The BIG Picture

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i.e., half baked ideas....

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Much heated discussion...

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Nuclear Matter (NM): QCD at nonzero density, T ~ 0

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Quantum computers? "Merons" Weise, Chandrasekhar...

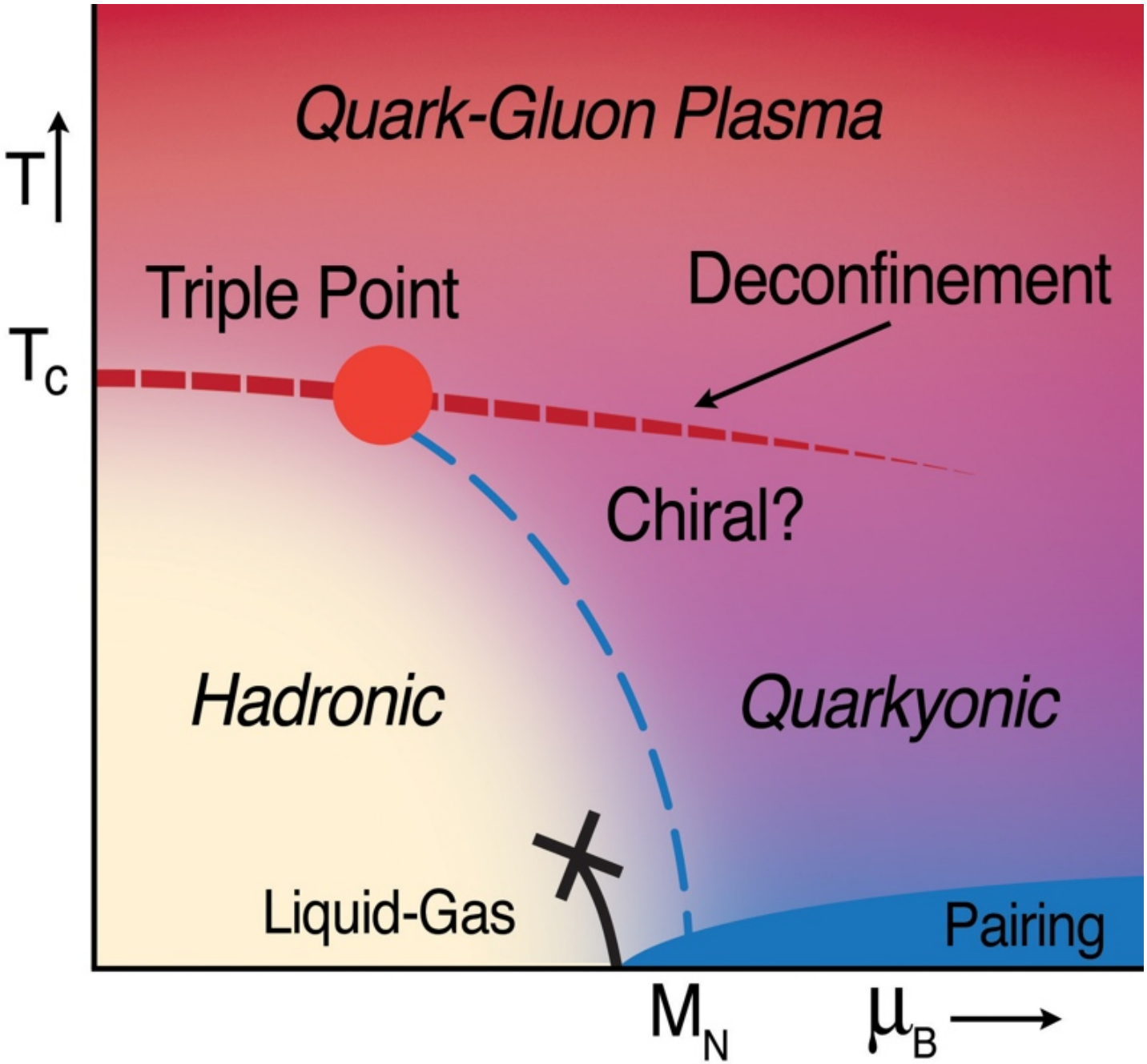
Exp'y: Out in μ, down in T! - RHIC, FAIR, NICA, FRIB...

Cohen

In trying to chart this new land the explorer must rely on the tools at his deposal although they may be crude.

What is “Quarkyonic”?

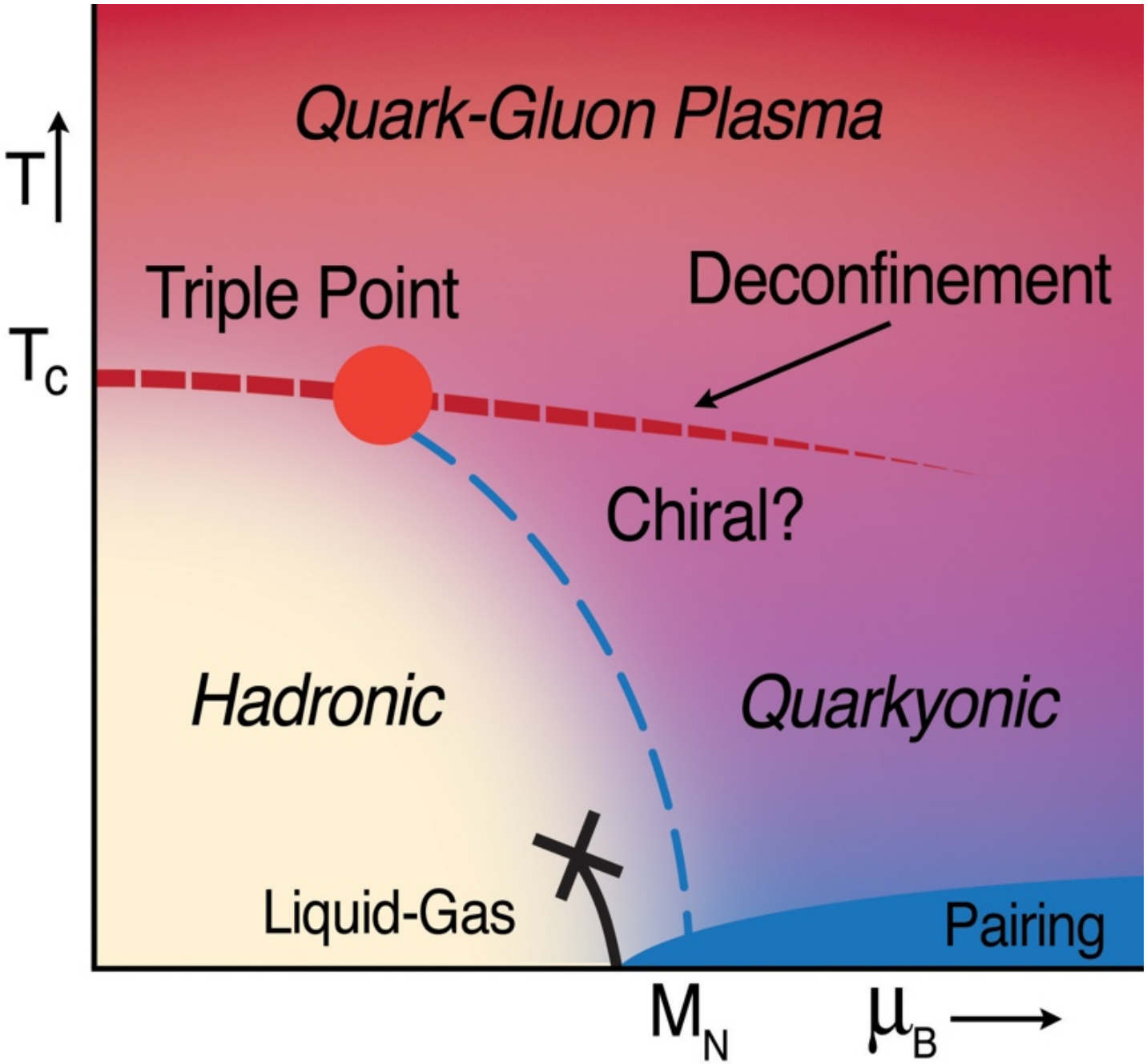
What is "Quarkyonic"?



Andronic +... arXiv:0911.4806

What is "Quarkyonic"?

Fermi *surface* of Nuclear Matter is *not* that of quarks until *very* high density



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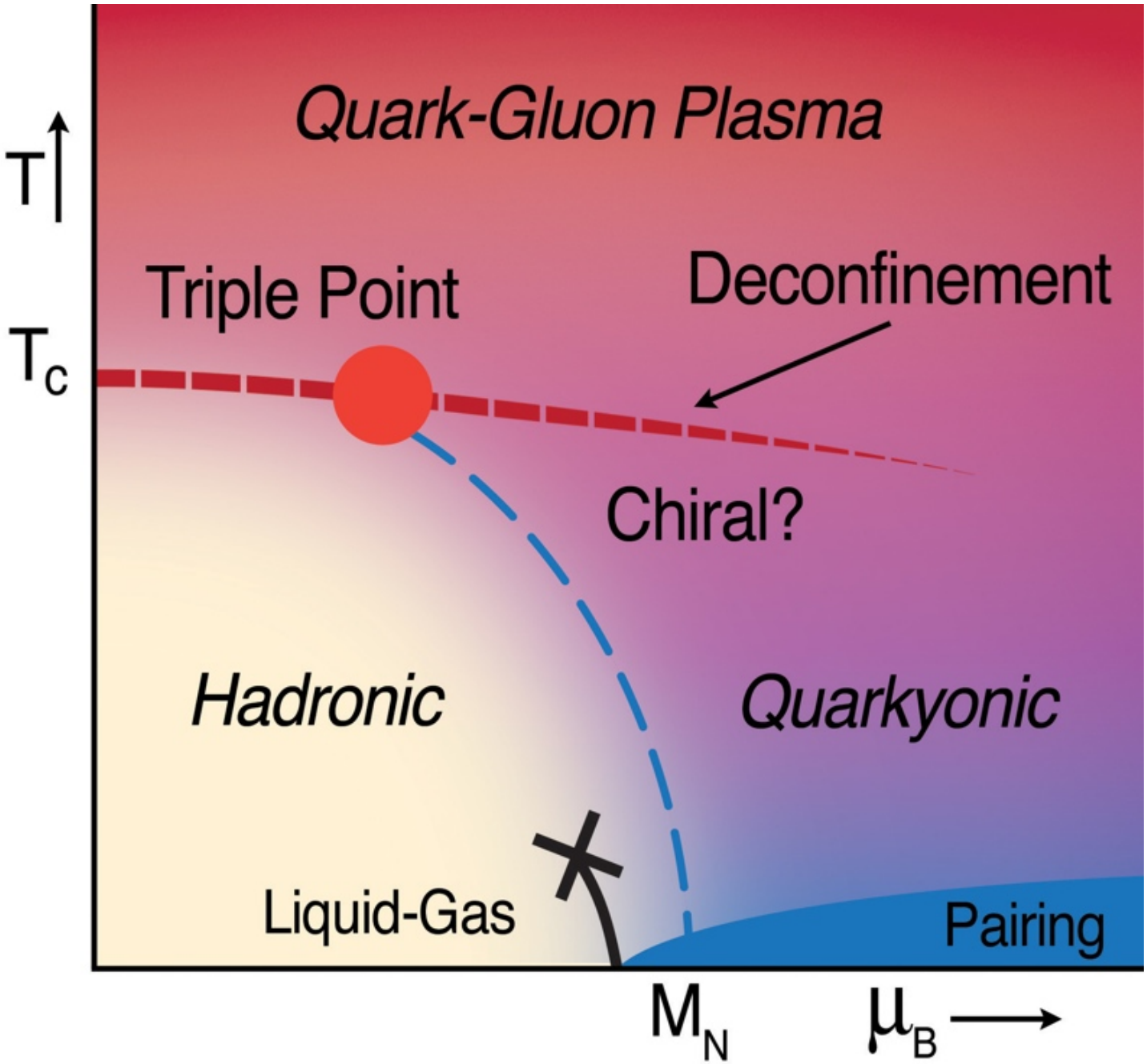
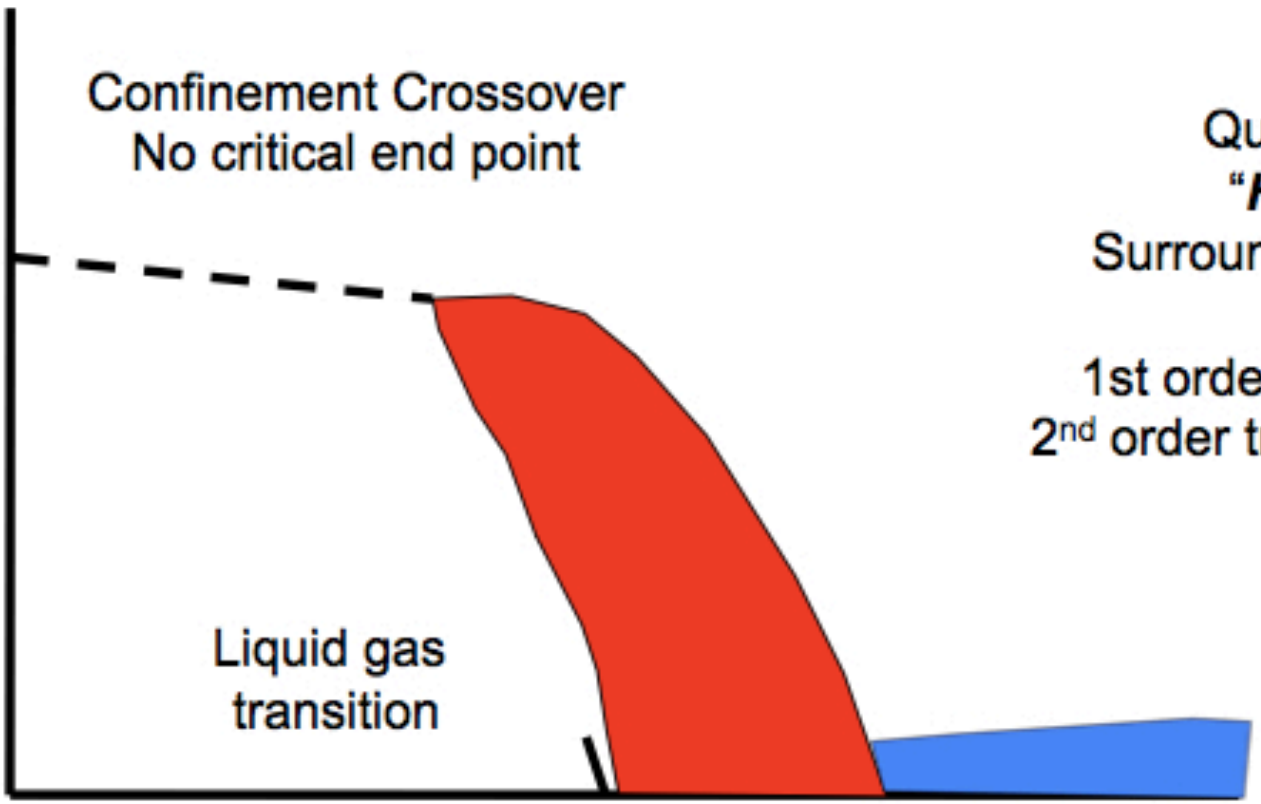
Really great ideas aren't precisely defined, and mean different things to different people..



Andronic +... arXiv:0911.4806

Monday: happy day!

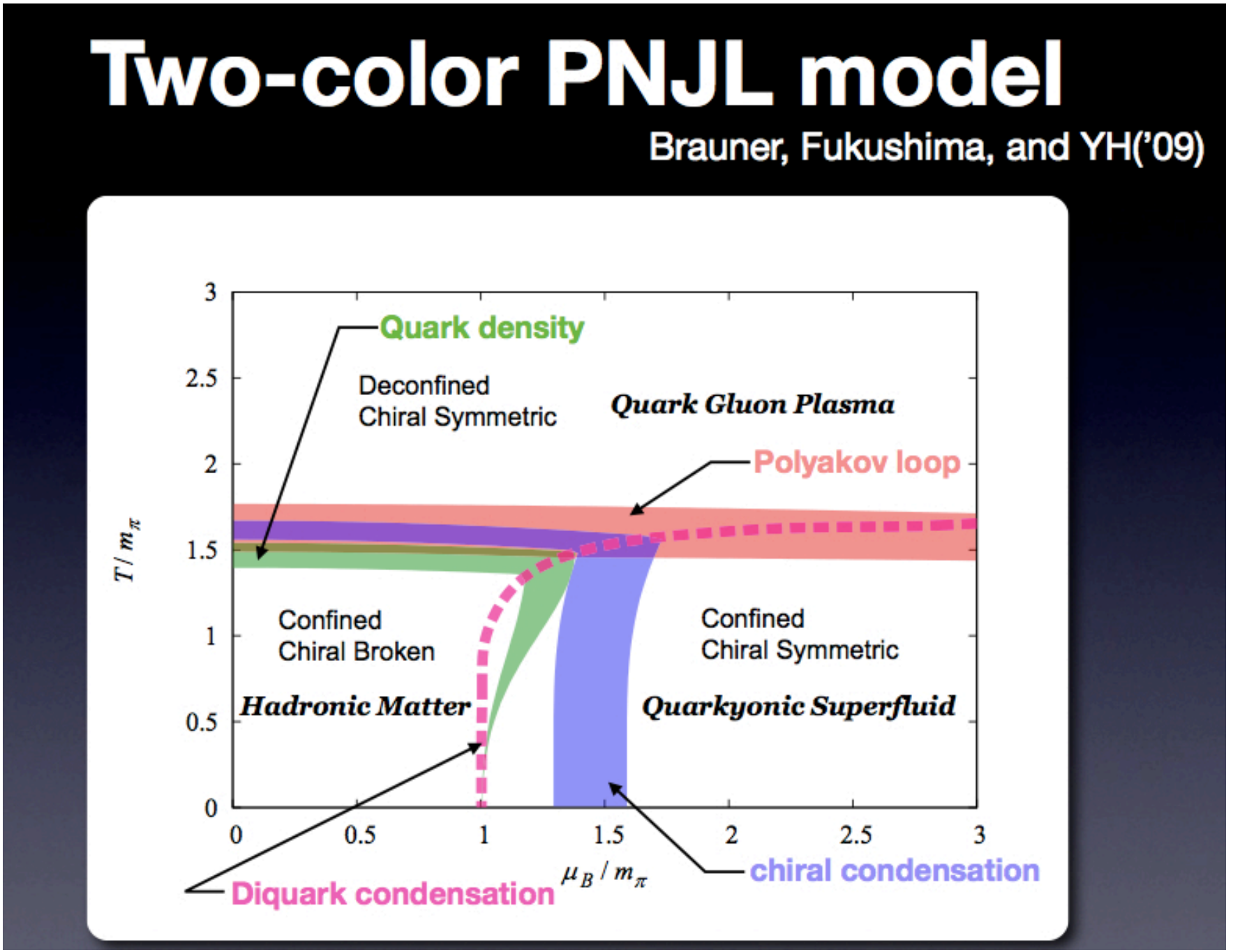
McLerran's "Happy Island"



Quarkyonic Matter
"***Happy Island***"
Surrounded by line of phase transitions
1st order transition line: cliffs
2nd order transition lines: beaches

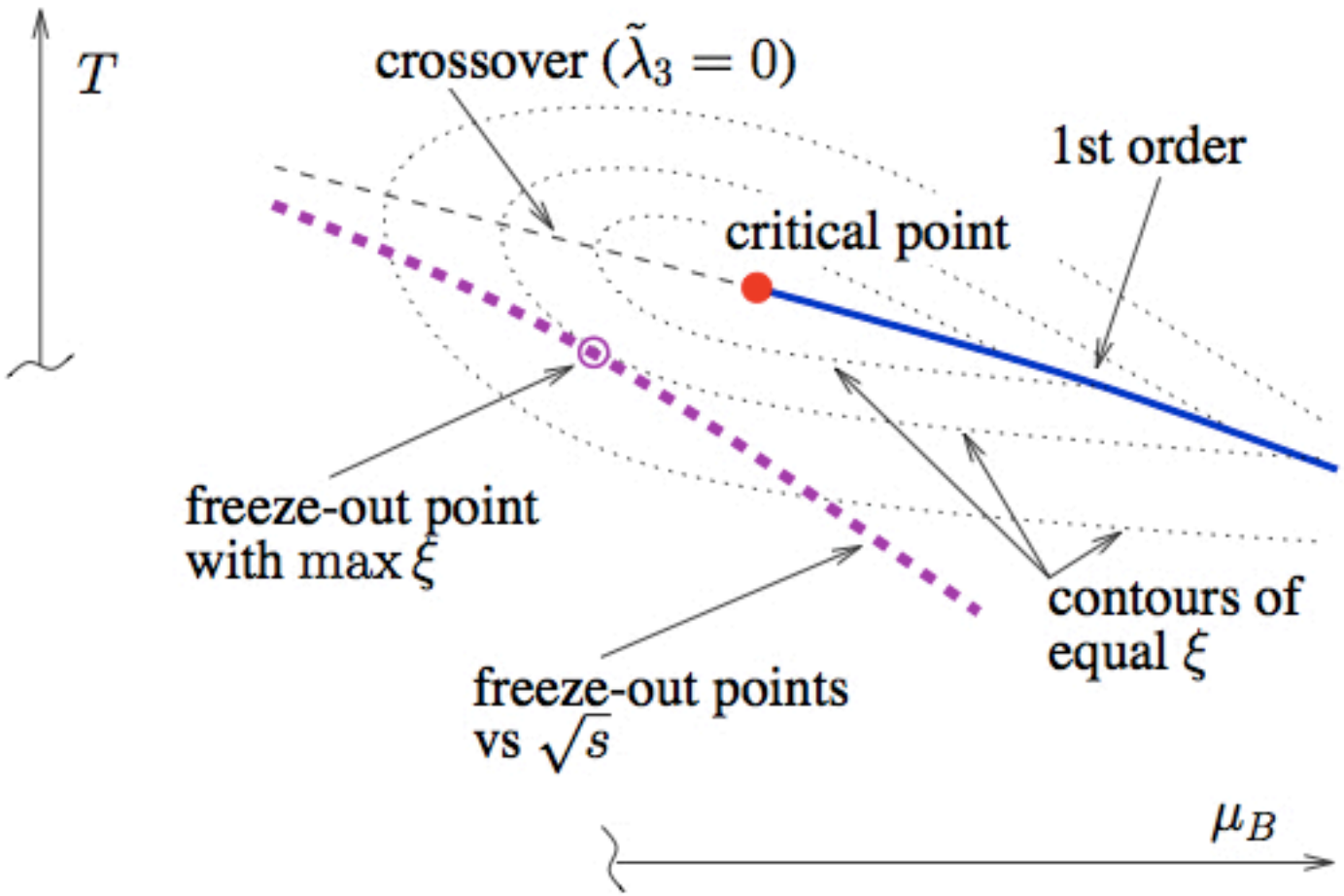
Color
Superconductivity

Hidaka's "Happy Island"?



Stephanov: signals of a critical endpoint

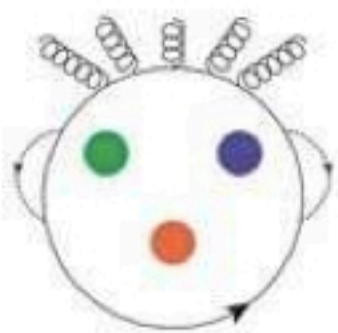
Energy scan and fluctuation signatures



Alkofer's "Happy Face"

Note: Not yet understood relations between different approaches, definitely not mutually exclusive.

Also known as the *The Many Faces of QCD*

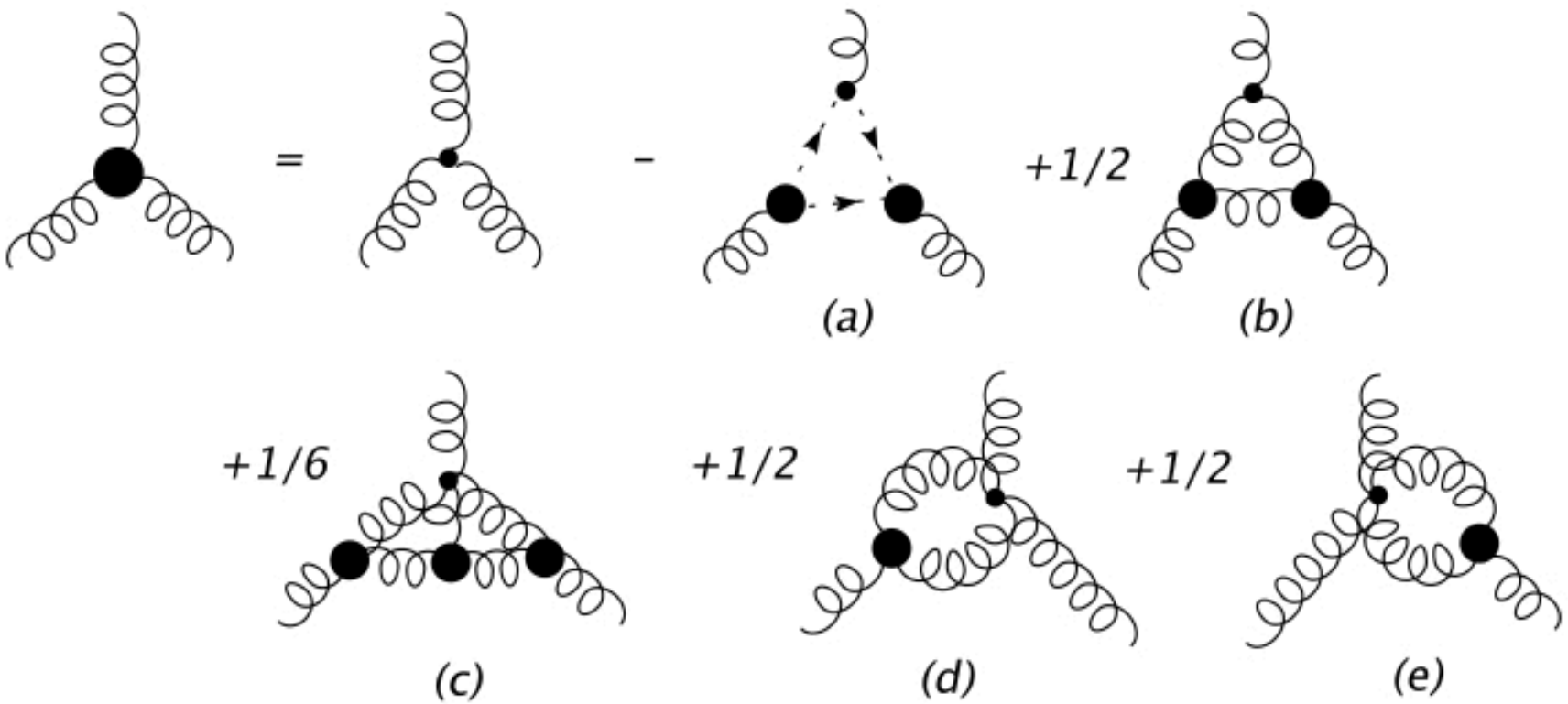


Alkofer: Schwinger-Dyson eq.'s

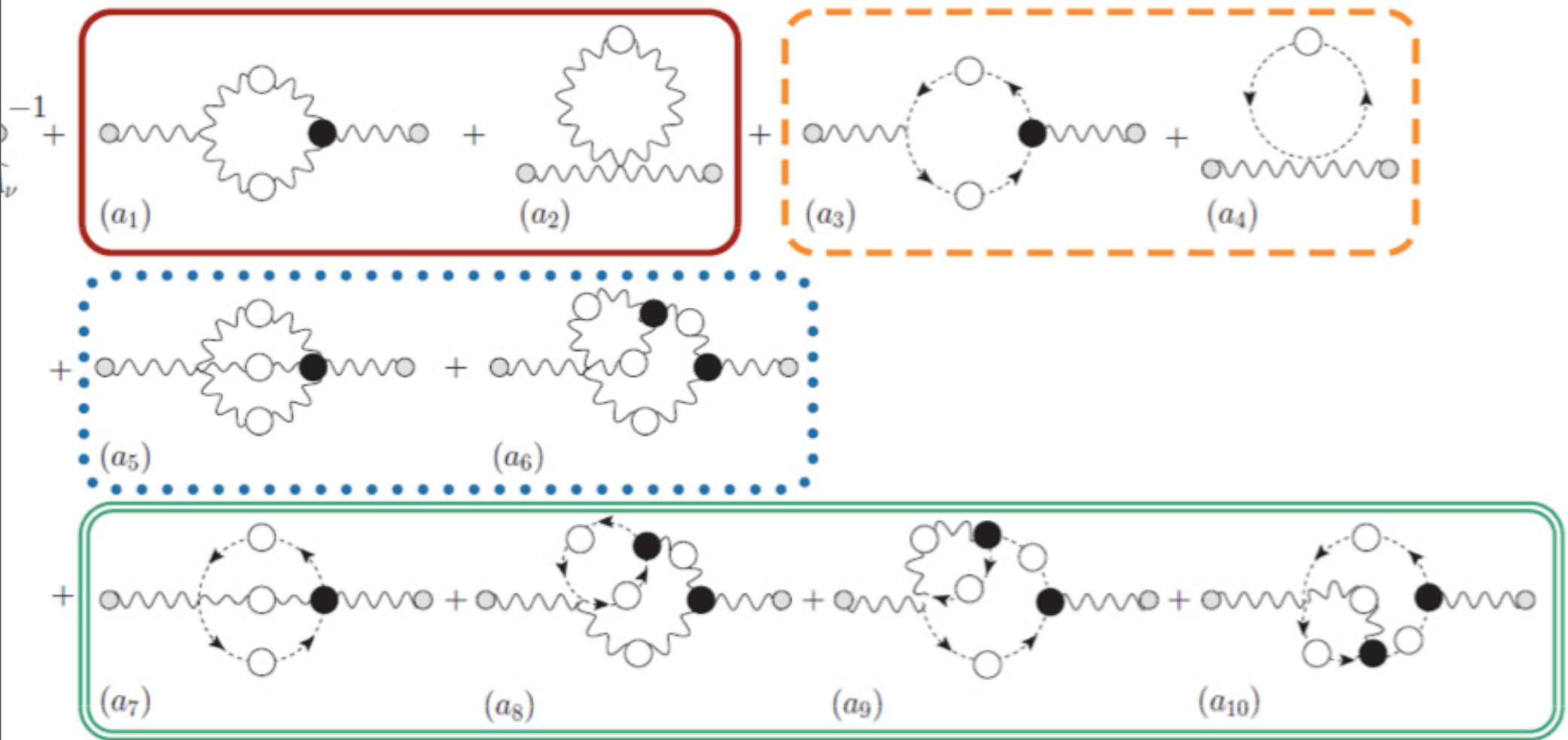
R. A., C. S. Fischer, F. Llanes-Estrada, Phys. Lett. **B611** (2005) 279.

Apply asymptotic expansion to all primitively divergent Green functions:

Skeleton expansion &
generalized formulas (neg. dim.) for Feynman integrals:



Papavassiliou: Schwinger-Dyson eq.'s



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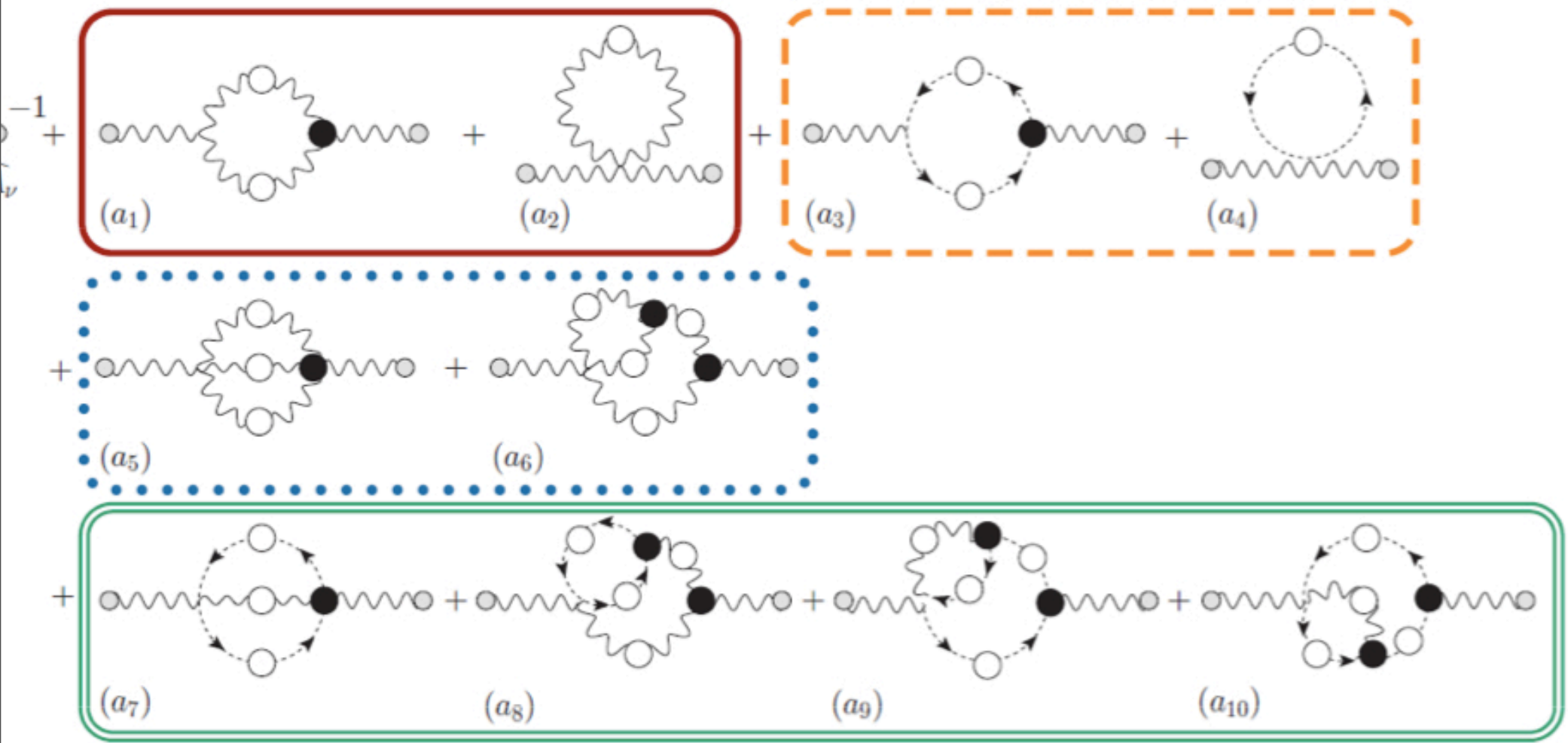


Nuclear matter: *historic* opportunity for approximate analytic methods

Cohen: Novel limits of large N_c

For N_c=3, (anti)-fund. rep. = anti-symmetric (AS) 2-index tensor
Considers large N_c limit with AS quarks
At high μ, BCS wins over chiral spiral

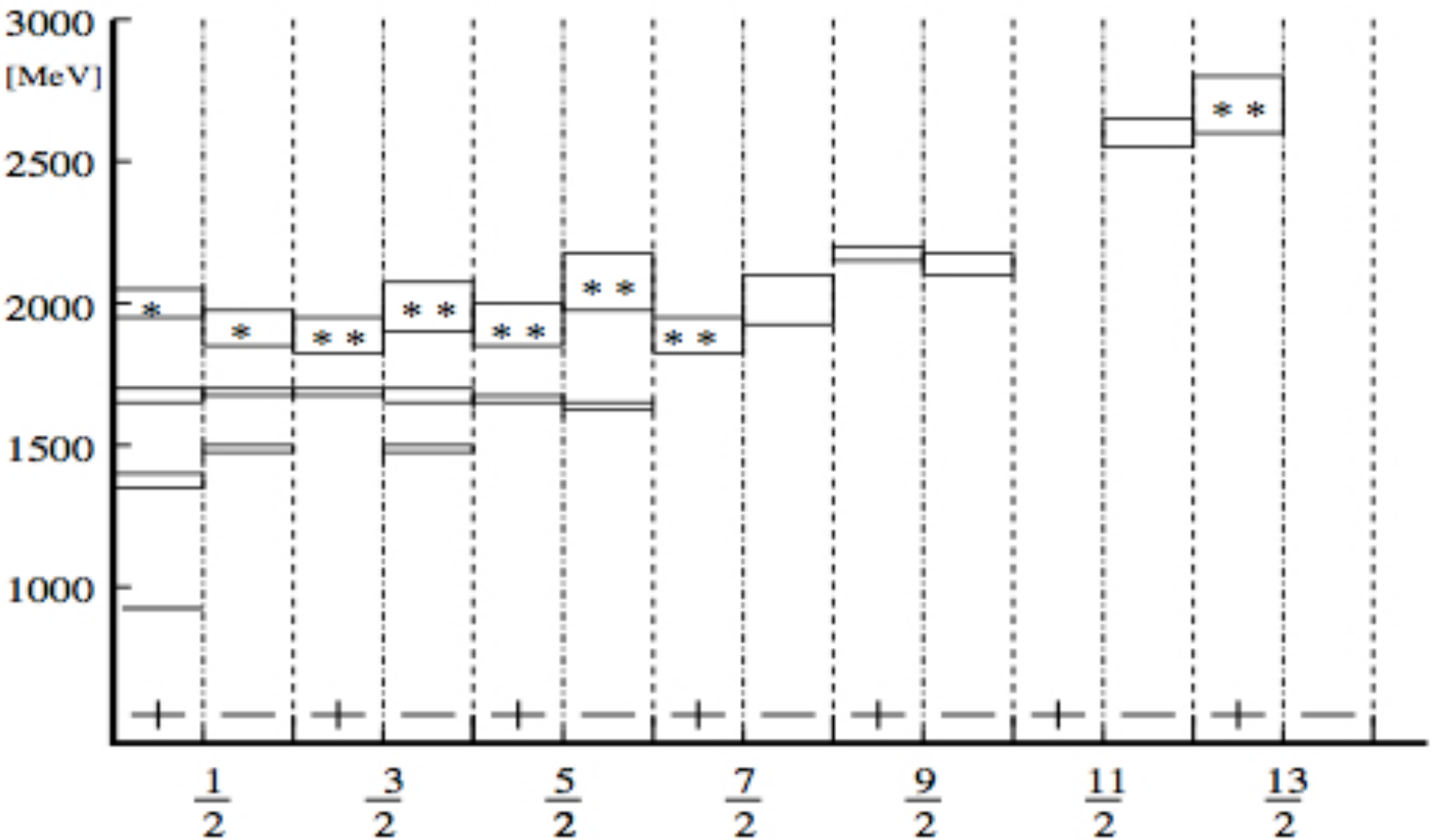
But: for baryons, $g_A \sim N_c$ (*naive* quark model) and $g_A \sim N_c^2$ (AS)

QCD: exp.'y, $g_A \sim 1.2$. "Close" to $g_A = (N_c+2)/3 = 5/3$?

"Dichotomous" baryon: for two flavors, form pairs with zero spin and zero isospin. Then $g_A \sim 1$, not N_c.
(Hidaka, Kojo, McLerran, and RDP arXiv:1004.2661)

Lattice will let us know *soon*! For N_c=5, is $g_A \sim 7/3$ or ~ 1?

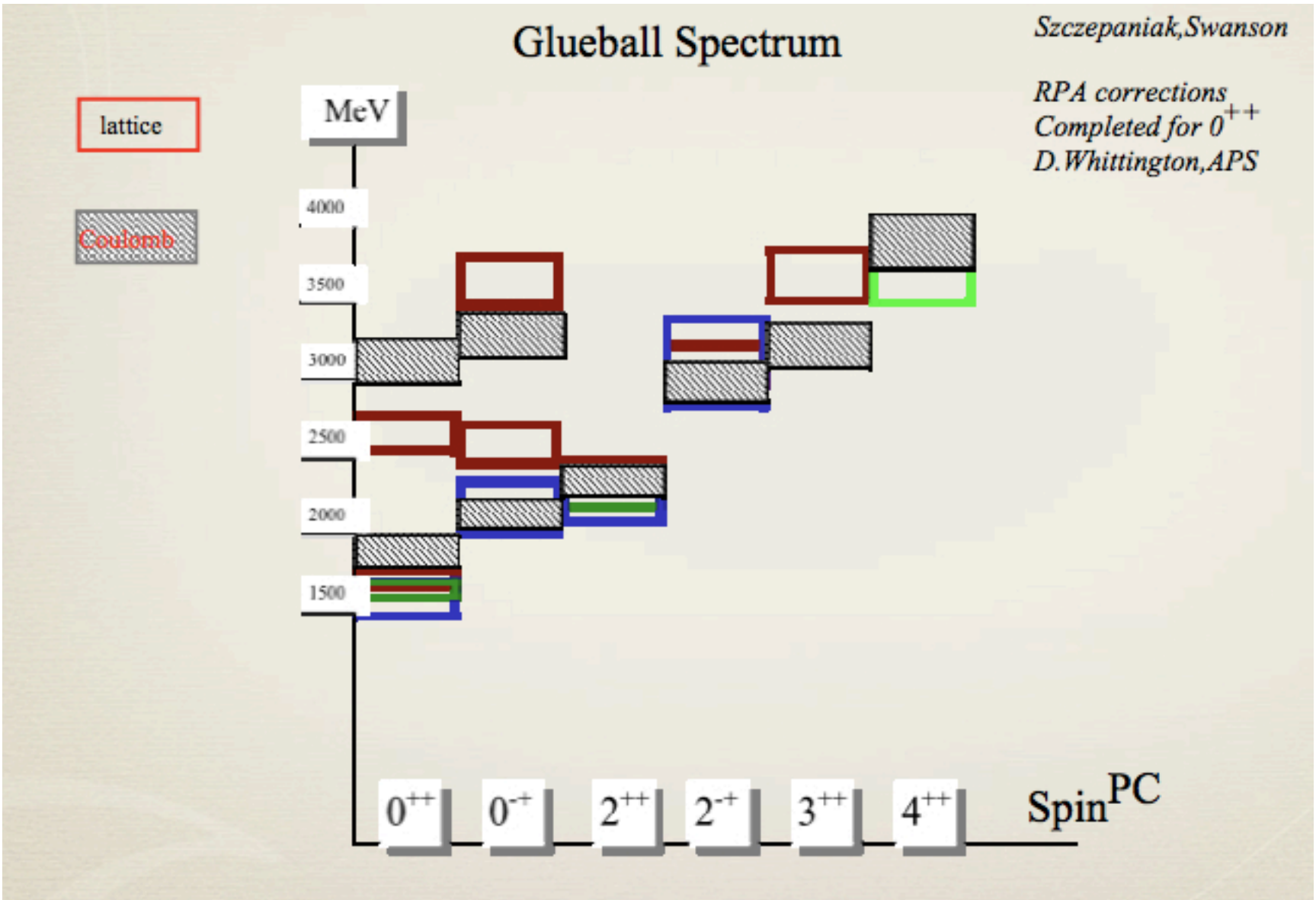
Glozman: *approximate* chiral symmetry for baryonic excitations (*not* nucleon, Δ)



Tuesday:
chiral spirals galore;
NM *computable* from lattice

Szczepaniak

Glueballs from Coulomb gauge vs lattice: close agreement!



Thies: soluble models in 1+1 dim.'s

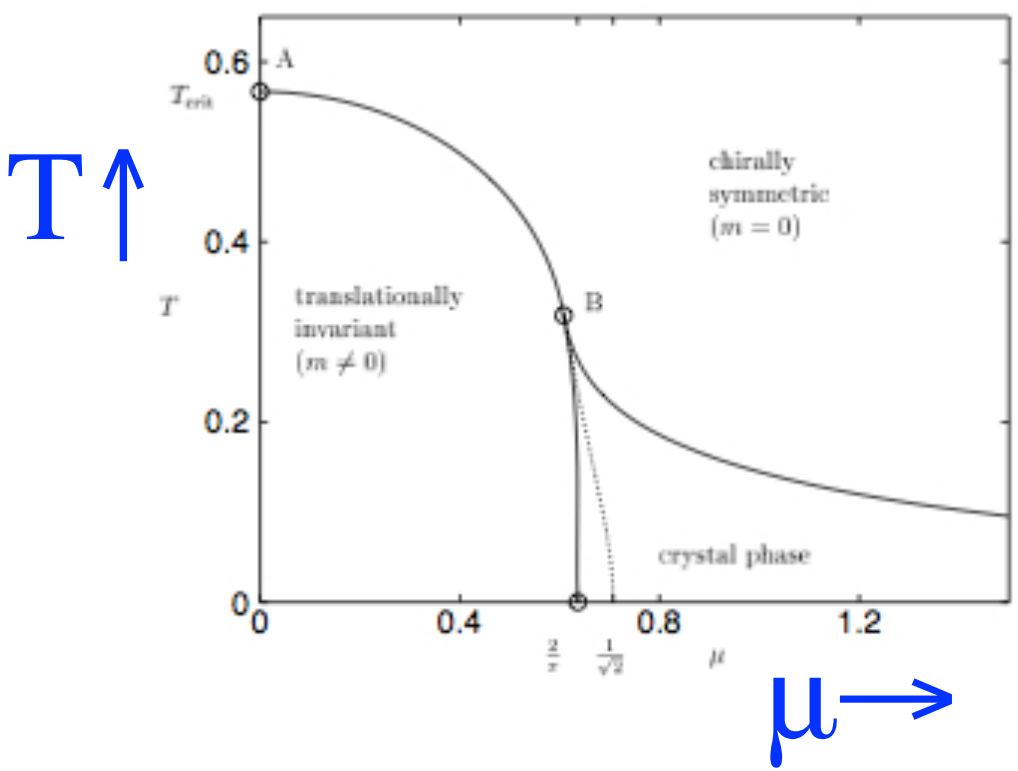
1+1 dim.'s, chiral spirals (CSs) *ubiquitous* at $T = 0$, $\mu \neq 0$

CSs in 3+1 dim? *Closely* analogous to pion condensation

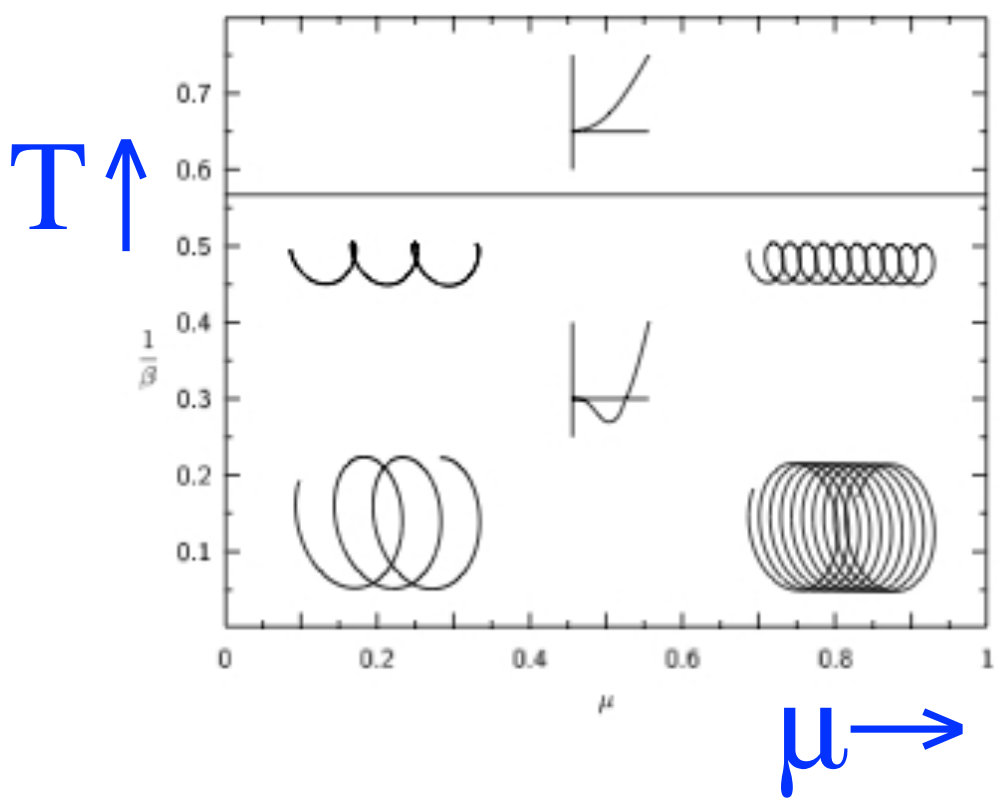
Discrete Chiral Sym. (χS): restoration of χS at $T_c = T_c(\mu)$

Continuous χS: T_c for restoration of χS *independent* of μ

Gross-Neveu



chiral Gross-Neveu



N.B.: chiral spirals *always* occur in 1+1 dim., even for *massive* fields!

Kojo: patches of chiral spirals

In 3+1 dimensions, a confining potential gives chiral spirals!

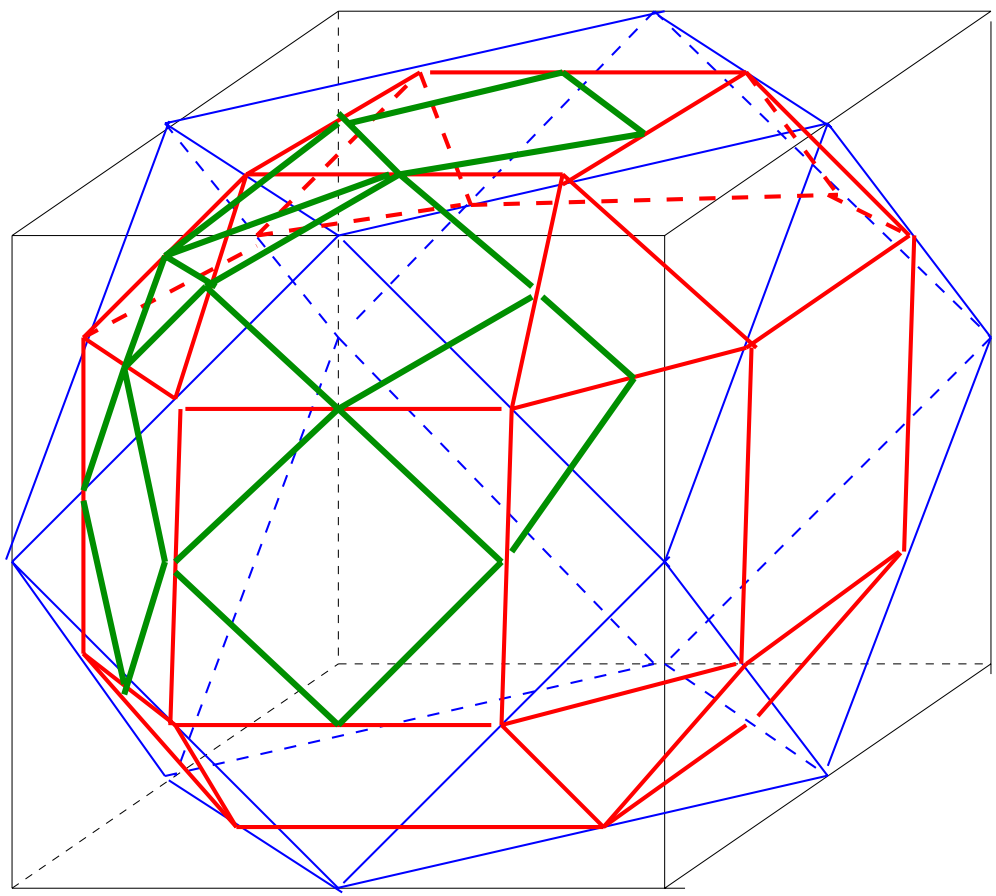
(Park, Rho, Wirzba & Zahed arXiv:hep-ph/9910347)

Reduction from 3+1 to 1+1 dimensions? Planar structure?

No: Fermi surface covered with patches of chiral spirals.

(PRWZ'99, Shuster & Son arXiv:hep-ph/9905458)

patches increases with density, so series of *discrete* phase transitions.

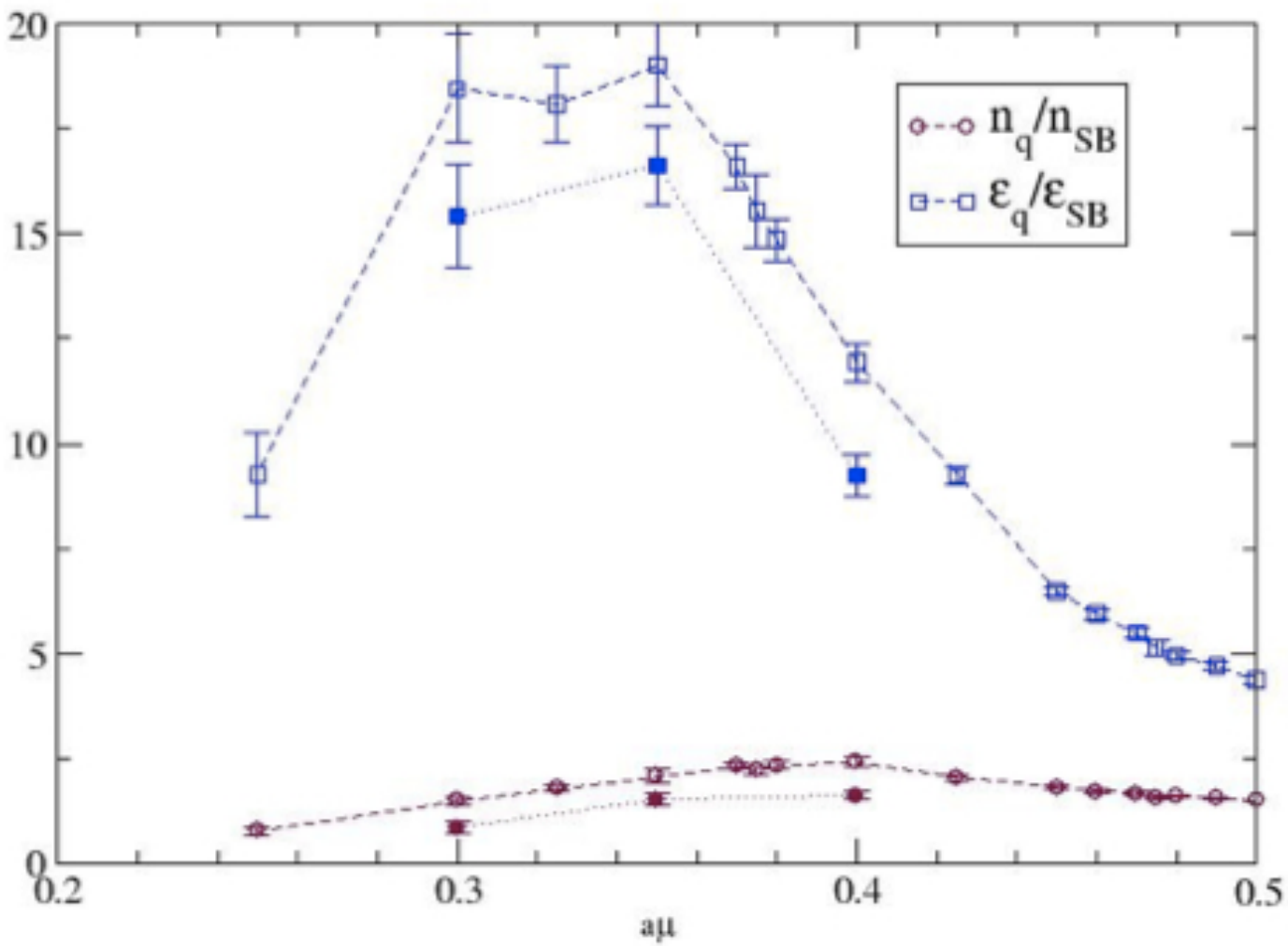


Skullerud: Two color QC_2D at $\mu \neq 0$

N_c=2: baryons are bosons, not like N_c=3

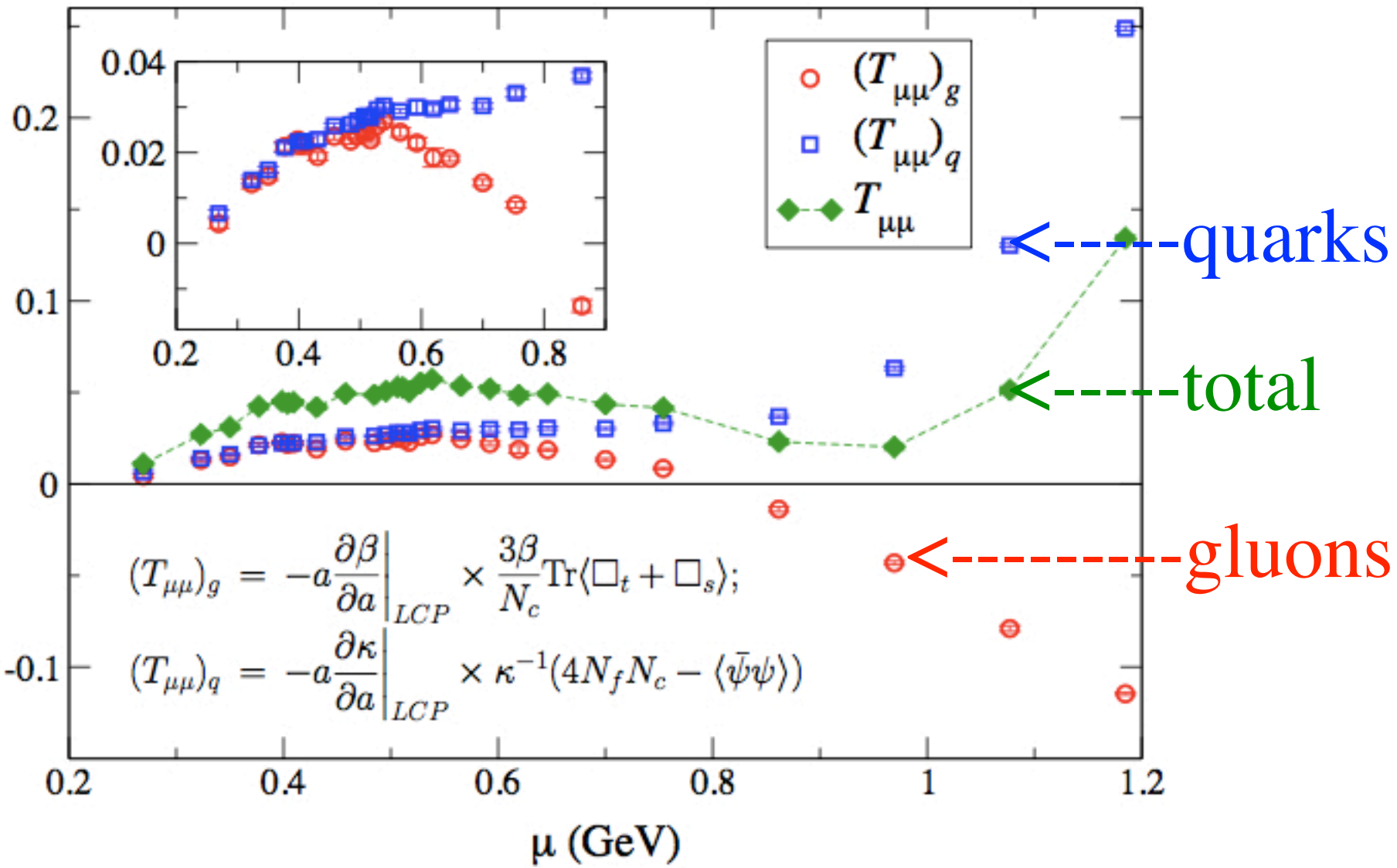
But *NO* sign problem. So can do Monte Carlo.

In *confined* phase, *huge* peak in energy/(ideal energy)~10!



Hands: Two color QC_2D at $\mu \neq 0$

In deconfined regime, trace of energy-momentum tensor for quarks and gluons *split*



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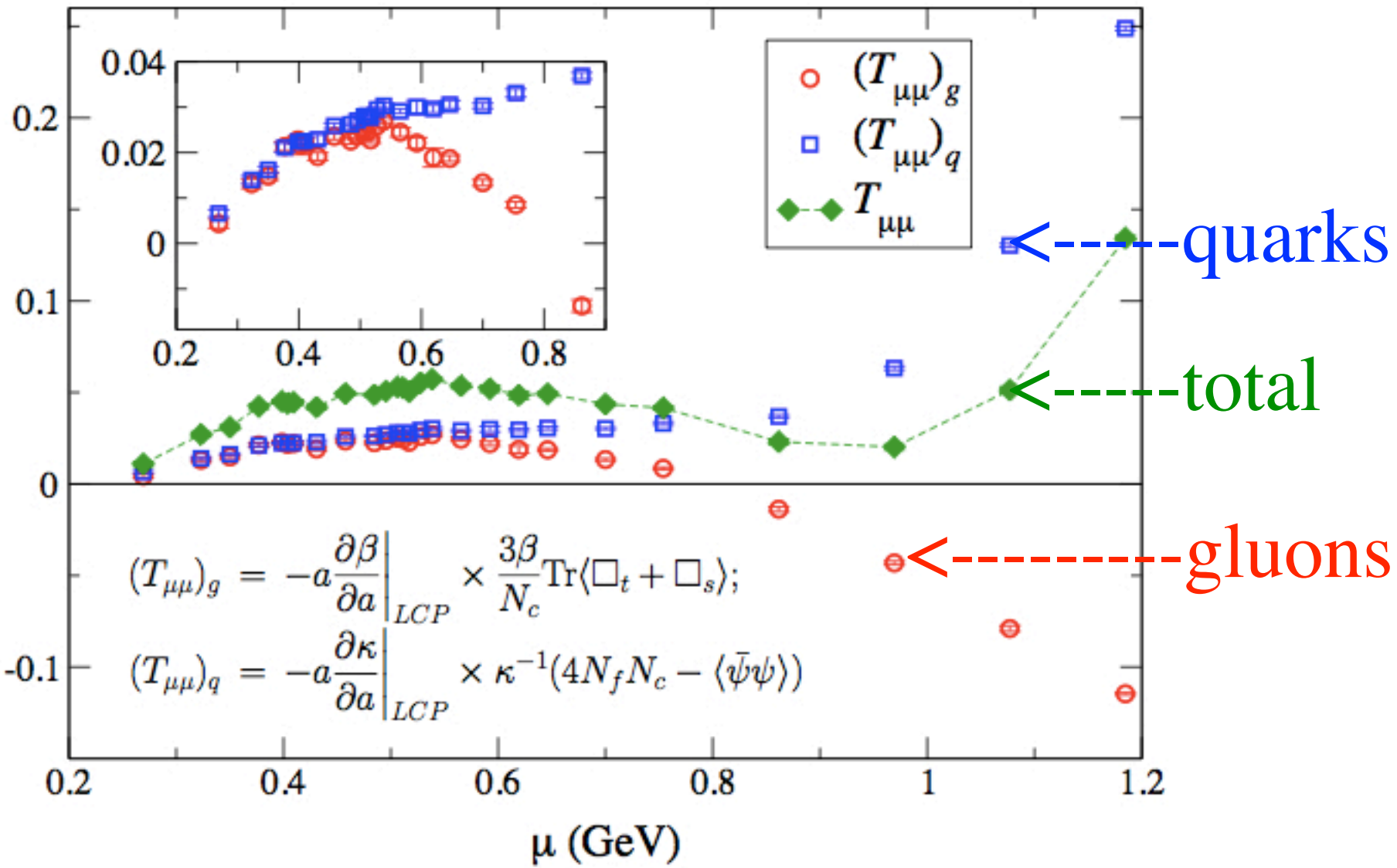
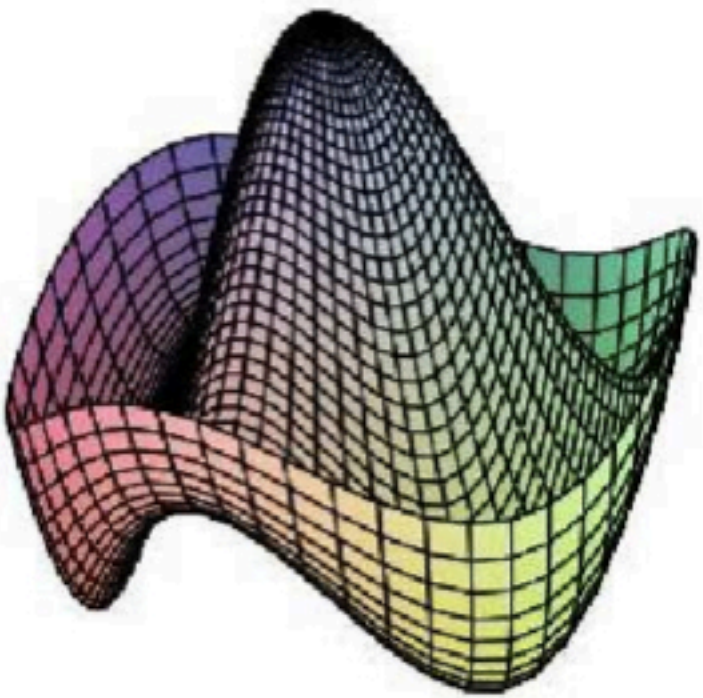
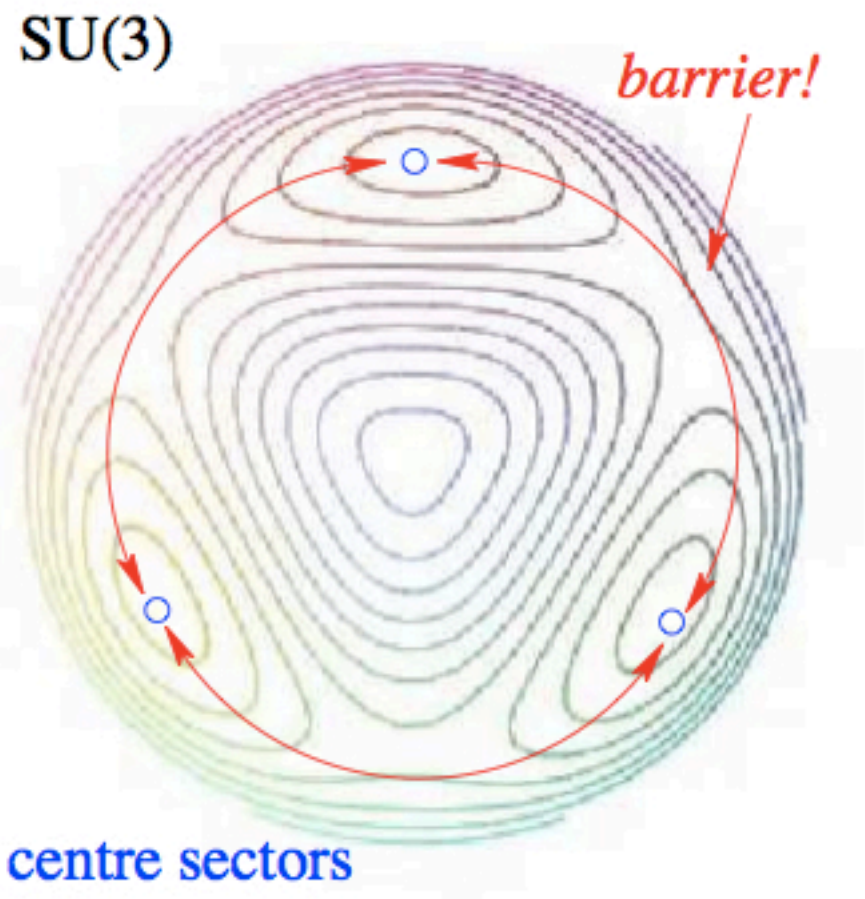


QC_2D at $\mu \neq 0$ *crucial* test for models of NM

Langfeld: Z(3) tunneling

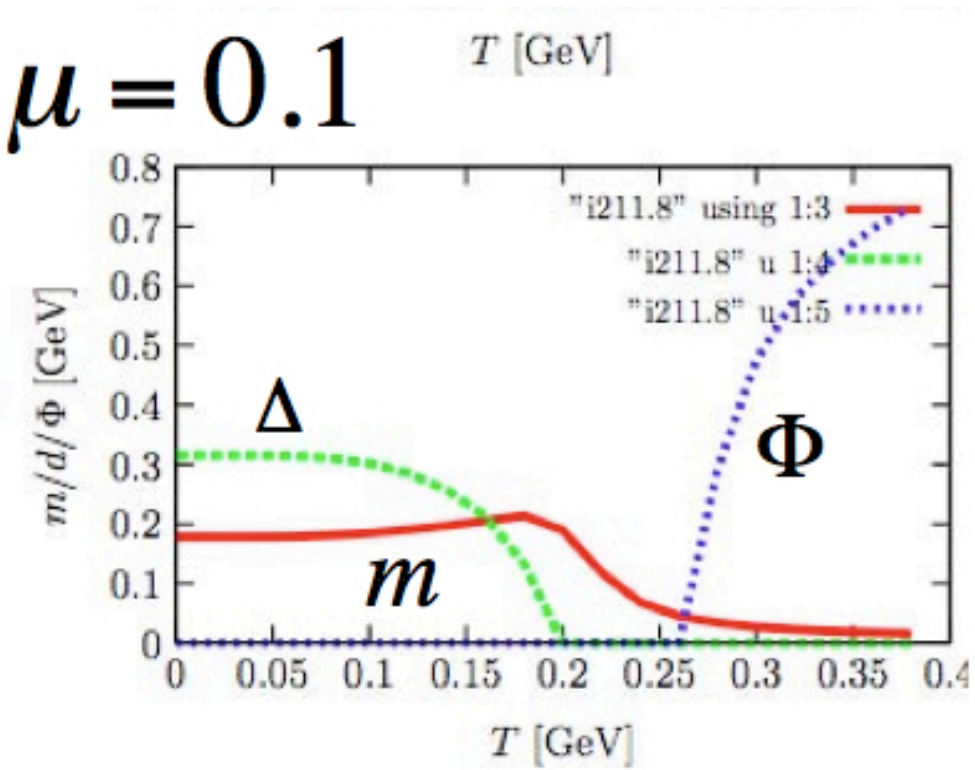
Shows Z(3) center sector tunnels in "confined" phase with *dynamical* quarks. "Fermi"-Einstein condensation.

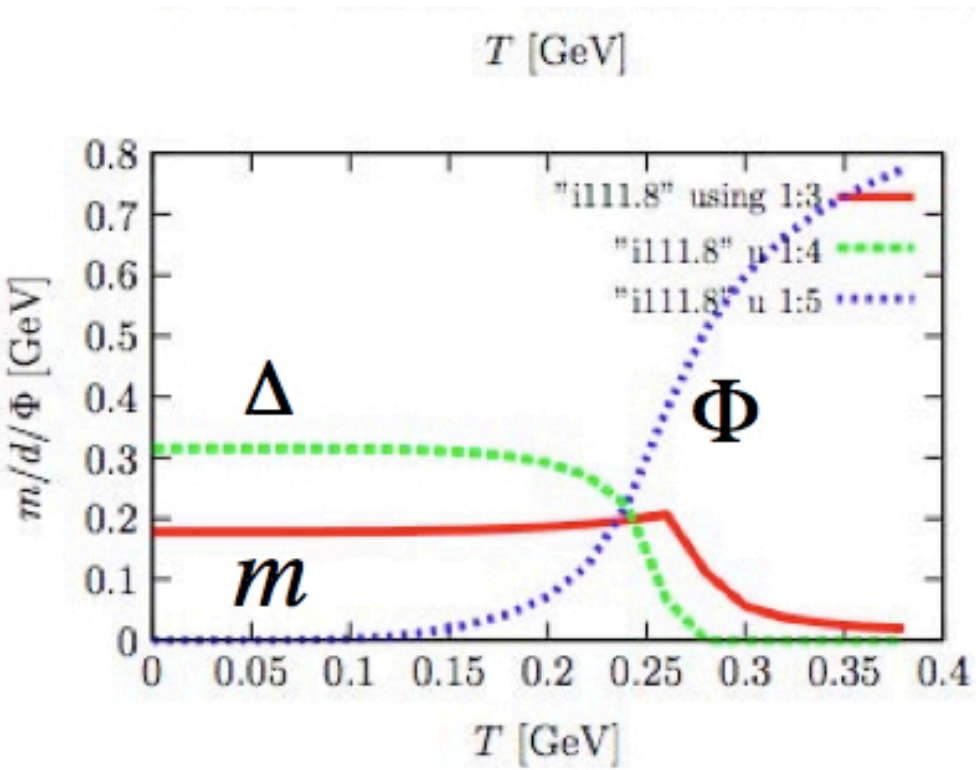




Toki: QC$_2$D in FWpPNJL model

Fukushima/Weise/pisarski/Polyakov = FWpPNJL model: compute chiral (Δ) and diquark (Φ) condensates at $\mu \neq 0$

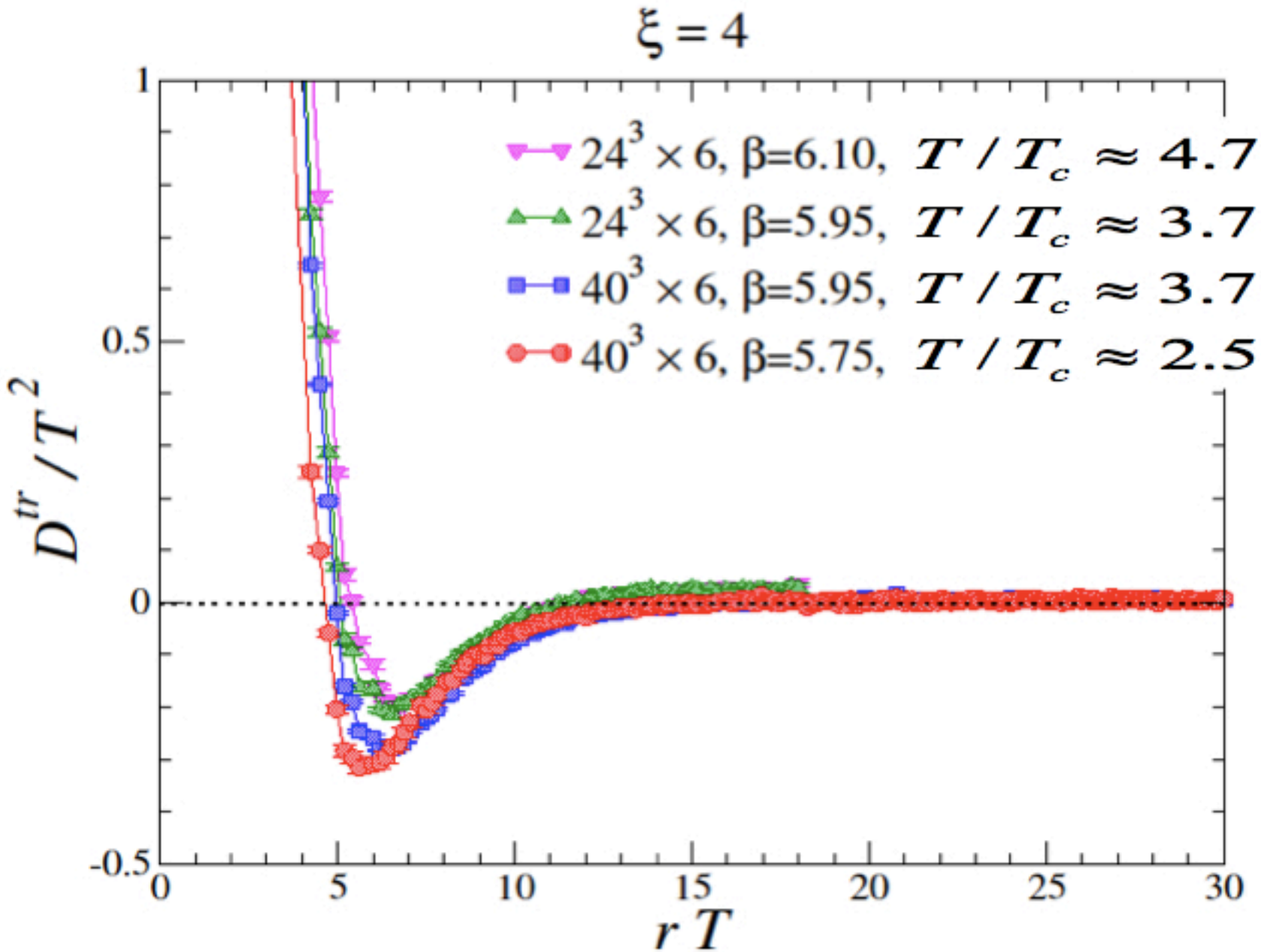




Wednesday:
the miraculous success of statistical models

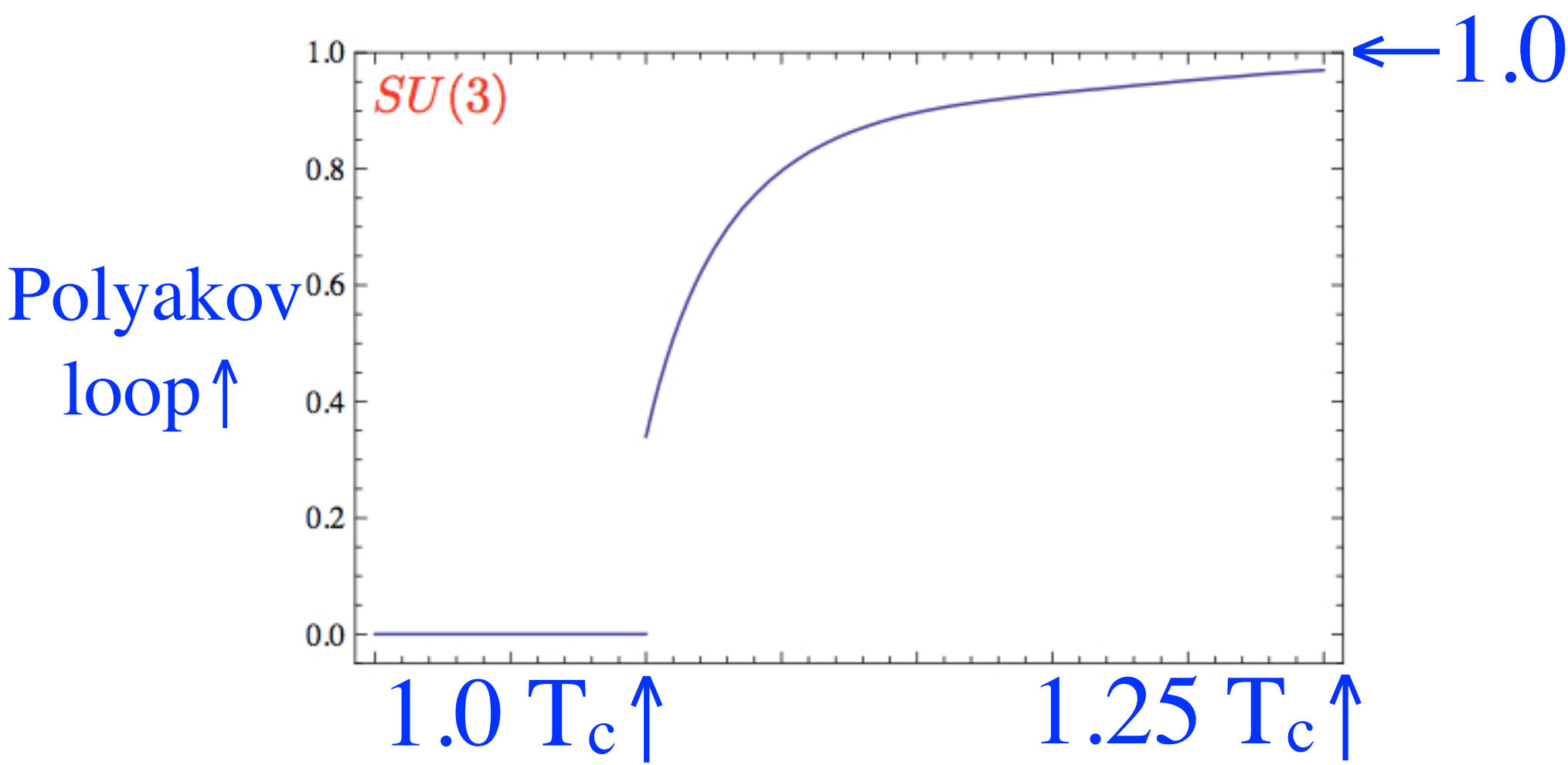
Nakamura: gluon propagators

Transverse gluon propagators at $T > T_c$, coordinate space



Pawlowski: Functional Ren. Group (FRG)

FRG finds Polyakov loop near one *very* quickly, by 1.25 T_c.
Lattice: loop only near one at *much* higher T, ~ 4.0 T_c.
Dumitru, Hidaka, RDP... '10: singlet potential => lattice Polyakov loop has *large* finite renormalization. => FRG correct, loop goes to near one *very* quickly.
Implications for phenomenology? Braun-Munzinger, Stachel, Redlich...

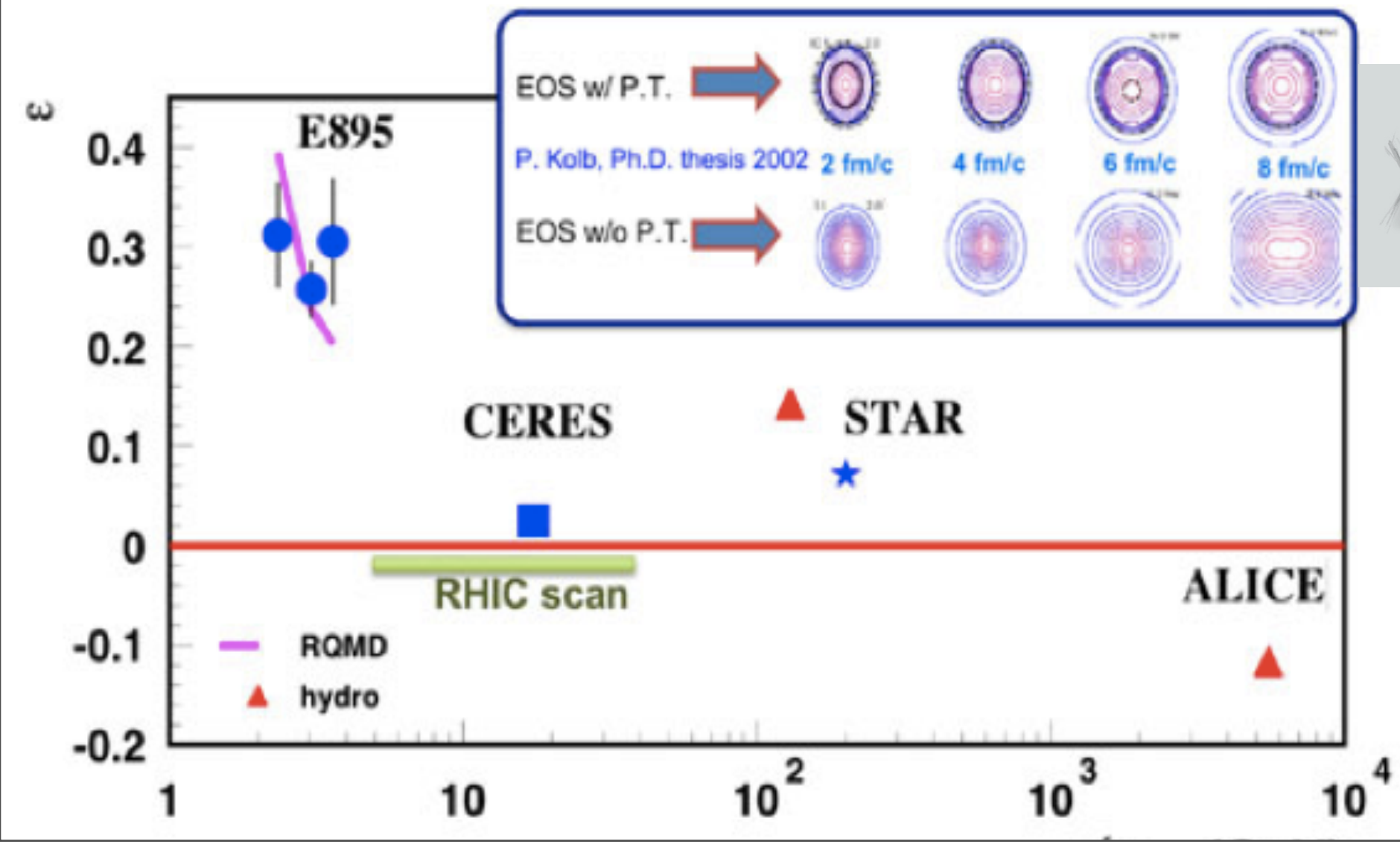


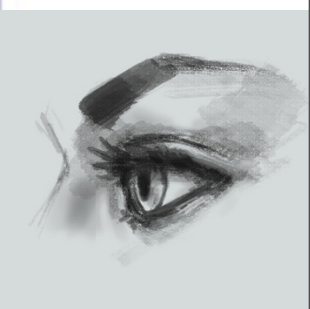
Sorensen: low energy run at RHIC

Elliptic flow v_2 = *momentum* eccentricity.

Spatial eccentricity: HBT radii vs. reaction plane.

Not monotonic with energy from AGS/SPS/RHIC/LHC?





Braun-Munzinger: *miracle* of statistical models

Elementary statistical models work *extremely* well for AA: even ^{3}He!

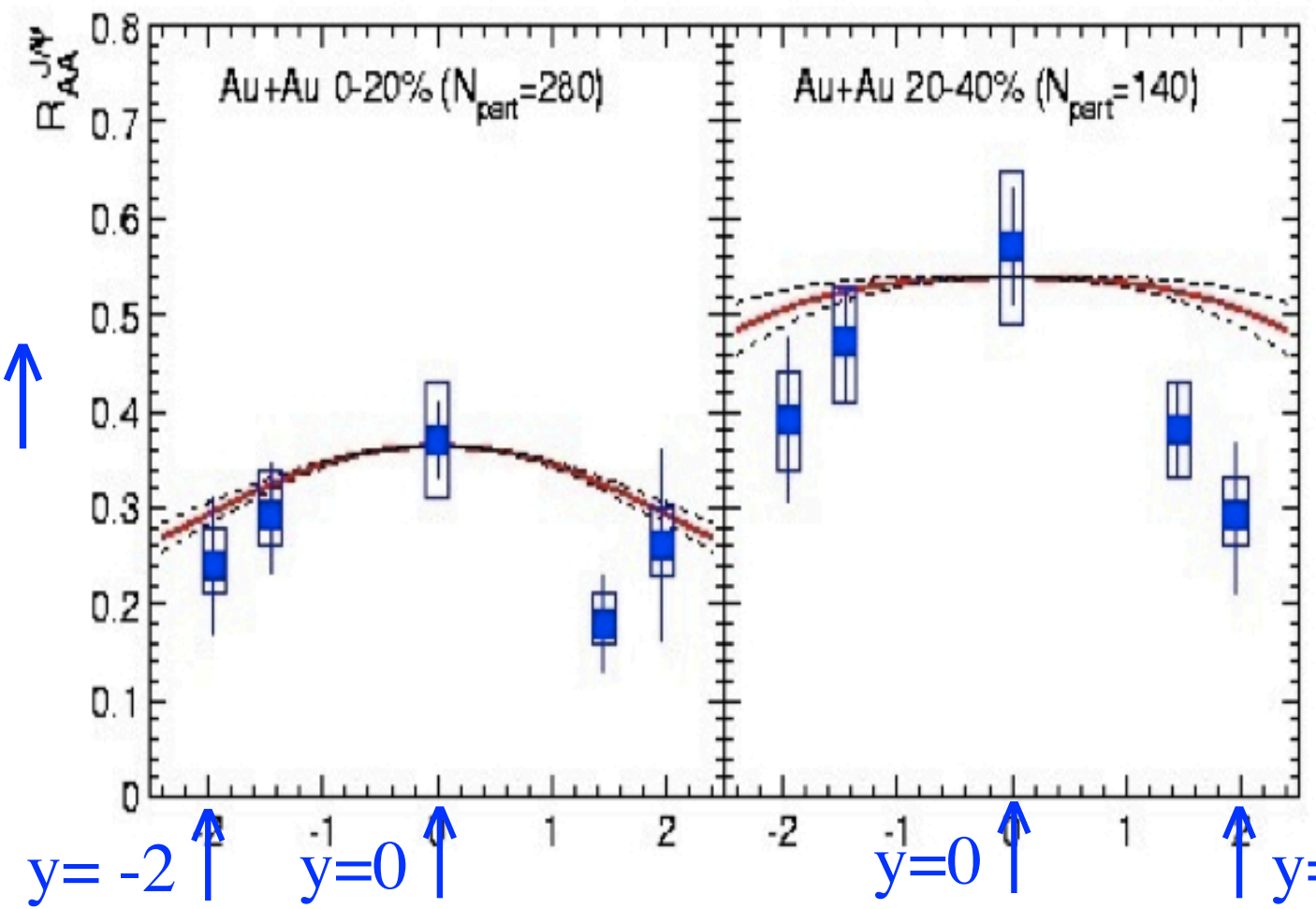
Statistical models do *not* work for e+e-, etc.: only for AA

For J/Ψ: charm quarks produced in hard collisions,

with statistical hadronization at phase boundary.

Then J/Ψ suppression smallest at *zero* rapidity:

$R_{J/\Psi}$ ↑



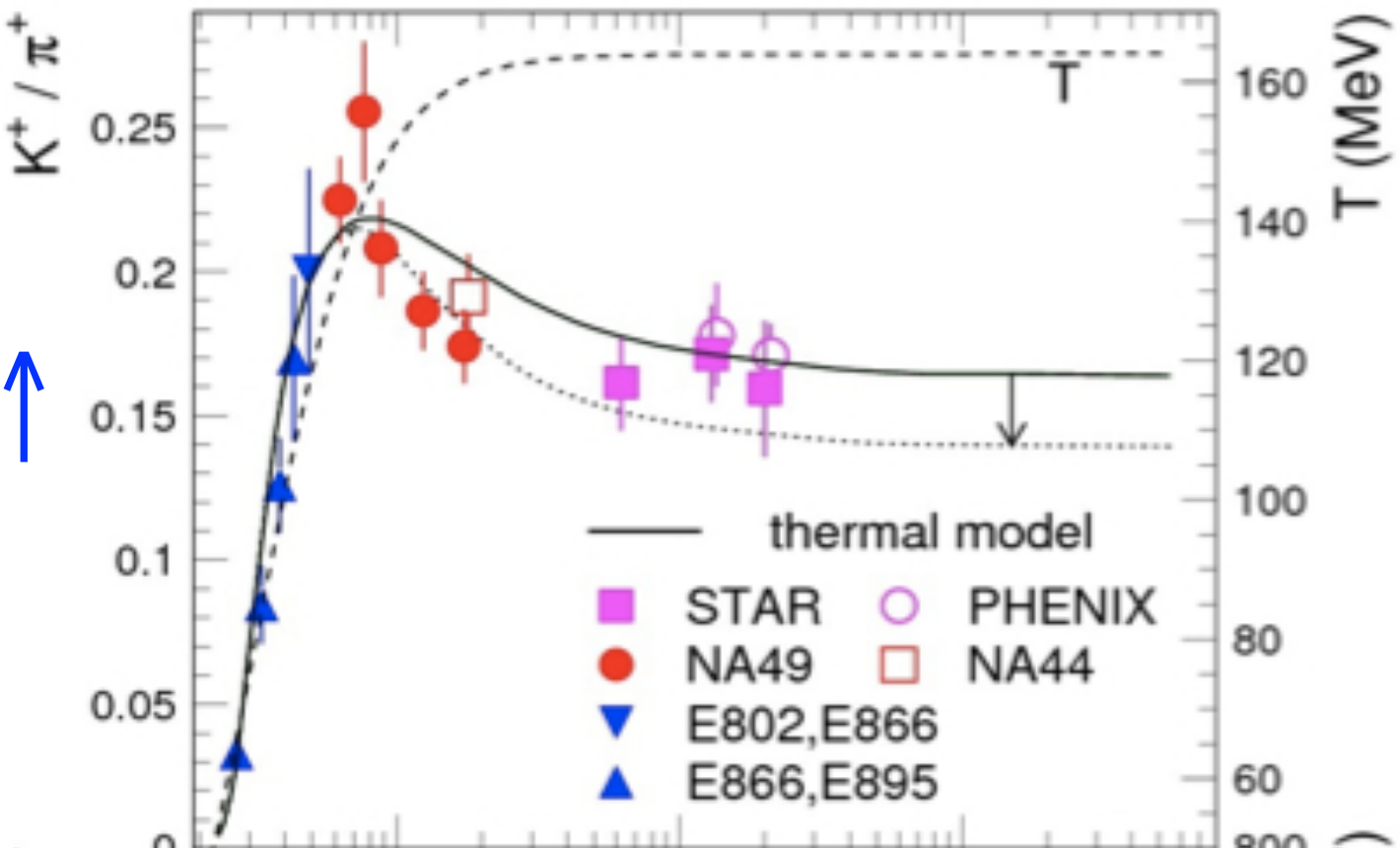
Stachel: statistical models explain "Matterhorn"

"Matterhorn": enhancement of K^+/π^+ +... around $\sqrt{s}$ = 10 GeV

Gazdzicki & Gorenstein '99: signal of deconfinement?

Now: explained by statistical model, change in T and μ near

"*Quarkyonic triple point*" Andronic +... arXiv:0911.4806



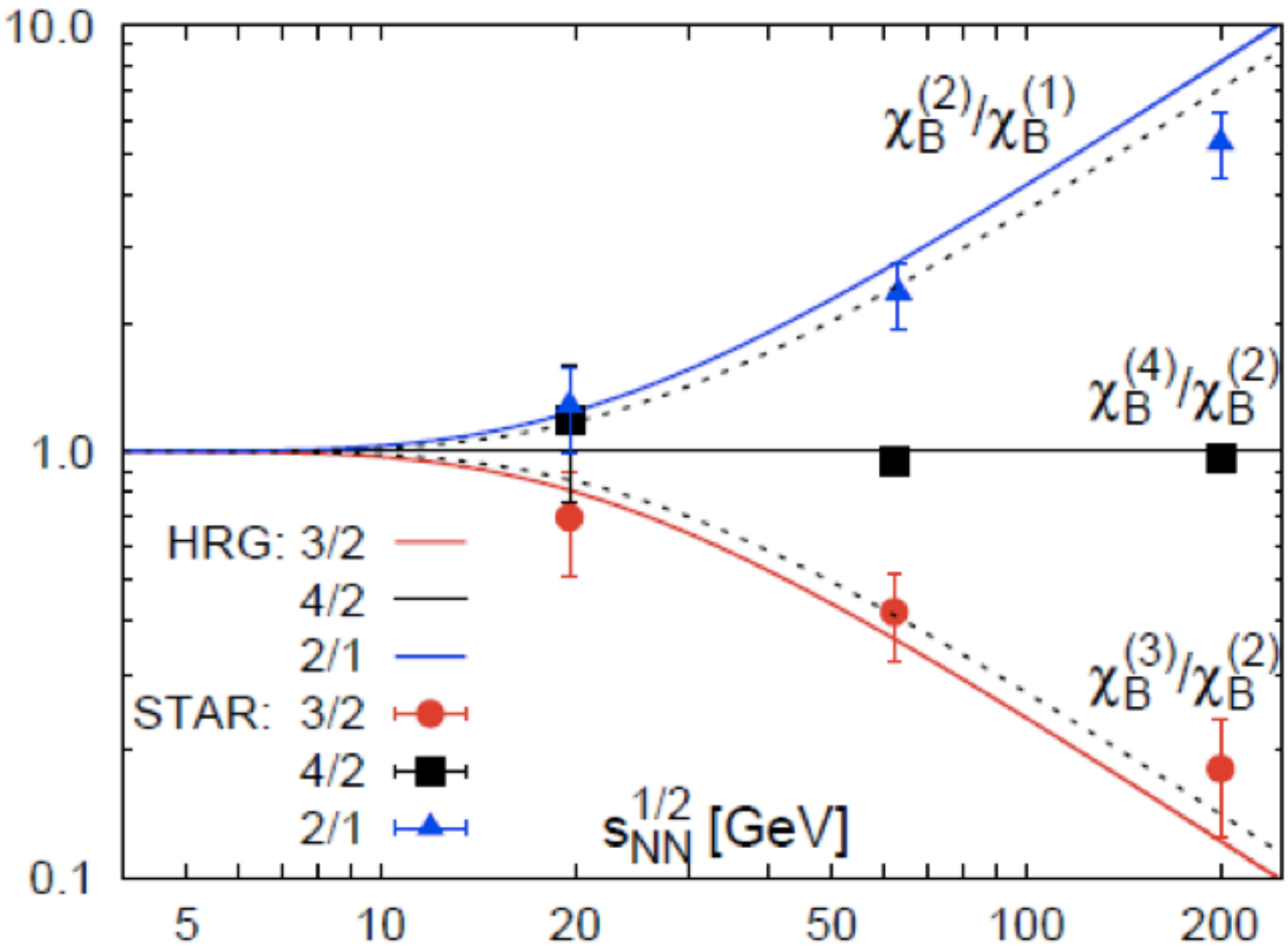
$K^+/\pi^+ \uparrow$

S

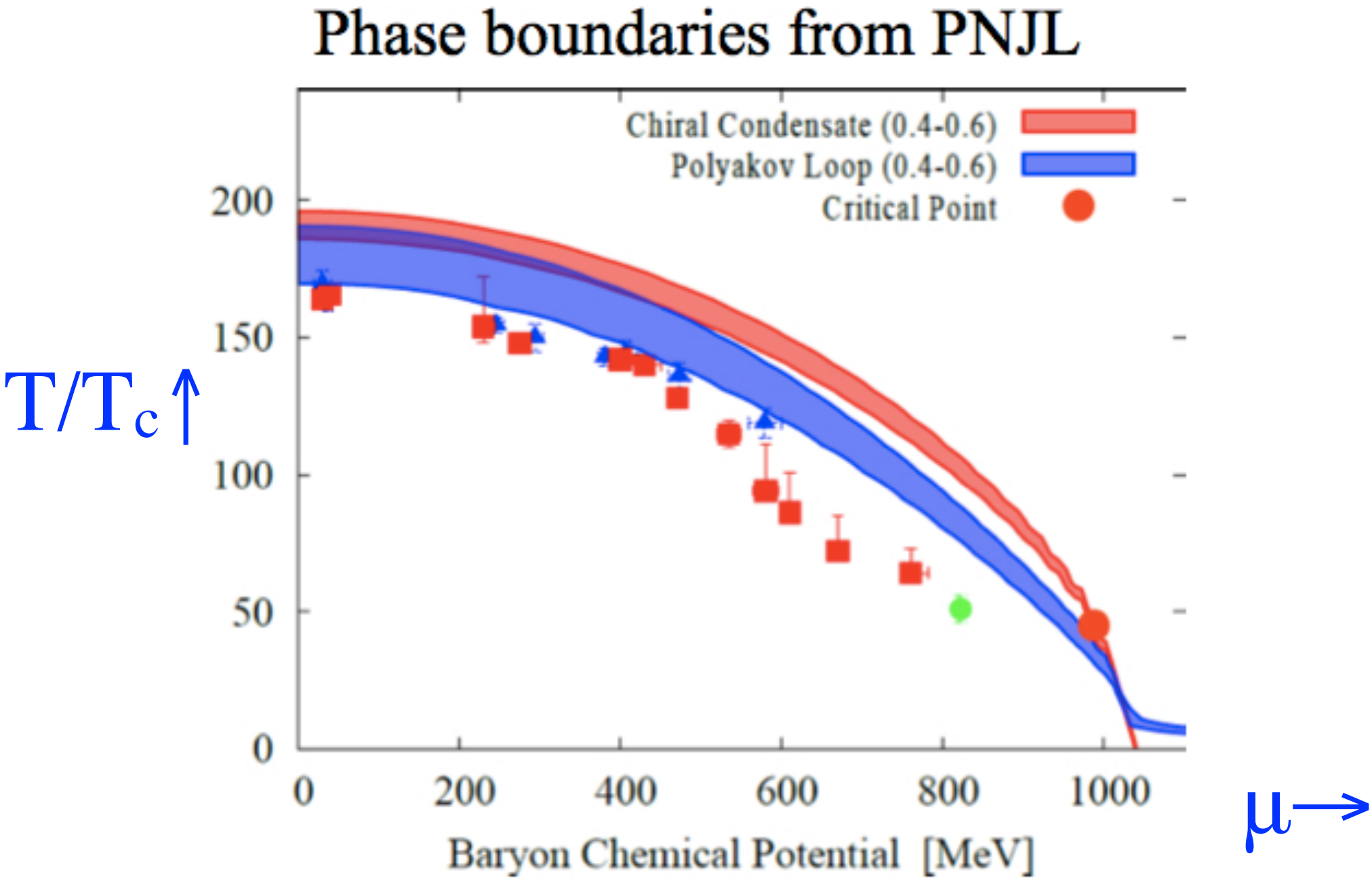
10 GeV ↑ ↑ 10^2 GeV

Redlich: statistical models explain *fluctuations*!

Functional ren. group for FWpPNJL models;
right critical behavior in O(4)
Statistical models describe not just chemical equilibrium correctly,
but even fluctuations.



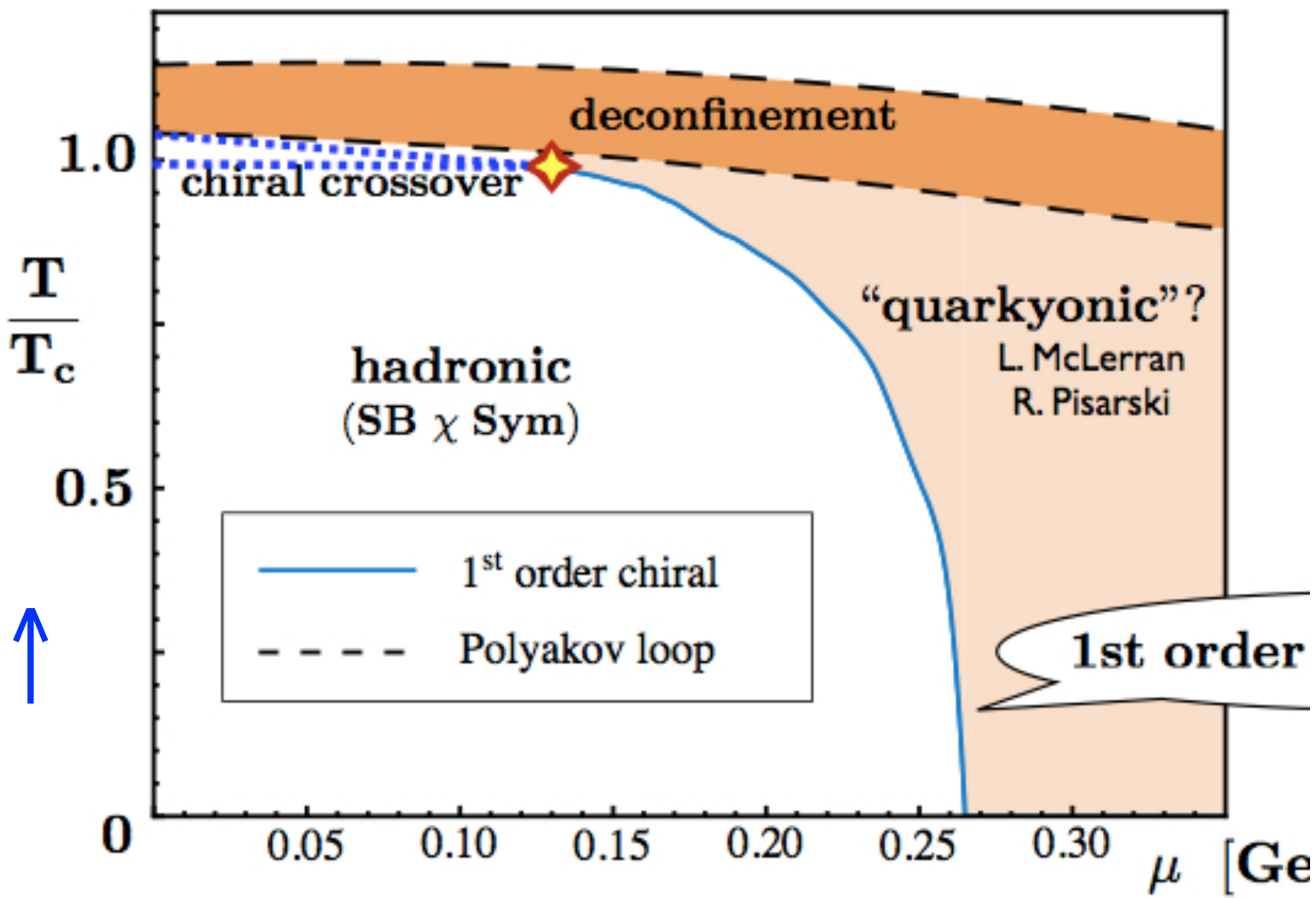
Fukushima: $T_{ch} > T_d$ in FWpPNJL models



Thursday:
FWpPNJL and
Sakai-Sugimoto models

Weise: non-local FWpPNJL model

Non-local 3-flavor FWpPNJL model: momentum dependent mass
As μ increases, $T_{deconfinement}$ changes little, T_{chiral} a lot: quarkyonic!

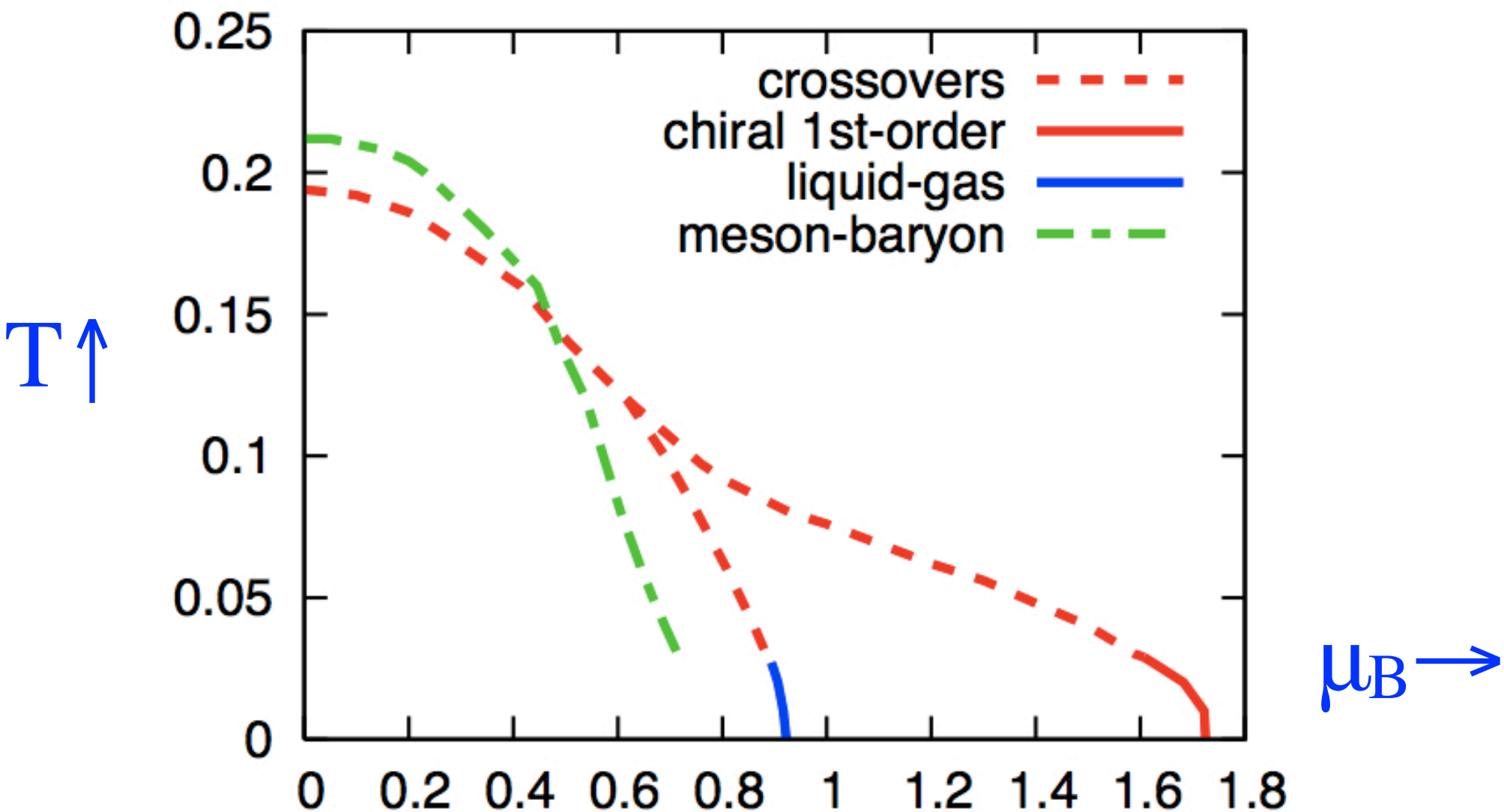


$T/T_c \uparrow$

$\mu \rightarrow$

Sasaki: parity doubled baryons

deTar & Kunihiro ’89: parity doubled baryons.
Important paradigm for chirally symmetric Nuclear Matter
Parity partner of nucleon? If N*, with mass 1545 GeV:



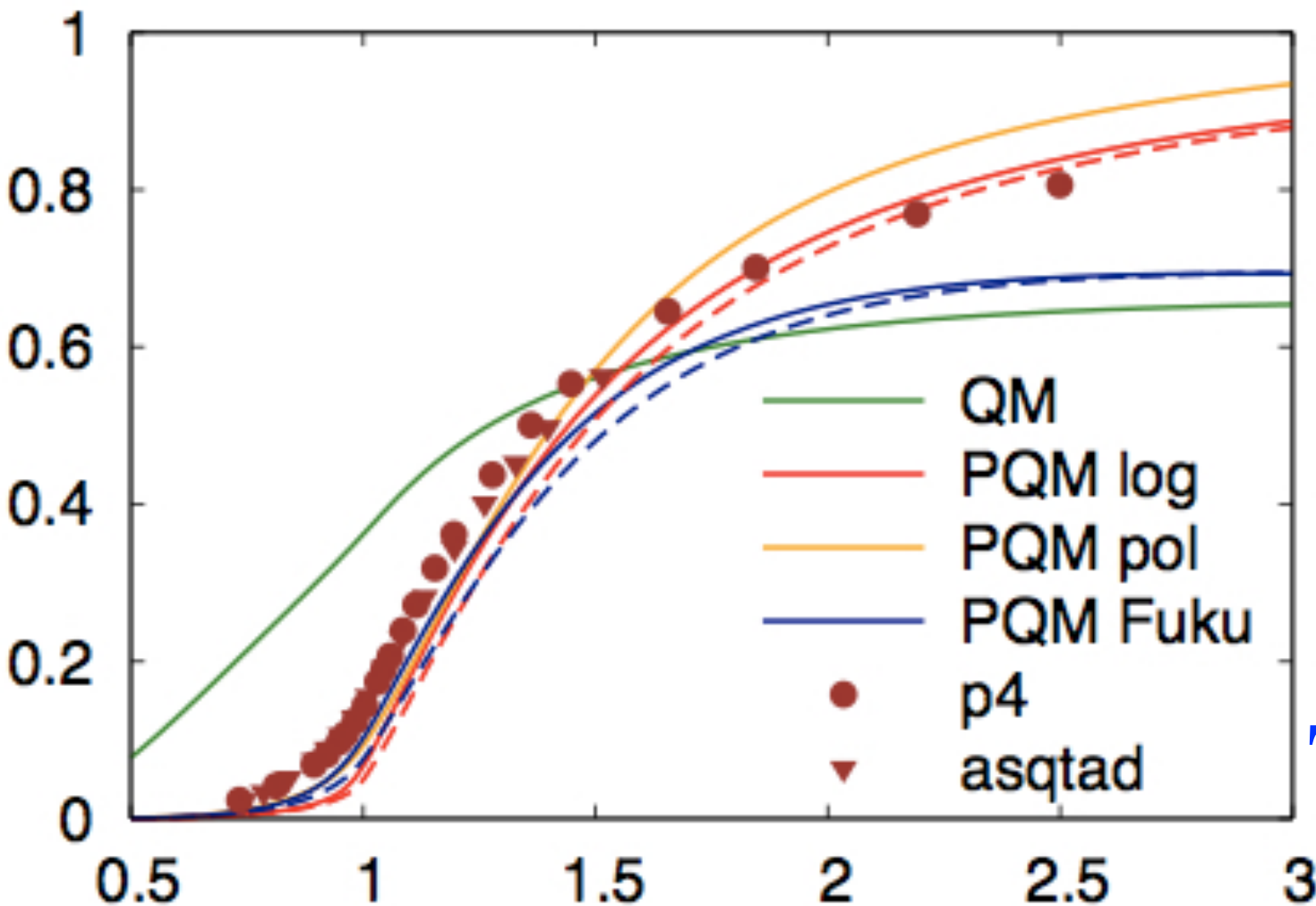
Schaefer: FWpPNJL plus mesons

FWpPNJL model + mesons. *Excellent* description at $T \neq 0$, $\mu = 0$.

Applicability of FWpPNJL model at $\mu \neq 0$?

Where's the beef (baryons)?

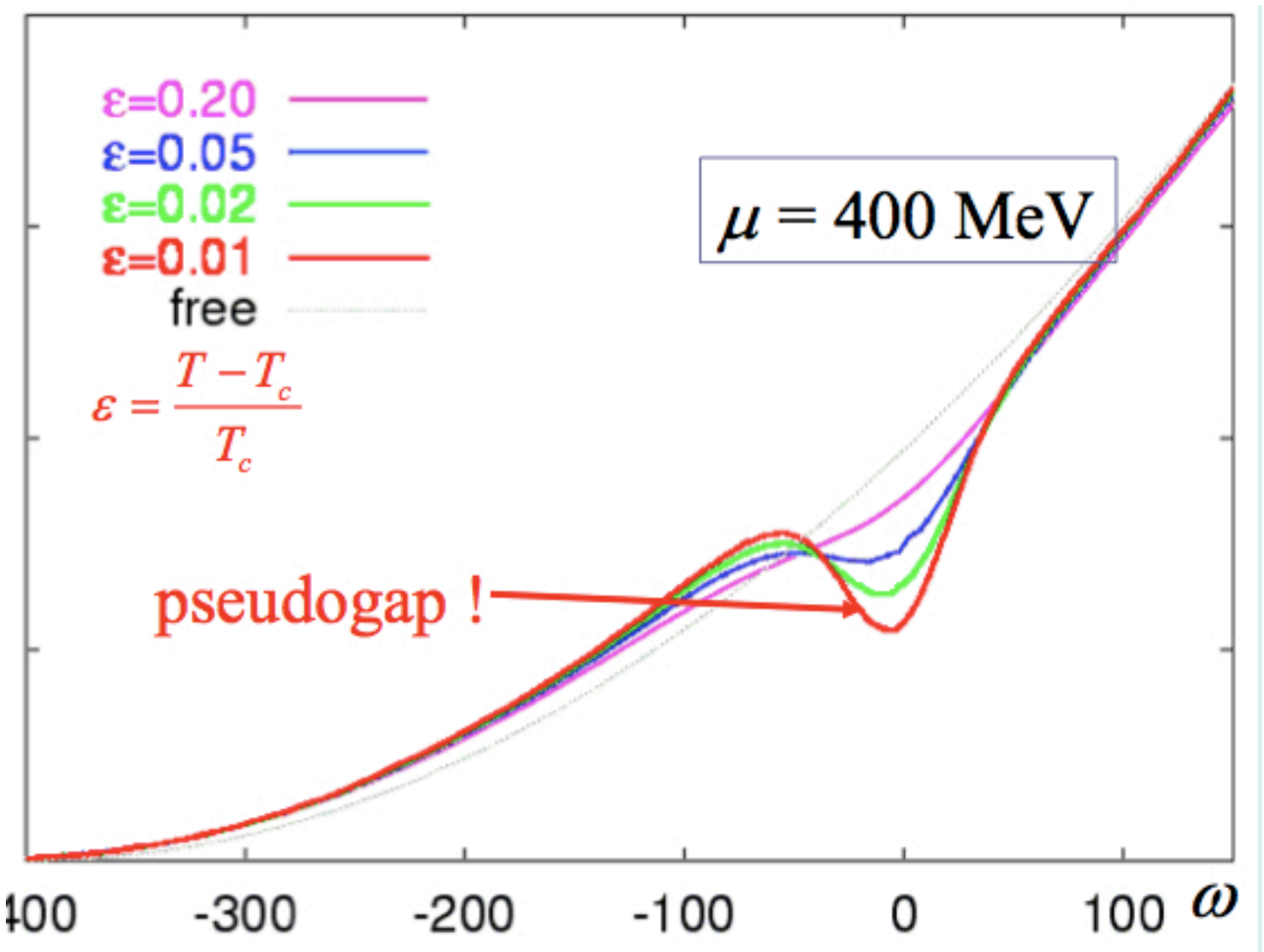
$p/p_{ideal} \uparrow$



$T \rightarrow$

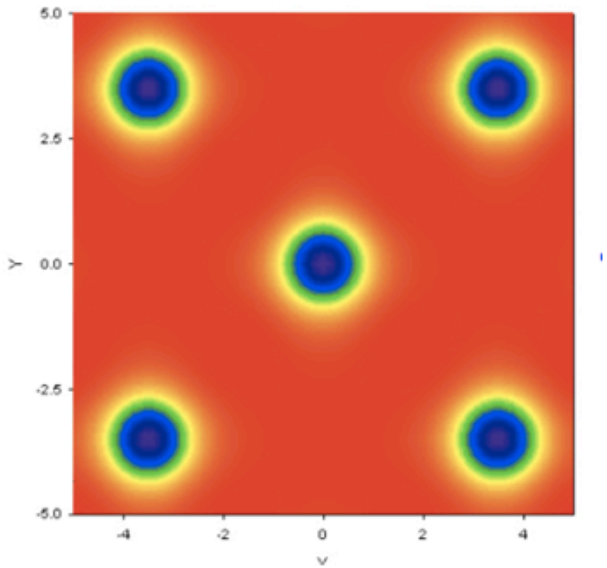
Kunhiro: pseudogap in CSC

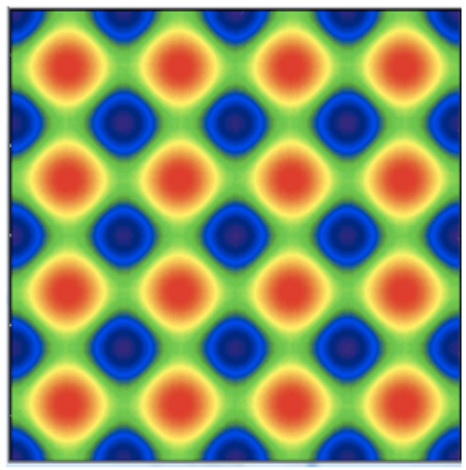
Assume μ large enough to have Color SuperConductivity (CSC)
Assume T > restoration of CSC. Find *non*-Fermi liquid behavior

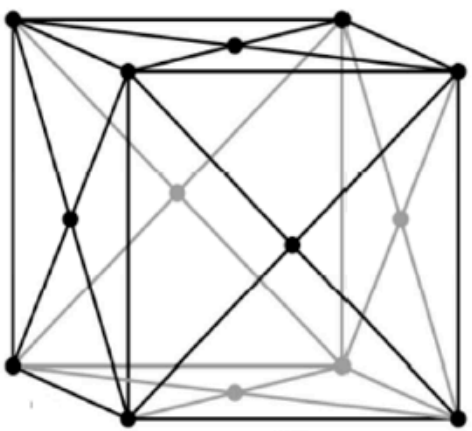


Rho: The Skyrmion strikes back!

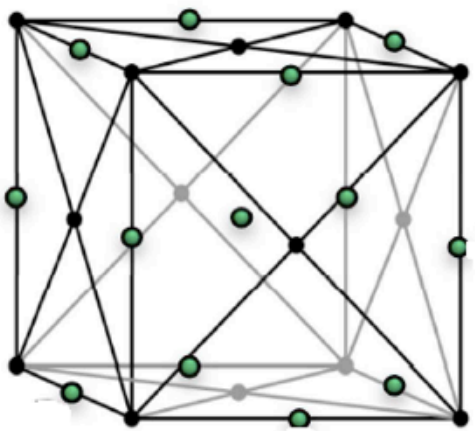
As nuclear density increases, one goes from
FCC crystal of Skyrmions to BCC crystal of *half*-Skyrmions







Increasing
density

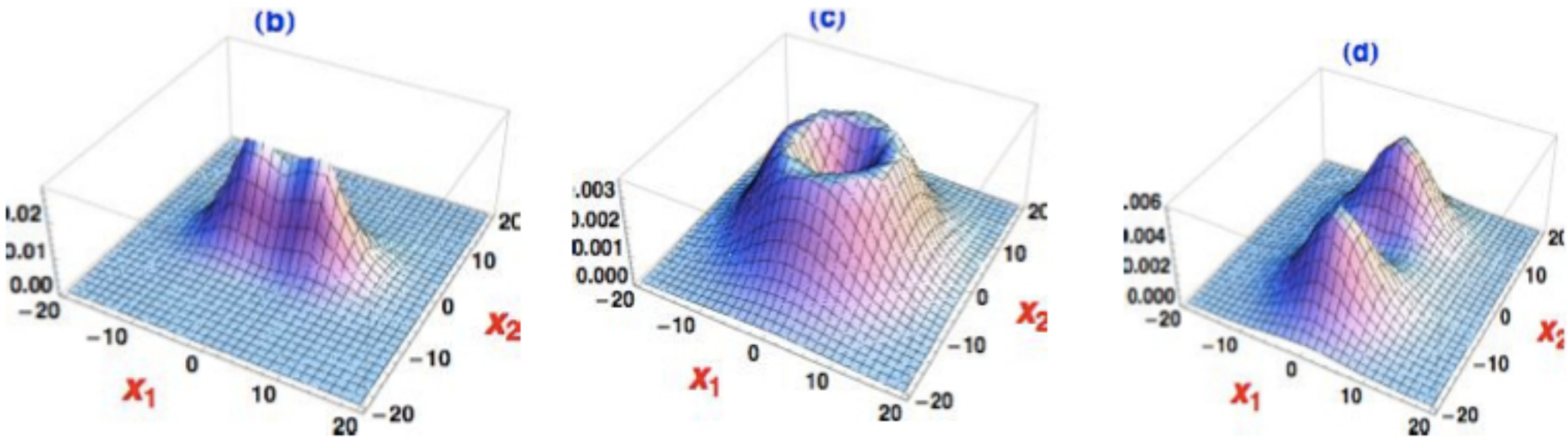


Instantons:
FCC

½ instantons
(dyons): BCC

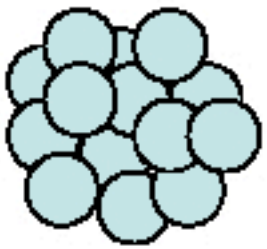
Zahed: holographic baryons

Nucleon as 5-dimensional instanton:



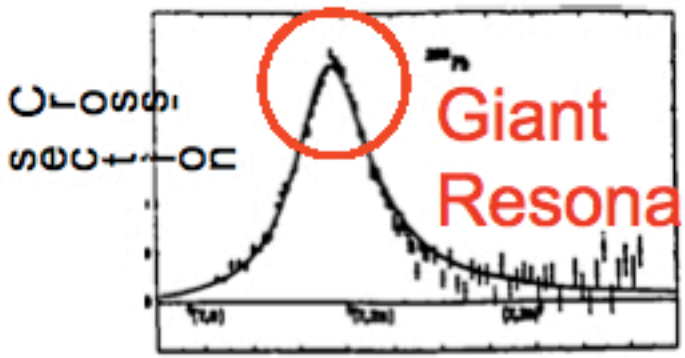
Hashimoto: holographic NM

Solve "holographic" QCD, Sakai-Sugimoto model. *Wealth of results!*



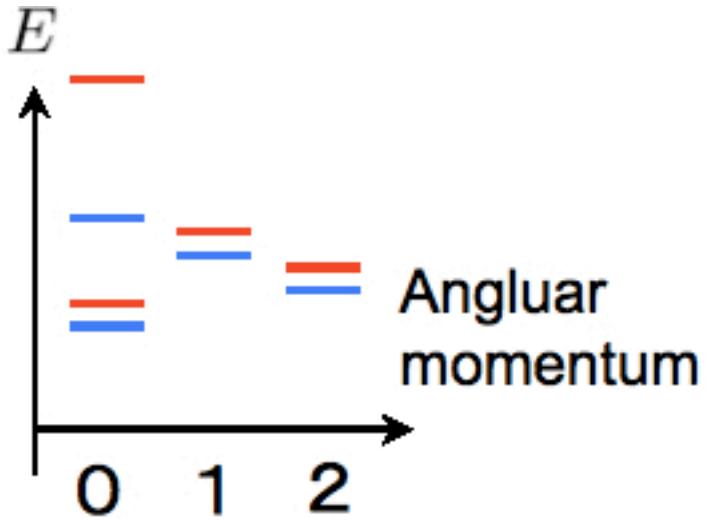
Nuclear oscillation (Collective)

Experiment : Pb nucleus



E: injected photon

(Excitation energy E)



$E = 80k^{-1/3}$ [MeV]

k : mass number

Nuclear matrix model in the large k limit :

$$E = \sqrt{\frac{2^3\, c\, N_c}{3^5}}\sqrt{\rho_0 M_{\rm KK}^3}\, k^{-1/3}$$

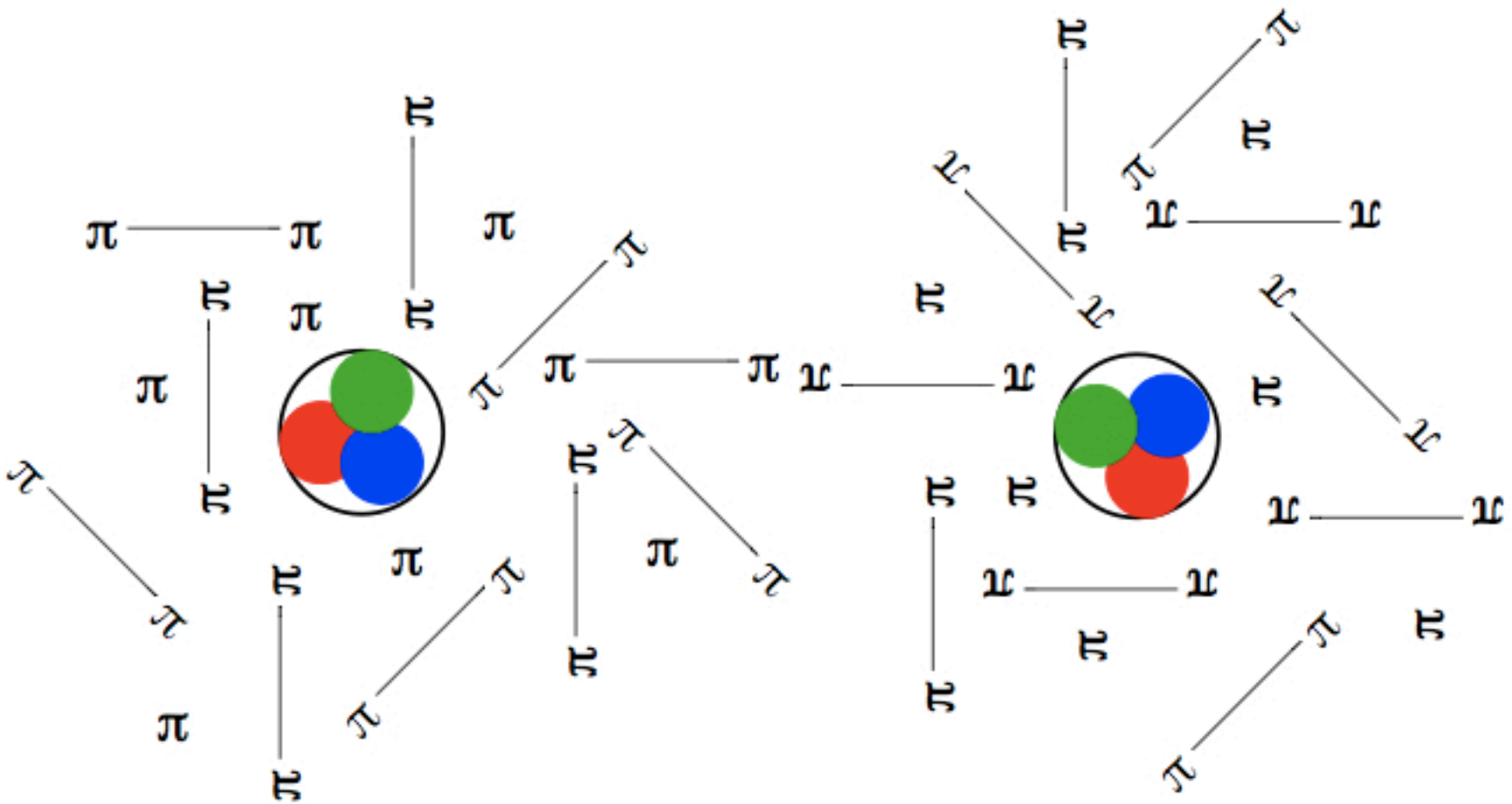
$$c = 2.23,\ 3.68,\ 4.75,\ \cdots$$

k-dependence reproduced

Friday:
Models of NM

de Forcrand: NM in (lattice) strong coupling

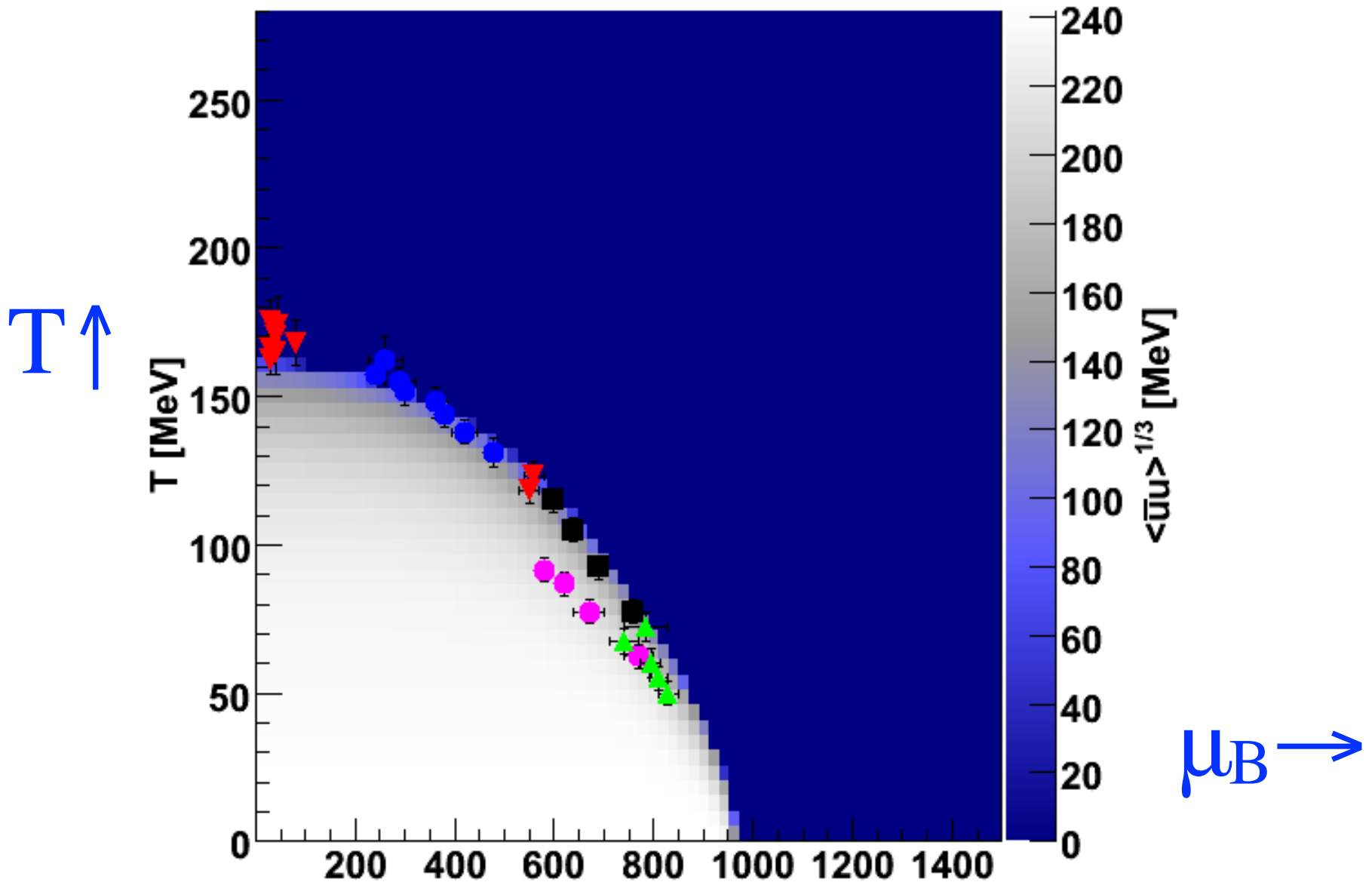
Strong coupling expansion of *lattice* QCD. Soluble!
Baryons make self avoiding loops, interact through pion clouds.
Pions clouds don't interact, but with valence quarks in baryons.
Exchange meson potential without exchanging mesons!



Blaschke: beyond MF for FWpPNJL

Work beyond Mean Field (MF) for a FWpPNJL model.

Changes shape of the phase diagram



To quote Tom Cohen:

To quote Tom Cohen:

Perhaps with enough Prosecco I could be convinced of this

But it would take **a lot** Prosecco

Schladming Winter School

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49. Internationale Universitätswochen für Theoretische Physik

Physics at all scales:
The Renormalization Group

Schladming, Styria, Austria, February 26 - March 5, 2011

Jürgen Berges (TU Darmstadt)	**Nonequilibrium Renormalization Group**
Sebastian Diehl (University of Innsbruck)	**Ultracold Quantum Gases and the Functional Renormalization Group**
Richard J. Furnstahl (Ohio State University)	**The Renormalization Group in Nuclear Physics**
Anna Hasenfratz (University of Colorado)	**Exploring the Conformal Window**
Daniel Litim (University of Sussex)	**Gravity and the Renormalization Group**