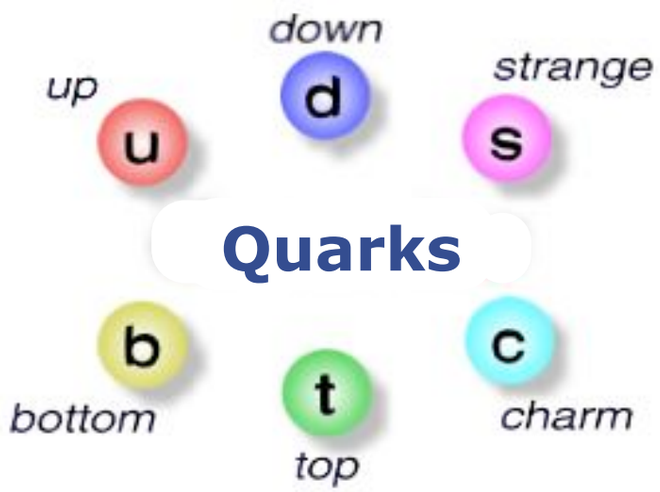
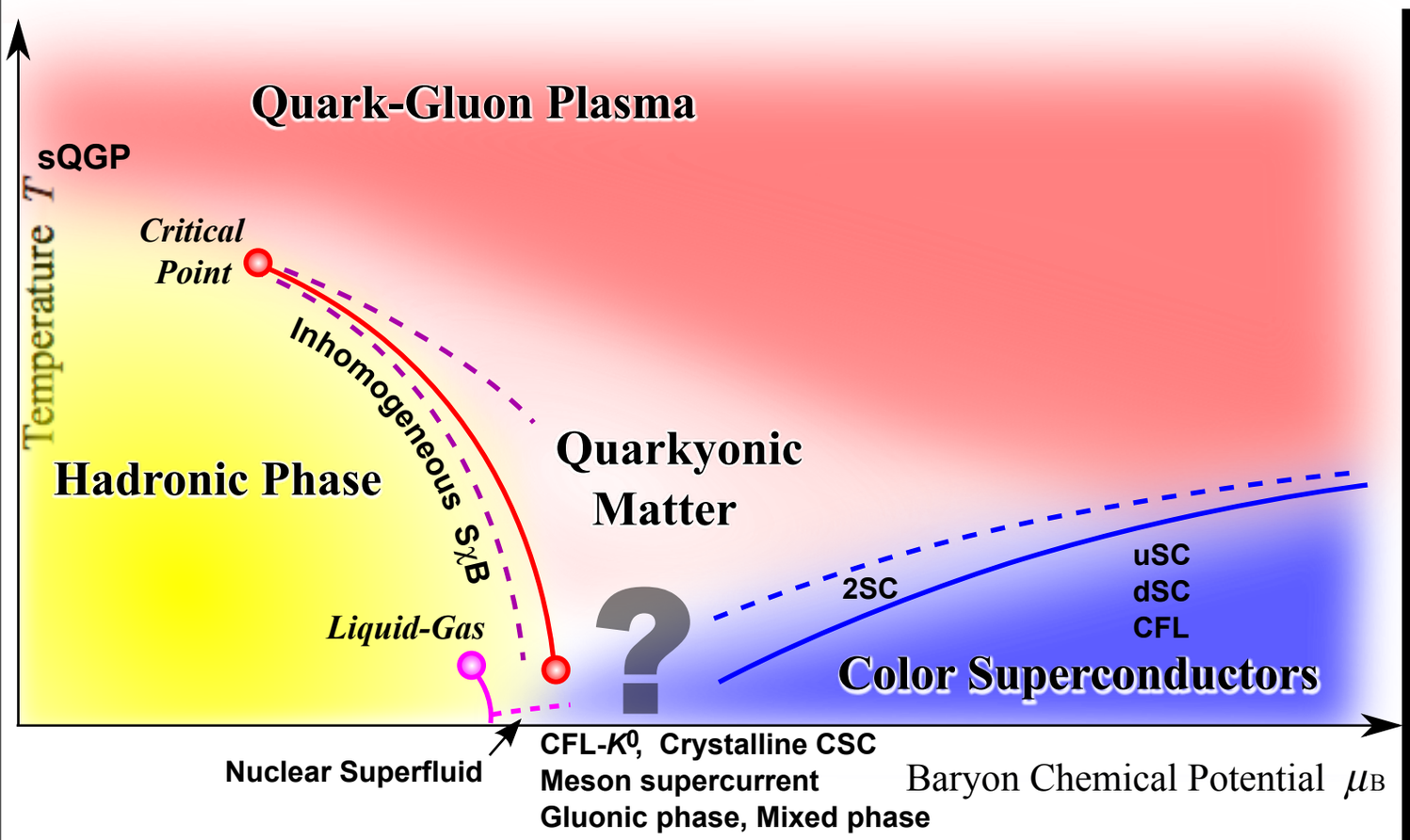
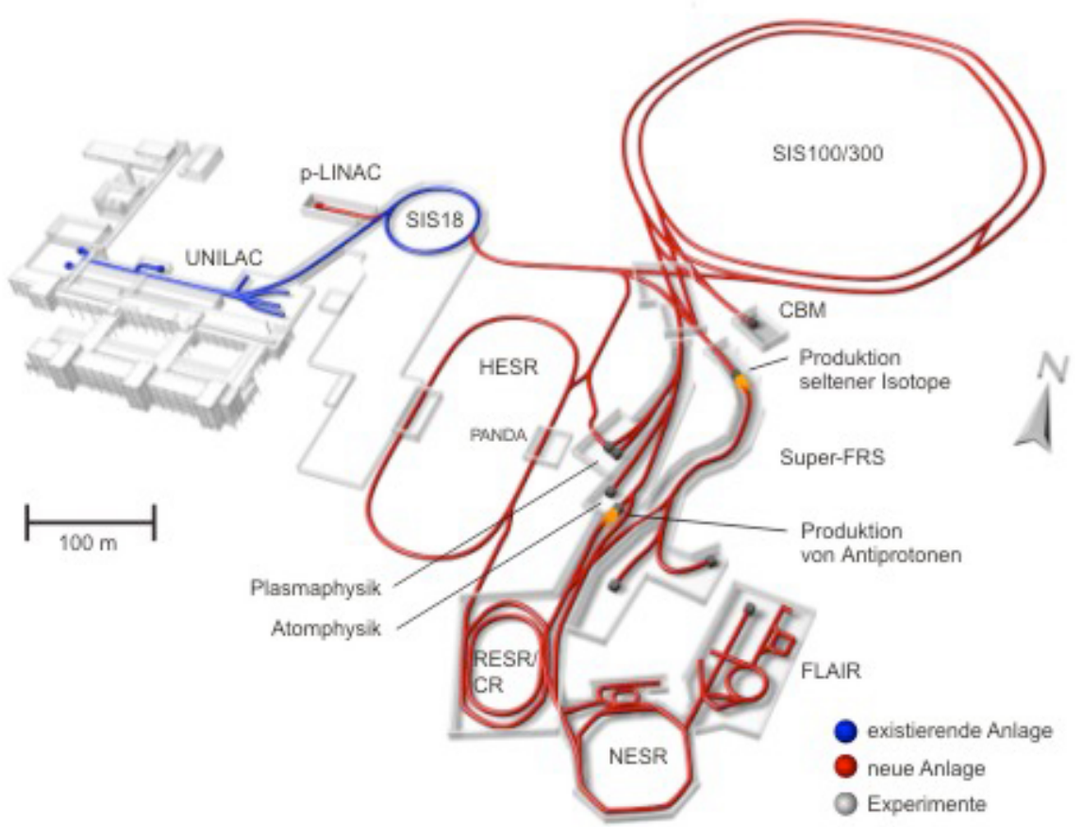
QCD

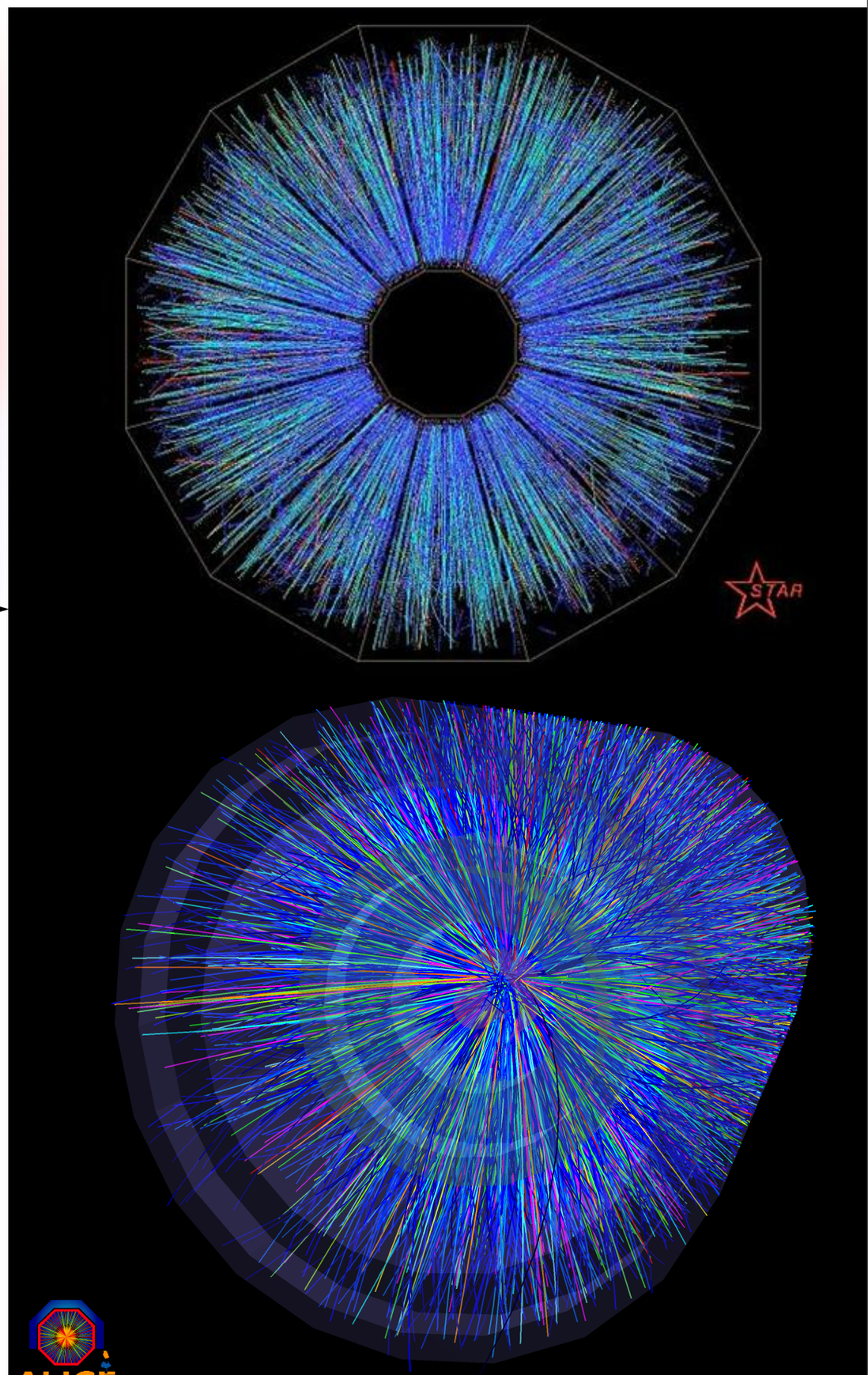


Gluons

Heavy ion collisions

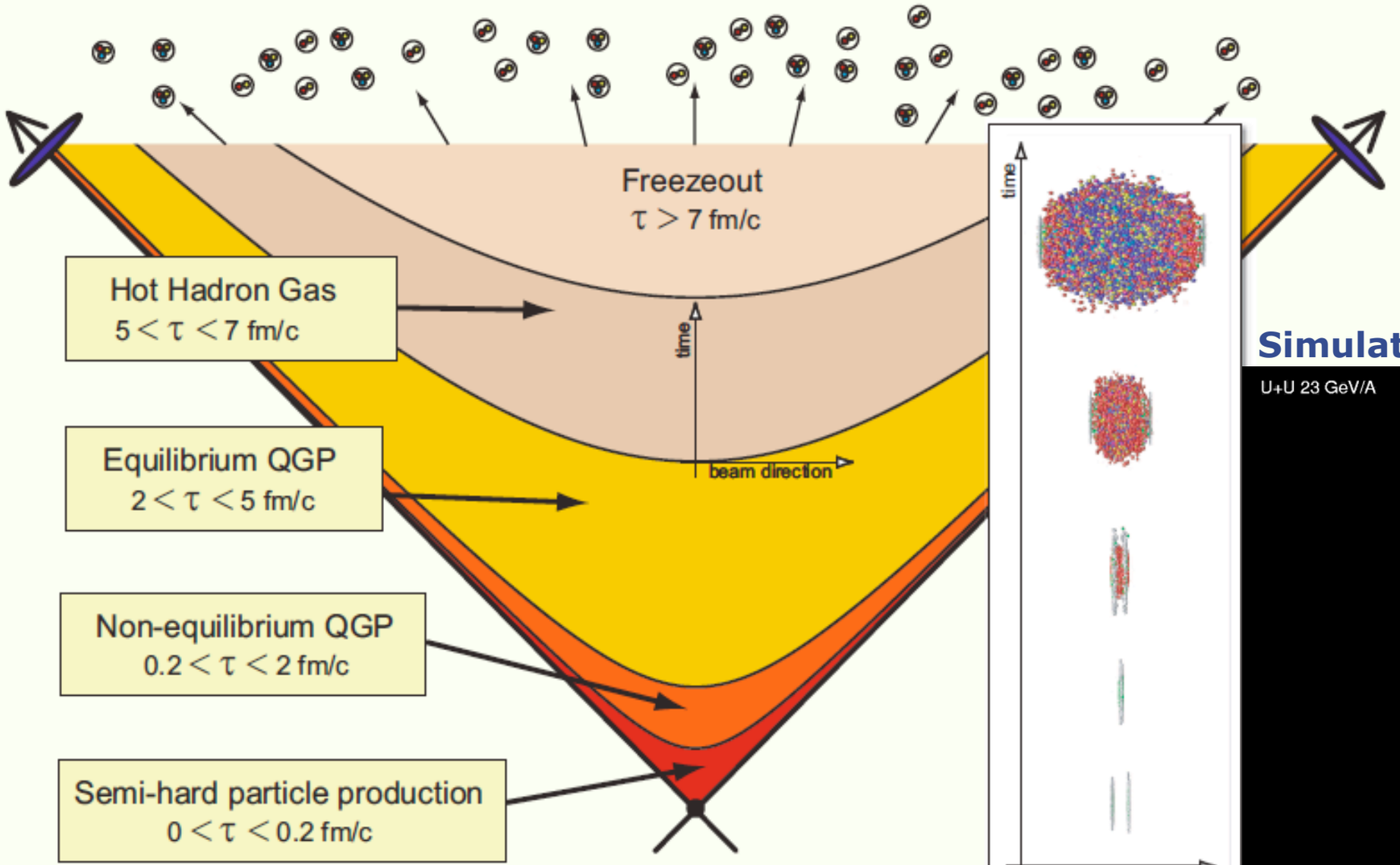




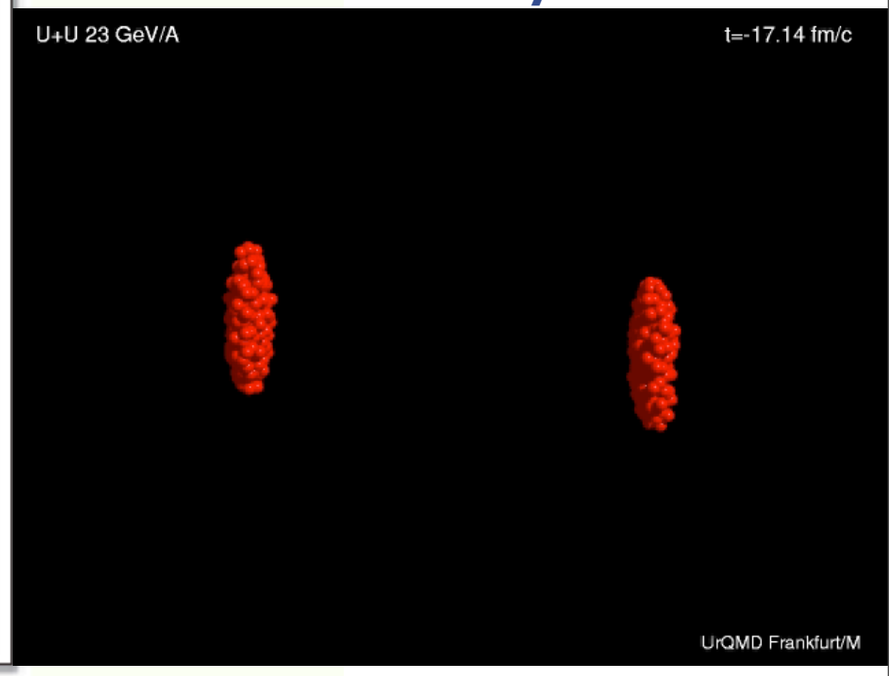


Heavy ion collisions

Heavy-ion collision timescales and "epochs" @ RHIC



Simulation of a heavy ion collision



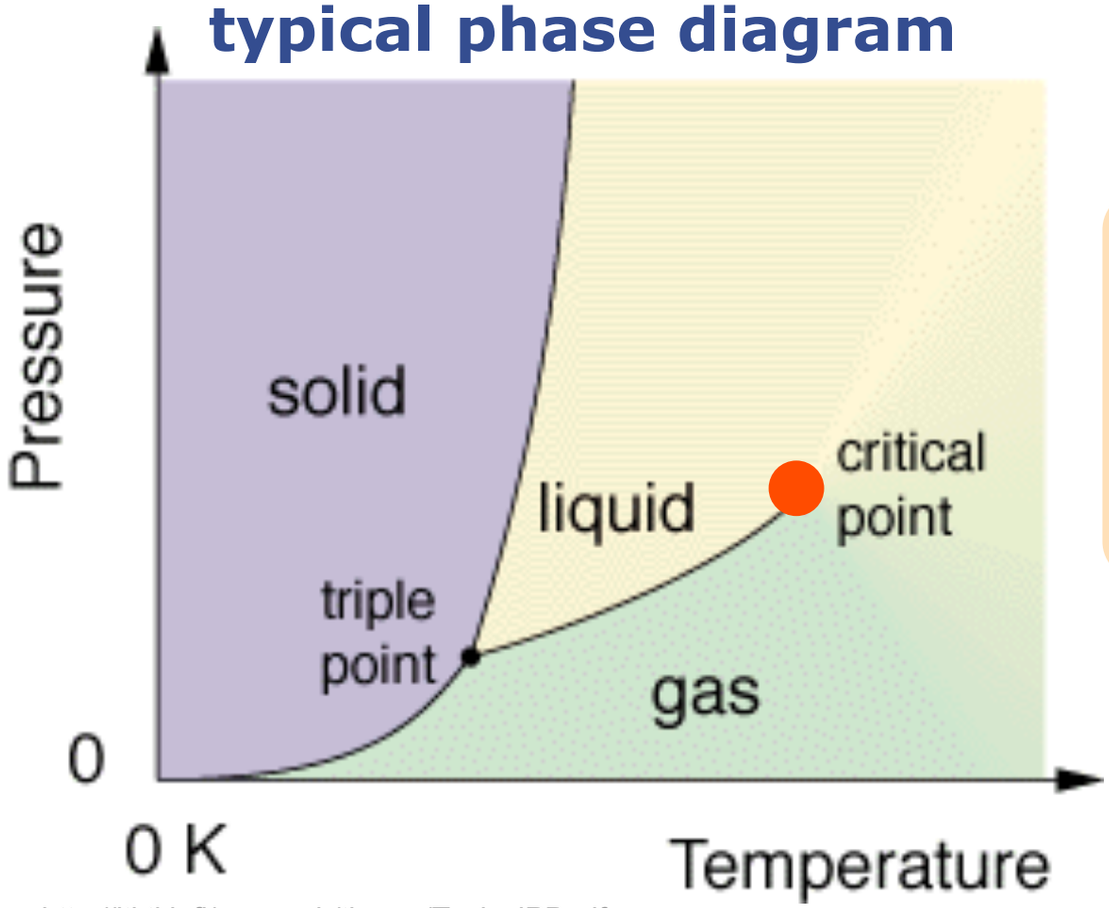
UrQMD Frankfurt/M

Strickland

*1 fm/c $\simeq 3 \times 10^{-24}$ seconds

Phase diagrams & order parameters

typical phase diagram



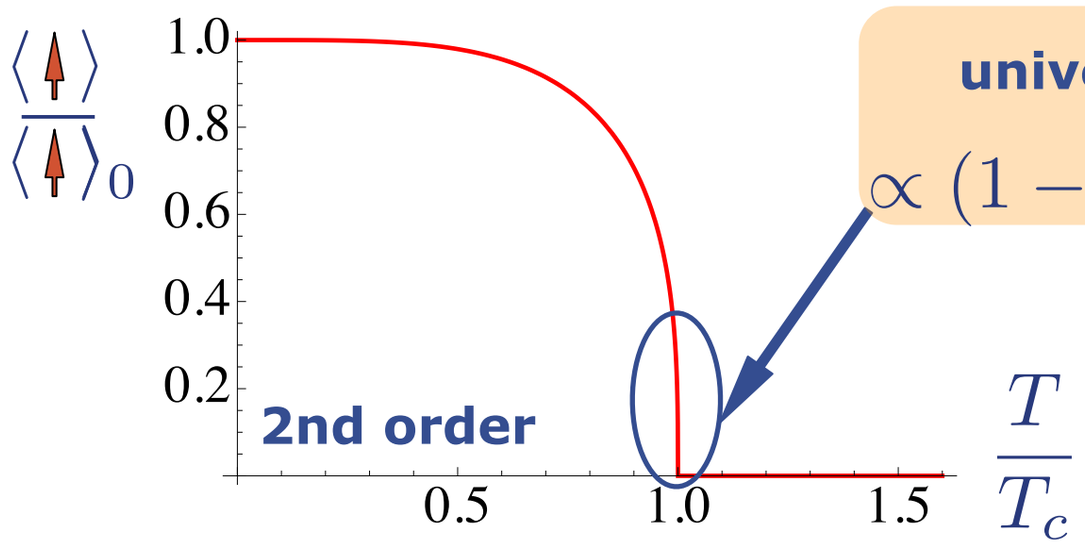
http://ltl.tkk.fi/research/theory/TypicalPD.gif

Order parameter: density

density jumps	1st order phase transition
derivative of density jumps	2nd order phase transition
density smooth	cross-over

Ising model in 3d: $(\downarrow\uparrow)$-spin system

Order parameter: $\langle\uparrow\rangle$

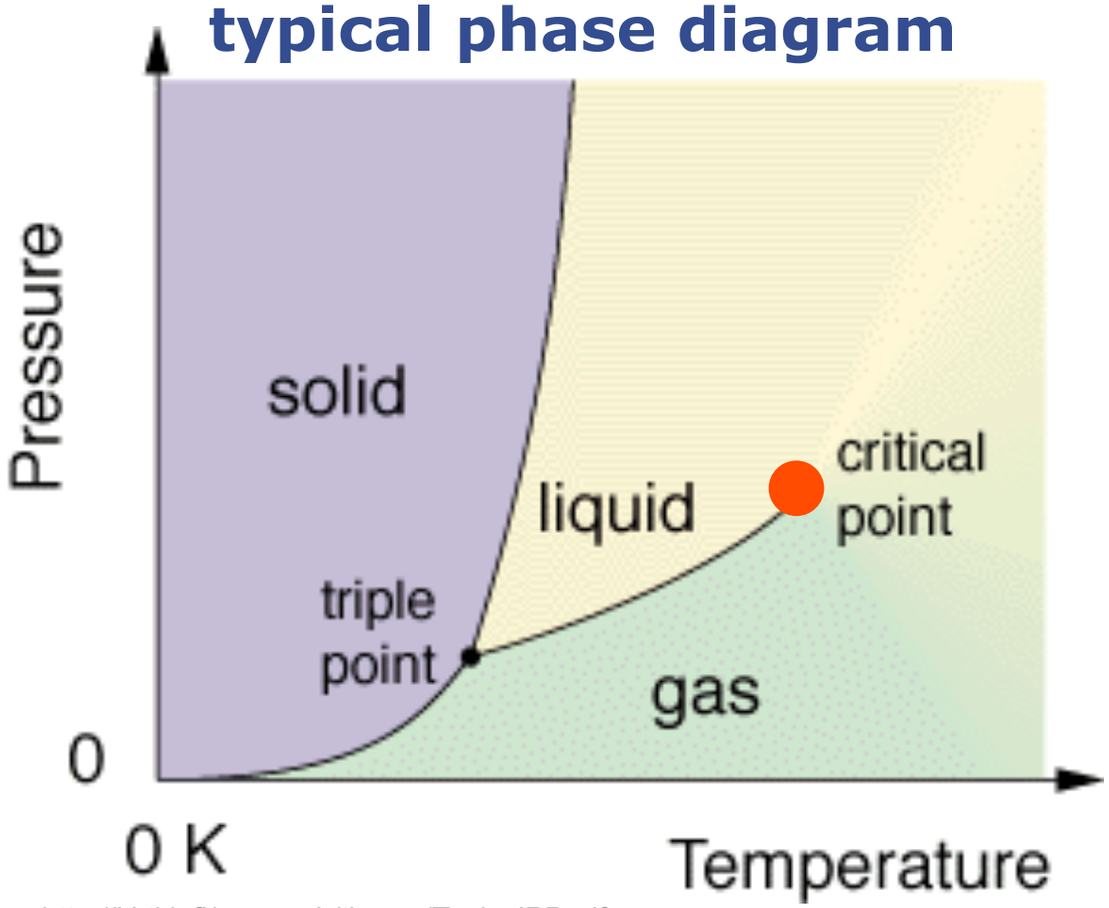


universal for Z_2

$$\propto (1 - T/T_c)^{0.325\ldots}$$

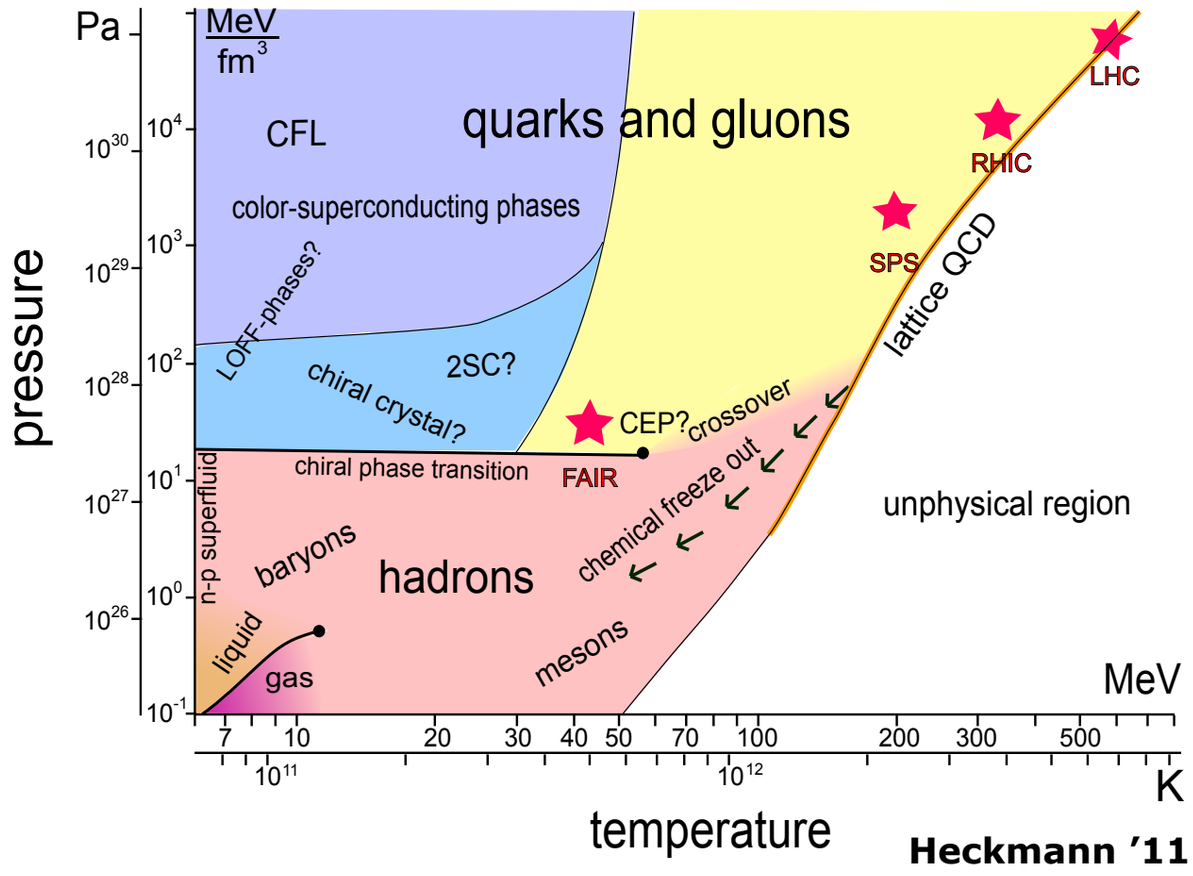
Phase diagrams & order parameters

typical phase diagram



http://ltl.tkk.fi/research/theory/TypicalPD.gif

phase diagram of QCD



Heckmann '11

Phases of QCD

quarks massless - massive

quarks confined - deconfined

Phase diagram of QCD

Temperature T

Quark-Gluon Plasma

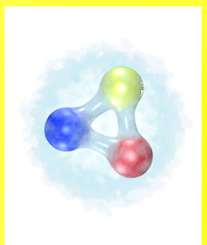
sQGP

Critical Point

Inhomogeneous $S\chi B$

Quarkyonic Matter

Hadronic Phase



Liquid-Gas

?

2SC

uSC
dSC
CFL

Color Superconductors

Nuclear Superfluid

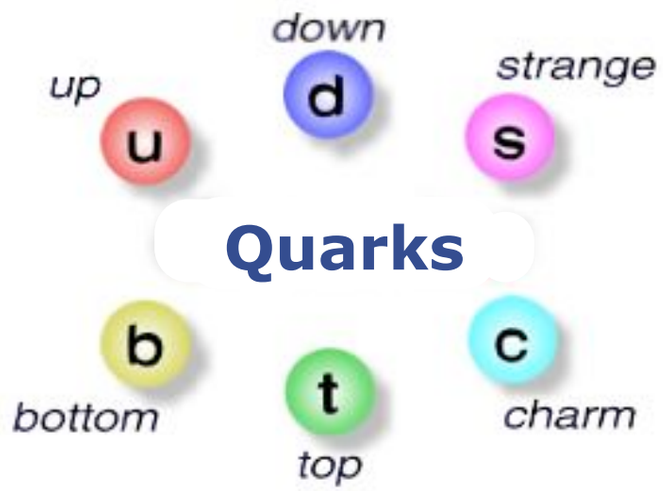
CFL-K^0, Crystalline CSC
Meson supercurrent
Gluonic phase, Mixed phase

Baryon Chemical Potential μ_B

baryonic density

Fukushima

QCD, asymptotic freedom and all that



Gluons

QCD, asymptotic freedom and all that

Action and interactions

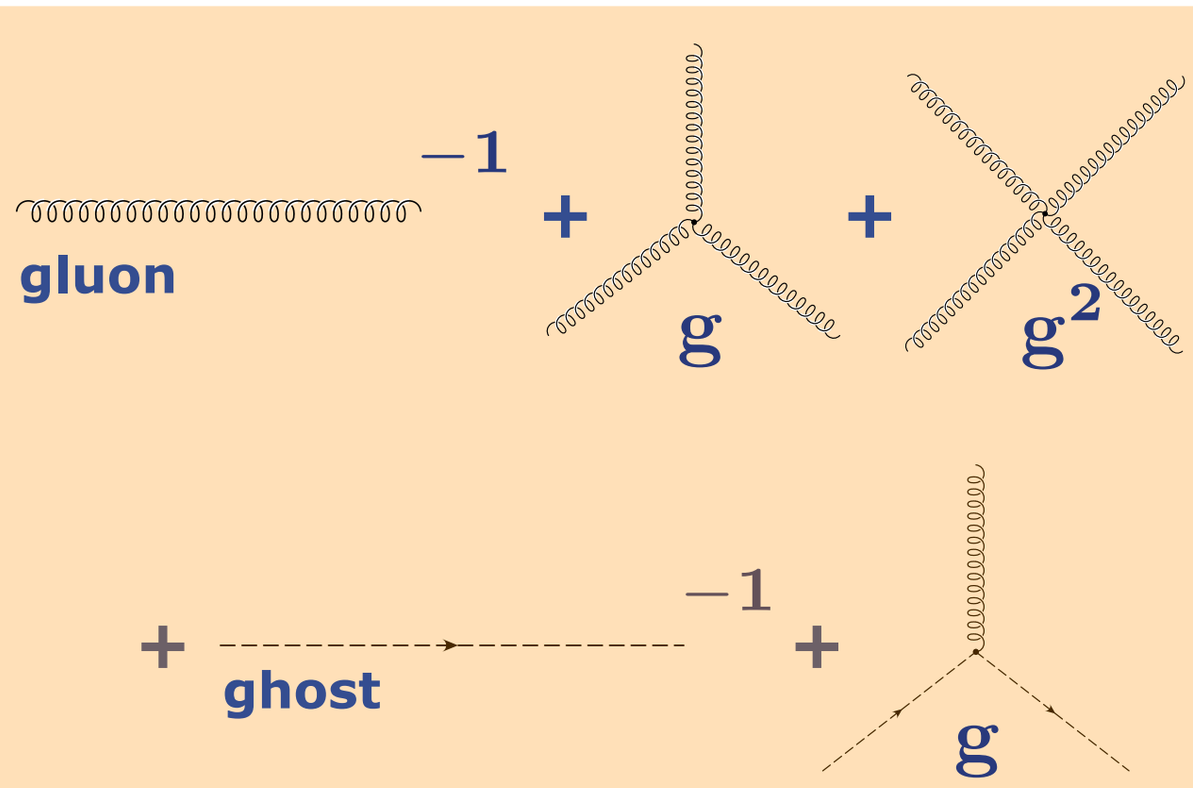
QCD action S_{QCD}

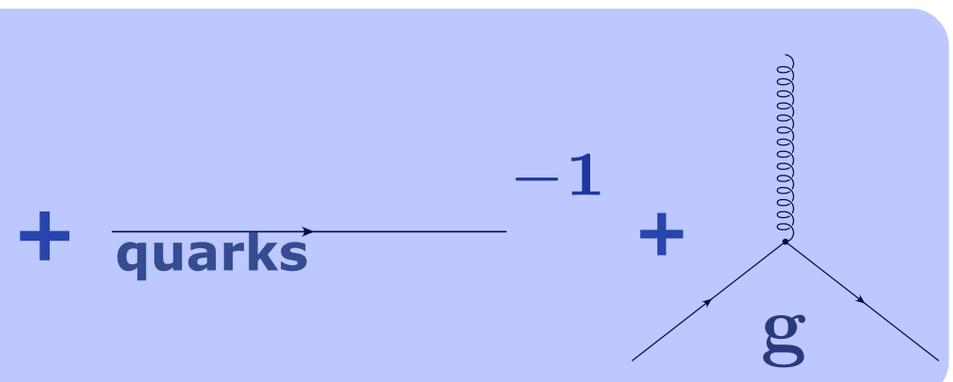
Yang-Mills **gauge fixing**

$$\frac{1}{4}\int_x F^a_{\mu\nu}F^a_{\mu\nu} + \frac{1}{2\xi}\int_x \left(\partial_\mu A^a_\mu\right)^2 + \int_x \bar{c}^a \partial_\mu D^{ab}_\mu c^b + \int_x \bar{q}\cdot\left(i\not{D} + i\,m_\psi + i\mu\gamma_0\right)\cdot q$$

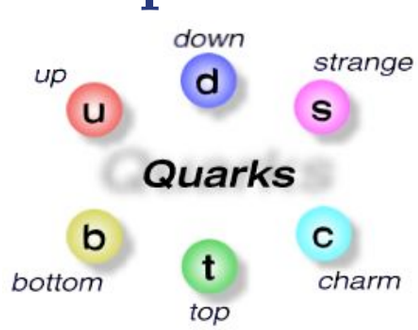
gluon **ghost** **quarks**

Pure gauge theory **matter sector**





$$N_f = 6$$



QCD, asymptotic freedom and all that

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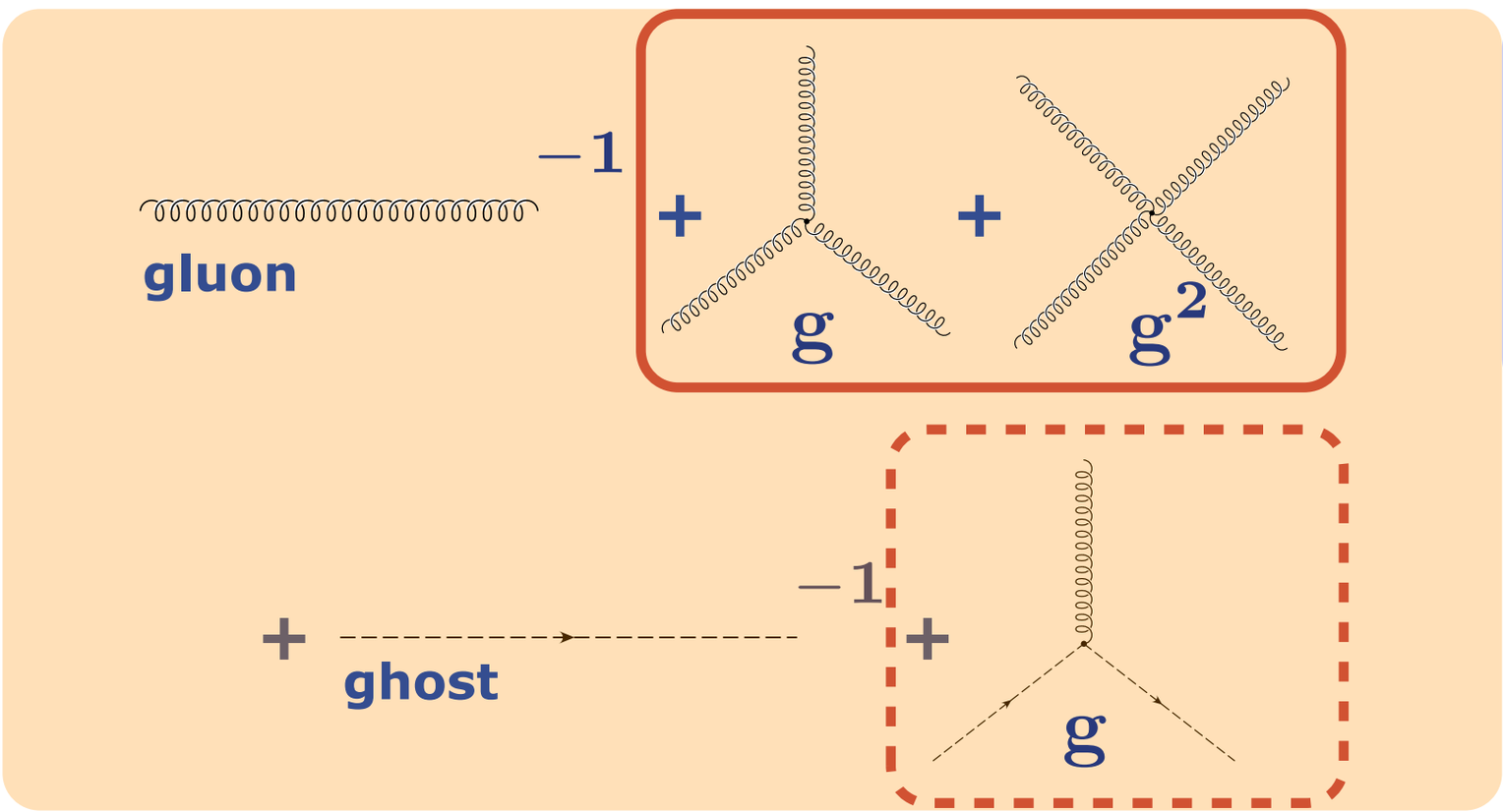
gluon **ghost** **quarks**

Pure gauge theory **matter sector**



purely non-Abelian

QCD, asymptotic freedom and all that

Action and interactions

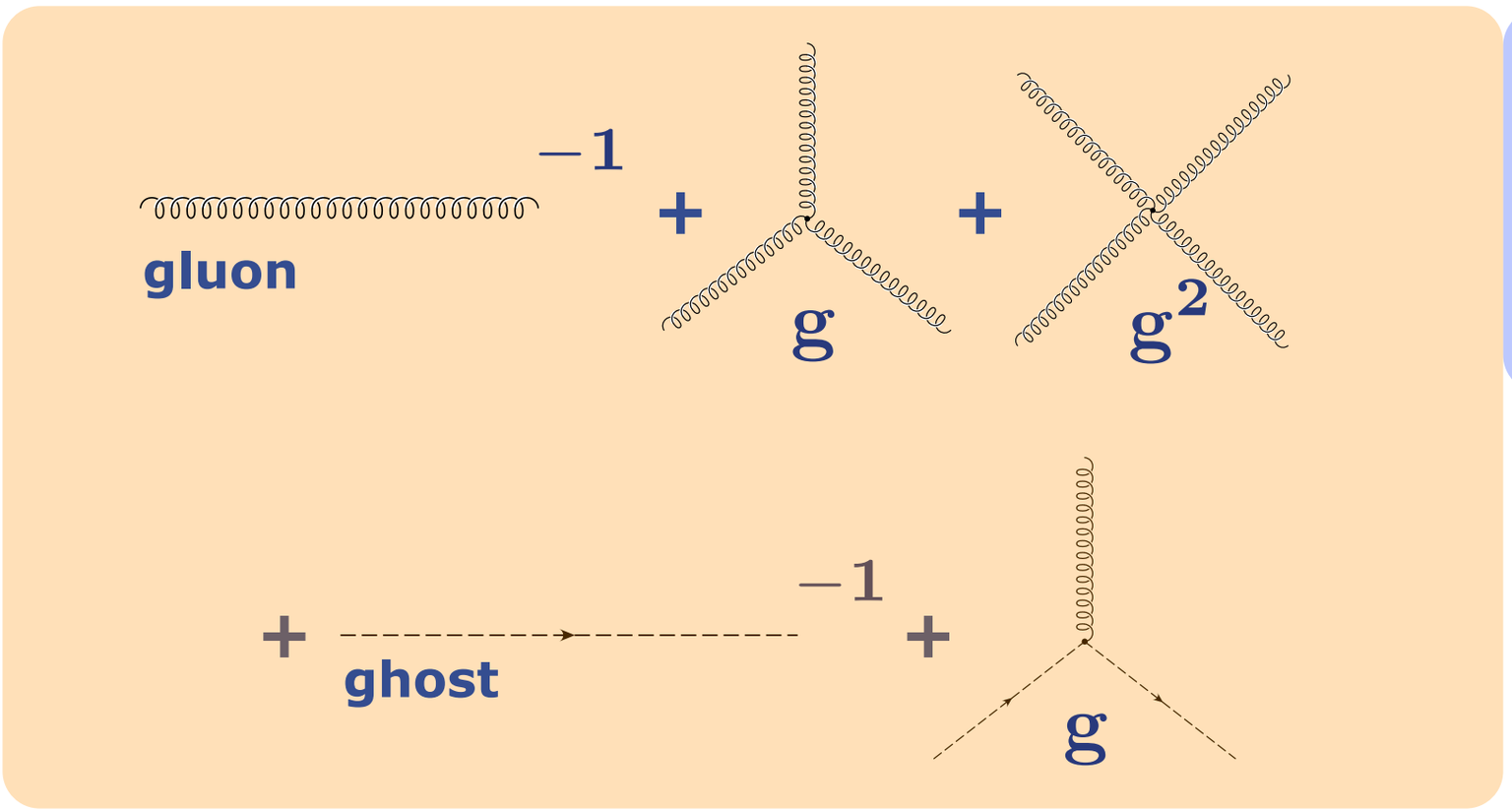
QCD action S_{QCD}

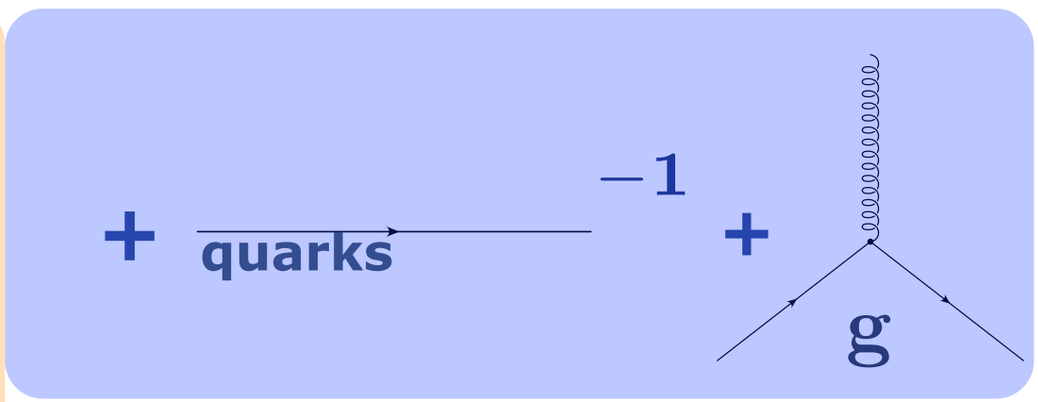
Yang-Mills **gauge fixing**

$$\frac{1}{4}\int_x F^a_{\mu\nu}F^a_{\mu\nu} + \frac{1}{2\xi}\int_x \left(\partial_\mu A^a_\mu\right)^2 + \int_x \bar{c}^a \partial_\mu D^{ab}_\mu c^b + \int_x \bar{q}\cdot\left(i\not{D} + i\,m_\psi + i\mu\gamma_0\right)\cdot q$$

gluon **ghost** **quarks**

Pure gauge theory **matter sector**



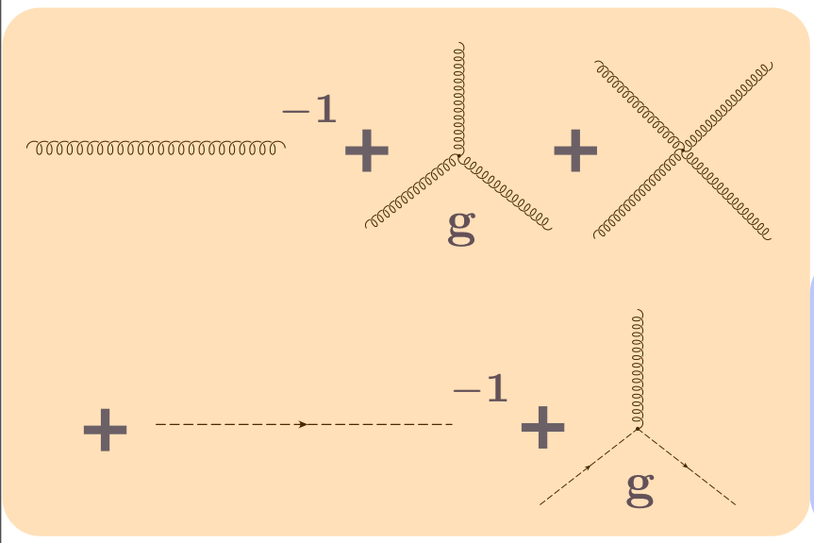


parameters

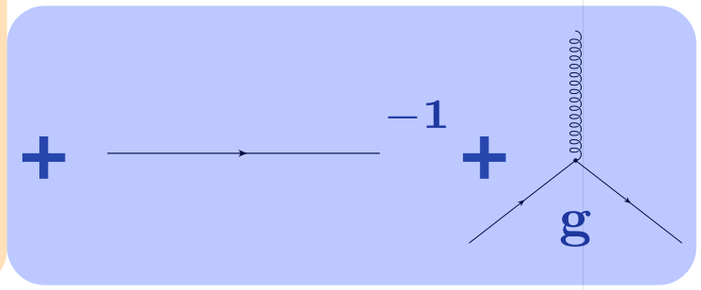
- 1 coupling g
- mass matrix m_ψ $\mathrm{N_f}\times\mathrm{N_f}$

QCD, asymptotic freedom and all that

Running coupling at low and high energies



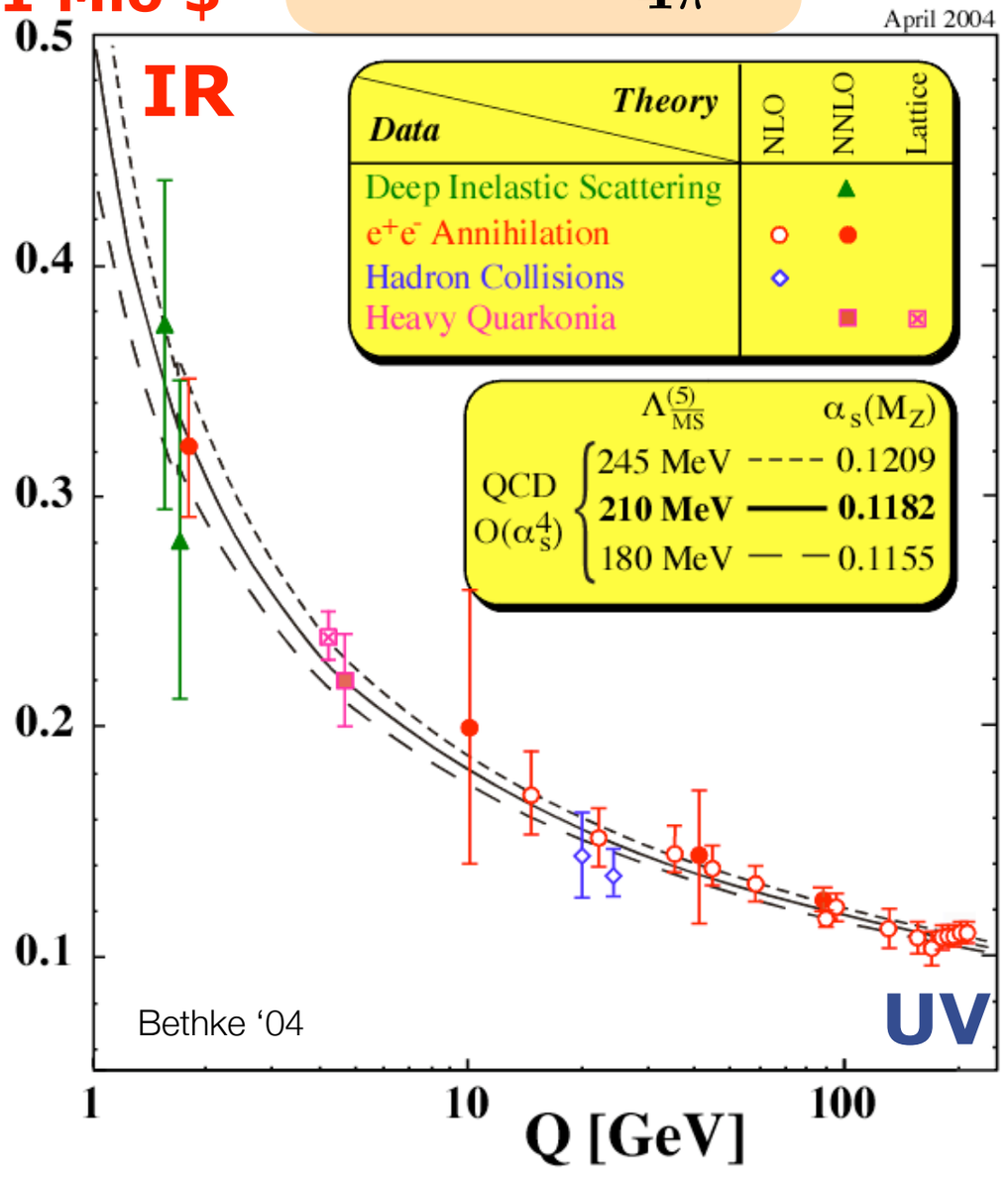
Pure gauge theory



matter sector

Millenium Prize 1 Mio $

$$\alpha_s(Q) = \frac{g^2(Q)}{4\pi}$$

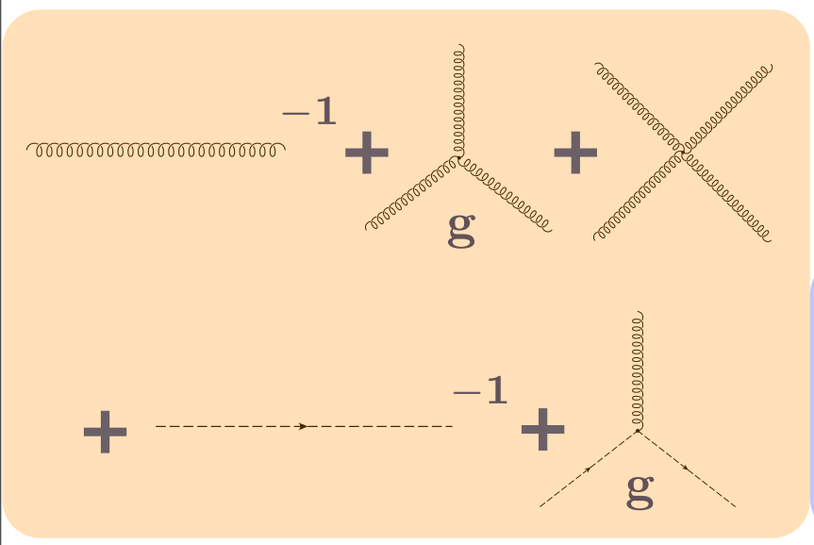


Nobel Prize '04

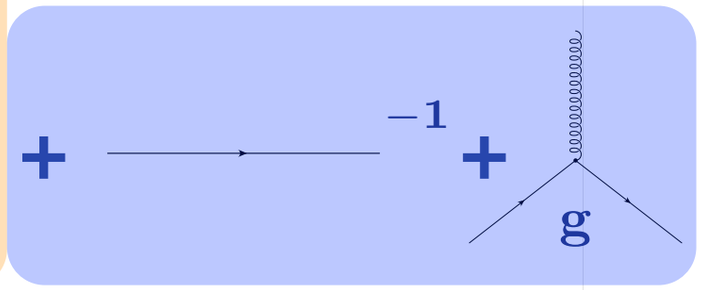
Gross, Politzer, Wilczek

QCD, asymptotic freedom and all that

Running coupling at low and high energies



Pure gauge theory



matter sector

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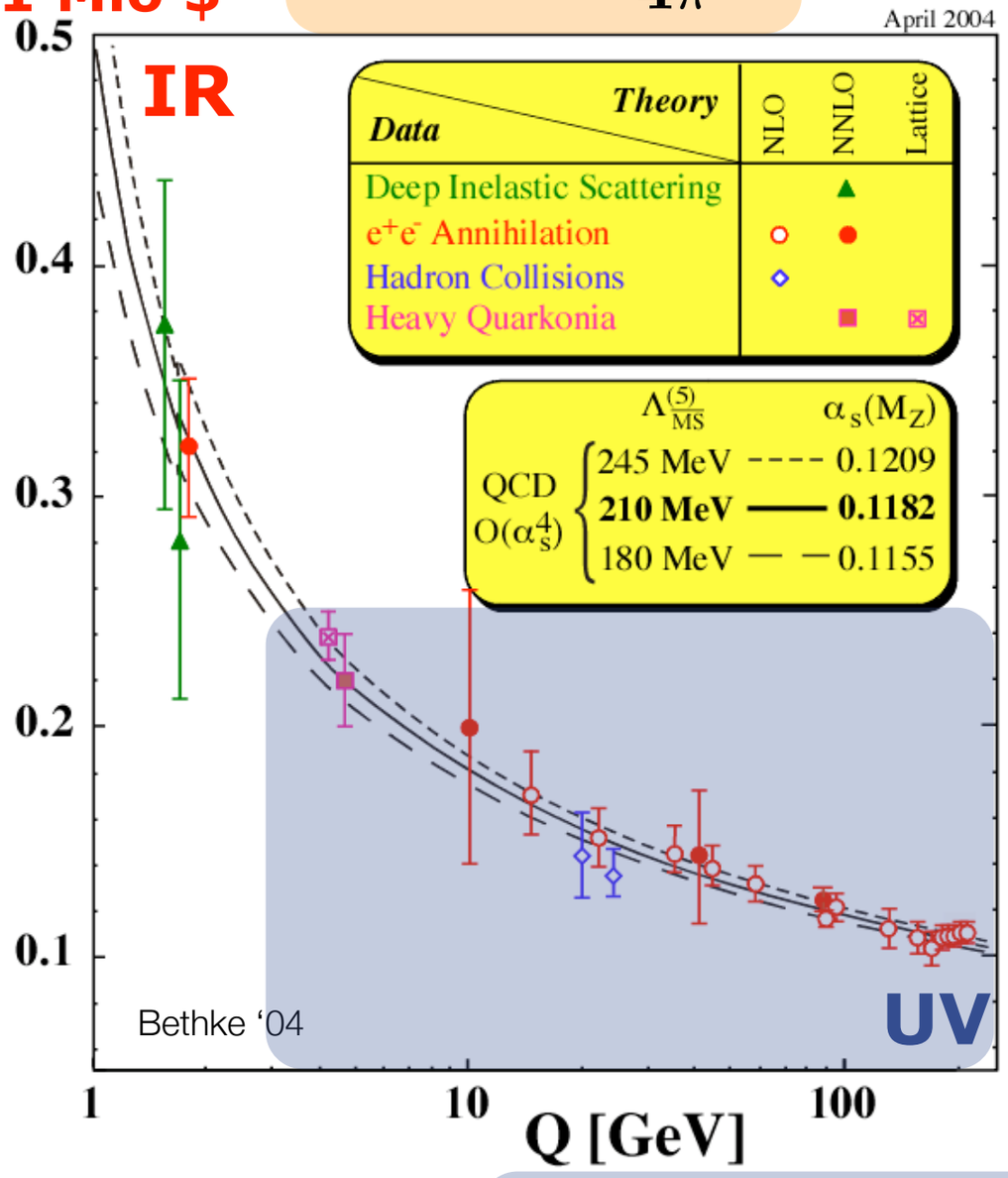


- **UV: asymptotic freedom**

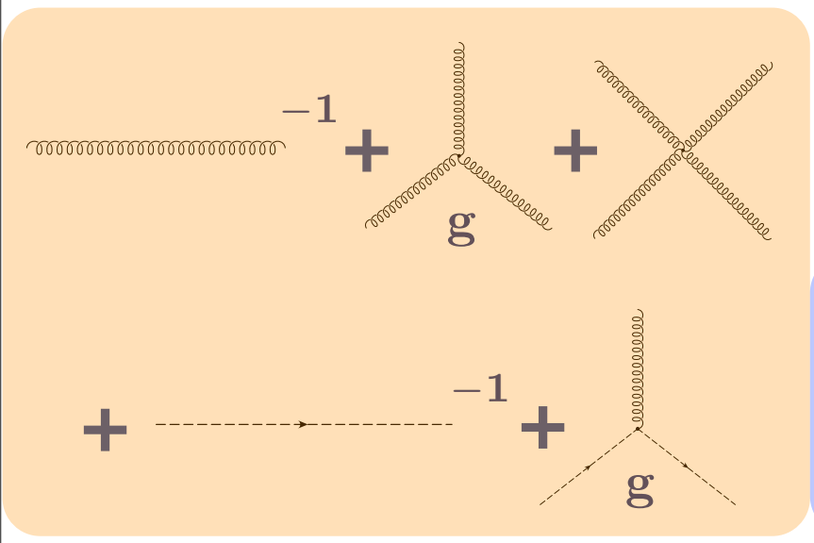
$$\alpha_s(Q \to \infty) = 0$$

Nobel Prize '04

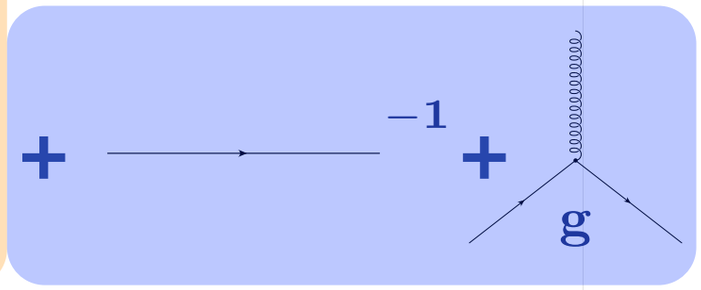
Gross, Politzer, Wilczek

QCD, asymptotic freedom and all that

Running coupling at low and high energies



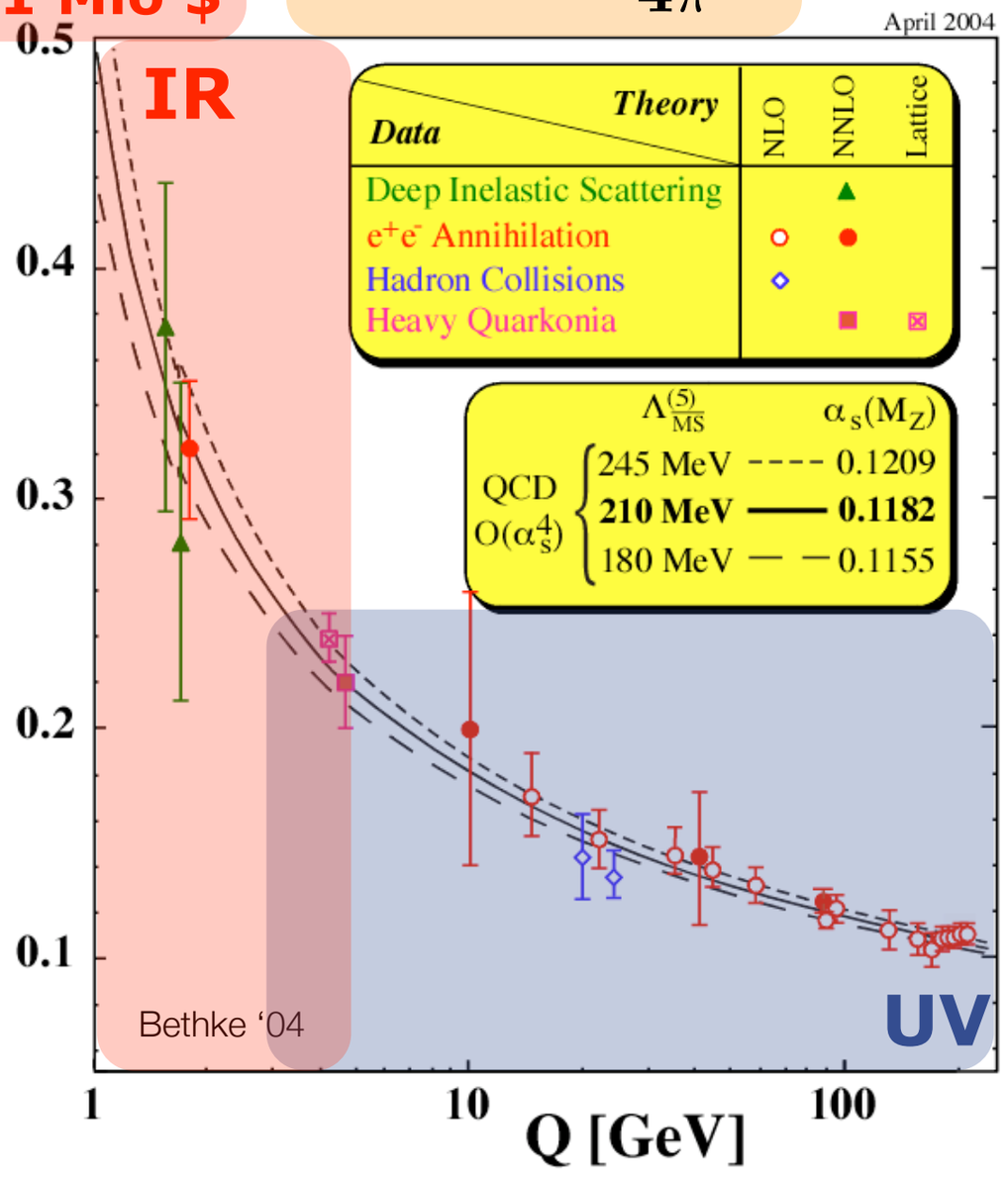
Pure gauge theory



matter sector

Millenium Prize 1 Mio $

$$\alpha_s(Q) = \frac{g^2(Q)}{4\pi}$$



- **UV: asymptotic freedom**

$$\alpha_s(Q \to \infty) = 0$$

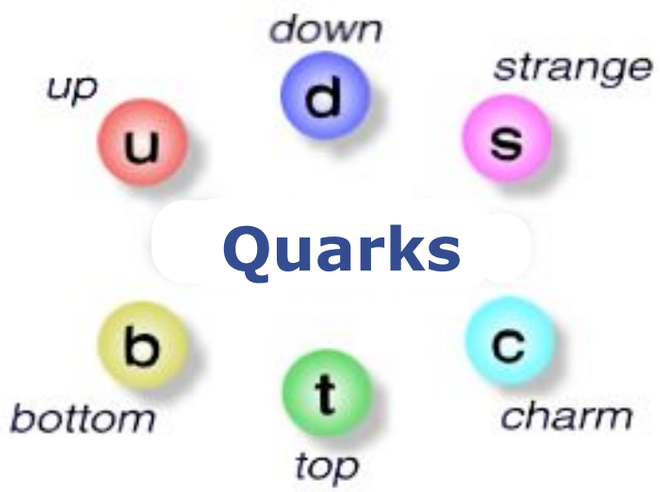
- **IR: failure of perturbation theory**

$$\alpha_s(\Lambda^2_{\rm QCD}) = \infty \quad \text{at} \quad \Lambda_{\rm QCD} = 217^{+25}_{-23}\ \text{MeV}$$

Nobel Prize '04

Gross, Politzer, Wilczek

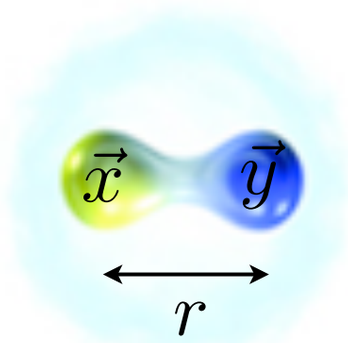
Confinement



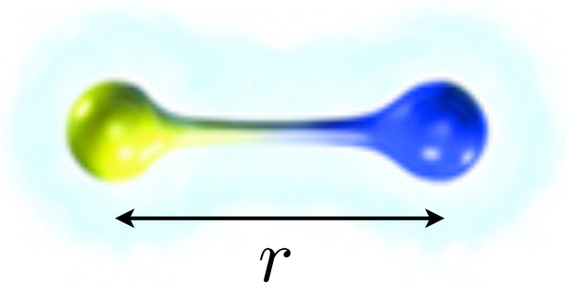
Gluons

Confinement

Free energy $F_{q\bar{q}}$ of a quark - antiquark pair

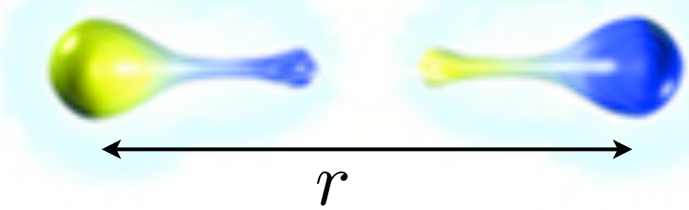


$$F_{q\bar{q}} \simeq -\frac{1}{r}$$

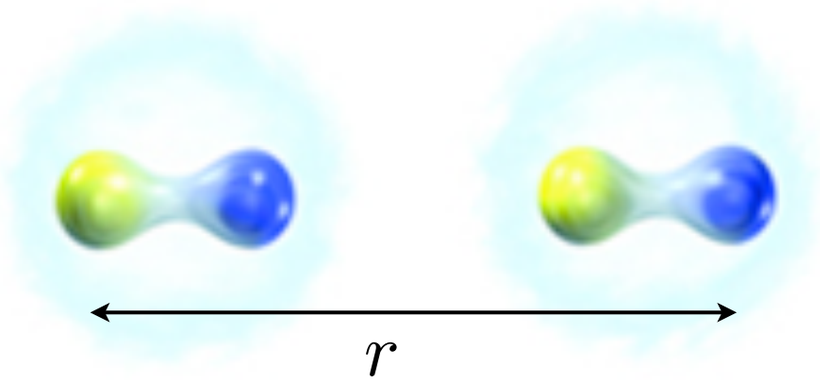


$$F_{q\bar{q}} \simeq \sigma r$$

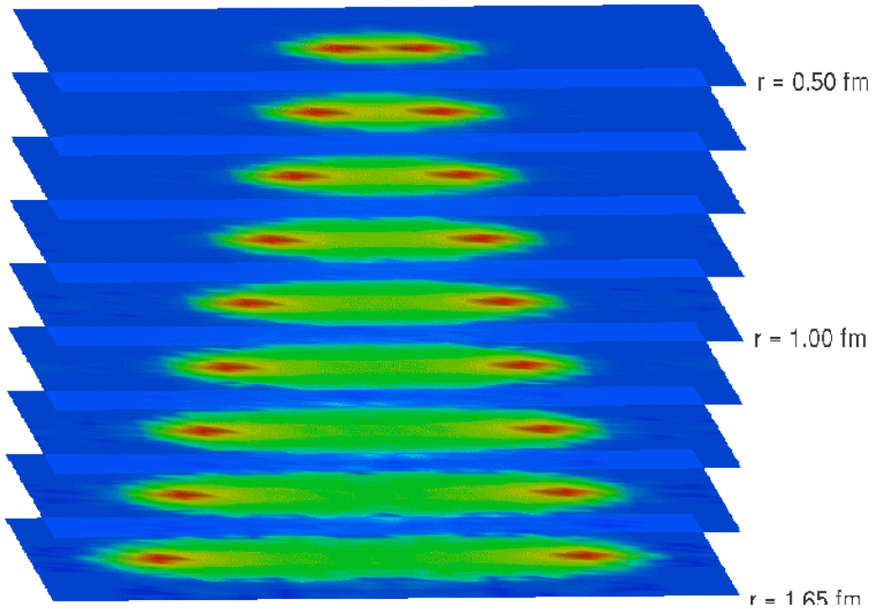
string breaking at $\mathrm{r} \approx 1\mathrm{fm}$



$$F_{q\bar{q}} \simeq \text{const.}$$

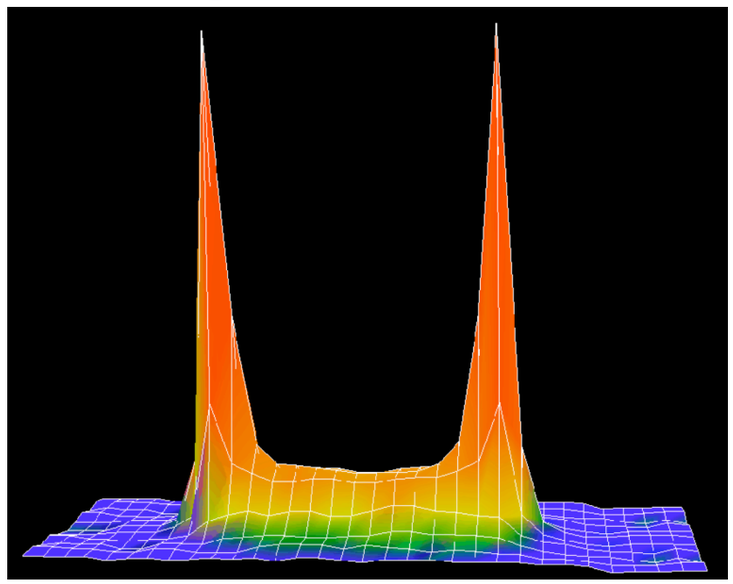


gauge theory



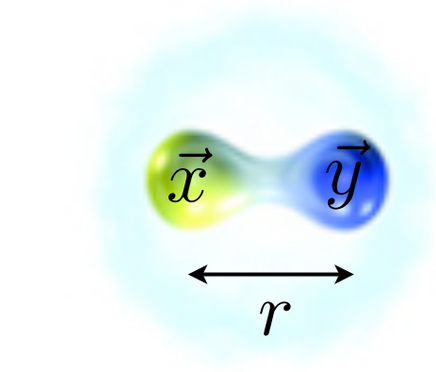
Energy density

Bali et al. '94

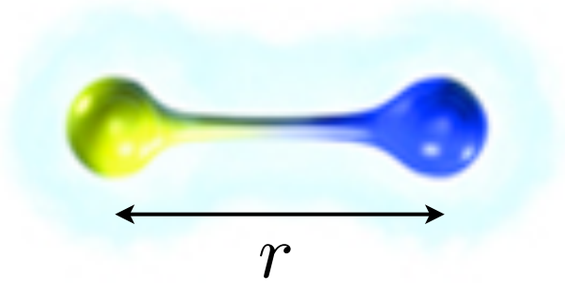


Confinement

Free energy $F_{q\bar{q}}$ of a quark - antiquark pair

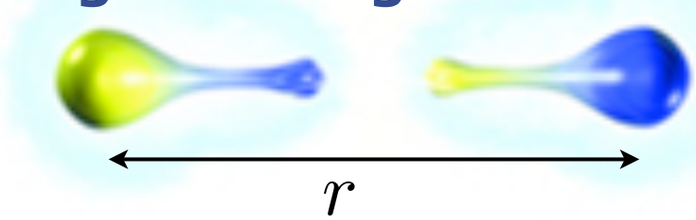


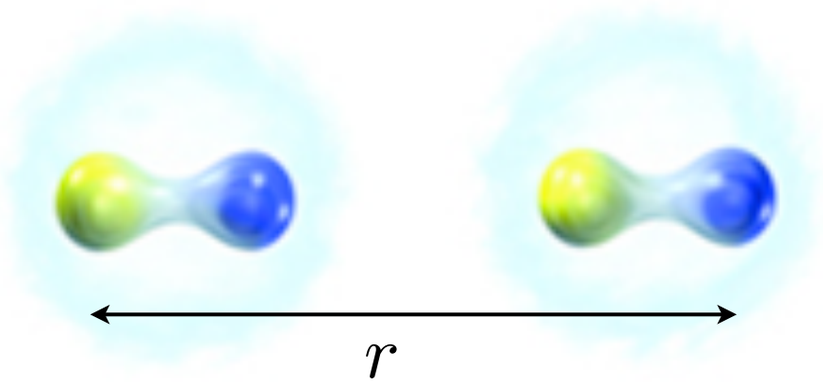
$$F_{q\bar{q}} \simeq -\frac{1}{r}$$



$$F_{q\bar{q}} \simeq \sigma r$$

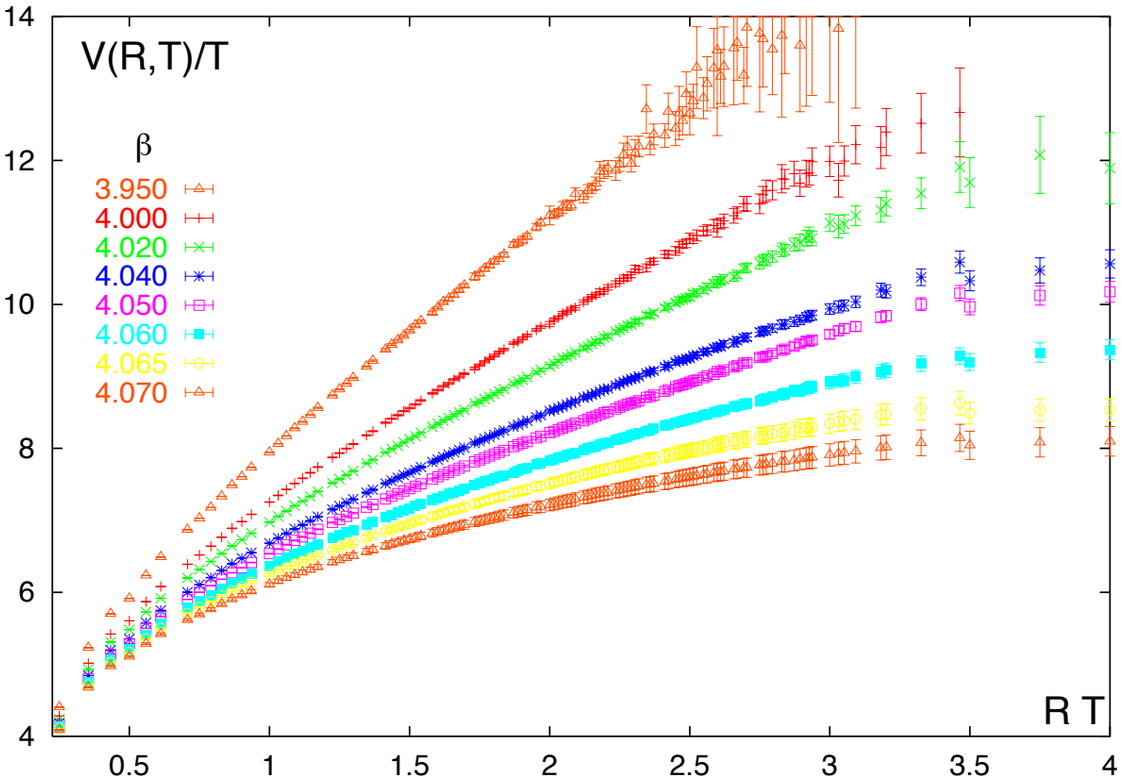
string breaking at $\mathrm{r} \approx 1\mathrm{fm}$





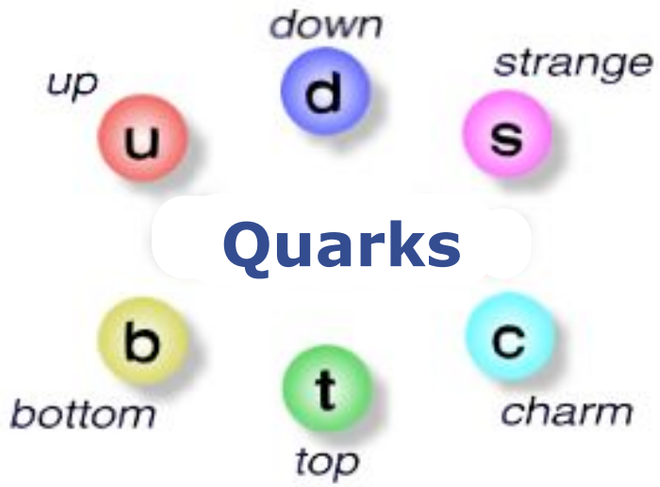
$$F_{q\bar{q}} \simeq \text{const.}$$

pure gauge theory



Kaczmarek et al '99

Chiral symmetry breaking $\Delta m_{\chi SB} \approx 400\,\mathrm{MeV}$



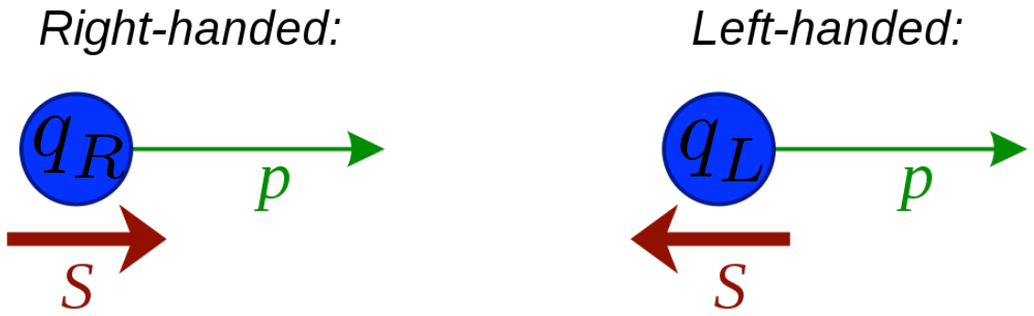
$\mathbf{N_f = 2 + 1}$

Generation	first	second	third	Charge
Mass [MeV]	1.5-4	1150-1350	170×10^3	
Quark	u	c	t	$\frac{2}{3}$
Quark	d	s	b	$-\frac{1}{3}$
Mass [MeV]	4-8	80-130	$(4.1\text{-}4.4)\times10^3$	

$\Lambda_{\mathrm{QCD}} = 217^{+25}_{-23}$ MeV

Chiral symmetry breaking

- **Chirality for massless particles**



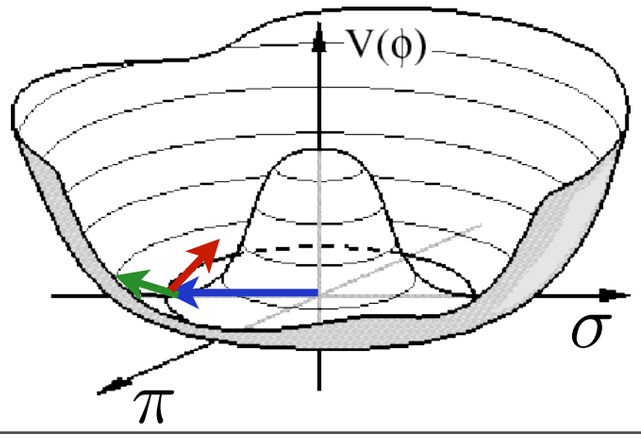
- **Order parameter**

$$\sigma = \langle \bar{q} q \rangle$$ **chiral condensate**

- **Chiral symmetry** $\sigma = 0$

- **Symmetry broken** $\sigma \neq 0$

- **Meson potential**



Chiral symmetry breaking

physical masses

chiral symmetry breaking: $\Delta m_{\chi SB} \approx 400\,\mathrm{MeV}$

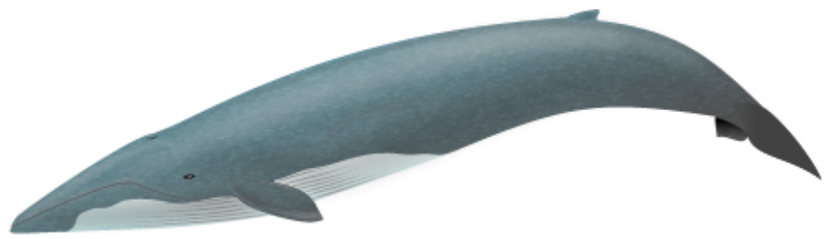
up

down

charm

strange

top



bottom

2 light flavours, one heavy flavour 2+1

Phase diagram of QCD

Temperature T

Quark-Gluon Plasma

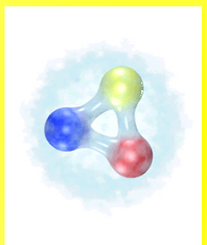
sQGP

Critical Point

Inhomogeneous $S\chi B$

Quarkyonic Matter

Hadronic Phase



Liquid-Gas

?

2SC

uSC
dSC
CFL

Color Superconductors

Nuclear Superfluid

CFL-K^0, Crystalline CSC
Meson supercurrent
Gluonic phase, Mixed phase

Baryon Chemical Potential μ_B

baryonic density

Fukushima