What this talk won't give you

Equation of state of dense nuclear matter in MeV

So...why care?

We suggest:

Not just hadronic matter vs dense quarks

Also: intermediate region, "quarkyonic"

Spatially inhomogenous phases may dominate for *all* relevant densities

But at "high" temperature these are *dominated* by fluctuations

A pseudo-Lifshitz point in QCD

RDP, VV Skokov & A Tsvelik, 1801.08156

Fluctuations and chiral spirals in QCD

1. Standard phase diagram in T & μ: critical end-point (CEP)
   Not seen in lattice

2. Quarkyonic phase at large N_c and $N_c = 2$ (lattice)

3. Chiral Spirals in Quarkyonic matter: sigma models, SU(N) and U(1)

4. Phase diagram: pion/kaon condensates & Chiral Spirals

just a 1st order line, with *large* fluctuations near a pseudo-Lifshitz point

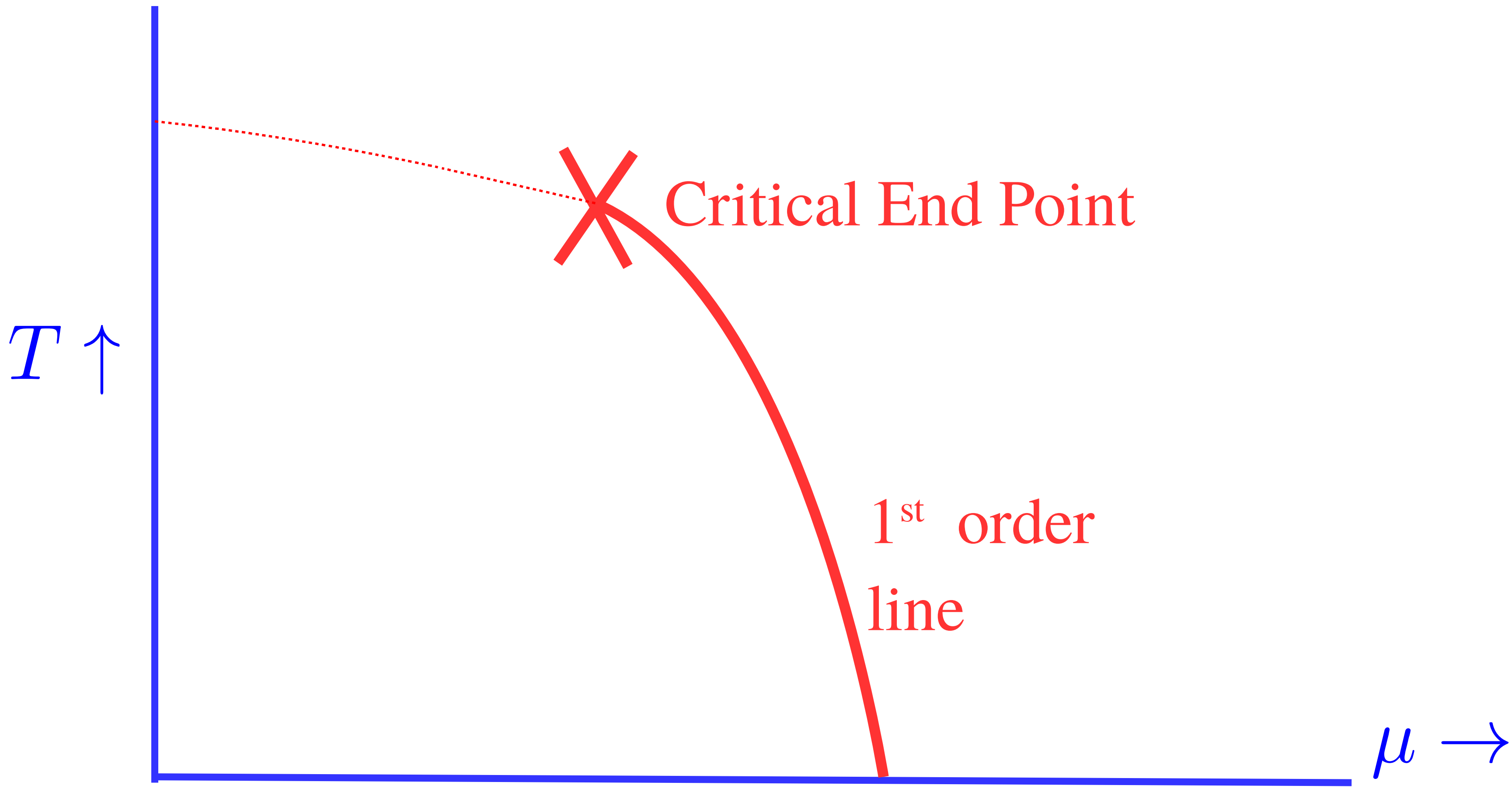
Phase diagram for QCD in T & μ: CEP?

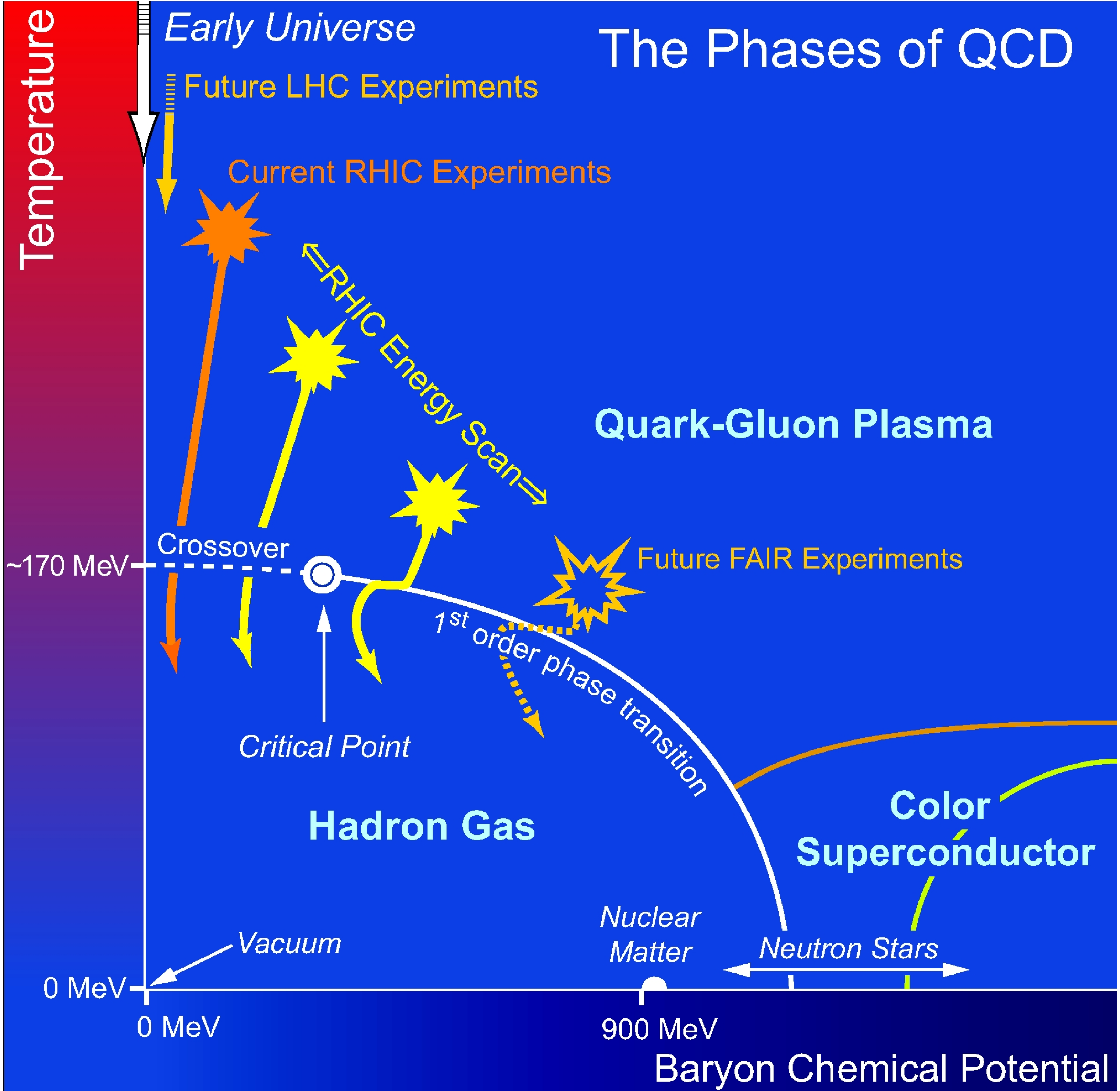
Lattice: at $\mu = 0$, $T_{ch} \sim 154 \pm 9$ MeV, crossover

Quarks drive a 4-pt scalar coupling negative, could turn into 1st order

Asakawa & Yazaki ‘89, Stephanov, Rajagopal & Shuryak ‘98 & ‘99

Must do so at a Critical End Point (CEP), true 2nd order phase transition





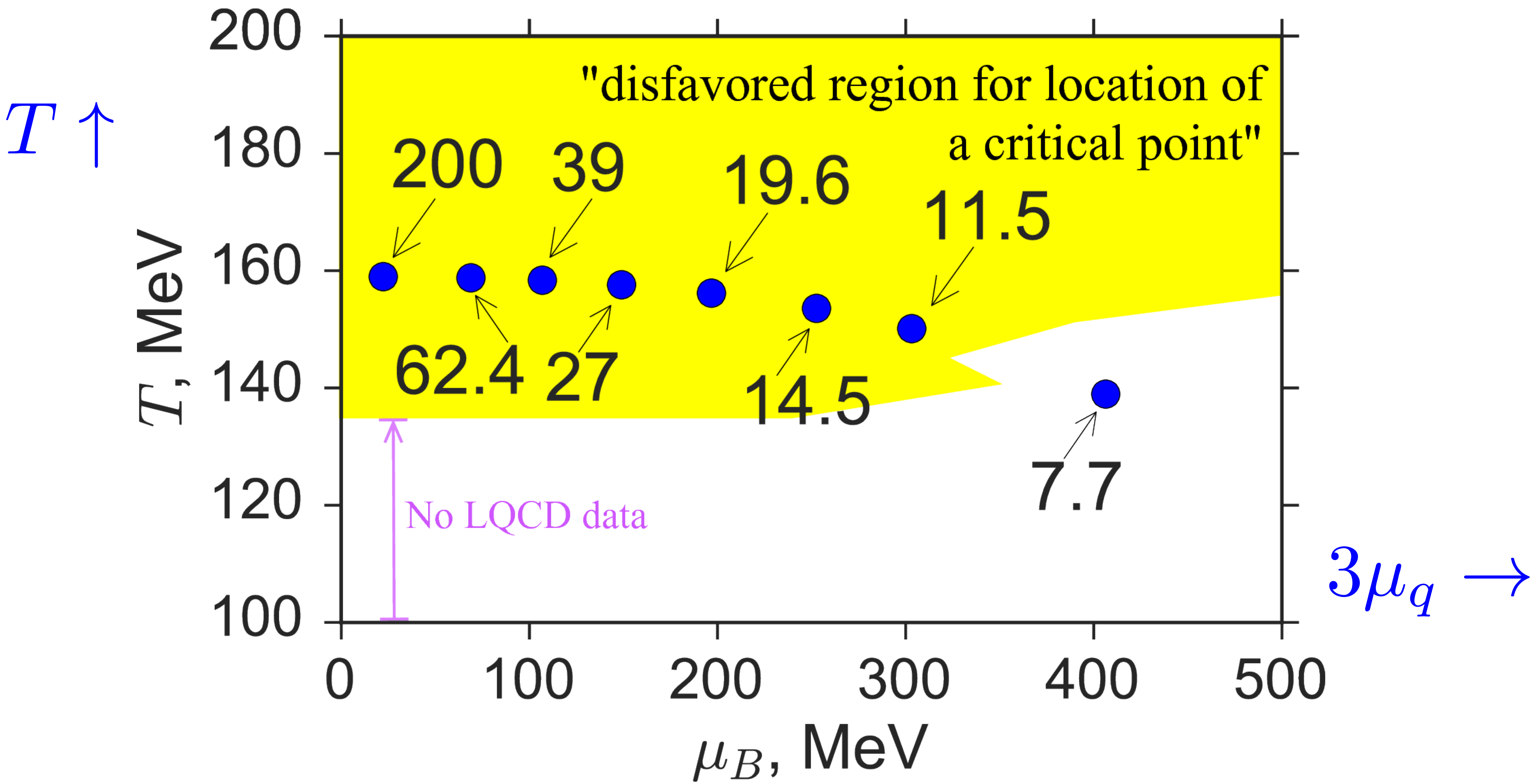
The Phases of QCD
Temperature
Early Universe
Future LHC Experiments
Current RHIC Experiments
⇐RHIC Energy Scan⇒
Quark-Gluon Plasma
Crossover
~170 MeV
Critical Point
Future FAIR Experiments
1st order phase transition
Hadron Gas
Color Superconductor
Nuclear Matter
Neutron Stars
Vacuum
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential

Hot QCD: no CEP nearby

Lattice: Hot QCD, 1701.04325

Expand about $\mu = 0$, power series in μ^{2n}, n = 1, 2, 3.

Estimate radius of convergence. *No* sign of CEP by $\mu_{qk} \sim T$

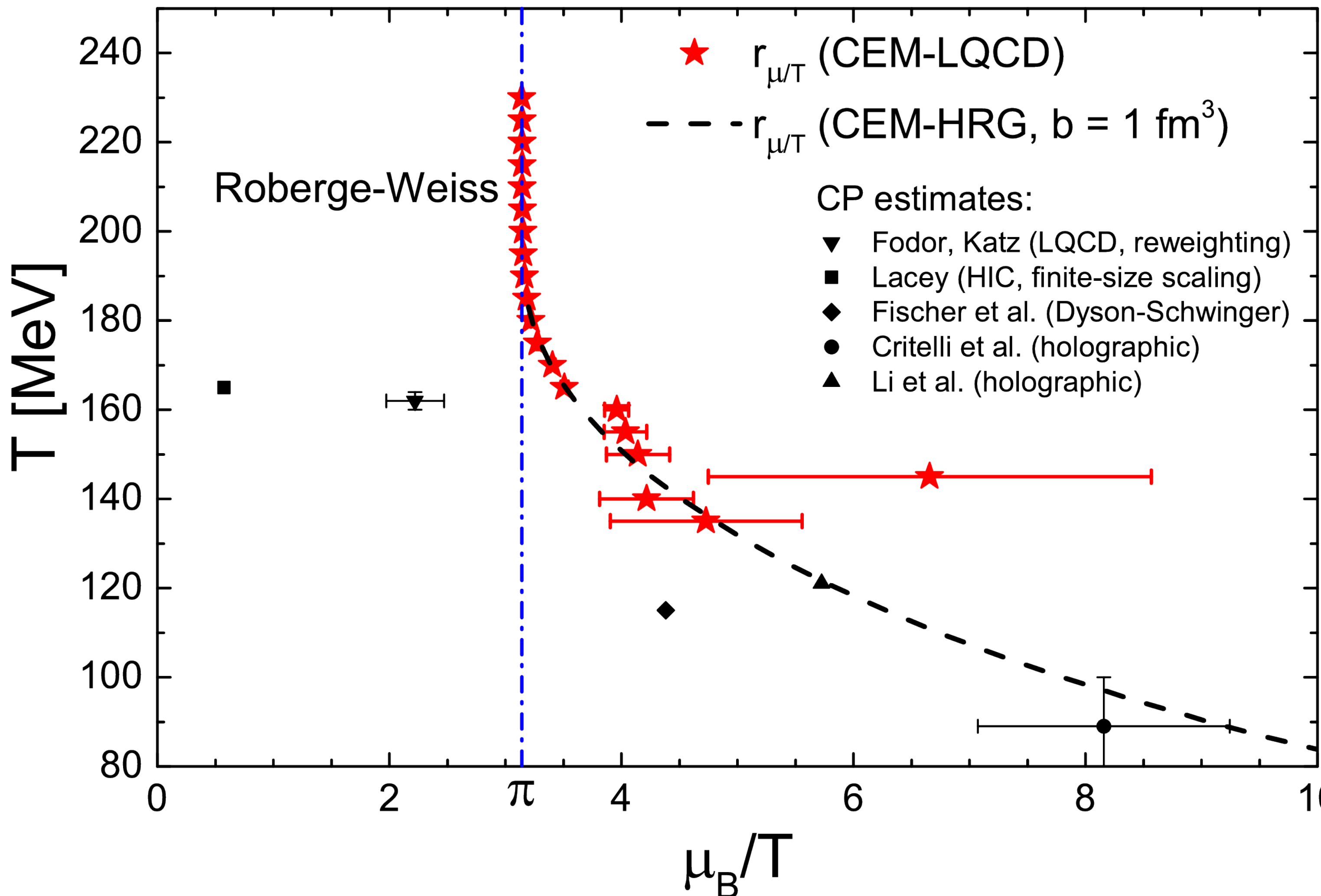


Cluster expansion: no CEP nearby

Lattice: Vovchenko, Steinheimer, Philipsen & Stoecker, 1701.04325

Use cluster expansion method, different way of estimating power series in μ

No sign of CEP by $\mu_{qk} \sim T$



$3\mu_{qk} \rightarrow$

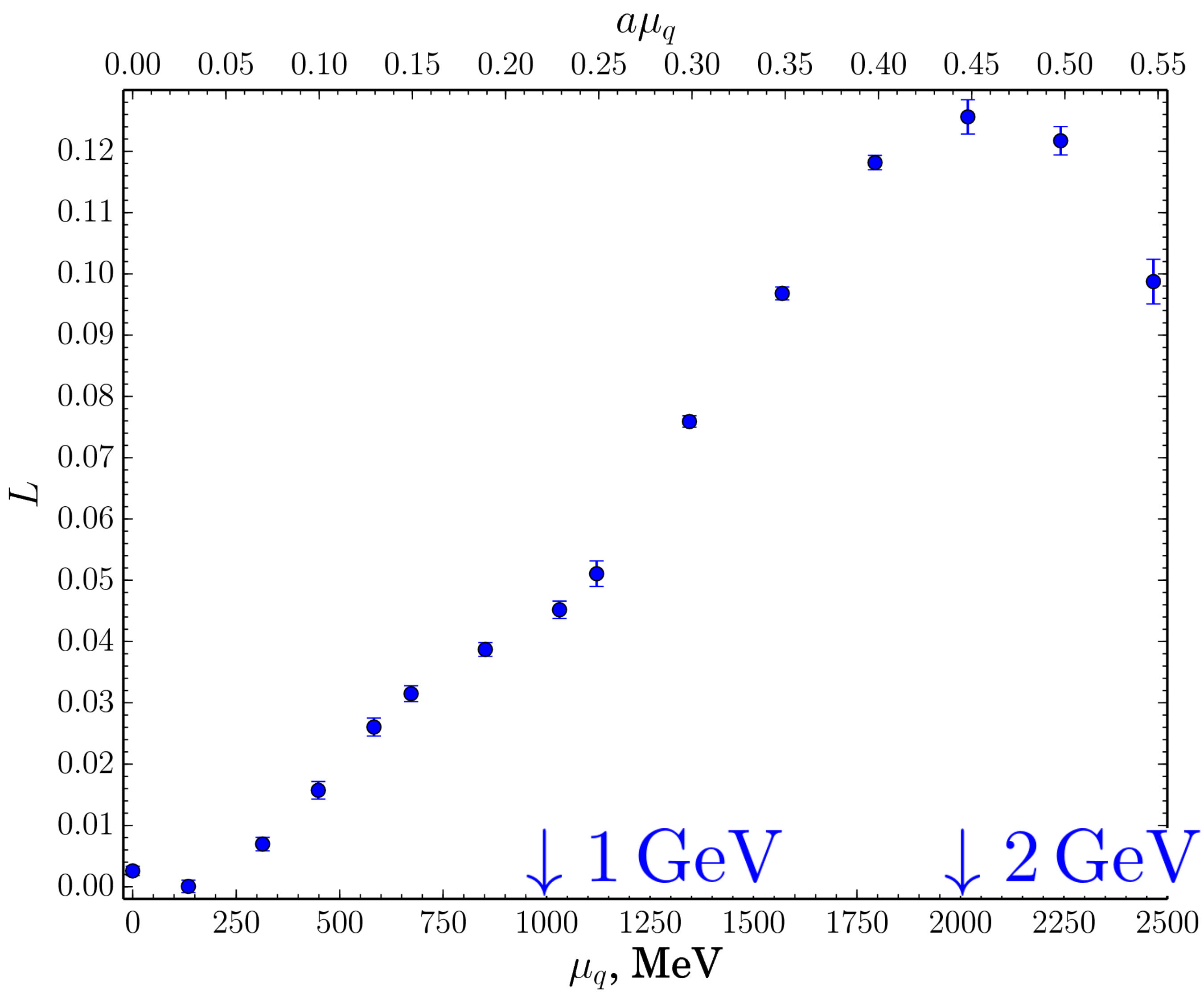
Lattice for T = 0, $\mu \neq 0$, *two* colors

Lattice: Bornyakov et al, 1711.01869. No sign problem for $N_c = 2$. Two flavors.

Heavy pions, $m_\pi \sim 740$ MeV. $\sqrt{\sigma} = 470$ MeV. 32^4 lattice, a ~ .04 fm

Physics differs (Bose-Einstein condensation of baryons). *Bare* Polyakov loop:

$\langle \text{loop} \rangle \uparrow$



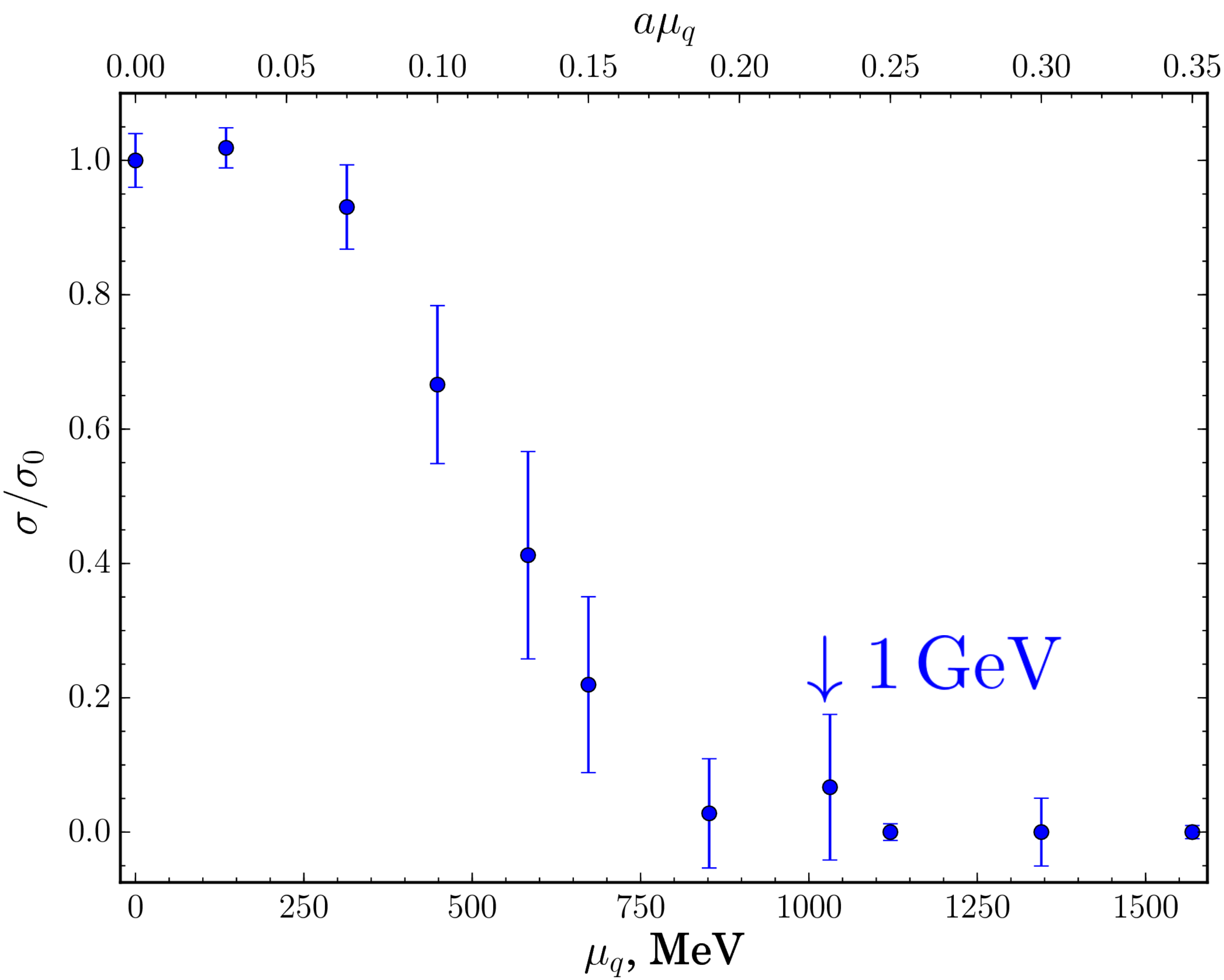
$\mu_{qk} \rightarrow$

Lattice for T = 0, μ ≠ 0, *two* colors

Lattice: Bornyakov et al, 1711.01869.

String tension in time: decreases to ~ 0 by μ ~ 750 MeV

$\frac{\sigma_{time}}{\sigma} \uparrow$

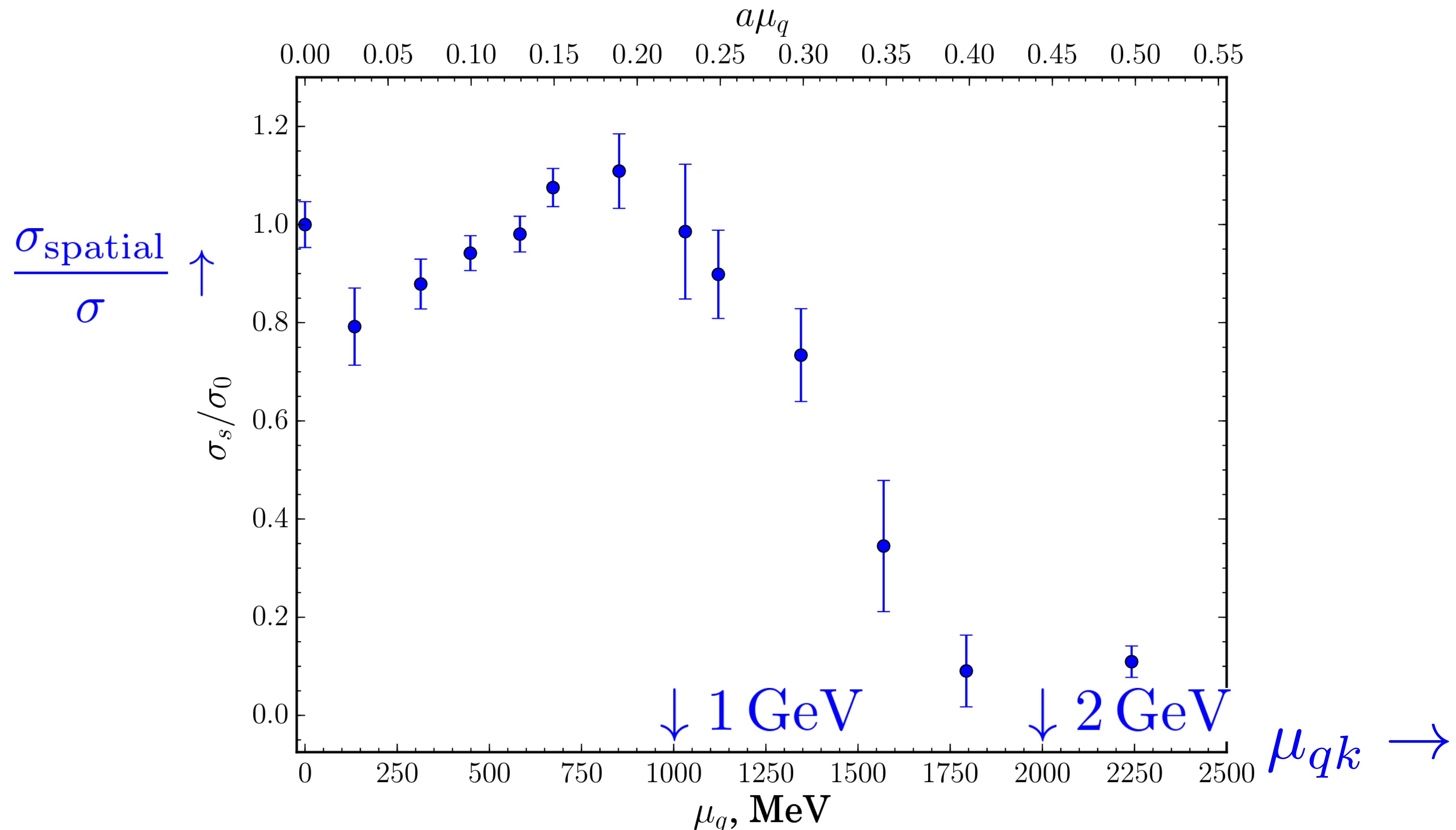


$\mu_{qk} \longrightarrow$

Lattice for T = 0, μ ≠ 0, *two* colors

Lattice: Bornyakov et al, 1711.01869.

Spatial string tension increases to μ ~ 1 GeV, decreases, ~ 0 by μ ~ 2 GeV



Phases for $N_c = 2$, $T \sim 0$, $\mu \neq 0$

Braguta, Ilgenfritz, Kotov, Molochkov, & Nikolaev, 1605.04090 (earlier: Hands, Skellerud + …)

Lattice: $N_c = 2$, $N_f = 2$. $m_\pi \sim 400$ MeV, fixed $T \sim 50$ MeV, vary μ.

Hadronic phase: $0 \leq \mu < m_\pi/2 \sim 200$ MeV. Confined, independent of μ

Dilute baryons: $200 < \mu < 350$. Bose-Einstein condensate (BEC) of diquarks.

Dense Baryons: $350 < \mu < 600$. Pressure *not* perturbative, BEC

Quarkyonic: $600 < \mu < 1100$: pressure ~ perturbative, but excitations *confined*

(Wilson loop ~ area)

Perturbative: $1100 < \mu$, but μa too large.

Quarkyonic matter

McLerran & RDP 0706.2191

At large N_c, $g^2 N_c \sim 1$, $g^2 N_f \sim 1/N_c$, so need to go to *large* $\mu \sim N_c^{1/2}$.

$$m^2_{Debye} = g^2((N_c + N_f/2)T^2/3 + N_f \mu^2/(2\pi^2))$$

Doubt large N_c applicable at $N_c = 2$.

When does perturbation theory work?

$T = \mu = 0$: scattering processes computable for momentum $p > 1$ GeV

$T \neq 0$: $p > 2 \pi T$, lowest Matsubara energy

$\mu \neq 0$, $T = 0$: μ is like a scattering scale, so *perhaps* $\mu_{pert} \sim 1$ GeV.
At least for the pressure. Excitations determined by region near Fermi surface

Possible phases of cold, dense quarks

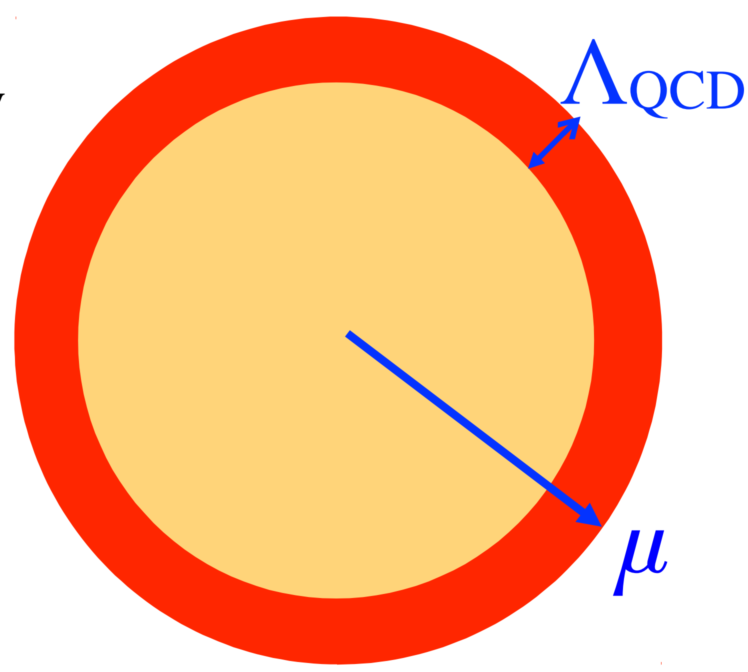
Confined: $0 \leq \mu < m_{baryon} /3$. μ doesn't matter

Dilute baryons: m_{baryon} 3 $< \mu < \mu_{dilute}$: . Effective models of baryons, pions

Dense baryons: $\mu_{dilute} < \mu < \mu_{dense}$. Pion/kaon condensates.

Quarkyonic: $\mu_{dilute} < \mu < \mu_{perturbative}$. 1-dim. chiral spirals.

Perturbative: $\mu_{perturbative} < \mu$. Color superconductivity



$\mu_{perturbative} \sim 1$ GeV?

Dense baryons and quarkyonic *continously* related.

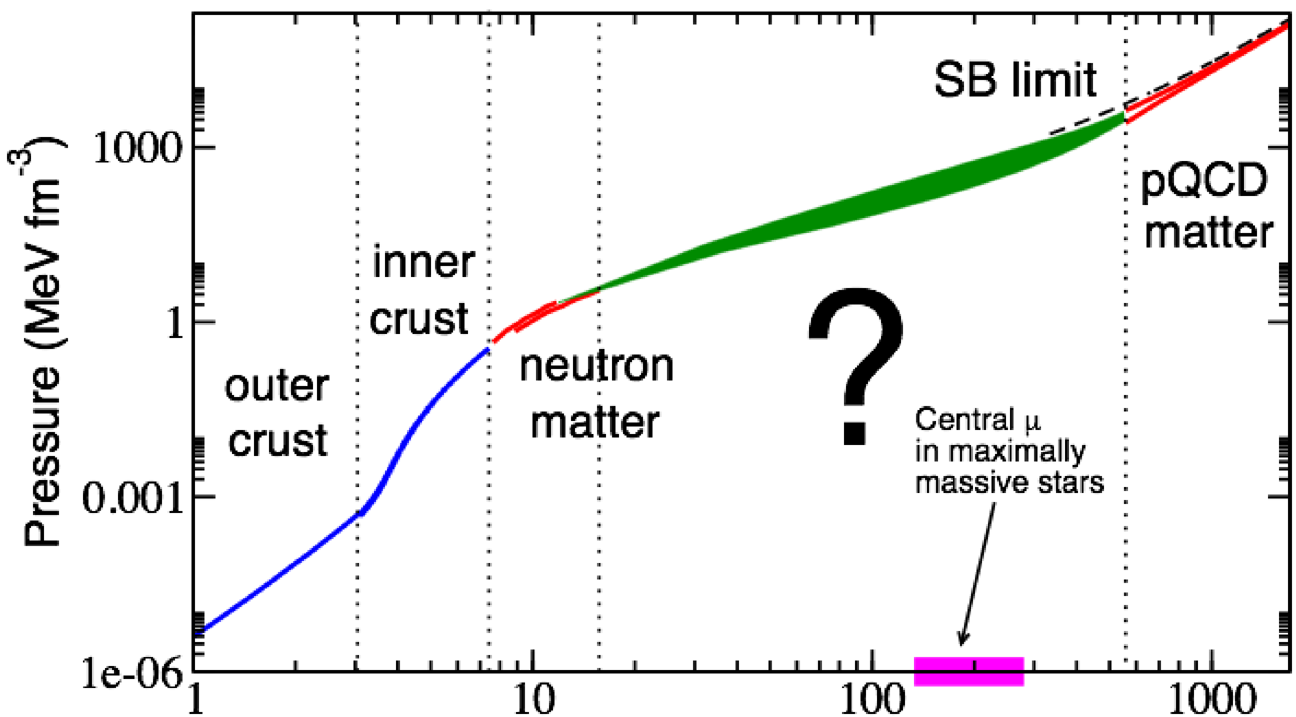
U(1) order parameter in both.

Relevance for neutron stars

Fraga, Kurkela, & Vuorinen 1402.6618.

Maximum μ may reach quarkyonic (for pressure), but true perturbative?

Ghisoiu, Gorda, Kurkela, Romatschke, Säppi, & Vuorinen, 1609.04339: pressure(μ) ~ g^6.
Will be able to compute Λ_{pert} = # μ. # ~ 1?



μ→

$\mu_q - m_B/3 \rightarrow$

Dense Baryons	Quarkyonic	Perturbative

Quarkyonic matter: 1-dim. reduction

Kojo, Hidaka, McLerran & RDP 0912.3800: as toy model, assume confining potential

$$\Delta_{00} = \frac{\sigma_0}{(\vec{p}^{\,2})^2} \; , \; \Delta_{ij} \sim \frac{1}{p^2}$$

Near the Fermi surface, reduces to effectively 1-dim. problem in patches.
For *either* massless or massive quarks, excitations have zero energy about Fermi surface; just Fermi velocity $v_F < 1$ if $m \neq 0$.

Spin in 4-dim. -> "flavor" in 1-dim., so *extended* $2N_f$ flavor symmetry, $SU(N_f)_L x SU(N_f)_R$ -> $SU(2\,N_f)_L x SU(2\,N_f)_R$. Similar to Glozman,1511.05857.

Extended 2 N_f flavor sym. broken by transverse fluctuations, only approximate.

Number of patches $N_{patch} \sim \mu/\sigma_0$, so spherical Fermi surface recovered as σ_0 -> 0

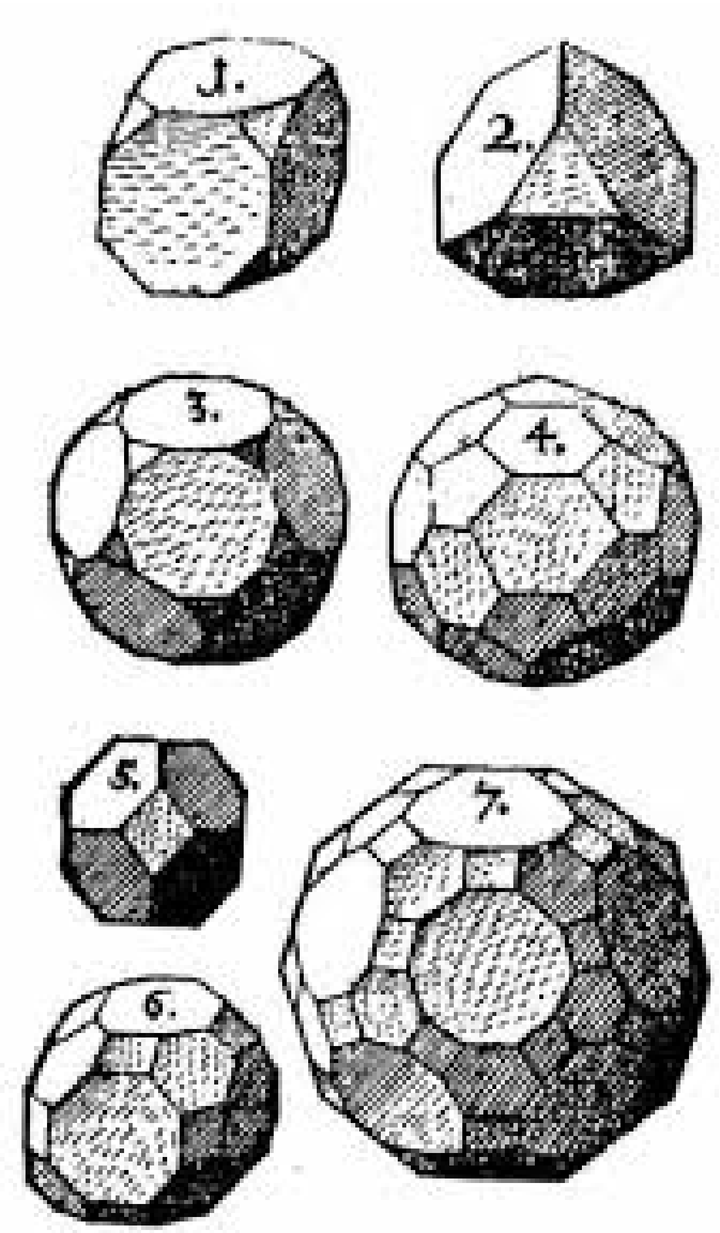
Transitions with # patches

Minimal number of patches = 6.

Probably occurs in dense baryonic phase.

In quarkyonic, presumably weak 1st order transitions as # patches changes.

Like Keplers....



Chiral spirals in 1+1 dimensions

In 1+1 dim., can eliminate μ by chiral rotation:

$$q' = \mathrm{e}^{i\mu z \Gamma_5} q \ , \ \overline{q}(\not{D} + i\mu\Gamma_0)q = \overline{q}' \not{D} q' \ , \ \Gamma_5 \Gamma_z = \Gamma_0$$

Thus a constant chiral condensate automatically becomes a chiral spiral:

$$\overline{q}' q' = \cos(2\mu z)\overline{q}q + i\sin(2\mu z)\overline{q}\gamma_5 q$$

Argument is only suggestive.

N.B.: anomaly ok, gives quark number: $\langle \overline{q}\Gamma_0 q \rangle = \mu/\pi$

Pairing is between quark & quark-hole,both at edge of Fermi sea.
Thus chiral condensate varies in z as ~ 2 μ.

Bosonization in 1+1 dimensions

Do not need detailed form of chiral spiral to determine excitations.

Use bosonization. For one fermion,

$$\overline{\psi}\ \partial\!\!\!/\ \psi \leftrightarrow (\partial_i \phi)^2$$

ϕ corresponds to U(1) of baryon number. In general, non-Abelian bosonization.

For flavor modes,

$$\mathcal{S}_{eff}^{flavor} = \int dt \int dz\ 3\ \frac{1}{16\pi}\ \mathrm{tr}(\partial_\mu U^\dagger)(\partial_\mu U) + \ldots$$

where U is a SU(2 N_f) matrix.

Do not show Wess-Zumino-Witten terms for level 3 = # colors.

Also effects of transverse fluctuations, reduce SU(2 N_f) -> SU(N_f); quark mass

Lastly, SU(3) + level 2 N_f sigma model. Modes are gapped by confinement.

Pion/kaon condensates & U(1) phonon

Overhauser '60, Migdal '71....Kaplan & Nelson '86...

Pion/kaon condensate:

$$\langle \overline{q}_L q_R \rangle \sim \langle \Phi \rangle \sim \Phi_0 \; \exp(i(qz + \phi)t_3)$$

Condensate along σ and π^0 => t_3. Kaon condensate σ and K, etc.

Excitations are the SU(N_f) Goldstone bosons *and* a "phonon", φ.

Phases with pion/kaon condensates and quarkyonic Chiral Spirals both spontaneously break U(1), have associated massless field.

Continuously connected: SU(N_f) of π/K condensate => ~ SU(2 N_f) of CS's. Fluctuations same in both.

Perhaps WZW terms for π/K condensates?

Anisotropic fluctuations in Chiral Spirals

Spontaneous breaking of global symmetry =>
Goldstone Bosons have derivative interactions, ~ ∂^2

π/K condensates and CS's break both global *and* rotational symmetries

Interactions along condensate direction usual quadratic, ~ $\partial_z^{\,2}$

But those quadratic in transverse momenta, ~ $\partial_\perp^{\,2}$,*cancel, leaving quartic*, ~ $\partial_\perp^{\,4}$.

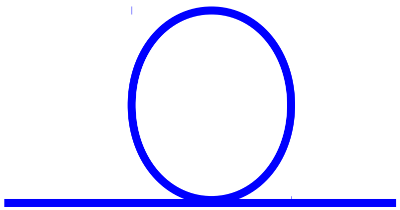
$$\mathcal{L}_{eff} = f_\pi^2 |(\partial_z - i k_0) U|^2 + \kappa |\partial_\perp^2 U|^2 + \ldots$$

Valid for *both* the U(1) phonon φ and Goldstone bosons U

Hidaka, Kamikado, Kanazawa & Noumi 1505.00848;
Lee, Nakano, Tsue, Tatsumi & Friman, 1504.03185; Nitta, Sasaki & Yokokura 1706.02938

No long range order in Chiral Spirals

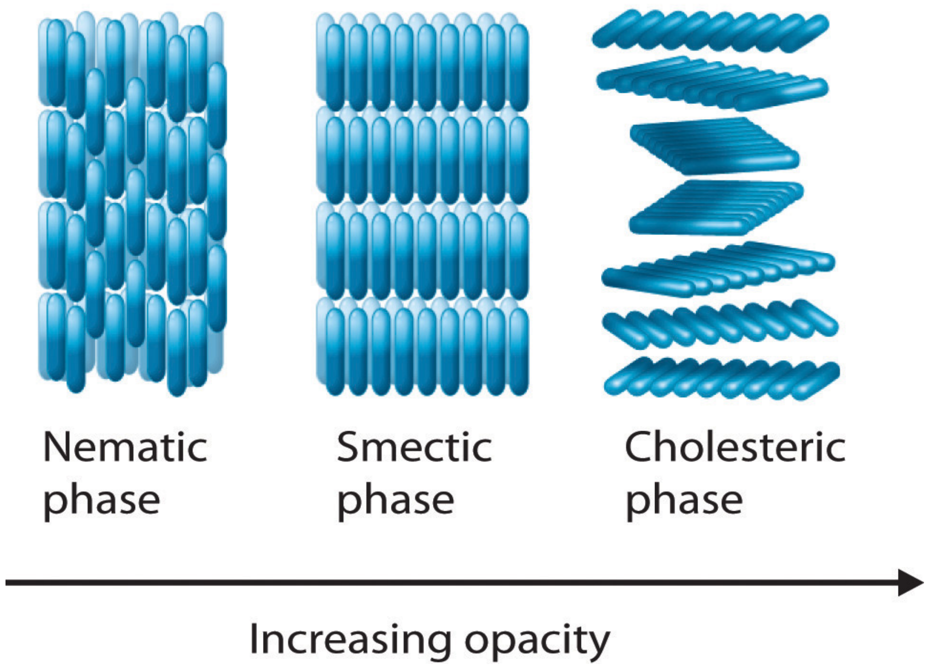
Consider tadpole diagram with anisotropic propagator



$$\int d^2k_\perp\, dk_z \, \frac{1}{(k_z - k_0)^2 + (k_\perp^2)^2} \sim \int d^2k_\perp \, \frac{1}{k_\perp^2} \sim \log \Lambda_{\rm IR}$$

Old story for π/K condensates: Kleinert '81; Baym, Friman, & Grinstein, '82 .

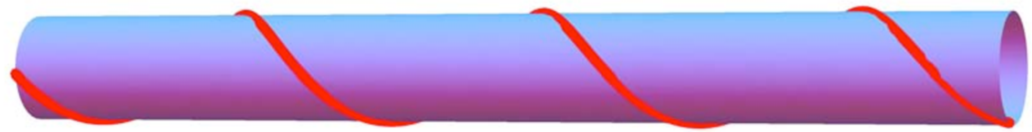
Similar to smectic-C liquid crystals:
ordering in one direction,
liquid in transverse.
Hence anisotropic propagator



Chiral Spirals in 1+1 dimensions

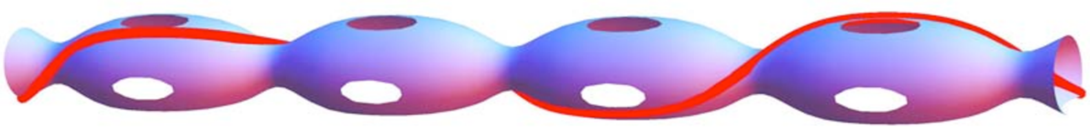
Chiral Spiral (CS) ~ Migdal's pion condensate:

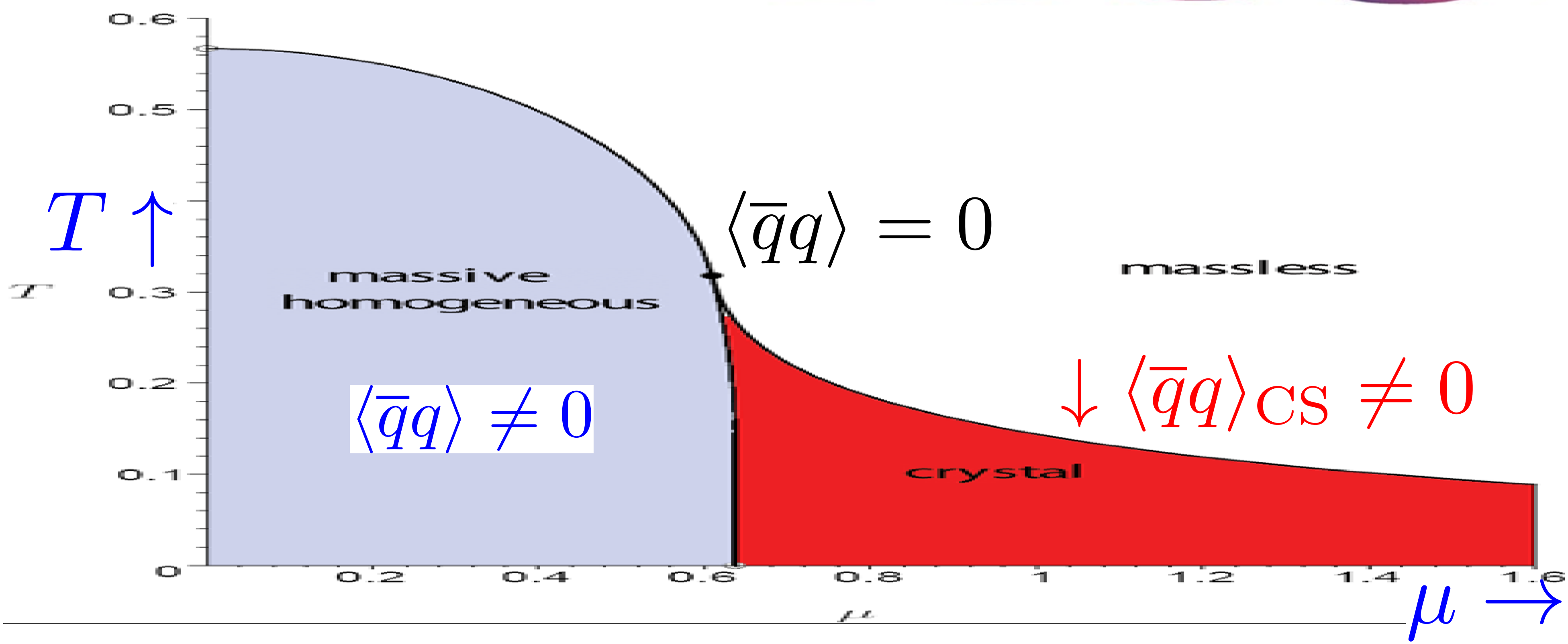
$$(\sigma, \pi^0) = f_\pi(\cos(k_0 z), \sin(k_0 z))$$



Ubiquitous in 1+1 dimensions: Basar, Dunne & Thies, 0903.1868; Dunne & Thies 1309.2443+ ...

Wealth of exact solutions, phase diagrams at *infinite* N_f.

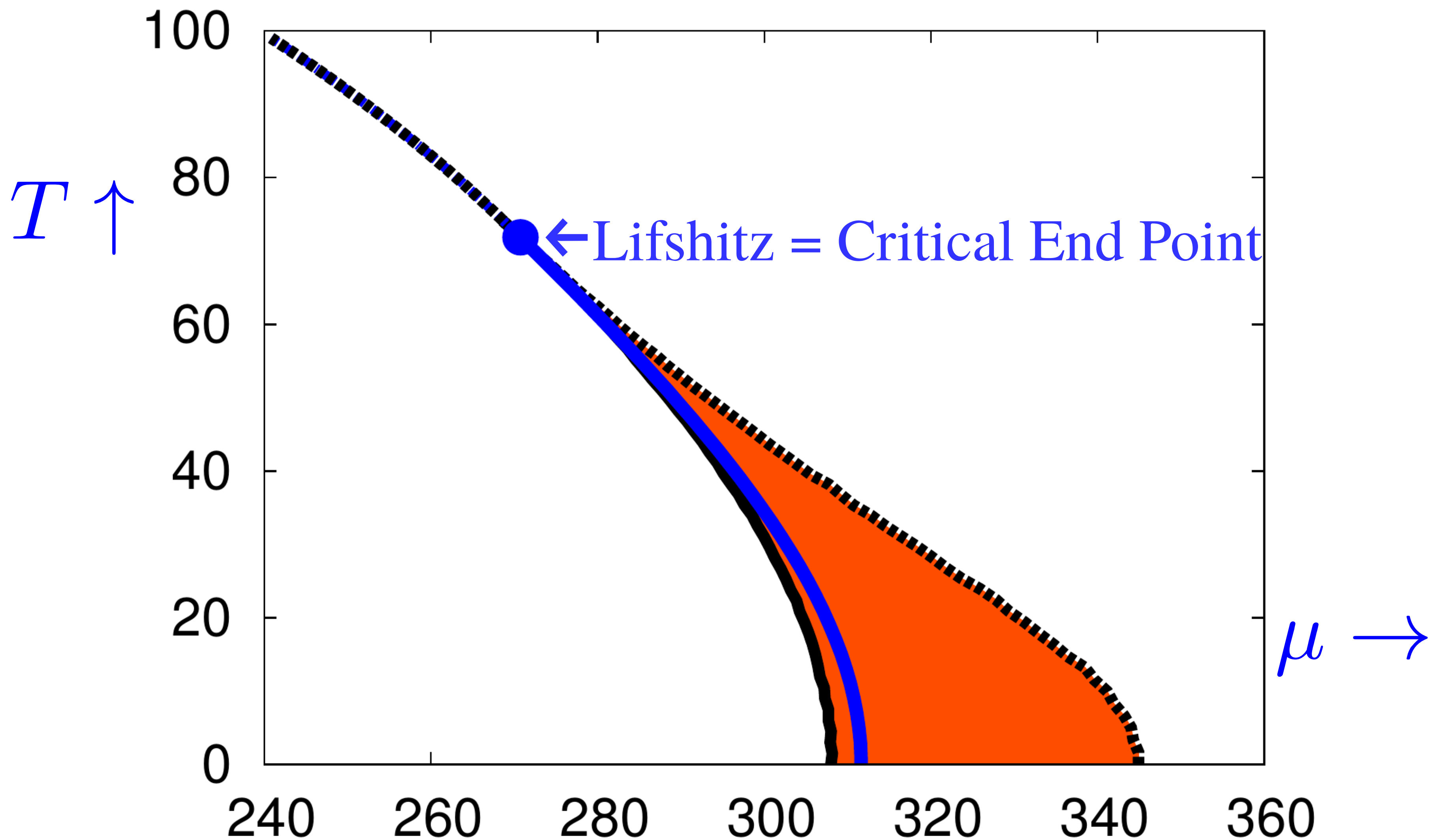




Chiral Spirals in 3+1 dimensions

In 3+1, *common* in NJL models: Nickel, 0902.1778 + ...Buballa & Carignano 1406.1367 + ...

In reduction to 1-dim, $\Gamma_5^{\text{1-dim}} = \gamma_0 \gamma_z$, so chiral spiral between $\overline{q}q$ & $\overline{q}\gamma_0\gamma_z\gamma_5 q$



NJL models and Lifshitz points

Consider Nambu-Jona-Lasino models.

Nickel, 0902,1778 & 0906.5295 + ... + Buballa & Carignano 1406.1367

$$\mathcal{L}_{\rm NJL} = \overline{\psi}(\partial\!\!\!/ + g\sigma)\psi + \sigma^2$$

Integrating over ψ,

$$\mathrm{tr}\,\log(\partial\!\!\!/ + g\,\sigma) \sim \ldots + \kappa_1((\partial\sigma)^2 + \sigma^4) + \ldots$$

Due to scaling, ∂ -> $\lambda\partial$, σ -> $\lambda\sigma$.

Consequently, in NJL @ 1-loop, *tricritical = Lifshitz point.*

Special to including only σ at one loop.

Not generic: violated by the inclusion of more fields, to two loop order, etc.

Improved gradient expansion near critical point:

Carignano, Anzuni, Benhar, & Mannarelli, 1711.08607.

Both of these phase diagrams are *dramatically* affected by fluctuations:

no true Lifshitz point in 1+1 or 3+1 dimensions

Standard phase diagram

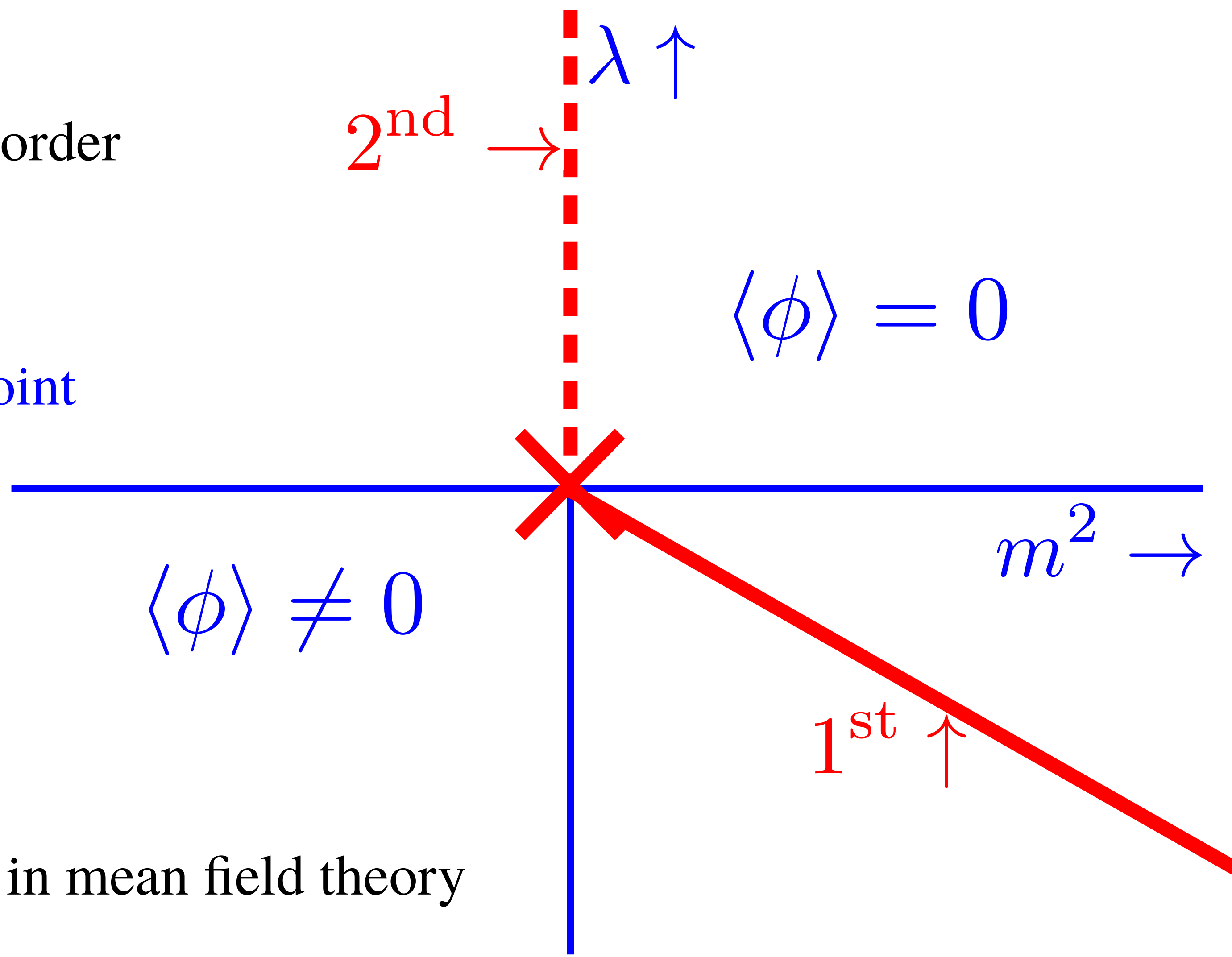
Trade T & μ for m^2 & λ.

Two phases, symmetric & broken

$$\mathcal{L} = (\partial_\mu \phi)^2 + m^2\phi^2 + \lambda\phi^4 + \kappa\phi^6$$

$m^2 = 0$, $\lambda > 0$: usual 2nd order

$m^2 = \lambda = 0$: tricritical point

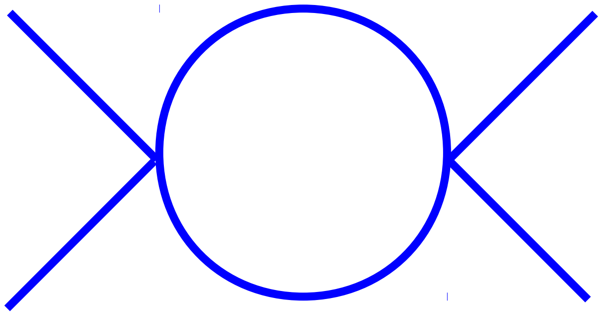


$m^2 > 0$, $\lambda < 0$: 1st order in mean field theory

Usual critical dimensions

φ^4: $d_{upper} = 4$: expand in $d = 4 - \varepsilon$ dimensions

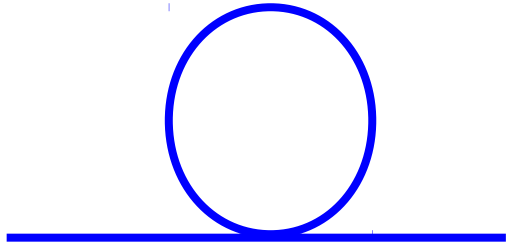
$$\int d^4k \, \frac{1}{(k^2)^2} \sim \log \Lambda_{\rm UV}$$



φ^4: $d_{lower} = 2$: expand in $2 + \varepsilon$ dimensions

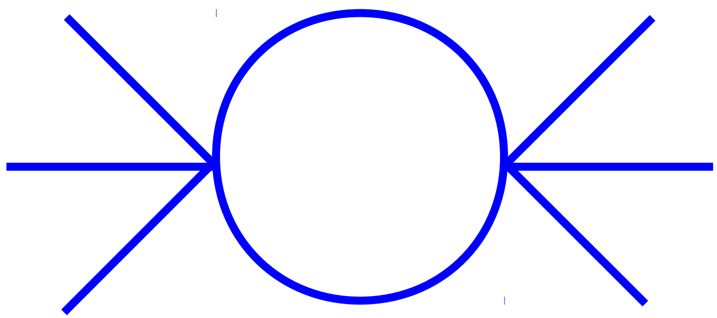
always disordered when $d < 2$

$$\int d^2k \, \frac{1}{k^2} \sim \log \Lambda_{\rm IR}$$



φ^6: $d_{critical} = 3$: at tricritical point, log corrections

$$\int d^3k_1 \int d^3k_2 \, \frac{1}{(k_1)^2 (k_2)^2 (k_1 + k_2)^2} \sim \log \Lambda_{\rm UV}$$



Lifshitz points

To get a Chiral Spiral (CS):

$$\mathcal{L}_{CS} = (\partial_0 \phi)^2 + Z(\partial_i \phi)^2 + \frac{1}{M^2}(\partial_i^2 \phi)^2 + m^2 \phi^2 + \lambda \phi^4$$

Need higher (spatial) derivatives for stability. Then CS occurs when Z < 0.

Can*not* have higher derivatives in time or theory is acausal.

In gravity, models with higher derivatives are renormalizable:

$$\mathcal{L}_{\rm ren.gravity} = \frac{1}{16\pi G} R + \alpha_1 R^2 + \alpha_2 R_{\mu\nu}^2$$

but acausal. Hořava-Lifshitz gravity: add higher derivatives only in space

Hořava 0901.3775 + ...

$$\mathcal{L}_{\rm Horava-Lifshitz} = \frac{1}{16\pi G} R + \beta_1 R_{ij}^2 + \ldots$$

Only two time derivatives, so causal. Flows into Einstein gravity in the infrared.

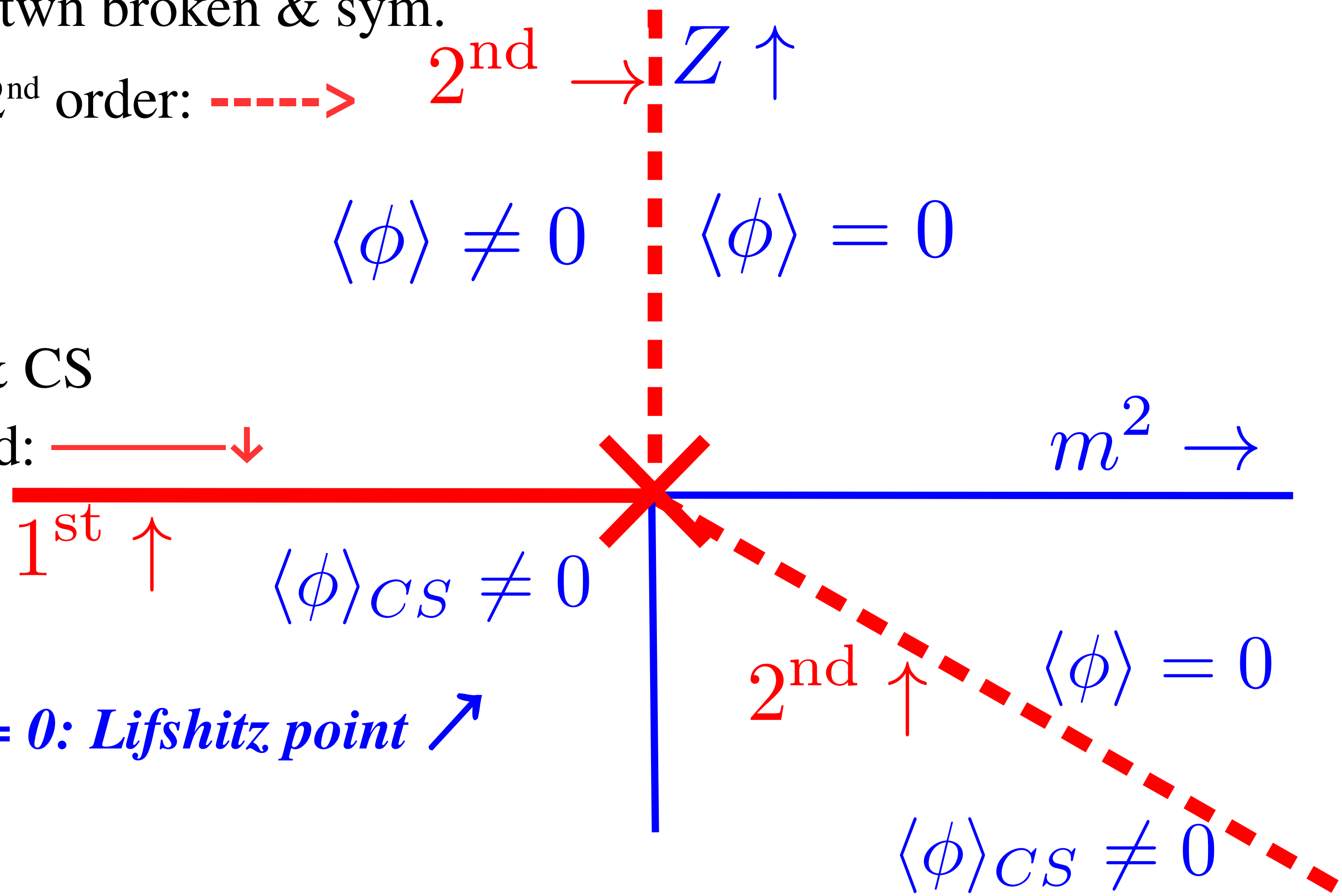
Lifshitz phase diagram in mean field theory

Phase diagram in Z & m^2: *three* phases, symmetric, broken, *and* Chiral Spiral

Hornreich, Luban, Shtrikman, PRL '75, Hornreich J. Magn. Matter '80...Diehl, cond_mat/0205284 + ...

$m^2 = 0$, $Z > 0$: btwn broken & sym.

usual 2nd order: ----->



$m^2 < 0$, $Z = 0$: broken & CS

$1^{\rm st}$ order in mean field: ——↓

X at origin, $m^2 = Z = 0$: Lifshitz point ↗

$m^2 > 0$, $Z < 0$: btwn CS & broken ----- ↗

2nd order in mean field, but *fluctuations?*

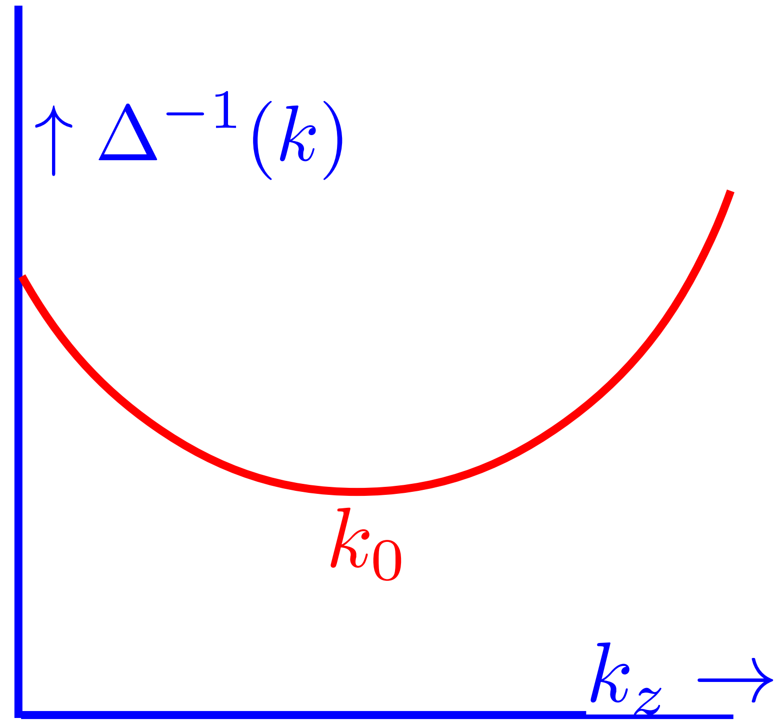
Symmetric to CS: 1D (Brazovski) fluctuations

Consider $m^2 > 0$, $Z < 0$: minimum in propagator at *non*zero momentum

Brazovski '75; Hohenberg & Swift '95 + ... ;

Lee, Nakano, Tsue, Tatsumi & Friman, 1504.03185; Yoshiike, Lee & Tatsumi 1702.01511

$$\Delta^{-1} = m^2 + Z\,k^2 + k^4/M^2$$
$$= m^2_{\rm eff} - 2\,Z\,k_z^2 + O(k_z^3, k_z k_\perp^2)$$



$k=(k_\perp,k_z-k_0)$: *no* terms in $k_\perp^{\,2}$, *only* $(k_\perp^{\,2})^2$.

Due to spon. breaking of rotational sym.

1-loop tadpole diagram:

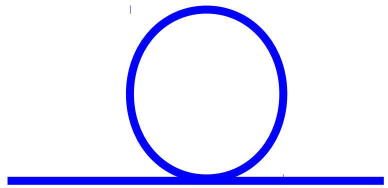
$$\int d^3k\,\frac{1}{k_z^2+m^2_{\rm eff}+\ldots} \sim M^2 \int \frac{dk_z}{k_z^2+m^2_{\rm eff}} \sim \frac{M^2}{m_{\rm eff}}$$

Effective reduction to 1-dim for any spatial dimension d, any global symmetry

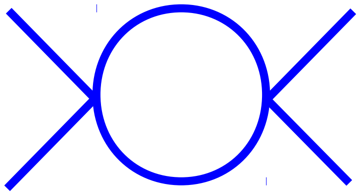
1^{st} order transition in 1-dim.

Strong infrared fluctuations in 1-dim., both in the mass:

$$\Delta m^2 \sim \lambda \int d^3k \, \frac{1}{k_z^2 + m_{\rm eff}^2 + \ldots} \sim \lambda \, \frac{M}{m_{\rm eff}}$$



and for the coupling constant:

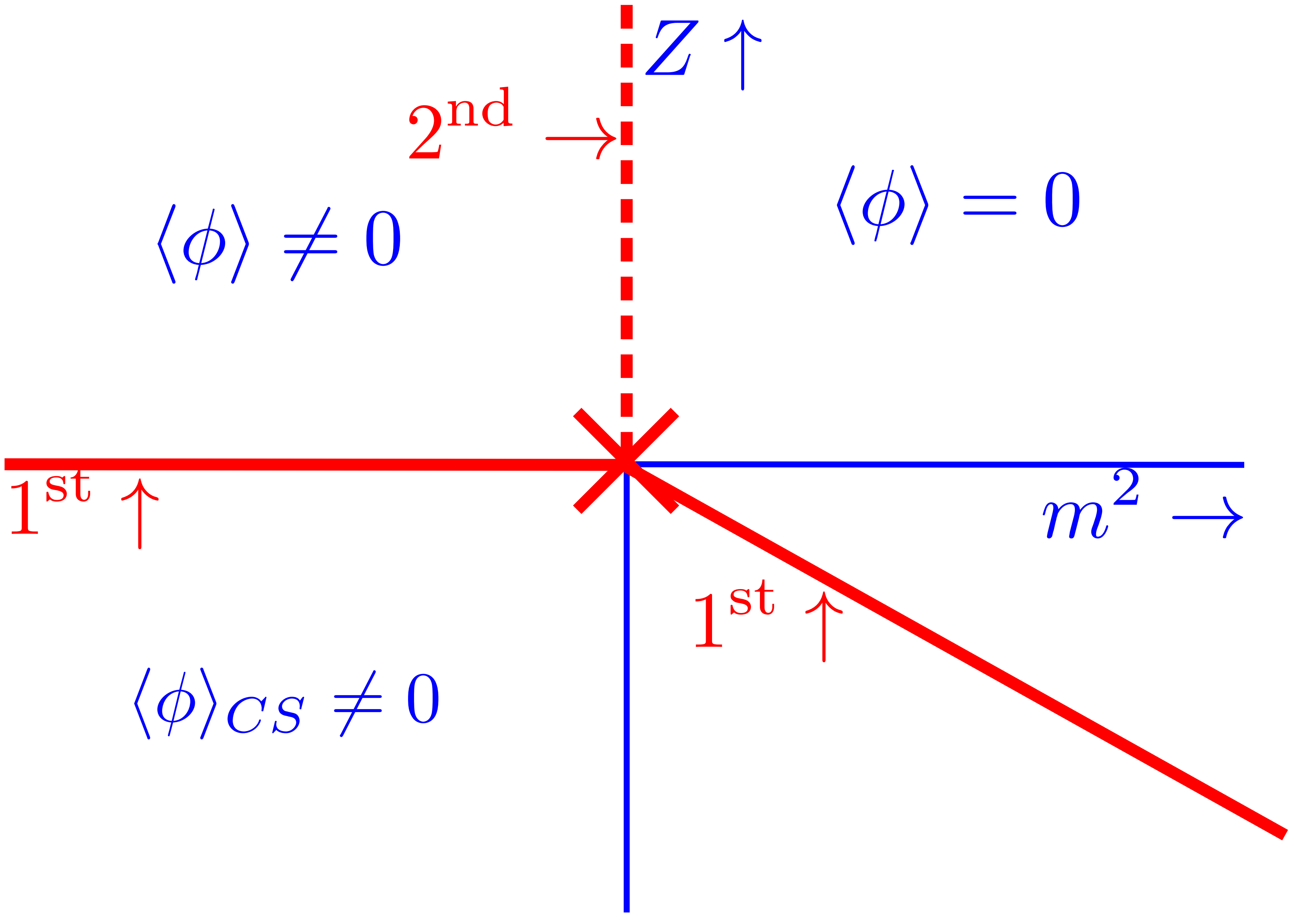


$$\Delta \lambda \sim -\lambda^2 \int \frac{d^3k}{(k_z^2 + m_{\rm eff}^2 + \ldots)^2} \sim -\lambda^2 M^3 \int_{m_{\rm eff}} \frac{dk_z}{k_z^4} \sim -\lambda \, \frac{M^3}{m_{\rm eff}^3}$$

Can*not* tune $m_{\rm eff}^2$ to 0: $\lambda_{\rm eff}$ goes negative, 1^{st} order trans. induced by fluctuations

Not like other 1st order fluc-ind'd trans's: just that in 1-d, $m_{\rm eff}^2 \neq 0$ always

Lifshitz phase diagram, with eff. 1-D fluc.'s



What about fluctuations at the Lifshitz point?

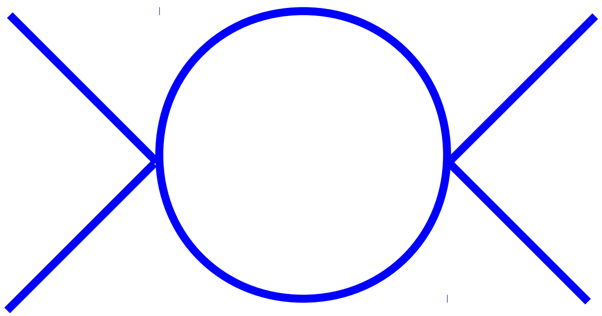
Critical dimensions at the Lifshitz point

At the Lifshitz point, Z=m=0, massless propagator ~ $1/k^4$

$$\mathcal{L}_{\mathrm{Lifshitz}} = (\partial^2\phi)^2 + \lambda\phi^4$$

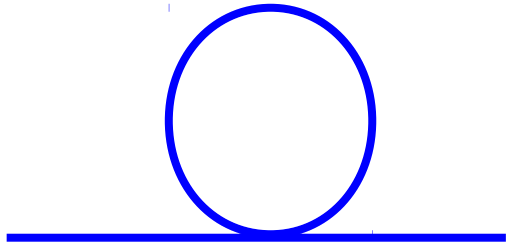
$d_{upper} = 8$: expand in d = 8 – ε dimensions

$$\int d^8k \, \frac{1}{(k^4)^2} \sim \log \Lambda_{\mathrm{UV}}$$



$d_{lower} = 4$: expand in d = 4 + ε dimensions

$$\int d^4k \, \frac{1}{k^4} \sim \log \Lambda_{\mathrm{IR}}$$



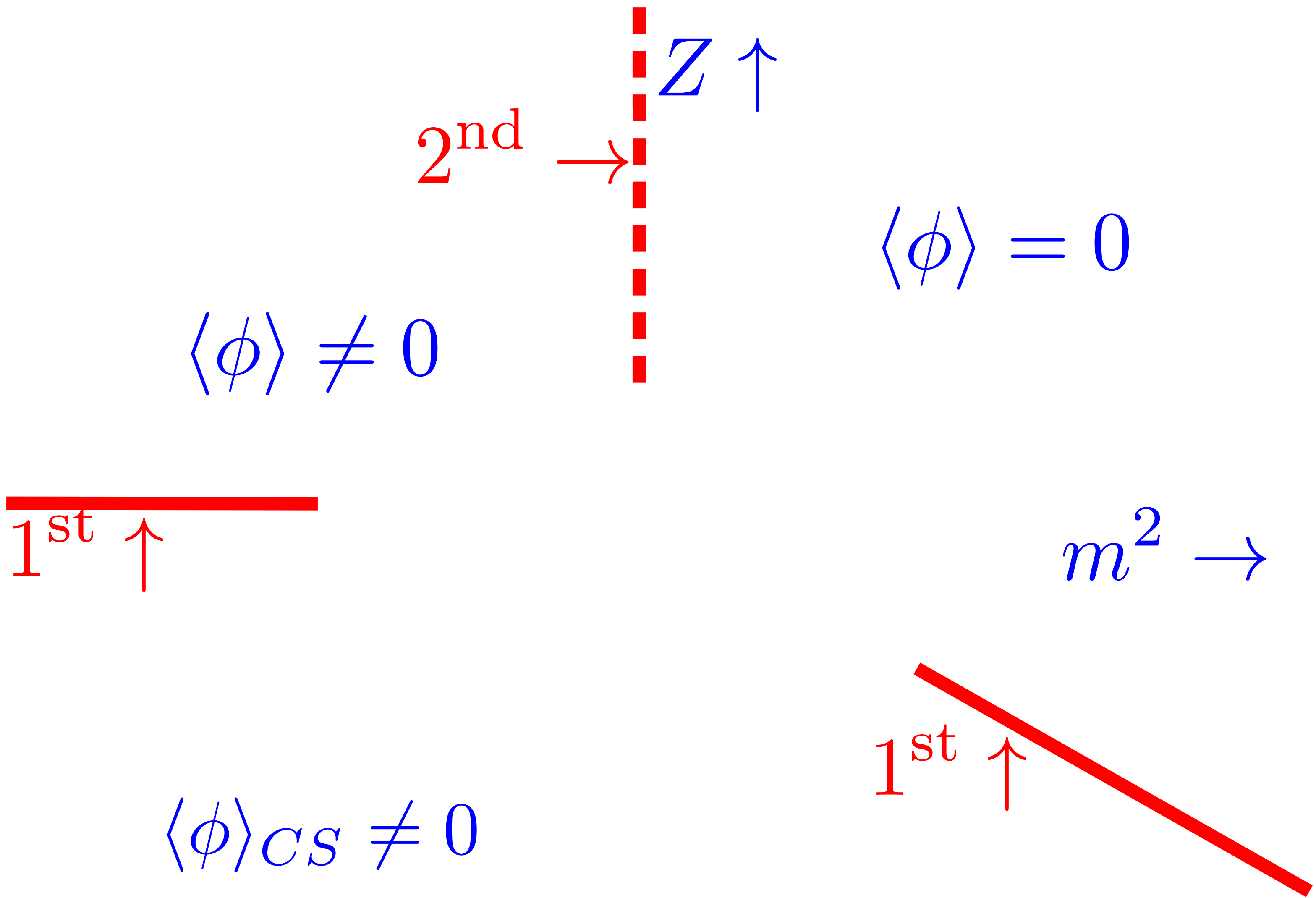
$d = 3 < d_{lower}$: there is *NO* (isotropic) Lifshitz point in *three* dimensions

...+ Bonanno & Zappala, 1412.7046; Zappala, 1703.00791

Infrared fluctuations *always* generate a mass gap *dynamically*.

Phase diagram with*out* a Lifshitz point?

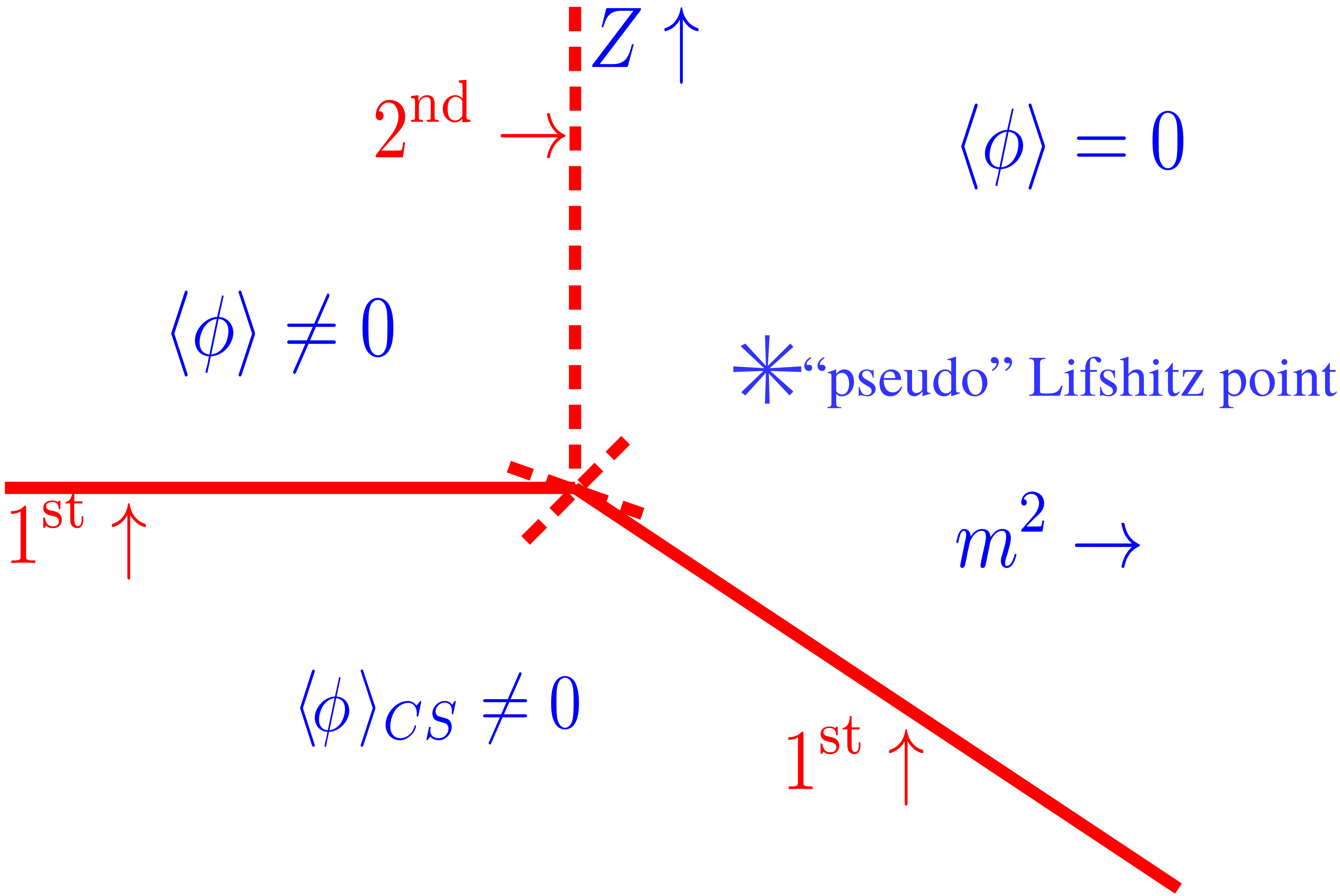
Have three phases, three lines of phase transition far from the would be Lifshitz point. *How can they connect?*



A: looks like Lifshitz point, but isn't

All three lines connect, endpoint is *same* universality class as 2nd order line

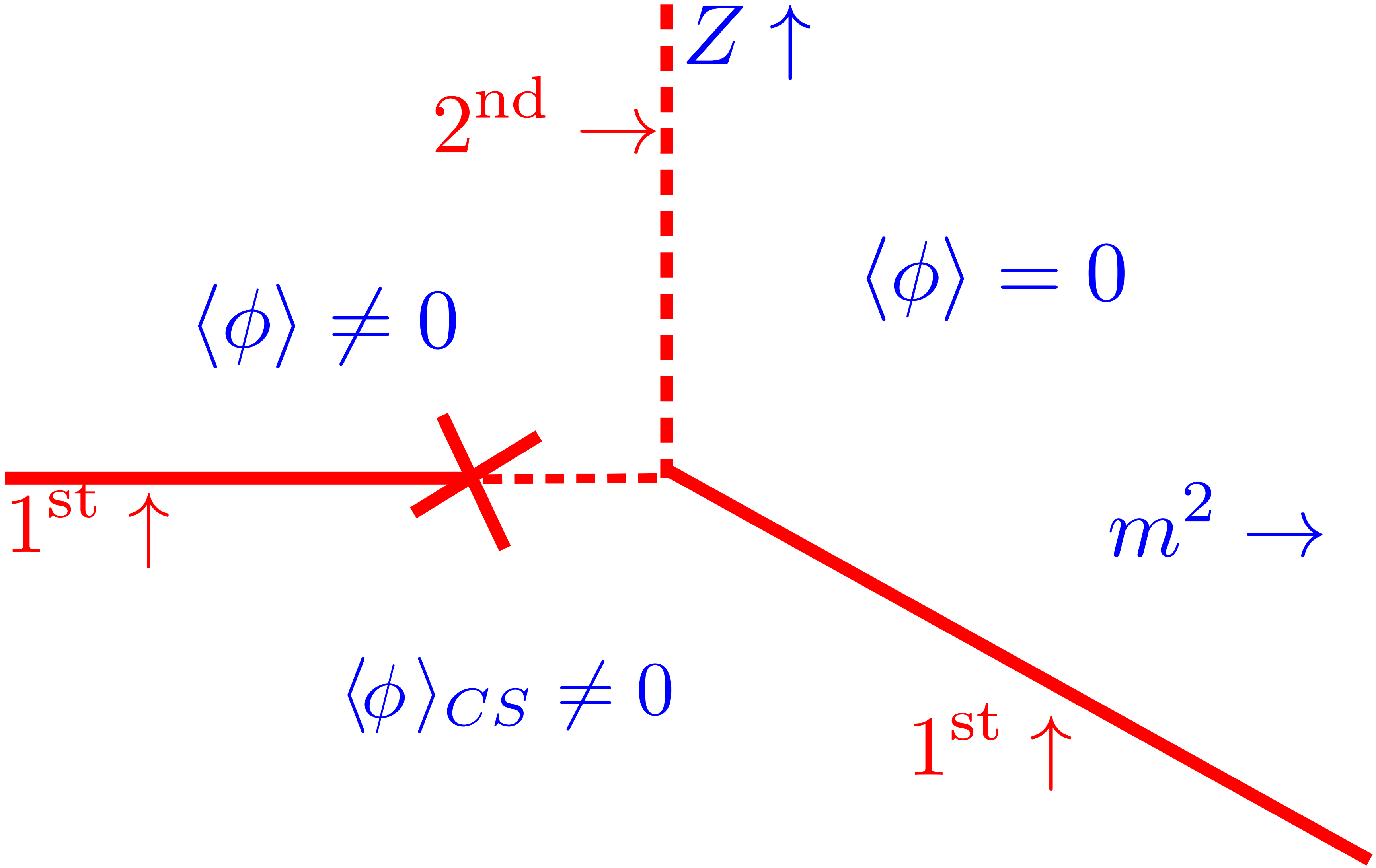
Unbroken line of 1st order transitions, with "pseudo"-Lifshitz point



B: 1st order line between broken/CS phases ends

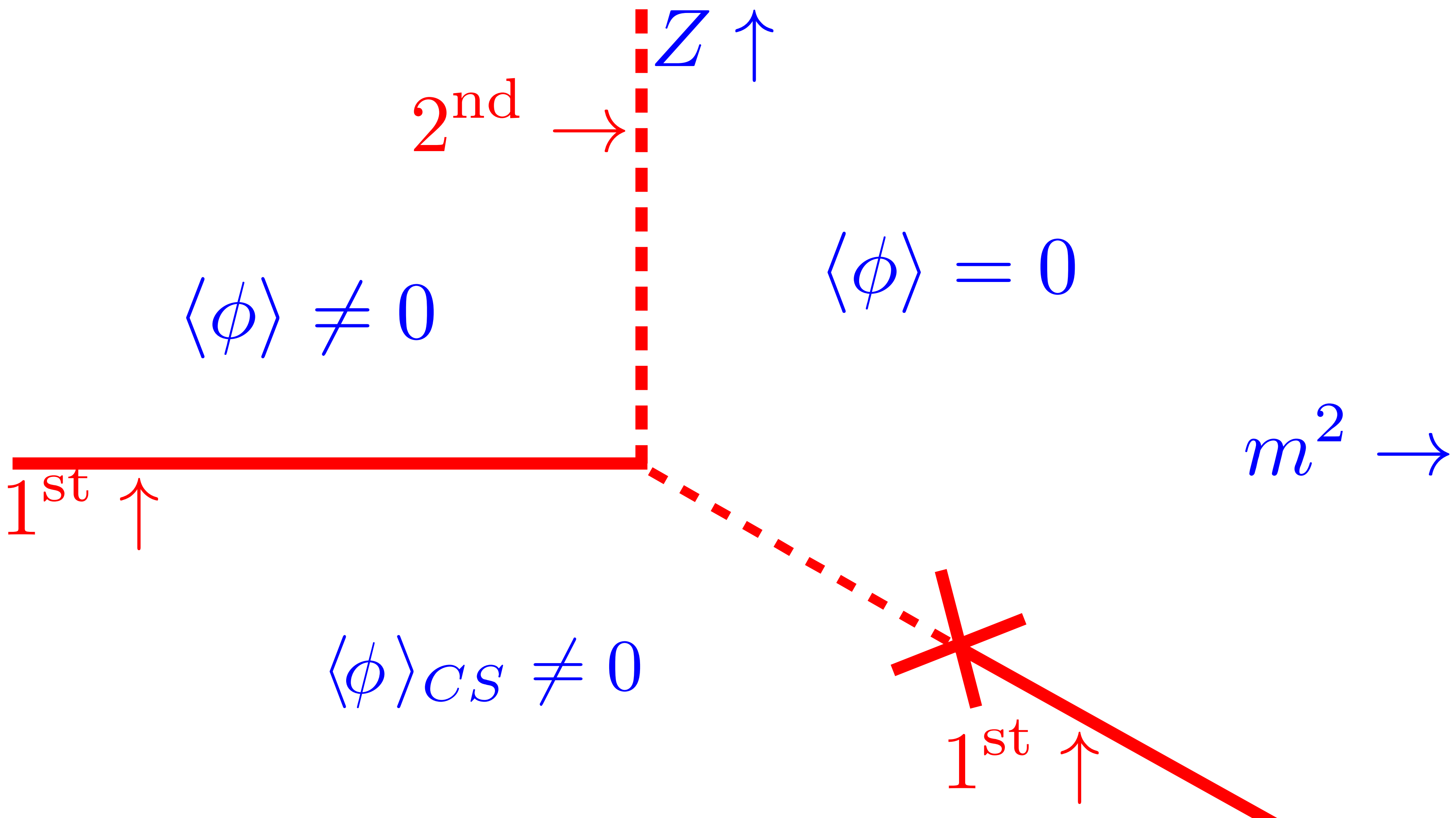
U(1) sym. bkg'g between CS and other phases.

Could be line of second order transitions between broken & CS phases



C: Brazovski 1st order CS/sym. line ends

Brazikovski 1st order line ends in critical endpoint, turns into 2nd order line



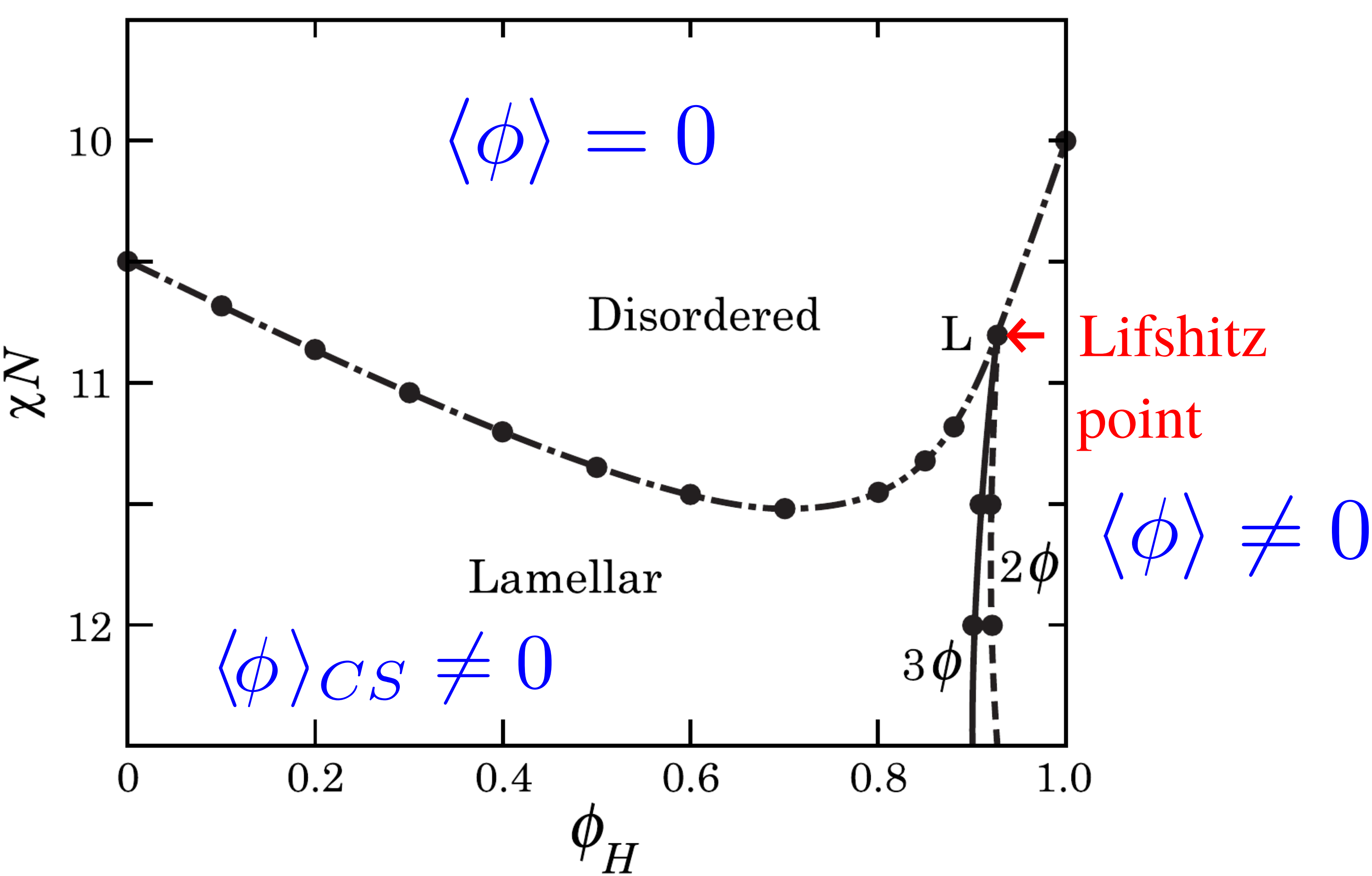
Lifshitz points in inhomogenous polymers: mean field

Fredrickson & Bates, Jour. Polymer Sci. 35, 2775 (1997);

Fredrickson, "The equilibrium theory of inhomogenous polymers", pg. 390.

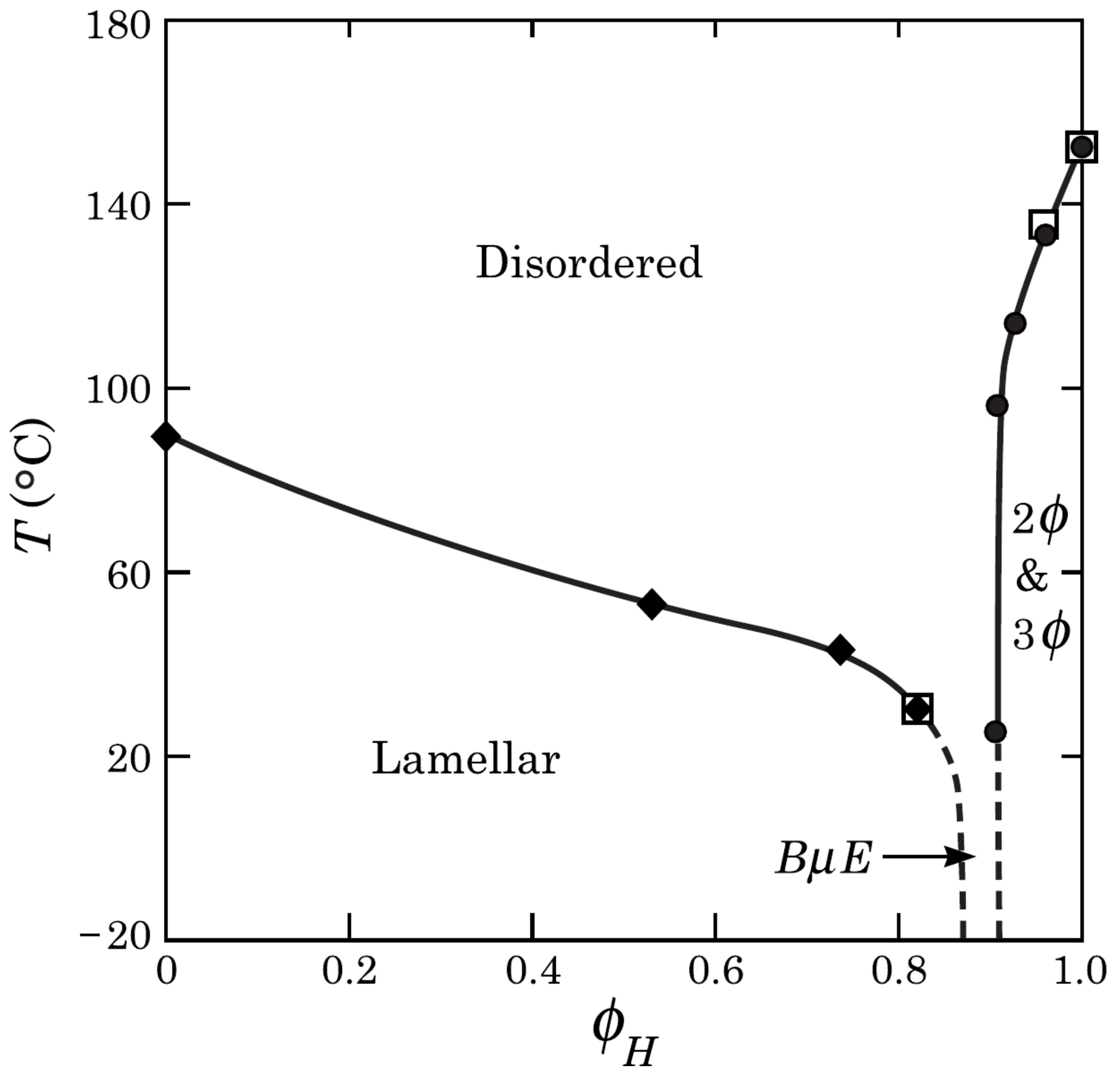
Polymers A & B, for blend with A, B, & A+B

Have disordered, separated, and "lamellar" phases



Inhomogenous polymers: *no* Lifshitz point

From exp. & Monte Carlo, Lifshitz point wiped out by fluctuations.
"bicontinuous microemulsion"appears "structured, fluctuating disordered phase"
Appears to support (A)...

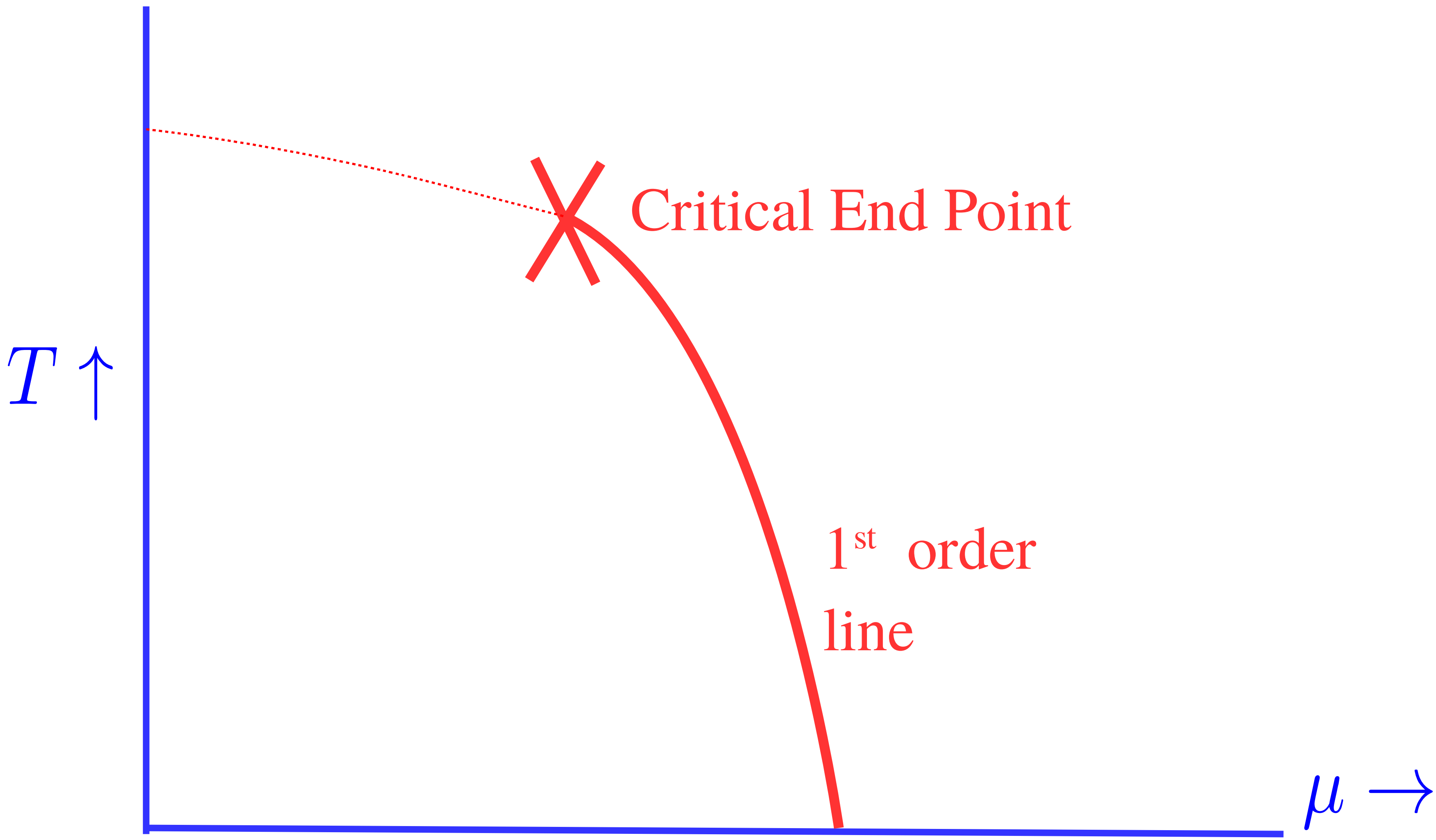


Phase diagram for QCD in T & μ: usual picture

Two phases, one Critical End Point (CEP)

between crossover and line of 1st order transitions

Ising fixed point, dominated by *massless* fluctuations at CEP

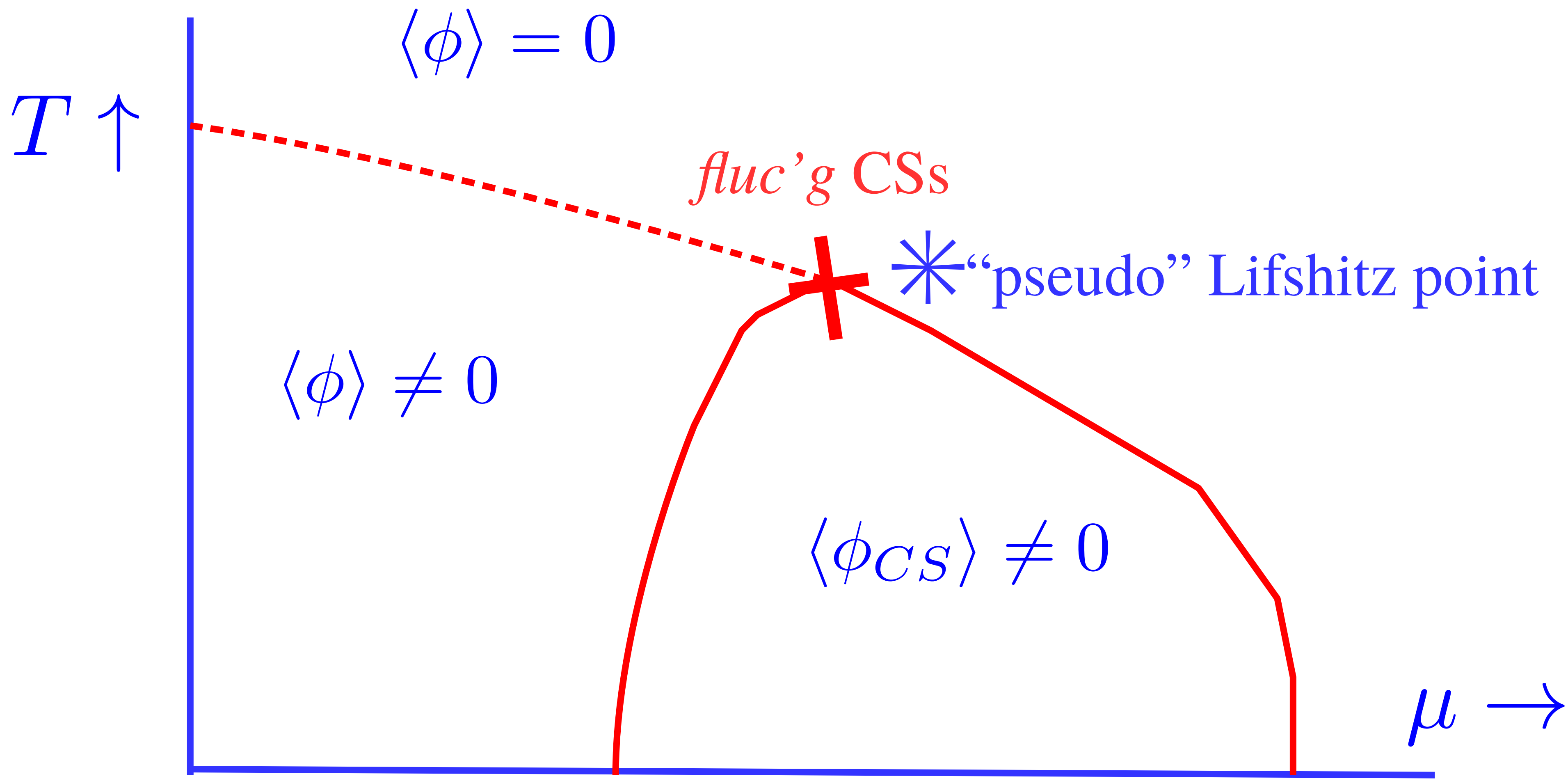


Possible phase diagram: chiral limit

In chiral limit, three phases. 2nd order line, endpoint in same universality class

“Pseudo” Lifshitz point with *large* fluctuations.

In CS, large fluc.’s at *non*zero momenta, ~ k_0 .

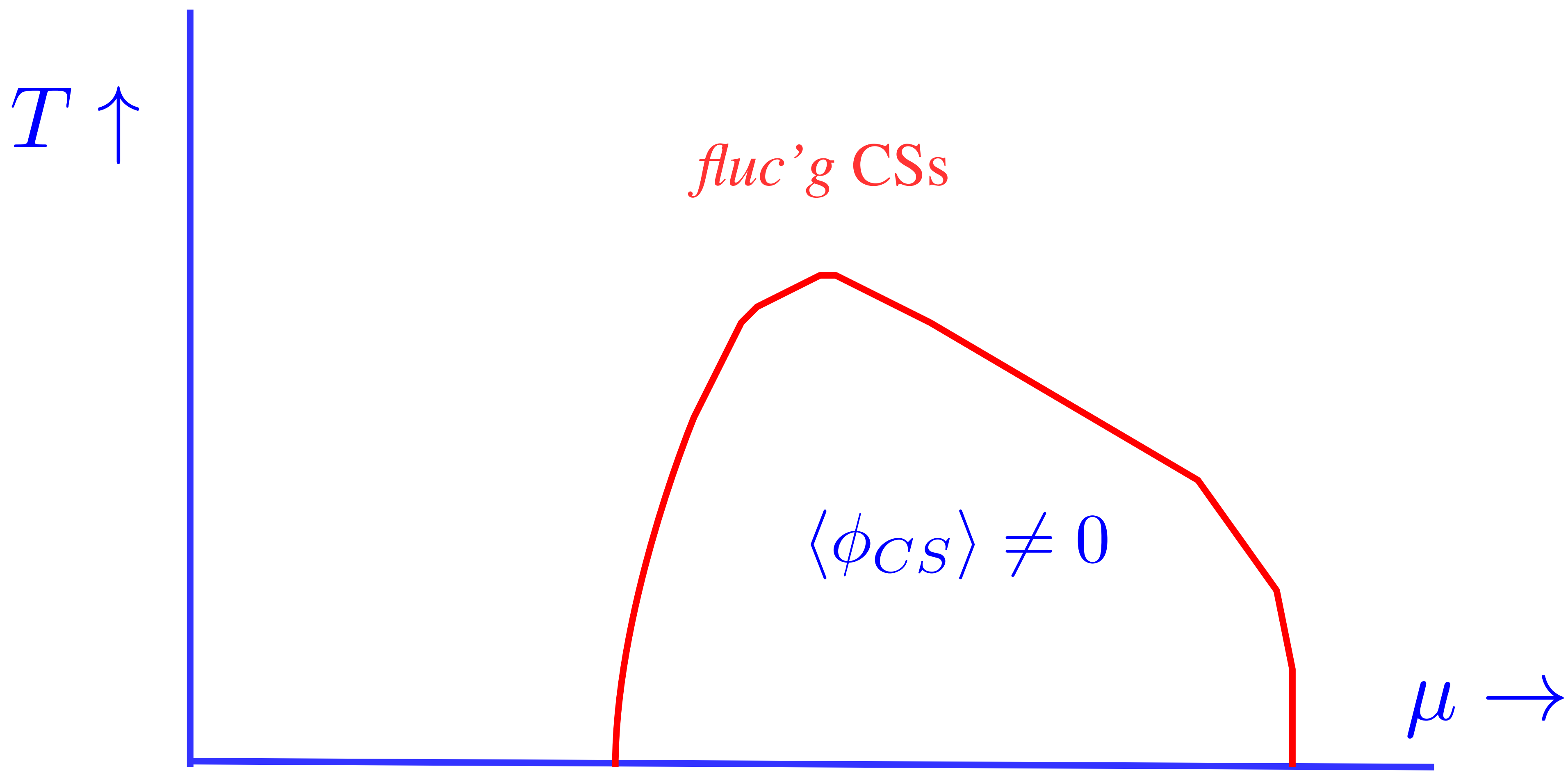


Possible phase diagram: near chiral limit

2nd order line washed out, leaving *only* a 1st order line marking CS phase

Can show: T_{max} of first order line has equal densities (entropies differ)

Punchline: *no* critical endpoint. Region where CS's have *large* fluctuations

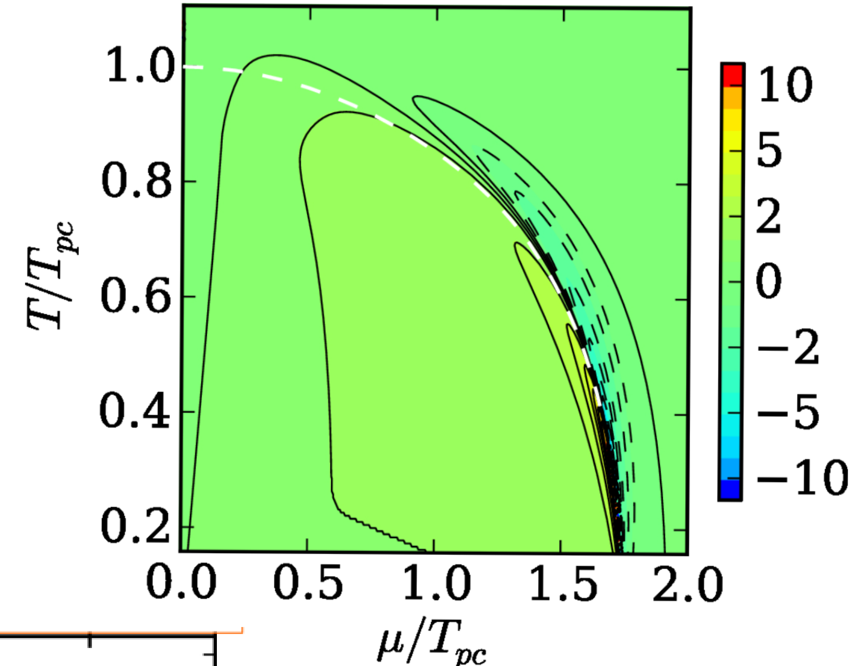


Beam Energy Scan and cumulants

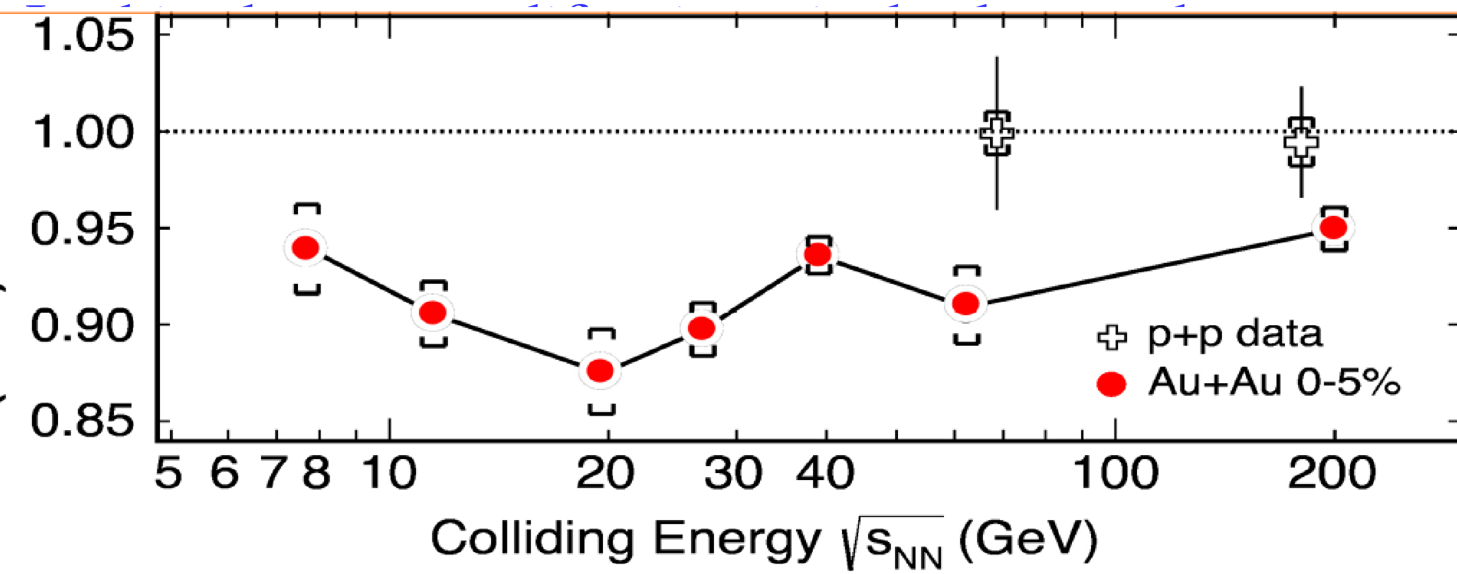
To look for Critical End Point, typically compute cumulants

$$c_n = \frac{\partial^n}{\partial \mu^n} p(T, \mu)$$

Expectation from theory, to right: corrections to c_3 are *positive*



But STAR finds that the corrections to c_3, below, are *negative*



$$\frac{c_3}{c_2} \uparrow$$

Divided by Skellam

Fluctuations at 7 GeV

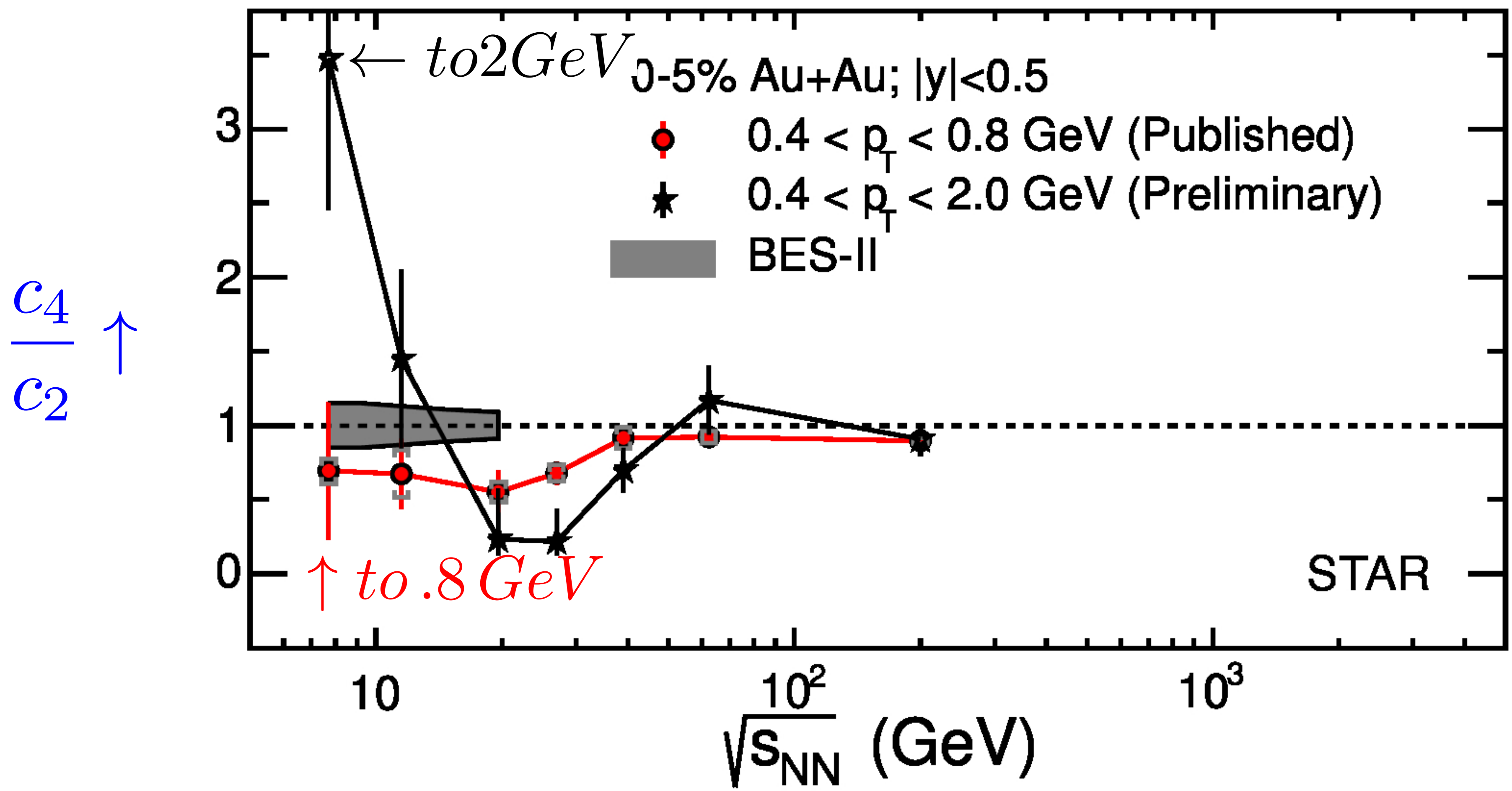
Beam Energy Scan, down to 7 GeV.

Fluctuations *MUCH* larger when up to 2 GeV than to 0.8 GeV

Trivial multiplicity scaling? ... or Chiral Spiral?

But fluctuations in nucleons, not pions.

X. Luo & N. Xu, 1701.02105, fig. 37; Jowazee, 1708.03364



Suggestion for experiment

For *any* sort of periodic structure (1D, 2D, 3D...),

fluctuations concentrated about some characteristic momentum k_0

So "slice and dice": bin in intervals, 0 to .5 GeV, .5 to 1., etc.

If peak in fluctuations in a bin not including zero, *may* be evidence for $k_0 \neq 0$.

If periodic structure, fluctuations must go *up* as $\sqrt{s}$ goes *down,* since μ increases

Gertrude Stein about Oakland, California, ~ 1890:

“There’s no there, there.”

Beam Energy Scan at RHIC,
FAIR, NICA, JPARC:

There *is* a there, there

But what is it?


FUTURE'S SO BRIGHT
GOTTA WEAR SHADES