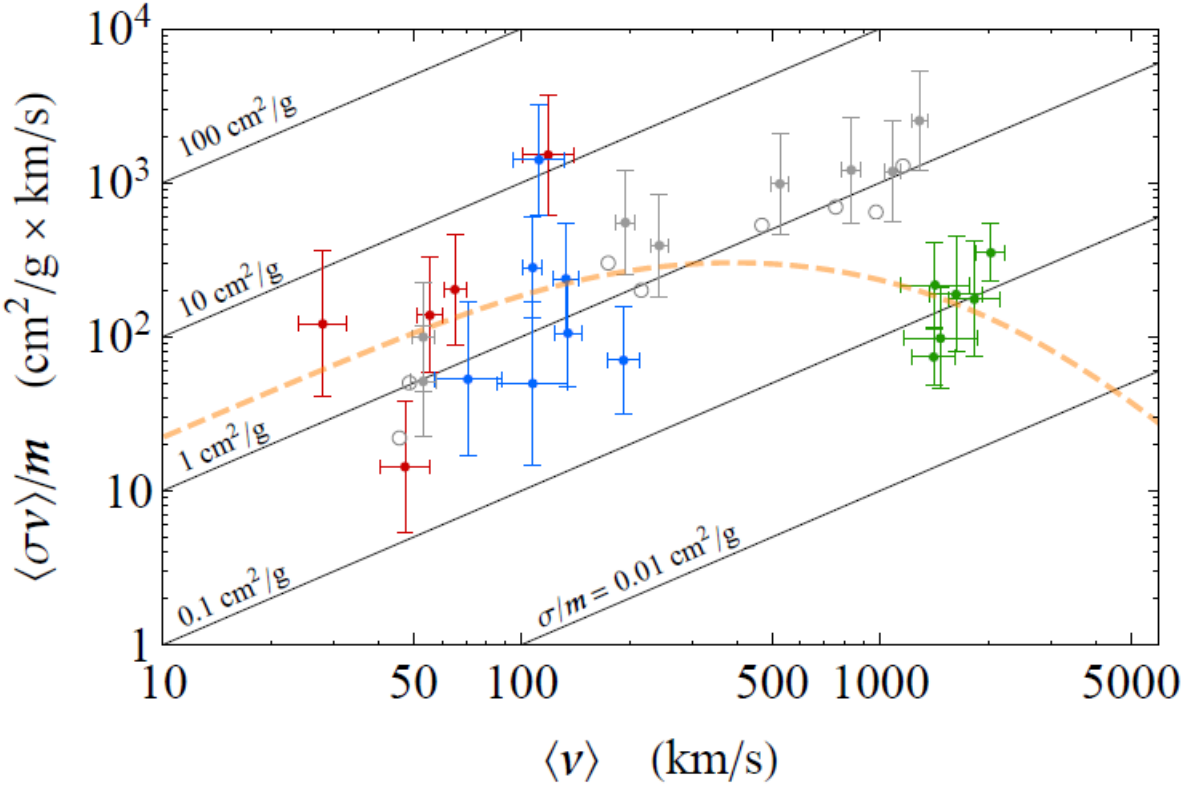
Preferred Scattering



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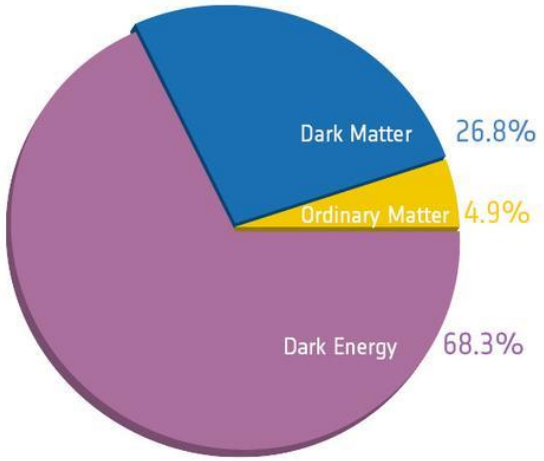
A Different Coincidence



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

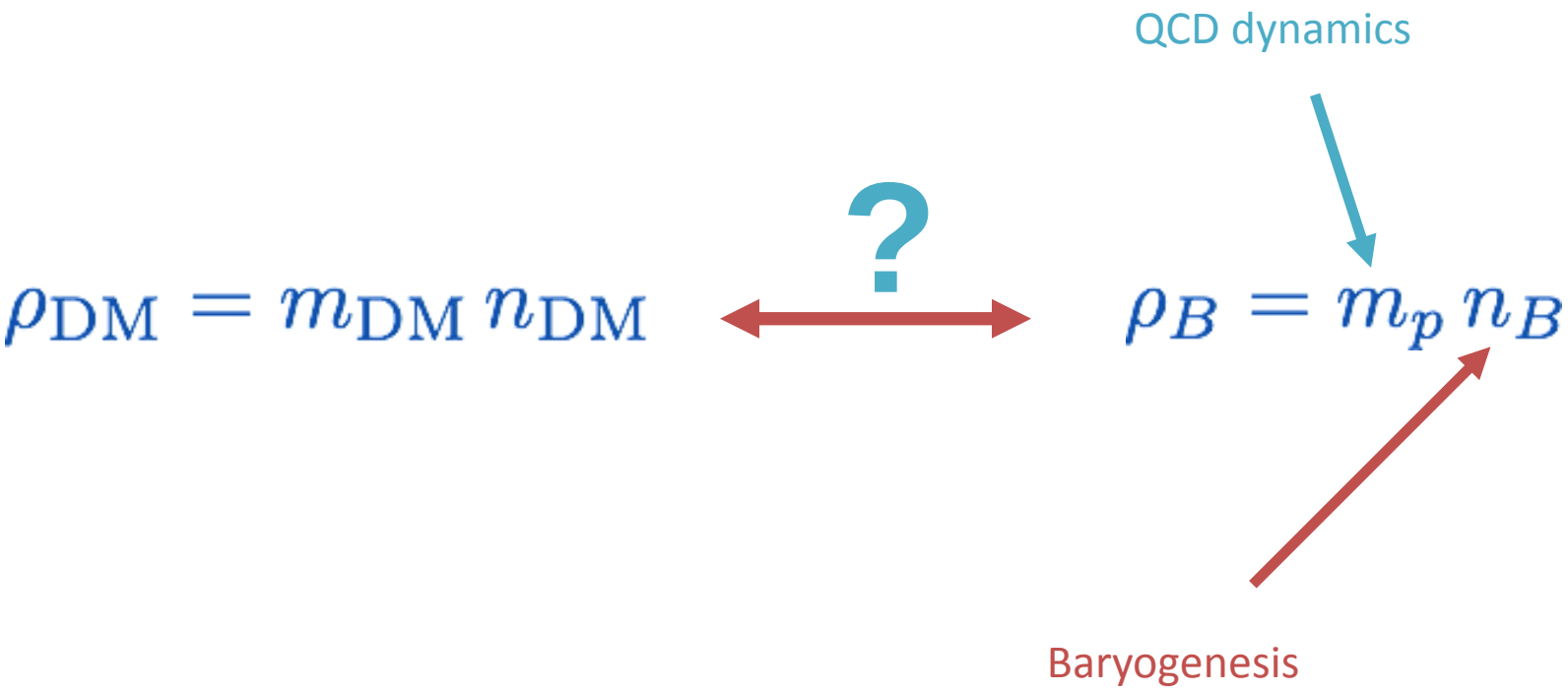
A hint from nature?

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

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

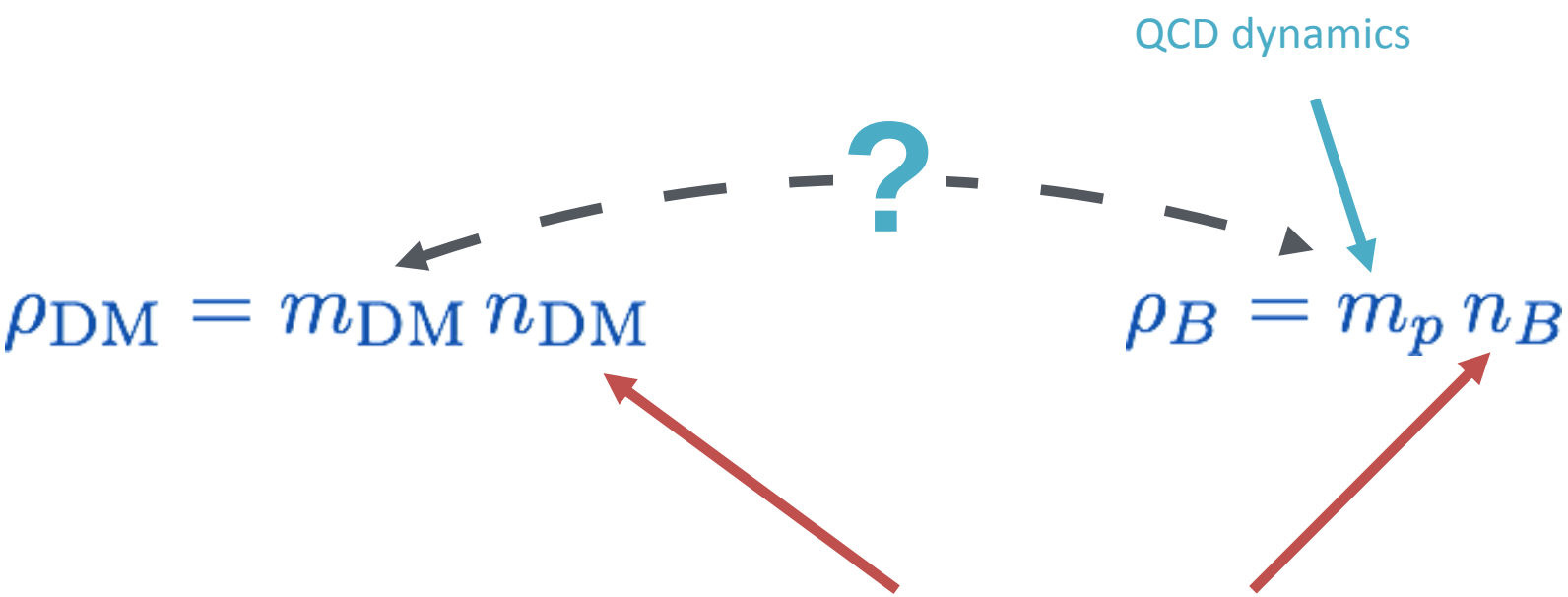
A hint from nature?

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



Asymmetric DM

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

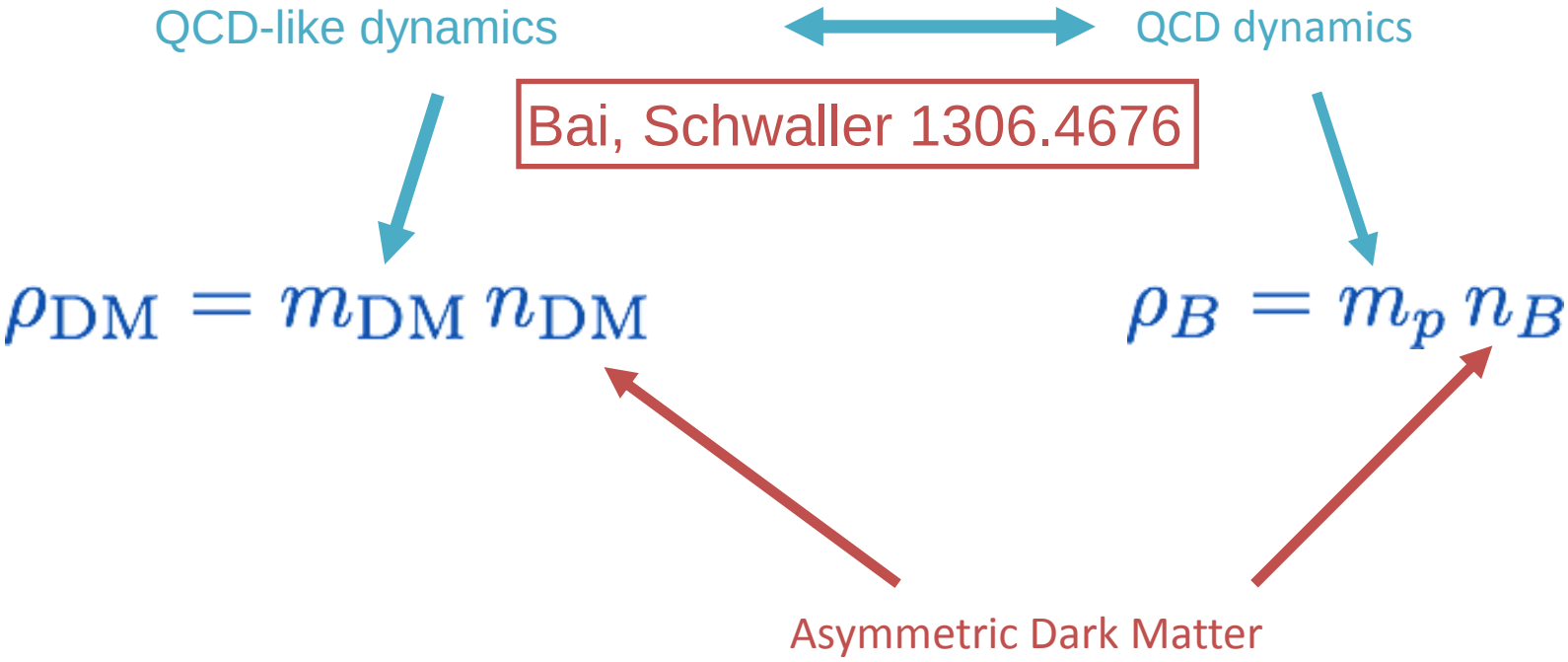


Asymmetric Dark Matter
e.g. Nussinov; Barr; Barr, Chivukula, Farhi; Gudnason, Kouvaris, Sannino; Kitano, Low; Luty, Kaplan, Zurek; Buckley, Randall; Davoudiasl, Morrissey, Sigurdson, Tulin; Shelton, Zurek; Falkowski, Rudermann, Volanski; N. Rius et al; S. Davidson et al; Servant, Tulin; …

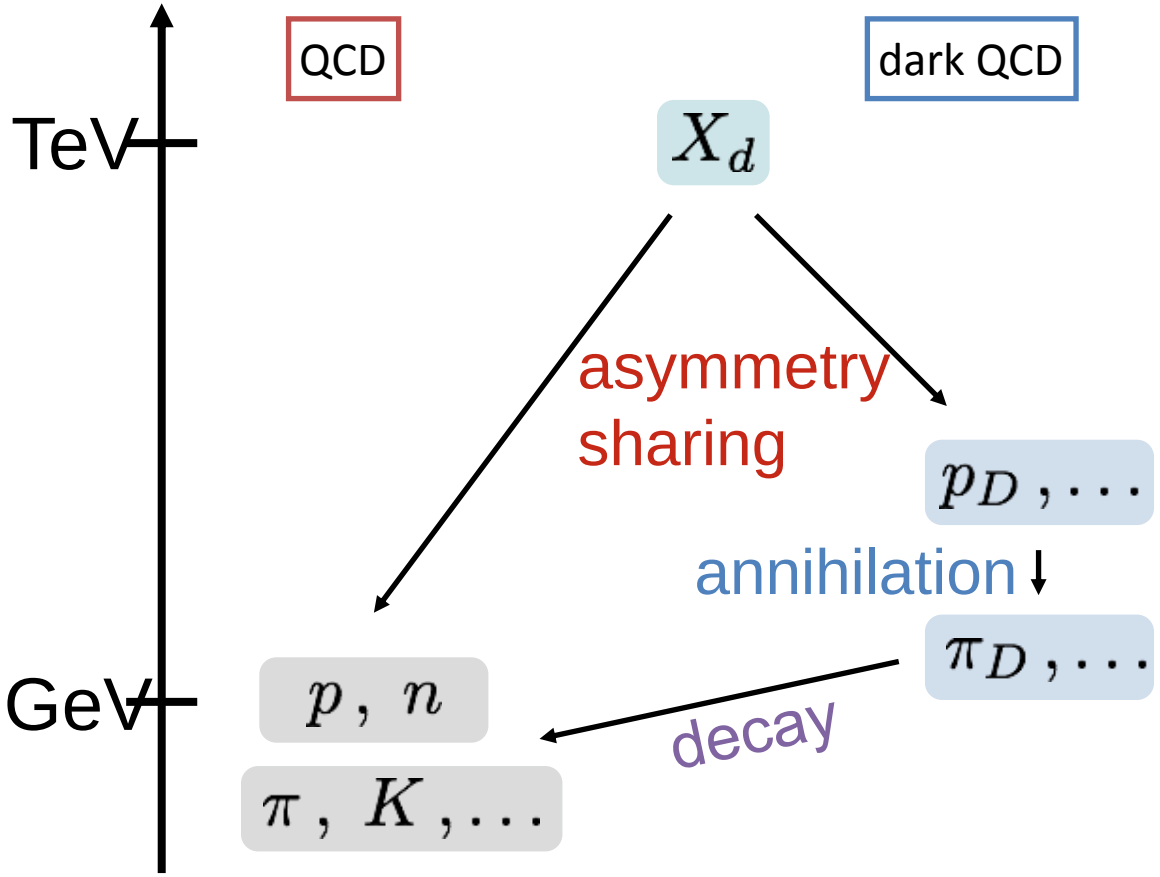
Reviews: Petraki, Volkas, 2013; Zurek 2013;

Dark QCD

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



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

Features

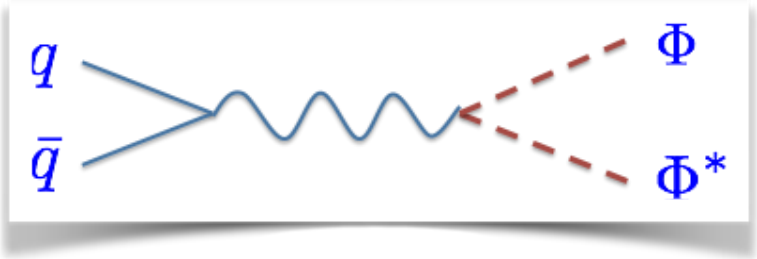
- Relic density fine, without direct detection trouble
- Symmetric component annihilation:
  - $p_D \bar{p}_D \to \pi_D \pi_D$ very efficient
  - $\pi_D \to SM$ transfers entropy back to SM
- DM self interaction mediated by dark pions, might help with structure formation issues

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
- Mediator:
  - Bifundamental scalar Φ $\mathcal{L} \supset \kappa \Phi \bar{Q}_D d_R$

Collider Signature

- Pair production of heavy bi-fundamental fields:



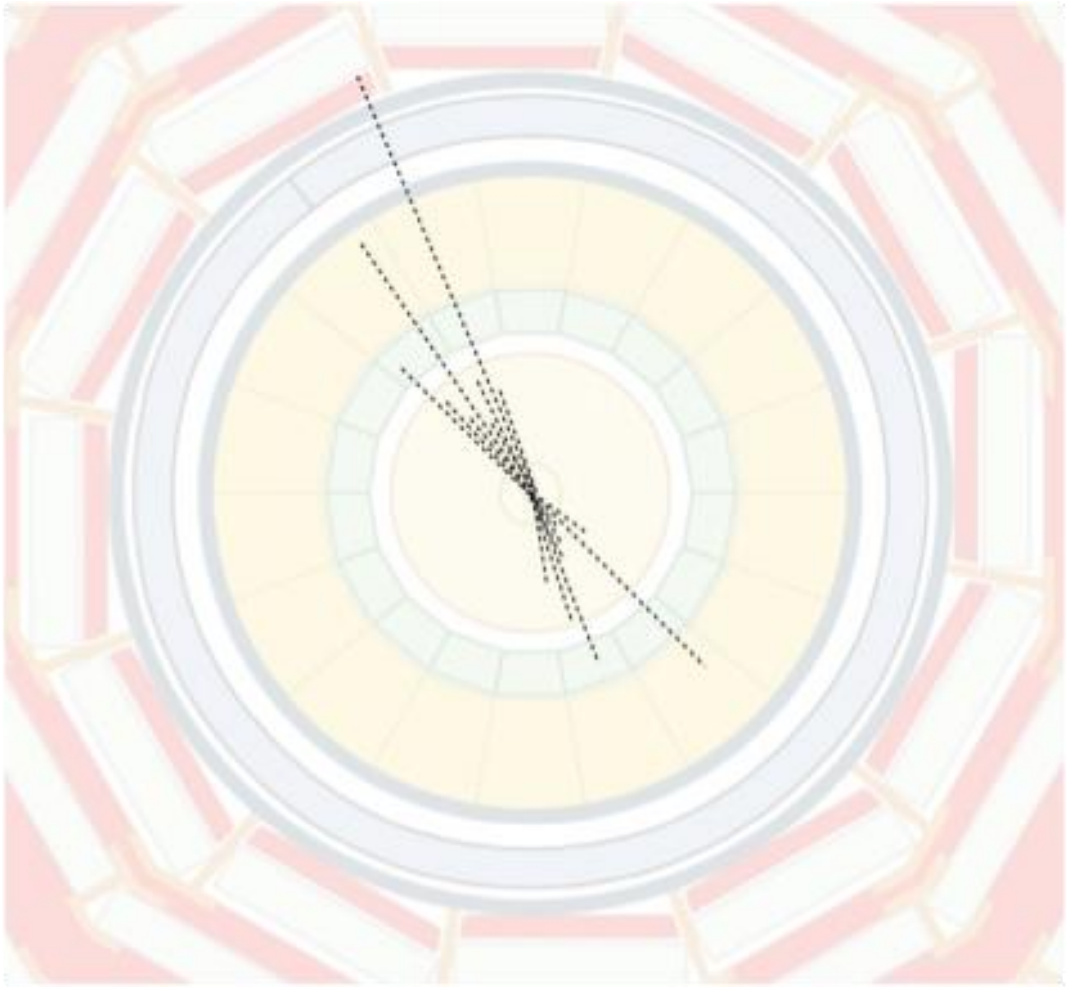
- Decay to quark - dark quark pairs
  - two QCD-jets
  - two "Emerging Jets":
    dark quarks shower and hadronize in dark sector
    decay back to SM jets with displaced vertices

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

Emerging Jets at the LHC

- Dark meson jets from dark parton shower
- Macroscopic lifetime for

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

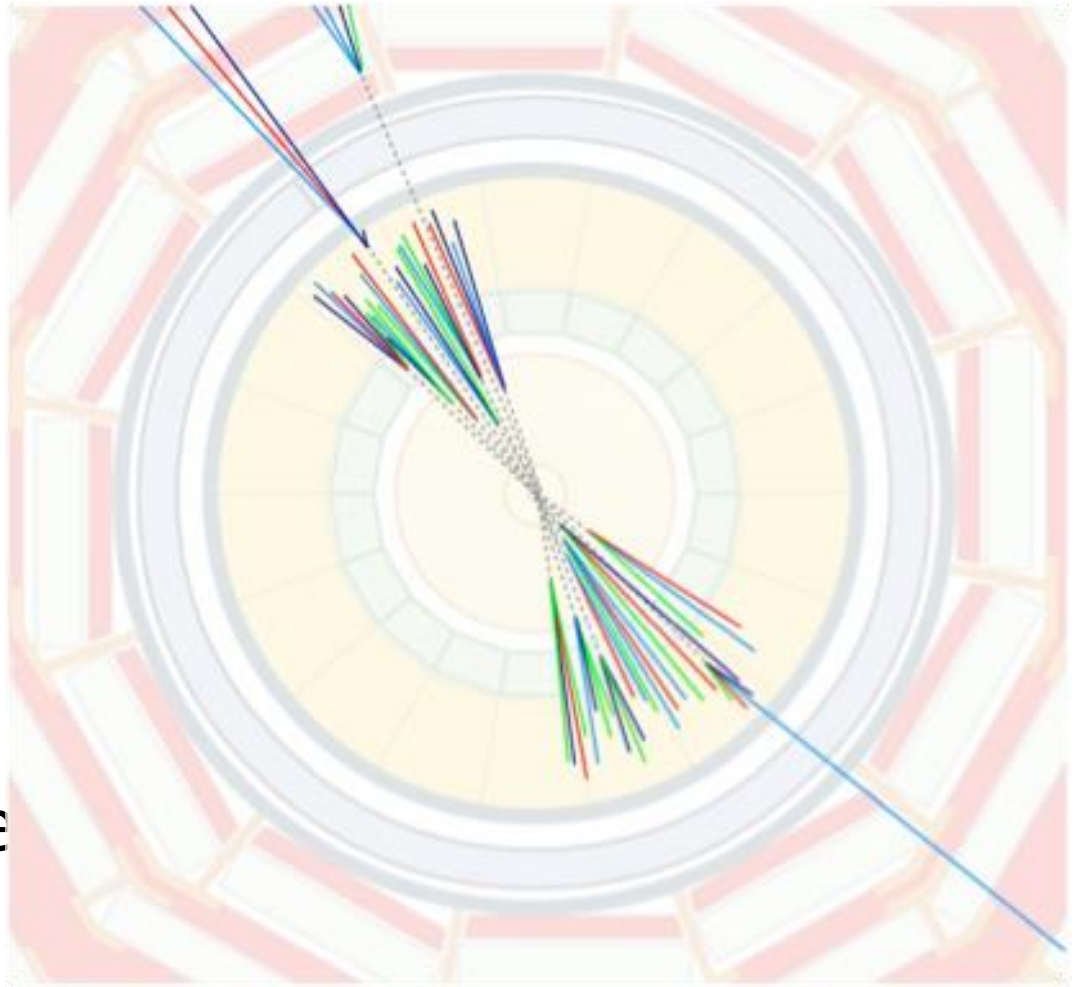


Emerging Jets at the LHC

- Decay back to SM quarks
- Jets emerge at distance

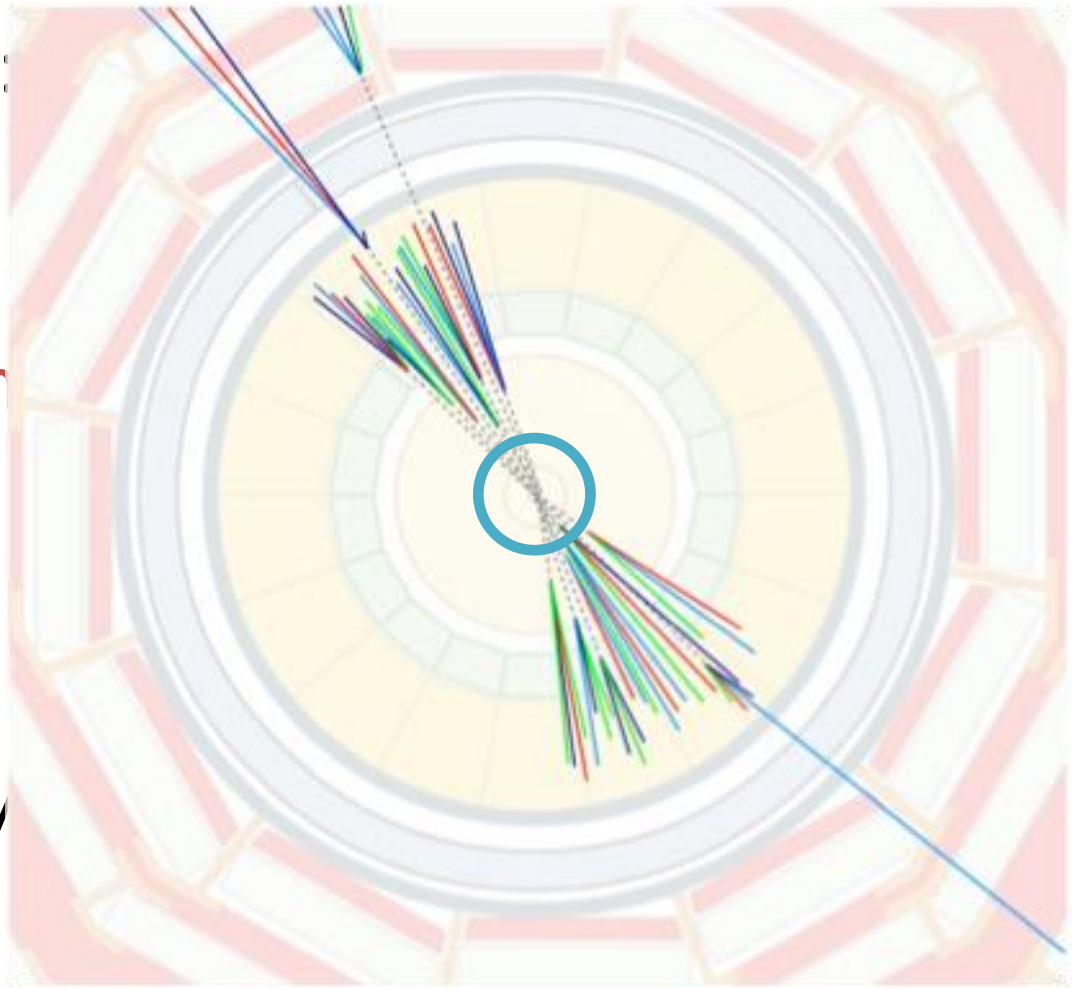
  $c\tau$

- Several displaced vertices inside a jet “cone”



Emerging Jets at the LHC

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

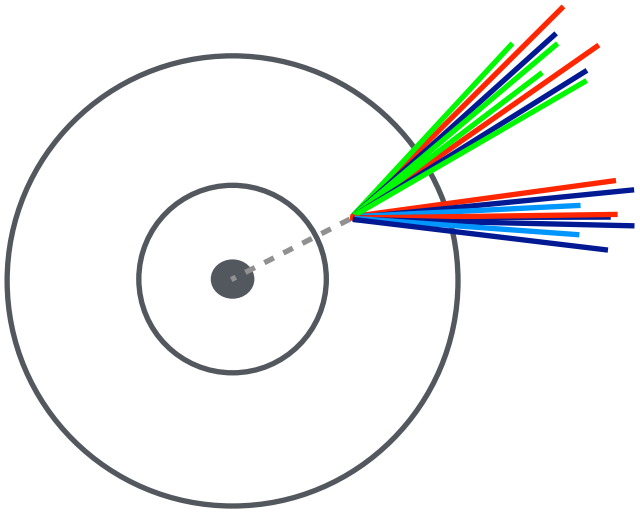


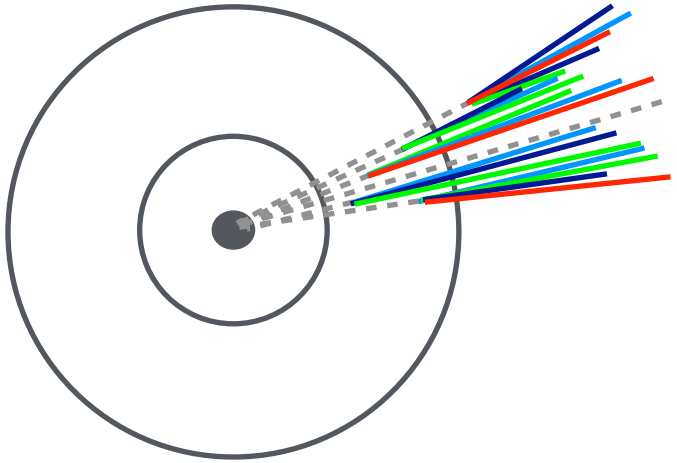
Existing displaced jet searches

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

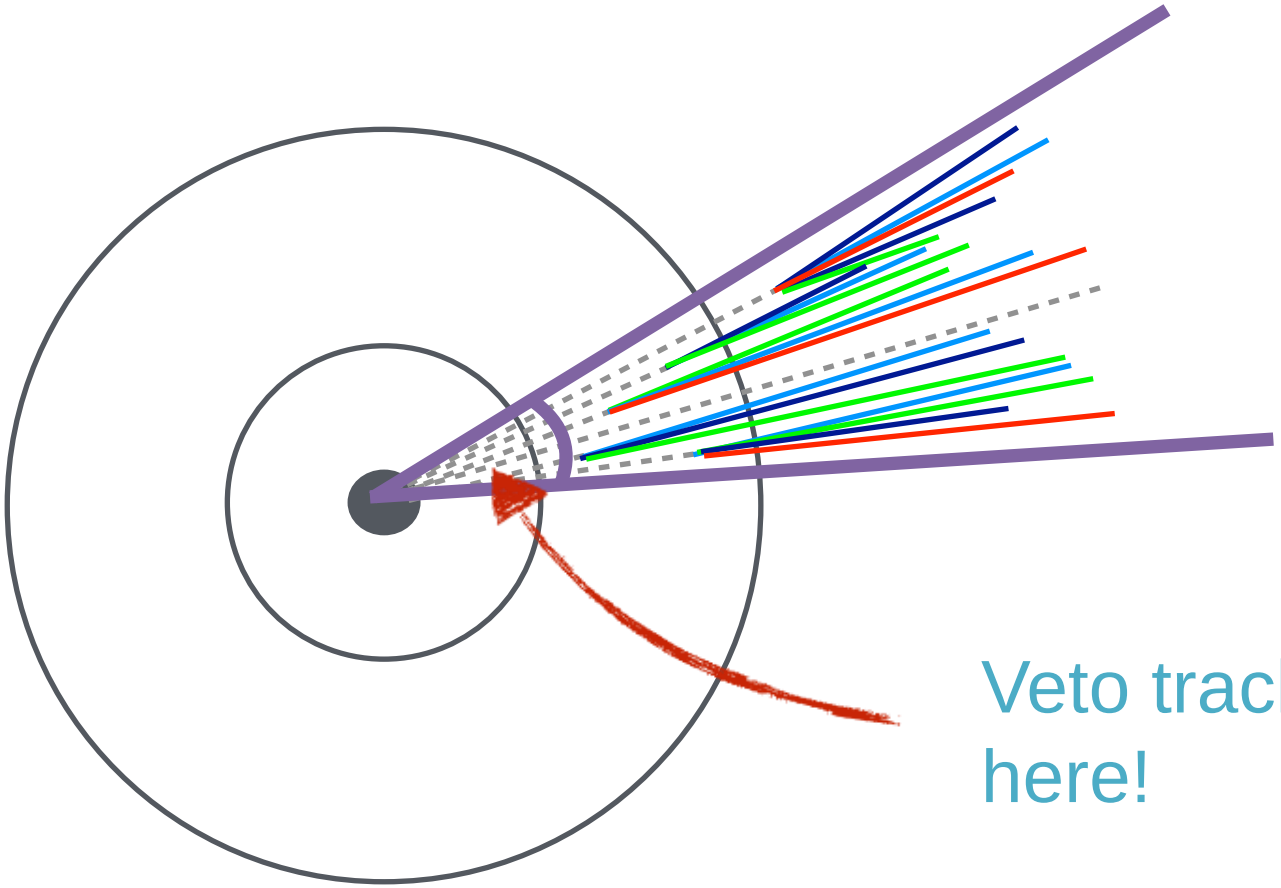
Main differences:

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

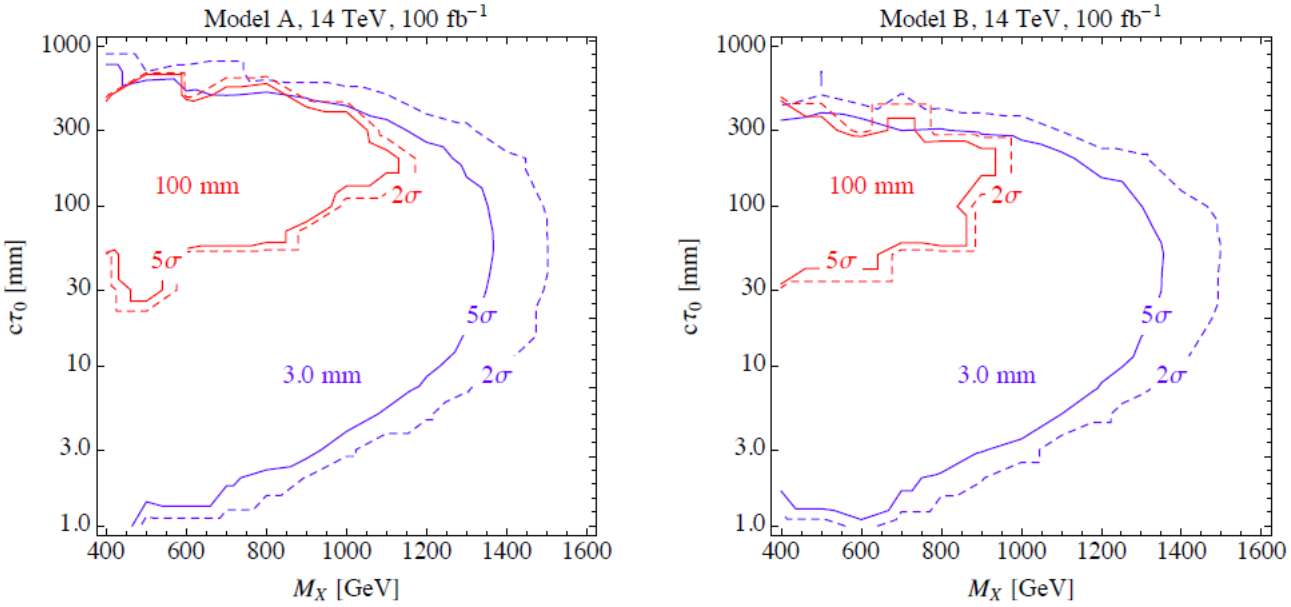




Strategy



Reach ATLAS/CMS

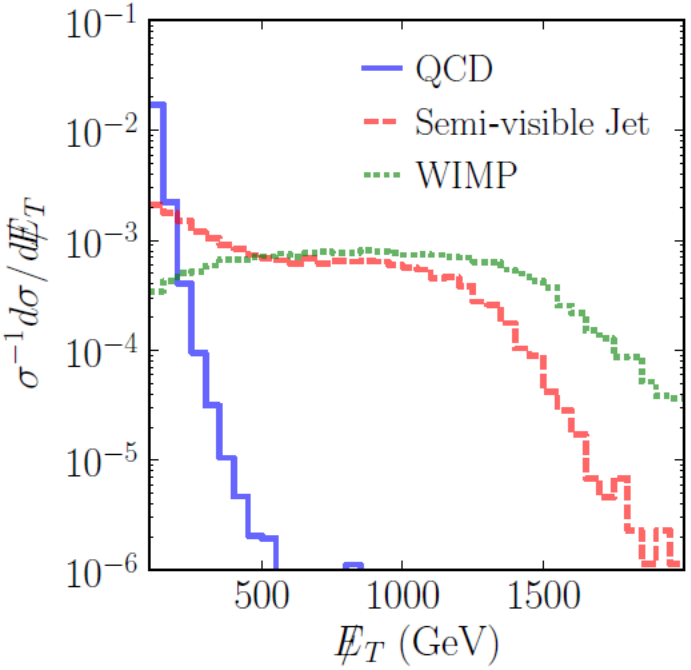


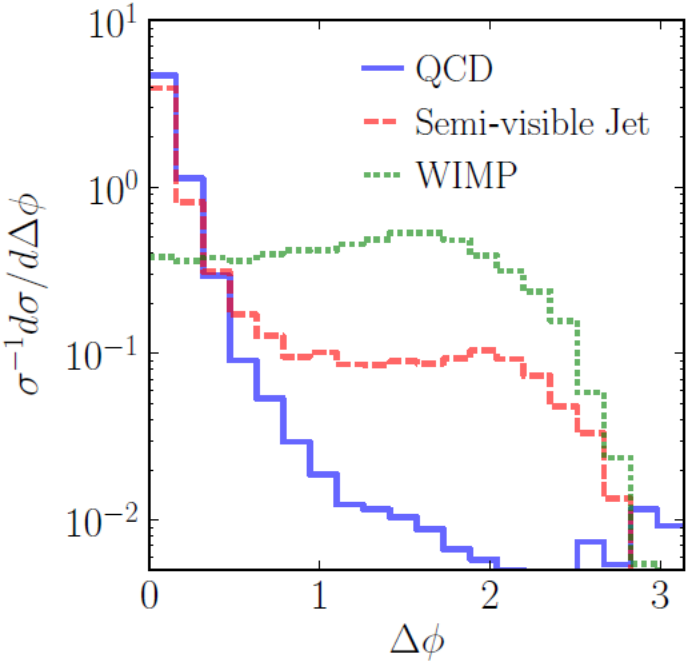
Schwaller, Stolarski, Weiler 1502.05409

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

Prompt Decays

- If the new jets are prompt, then we have missing energy inside jets
- Can still require large missing energy as a more standard DM search
  - Lose the ability to require MET not along jet direction

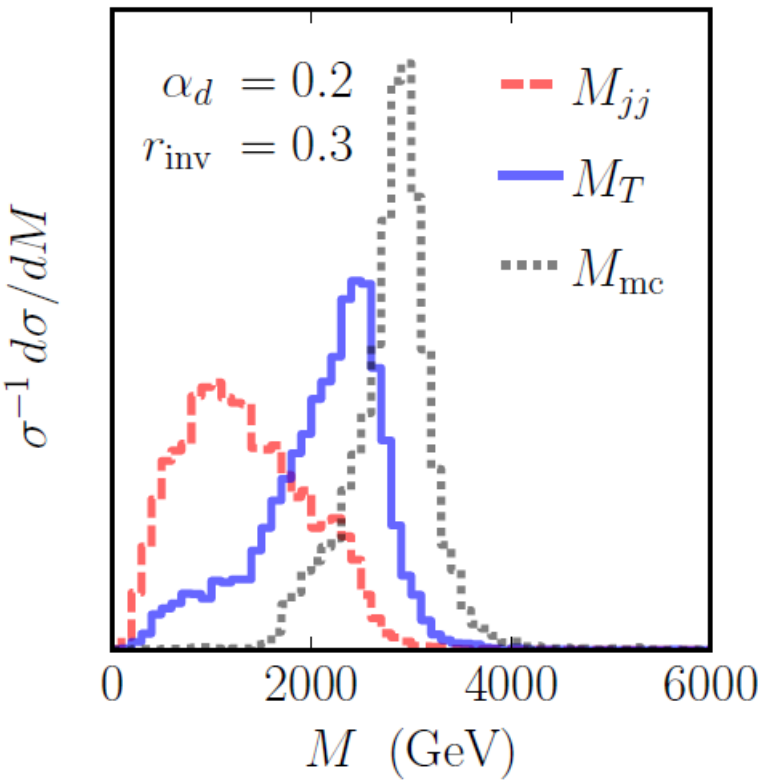




Cohen, Lisanti, Lou 1503.00009

Other Kinematics

- If these new jets are produced through a resonance, transverse mass can give discrimination
- Escapes the loss of signal due to cuts on delta-phi



Cohen, Lisanti, Lou 1503.00009

Conclusions

- WIMPs are well worth looking for…
  - but we haven't seen them
- Other, non-thermal DM is definitely possible
- Can have very different phenomenology
  - Needs to be thought about carefully
- New collider techniques can be required to see these distinct signatures
- Always look everywhere you can!