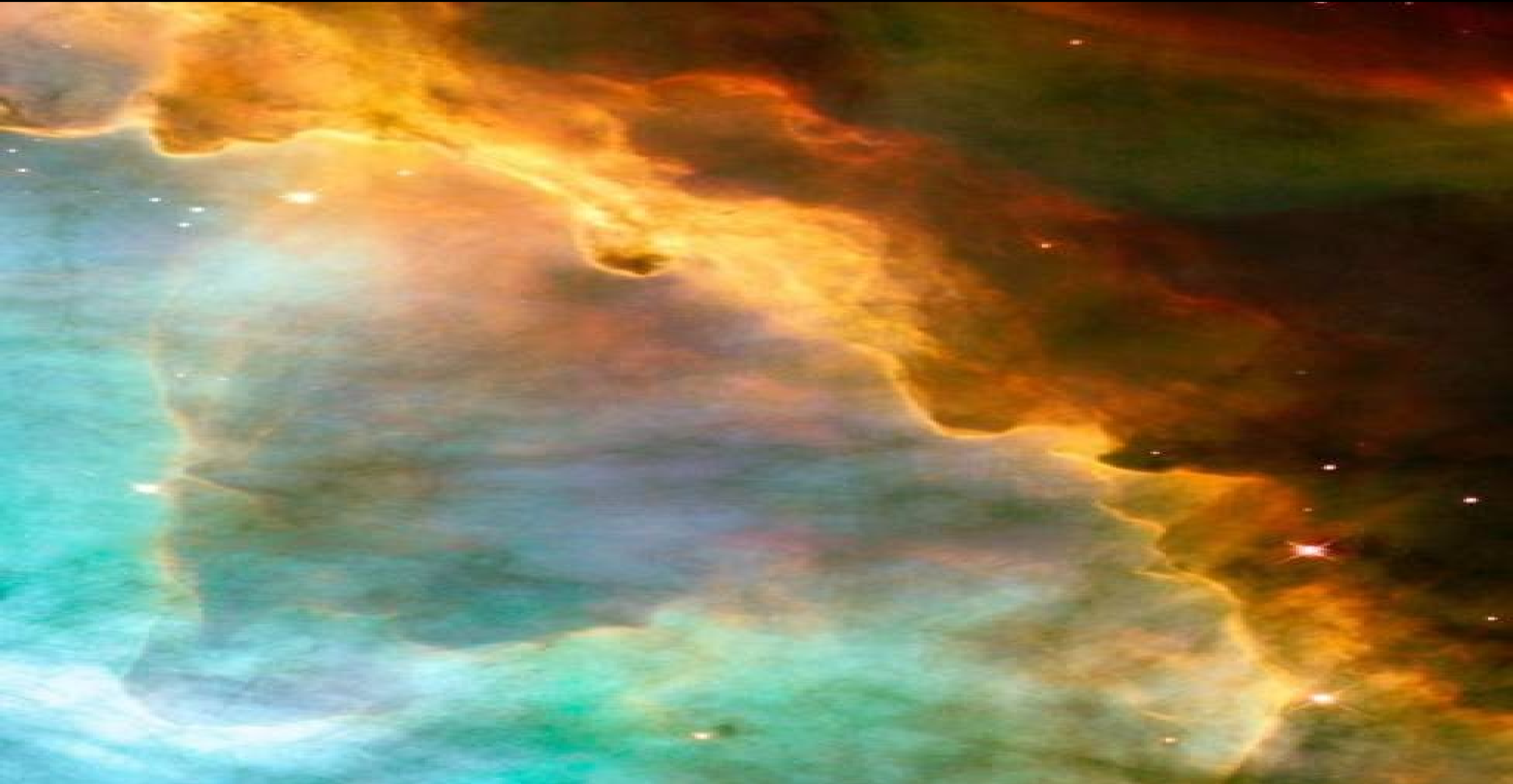
The hadronization line in stringy quark matter



Dictionary.refrence.com/search?q=stringy

- Modern Language Assciation, Random House Inc. 2008

1. Resembling a string or strings, consisiting of strings or stringlike pieces: stringy weeds; a stringy fiber
2. Coarsely or toughly fibrous, as meat
3. Sinewy or wiry, as a person
4. Ropy, as a glutinous liquid

- The American Heritage Dictionary of the English Language, Houghton Mifflin Co. 2006

1. Consisting of, resembling or containing strings or a string
2. Slender and sinewy; wiry
3. Forming strings, as a viscous liquid; ropy.

Dictionary.refrence.com/search?q=stringy

- **On-line Medical Dictionary, 1997-98 Academic Medical Publishing & CancerWEB**

1. **Consisting of strings or small thraeds; fibrous; filamentous; as a stringy root.**
2. **Capable of being drawn into a string; as a glutinous substance; ropy; viscid; gluely.**
3. Stringy bark, a name given in Australia to several trees of the genus Eucalyptus (as E. amygdalina, obliqua, capitellata, macrorhyncha, piperita, pilularis and tetradonta), which have a fibrous bark used by the aborigines for making cordage and cloth**.**

The hadronization line in stringy quark matter

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- How can be E / N = 6 T ?
- Stringy corrections to QGP
- High-T equation of state
- The zero pressure line

NFQCD Workshop, Yukawa Institute, Kyoto, February 13, 2008.


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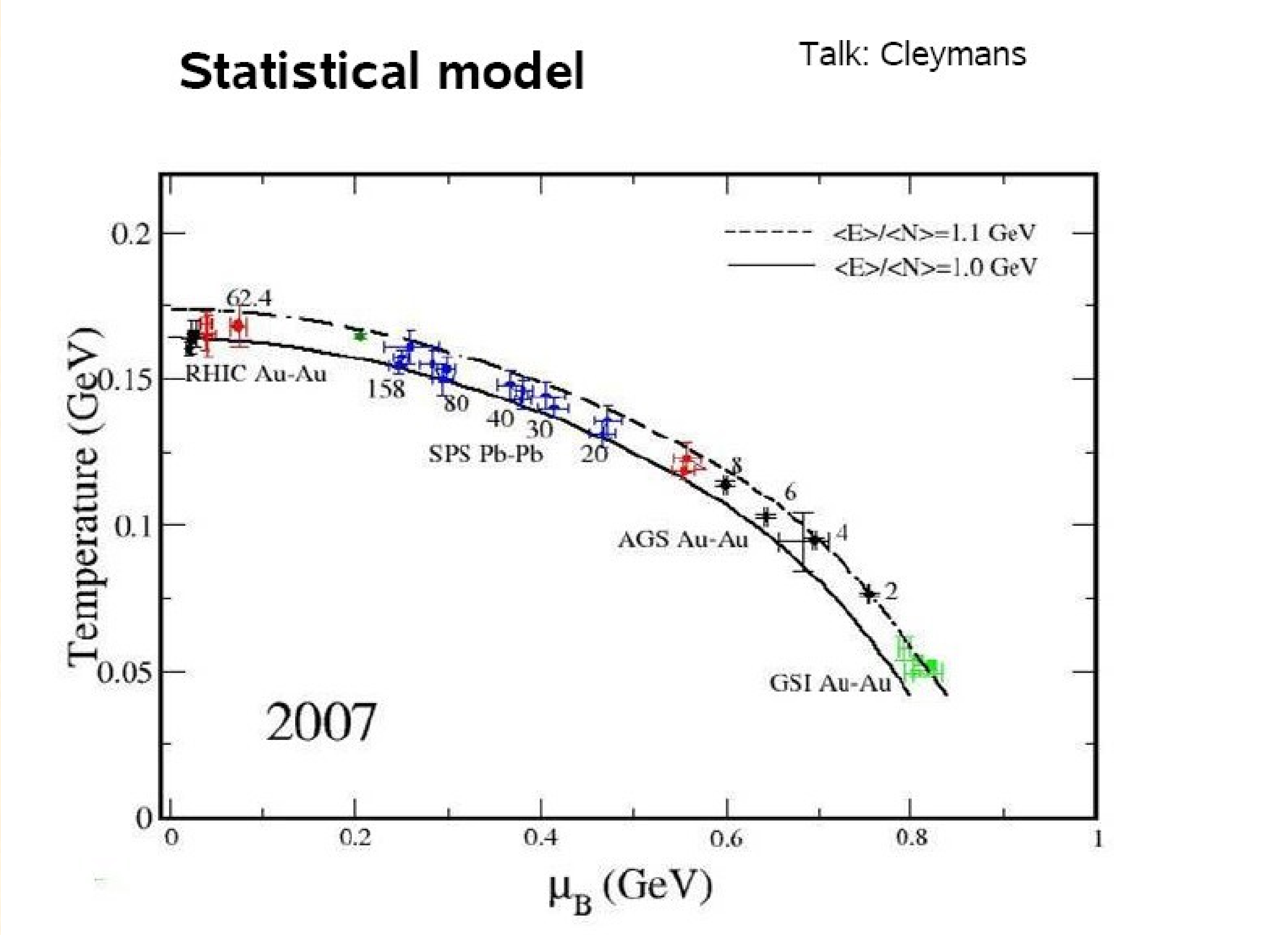
Statistical Model

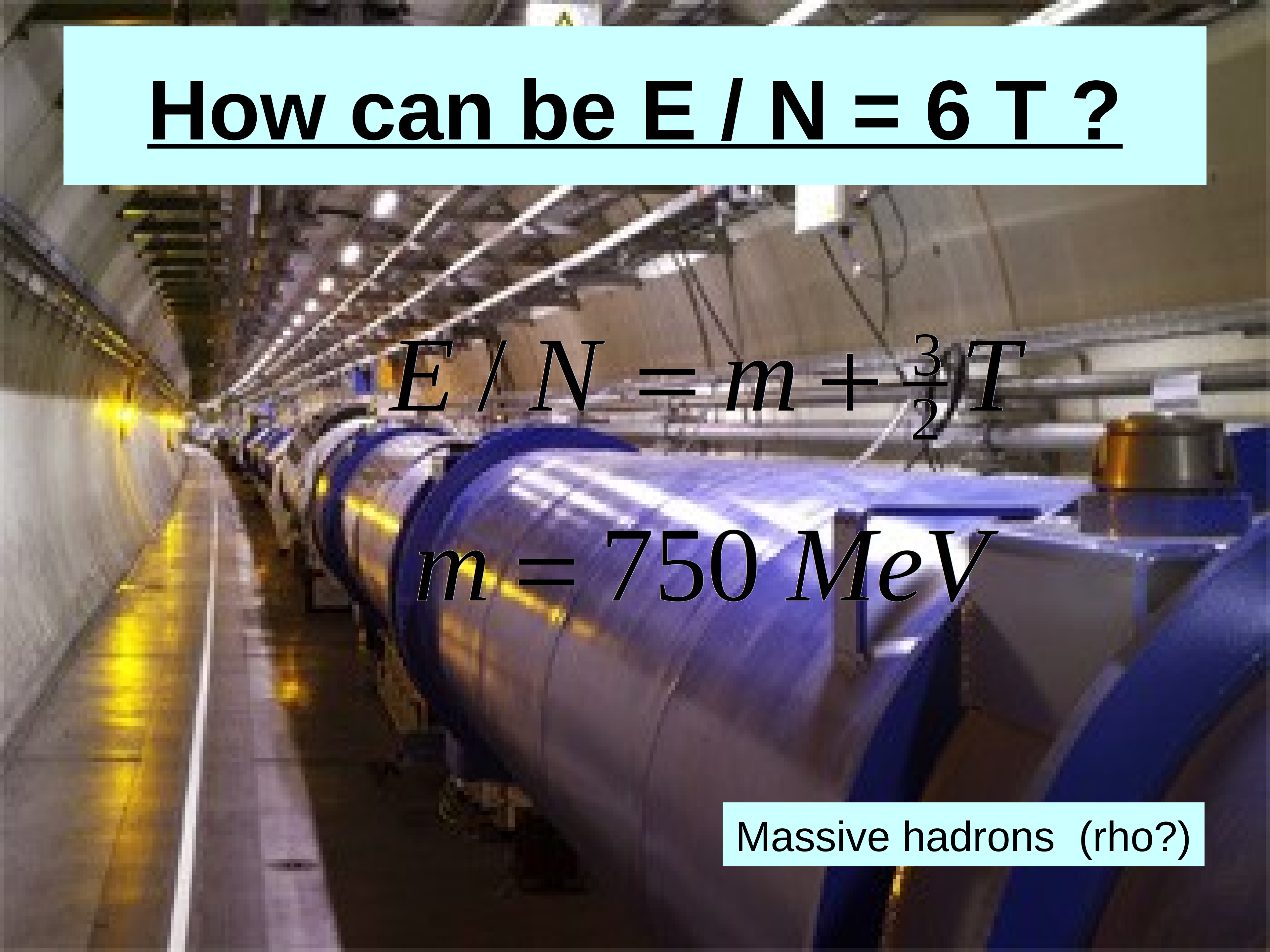


How can be E / N = 6 T ?

$$T = 167\ MeV$$

$$E / N = 1\,GeV$$

Statistical Model: hadronization point around μ = 0 (RHIC, LHC)



<u>How can be E / N = 6 T ?</u>

$$E / N = m + \frac{3}{2} T$$

$$m = 750\ MeV$$

Massive hadrons (rho?)

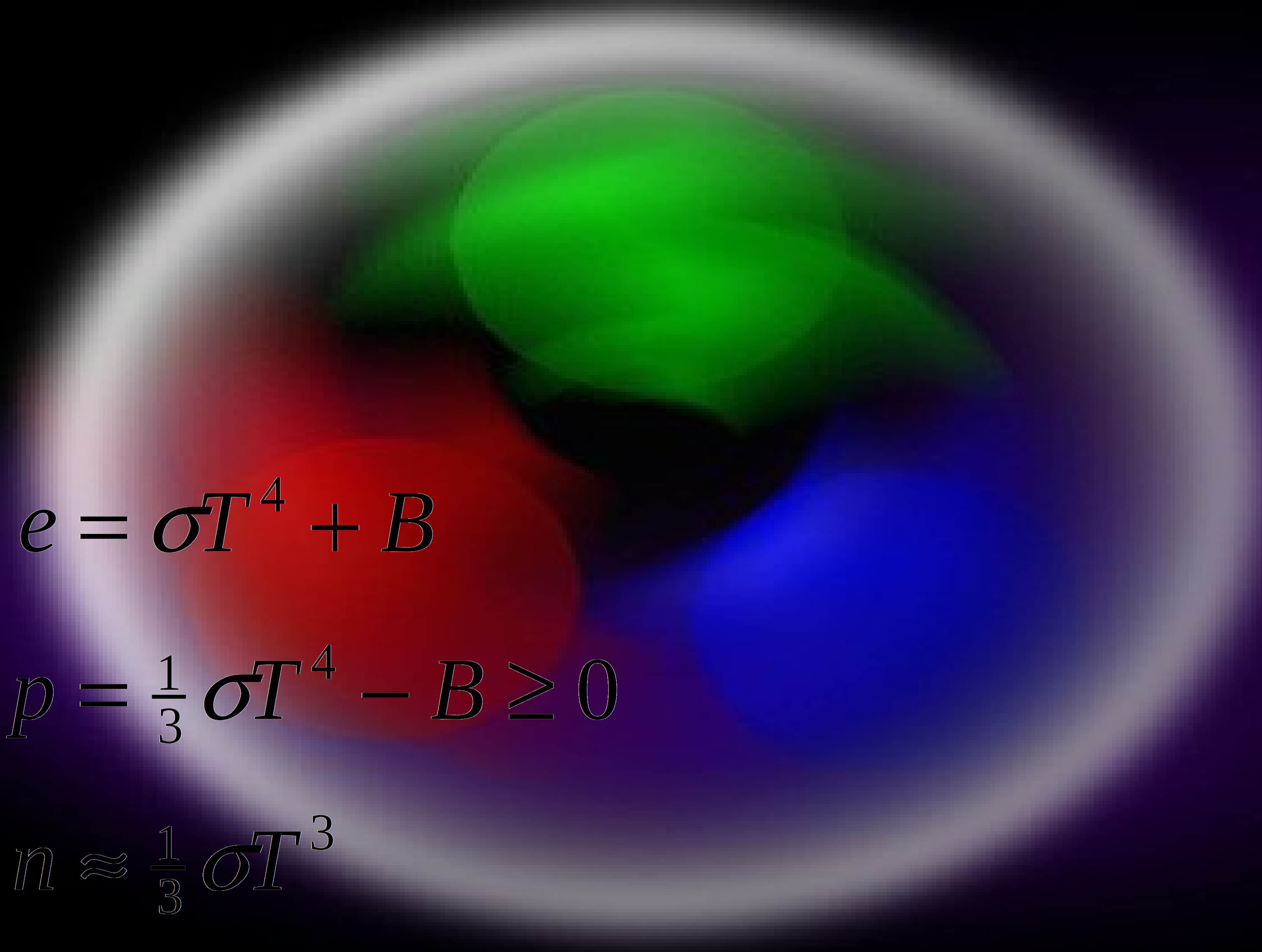
How can be E / N = 6 T ?

$$E / N = 3T$$

$$m = 0$$

Ideal gas of radiation

How can be E / N = 6 T ?



$$e = \sigma T^4 + B$$

$$p = \frac{1}{3}\sigma T^4 - B \geq 0$$

$$n \approx \frac{1}{3}\sigma T^3$$

$$E / N = e / n \leq 4T$$

Bag Model for QGP

How can be E / N = 6 T ?

Stringy Massless QGP

$$f = f_{id}(n,T) + \tfrac{3}{2} A n^{2/3}$$

$$e = e_{id} + \tfrac{3}{2} A n^{2/3}$$

$$p = p_{id} - \tfrac{1}{2} A n^{2/3}$$

$$\left.\frac{e}{n}\right|_{p=0} = \left.\frac{e_{id} + 3p_{id}}{n}\right|_{m=0} = \left.\frac{6p_{id}}{n}\right|_{\text{Boltzmann}} = 6T$$

How can be E / N = 6 T ?

Stringy Massless QGP

$$n \cdot \sigma \langle \ell \rangle = \sigma \, g \, n^{-1/3} n = \tfrac{3}{2} A n^{2/3}$$

$$f = f_{id}(n,T) + \tfrac{3}{2} A n^{2/3}$$

$$e = e_{id} + \tfrac{3}{2} A n^{2/3}$$

$$p = p_{id} - \tfrac{1}{2} A n^{2/3}$$

$$\left.\frac{e}{n}\right|_{p=0} = \left.\frac{e_{id} + 3 p_{id}}{n}\right|_{m=0} = \left.\frac{6 p_{id}}{n}\right|_{\text{Boltzmann}} = 6T$$

How can be E / N = 6 T ?

This is more generally true!

- **correction depends on**

$$c = \sum_i c_i \, n_i$$

- **constituents are massless**

$$p_{id} = T^4 \cdot \phi\left({}^{\mu_B}\!/_{T} \right)$$

- **Boltzmann approximation is acceptable**

$$p_{id} = T \cdot \sum_i n_i$$

Stringy corrections to QGP

$$c = \sum_i c_i n_i$$

color density

$$f = f_{id} + \tfrac{1}{1-\gamma} A c^{1-\gamma}$$

free energy density

fractional power

$$\mu_i = \mu_{id} + A c^{-\gamma} c_i = q_i \mu_B$$

chemical potential

$$p = p_{id} - \tfrac{\gamma}{1-\gamma} A c^{1-\gamma}$$

pressure

$$e = e_{id} + \tfrac{1}{1-\gamma} A c^{1-\gamma}$$

energy density

Stringy corrections to QGP

Consistent solution for color density in equilibrium:

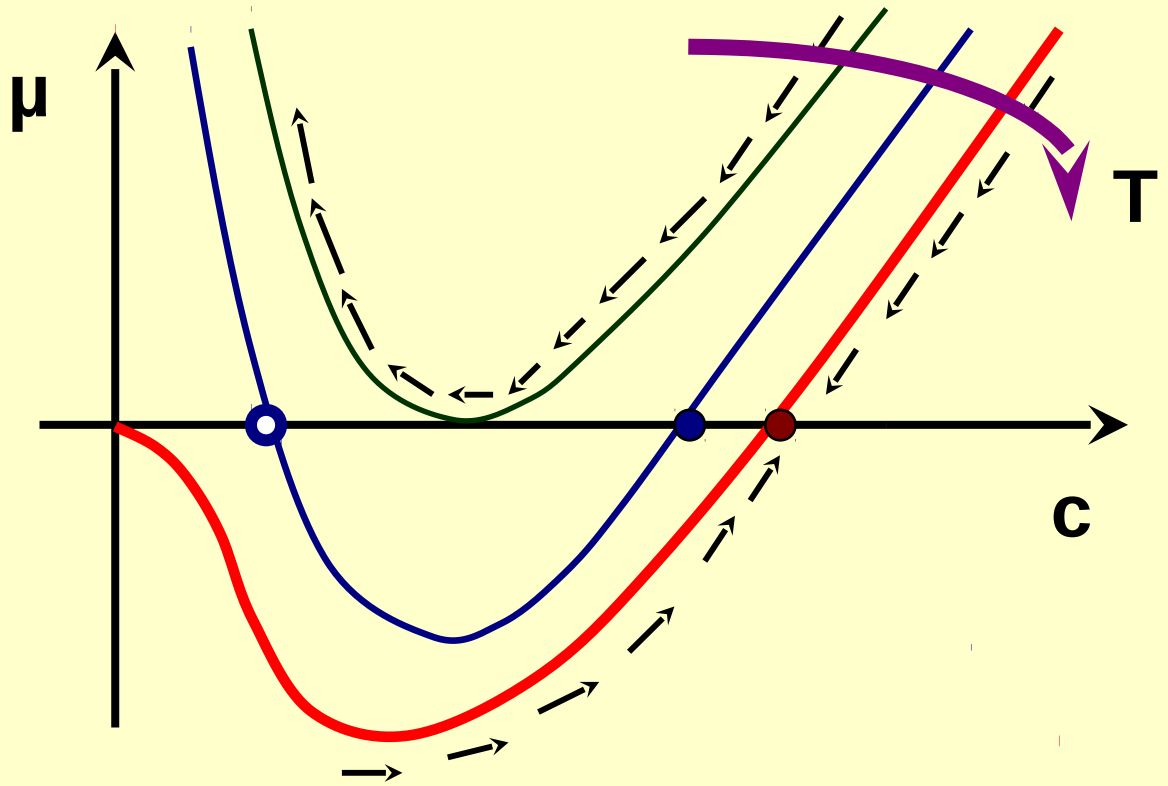
$$c = \sum_i c_i \, d_i \, n_{id}\left(T, q_i \mu_B - A c_i c^{-\gamma}\right)$$

$$\Rightarrow \quad c = c\left(T, \mu_B\right)$$

It exists only beyond an endline in T - μ

Stringy corrections to QGP

Consistent solution for color density in equilibrium:



It exists only beyond an endline in T - μ

Stringy corrections to QGP

One massless component, Boltzmann approximation:

$$c = \frac{d}{\pi^2} T^3 \; e^{q\mu_B/T} \; e^{-Ac^{-\gamma}/T}$$

$$z = \frac{A}{T} c^{-\gamma}, \quad \alpha = \frac{A}{T}\left(\frac{d}{\pi^2} T^3 \; e^{q\mu_B/T} \right)^{-\gamma}$$

$$z = \alpha \, e^{\gamma z}, \quad z = -\frac{1}{\gamma} W(-\gamma\alpha)$$

The solution is related to Lambert's function

Stringy corrections to QGP

Endline: last possible solution

Boltzmann approximation

$$z = \alpha\, e^{\gamma z}, \quad 1 = \gamma \alpha\, e^{\gamma z}$$

$$\Rightarrow\; z_E = \tfrac{1}{\gamma} \qquad \Rightarrow \qquad \alpha_E = \tfrac{1}{\gamma} e^{-1}$$

$$\mu_B = \frac{3\gamma + 1}{\gamma q} T \ln \frac{T_E}{T}$$

It is near to the zero pressure line for low chemical potential

Stringy corrections to QGP

End temperature: last possible solution at μ = 0

Boltzmann approximation

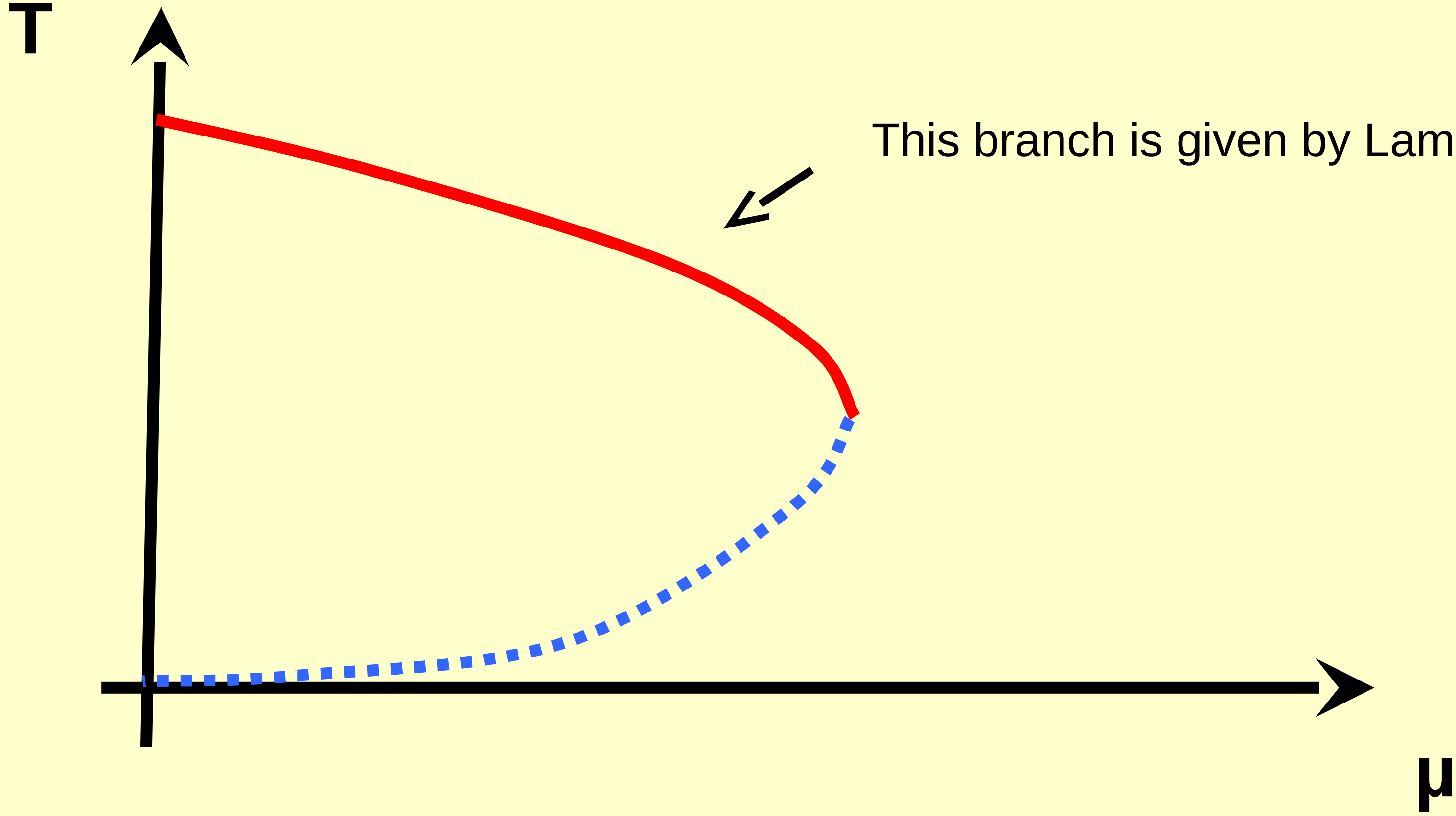
$$T_E = \left[\left(\frac{d}{\pi^2} \right)^{-\gamma} \gamma e A \right]^{\frac{1}{1+3\gamma}}$$

It is near to the zero pressure line for low chemical potential

Stringy corrections to QGP

Boltzmann approximation

Endline: last possible solution



The zero pressure line

Zero pressure in the Boltzmann approximation

$$p = cT\left(1 - \tfrac{\gamma}{1-\gamma}\, z\right)$$

$$\Rightarrow\; z_0 = \tfrac{1-\gamma}{\gamma} \qquad \Rightarrow \qquad \alpha_0 = \left(\tfrac{1}{\gamma} - 1\right) e^{\gamma-1}$$

$$\mu_B = \frac{3\gamma+1}{\gamma q}\, T \ln\frac{T_0}{T}, \qquad \frac{T_0}{T_E} = \left(1-\gamma\right)^{-\frac{1}{3\gamma+1}}\; e^{-\frac{\gamma}{3\gamma+1}}$$

Endline and zero pressure line are relatively close! (T0 ≈ 1.04 TE)

E/N at the zero pressure line

General relations

$$\left.\frac{e}{n}\right|_{p=0} = \frac{\sum\left[e_{id} + \frac{1}{\gamma}\, p_{id}\right]}{\sum n_{id}}$$

$$\left.\frac{e}{n}\right|_{p=m=0} = \left(3+\tfrac{1}{\gamma}\right) T\, \frac{\sum d_i \Phi_i(\tilde{\mu}_i / T)}{\sum d_i \varphi_i(\tilde{\mu}_i / T)}$$

$$\left.\frac{e}{n}\right|_{p=m=0,\ \mathrm{Boltzmann}} = \left(3+\tfrac{1}{\gamma}\right) T$$

This is independent of the value of the string tension!

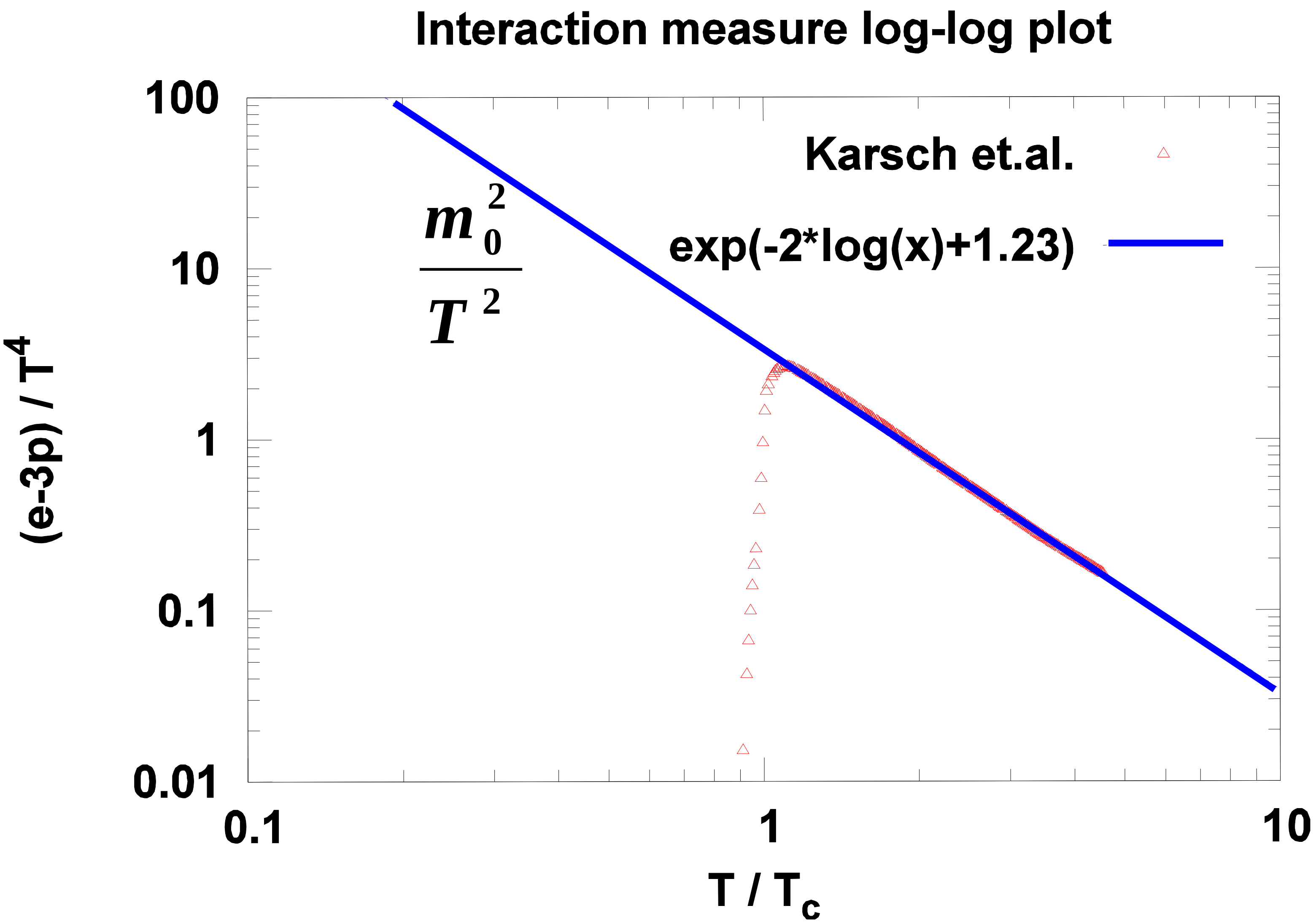
High – T equation of state

$$\frac{e-3p}{T^4} = \frac{1+3\gamma}{1-\gamma}\,\frac{A}{T^4}\,c^{1-\gamma} \sim T^{-3\gamma-1}$$

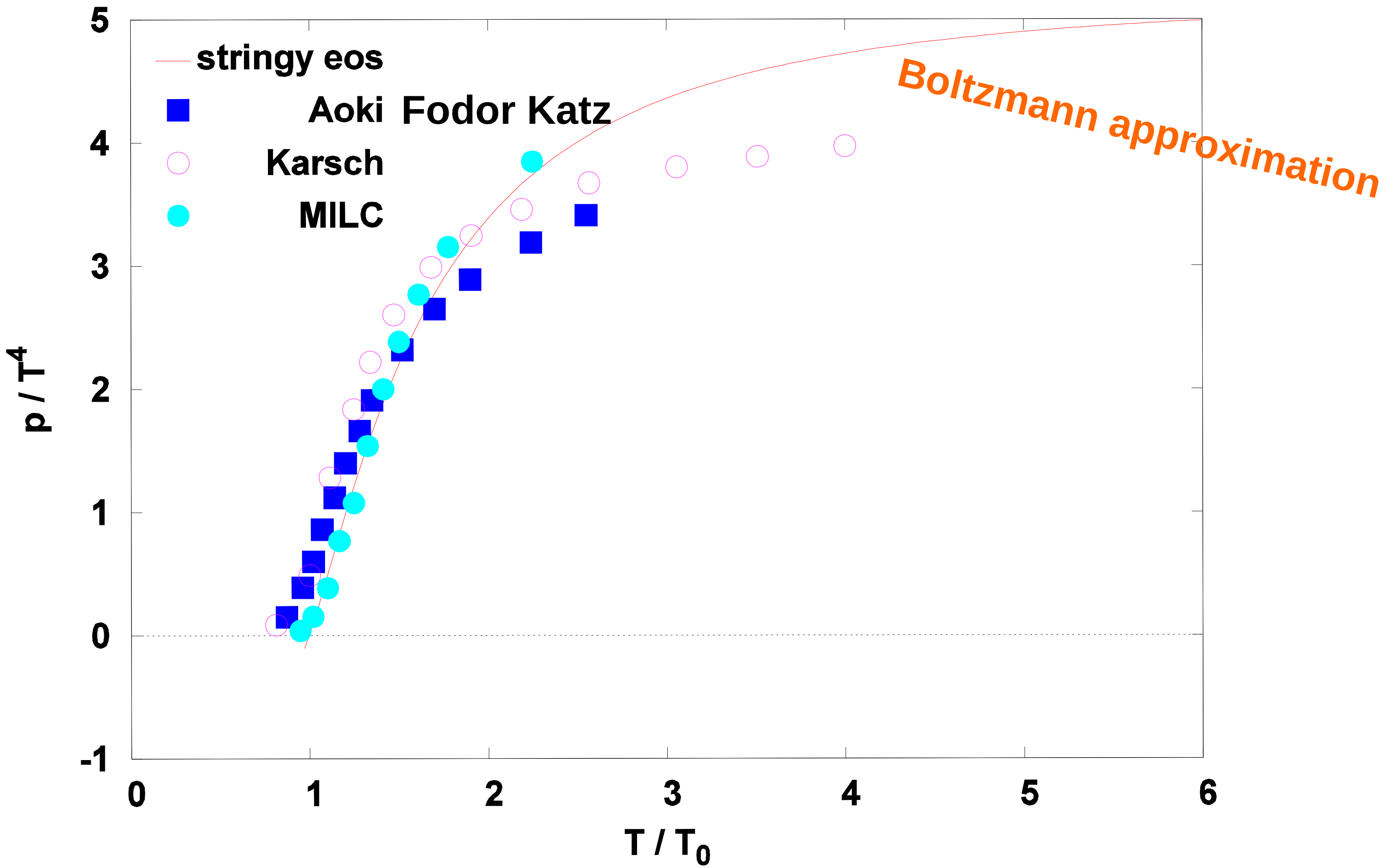
$$\text{lattice QCD}:$$

$$3\gamma+1=2 \quad \rightarrow \quad \gamma = 1/3$$

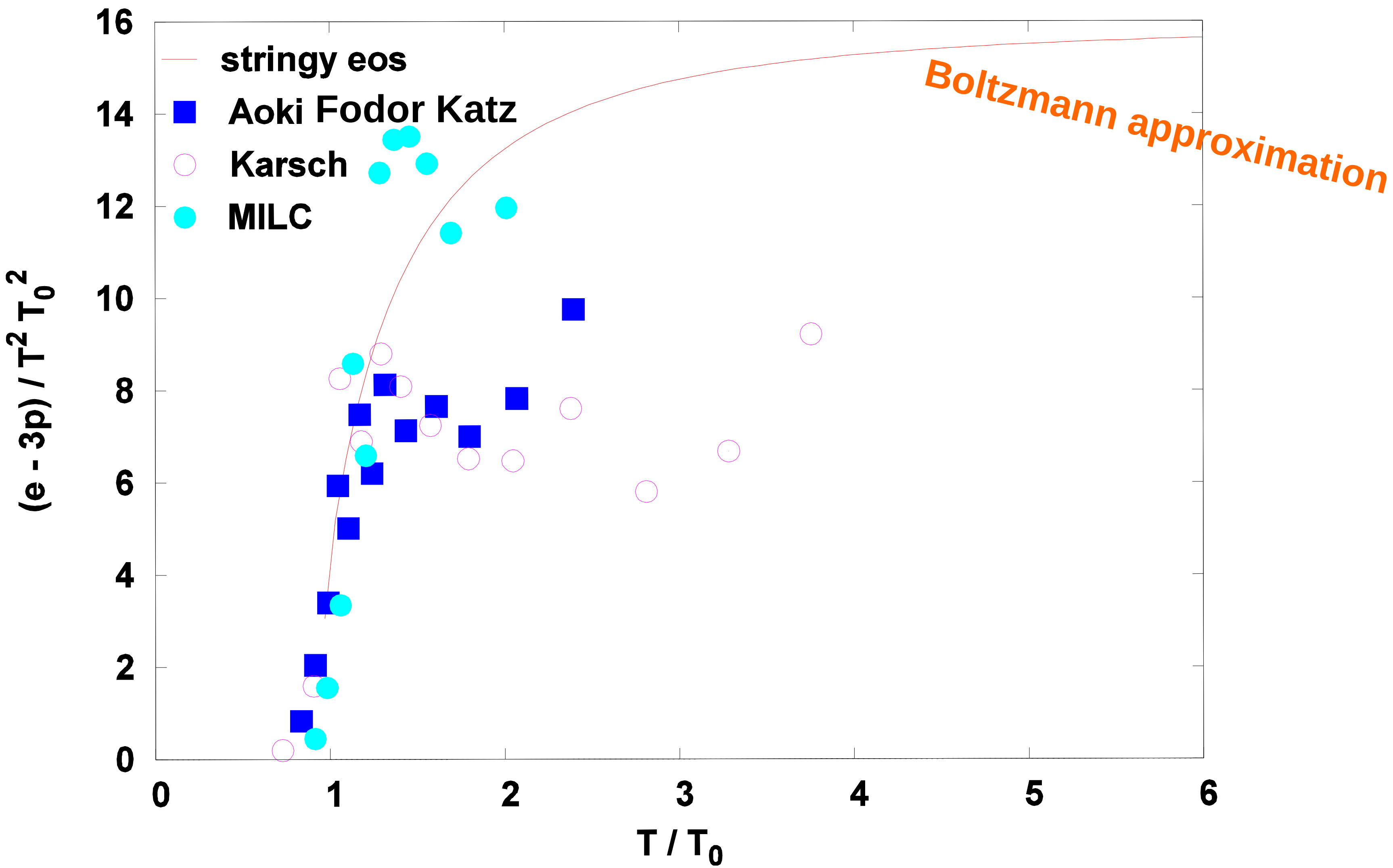
High-T behavior of lattice eos



High-T behavior of lattice eos



High-T behavior of lattice eos



Where to stop with the Boltzmann approximation?

Fermi integral ≈ Boltzmann integral for negative or zero μ.

$$q\mu_B - Ac^{-\gamma} \le 0$$

$$\frac{q\mu_B}{T} = \left(3 + \tfrac{1}{\gamma}\right) \ln \frac{T_E}{T} \le z_E = \frac{1}{\gamma}$$

$$T_E > T > T_E \, e^{-1/2} \approx 0.6\, T_E$$

The endline does not turn back!

$$T_{\max} = T_E \, e^{-1}$$

The zero pressure line

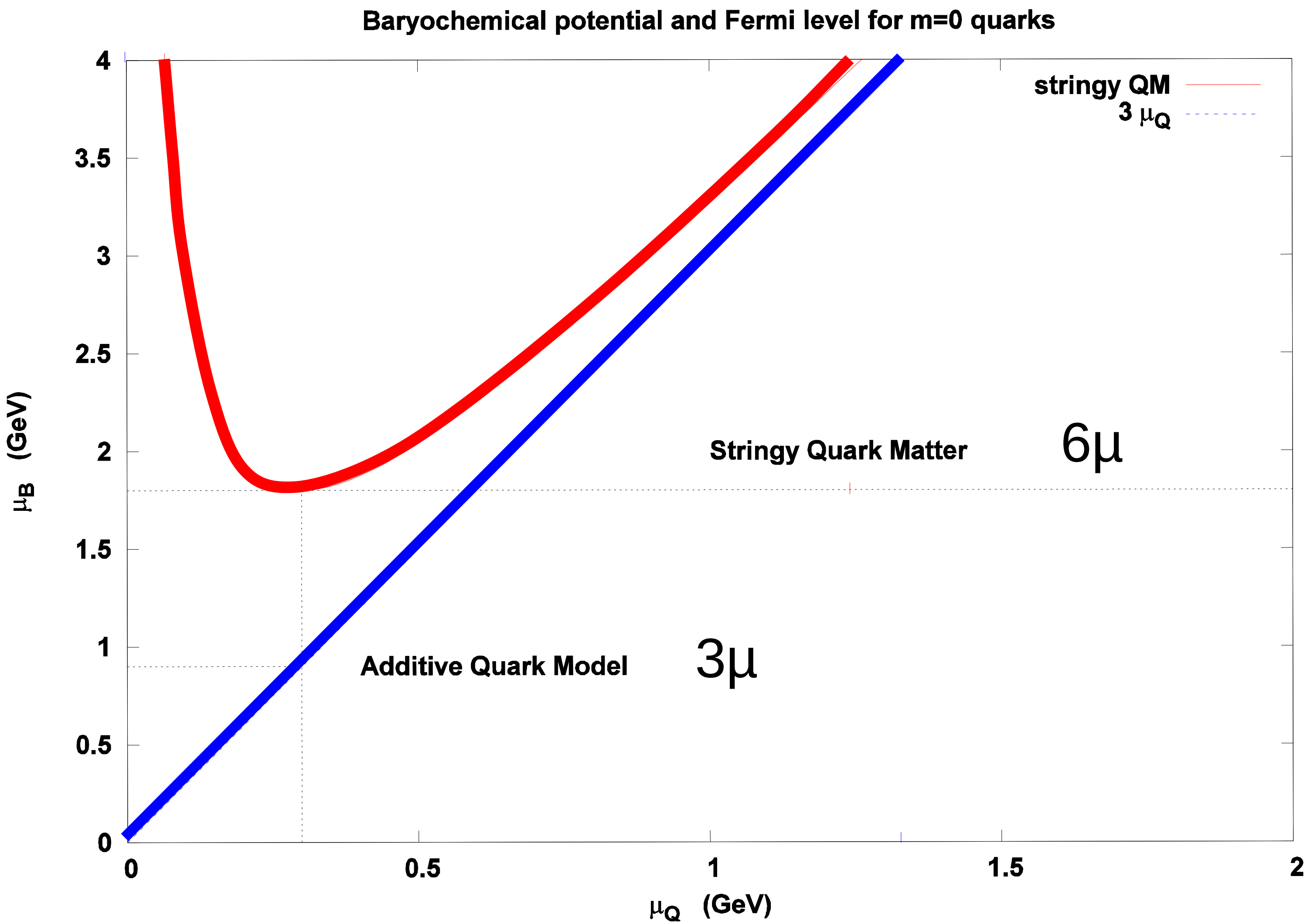
Fermions (quarks only) at T = 0

$$c = \frac{dc_q}{6\pi^2}\left(q\mu_B - Ac^{-1/3}c_q\right)^3$$

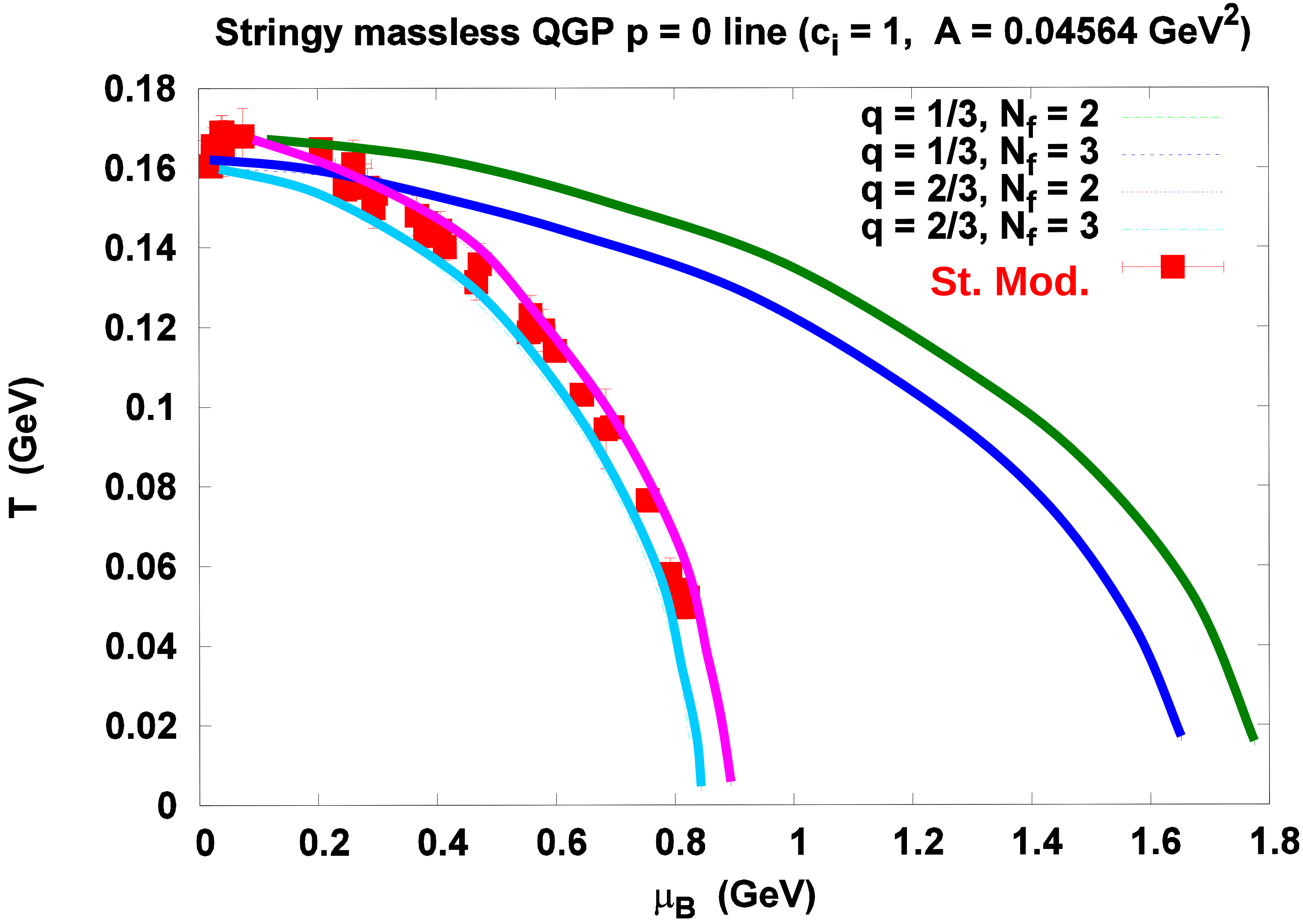
$$c = c_q\left[\tfrac{q\mu_B}{2B} + \sqrt{\frac{q^2\mu_B^2}{4B^2} - \frac{\tilde{A}}{B}}\right]^3, \quad \left.\frac{e}{n}\right|_{p=0,\,T=0} = q\mu_B$$

$$\mu_0^Q = \tfrac{3}{2\sqrt{2}}\mu_E \approx 1.06\mu_E \approx 10.4\,T_0^{QGP} \approx 1.74\,\mathrm{GeV}$$

The endpoint at T=0



The zero pressure line

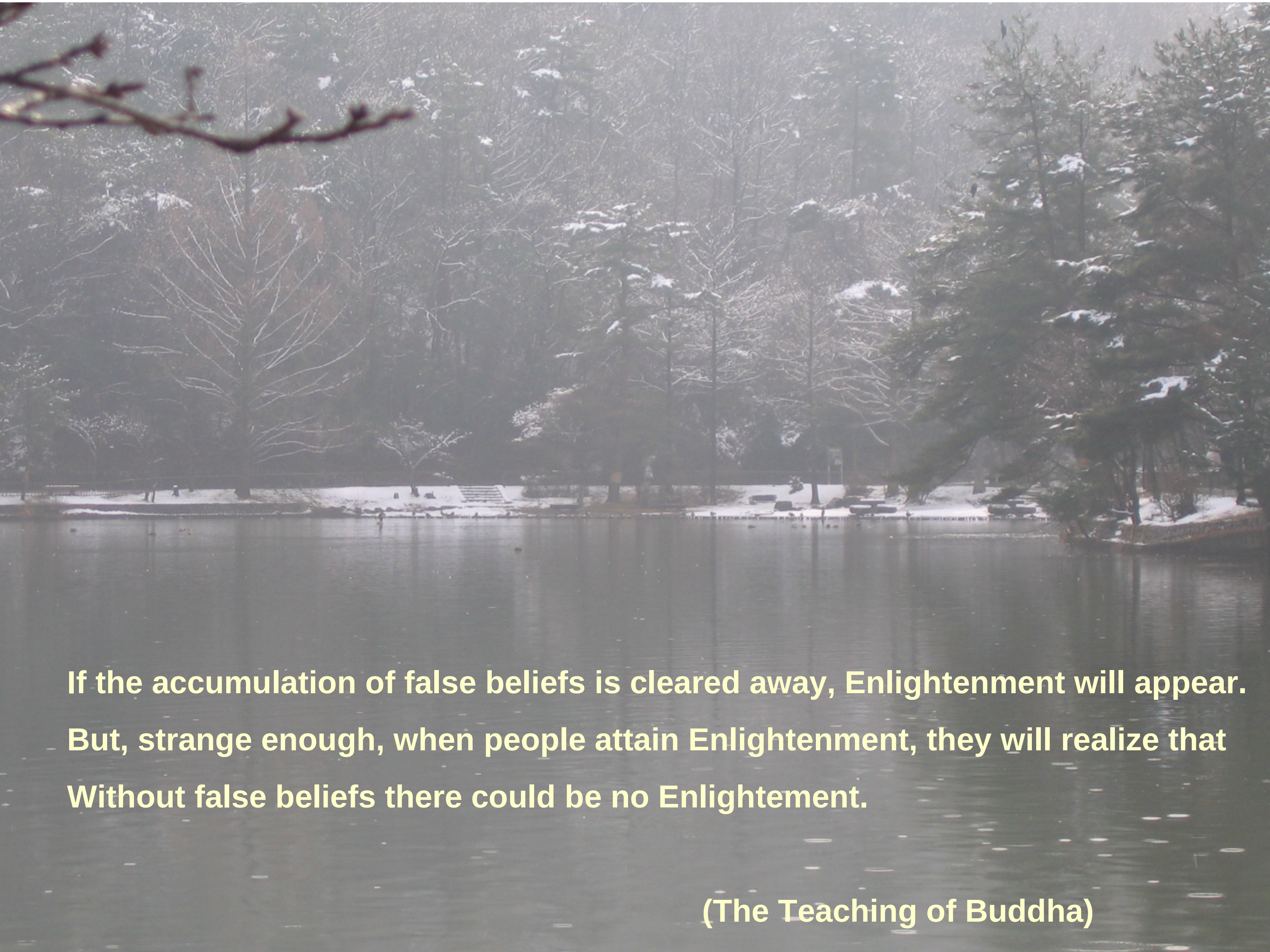


Summary

- E / N = 6T only from stringy massless QGP
- fractional power is 1/3 from high-T lattice eos
- zero pressure line and endpoint of solution are close
- at finite baryon density and zero temperature

  the hadronization line is at mu_B = 3 k_F
- at any temperature IR effects may be present

  (already a small string tension makes E / N = 6T)



If the accumulation of false beliefs is cleared away, Enlightenment will appear. But, strange enough, when people attain Enlightenment, they will realize that Without false beliefs there could be no Enlightement.

(The Teaching of Buddha)

Bibliography

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- **hep-ph / 98083941,** **T.S.Biro, P.Levai, J.Zimanyi and C.Traxler: Hadronization in heavy ion collisions, PRC59, ……, 1999**
- **T.S.Biro, A.A.Shanenko and V.D.Toneev: Toward Thermodynamic Consistency of Quasiparticle Picture, Phys.Atomic Nuclei 66, 982, 2003**
- **J.Cleymans, H.Oeschler, K.Redlich, S.Wheaton, PRC73, 034905, 2006.**


Discussion

FAQ

- What is actually non-perturbative at T > Tc ? (low Q2 pairs)
- What is non-particle like (stringy) at T > Tc ? (interaction)
- Are all color charges stringed at T > Tc? No! (a small fraction suffices for the effect.)
- Asymptotic freedom is incomplete at any finite temperature. Why and what is the quantitative measure of this effect? →

Arguments

<u>Non-perturbative effects at arbitrary high temperature:</u>

1. **Thermal distribution of Q^2**
2. **NP order parameter: cut-off in Q^2**
3. **Its thermal expectation value → order of NP effects**
4. **high-T expansion**

□□→ high-T NP terms in EoS (pressure, int.mesure)

Pressure: NP effects at any T

$$p = p_P \int_{\Lambda^2}^{\infty} P(Q^2)dQ^2 + p_{NP} \int_{0}^{\Lambda^2} P(Q^2)dQ^2$$

$$\int_{0}^{\Lambda^2} P(Q^2)dQ^2 = \int_{0}^{\Lambda^2/T^2} f(x)dx$$

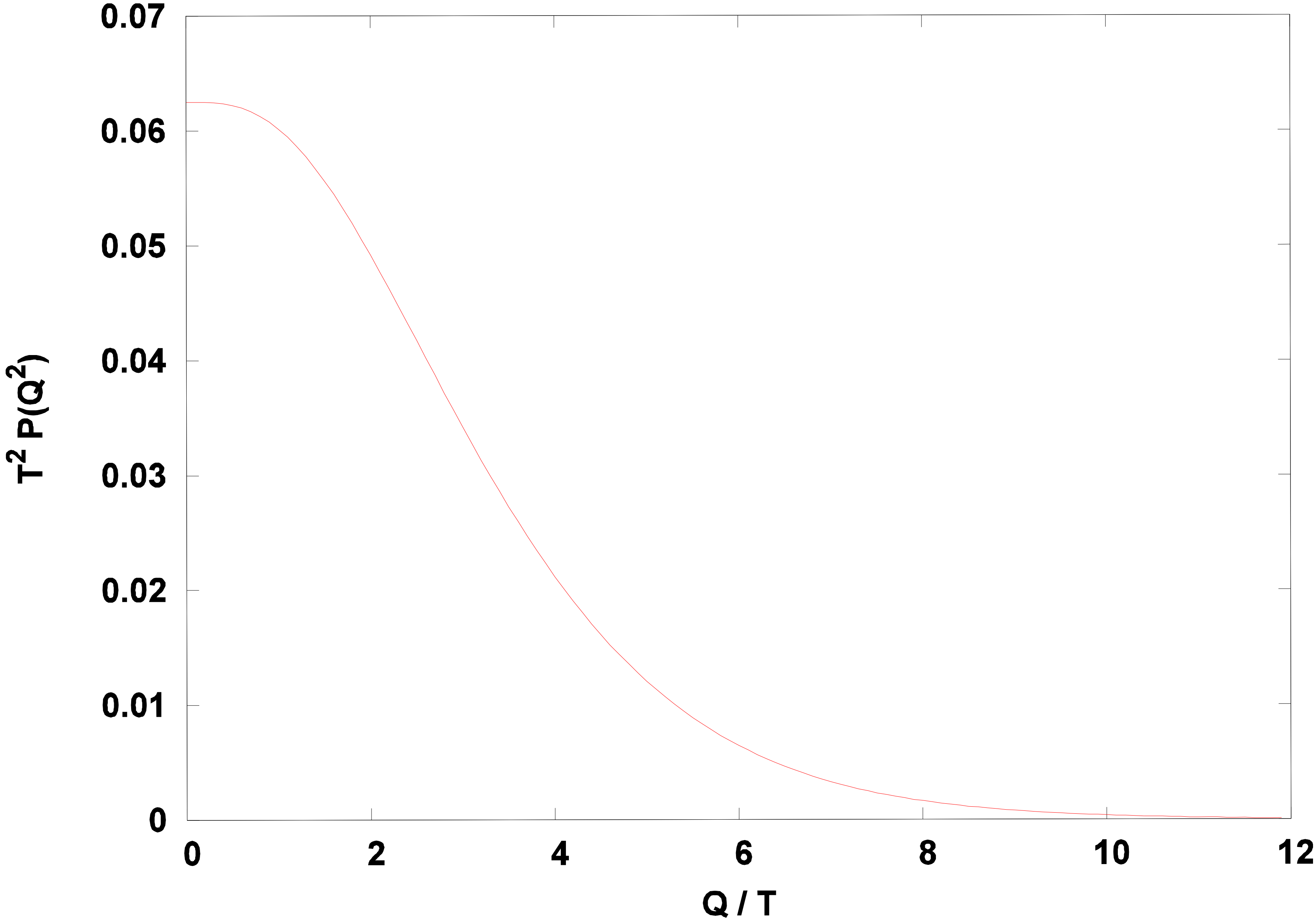
$$p = p_p - (p_p - p_{NP}) \begin{cases} 1 & (T << \Lambda) \\ \Lambda^2/T^2 \; f(0) & (T >> \Lambda) \end{cases}$$

If it were f(0) = 0, then the QGP pressure would be free of NP effects!

Thermal distribution of Q^2

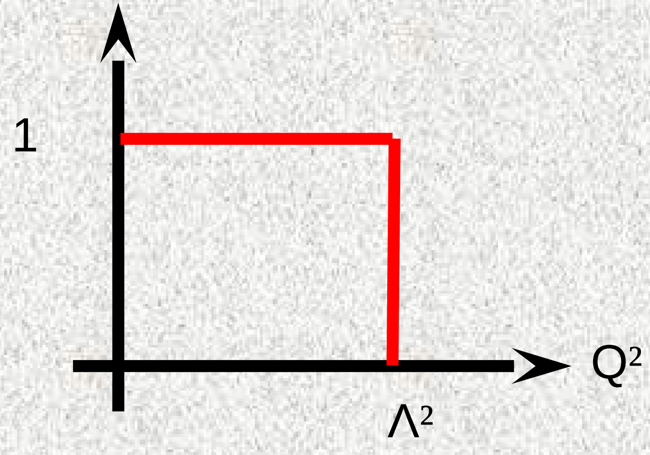
$$P(Q^2) = \frac{\iint dE_1 dE_2 d\theta\, E_1^2 E_2^2\, e^{-\beta(E_1+E_2)}\, \delta\left(Q^2 - 2E_1E_2(1-\cos\theta)\right)}{\iint dE_1 dE_2 d\theta\, E_1^2 E_2^2\, e^{-\beta(E_1+E_2)}}$$

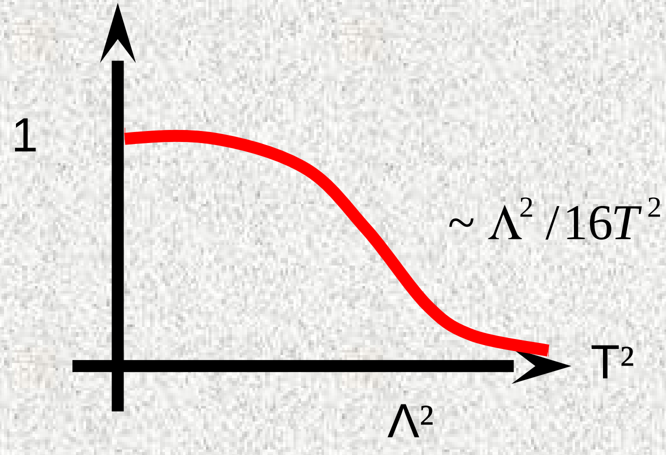
$$P(Q^2) = \frac{1}{64T^2}\left(\frac{Q^3}{T^3}K_1\left(\frac{Q}{T}\right) + 2\frac{Q^2}{T^2}K_2\left(\frac{Q}{T}\right)\right)$$

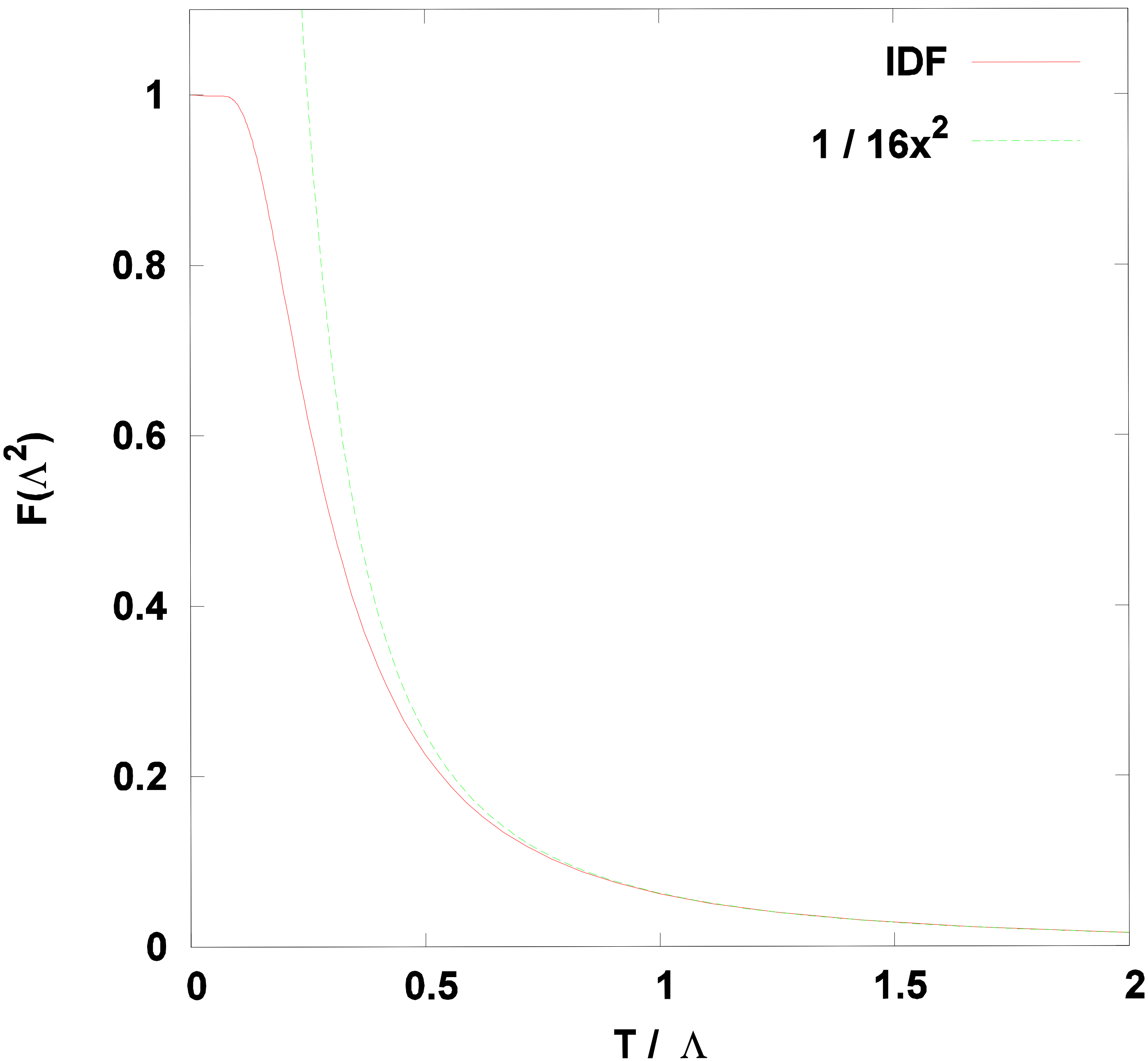

0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
T2 P(Q2)
0
2
4
6
8
10
12
Q / T

Thermal expectation of NP order parameter

$$\left\langle \Theta\left(\Lambda^2 - Q^2\right) \right\rangle = \int_0^{\Lambda^2} P(Q^2)\, dQ^2$$



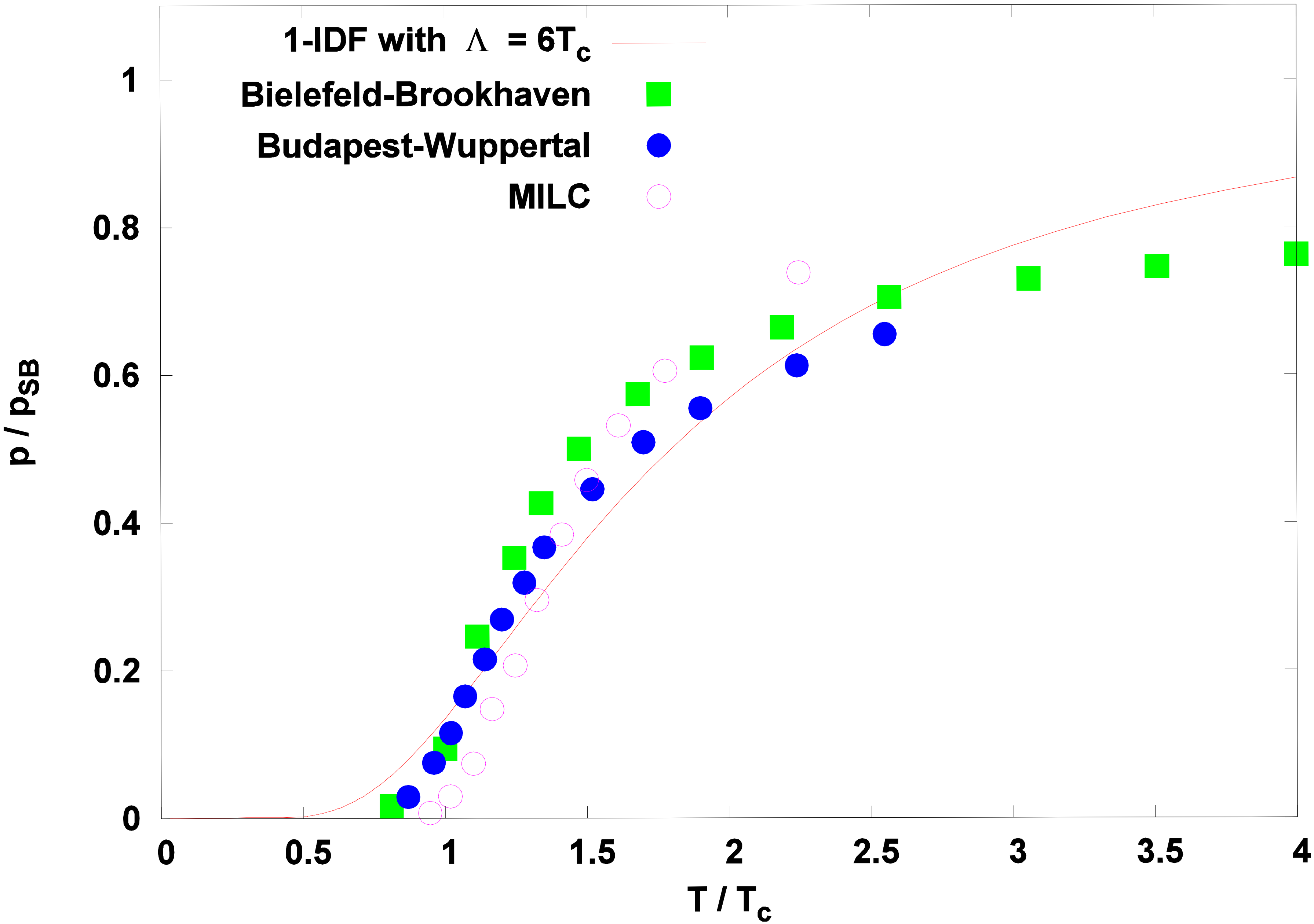


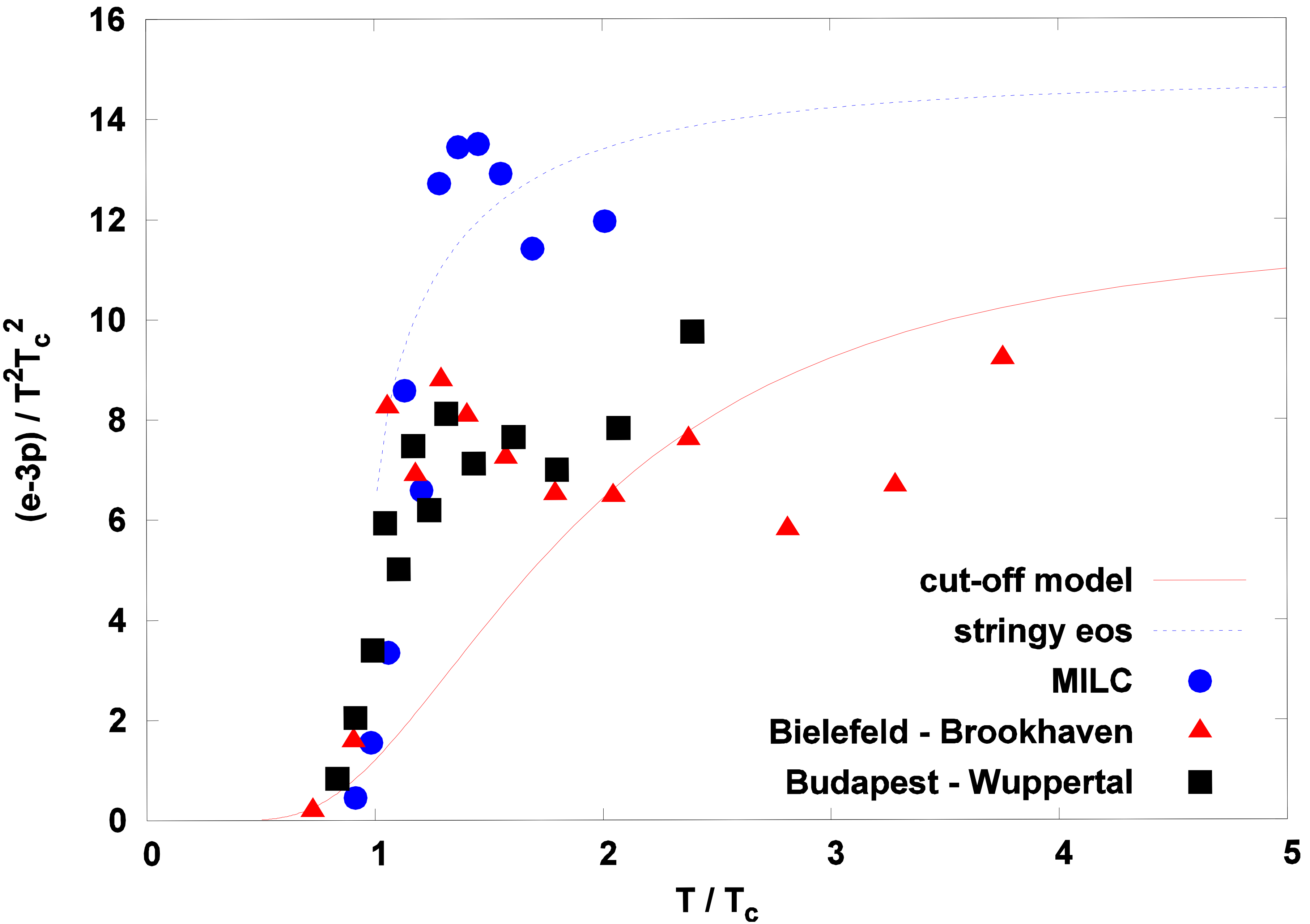

IDF
1 / 16x^2
F(Λ^2)
T / Λ
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2

NP effects at high T in the EoS

$$p = \frac{1}{3}\kappa T^4 - c_{NP}\Lambda^2 T^2$$

$$e - 3p = 2c_{NP}\Lambda^2 T^2$$


1-IDF with Λ = 6T_c
Bielefeld-Brookhaven
Budapest-Wuppertal
MILC
p / p_SB
T / T_c
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2
2.5
3
3.5
4



(e-3p) / T2Tc2
T / Tc
0
2
4
6
8
10
12
14
16
0
1
2
3
4
5
cut-off model
stringy eos
MILC
Bielefeld - Brookhaven
Budapest - Wuppertal

To do list

1. Include massive quarks (strange)
2. Compare stringy matter and quasiparticle mass effects

   to leading order at high T
3. Compare stringy eos with power-law tail effects
4. Compare with other simple ideas, like Q2 cutoff