Quantum decoherence from classical coherence @ RHIC

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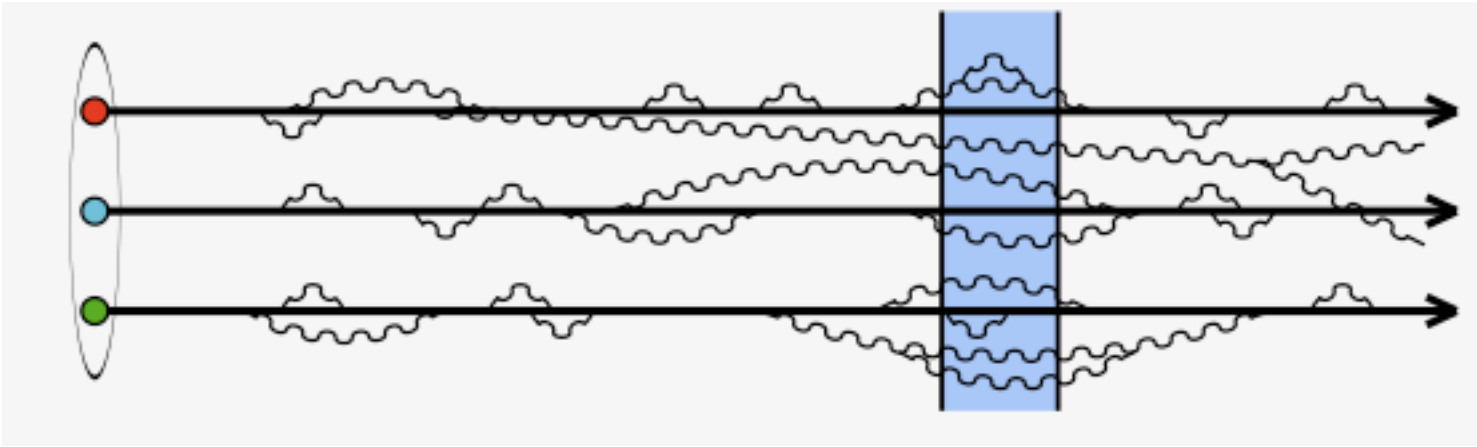
Talk Outline

- **Classical coherence in nuclear wavefunction (CGC)**
  – frozen multi-parton correlations

- **Quantum decoherence – high energy factorization**
  & key role of quantum fluctuations

- **Early time interplay of classical & quantum effects generates**
  i) long range rapidity correlations -> the ridge
  ii) explosive sphaleron transitions -> LSPV
  iii) early isotropization -> perfect fluidity

Classical coherence

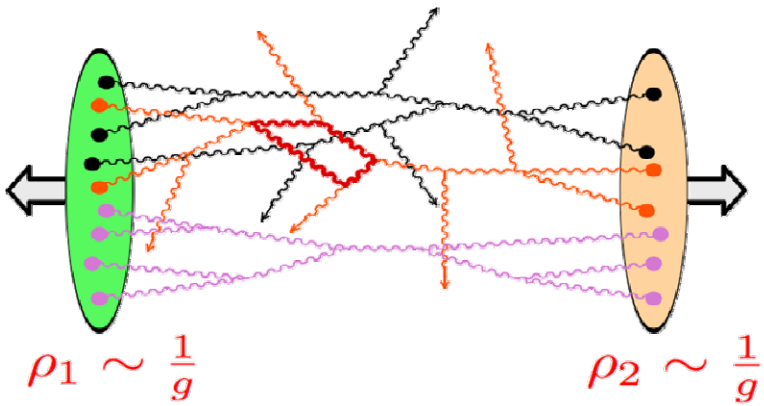


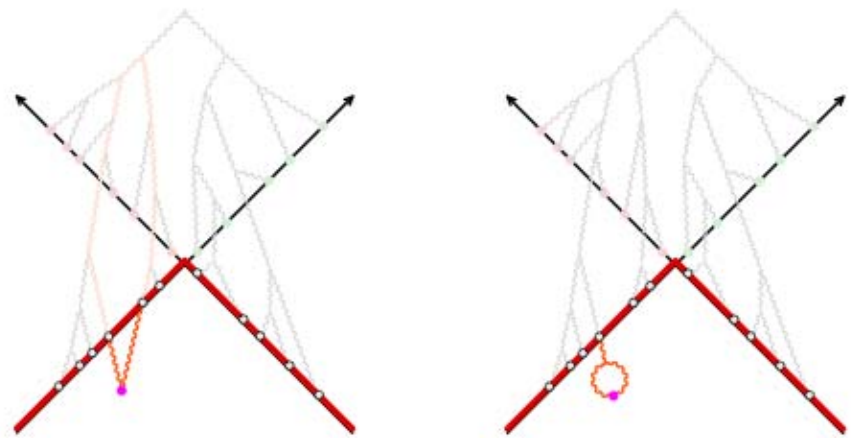
Wee parton fluctuations are time dilated on typical interaction time scales

High mode occupancy ($1/\alpha_S$) -> classical fields

N-parton correlations & their energy evolution given by "universal" density matrices W[ρ]

Quantum decoherence - I





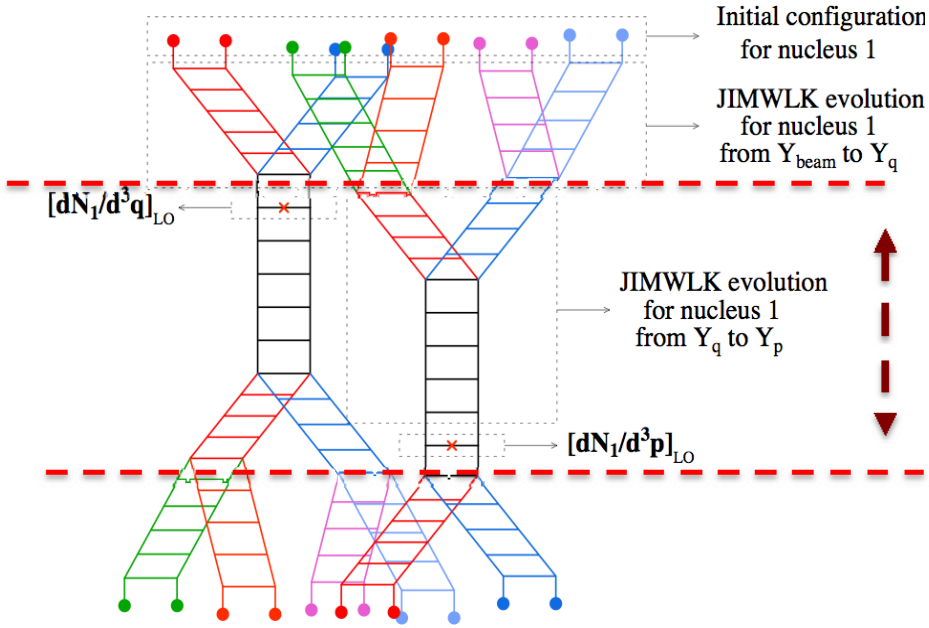
Loop corrections for t <0 – naively suppressed by α_S but there are $\alpha_S Y$ terms as large as classical term for $Y \geq 1/\alpha_S$ -- all order resummation- absorb in W[ρ] (JIMWLK eqn.)

Quantum corrections that "talk" to both nuclei – are suppressed – high energy factorization

Gelis, Lappi, RV PRD 78, 054019, 054020 (2008)

Quantum decoherence - II

Gelis,Lappi,RV PRD (2009)



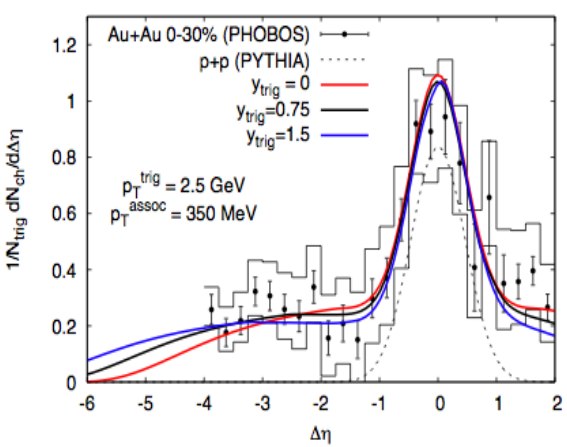
$W[\rho_1]$

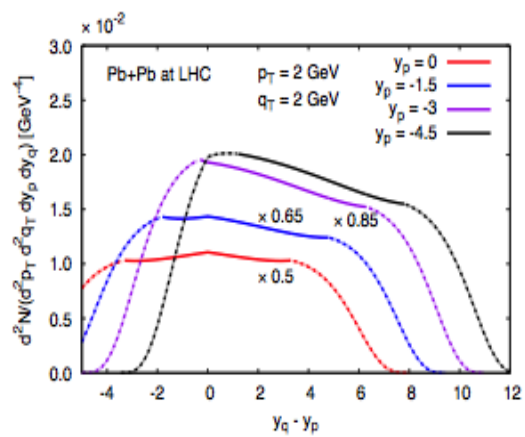
ΔY

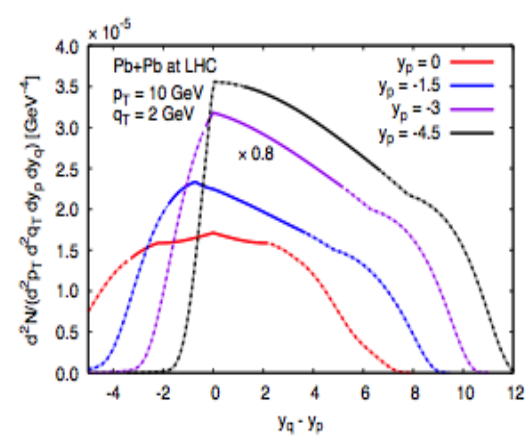
$W[\rho_2]$

Long range correlations probe multi-parton correlations in nucl. wave fns.

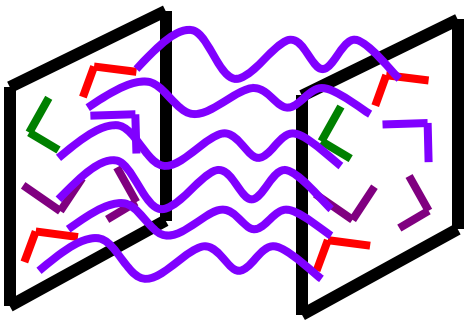
Dusling,Gelis,Lappi,RV, NPA (2010)





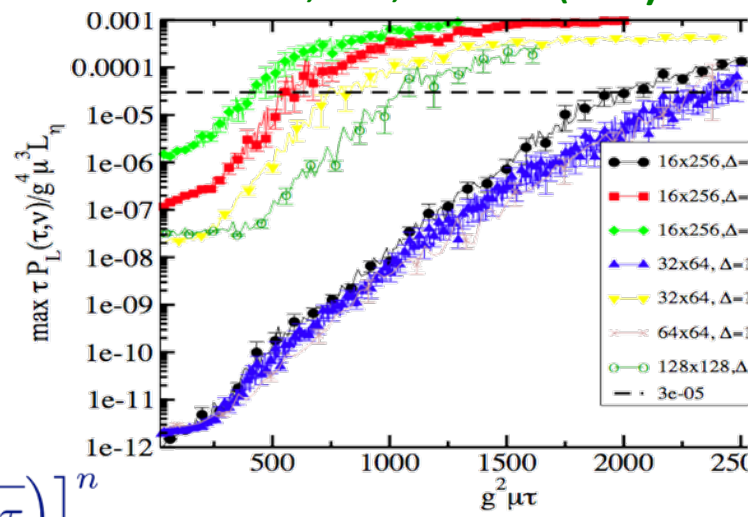


Quantum decoherence - III



Quant. fluct.
grow exponentially
after collision

Romatschke,RV (2005,2006)
Fukushima,Gelis,McLerran (2007)



"Resum" secular divergences: $\left[\alpha_S \exp\left(\sqrt{Q_S \tau}\right)\right]^n$

$$\frac{dN_{\rm LO+NLO}}{dY d^2p_\perp} = \int [D\rho_1][D\rho_2] Z_{{\rm Y}_{\rm beam}-{\rm Y}}[\rho_1] Z_{{\rm Y}_{\rm beam}+{\rm Y}}[\rho_2]$$
$$\times \int [Da(u)] \tilde{G}[a] \frac{dN_{\rm LO}[A_{\rm cl.} + a(u)]}{dY d^2p_\perp}\Bigg|_{\rho_1,\rho_2}$$

"Holy Grail" Functional

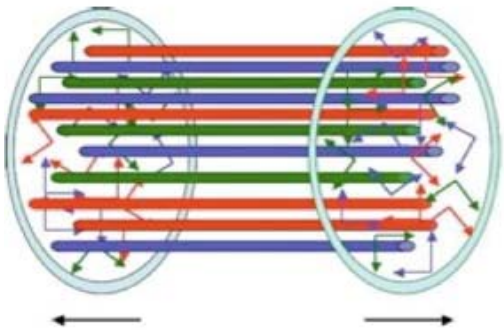
Why care ?

Gelis, Lappi, RV (2007)

Why quantum fluctuations matter…

$$A^\mu(x_\perp,\tau,\eta) = A^\mu_{\rm LO}(x_\perp,\tau) + a^\mu(x_\perp,\eta,\tau)$$

O (1/g) O(1)



LO Glasma flux tubes are boost invariant

$$\langle T^{\mu\nu}_{\rm LO}(\tau=0^+)\rangle = \begin{pmatrix} \varepsilon_0 & 0 & 0 & 0 \\ 0 & \bar{\varepsilon} & 0 & 0 \\ 0 & 0 & \bar{\varepsilon} & 0 \\ 0 & 0 & 0 & \varepsilon_0 - 2\bar{\varepsilon} \end{pmatrix}$$

Dumitru,Gelis,McLerran,RV (2008)

Very anisotropic distribution – far from ideal hydrodynamics

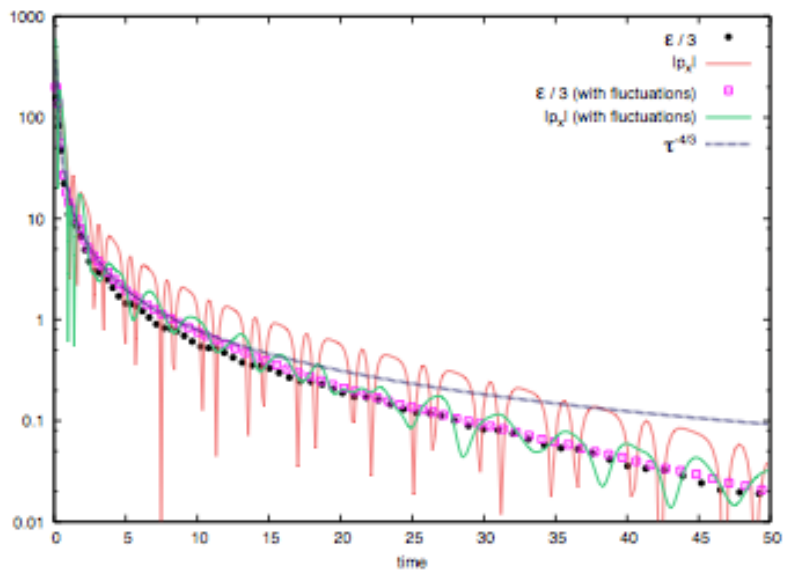
Quantum fluctuations – if unstable – can isotropize the system in $\tau \sim 1/Q_S$

Early onset of "ideal" hydro – more justifiable use of CGC initial conditions

Perfect fluidity without thermalization

Dusling, Epelbaum, Gelis, RV

Quantum averaging and phase decoherence seen in massless scalar Φ^4 theory

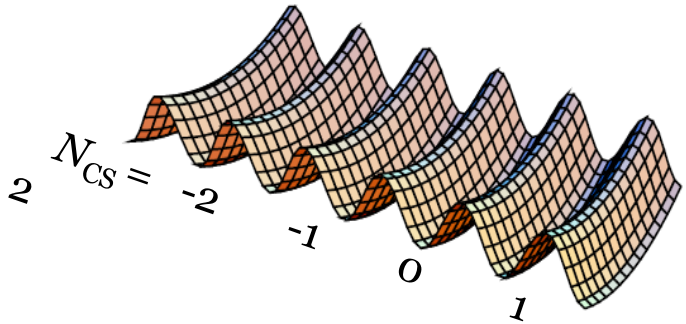


Quantum averaged solutions show early onset of ideal hydro behavior

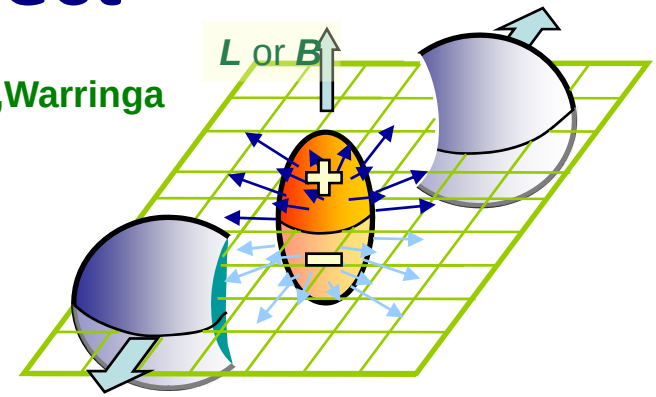
Very similar to mechanism for preheating in the early universe during inflation

Kofman, Linde, Starobinsky (1994) ;
D.T. Son; Khlebnikov, Tkachev (1996)

Chiral Magnetic Effect



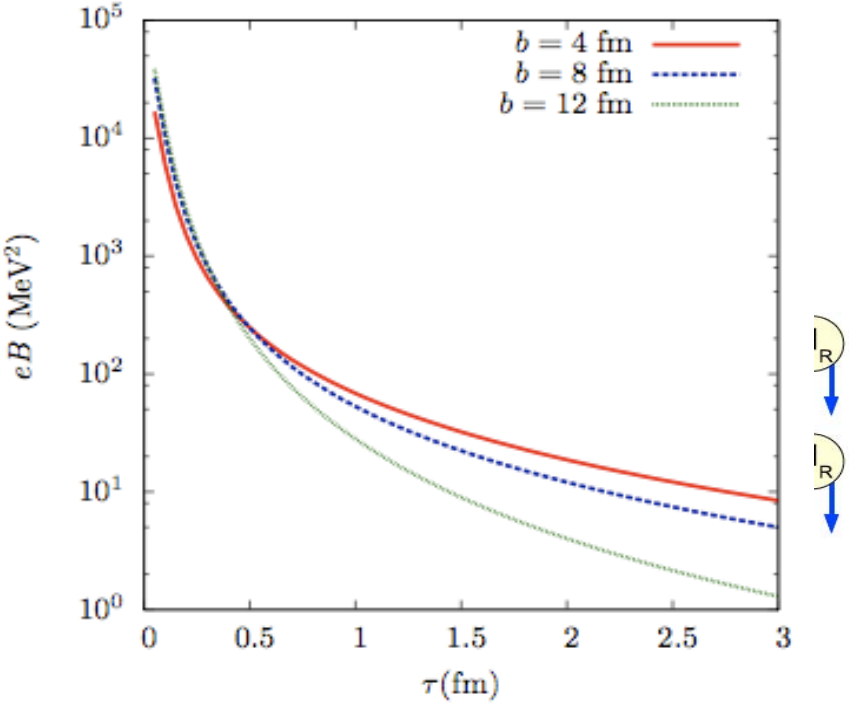
Kharzeev,McLerran,Warringa

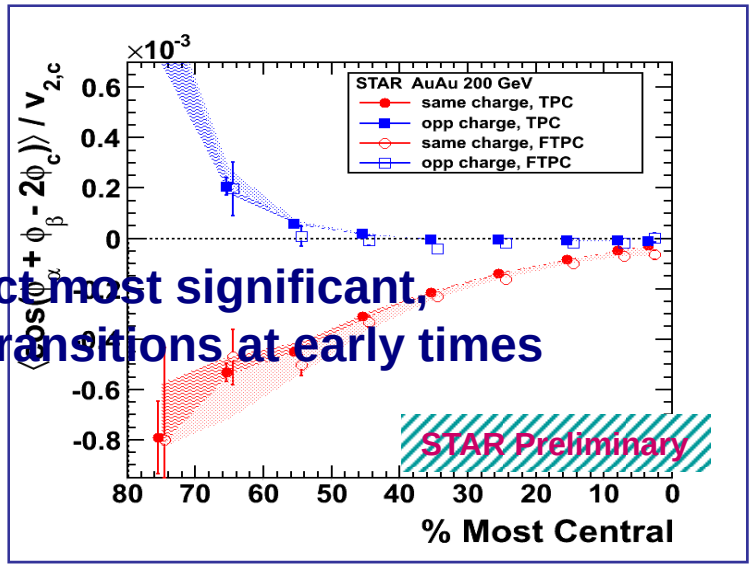


Topological fluctuations
-sphaleron transitions in Glasma

+

External (QED) magnetic field





Effect most significant, for transitions at early times

Possible experimental signal of charge separation (Voloshin, Quark Matter 2009)

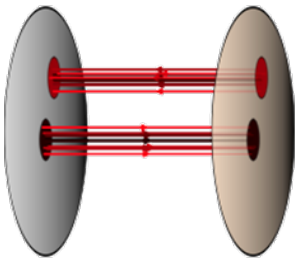
Sphaleron transitions in the Glasma

$$\Gamma_{\text{sphal.}} \equiv \frac{\langle(\Delta N_{\text{cs.}})^2\rangle}{Vt} = \int d^4x \langle \frac{g^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}(x) \frac{g^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}(0)\rangle$$

Measures diffusion rate of topological number

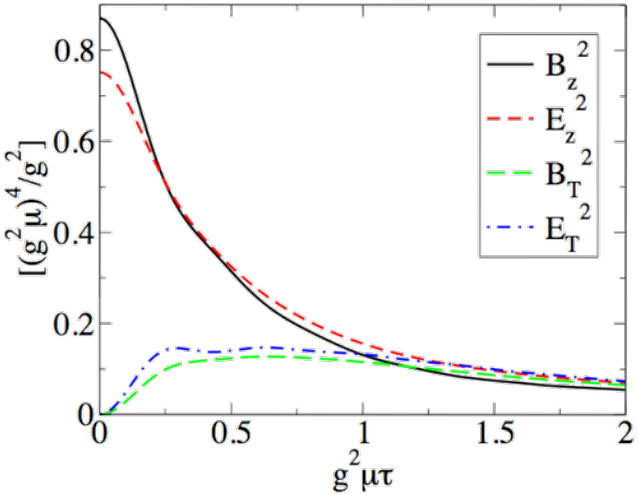
In QCD: Gregoriev, Rubakov; Ambjorn, Krasnitz; Moore

$$\frac{dN_{cs.}}{d^4x} = \frac{g^2}{8\pi^2}\text{Tr.}\vec{E}\cdot\vec{B}$$



In the Glasma, E⋅B ≠ 0 at early times

Pert.: Kovner, McLerran, Weigert (1995)
Non. Pert. : Krasnitz, RV (1998)
Lappi, McLerran (2006)



Generate Chern-Simons charge!

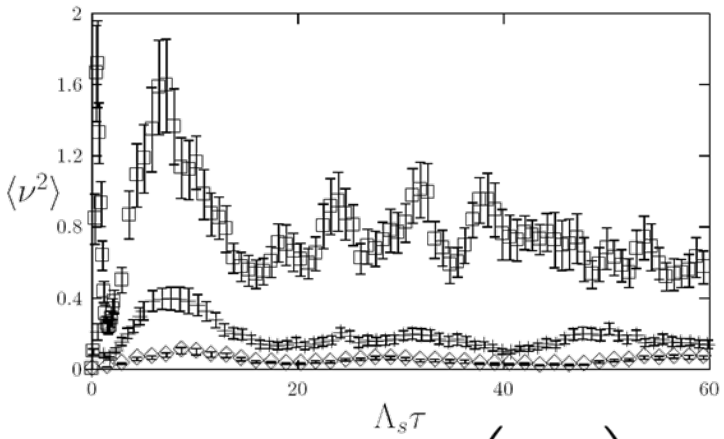
Kharzeev, Krasnitz, RV (2002)
Kharzeev, Fukushima, Warringa (2010)

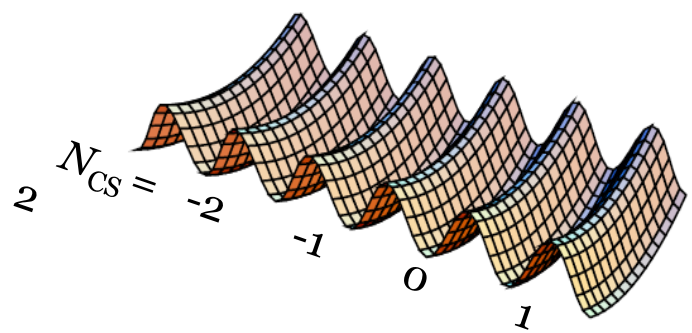
No-Go Theorem

Kharzeev, Krasnitz, RV (2002)

- **If gauge field configurations are boost invariant => 2+1-D dynamics, sphaleron transitions are not allowed; N_{CS} is gauge invariant**

$$\Pi_2(SU(2)) = 0 \qquad \Pi_3(SU(2)) = Z$$





$$\langle \nu^2 \rangle = C \left(\frac{R^2}{\frac{1}{Q_S^2}} \right)$$

- **Chern-Simons # fluctuations but no random walk in periodic potential**

Why quantum fluctuations matter… (once more, with feeling)

- **If boost invariance is violated (by quant. fluct.), sphaleron transitions can go!**

- **The same quantum fluctuations that govern isotropization also govern large sphaleron transitions**

- **Important to compute the "Holy Grail" spectrum of fluctuations at early times – not easy (exploding fluctuations in rapidly expanding background)**
  (Dusling,Gelis,Srednyak,RV)

Outlook

- Quantum decoherence important for full picture of non-equilibrium Glasma physics

  - long range rapidity correlations (Glasma flux tubes)

  early thermalization, topological fluctuations

- Can be computed in a first principles *ab initio* approach in weak coupling (can also compute quark charge separation – Gelis, Lappi, Kajantie (2006))

- Important (unanswered) question: how to follow the dynamical evolution of CME generated at late times- effective theories, hydro ?