QCD in extreme conditions color glasses and quark condensates

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Aim of the talk: qualitative and semiquantitative description of hadronic matter

In particular we want to clarify

- What we know about the properties of matter at high energy scales
- What are quark and gluon condensates
- What is the **Color Glass Condensate (CGC)**

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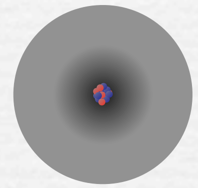
- What is the **Color Glass Condensate (CGC)**

Along the way...
We shall define what are quark and gluon condensates and what are **partons**

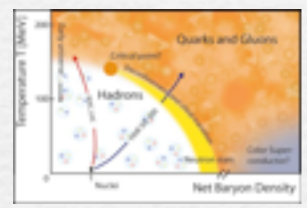
We shall use quantum physics, electrodynamics, special relativity but almost no quantum field theory

Outline

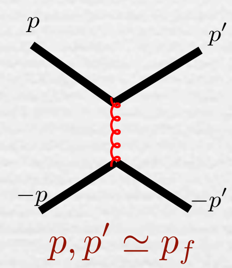
- What is matter made of ?



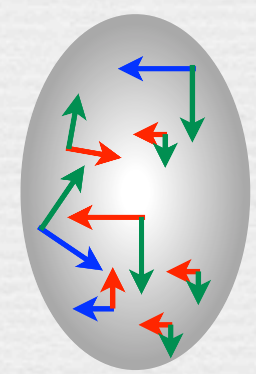
- Phases of matter



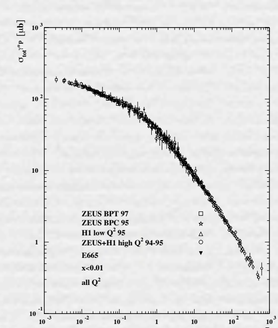
- Condensates



- Saturation and Color Glasses



- Phenomenology



Dare pondus idonea fumo

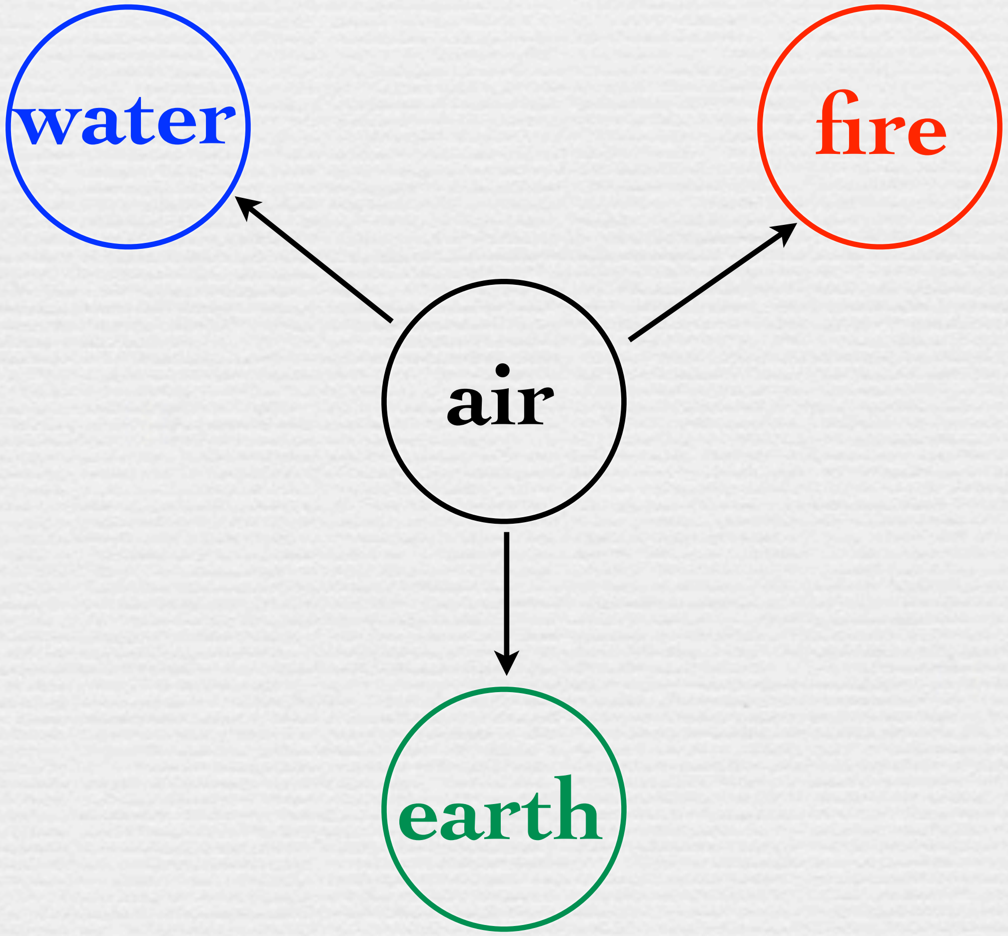
Aulo Persio Flacco, Satira V

What is matter made of ?

Ancient Greek view

Reductionism: complex objects are made by simple objects

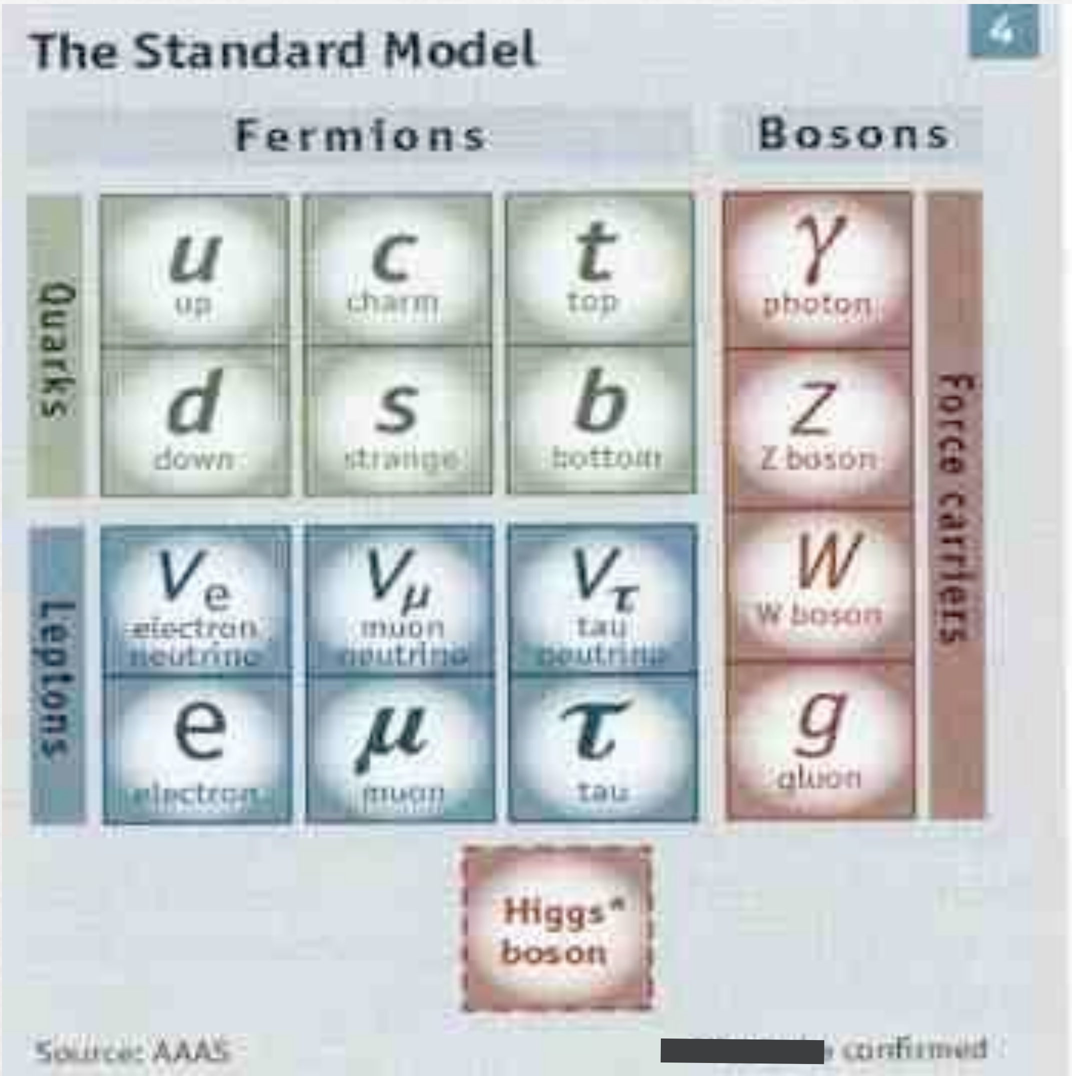
For Anaximenes of Mileto, **air** is the elementary object, the **archè**



water, fire and earth are condensed states of air

Matter is made by water, earth and fire in different states of aggregation

Particle physicist:
Matter is made by **elementary particles in different states of aggregation**



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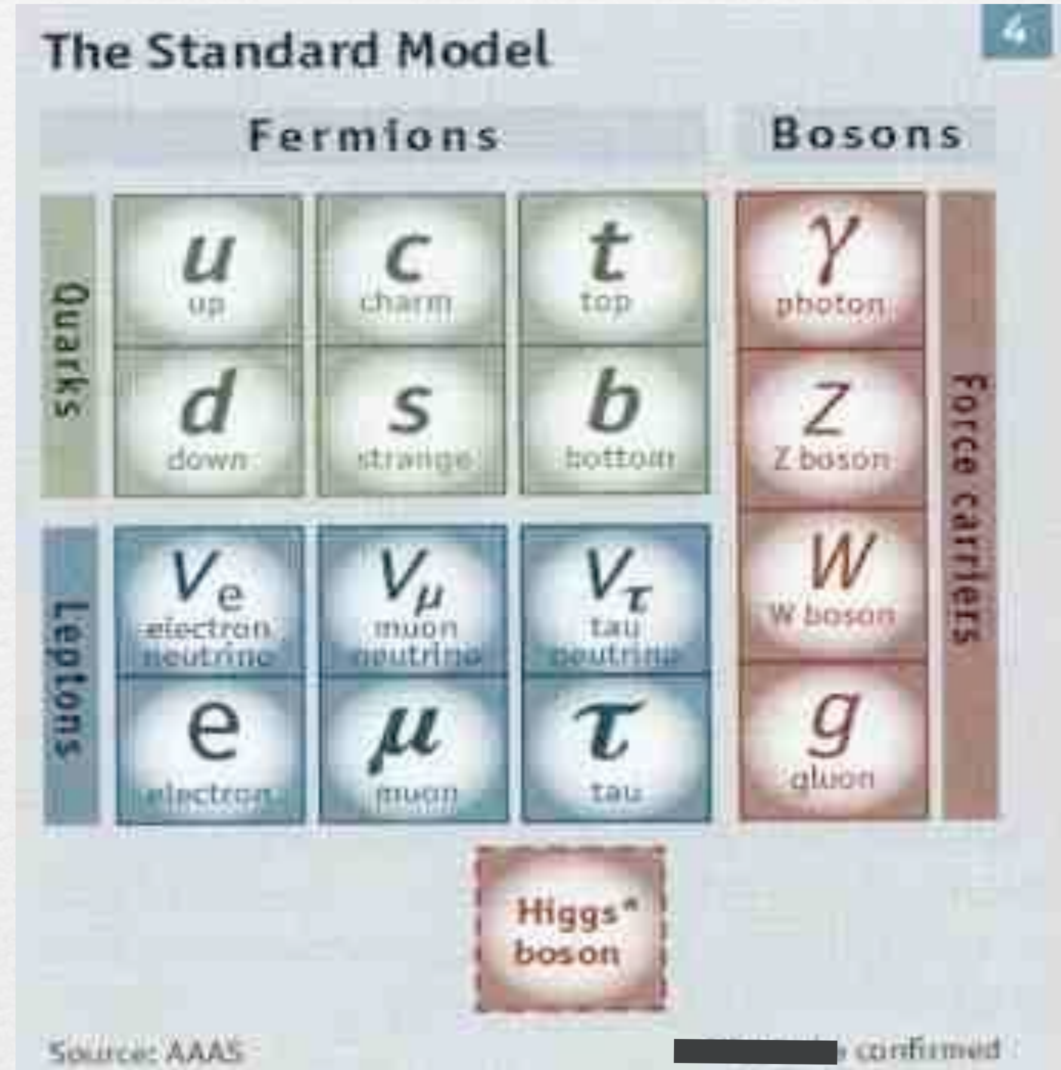


I will try to convince you that **any reductionist approach is inadequate**. Matter description by **effective degrees of freedom and effective couplings**, depending on

the thermodynamic state
the energy of the probe
the kinematic state of the observer

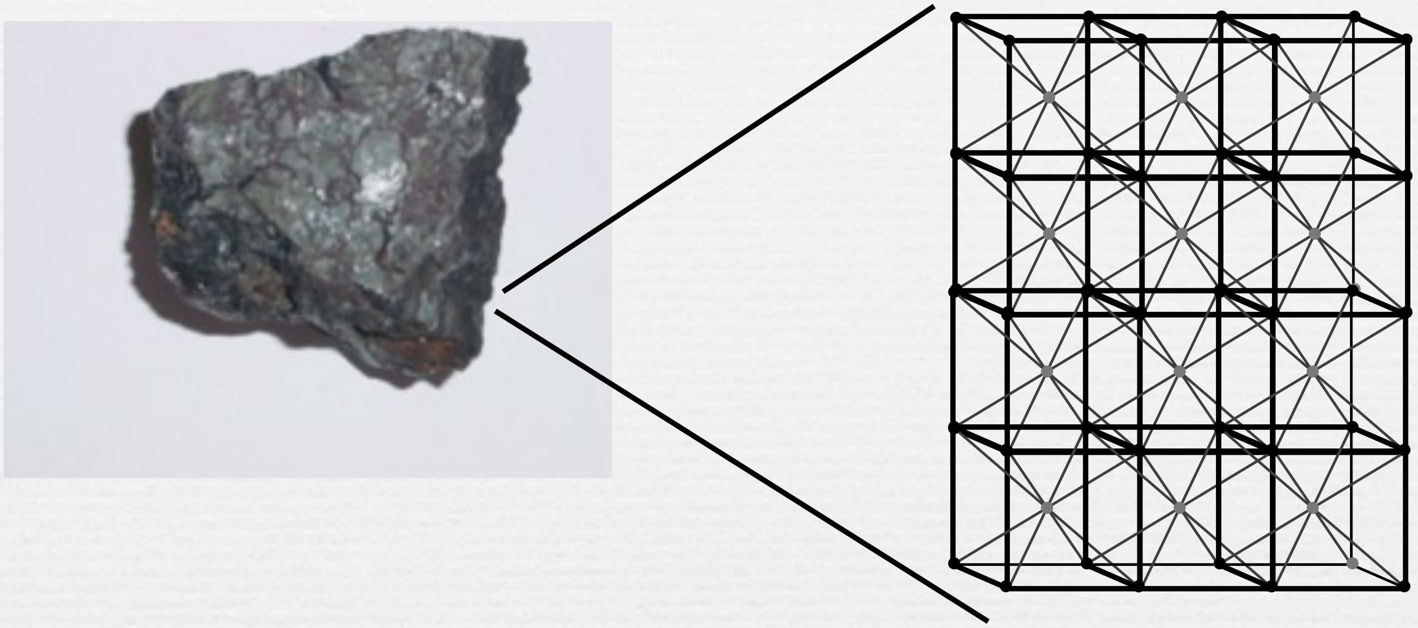
Changing the energy scale

iron

Changing the energy scale

iron

Changing the energy scale



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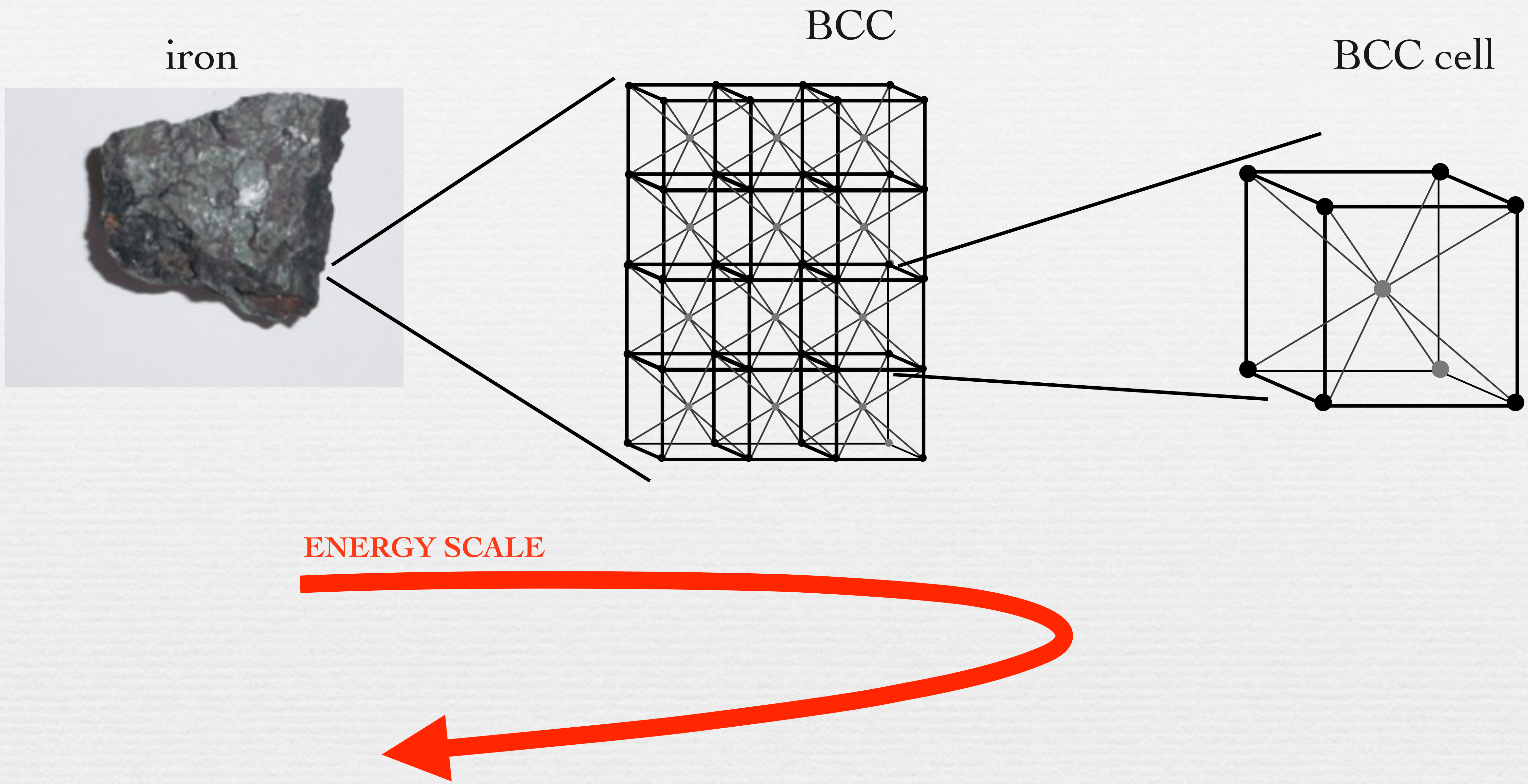

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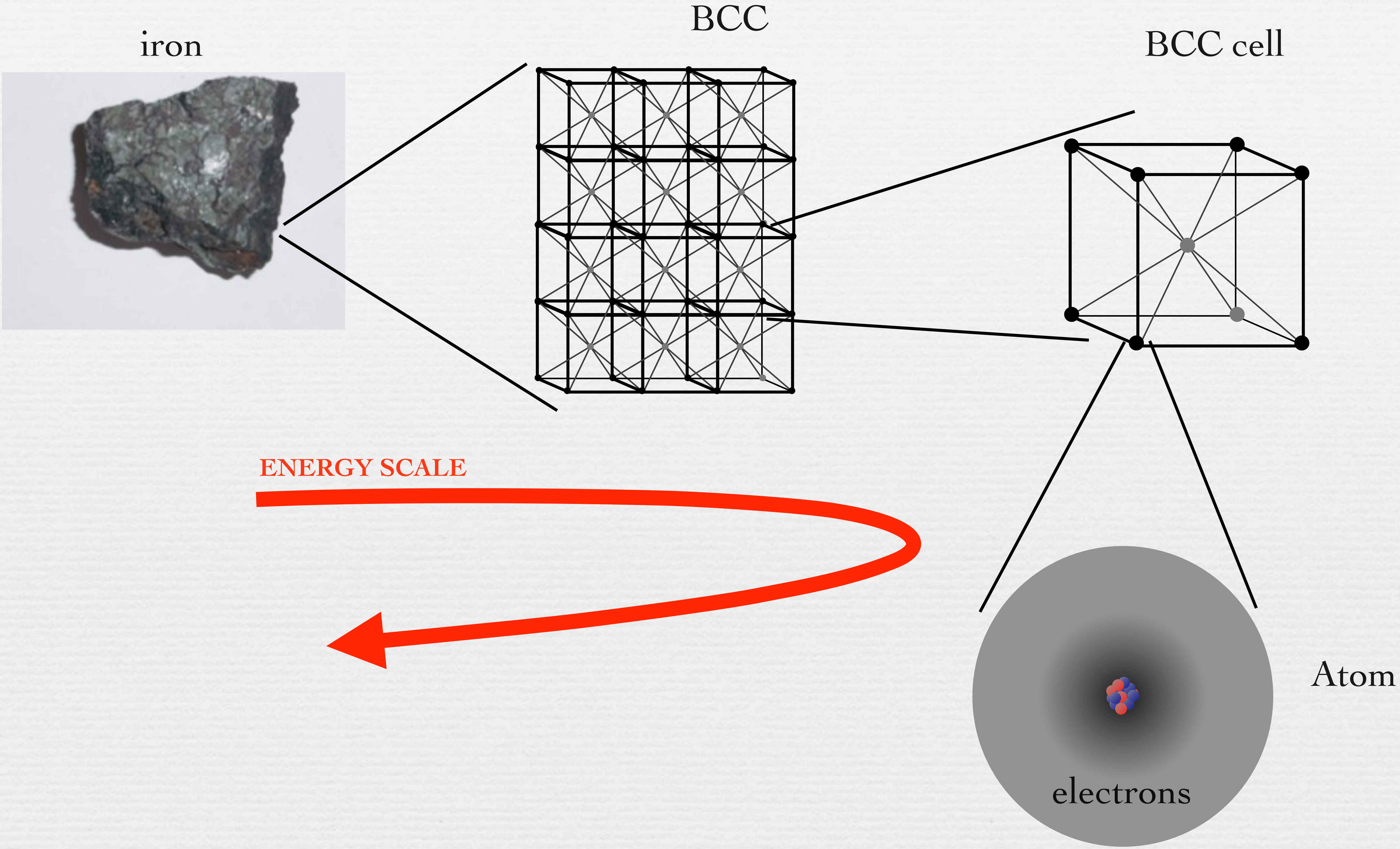

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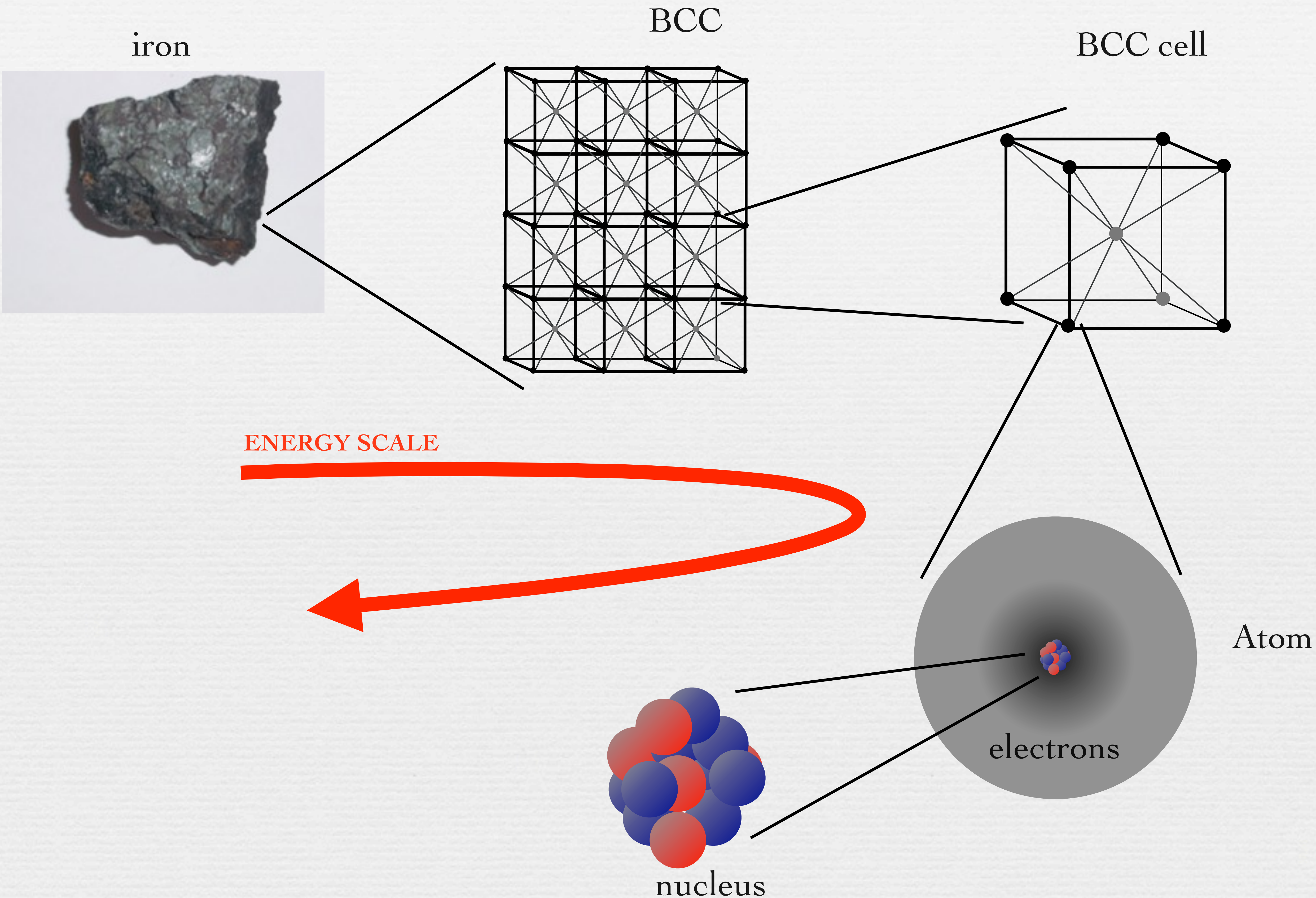

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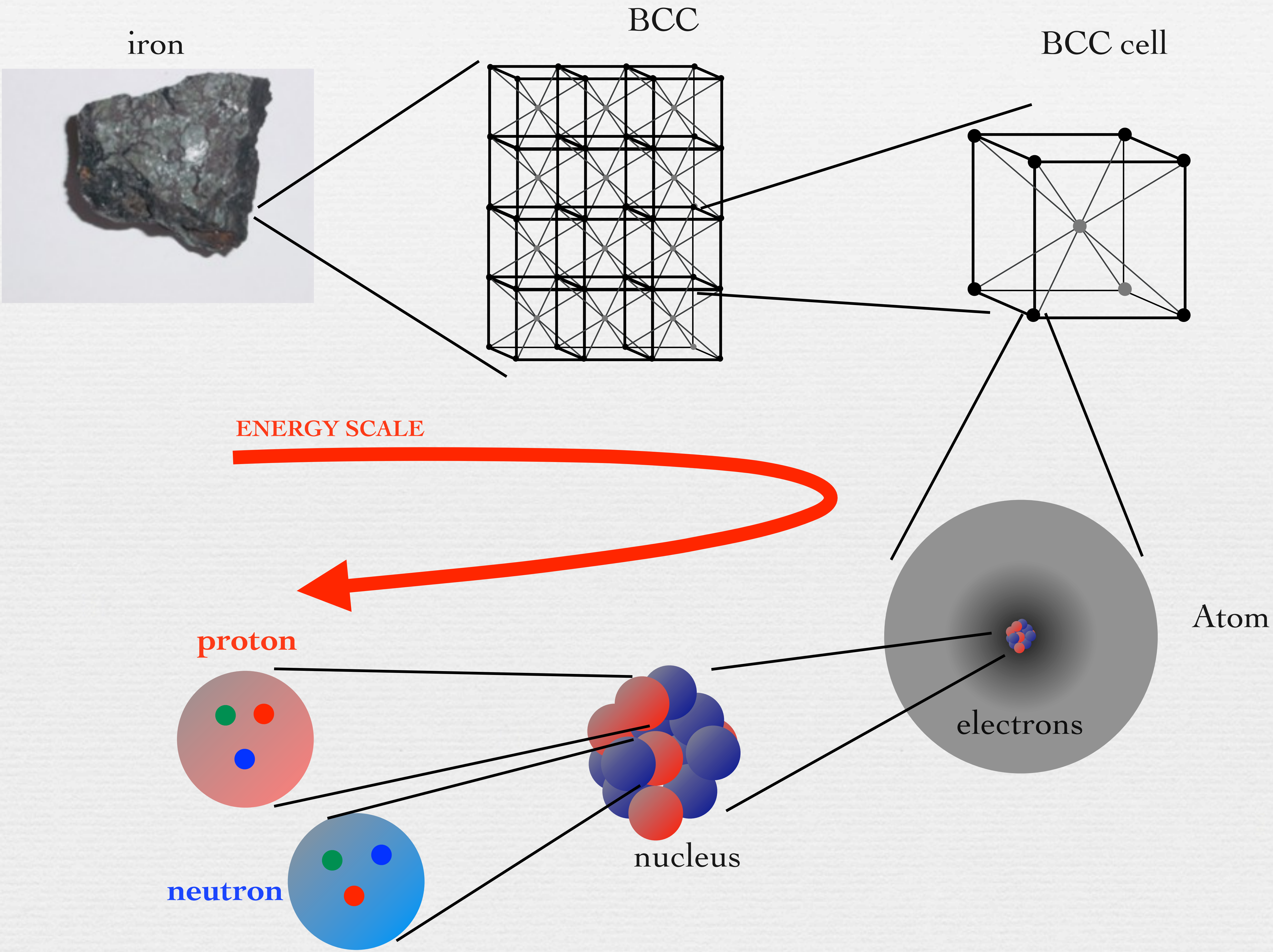

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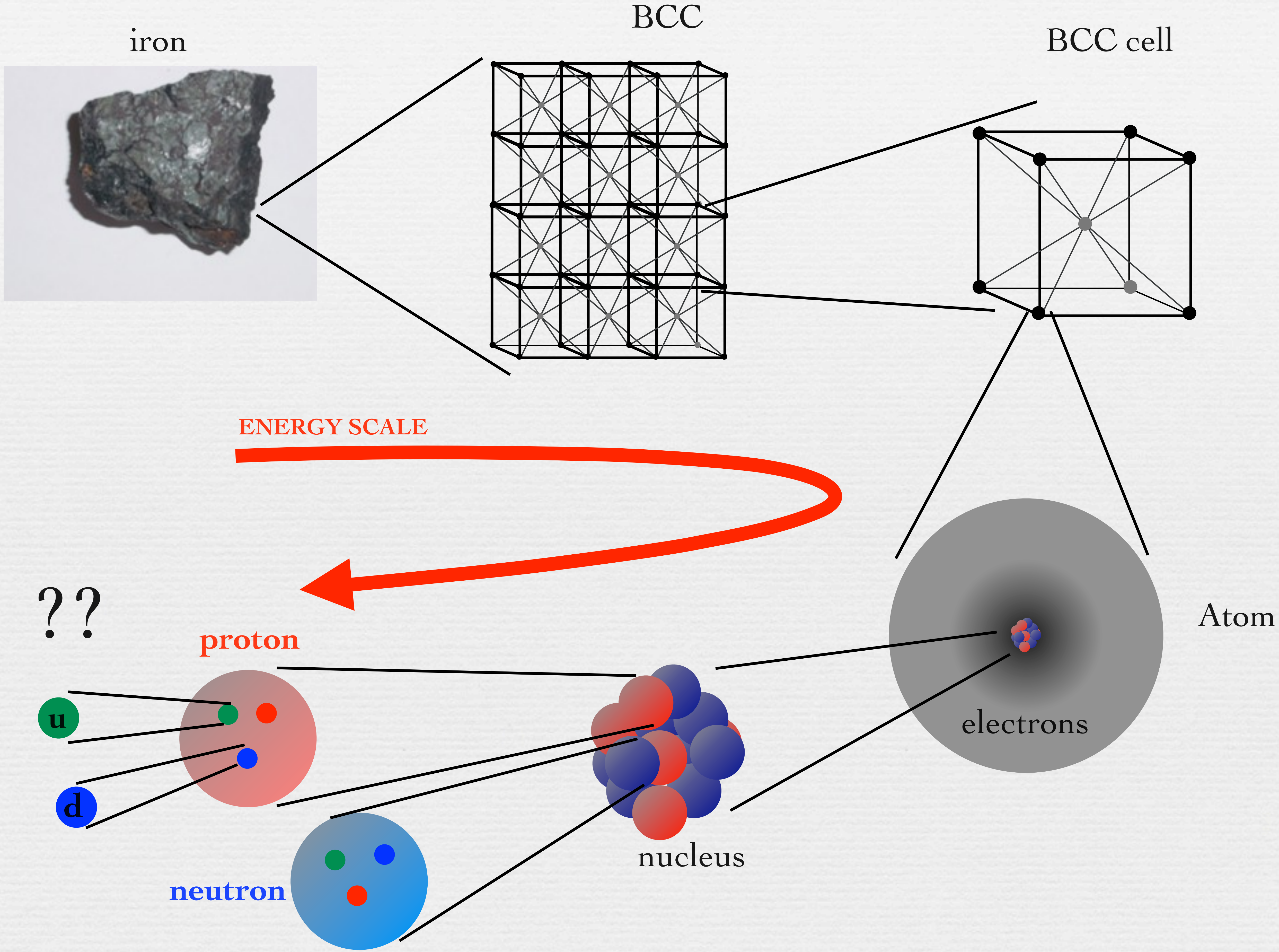
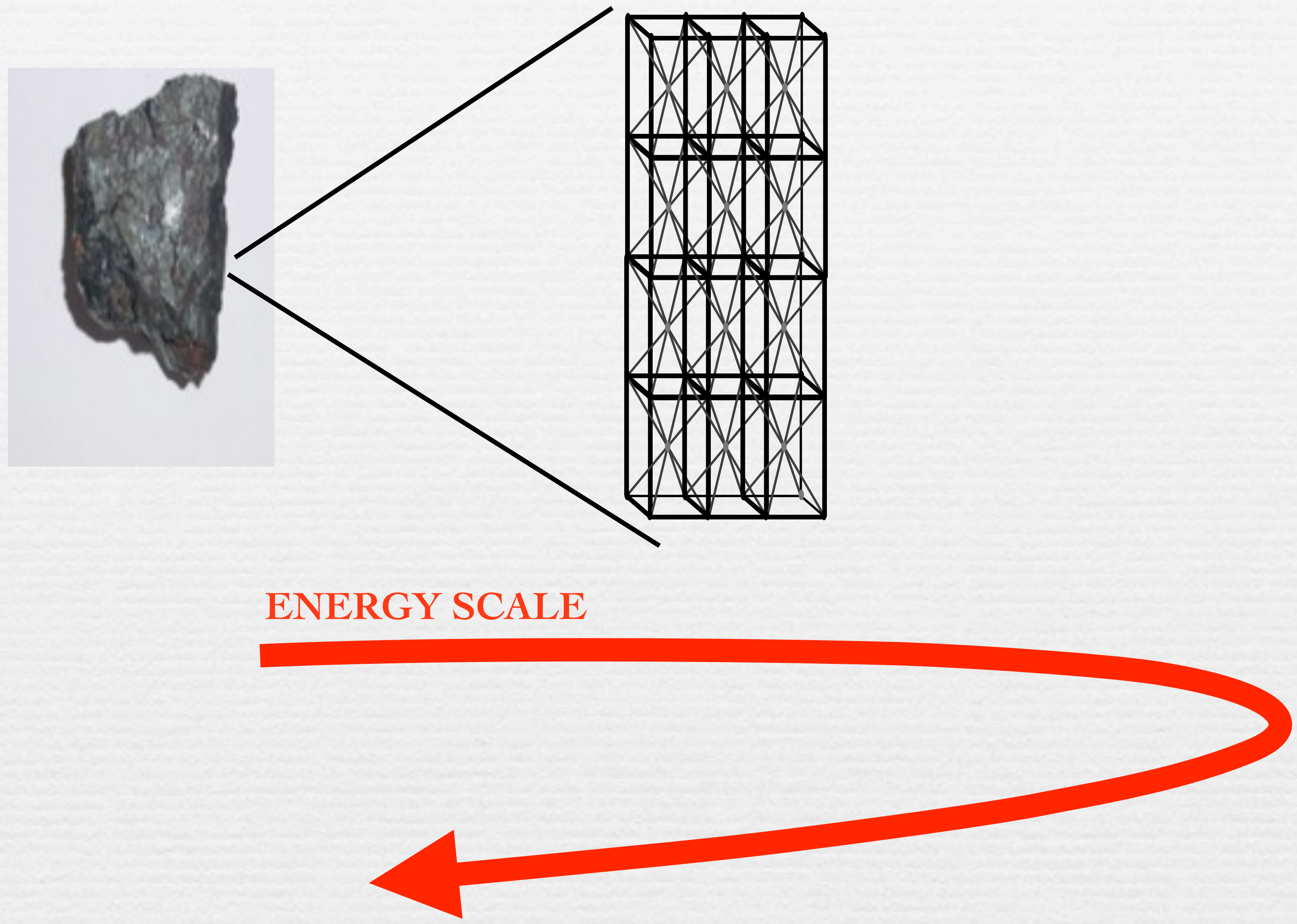


Boosting

ENERGY SCALE

Boosting



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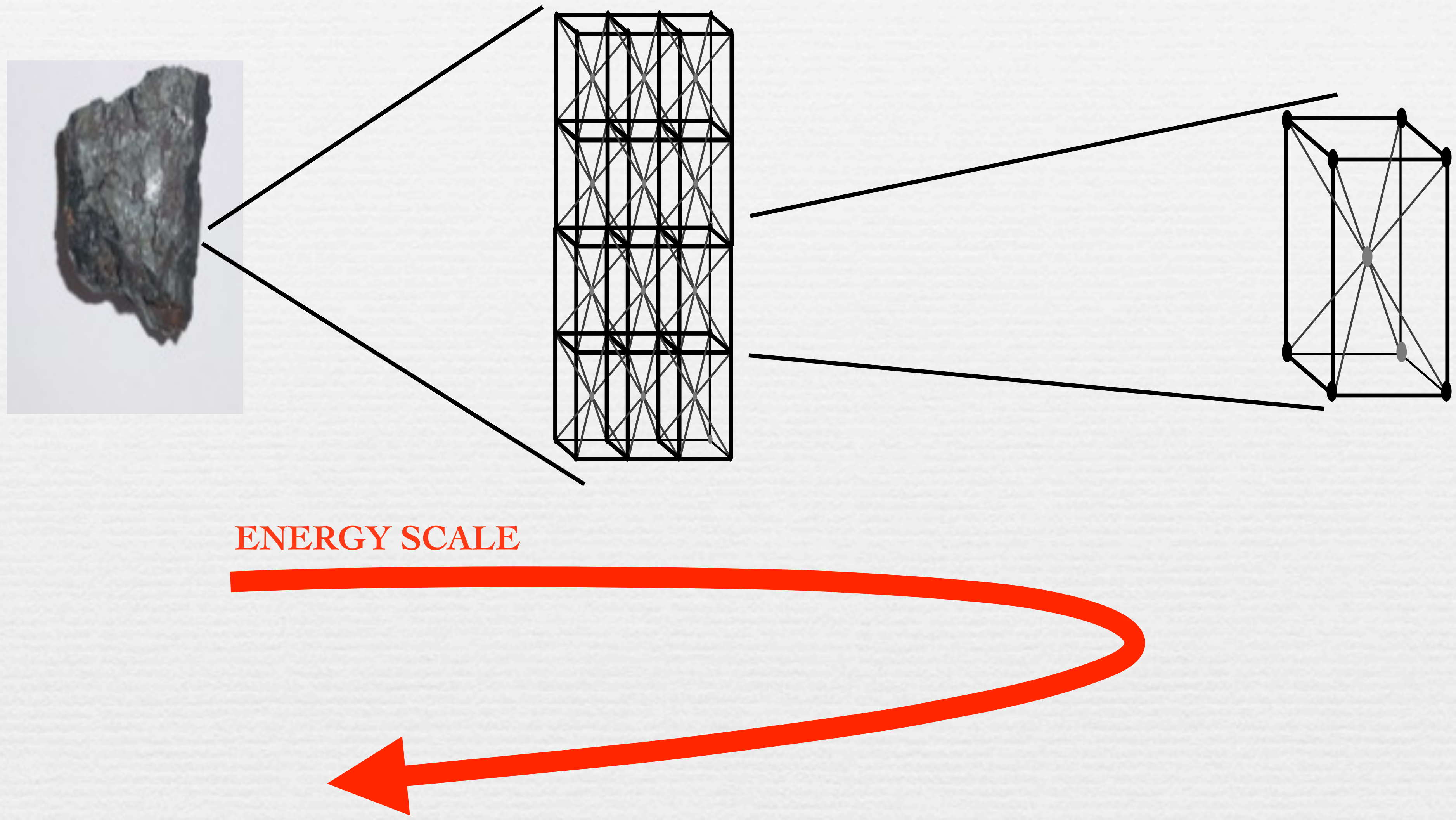

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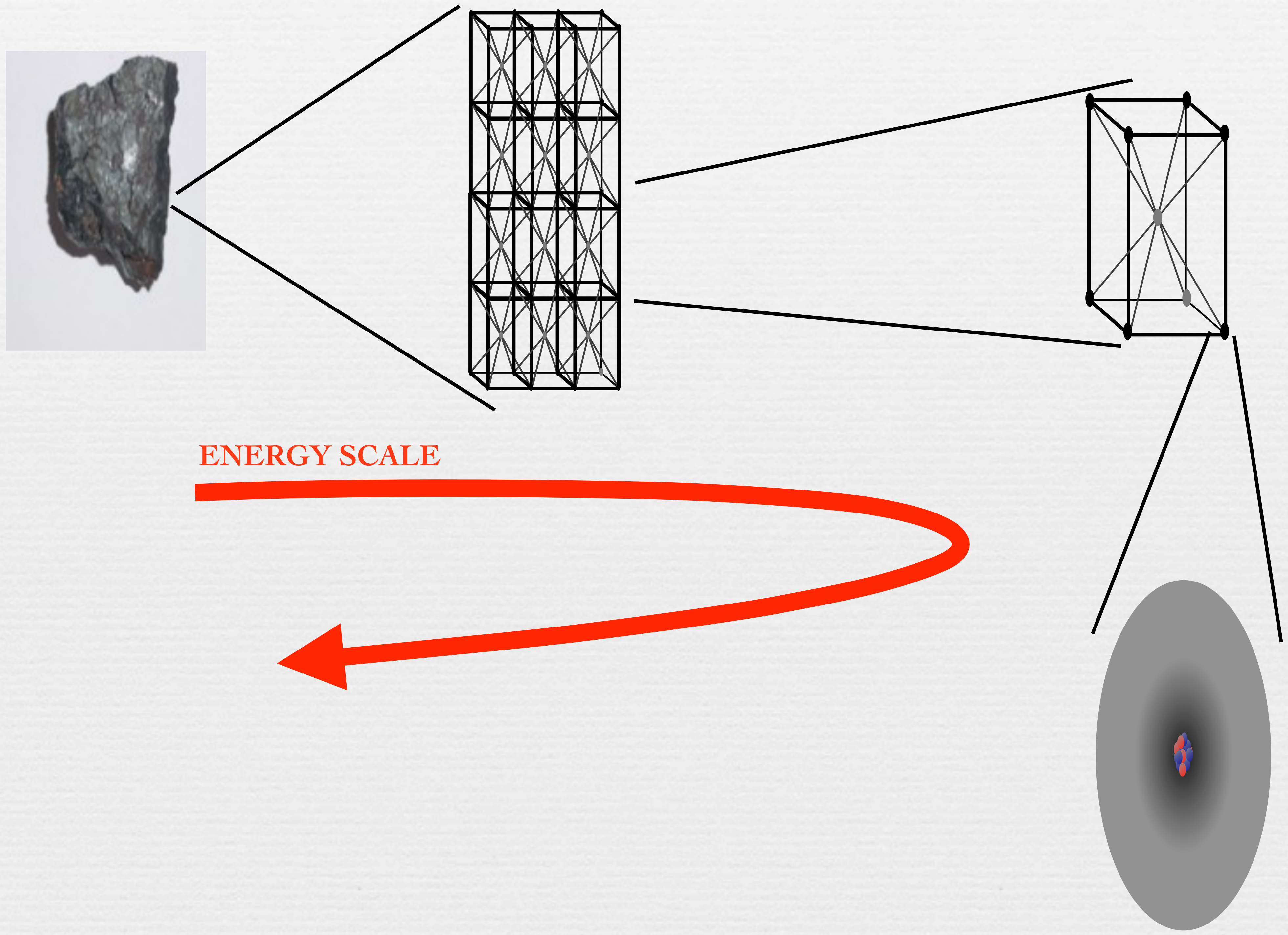

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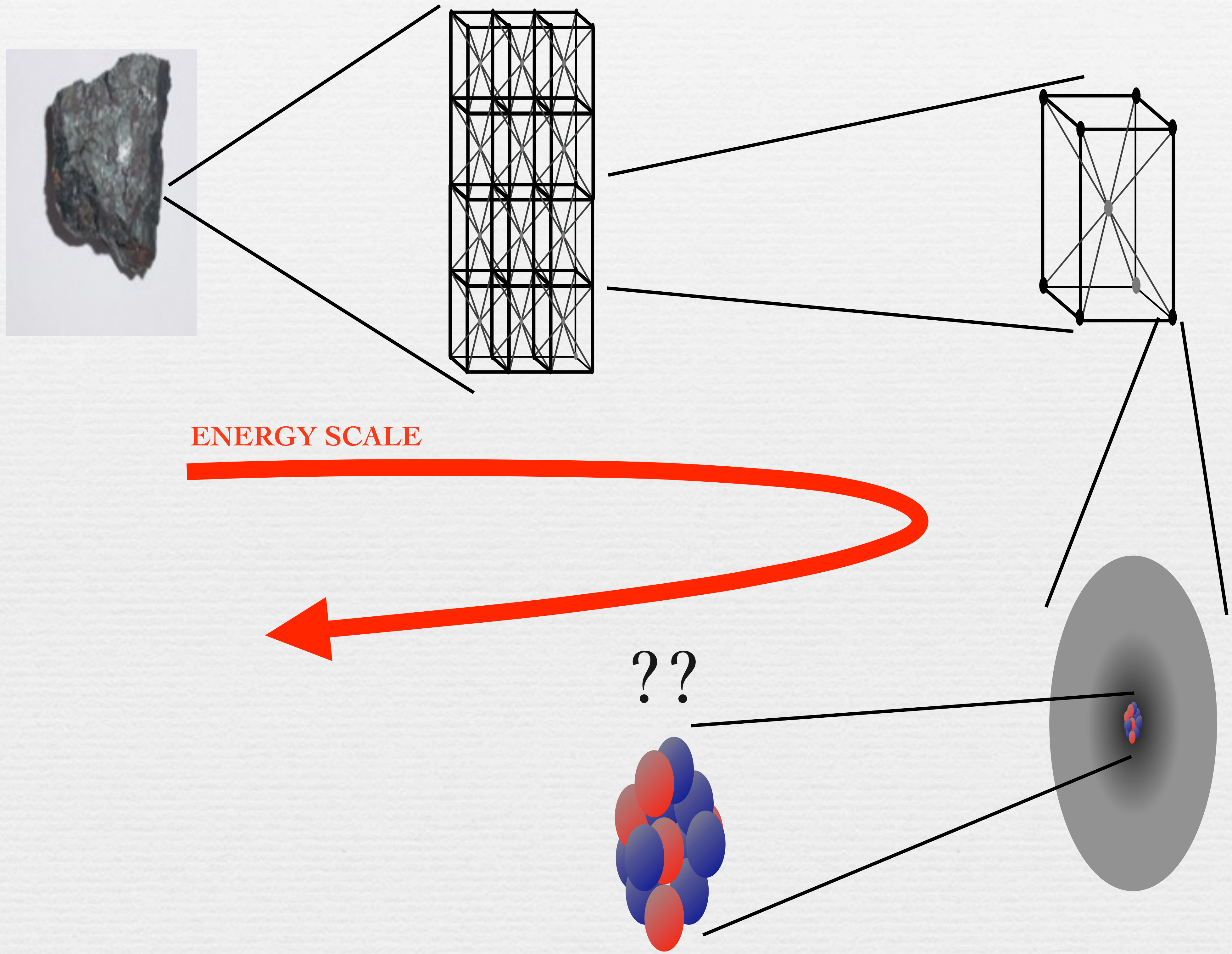

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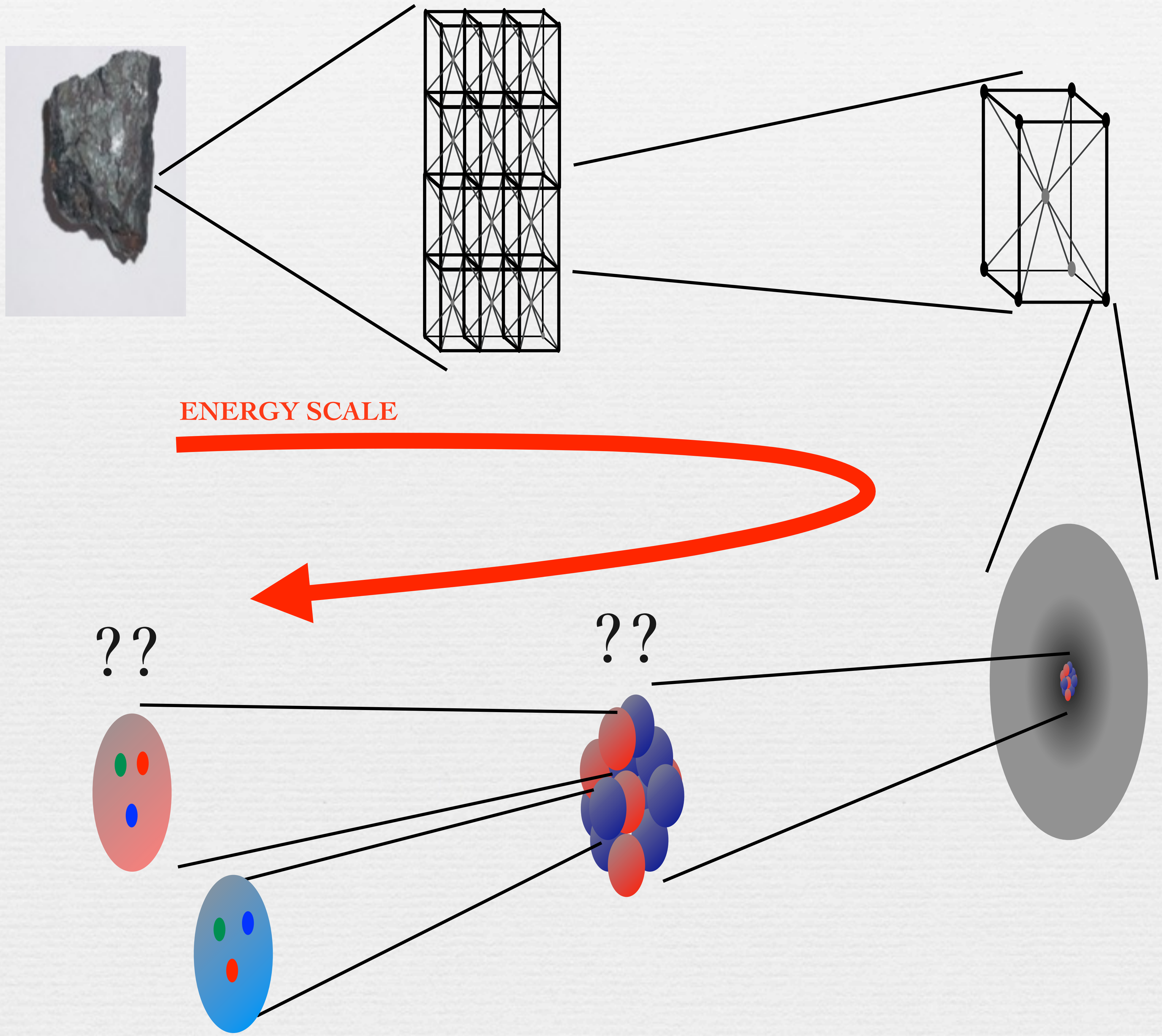

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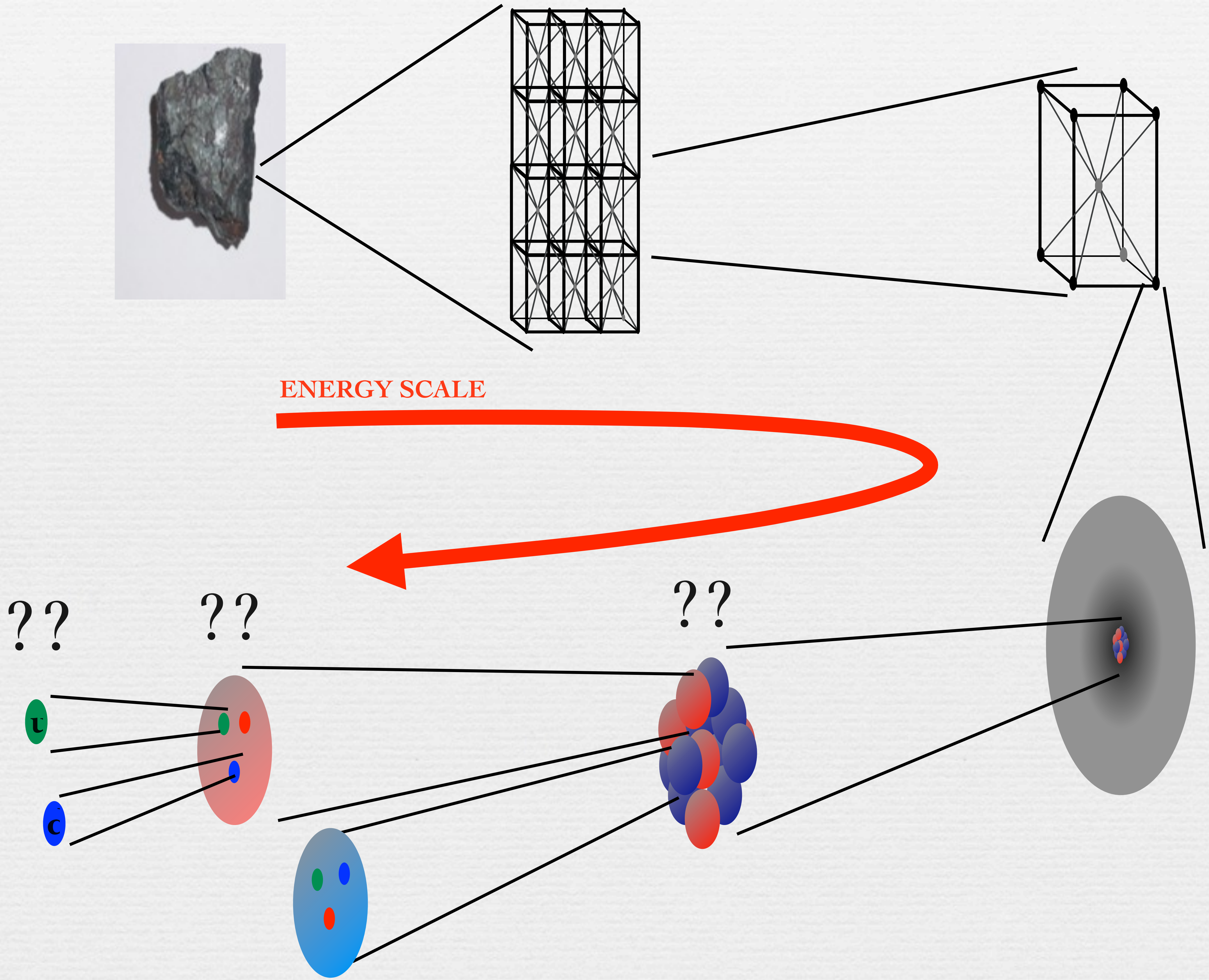
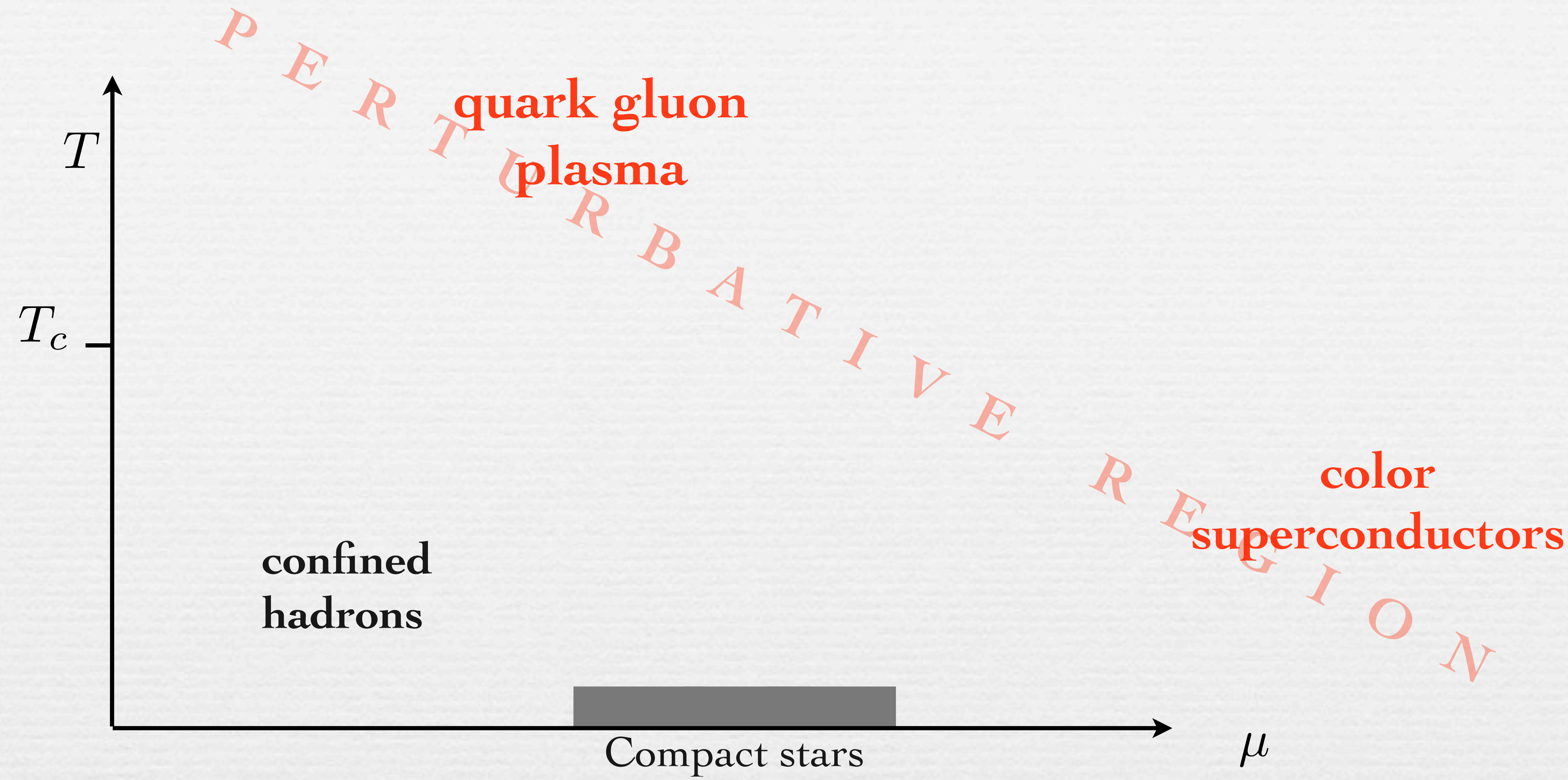


Phases of matter

(what we know and... what we know we don't know)

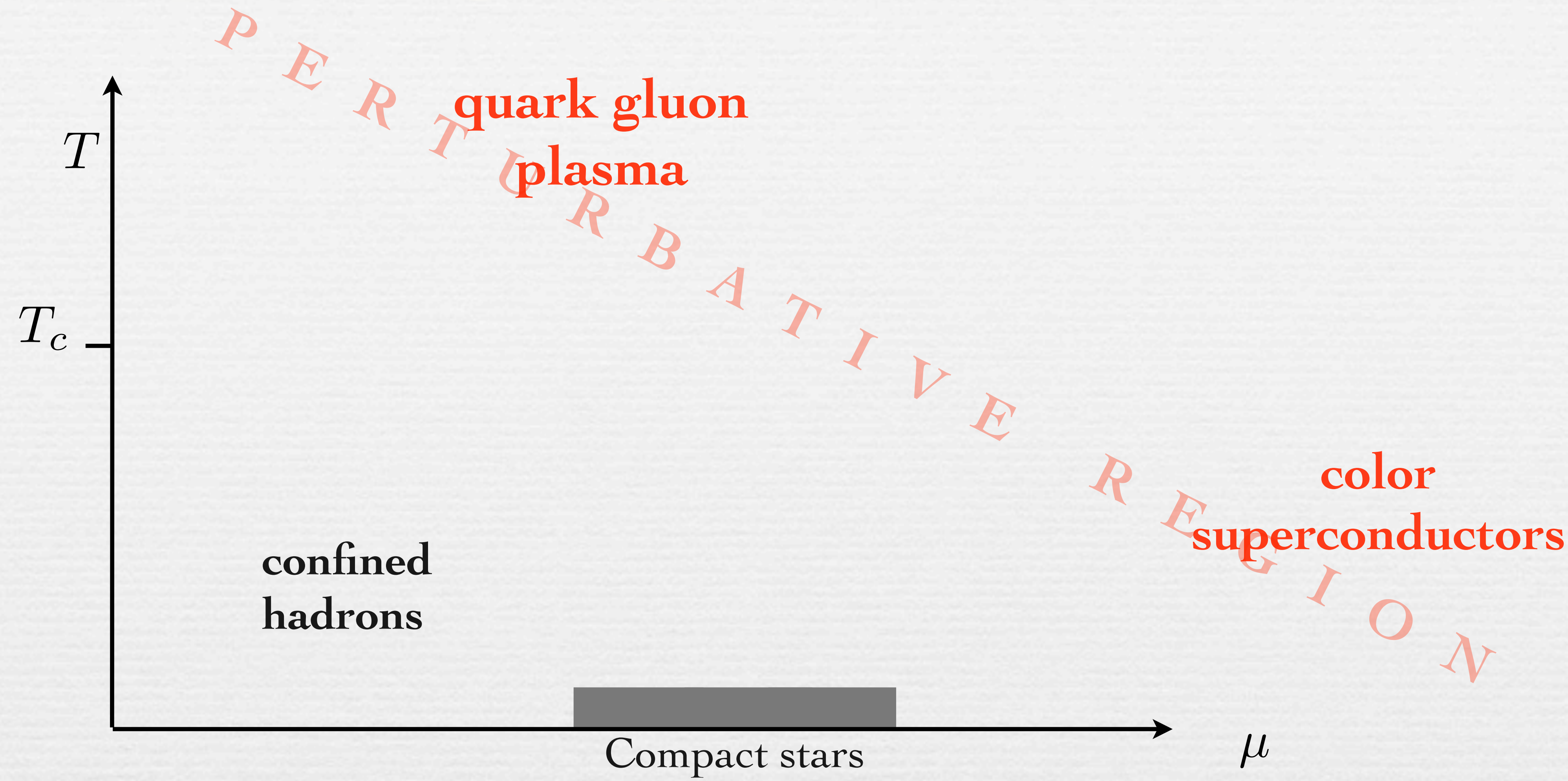
The thermodynamic state

Heating and/or squeezing baryonic matter



Heating and/or squeezing baryonic matter

Few pieces of information are available



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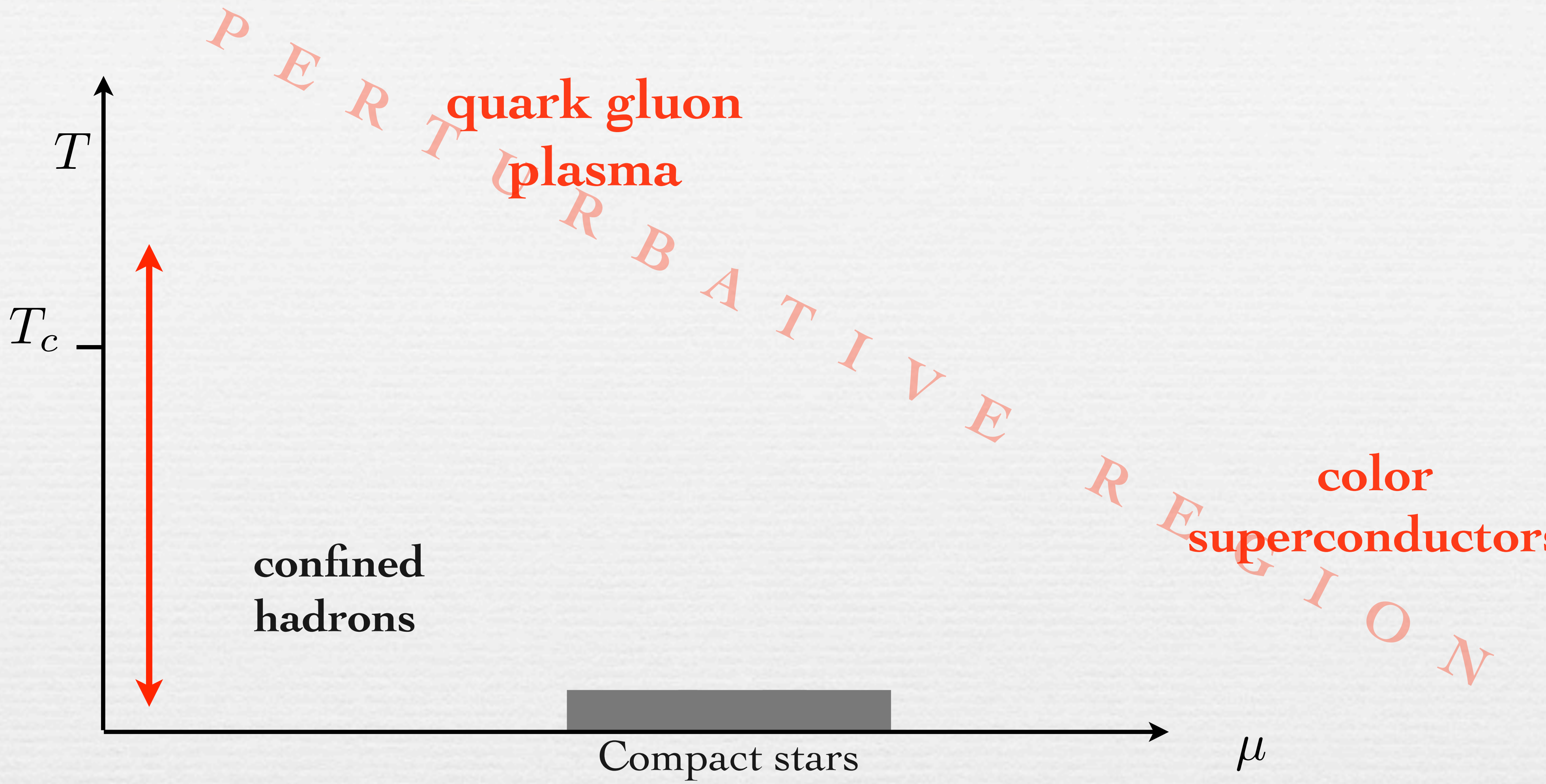

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HOT MATTER

RHIC
LHC

Heating and/or squeezing baryonic matter

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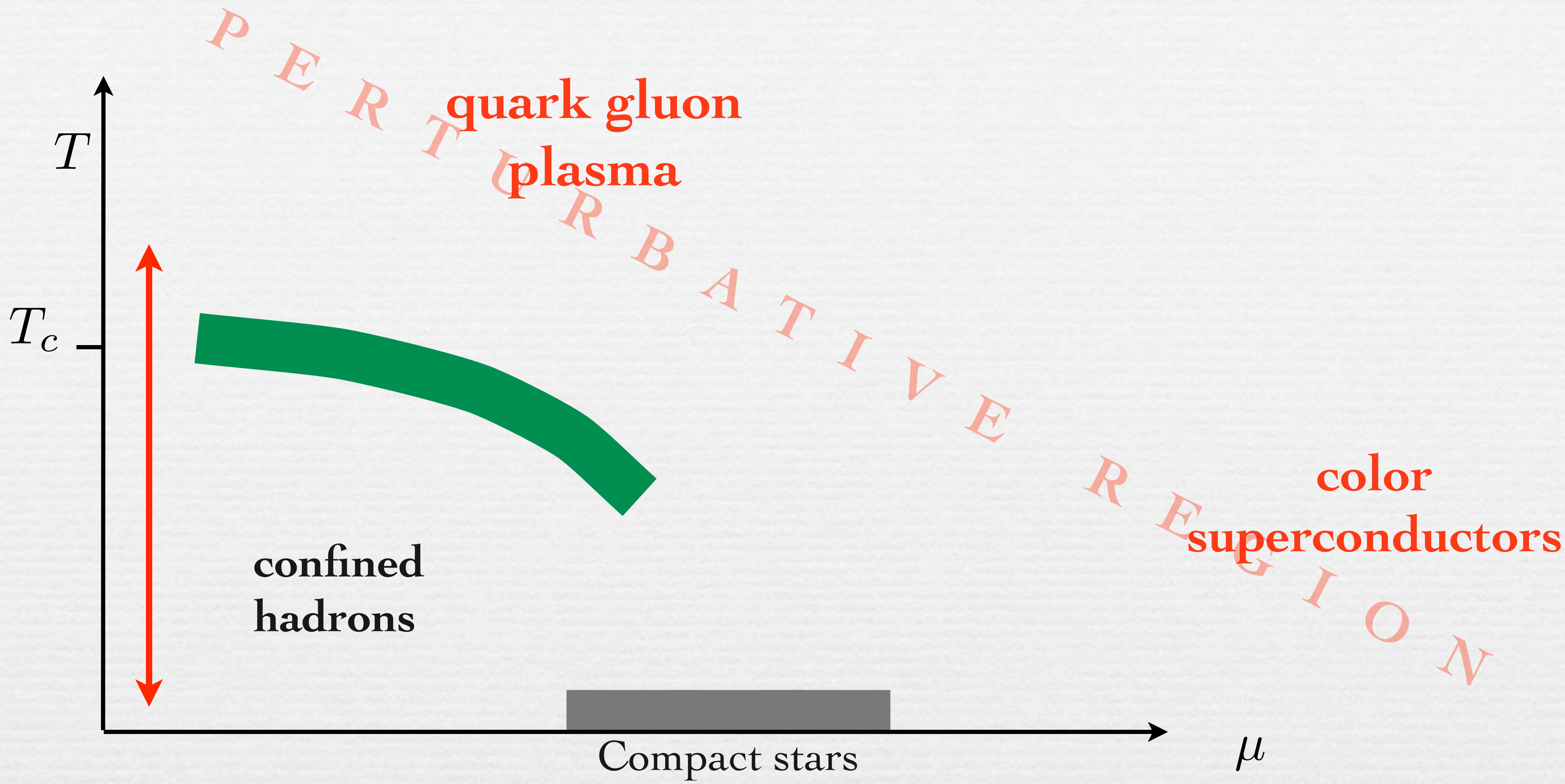

HOT MATTER	ENERGY-SCAN
RHIC LHC	RHIC NA61/SHINE@CERN-SPS CBM@FAIR/GSI MPD@NICA/JINR

Heating and/or squeezing baryonic matter

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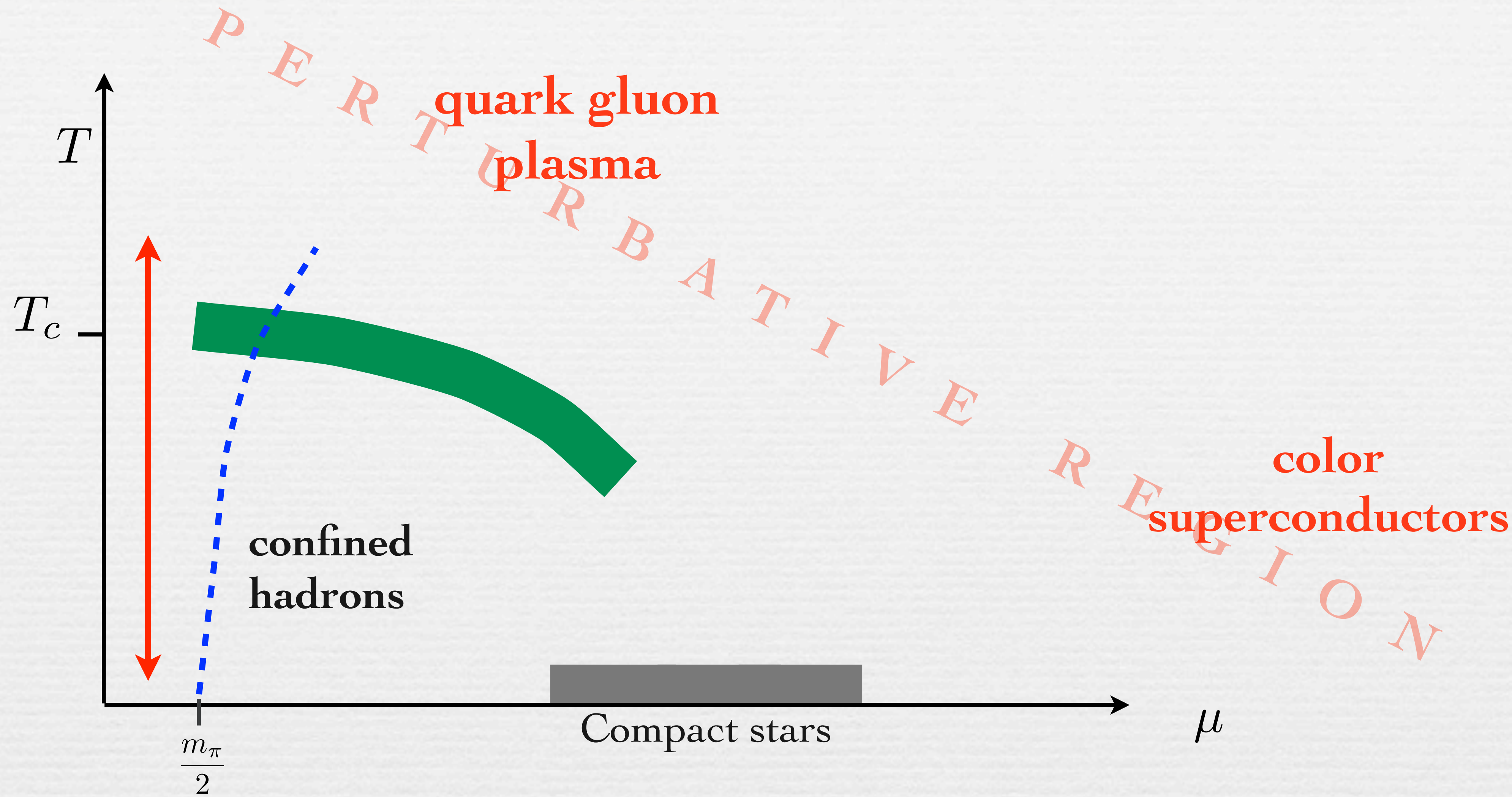

HOT MATTER	ENERGY-SCAN	LATTICE QCD
RHIC	RHIC	Various methods.
LHC	NA61/SHINE@CERN-SPS	At finite chemical potential
	CBM@FAIR/GSI	“sign problem”
	MPD@NICA/JINR	Strong coupling expansion

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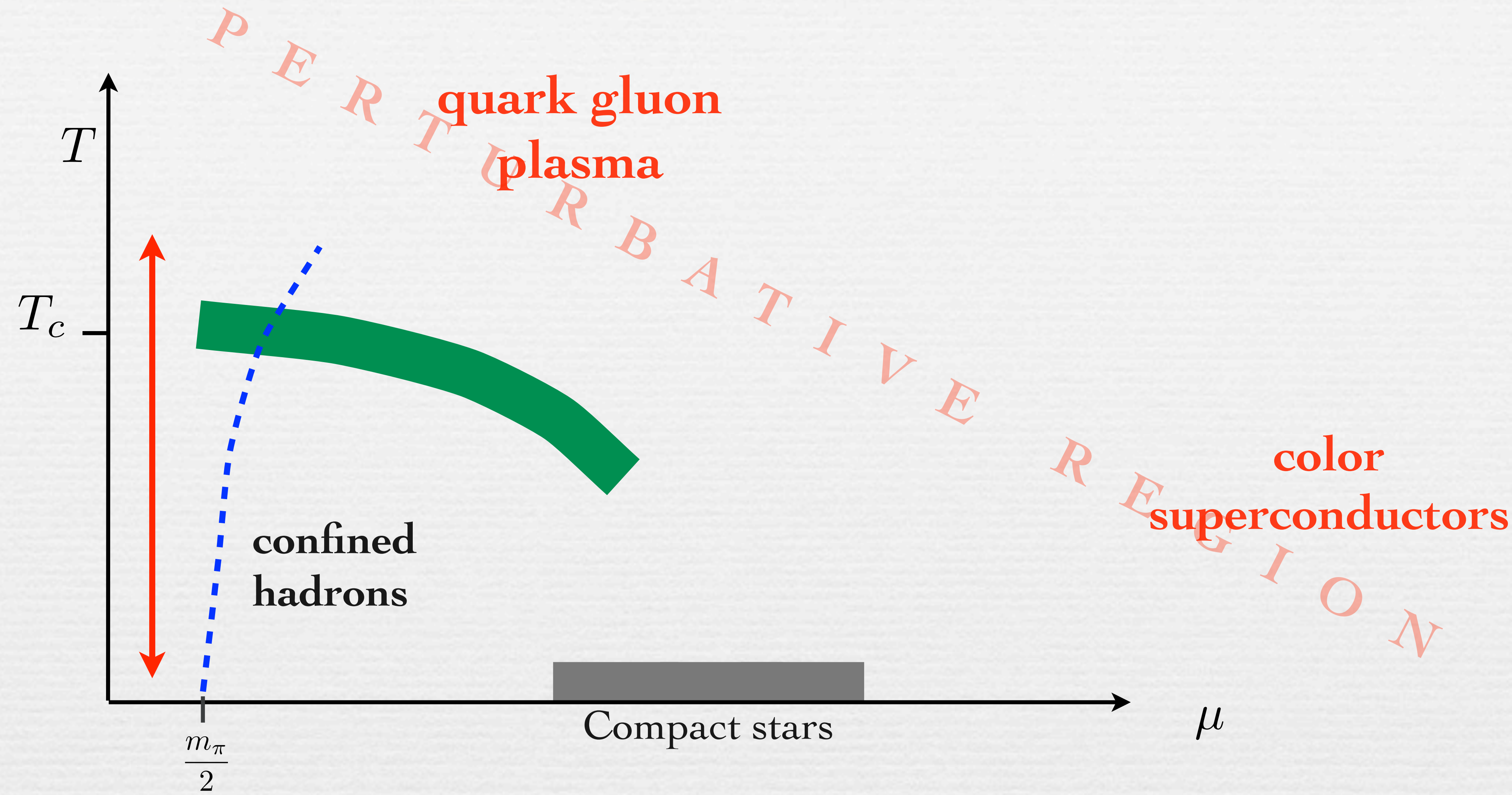
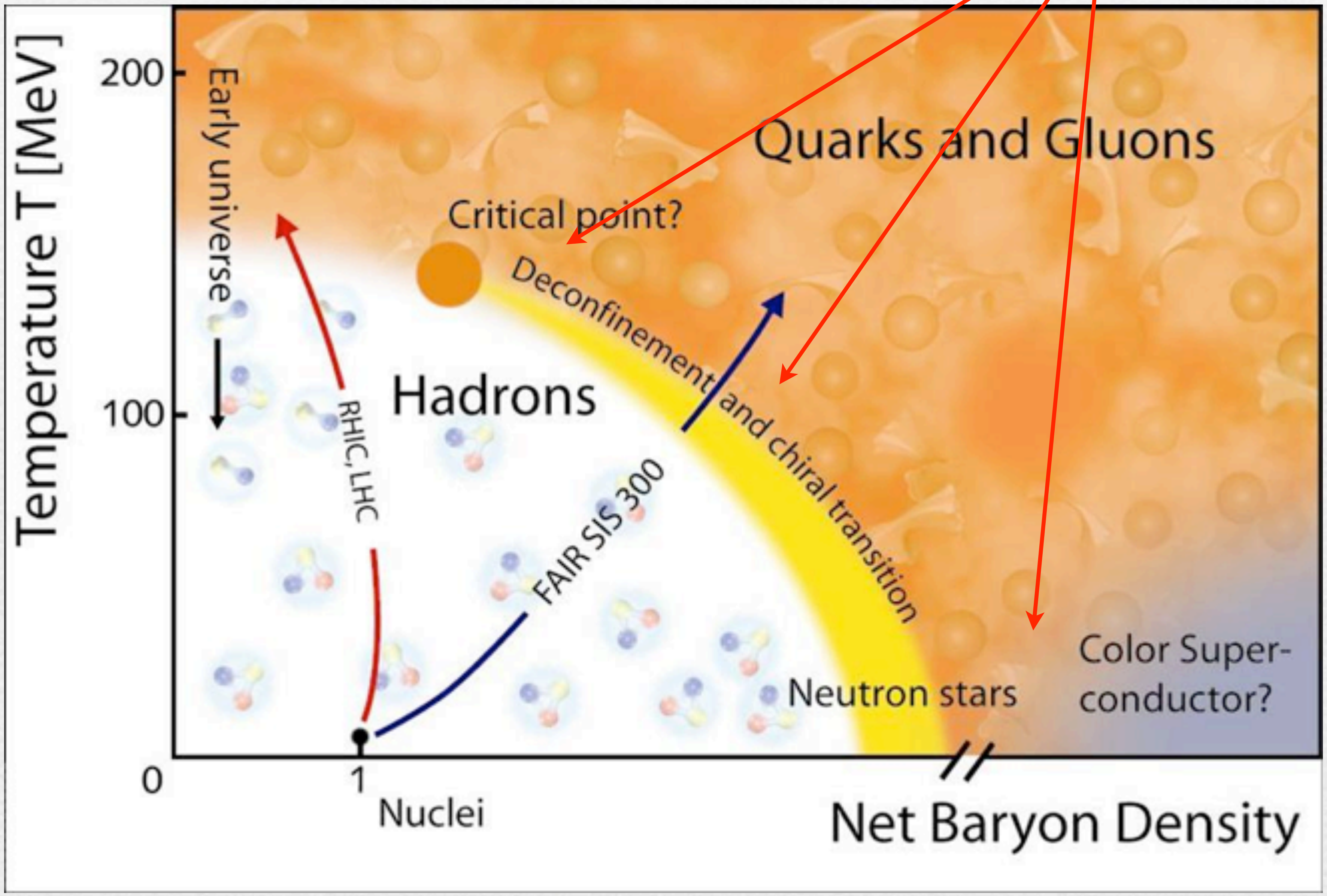


HOT MATTER	ENERGY-SCAN	LATTICE QCD	EMULATION
RHIC LHC	RHIC NA61/SHINE@CERN-SPS CBM@FAIR/GSI MPD@NICA/JINR	Various methods. At finite chemical potential "sign problem" Strong coupling expansion	Ultracold fermionic atoms as tabletop analogous of QCD

How we think it should be

what we know we don't know



http://homepages.uni-regensburg.de/~sow28704/ftd_lqcd_ss2012/ftd_lqcd_ss2012.html

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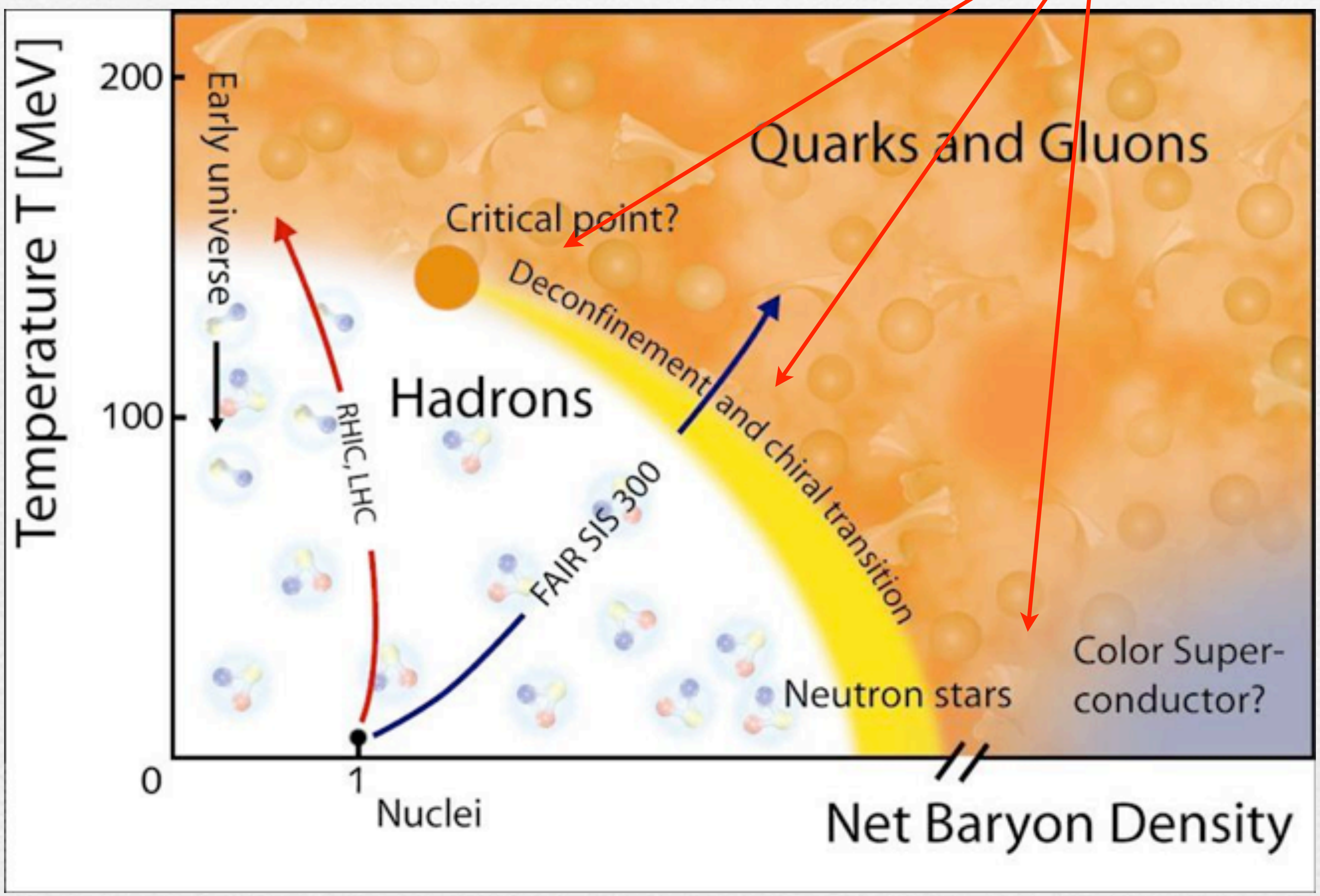

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How do quark and gluons behave at large energy scales?
Where is the Color Glass Condensate?

CONDENSATES

Def. Quantum condensate: a macroscopic fraction of particles occupy the same quantum state

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Example: **Bose-Einstein Condensate (BEC)** of $^4\mathrm{He}$ below a critical temperature

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Example: **Bose-Einstein Condensate (BEC)** of $^4\mathrm{He}$ below a critical temperature

The condensation results in a spontaneous symmetry breaking of some global or local symmetry

Example: **the number of particles of a certain type**

CAN QUARK CONDENSE?

Degenerate fermionic systems with an attractive interaction can form Cooper pairs

$$\langle \psi \psi \rangle$$

Cooper pairs “behave as bosons” and can condense

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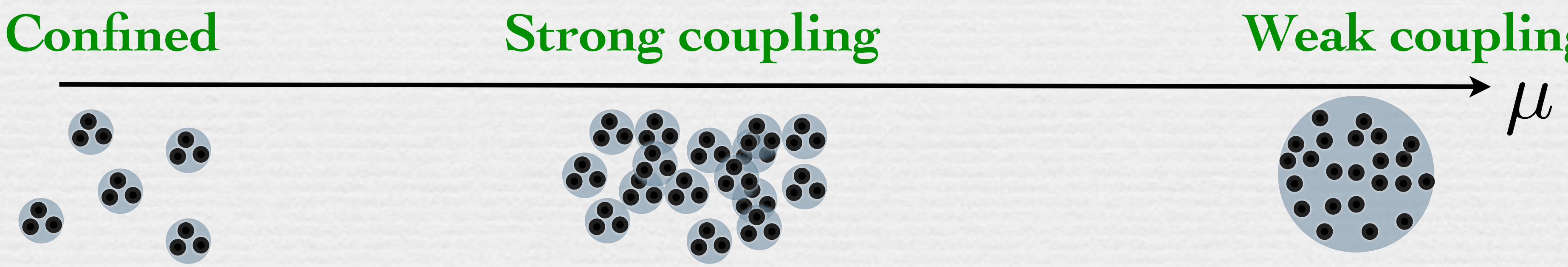

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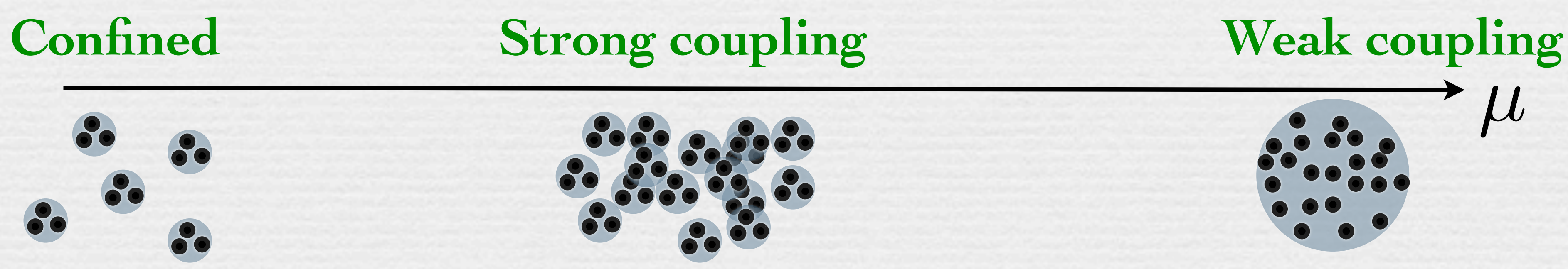

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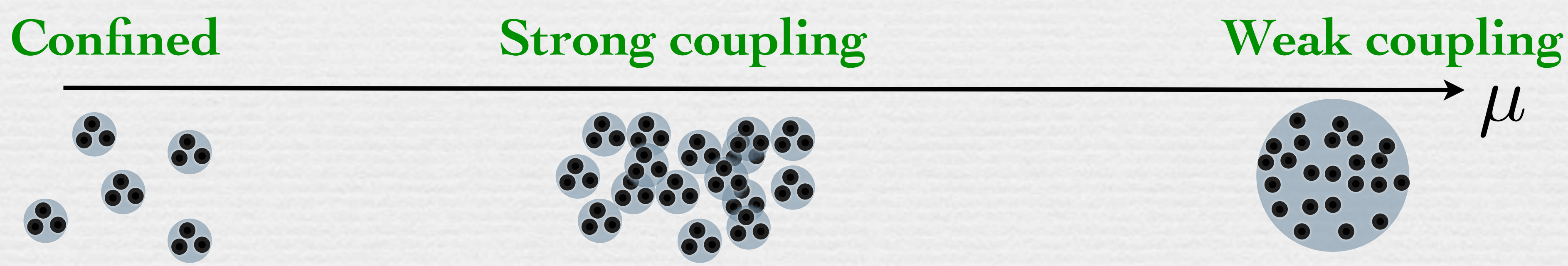
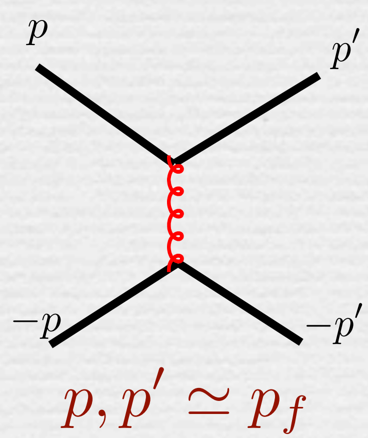
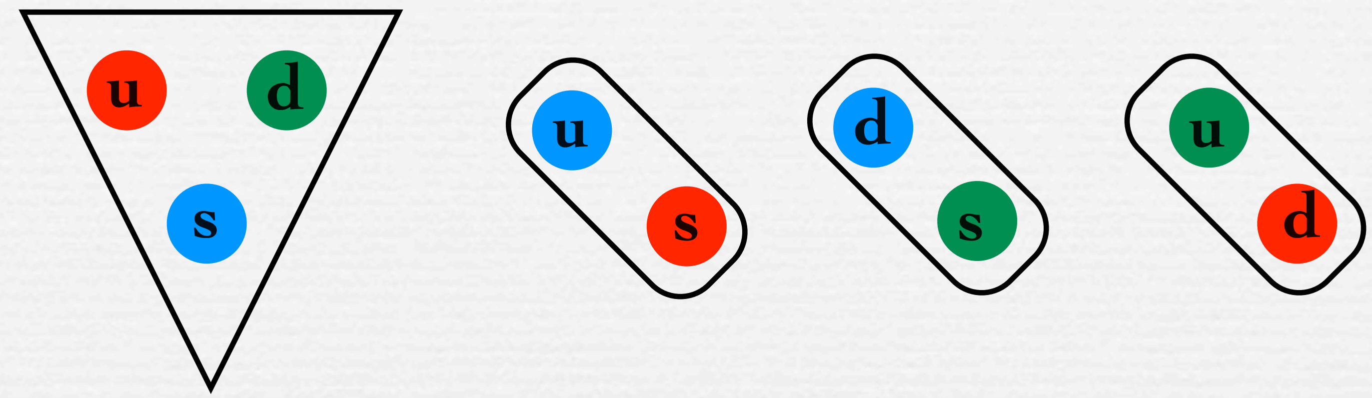


Degenerate system of quarks

Attractive interaction between quarks for example by a gluon exchange



Color-flavor locking and beyond



CFL condensate

(Alford, Rajagopal, Wilczek hep-ph/9804403)

quarks of all flavors and colors form Cooper pairs

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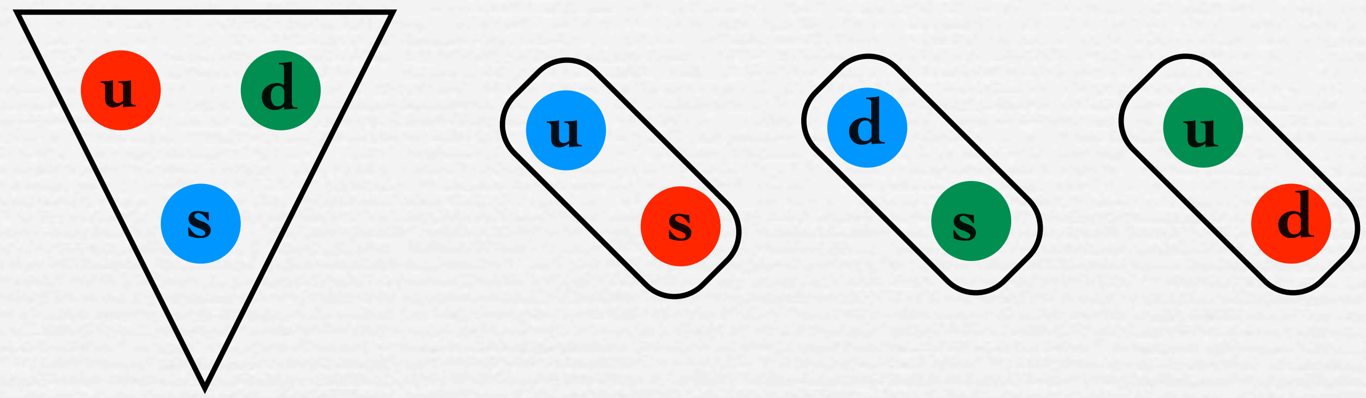

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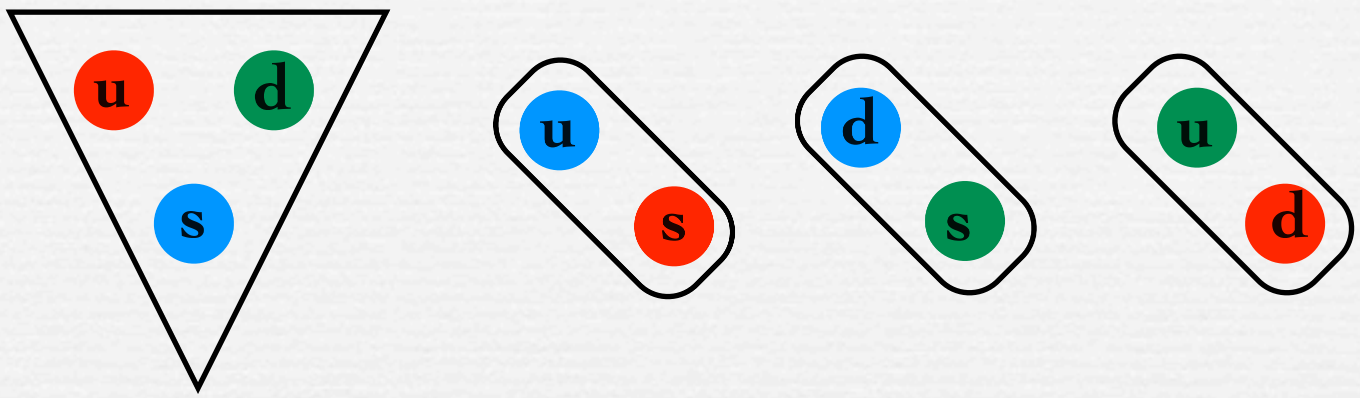

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In compact stars the condition may favor inhomogeneous condensates

R. Anglani, R. Casalbuoni, M. Ciminale, R. Gatto, N. Ippolito, M.M., M. Ruggieri. arXiv:1302.4264 soon on RMP

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Rev. Mod. Phys. 85, 299

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This condensate brakes the scale symmetry of QCD

Glueballs and gluon condensates should not be confused with the "color glass condensate"

The kinematic state of the observer

Lorentz boost effectively change the interaction strength

In flight pion decay

Pion rest frame

$v_\pi = 0$

$\tau \simeq 2.5 \times 10^{-8} \mathrm{sec}$

$l_{\mathrm{decay}} \simeq 7.5\mathrm{m}$

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In flight pion decay

$$\gamma = \frac{1}{\sqrt{1 - v_\pi'^2}}$$

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Lab frame

$v'_\pi = 0.99$

$\tau' = \gamma\,\tau \simeq 1.7 \times 10^{-7}\mathrm{sec}$

$l'_{\mathrm{decay}} \simeq 53\mathrm{m}$

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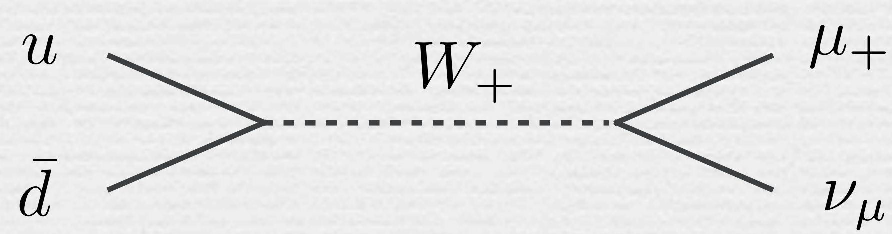
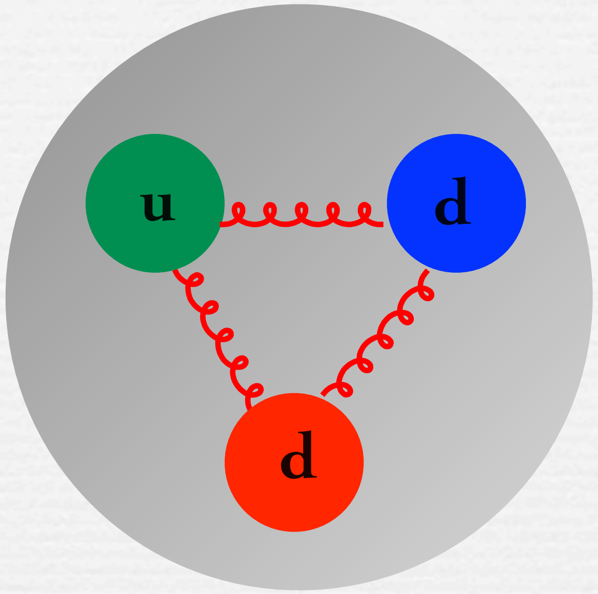
In the Lab frame we do “effectively” see a smaller coupling



$$\Gamma = \frac{1}{\tau} \propto G_{\text{F}}^2 \qquad \Gamma' = \frac{1}{\tau'} \propto (G'_{\text{F}})^2 \qquad G'_{\text{F}} = G_{\text{F}}/\sqrt{\gamma}$$

NUCLEON REST FRAME



quarks constituent masses

$$M_u \simeq M_d \simeq 336 \text{ MeV}$$

We can **effectively** describe a nucleon and the low lying baryonic states as three quarks bound by springs (harmonic oscillators)

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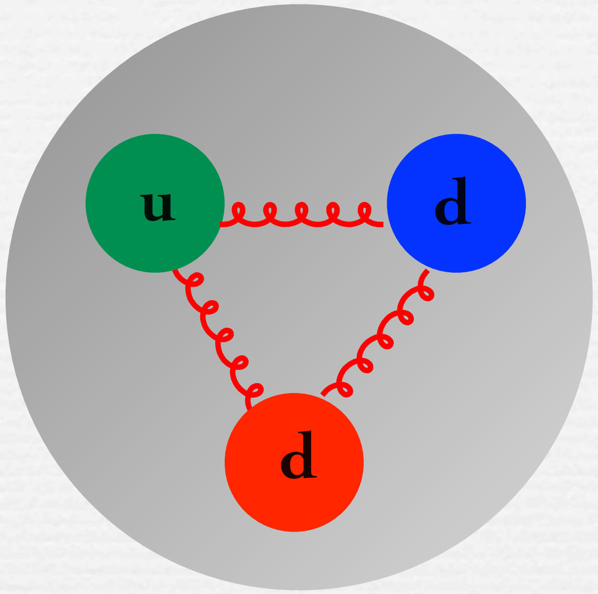

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Nucleons are not bound states of quarks

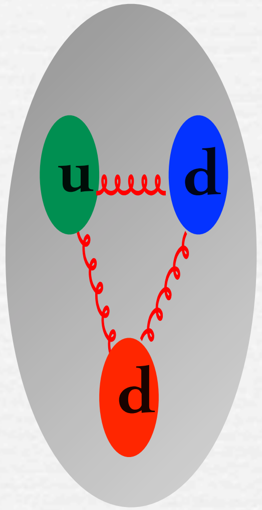
$m_u \simeq m_d \simeq 5$ MeV $\qquad M_{\rm p} \simeq 1$ GeV

A nucleon is a confined state of quarks and gluons

- **We cannot break a nucleon in a lighter object.**

It does not matter how large is the energy of a particle that hits a nucleon, in the final state there will always be a nucleon

Boosting a nucleon



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We want to stick with the quantum mechanical description in terms of springs

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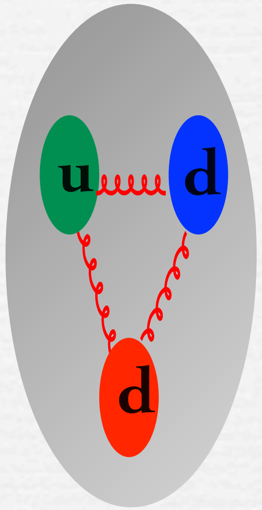

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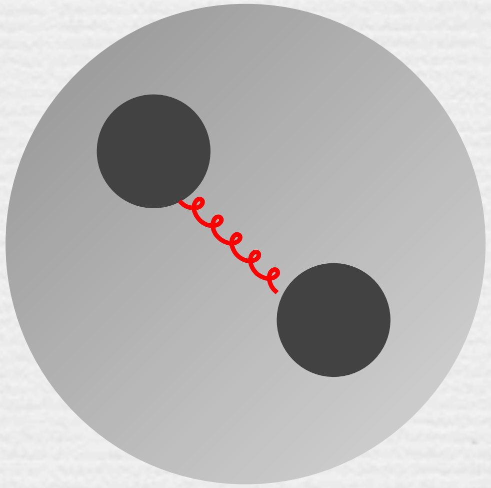

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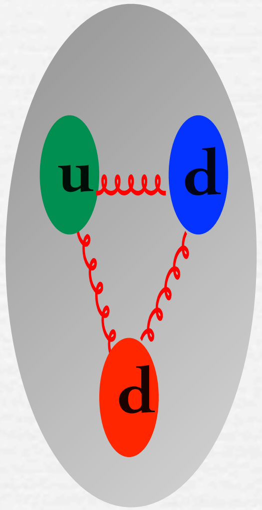

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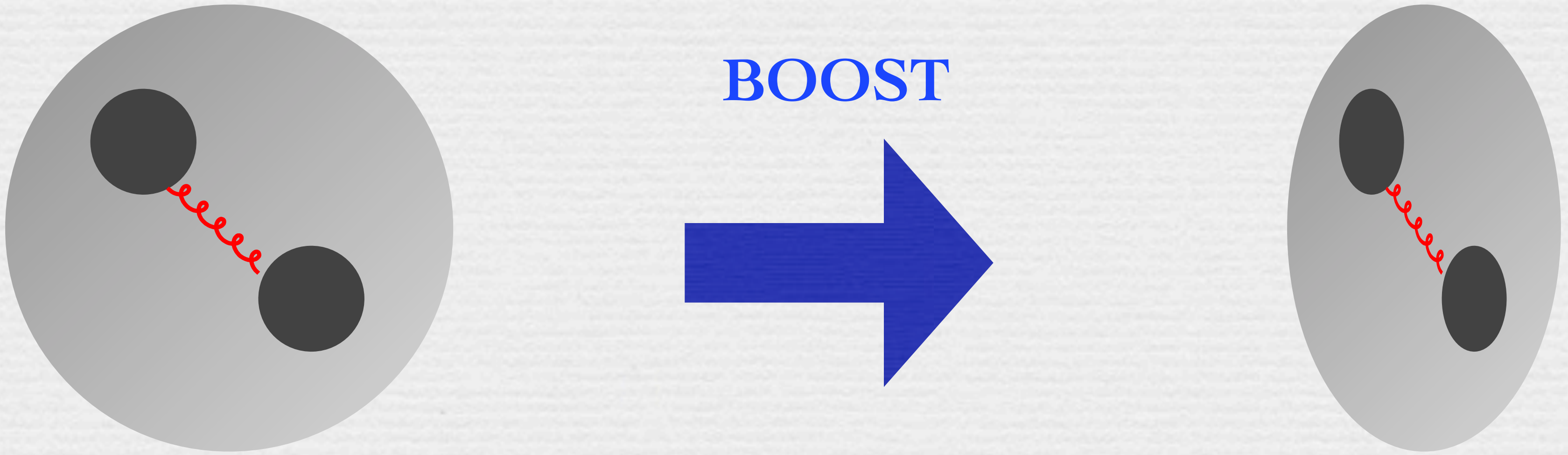

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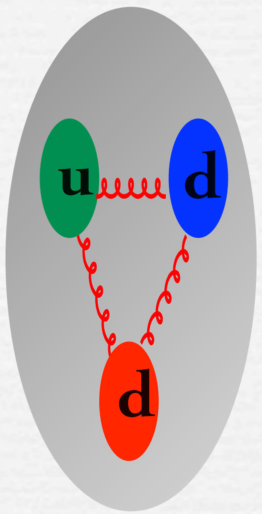

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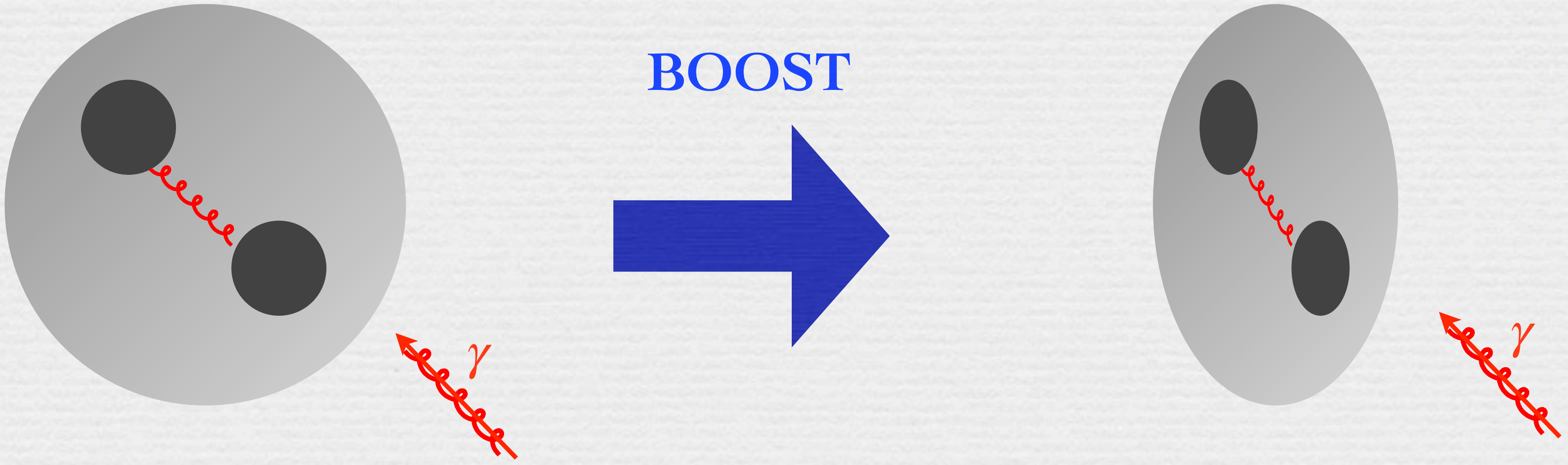

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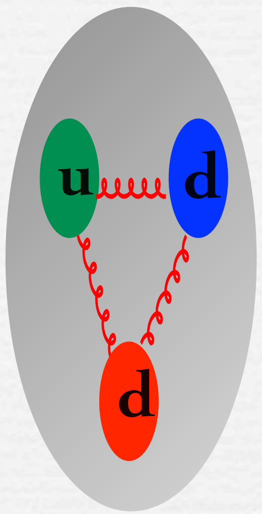

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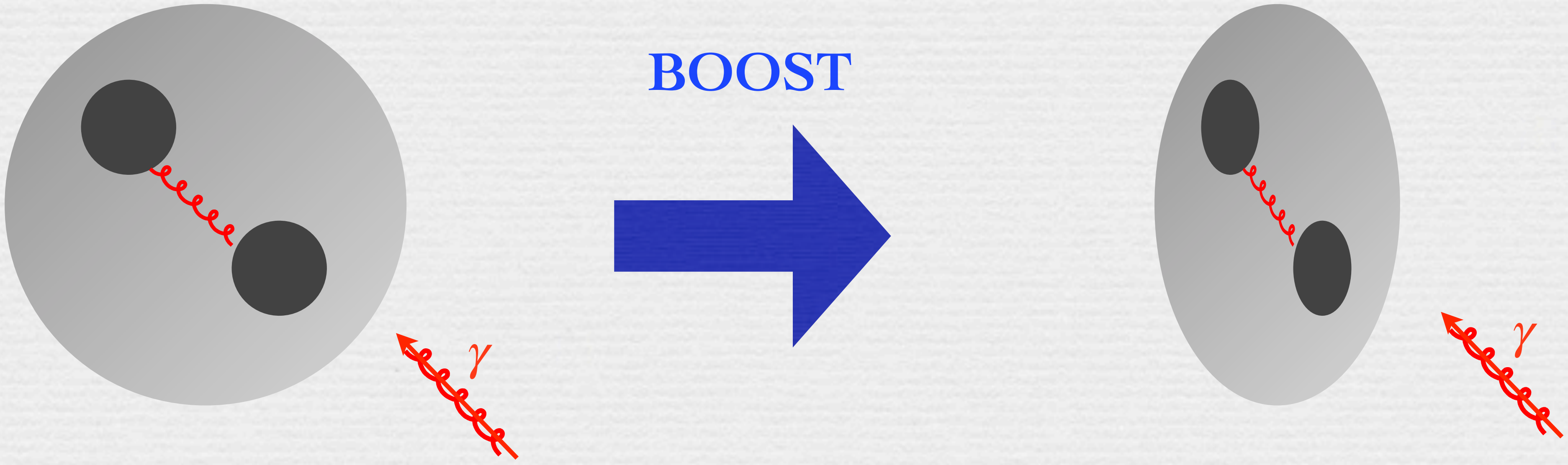
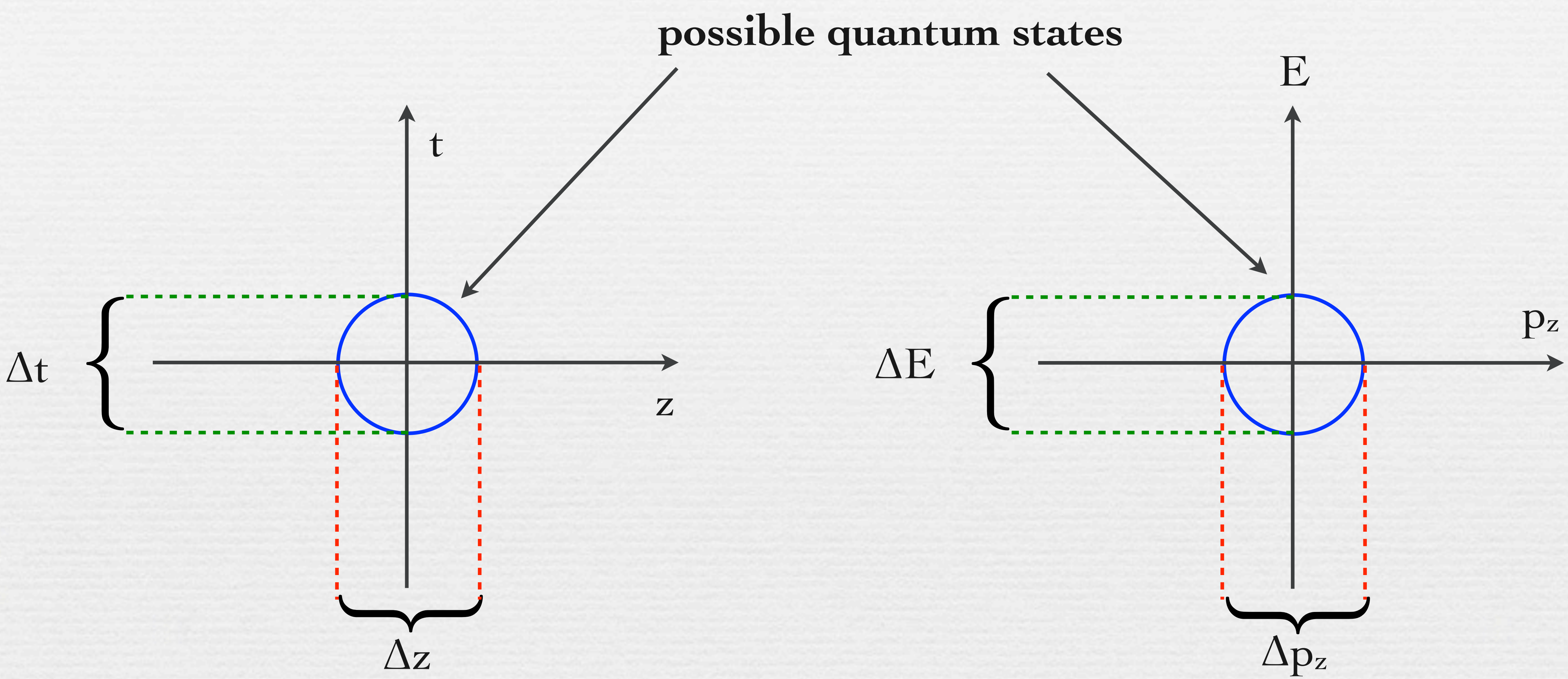


What does the photon see in the boosted case?
We want to find out how boost change the interaction strength and the degrees of freedom

TOY MODEL

(two quarks interacting by an elastic force)

Y.S.Kim and M.E. Noz, "Theory and applications of the Poincaré group"
Y.S.Kim, PRL 63, 348 (1989)



Δt time "Fourier" uncertainty

ΔE energy "Fourier" uncertainty

Δz space uncertainty

Δp momentum uncertainty

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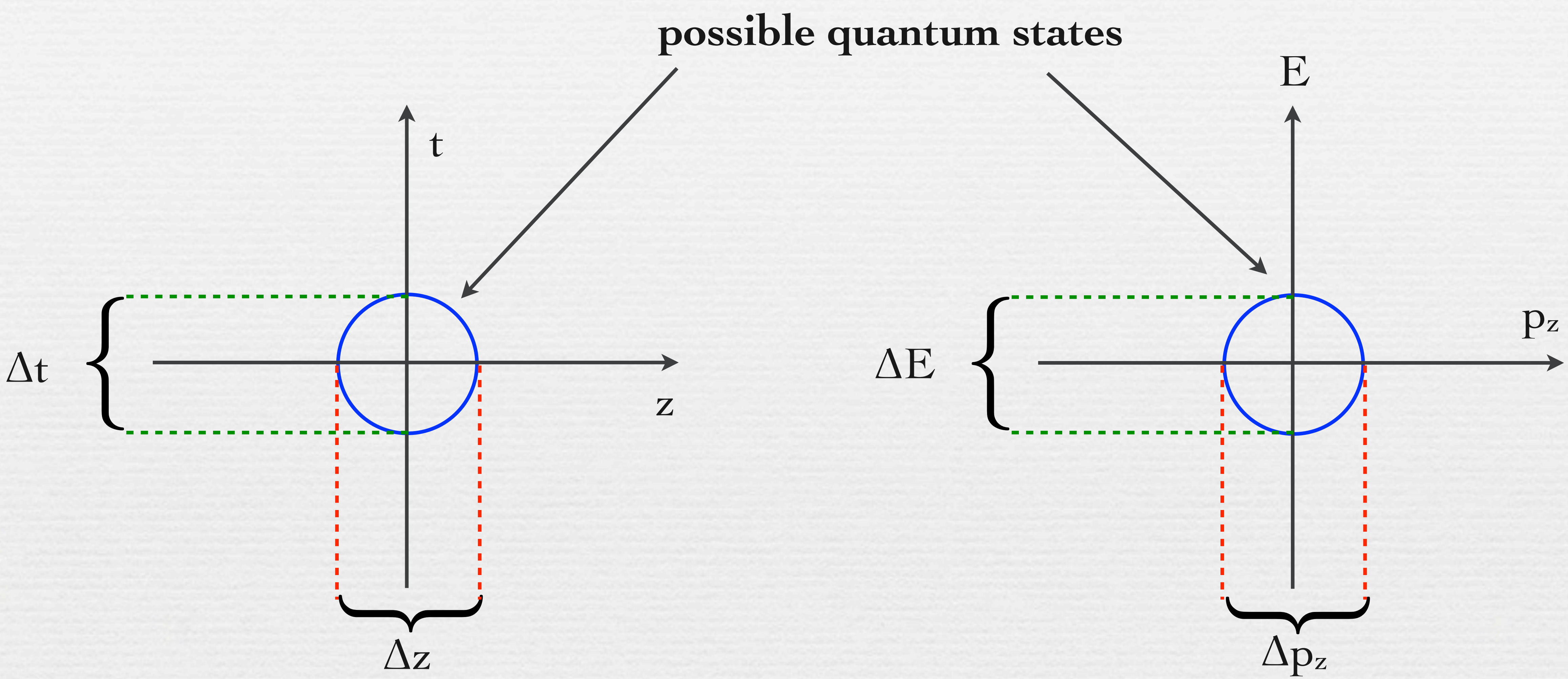


Δt time “Fourier” uncertainty

ΔE energy “Fourier” uncertainty

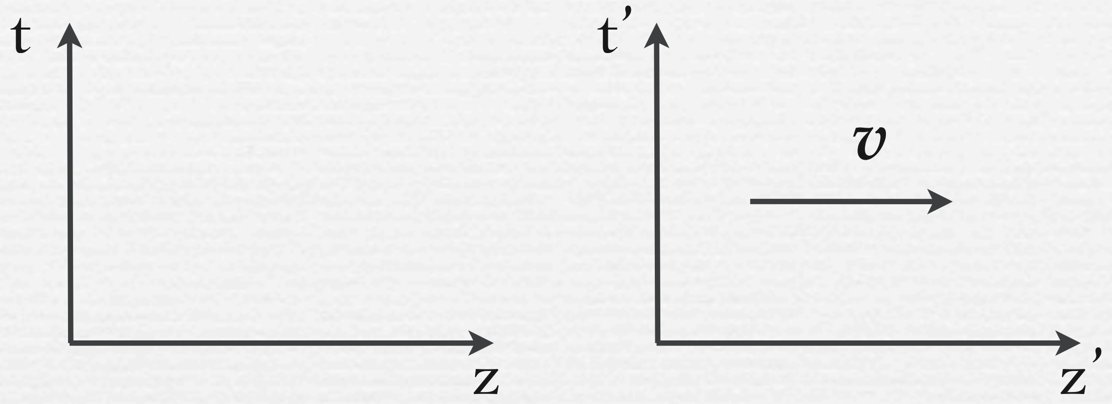
Δz space uncertainty

Δp momentum uncertainty

ground state wave function

$$\psi(z,t) \propto e^{-\omega^2 \frac{z^2+t^2}{2}}$$

Boost along z



$$\begin{pmatrix} t' \\ z' \end{pmatrix} = \begin{pmatrix} \cosh\phi & -\sinh\phi \\ -\sinh\phi & \cosh\phi \end{pmatrix} \begin{pmatrix} t \\ z \end{pmatrix}$$

$$\cosh\phi = \gamma = \frac{1}{\sqrt{1-v^2}}$$

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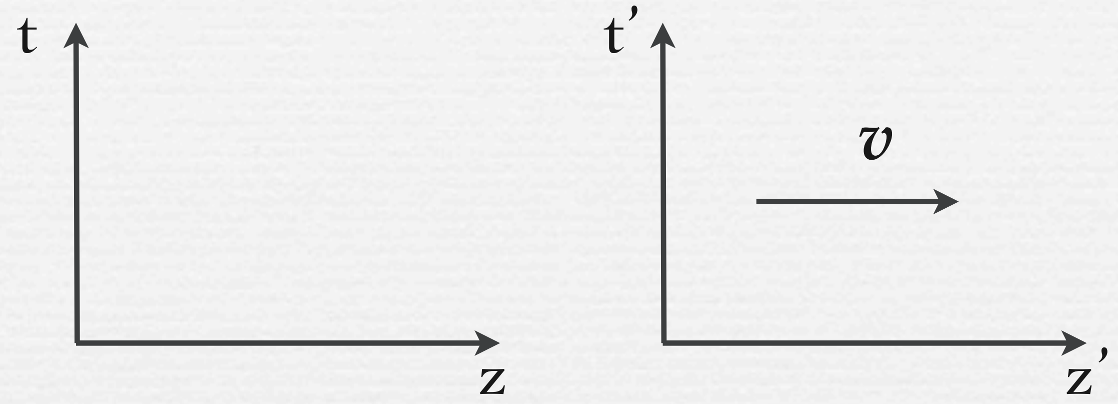

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light-cone coordinates

$$z_\pm = (t \pm z)/\sqrt{2}$$

$$p_\pm = (E \pm p_z)/\sqrt{2}$$

boost along z

$$z_\pm \to e^{\pm\phi} z_\pm$$

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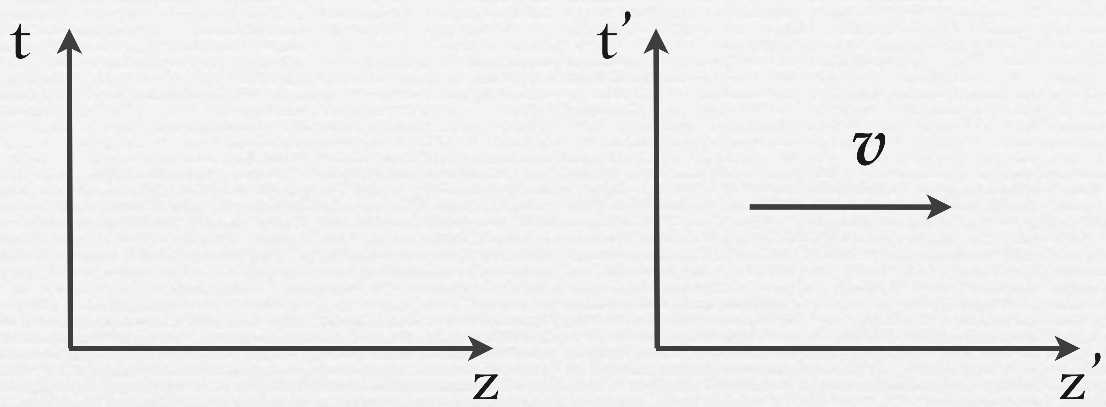

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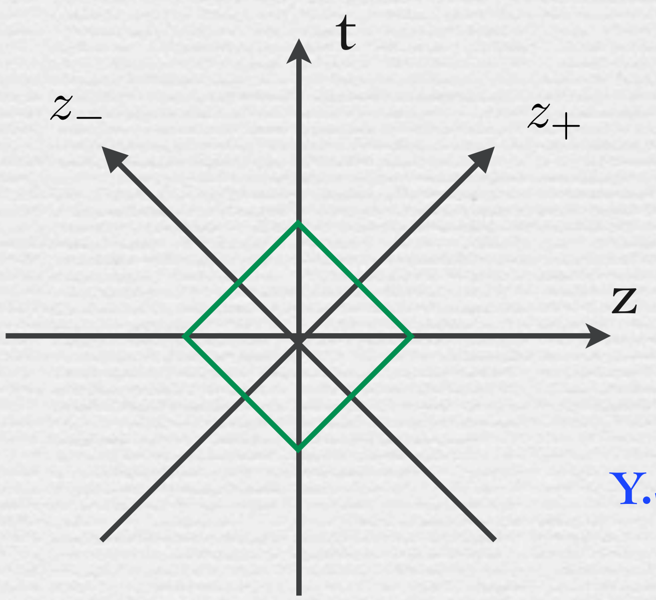
Boosts as area
preserving transformations

$$z_+ z_- \to e^{+\phi} z_+ \, e^{-\phi} z_- = z_+ z_-$$



Y.S.Kim PRL 63, 348 (1989)

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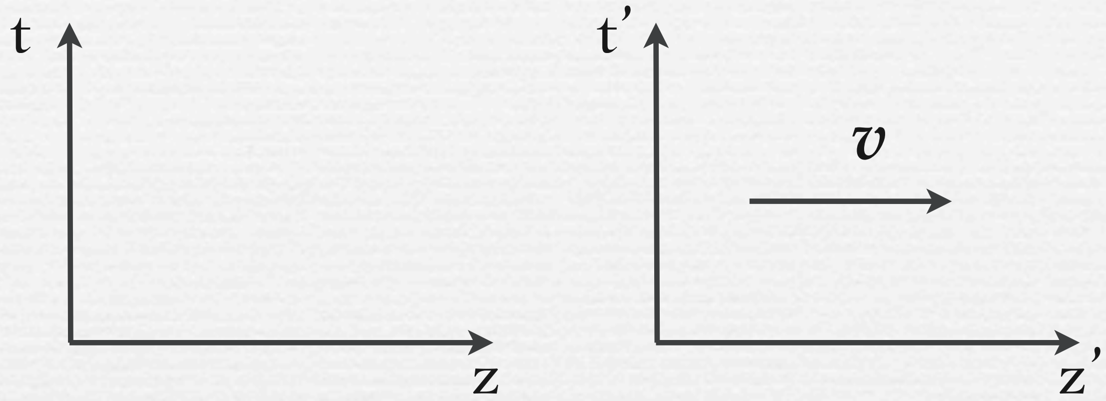

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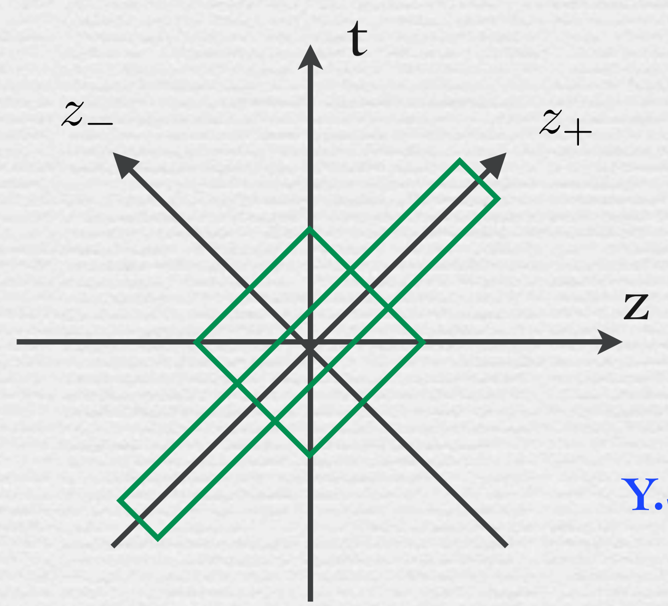
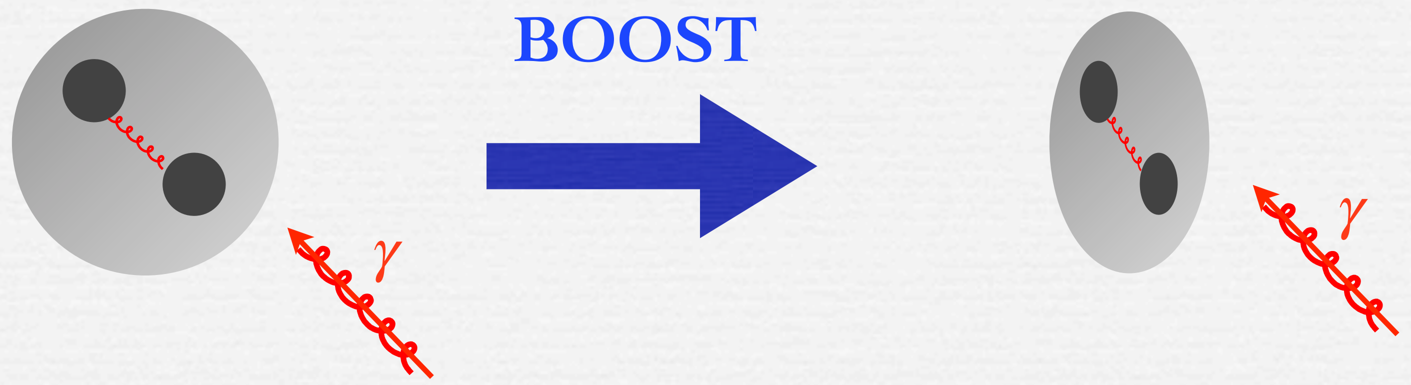


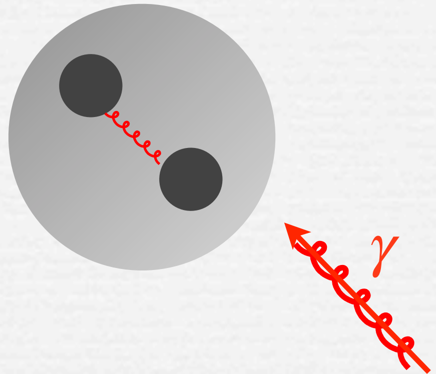
Y.S.Kim PRL 63, 348 (1989)

System is at rest

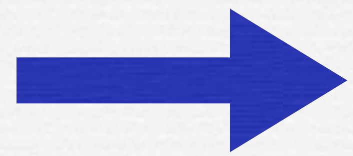


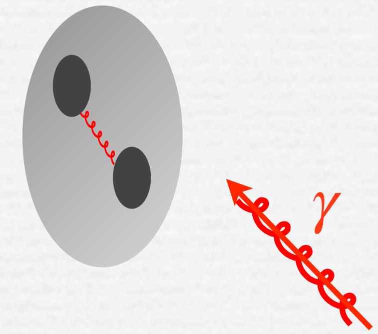
Boosted system

System is at rest



BOOST





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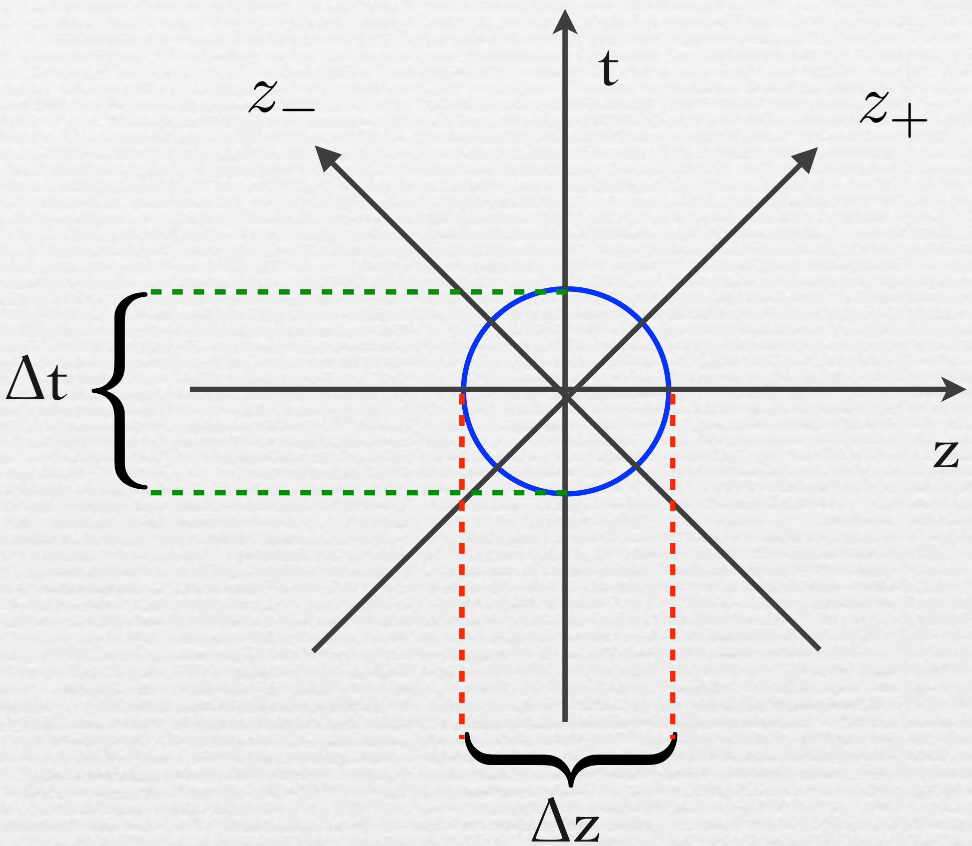
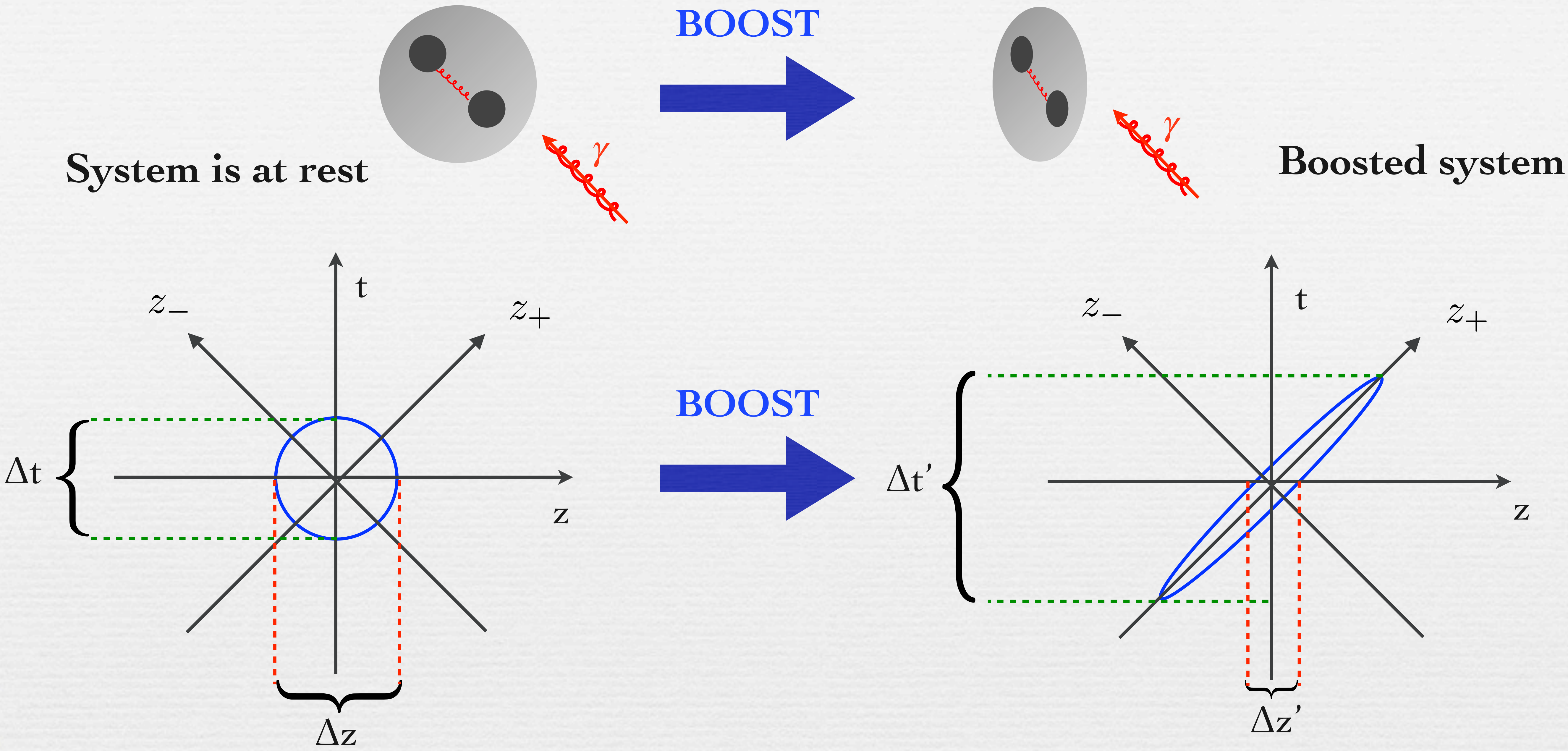
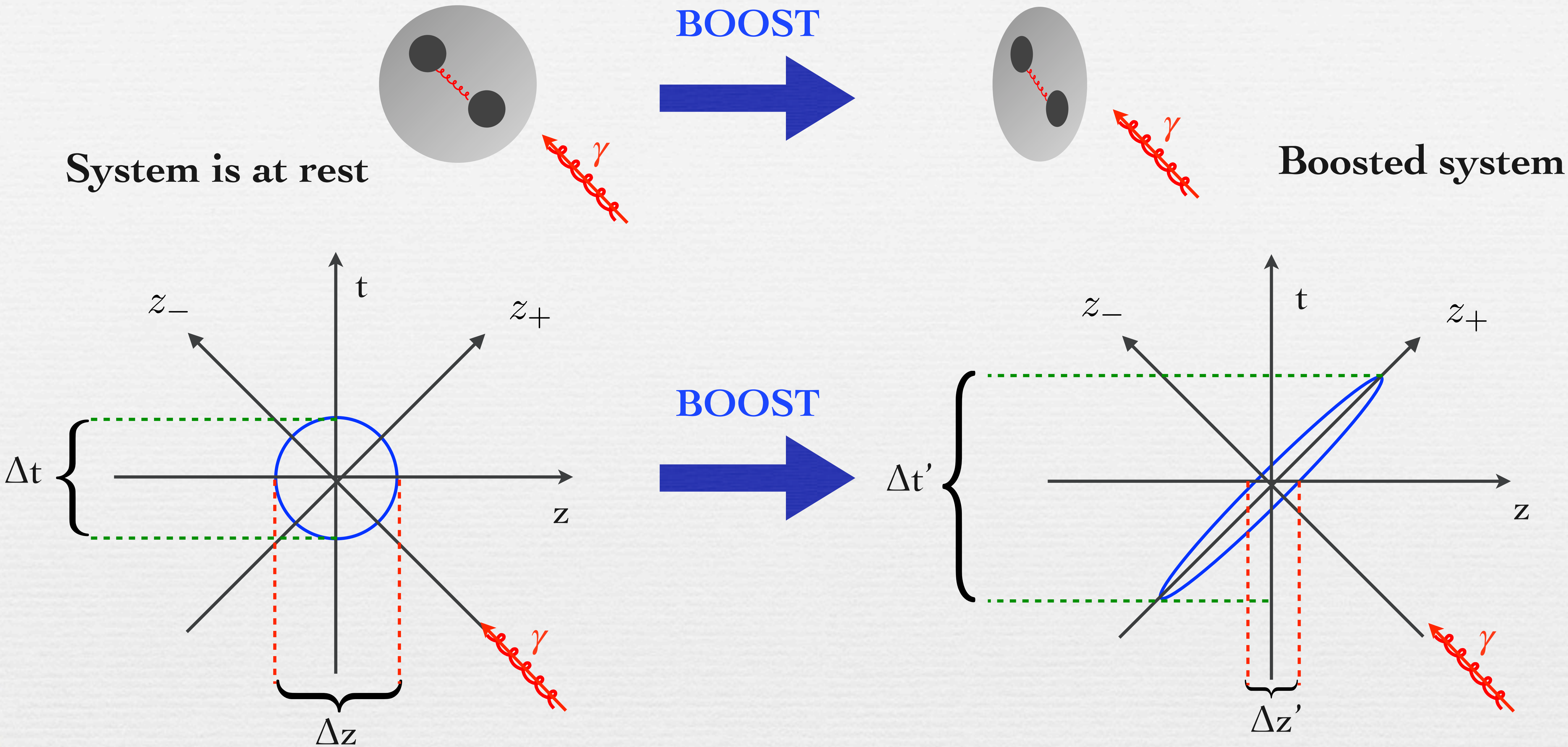
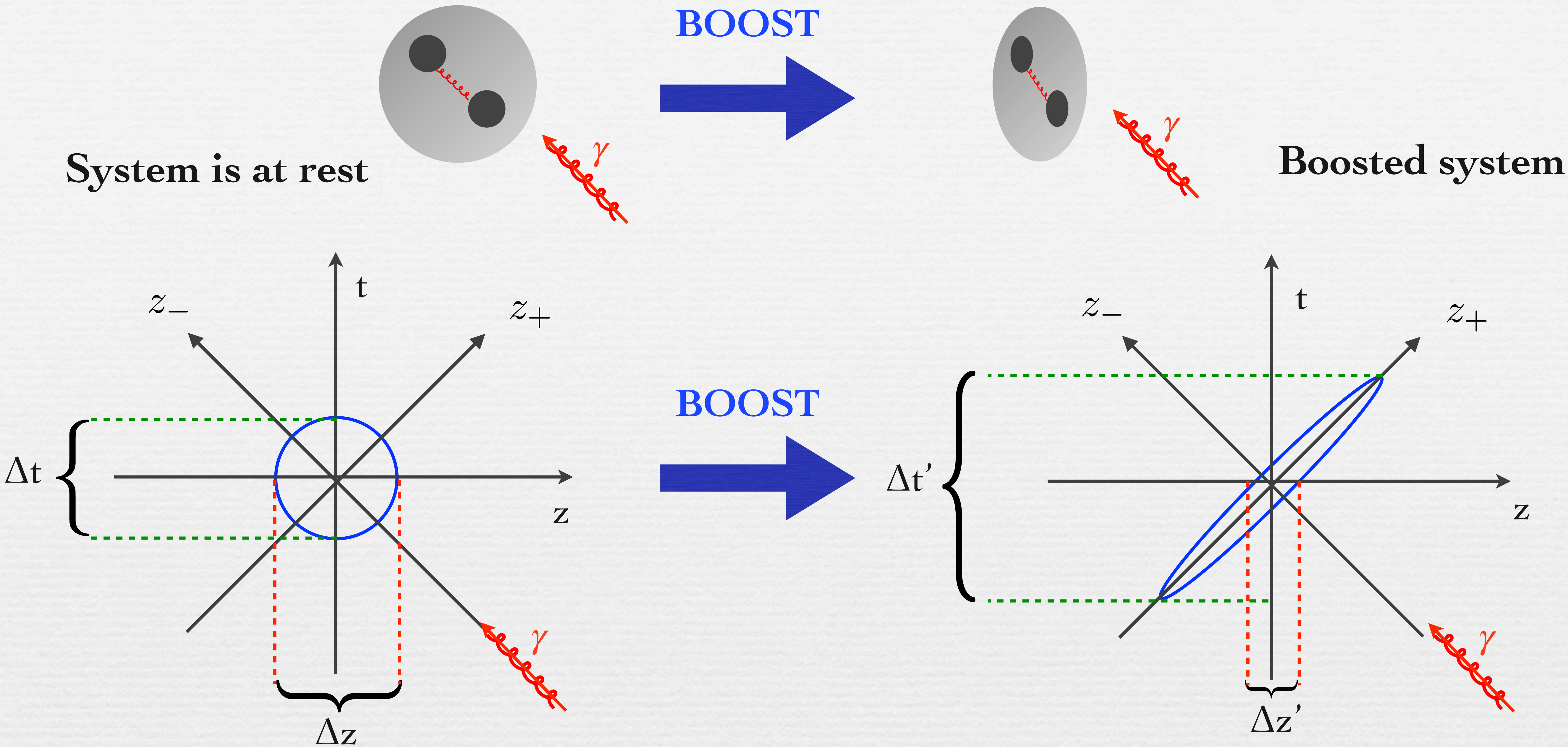



BOOST
System is at rest
γ
Boosted system
t
z_-
z_+
z
Δt
Δz
BOOST
Δt'
Δz'



The photon sees two heavy quarks interacting by a spring.
Effective description: massive constituent quarks in a harmonic potential

The photon sees a harmonic oscillator with a small spring tension.
Effective description: interacting system of massless particles (partons).



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The partonic description holds only in the frame in which the nucleon moves at high speed.
IMF: infinite momentum frame, nucleons have velocity close to *c*

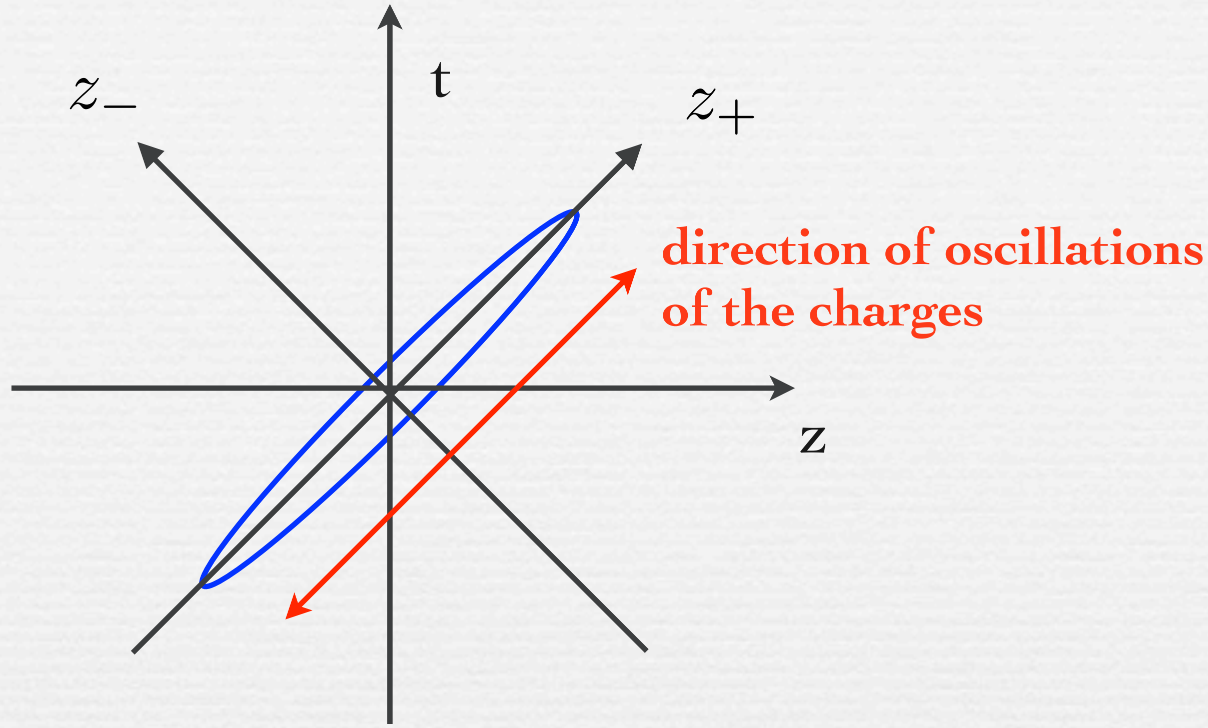
SATURATION AND “COLOR GLASSES”

Basic references

Gribov, Levin, Ryskin, Phys. Rep.100 (1983),1
McLerran, Venugopalan, Phys.Rev. D 49 (1994) 2233, 3352; D50 (1994) 2225
A.H. Mueller, hep-ph/9911289

See also M. Nardi http://oldsite.to.infn.it/qgp/lect05/CGC.ppt

Oscillating partons produce currents



Partons have **color charge**. The associated current is $J^{\mu}_{a} = \delta^{\mu +}\delta(z^{-})\rho_a(x,y)$

Given the time dilation, the charge distribution is "frozen" but changes from event to event

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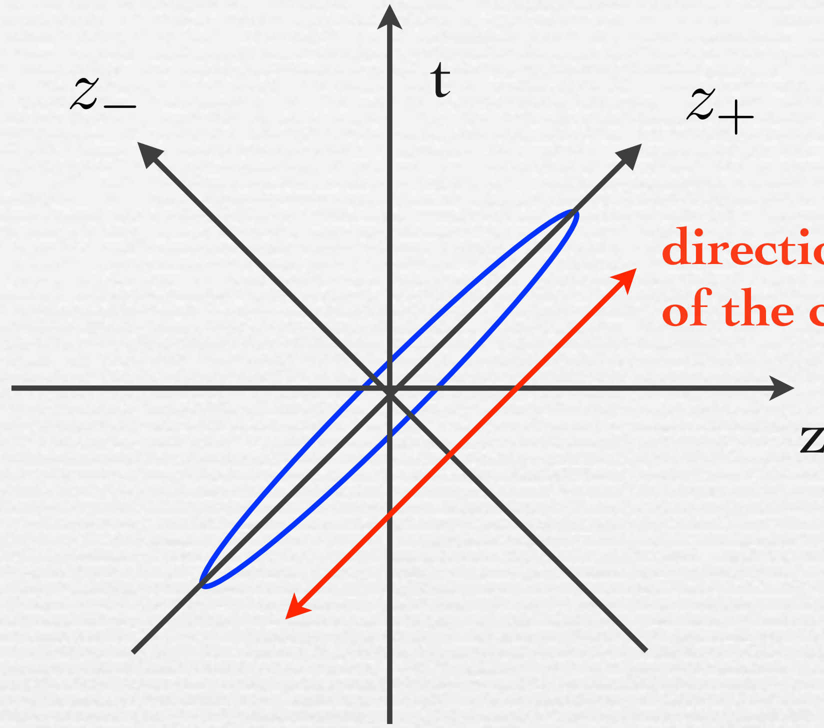

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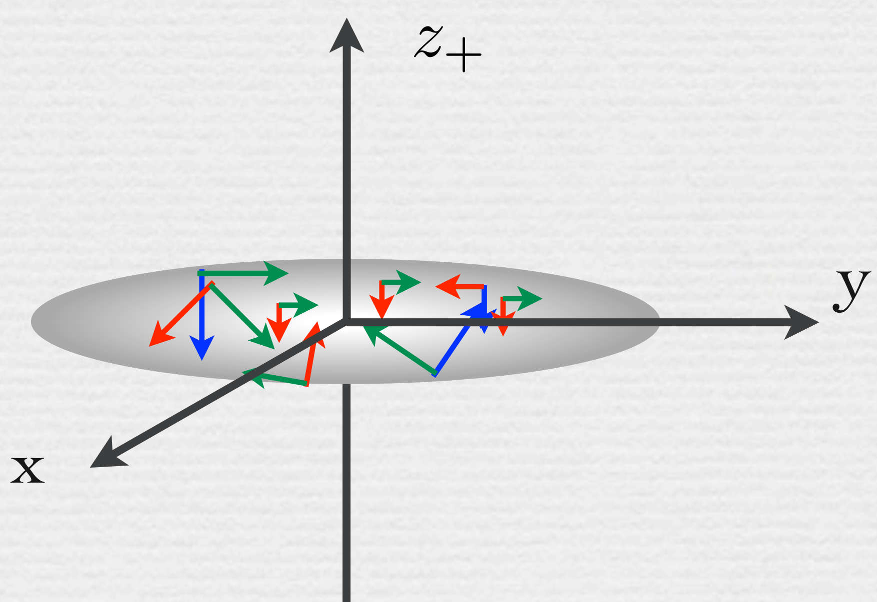
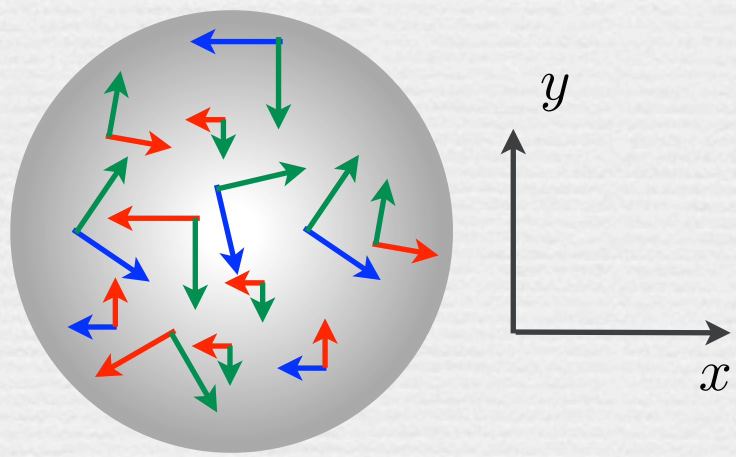


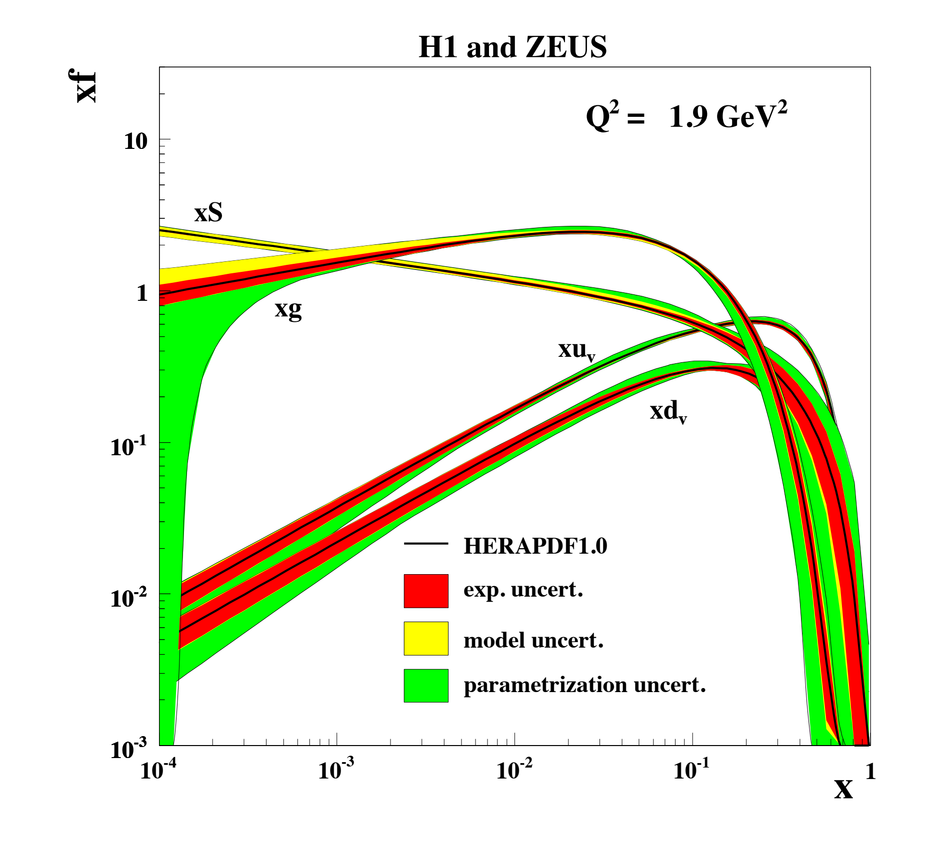


Gauge fields are generated in the x-y plane

CAN WE SEE ALL OF THIS?

Deep inelastic scattering gives information on the content of a nucleon.

The information depends on the energy of the probe.



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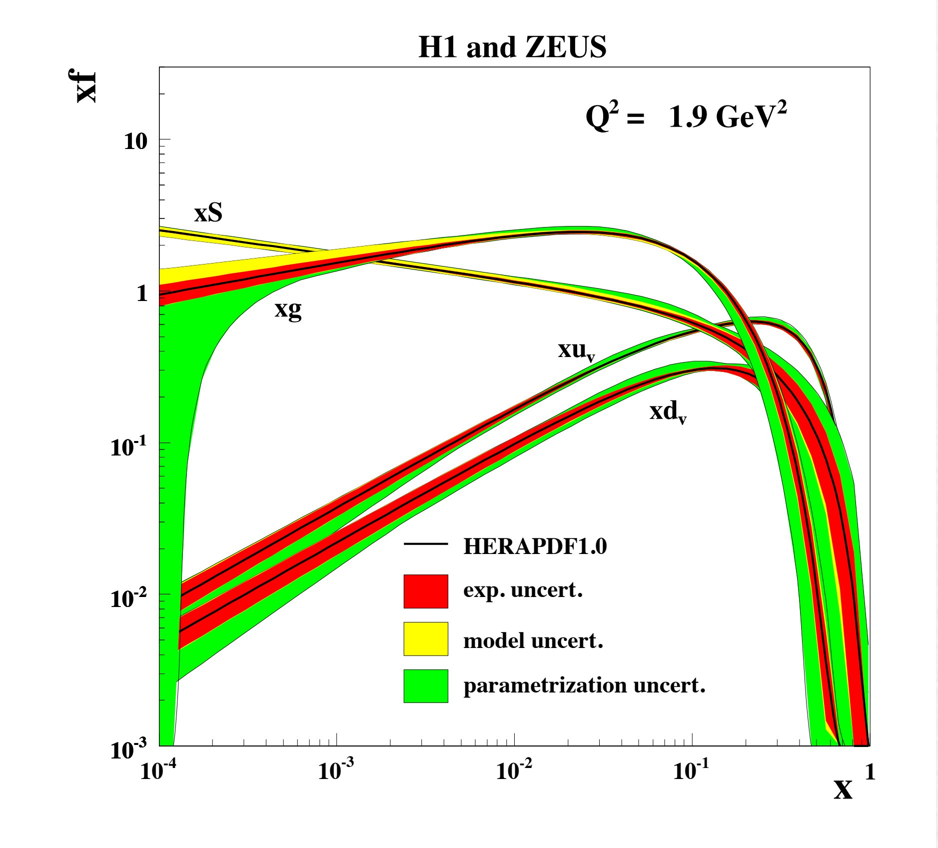

f(x) parton distribution function: probability that the hit parton has a fraction x of the proton momentum

$$\sum_i \int dx\, x\, f_i(x) = 1$$

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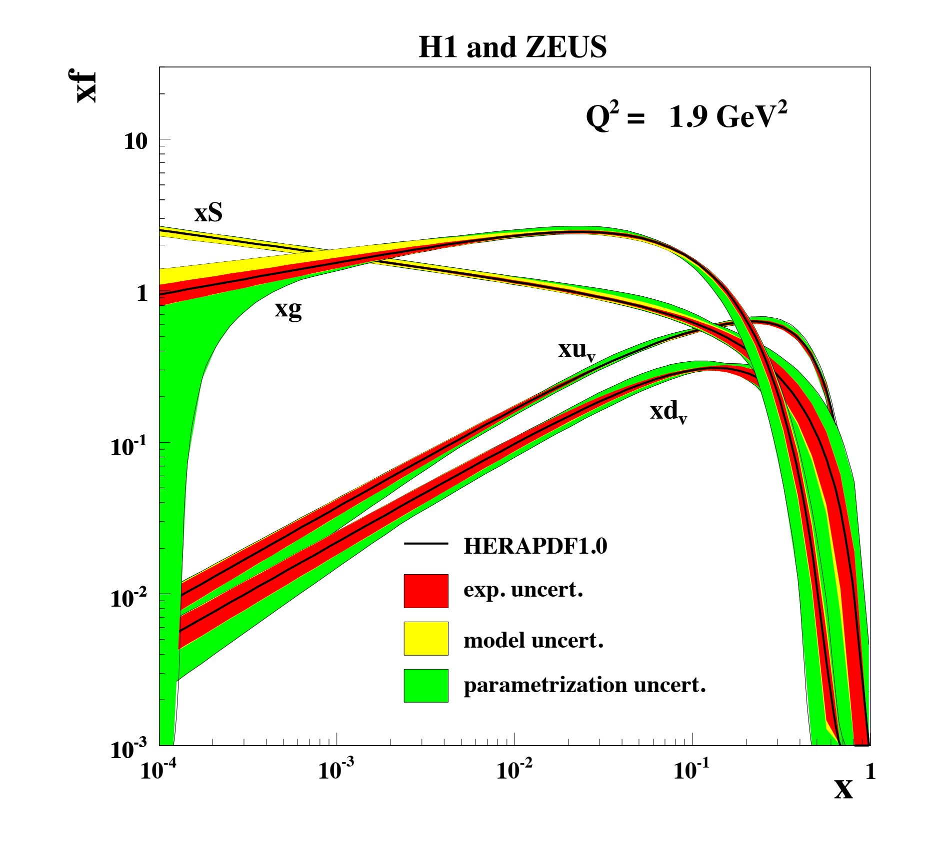

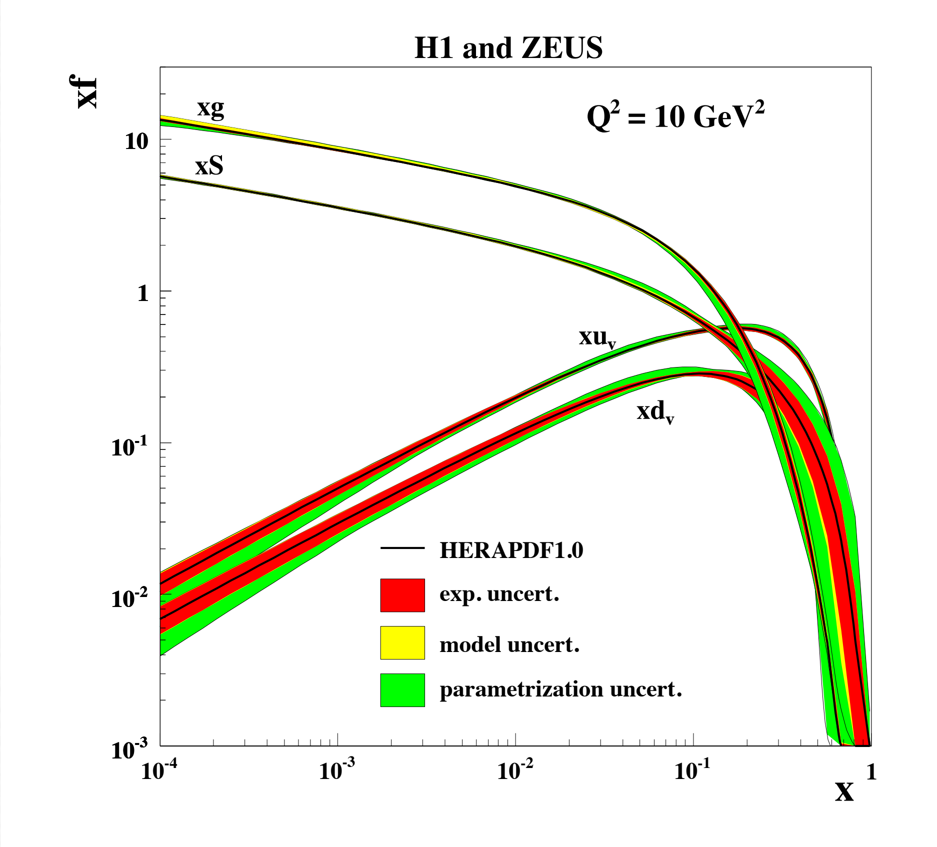

At large virtuality (large **Q**) and small x there are mostly gluons (and sea quarks)

The CGC is a description of the nucleon at small x and large Q

First remarks on the Color Glass Condensate (CGC):

The CGC is a description of relativistic nuclei

- By a particular kinematic observer (moving at infinite velocity)

- In a particular range of energies (larger than the confining scale)

- For a particular class of processes (when collective gluonic phenomena are relevant)

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What do heavy ion collision tell?

Ultrarelativistic heavy ion collision

STANDARD DESCRIPTION

$t = -1\mathrm{fm}$

Ultrarelativistic heavy ion collision

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$t = -1\text{fm}$

$t = 0$

Ultrarelativistic heavy ion collision

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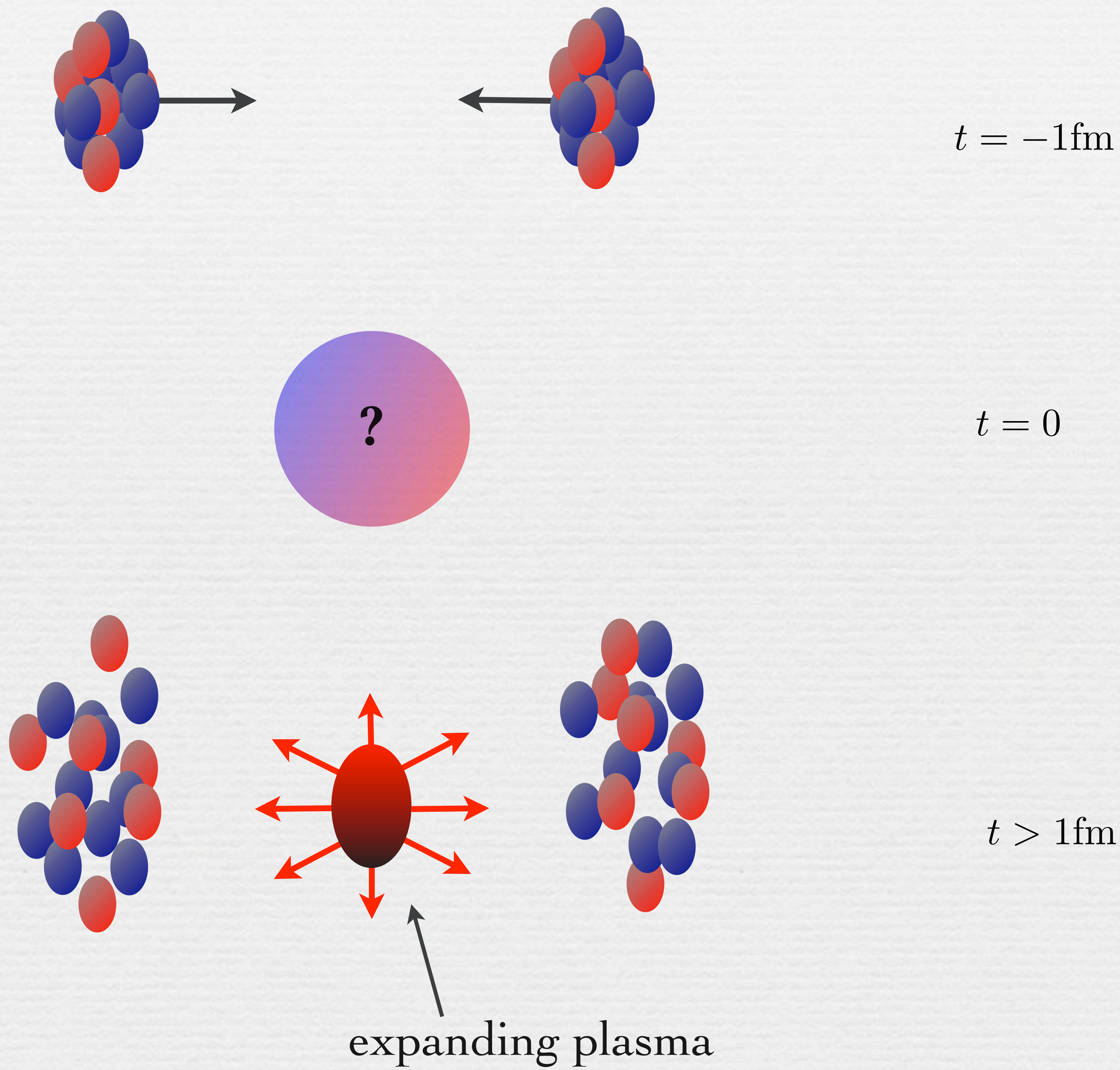
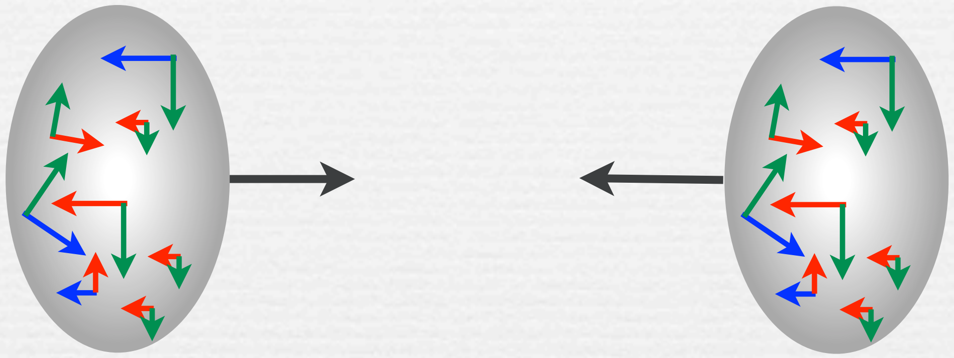


Ultrarelativistic heavy ion collision

CGC+GLASMA DESCRIPTION



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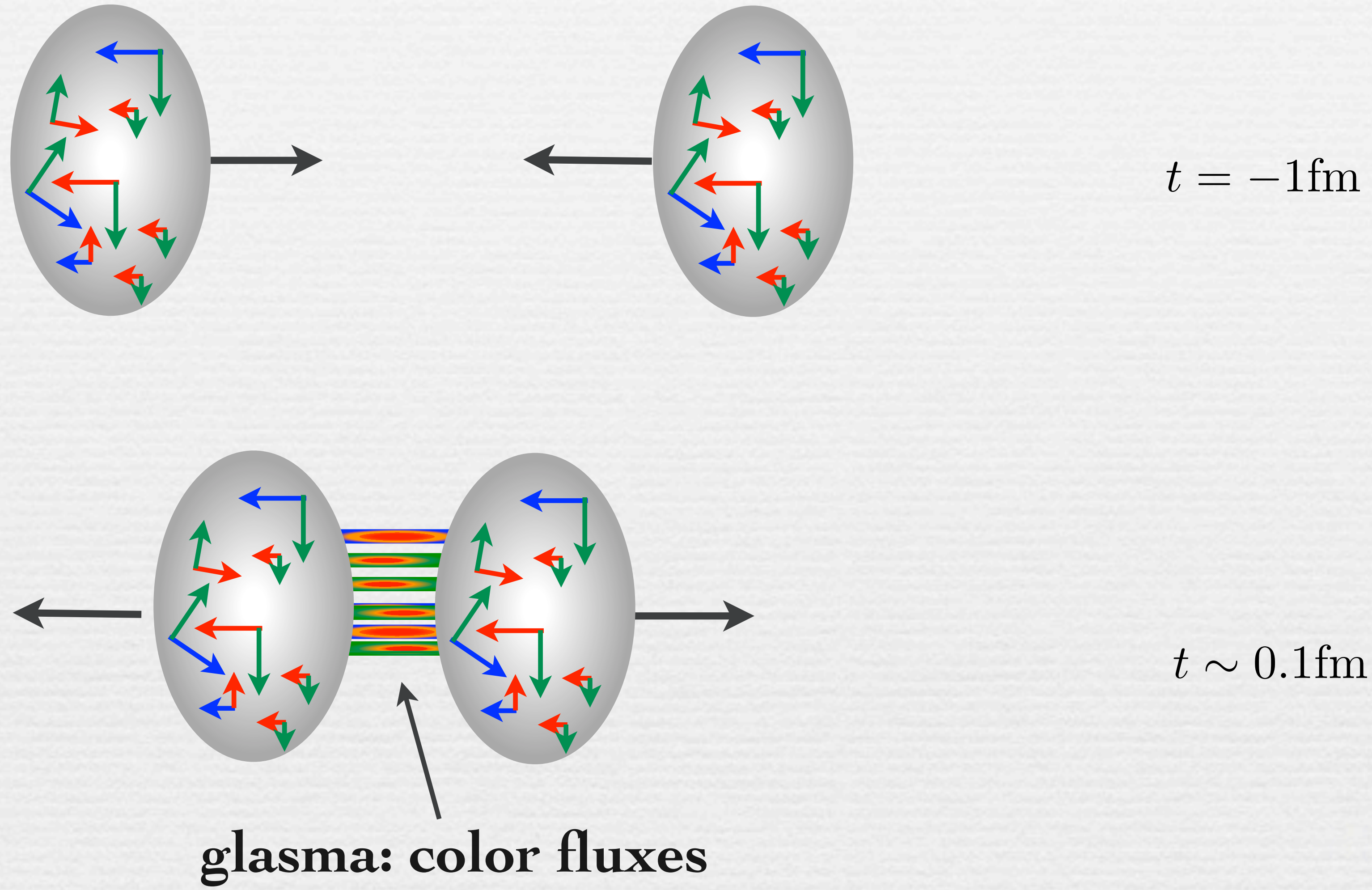
CGC+GLASMA
DESCRIPTION



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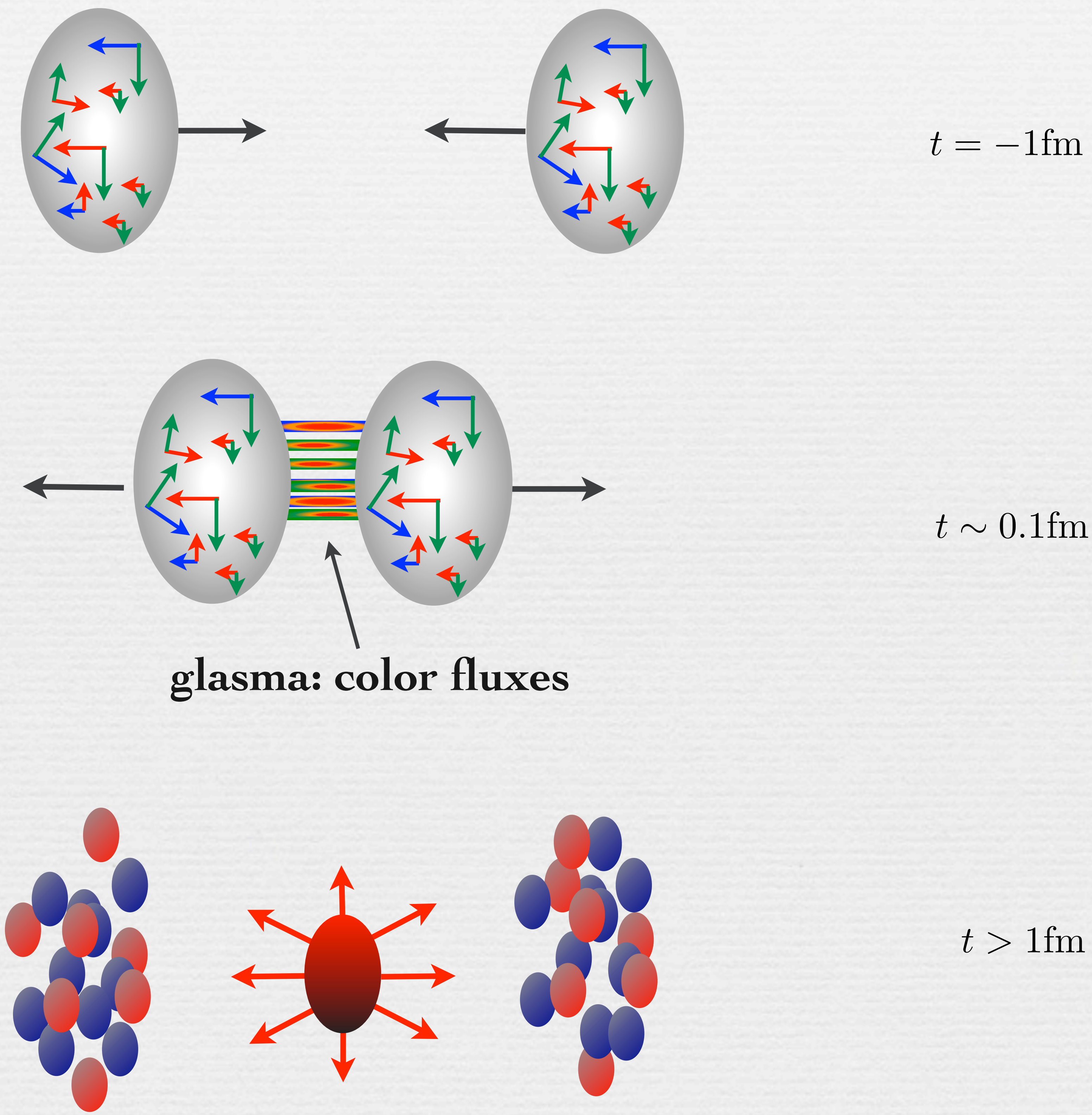
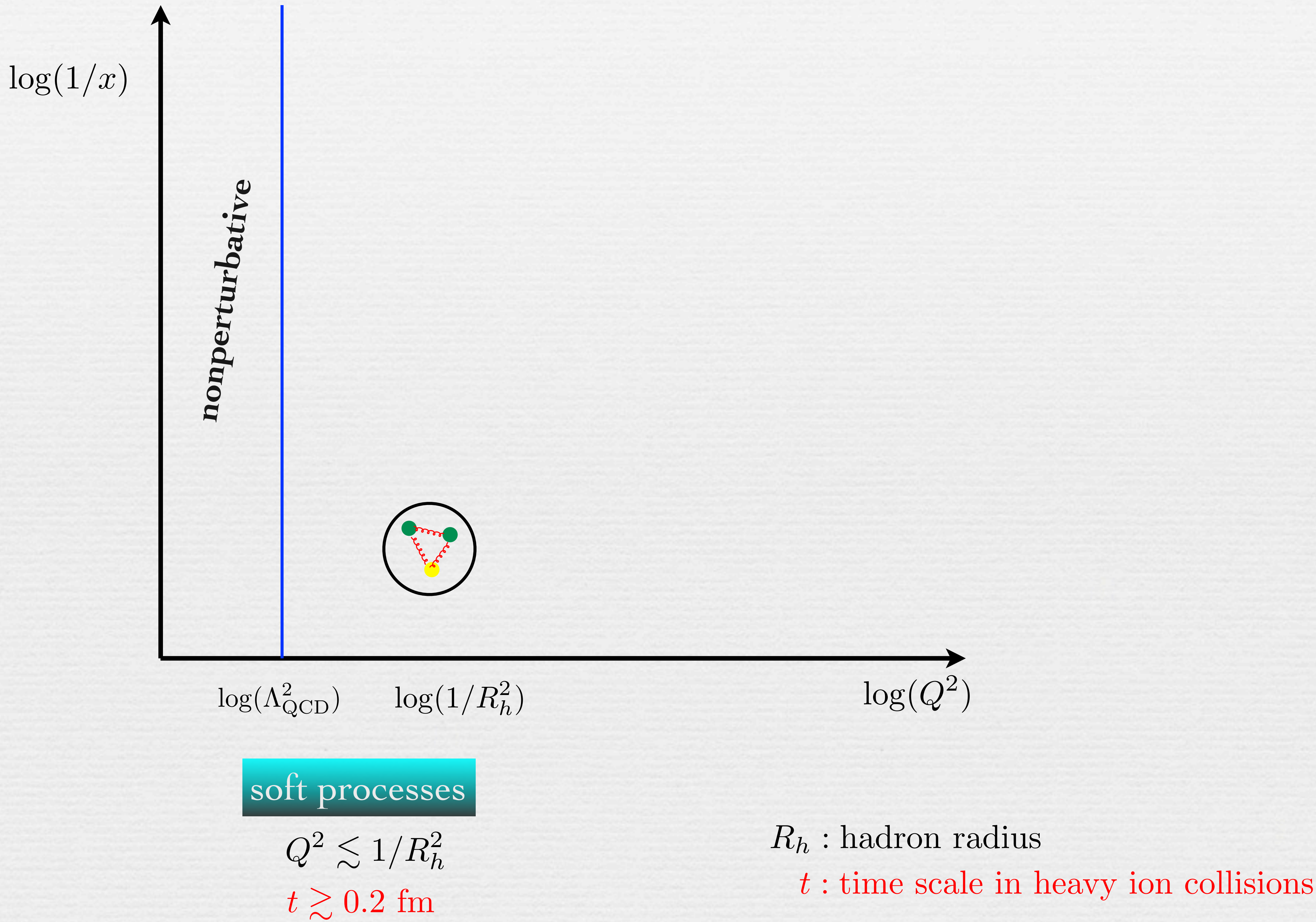
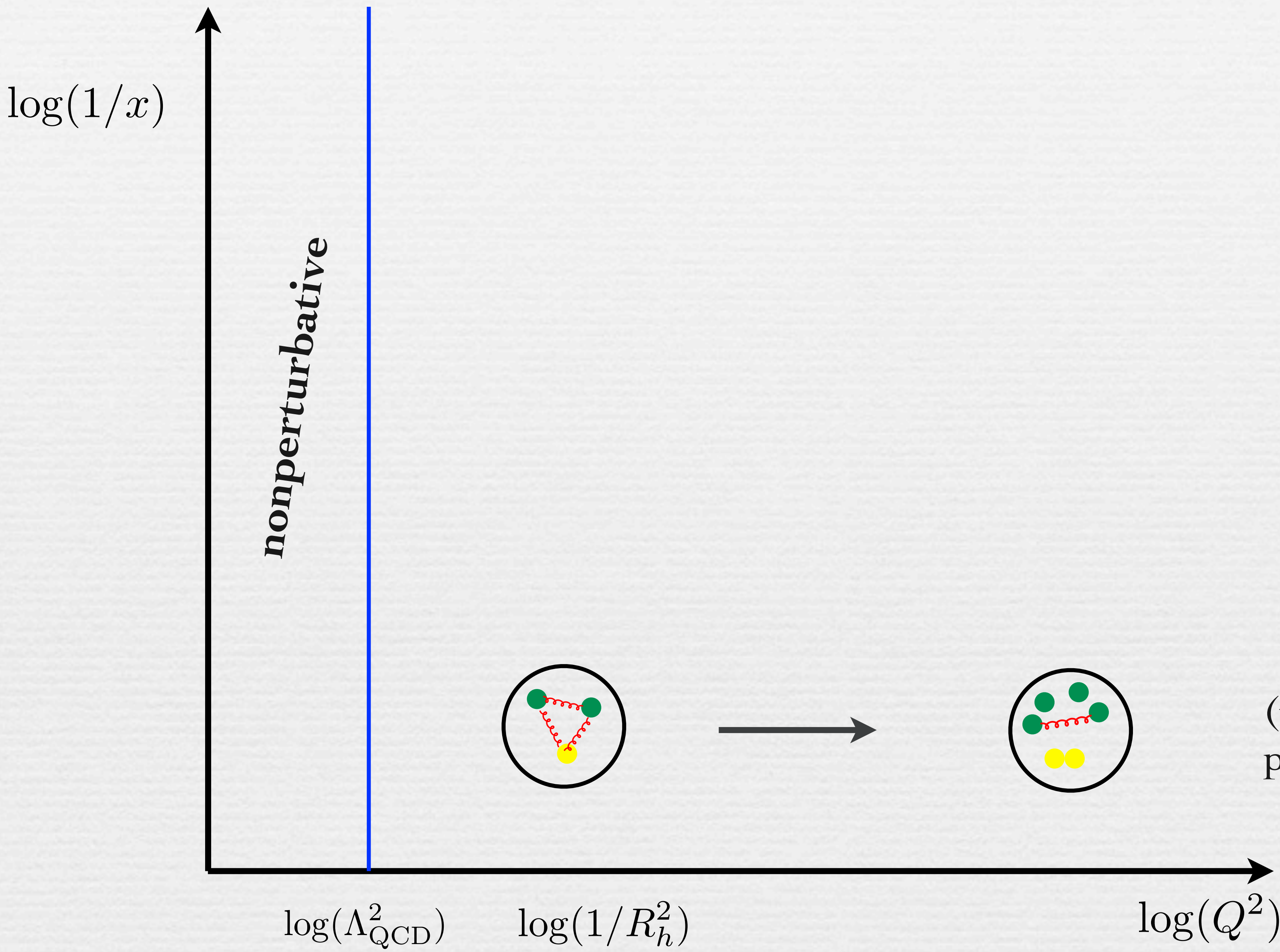




$\log(1/x)$
nonperturbative
$\log(\Lambda^2_{\rm QCD})$
$\log(1/R_h^2)$
$\log(Q^2)$
soft processes
$Q^2 \lesssim 1/R_h^2$
$t \gtrsim 0.2$ fm
R_h : hadron radius
t : time scale in heavy ion collisions



hard processes

$x \sim 1$

$t \lesssim 0.1$ fm

(the virtual probe hits one single parton)

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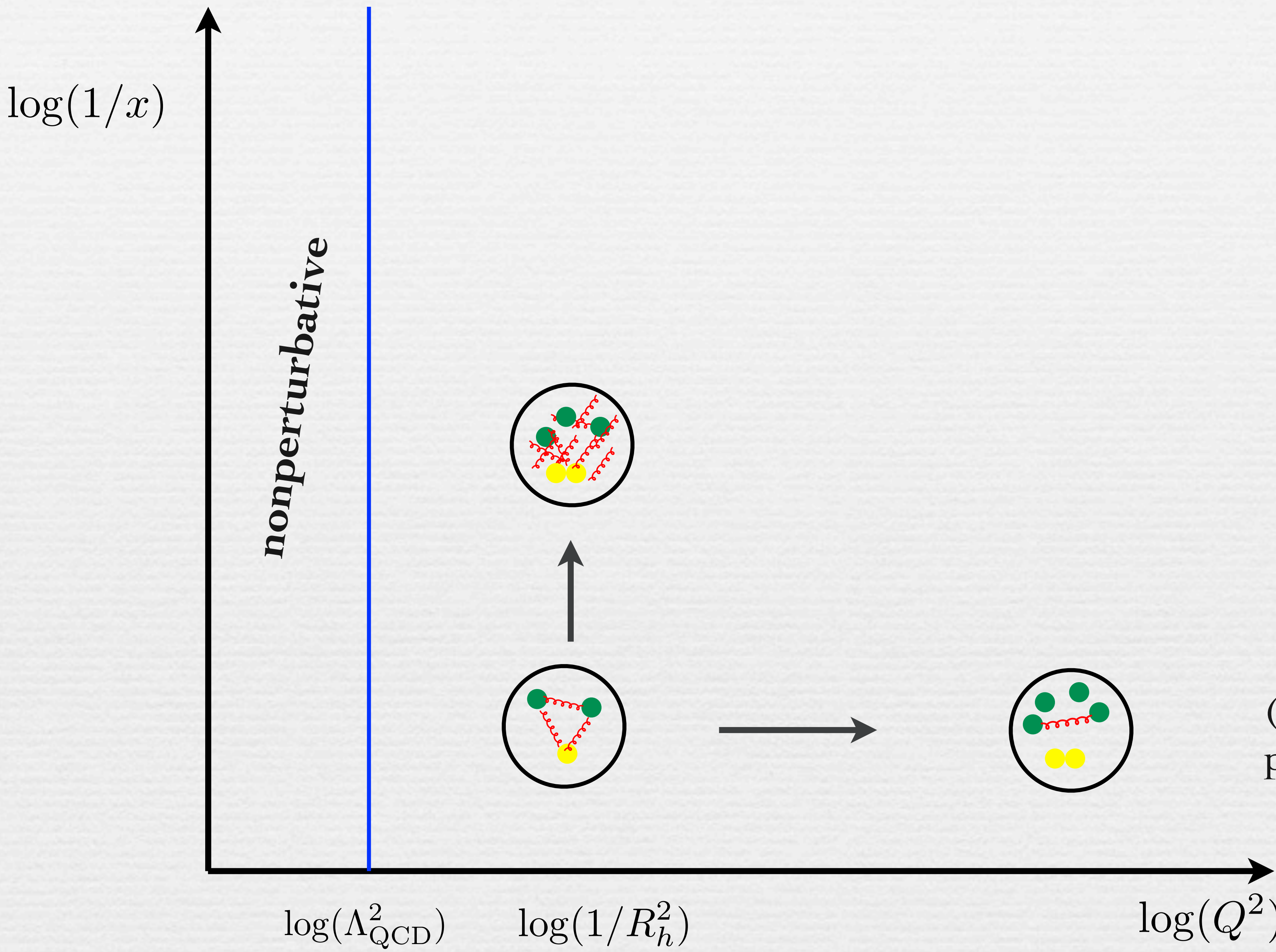

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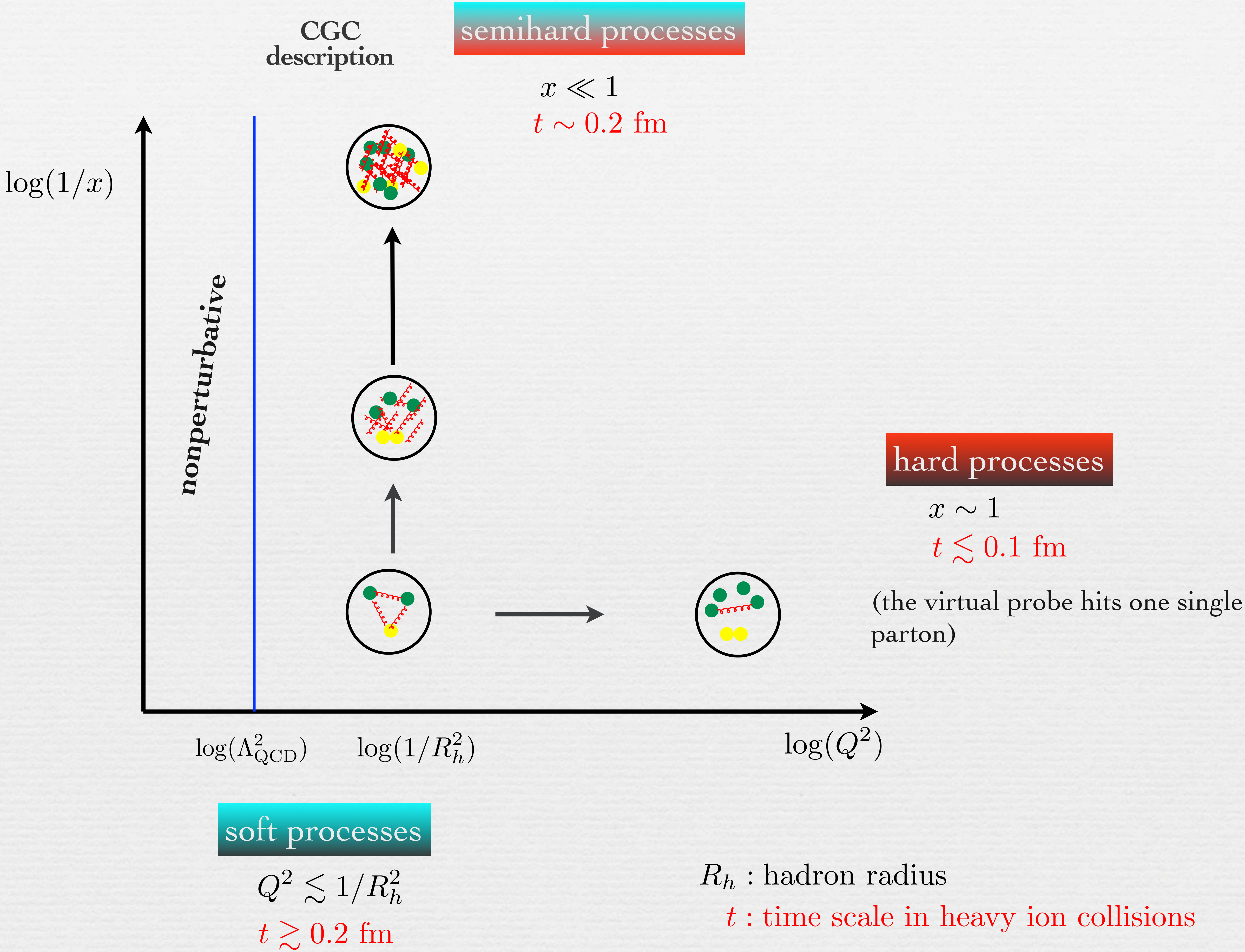

CGC description
semihard processes
$x \ll 1$
$t \sim 0.2$ fm
$\log(1/x)$
nonperturbative
hard processes
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$t \lesssim 0.1$ fm
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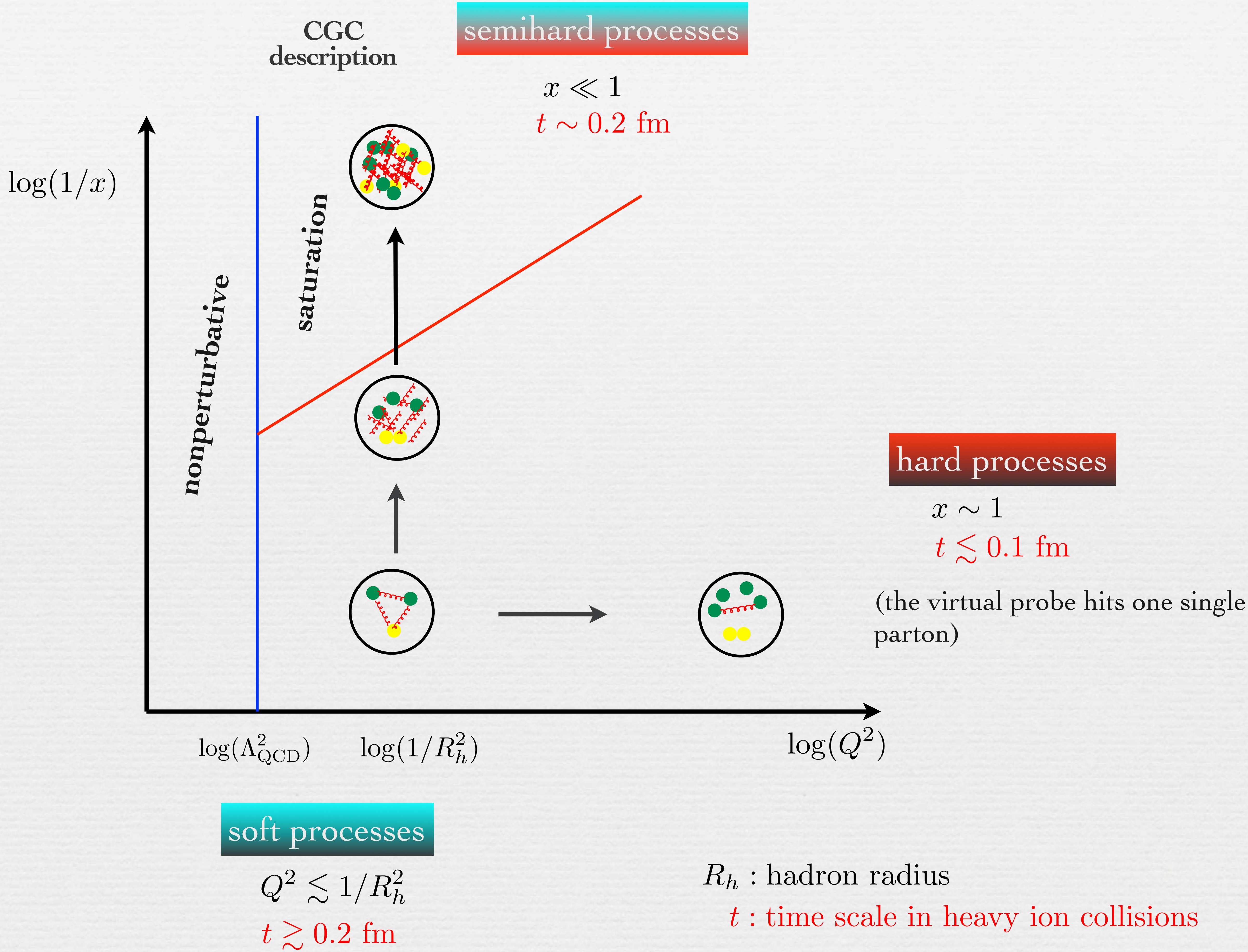

CGC description
semihard processes
$x \ll 1$
$t \sim 0.2$ fm
$\log(1/x)$
saturation
nonperturbative
hard processes
$x \sim 1$
$t \lesssim 0.1$ fm
(the virtual probe hits one single parton)
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EVOLUTION AS REACTION-DIFFUSION

The mean field evolution of the average number of gluons is determined by the **Balitsky-Kovchegov (BK)** equation

$$r \equiv \log(k_\perp^2)$$

$$\frac{\partial n}{\partial y} \simeq \omega \alpha_s n + \chi \alpha_s \nabla_r^2 n - \beta \alpha_s^2 n^2$$

Analogous to the Fisher-Kolmogorov-Petrovsky-Pisconov **(FKPP)** describing the evolution of a system with **chemical reactions** and **diffusion**.

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change of the number of gluons as a result of a change in rapidity $y \sim \log(1/x)$

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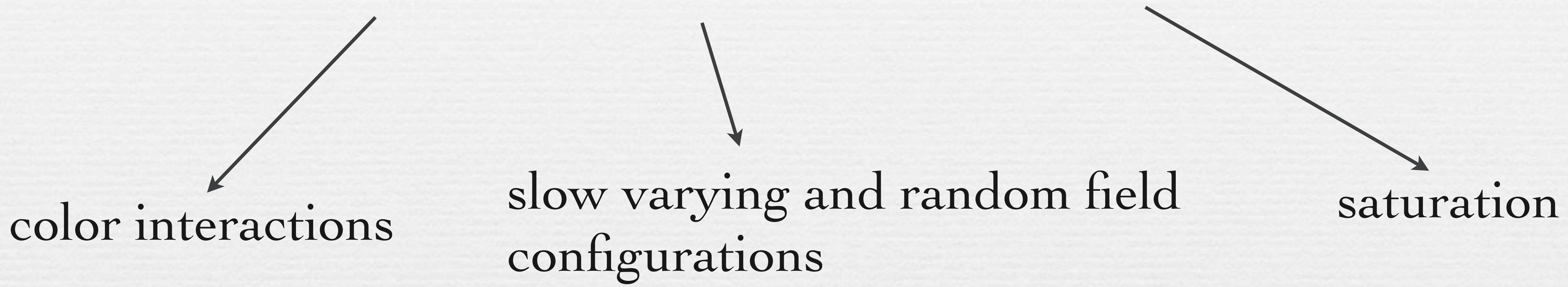
change of the number of gluons as a result of a change in rapidity $y \sim \log(1/x)$

$\bar{n} = \omega/(\alpha_s \beta)$ **fixed point of the FKPP/BK. Here saturation stops**

Q_s typical $k_\perp$ at which saturation happens

The CGC is a description of relativistic nuclei: it describes the system before the relativistic heavy ion collision takes place

"COLOR GLASS CONDENSATE"



The CGC is a description of relativistic nuclei: it describes the system before the relativistic heavy ion collision takes place

"COLOR GLASS CONDENSATE"

color interactions

slow varying and random field configurations

saturation

SEMIQUANTITATIVE DESCRIPTION

1) *Saturated system of gluons*

2) *EFT with a separation of scale in x*

3) *Evolution with diffusion-like equation*

WHAT IS A GLASS?

"Amorphous solid"

In general the large viscosity does not allow the atoms to reach their equilibrium crystalline configuration

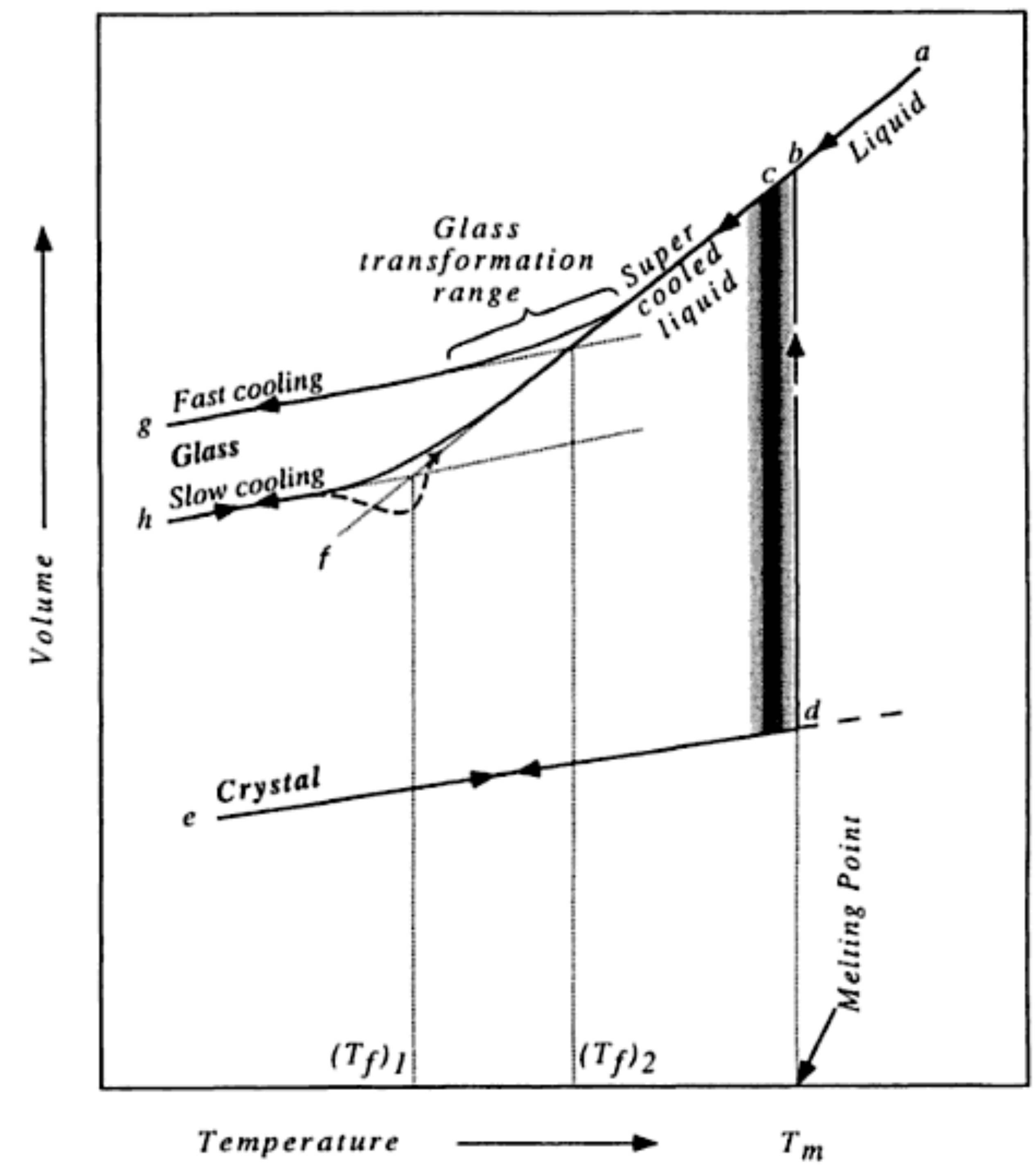


Figure 2-1. The volume–temperature diagram for a glass-forming liquid.

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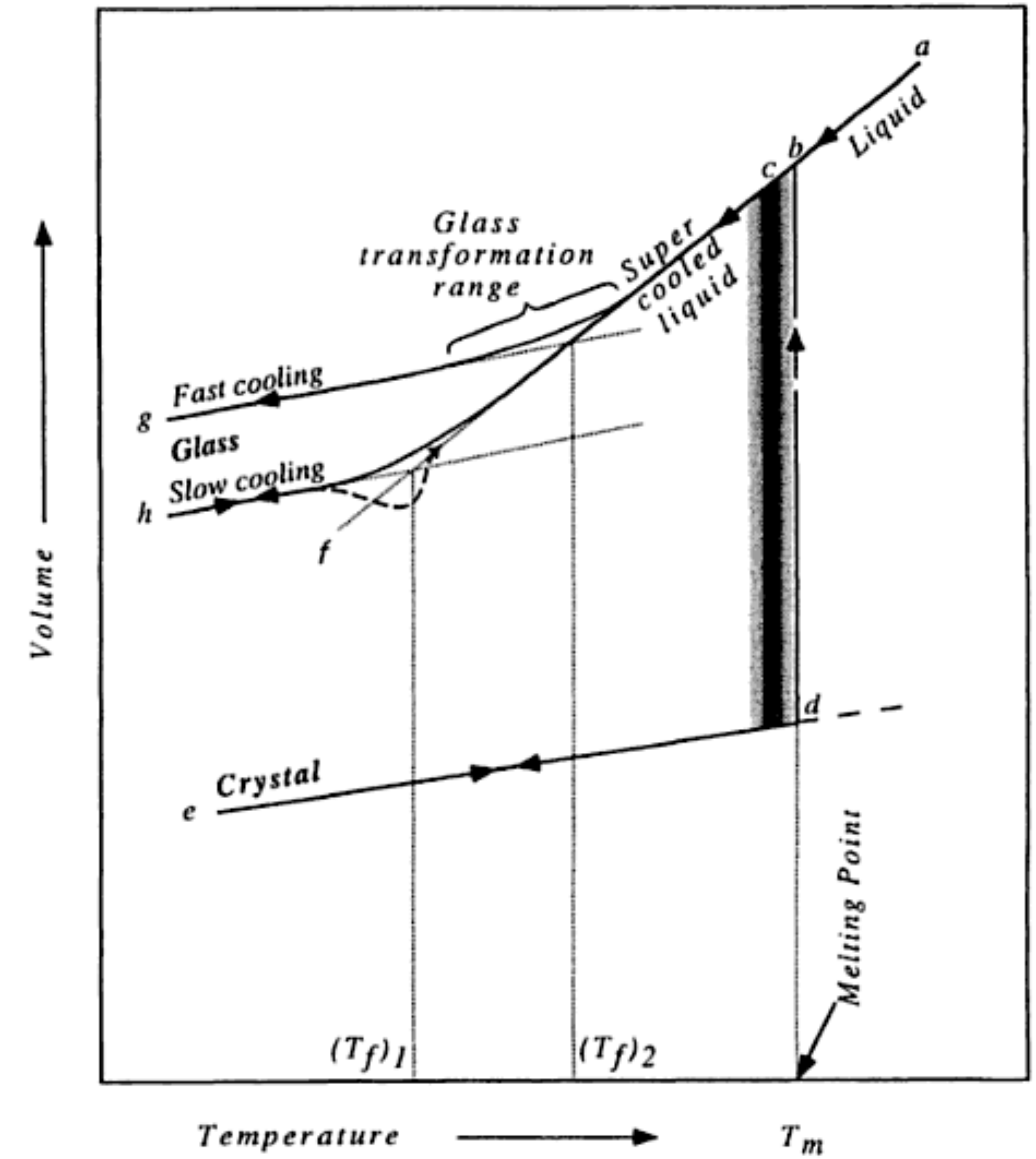
Thermodynamically metastable
it can make a transition to the crystalline phase in any moment



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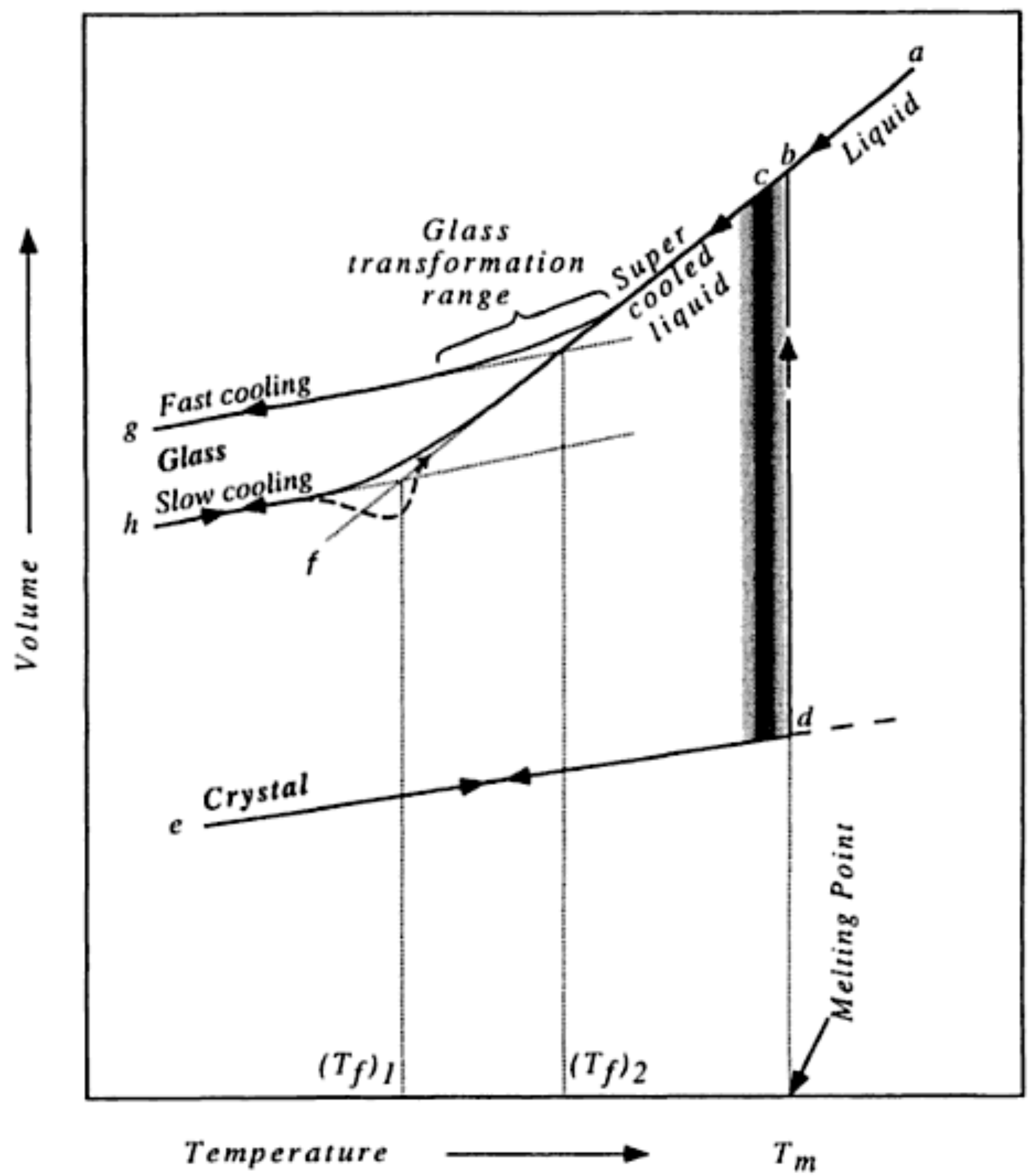


Figure 2-1. The volume–temperature diagram for a glass-forming liquid.

The Color Glass Condensate does not have these features

PHENOMENOLOGY

High energy processes: electron-nucleus DIS, Heavy Ion collisions (J/Psi, Collective phenomena, particle yields..)

Examples of work done by our colleagues

J/Psi production M. Nardi et al. Phys.Rev.Lett. 102 (2009) 152301, Nucl.Phys. A826 (2009) 230-255

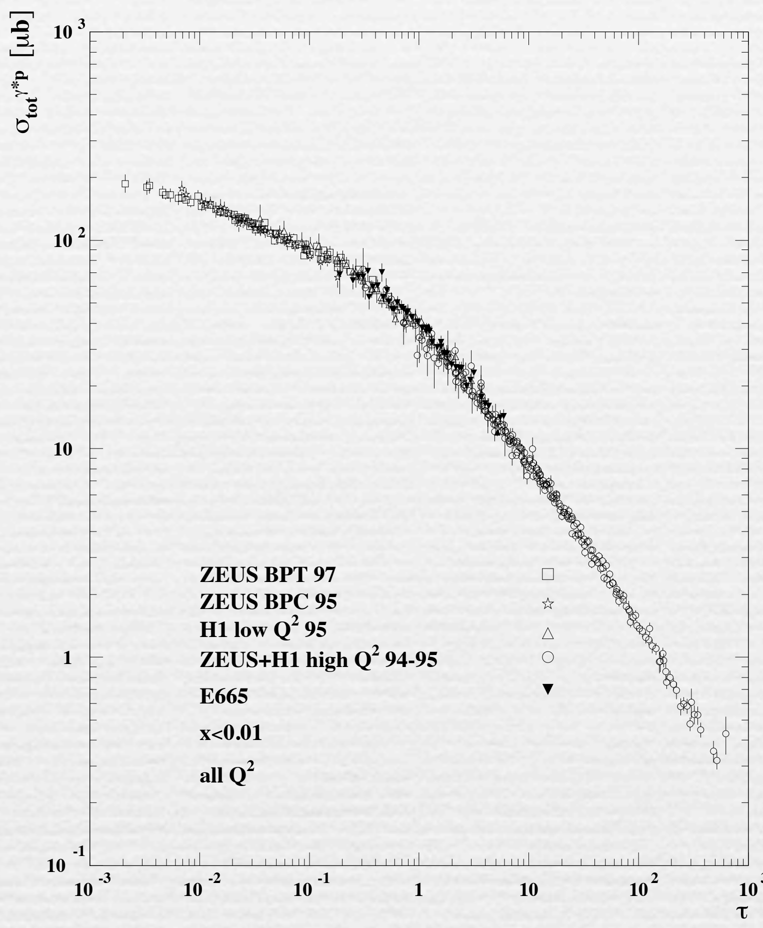
Collective Flow study M. Ruggieri, F. Scardina, S. Plumari, V. Greco, Phys.Lett. B727 (2013) 177-181

GEOMETRICAL SCALING

A. M. Stasto et a. Phys. Rev. Lett. 86 (2001) 596

DIS electron-proton data of HERA at small x depend only on

$$\tau = Q^2 R_0(x)^2 \propto Q^2 x^\lambda$$



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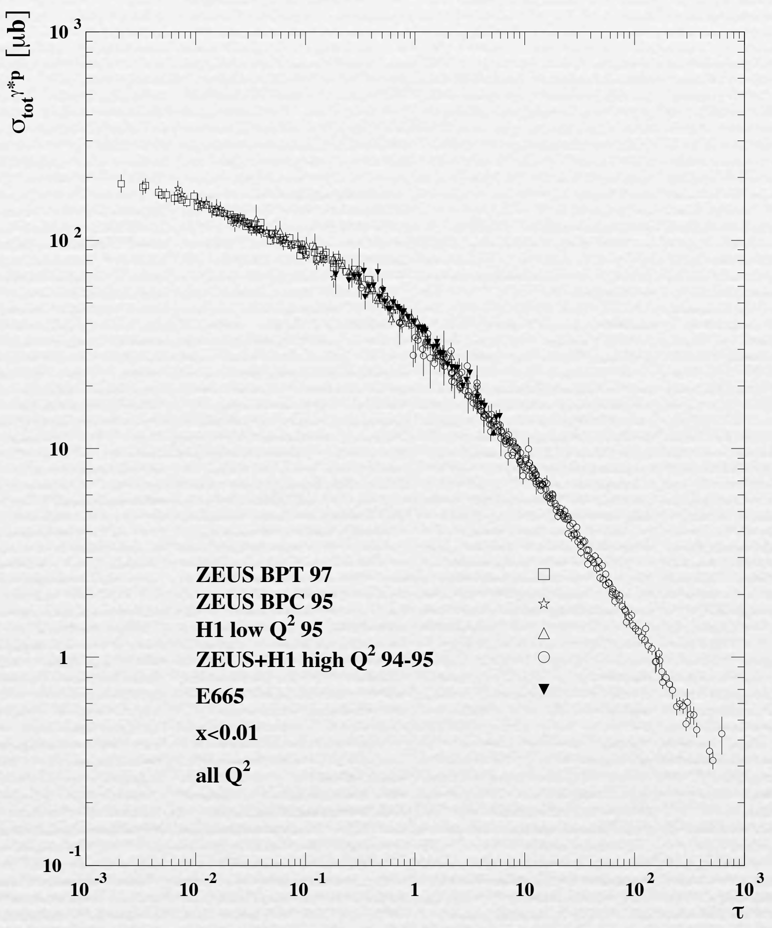

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"saturation interpretation": exists an internal scale $Q_{\rm sat}(x) = 1/R_0(x)$

For geometrical scaling at RHIC and LHC, see C. Klein-Bösing, L. McLerran 1403.1174

Conclusions

- *The description of matter depends on the thermodynamic state, on the energy of the probe and on the kinematic state of the observer*
- *Quark and gluon condensates are predicted by QCD (but yet they need some work)*
- *The CGC describes the state of relativistic nuclei before the collision*
- *There are experimental indications of the CGC*

BACKUP

What is hadronic matter

Def. Hadrons are all the strongly interacting particles (L.B.Okun)

composite hadrons
- Baryons: protons, neutrons, ...
- Mesons: pions, kaons, ...

elementary hadrons
- Quarks: up, down, strange, charm, bottom, top
- Gluons: 8 vector bosons

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Elementary strong interactions are described by quantum chromodynamics (QCD)

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Elementary strong interactions are described by quantum chromodynamics (QCD)

fundamental concepts

- QCD is a confining theory
- QCD is a non abelian asymptotically free theory

QCD is a confining theory

Low energy nuclear physics

Mass of a nucleus: mass of nucleons - binding energy

Nuclei are bound states of nucleons (protons and neutrons)

- **There exist processes that break heavy nuclei to lighter nuclei**

Low energy nuclear physics

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Nucleons are not bound states of quarks

Talking about the binding energy of quarks in a nucleon is nonsense

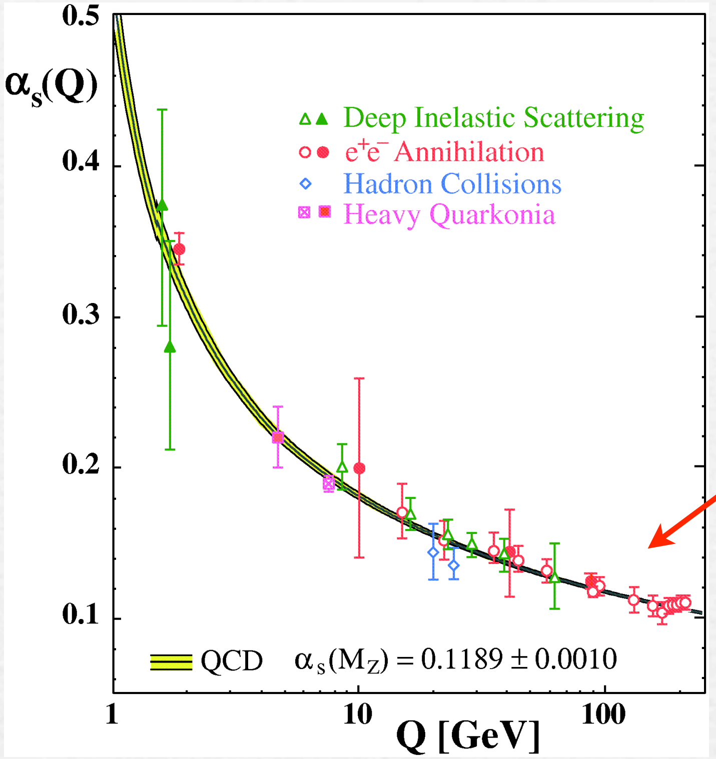
$$m_u \simeq m_d \simeq 5 \text{ MeV} \qquad\qquad M_{\rm p} \simeq 1 \text{ GeV}$$

A nucleon is a confined state of quarks and gluons

- **We cannot break a nucleon in a lighter object.**

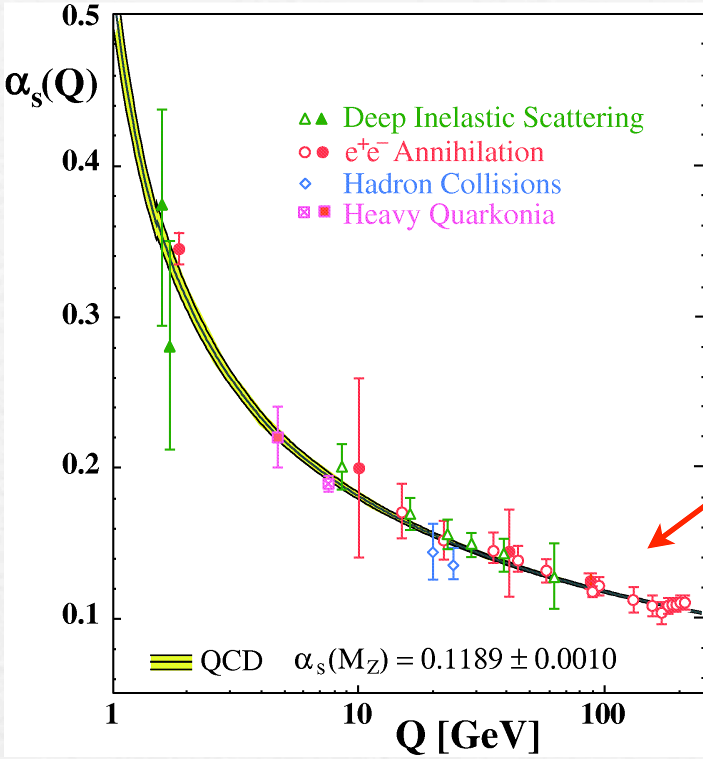
It does not matter how large is the energy of a particle that hits a nucleon, in the final state there will always be a nucleon

QCD is an asymptotically free theory



Asymptotic freedom of QCD:
The strong coupling becomes small at large energies

Necessary (but not sufficient) condition to make **quantitatively reliable predictions** is that the **coupling is small**



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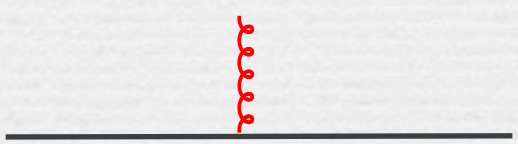
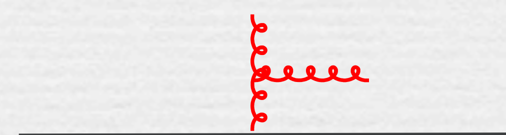
Abelian theory



Non-abelian theory



In a non-abelian theory the gauge fields interact among themselves
At high energy, the probability that a gluon emits a gluon is given by

$$\alpha_s \log(1/x)$$

where x is the fraction of energy carried by the gluon

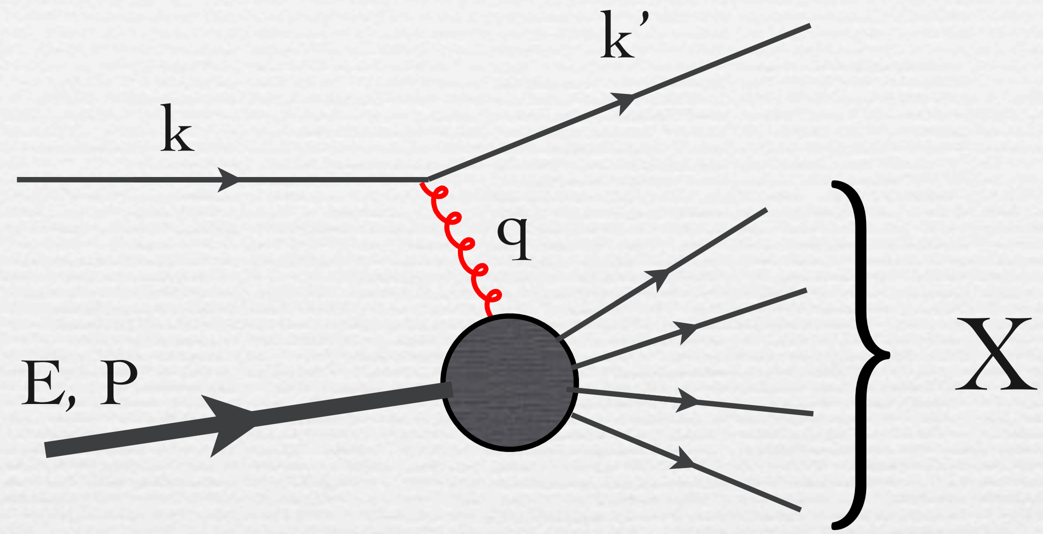
QCD at large Q and x is "easy": few weakly interacting gluons

At small x the logarithms must be added up!!

DEEP INELASTIC SCATTERING

Information on the internal structure of a nucleon by high energy electron scattering

Any frame

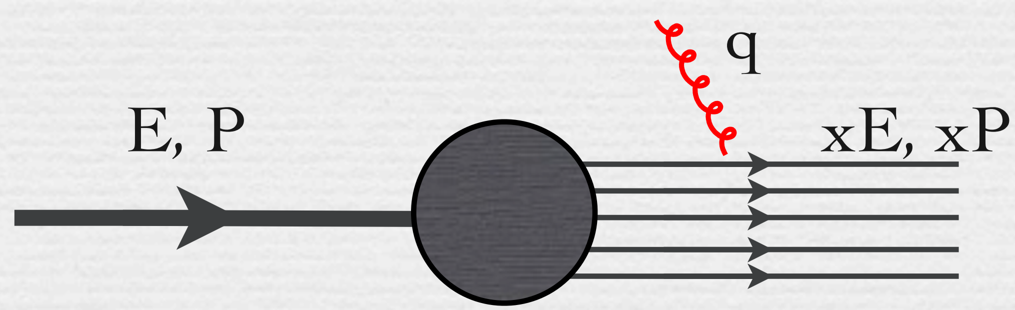


$s = (P + k)^2$

$Q^2 = -q^2$

$\omega = (2P \cdot q)/Q^2$

IMF frame
partonic picture



$x = 1/\omega$

Regge-Gribov limit

Q^2 fixed and large, $x \to 0$, $s \to \infty$

SATURATION

At small x, how is it possible to pack many gluons in a proton?

Phase space density $$\frac{(2\pi)^3}{2(N_c^2-1)}\frac{dN_g}{dy\, d^2p_T\, d^2x_T} = n$$

A simple model. Suppose gluons obey the potential

$$V = \begin{cases} -n & \text{large distance} \\ +\alpha_s n^2 & \text{short distance} \end{cases}$$

balance at $n \sim 1/\alpha_s$

The balance depends on the coupling and therefore on the energy

$R_{\rm sat} \sim 1/Q_{\rm sat}$ Typical distance for color neutralization.
The hadron is effectively a system of color singlets if the probe sees structures with $R_{\rm sat} < R < R_h$

JIMWLK-like EVOLUTION

Per ogni valore di $Y = \log(1/x)$ possiamo calcolare

$$\langle O \rangle_Y = \int [D\rho]\, W_x[\rho]\, O_Y[\rho]$$

Jalilian, Iancu, McLerran, Weigert, Leonidov, Kovner

se conosciamo la distribuzione W_x

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Si assume che ad una certa scala

$$W_{x_0} = \exp\left[- \int \boldsymbol{d}^2 x_\perp \frac{\rho_a(x_\perp)\rho_b(x_\perp)}{2\mu^2} \right]$$

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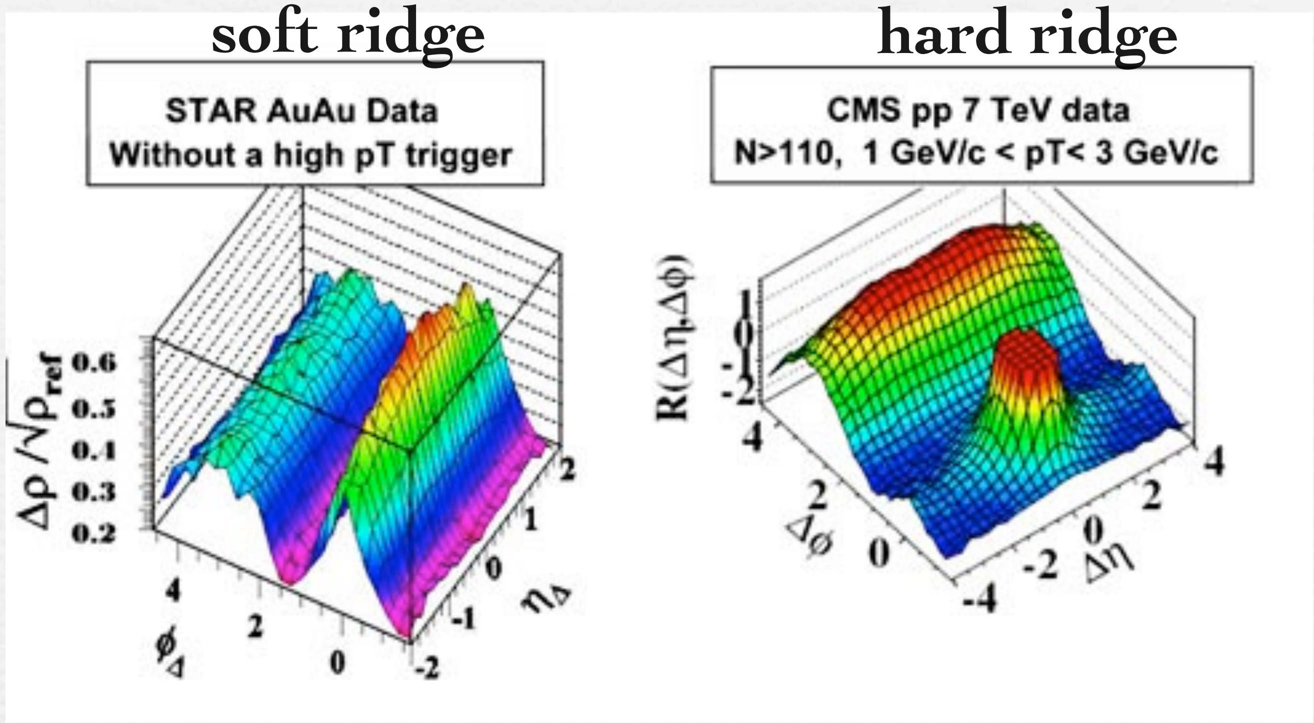
L.D. McLerran, R. Venugopalan, Phys. Rev. D 49, 2233 (1994). ibid. D 49, 3352 (1994); D 50, 2225 (1994).

E poi si fa evolvere in funzione di *x*.
La separazione di scala è arbitraria e quindi abbiamo un RG tipo Wilson.

THE RIDGE

correlazioni a grande rapidità
(distanza angolare azimutale)



Le "final state interactions" spesso cancellano l'informazione sullo stato iniziale.
Molti osservabili in A+A collisions non sono quindi legati al CGC.

Una eccezione è il "ridge": la correlazione adronica a grande rapidità

$$t_{\max} \sim t_{\text{freezout}} e^{-|\Delta\eta|/2} \simeq t_{\text{sat}} \sim 1/Q_{\text{sat}}$$

Quindi questa correlazione potrebbe essere generata dal glasma + expanding flow

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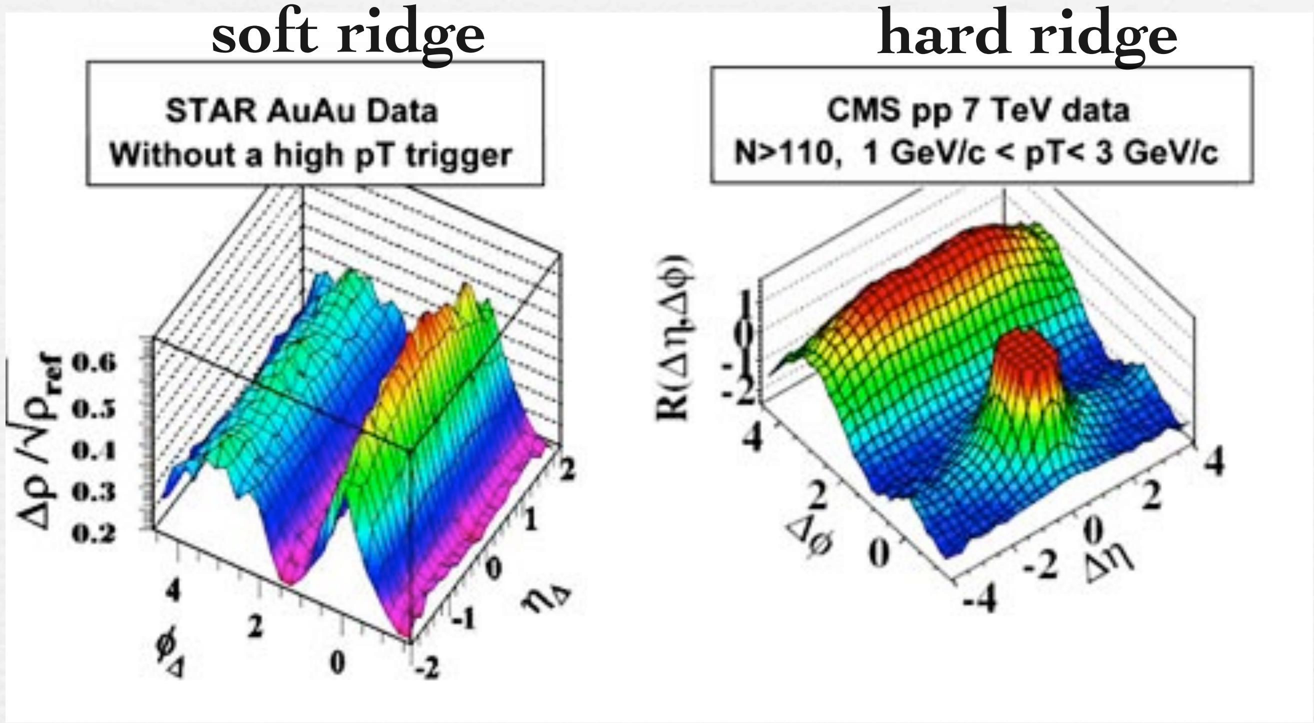

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Spiegazioni teoriche alternative: hydrodynamic flows, local hot spots, initial-state fluctuations, parton cascades, momentum kick model, pQCD modeling

Rapidities

Standard Lorentz

$$E = m\cosh\phi$$
$$p = m\sinh\phi$$

$$\phi = \frac{1}{2}\log\left(\frac{E+p}{E-p}\right)$$

"angolo" che ci consente di passare dal nostro frame a quello della particella

Experimental

$$y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$$

un boost di y ci porta nel frame in cui la particella ha solo impulso traverso

Pseudorapidity

$$\eta = -\log(\tan(\theta/2)) = \frac{1}{2}\log\left(\frac{p+p_z}{p-p_z}\right)$$

qui θ è l'angolo azimutale. $\theta = 0$ corrisponde al beam axis (forward rapidity)

Se la materia è “contratta”, allora le interazioni stesse devono cambiare.

Ad esempio, se voglio trovare nel mio sistema di riferimento la configurazione di equilibrio di un cristallo in moto devo sapere come cambiano gli accoppiamenti

comoving observer **boosted observer**

Come funziona ?

TEORIA EFFETTIVA DEL CGC

“small” x gluons, occupano in gran numero gli stessi stati quantici: **classical fields**

“large” x gluons, campi dinamici: **sorgenti**

$$J_a^\mu = \delta^{\mu +}\delta(z^-)\rho_a(\boldsymbol{z}_\perp)$$

congelate dalla dilatazione temporale

la corrente ha solo componente lungo z^+

i campi sono “schiacciati” nella coordinata $z^- = 0$

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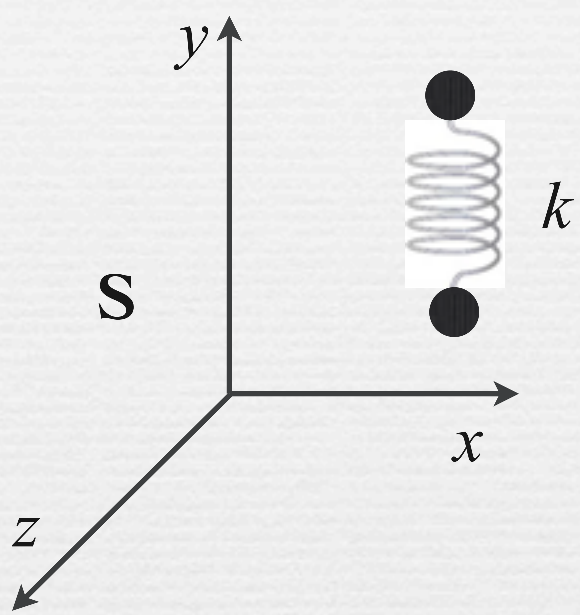
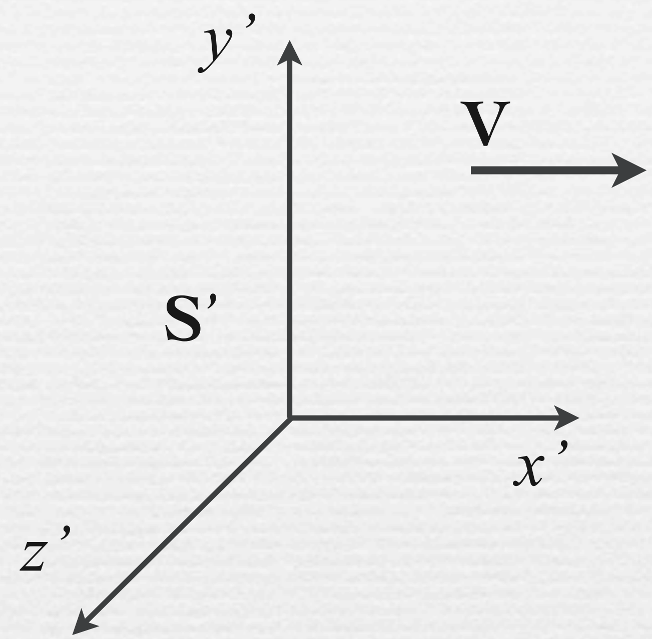
La distribuzione di cariche e dei campi cambia da evento ad evento.
Però deve essere possibile una descrizione che tenga conto della **saturazione**, che è invece "universale".
Analogo problema negli spin glasses.

For simplicity, consider just two particles bound by a spring

comoving observer



boosted LAB observer



$$F_y = -k\Delta y$$

$$F'_y = -k'\Delta y'$$

If the spring is static in the S rest frame the equilibrium force is

$$F'_y = F_y/\gamma$$
$$\Delta y' = \Delta y$$

therefore

$$k' = k/\gamma$$

The spring has a lower elastic constant in the comoving reference frame!

When the spring is oscillating, due to time dilation, we see slowly moving bodies