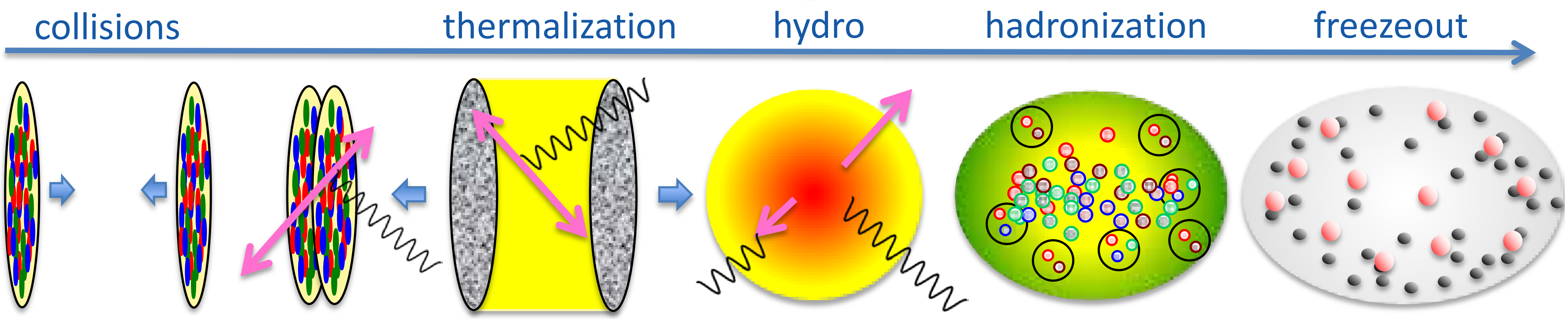
Quark matter 2012
理論の新展開

日高義将
(理研)

野中さんのスライドより(熱場の量子論2012)

Relativistic Heavy Ion Collisions



Pre-Equilibrium & Initial State

Global &Collective Flow

Correlations & Fluctuations

QCD at Finite Temperature and Density

QCD Phase Diagram

Hadron Thermodynamics and Chemistry

Electro-Weak Probes
Jets
Heavy flavor &Quarkonia

QM2011の重要な結論

- 今回ほど初期条件の重要性が決定的に認識された会議は無かった。

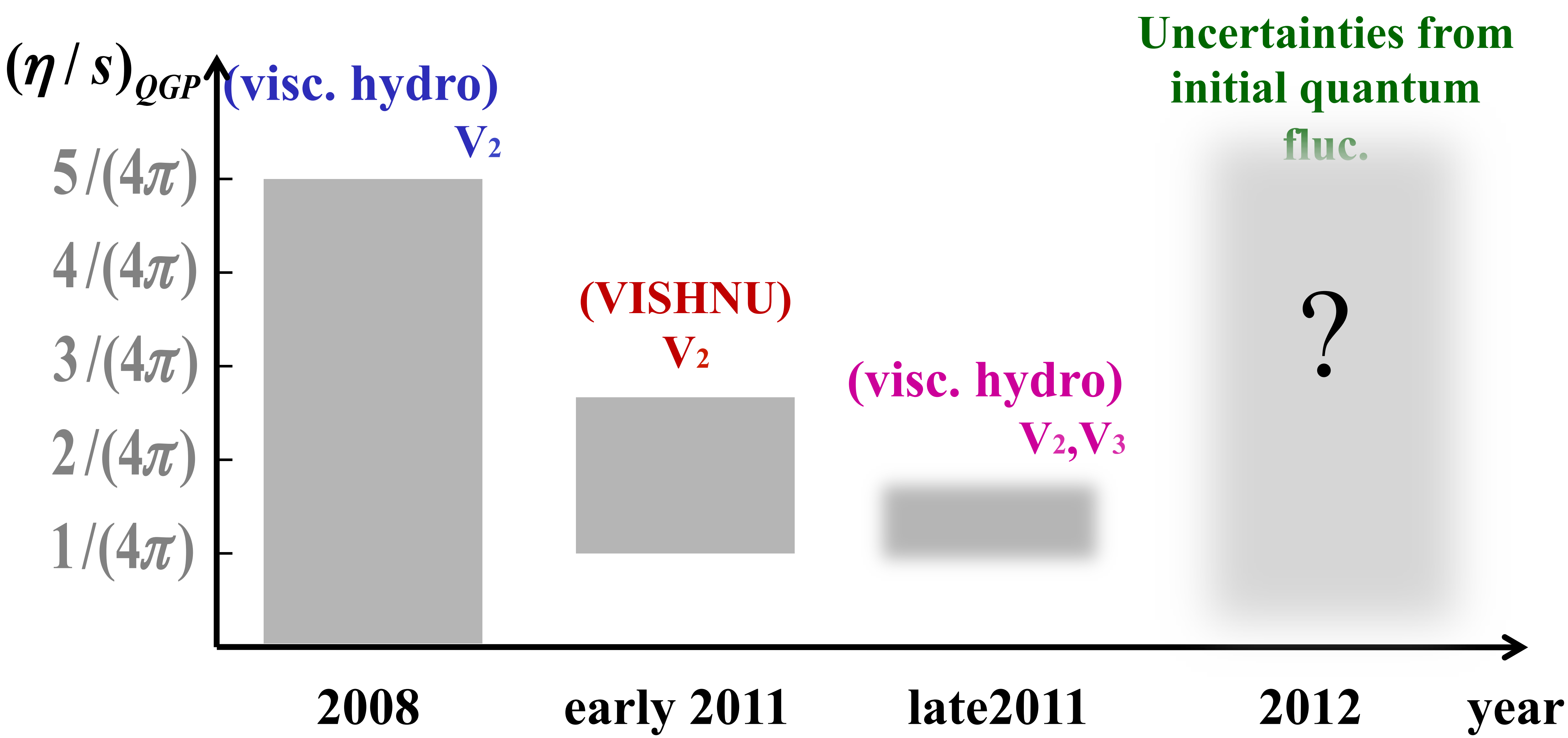
Away-side jetのdouble hump structureやRidge の正体は、<u>**初期条件の揺らぎの物理**</u>であることが、higher harmonicsの解析で明らかになった。v_3 !!

Mach cone は、ジェットと媒質の相互作用による効果であるから、それは「ダイナミカル」な効果として出現するもの。なので、その描像は死んだ。一方、Ridge とは、ジェット周りの粒子の尾根構造をいい、特定の物理機構を示唆していない。なので、ridgeが死んだというのではなく、ridgeの原因が、初期条件の揺らぎだった、ということ

→ 詳しくは江角さんの解説参照

さらに、v3の詳細な解析は初期条件に対するconstraintを与える

Plenary talk by H. Song



$$1\times(1/4\pi) \leq (\eta/s)_{QGP} \leq 2.5\times(1/4\pi)$$

Main uncertainties come from initial conditions

MC-KLN, larger ε_2 ⟶ HIGHER value of QGP viscosity

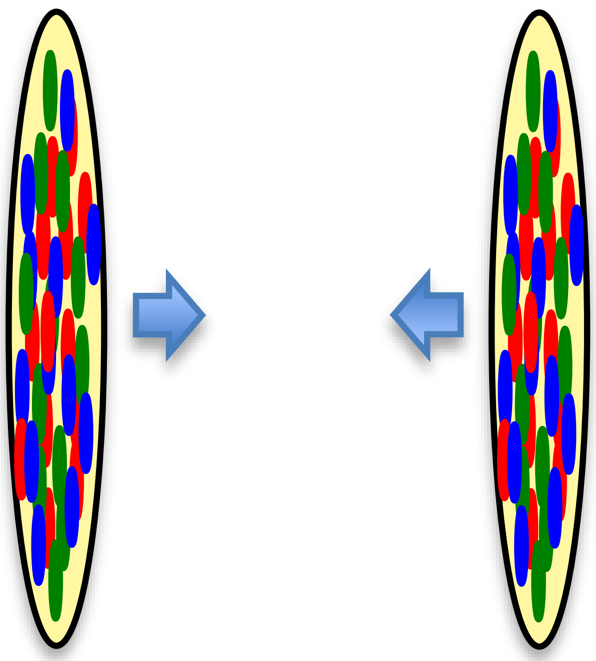
MC-Glauber, smaller ε_2 ⟶ LOWER value of QGP viscosity

衝突初期の量子ゆらぎ

流体のゆらぎ

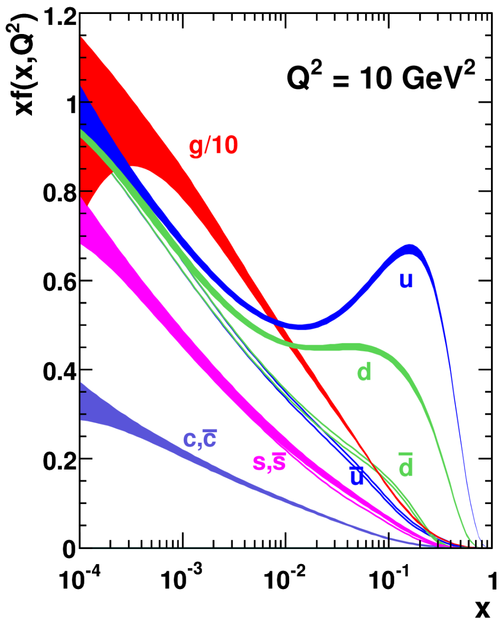
輸送係数などの理論的精密計算に向けて

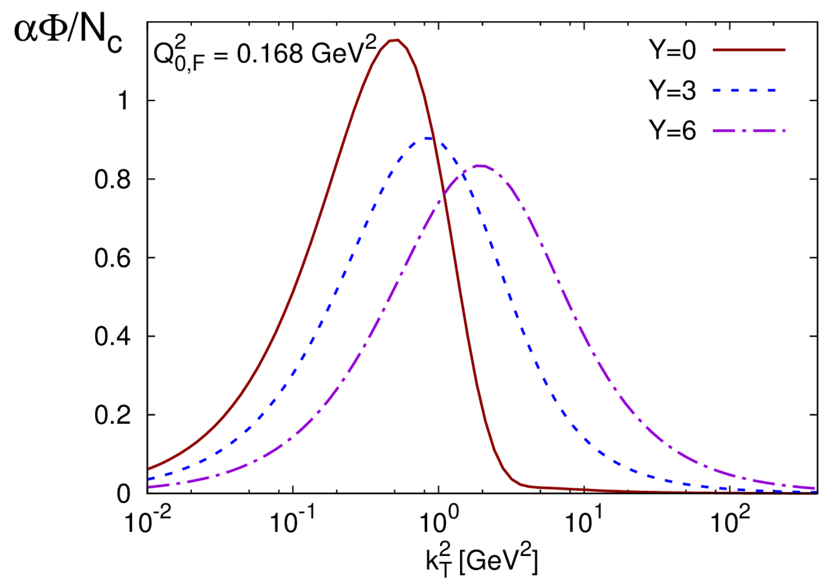
衝突前



The proton pre-collision

Our field has a good understanding of the proton wave-function:

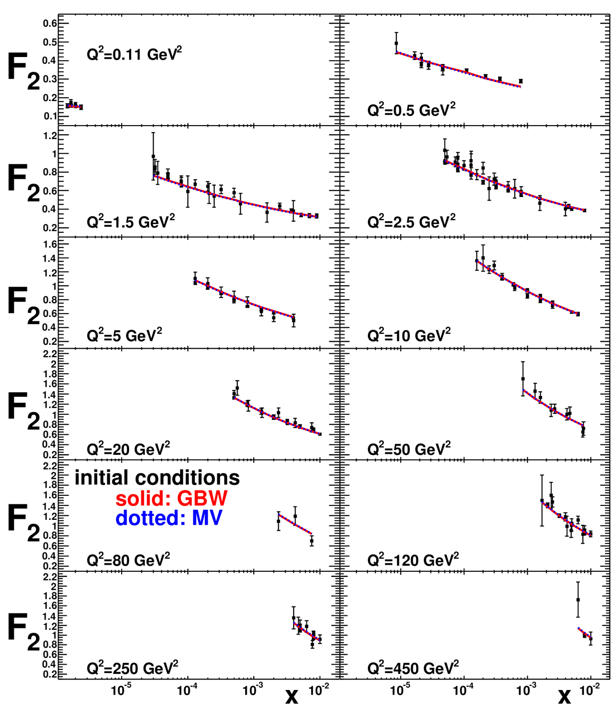


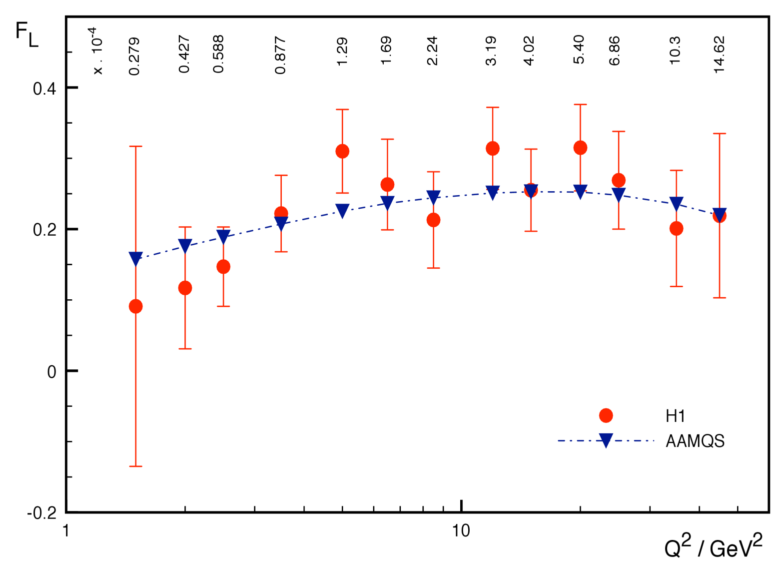


NLO DGLAP fits:
http://mstwpdf.hepforge.org/

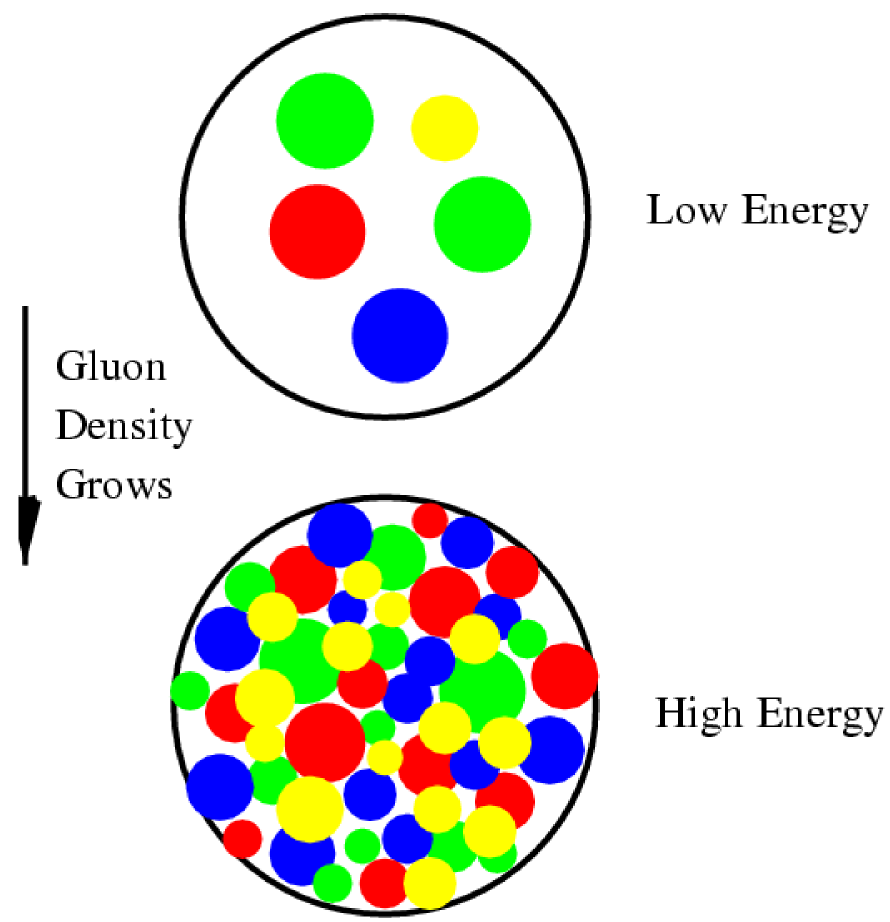
NLO-BK:
Balitsky, Chirilli PRD 77 014019
Kovchegov, Weigert NPA 784 188
Albacete, Kovchegov PRD 75 125021

15 years of HERA data support this picture:





Albacete, Milhano, Quiroga-Arias ,Rojo,
arXiv:1203.1043 (2012).
Quiroga-Arias, Albacete, Armesto, Milhano, Salgado,
J.Phys.G G38 (2011) 124124.
Albacete, Armesto, Milhano, Salgado,
PRD80 (2009) 034031.

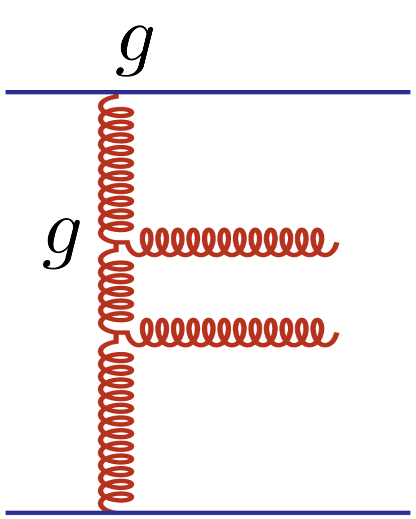


Plenary talk by Dusling

Power counting in QCD: multiparticle production

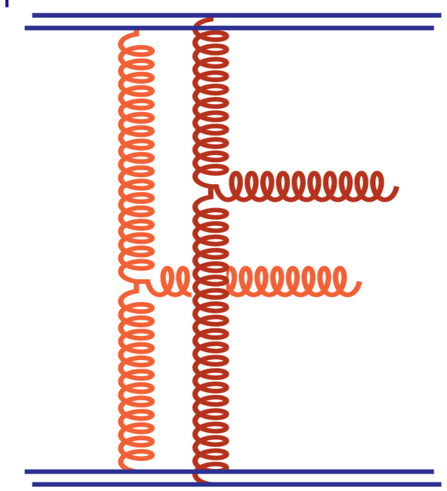
Low color charge density (min bias):

Jet graph:



$\mathcal{O}\left(\alpha_s^4\right)$

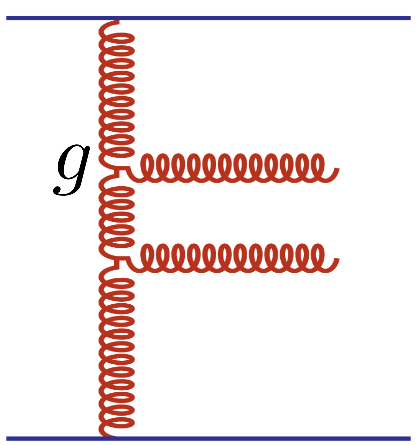
Glasma graph:



$\mathcal{O}\left(\alpha_s^6\right)$

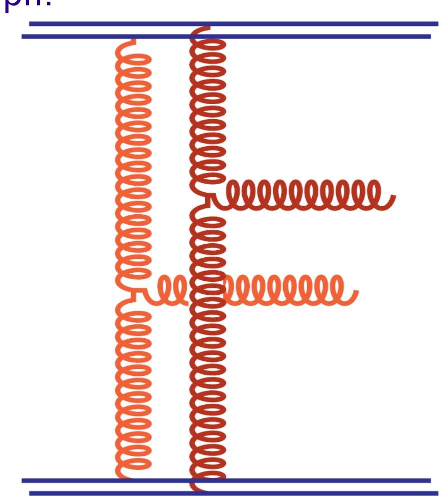
High color charge density (central):

Jet graph: $g \to 1/g$



$\mathcal{O}\left(1\right)$

Glasma graph:



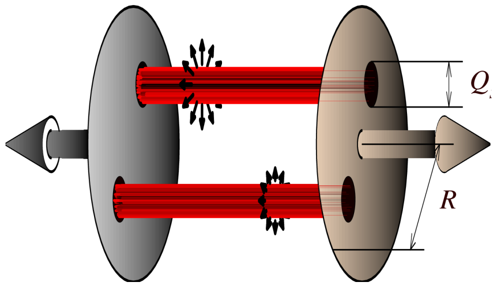
$\mathcal{O}\left(\alpha_s^{-2}\right)$

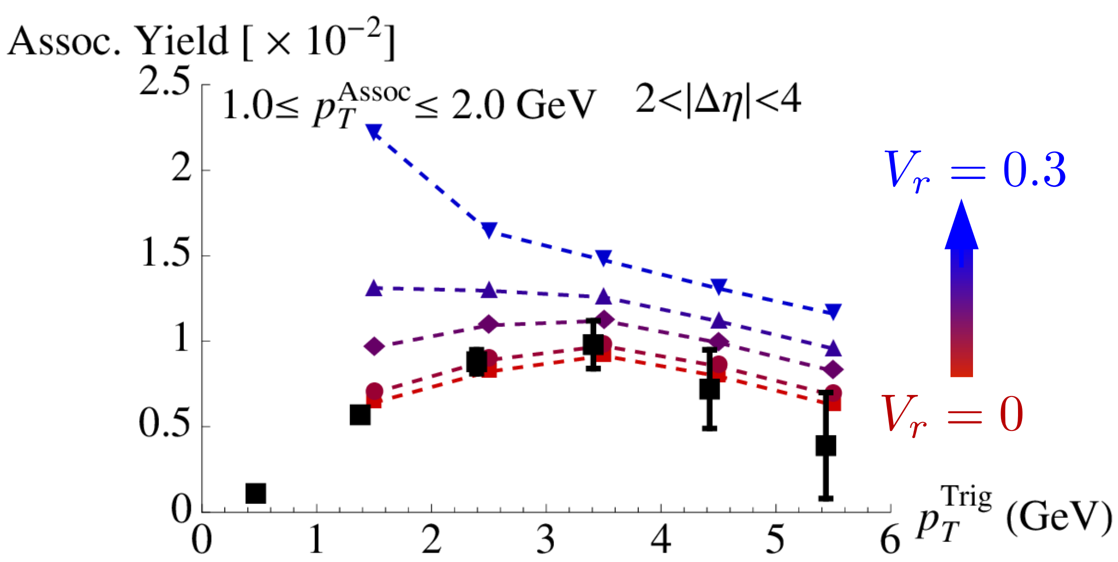
Expect α_s^8 enhancement of "Glasma" graph! Is this seen in the data?

Plenary talk by Dusling

p+p vs A+A

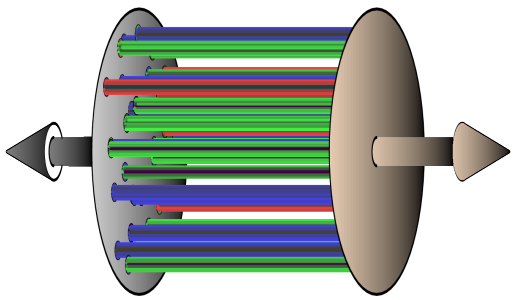
In p+p we are seeing the intrinsic collimation from a single flux tube

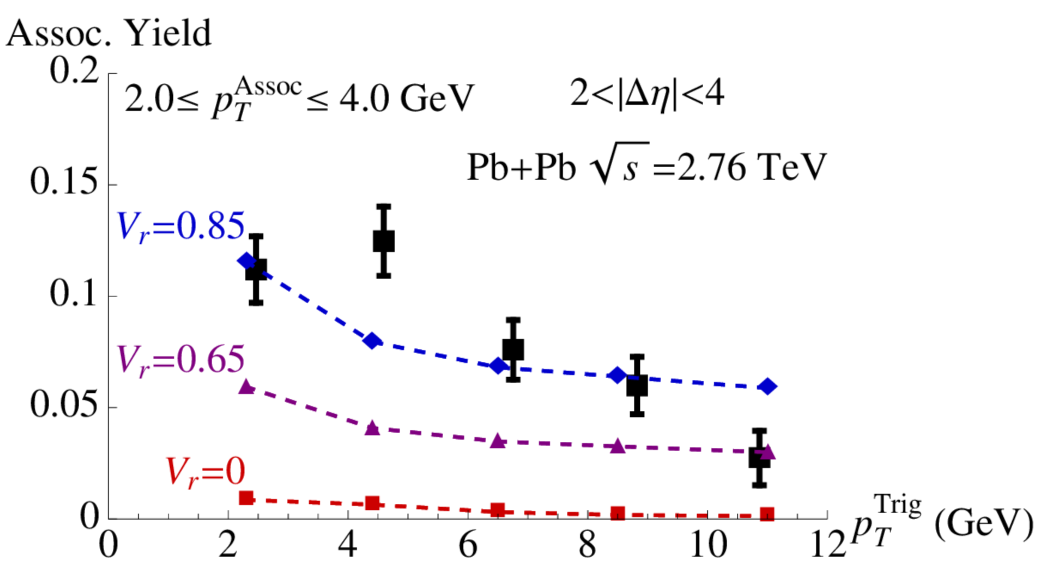




Increasing transverse flow in p+p creates a discrepancy with data.

In A+A there are many such tubes each with an intrinsic correlation enhanced by flow



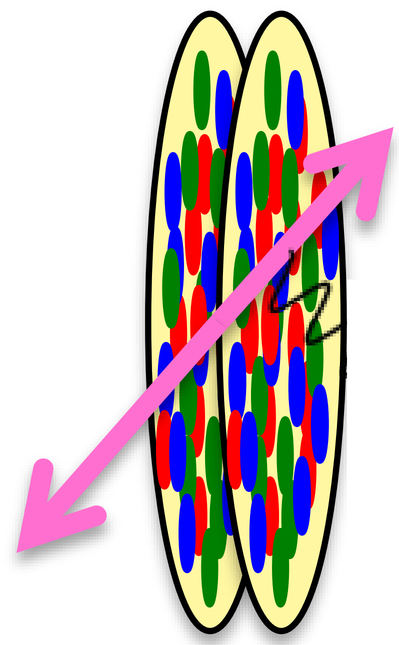


Yet, transverse flow is needed to explain identical measurements in Pb+Pb

Are we sure the A+A ridge is probing the nuclear wavefunction?

Dusling, Venugopalan, PRL 108, 262001 (2012).

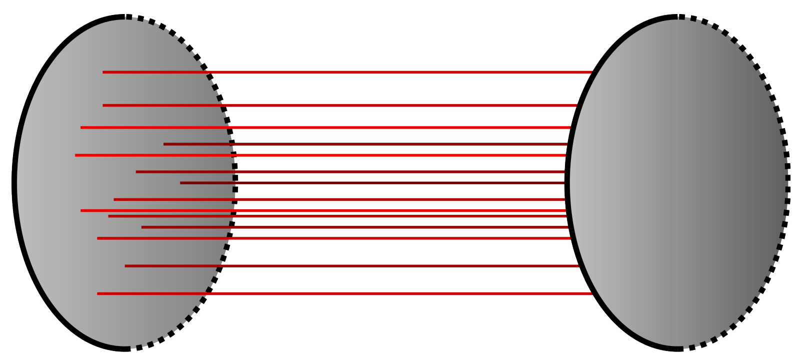
衝突直後



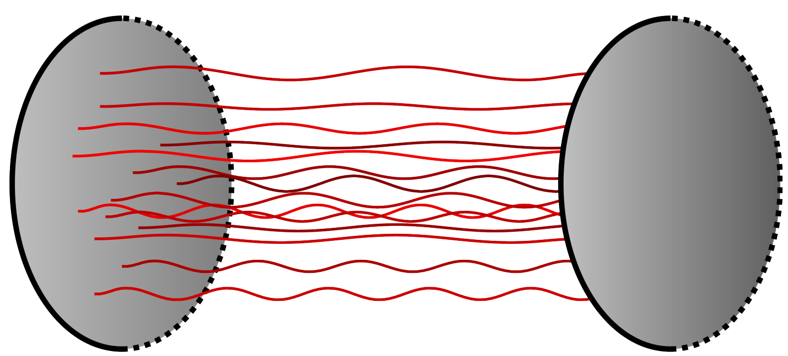
強い場⇒Tree levelがLeading order

古典Yang-Millsのシミュレーション

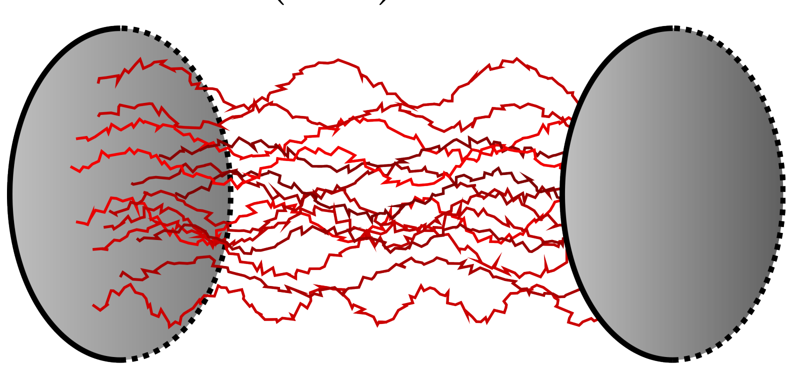
$\tau = 0:$

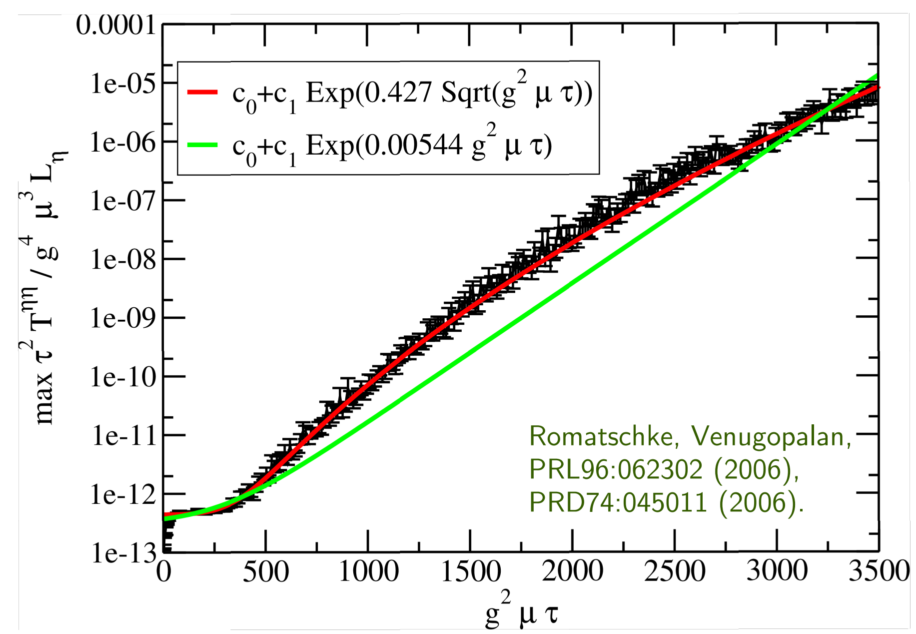


$\tau = 0^+:$



$\tau \gtrsim Q_s^{-1} \ln^2 \left(g^{-1}\right):$





Perturbative expansion breaks down at

$$\tau_{\max} = Q_s^{-1} \ln^2 \left(g^{-1}\right)$$

requiring a resummation of all terms like

$$\left[g \exp\left(\sqrt{Q_s \tau}\right)\right]^n$$

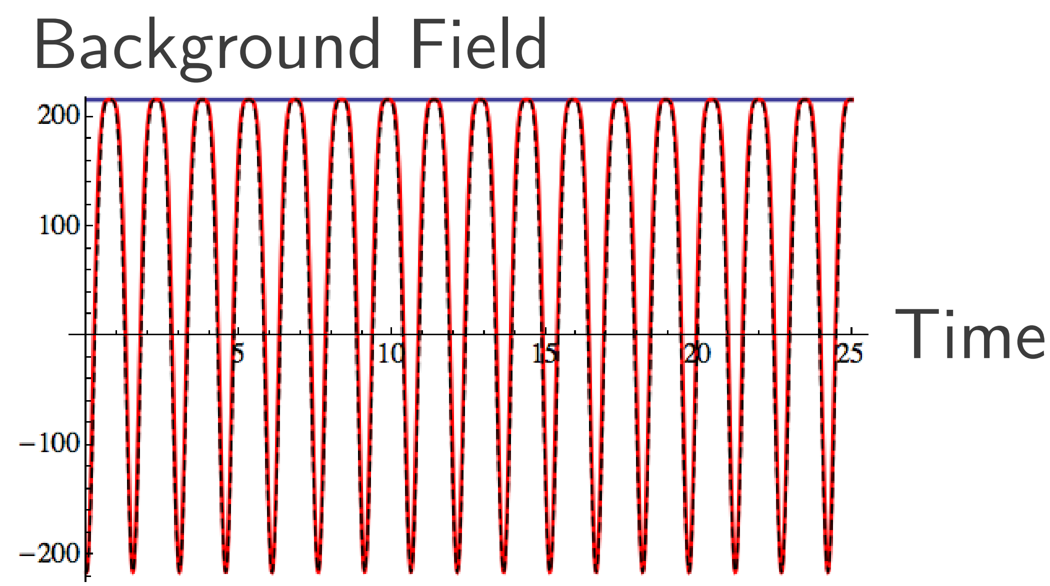
See also:
Berges, Scheffler, Sexty, PRD77:034504 (2008),
PLB677 210-213 (2009), PLB681 362-366 (2009).
Berges, Scheffler, Schlichting, Sexty, PRD85:034507 (2012).
Kunihiro, Muller, Ohnishi, Schafer, Takahashi, Yamamoto,
PRD82:114015 (2010). Fukushima, Gelis, NPA874:108 (2012)

Plenary talk by Dusling

Weak coupling: amplification of quantum fluctuations

Consider a homogeneous scalar field:

$$\partial_t^2 \phi_0 + V'(\phi_0) = 0$$

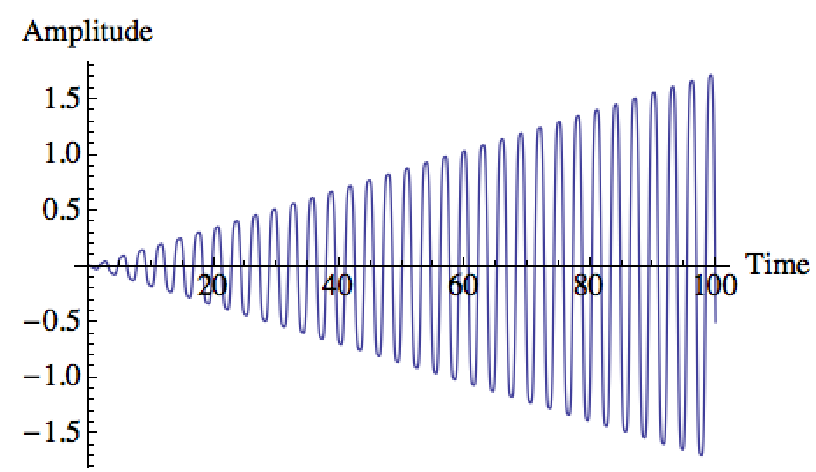


Adding fluctuations to the background field

$$\phi(t, \mathbf{x}) = \phi_0(t) + a_{\mathbf{k}}(t)\cos(\mathbf{k}\cdot\mathbf{x})$$

results in the linearized EoM for small fluctuations: $\ddot{a}_{\pm\mathbf{k}} + \left[\mathbf{k}^2 + V''(\phi_0(t))\right] a_{\pm\mathbf{k}} = 0$

Certain amplitudes grow with time:

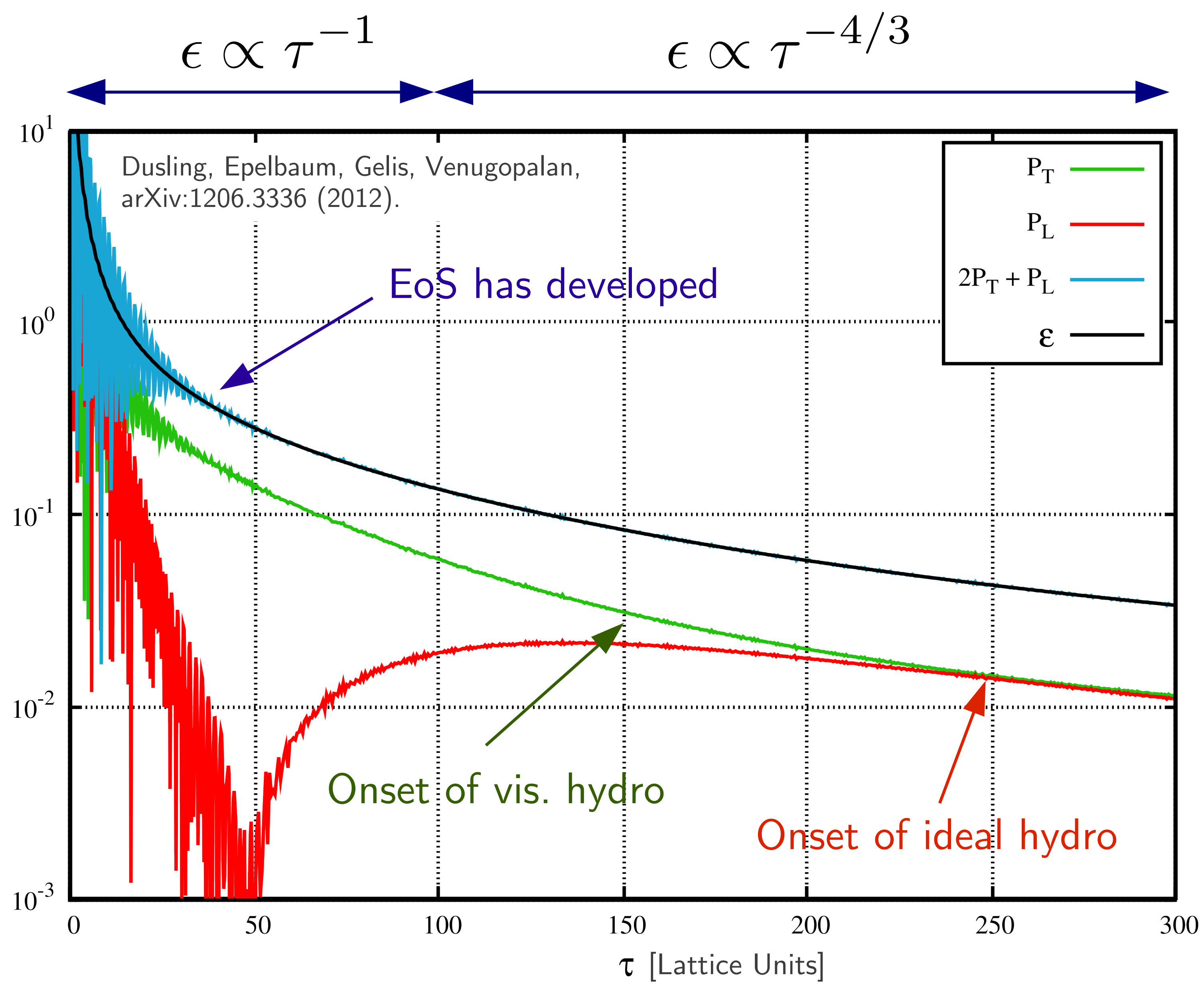


When $\mathbf{gt} \sim \mathbf{1}$ these terms need to be resummed.

Plenary talk by Dusling

膨張系, スカラー理論

Longitudinally expanding non-linear scalar field



Have a proof of principle for scalar fields: what about QCD?

Plenary talk by Dusling

Master formula: The first Fermi

Any inclusive observable:

From solutions of B-JIMWLK

$$\langle T^{\mu\nu}(\mathbf{x},t)\rangle_{\mathrm{LLx+LInst.}} = \int [D\rho_1 D\rho_2]\, W_{x_1}[\rho_1]\, W_{x_2}[\rho_2]$$
$$\times \int [\mathcal{D}\alpha]\, F_0[\alpha]\;\; T^{\mu\nu}_{\mathrm{LO}}[A[\rho_1,\rho_2]+\alpha](\mathbf{x},t)$$

Gauge invariant spectrum of fluctuations:

$$F_0[\alpha] \propto \exp\left[-\frac{1}{2}\int_\Sigma d^3\boldsymbol{u}\, d^3\boldsymbol{v}\;\alpha(\boldsymbol{u})\,\Gamma_2^{-1}(\boldsymbol{u},\boldsymbol{v})\,\alpha(\boldsymbol{v})\right]$$

From solution of 3+1D classical Yang-Mills Eqs.

Dusling, Gelis, Venugopalan,
Nucl. Phys. A872 161-195 (2011).

Talk by Raju Venugopalan, Wed. 12pm

Berges, Schlichting, 1209.0817

流体におけるゆらぎ

ゆらぎの入った流体

$$T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + \Delta T^{\mu\nu} + S^{\mu\nu}, \quad J^{\mu} = nu^{\mu} + \Delta J^{\mu} + I^{\mu}$$

Stochastic sources $S^{\mu\nu} = S^{\mu\nu}$ and I^{μ}

$$\left\langle S^{\mu\nu}(x) S^{\alpha\beta}(y) \right\rangle = 2T\left[\eta\left(h^{\mu\alpha}h^{\nu\beta} + h^{\mu\beta}h^{\nu\alpha}\right) + \left(\zeta - \tfrac{2}{3}\eta\right)h^{\mu\nu}h^{\alpha\beta}\right]\delta^{4}(x-y)$$

$$\left\langle S^{\mu\nu}(x) I^{\alpha}(y) \right\rangle = 0$$

$$\left\langle I^{\mu}(x) I^{\nu}(y) \right\rangle = 2\lambda\left(\frac{nT}{w}\right)^{2} h^{\mu\nu}\delta^{4}(x-y)$$

Talk by Stephanov

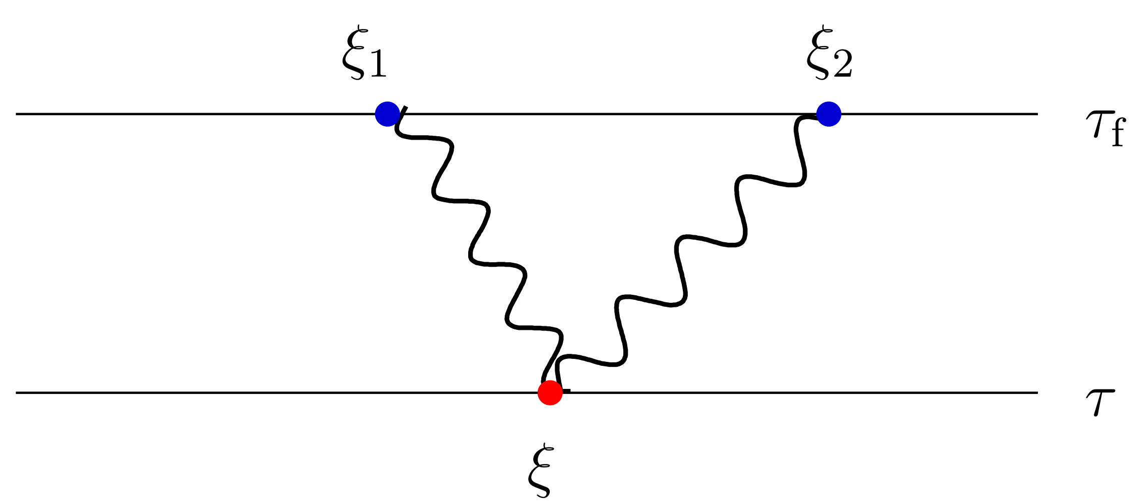
Correlations

The equal-(proper)time correlation function at freeze-out time $\tau_{\rm f}$:

$$\langle\, \rho(\xi_1, \tau_{\rm f})\, \rho(\xi_2, \tau_{\rm f})\,\rangle = \frac{2}{A}\int_{\tau_0}^{\tau_{\rm f}} \frac{d\tau}{\tau^3}\,\frac{\nu}{\epsilon + P}\underbrace{\int_{-\infty}^{\infty} d\xi\, G_\rho(\xi_1 - \xi; \tau_{\rm f}, \tau) G_\rho(\xi_2 - \xi; \tau_{\rm f}, \tau)}_{G_{\rho\rho}(\Delta\xi;\tau_{\rm f},\tau)}\,.$$

Convenient variable $\rho \equiv \delta s/s$. Convenient notation: $\nu \equiv \dfrac{4\eta/3 + \zeta}{s}$.

Every point ξ, τ is a source of noise, $\rho = G_\rho \circ f$: $[S^{\mu\nu} = \Delta^{\mu\nu}(\epsilon + P) f]$



Talk by Stephanov

- Disentangling correlation sources:

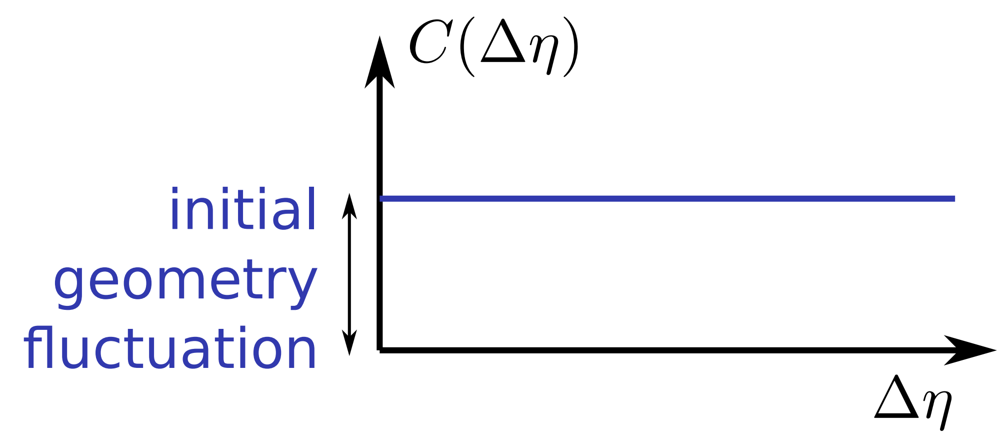
Fluctuations of initial conditions produce $\Delta\eta$-independent correlation.

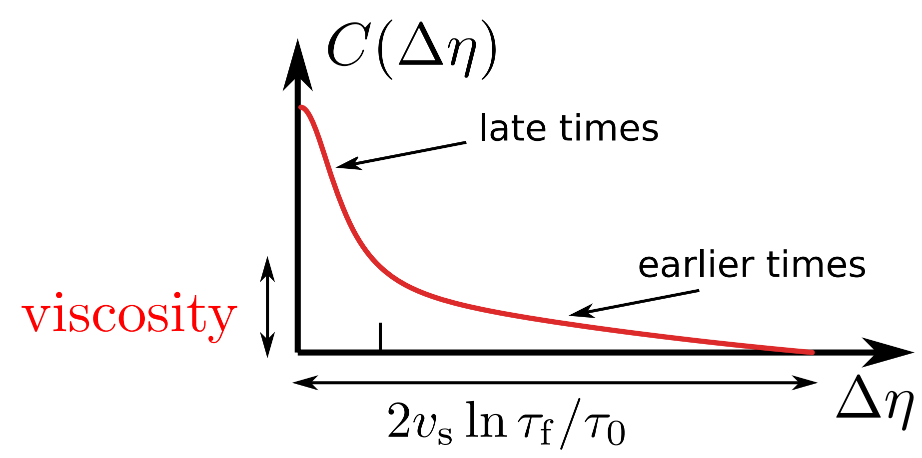
Hydrodynamic noise has local origin and produces characteristic $\Delta\eta$ dependence:

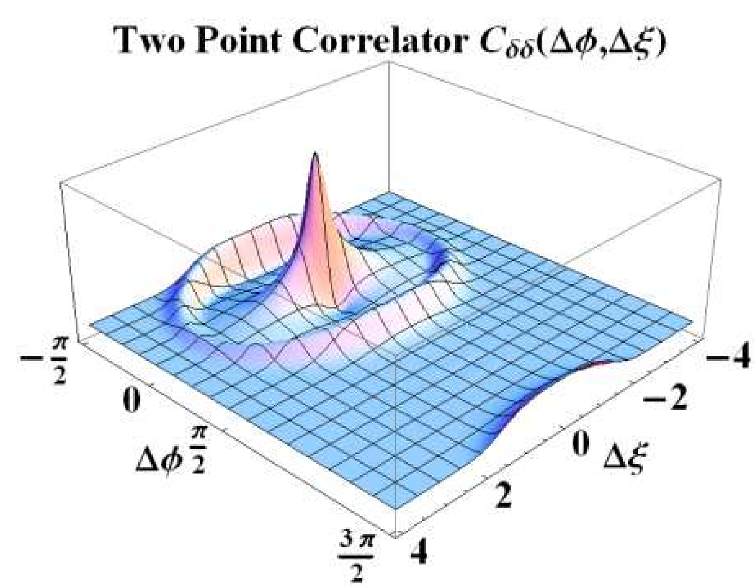
with magnitude proportional to viscosity.

- More can be learned from 2D $\Delta\phi, \Delta\eta$ correlations.

Analytical work is in progress (Todd Springer, Saturday).





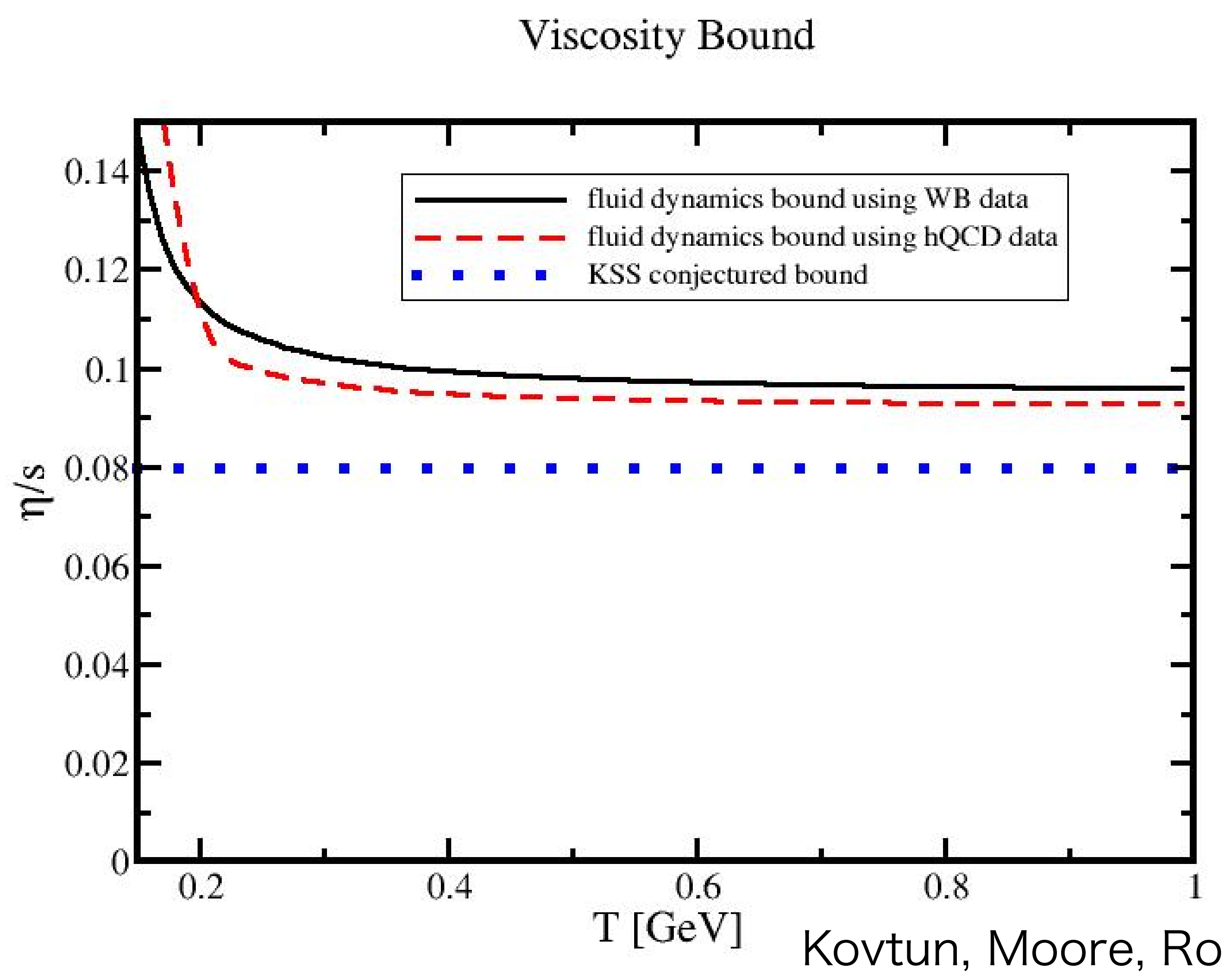


Talk by R. Romatschke

流体モードの自己相互作用による
ずれ粘性の熱ゆらぎ補正

A viscosity bound from fluid dynamics

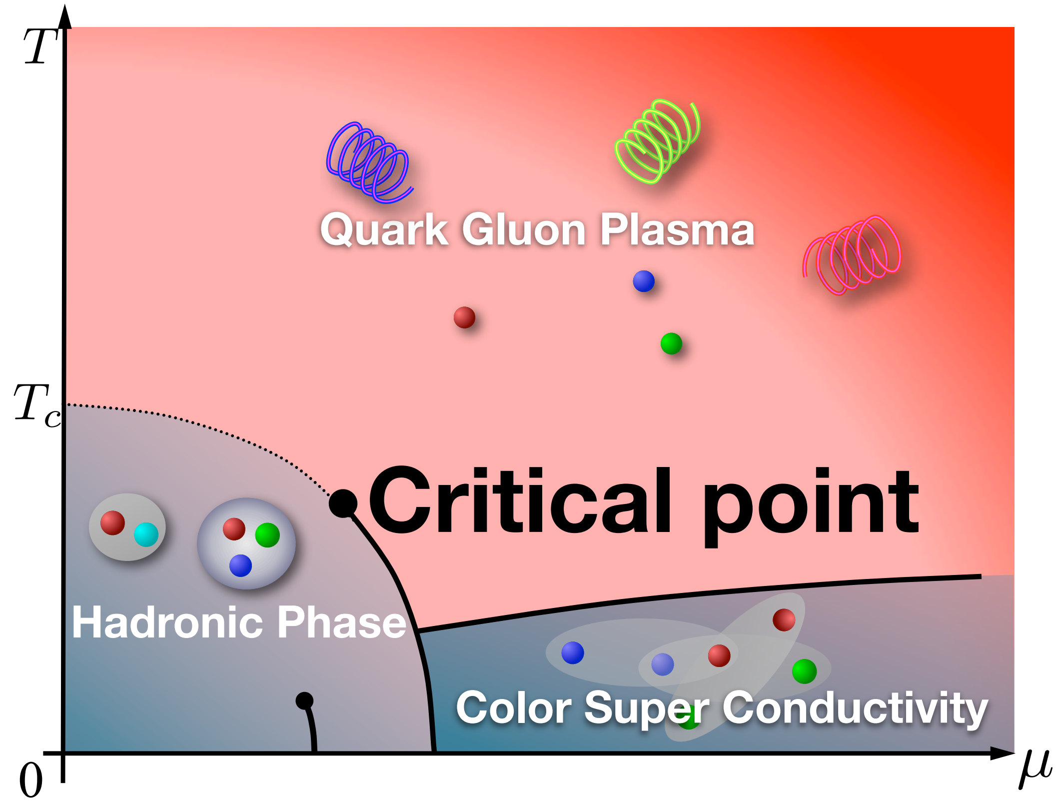
For QCD one finds for η/s in units of $\hbar = k_B = 1$



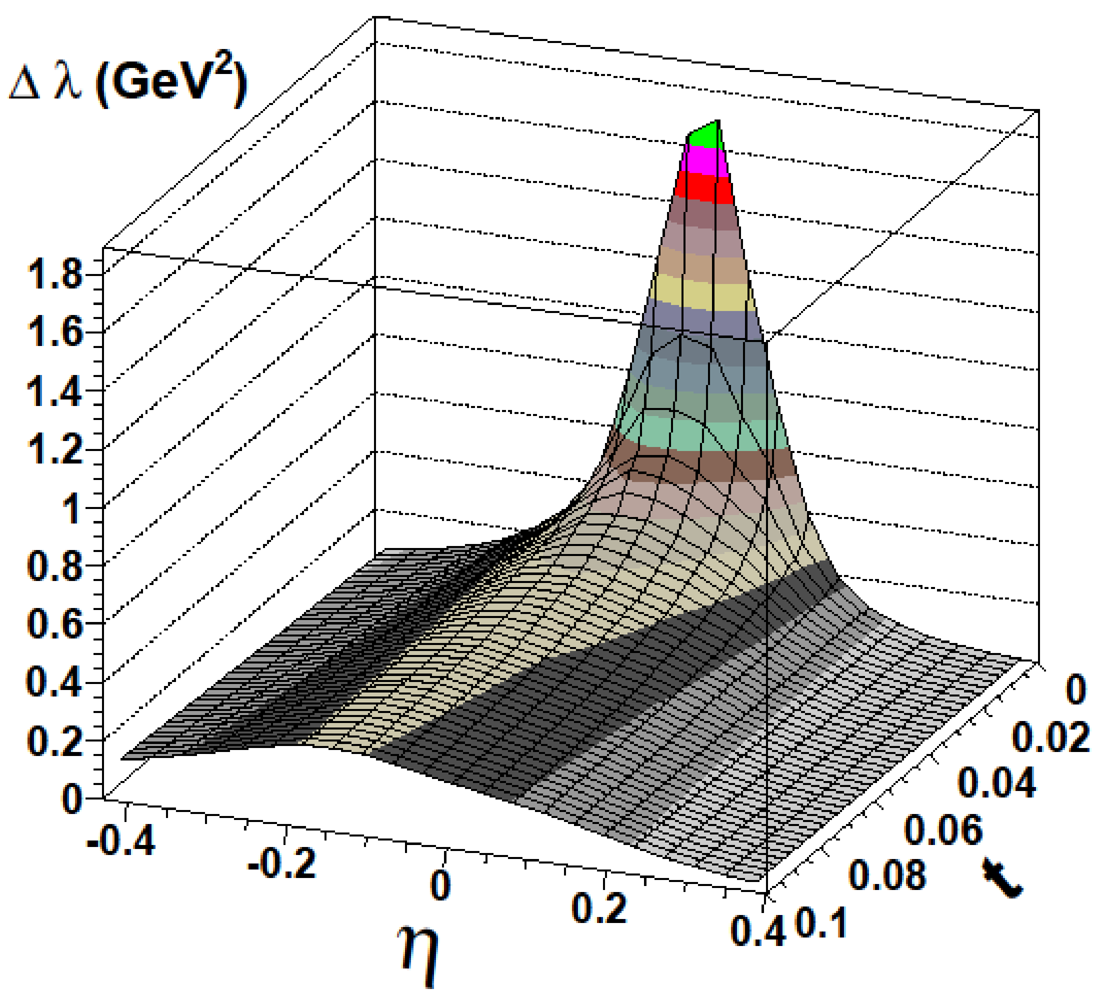
Kovtun, Moore, Romatschke, 1104.1586

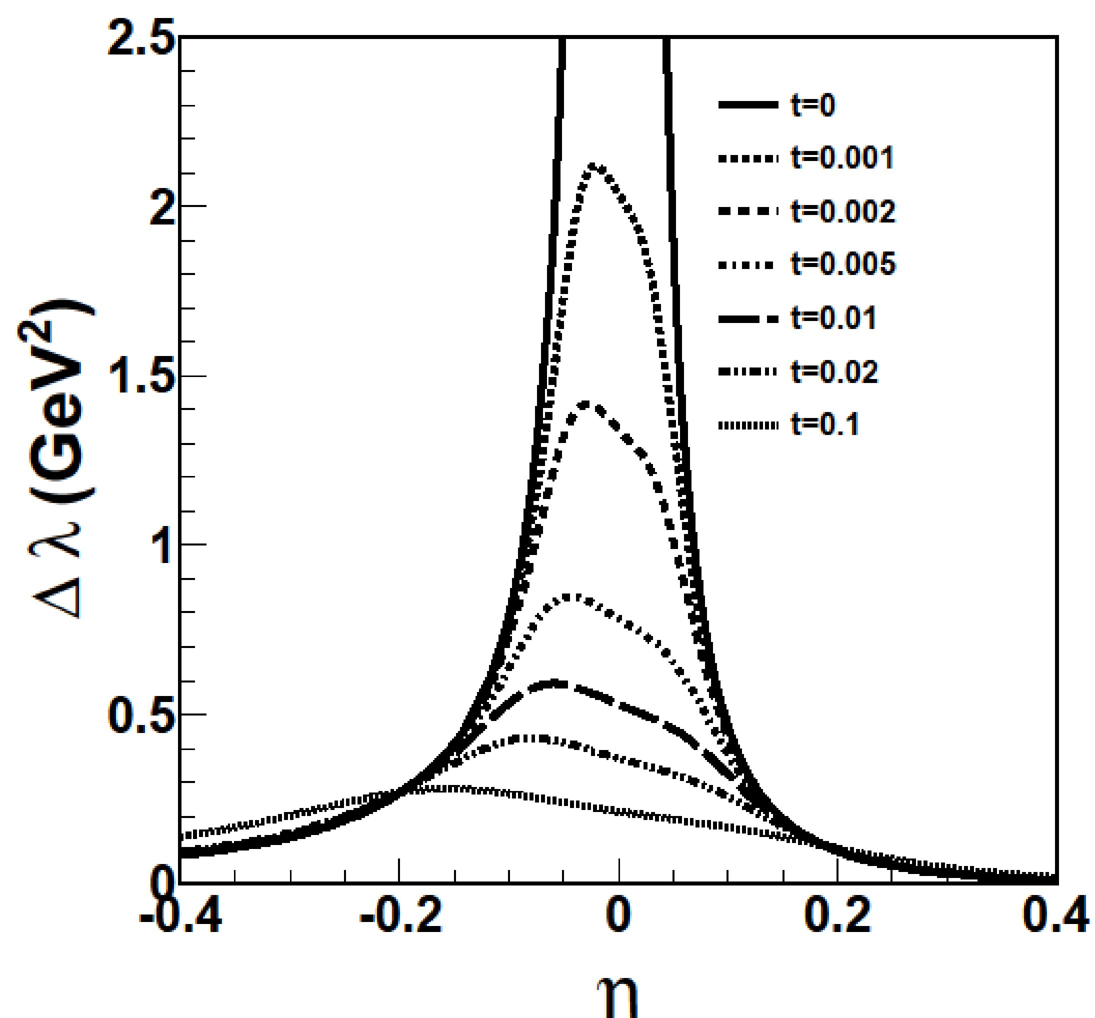
cf. for Fermi gas, Chafin, Schafer, 1209.1006

Talk by Kapusta

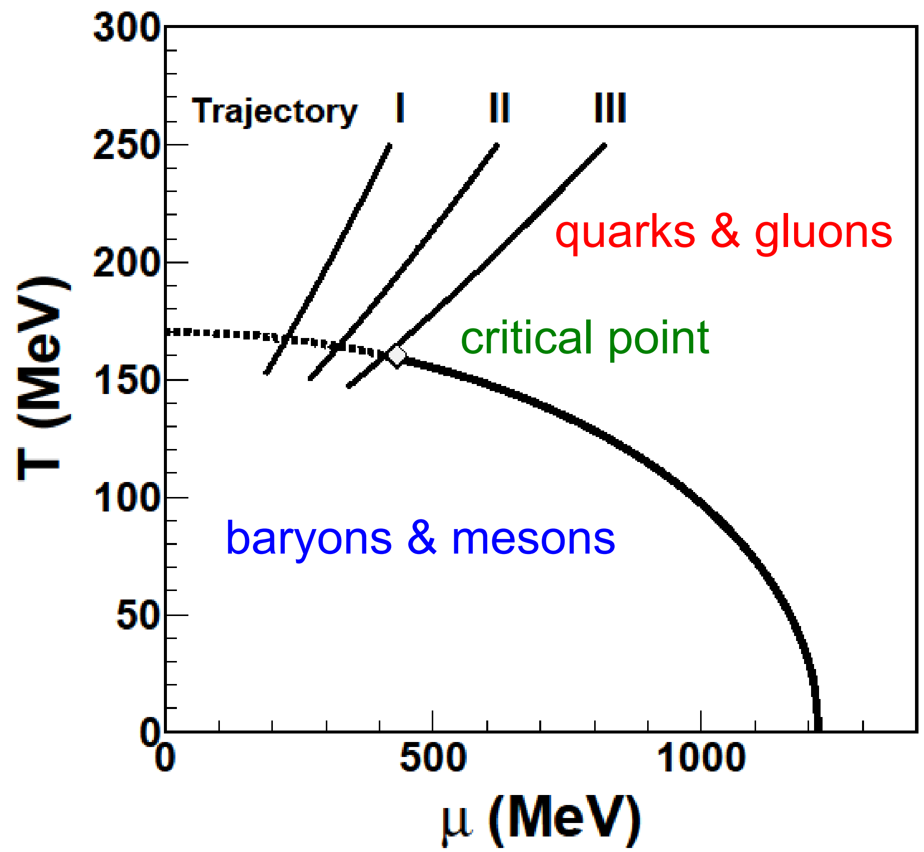


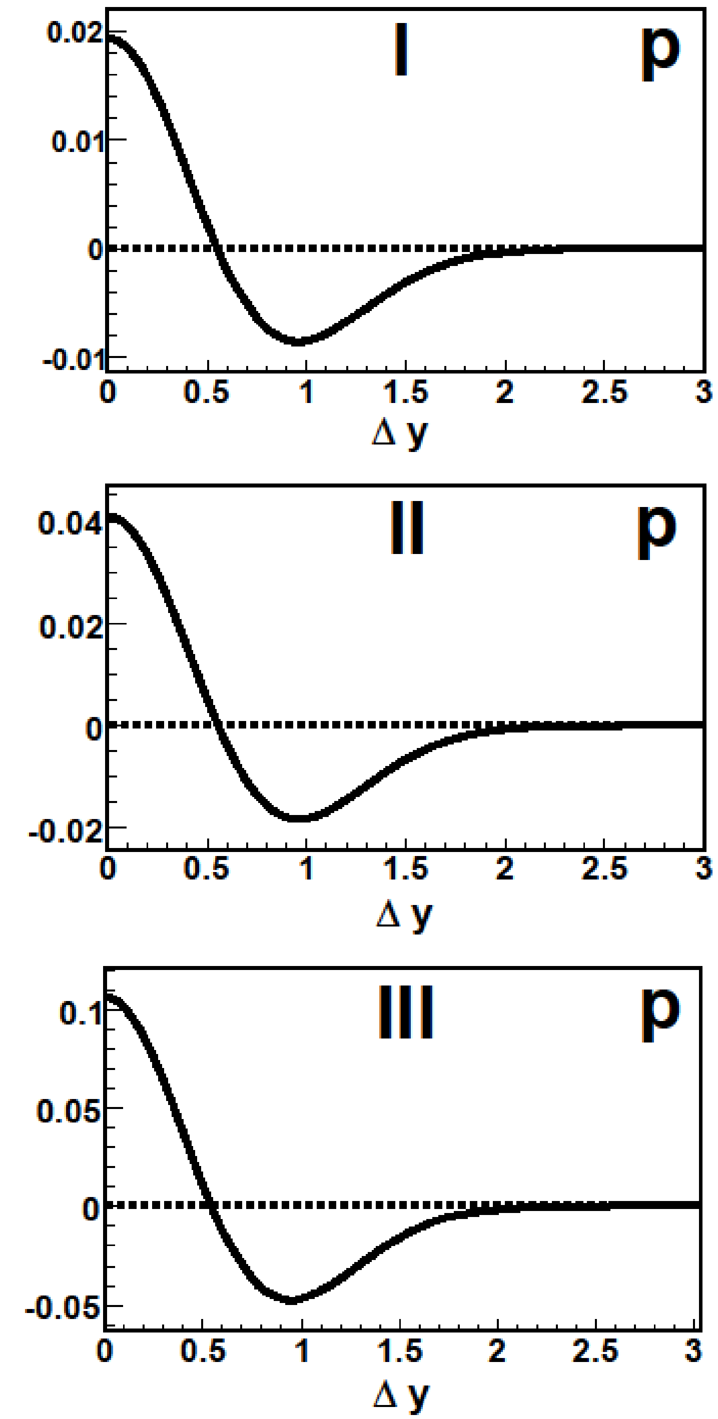
QCD臨界点で
熱伝導率は発散





Talk by Kapusta





Magnitude of proton correlation function depends strongly on how closely the trajectory passes by the critical point

$$\left\langle \frac{dN(y_2)}{dy_2}\frac{dN(y_1)}{dy_1} - \left\langle \frac{dN}{dy} \right\rangle^2 \right\rangle \left\langle \frac{dN}{dy} \right\rangle^{-1}$$

Poster by Murase

1次の流体のゆらぎ:White noise
高次の流体のゆらぎ: Colored noise

■ **Fluctuation Dissipation Relation**

$$\langle \delta\pi^{\mu\nu}(x)\delta\pi_{\alpha\beta}(x')\rangle = TG_\pi(x-x')\cdot g^{\langle\mu}{}_{\langle\alpha}g^{\nu\rangle}{}_{\beta\rangle},$$
$$\langle \delta\Pi(x)\delta\Pi(x')\rangle = TG_\Pi(x-x'),$$
$$\langle \delta\nu_i^\mu(x)\delta\nu_j^\alpha(x')\rangle = TG_{ij}(x-x')\cdot(-\Delta^{\mu\alpha}).$$

$G(x)$: Extended for $x^0<0$ as even functions

Non-zero correlation in different time → ***Colored Noise***

輸送係数などの精密理論計算へ

Thermal Photon Production at NLO

Talk by Derek Teaney

$$2k(2\pi)^3\frac{d\Gamma}{d^3k} = \text{Photon emission rate per phase-space}$$

The photon emission rate at weak coupling:

- The rate is function of the coupling coupling constant and k/T:

$$2k(2\pi)^3\frac{d\Gamma}{d^3k} \propto e^2T^2\Big[\underbrace{O(g^2\log) + O(g^2)}_{\text{LO AMY}} + \underbrace{O(g^3\log) + O(g^3)}_{\text{From soft } gT \text{ gluons, } n_B \simeq \frac{T}{\omega} \simeq \frac{1}{g}} + \ldots$$

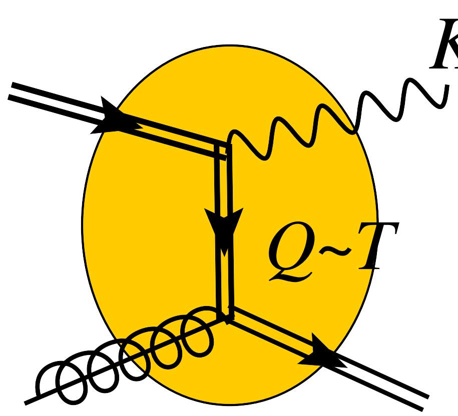
$O(g^3)$ is closely related to open issues in energy loss:

- At NLO must include drag, collisions, bremsstrhalung, and kinematic limits

Talk by Derek Teaney

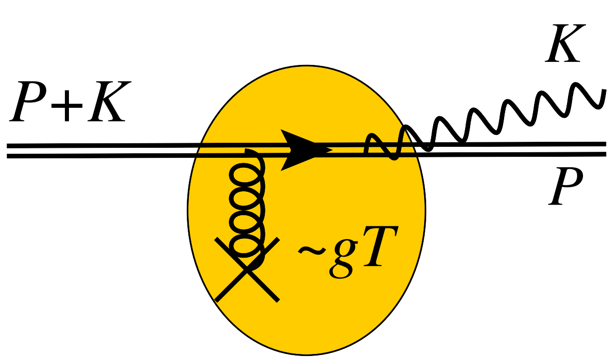
Three rates for photon production at Leading Order — Baier, Kapusta, AMY

1. Hard Collisions – a $2 \leftrightarrow 2$ processes



$$\sim e^2 \underbrace{m_\infty^2}_{g^2 C_F T^2/4} \times \underbrace{n_F(k)}_{\text{fermi dist.}} \times \left[\log(T/\mu) + C_{2to2}(k)\right]$$

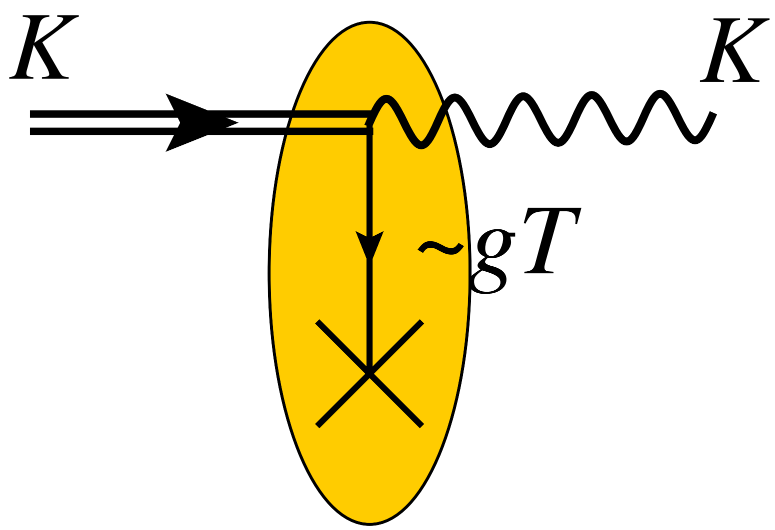
2. Collinear Bremmstrahlung – a $1 \leftrightarrow 2$ processes



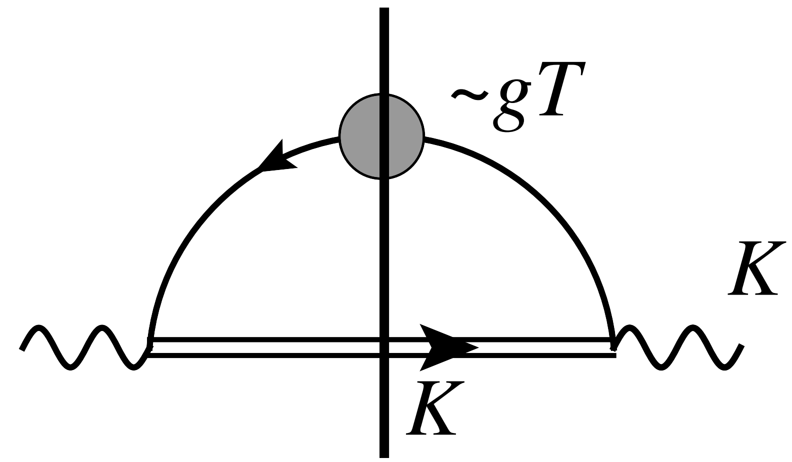
$$\sim e^2 m_\infty^2 n_F \left[\underbrace{C_{\rm bremm}(k)}_{\text{LPM + AMY and all that stuff!}} \right]$$

Talk by Derek Teaney

3. Quark Conversions – $1 \leftrightarrow 1$ processes (analogous to drag)



or



$$= \sim e^2 m_\infty^2 n_F \left[\log(\mu_\perp / m_\infty) + C_{\rm cnvrt}\right]$$

Full LO Rate is independent of scale $\mu_\perp$:

$$2k \frac{\mathrm{d}\Gamma}{\mathrm{d}^3 k} \propto e^2 m_\infty^2 n_F \Big[\log\left(T/m_\infty\right) + \underbrace{C_{\rm cnvrt} + C_{\rm bremm}(k) + C_{\rm cnvrt}}_{\equiv\, C_{LO}(k)} \Big]$$

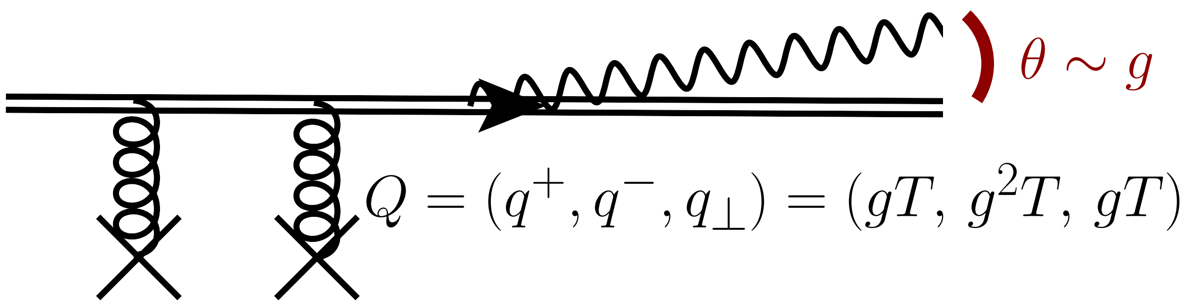
Talk by Derek Teaney

$O(g)$ Corrections to Hard Collisions, Bremm, Conversions:

1. No corrections to Hard Collisions:

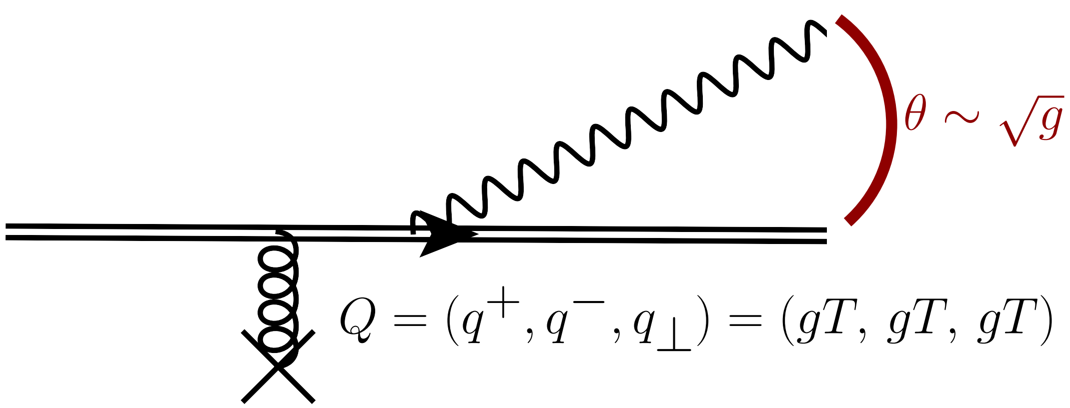
2. Corrections to Bremm:

   (a) Small angle bremm. Corrections to AMY coll. kernel. (Caron-Huot)



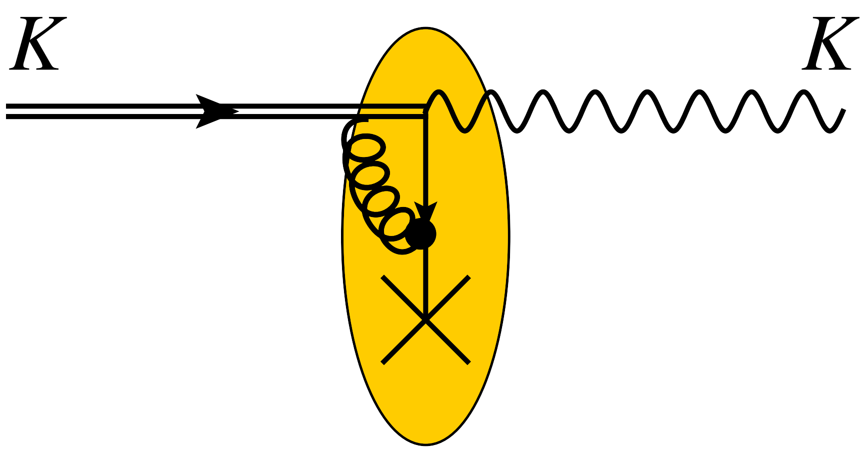
$$C_{LO}[q_\perp] = \frac{Tg^2 m_D^2}{q_\perp^2(q_\perp^2 + m_D^2)} \rightarrow \text{A complicated but analytic formula}$$

   (b) Larger angle bremm. Include collisions with energy exchange, $q^- \sim gT$.

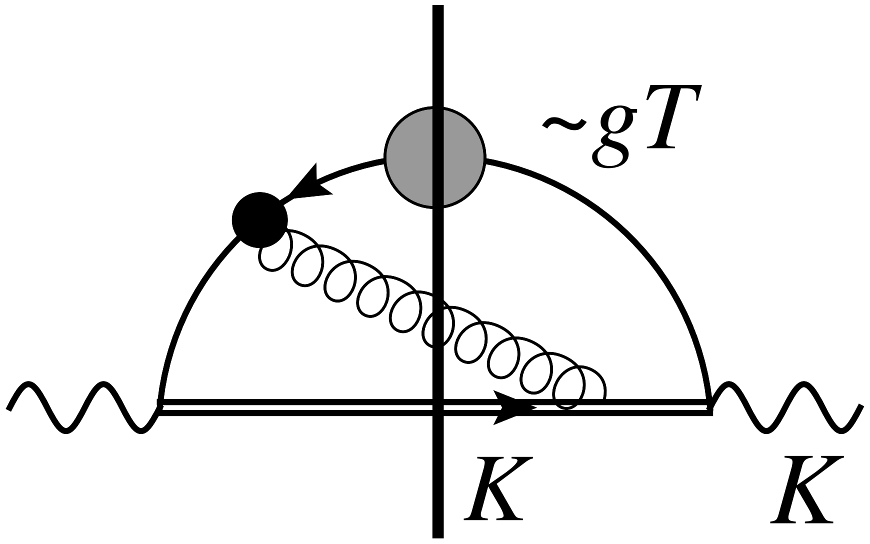


Talk by Derek Teaney

3. Corrections to Conversions:



or



Simon Caron-Huot

- Doable because of HTL sum rules (light cone causality)
- Gives a numerically small and momentum indep. contribution to the NLO rate

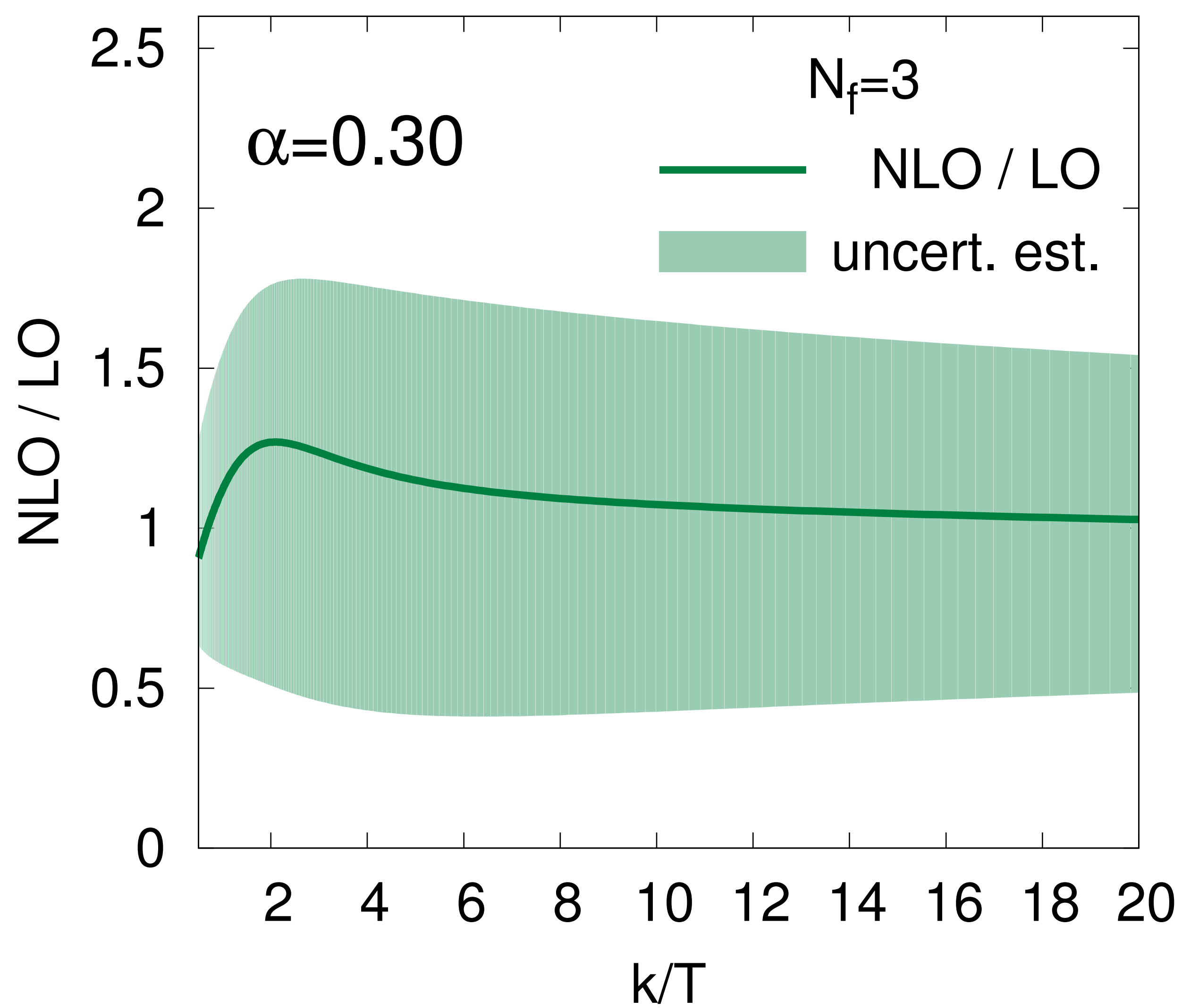
Full results depend on all these corrections.

These rates smoothly match onto each other as the kinematics change.

Talk by Derek Teaney

NLO Results: $\sim g^3 \log(1/g) + g^3$

$$2k\frac{d\delta\Gamma_{LO}}{d^3k} \propto e^2 m_\infty^2 n_F(k)\Bigg[\overbrace{\frac{\delta m_\infty^2}{m_\infty^2}\log\left(\frac{\sqrt{2Tm_D}}{m_\infty}\right)}^{\text{conversions}} + \overbrace{\frac{\delta m_\infty^2}{m_\infty^2}C_{\text{large}-\theta}(k)}^{\text{large-}\theta\text{-bremm}} + \overbrace{\frac{g^2 C_A T}{m_D}C_{\text{small}-\theta}(k)}^{\text{small-}\theta\text{-bremm}}\Bigg]$$



Many things can be computed next (e.g. shear viscosity and e-loss)

まとめ

初期の量子ゆらぎの計算可能に.

⇒流体の初期状態へ

ゆらぎの入った流体の粒子相関

Arnold, Moore, and Yaffeの結果を超えたNLOの

摂動計算が可能になってきた.

他にも色々な発展

Lattice QCD, Heavy quark, Jet, energy loss, ...