“Generalized” bag models for the QCD pressure

Models for the pressure in QCD in hydrodynamics:

$T > T_c$: (semi) ideal gas plus MIT bag constant.

$T < T_c$: hadron resonance gas

2007: Lattice results with dynamical quarks *not* near continuum limit.

Today: try to extract *general* properties with *simple* models

Suggest:

$T > 1.1\ T_c$: “generalized bag model”

T: $0.9\ T_c$ to $1.1\ T_c$: *nearly* critical region

$T < 0.9\ T_c$: hadron resonance gas

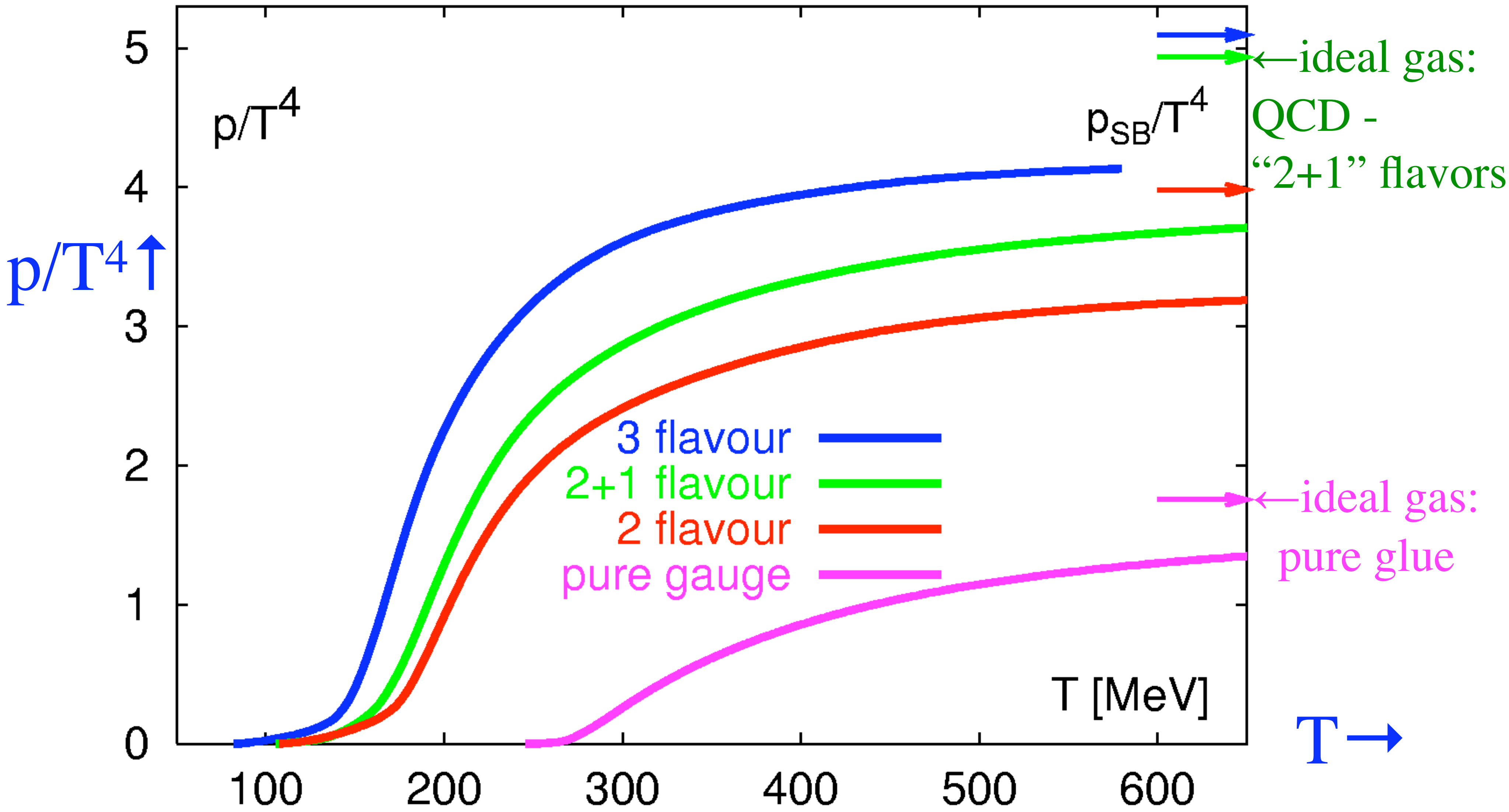
Lattice: pressure with, and without, quarks

Adding quarks, ideal gas value increases by ~ 3.

"T_c" decreases. Today: ~ 190 ± ? MeV Not 1st order, *crossover.*

Pressure nonzero < T_c : from pions, kaons..., masses ~ T_c

Pressure within 20% of ideal by ~ 3 × T_c. Curves *seem* very different

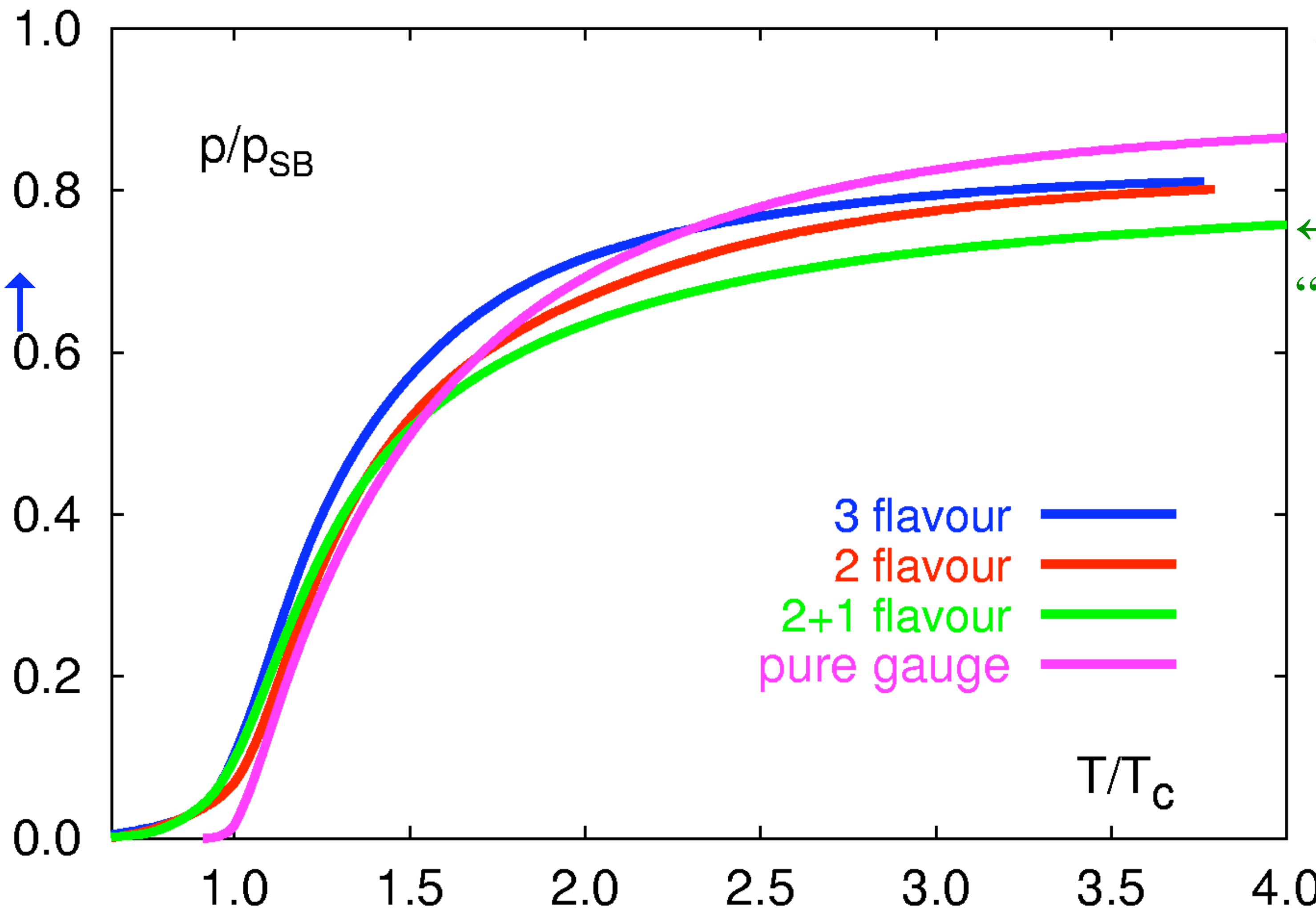


“Flavor independence”

Bielefeld: scale p by p_{ideal}, T by T_c: *nearly* univeral form for pressure

Not exact, approximate. Now concentrate on the differences.

$\frac{p(T)}{p_{ideal}(T)}$ ↑



← 1.0

← QCD: “2+1” flavors

T/T_c →

Some elementary thermodynamics

Let e(T) = energy, p(T) = pressure

$$\frac{e-3p}{T^4} = T \frac{\partial}{\partial T} \, \frac{p(T)}{T^4}$$

e - 3p = trace of energy momentum tensor.

Measures deviation from conformally symmetric limit.

More prosaically: if

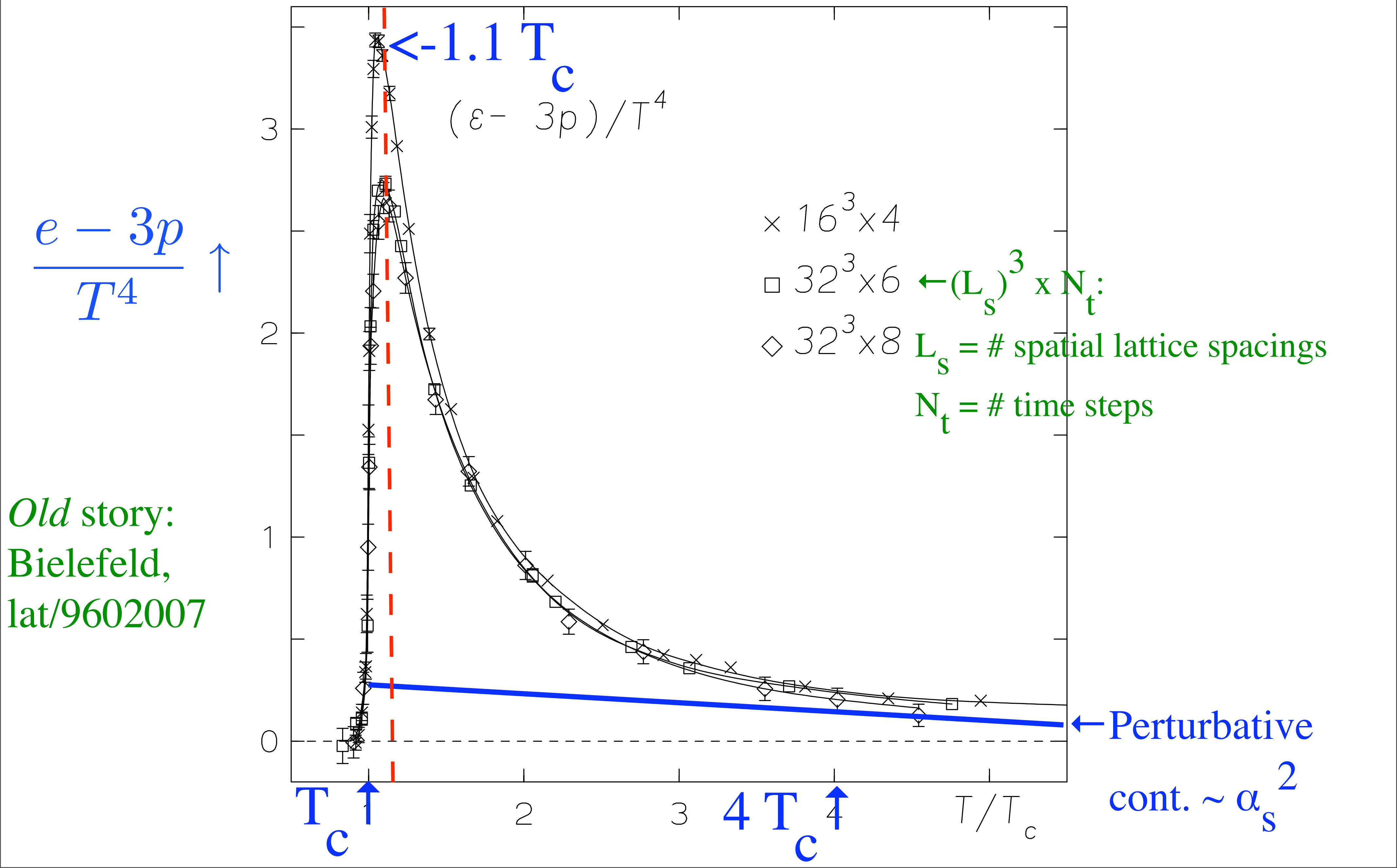
$$p(T) = c_4 T^4 + c_2 T^2 + c_0 + \ldots$$

for constant c_4, c_2, c_0, (e-3p)/T^4 "strips" off T^4 term, leaving *non*-ideal terms:

$$\frac{e-3p}{T^4} \times T^2 = -2\, c_2 - 4\, \frac{c_0}{T^2} + \ldots$$

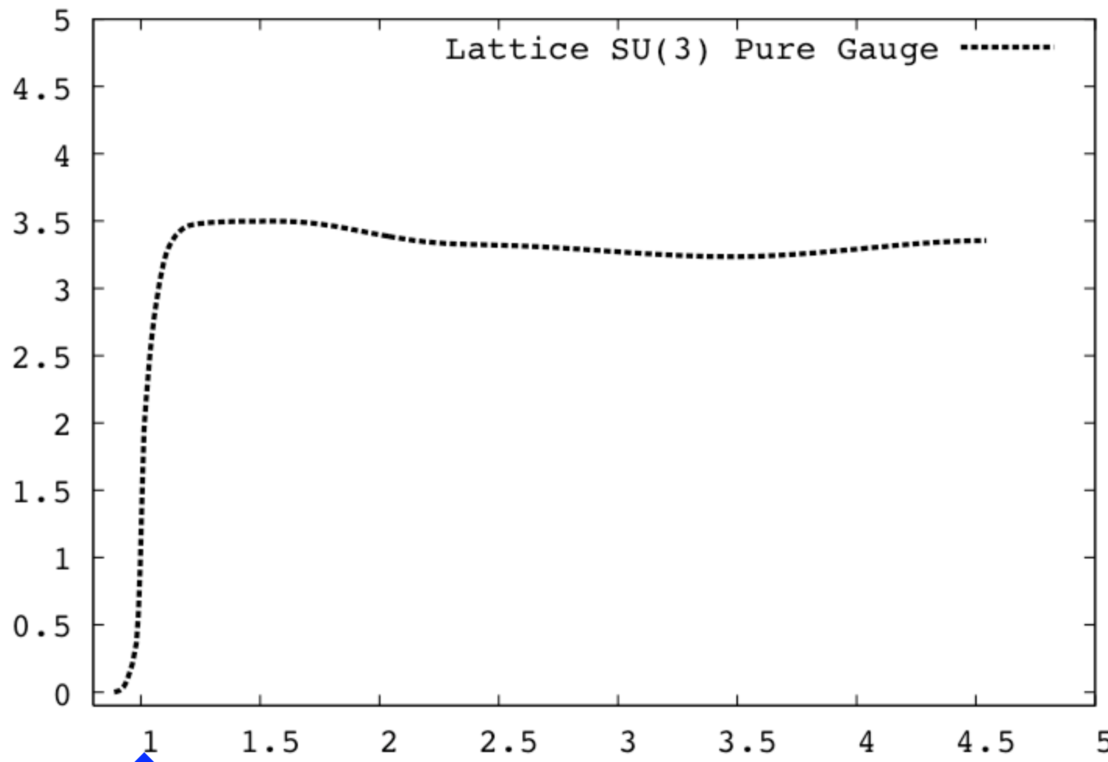
Lattice: *pure* SU(3) glue, *no* quarks

Pure glue: N_t = # time steps. Claim: N_t = 6,8 *close* to continuum limit



“Fuzzy” bag picture

$$\frac{e-3p}{T^4} \times T^2 \uparrow$$



$T/T_c \rightarrow$

$T_c \uparrow$ $4\,T_c \uparrow$

For T: 1.1 T_c to 4.0 T_c, pressure sum of just T^4 and T^2 terms!
Since pressure vanishes at T_c, know constant in front of T^2 term:

$$p(T) \approx f_{pert}\left(T^4 - T_c^2\, T^2\right)$$

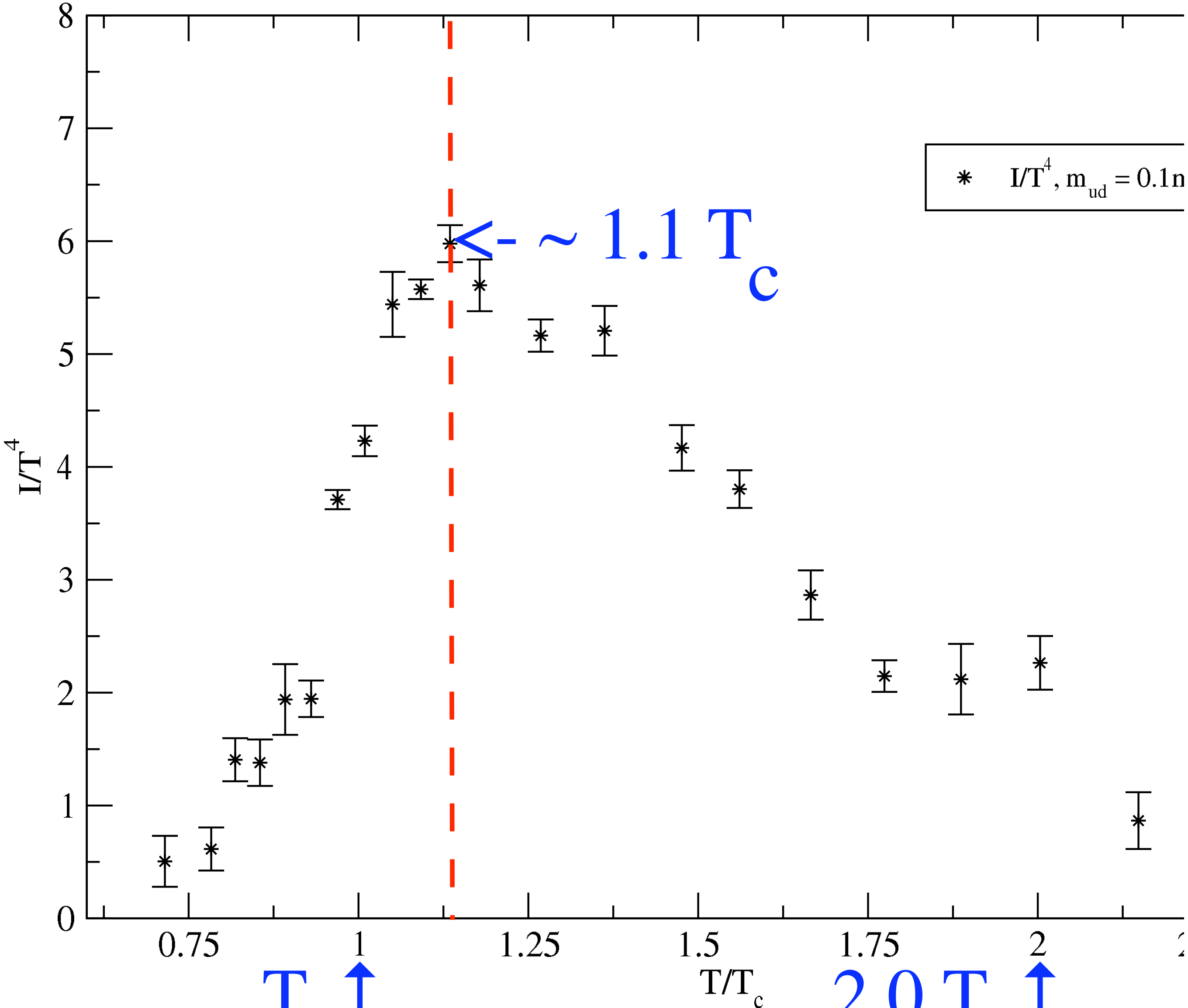
f_{pert} ~ constant, T: 1.1 T_c to 4.0 T. For f_{pert} , weak coupling resummations of perturbation theory work down to T_c

Lattice: SU(3) glue *with* quarks

From MILC collaboration: L. Lefkova, private comm.

Peak in (e-3p)/T^4 at ~ 1.1 T_c. *Much* broader peak, both above and below T_c.

$$\frac{e-3p}{T^4} \uparrow$$

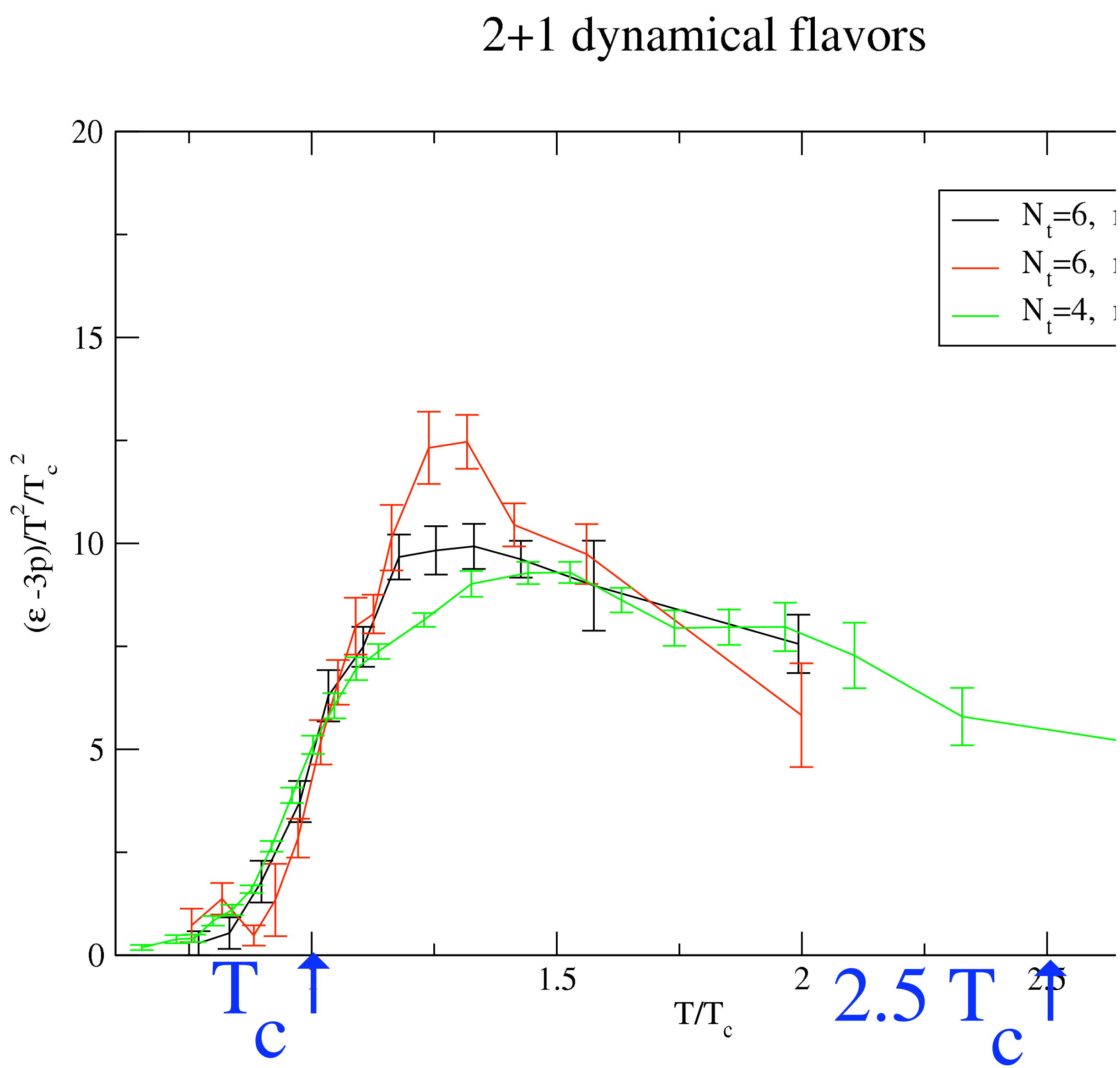


$T/T_c \rightarrow$

$T_c \uparrow$ 2.0 $T_c \uparrow$

Lattice: SU(3) glue *with* quarks

$$\frac{e-3p}{T^4} \times T^2 \uparrow$$



T/T_c →

Not just T² term in pressure: also “MIT” bag term.

“Generalized” bag model

Above maximum in (e-3p)/T^4: $T > \sim 1.1\ T_c$

pressure = T^4 times powers series in $1/T^2$:

$$p(T) = f_{pert}\, T^4 - B_{fuzzy}\, T^2 - B_{MIT} + \ldots$$

B_{fuzzy} “fuzzy” bag constant: dominates MIT bag constant, B_{MIT}, away from T_c

Resummations of perturbation theory contribute only to $f_{pert}(g^2)$:
should work down to T_c without difficulty.

Perturbation theory fails because of *non*-perturbative terms, powers in $1/T^2$.

For hydro.: corrections to ideality are not $1/T^4$, as in MIT bag model, but $1/T^2$.

Does it matter much? Maybe not. But it *is* what the lattice shows.

“Critical” region: T: 0.9 T_c -> 1.1 T_c

What about *below* peak in $(e-3p)/T^4$? Say, T: 0.9 T_c -> 1.1 T_c.

While $(e-3p)/T^4$ is big, in absolute terms, the pressure (p/T^4) is *small*.

For pure glue, *one* light mode about T_c: Polyakov loop.

For QCD, at least *four* light modes:

Polyakov loop

4 modes for chiral symmetry restoration: sigma, + 3 pi’s.

Light eta? (if axial U(1) restored)

Suggestion: model with one light mode (+ heavy modes to avoid transitions)

Vary how light mass gets: will change minimum in speed of sound at T_c.

Will change hydro. results dramatically.