Self-Organized Criticality and High Energy Hadron Production

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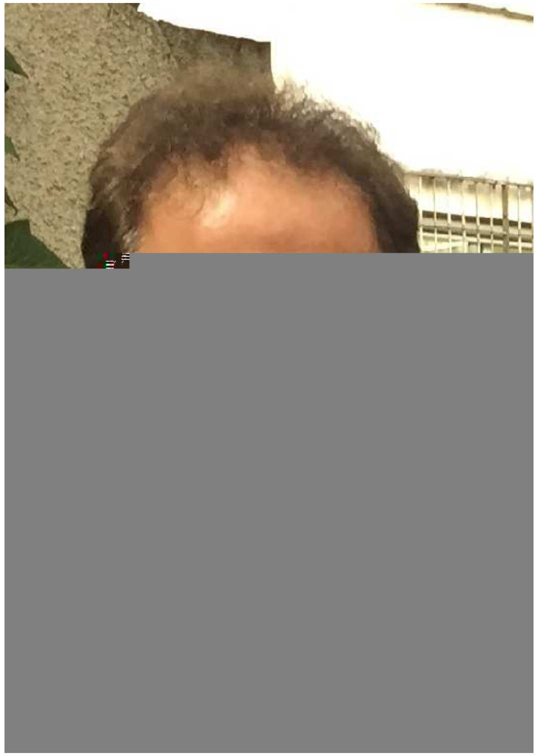

Lieber David:

Herzliche Glückwünsche!

Happy Birthday!

Wszystkiego Najlepszego!

Ultimate topics of physics, last half 1900:

- what are the smallest constituents of matter?
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Sounds familiar:

A. Michelson (Nobel Prize in Physics 1907):

Annual Register 1896, Ryerson Physical Laboratory

...it seems probable that most of the grand underlying principles of physics have been firmly established....

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Turn of century: change of paradigm

Per Bak, How Nature Works, 1996

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New Concepts:

- complexity, emergence, chaos
- non-equilibrium behavior, self-organization

1 Criticality

Correlation between constituents (spins, particles,...), next neighbor interaction, at separation r of a many-body system with control parameter T ("temperature")

$$\Gamma(r, T) \; \square \; \frac{a}{r^p} \exp - r/\lambda,$$

emergent correlation length $\lambda(T)$; power-law exponent $p \; \square \; 1$.

Correlation is scale-dependent, r/λ,

$$\frac{\Gamma(2r, T)}{\Gamma(r, T)} = (1/2)^p \exp - r/\lambda$$

At critical point, $\lambda \to \infty$, so that

$$\Gamma(r, T_c) \; \square \; \frac{a}{r^p}$$

and hence relative correlation

$$\frac{\Gamma(2r, T_c)}{\Gamma(r, T_c)} = (1/2)^p$$

becomes scale-invariant: independent of r, no self-organized scale.

2 Self-Organized Criticaliy

Equilibrium: □ control parameter T, order parameter $m(T)$; criticality: an outside operator tunes adiabatically $T \rightarrow T_c$, order parameter changes abruptly.

□ Tuning control parameter changes order parameter

Non-equilibrium; systems evolve on their own, no tuning operator; given suitable dynamics, they converge to a critical point ("critical attractor").

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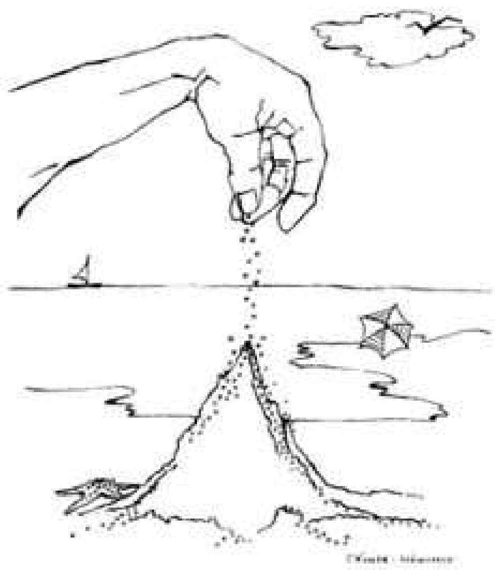
Per Bak: sand-pile scenario



pour sand slowly onto a flat surface
slope G of sand-pile increases
eventually G reaches a critical value G_c,
avalanches descend
keep pouring, more avalanches
record over time the size s
and the number n(s) of avalanches

Result:

$$n(s) = \left(\frac{a}{s}\right)^p \quad \rightarrow \quad \log n(s) = p \log s + \text{const.}; \qquad \frac{n(s)}{n(2s)} = (1/2)^p \equiv f(s)$$

constant input (pouring sand) drives system to critical slope, produces as output avalanches with power-law size distribution, scale-invariant ratios

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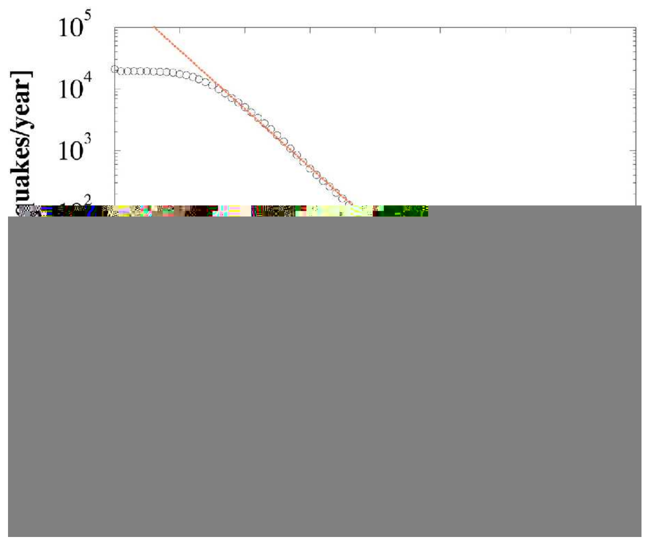
Another application: earthquakes in New Mexico

strenghth on Richter scale s gives log n(s) = p log s + const.; 6 orders magnitude!

input: increasing pressure of earth crust

output: earthquake of size s



low s deviations:
difficulties in measuring small earthquakes

very simple example of scale-invariance: ordered partitioning of integers n

$$n = 3 : 3, 2 + 1, 1 + 2, 1 + 1 + 1 \qquad q(3) = 4$$

in general, number q(n) of partitions:

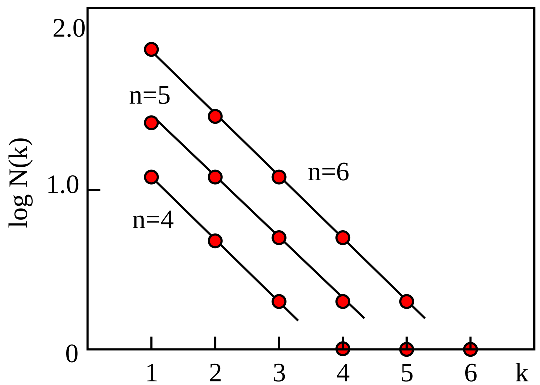
$$q(n) = 2^{n-1} = \frac{1}{2}\exp\{n \ln 2\}.$$

(NB: unordered is more di□cult, Hardy & Ramanujan)

Problem: given n, how often does k occur in the set of all its partitionings?

what is the strength of k? → number of its partitionings

$$s(k) = q(k) = \frac{1}{2}\exp(k \ln 2)$$



SOC: scale-invariant power-law behaviour

$$N(k, n) = \alpha(n)[q(k)]^{-p}$$

$$\rightarrow \log N(k) = -k(p \log e \ln 2) + \text{const.}$$

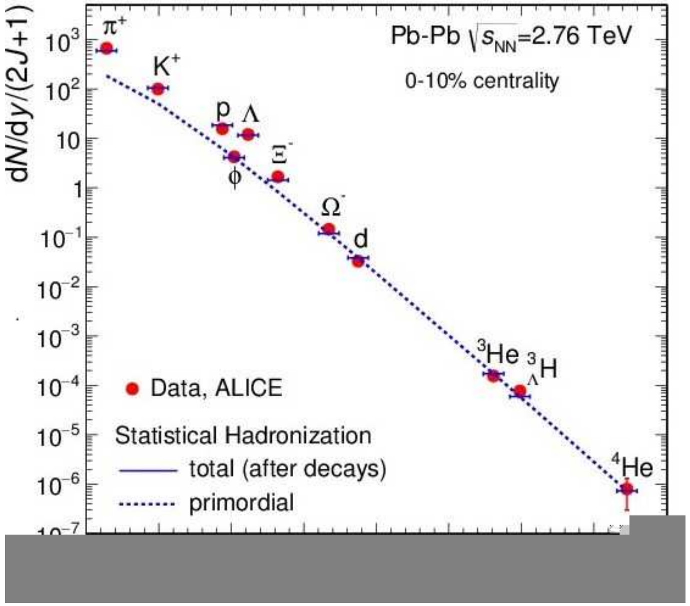
high energy hadroproduction data:

relative species abundances are xed
by yields at T_c (\chemical freeze-out"):

ideal hadronic resonance gas at T_c with
vacuum masses predicts \all" abundances

caveat: in $e^+ e$; pp all hadrons,
in AA stable hadrons.

Not compatible with equilibrium QCD matter
below T_c.



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problem for conventional scenario:

why chemical freeze-out at T_c?
why abundance ratios at T_c with vacuum masses?

xed ratioss & vacuum masses at T_c { eat your cake and still have it...

recent further di culty (ALICE Pb-Pb LHC data):
abundances of light nuclei (deuteron, helium, triton) dete rmined by Boltzmann
factor at T_c, although they cannot exist in such a medium.

SOC scenario:

non-equilibrium parton system (pouring sand) converges towards pseudo-critical point, at that point breaks up into all permissible hadron states (avalanches).

absorptive state SOC: colored parton system converges towards pseudo-critical point of color absorption, at that point it breaks up into all possible color neutral states.

crucial di erence; in SOC, hot colored partonic medium is quenched by cold color-neutral physical vacuum ! free color-neutral hadrons, no subsequent hot interacting hadronic medium.

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SOC: number $N(m)$ of produced hadrons of mass m from scale-invariant form

$$N(m) = \ [\ (m)]^{p}$$

in terms of resonance strength (m).

Take (m) from composition law number of states (Hagedorn bootstrap)

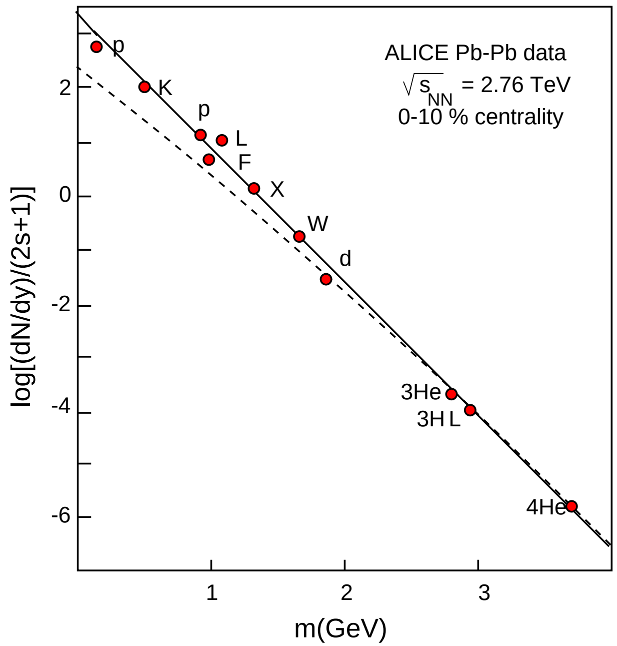
$$\log N(m) = m\left(\frac{p\log e}{T_H}\right)\left[1\ \left(\frac{aT_H}{m}\right)\ln(1+\frac{m}{0})\right] + \mathrm{const}\ :$$

Compare to ALICE data for Pb-Pb collisions at $\sqrt{s} = 2.76$ GeV, using simplified form

$$\log[(dN/dy)/(2s+1)] \simeq m \left(\frac{\log e\, p}{T_H} \right) + A;$$

with $T_H = 155$ MeV, fit values $p = 0.9$, $A = 3.4$

include correction terms: dashed line needed for resonance decay production



elementary collisions isolated hadrons in avalanche

high energy AA collisions:
interactions between "debris" can affect resonance production (; K ;);
but the result is not the finite temperature equilibrium hadronic medium of QCD

Conclude:

Non-equilibrium colored parton beam converges as function of rapidity towards (pseudo-critical) attractor color absorbing state;

at that point, quenching leads to color neutrality in form of an avalanche of hadrons, with scale-invariant mass distribution;

at successive rapidities, successive avalanches; sum over all hadron distributions corresponds to thermal distribution at T_c.