# Colored Dark Matter

based on: 1801.01135 with de Luca, Redi, Smirnov, Strumia

SCUOLA
NORMALE
SUPERIORE

INFN

# The model

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

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

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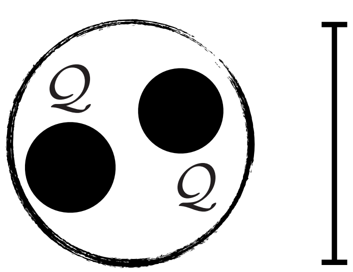
**$\mathcal{Q}$ -onlyum**




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

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

**DM candidate**

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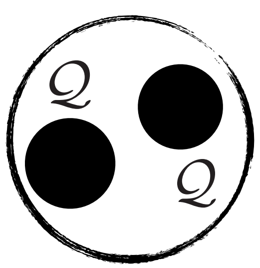


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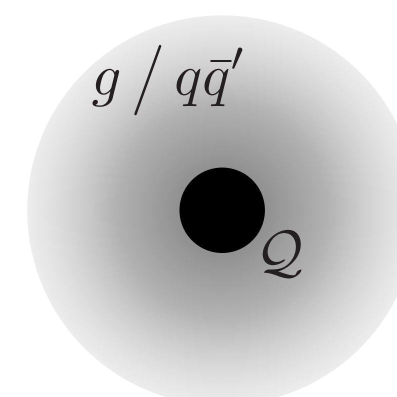
## Hybrids

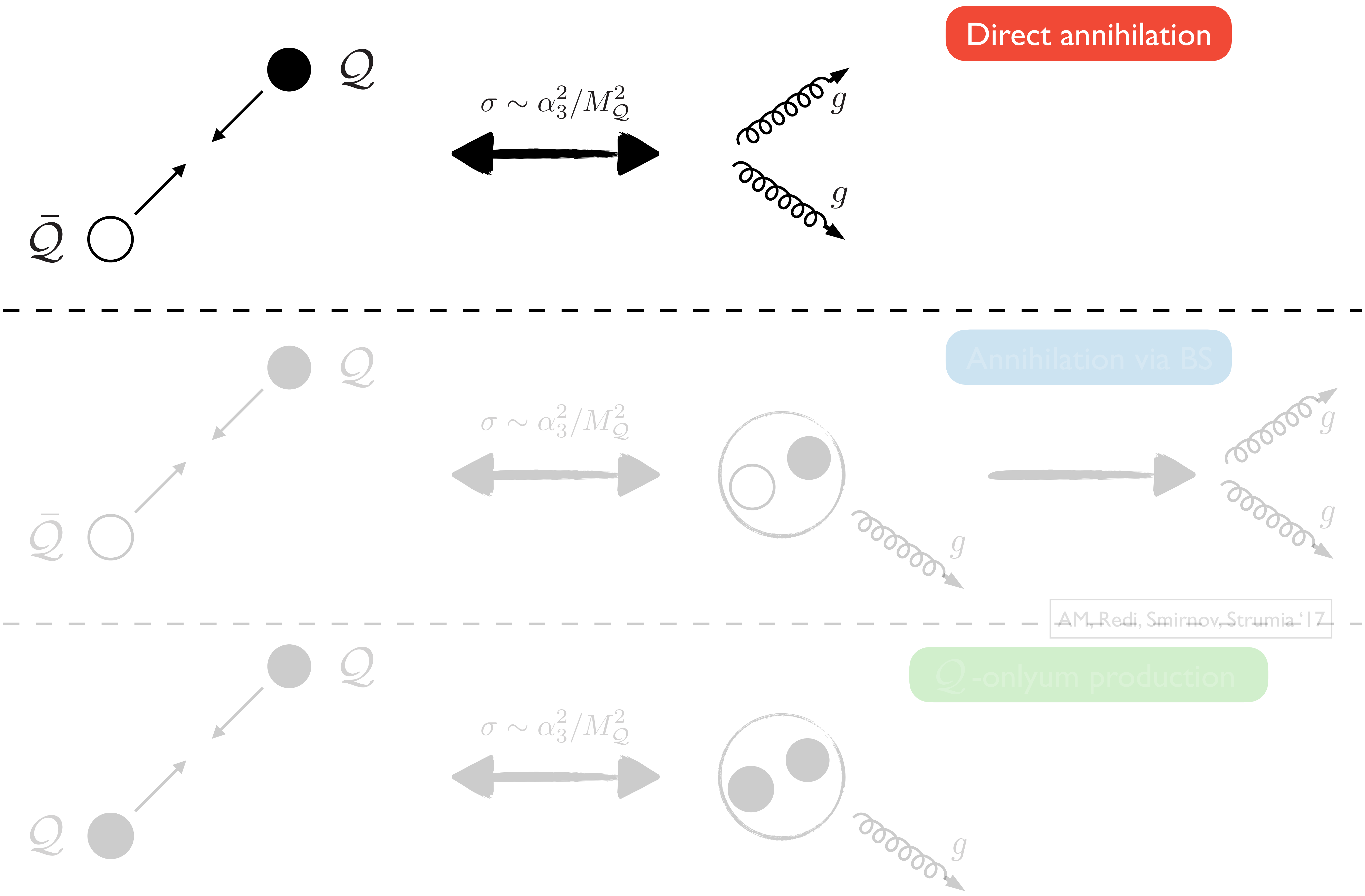
$$\sim \frac{1}{\Lambda_{\mathrm{QCD}}}$$




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

**Dangerous**

# (Pre-confinement) **Cosmological evolution**



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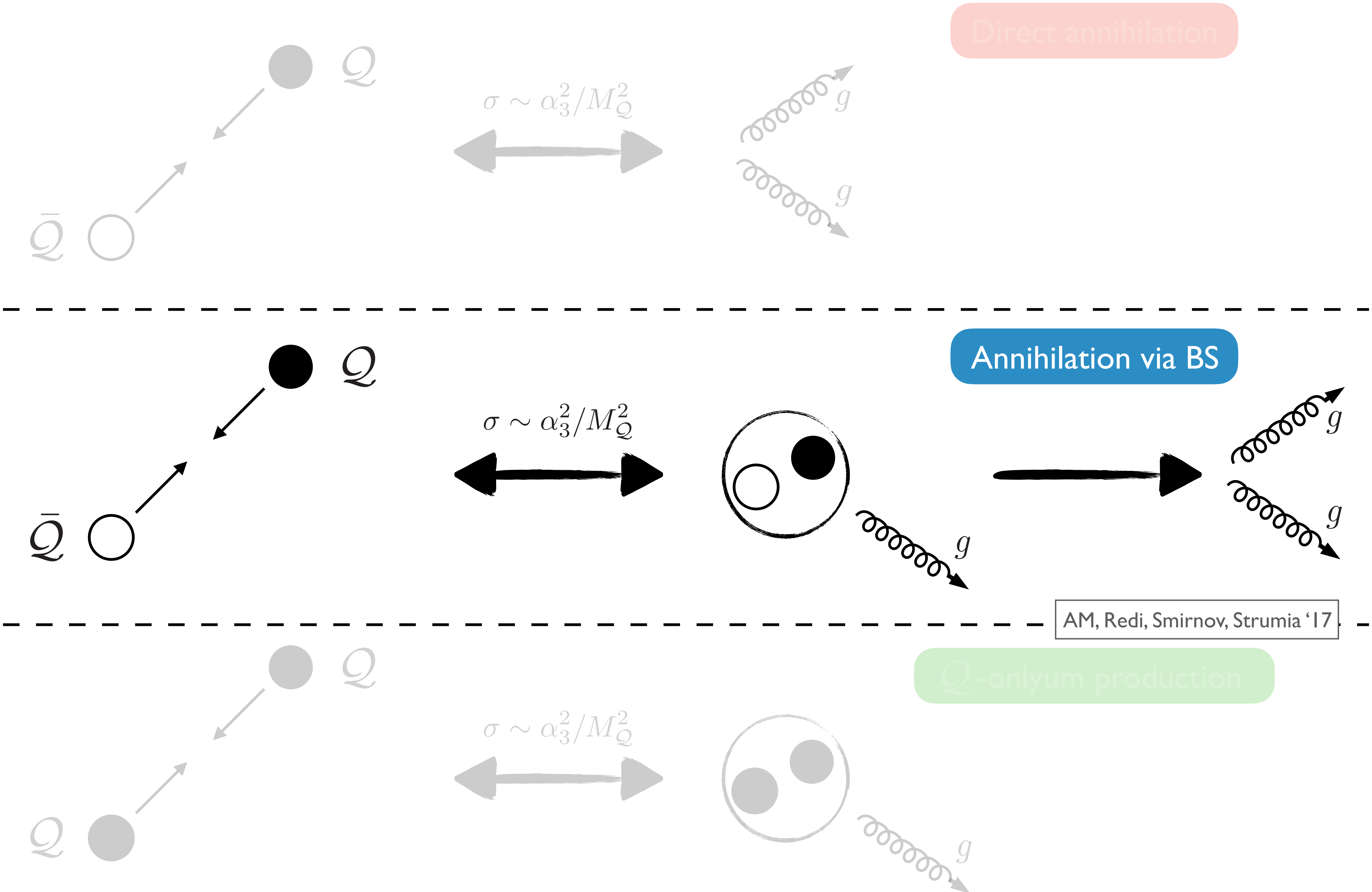

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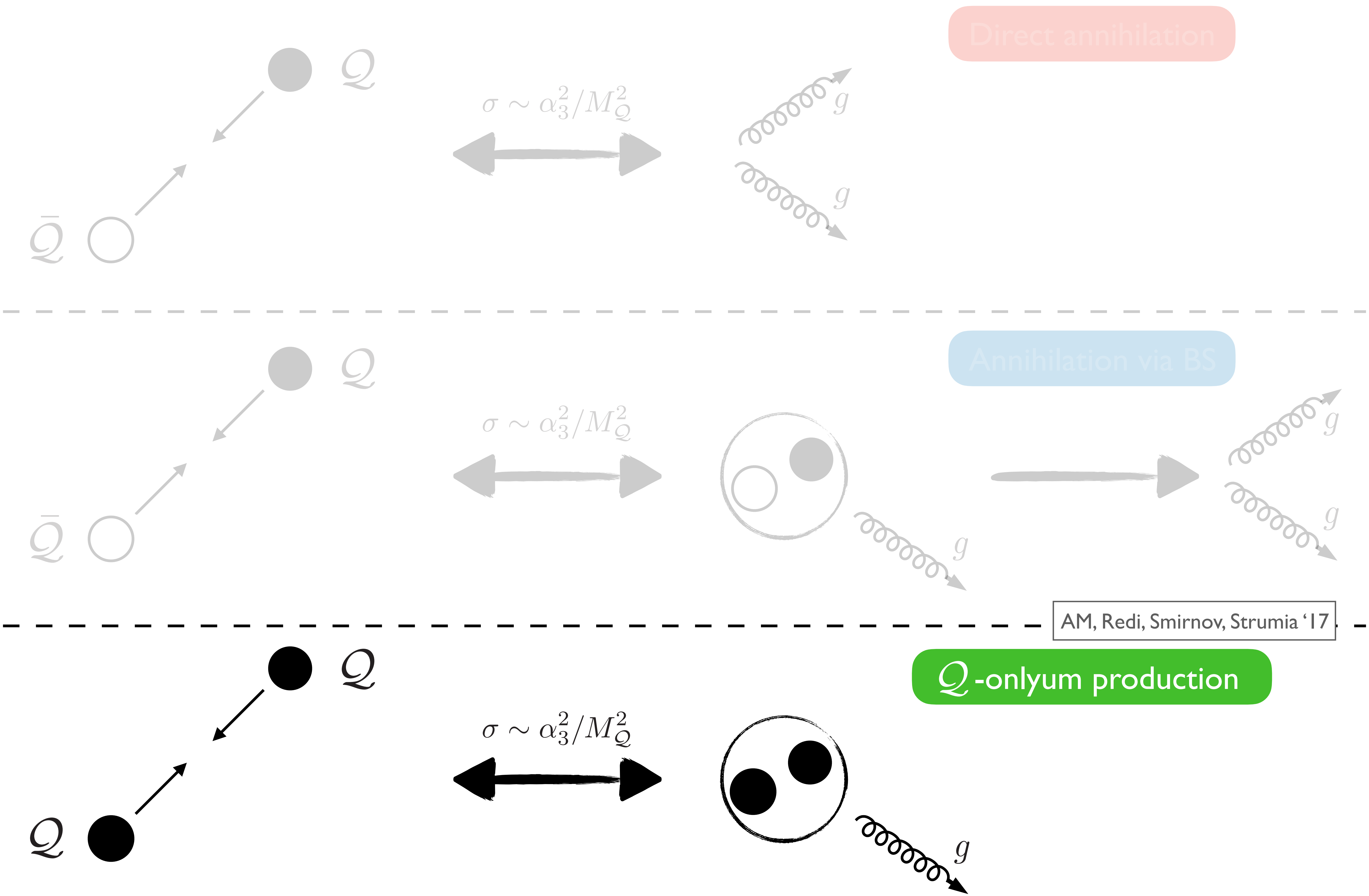

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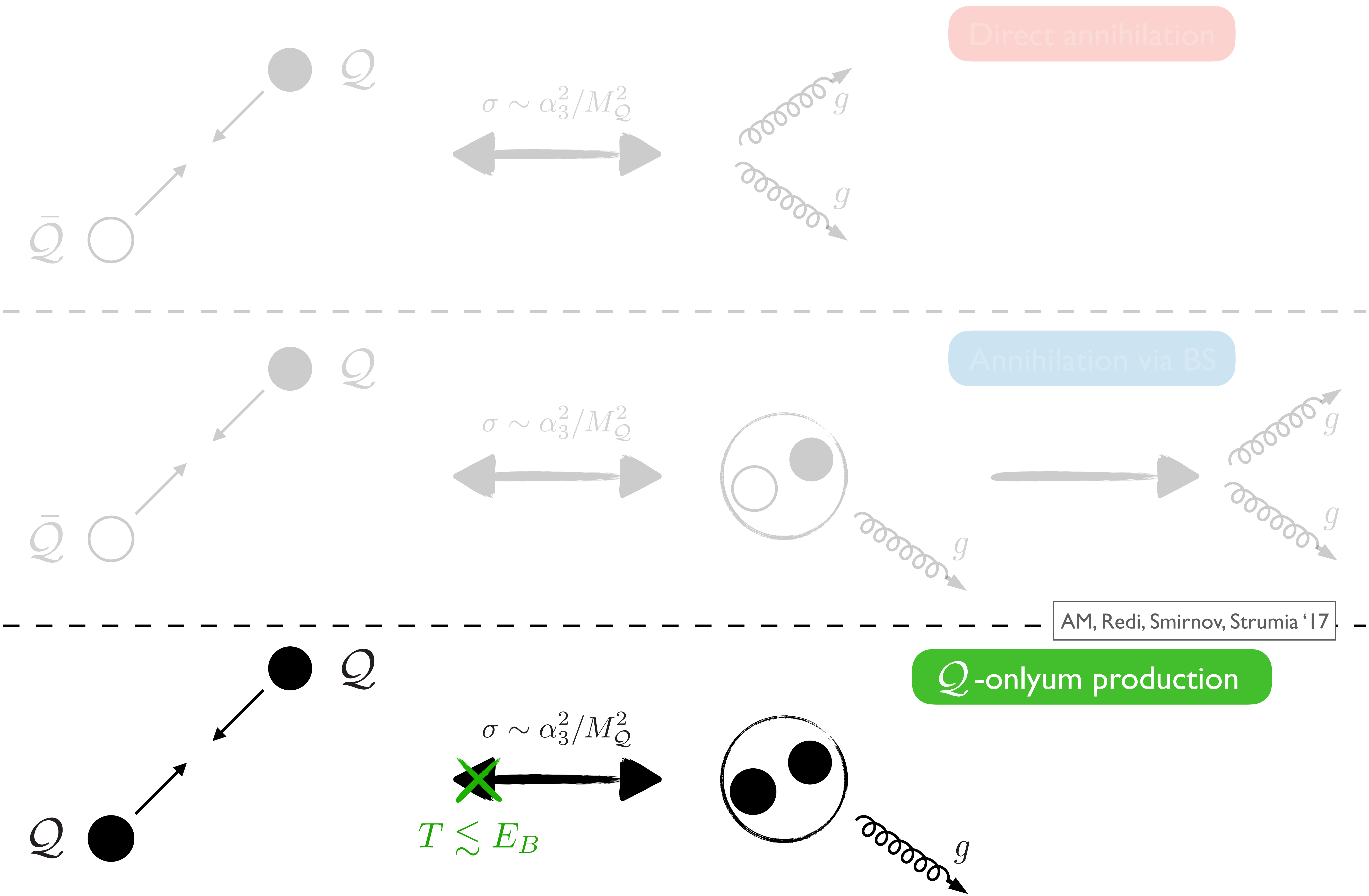

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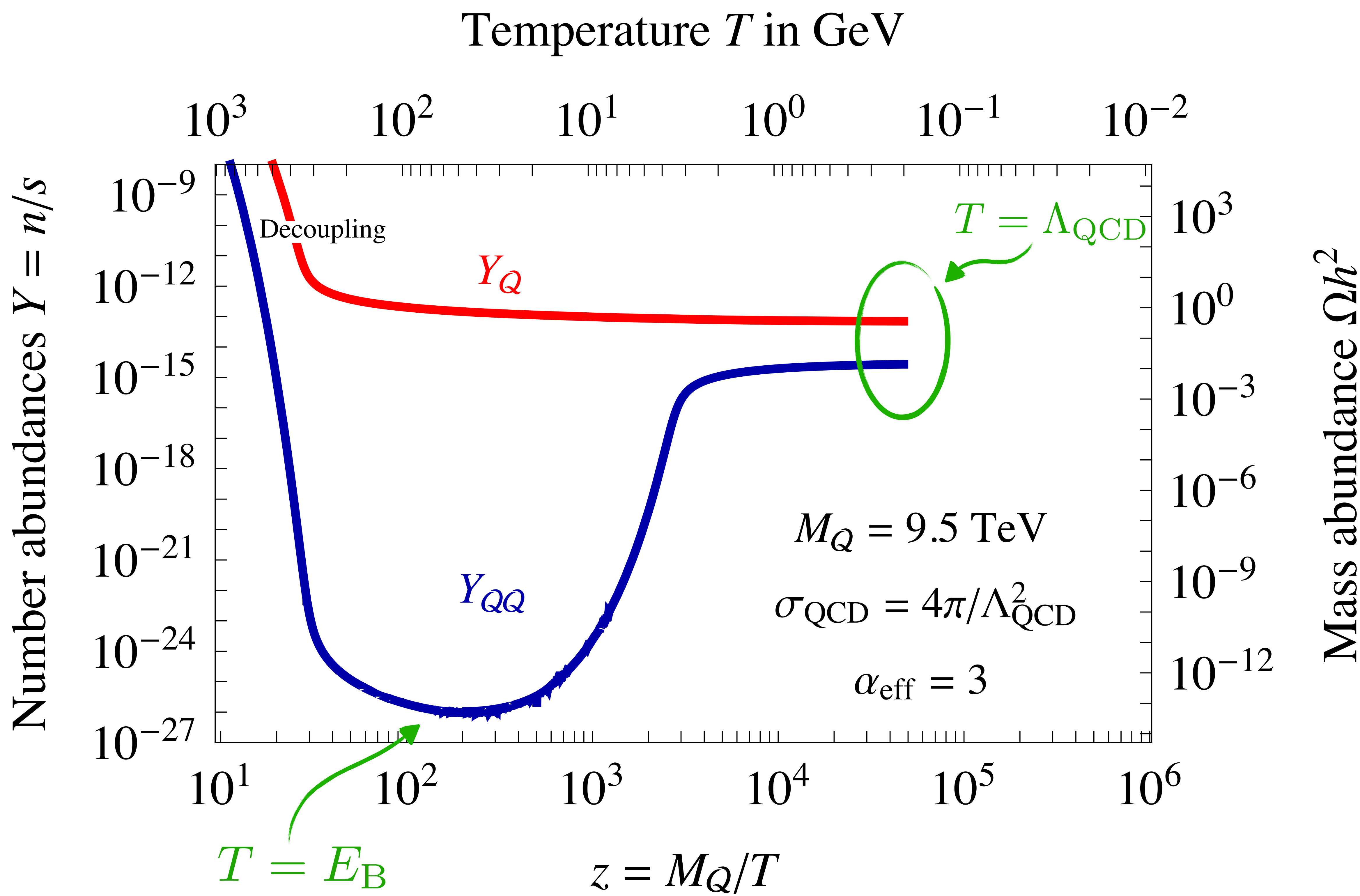

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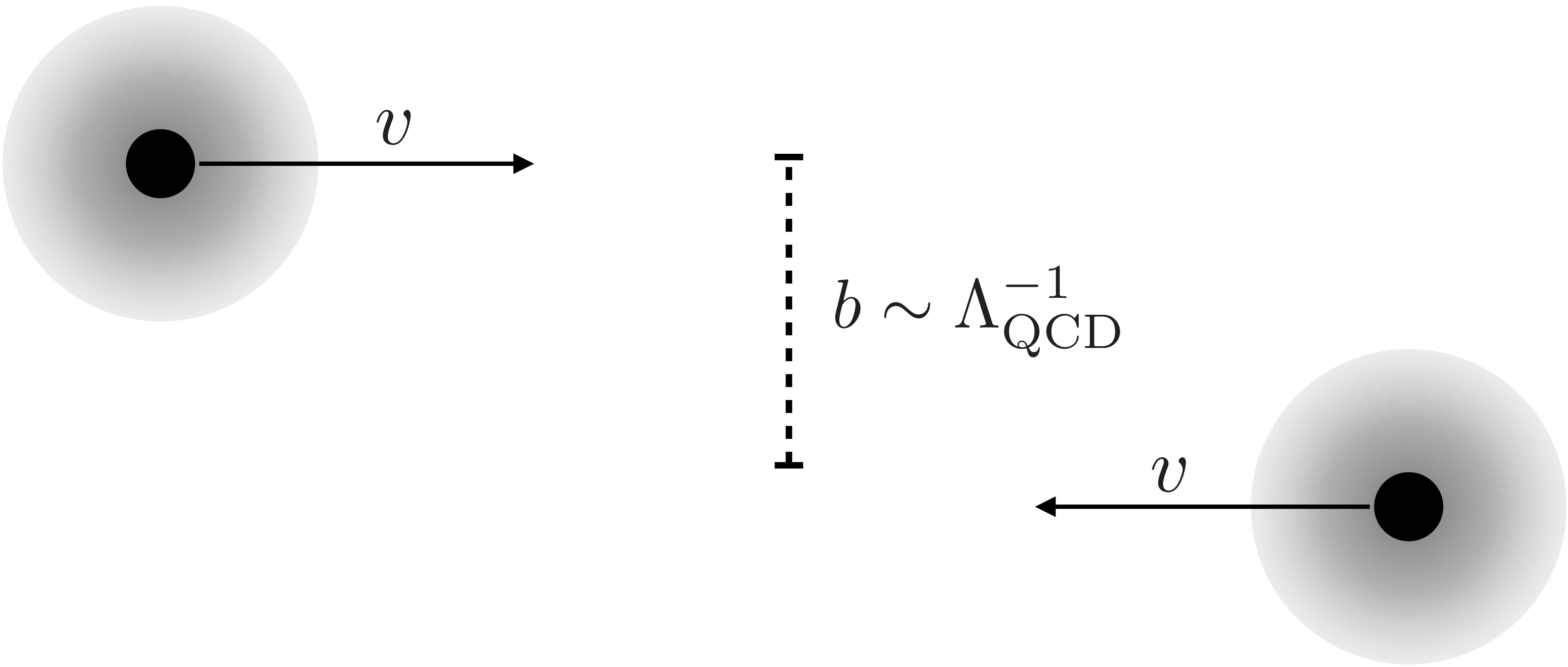
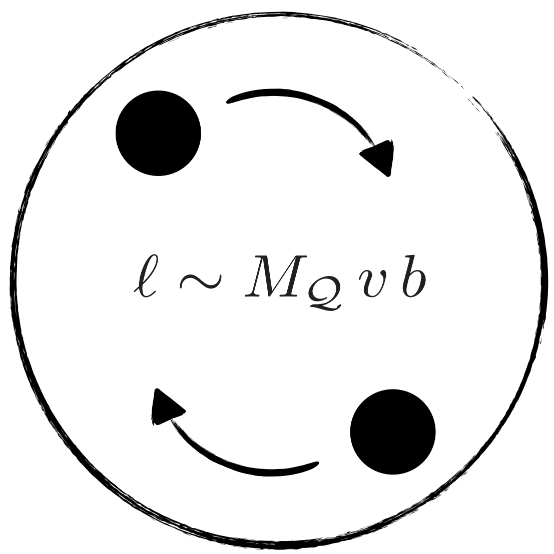


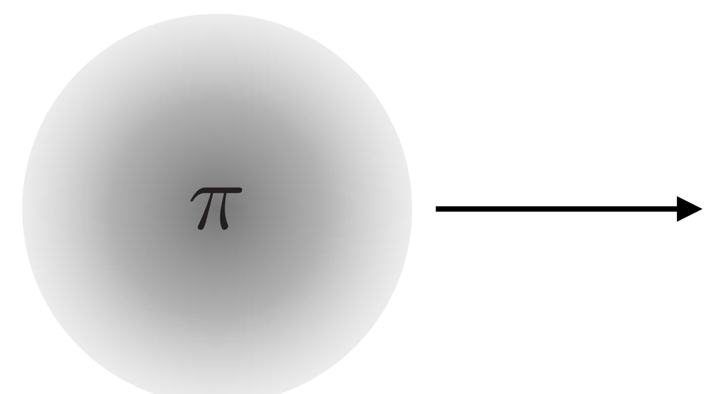

hybrids can collide with large impact parameters, giving rise to self scattering cross-sections of typical QCD size:

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

# (Post-confinement) **Cosmological evolution**

in hybrids collisions $\mathcal{Q}$-onlyum hadrons or unstable $\mathcal{Q}\bar{\mathcal{Q}}$ can be formed



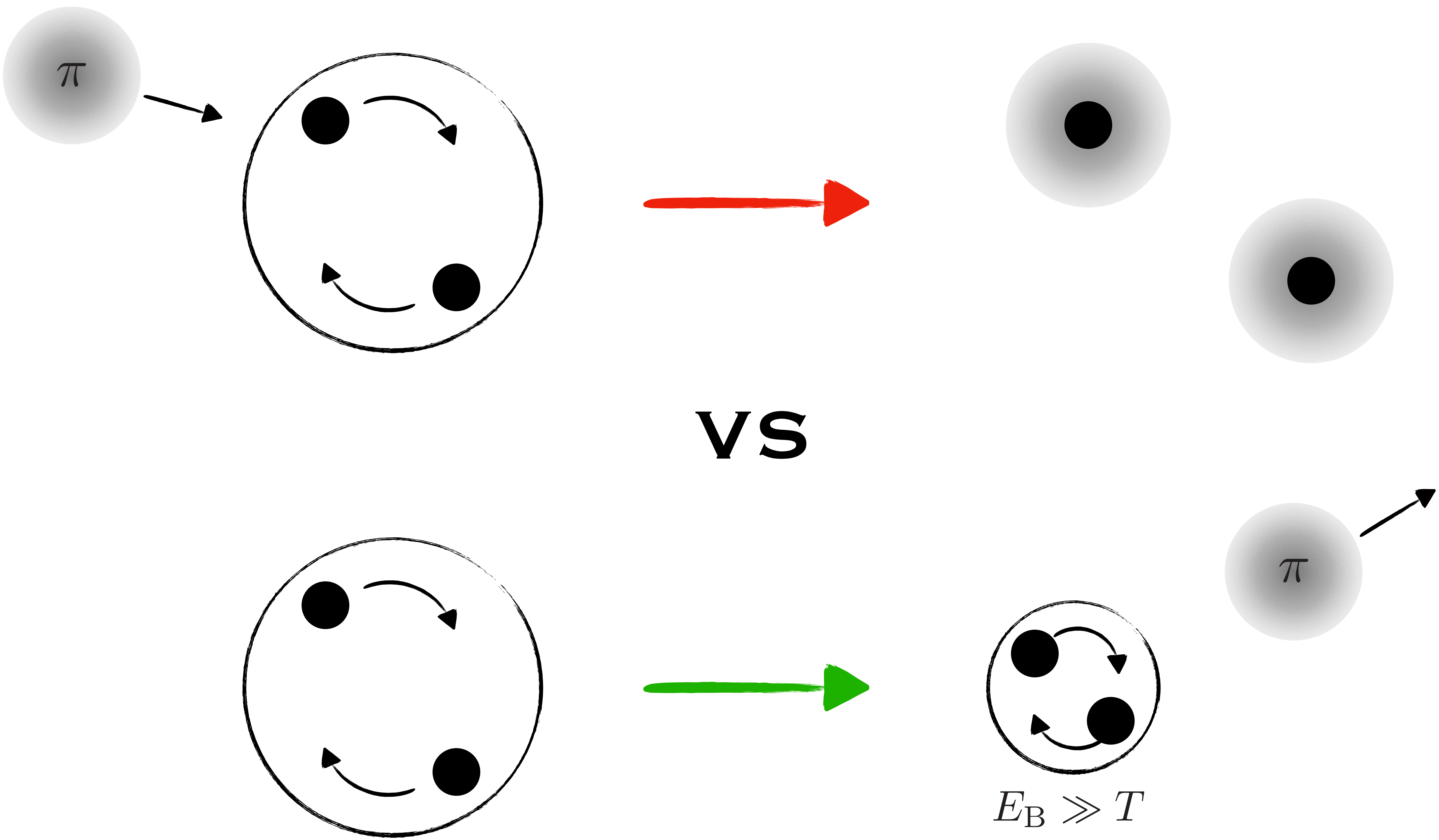




$$E_{\rm B}^{*} \ll E_{\rm B,\,0} \sim \alpha_3^2 M_{\mathcal{Q}}$$

$\mathcal{Q}$-onlyum are typically formed in states with large angular momenta

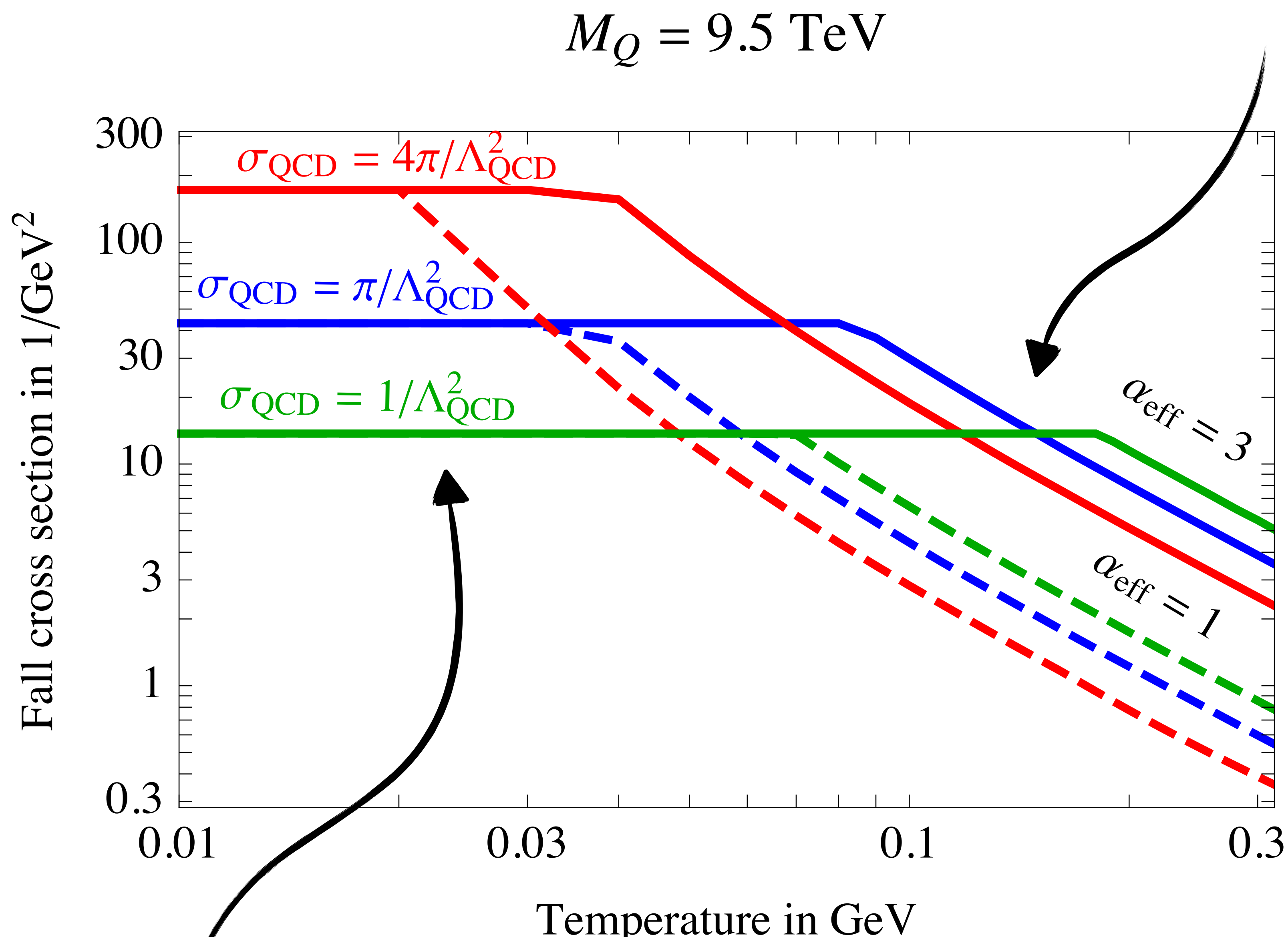
# (Post-confinement) **Cosmological evolution**

after formation $\mathcal{Q}\mathcal{Q}$ states can can break or fall to an unbreakable (deep enough) level



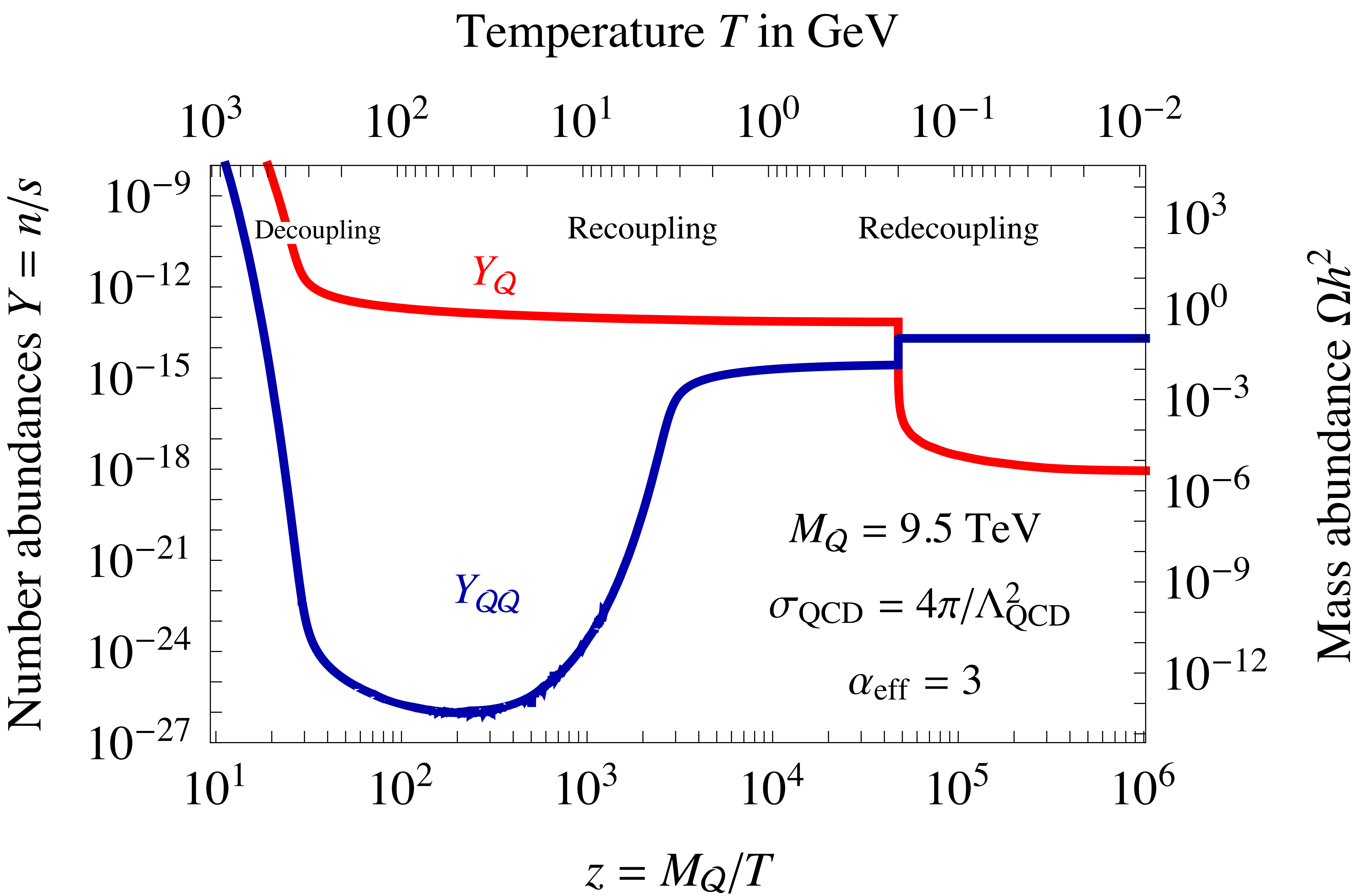
# (Post-confinement) **Cosmological evolution**

for $T >> m_\pi$ the effective cross section to form an unbreakable $\mathcal{Q}$-onlyum is reduced compared to the geometric one




at low temperatures all the $\mathcal{Q}$-onlyum manage to reach an unbreakable state

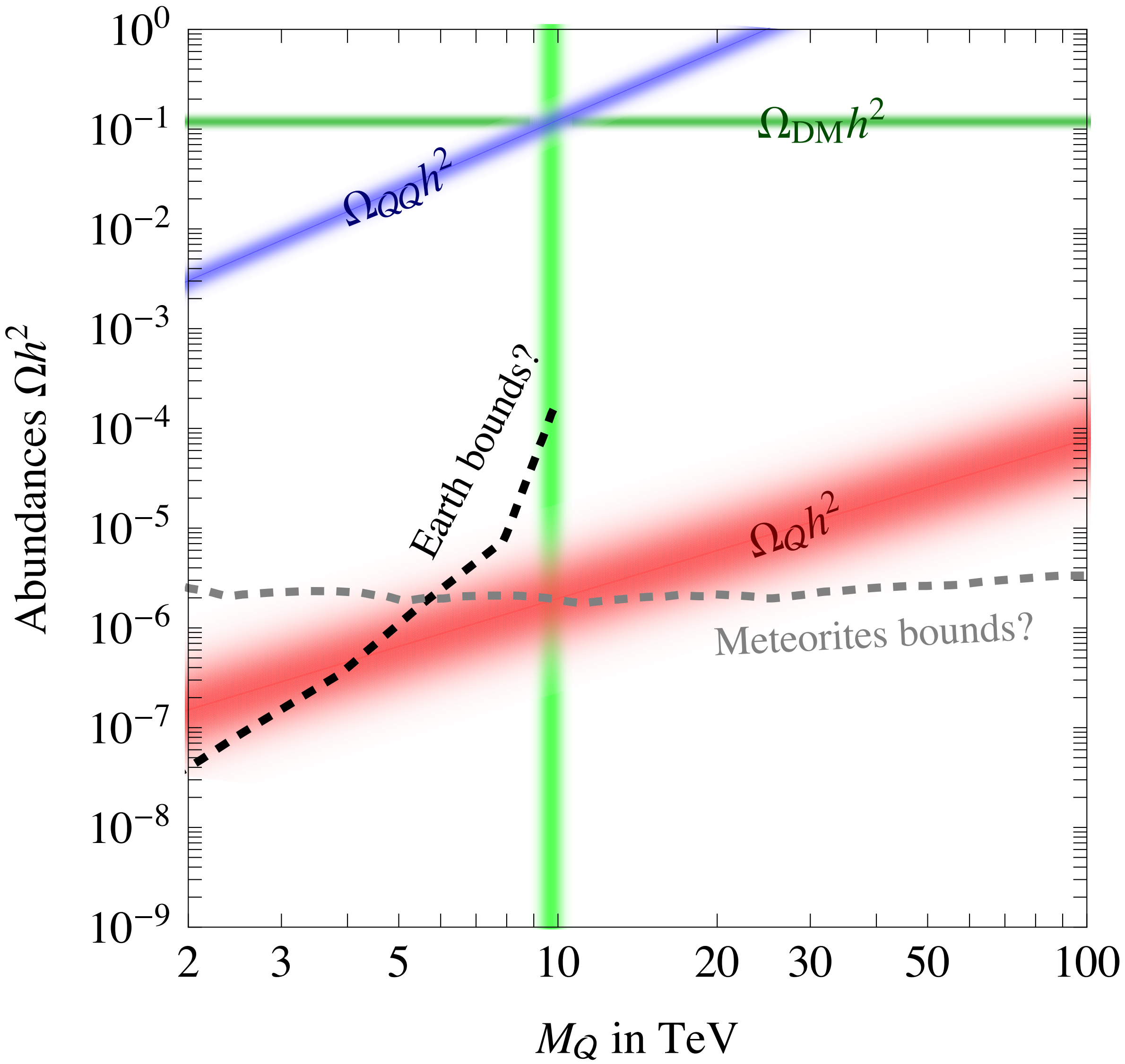
# (Post-confinement) **Cosmological evolution**

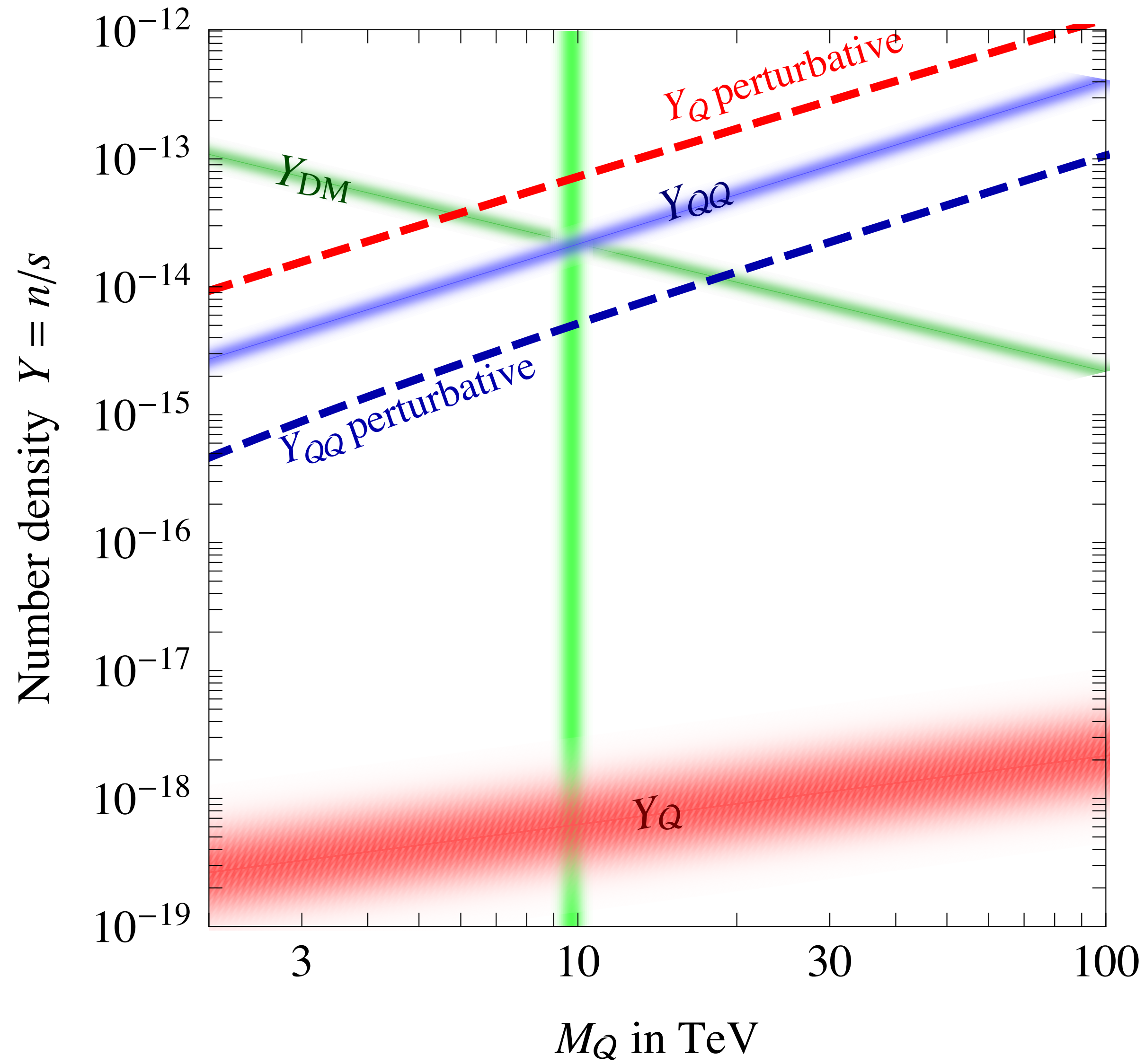


# Relic abundances

$$M_{\mathcal{Q}} \simeq 9.5\,\mathrm{TeV}$$

$$\Omega_{\mathrm{hyb}} \sim 10^{-5}\Omega_{\mathrm{DM}}$$



# Dark Matter signals

# DM direct detection

$\mathcal{Q}\mathcal{Q}$ interacts with gluons through induced chromo-dipole moments analogous to Rayleigh scattering hydrogen/light

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

the polarizability coefficient is:

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

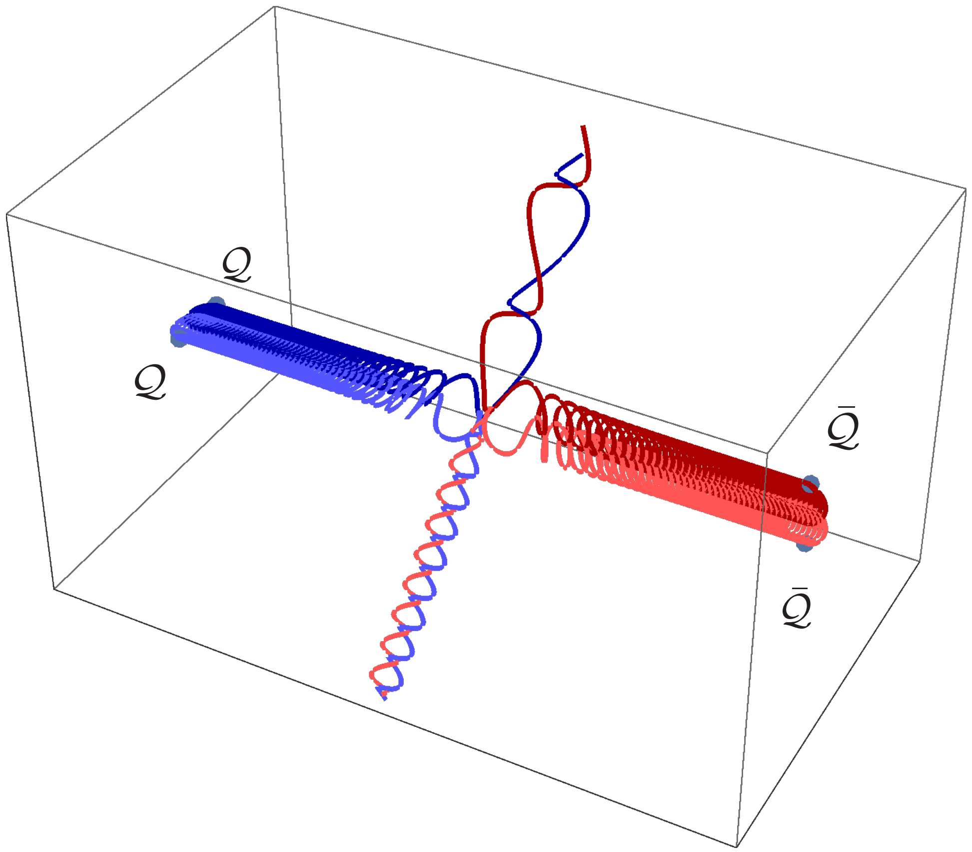
this gives a SI cross section slightly below XENON1T bounds

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

# DM indirect detection

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

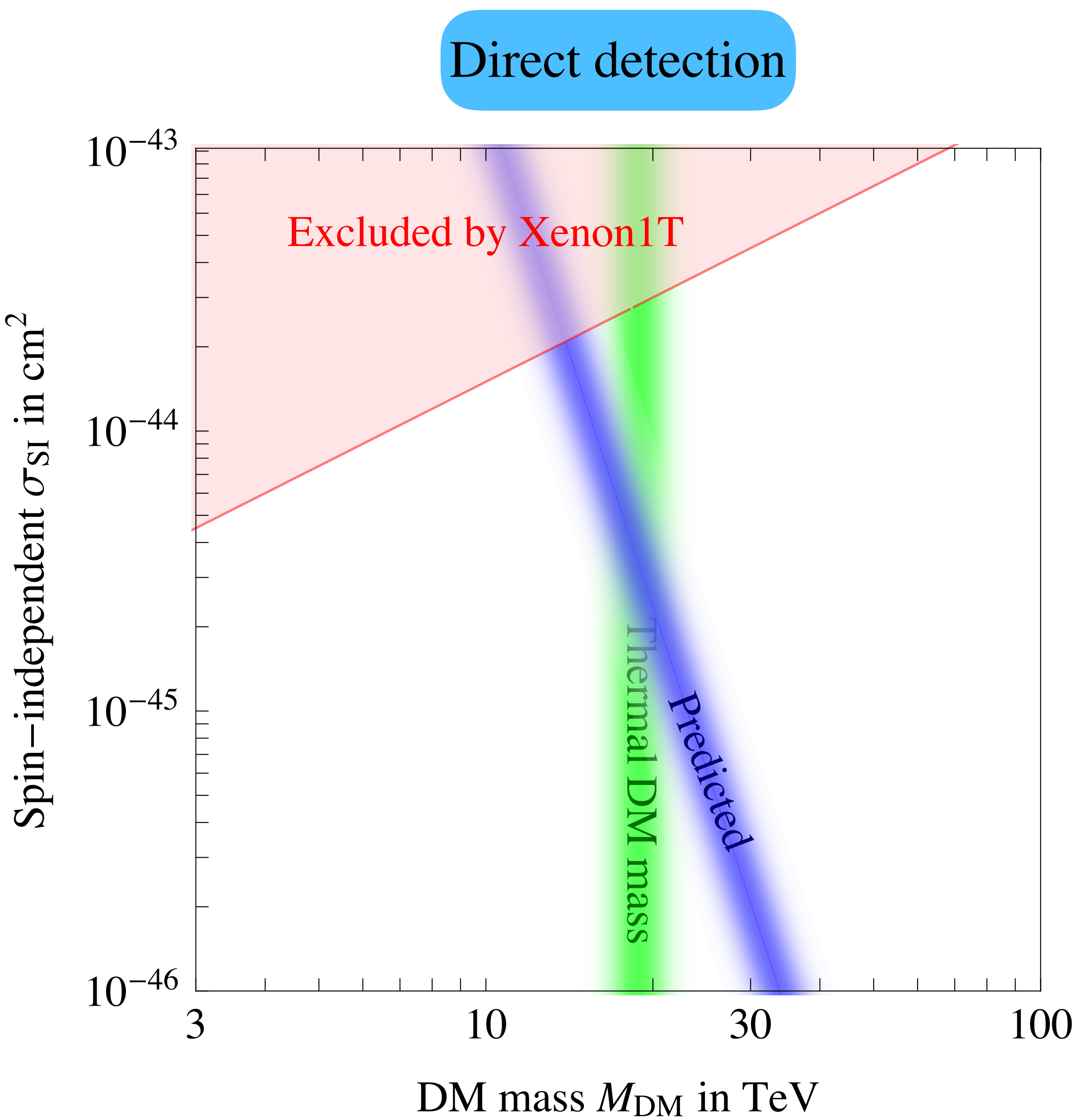
$$(\mathcal{Q}\mathcal{Q}) + (\bar{\mathcal{Q}}\bar{\mathcal{Q}}) \to (\mathcal{Q}\bar{\mathcal{Q}}) + (\mathcal{Q}\bar{\mathcal{Q}}) \to \text{SM}$$

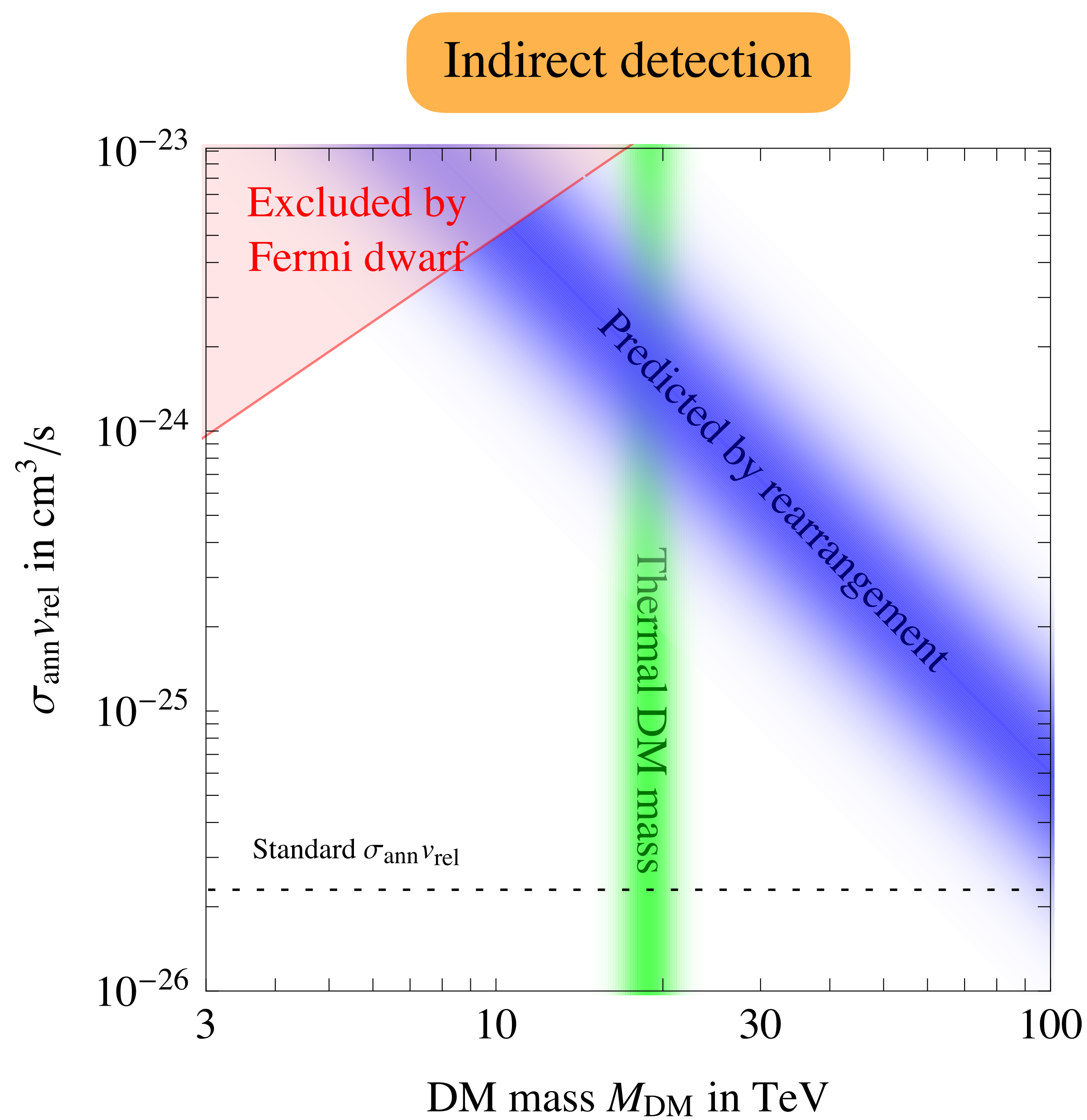



the recombination cross section is $\sim \alpha_3^3$ bigger than the one for direct annihilation

$$\sigma_{\text{ann}} v_{\text{rel}} \sim \frac{\pi a^2 v_{\text{rel}}/2}{\sqrt{E_{\text{kin}}/E_B}} = \frac{\sqrt{2}\pi}{3 M_{\mathcal{Q}}^2 \alpha_3} = 1.5\ 10^{-24} \frac{\text{cm}^3}{\text{sec}}$$

# DM direct & indirect detection bounds



# Collider detection of $\mathcal{Q}$

$\mathcal{Q}$ 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

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

$\sqrt{s} \sim 65\,\mathrm{TeV}$ is needed to discover $\mathcal{Q}$ with $M_{\mathcal{Q}} \sim 9.5\mathrm{TeV}$

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

Grilli di Cortona, Hardy, Powell

# Hybrids signals/bounds

# Direct detection of hybrids

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 $\Omega_{\mathrm{hyb}} = \Omega_{\mathrm{DM}}$

but not if $\Omega_{\mathrm{hyb}} = 10^{-5}\Omega_{\mathrm{DM}}$

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# 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 $\mathcal{Q}q\bar{q}'$ pions can mediate long ranges forces.
So we expect they do

for iso-spin singlet $\mathcal{Q}g$ 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'

Norman, Gazes, Bennett 86'

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

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

$$\left.\frac{N_{\rm hyb}}{N_n}\right|_{\rm Earth} = \frac{M}{M_Q}\frac{m_N}{M_{\rm Earth}} \approx 4\ 10^{-19}$$

# Searches for heavy nuclei in 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

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

estimated scaling typical neutron-capture cross sections

# Conclusions

**DM can be made of two color octet with mass around 9.5 TeV**

**Direct detection signals within the reach of future experiments**

**Indirect detection signals enacted by recombination**

**Manifest as stable tracks at collider, 65 TeV needed**

**Look for heavy isotopes**

# *Backup slides*

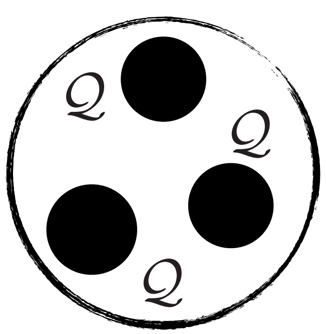
# Why adjoint representation?

We could have chosen

$$\mathcal{Q} = (3,1)_0$$

in this case the new hadron would have been

## $\mathcal{Q}$ -onlyum

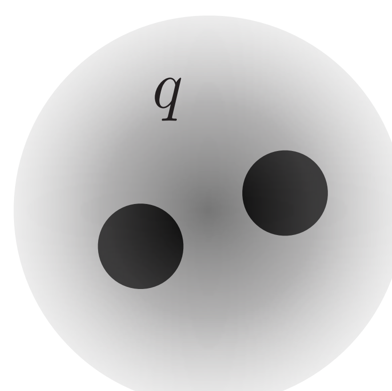



$$\sim \frac{1}{\alpha_3 M_{\mathcal{Q}}}$$

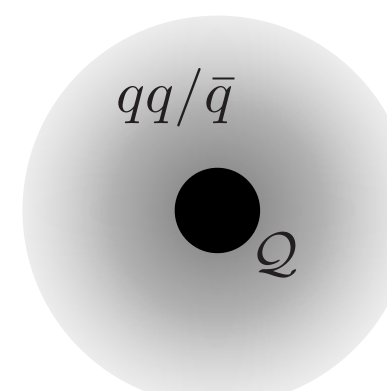
$$E_B \sim \alpha_3^2 M_{\mathcal{Q}}$$

**DM candidate**

## Hybrids




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

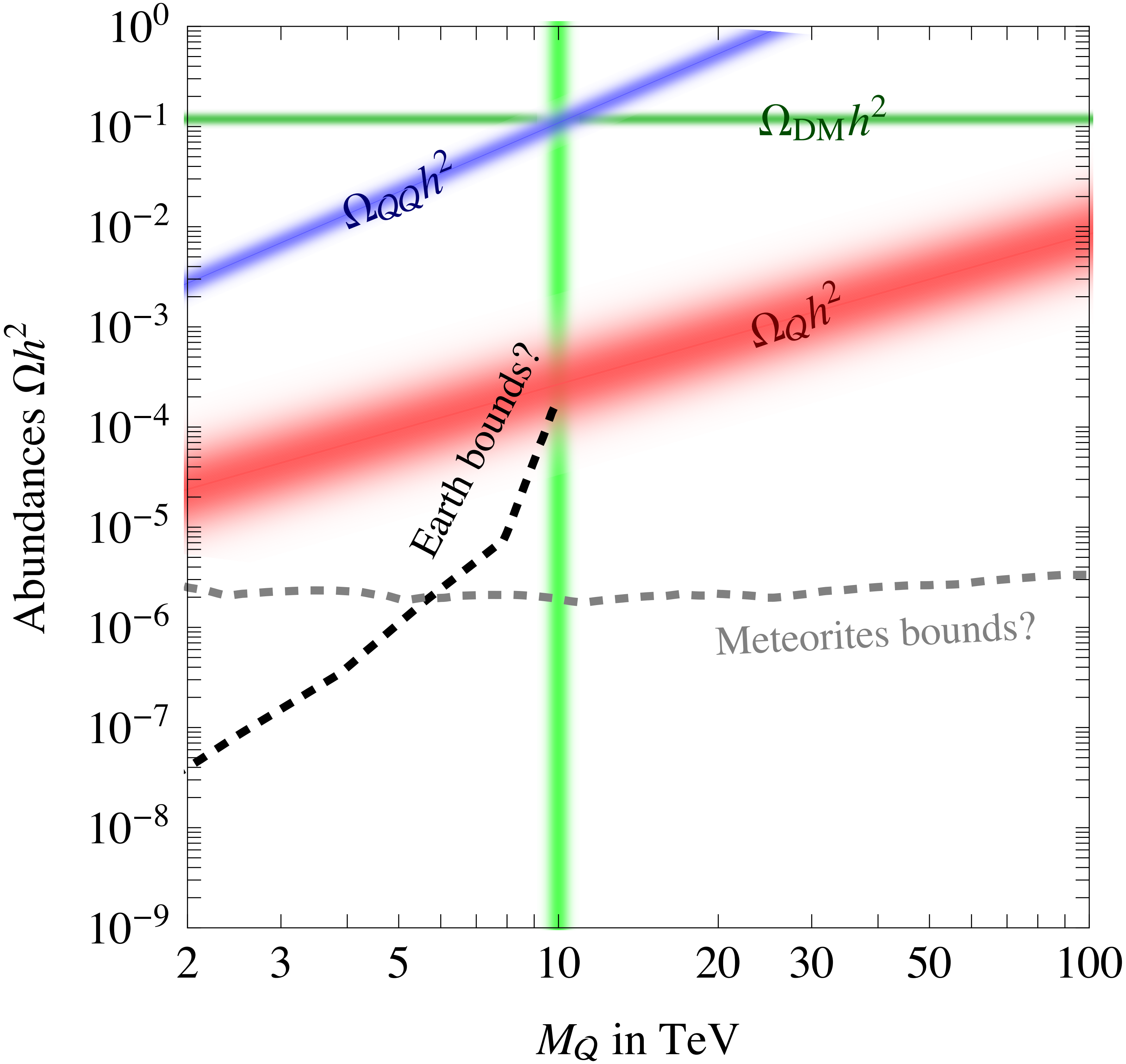



$E_B \sim \Lambda_{\rm QCD}$ **&** $\sigma \sim \Lambda_{\rm QCD}^{-2}$

→ fractional charge ←

**Too Dangerous**

# The worst case scenario



# Smooth re-coupling