(Quark) gluon plasma off equilibrium

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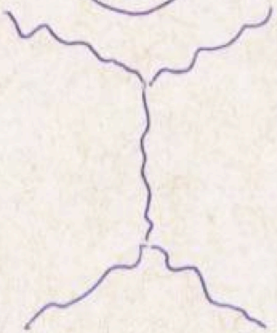
--- RANP, Rio de Janeiro, September 2013 ---

equilibration: Boltzmann eqn $\boxed{Df = C[f]}$

α^2



$\Delta n = 0$

α^3

$\Delta n \neq 0$

$f_{ini} \xrightarrow[\text{evolution}]{\text{non-lin}} f_{fin}$ KNOWN

$$f_{ini} \longrightarrow f_{eq} = \left(e^{\frac{\omega_k - \mu}{T}} - 1\right)^{-1} + \underbrace{\delta(\vec{k})\, n_c}_{\text{CONDENSATE}}$$

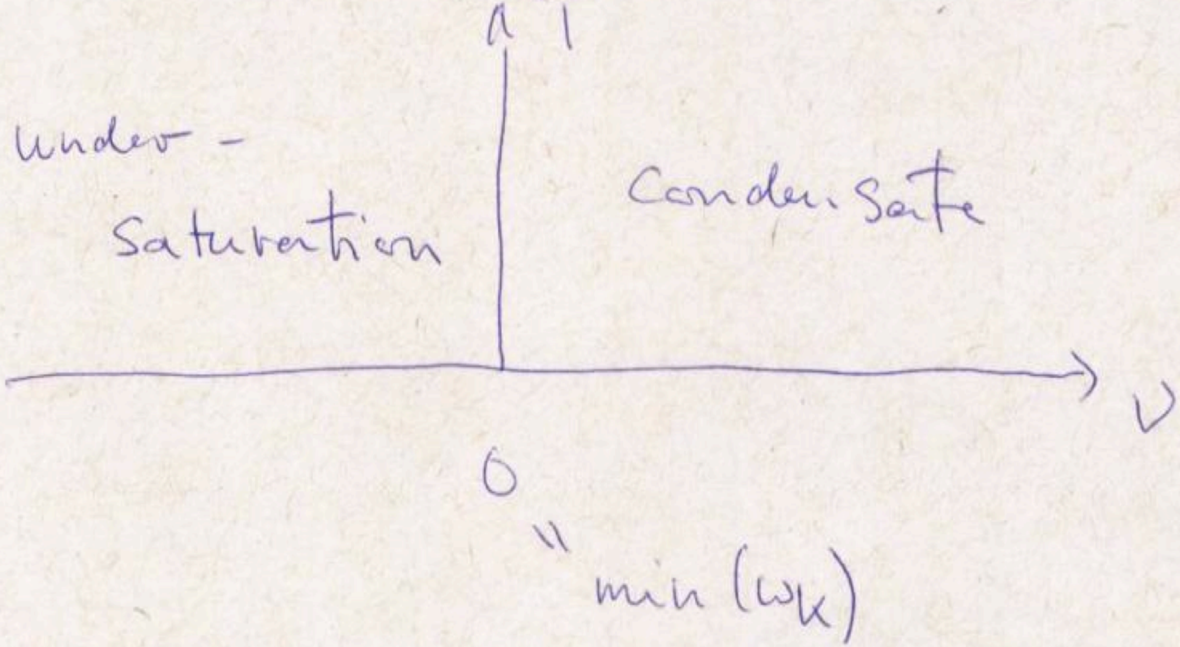
eq. params : $T, \underbrace{\mu \leq \min(\omega_k),\ n_c}$

$$\nu = \begin{cases} \mu \\ n_c^{1/3} \end{cases}$$

conservation of energy & particle number

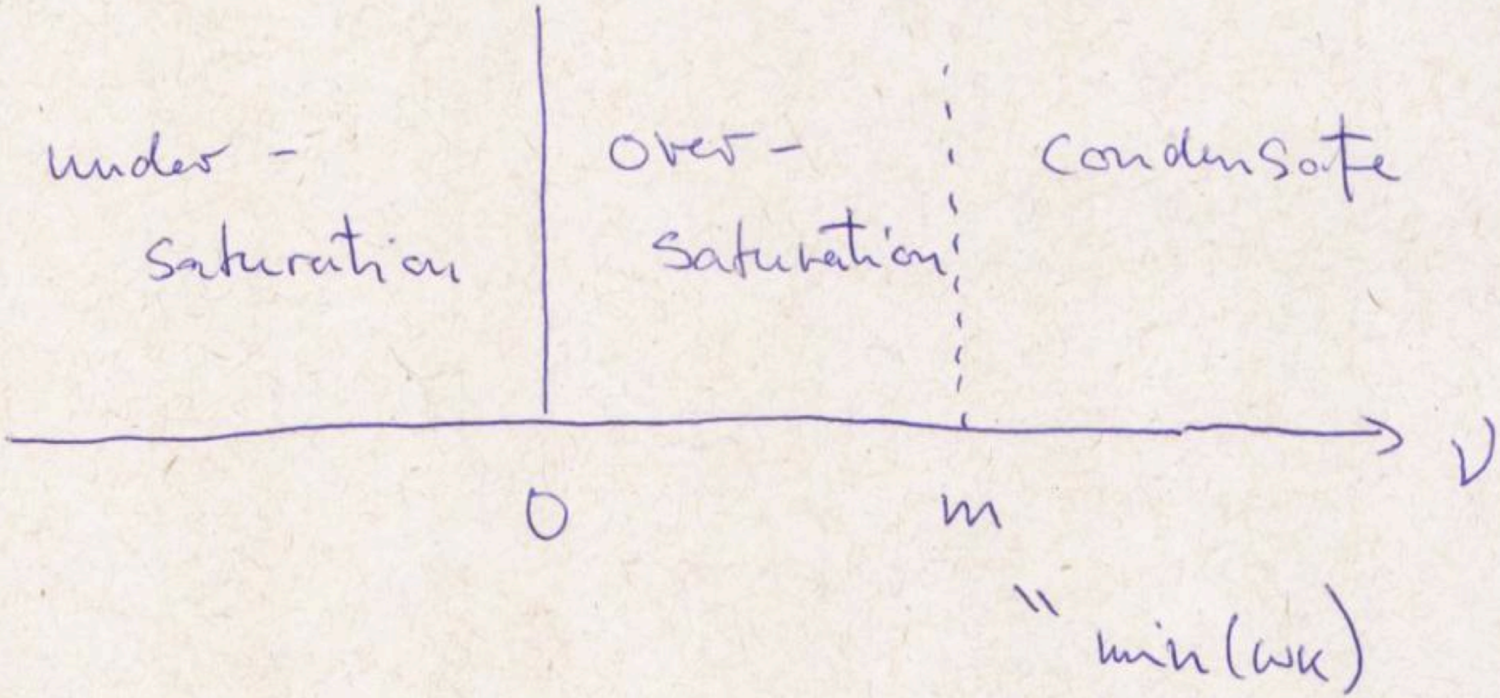
$$\left.\begin{aligned} e[f_{ini}] &= e_{eq}(T, \nu) \\ n[f_{ini}] &= n_{eq}(T, \nu) \end{aligned}\right\} \quad T, \nu$$

phase diagram $\omega_k = k$



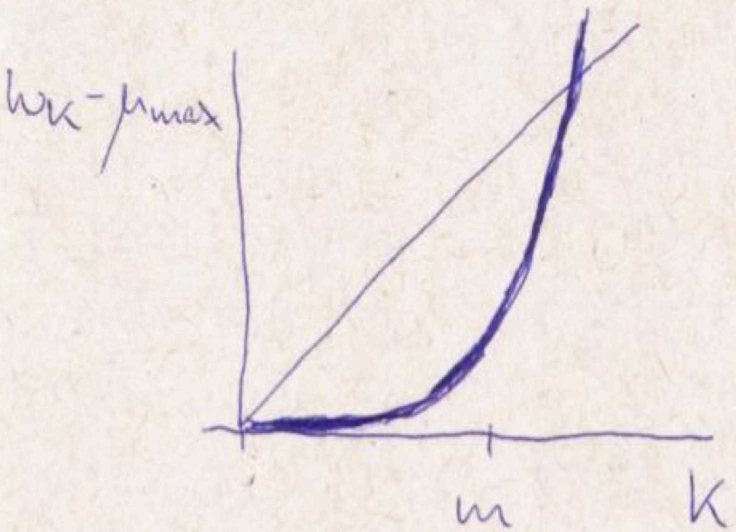
(Self-) interaction 

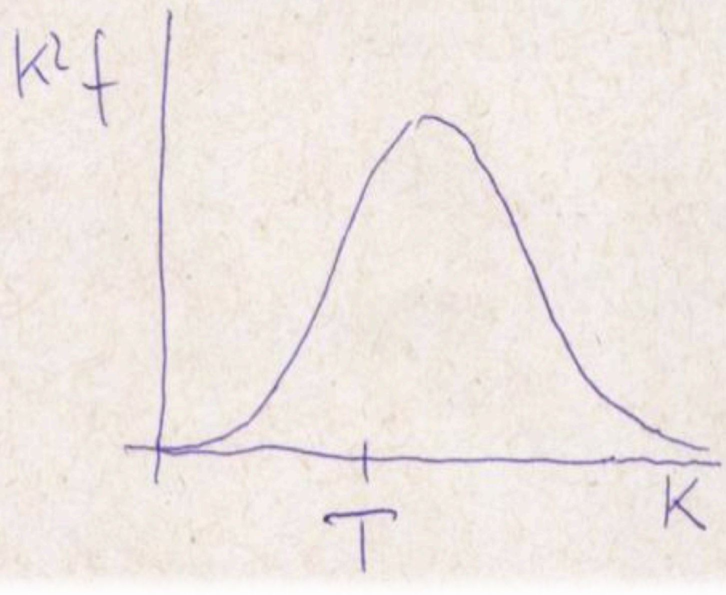
$$m \sim gT \quad (\text{at } \mu = 0)$$



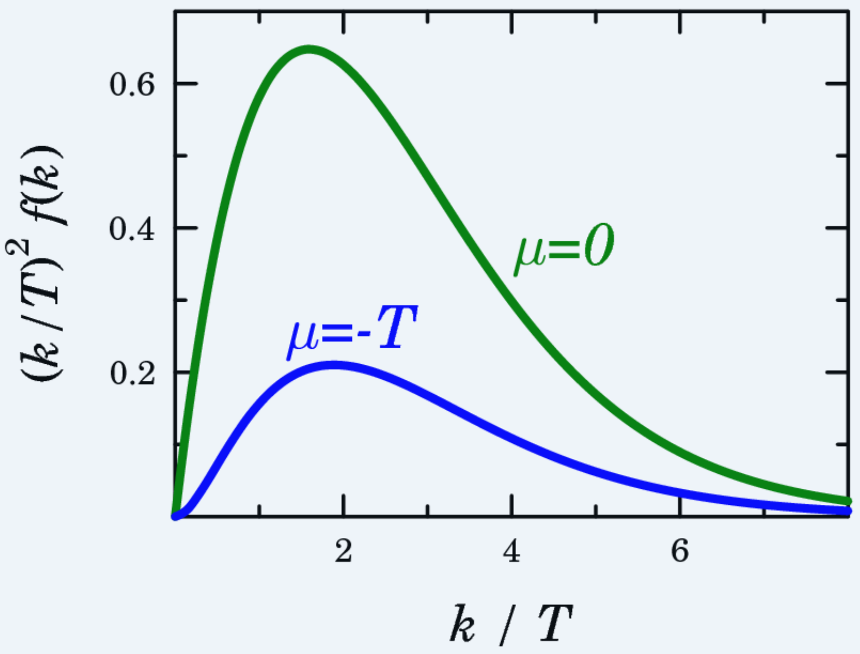
$m \sim gT$ ... Can this have a "massive effect"?

$$\omega_k - \mu_{max} = \begin{cases} k & \text{massless} \\ \sqrt{k^2+m^2} - m = \frac{k^2}{2m} + \dots & \text{massive} \end{cases}$$

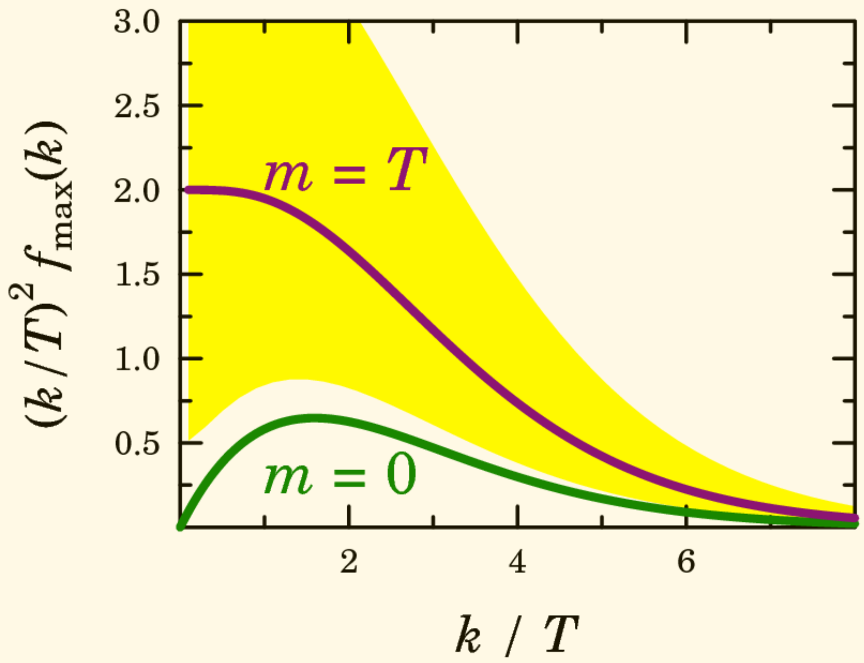




m = 0, under saturation



m > 0, over saturation



Quasiparticle model @ saturation $\nu = 0$

T-dependent QP mass $\boxed{m(T)}$

thermodynamics

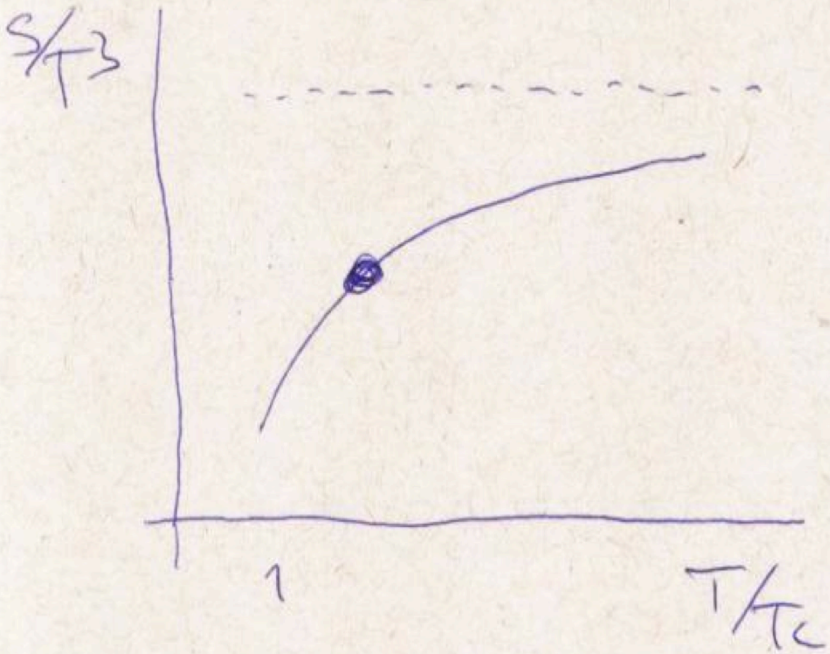
$$p(T) = p^{id}(T; m^2(T)) - \boxed{B(T)}$$

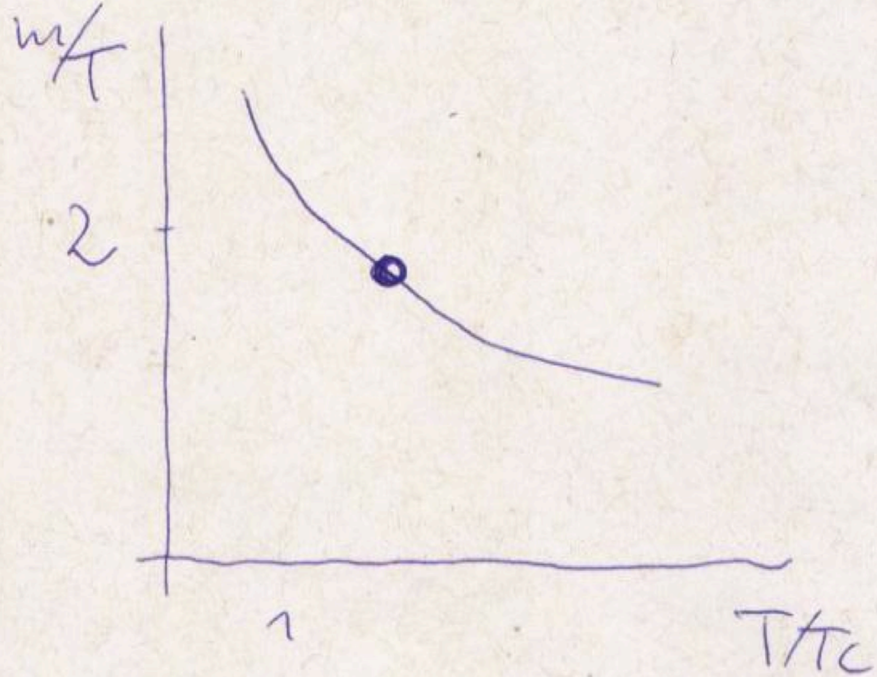
$$s(T) = \frac{\partial p}{\partial T} = \frac{\partial p^{id}}{\partial T}\Big|_m + \underbrace{\frac{\partial p^{id}}{\partial m^2}\frac{dm^2}{dT} - \frac{dB}{dT}}_{\stackrel{!}{=}\, 0}$$

$$\equiv s^{id}(T, m^2(T))$$

$$B(T) = B_0 + \int_{T_0}^{T} dT' \, \frac{\partial p^{id}}{\partial m^2}\frac{dm^2}{dT}$$

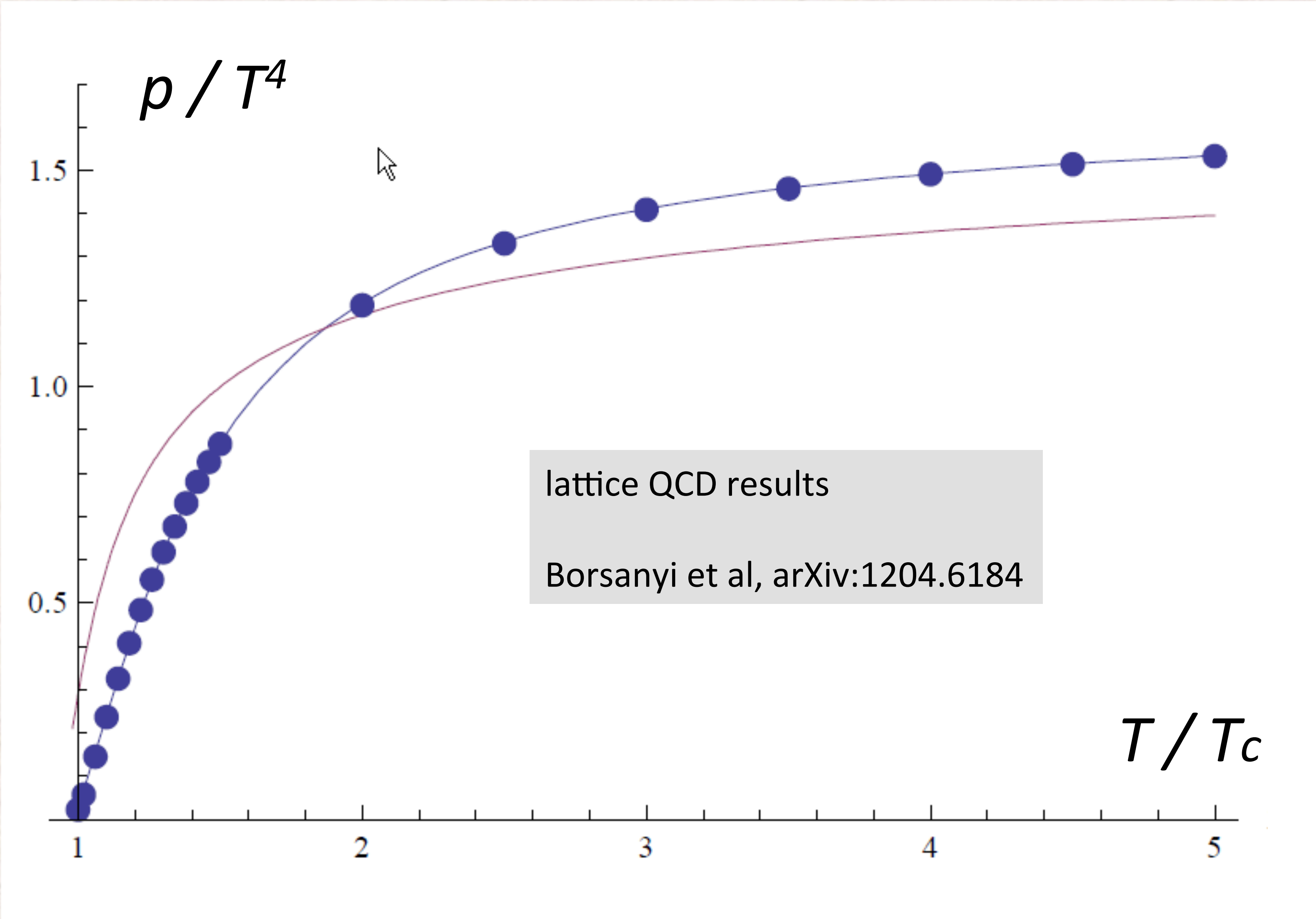
"mapping"





$$m^2(T) = \# \, \underbrace{g_{eff}^2(T)} \, T^2$$

QCD: $\sim \frac{1}{\ln T}$



p / T4
1.5
1.0
0.5
lattice QCD results
Borsanyi et al, arXiv:1204.6184
T / Tc
1
2
3
4
5

QP model off-saturation $m(T,\mu)$

$$p(T,\mu) = p^{id}(T,\mu;m^2(T,\mu)) - B(T,\mu)$$

$$s(T,\mu) = s^{id}(T,\mu;m^2(..)) + \frac{\partial p^{id}}{\partial m^2}\frac{\partial m^2}{\partial T} - \frac{\partial B}{\partial T}$$

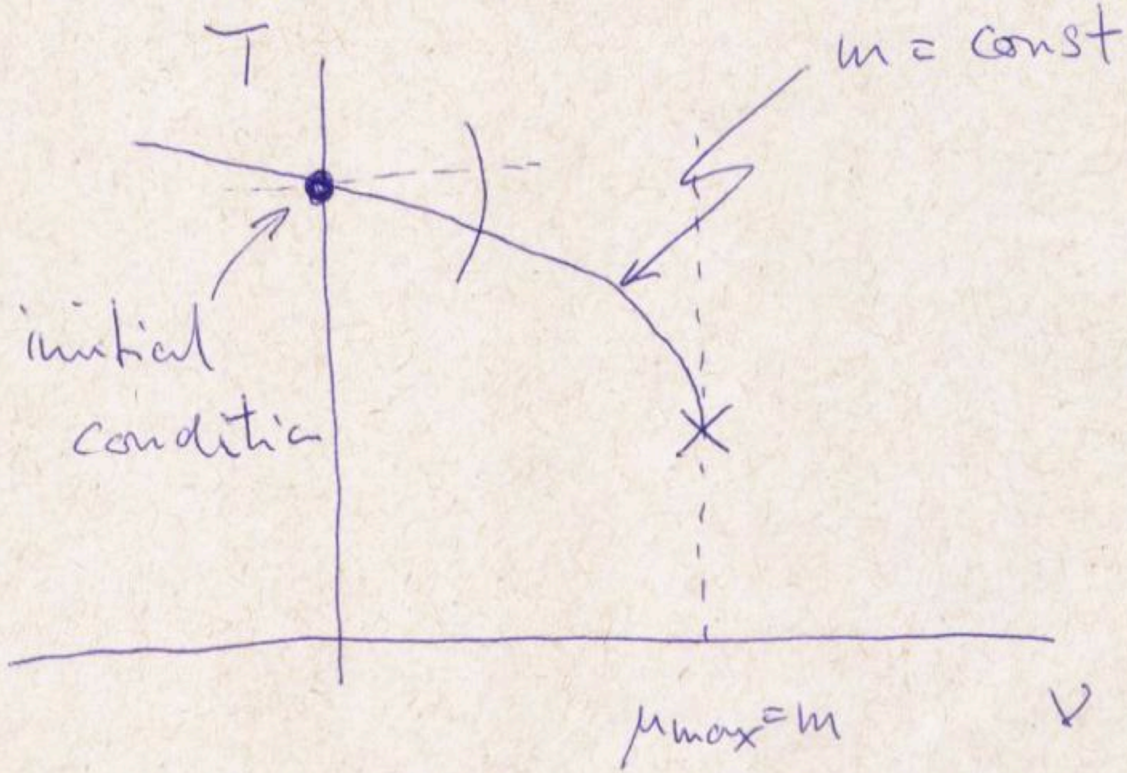
$$n(T,\mu) = n^{id}(T,\mu;m^2(..)) + \frac{\partial p^{id}}{\partial m^2}\frac{\partial m^2}{\partial \mu} - \frac{\partial B}{\partial \mu}$$

Maxwell: $\partial n/\partial T \stackrel{!}{=} \partial s/\partial \mu$

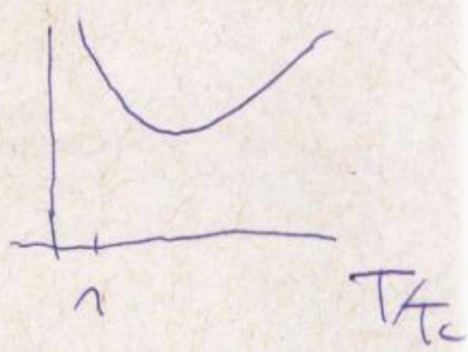
$$\boxed{\frac{\partial h}{\partial T}\frac{\partial m^2}{\partial \mu} = \frac{\partial h}{\partial \mu}\frac{\partial m^2}{\partial T}}$$ where $h = \frac{\partial p^{id}}{\partial m^2}$

flow eqn $\quad \frac{\partial m^2}{\partial \mu} + A(T, \mu, m^2) \frac{\partial m^2}{\partial T} = 0 \cdot m^2$

method of characteristics

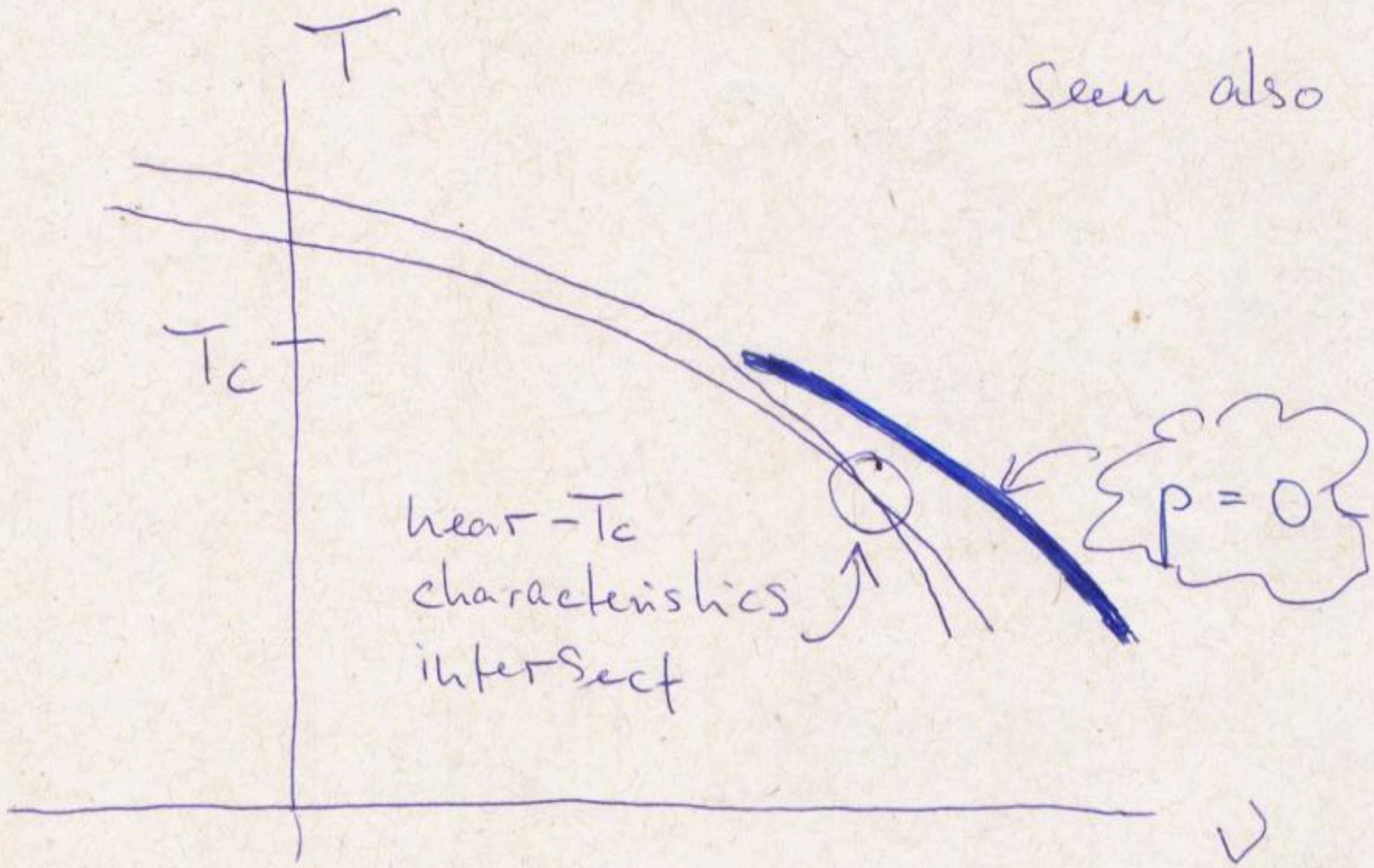


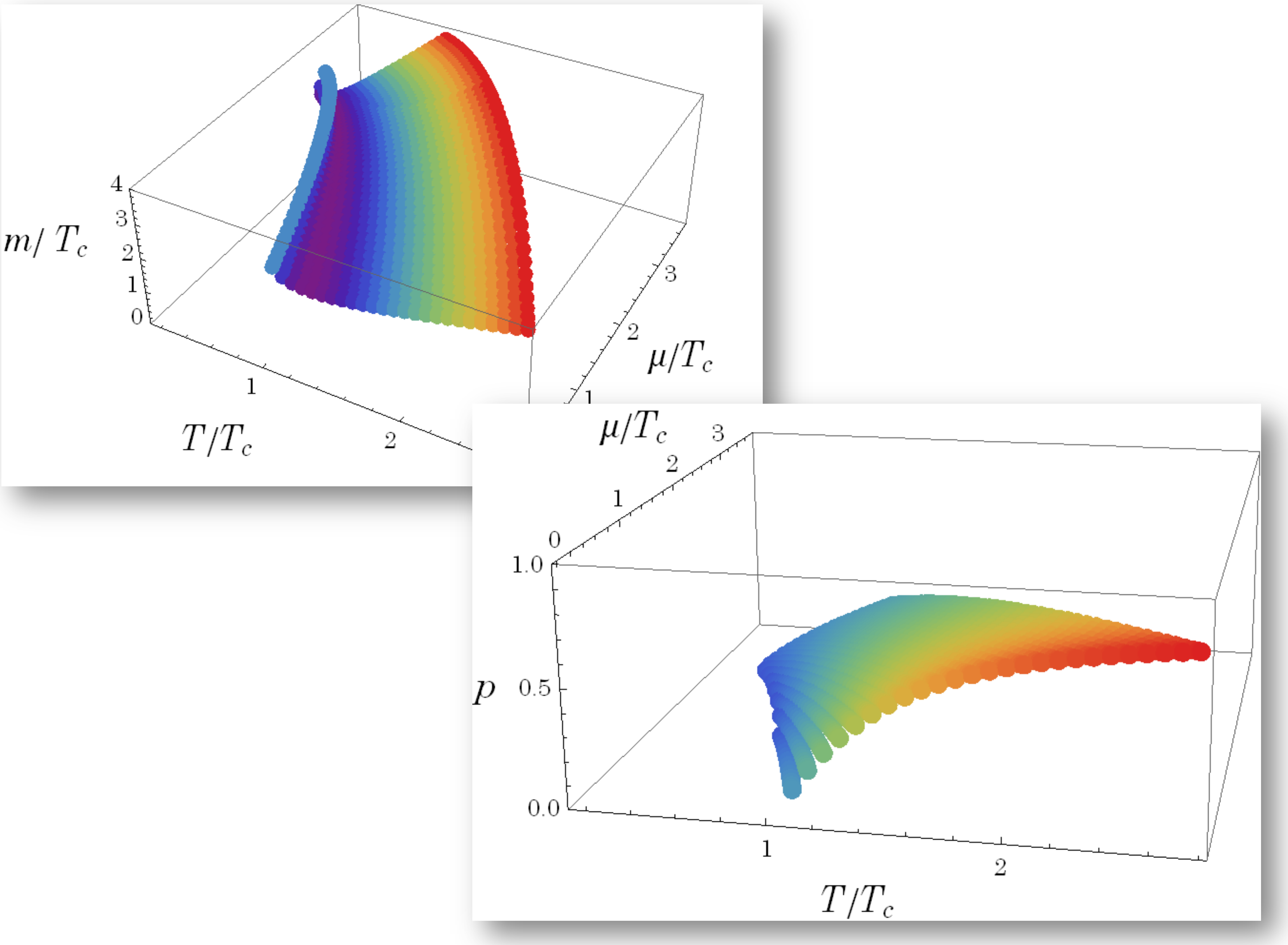
reflection of $\nu = 0$



Multivalent solution & phase stability

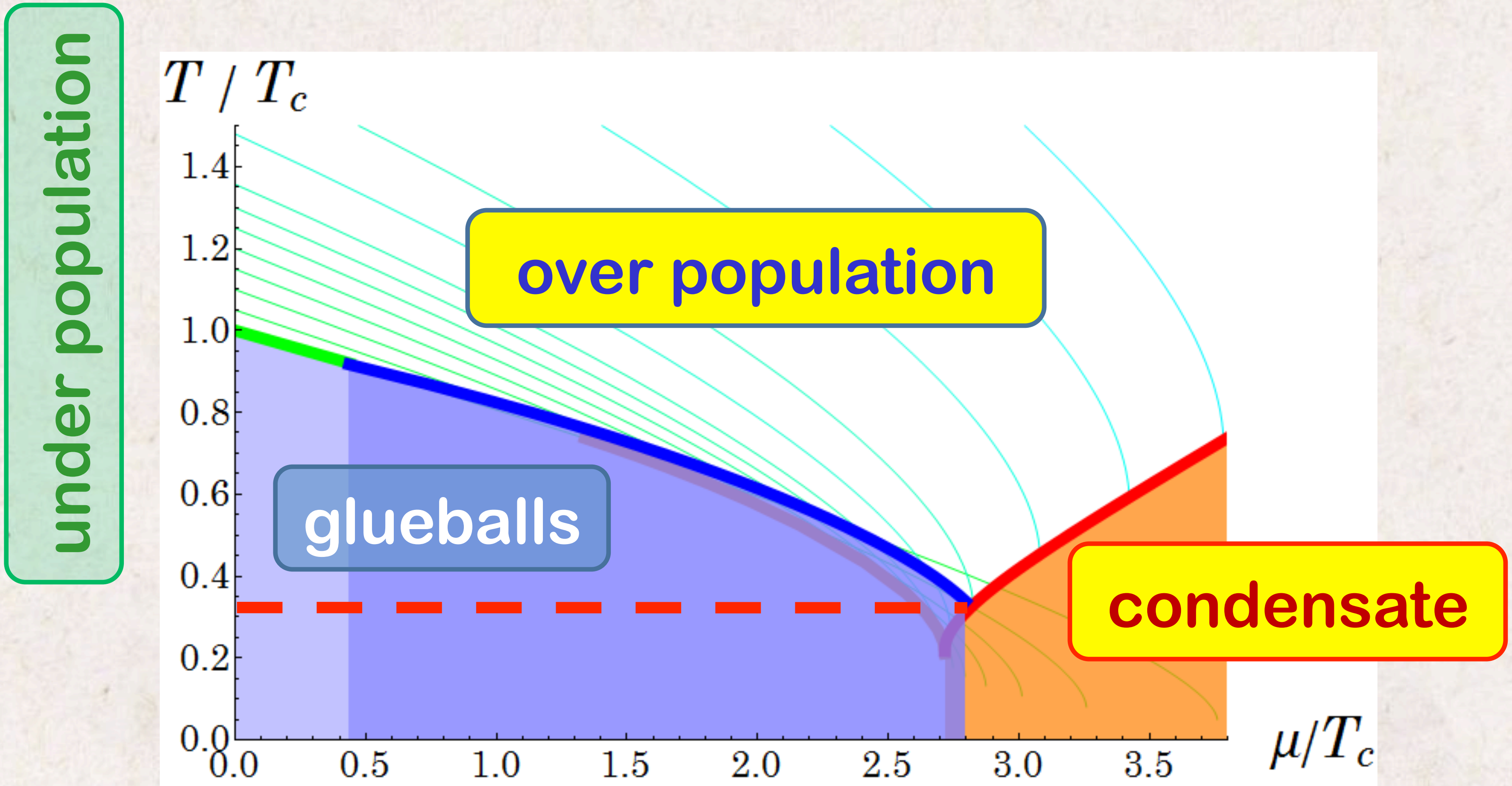
Seen also for QGP



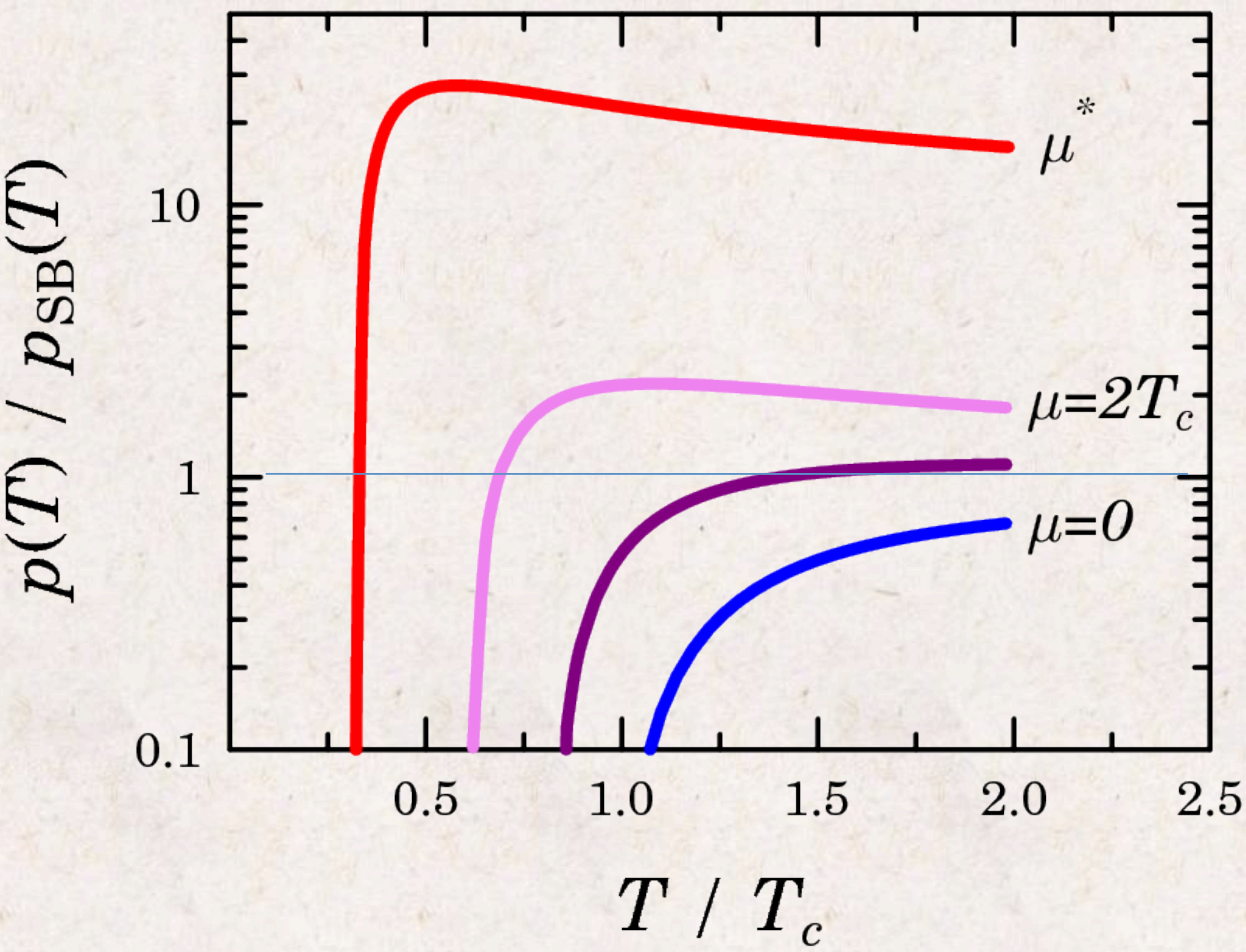


m/T_c
4
3
2
1
0
1
2
T/T_c
3
2
1
μ/T_c
μ/T_c
3
2
1
0
1.0
0.5
0.0
p
1
2
T/T_c

Phase diagram



Thermodynamics



Resumé

* (Q)GP can exist in "over populated" state far below "T_c" **over-cooling**

* pressure, energy density etc can exceed SB values by an order of magnitude

(NB: mind the assumptions)

Phase diagram