Heavy quarkonia at finite temperature: The EFT approach

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5th Vienna Central European Seminar on QFT
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Outline

- Motivation
- Introduction to Effective Field Theories at T=0
- The EFT approach for quarkonia at finite temperature
- Conclusions
- Talk based on

N. Brambilla, J. Ghiglieri, A. Vairo, and P. Petreczky, Phys. Rev. **D78**, 014017 (2008)

Motivations

- Effective Field Theories of QCD have been successful in the last decades on a variety of physical problems
- Examples:
  - ChPT for the study of low-energy hadronic physics
  - Non-Relativistic QCD / potential NRQCD for heavy quarkonium physics

- EFTs prove to be a valuable computational tool for physical problems characterized by various sufficiently separated energy scales
- An EFT is constructed by integrating out modes of energy and momentum larger than the cut-off μ

$$\mathcal{L}_{\rm EFT} = \sum_n c_n(E_\Lambda/\mu)\frac{O_n(\mu)}{E_\Lambda}$$

Wilson coefficient

Low-energy operator/ cutoff

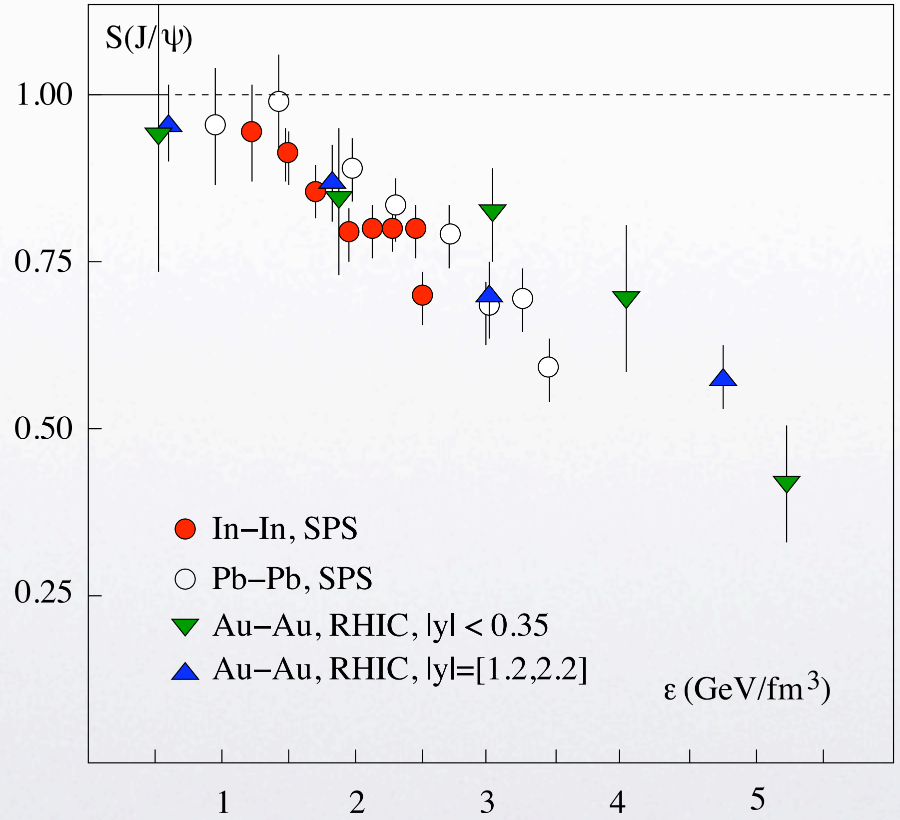
- The Wilson coefficient are obtained by matching appropriate Green functions in the two theories

Goal

- Our goal is then to extend the well-established T=0 EFT formalism for heavy quarkonia to the finite temperature situation

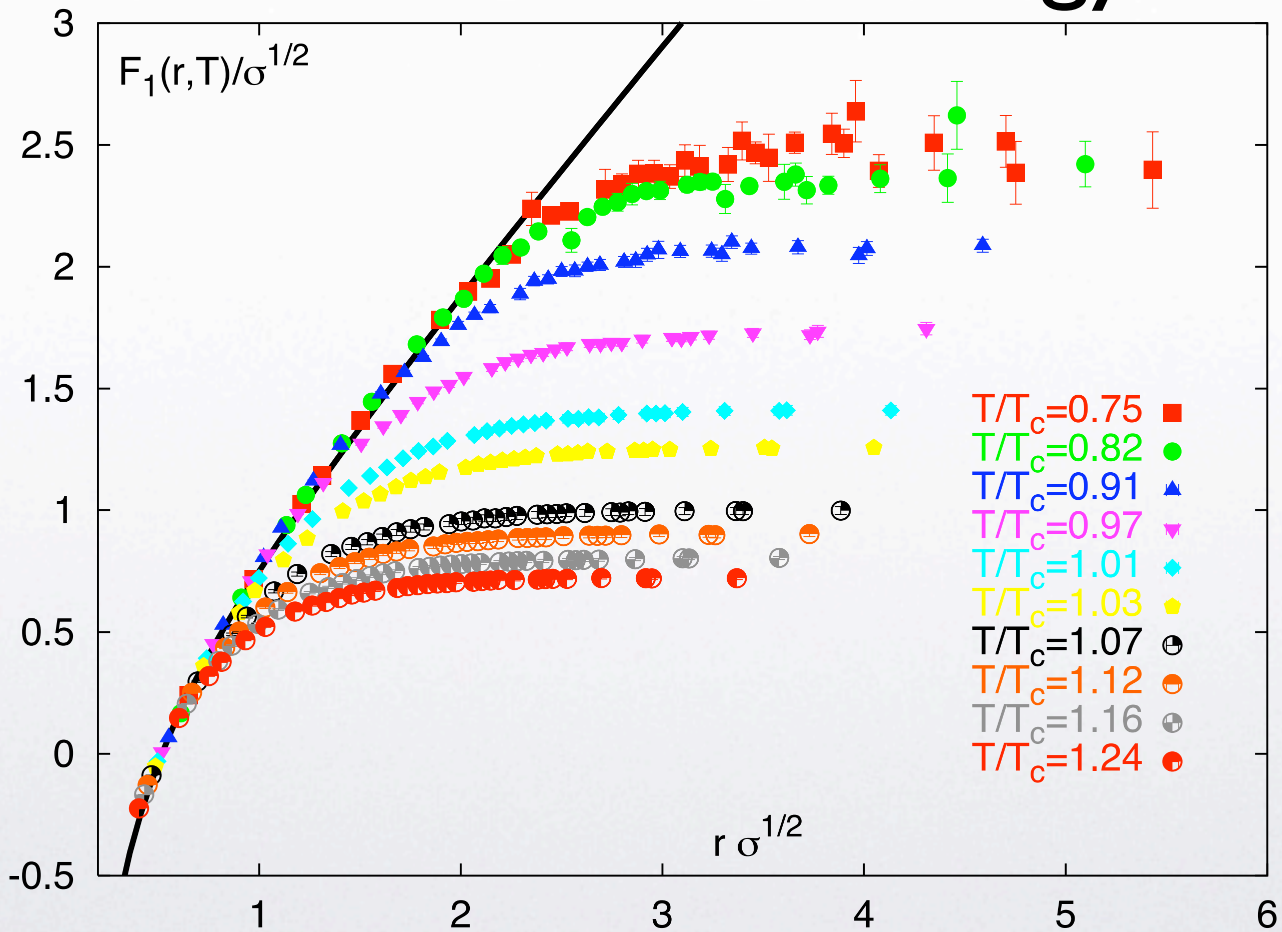
Physical picture

- Hypothesis of quarkonium ($Q\overline{Q}$) dissociation in a thermal medium (QGP) due to color screening (Matsui, Satz, 1986)
- Can thus quarkonium dissociation be a signature of QGP formation?



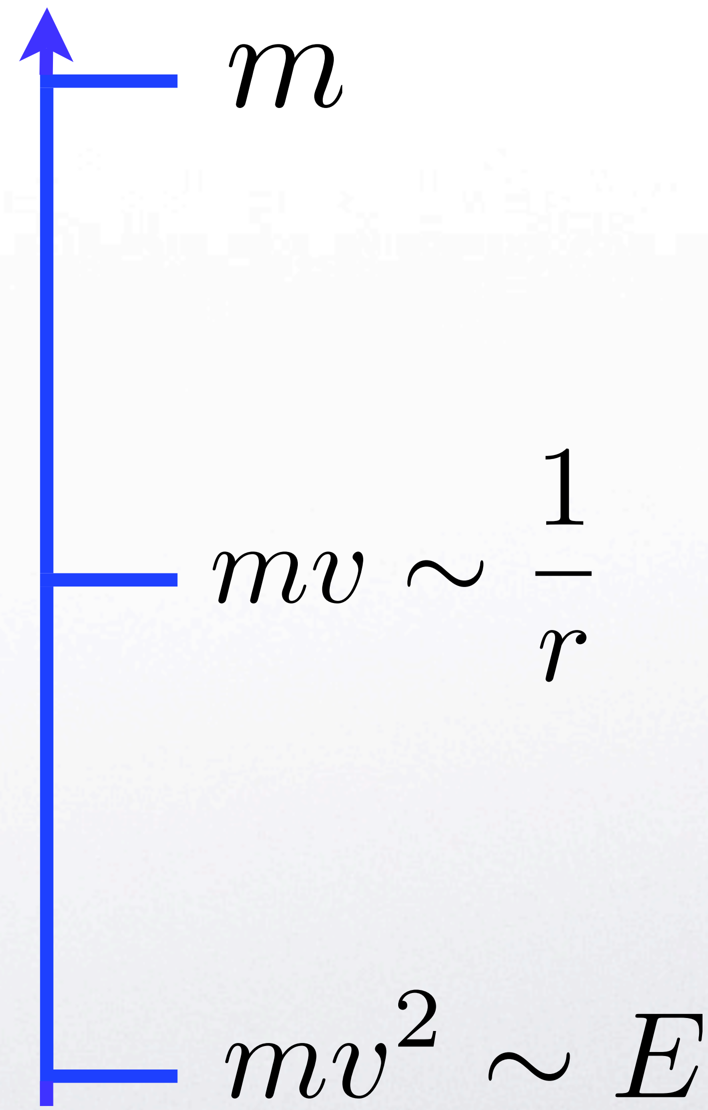
Physical picture

- Past studies based mainly on phenomenological potential models or lattice computations of the free energy



T=0 NR EFTs: a Short Primer

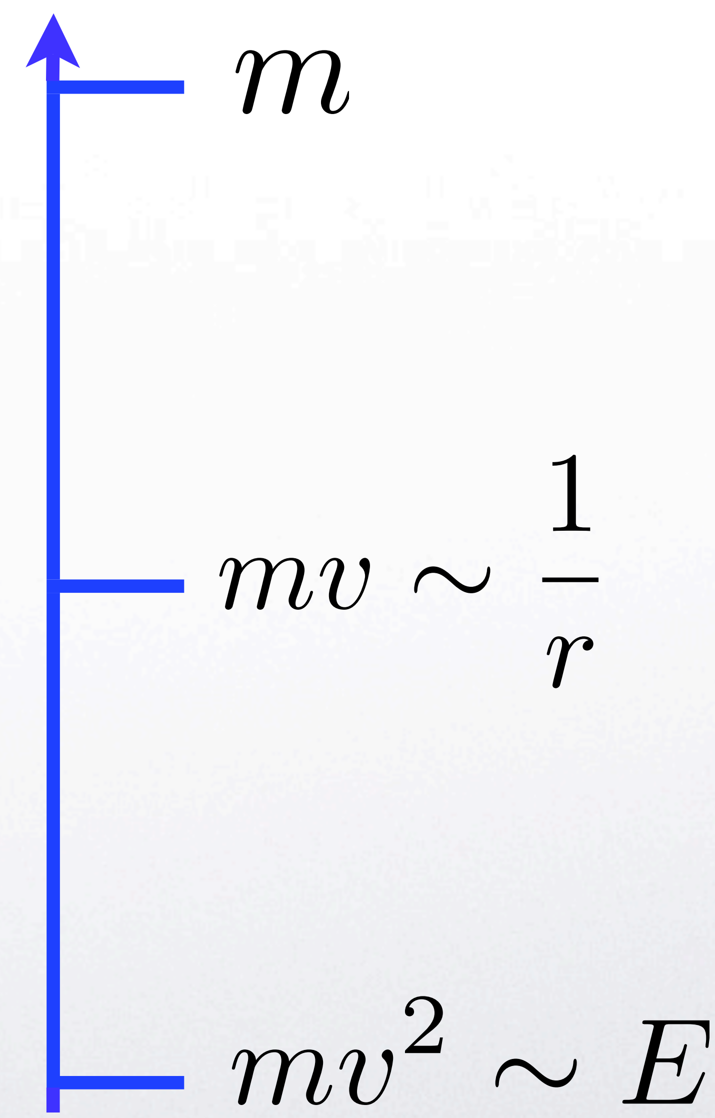
- Non-relativistic $Q\overline{Q}$ bound states are characterized by the hierarchy of the mass, energy and momentum scales



T=0 NR EFTs: a Short Primer

- Non-relativistic $Q\overline{Q}$ bound states are characterized by the hierarchy of the mass, energy and momentum scales

- One can then expand observables in terms of the ratio of the scales and construct a *hierarchy of EFTs* that are equivalent to QCD order-by-order in the expansion parameter



T=0 Scales

$$m$$

$$mv \sim \frac{1}{r}$$

$$mv^2 \sim E$$

T=0 Scales

m

$mv \sim \frac{1}{r}$

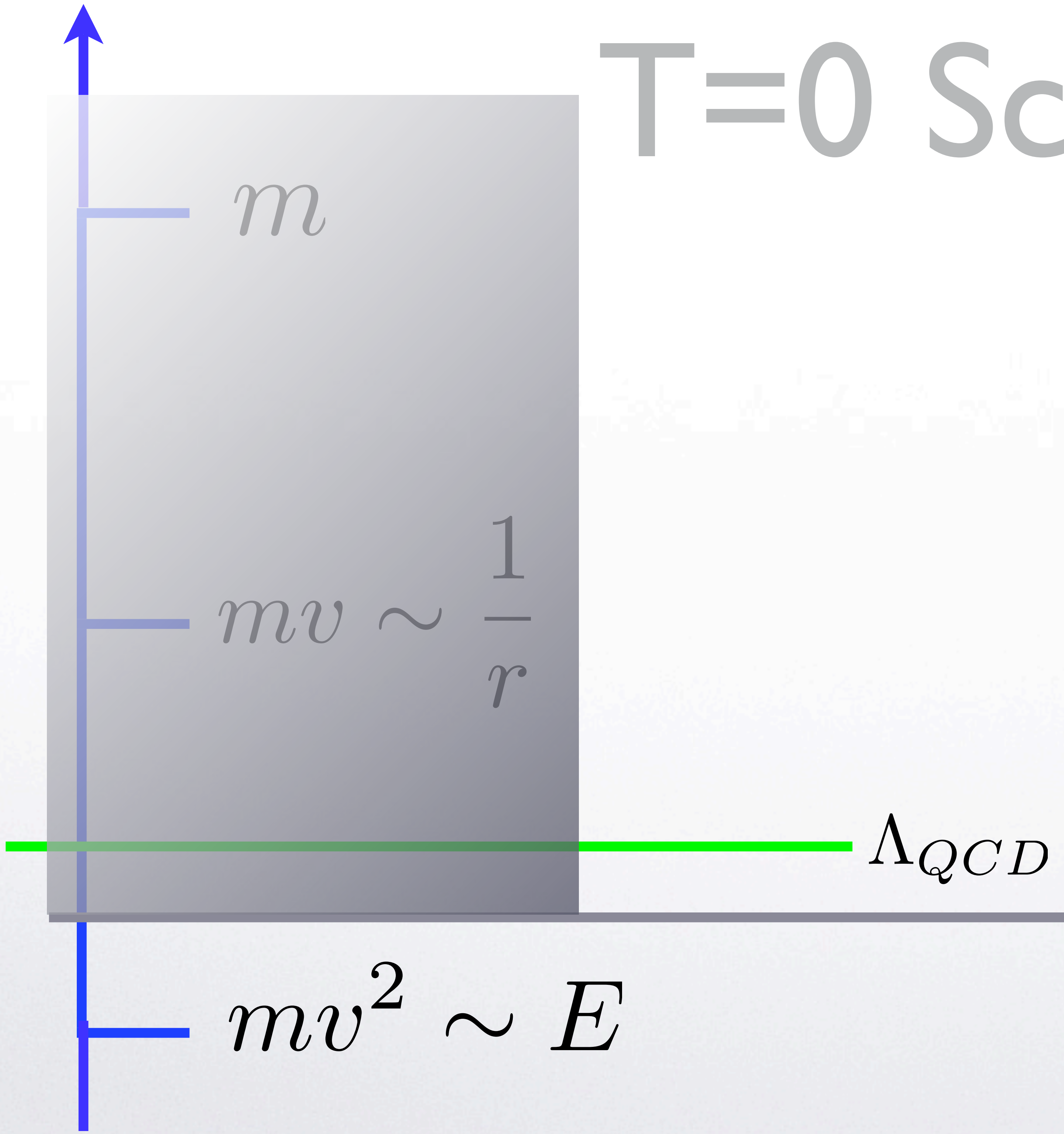
$mv^2 \sim E$

Integration of the mass scale: NRQCD

T=0 Scales

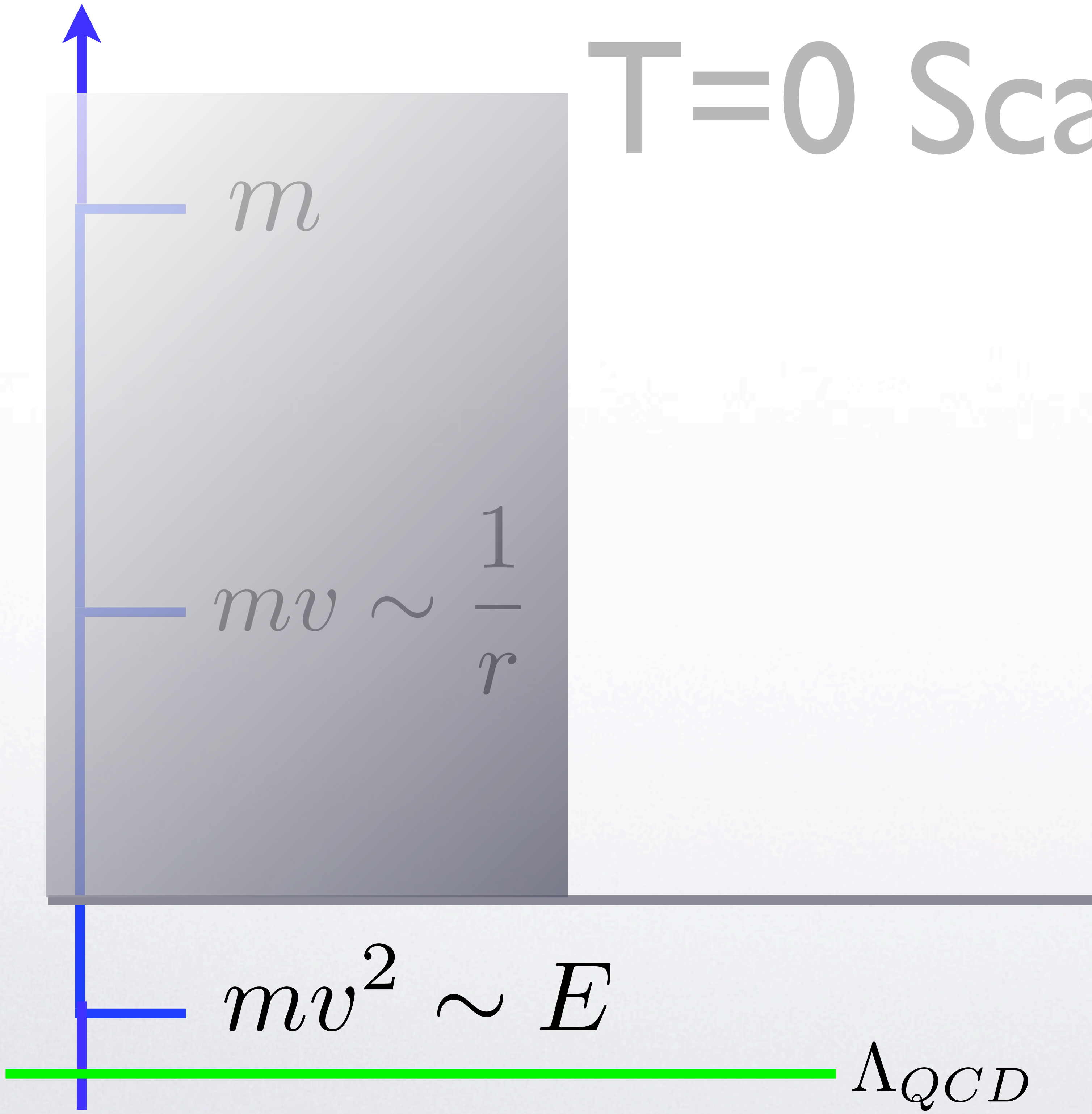
Integration of the soft (momentum transfer) scale:
pNRQCD

T=0 Scales



Integration of the soft (momentum transfer) scale:
pNRQCD

T=0 Scales



Integration of the soft (momentum transfer) scale: pNRQCD

Weakly coupled pNRQCD

- Degrees of freedom: $Q\overline{Q}$ states with energy $E \sim \Lambda_{QCD}, mv^2$ and momentum $p \lesssim mv$
  Singlet and octet color states
- Gluons with energy/momentum $\lesssim mv$
- Gluon fields are multipole-expanded in the centre of mass coordinate R $A(R,r,t) = A(R,t) + \mathbf{r} \cdot \nabla A(R,t) + \dots$
- Expansion in $\alpha_s(m)$, $\frac{1}{m}$ and r
- Potential as a Wilson coefficient, receives contributions from all higher scales

Thermodynamical scales

- The thermal medium introduces new scales in the physical problem
  - The temperature
  - The electric screening scale (Debye mass)
  - The magnetic screening scale (magnetic mass)
- In the weak coupling assumption these scales develop a hierarchy

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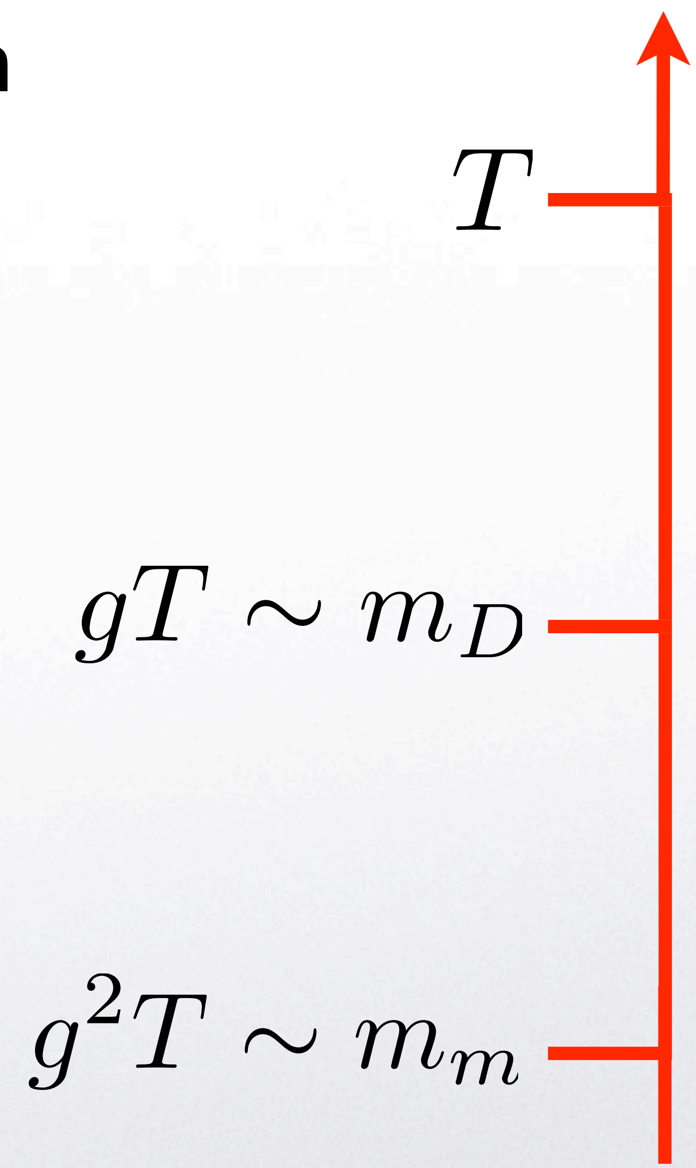
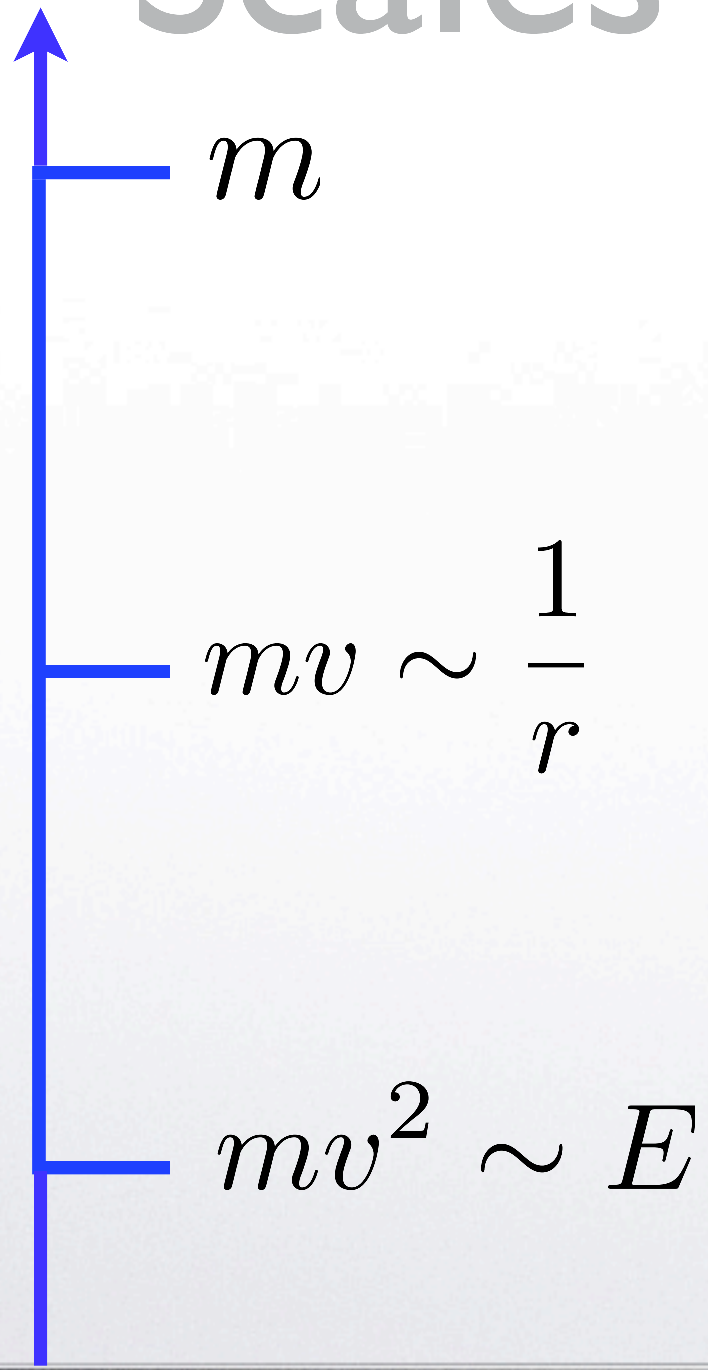


Scales of the problem



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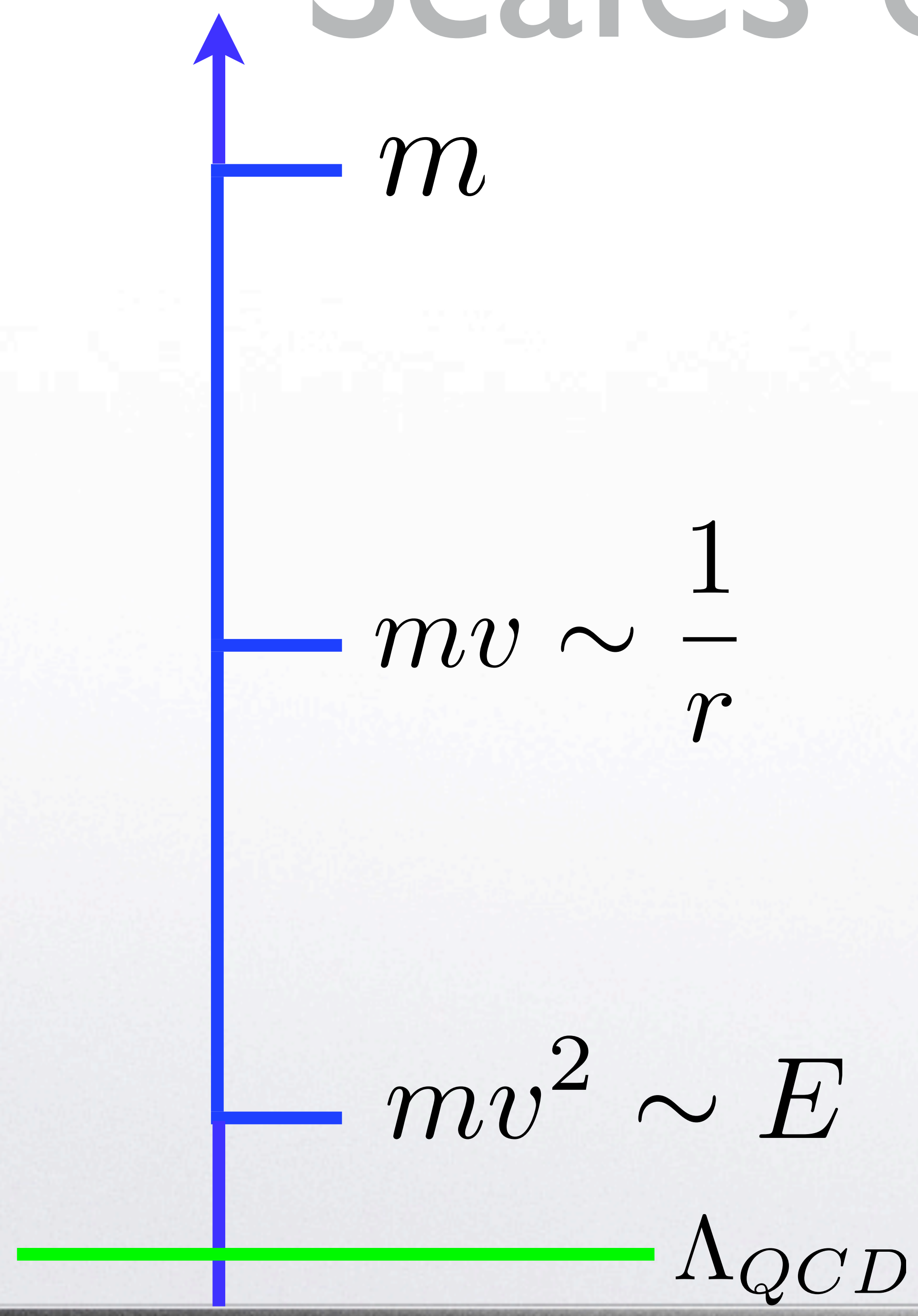

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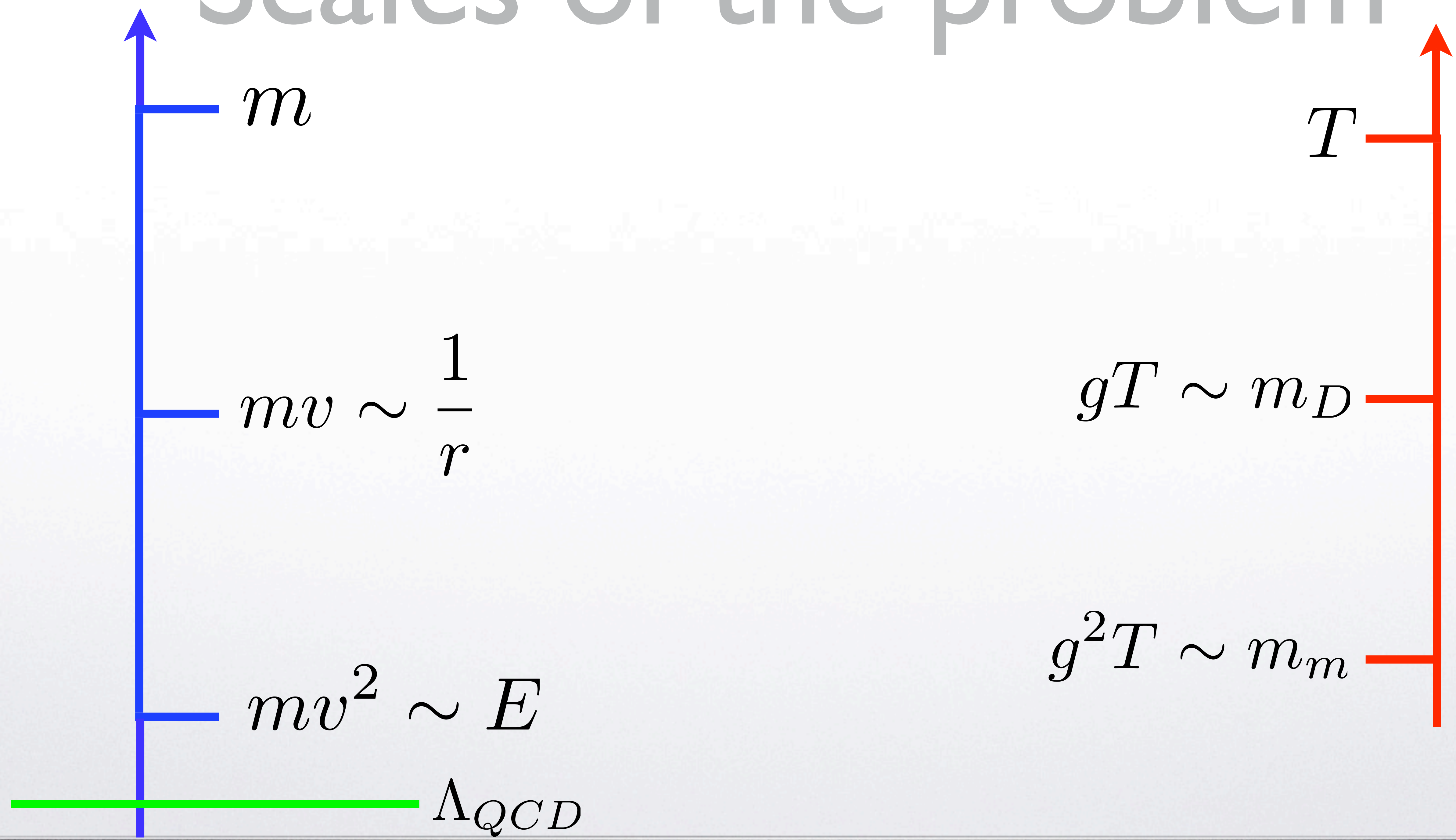

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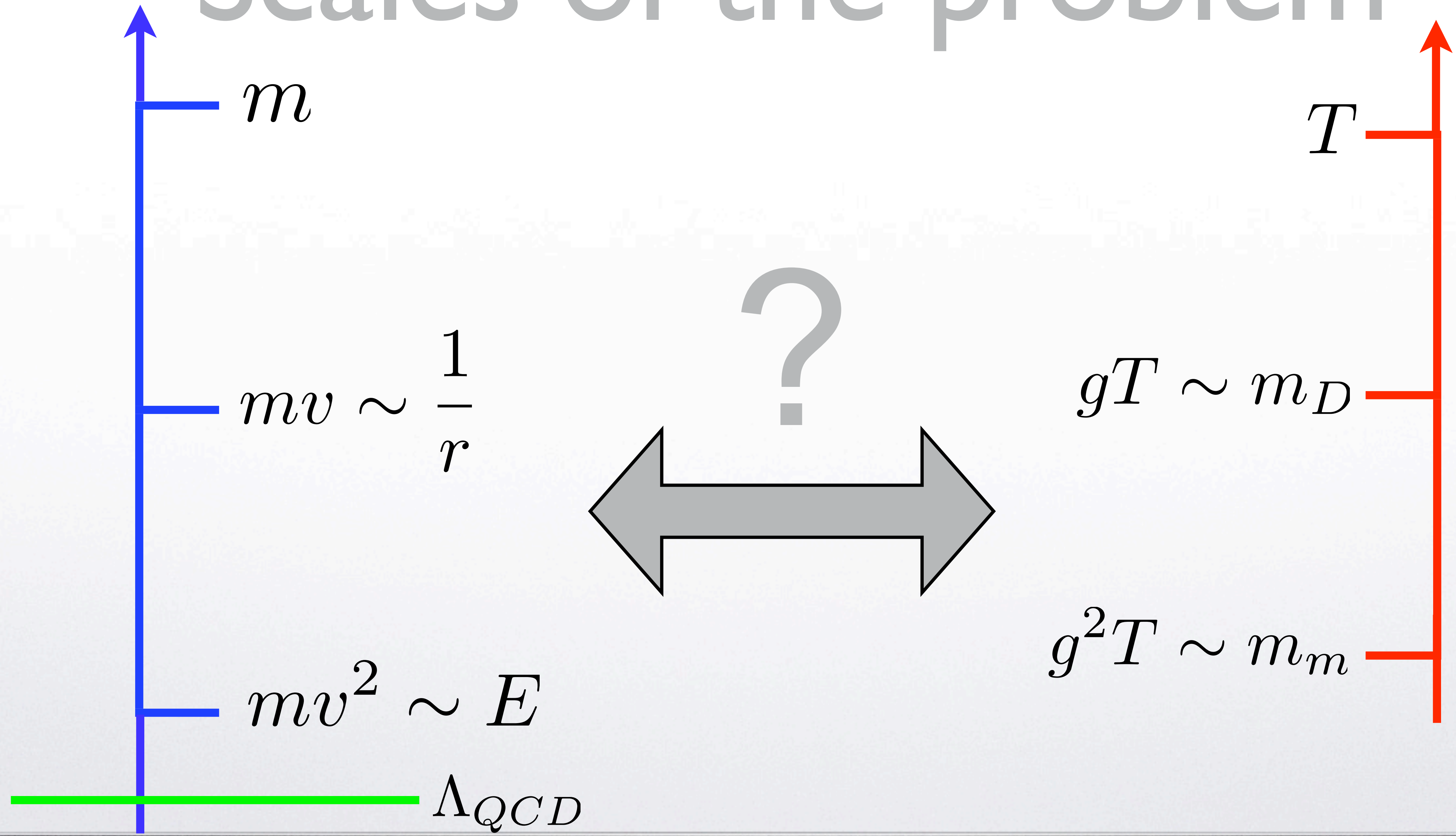
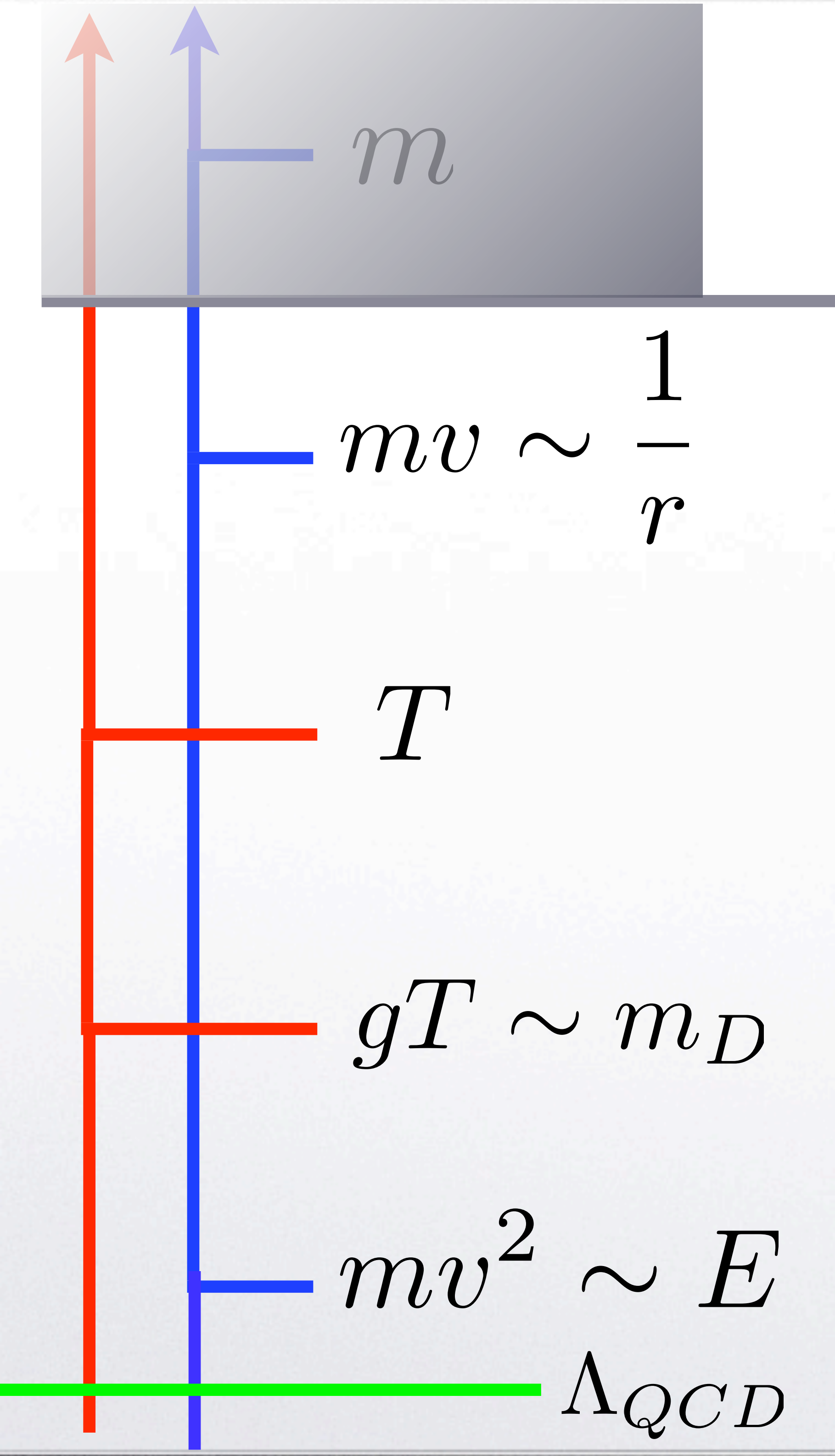


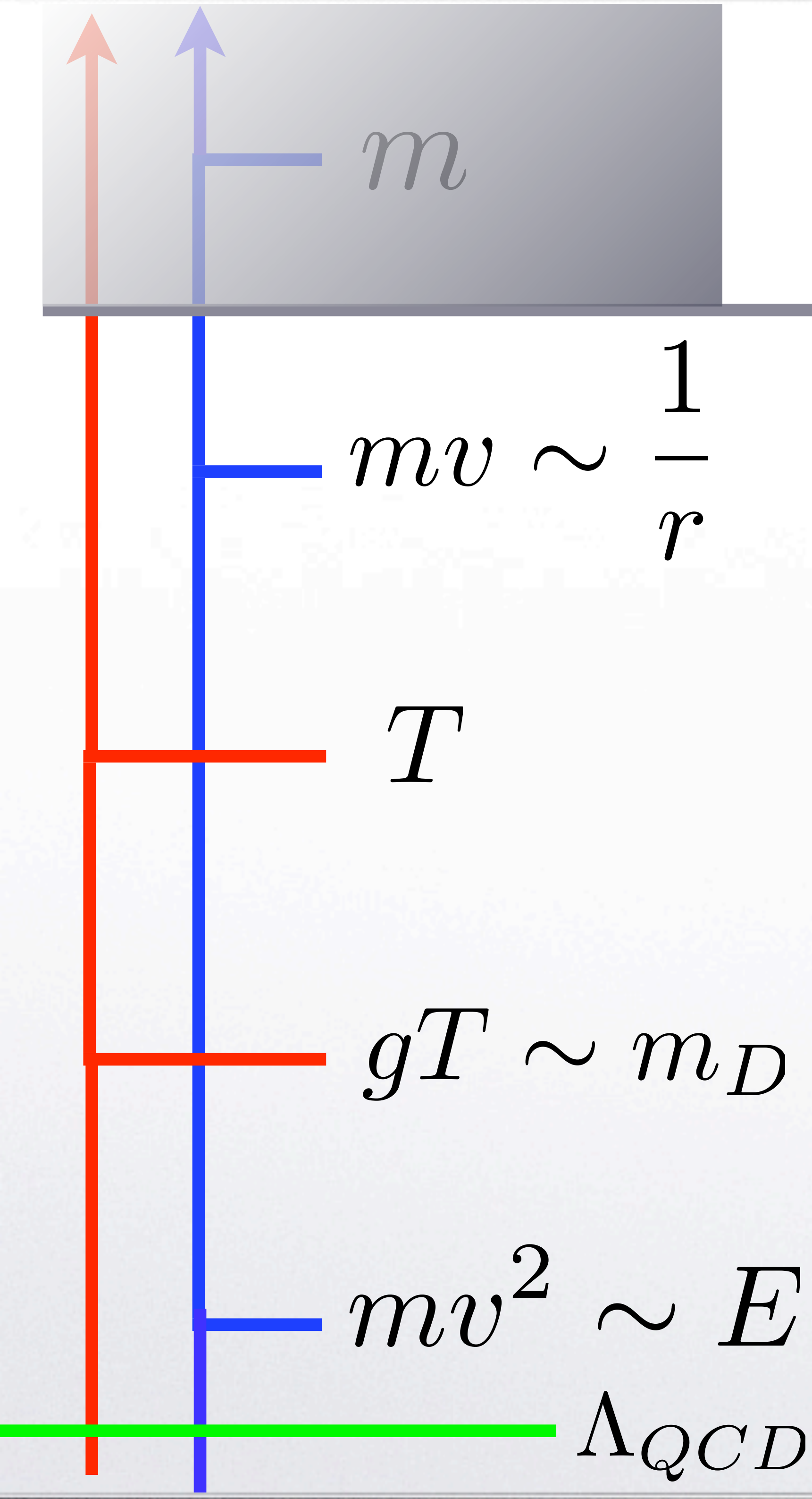
Scales of the problem

- In our work various possibilities have been studied, from $T \ll E$ to $m \gg T \gg 1/r \sim m_D$
- Here we illustrate the intermediate case $$m \gg 1/r \gg T \gg m_D \gg E$$
- A good showcase of the EFT approach with the interplay of different scales
- We don't consider the (suppressed) magnetic mass effects

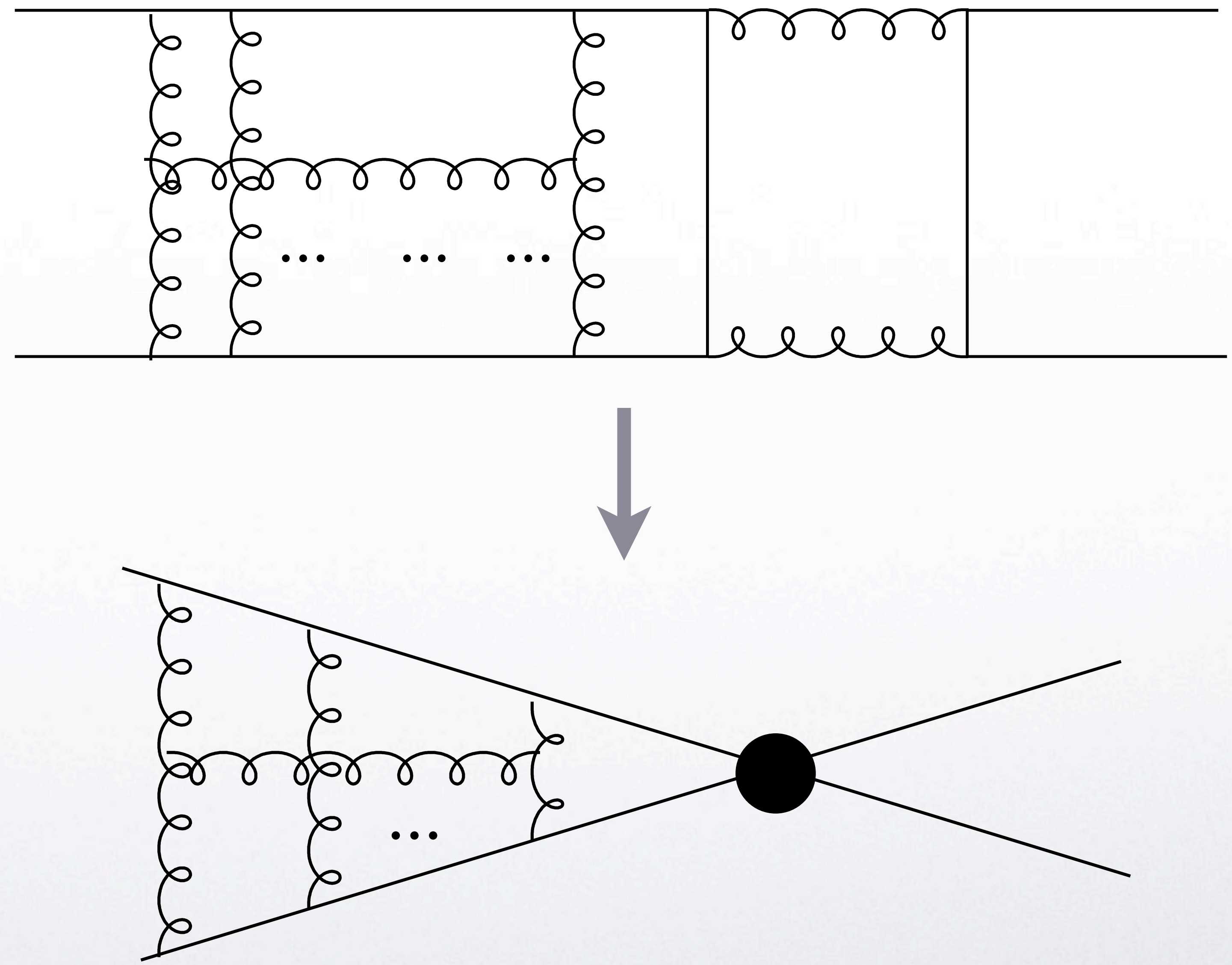


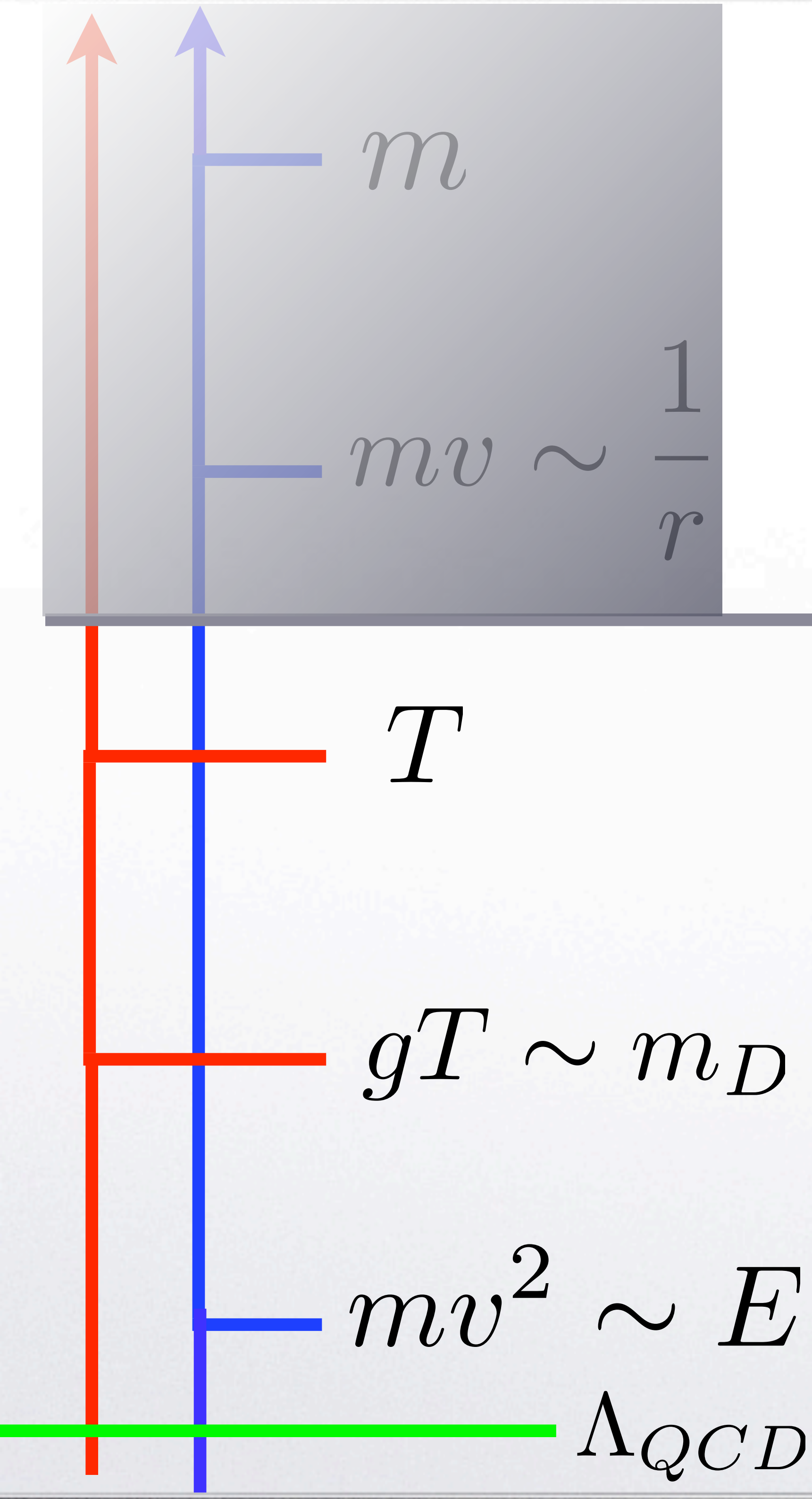
Mass scale

- QCD ⇒NRQCD
- We only consider the leading term $\left(\frac{1}{m}\right)^0$, corresponding to treating heavy quarks/antiquarks as static sources
- So far everything goes exactly as in the T=0 case



Mass scale

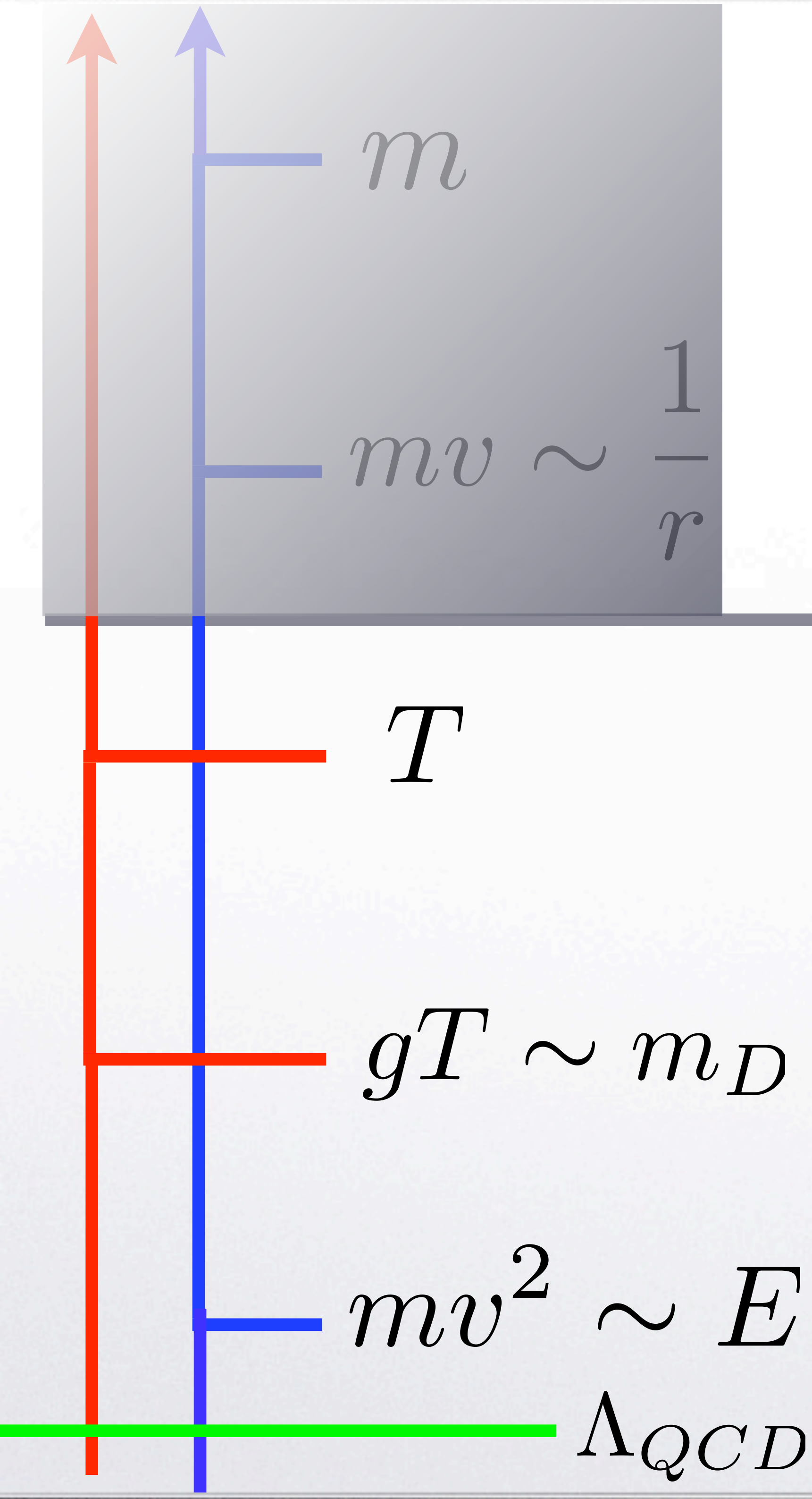


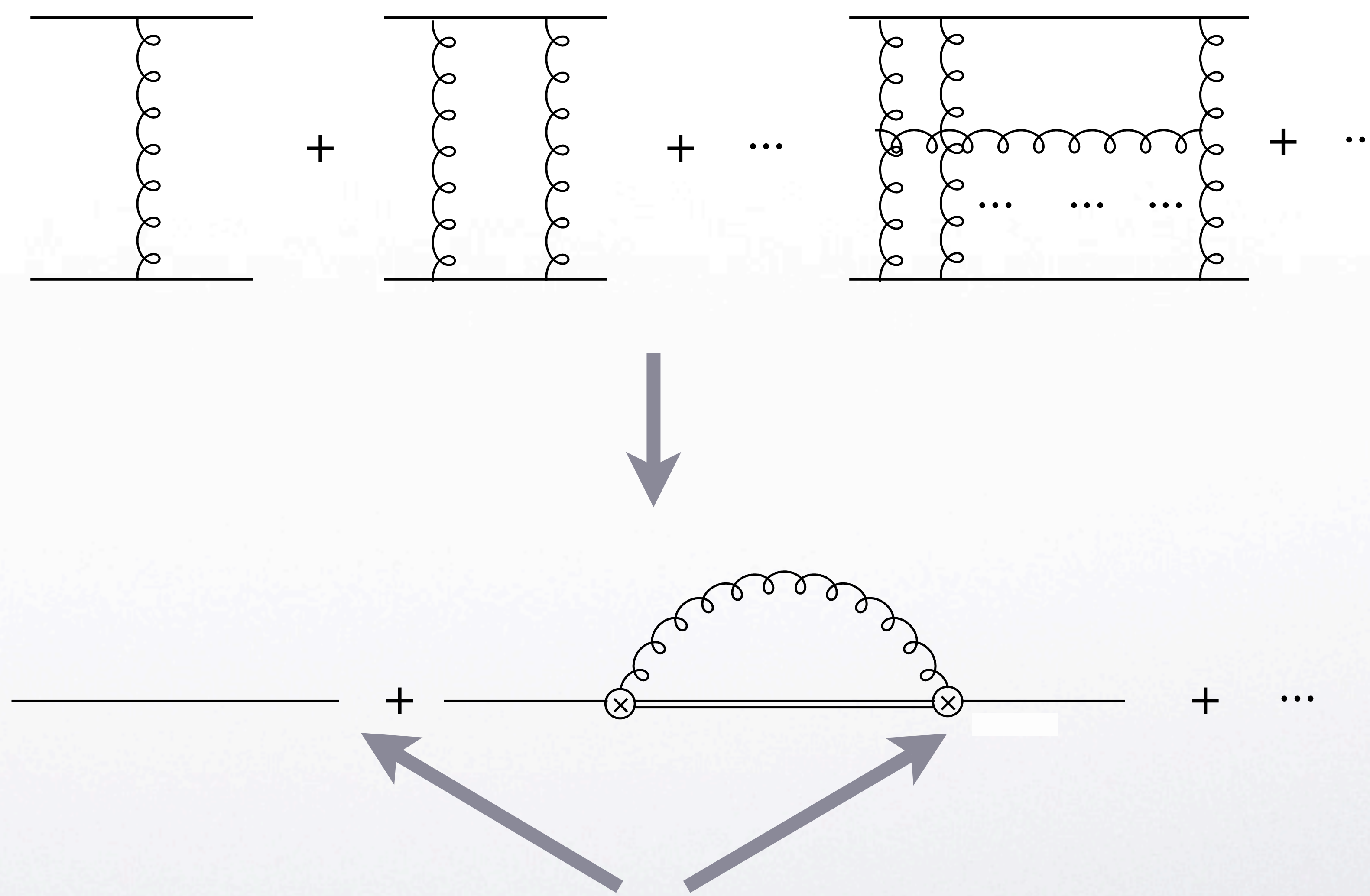


Soft scale

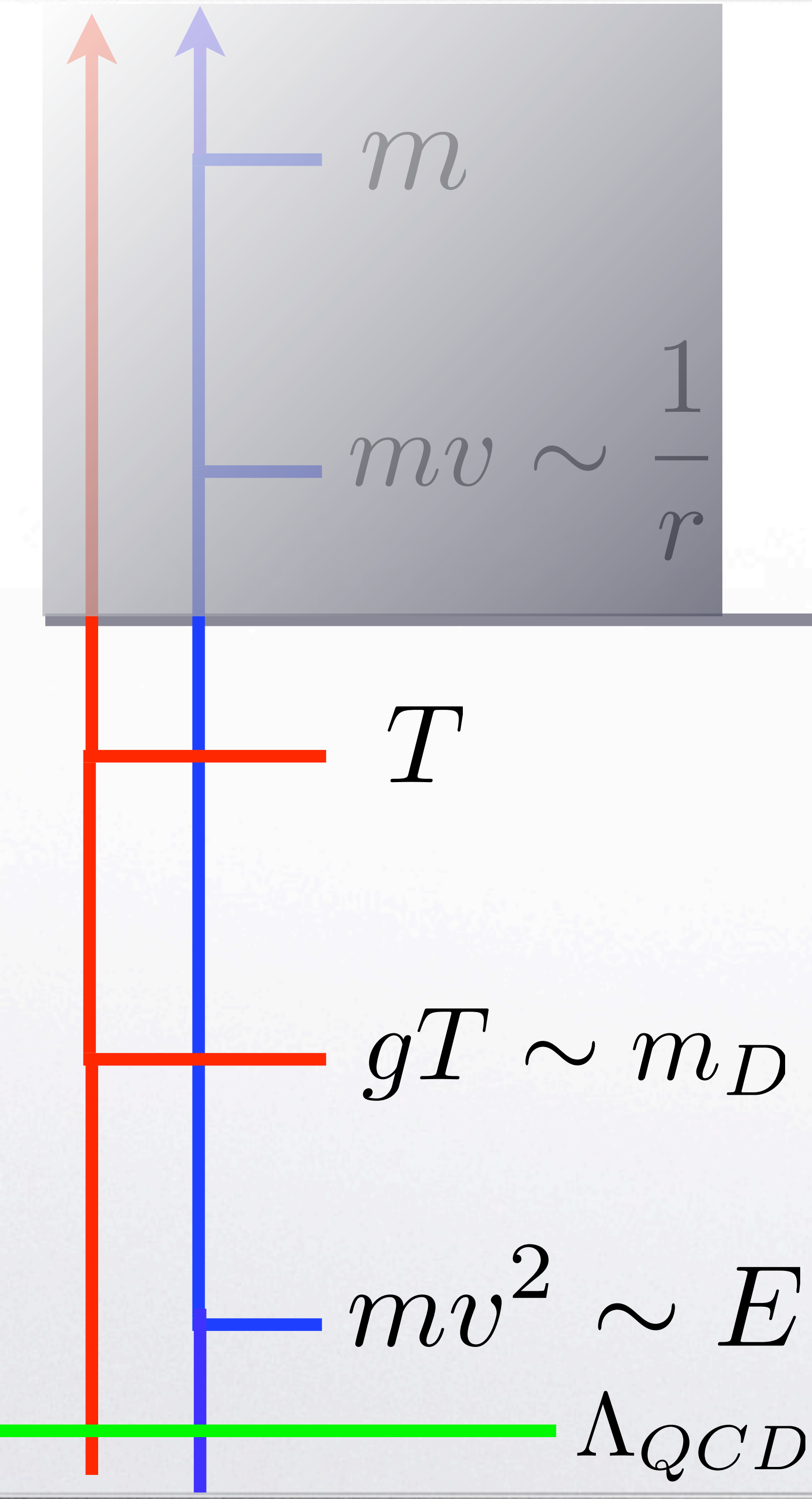
- NRQCD ⇒pNRQCD
- Integrating out the soft modes causes the singlet and octet potentials to appear

Soft scale



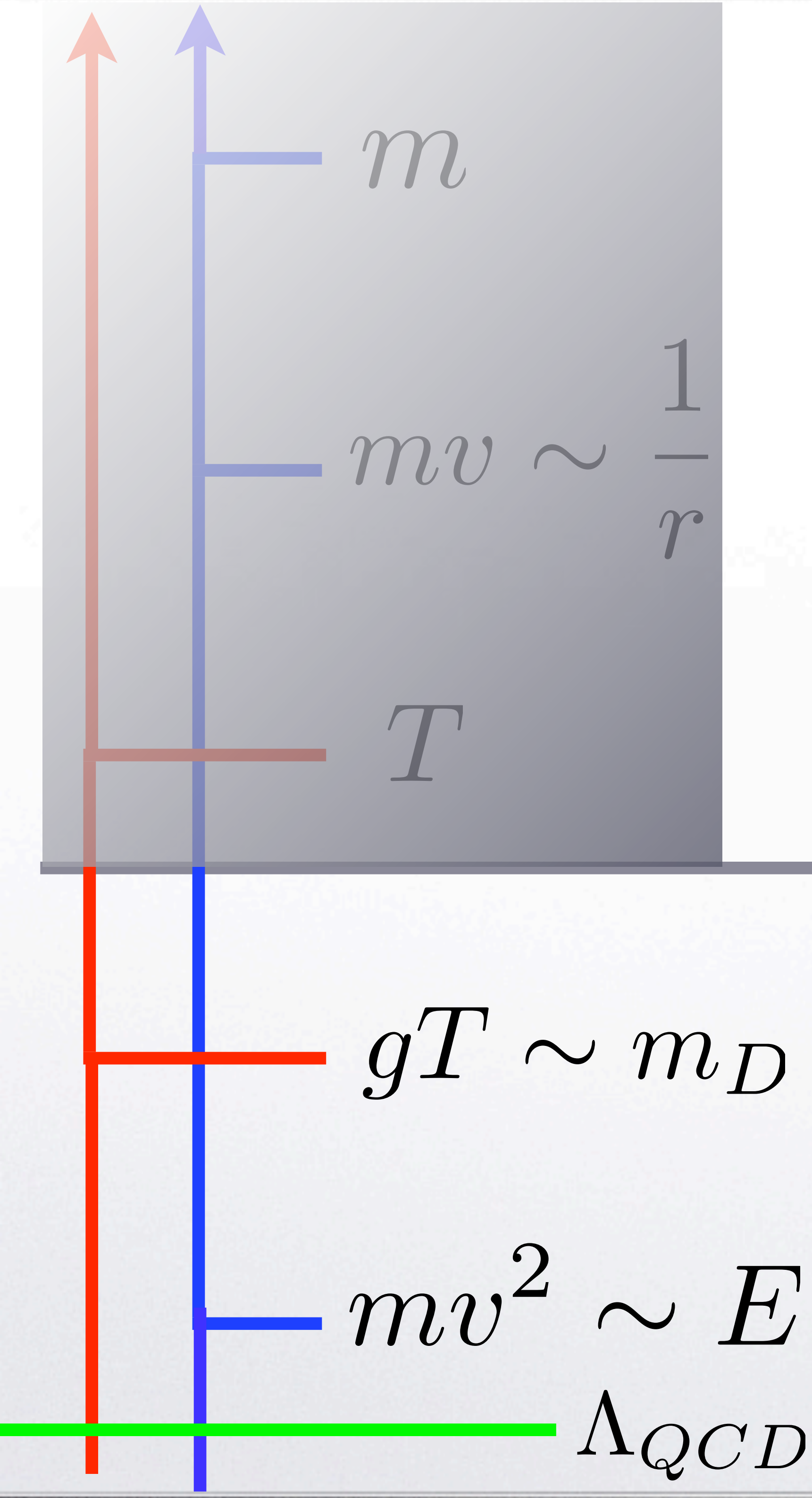


$$\frac{1}{E - p^2/m - V(r)}$$



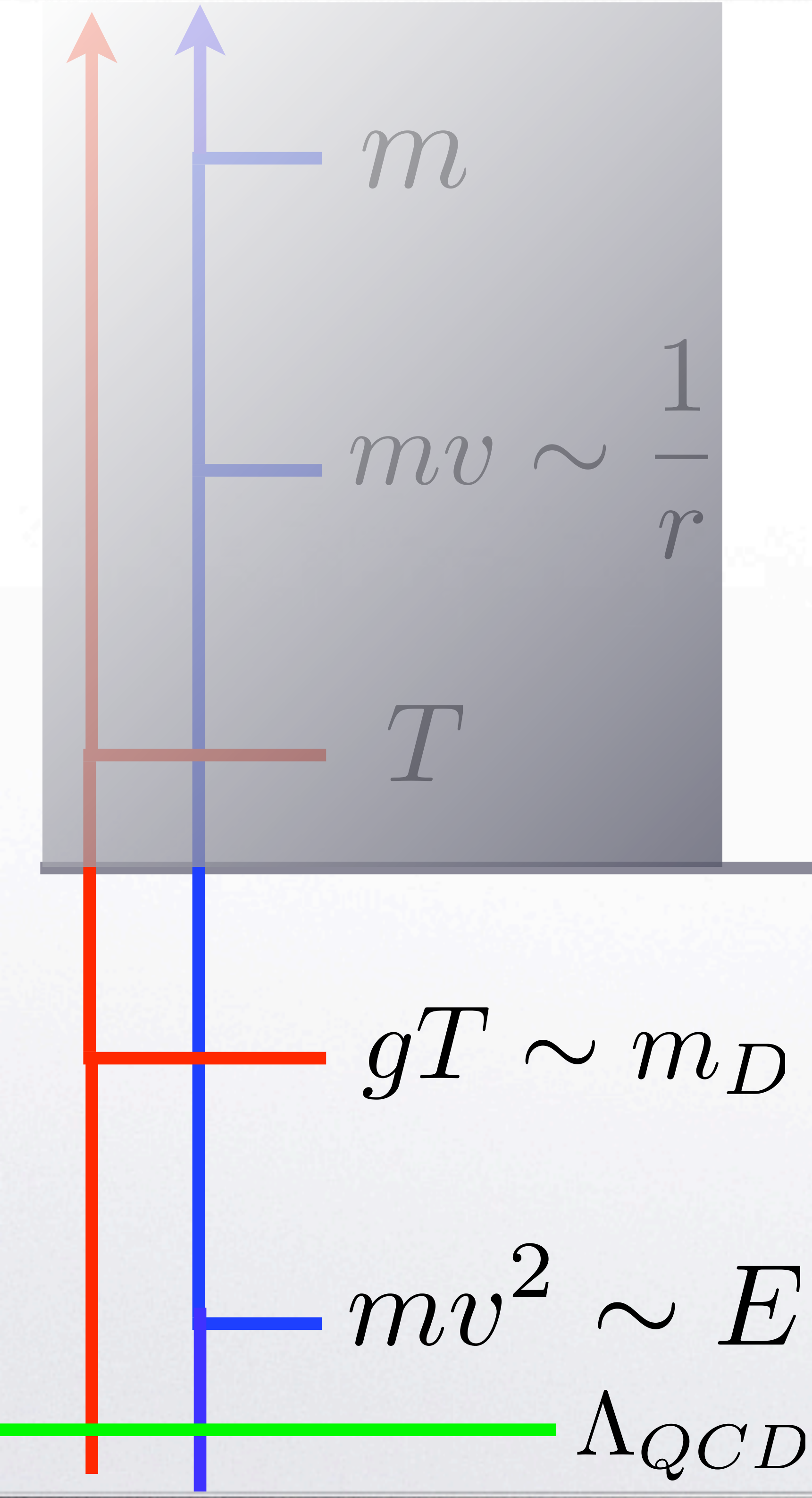
The static potential

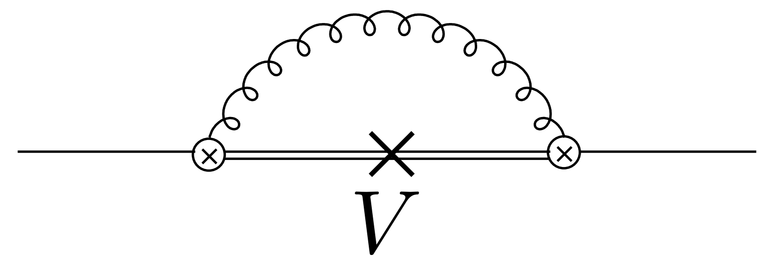
$$
\begin{aligned}
V_s(r,\mu) &= -C_F \frac{\alpha_{V_s}(1/r)}{r} \\
&= -C_F \frac{\alpha_s(1/r)}{r} \left\{ 1 + \frac{\alpha_s(1/r)}{4\pi} a_1 + \left(\frac{\alpha_s(1/r)}{4\pi} \right)^2 a_2 \right. \\
&\quad \left. + \quad \cdots \quad \right\}
\end{aligned}
$$



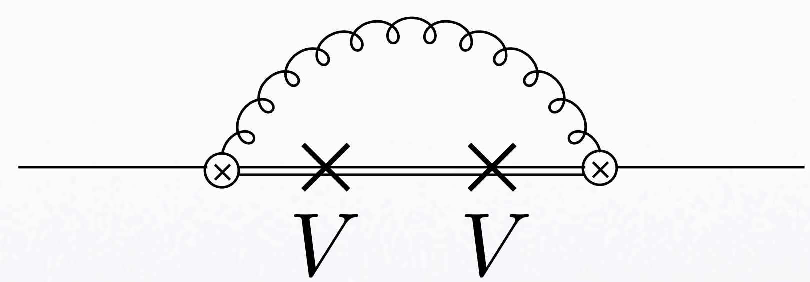
The temperature

- First thermal corrections to the potential
- Corrections appear as loops in the effective theory
- Real and imaginary parts, contributing to energy and decay width observables



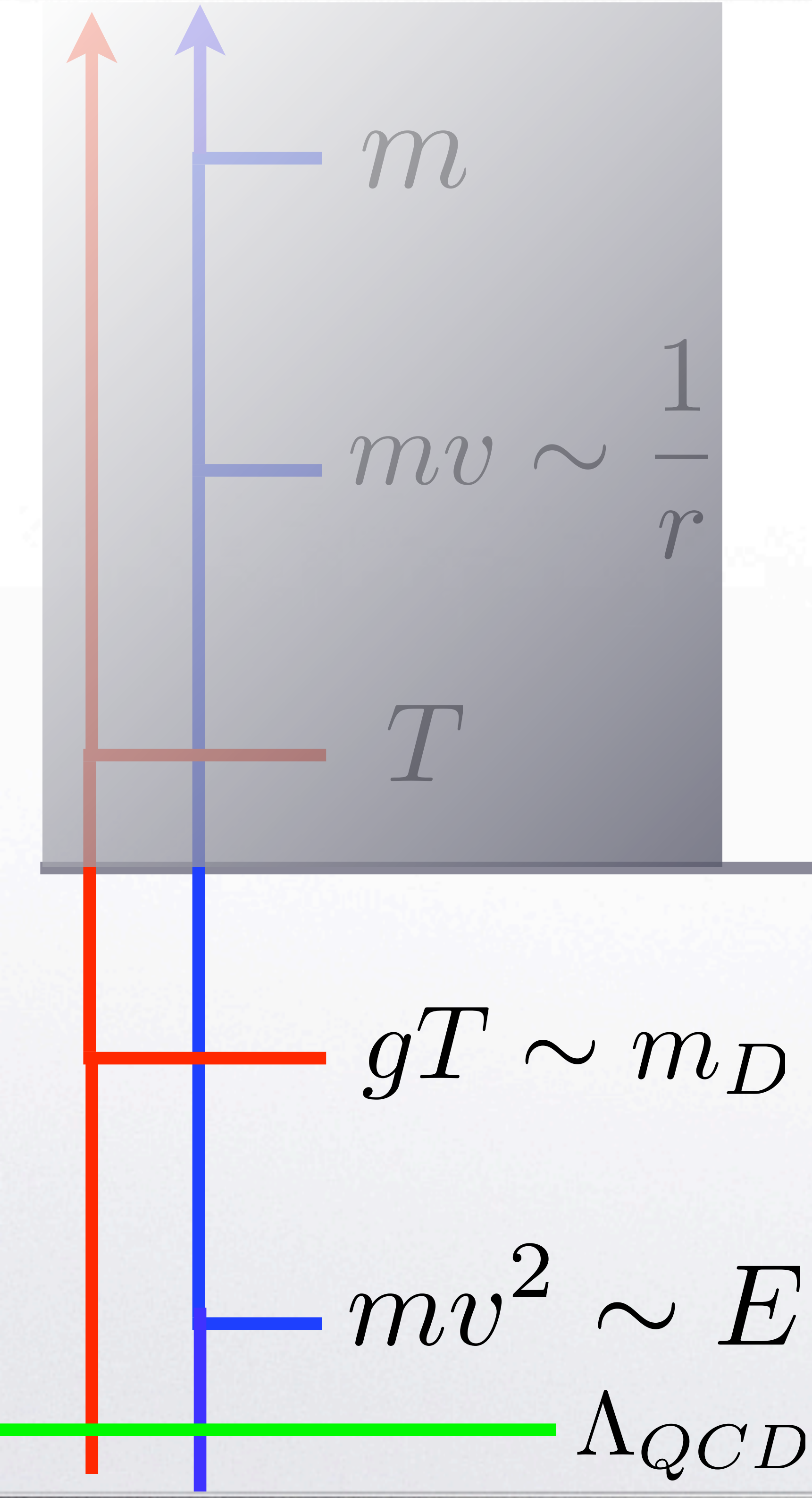


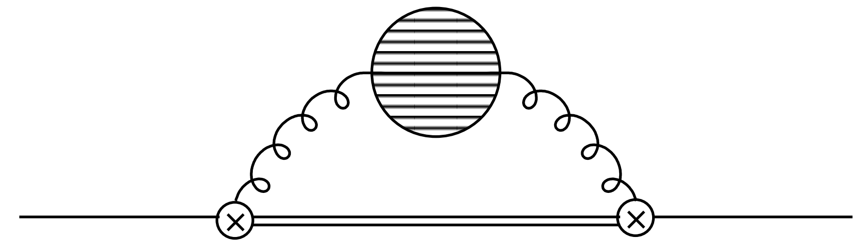
$$\mathrm{Re}\ \delta V_s(r) = \frac{\pi}{9} N_c C_F\, \alpha_s^2\, r\, T^2 \qquad \sim g^2 r^2 T^3 \times \frac{V}{T}$$



$$\mathrm{Im}\ \delta V_s(r) = -\frac{N_c^2 C_F}{6}\, \alpha_s^3\, T \qquad \sim g^2 r^2 T^3 \times \left(\frac{V}{T}\right)^2$$

- The imaginary part correspond to singlet-to-octet thermal breakup





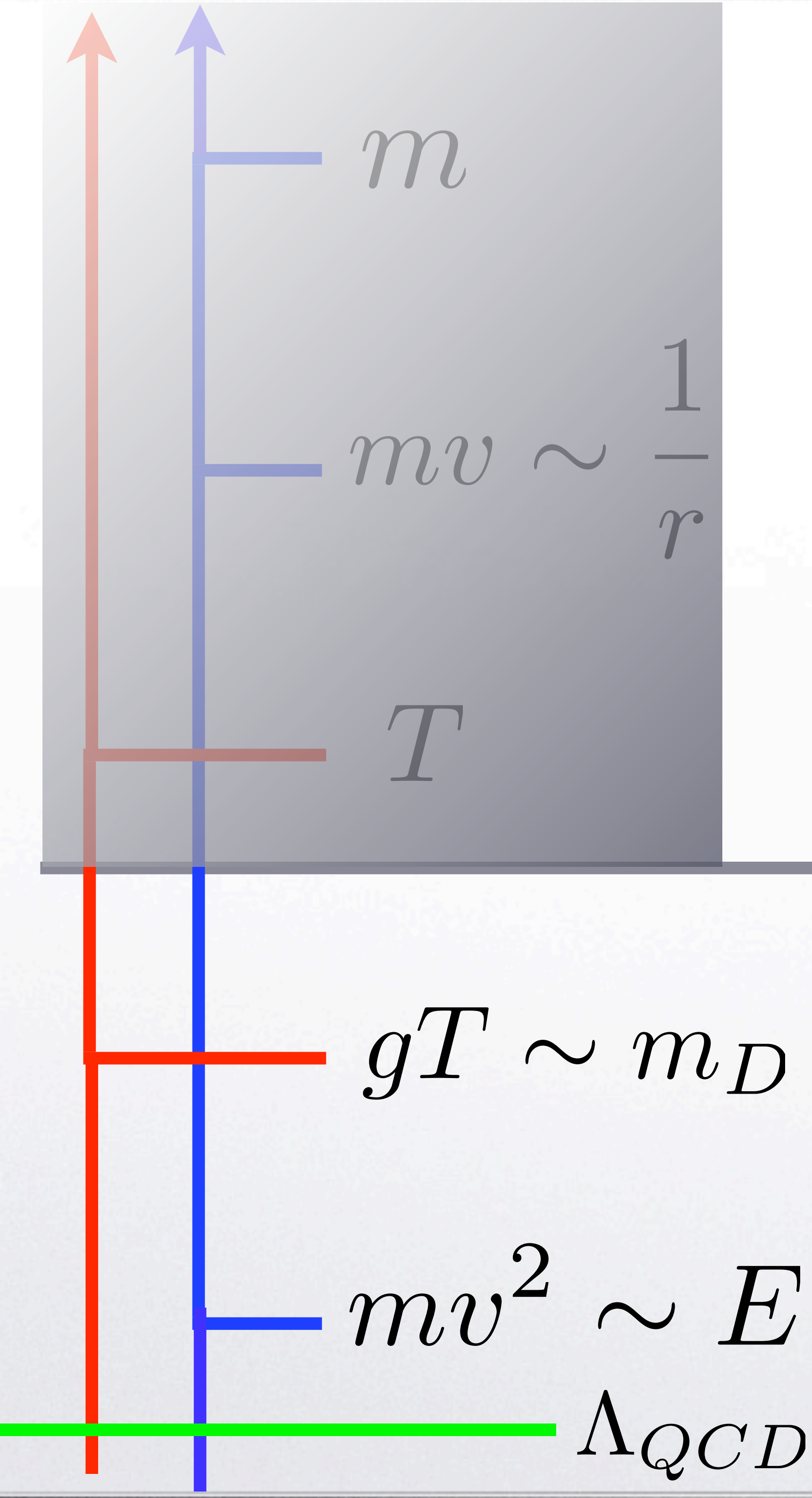
$$\mathrm{Re}\,\delta V_s(r) = -\frac{3}{2}\zeta(3)\,C_F\,\frac{\alpha_s}{\pi}\,r^2\,T\,m_D^2$$

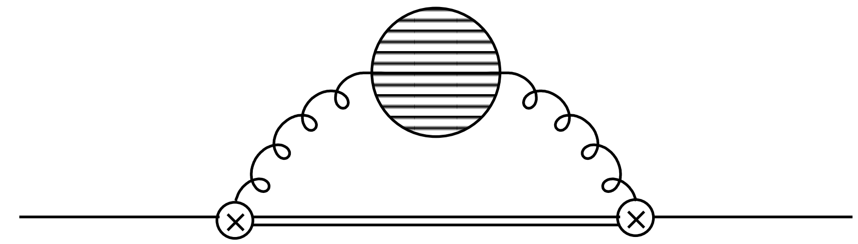
$$+\frac{2}{3}\zeta(3)\,N_c C_F\,\alpha_s^2\,r^2\,T^3 \qquad \sim g^2 r^2 T^3 \times \left(\frac{m_D}{T}\right)^2$$

$$\mathrm{Im}\,\delta V_s(r) = +\frac{C_F}{6}\alpha_s\,r^2\,T\,m_D^2\,\left(\frac{1}{\epsilon}+\gamma_E+\ln\pi - \ln\frac{T^2}{\mu^2}+\frac{2}{3}-4\ln 2-2\frac{\zeta'(2)}{\zeta(2)}\right)$$

$$+\frac{4\pi}{9}\ln 2\,N_c C_F\,\alpha_s^2\,r^2\,T^3$$

$$\sim g^2 r^2 T^3 \times \left(\frac{m_D}{T}\right)^2$$





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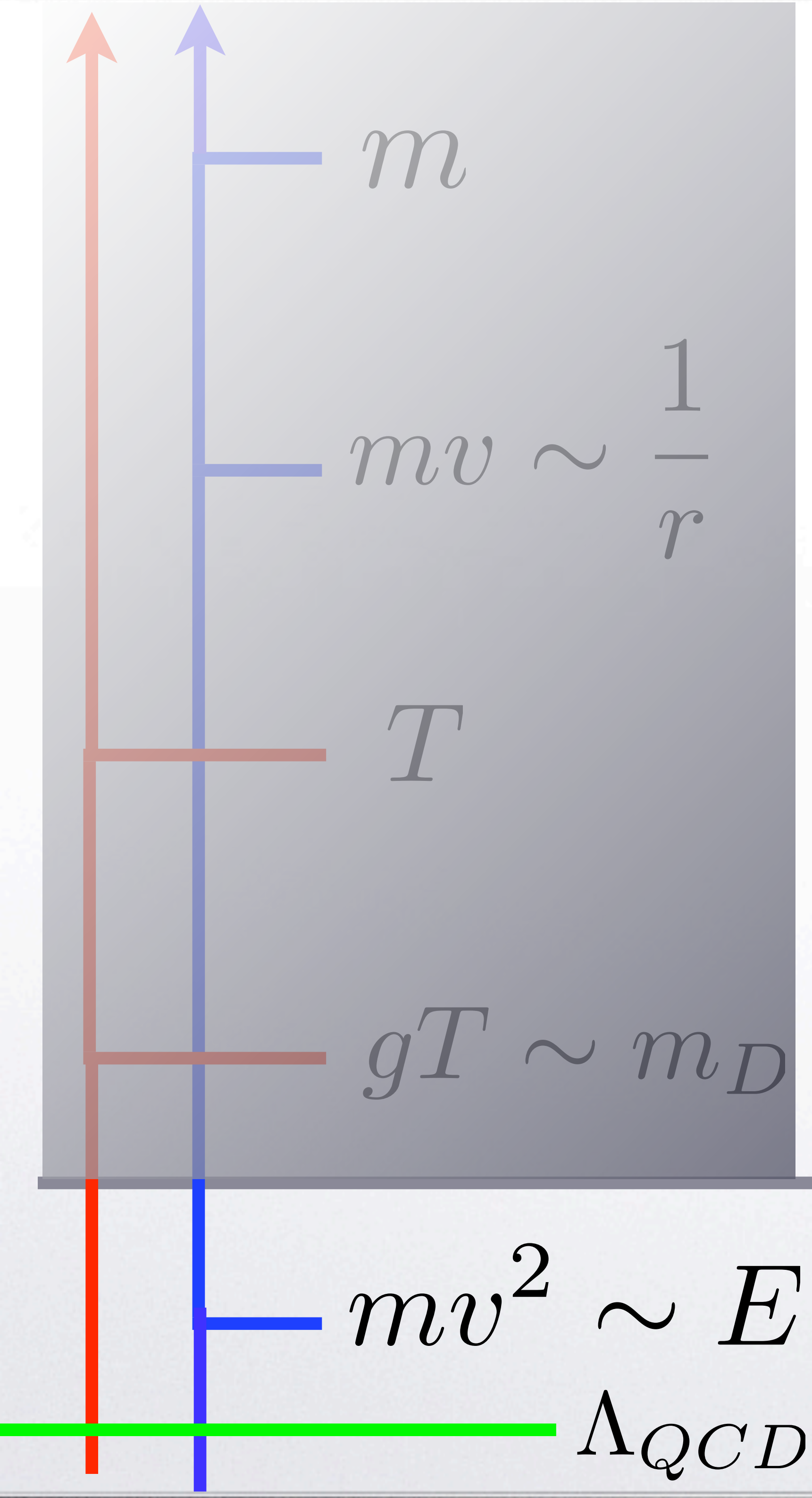
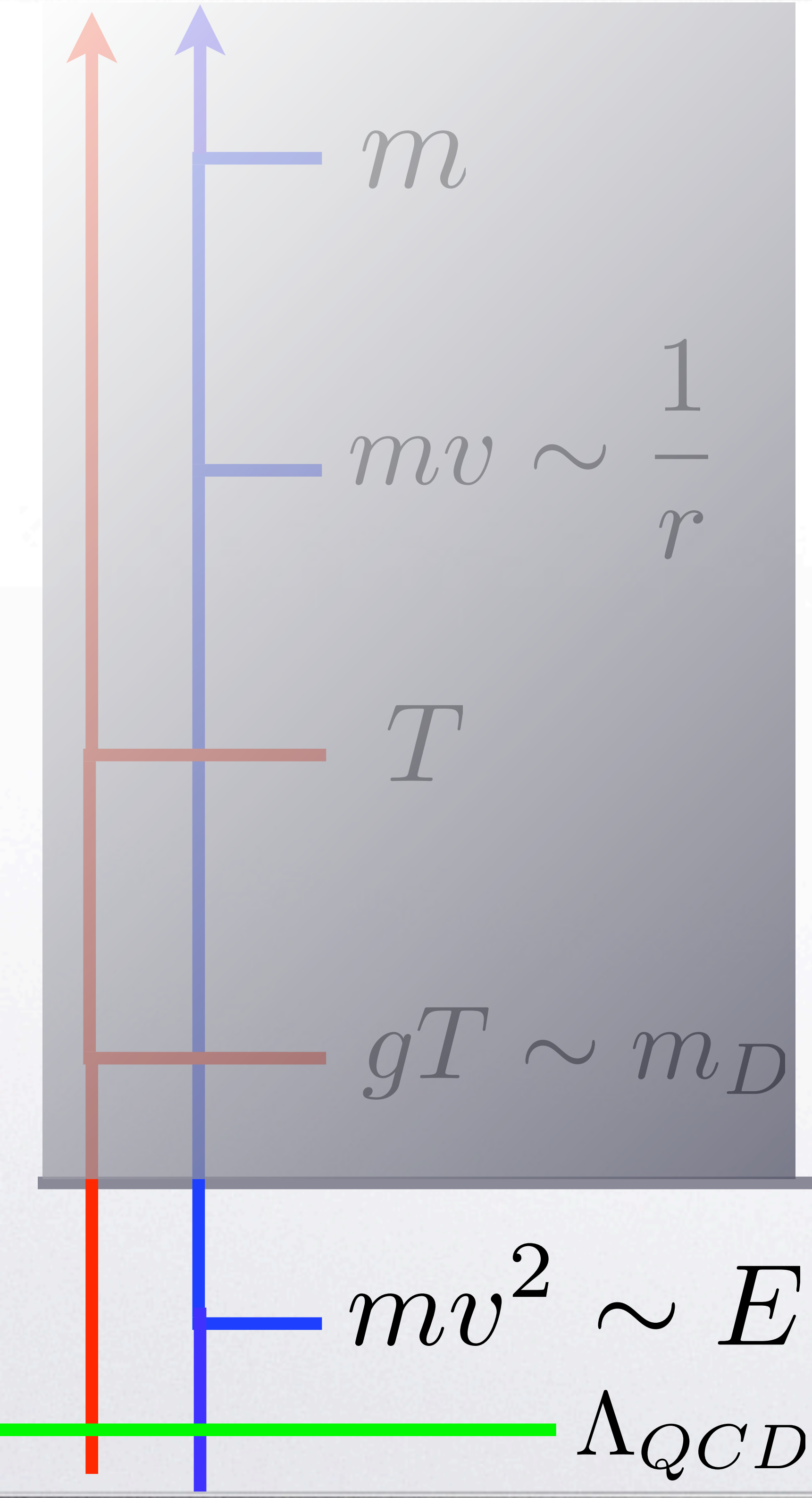
$$\mathrm{Im}\,\delta V_s(r) = +\frac{C_F}{6}\alpha_s\,r^2\,T\,m_D^2\left(\frac{1}{\epsilon} + \gamma_E + \ln\pi - \ln\frac{T^2}{\mu^2} + \frac{2}{3} - 4\ln 2 - 2\frac{\zeta'(2)}{\zeta(2)}\right) + \frac{4\pi}{9}\ln 2\,N_c C_F\,\alpha_s^2\,r^2\,T^3$$

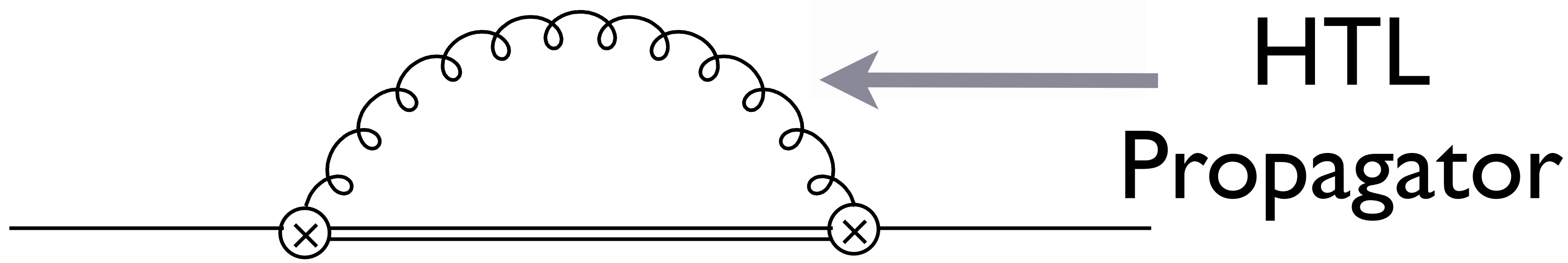
$$\sim g^2 r^2 T^3 \times \left(\frac{m_D}{T}\right)^2$$

The Debye Mass



- After having integrated out the temperature Hard Thermal Loop contributions have to be resummed, giving the longitudinal gluon propagator a mass and and imaginary part
- This contribution cancels the divergence in the previous expression

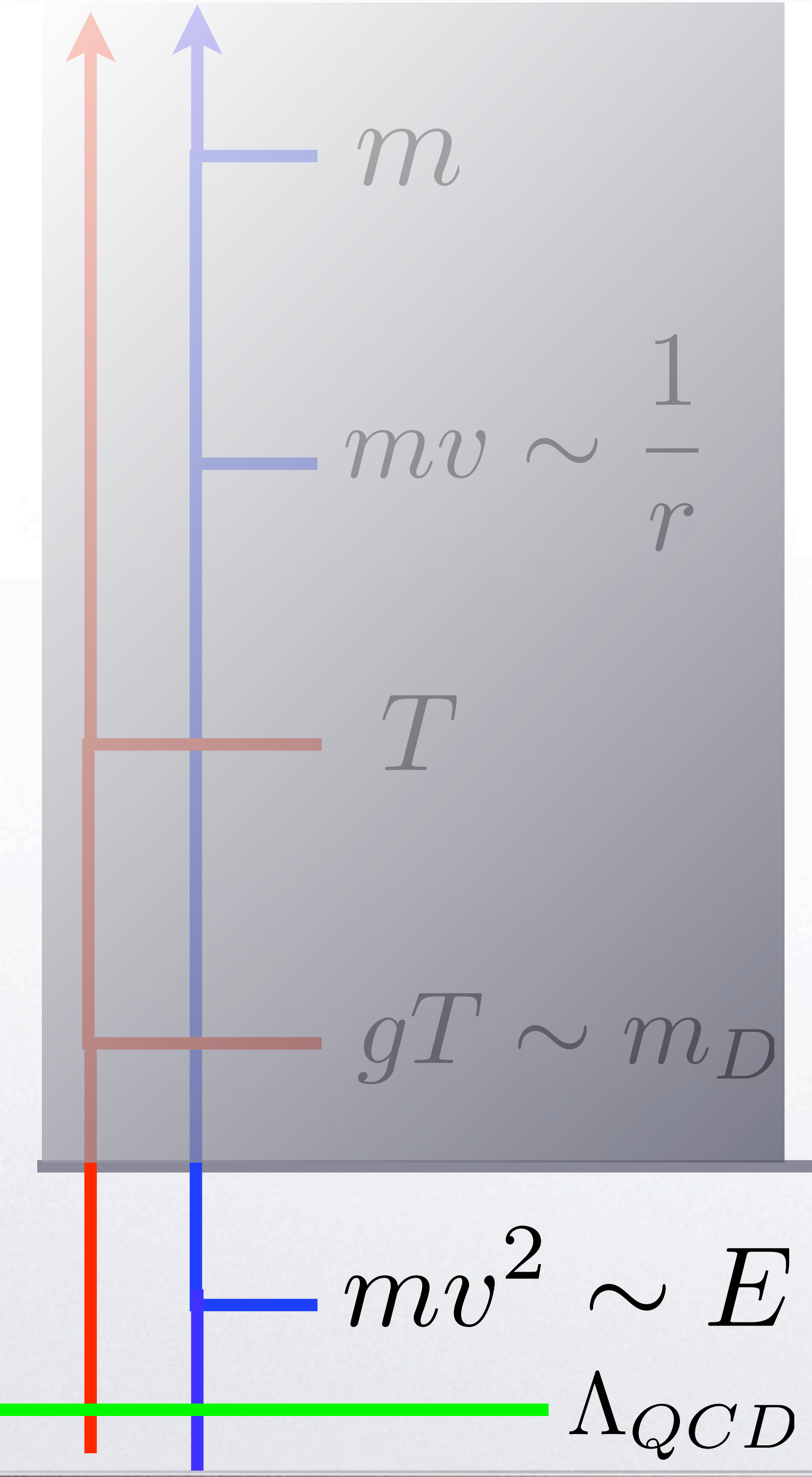


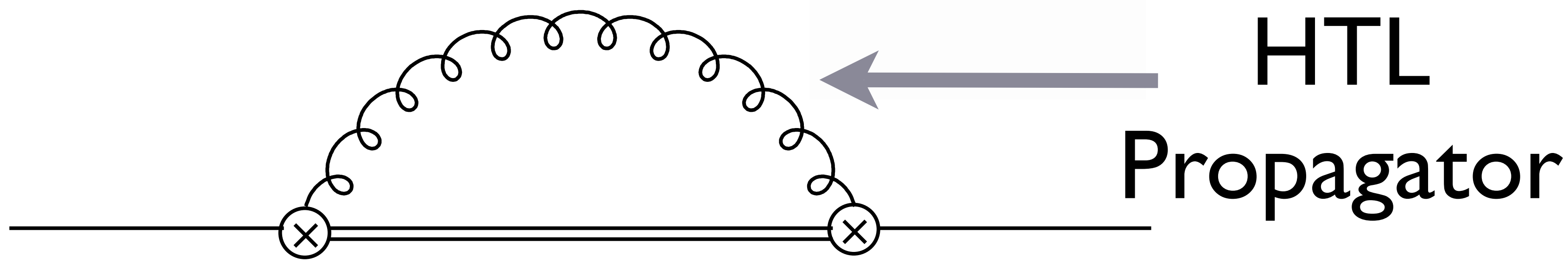


$$\text{Re}\ \delta V_s(r) \sim g^2 r^2 T^3 \times \left(\frac{m_D}{T}\right)^3$$

$$\text{Im}\ \delta V_s(r) = -\frac{C_F}{6}\,\alpha_s\, r^2\, T\, m_D^2 \left(\frac{1}{\epsilon} - \gamma_E + \ln \pi + \ln \frac{\mu^2}{m_D^2} + \frac{5}{3}\right)$$

- The real part is suppressed but the imaginary part indeed cancels the divergence





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Summing up

$$\mathrm{Re}\, V_s = -C_F \frac{\alpha_{V_S}}{r} + \frac{\pi}{9} N_c C_F \, \alpha_s^2 \, r \, T^2$$
$$-\frac{3}{2}\zeta(3)\, C_F \, \frac{\alpha_s}{\pi} \, r^2 \, T \, m_D^2 + \frac{2}{3}\zeta(3) \, N_c C_F \, \alpha_s^2 \, r^2 \, T^3$$

$$\mathrm{Im}\, V_s = \frac{N_c^2 C_F}{6} \, \alpha_s^3 \, T - \frac{4\pi}{9} \ln 2 \; N_c C_F \, \alpha_s^2 \, r^2 \, T^3$$
$$-\frac{C_F}{6} \alpha_s \, r^2 \, T \, m_D^2 \, \left(2\gamma_E - \ln \frac{T^2}{m_D^2} - 1 - 4 \ln 2 - 2 \frac{\zeta'(2)}{\zeta(2)} \right)$$

- The imaginary part of the static potential gives the decay width , which has two origins: singlet-to-octet breakup and Landau damping. The former is suppressed by $\left(\frac{E}{m_D}\right)^2$ vs the latter

Summing up

$$\mathrm{Re}\, V_s = -C_F \frac{\alpha_{V_S}}{r} + \frac{\pi}{9} N_c C_F \,\alpha_s^2\, r\, T^2 - \frac{3}{2}\zeta(3)\, C_F\, \frac{\alpha_s}{\pi}\, r^2\, T\, m_D^2 + \frac{2}{3}\zeta(3)\, N_c C_F\, \alpha_s^2\, r^2\, T^3$$

$$\mathrm{Im}\, V_s = \frac{N_c^2 C_F}{6}\,\alpha_s^3\, T - \frac{4\pi}{9}\ln 2\, N_c C_F\, \alpha_s^2\, r^2\, T^3 - \frac{C_F}{6}\alpha_s\, r^2\, T\, m_D^2 \left(2\gamma_E - \ln\frac{T^2}{m_D^2} - 1 - 4\ln 2 - 2\frac{\zeta'(2)}{\zeta(2)}\right)$$

- The imaginary part of the static potential gives the decay width , which has two origins: singlet-to-octet breakup and Landau damping. The former is suppressed by $\left(\frac{E}{m_D}\right)^2$ vs the latter

Conclusions

- We have shown how to employ the EFT approach to deal with a problem characterized by various separated energy scales

- We have obtained new result in the intermediate regime $m \gg 1/r \gg T \gg m_D \gg E$ which could be relevant for LHC phenomenology

- We have introduced a new mechanism of thermal decay