Title: Nuclear Theory/Heavy Ions 3

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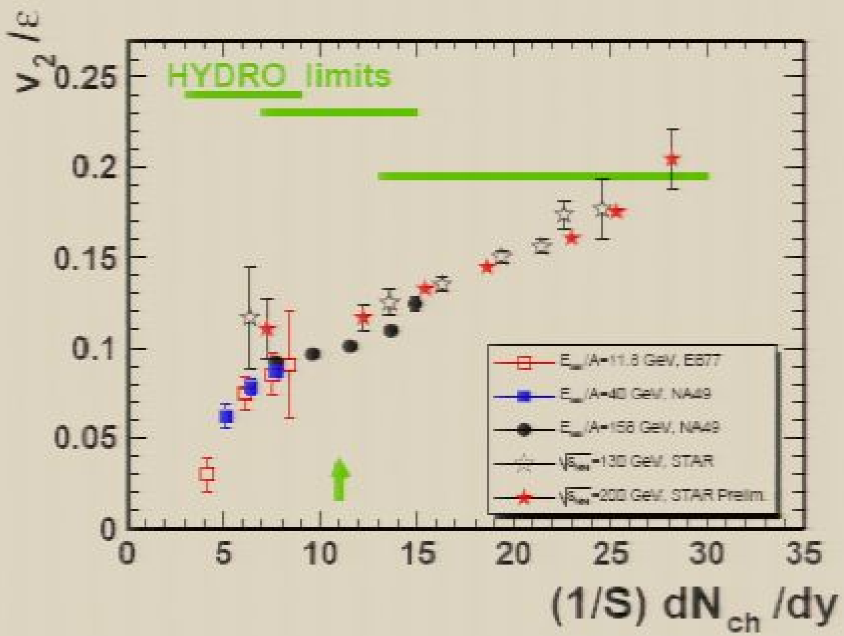
URL: http://pirsa.org/06060035

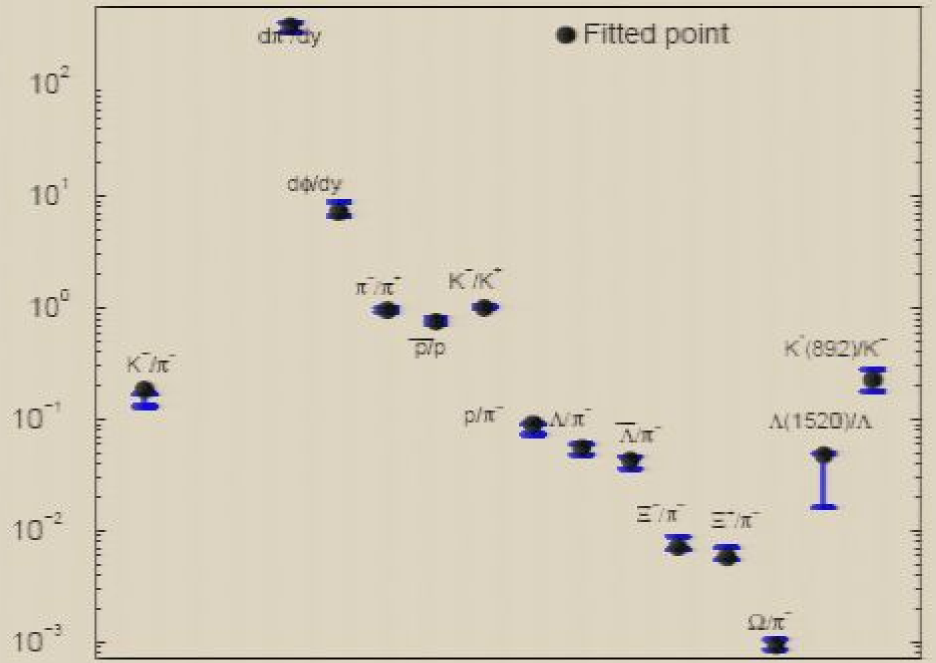
Abstract:

Is statistical mechanics applicable to heavy ion collisions?



Encouraging result: Ideal hydrodynamics seems to work at RHIC:
it describes the dependance of the flow eccentricity on the initial geometrical eccentricity
some kind of local thermalization is in order early in the evolution of the system (when eccentricity and is maximum)!
How thermalized is the system at freeze-out?

Let's integrate the fluid and use statistical mechanics+PDG listing of resonances (the "energy levels") to model the observed average particles yields at freeze-out.



considerable phenomenological success

Plots like this shown at most workshops on the subject.

At Au-Au RHIC collisions, fitting $T, \mu_B \Rightarrow$ a "nice-looking" plot with nearly all particles accounted for. But...

Objection I

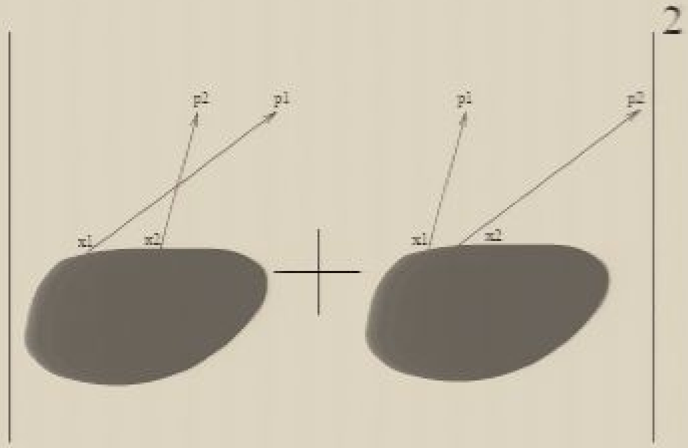
But does this prove "equilibrium" is really there?

- We always knew soft hadronic abundances were approximately exponential. Are $T, \mu, Volume$ "real", or are they "epicycles"?

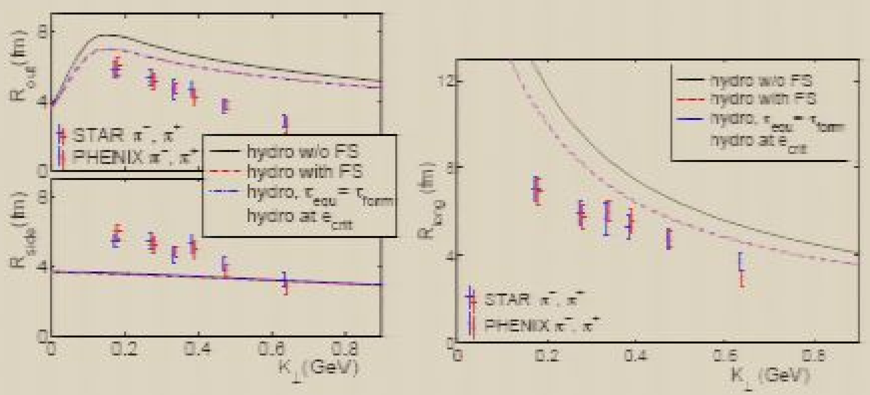
- Becattini has done thermal fits for $p-p, e^+ - e^-$. Does that mean these systems are equilibrated? Or not? most points fit, some fail quite badly. but, some particle yields fail in A-A systems as well. When does true equilibration kick in?

Objection II

direct measurement of the spacetime distribution of the fireball (possible through interferometry)



not reproduced by same hydrodynamics



The break-up of the system is not as yet understood.

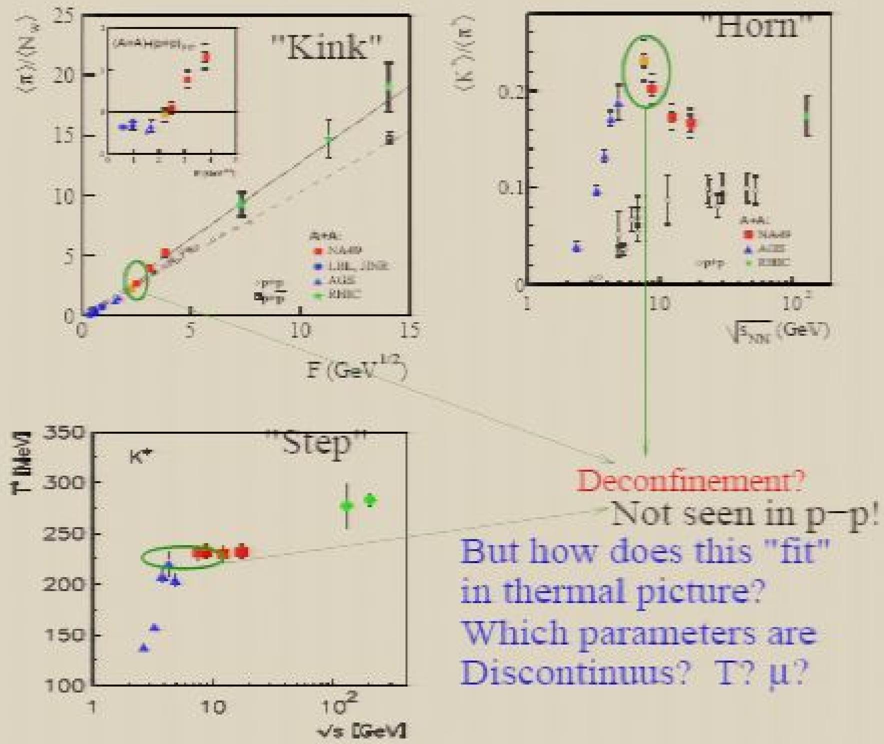
Objection III (and the most important one!):
Can statistical fit results make a connection to the

- Systematic dependance on system size and energy of the freeze-out bulk properties ? (Temperature and μ_B)

- Interpret any obtained trend in terms of statistical physics, e.g. by highlighting a phase transition?

As of now, no consensus on this.

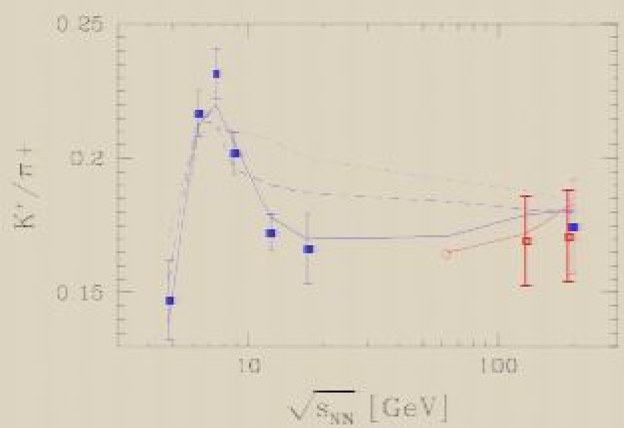
E.g.: The "horn","kink","step":Coinciding discontinuities of $\langle N_\pi \rangle / N_{part}$ (Tracks entropy density), K^+/π^+ (tracks strangeness/entropy), step in "slope in p_T distribution (could signify latent heat)



We don't know... many interpretations!

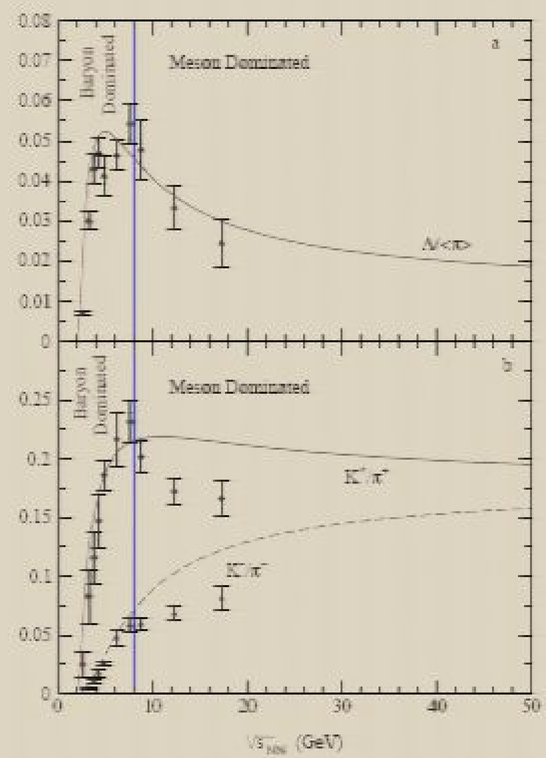
- Original suggestion: Strangeness/entropy change QGP (Gazdzicki/Gorenstein. Kink due to enthropy density increase). But this was a toy model, with no chemical potentials or resonance decay tree.

- Along similar lines: Chemical non-equilibrium from phase transition (Rafelski/Letessier)
Large entropy,strangeness content in QGP — over-saturated phase space at freeze-out



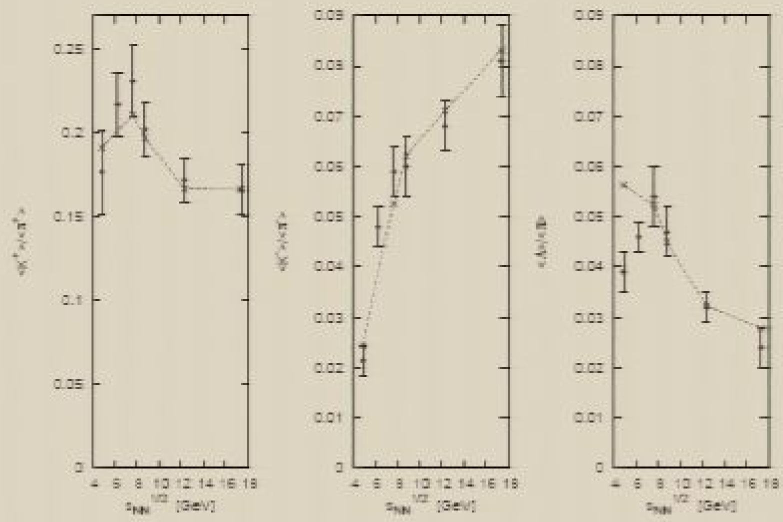
Discontinuity in T (super-cooling)and quark-anti-quark abundance (Over-saturation) at and after horn. But many fit parameters ⇒ overfitting?

But other ideas exist... Transition from "baryon dominated" to "meson dominated" regime (Cleymans/Redlich/Kampfer/Wheaton)



Discontinuity in chemical potentials.
Does not explain sharpness of K/π peak but still...

...or $K - \pi$ non-equilibrium plus shorter interaction time at high-energy (Tomasik)



Discontinuity in Equilibration/System duration.
It would be great to rule out some of these models!

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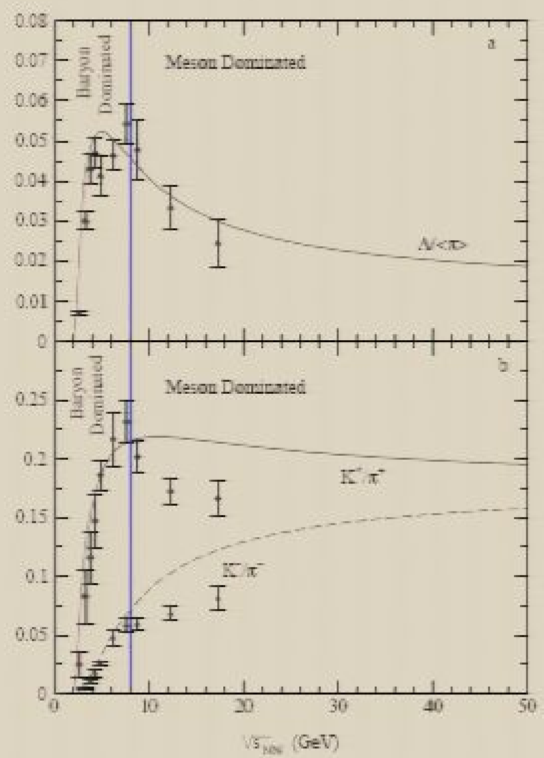

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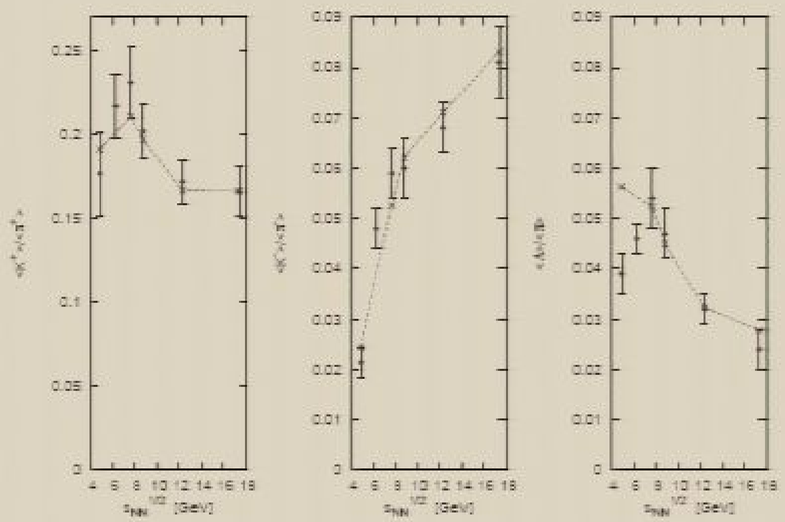

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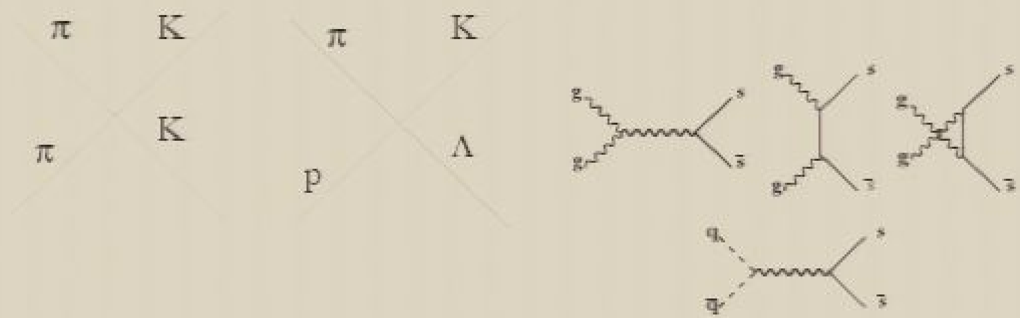
Experiment II: Strangeness Enhancement

Koch, Rafelski, Muller 1982, 1986: QGP kinetics more efficient at producing $s\overline{s}$ than HG kinetics



- Faster equilibration time

$$Q_{hadrons} \sim 500MeV \qquad Q_{QGP} = 2m_s \sim 200MeV$$

- More $s\overline{s}$ at equilibrium

$$\frac{m_{K,\Lambda,...}}{T} \ll \frac{m_s}{T}$$

(Over-saturated strangeness state occupancy at freeze-out?)

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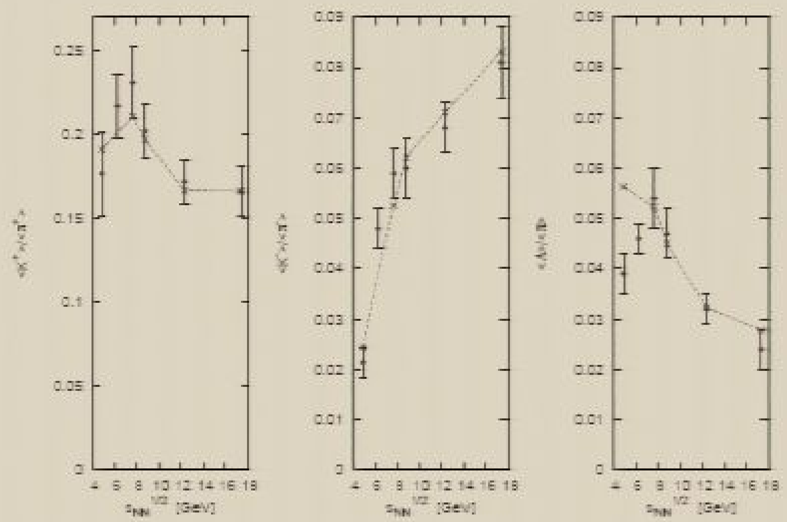

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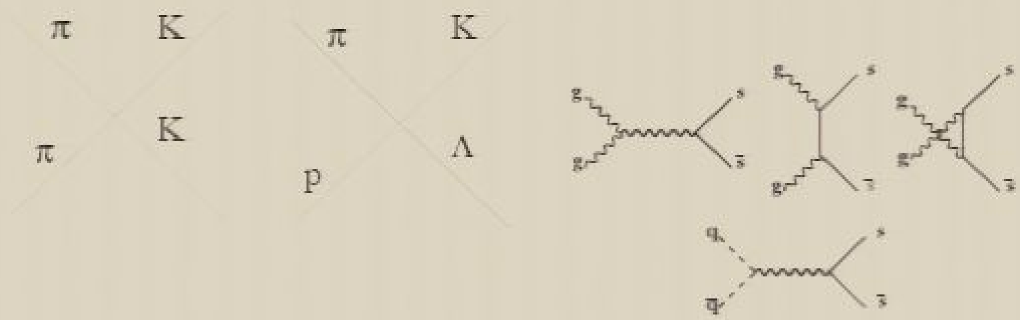

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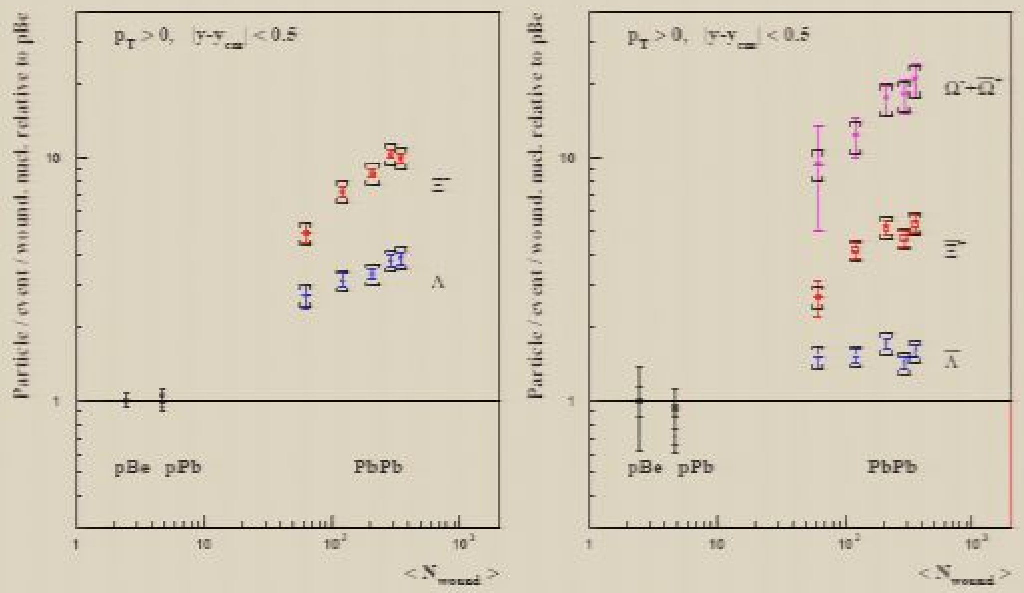
Enhancement, defined as...

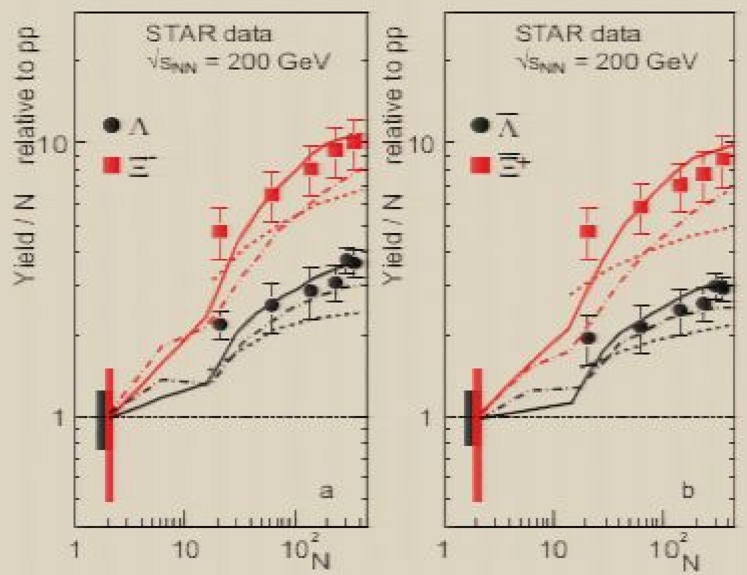


$$\frac{N^{AA}/N^{AA}_{part}}{N^{pp}/N^{pp}_{part}}$$

is definitely there, as much as ~ 20 for $\overline{\Omega}$. But the interpretation of this has been subject to controversy: How does enhancement of strangeness w.r.t. system size fit within the thermal picture?

When fitting yields a consistent picture emerges

Extra strangeness is due to higher strangeness content and Volume at freeze-out, as expected if A-A system lived in phase efficient at producing strangeness

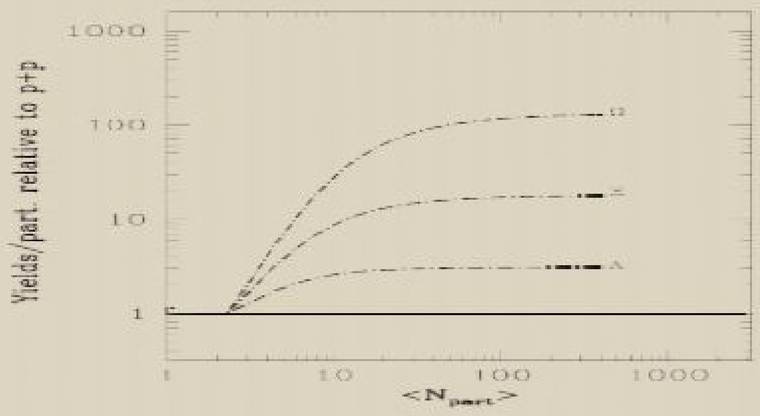


good quantitative description, nucl-th/0506044
But not the only one...

QGP enhancement or Canonical suppression

$$\lim_{V \to \infty} \frac{< N >_{CE}}{< N >_{GCE}} = 1$$

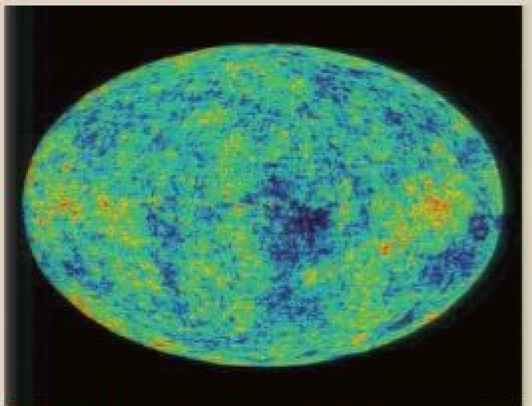
but away from thermodynamic limit— additional suppression, nonlinear in volume (Hamieh, Tounsi, Becattini, Kera



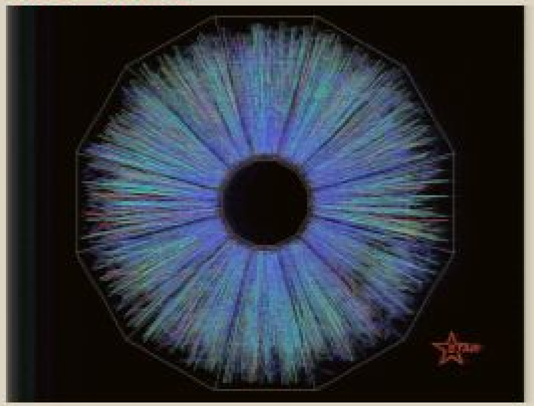
- Could strangeness enhancement be caused by the fact that p-p is far from the thermodynamic limit, while A-A is close to it? Is p-p particle production also governed by equilibrium statistics?
- Or could we be seeing 2 different production mechanisms, one (p-p) based on hadronic physics, the other one on QGP?

Many physically different scenarios fitting the same data

In short, we need something like this:



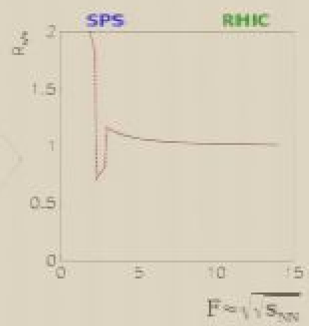
For this:



Fluctuations

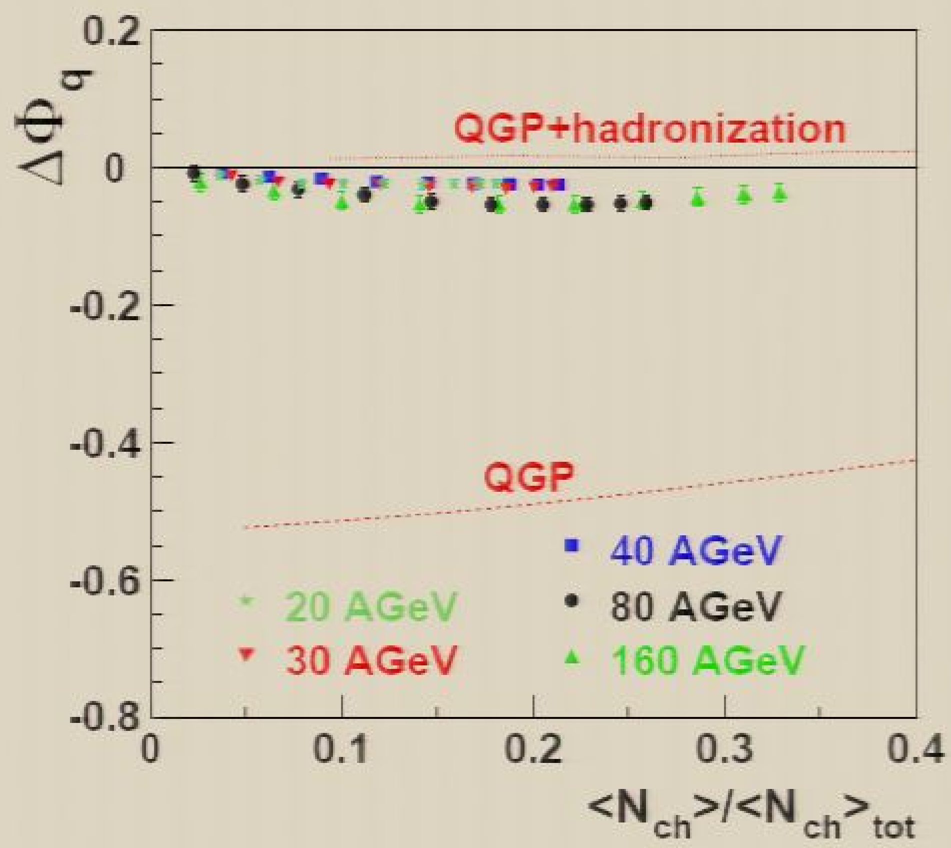
An anomalous enhancement of fluctuations has been proposed as a signature for non-trivial dynamics

- An enhancement of charge fluctuations has been suggested as a signature of a critical point (Stephanov, Rajagopal, Shuryak).
- A suppression of charge fluctuations has been suggested as a signature of QGP (Jeon,Koch).
- If the "step" in spectra is due to a latent heat, K/π fluctuations should also be suppressed



Problem: Some of these effects are anti-correlated. So are parameters (Eg T,flow, volume in a 1st order transition)

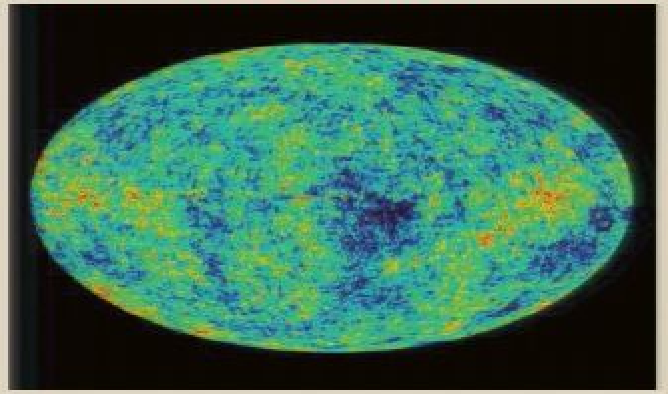
It is fair to say no surprise emerges from data (modeled by hadron gas microscopic models, and no marked energy dependance)



Does that mean fluctuations are not a useful observable?

Not so fast.

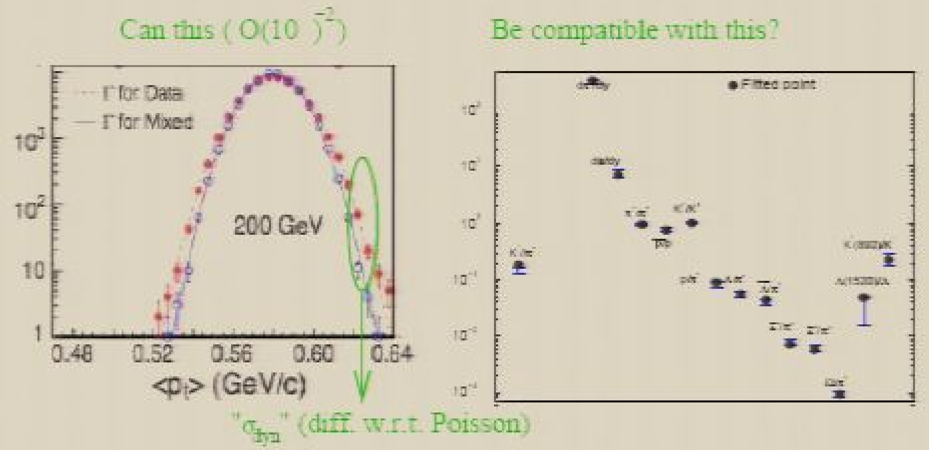
This ($\sim 10^{-6}$) "fluctuation" yielded no surprises either!
Yet lots of insights were obtained.



It's usefullness comes from the fact that models "fitting" other things (today's universe) give very different predictions for it

Fits given earlier are estimates, did not take other precision data into account... Such as particle yields

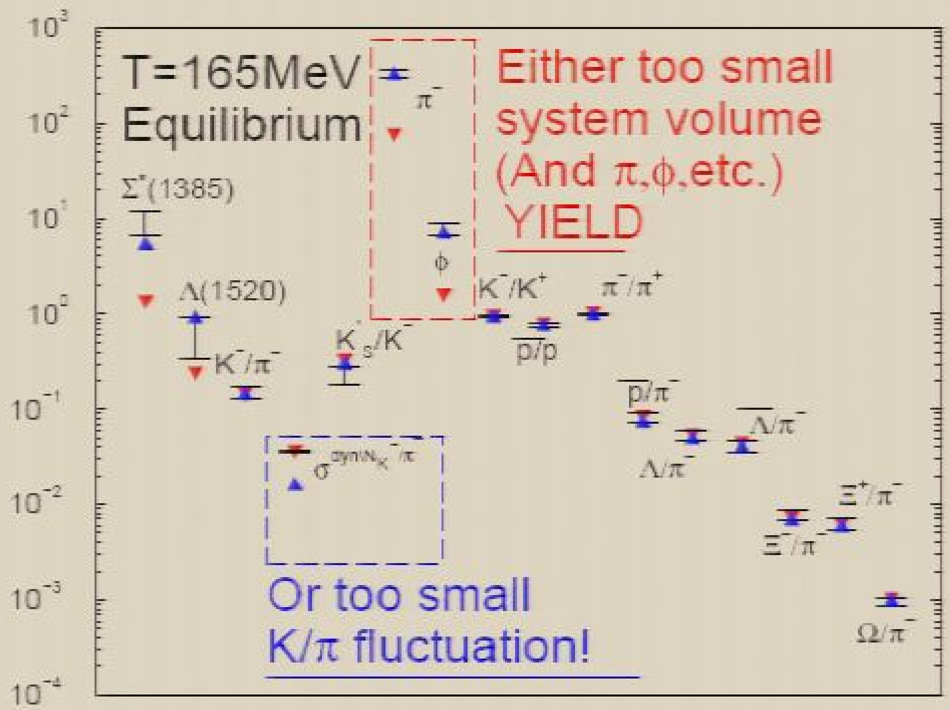
Can models based on statistical mechanics+Strong interactions account for particle yields and fluctuations? A quantitative analysis could beat the "correlations between parameters" problem mentioned before.



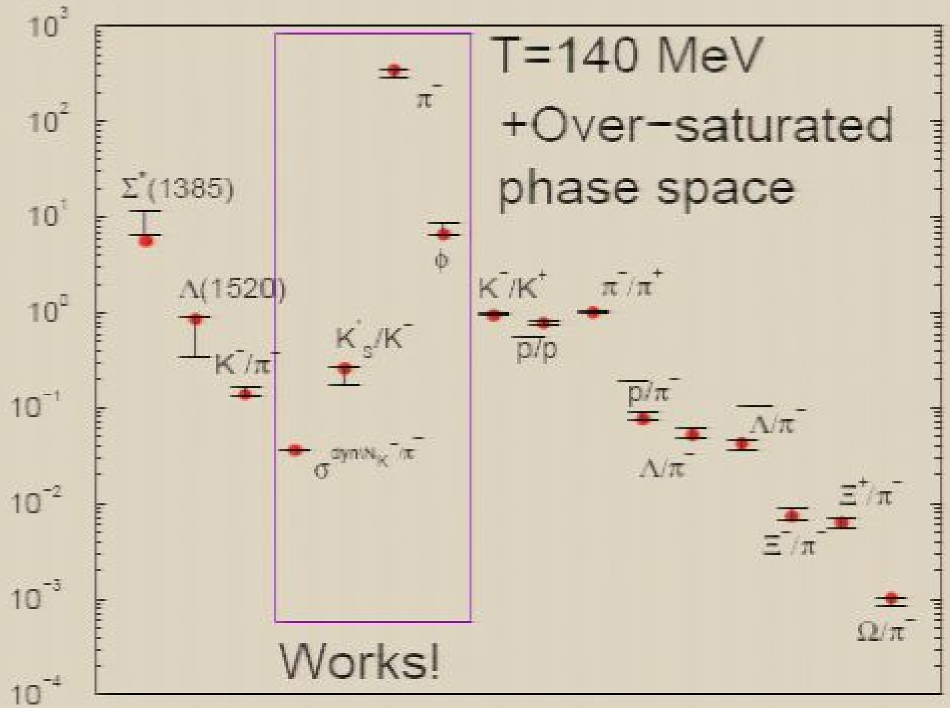
- Deviation from Poisson due to physics $\sim 10^{-2}\%$ yet contains "a lot of physics"

- A basic test of statistical mechanics: Can yields and fluctuations be described by the same T, μ,system Volume? Never been done!

Result I



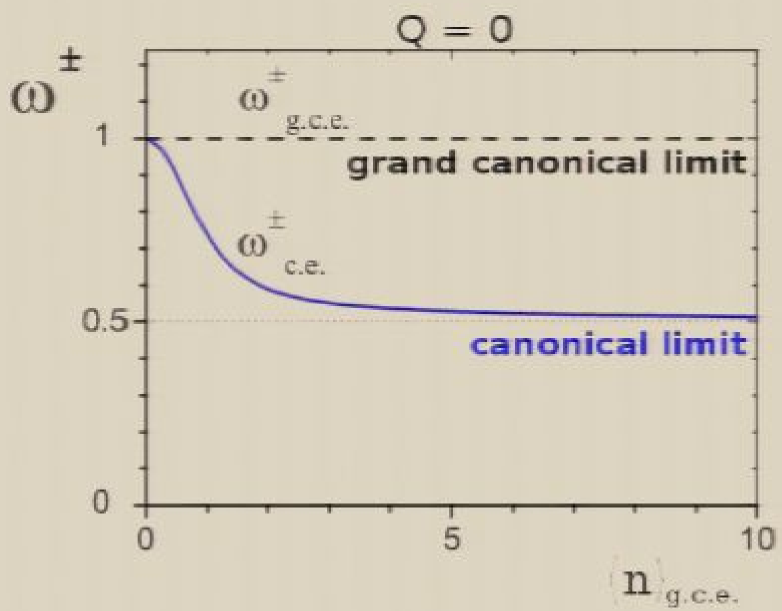
Equilibrium statistical mechanics can-not explain both yields and fluctuations with same T,chemical potentials



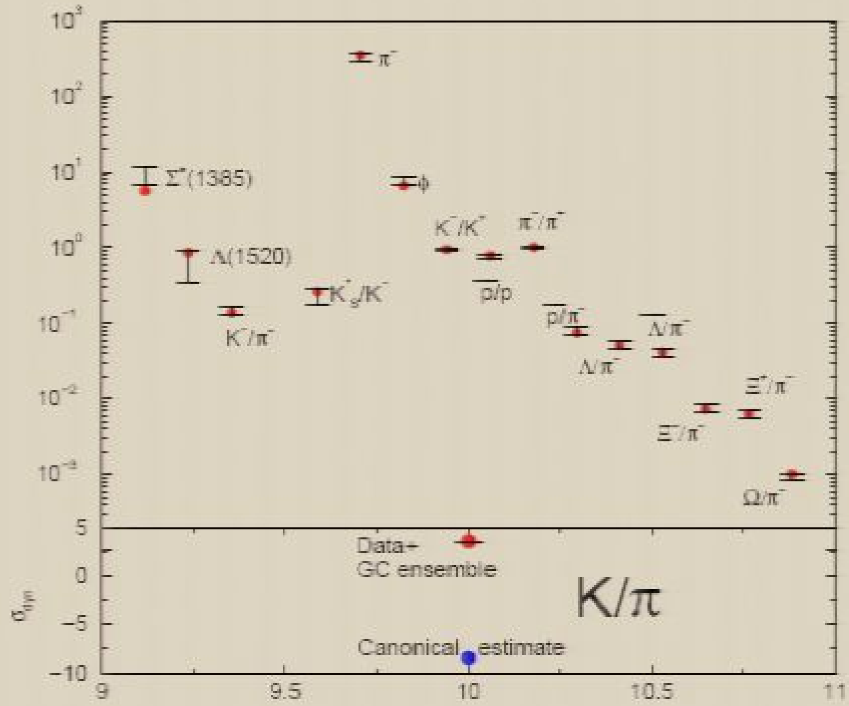
but it works if Supercooling + light quark (∼ pion) abundance above equilibrium! (Rafelski-Letessier scenario for the "horn" explanation) Expected if there is a phase transition from high entropy phase!.
Do I believe this? Don't know. But if forthcoming π^+/π^- and p/π^- fluctuation fits, I might!.

Result II: Is strangeness production canonical or grand-canonical? Fluctuations: The ensemble-O-meter

The dependance of fluctuations on yields is Ensemble-specific (Begun, Gorenstein, Gazdzicki, Zozulya)



It is very unlikely for the incorrect ensemble to describe both yields and fluctuations with the same parameters



Canonical ensemble calculation of fluctuations from best yields fails badly. Grand canonical does OK.
Grand Canonical ensemble physically more appropriate for describing strangeness!
Not good for strangeness canonical suppression!
Good for idea that strangeness is locally equilibrated in a fluid.

(Future) result III: fluctuations mapping freeze-out!

Fluctuations CORRELATED by resonance decays

$$(\Delta Q)^2 = \left\langle(\Delta N)^2\right\rangle + \left\langle(\Delta \overline{N})^2\right\rangle - 2\underbrace{\left(\left\langle N\overline{N}\right\rangle - \langle N\rangle \left\langle\overline{N}\right\rangle\right)}_{\rho\to N\overline{N}}$$

$$\sigma_{K/\pi} = \frac{\left\langle(\Delta K)^2\right\rangle}{\langle K\rangle^2} + \frac{\left\langle(\Delta \pi)^2\right\rangle}{\langle \pi\rangle^2} - \frac{2}{\langle K\rangle\langle\pi\rangle}\underbrace{\langle \Delta K \Delta\pi\rangle}_{K^*\to K\pi}$$

Correlation, by definition, happens at chemical freeze-out, where multiplicities are fixed!

Resonances can also be detected by invariant mass reconstruction . This method, however, gives final resonance abundance, , after all rescattering ceased.

The next step: K^-/π^+ fluctuations

At RHIC this is simple, since $K^+ \simeq K^-$, $\pi^+ \simeq \pi^-$

$$\langle \pi^- \rangle \left(\underbrace{(\sigma_{dyn}^{K^-/\pi^-})^2}_{no\ \ resonances} - \underbrace{(\sigma_{dyn}^{K^+/\pi^-})^2}_{K^*(892)\to K^+\pi^-} \right) \simeq \frac{\langle \Delta\pi^+ \Delta K^- \rangle}{\langle K^- \rangle} \sim$$

$$\sim \left[\frac{K^*(892)}{K^-} \right]_{chemical\ \ f.o.} \qquad vs \qquad \left[\frac{K^*(892)}{K^-} \right]_{thermal\ \ f.o.}$$

From best fit (non-equilibrium) at $\Delta Y = 0.1$, $\sigma_{K^+/\pi^-} \simeq 3.10\%$
(vs $\sigma_{K^+/\pi^+} \simeq 3.61\%$ and $K^{*0}(892)/K^- \sim 0.3.$)

If that fits Evidence for sudden freeze-out!

If that does not fit

- $\left[\sigma_{dyn}^{K^+/\pi^-} \right]_{exp} < \left[\sigma_{dyn}^{K^+/\pi^-} \right]_{theory}$
  $\Rightarrow$ Evidence for long re-interacting phase
- $\left[\sigma_{dyn}^{K^+/\pi^-} \right]_{exp} > \left[\sigma_{dyn}^{K^+/\pi^-} \right]_{theory}$
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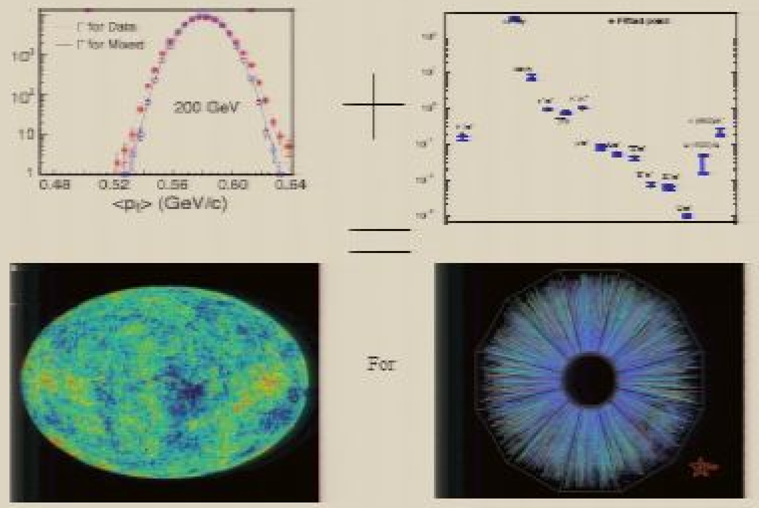
(few) Conclusions and (lots of) outlook:

Considering yields+Fluctuations could do for heavy ion phenomenology what CMB did for cosmology!



We await further precision data from RHIC and SPS experiments!

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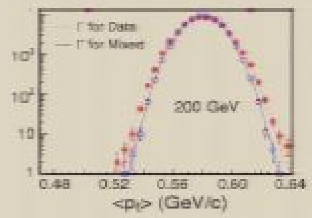

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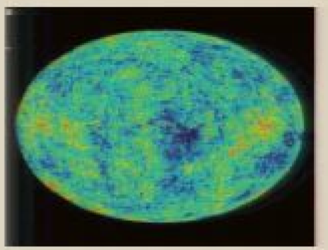

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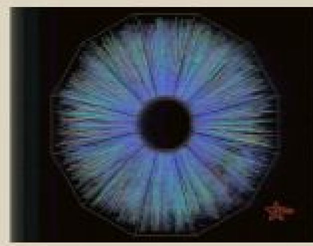

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