– Springer Lecture –

Horizons, Causality and Information Transfer

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based on joint work with

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Horizons

- **In our terrestrial world, horizons are elusive:**
  approach a horizon & it recedes, so you cannot cross it.
- **In special relativity, speed of light defines event horizon**
  separating past, future and elsewhere.
- **In general relativity, $\exists$ event horizon of black holes**
  separating inside and outside:
  you can never see something crossing it, and
  if you cross it yourself, you can never return.

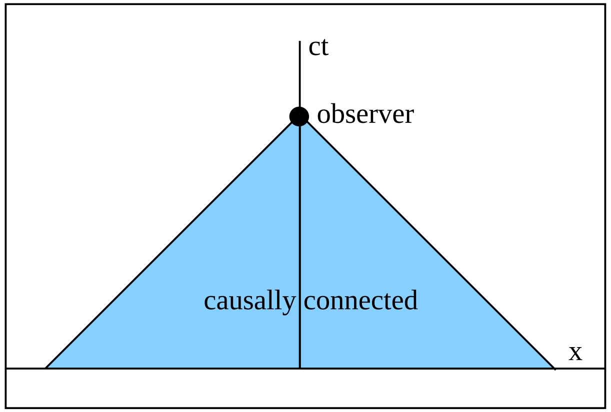
Horizons were central to human thinking for a long time:

- **In Greek mythology $\exists$ River Lethe**
  the river of oblivion, of forgetting,
  when you cross it, you loose all memory of the past.

Conclude: Horizons are limits to information transfer.

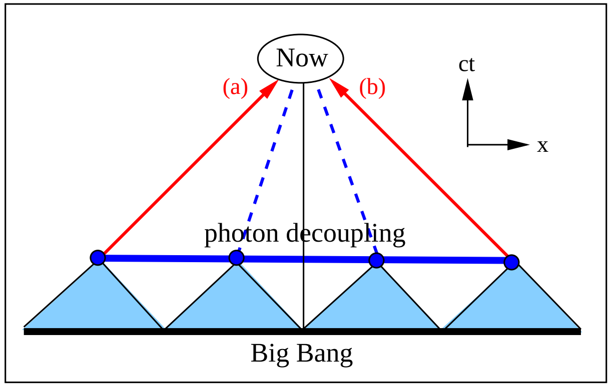
Information tranfer $\sim$ speed of light $\sim$ causality constraints

Observer at point $x = 0$ & time ct_0 can receive information only from points $|x| \leq ct_0 - ct$;



all events at $|x| > ct - ct_0$ are causally disconnected:
they are beyond causal horizon.

In cosmology $\Rightarrow$ horizon problem
photons (a) and (b) come
from regions causally disjoint
at time of last scattering.



cannot communicate, but both $\Rightarrow$ temperature 2.725°K.

Our topic:

Causality (communication via finite speed of light) divides space-time for strong interactions into regions which cannot communicate with each other.

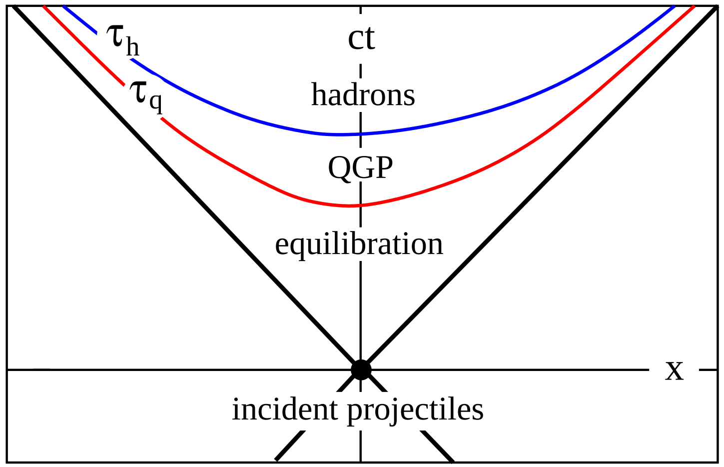
Consider boost-invariant

hadron production

in high energy collision;

QGP formation $(ct)^2 - x^2 = \tau_q^2$

hadronisation $(ct)^2 - x^2 = \tau_h^2$

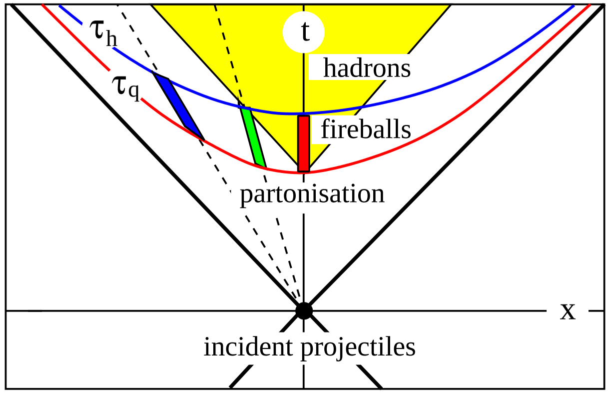


Collision produces QGP fireballs, one at rest in CMS and others moving ever faster ("inside-outside cascade")

When can these fireballs communicate with each other?

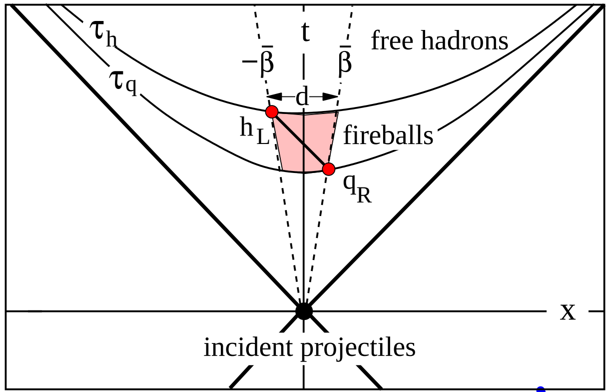
fireballs at large rapidity
are beyond causal horizon
for fireball at rest in CMS;

causal extent of a single fireball?



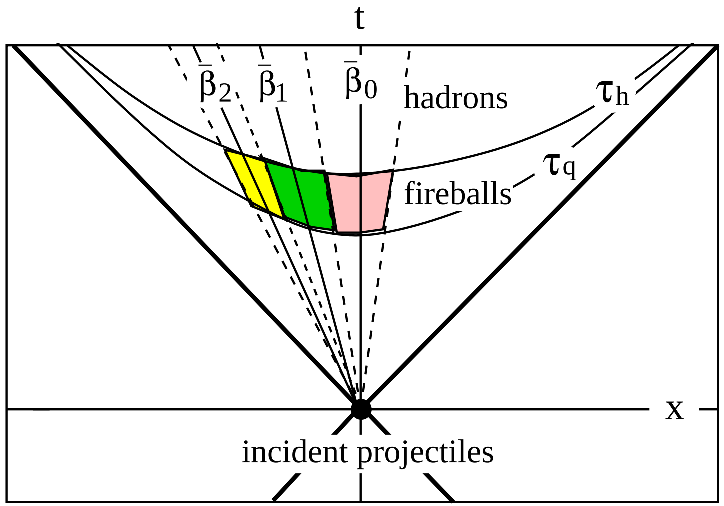
define "one" fireball as
causally connected region:
$\longrightarrow$ spatial size

$$d = \sqrt{\frac{\tau_h}{\tau_q}(\tau_h - \tau_q)}$$



effective fireball size depends on QGP life-time result:

QGP space-time
is partitioned into
causally disjoint regions



Consequence:

local conservation of
discrete quantum numbers

$\longrightarrow$ local strangeness compensation [Hagedorn, Redlich]

strangeness must be conserved within a volume of size

$$d = \sqrt{\frac{\tau_h}{\tau_q}(\tau_h - \tau_q)} \quad \text{with } V(d) < V(\text{global})$$

What does that mean? $\Rightarrow$ effective strangeness suppression

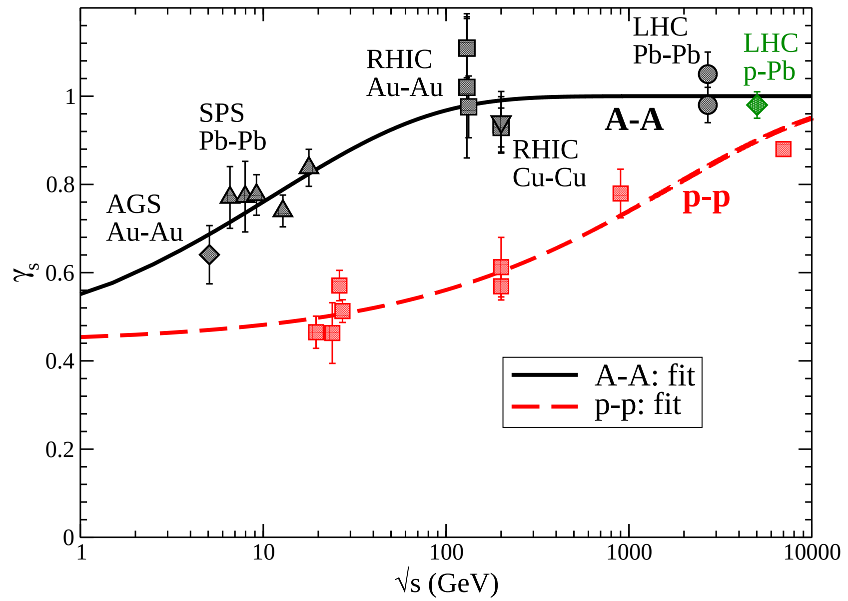
[Hamie,Redlich,Tounsi 2000]

Recall:

– hadron abundances in high energy collisions
$\sim$ ideal resonance gas

– strange particle suppression, via γ_s^n for hadrons with
n quarks/antiquarks

NB:
more suppression
in pp than in AA;
why?



Local strangeness conservation implies V_c plays role of γ_s:

$$Z(T, V, \gamma_s) \sim Z(T, V, V_c)$$

why is $\gamma_s \sim V_c$ smaller in pp than in AA collisions?

Causality → correlation volume

$$d = \sqrt{\frac{\tau_h}{\tau_q}(\tau_h - \tau_q)} = \text{in terms of measurable quantities?}$$

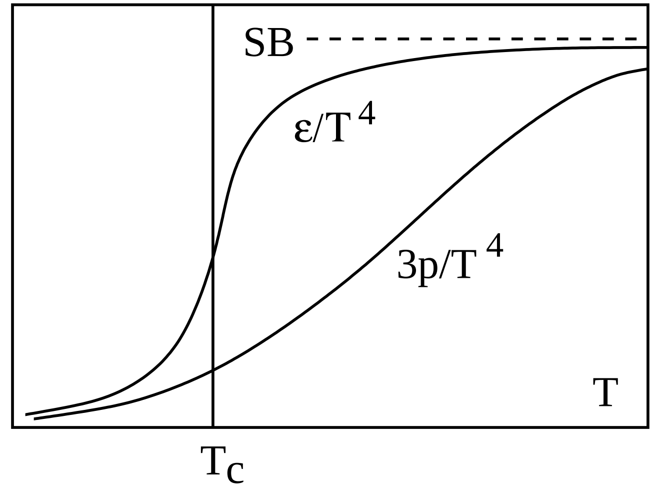
Boost-invariant production → 1-d hydrodynamic expansion

$$\frac{d\epsilon}{d\tau} = -\frac{(\epsilon + p)}{\tau}$$

→ correlation of proper time τ & energy density/pressure

to solve, need QGP equation of state

express $\epsilon(p)$,
solve hydro eq'n.



- ideal QGP, massless quarks ($p = \epsilon/3$): $$\frac{\tau_h}{\tau_q} = \left(\frac{\epsilon_q}{\epsilon_h}\right)^{3/4}$$
- neglect pressure ($p = 0$): $$\frac{\tau_h}{\tau_q} = \left(\frac{\epsilon_q}{\epsilon_h}\right)$$
- get EoS from lattic QCD ($p = a\epsilon,\ 0 < a < 1/3$)

$$\frac{\tau_h}{\tau_q} = \left(\frac{\epsilon_q}{\epsilon_h}\right)^{1/(1+a)} .$$

hadronisation energy density $\sim$ universal confinement value

$$\epsilon_h \simeq 0.4 - 0.6 \ \mathrm{GeV/fm^3}$$

equilibration time $\sim$ universal value τ_q

leads to crucial result, independent of detailed EoS form:

size $d(s)$ of correlation region is fully determined by initial energy density $\epsilon_q(s)$ at collision energy $\sqrt{s}$.

If $d(s) \sim \gamma_s(s)$ determines strangeness suppression,
then $\gamma_s(s)$ must be a universal function of $\epsilon_q(s)$

- **eliminate s and consider $\gamma_s(\epsilon_q)$:**

$$\epsilon_q \, \tau_q \simeq \frac{1.5 \, m_T}{\pi R_x^2} \left(\frac{dN}{dy}\right)^x_{y=0}, \text{ with } x \sim pp, pA, AA$$

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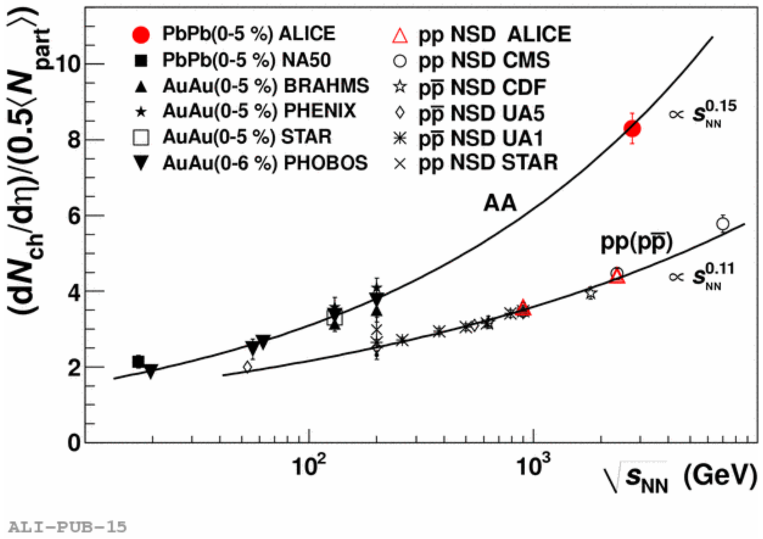
multiplicity data as $f(s)$:

$$\left(\frac{dN}{dy}\right)^{AA}_{y=0} = a_A(\sqrt{s})^{0.3} + b_A$$

$$\left(\frac{dN}{dy}\right)^{pp}_{y=0} = a_p(\sqrt{s})^{0.22} + b_p$$



$$a_A = 0.7613,\ b_A = 0.0534;\quad a_p = 0.797;\ b_p = 0.04123$$

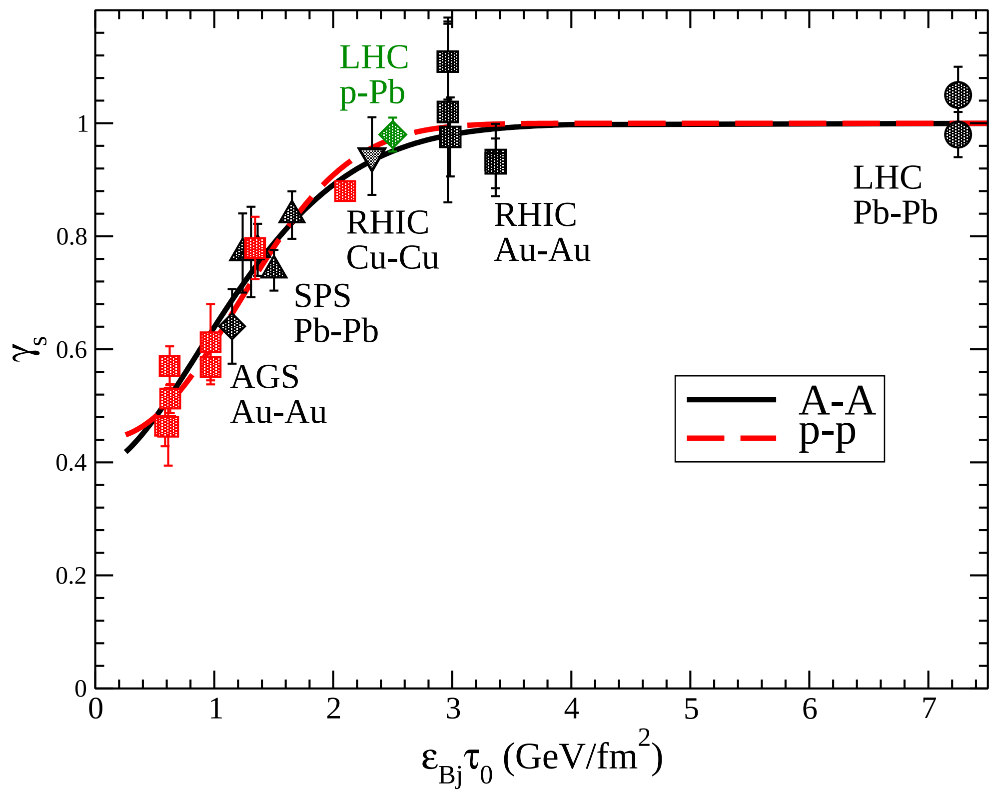
strangeness suppression as $f(s)$:

$$\gamma_s^A(s) = 1 - c_A \exp\left(-d_A\sqrt{A\sqrt{s}}\right)$$

$$\gamma_s^p(s) = 1 - c_p \exp\left(-d_p s^{1/4}\right),$$

$$c_A = 0.606,\ d_A = 0.0209;\quad c_p = 0.5595;\ d_p = 0.0242$$

Can now plot γ_s vs. ϵ_q and compare to AA, pA, pp data



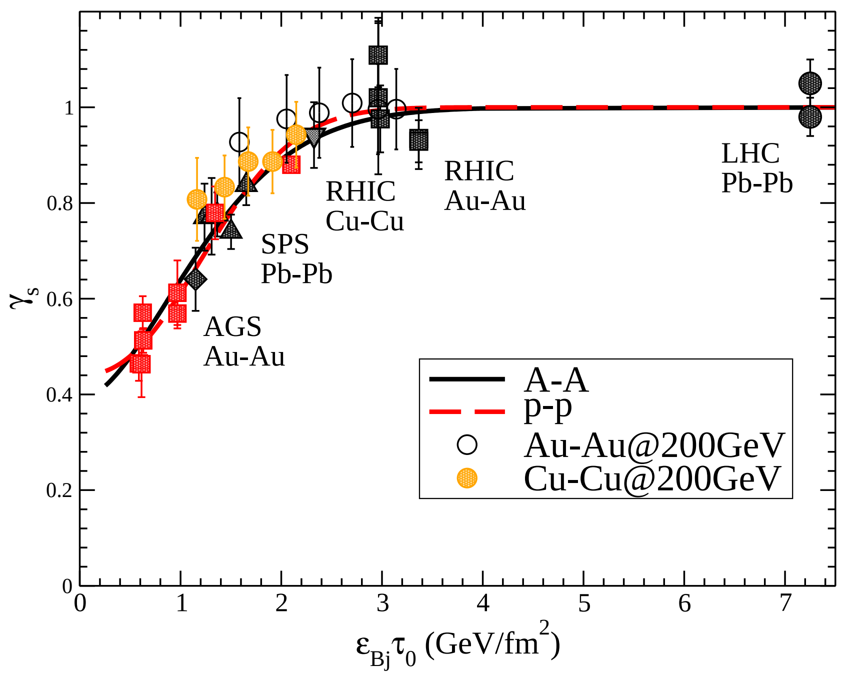
conclude:

- $\gamma_s(\epsilon_q)$ curves for pp and AA coincide
- $\gamma_s(\epsilon_q)$ data for pp, pA, AA agree with prediction

Further test: vary centrality of AA collision at fixed s

$$\epsilon_0^{N_p}\ \tau_0 = \frac{1.5\, m_T(0.5N_p)}{\pi R^2_{N_p}} \left(\frac{dN}{dy}\right)^{AA}_{y=0}$$

with N_p for the number of participants. Compare γ_s to $\epsilon_0^{N_p}$ for $Au - Au$ and $Cu - Cu$ data at 200 GeV (RHIC)



• Conclude:

strangeness suppression is uniquely determined by
initial energy density in ***pp*, *pA*, *AA*** collisions

• Why?

– strangeness conservation must hold in causally connected space-time regions ("windows" between ϵ_q and ϵ_h)

– their size is determined by the initial energy density

– their size grows with increasing s, A, $\Rightarrow$ grand canonical ensemble, no more strangeness suppression

– corollary: for pp at sufficiently large s, $\gamma_s \longrightarrow 1$

P. Castorina & H. Satz, Int. J. Mod. Phys. E23 (2014) 1450019.

P. Castorina & H. Satz, arXiv:1601.01454

P. Castorina, S. Plumari and H. Satz, arXiv:1603.06529