LHC/RHIC: **GlueBall Factory**! ... but **where** are all the GlueBalls gone?

Early proposals for two phase transitions and two timescales in RHICs:

Svetitsky&Yaffe, Pisarski&Wilczek, Raha&Sinha, Shuryak et al…

1. CGC Gluon Supersaturation

2. Gluon Equilibration

3. First Transition: 1.Order Phase Transition in YM pure gauge theory

4. Pure Gauge Theory vs. “physical” 2+1 N_f QCD

5. Glue Plasma vs Quark-Gluon Plasma 2.Transition: hadronization ?

6. Observable signals for GlueBalls in high multiplicity pp, pA - AA ?

- HagedornStates, hadron ratios, pt-distributions, Flow&**Ridge** pp & pA
- plus Dileptons, Photons, Centauros,… vs. **Multiplicity in pp**, pA…

Horst Stoecker, **CCNU, Wuhan** and GSI Helmholtzzentrum f. Schwerionenphysik

Judah M. Eisenberg Professor Laureatus, ITP & FIAS, Goethe Univ. Frankfurt

Acknowledgements

Transport colleagues: Zhou, Seizel, Xu, Zhuang, C. Greiner...

Hagedorn dynamics: Beitel, Gallmeister, C. Greiner...

FIAS: Schramm, Dietrich, Struckmeier, Vasak, ...

Early phase e-m probes colleagues: Raha, Sinha, Gorenstein, Vovchenko, Satarov, Mishustin, A. Srivastava, Csernai ...

Lattice colleagues: Fodor, Borsanyi, Szabo, Karsch, Philipsen...

Experimentalists: Giubellino, Harris, Oeschler, PBM, Masc..

Traditional picture of QCD matter in Heavy Ion Collisions

Initial Color Glass Condensate → Glasma thermalizes → fast equilibration of Gluons and Light flavor quarks high pressure, entropy → hydrodynamic expansion → flow as excellent probe of QCD matter.

↓

Hadronization@T=155MeV: crossing of 2+1 flavor QCD.

↓

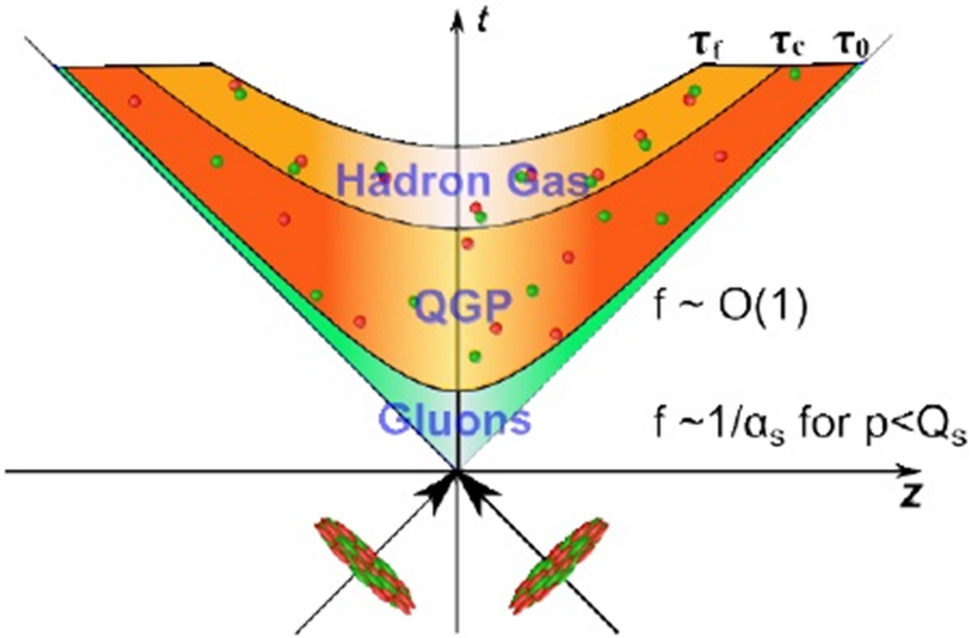
Hadronic yields and v_n at RHIC and LHC measured.

↓

Comparison of HRG, T= 155 MeV, with LHC data tests our understanding of QCD matter.

Introduction : Fast thermalization

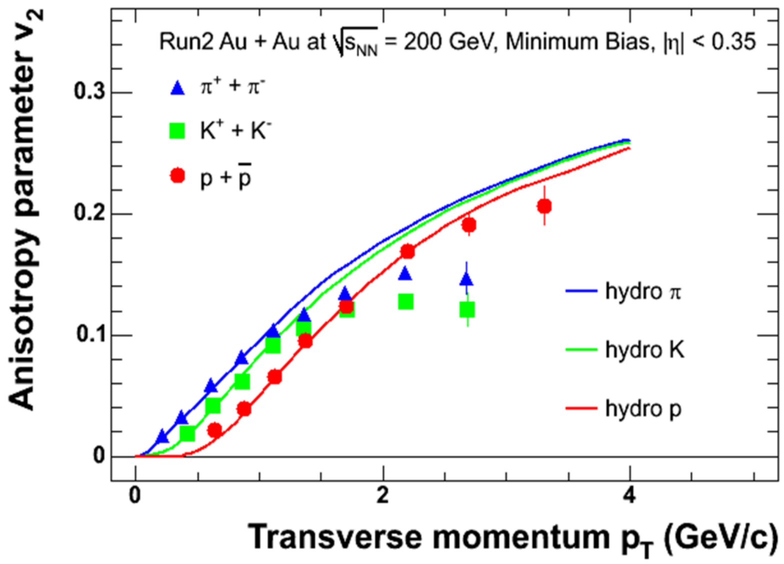
"how the systems evolve to thermal equilibrium in a very short time scale"

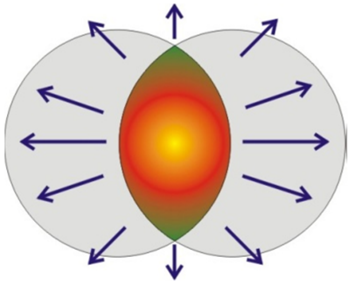


Initial: far from equilibrium

$f \sim O(1)$

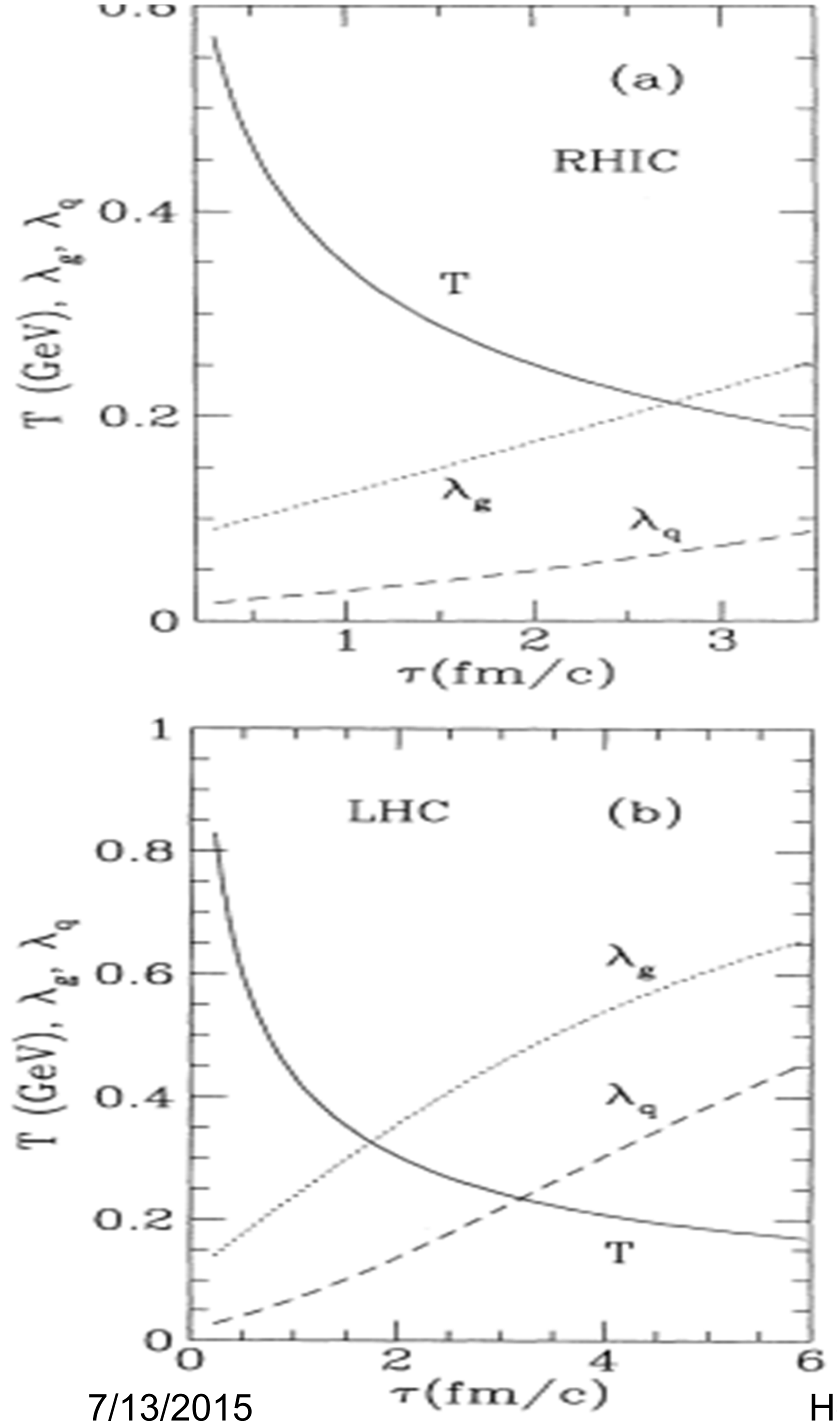
$f \sim 1/\alpha_s$ for $p<Q_s$





2+1 QCD Hydrodyna.
Onset time ~ 1fm/c ?

BMW: Early stage **NO QCD** ! Pure glue.

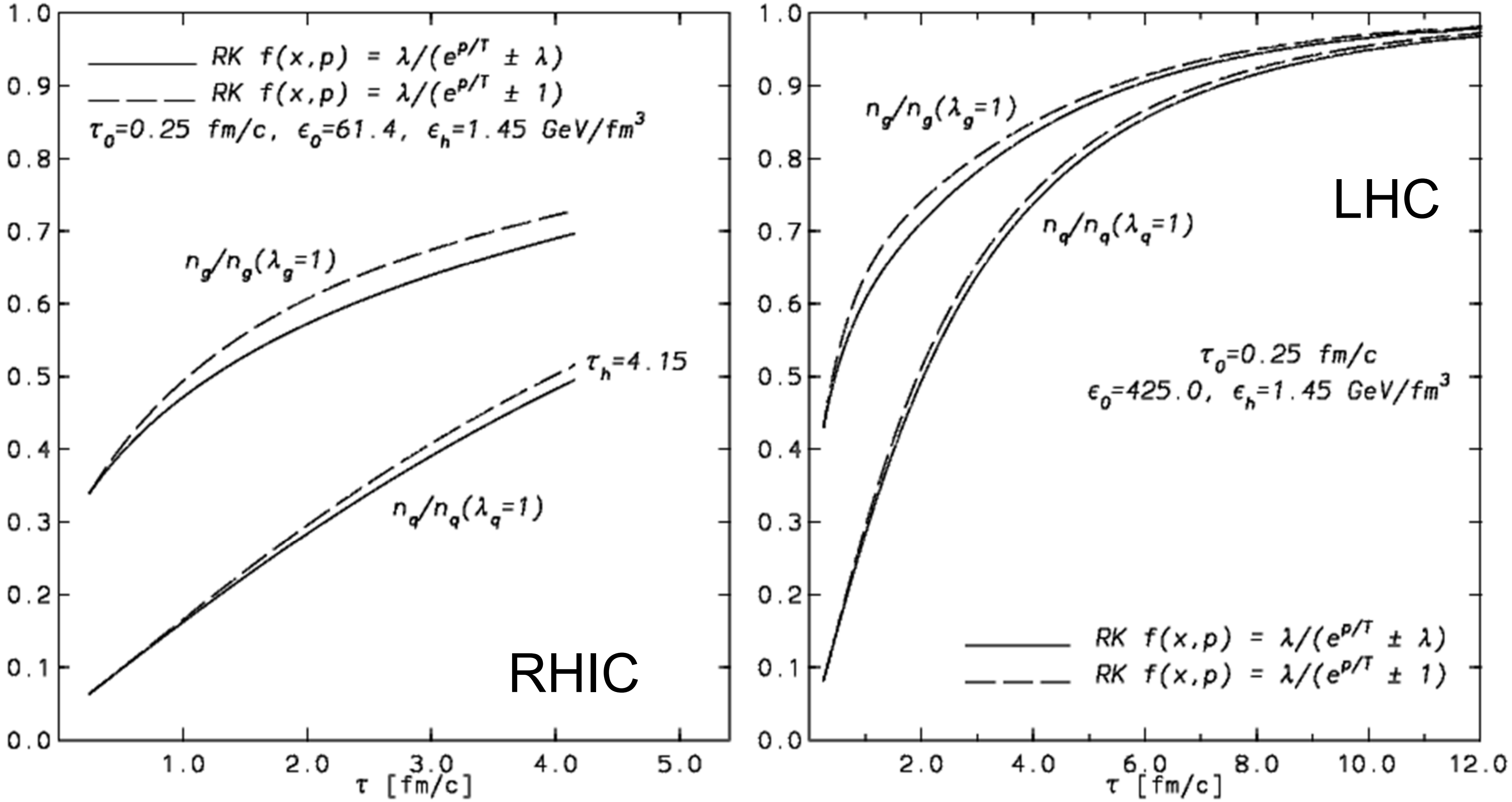


Time evolution of fugacity of gluons and quarks (g, q) from pQCD-based rate eq.

T. S. Biró, B. Mueller, X. Wang,

BMW , PRC48,1275 (1993)

$$(fugacity = n / n^{eq})$$

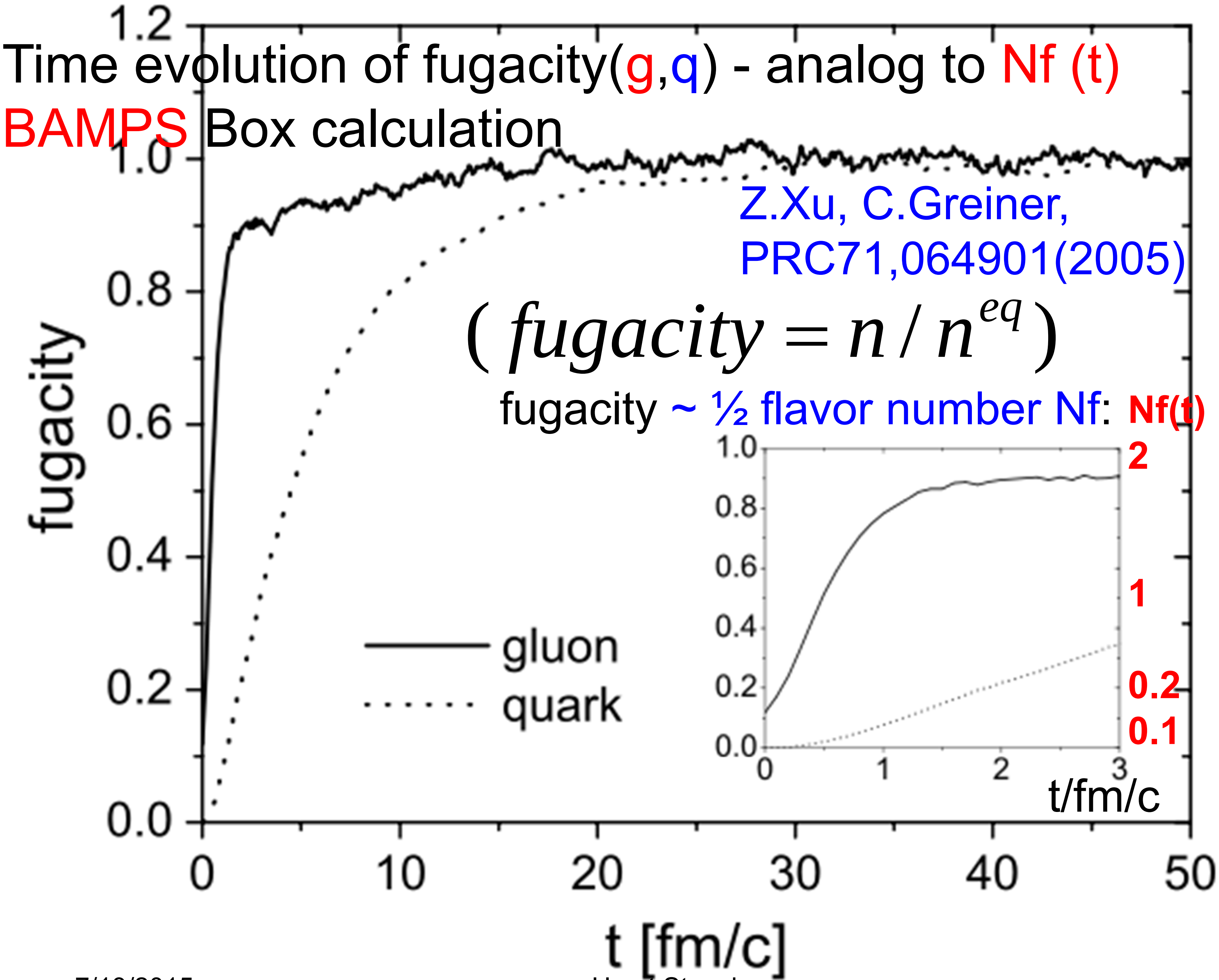


Rate equation calculation

D.M. Elliott, D.H. Rischke,Nucl.Phys. A671,583 (2000)

Time evolution of fugacity(g,q) - analog to Nf (t)

BAMPS Box calculation



Z.Xu, C.Greiner,
PRC71,064901(2005)

$$(\,fugacity = n/n^{eq}\,)$$

fugacity ~ ½ flavor number Nf:

Introducing the Color Glass Condensate

CGC=effective field theory for hadrons at <u>high energy limit</u>

- high energy (time dilation) $\Big\{$ fluctuation(sea partons) lifetime / internal interaction time scales $\Big\}$ $\Longrightarrow$ small x ($x \sim p_z / E_{hadron}$)l

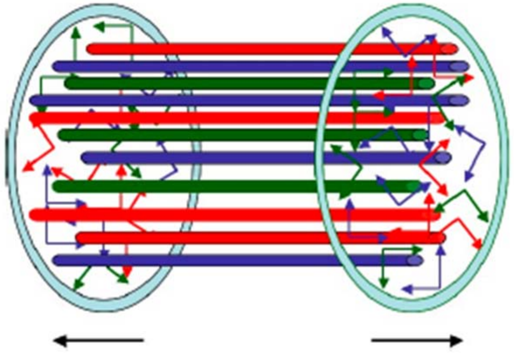
gluon number increase at small x with increasing energy

- gluon fusion $f \sim f^2 \alpha_s \Longrightarrow f \sim 1/\alpha_s$ **Saturation**
- **Saturation momentum Qs(~GeV)** $xG(x,Q^2)/Q^2 \rightarrow 1/\alpha_s$

$\Rightarrow$ $f \sim 1/\alpha_s (Q < Q_s)$ this feature can be inherited by initial Glasma through indirect way

Introducting the Glasma

Glasma=non-equilibrium state in between CGC and QGP



- using CGC as initial states for nuclei

⟹ $$T^{\mu\nu} = diag(\varepsilon, \varepsilon, \varepsilon, -\varepsilon)$$

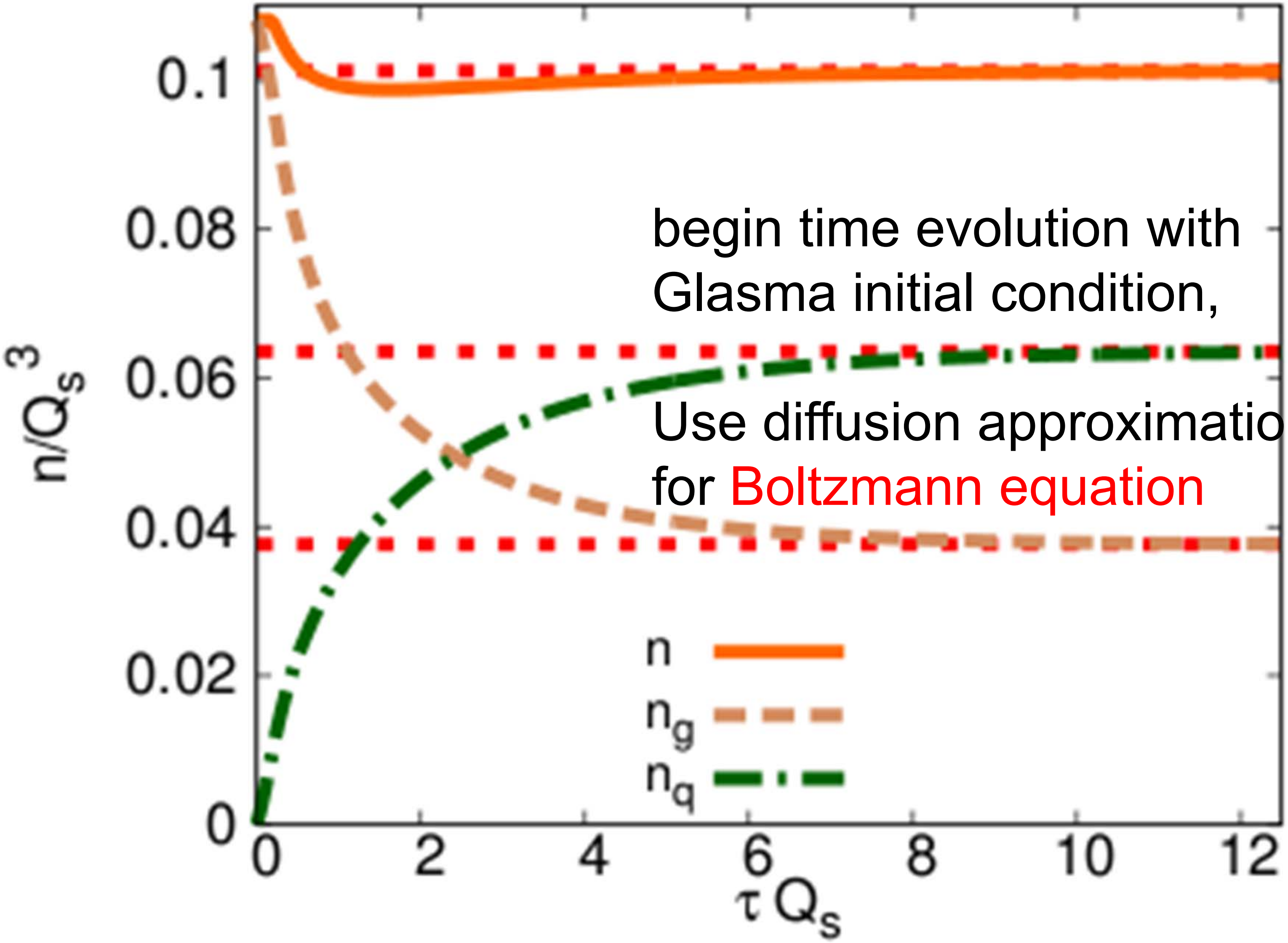
highly anisotyopic initial glasma fields

(won't last longer than 1/Qs)

- **Instabilities** -->wide range of unstable modes (up to Qs) grow exponentially untill saturation density

⟹ $\left\{ \begin{array}{l} \text{redistribute momentum ---> } \textbf{isotropization} \\ \text{free up quanta from classical field} \end{array} \right.$

⤷ $$f_0 = 1/\alpha_s (p < Q_s)$$ **initial condition amenable for kinetic theory**



begin time evolution with Glasma initial condition,

Use diffusion approximation for Boltzmann equation

Jean-Paul Blaizot, Bin Wu, Li Yan, Nucl.Phys. A930,139(2014)

Introducting: Overpopulation

Overpopulation = the system contain more gluons than can be accommodated by a Bose-Einstein distribution

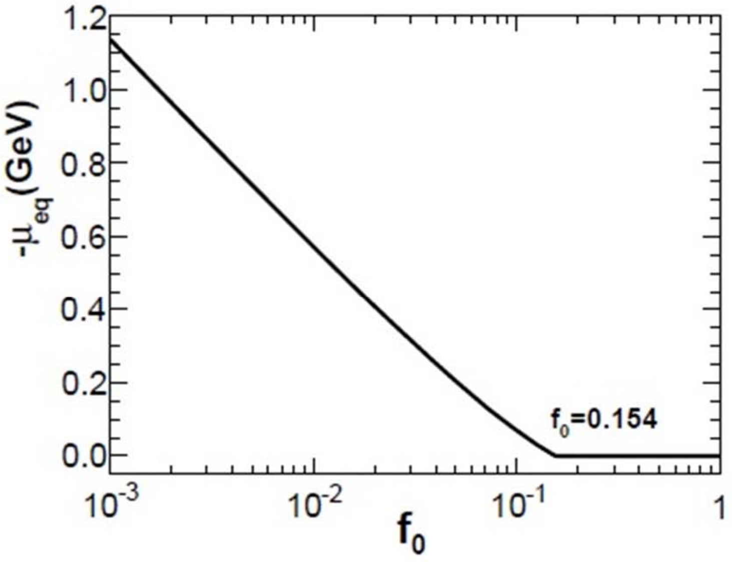
initially: $f_{init}(p) = f_0\theta(1 - p/Q_s)$ expected final: $f_{eq}(p) = 1/(e^{(p-\mu_{eq})/T_{eq}} - 1)$

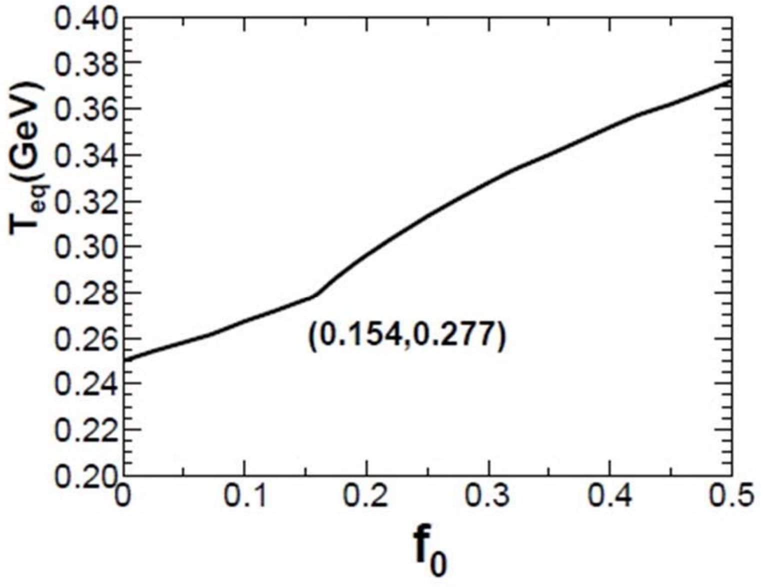
$$\varepsilon_{eq}(T_{eq}, \mu_{eq}) = \varepsilon_0 = \int \frac{d^3p}{(2\pi)^3} \frac{p}{e^{(p-\mu_{eq})/T_{eq}} - 1}$$

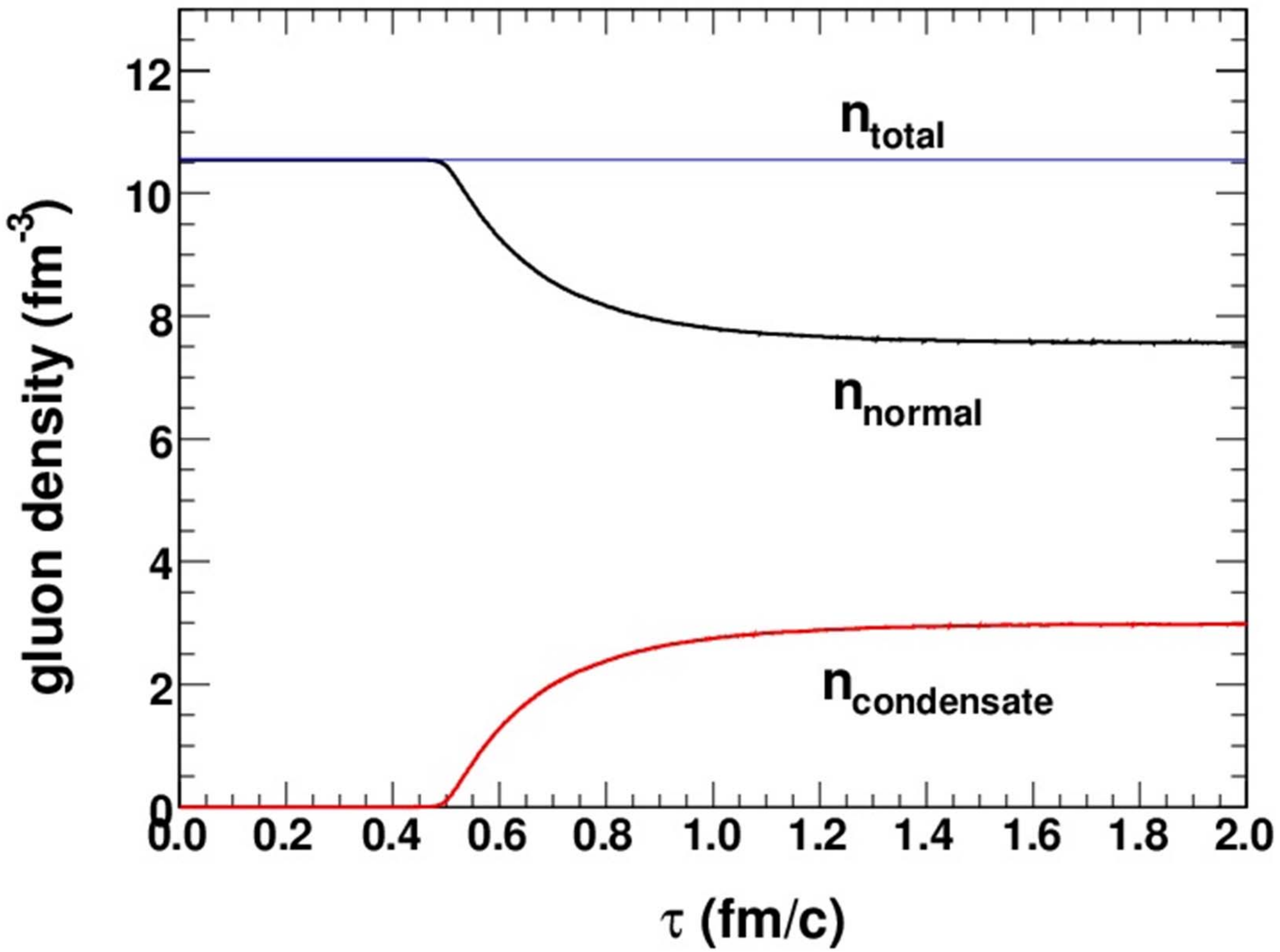
$$n_{eq}(T_{eq}, \mu_{eq}) = n_0 = \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{(p-\mu_{eq})/T_{eq}} - 1}$$

$f_{critical} = f_0 = 0.154$

even for $\alpha_s \sim 0.3$,
still highly overpopulated

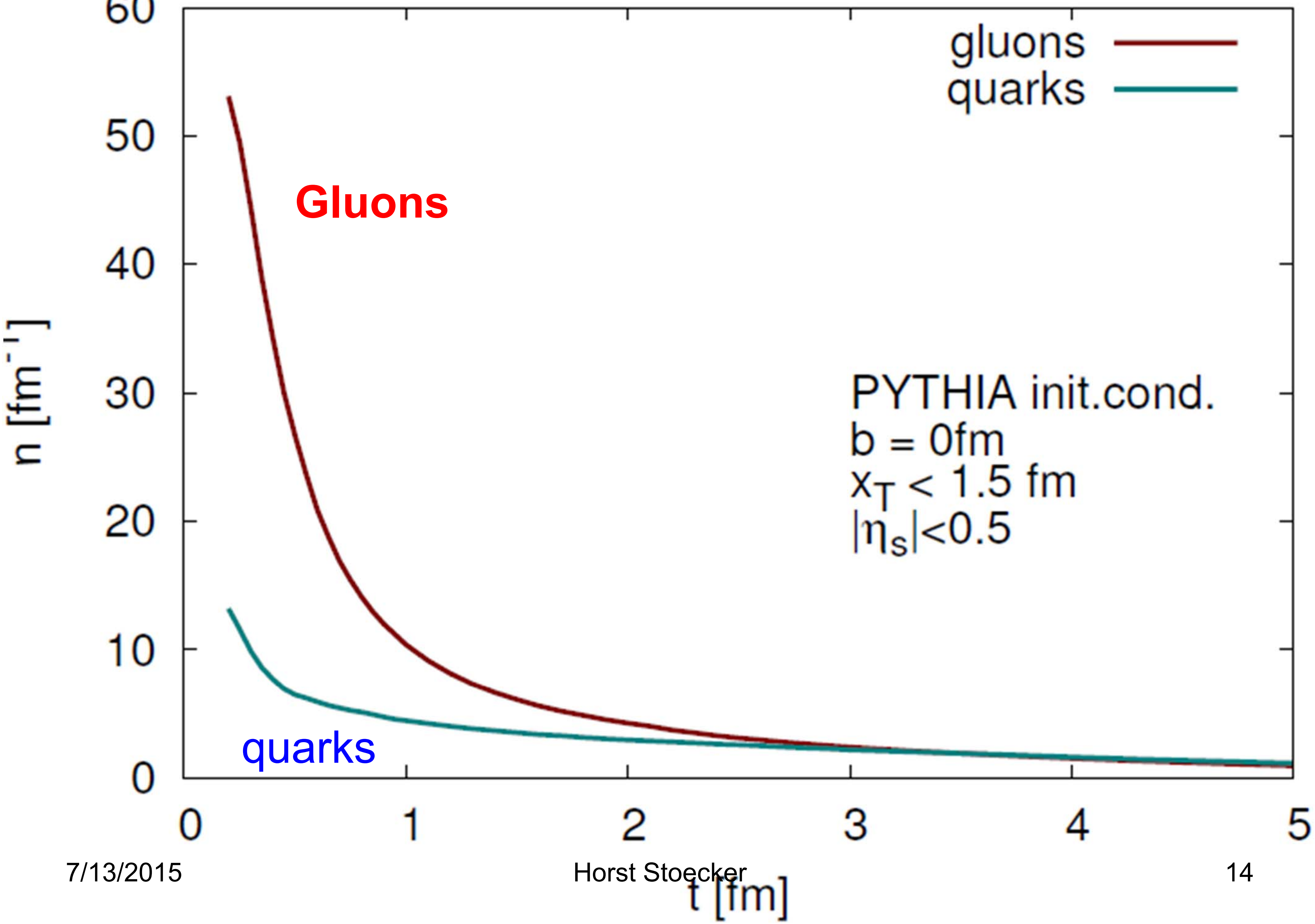






Kai Zhou, Zhe Xu, Carsten Greiner,

Gluon yields & quark yields, F. Senzel, Z. Xu, C. Greiner BAMPS



Extreme Computing Challenges !!! => the **FAIR** Tier 0 **GreenCube** Data Center

*****No. 1*** Green500: Nov. 2014**

5.27 GFlops/Watt - World Record

L-CSC GSI Darmstadt PUE <1.07

powerefficient Supercomputer

AMD FirePro GPU, Intel Xeon CPU

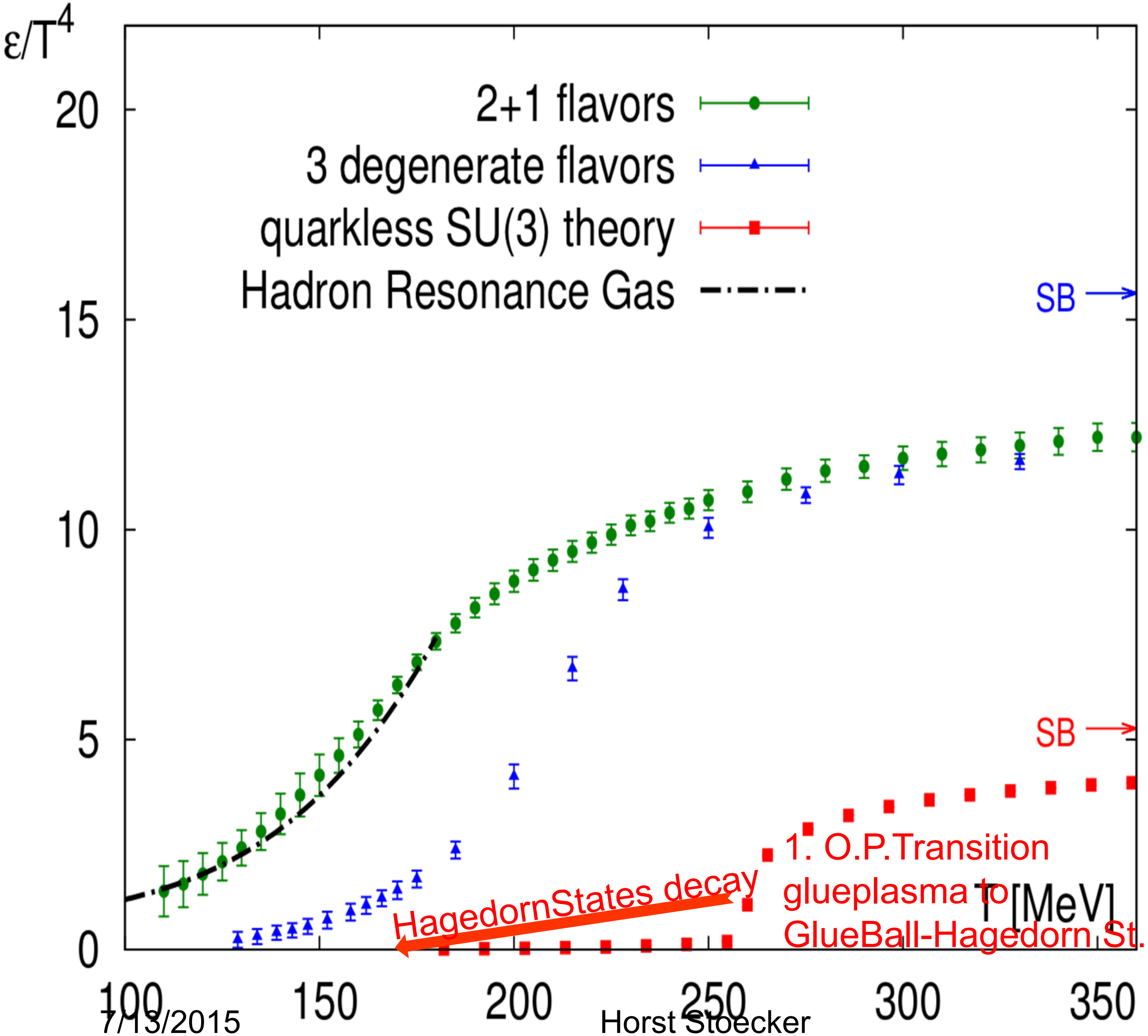
Tier-0 data center: FAIR **GreenCube**

Helmholtz funding 770 Racks 2.2m

- 12 M€ building cost
- 7 M€ initial HPC installation
- Completion of CC in Q4/2015
- Max cooling power 12 MW
- Fully redundand (N+1)

Lattice QCD vs pure YM: glueballs

Pure YM LGT vs. 2+1 flavor Lattice QCD
Energy density (EoS) DIFFERENT for different quark masses



Energy density from Wuppertal-Budapest: JHEP 1011, 2010,077; PLB730, 2014, 99

“physical point” 2+1
T_c.o. = 155 MeV

N_f = 3, $m_{u,d} = m_s$
T_c.o. = 220 MeV

pure gauge YM
T_c = 270 MeV

Quenched: JHEP 1207, 2012, 056

Time evolution of high multiplicity pp at RHIC and LHC in pure YM scenario

Alternate Scenario: pure gauge matter in pp, pA – AA ?

Initial Color Glass Condensate ➡ Glasma thermalizes
fast equilibration of Gluons, slow equil. of quarks
high pressure, entropy gluon plasma
➡ fast hydrodynamic expansion of gluon plasma.

⬇

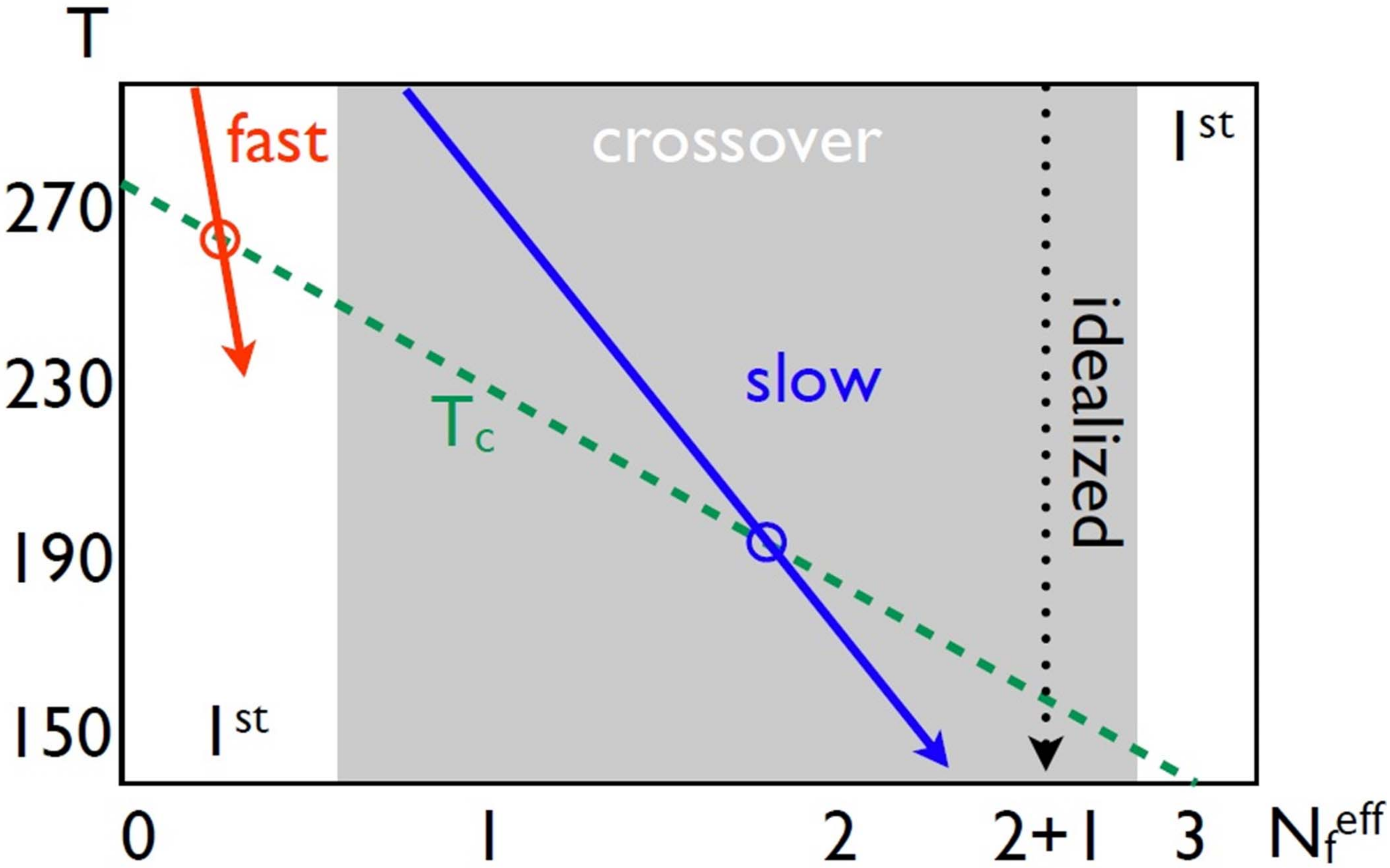
1. Order Phase Transition at T_c = 270 MeV of flavorless QCD.

⬇

Transition from glue plasma in GlueBall fluid

⬇

Glueballs' Hagedorn states decay directly into Hadrons
Comparison of theory with the experiments tests our understanding of QCD matter.


T
270
230
190
150
0
1
2
2+1
3
N_f^eff
fast
crossover
1st
slow
idealized
Tc
1st

Eff.Nf(t)

0.0

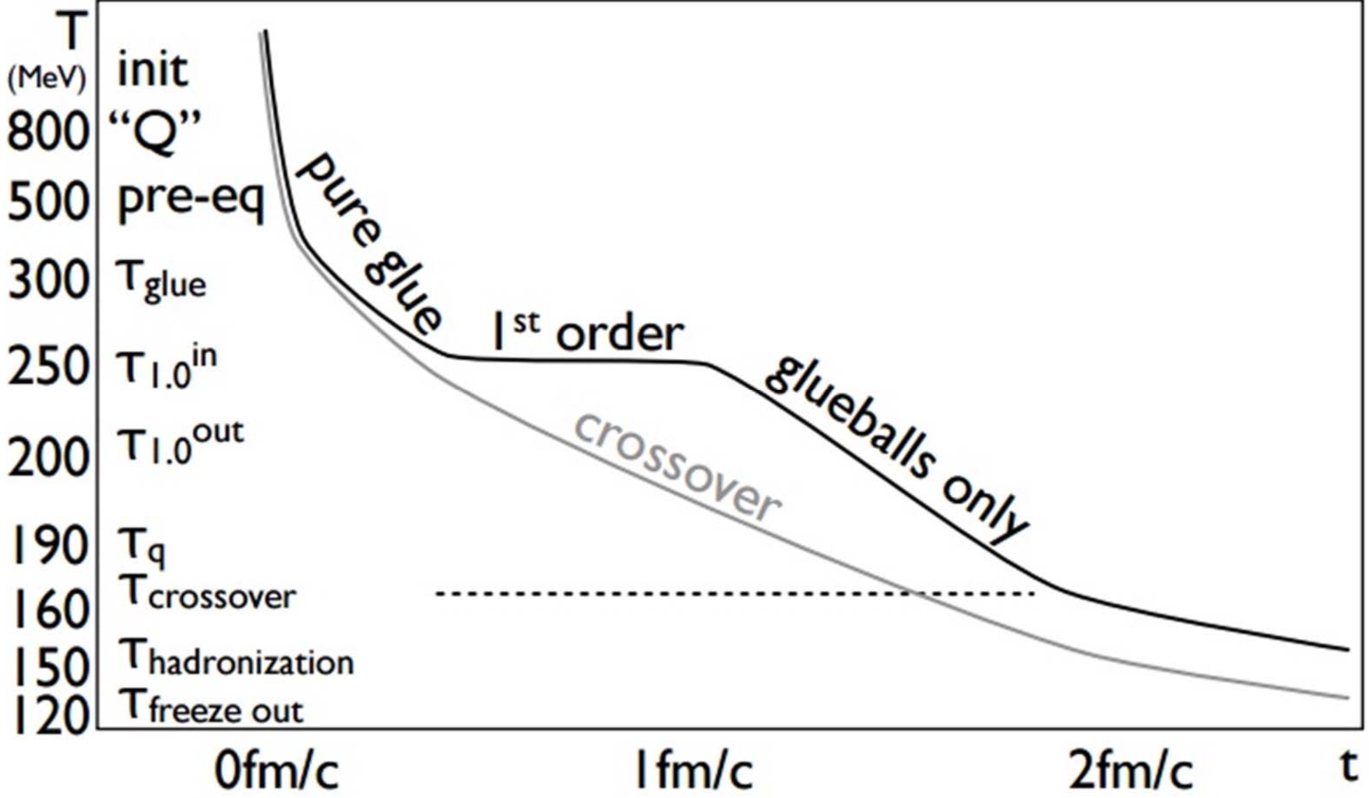
0.1

0.2

0.3

0.6

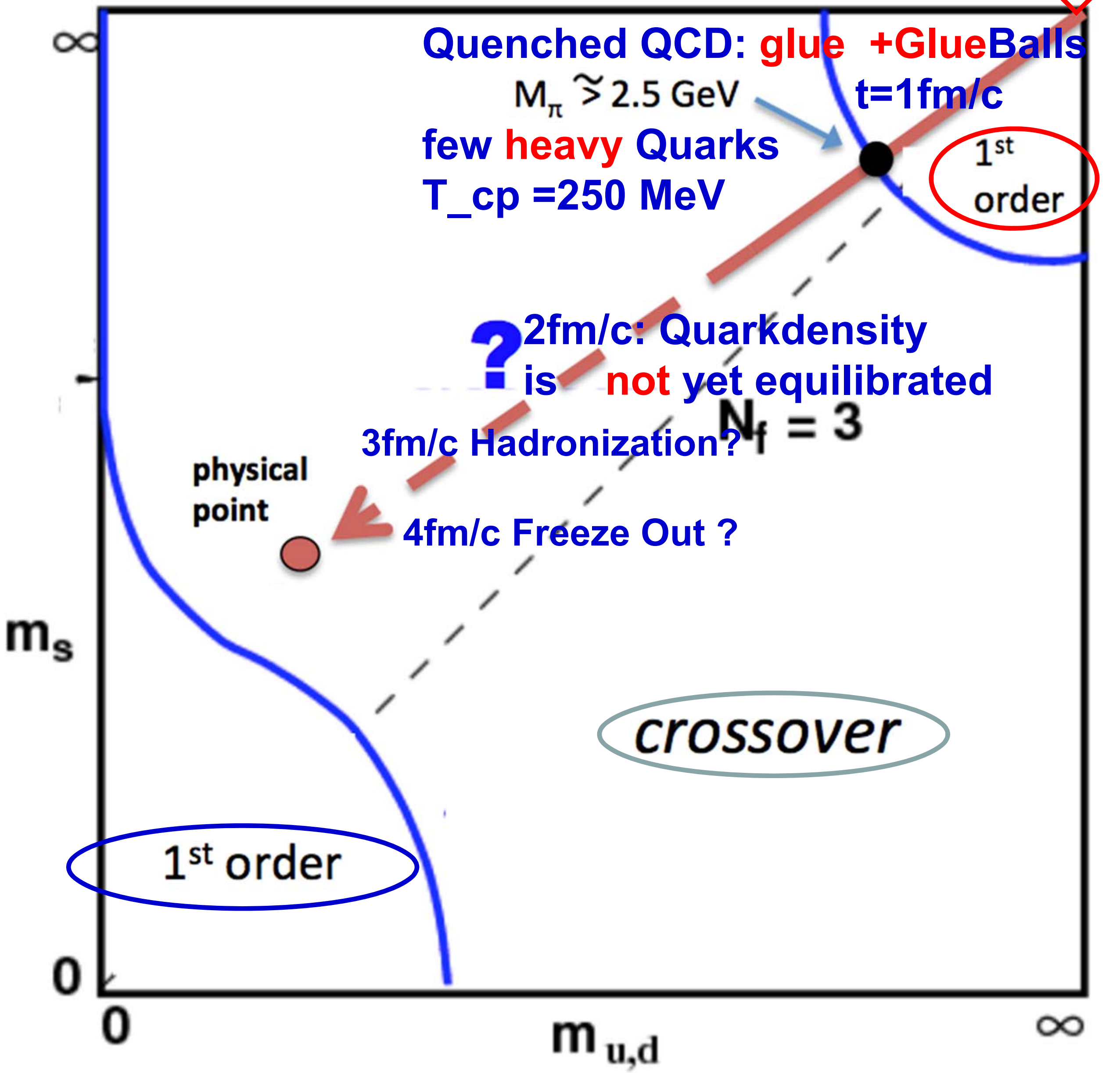
0.9



Eff.Nf(t): 0.0 0.1 0.2 0.3 0.6 0.9 ….

Theory Columbia Plot: Order of Phase Transition

LHC/FCC: time evol. high mult. pp & AA



pure gauge: glue only!

t=0.1fm/c : No Quarks !

Quenched QCD: glue +GlueBalls

t=1fm/c

few heavy Quarks

T_cp =250 MeV

?2fm/c: Quarkdensity is not yet equilibrated

3fm/c Hadronization?

4fm/c Freeze Out ?

„Time dependence“ in Columbia plot: N_f (t)

pp (& AA?) initial: Color Glass Condensate t=0.1fm/c:
glue thermalizes fast ~ pure glue-plasma: N_f (t=0.1)=0.1

Expansion

Pure Yang Mills Lattice gauge theory:
1. Order Phase Transition @ **T_c = 270MeV**
From glue plasma to GlueBall fluid

Expansion to critical point
T_cp =240 MeV t~2 fm/c

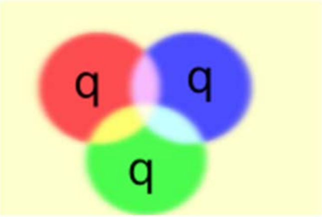
more and more quarks produced
N_f (t=2fm/c) ~ 0.6
GlueBalls, Hagedorn States Mix

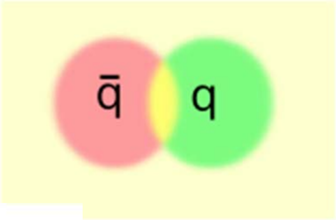
Sequential 2-body decays of Glueball-Hagedorn States can well explain the observed hadron yield ratios.

Glueballs !?

Beyond standard quark configurations

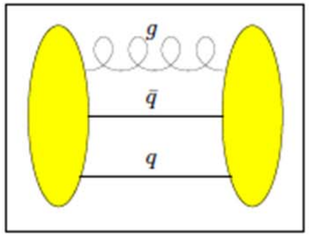
- QCD allows much more than what we have observed:



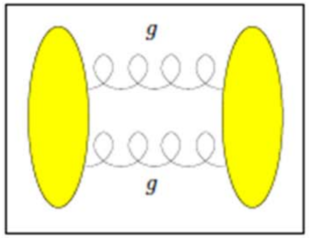


Mesons

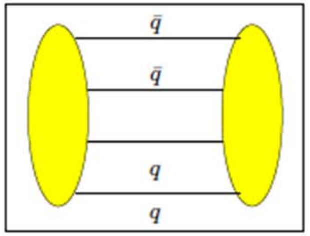
Exotica



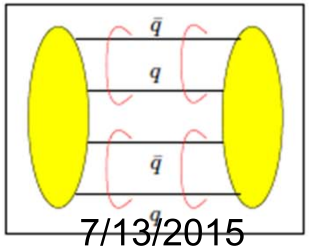
hybrid:
with gluon excitation



glueball:
pure gluon state



4 quark state:
compact 4–quark state

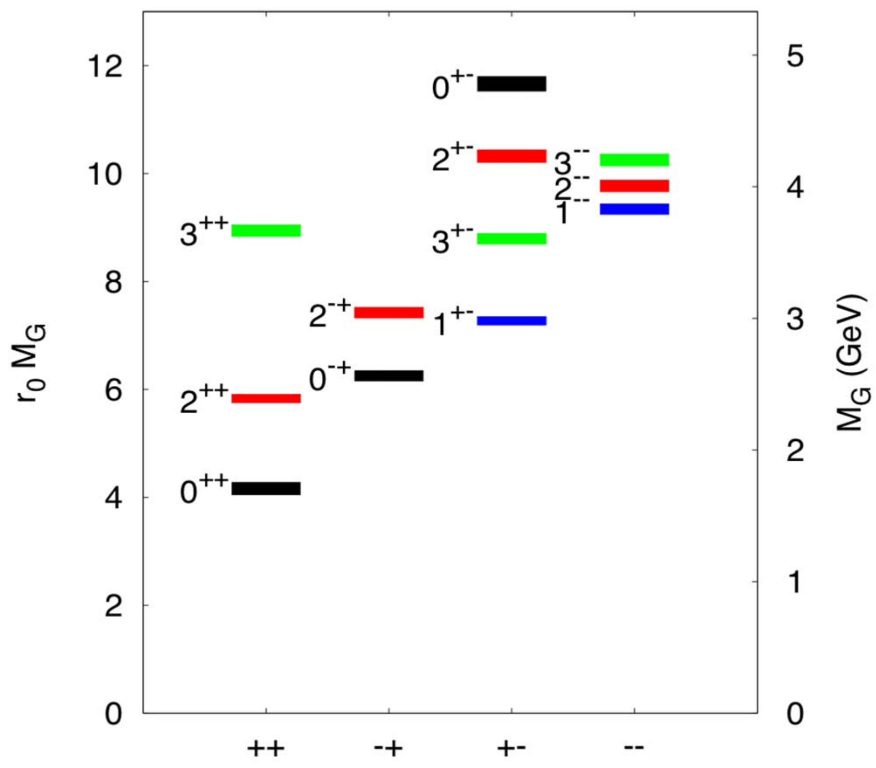


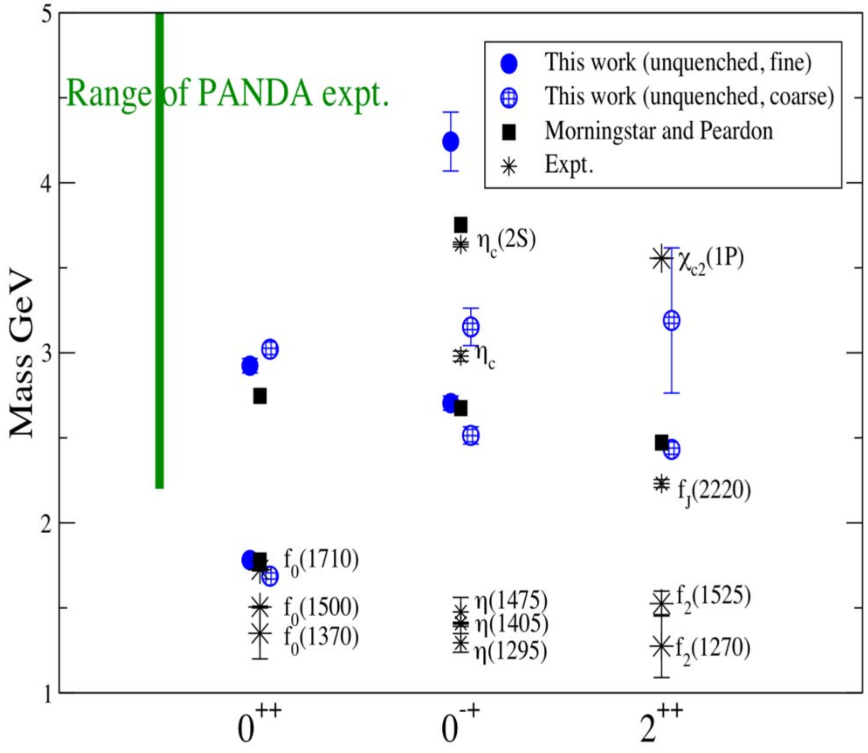
hadronic molecule:
bound state of two mesons

may have J^{PC} not allowed for $q\bar{q}$

Courtesy C. Hanhart

Glueball spectrum





Quenched results:
Morningstar-Peardon
Phys.Rev. D73 014516 ('06)

First unquenched results:
pion mass 360 MeV
UKQCD coll. PRD82 ('10) 34501

GlueBall-Matter at RHIC, LHC, FCC

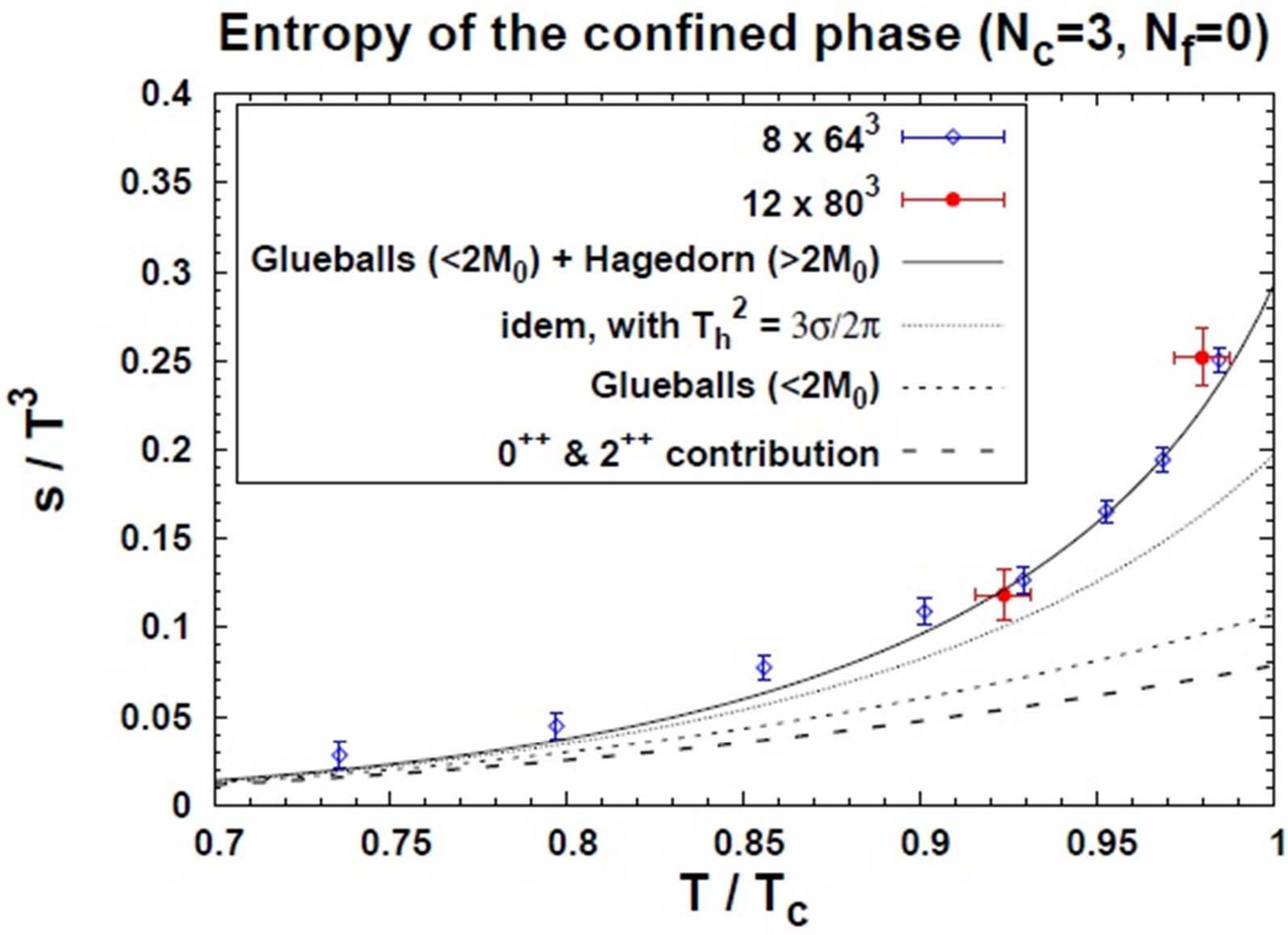
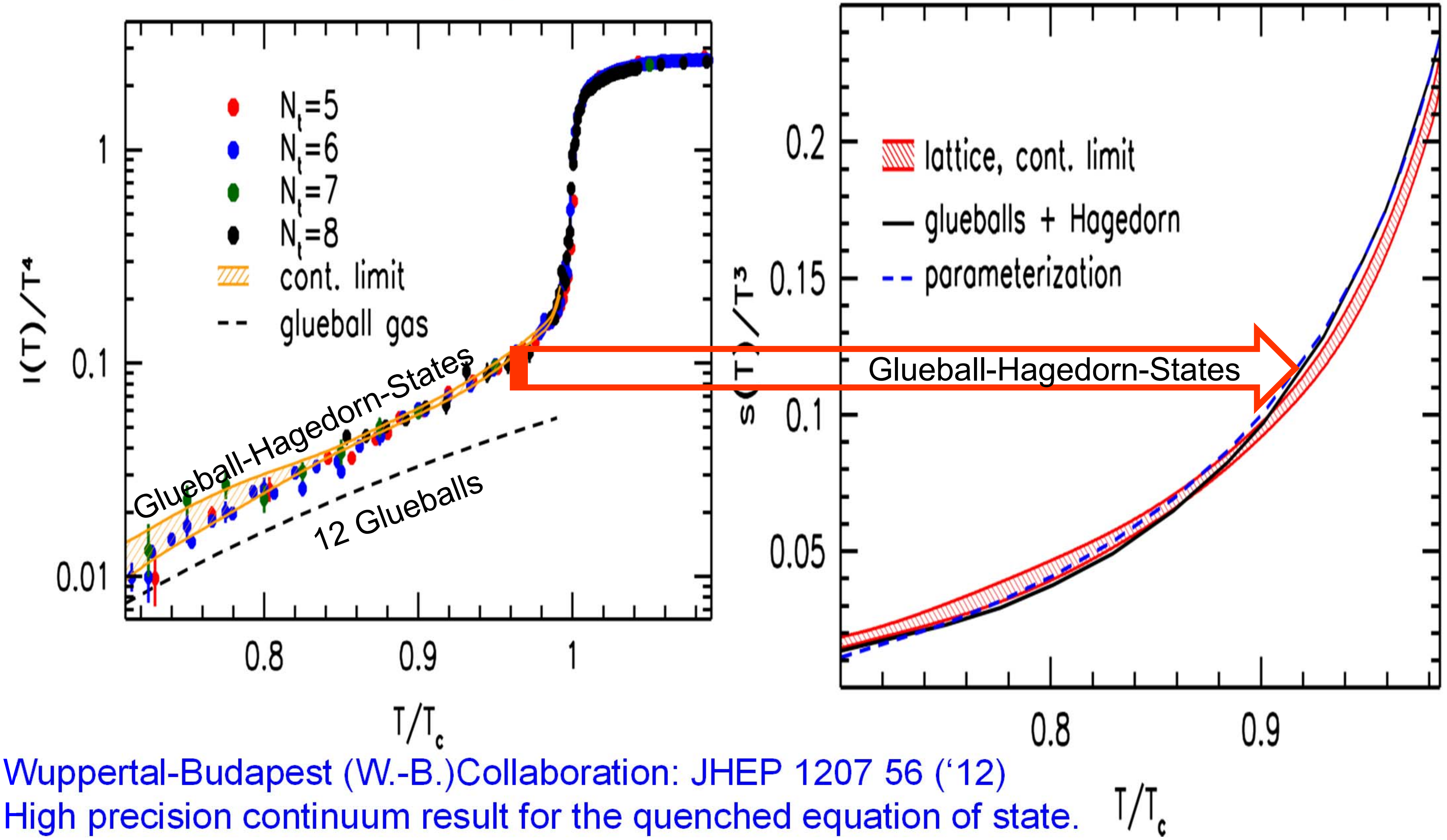


FIG. 3: The entropy density in units of T^3 for $LT = 8$. We applied a (modest) volume-correction to the $N_t = 12$ data.

Thermodynamcs of the GlueBall fluids



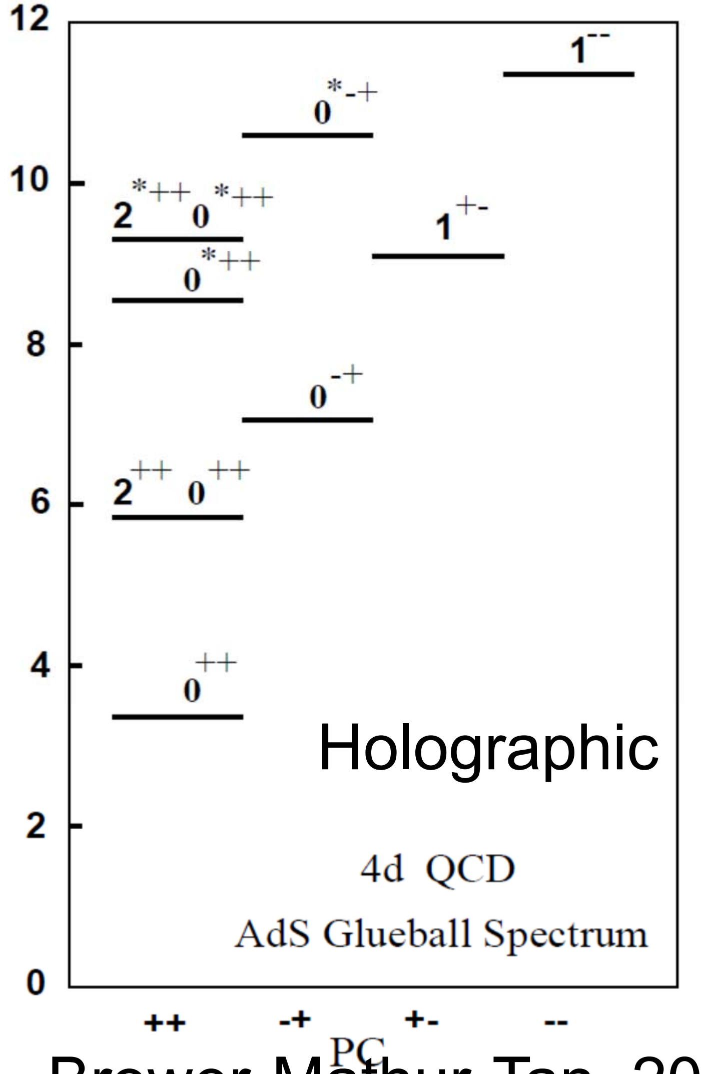
Wuppertal-Budapest (W.-B.)Collaboration: JHEP 1207 56 (‘12)
High precision continuum result for the quenched equation of state.
The low temperature behavior up to the transition point
can be described by the glueball spectrum.
W.-B. used 12 glueball states from Morningstar-Peardon
plus a Hagedorn particle tower (as proposed by Harvey Meyer).

Holographic vs. lattice glueball spectra

Seiji Terashima,YITP,Kyoto,
Koji Hashimoto,Riken, Chung-I Tan,Brown

Holographic vs. lattice glueball spectra

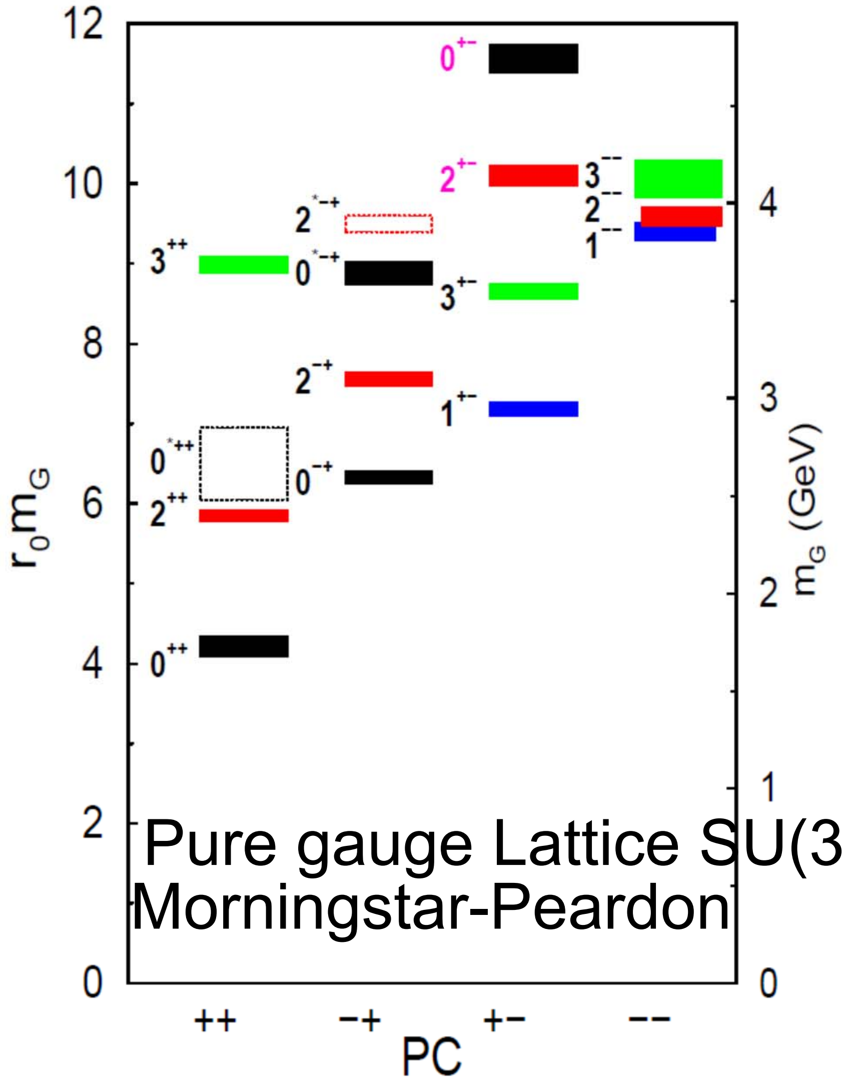
Seiji Terashima,YITP,Kyoto, Koji Hashimoto,Riken, Chung-I Tan,Brown, arXiv:0709.2208



Holographic

Brower-Mathur-Tan, 2000

$P_\tau = -1$ dropped



Pure gauge Lattice SU(3)
Morningstar-Peardon

Adding quarks in AdS/CFT: holographic QCD

Terashima et al

- Adding Nf flavors → adding another kind of D-branes as probe.

Karch-Katz
Myers et.al.
Sakai-Sugimot

- Here, we add Nf pairs of D8-brane and anti-D8-brane. This model has spontaneously broken chiral symmetry, so there is massless pion.

Let us consider gravity dual, i.e. the D8-branes in the Witten's background. (D8-brane and anti-D8-brane are connected and become smooth curved D8-branes as a result of the curved background.)

The D8-brane action is

$$S_{\mathrm{D8}} = -(2\pi\alpha')^2 \mathcal{T}_{\mathrm{D8}} \mathrm{Tr} \int d^9x \, e^{-\Phi} \sqrt{-\det \tilde{g}} \, \frac{1}{4} \, \tilde{g}^{PR} \tilde{g}^{QS} F_{PQ} F_{RS} + S_{\mathrm{Chern-Simons}}$$

where F is the field strength of the 9-dim. gauge fields on the

Generic feature of holographic glueball decay

Terashima et al

- Glueballs are obviously flavor-blind. Thus couplings to mesons are universal against flavors.
- From the D8-brane action,

$$S_{\mathrm{D8}} = -(2\pi\alpha')^2 \mathcal{T}_{\mathrm{D8}} \mathrm{Tr} \int d^9x \, e^{-\Phi} \sqrt{-\det \tilde{g}} \, \frac{1}{4} \, \tilde{g}^{PR} \tilde{g}^{QS} F_{PQ} F_{RS} + S_{\mathrm{Chern-Simons}}$$

we see that

(1) No glueball interaction involving more than two pions. because

π appears in A_z but there are no $(A_z)^n$ terms with $n > 2$

Decay of any glueball to 4 π_0 is suppressed. Prediction of the holographic QCD!

(2) Direct couplings of a glueball with more than five meson are suppressed. (implies "vector meson dominance"): No A^5 term

These are from "Holographic gauge" choice

But no mixing between lightest glueball and meson

Terashima et al

- Scalar mesons = transverse scalar of D8-branes, denoted by y, which is essentially τ.
- Terms linear in y in the D8-action is:

$$
\begin{aligned}
&g_{\nu y}|_{y=0}\partial_\mu y(z,x^\mu), \quad && g_{\nu y}|_{y=0}\partial_z y(z,x^\mu),\\
&y[\partial_y g_{\tau\tau,rr,\mu r,\mu\nu}]_{y=0}, \quad && y[\partial_y \phi]_{y=0},\\
&g_{zy}|_{y=0}\partial_\mu y(z,x^\mu), \quad && g_{zy}|_{y=0}\partial_z y(z,x^\mu),
\end{aligned}
$$

All of these vanish for the lightest glueball.
No mixing with mesons at order $1/\sqrt{N_c}$
This is very important to distinguish the glueball and meson.

Decay of lightest scalar glueball

Terashima et al

Lightest glueball mass is $M = \sqrt{7.31/9} M_{KK}$

ρ meson mass is $m_\rho = \sqrt{\lambda_1} M_{KK} = \sqrt{0.669} M_{KK}$

We have $m_\rho < M < 2m_\rho$. Thus no 2 ρ-meson decay in holographic QCD

(In the experiment, M=1507MeV, mρ=775MeV)

We will use

$$\lambda N_c/108\pi^3 = 7.45 \times 10^{-3}$$

$$N_c = 3$$

Possible decay process (from kinematics)

(a) $G \rightarrow \pi\pi$ (figure 1)

(b) $G \rightarrow \rho\pi\pi,\quad G \rightarrow \rho\rho \rightarrow \rho\pi\pi$ (figure 2)

(c) $G \rightarrow \rho\pi\pi \rightarrow \pi\pi\pi\pi,\quad G \rightarrow \rho\rho \rightarrow \pi\pi\pi\pi$ (figure 3)

(d) $G \rightarrow \eta'\eta'$ (figure 1)

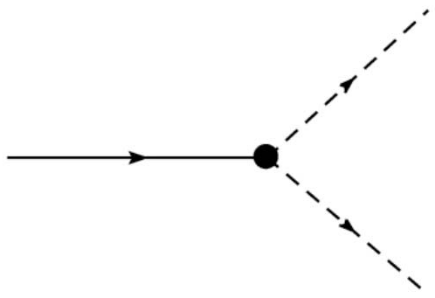


Figure 1: A glueball G decaying to two pions π.

Branching ratio for f0(1500):

(a) 35%
(b)+(c) 49%
(d) 7 %

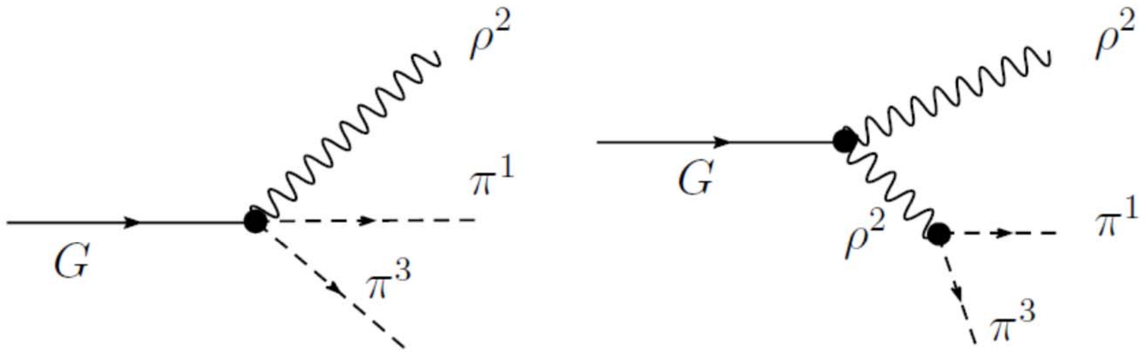


Figure 2: A glueball G decaying to two pions π and a single ρ. There are two graphs, the decay with a single vertex (Left) and the decay with two vertices (Right).

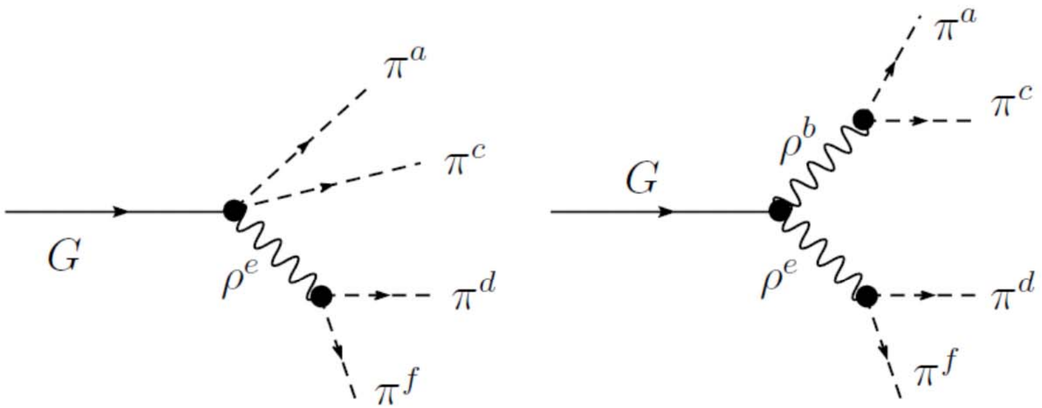


Figure 3: A glueball G decaying to four pions π. There are two graphs, the decay with two vertices (Left) and the decay with three vertices (Right).

From the effective action we have, we can compute the decay width.

For $G \to \pi\pi$ $$\frac{\Gamma_{G\to\pi\pi}}{M} = 0.040.$$

Experimentally, $$\frac{\Gamma^{(\mathrm{ex})}_{G\to\pi\pi}}{M} = \frac{109}{1507} \times 34.9\% = 0.0252.$$

Good agreement.

$G \to \rho\pi\pi$ and $G \to 4\pi$

$$\frac{\Gamma_{G\to\rho\pi\pi}}{M} = \sim 1.3 \times 10^{-6} \qquad \frac{\Gamma_{G\to 4\pi}}{M} \sim 2.2 \times 10^{-5}$$

This is too small, but if we set M/m_ρ to the experimental value by hand, we have

$$\frac{\Gamma_{G\to\rho\pi\pi}}{M} = 0.096 \qquad \frac{\Gamma_{G\to 4\pi}}{M} \sim 0.0087$$

Thus $$\frac{\Gamma_{G\to 4\pi} + \Gamma_{G\to\rho\pi\pi}}{M} \sim 0.105$$

Experimentally, $$\frac{\Gamma^{(\mathrm{ex})}_{G\to 4\pi}}{M} = \frac{109}{1507} \times 49.5\% = 0.0358$$

Consistent

(In particular, taking into accont the masslessness of the pions)

Terashima et al: First attempt in computing decays of glueballs to mesons using a holographic QCD (Sakai-Sugimoto model).

The holographic QCD is, in principle, equivalent to QCD.
We therefore expect that the holographic approach should provide interesting information on strong coupling physics of QCD.

Explicit couplings between the lightest glueball and the mesons are given, and the associated decay products/widths are calculated.

Our results are consistent with the experimental data of the decay for the f0(150
which is thought to be the best candidate of a glueball in the hadronic spectrum.

We have shown that there is no mixing with the mesons at the leading order.
Decay of any glueball to 4 π_0 is suppressed.
This is a prediction of the holographic QCD!

Decay of Hagedorn state glueballs

Beitel, Gallmeister, Carsten Greiner

Bootstrap (courtesy Max Beitel, Kai Gallmeister, Carsten Greiner)

cf. S. Frautschi, PRD 3 (1971) 2821
C. Hamer, S. Frautschi, PRD 4 (1971) 2125

- Assumption: only 2-body (detailed balance!)

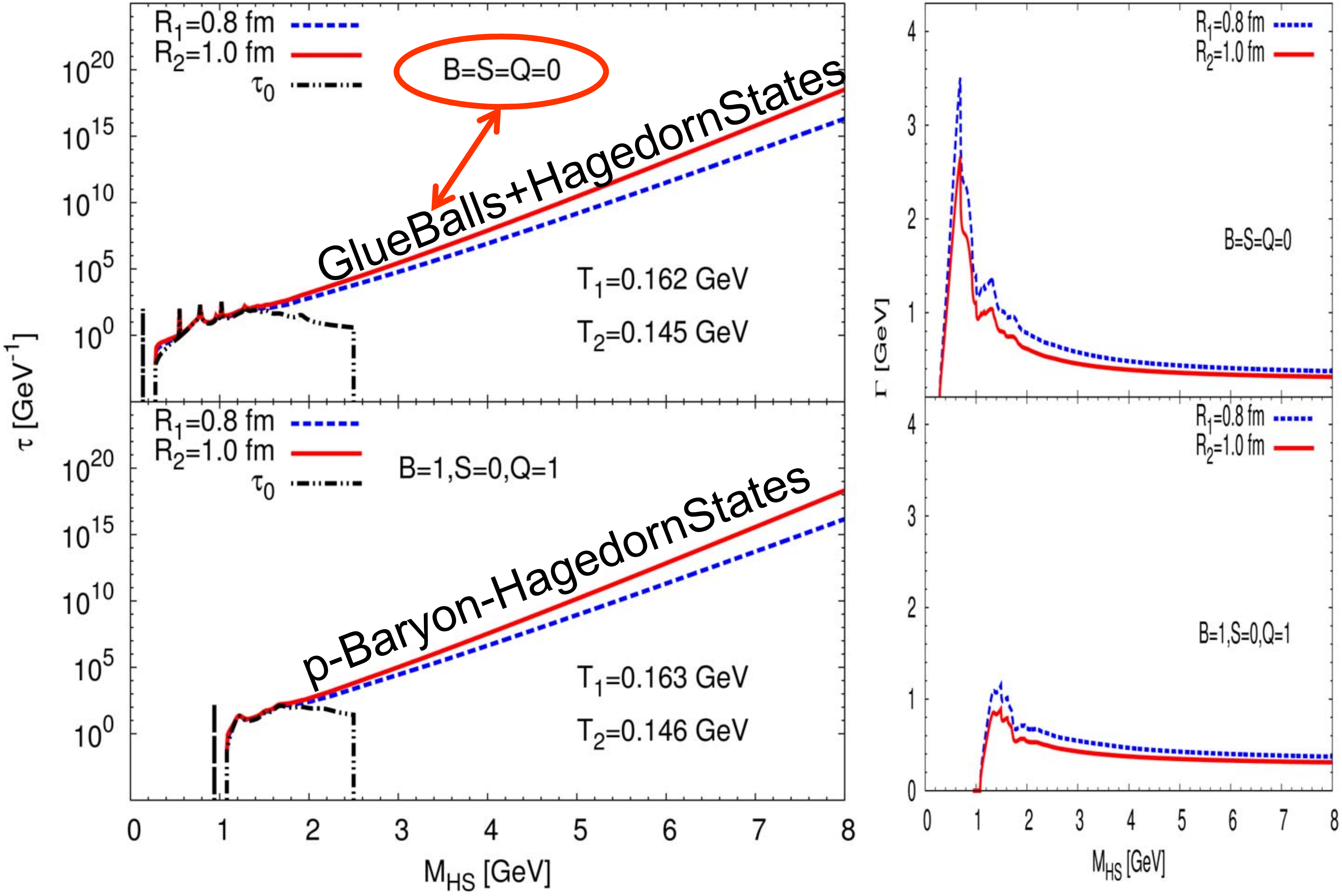
$$\vec{C} = (B, S, Q)$$

- Bootstrap equation
- $$\tau_{\vec{C}}(m) = \frac{R^3}{3\pi\, m} \sum_{\vec{C}_1,\vec{C}_2} \iint \mathrm{d}m_1 \mathrm{d}m_2\, m_1 \tau_{\vec{C}_1}(m_1)\, m_2 \tau_{\vec{C}_2}(m_2) \times\ p_{\mathrm{cm}}(m, m_1, m_2)\, \delta(\vec{C} - \vec{C}_1 - \vec{C}_2)$$

- Total decay width (via detailed balance)

$$\Gamma_{\vec{C}}(m) = \frac{\sigma}{2\pi^2\, \tau_{\vec{C}}(m)} \sum_{\vec{C}_1,\vec{C}_2} \iint \mathrm{d}m_1 \mathrm{d}m_2\, \tau_{\vec{C}_1}(m_1)\, \tau_{\vec{C}_2}(m_2) \times\ p^2_{\mathrm{cm}}(m, m_1, m_2)\, \delta(\vec{C} - \vec{C}_1 - \vec{C}_2)$$

GlueBalls & Hagedorn-States: exponentially increasing Mass-Spectra, Width

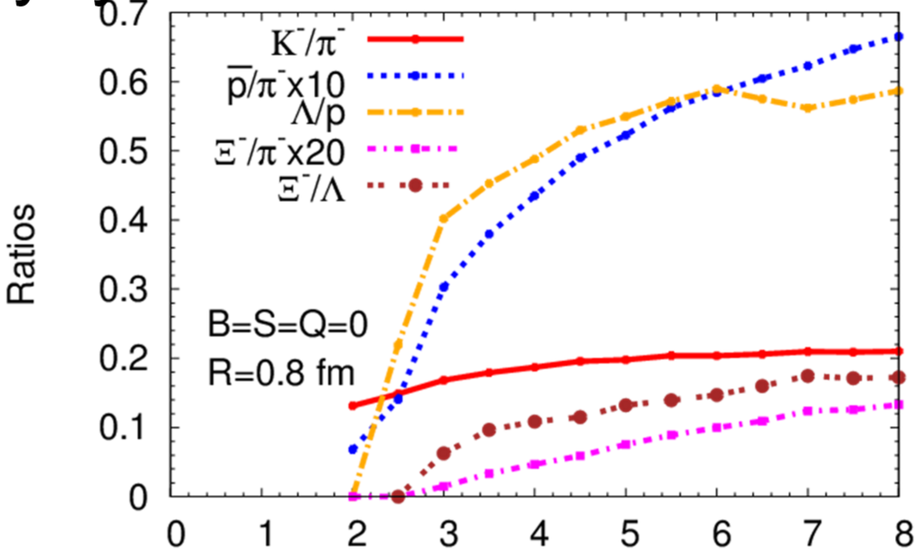


T quite independent of charges

Single HS cascading decay: yield ratios vs ALICE

data: ALICE @ LHC $\mathrm{p-p}: \sqrt{s_{NN}} = 0.9\,\mathrm{TeV}$

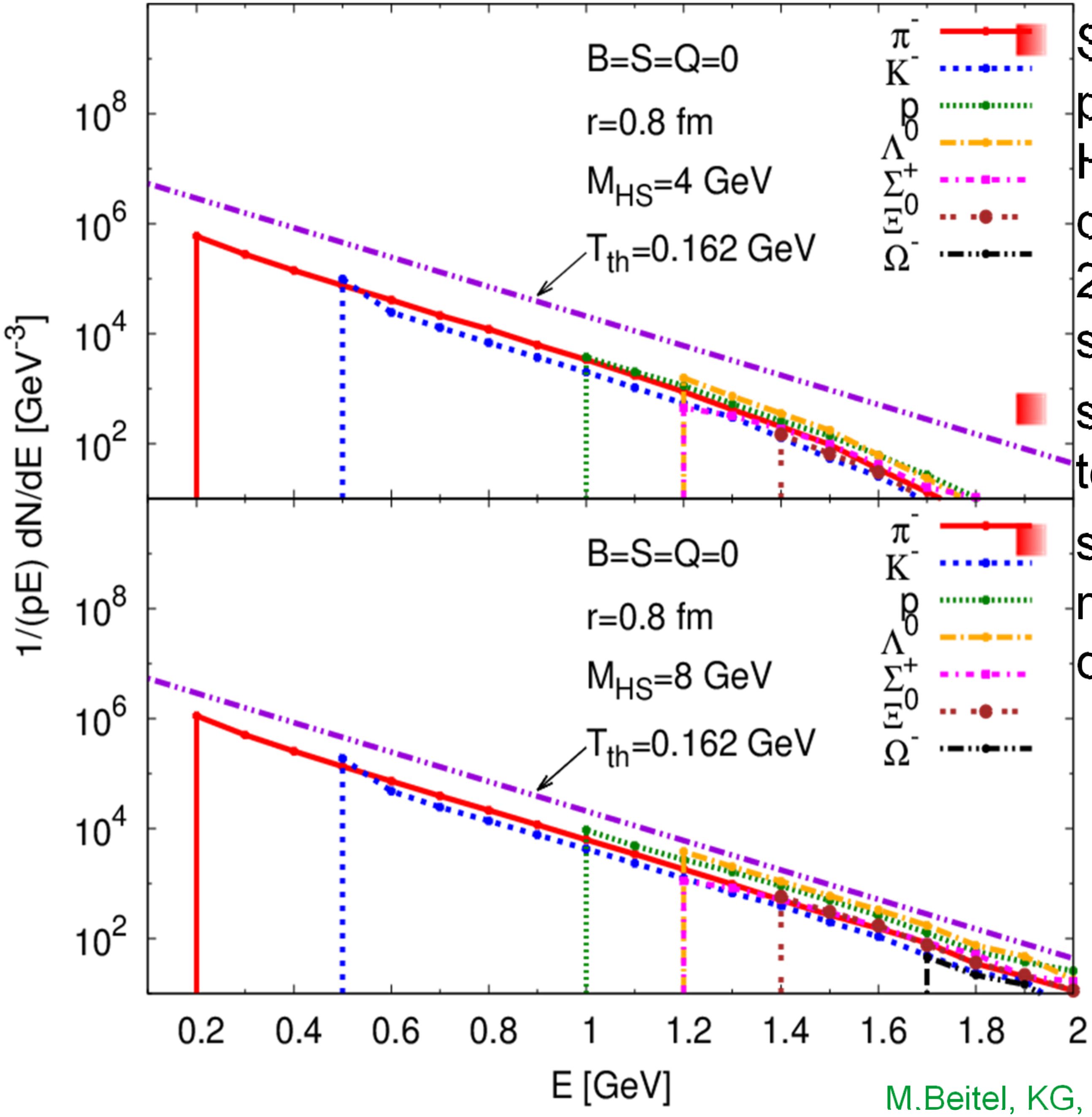
$\mathrm{Pb-Pb}: \sqrt{s_{NN}} = 2.8\,\mathrm{TeV}$



	p-p	Pb-Pb	4 GeV	8 GeV
K^-/π^-	0.123(14)	0.149(16)	0.187	0.210
$\overline{p}/\pi^-$	0.053(6)	0.045(5)	0.043	0.066
Λ/π^-	0.032(4)	0.036(5)	0.021	0.038
$\Lambda/\overline{p}$	0.608(88)	0.78(12)	0.494	0.579
Ξ^-/π^-	0.003(1)	0.0050(6)	0.0023	0.0066
$\Omega^-/\pi^- \cdot 10^{-3}$	—	0.87(17)	0.086	0.560

M.Beitel, KG, C.Greiner, PRC 90 (2014) 045203

Slope of Single 4-GeV GlueBall-like Hagedorn State seq. 2-body decay cascade



- Spectra/slopes of decay products of each single Hagedorn State cascading a sequential 2-body decay chain: slopes look thermal !!!
- slopes equal Hagedorn temperature !
- slope independent of mass, radius, charges of Hagedorn State

M.Beitel, KG, C.Greiner, PRC 90 (2014) 045203

Dileptons and Photons from pure glue scenario
VoloGorenstein, Satarov, Mishustin, Csernai et al.

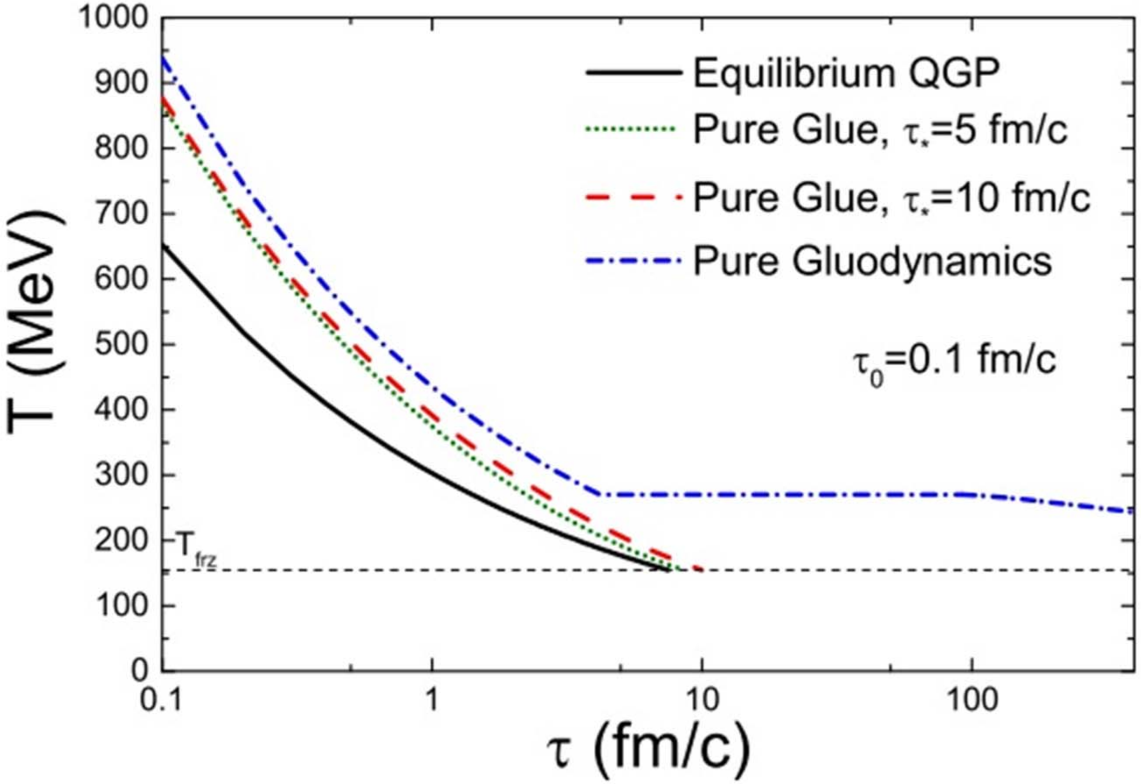


FIG. 6: Dependence of the temperature on the proper time τ for three different system evolution scenarios with $\tau_0 = 0.1$ fm/c, $\tau_* = 5$ fm/c and 10 fm/c.

Eff.Nf(t)

0.0

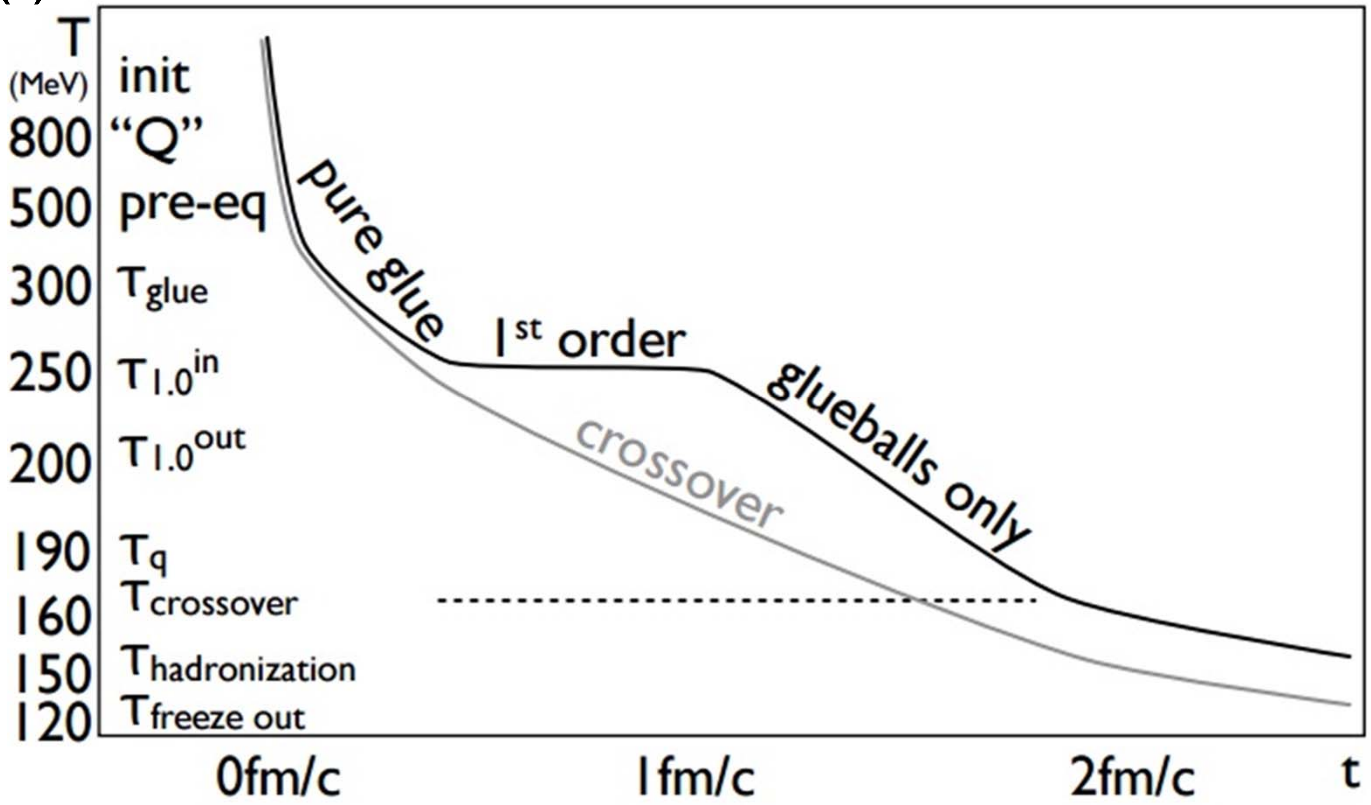
0.1

0.2

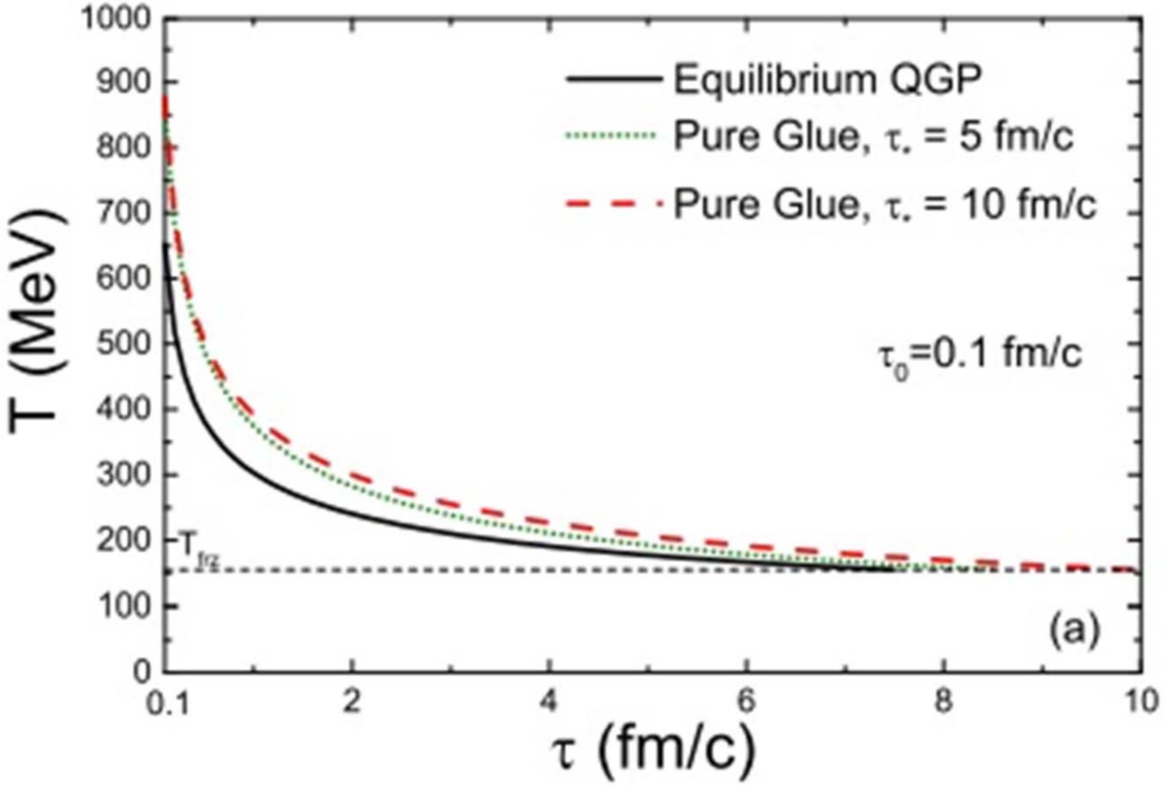
0.3

0.6

0.9



Eff.Nf(t): 0.0 0.1 0.2 0.3 0.6 0.9 ….



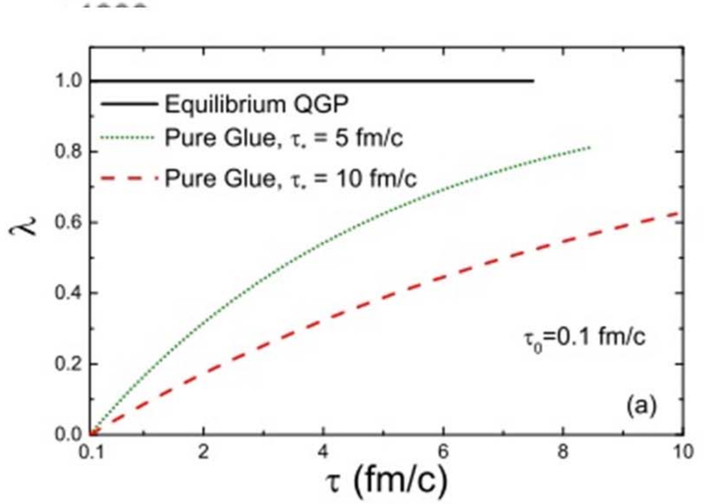


FIG. 1: (Color online) Dependence of $\lambda(\tau)$ on th

scenarios with (a) $\tau_0 = 0.1$ fm/c, (b) $\tau_0 = 0.5$ fm

FIG. 2: (Color online) Dependence $T(\tau)$ of the temperature on the proper tim

system evolution scenarios with (a) $\tau_0 = 0.1$ fm/c, (b) $\tau_0 = 0.5$ fm/c, and $\tau_* =$

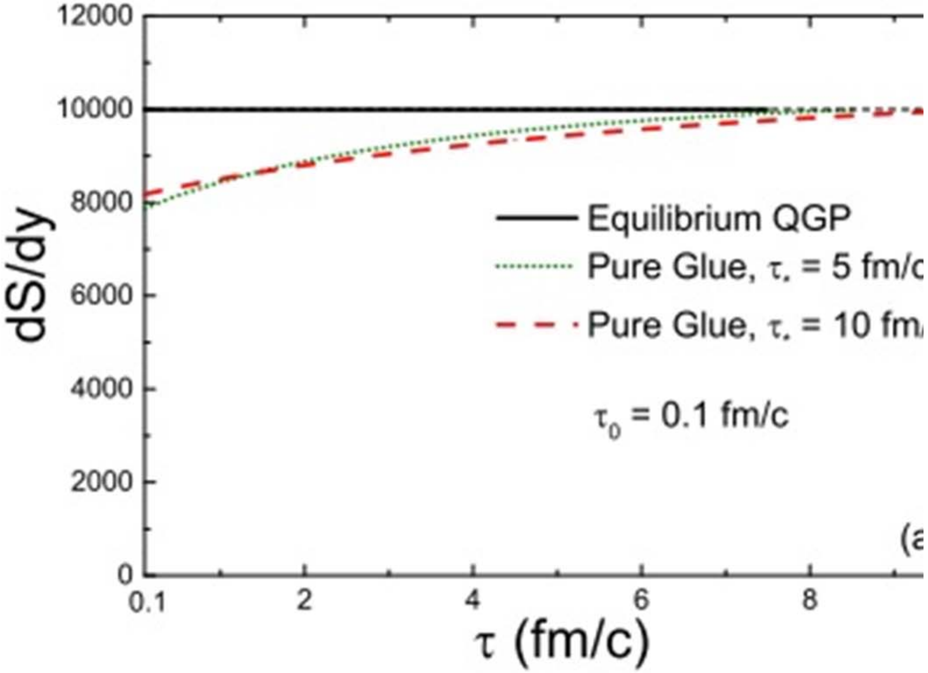


FIG. 3: The τ-dependence of entropy per u

evolution scenarios with (a) $\tau_0 = 0.1$ fm/c, (

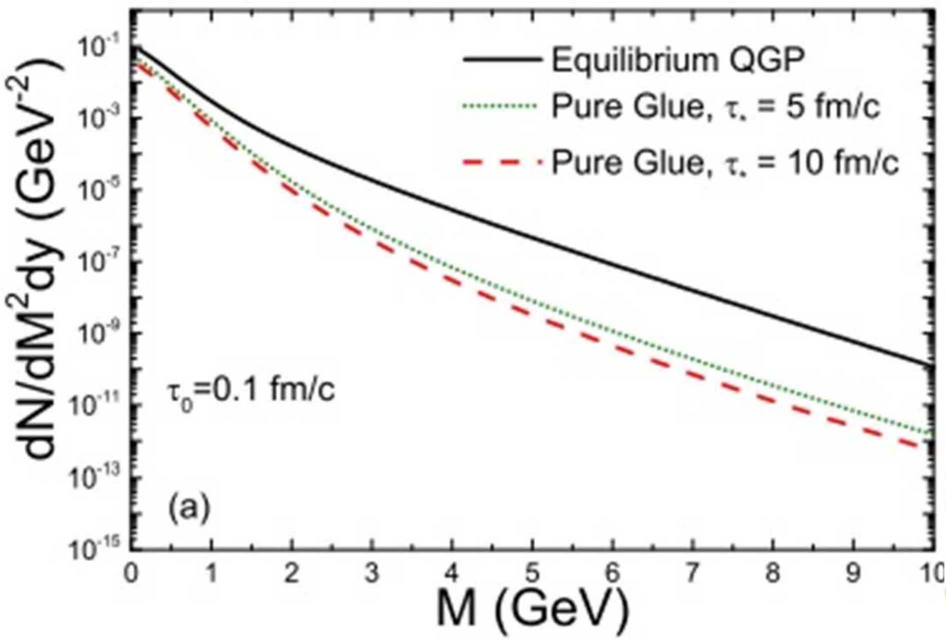


FIG. 4: The thermal dilepton emission rate per invariant mass squared M^2 and unit rapid

calculated for two different system evolution scenarios with (a) $\tau_0 = 0.1$ fm/c, (b) $\tau_0 = 0.5$ fm

and $\tau_* = 5$ fm/c and 10 fm/c.

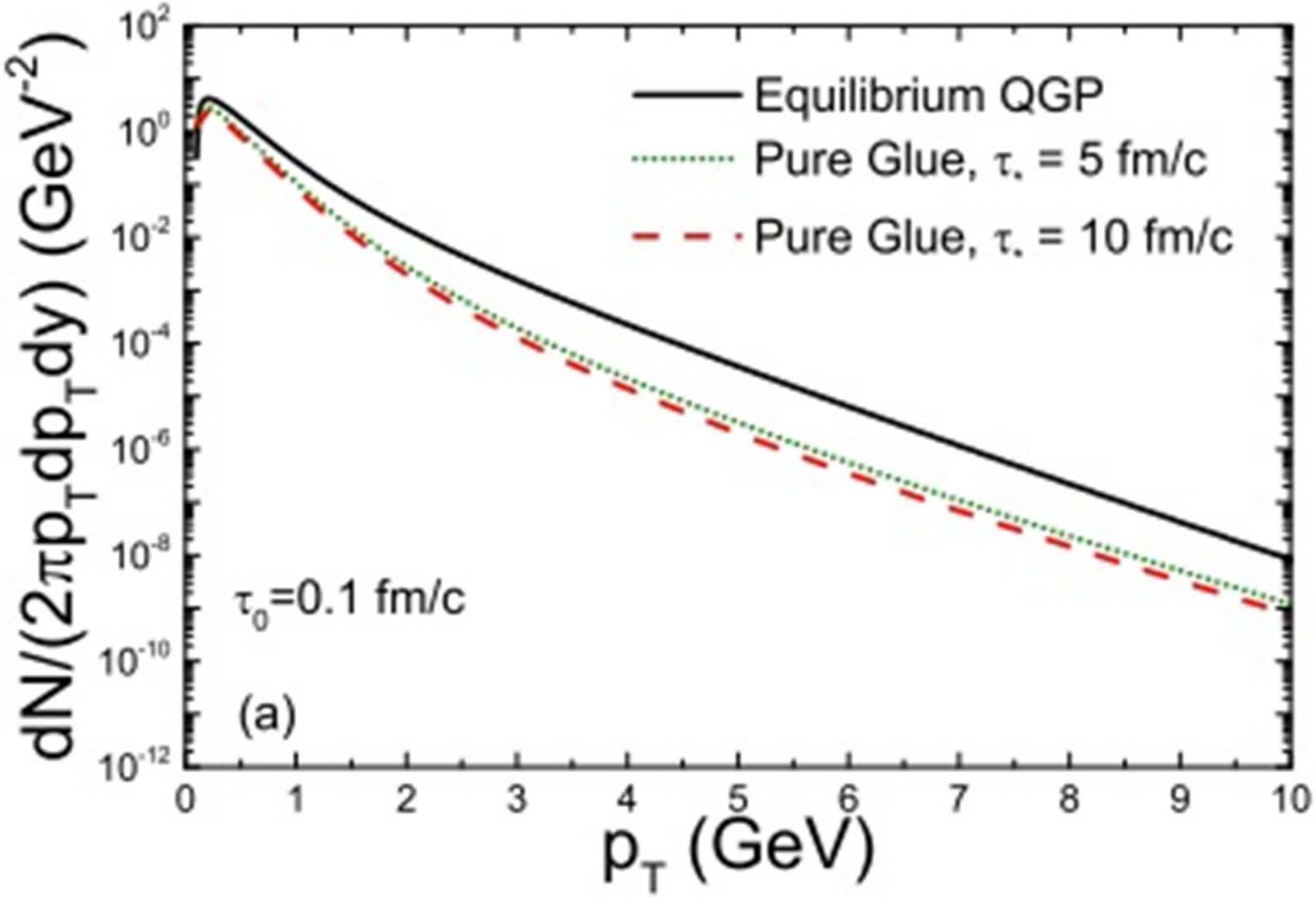


FIG. 5: The transverse distribution of the ther
formed with (a) $\tau_0 = 0.1$ fm/c, (b) $\tau_0 = 0.5$ fm/c

Photons

Signatures for pure glue->glueball scenario:

New event-class in high multiplicity pp & pA at RHIC and LHC

time dependence in Columbia plot …... **LHC – the Glueball Factory**…

- violent pp (& AA) collisions
- initial state at LHC:
- Color Glass Condensate
- t=0.1fm/c: glue thermalizes
- **pure glue-plasma** created

- Quenched Lattice SU(3)_c :
- **T_c =270MeV**
- glue plasma -> **GlueBall fluid**
- 1. Order Phase Transition

- Expansion to critical point
- **T_cp =240 MeV** t~1-2 fm/c
- **GlueBalls** + Hagedorn States Mix

- more and more quarks produced: **T_co =155MeV** crossover transition

- **Observables** from Columbia plot
- T>T_cp: **Zero e.m. radiat**ion
- Measure Dilepton intermed. mass
- T_c: **Flow collapse** as barometer
- T_cp: **Critical Scattering (MG,WG)**,
- Kurtosis , # fluctuations

- T_c ~ 2*T_co =>
- P_t(pp) ~ **2***p_t(AA)

- M_GlueBalls<2GeV: „**No**“ Baryons
- **p/pi=0** : Yield p+pBar**<<**mesons
- Lightest GlueBall decays:
- - No decays to 2 Omega no 2 Rho

- Glue Flavor blind !
- **K/pi=1** Yields: Kaons ~ pions

Outlook: Alternative Class of High M events in pp, pA @ LHC – AA?

Initial Color Glass Condensate → Glasma thermalizes
fast equilibration of gluons, slow equil. of quarks
high pressure, entropy in gluon plasma
→ fast hydrodynamic expansion of gluon plasma.

↓

1. Order Phase Transition at T_c = 270 MeV of flavorless QCD.

↓

Transition from glue plasma in GlueBall fluid

↓

Glueballs' Hagedorn states decay directly into Hadrons
Comparison of theory with the experiments tests our understanding of QCD matter.

Wholehearted Congratulations, from all of us, Miklos!

Many thanks, for Your Splendid Hospitality,
to the Wigner Institute

- from the Wuhan Faculty !