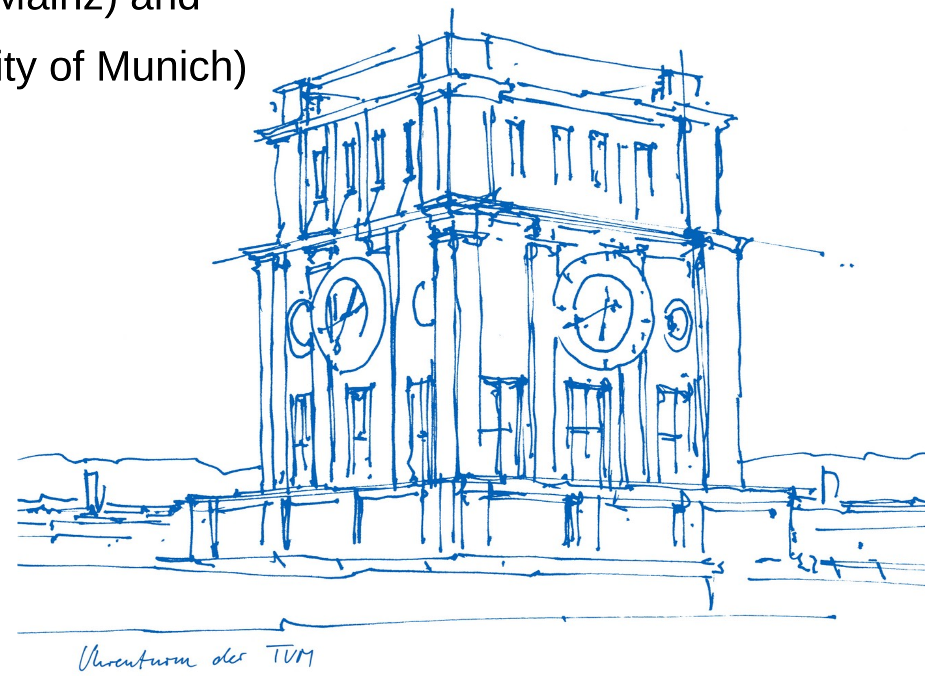
Challenging Dark QCD Dark Matter Models with Heavy Quarks

Based on a work in preparation with

Mathias Becker (JGU Mainz), Julia Harz (JGU Mainz) and

Martin Napetschnig (TUM - Technical University of Munich)



TeV Particle Astrophysics 2023 (TeVPA 2023)

Session: **Particle Physics**

Archivio di Stato di Napoli

Thursday, September 14th, 2023

Why a Non-Abelian dark sector?

Dark matter as a **composite bound state** from a confining dark force has attracted interest in recent literature.

Stable, neutral and **self-interacting** dark matter candidates emerge naturally.

Prediction of unique and interesting **signals at colliders**.

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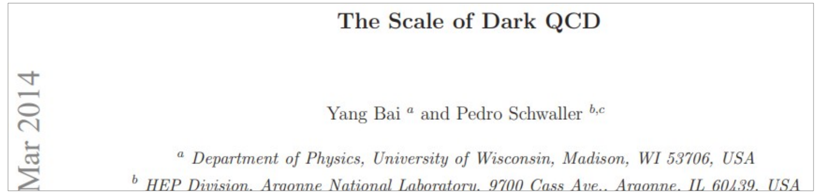
The Scale of Dark QCD

Mar 2014

Yang Bai [a] and Pedro Schwaller [b,c]

[a] Department of Physics, University of Wisconsin, Madison, WI 53706, USA

[b] HEP Division, Argonne National Laboratory, 9700 Cass Ave., Argonne, IL 60439, USA

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Emerging Jets

Pedro Schwaller[*a], Daniel Stolarski[†a], and Andreas Weiler[‡a,b]

[a]CERN TH-PH Division, Meyrin, Switzerland
[b]DESY, Notkestrasse 85, D-22607 Hamburg, Germany

May 2015

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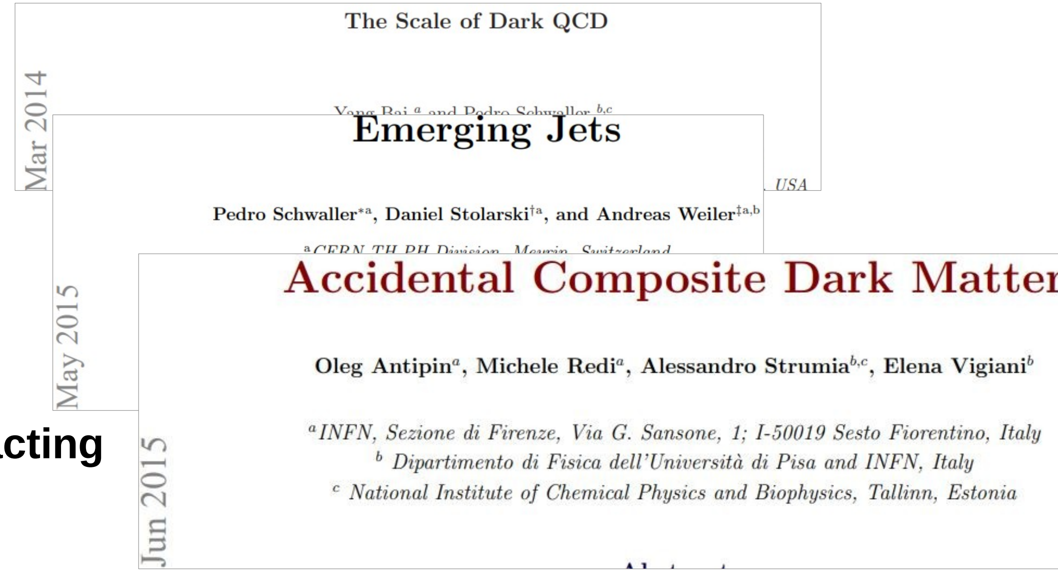
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Accidental Composite Dark Matter

Oleg Antipin[a], Michele Redi[a], Alessandro Strumia[b,c], Elena Vigiani[b]

[a] *INFN, Sezione di Firenze, Via G. Sansone, 1; I-50019 Sesto Fiorentino, Italy*

[b] *Dipartimento di Fisica dell'Università di Pisa and INFN, Italy*

[c] *National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

Jun 2015

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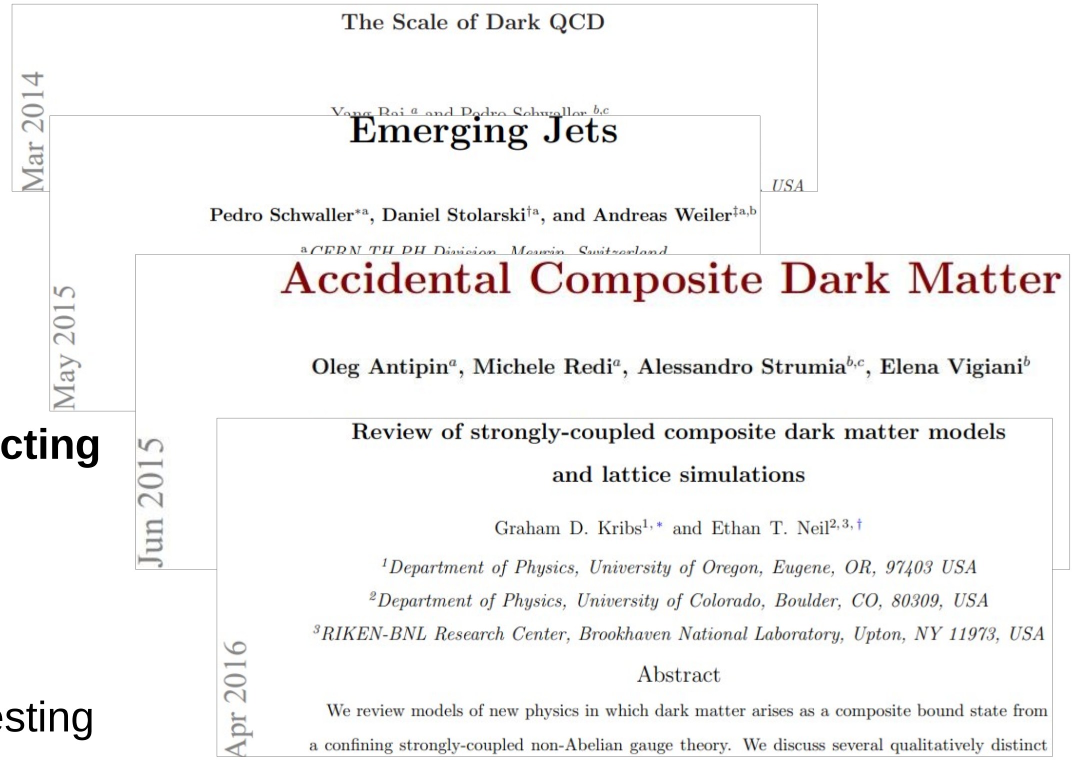
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Jun 2015

Review of strongly-coupled composite dark matter models and lattice simulations

Graham D. Kribs[1,*] and Ethan T. Neil[2,3,†]

[1]Department of Physics, University of Oregon, Eugene, OR, 97403 USA

[2]Department of Physics, University of Colorado, Boulder, CO, 80309, USA

[3]RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

We review models of new physics in which dark matter arises as a composite bound state from a confining strongly-coupled non-Abelian gauge theory. We discuss several qualitatively distinct

Apr 2016

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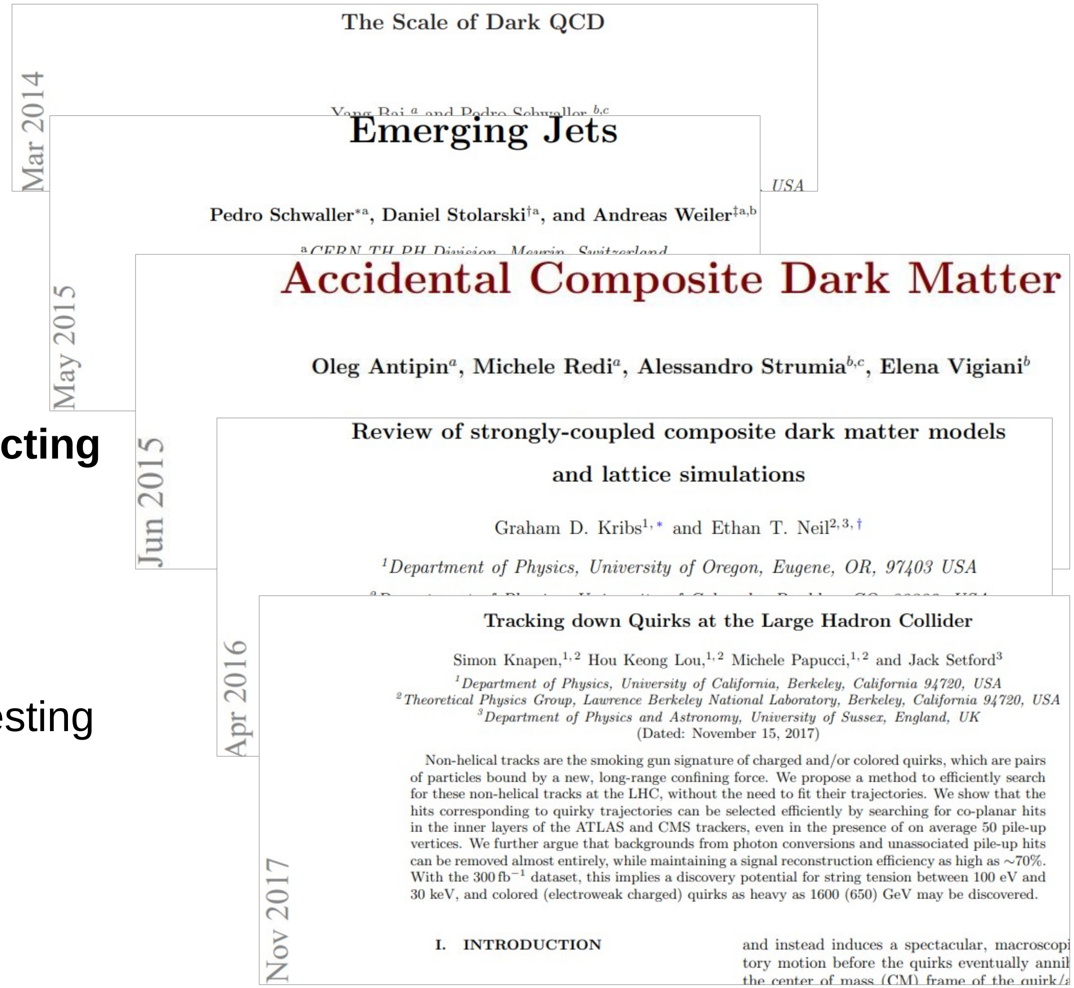

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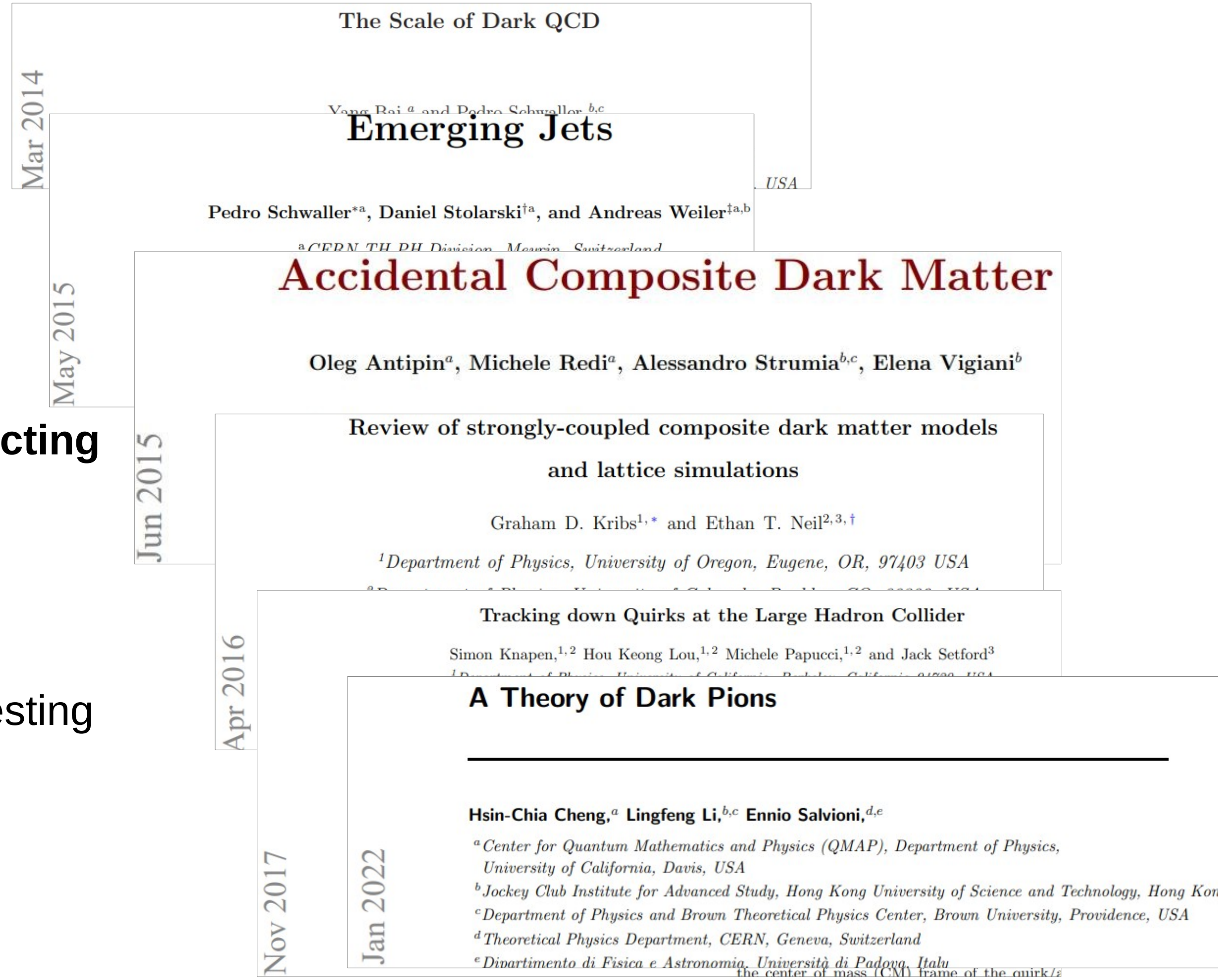
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Simon Knapen,[1,2] Hou Keong Lou,[1,2] Michele Papucci,[1,2] and Jack Setford[3]

Jan 2022

A Theory of Dark Pions

Hsin-Chia Cheng,[a] Lingfeng Li,[b,c] Ennio Salvioni,[d,e]

[a]Center for Quantum Mathematics and Physics (QMAP), Department of Physics, University of California, Davis, USA
[b]Jockey Club Institute for Advanced Study, Hong Kong University of Science and Technology, Hong Kong
[c]Department of Physics and Brown Theoretical Physics Center, Brown University, Providence, USA
[d]Theoretical Physics Department, CERN, Geneva, Switzerland

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SFB 1258 Neutrinos Dark Matter Messengers

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Jun 2022 — Jet Substructure from Dark Sector Showers

Timothy Cohen,[a] Joel Doss,[a] and Marat Freytsis[b]

[a]*Institute for Fundamental Science, Department of Physics, University of Oregon, Eugene, OR 97403*

[b]*NHETC, Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08854*

E-mail: tcohen@uoregon.edu, jdoss@uoregon.edu, marat.freytsis@rutgers.edu

What can we learn about Dark QCD (dQCD) at colliders?

Quirks

$\Lambda < m_Q \lesssim \sqrt{s}$

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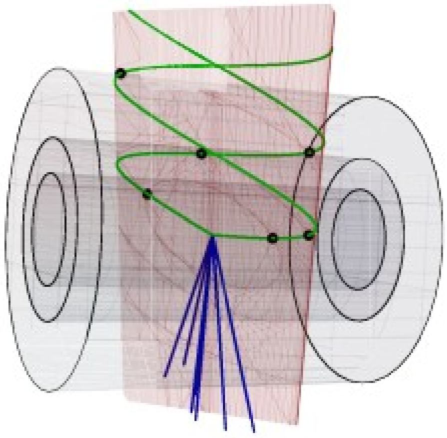

Emerging/semivisible jets, dark showers, Long Lived Particles (LLPs)

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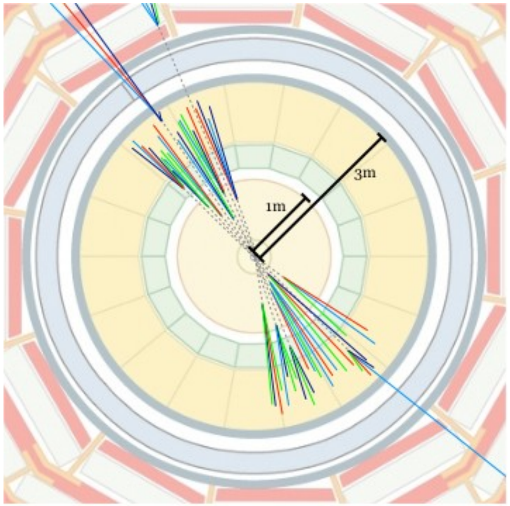

Soft Unclustered Energy Patterns (SUEPs, or *soft bombs*)

Triggering soft bombs at the LHC, S. Knapen et al. (2017)

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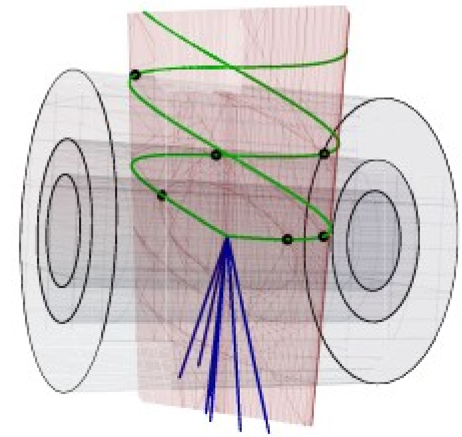

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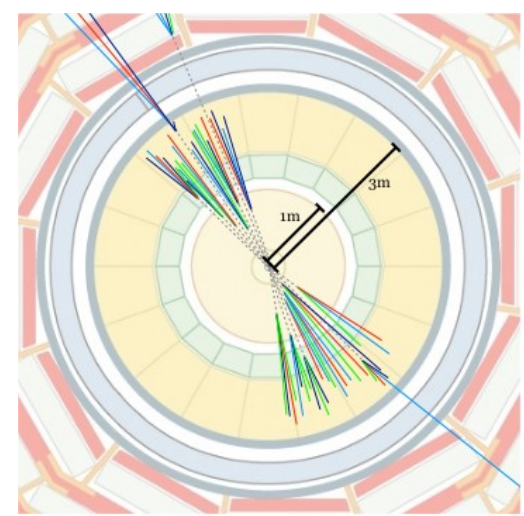

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→ **rich phenomenology!**

General Setup

Lagrangian of a dark SU(N_d) gauge theory with **heavy quarks ($m_Q > \Lambda_{dQCD}$)**, which **can be charged** under the SM or as well be **SM singlets**.

$$\mathcal{L}_{\mathrm{dQCD}} = -\frac{1}{2}\mathrm{tr}\left(G_{d,\,\mu\nu}G_d^{\mu\nu}\right) + \sum_{i=1}^{N_f} \overline{Q_d}\left(i\left(\partial\!\!\!/ - ig_d G\!\!\!/_d\right) - m_{Q_d,i}\right)Q_d$$

Gauge groups SO(N) and Sp(2N) have also been considered in the literature

Accidental Composite Dark Matter, O. Antipin et al. (2015)

Low-enegy effective description of dark Sp(4) theories, S. Kulkarni et al. (2022)

Confinement scale Λ_{dQCD} is identified with the **one-loop Landau pole**

$$\alpha_d(m_Q) = \frac{2\pi}{\beta_0 \ln\left(\frac{m_Q}{\Lambda_{\mathrm{dQCD}}}\right)}, \quad \beta_0 = \frac{11N_d - 2N_F}{3}$$

If no other portal to the SM is included, confinement scale and quark mass(es) **fix all the free parameters** of the theory.

Dark baryon number and dark species number are *accidental global symmetries* that ensure **stability** of dark hadrons.

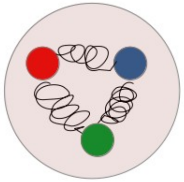
Particle spectrum

Particle spectrum

Baryons made of N_d dark quarks → **DM candidate**.

Stable up to dimension $3/2*(N_d + 1)$ operators for $SU(N_d$ odd) (fermionic DM).

and stable up to dimension $(3/2*N_d + 2)$ operators for $SU(N_d$ even) (bosonic DM).



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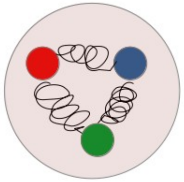

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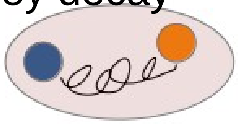
Mesons made of quark-antiquark: Stable against a decay into the SM up to dimension 5. Without accidental symmetries (G-parity, flavour conservation) protecting them, they decay quickly into glueballs.



Model for Thermal Relic Dark Matter of Strongly Interacting Massive Particles, Y. Hochberg et al. (2015)
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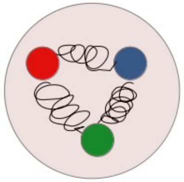

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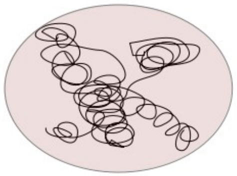
Glueballs (GBs) as the **lightest hadrons** in the heavy quark case. Stable up to dimension 6.

Pure glue *thermal* dark matter is **excluded by overclosure**.



Hidden SU(N) glueball dark matter, A. Soni and Y. Zhang (2016)
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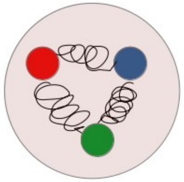

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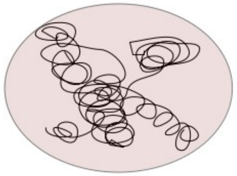

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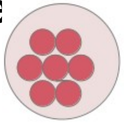
Dark nuclei: If a light mediator is added to the model, **dark nucle**  **nesis** is feasible.
Big Bang Darkleosynthesis, G. Krnjaic and K. Sigurdson (2014)
Dark Nuclei I & II, W. Detmold et al. (2014)
Big Bang Synthesis of Nuclear Dark Matter, E. Hardy et al. (2014)

Links to the Standard Model

The basic Lagrangian is $\mathcal{L}_{\text{dQCD}} = -\frac{1}{2}\text{tr}\left(G_{d,\mu\nu}G_d^{\mu\nu}\right) + \sum_{i=1}^{N_f} \overline{Q_d}\left(i\left(\partial\!\!\!/ - ig_d G\!\!\!/_d\right) - m_{Q_d,i}\right)Q_d$

We study two different portals to the SM:

1) Gauge portal: N_F = 1 dark quark flavour **V** as a weak isospin triplet similar to ***wino DM (two free parameters only)***:

$$\mathcal{L}_{\text{int}} = ig_W\gamma^\mu\,\overline{\mathbf{Q}}_{\mathbf{d}}\cdot\left(\mathbf{W}_\mu\times\mathbf{Q}_{\mathbf{d}}\right)$$

2) Higgs portal: N_F = 2 dark flavours: one isospin doublet quark **L** (similar to ***Higgsino DM***) + one (lighter) SM singlet quark **N (four free parameters: {mN, Λ_{dQCD}, y_d, m_L})**.

$$\mathcal{L}_{\text{int}} = g_W\,\overline{L}\,W\!\!\!/\,L + \left(y_d\,\overline{L}\,H\,N + \text{h.c.}\right)$$

Further options considered in the literature:

Z' mediator with/without kinetic mixing

Aidnogenesis via Leptogenesis and Dark Sphalerons, M. Blennow et al. (2010)

Glueballs in a Thermal Squeezeout Model, P. Asadi et al. (2022)

Dark scalar as a bifundamental mediator

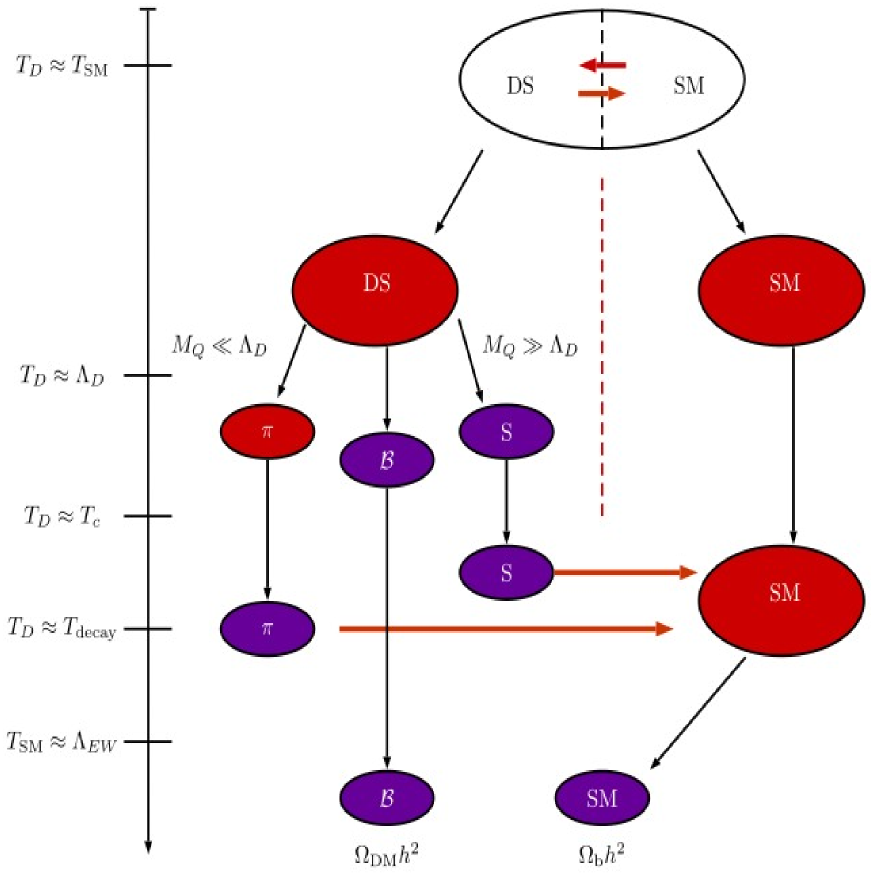
Emerging Jets, P. Schwaller, D. Stolarski and A. Weiler (2015)

Thermal History of dark QCD

Confining phase transition happens before or after dark matter (chemical) freeze-out → **Both processes reduce the dark matter abundance**.

After confinement, the lightest dark sector particles are non-relativistic GBs and the thermal contact with the SM bath is lost → **the dark sector has it‘s own temperature evolution and is hotter than the SM leading to an early matter dominated period**!

At late times, the decay of GBs leads to a washout of the DM density → **Third process that depletes the DM density**.



*Thermal history of composite dark matte*r, N. A. Dondi et al. (2020)

Squeezeout of Dark Matter

It has been found that in the case of a **first order** confining phase transition with **heavy quarks**, the phase transition drastically depletes the dark matter abundance via the squeezeout effect.

Accidentally Asymmetric Dark Matter, P. Asadi et al. (2021)
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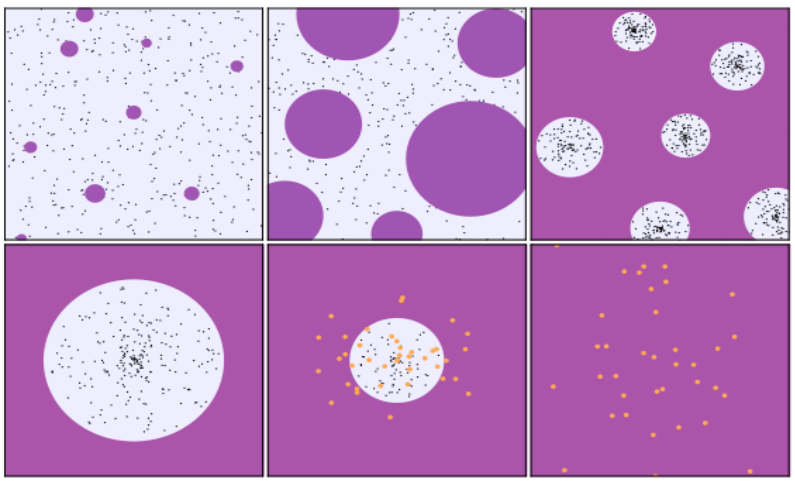

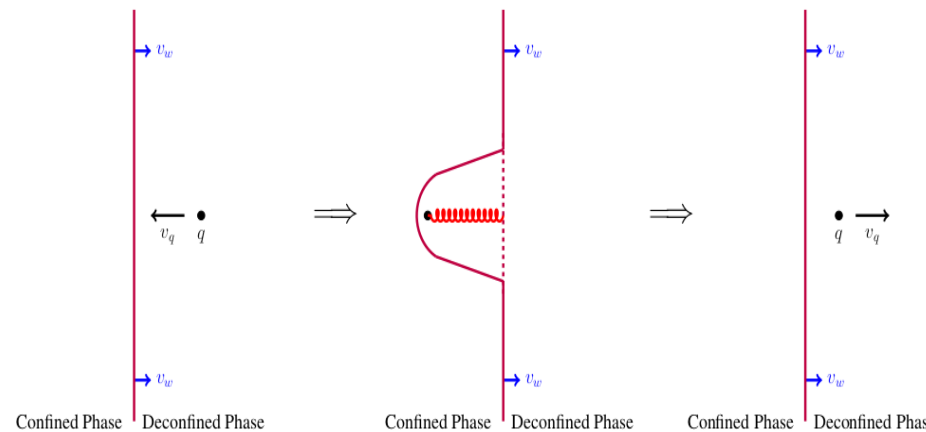

Heavy fundamental quarks can not enter the confined-phase bubble since colour string breaking is exponentially suppressed. Only a statistical excess fraction of $\sqrt{N_q^{\text{initial}}}$ quarks in the deconfined pockets survives the phase transition → **dramatic decrease of the dark matter abundance!**

Phase transitions:
Lattice QCD as a tool

Dark matter relic abundance depends
crucially on whether
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In SU(3)$_d$ we can use the *Columbia plot* and lattice data
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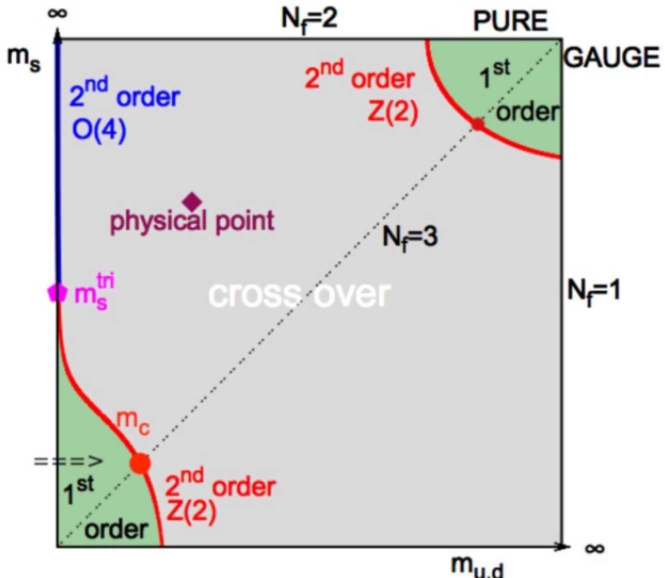

On the existence of a phase transition for QCD with three light quarks, F. R. Brown et al. (1990)

Phase transitions: Lattice QCD as a tool

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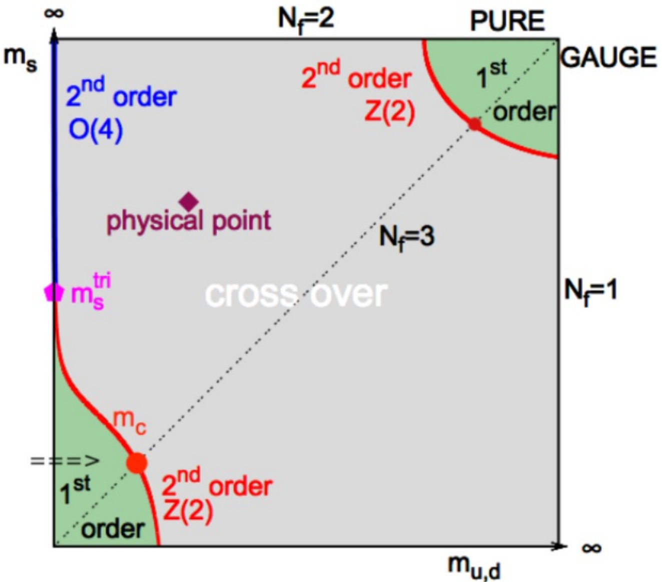
In $SU(3)_d$ we can use the *Columbia plot* and lattice data to find the **transition** from the (weak) **1st order phase transition to a crossover.**

Recent results indicate that the **critical ratio** is given by

$$\left(\frac{m_Q}{\Lambda_{\text{dQCD}}}\right)_{\text{crit}} \lesssim 10$$



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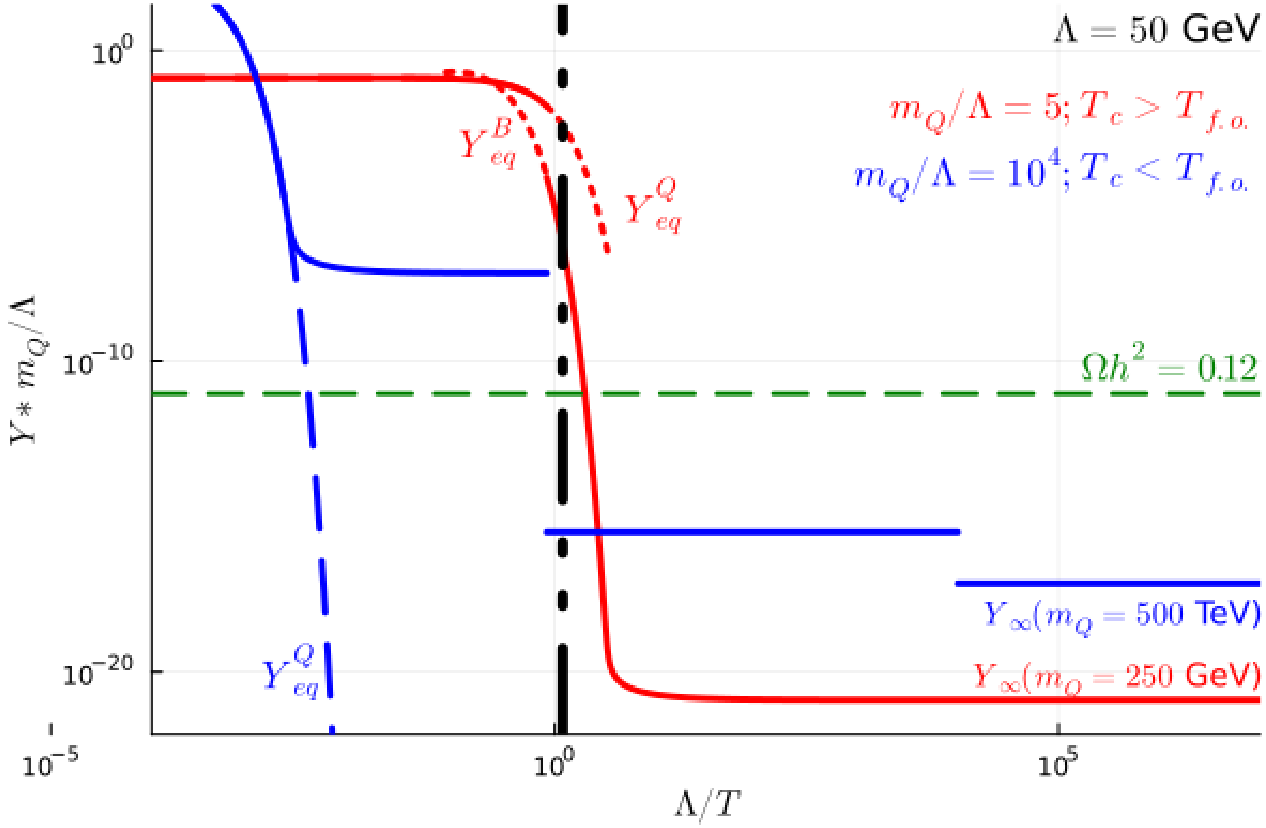
The QCD Deconfinement Critical Point for N_f = 2 Flavours of Staggered Fermions, R. Kaiser et al. (2022)

Phase structure of QCD for heavy quarks, C. S. Fischer et al. (2015)

Phase structure of finite temperature QCD in the heavy quark region, H. Saito et al. (2011)

Thermal History for Heavy Quarks



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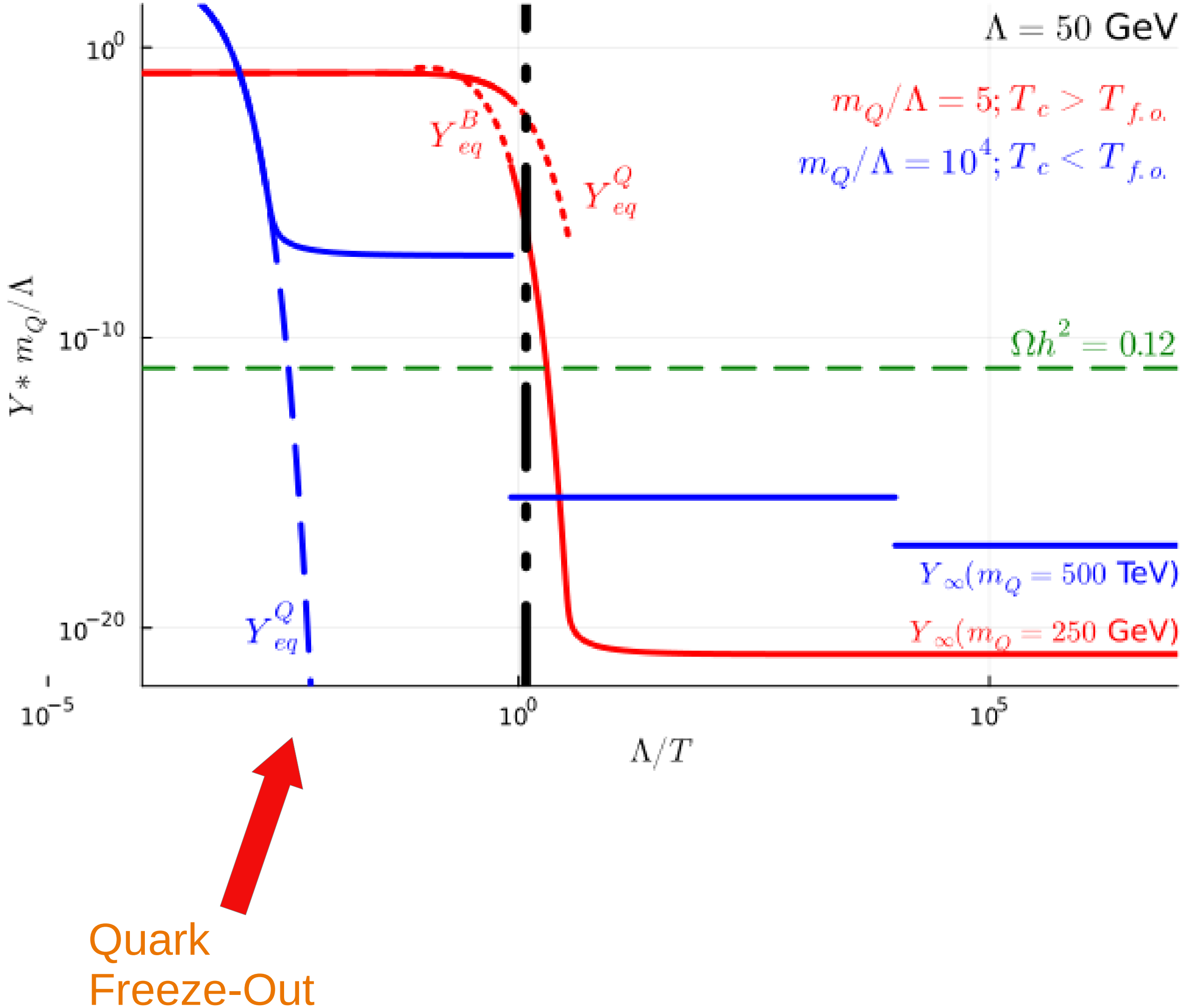

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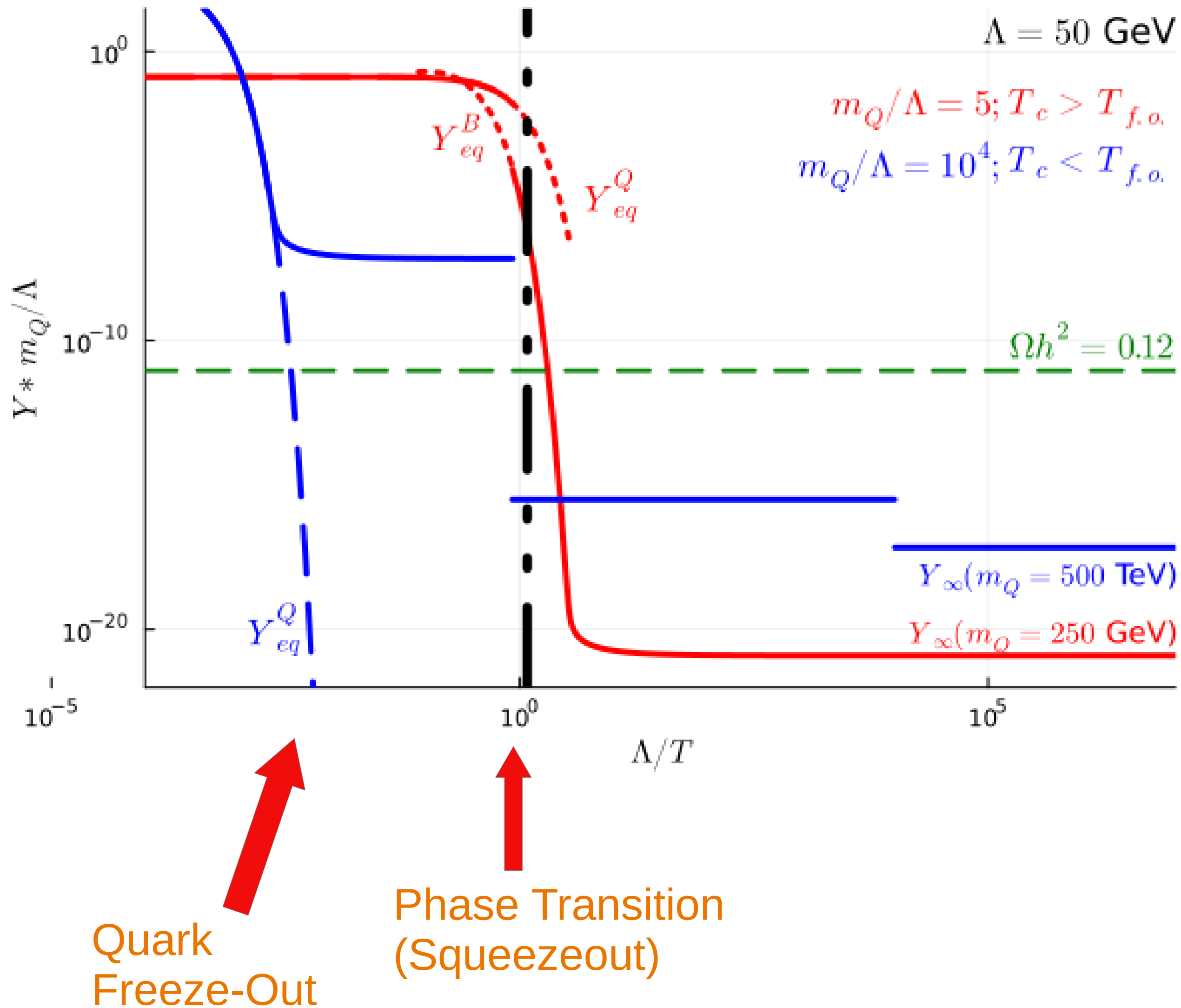

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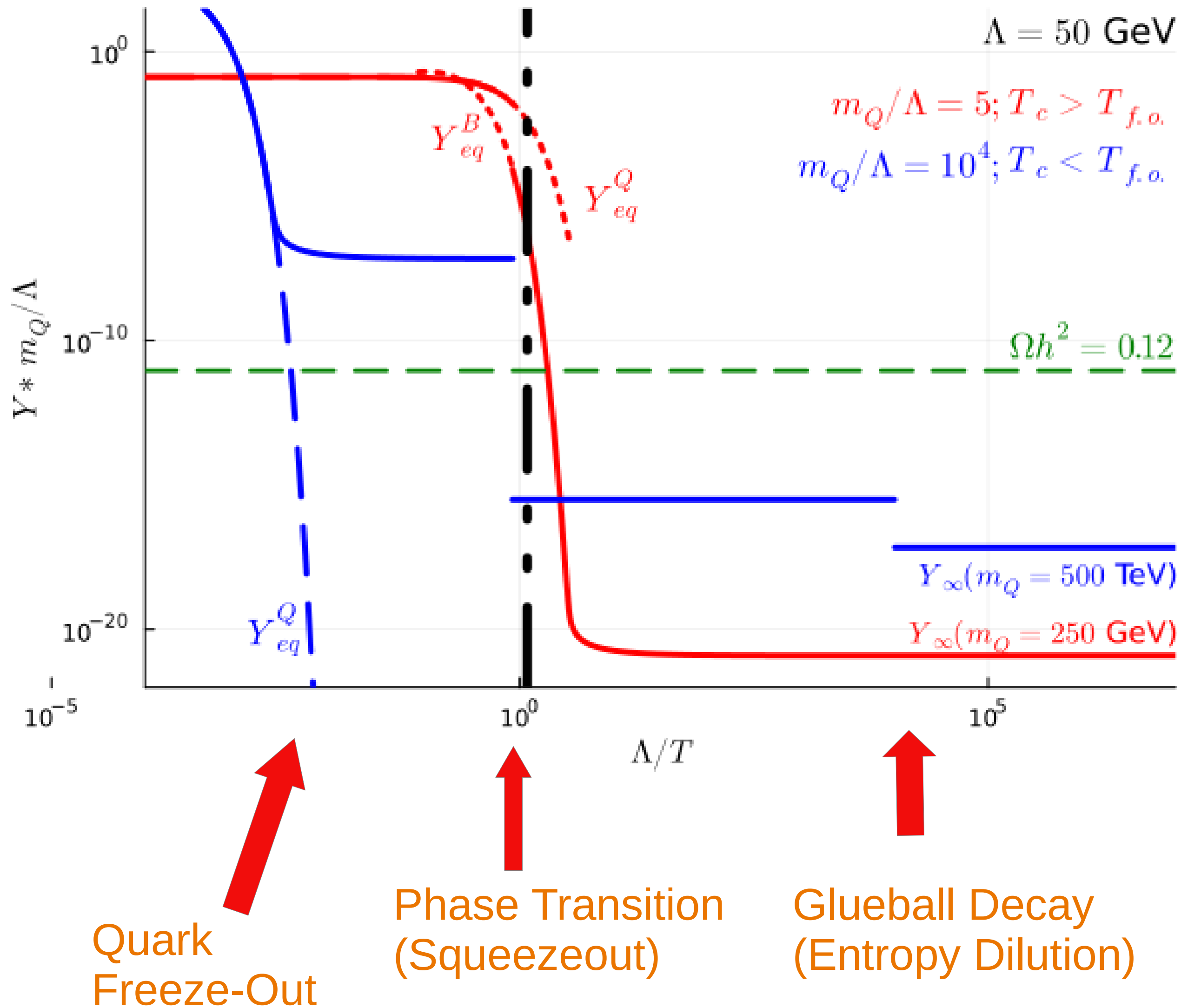
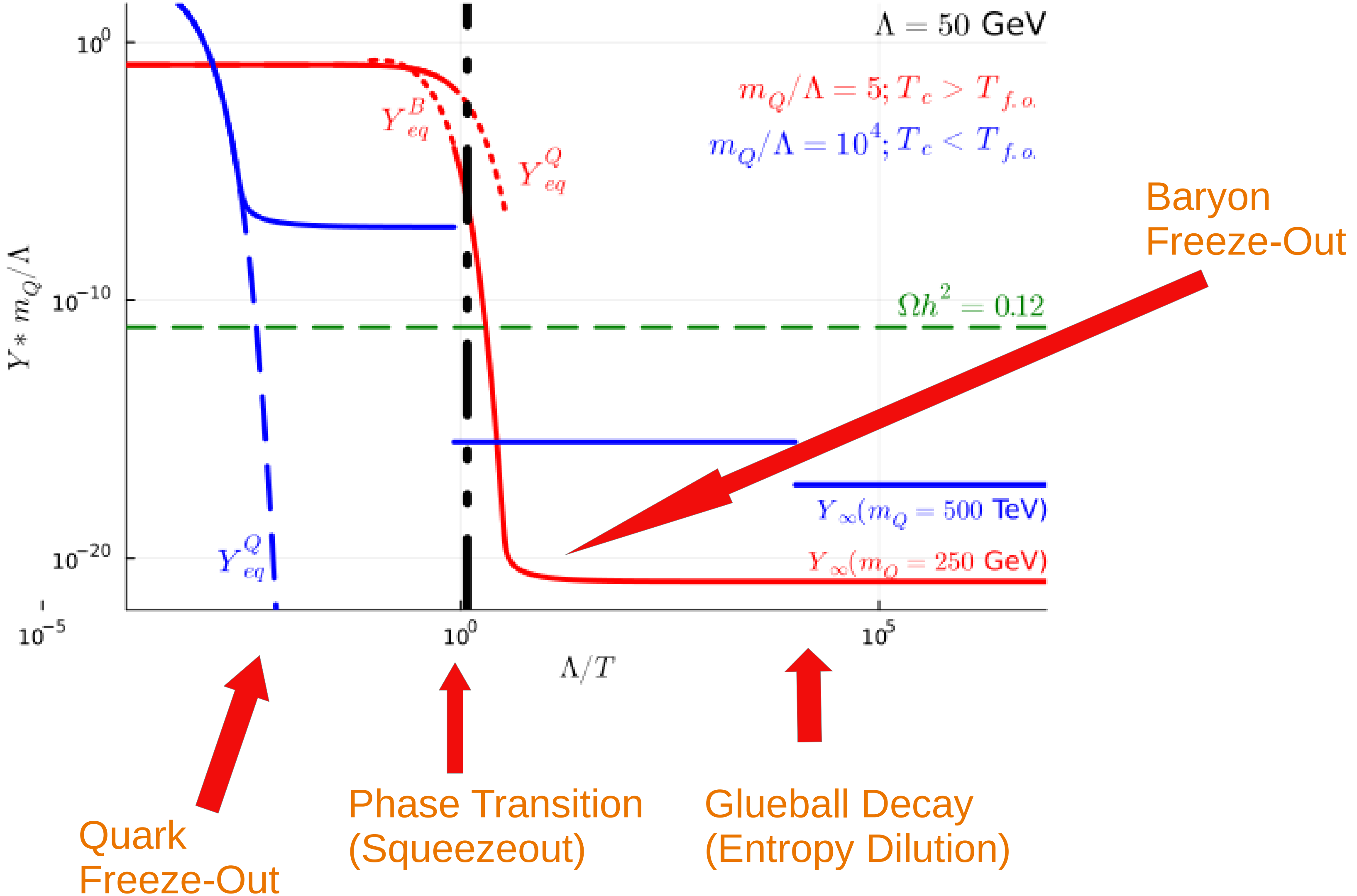


Thermal History for Heavy Quarks



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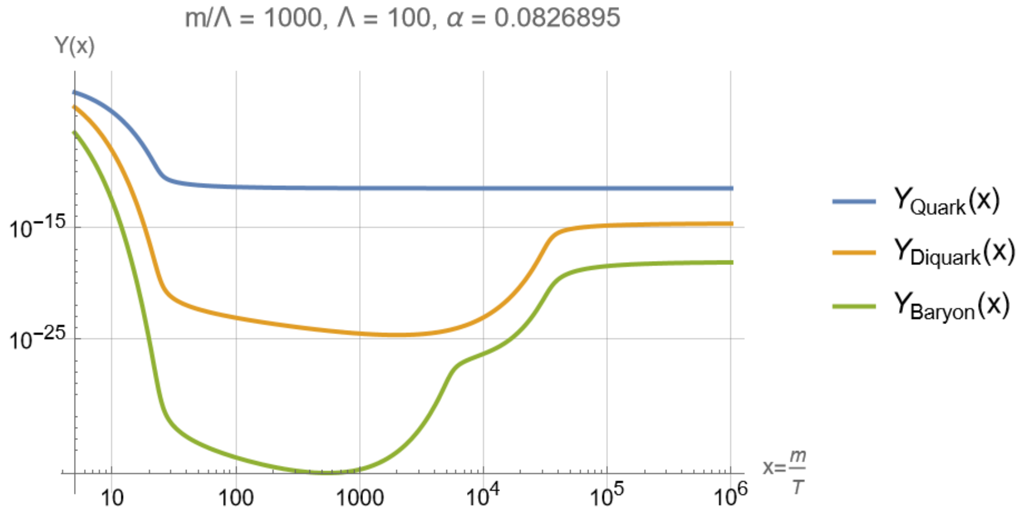

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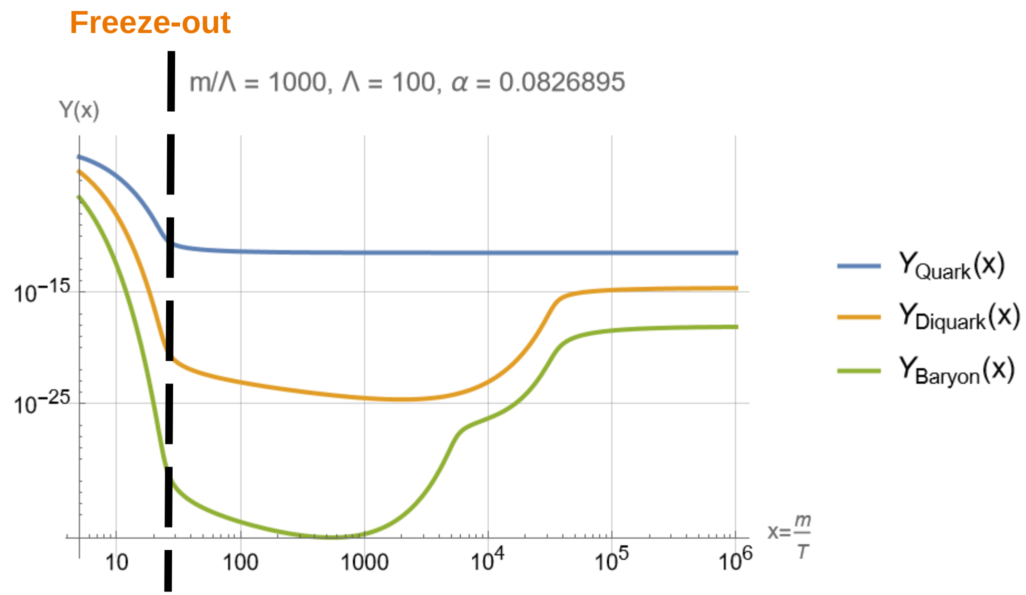

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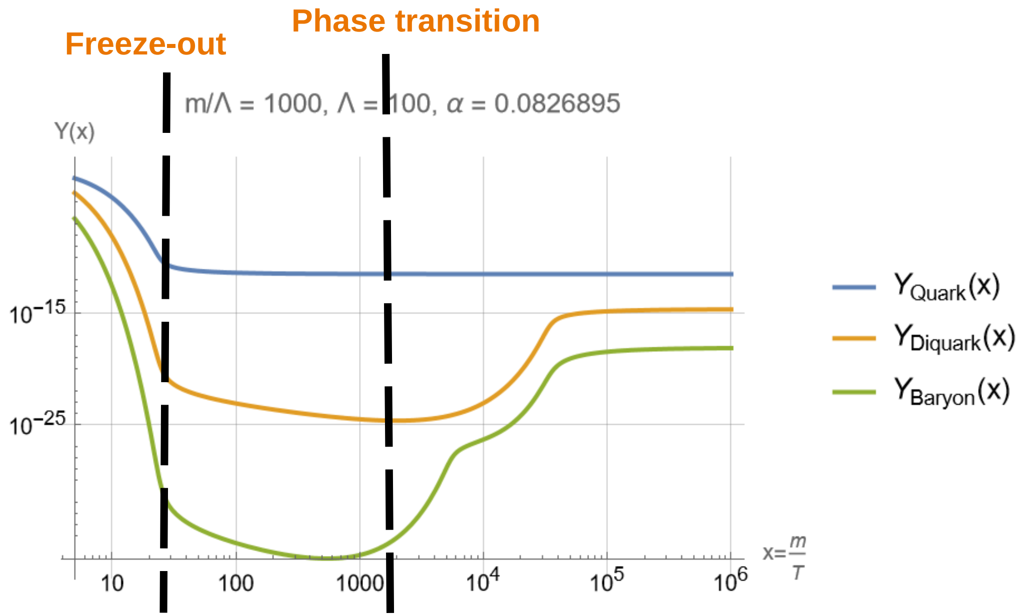

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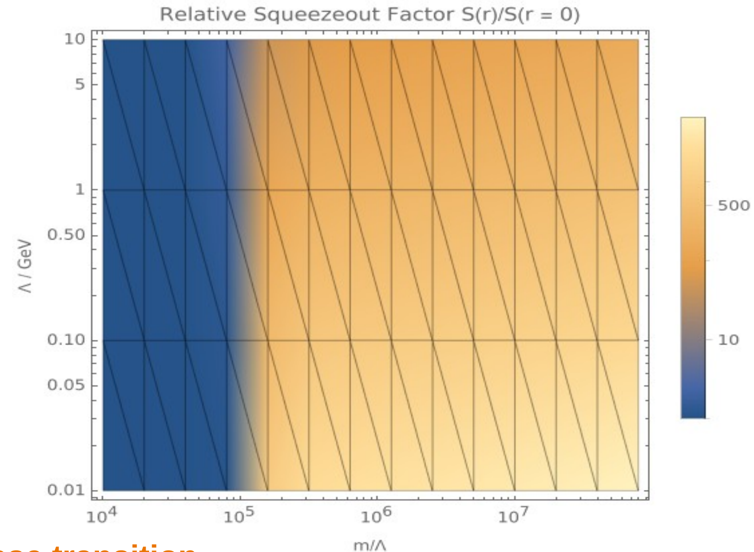

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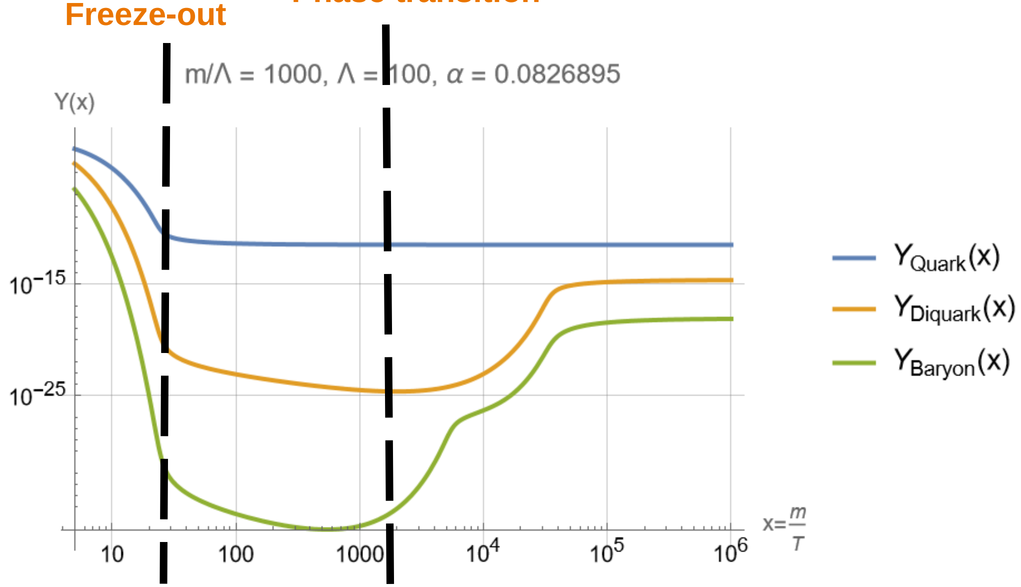

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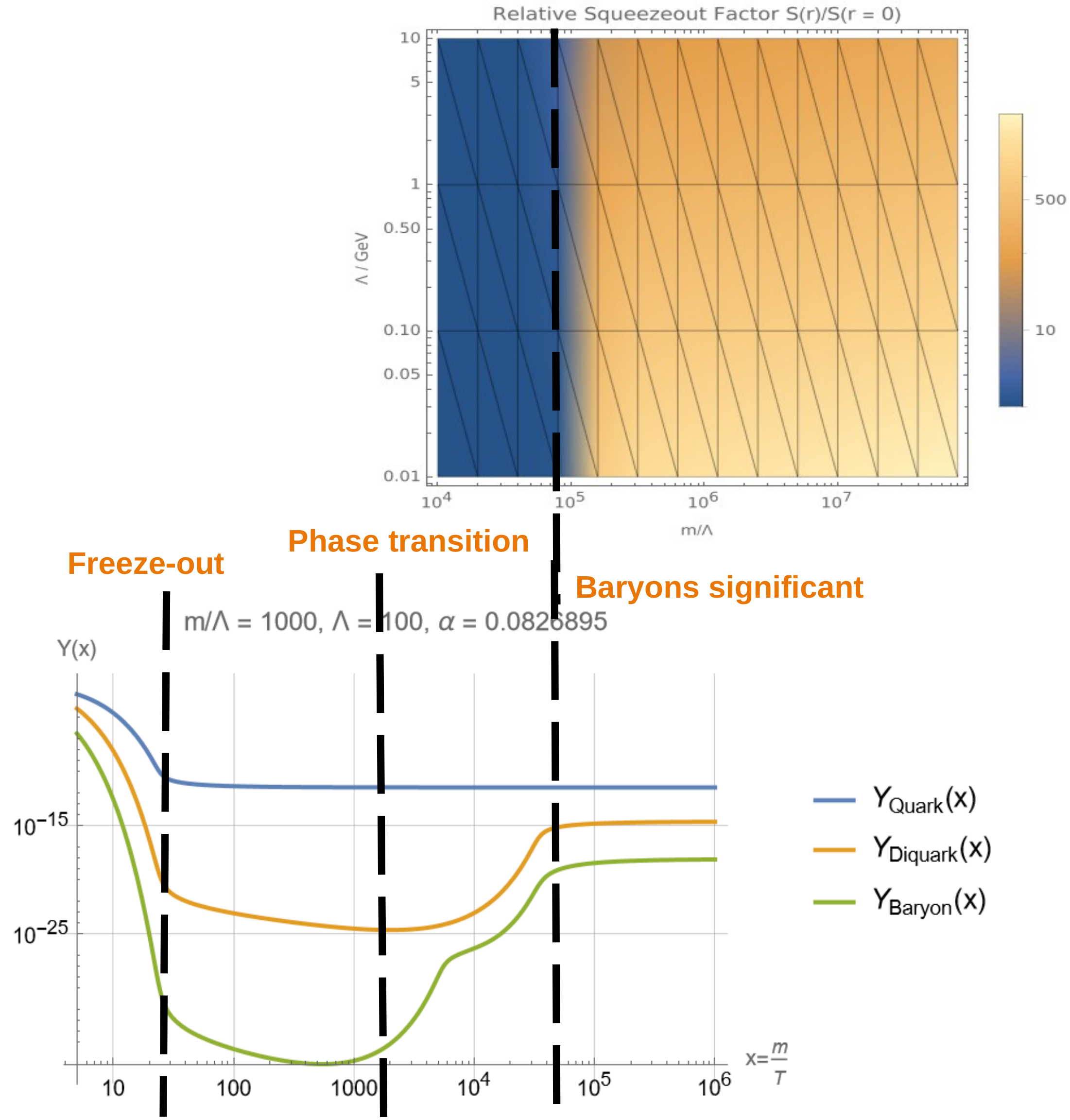
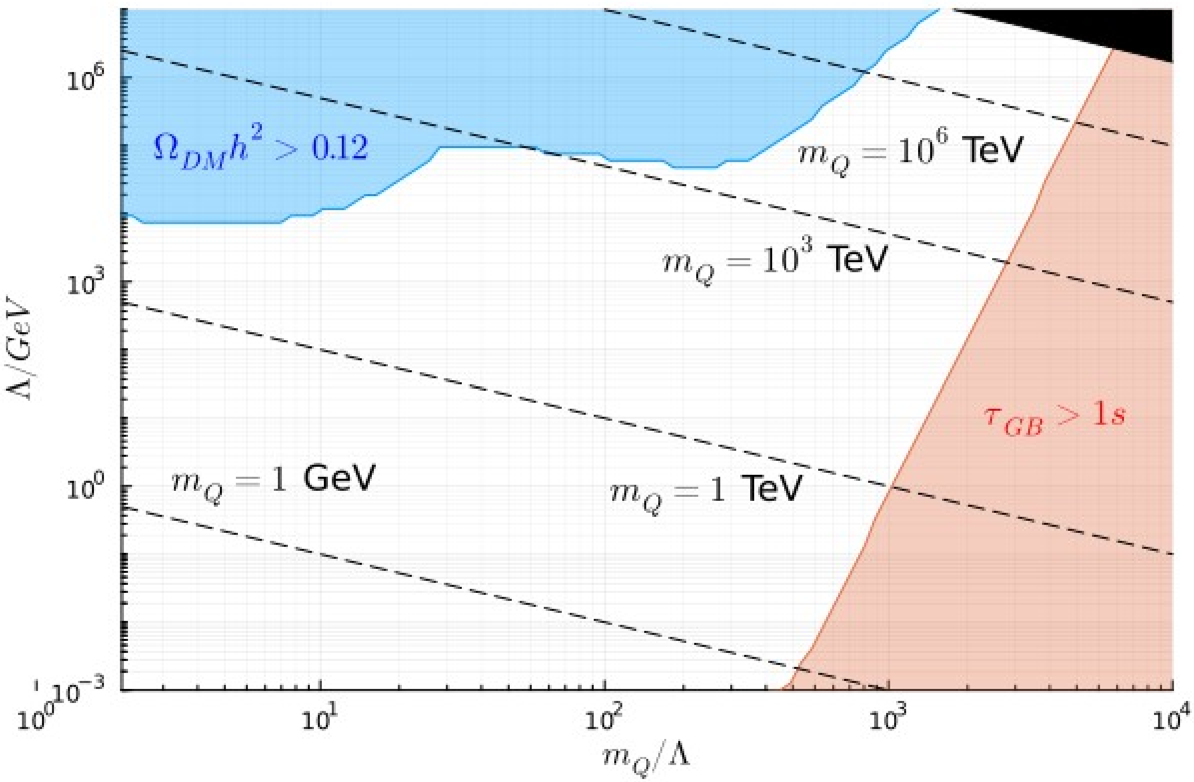


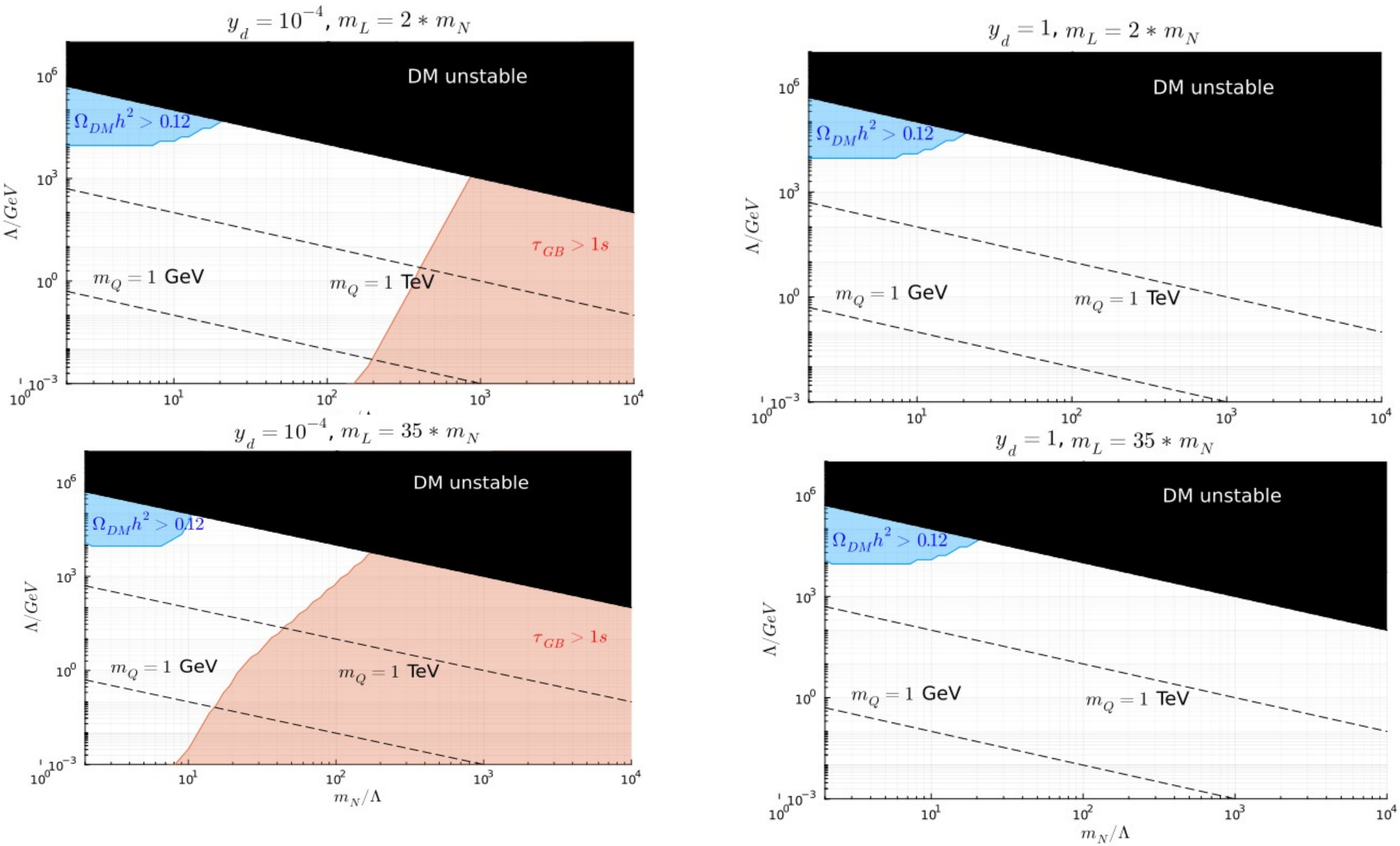
Results for the $SU(2)_L$ Gauge Portal Model

Two free parameters: Λ_{dQCD}, m_Q



Results for the
N+L Higgs Portal Model

Four parameters: Λ_{dQCD}, m_N, m_L, y_d



Summary

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Phenomenology strongly depends on the **hierarchy between m_Q and Λ_{dQCD}**.

In models with **heavy quarks**, the DM density gets heavily depleted due to the **squeezeout** mechanism leading to **very high DM masses (PeV instead of TeV)**. Yet we may **constrain parameter space** with current data.

Thank you for your attention

Backup Slides

Baryon – Antibaryon interactions

It has been argued in the literature, that heavy baryons annihilate in a **rearrangement process** into three mesons.

The relic abundance of long-lived heavy coloured relics, J. Kang et al. (2008)

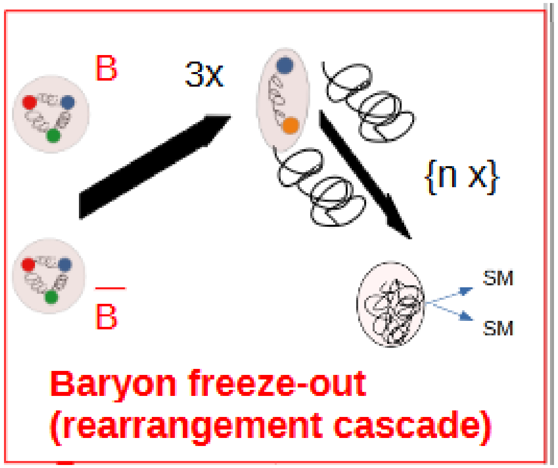
Dark Matter as a weakly coupled Dark Baryon, A. Mitridate et al. (2017)

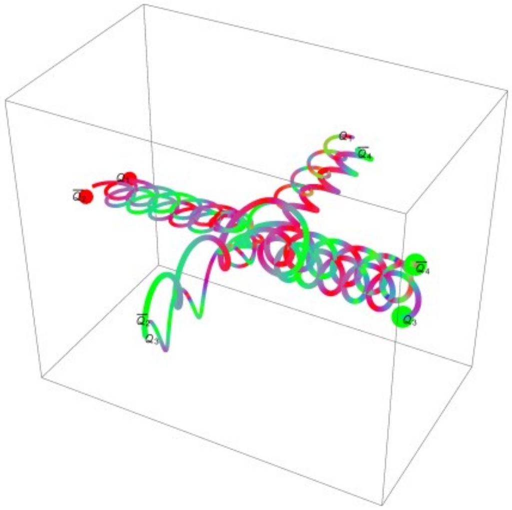
Dark Quarkonium formation in the Early Universe, M. Geller et al. (2018)

Cross Section is **strongly enhanced:**

$$\sigma_{\mathcal{B}-\overline{\mathcal{B}}} = \frac{4\pi R_{\mathcal{B}}^2}{\sqrt{\frac{E_{\text{kin}}}{E_{\mathcal{B}}}}}$$

$$< \sigma_{\mathcal{B}-\overline{\mathcal{B}}} v_{\text{rel}} >= \frac{\sqrt{8N_d}\pi}{C_F \alpha_d m_Q^2}$$





Thermal history of composite dark matter, N. A. Dondi et al. (2020)

Strongly and weakly coupled dark baryons

Toy model for interaction via the *Cornell potential*

$$V_{\text{eff}}(r) = -\frac{\alpha'}{r} + \sigma r + \frac{n^2}{2\mu r^2},$$

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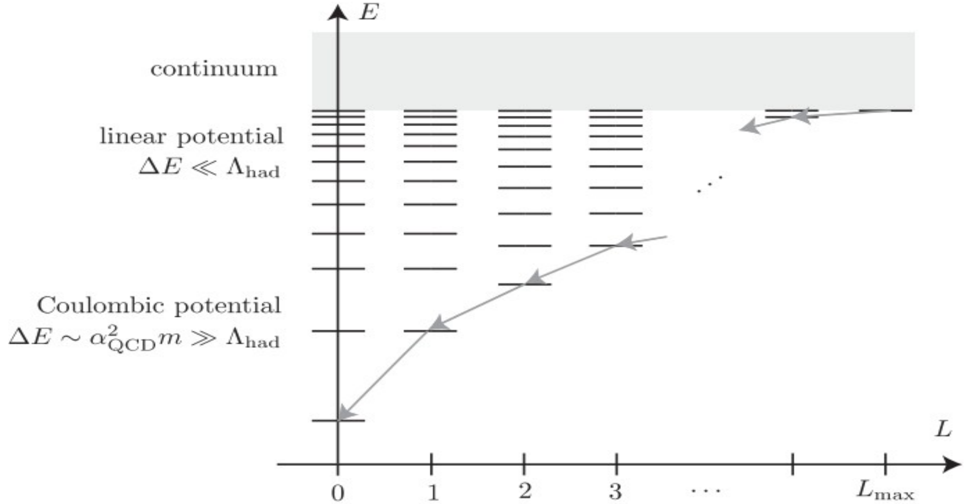

The Relic Abundance of Long-Lived Heavy Colored Particles, J.Kang et al. (2008)

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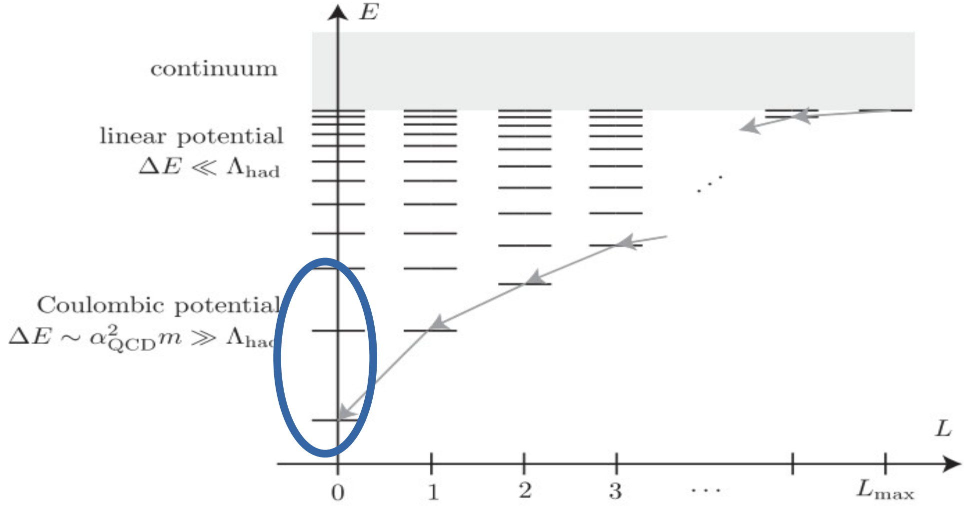

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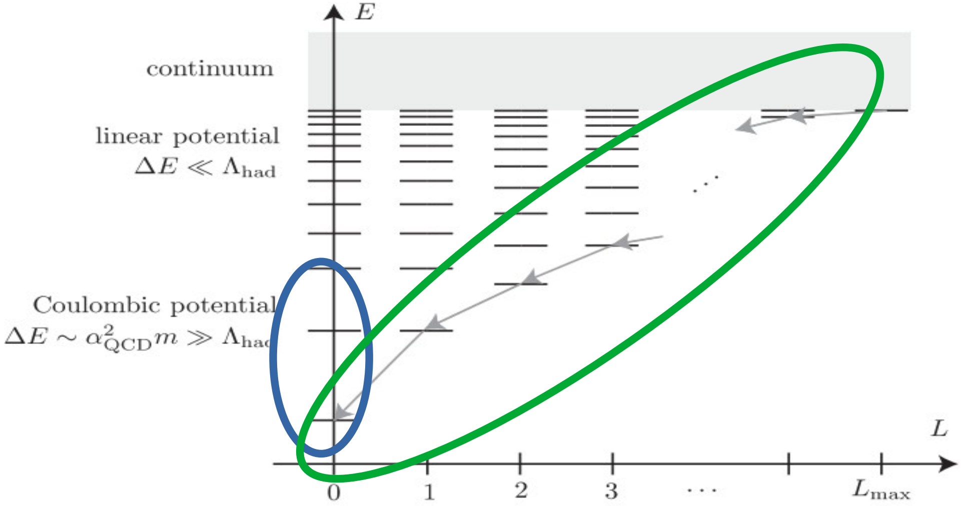

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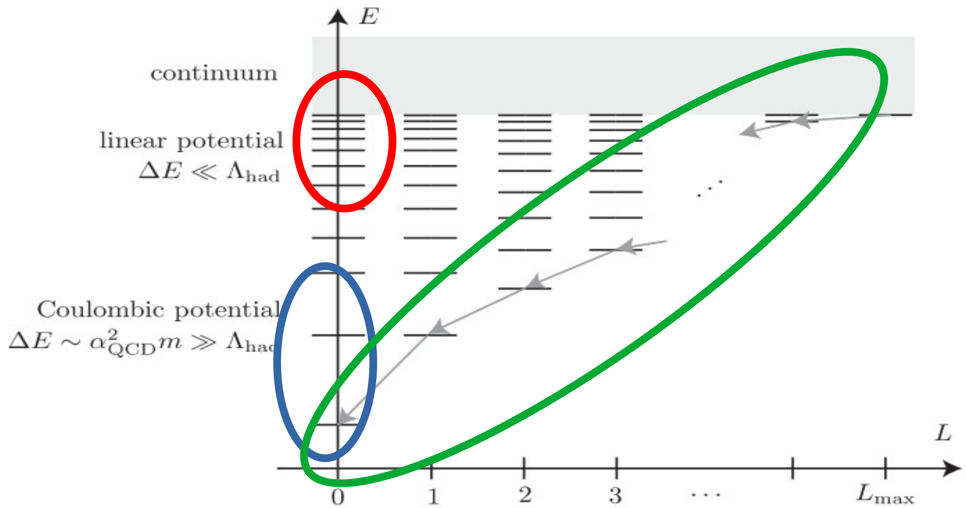

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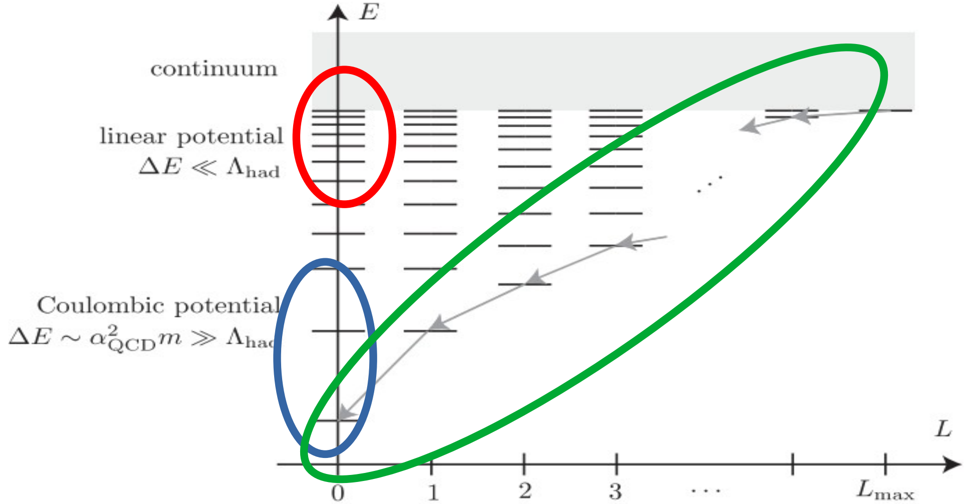

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