iagram at ensityQCD phase diagram: from heavy ion collisions to neutron star mergers

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Darmstadt, 10.04.14

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ween lattice and functional communities

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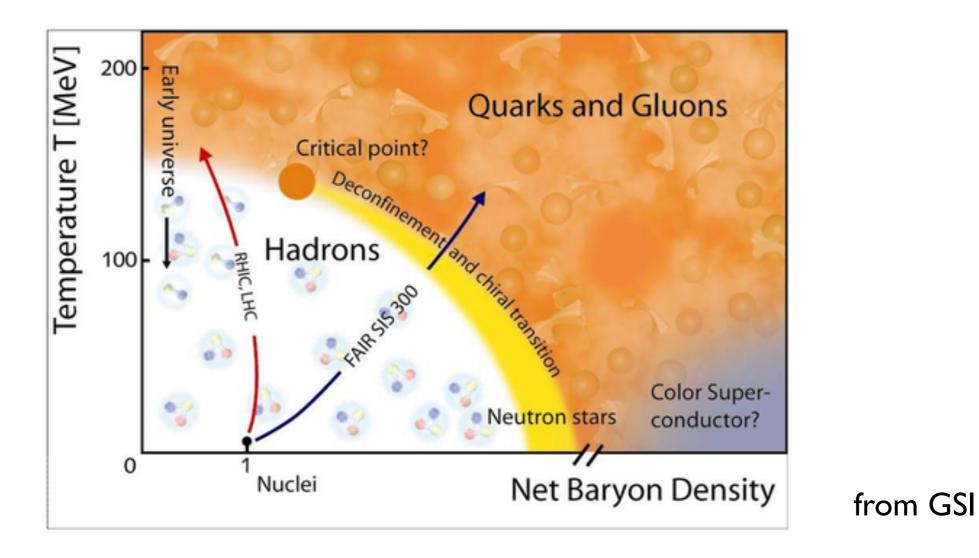




MAIN



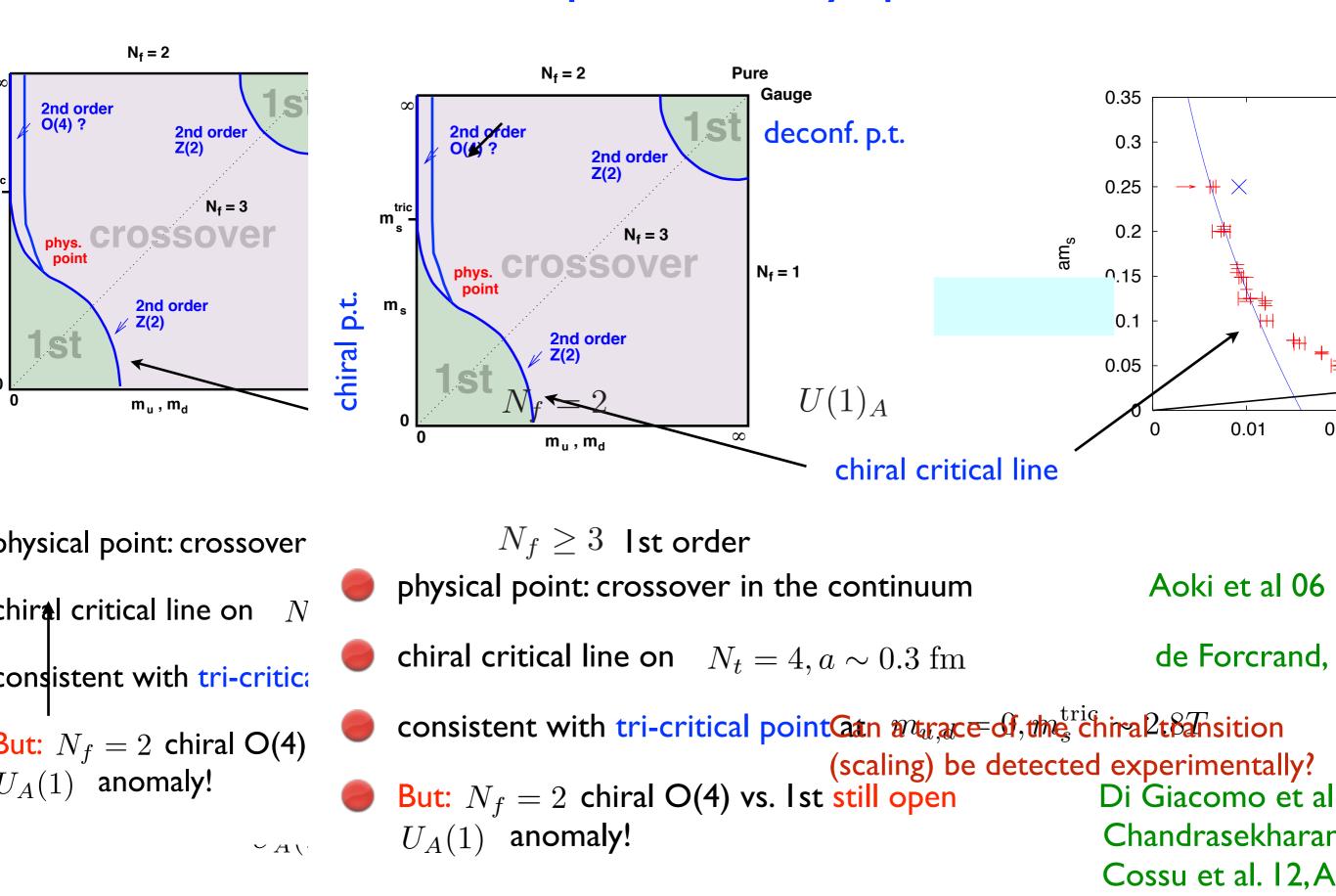
The QCD phase diagram



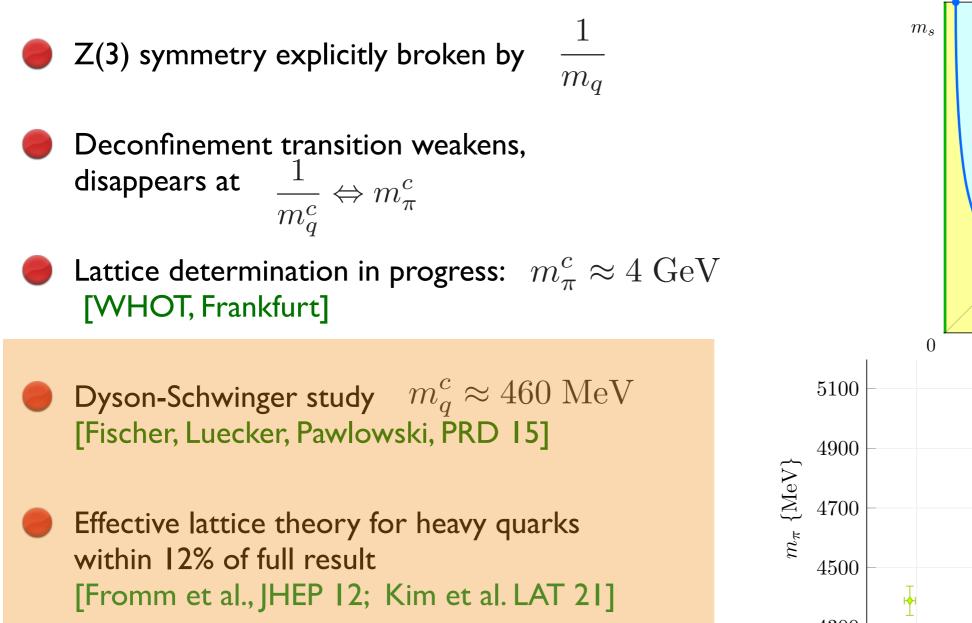
Fundamental for particle-, nuclear-, astro- physics and cosmology, textbook knowledge!
 Non-perturbative nature/confinement prevents perturbative solution

• "Sign problem" prevents Monte Carlo simulation (NP-hard problem?)

rder of p.t., arbiard Order of p.t., arbitrary quark masses $\mu=0$

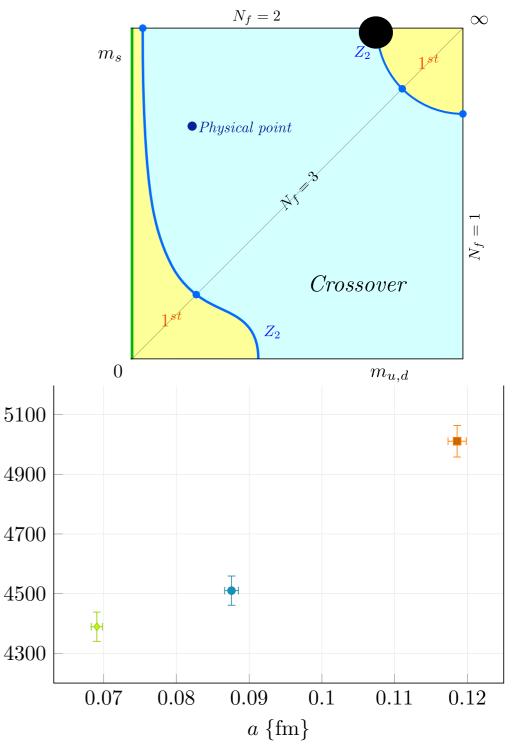


Heavy mass corner: bench mark for effective theories



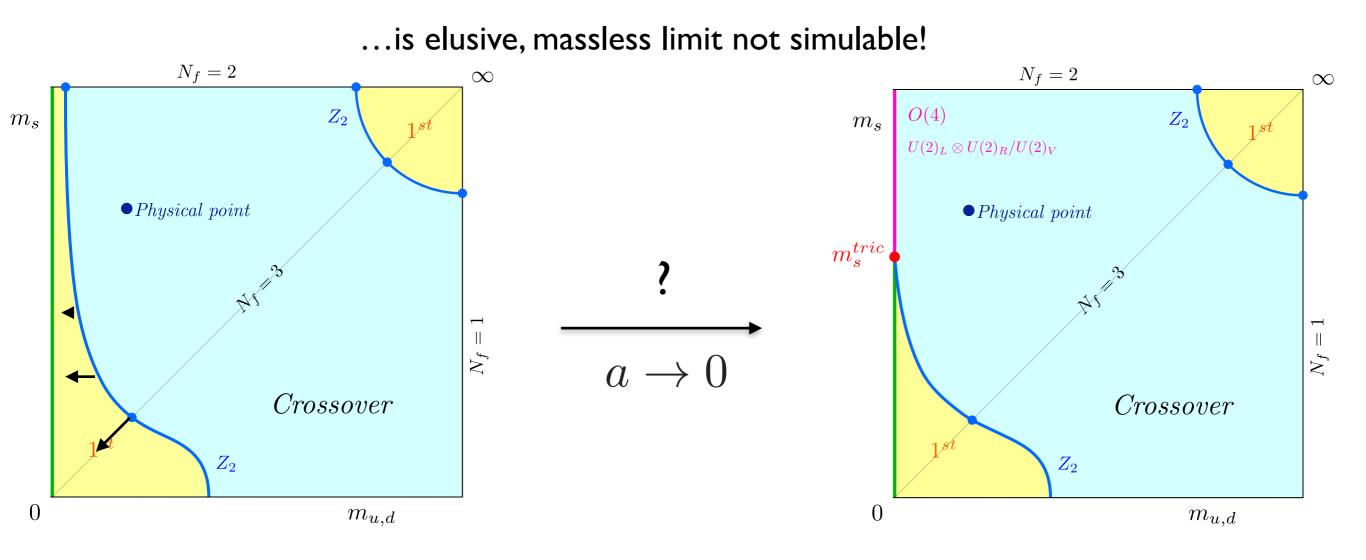
Also applicable to finite μ_B

Nuclear liquid gas transition from QCD! [Fromm et al., PRL 12]



Cuteri, O.P., Schön, Sciarra, PRD 21

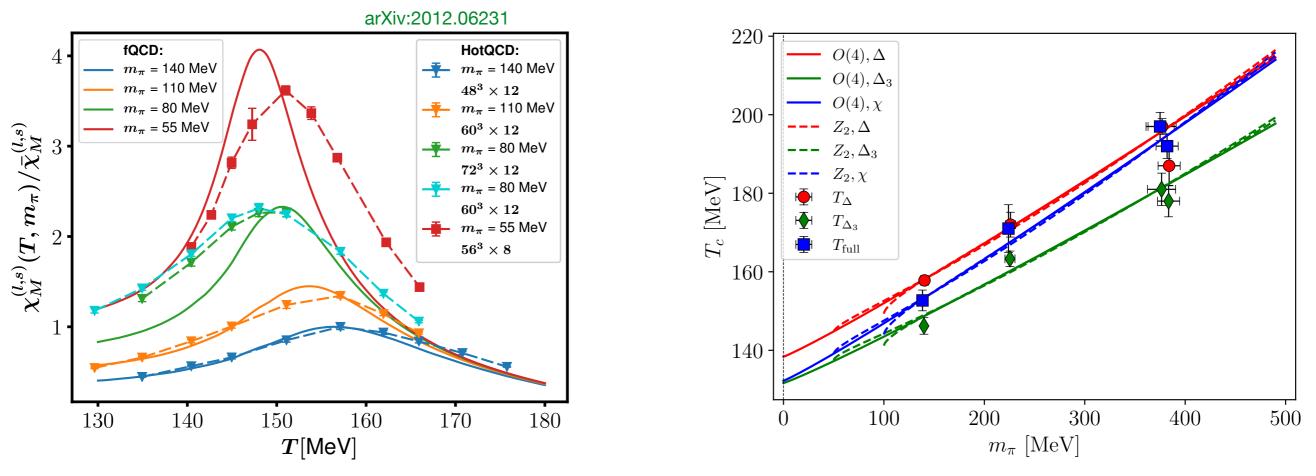
The nature of the QCD chiral transition



- Coarse lattices or unimproved actions: I st order for $N_f = 2, 3$
- Ist order region shrinks rapidly as $\,a
 ightarrow 0$
- Improved staggered actions: no 1st order region so far, even for $N_f = 3 m_{PS} > 45 MeV$

Details and references: [O.P., Symmetry 13, 2021]

From the physical point to the chiral limit



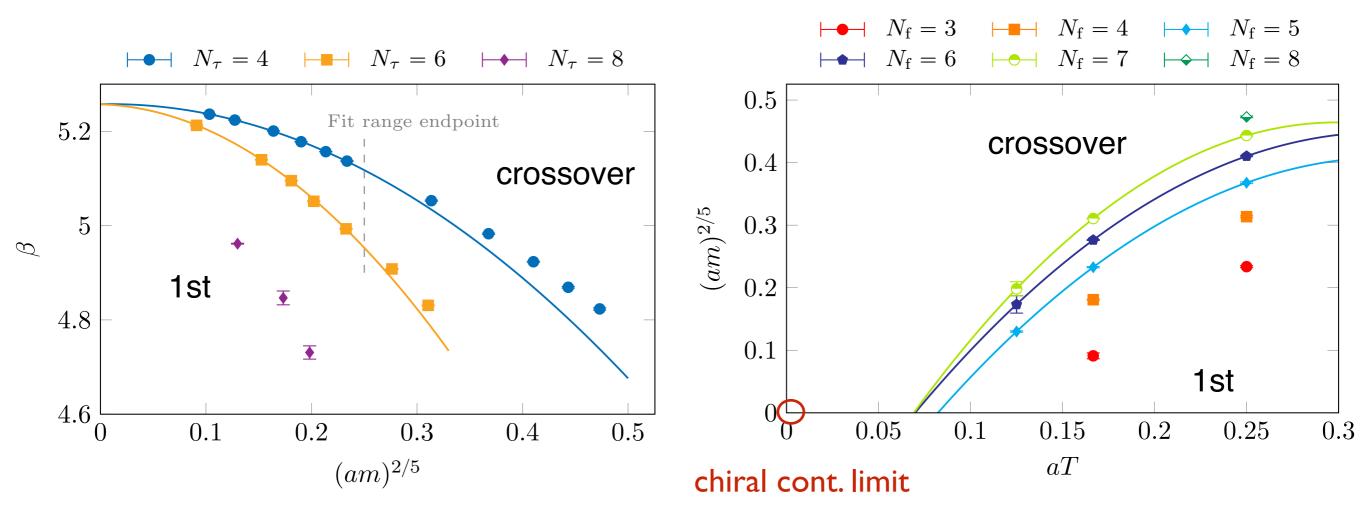
[HotQCD, PRL 19] HISQ (staggered)

[Kotov, Lombardo, Trunin, PLB 21] Wilson twisted mass

- $T_c^0 = 132_{-6}^{+3} \text{ MeV}$ $T_{pc}(m_l) = T_c^0 + K m_l^{1/\beta\delta}$ $T_c^0 = 134_{-4}^{+6} \text{ MeV}$
 - Keep strange quark mass fixed, crossover gets stronger as chiral limit approached
 Cannot distinguish between Z(2) vs. O(4) exponents, need exponential accuracy!
 Determination of chiral critical temperature possible, but not the order of the transition
 Comparison with fRG: T⁰_c ≈ 142MeV, "most likely O(4)" [Braun et al., PRD 20,21]

Nature of chiral transition as function of N_f

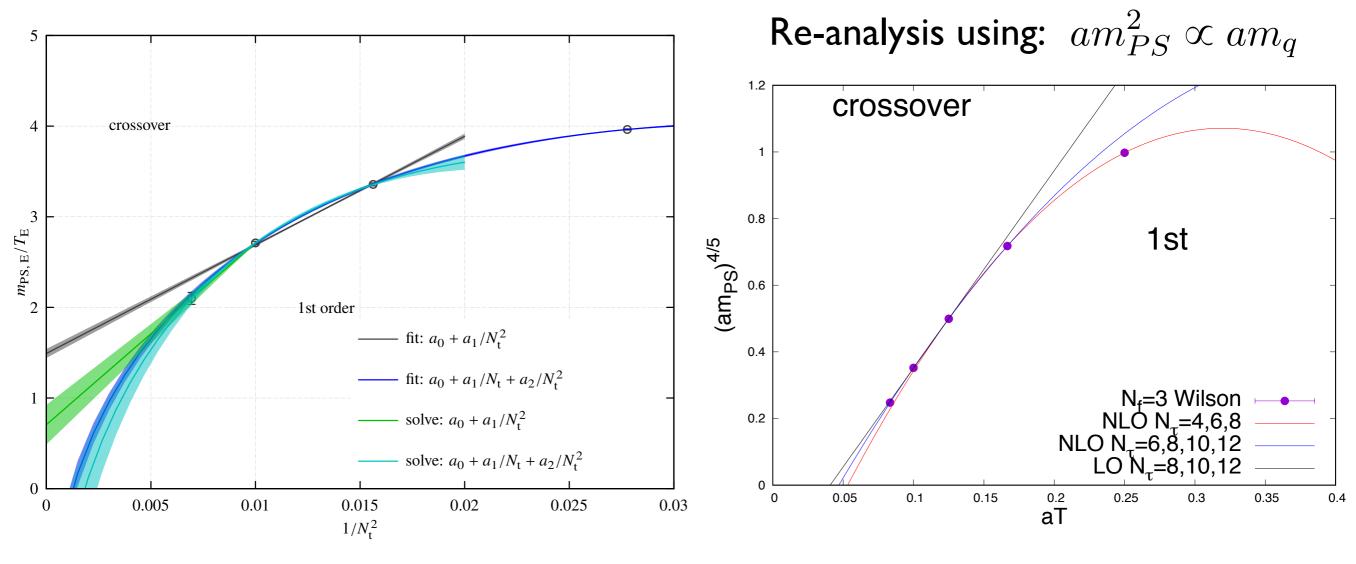
[Cuteri, O.P., Sciarra, JHEP 21] $N_{\mathrm{f}} \in [2,8]$ standard staggered



- Tricritical endpoints+scaling of chiral critical boundary
- Known exponents, i.e. chiral extrapolation is possible!
- Finite $N_{\tau}^{\text{tric}}(N_f)$ implies second-order transition in chiral continuum limit!

Nf=3 O(a)-improved Wilson fermions

[Kuramashi et al. PRD 20] $m_{\pi}^{c} \leq 110 \text{ MeV}$ $N_{\tau} = 4, 6, 8, 10, 12$

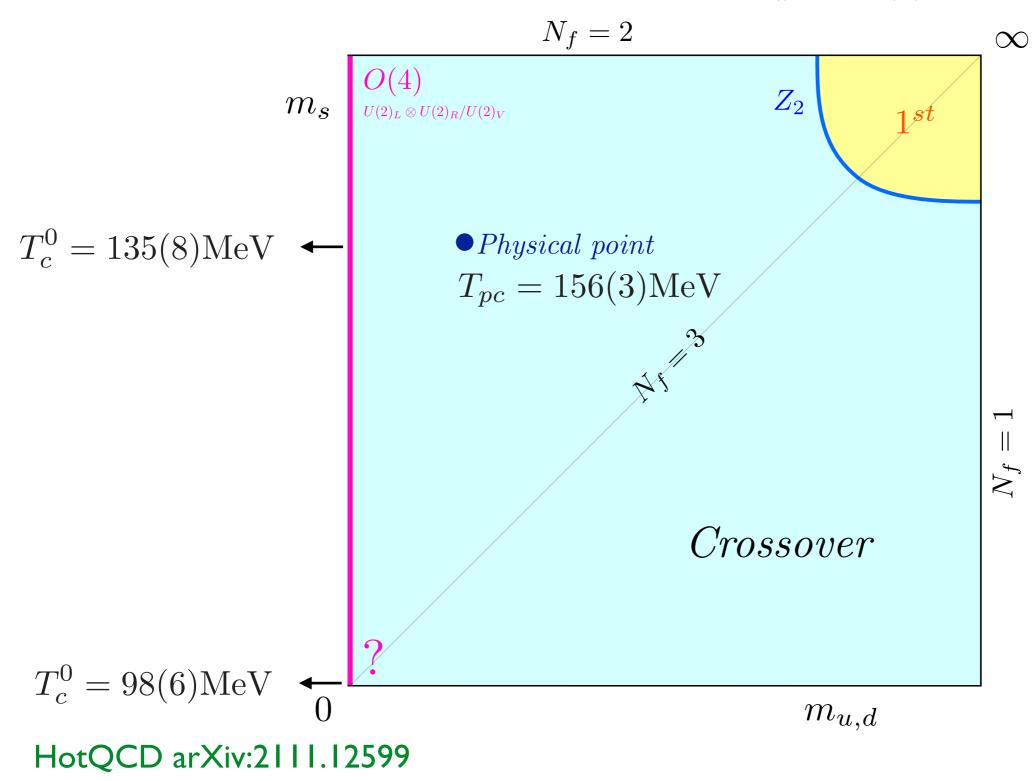


[Cuteri, O.P., Sciarra, JHEP 21]

Tricritical scaling, Nf=3 consistent with staggered, 2nd order in continuum!

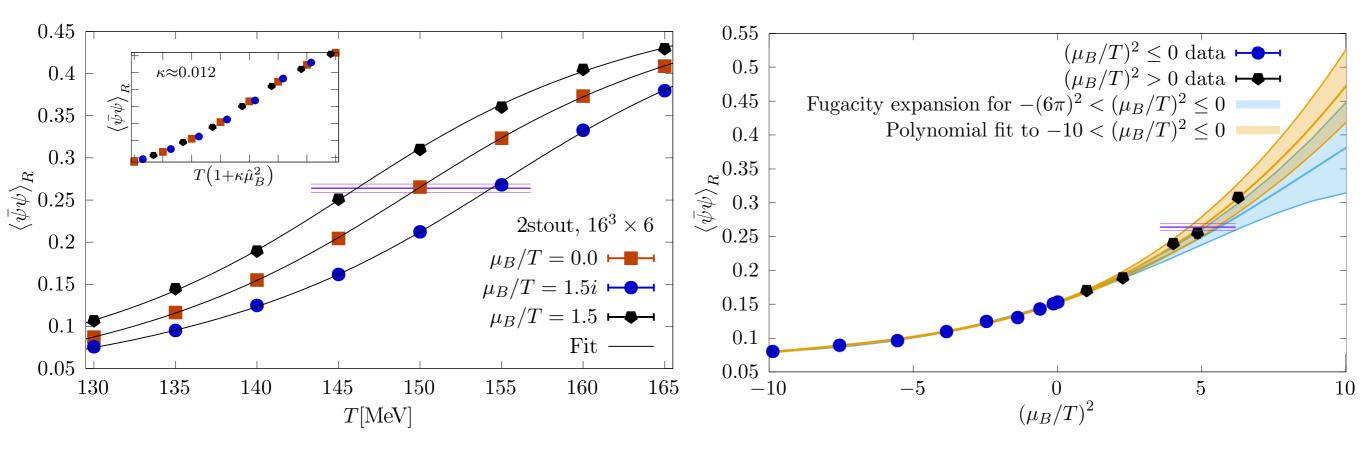
The emerging final(?) Columbia plot

 $m_{\pi}^c \approx 4.0(4) \text{ GeV}, T_c \approx 285(10) \text{ MeV}$



on number susceptibilities at µ bezing have recently been por partechin tattice QGD [16, lattice QCD [16, cting the Fourier coefficients ^{1}b 18 and ^{0}b A from prison with the predictive and a can test the predictive power of the CEM. parts on with these fattice data called Stephens the temperature dependence of $\chi_{4}^{a}\chi_{4}^{a}$, $\chi_{5}^{a}/\chi_{2}^{b}$, and χ_{8}^{b} , calculated in CEM and numbrapenanaptidepeirdentee given Persture are den prine dan under PM preven par and ters of on t calculations use the wappenal Budapest data (P) for b₁(T) and b₂(T) as an input and are therefore labeled ed Frausie Wappfendid IBudapusch 200 and i Enter ONE consultation set as a first of the source of the the GEN Bankapesodata an lexion can be and the second of the lattice data for χ^B/γ^B and χ^B although these data are still preliminary and the second s molevioesults baryon un mitatus sugertinenties itby the version detus kods view and a properties to be a second as no suice the second second as no suice the second second second as no suice the second second as no suice the second s alue. Draminteresting cjentizare tes fix and then the Qenderal about the data on MITHE OCHIER ON COMPANY AND BURGER AND BOSSIDE STRUCTURE DE COMPANY AND STRUCTURE S misginar prase otain GEMACS word stars Buckeyest / COE approximate Iswown has the CEM by two parameters t the negative dip in χ_6^B/χ_2^B cannabity be considered as can unambiguous right of chiral rature from two independent combinations of baryon number susceptibilities by refersing EB. (6). We demonstrate his μ_B *the fourier coefficients* b_1 and b_2 coefficients reconstructed from the HotoCD collaboration's lattice data on $T_{pc}(0)$ *the fourier coefficients* b_1 and b_2 coefficients reconstructed from the HotoCD collaboration's lattice data on $T_{pc}(0)$ *the fourier coefficients* b_1 and b_2 coefficients reconstructed from the HotoCD collaboration's lattice data on $T_{pc}(0)$ *the fourier coefficients* b_1 and b_2 coefficients reconstructed from the HotoCD collaboration's lattice data on $T_{pc}(0)$ *the fourier coefficients* b_1 and b_2 coefficients reconstructed from the HotoCD collaboration's lattice data on $T_{pc}(0)$ *the fourier coefficients* b_1 and b_2 coefficients reconstructed from the HotoCD collaboration's lattice data on $T_{pc}(0)$ *the fourier coefficients* b_1 and b_2 coefficients he wuppertal-Budapest collaboration, shown in Fig. 3 by the blue susceptibilities at a given temperature are determined in the CEM by two parameters. Action rier coefficients b_1 and b_1 . One can now consider a reverse prescription – assuming [Bellwied et al, PLB 15] M ansatz one can extract the values of b_1 and b_2 at a given temperature from image μ , stout-smeared staggered ions of baryon number susceptibilities by reversing Eq. (6). We demonstrate this image μ , stout-smeared staggered this hyperbolic field in the staggered staggered by the staggered staggered staggered by the staggered staggered staggered by the staggered staggered staggered staggered staggered by the staggered [Bonati et al, NPA 19] [Bonati et al, PRD 18] tice QCD data of the HotQCD collaboration for χ_2^B and $\chi_4^B/\chi_2^B.0.0$ temperature Taylor, HISQ [HotQCD, PLB 19] and b_2 coefficients, reconstructed from the HotQCD collaboration's lattice data on . (6)], is shown in Fig. by the green symbols. The extracted values agree rather ry μ_B data of the Wuppertal-Pudapest collaboration, shown in Fig. 3 by the blue μ_B $\mu_B^{cep} > 3.1 T_{pc}(0) \approx 485 \text{ MeV}$ $T_{pc} > T_c > T_{tric} > T_{cep}$

Critical endpoint: reweighting LQCD revisited

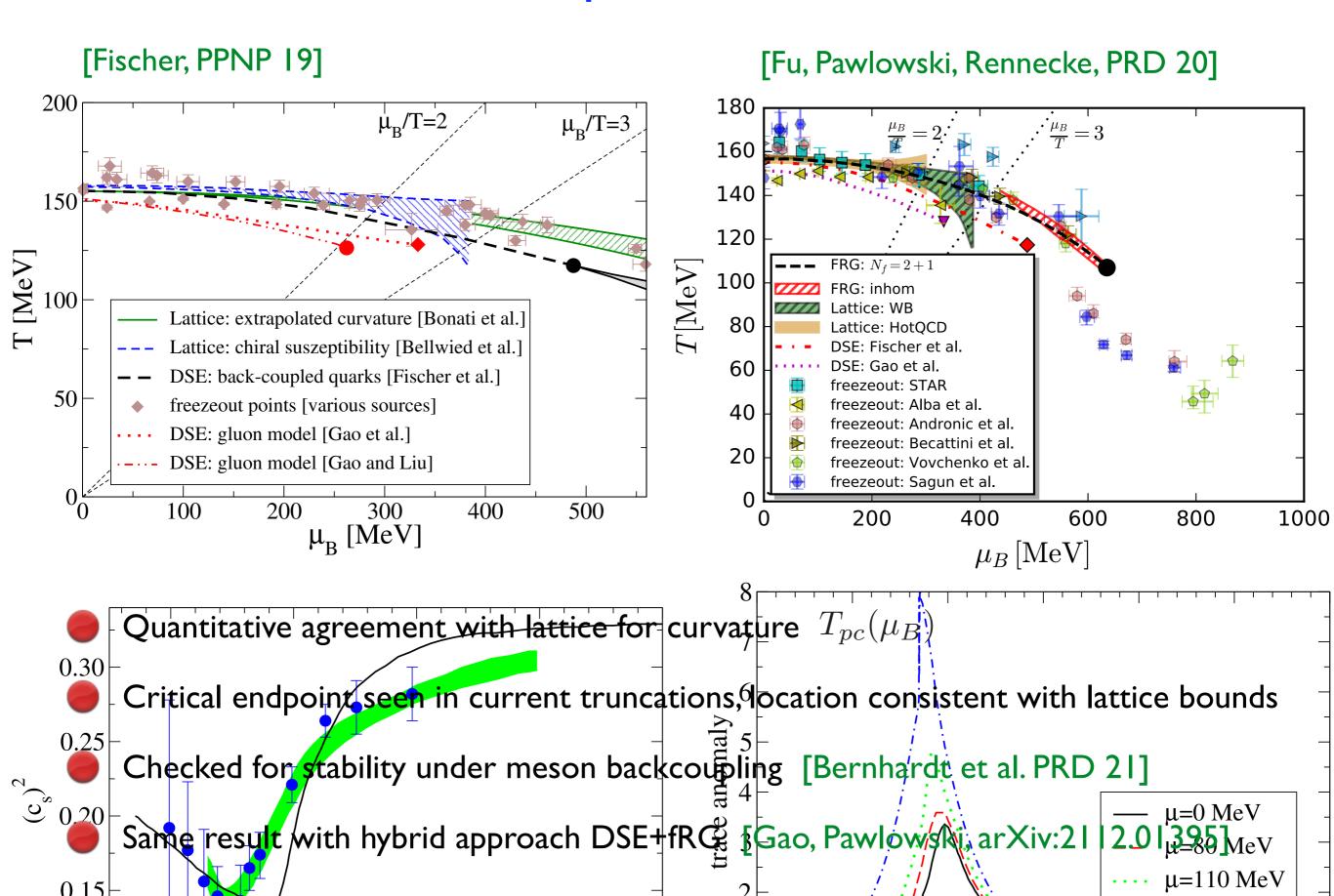


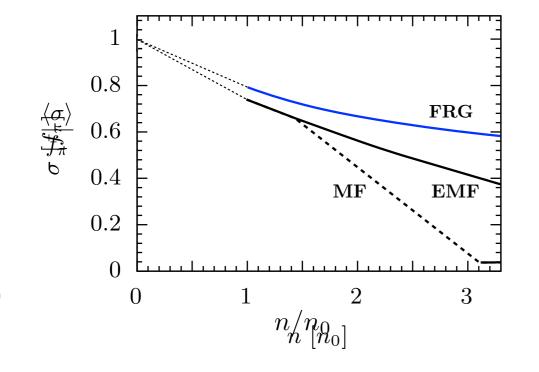
[Borsanyi et al., arXiv:2108.09213]

- Fodor, Katz result from 2001 shows gap of rooted staggered fermions, not phase transition [Giordano et al., PRD 20]
- New treatment rooted determinant + reweighting in sign only [Giordano et al. JHEP 20]

Simulation with stout-sm. staggered action, $N_{ au}=6$: no sign of criticality for $\mu_B < 2.5T$

Critical endpoint: DSE and fRG





ler parameter of symmetric nuclear matter at eld model with included vacuum term versus the Discontinuities in σ indicate phase transitions ween are obtained from Maxwell constructions.

sible scenario

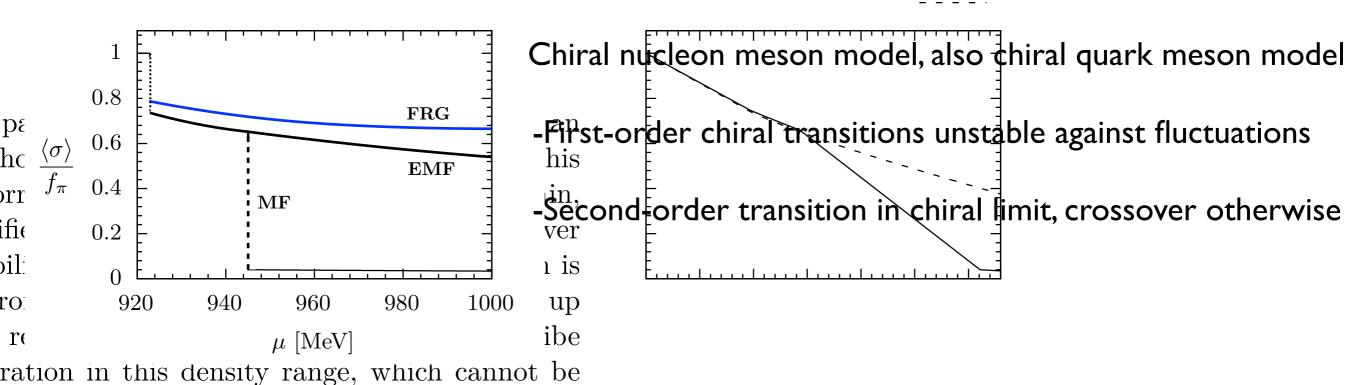
al limit: all second order

ical masses: all crossover

sistent with all available lattice results

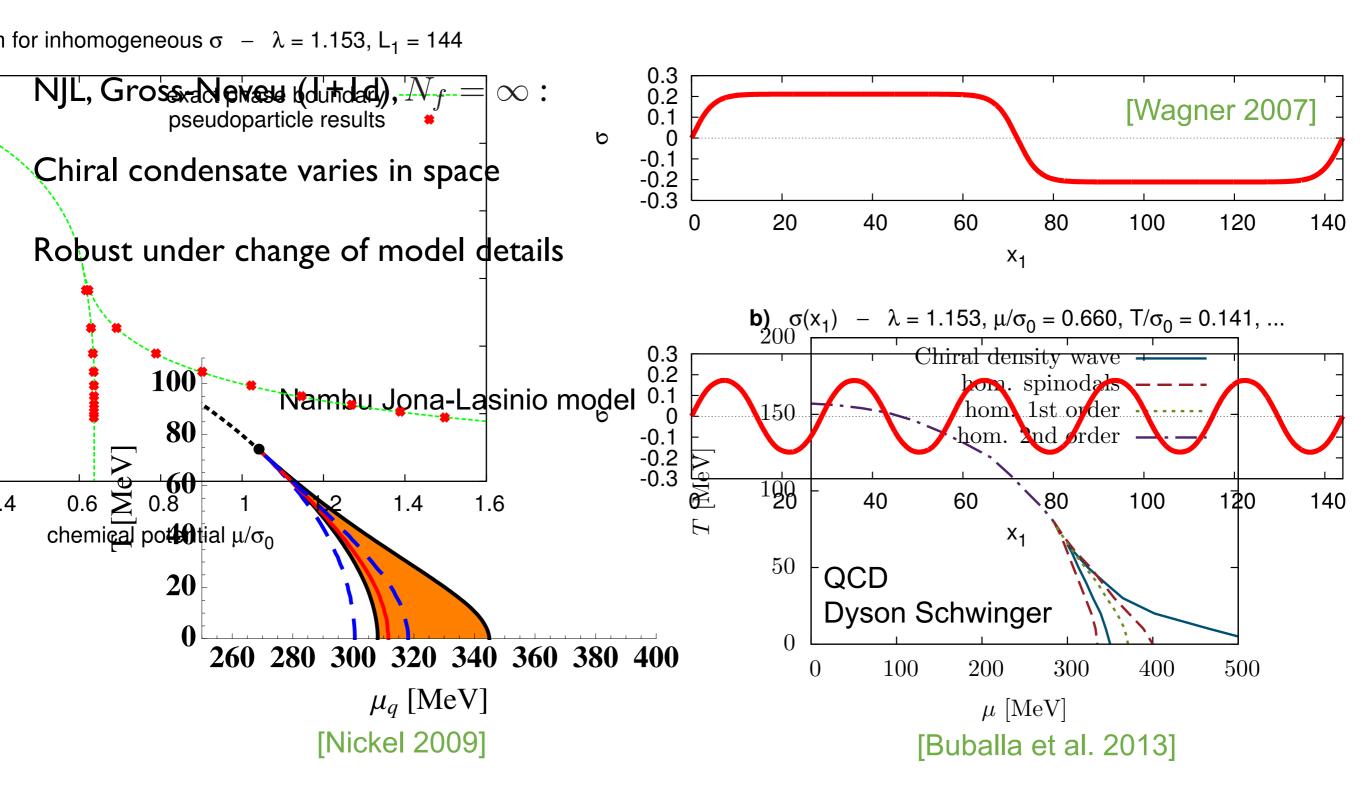
Predicted by some models:

[Brandes, Kaiser, Weise, arXiv:2103.06096]



Inhomogeneous phases

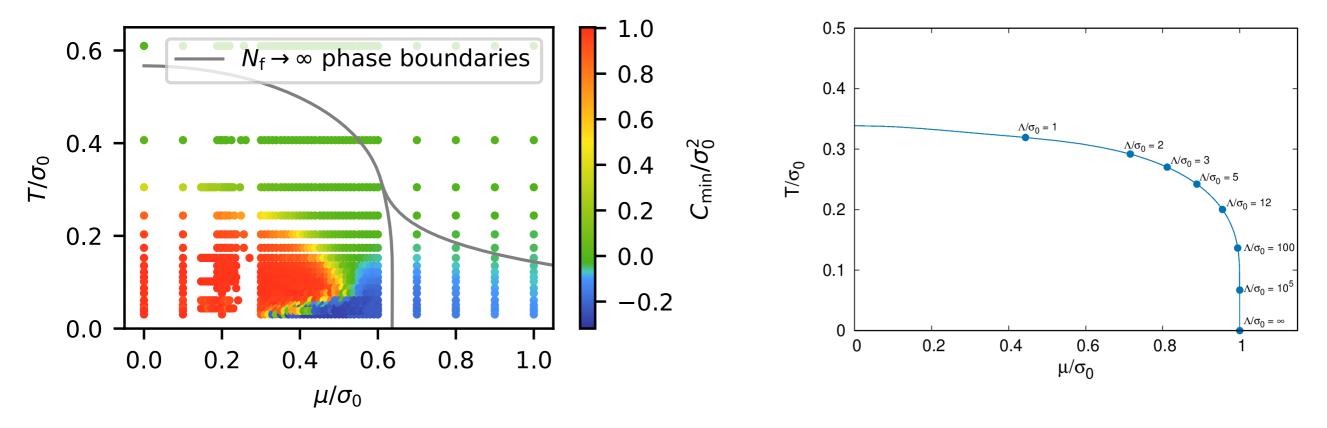
QCD-inspired (symmetry!) models exhibit inhomogeneous phases, what about...QCD?



Gross-Neveu, systematic investigations

$$1 + 1d, N_f = 8$$
 [Lenz et al., PRD 20]

 $2 + 1d, N_f = \infty$ [Buballa et al., PRD 21]



First fully non-perturbative lattice observation of an inhomogeneous phase!

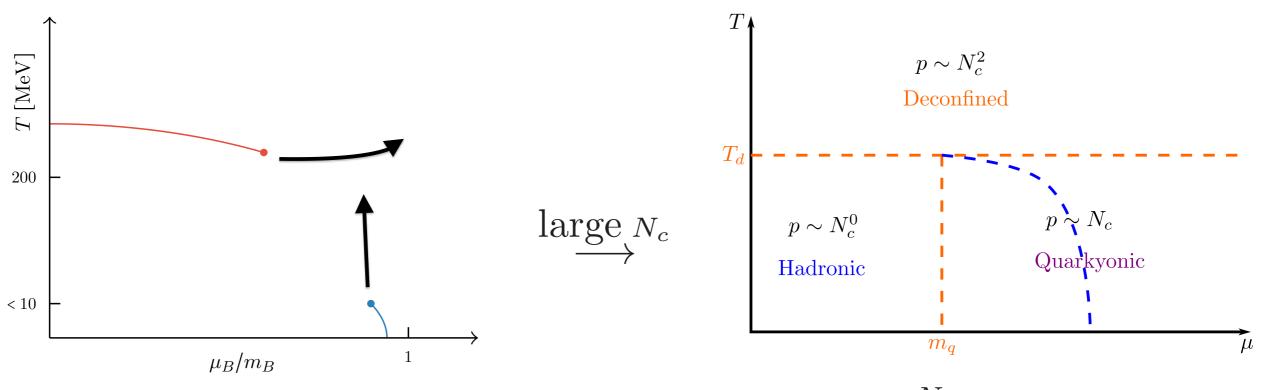
Stability analysis continuum: Inhomogeneous phase depends on UV cutoff

Lattice:

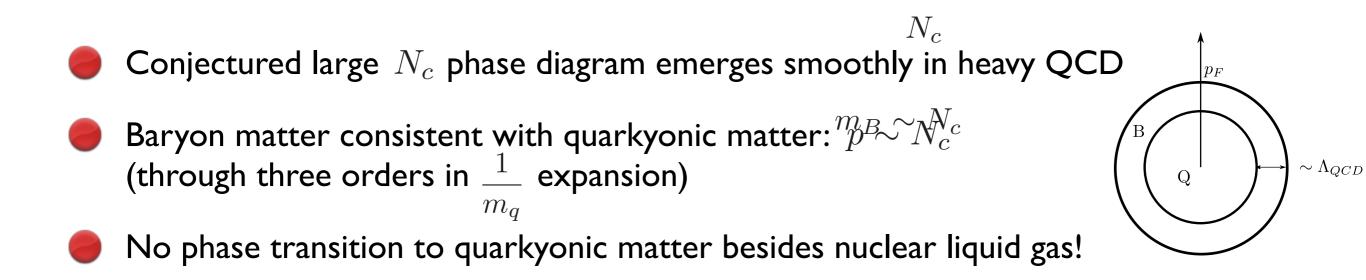
Inhom. phase discretisation-dependent, so far no sign of it when cutoff is removed

General N_c and quarkyonic matter in 3+1d QC below he large.

Wilson LQCD with heavy quarks [O.P., Scheunert, JHEP 19]



 N_c [Pisapski, McLerran, NPA 07]



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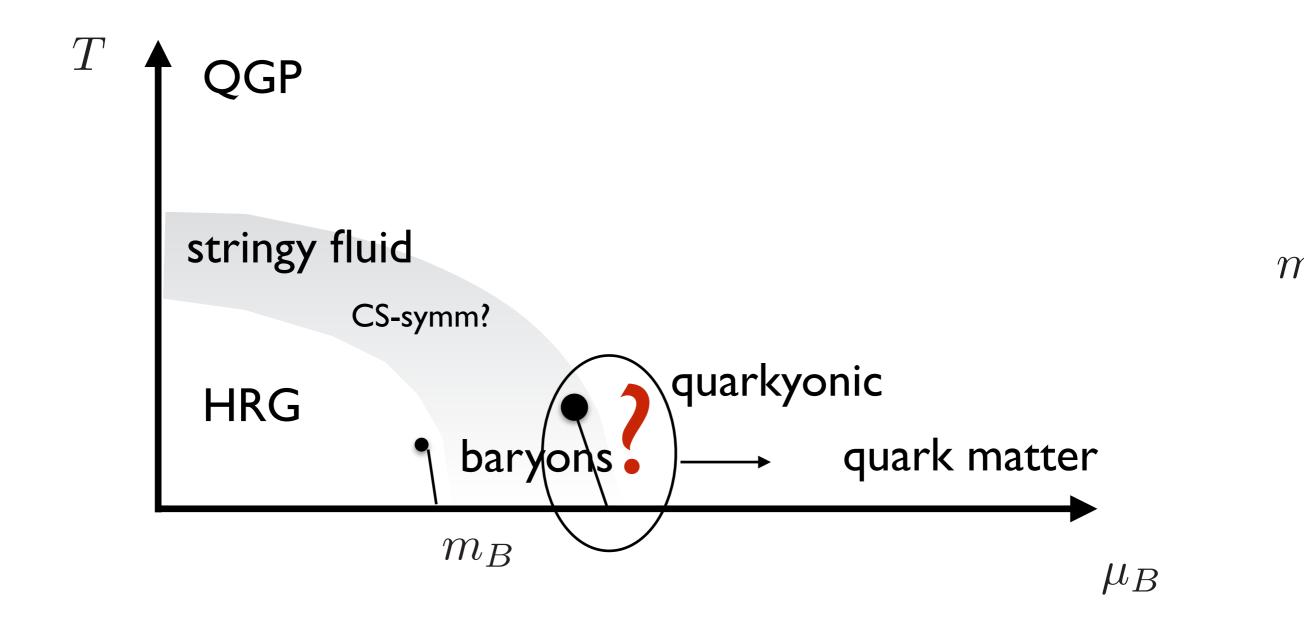
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ding transformations are a grievial general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go map acing the general convex of Eq. (26) obtained go (26) obtained go (26) obtained go (26) acing the general convex of Eq. (26) obtained go (26) acing the general convex of Eq. (26) obtained go (26) acing the general convex of Eq. (26) acing the general in (38). Also³² Also³² a symmetry of the quark - chromo-electric interaction ferms under SU the sublet where $\frac{1}{2}$ and the sublet of the sublet strength of the sublet of the subl C(²) 0 10⁻⁵ $(V_{\text{textr,}}, V_{ty}, A_x, A_y, T_t X_t)$ $Q = \int d^3x \ \psi^{\dagger}(x)\psi(x),$ $(V_t, A_t, T_x, T_y, X_x, X_y) \stackrel{\text{10}^{\circ}}{:}$

ne multiplets of the isovector apprators that as discussed in the present paper, the favor dusym eracy within both, the (39) aseweid ashtarge (40) sousting ets, invariant degeneracy of the wormalized e multiplet (4) is also consistent with free non-interacting grangy field is also State Philadounilar bilinears are not subject to **360 May** degeneracy. bilinears are not subject to 3234 degeneracy. $3^{a} S_{2} \times SU(4)^{a}$ multiplets in addition also include the isoscalar partners of 45054 alar partners of 45054 since F_{x} in Eq. (40). The *U* is (almost) exact, as can be seen from the left panel in T_t is the V_y and V_t a since F_{x} is T_{x} , T_x , T_y , X_x and X_y in Eq. (40). The *U* is play sizable residual violations, but for T = 380 MeV V_y and V_t a

Conclusions



Conclusions

