Probing the QCD phase diagram in heavy-ion collisions

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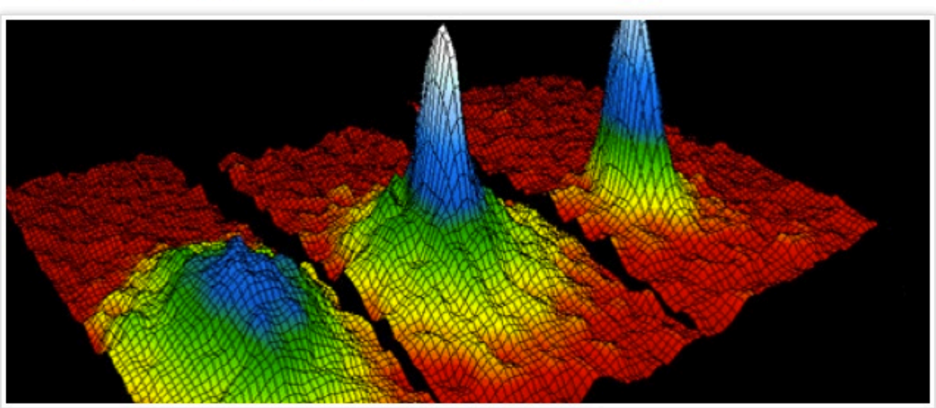
Forschungsschwerpunkte

Modelle und Simulation



FWF Der Wissenschaftsfonds.

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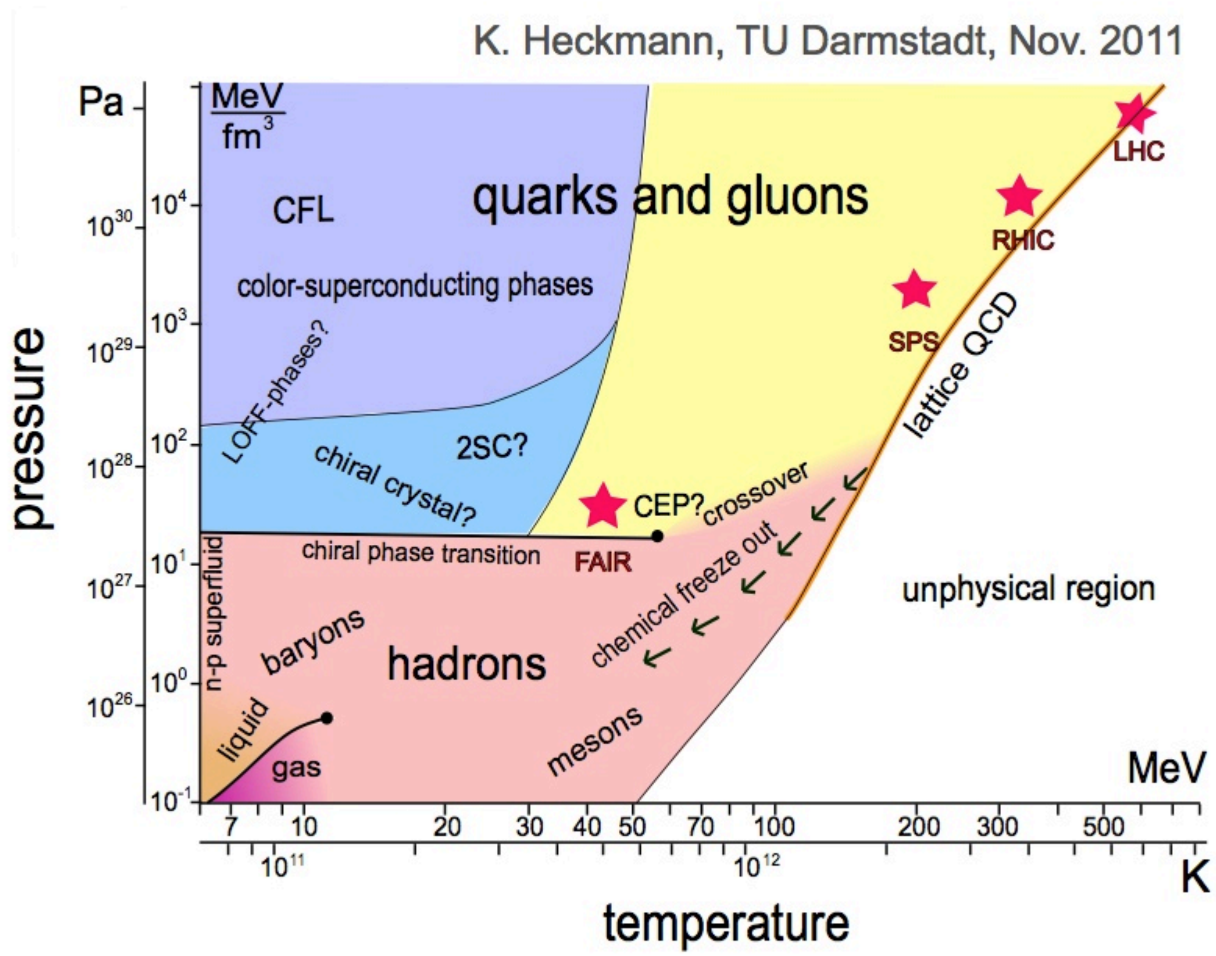
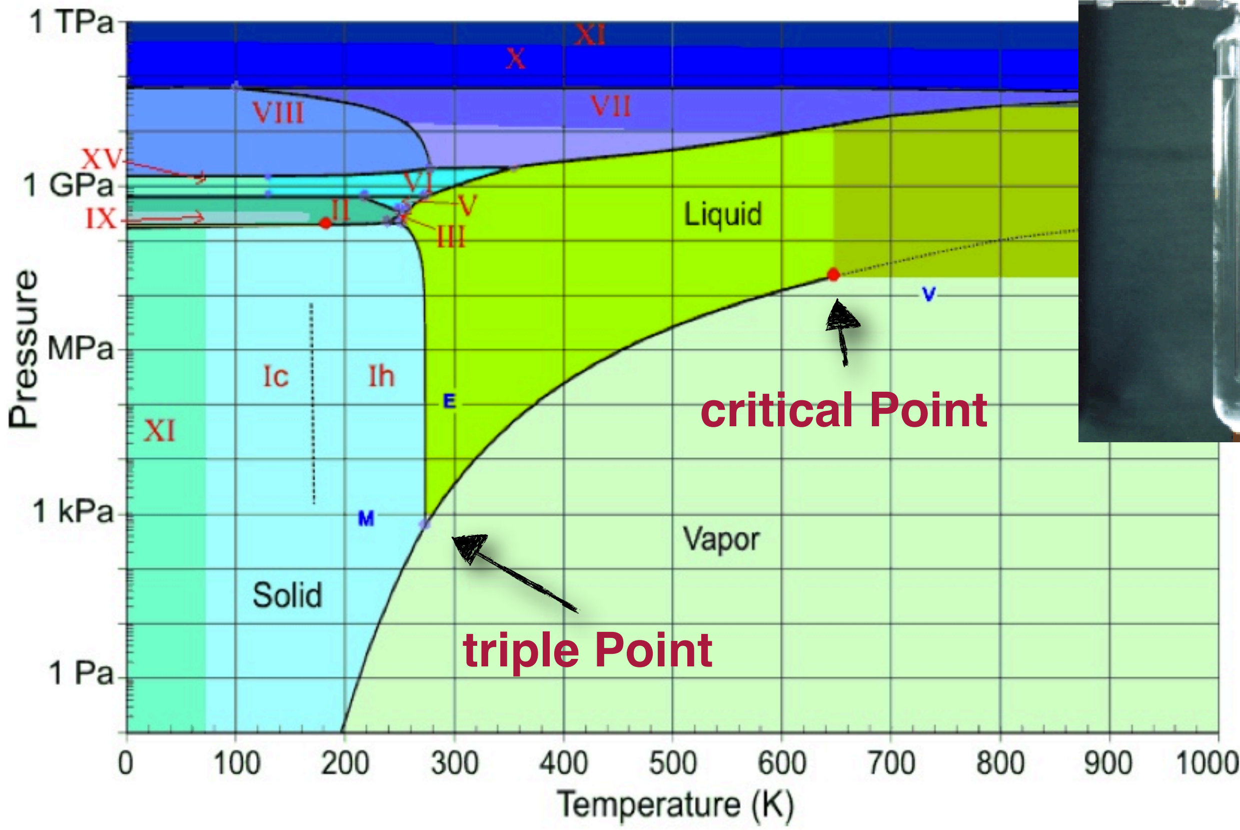
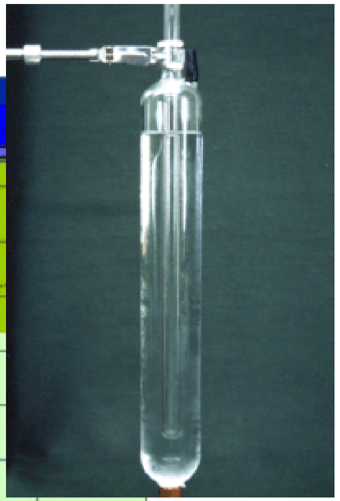
Phase diagrams

... of strongly-interacting matter



... of water





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Heavy-Ion Collision Experiments

Aim: create hot and dense QCD matter - elucidate its properties

QCD under extreme conditions is a very active field (July 2013)

- Goals of HIC Experiments: learn QCD matter Equation of State
- Understanding fundamental phenomena:
    - color confinement
    - nature of chiral and deconfinement transition
    - early Universe history
    - nuclear matter
    - properties of stars
    - ...

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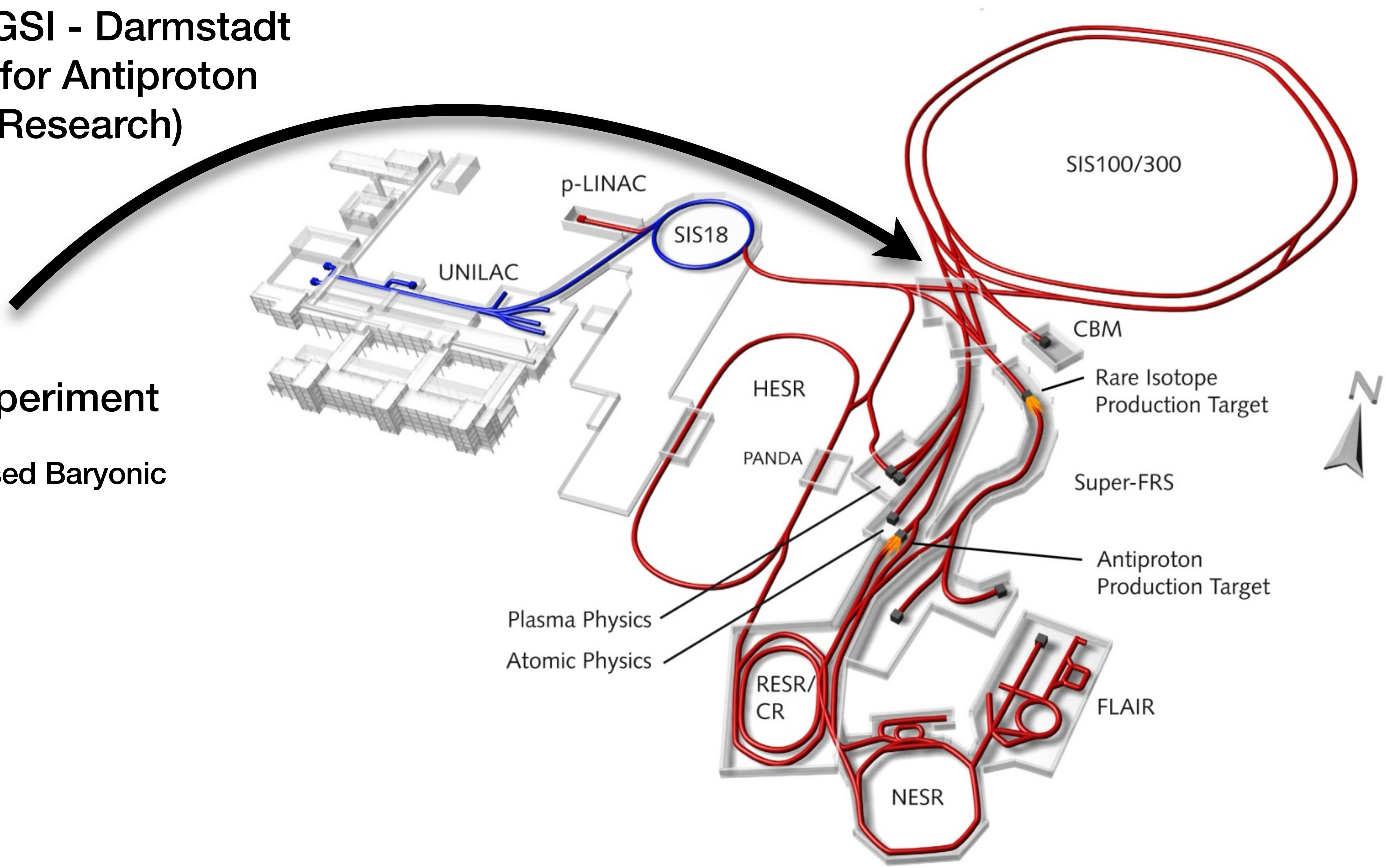
Heavy-Ion Collision Experiments

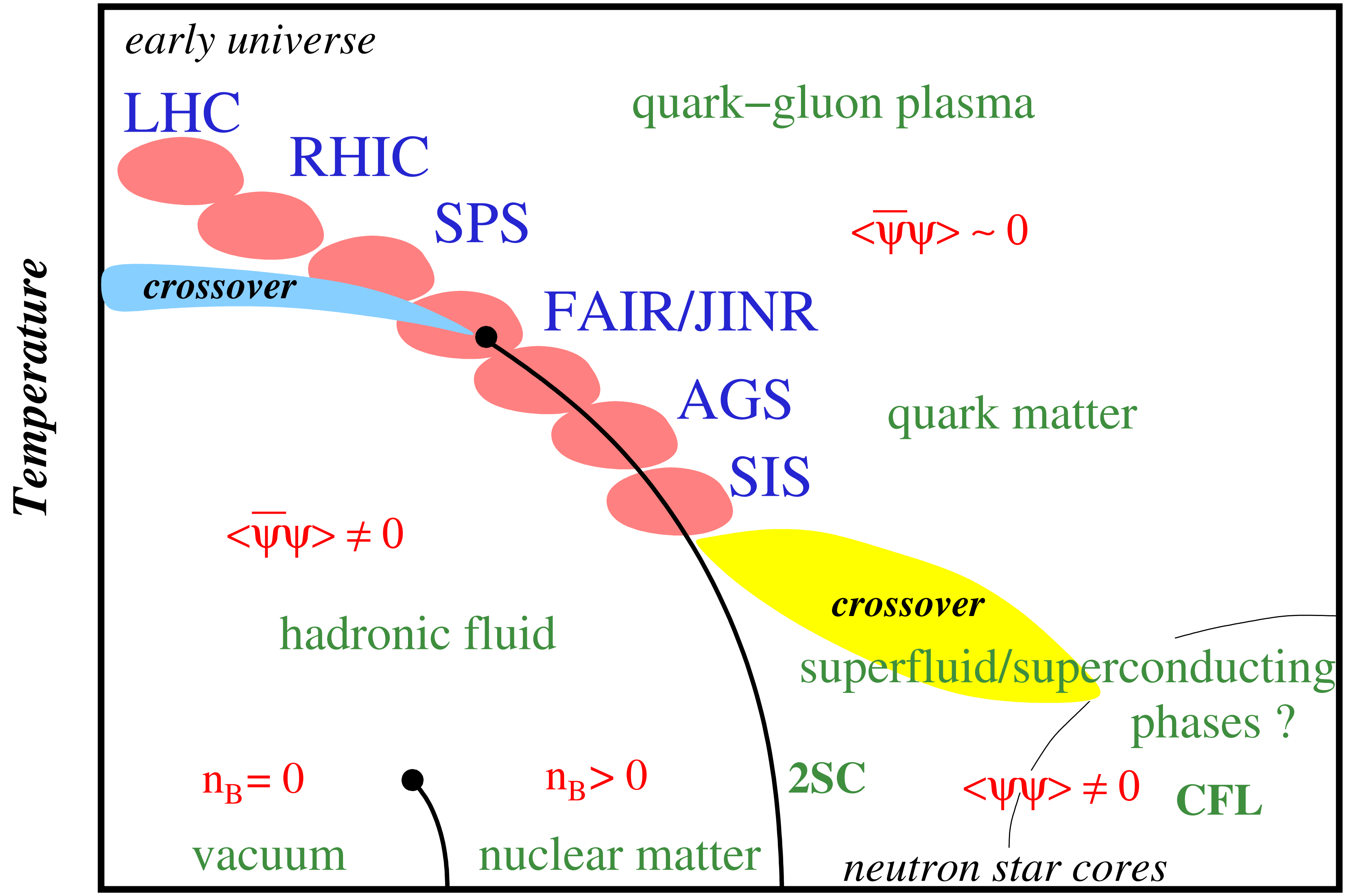
FAIR @ GSI - Darmstadt
(Facility for Antiproton
and Ion Research)

CBM experiment

(Compressed Baryonic
Matter)

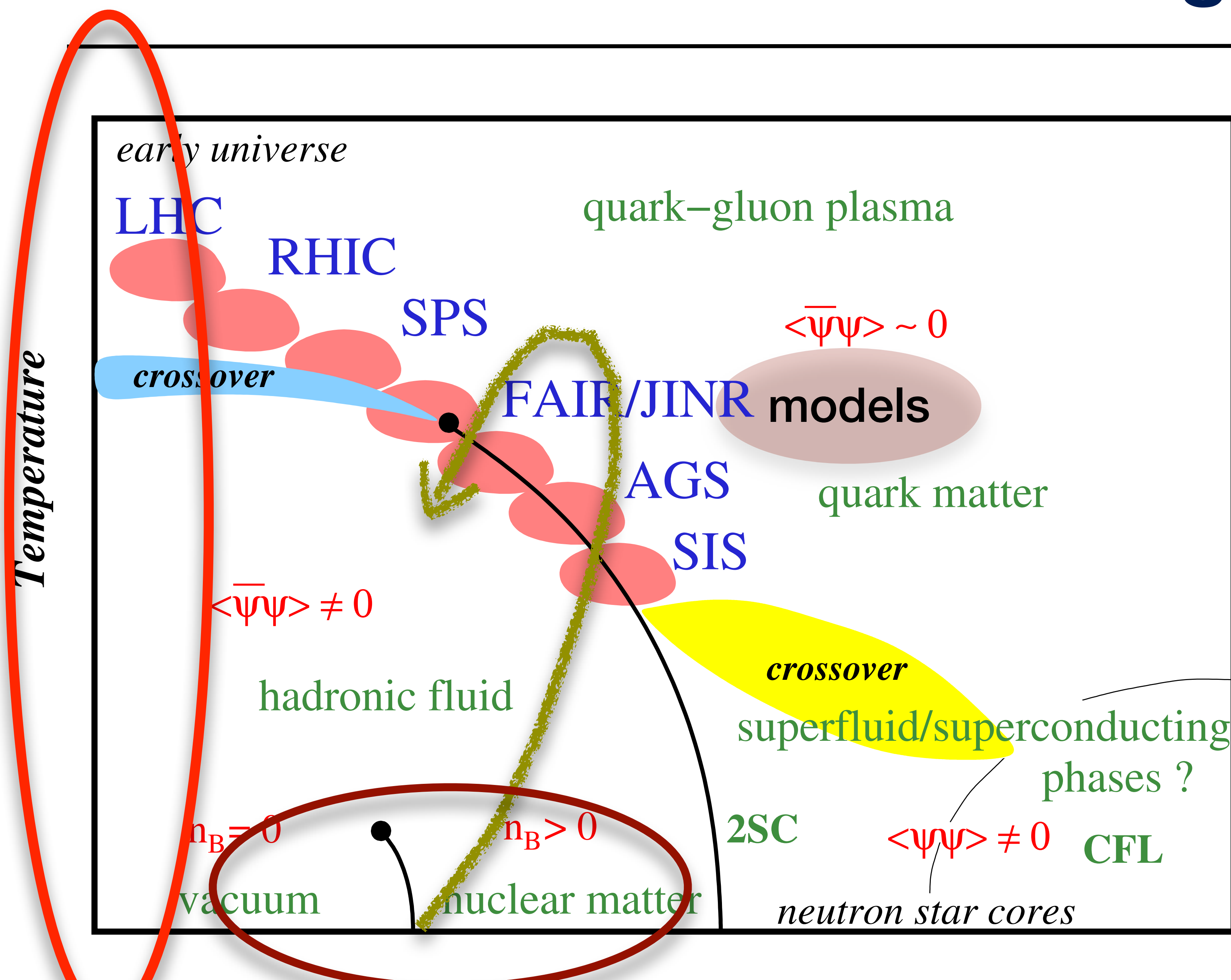


QCD Phase diagram



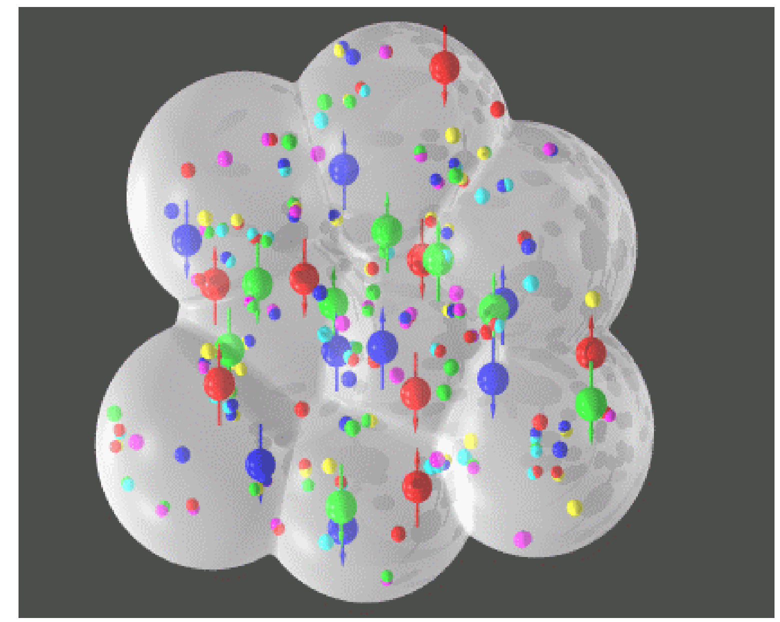
- Existence / location of critical point (CEP)
- details of phase transitions
- properties of quarks and gluons in plasma (QGP)

QCD Phase diagram

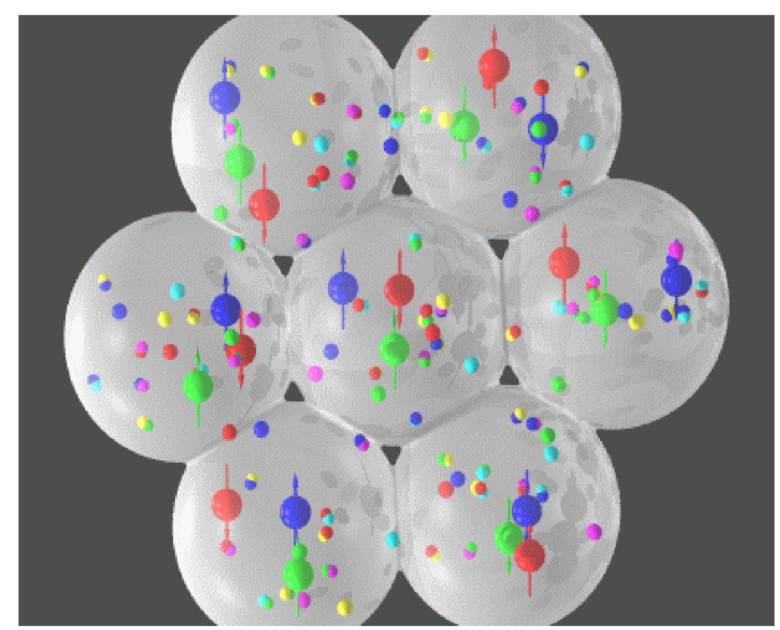


Lattice simulations

nuclear physics



plasma phase



nuclear matter

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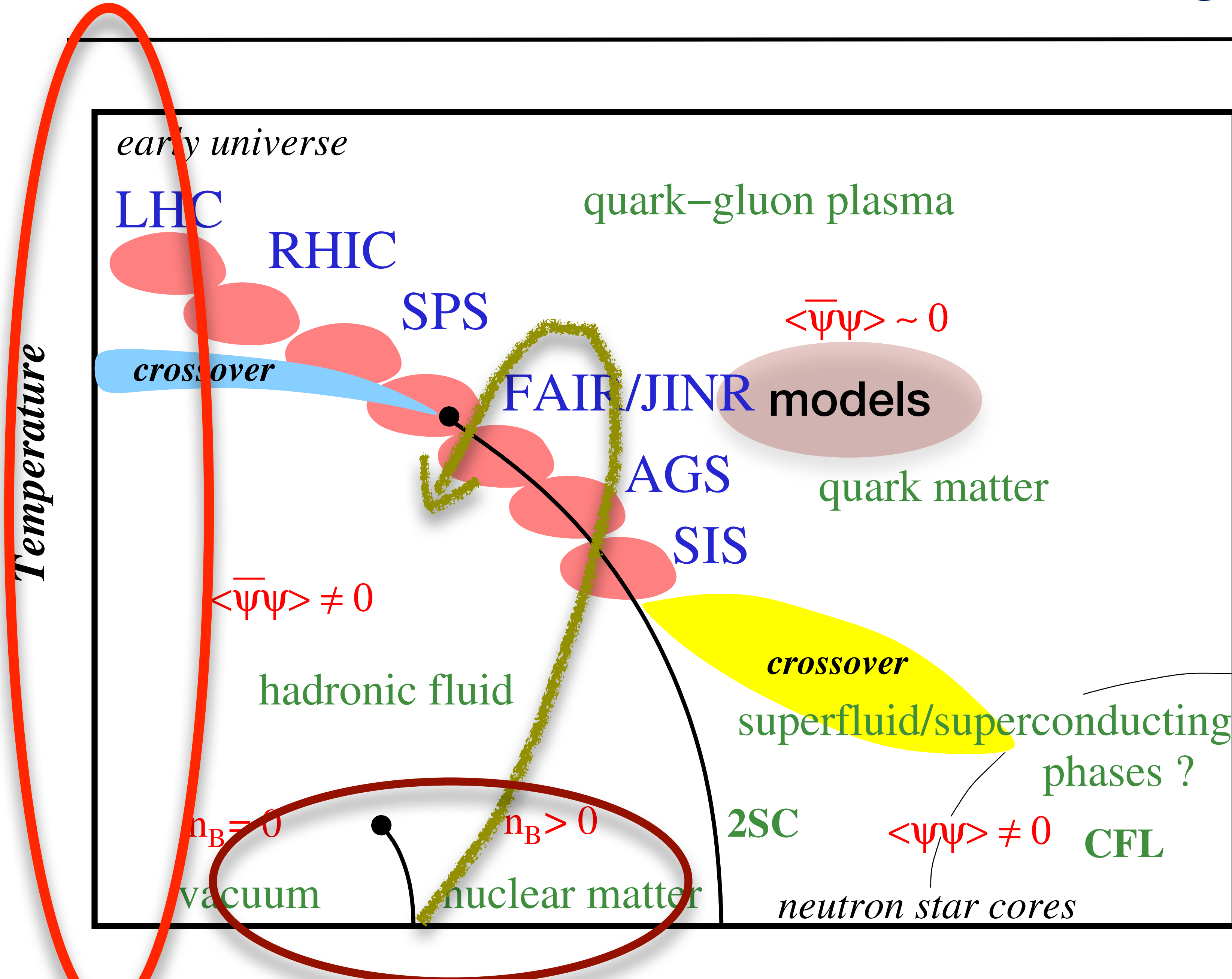
QCD Phase diagram



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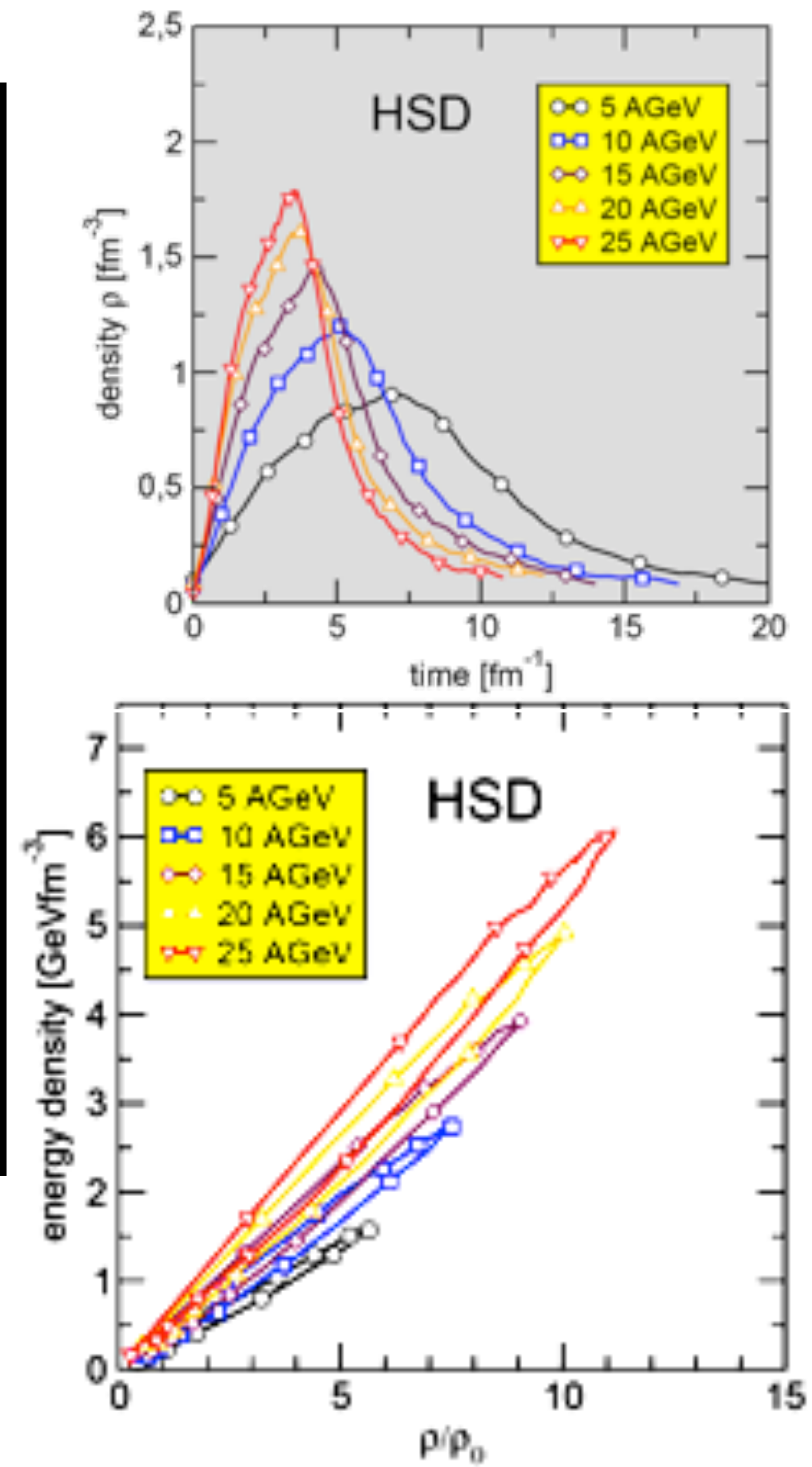

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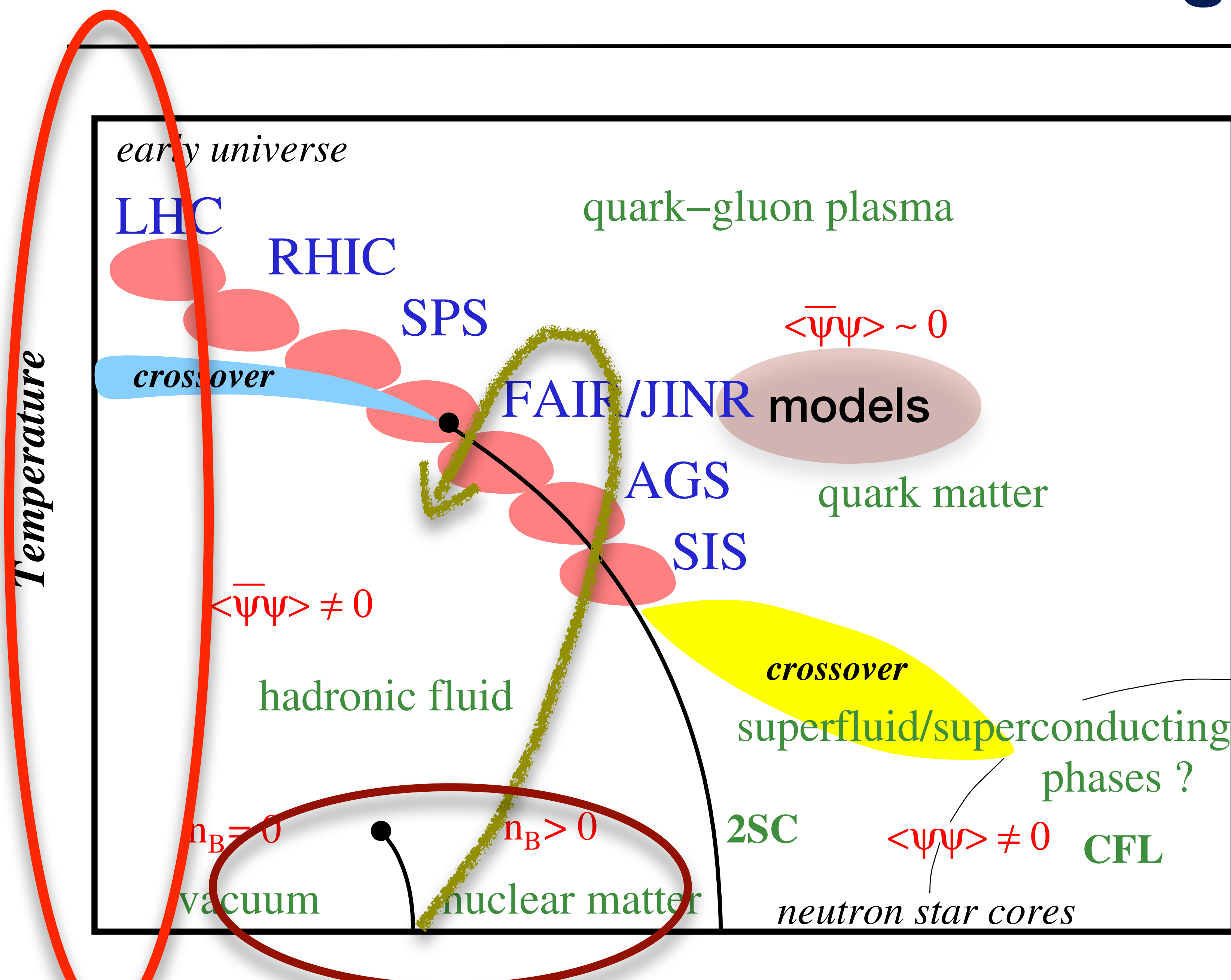

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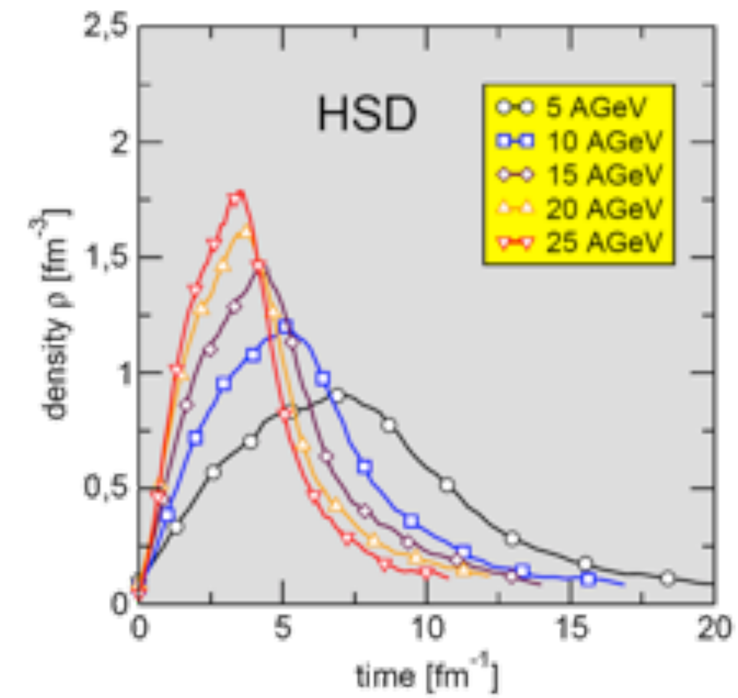

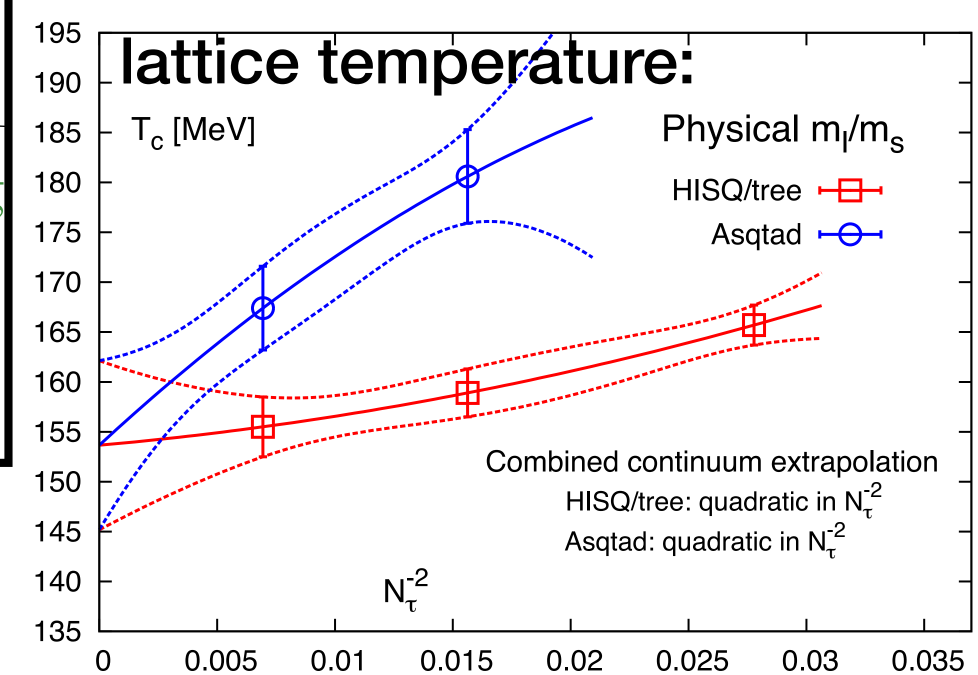

courtesy of F. Karsch

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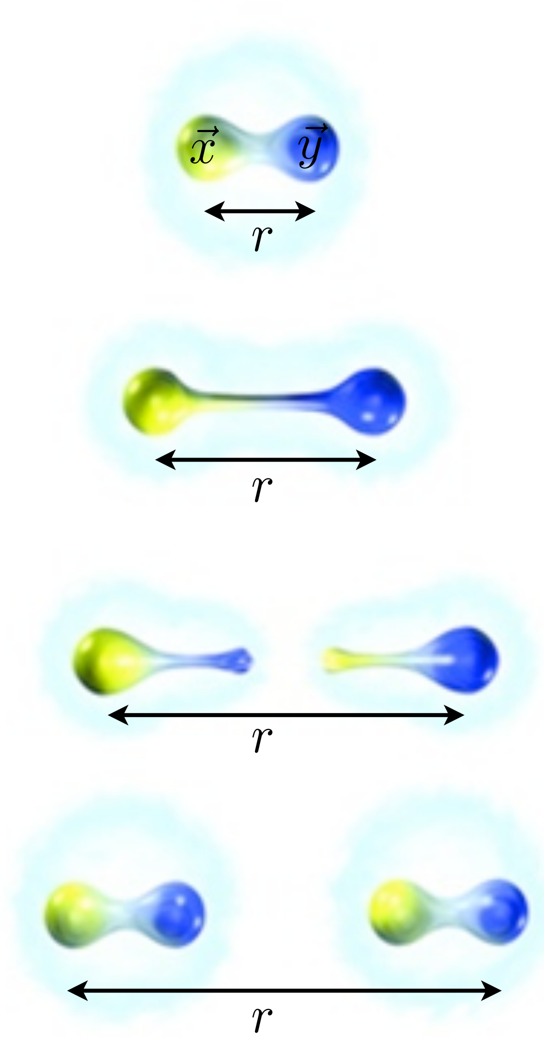
Confinement

Two important properties of low-energy QCD: **1. Confinement**

color confinement: not quarks are detected but baryons, mesons, etc...

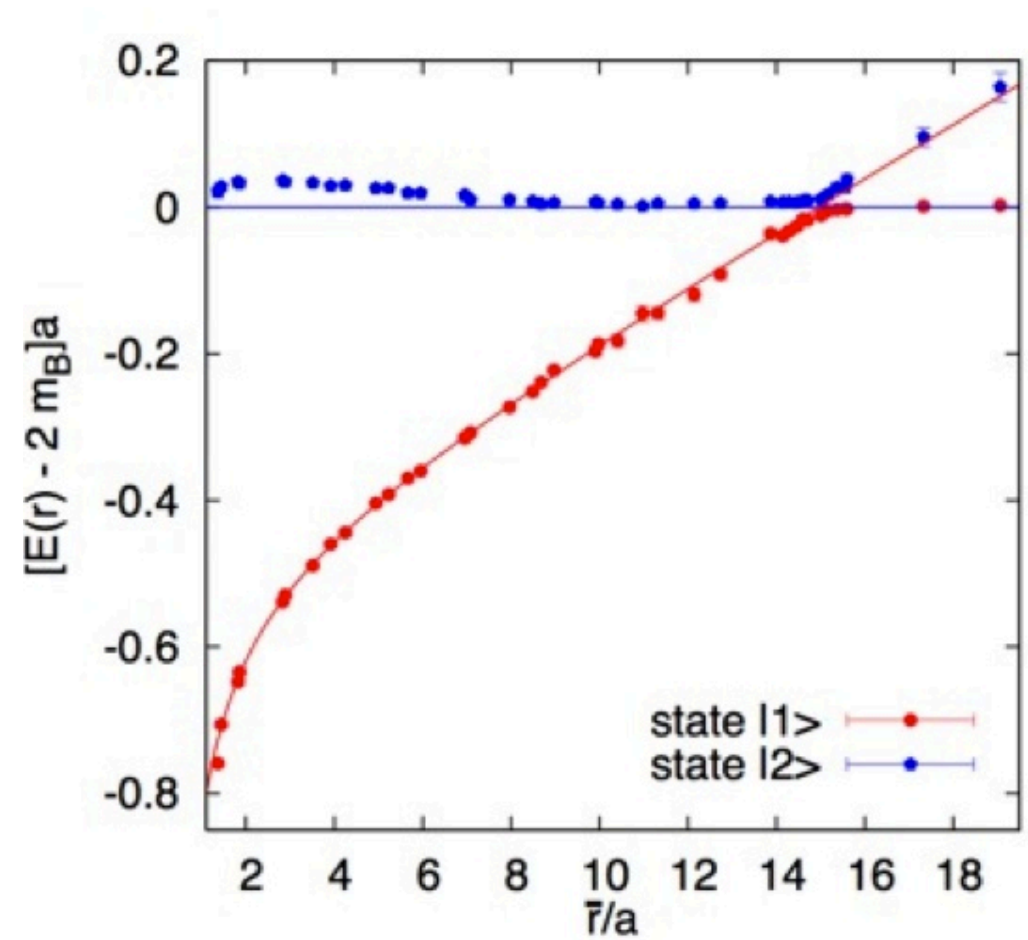
Yang-Mills theory with infinitely heavy test quarks: string tension



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

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

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



Bali et al. [SESAM Collaboration], PRD 71 (2005) 114513

QCD order parameters

1. quark confinement: Polyakov loop Φ (and $\bar{\Phi}$)

deconfinement transition in Euclidean spacetime

traced Polyakov loop: $l(\vec{x}) = \frac{1}{N_c} \mathrm{Tr}_c \mathcal{P} \exp \left\{ -ig \int_0^{\beta=1/T} dx_4 A_4(x_4, \vec{x}) \right\}$

under gauge transformation: $l \to z_k l$

Center symmetry

center of SU(N_c): Z_{N_c} elements of the center commute with all group elements

$$\longrightarrow \quad z_k = \exp(2\pi i k/N_c)\mathbf{1} \qquad k = 0, \ldots, N_c - 1$$

QCD order parameters

1. quark confinement: Polyakov loop Φ (and $\bar{\Phi}$)

deconfinement transition in Euclidean spacetime

- quark fields break center symmetry explicitly

➡ center symmetry exact only in pure gluonic theory (YM)

- expectation value of traced Polyakov loop:

$$\Phi = \langle l(\vec{x}) \rangle = \exp(-\beta F_q) \quad ; \quad \bar{\Phi} = \langle l^\dagger(\vec{x}) \rangle = \exp(-\beta F_{\bar{q}})$$

Free energy F_q of a static quark (similar for antiquark) in hot gluonic medium

QCD order parameters

1. quark confinement: Polyakov loop Φ (and $\bar{\Phi}$)

deconfinement transition in Euclidean spacetime

- in **confining** phase: free energy of single quark **diverges** ($F_q \to \infty$)

$$\Phi \to 0$$

- potential between a quark and antiquark increases linearly at long distances

  $(F_{\bar{q}q}(r \to \infty) \to \sigma r)$

  correlations **vanish**: $\langle l^\dagger(r \to \infty) l(0) \rangle \to 0$

- Expected behavior of **Polyakov loop in pure Yang-Mills**

Confined (disordered) phase

- free energy $F_q \to \infty$
- Polyakov loop $\Phi = 0$
- correlations:

$$\langle l^\dagger(r \to \infty) l(0) \rangle \to 0$$

Deconfined (ordered) phase

- free energy $F_q < \infty$
- Polyakov loop $\Phi \neq 0$
- correlations:

$$\langle l^\dagger(r \to \infty) l(0) \rangle \to |\langle l \rangle|^2 \neq 0$$

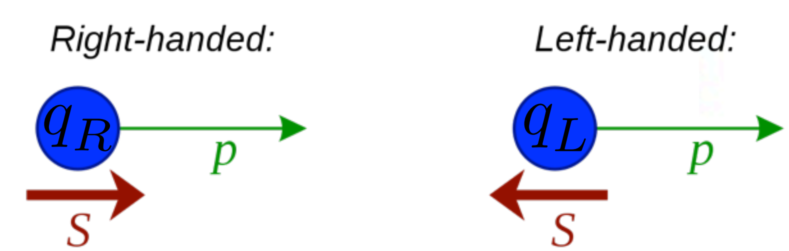
QCD order parameters

2. chiral symmetry breaking: chiral condensate $\langle\bar{q}q\rangle$

- chiral symmetry in vacuum **spontaneously** broken (this is the source of hadron masses)
- classical QCD symmetry: $SU(N_f)_L \times SU(N_f)_R \times U(1)_B \times U(1)_A$ in **chiral limit**
- spontaneous chiral symmetry breaking

$$SU(N_f)_{L+R\equiv V} \times U(1)_B$$

$\to N_f^2 - 1$ massless Nambu-Goldstone bosons ($N_f > 1$)



- chiral condensate

$$\langle\bar{q}q\rangle = \langle\bar{q}_R q_L + \bar{q}_L q_R\rangle \qquad q_{R/L} = \frac{1}{2}(1 \pm \gamma_5)q$$ right/left projected fields

- Expected behavior of **chiral condensate**

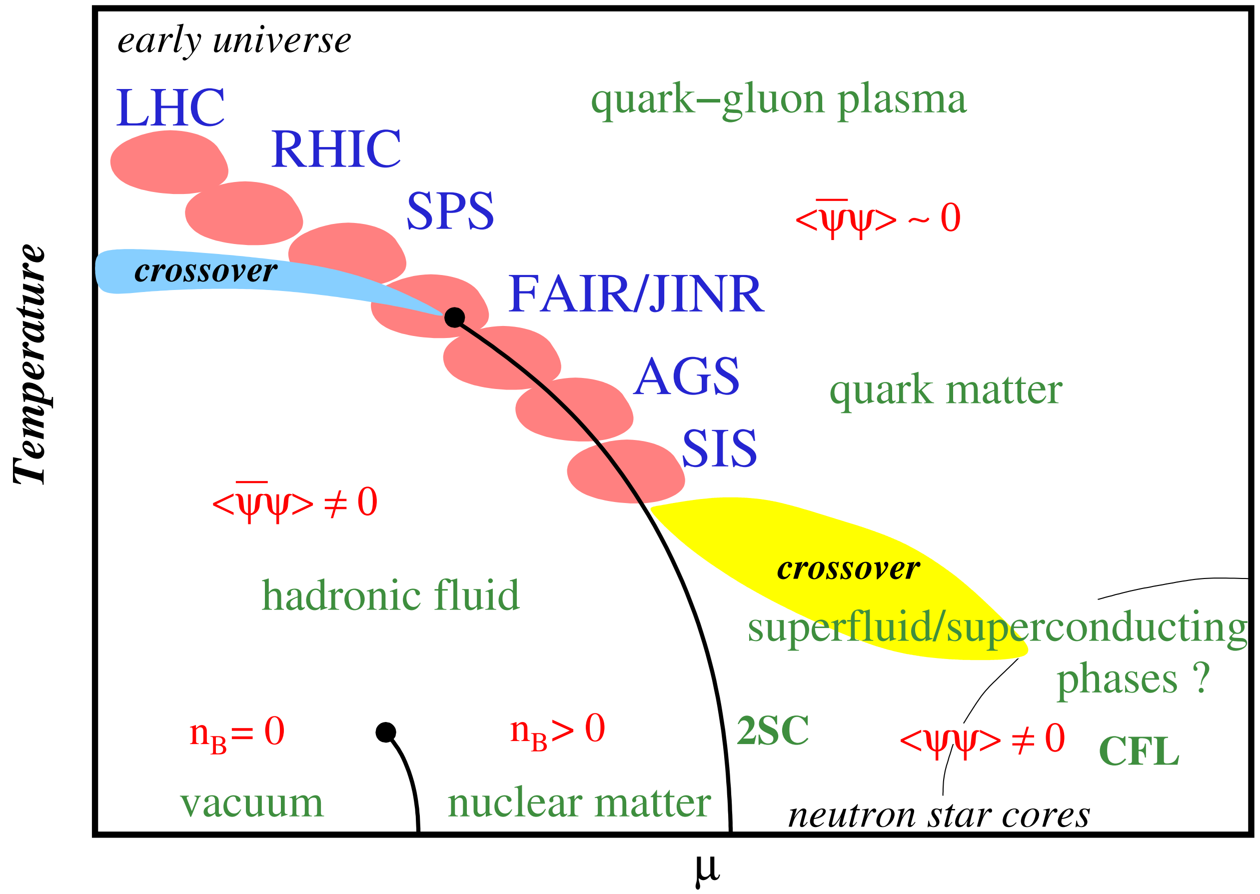
Broken (ordered) phase

- condensate $\langle\bar{q}q\rangle \neq 0$

Symmetric (disordered) phase

- condensate $\langle\bar{q}q\rangle \neq 0$

Conjectured QC_3D phase diagram



at densities/temperatures of interest
only model calculations available

➜ can one improve the model calculations?

➜ remove model parameter dependency

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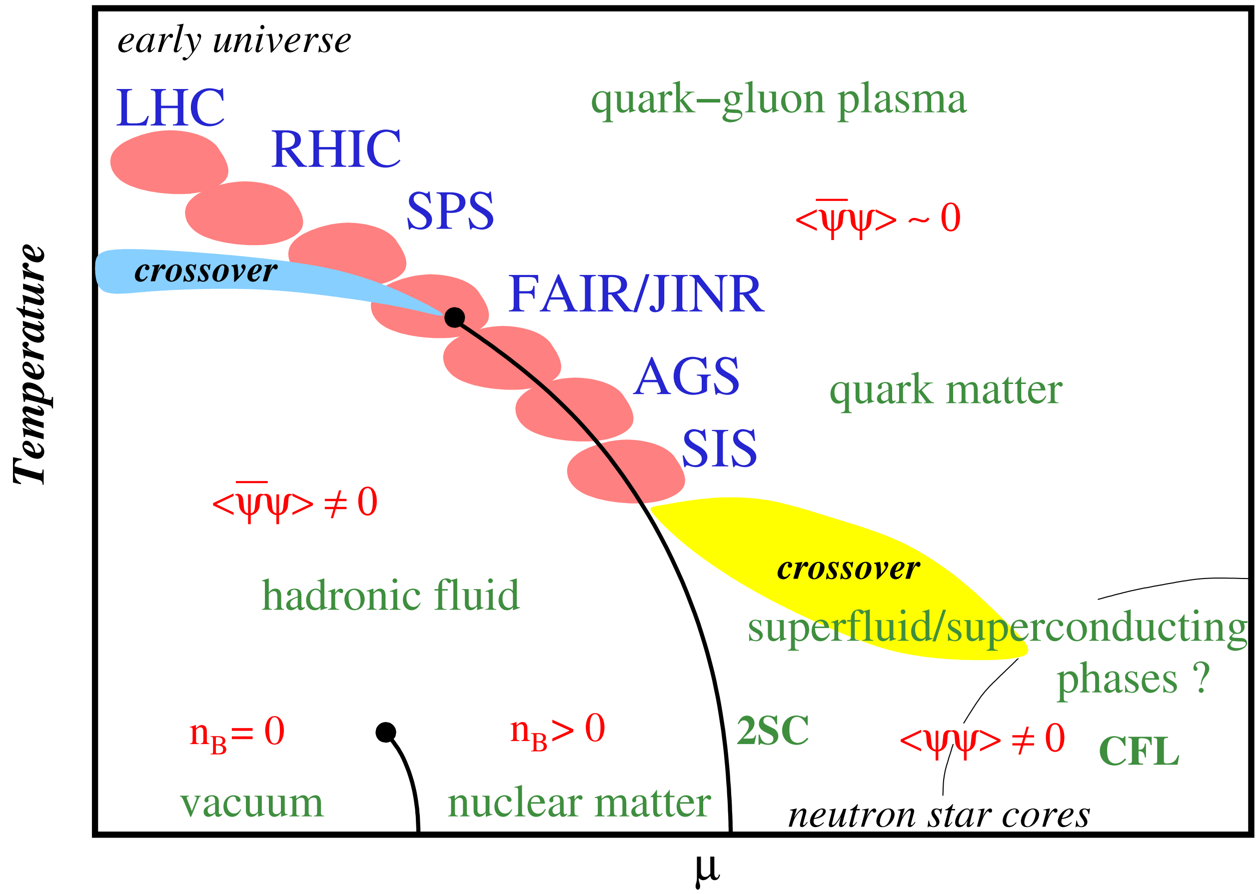
Conjectured QC$_3$D phase diagram



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Theoretical questions:

related to chiral & deconfinement transition

- **CEP:** existence/location/number
- **Quarkyonic phase:** coincidence of both transitions at $\mu = 0$ & $\mu > 0$?
- relation between chiral & deconfinement?
  chiral CEP/deconfinement CEP?
- **finite volume effects?**
  ➜ lattice comparison
- **role of fluctuations?** so far mostly mean-field results **effects of fluctuations are important**

  e.g. size of critical region around CEP
- **What are good experimental signatures?**

  ➜ higher moments more sensitive to criticality
  deviation from HRG model for

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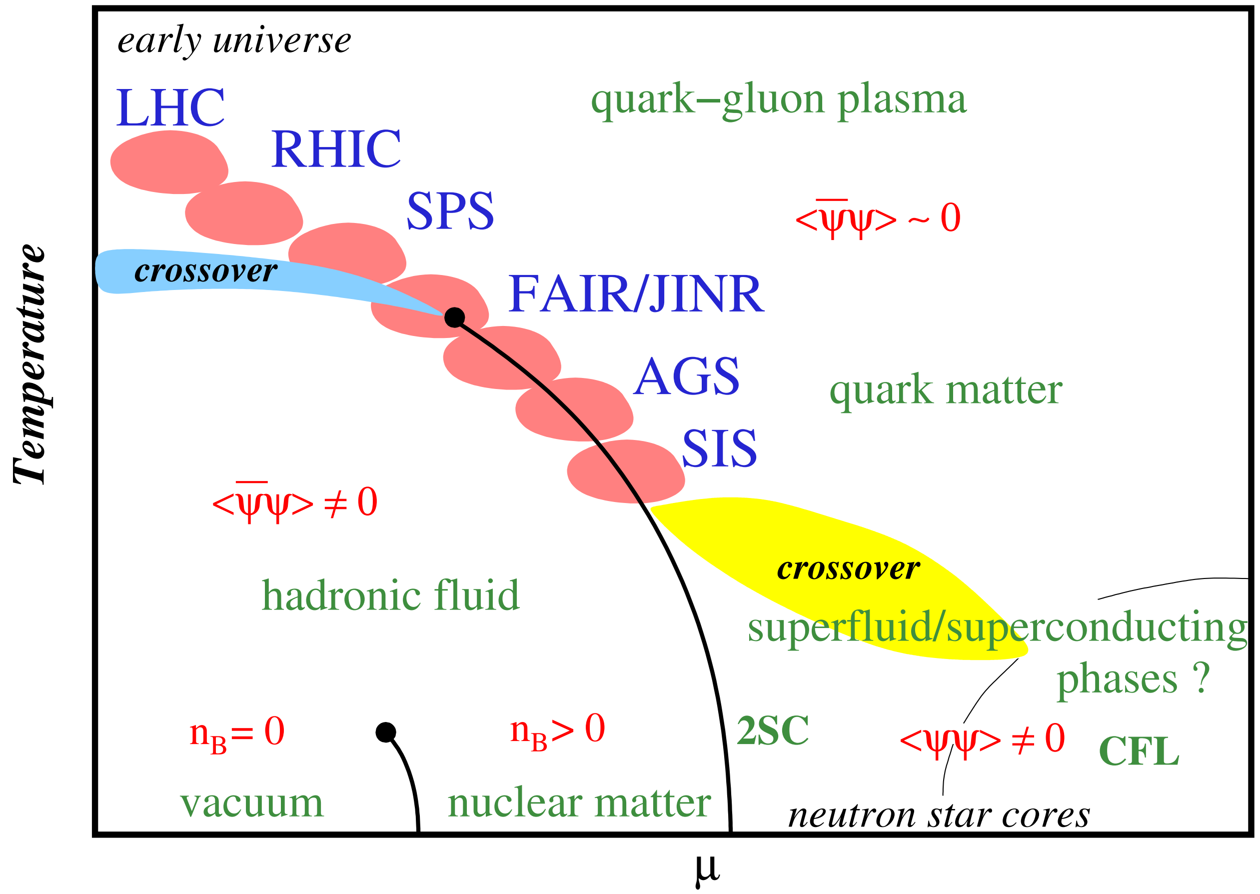

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  e.g. size of critical region around CEP
- **What are good experimental signatures?**

  ➜ higher moments more sensitive to criticality deviation from HRG model for

<u>non-perturbative continuum functional methods</u>

➜ complementary to lattice

⇒ no sign problem μ>0 ⇒ chiral symmetry/fermions/small masses/chiral limit

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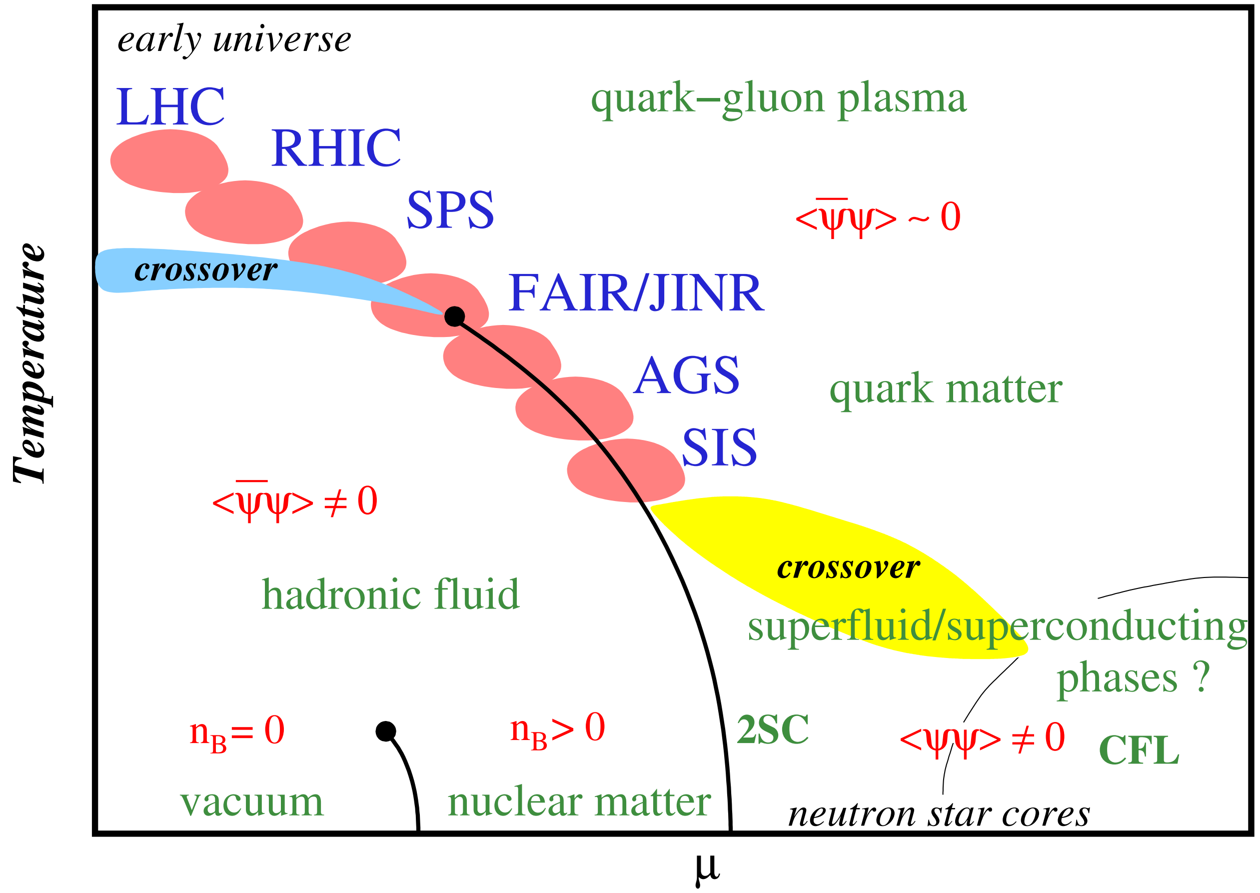
Conjectured QC$_3$D phase diagram



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Method of choice: **Functional Renormalization Group (FRG)**

e.g. (Polyakov)-quark-meson model truncation

- good description for chiral sector
- implementation of gauge dynamics (deconfinement sector)

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Agenda

- QCD-like model studies

  chiral and deconfinement aspects

  two and three flavor

- Mean-field approximation vs. Renormalization Group methods

- role of baryons - two color QCD

Polyakov-Quark-Meson (PQM) Model

Chiral effective model:

- quarks: ψ
- mesons: σ, $\vec{\pi}$
- gauge fields: A_μ^a in $D_\mu = \partial_\mu + iA_\mu \to$ Polyakov-loop (PQM) model

PQM Lagrangian: [BJS, J. Pawlowski, J. Wambach 2007]

$$\begin{aligned} \mathcal{L}_{\mathrm{PQM}} &= \bar{\psi}\left(\not{D} + g(\sigma + i\gamma^5 \vec{\pi}\vec{\tau}) - \mu\gamma^0\right)\psi \\ &+ \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \vec{\pi})^2 + V(\vec{\phi}) \end{aligned}$$

Mean-Field Approximations (MFA)

Integration of quarks, neglect bosonic fluctuations

Grand potential

$$\Omega(T,\mu;\sigma) = \Omega_{\rm vac} + \Omega_{\rm T} + V_{\rm MF}(\sigma) \qquad (+\mathcal{U}_{\rm Poly}(\Phi)\ )$$

vacuum term: sharp three-momentum cutoff

$$\Omega_{\rm vac}(\Lambda) = -4\int^{\Lambda}\frac{d^3p}{(2\pi)^3}\sqrt{\vec{p}^2+m_q^2}$$

for each cutoff: adjust model parameters like f_π, m_σ, m_π

standard MFA: no-sea term $\Lambda = 0$

Chiral transition

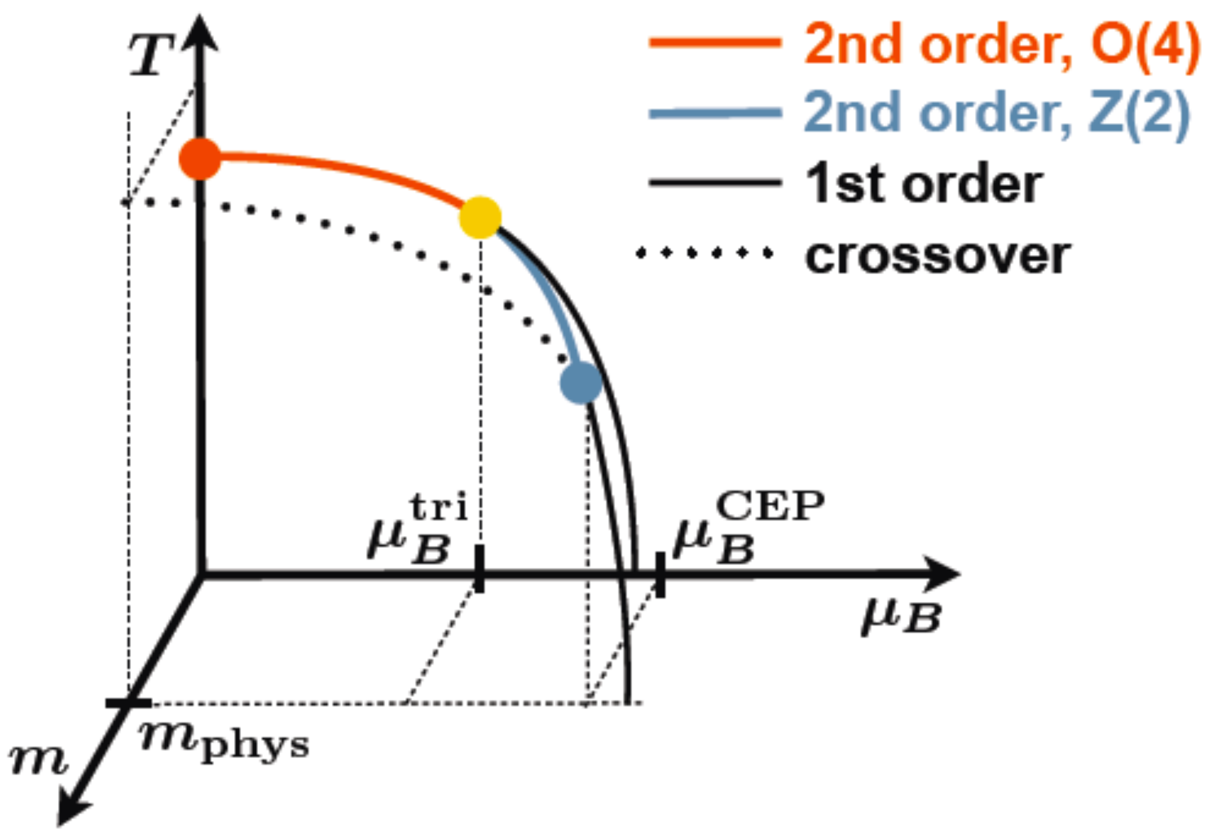
Fluctuations of oder parameter $\to \infty$ at 2nd order transition

critical fluctuations ➜ phase boundary?

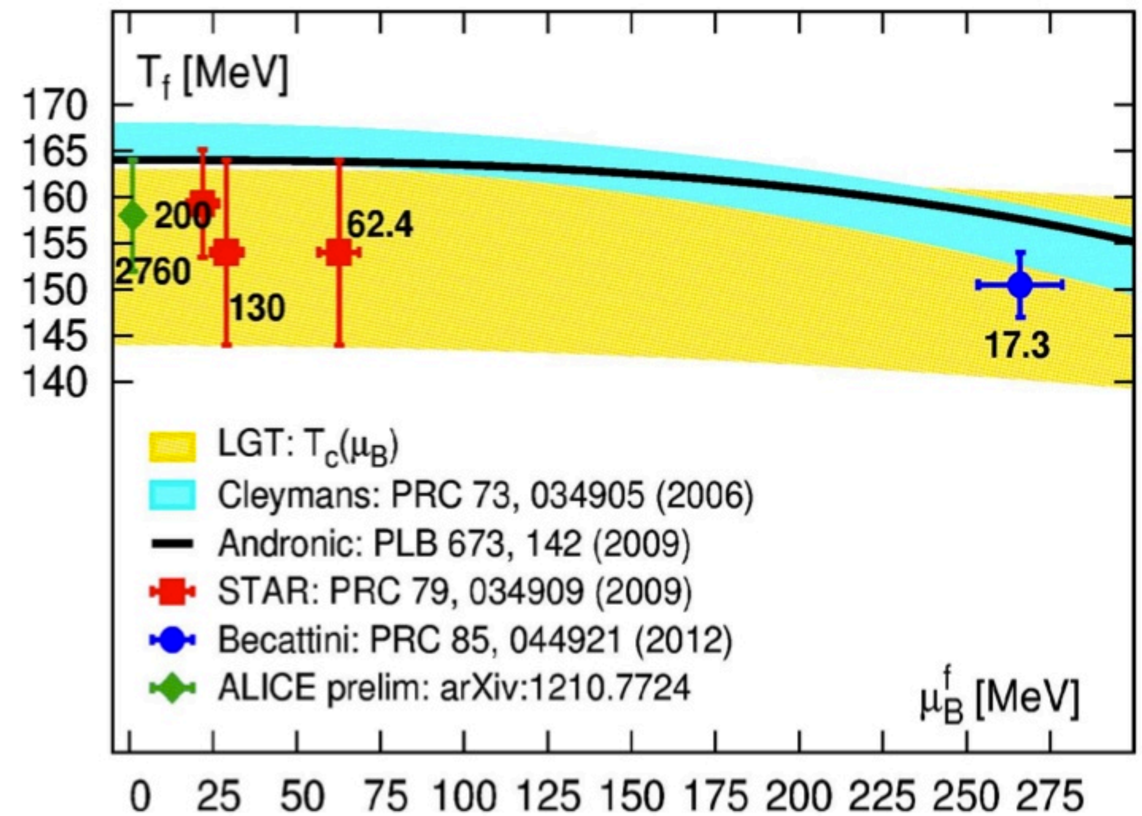
How can we probe a transition?

- singular behaviour in $\frac{\partial^n p(X)}{\partial X^n}$ with $X = T, \mu, \ldots$
- higher order cumulants $c_n \equiv \frac{\partial^n p(T,\mu)}{\partial(\mu/T)^n}$

. . . more sensitive to criticality



freeze-out close to chiral crossover line



[HotQCD, QM 2012]

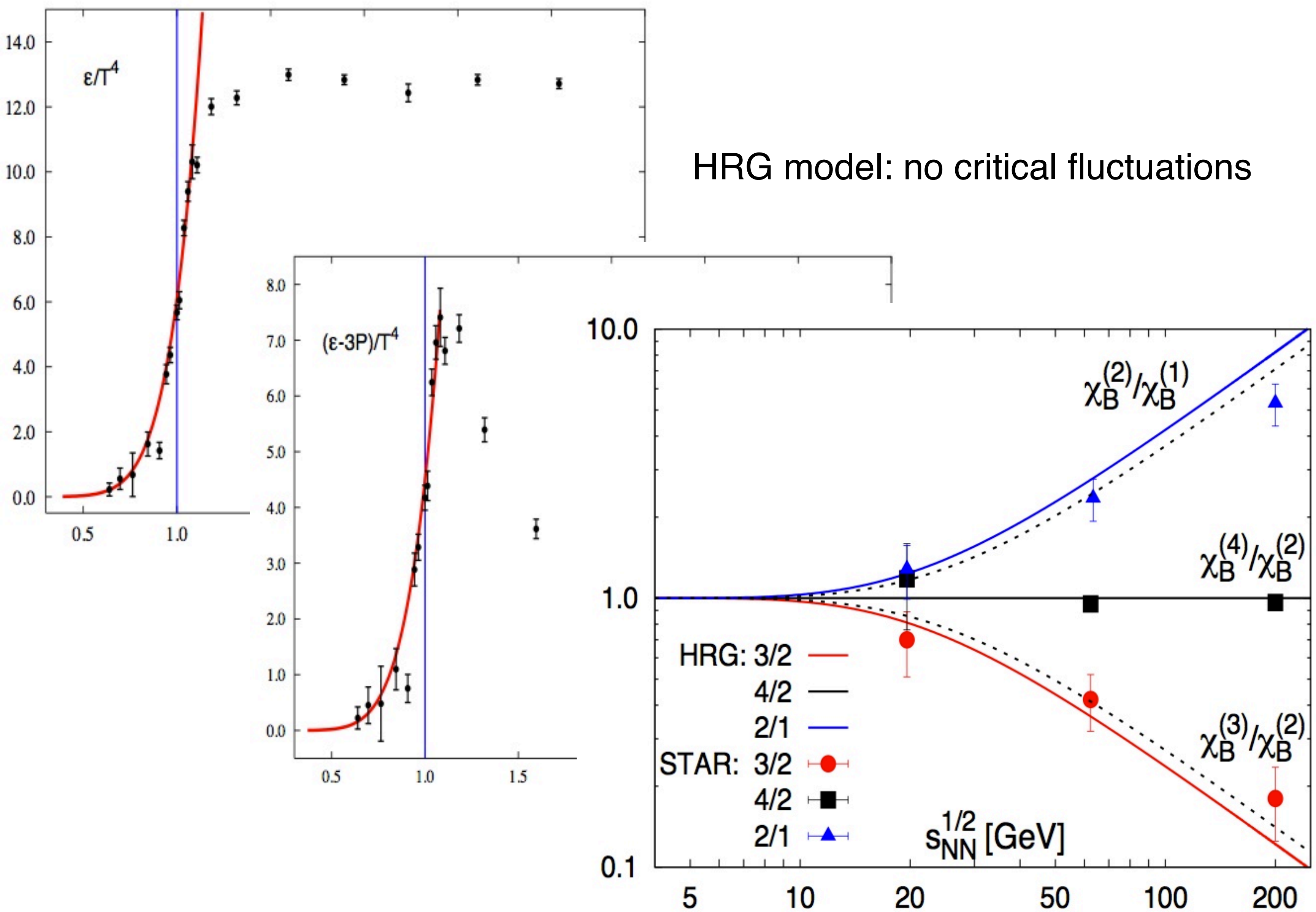
Hadron Resonance Gas (HRG) Model

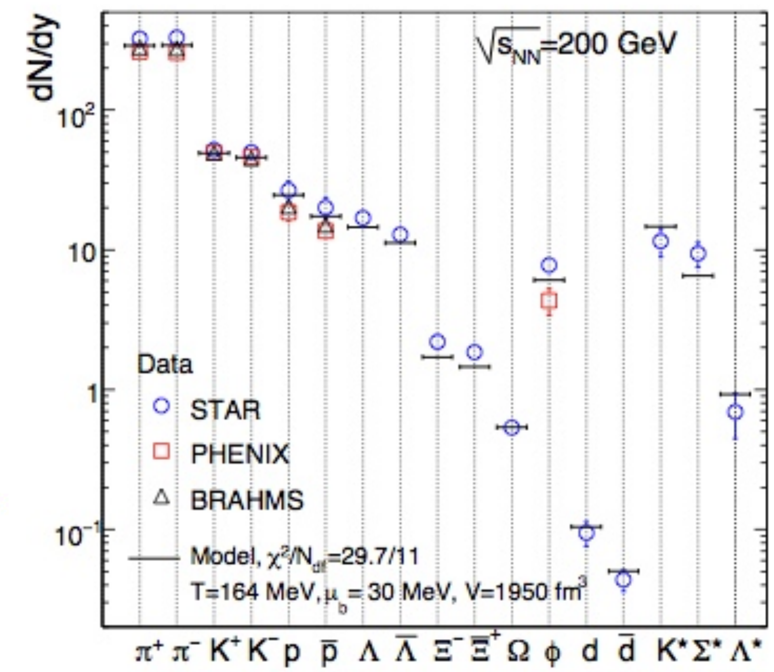
HRG model: good lattice data description

HRG model versus experiment

[Andronic et al. 2011]

HRG model: no critical fluctuations





[Karsch, Redlich 2010]

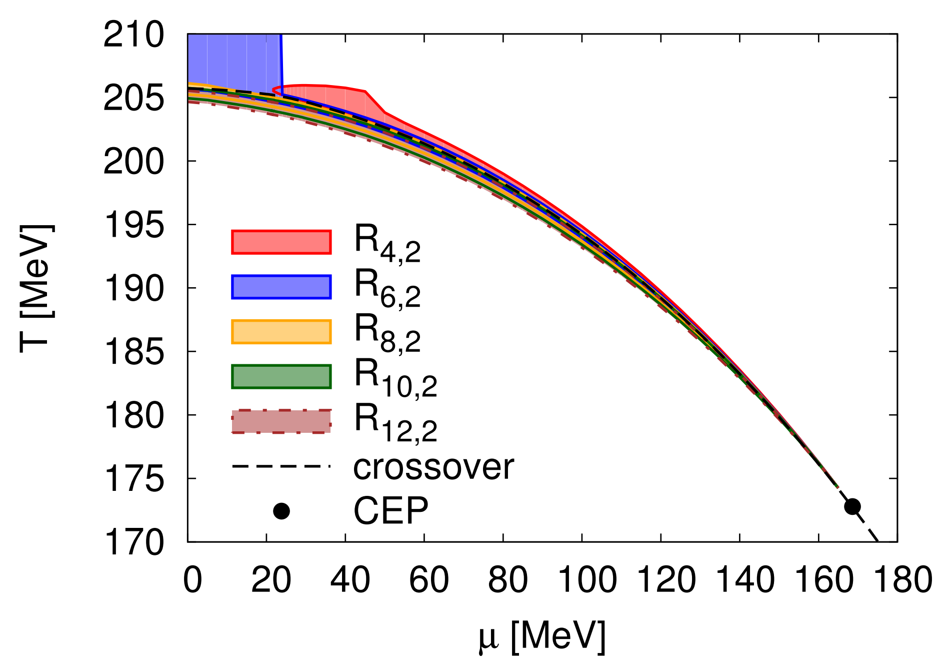
Role of vacuum term in (P)QM models

Fluctuations of higher moments exhibit **strong variation from HRG model**

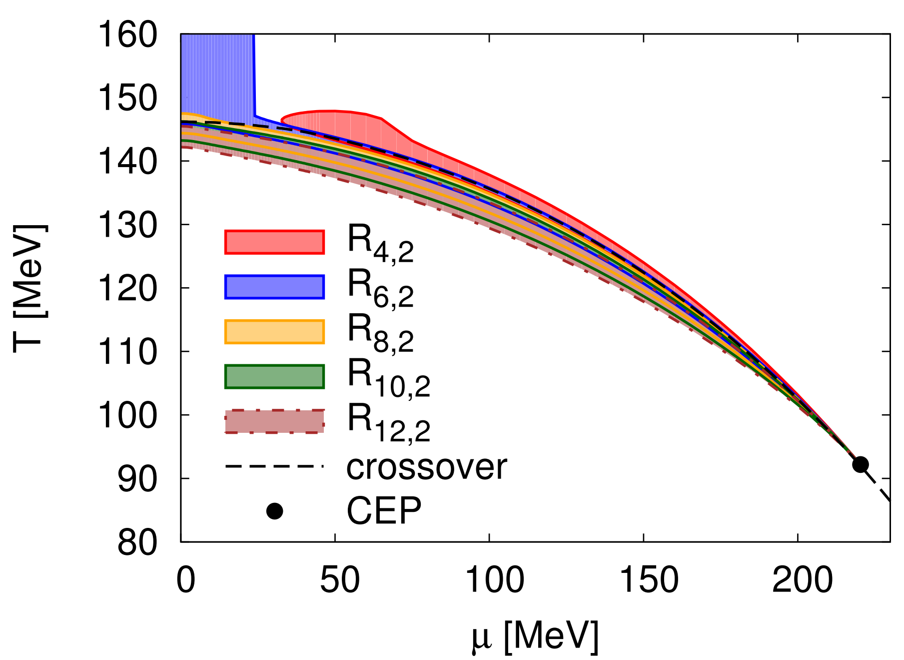
[Karsch, Redlich, Friman, Koch et al. 2011]

- $\rightarrow$ turn negative
- higher moments: $R^q_{n,m} = c_n/c_m$
- regions where $R_{n,2} < 0$ along crossover in the phase diagram

unquenched PQM MFA



QM MFA w/o vacuum



role of vacuum term in (P)QM models see [BJS, M. Wagner 2012]

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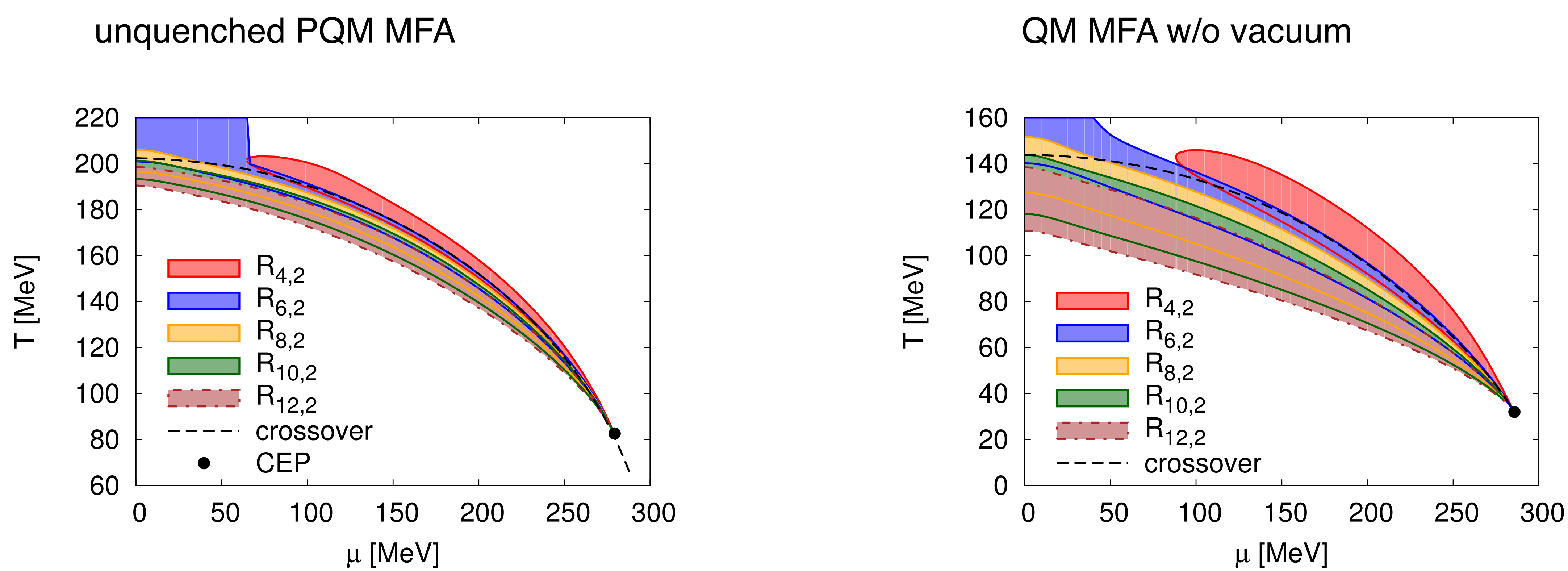


role of vacuum term in (P)QM models see [BJS, M. Wagner 2012]

Mean-Field PQM N_f=2+1

Two improvements:

1. sea contribution

no-sea: red dashed line

sea: green line (vacuum term included)

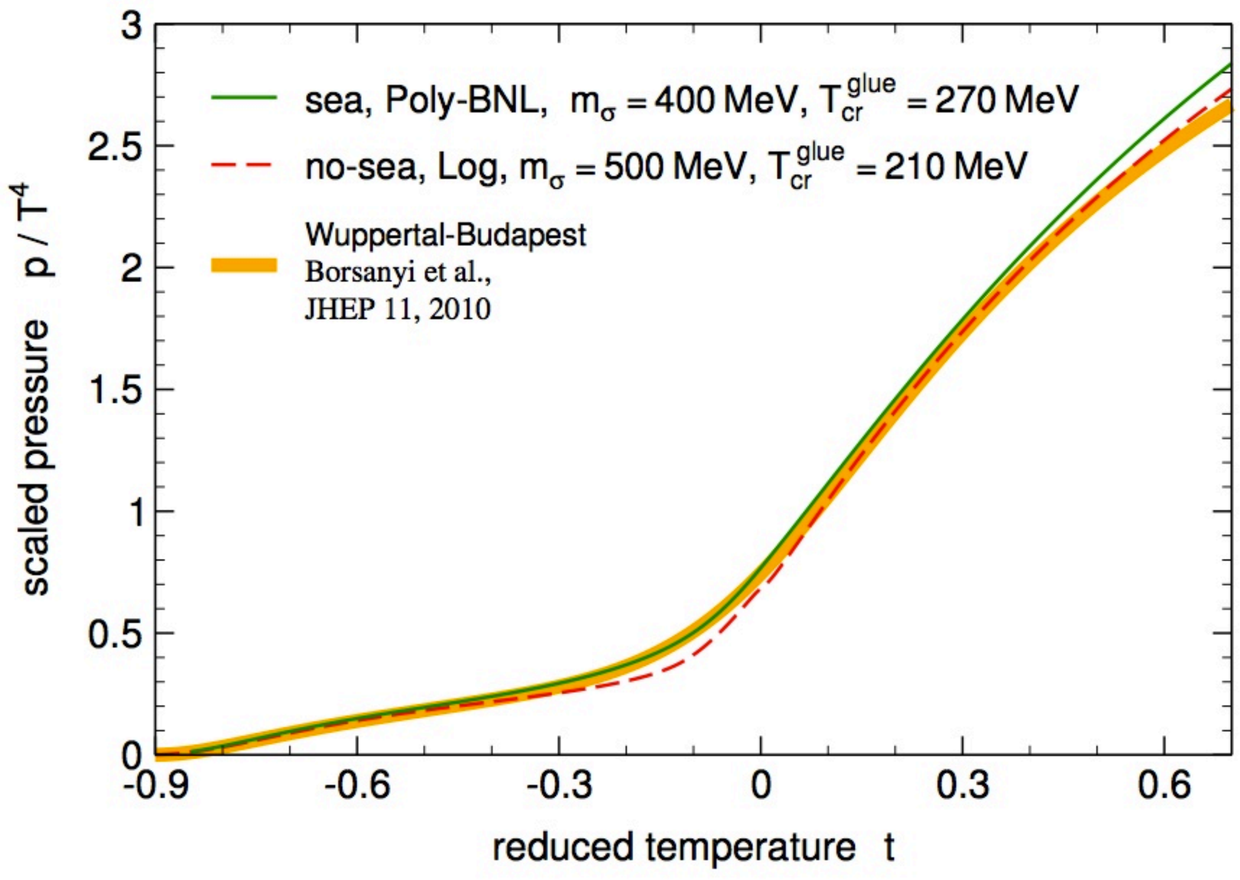
2. matter back-coupling

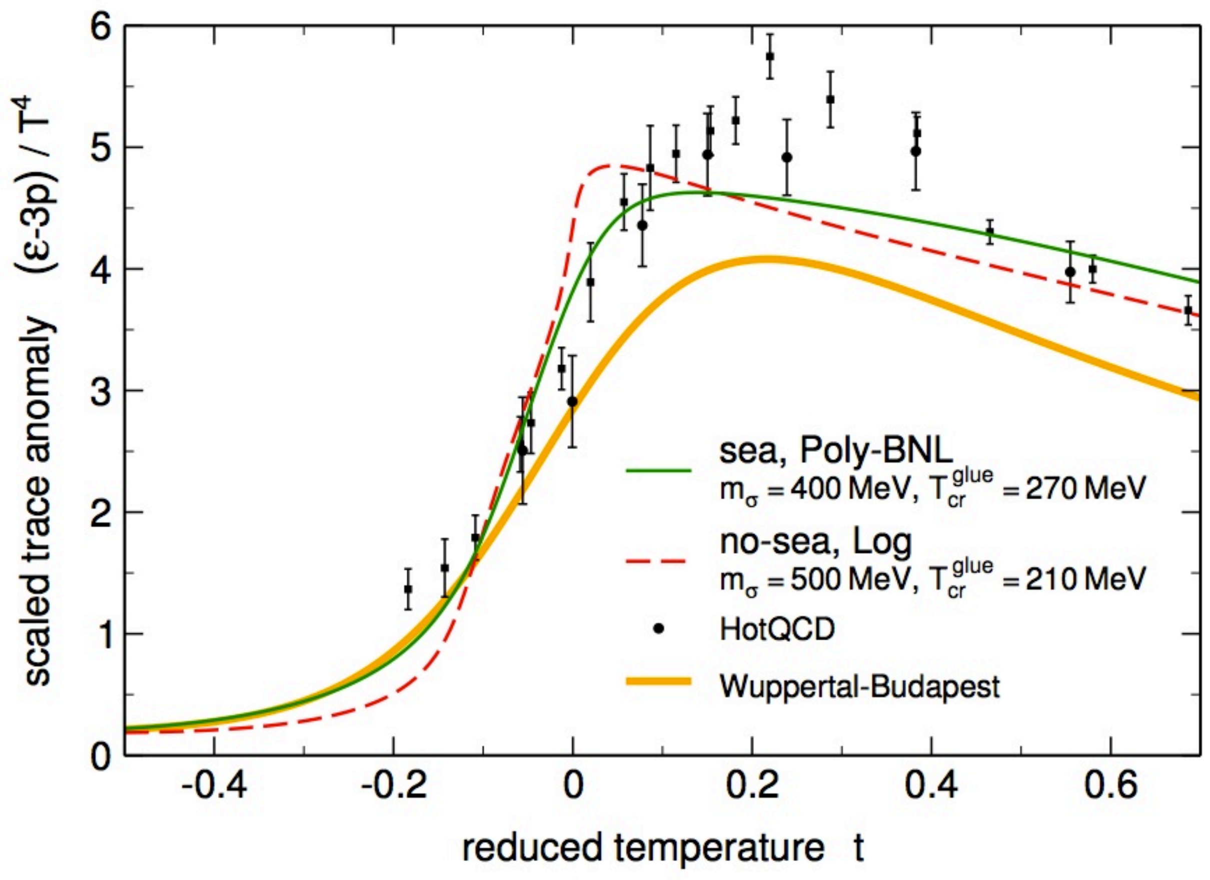
an effective unquenching

$$\mathcal{U}_{glue}(t_{glue}) = \mathcal{U}_{\rm YM}(t_{\rm YM})$$

with $t_{\rm YM}(t_{glue}) = 0.57\, t_{\rm glue}$

[Herbst, Mitter, Stiele, Pawlowski, BJS, Schaffner-Bieleich in preparation 2013]





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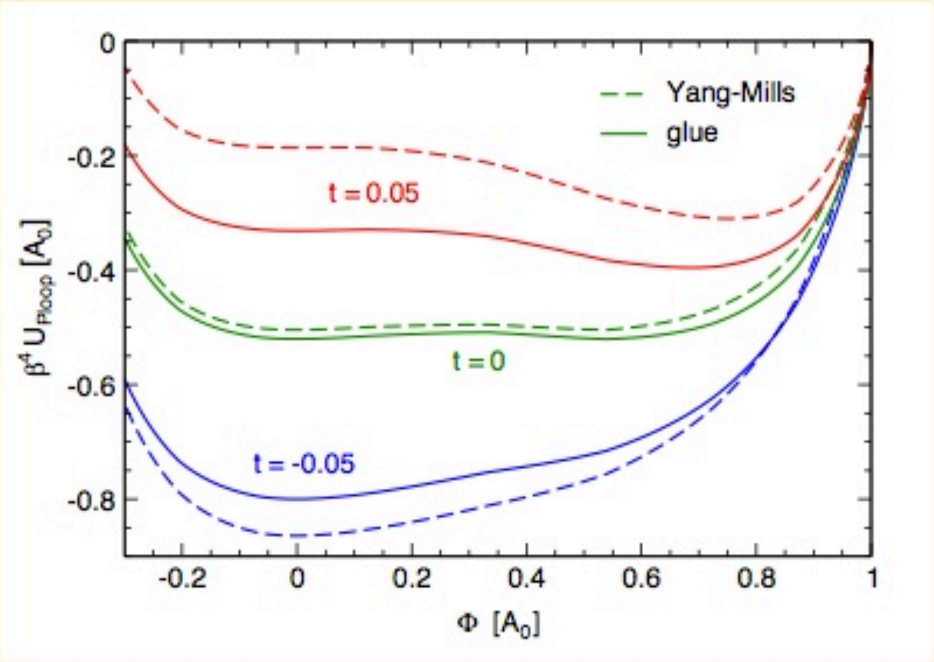
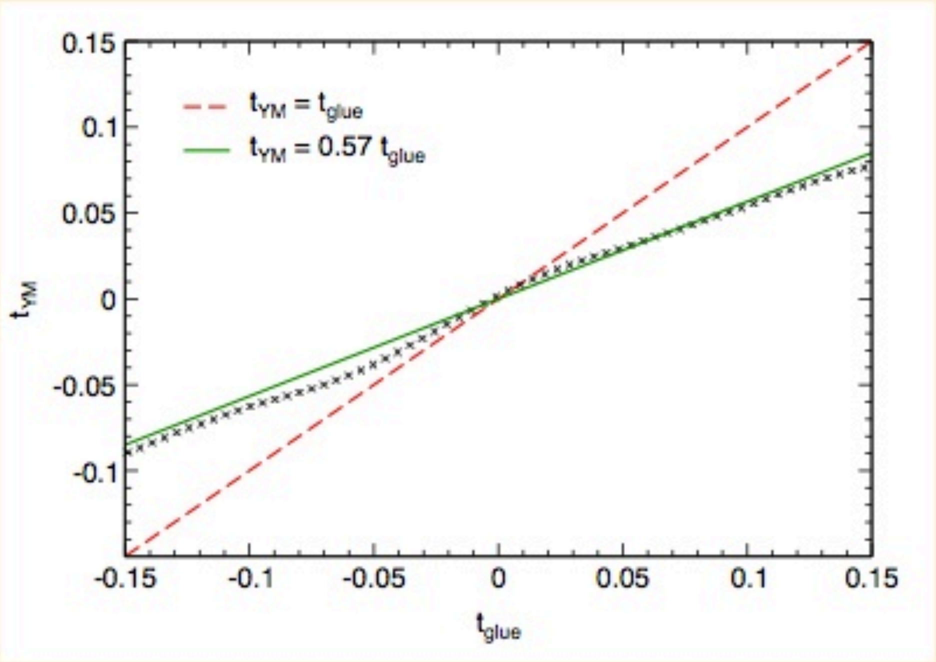
Matching the scales with FRG

Map between Yang-Mills and glue potential: $t_{\text{YM}}\left(t_{\text{glue}}\right)$

L. M. Haas, RS, J. Braun, J. M. Pawlowski, J. Schaffner-Bielich, PRD 87, 076004, 2013





$\rightarrow\ t_{\text{YM}}\left(t_{\text{glue}}\right)$ $\qquad$ $t_{\text{YM}} = 0.57\, t_{\text{glue}}$ $\qquad$ $\partial t_{\text{YM}} / \partial t_{\text{glue}} < 1$

$$\Rightarrow \quad \mathcal{U}_{\text{glue}}(t, \Phi) = \mathcal{U}_{\text{YM}}\left(t_{\text{YM}}(t), \Phi\right)$$

R. Stiele Heidelberg University $\qquad$ Thermodynamics, Phase Structure & Nucleation in the PQM model

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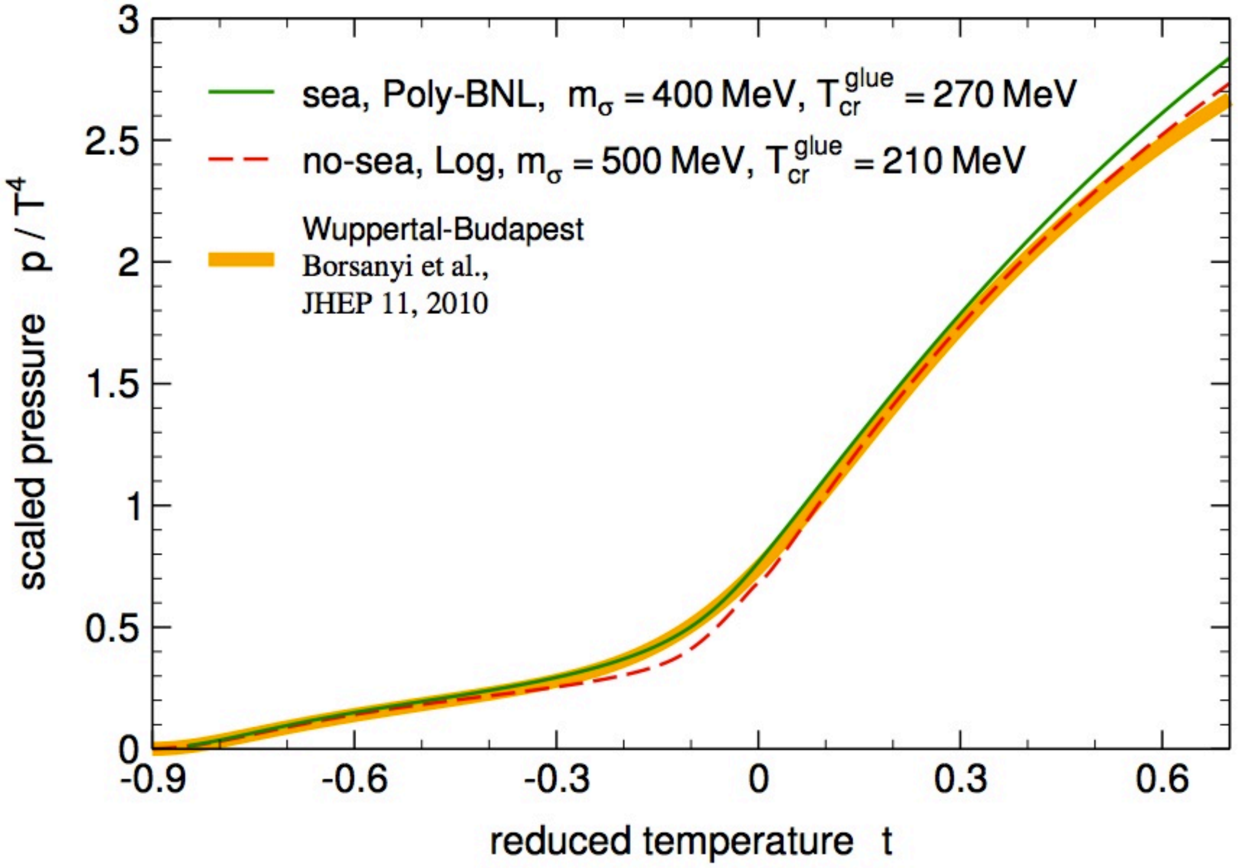

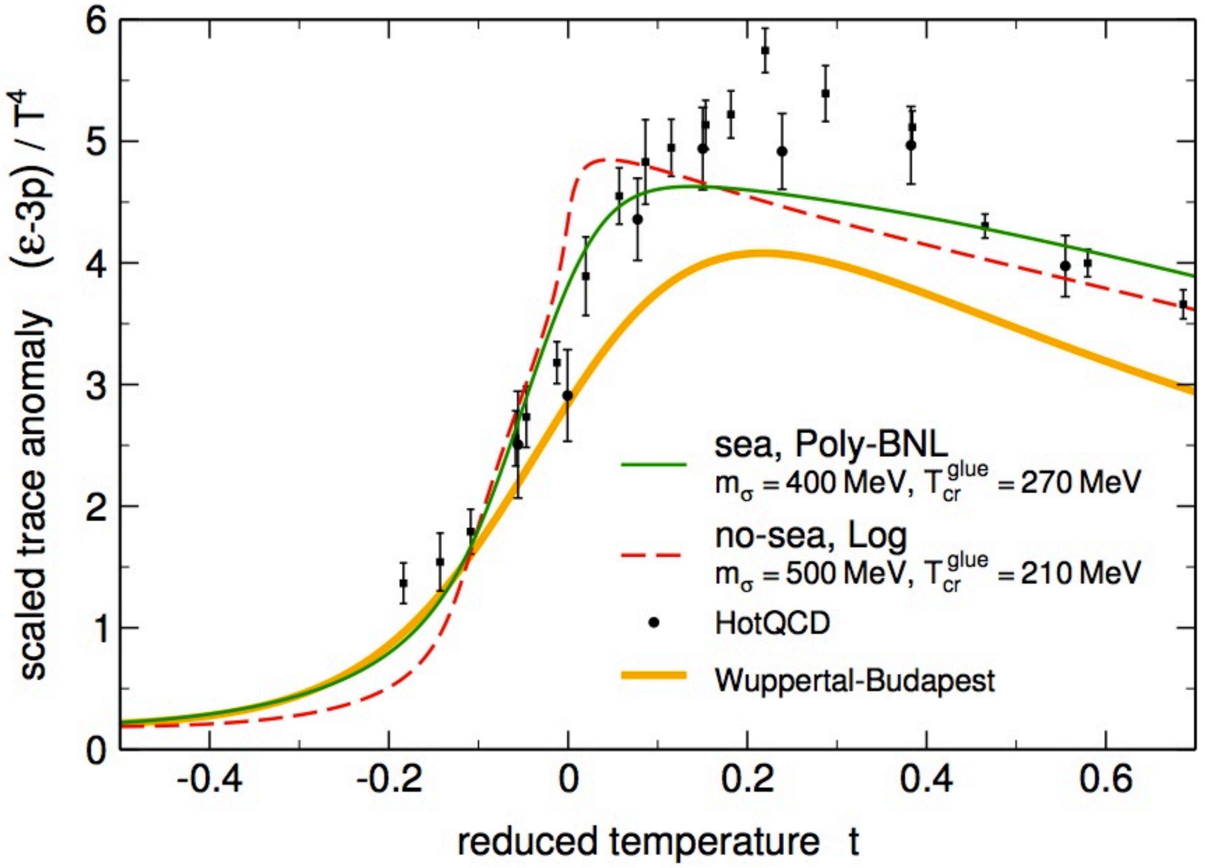

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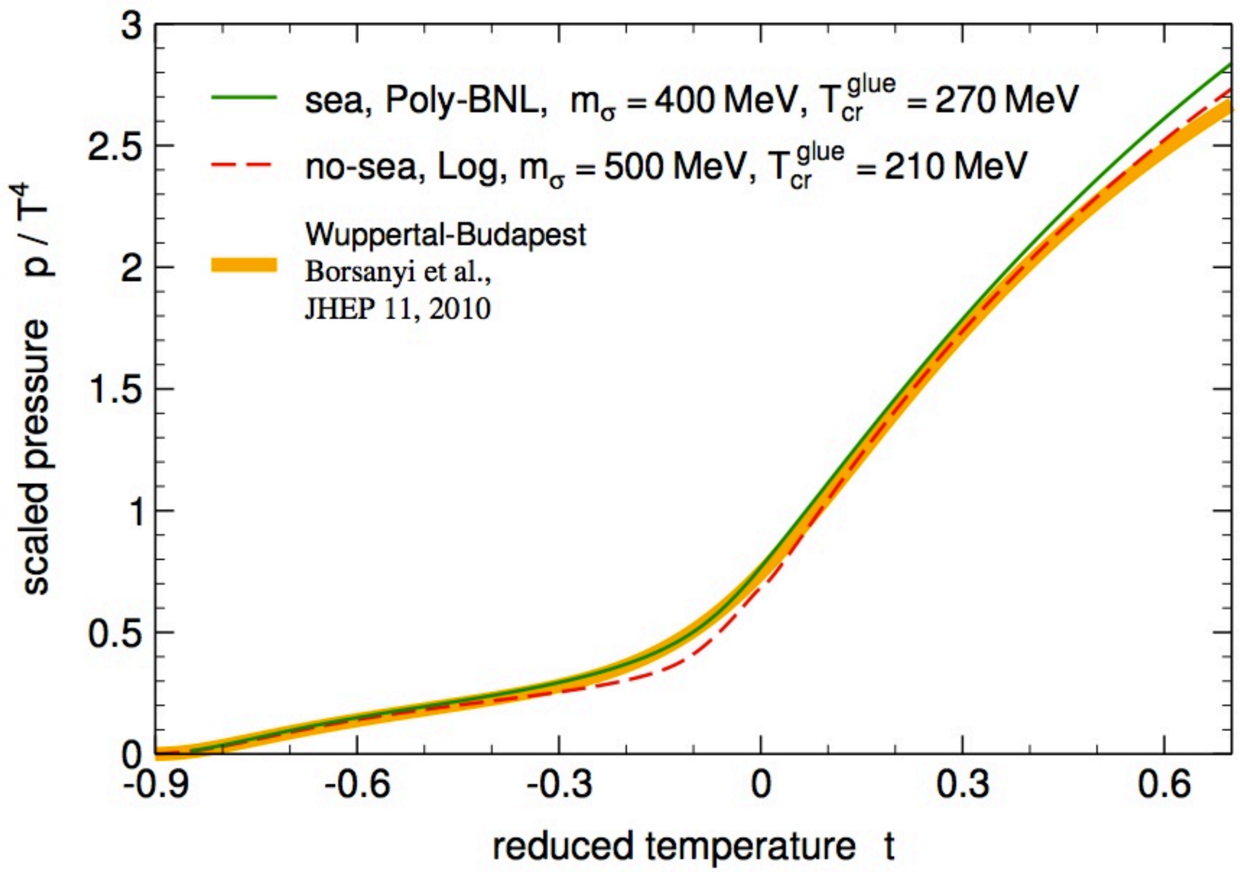
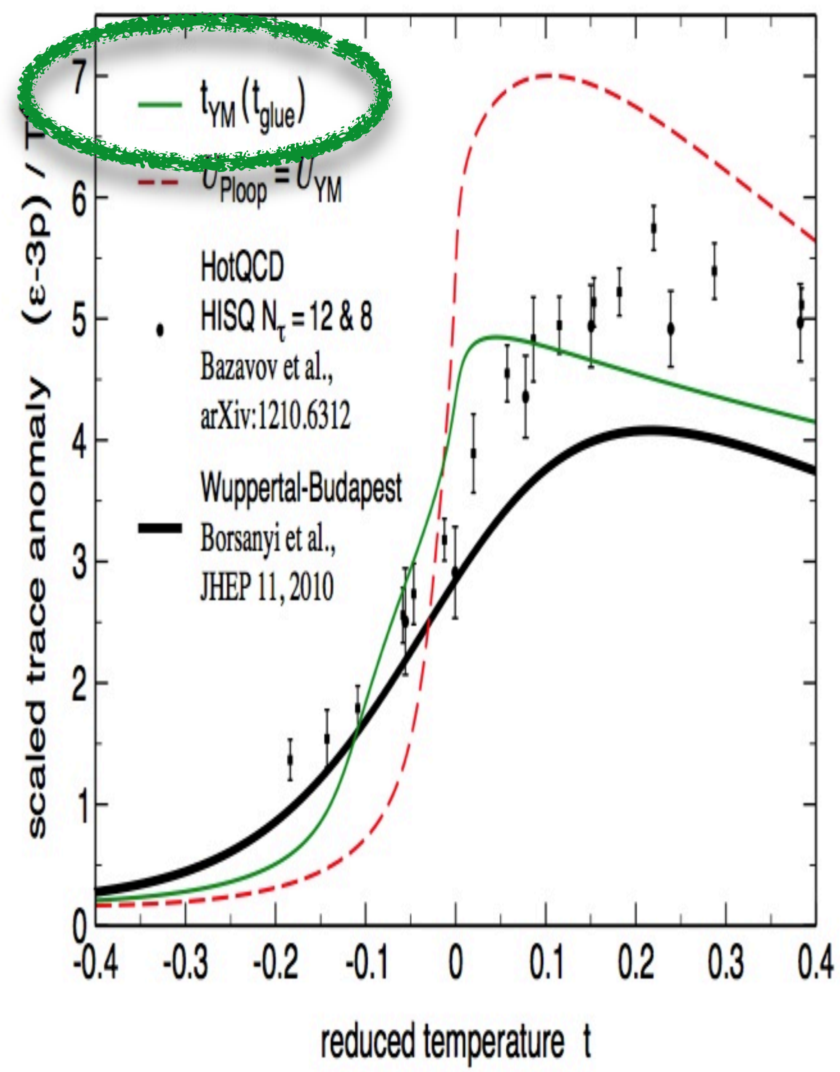
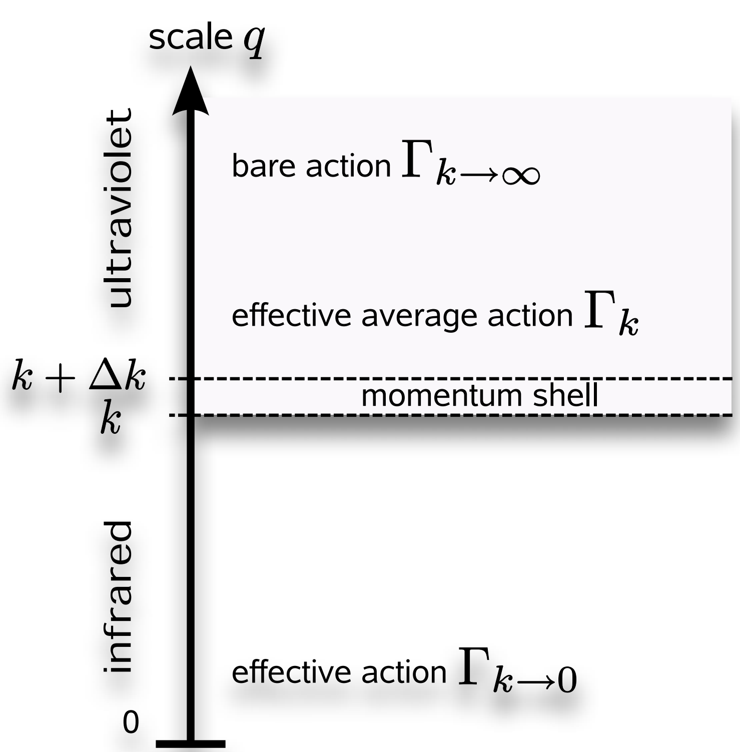




Functional RG (FRG) Approach

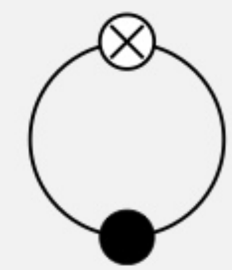
- $\Gamma_k[\phi]$ scale dependent effective action $t = \ln(k/\Lambda)$ R_k regulators $\Gamma_k^{(2)} = \dfrac{\delta^2 \Gamma_k}{\delta\phi\delta\phi}$



FRG (average effective action)

$$\partial_t \Gamma_k[\phi] = \frac{1}{2} \mathrm{Tr}\, \partial_t R_k \left(\frac{1}{\Gamma_k^{(2)} + R_k} \right)$$

$$k\partial_k \Gamma_k[\phi] \sim \frac{1}{2}$$



[Wetterich 1993]

- Ansatz for Γ_k: Leading order derivative expansion arbitrary potential

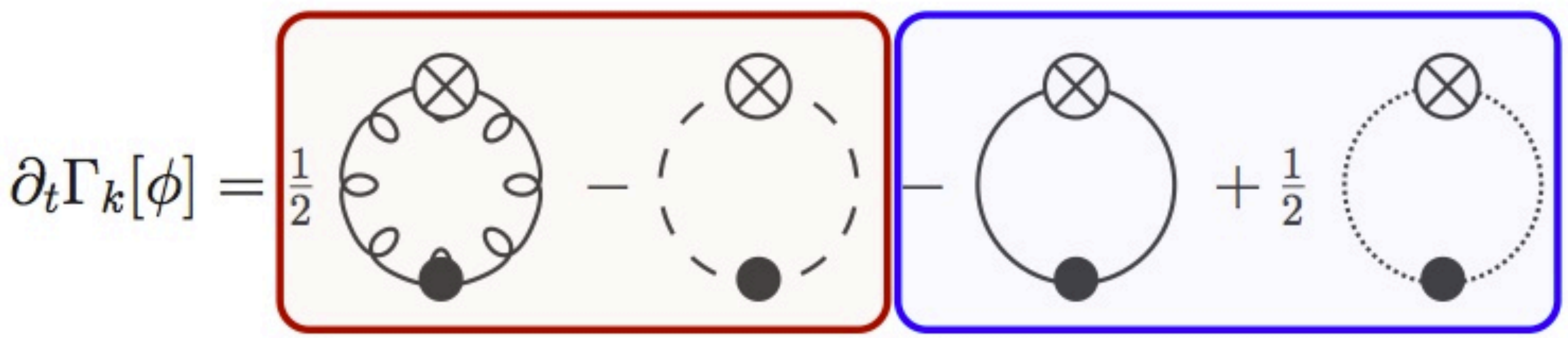
$$\Gamma_k = \int d^4x \bar{q}[i\gamma_\mu\partial^\mu - g(\sigma + i\vec{\tau}\vec{\pi}\gamma_5)]q + \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\vec{\pi})^2 + V_k(\phi^2)$$

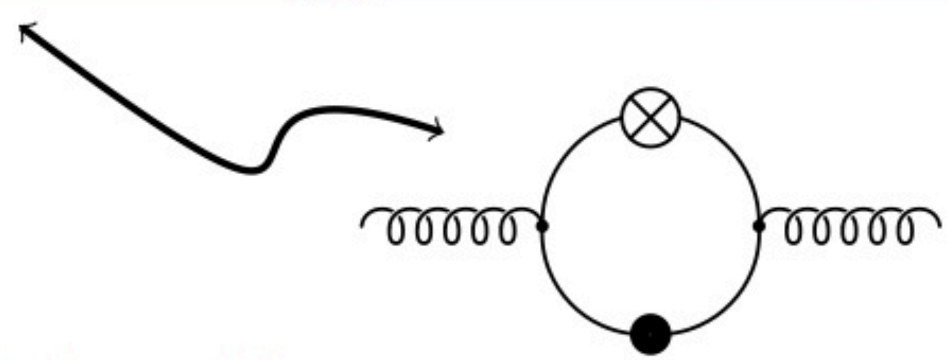
$$V_{k=\Lambda}(\phi^2) = \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2 - v^2)^2 - c\sigma$$

FRG and QCD

full dynamical QCD FRG flow: fluctuations of
gluon, ghost, quark and meson (via hadronization) fluctuations

Braun, Fister, Haas, Marhauser, Pawlowski; 2009



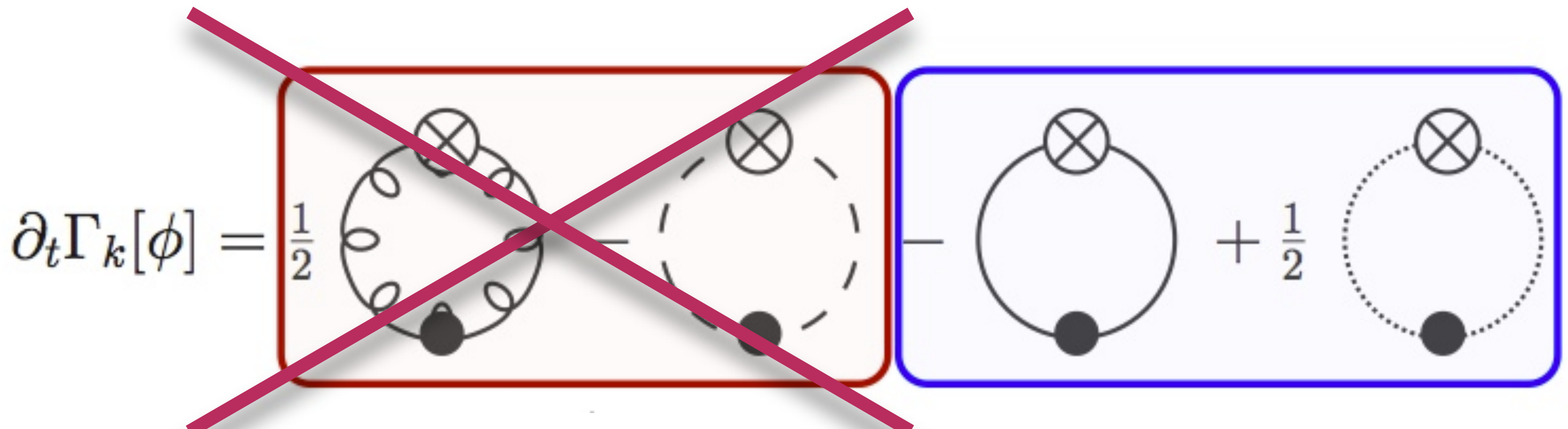


in presence of dynamical quarks:
gluon propagator modified:

$\Rightarrow$ pure Yang Mills flow $+$ matter back-coupling

FRG: quark-meson truncation

First step: flow for **quark-meson** model truncation: neglect **YM contributions**



Flow for quark-meson truncation

Two quark flavor

$$\Gamma_k = \int d^4x \left\{ \bar{\psi}(\partial\!\!\!/ + \mu\gamma_0 + ih(\sigma + i\gamma_5\vec{\tau}\vec{\pi}))\psi + \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\vec{\pi})^2 + \Omega_k(\sigma,\vec{\pi}) \right\}$$

$$\Omega_k(\sigma,\vec{\pi}) = \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2 - \nu^2)^2 - c\sigma$$

flow for grand potential [BJS, J.Wambach]

$$\partial_t\Omega_k(T,\mu;\phi) = \frac{k^4}{12\pi^2}\left[\frac{3}{E_\pi}\coth\left(\frac{E_\pi}{2T}\right) + \frac{1}{E_\sigma}\coth\left(\frac{E_\sigma}{2T}\right) - \frac{2N_cN_f}{E_q}\left\{\tanh\left(\frac{E_q-\mu}{2T}\right) + \tanh\left(\frac{E_q+\mu}{2T}\right)\right\}\right]$$

$$E_\pi^2 = 1 + 2\Omega_k'/k^2\ , \qquad E_\sigma^2 = 1 + 2\Omega_k'/k^2 + 4\phi^2\Omega_k''/k^2\ , \qquad E_q^2 = 1 + g^2\phi^2/k^2$$

$$\phi \sim \langle\bar{q}q\rangle\ , \qquad \Omega_k' = \partial\Omega_k/\partial\phi \qquad \text{etc}$$

- quark fluctuations: chiral symmetry breaking
- meson fluctuations: chiral symmetry restoration

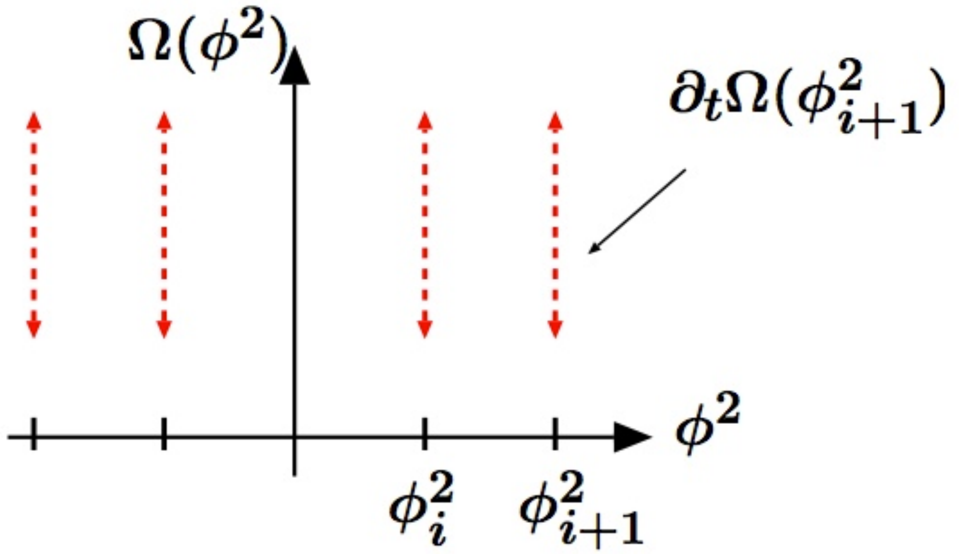
Solving Flow Equations

two strategies

1. Taylor expansion around some point

$$V_k(\phi) = \sum_{n=1}^{N_{\max}} \frac{a_{k,2n}}{n!}(\phi^2 - \phi_0^2)^n$$

2. Expansion on a grid (1-dim.)



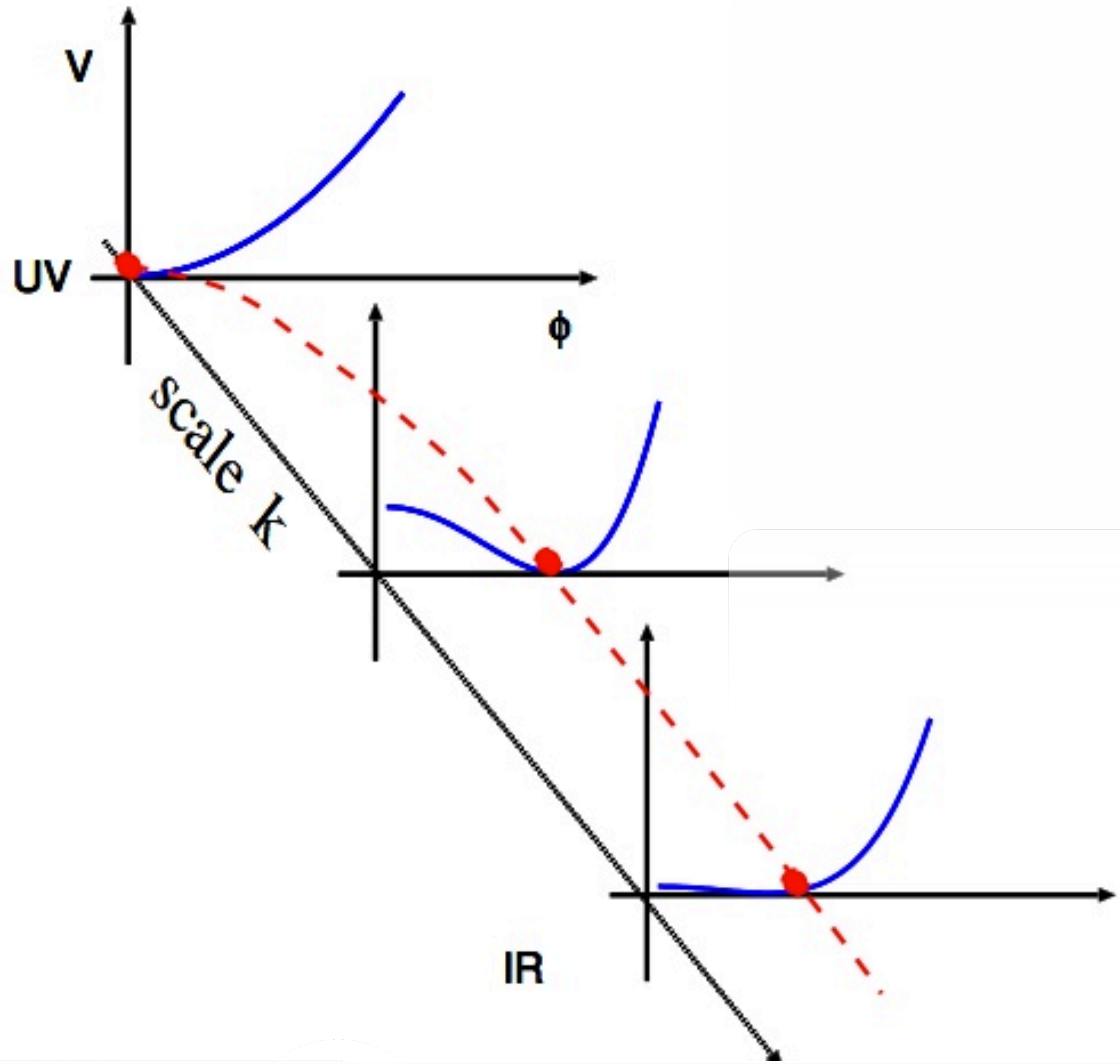
- initial condition at high UV cutoff (symmetric potential)

$$V_\Lambda(\phi) = \frac{\lambda_\Lambda}{4}(\phi^2)^2$$

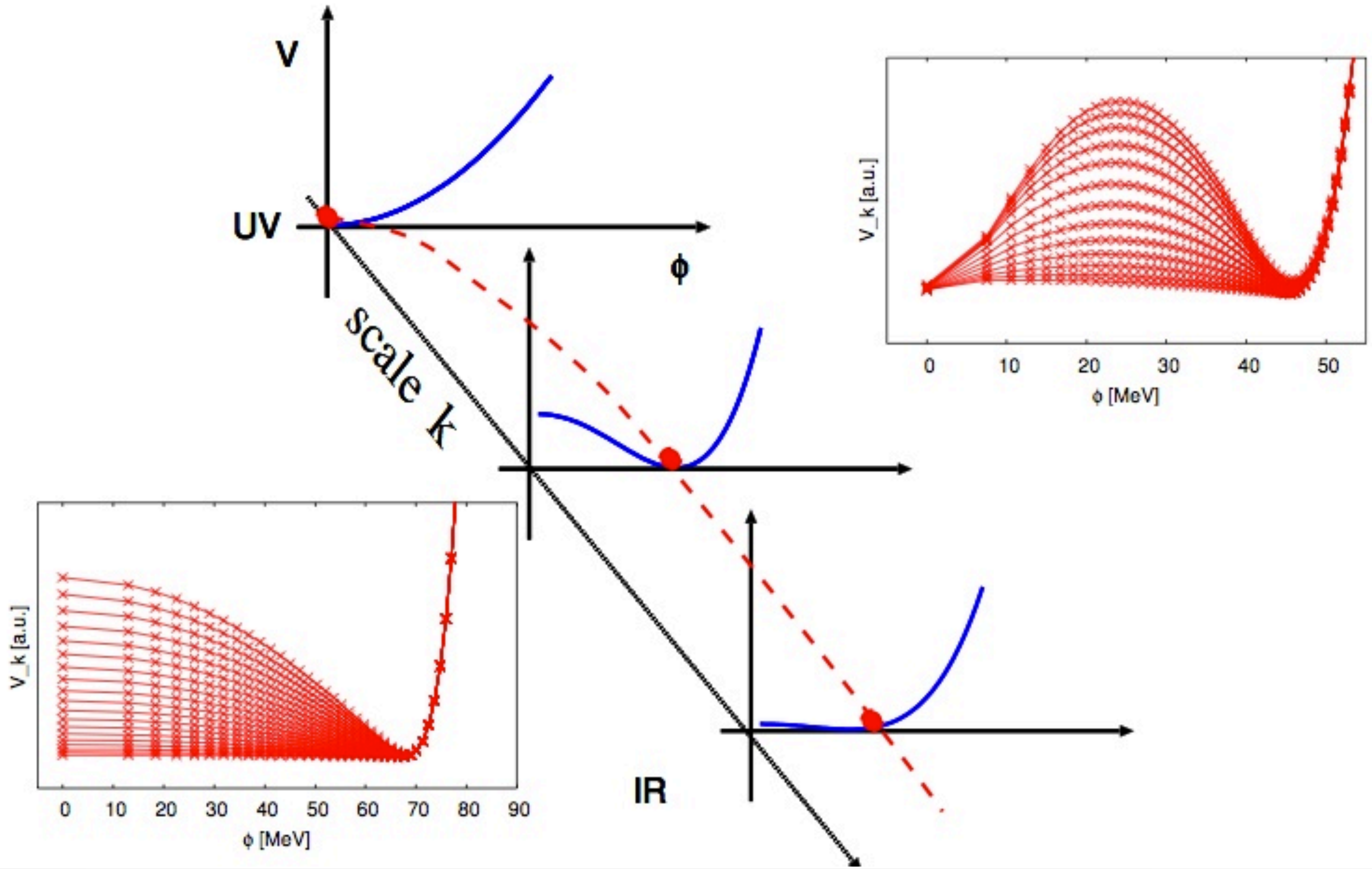
- Fix UV parametrization such to reproduce IR physics

$$\phi_{k\to 0} \equiv f_\pi \sim 93 \text{ MeV}$$

Scale evolution towards the IR



Scale evolution towards the IR



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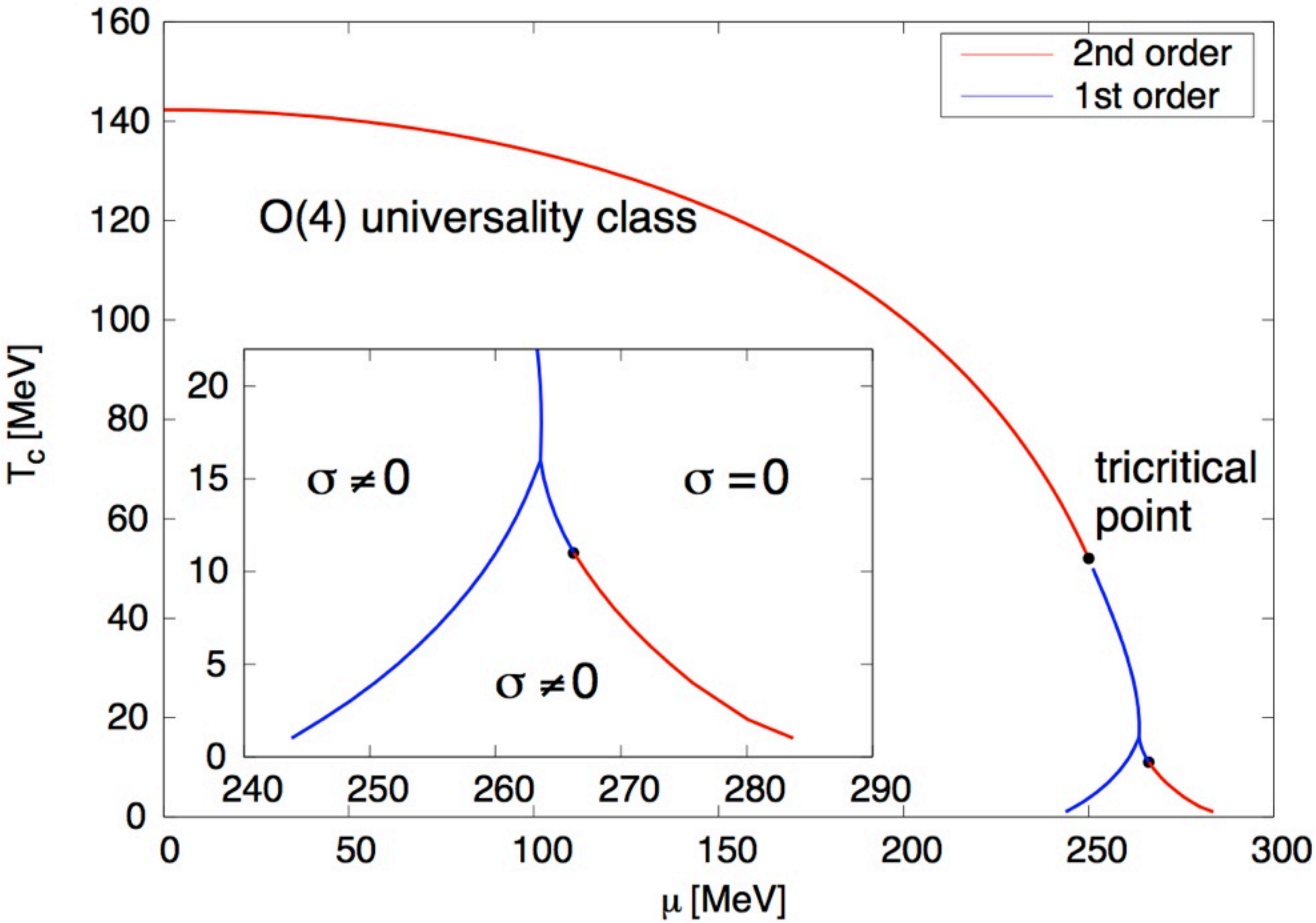
Phase diagram N_f=2 QM truncation

$O(4) \sim SU(2) \times SU(2)$ chiral limit no spinodal lines!

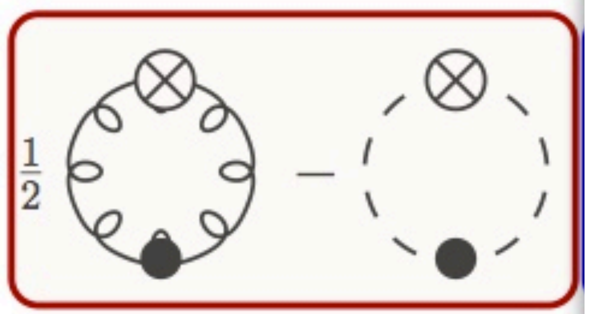


FRG and QCD

full dynamical QCD FRG flow: fluctuations of
gluon, ghost, quark and meson (via hadronization) fluctuations

Braun, Haas, Marhauser, Pawlowski; 2009

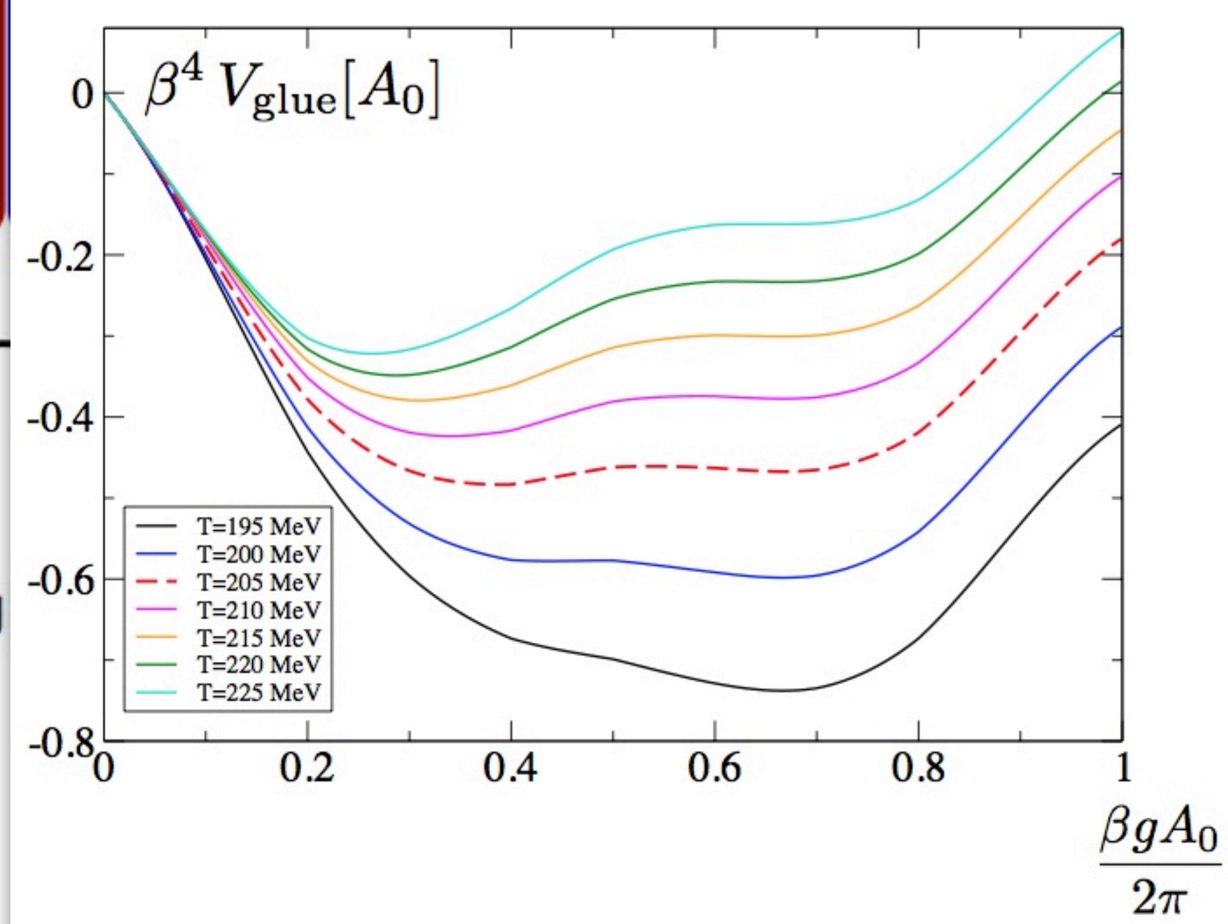
$$\partial_t \Gamma_k[\phi] =$$



in presence of dynamical quarks:
gluon propagator modified:

$\Rightarrow$ pure Yang Mills flow + matter back-coupling

Glue potential



[Haas, Stiele, Braun, Pawlowski, Schaffner-Bielich, (2013)]

pure Yang Mills flow
replaced by eff. Polyakov-loop potential $\mathcal{U}_{\rm Pol}$:
(fit to lattice YM thermodynamics)

FRG and QCD

full dynamical QCD FRG flow: fluctuations of
gluon, ghost, quark and meson (via hadronization) fluctuations

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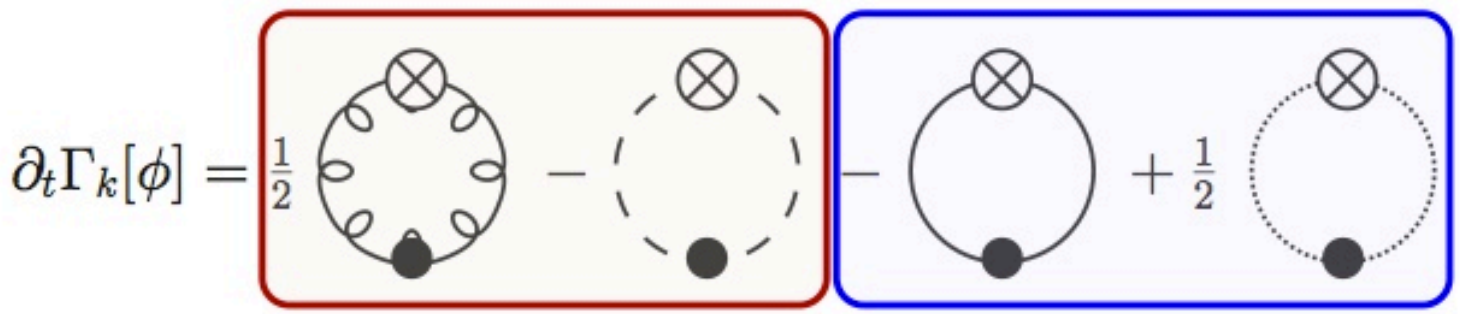

in presence of dynamical quarks:
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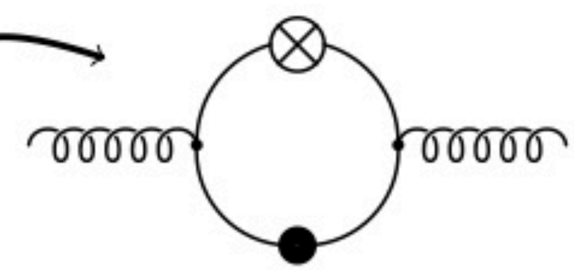
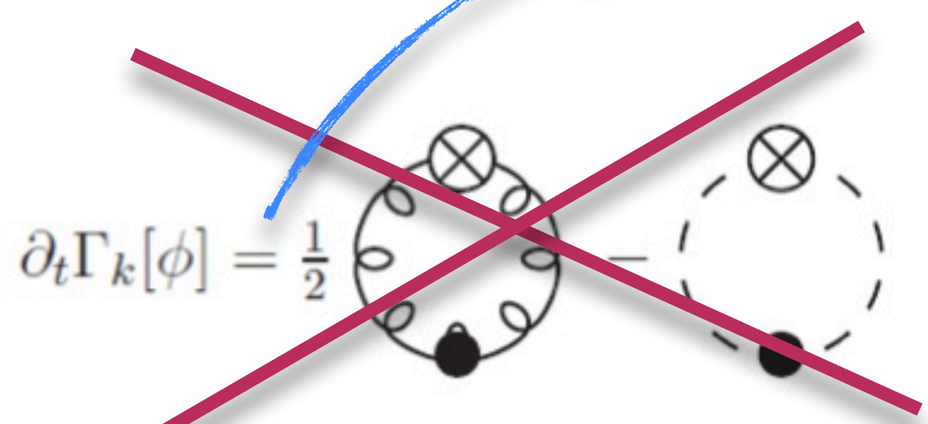


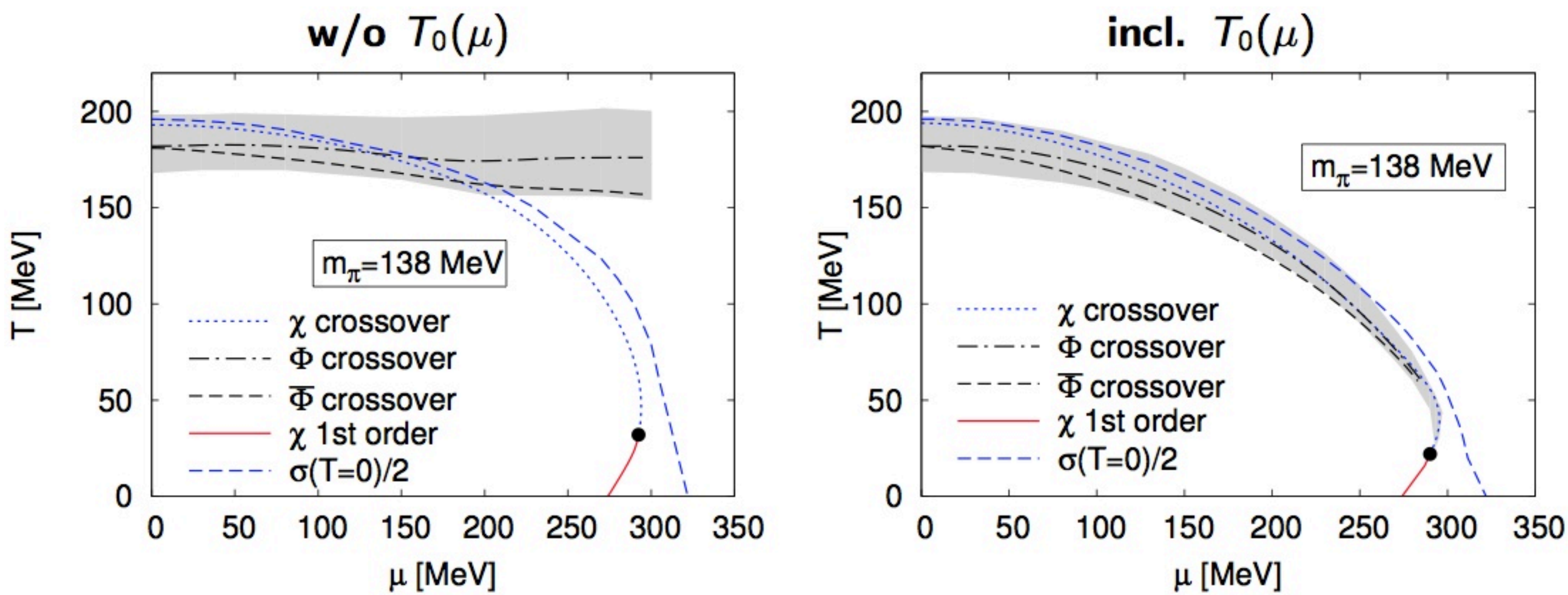
$\Rightarrow$ pure Yang Mills flow + matter back-coupling

$\to \mathcal{U}_{\mathrm{Pol}}(\Phi)$

pure Yang Mills flow
replaced by eff. Polyakov-loop potential $\mathcal{U}_{\mathrm{Pol}}$:
(fit to lattice YM thermodynamics)



FRG: Quark-Meson with Polyakov



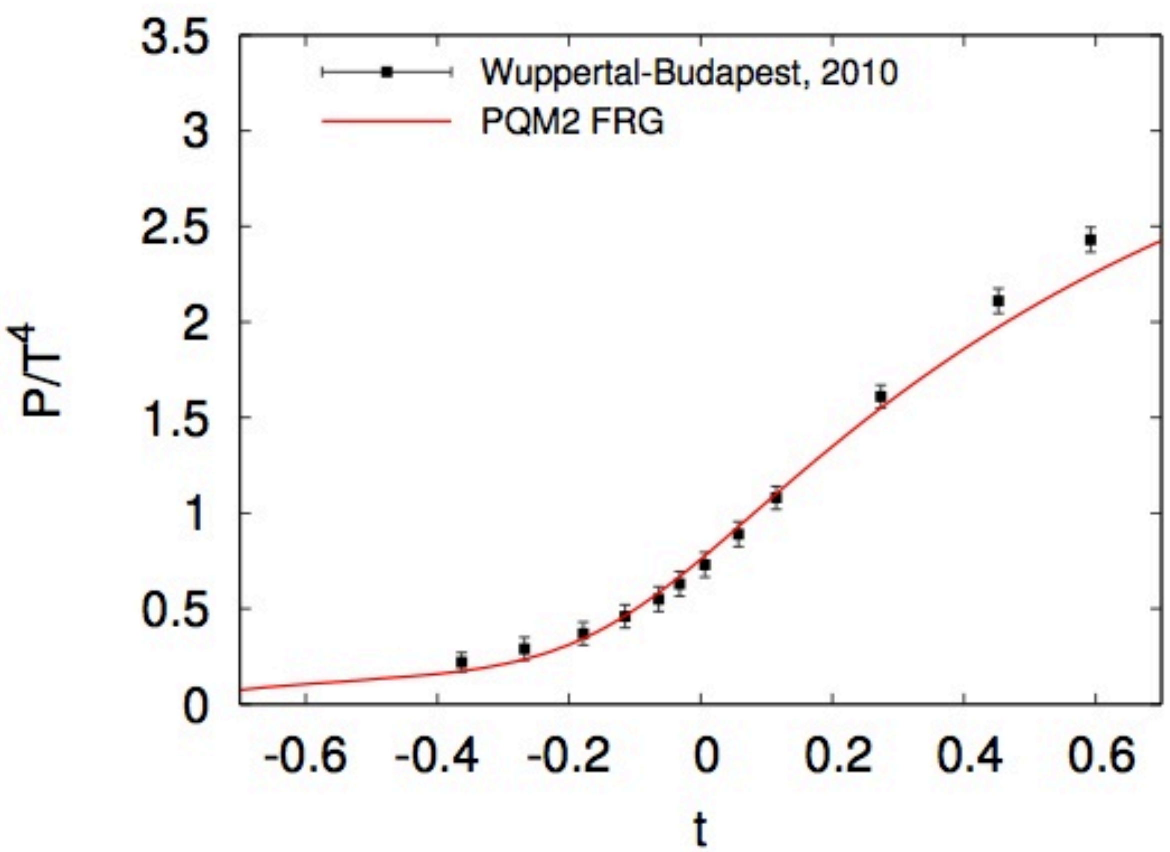
[Herbst, Pawlowski, BJS 2010,2013]

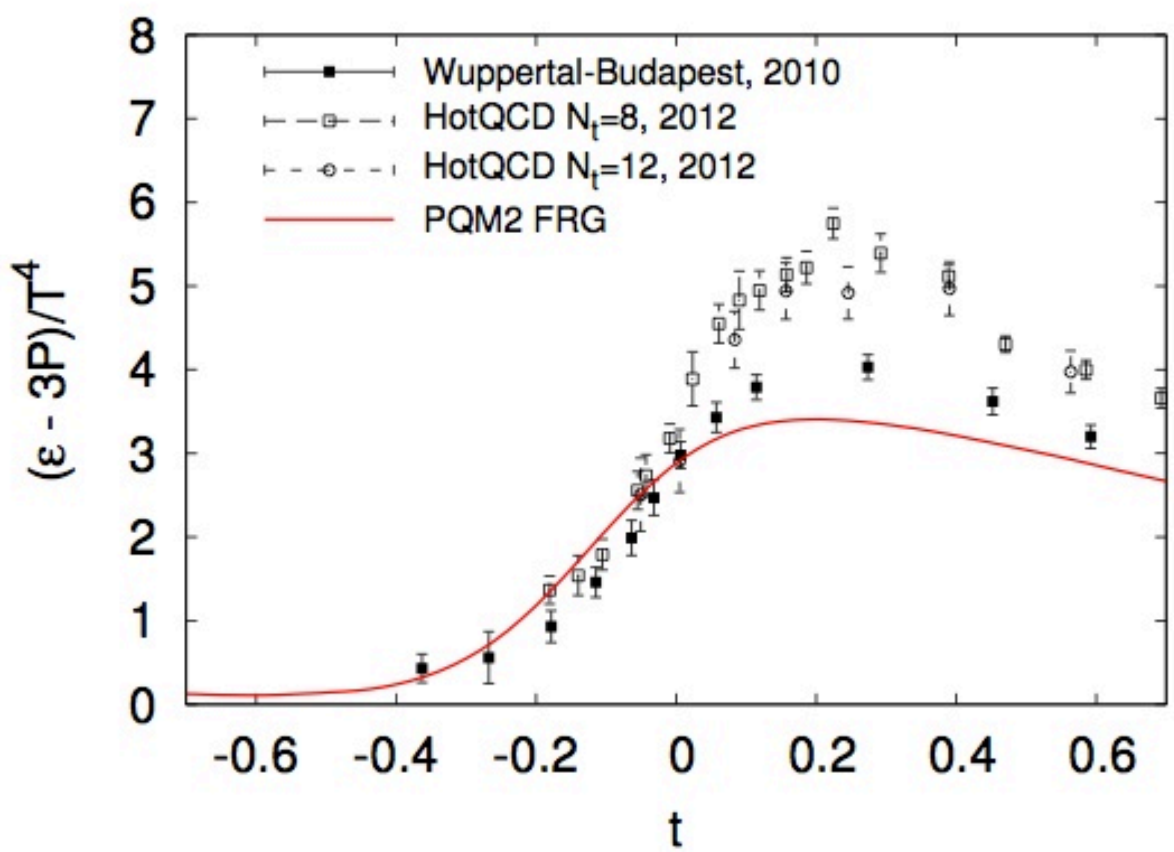
FRG: Quark-Meson with Polyakov

Pressure and interaction measure in comparison with lattice data (polynomial Polyakov-loop potential)

$N_f = 2$

[Herbst, Mitter, Stiele, Pawlowski, BJS, Schaffner-Bieleich in preparation 2013]



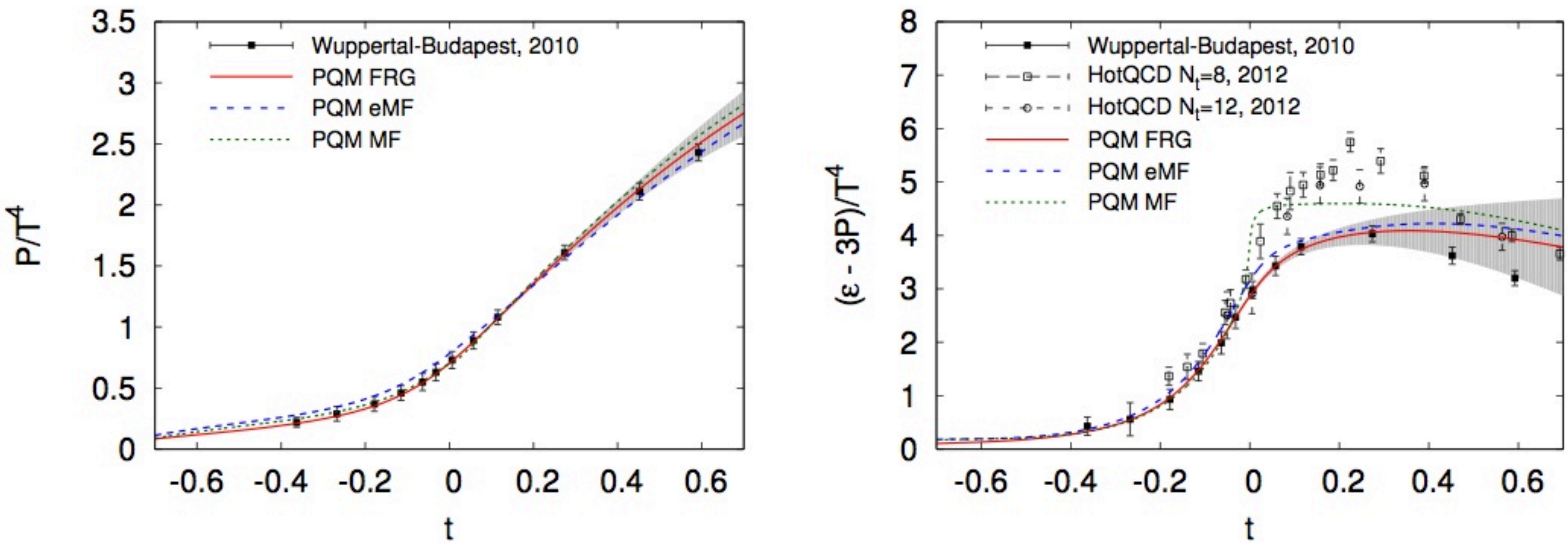


FRG: Quark-Meson with Polyakov

Pressure and interaction measure in comparison with lattice data (**polynomial** Polyakov-loop potential)

$N_f = 2+1$

[Herbst, Mitter, Stiele, Pawlowski, BJS, Schaffner-Bieleich in preparation 2013]

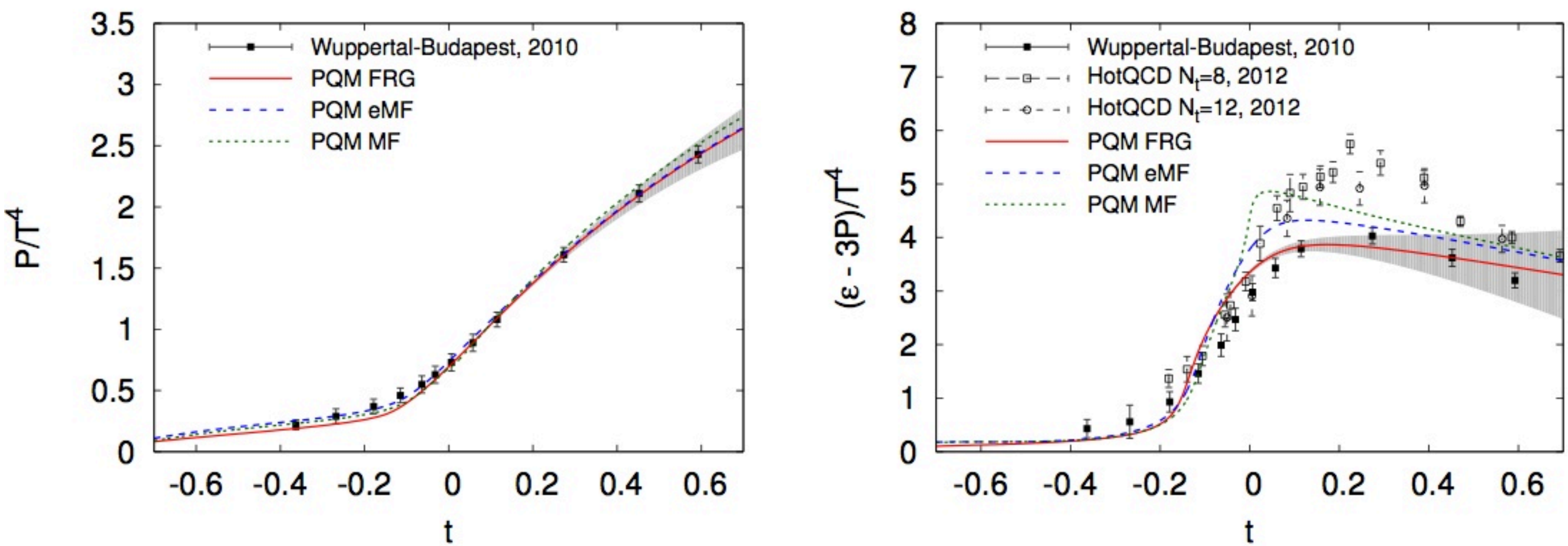


FRG: Quark-Meson with Polyakov

Pressure and interaction measure in comparison with lattice data (**logarithmic** Polyakov-loop potential)

$N_f = 2+1$

[Herbst, Mitter, Stiele, Pawlowski, BJS, Schaffner-Bieleich in preparation 2013]



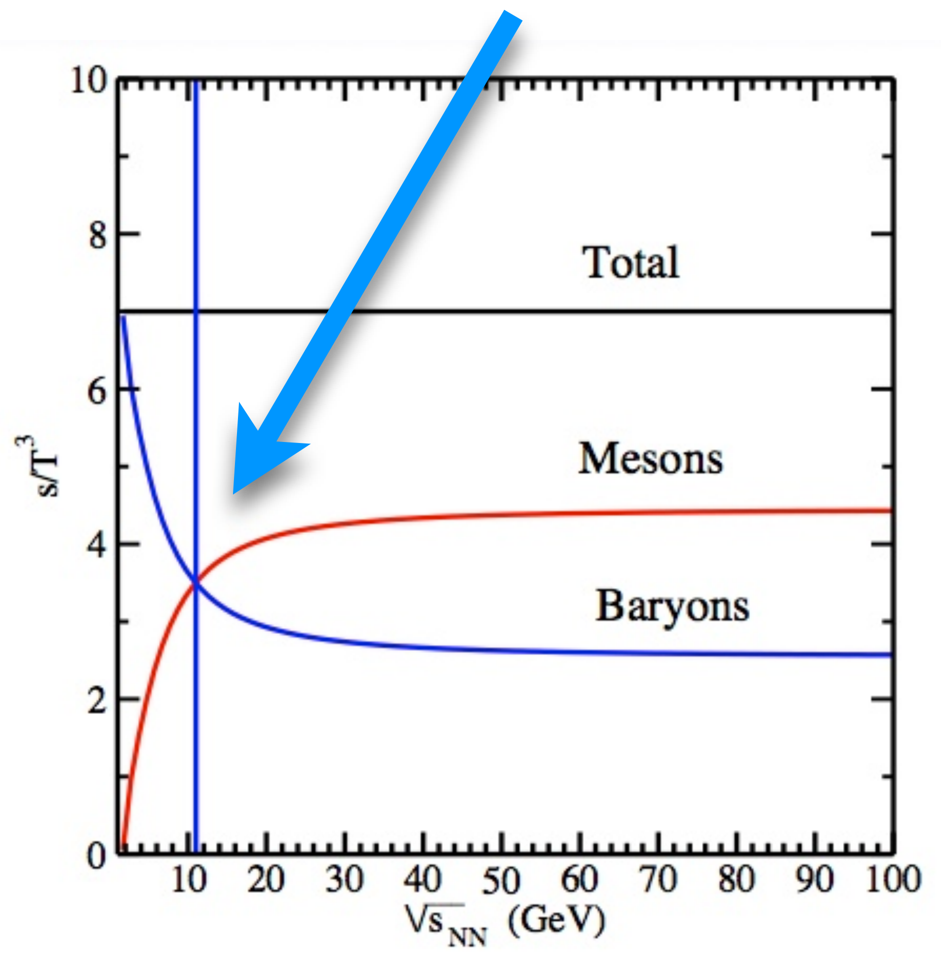
Role of Baryons?

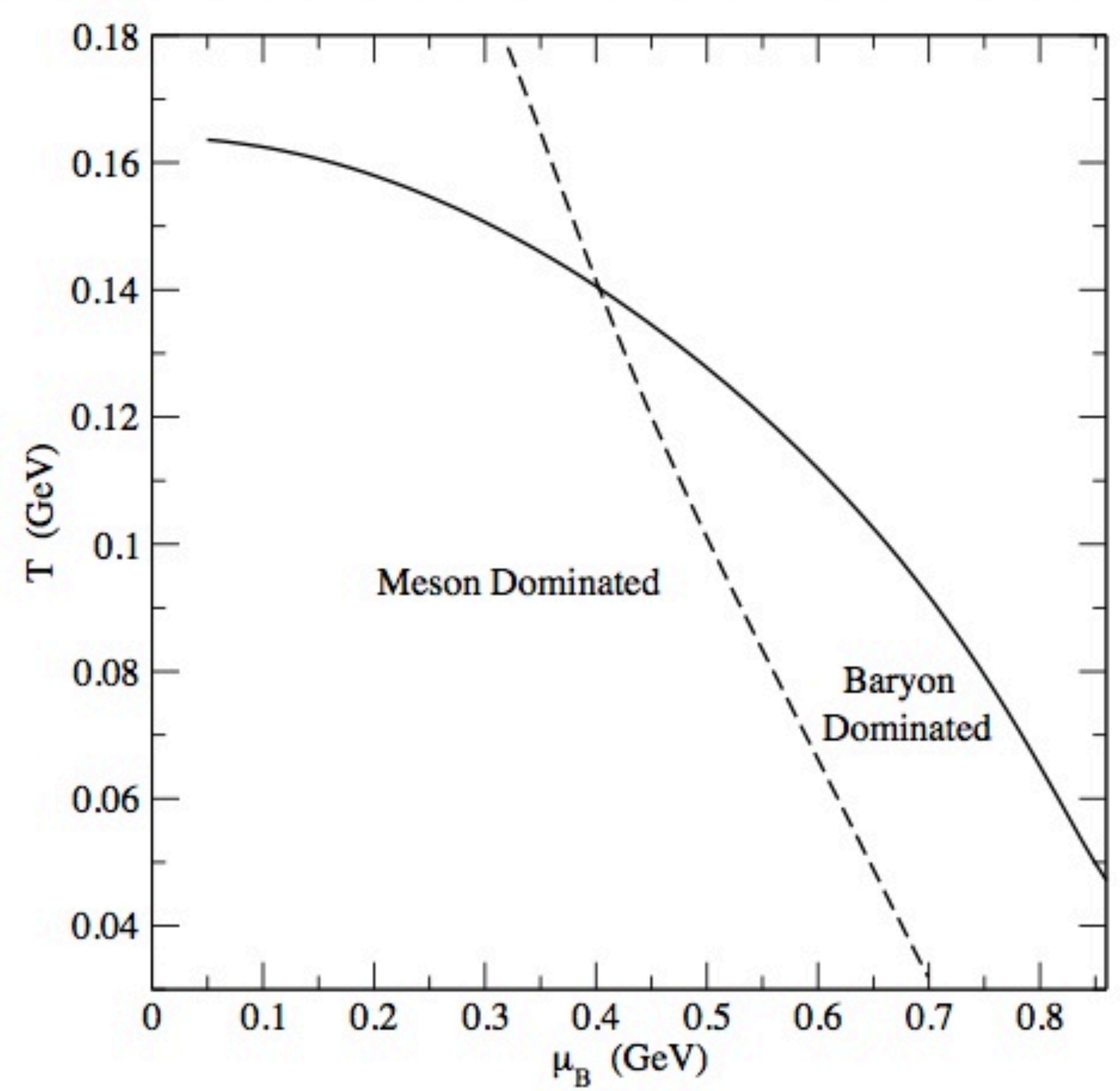
Statistical-thermal model analysis

High chemical potential: baryons more important but usually neglected in FRG

in stat. model: e.g. peak in

ratios “the horn”





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$\mathbf{N_c = 2}$ QCD

QC2D becomes simpler: **no sign problem**
lattice simulations ⇔ functional methods

inclusion of baryonic degrees of freedom simpler:

Scalar diquarks play a dual role as **bosonic baryons**

relativistic analog of models for ultracold quantum gases

color-neutral bound states of two quarks (**bosonic [anti]diquarks**)

enlarged flavor symmetry: $SU(4) \cong SO(6)$ ($\mu = 0$)

replaces usual chiral $SU(2)_L \times SU(2)_R \times U(1)_B$

- Symmetry breaking: $SU(2N_f) \to Sp(N_f)$ [or $SO(6) \to SO(5)$

➜ 5 Goldstone bosons: 3 pions and 2 (anti)diquarks

Quark-Meson-Diquark (QMD) Model

Chiral effective model:

- quarks: ψ
- mesons: σ, $\vec{\pi}$
- diquarks (baryons): $\mathrm{Re}\Delta, \mathrm{Im}\Delta$
- gauge fields: A_μ^a in $D_\mu = \partial_\mu + iA_\mu \to$ Polyakov-loop extended (PQMD) model [arXiv:1306.2897]

QMD Lagrangian: [N. Strodthoff, BJS, L. von Smekal 2012]

$$
\begin{aligned}
\mathcal{L}_{\mathrm{QMD}} \quad = \quad & \bar{\psi}\left(\not{D} + g(\sigma + i\gamma^5\vec{\pi}\vec{\tau}) - \mu\gamma^0\right)\psi \\
& + \frac{g}{2}\left(\Delta^*(\psi^T C\gamma^5\tau_2 S\psi) + \Delta(\psi^\dagger C\gamma^5\tau_2 S\psi^*)\right) \\
& + \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\vec{\pi})^2 + V(\vec{\phi}) \\
& + \frac{1}{2}\left((\partial_\mu - 2\mu\,\delta_\mu^0)\Delta\right)(\partial_\mu + 2\mu\,\delta_\mu^0)\Delta^*
\end{aligned}
$$

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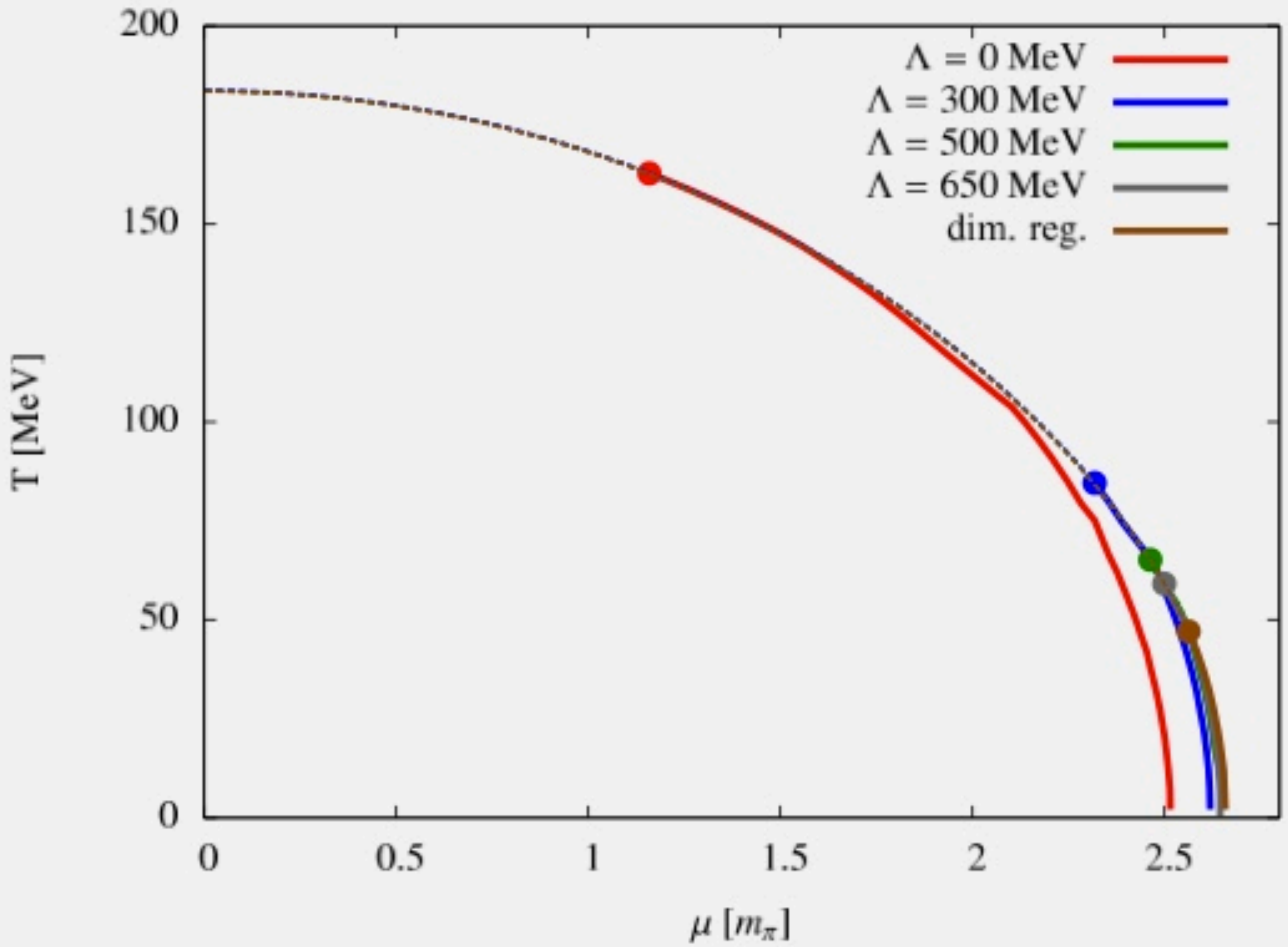
Phase diagram in MFA

Influence of Ω_{vac} on CEP for various Λ's compared to dimensional regularization



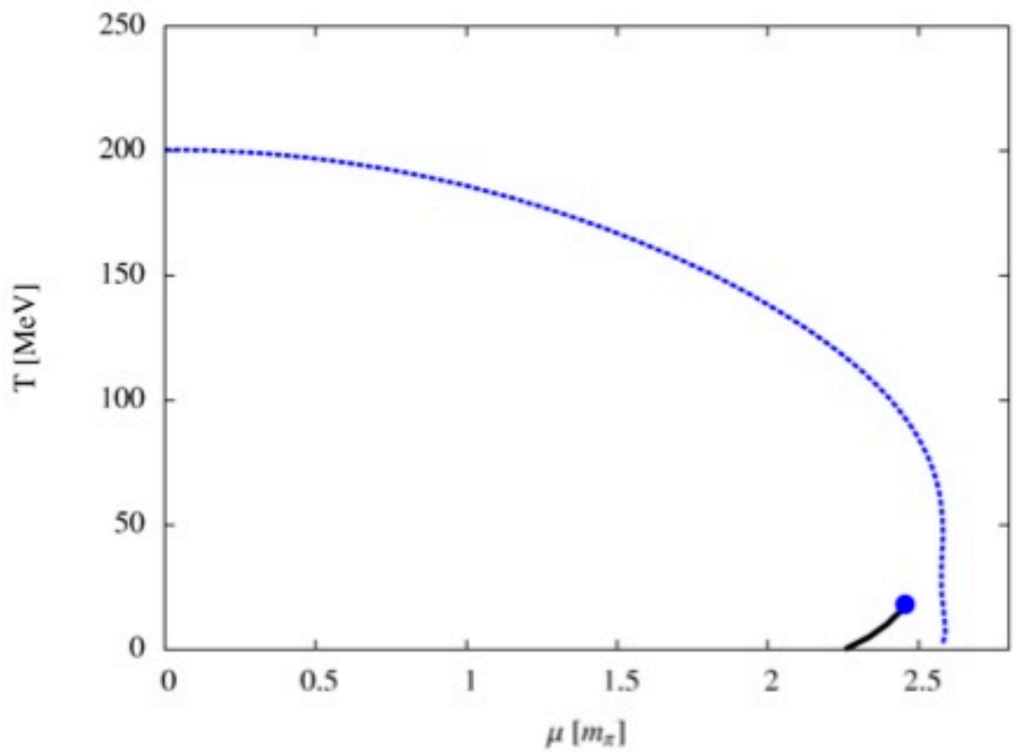
- no diquark condensation ($d = 0$)
- $O(6)$-symmetric potential $V_{\text{MF}} = V_{\text{MF}}(\phi^2)$ where $\vec{\phi} = (\sigma, \vec{\pi}, \text{Re}\Delta, \text{Im}\Delta)$ ➜ 1-dim. field variable

- 1^{st} order chiral transition
- CEP around $\mu \approx 2.5 m_\pi$

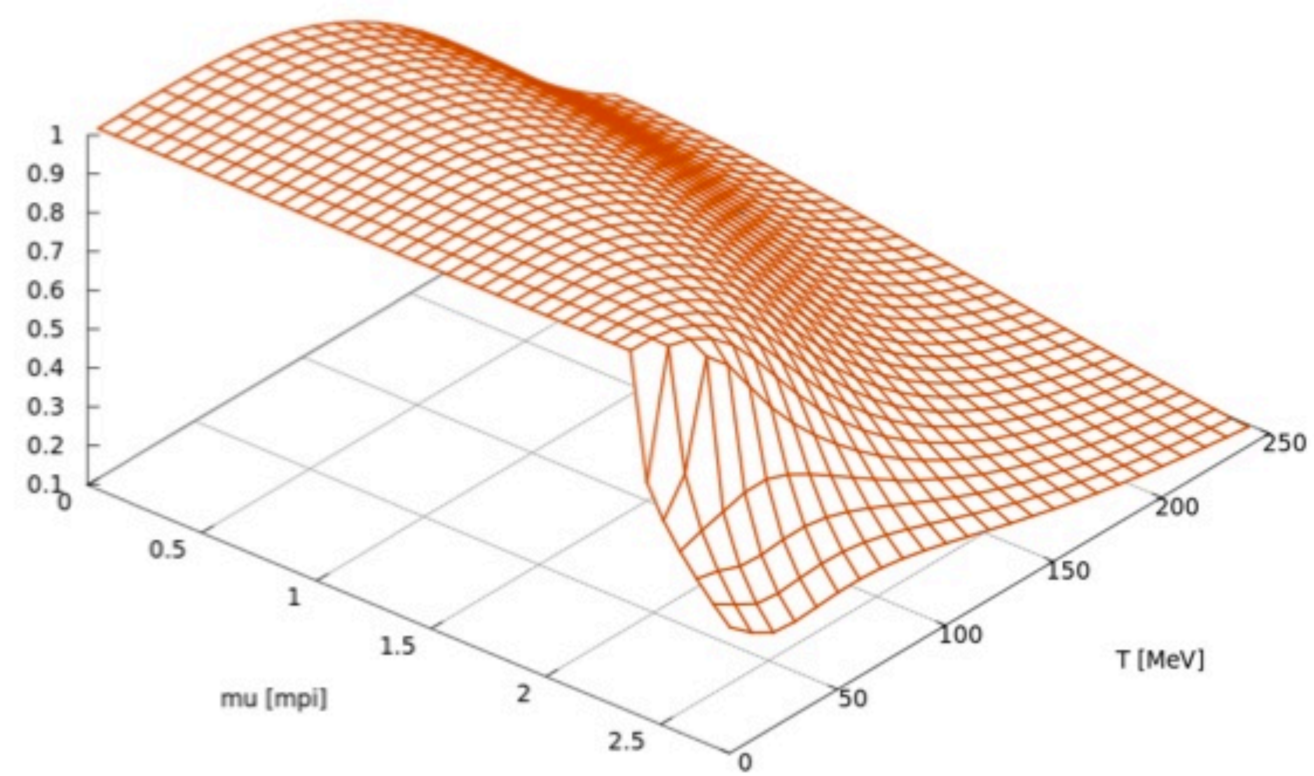
[N. Strodthoff, BJS, L. von Smekal; 2012]

Phase diagram with FRG

- no diquark condensation:
- $O(6)$-symmetric potential $U_k = U_k(\phi^2)$



- chiral condensate $\langle \bar{q}q \rangle / \langle \bar{q}q \rangle_0$



▷ "typical" RG phase diagram

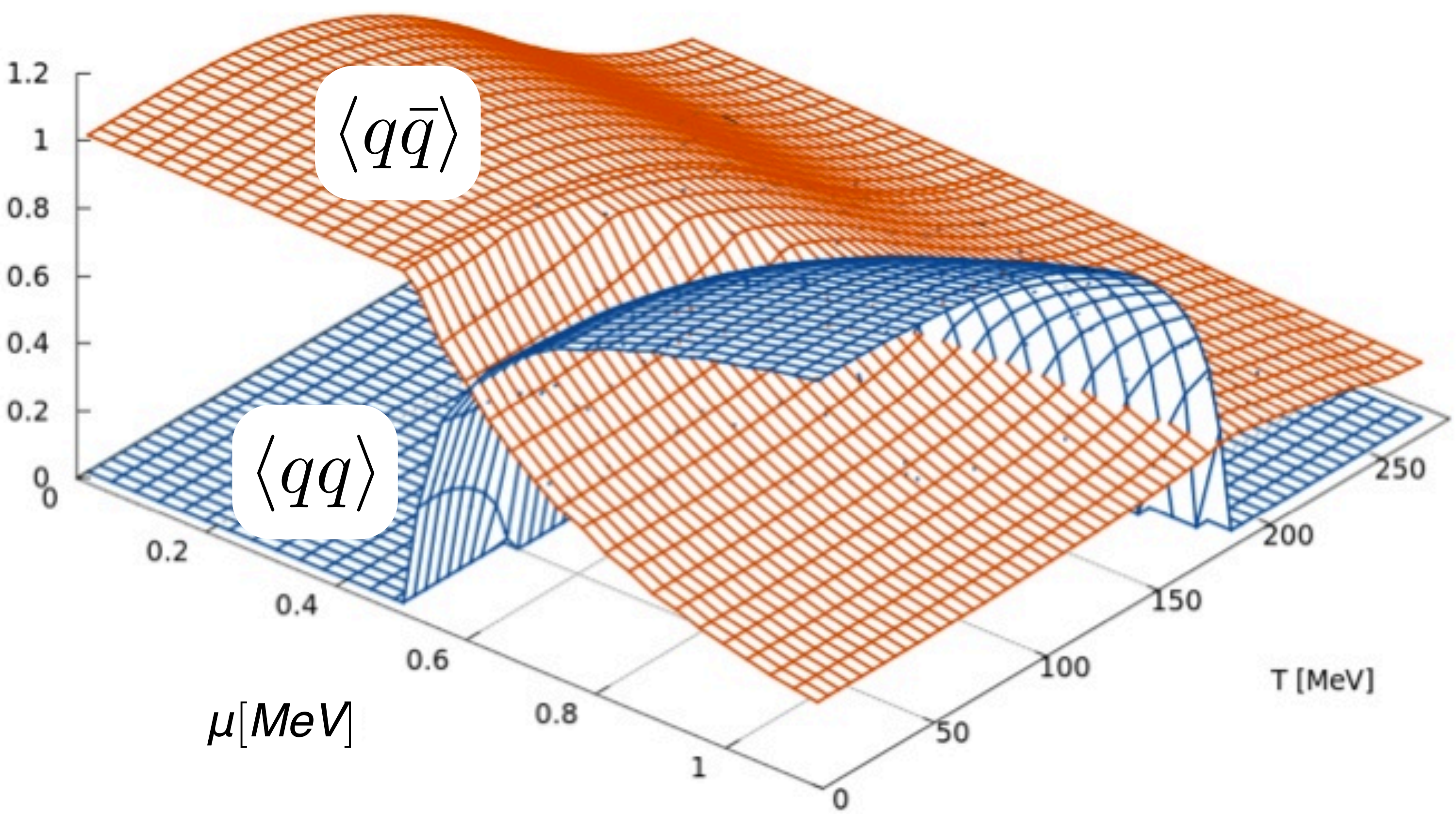
back-bending 1st order line with a CEP

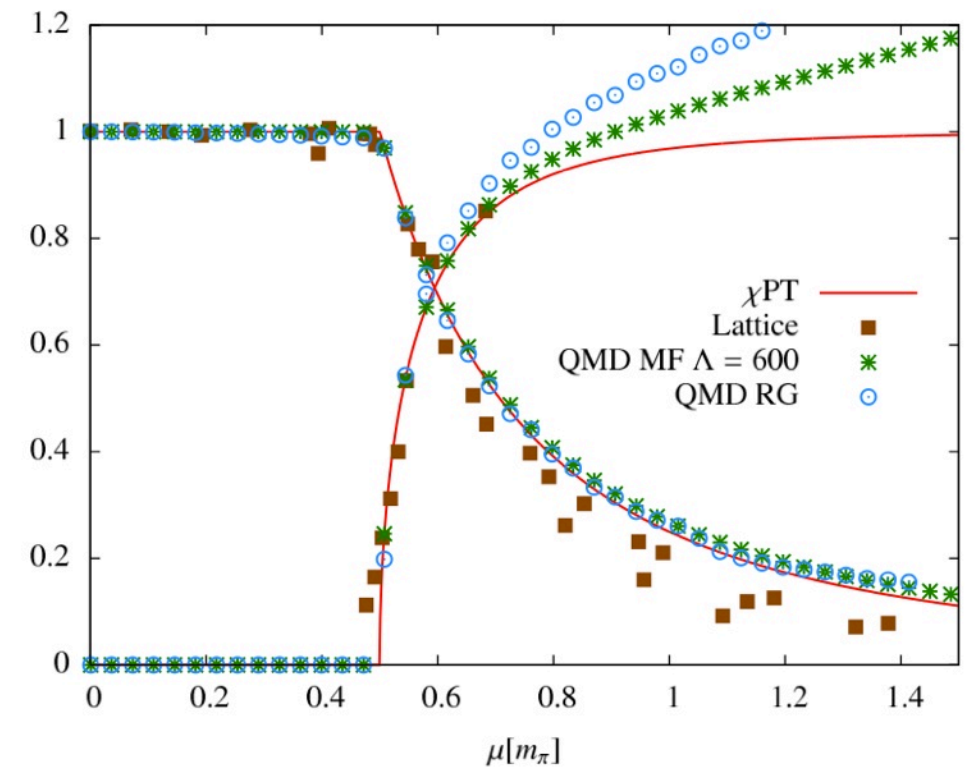
[Strodthoff, BJS, von Smekal; 2012]

Including diquarks

Symmetry breaking $SO(6) \longrightarrow SO(3) \times SO(2)$

need two condensates: chiral: $\langle q\bar{q}\rangle$ and diquark condensate: $\langle qq\rangle$



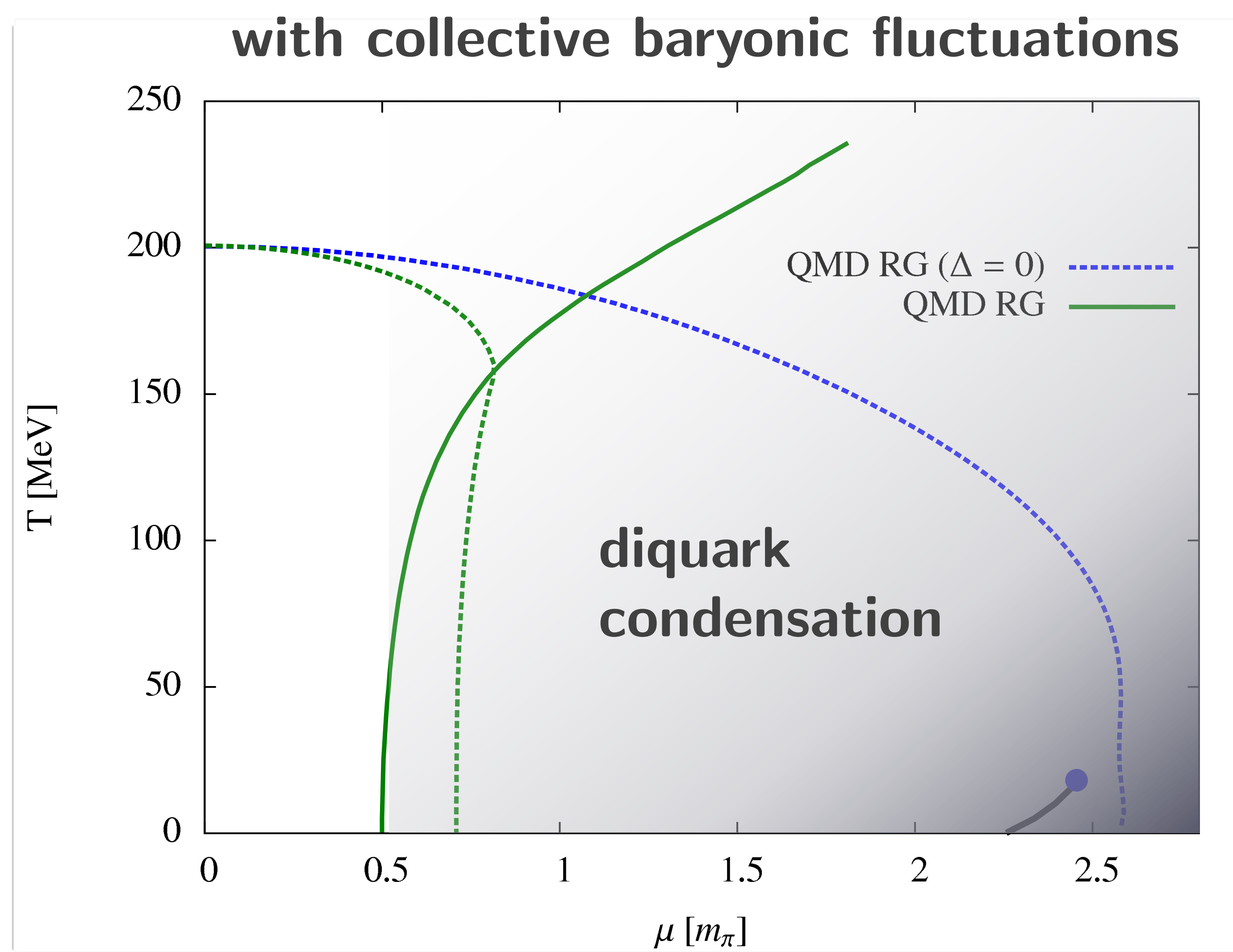


diquark condensation at $\mu_c = m_B/N_c$

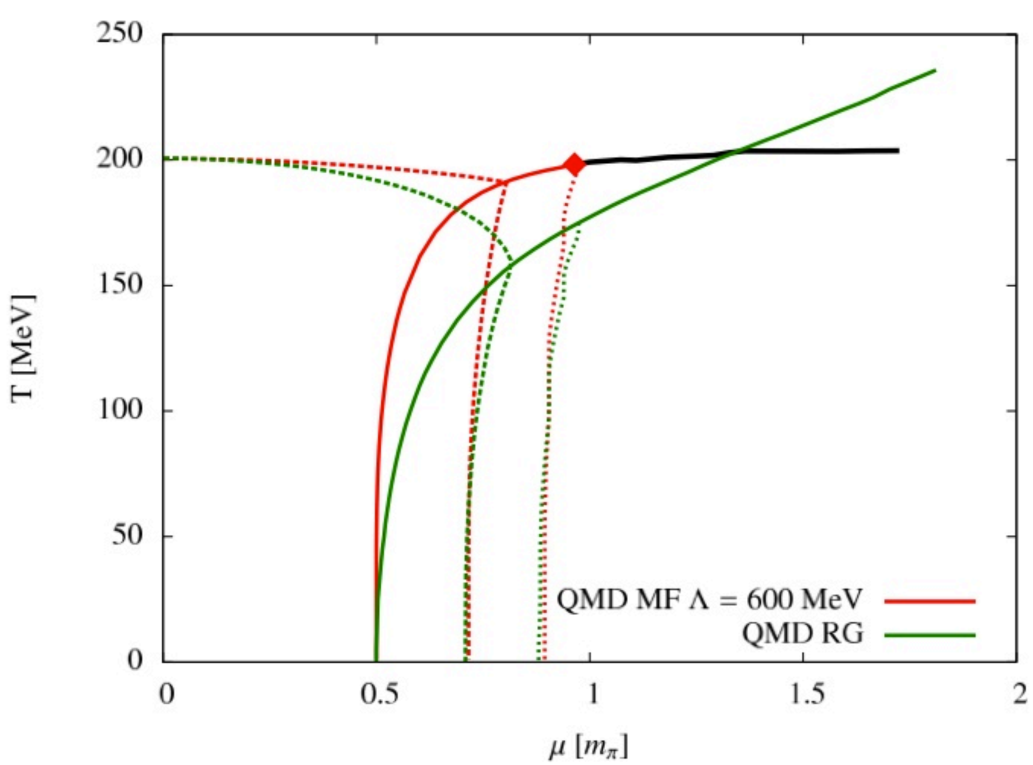
[N. Strodthoff, BJS, L. von Smekal 2012]

Phase diagrams

[N. Strodthoff, BJS, L. von Smekal 2012]



FRG versus MFA: TCP is a MFA artefact



- no low-T 1^{st} order transition, no CEP at $\mu \sim 2.5\ m_\pi$!

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Summary & Conclusions

- QCD-like model studies for two and three flavors

- effects of quantum and thermal fluctuations on QCD phase structure

- QCD for two colors: towards an understanding of role of baryons on phase structure

- existence of critical points in phase diagram

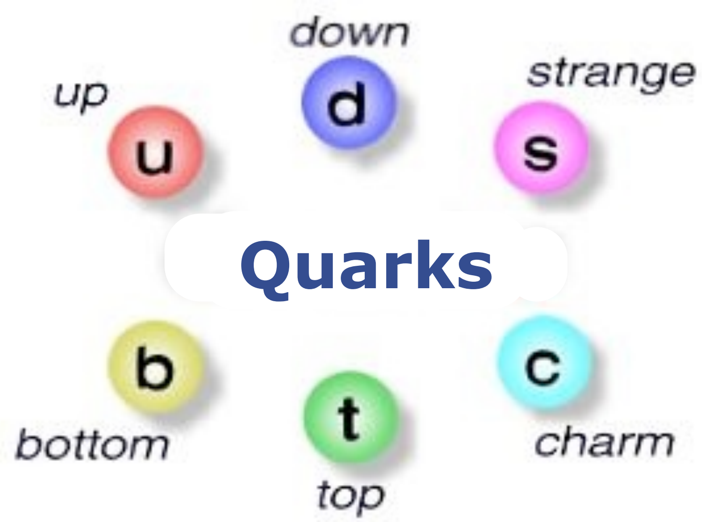
functional approaches (e.g. FRG) are suitable and controllable tools to investigate the QCD phase diagram and its boundaries

Backup material

Dynamical chiral symmetry breaking

Two important properties of low-energy QCD: **2. Dynamical chiral SB**

dynamical quark mass generation via weak and strong force



Yoichiro Nambu,
Nobel prize 2008

	u	d	s	c	b	t
M_{weak} $[MeV/c^2]$	3	5	80	1200	4500	176000
M_{strong} $[MeV/c^2]$	350	350	350	350	350	350
M_{total} $[MeV/c^2]$	350	350	450	1500	4800	176000