~~QGP~~ & Fluctuations

1. Lattice pressure, $N_f = 0$ & $N_f \neq 0$

   "Universality" of $\frac{p}{T^4}$

2. "QGP" as condensate of Polyakov loops ℓ

3. Fluctuations in ℓ $\Rightarrow$

   nonstatistical fluc's in AA coll.'s

RDP '00

RDP & A. Dumitru '00

Lattice - $N_f = 0$

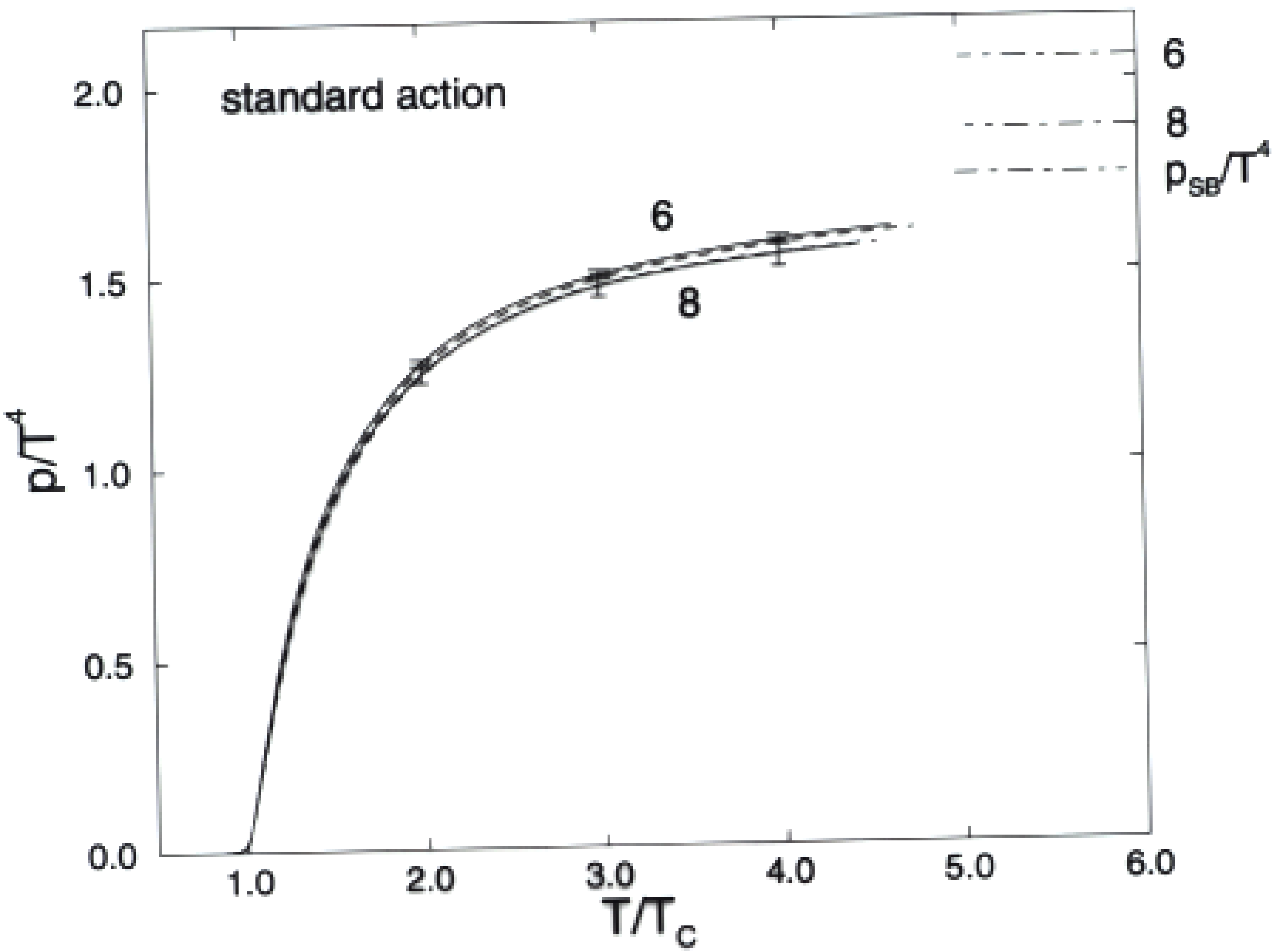
$T < T_c$: $p \approx 0$!

$T > T_c$: $\frac{p}{T^4}$ rapidly $\rightarrow$ ideal gas

$\frac{p}{T^4} \uparrow$

$T/T_c \longrightarrow$

CP-PACS, hep-lat/9905005



standard action
6
8
p_{SB}/T^4
6
8
p/T^4
T/T_c
0.0
0.5
1.0
1.5
2.0
1.0
2.0
3.0
4.0
5.0
6.0

Quasiparticle Models

Ideal, "massive" QP's:

$$p_{QP} \sim \# \, \mathrm{tr} \, \ln(-\partial^2 + m_{QP}^2) + \ldots$$

$$m_{QP} \sim g\,T$$

asymptotic freedom $\Rightarrow g^2 \sim \dfrac{1}{\ln T}$ $\quad g \uparrow$ as $T \downarrow$

$T \to T_c$: $m_{QP} \to \infty \Rightarrow p \to 0$

N.B.: $\xi_{QP} \sim \dfrac{1}{m_{QP}} \to 0$

"Works"!

Quasiparticle Models

Karsch '88

Rischke, Gorenstein, Stöcker, Greiner '90

Peshier, Kampfer, Pavlenko, Soff '96

Levai, Heinz '98

Hard Thermal Loop-ish

Andersen, Braaten, Strickland '99, '00

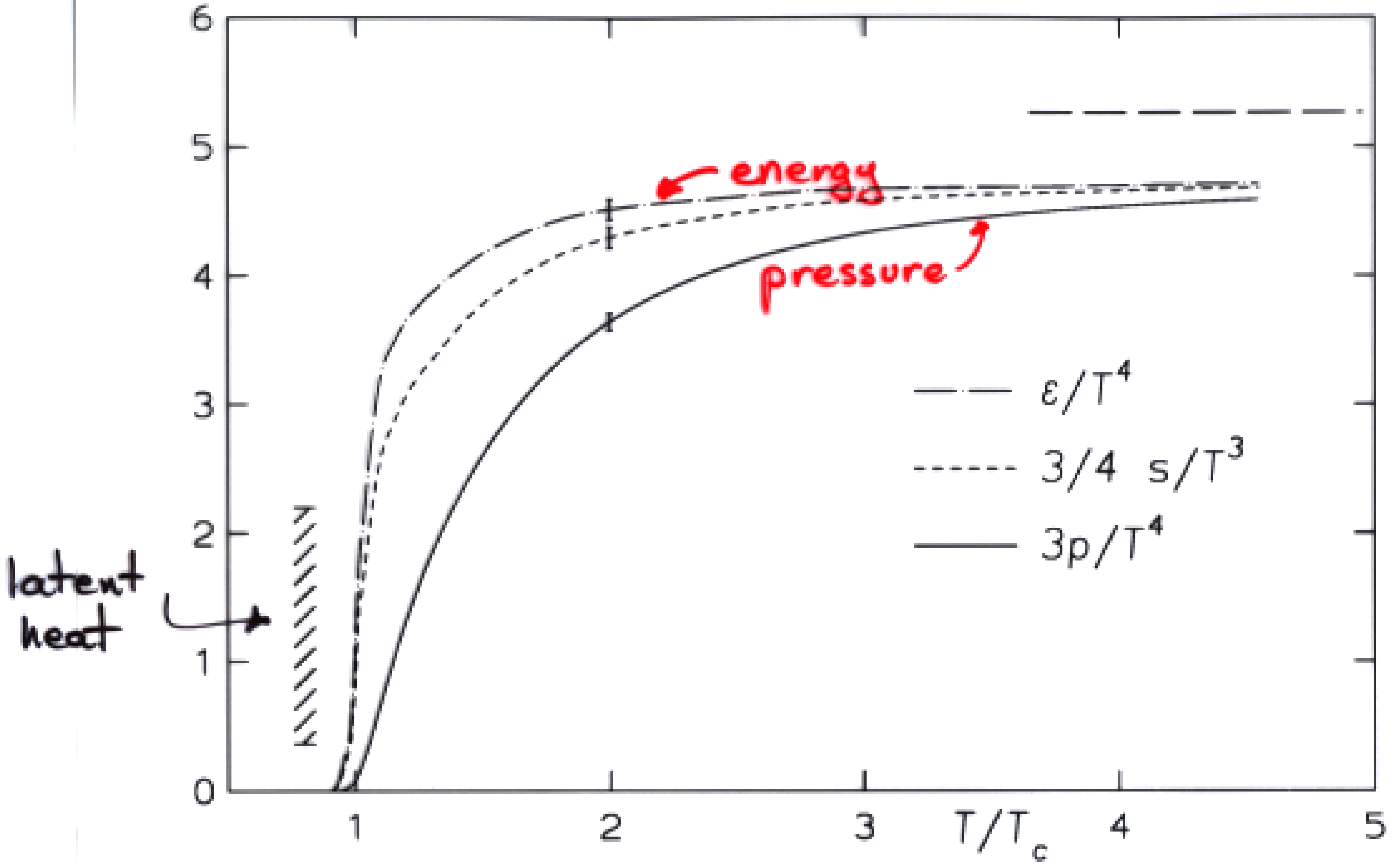
Blaizot, Iancu, Rebhan '99, '00

Peshier '99, '00

+ Lattice

Kajantie, Laine, Rummukainen
& Schroder '00

$N_f = 0$ SU(3) thermo. '97 Bielefeld



pure SU(3)

lat/9706006 Karsch

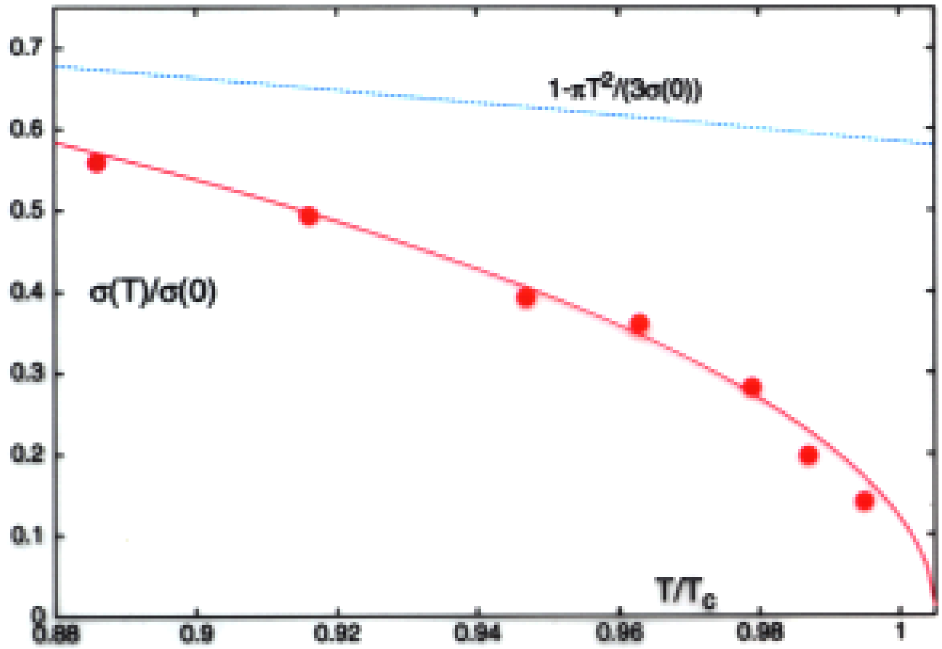
$N_f = 0 \quad SU(3)$

$\frac{\Delta\varepsilon}{\varepsilon_{ideal}} \sim \frac{1}{3} \Rightarrow$ weakly 1^{st} order

$T < T_c$

$\frac{\sigma(T_c)}{\sigma(0)} \sim \frac{1}{10} \Rightarrow$ nearly 2^{nd} order

string tension



lat/9908010 Kaczmarek+...

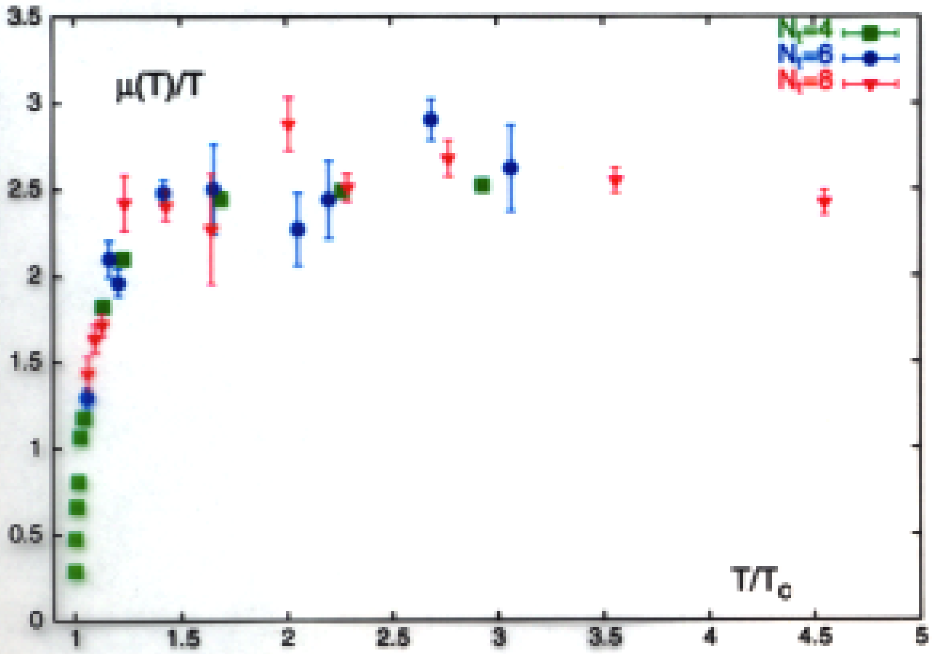
$N_f = 0 \quad SU(3)$

$T > T_c$: $\quad M \cong \dfrac{m_{debye}}{T}$

$$\frac{M(T_c^+)}{M(2T_c)} \sim \frac{1}{10}$$

$\Rightarrow \xi \sim 1/M$, $1/\sigma$ increases by ~ 10 near T_c

vs <u>decrease</u> of ξ_{QP} near T_c



lat/9908010 Kaczmarek + . . .

"Universality" of pressure

$N_f \neq 0$ vs $N_f = 0$:

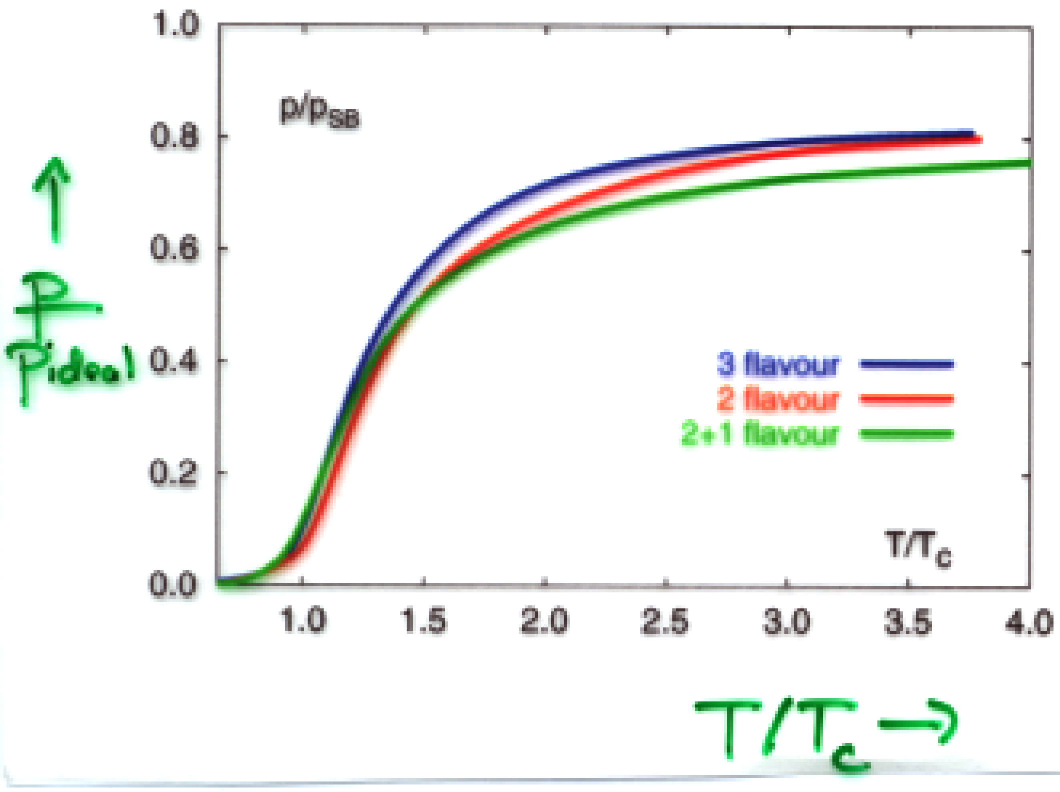
T_c changes

P_{ideal}/T^4 changes

but

$P\left(\frac{T}{T_c}\right) / P_{ideal} \approx$ universal

$T < T_c$: $p \approx 0$



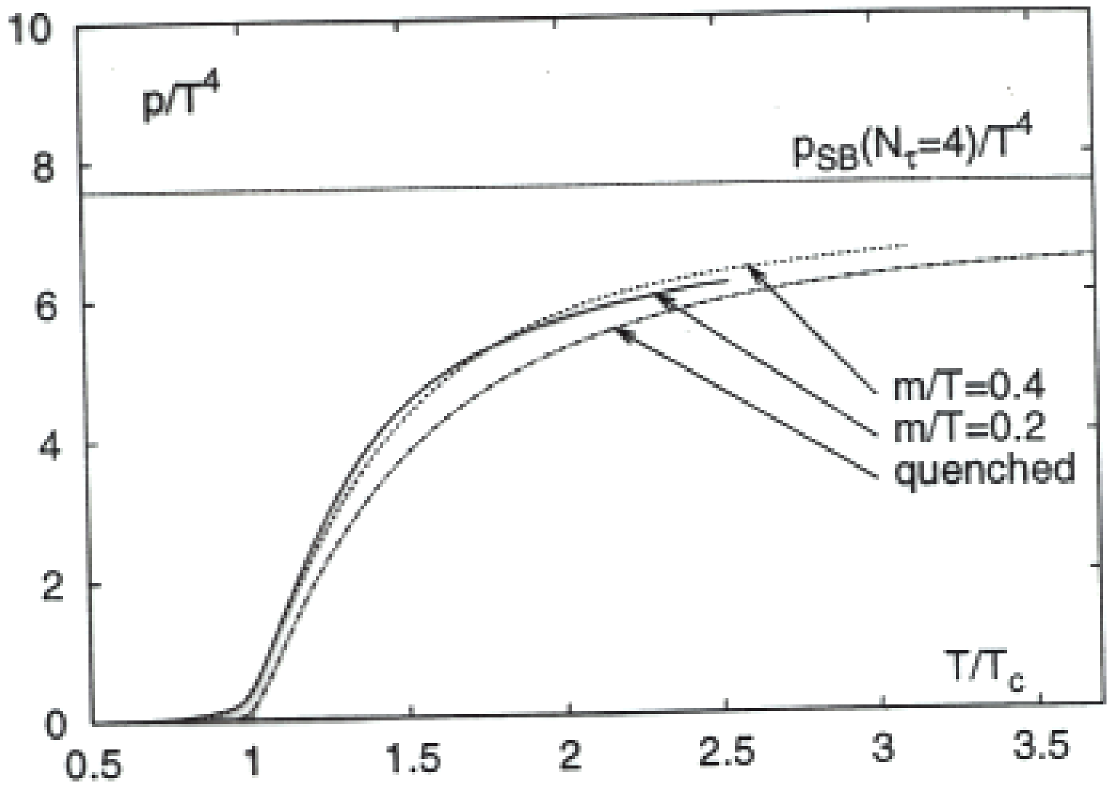
hep-lat/0002003

"Universality" of p/T^4

$N_f = 4$, $m = .2, .4\ T$

vs $N_f = 0$

$\frac{p}{T^4}$ ↑



hep-lat/9706006

T/T_c →

Wilson lines, Polyakov loops

In imaginary time

$$L = \mathbb{P}\, e^{ig\int_0^{1/T} A_0\, dx}$$

= (thermal) Wilson line

= 3×3 matrix

$$\ell = \mathrm{tr}\, L$$ = Polyakov loop

old stuff:

Z(3) sym.: 't Hooft '79

$T \neq 0$: Polyakov '78 Susskind '79

Svetitsky & Yaffe '82

Banks & Ukawa '83

Order vs N_c

Deconfining transition @ T_c

N_f = # flavors = 0

N_c = # colors

N_c	order
2	2^{nd}
	Engels +... '89 → '99
3	nearly 2^{nd}
	many...
4	1^{st}
	Ohta & Wingate '00
∞	1^{st}
	Gocksch & Neri '83

$N_c = 3$ is nearly 2^{nd} order because

$N_c = 3$ is near $N_c = 2$ - NOT $N_c = \infty$!

L's "explain" order vs N_c

L's vs A_0's

Kajantie + ... '00 :

$$V^{eff} = +\frac{1}{2} m^2_{Debye} \, tr A_0^2 + \lambda \, tr A_0^4 + \ldots$$

$\hookrightarrow g^2 T^2$ $\qquad$ $\hookrightarrow g^4 T$

$V^{eff}(A_0)$: $T : \infty \to$ "$2T_c$"

"$2T_c$" $\to T_c$: need $V^{eff}(L)$

$$V^{eff} = \left(- c_2 \, |tr L|^2 + c_4 \, |tr L^2|^2 \right) T^4$$

L dimensionless $\Rightarrow$ overall T^4

Matching @ "$2T_c$",

$$V(A_0) \longleftrightarrow V(L)$$

non-perturbative

L's & HTL's

Static, $\sim g^2$:

$$V^{eff} = \frac{1}{2} m^2_{Debye} \, \mathrm{tr}\, A_0^2$$

Dynamic:

$\mathrm{tr}\, A_0^2 \rightarrow$ Hard Thermal Loops

= Nonabelian RPA

Static, $\sim g^4$:

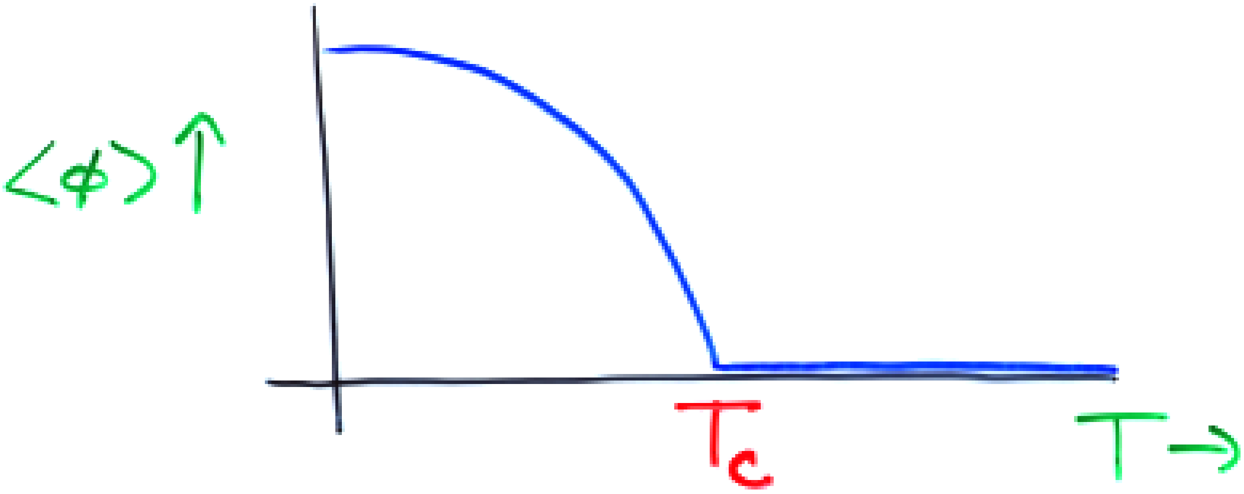
$+ \lambda \, \mathrm{tr}\, A_0^4 \rightarrow$ dynamic ?

More generally:

L = thermal Wilson line

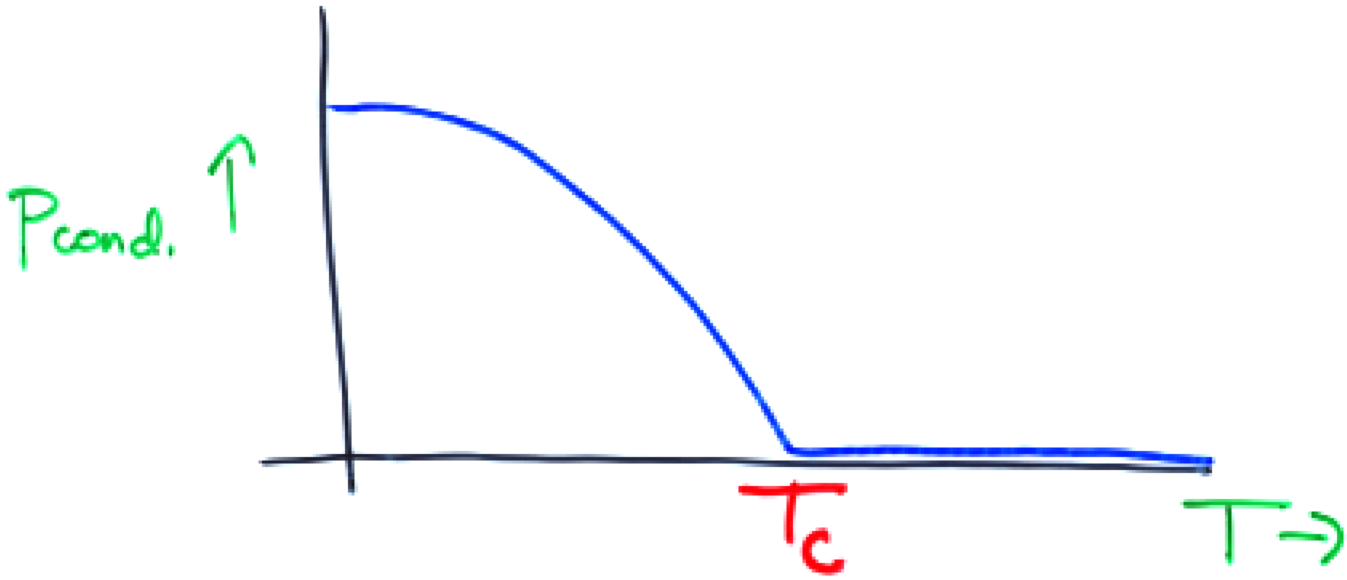
in real time ?

"Usual" Broken Symmetry

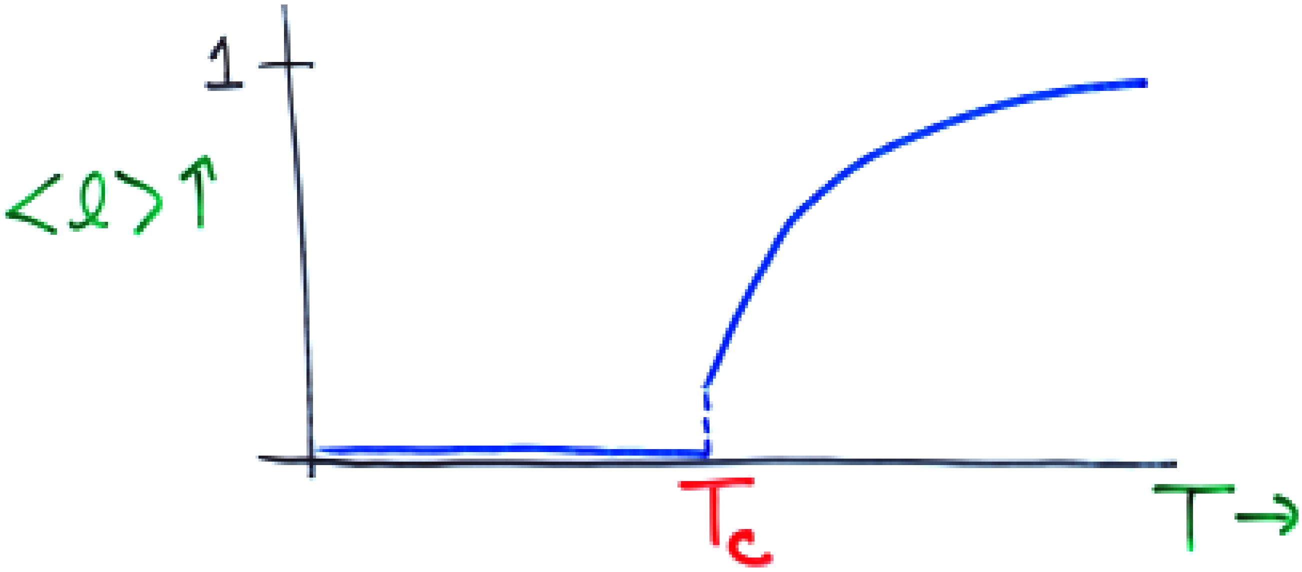


$$V = 2 b_2 \phi^2 + b_4 \phi^4$$

pressure $= -V(\phi_0) = b_2^2\, b_4$



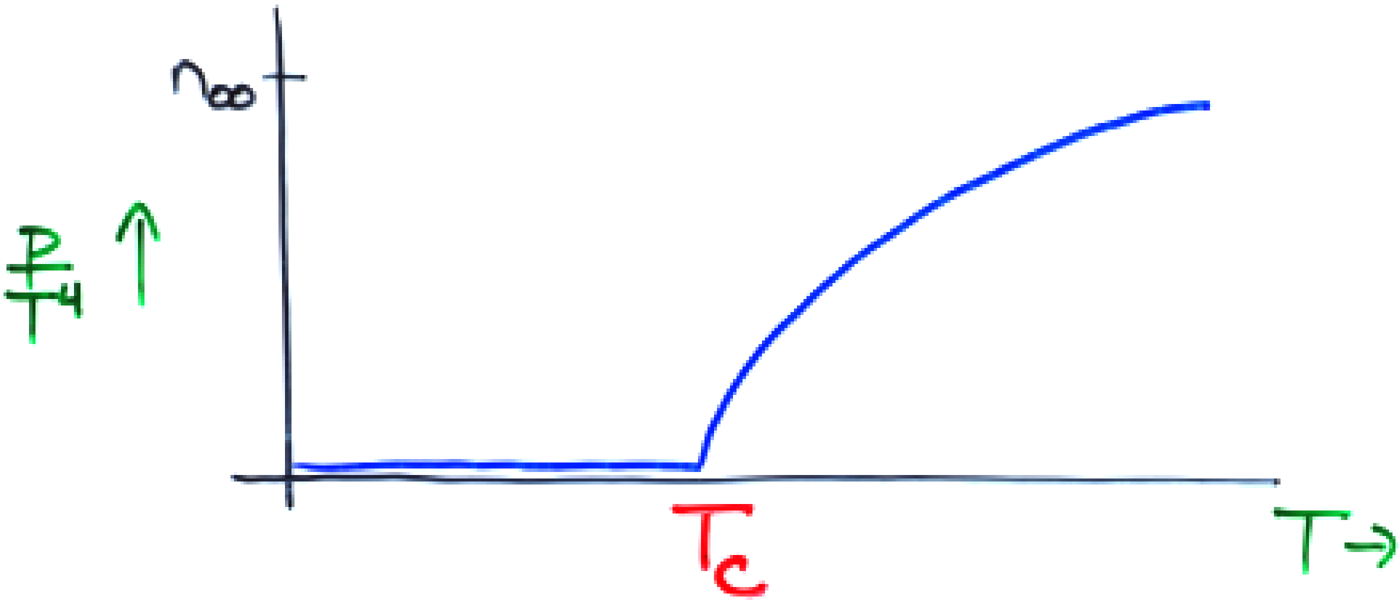
Polyakov Loops & pressure



$$V = \left(2 b_2 |\ell|^2 + (|\ell|^2)^2 \right) b_4 T^4$$

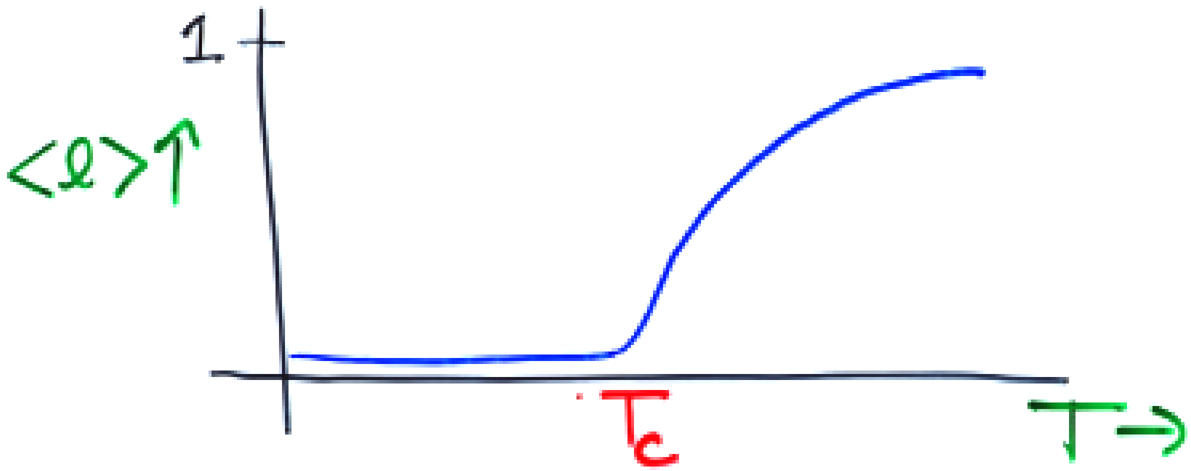
ℓ dim. less $\Rightarrow$ overall T^4 !

$+ b_3 \ell^3$: nearly 2^{nd} order $\Rightarrow$ b_3 small

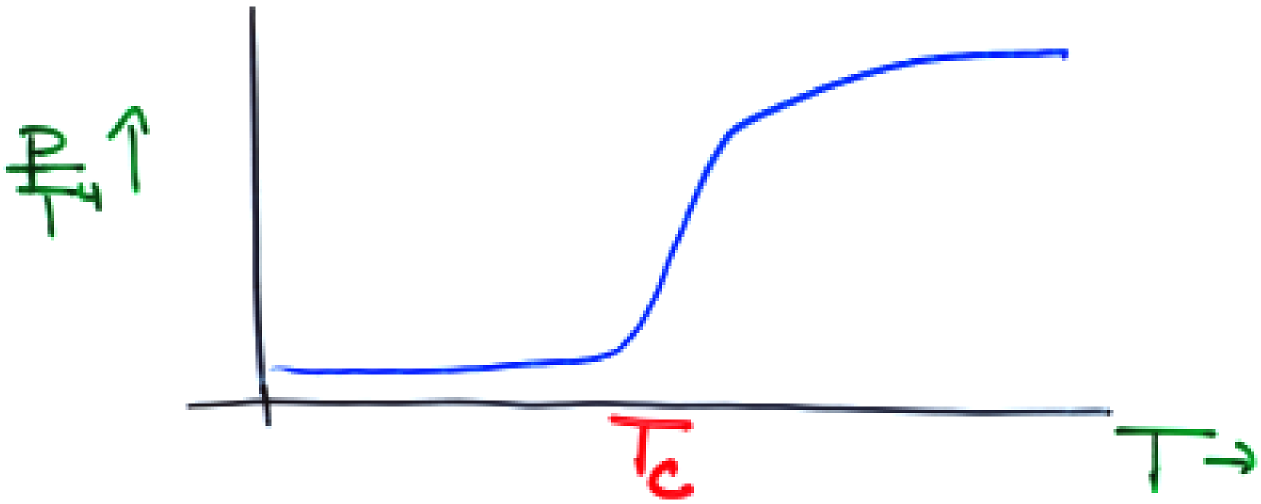


$N_f \neq 0$

$\langle \ell \rangle \neq 0 \quad \forall T$



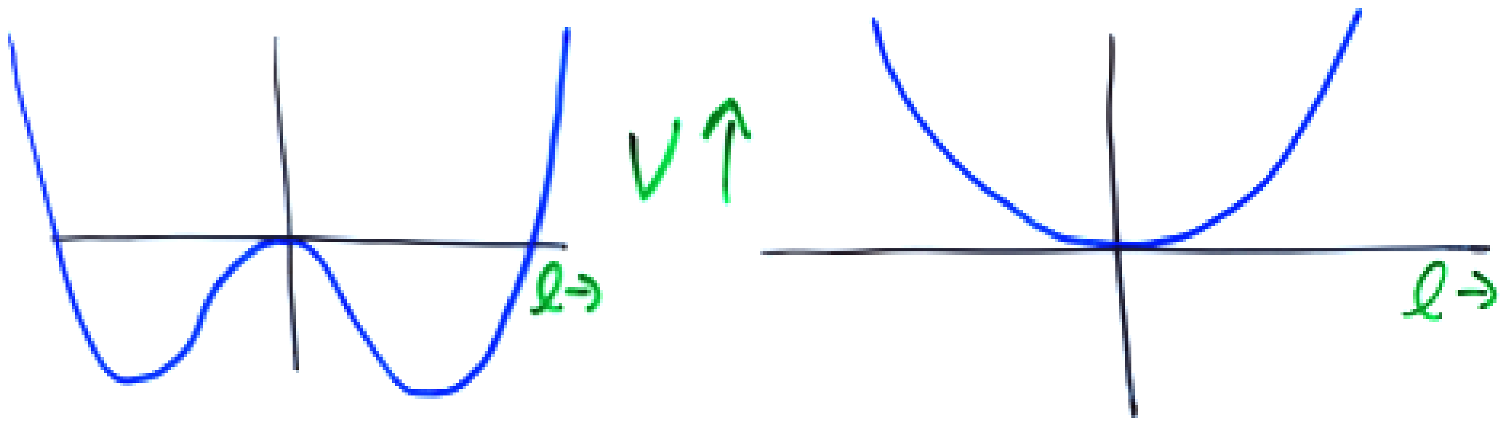
$$V = (b_1 \ell + 2b_2 |\ell|^2 + (|\ell|^2)^2)\, b_4 T^4$$
$$+ \ell^3 \ldots$$



p small @ $T < T_c \Rightarrow$ p dominated by $V(\ell)$

ξ increases by -?- 5 as $T \rightarrow T_c$

ℓ's "ringing" into π's



$T > T_c$ $\qquad\qquad$ $T < T_c$

As system cools through T_c,

$\langle \ell^2 \rangle$ fluctuates

$\Rightarrow \langle \pi^2 \rangle$ fluctuates

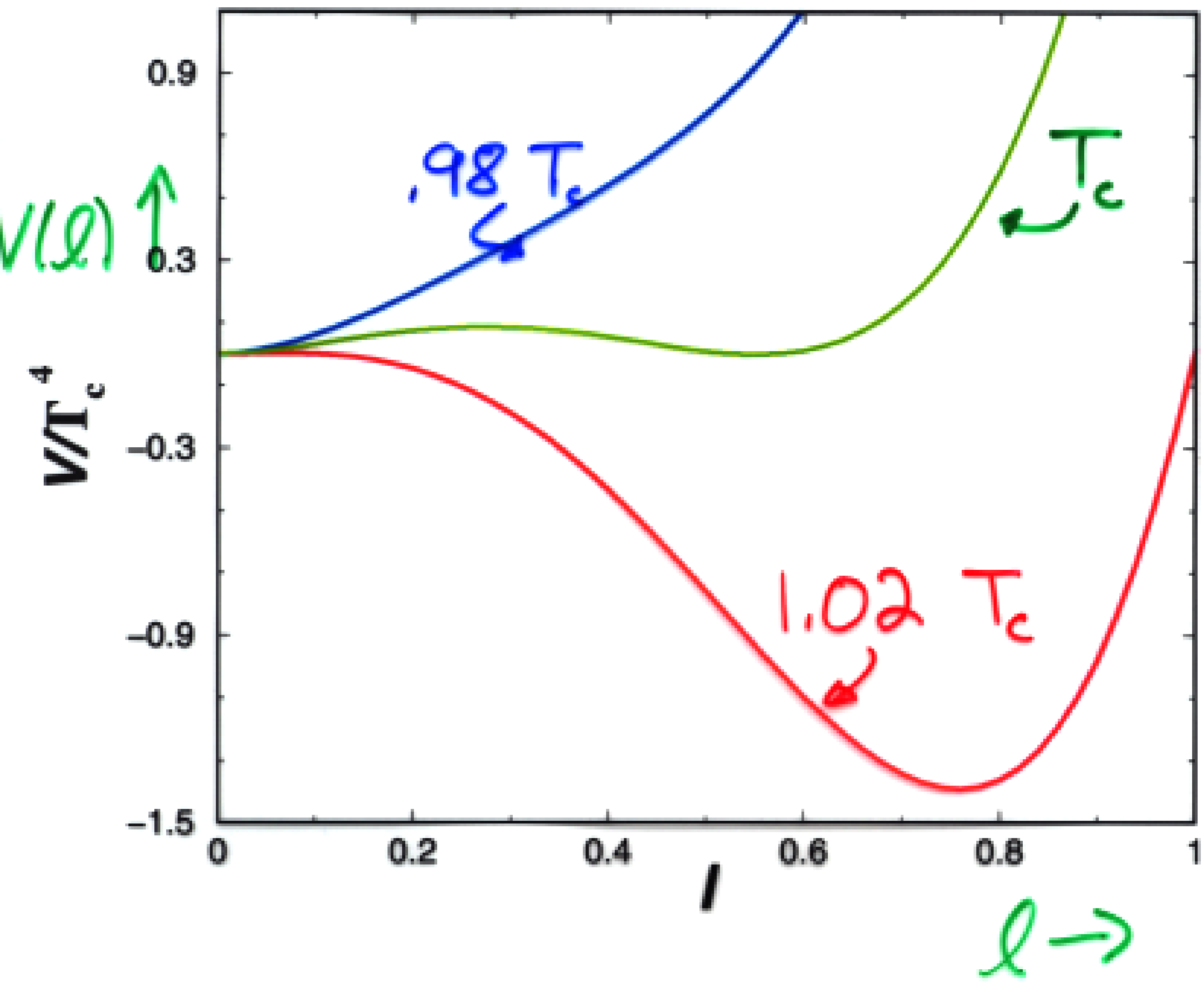
$T > T_c$: all pressure in $V(\ell)$

$\Rightarrow$ <u>BIG</u> fluctuations

Fit $V(\ell)$ to pressure

Rapid change in V near T_c

$\Rightarrow$ "quench" good approx.



ℓ's & π's

$$\mathcal{L}_\ell = \underbrace{\frac{3}{g^2}}\, T^2 \, |\partial_\mu \ell|^2 - V(\ell)$$

$= \text{coeff.} \ \operatorname{tr} |D_i L|^2$

coeff. $|\partial_i \ell|^2$? $|\partial_0 \ell|^2$?

$\mathcal{L}_\phi$ = linear σ-model, $\phi = (\sigma, \vec{\pi})$

$N_f = 2$, $m_\pi \neq 0$

$$\mathcal{L}_{\ell\phi} = -\frac{h^2}{2} T^2 \phi^2 |\ell|^2$$

h : $m_\pi (T > T_c)$, Gavai & Gupta
hep-lat/0004011

Solve classically $\bar{c}$
Hartree approx.

(Analysis)
Just like DCC's
Rajagopal & Wilczek

In one "domain" of ℓ,

big fluc's in ℓ

$\Rightarrow$ big fluc's in $E_\pi \sim 10\%$!

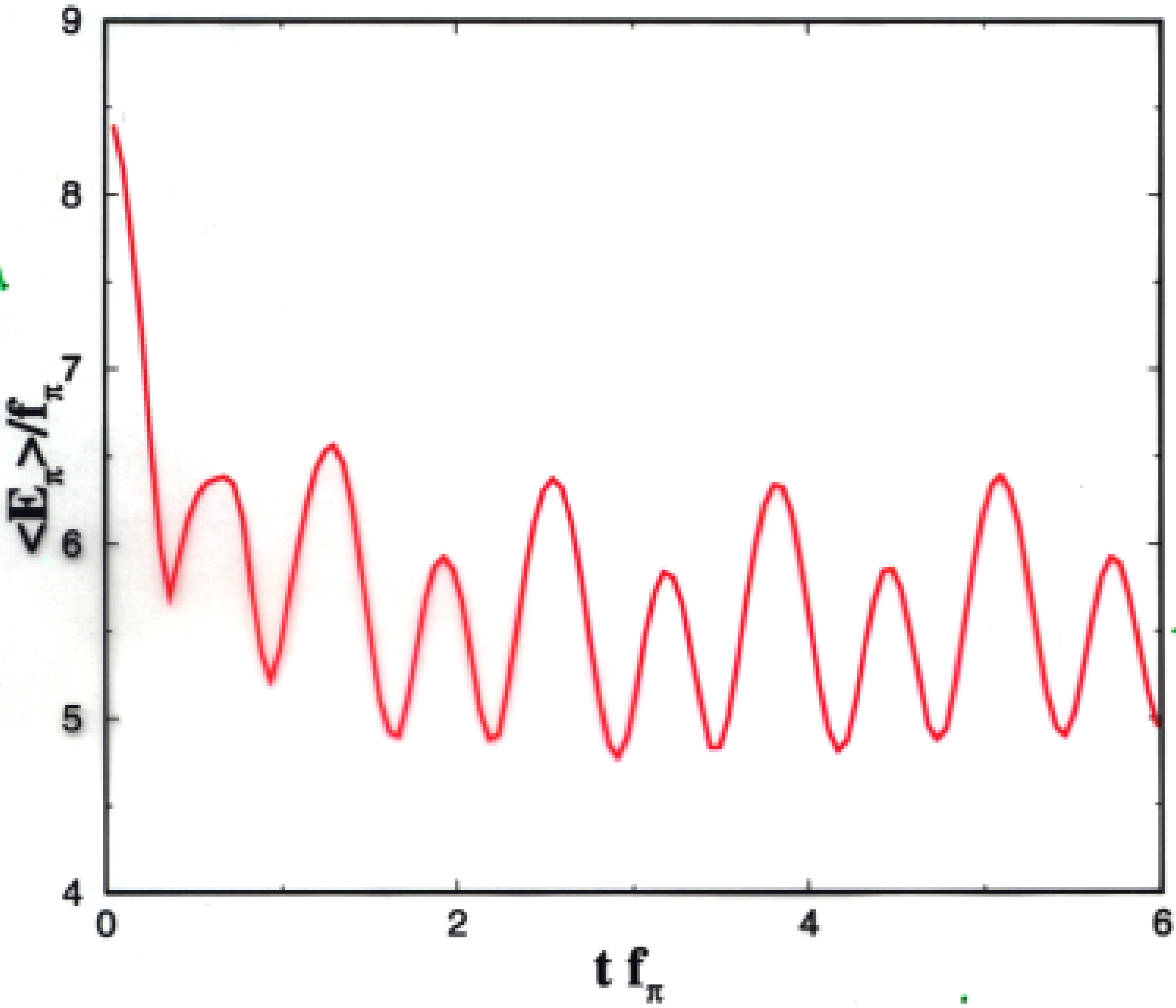
here: fluc's in $\langle p_t \rangle$ for "most"

= <u>hard</u> π's, K's . . .

critical end-point   Rajagopal, Shuryak, & Stephanov

fluc's for <u>soft</u> π's

$\frac{E_\pi}{f_\pi} \uparrow$



~ 500 MeV

time $\rightarrow$

Event by event fluc.'s

Only "domains" < ξ_e casually connected

Nearly 2nd order trans.

$\Rightarrow \xi_e \sim 1$ fm @ T_c "big"

fluc.'s in $p_t \sim \dfrac{10\% \text{ in } 1 \text{ "domain"}}{\sqrt{\# \text{ "domains"}}}$

300 / unit rapidity?

$\simeq$ .6 %

~~Measurable~~ Measured?

N.B. : want small bins in rapidity, angle

vs. statistics

vs centrality ?