

Национальный исследовательский ядерный университет «МИФИ»

# КОСМОЛОГИЧЕСКАЯ ЭВОЛЮЦИЯ СОСТОЯНИЙ, ОБРАЗУЕМЫХ ТЯЖЕЛЫМИ СТАБИЛЬНЫМИ КВАРКАМИ. ЗАРЯДОВО АСИММЕТРИЧНЫЙ СЛУЧАЙ

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# Введение

$$n_u < n_{\bar{u}}$$

$$m_U = 3,5 * S_6 \text{ TeV}$$

$$S_6 > 0,2$$

$$\kappa \cdot 3m_U \sim \kappa_b \cdot 5m_p \Rightarrow \kappa \sim \kappa_b \cdot \frac{5m_p}{3m_U} \approx \frac{3.6 \cdot 10^{-14}}{S_6},$$

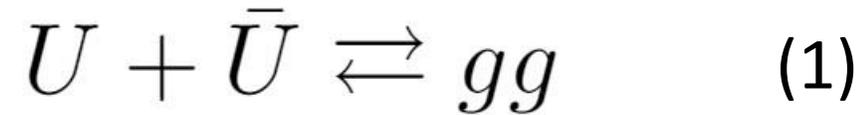
$$\kappa = \frac{n_{\bar{U}} - n_U}{S}$$

Закалка тяжелых кварков:

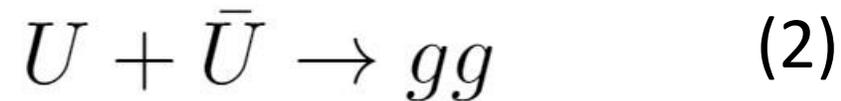
$$100S_6 GeV = \frac{1}{20}m_U < T < m_U = 3.5S_6 TeV$$

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Равновесие смещается в сторону реакции (2):



↓



## Закалка тяжелых кварков:

$$100S_6 GeV = \frac{1}{20}m_U < T < m_U = 3.5S_6 TeV$$

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$$\begin{cases} \frac{dn_U}{dt} + 3H\bar{n}_U = \langle\sigma v\rangle (n_{eqU}n_{eq\bar{U}} - n_Un_{\bar{U}}) \\ \frac{dn_{\bar{U}}}{dt} + 3Hn_U = \langle\sigma v\rangle (n_{eqU}n_{eq\bar{U}} - n_Un_{\bar{U}}) \end{cases}$$

$$n_{eq} = gS \left(\frac{mT}{2\pi}\right)^{3/2} \exp\left(-\frac{m}{T}\right)$$

$$n_{U,\bar{U}} = n_{eq} \exp\left(\pm\frac{\mu}{T}\right)$$

## Закалка тяжелых кварков:

$$100S_6 GeV = \frac{1}{20}m_U < T < m_U = 3.5S_6 TeV$$

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$$\begin{cases} r_+(x \approx 0) \approx \frac{\kappa r_{+f}}{(\kappa + r_{+f})e^{\kappa J} - r_{+f}} \\ r_-(x \approx 0) \approx \frac{\kappa r_{-f}}{r_{-f} - (r_{-f} - \kappa)e^{-\kappa J}} \end{cases}, \text{ где } J = \int_0^{x_f} f_1 \langle \sigma v \rangle dx = \frac{1.3 \cdot 10^{12}}{S_6 \left(1 - \frac{\ln S_6}{30}\right)}$$
$$x = \frac{T}{m_U}$$
$$r_{\pm} = \frac{n_{U, \bar{U}}}{s}$$

# Закалка тяжелых кварков:

$$100S_6 GeV = \frac{1}{20}m_U < T < m_U = 3.5S_6 TeV$$

$m_U, TeV$	$\kappa, 10^{-14}$	$r_U, 10^{-13}$	$r_{\bar{U}}, 10^{-13}$
2	1,80	7,72	7,90
1,9	1,89	7,34	7,53
1,8	2,00	6,95	7,15
1,7	2,11	6,57	6,78
1,6	2,25	6,18	6,41
1,5	2,40	5,79	6,03
1,4	2,57	5,40	5,66
1,3	2,76	5,01	5,29
1,2	3,00	4,62	4,92
1,1	3,27	4,22	4,55
1	3,60	3,82	4,18
0,9	4,00	3,41	3,81
0,8	4,50	3,00	3,45
0,7	5,14	2,58	3,09
0,6	6,00	2,15	2,75
0,5	7,20	1,70	2,42
0,4	9,00	1,24	2,14
0,3	12,00	0,74	1,94
0,2	18,00	0,25	2,05

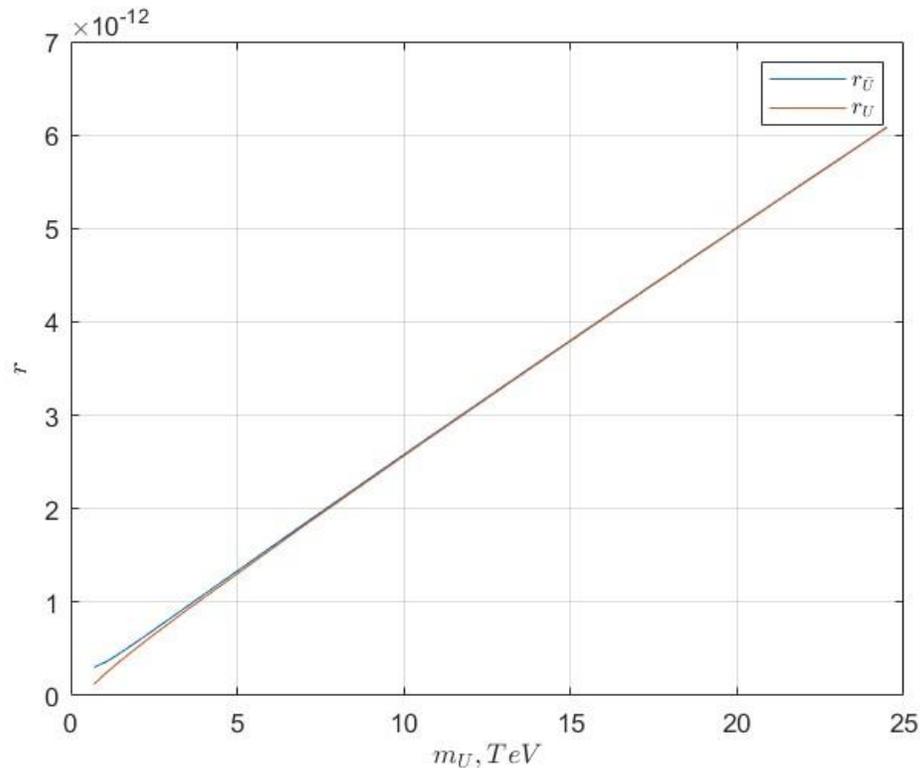


Рис. 1: График зависимости  $r_U$  и  $r_{\bar{U}}$  от  $m_U$

Таблица 1: Численные значения для концентраций при разных массах  $U$  кварка на этапе закалки

# Кластеризация тяжелых кварков

$$0.5S_6 GeV < T < I_U \approx \frac{\alpha_c^2 m_U}{4} = 15S_6 GeV$$

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$$U + \bar{U} \rightarrow U\bar{U} + g$$

$$U\bar{U} \rightarrow gg$$

$$\tau_0 = \frac{2}{m_U \alpha^5}$$

$$R = n \langle \sigma v \rangle \sim g_S T^3 * \frac{\alpha^2}{m_U^2} \approx g_s \frac{\alpha^8 m_U}{64}; \quad t \sim \frac{1}{R}, \quad g_S = 16 \Rightarrow t \sim \frac{4}{\alpha^8 m_U} \approx \underline{\underline{2000\tau_0}}$$

# Кластеризация тяжелых кварков

$$0.5S_6 GeV < T < I_U \approx \frac{\alpha_c^2 m_U}{4} = 15S_6 GeV$$


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$$U + U \rightleftharpoons UU + g$$

$$UU + U \rightarrow UUU$$

$$UU + \bar{U} \rightarrow U$$

$$UUU + \bar{U} \rightarrow UU$$

$$UUU + \bar{U}\bar{U} \rightarrow U$$

$$UU + \bar{U}\bar{U} \rightarrow gg$$

$$\bar{U} + \bar{U} \rightleftharpoons \bar{U}\bar{U} + g$$

$$\bar{U}\bar{U} + \bar{U} \rightarrow \bar{U}\bar{U}\bar{U}$$

$$\bar{U}\bar{U} + U \rightarrow \bar{U}$$

$$\bar{U}\bar{U}\bar{U} + U \rightarrow \bar{U}\bar{U}$$

$$\bar{U}\bar{U}\bar{U} + UU \rightarrow \bar{U}$$

$$UUU + \bar{U}\bar{U}\bar{U} \rightarrow gg$$

$$\langle \sigma v \rangle = \pi \left( \frac{m}{T} \right)^{0.9} \left( \frac{\alpha}{m} \right)^2$$

$$\langle \sigma v \rangle_{UU+g} = \frac{64\pi^4 \cdot m_e e^{10}}{3\sqrt{3} \cdot ch^6} \frac{z^4}{\nu^3 n^5}$$

↓

$$\langle \sigma v \rangle_{UU+g} = \frac{64\pi^4}{3\sqrt{3}} \cdot \frac{\alpha^5 m_U}{T^3}$$

# Кластеризация тяжелых кварков

$$0.5S_6 GeV < T < I_U \approx \frac{\alpha_c^2 m_U}{4} = 15S_6 GeV$$


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$$\left\{ \begin{array}{l} \frac{dr_U}{dT} = -\frac{\pi \cdot s}{HT} \left(\frac{m}{T}\right)^{9/10} \left(\frac{\alpha}{m}\right)^2 \left( -r_U^2 + \frac{64\pi^3 \alpha^3}{3\sqrt{3}} \left(\frac{m}{T}\right)^{2.1} r_{UU} r_g - r_U r_{\bar{U}} - \frac{r_U r_{UU}}{1.5^{1.1}} \right. \\ \quad \left. - \frac{r_U r_{\bar{U}\bar{U}}}{1.5^{1.1}} - \frac{r_U r_{\bar{U}\bar{U}\bar{U}}}{2^{1.1}} + \frac{r_{UU} r_{\bar{U}}}{1.5^{1.1}} + \frac{r_{UUU} r_{\bar{U}\bar{U}}}{2.5^{1.1}} \right) \\ \frac{dr_{UU}}{dT} = -\frac{\pi \cdot s}{HT} \left(\frac{m}{T}\right)^{9/10} \left(\frac{\alpha}{m}\right)^2 \left( r_U^2 - \frac{64\pi^3 \alpha^3}{3\sqrt{3}} \left(\frac{m}{T}\right)^{2.1} r_{UU} r_g - \frac{r_U r_{UU}}{1.5^{1.1}} - \frac{r_{UU} r_{\bar{U}}}{1.5^{1.1}} - \frac{r_{UU} r_{\bar{U}\bar{U}}}{2^{1.1}} \right. \\ \quad \left. + \frac{r_{UUU} r_{\bar{U}}}{2^{1.1}} - \frac{r_{UUU} r_{\bar{U}\bar{U}\bar{U}}}{2.5^{1.1}} \right) \\ \frac{dr_{UUU}}{dT} = -\frac{\pi \cdot s}{HT} \left(\frac{m}{T}\right)^{9/10} \left(\frac{\alpha}{m}\right)^2 \left( \frac{r_U r_{UU}}{1.5^{1.1}} - \frac{r_{UUU} r_{\bar{U}}}{2^{1.1}} - \frac{r_{UUU} r_{\bar{U}\bar{U}}}{2.5^{1.1}} - \frac{r_{UUU} r_{\bar{U}\bar{U}\bar{U}}}{3^{1.1}} \right) \\ \frac{dr_{\bar{U}}}{dT} = -\frac{\pi \cdot s}{HT} \left(\frac{m}{T}\right)^{9/10} \left(\frac{\alpha}{m}\right)^2 \left( -r_{\bar{U}}^2 + \frac{64\pi^3 \alpha^3}{3\sqrt{3}} \left(\frac{m}{T}\right)^{2.1} r_{\bar{U}\bar{U}} r_g - r_U r_{\bar{U}} - \frac{r_{\bar{U}} r_{\bar{U}\bar{U}}}{1.5^{1.1}} \right. \\ \quad \left. - \frac{r_{\bar{U}} r_{UU}}{1.5^{1.1}} - \frac{r_{\bar{U}} r_{UUU}}{2^{1.1}} + \frac{r_{\bar{U}\bar{U}} r_U}{1.5^{1.1}} + \frac{r_{\bar{U}\bar{U}\bar{U}} r_{UU}}{2.5^{1.1}} \right) \\ \frac{dr_{\bar{U}\bar{U}}}{dT} = -\frac{\pi \cdot s}{HT} \left(\frac{m}{T}\right)^{9/10} \left(\frac{\alpha}{m}\right)^2 \left( r_{\bar{U}}^2 - \frac{64\pi^3 \alpha^3}{3\sqrt{3}} \left(\frac{m}{T}\right)^{2.1} r_{\bar{U}\bar{U}} r_g - \frac{r_{\bar{U}} r_{\bar{U}\bar{U}}}{1.5^{1.1}} - \frac{r_U r_{\bar{U}\bar{U}}}{1.5^{1.1}} - \frac{r_{UU} r_{\bar{U}\bar{U}}}{2^{1.1}} \right. \\ \quad \left. + \frac{r_{\bar{U}\bar{U}\bar{U}} r_U}{2^{1.1}} - \frac{r_{\bar{U}\bar{U}} r_{UUU}}{2.5^{1.1}} \right) \\ \frac{dr_{\bar{U}\bar{U}\bar{U}}}{dT} = -\frac{\pi \cdot s}{HT} \left(\frac{m}{T}\right)^{9/10} \left(\frac{\alpha}{m}\right)^2 \left( \frac{r_{\bar{U}} r_{\bar{U}\bar{U}}}{1.5^{1.1}} - \frac{r_{\bar{U}\bar{U}\bar{U}} r_U}{2^{1.1}} - \frac{r_{\bar{U}\bar{U}\bar{U}} r_{UU}}{2.5^{1.1}} - \frac{r_{UUU} r_{\bar{U}\bar{U}\bar{U}}}{3^{1.1}} \right) \end{array} \right.$$

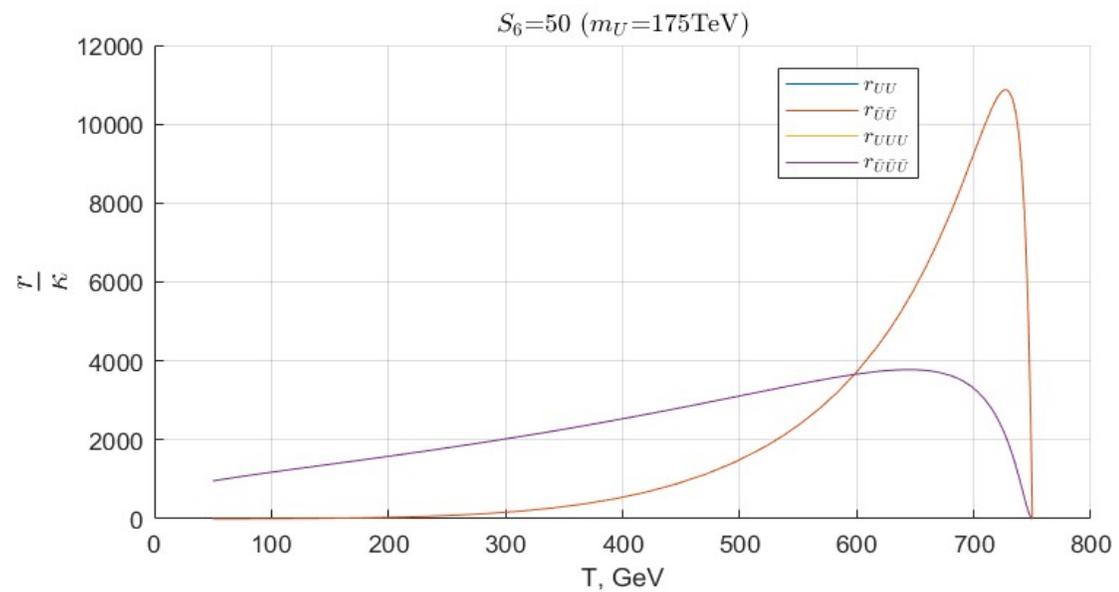
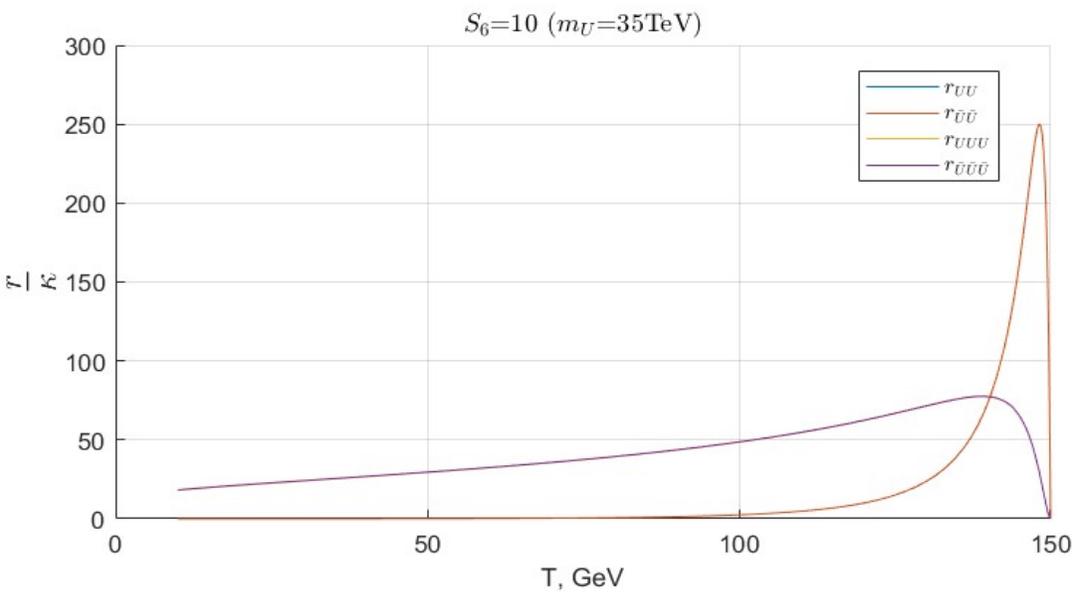
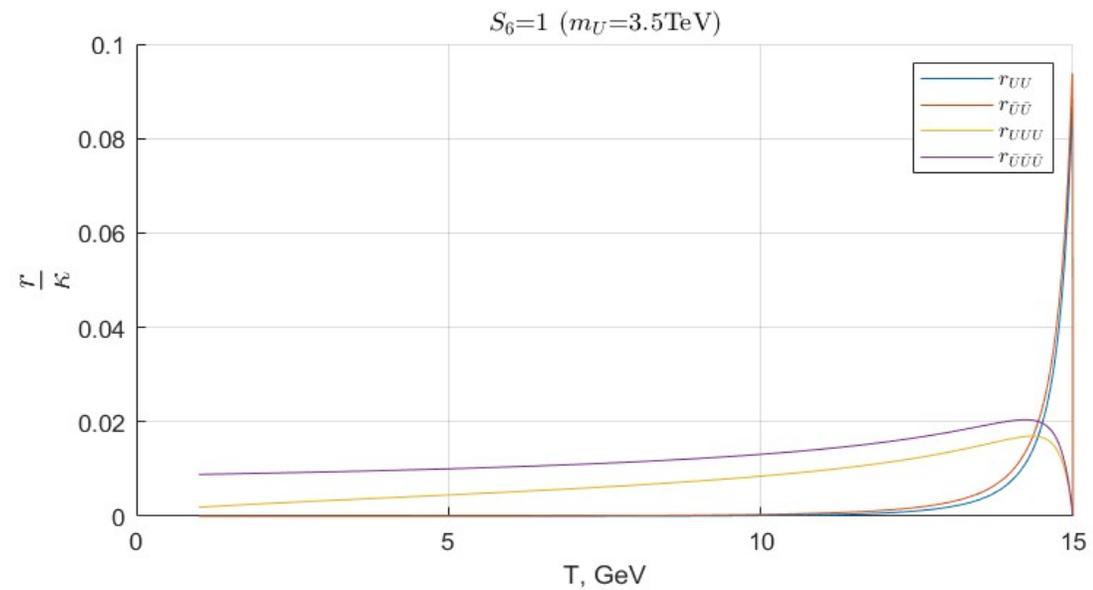
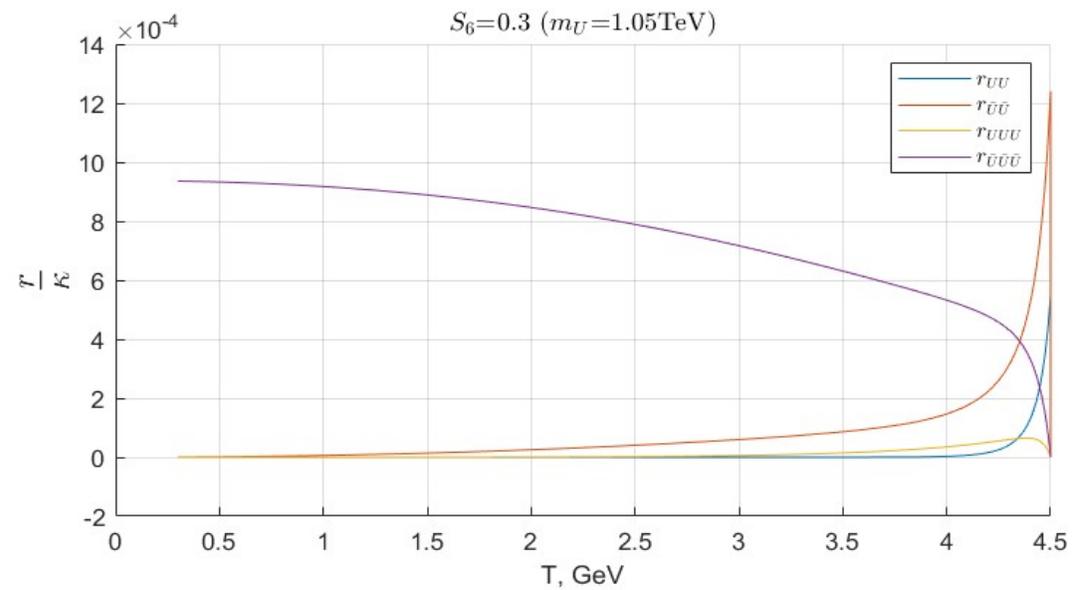


Рис. 2: График зависимости  $\frac{r_i}{\kappa}$  от  $m_U$

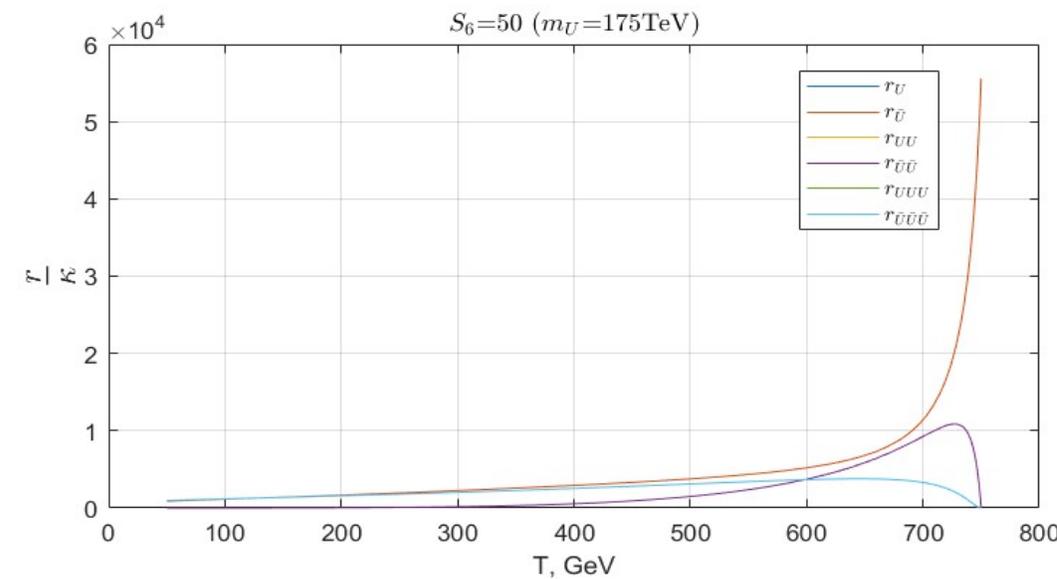
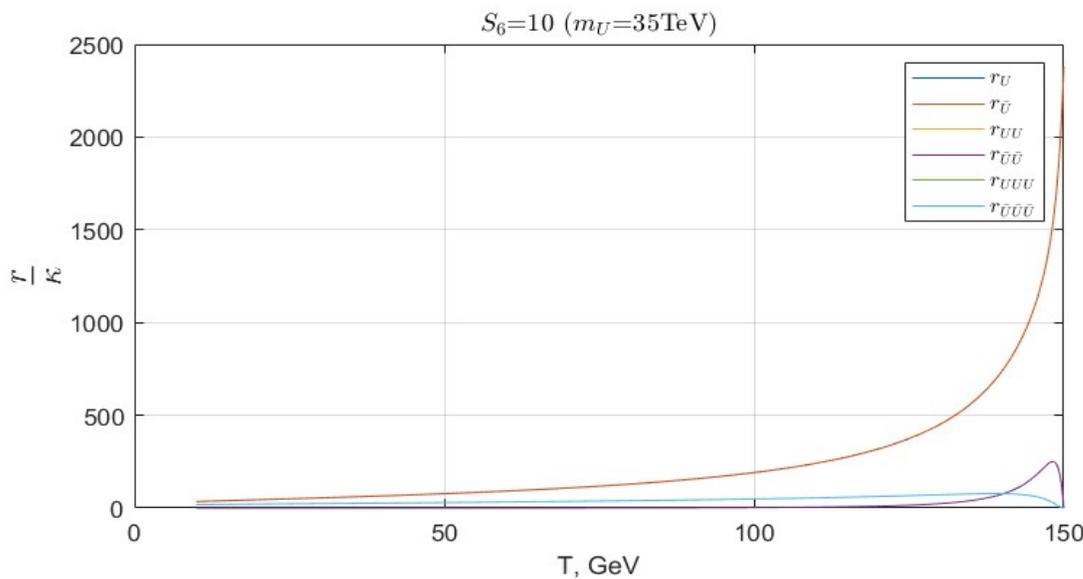
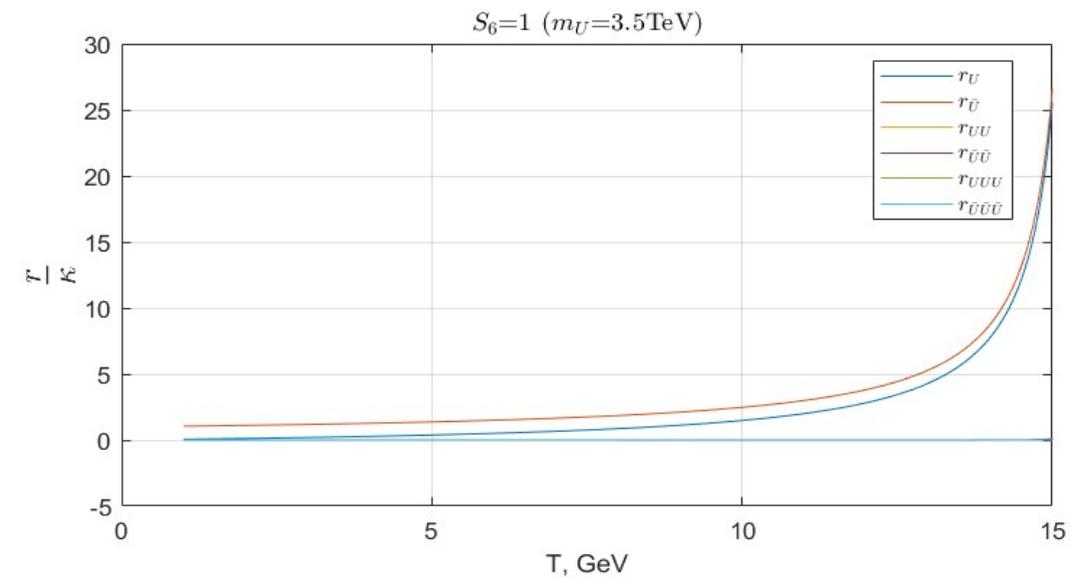
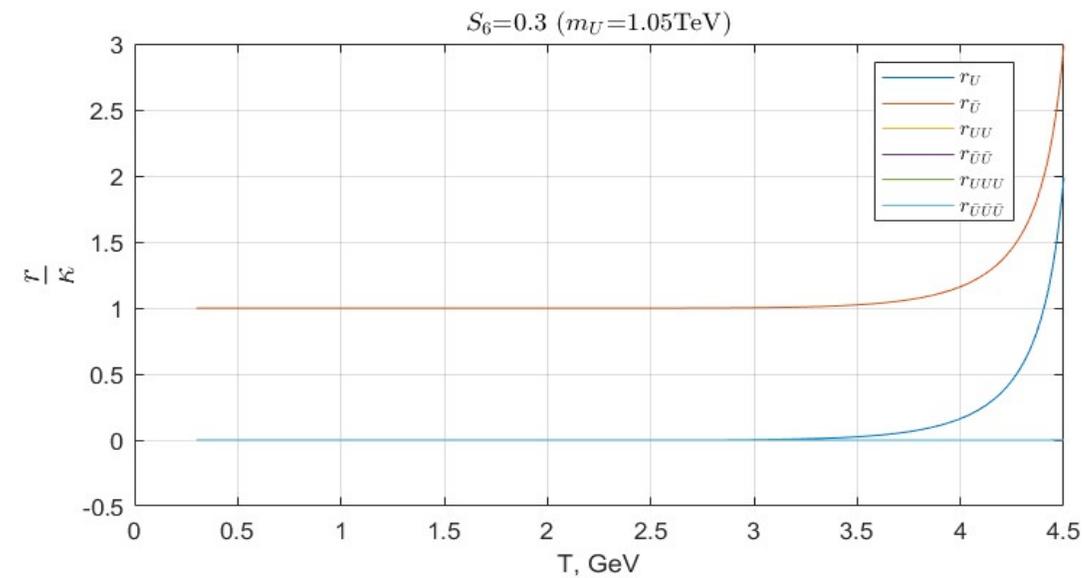


Рис. 3: График зависимости  $\frac{r}{\kappa}$  от  $m_U$

# Кластеризация тяжелых кварков

$$0.5S_6 GeV < T < I_U \approx \frac{\alpha_c^2 m_U}{4} = 15S_6 GeV$$


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$m_U, TeV$	$r_U$	$r_{\bar{U}}$	$r_{UU}$	$r_{\bar{U}\bar{U}}$	$r_{UUU}$	$r_{\bar{U}\bar{U}\bar{U}}$
0.7	9.5e-22	1.7e-13	2.6e-23	8.4e-20	1.5e-28	2.4e-16
1.4	6.8e-21	8.9e-14	2.6e-23	4.2e-20	5.8e-21	9.8e-17
2.1	2.1e-17	5.9e-14	5.2e-22	2.8e-20	1.8e-18	1.3e-16
2.8	5.1e-16	4.5e-14	5.8e-22	2.2e-20	1.9e-17	2.1e-16
3.5	2.1e-15	3.7e-14	3.7e-22	2.0e-20	6.7e-17	3.1e-16
10	3.2e-14	4.3e-14	4.3e-20	7.5e-20	3.5e-15	4.1e-15
14	4.5e-14	5.3e-14	1.2e-19	1.6e-19	7.8e-15	8.5e-15
21	7.2e-14	7.7e-14	4.7e-19	5.2e-19	2.1e-14	2.2e-14
31	1.1e-13	1.1e-13	1.7e-18	1.8e-18	5.2e-14	5.3e-14
70	2.4e-13	2.5e-13	2.2e-17	2.2e-17	2.0e-13	2.0e-13
105	3.7e-13	3.7e-13	8.1e-17	8.1e-17	3.6e-13	3.6e-13

Таблица 2: Численные значения для концентраций при разных массах  $U$  кварка на этапе кластеризации

# Кластеризация тяжелых кварков

$$0.5S_6 GeV < T < I_U \approx \frac{\alpha_c^2 m_U}{4} = 15S_6 GeV$$


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$$\langle \sigma v \rangle_{ion} = \int_I^{\text{inf}} \left( \frac{d\langle \sigma v \rangle_1}{dE_g} + \frac{d\langle \sigma v \rangle_2}{dE_g} \right) \frac{dE_g}{\exp(E_g/T) - 1}$$

$$\begin{aligned} \langle \sigma v \rangle_1 = & \frac{\pi\alpha}{(m_q E_g)} \frac{2^{4l} l^2 (n+1)! \{(1+\eta^2) \dots [(l-1)^2 + \eta^2]\}}{3 (2l+1)!(2l-1)!(n-l-1)!} \\ & \times \frac{\exp[-4\eta \cot \rho^{-1}]}{1 - e^{-2\pi\eta}} \frac{\rho^{2l+2}}{(1+\rho^2)^{2n-2}} \times [G_l(l, l+1-n, \eta, \rho) - \frac{1}{(1+\rho^2)^2} G_l(l, l-1-n, \eta, \rho)]^2 \end{aligned}$$

$$\begin{aligned} \langle \sigma v \rangle_2 = & \frac{\pi\alpha}{(m_q E_g)} \frac{2^{4l+6}}{3} \frac{(l+1)^2 (n+1)! \{(1+\eta^2) \dots [(l+1)^2 + \eta^2]\}}{(2l+1)(2l+1)!(2l+21)!(n-l-1)![(l+1)^2 + \eta^2]} \\ & \times \frac{\exp[-4\eta \cot \rho^{-1}]}{1 - e^{-2\pi\eta}} \frac{\rho^{2l+4}\eta^2}{(1+\rho^2)^{2n}} \times [(l+1-n)G_{l+1}(l, l+1-n, \eta, \rho) - \frac{l+1+n}{1+\rho^2} G_{l+1}(l, l-n, \eta, \rho)]^2 \end{aligned}$$

# Кластеризация тяжелых кварков

$$0.5S_6 GeV < T < I_U \approx \frac{\alpha_c^2 m_U}{4} = 15S_6 GeV$$

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$$\sigma_{rec} = \frac{2^8 \pi^2}{3} \frac{\eta^6 e^{4\eta \arctan(1/\eta)}}{(1 - e^{-2\pi\eta})(\eta^2 + 1)^2 \mu} \frac{\alpha 1.202 + 0.5782 \ln \eta^2 + 1 + 0.2148 \ln \eta^2 + 1^2}{1 + 0.3425 \ln \eta^2 + 1}$$

$$G_l(-m, \eta, \rho) = \sum_{s=0}^{2m} b_s \rho^s; \quad \eta = \sqrt{\frac{I}{E_g - I}}; \quad \rho = \eta/n$$

# Кластеризация тяжелых кварков

$$0.5S_6 GeV < T < I_U \approx \frac{\alpha_c^2 m_U}{4} = 15S_6 GeV$$


---

$$\left\{ \begin{array}{l} \frac{dr_U}{dT} = -\frac{s}{HT} \left( -\langle \sigma v \rangle_{rec11} r_U^2 + \langle \sigma v \rangle_{ion} r_{UU} r_g - \langle \sigma v \rangle_{rec11} r_U r_{\bar{U}} - \langle \sigma v \rangle_{rec12} r_U r_{UU} \right. \\ \qquad \qquad \qquad \left. - \langle \sigma v \rangle_{rec12} r_U r_{\bar{U}\bar{U}} - \langle \sigma v \rangle_{rec13} r_U r_{\bar{U}\bar{U}\bar{U}} + \langle \sigma v \rangle_{rec12} r_{UU} r_{\bar{U}} + \langle \sigma v \rangle_{rec23} r_{UUU} r_{\bar{U}\bar{U}} \right) \\ \frac{dr_{UU}}{dT} = -\frac{s}{HT} \left( \langle \sigma v \rangle_{rec11} r_U^2 - \langle \sigma v \rangle_{ion} r_{UU} r_g - \langle \sigma v \rangle_{rec12} r_U r_{UU} - \langle \sigma v \rangle_{rec12} r_{UU} r_{\bar{U}} \right. \\ \qquad \qquad \qquad \left. - \langle \sigma v \rangle_{rec22} r_{UU} r_{\bar{U}\bar{U}} + \langle \sigma v \rangle_{rec13} r_{UUU} r_{\bar{U}} - \langle \sigma v \rangle_{rec23} r_{UUU} r_{\bar{U}\bar{U}\bar{U}} \right) \\ \frac{dr_{UUU}}{dT} = -\frac{s}{HT} \left( \langle \sigma v \rangle_{rec12} r_U r_{UU} - \langle \sigma v \rangle_{rec13} r_{UUU} r_{\bar{U}} - \langle \sigma v \rangle_{rec23} r_{UUU} r_{\bar{U}\bar{U}} - \langle \sigma v \rangle_{rec33} r_{UUU} r_{\bar{U}\bar{U}\bar{U}} \right) \\ \frac{dr_{\bar{U}}}{dT} = -\frac{s}{HT} \left( -\langle \sigma v \rangle_{rec11} r_{\bar{U}}^2 + \langle \sigma v \rangle_{ion} r_{\bar{U}\bar{U}} r_g - \langle \sigma v \rangle_{rec11} r_U r_{\bar{U}} - \langle \sigma v \rangle_{rec12} r_{\bar{U}} r_{\bar{U}\bar{U}} \right. \\ \qquad \qquad \qquad \left. - \langle \sigma v \rangle_{rec12} r_{\bar{U}} r_{UU} - \langle \sigma v \rangle_{rec13} r_{\bar{U}} r_{UUU} + \langle \sigma v \rangle_{rec12} r_{\bar{U}\bar{U}} r_U + \langle \sigma v \rangle_{rec23} r_{\bar{U}\bar{U}\bar{U}} r_{UU} \right) \\ \frac{dr_{\bar{U}\bar{U}}}{dT} = -\frac{s}{HT} \left( \langle \sigma v \rangle_{rec11} r_{\bar{U}}^2 - \langle \sigma v \rangle_{ion} r_{\bar{U}\bar{U}} r_g - \langle \sigma v \rangle_{rec12} r_{\bar{U}} r_{\bar{U}\bar{U}} - \langle \sigma v \rangle_{rec12} r_U r_{\bar{U}\bar{U}} - \langle \sigma v \rangle_{rec22} r_{UU} r_{\bar{U}\bar{U}} \right. \\ \qquad \qquad \qquad \left. + \langle \sigma v \rangle_{rec13} r_{\bar{U}\bar{U}\bar{U}} r_U - \langle \sigma v \rangle_{rec23} r_{\bar{U}\bar{U}} r_{UUU} \right) \\ \frac{dr_{\bar{U}\bar{U}\bar{U}}}{dT} = -\frac{s}{HT} \left( \langle \sigma v \rangle_{rec12} r_{\bar{U}} r_{\bar{U}\bar{U}} - \langle \sigma v \rangle_{rec13} r_{\bar{U}\bar{U}\bar{U}} r_U - \langle \sigma v \rangle_{rec23} r_{\bar{U}\bar{U}\bar{U}} r_{UU} - \langle \sigma v \rangle_{rec33} r_{UUU} r_{\bar{U}\bar{U}\bar{U}} \right) \end{array} \right.$$

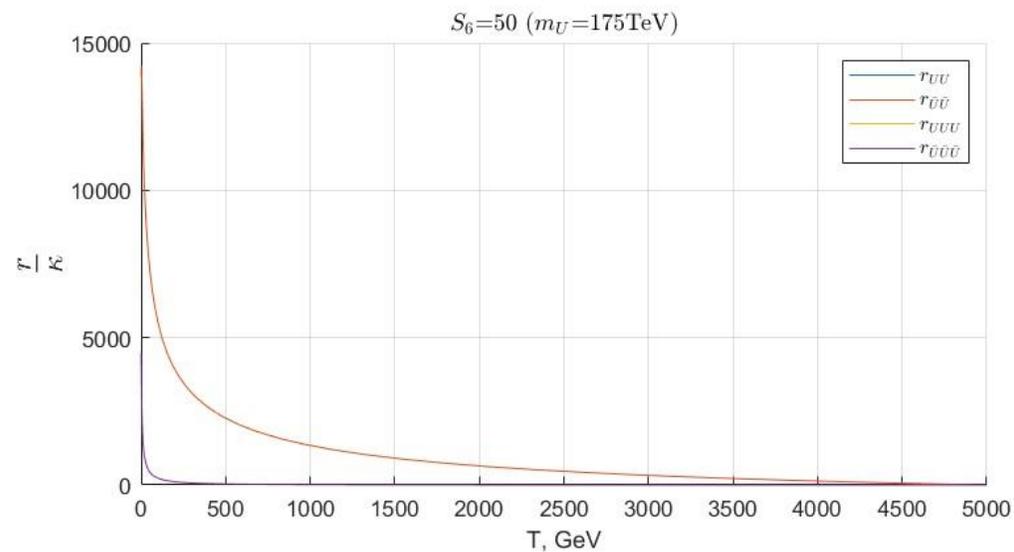
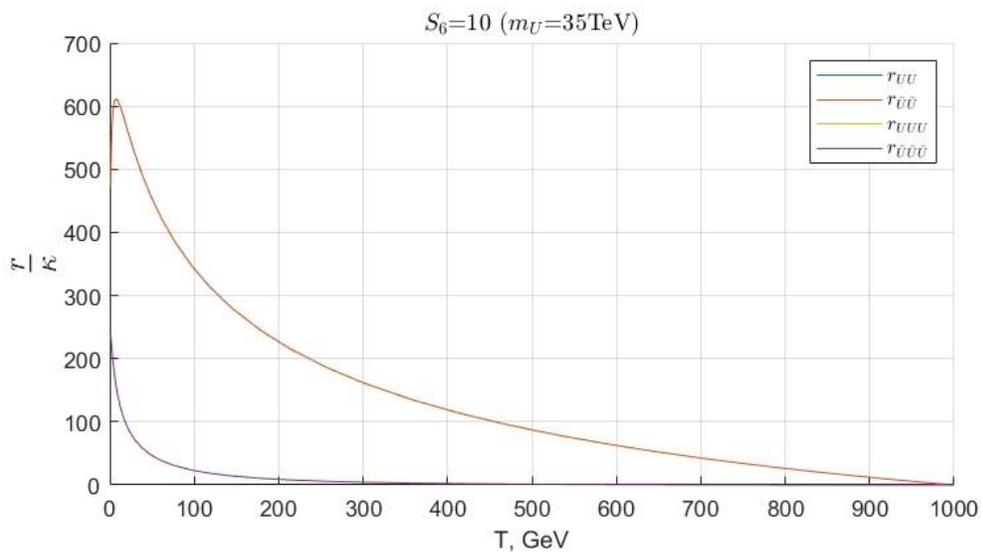
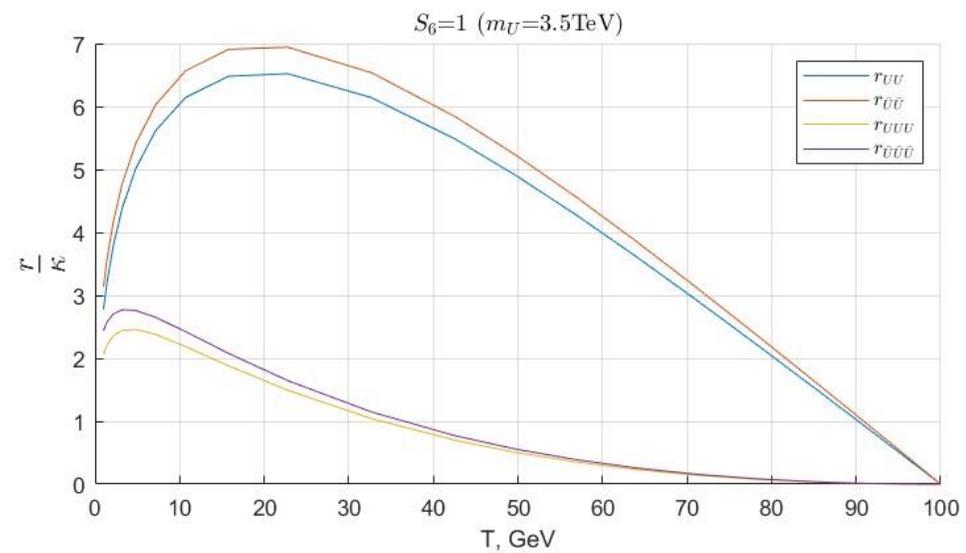
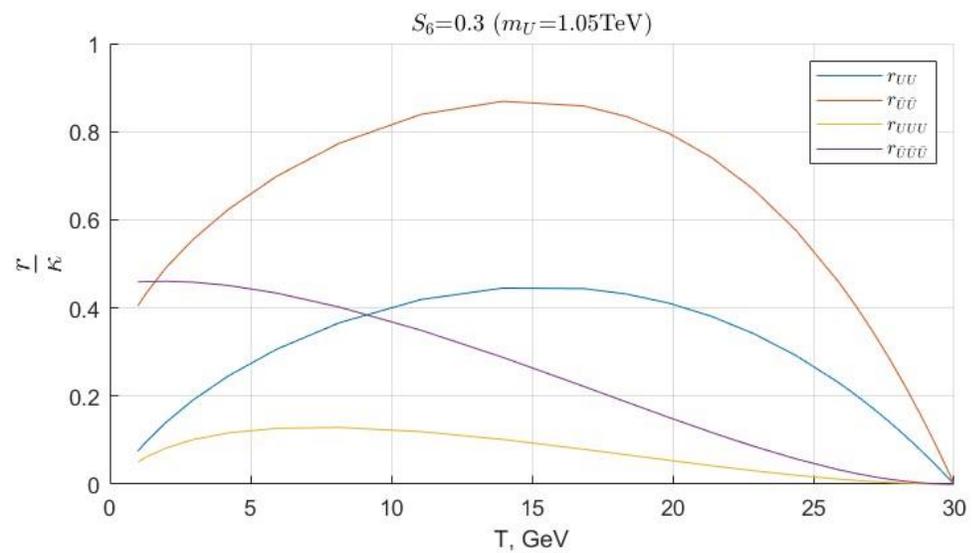


Рис. 4: График зависимости  $\frac{r}{k}$  от  $m_U$

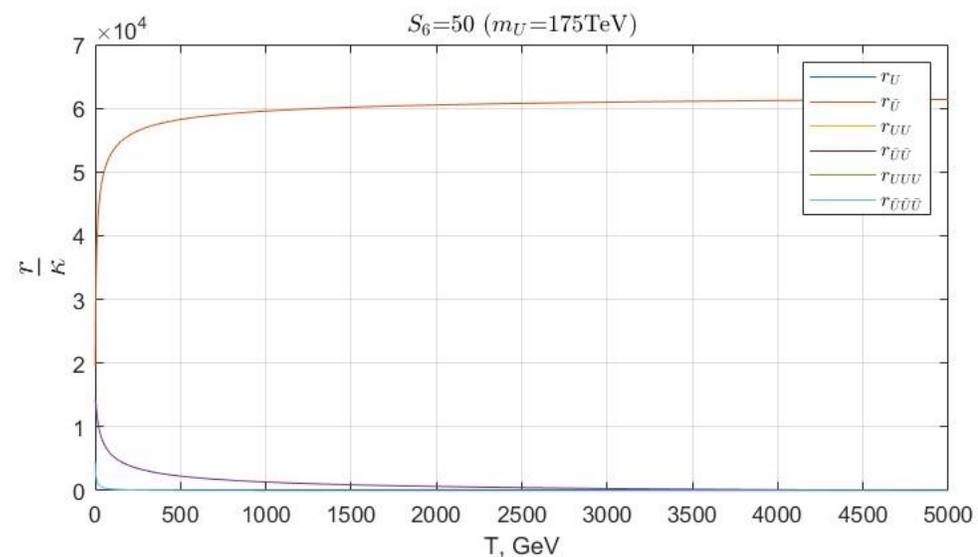
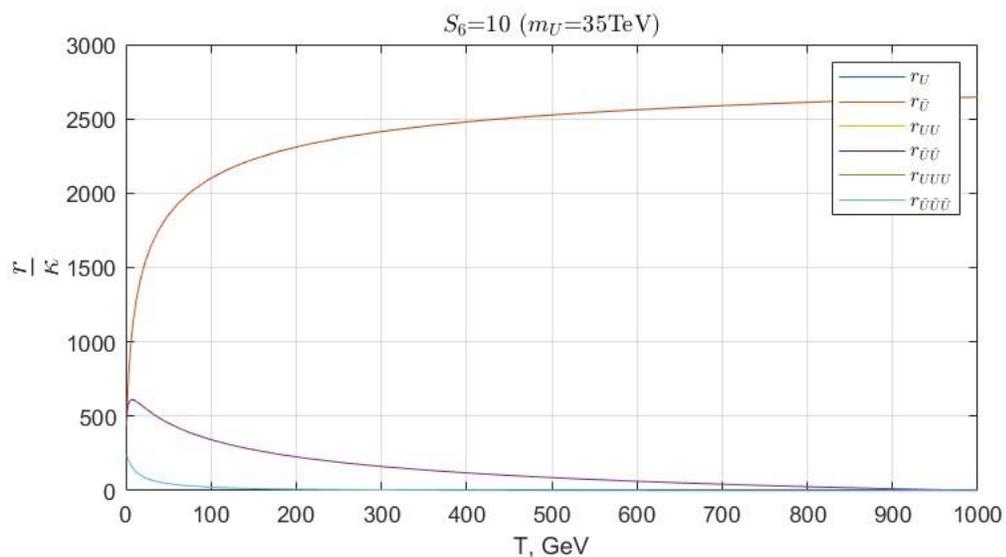
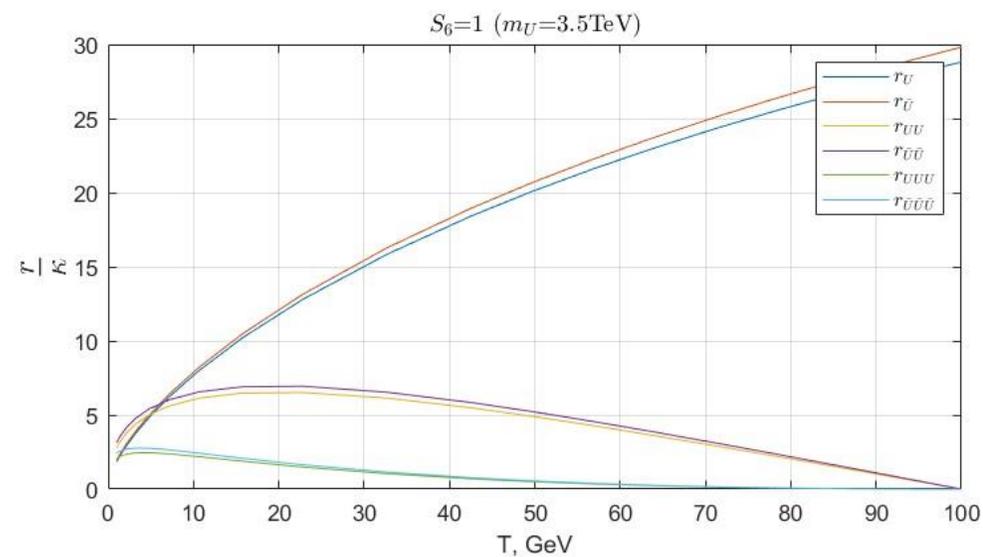
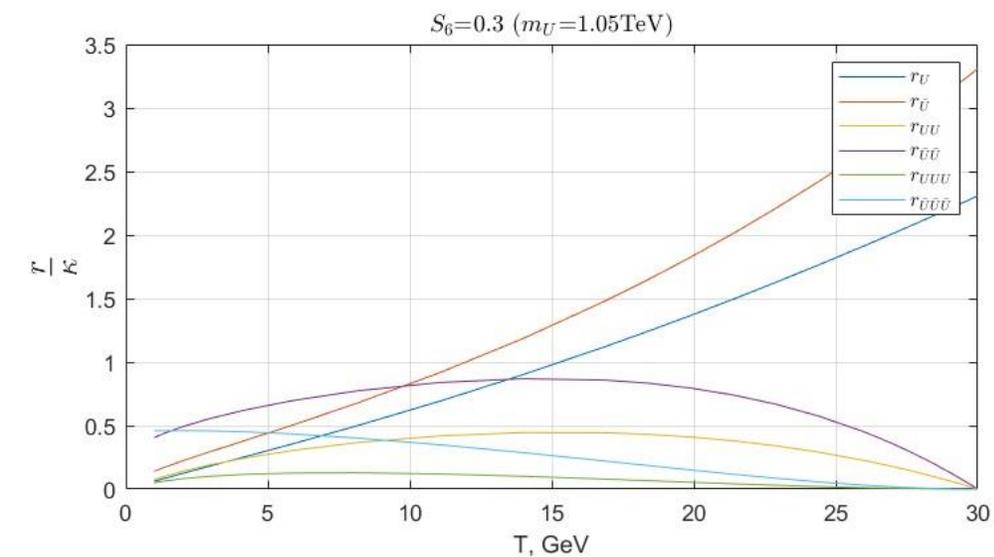


Рис. 5: График зависимости  $\frac{r}{\kappa}$  от  $m_U$

# Заключение

- В дальнейшем планируется рассмотреть дальнейшую эволюцию: формирование устойчивых систем из тяжелых и легких кварков и их предполагаемые концентрации в нашей Вселенной
- Оценить, насколько подавляется положительно заряженная компонента
- Найти эффективный путь подавления положительно заряженной компоненты

Спасибо за внимание!