Stay home & Save lives

Jetomography of quark-gluon plasma in heavy-ion collisions

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QCD: Theory for strong interaction

$$\mathcal{L}_{\rm QCD} = \sum_f \bar{\psi}_f \gamma_\mu \left(i\partial^\mu - g A_a^\mu \frac{\lambda_a}{2} - m \right) \psi_f - \frac{1}{4} \sum_a F_a^{\mu\nu} F_{a,\mu\nu}$$

- SU(3) gauge symmetry (non-Abelian)
  - Asymptotic freedom & Confinement

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

- Chiral symmetry and its spontaneous breaking

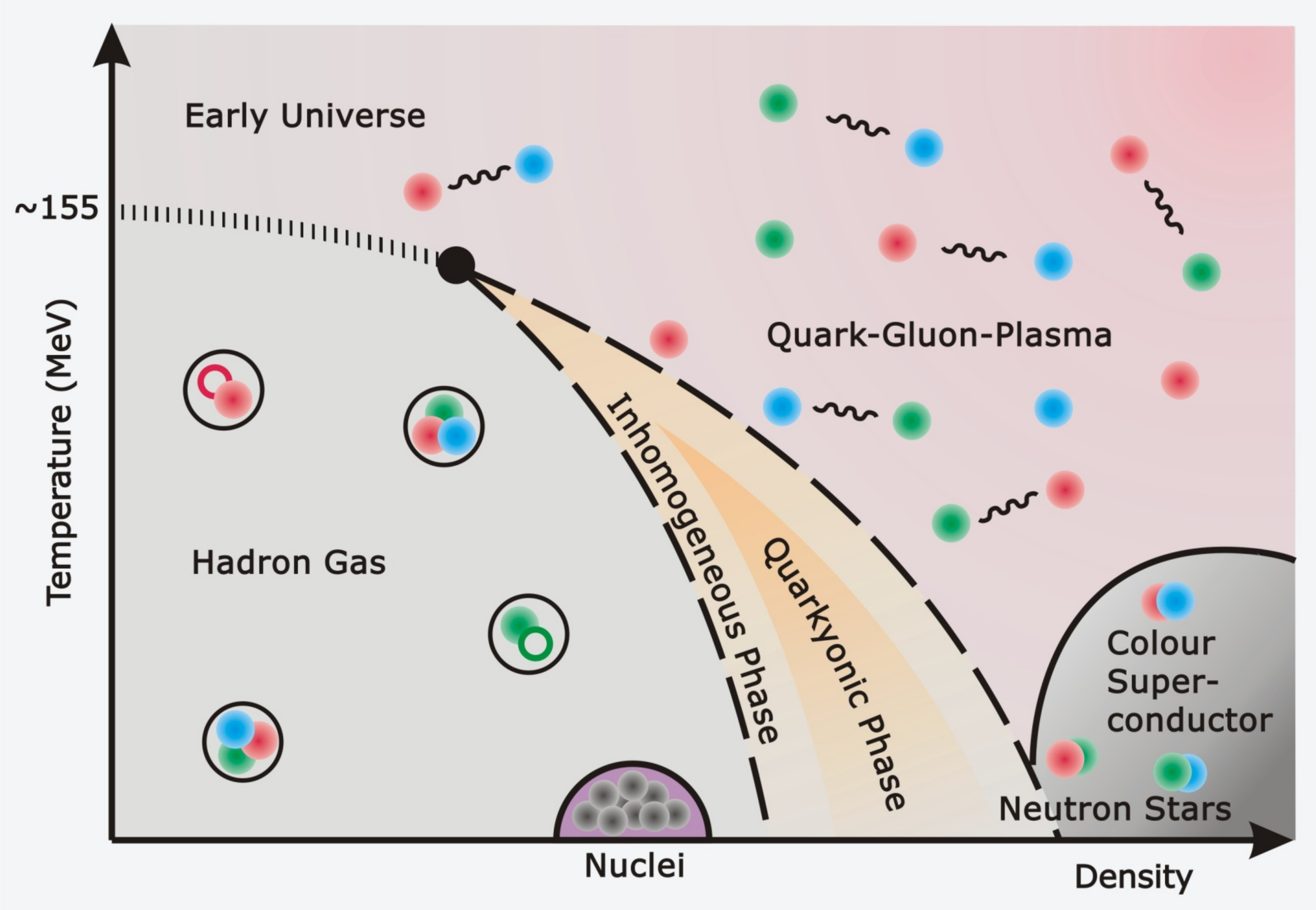
$$\langle \bar{\psi}\psi \rangle \neq 0$$

  - Goldstone boson and chiral condensate
- Scale and $U_A(1)$ anomaly

$$\langle F^{\mu\nu} F_{\mu\nu} \rangle \neq 0$$

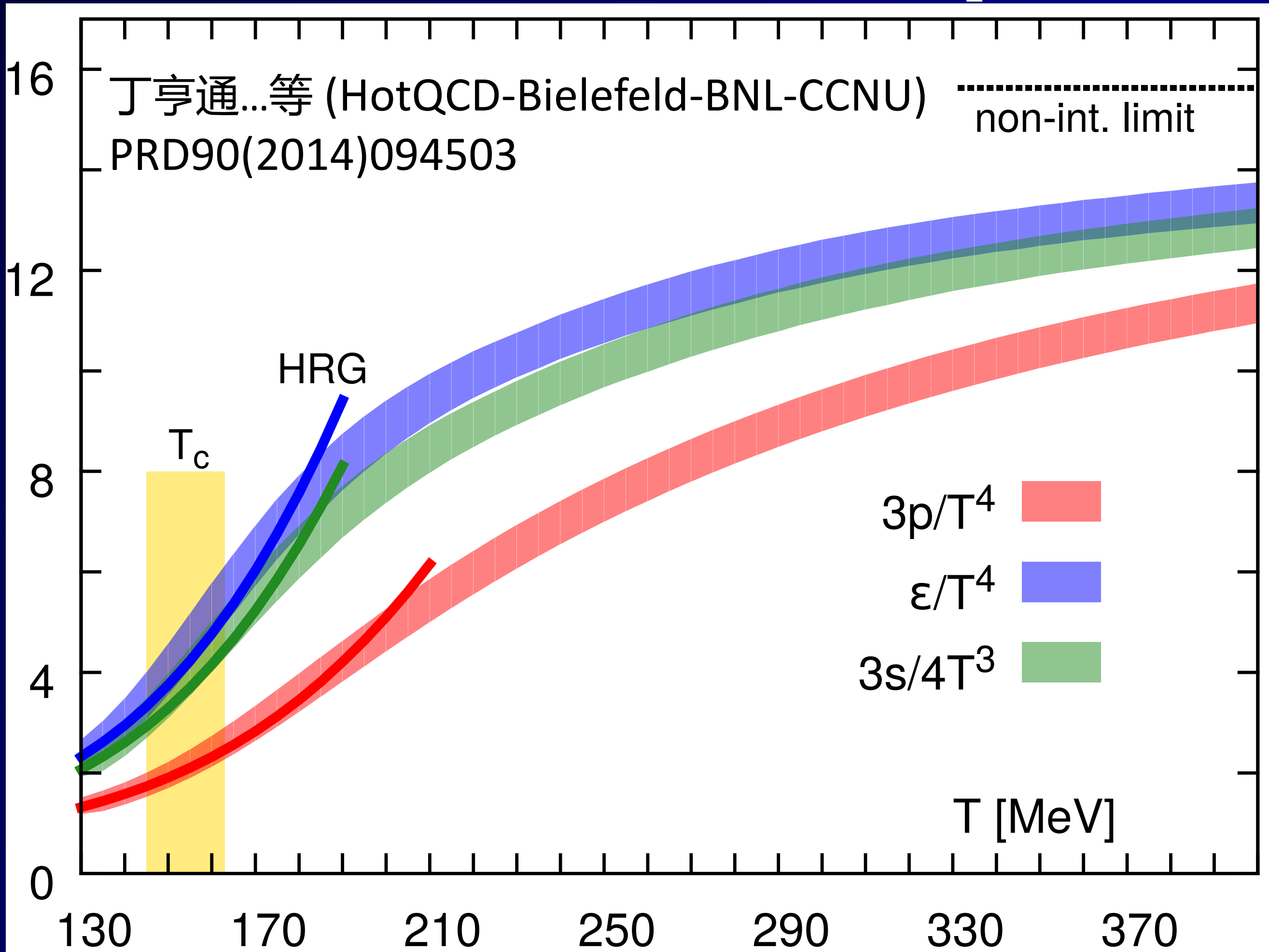
- ….

Phase structure of QCD Matter



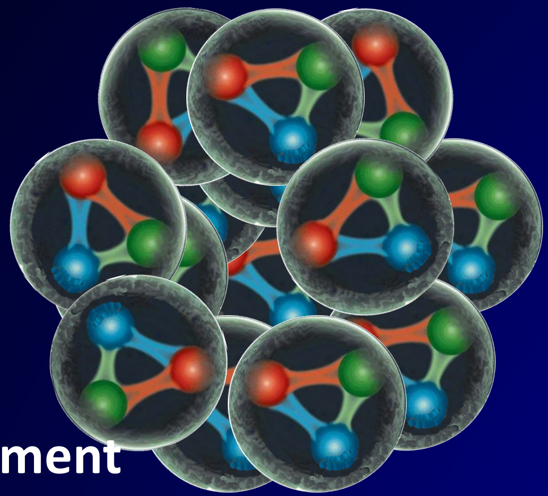
EOS from lattice QCD

$$\epsilon_{SB} = \left[6n_f \frac{7\pi^2}{120} + 16\frac{\pi^2}{30}\right] T^4$$



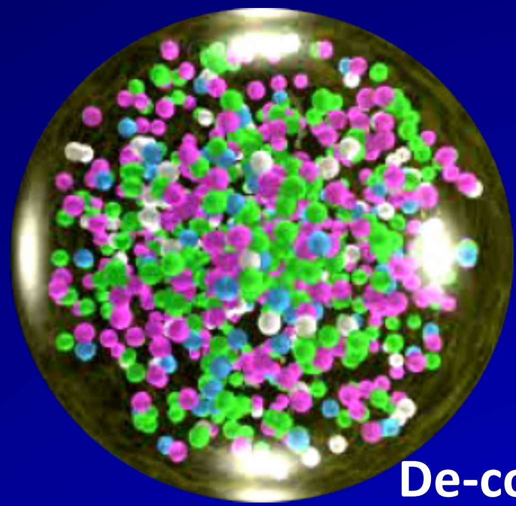
At T ~ 5T_c, ε still 80% of the Stefan-Boltzmann value: quasi-particle modes at high T

QGP in heavy-ion collisions



confinement

High T, μ



De-confinement

nucleus

quark-gluon plasma (QGP)

Properties of QGP

- Space-time profile: $$T_{\mu\nu}(x) : T(x), u(x)$$
- EOS: $$T_{\mu\nu} \Longleftrightarrow \epsilon, P, s, c_s^2 = \partial p / \partial \epsilon$$
- Bulk transport: $$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt dx e^{i\omega t} \langle [T_{xy}(0), T_{xy}(x)] \rangle$$
- EM response: $$W_{\mu\nu}(q) = \int \frac{d^4x}{4\pi} e^{iq\cdot x} \langle j_\mu(0) j_\nu(x) \rangle$$
- Jet transport: $$\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int \frac{dy^-}{\pi} \langle F^{\sigma+}(0) F_\sigma^{+}(y) \rangle$$
- …

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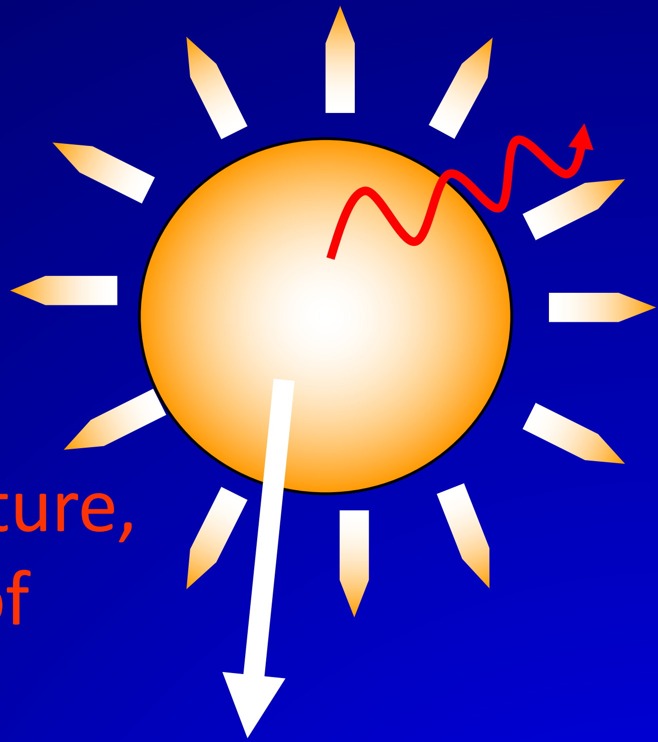
Properties of QGP in A+A Collisions

Dynamical System:

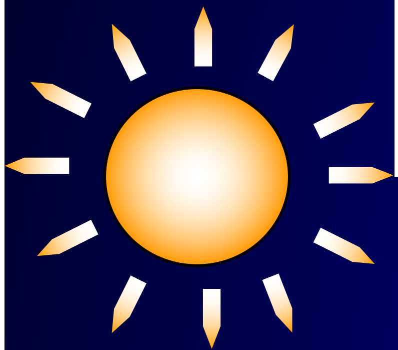


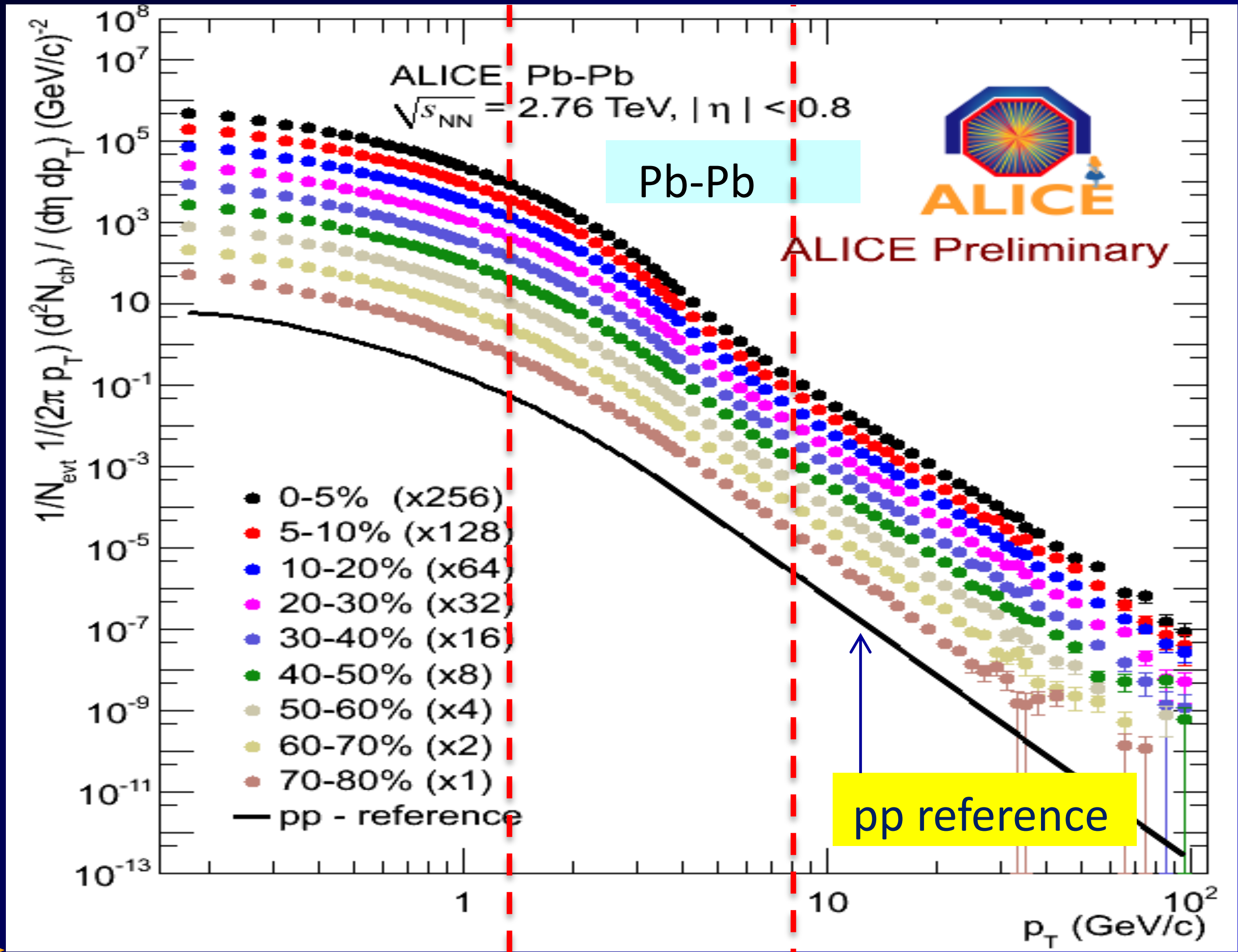
- Soft probes: collective flow - bulk properties, EoS, transport properties

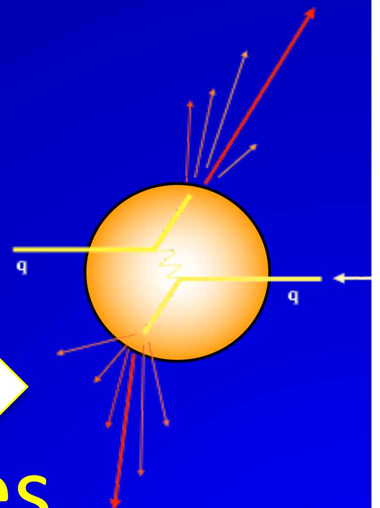
- EM Probes: EM emission – Temperature, EM response, medium modification of resonances

- Hard probes: Jet quenching – Jet transport coefficients

Hard and soft probes







soft probes

hard probes

Collective flow of QGP

- Hydrodynamics: $$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \Delta T^{\mu\nu}$$

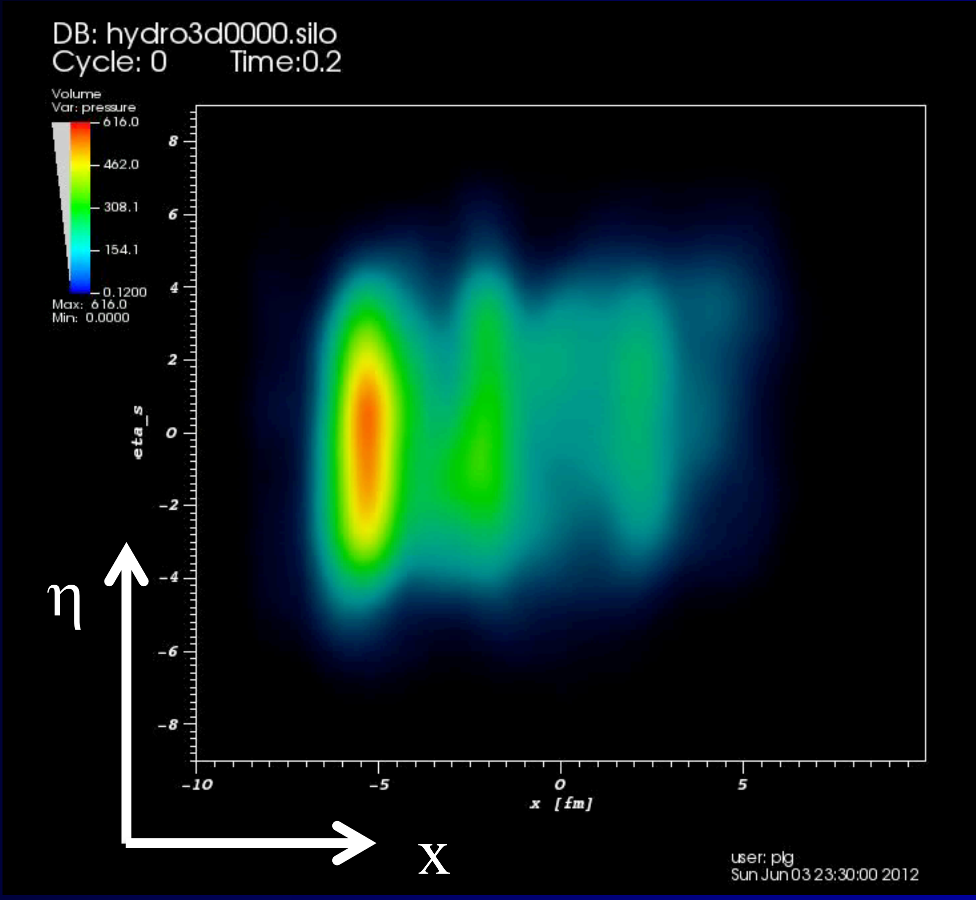
$$\Delta T^{\mu\nu} = \eta(\Delta^\mu u^\nu + \Delta^\nu u^\mu) + (\frac{2}{3}\eta - \zeta)H^{\mu\nu}\partial_\rho u^\rho$$

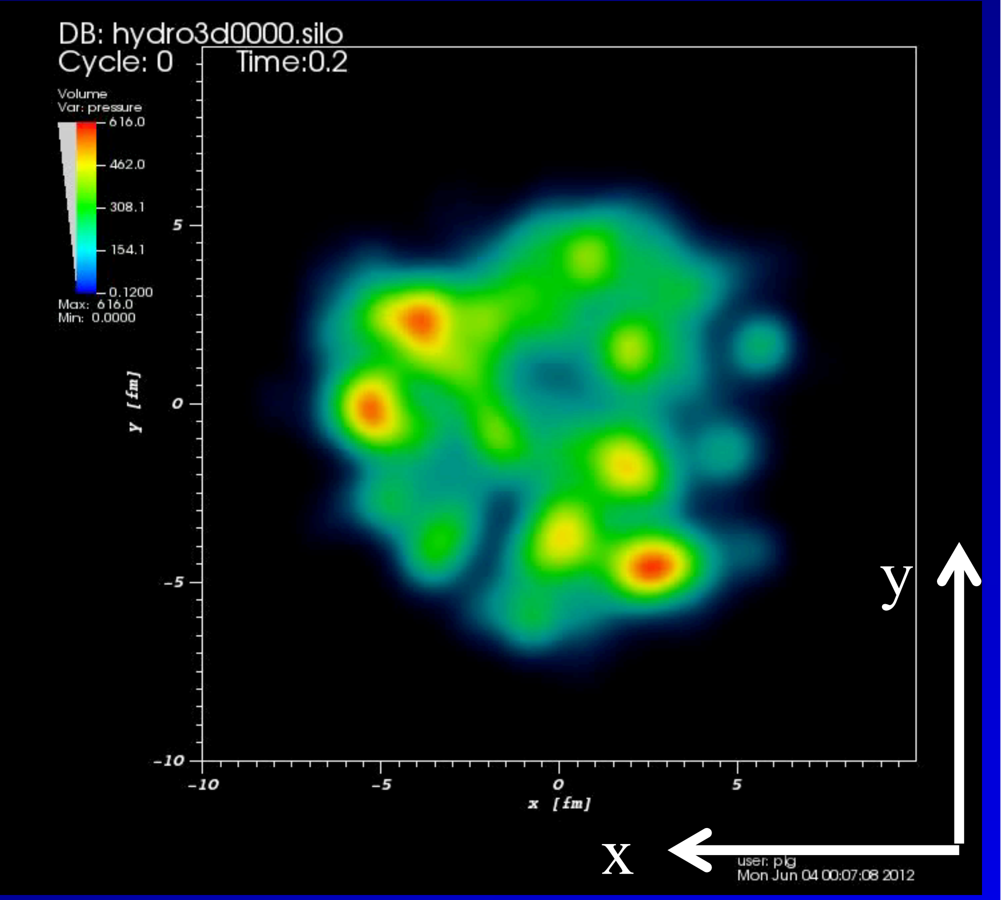
  – a low-momentum effective theory
  – Inputs from first principle QCD (lattice QCD) EoS p(ε), transport coefficients ξ(T), ζ(T) (??)
  – Initial condition: parton prod. & thermalization

Anisotropic hydro expansion

with 3D fluctuating initial conditions

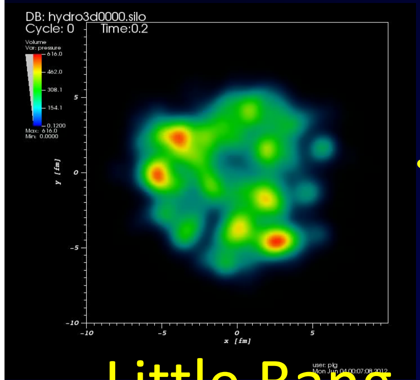
庞龙刚 （2013）





(3+1)D ideal hydro with AMPT initial condition (Pang & XNW'13)

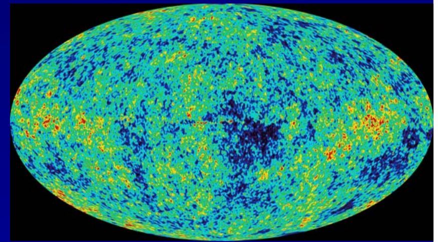
Anisotropic flow of QGP



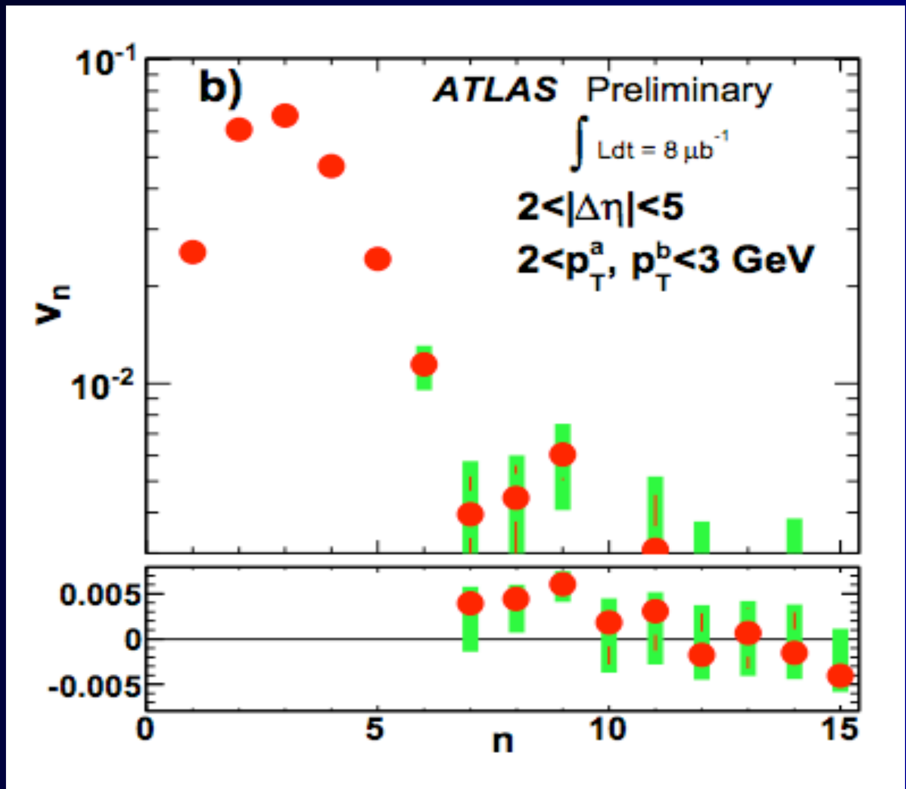
Little Bang

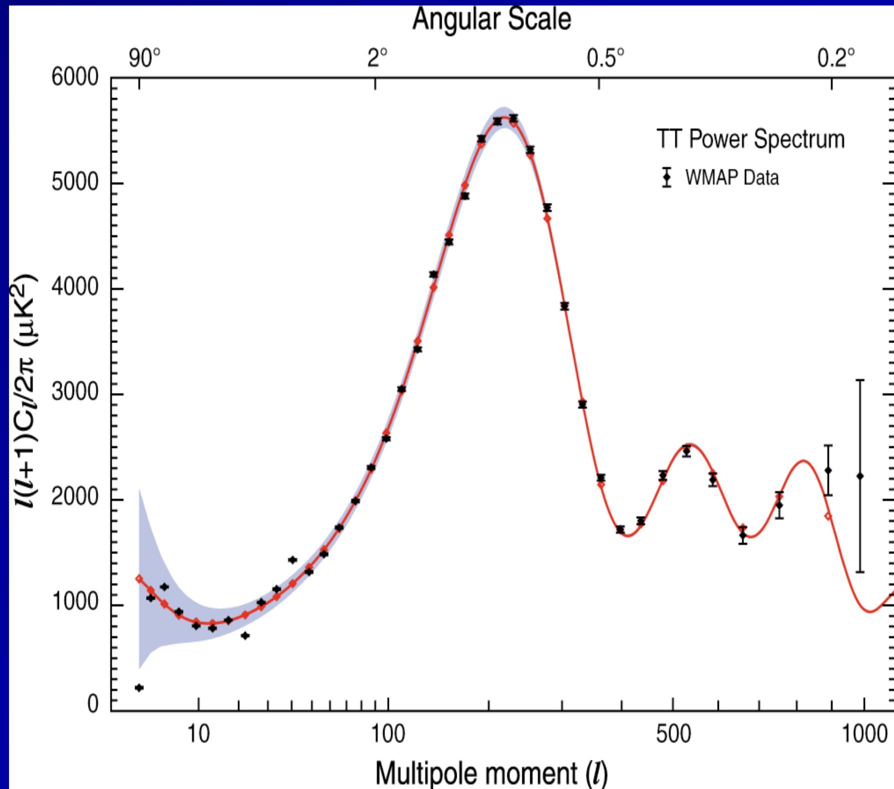
$$f(\phi) = f_0 \left[1 + 2 \sum_{n=1} v_n \cos n(\phi - \Psi_n) \right]$$

$$\Psi_n = \frac{1}{n} \arctan \frac{\langle p_T \sin(n\phi) \rangle}{\langle p_T \cos(n\phi) \rangle}$$



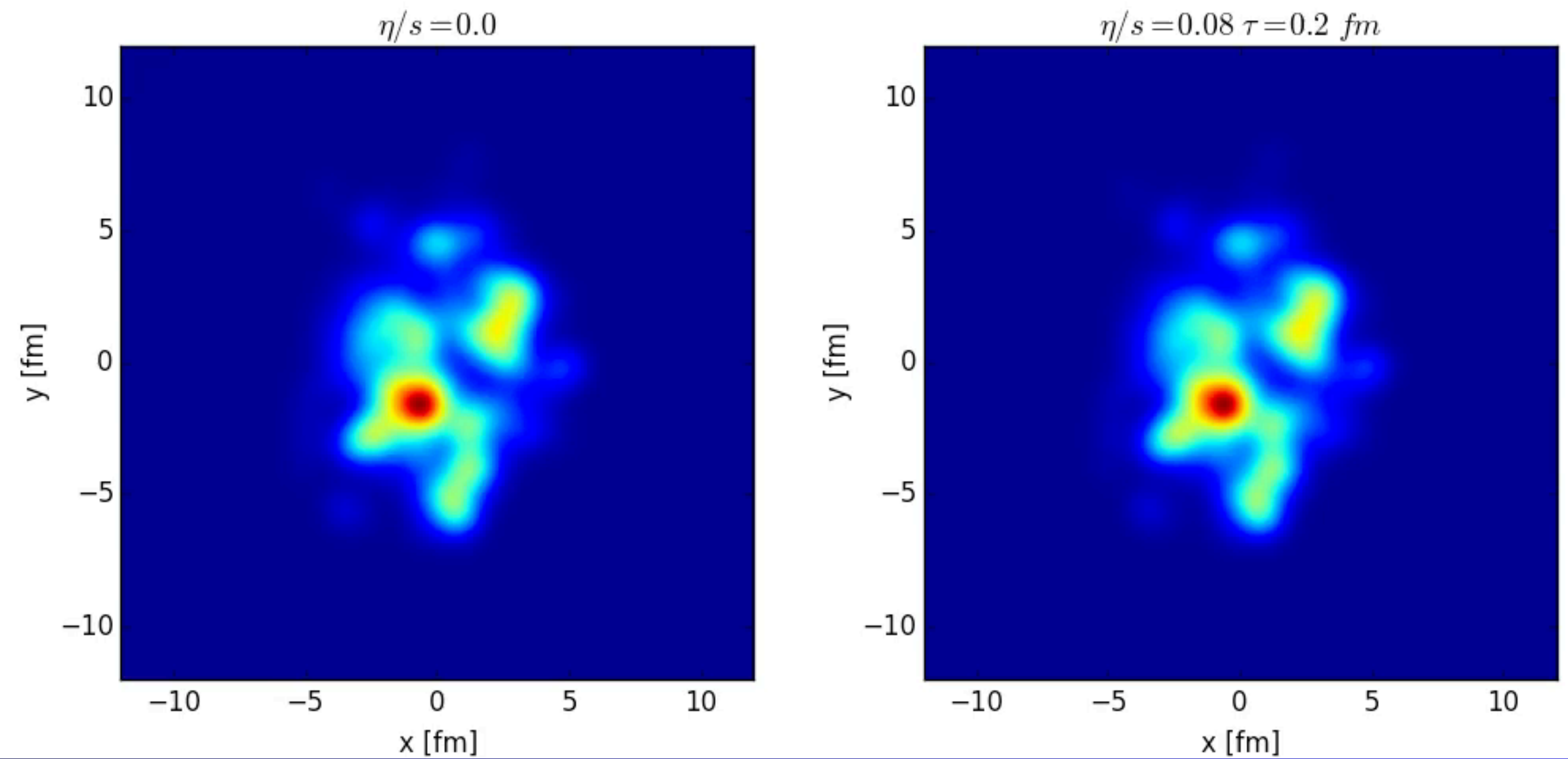
Big Bang





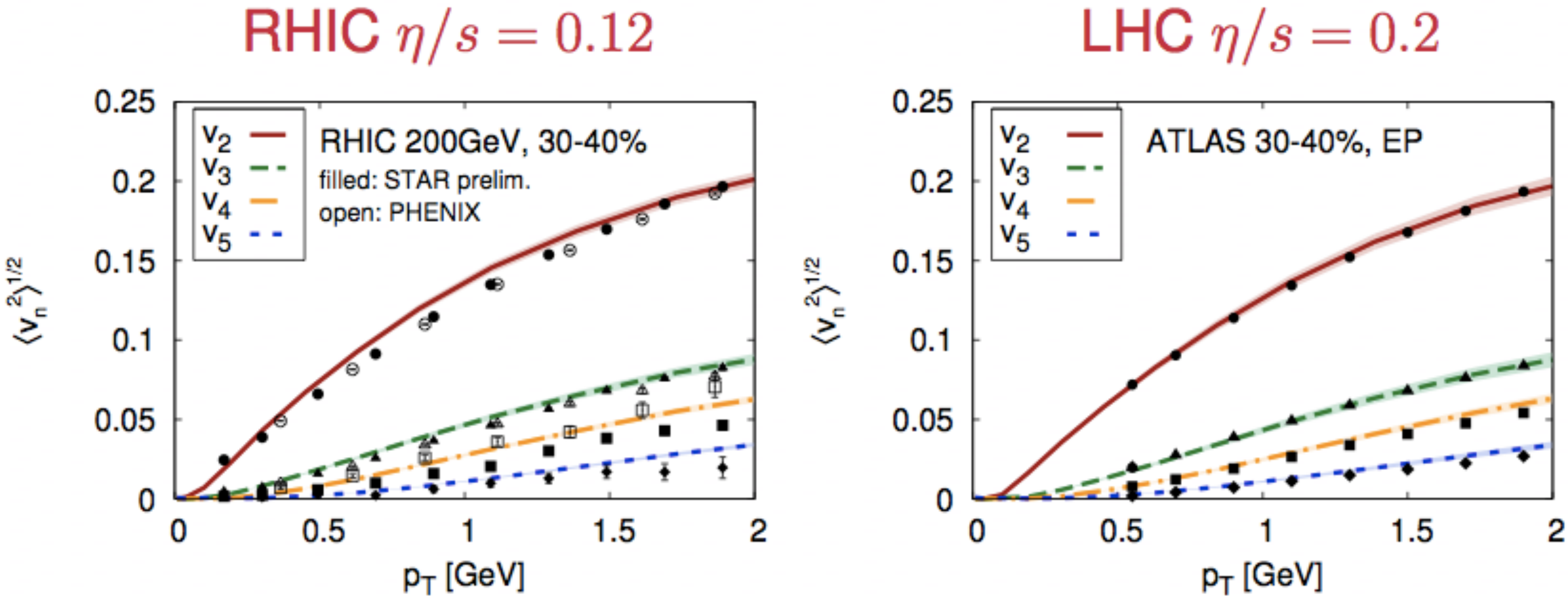
Effect of viscosity

庞龙刚（2015）



Viscosity of QGP in A+A collisions

Gale, Jeon, Schenke, Tribedy & Venugopalan 2013

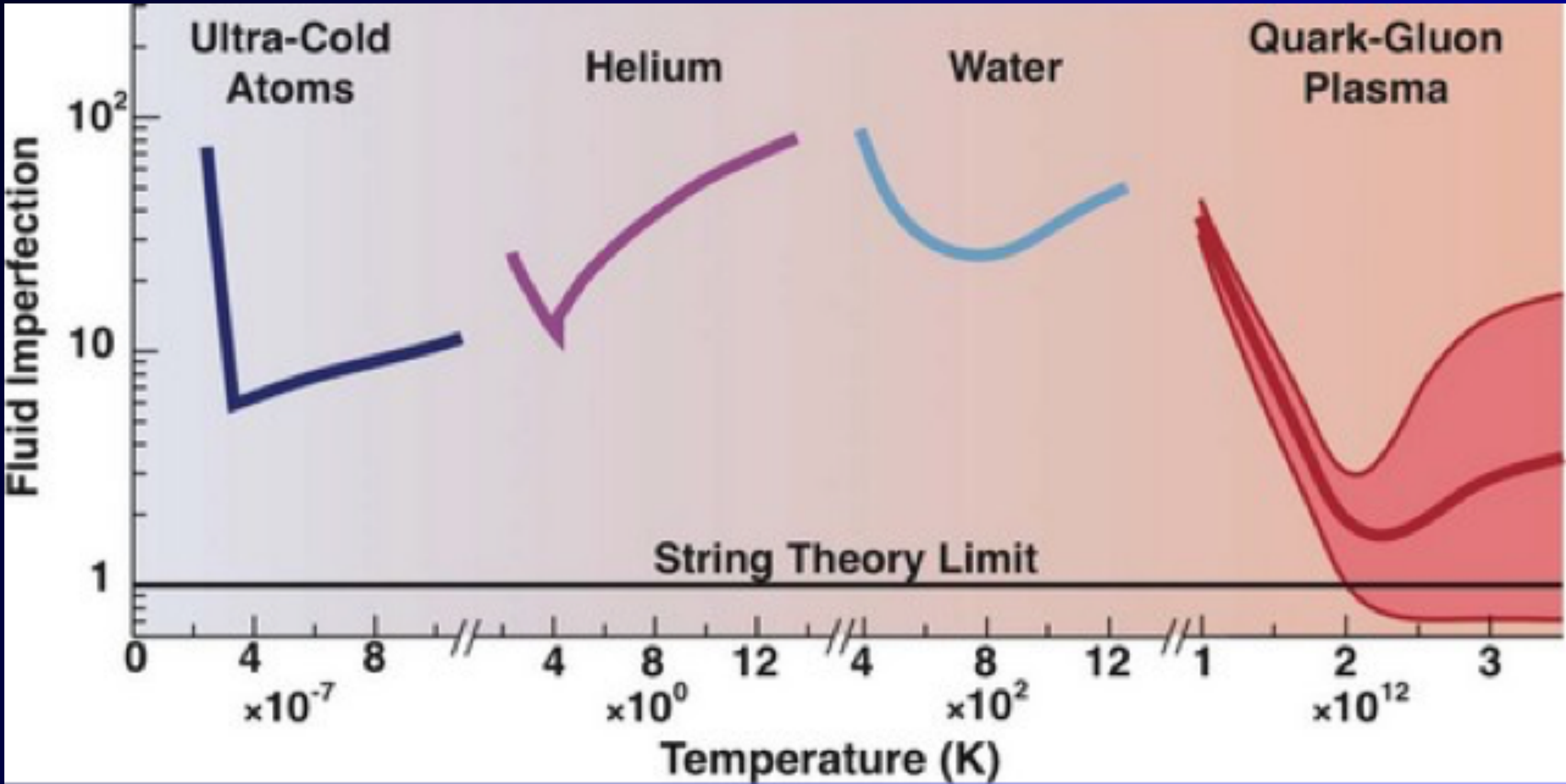


Fluctuation + viscous hydro required to fit all v_n

Viscosity at LHC is larger than at RHIC

QGP: a perfect fluid

η/s



Transport properties of QCD matter

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt dx e^{i\omega t} \langle [T^{ij}(x,t), T^{ij}(0,0)] \rangle$$

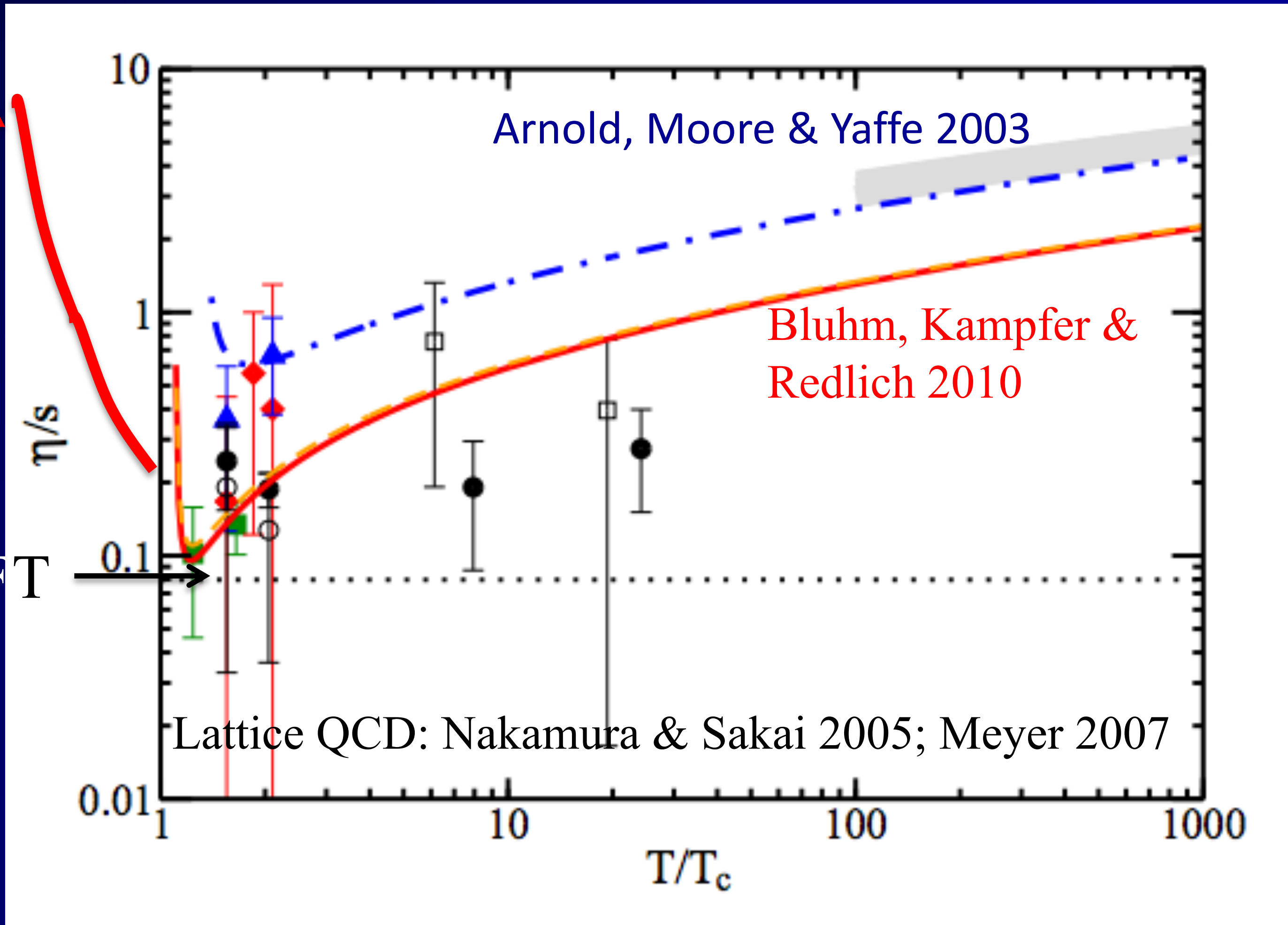
$$\frac{\eta}{s} = \frac{15}{16\pi} \frac{f_\pi^4}{T^4}$$

pion gas

Prakash'93

$$\frac{1}{4\pi}$$

AdS/CFT



Transport properties of QCD matter

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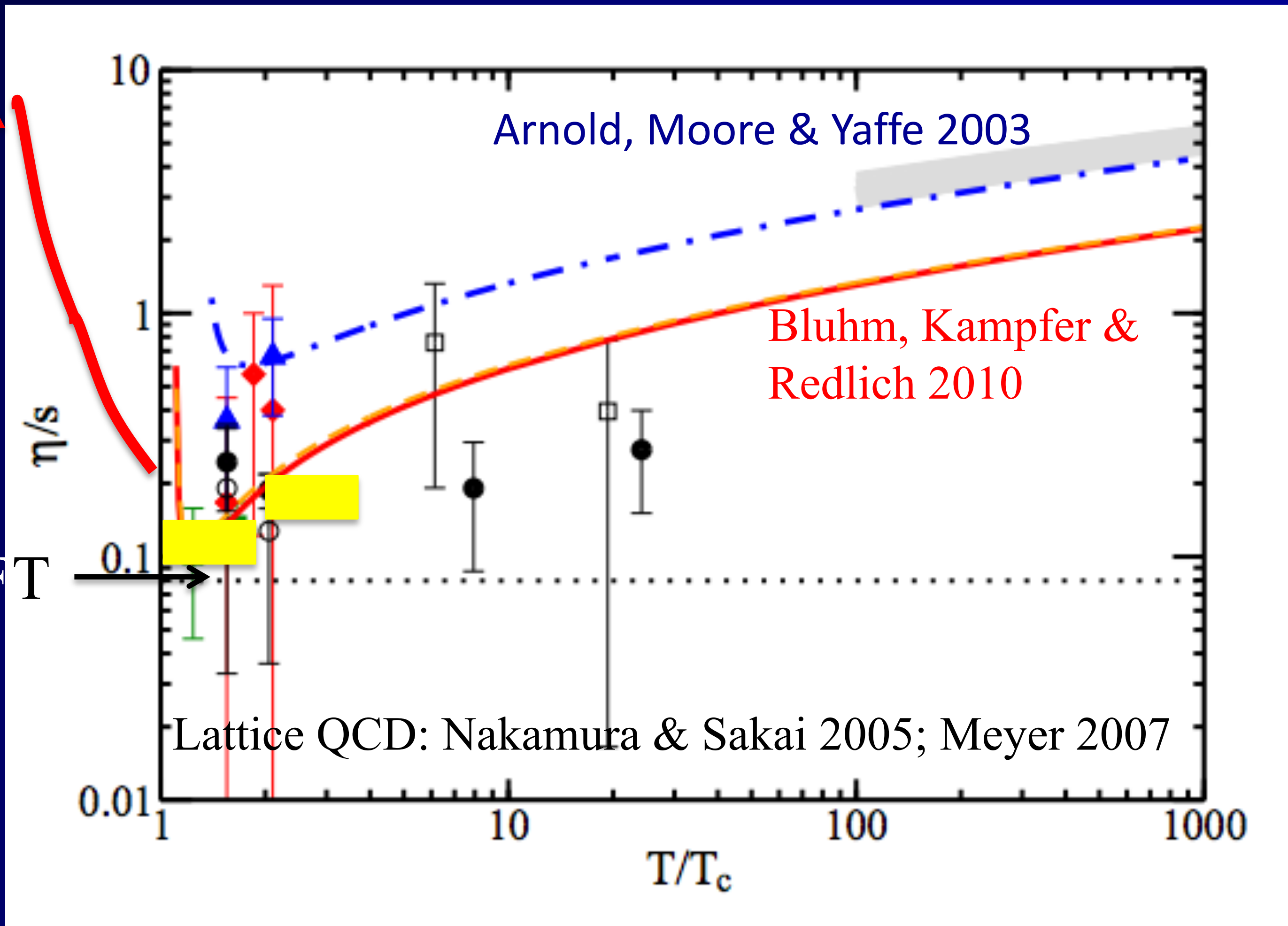
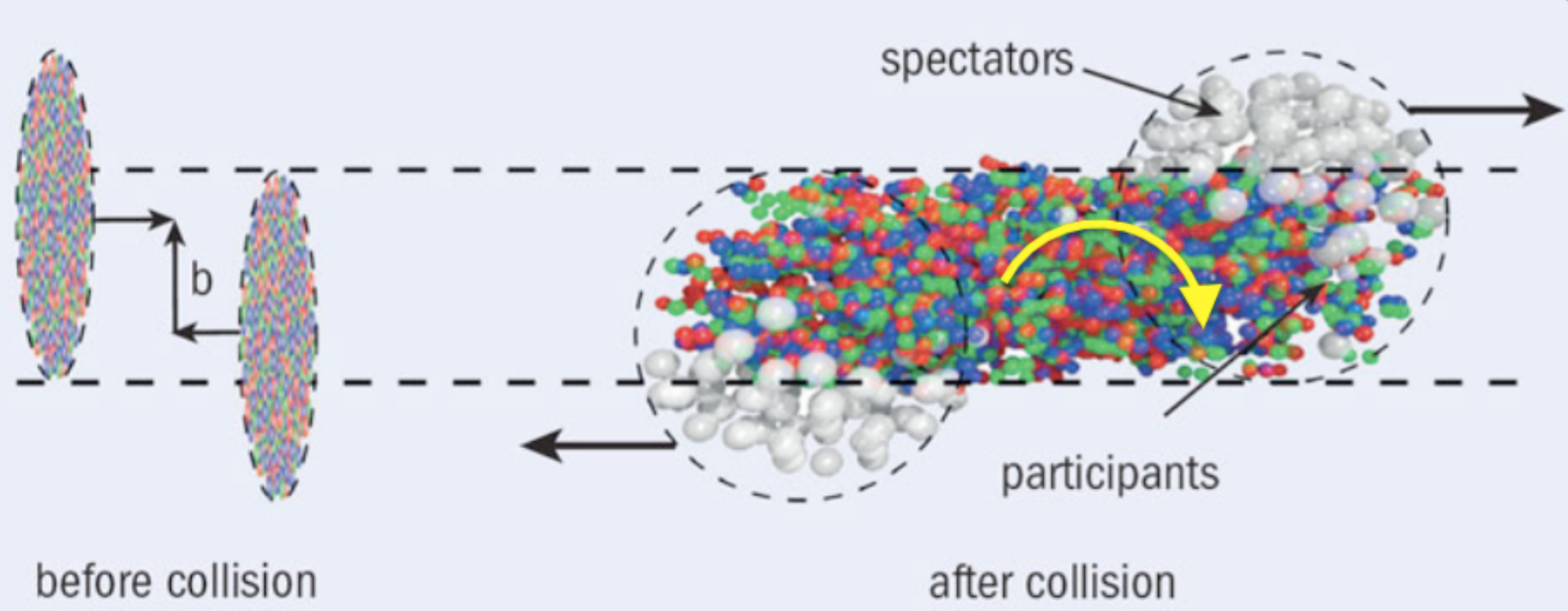
$$\frac{\eta}{s} = \frac{15}{16\pi} \frac{f_\pi^4}{T^4}$$

pion gas
Prakash'93

$$\frac{1}{4\pi}$$ AdS/CFT



Vorticity in QGP

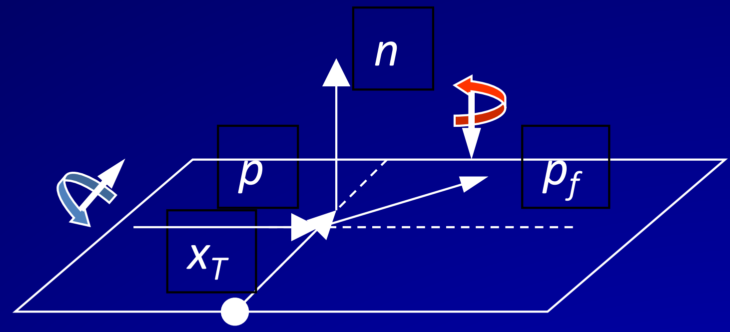


Non-vanishing local vorticity $\vec{\omega} = \vec{\nabla} \times \vec{v}$

Global quark polarization

Liang and XNW, PRL 94(2005)102301

$$P_q = -\pi \frac{\mu p}{2E(E+m_q)}$$

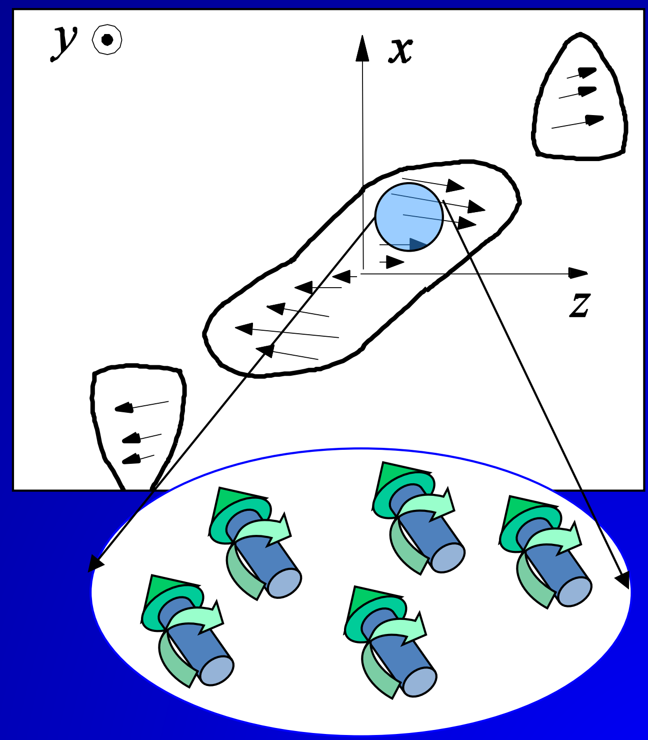


μ: Debye mass → 1/interaction length

p/μ: Local orbital angular momentum

Spin-orbital coupling → quark polarization

Global hyperon polarization !

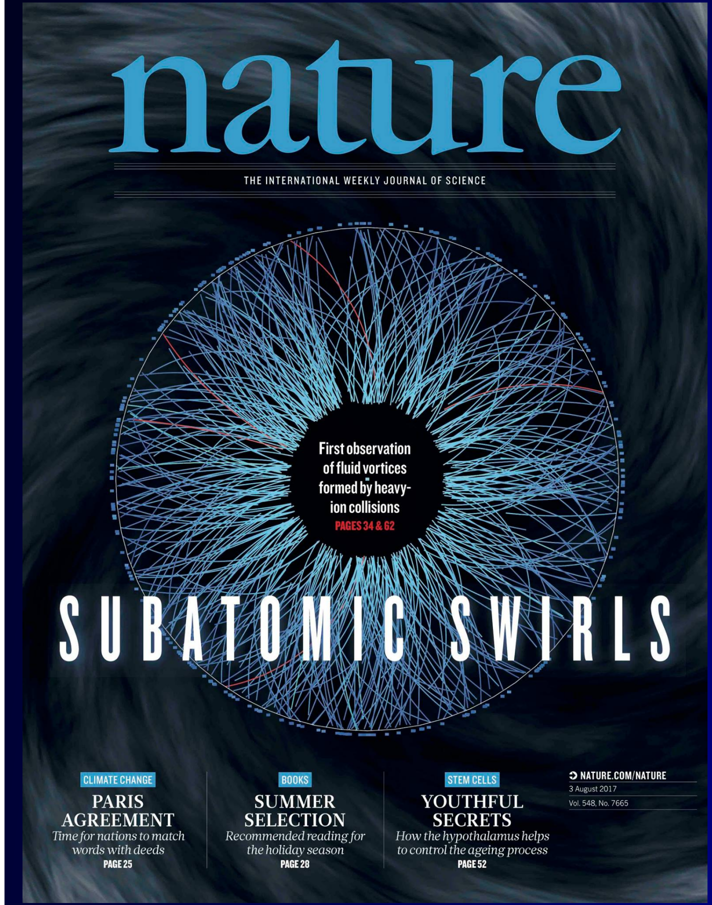


Lambda Polarization at RHIC

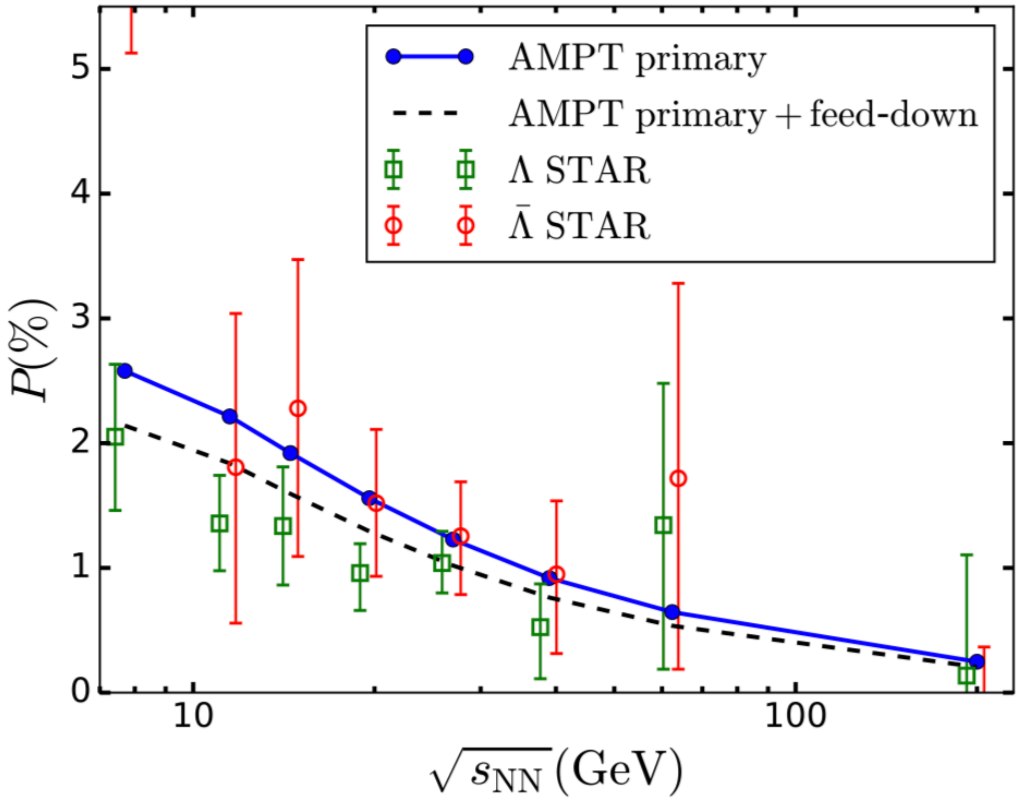
$$P_{\pm} \sim \exp\left(\pm\frac{\omega}{2T}\right)$$

$$\omega \approx (9 \pm 1) \times 10^{21}/\text{sec}$$

The fastest rotating matter in nature

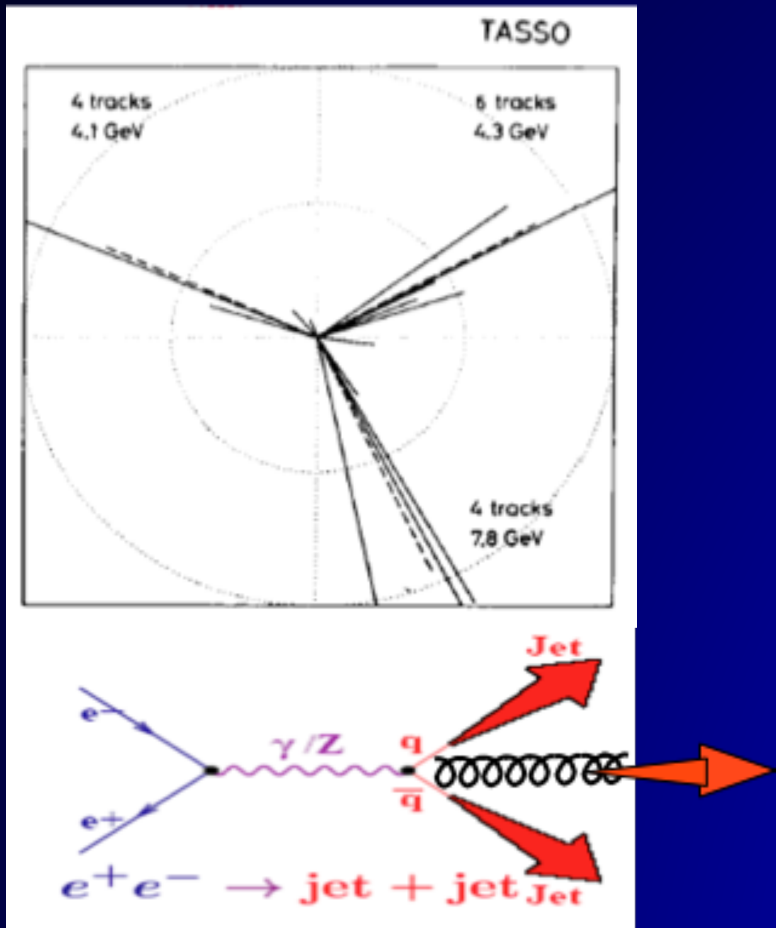


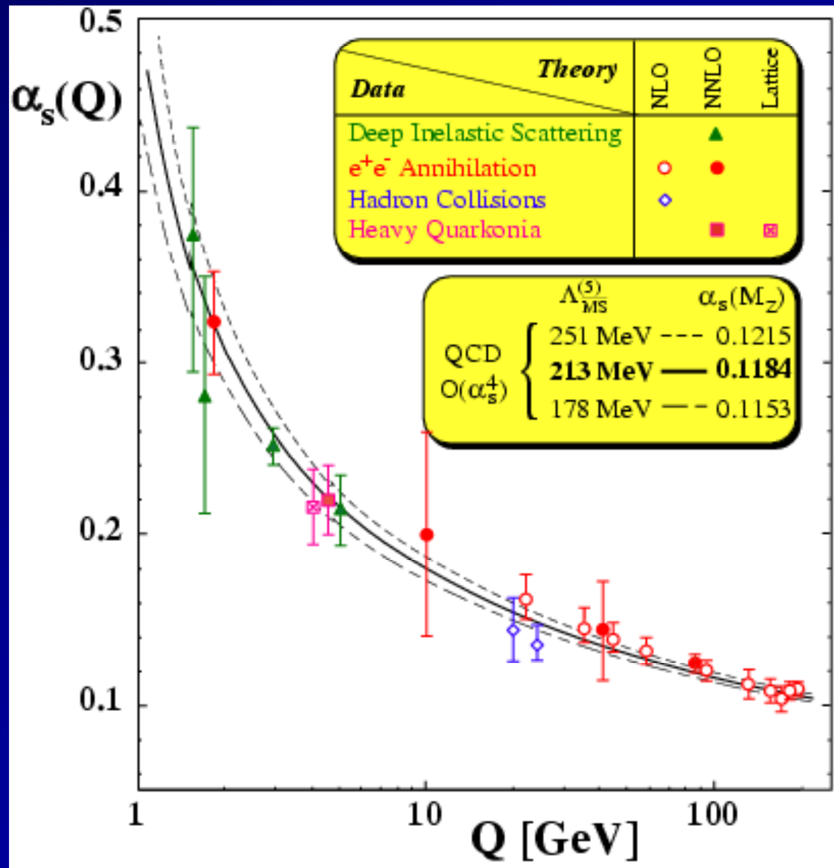
Li, Pang, Wang & Xia, PRC96 (2017) 054908



Jets in high-energy collisions

--tools for studying QCD and new discoveries

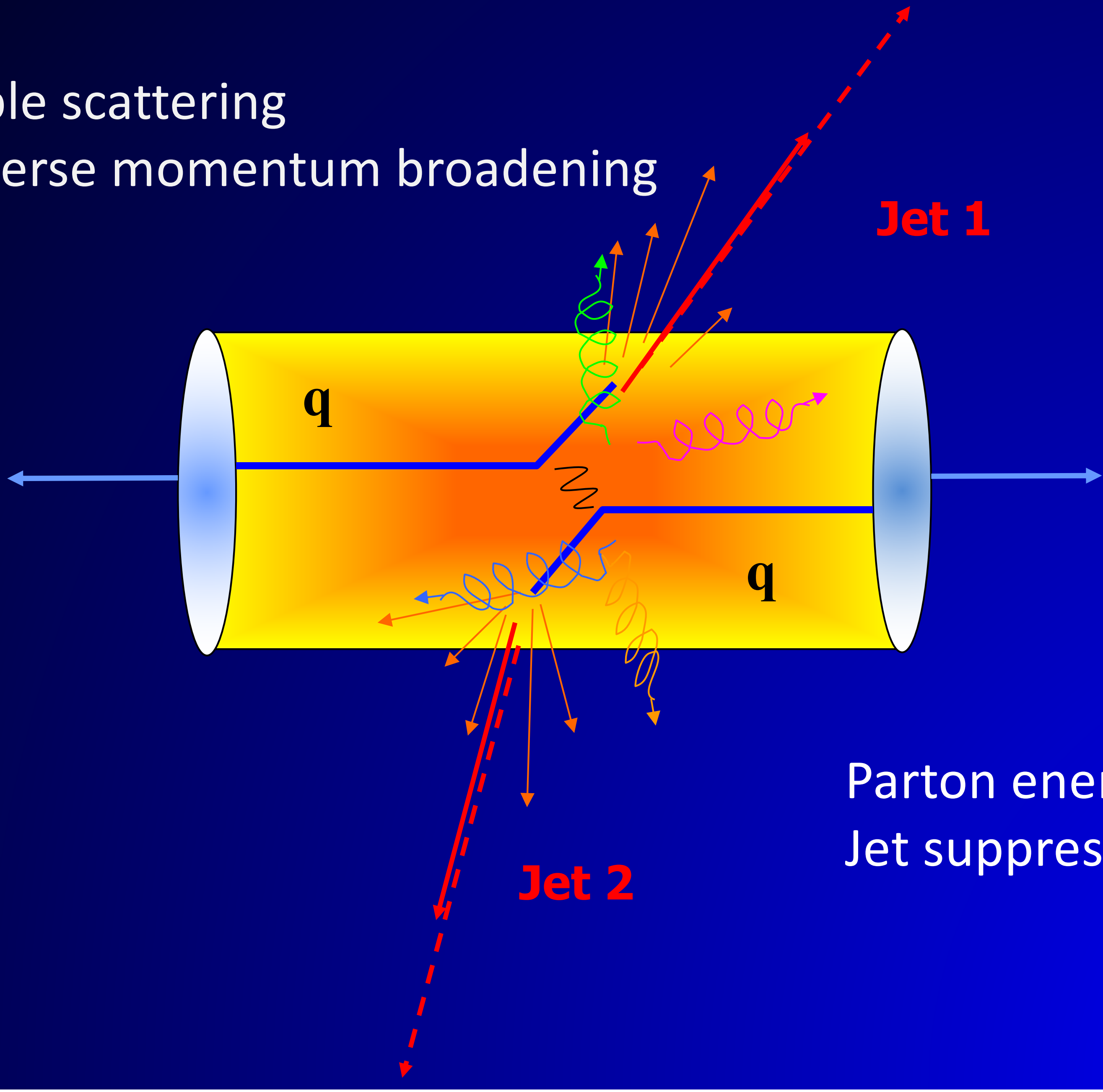




S Bethke J. Phys. G26 (2000) R27

Jetomography of QGP

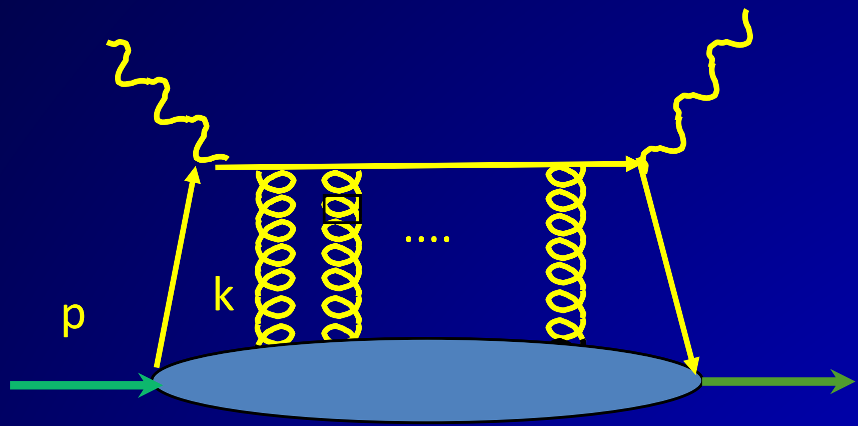
Multiple scattering
Transverse momentum broadening



Parton energy loss
Jet suppression

Parton scattering in medium

$$f_A^q(x,\vec{k}_\perp) = \int \frac{dy^-}{4\pi}\frac{d^2y_\perp}{(2\pi)^2} e^{ixp^+y^- - i\vec{k}_\perp\cdot\vec{y}_\perp} \langle A|\bar{\psi}(0)\gamma^+\mathcal{L}(0,y)\psi(y)|A\rangle$$



$$f_A^q(x,\vec{k}_\perp) \approx \frac{A}{\pi\Delta}\int d^2q_\perp \exp\left[-\frac{(\vec{k}_\perp - \vec{q}_\perp)^2}{L\hat{q}}\right] f_N^q(x,\vec{q}_\perp)$$

p_T broadening and Jet transport coefficient:

$$\hat{q}(y) = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\rho(y)xG(x)|_{x\approx 0}$$

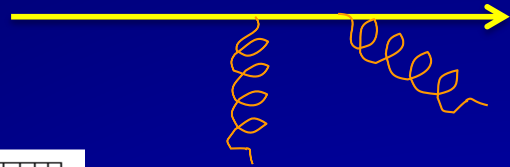
pQCD (BDMPS'96)

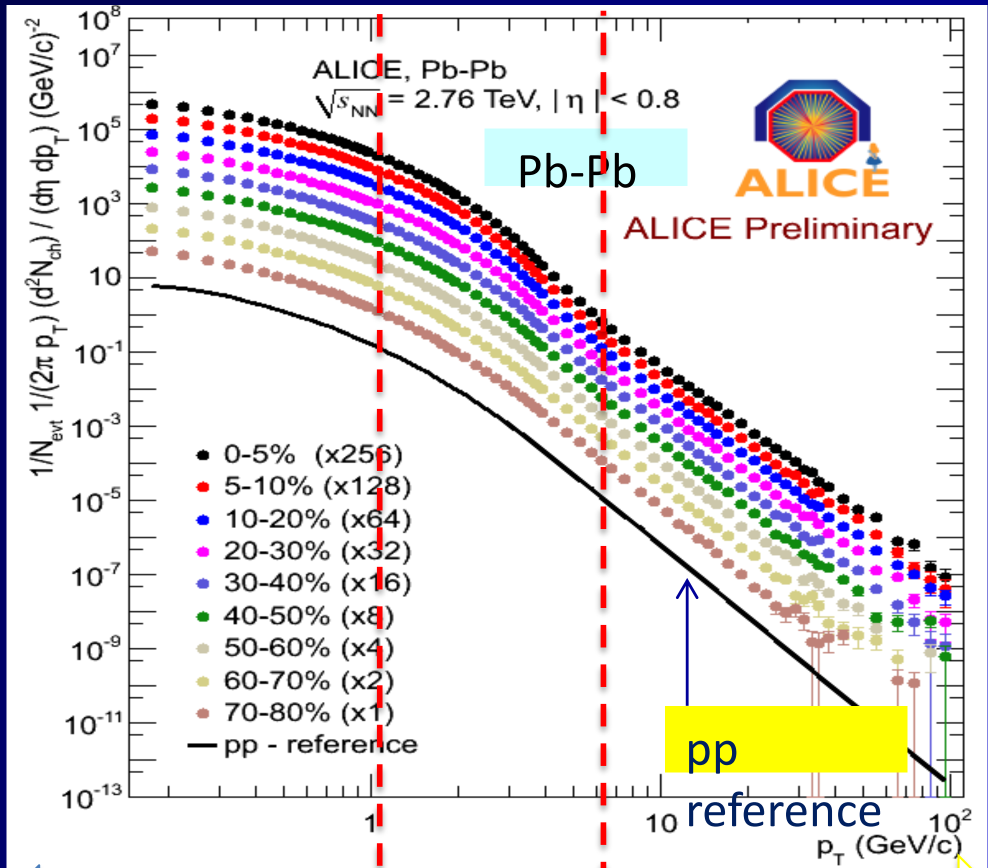
AdS/CFT (Liu,Rajagopal &Wideman'06)

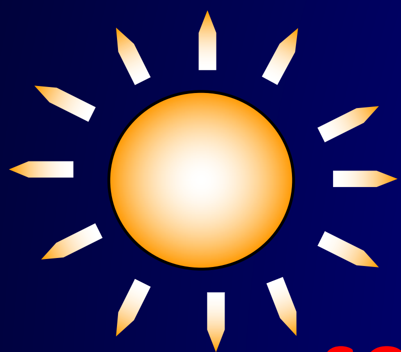
lattice QCD (Majumder'12)

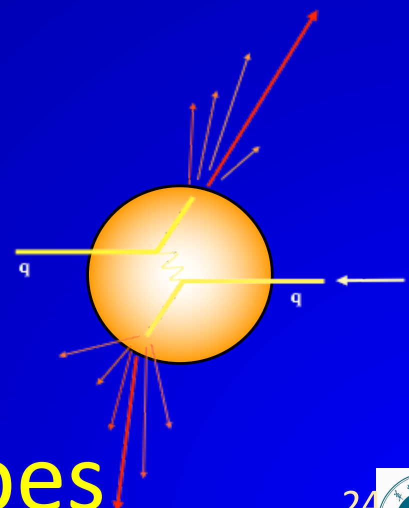
Parton energy loss and jet quenching

$$\frac{dE_{rad}}{dx} \approx \frac{2C_A\alpha_s}{\pi}\hat{q}(x)\int dz \frac{d\ell_\perp^2}{\ell_\perp^4} zP(z)\sin^2\frac{\ell_\perp^2(x-x_0)}{4z(1-z)E}$$





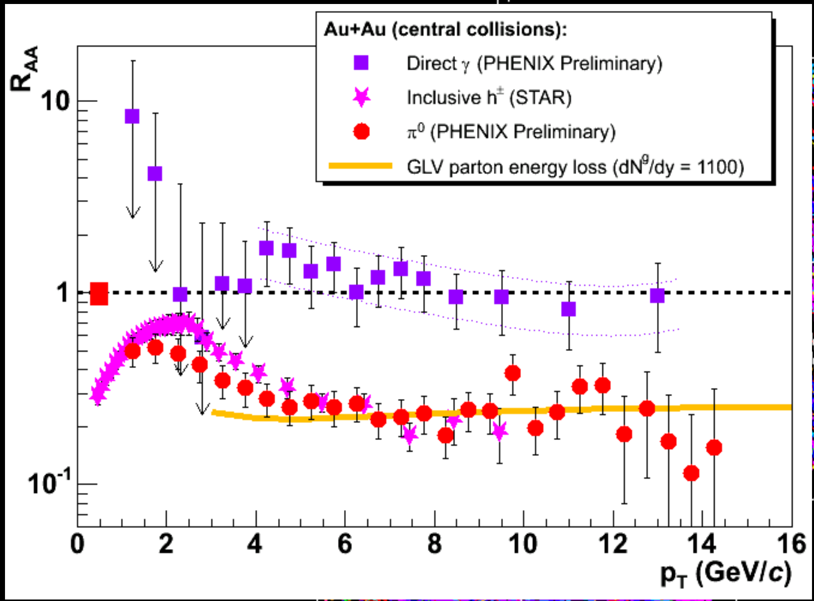


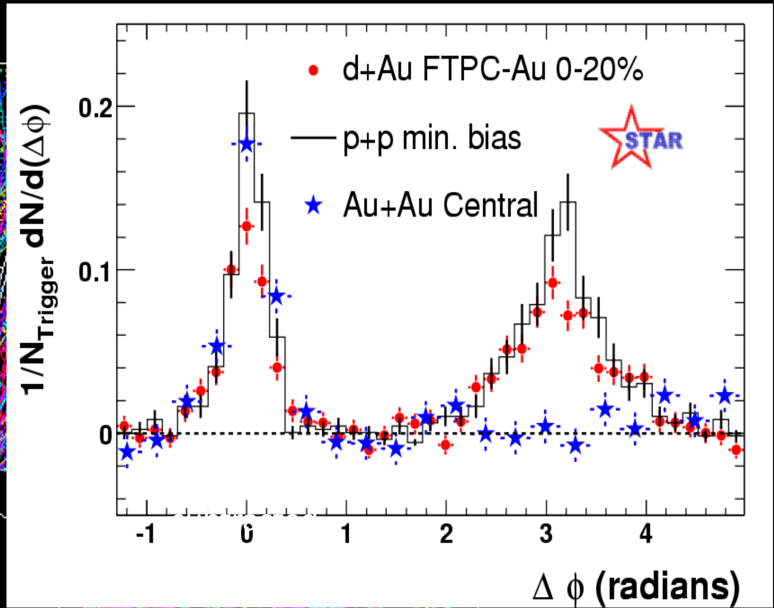


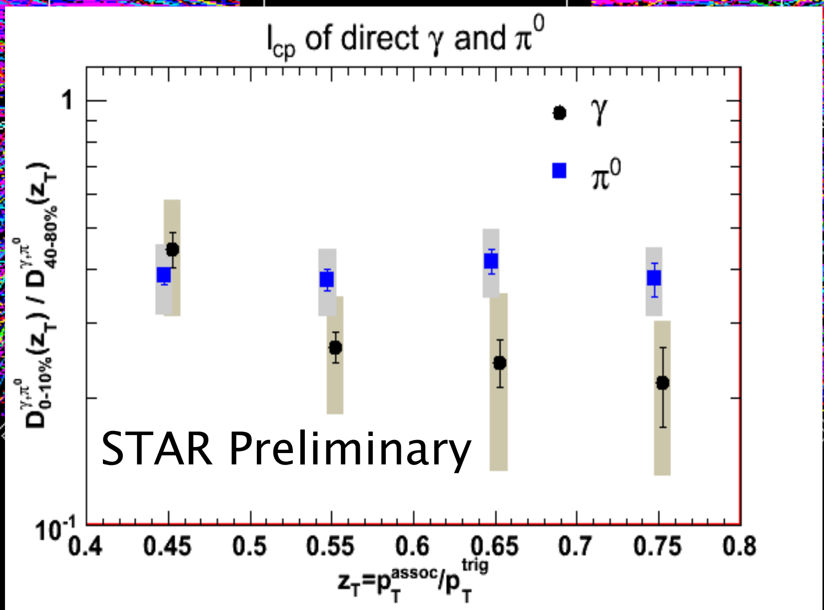
soft probes

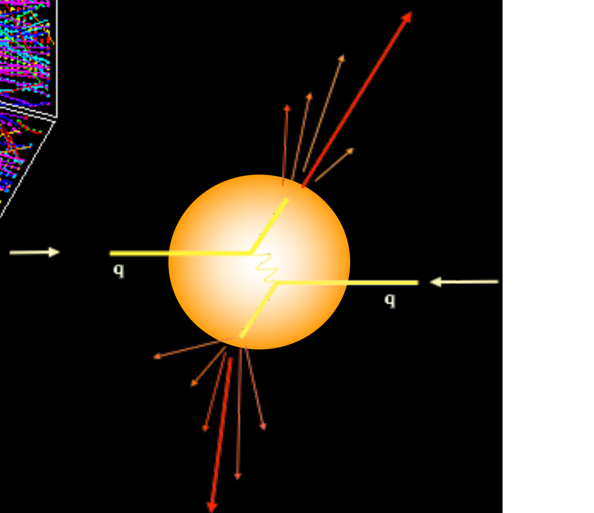
hard probes

Jet Quenching phenomena at RHIC





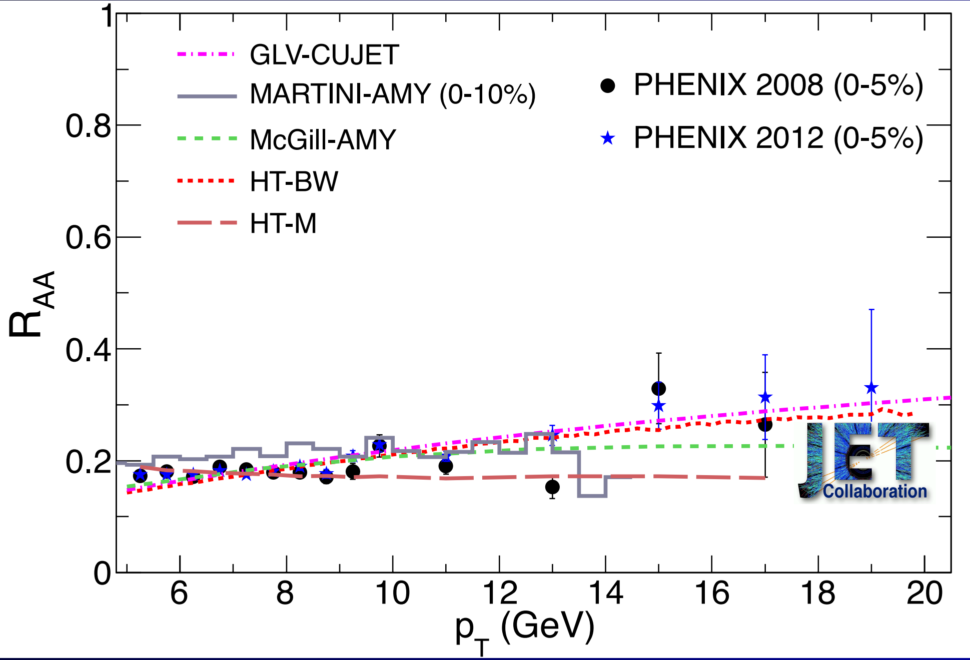




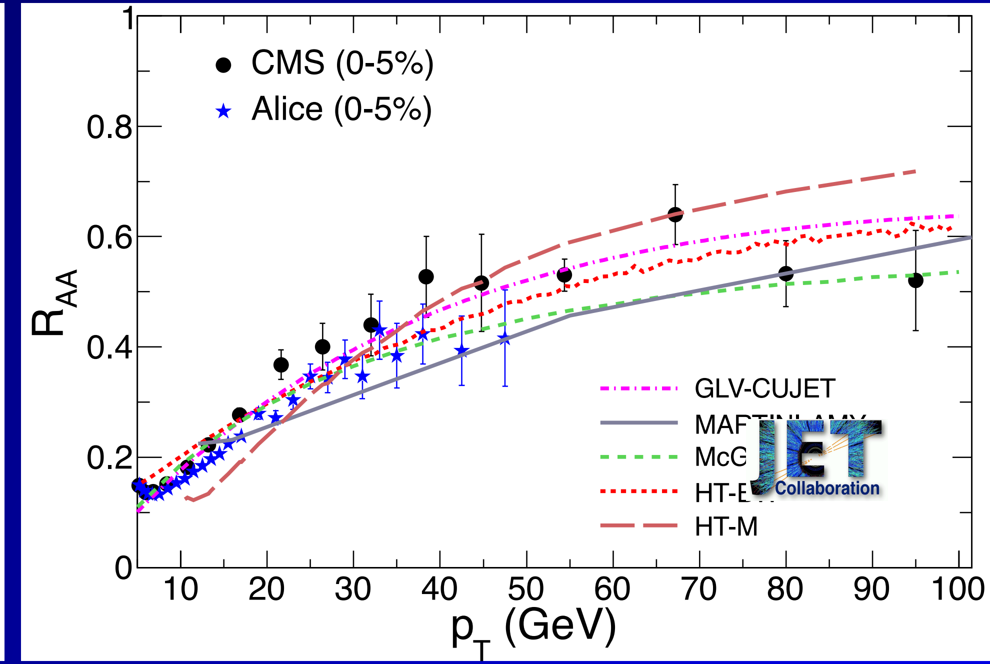
Jet quenching phenomenology

Suppression of single hadron spectra at RHIC and LHC

Best χ^2 fits with different model calculations :



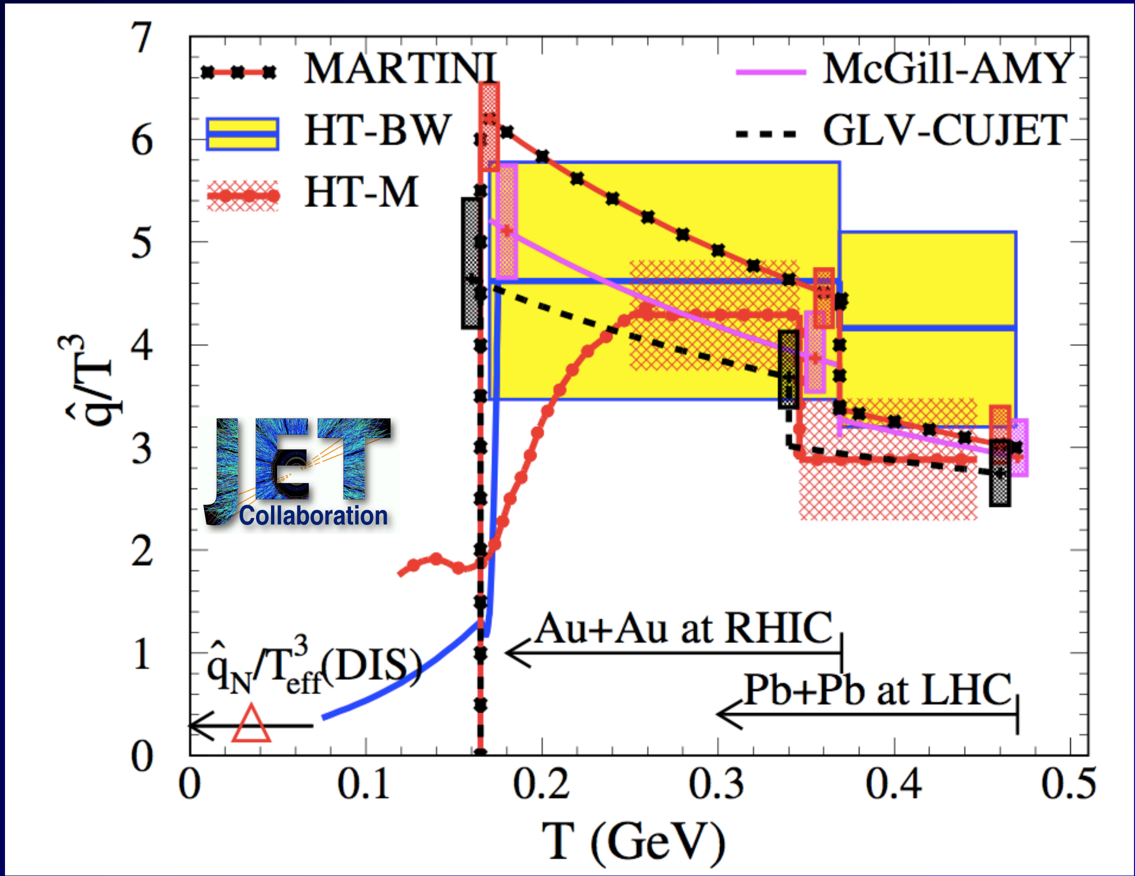
RHIC



LHC

Jet transport coefficient

JET Collaboration: arXiv:1312.5003

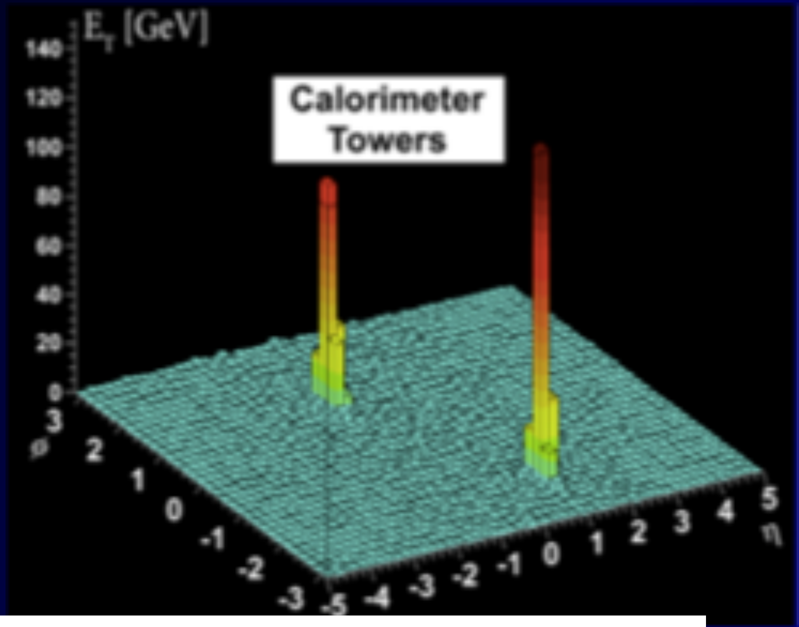


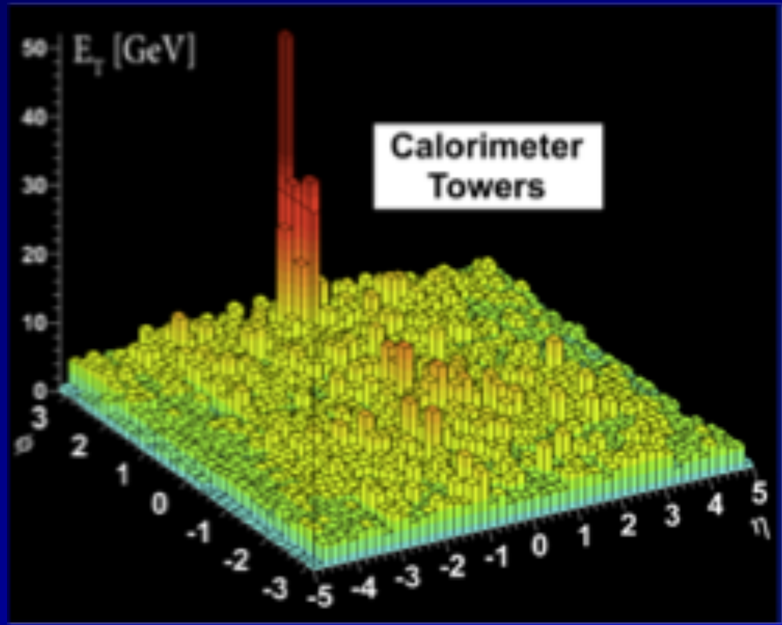
$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \;\; \mathrm{at} \;\; \begin{matrix} \mathrm{T{=}370\ MeV}, \\ \mathrm{T{=}470\ MeV}, \end{matrix}$$

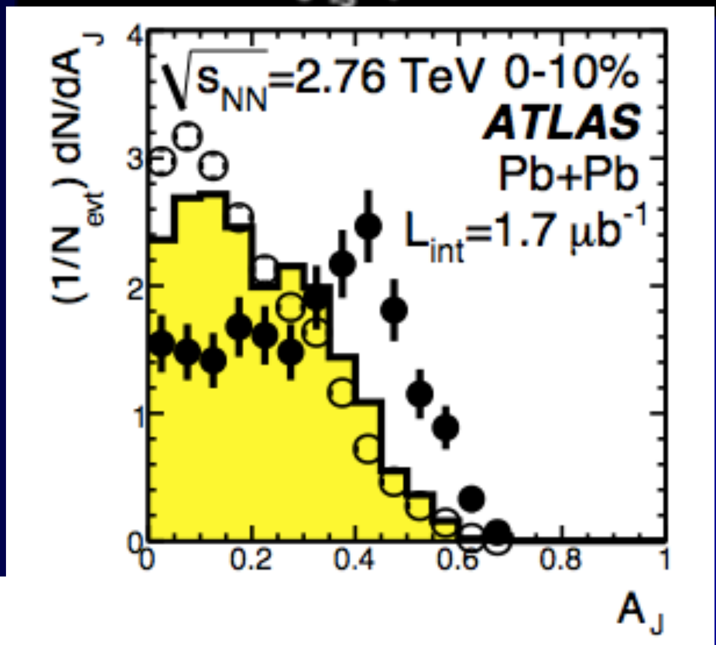
RHIC

LHC

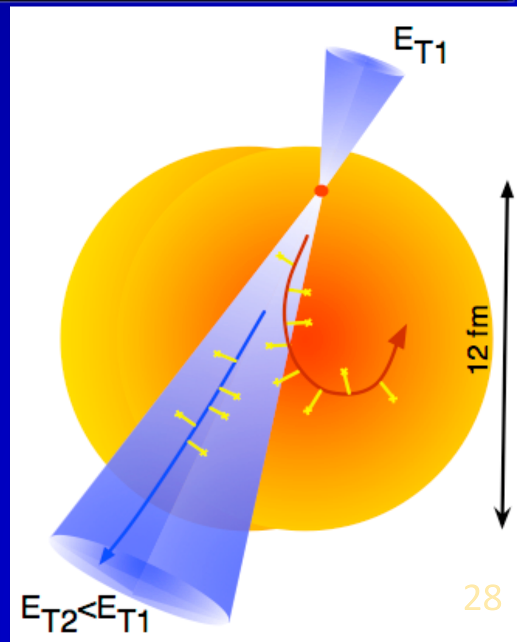
Dijet asymmetry at LHC







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



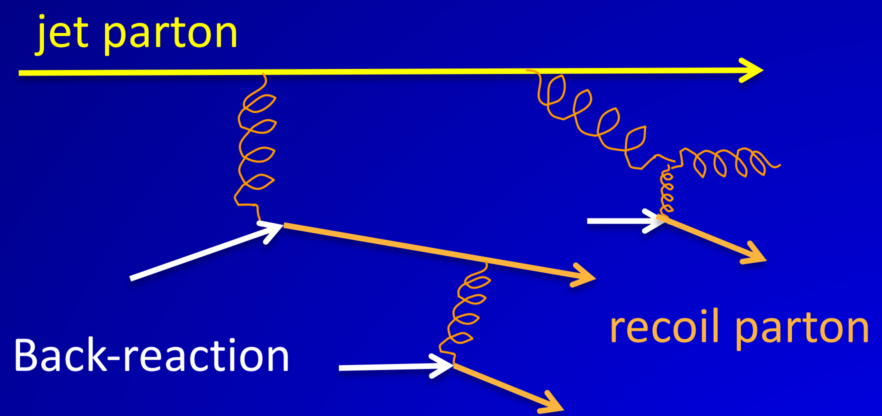
Jet-induced medium response

LBT: Linear Boltzmann Transport

$$p_1 \cdot \partial f_1 = -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) |M_{12\to 34}|^2 (2\pi)^4 \delta^4 (\sum_i p_i) + \text{inelastic}$$

Induced radiation $$\frac{dN_g}{dz d^2 k_\perp dt} \approx \frac{2 C_A \alpha_s}{\pi k_\perp^4} P(z) \hat{q}(\hat{p}\cdot u) \sin^2 \frac{k_\perp^2 (t-t_0)}{4z(1-z)E}$$

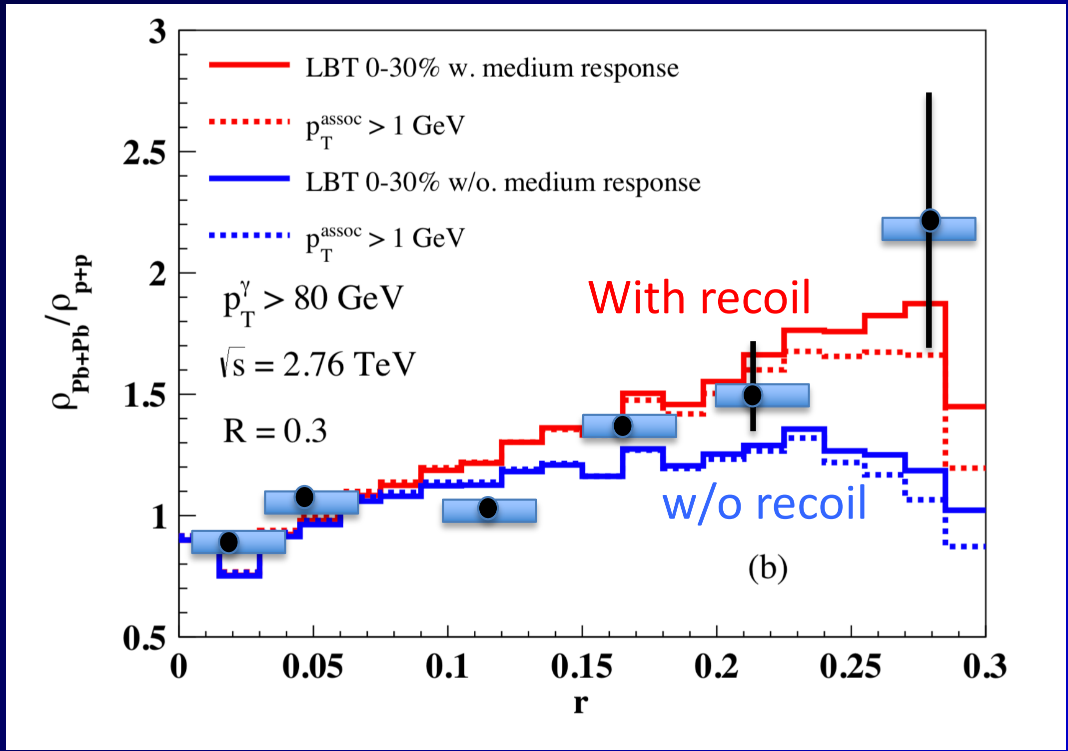
- pQCD elastic and radiative processes (high-twist)
- Transport of medium recoil partons (and back-reaction)
- CLVisc 3+1D hydro bulk evolution



Li, Liu, Ma, XNW and Zhu, PRL 106（2010）012301
XNW and Zhu, PRL 111 (2013) 062301; He, Luo, XNW & Zhu, PRC91 (2015) 054908;

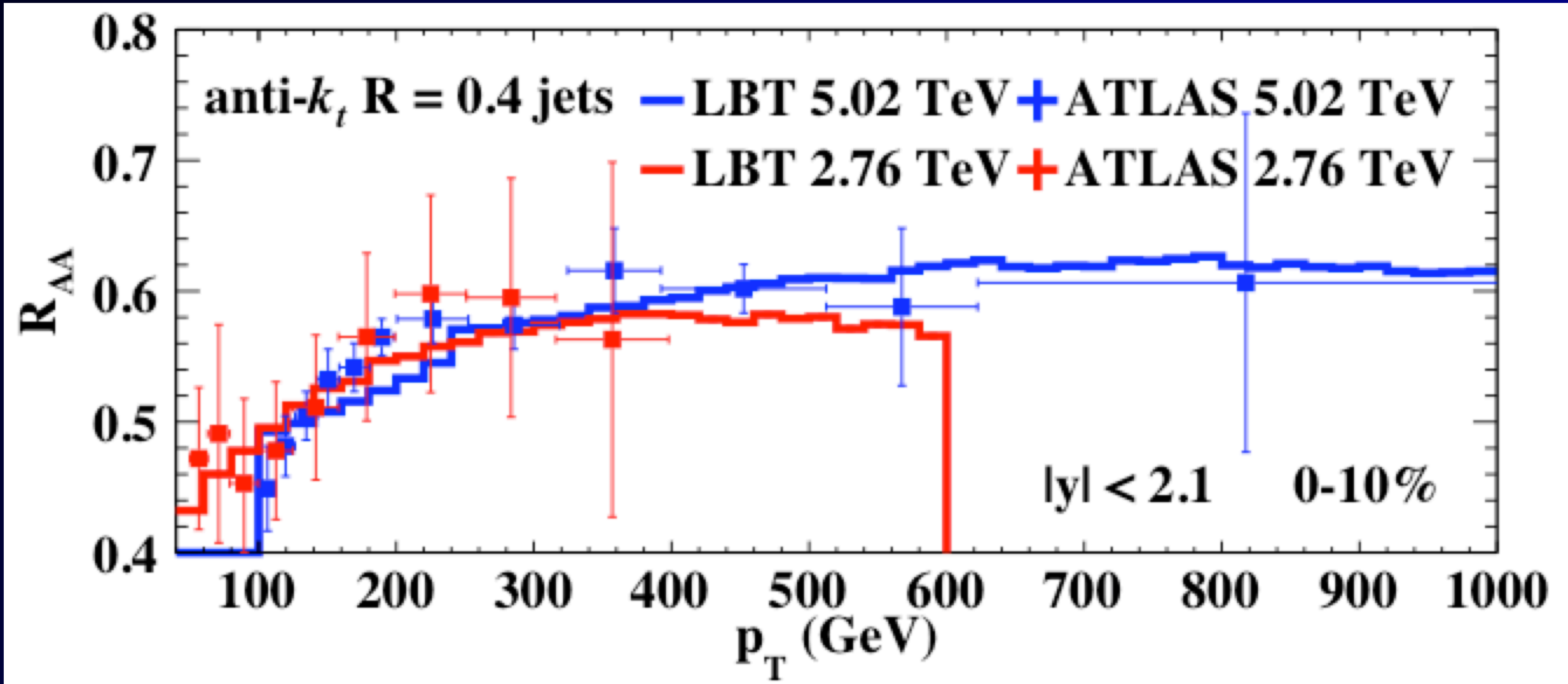
Medium response in gamma-jet profile

Enhancement of jet shape at larger r



Luo, Cao, He & XNW, arXiv:1803.06785

Energy and pT dependence

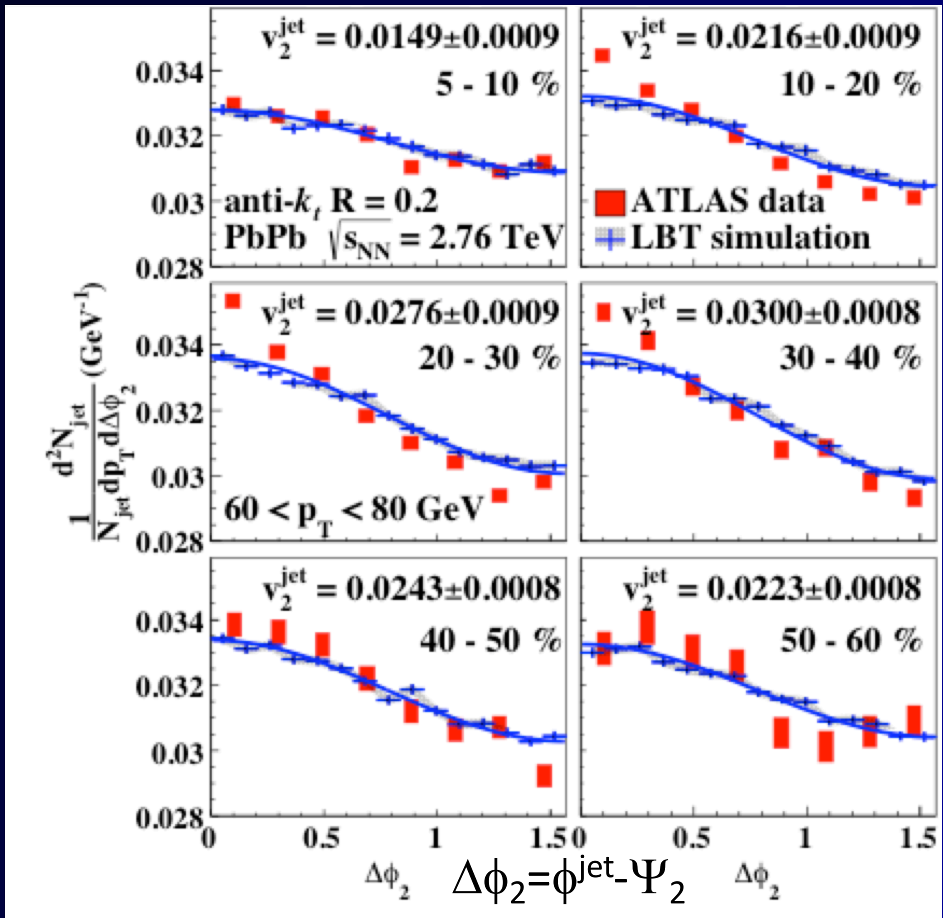


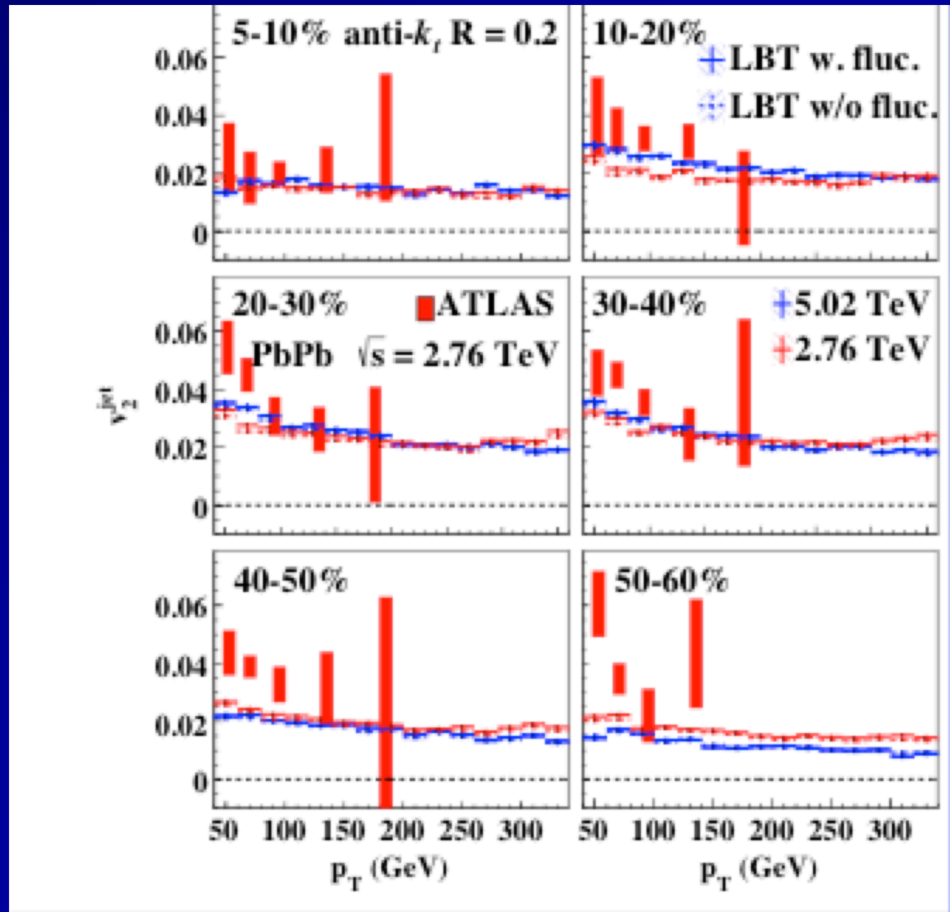
He, Cao, Chen, Luo, Pang & XNW 1809.02525

Weak pT dependence: initial jet spectra and pT dependence of energy loss ΔE
Week energy dependence: increase of jet energy loss and the slope of initial spectra

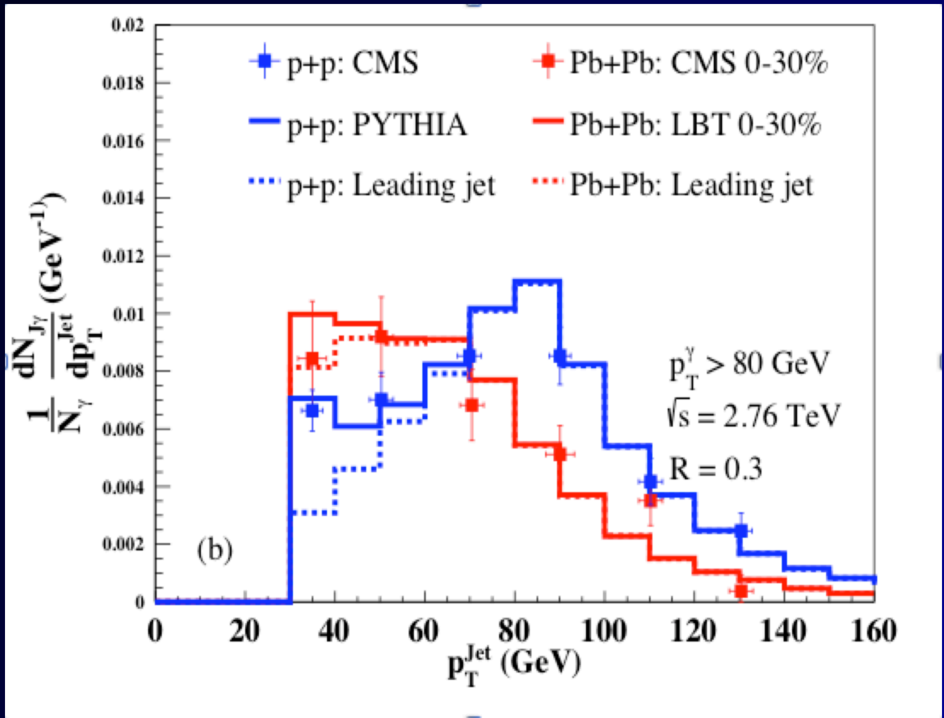
Single jet anisotropy

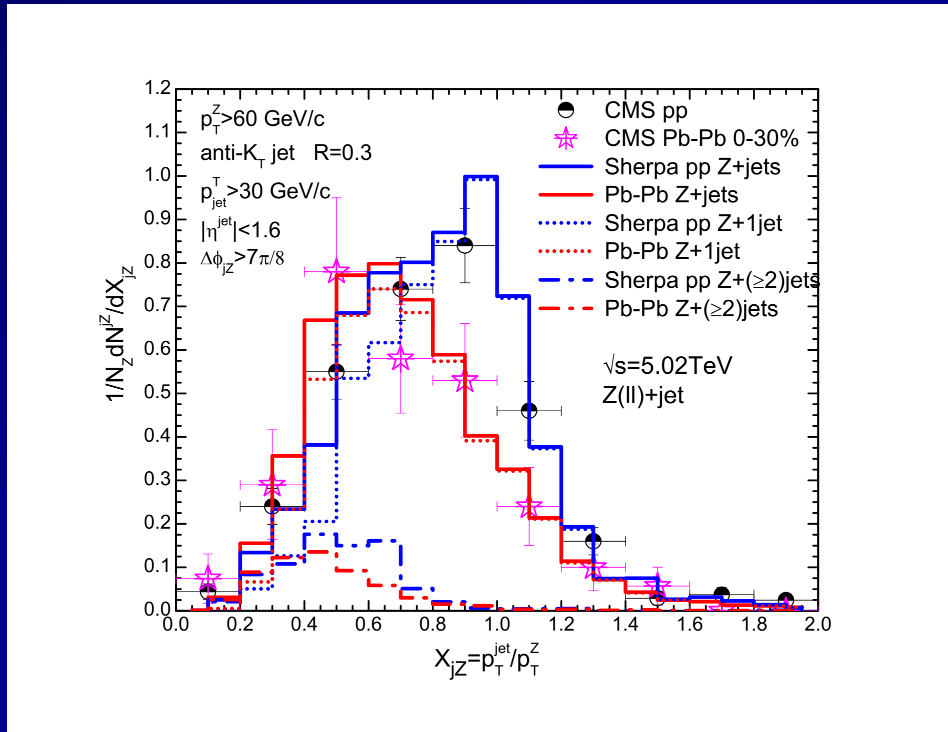
$$v_n^{\text{jet}} = \frac{\langle\langle v_n \cos[n(\phi^{\text{jet}} - \Psi_n)]\rangle\rangle}{\sqrt{\langle v_n^2 \rangle}}$$





Jet energy loss and $\gamma(Z^0)$-jet asymmetry





Luo, Cao, He & XNW, PLB782(18)707

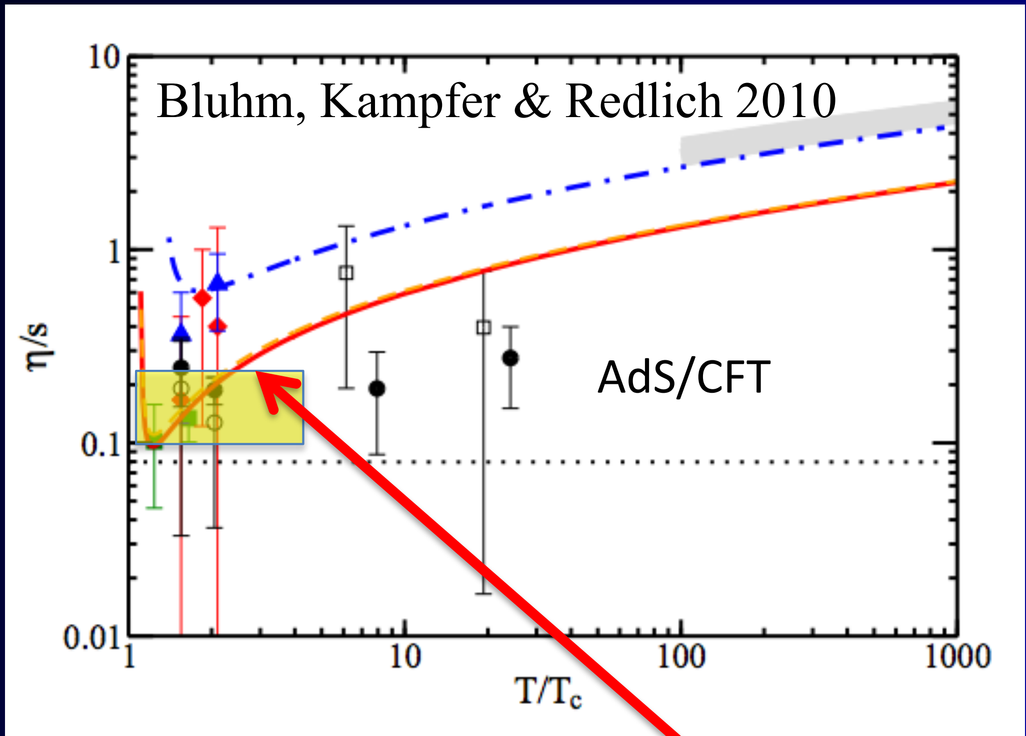
Zhang, Luo, XNW, Zhang, arXiv:1804.11041

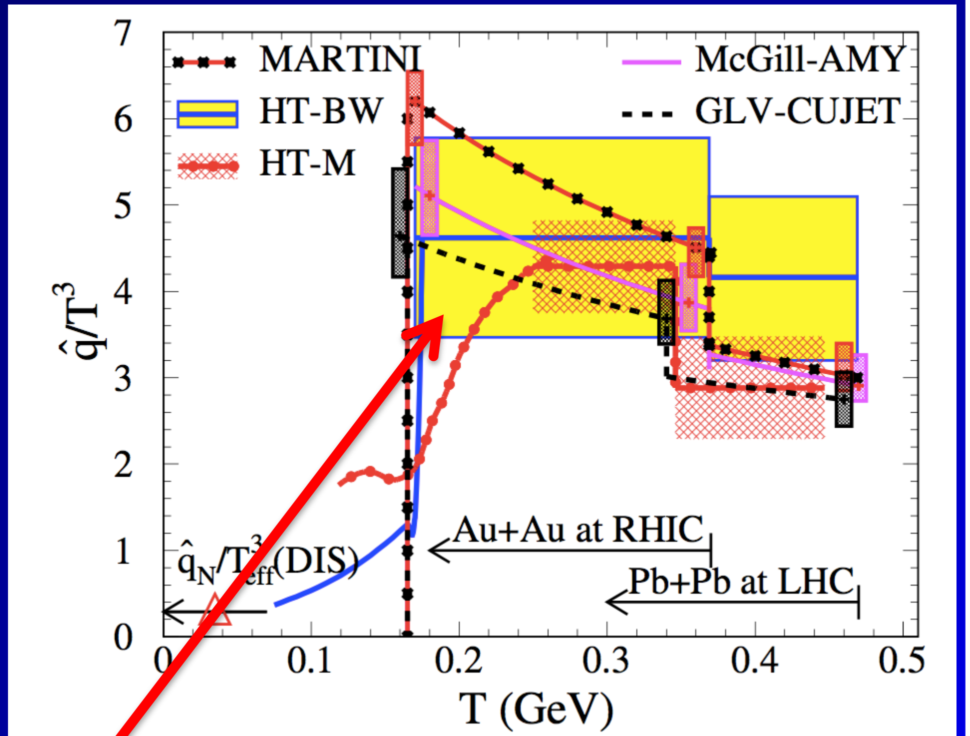
Summary

QGP in heavy-ion collisions: most perfect, vertical and opaque fluid

Hard probes and anisotropic flows provide unprecedented constraints on the transport properties of the QGP in A+A

Future: mapping out T-dependence at RHIC & LHC





$$\frac{\eta}{s} \geq \frac{3T^3}{2\hat{q}}$$

Majumder, Muller & XNW 2007