STRANGENESS AND THE DISCOVERY OF QUARK-GLUON PLASMA

Shanghai, Fudan University, August 20, 2004

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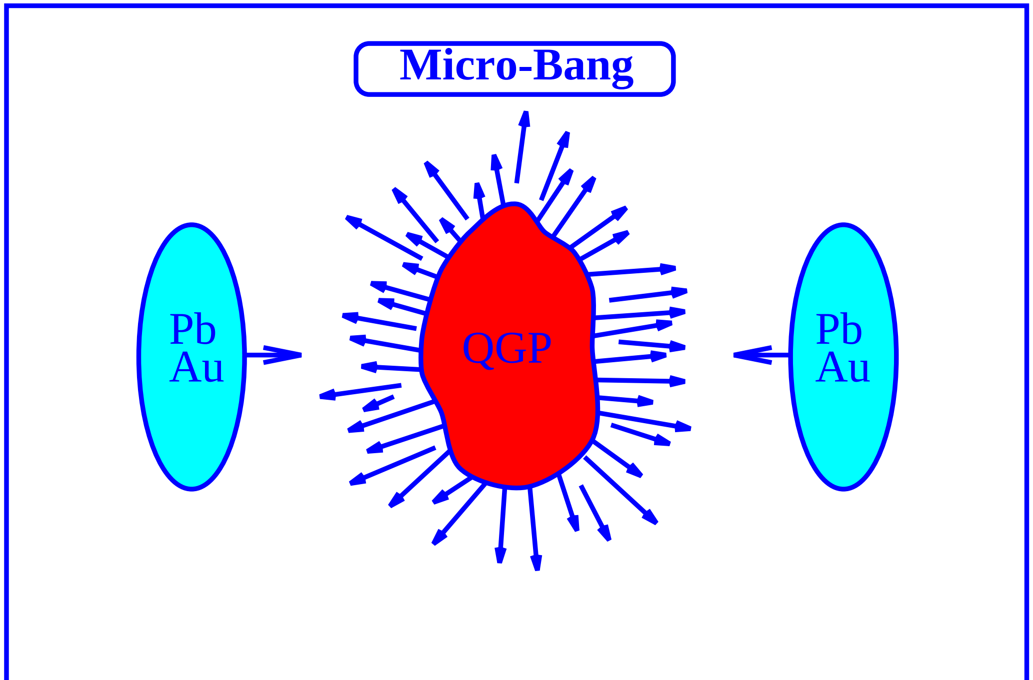
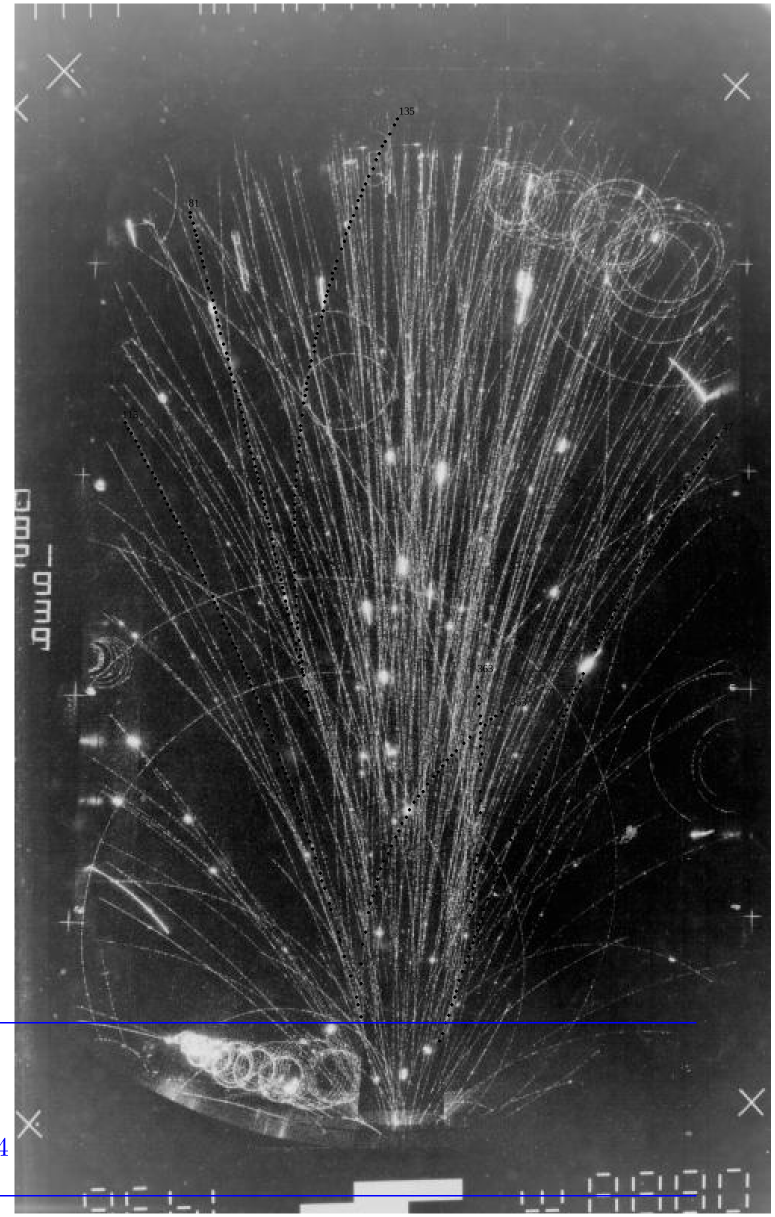
Supported by a grant from the U.S. Department of Energy, DE-FG02-04ER41318.

20 YEARS OF RESEARCH: THE EARLY UNIVERSE IN THE LABORATORY



Big-Bang	Micro-Bang
$\tau \simeq 10\mu s$	$\tau \simeq 4\ 10^{-23}$s
$N_B / N \simeq 10^{-10}$	$N_B / N \simeq 0.1$

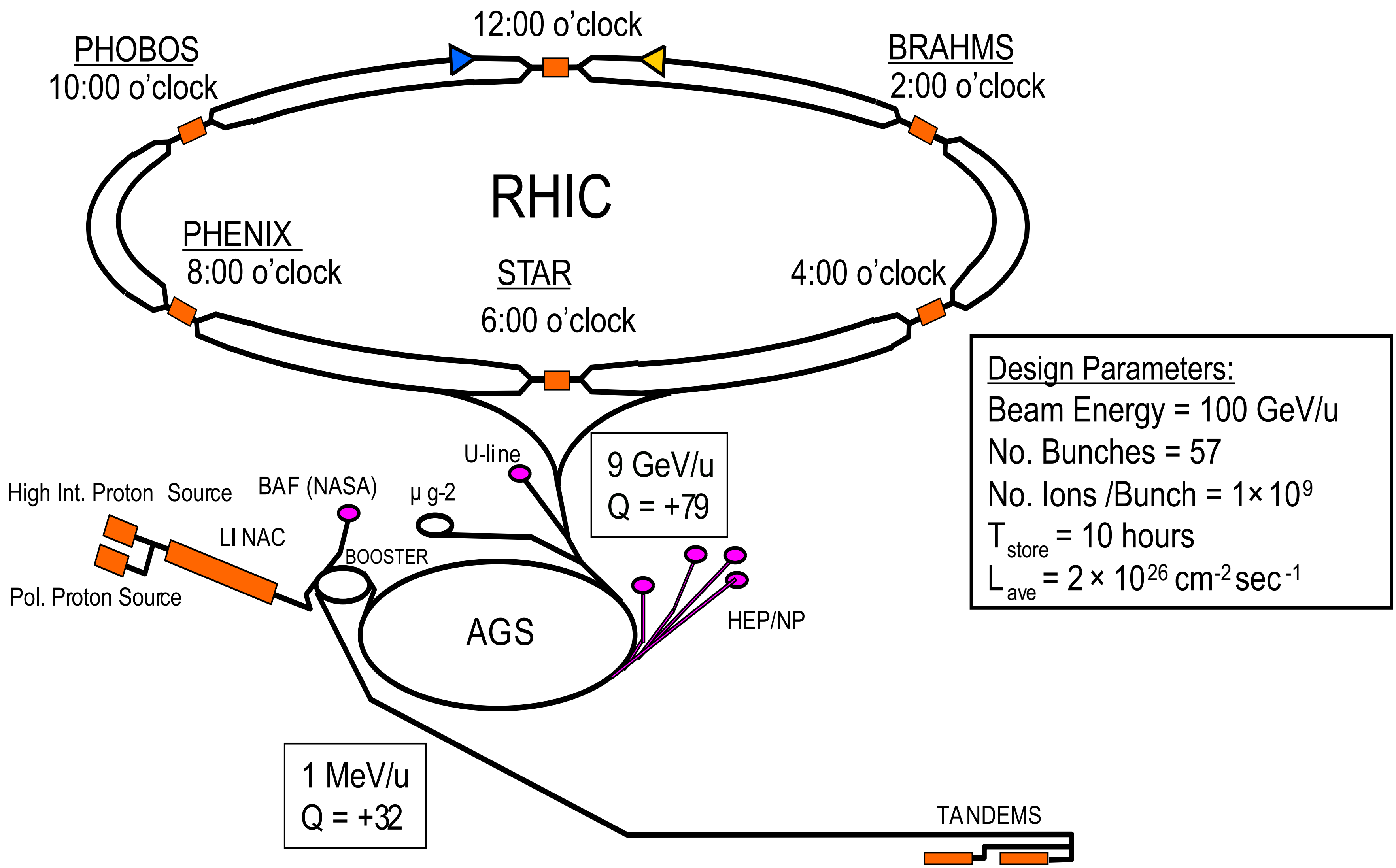


S–Ag Reaction at 200AGeV

Order of Magnitude

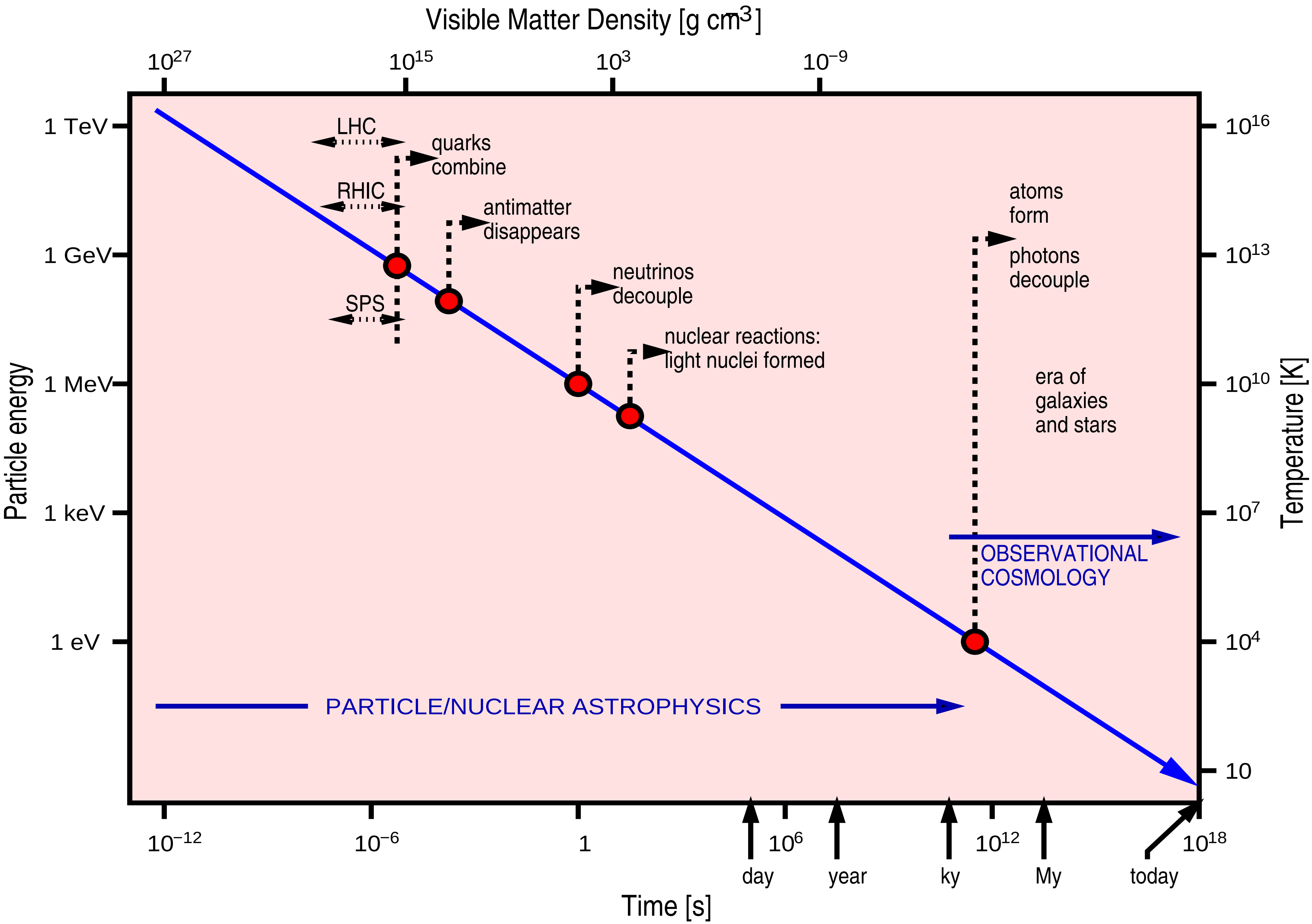
ENERGY density	ϵ	$\simeq$ 1–**5GeV/fm**^{3} = 1.8–9 10^{15}**g/cc**
Latent vacuum heat	B	$\simeq$ 0.1–**0.4GeV/fm**^{3} $\simeq$ (166–234**MeV**)^4
PRESSURE	P	$= \frac{1}{3}\epsilon = 0.52\ 10^{30}$ **barn**
TEMPERATURE	T_0, T_f	**300–250, 175–145 MeV;** **300MeV$\simeq$3.5** 10^{12}**K**

BROOKHAVEN NATIONAL LABORATORY



Relativistic Heavy Ion Collider: RHIC

Particle/nuclear era in the evolution of the Universe



Vacuum and RHIC

We aim to verify the new paradigm: the Vacuum structure causes quark confinement and determines hadron structure (masses etc).

Quantum fluctuations/structure is present in 'space devoid of matter'

Quantum vacuum is polarizable: see atomic level shifts
Quantum structure of gluon-quark fluctuations:
glue and quark condensate

$$\langle V|\frac{\alpha_s}{\pi}G^2|V\rangle \simeq (2.3\pm 0.3)10^{-2}\mathrm{GeV}^4 = [390(12)\,\mathrm{MeV}]^4\,,$$

$$\langle V|G^a_{\mu\nu}|V\rangle = 0, \qquad G^2 \equiv \sum_a G^a_{\mu\nu}G_a^{\mu\nu} = 2\sum_a[\vec{B}_a^{\,2} - \vec{E}_a^{\,2}]\,,$$

$$\langle V|\bar{u}u + \bar{d}d|V\rangle = -2[225(9)\,\mathrm{MeV}]^3\,.$$

Vacuum and Laws of Physics

Vacuum structure controls early Universe properties
Vacuum determines inertial mass of all matter particles

$$m_i = g_i\langle V|h|V\rangle\,,$$

Vacuum determines interactions, symmetry breaking, etc.....

What is QGP, and how we go about to find it

Domain of (space, time) much larger than normal hadron size in which color-charged quarks and gluons are propagating constrained by external 'frozen vacuum' which abhors color.

We expect a pronounced boundary in temperature and density between confined and deconfined phases of matter: phase diagram. Deconfinement expected at both high temperature and at high matter density. In finite size systems always a 'transformation', not a sharp boundary.

What we need as background knowledge:

1) QGP equilibrium properties from QCD-lattice,
2) Understanding how to adapt these to the environment of heavy ion reactions,
3) Model of QGP hadronization into final particles,
4) Sensitive signatures of deconfinement: final particles always hadrons.

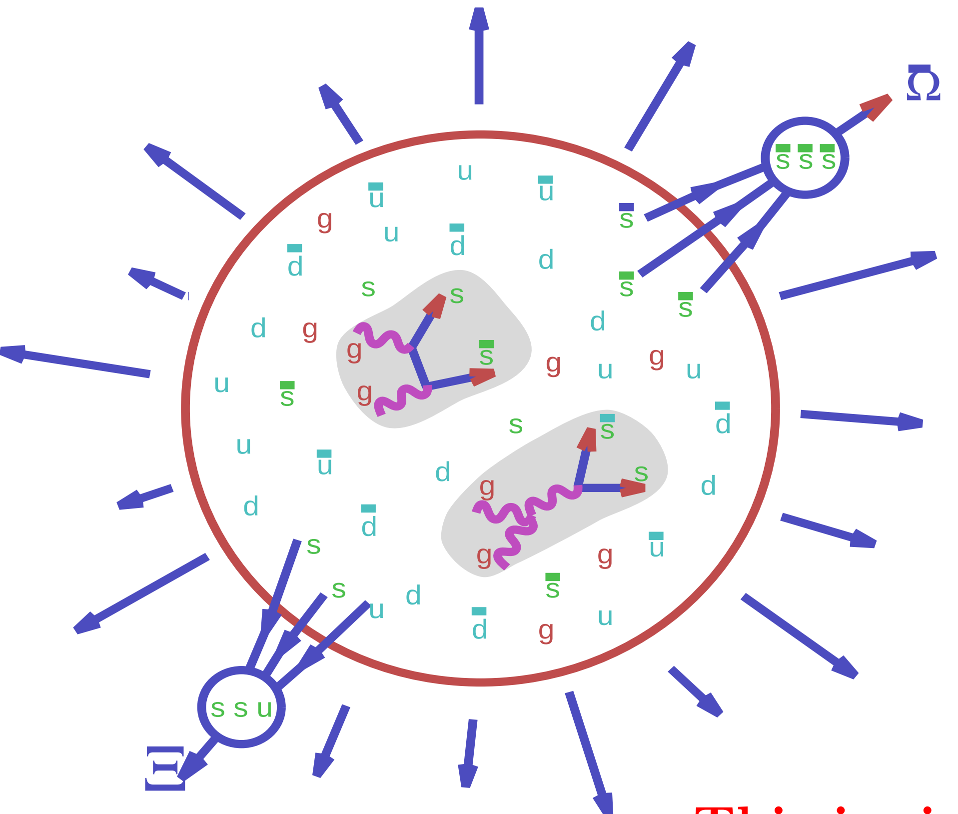
NOT A SINGLE SMOKING GUN type observation, NOT a'new' particle.
We need to pursue global, systematic and physics-consistent understanding of all experimental results. Where we are not able (yet) to evaluate results in detail, at least in principle interpretation should be available.

When reaching a consensus about discoveries, we are also remembering the difference between: verified predictions, accompanied by expected global behavior, and inventive/clever often negative post-dictions, limited in scope to punctual experimental data interpretation.

QGP is FULL OF STRANGENESS AND ENTROPY

Observables: STRANGENESS s AND ENTROPY S

Stable matter is made of only up and down quarks, strange flavor is always almost all newly made.



In the QGP hadrons are dissolved into an entropy rich partonic liquid.

TWO STEP MECHANISM of (strange) hadron formation from QGP:

1. **$GG \rightarrow s\bar{s}$ in QG-plasma**
2. **hadronization of pre-formed $s, \bar{s}$ quarks**

Excess of strangeness and even more of complex rarely produced multi strange (anti)particles from QGP enabled by coalescence between $s, \bar{s}$ quarks made earlier in QCD based microscopic reactions.

This is signature of quark mobility in the source.

Experimental observable: Enhanced production of strange anti-baryons, progresses strongly with strangeness content of the particle, increases gradually with reaction volume and energy. First seen at SPS at CERN by WA97, recent work by NA57, NA49, and STAR at RHIC collaborations. Predictions developed in detail 1981–1991 prior to experimental results.

Why Strangeness is a diagnostic tool

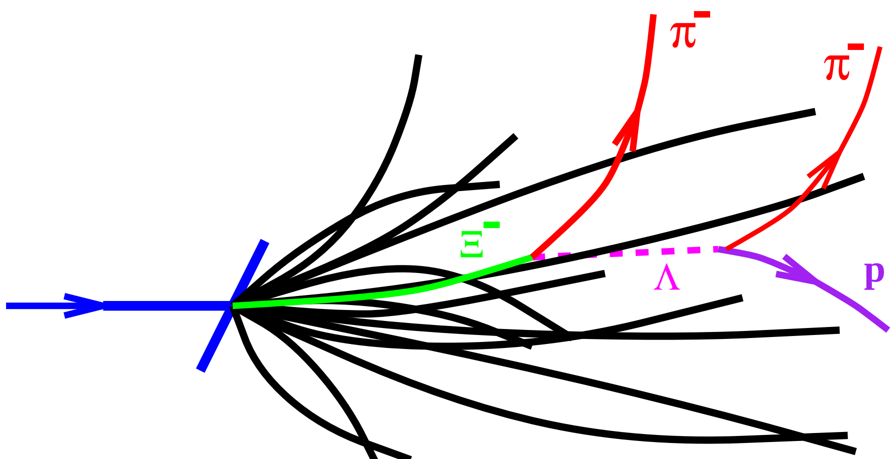
EXPERIMENTAL REASONS

- **There are many strange particles allowing to study different physics questions** $(q = u, d)$**:**

$$\phi(s\bar{s}),\quad K(q\bar{s}),\quad \overline{K}(\bar{q}s),\quad \Lambda(qqs),\quad \overline{\Lambda}(\bar{q}\bar{q}\bar{s}),$$

$$\Xi(qss),\quad \overline{\Xi}(\bar{q}\bar{s}\bar{s}),\quad \Omega(sss),\quad \overline{\Omega}(\bar{s}\bar{s}\bar{s})\quad \ldots\textbf{resonances}\ldots$$

- **Strange hadrons are subject to a self analyzing decay within a few cm from the point of production;**



- **Production rates hence statistical significance is high; (strong interaction reaction cross sections)**

THEORETICAL CONSIDERATIONS

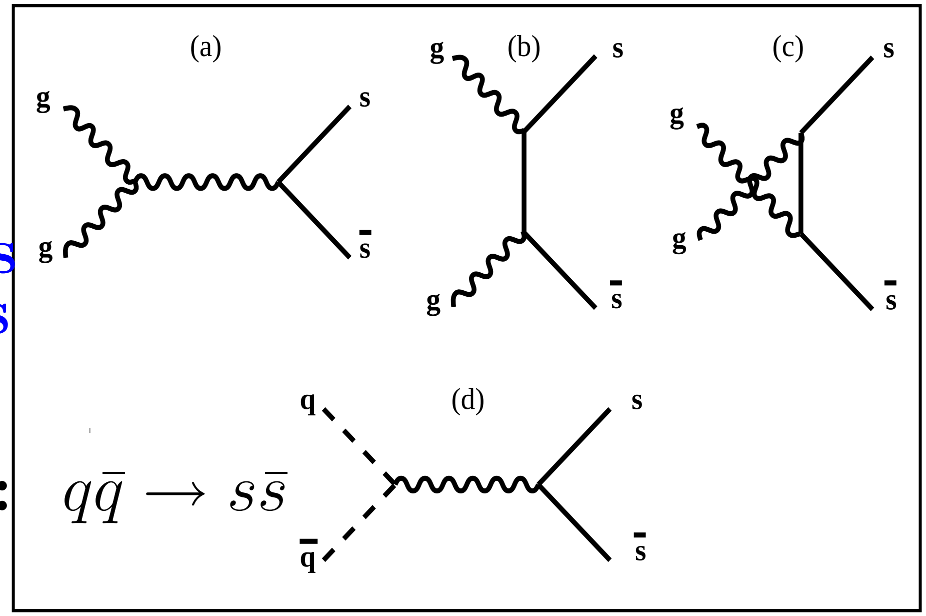
- **production of strangeness in gluon fusion** $\boxed{GG \to s\bar{s}}$
  strangeness linked to gluons from QGP;

dominant processes:

$$GG \to s\bar{s}$$

abundant strangeness
=evidence for gluons

10–15% of total rate:



- **coincidence of scales:**

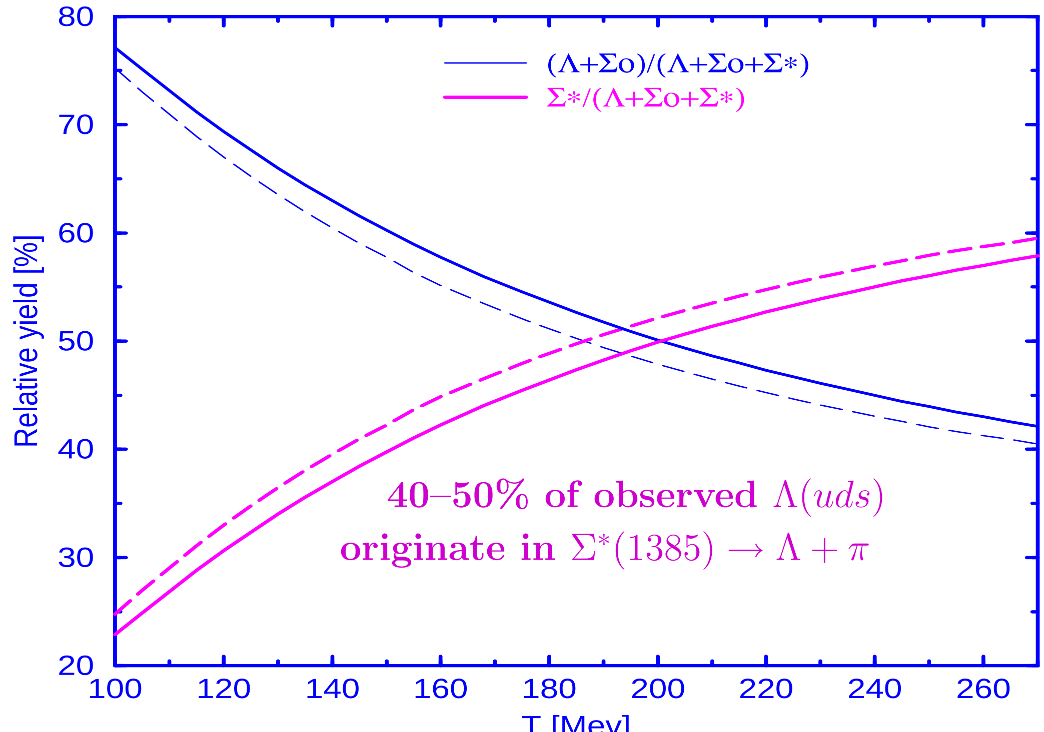
$$\boxed{m_s \simeq T_c} \to \boxed{\tau_s \simeq \tau_{\rm QGP}} \to$$

strangeness a clock for QGP phase

- $\boxed{\bar{s} \simeq \bar{q}} \to$ **strange antibaryon enhancement**
  at RHIC (anti)hyperon dominance of (anti)baryons.

II: Strange hadron resonances: A PROBE OF hadronization dynamics

direct experimental measurement!

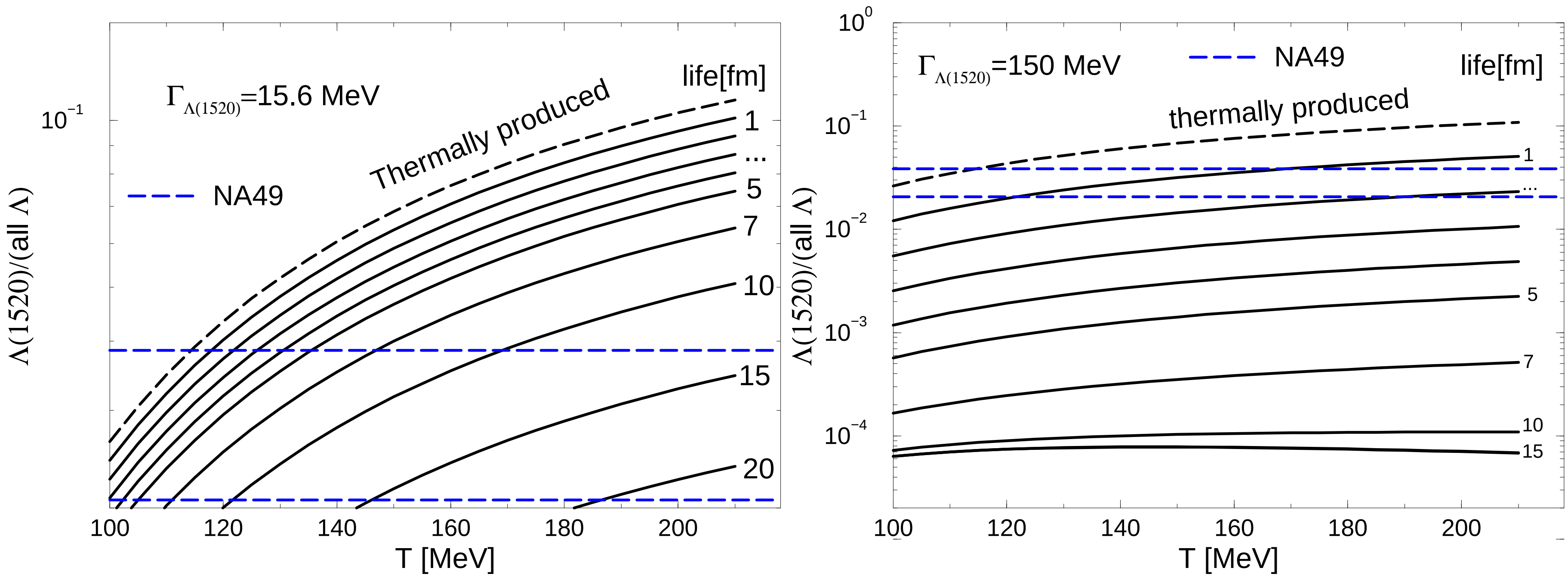


$\Sigma^*(1385) \rightarrow \Lambda + \pi$ **decay width of** $\Gamma_{\Sigma^*} = 35$ **MeV=1/(5.6 fm) assures that some decays occur within, and some outside the hadron matter – large fraction of decays within matter would be unreconstructable due to scattering of decay products. Same is true for observed** $\Gamma_{K^*(892)} = 50$ **MeV=1/(4 fm).**

Observable yields of unstable particles such as $\Sigma^*(1385)(qqs), K^*(892)(q\bar{s})$ **are sensitive to rescattering in medium of their decay products.**

Other candidates for study $\Gamma_{\Lambda(1520)} = 15.6$**MeV=1/(12.6 fm). Complication: QUENCHING of width in medium, metastable resonances such as** $\Lambda(1520)$ **may dissolve in medium. Effect first explored in a paper with Pin-Zhen Bi in early 90's, addressing medium modification of the** $\phi(s\bar{s})$**. The effect may have been discovered in** $\Lambda(1520)$**.**

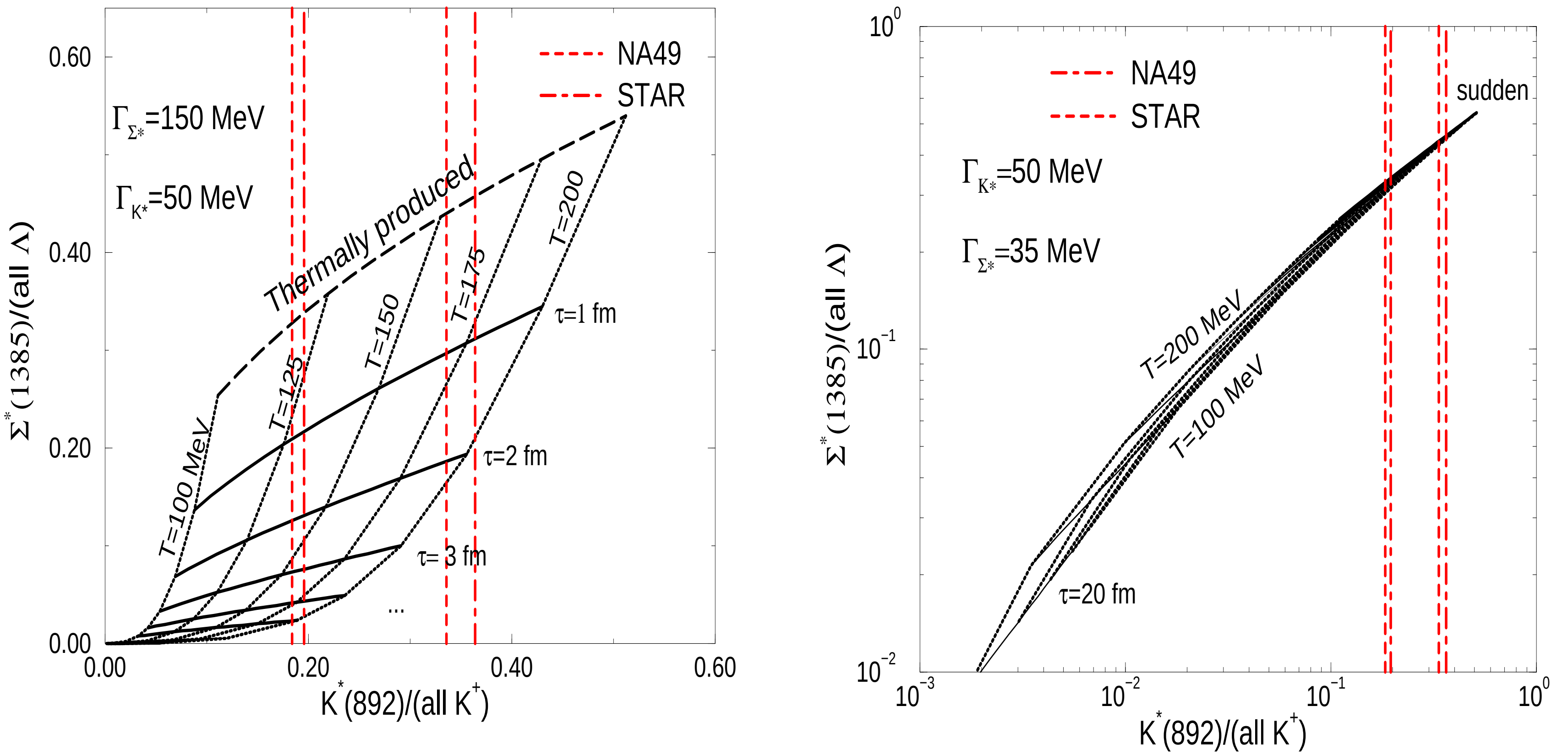
Yields as function of t and T



Relative $\Lambda(1520)/$(all Λ) yield as function of freeze-out temperature T. Dashed - thermal yield, solid lines: observable yield for evolution lasting the time shown (1....20 fm) in an opaque medium.
LEFT: natural $\Gamma_{\Lambda(1520)} = 15.6$MeV, RIGHT: quenched $\Gamma^*_{\Lambda(1520)} = 150$MeV.
NA49 measures in $pp \simeq 0.11 \pm 0.02$, in Pb–Pb $\simeq 0.025 \pm 0.008$ (horizontal lines).

HOW TO FIX value of Γ^*?

Evaluate TWO resonances; EXAMPLE



Dependence of the combined Σ^*/(all Λ) with $K^*(892)$/(all K) signals on the chemical freeze-out temperature and HG phase lifetime.

LEFT: quenched $\Gamma_{\Sigma^*} = 150$ **RIGHT** **natural widths**

J.R., J. Letessier and G. Torrieri, Phys. Rev. C64, 054907 (2001) and C65, 069902(E) (2002).

III: Sudden Hadronization

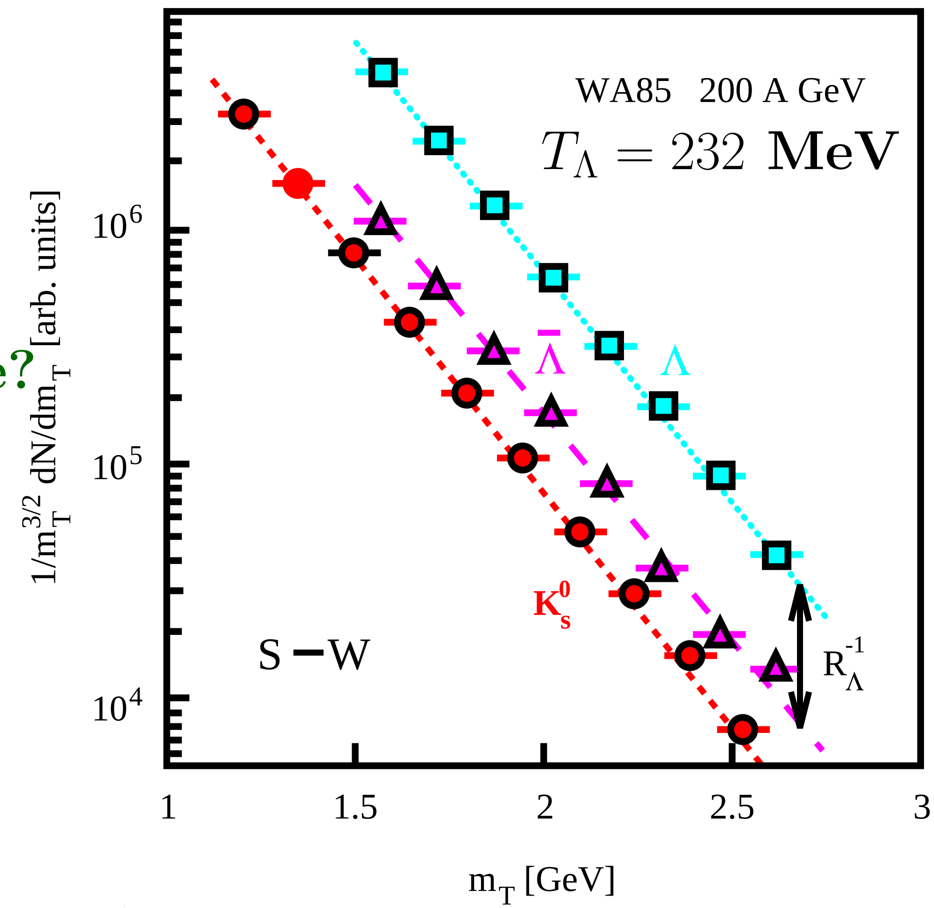
Since 1982 we assumed sudden breakup of QGP into hadrons and thus preservation of hadronic signatures of deconfinement. Other workers explored a range of alternate models, and there were speculations that there would be an extremely long lived transformation stage. HOW CAN ONE DECIDE THIS EXPERIMENTALLY??

Experiments since 1991 (WA85, WA97) see identical shape of $m_\perp$ spectra of strange baryons and antibaryons, obtained in central reactions at CM rapidity, also observed by NA49, and very precisely at RHIC.

Interpretation: Common matter-antimatter formation mechanism, little reannihilation in sequel evolution.

Appears to be DIRECT emission by a quark source into vacuum. Fast hadronization confirmed today by HBT particle correlation analysis, which yields a nearly energy independent size of hadron fireball with short lifespan of pion production.

High $m_\perp$ slope universality



Discovered in S-induced collisions, pronounced in Pb-Pb Interactions.

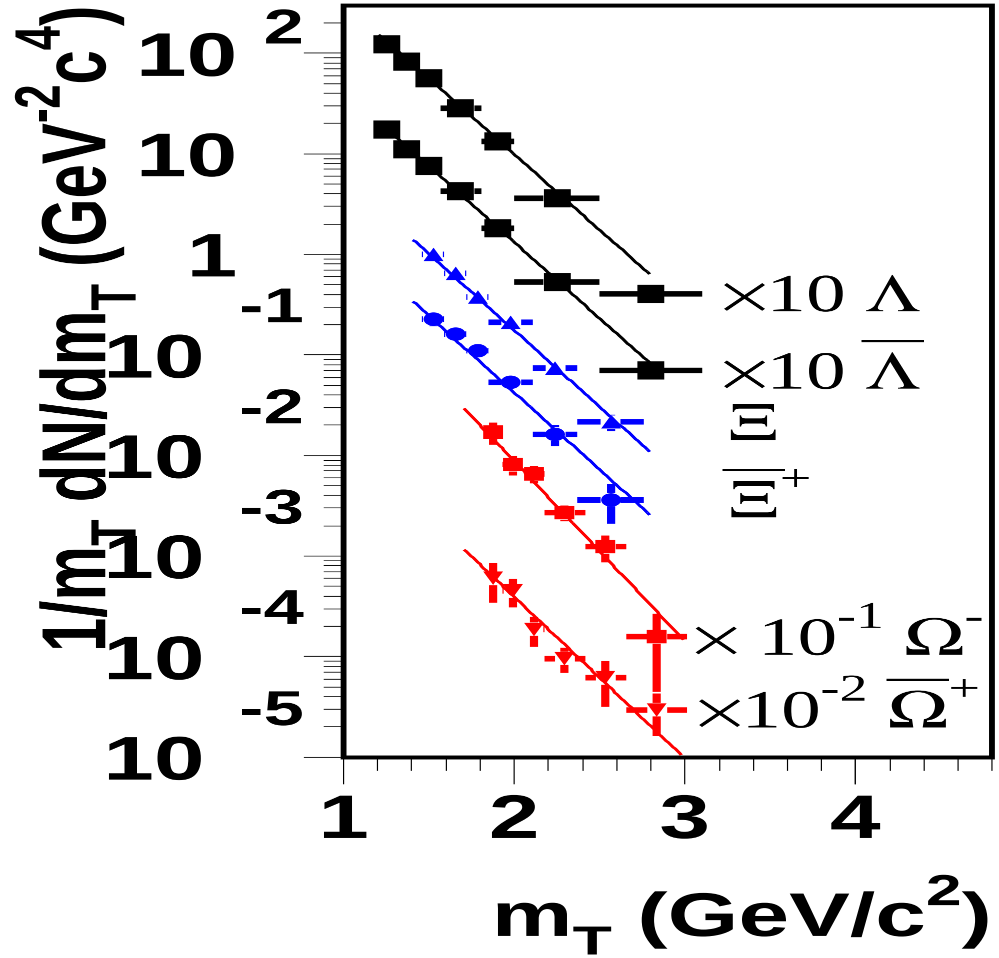
Why is the slope of baryons and antibaryons in baryon-rich environment precisely the same?

Why is the slope of different hyperons in same m_t range the same?

Analysis+our hypothesis 1991: QGP quarks coalescing in SUDDEN hadronization

This allowed the study of ratios of particles measured only in a fraction of phase space

WA97	$T_\perp^{\rm Pb}$ **[MeV]**
$T^{\rm K^0}$	**230 ± 2**
T^{Λ}	**289 ± 3**
$T^{\overline{\Lambda}}$	**287 ± 4**
T^{Ξ}	**286 ± 9**
$T^{\overline{\Xi}}$	**284 ± 17**
$T^{\Omega+\overline{\Omega}}$	**251 ± 19**



Λ within 1% of $\overline{\Lambda}$

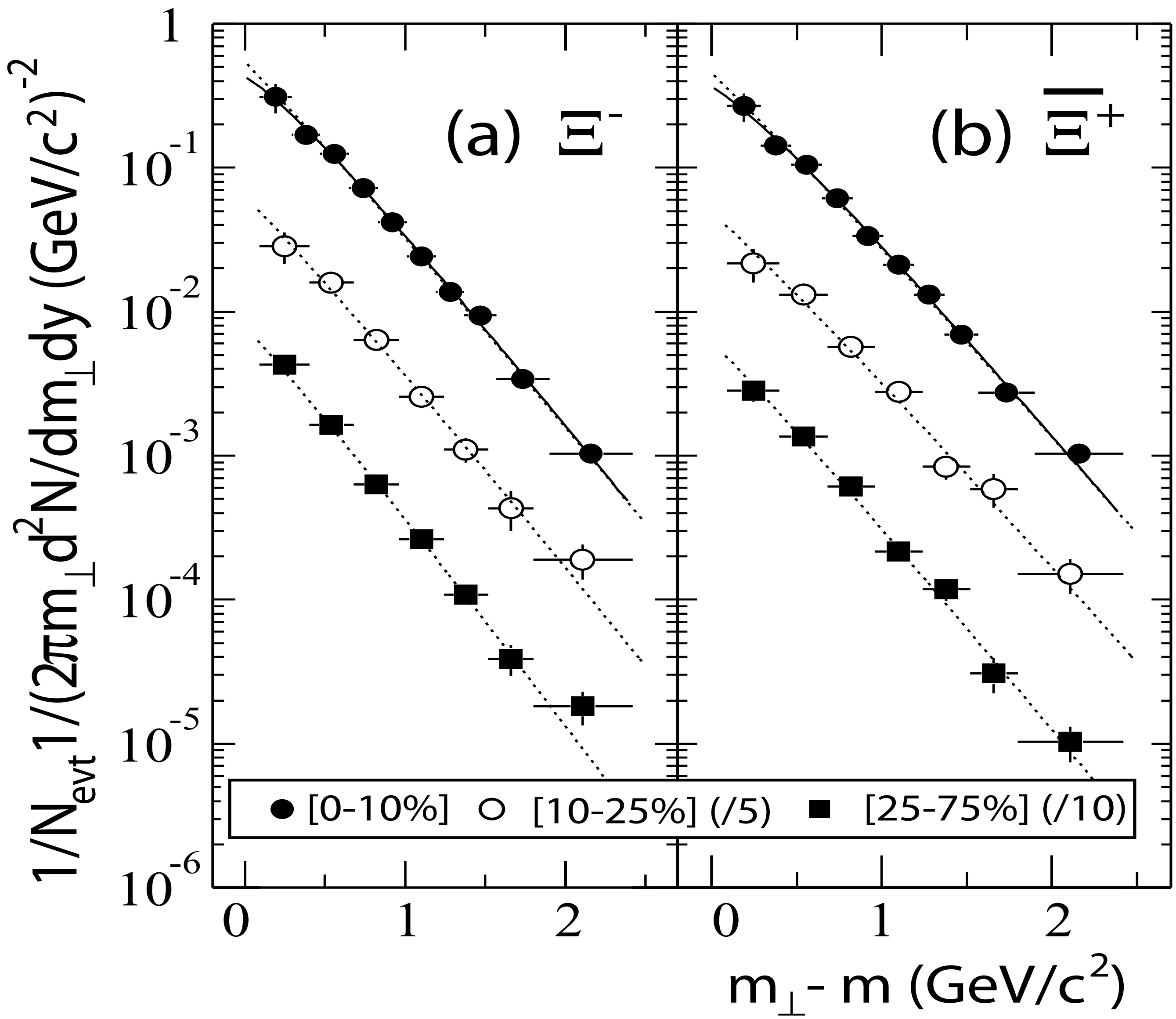
Kaon – hyperon difference: EXPLOSIVE FLOW effect

Spectra at RHIC-STAR 130+130 A GeV show the same effect

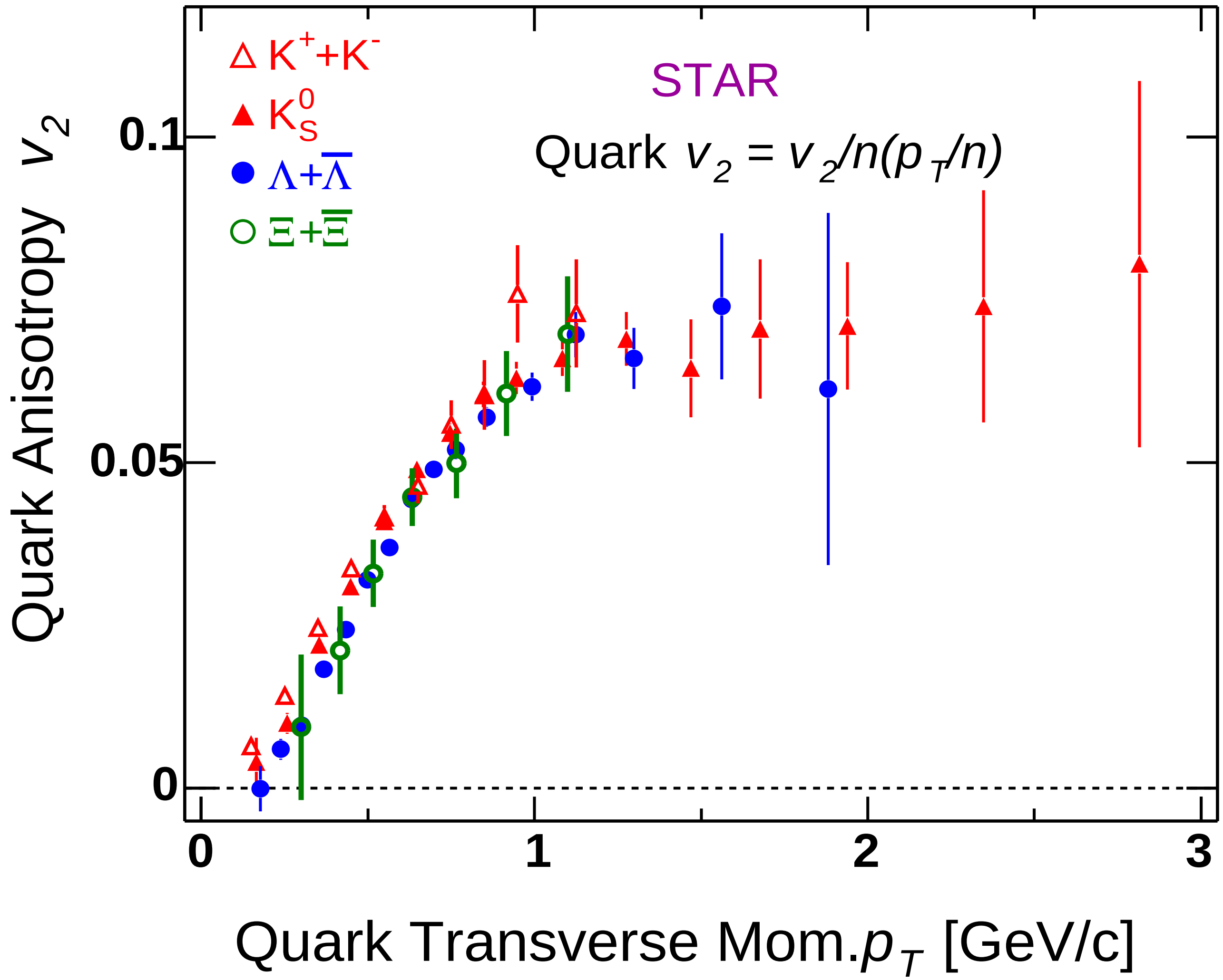
h^-		Exponential Fit		Boltzmann Fit	
centrality		dN/dy	$T_{\rm E}$(MeV)	dN/dy	$T_{\rm B}$(MeV)
260.3±7.5	Ξ^-	**2.16±0.09**	**338±6**	**2.06±0.09**	**296±5**
	$\bar\Xi^+$	**1.81±0.08**	**339±7**	**1.73±0.08**	**297±5**
163.6±5.2	Ξ^-	**1.22±0.11**	**335±16**	**1.18±0.11**	**291±13**
	$\bar\Xi^+$	**1.00±0.10**	**349±17**	**0.97±0.10**	**302±13**
42.5±3.0	Ξ^-	**0.28±0.02**	**312±12**	**0.27±0.02**	**273±10**
	$\bar\Xi^+$	**0.23±0.02**	**320±11**	**0.22±0.02**	**280±9**

$m_\perp$ **spectra of** $\Xi^-, \overline{\Xi^-}$**, for three centrality bins 0-10%, 10-25% and 25-75% with** $h^-{=}dN_{h^-}/{\rm d}\eta|_{|\eta|<0.5}$**. Statistical and** $p_\perp$ **dependent systematic uncertainties are presented. The** $p_\perp$ **independent systematic uncertainties are 10%. (STAR Collaboration, PRL92 (2004) 182301)**

$\Xi^-, \overline{\Xi^-}$ Spectra RHIC-STAR 130+130 A GeV



Early Quark Thermalization and COMMON COLLECTIVE Flow



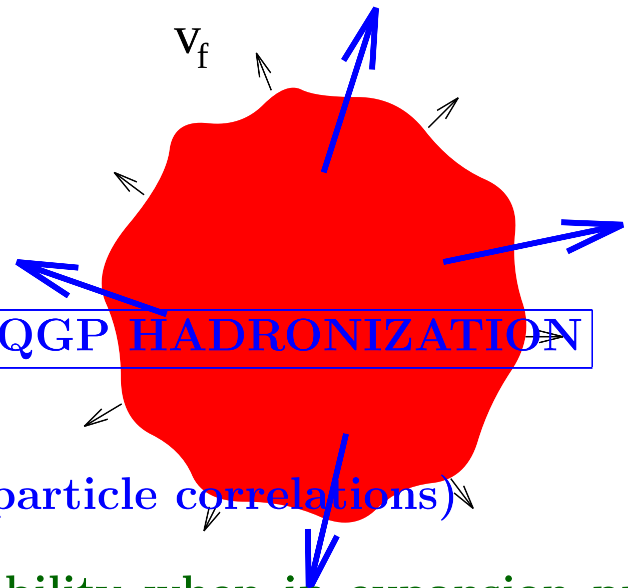
A superb confirmation that dynamics of the fireball is in partonic degrees of freedom, UCLA, P. Sorenson and Huan-Zhong Huang

DIRECT PARTICLE PRODUCTION

Common formation mechanism for all particles, for antimatter little reannihilation in sequel evolution.

Appears to be direct emission by a quark source into vacuum.

Practically no hadronic ‘phase’!
No ‘mixed phase’ either!
Direct emission of free-streaming hadrons from exploding QGP



Develop analysis tools viable in SUDDEN QGP HADRONIZATION

SLOW transformation is in contradiction to experiment (single particle spectra, 2-particle correlations)

Reaction mechanism: filamentation instability when in expansion pressure reverses (L. Csernai, Bergen et al, JR et al).

NEXT:
1) Flow of matter and supercooling
2) Production of final state particles in Statistical Hadronization

Super-cooling WIND of a fast expanding fireball

P and ε: local in QGP particle pressure, energy density, $\vec{v}$ local flow velocity. The pressure component in the energy-momentum tensor:

$$T^{ij} = P\delta_{ij} + (P+\varepsilon)\frac{v_i v_j}{1-\vec{v}^2}\,.$$

The rate of momentum flow vector $\vec{\mathcal{P}}$ at the surface of the fireball is obtained from the energy-stress tensor T_{kl} :

$$\vec{\mathcal{P}} \equiv \widehat{\mathcal{T}}\cdot\vec{n} = P\vec{n} + (P+\varepsilon)\frac{\vec{v}_{\rm c}\,\vec{v}_{\rm c}\cdot\vec{n}}{1-\vec{v}_{\rm c}^{\,2}}\,.$$

The pressure and energy comprise particle and the vacuum properties: $P = P_{\rm p} - \mathcal{B}\,, \quad \varepsilon = \varepsilon_{\rm p} + \mathcal{B}\,.$ Condition $\vec{\mathcal{P}} = 0$ reads:

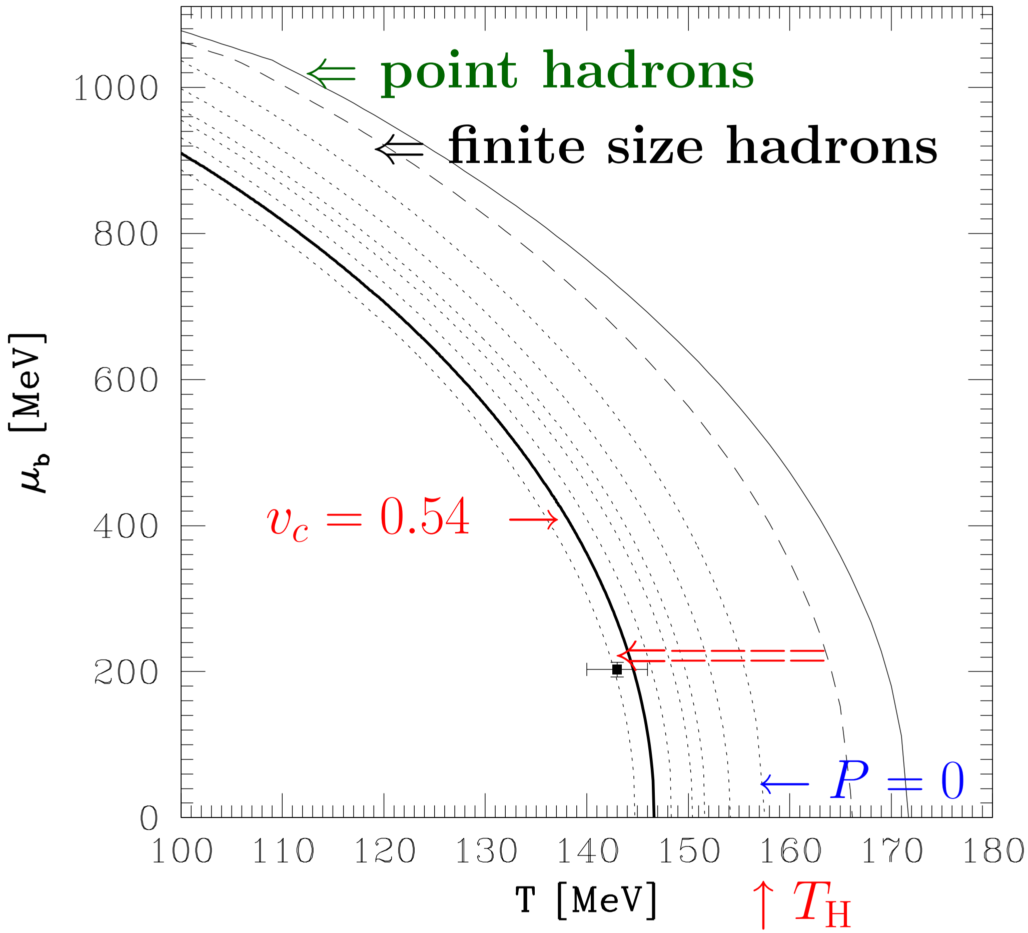
$$\mathcal{B}\vec{n} = P_{\rm p}\vec{n} + (P_{\rm p}+\varepsilon_{\rm p})\frac{\vec{v}_{\rm c}\,\vec{v}_{\rm c}\cdot\vec{n}}{1-v_{\rm c}^2}\,,$$

Multiplying with $\vec{n}$, we find,

$$\mathcal{B} = P_{\rm p} + (P_{\rm p}+\varepsilon_{\rm p})\frac{\kappa v_{\rm c}^2}{1-v_{\rm c}^2}\,, \qquad \kappa = \frac{(\vec{v}_{\rm c}\cdot\vec{n})^2}{v_{\rm c}^2}\,.$$

This requires $P_{\rm p} < \mathcal{B}$: QGP phase pressure P must be NEGATIVE. A fireball surface region which reaches $\mathcal{P} \to 0$ and continues to flow outward is torn apart in a rapid instability. This can ONLY arise since matter presses again the vacuum which is not subject to collective dynamics.

Phase boundary and 'wind' of flow of matter



Solid: point hadrons T_p
Dashed: finite size

Dotted: $T_c(\mu_b)|_{P_{eff}-\mathcal{B}=0}$ for $v^2 = 0, 1/10, 1/6, 1/5, 1/4, 1/3$**.**

Thick solid: breakup with $v = 0.54$ **(**$\kappa = 0.6$**)**
PRL 85 (2000) 4695

DEEP SUPERCOOLING by 20 MeV

$T_H = 158$ **MeV Hagedorn temperature where** $P = 0$**, no hadron** P
$T_f \simeq 0.9 T_H \simeq 143$ **MeV is where supercooled QGP fireball breaks up**
equilibrium phase transformation is at $\simeq 166$**.**

IV: Strangeness in QGP

1. **TOTAL STRANGENESS YIELD:** **strangeness/baryon** **depends primarily on initial conditions and (less) on evolution dynamics**
(how long the system is at which T)

$\gamma_s^{\rm QGP}$: is QGP near chemical equilibrium?

$$\gamma_{\rm s,q}^{\rm QGP} = \left.\frac{n_{\rm s,q}(t, T(t))}{n_{\rm s,q}(\infty, T(t))}\right|_{\rm QGP} \to 1?$$

2. **Strangeness overpopulation at QGP BREAK-UP:**
QGP phase space is squeezed into a smaller number of HG phase space cells: $\gamma_{\rm s}^{HG} \simeq (2...5)\gamma_{\rm s}^{\rm QGP}$

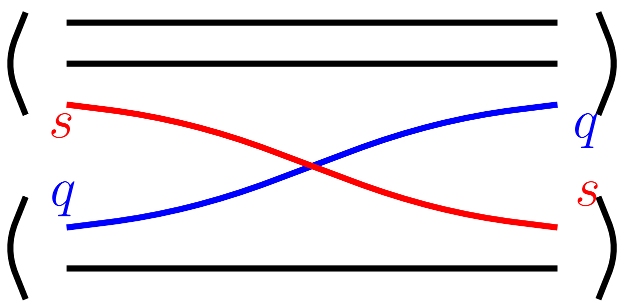
3. **WE NEED ALSO TO CONSIDER QGP ENTROPY enhancement expressed in** $e^{m_\pi/(2T)} > \gamma_q^{\rm HG} > 1$
over population of pion phase space is ENTROPY enhancement

FOUR QUARKS: $s, \bar{s}, q, \bar{q} \rightarrow$ FOUR CHEMICAL PARAMETERS

γ_i controls overall abundance of quark $(i = q, s)$ pairs	Absolute chemical equilibrium
λ_i controls difference between strange and non-strange quarks $(i = q, s)$	Relative chemical equilibrium

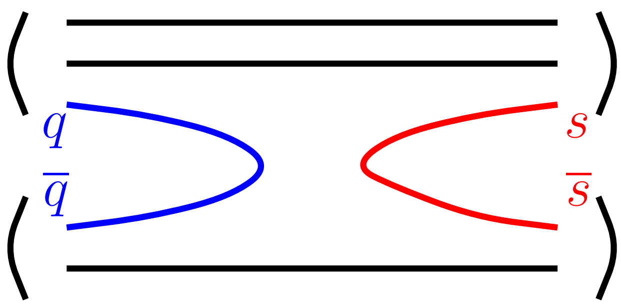
HG-EXAMPLE: redistribution, Relative chemical equilibrium

production of strangeness Absolute chemical equilibrium



EXCHANGE REACTION

λ_i



PAIR PRODUCTION REACTION

γ_i

STRANGENESS YIELD IN QGP and $\gamma_s^{QGP}/\gamma_q^{QGP}$

$$\frac{\rho_s}{\rho_b} = \frac{s}{q/3} = \frac{\gamma_s^{QGP}\frac{3}{\pi^2}T^3(m_s/T)^2K_2(m_s/T)}{\gamma_q^{QGP}\frac{2}{3}\left(\mu_q T^2 + \mu_q^3/\pi^2\right)}, \to \frac{s}{b} \simeq \frac{\gamma_s^{QGP}}{\gamma_q^{QGP}}\frac{0.7}{\ln\lambda_q + (\ln\lambda_q)^3/\pi^2}.$$

assumption: $\mathcal{O}(\alpha_s)$ interaction effects cancel out between b, s

We consider $m_s = 200$ MeV and hadronization $T = 150$ MeV,

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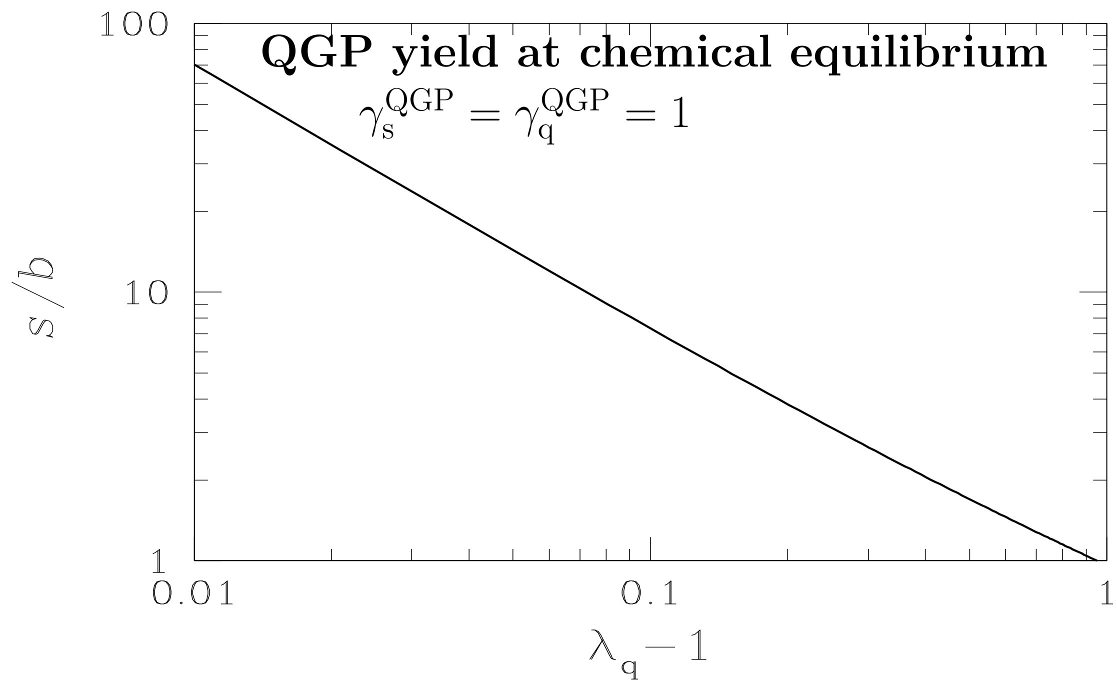

At SPS λ_q=1.5–1.6, implies $s/b \simeq 1.5$.

Observation: $s/b \simeq 0.75 \to \gamma_s^{QGP}/\gamma_q^{QGP} = 0.5$ at SPS

Similarly for RHIC at $\sqrt{s_{NN}} \geq 130$ GeV we have $1 \leq \lambda_q \leq 1.1$ and a comparison of the actual s/b yield allows to estimate $\gamma_s^{QGP}/\gamma_q^{QGP}$=0.7–0.8 at RHIC-130.

CAN WE ESTIMATE THE EXPECTED $\gamma_s^{\rm HG}$?

COMPUTE EXPECTED RATIO OF $\gamma_{\rm s}^{\rm HG}/\gamma_{\rm s}^{\rm QGP}$

In sudden hadronization, $V^{\rm HG} \simeq V^{\rm QGP}$, $T^{\rm QGP} \simeq T^{\rm HG}$,
the chemical occupancy factors accommodate the different magnitude of particle phase space.

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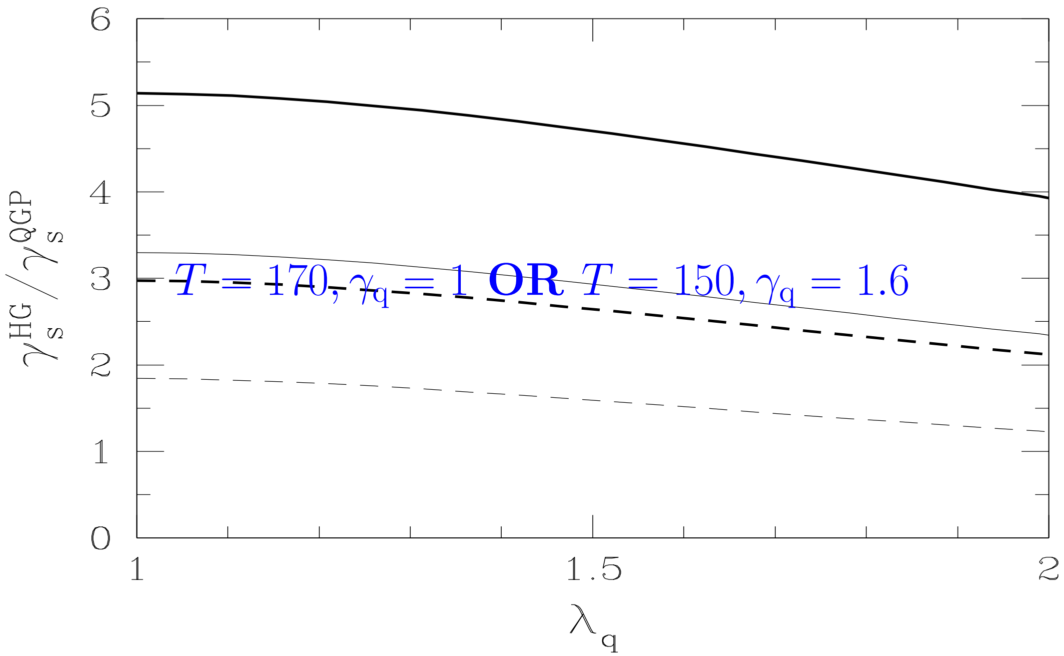
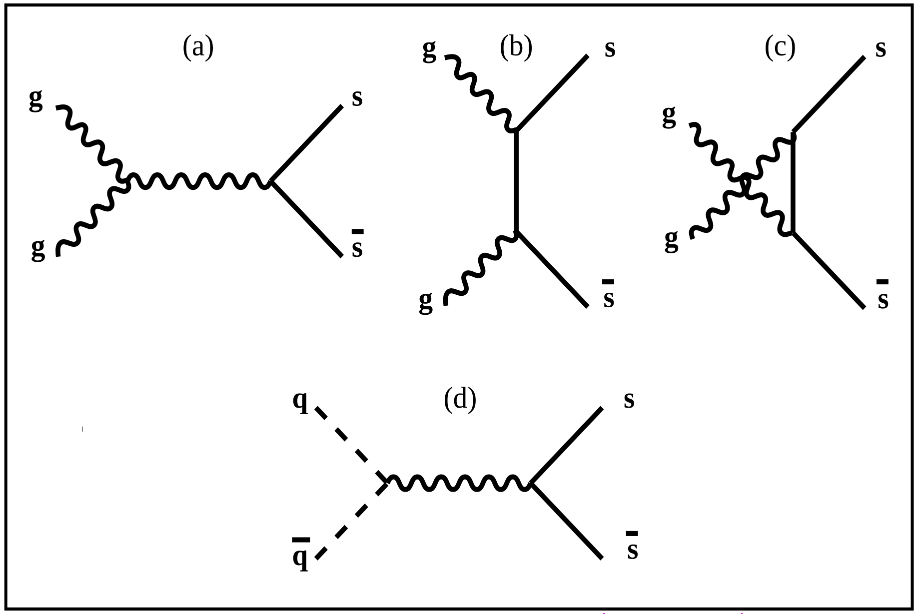


$\gamma_{\rm s}^{\rm HG}/\gamma_{\rm s}^{\rm QGP}$ in sudden hadronization as function of $\lambda_{\rm q}$. Solid lines $\gamma_{\rm q} = 1$, and short dashed $\gamma_{\rm q} = 1.6$. Thin lines for $T = 170$ and thick lines $T = 150$ MeV, common to both phases.

$$\gamma_s^{\rm HG} \simeq 2...5\gamma_s^{\rm QGP}$$

Kinetic description of strangeness production



The generic angle averaged cross sections for (heavy) flavor s, $\bar{s}$ production processes $g+g\to s+\bar{s}$ and $q+\bar{q}\to s+\bar{s}$, are:

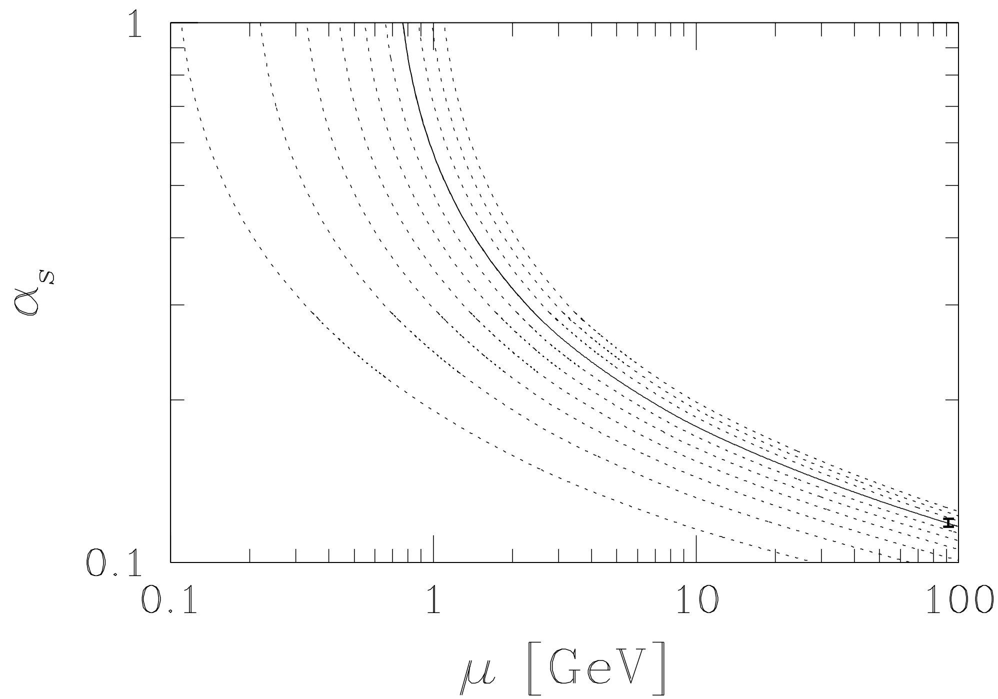
$$\bar{\sigma}_{gg\to s\bar{s}}(s) = \frac{2\pi\alpha_{\rm s}^2}{3s}\left[\left(1+\frac{4m_{\rm s}^2}{s}+\frac{m_{\rm s}^4}{s^2}\right)\tanh^{-1}W(s)-\left(\frac{7}{8}+\frac{31m_{\rm s}^2}{8s}\right)W(s)\right],$$

$$\bar{\sigma}_{q\bar{q}\to s\bar{s}}(s) = \frac{8\pi\alpha_{\rm s}^2}{27s}\left(1+\frac{2m_{\rm s}^2}{s}\right)W(s)\,. \qquad W(s)=\sqrt{1-4m_{\rm s}^2/s}$$

Infinite QCD resummation: running $\alpha_{\rm s}$ and $m_{\rm s}$ taken at the energy scale $\mu\equiv\sqrt{s}$.
USED: $m_s(M_Z)=90\pm 20\%$ MeV $m_s(1\,\textbf{GeV})\simeq 2.1 m_s(M_Z)\simeq 200$**MeV.**

WHY PERTURBATIVE STRANGENESS WORKS

An essential prerequirement for the perturbative theory of strangeness production in QGP, is the relatively small experimental value $\alpha_s(M_Z) \simeq 0.118$, which has been experimentally established in recent years.



$\alpha_s^{(4)}(\mu)$ as function of energy scale μ for a variety of initial conditions. Solid line: $\alpha_s(M_Z) = 0.1182$ (experimental point, includes the error bar at $\mu = M_Z$).

At the scale of just above 1 GeV where typically thermal strangeness production in RHIC QGP occurs, perturbative theory makes good sense but is not completly reliable. Had $\alpha_s(M_Z) > 0.125$ been measured 1996 than our approach from 1982 would have been invalid.

Thermal averge of (strangeness p[roduction) reaction rates

Kinetic (momentum) equilibration is faster than chemical, use thermal particle distributions $f(\vec{p}_1, T)$ to obtain average rate:

$$\langle \sigma v_{\rm rel} \rangle_T \equiv \frac{\int d^3p_1 \int d^3p_2 \sigma_{12} v_{12} f(\vec{p}_1, T) f(\vec{p}_2, T)}{\int d^3p_1 \int d^3p_2 f(\vec{p}_1, T) f(\vec{p}_2, T)} \,.$$

Invariant reaction rate in medium:

$$A^{gg\to s\bar{s}} = \frac{1}{2}\rho_g^2(t)\, \langle \sigma v \rangle_T^{gg\to s\bar{s}}, \quad A^{q\bar{q}\to s\bar{s}} = \rho_q(t)\rho_{\bar{q}}(t) \langle \sigma v \rangle_T^{q\bar{q}\to s\bar{s}}, \quad A^{s\bar{s}\to gg,q\bar{q}} = \rho_s(t)\, \rho_{\bar{s}}(t)\, \langle \sigma v \rangle_T^{s\bar{s}\to gg,q\bar{q}}.$$

$1/(1+\delta_{1,2})$ **introduced for two gluon processescompensates the double-counting of identical particle pairs, arising since we are summing independently both reacting particles.**

This rate enters the momentum-integrated Boltzmann equation which can be written in form of current conservation with a source term

$$\partial_\mu j_s^\mu \equiv \frac{\partial \rho_s}{\partial t} + \frac{\partial \vec{v} \rho_s}{\partial \vec{x}} = A^{gg\to s\bar{s}} + A^{q\bar{q}\to s\bar{s}} - A^{s\bar{s}\to gg,q\bar{q}}$$

Strangeness density time evolution

in local restframe ($\vec{v}$) we have :

$$\frac{d\rho_s}{dt} = \frac{d\rho_{\bar{s}}}{dt} = \frac{1}{2}\rho_g^2(t)\,\langle\sigma v\rangle_T^{gg\to s\bar{s}} + \rho_q(t)\rho_{\bar{q}}(t)\langle\sigma v\rangle_T^{q\bar{q}\to s\bar{s}} - \rho_s(t)\,\rho_{\bar{s}}(t)\,\langle\sigma v\rangle_T^{s\bar{s}\to gg,q\bar{q}}$$

Evolution for s and $\bar{s}$ identical, which allows to set $\rho_s(t) = \rho_{\bar{s}}(t)$.
Use detailed balance to simplify

$$\frac{d\rho_s}{dt} = A\left(1 - \frac{\rho_s^2(t)}{\rho_s^2(\infty)}\right), \qquad A = A^{gg\to s\bar{s}} + A^{q\bar{q}\to s\bar{s}}$$

The generic solution at fixed T ($\rho \propto \tanh$) implies that in all general cases there is an exponential approach to chemical equilibrium

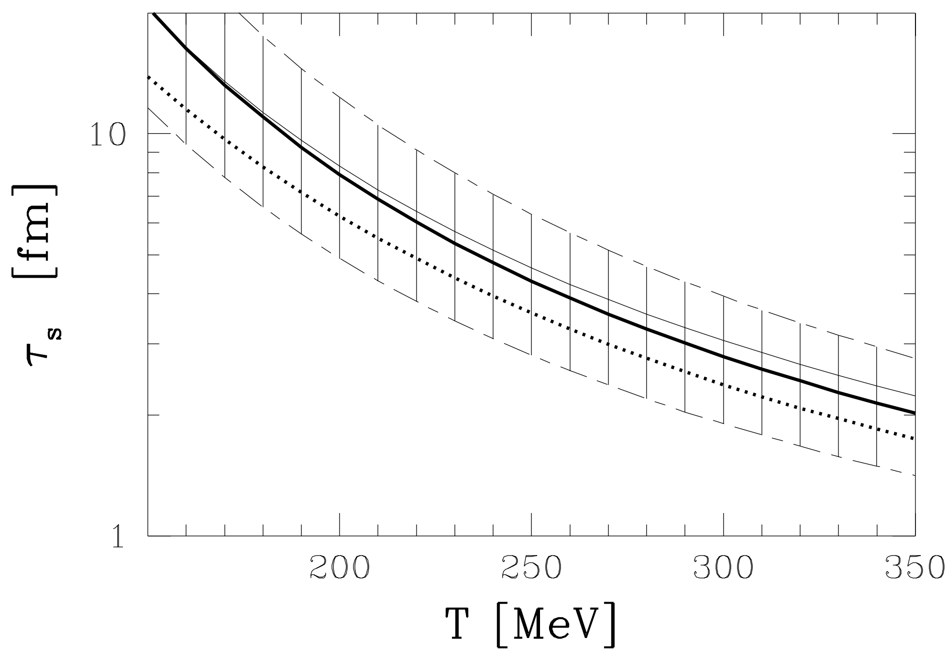
$$\frac{\rho_s(t)}{\rho_s^\infty} \to 1 - e^{-t/\tau_s}$$

with the characteristic time constant τ_s:

$$\tau_s \equiv \frac{1}{2}\frac{\rho_s(\infty)}{(A^{gg\to s\bar{s}} + A^{q\bar{q}\to s\bar{s}} + \ldots)}$$

$$A^{12\to 34} \equiv \frac{1}{1+\delta_{1,2}}\rho_1^\infty\rho_2^\infty\langle\sigma_s v_{12}\rangle_T^{12\to 34}.$$

Characteristic time constant and γ_s-evolution



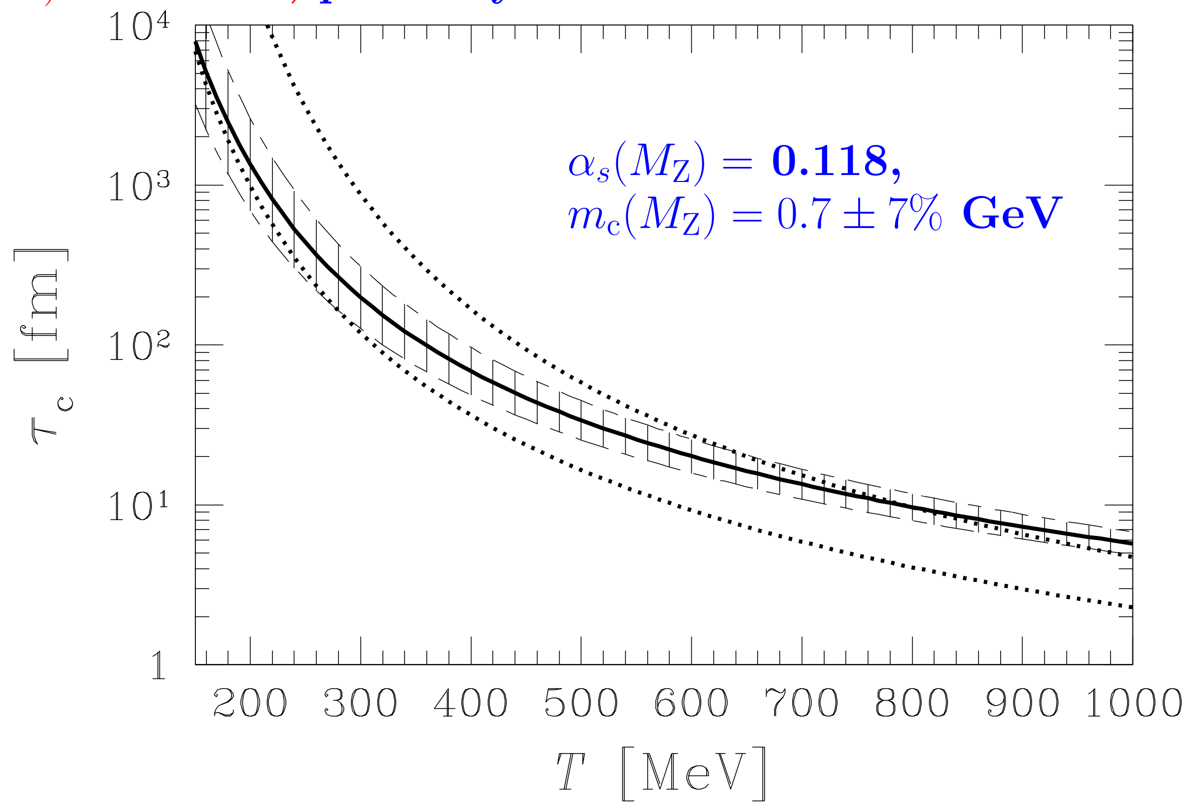
$\sigma_{\rm QCD}^{\to s\bar s}$ **gives** τ_s **similar to lifespan of the plasma phase!**
Strange quark pair production dominated by gluon fusion: $G+G\to s\bar s$**, also some (10%)** $q\bar q\to s\bar s$, **present; this is due to gluon collision rate.**
ENTROPY CONSERVING expansion i.e. at SPS T^3V **=Const. (not yet long. scaling):**

$$2\tau_s\frac{dT}{dt}\left(\frac{d\gamma_s}{dT}+\frac{\gamma_s}{T}z\frac{K_1(z)}{K_2(z)}\right)=1-{\gamma_s}^2\,,\quad \gamma_s(t)\equiv n_s(t)/n_s^\infty\,,\quad z=\frac{m_s}{T}\,,\quad K_i:\mathrm{Besself.}$$

Once γ_s **known,** $\langle\rho_s(t)\rangle=\langle\bar\rho_s(t)\rangle=\int dx^3\rho_s^\infty(T(t,x))\gamma_s(T(t,x),\dot T(t,x))$;
evolution till $t\to t_f$**,but effectively production stops for** $T<180$ **MeV.**

What about charm? $m_s \to m_c$

We expect that thermal charm production is of relevance only for $T \to m_c(1\,\mathbf{GeV}) \simeq 1.5\,\mathbf{GeV}$, probably not accessible.



Lower dotted line: for fixed $m_c = 0.9\,\mathbf{GeV}$, $\alpha_s = 0.35$;
upper doted line: for fixed $m_c = 1.5\,\mathbf{GeV}$, $\alpha_s = 0.4$.
Equillibrium density for $\rho_c^\infty(m_c \simeq 1.5\,\mathbf{GeV})$.

Charm is produced relatively abundantly in first parton collisions. Benchmark: 10 $c\bar{c}$ pairs in central Au–Au at RHIC-200. This yield is greater than the expected thermal equilibrium yield at hadronization of QGP. Charmonium enhancement by recombination.

OBJECTIVE: Physical properties of the source at hadronization
NEED the phase space of hadronic particles in great precision.

V: SHARE – FERMI STATISTICAL HADRONIZATION MODEL

The thermal emitted particles production yield dN_i within the time

$T_{\rm f}$	Local rest frame chemical freeze-out temperature
v_h,$v_{\rm f}$	Hadronization, Local flow speed of emitting source
$\lambda_{\rm s}$, $\lambda_{\rm q}$	Chemical fugacities describe conserved quantum number
$\gamma_{\rm s}$, $\gamma_{\rm q}$	Phase space occupancies describe quark pair yield

dt **from a locally at rest surface element** dS**:**

$$dN_i = \frac{dSd^3p}{(2\pi)^3} A_i v_i dt \,.$$

$v_i = dz/dt$ **is the particle velocity normal to the surface element** dS**.**
In a thermal quark-gluon source, phase space factor A_i **is:**

$$A_i = g_i \lambda_i \gamma_i e^{-E_i/T} \,, \qquad \lambda_i = \prod_{j\in i} \lambda_j \,, \quad \gamma_i = \prod_{j\in i} \gamma_j \,, \quad E_i = \sum_{j\in i} E_j \,,$$

RATIOS OF PARTICLE YIELDS FIX CHEMICAL PARAMETERS

$$R_\Lambda = \frac{\overline{\Lambda}}{\Lambda} = \frac{\overline{\Lambda} + \overline{\Sigma}^0 + \overline{\Sigma}^* + \cdots}{\Lambda + \Sigma^0 + \Sigma^* + \cdots} = \frac{\bar{s}\bar{q}\bar{q}}{sqq} = \lambda_{\rm s}^{-2}\lambda_{\rm q}^{-4} = e^{2\mu_{\rm S}/T}e^{-2\mu_b/T}\,.$$

$$R_\Xi = \frac{\overline{\Xi^-}}{\Xi^-} = \frac{\overline{\Xi^-} + \overline{\Xi^*} + \cdots}{\Xi^- + \Xi^* + \cdots} = \frac{\bar{s}\bar{s}\bar{q}}{ssq} = \lambda_{\rm s}^{-4}\lambda_{\rm q}^{-2} = e^{4\mu_{\rm S}/T}e^{-2\mu_b/T}\,.$$

Sensitivity to nonequilibrium occupancy factors γ_i derives from comparison of hadron yields with differing q, s quark content e.g.:

$$\frac{\Xi^-(dss) + \Xi * +...}{\Lambda(dds) + \Lambda * +.....} \propto \frac{\gamma_d\gamma_s^2}{\gamma_d^2\gamma_s}\;\frac{g_\Xi\lambda_d\lambda_s^2}{g_\Lambda\lambda_d^2\lambda_s}\,.$$

note: $\gamma_q^2 \equiv \gamma_u\gamma_d, \quad \gamma_u \simeq \gamma_d$. **Observation of $\gamma_q > 1, \gamma_s > 1$ implies rapid expansion of near equilibrium QGP, with final hadrons emitted directly from deconfined state.**

Complete description of all hadron yields

We note above the presence of resonance decays. Full analysis requires a significant effort with 1000's of decaying states. A public package SHARE Statistical Hadronization with Resonances is available at http://www.physics.arizona.edu/~torrieri/SHARE/share.html developed by Kraków-Tucson collaboration.

Lead author: Giorgio Torrieri.

The complete statistical hadronization model allows precise description of all hadron yields, including resonances at all energies. The myth that resonances are not described within the same scheme is due to the limited model applied by some other groups wich omits one or more key properties required. We find that Single freeze-out model as proposed in 1991 suffices when we consider:

1. **Complete tree of resonance decays** **please note: not only for yields but also most important for spectra.**
2. **WIDTH of the resonances (needed to describe resonance yields)**
3. **Chemical off-equilibrium in hadron yields (if QGP near equilibrium, it is not present in the hadron sector, as the transformation is sudden).**

Look for a few publications using the SHARE package on line.

PARTICLE ABUNDANCES

$\pi(q\bar{q}) \sim \gamma_q^2 \qquad N(qqq) \sim \gamma_q^3 \lambda_q^3; \qquad \overline{N}(\bar{q}\bar{q}\bar{q}) \sim \gamma_q^3 \lambda_q^{-3}$

QUANTUM STATISTICS

$$\frac{N_\pi}{V} = g_\pi \int \frac{d^3p}{(2\pi)^3} \frac{1}{\gamma_q^{-2} e^{\sqrt{m_\pi^2 + p^2}/T} - 1}, \qquad \gamma_q^2 < e^{m_\pi/T} \simeq (1.6)^2$$

$$\frac{N}{V} = g_N \int \frac{d^3p}{(2\pi)^3} \frac{1}{1 + \gamma_q^{-3} \lambda_q^{-3} e^{E/T}} \qquad \frac{\overline{N}}{V} = g_N \int \frac{d^3p}{(2\pi)^3} \frac{1}{1 + \gamma_q^{-3} \lambda_q^{+3} e^{E/T}}$$

$$\mu_N^{\rm eff} = 3T(\ln \lambda_q + \ln \gamma_q); \qquad \mu_{\overline{N}}^{\rm eff} = -3T(\ln \lambda_q - \ln \gamma_q)$$

---

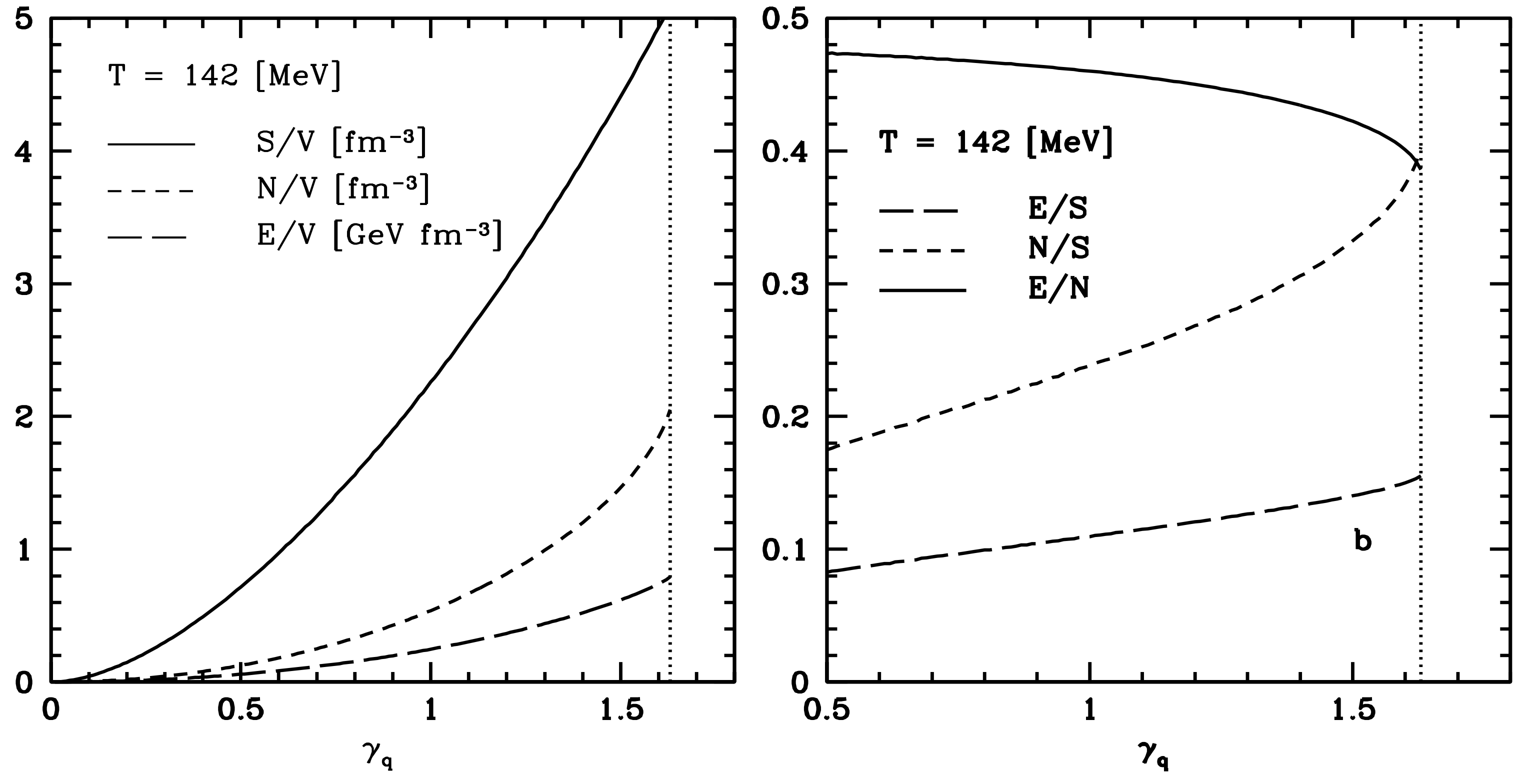
presence of γ, λ is simply allowing to assign different potentials for particles and antiparticles else $\bar{\mu} = -\mu$

$\gamma_q^2 \to e^{m_\pi/T}$: A way to 'consume' excess of QGP entropy

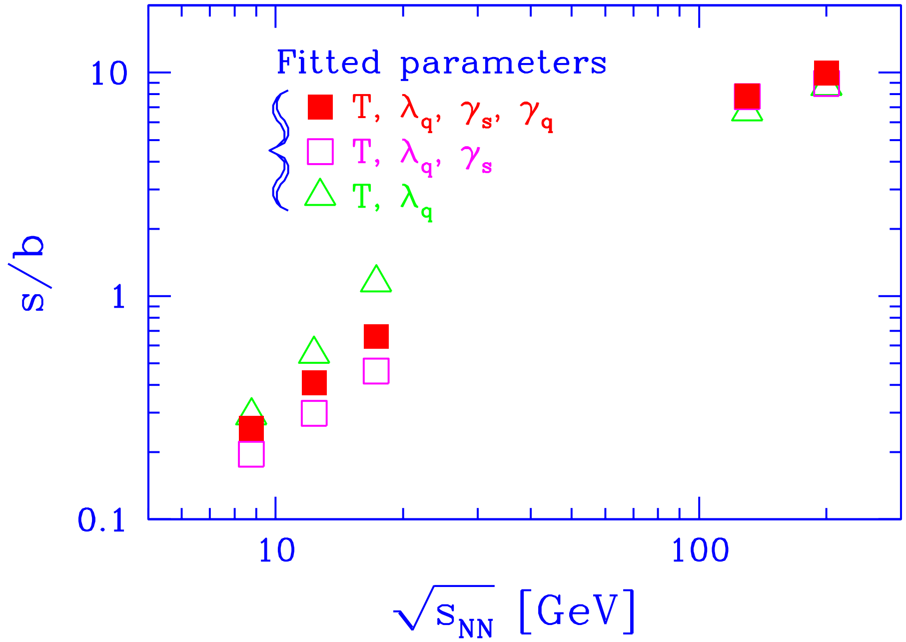
Maximization of entropy density in pion: gas. $E_\pi = \sqrt{m_\pi^2 + p^2}$

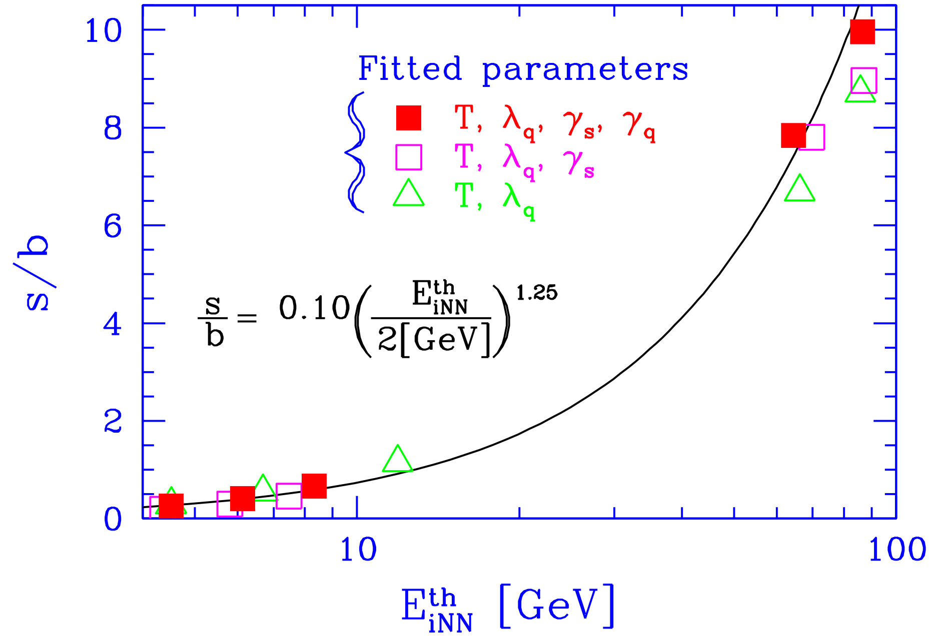
$$S_{\rm B,F} = \int \frac{d^3p\, d^3x}{(2\pi\hbar)^3} \left[\pm(1\pm f)\ln(1\pm f) - f\ln f\right], \qquad f_\pi(E) = \frac{1}{\gamma_q^{-2} e^{E_\pi/T} - 1}.$$

Pion gas properties: N**-particle,** E**-energy,** S**-entropy,** V**-volume as function of** γ_q**.**



FROM SPS to RHIC: STRANGENESS vs NET BARYON CONTENT

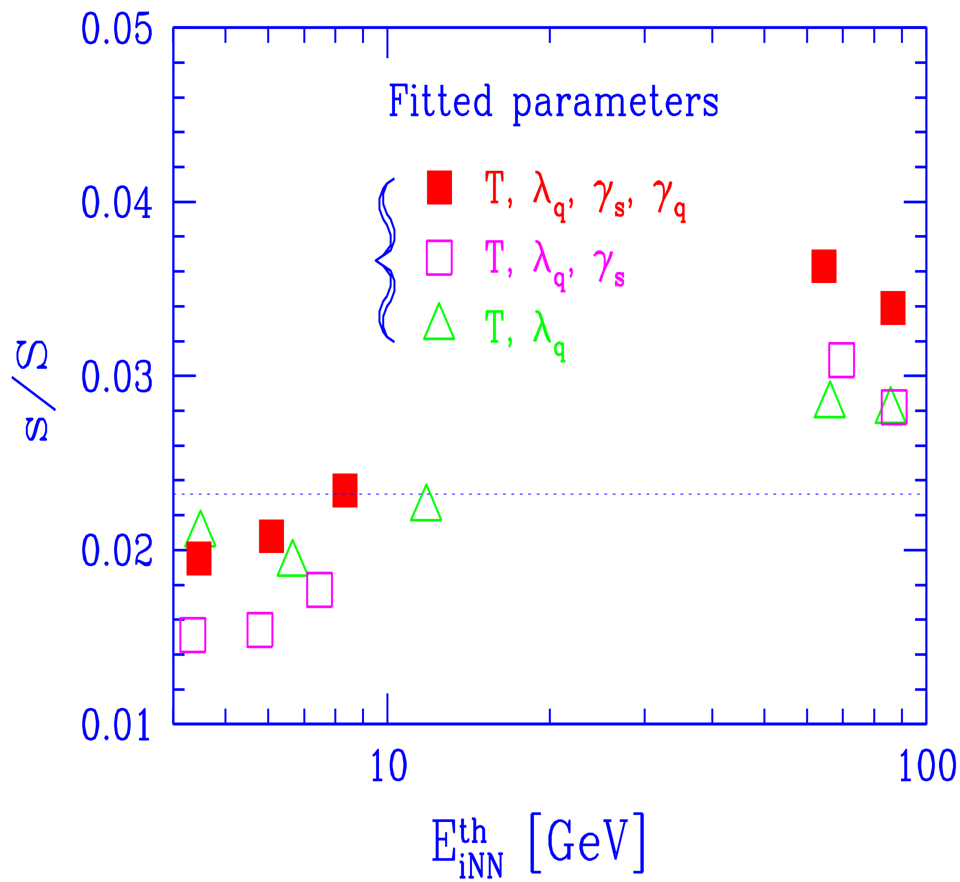




Strangeness per thermal baryon participating in the reaction grows rapidly and continuously. Gluon based thermal production mechanism UNDERSTOOD.
Strangeness production rises faster than entropy.
YIELD MUCH GREATER THAN IN NN-REACTIONS

OUTLOOK:
Soon at LHC – charm takes over from strangeness – an experimental challenge

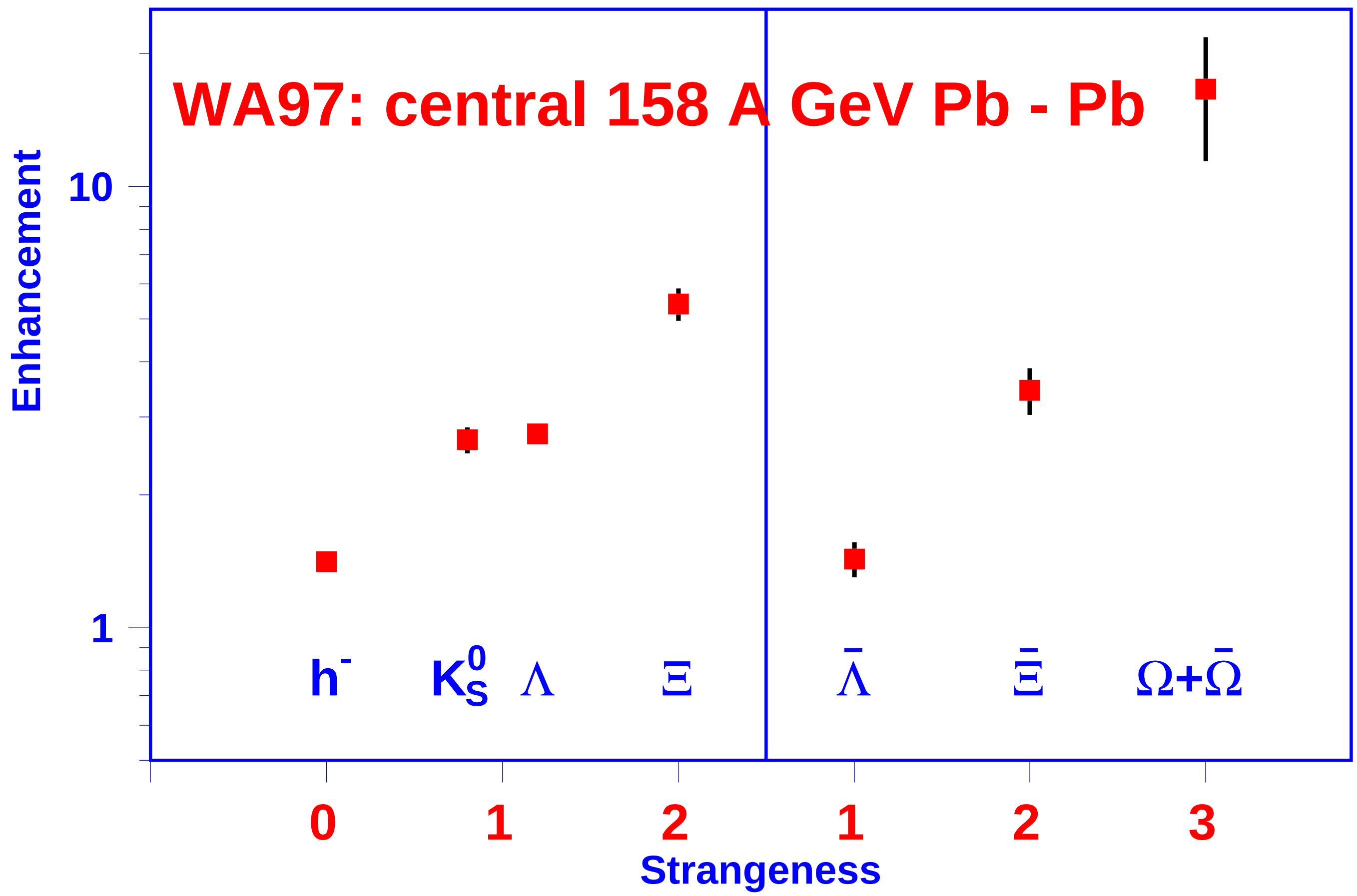
YET MORE INTERESTING: STRANGENESS/ENTROPY CONTENT



From AGS to SPS: step up by 50% (not shown) and second step-up by 50% in strangeness per entropy between SPS and RHIC
Strangeness production rises with energy faster than production of entropy.

New physics at RHIC compared to SPS
New physics at SPS compared to AGS.

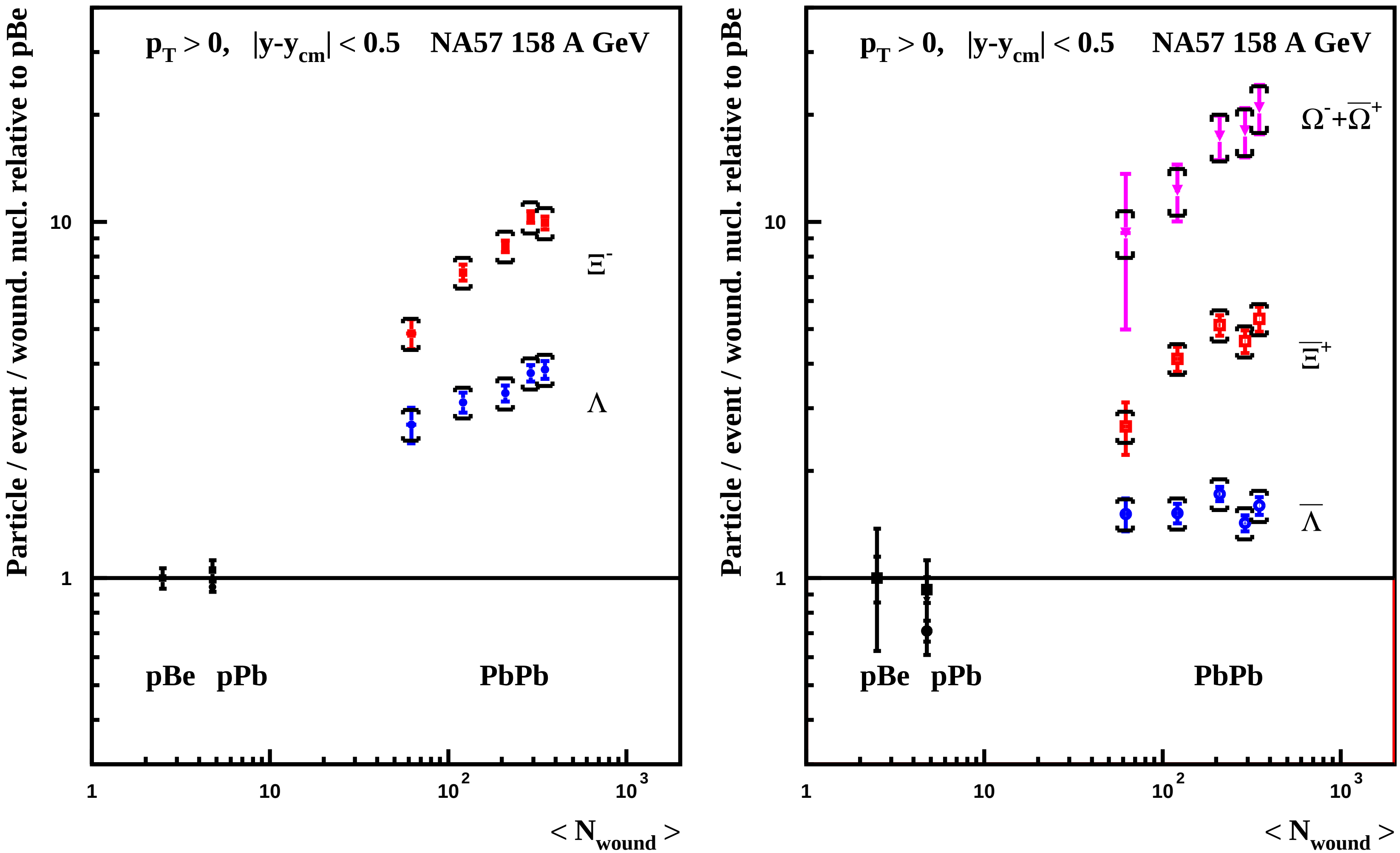
VI: (MULTI)STRANGE (ANTI)HYPERON ENHANCEMENT



Enhancement GROWTH with
strangeness   antiquark content.

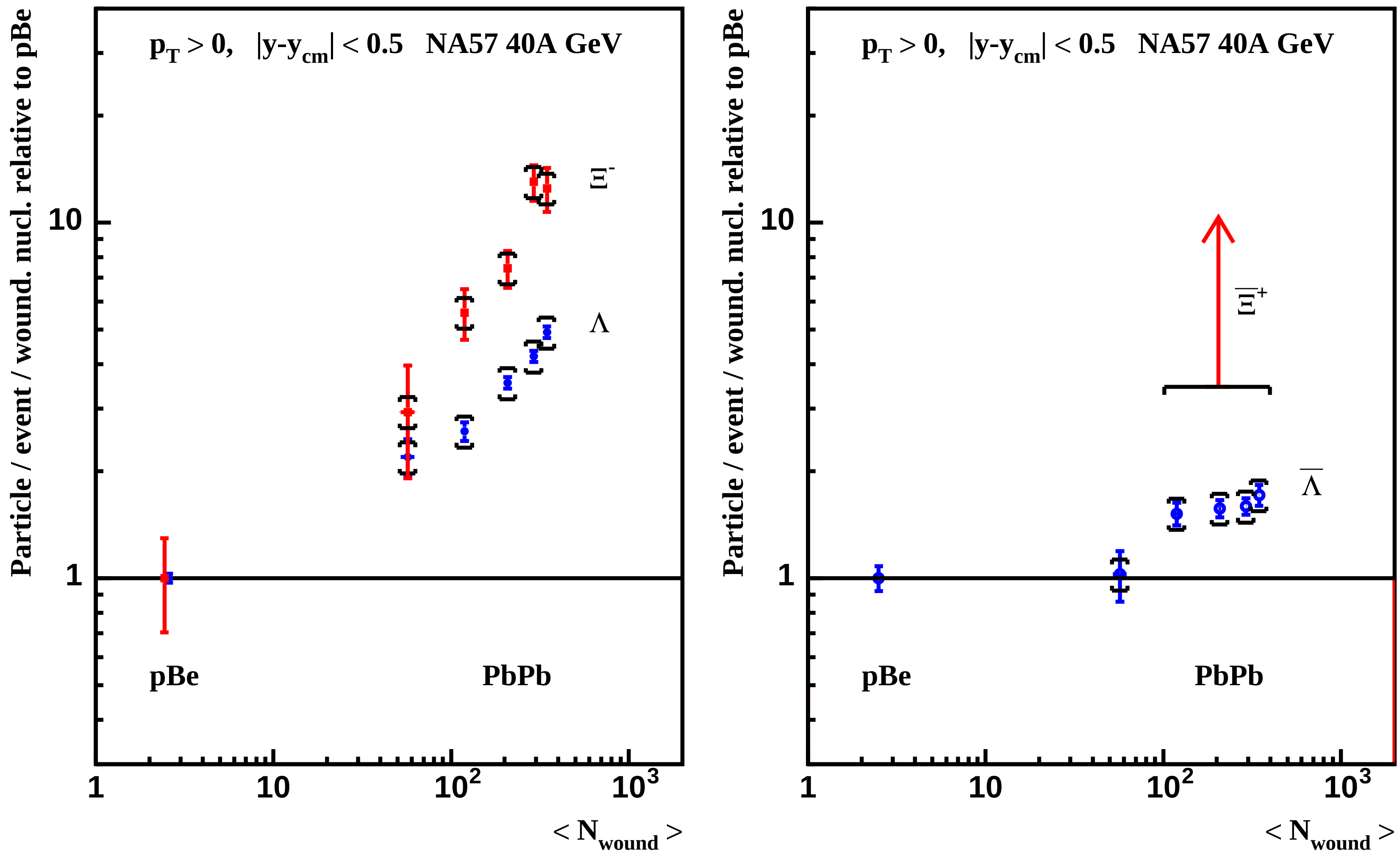
Enhancement is here defined with respect to the yield in p–Be collisions, scaled up with the number of collision 'wounded' nucleons.

ENHANCEMENT AS FUNCTION OF REACTION VOLUME



Note the gradual onset of enhancement with reaction volume.
“Canonical enhancement” (a hadronic equilibrium model) is grossly inconsistent with these results. Gradual enhancement shown predicted by kinetic strangeness production.

ENHANCEMENT at low SPS Energy



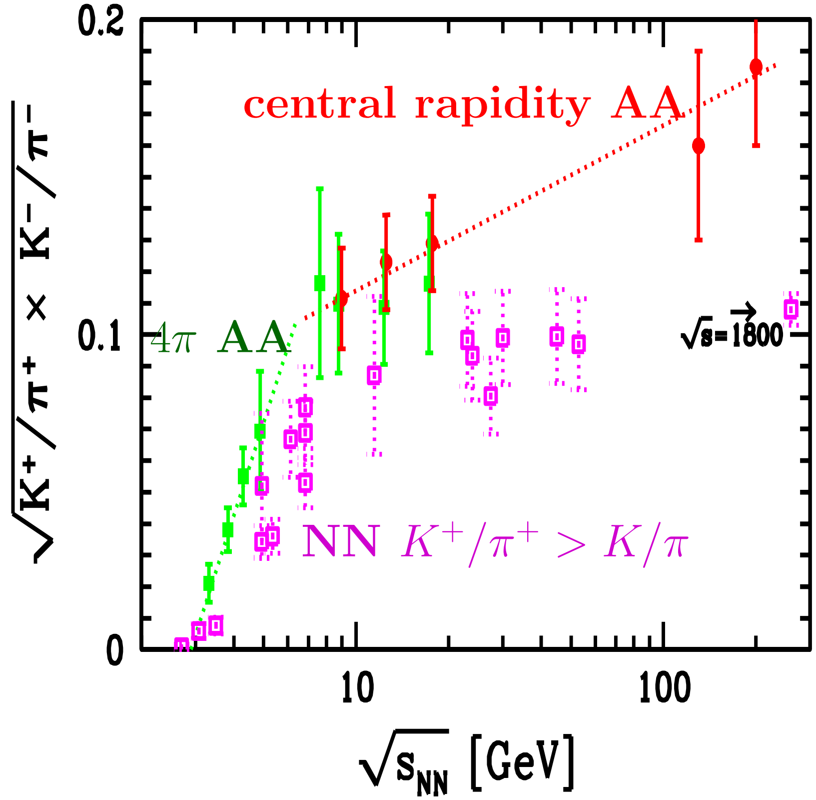
At 40A GeV we still see a strong volume dependent hyperon enhancement, in agreement with expectations for deconfined state formation.

Probing strangeness excitation by ratio K/π

The particle yield products

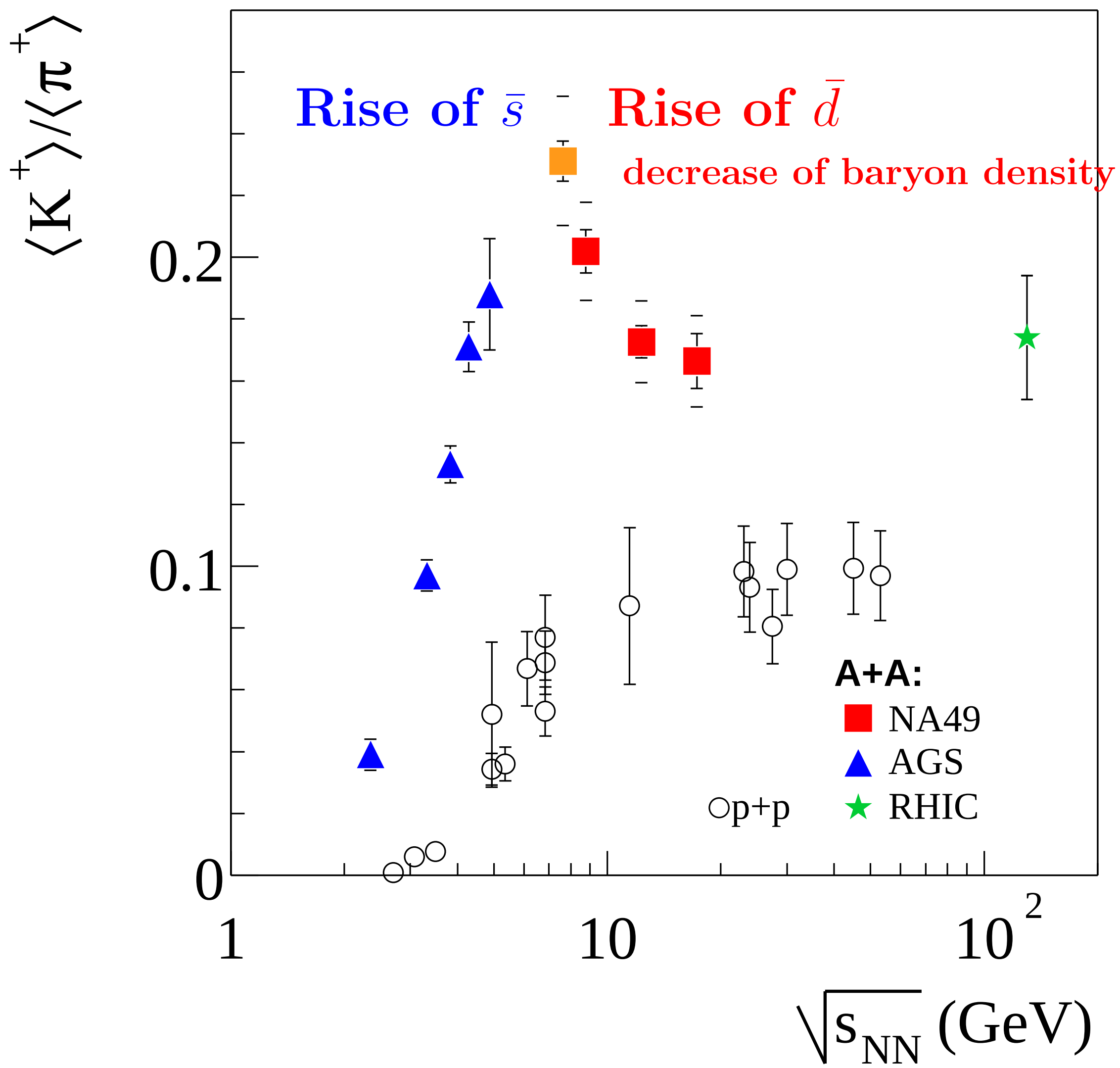
$$K \equiv \sqrt{K^+(u\bar{s})K^-(\bar{u}s)} \propto \sqrt{\lambda_u/\lambda_s\ \lambda_s/\lambda_u} \qquad \pi \equiv \sqrt{\pi^+(u\bar{d})\pi^-(\bar{u}d)} \propto \sqrt{\lambda_u/\lambda_d\ \lambda_d/\lambda_u}$$

are less dependent on chemical conditions including baryon density.



There is a notable enhancement in K/π above the K^+/π^+ ratio recorded in pp reactions, which provides an upper limit on K/π. There is a clear change in the speed of rise in the K/π ratio at the lower energy limit at SPS; This combined with change in nuclear compression results in a peak in the K^+/π^+.

NA49/Marek Gaździcki STUDY $\bar{s}/\bar{d}$ ENHANCEMENT



The 'peak' is result of two effects: approach to saturation of strangeness, followed by increased baryon transparency signaling a change in reaction mechanism. Possibly, deconfinement!

Is QGP discovered??

Predicted QGP behavior confirmed by strangeness and strange antibaryon enhancement experiments, verifies strange quark mobility. Enhanced source entropy content consistent with gluon degrees of freedom, expected given strangeness enhancement. Chemical properties consistent with sudden hadron production in fast breakup of QGP.

Furthermore: quark coalescence explains features of non-azimuthally symmetric strange particle production. Early thermalization and strange quark participation in matter flow.

Strangeness excitation function fingerprints QGP as the new state of matter:
Probable onset of 'valon' quark deconfinement at AGS;
between SPS and RHIC entropy and strangeness change 2nd time

SO WHAT??

This is not the end of the story, but its beginning. We will soon know how did the quark-gluon Universe hadronizes and how did the antimatter component disappear.

Hadronization of the Quark Universe

The expanding hot deconfined Universe cools, the hot quark-gluon plasma freezes into individual hadrons. In laboratory we do this suddenly, in the early Universe slowly as seen on time scale of strong interactions.

STRONG INTERACTIONS TIME CONSTANT:
Nucleon size / light velocity $\simeq 10^{-23}\mathbf{s}$

UNIVERSE HADRONIZATION TIME CONSTANT:

$$\tau_{\rm U} = \sqrt{\frac{3c^2}{32\pi G\mathcal{B}}} = 36\,\mu\mathbf{s}\,\sqrt{\frac{\mathcal{B}_0}{\mathcal{B}}}, \qquad \mathcal{B}_0 = 0.19\,\frac{\mathbf{GeV}}{\mathbf{fm}^3}$$

$4\mathcal{B}$ **is energy density inside particles like protons, and is the amount of energy required per unit of volume to deconfine quarks.**

Production of Matter of our cosmic era

Our objective is to understand the chemical conditions at the emergence of matter as we know it today in the early Universe period at hadronization of quark-gluon plasma. This establishes the initial particle densities which can be followed to the end of the hadron gas era.

Quantitative Tasks

1) Identify the chemical conservation laws constraining potentials $\mu(T)$ and the pertinent conservation laws;

2) Trace out chemical potentials as function of temperature, which itself we can study separately as function of time (see above) – this separation is convenient given the lack of knowledge about dark matter;

3) Evaluate the chemical (particle) flavor composition of the Universe during evolution toward the condition of neutrino decoupling at

$$T \simeq 1\,\mathbf{MeV} \qquad t \simeq 10\,s$$

4) Explore the quark-hadron phase transformation dynamics, and establish potential for conserved quantum (baryon, electrical charge) number distillation;

Constraint conditions in hadronization of the early Universe

The three chemical potentials not constrained by chemical reactions are obtained from the physical constraints:

i. *Local electrical charge neutrality* **($Q = 0$):**

$$n_Q \equiv \sum_i Q_i\, n_i(\mu_i, T) = 0,$$

where Q_i and n_i are the charge and number density of species i.

ii. *Net lepton number equals net baryon number* **($L = B$):**

$$n_L - n_B \equiv \sum_i (L_i - B_i)\, n_i(\mu_i, T) = 0,$$

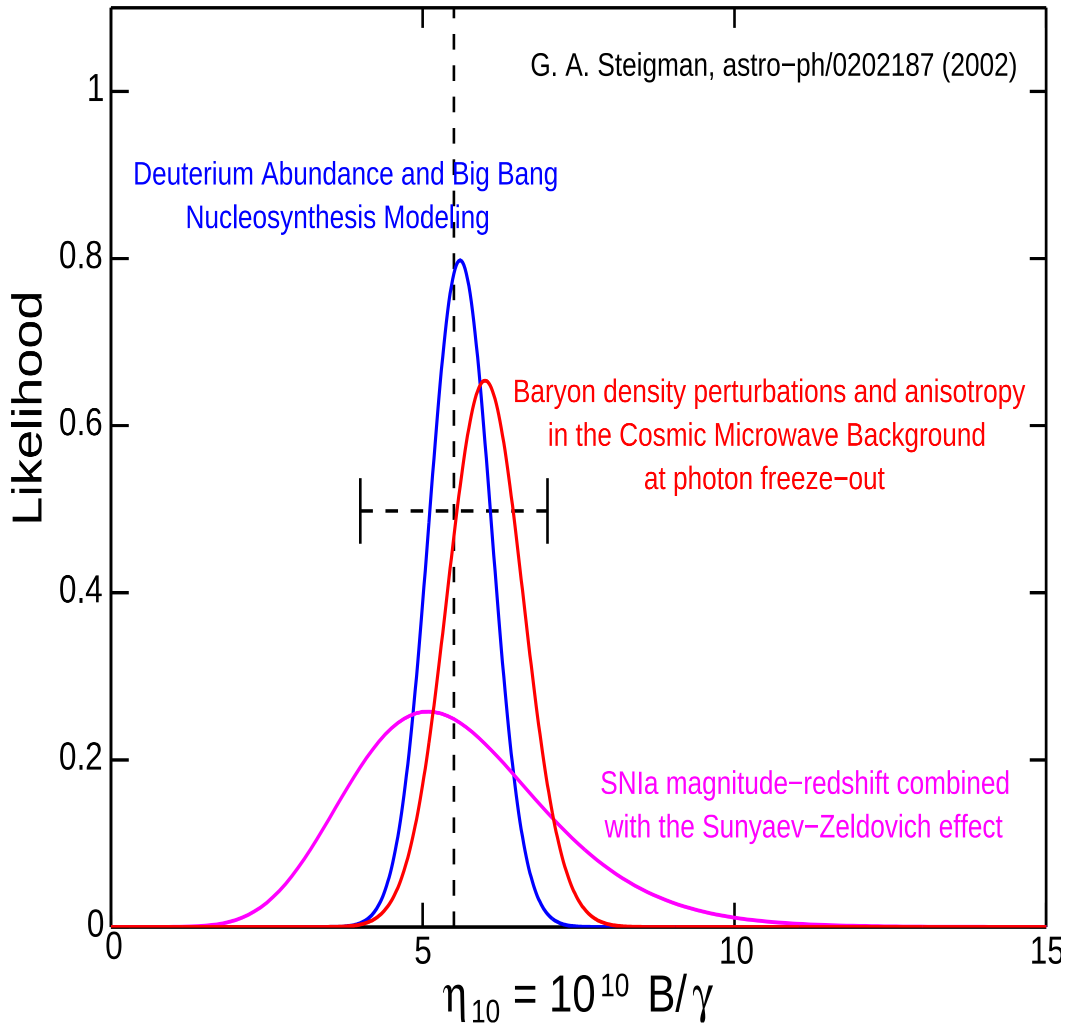
(standard condition in baryo-genesis models, generalization to finite $B - L$ easily possible)

iii. Universe evolves adiabatically i.e. at *constant in time entropy-per-baryon S/B*

$$\frac{\sigma}{n_B} \equiv \frac{\sum_i \sigma_i(\mu_i, T)}{\sum_i B_i\, n_i(\mu_i, T)} = 1.3 \pm 0.1 \times 10^{10} \;\Longleftarrow\; \textit{how do we know this?}$$

Baryon to photon ratio in the Universe

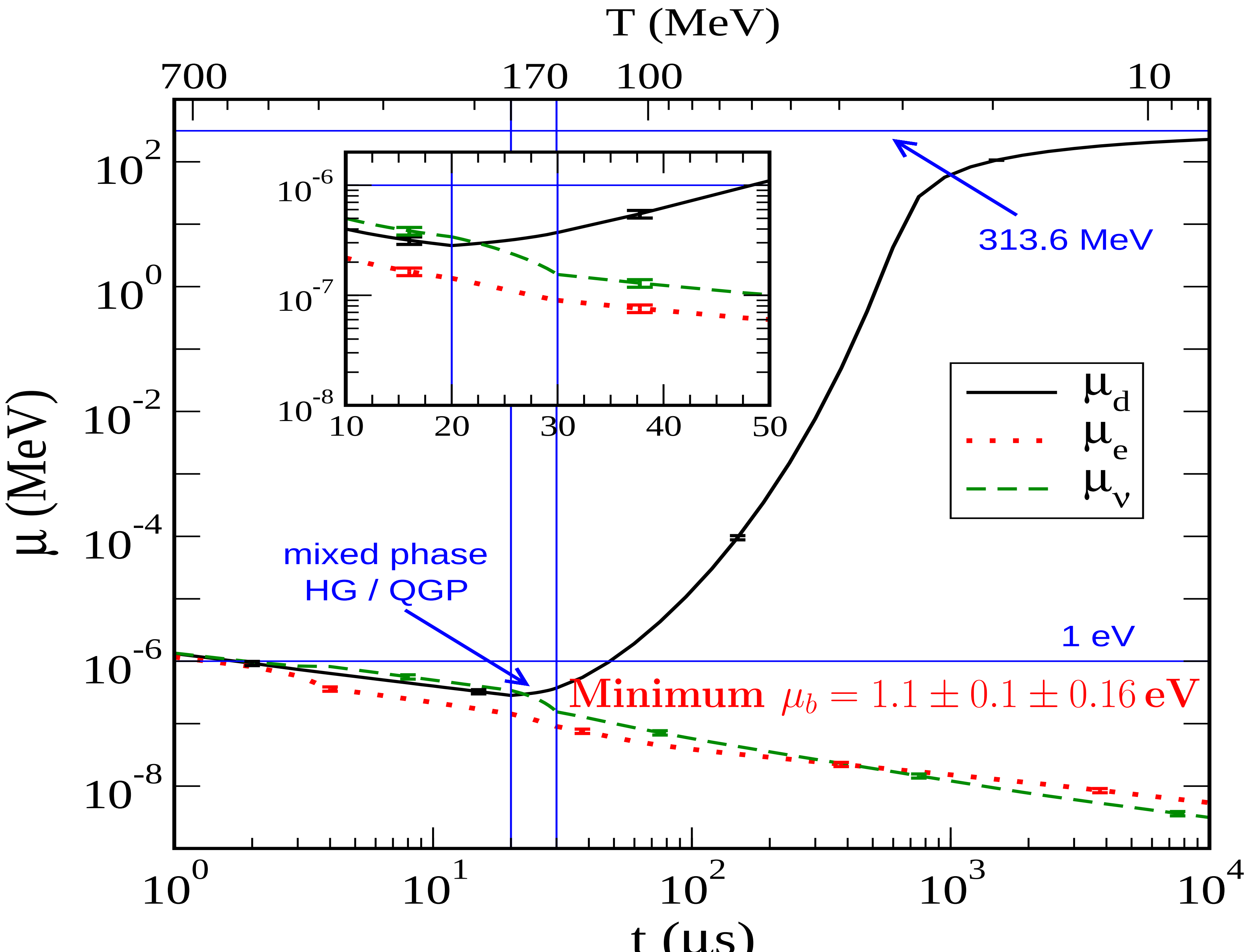
OLD: $\eta \equiv n_{\rm B}/n_\gamma = 5.5 \pm 1.5 \times 10^{-10}$; **W-MAP:** $\eta = 6.1^{+0.3}_{-0.2} \times 10^{-10}$;



This yields entropy per baryon: $\frac{S}{n_{\rm B}} = \frac{S}{n_\gamma}\frac{n_\gamma}{n_{\rm B}} = \frac{8.0}{\eta} = 1.3 \pm 0.1\, 10^{10}$

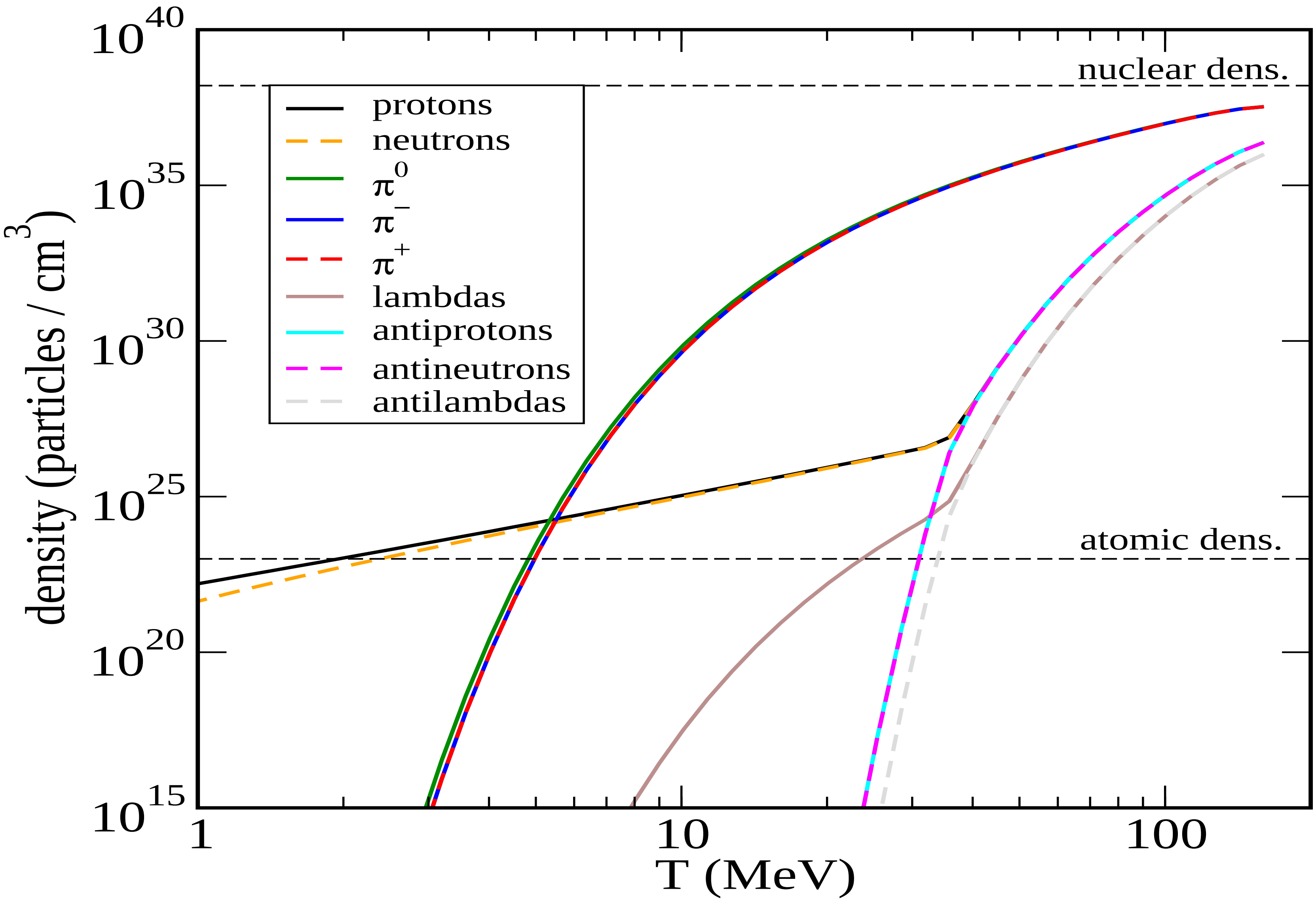
$(S_\gamma + S_\nu + S_i)/n_\gamma$ **is evaluated using stat.mech. and remembering** e^+e^- **reheating of photons.**

TRACING μ_d IN THE UNIVERSE



Minimum $\mu_b = 1.1 \pm 0.1 \pm 0.16\,\mathbf{eV}$

Hadronic Particle Densities



Note the baryon freeze-out at $T \simeq 37$ MeV and that pion density remains at baryon density down to $T \simeq 4.5$ MeV

FINAL REMARKS

The deconfinement specific hadronic 'deep' probes are entropy and strangeness. These probes are fully consistent with deconfinement/QGP at SPS and at RHIC

We have control of statistical models and chemical potentials, particle abundances, but not yet of phase transformation dynamics.

Theoretical study of the QGP phase and hadronization of the early Universe beginning at $t = 10\,\mu s$ is possible