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Thermal hadronisation in QCD via the Unruh radiation

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Online seminar : Selected topics in heavy-ion collisions

Indico page : https://indico.cern.ch/event/1103564/

Please do consider the points below before deciding about your approach towards this talk!

- Context of this talk
- There are no conclusions
- Authority versus scientific method
- What I say here can be wrong! - It applies to all the talks!
- Suggestion: Consider it as a provocation to know & think about it further.

Outline

- Reminder : Thermal hadron production in high energy collisions
- The quest for a thermalisation mechanism

} The problem

- Gravitation v/s QCD: Blackholes and Whiteholes
- Rindler horizon and the Unruh effect
- Thermalisation via the Unruh radiation
- Temperature of the Hawking radiation from Unruh effect

} Unruh effect

- Classical and quantum event horizon in two -jet e^+e^- annihilation
- Thermal hadron production in e^+e^- annihilation
- Temperature and multiplicity from the Unruh formulation
- Hadron-Hadron collisions and whitehole fusion
- Stochastic thermalisation in heavy-ion collisions

} QCD analogy

Reminder : Thermal hadron production in high energy collisions

Thermal Model:

Grand Canonical Ensemble $[T, \mu, V]$ & Z → Hadron multiplicity as a function of $[T, \mu, V]$

High Energy Experiments:

Large and small systems e^+e^-, hh, AA → Experimental Hadron multiplicity distribution

Hadron multiplicity as a function of $[T, \mu, V]$ ⟷ The equations **can be fitted** with data and the $[T, \mu, V]$ of the best fit is extracted ⟷ Experimental Hadron multiplicity distribution

If this works out well, we say that the experimental system has a thermal behaviour

Reminder : Thermal hadron production in high energy collisions

Blast Wave Model:

Grand Canonical Ensemble $[T, \mu, V]$ & Z → Hadron Spectra as a function of $[T, \mu, V]$

High Energy Experiments:

Large and small systems e^+e^-, hh, AA → Experimental Hadron Spectra

Hadron Spectra as a function of $[T, \mu, V]$ ⟷ Experimental Hadron Spectra

The equations **can be fitted** with data and the $[T, \mu, V]$ of the best fit is extracted

If this works out well, we say that the experimental system has a thermal behaviour

Reminder : Thermal hadron production in high energy collisions

Hydro Models:

Assumes local thermal and chemical equilibrium → Hadron Spectra and elliptic flow predictions

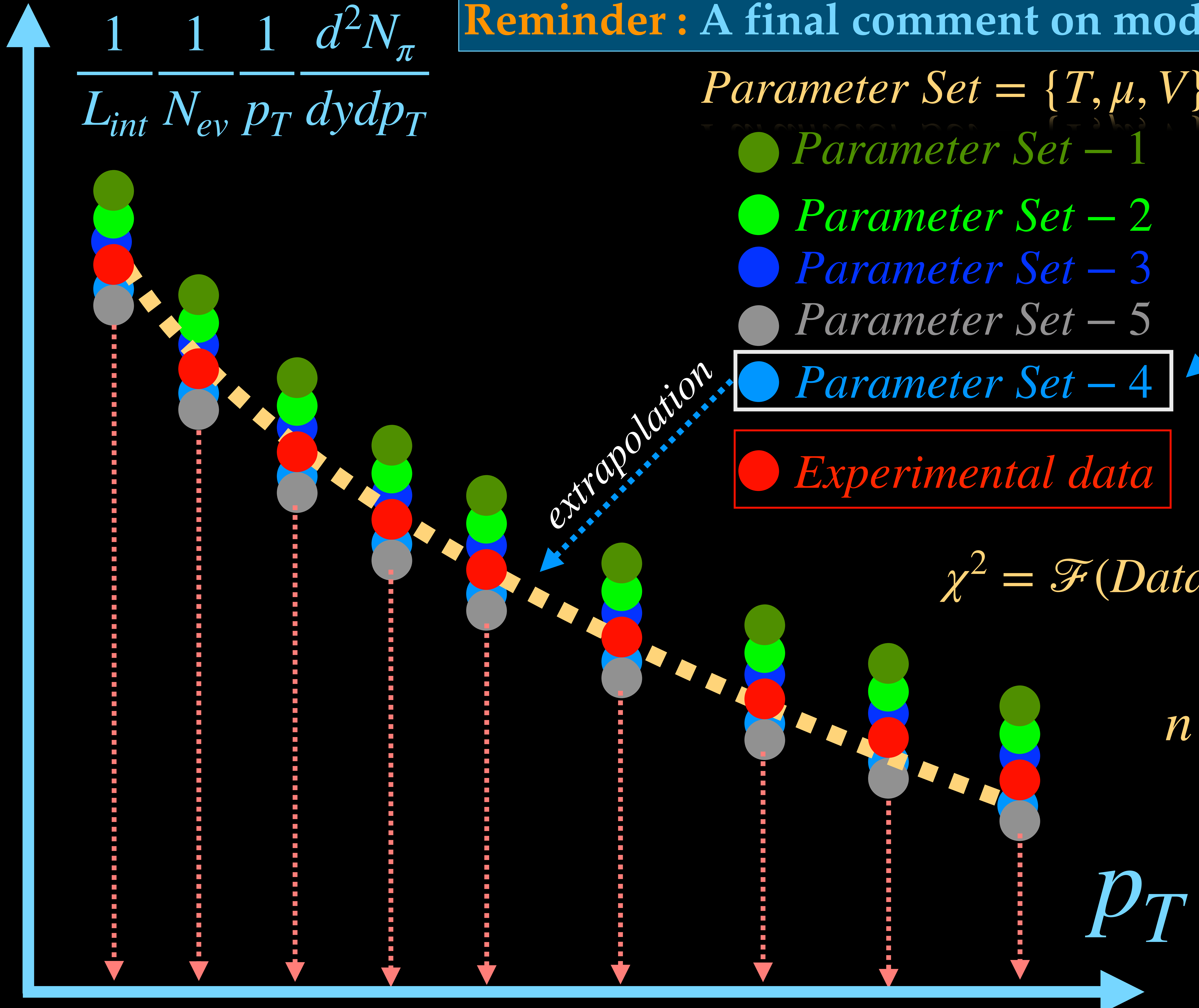
High Energy Experiments:

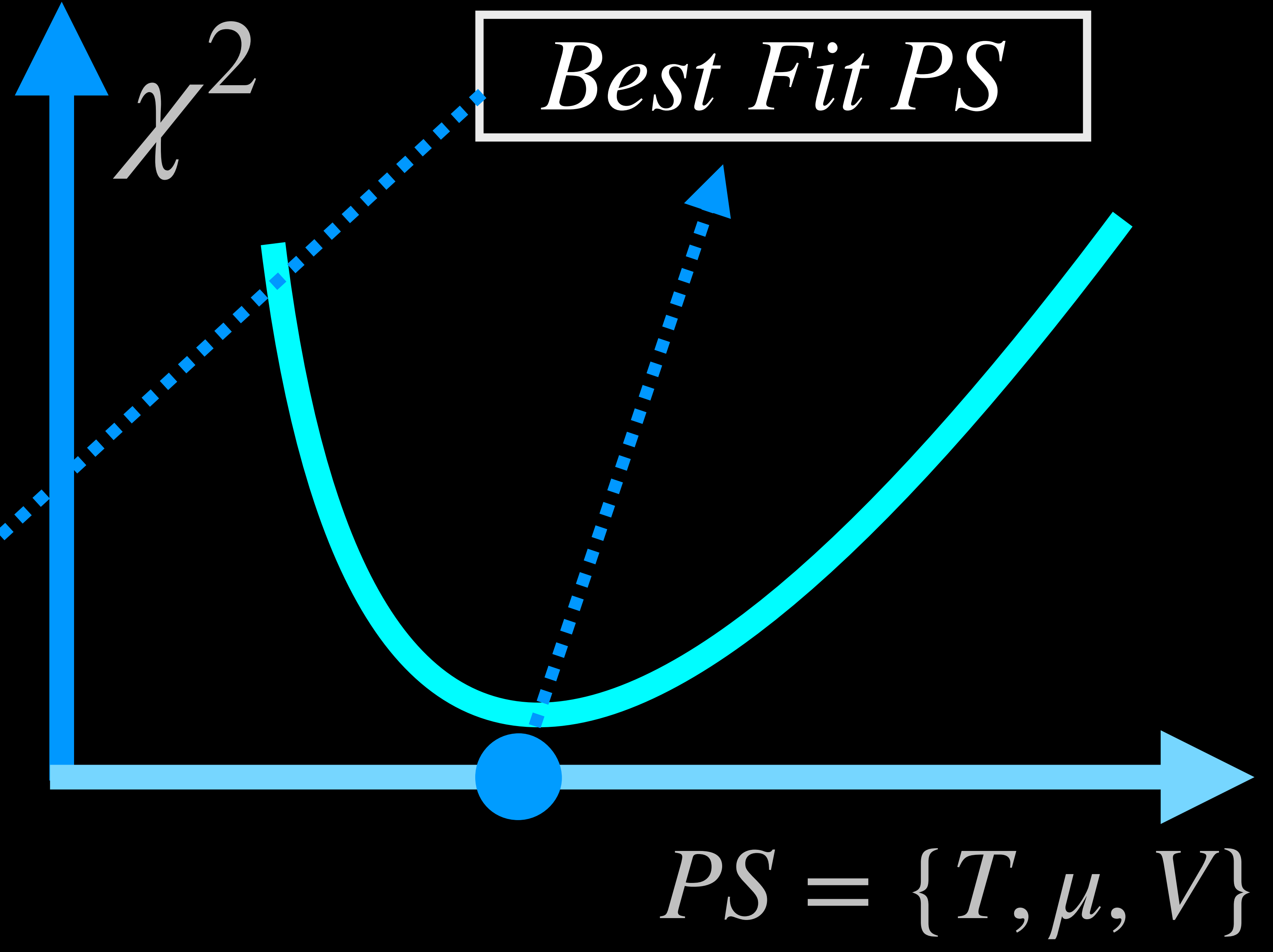
Large and small systems e^+e^-, hh, AA → Experimental Hadron Spectra & v_2

Hadron Spectra and elliptic flow predictions ↔ The results **can be fitted** with data and the parameter values are extracted ↔ Experimental Hadron Spectra & v_2

If this works out well, we say that the experimental system has a thermal behaviour

Reminder : A final comment on model v/s data





$$\chi^2 = \mathcal{F}(Data\ Point - Theory\ Point, Errors)$$

$$n.d.f = no : data\ points - 1$$

$$\frac{\chi^2}{n.d.f} \sim 1.0 \rightarrow Good\ Fit$$

Reminder : Thermal hadron production in high energy collisions

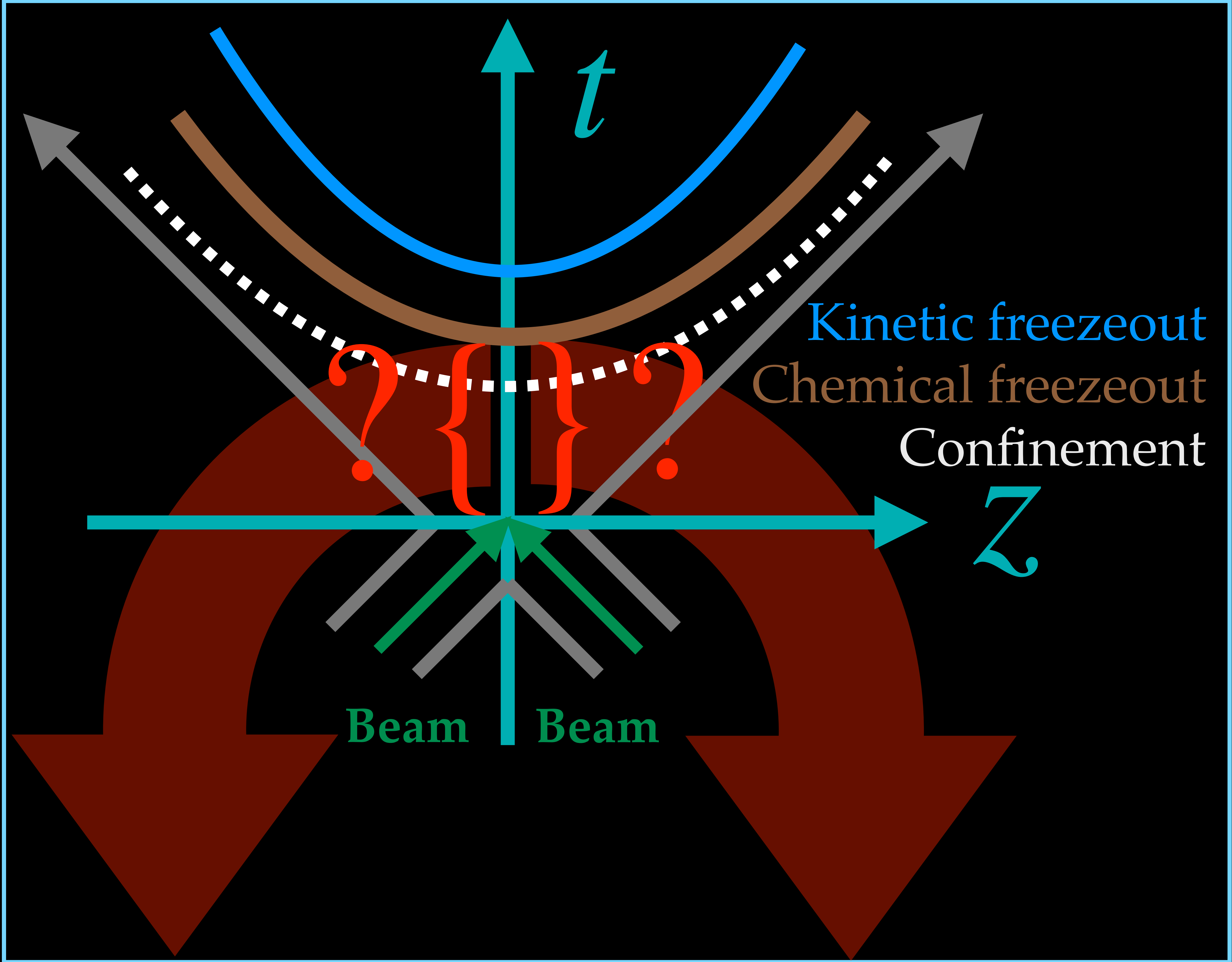
System		Possible explanation for the observed thermal behaviour
Heavy-Ion collisions	→	**Kinetic thermalisation:** Elastic two, three and multi parton scattering leading to an isotropic momentum distribution in due course of time.
h-h collisions	→	**Not possible** via kinetic thermalisation
e^+e^-collisions	→	**Not possible** via kinetic thermalisation

Why? → **Kinetic thermalisation requires many constituents, sufficiently large interaction cross sections and sufficiently long time which are absent in small and elementary collisions**

What can then be the possible mechanism behind the observed thermal behaviour of supposedly non-thermal systems ?

Are we really observing quark gluon plasma in heavy-ion collisions?

Responses to the question on the ensemble and partition function in thermal models

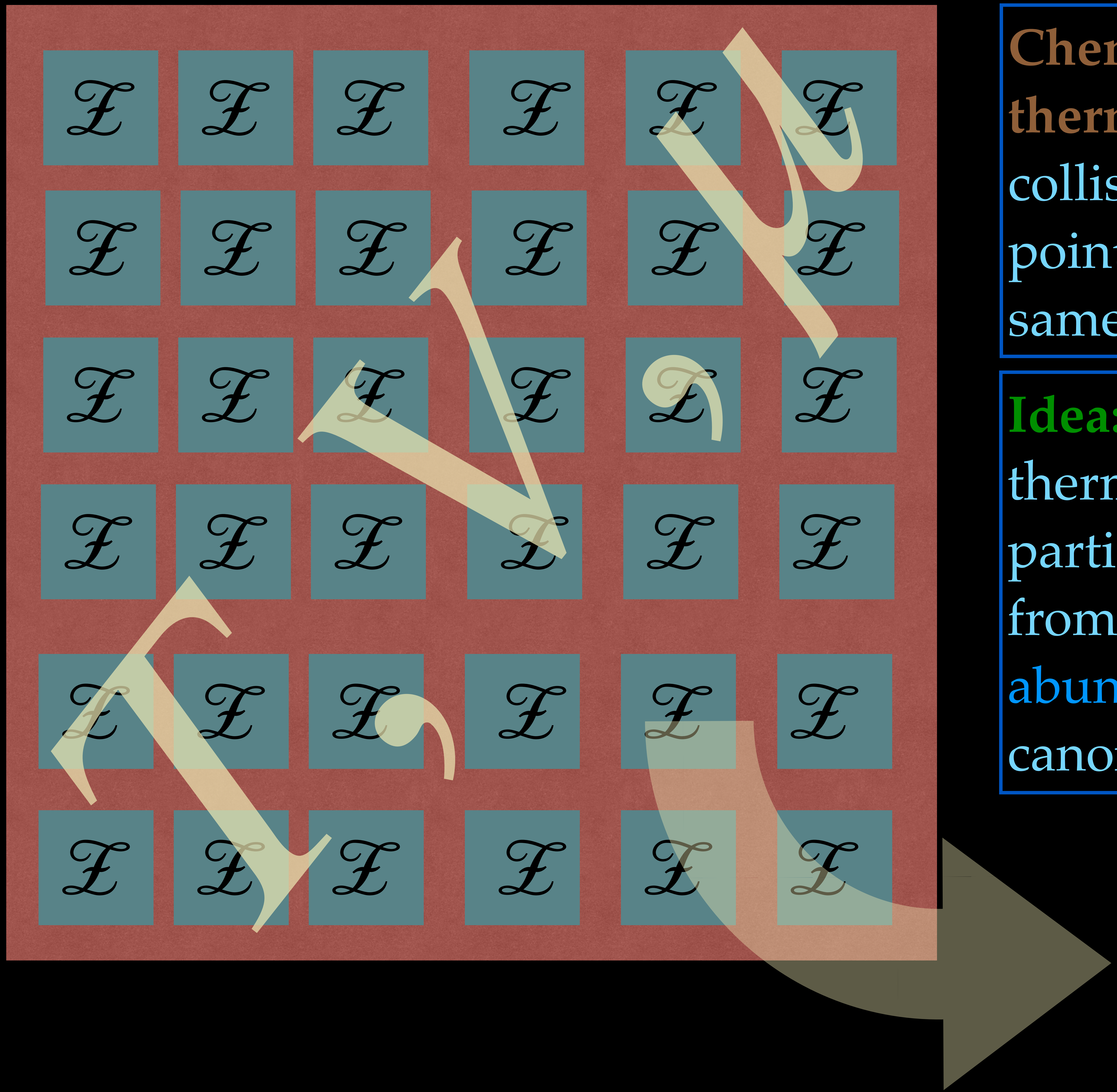


Chemical freezeout is the point where the thermal models are focusing: The inelastic collisions between the constituents stops at this point. Hence the particle numbers remain the same from this point onwards in time.

Idea: If we assume that the system is made up of thermally equilibrated non interacting group of particles at this point in time, then what follows from such a system (like multiplicity, particle abundance etc) can be calculated using the grand canonical partition function $\mathcal{Z}(T, \mu, V)$.

One way to understand the problem: If a thermal system has to be formed at the chemical freezeout, then what kind of mechanism should be happening early in time? If we see such a behaviour in small collision systems, what kind of mechanism can claim the responsibility?

Responses to the question on the ensemble and partition function in thermal models



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Non interacting group of ensembles

What could be the solution to the problem of thermalisation in *non-thermal* systems?

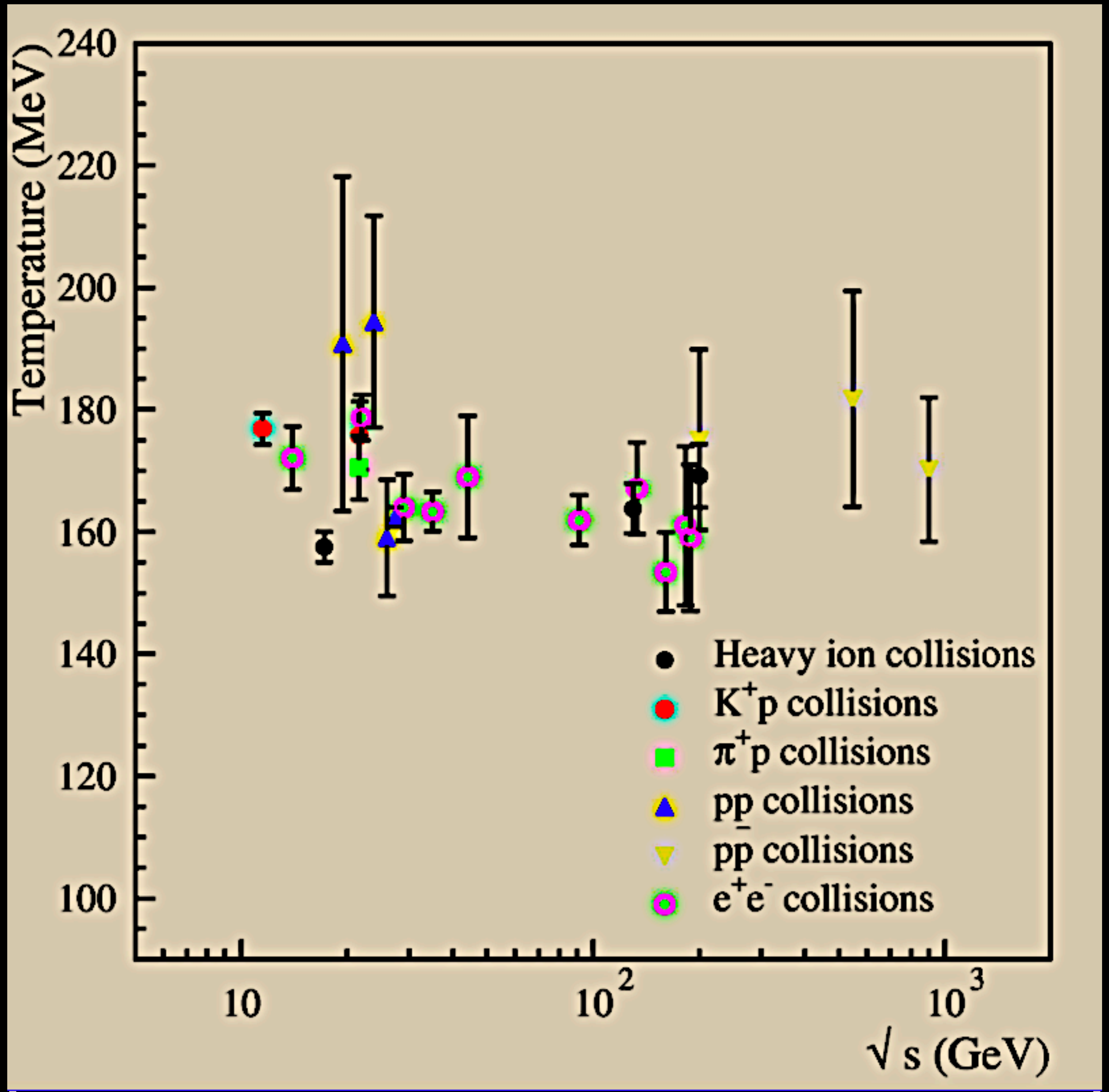
- Hagedorn proposed in 1965 that there should exist a critical behaviour of the hadron gas at high T

- He studied the number of hadron species as a function of their mass and found that the following exponential dependence can describe the available experimental data:

$$\rho(m) = \frac{A}{m^2 + 500} exp(m/T_H)$$ where $\rho(m)$ is the density of hadron species per mass unit and T_H is a parameter.

- From the experimental dataset $T_H \sim 180$ MeV when all the known baryon and meson resonances are considered.

- Form of $\rho(m)$ will induce divergences for the partition function that describes the statistical properties of a hadron gas for $T > T_H$.



Reminder: **T from thermal fit**
arXiv:0907.1031v1 [nucl-th]

Rolf Hagedron: ***"Hadrons are born into thermal equilibrium."***

What could be the solution to the thermalisation problem?

We come to the point that we surely need a mechanism in which the particles are produced according to the maximum entropy principle, leading to a thermal bath of it for the observers.

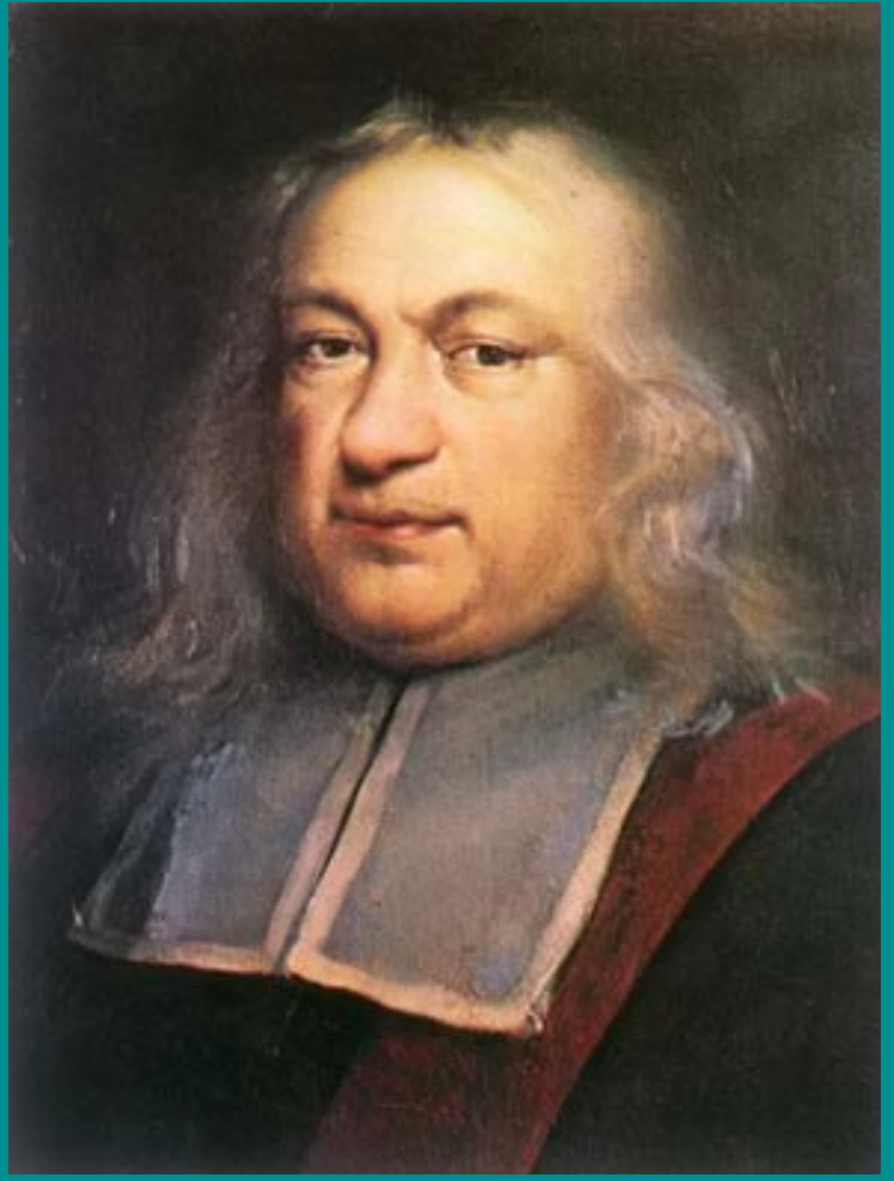
- Such a mechanism of thermal production of particles called the Unruh effect does exist in relativity.
- Kharzeev & Tuchin in 2004-05: Proposed Unruh effect as the responsible mechanism for thermal production of hadrons in high energy collisions.

Nutshell: Passing colour charge disturbs the vacuum. It recovers by hadron production according to the maximum entropy principle.
Conjecture: Colour confinement ~ black hole physics

Seemingly distinct but not so distinct topics: Wiles's proof of Fermat's last theorem.

Fermat's Last Theorem formulated in 1637, states that no three distinct positive integers a, b, and c can satisfy the equation $a^n + b^n = c^n$ for $n > 2$

The modularity theorem states that any elliptic curve over can be obtained via a rational map with integer coefficients from the classical modular curve for some integer ; this is a curve with integer coefficients with an explicit definition.



Pierre de Fermat

Proving the modularity theorem or Taniyama–Shimura conjecture was the way to prove the Fermat's last theorem!.

Andrew Wiles

Gravitation versus QCD : Blackholes & Whiteholes

Quantum Chromodynamics has colour confinement: The fundamental particles (quarks and gluons) are *coloured*, and colour confinement does not allow them to exist as individual entities in the world we can observe, though we can register their effects. **Thus a single quark or gluon can never be observed as an isolated object, in contrast to a single proton or electron.**

Gravitational blackhole: A black hole is the final stage of a neutron star after gravitational collapse. It has a mass M concentrated in such a small volume that the resulting gravitational field confines all matter and even photons to remain inside the “event horizon” R of the system: no causal connection with the outside world is possible.

A conceptual analogy?: Could it be that a hadron, containing coloured constituents that cannot get out, is something like a blackhole (or whitehole rather) of strong interaction physics?

Gravitation versus QCD : Blackholes & Whiteholes

The space-time metric:

$$ds^2 = g_0 dt^2 - g_0^{-1} dr^2 - d^2\Omega$$

r and Ω specifying the spatial part, and t the time. If the space is flat, then $g_0 = 1$.

The event horizon of a spherical blackhole:

$g_0 = 0 \rightarrow$ Point at which this metric is so deformed that space and time interchange.

The Einstein's field equations gives:

$g_0 = 1 - \dfrac{2GM}{r}$ which leads to the

Schwarzschild radius of a black hole:

$R = 2GM$ **where** G is gravitational constant & M is mass of the system.

L.Z. Fang, R. Ruffini, Basic Concepts in Relativistic Astrophysics (World Scientific, Singapore, 1983)

Gravitation versus QCD : Blackholes & Whiteholes

- **The Schwarzschild radius of a typical hadron, assuming a mass *m* 1 GeV**

$$R_g^{had} = 1.38 \times 10^{-38} GeV^{-1} \sim 2.7 \times 10^{-39}\ \text{fm}$$

- **What does it mean?:** To become a gravitational black hole, the mass of the hadron would thus have to be compressed into a volume more than 10^{100} times smaller than its actual volume (with a radius of about 1 fm).

- **The strong Schwarzschild radius of a hadron:** We change the interaction from gravitation to strong force, we gain in the resulting **strong Schwarzschild radius** R_s^{had} is given by

$$R_s^{had} = \frac{2\alpha_s}{m}$$

which for the limiting value of the strong coupling $\alpha_s \sim 3$ gives $R_s^{had} = 1.2$ fm.

The confinement radius of a hadron is about the size of its *strong Schwarzschild radius*. Hence, one may imagine the quark confinement as the strong force version of the gravitational confinement in black holes

Lett. Nuovo Cim. **15**, 347 (1976) ; Phys. Lett. B **611**, 279 (2005) ; Phys. Rev. **D18**, 4596 (1978)

The Unruh Effect in an accelerated frame of reference

Stephen Hawking: Showed that the quantum tunnelling of particles through the blackhole event horizon from inside will result in the emission of thermal radiation. [1]

William. G. Unruh: Found that an observer in a reference frame undergoing constant acceleration would see the physical vacuum as a thermal medium of a temperature determined by its acceleration. This temperature called the Unruh temperature. [2]

Hawking & Unruh radiations: The equivalence principle between gravity and accelerated frames made the Hawking radiation a special case of the mechanism found by Unruh.

Schwinger mechanism: Responsible for particle production in a strong electric field was also found to be closely related to Unruh radiation. [Schwinger: 3] [Connections: 4-8]

We are in search for a thermal production mechanism: Is it possible to describe the observed thermal hadron production in high energy collisions (*where the strong interaction physics is dominant*) in terms of the thermal radiation from an event horizon?

The Unruh Effect in particle production: Short version

William. G. Unruh

A non-inertial observer experiences thermal radiation with temperature known as the Unruh temperature given by:

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

where a is the acceleration of the non-inertial observer whereas the inertial observer detects the vacuum.

Thermal hadron production via Unruh effect

- **Creation of particle requires some amount of energy.**
- **It leads to the deceleration of the initial particles during the scattering process.**
- **The decelerating particle may be considered as a non-inertial observer.**
- **The created particles are thus emitted in a completely thermal state from the horizon.**
- **Thermalisation is a consequence of the influence of the horizon as a thermal bath.**

W.G. Unruh, Phys. Rev. D 14, 870 (1976) ; D. Kharzeev, K. Tuchin, Nucl. Phys. A 753, 316 (2005)

The Unruh Effect in particle production: Short history of important papers

- Prog. Theor. Phys. Supplement 168, 338 (2007); Eur. Phys. J. C 52, 187 (2007: Deceleration and particle creation were considered via the string tension and the string breaking mechanism:

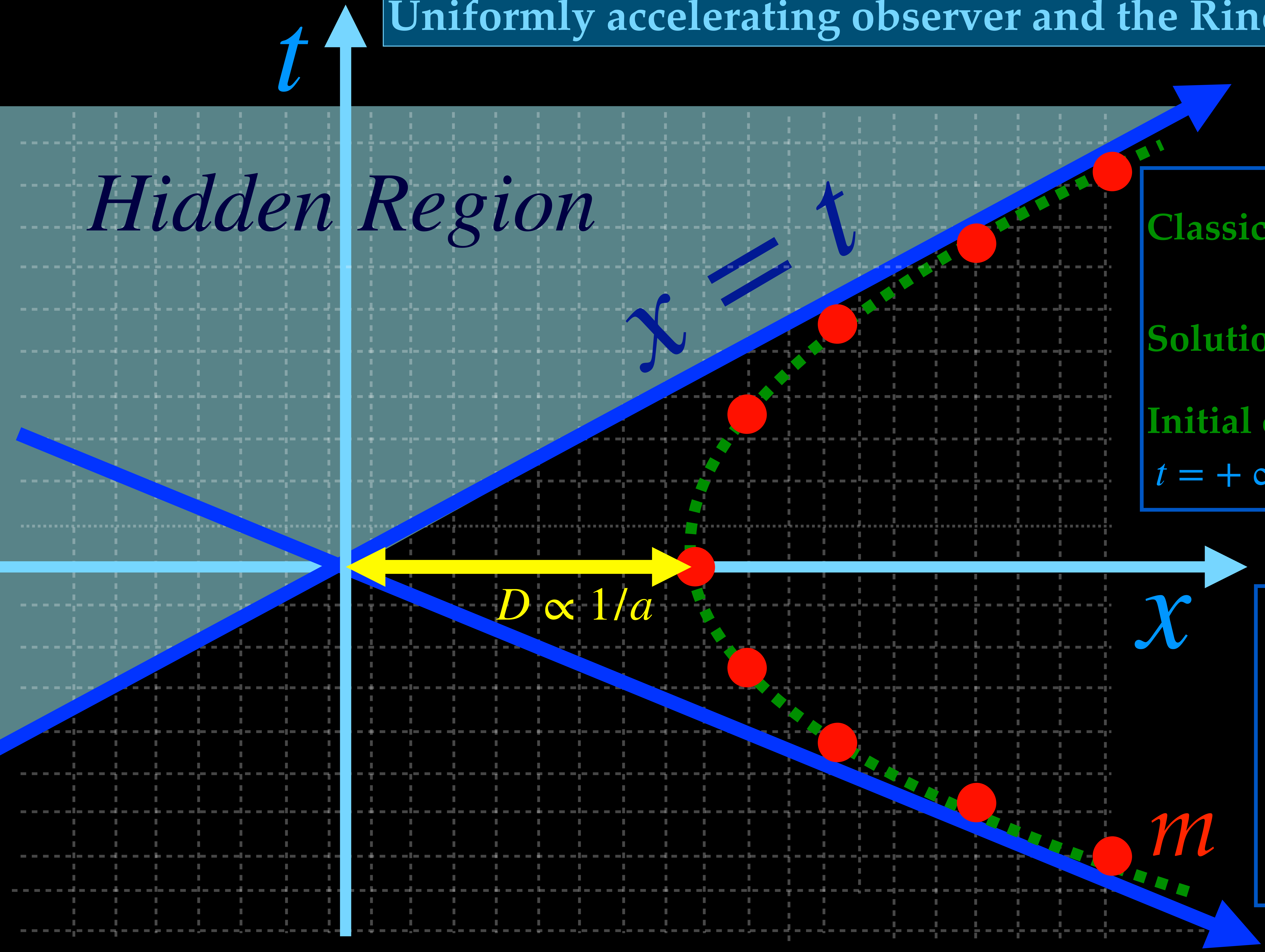
- Eur. Phys. J. C 56, 493 (2008: Comparison of the Unruh approach and experimental data

- Phys. Rev. D 77, 124034 (2008): Parameters of the black hole that reproduces yields and energy spectra of particles emitted in high energy scattering processes at the Hagedorn temperature.

- Nucl. Phys. A 853, 153 (2011): An analysis of the P and CP violation via the Unruh mechanism.

- Phys. Lett. B 708, 276 (2012): Shows the discrepancy between the Unruh approach and the RHIC data on photon emission.

Uniformly accelerating observer and the Rindler horizon



Classical E.O.M: $F = \frac{d}{dt}\frac{mv}{\sqrt{1-v^2}}$

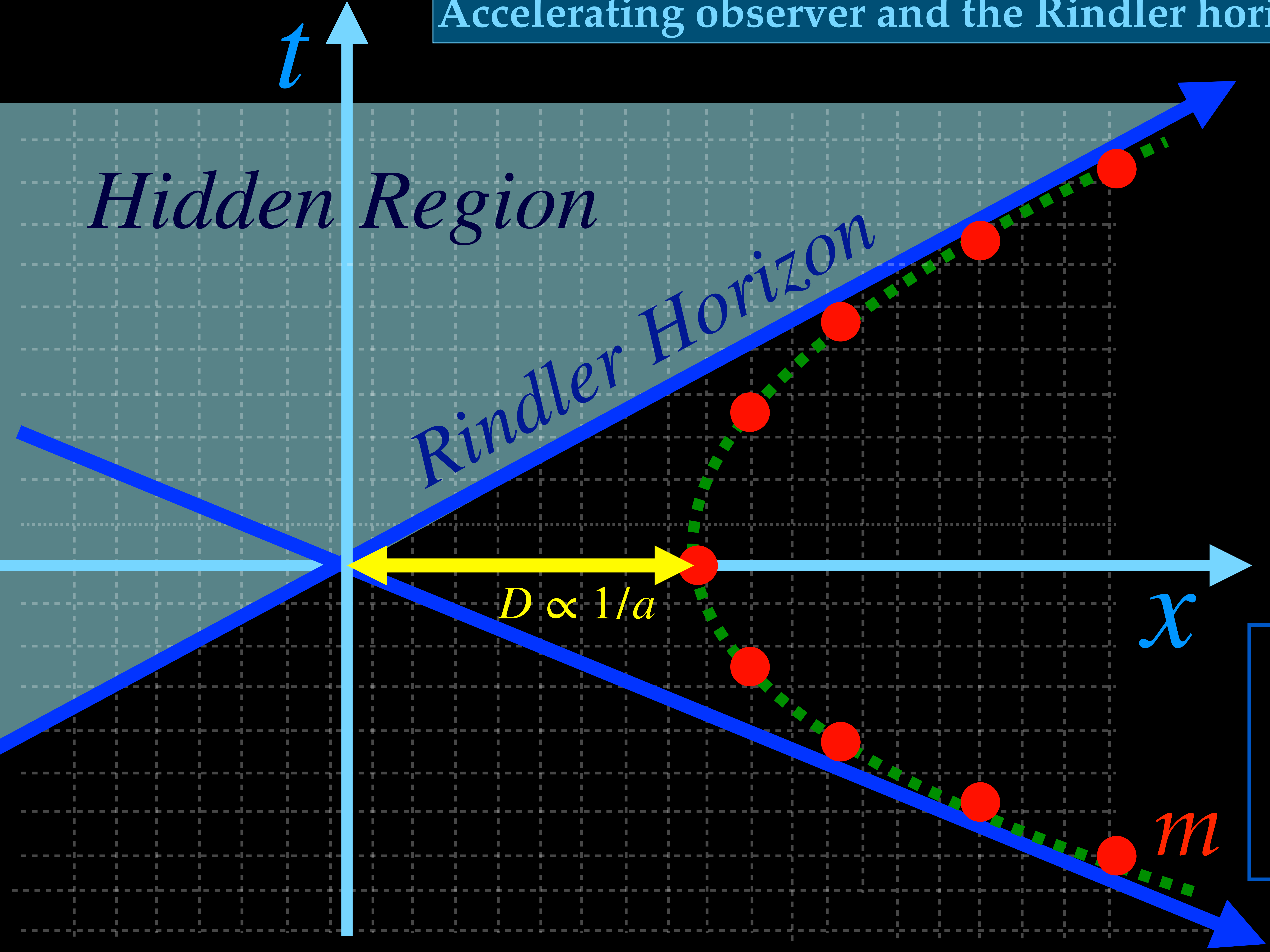
Solution : $x = \frac{1}{a}\cosh a\tau$; $t = \frac{1}{a}\sinh a\tau$

Initial conditions :

$t = +\infty; x = +\infty$; $t = -\infty; x = +\infty$

There exists a region in the universe, bounded by the $x = t$ line which the particle m can never be reached as long as it accelerates.

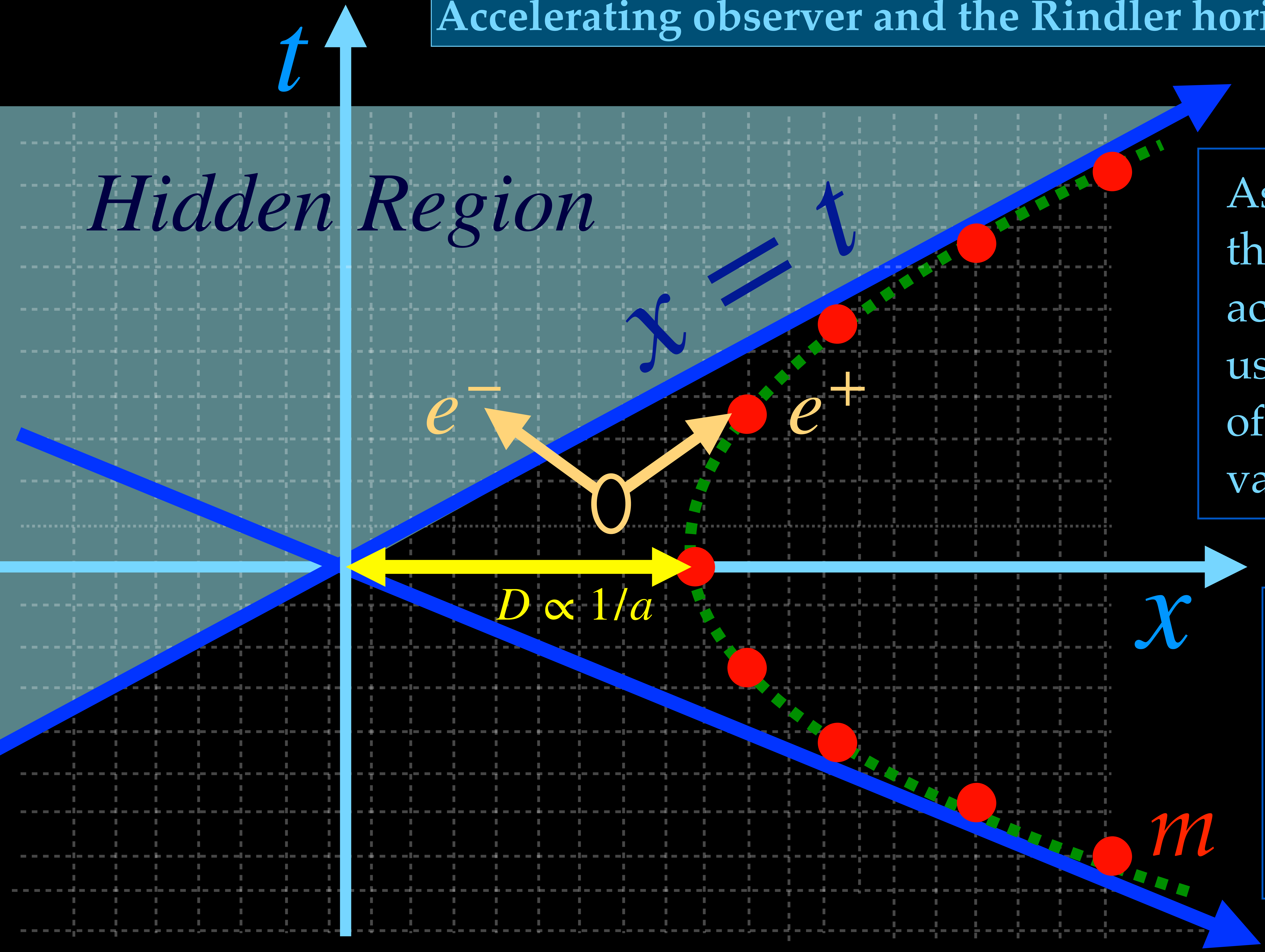
Accelerating observer and the Rindler horizon



Wolfgang Rindler

A uniform acceleration 'a', simply results in an event horizon called the **Rindler horizon**

Accelerating observer and the Rindler horizon



As the mass passes through the vacuum, a part of its acceleration energy can be used to excite on-shell one of the ever-present virtual vacuum fluctuations.

The e^+ is absorbed by the detector on m, while the e^- disappears beyond the Rindler horizon.

The Unruh Effect in an accelerated frame of reference

Equivalent scenario: The e^- emitted from m reaches the hidden region by quantum tunnelling through the event horizon. (This behaviour is closely connected with the quantum entanglement and Einstein Pedolsky Rosen effect [9,10])

Since the e^- went to the event horizon the Observer on m measuring the e^+ has only incomplete information

For the observer in the hidden region who can never access e^+ : Because of this principal lack of complete information, either observer can only see thermal radiation. It leads to th the observer on m seeing the physical vacuum as a thermal medium, *a heat bath of electrons,* with Unruh temperature

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

The observer in the hidden region registers the passage of m by measuring radiation of the same temperature.

Temperature of the Hawking radiation from Unruh formulation

The formulation can be used to derive the temperature of the Hawking radiation. For acceleration due to gravity, the force is given by:

$$F = ma = \frac{GMm}{R^2}$$

So that the acceleration becomes:

$$a = \frac{GM}{R^2} = \frac{1}{4GM}$$

(We get this by setting $g_0 = 0$ leading to the Schwarzschild radius $R = 2GM$).

The Unruh temperature for this acceleration is then:

$$T_{BH} = \frac{1}{8\pi GM}$$

which is the temperature for Hawking radiation from a black hole.

Temperature of the Hawking radiation from Unruh formulation

- For a Reissner-Nordström black hole with an overall charge Q, the equation for the force has to be modified to include the Coulomb force.

- One can obtain the Hawking temperature for such a charged blackhole as:

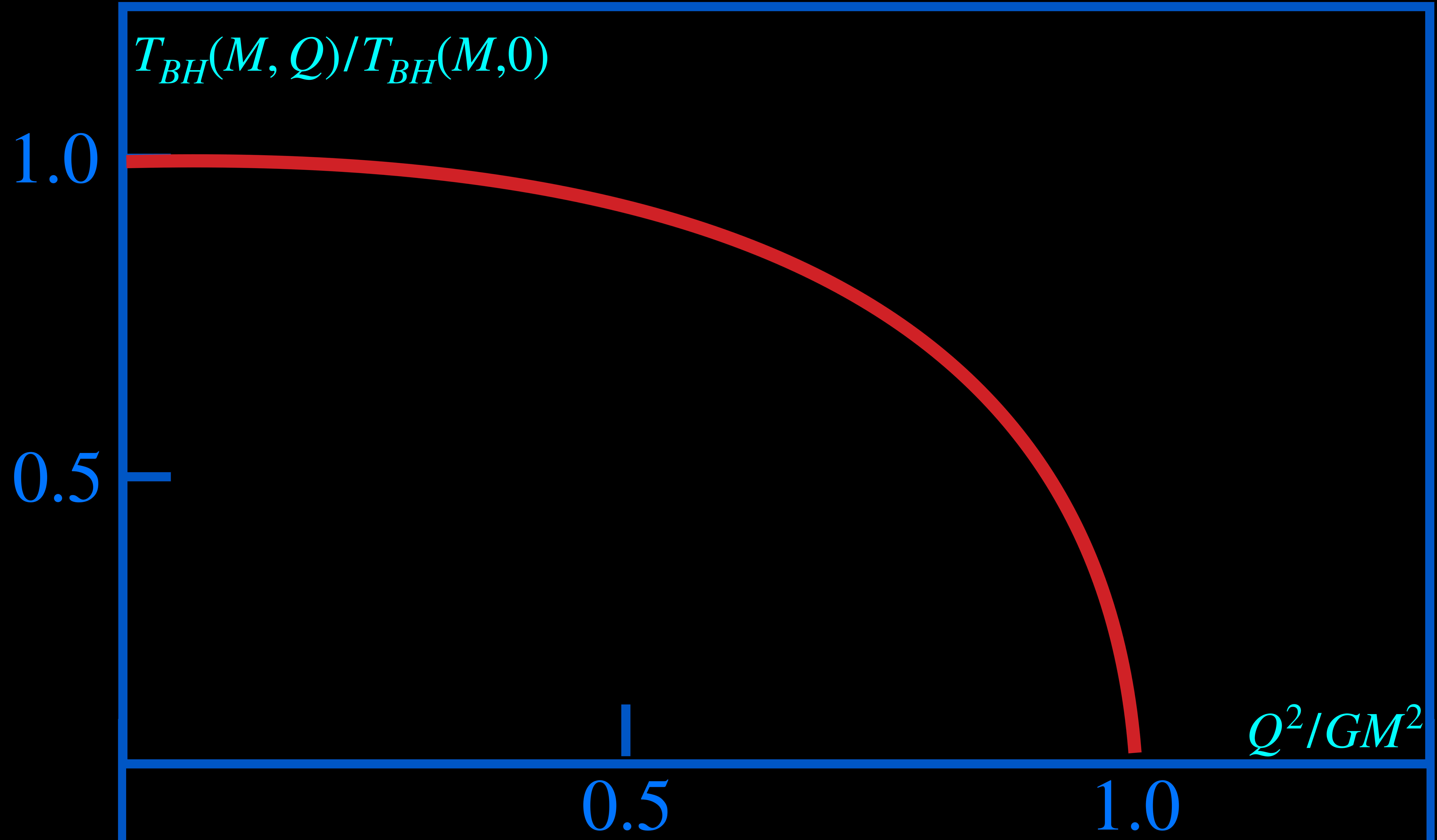
$$T_{BH}(M, Q) = T_{BH}(M, 0)\frac{4\sqrt{1 - Q^2/GM^2}}{(1 + \sqrt{1 - Q^2/GM^2})^2}$$

where M is the mass and Q , the charge.

- For $Q = 0$, it is seen to reduce to the temperature of the Schwarzschild black hole, while for $Q^2 = GM^2$ (*Extremal Reissner-Nordström black hole*) the temperature vanishes.

- The charge dependence on the Hawking temperature results in a *phase diagram* in T and $Q2$ which is similar to that of the conjectured QCD phase diagram.

Temperature of the Hawking radiation from Unruh formulation



Radiation temperature for a charged black hole

Is there a relation between critical behaviour and the existence of an event horizon?

We will not discuss it in this talk though!

Schwinger mechanism of pair production from the Unruh formulation

- In a strong electric field E, the physical vacuum becomes unstable against pair production [3].

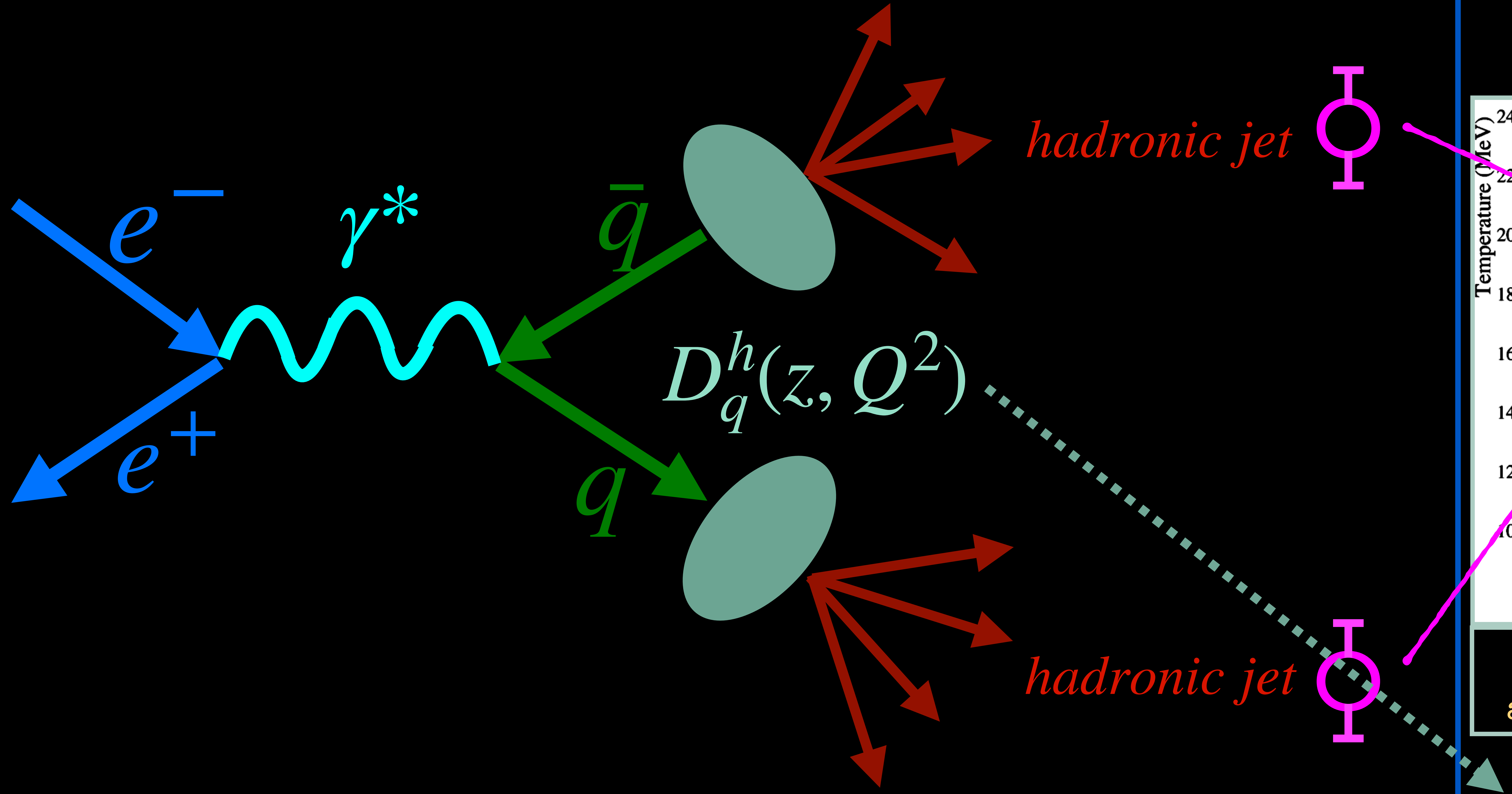
- When the local energy density becomes larger than the mass of an electron-positron pair, the field energy brings an e^-e^+ pair on-shell from the the vacuum. The probability for this process is given by $P(m, E) \sim exp(\pi m^2/eE)$ where e is the charge of the electron.

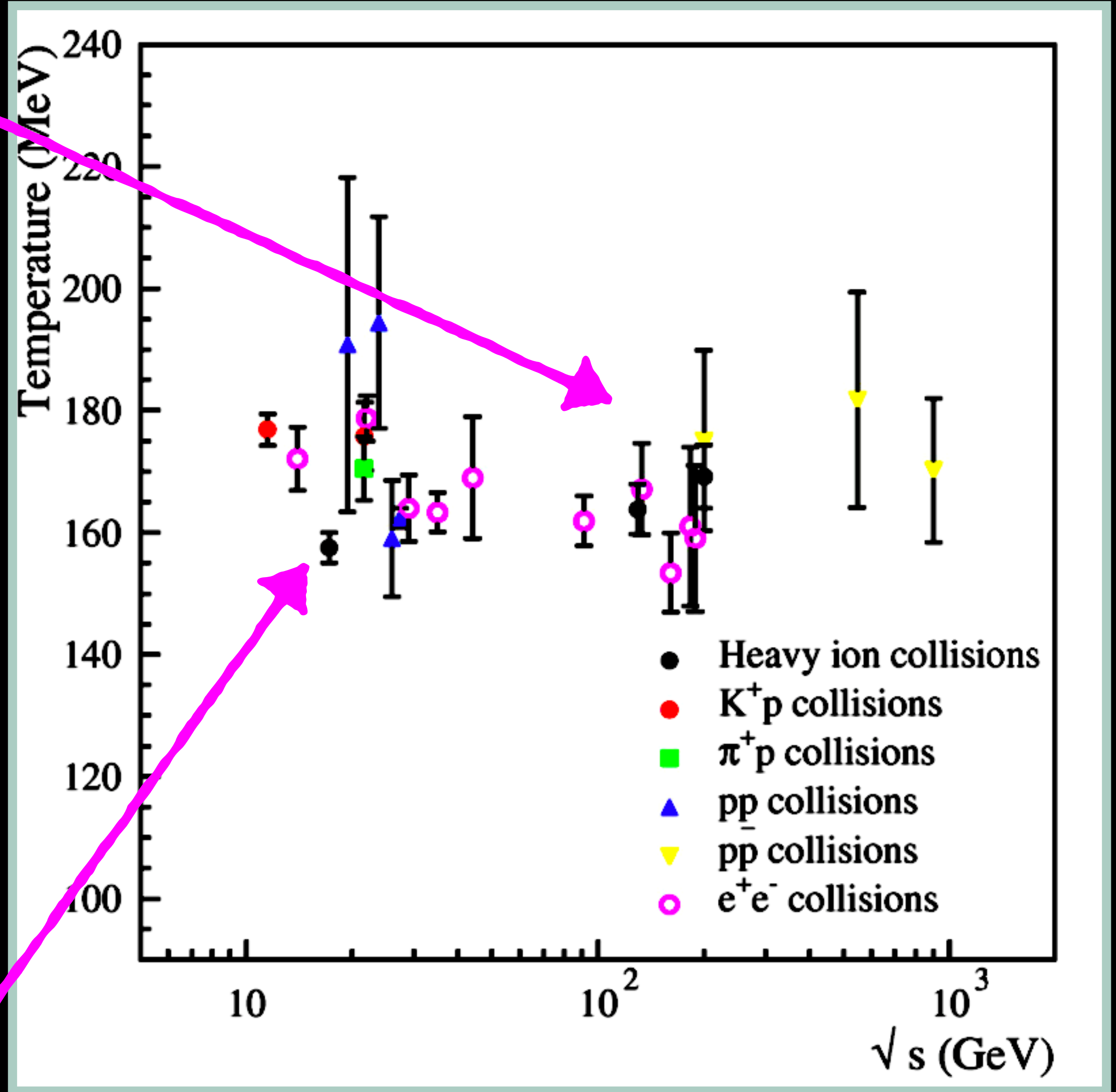
- With the equation of motion $F = eE = (m/2)a$ where $m/2$ is the reduced mass of an electron in the pair, we obtain the Unruh temperature as: $T_U = \frac{a}{2\pi} = \frac{eE}{\pi m}$ which with $P(m, E) \sim exp(\pi m^2/T_U)$ gives the Schwinger form. [Schwinger: 3] [Connections: 4-8]

An event horizon does not allow information transfer across it. It can only be passed by quantum tunnelling, leading to the thermal radiation on the other side.

Let's now move to a QCD system.

Pair production and string breaking in two-jet e^+e^- annihilation





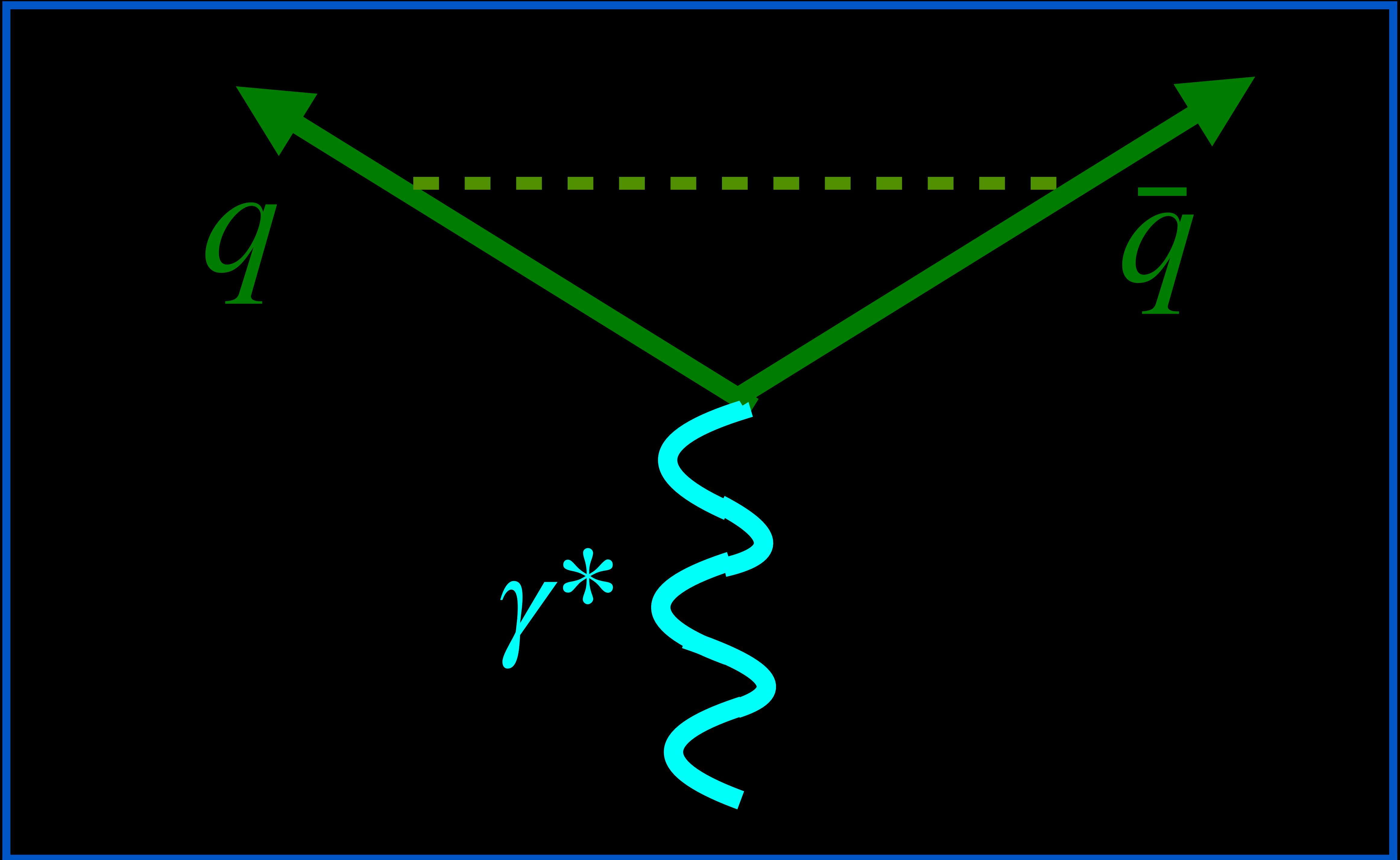
Reminder: T from thermal fit

arXiv:0907.1031v1 [nucl-th]

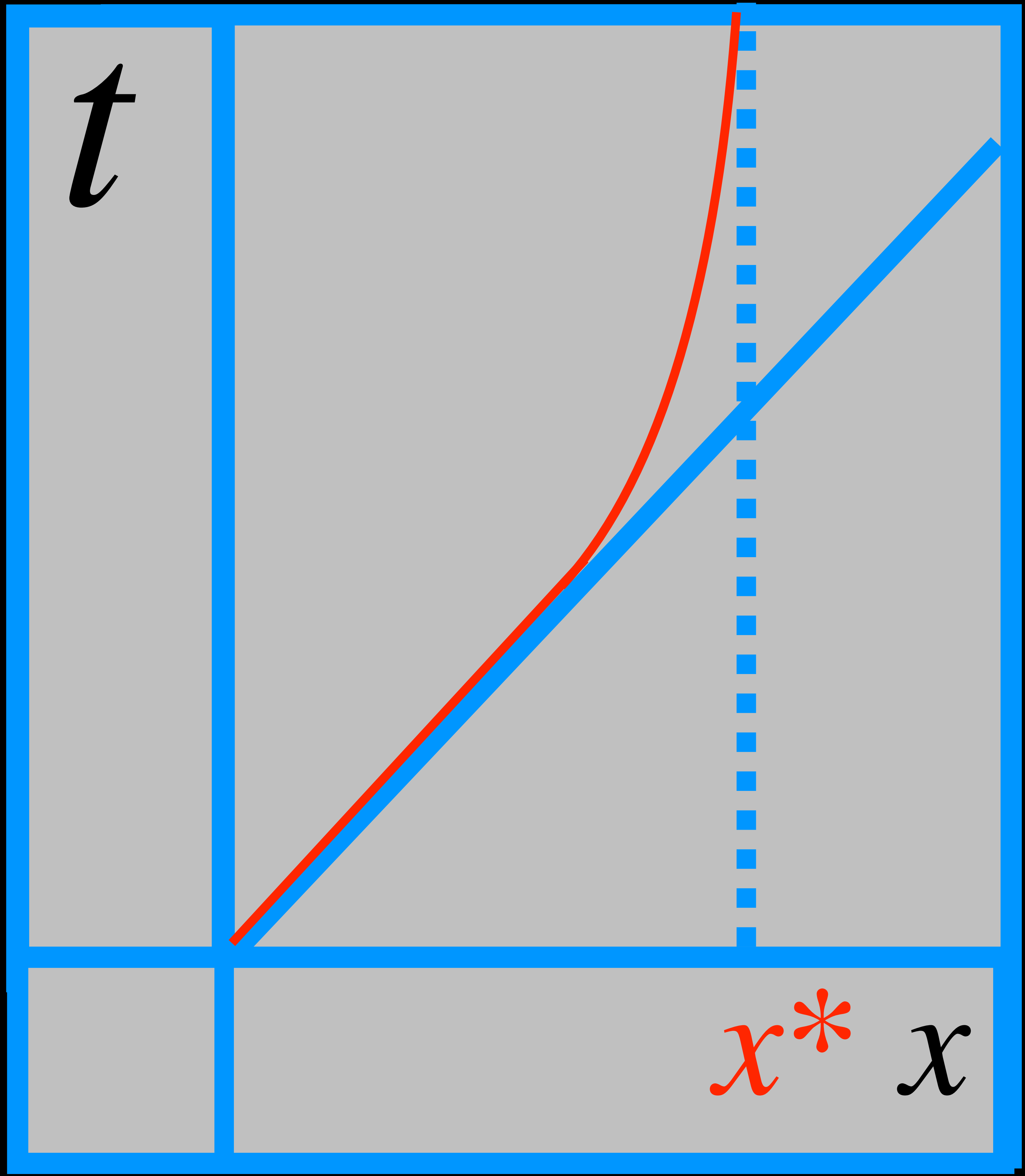
Lowest Order diagram: $e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q} \rightarrow hadrons\ @\sqrt{s}$

We will hopefully discuss about it in the last(jet) talk

Hadron production in e^+e^- annihilation: Classical event horizon



Quark pair production in e^+e^- annihilation



- The $q\bar{q}$ remains subjected to a binding force which increase with separation.
- We consider the binding force as a classical string with a string tension σ.
- It provides a constant confining force resulting in the hyperbolic motion[16].

Hadron production in e^+e^- annihilation: Classical event horizon

- At $t = 0$ the quark pairs separate with velocity $v_0 = p/p_0$ where p is the momentum, $p_0 = \sqrt{p^2 + m^2} \sim \sqrt{s}/2$ (energy of the primary q in c.m.s) and m the effective quark mass.
- The string potential $V = x\sigma$ where x is the $q\bar{q}$ separation distance. The classical event horizon can be defined as the value *of* x for which the initial kinetic energy becomes equal to the potential energy:

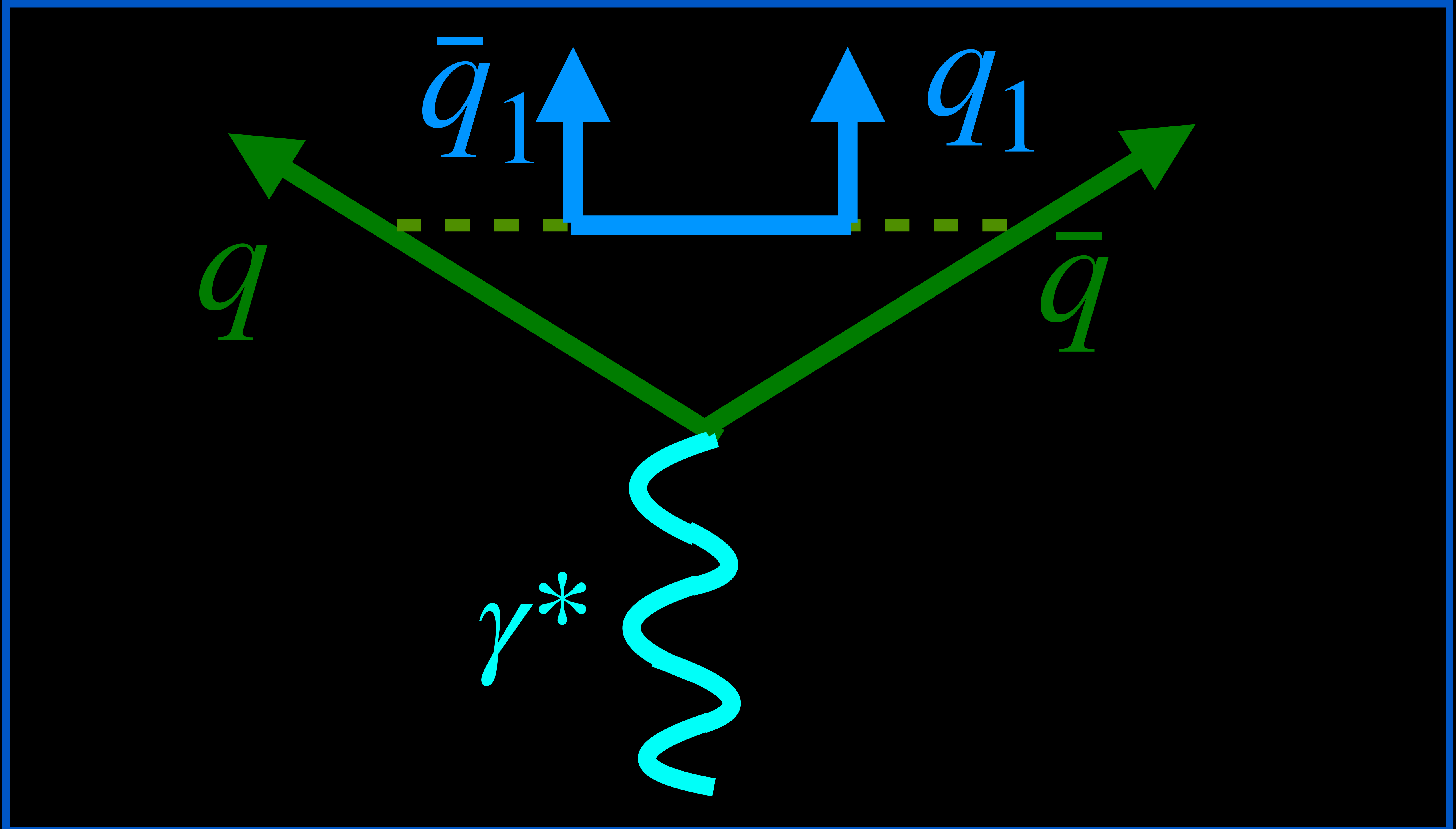
$$\frac{m}{\sqrt{1 - v_0^2}} = x^*\sigma \rightarrow x^* = \frac{p_0 - m}{\sigma} \sim \frac{\sqrt{s}}{2m\sigma}$$

- At this point, the $q\bar{q}$ separation to an arbitrary far range becomes feasible provided that the initial energy was high enough.

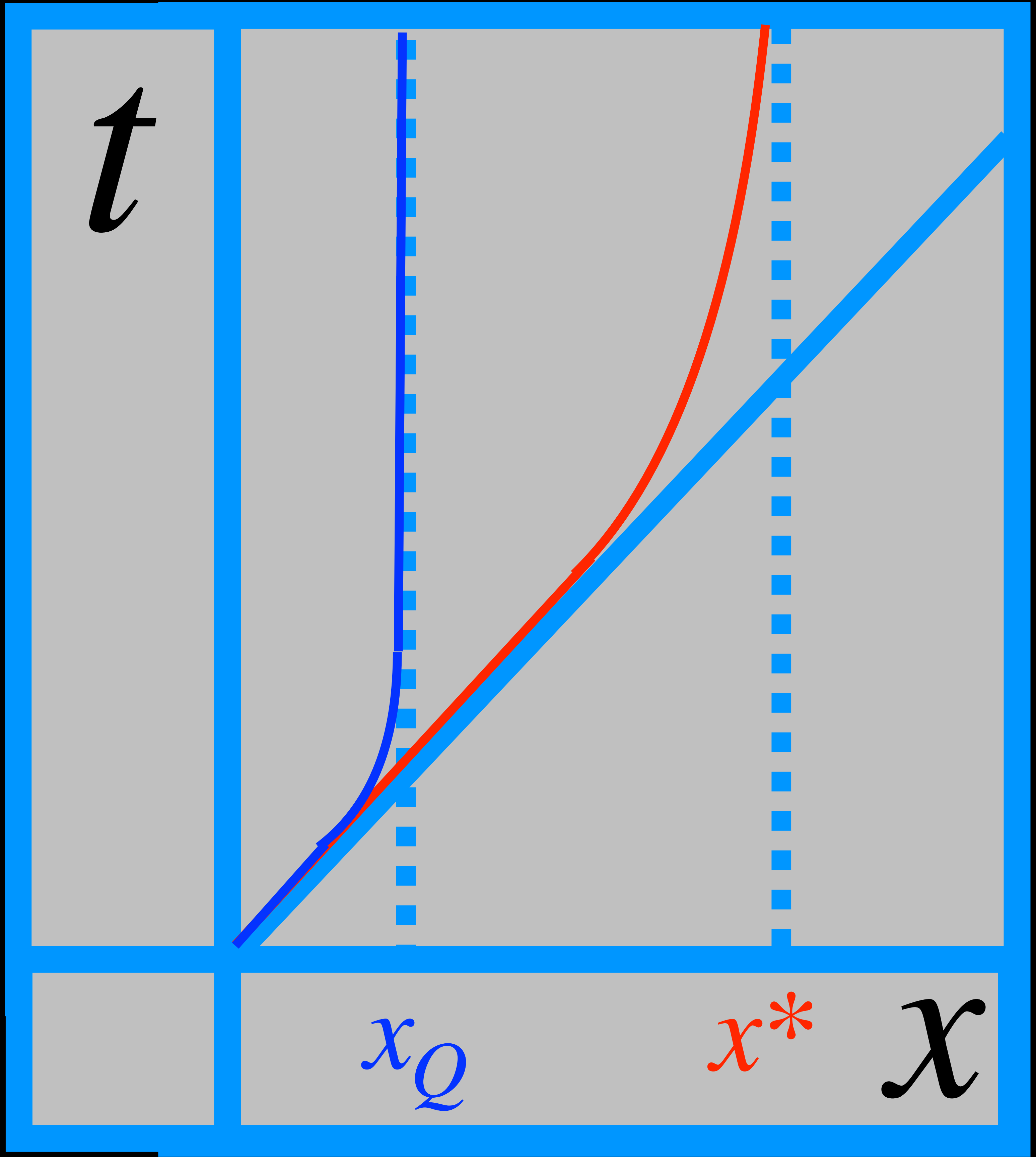
This treatment clearly violates the QCD colour confinement!.

Why? → ***$q\bar{q}$* is not classical:** The background medium of the $q\bar{q}$ contains virtual $q\bar{q}$ pairs. It is not possible to increase the potential energy of a given $q\bar{q}$ state beyond the threshold value necessary to bring such a virtual pair on-shell.

Hadron production in e^+e^- annihilation: Quantum event horizon



Secondary quark production in e^+e^- annihilation

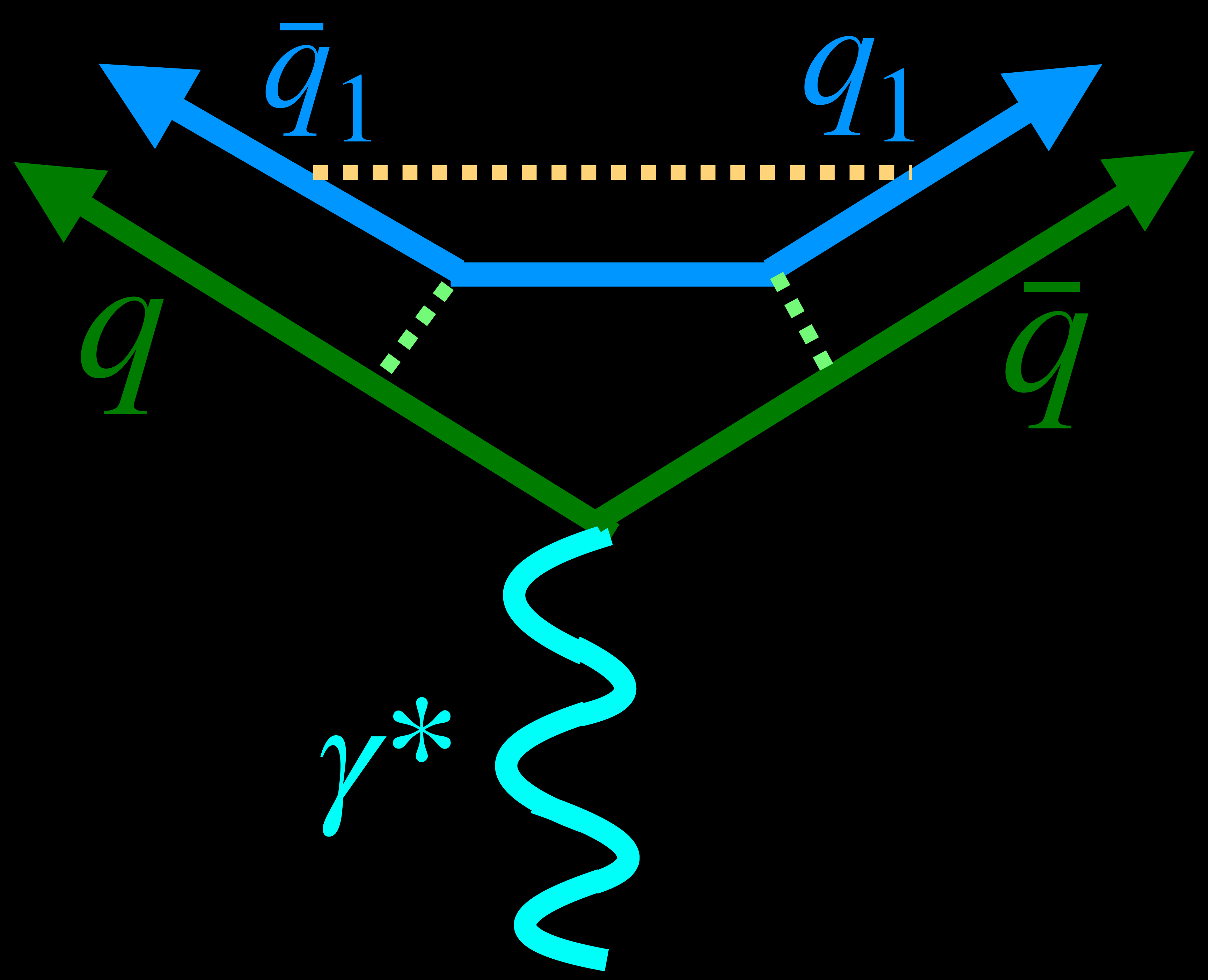


- When string tension $\sigma \geq 2m$, it becomes energetically favourable to produce a further $q\bar{q}$ pair and start two new string configuration than continue stretching the primary string.
- The resulting quantum event horizon at $x_Q \sim 2m$ reaches ahead of the classical event horizon.
- **Allowed separation distance for the $q\bar{q}$ pair, *the colour confinement radius*, $r_q = x^*/2 \sim m/\sigma$ is independent on the initial energy of the primary quarks.**

Hadron production in e^+e^- annihilation: Hadron cascade mechanism

- Initially we have $[q\bar{q}]$ pair which is separating (*Square bracket is for colour neutrality*). When $\sigma \geq 2m$ a further colour-neutral pair $[q[\bar{q}_1 q_1]\bar{q}]$ excited from the vacuum by two-gluon exchange [12,13].
- The $\bar{q}_1$ screens the primary q from its original partner $\bar{q}$. Similarly q_1 screens primary antiquark from its original partner q.

- The $\bar{q}_1 q_1$ is at rest in the c.m.s. But each of its constituents has a transverse momentum k_T
- k_T *is* determined by the transverse dimension r_T of the *flux tube* resulting from the connecting string through the uncertainty relation.
- k_T has to be considered in the effective quark mass calculation to estimate the $q\bar{q}$ separation distance at the point of pair production.



Hadron production in e^+e^- annihilation: Hadron cascade mechanism

- The thickness of the flux tube connecting the $q\bar{q}$ pair is in string theory given by

$$r_T^2 = \frac{2}{\pi\sigma}\frac{1}{2k+1}$$

k is the string length in units of an intrinsic vibration measure. [14]

- For the strings of 1-2 fm range, SU(2) LGT predicts that the the first string excitation dominates [15]. Hence we can write $r_T \sim \sqrt{\frac{2}{\pi\sigma}}$

- The uncertainty relation would then give: $k_T \sim \sqrt{\frac{\pi\sigma}{2}}$.

- The pair production separation distance for the quantum horizon then becomes:

$$\sigma x_q = 2\sqrt{x^2 + k_T^2} \rightarrow x_q \sim \frac{2}{\sigma}\sqrt{x^2 + \pi\sigma/2} \sim \sqrt{2\pi/\sigma} \approx 1\text{fm with } \sigma = 0.2GeV^2 \;\&\; m_q^2 << \sigma$$

Hadron production in e^+e^- annihilation: Hadron cascade mechanism

- **To form two eventual hadrons $q\bar{q}_1$ and $\bar{q}q_1$:** The force between q and $\bar{q}_1$ would have to accelerate $\bar{q}_1$ from rest to about half of the momentum of q. We thus have a constantly accelerating $\bar{q}_1$ and a constantly decelerating q *(Similar is the case with the $\bar{q}q_1$ pair).*

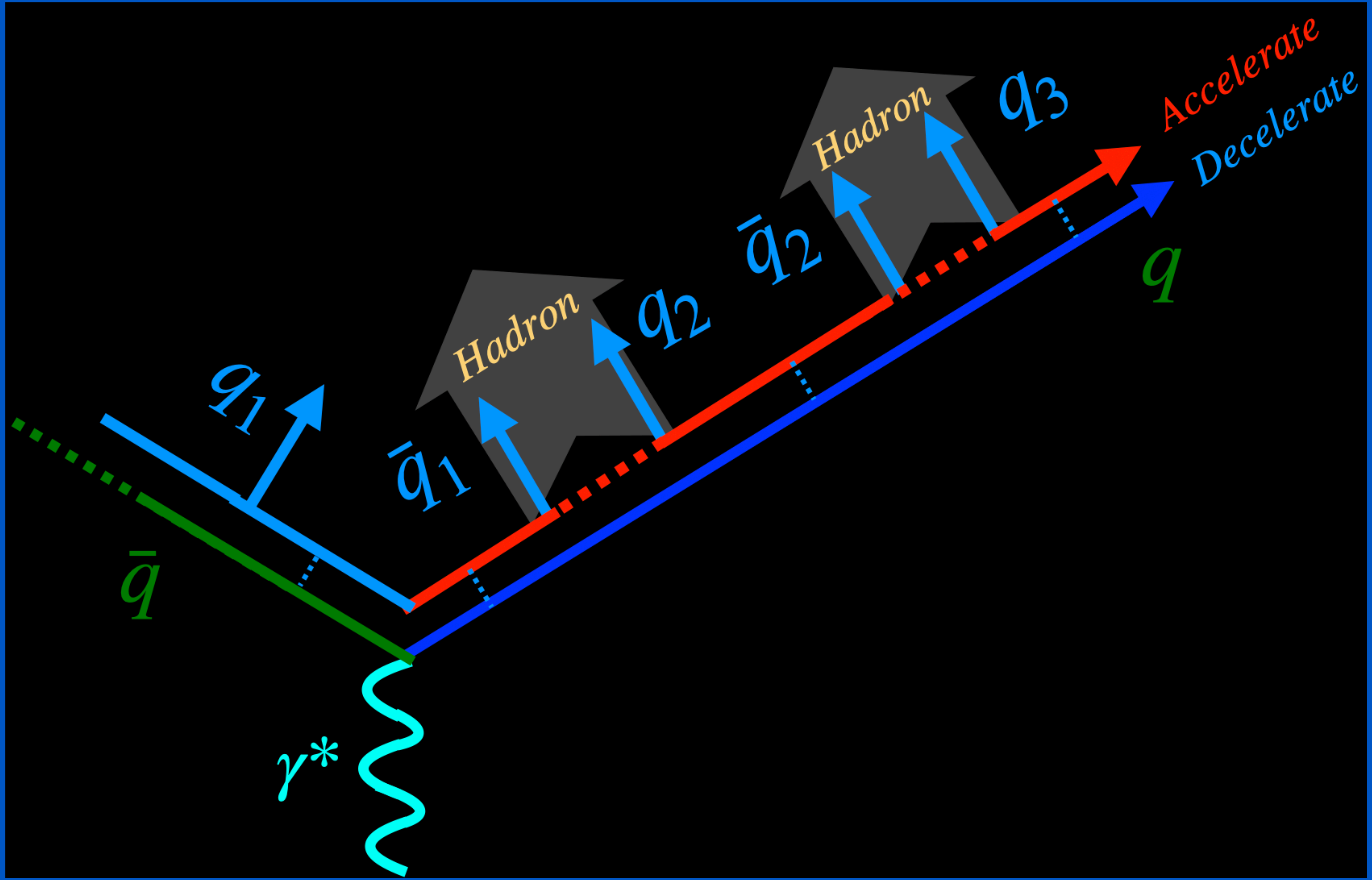
- **To separate $q\bar{q}_1$ and $\bar{q}q_1$:** The string potential corresponding to the colour confinement of the newly formed $q_1\bar{q}_1$ pair has to be overcome while the the primary string remains unbroken.

- **To break the binding of $q_1\bar{q}_1$:** q_1 has to tunnel through the barrier of the confining potential provided by $\bar{q}_1$ (*and vice versa*). The longitudinal force of the q on the $\bar{q}_1$, and of the $\bar{q}$ on the q_1 *will* results in a longitudinal acceleration and ordering of q_1 and $\bar{q}_1$.

- **When $\sigma x(q_1\bar{q}_1) = 2\sqrt{m_q^2 + k_T^2}$: The $\bar{q}_1$ reaches its $q_1\bar{q}_1$ horizon, the new string $\{q_1\bar{q}_1\}$ has the energy needed to produce a further new pair $q_2\bar{q}_2$. The $\bar{q}_2$ screens primary q from q_1 and forms a new string $\{\bar{q}_1q_2\}$.**

Hadron production in e^+e^- annihilation: Hadron cascade mechanism

- The original string is the broken and the remaining pair $\bar{q}_1 q_2$ forms a colour neutral bound state which is emitted as Unruh radiation in the form of a hadron.
- The relative weights of the different possible states is governed by the corresponding T_U



Schematics of the string breaking and hadron cascade mechanism

Hadron production in e^+e^- annihilation: Hadron cascade mechanism

STEP-1: The colour field created by the separating q & $\bar{q}$ produces a further pair $q_1\bar{q}_1$ and then provides an acceleration of the q_1, increasing its longitudinal momentum.

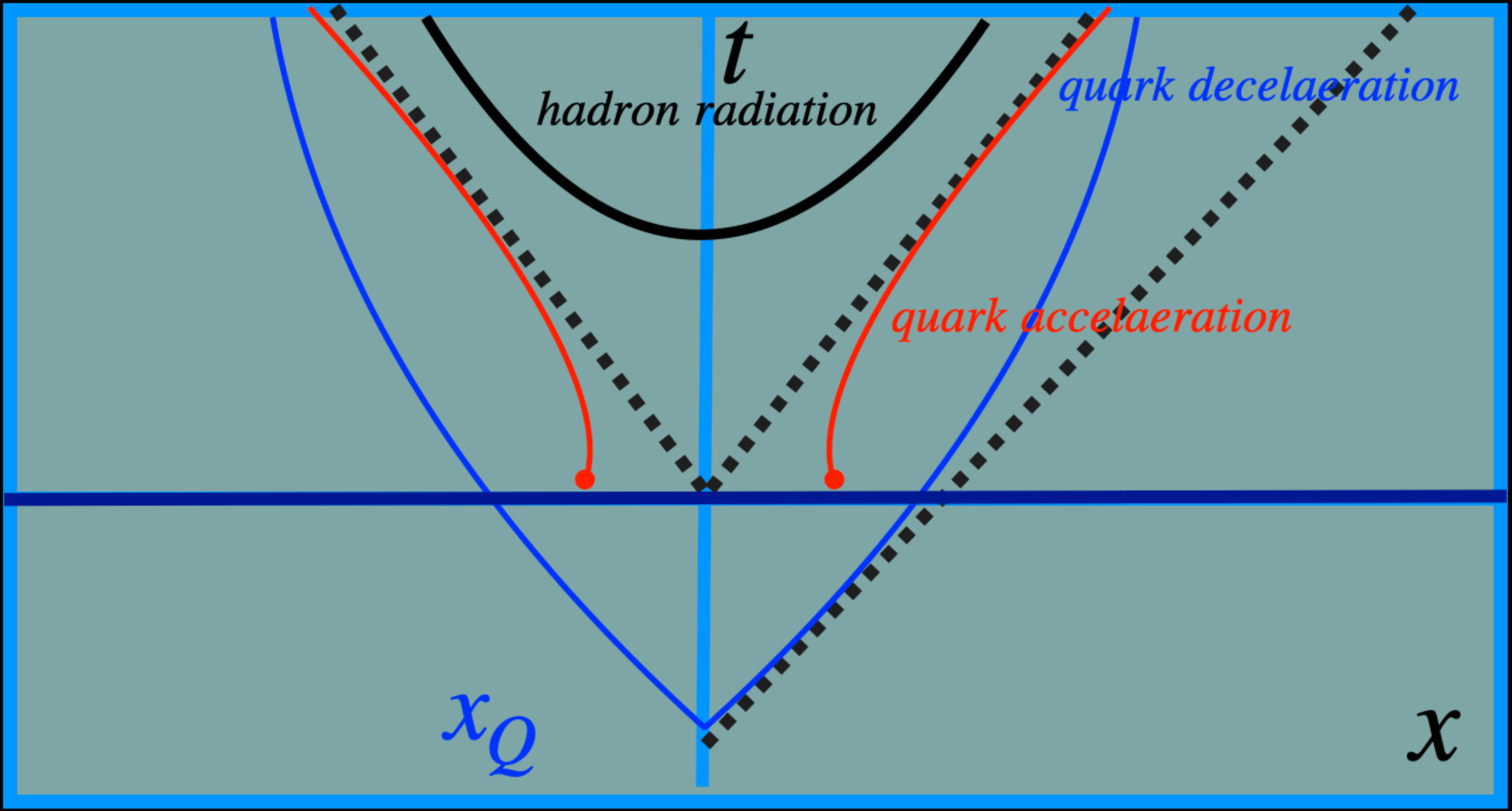
STEP-2: When it reaches the $q_1\bar{q}_1$ confinement horizon, another pair $q_2\bar{q}_2$ is excited. The state $\bar{q}_1 q_2$ is emitted as a hadron while the $\bar{q}_2$ together with the primary q forms a new flux tube.

STEP-3: On a step by step basis, the cascading pattern increases the longitudinal momentum of the accompanying $\bar{q}_i$ as well as that of the emitted hadron.

STEP-4: Together with the energy of the produced pairs, it causes a corresponding deceleration of the primary quarks q and $\bar{q}$ so as to maintain overall energy conservation.

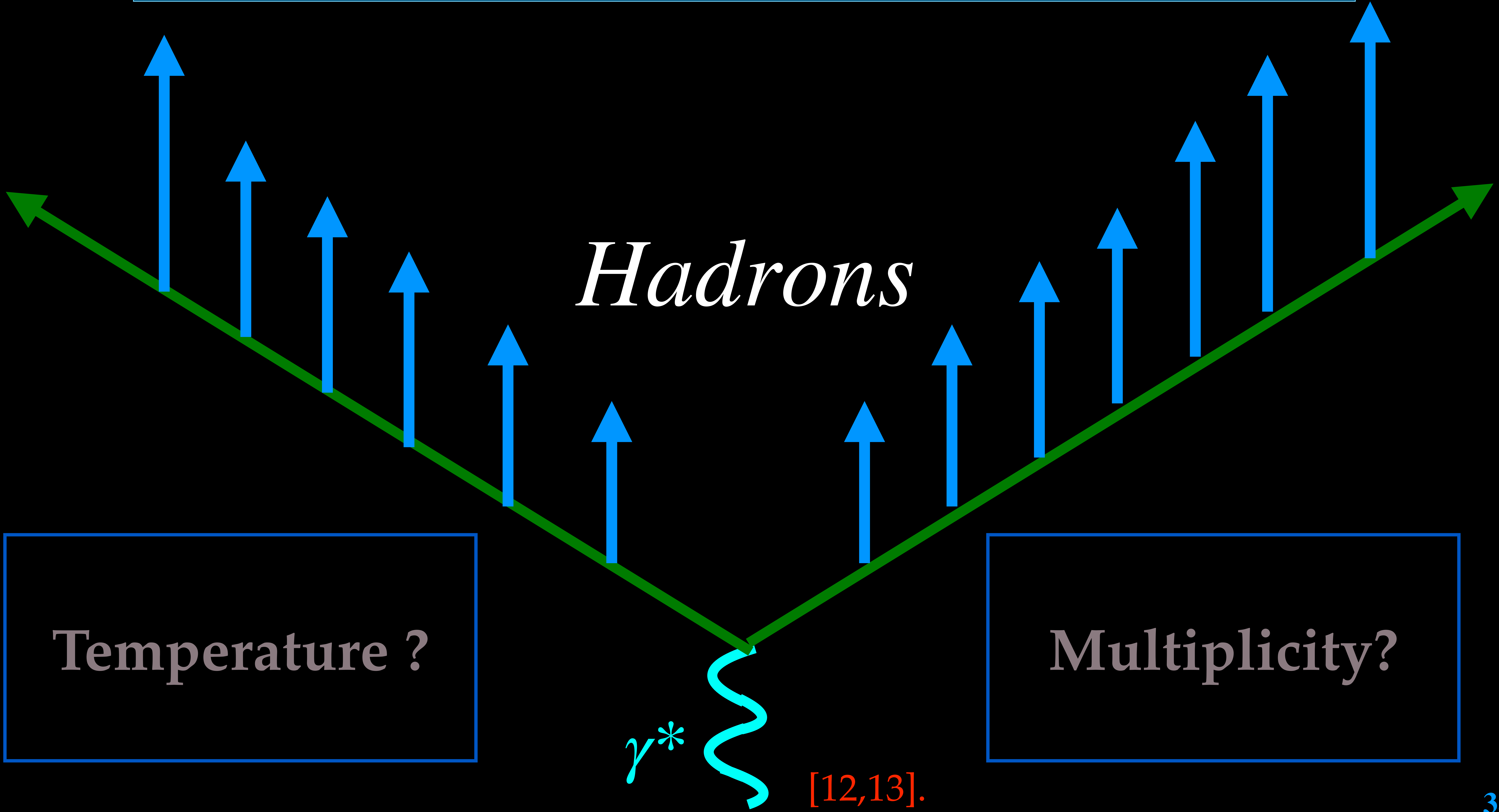
STEP-5: The energy loss and deceleration of q together with the acceleration of the accompanying $\bar{q}_i$ from the successive pairs, brings q & $\bar{q}_i$ closer in momentum (initial separation ~ $\sqrt{s}/2$) until they finally are combined into a hadron to end the cascade.

Hadron production in e^+e^- annihilation: Hadron cascade mechanism



The world line given by the acceleration $\bar{q}_i \to \bar{q}_{i+1}$ *or* $q_i \to q_{i+1}$ and that of the formation threshold of $[\bar{q}_i q_{i+1}]$ and its antiparticle [11].

Hadron production in e^+e^- annihilation: Hadron cascade mechanism



Temperature ?

Multiplicity?

[12,13].

Temperature of the hadronic Unruh radiation

- The the produced antiquark $\bar{q}_1$ is accelerated by the primary quark q because of the string tension. Similarly the $\bar{q}_2$ and so on along the cascade.
- The anti quark acceleration (*as well as the quark acceleration along the primary $\bar{q}$ direction*) becomes:

$$a_q = \frac{\sigma}{\sqrt{m_q^2 + k_T^2}} = \frac{\sigma}{w_q}$$

- The string breaks for x_q: The uncertainty relation $k_q \sim 1/x_q$ gives $w_q = \sqrt{m_q^2 + [\sigma^2/4m_q^2 + 2\pi\sigma]}$
- The resulting Unruh temperature for a negligible bare quark mass is: $T_U = \frac{\sigma}{2\pi} w_q \sim \sqrt{\frac{\sigma}{2\pi}}$
- For the canonical string tension range $\sigma = 0.16 - 0.20\ GeV^2$, we get $T_U = 160 - 180$ MeV.

This is a parameter-free prediction of the temperature governing hadron production e^+e^-annihilation which agrees well with the lattice statistical QCD evaluation.

The dependence of Unruh temperature on the quark masses

- **For strange quarks ($m_s = 100$ MeV) quark mass dependence on T_U is not negligible:** The Unruh radiation of a meson containing one strange (s) and one non-strange (q) quark is determined by the average acceleration:

$$a_q = \frac{w_q a_q + w_s a_s}{w_q + w_s} = \frac{\sigma}{w_q + w_s}$$

- **The T_U for the strange meson is given by** $T_U(qs) = \dfrac{\sigma}{\pi(w_q + w_s)}$; $T_U(ss) = \dfrac{\sigma}{2\pi w_s}$

  For $\sigma \sim 0.2GeV^2$ & $m_s = 0.1GeV$: $T_U(qq) = 178MeV$; $T_U(qs) = 167MeV$; $T_U(qs) = 157MeV$

- **Strangeness suppression is natural:** The relative abundance of a given species is determined by its hadronisation $N_{qq} \sim exp(-m(qq)/T_{qq})$. The decrease of the temperature for mesons containing s- quarks corresponds to an effective suppression of such states[19].

Leading the logic to the baryons would lead to five different Unruh temperatures, dependent on σ & m_s whose values are known → **Effectively making T_U a parameter free entity.**

Multiplicity of the hadronic Unruh radiation

- **Multiplicity $\nu(s)$ is the number of emitted hadrons.** The classical string length, in the absence of quantum pair formation, is given by the classical turning point x^*.
- **The thickness of a flux tube** of such an *overstretched* string is given by

$$R_T^2 = \frac{2}{\pi\sigma}\sum_{k=0}^{K}\frac{1}{2k+1} \sim \frac{2}{\pi\sigma}\ln 2K \sim \frac{2}{\pi\sigma}\ln\sqrt{s}$$ where K is the is the string length [14,17].

This relation understood as a consequence of parton random walk or Gribov diffusion which responsible for diffraction cone shrinkage in high–energy hadron scattering.

- **Coming to the quantum picture :** Pair production causes the string to break whenever it is stretched to the length x_Q at a thickness r_T. **The multiplicity is then given by the ratio of the classical to quantum transverse flux tube areas:** $\nu(s) \sim \frac{R_T^2}{r_T^2} \sim \ln\sqrt{s}$

$\nu(s)$ is found to grow logarithmically with $\sqrt{s}$ as is observed experimentally.

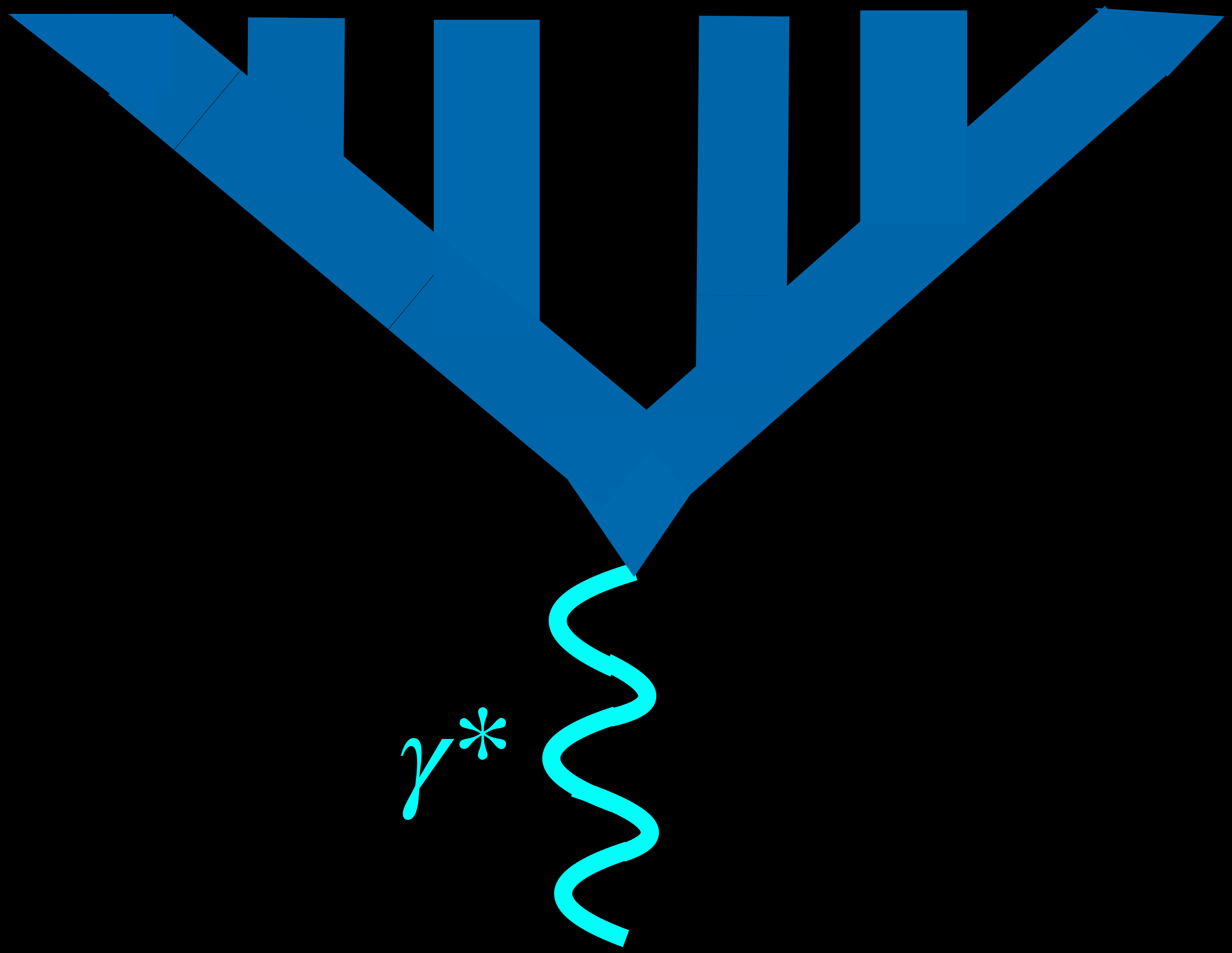
Partonic evolution and saturation effects in the Unruh approach

- **Parton evolution is neglected:** The parton evolution can cause the emitted radiation to start another cascade of the same type. Such evolution effects result eventually in a stronger increase of the multiplicity.

- **Hard processes:** The Unruh hadronisation mechanism does not affect the formation of hard processes at early times which are responsible for an additional growth of the measured multiplicity.

- **Parton saturation is neglected:** At sufficiently high energy, stronger colour fields can lead to **gluon saturation** and thus to a **higher temperature** determined by the saturation momentum. The resulting system then first expands and subsequently hadronises at the universal temperature determined by the string tension[7,18].

From e^+e^- annihilation to Hadron-Hadron and Nucleus-Nucleus collisions



The virtual photon γ^* produces a confined coloured $q\bar{q}$ pair as a colourless or white hole. For a hadron hadron collisions, two incident colourless/whiteholes fuse to form a new system of the same kind.

e^+e^- annihilation
Whitehole creation

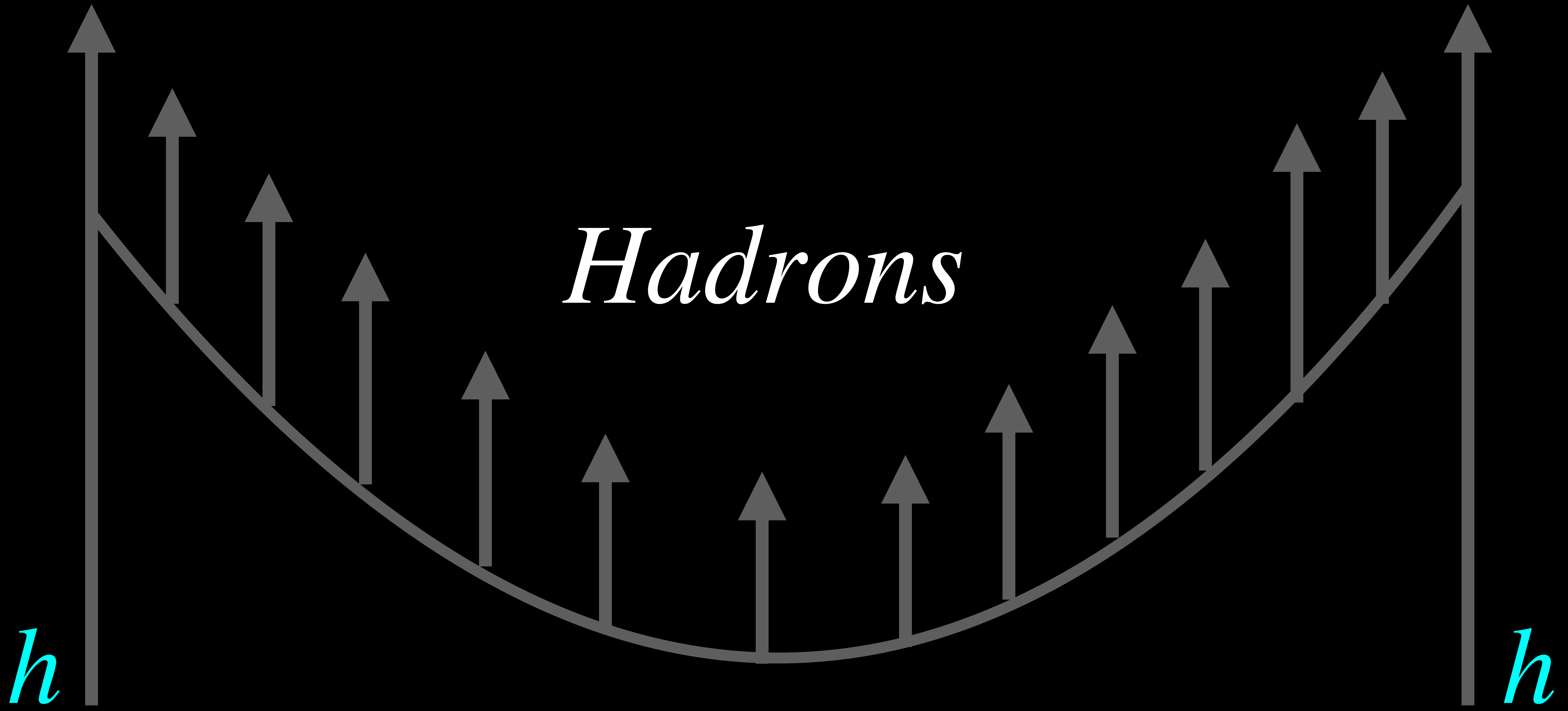
From e^+e^- annihilation to Hadron-Hadron and Nucleus-Nucleus collisions

Hadronic collision: Two incident colourless holes fuse to form a new system of the same kind.

e^+e^- annihilation
Whitehole creation

Hadron-hadron collision
Whitehole fusion

From e^+e^- annihilation to Hadron-Hadron and Nucleus-Nucleus collisions

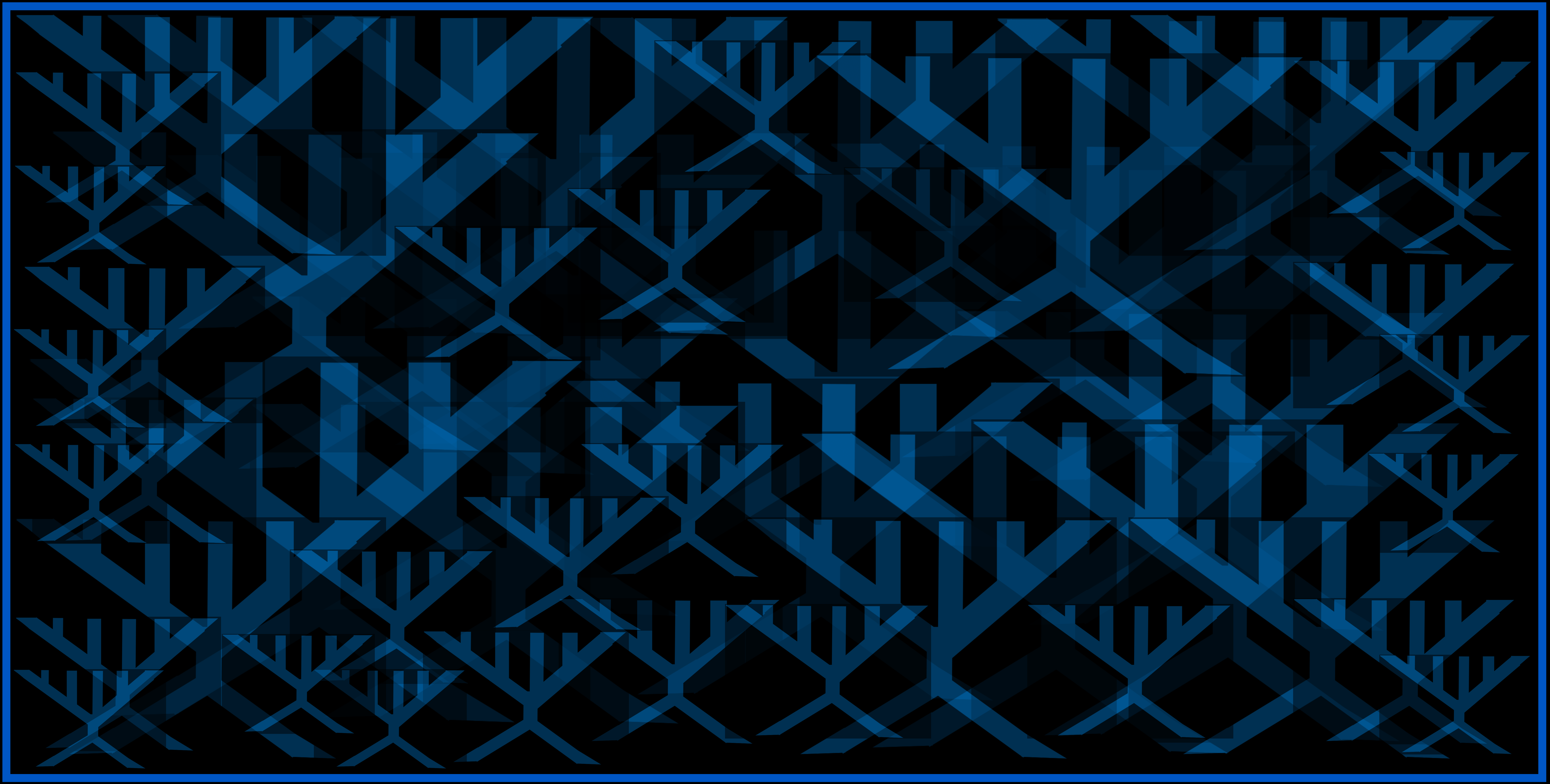


The resulting string or strong colour field produces a sequence of $q\bar{q}$ pairs of increasing c.m.s momentum, leading to the well-known multi-peripheral hadron-production cascade.

The parton evolution and saturation will affect the multiplicity, but not the relative abundance.

From e^+e^- annihilation to Hadron-Hadron and Nucleus-Nucleus collisions

Nuclear collision: A superposition of several tunnelling cascades with possible interference



Stochastic thermalisation in high energy collisions

- Hawking-Unruh radiation provides a stochastic rather than kinetic approach to equilibrium. The barrier to information transfer presented by the event horizon requires that the resulting radiation states excited from the vacuum are distributed according to maximum entropy (See also [20,21] for the old proposals)

The produced state is selected at random from the set of all states corresponding to this temperature. So it is like throwing dice to reach equilibrium

- The ensemble of all produced hadrons then results in the same equilibrium distribution as would be obtained in hadronic matter by kinetic equilibration. The observer cannot tell whether the observed equilibrium was attained by stochastic selection or by kinetic thermalisation.

- **In the case of a heavy-ion collision (with supposedly a QGP formation in it):** The hadronisation occurs when cooling and expansion favours to separate a given quark from any possible antiquark partner by more than the canonical hadronic distance. Through expansion, all the coloured quarks thus are forced to reach their event horizons leading to hadronic Unruh radiation which is thermal[11].

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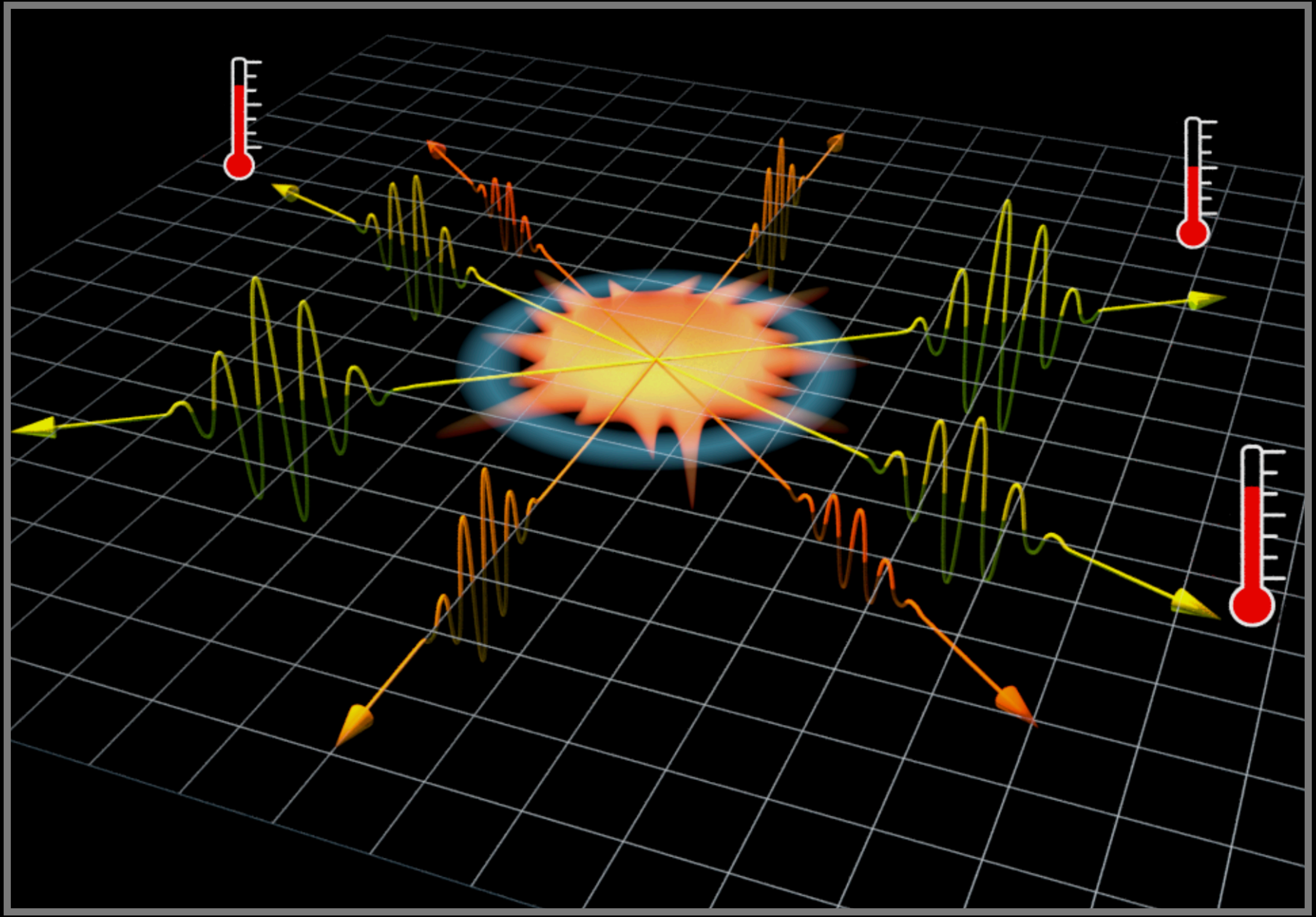

Thanks for your attention!

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