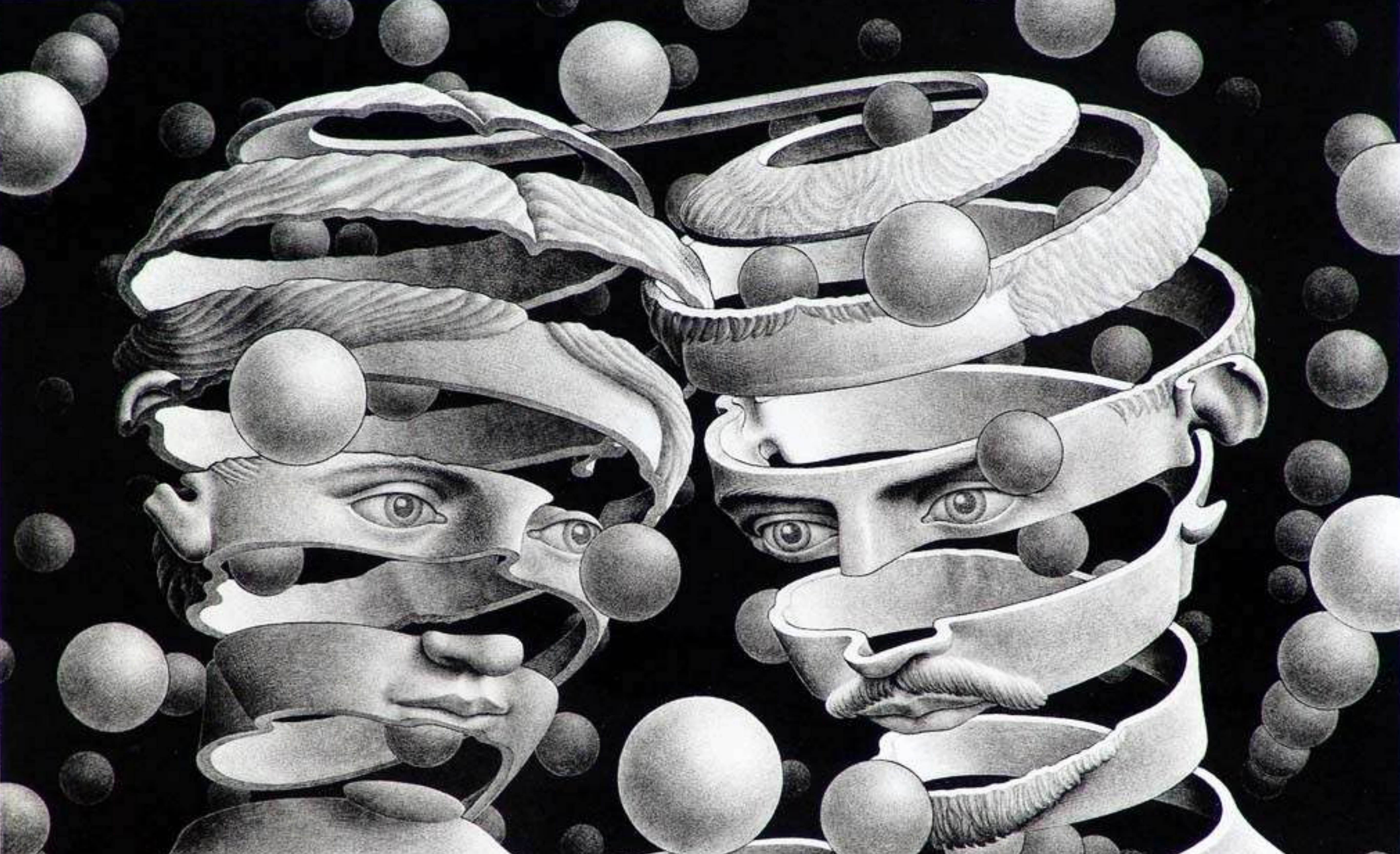


Bindings in the Dark

bound states in DM phenomenology

Andrea Mitridate

SCUOLA NORMALE SUPERIORE

INFN

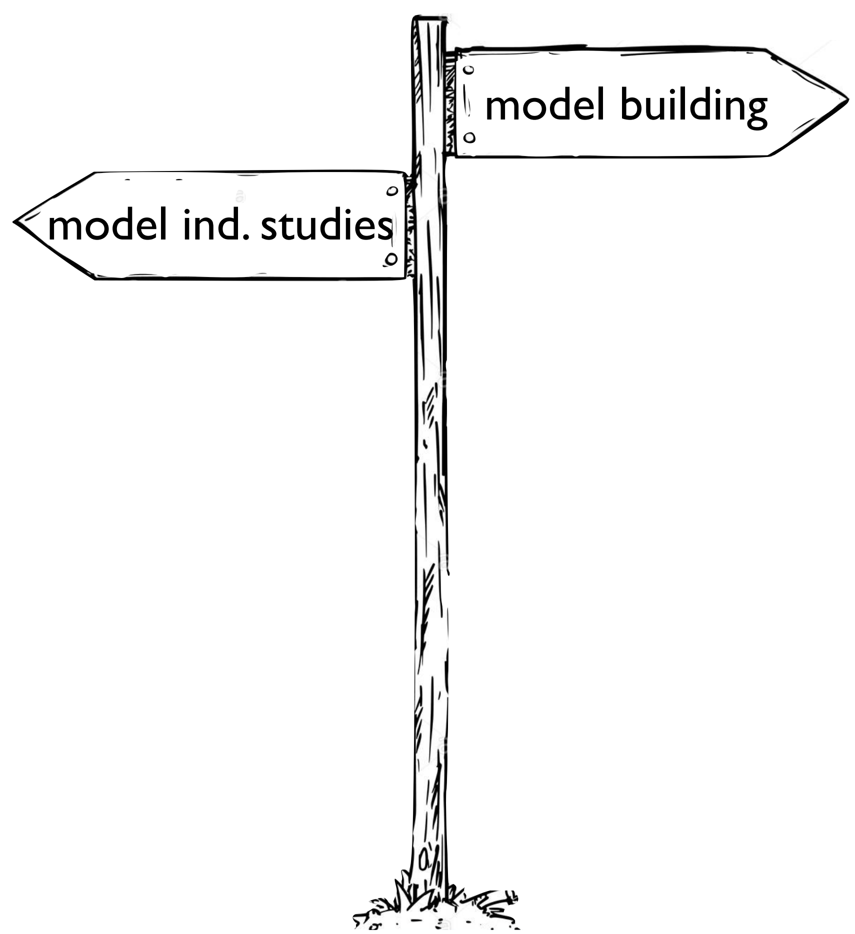
how to tackle the DM problem

proposal for new experiments

bounds on DM properties using astro/cosmo data

studies on DM production mechanisms

…



explain DM

+

origin of the weak scale

or/and

baryogenesis

or/and

strong CP problem

…

how to tackle the DM problem

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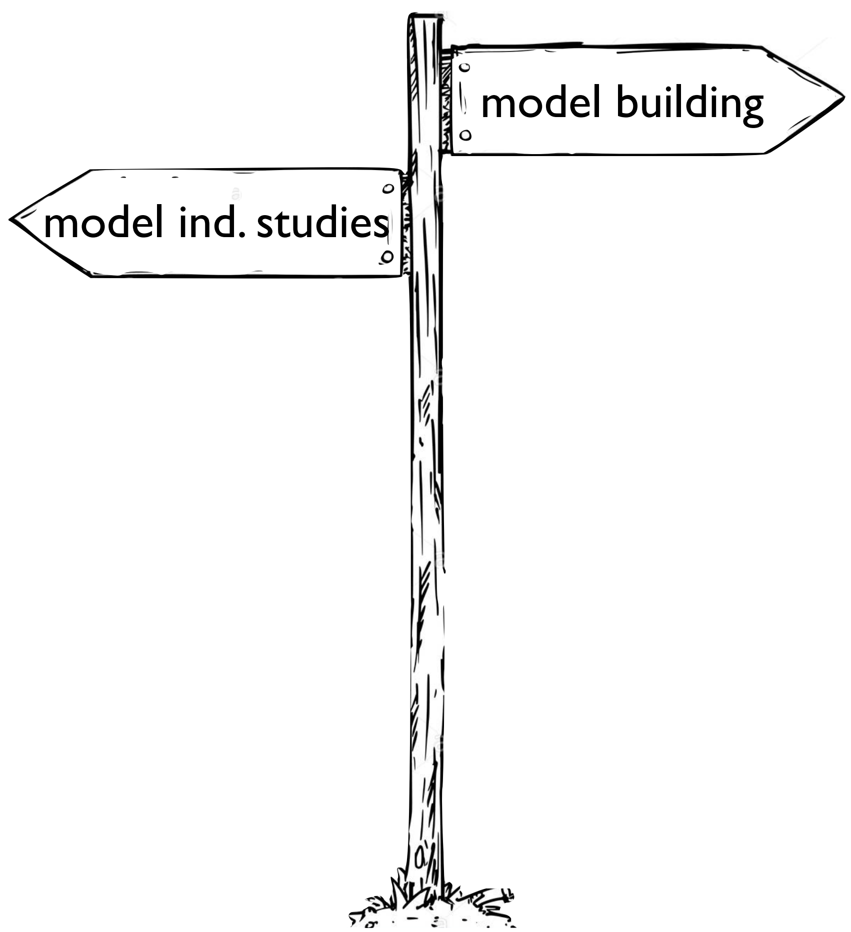

explain DM

+

origin of the weak scale

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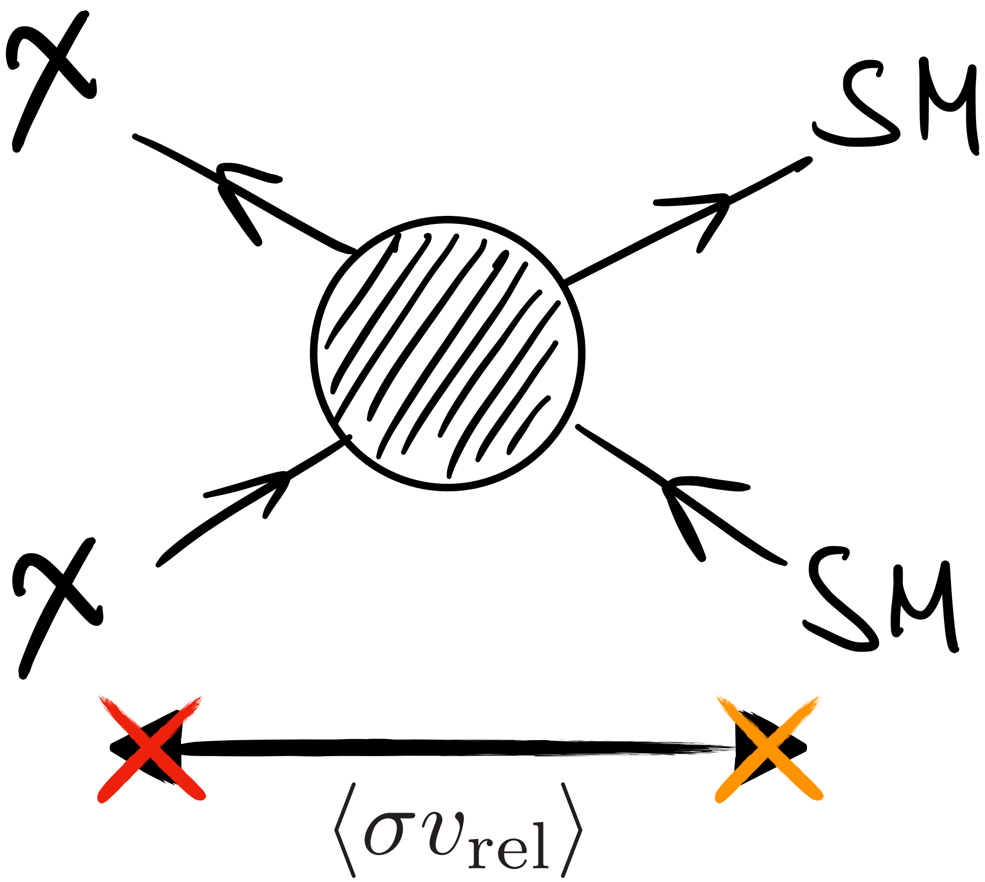
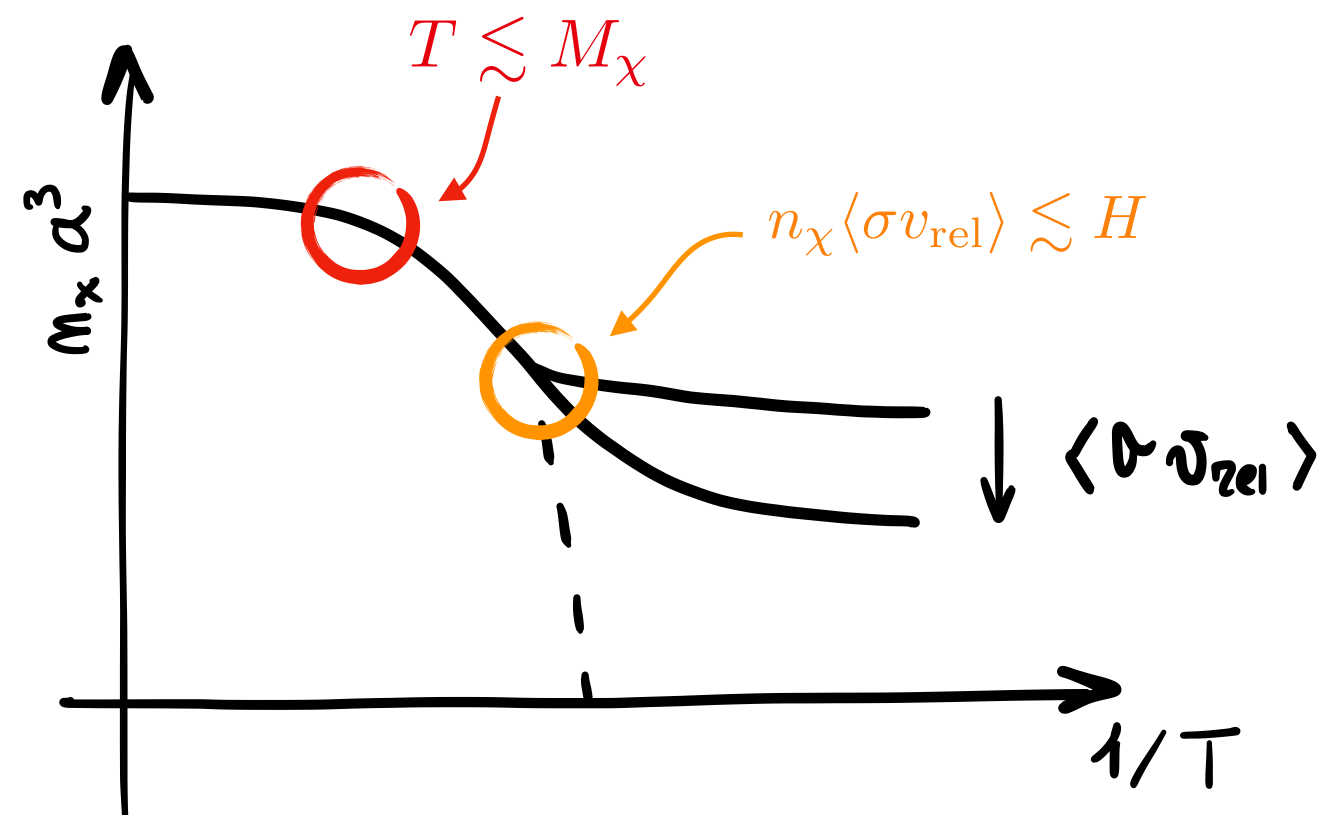
...

Chapter 1

bound states and thermal relics

the standard thermal picture





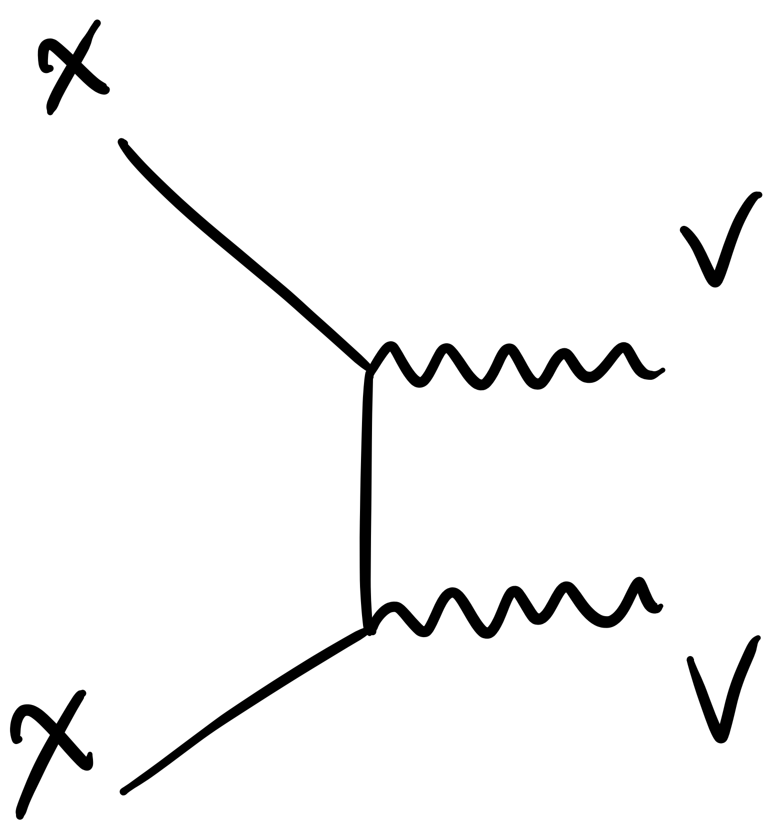
$$\Omega_{\rm DM} h^2 \simeq \frac{10^{-10}\,{\rm GeV}^{-2}}{\langle \sigma_A v \rangle}$$

WIMP(-like) relics

based on JCAP 1705 (2017) no. 05, 006

χ belongs to a representation R of a weakly coupled gauge group with vector mediators V_a

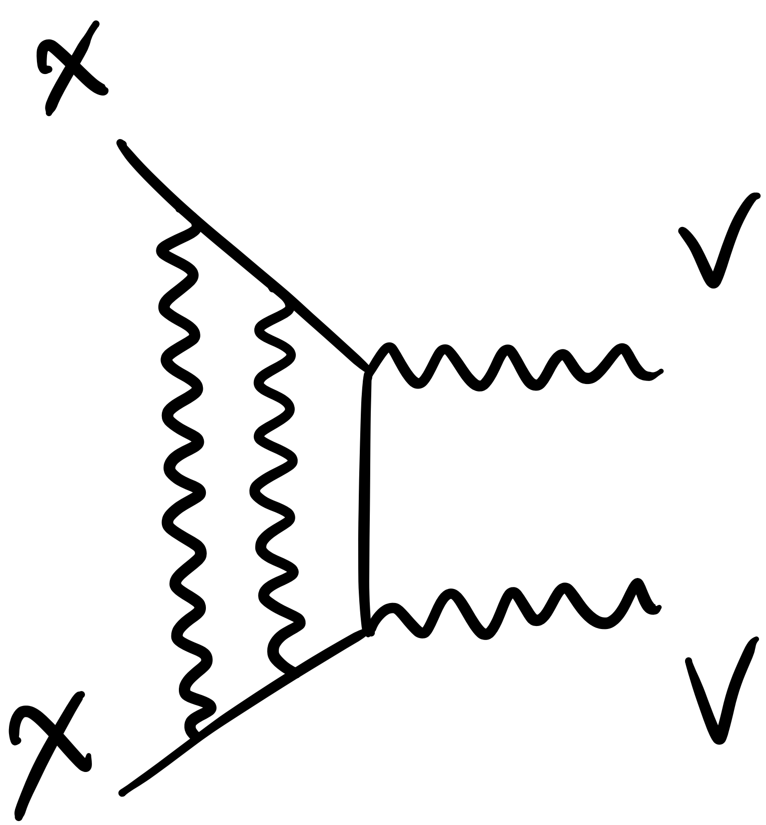
interactions associated to this group set the relic density



$$\langle \sigma v_{\rm rel} \rangle \simeq \frac{\pi \alpha^2}{M_\chi^2}$$

χ belongs to a representation R of a weakly coupled gauge group with vector mediators V_a

interactions associated to this group set the relic density



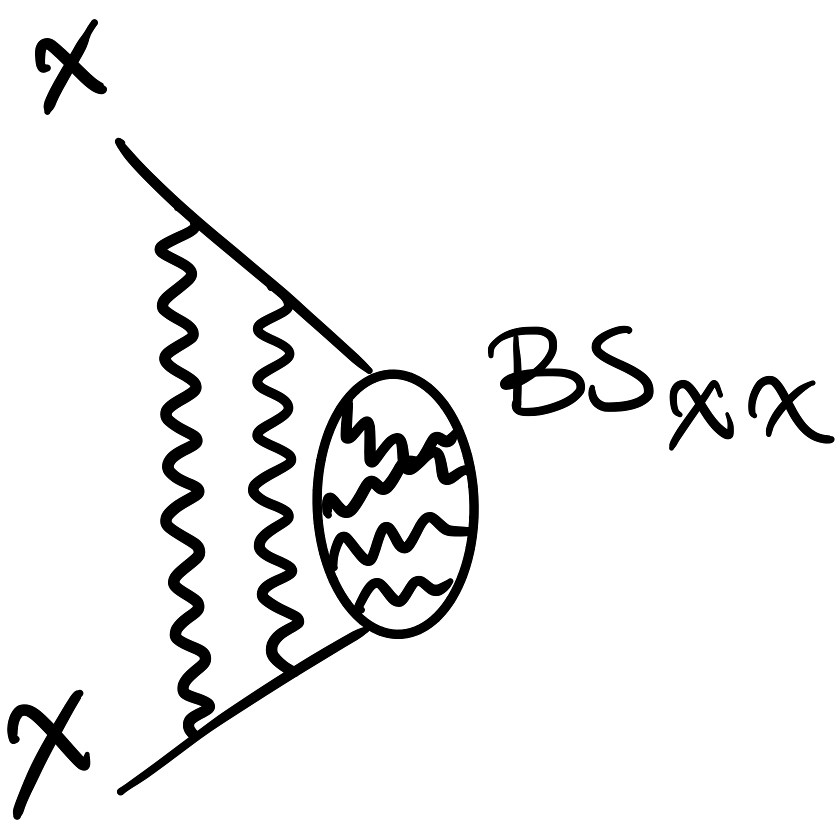
If the interaction is long ranged ($\alpha M_\chi > M_V$), non perturbative effects can spoil the perturbative results

$$\langle \sigma v_{\rm rel} \rangle \simeq S_{\rm Som} \frac{\pi \alpha^2}{M_\chi^2} \sim \frac{\alpha}{v_{\rm rel}} \frac{\pi \alpha^2}{M_\chi^2}$$

[Sommerfeld (1931); Hisano et al. (2002); …]

χ belongs to a representation R of a weakly coupled gauge group with vector mediators V_a

interactions associated to this group set the relic density

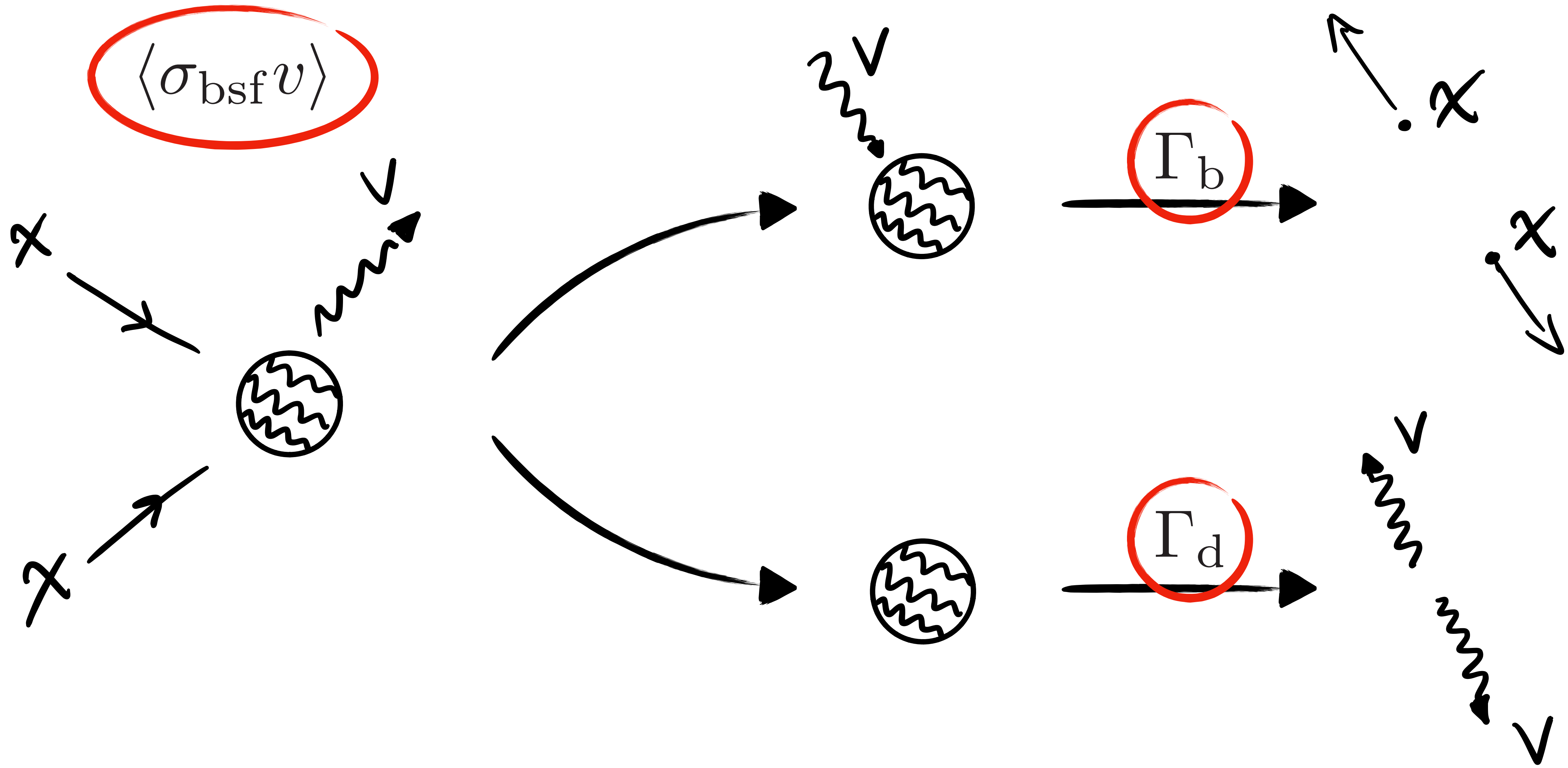


If the interaction is long ranged ($\alpha M_\chi > M_V$), non perturbative effects can spoil the perturbative results

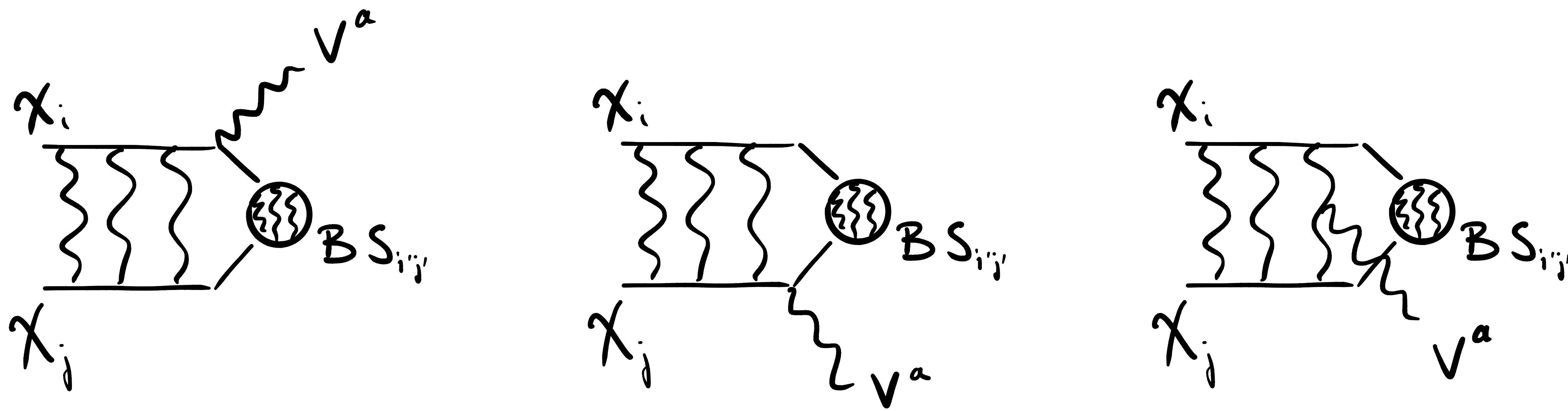
$$\langle \sigma v_{\rm rel} \rangle \simeq (S_{\rm Som} + S_{\rm BS}) \frac{\pi \alpha^2}{M_\chi^2}$$

Scalar mediator: Wise et al. (2014)
Abelian gauge theory: Petraki et al. (2014)
QCD in the perturbative regime: Ellis (2015)

how bound states get in the game



$$\langle \sigma v \rangle \longrightarrow \langle \sigma v \rangle + \mathrm{BR}\, \langle \sigma_{\rm bsf} v \rangle \qquad \mathrm{BR} = \frac{\langle \Gamma_{\rm d} \rangle}{\langle \Gamma_{\rm d} + \Gamma_{\rm b} \rangle}$$



$$\mathscr{A}_{p,nlm} \approx \langle \psi_{n\ell m, i'j'} V_a | H_I | \phi_{pl,ij} \rangle$$

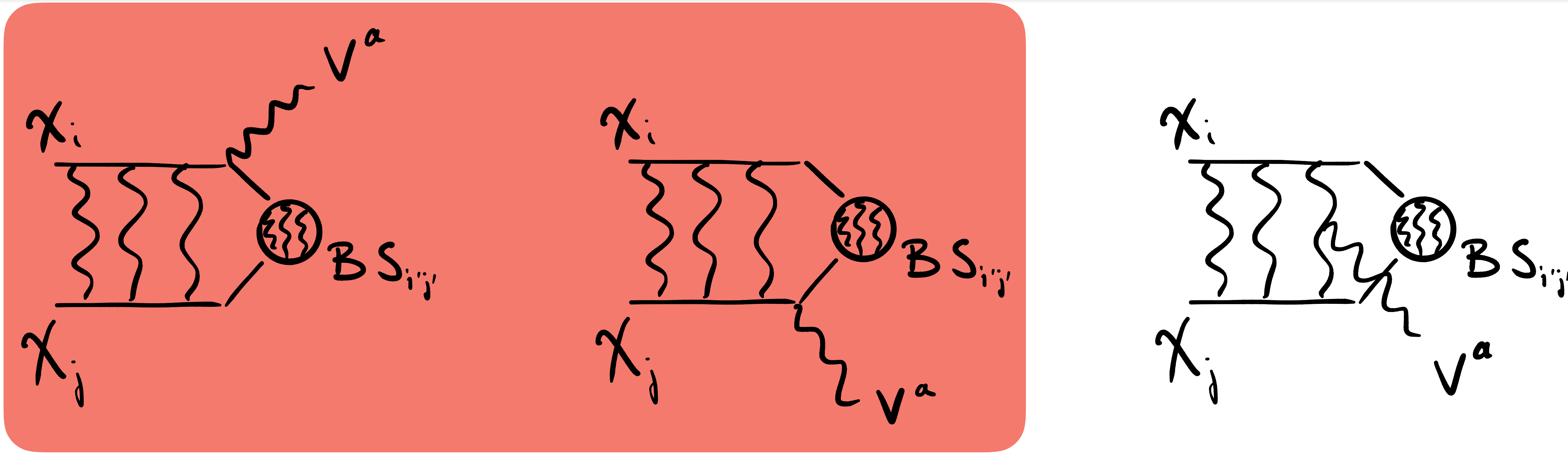
$$H_I = -\frac{g}{M_\chi}\left(\vec{A}^a \cdot \vec{p}_1 T^a_{i'i}\delta_{jj'} + \vec{A}^a \cdot \vec{p}_2 \overline{T}^a_{j'j}\delta_{ii'}\right) + \left(g\alpha \vec{A}^a(0)\cdot \hat{r}\, e^{-M_a r}\right) T^b_{i'i}\overline{T}^c_{j'j} f^{abc}$$

$$R \otimes R' = \sum_J J$$

wave-functions are solution of

$$-\frac{\nabla^2 \psi}{M_\chi} + V\psi = E\psi$$

$$V = -\frac{\alpha_{eff}}{r} e^{-M_V r} \qquad \alpha_{eff} = \alpha(C_J - C_R - C_{R'})$$



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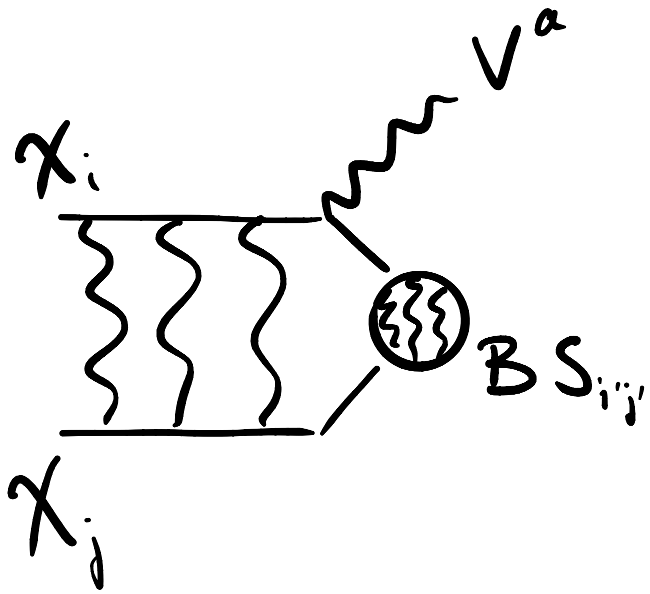

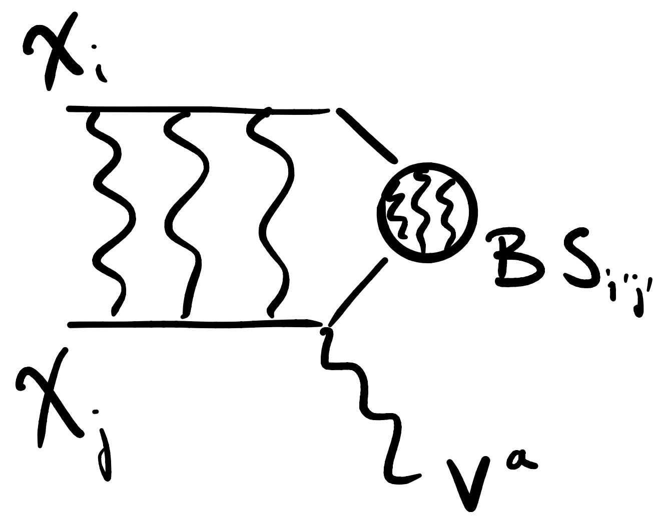

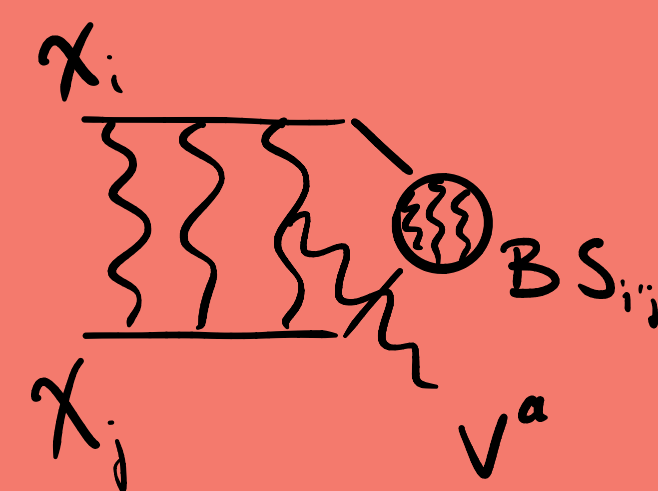

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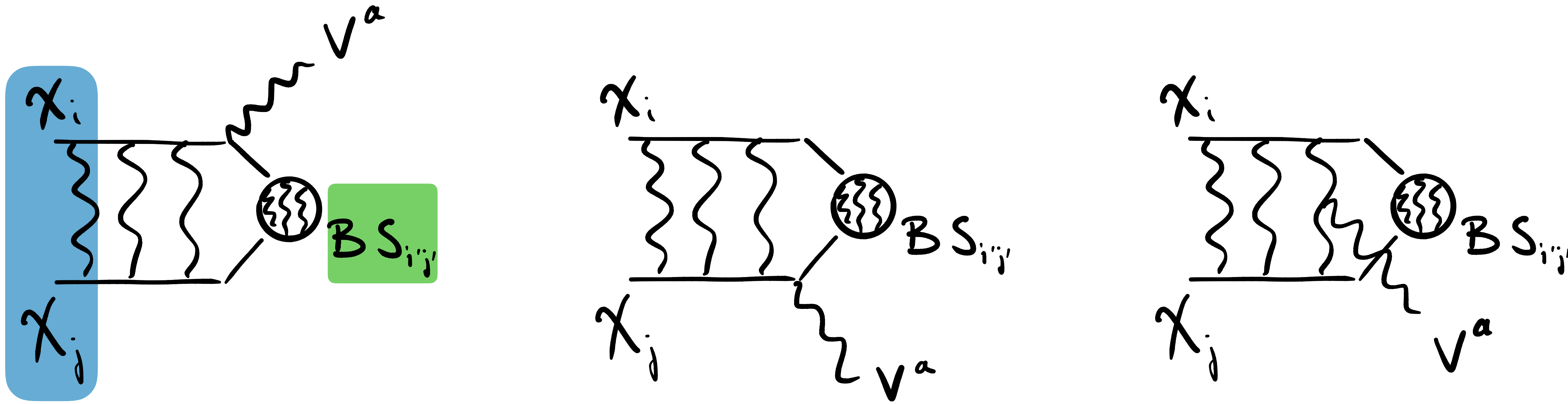

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In general BS cross sections have to be computed numerically, however for $M_V = 0$ we can get an analytic expressions, e.g.

$$(\sigma v_{\text{rel}})^{n=1,\ell=0}_{\text{bsf}} = \sigma_0 \lambda_i (\lambda_f \zeta)^5 \frac{2S+1}{g_\chi^2} \frac{2^{11}\pi(1+\zeta^2\lambda_i^2)e^{-4\zeta\lambda_i \operatorname{arccot}(\zeta\lambda_f)}}{3(1+\zeta^2\lambda_f^2)^3\,(1-e^{-2\pi\zeta\lambda_i})} \times \sum_{aMM'} \left| C_{\mathcal{J}}^{aMM'} + \frac{1}{\lambda_f} C_{\mathcal{T}}^{aMM'} \right|^2$$

Physics becomes more clear in the limit $v_{rel} \ll \alpha$

$$(\sigma v_{\text{rel}})^{n=1,\ell=0}_{\text{bfs}} \propto \frac{\pi\alpha^2}{M_\chi^2} \times \frac{\lambda_i^3 \alpha}{\lambda_f v_{\text{rel}}} \times \sum_{aMM'} \left| C_{\mathcal{J}}^{aMM'} + \frac{1}{\lambda_f} C_{\mathcal{T}}^{aMM'} \right|^2$$

$$+ \left(g\alpha \vec{A}^a(0) \cdot \hat{r}\, e^{-M_a r} \right) T^b_{i'i} \overline{T}^c_{j'j} f^{abc}$$

wave-functions are solution of

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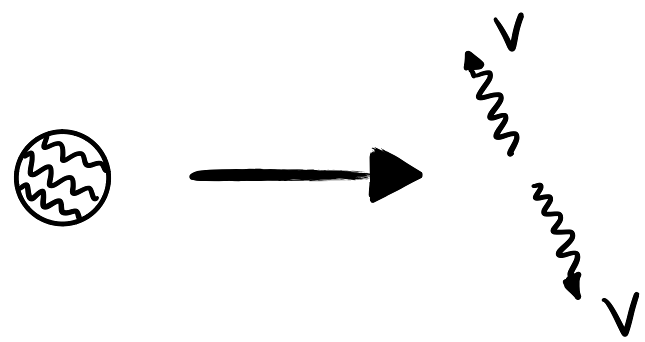
decay and breaking rates

Decay



decays happen mostly in the $\ell = 0$ states

Spin 0

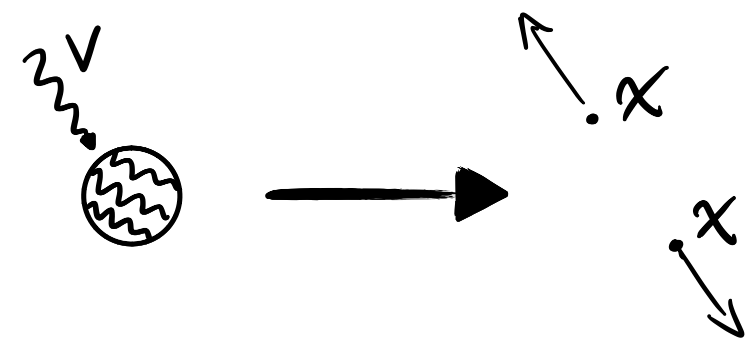
$$\Gamma_d\left(B_{n0} \to VV\right) \propto \alpha_{eff}^5 M_\chi$$

Spin 1

$$\Gamma_d\left(B_{n0} \to \bar{f}f\right) \propto \alpha_{eff}^5 M_\chi$$

$$\Gamma_d\left(B_{n0} \to VVV\right) \propto \alpha_{eff}^6 M_\chi$$

Break



breaking rate is related to formation cross section by the Milne relation

$$2n_B\Gamma_b = (n_\chi^{eq})^2\langle\sigma_{\rm bsf}v_{rel}\rangle$$

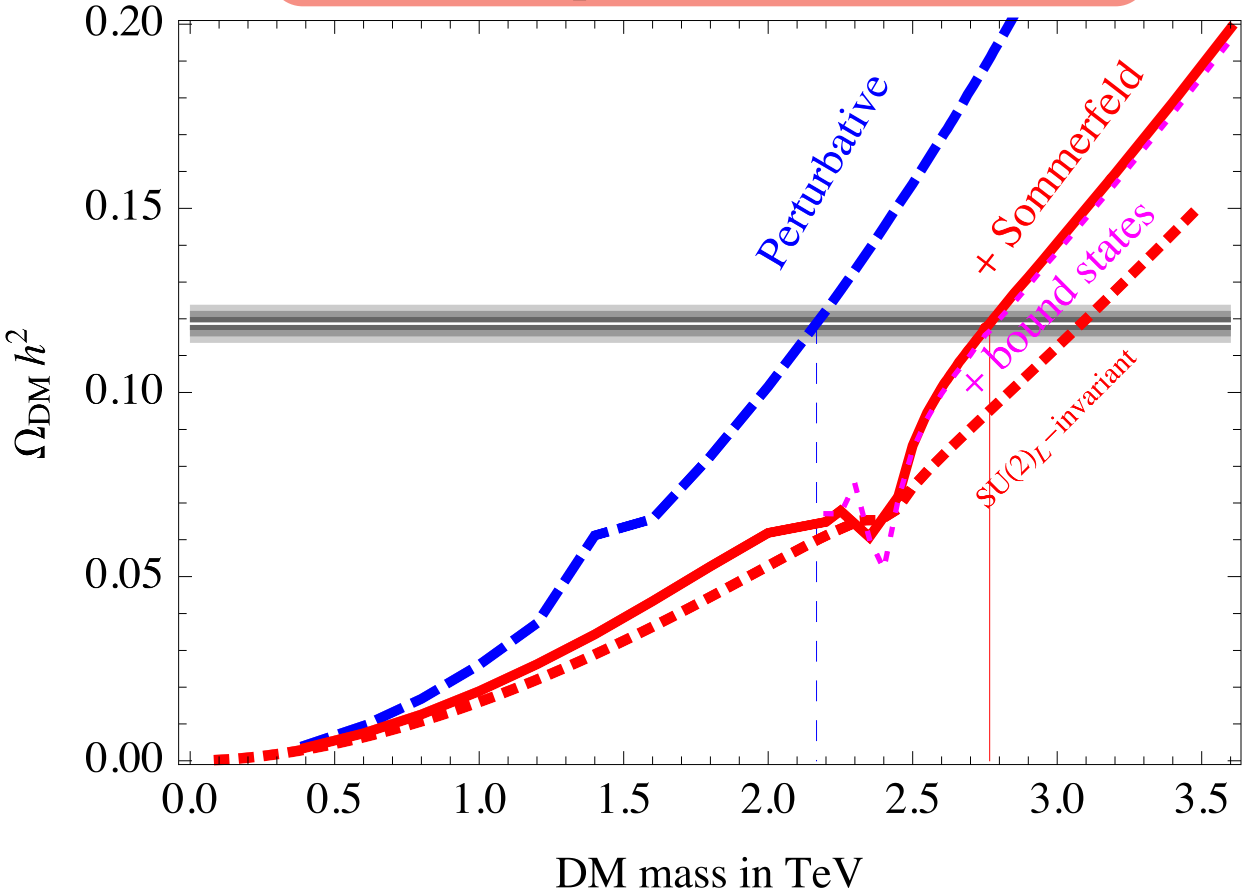
in the non-relativistic limit it reduces to

$$\Gamma_b \propto \left(M_\chi T\right)^{3/2} e^{-E_B/T}\langle\sigma_{\rm bsf}v_{rel}\rangle$$

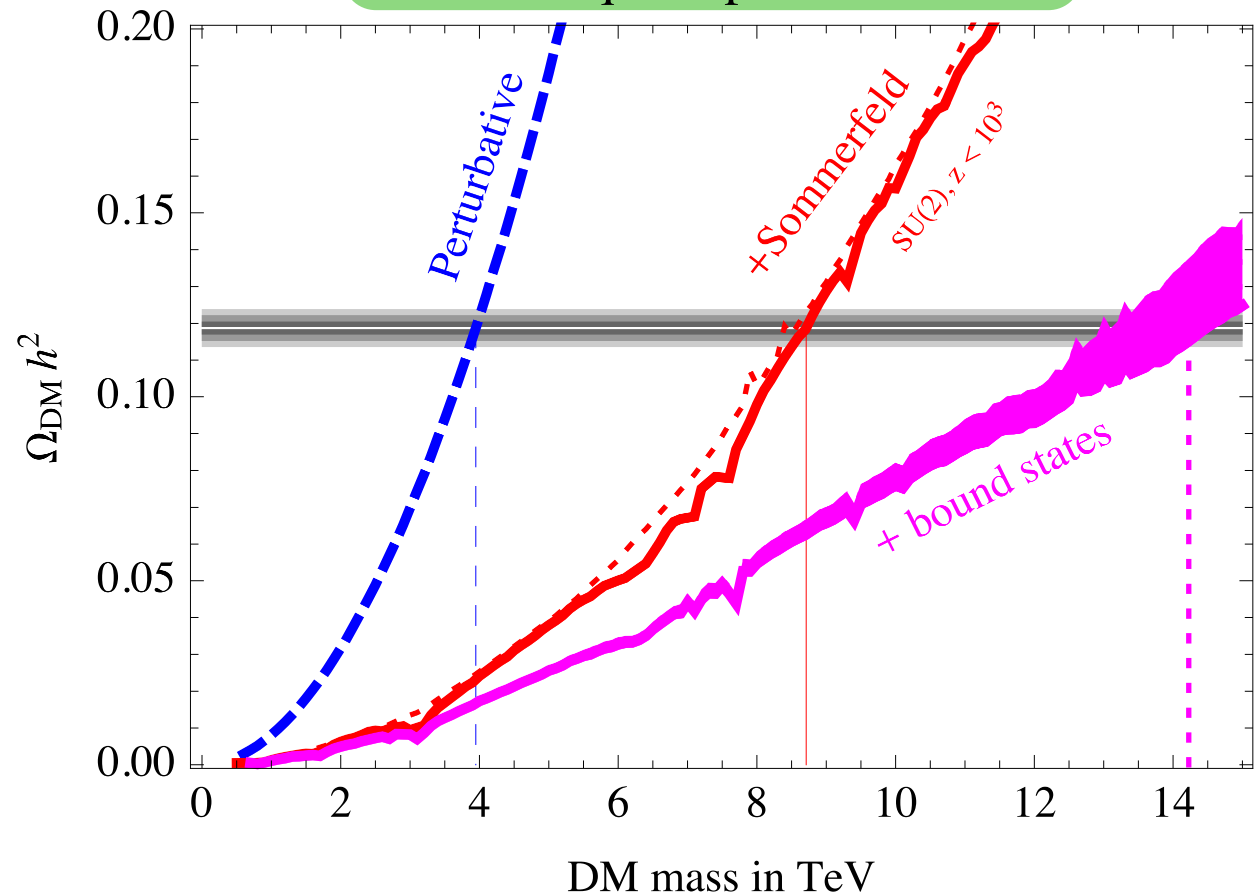
bound state formation is important when $\Gamma_d \gg \Gamma_b$

application to minimal DM candidates

Fermion triplet with $Y = 0$ ('wino')

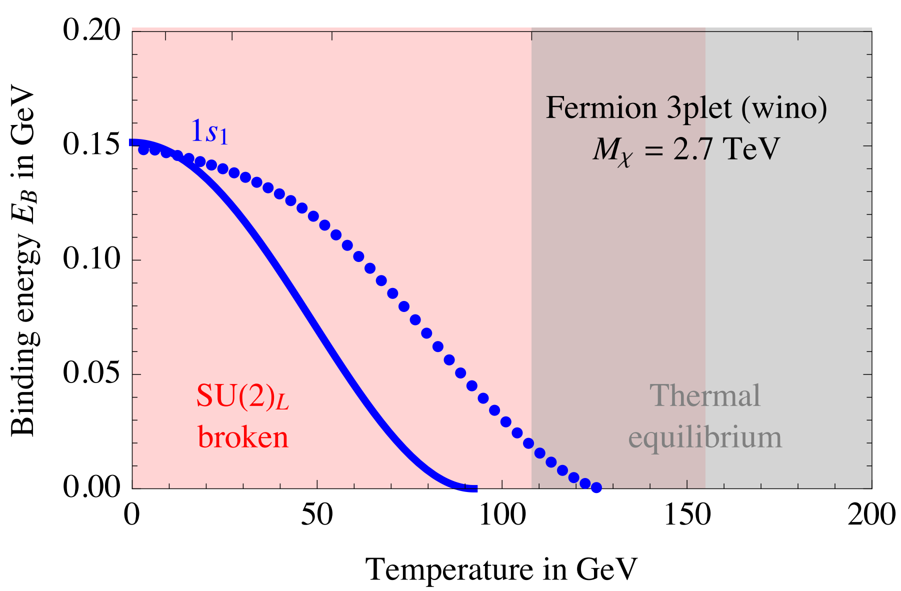


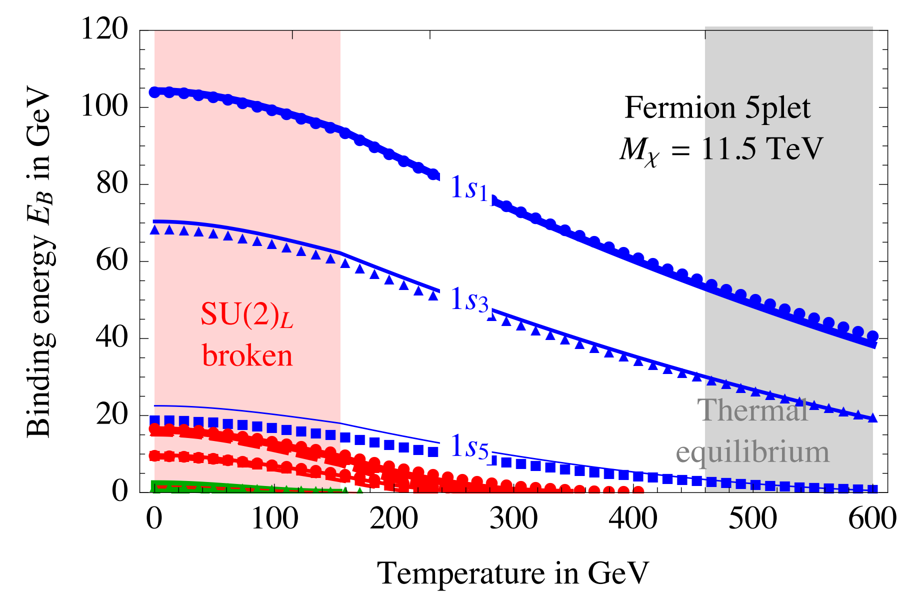
Fermion quintuplet with $Y = 0$



no substantial **effect** because bound states are too shallow

60% effect due to the presence of deep bound states





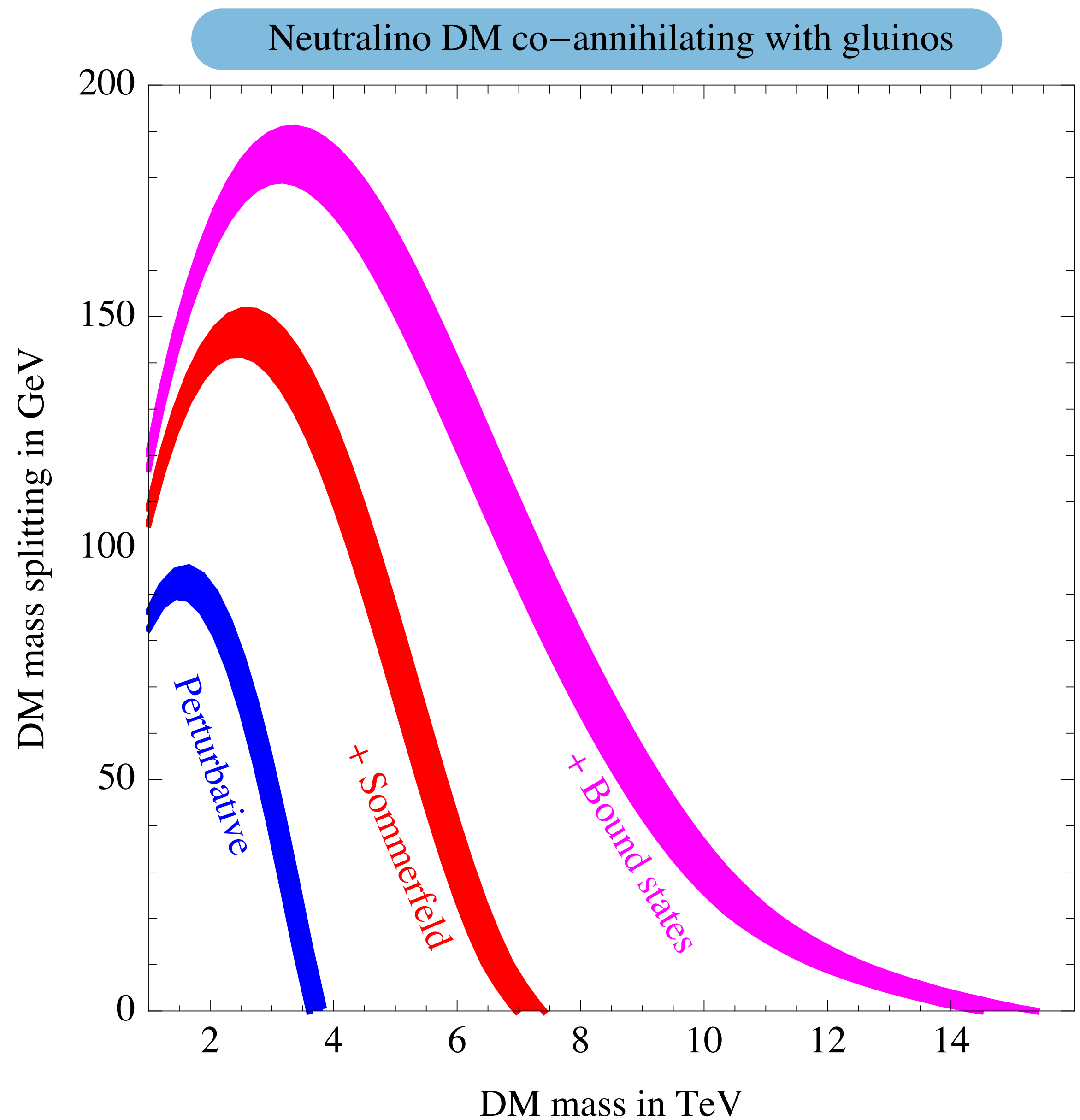
application to coannihilating DM

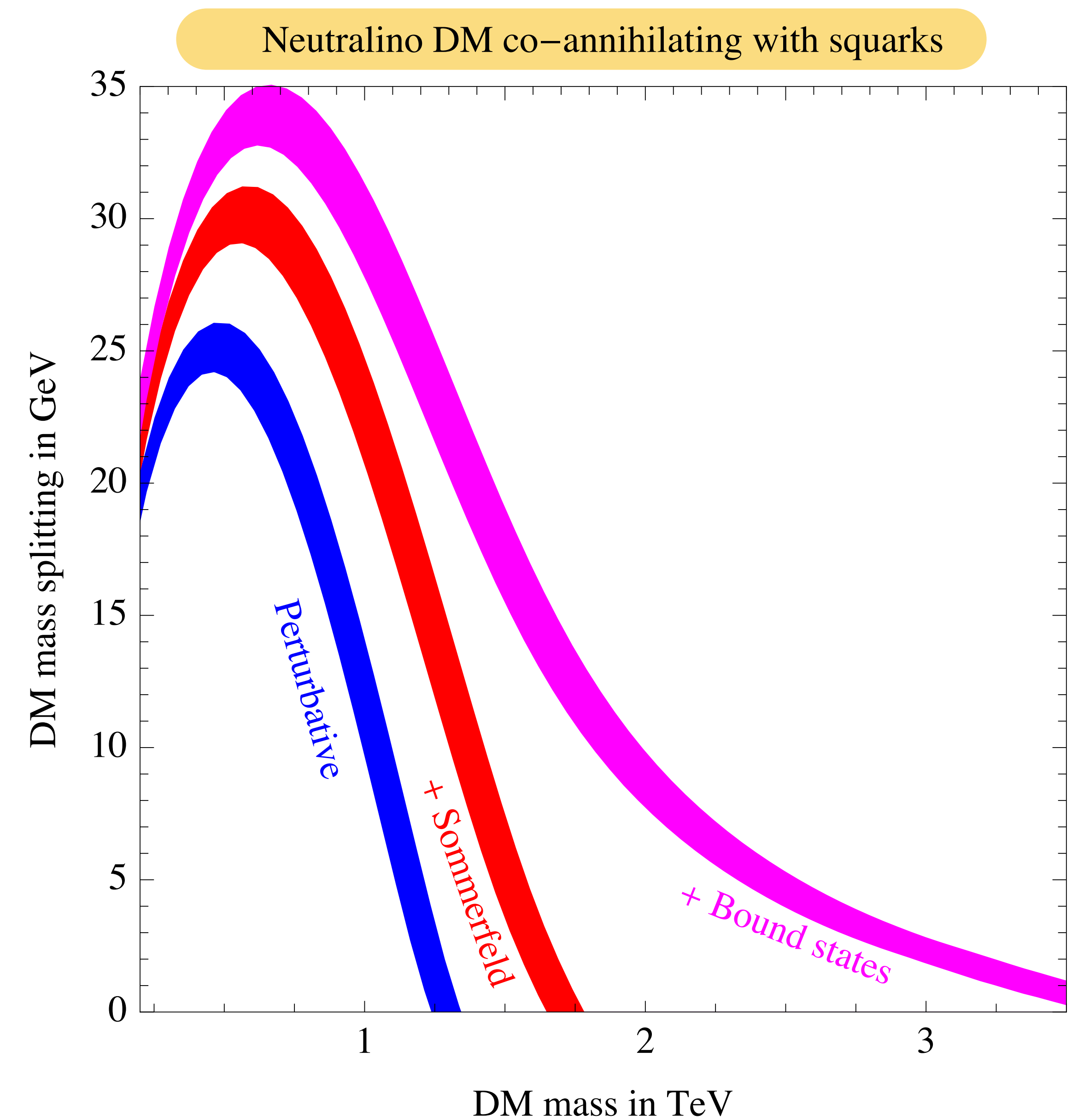
DM candidate

colored partner

$$\chi + \mathrm{SM} \to \tilde{\chi} + \mathrm{SM}$$

$$\tilde{\chi} + \tilde{\chi} \to \mathrm{SM} + \mathrm{SM}$$





colored(-like) relics

based on PRD 99 (2019) no.1

colored-like scenarios

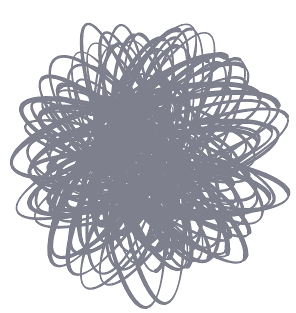
χ belongs to a representation R of a confining gauge group with confinement scale $\Lambda < M_\chi$

interactions associated to this group set the relic density

below the confinement scale

light d.o.f

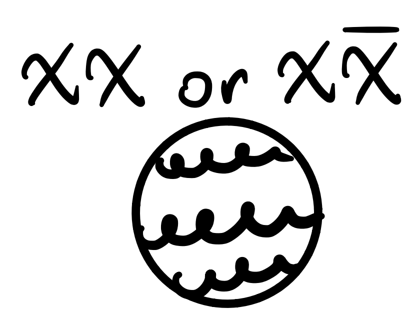
pion-like states if light ($M < \Lambda$) particles are present
or
glueball states otherwise

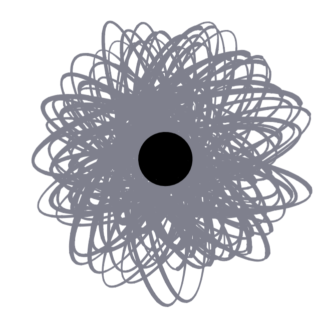


$M \sim \Lambda$

heavy d.o.f

bound states made of χ only
and
bound states of χ and light particles/mediators

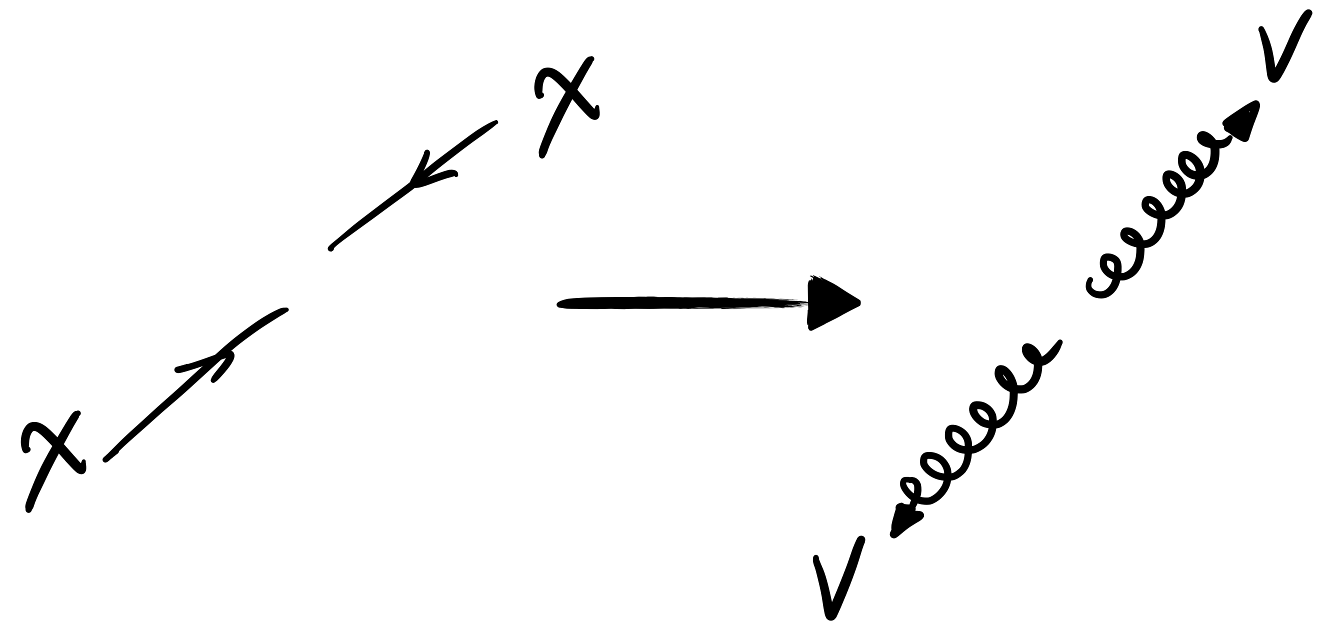




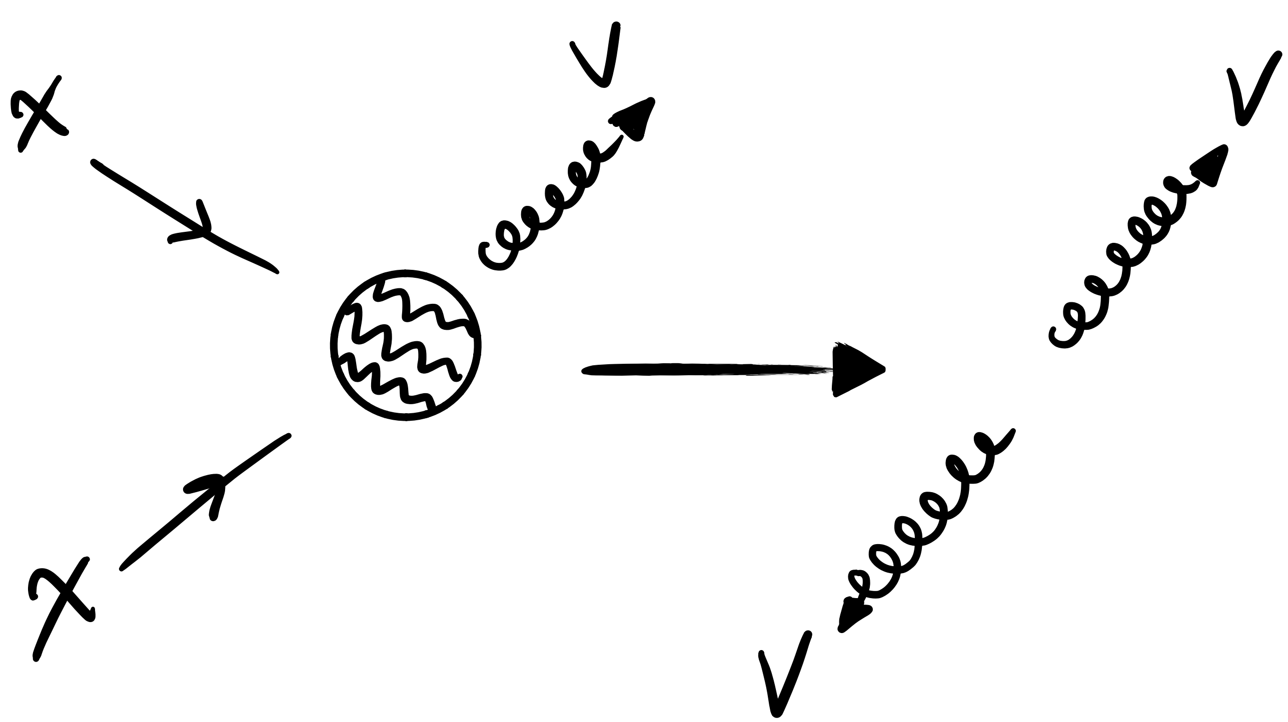
$M \sim M_\chi$

what does not change

at $T > \Lambda$ everything goes like in the weakly coupled scenario



direct annihilation (enhanced by Sommerfeld effects)

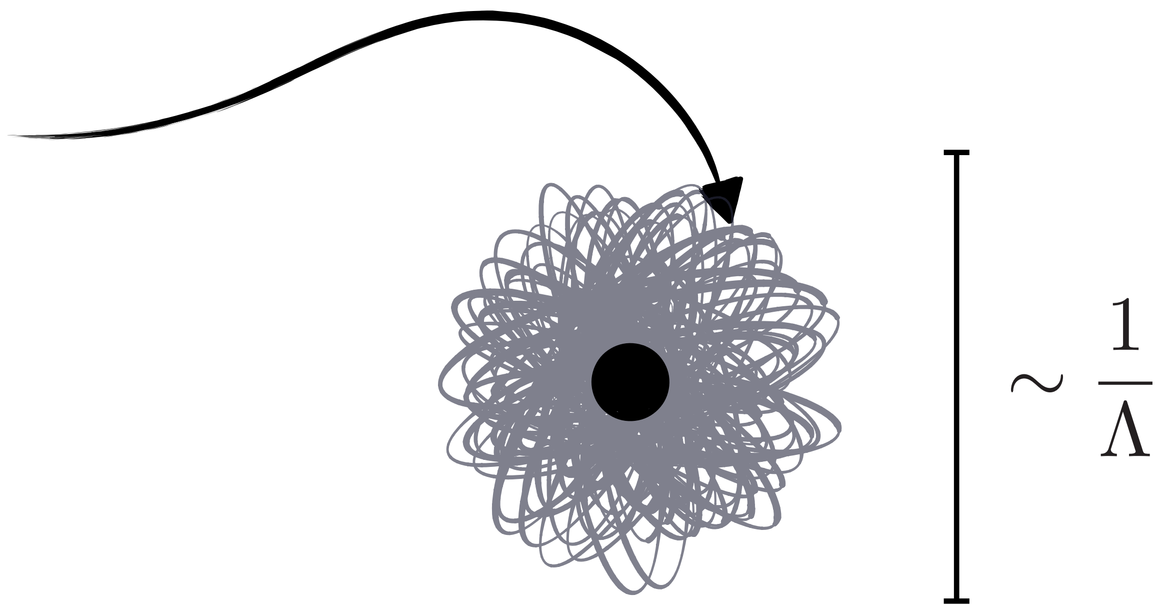


annihilation mediated by perturbative production of unstable bound states at $T < \Lambda$ everything confines into (dark) color singlet states

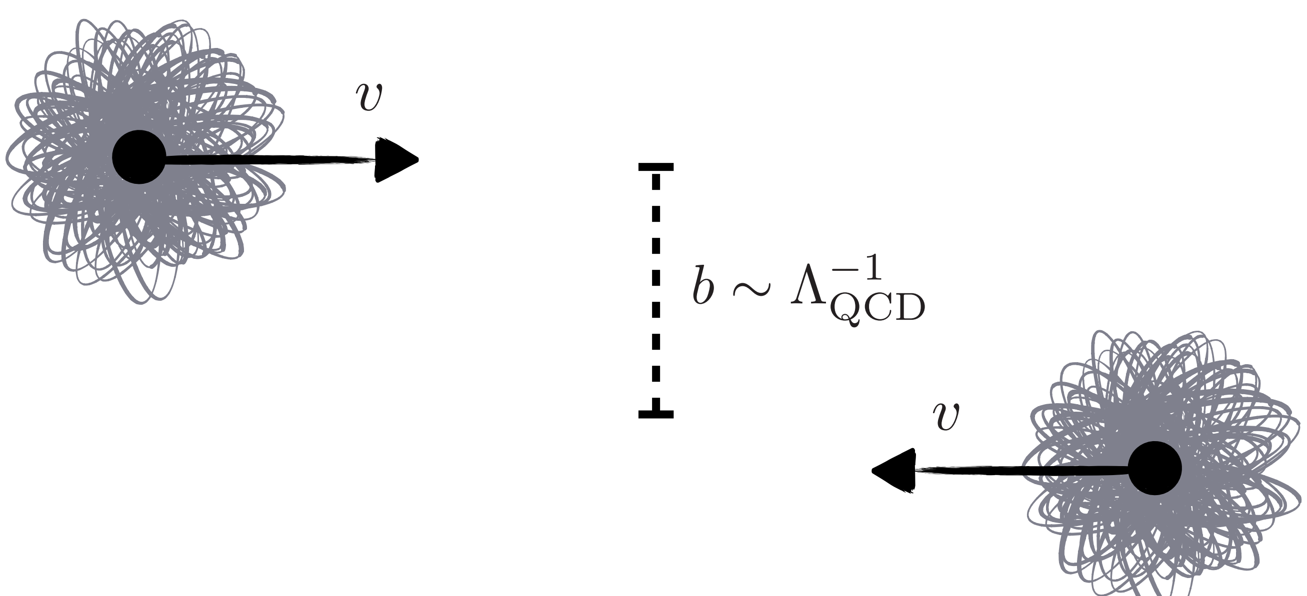
in the QCD case

$R = \square \longrightarrow qq$ or $\bar{q}$

$R = \mathrm{Adj} \longrightarrow q\bar{q}$ or g

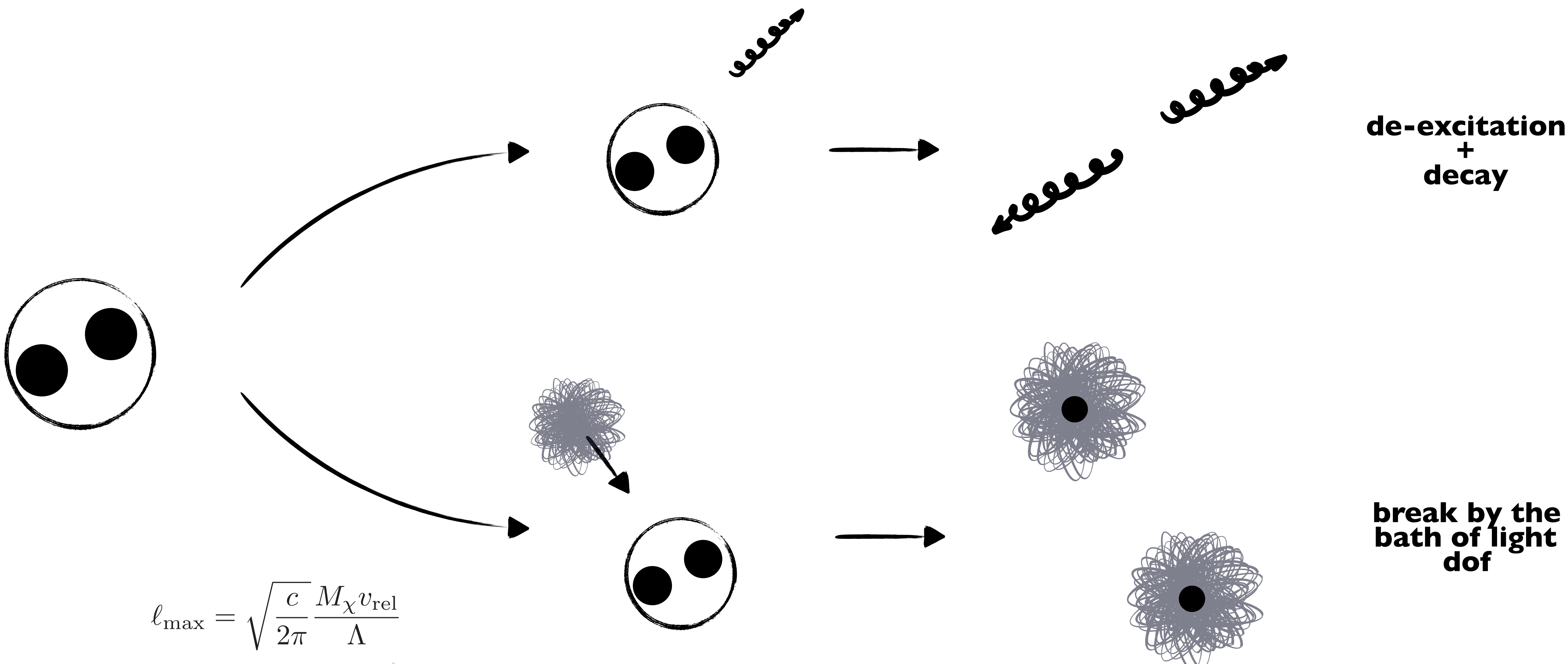


these states collide with large impact parameters, giving rise to self scattering cross-sections of typical QCD size



$$\sigma \sim \Lambda_{\mathrm{QCD}}^{-2} \gg \alpha_3^2/M_{\mathcal{Q}}^2$$

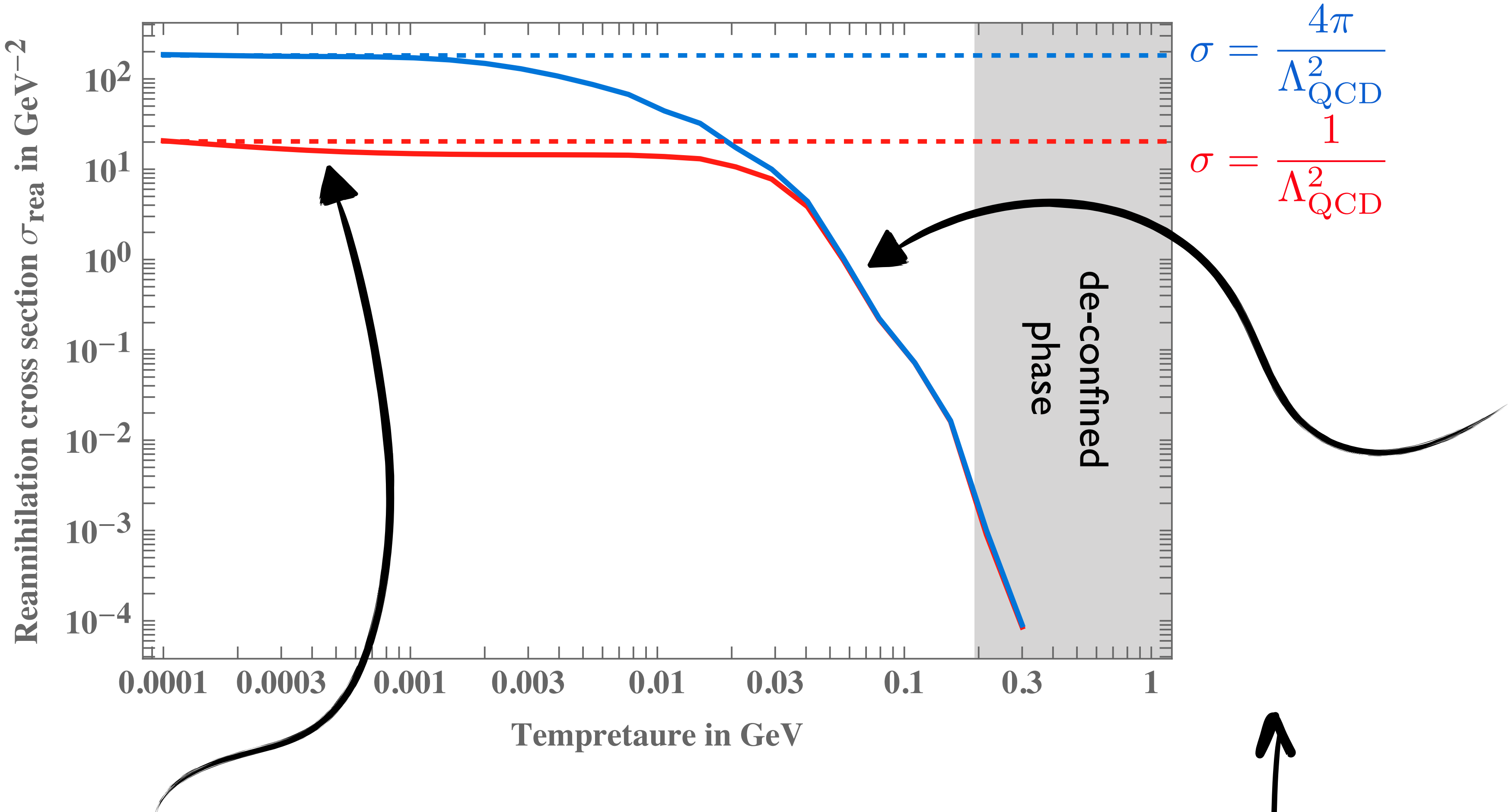
$\chi\chi$ **bound states can form in such collisions**



$$\ell_{\max} = \sqrt{\frac{c}{2\pi}\frac{M_\chi v_{\rm rel}}{\Lambda}}$$

$$\sigma_{\rm rea} = \sum_{\ell=0}^{\ell_{\max}} \wp_\ell \sigma_\ell \qquad \sigma_\ell \simeq 2\pi \frac{2\ell+1}{M_\chi^2 v_{\rm rel}^2}$$

simulating numerically the dynamic of the system we computed the $\wp_\ell$ for the QCD case



at $T >> m_\pi$ the effective re-annihlation cross section is reduced compared to the geometric one

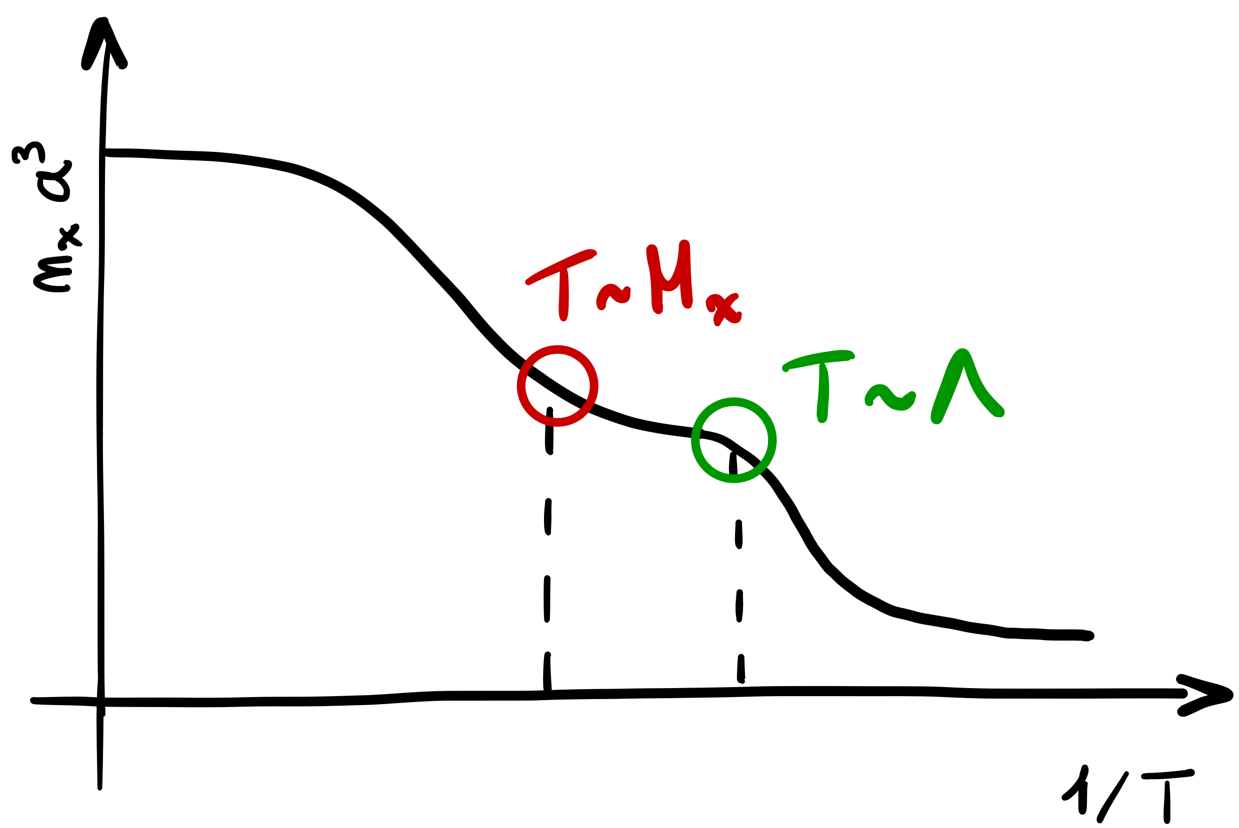
at low temperatures all the ℓ-states manage to decay

$$\Downarrow$$

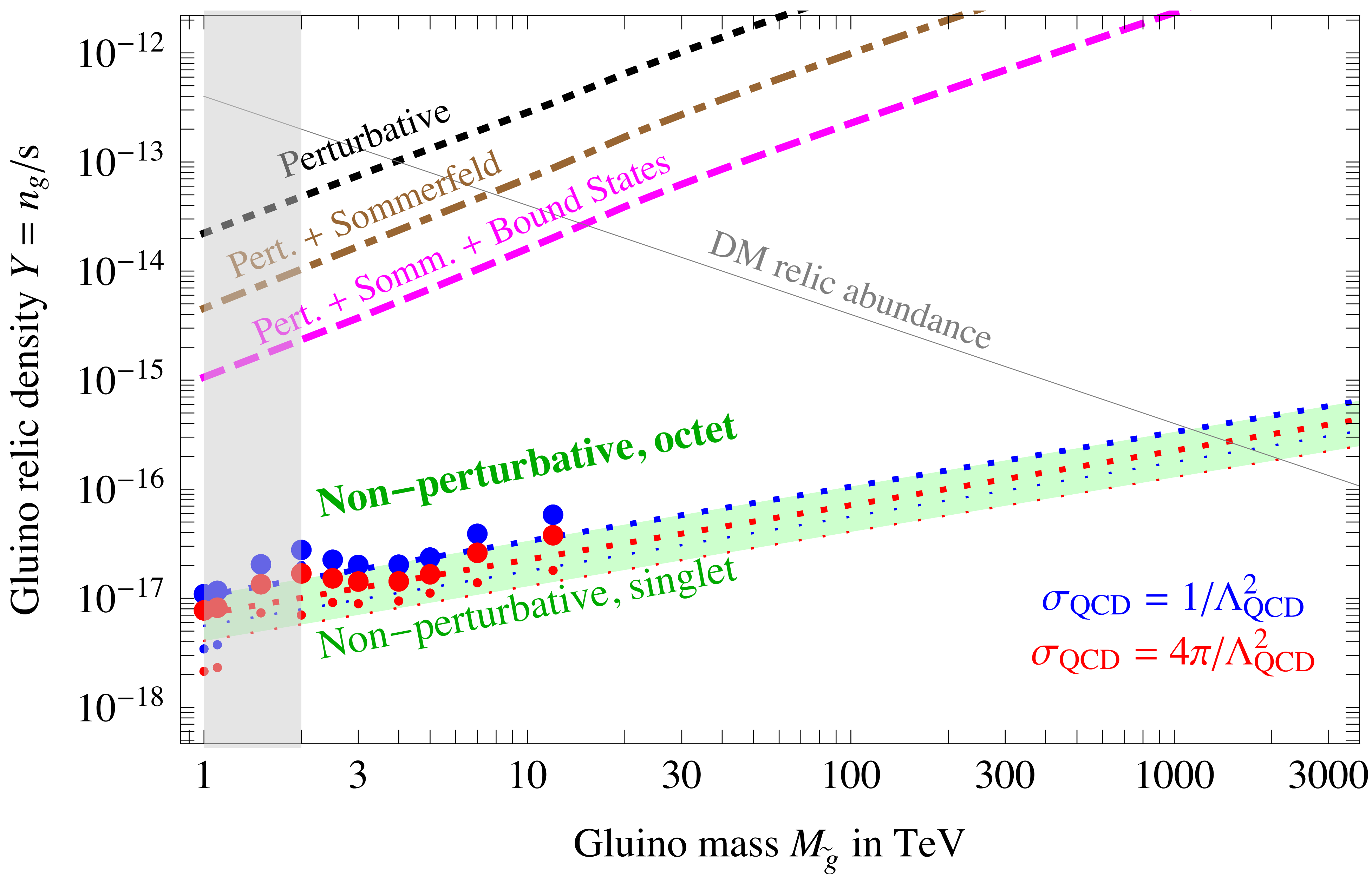
$$\wp_\ell = 1$$

$$\Downarrow$$

$$\sigma_{rea} = \frac{c}{\Lambda^2}$$



application: long-lived gluino relic



Chapter 2

bound states as the Dark Matter

Dark Matter as a QCD bound state

based on PRD 97 (2018) no.11

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \bar{\mathcal{Q}}\left(i\not{D} - M_{\mathcal{Q}}\right)\mathcal{Q}$$

$$\mathcal{Q} = (8,1)_0$$

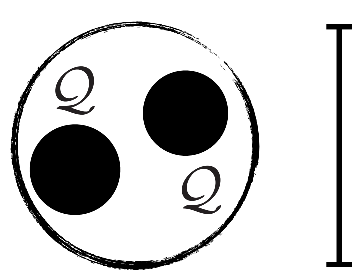
the model

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\mathcal{Q}}\left(i\not{D} - M_{\mathcal{Q}}\right)\mathcal{Q}$$

$$\mathcal{Q} = (8,1)_0$$

new (stable) hadrons are expected

$\mathcal{Q}$ -onlyum



$$\sim \frac{1}{\alpha_3 M_{\mathcal{Q}}}$$

$$E_B \sim \alpha_3^2 M_{\mathcal{Q}}$$

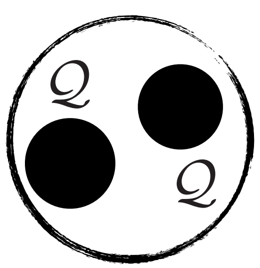
DM candidate

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\mathcal{Q}} \left(i \not{D} - M_{\mathcal{Q}} \right) \mathcal{Q}$$

$$\mathcal{Q} = (8, 1)_0$$

new (stable) hadrons are expected

$\mathcal{Q}$ -onlyum



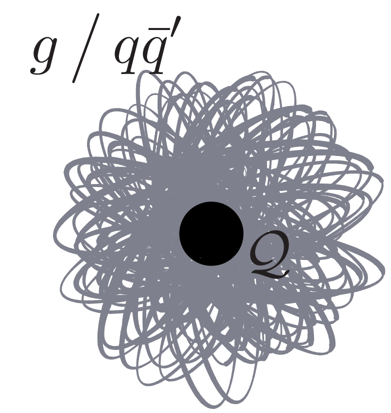
$\sim \frac{1}{\alpha_3 M_{\mathcal{Q}}}$

$$E_B \sim \alpha_3^2 M_{\mathcal{Q}}$$

DM candidate

Hybrids

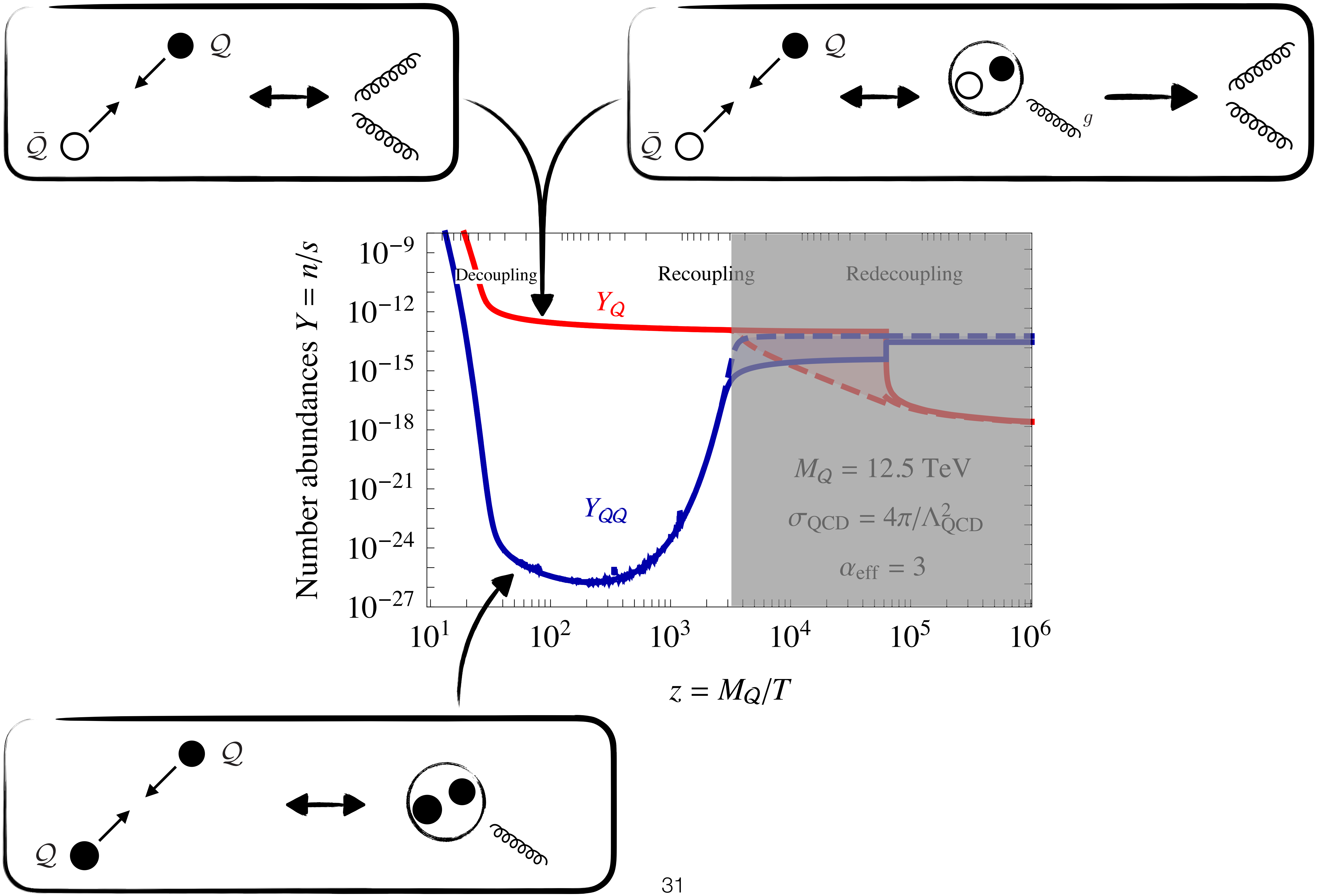
$\sim \frac{1}{\Lambda_{\rm QCD}}$



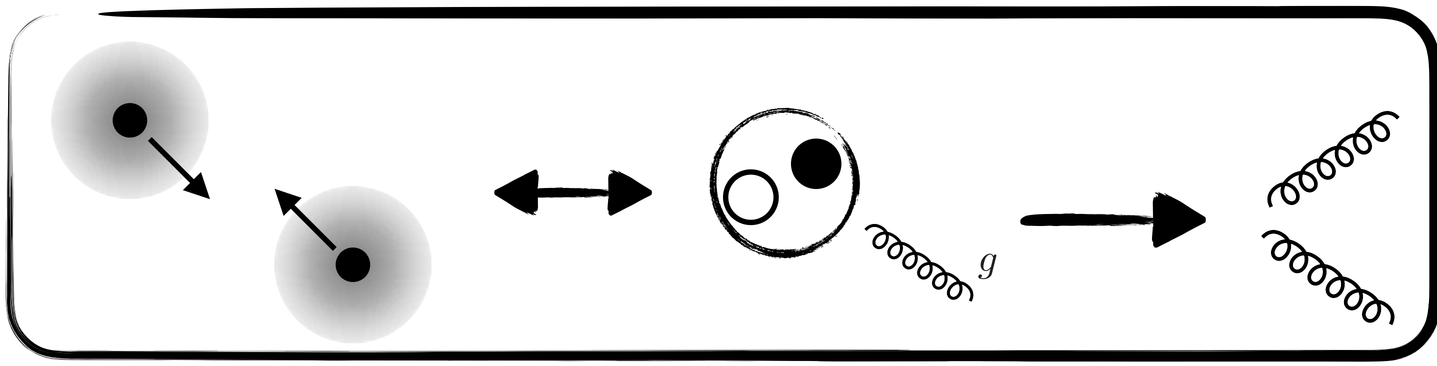
$$E_B \sim \Lambda_{\rm QCD} \quad \& \quad \sigma \sim \Lambda_{\rm QCD}^{-2}$$

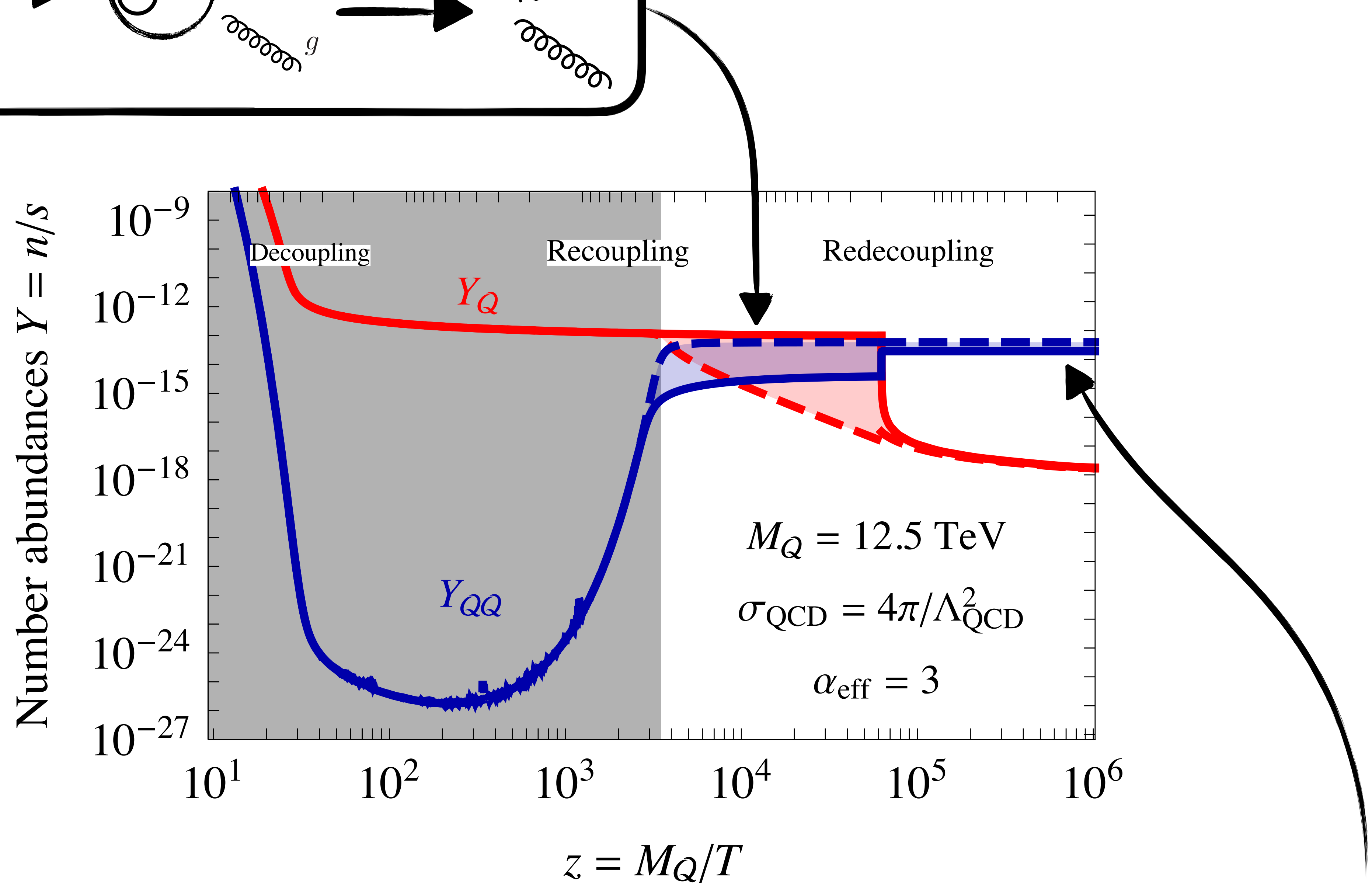
Dangerous

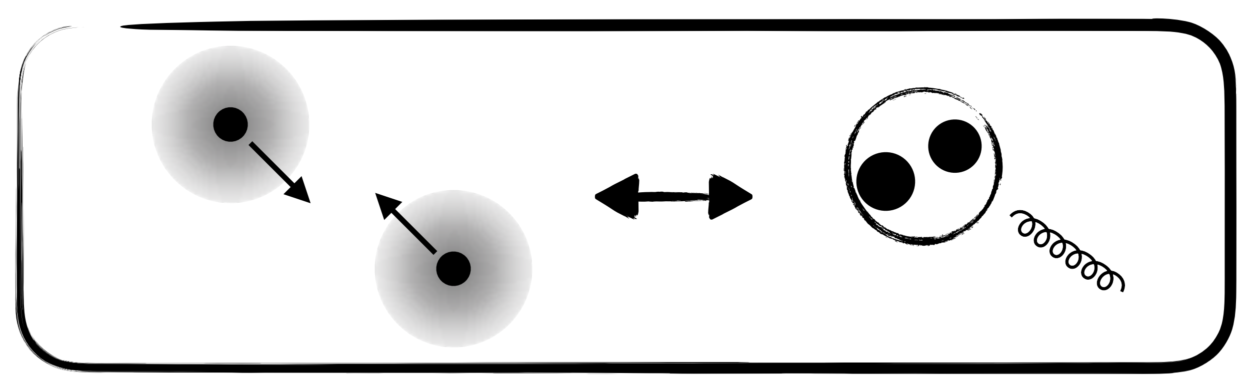
(pre-confinenemt) cosmological evolution



(post-confinenemt) cosmological evolution

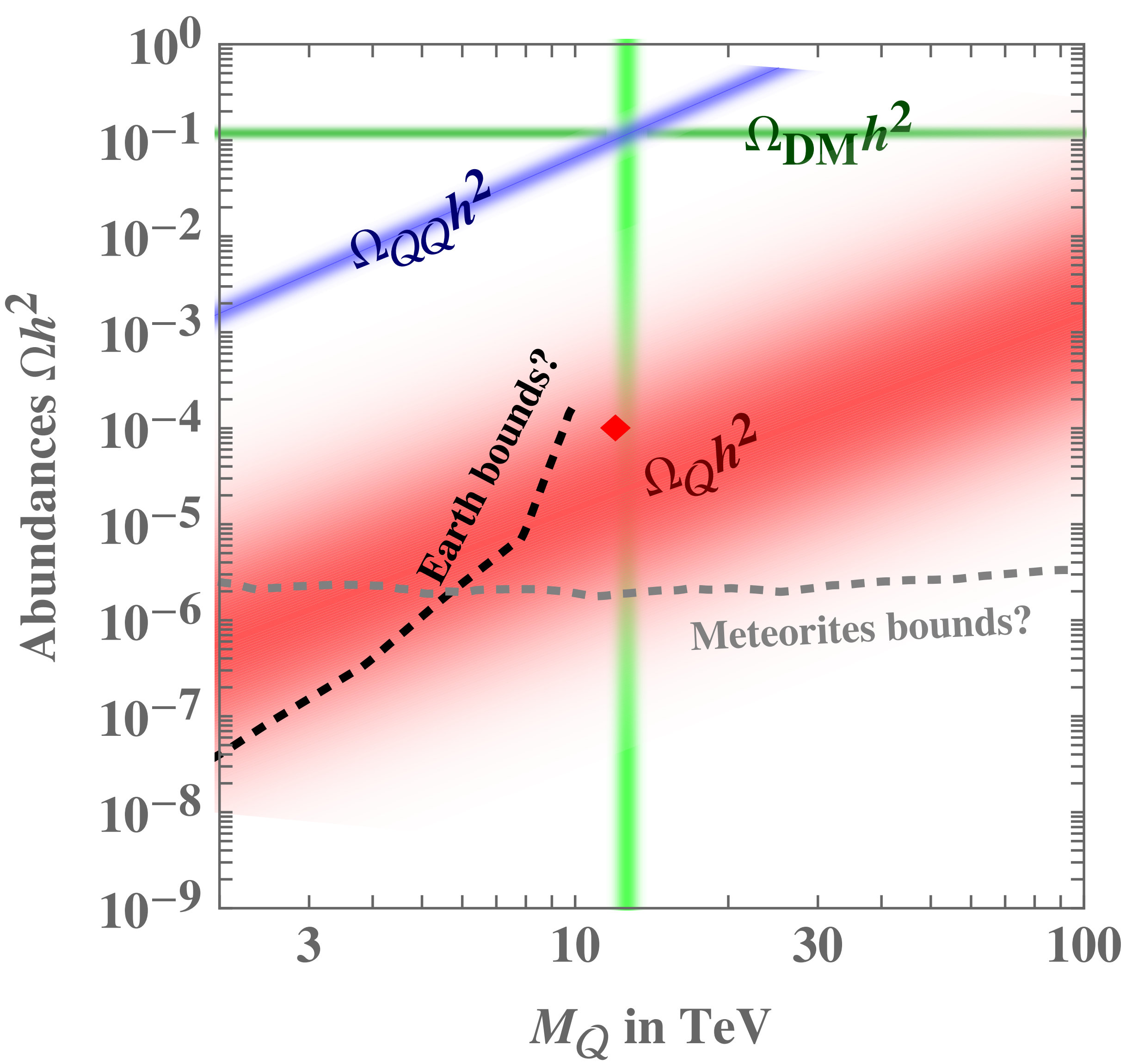


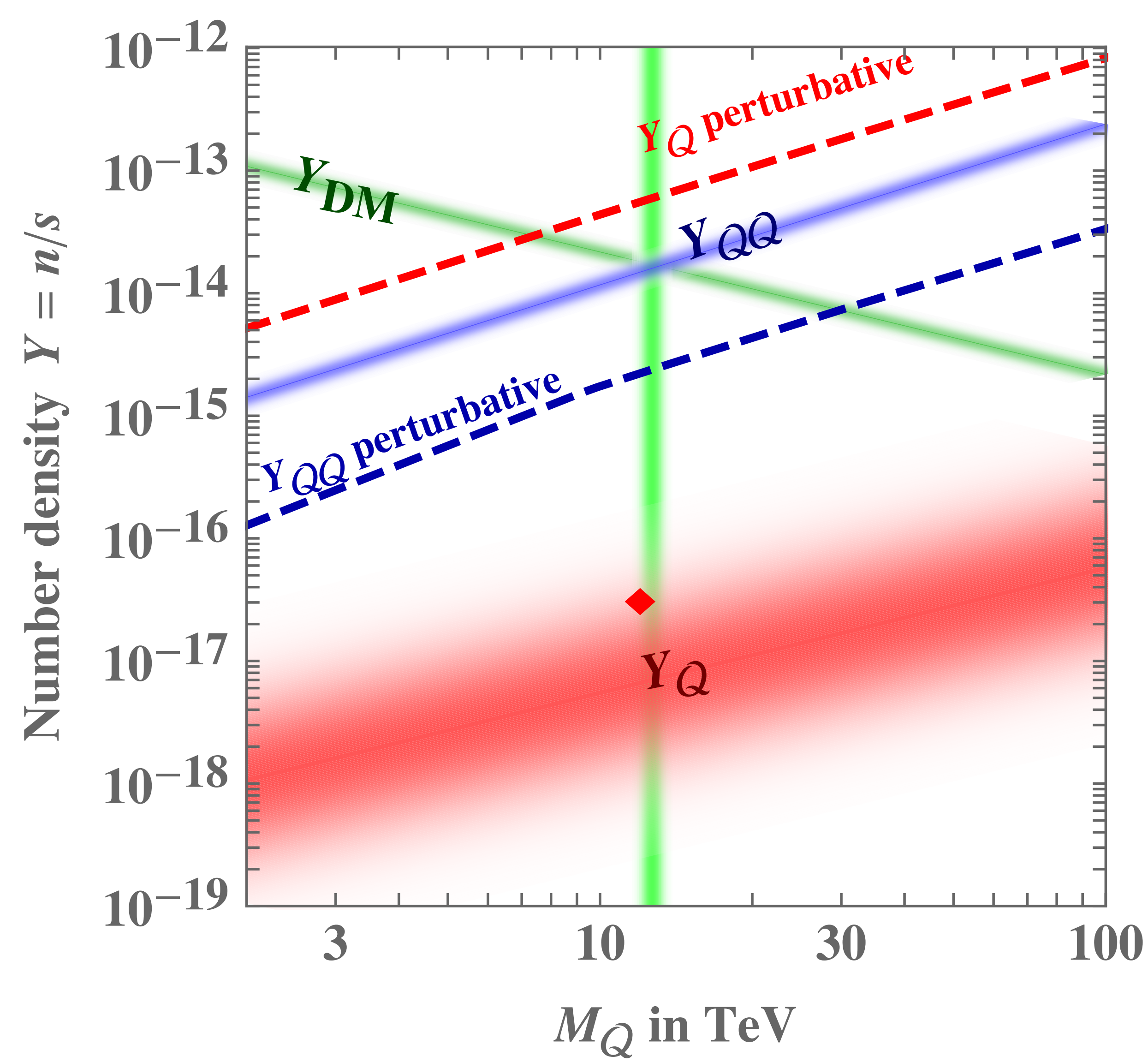




$M_Q \simeq 12.5\,\text{TeV}$

$\Omega_{\rm hyb} \sim 10^{-4}\,\Omega_{\rm DM}$





Dark Matter signals

QQ interacts with gluons through induced chromo-dipole moments analogous to Rayleigh scattering hydrogen/light

$$\mathscr{L}_{\rm eff} = c_E M_{\rm DM} \bar{B} B\, \vec{E}^{a2}$$

the polarizability coefficient is:

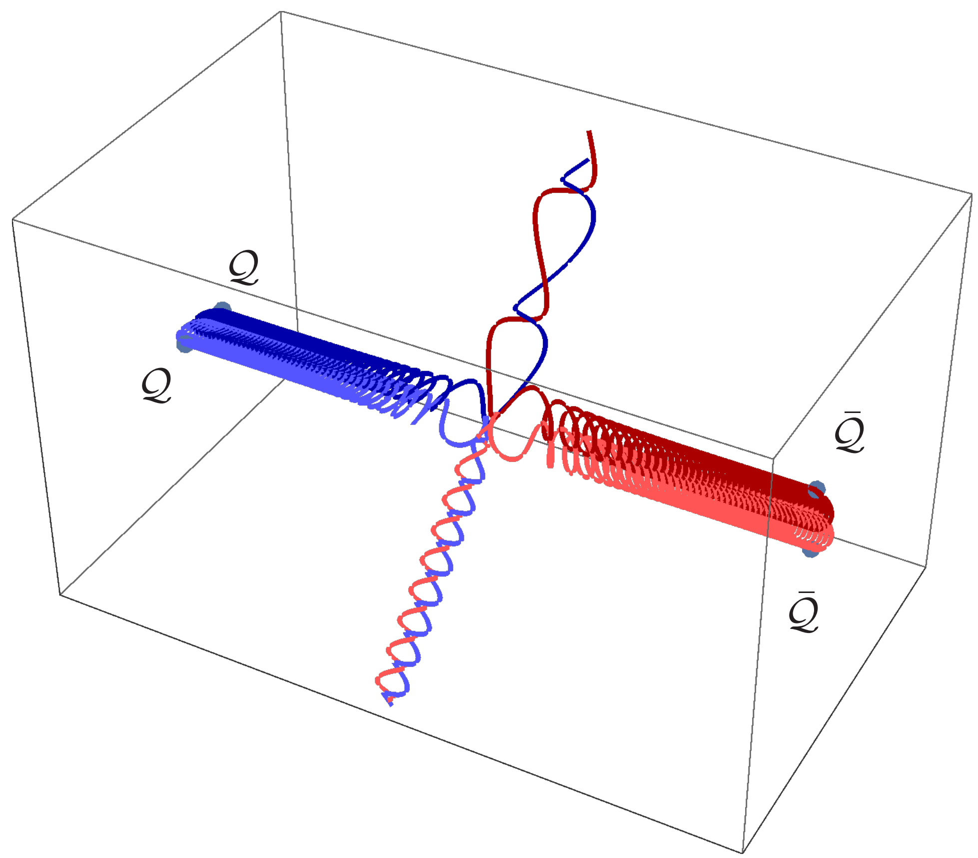
$$c_E = \pi \alpha_3 \langle B | \vec{r} \frac{1}{H_8 - E_{10}} \vec{r} | B \rangle \simeq 1.5\, \pi a^3$$

this gives a SI cross section slightly below XENON1T bounds

$$\sigma_{\rm SI} = 2.3\ 10^{-45}\ {\rm cm}^2 \times \left(\frac{20{\rm TeV}}{M_{\rm DM}}\right)^6 \left(\frac{0.1}{\alpha_3}\right)^8 \left(\frac{c_E}{1.5\pi a^3}\right)^2$$

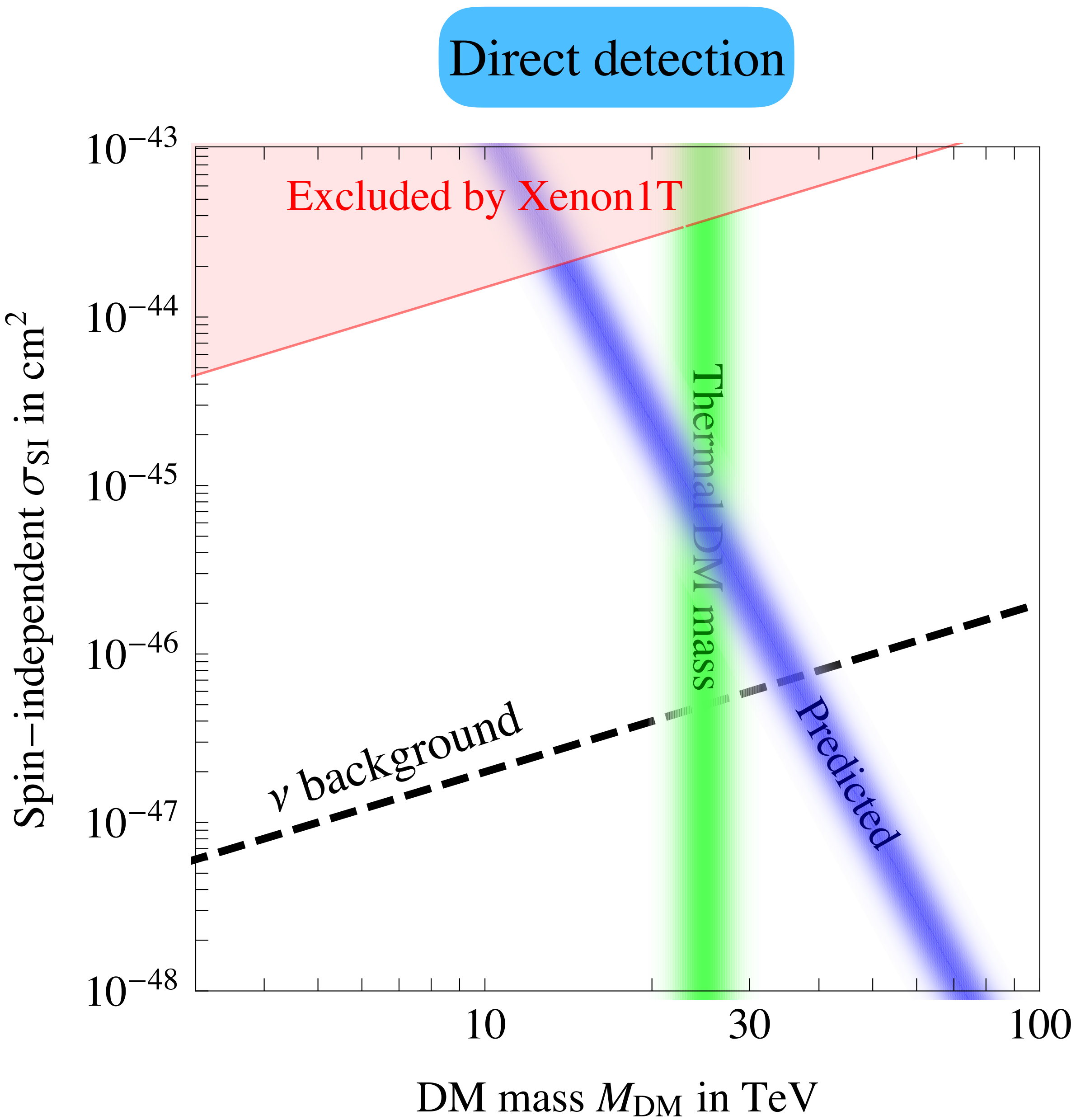
DM annihilation is dominated by recombination followed by a decay into SM particles

$$(\mathcal{Q}\mathcal{Q}) + (\bar{\mathcal{Q}}\bar{\mathcal{Q}}) \to (\mathcal{Q}\bar{\mathcal{Q}}) + (\mathcal{Q}\bar{\mathcal{Q}}) \to \mathrm{SM}$$

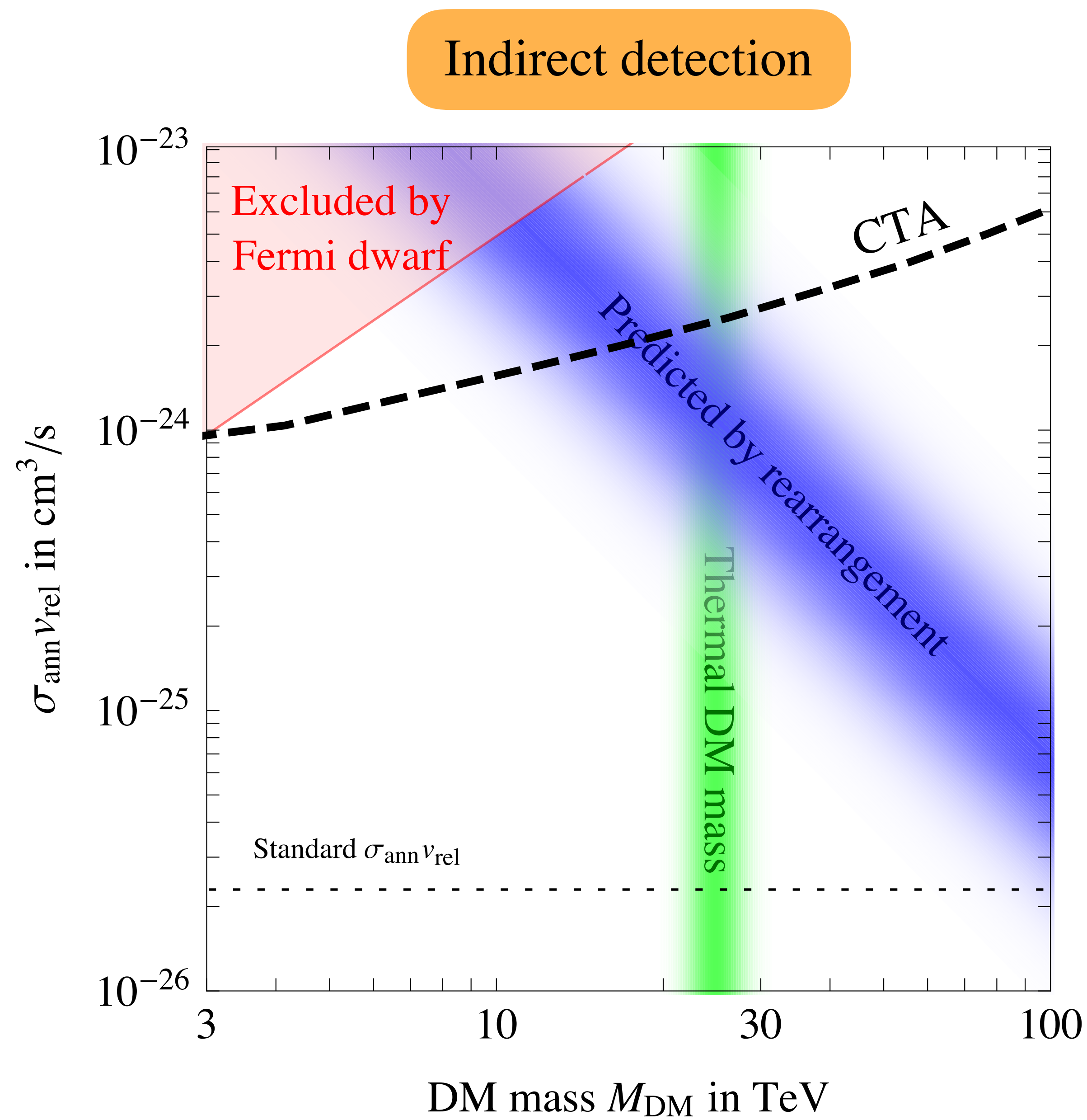


the recombination cross section is $\sim \alpha_3^4/v_{\rm rel}$ bigger than the one for direct annihilation

$$\sigma_{\rm ann} v_{\rm rel} \sim \pi a^2 v_{\rm rel} \sim 4\ 10^{-25}\,\frac{\rm cm^3}{\rm s}$$



Direct detection
Excluded by Xenon1T
Thermal DM mass
Predicted
ν background
Spin−independent σ_{SI} in cm^2
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10
30
100
DM mass M_{DM} in TeV



Indirect detection
Excluded by
Fermi dwarf
CTA
Predicted by rearrangement
Thermal DM mass
Standard $\sigma_{ann} v_{rel}$
$\sigma_{ann} v_{rel}$ in cm^3/s
10^{-23}
10^{-24}
10^{-25}
10^{-26}
3
10
30
100
DM mass M_{DM} in TeV

$\mathcal{Q}$ can be pair produced through QCD interactions

$$p + p \to \mathcal{Q} + \bar{\mathcal{Q}}$$

and then hadronize into stable or long lived hadrons which give rise to (charged) tracks

$$\mathcal{Q} \to \mathcal{Q}g \qquad \textbf{or} \qquad \mathcal{Q} \to \mathcal{Q}q\bar{q}'$$

$\sqrt{s} \sim 85\,\mathrm{TeV}$ is needed to discover $\mathcal{Q}$ with $M_{\mathcal{Q}} \sim 12.5\,\mathrm{TeV}$

$\sqrt{s} \sim 100\,\mathrm{TeV}$ would be sensitive up to $M_{\mathcal{Q}} \lesssim 15\mathrm{TeV}$

Grilli di Cortona, Hardy, Powell

Hybrids signals/bounds

hybrids in the galactic halo hit the Earth with energies $E_0 = M_{\mathcal{Q}} v^2/2 \sim \mathrm{MeV}$

but then they lose energy due to interaction with matter

Starkman et al. 90'

$$E = E_0 \exp\left(-x/x_0\right)$$

$$x_0 = \frac{\rho N_A \sigma_A}{M_{\mathcal{Q}}} \sim 100\,\mathrm{m} \ll$$ atmosphere thickness

hybrids reach underground detectors with energies below typical thresholds $\mathcal{O}\left(\mathrm{keV}\right)$

Mack, Beacom, Bertone 07'

hybrids are still excluded by balloon searches or Earth over-heating if $\Omega_{\rm hyb} = \Omega_{\rm DM}$

but not if $\Omega_{\rm hyb} \sim 10^{-4}\,\Omega_{\rm DM}$

direct detection of hybrids

hybrids in the galactic halo hit the Earth with energies

but then they lose energy due to interaction with matter

Starkman et al. 90'

$$E = E_0 \exp\left(-x/x_0\right) \qquad x_0 = \frac{\rho N_A \sigma_A}{M_Q} \sim 100\,\mathrm{m} \ll$$

hybrids reach underground detectors with energies below typical thresholds

Mack, Beacom, Bertone 07'

hybrids are still excluded by balloon searches or Earth over-heating if $\Omega_{\rm hyb} = \Omega_{\rm DM}$

but not if $\Omega_{\rm hyb} \sim 10^{-4}\,\Omega_{\rm DM}$

searches for heavy nuclei in terrestrial samples

Hemmick et al. 89'

Norman, Gazes, Bennett 86'

*****CAUTION*****

*****not clear whether or not hybrids bind to nuclei*****

for iso-spin triplet $Qq\bar{q}'$ pions can mediate long ranges forces.
So we expect they do

for iso-spin singlet Qg pions cannot mediate long ranges forces.
They do not bind? They bind only to big nuclei?

*****the following bounds apply only if they do bind*****

searches for heavy nuclei in terrestrial samples

Hemmick et al. 89'

$$\frac{N_{\rm hyb}}{N_n} < \begin{cases} 10^{-14} & \text{Oxygen} \\ 10^{-16} & \text{Enriched C} \\ 10^{-12} & \text{Iron} \end{cases}$$

Norman, Gazes, Bennett 86'

hybrids get captured and thermalized in the upper atmosphere

$$M \sim \rho_{\rm hyb} v_{\rm rel} \times \pi R_E^2 \times \Delta t \sim 2.5\ 10^{10}\,{\rm kg}$$

then collisions in the Earth atmosphere could make hybrid N, O, He kept in the crust by electromagnetic binding

$$\left.\frac{N_{\rm hyb}}{N_n}\right|_{\rm Earth} = \frac{M}{M_Q}\frac{m_N}{M_{\rm Earth}} \approx 4\ 10^{-18}$$

searches for heavy nuclei in terrestrial meteorites

limits by meteorites samples give

$$\frac{N_{\rm hyb}}{N_n} < 4 \times 10^{-14}$$

Polikanov et al. 91'

meteorites capture hybrids only if they bind to nuclei

$$\left.\frac{N_{\rm SIMP}}{N_n}\right|_{\rm meteorite} = n_{\rm SIMP}\sigma_{\rm capture}v_{\rm rel}\Delta t \approx 10^{-14}\frac{\sigma_{\rm capture}}{0.01/\Lambda_{\rm QCD}^2}$$

estimated scaling typical neutron-capture cross sections

Dark Matter as a dark bound state

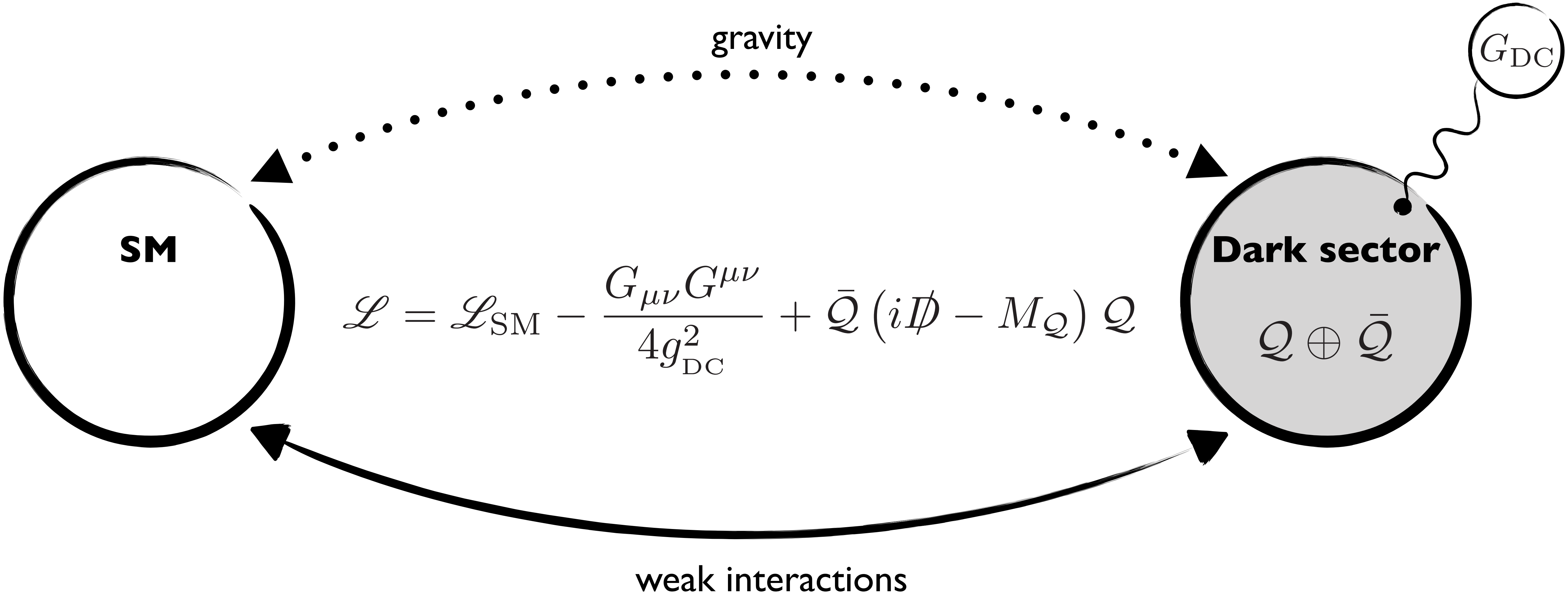
based on JHEP 1710 (2017) 210 **and** JHEP 1902 (2019) 187

problem: we need (at least) a new stable particle

analogy: proton is stable due to accidental baryon number

idea: DM accidentally-stable bound state of a strongly-coupled gauge dynamics

the model



$$\mathscr{L} = \mathscr{L}_{\rm SM} - \frac{G_{\mu\nu}G^{\mu\nu}}{4g^2_{\rm DC}} + \bar{\mathcal{Q}}\left(i\not{D} - M_{\mathcal{Q}}\right)\mathcal{Q}$$

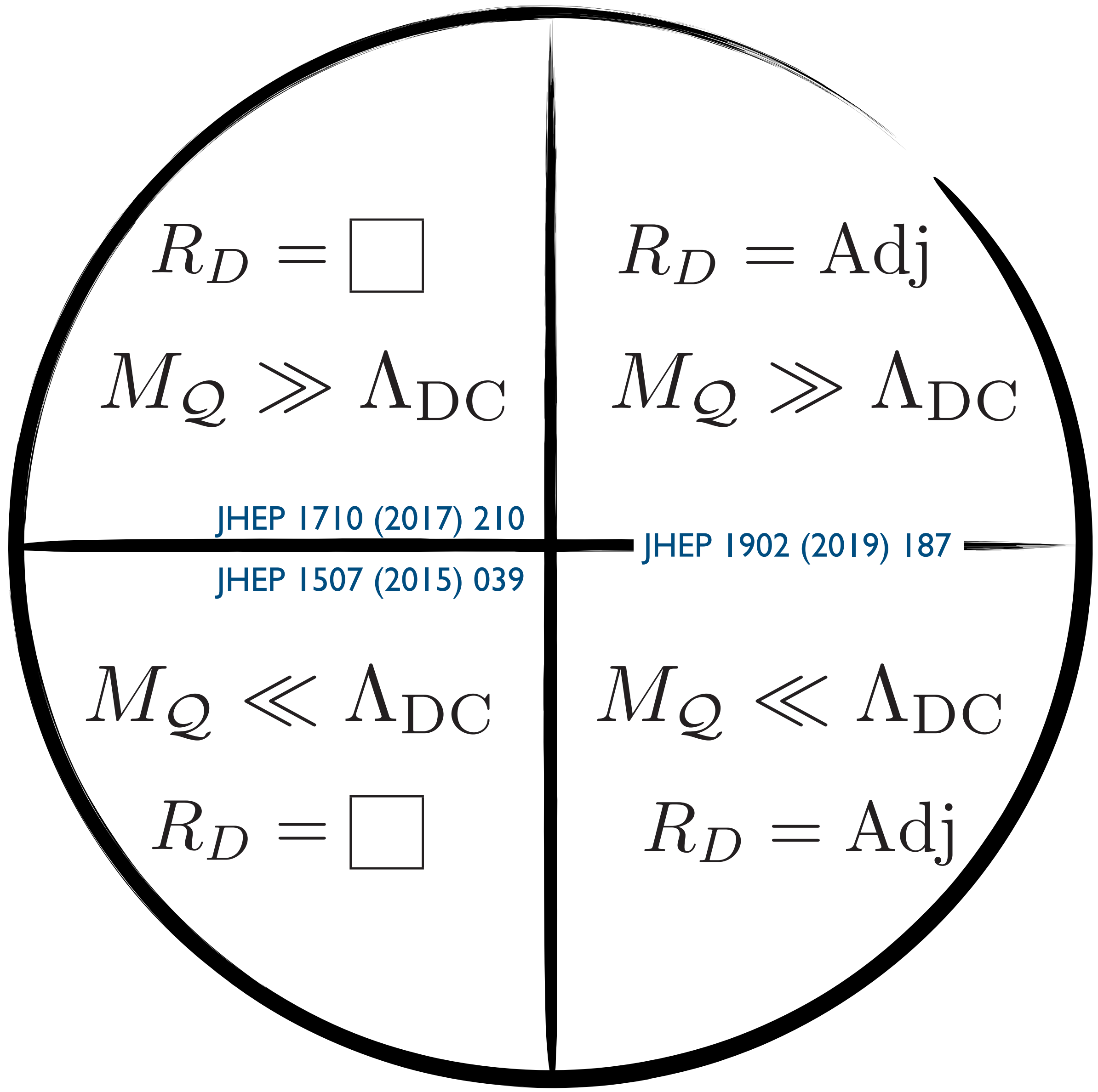
$\mathcal{Q}$: ● $= (R_D, R_{\rm SM})$

$\overline{\mathcal{Q}}$: ○ $= (\bar{R}_D, \bar{R}_{\rm SM})$

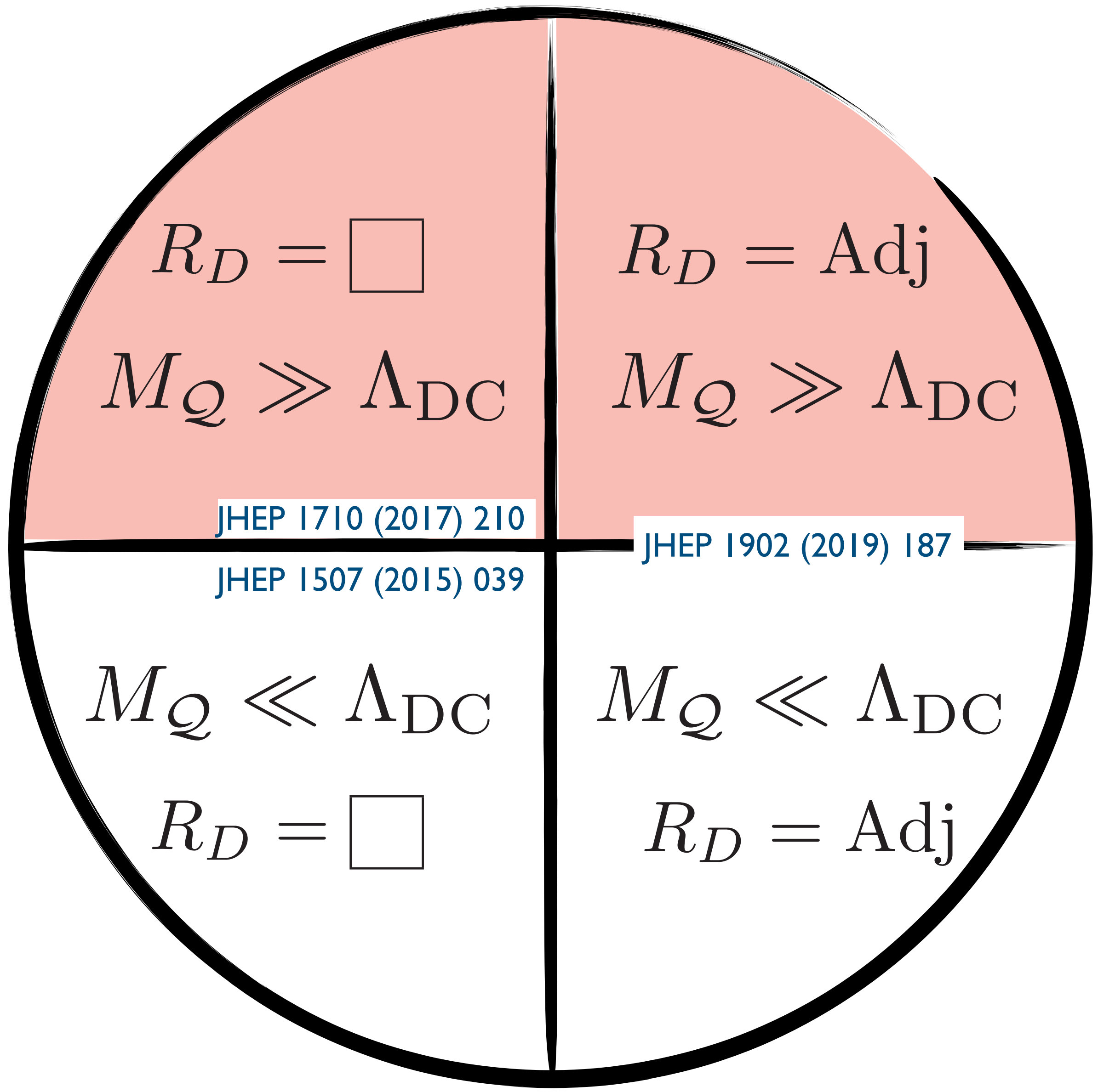
free parameters

$M_{\mathcal{Q}}$ **&** $\Lambda_{\rm DC}$

the benchmark scenarios



the benchmark scenarios



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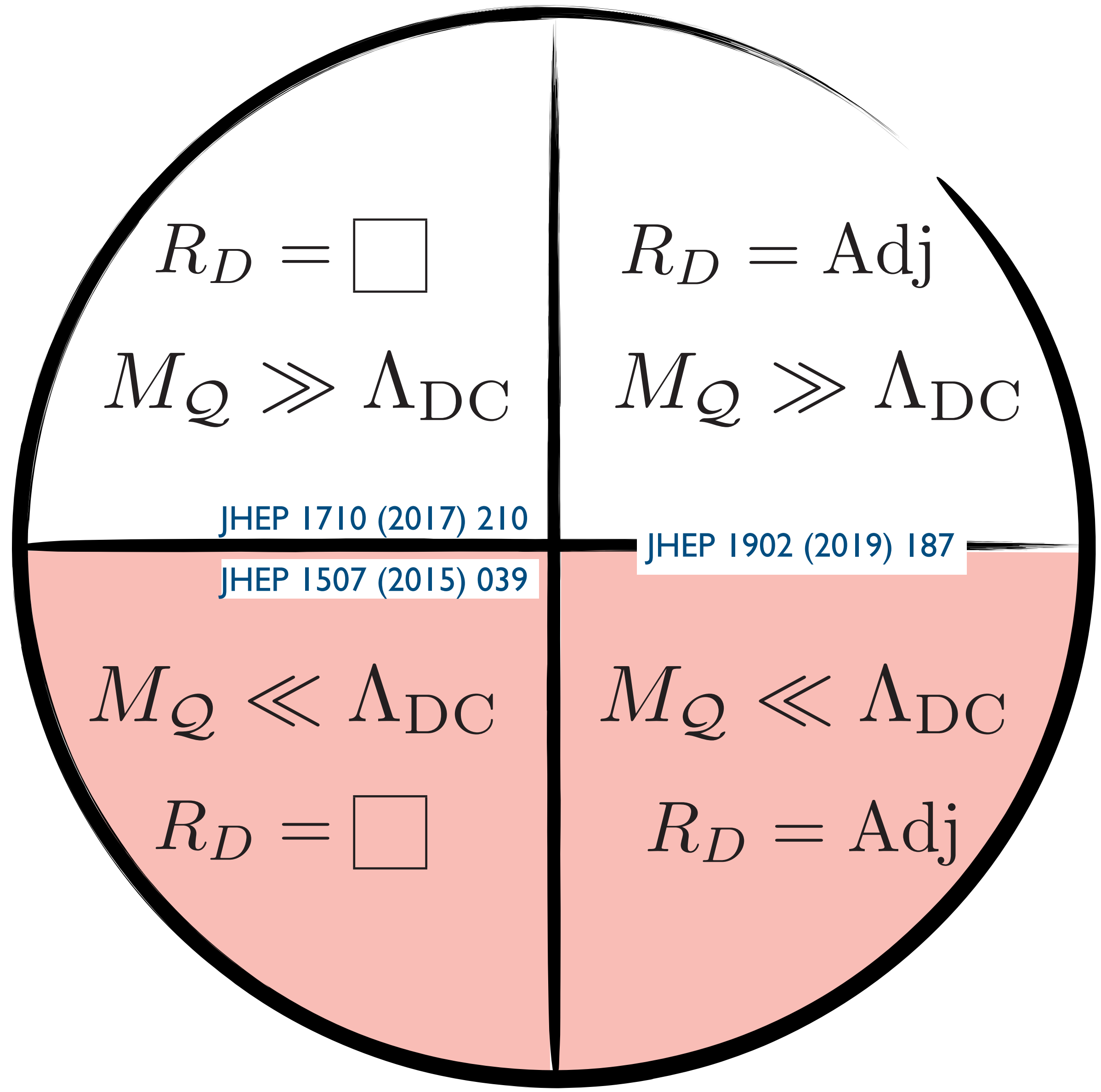
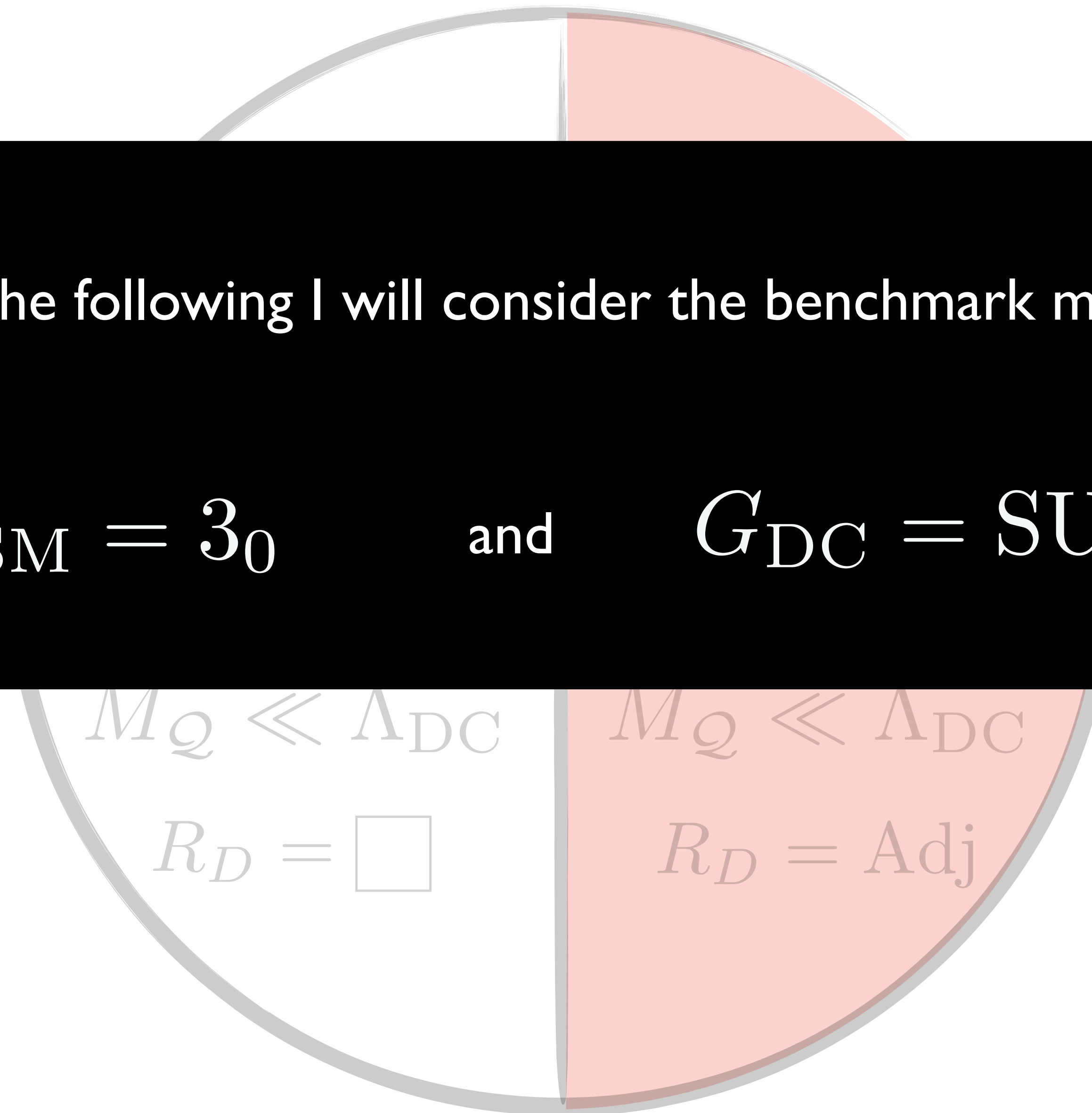


the benchmark scenarios



in the following I will consider the benchmark model

$$R_{\rm SM} = 3_0 \quad \text{and} \quad G_{\rm DC} = \mathrm{SU}(3)$$

the heavy regime

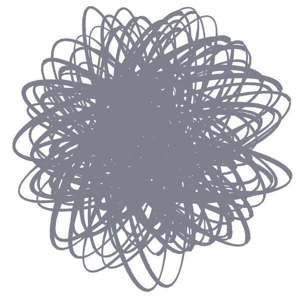
$$M_{\mathcal{Q}} \gg \Lambda_{\rm DC}$$

lightest d.o.f

$R_D = \square$

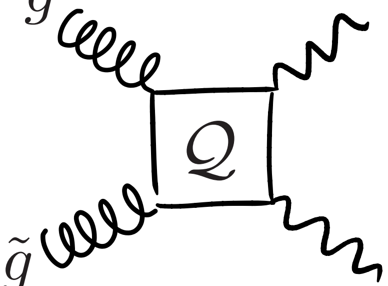
$R_D = \text{Adj}$

Φ



glueballs

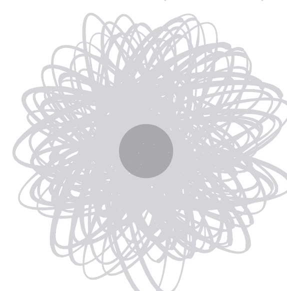
$M_\Phi \sim 7\Lambda_{\rm DC}$



DM candidate

$R_D = \text{Adj}$

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



gluequark

$M_\chi \sim M_\mathcal{Q}$

$\mathbb{Z}_2 : \mathcal{Q} \to -\mathcal{Q}$ up to dim. 6 op.

$$\mathcal{O}_6 = \frac{g_{\rm UV}^2}{\Lambda_{\rm UV}^2}\ell H G_{\mu\nu}\sigma^{\mu\nu}\mathcal{Q}$$

$R_D = \square$

$\mathcal{B} \sim (\mathcal{Q}\mathcal{Q}\mathcal{Q})$

dark baryon

$M_\mathcal{B} \sim 3M_\mathcal{Q}$

$\mathcal{Q} \to e^{i\alpha}\mathcal{Q}$ up to dim. 6 op.

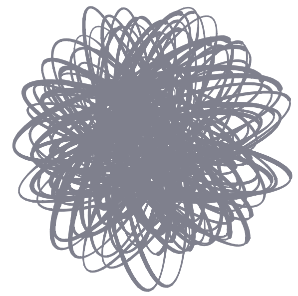
$$\mathcal{O}_6 = \frac{g_{\rm UV}^2}{\Lambda_{\rm UV}}\mathcal{Q}\mathcal{Q}\mathcal{Q}\psi_{\rm SM}$$

lightest d.o.f

$R_D = \square$

$R_D = \mathrm{Adj}$

Φ



glueballs

$$M_\Phi \sim 7\Lambda_{\rm DC}$$

$$\tau_\Phi \sim 1.4\,{\rm s}\left(\frac{3}{N_{\rm DC}}\right)^2\left(\frac{500\,{\rm GeV}}{M_\Phi}\right)^9\left(\frac{M_{\mathcal{Q}}}{100\,{\rm TeV}}\right)^8$$

DM candidate

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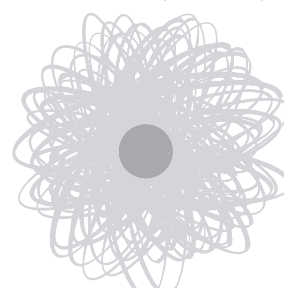

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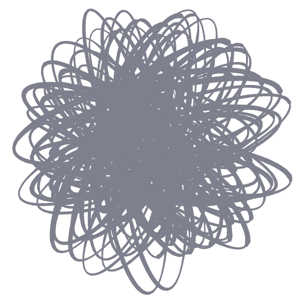
lightest d.o.f

$R_D = \square$ → $R_D = \text{Adj}$

Φ



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$R_D = \text{Adj}$ →

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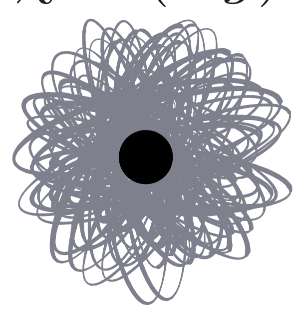

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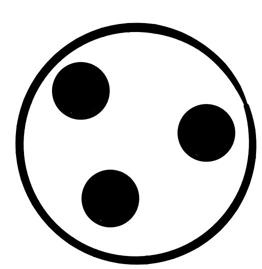
$R_D = \square$ →

$\mathcal{B} \sim (\mathcal{QQQ})$



dark baryon

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$$\mathcal{Q} \to e^{i\alpha}\mathcal{Q}$$ up to dim. 6 op.

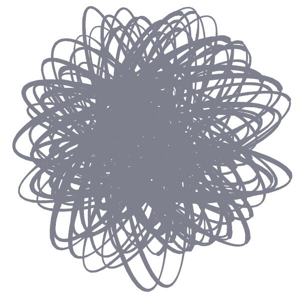
$$\mathcal{O}_6 = \frac{g_{\rm UV}^2}{\Lambda_{\rm UV}}\mathcal{QQQ}\,\psi_{\rm SM}$$

lightest d.o.f

$R_D = \square$

$R_D = \mathrm{Adj}$

Φ



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DM candidate

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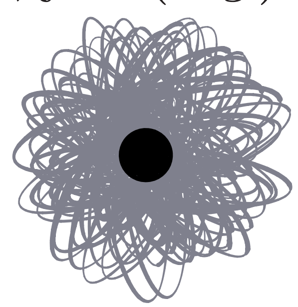


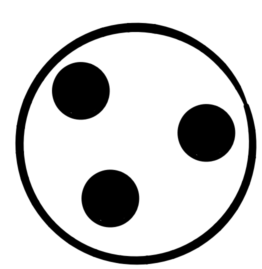
gluequark

$$M_\chi \sim M_{\mathcal{Q}}$$

$$\tau_\chi \sim 10^{28}\,{\rm s}\left(\frac{100\,{\rm TeV}}{M_{\mathcal{Q}}}\right)^5\left(\frac{\Lambda_{\rm UV}}{10^{18}\,{\rm GeV}}\right)^4$$

$R_D = \square$

$\mathcal{B} \sim (\mathcal{Q}\mathcal{Q}\mathcal{Q})$



dark baryon

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$$\mathcal{O}_6 = \frac{g_{\rm UV}^2}{\Lambda_{\rm UV}}\mathcal{Q}\mathcal{Q}\mathcal{Q}\,\psi_{\rm SM}$$

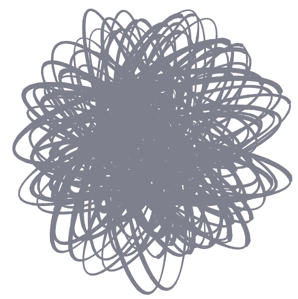
the spectrum

lightest d.o.f

$R_D = \square$ → glueballs

$R_D = \mathrm{Adj}$

Φ



glueballs

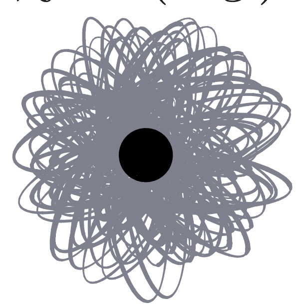
$$M_\Phi \sim 7\Lambda_{\rm DC}$$

$$\tau_\Phi \sim 1.4\,\mathrm{s}\left(\frac{3}{N_{\rm DC}}\right)^2\left(\frac{500\,\mathrm{GeV}}{M_\Phi}\right)^9\left(\frac{M_\mathcal{Q}}{100\,\mathrm{TeV}}\right)^8$$

DM candidate

$R_D = \mathrm{Adj}$ → gluequark

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



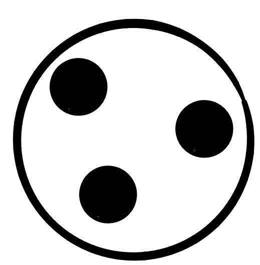
gluequark

$$M_\chi \sim M_\mathcal{Q}$$

$$\tau_\chi \sim 10^{28}\,\mathrm{s}\left(\frac{100\,\mathrm{TeV}}{M_\mathcal{Q}}\right)^5\left(\frac{\Lambda_{\rm UV}}{10^{18}\,\mathrm{GeV}}\right)^4$$

$R_D = \square$ → dark baryon

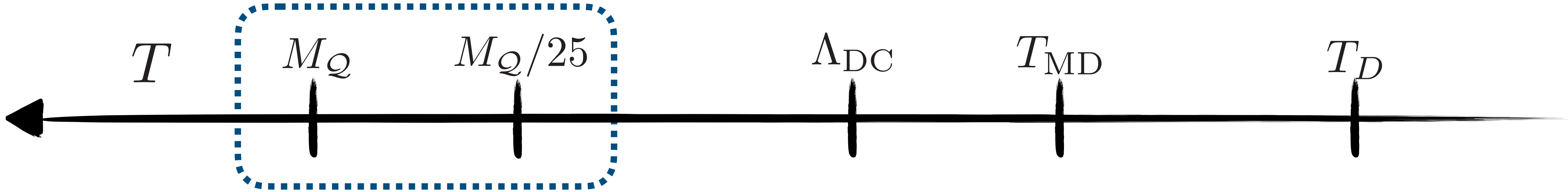
$\mathcal{B} \sim (\mathcal{QQQ})$



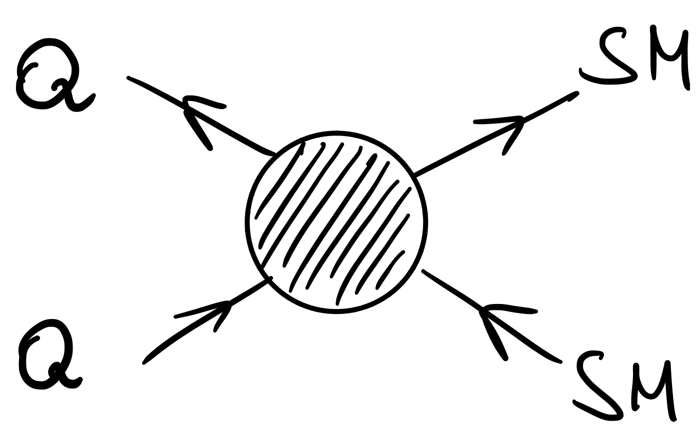
dark baryon

$$M_\mathcal{B} \sim 3M_\mathcal{Q}$$

$$\tau_\mathcal{B} \sim \frac{10^{28}}{N_{DC}^5}\,\mathrm{s}\left(\frac{100\,\mathrm{TeV}}{M_\mathcal{Q}}\right)^5\left(\frac{\Lambda_{\rm UV}}{10^{18}\,\mathrm{GeV}}\right)^4$$

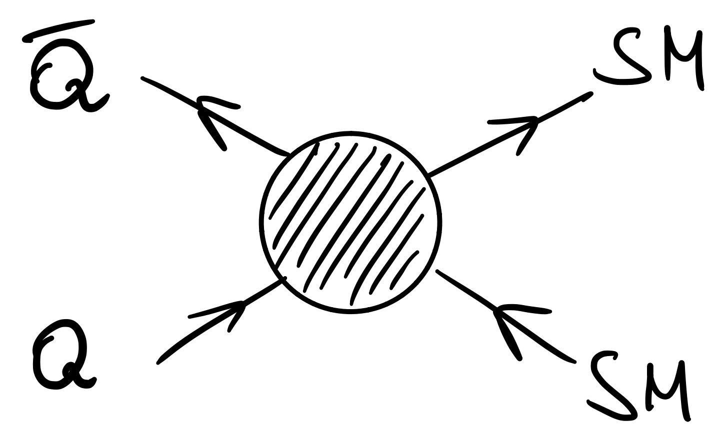


$R_D = \text{Adj}$



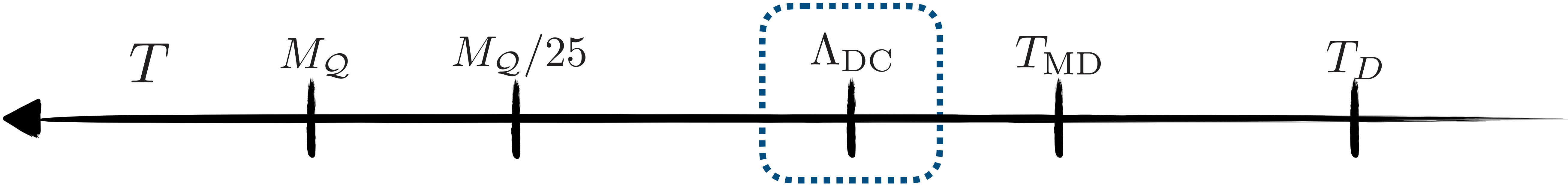
$$\langle \sigma v_{\rm rel} \rangle \simeq \frac{\pi \alpha_{\rm D}^2}{M_{\mathcal{Q}}^2}$$

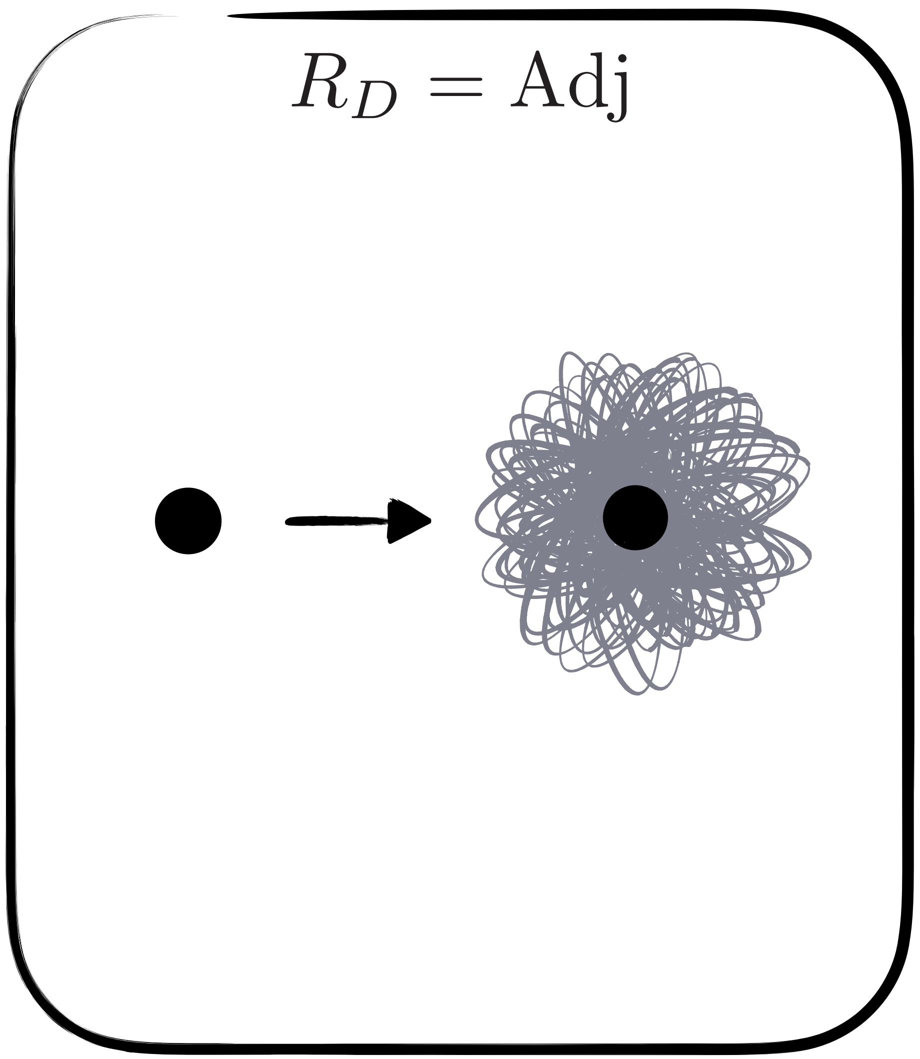
$R_D = \square$

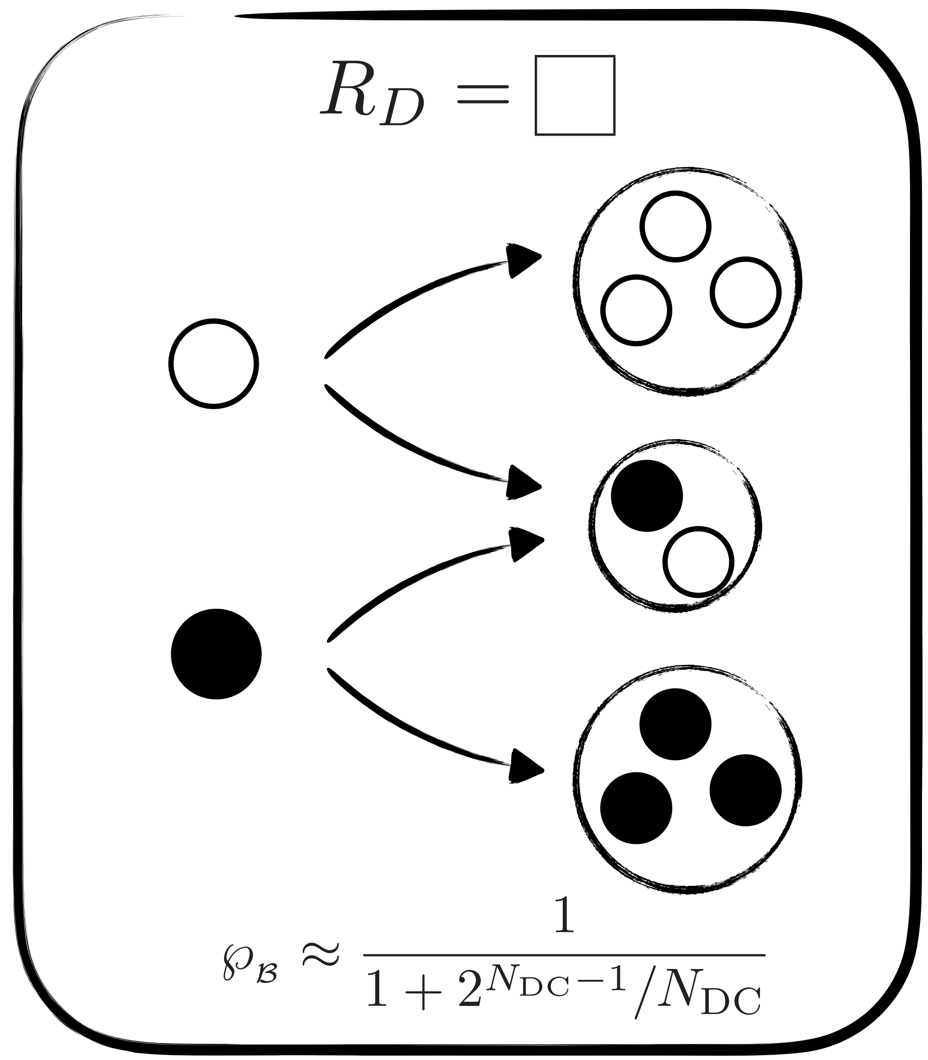


$$\langle \sigma v_{\rm rel} \rangle \simeq \frac{\pi \alpha_{\rm D}^2}{M_{\mathcal{Q}}^2}$$

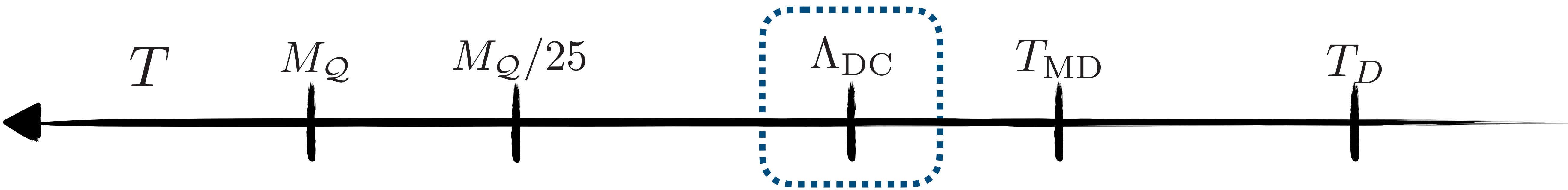
thermal history: confinement

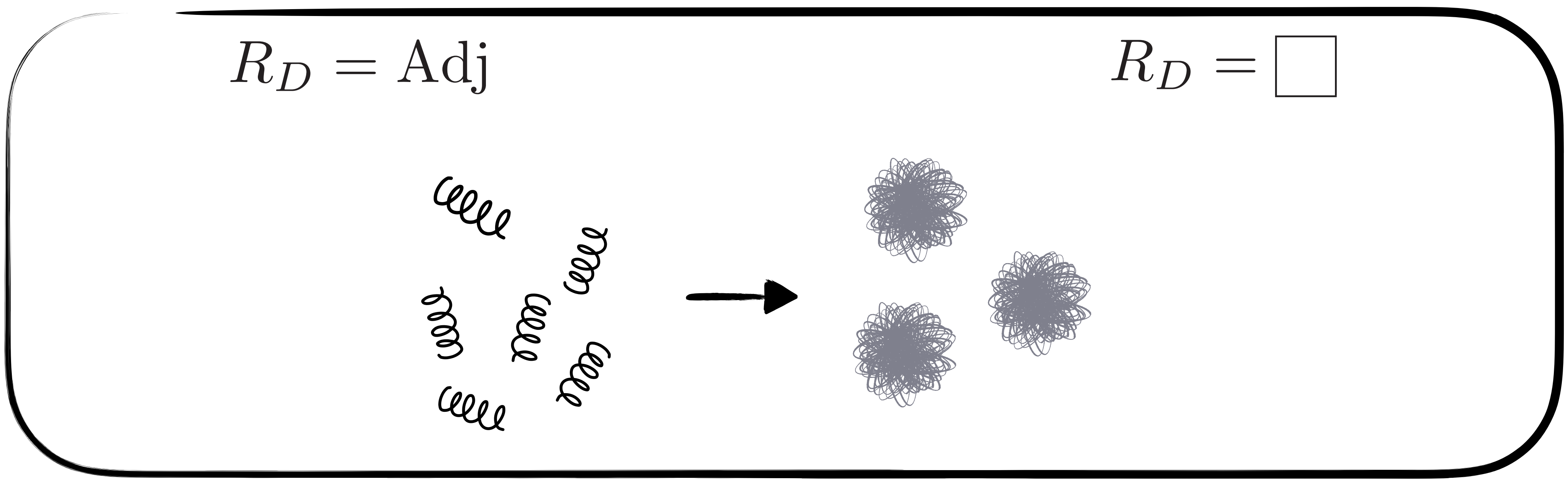






thermal history: dilution

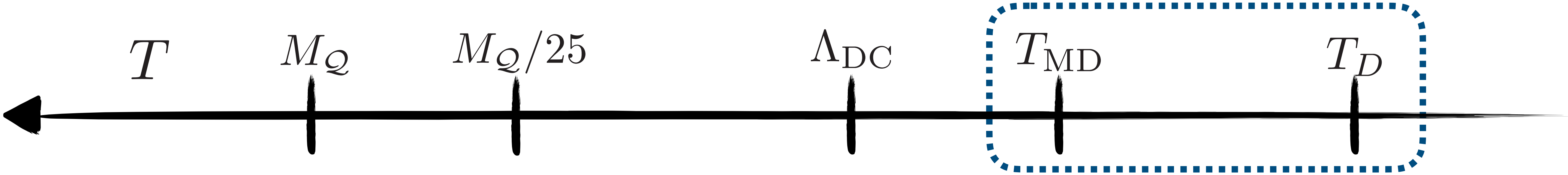




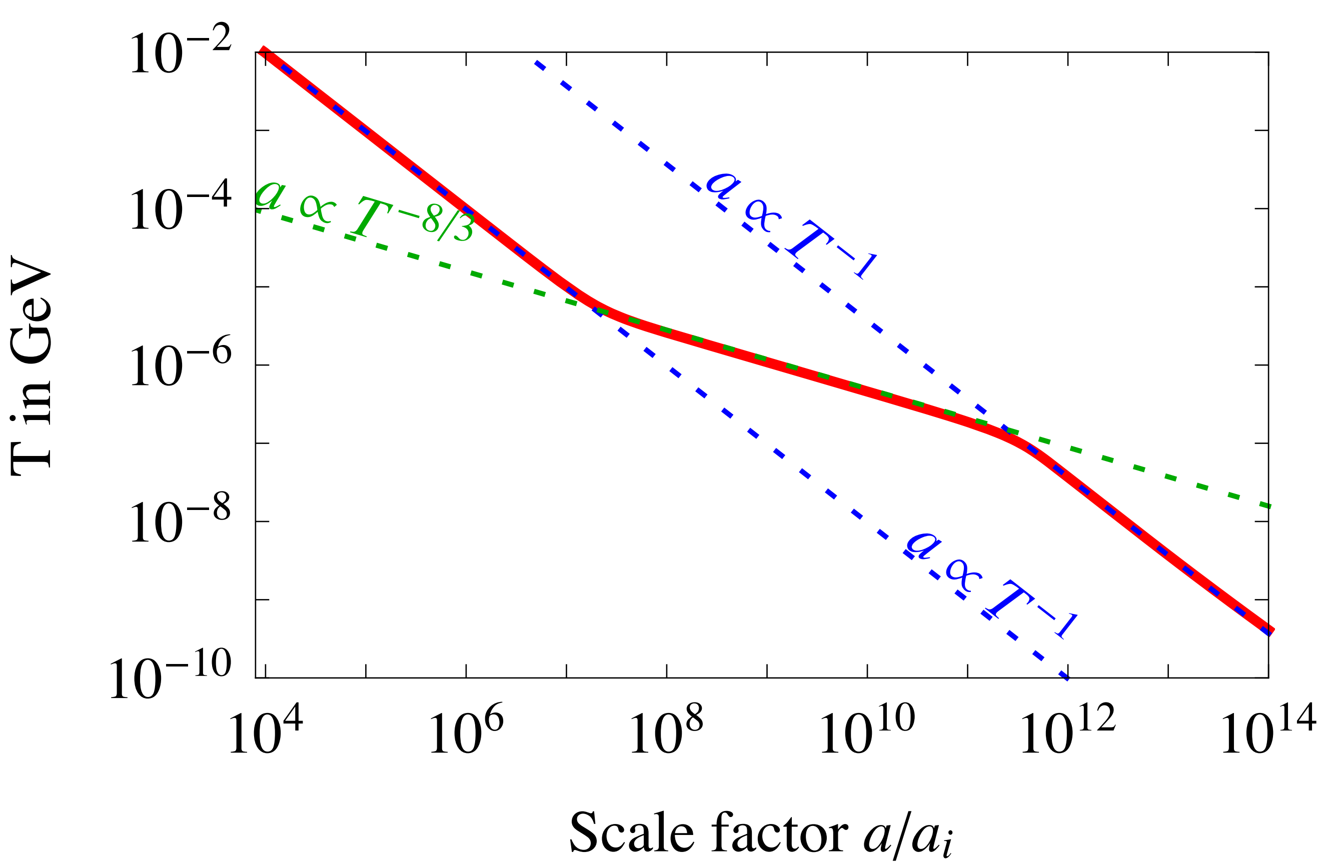
energy density in glueball just after confinement is huge even if they are a non relativistic species

$$\rho_\Phi \approx g^*_{\rm D} \Lambda^4_{\rm DC} \qquad \textbf{vs} \qquad \rho_{\rm r} \approx g^*_{\rm SM} \Lambda^4_{\rm DC}$$

thermal history: dilution



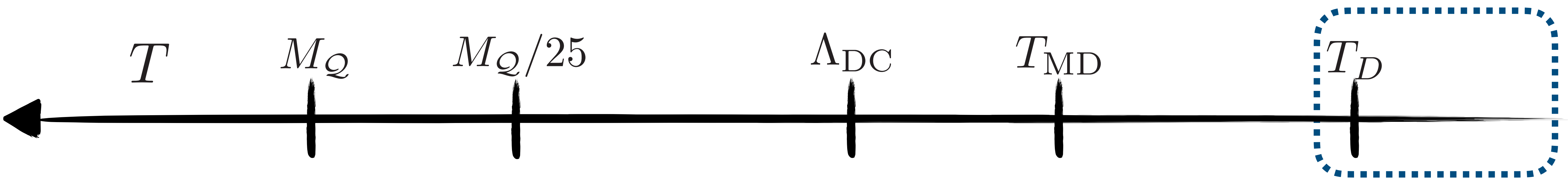
decays of this large amount of energy during an early stage of matter domination leads to a non-standard scaling:



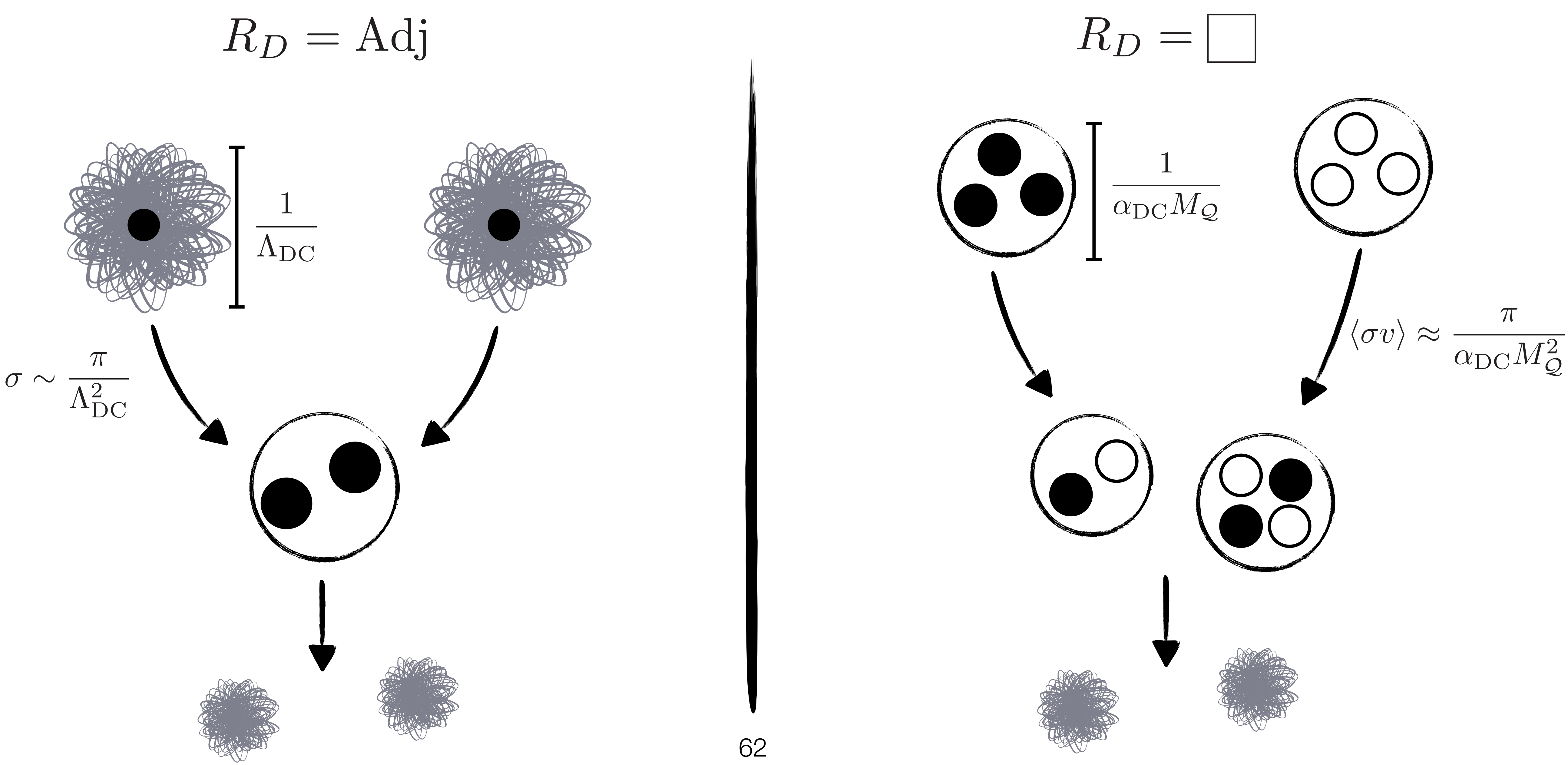
$a \propto T^{-8/3}$ instead of $a \propto T^{-1}$

$$\Omega_{\rm DM} = \Omega_{\rm DM}^{\rm naive} \left(\frac{T_D}{T_{MD}} \right)^5$$

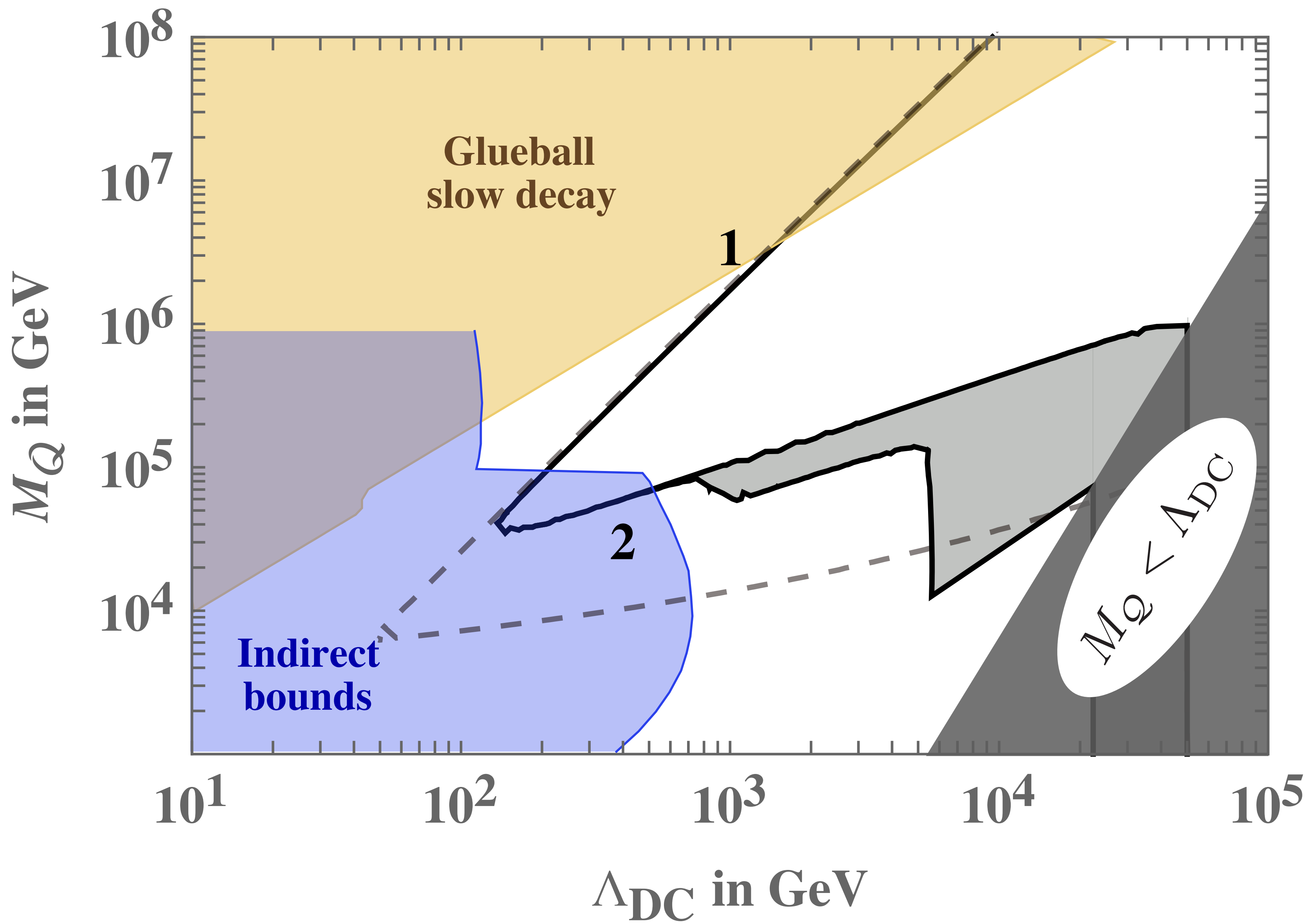
thermal history: reannihilation



a second stage of annihilation can take place due to the large self scattering cross section of the DM



e.g. in the Adj model we get



① dilution dominates and prevent reannihilation

② reannihilation sets the final relic density

the light regime

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

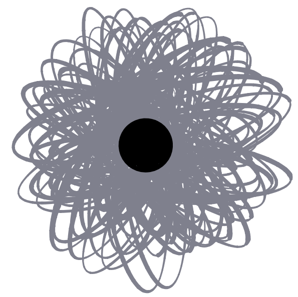
the spectrum

$R_D = \mathrm{Adj}$

DM candidate

$R_D = \square$

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

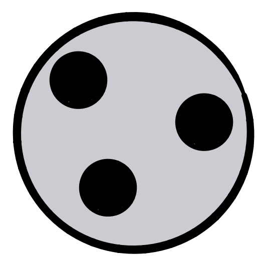


gluequark

$$M_\chi \sim \Lambda_{\rm DC}$$

$$\tau_\chi \sim 10^{28}\,\mathrm{s}\left(\frac{100\,\mathrm{TeV}}{M_\mathcal{Q}}\right)^5\left(\frac{\Lambda_{\rm UV}}{10^{18}\,\mathrm{GeV}}\right)^4$$

$\mathcal{B} \sim (\mathcal{Q}\mathcal{Q}\mathcal{Q})$



dark baryon

$$M_\mathcal{B} \sim 3\Lambda_{\rm DC}$$

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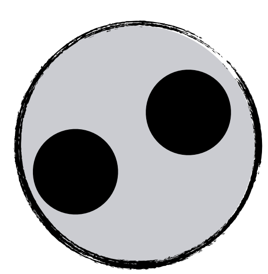
lightest d.o.f

$R_D = \mathrm{Adj}$

$\pi \sim (\mathcal{Q}\mathcal{Q})$



pions

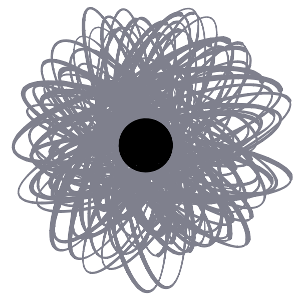
$\mathrm{SU}(3) \to \mathrm{SO}(3)$ five PNGB in a 5_0

$$m_\pi^2 \sim M_\mathcal{Q}\Lambda_{\rm DC} + \frac{9}{2\pi}\Lambda_{\rm DC}^2$$

DM candidate

$R_D = \text{Adj}$

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



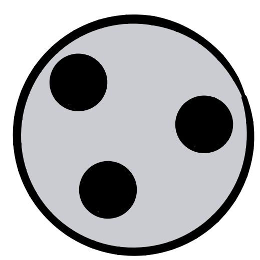
gluequark

$$M_\chi \sim \Lambda_{\rm DC}$$

$$\tau_\chi \sim 10^{28}\,\text{s}\left(\frac{100\,\text{TeV}}{M_\mathcal{Q}}\right)^5\left(\frac{\Lambda_{\rm UV}}{10^{18}\,\text{GeV}}\right)^4$$

$R_D = \square$

$\mathcal{B} \sim (\mathcal{QQQ})$



dark baryon

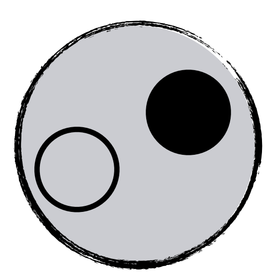
$$M_\mathcal{B} \sim 3\Lambda_{\rm DC}$$

$$\tau_\mathcal{B} \sim \frac{10^{28}}{N_{DC}^5}\,\text{s}\left(\frac{100\,\text{TeV}}{M_\mathcal{Q}}\right)^5\left(\frac{\Lambda_{\rm UV}}{10^{18}\,\text{GeV}}\right)^4$$

lightest d.o.f

$R_D = \square$

$\pi \sim (\mathcal{Q}\bar{\mathcal{Q}})$



pions

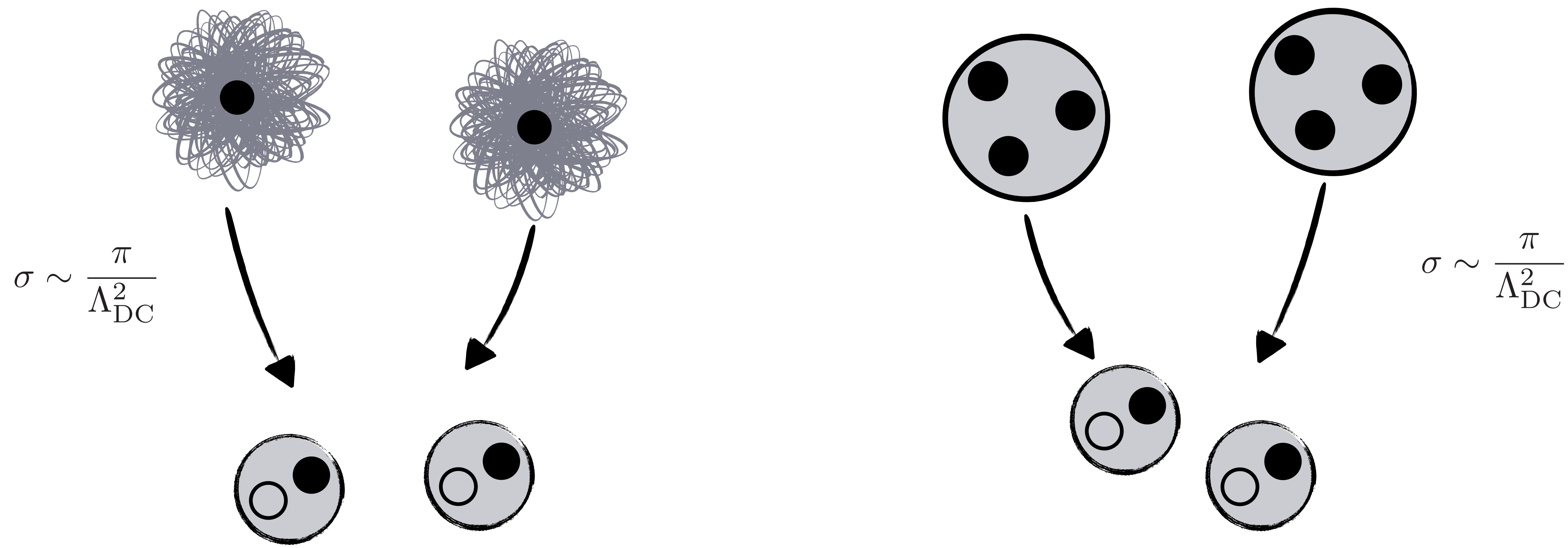
$\text{SU}(6) \to \text{SO}(6)$ eight PNGB in a $3_0 \oplus 5_0$

$$m_\pi^2 \sim M_\mathcal{Q}\Lambda_{\rm DC} + \frac{9}{2\pi}\Lambda_{\rm DC}^2$$

thermal history

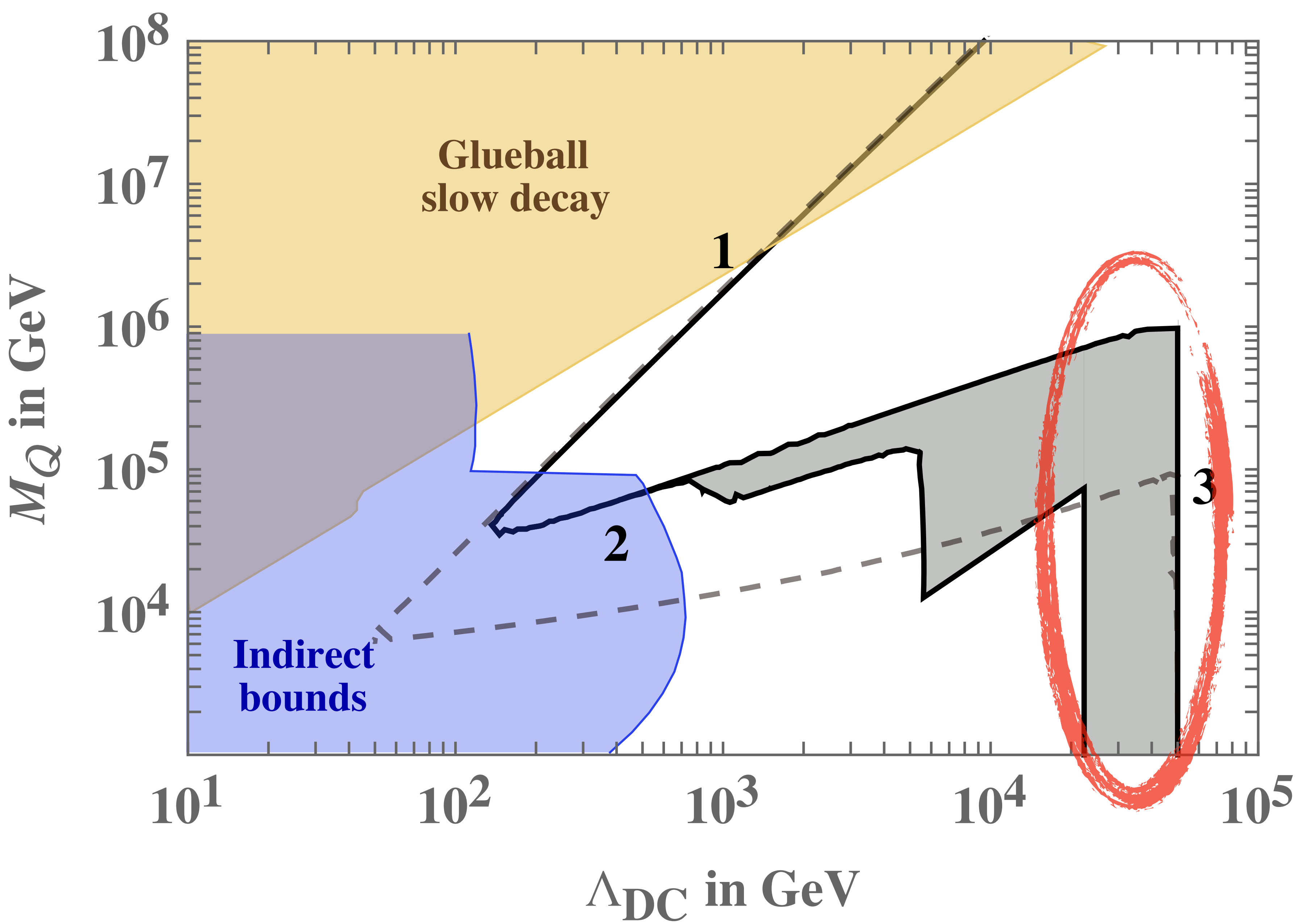
only one relevant scale in the game: $\Lambda_{\rm DC}$

$R_D = \text{Adj}$ $\qquad$ $R_D = \square$



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

e.g. in the Adj model we get



experimental signatures

experimental searches and cosmological constraints

residual annihilations or decays of DM particles could give rise to indirect detection signals

large uncertainties on the annihilation cross section

best guess

$$\mathrm{Adj} \longrightarrow \sigma v \sim \frac{1}{\Lambda_{\mathrm{DC}}^2}$$

$$\square \longrightarrow \sigma v \sim \frac{\pi}{\alpha_{\mathrm{DC}} M_Q^2}$$

higher dim. operators can induce DM decays

$$\tau_{\mathrm{DM}} \sim \frac{\Lambda_{\mathrm{UV}}^4}{M_{\mathrm{DM}}^5}$$

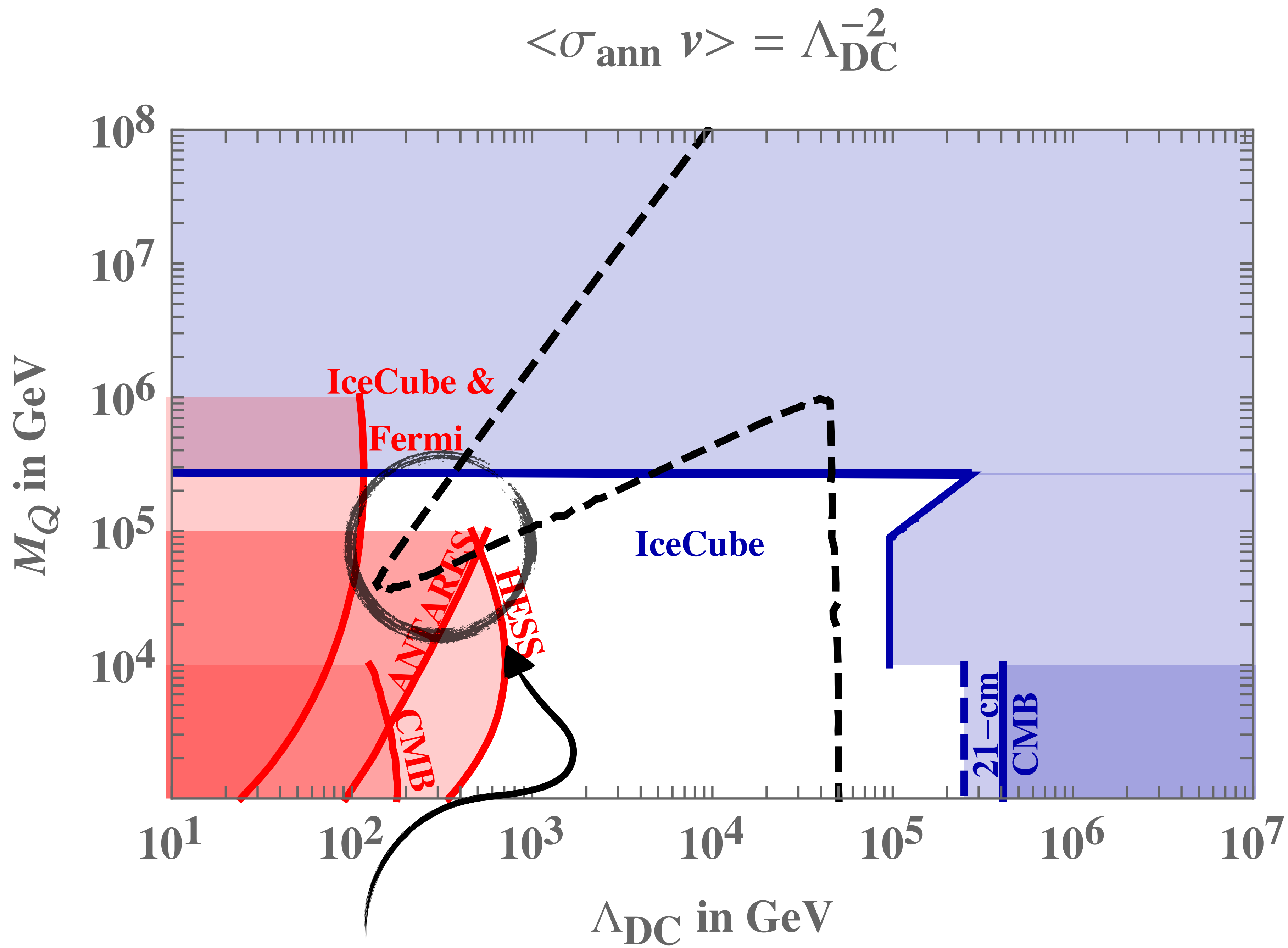
CMB spectral distortions

21 cm signal

cosmic ray observations

experimental searches and cosmological constraints

e.g. in the Adj. model we get



masses up to 100 TeV can be tested because of the huge enhancement of annihilation cross sections

conclusions

bound states can give $\mathcal{O}(1)$ corrections to thermal relic densities

DM itself can be in the for of bound states

bound state can enhance indirect detection signal

bound state DM can be much heavier than usual WIMP