QCD Phase Structure and Compact Objects

Bernd-Jochen Schaefer

Bundesministerium für Bildung und Forschung
Germany

Justus-Liebig-Universität Giessen
Germany

HIC for FAIR
Helmholtz International Center
Germany

October 11th, 2019

40th Max Born Symposium – Three Days on Strong Correlations in Dense Matter

9-12 October 2019
University of Wrocław

Yerevan, 22.9.2019

Thank you, David, for an unforgettable birthday

Yerevan, 22.9.2019

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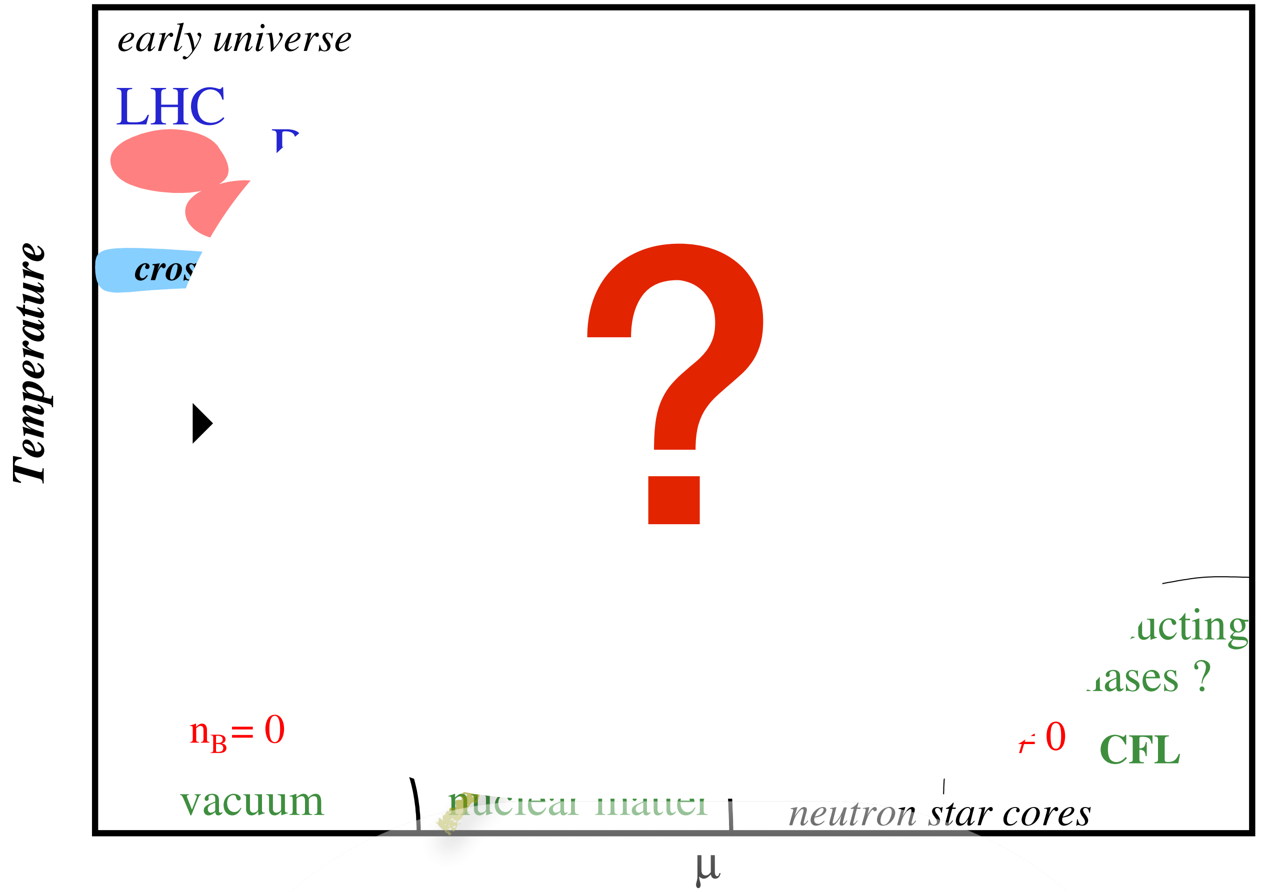
QC₃D phase structure



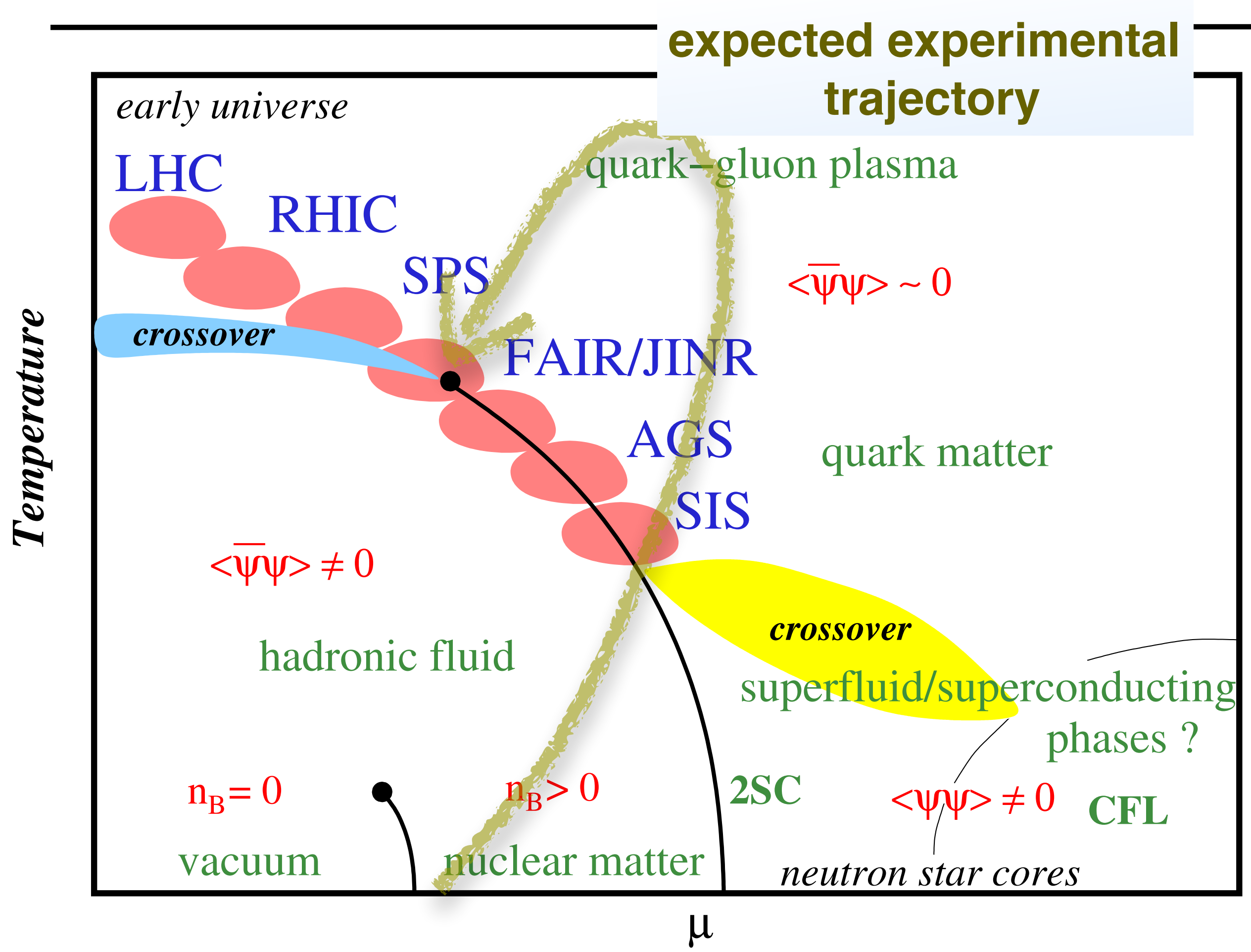
vacuum ↔ nuclear matter/transition &

only corners of the QCD phase diagram

are known from

"first principles" QCD

conjectured QC$_3$D phase structure



knowledge so far

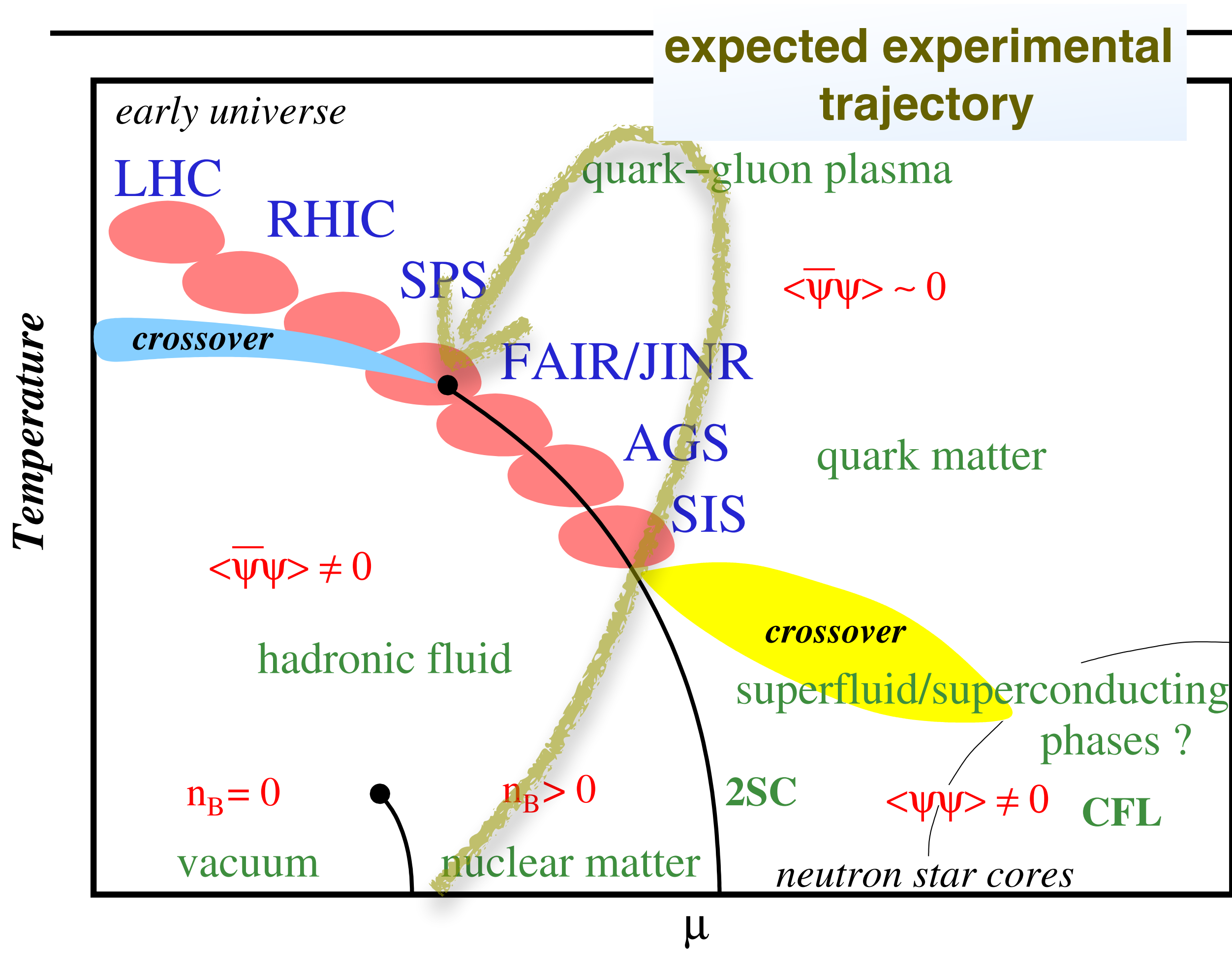
mostly based on model calculations

assumptions:

equilibrium, homogeneous phases,

infinite volume, ...

conjectured QC_3D phase structure



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Open issues

- **CEP:** existence/location/number
- relation between chiral & deconfinement?

  chiral ⇔ deconfinement CEP?
- **Quarkyonic phase:** coincidence of both transitions at μ=0 & μ>0?
- **inhomogeneous phases?** ➜ more favored?
- **axial anomaly restoration** around chiral transition?
- **finite volume effects?** ➜ lattice comparison/ influence boundary conditions
- **role of fluctuations?** so far mostly Mean-Field results

  ➜ **effects of fluctuations important**

  examples: size of crit reg. around CEP
- **What are good experimental signatures?**

  ➜ cumulants?

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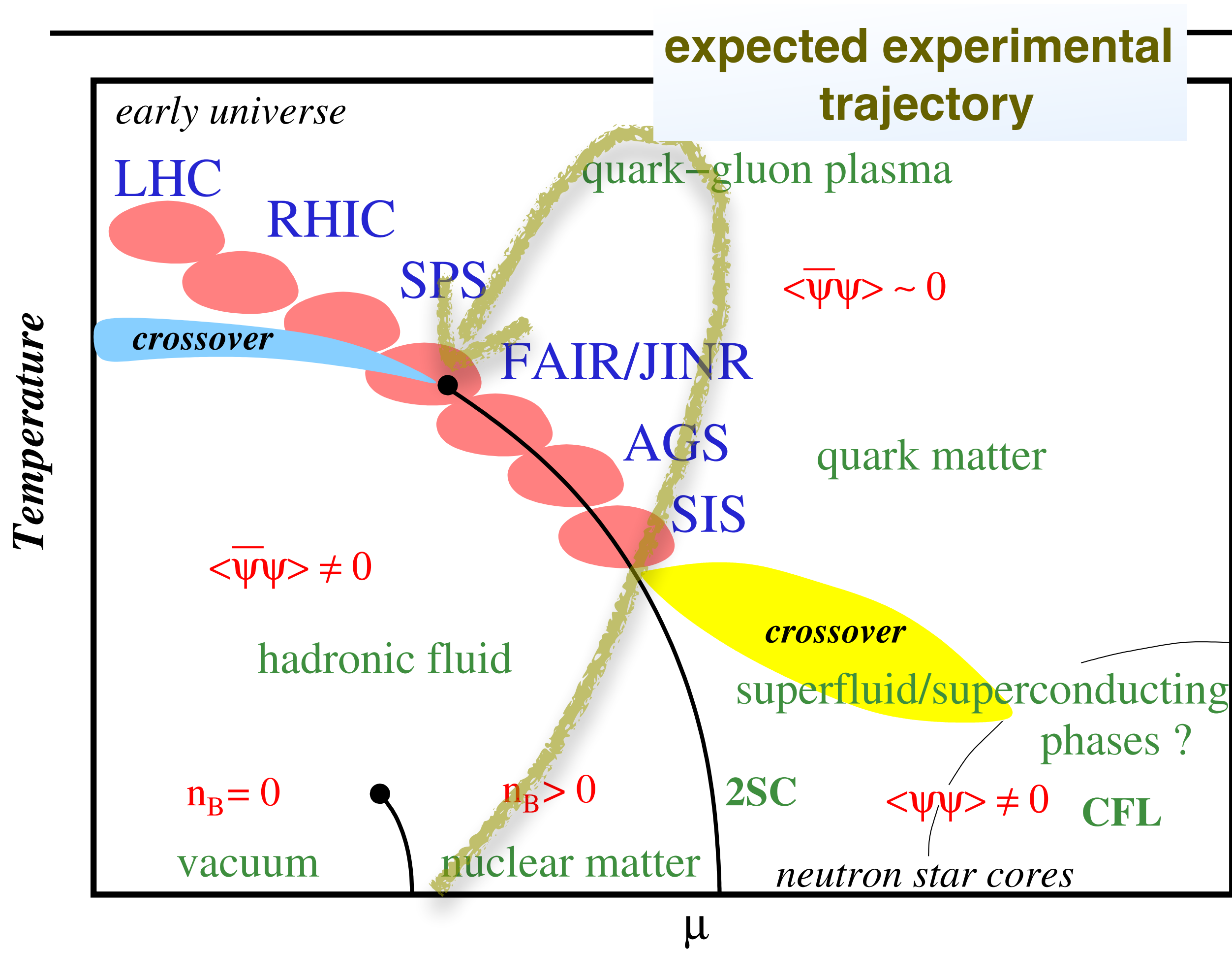
conjectured QC$_3$D phase structure



Theory:

➜ Lattice: but simulations restricted to small μ

➜ Models: effective theories

parameter dependency

➜ **Functional QFT approaches:**
FRG, DSE, nPI, Variational Methods

knowledge so far

mostly based on model calculations

assumptions:

equilibrium, homogeneous phases,

infinite volume, ...

Theoretical aim:

deeper understanding & more realistic HIC description

➜ solution of QCD for all densities

conjectured QC_3D phase structure

our method of choice

Functional Renormalization Group

(FRG)

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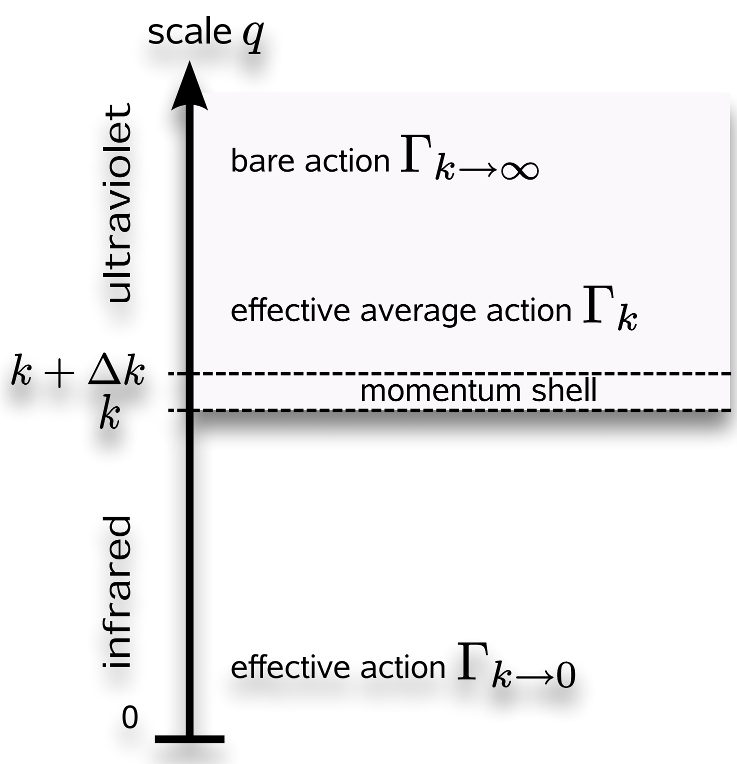
Functional Renormalization Group

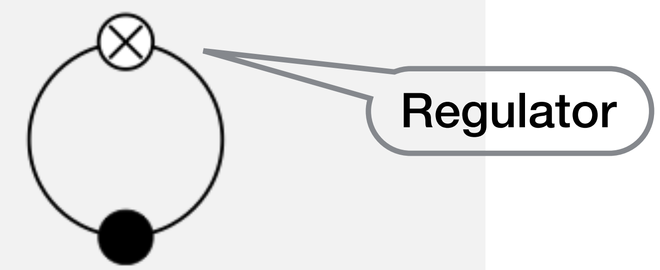
- $\Gamma_k[\phi]$ scale dependent effective action $\quad t = \ln(k/\Lambda) \quad R_k$ regulators $\quad \Gamma_k^{(2)} = \frac{\delta^2 \Gamma_k}{\delta\phi\delta\phi}$



FRG (average effective action)

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

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



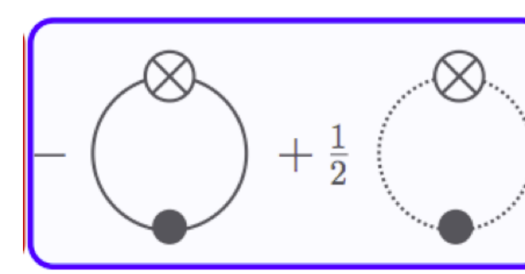
[Wetterich 1993]

- Ansatz for Γ_k: Example: Quark-Meson truncation in leading order derivative expansion

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

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

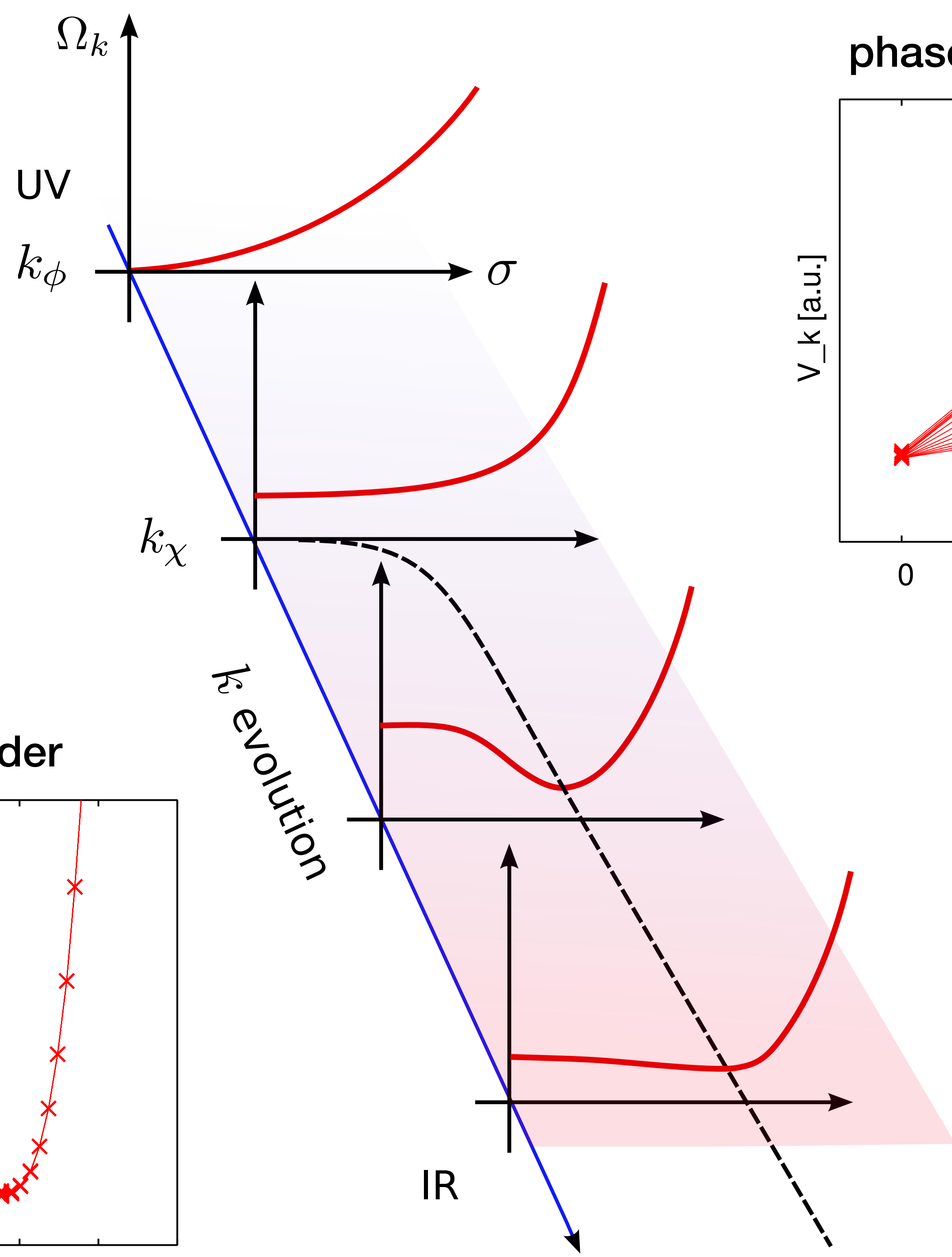
arbitrary potential



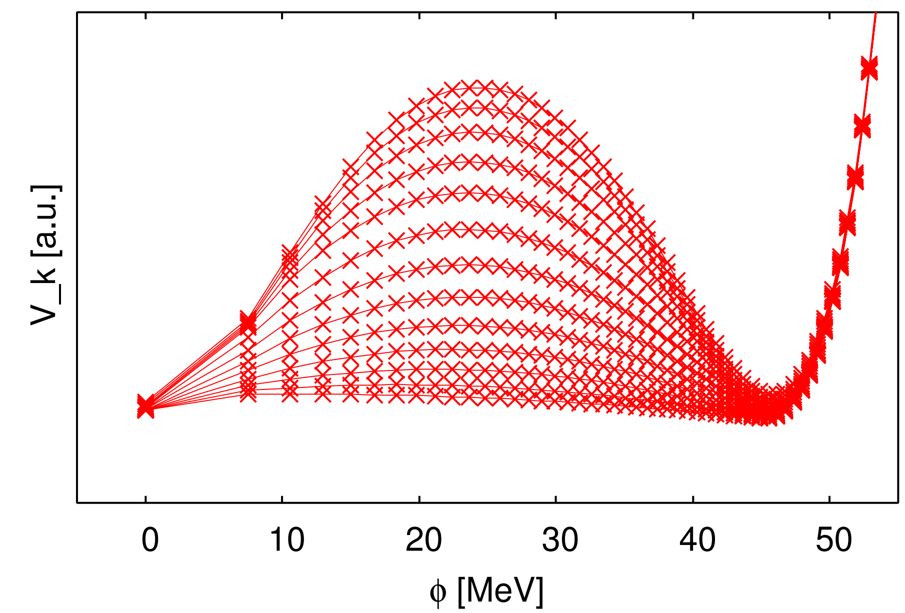
RG scale evolution

Input: potential at high scales

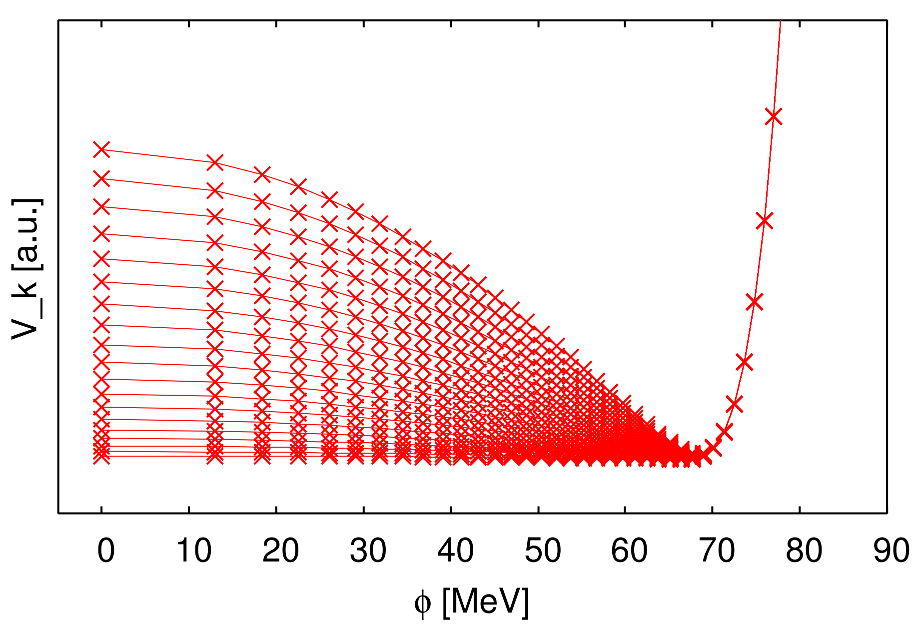
e.g. Meson potential or QCD ...



phase transition: First order



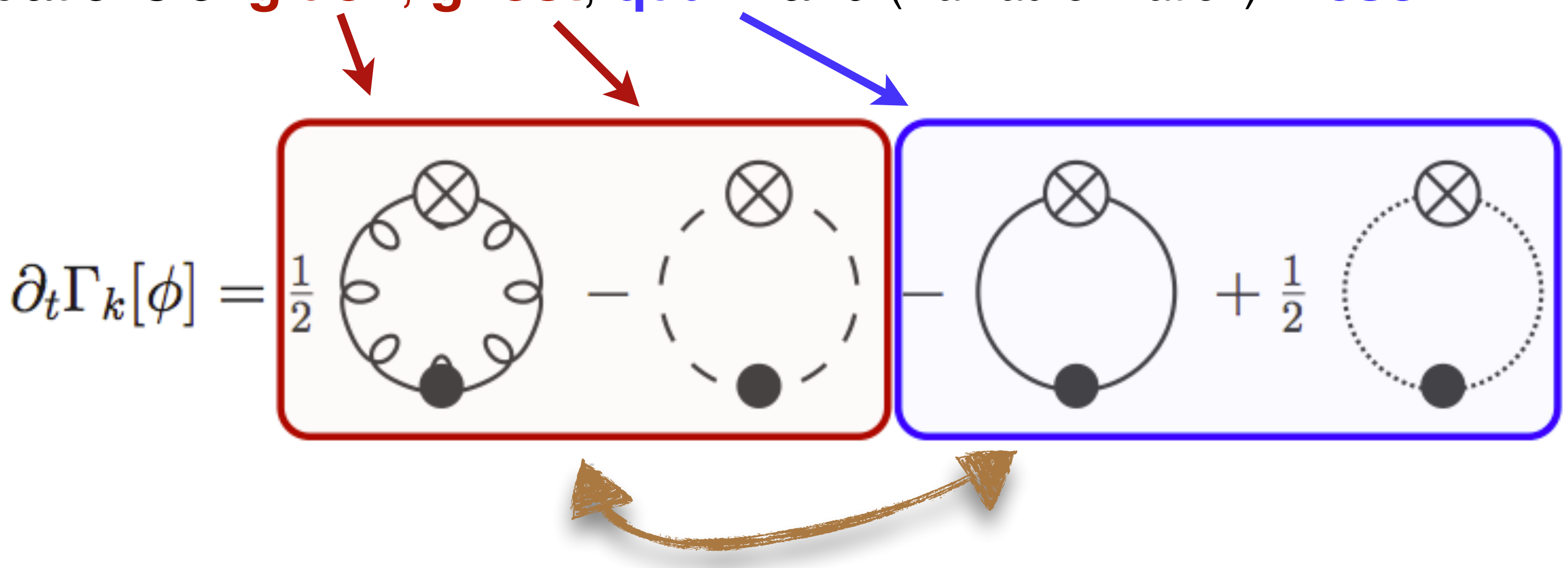
phase transition: Second Order



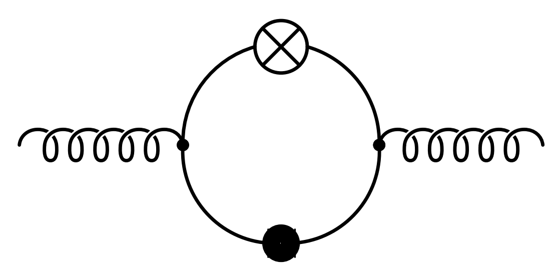
FRG and QCD

- **full dynamical QCD FRG flow:** [fQCD: Pawlowski, Rennecke et al. since 2009]

fluctuations of **gluon**, **ghost**, **quark** and (via hadronization) **meson**



in presence of **dynamical quarks**:
gluon propagator is modified

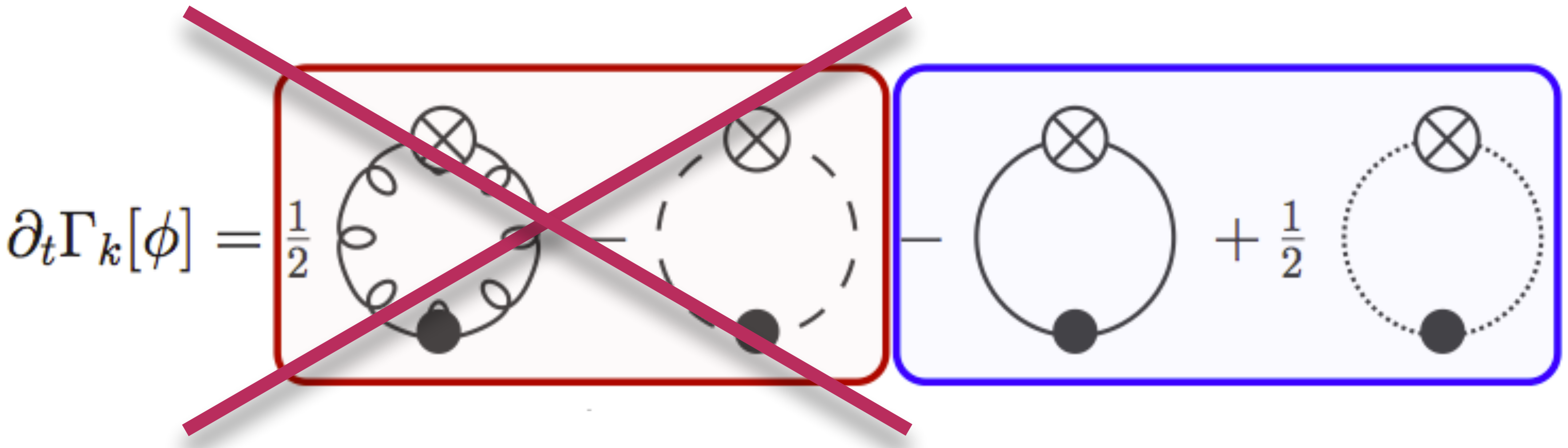


pure Yang Mills flow + matter back-coupling

FRG: quark-meson truncation

chiral phase transition:

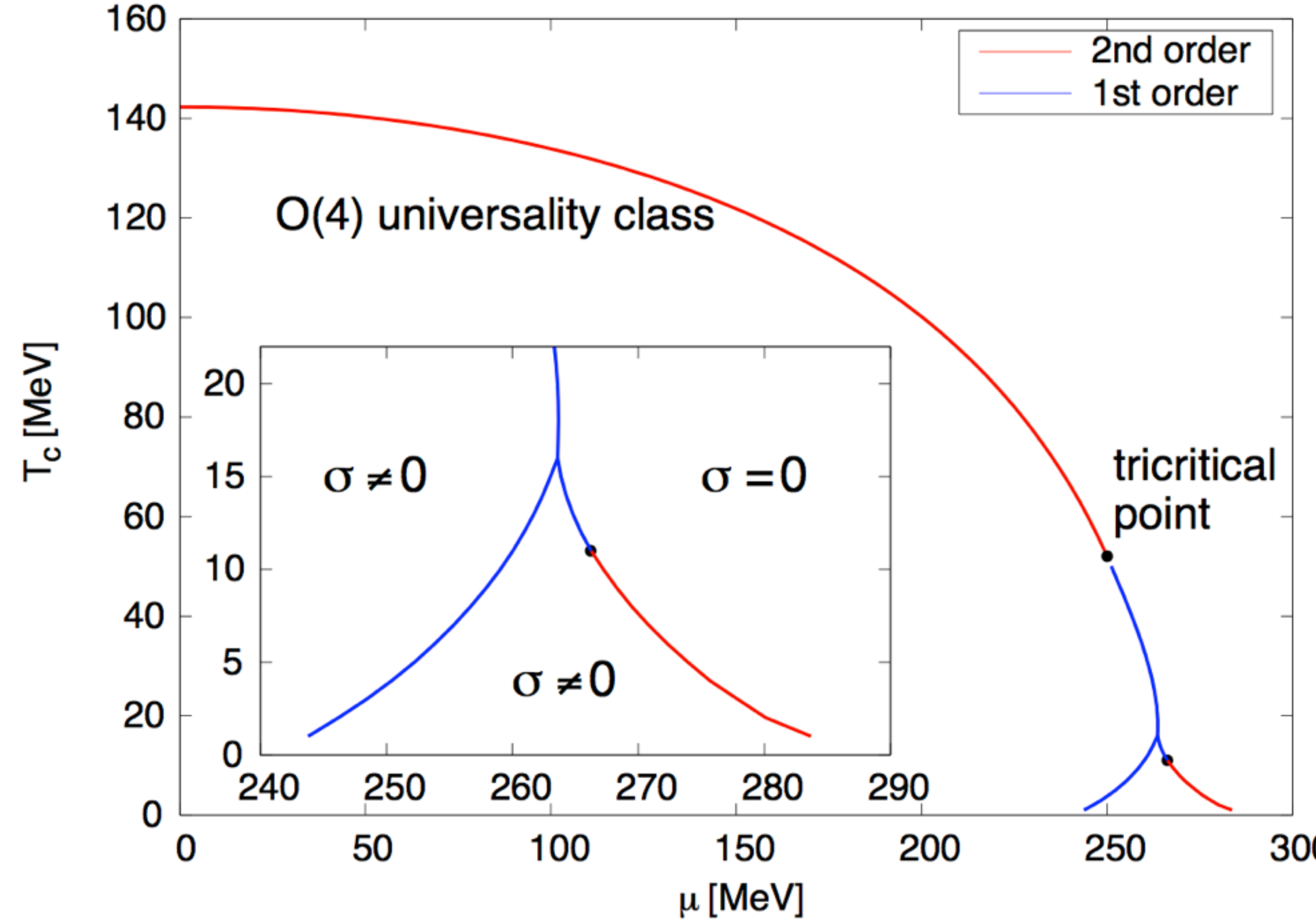
flow for **quark-meson** model truncation:
neglect
YM contributions and bosonic fluctuations



**without bosonic fluctuations:
extended Mean-field approximation**

Phase diagram N_f=2

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



[BJS, Wambach 2005]

Phase diagram N_f=2

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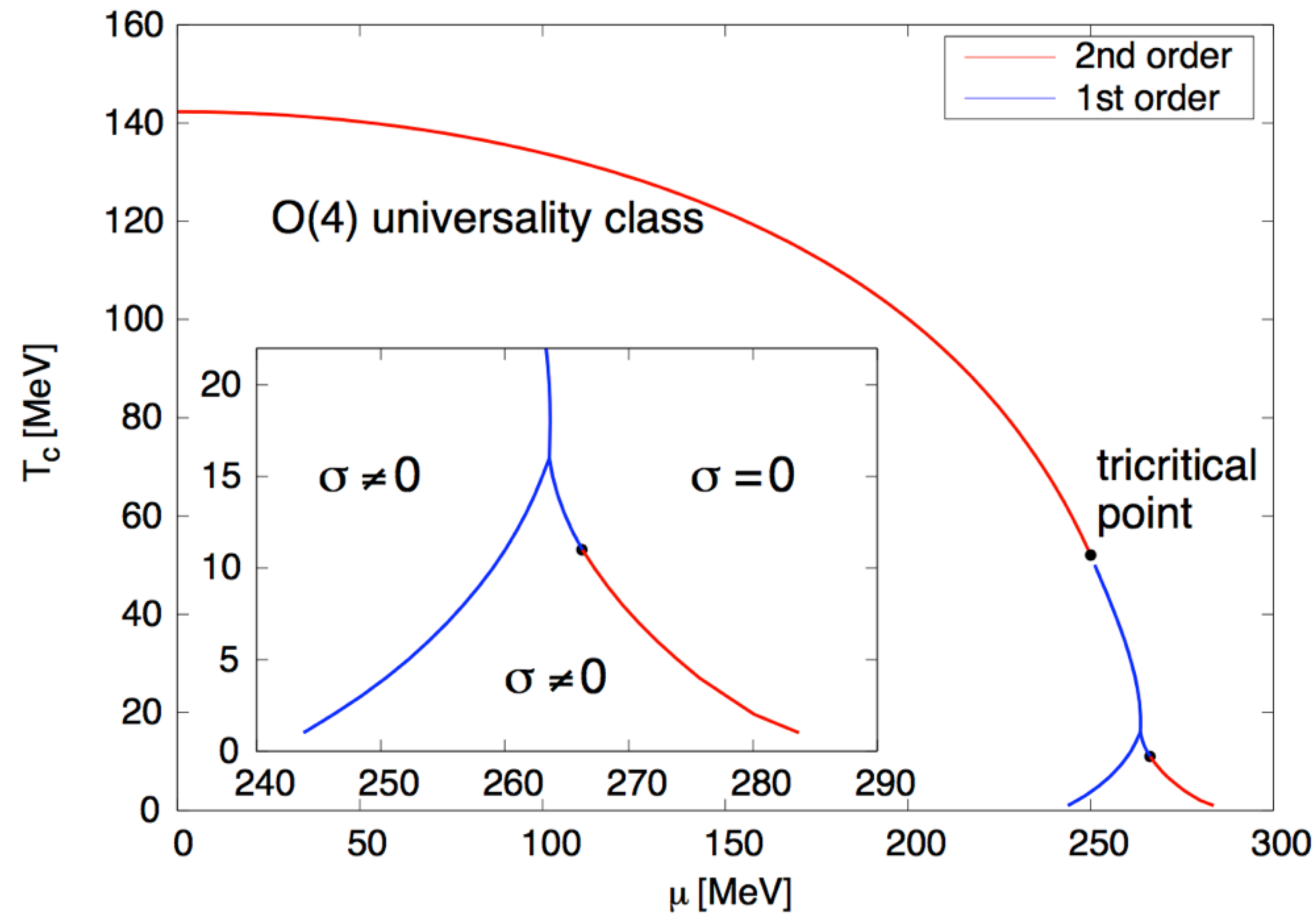
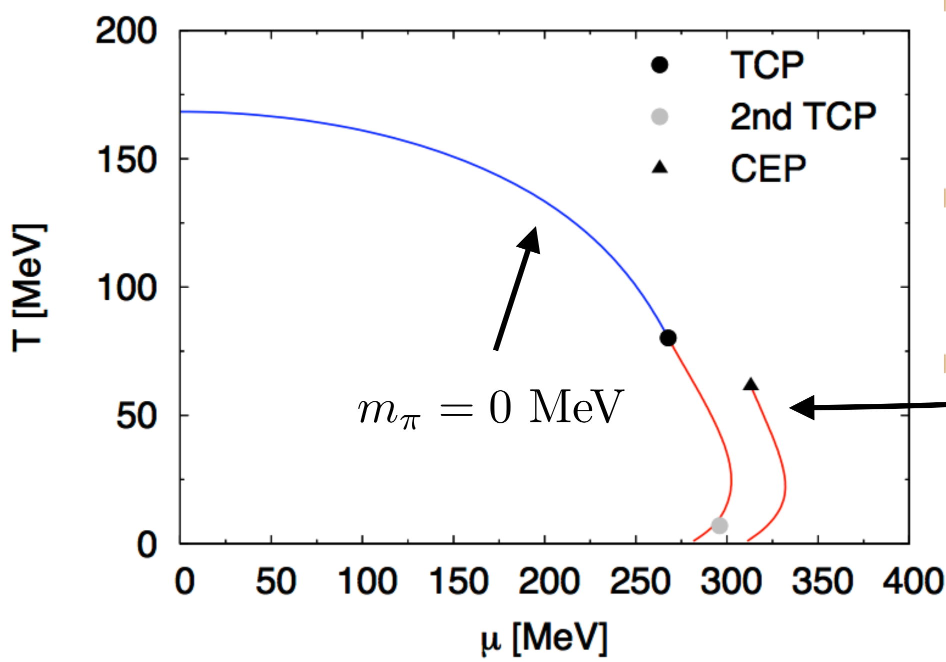


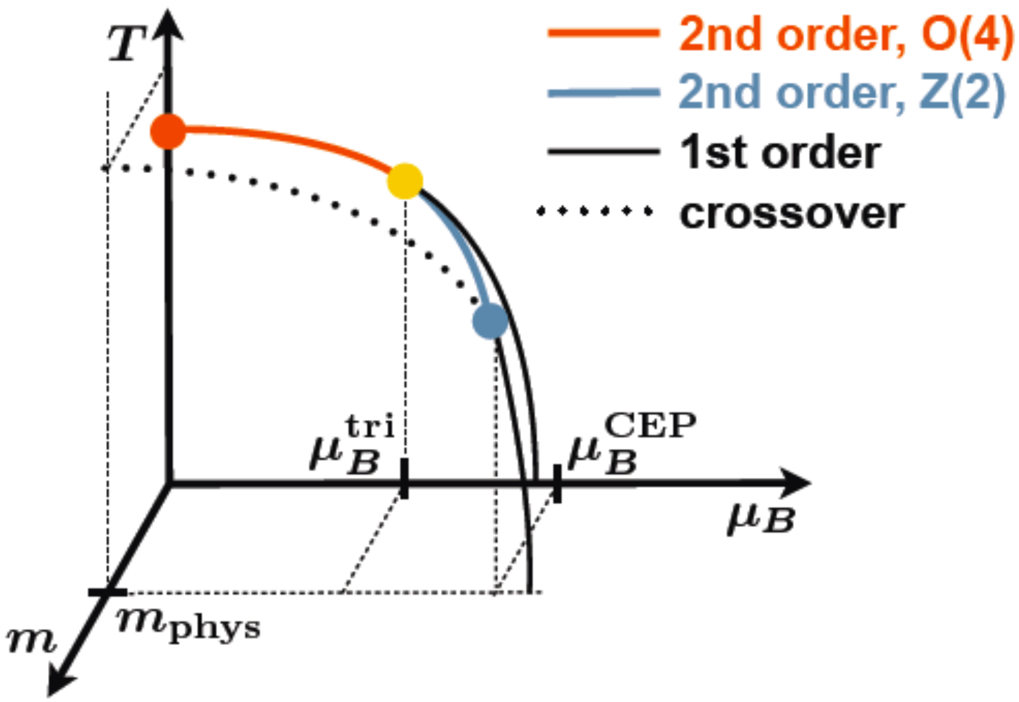
[BJS, Wambach 2005]



$m_\pi = 138$ MeV

⬅ two phase diagrams

Phase diagram N_f=2



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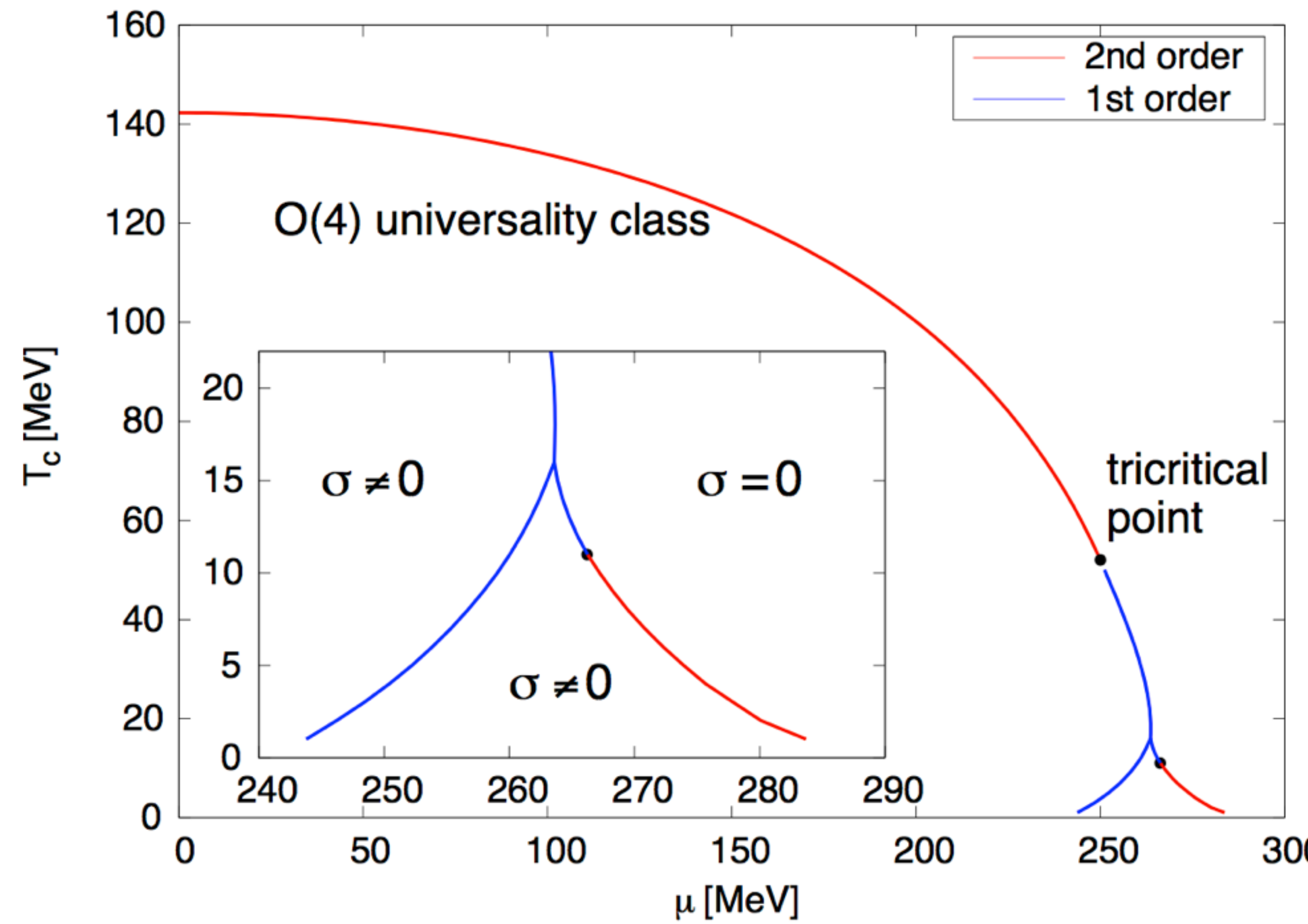
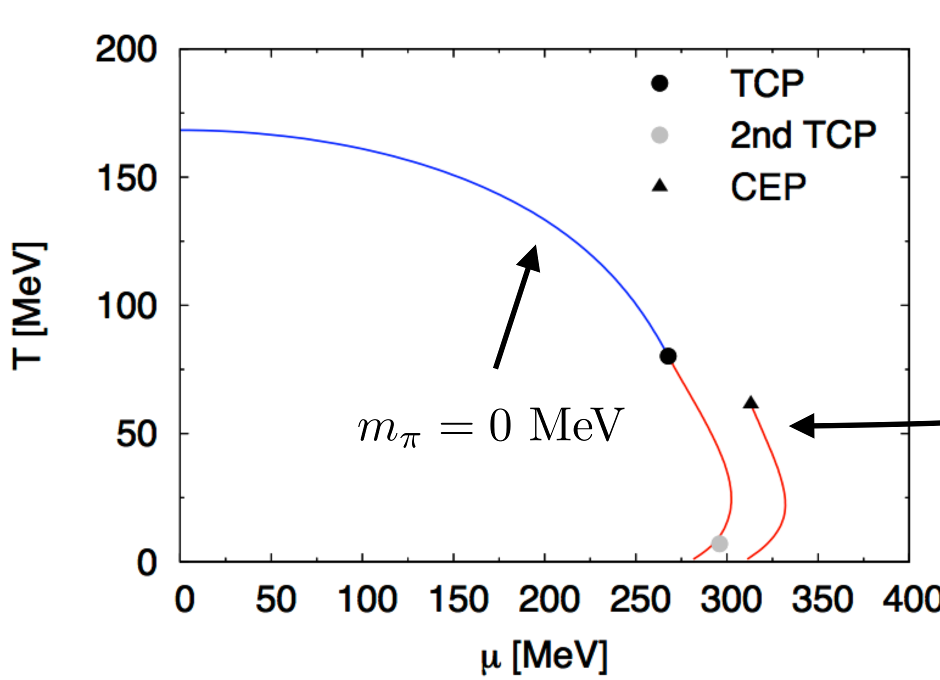


[BJS, Wambach 2005]



$m_\pi = 138$ MeV

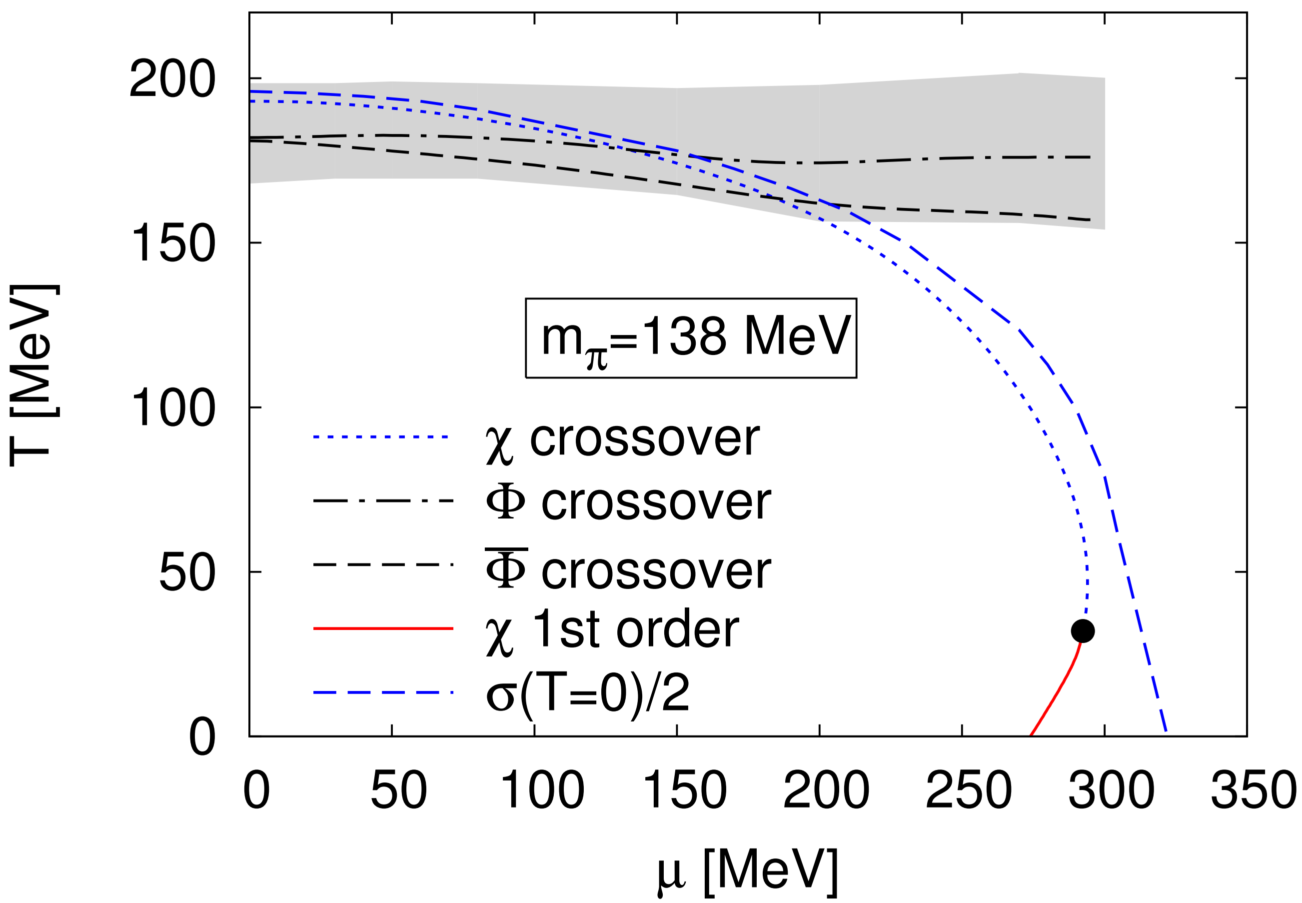
⬅ two phase diagrams

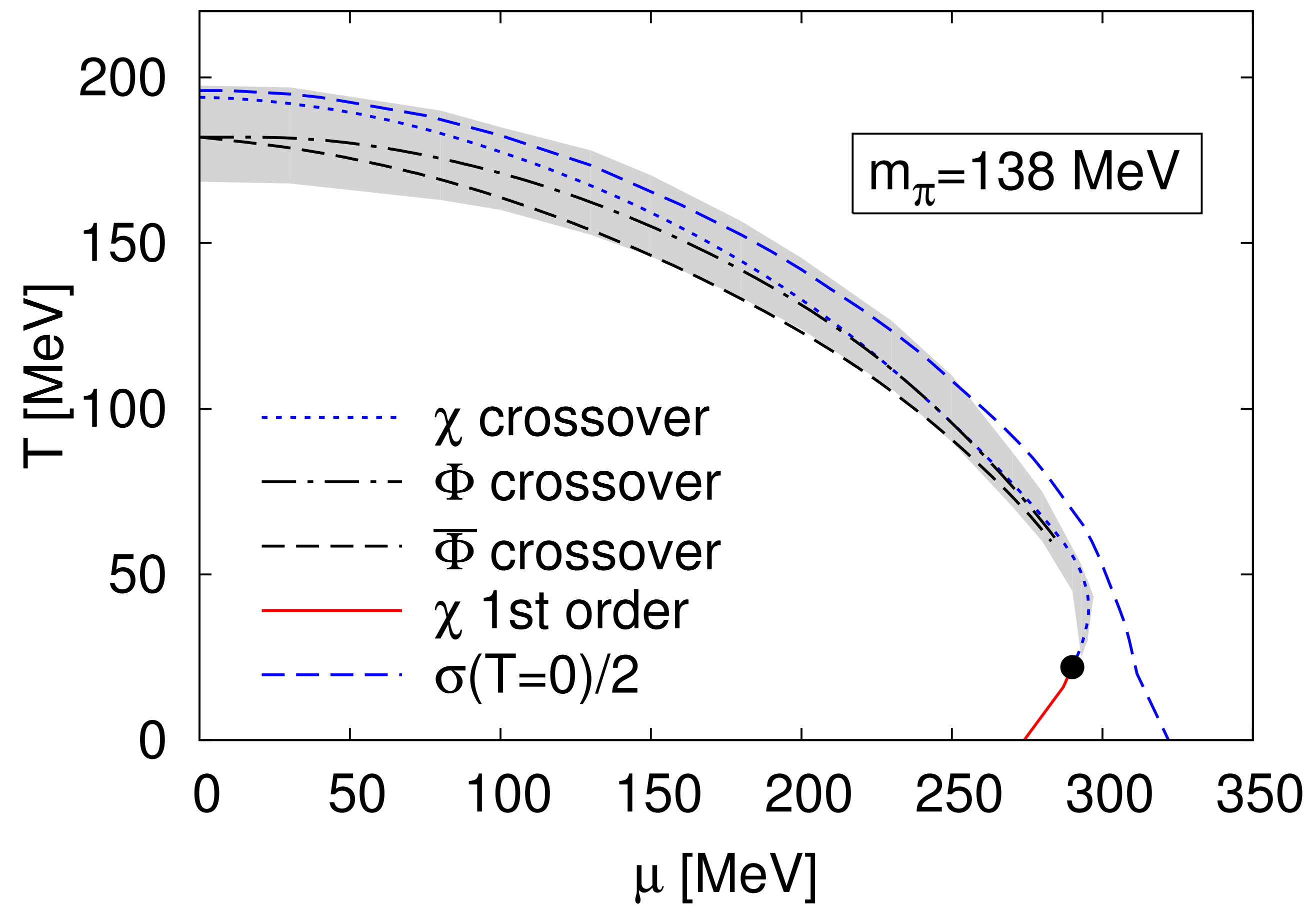
FRG: Quark-Meson with Polyakov

N_f =2 quark flavor

without back reaction $(T_0(\mu) = \text{const})$

with back reaction $(T_0(\mu))$





[Herbst, Pawlowski, BJS 2010,2013]

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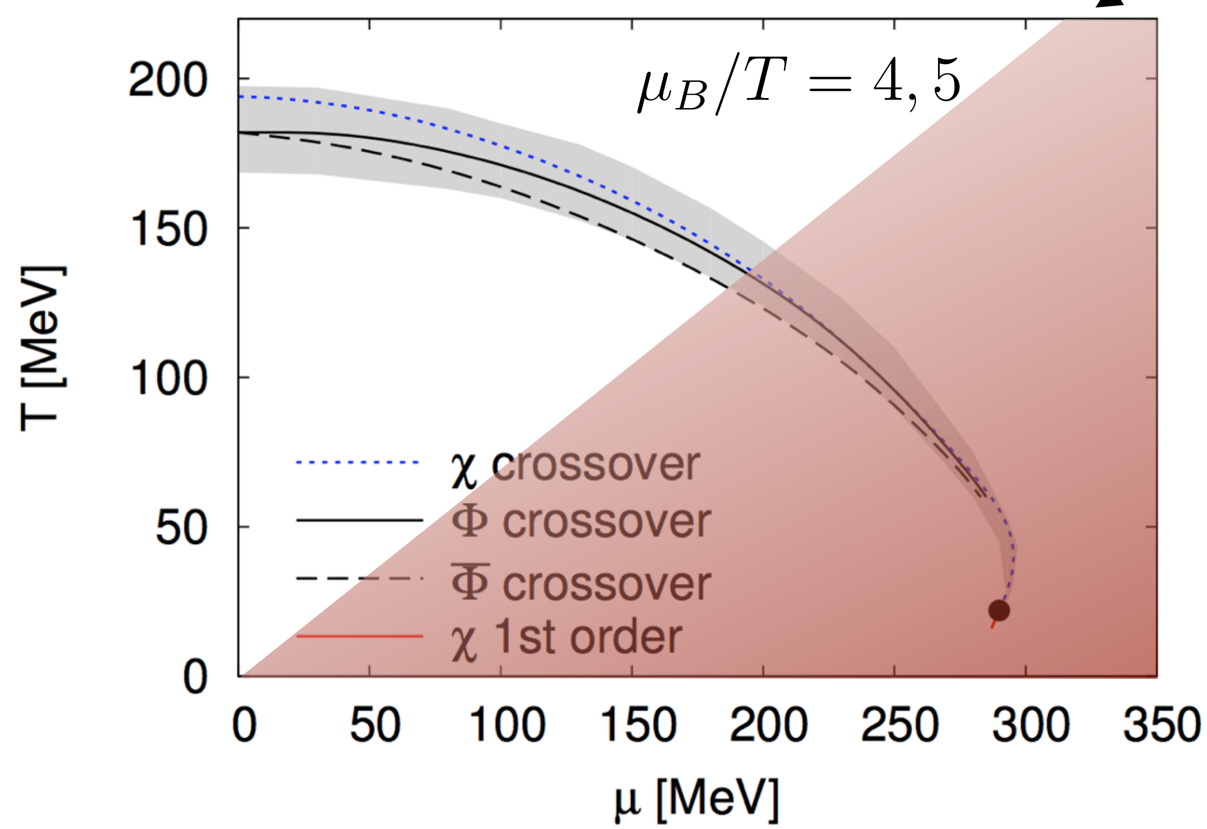
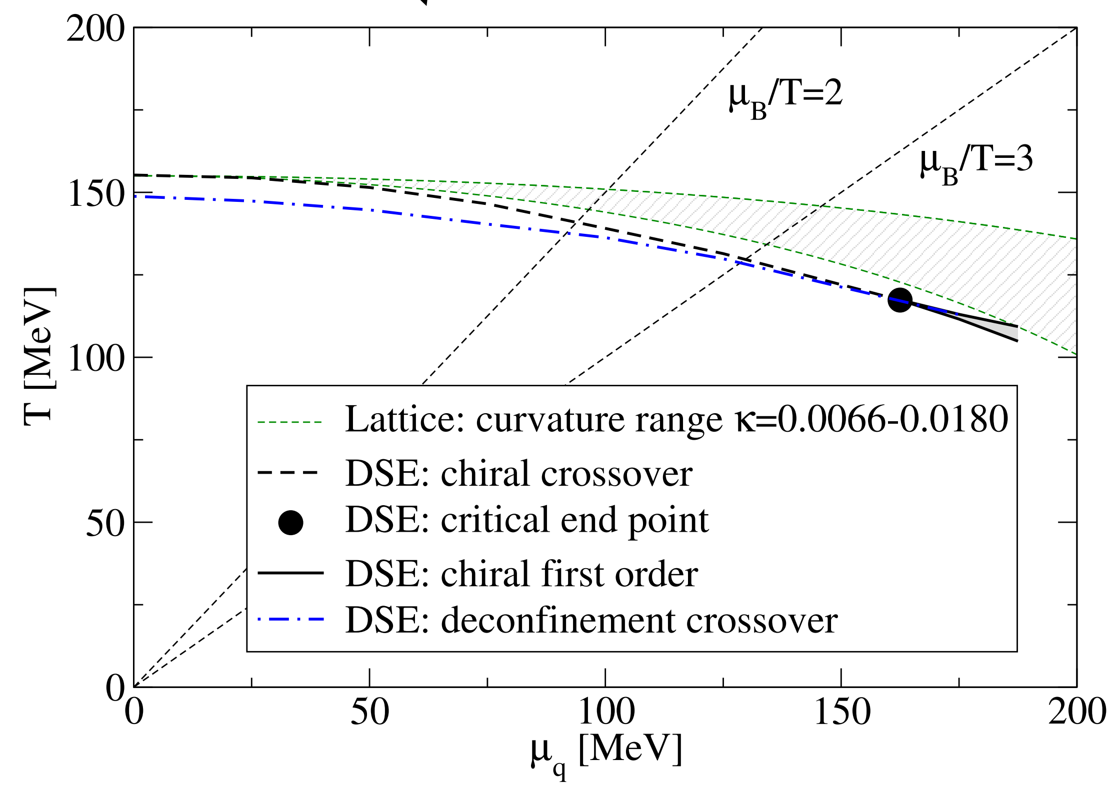
Critical Endpoint ?

Exact location of CEP **not** (**yet**) accessible with lattice, FRG & DSE



[Herbst, Pawlowski, BJS 2011]



[Fischer, Luecker, Welzbacher 2014]

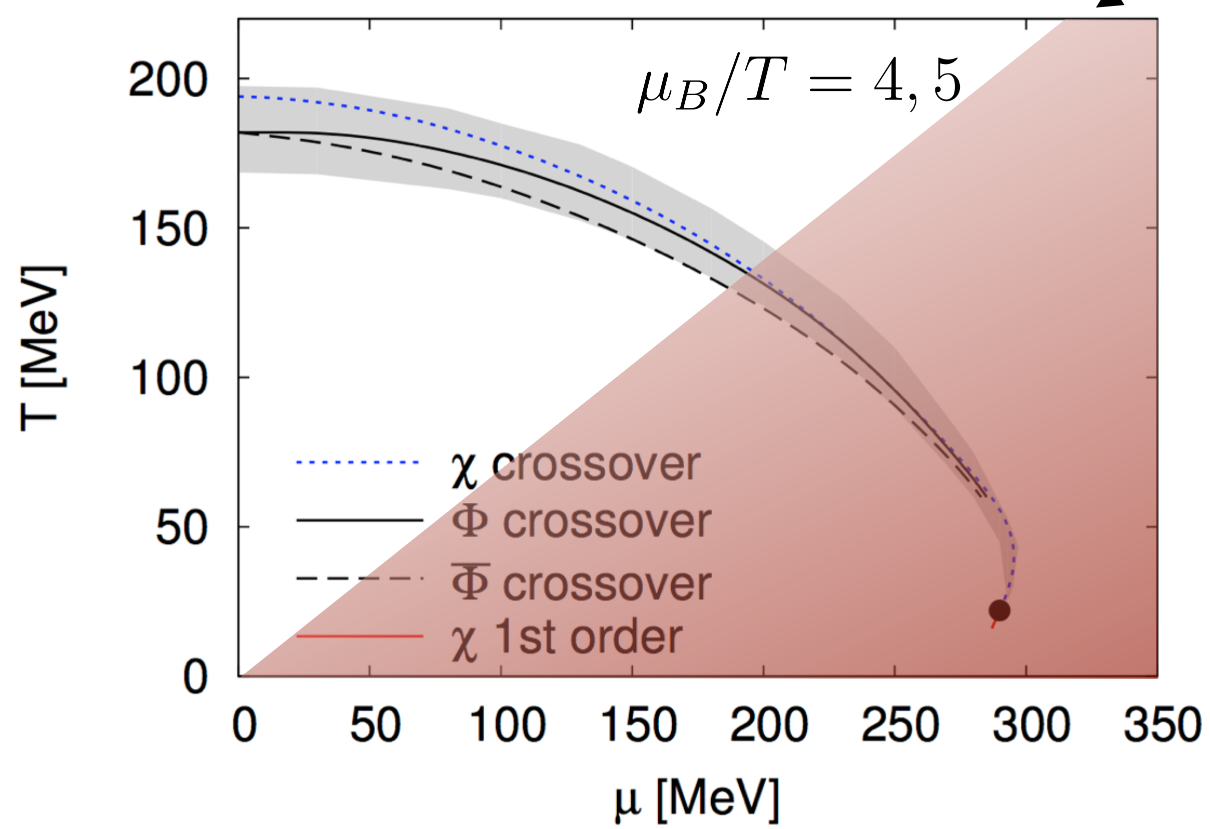
so far:

we can exclude CEP for small densities: $\mu_B/T<3$

Higher densities: dynamical baryons needed! ➜ relevant for neutron star EoS

Critical Endpoint ?

Exact location of CEP **not** (**yet**) accessible with lattice, FRG



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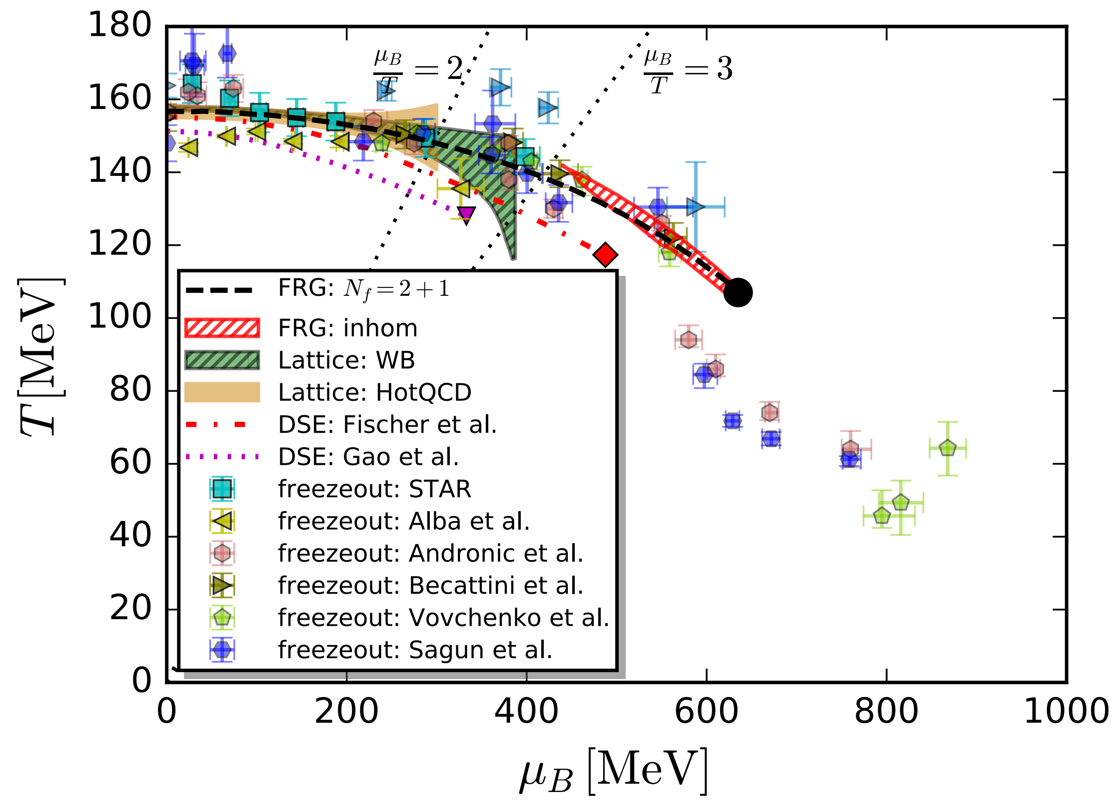


[Fu, Pawlowski, Rennecke 2019]

so far:

we can exclude CEP for small densities: $\mu_B/T<3$

Higher densities: dynamical baryons needed! ➜ relevant for neutron star EoS

FRG and truncations

FRG has a controlled truncation scheme

Compare different orders

Different FRG truncations

[Rennecke, BJS 2018]

- different truncations:

$$\Gamma_k = \int_x \Big\{ \bar{q}\, Z_{q,k} \big(\gamma_\mu \partial_\mu + \gamma_0 \mu\big) q + \bar{q} h_k \cdot \Sigma_5 q + \mathrm{tr}\big(Z_{\Sigma,k}\, \partial_\mu \Sigma \cdot \partial_\mu \Sigma^\dagger\big) + \tilde{U}_k(\Sigma) \Big\}$$

truncation	running couplings
LPA′+Y	$\bar{\tilde{U}}_k,\ \bar{h}_{l,k},\ \bar{h}_{s,k},\ Z_{l,k},\ Z_{s,k},\ Z_{\phi,k}$
LPA+Y	$\bar{\tilde{U}}_k,\ \bar{h}_{l,k},\ \bar{h}_{s,k}$
LPA	$\bar{\tilde{U}}_k$

LPA = local potential approximation = leading order derivative expansion

Y = Yukawa coupling running

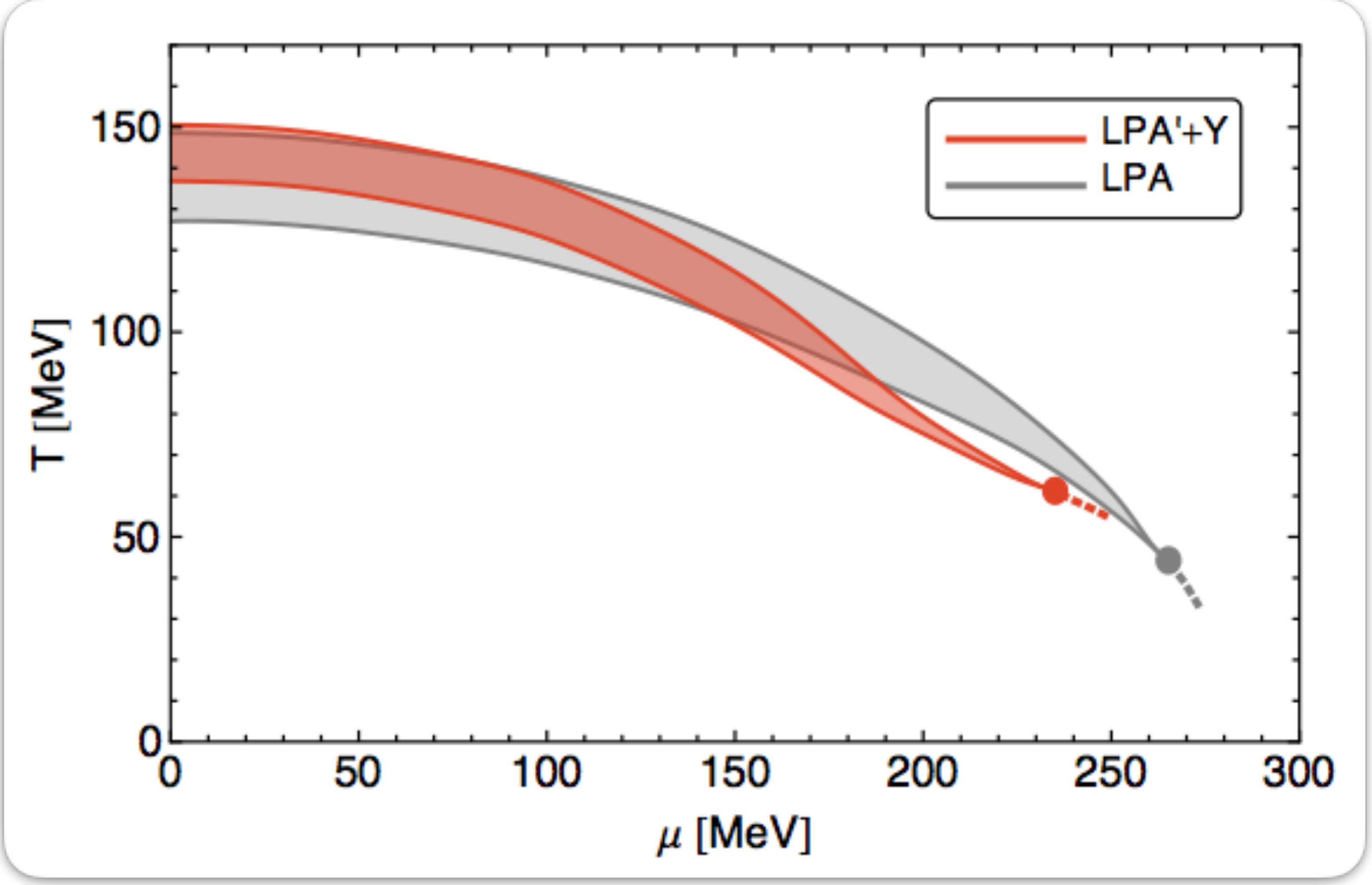
LPA’ = beyond local potential approximation include wave function renormalization

Chiral Phase Diagram

- Critical Endpoint for different truncations:

[Rennecke, BJS 2018]

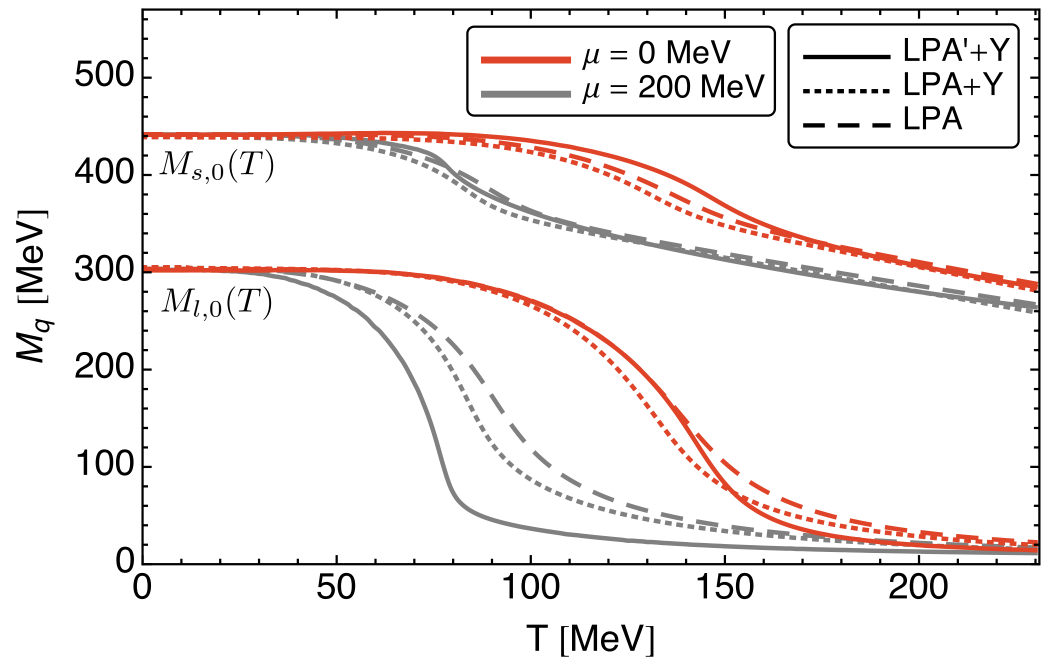
truncation	running couplings	$(T_{\mathrm{CEP}}, \mu_{\mathrm{CEP}})$ [MeV]
LPA′+Y	$\tilde{\bar{U}}_k,\ \bar{h}_{l,k},\ \bar{h}_{s,k},\ Z_{l,k},\ Z_{s,k},\ Z_{\phi,k}$	(61,235)
LPA+Y	$\tilde{\bar{U}}_k,\ \bar{h}_{l,k},\ \bar{h}_{s,k}$	(46,255)
LPA	$\tilde{\bar{U}}_k$	(44,265)



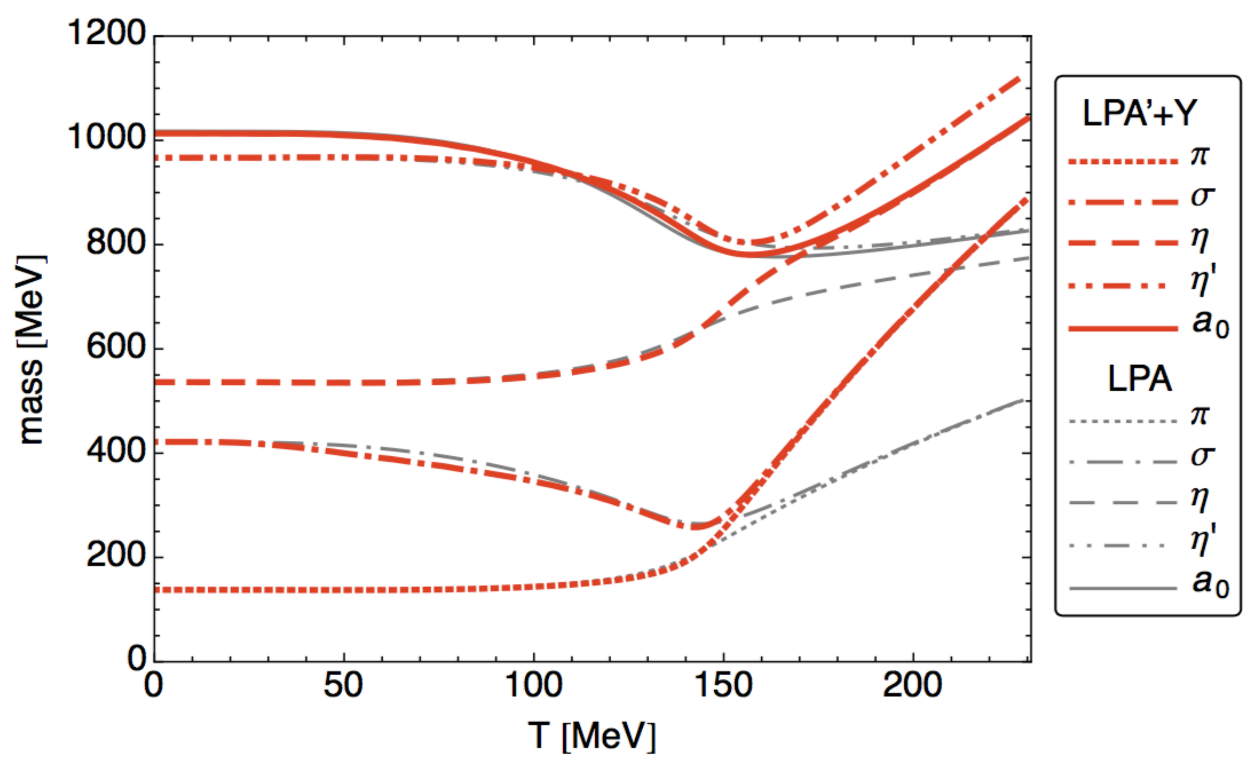
Masses

[Rennecke, BJS 2018]

- quark masses



- meson masses



driven by the mesonic wave-function renormalization

mesons decouple more rapidly beyond LPA

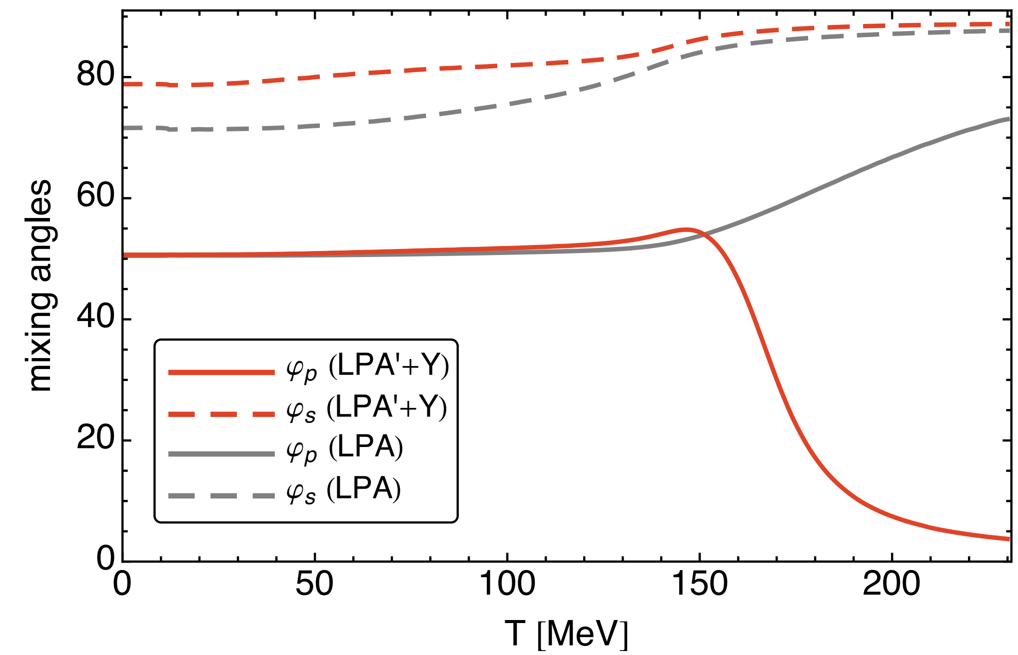
Chiral multiplets

[Rennecke, BJS 2018]

- mixing angles determine light and strange quark content of σ, f0, η, η' mesons

$$\begin{pmatrix} f_0 \\ \sigma \end{pmatrix} = \begin{pmatrix} \cos\varphi_s & -\sin\varphi_s \\ \sin\varphi_s & \cos\varphi_s \end{pmatrix} \begin{pmatrix} \sigma_l \\ \sigma_s \end{pmatrix}$$

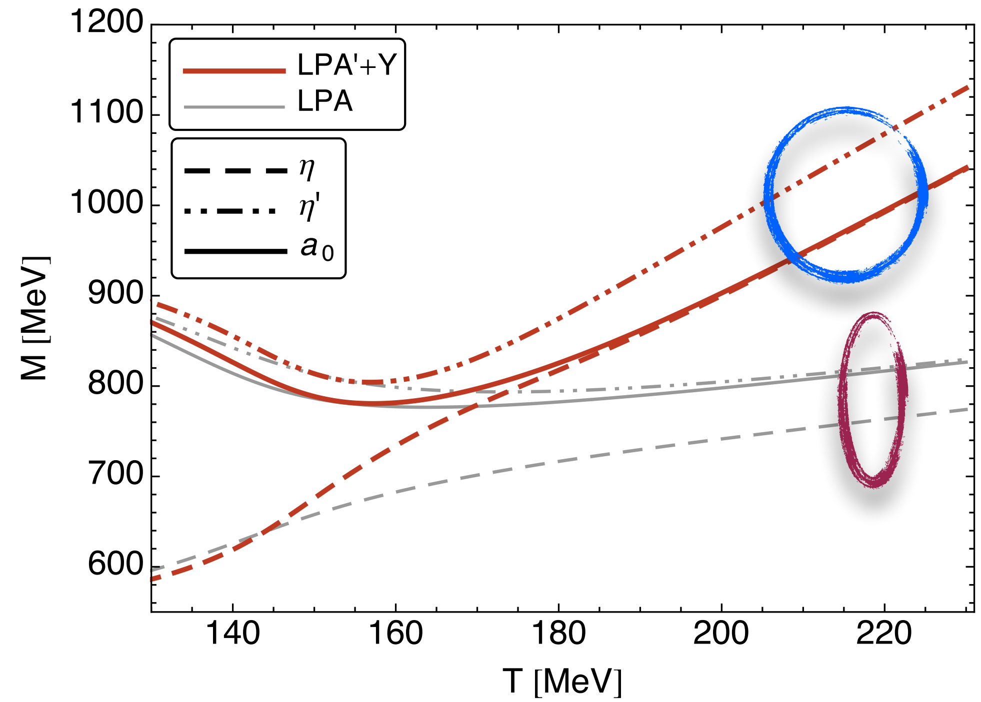
$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\varphi_p & -\sin\varphi_p \\ \sin\varphi_p & \cos\varphi_p \end{pmatrix} \begin{pmatrix} \eta_l \\ \eta_s \end{pmatrix}$$



significant effects on pseudoscalar mixing beyond LPA!

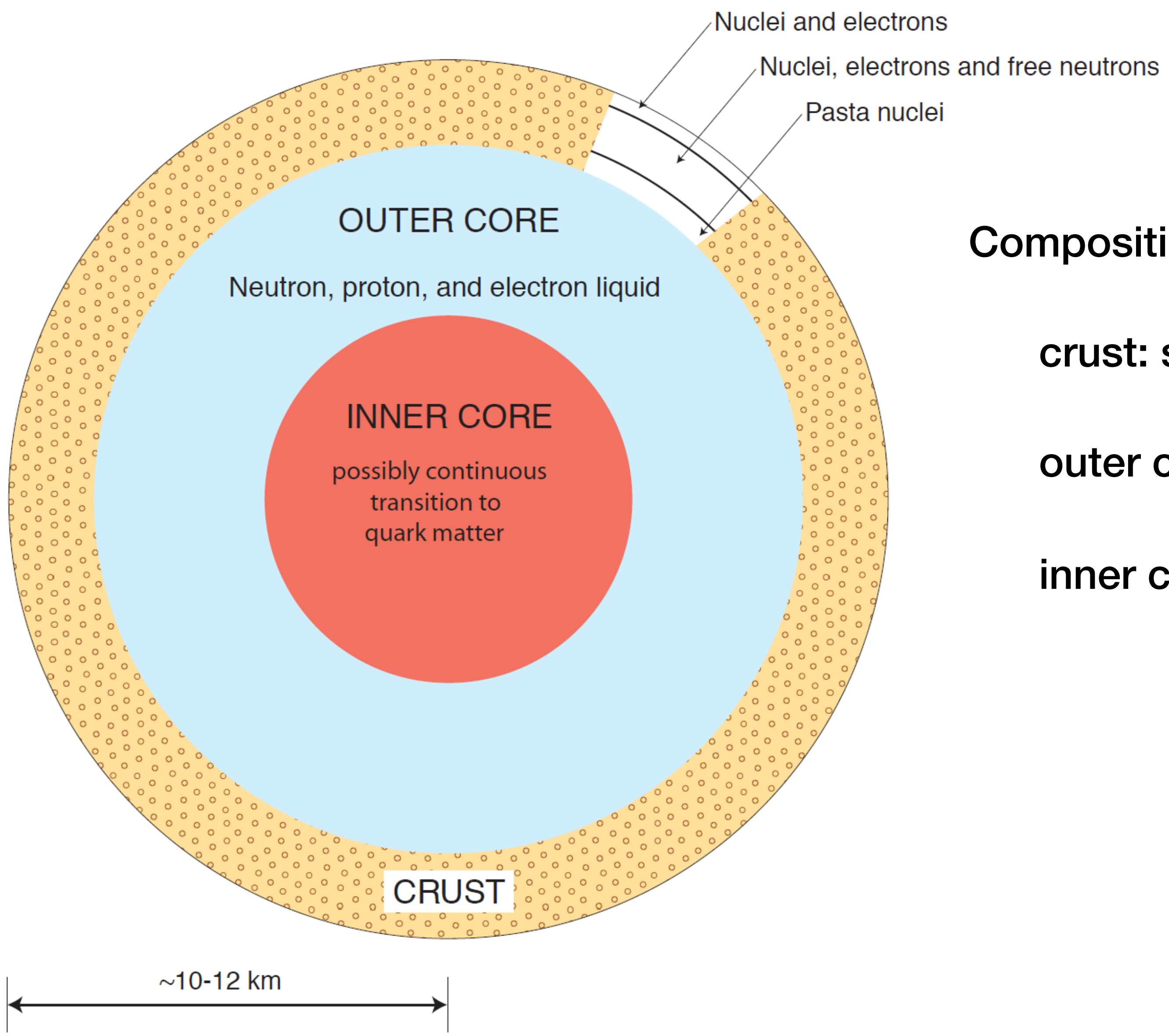
consequence: chiral partners of η and η' change!

mean-field/LPA	LPA′ + Y
(η, f_0)	(η, a_0)
(η', a_0)	(η', f_0)



Neutron Stars

[Baym 2019]



Current mass benchmark:

pulsar J0348+0432 with ~ 2 $M_\odot$

Composition:

crust: solid with transition to liquid nuclear matter

outer core: up to ~ 2 ρ_0

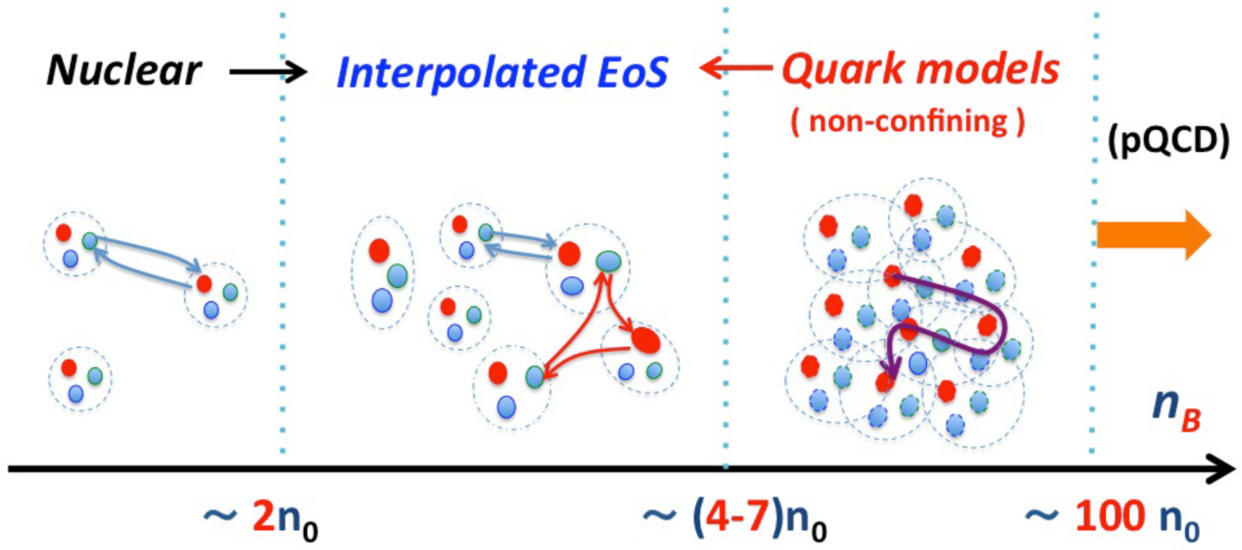
inner core: quark matter?

hyperons?

strangeness?

Equation of State

[Baym 2018]



Experimental constraints:

Radius ~ 10 - 14 km

Mass > 2 Msol

constraints on tidal deformability

Nuclear phase:

restrictions on EoS
at low densities
from nuclear physics

Quark phase:

mostly mean-field investigations
like NJL-type or phenomenological
models

[Hebeler, Lattimer, Pethick,Schwenk et al. 2010]

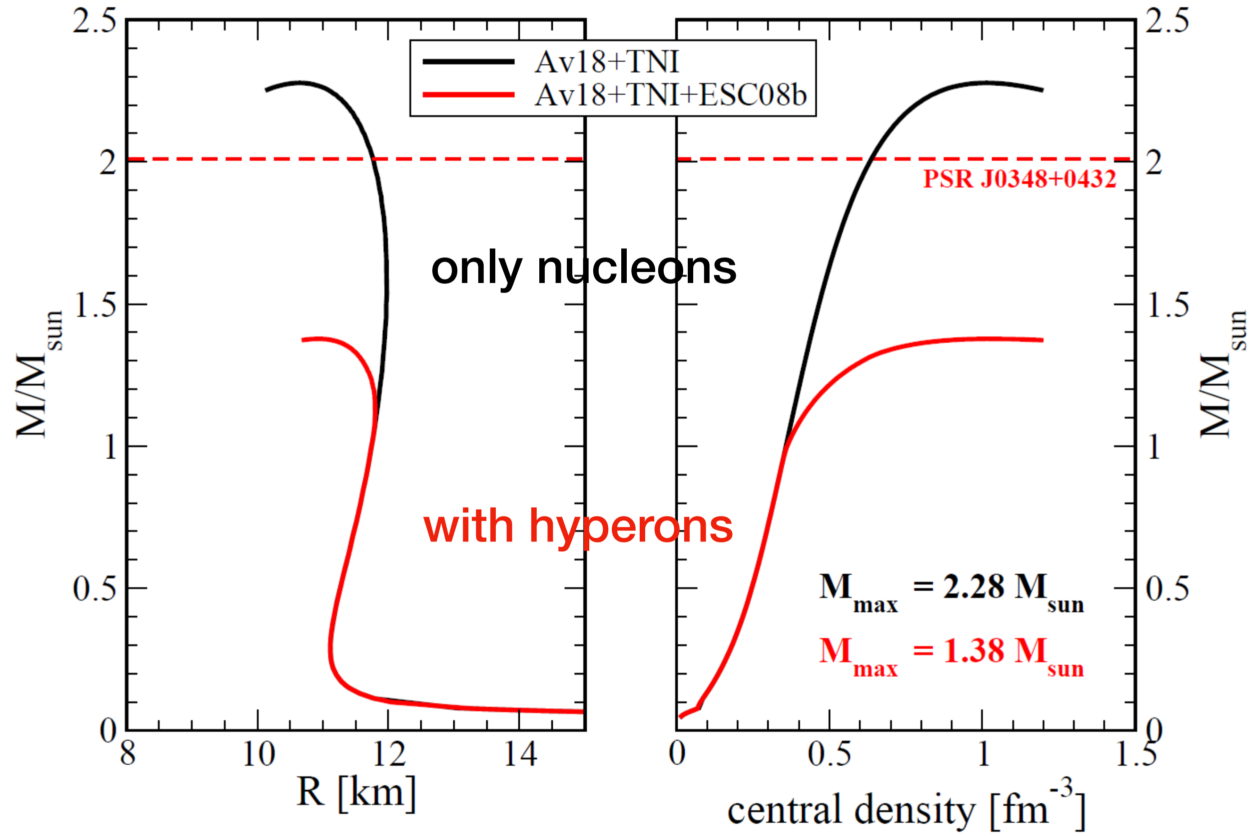
[Schaffner-Bielich et al. 2008]

[Blaschke, Fischer, Oertel et al. 2018]

combination:
Maxwell construction or continuous interpolation

Mass-Radius relation

[Bombaci 2016] hyperons puzzle



Further constraints:

stability under radial oscillations:

causality:

charge neutrality: $n_p = n_e + n_\mu$

beta equilibrium: $\mu_n = \mu_p + \mu_e$

➜ electrons and muons as free Fermi gas to energy density and pressure

General issues:

many EoS look similar ➜ similar mass-radius relation
➜ masquerade problem [Alvarez-Castillo, Blaschke 2014]

onset of strangeness in hadronic / quark phase or not at all?
➜ hyperon puzzle [Djapo, BJS, Wambach 2010]

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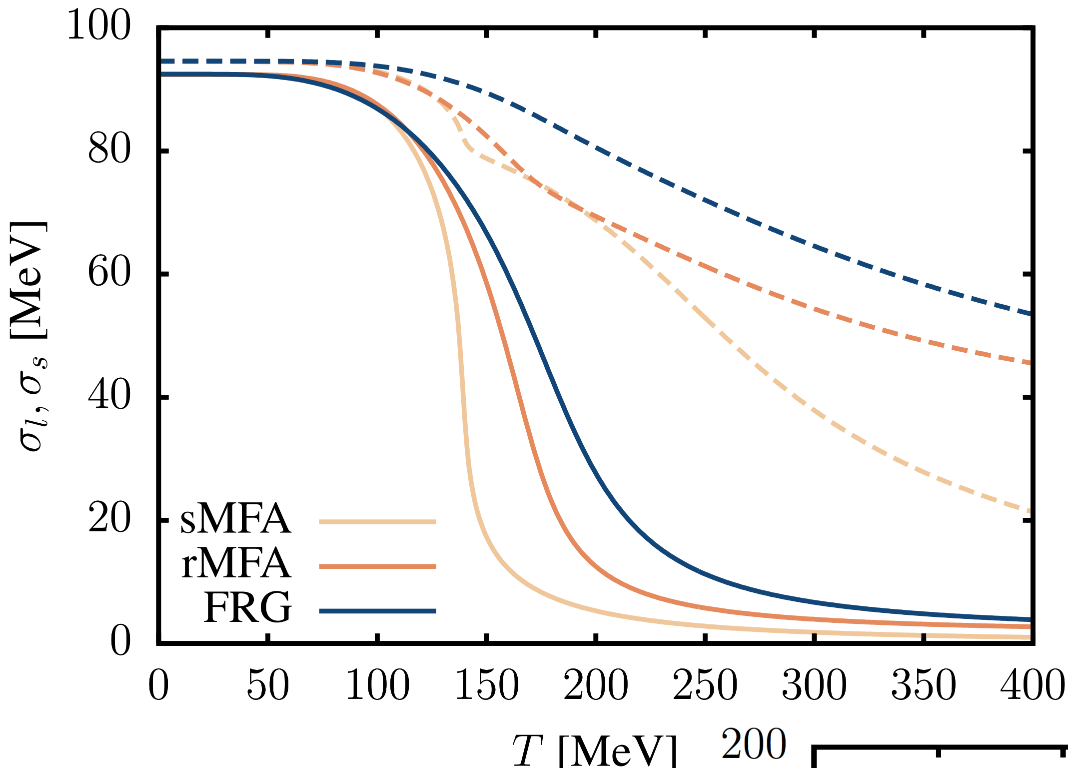
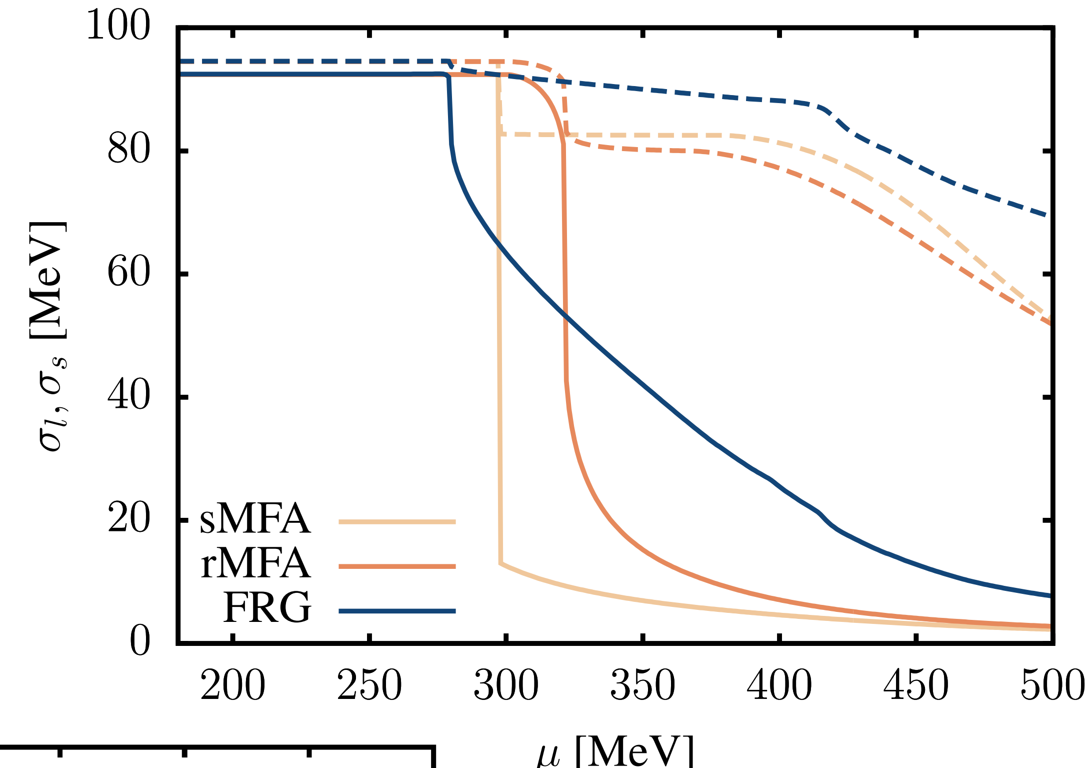
Phase diagrams





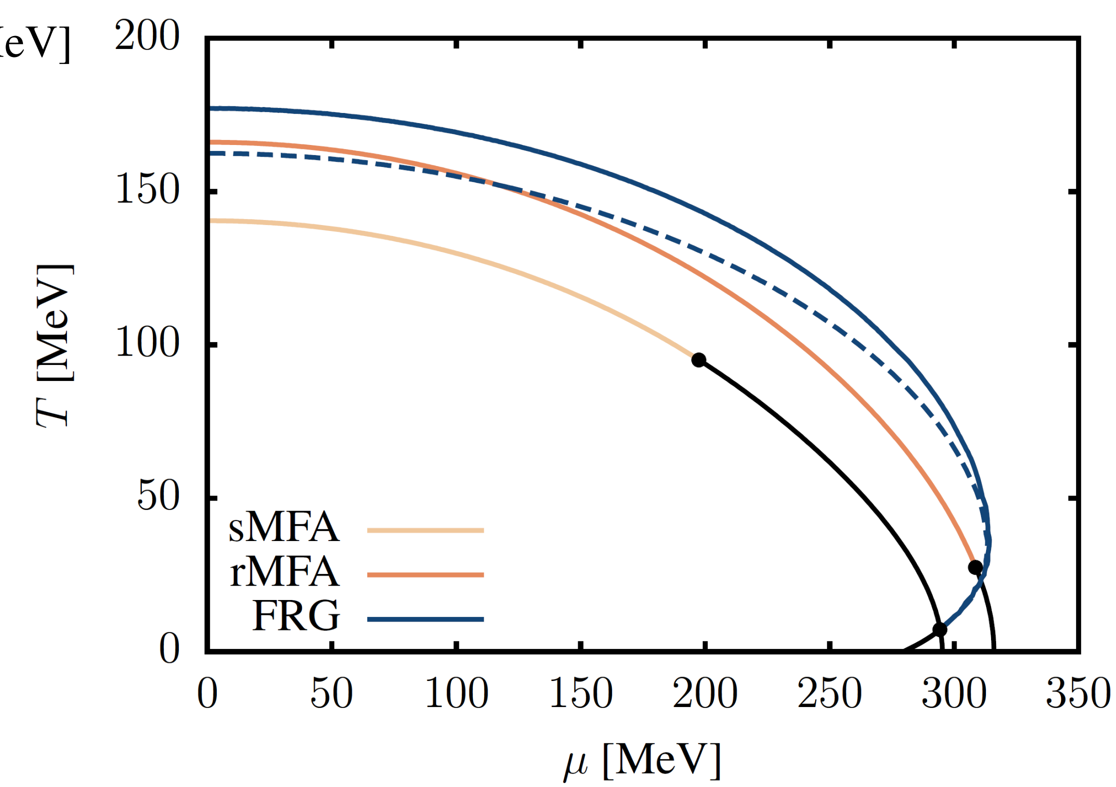
[Otto, Oertel, BJS to be publish]

dashed lines:

$N_f = 2+1$

solid lines:

$N_f = 2$



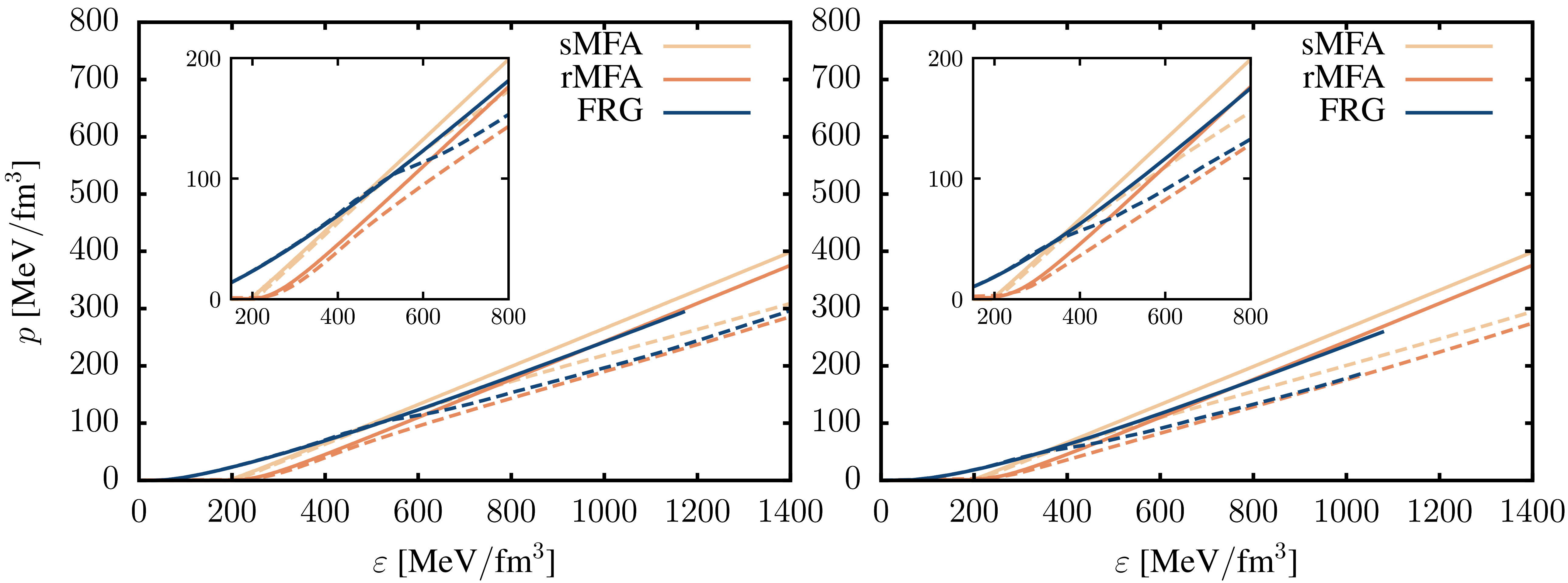
sMFA: no quark loop vacuum

rMFA: with quark loop vacuum

FRG: all quark & meson loops

EoSs for quark matter

[Otto, Oertel, BJS to be publish]



symmetric matter

β-stable and charge neutral matter

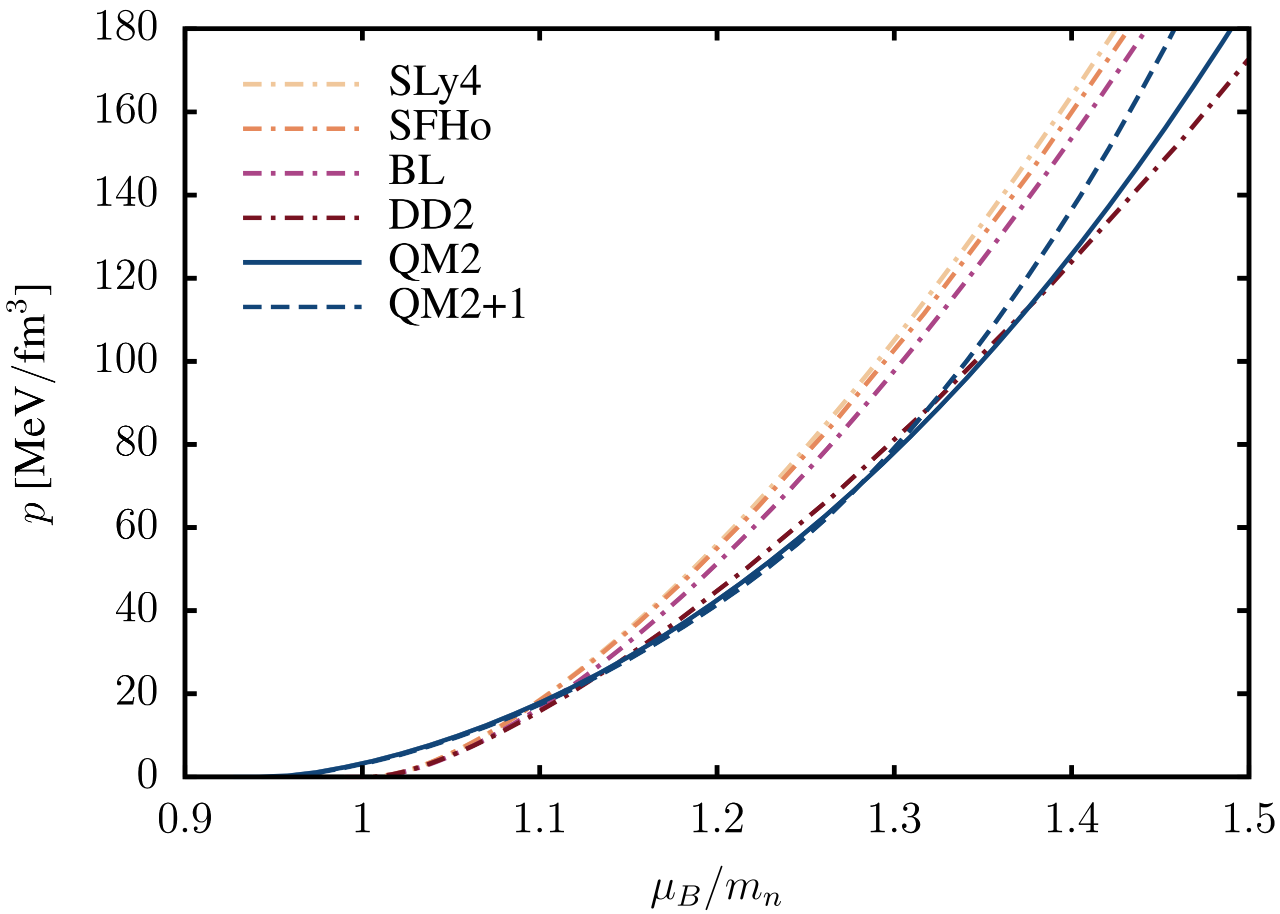
dashed lines: $N_f = 2+1$

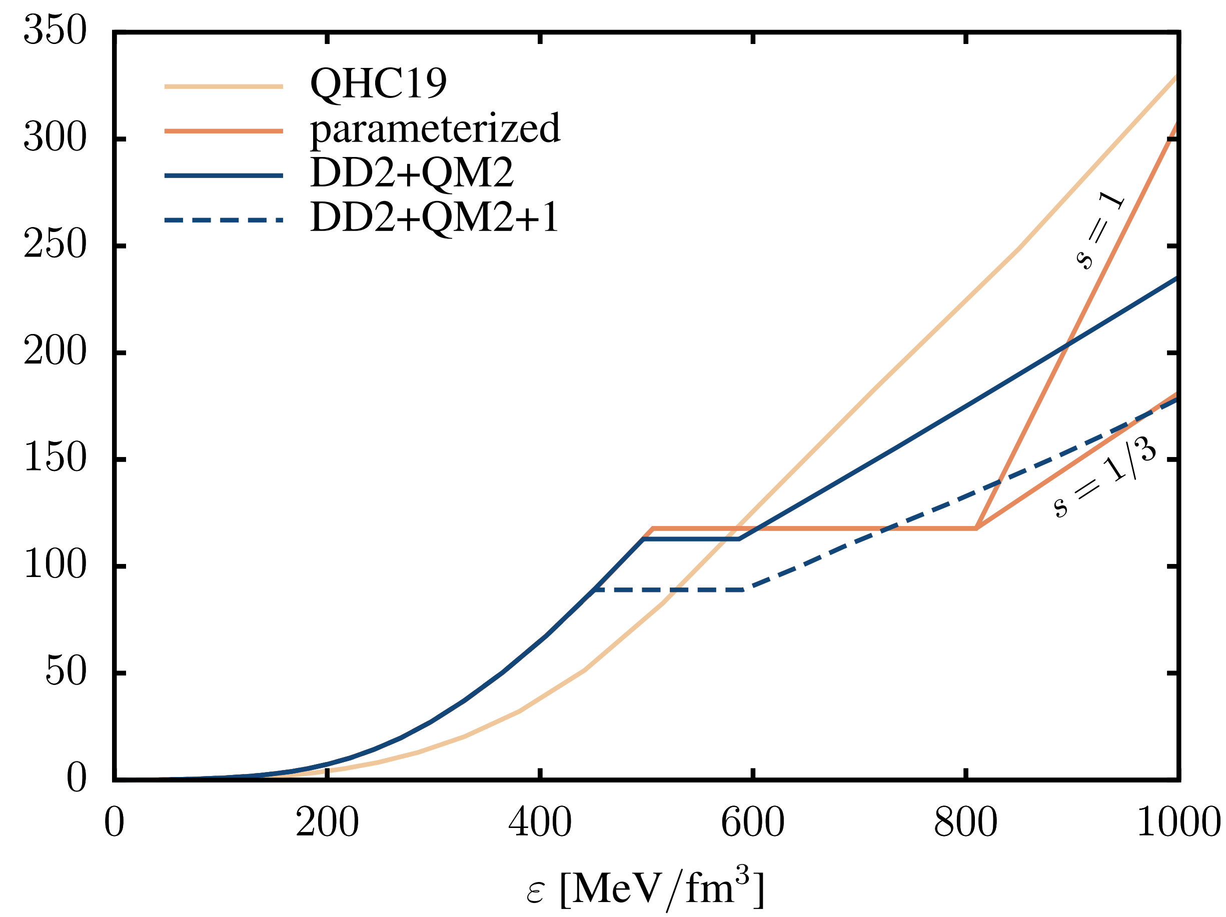
solid lines: $N_f = 2$

Hadronic and Quark EoSs

[Otto, Oertel, BJS to be publish]

s = constant speed of sound





hadronic EoSs

hadronic and quark matter

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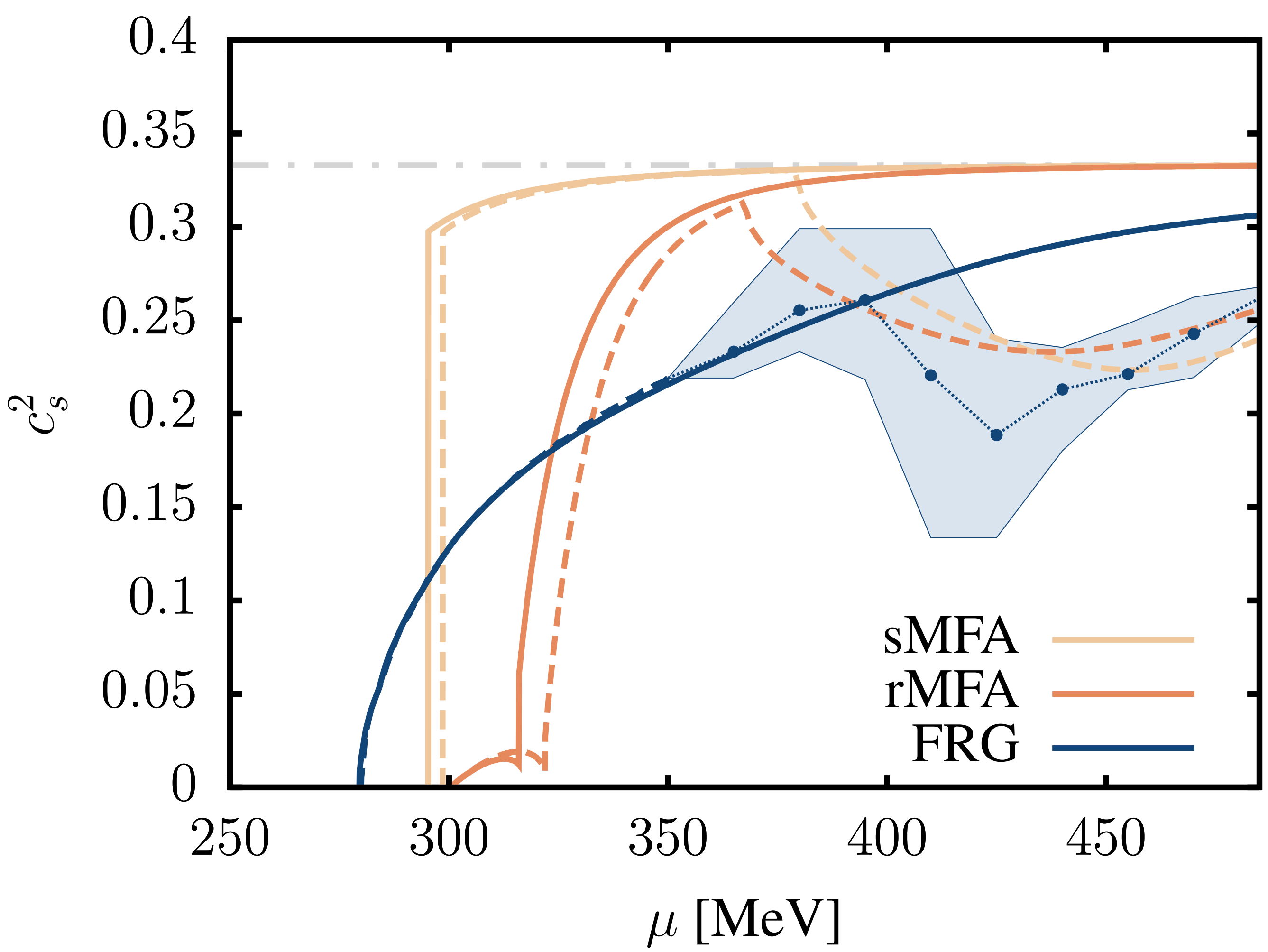
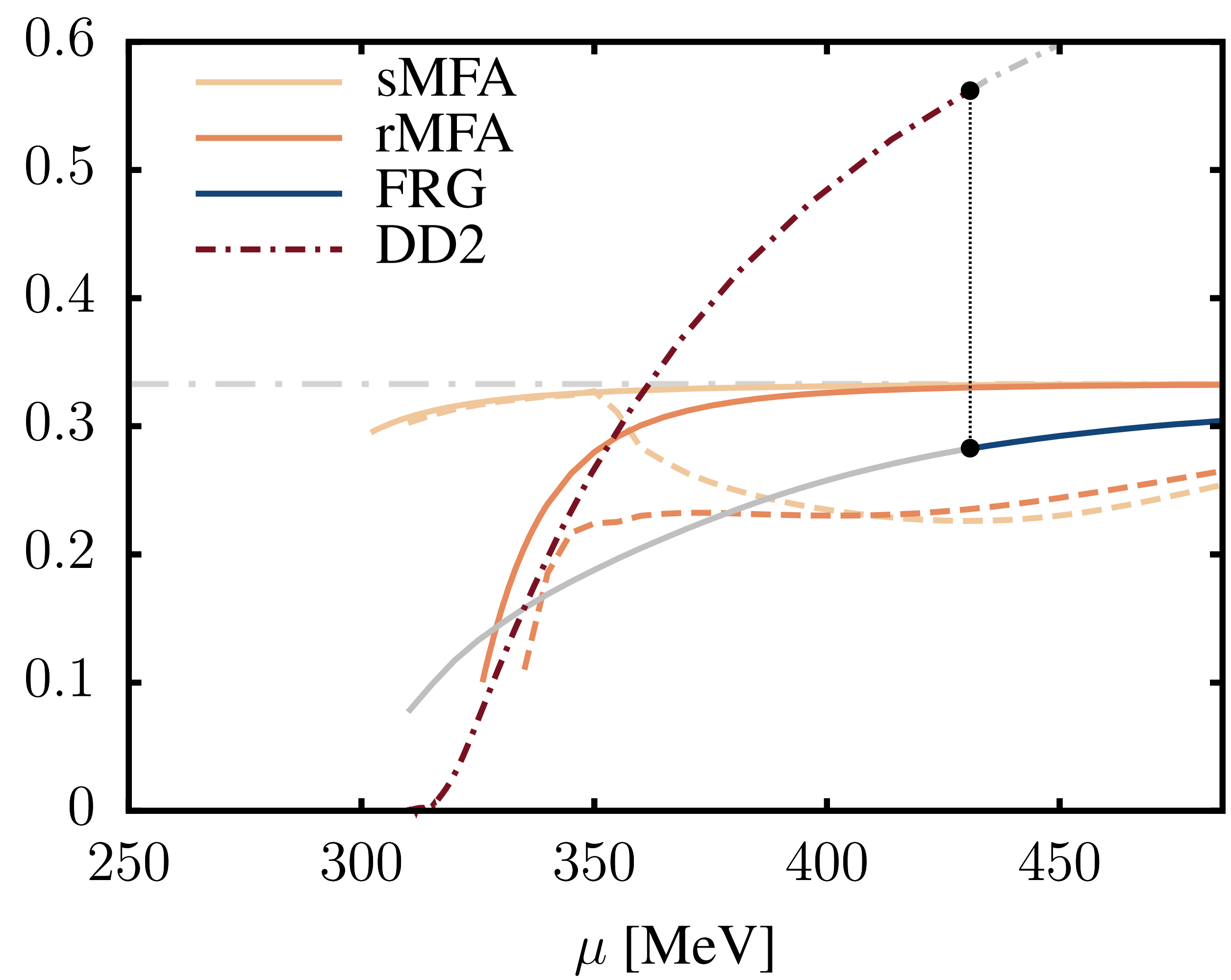
Speed of sound

[Otto, Oertel, BJS to be publish]



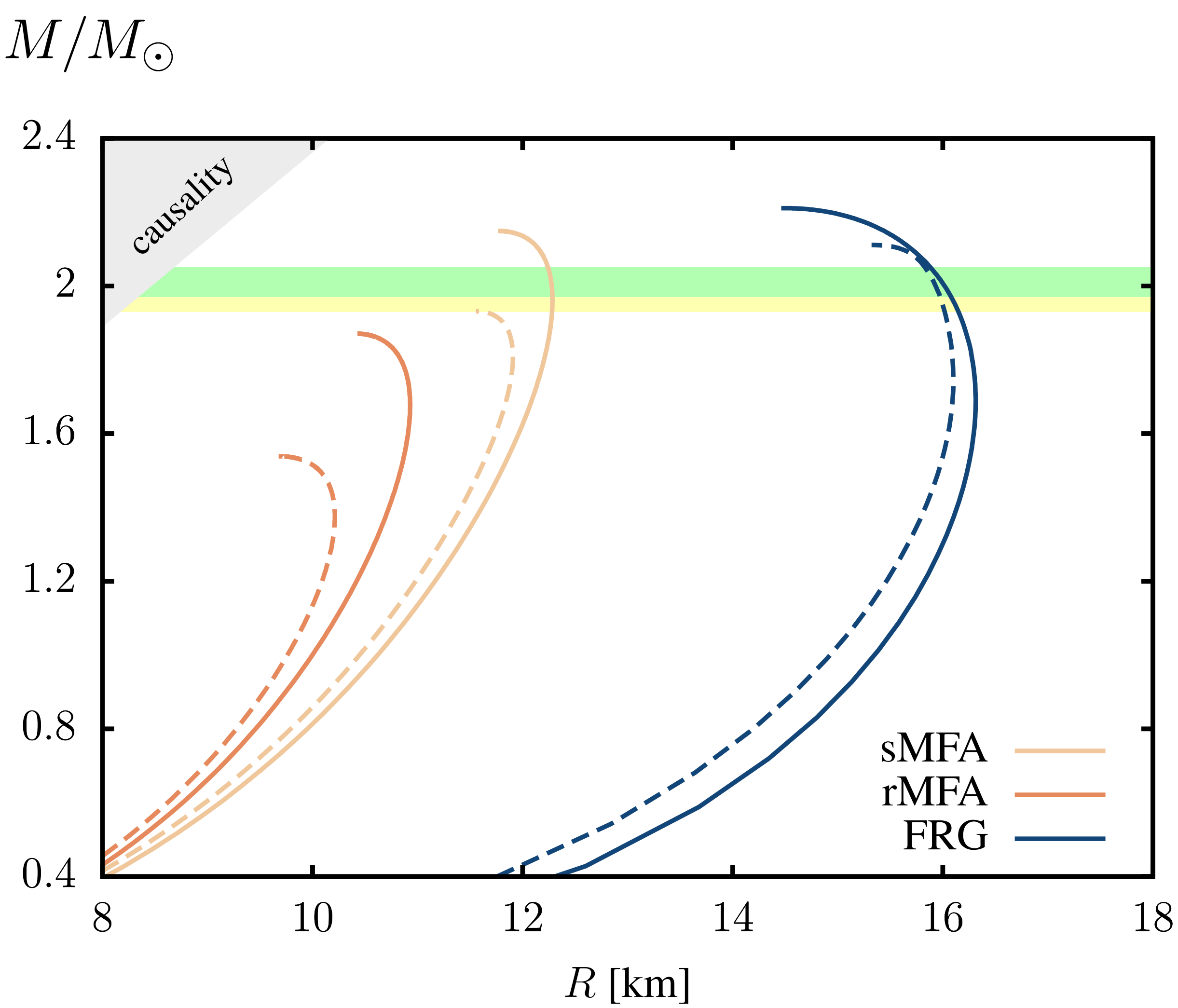
symmetric matter



β-stable and charge neutral matter

Mass-Radius relation

[Otto, Oertel, BJS to be publish]



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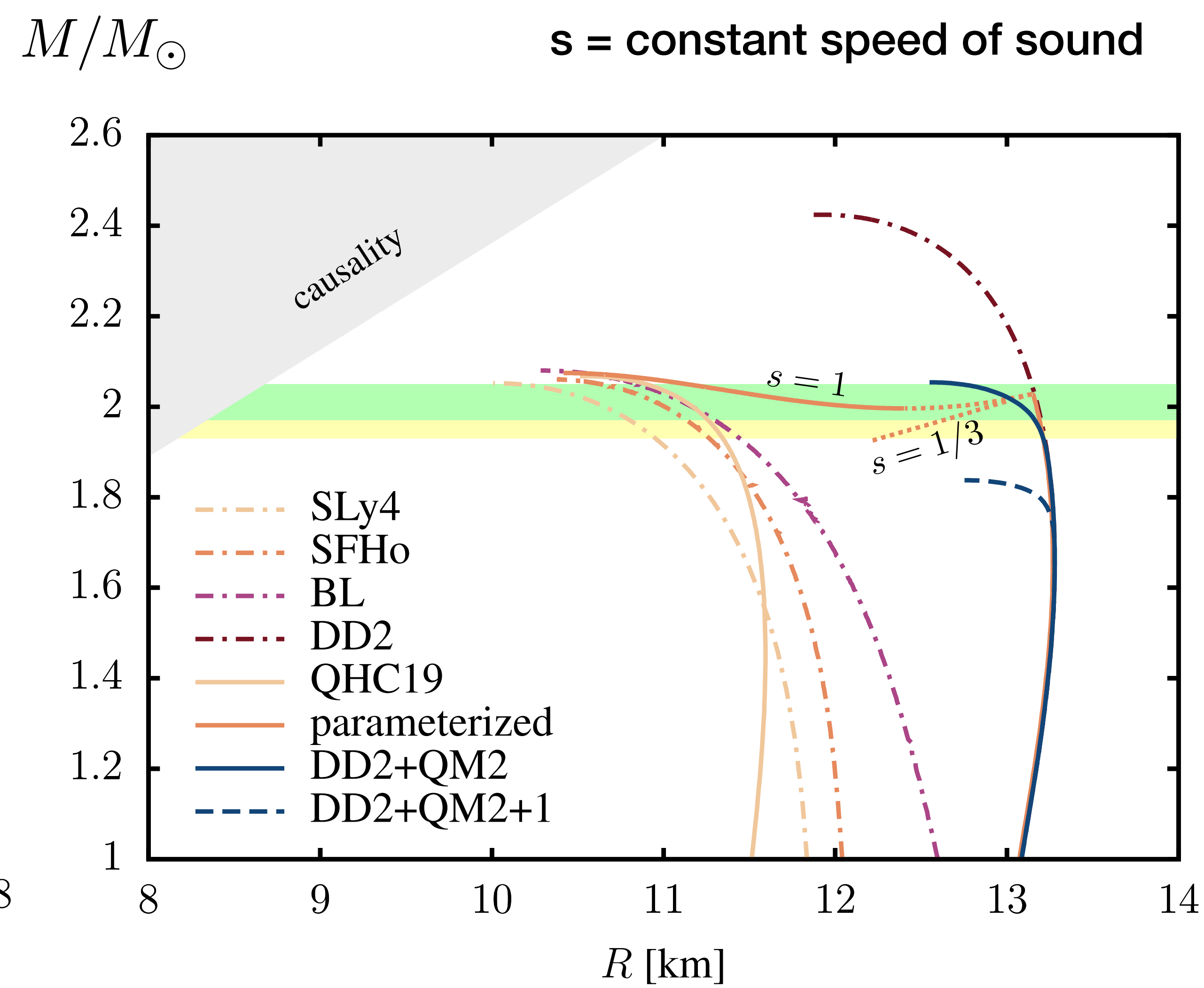

pure quark matter

hadronic EoSs

hadronic and quark matter

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Summary

- ► quantum and thermal fluctuations on QCD phase diagram via

  FRG investigation with different truncations: LPA, LPA', LPA'+Y

➜ fluctuations are important (beyond LPA)

➜ mass sensitivity of the chiral phase structure (Columbia plot)

➜ neutron star matter with the FRG

Columbia plot

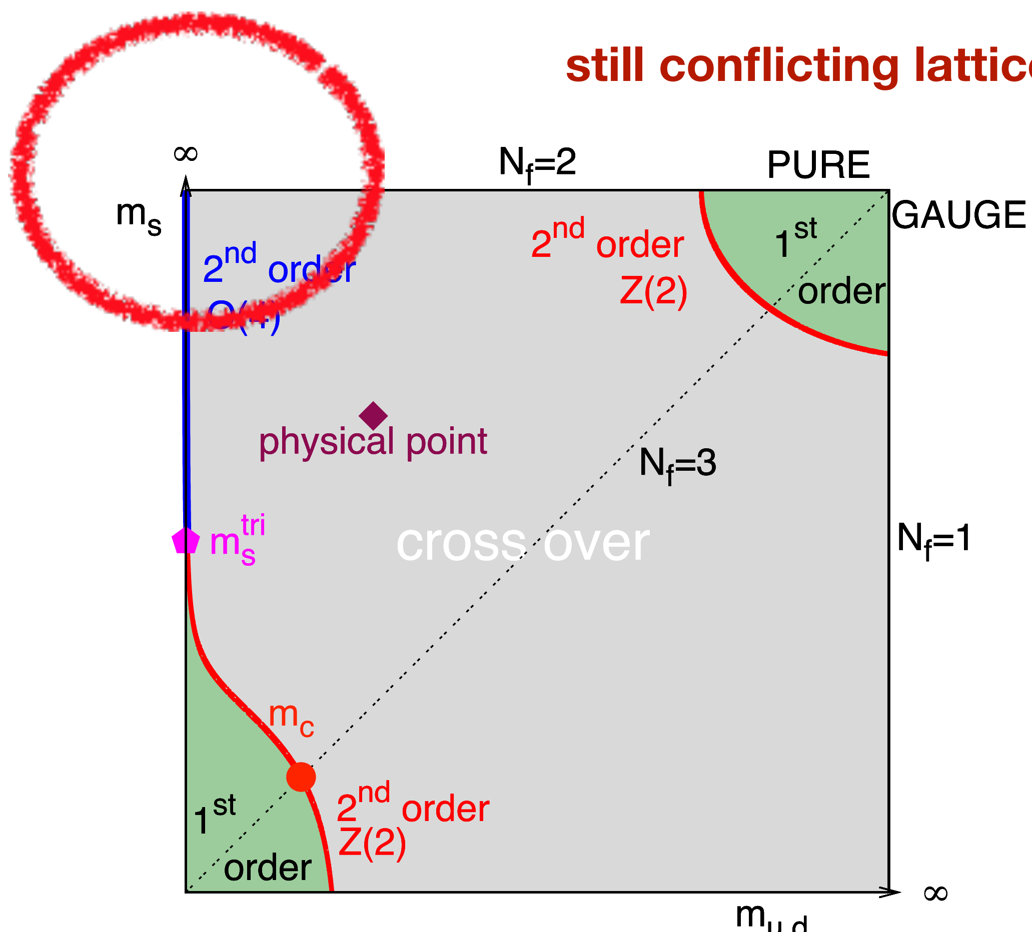
For physical quark masses: smooth phase transitions ➜ deconfinement: analytic change of d.o.f.

➜ associated global QCD symmetries only exact in two mass limits

1.infinite quark masses (center symmetry) — Order parameter: VEV of traced Polyakov loop(s)

2. massless quarks (chiral symmetry) — Order parameter: chiral condensate(s)

still conflicting lattice results!



[de Forcrand D'Elia 2017]

open issue: Nf=2: O(4)? $U(2)_L \times U(2)_R / U(2)_V$?

➜ similar crit. exponents

or even 1st order?

➜ dep. on strength of axial anomaly!

- **example:**

if $U_A(1)$ broken @T_c ➜ O(4) universality

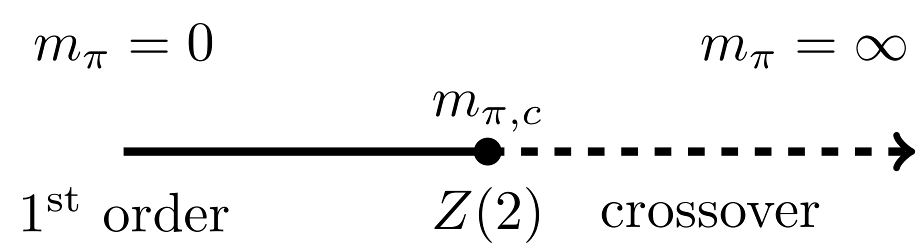
➜ there exist tricritical m^{tri}_s

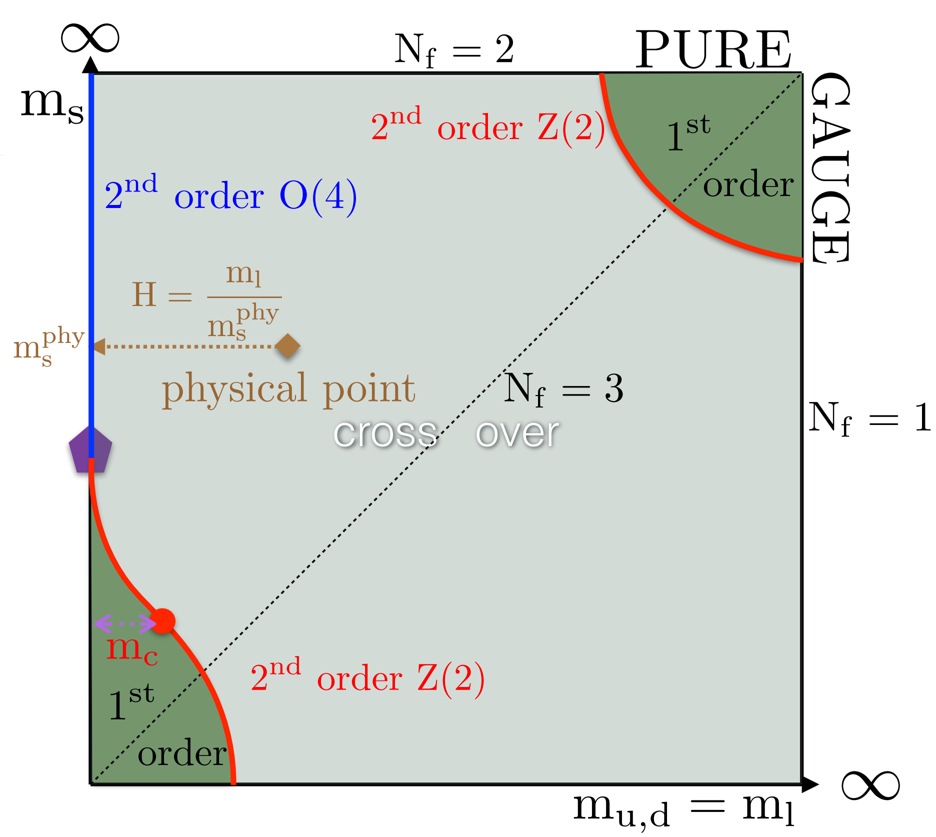
Columbia plot

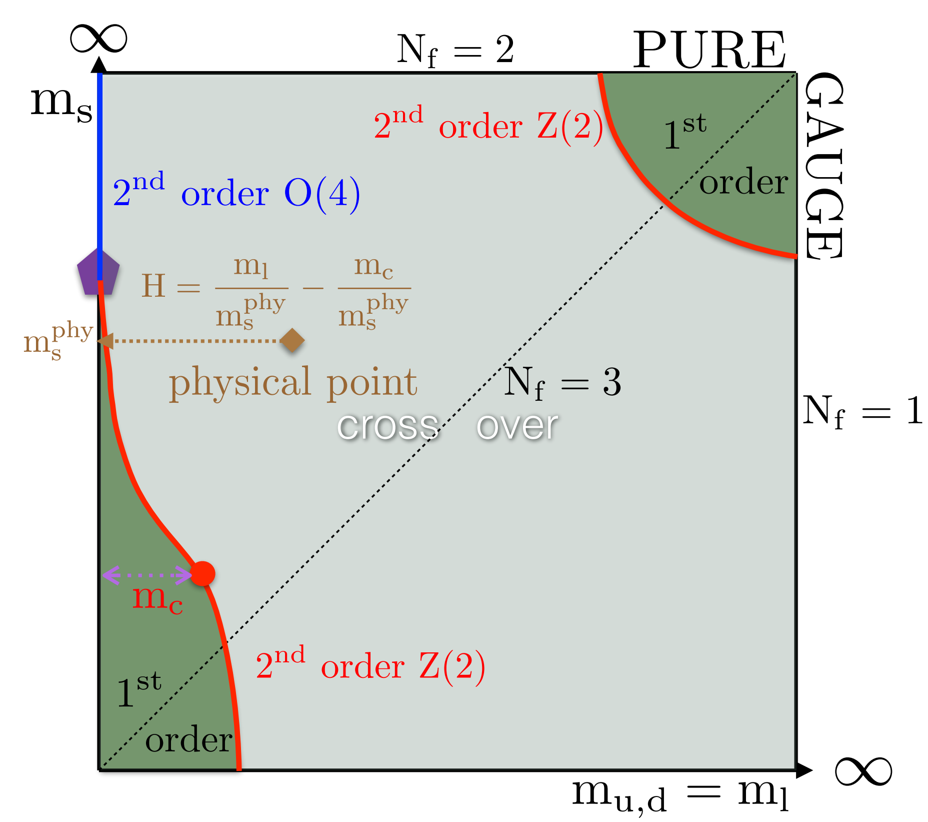
location of tri-critical point still an open question (maybe shifts to infinite strange quark mass)

below physical point

above physical point







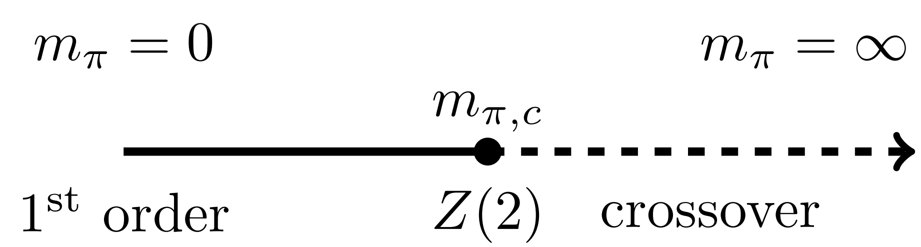
[HotQCD 2019]

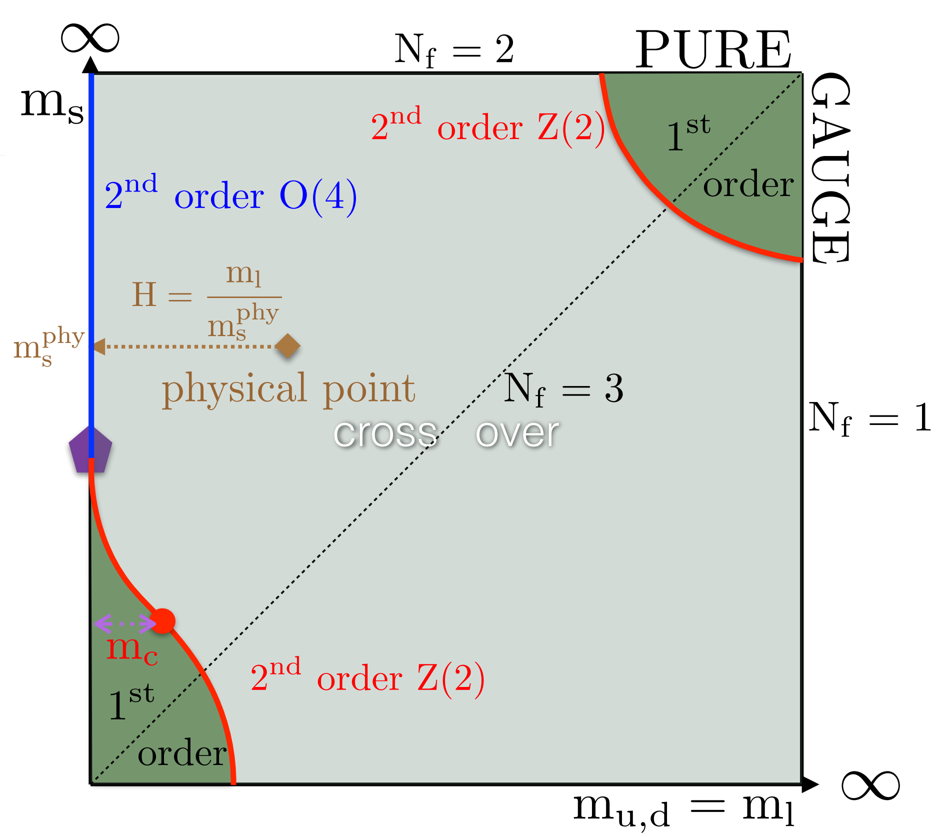
Columbia plot

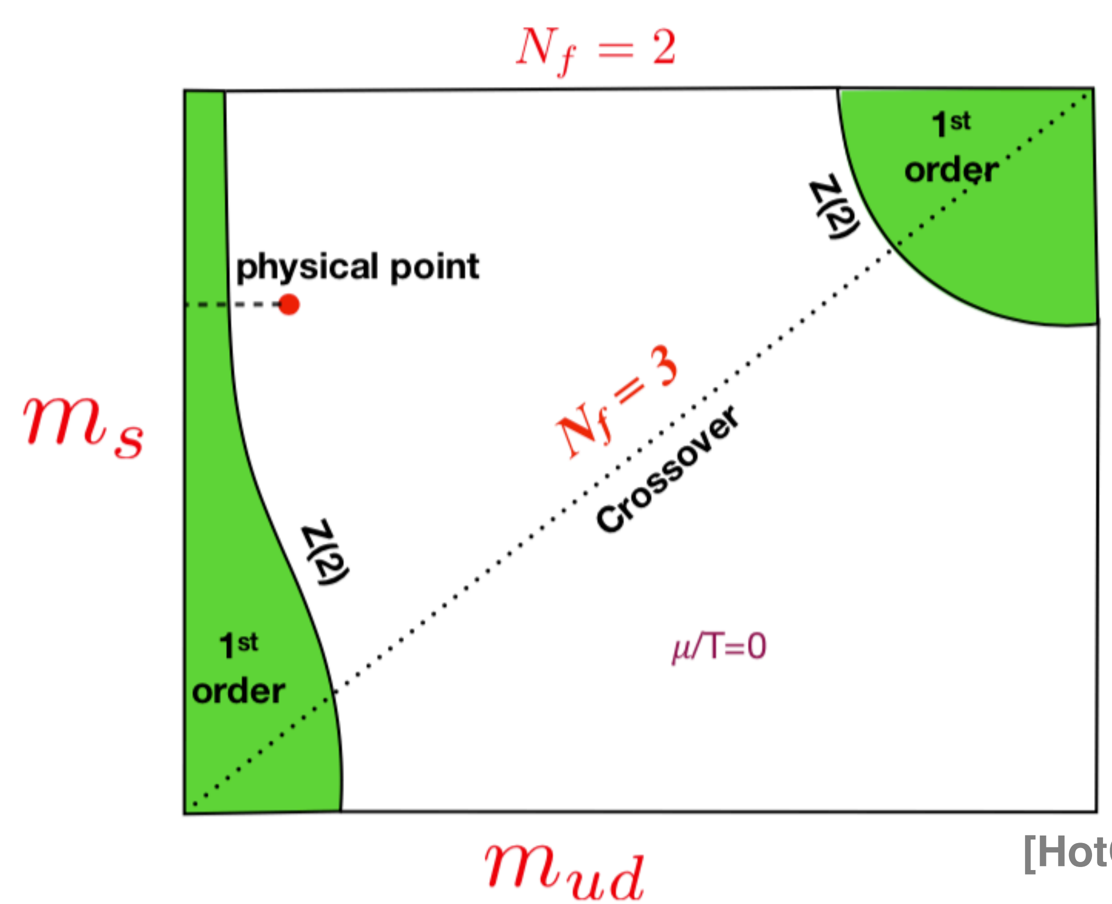
location of tri-critical point still an open question (maybe shifts to infinite strange quark mass)

below physical point

above physical point







[HotQCD 2019]

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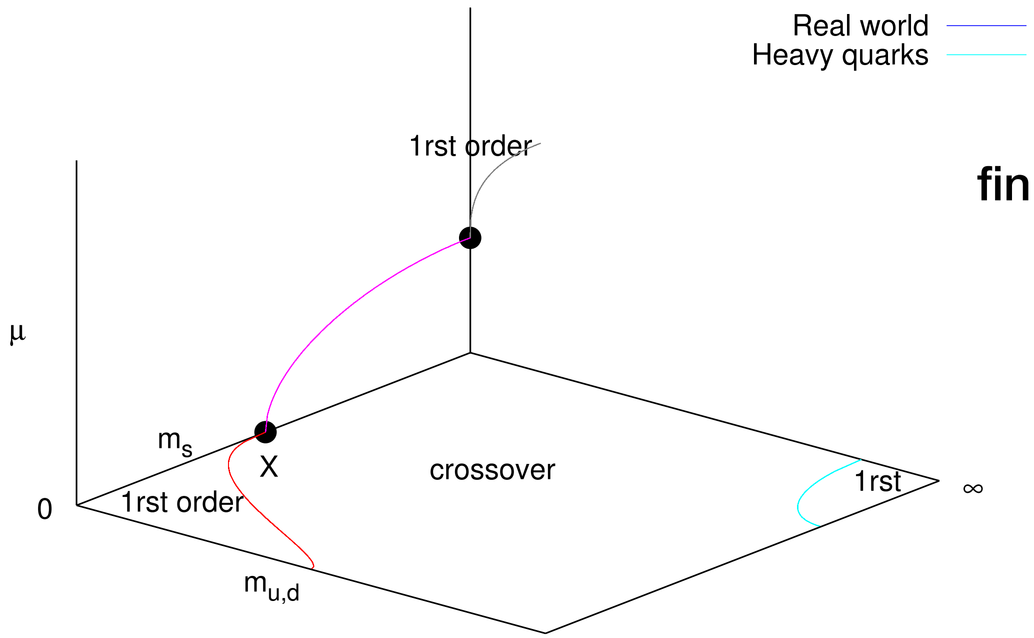
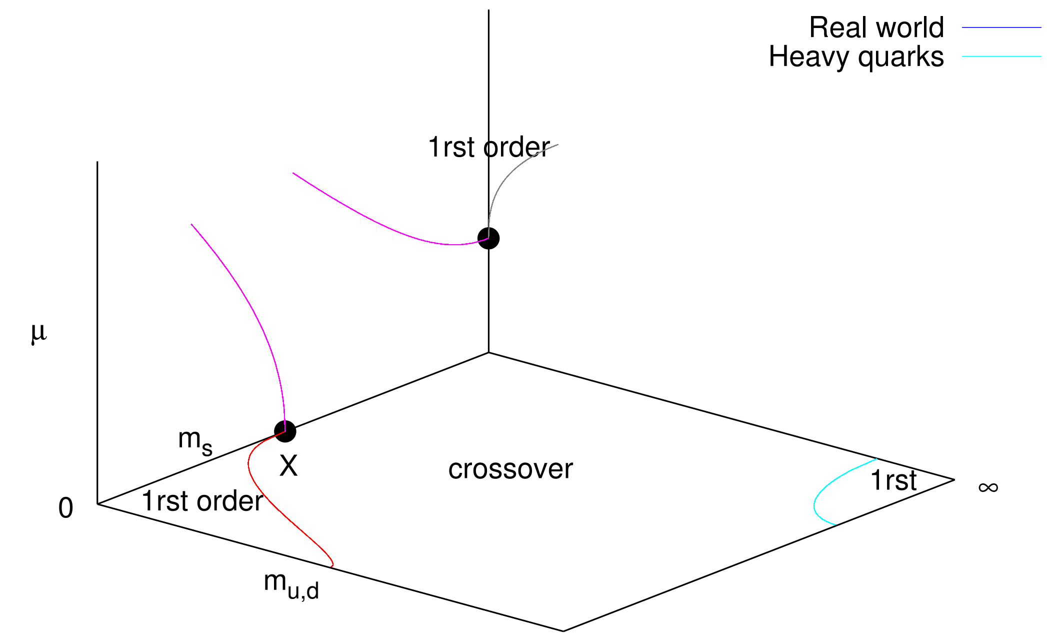
Columbia plot (MFA)

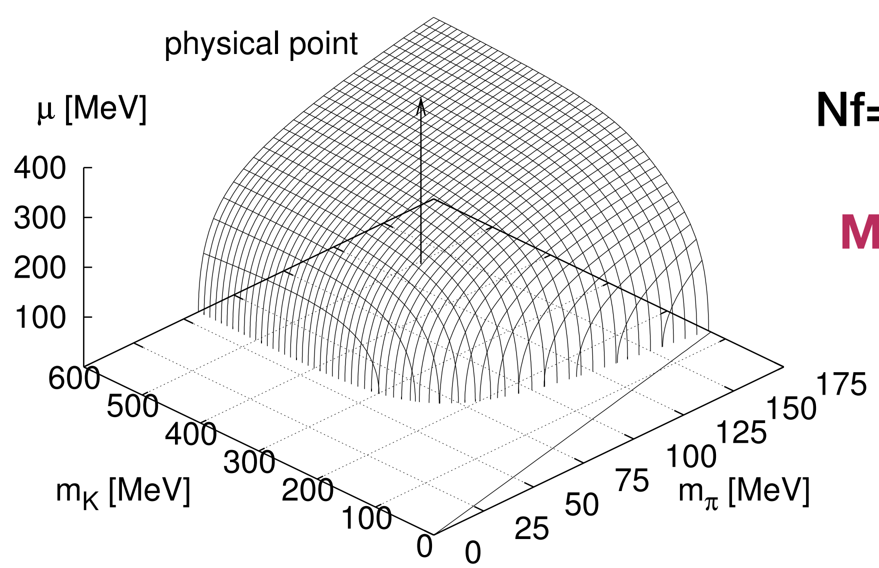
chiral critical surface
standard scenario



chiral critical surface
non-standard scenario



finite chemical potential

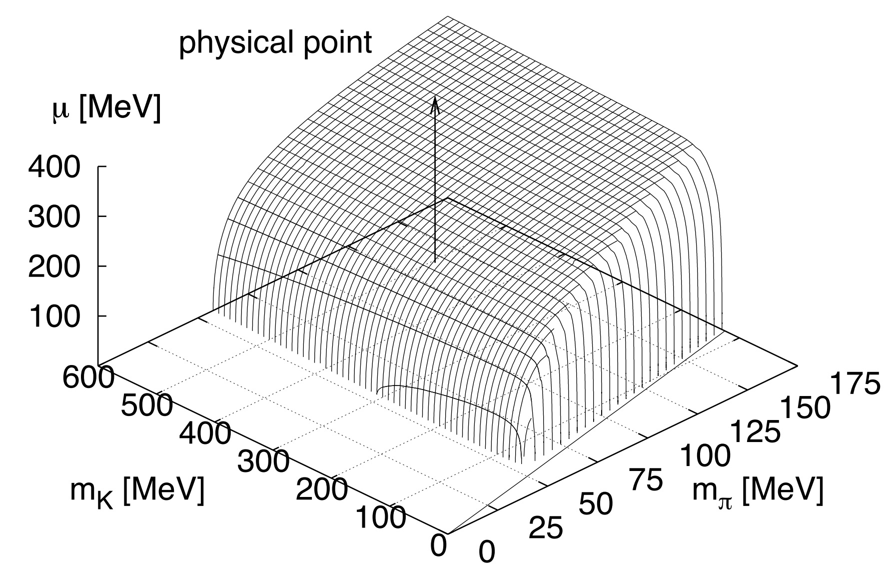


with $U_A(1)$-anomaly

Nf=2+1 quark-meson model

Mean-field approximation

[BJS, M. Wagner 2009]



without $U_A(1)$-anomaly

Columbia plot (FRG)

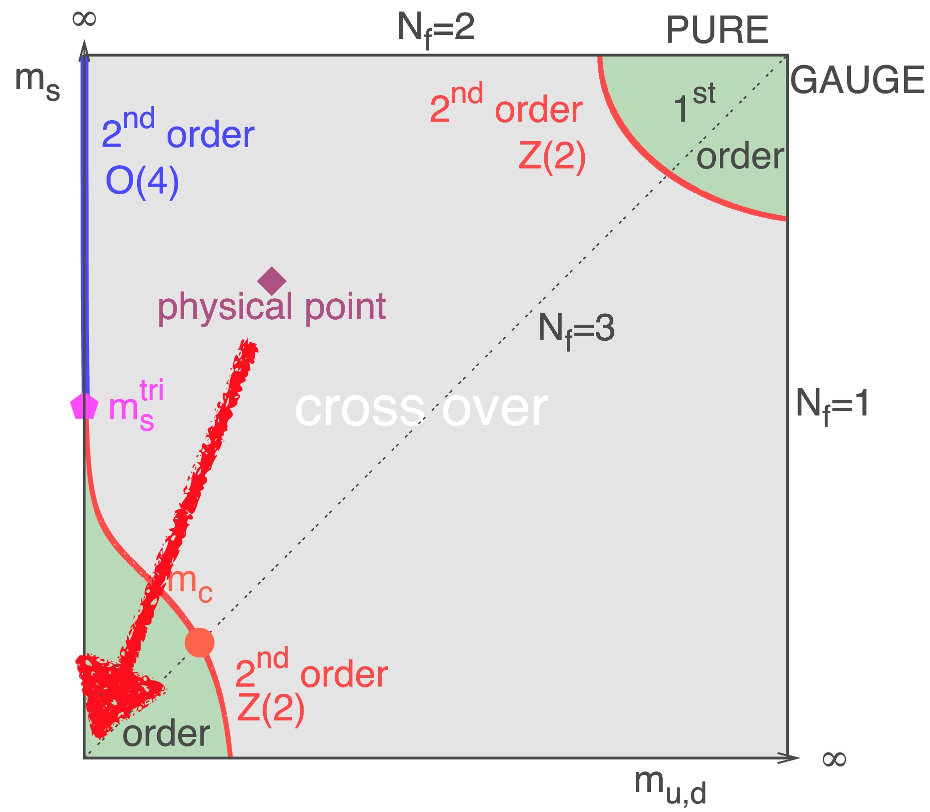
Nf=2+1 FRG QM truncation:

initial action in the UV: 7 parameters, (4 couplings, 2 explicit symmetry breaking, 1 ‘t Hooft determinant)
axial $U_A(1)$ symmetry: on or off

How to fix initial action in the UV away from the physical mass point?

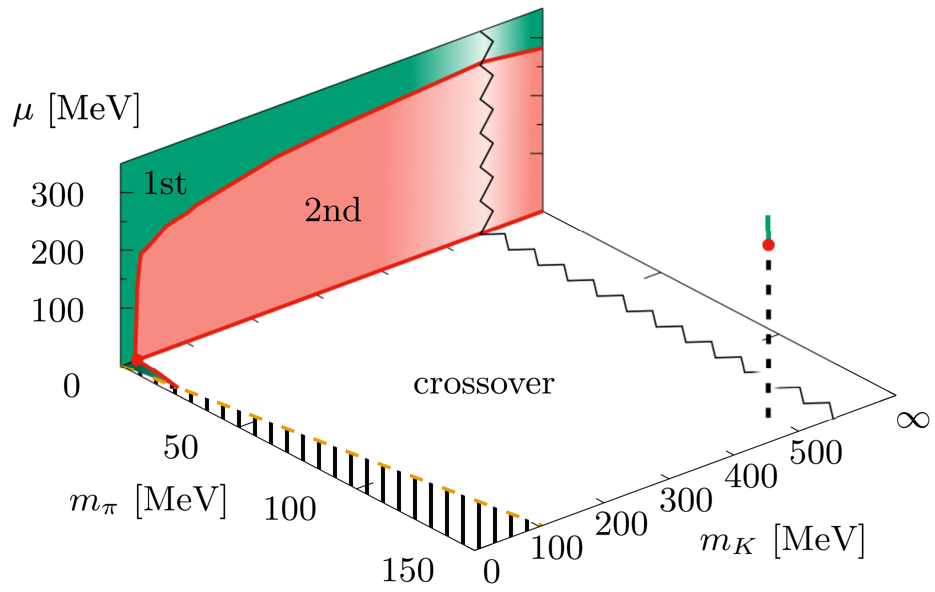
α=1 physical mass point

α=0 chiral limit

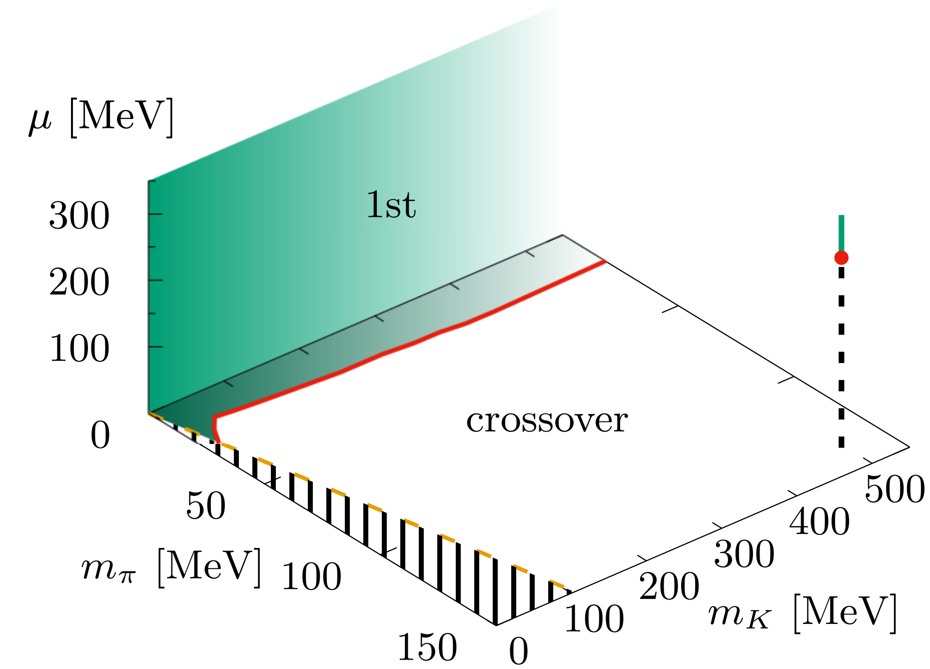


Columbia plot (FRG)

FRG



all fluctuations
quarks & mesons



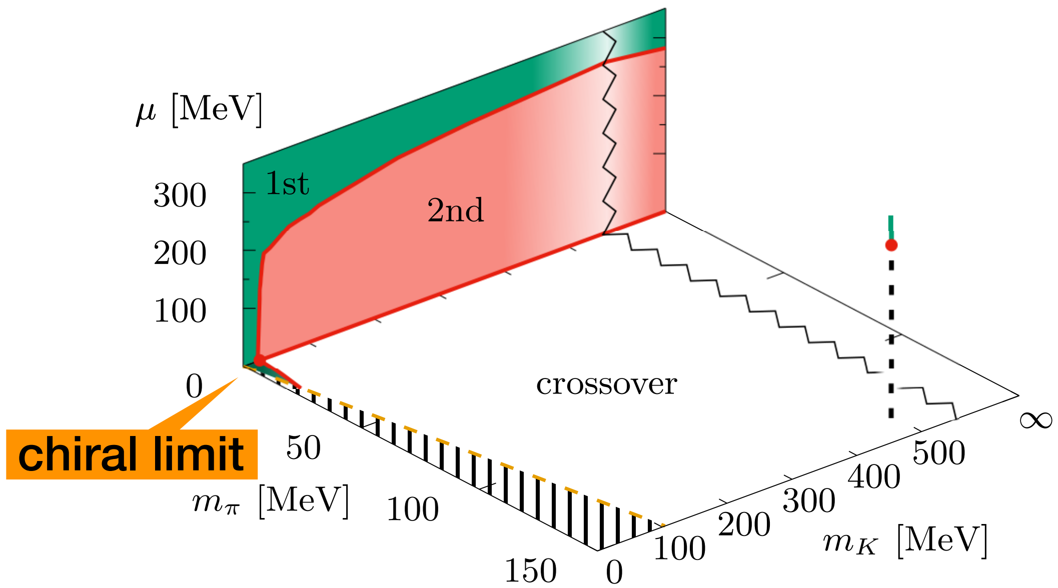
with $U_A(1)$-anomaly

without $U_A(1)$-anomaly

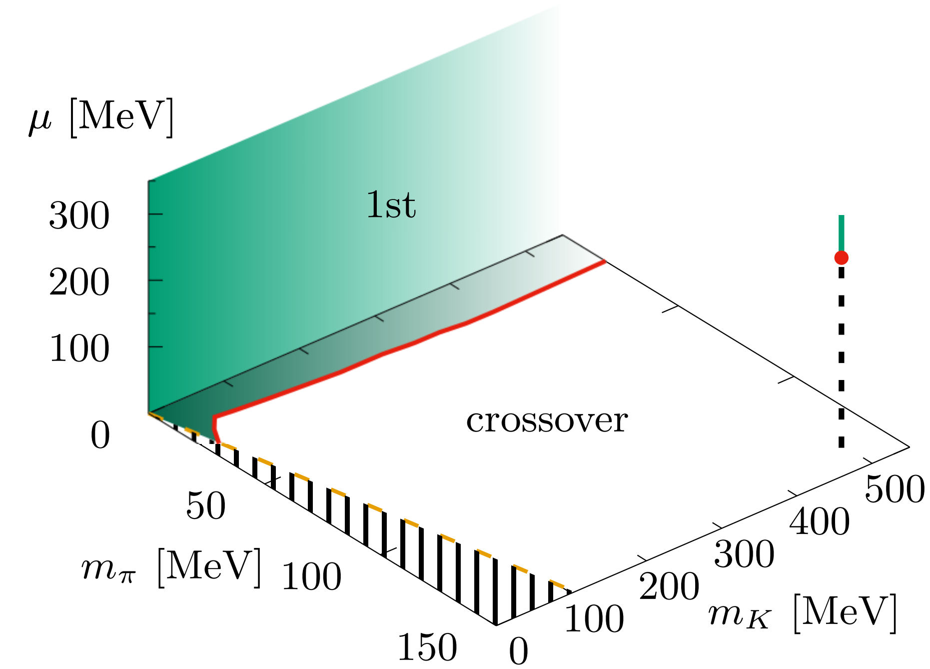
[Resch, Rennecke, BJS 2019]

Columbia plot (FRG)

FRG



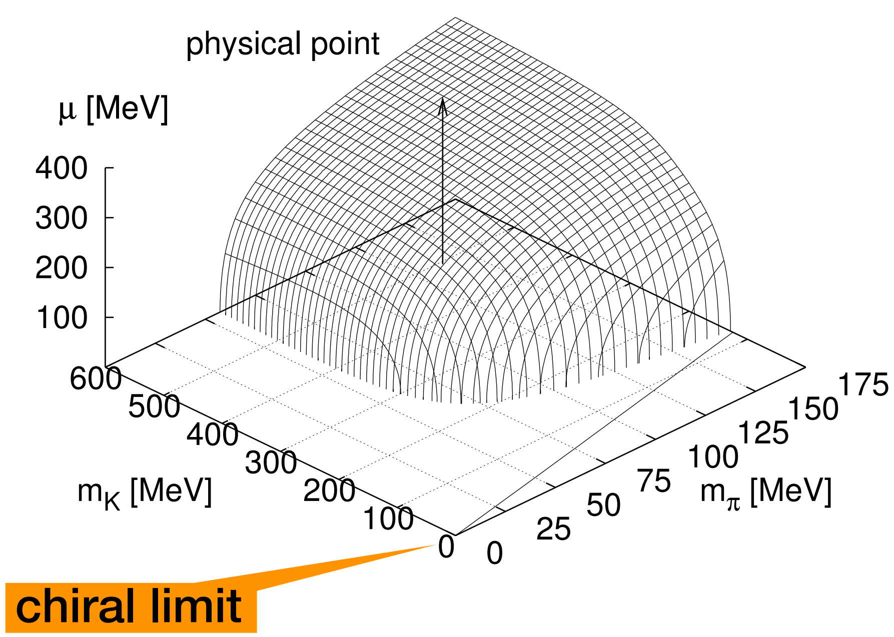
all fluctuations
quarks & mesons

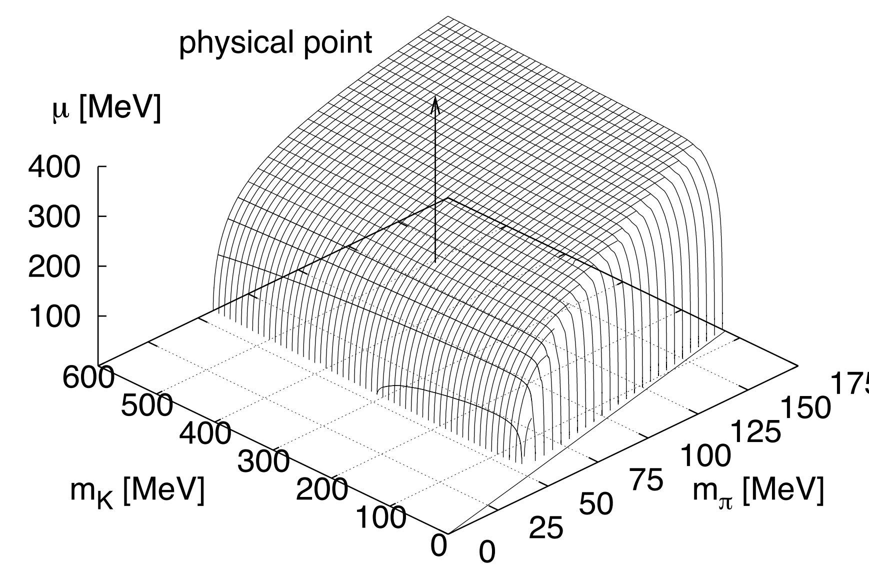


with $U_A(1)$-anomaly

without $U_A(1)$-anomaly

Mean-field analysis



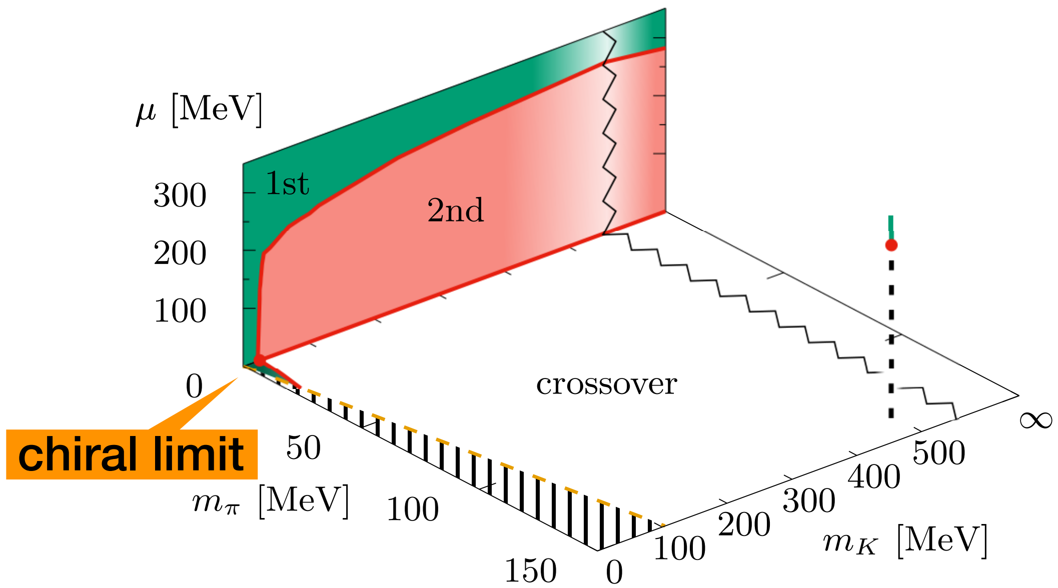


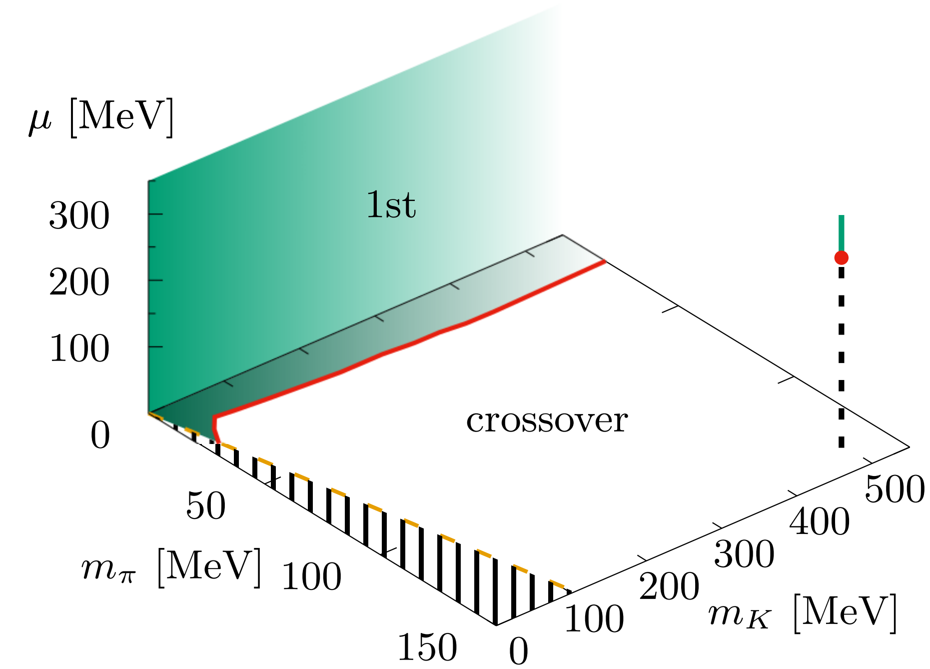
[Resch, Rennecke, BJS 2019]

Columbia plot (FRG)

FRG

all fluctuations
quarks & mesons



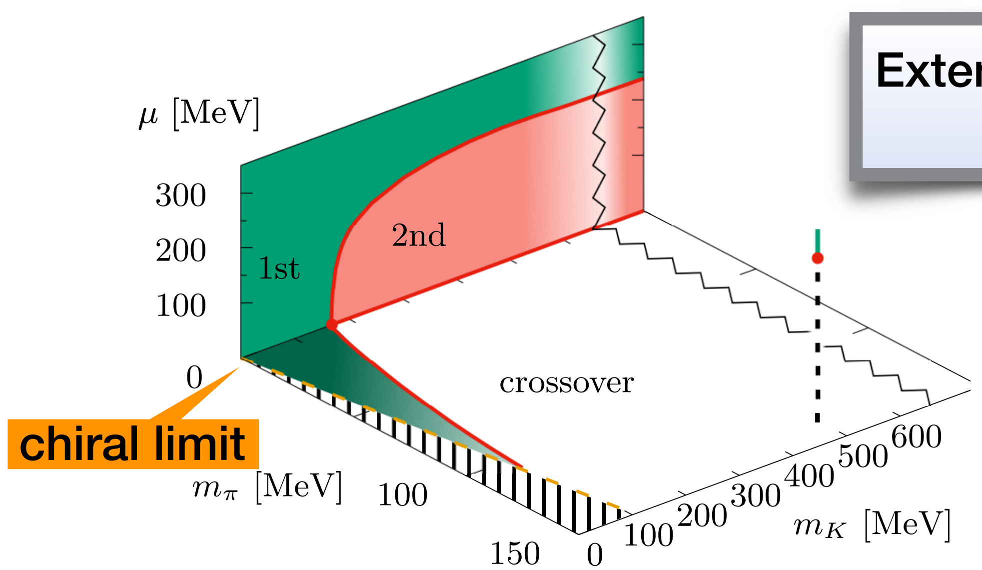


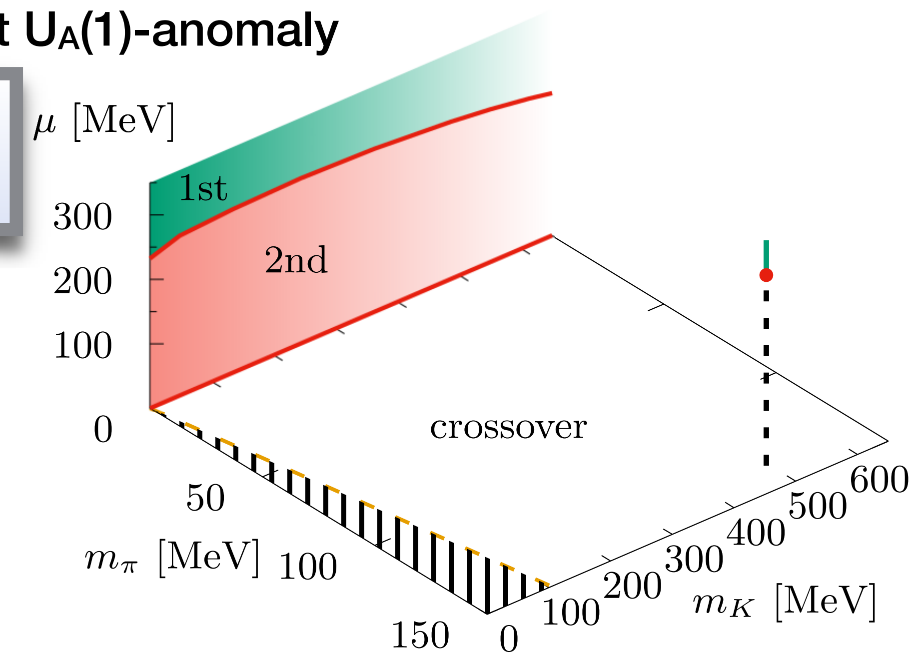
with $U_A(1)$-anomaly

without $U_A(1)$-anomaly

Extended Mean-field analysis

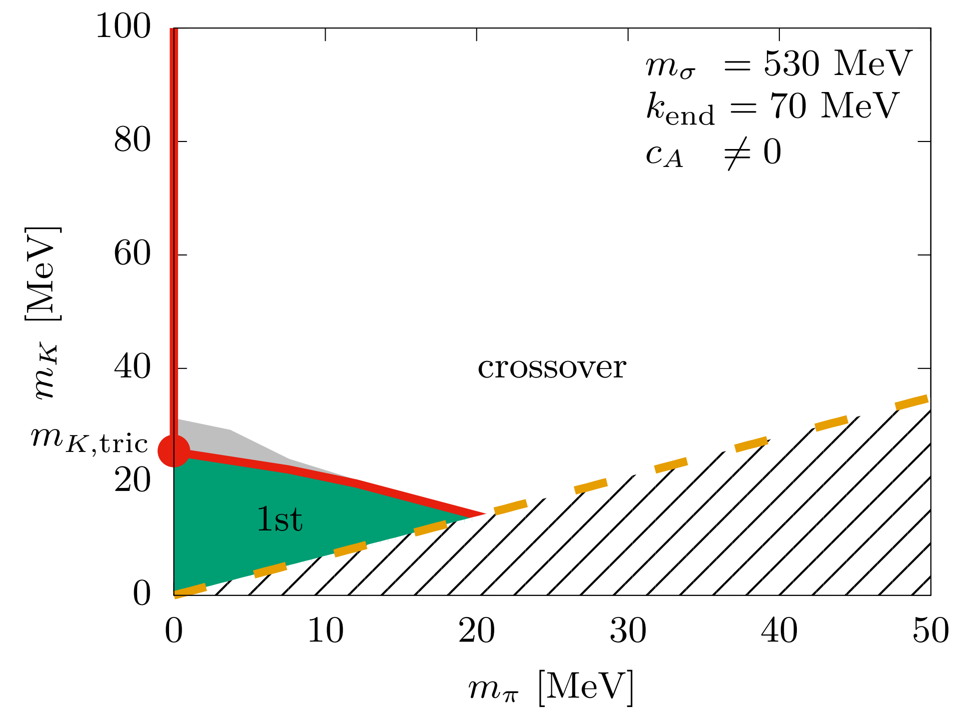
influence of vacuum
fluctuations of quarks





[Resch, Rennecke, BJS 2019]

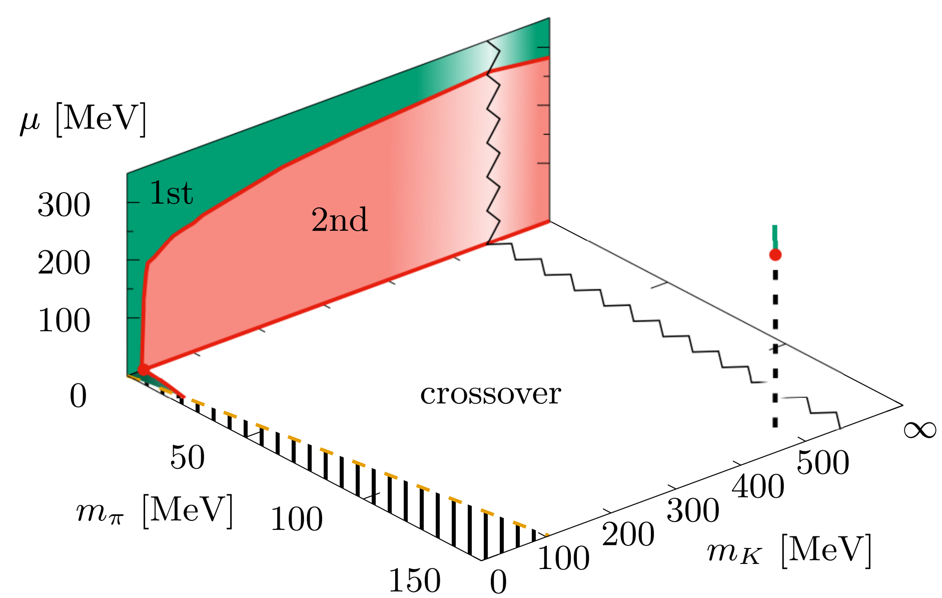
Columbia plot with the FRG



findings:

1. conventional bending of chiral critical surface
   ➜ critical endpoint @ physical mass point
2. tricritical strange quark mass far away from light chiral limit
3. First-order region around chiral limit very small
   ➜ in agreement with lattice
   [Enrödi, et al. 2007, de Forcrane et al. 2017]
4. Nf=2+1 ➜ Nf=2 analytically connected two-flavor chiral limit

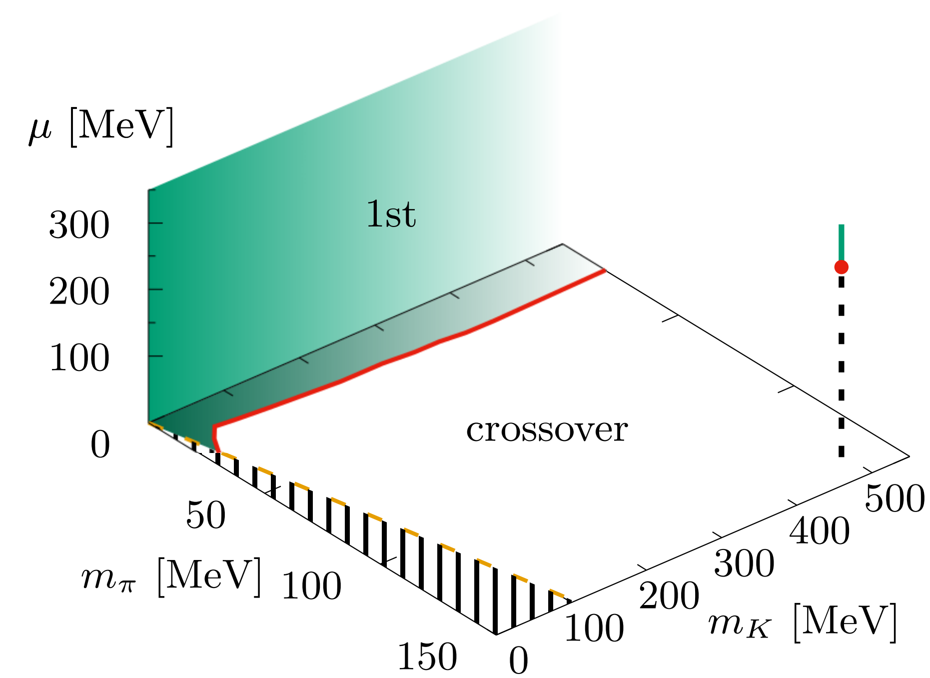
influence of axial anomaly on chiral critical line



with $U_A(1)$-anomaly

FRG

all fluctuations
quarks & mesons



without $U_A(1)$-anomaly

[Resch, Rennecke, BJS 2019]