Dark Matter from adjoint fermions

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Work in progress with R. Contino, A. Mitridate and M. Redi

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Dark matter: the general context

Hope : DM interacts non-gravitationally with Standard Model particles

Hint : non renormalizable interactions expected from a generic EFT point of view

Dark matter: the general context

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Hint : non renormalizable interactions expected from a generic EFT point of view

- Feeble interactions:
  - axions, hidden sectors, freeze-in dark matter, …
- Standard Model interactions:
  - QCD
  - ElectroWeak → WIMP: $M \sim \mathcal{O}(100\,\mathrm{GeV} \div 10\,\mathrm{TeV})$

Composite DM:
- heavier
- accidentally stable

The successful paradigm of the Standard Model

- Global symmetries are accidental
  - renormalizable lagrangian
  - higher-dimensional operators become irrelevant in the IR
  - accidental symmetries emerge in the IR

    flavour symmetries and custodial $\mathrm{SO}(3)$

    Baryon number $\mathrm{U}(1)_{\mathrm{B}}$ and lepton number $\mathrm{U}(1)_{\mathrm{L}}$

- Fermions in complex representations
  - masses generated dynamically

Composite dark matter

Idea: dark matter is a composite state of a new strong dynamics stable thanks to an accidental symmetry

- Requirements:
  - new fermions charged under both G_{DC} and G_{SM}
  - dark sector dynamics does not break G_{SM} → irreps real/vectorlike under G_{SM}

"Vectorlike Confinement"
Kilic, Okui, Sundrum JHEP 1002 (2010) 018

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  - Fermions in complex representations?

G_{DC} simple → fermion condensate breaks dynamically G_{DC} → "Tumbling" NPB 169 (1980) 373 Raby, Dimopoulos, Susskind

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$\mathrm{G_{DC}^{strong}} \times \mathrm{U(1)_{DC}}$ → Y. Nomura et al. PRD 94 (2016) 035013

+ SM quantum numbers Contino, Podo, Revello, work in progress

Composite dark matter

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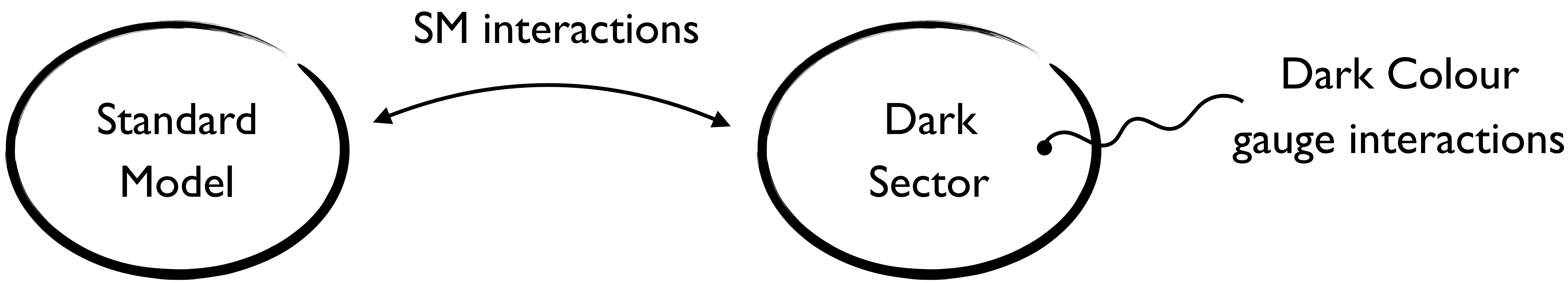
  - in this talk: fermion in real representations under $\mathrm{G_{DC}}$

↓

Similarly to QED/QCD vs SM

Classes of composite DM candidates



Candidate	Accidental symmetry	Breaking
Dark baryon	Dark baryon number $U(1)_{DB}$	dim-6 $\psi\psi\psi\,\psi_{\rm SM}$
Dark meson	Species number $U(1)_i$	dim-4
	G-parity	dim-5

Antipin, Redi, Strumia, Vigiani JHEP 1507 (2015) 039

Mitridate, Redi, Smirnov, Strumia JHEP 1710 (2017) 210

Gluequark DM

Gauge group	Adjoint fermions
$\mathrm{SU}(N)_{\mathrm{DC}} \times G_{\mathrm{SM}}$	$\mathcal{Q} = (\mathrm{adj}, \mathrm{r})$

adj : adjoint of $\mathrm{SU}(N)_{\mathrm{DC}}$

r : representation of G_{SM}

$$\delta\mathcal{L} = \mathcal{Q}^{\dagger}\sigma^{\mu} i D_{\mu}\mathcal{Q} - M\mathcal{Q}\mathcal{Q}$$

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GlueQuark

$$\chi \sim (\mathcal{Q}g)$$

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- Explicit mass term $M_{\mathcal{Q}}$
- Confinement scale Λ_{DC}

<u>Accidental stability</u>

- $\mathbb{Z}_2$ symmetry: $\mathcal{Q} \longrightarrow -\mathcal{Q}$
- Lightest $\mathbb{Z}_2$ odd states are accidentally stable

Boddy, Feng, Kaplinghat, Tait PRD 89 (2014) 115017 → glueballino in the context of SUSY

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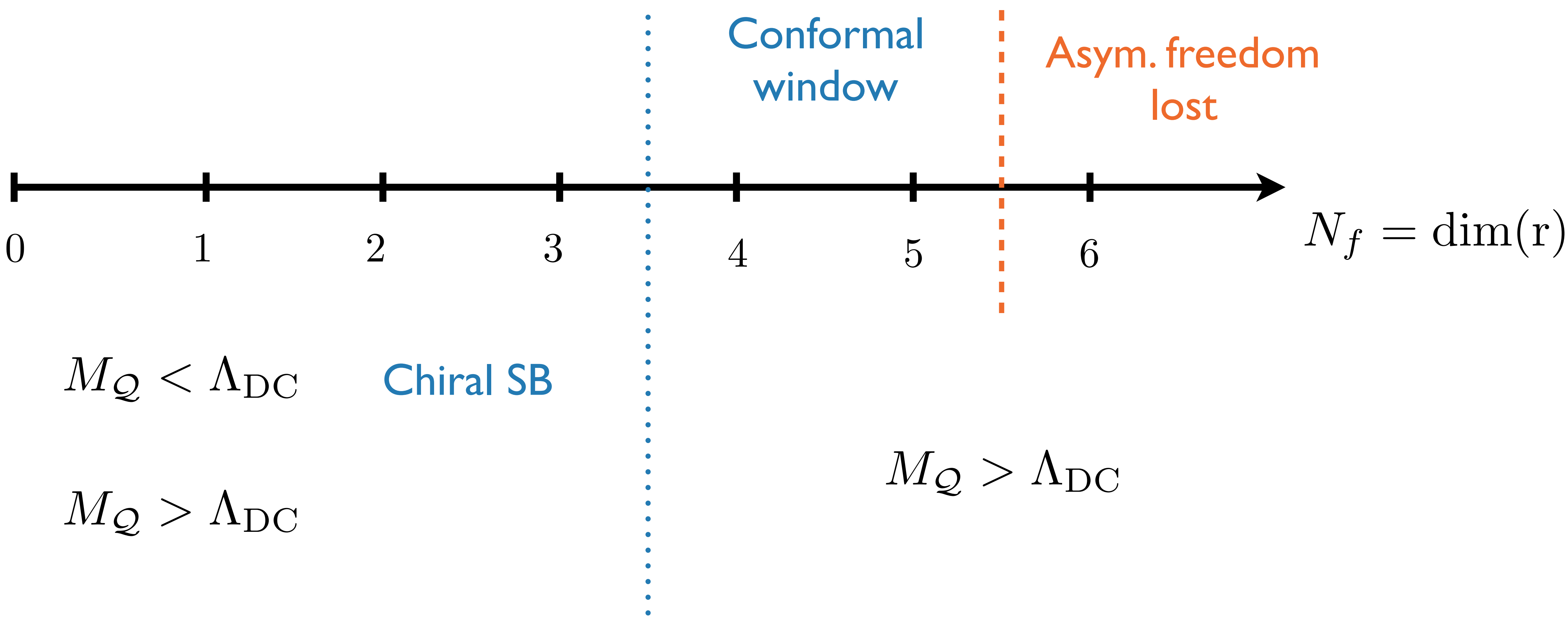

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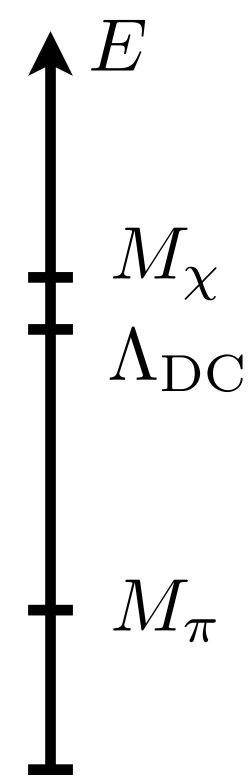
$$\delta\mathcal{L} = \mathcal{Q}^{\dagger}\sigma^{\mu} i D_{\mu}\mathcal{Q} - M\mathcal{Q}\mathcal{Q}$$

$$M_{\mathcal{Q}} < \Lambda_{\mathrm{DC}}$$



- Mesons $(\mathcal{Q}\mathcal{Q})$

  N_f light Weyl fermions $\mathrm{SU}(\mathrm{N_f}) \longrightarrow \mathrm{SO}(\mathrm{N_f})$

- Gluequark χ : dark quark - dark gluon bound state

$$\chi \sim (\mathcal{Q}g)$$

Gluequark DM

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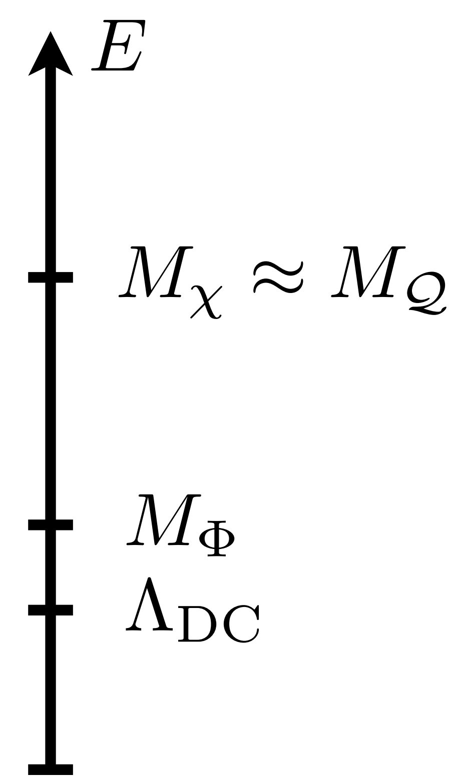

- Dark glueball Φ : gluonium bound state

$$M_\Phi \sim 7\,\Lambda_{\mathrm{DC}}$$

- Gluequark χ : dark quark - dark gluon bound state

$$\chi \sim (\mathcal{Q}g) \qquad\qquad M_{\mathcal{Q}} \gg \Lambda_{\mathrm{DC}} \Rightarrow M_\chi \approx M_{\mathcal{Q}}$$

Viable Gluequark DM models

- DM candidate EM neutral
- No Landau poles below $M_{\rm Pl}$

	$\rm SU(2)_L \times U(1)_Y$	Accidental symmetry	$N_{\rm DC}$
$N_f = 1$	$1_0 = N$	$\mathbb{Z}_2$ broken by dim-6	
$N_f = 3$	$3_0 = V$	$\mathbb{Z}_2$ broken by dim-6	≤ 3
$N_f = 4$	$2_{+\frac{1}{2}} \oplus 2_{-\frac{1}{2}} = L + \bar{L}$	$\rm U(1)$ broken by dim-5	≤ 4
$N_f = 5$	$5_0 = F$	$\mathbb{Z}_2$ broken by dim-7	✘
$N_f = 6$	$3_{+1} \oplus 3_{-1} = T + \bar{T}$	$\rm U(1)$ broken by dim-6	≤ 2
$\vdots$	$\vdots$	$\vdots$	$\vdots$

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SUSY			
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✔ $N_f=3$ (Best candidate)	$3_0 = V$	$\mathbb{Z}_2$ broken by dim-6	≤ 3
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Non-renormalizable operators and decay

$M_{\mathcal{Q}} > \Lambda_{\rm DC}$

- <u>Gluequark</u> χ

Dim 6 operators: $\Delta\mathcal{L} \sim \frac{g_X^2}{\Lambda_{\rm UV}^2} H\sigma^i l \mathcal{Q}_a^i \sigma^{\mu\nu} G^a_{\mu\nu}$

Decay width $\Gamma(\chi \to h\nu) \sim 2.5 \times 10^{-50}\,\mathrm{TeV}\, g_X^4 \left(\frac{10^{15}\mathrm{GeV}}{\Lambda_{\rm UV}}\right)^4 \left(\frac{\Lambda_{\rm DC}}{1\mathrm{TeV}}\right)^4 \left(\frac{M_{\mathcal{Q}}}{100\mathrm{TeV}}\right)$

Cosmological stability: $\tau_\chi > 10^{17}\,\mathrm{s}$ → $\Gamma < 6.5 \times 10^{-45}\,\mathrm{TeV}$

Bounds from CMB, 21cm: $\tau_\chi > 10^{24}\,\mathrm{s}$ → $\Gamma < 6.5 \times 10^{-52}\,\mathrm{TeV}$

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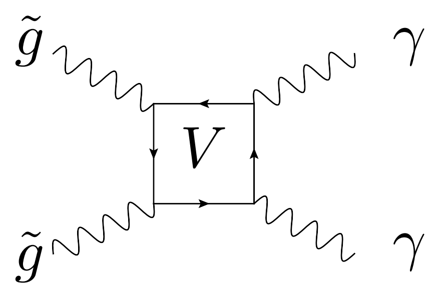
- <u>Dark glueball</u> Φ



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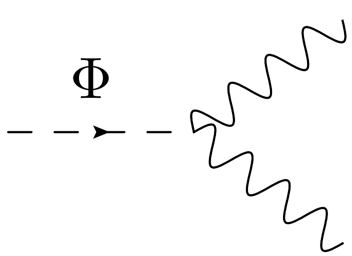


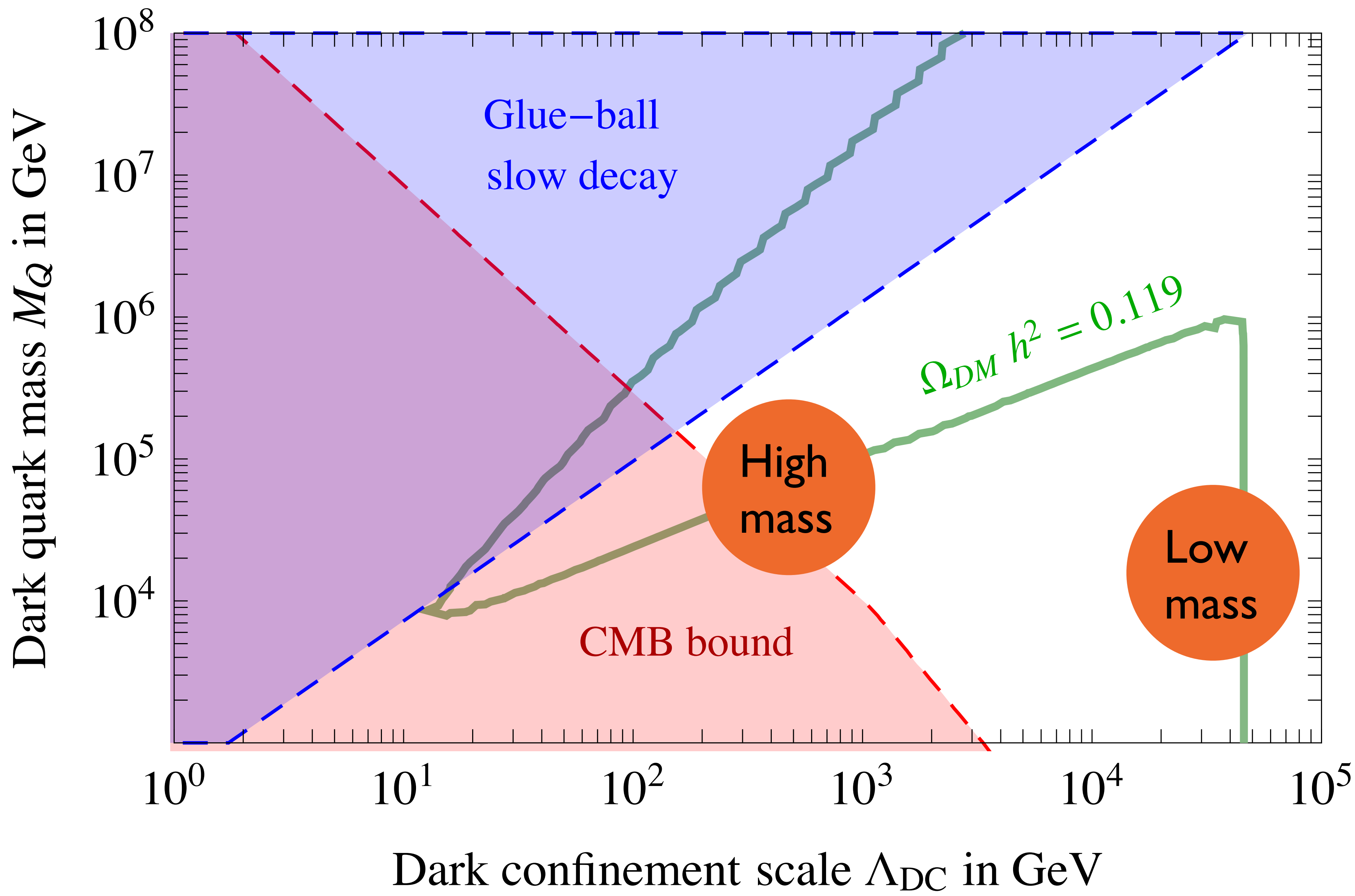
$\Gamma_\Phi \sim 10^{-2}\frac{\Lambda_{\rm DC}^9}{M_\mathcal{Q}^8}$

Stable glueballs: ✗ too large relic density

Bounds from CMB, BBN, indirect: $\tau_\Phi < 1\,{\rm s}$

Relic density

$\mathrm{SU}(3)_{\mathrm{DC}} \quad \mathcal{Q} = 3_0 = V$



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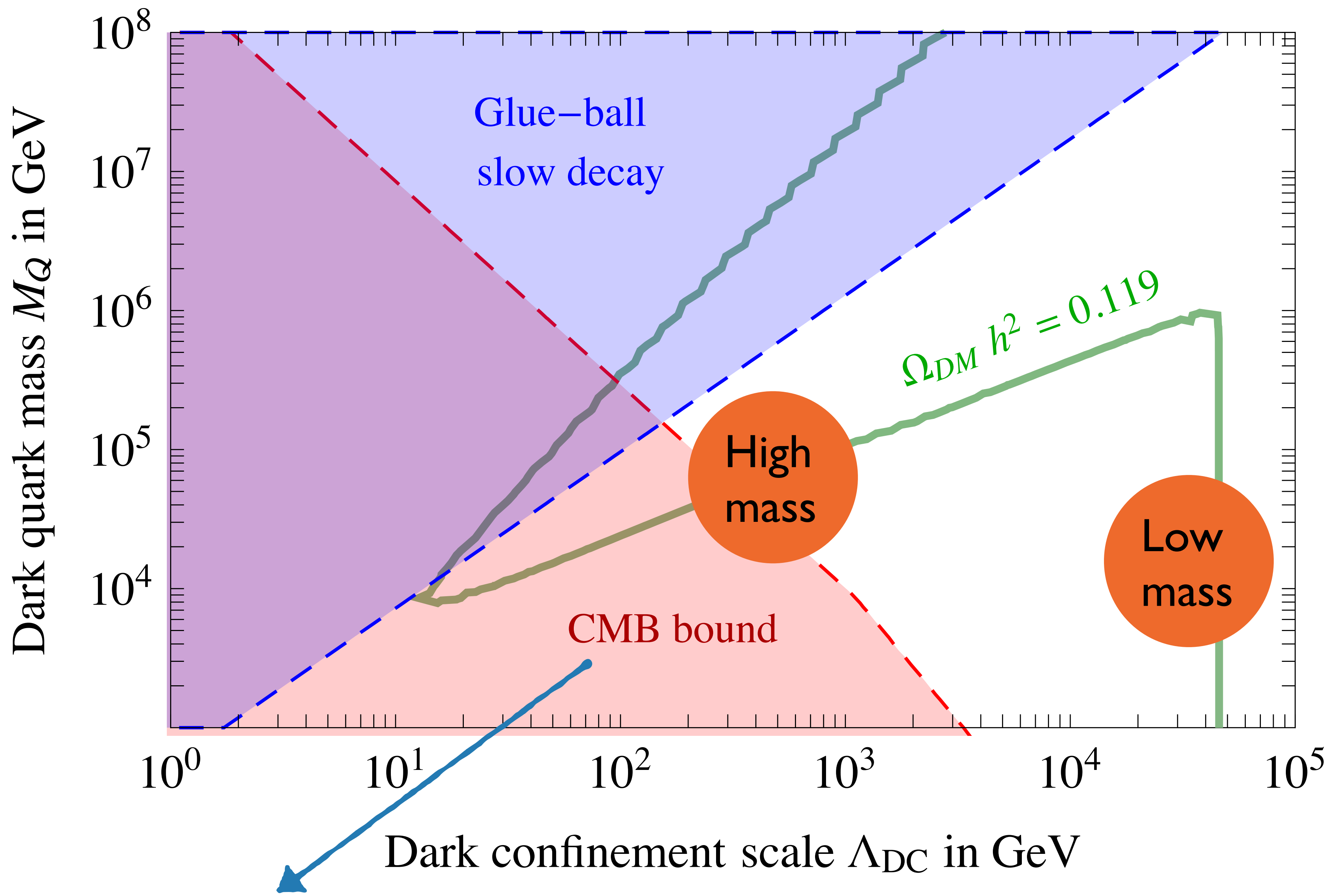
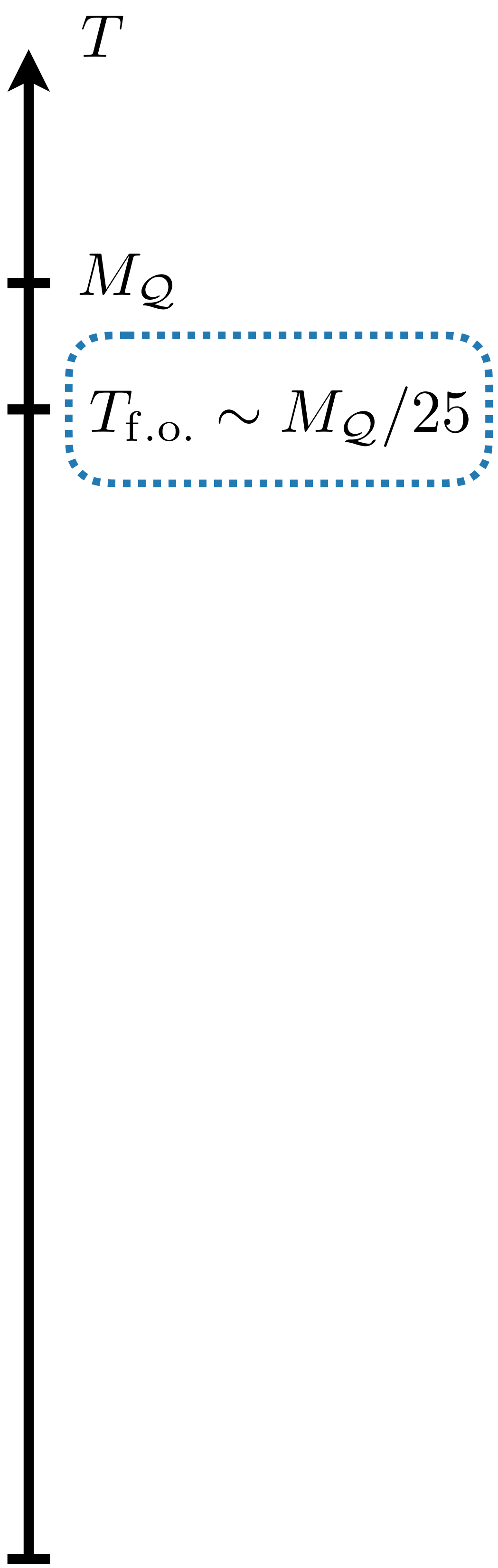


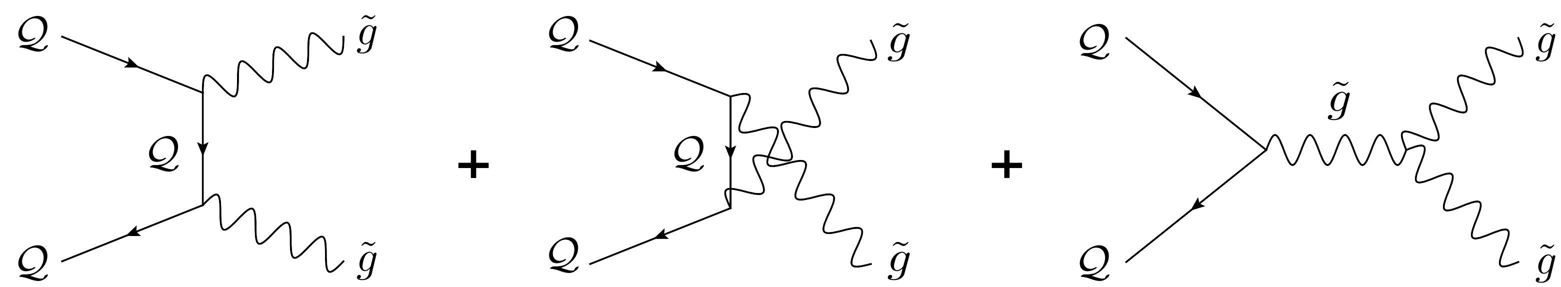
Gluequark annihilations distort the CMB spectrum

Thermal history

$M_{\mathcal{Q}} > \Lambda_{\rm DC}$



Perturbative freezeout: $n_{\mathcal{Q}}\, \sigma_{\rm ann}\, v \lesssim H$



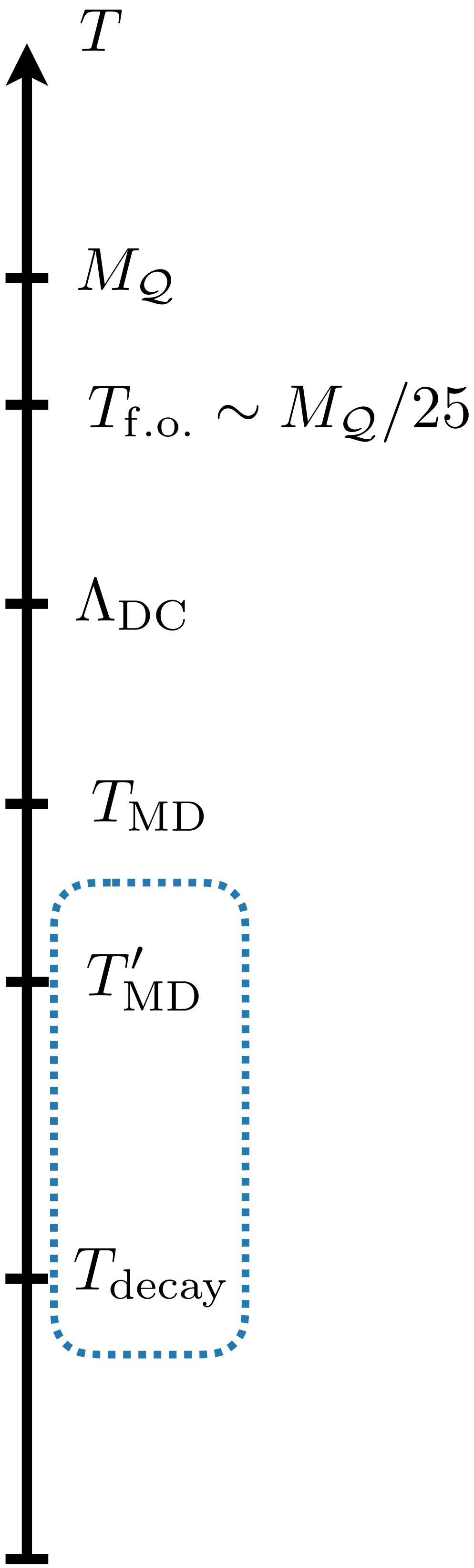
$$\langle \sigma\, v \rangle = \frac{27\,\pi}{32} \frac{\alpha_{\rm DC}^2}{M_{\mathcal{Q}}^2} + \mathcal{O}(v)$$

↓

$$n_{\mathcal{Q}}\, a^3 \sim \text{const}$$

Thermal history

$M_{\mathcal{Q}} > \Lambda_{\rm DC}$



Confinement

Dark gluons → Dark glueballs

$$\rho_G = (N_{\rm DC}^2 - 1)\frac{\pi^2}{30}T_{\rm conf}^4 \qquad \rho_{\rm M,i}$$

Thermal history

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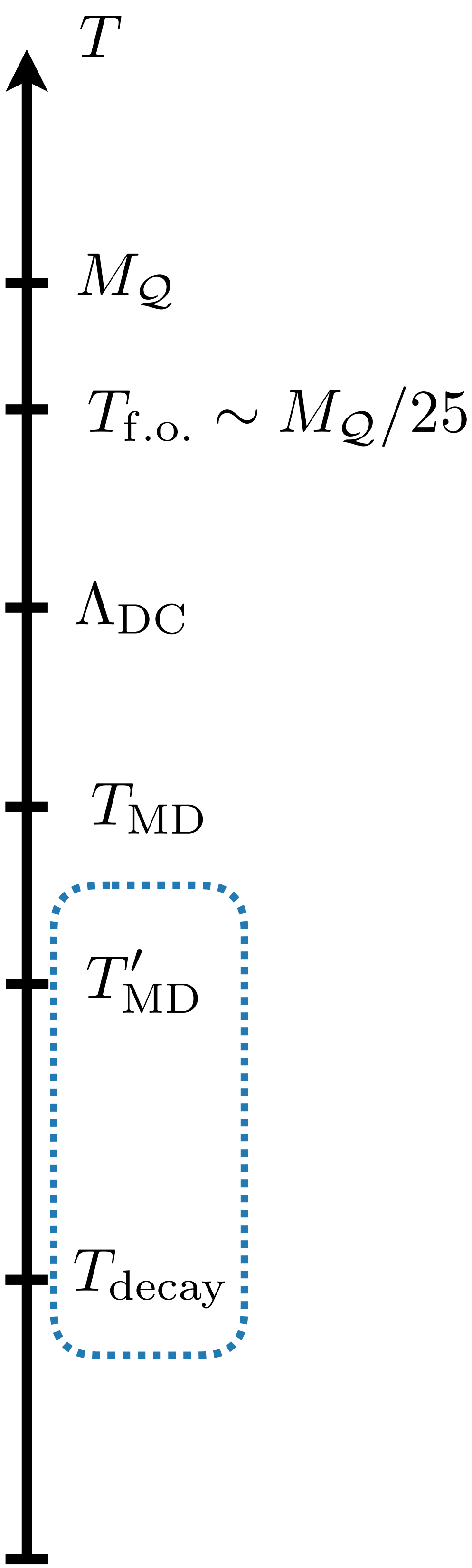

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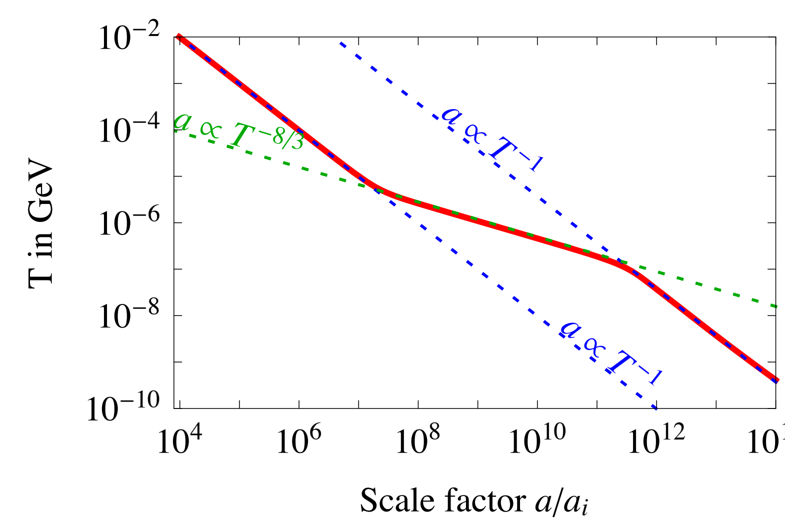
$$\begin{cases} \dot\rho_M = -3H\rho_M - \Gamma_\phi\,\rho_M \\ \dot\rho_R = -4H\rho_R + \Gamma_\phi\,\rho_M \end{cases}$$

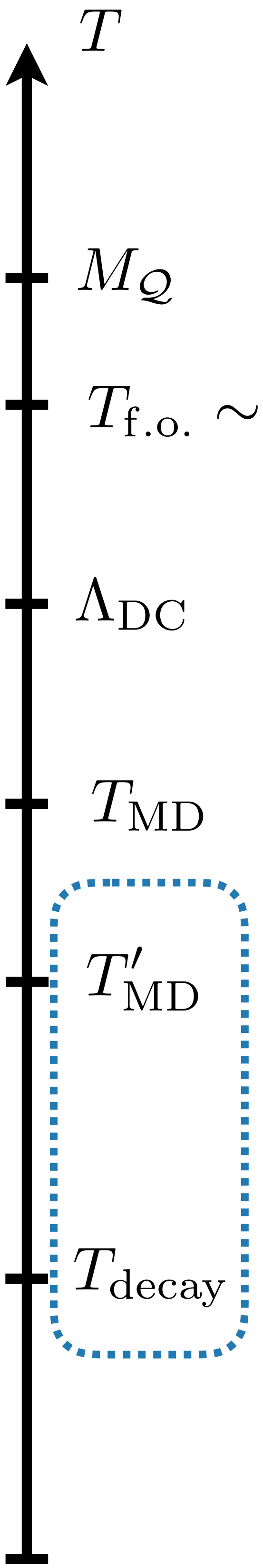
→



$$a \propto T^{-\frac{8}{3}}$$

Thermal history

$M_Q > \Lambda_{DC}$



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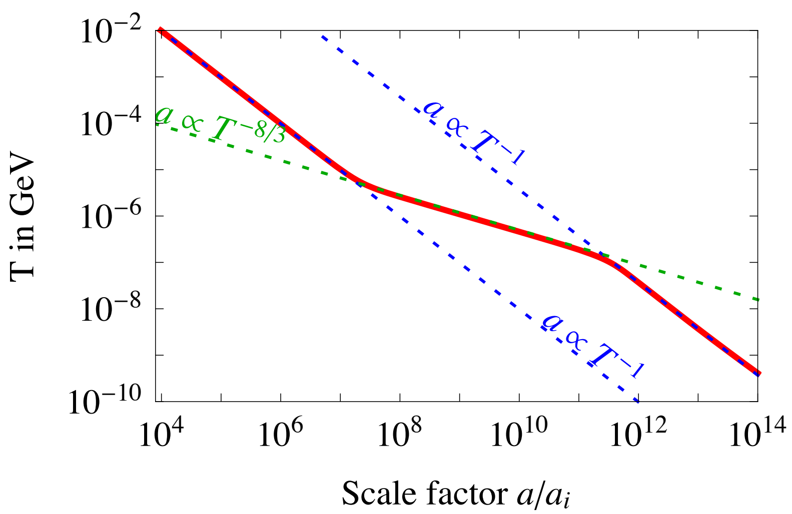


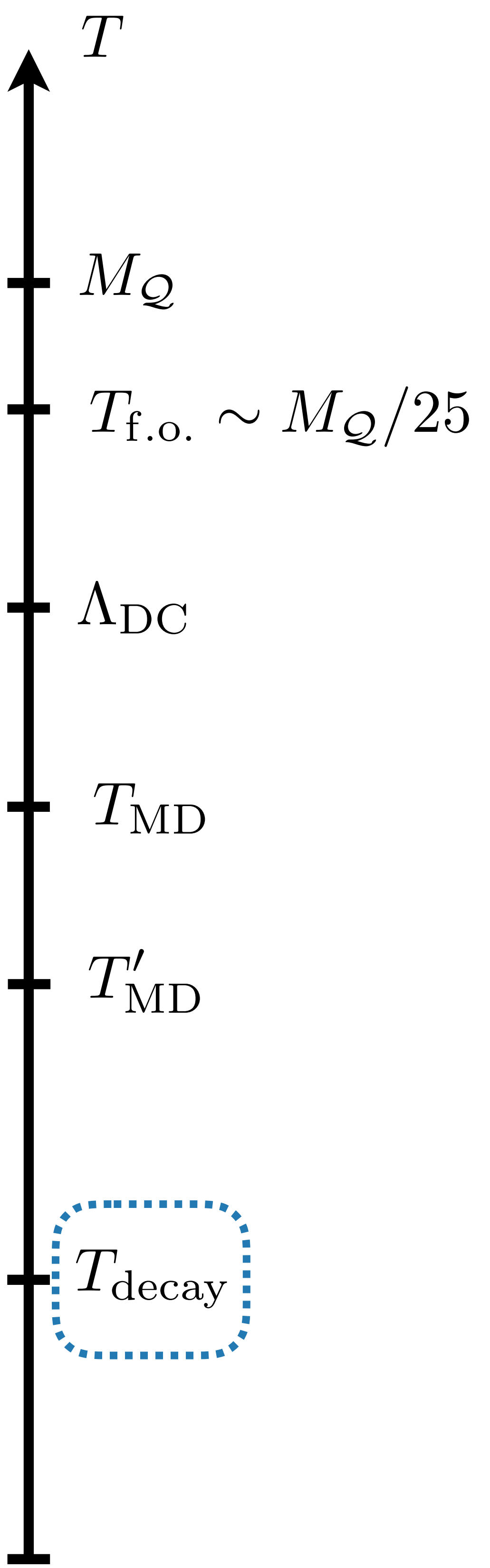
$$a \propto T^{-\frac{8}{3}}$$

Dilution ! $\Omega_{DM} = \Omega_{DM}^{naive}\left(\frac{T_{decay}}{T'_{MD}}\right)^5$

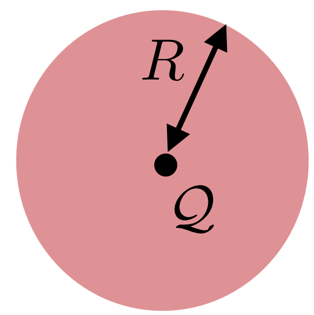
Kolb, Turner - "The Early Universe"

Thermal history

$M_{\mathcal{Q}} > \Lambda_{\rm DC}$



Non-perturbative annihilation:

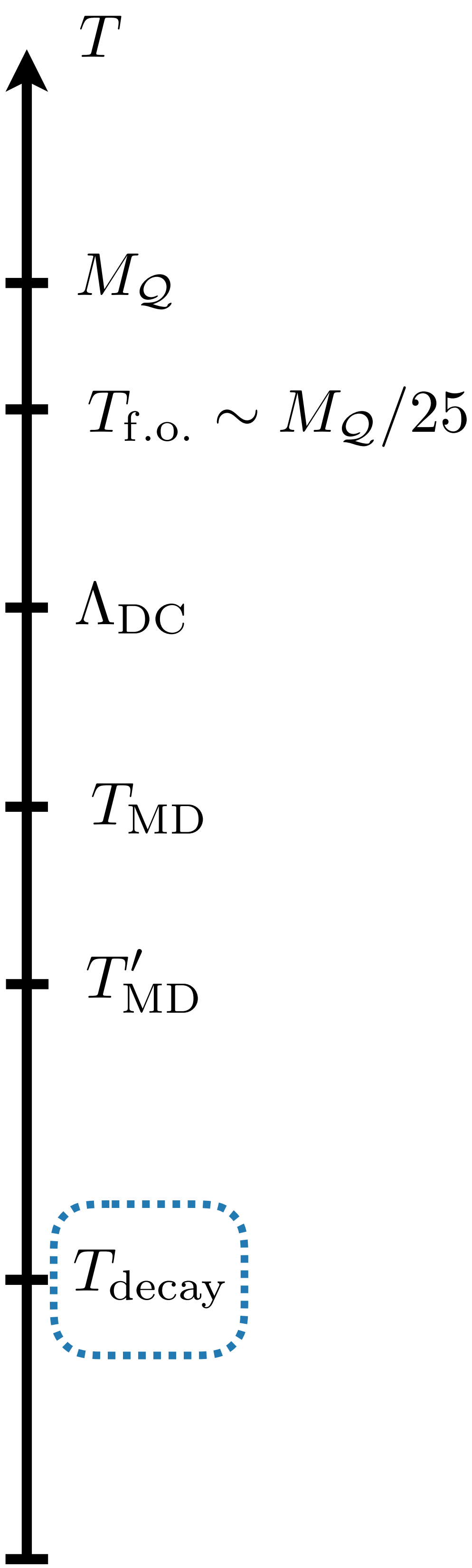


$$R \sim \frac{1}{\Lambda_{\rm DC}} \quad \text{but} \quad M_{\mathcal{Q}} \gg \Lambda_{\rm DC}$$

Gluequark is heavy and large !

Thermal history

$M_{\mathcal{Q}} > \Lambda_{\rm DC}$



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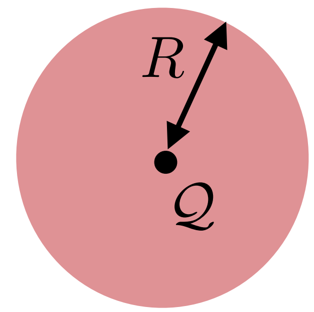


$R \sim \dfrac{1}{\Lambda_{\rm DC}}$ but $M_{\mathcal{Q}} \gg \Lambda_{\rm DC}$

Gluequark is heavy and large !

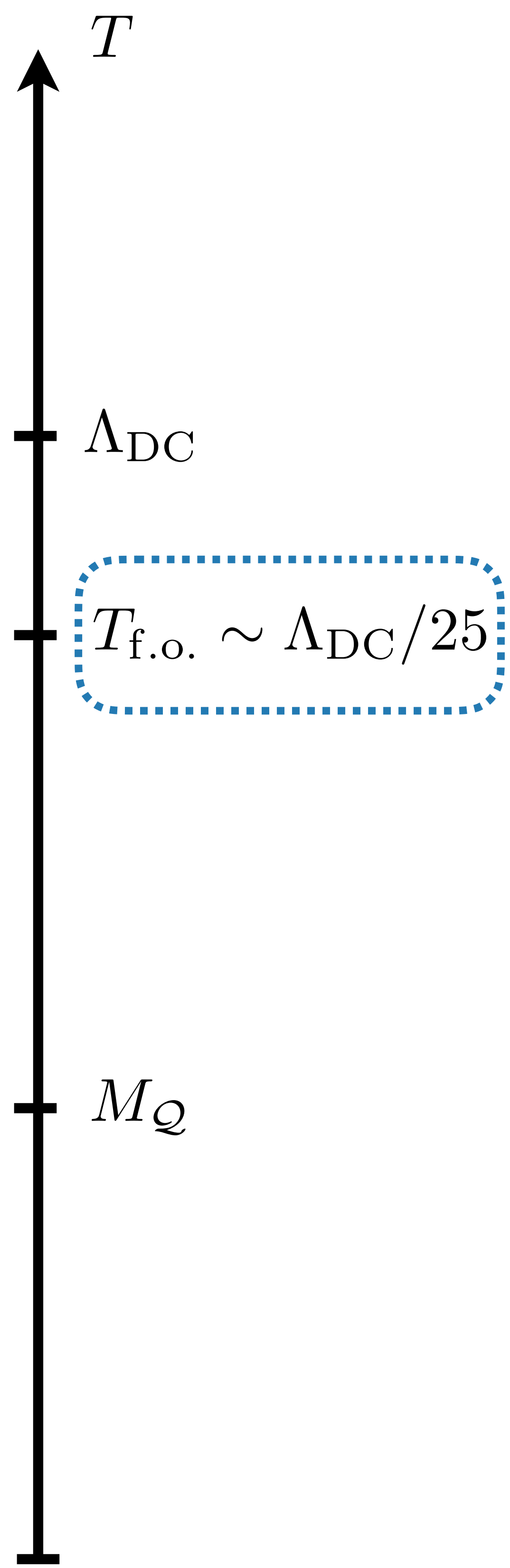
$$\chi\,\chi \longrightarrow (\mathcal{Q}\mathcal{Q})^* + \Phi \longrightarrow n\,\Phi \quad \longrightarrow \quad \sigma \sim \frac{\pi}{\Lambda_{\rm DC}^2}$$

Efficient when glueballs decay

↓

2nd phase of annihilation $\quad \Omega_{\rm DM} \propto \dfrac{M_{\mathcal{Q}}}{T_{\rm decay}} \dfrac{1}{\langle \sigma v \rangle}$

Thermal history



Freeze-out is non perturbative

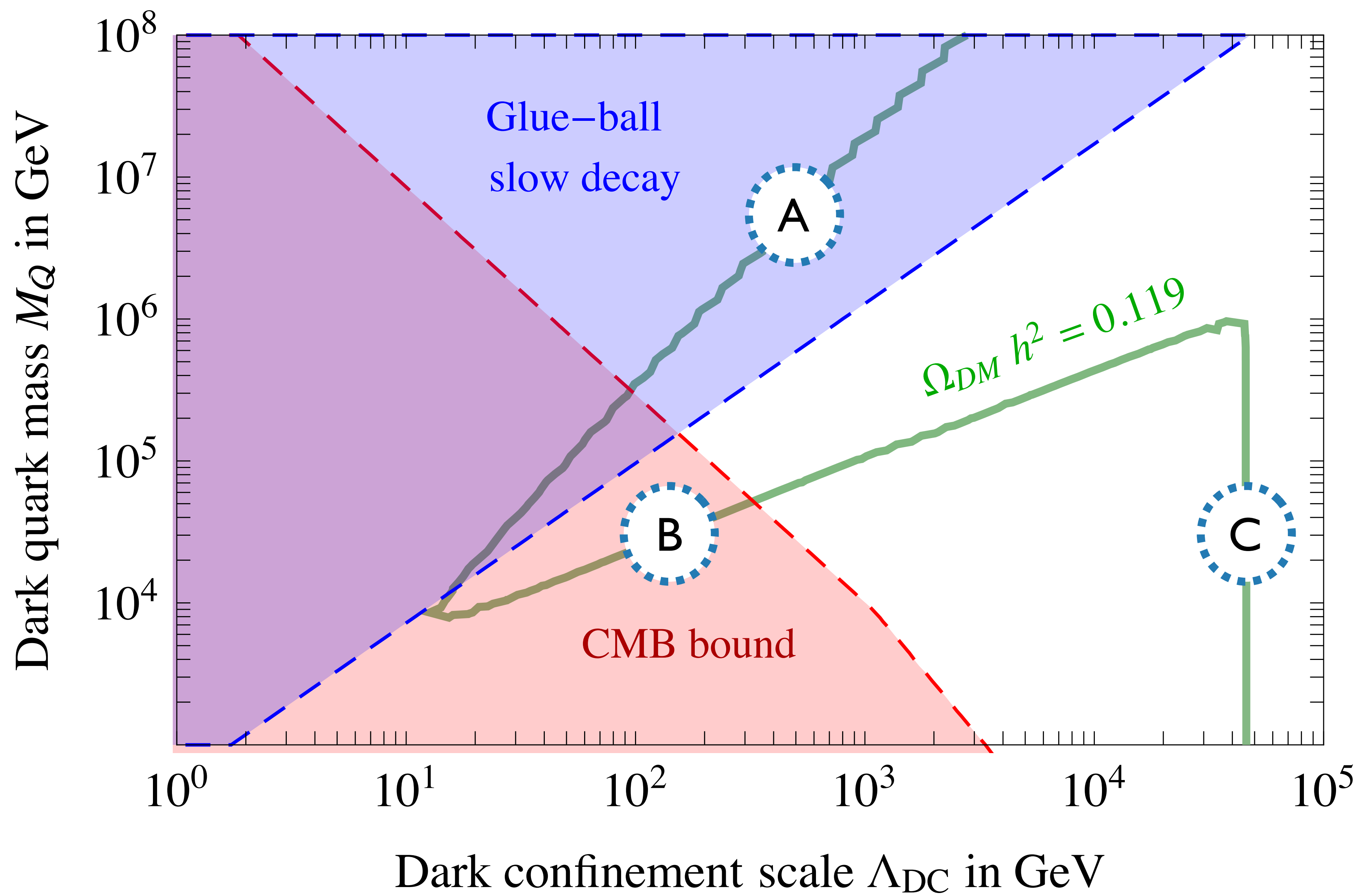
$$\chi\,\chi \longrightarrow (\mathcal{Q}\mathcal{Q})^* + \Phi \longrightarrow n\,\Phi \quad \rightarrow \quad \sigma \sim \frac{\pi}{\Lambda_{\rm DC}^2}$$

Only one scale is relevant for the gluequark: $M_\chi \sim \Lambda_{\rm DC}$

↓

$$\Omega_{\rm DM} \propto \frac{M_\chi}{T_{\rm f.o.}} \frac{1}{\langle \sigma v \rangle} \propto \Lambda_{\rm DC}^2$$

Results - benchmark model: $\mathrm{SU}(3)_{\mathrm{DC}} \quad \mathcal{Q} = 3_0 = V$



- A: Dilution from glueball decay dominates
- B: Non-perturbative annihilation occurs
- C: Perturbative freeze-out does not occur

Conclusions and outlook

- Gluequark DM has distinctive features:
  - candidate is heavy *and* large (for $M_{\mathcal{Q}} > \Lambda_{\mathrm{DC}}$)
  - rich thermal history
  - $\mathbb{Z}_2$ accidental symmetries

- Relic abundance set by competing effects:
  - dilution from glueball decay
  - non-perturbative annihilation

Conclusions and outlook

- Gluequark DM has distinctive features:
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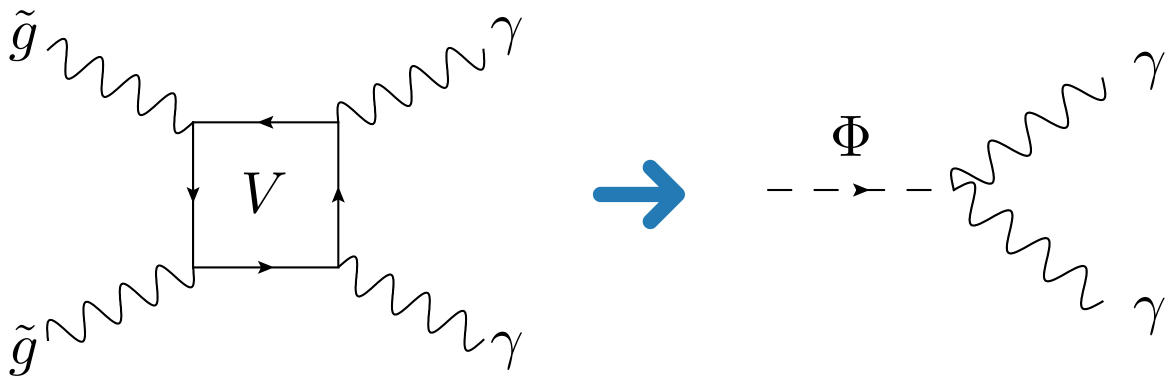
- Relic abundance set by competing effects:
  - dilution from glueball decay
  - non-perturbative annihilation
- To do:
  - study models with hypercharge ($L\,\bar{L}$)
  - phenomenology of the low mass branch (prediction: pions in the few TeV region)
  - study possible signatures of the heavy mass branch

Backup Slides

Glueball decay

Dark glueball Φ



Glueballs can decay to SM particles

Interactions mediated by heavy dark quarks (dim 8 operator)

$$\Delta\mathcal{L} \sim N_{\rm DC}\,\frac{g_{\rm DC}^2}{16\pi^2}\,\frac{g^2}{M_{\mathcal{Q}}^4}\,(G^a_{\mu\nu})^2(W^i_{\mu\nu})^2 \quad \xrightarrow{E<\Lambda_{\rm DC}} \quad \Delta\mathcal{L} \sim N_{\rm DC}\,\frac{g_{\rm DC}^2}{16\pi^2}\,\frac{g^2}{M_{\mathcal{Q}}^4}\,\frac{\Lambda_{\rm DC}^3}{4\pi}\,\Phi(W^i_{\mu\nu})^2$$

Large hierarchy: glueball can be long-lived or stable on cosmological scales

$$\Gamma_\Phi \sim 10^{-2}\,\frac{\Lambda_{\rm DC}^9}{M_{\mathcal{Q}}^8}$$

Glueball relic abundance

Parameter space region with stable dark glueballs: what is their thermal relic density?

After kinetic decoupling, the temperatures in the two sectors evolve independently

The entropies are both separately conserved → $\begin{cases} s\, a^3 = \text{const} \\ s'\, a^3 = \text{const} \end{cases}$ $\xi \equiv \frac{s}{s'} = \text{const}$

$T_{\text{k.d.}} \sim 100 \text{ MeV}$ $1 \lesssim \xi \lesssim 4$ cf. Hall et al., Astrophys.J. 398 (1992) 43

The glueball relic abundance can be expressed in term of ξ

$$\Omega_\Phi\, h^2 = 0.04\, \frac{M_\Phi}{\xi\, \text{eV}}$$

Dark glueballs could be a dark matter component if $M_\Phi \lesssim 3\, \xi \text{ eV} \lesssim 15 \text{ eV}$

Constraints on glueballs

- Stable glueballs $\tau_\Phi > 10^{17}\,\mathrm{s}$
  - relic abundance
  - effective number of relativistic degrees of freedom (BBN + CMB)
  - structure formation (galaxies + matter power spectrum)

- Long lived glueballs $1\,\mathrm{s} < \tau_\Phi < 10^{17}\,\mathrm{s}$
  - primordial light elements abundances (BBN)
  - diffuse gamma rays

Gluequark stability

Gluequark χ

Lightest component accidentally stable thanks to dark parity

Dim 6 operators: $\Delta\mathcal{L} \sim \frac{g_X^2}{\Lambda_{\rm UV}^2} H\sigma^i l \mathcal{Q}_a^i \sigma^{\mu\nu} G_{\mu\nu}^a \xrightarrow{E < \Lambda_{\rm DC}} \Delta\mathcal{L} \sim \frac{g_X^2}{\Lambda_{\rm UV}^2} \frac{\Lambda_{\rm DC}^2}{4\pi} H\sigma^i l \chi^i$

Decay width of order

$$\Gamma(\chi \to h\nu) \sim 2.5 \times 10^{-50}\,\text{TeV}\, g_X^4 \left(\frac{10^{15}\text{GeV}}{\Lambda_{\rm UV}}\right)^4 \left(\frac{\Lambda_{\rm DC}}{1\text{TeV}}\right)^4 \left(\frac{M_{\mathcal{Q}}}{100\text{TeV}}\right)$$

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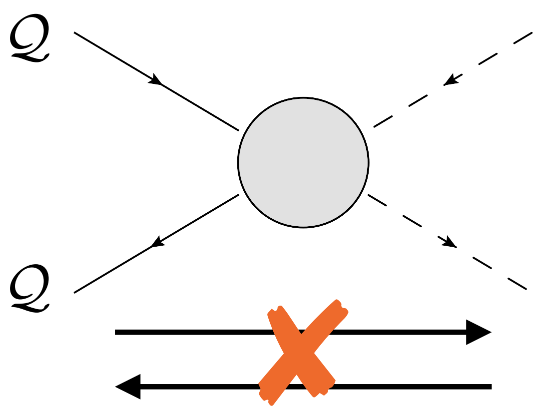
Gluequark perturbative freeze-out



Number changing interactions are efficient

$$n_{\mathcal{Q}} \propto e^{-T/M_{\mathcal{Q}}}$$

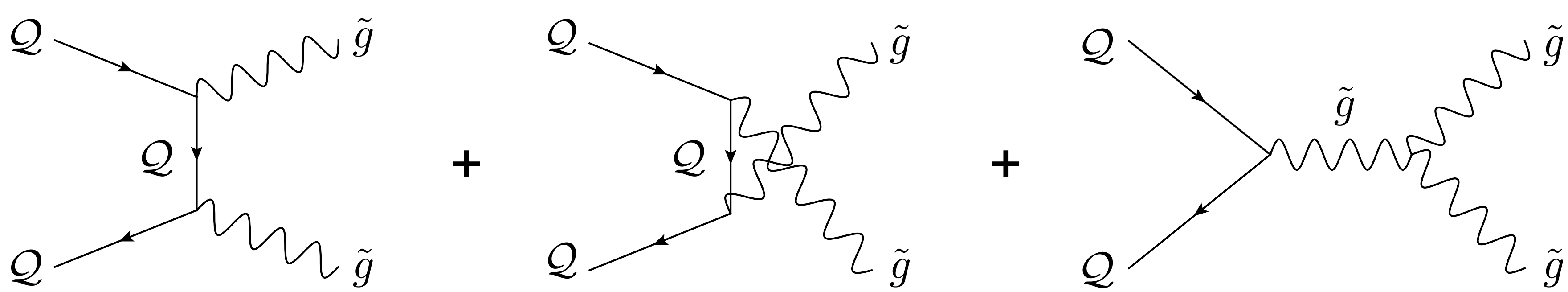
→

$$n_{\mathcal{Q}}\, \sigma_{\rm ann}\, v \lesssim H$$

Inefficient interactions: freeze-out

$$n_{\mathcal{Q}}\, a^3 \sim \text{const}$$

Annihilations in dark gluons are more efficient than electroweak processes



The calculation is non-trivial due to the non-abelian structure of the gauge interactions

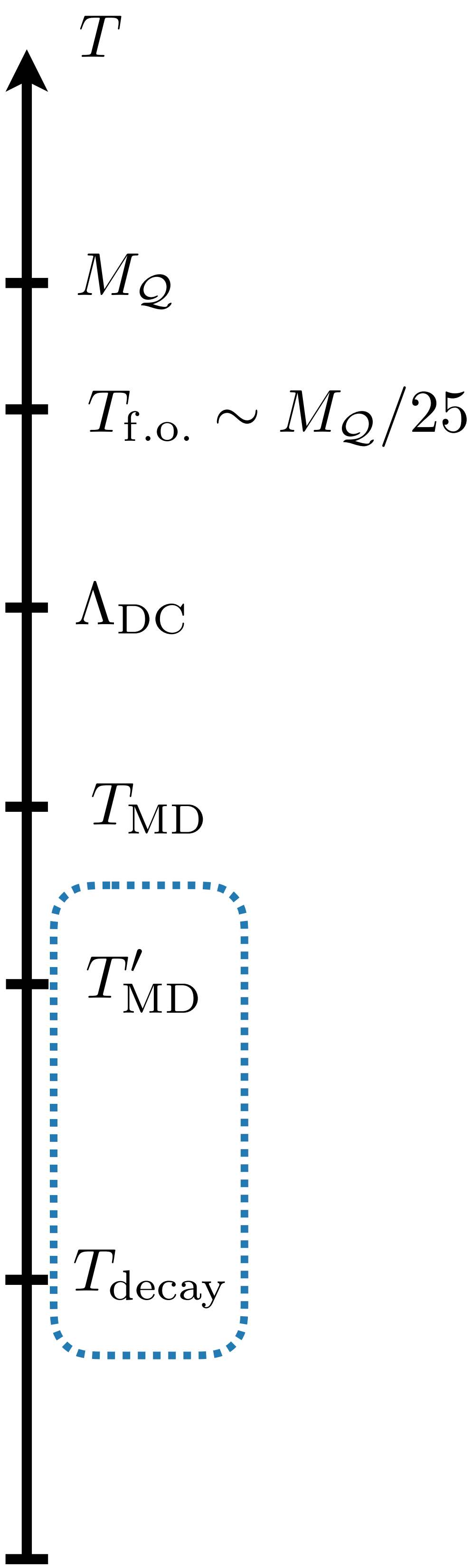
$$\langle \sigma\, v \rangle = \frac{27\,\pi}{32} \frac{\alpha_{\rm DC}^2}{M_{\mathcal{Q}}^2} + \mathcal{O}(v)$$

Long range interactions included in the calculation (Sommerfeld effect)

Relic abundance determined solving the Boltzmann equation

Dilution

$M_Q > \Lambda_{\rm DC}$



Confinement

Dark gluons → Dark glueballs

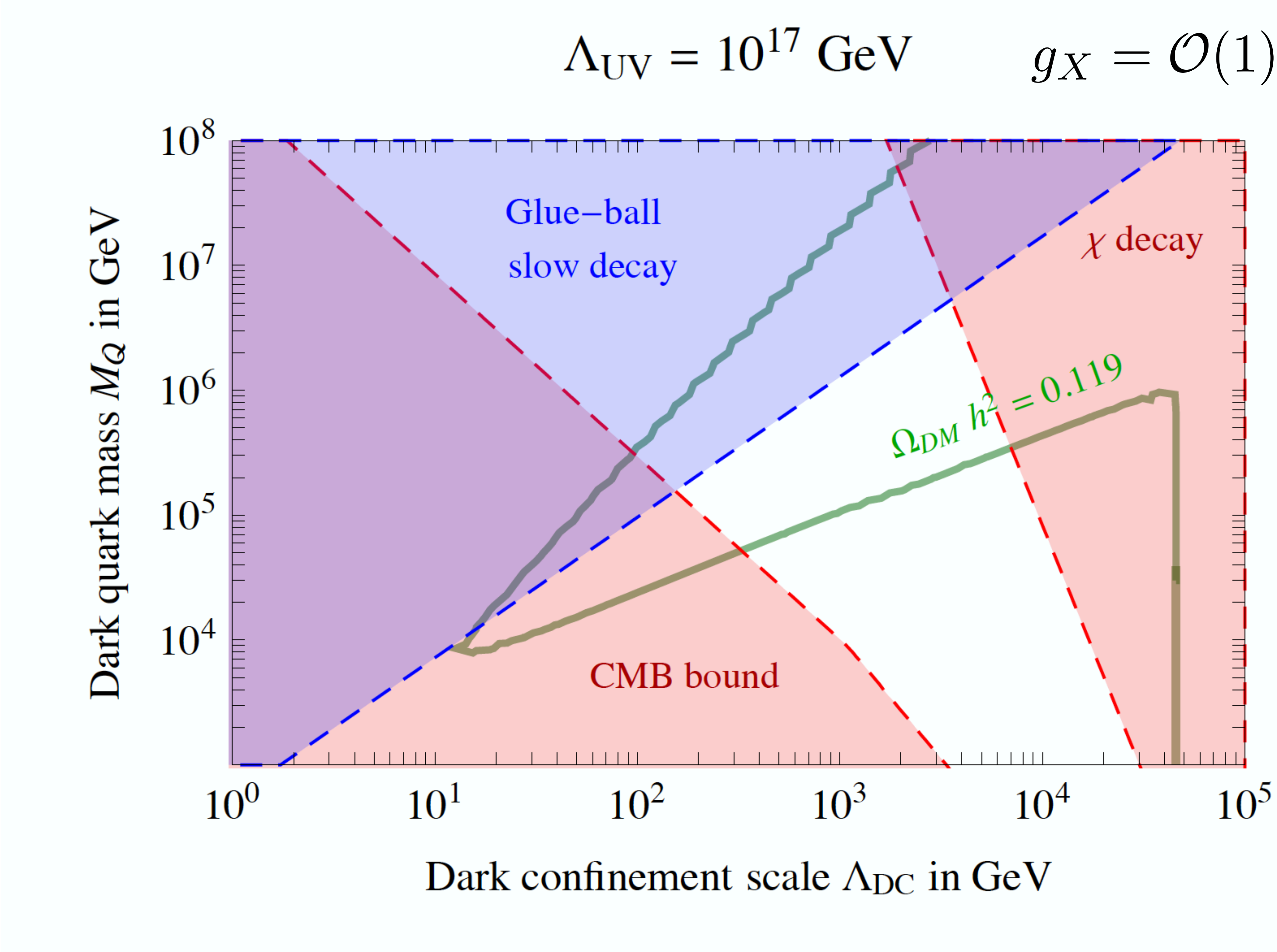
$$\rho_G = (N_{\rm DC}^2 - 1)\frac{\pi^2}{30}T_{\rm conf}^4 \rightarrow \rho_{\rm M,i}$$

$$\begin{cases} \dot\rho_M = -3H\rho_M - \Gamma_\phi\,\rho_M \\ \dot\rho_R = -4H\rho_R + \Gamma_\phi\,\rho_M \end{cases}$$

$$\begin{cases} \rho_M = \rho_{M,i}\left(\frac{a_i}{a}\right)^3 e^{-\Gamma_\phi(t-t_i)} \\ \rho_R = \rho_{R,i}\left(\frac{a_i}{a}\right)^4 + \frac{2}{5}\sqrt{\frac{3}{8\pi}}\Gamma_\phi\, M_{\rm Pl}\,\rho_{M,i}^{1/2}\left[\left(\frac{a_i}{a}\right)^{3/2} - \left(\frac{a_i}{a}\right)^4\right] \end{cases}$$

$$\rho_R \propto T^4 \longrightarrow a \propto T^{-\frac{8}{3}}$$

DM decay


$\Lambda_{UV} = 10^{17}$ GeV
$g_X = \mathcal{O}(1)$
Glue–ball
slow decay
χ decay
$\Omega_{DM}\, h^2 = 0.119$
CMB bound
Dark quark mass M_Q in GeV
Dark confinement scale Λ_{DC} in GeV
10^8
10^7
10^6
10^5
10^4
10^0
10^1
10^2
10^3
10^4
10^5