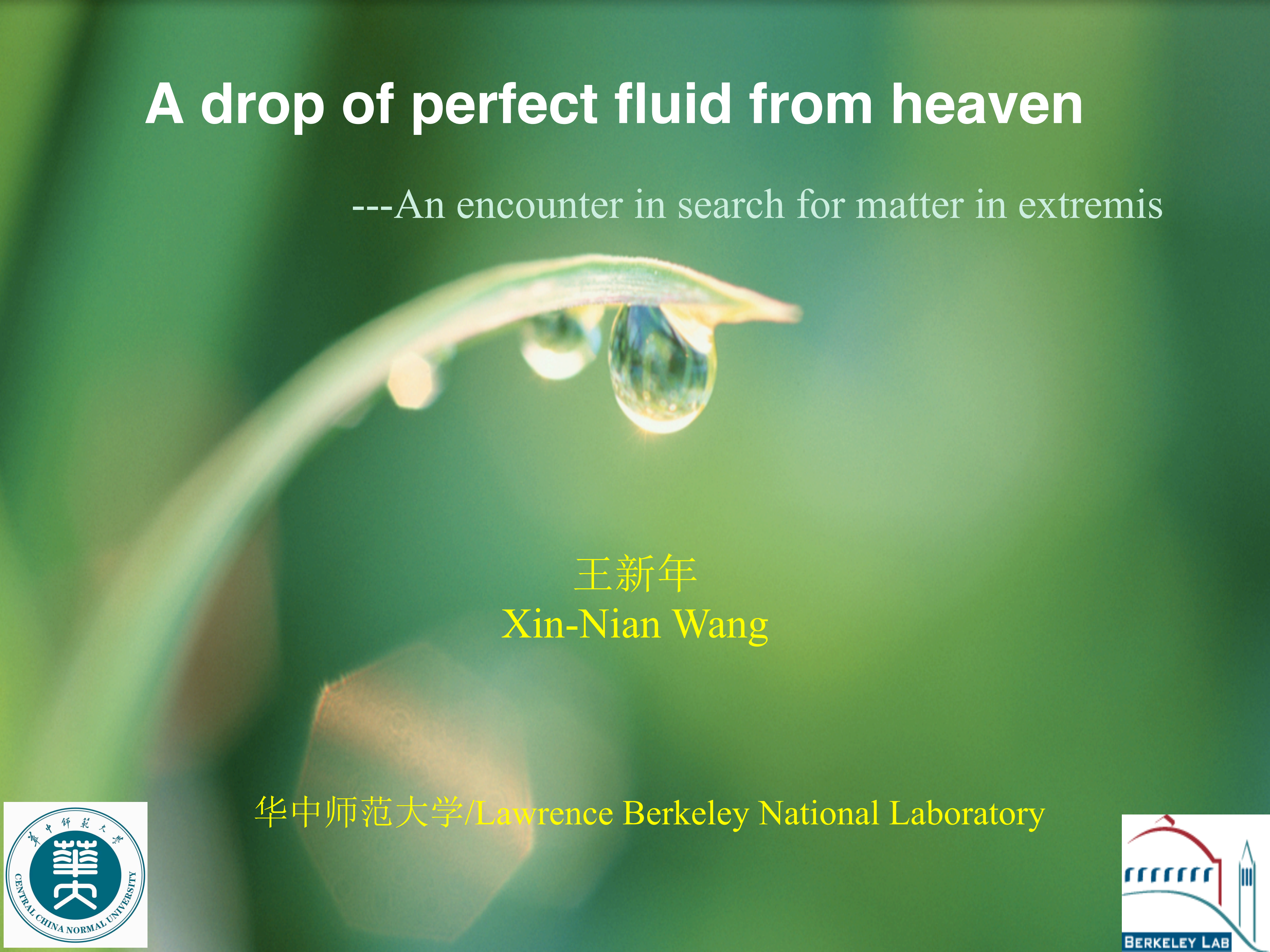

A drop of perfect fluid from heaven

---An encounter in search for matter in extremis

王新年
Xin-Nian Wang

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Phases of Matter

火 (gas)

水 (liquid)

土 (solid)

Bose-Einstein condensate, fermionic condensate,
superfluids, supersolids, paramagnetic,
ferromagnetic, liquid crystals, …

Quark-gluon Plasma (QGP)

Symmetries & Anomalies

QCD Theory

$$L_{QCD} = \sum_{f=1}^{n_f} \bar{\psi}\gamma_\mu (i\partial^\mu - gA_a^\mu \frac{\lambda_a}{2} - m)\psi - \frac{1}{4}\sum_a F_a^{\mu\nu} F_{a,\mu\nu}$$

- SU(3) gauge symmetry (non-Abelian)
- Chiral symmetry and its spontaneous breaking
- Scale and $U_A(1)$ anomaly
- …

Scale Anomaly

- Scale invariance (massless quarks)

$$\psi(x) \rightarrow \lambda^{3/2}\psi(\lambda x); \quad A_\mu(x) \rightarrow \lambda A_\mu(\lambda x)$$

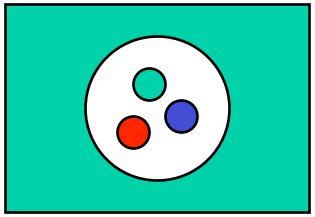
$$J^\mu_{scale}(x) = x_\nu T^{\mu\nu}(x) \qquad \partial_\mu J^\mu_{scale}(x) = T^\mu_\mu(x) = 0$$

- Quantum interaction → renormalization of g(Λ_{QCD})
  - Break scale invariance → scale anomaly

$$T^\mu_\mu = \frac{\alpha_s}{12\pi} F^{\mu\nu}_a F^a_{\mu\nu} \qquad \langle T^\mu{}_\mu \rangle = \varepsilon - 3P$$

QCD Phase transition

$$\left\langle \frac{\alpha_s}{\pi} F^2 \right\rangle = 0.015\ \mathrm{GeV}^4 \qquad \left\langle \frac{\alpha_s}{12\pi} F_a^{\mu\nu} F_{a\mu\nu} \right\rangle \equiv 4B$$



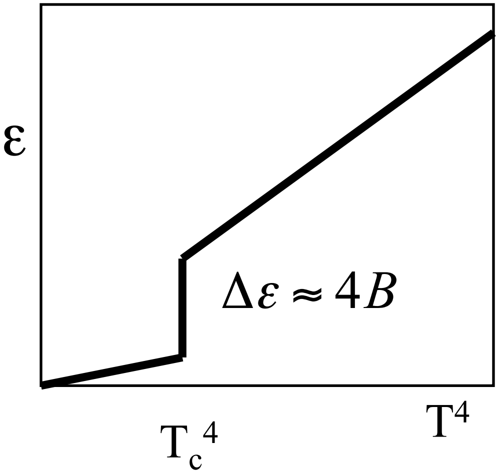
Gluon condensate $\qquad \varepsilon_0 = B, \quad \mathrm{P}_0 = -B \qquad$ Bag model

QGP:

$$P = \frac{1}{3}\varepsilon_{q,g} - B$$

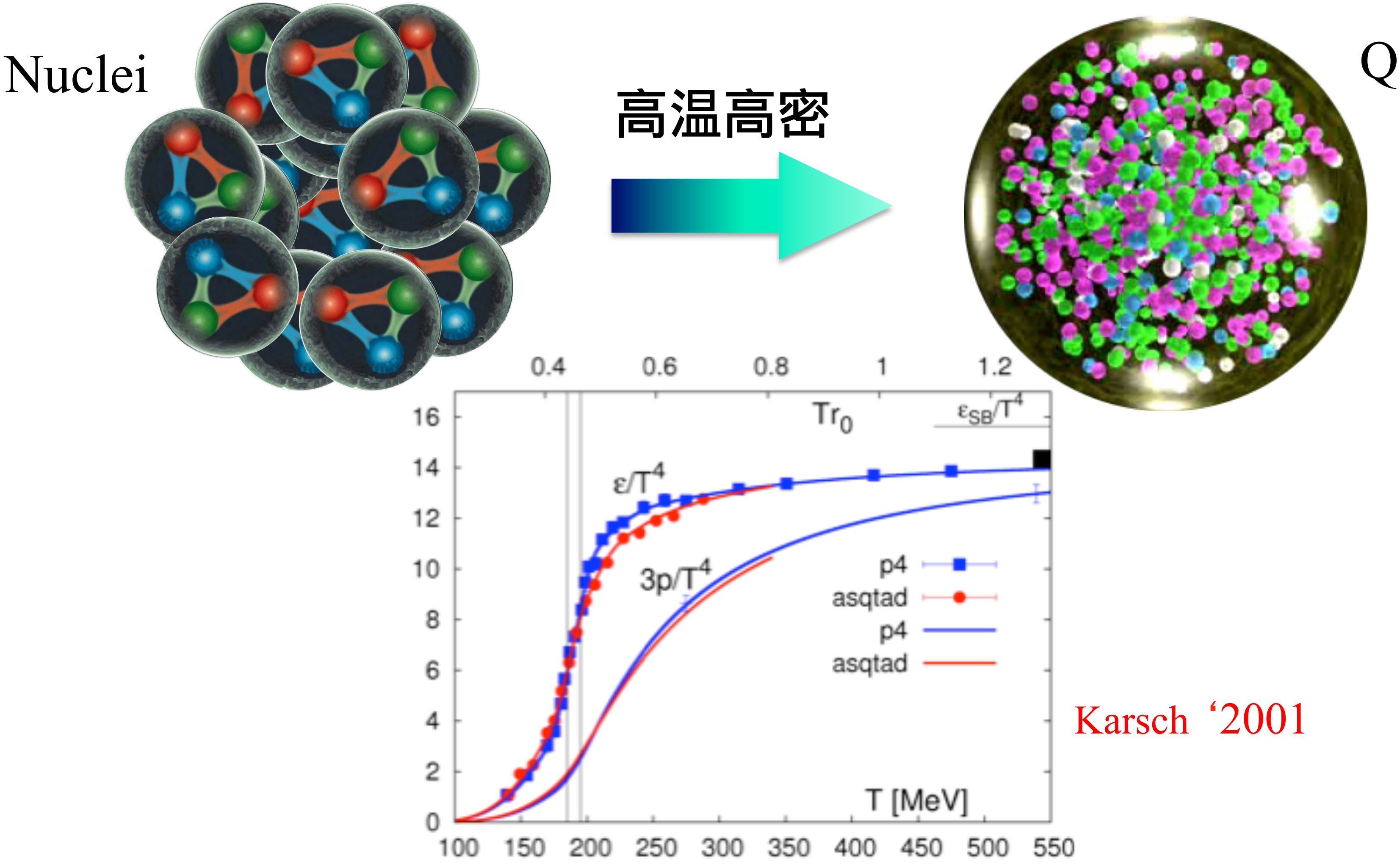
Pion gass

$$P = \frac{1}{3}\varepsilon_\pi$$



$$P_{q+g}(T_c) = P_\pi(T_c) \Rightarrow T_c \approx 0.72 B^{1/4} \quad (\mu = 0)$$

Phase Transition in Lattice QCD



Karsch ‘2001

$$T_c = 170 \pm 8 \ MeV$$

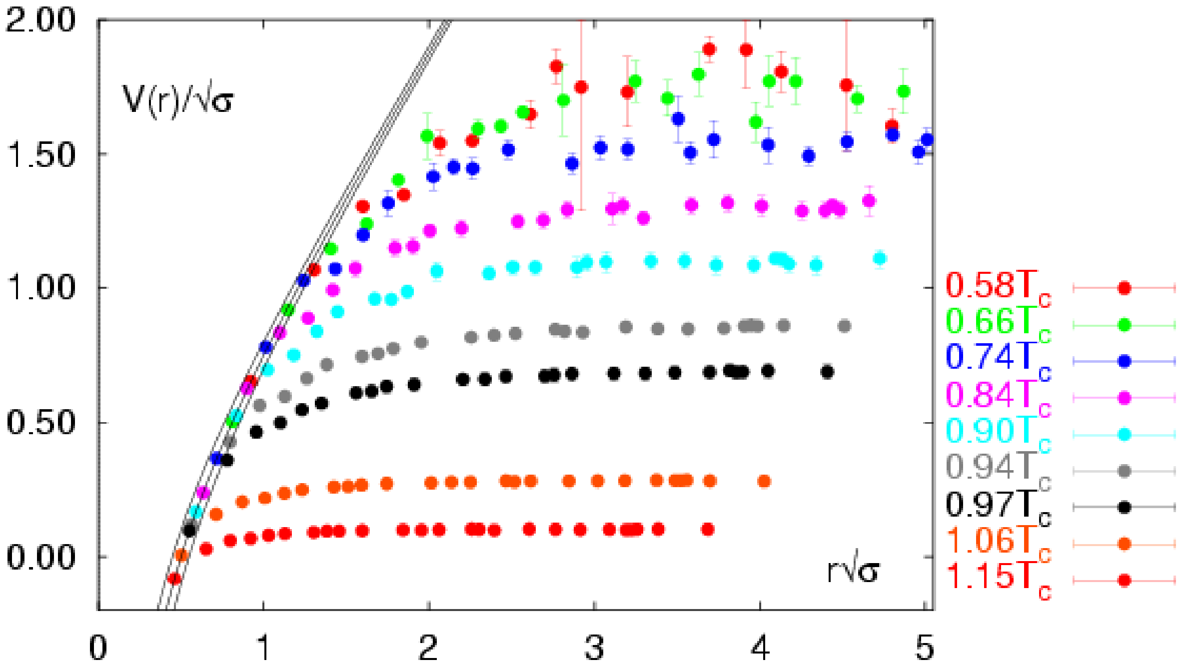
$$\varepsilon_c = 1.7 \pm 0.3 \ \ GeV / fm^3$$

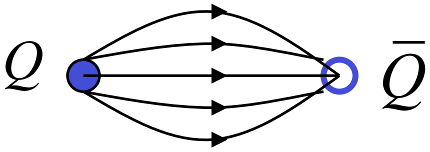
Confinement-deconfinement

SU(3) non-Abelian gauge interaction → confinement

$$V(r) = -\frac{\alpha}{r} + \sigma r$$

Heavy quark potential:





Karsch, Laermann and Peikert 2001

J/Ψ suppression

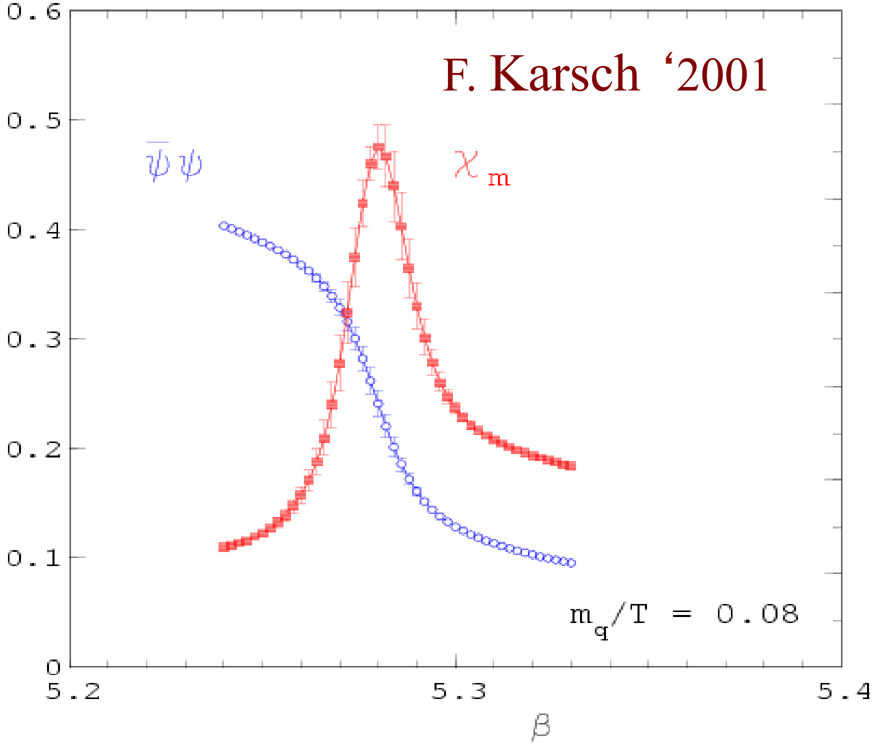
Chiral Symmetry

$$\langle \bar{\psi}\psi \rangle \neq 0$$

$$SU(3)_L \otimes SU(3)_R \rightarrow SU(3)$$

Spontaneously broken:

Goldstone bosons (π,K,η)



$$T_c = 170 \pm 8 \ MeV$$

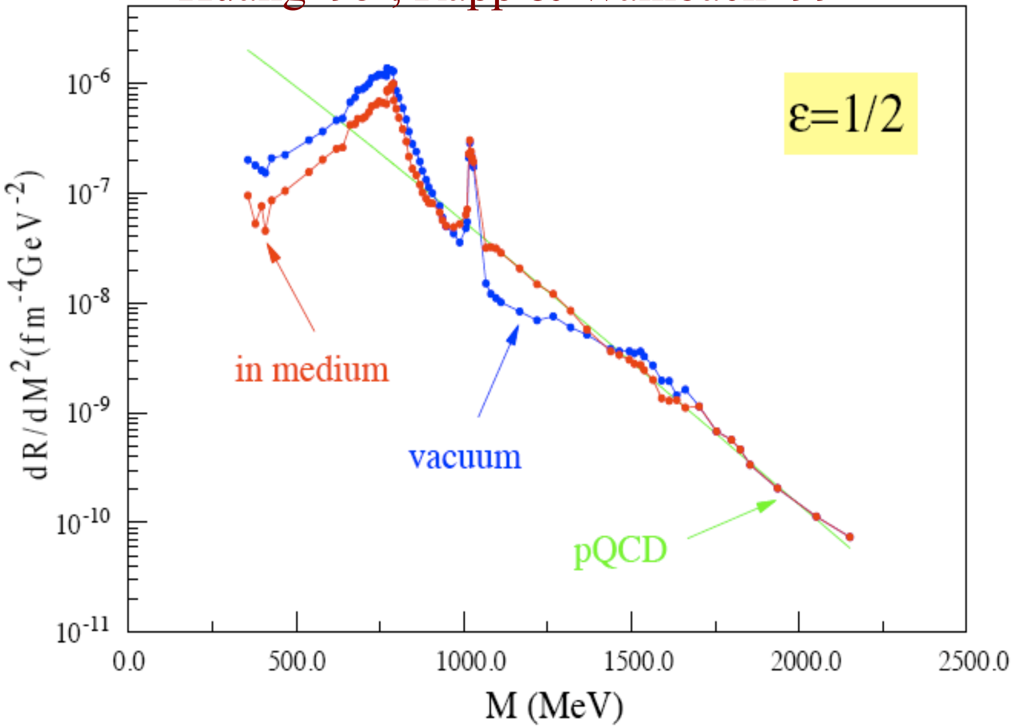
Properties of hadrons in medium

Mixing between vector & axial-vector correlators at finite T

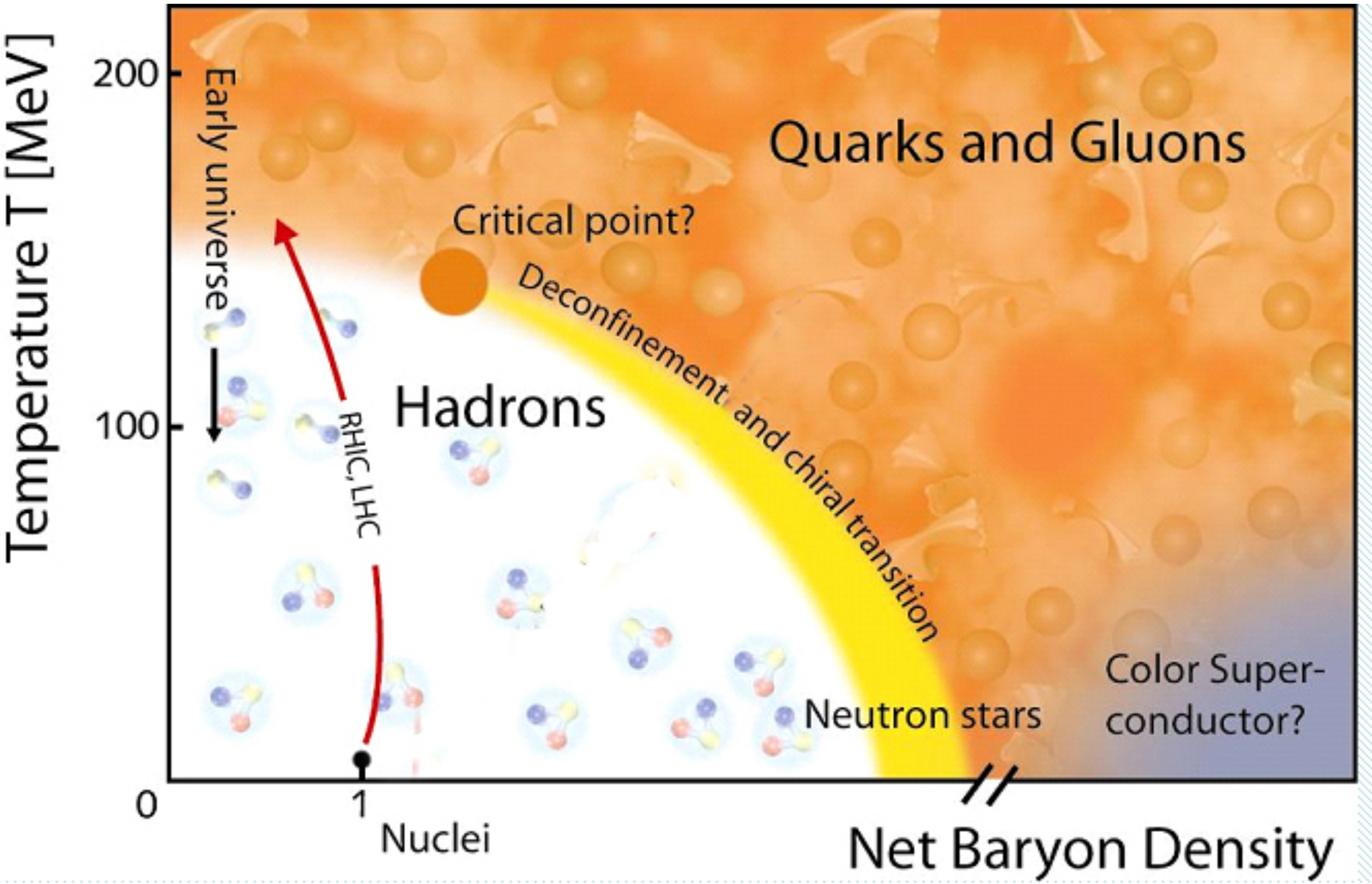
$$\begin{aligned}\Pi_V^{\mu\nu}(q) &= (1-\epsilon)\,\Pi_V^{\circ\mu\nu}(q)+\epsilon\,\Pi_A^{\circ\mu\nu}(q)\\ \Pi_A^{\mu\nu}(q) &= (1-\epsilon)\,\Pi_A^{\circ\mu\nu}(q)+\epsilon\,\Pi_V^{\circ\mu\nu}(q)\end{aligned}$$

$$\epsilon=\frac{T^2}{6f_\pi^2}$$

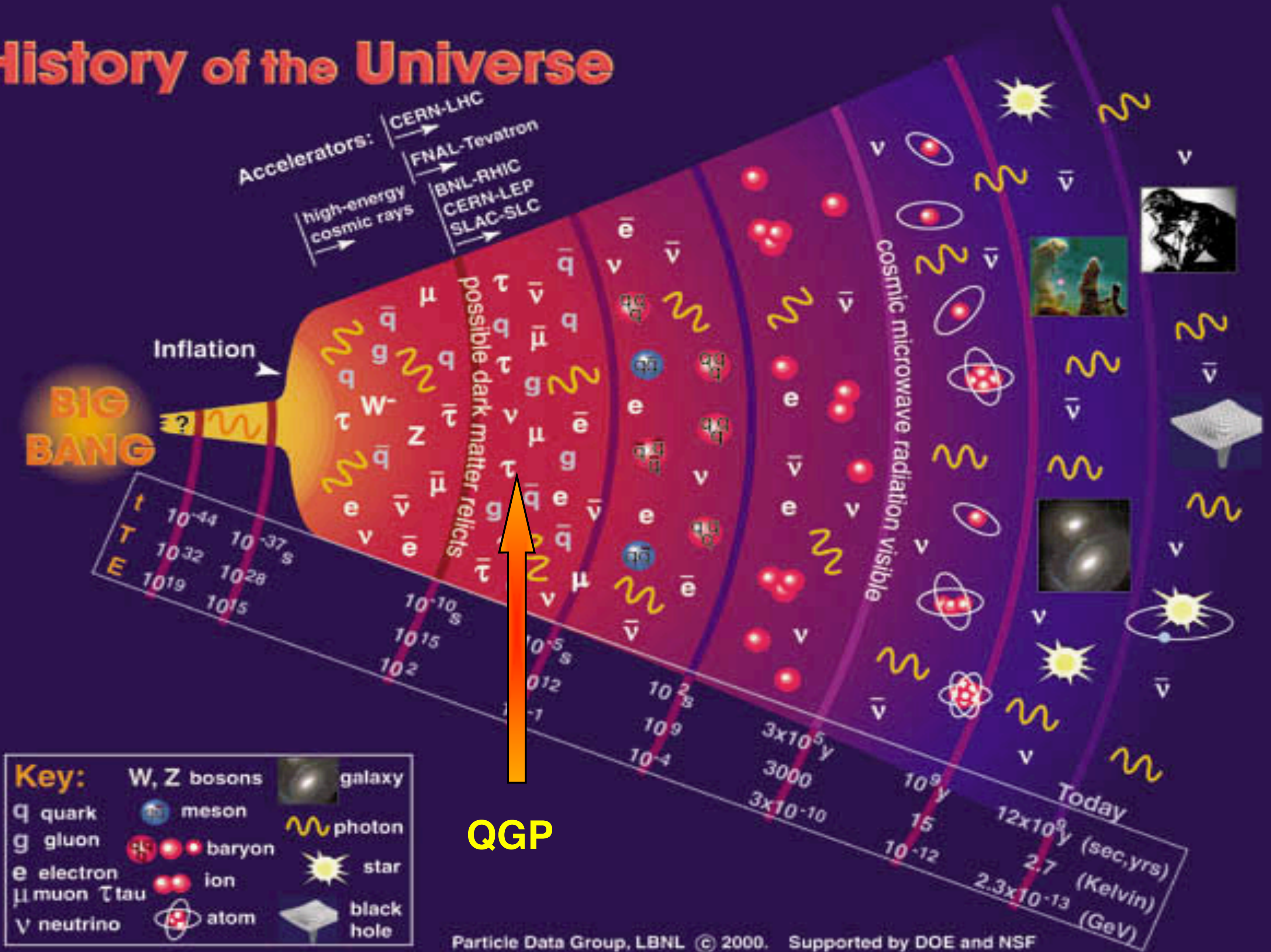
Huang' 95 , Rapp & Wambach' 99



QCD Phase Diagram

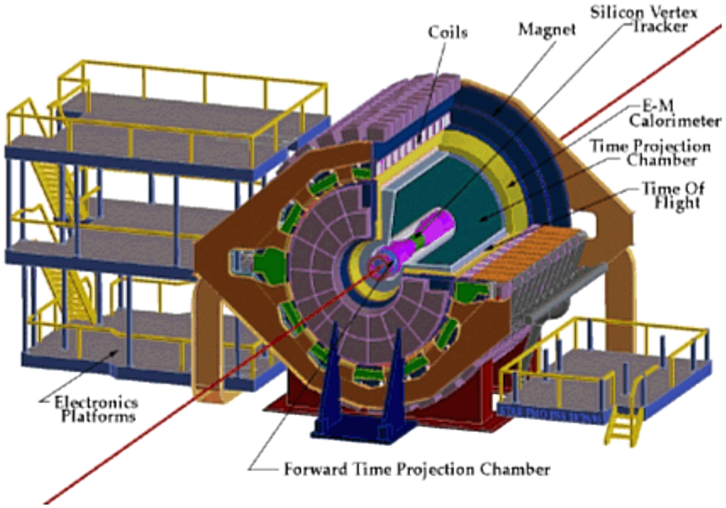


History of the Universe



Particle Data Group, LBNL © 2000. Supported by DOE and NSF

Relativistic Heavy-ion Collider



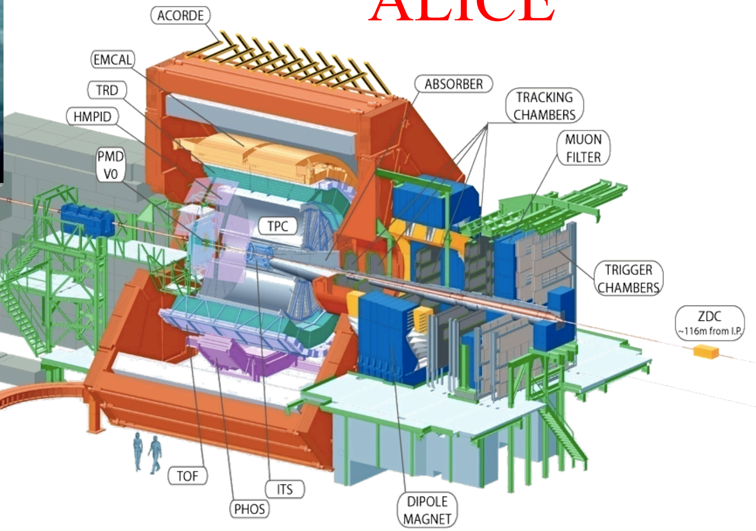
STAR Collaboration

China: USTC, Tsinghua, CCNU
SINAP, Shandong U. , IMP

LHC: the next frontier

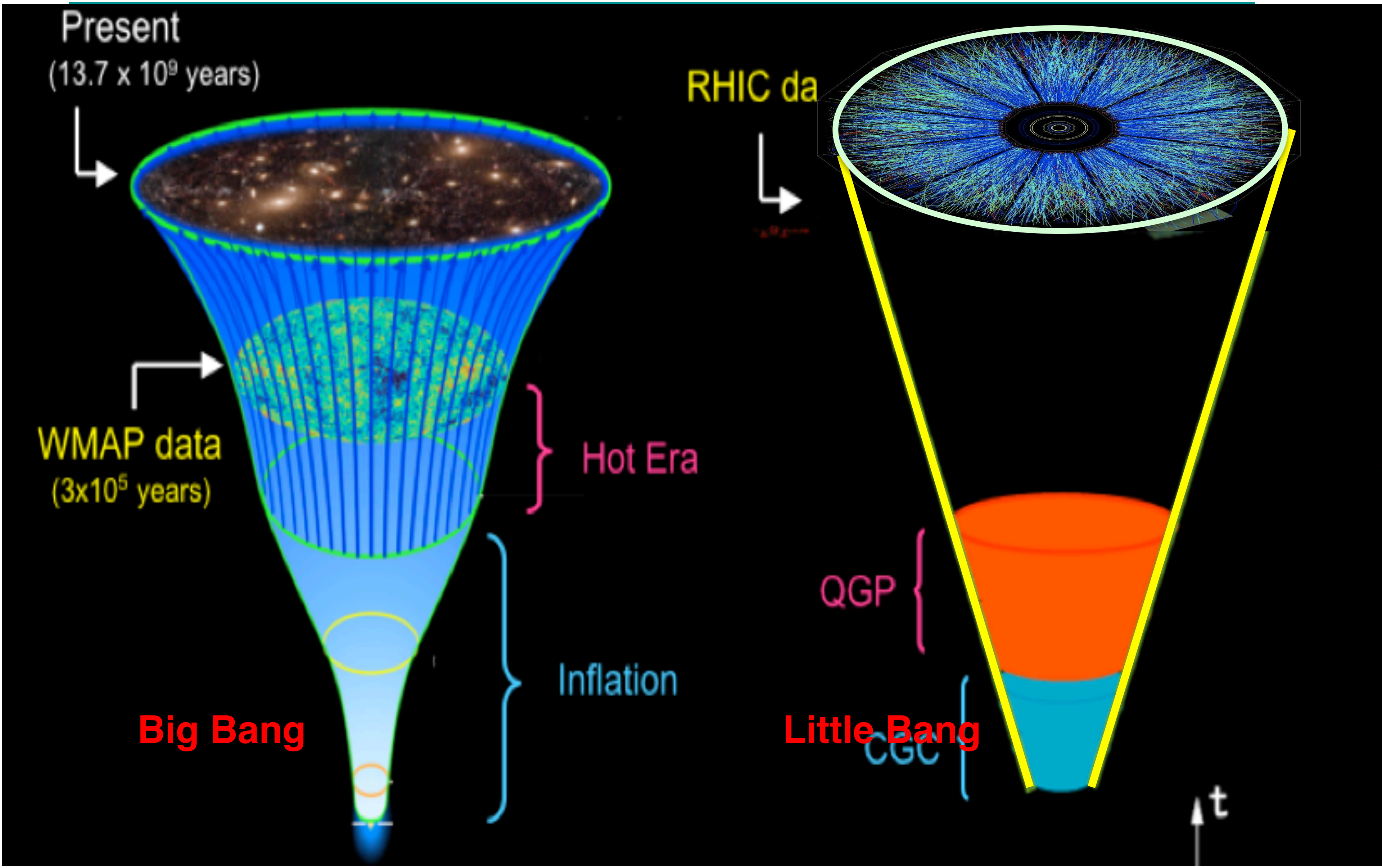
Higher temperature,
Longer lifetime
More abundance of
hard probes

ALICE



China: CCNU, CIAE
HUST

Heavy-ion experiments



Big Bang

Little Bang

QGP at RHIC: Transient Matter

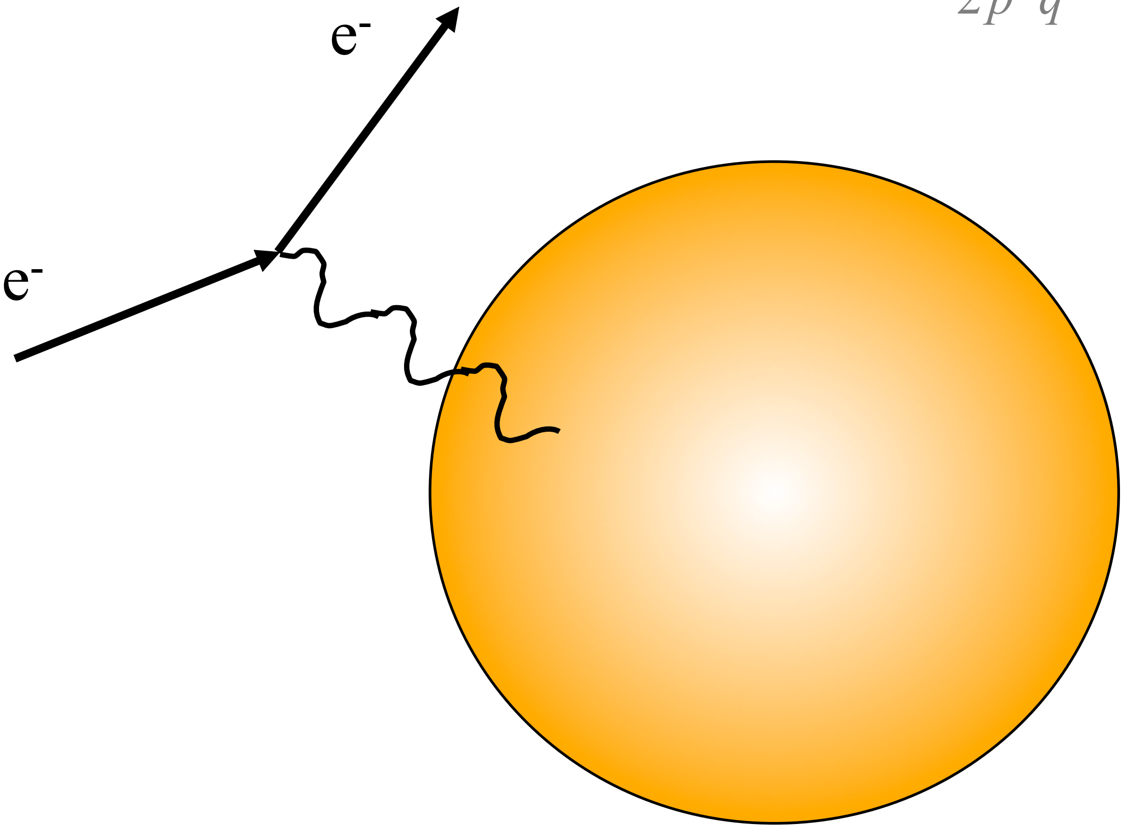
Animation by Jeffery Mitchell

- **Transient Matter:**
- **Short life-time:**
  t ~ few fm/c ~10^{-25} seconds
- **Small size:**
  R~10 fm ~ 10^{-14} m
- **Rapid expansion**

Probing Nuclear Matter

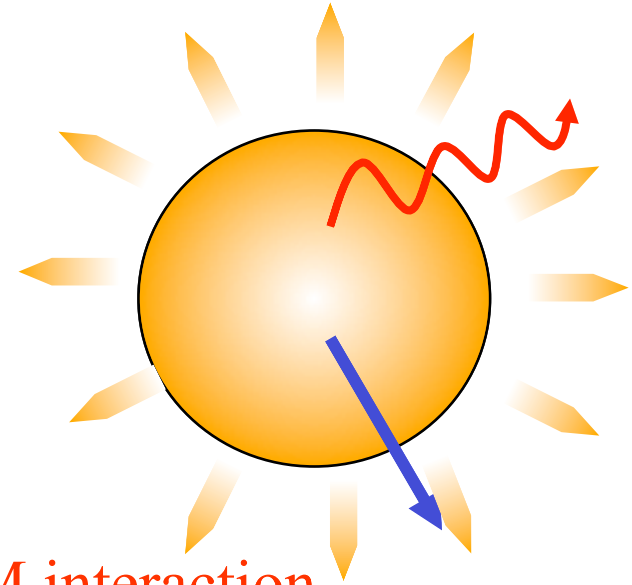
$$W_{\mu\nu}(q) = \frac{1}{4\pi}\int d^4x e^{iq\cdot x} \langle A | j_\mu^{em}(0) j_\nu^{em}(x) | A \rangle = -e_T^{\mu\nu} F_1(x_B) + e_L^{\mu\nu} F_2(x_B)$$

$$x_B = \frac{Q^2}{2p\cdot q}$$



Medium Response

$$W_{\mu\nu}(q) = \frac{1}{4\pi}\int d^4x e^{iq\cdot x}\langle\langle \mathcal{T}\{j_\mu^{em}(0)j_\nu^{em}(x)\}\rangle\rangle$$



Dynamic System:

- EM emission: Medium response to EM interaction

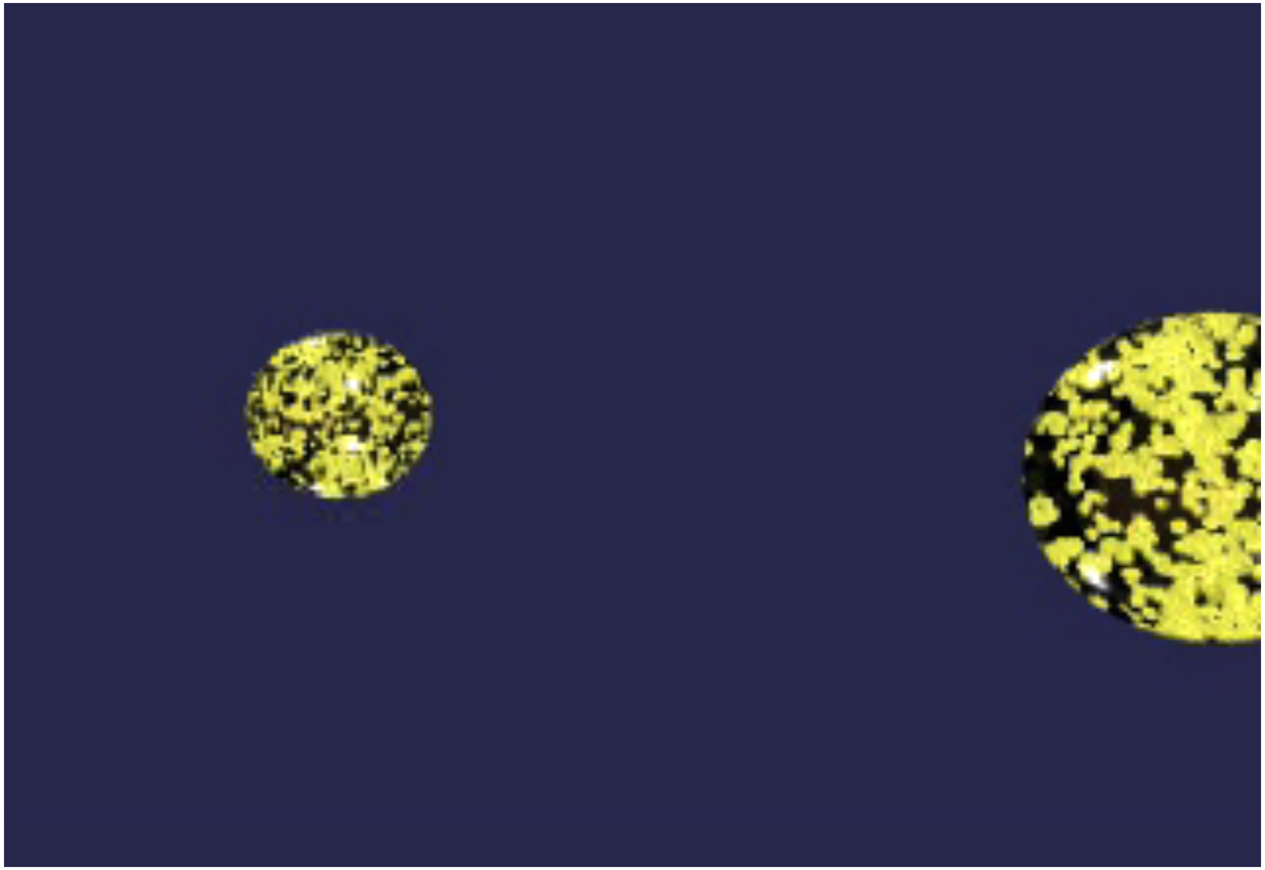
  γ production, J/Ψ suppression

- Hard probes: Medium response to strong interaction

  Jet quenching

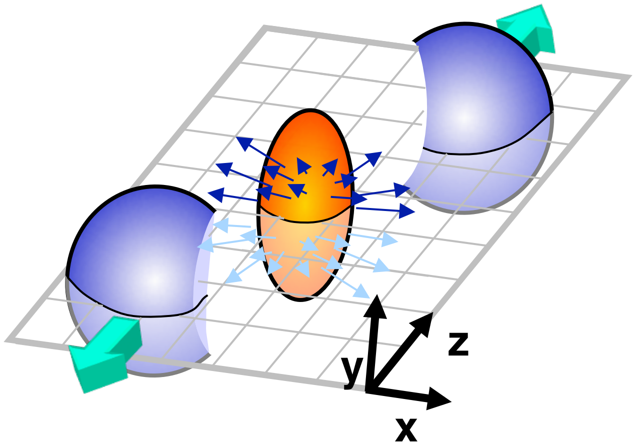
- Soft hadrons: Bulk properties of medium, collective behavior

Flow in non-central collisions

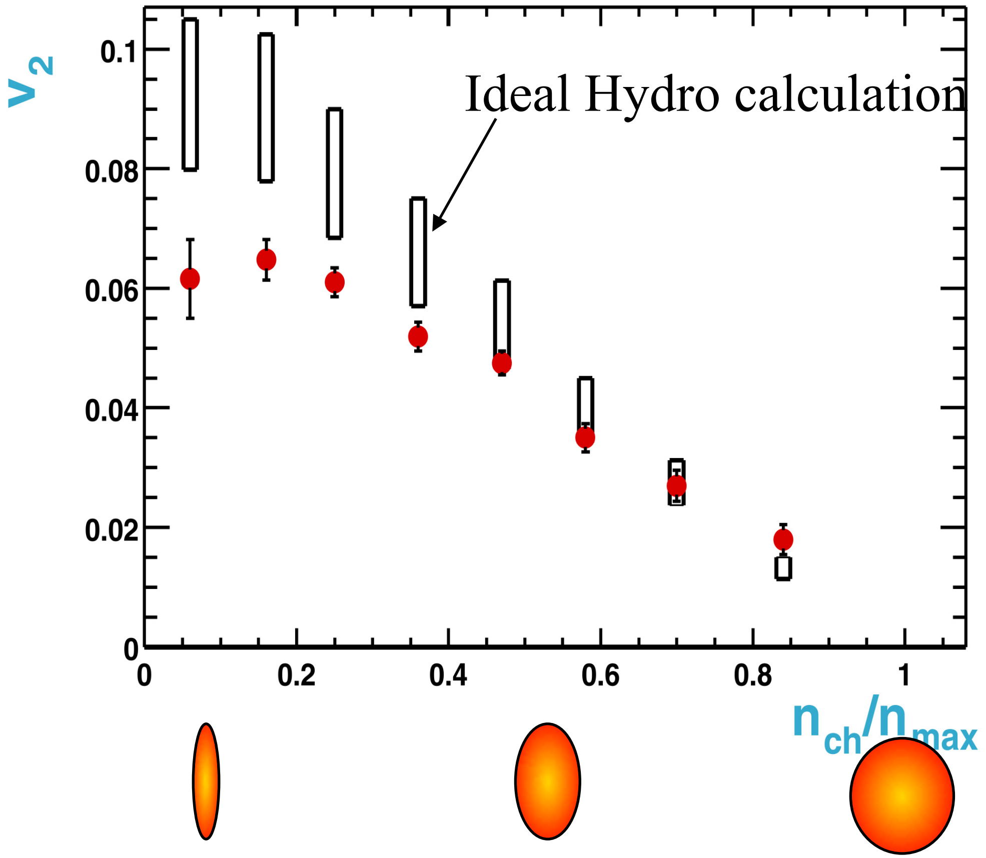


Animation by Jeffery Mitchell

Elliptic Flow



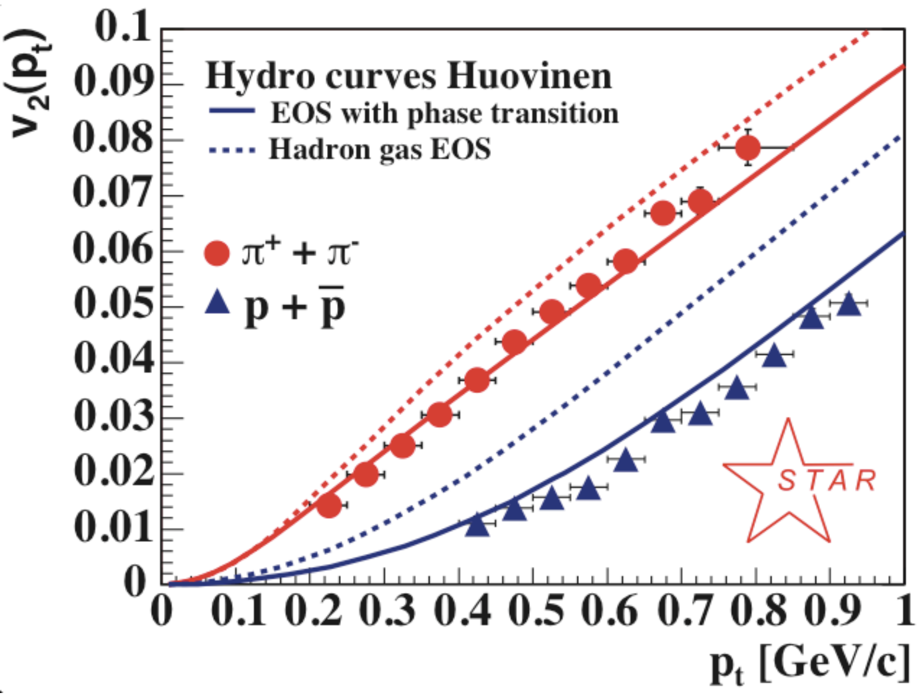
$$\frac{dN_{ch}}{d\varphi} = N_0(1+v_1\cos\varphi+2v_2\cos 2\varphi+\cdots)$$



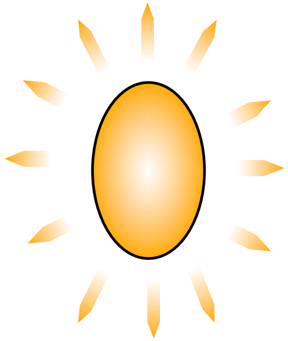
Pressure gradient anisotropy

$$v_2 = \langle \cos 2\varphi \rangle$$

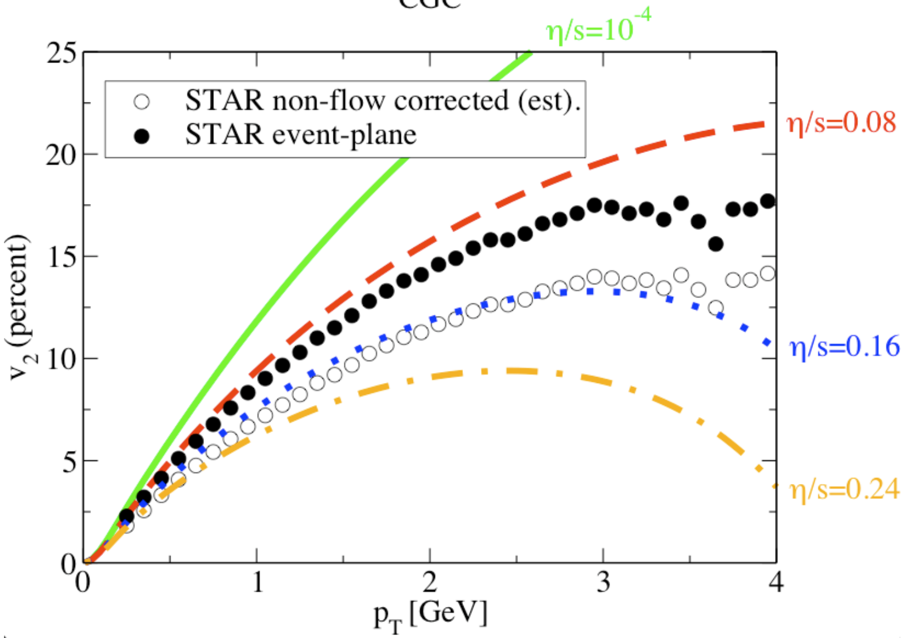
A perfect fluid?



$$\partial_\mu T^{\mu\nu} = 0$$ Ideal Hydrodynamic



CGC



Constraint on shear viscosity:

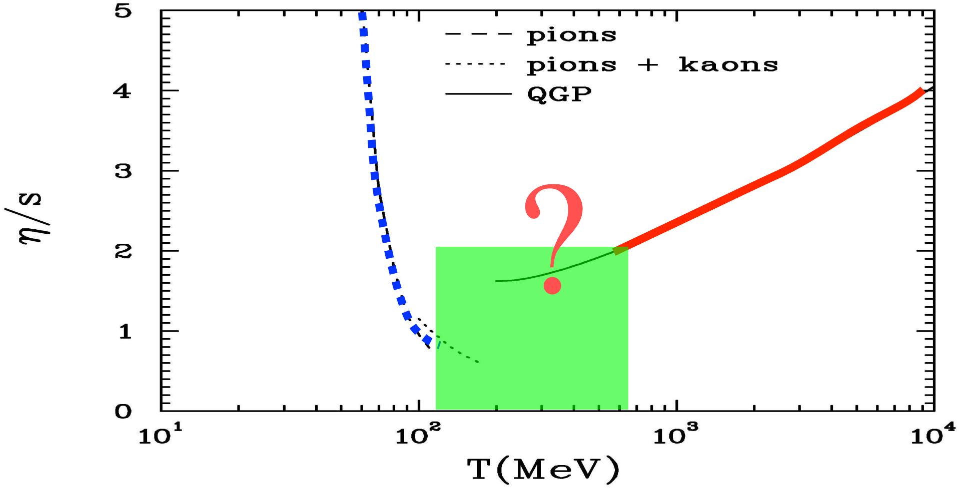
$\eta/s < 0.16$ Luzum & Romatschgke 08

$H_2O : \eta/s : 10$

Viscosity of QCD Matter

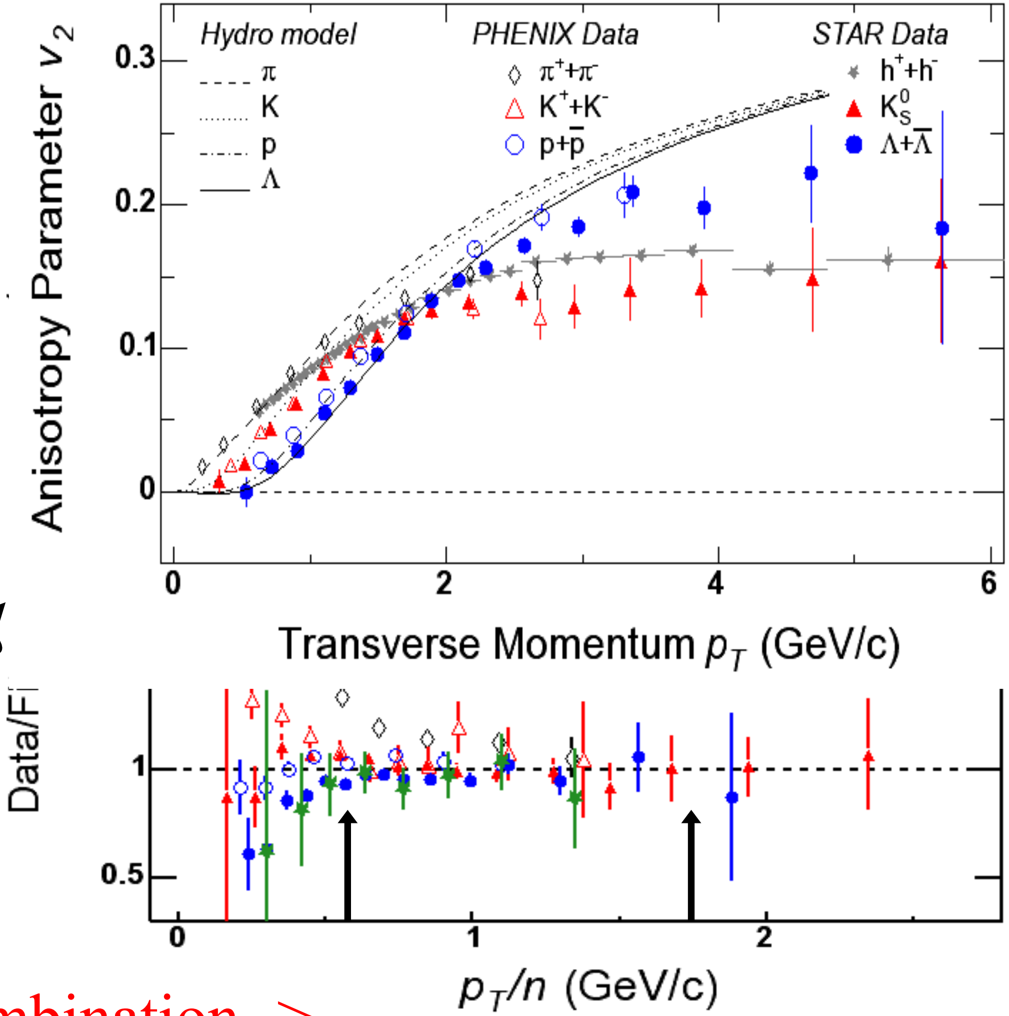
- Hadron gas at low temperature:
  - Chiral perturbation theory: $$\frac{\eta}{s} = \frac{15}{16\pi}\frac{f_\pi^4}{T^4}$$ Prakash *et al*
- QGP at high temperature:
  - Perturbative QCD $$\eta / s \approx \frac{0.022}{\alpha_s^2 \log(1/\alpha_s)}$$ Arnold, Moore, Yaffe

Q. Wang, et al

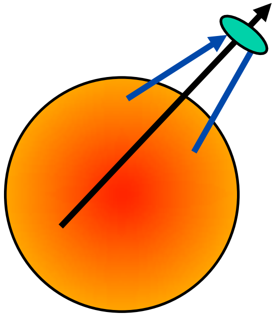


Kapusta, Csernai & McLerran

Partonic flows



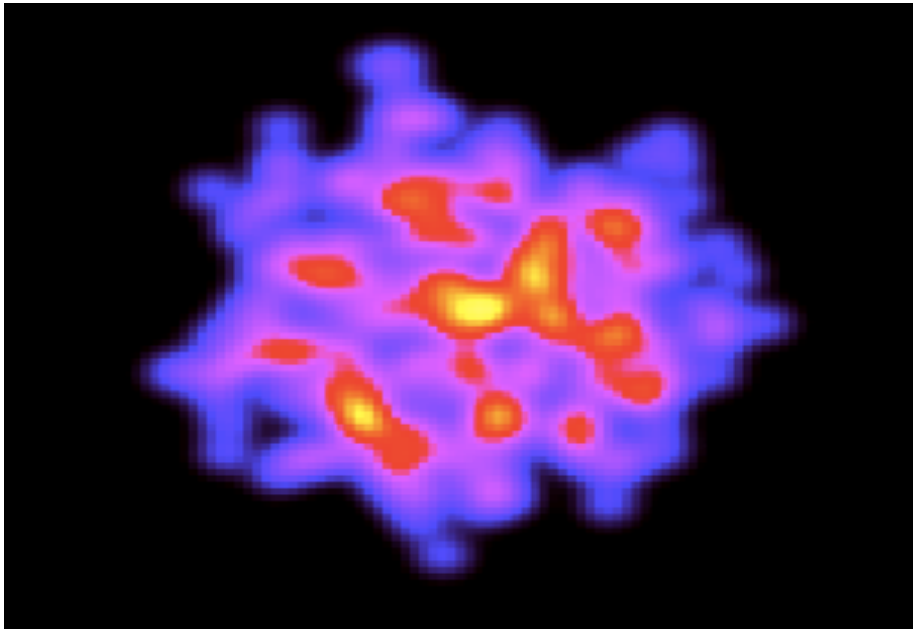
n = number of constituent quarks



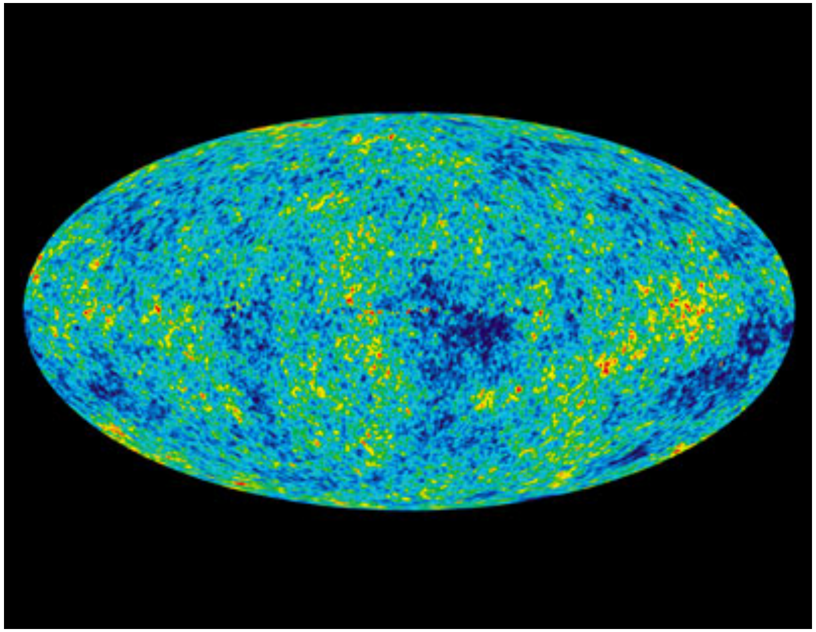
Parton recombination -> Partonic degrees of freedom

Initial Anisotropy and final correlation

Heavy-ion Collisions



CMB

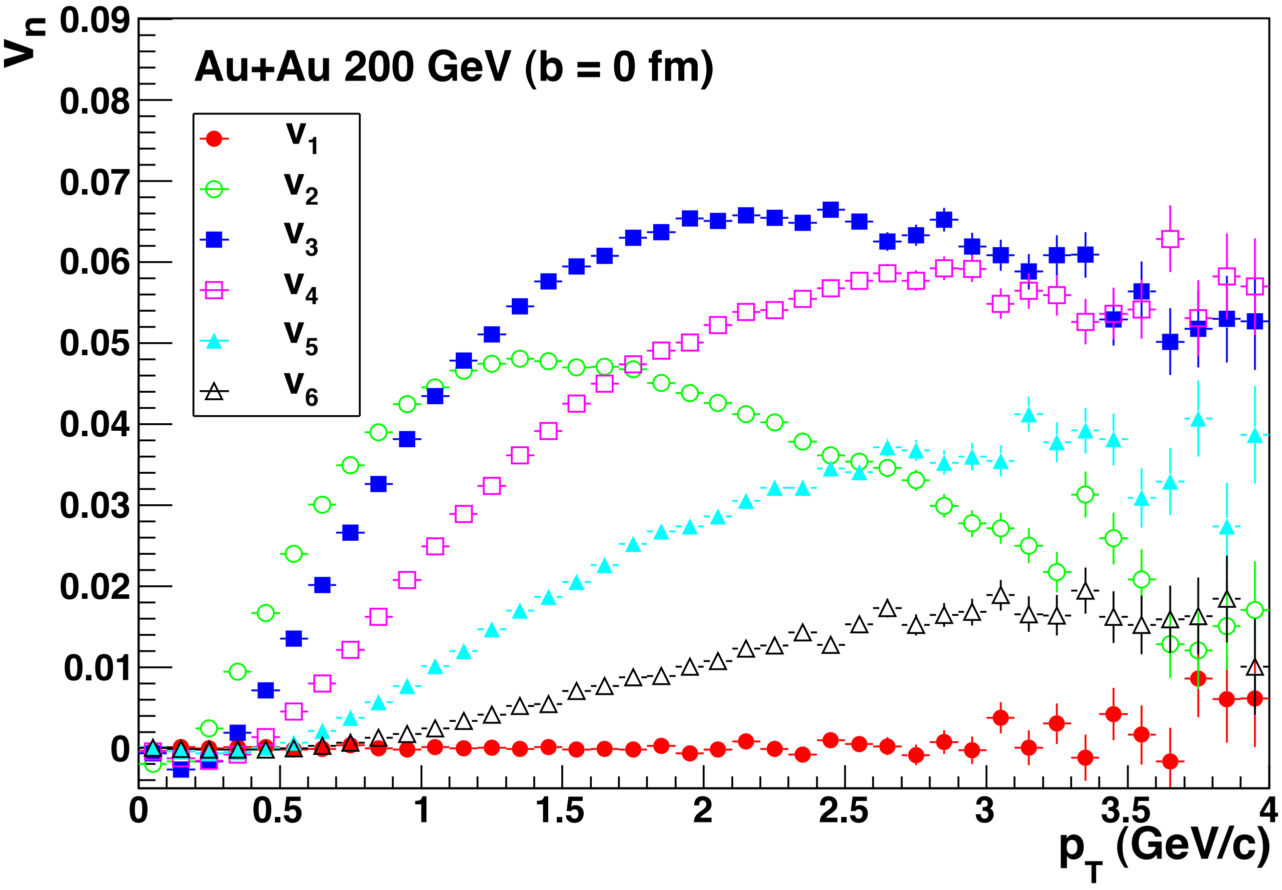


Event-by-event hydro

$$\partial_\mu T^{\mu\nu} = 0$$

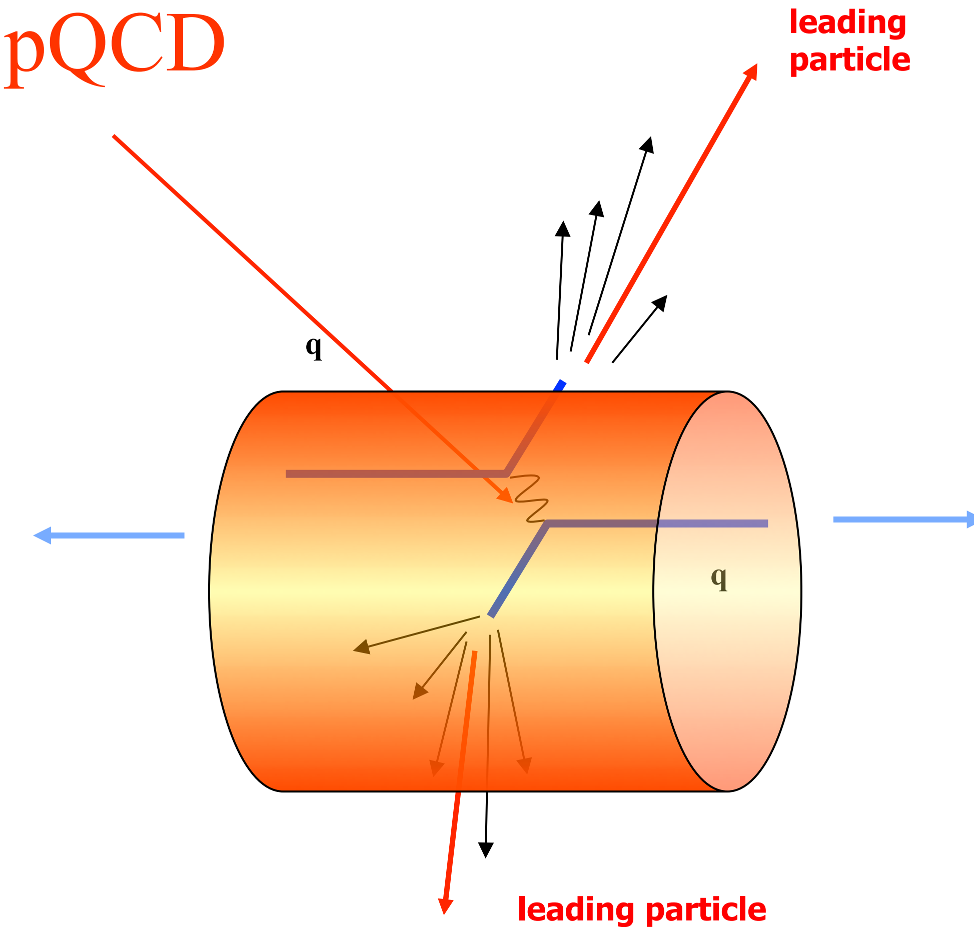
$$f(\phi) = N_0 \left[1 + \sum_{n=1}^{\infty} 2 v_n \cos n(\phi - \psi_n) \right]$$

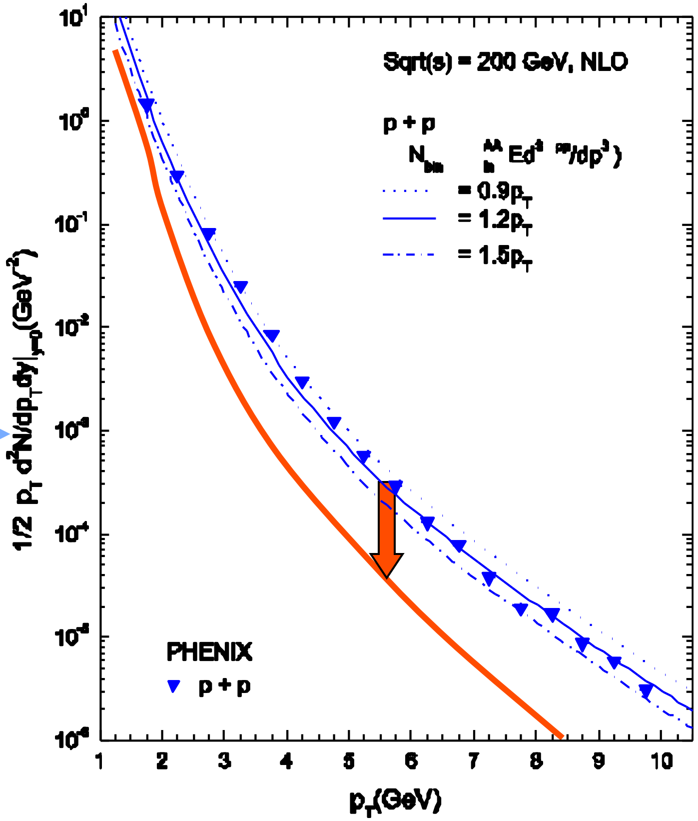
Anisotropy of the Little Bang



马国亮 & 王新年, PRL106 (2011) 162301

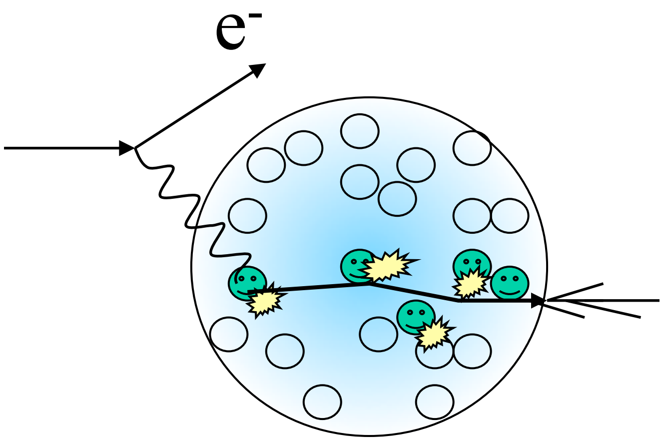
Jets in heavy-ion collisions





Bjorken' 82, XNW & Gyulassy' 92

Jet Quenching & Energy Loss

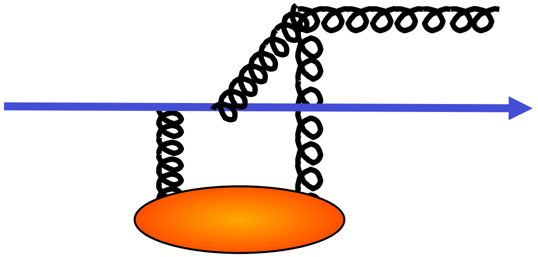


$$D_{h/a}(z_h) \quad \Rightarrow \tilde{D}_{h/a}(z, \Delta E)$$

$$\left\langle \Delta z_g \right\rangle = \int_0^{Q^2} dl_T^2 \int_0^1 dz \frac{1+(1-z)^2}{l_T^4} \frac{C_A \alpha_s^2}{N_c} \int dy \rho(y) x_T G(x_T) \left[1 - \cos(x_L p^+ y)\right]$$

What Jets Probe

$$\frac{\Delta E}{E} = \frac{3C_A\alpha_s}{4}\int dy\,\rho_g(y)\,y\tilde{q}(y)\ln\frac{3ET}{\mu^2}$$



Target density profile

$$\tilde{q} = \int_{\mu^2}^{\omega E/2} dq_\perp^2 \frac{d\sigma_q}{dq_\perp^2} q_\perp^2 = \frac{\pi}{N_c}\alpha_s\int\frac{d\xi}{p^+}\langle F(0)F(\xi)\rangle$$

$$\Delta E \propto L^2$$

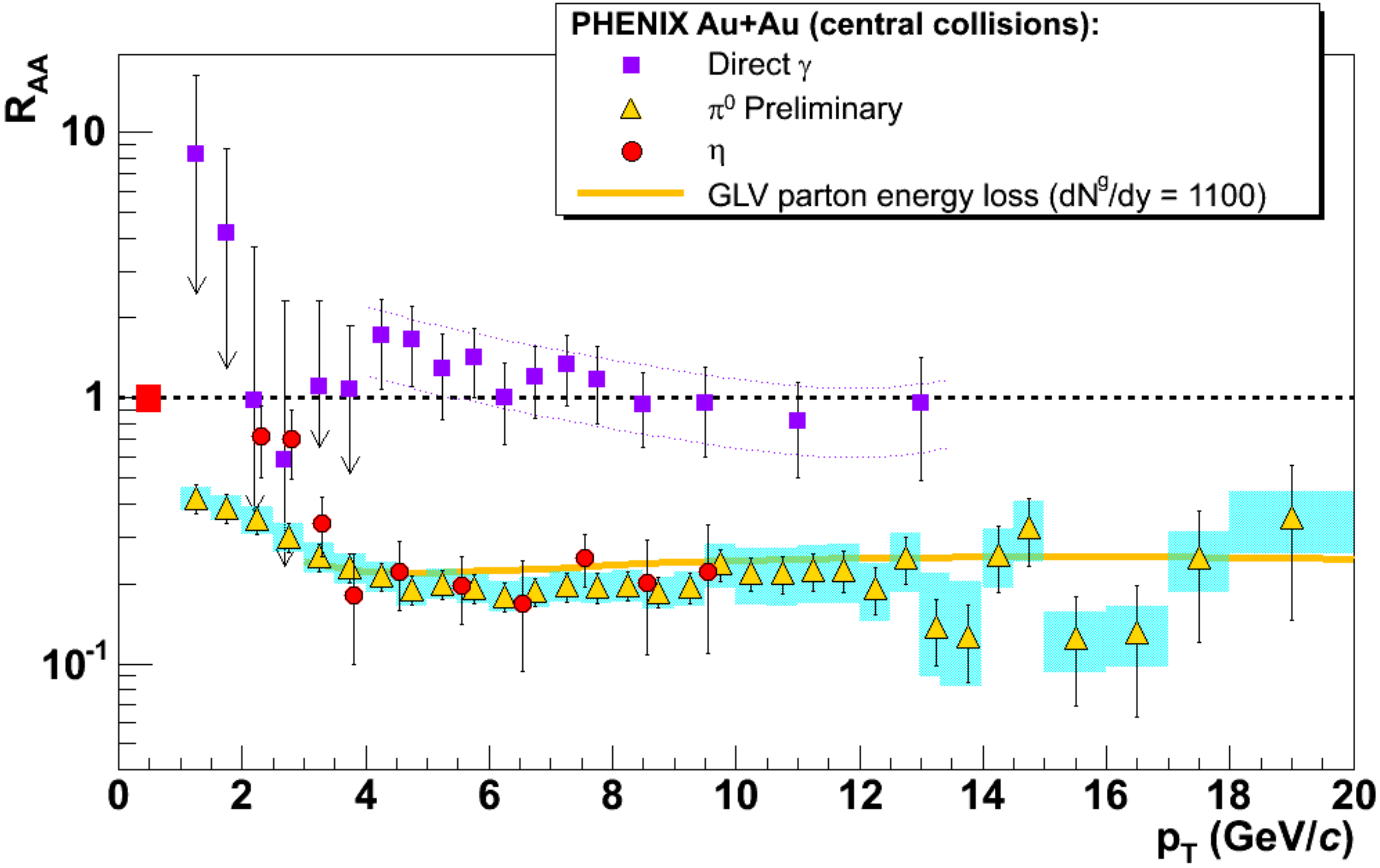
Transport coefficient

$$\hat{q} = \rho_g\tilde{q} = \left\langle\frac{q_\perp^2}{\lambda}\right\rangle$$

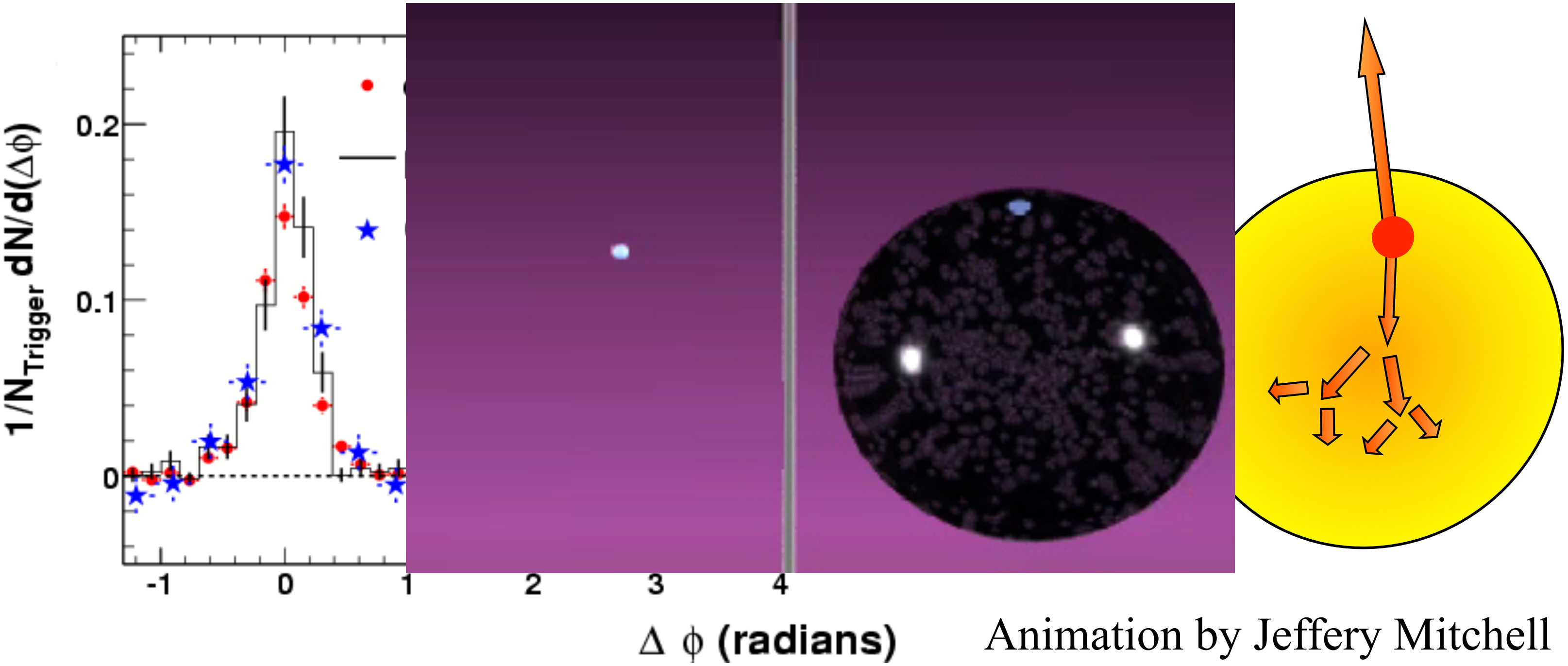
BDPM
Gyulassy Vitev Levai
Guo &XNW
Wiedemann

Jet Tomography

Single hadron suppression



Suppression of away-side jet



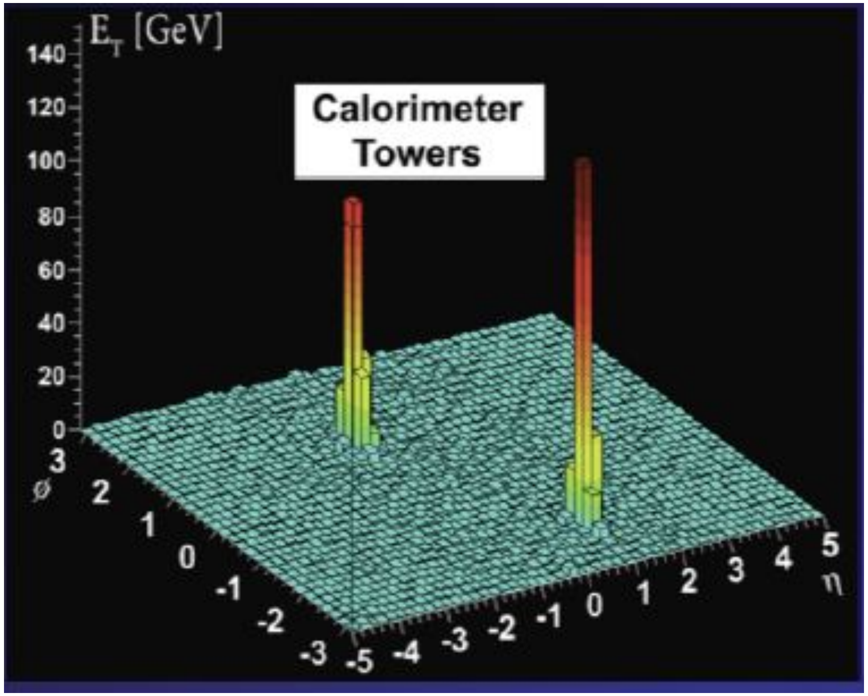
Animation by Jeffery Mitchell

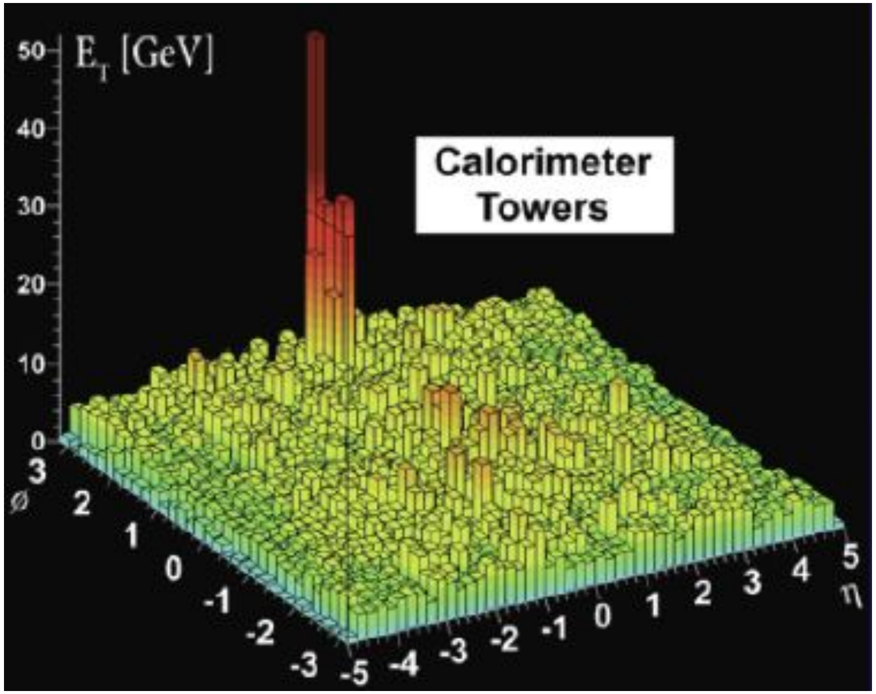
$$\left(\frac{dE}{dx}\right)_0 \approx 13.8 \pm 3.9\ \text{GeV/fm} \Longleftrightarrow \left(\frac{dE}{dx}\right)_{\text{cold matter}} \approx 0.5\ \text{GeV/fm}$$

$$\tau_0 = 0.2\ \text{fm/c}$$

Initial Density about 30 times of that in a Cold Au Nucleus

Jet quenching at LHC



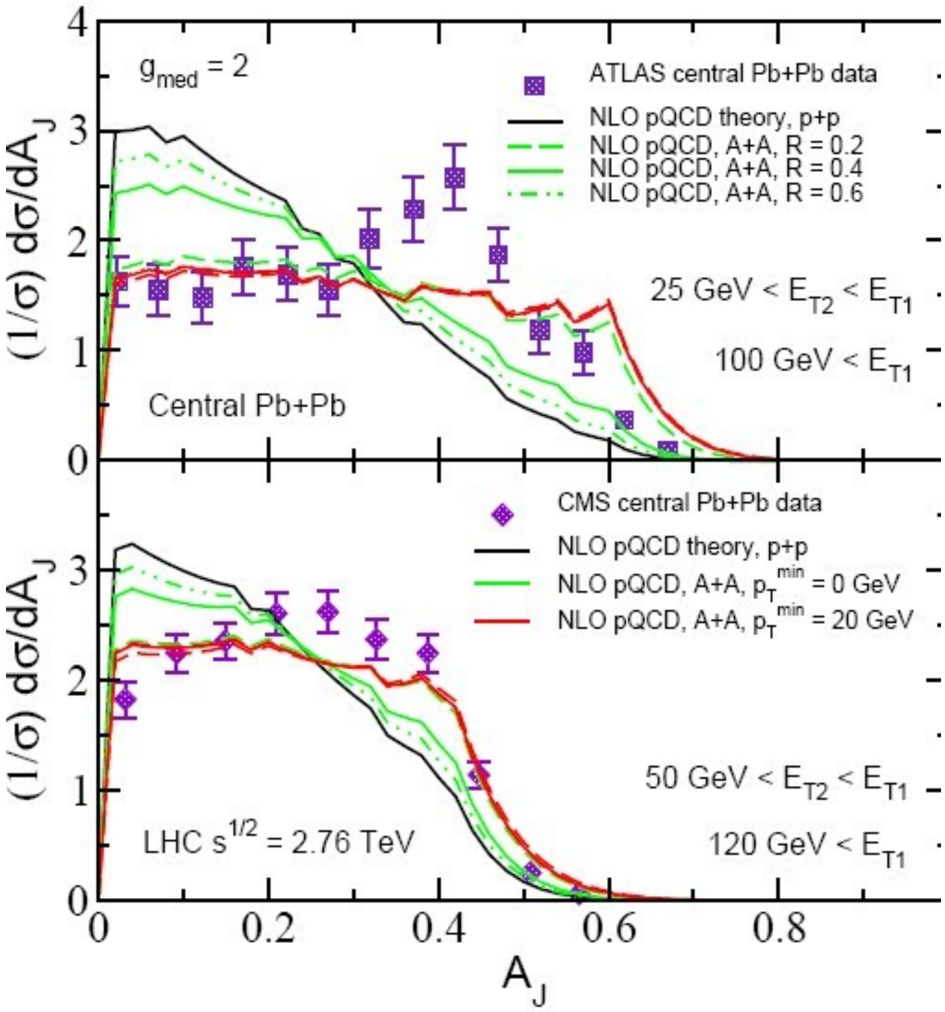


ATLAS, arXiv:1011.6182; CMS, arXiv: 1102.1957.

Jet unbalance

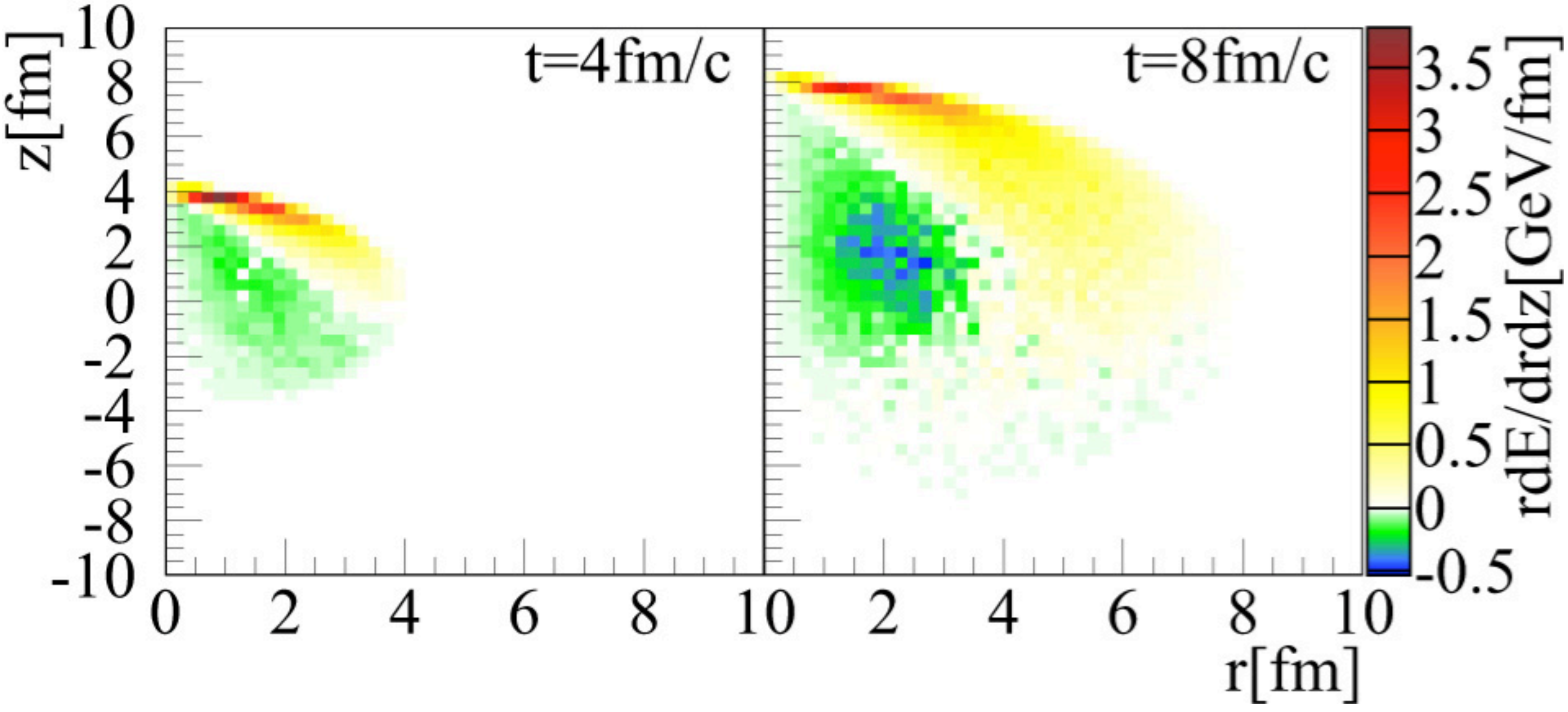
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

何云存, Vitev & 张本威
arXiv: 1105.2566



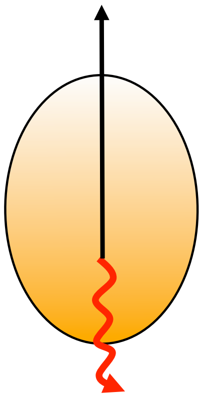
Where does a jet's energy go?

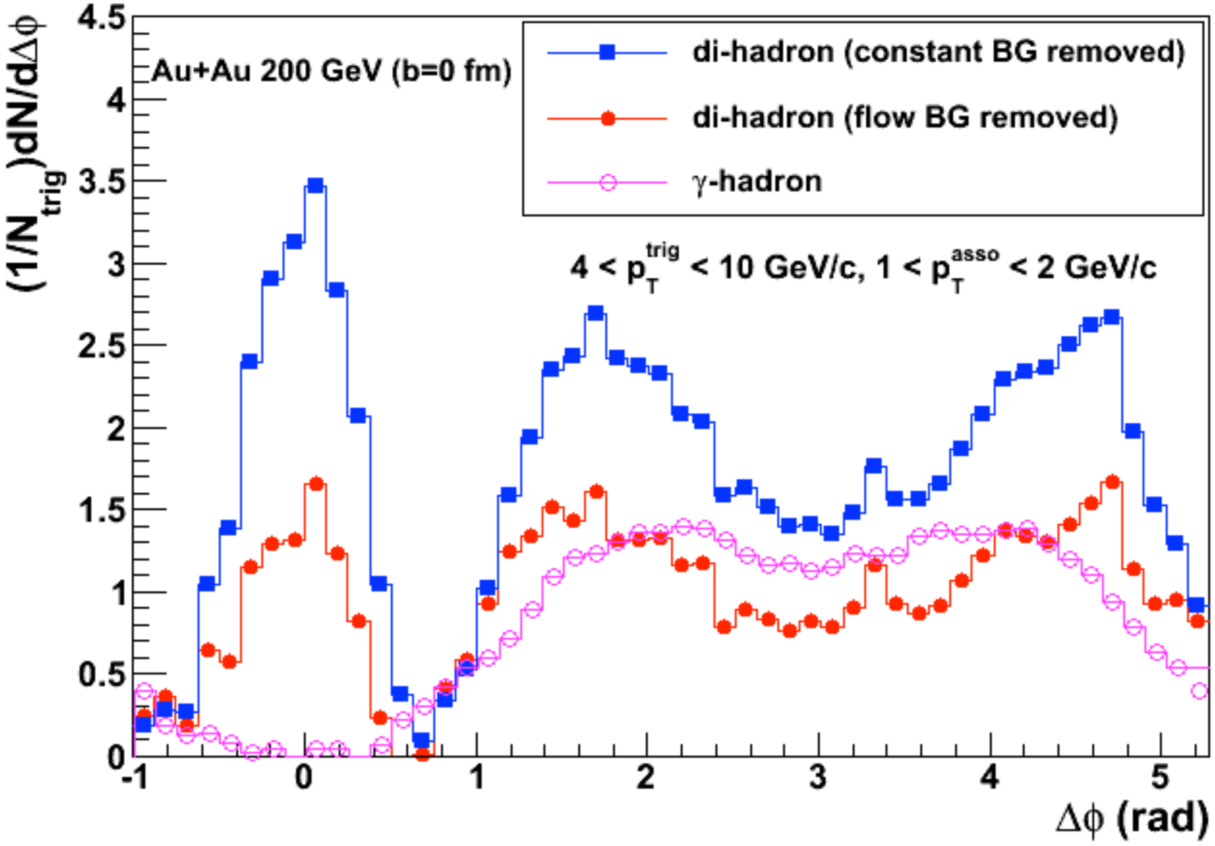
$$p \cdot \partial f(p) = C(p)$$

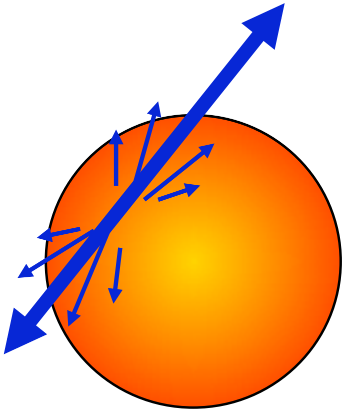


李汉林, 刘复明, 马国亮, 朱燕 & 王新年, PRL106 (2011) 012301

Measuring medium excitation

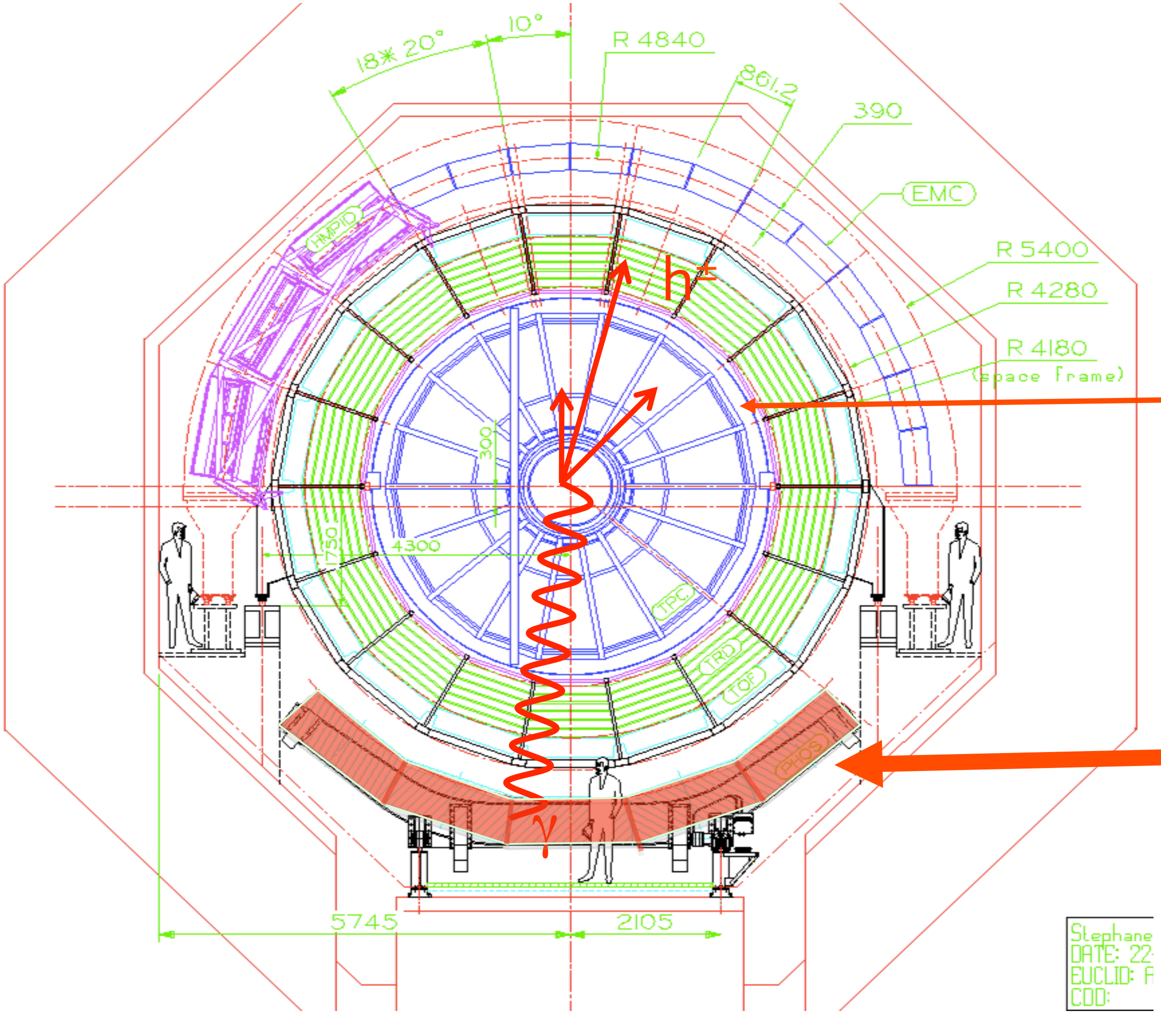






PHOS in ALICE

FEE: IOPP/CCNU, CIAE,HUST



Charged hadrons:

CB

$\Delta\phi = 360^\circ$ $|\eta| < 0.9$

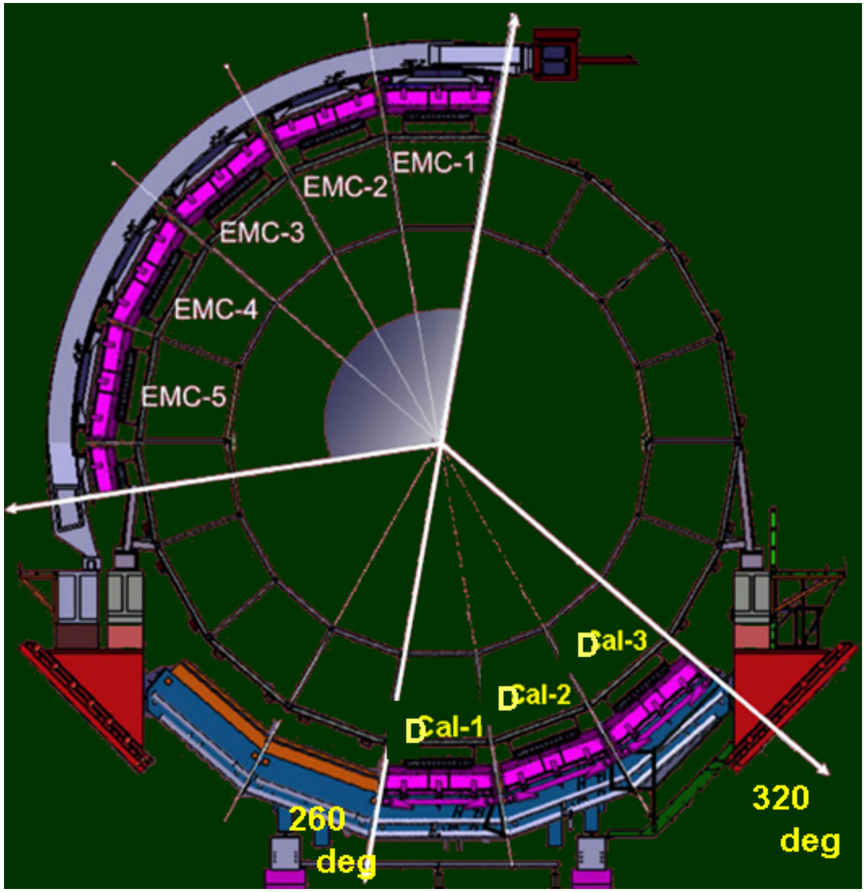
Photons:

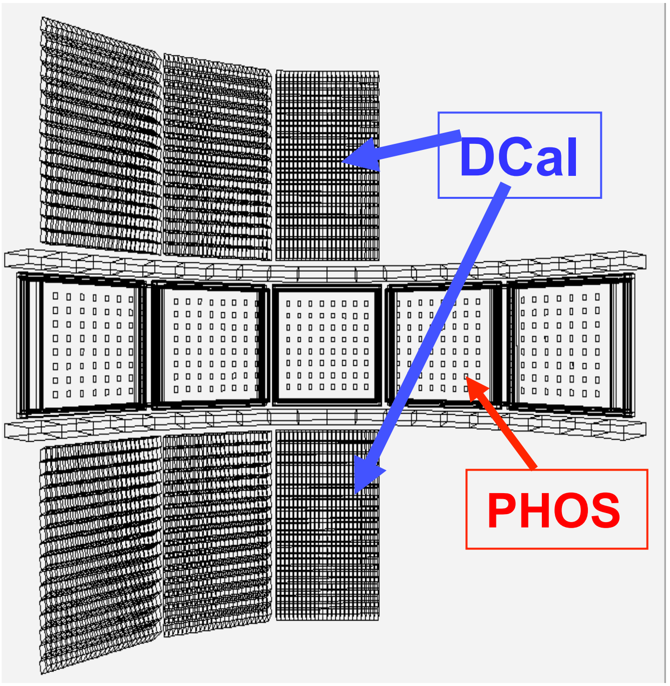
PHOS

$\Delta\phi = 100^\circ$ $|\eta| < 0.12$

DCAL: extend EMCAL and PHOS capability

Under construction by the institutes from China, Japan, France, Italy and USA





CCNU is responsible for the construction of one super-module

Summary

- Heavy-ion collisions can test many properties of QCD
  - Deconfinement phase transition
  - Chiral symmetry restoration
- Current RHIC data indicate formation of strongly interacting QGP with smal viscosity: “perfect fluid”
- Microscopic properties of sQGP
- LHC is another frontier in the search for matter in extremis

Collective evidence for sQGP at RHIC & LHC

Strong jet quenching --- high temperature and density
Strong v_2 flow and quark number scaling --- partonic flow
Large anisotropy v_n --- not possible due to hadronic interaction

Back up slides

$U_A(1)$ Anomaly

U(1) and $U_A(1)$ Symmetry: $U = e^{-i\alpha}, \quad U_A = e^{-i\alpha\gamma_5}$

(Classically) conserved current: $V_0^\mu = \bar{\psi}\gamma^\mu\psi \qquad A_0^\mu = \bar{\psi}\gamma^\mu\gamma_5\psi$

Spontaneous chiral symmetry breaking → 9th Goldstone boson (η_0)

$A_0{}^\mu$ not a conserved current

$$\partial_\mu A_0^\mu = \frac{2n_f}{16\pi}\alpha_s F_{\mu\nu}^a \tilde{F}_a^{\mu\nu}$$

$U_A(1)$ is broken in quantum theory: Chiral anomaly

Alder&Jackiw

$$m_{\eta_0}^2 = -i\frac{2n_f}{f_\pi^2}\left(\frac{\alpha_s}{16\pi}\right)^2 \int d^4x \langle 0|T\{F\tilde{F}(x), F\tilde{F}(0)\}|0\rangle_{YM}$$

$$\Downarrow$$

$$\langle \nu^2 \rangle_{YM}$$

Topological susceptibility

Chiral Symmetry

Chirality of massless quarks: $\psi_R = \frac{1}{2}(1-\gamma_5)\psi \qquad \psi_L = \frac{1}{2}(1+\gamma_5)\psi$

Chiral symmetry: $\psi_L \to e^{-i\vec{\theta}_L\vec{\lambda}}\psi_L \qquad \psi_R \to e^{-i\vec{\theta}_R\vec{\lambda}}\psi_R$

Or alternatively: $U_V = e^{-i\vec{\theta}\vec{\lambda}/2}, \quad U_A = e^{-i\gamma_5\vec{\theta}\vec{\lambda}/2}$

Conserved currents: $V_a^\mu = \bar{\psi}\gamma^\mu \frac{\lambda_a}{2}\psi \qquad A_a^\mu = \bar{\psi}\gamma^\mu\gamma_5\frac{\lambda_a}{2}\psi$

Spontaneously broken: $\langle\bar{\psi}\psi\rangle \neq 0$

$SU(3)_L \otimes SU(3)_R \to SU(3)$ Goldstone bosons (π,K,η)

Running of $\alpha_s(Q)$

SU(3) Gauge Symmetry
Non-abelian interaction

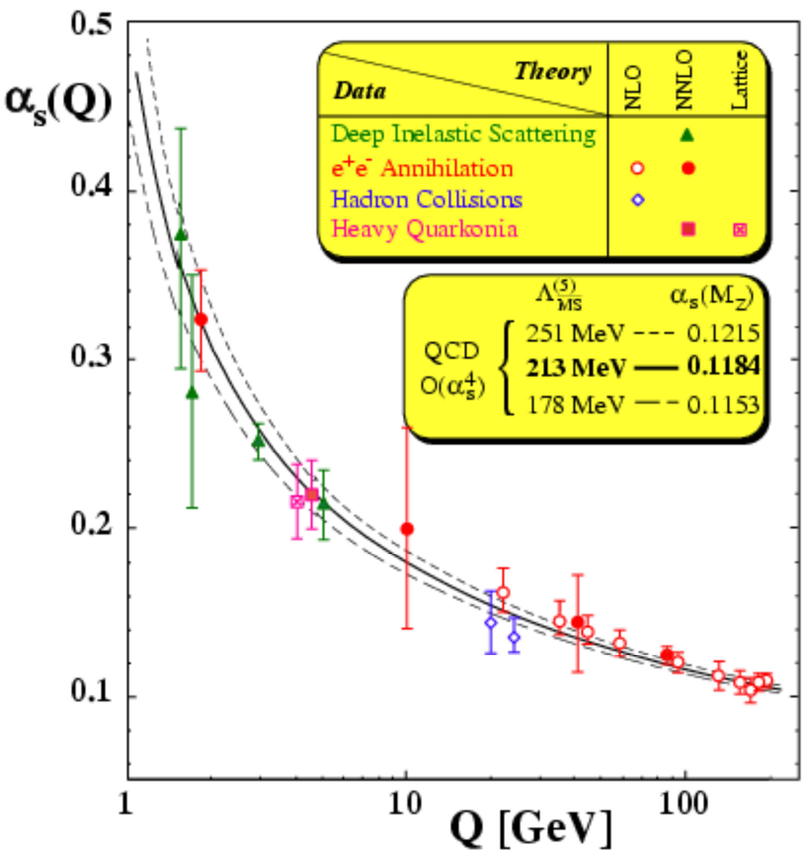
⇩

Anti-screening of color

$$\alpha_s(Q^2) = \frac{4\pi}{(11-\frac{2}{3}n_f)\ln(Q^2/\Lambda^2_{QCD})}$$

Asymptotic freedom

Gross,Wilczek;Politzer (73)



S Bethke J.Phys. G26 (2000) R27

Ideal Gas Approximation

- Leading orders in perturbation (Kapusta)

$$Z = \int d[\phi] \exp\left(\int_0^{1/T} d\tau \int d^3x L(\phi) \right)$$

$$\varepsilon_q + \varepsilon_{\bar{q}} = 6n_f \left[\frac{7\pi^2}{120} T^4 \left(1 - \frac{50}{21\pi}\alpha_s \right) + \left(\frac{1}{4}\mu^2 T^2 + \frac{\mu^4}{8\pi^2} \right)\left(1 - \frac{2}{\pi}\alpha_s \right) \right]$$

$$\varepsilon_g = 16\frac{\pi^2}{30} T^4 \left(1 - \frac{15}{4\pi}\alpha_s\right)$$

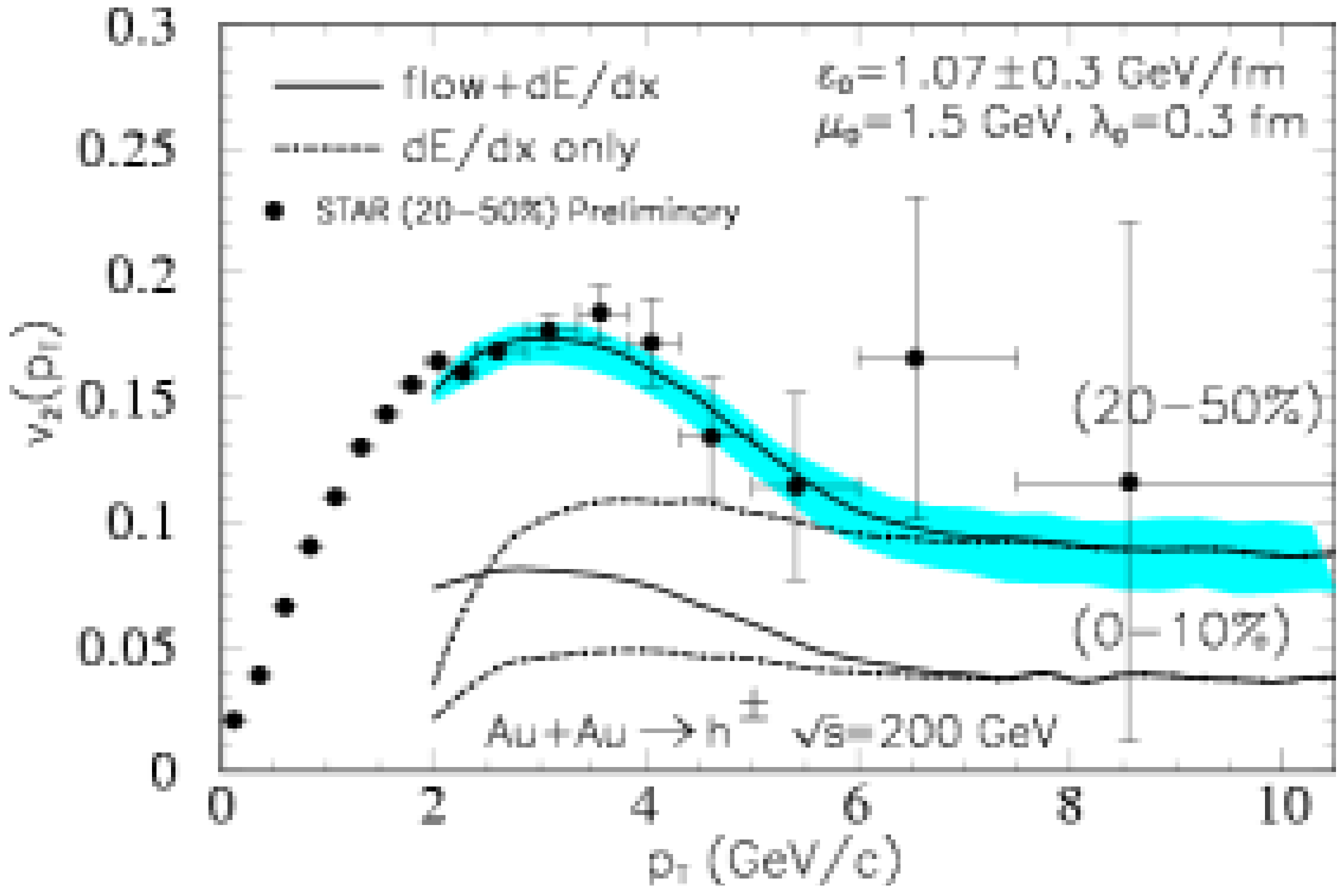
- Failure of simple perturbation: (non-convergenceg g~1)
  (Arnold & Zhai ’94)

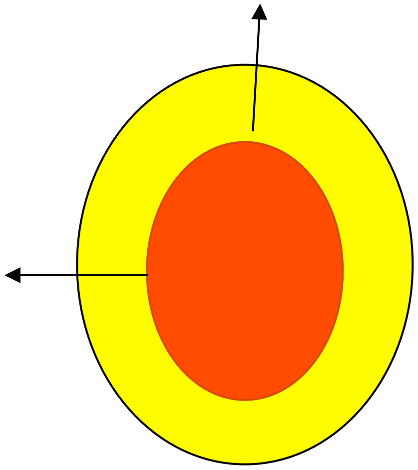
$$P = P_0 \left[1 - 0.095g^2 + 0.12g^3 + \left(0.09\ln g - 0.007 - 0.013\ln\frac{\mu}{2\pi T} \right) g^4 + \cdots \right]$$

  - Expand contributions from soft modes k~ gT in terms of g.

Azimuthal anisotropy I

$$\frac{dN_{ch}}{d\varphi} = N_0(1 + v_1 \cos\phi + 2v_2 \cos 2\phi + \cdots)$$





Single hadron

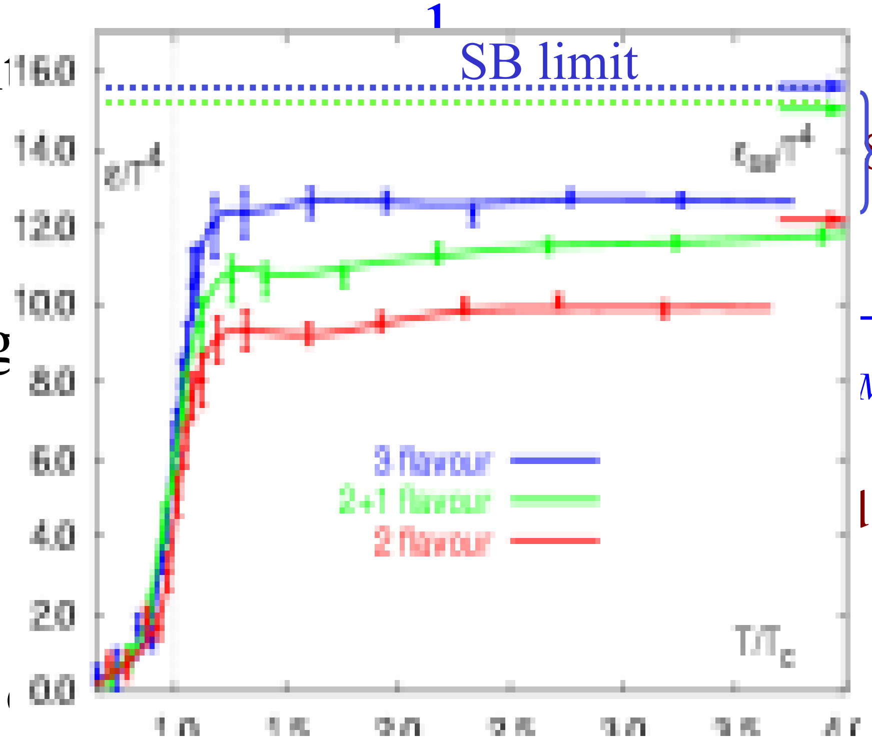
Super YM: Strong Coupling System

Entropy density $$S_{SYM}/S_0 = \frac{3}{4}\left[1+\frac{15}{8}\varsigma(3)(2g_{YM}^2N)^{-3/2}+\ldots\right]$$

Guber, Klebanov, Tseytlin ‘1998

Small viscosi

1



Son & Starinets ‘02

25 %

Jet quenching

$_{M}N_c \quad T^3$

l Wiedemann ‘ 2006

Heavy quark (