Photon Emission near a Critical Point

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Es ist schon Alles gesagt worden,
aber noch nicht von Allen!

- photon emissivities: L(QCD) → LsM (F. Wunderlich) — FAIR & NICA
- viscosities: L(QCD) → Holography (R. Yaresko, J. Knaute*) — RHIC & LHC
- dN_ch / dy: L(QCD) → Hydro + CF f.o. (G. Schlisio) — LHC

* now in Princeton

Partner von DRESDEN concept exzellenz-dresden.de

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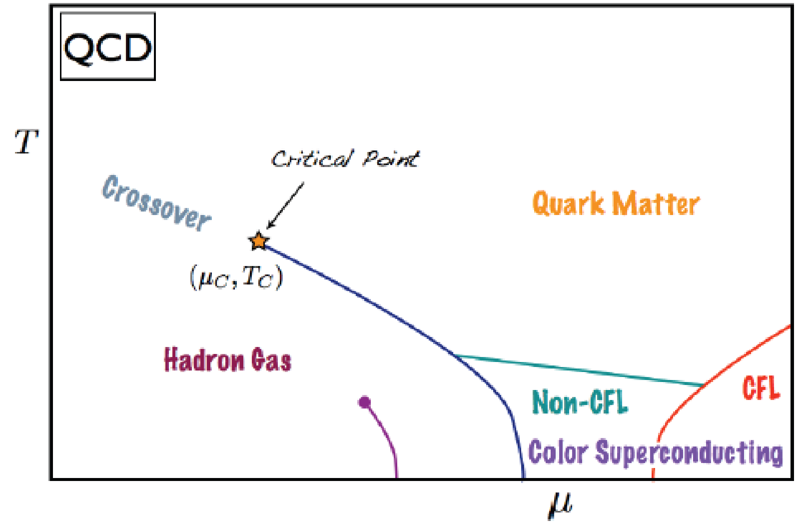
1. Photon Emissivities and CEP

Hypothesis: a second first-order transition in QCD phase diagram at mu > 0



deWolfe, Gubser, Rosen, PRD (2011)

reminder: QCD (mu = 0) displays a cross over,
no reliable lattice data for mu >> 0

options for the phase transition:
hadron-quark vs. gas-liquid
→ different p_c(T) curves,
different isentropic curves

Steinheimer, Randrup, Koch, PRC (2014)
Hempel, Dexheimer, Schramm, Iosilevskiy, PRC (2013)

Toy Models (i) CEP

s(T,mu) = s_reg (T,mu) + s_sing (T,mu)

3D Ising with proper crit. exps.

Bluhm, BK, PoS (2006)
based on Nonaka, Asakawa, PRC (2005)
based on Giuda, Zinn-Justin, NPB (1997)

special construction

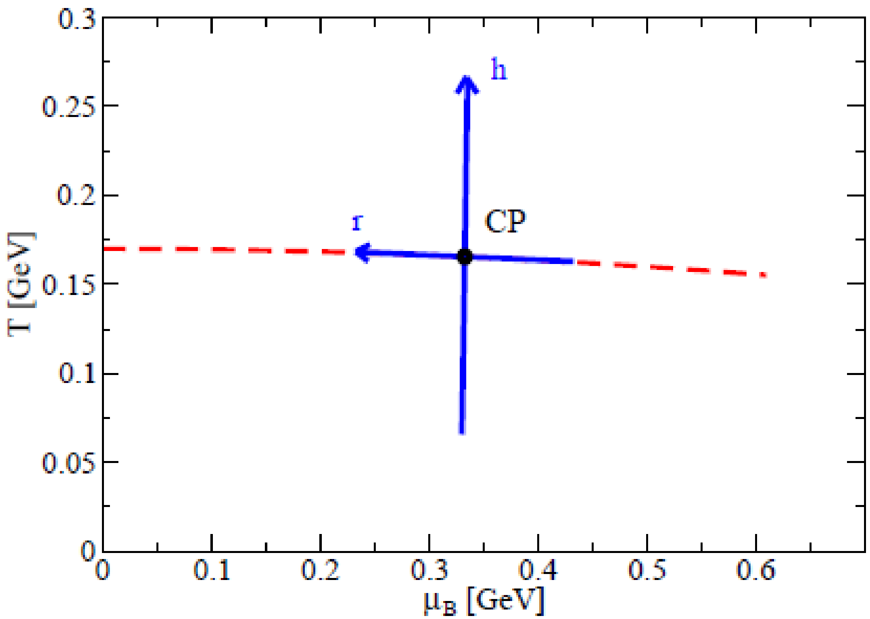
G(r,h): Gibbs free energy
M(r,h): magnetization
h: external mag. field
r = (T – Tc) / Tc

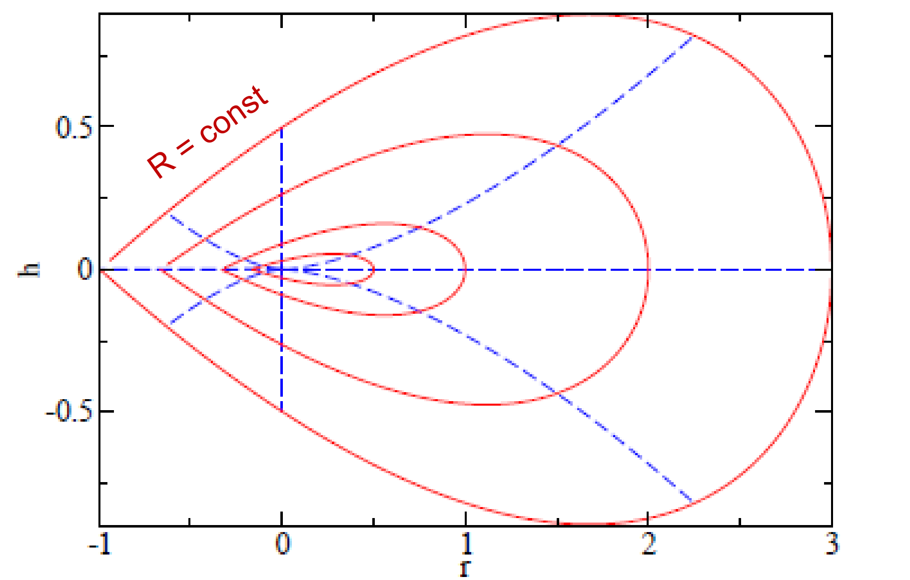
$$G = h_0 M_0 R^{2-\alpha} g(\theta) - Mh$$

$$r = R\,(1-\theta^2)\,,$$

$$h = h_0 R^{\beta\delta} \sum^{2} a_{2i+1}\,\theta^{2i+1}\,,$$

$$\sum_{i=0}^{2} a_{2i+1}\theta^{2i+1}\left(1-\theta^2+2\beta\theta^2\right) = 2(2-\alpha)\theta g(\theta) + (1-\theta^2)g'(\theta)$$



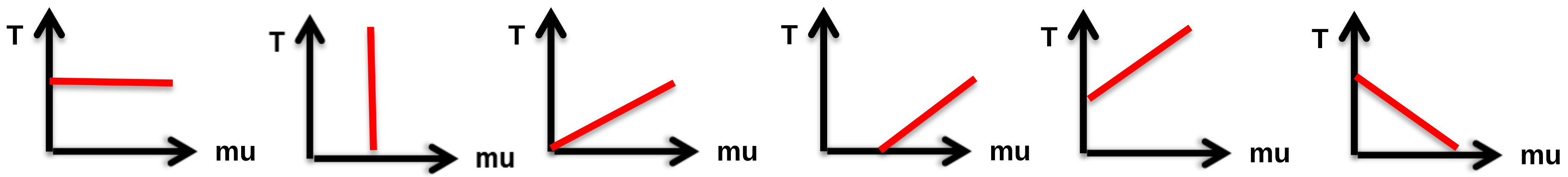


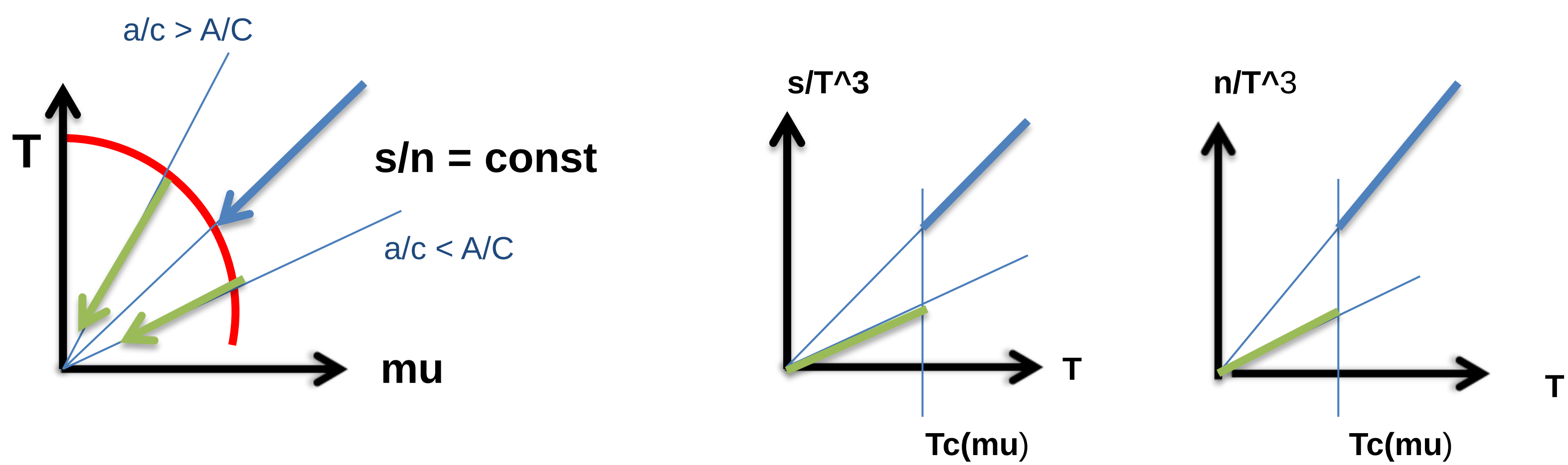
Toy Models (ii) 1st order transition

ad hoc construction: two-phase model

p1 = a T^4 + c mu^4 – b
p2 = A T^4 + C mu^4 - B

phase border curve/coexistence region: p1 = p2 → Tc(mu), pc(T) etc.





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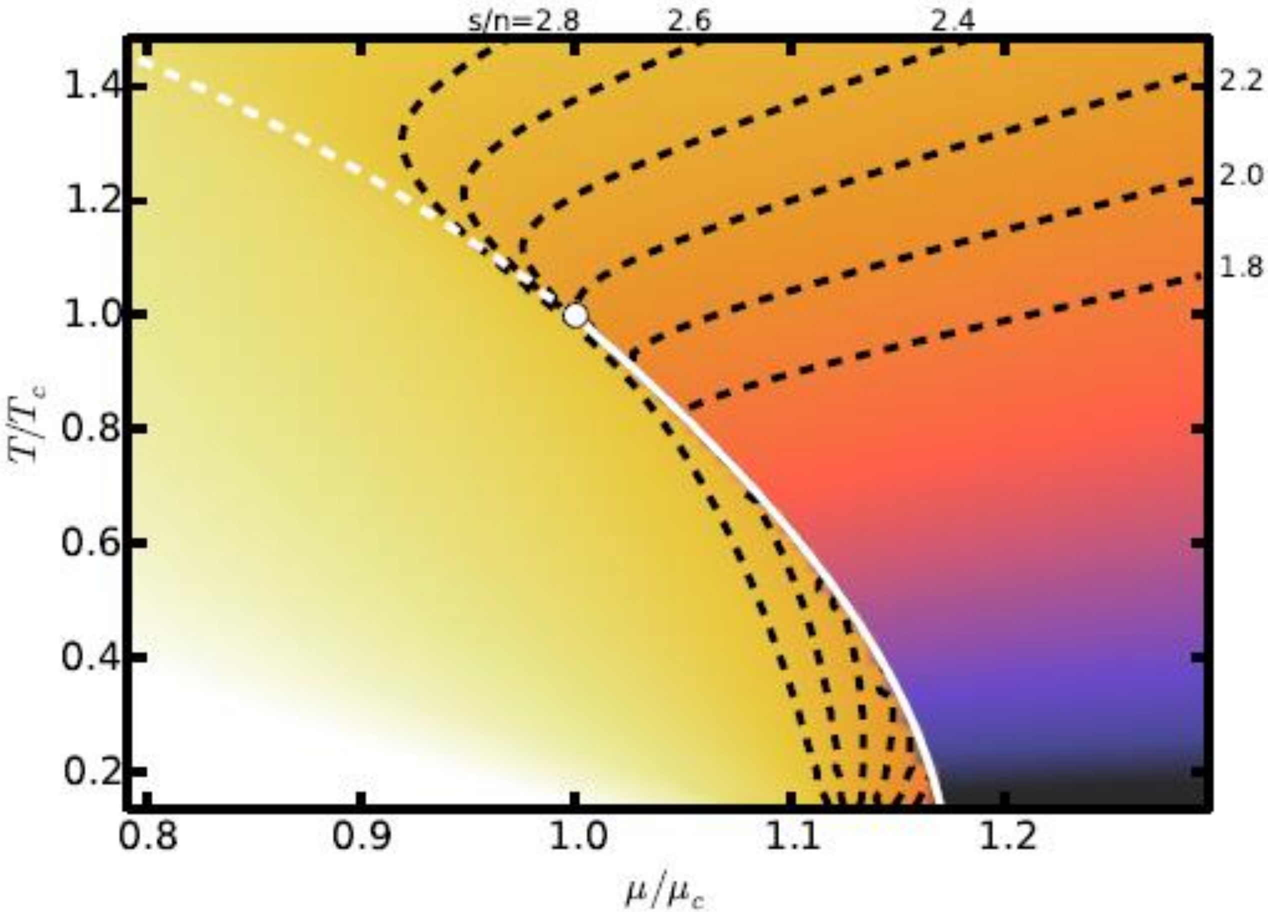
$$\mathscr{L}_{\mathrm{L\sigma M}} = \bar{q}(i\partial\!\!\!/ - g(\sigma + i\gamma_5\tau\pi))q - \mathscr{L}_{km} - U(\sigma,\pi),$$

$$U(\sigma,\pi) = \frac{\lambda}{4}(\sigma^2 + \pi^2 - \zeta)^2 - H\sigma,$$

$$\mathscr{L}_{km} = \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma + \partial_\mu\pi\partial^\mu\pi),$$

one alternative:
PNJL: J.M. Torres-Rincon

CEP discussion:
Scavenius, Mocsy, Mishustin, Rischke, PRC (2001)
Schaefer, Wambach, NPA (2005)
Schaefer, Pawlowski, Wambach, PRD (2007)
Herbst, Pawlowski, Schaefer PLB (2011)



$$\Omega_{\rm MFA} = \Omega_{qq}\Big|_{m_q=gv} + U(v,0),$$

sigma pi

$$m_q^* = gv$$

$$m_\sigma^{*\,2} = \frac{\partial^2 \Omega_{qq}|_{m_q=gv}}{\partial v^2} + \lambda(3v^2-\zeta),$$

$$m_\pi^{*\,2} = 2g^2 \frac{\partial \Omega_{qq}}{\partial m_q^2}\Big|_{m_q=gv} + \lambda(v^2-\zeta),$$

$$0 = \frac{\partial \Omega_{qq}|_{m_q=gv}}{\partial v} + \lambda(v^3 - v\zeta) - H,$$

$$\Omega_{\rm LFA} = \langle U(v+\Delta,\pi)\rangle + \langle \Omega_{qq}(m_q)\rangle - \frac{1}{2}m_\sigma^2\langle\Delta^2\rangle - \frac{1}{2}m_\pi^2\langle\pi^2\rangle + \Omega_\pi + \Omega_\sigma,$$

$$m_q^* = g\left\langle\sqrt{\sigma^2+\boldsymbol{\pi}^2}\right\rangle,$$

$$m_\sigma^{*\,2} = \left\langle\frac{\partial^2\Omega_{qq}}{\partial\Delta^2}\right\rangle + \lambda(3v^2+3\langle\Delta^2\rangle+\langle\boldsymbol{\pi}^2\rangle-\zeta),$$

$$m_\pi^{*\,2} = \left\langle\frac{\partial^2\Omega_{qq}}{\partial\pi_a^2}\right\rangle + \lambda(v^2+\langle\Delta^2\rangle+\frac{5}{3}\langle\boldsymbol{\pi}^2\rangle-\zeta),$$

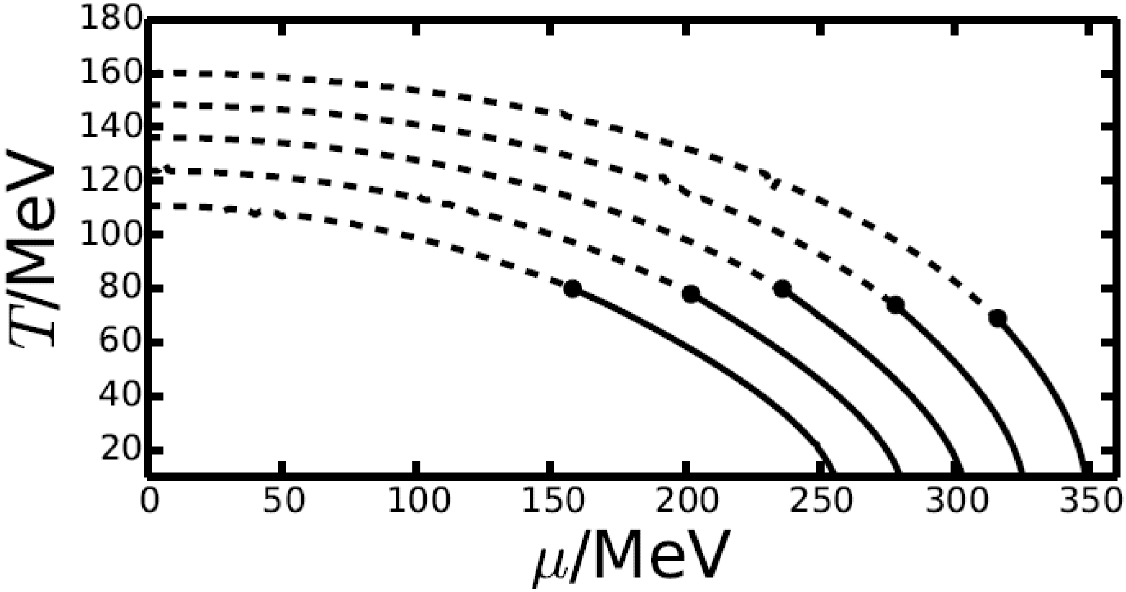
$$0 = \lambda v(v^2+3\langle\Delta^2\rangle+\langle\boldsymbol{\pi}^2\rangle-\zeta) - H,$$

$$\langle\Delta^2\rangle, \langle\pi_a^2\rangle = 2\partial\Omega_{\sigma,\pi}/\partial(m_{\sigma,\pi_a}^2).$$

Mocsy, Mishustin, Ellis, PRC (2004)
Bowman, Kapusta, PRC (2009)
Ferroni, Koch, Pinto, PRC (2010)

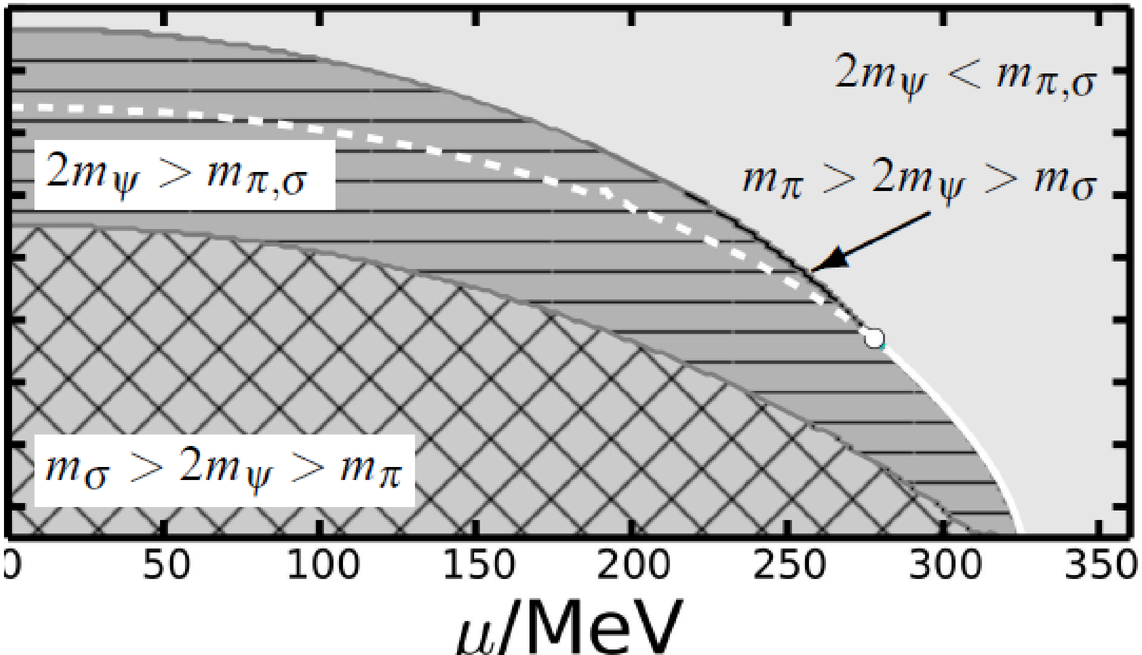
parameters: g = 3.387, ξ = 7874 MeV^2, λ = 27.8, H = 1760000 MeV^3

(from vacuum values of m_q, m_pi, m_sigma, f_pi)

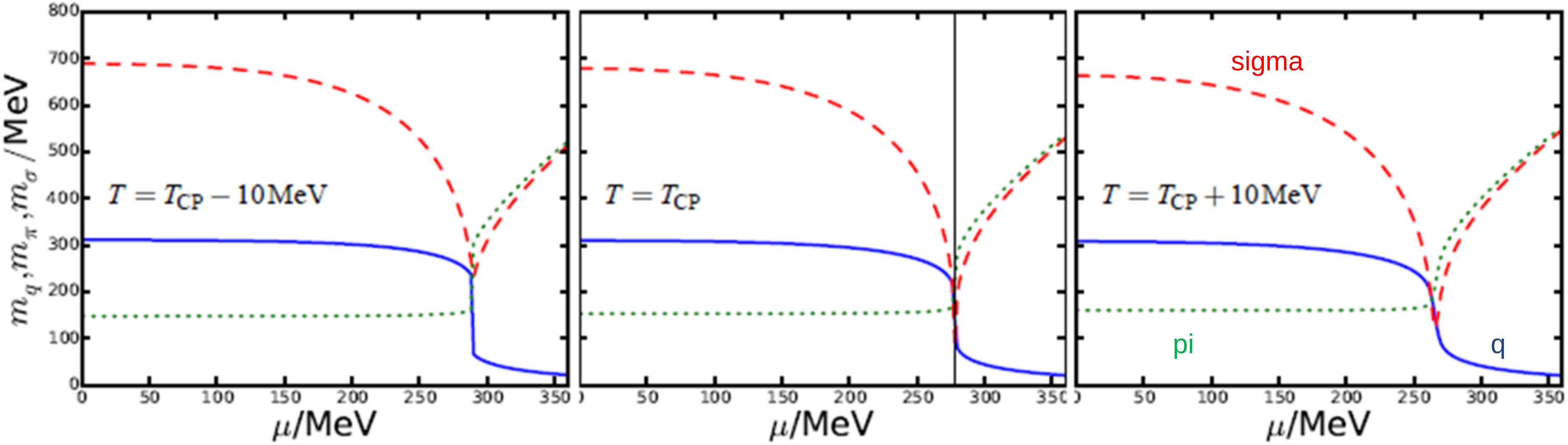


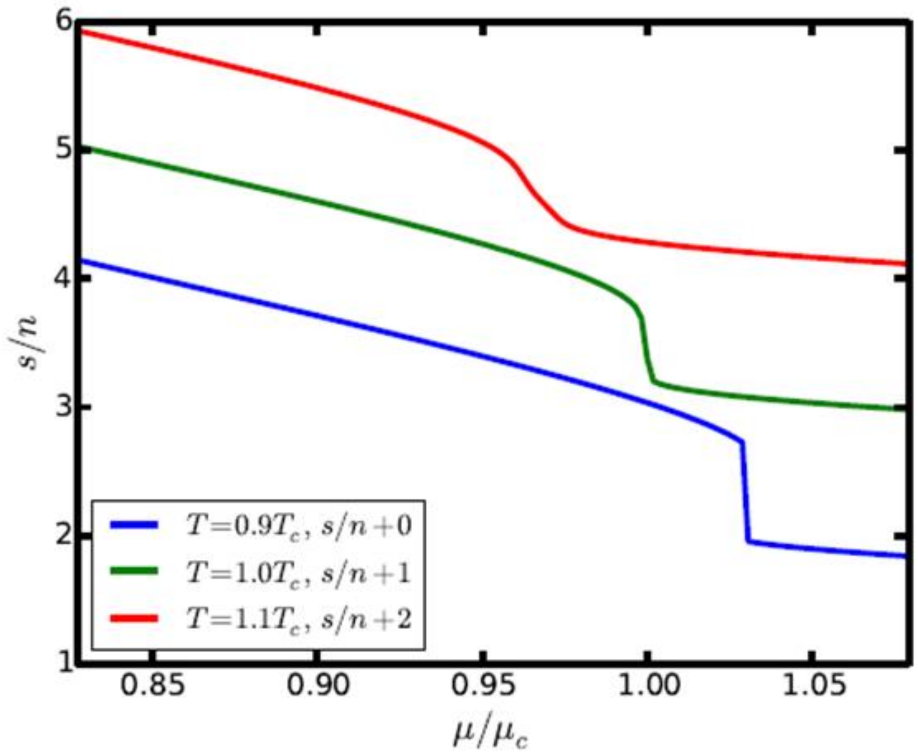
m_s from 400 MeV(top)
to 800 MeV (bottom)

note: improper CEP
proper 1st oder transition



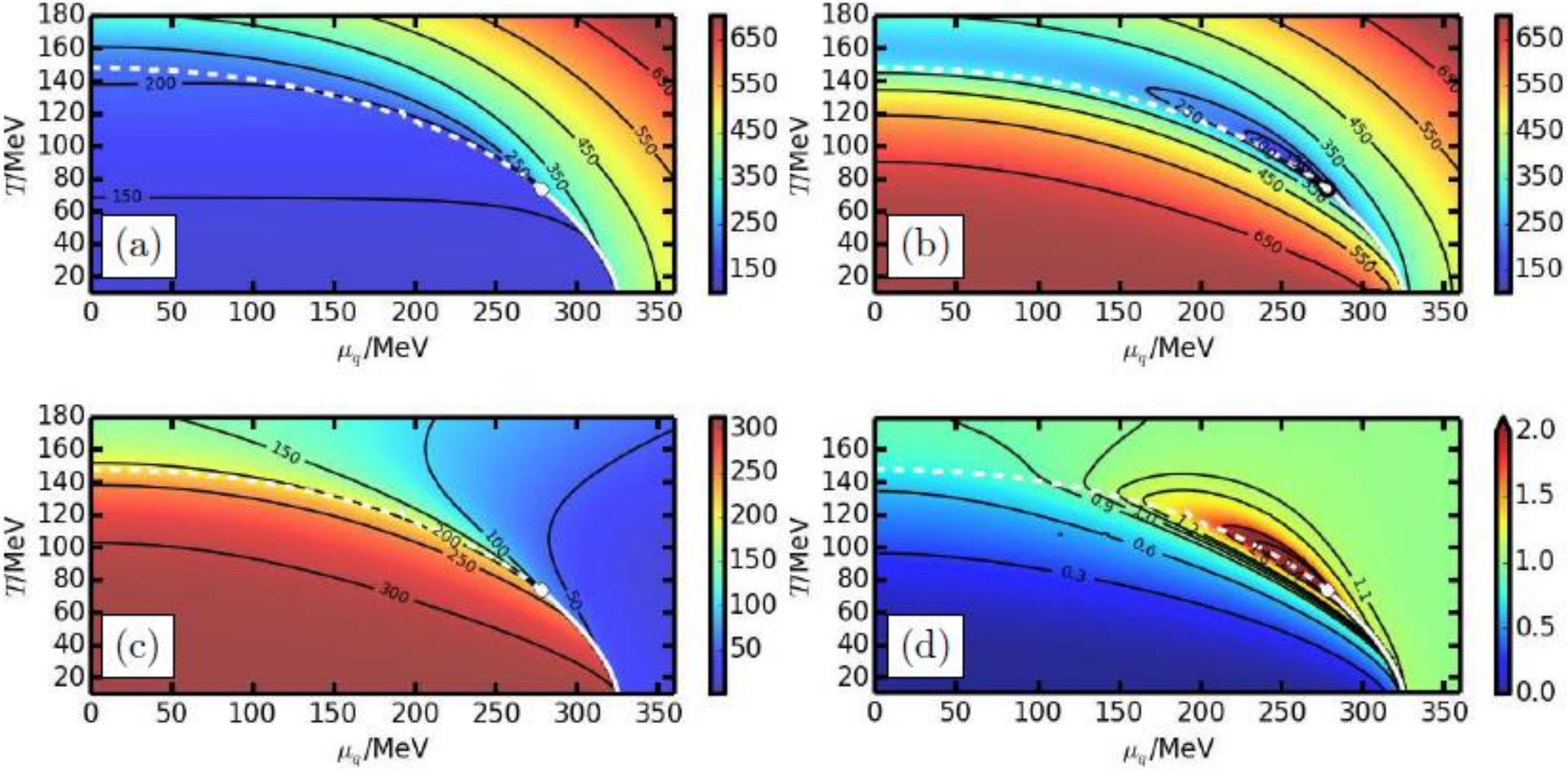
pattern of mass relations
changes over the phase plane





disclaimer:

- at T = 0 too small pressure (no proper baryons)
- LsM is of gas-liquid type



(a) pion mass (b) sigma mass
(c) quark mass (d) quark susceptibility (norm.)

wishful thinking: m(T, mu) reflect phase diagram

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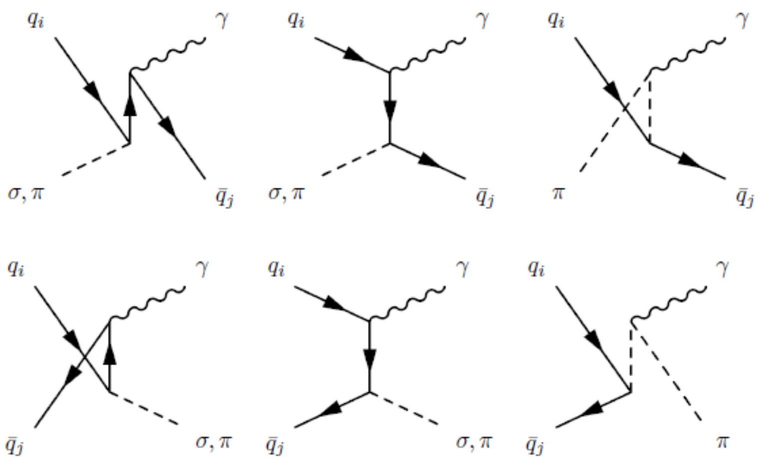
coupling in photons

$$\mathcal{L}_{\gamma\mathrm{L}\sigma\mathrm{M}} = \mathcal{L}_{\mathrm{L}\sigma\mathrm{M}} + \mathcal{L}_\gamma + \mathcal{L}_{\mathrm{int}},$$
$$\mathcal{L}_{\mathrm{int}} = -eQ_f\bar{\psi}\not{A}\psi + \frac{1}{2}e^2\pi^+\pi^-A^\nu A_\nu + \frac{1}{2}eA_\nu(\pi^-\partial^\nu\pi^+ + \pi^+\partial^\nu\pi^-),$$

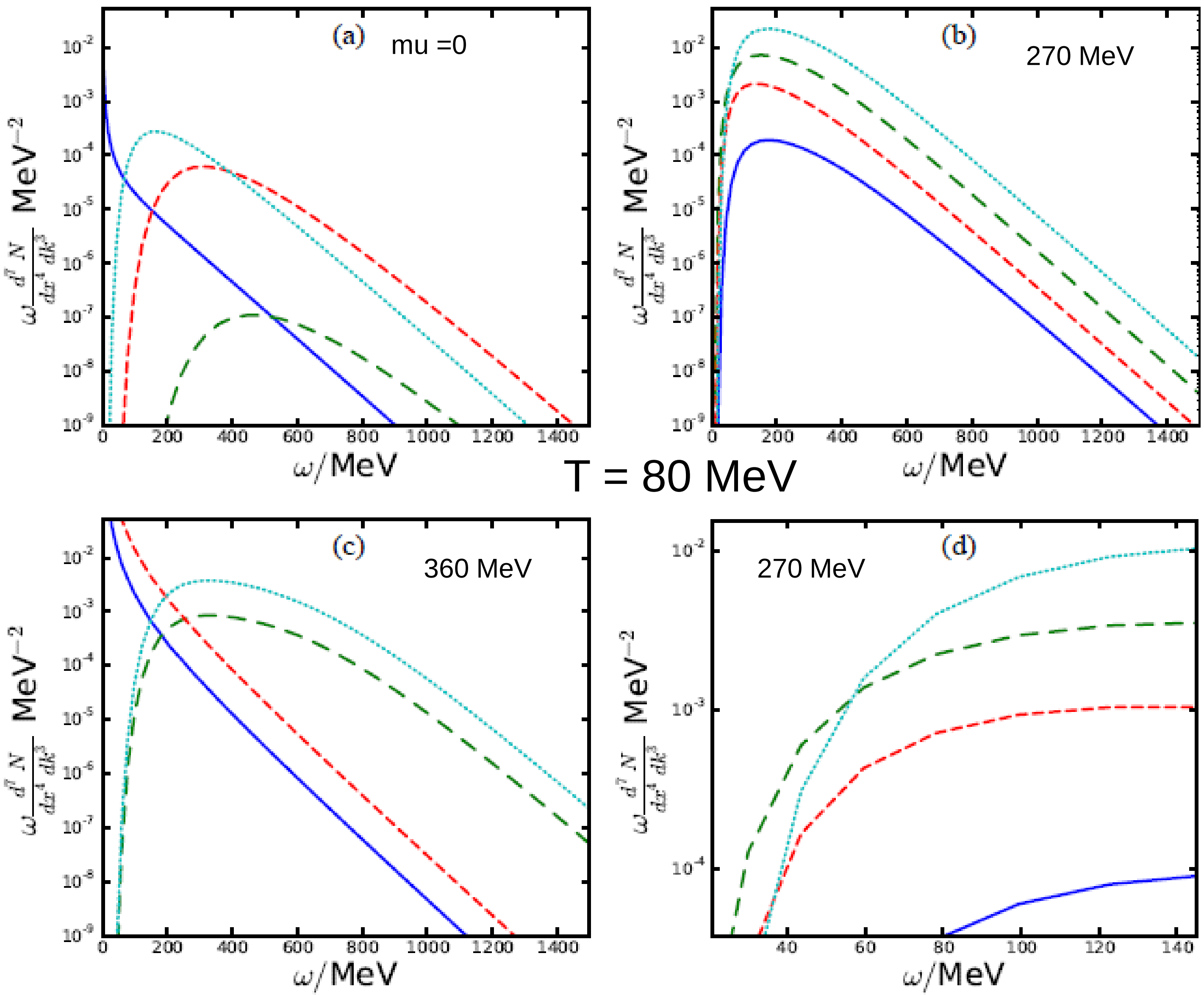


NJL analog:
Fukushima, Ruggieri, Gatto, PRD (2010)
LsM:
Mizher, Chernodub, Fraga, PRD (2010)

$$q_i + \sigma, \pi \to q_j + \gamma \quad \text{(Compton scatterings off quarks)},$$
$$\bar{q}_i + \sigma, \pi \to \bar{q}_j + \gamma \quad \text{(Compton scat. off antiquarks)},$$
$$q_i + \bar{q}_j \to \sigma, \pi + \gamma \quad \text{(annihilations)}$$

checked by FeynCal

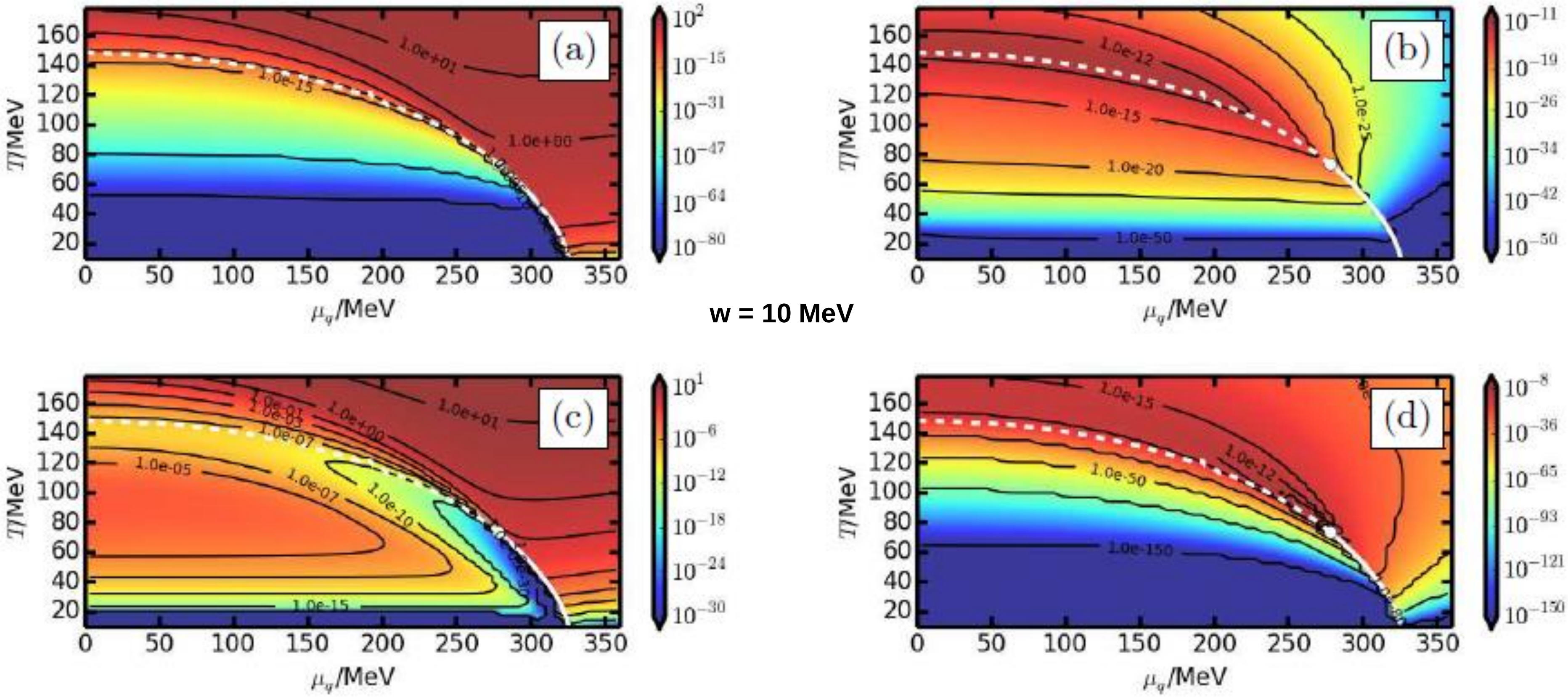
$$\omega\frac{d^7N_{12\to 3\gamma}}{dx^4dk^3} = C\int\frac{d^3p_1}{2p_1^0}\frac{d^3p_2}{2p_2^0}\frac{d^3p_3}{2p_3^0}\delta(p_1+p_2-p_3-k) \times|\mathscr{M}_{12\to 3\gamma}|^2 f_1(p_1)f_2(p_2)\big(1\pm f_3(p_3)\big).$$



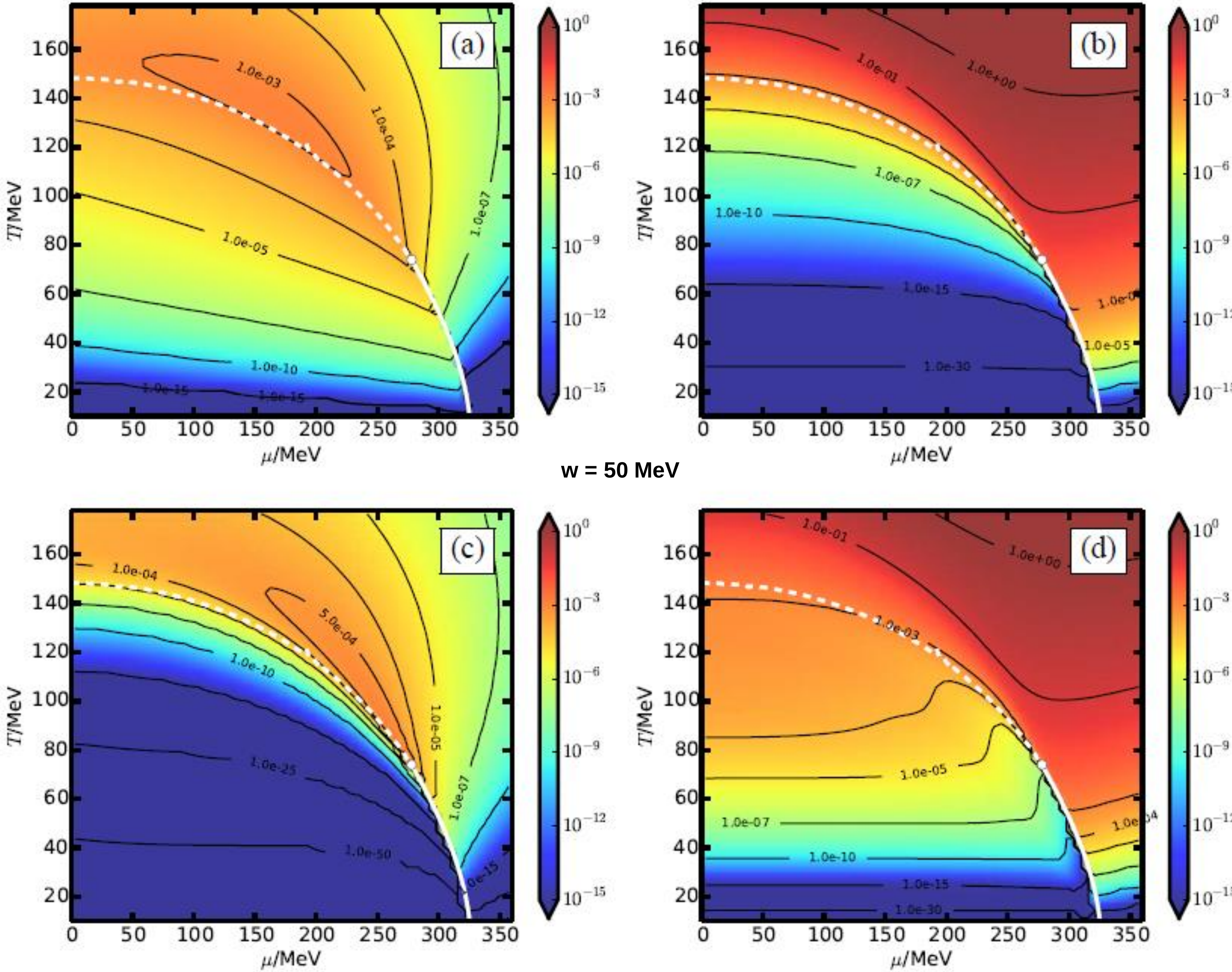
T = 80 MeV

q + pi → q + gam
q + sigma → q + gam
q + q_bar → pi + gam
q + q_bar → sigma + gam

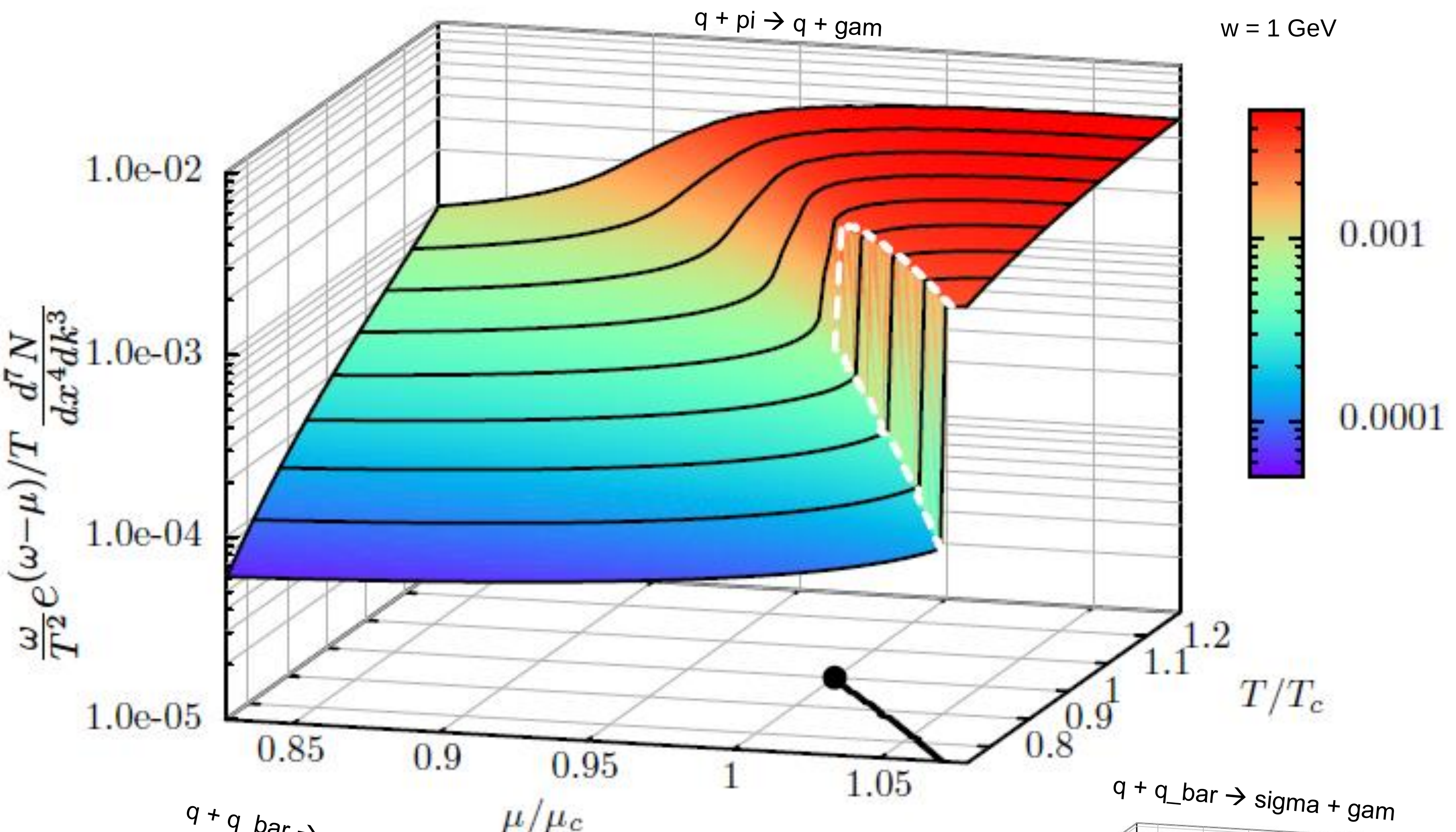
w d N / d^4 x d^3 k MeV^2

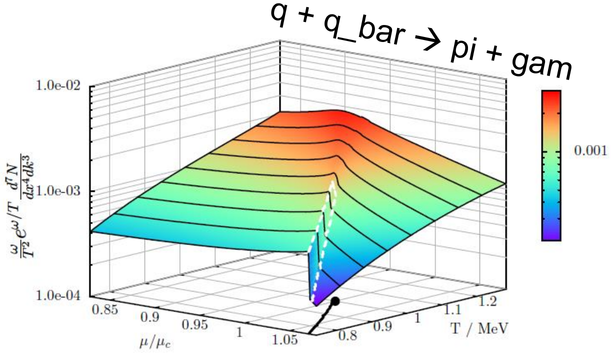


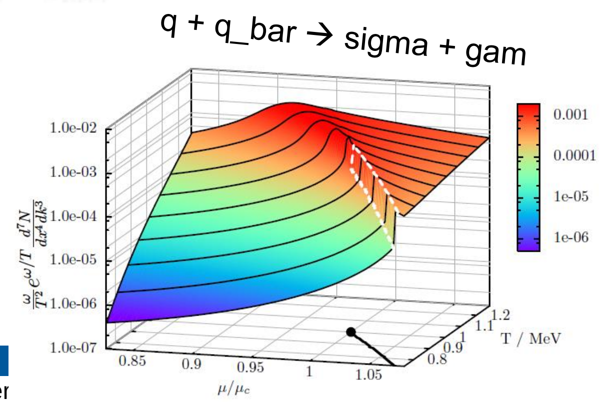
(a) q + q_bar → pi + gam
(b) q + pi → q + gam
(c) q + q_bar → sigma + gam
(d) q + sigma → q + gam



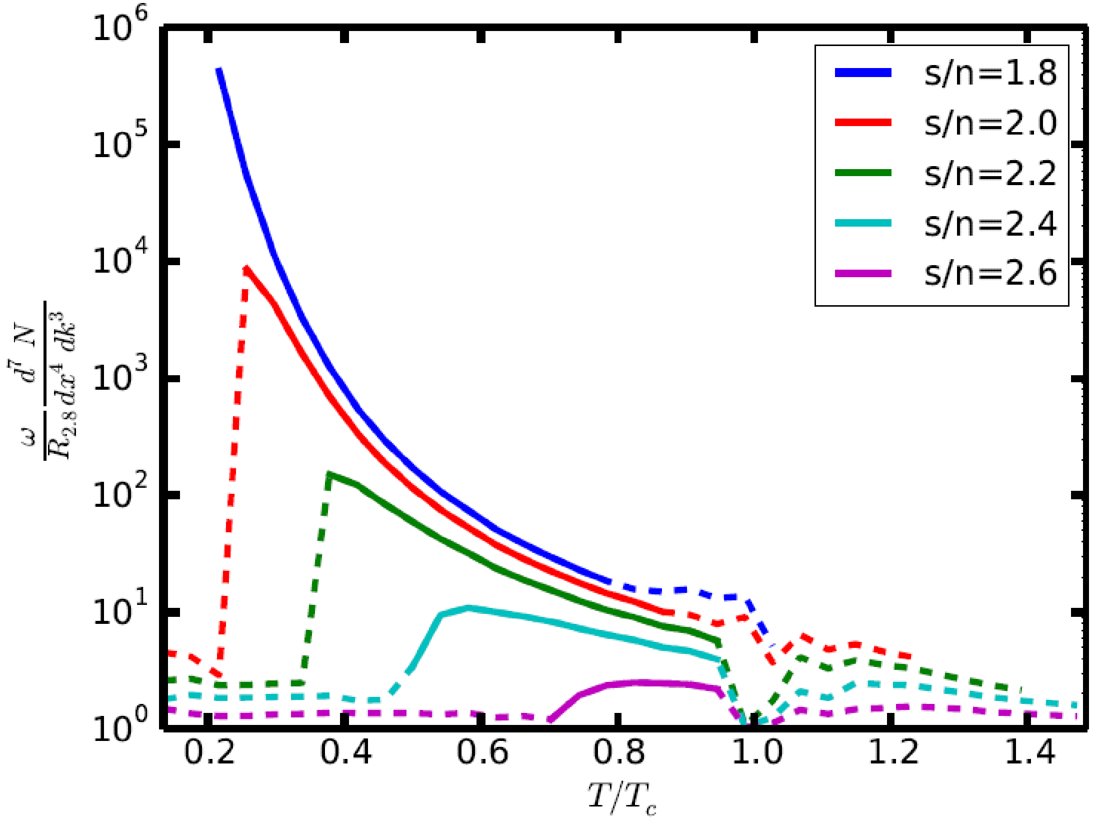
(a): $\psi + \pi \to \gamma + \psi$, (b): $\psi + \bar{\psi} \to \gamma + \pi$, (c): $\psi + \sigma \to \gamma + \psi$, (d): $\psi + \bar{\psi} \to \gamma + \sigma$.


q + pi → q + gam
w = 1 GeV
1.0e-02
1.0e-03
1.0e-04
1.0e-05
$\frac{\omega}{T^2} e^{(\omega-\mu)/T} \frac{d^7N}{dx^4 dk^3}$
0.85
0.9
0.95
1
1.05
μ/μ_c
0.8
0.9
1
1.1
1.2
T/T_c
0.001
0.0001


q + q_bar → pi + gam
1.0e-02
1.0e-03
1.0e-04
0.85
0.9
0.95
1
1.05
μ/μ_c
0.8
0.9
1
1.1
1.2
T / MeV
0.001

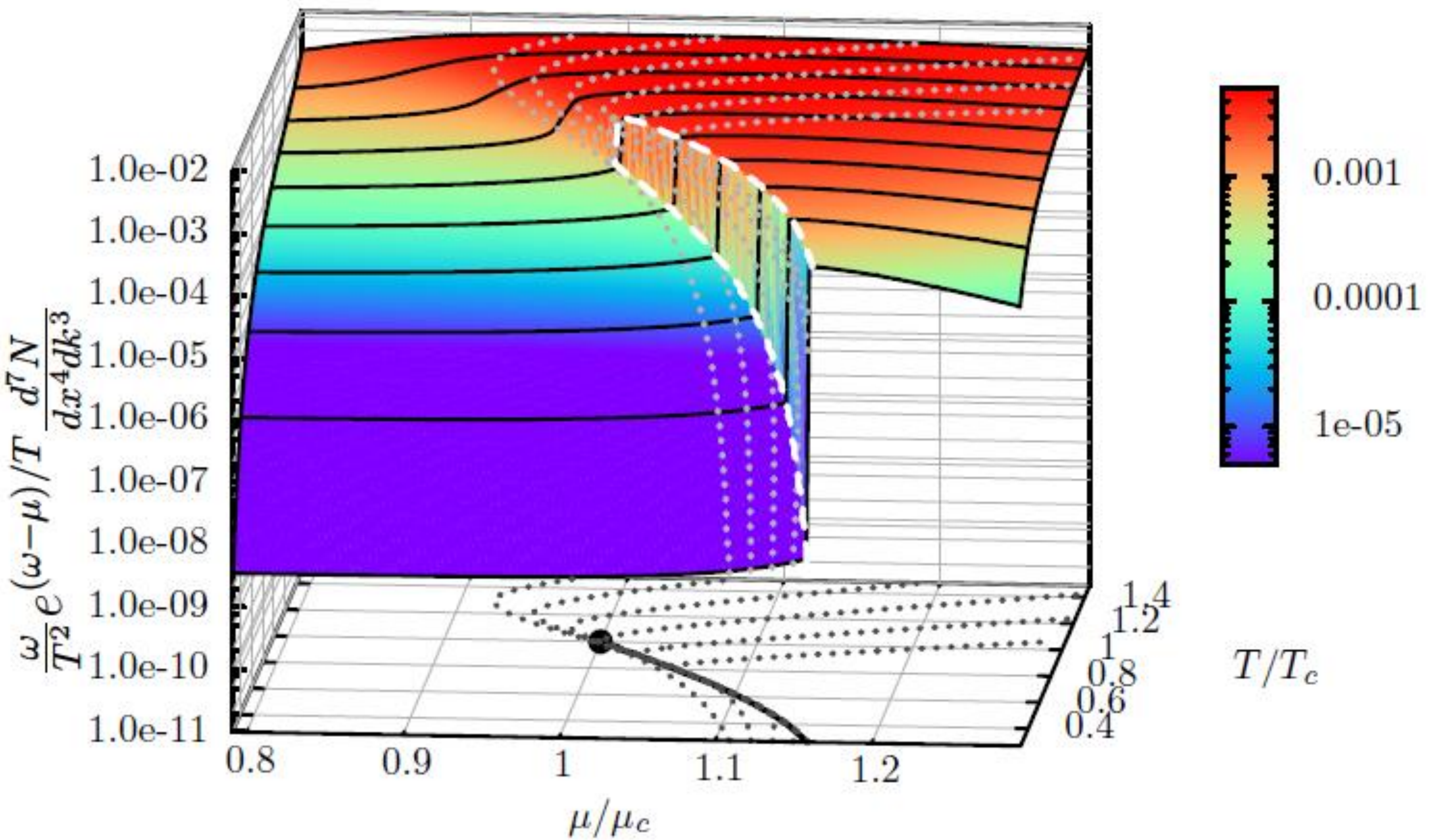

q + q_bar → sigma + gam
1.0e-02
1.0e-03
1.0e-04
1.0e-05
1.0e-06
1.0e-07
0.85
0.9
0.95
1
1.05
μ/μ_c
0.8
0.9
1
1.1
1.2
T / MeV
0.001
0.0001
1e-05
1e-06

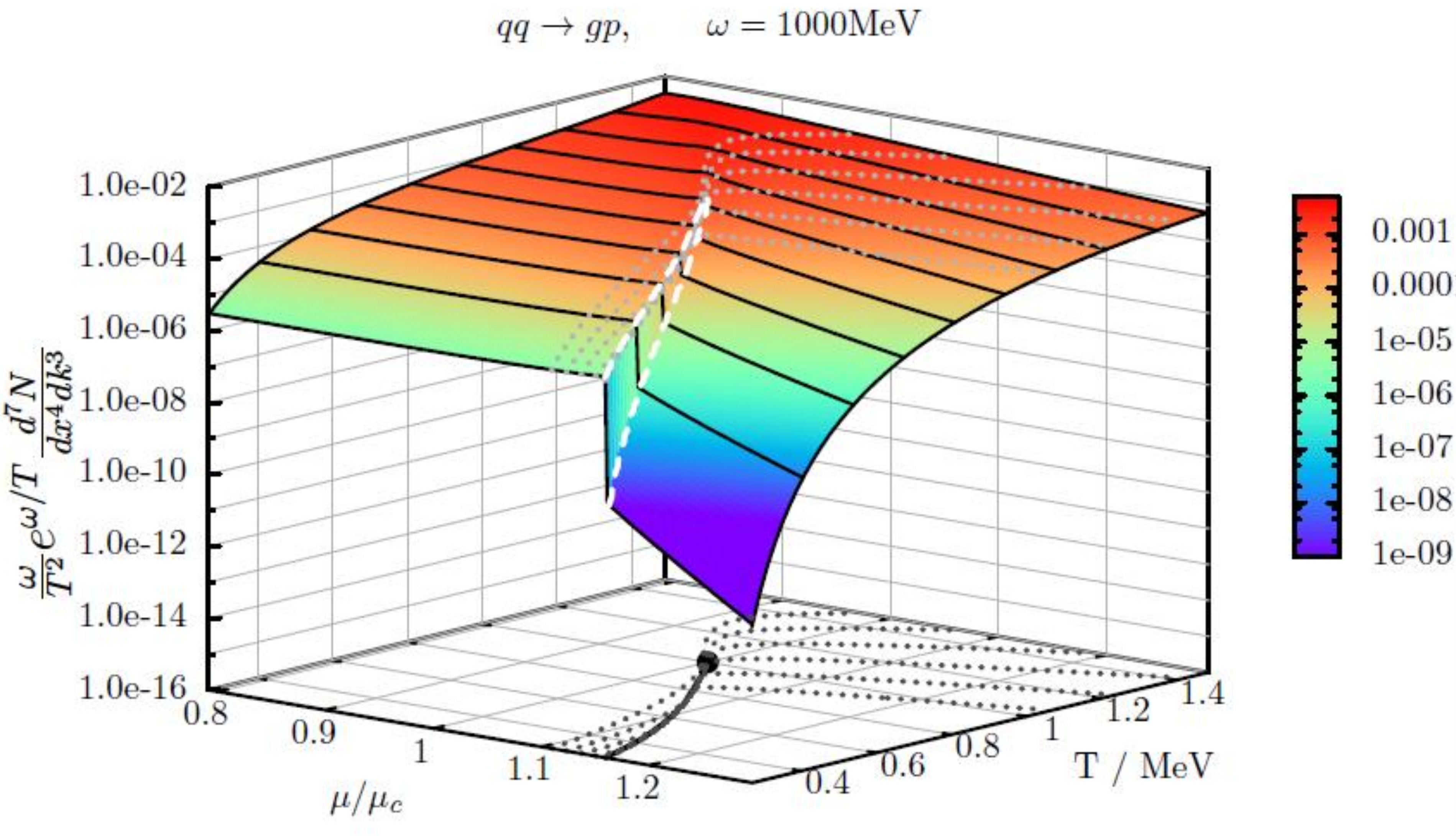
adiabatic expansion: s/n = const



reference: s/n = 2.8 (does not touch CEP and phase border curve

$qp \to gq, \qquad \omega = 1000\mathrm{MeV}$



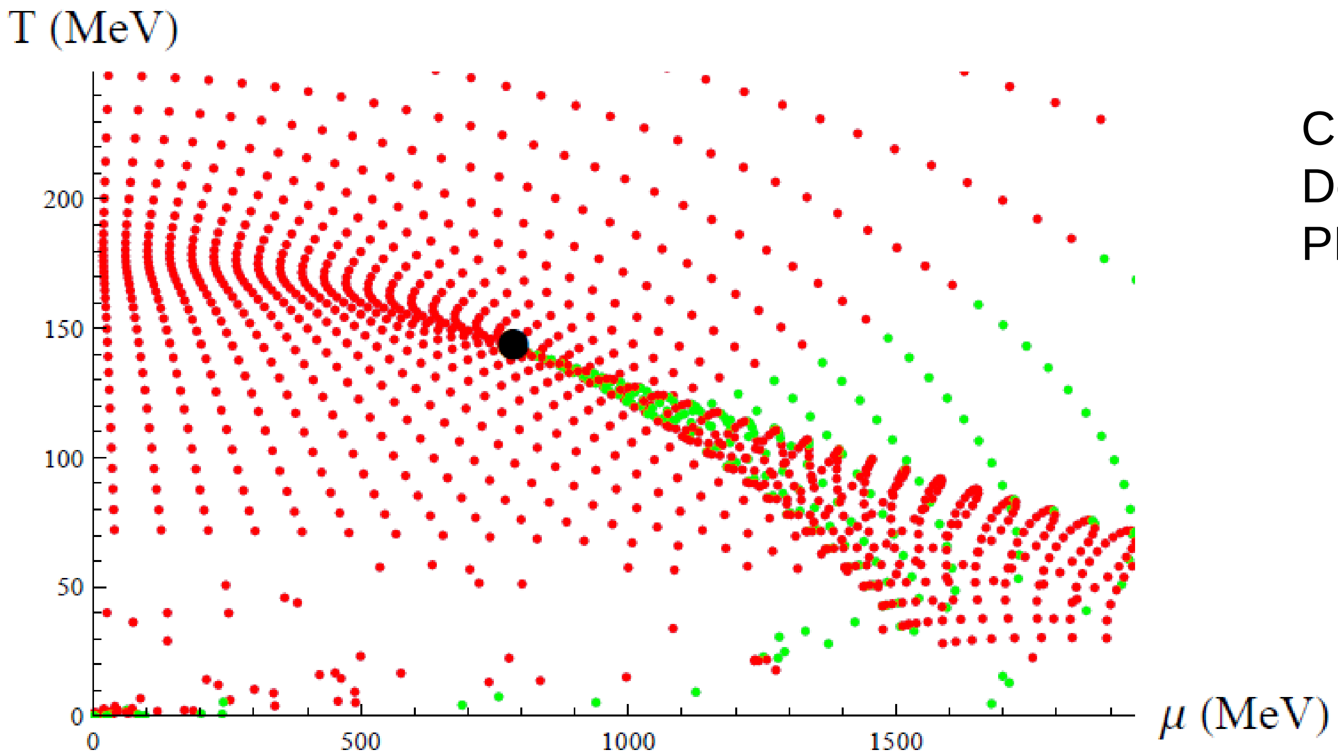


two effects: - rate(s) over T – mu plane reflect m(T, mu)

- adiabatic paths affected by phase border curve

we leave out the improper CEP (reminder: CEP → critical opalescence)

holographic avenues



Criticality at CEP:
DeWolfe, Gubser, Rosen
PRD (2011)

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Production of Prompt Photons: Holographic Duality and Thermalization
Baier, Stricker, Taanila, Vuorinen, Phys.Rev. D86 (2012) 081901

Holographic Dilepton Production in a Thermalizing Plasma
Baier,Stricker, Taanila, Vuorinen , JHEP 1207 (2012) 094

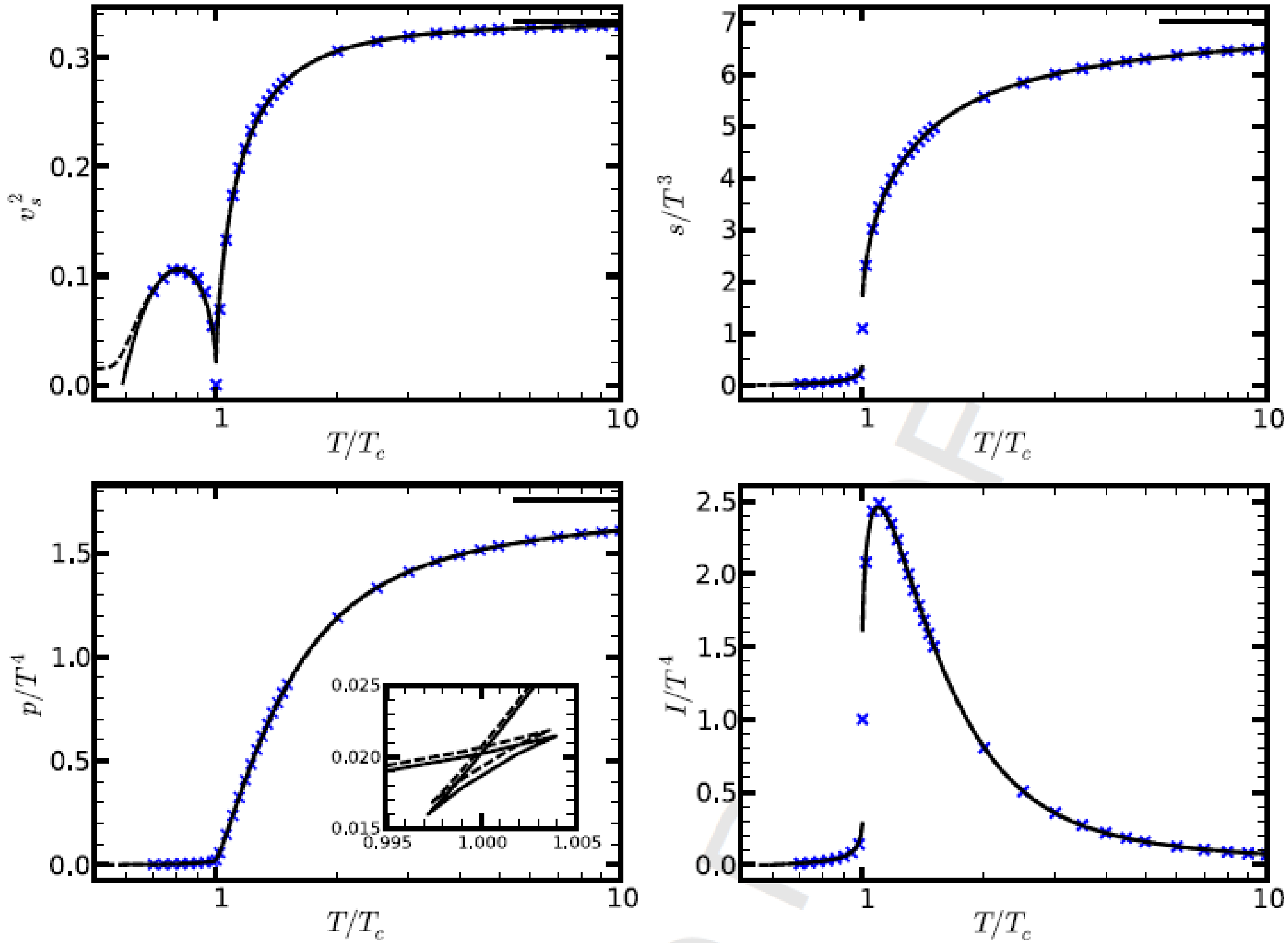
2. Viscosities: Holographic Input for midly NeD in HICs

1. Pure gluon medium: SU(3) – 1st order p.t.

exercise and model for early gluon-rich stage

QPM: Chabrobaty, Kapusta PRC (2012)
Bluhm, BK, Redlich, PRC (2012)

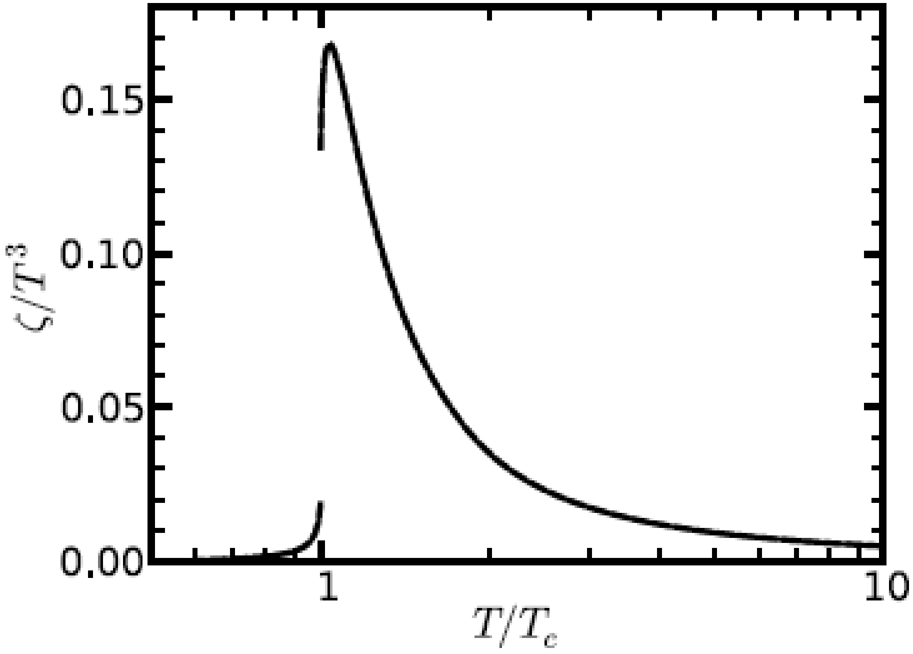
holography: Kiritsis et al.
Gubser et al.

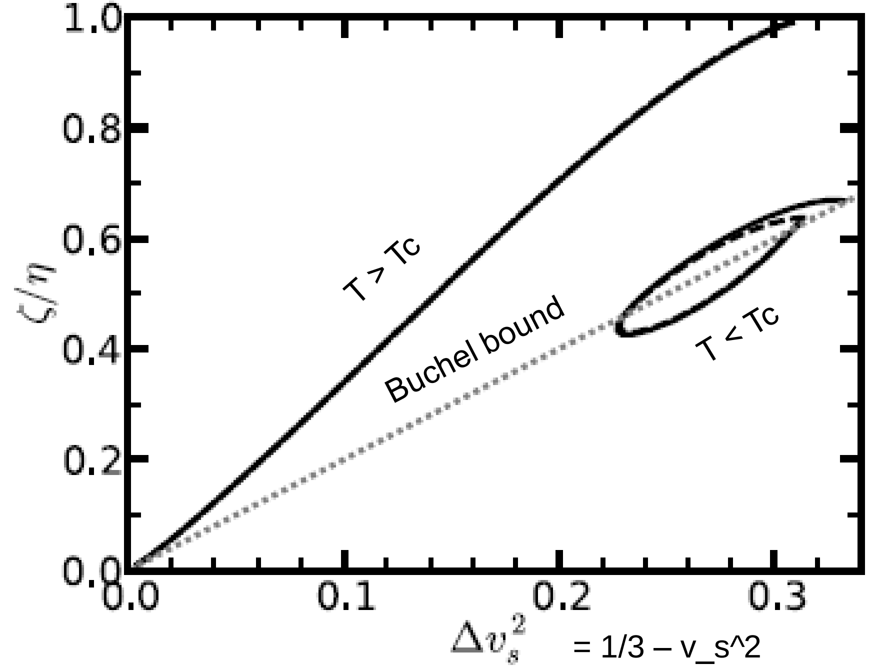


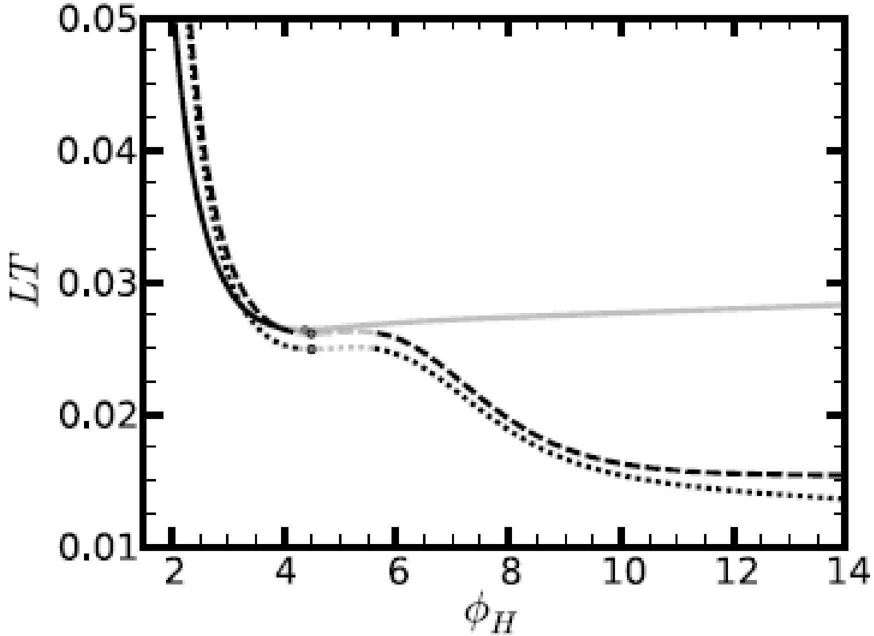
lattice data:
Borsanyi et al., JHEP (2012)

consistent with
Boyd et al., NPB (1996)

Yaresko, BK, PLB (2015)

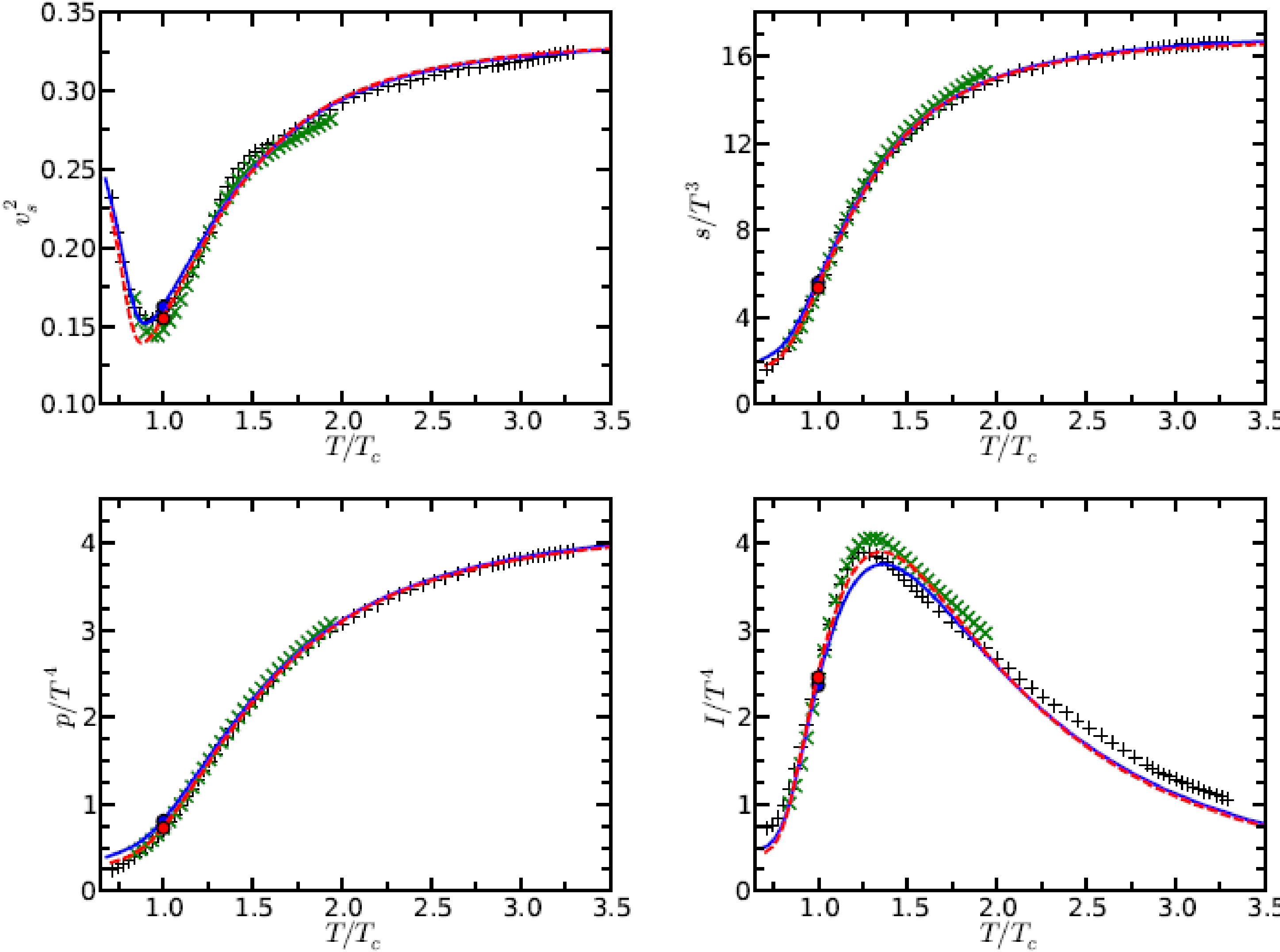






disclaimer: holographic model has eta/s = 1/ 4 pi

2. QCD: cross over – Tc → Tpc



lattice data:

+++: Borsanyi et al. PLB (2014)
xxx: Bazavov et al., PRD (2014)

Yaresko, Knaute, BK
EPJC (2015)

Holography

based on AdS/CFT correspondence

5D Riemann		4D Minkowski
class. gravity + fields		QFT (operators)
asymp. AdS + black hole	Hawking T Bekenstein-Hawking s	thermo-field theory
metric		energy-momentum tensor
dilaton		<(gluon field)^2>
tachyon		quark condensate

At $\mu = 0$, the equation of state, in parametric form, follows from [13]

$$LT(\phi_H) = \frac{V(\phi_H)}{\pi V(\phi_0)} \exp\Big(A(\phi_0) + \int_{\phi_0}^{\phi_H} d\phi \Big[\frac{1}{4X} + \frac{2}{3}X\Big]\Big), \quad (1)$$

$$G_5 s(\phi_H) = \frac{1}{4} \exp\Big(3A(\phi_0) + \frac{3}{4}\int_{\phi_0}^{\phi_H} d\phi \frac{1}{X}\Big), \quad (2)$$

for entropy density s and temperature T, where the scalar function $X(\phi; \phi_H)$ [14] is determined by the system (a prime means a derivative w.r.t. ϕ)

$$X' = -\Big(1 + Y - \frac{2}{3}X^2\Big)\Big(1 + \frac{3}{4X}\frac{V'}{V}\Big), \quad (3)$$

$$Y' = -\Big(1 + Y - \frac{2}{3}X^2\Big)\frac{Y}{X}, \quad (4)$$

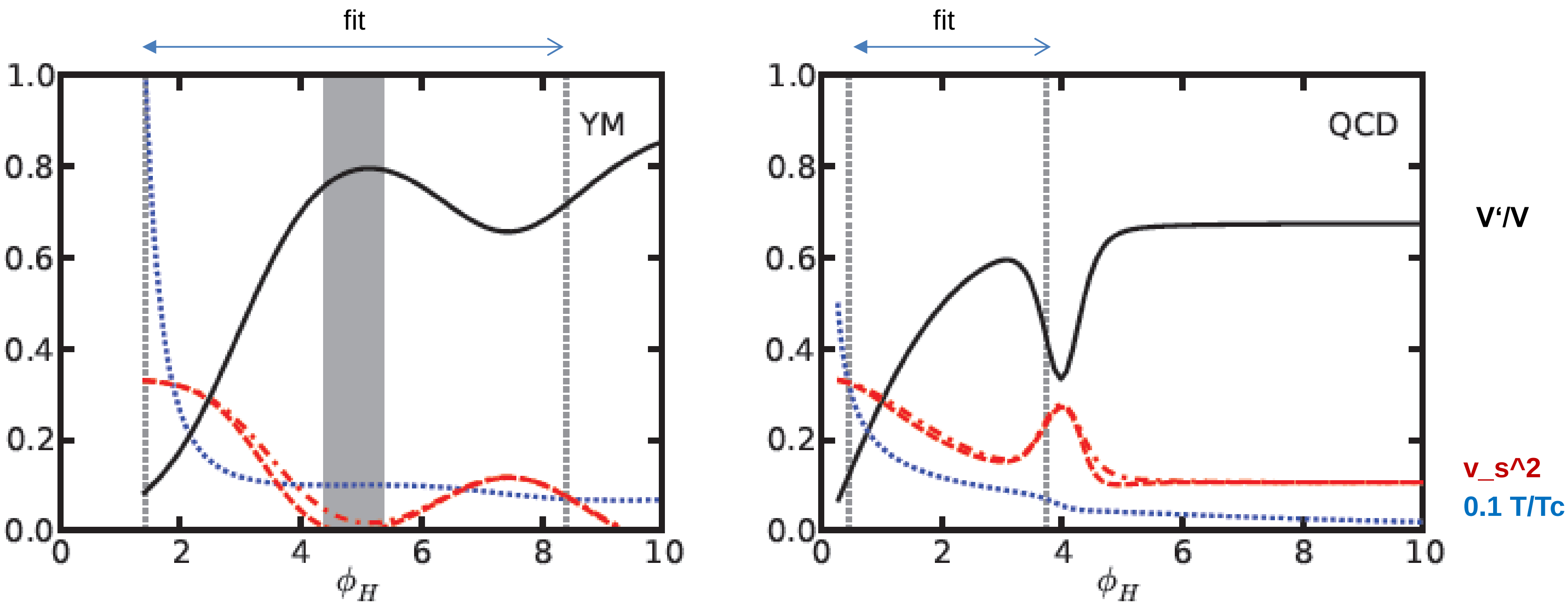
which is integrated from the horizon $\phi_H - \epsilon$ to the boundary ϕ_0 with initial conditions

$$X(\phi_H - \epsilon) = -\frac{3}{4}\frac{V'(\phi_H)}{V(\phi_H)} + \mathcal{O}(\epsilon^1), \quad (5)$$

$$Y(\phi_H - \epsilon) = -\frac{X(\phi_H - \epsilon)}{\epsilon} + \mathcal{O}(\epsilon^0), \quad (6)$$

and $\epsilon \to 0$. The quantity $A(\phi_0)$ encodes the near-boundary behavior of the model. We assume $L^2 V(\phi) \approx -12 + \frac{L^2 M^2}{2}\phi^2$ for $\phi \to \phi_0 = 0$ which results in $A(\phi_0) = \frac{\log \phi_0}{\Delta - 4}$, whereby we have set $L\Lambda = 1$ [13] and, as usual, $L^2 M^2 = \Delta(\Delta - 4)$. We consider $2 < \Delta < 4$.

adjusting potentials (phi self-interaction)



dream: lattice QCD thermodynamics → V(phi)

outlook: mu > 0 & phase diagram a la deWolfe, Gubser, Rosen

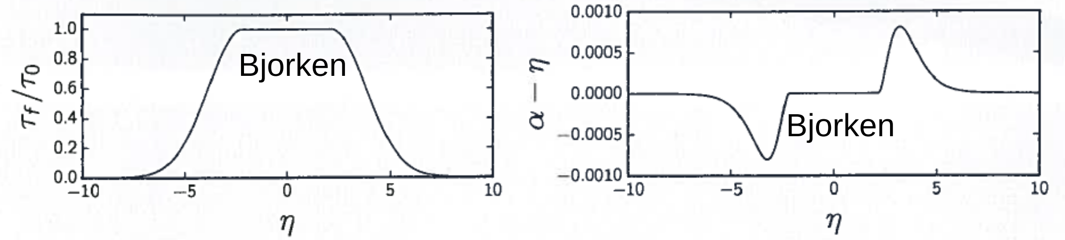
3. Longitudinal Dynamics

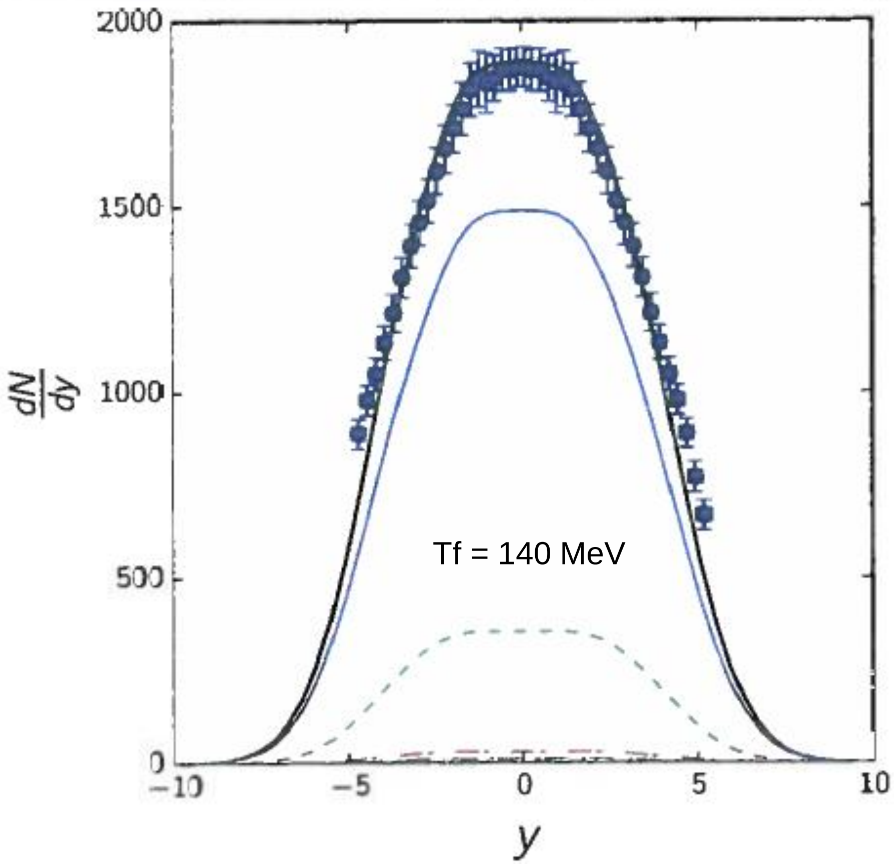
(i) CF freeze-out

$$\frac{dN}{dy} = \frac{A_\perp}{(2\pi)^2} \int d\chi \, \frac{g(\chi, y)}{f(\chi, y)} \, e^{-m f(\chi, y)} \left[m^2 + \frac{2m}{f(\chi, y)} + \frac{2}{f^2(\chi, y)} \right]$$

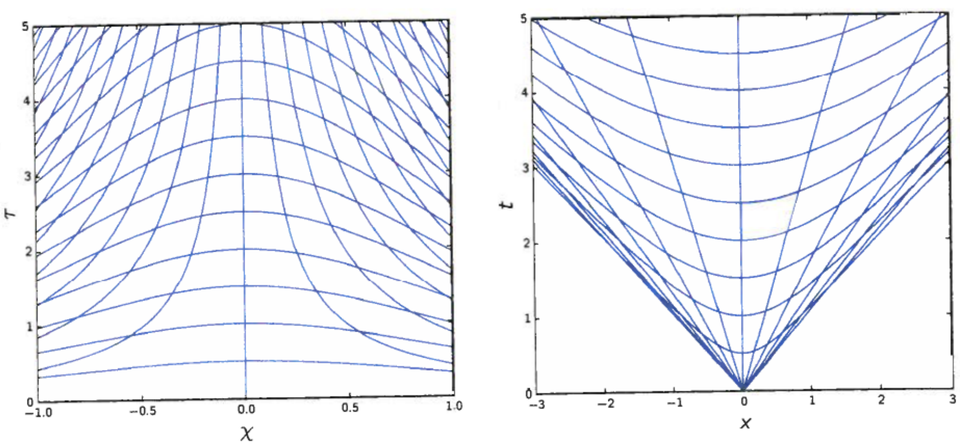
$$f(\chi, y) = \frac{1}{T_f} \cosh(y - \alpha(\chi)) \, ,$$

$$g(\chi, y) = \sinh(\chi - y) \, \partial_\chi \tau_f(\chi) + \tau_f(\chi) \cosh(\chi - y) \, .$$





Milne coordinates



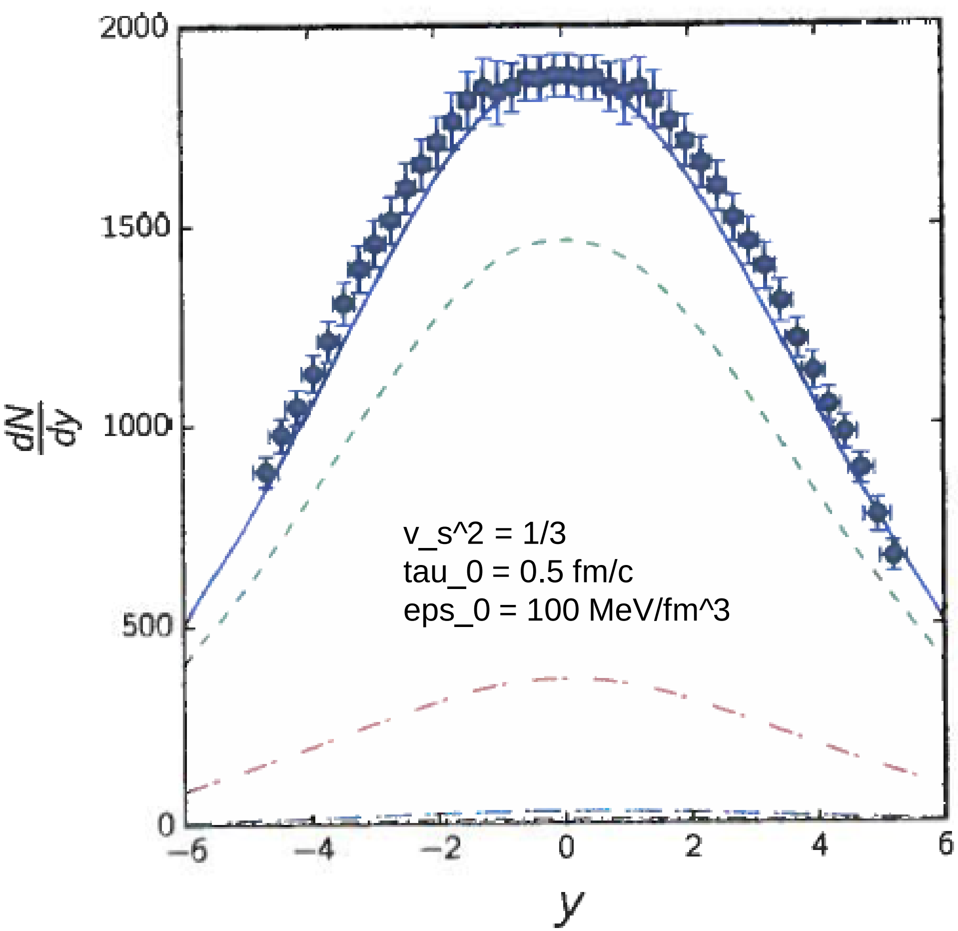
data: ALICE, PLB (2013)   Pb + Pb, sqrt(s_NN) = 2.75 TeV

(ii) dynamics

initial conds.

$$\epsilon(\tau_0, \chi) = \begin{cases} \varepsilon_0 & \text{für } |\chi| < a\,, \\ \varepsilon_0 e^{-b(\chi - a\,\mathrm{sign}(\chi))^2} & \text{für } |\chi| \geq a\,, \end{cases}$$

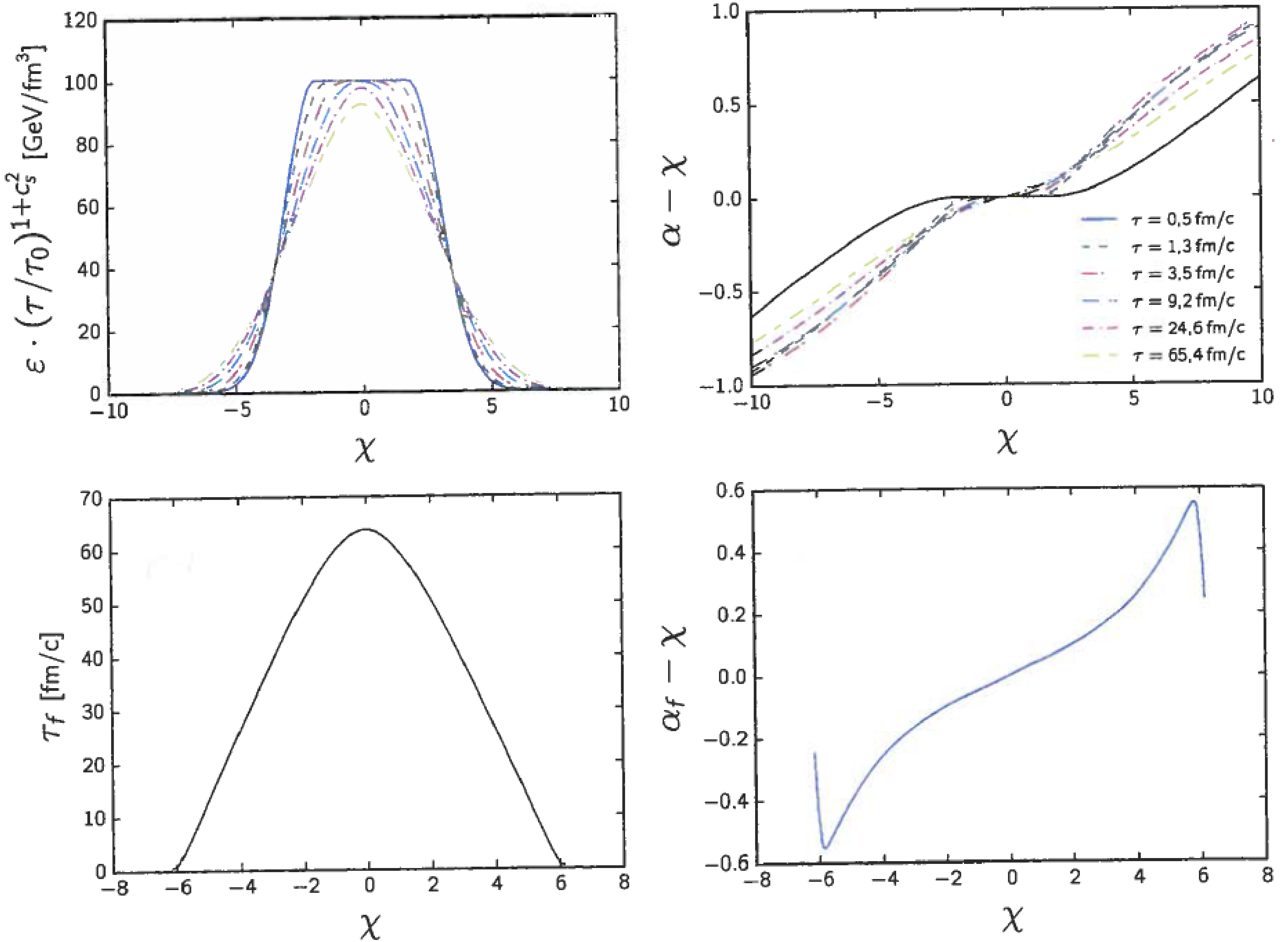
$$\alpha(\tau_0, \chi) = \begin{cases} \chi & \text{für } |\chi| < a\,, \\ \chi + b\,\mathrm{sign}(\chi)\left(\sqrt{0{,}1 \cdot (|\chi| - a)^2 + 1} - 1\right) & \text{für } |\chi| \geq a\,, \end{cases}$$



reminder:

Bjorken flow: $\epsilon(\tau)$

$\alpha = \chi$



$\varepsilon \cdot (\tau/\tau_0)^{1+c_s^2}$ [GeV/fm^3]
χ
$\alpha - \chi$
τ = 0,5 fm/c
τ = 1,3 fm/c
τ = 3,5 fm/c
τ = 9,2 fm/c
τ = 24,6 fm/c
τ = 65,4 fm/c
τ_f [fm/c]
$\alpha_f - \chi$

next step: inverting a heavy-ion collision

a la Stephanov, Yin (2014)

reformulate hydro in T, alpha coordinates
→ Chauchy problem from freeze-out into past
supposed (i) viscosities are small
(ii) 1+1 dynamics is applicable

1 + 1 hydro (two 1st order pDEs) → Chalatnikov eq. (one 2nd order pDEs)

Summary/Outlook

- photon emissivities: phase structure → rates,
  adiabatic expansion trajectories
  + phase mixture
- 1-dilaton holography: lattice QCD → V(phi) → viscosities,
  improvements: 2-field model with
  chiral condensate, non-zero mu
- dN/dy (ALICE) → f.o. hypersurface
  improvements: more dynamics + EoS