Terrestrial Mini-Bang: Transmuting a Color Glass Condensate into a Quark Gluon Plasma

Raju Venugopalan
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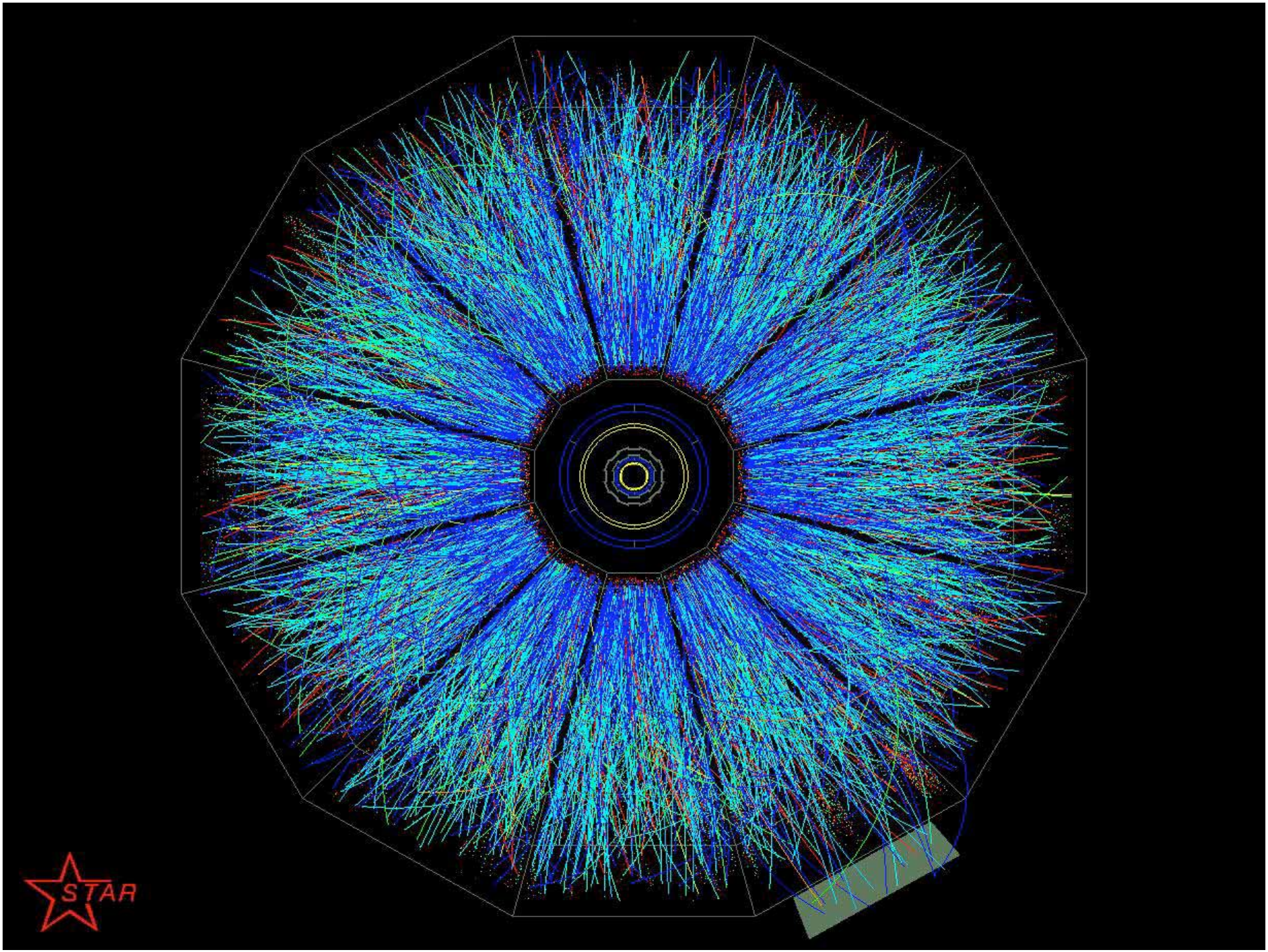
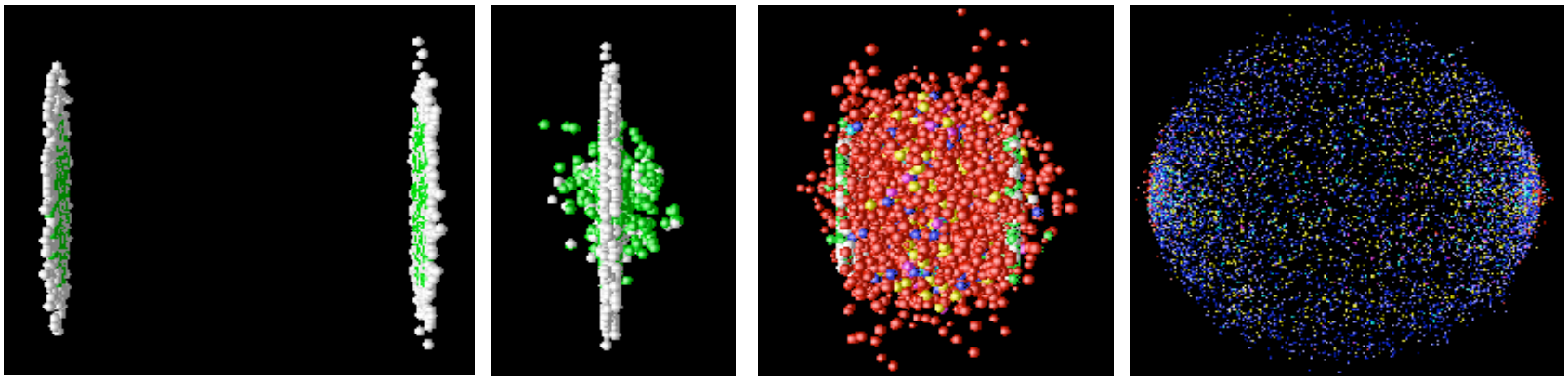

STAR


New York City
Long Island
RHIC


BRAHMS
Forward Spectrometer
PHOBOS
PHENIX
STAR
STAR Detector
RHIC
G-2
BOOSTER
LINAC
AGS

RHIC Collisions

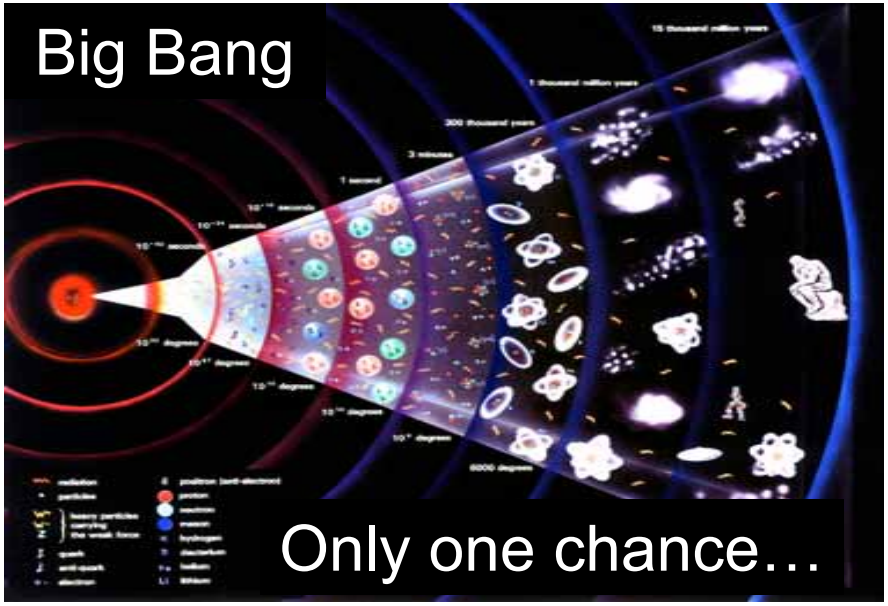
(VNI simulations)

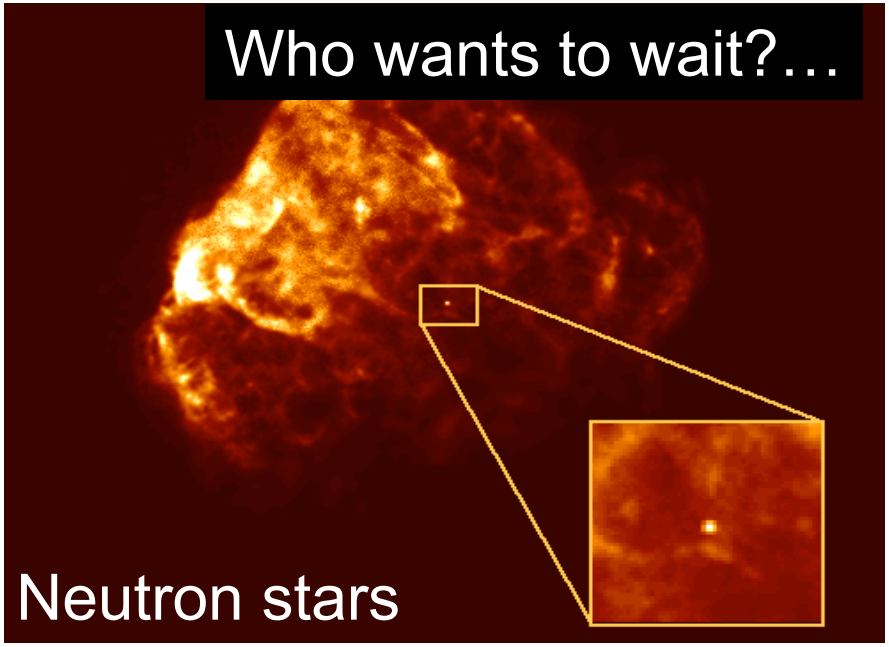


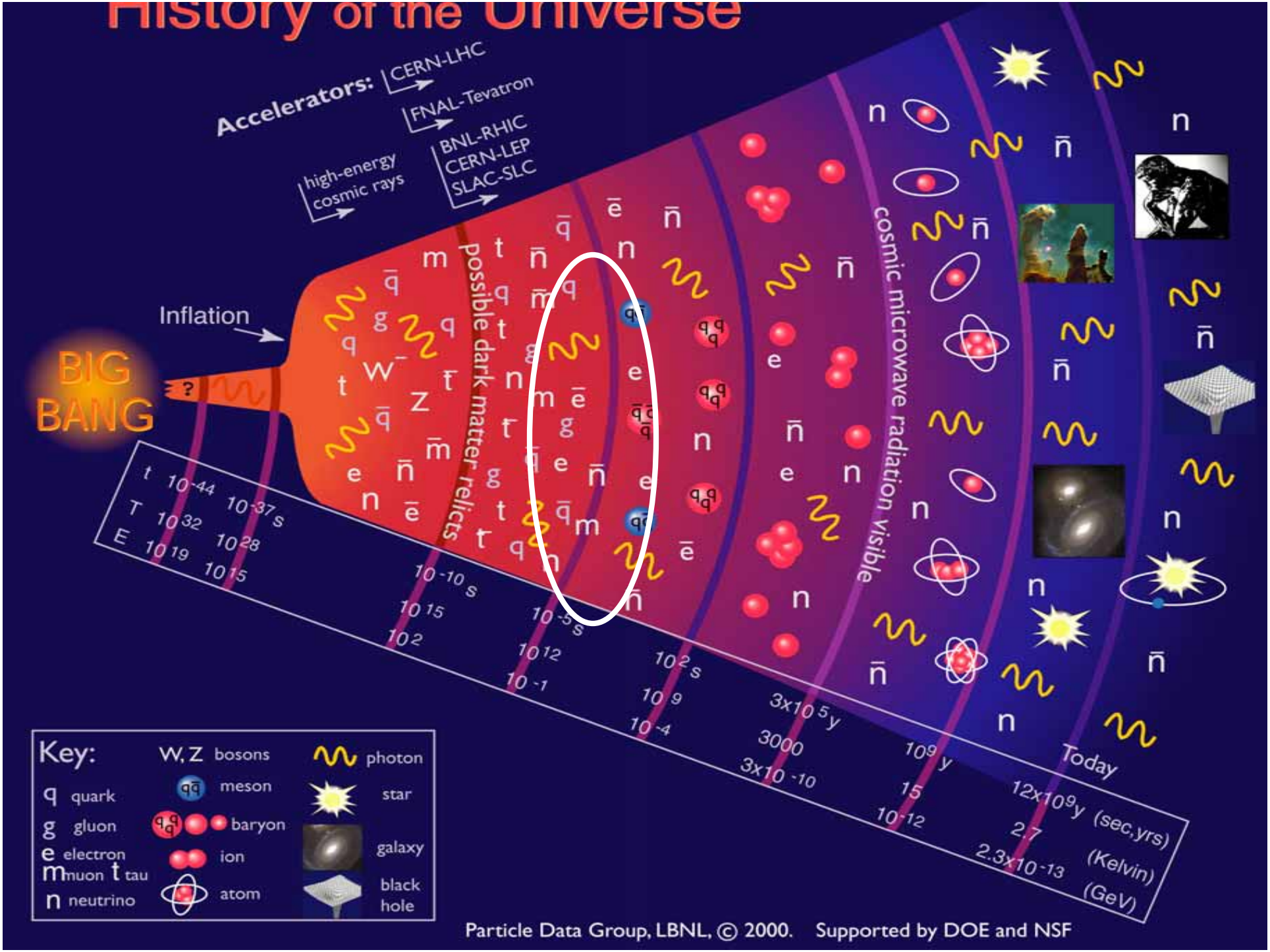
- Gold-Gold collisions at $\sqrt{s} = 200 \,/\, \mathrm{nucleon}$
- Polarized (and un-polarized) p-p collisions at $\sqrt{s} = 200 \,/\, \mathrm{nucleon}$
- Run 4- deuteron-Gold collisions at $\sqrt{s} = 200 \,/\, \mathrm{nucleon}$
- Future runs-other asymmetric nuclei, pp at 500 GeV, …

Where to study QCD matter

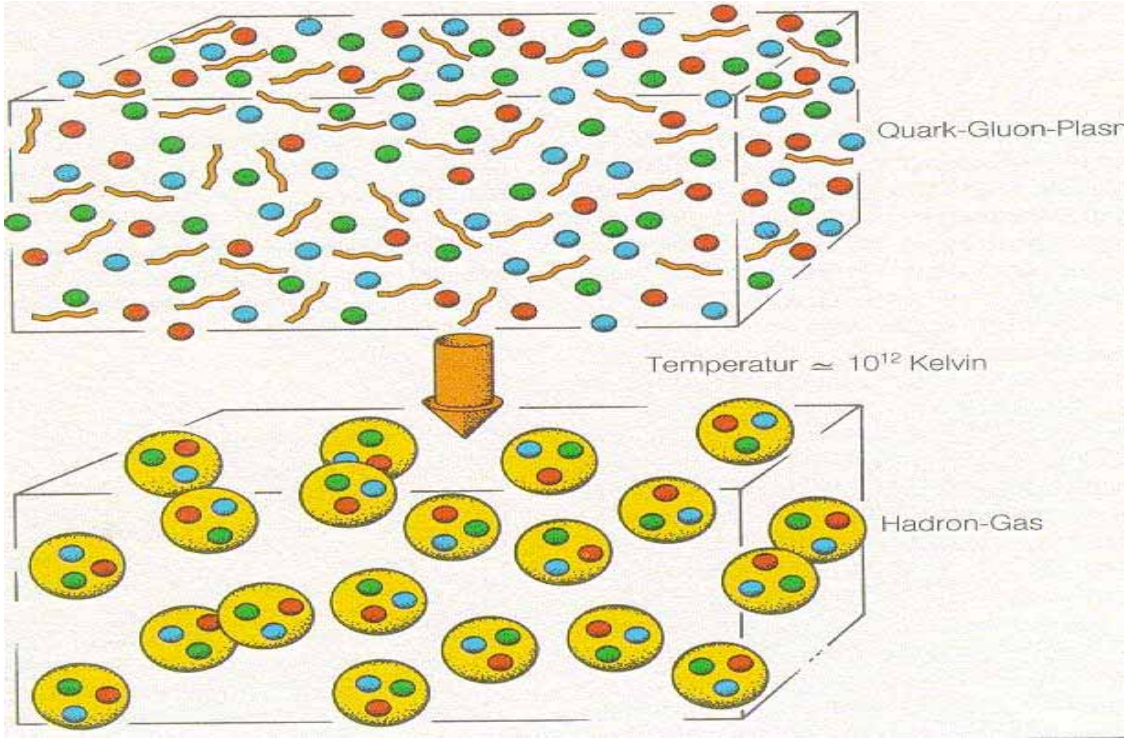
Peter Steinberg






History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

What is the QGP?



Heating QCD in a Box

$$\alpha_S \rightarrow \alpha_S(T) << 1 \text{ for } T >> \Lambda_{QCD}$$

Asymptotic Freedom => Deconfined quarks and gluons at high T

Collins and Perry (1974)

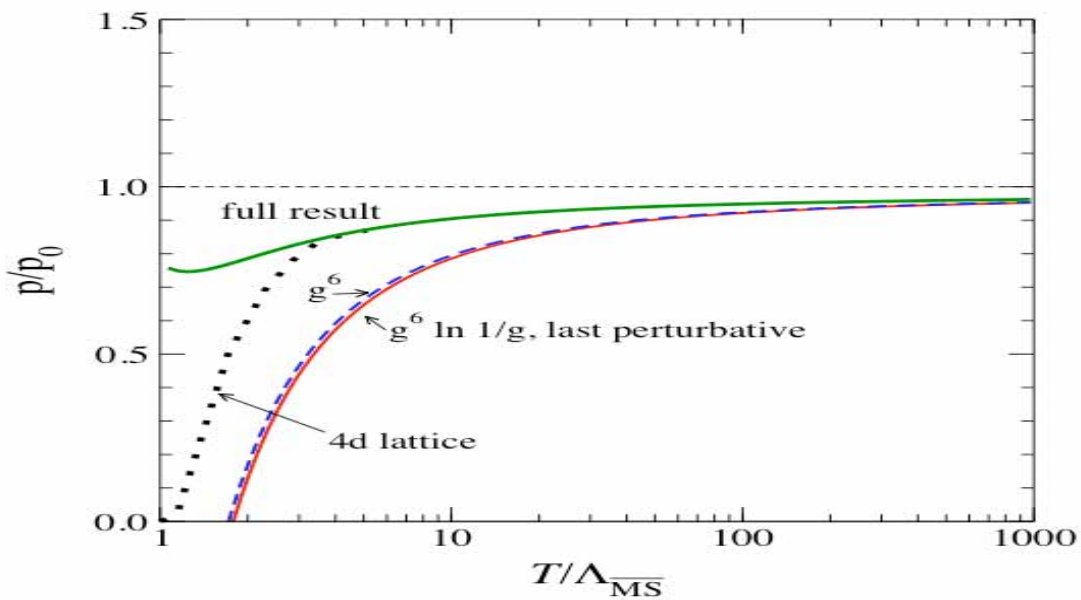
The "Unicorn":

Quark-Gluon Plasma =

Deconfined,
Chirally Symmetric "Phase"

Is the fabulous beast a chimera?

STATE OF THE ART PERTURBATION THEORY

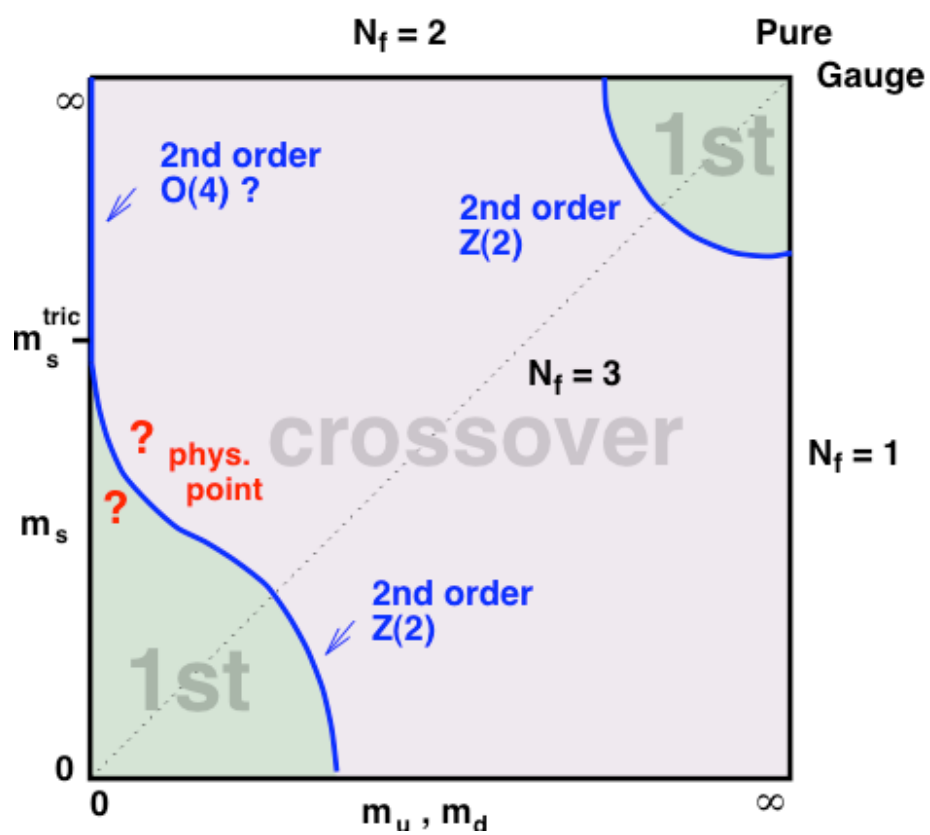


Very slow convergence of finite T perturbation theory!
May be Ok at 3-5 T_c

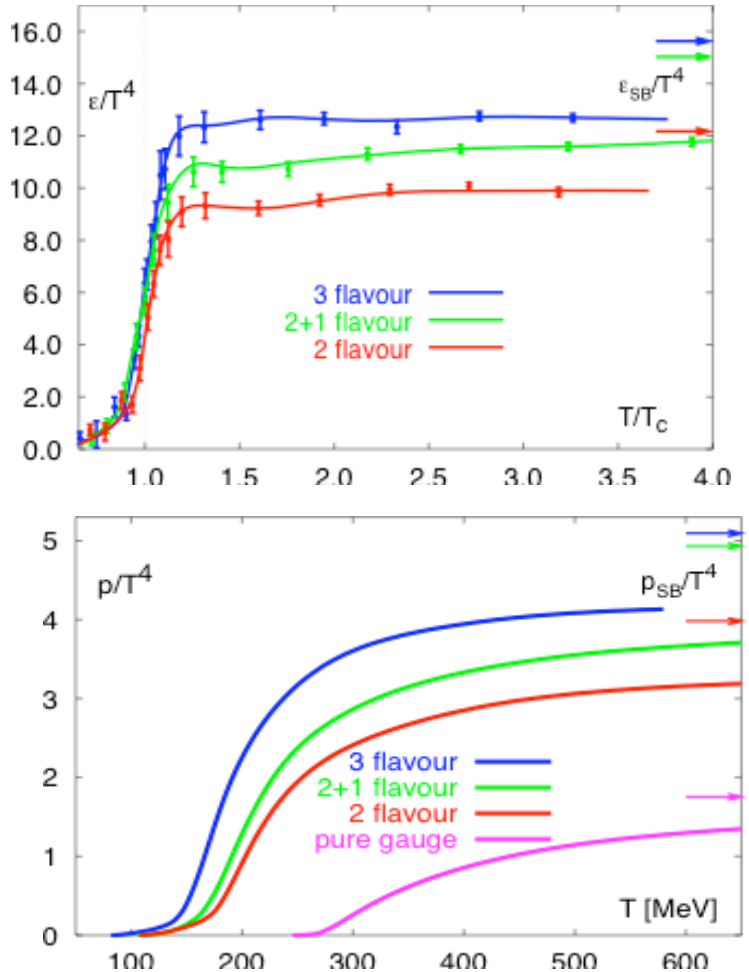
Kajantie et al.

QCD Phase Diagram as a function of quark mass

- **Lattice QCD**: first principles computation of *static* properties of finite T QCD at $T \sim T_c$

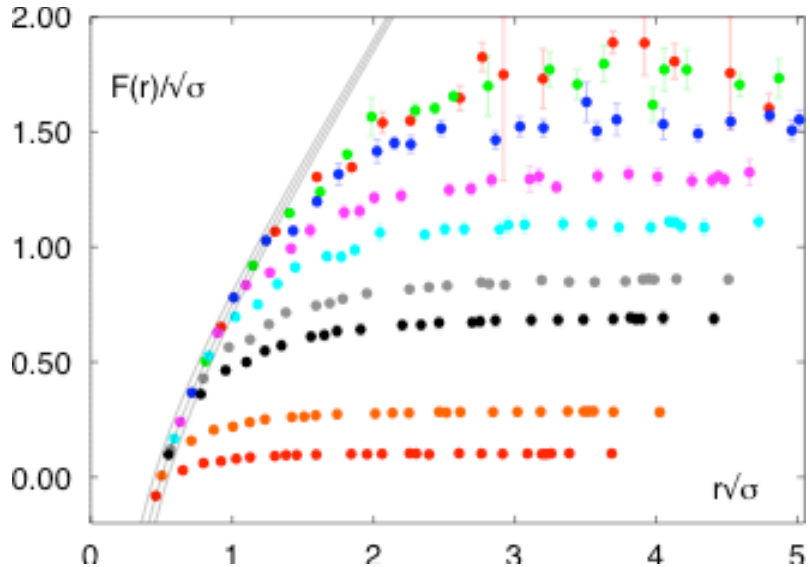


Equation of State from Lattice QCD

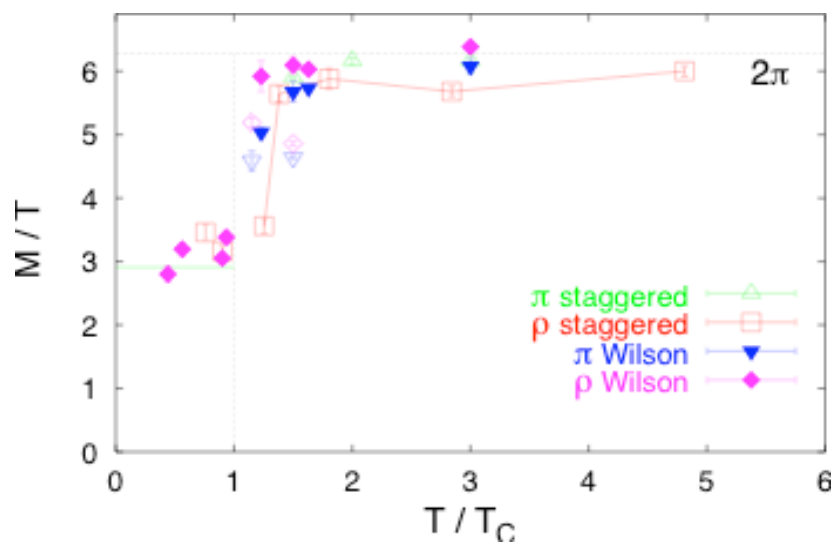


May be cross-over, but still rapid change in degrees of freedom!

- Static Quark Free Energy for $0.58 < T/T_c < 1.15$



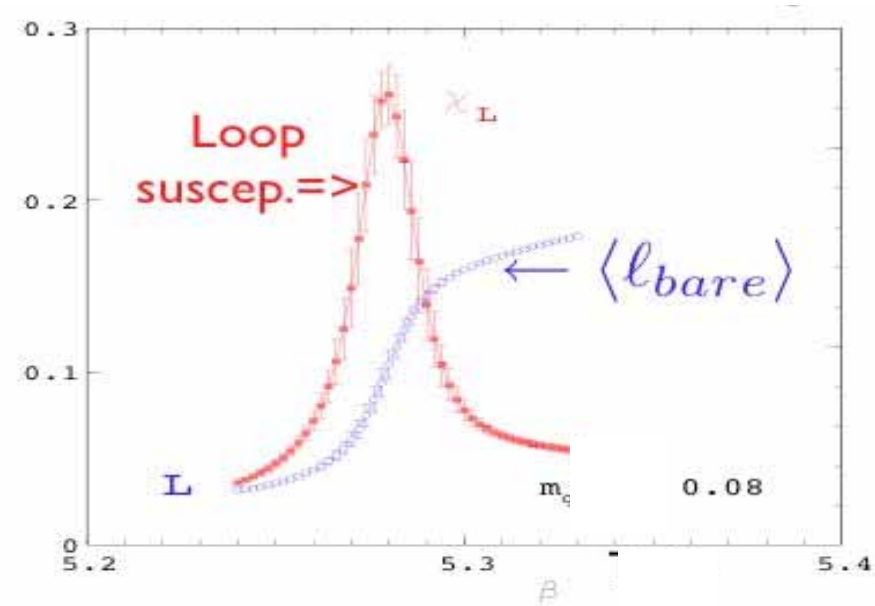
- Pseudo-scalar and vector screening masses



Chiral and deconfining transitions at same temperature?

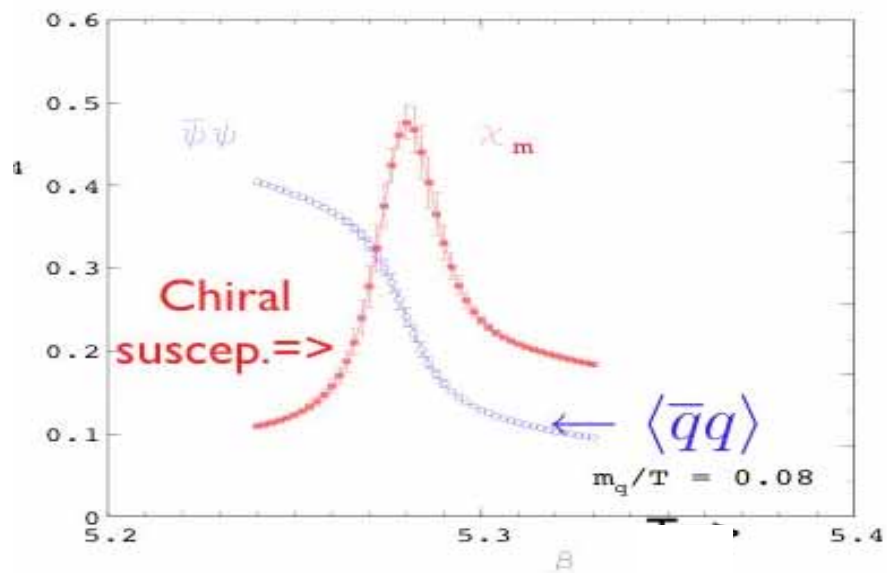
Polyakov loop

Deconfinement order
Parameter in pure gauge theory



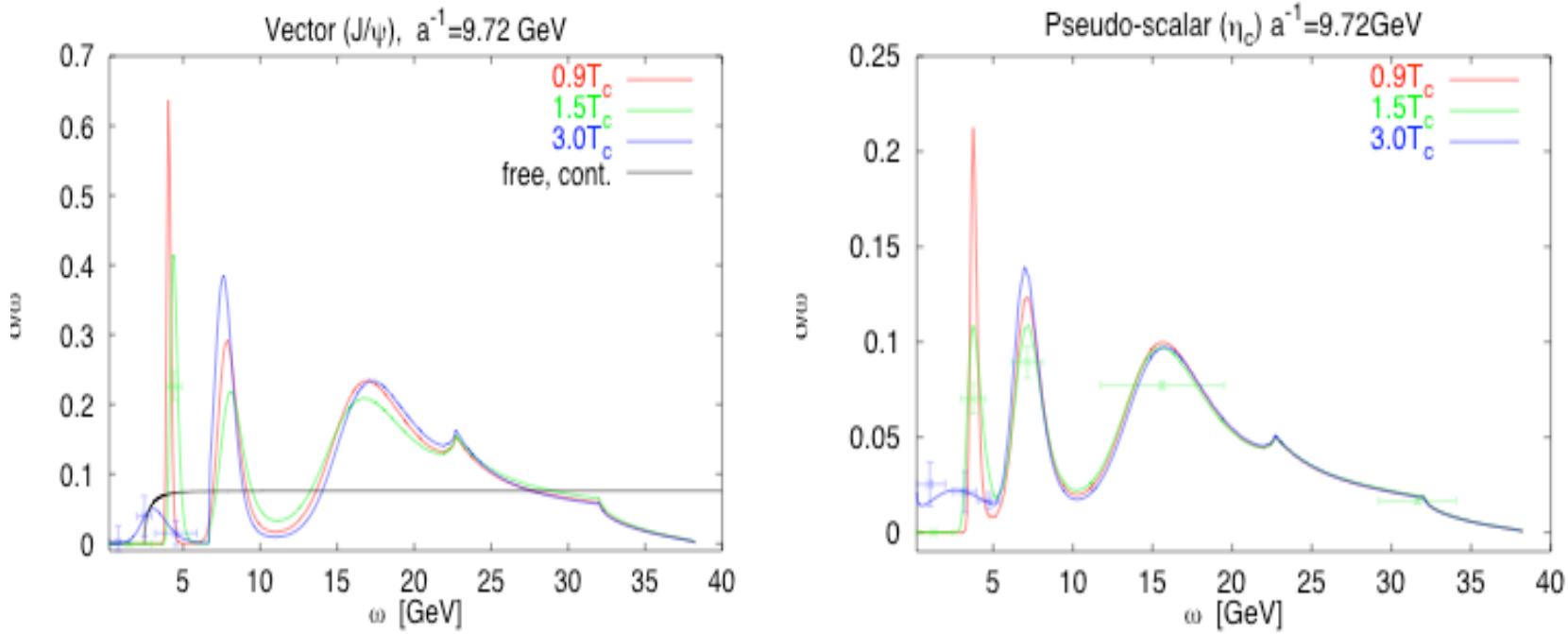
Chiral Condensate

Chiral order parameter



Signs of deconfinement and chiral restoration on lattice

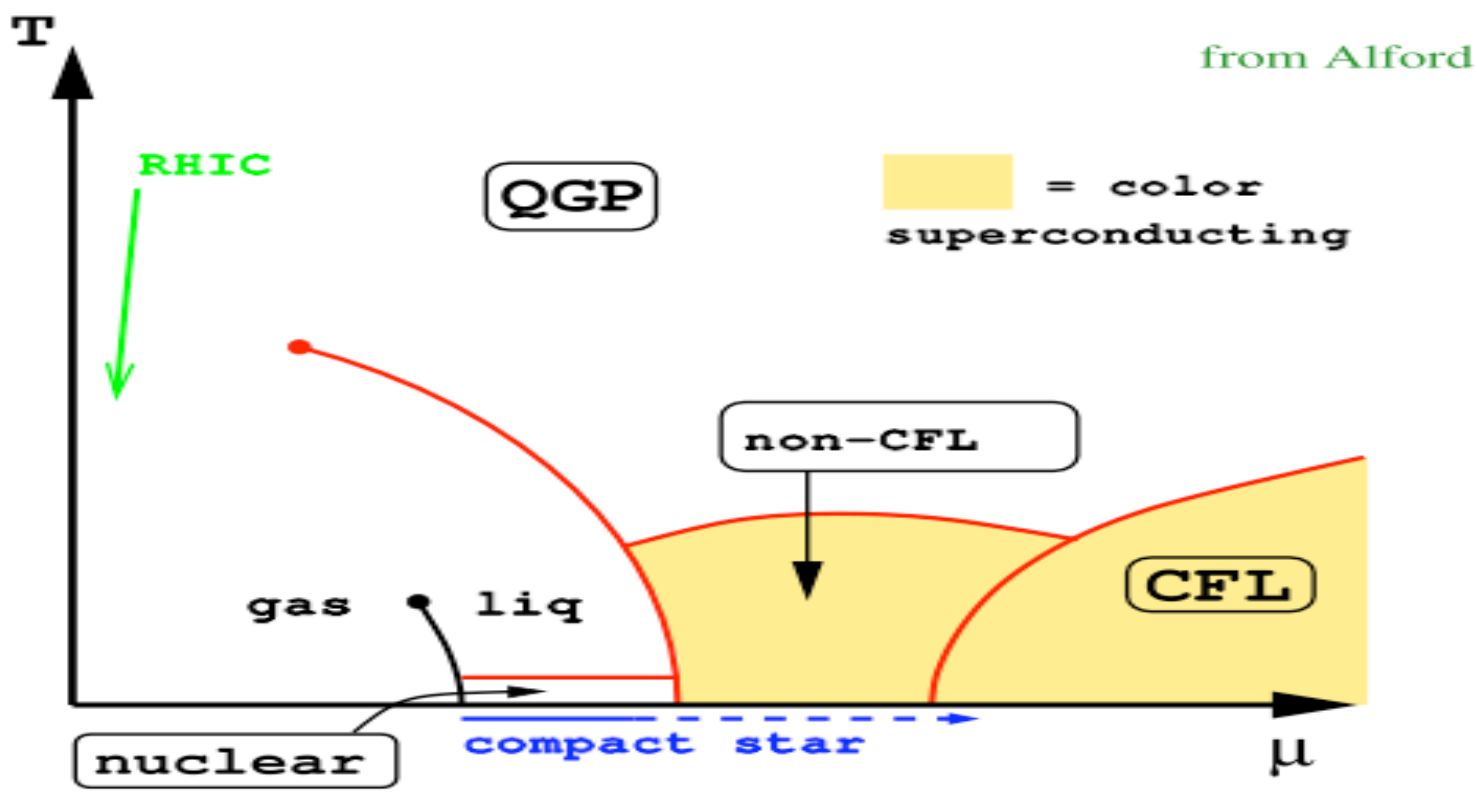
But… the picture is more complex!



Vector and pseudo-scalar spectral functions don't change significantly for T > T_c

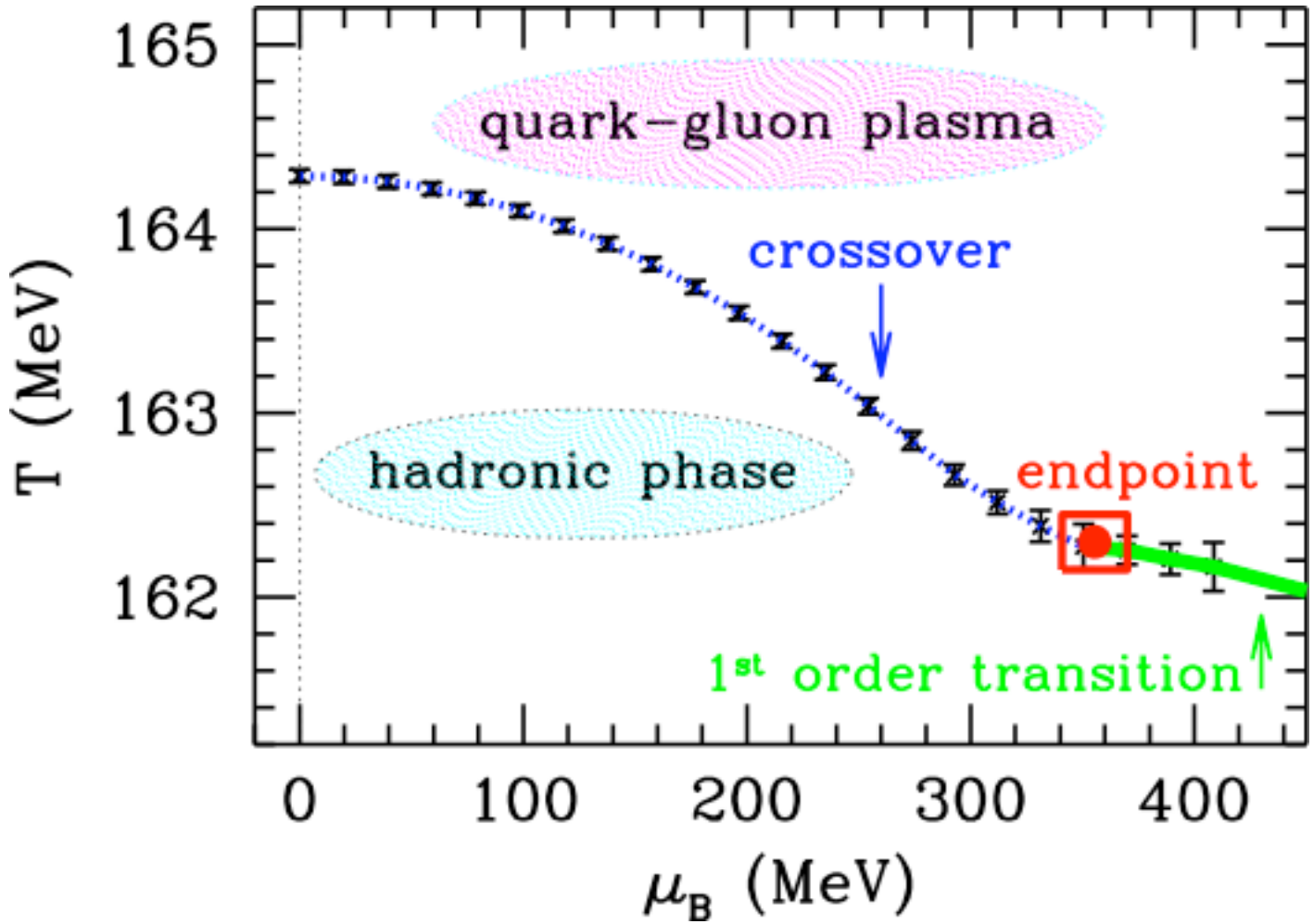
Petreczky et al. - Bielefeld Group

QCD at finite Density



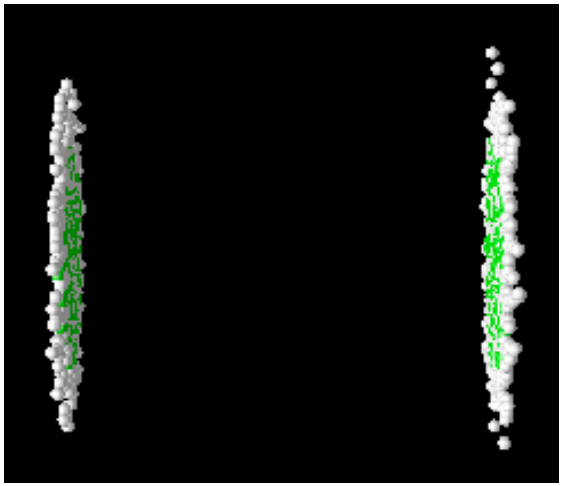
- $\alpha_s(\mu_B) << 1$ for $\mu_B >> \Lambda_{QCD}$

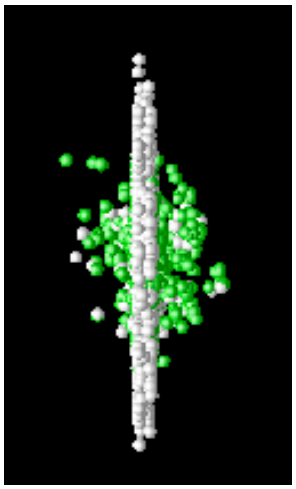
State of the Art Lattice Results on Phase Diagram

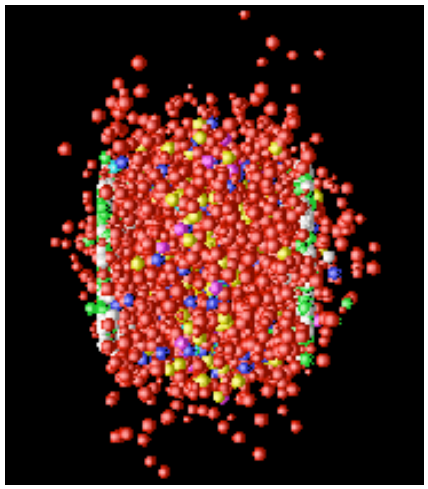


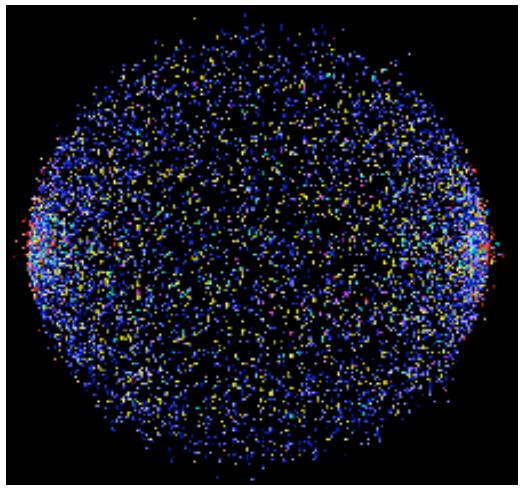
Fodor & Katz, hep-lat/0402006

Back to RHIC...



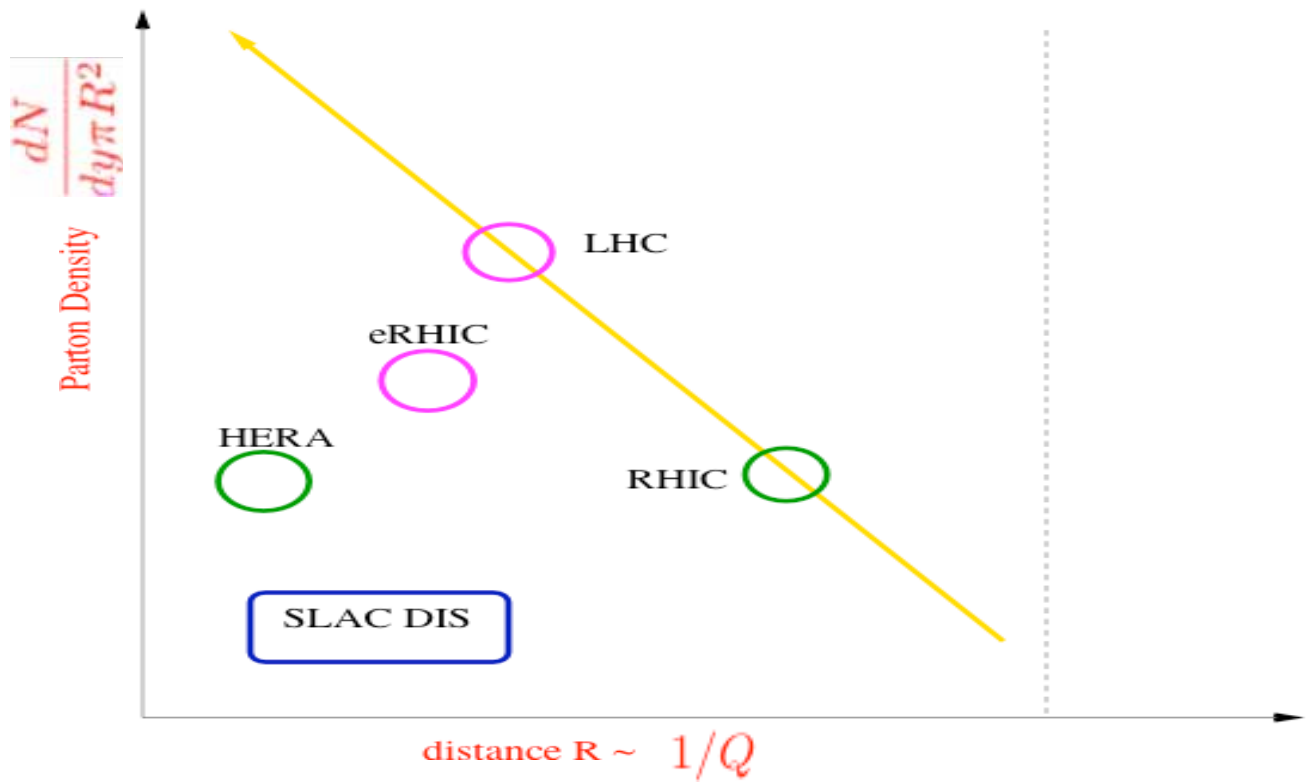






HEAVY-ION EXPERIMENTS

Facility	Location	System	Energy (CMS)
AGS	BNL, New York	Au+Au	2.6-4.3 GeV
SPS	CERN, Geneva	Pb+Pb	8.6-17.2 GeV
RHIC	**BNL, New York**	**Au+Au**	**200 GeV**
LHC	CERN, Geneva	Pb+Pb	5.5 TeV



Outstanding phenomenological questions

- Is high energy density bulk quark-gluon matter formed at RHIC?
- Does this matter thermalize to form a Quark Gluon Plasma? What can we learn about the properties of the QGP?
- Can we learn about “universal” properties of hadronic wavefunctions at high energies? (Color Glass Condensate)

Results from the RHIC Au-Au experiments:

Bulk features: Energy, Centrality & Rapidity dependence of inclusive hadron distributions.

Flavor: Baryon #, Strangeness, Charm.

Flow: Radial & Elliptic flow.

Hanbury-Brown-Twiss: Two particle Bose-Einstein correlations.

High p_t physics:

a) High p_t inclusive hadron spectrum relative to p-p (central/peripheral)

b) p_t dependence of azimuthal anisotropy,

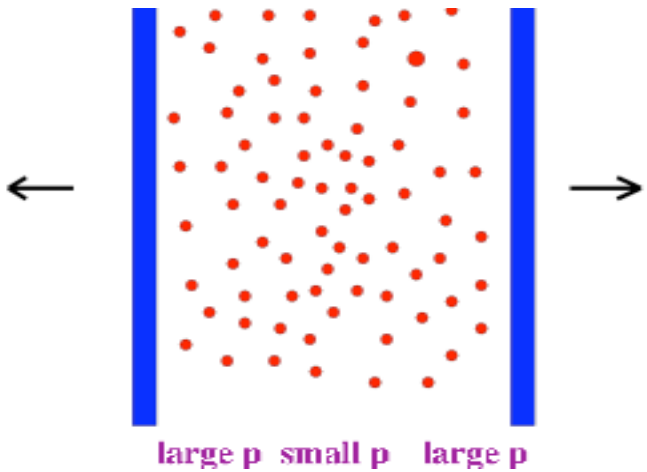
c) back-to-back jet correlations.

d) direct photons & di-leptons; J/psi's

Event-by-event physics:

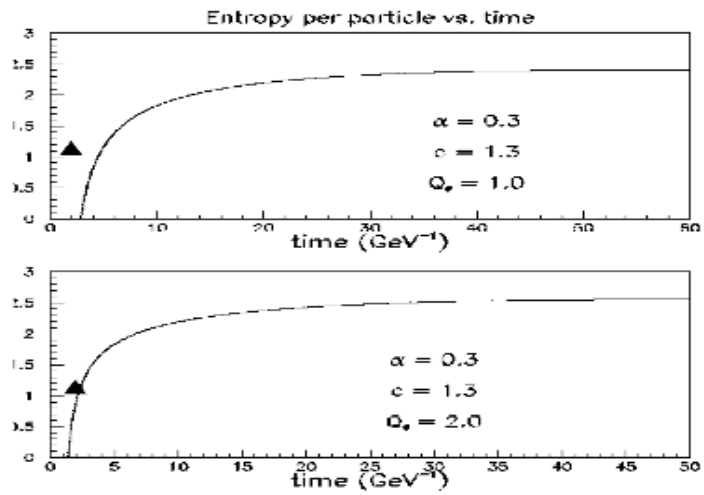
p-p and d-Au ``control experiments" crucial to develop consistent framework

Heavy-Ion Collisions-a violent dynamical system…
Is thermalization achieved?



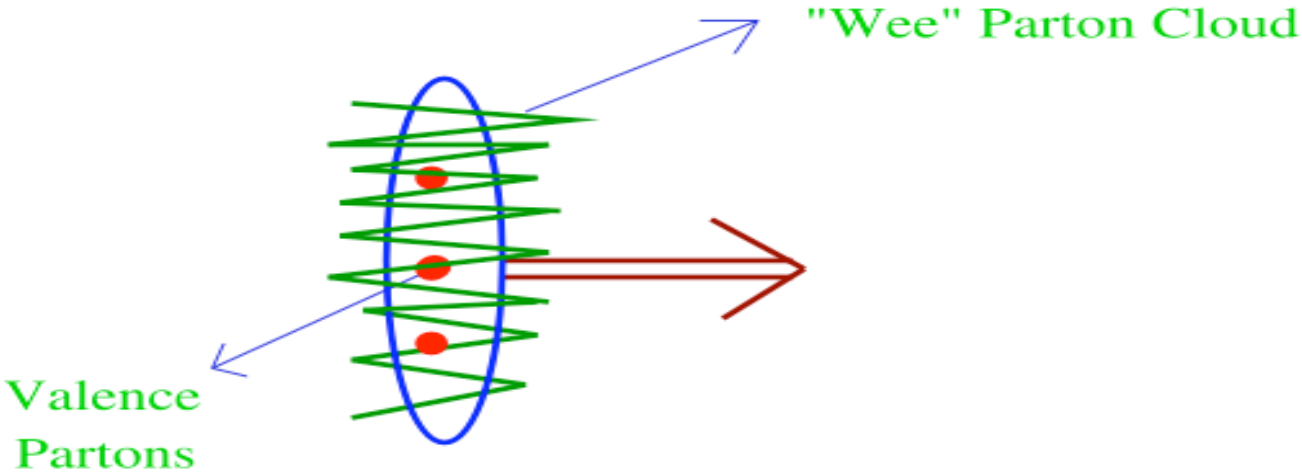
Require ratio of rates:

$$\frac{\Gamma_{\text{exp.}}}{\Gamma_{\text{coll.}}} << 1$$



Thermalization very sensitive to Initial Conditions

A hadron at high energies

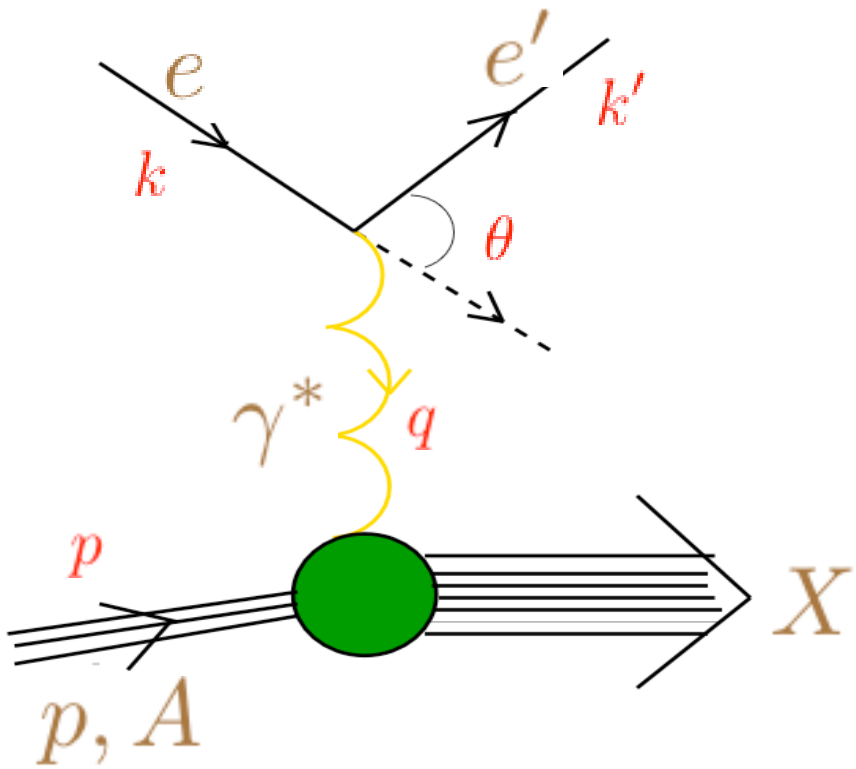


$$|h>=|qqq>+|qqqg>+\cdots+|qqq\cdots gggq\bar{q}>$$

Each wee parton carries only a small fraction $x^+ = k^+/P^+$ of the momentum P^+ of the hadron

What is the behavior of wee partons in a high energy hadron?

The DIS Paradigm



Kinematics:

$$s = (p+k)^2$$

$$Q^2 = -q^2 = 4E_e E_{e'} \sin^2\left(\frac{\theta}{2}\right)$$

$$x_{\mathrm{Bj}} = \frac{Q^2}{2M_p(E_e - E_{e'})} \equiv \frac{Q^2}{2p\cdot q}$$

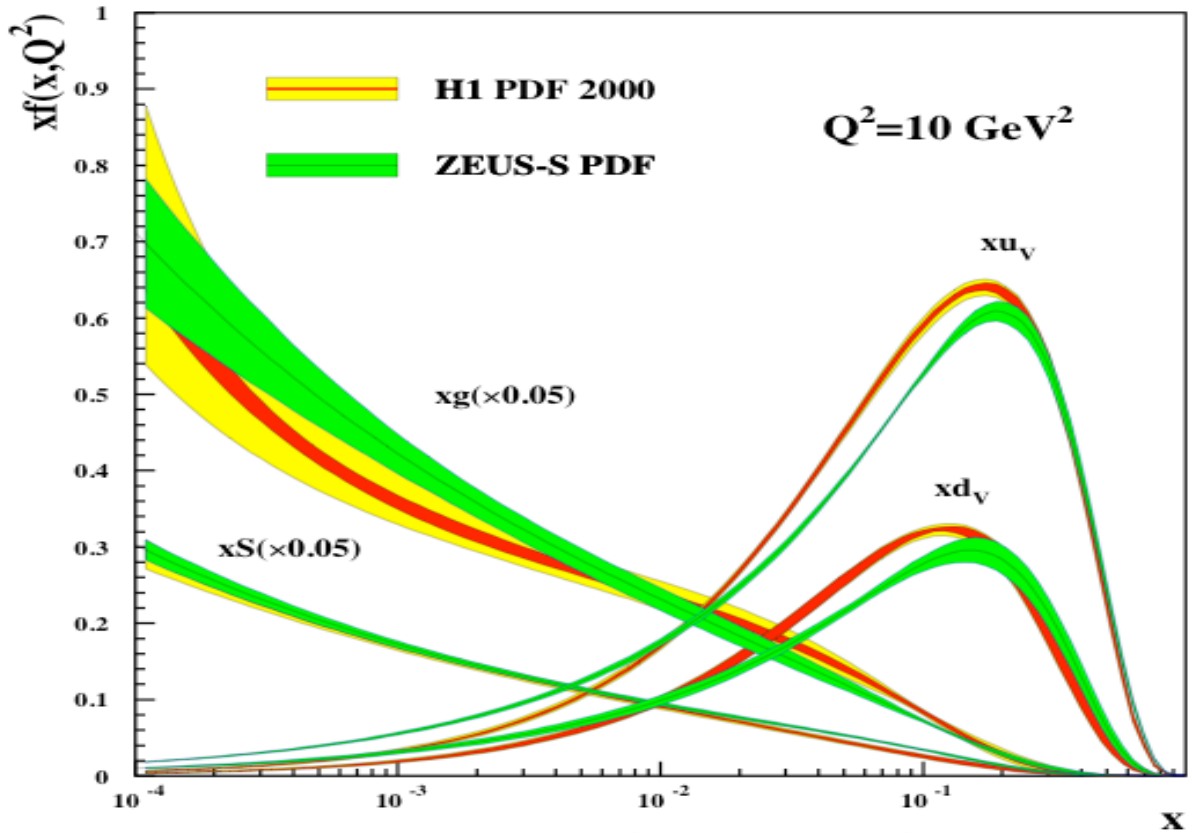
$$y = \left(1 - \frac{E_{e'}}{E_e}\right) = \frac{p\cdot q}{p\cdot k}$$

$$\boxed{x\,y \approx \frac{Q^2}{s}}$$

Cross-section:

$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha_{\mathrm{em.}}}{xQ^4}\left[y^2 x F_1(x,Q^2) + (1-y)F_2(x,Q^2)\right]$$

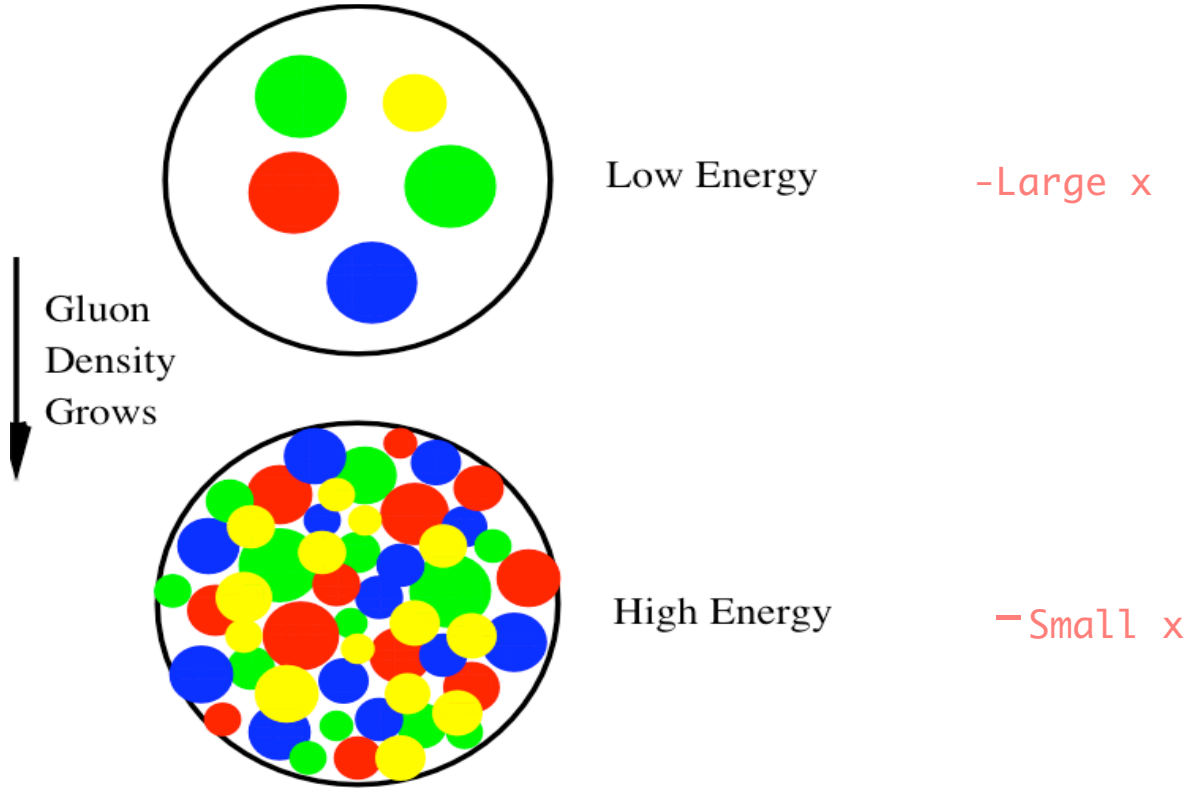
Born-Oppenheimer: separation of large x and small x modes



$$\tau_{\rm wee} \sim \frac{1}{k^-} = \frac{2k^+}{k_\perp^2} \equiv \frac{2x\,P^+}{k_\perp^2}$$

$$\tau_{\rm valence} = \frac{2P^+}{k_\perp^2} >> \tau_{\rm wee} \text{ for } x << 1$$

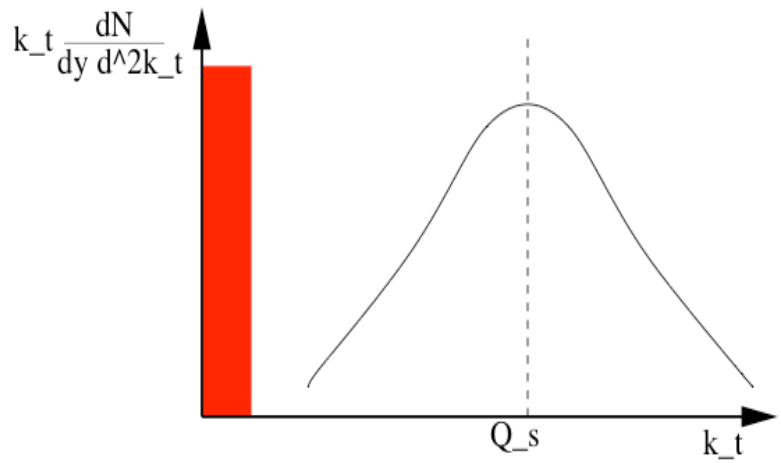
Valence partons are static over wee parton life times



Phase space density grows rapidly-BFKL evolution breaks down when phase space density f~ 1

Gluon density saturates at f= $\frac{1}{\alpha_S}$

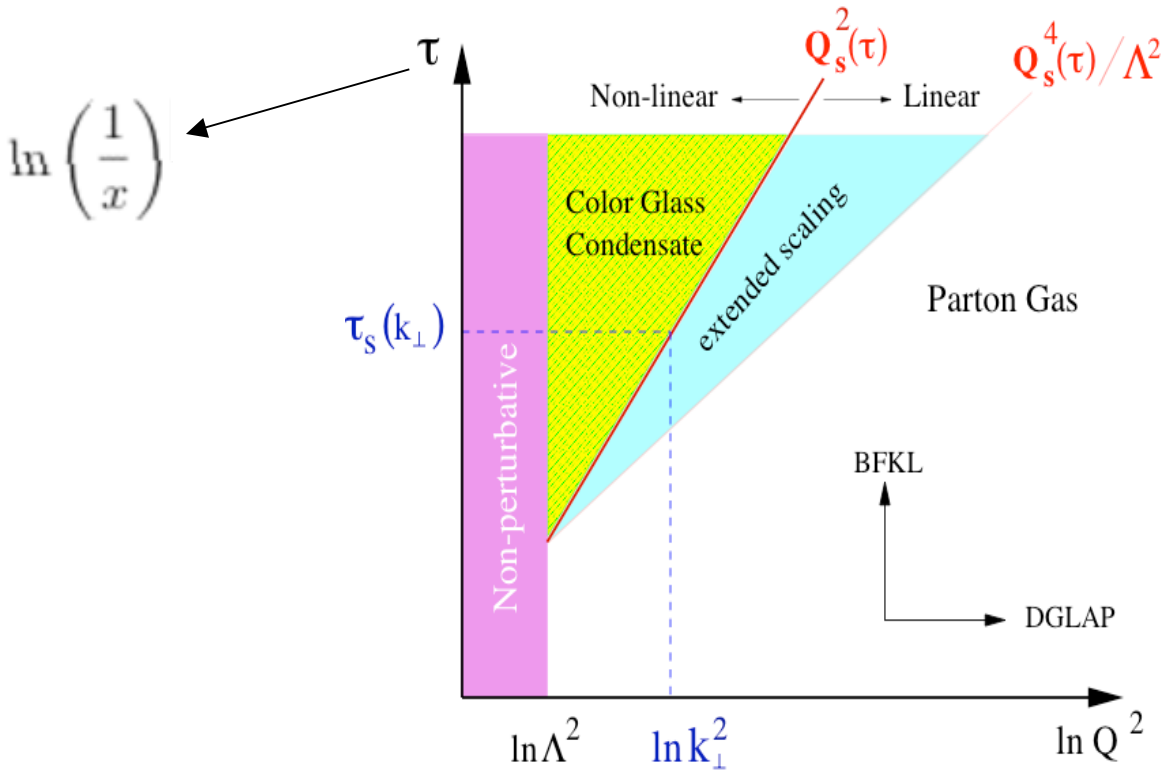
The Color Glass Condensate



- ✓ *Typical momentum of gluons is* Q_s
- ✓ *Bosons with large occupation #* $\sim \frac{1}{\alpha_S}$ *- form a condensate*
- ✓ *Gluons are colored*
- ✓ *Random sources evolving on time scales much larger than natural time scales-very similar to spin glasses*

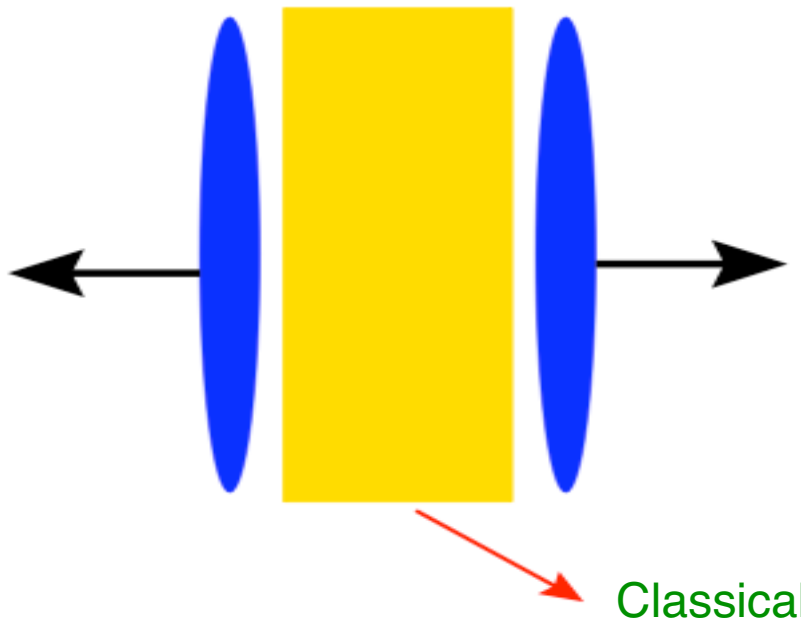
Hadron/nucleus at high energies is a Color Glass Condensate

Novel regime of QCD evolution at high energies



The Color Glass Condensate

Colliding Sheets of Colored Glass at High Energies



Classical Fields with occupation $\frac{1}{\alpha_S}$=

Initial energy and multiplicity of produced gluons depends on Q_s

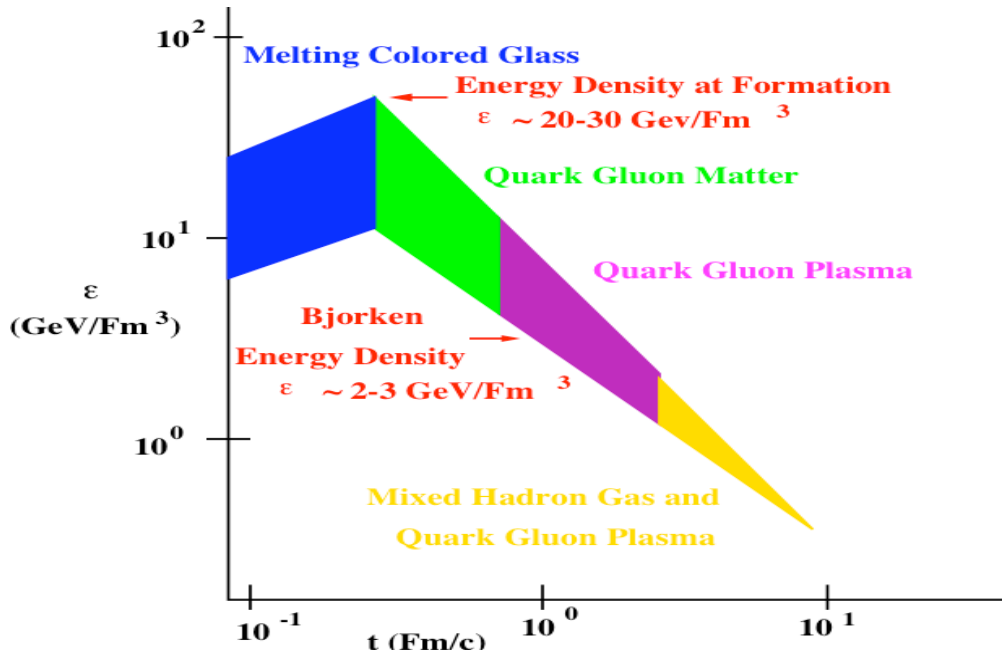
$$\frac{1}{\pi R^2}\frac{dE_\perp}{d\eta} = \frac{0.25}{g^2}Q_s^3$$

$$\frac{1}{\pi R^2}\frac{dN}{d\eta} = \frac{0.3}{g^2}Q_s^2$$

Classical approach breaks down at late times when f <<1

$$\tau >> \frac{1}{Q_s} \text{ but } \tau << R$$

Space-time evolution in heavy ion collisions



Initial conditions determined by saturation scale Q_s >> T_i

$$\varepsilon \propto \frac{Q_s^4}{\alpha_S} \text{ at } \tau \sim \frac{1}{Q_s}$$

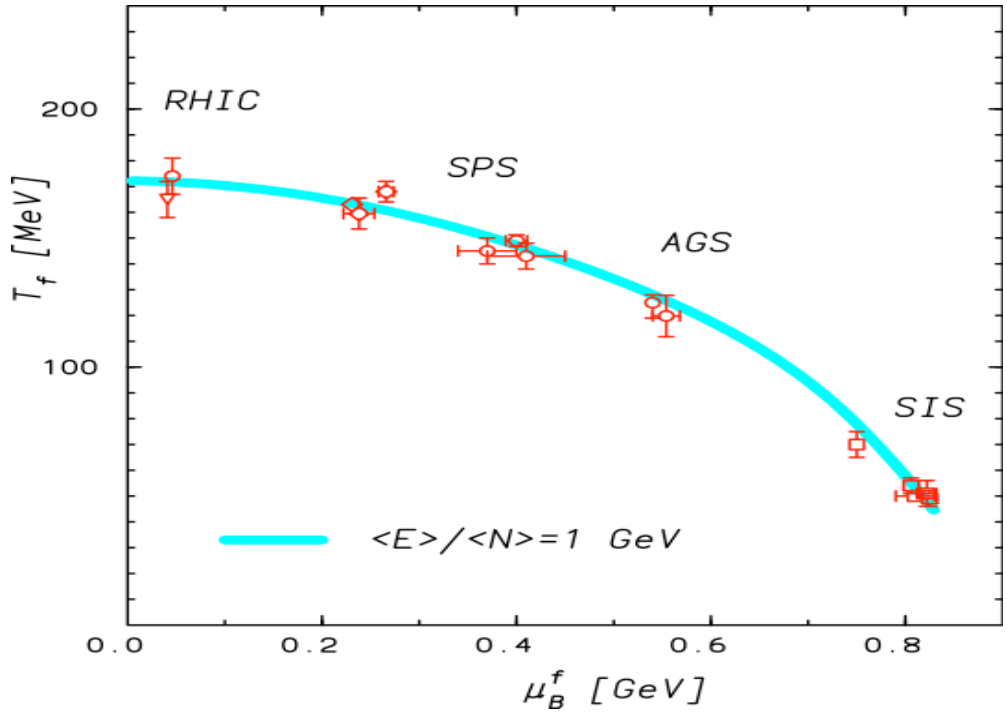
Q_s=1.4--2 GeV from HERA data extrapolations and numerical simulations

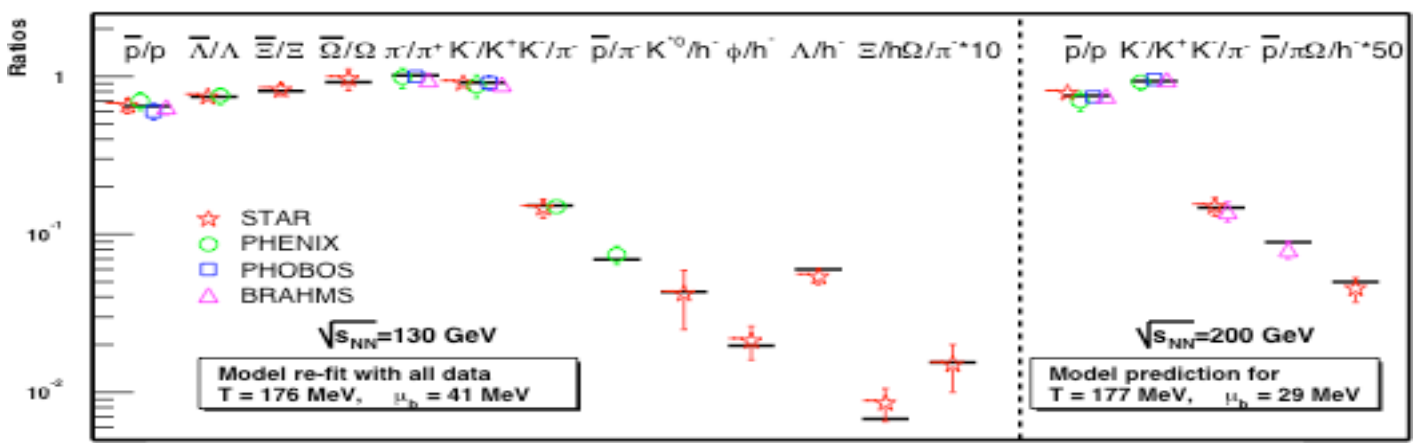
Do initial state (wave fn.) effects or final state (parton re-scattering) dominate in the space-time evolution?

Emerging Consensus…final state interactions are essential.

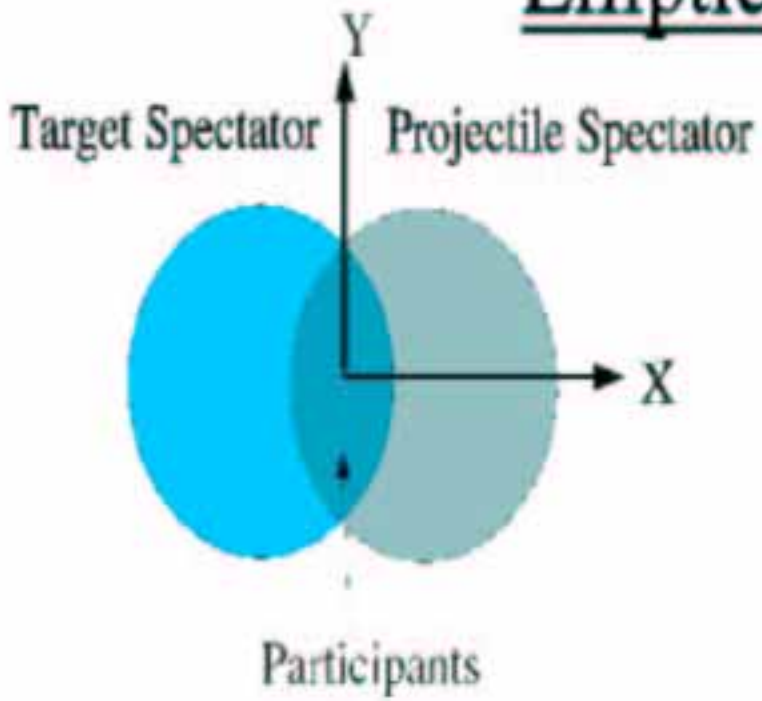
The evidence from low p_t physics

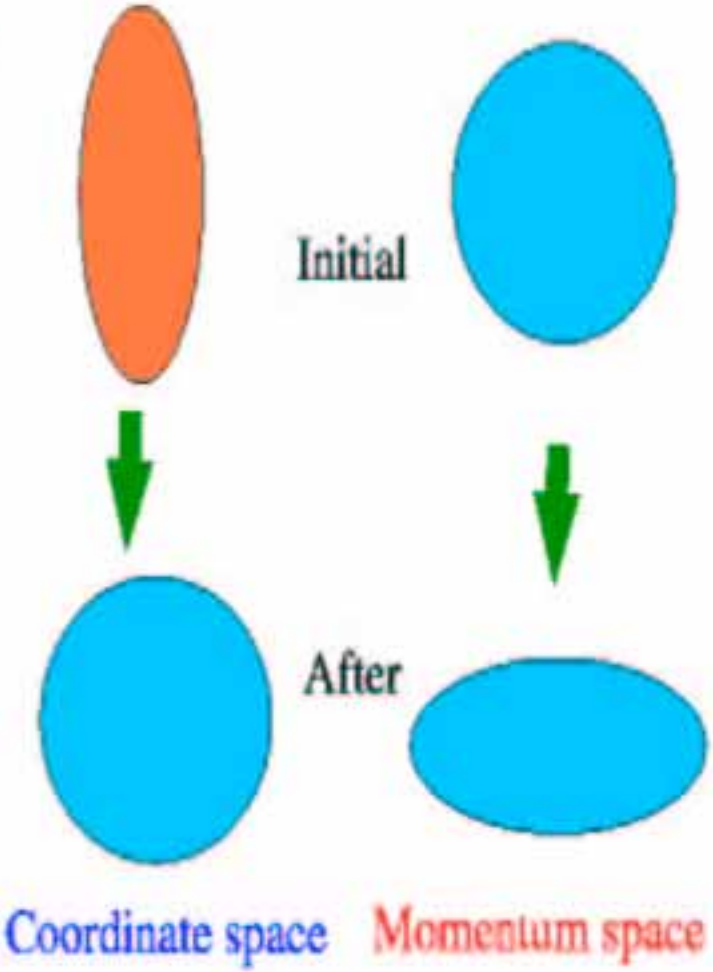
Thermal fits to
Particle ratios





Elliptic flow





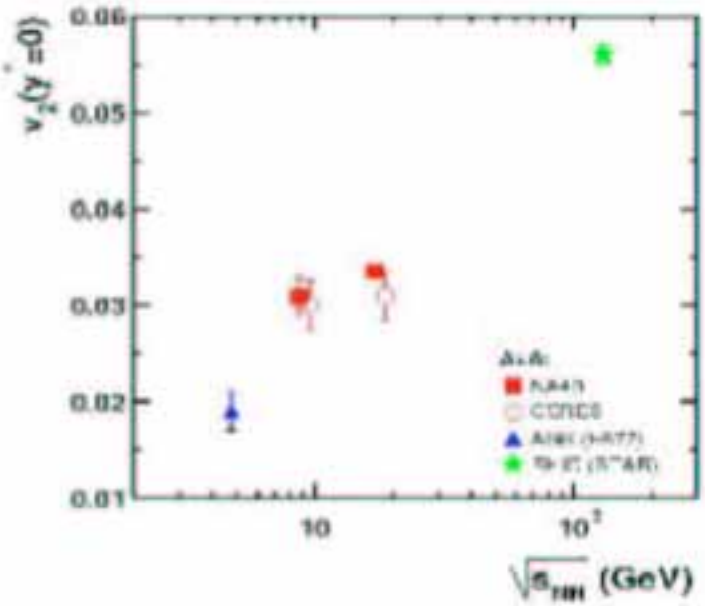
$$v_2 \equiv \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

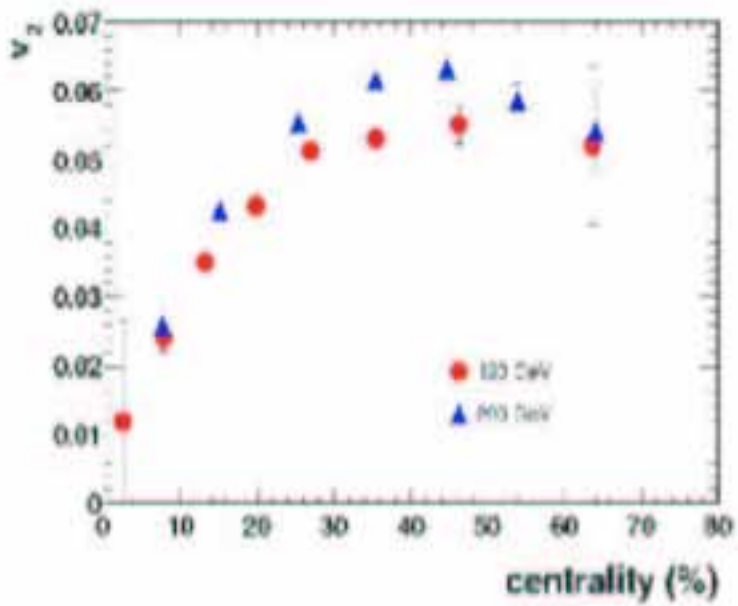
Idea : Interaction ⇨ convert space anisotropy to momentum anisotropy

S. A. Voloshin, QM02, nucl-ex0210014

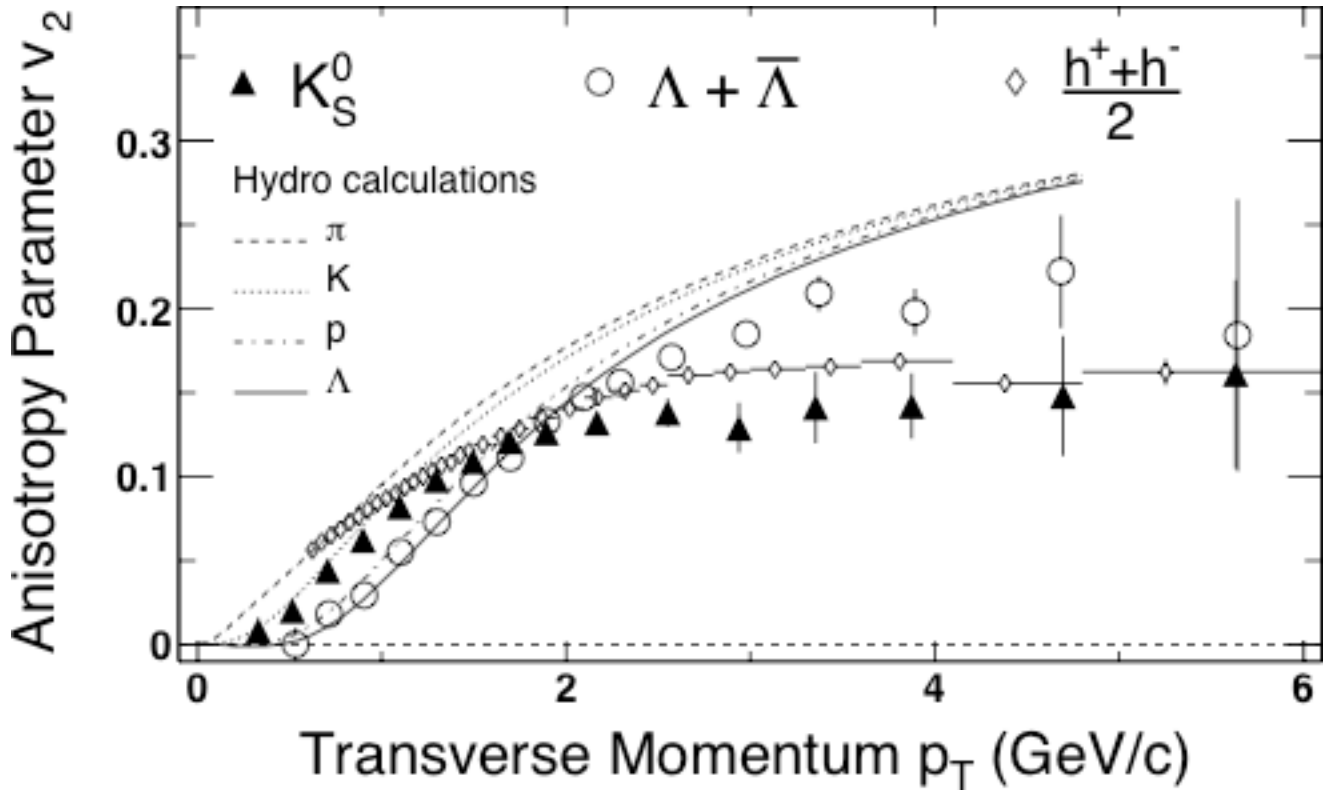
STAR, P.R.C66,034904(2002)

Large elliptic flow at RHIC



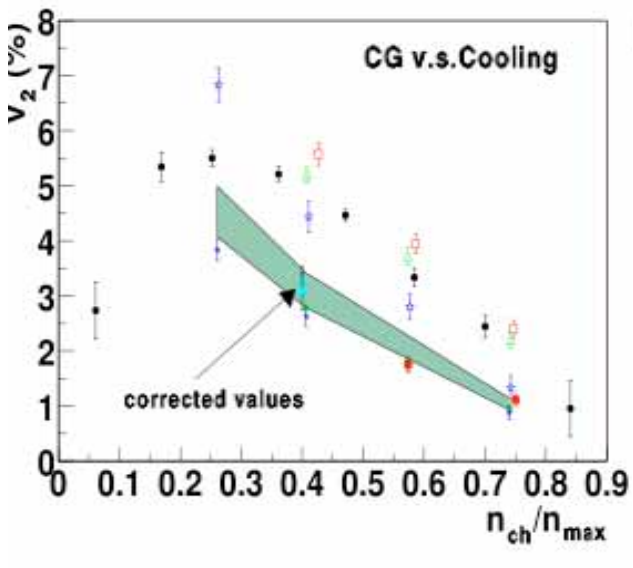


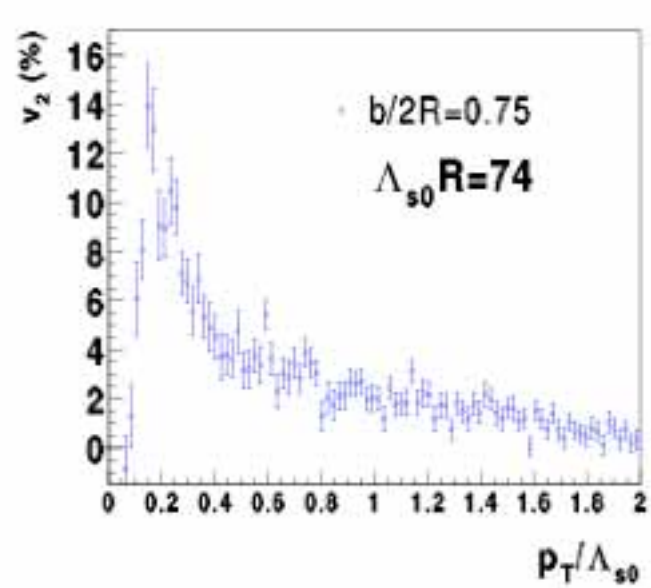
Large elliptic flow strongly indicates
Collectivity in final state



Flow of different particle species is consistent
With expectations from hydrodynamics

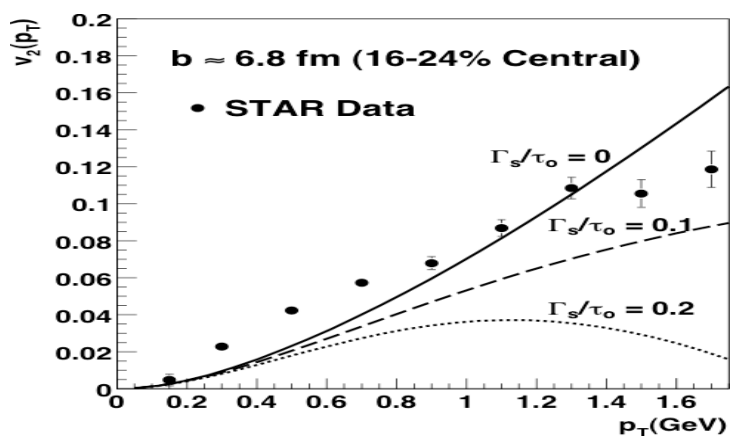
CGC computations dont give enough v_2: re-scattering essential!





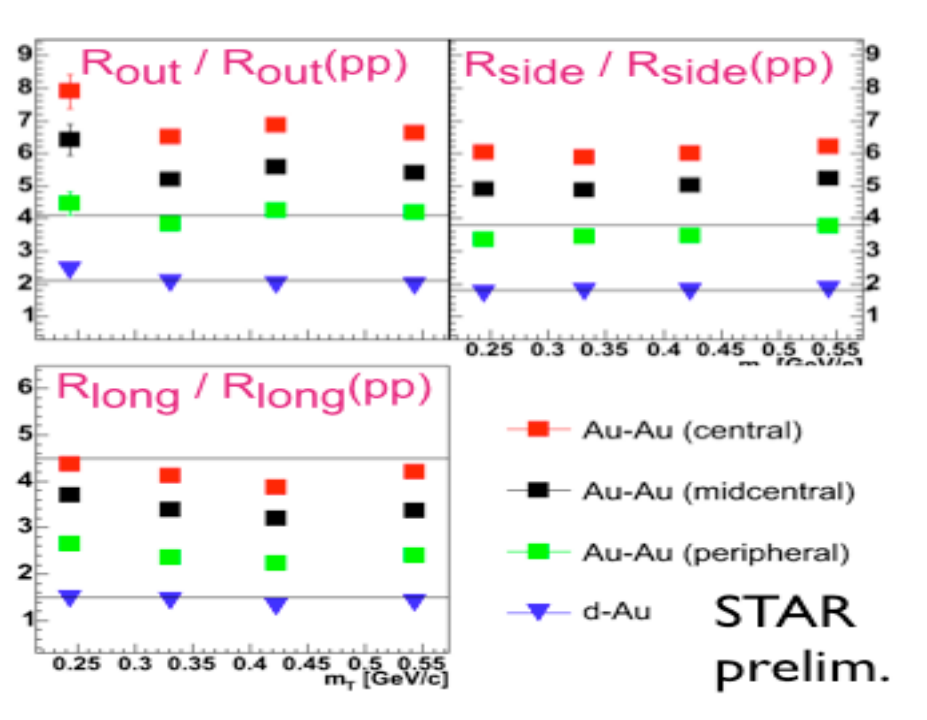
Early thermalization essential in hydro. Too much v_2?

Teaney: viscous effects may be important

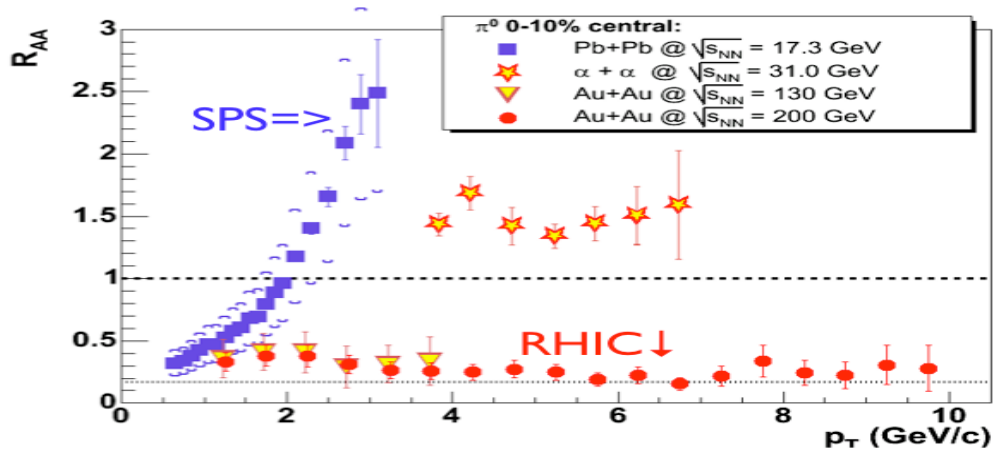


Consistent with lattice estimates of viscosity by S. Gupta

HBT: a major puzzle

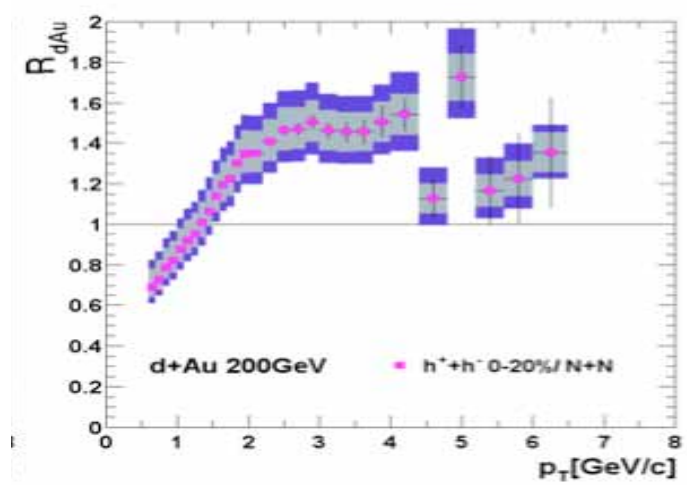


What is the evidence from high p_t?



- *Dramatic suppression out to 10 GeV-clearly distinct from SPS data.*

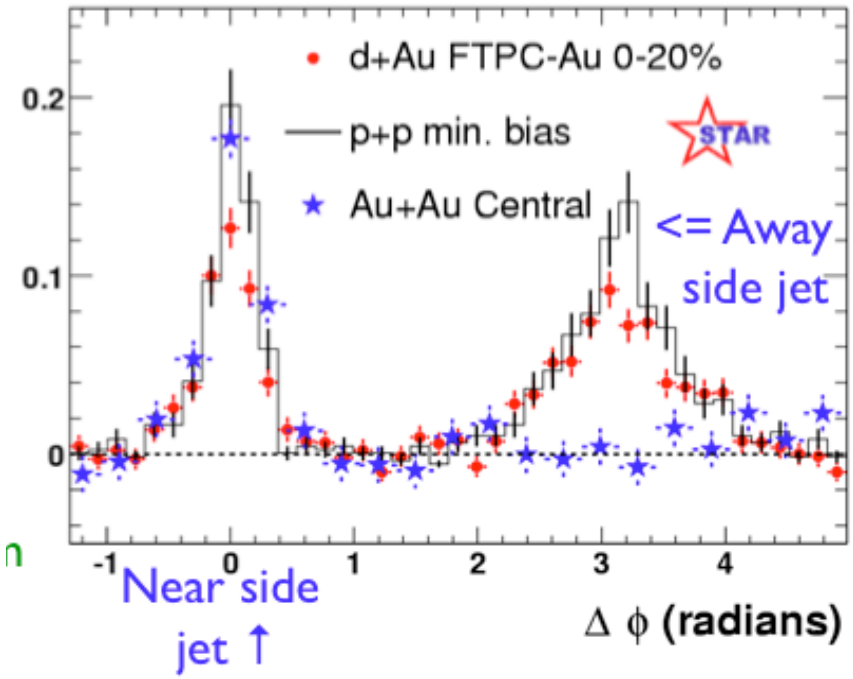
D-Au data clearly establishes it as final state effect
Color Glass alone would give 25-30% suppression

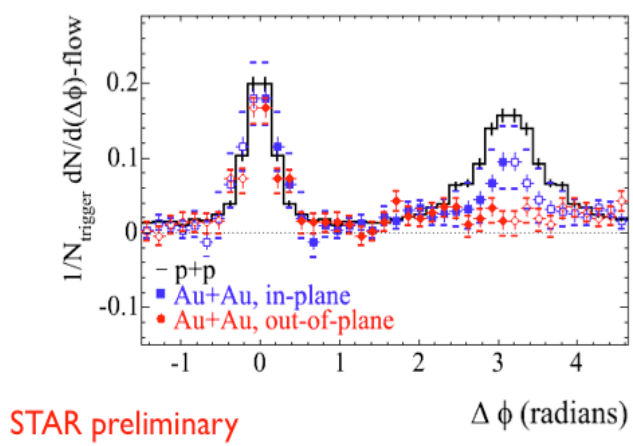


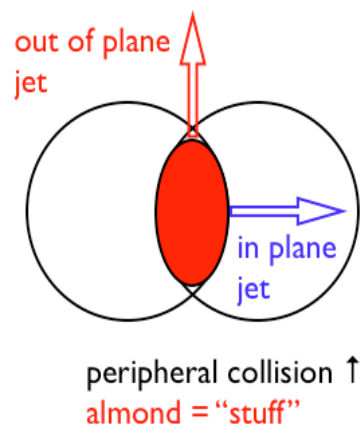
Natural explanation: partonic energy loss-not (pre-) hadron absorption

X.-N. Wang

Reconstructing Jets from Azimuthal correlations







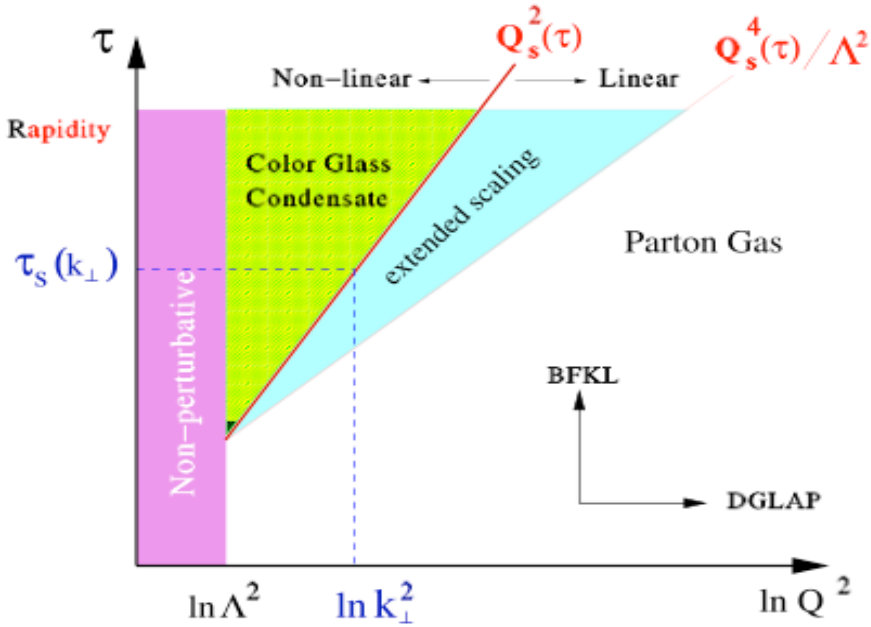
No sign of suppression at SPS-only broadening of backward jet

Evidence of novel final state effects

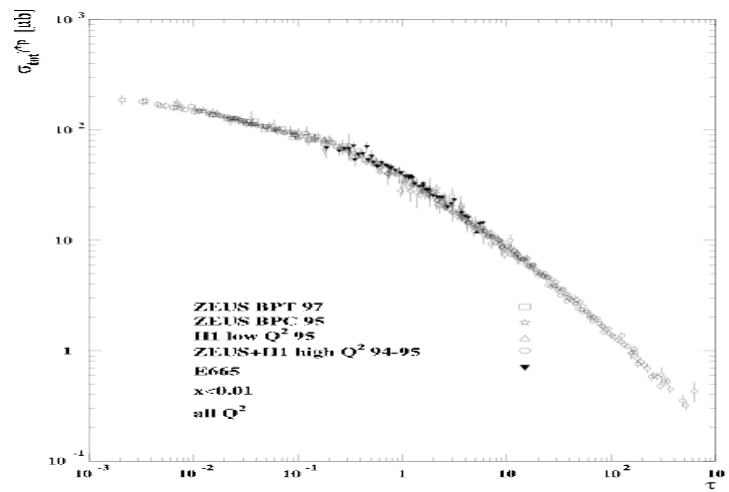
- Flow at low p_t
- high p_t suppression
- systematics of azimuthal correlations
- Clearly distinct from cold matter probed in d-Au

All models that explain these distinct features have to assume very dense, strongly interacting matter: consistent with the QGP …many open questions remain for RHIC to explore!

Novel regime of QCD evolution at high energies



Geometrical scaling seen at HERA-small x inclusive and diffractive data explained by color glass



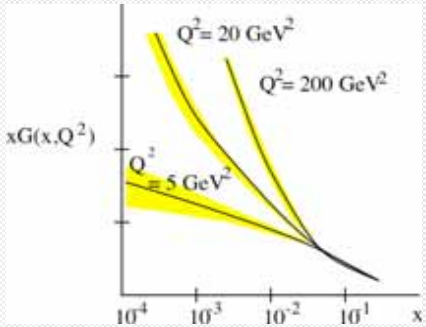
RHIC can discover a universal Color Glass regime of QCD in hadrons at high energies

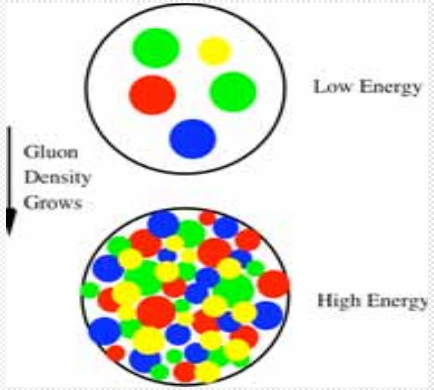
What is the CGC?

- Effective theory of QCD at high energies--small x

- Identifies right "universal" degrees of freedom at small x

- These satisfy non-linear evolutions eqns.-the JIMWLK eqns.- at small x

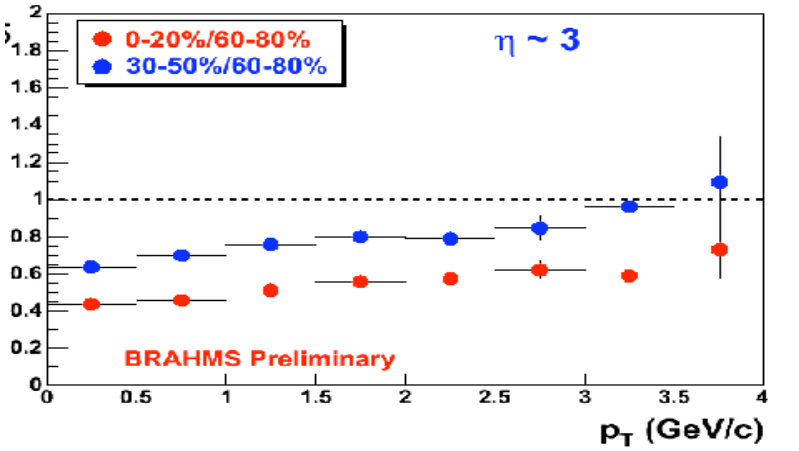




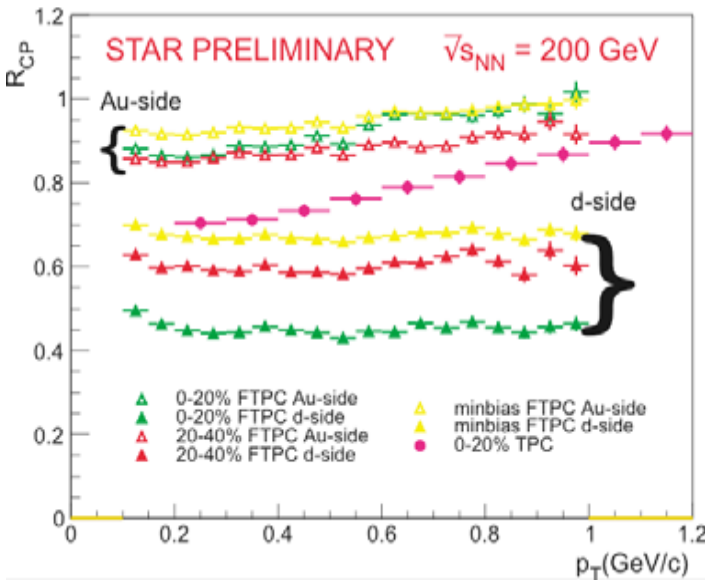
- *The CGC explains saturation/shadowing in a weak coupling partonic framework.*
- *It is a theory of the initial conditions in heavy ion collisions.*

The evidence for CGC from RHIC

Brahms forward data qualitatively different from $\eta = 0$



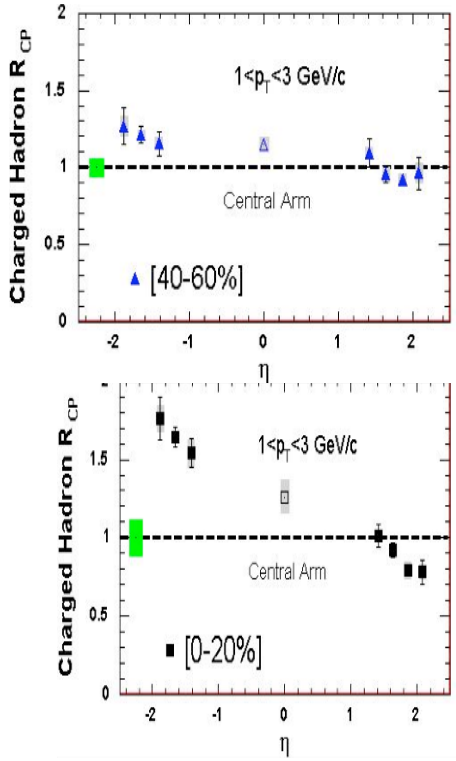
Enhanced by STAR data showing less suppression on Gold side



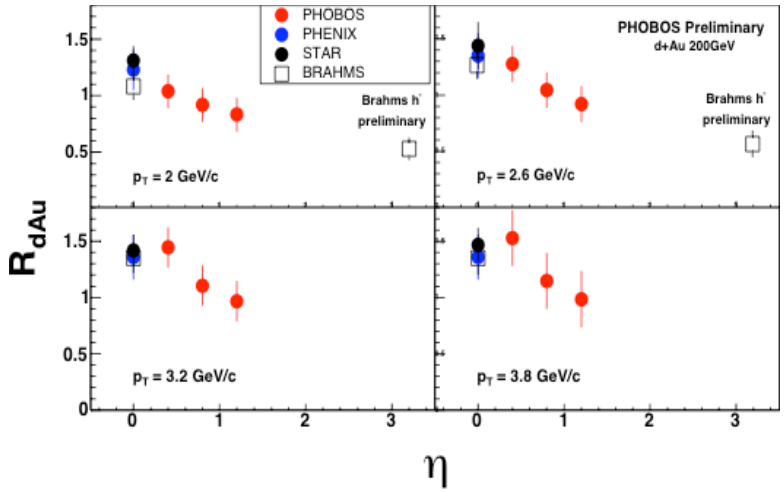
Going forward in rapidity => smaller x in the nucleus!

More on CGC from RHIC…

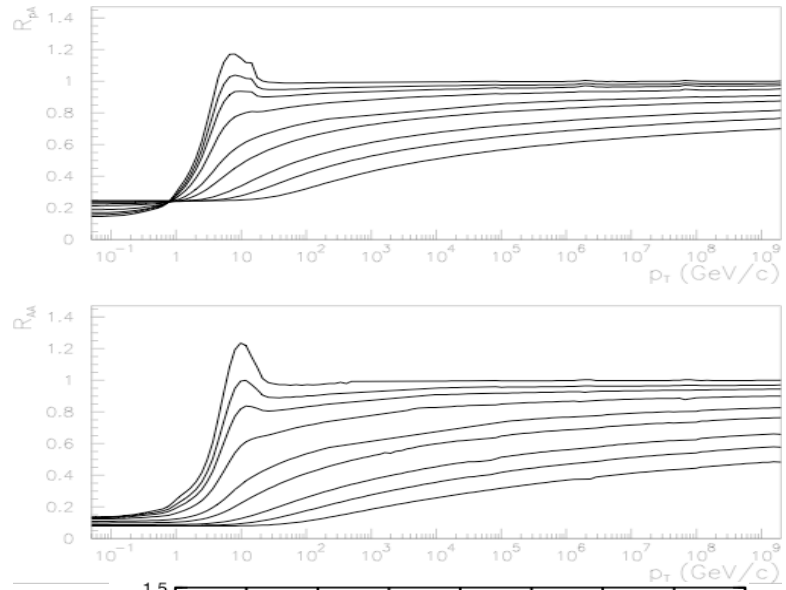
From the Phenix muon arms



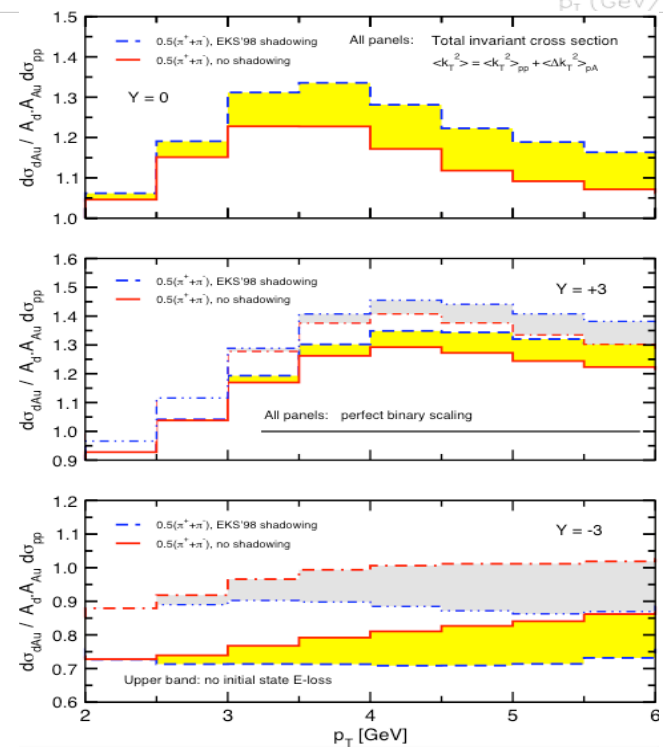
Phobos plot for different p_t



Qualitative behavior predicted from non-linear evolution



Different from initial shadowing predictions



More quantitative studies needed!

The emerging picture from RHIC

- Central rapidities at RHIC (x~10^-2) -weak initial state effects-strong final state effects

- At forward rapidities (x~10^-3) - strong initial state effects

Are these effects respectively the QGP & the CGC? Likely-next few runs may be decisive

What do we need to do ?

- Rare probes-photons, di-leptons, J/Psi

- Energy scan-especially interesting to establish differences with SPS as number density grows.

- Look forward--a d-Au program has great potential for new physics-may require significant detector upgrades. Tie-in with eRHIC?

Important lessons for LHC & eRHIC

- At LHC x~10^-3 , initial state shadowing may swamp Energy loss effects.

- At eRHIC, precocious saturation effects can be studied with larger Q^2 lever arm