Quark Confinement and Hadrosynthesis

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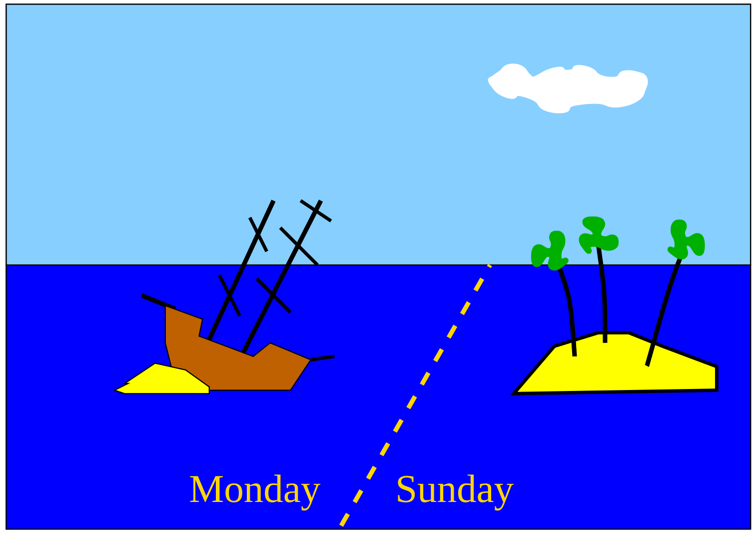
The Island of the Day before



The Island of the Day before

Roberto aveva deciso di concedere solo la metá del proprio spirito alle cose in cui credeva (o credeva di credere),

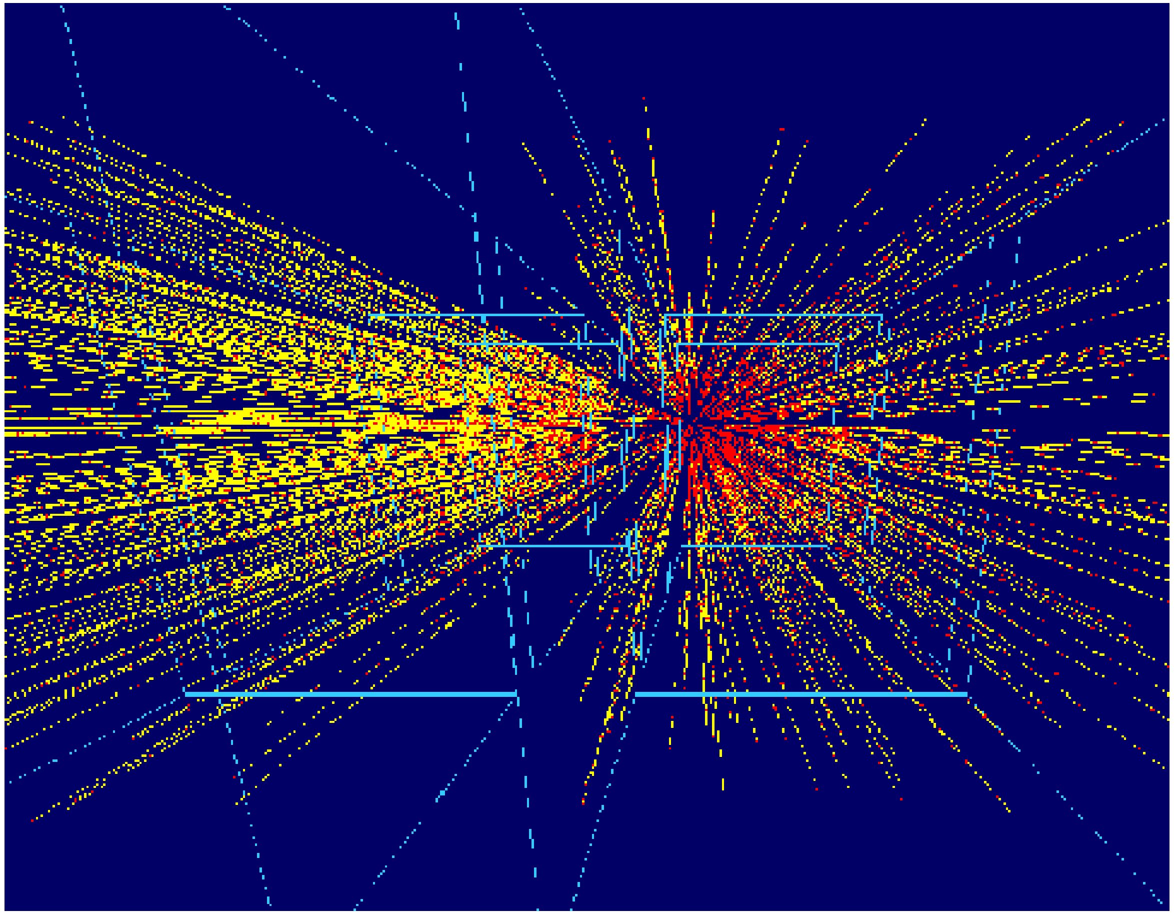
per tener l'altra disponibile nel caso che fosso vero il contrario.

Roberto had decided to reserve only half of his mind for the things which he believed (or believed to believe),

so that he would have the other half free in case the opposite should turn out to be true.

Collide at high energy two hadrons or two nuclei,
or annihilate an electron-positron pair – what happens?

**Collide at high energy two hadrons or two nuclei,
or annihilate an electron-positron pair – what happens?**



basic observation in all high energy multihadron production

thermal production pattern

Fermi, Landau, Pomeranchuk, Hagedorn

- species abundances $\sim$ ideal resonance gas at T_H
  $\pi, \eta, \rho, \omega, K, K^*, \phi, p, n, \Delta, N^*, \Lambda, \Sigma, \Xi, \Omega, \ldots$
- universal $T_H \simeq 170 \pm 20$ MeV for all (large) $\sqrt{s}$

caveats: baryon density, strangeness, heavy flavors, flow

begin by recalling what is "thermal" and what is the essential experimental result

1. Thermal Hadron Production

what is "thermal"?

- equal *a priori* probabilities for all states in accord with a given local average energy $\Rightarrow$ temperature T;

- grand canonical partition function of ideal resonance gas

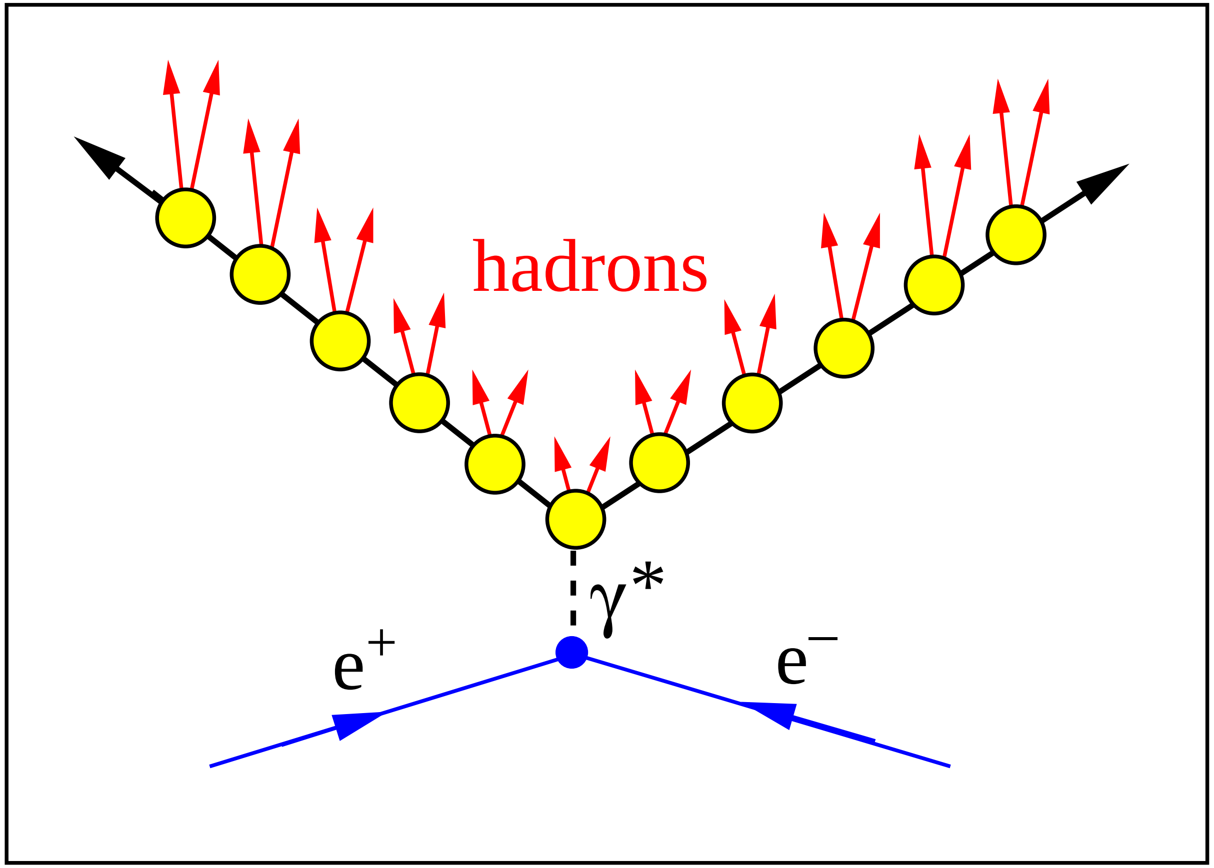
$$\ln Z(T) = V \sum_i \frac{d_i}{(2\pi)^3} \phi(m_i, T)$$

- Boltzmann factor

$$\phi(m_i, T) = \int d^3p \exp\{\sqrt{p^2 + m_i^2}/T\} \sim \exp -(m_i/T);$$

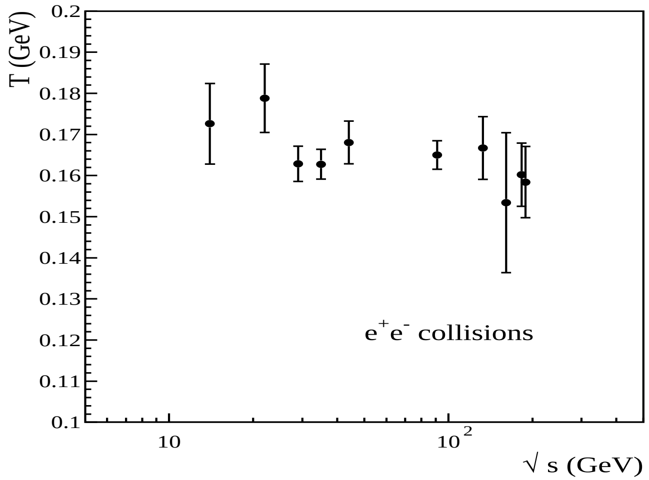
- relative abundances $$\frac{N_i}{N_j} = \frac{d_i \phi(m_i, T)}{d_j \phi(m_j, T)}$$

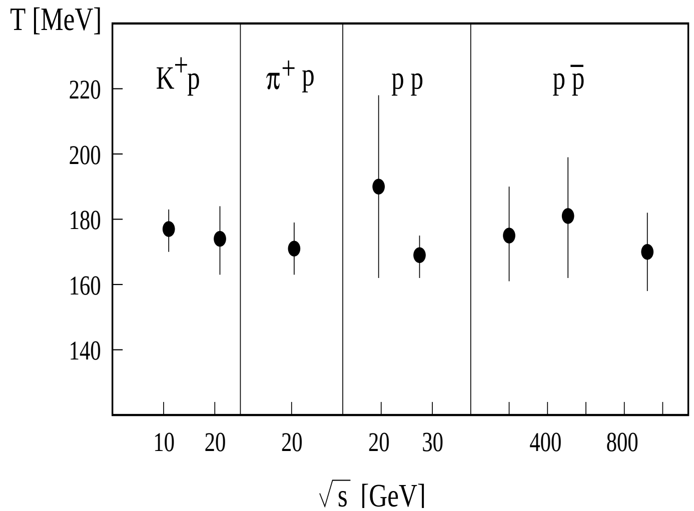
- rapidity distribution of identical fireballs


hadrons
γ*
e+
e−

Species abundances in elementary collisions

[Becattini et al. 1996 - 2008]





Conclude:

$$T_H = 170 \pm (10-20)\ \text{MeV};\ \gamma_s \simeq 0.5 - 0.7$$

independent of $\sqrt{s}$, incident production configuration

Heavy ion collisions

- temperature T, baryochem. pot. μ_B; $\mu_B \Downarrow$ for $\sqrt{s} \Uparrow$
- elementary high energy collisions low baryon content
- compare to species abundances for RHIC, peak SPS

SPS (Pb-Pb), $\sqrt{s} = 17$ GeV

$$T_H = 157.8 \pm 2.5 \text{ MeV}, \ \mu_B = 248.9 \pm 9.0 \text{ MeV}$$

RHIC (Au-Au), $\sqrt{s} = 130$, $y = 0$ GeV

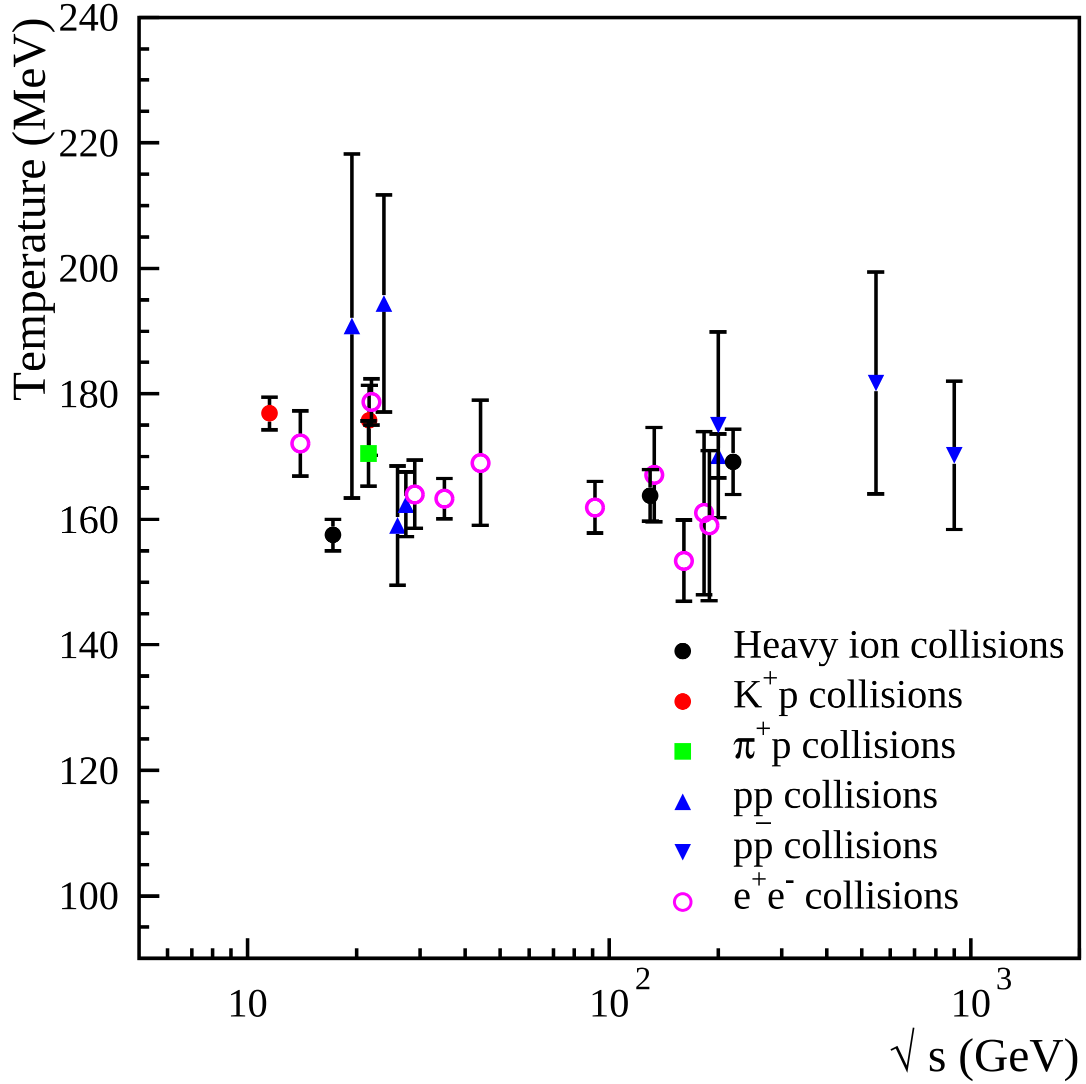
$$T_H = 163.8 \pm 4.1 \text{ MeV}, \ \mu_B = 36.3 \pm 10.2 \text{ MeV}$$

RHIC (Au-Au), $\sqrt{s} = 200$ GeV

$$T_H = 169.2 \pm 5.2 \text{ MeV}, \ \mu_B = 29.5 \pm 11.2 \text{ MeV}$$

in general $\gamma_s \simeq 0.8 - 1.1$

[Andronic, Braun-Munzinger & Stachel 2006, Becattini & Manninen 2008]



Temperature (MeV)
240
220
200
180
160
140
120
100
10
10 2
10 3
√ s (GeV)
Heavy ion collisions
K+p collisions
π+p collisions
pp collisions
pp̄ collisions
e+e- collisions

Conclude:

The hadron abundances in all high energy collisions (e^+e^- annihilation, hadron-hadron & nuclear collisions) are specified by an ideal resonance gas of a universal temperature

$$T_H \simeq 170 \pm 20 \text{ MeV}.$$

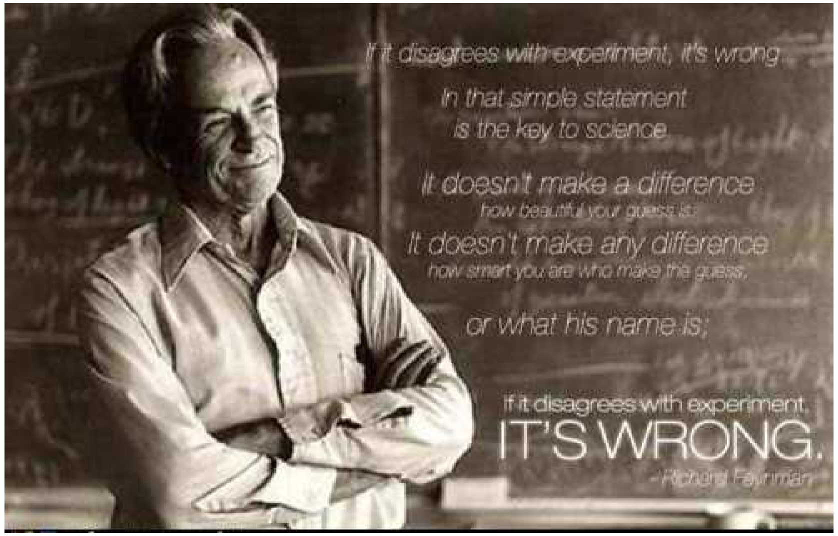
How can we understand this kind of thermal behavior?

Can we create matter through collision?

T. D. Lee → Li Keran

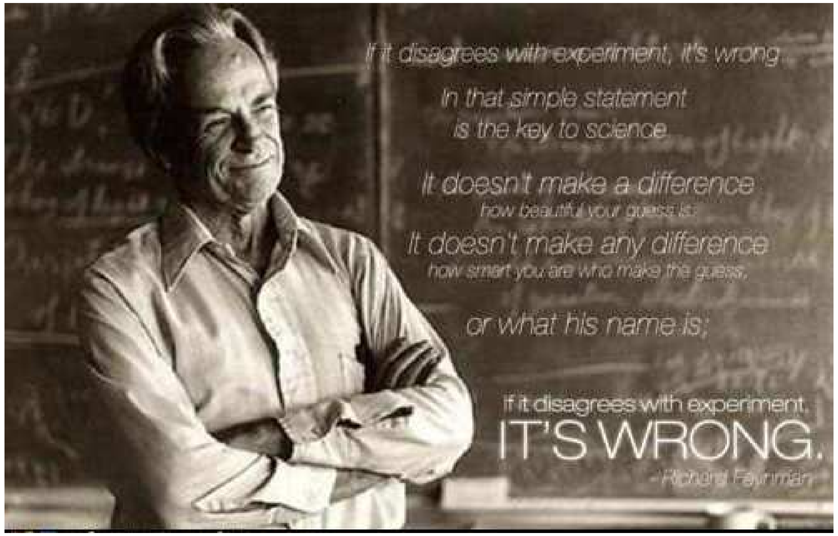
(1986)

Nuclei, as heavy as bulls, through collision generate new states of matter



Feynman's objection:

If I throw my watch
against the wall,
I get a broken watch,
not a
new state of matter.



Feynman's objection:

If I throw my watch against the wall, I get a broken watch, not a new state of matter.

But here the pieces of the watch are thermally distributed, with a universal temperature....

Why should high energy collisions show thermal behavior?

How is a thermal state attained ?

Conventional Approach

- kinetic theory, Boltzmann equation
- many particles, finite collision cross section, sufficient evolution time
- arbitrary starting configuration of particles, collisions and evolution towards maximum entropy, equilibration time to attain stable Boltzmann distribution.

this approach has determined most thinking about thermal behavior in QCD up to today:

parton collisions & equilibration, hadronization

Multiple parton interactions → kinetic thermalization?

Is this really possible in high energy collisions evolving in time?

or ∃ a "non-kinetic" mechanism producing statistical features?

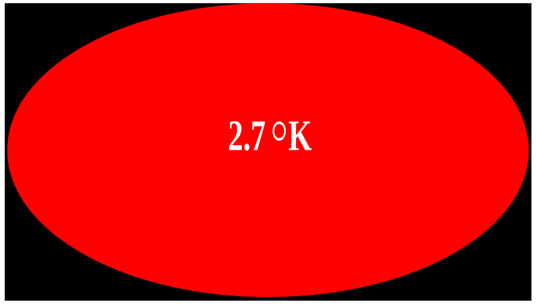
Multiple parton interactions $\longrightarrow$ kinetic thermalization?

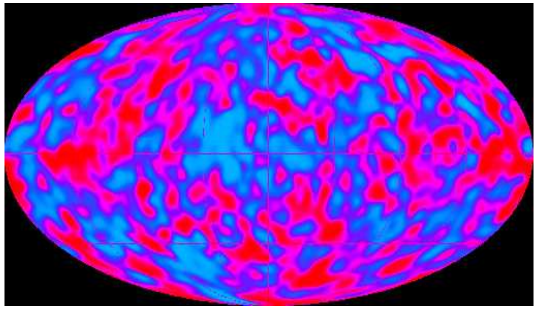
Is this really possible in high energy collisions evolving in time?

or $\exists$ a "non-kinetic" mechanism producing statistical features?

Prelude: Cosmic Thermalization

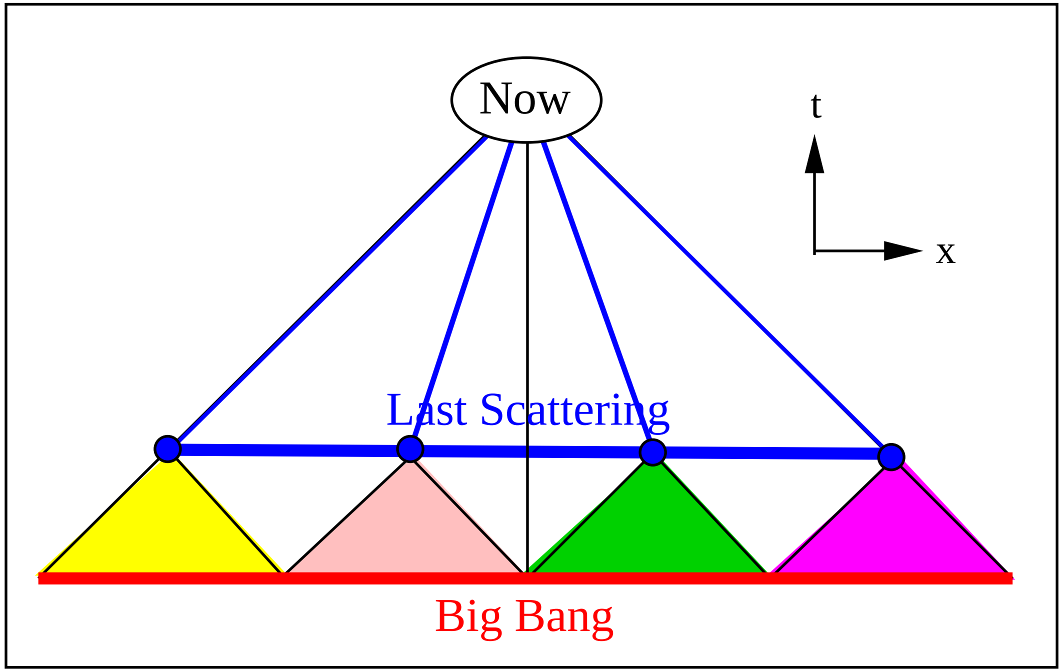
microwave background radiation





visible universe seen with low (10^{-2}) and with high (10^{-5}) resolution

radiation from the end of the "recombination era":
photons at $T \simeq 3000°$K, cosmic redshift $\longrightarrow$ 2.7° K



- same CBR temperature measured from regions of the Universe causally disconnected when CBR formed
- So how was equilibrium created?
- why does the orchestra play the same melody in tune if the players cannot communicate?

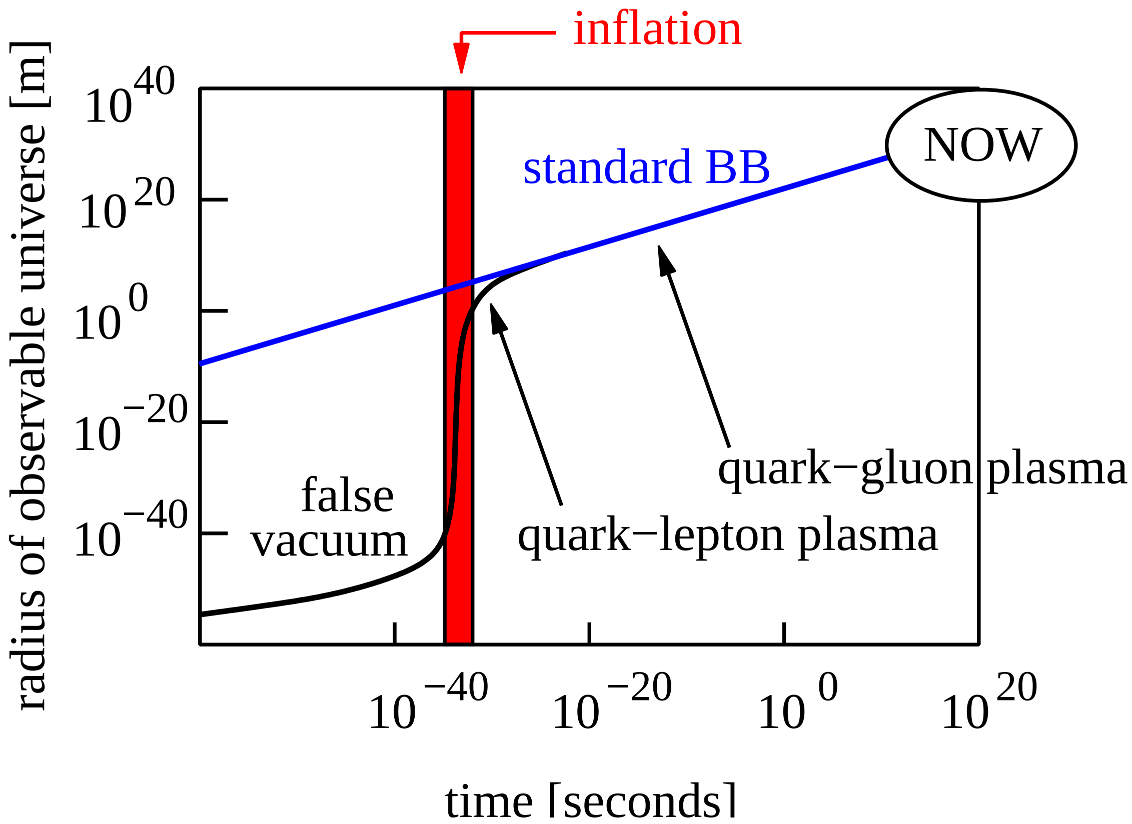
Alan Guth: The Purple Creatures

One can pretend, for the sake of discussion, that the Universe is populated by little purple creatures, each equipped with a furnace and a refrigerator, and each dedicated to the cause of creating a uniform temperature.

Those little creatures, however, would have to communicate at roughly 100 times the speed of light if they are to achieve their goal of creating a uniform temperature across the visible Universe by 300,000 years after the Big Bang. Since nothing can transmit energy faster than light, that cannot account for the uniformity.

The classical form of Big Bang theory requires us to postulate, without explanation, that the primordial fireball filled space from the beginning. The temperature was the same everywhere by assumption, not as a consequence of any physical process.

The solution proposed by Guth: <u>inflation</u>

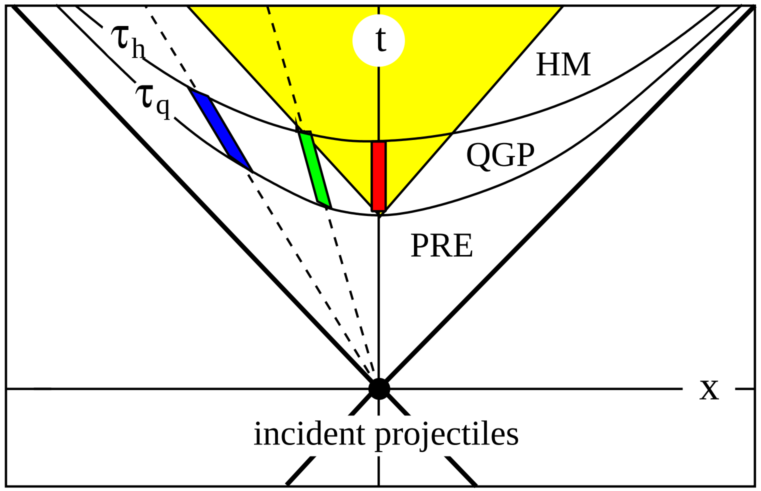


pre-inflationary "medium" is hot & equilibrated;

quarks & leptons in early universe "born in equilibrium".

high energy collisions:

fireballs produced at proper formation time $\tau^2 = t^2 - x^2$



fireballs at rapidities $\eta \geq (\tau_h^2 - \tau_q^2)/(\tau_h^2 + \tau_q^2)$

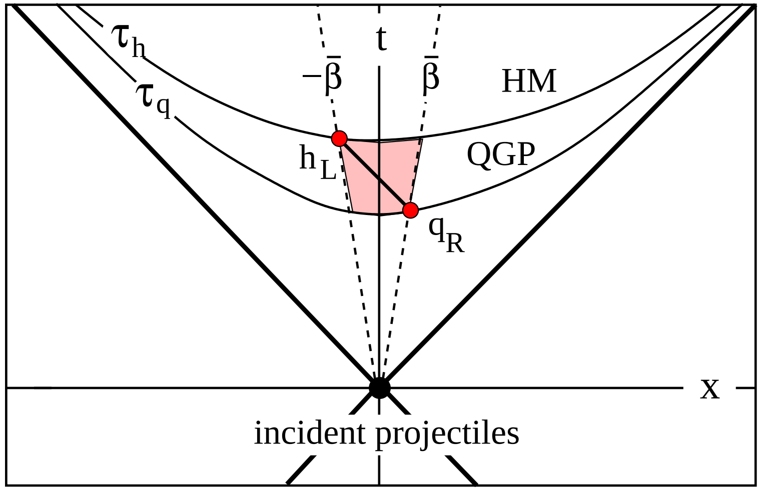
are causally disconnected from central fireball:

again $\exists$ horizon problem

size of fireball? causally connected space-time region

with $\bar{\beta} = (\tau_h - \tau_q)/(\tau_h + \tau_q)$

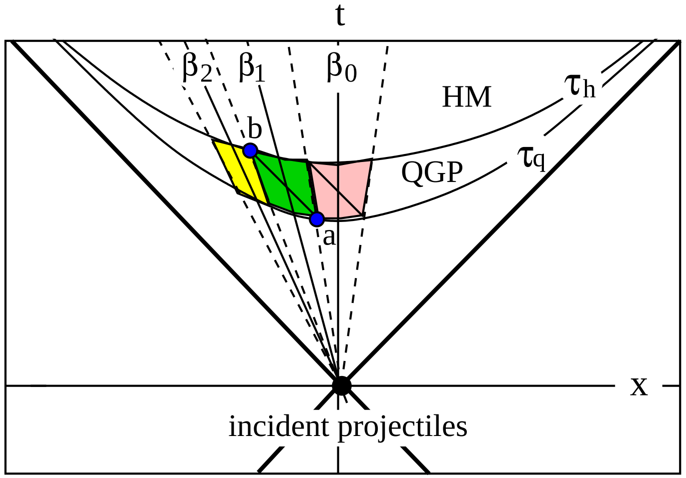
$$d = \sqrt{\tau_q/\tau_h}(\tau_h - \tau_q)$$



take $\tau_q = 1$ fm: QGP fireball parameters

τ_h [fm]	4	6	8
$\bar{\beta} = v/c$	0.6	0.7	0.8
η	0.7	0.9	1.0
d [fm]	1.5	2.0	2.5

fireballs partition entire QGP space-time band into causally disconnected regions:



Why do these non-communicating regions lead to the same hadronisation temperature?

⇒ identical thermal behavior must somehow arise locally

∃ a "non-kinetic, local" mechanism producing statistical features?

∃ a common origin of statistical hadron production in all high energy collisions?

$\mathcal{R}$ussian $\mathcal{F}$olklore:

Passing color charge disturbs vacuum,
vacuum recovers locally,
by producing hadrons according to maximum entropy.

What does that mean?

Confinement $\Rightarrow$ *Event Horizon* $\Rightarrow$ *Unruh Radiation*

[Castorina, Kharzeev, HS 2007]

2. Event Horizons & Hawking-Unruh Radiation

• Unruh radiation [Unruh 1976]

event horizon arises for systems in uniform acceleration

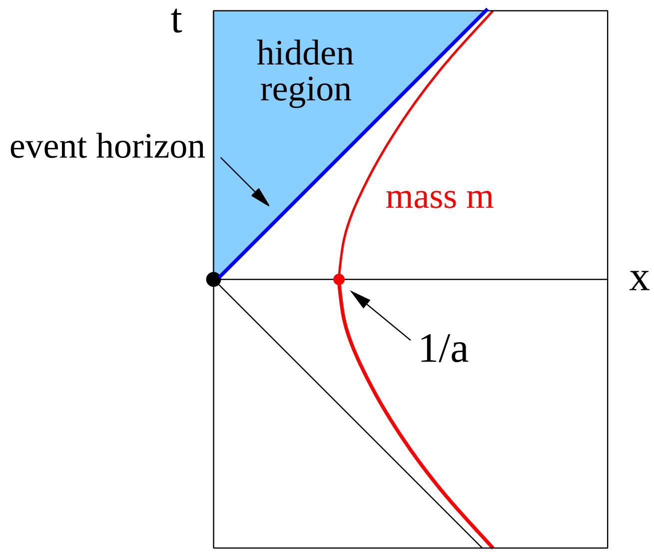
mass m in uniform acceleration a

$$\frac{d}{dt}\frac{mv}{\sqrt{1-v^2}} = F$$

$$v = dx/dt,\ F = ma,\ c = 1$$

solution: hyperbolic motion

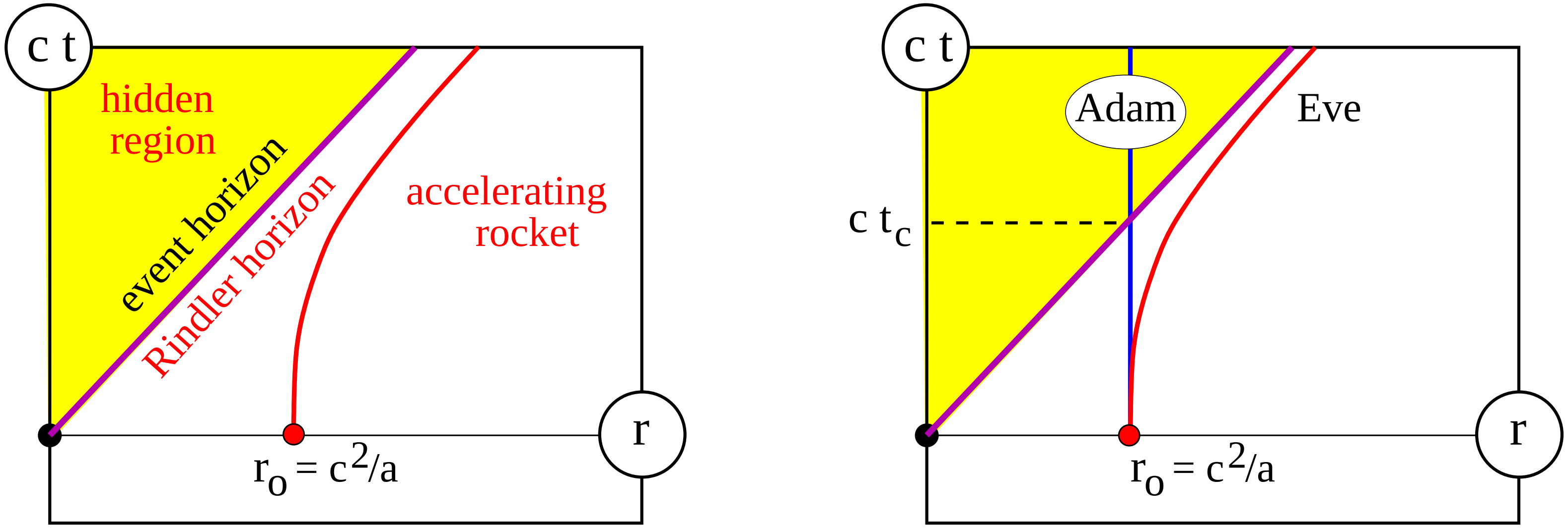
$$x = \frac{1}{a}\cosh a\tau \quad t = \frac{1}{a}\sinh a\tau$$



∃ event horizon: m cannot reach hidden region
observer in hidden region cannot communicate with m

event horizon: defines causal future for observer at r=0

Rindler horizon: defines accessibility limit for rocket



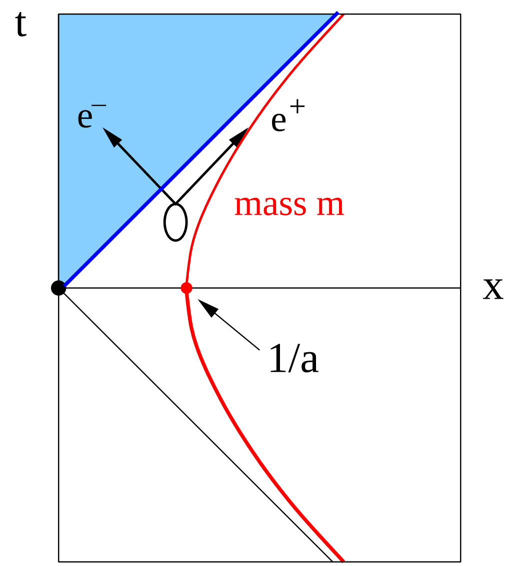
Adam and Eve: Adam remains, Eve leaves with rocket

after t_c, Adam can no longer send message to Eve

Eve can send message to Adam, but will never get answer:
for her, he's in a black hole (beyond her Rindler horizon)

Entanglement of Adam and Eve is destroyed

m passes through vacuum, can use part of acceleration energy to excite vacuum fluctuations on-shell



e^+ absorbed in detector on m
e^- disappears beyond event horizon

equivalent:
e^- tunnels through event horizon

broken "quantum entanglement"
$\sim$ Einstein-Podolsky-Rosen effect

observer on m as well as observer in hidden region have incomplete information: $\Rightarrow$ each sees <u>thermal radiation</u>

observer on m:
physical vacuum $\sim$ thermal medium of temperature T_U

observer in hidden region:
passage of $m \longrightarrow$ thermal radiation of temperature T_U

Unruh temperature

$$T_U = \frac{\hbar a}{2\pi c}$$

relativistic (c) quantum ($\hbar$)effect

Unruh temperature $$T_U = \frac{\hbar a}{2\pi c}$$

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Applications

- Black Holes

event horizon $R = 2GM$ (Schwarzschild radius)

$$F = ma = G\frac{Mm}{R^2} \Rightarrow a = \frac{GM}{R^2} = \frac{1}{4GM}$$

$$\Rightarrow T_U = \frac{a}{2\pi} = \frac{1}{8\pi GM} = T_{BH}$$

obtain temperature T_{BH} of Hawking radiation

[Hawking 1975]

- Schwinger Mechanism

in strong electric field $\mathcal{E}$, vacuum becomes unstable against pair production

$F = e\mathcal{E} = (m/2)a$ leads to production of pair of charges of mass m

$$T_U = \frac{a}{2\pi} = \frac{e\mathcal{E}}{\pi m}$$

$$P(m, \mathcal{E}) \sim \exp\{-m/T_U\} = \exp\{-\pi m^2/e\mathcal{E}\}$$

obtain Schwinger production probability $P(m, \mathcal{E})$

[Schwinger 1951]

In general: [T. D. Lee 1986, Parikh & Wilczek 2000]

event horizon $\sim$ information transfer forbidden

$\Rightarrow$ quantum tunnelling $\sim$ thermal radiation

3. Pair Production and String Breaking

Basic process:

two-jet e^+e^- annihilation, cms energy $\sqrt{s}$:

$$e^+e^- \longrightarrow \gamma* \longrightarrow q\bar{q} \longrightarrow \text{ hadrons}$$

$q\bar{q}$ separate subject to constant confining force $F = \sigma$

initial quark velocity $\quad v_0 = \dfrac{p}{\sqrt{p^2 + m^2}} \ , \quad p \simeq \sqrt{s}/2$

Solve $ma = \sigma$ (hyperbolic motion): [Hosoya 1979, Horibe 1979]

$$\tilde{x} = [1 - \sqrt{1 - v_0\tilde{t} + \tilde{t}^2}] \ , \ \tilde{x} = x/x_0 \ , \ \tilde{t} = t/x_0$$

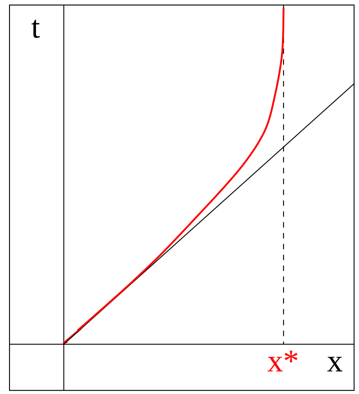
with $\quad x_0 = \dfrac{m}{\sigma}\dfrac{1}{\sqrt{1 - v_0^2}} = \dfrac{m}{\sigma}\,\gamma = \dfrac{1}{a}\,\gamma$

classical turning point $v(t^*) = 0$ at

$$x^* = x(t^*) = \frac{m}{\sigma}\gamma\left[1-\sqrt{1-(v_0/2)^2}\right] \simeq \frac{\sqrt{s}}{2\sigma}$$

$q\bar{q}$ can separate arbitrarily far
if $\sqrt{s}$ is large enough

What's wrong?



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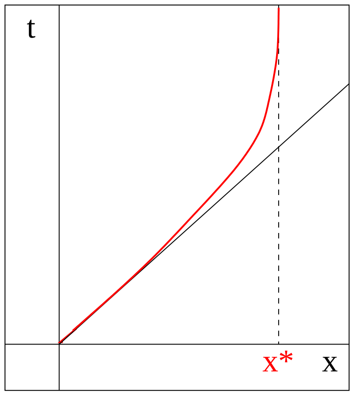


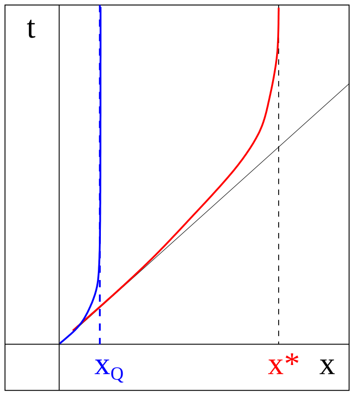
$q\bar{q}$ can separate arbitrarily far
if $\sqrt{s}$ is large enough

What's wrong?

classical event horizon

Strong field $\Rightarrow$ vacuum unstable
against pair production [Schwinger 1951]

when $\sigma x > \sigma x_Q \equiv 2m$
string connecting $q\bar{q}$ breaks

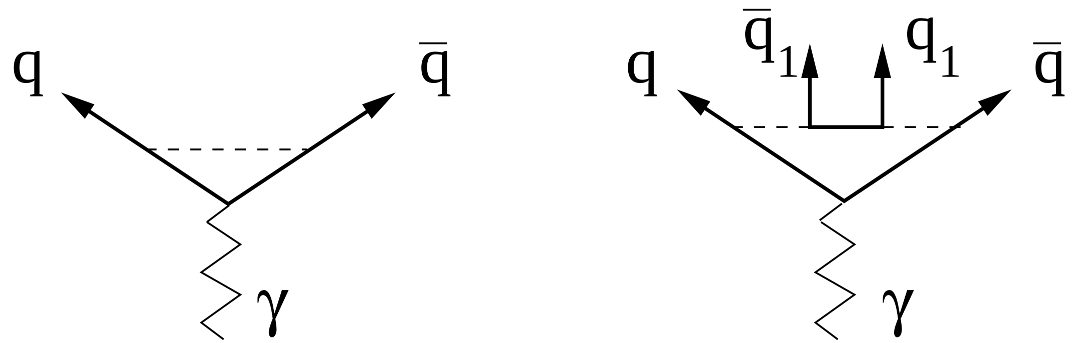


Result:

quantum event horizon

Hadron production in e^+e^- annihilation:

"inside-outside cascade" [Bjorken 1976]



$q\bar{q}$ flux tube has thickness $r_T \simeq \sqrt{\frac{2}{\pi\sigma}}$

$q_1\bar{q}_1$ at rest in cms, but $k_T \simeq \frac{1}{r_T} \simeq \sqrt{\frac{\pi\sigma}{2}}$

$q\bar{q}$ separation at $q_1\bar{q}_1$ production $\sigma x(q\bar{q}) = 2\sqrt{m^2 + k_T^2}$

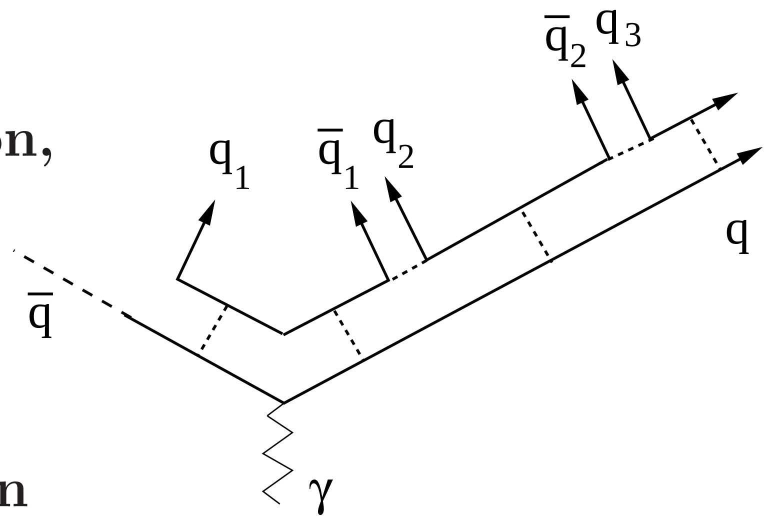
q_1 screens $\bar{q}$ from q, hence string breaking at

$$x_q \simeq \frac{2}{\sigma}\sqrt{m^2 + (\pi\sigma/2)} \simeq \sqrt{2\pi/\sigma} \simeq 1 \text{ fm}$$

new flux tubes $q\bar{q}_1$ and $\bar{q}q_1$
stretch $q_1\bar{q}_1$
to form new pair $q_2\bar{q}_2$

$$\sigma x(q_1\bar{q}_1) = 2\sqrt{m^2 + k_T^2}$$

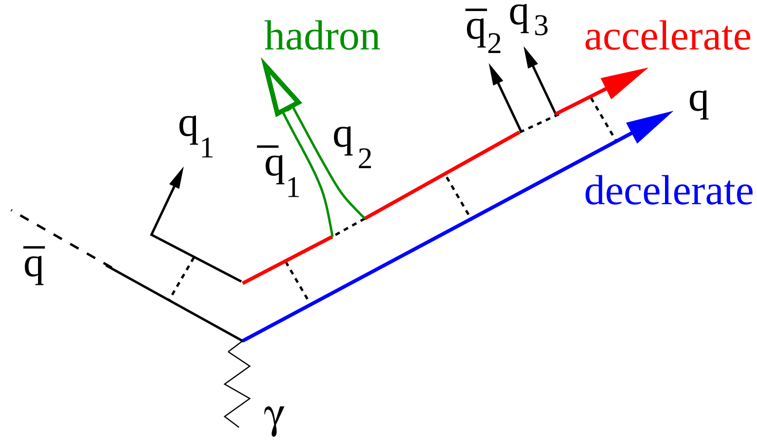
equivalent:
$\bar{q}_1$ reaches $q_1\bar{q}_1$ event horizon,
tunnels to become $\bar{q}_2$

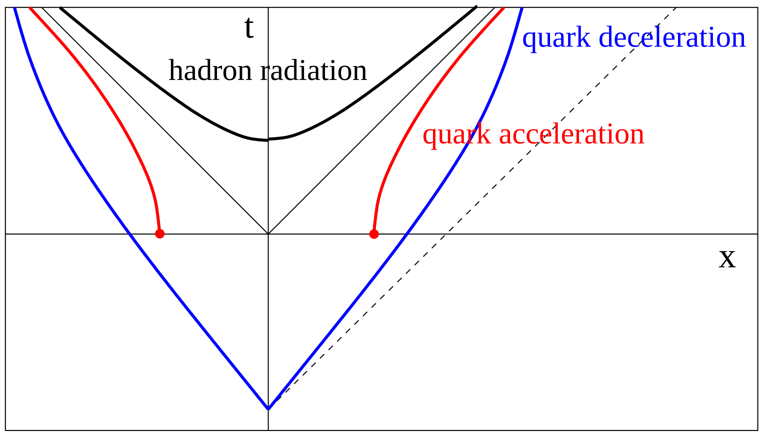


emission of hadron $\bar{q}_1 q_2$
as Hawking-Unruh radiation

self-similar pattern:

- **screening**
- **string breaking**
- **tunnelling**
- **quark acceleration /deceleration**
- **Hawking-Unruh radiation**





temperature of H-U radiation: what acceleration?

$(\bar{q}_1 \longrightarrow \bar{q}_2 \longrightarrow \bar{q}_3 \longrightarrow \ldots)$

$$a = F/m \ \Rightarrow \ a_q = \frac{\sigma}{w_q} = \frac{\sigma}{\sqrt{m_q^2 + k_q^2}}$$

string breaking & thickness determine $k_q \simeq \sqrt{\pi\sigma/2}$

$$\Rightarrow \quad a_q \simeq \frac{\sigma}{\sqrt{m_q^2 + (\sigma/2\pi)}}$$

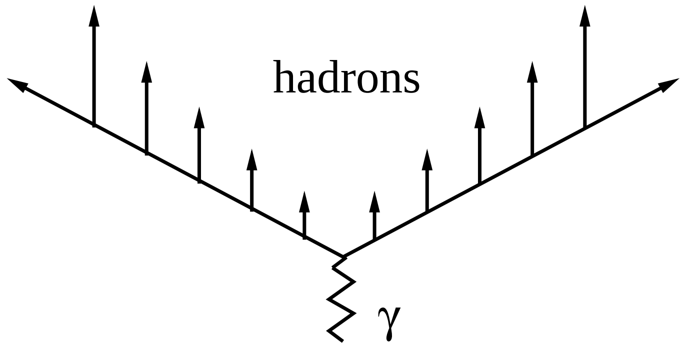
for light quarks, $m_q \ll \sqrt{\sigma} \simeq 420$ **MeV, hence**

$$T = \frac{a}{2\pi} \simeq \sqrt{\frac{\sigma}{2\pi}} \simeq 170 \text{ MeV}$$

temperature of hadronic Hawking-Unruh radiation

hadronization pattern:

hadron multiplicity?



thickness of classical “overstretched” string:

$$R_T^2 = \frac{2}{\pi\sigma} \sum_{k=0}^{K} \frac{1}{2k+1} \simeq \frac{2}{\pi\sigma} \ln 2K \simeq \frac{2}{\pi\sigma} \ln \sqrt{s}$$

quantum breaking at $x_q \sim r_T$, hence hadron multiplicity

$$\nu(s) \simeq \frac{R_T^2}{r_T^2} \simeq \ln \sqrt{s}$$

NB: parton evolution (minijets), multiple jets lead to stronger increase

4. Strangeness Production

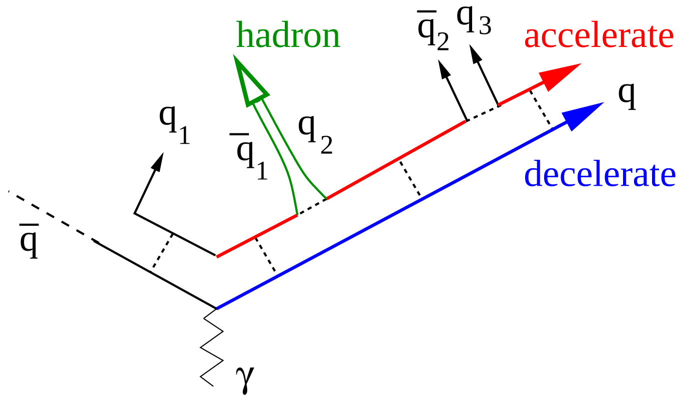
[Becattini, Castorina, Manninen, HS 2008]

Unruh temperature $\sim$ 1 / mass of secondary

we had for finite quark mass m_q

$$a_q \simeq \frac{\sigma}{\sqrt{m_q^2 + (\sigma/2\pi)}} \quad \Rightarrow \quad T_U = \frac{a_q}{2\pi}$$

produced meson consists of quarks $\bar{q}_1$ and q_2



meson containing two different quark masses
will have average acceleration

$$\bar{a}_{12} = \frac{w_1 a_1 + w_2 a_2}{w_1 + w_2} = \frac{2\sigma}{w_1 + w_2}; \quad w_i \simeq \sqrt{m_i^2 + (\sigma/2\pi)}$$

leading to

$$T(12) \simeq \frac{a_{12}}{2\pi}$$

easily extended to baryons; result: five temperatures

$$T(00) = T(000);\ T(s0);\ T(ss) = T(sss);\ T(00s);\ T(0ss)$$

fully determined by σ and m_s

T	[GeV]
$T(00)$	0.164
$T(0s)$	0.156
$T(ss)$	0.148
$T(000)$	0.164
$T(00s)$	0.158
$T(0ss)$	0.153
$T(sss)$	0.148

for $\sigma \simeq 0.17$ GeV^2 and $m_s \simeq 0.08$ GeV

obtain temperatures:

does this work?

analyse all high energy e^+e^- data

hadron production data in e^+e^- annhilation exist at

$$\sqrt{s} = 14,\ 22,\ 29,\ 35,\ 43, 91, 180 \text{ GeV}$$

(PETRA, PEP, LEP)

example:

long-lived hadrons produced at LEP for $\sqrt{s} = 91.25$ GeV fit data in terms of σ and m_s

result:

$\sigma = 0.169 \pm 0.002$ GeV^2

$m_s = 0.083$ GeV

χ^2/dof $= 23/12$

standard values:

$\sigma = 0.195 \pm 0.030$ GeV^2

$m_s = 0.095 \pm 0.025$ GeV

e^+e^- $\sqrt{s} = 91.2$ GeV				
species	measured			fit
π^+	8.50	$\pm$	0.10	8.30
π^0	9.61	$\pm$	0.29	9.67
K^+	1.127	$\pm$	0.026	1.089
K^0	1.038	$\pm$	0.001	1.049
η	1.059	$\pm$	0.996	0.910
ω	1.024	$\pm$	0.059	0.971
p	0.519	$\pm$	0.018	0.557
η'	0.166	$\pm$	0.047	0.096
ϕ	0.0977	$\pm$	0.0058	0.1060
Λ	0.1943	$\pm$	0.0038	0.1891
Σ^+	0.0535	$\pm$	0.0052	0.0437
Σ^0	0.0389	$\pm$	0.0041	0.0444
Σ^-	0.0410	$\pm$	0.0037	0.0400
Ξ^-	0.01319	$\pm$	0.0005	0.01269
Ω	0.00062	$\pm$	0.0001	0.00077

illustration:
ϕ production in H-U vs. standard statistical model

ϕ production density in standard statistical model

$$\langle n \rangle_\phi = 3\frac{Tm^2}{2\pi^2}\mathrm{K}_2(m/T)\ \gamma_S^2$$

with $T \simeq 165$ MeV, $\gamma_S \simeq 0.65$: $\langle n \rangle_\phi \simeq 1.85\ \gamma_S^2 \simeq 0.078$

NB: $\gamma_S^2 \simeq 0.42$ reduces equilibrium rate by more than 2

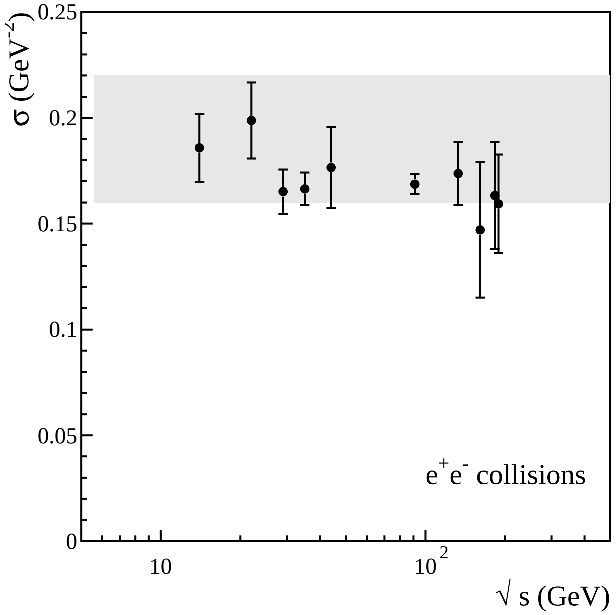
ϕ production density in H-U statistical model

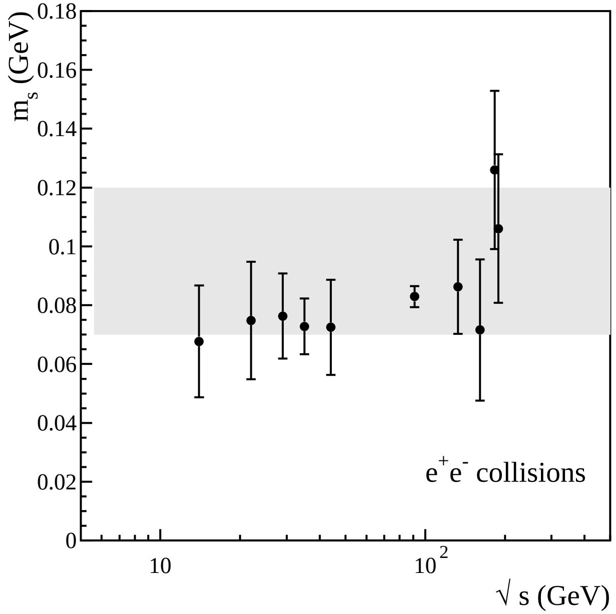
$$\langle n \rangle_\phi = 3\frac{T(ss)m^2}{2\pi^2}\mathrm{K}_2(m/T(ss))$$

with $T(ss) \simeq 148$ (*vs.* 164) MeV: $\langle n \rangle_\phi \simeq 0.077$

[NB: actual production rates $\sim$ heavy flavor decay]

results from all data





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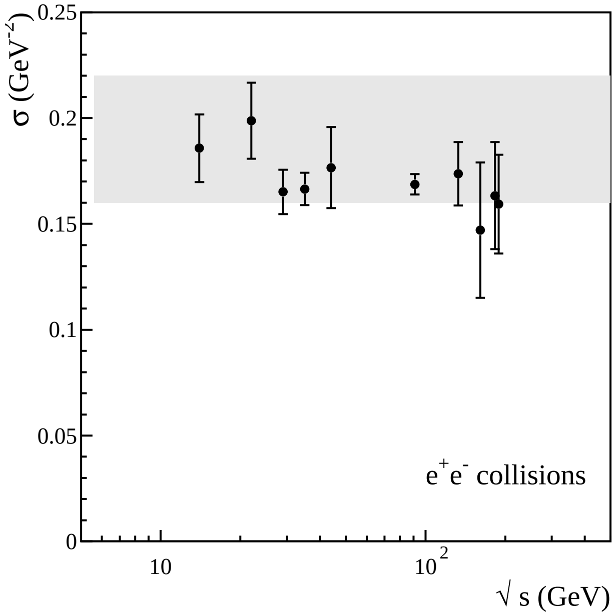
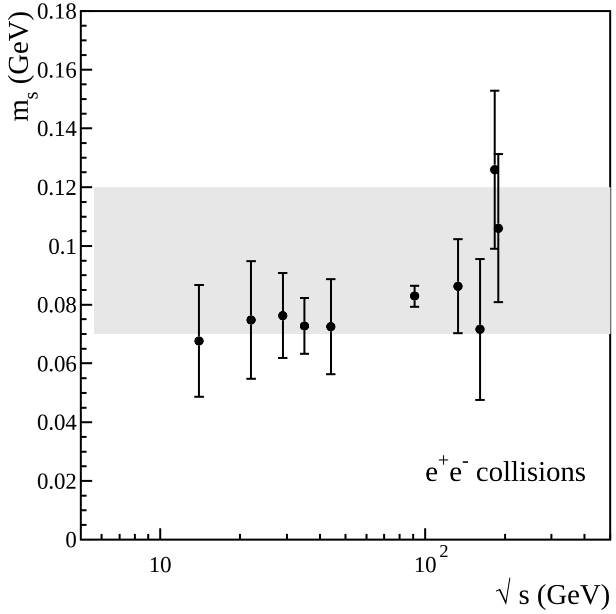




Conclude

thermal hadron production in e^+e^- annihilation, includ'g strangeness suppression, is reproduced parameter-free as Hawking-Unruh radiation of QCD

4. Kinetic vs. Stochastic Thermalization

Kinetic thermalization:

time evolution of given non-equilibrium configuration
(two parallel colliding parton beams)
through multiple collisions
to a time-independent equilibrium state
(quark-gluon plasma)
requires

- **many constituents**
- **sufficiently large interaction cross sections**
- **sufficiently long time**

thermal hadron production in e^+e^-, $pp/p\bar{p}$**?**

Hagedorn: *the emitted hadrons are "born into equilibrium"*

Hawking-Unruh radiation:

- **final state produced at random from the set of all states corresponding to temperature T_H determined by confining field**

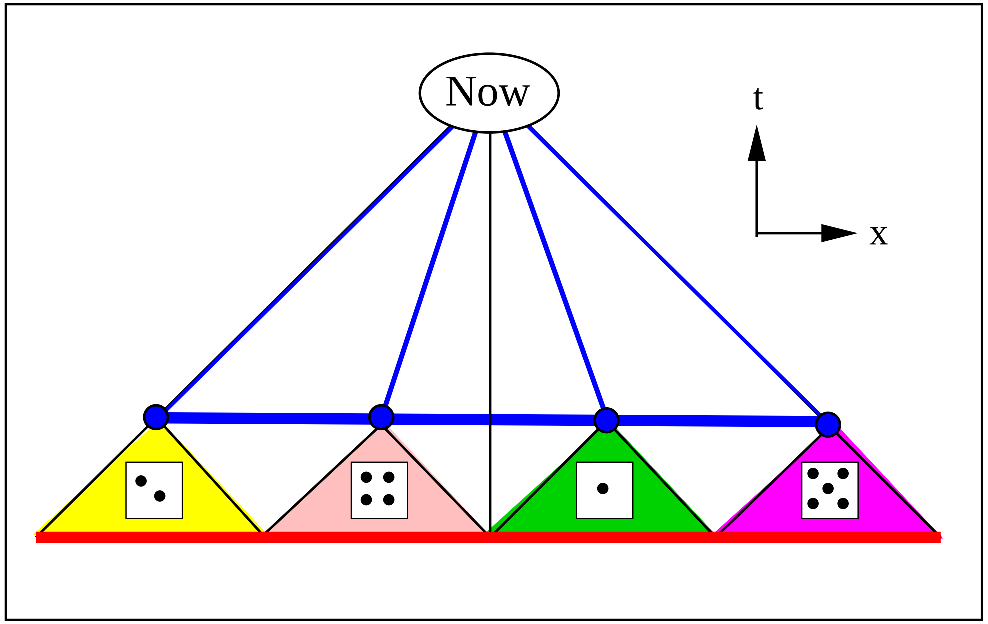
- **this set of all final states is same as that produced by kinetic thermalization**

- **measurements cannot tell if the equilibrium was reached by thermal evolution or by throwing dice:**

$\Rightarrow$ <u>Ergodic Equivalence Principle</u> $\Leftarrow$

gravitation $\sim$ acceleration **kinetic $\sim$ stochastic**

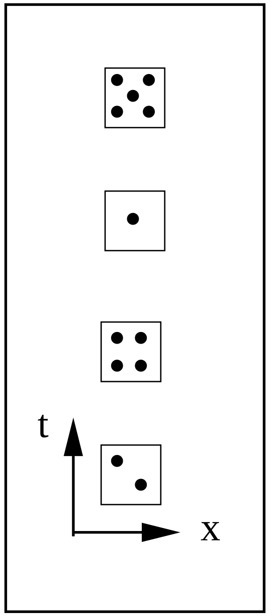
imagine a cosmic dice game: causally disjoint players



collect results from 1000 players:

result is the same

as a thousand throws of one player



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- Given string tension σ and strange quark mass m_s, obtain parameter-free description of thermal hadron production in high energy interactions.
- equivalence of kinetic vs. stochastic equilibration

God does play dice, but He sometimes throws them where they can't be seen.

Stephen Hawking