New physics – Theory

ten more years !

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RHIC: dedicated to QCD matter in extreme conditions
(temperature, density, color fields, …)

this talk: a few ideas for the decade before eRHIC
(incomplete & non-exclusive)

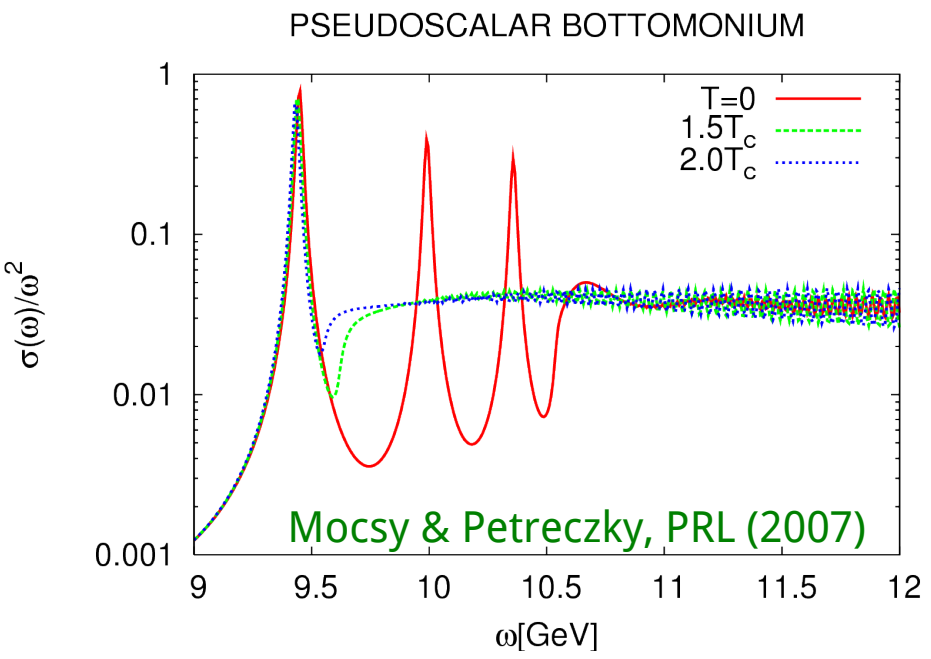
RHIC & AGS User's Meeting
June 17 – 20, 2014
BNL

Hot and dense QCD medium (AA, high-mult. pA?)

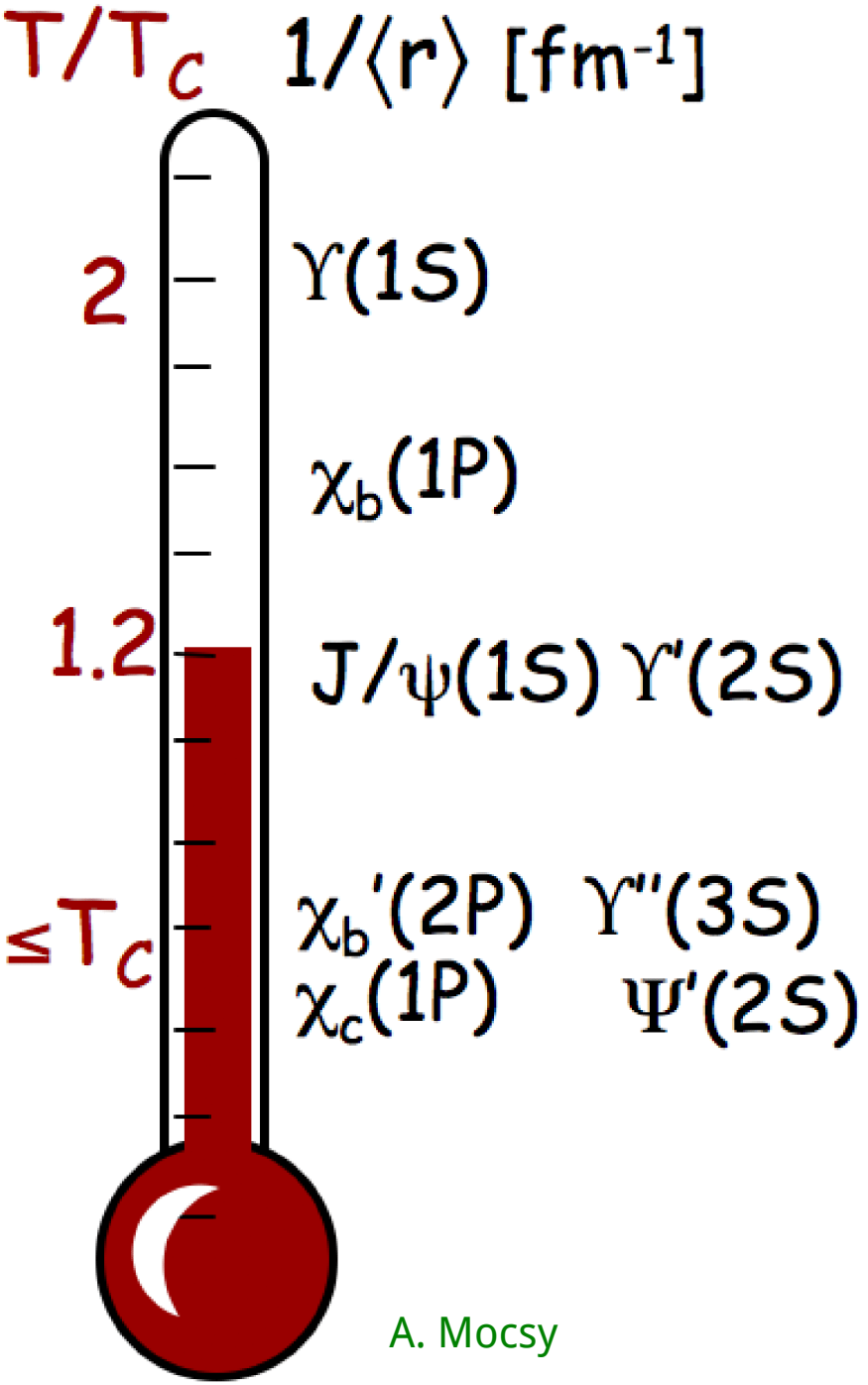
- 1st order phase transition / critical point at $\mu_B > 0$
- Quarkyonic matter
- Chiral magnetic effect
- Bulk viscosity
- Quarkonium (⟶ Debye screening, Landau damping ?)
- Equation of state (⟶ $(e\text{-}3p)/T^2 \sim$ const ?)

Establish screening scale

$$V(r) \sim \frac{g^2 C_F}{r} e^{-m_D r}$$

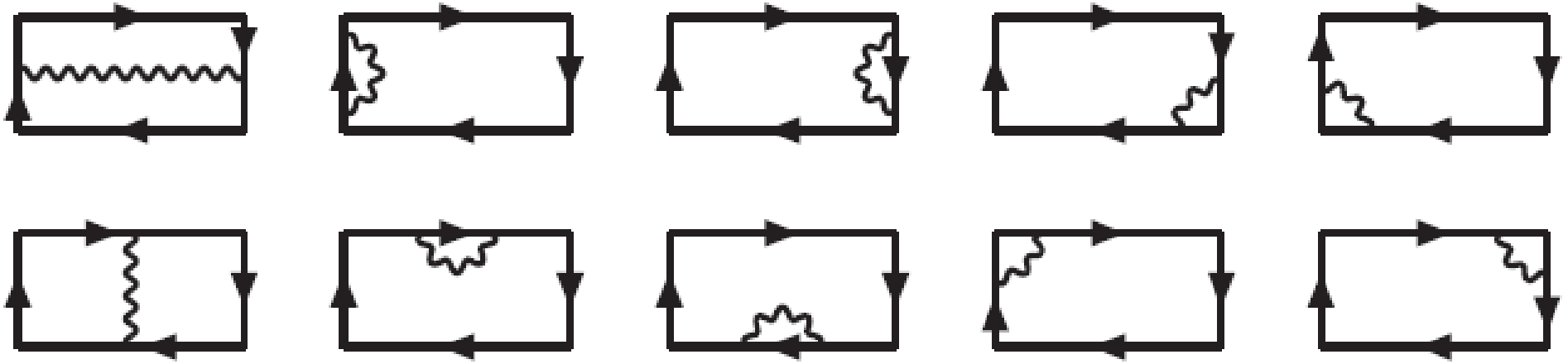


(in this plot the width is not physical)



A. Mocsy

HTL static Wilson loop:



M. Laine et al: hep-ph/0611300
N. Brambilla et al., arXiv:0804.0993

$$\rightarrow C_E(\tau, r) \rightarrow C_>(t, r): \quad i\partial_t C_>(t, r) = V_>(t, r)\, C_>(t, r)$$

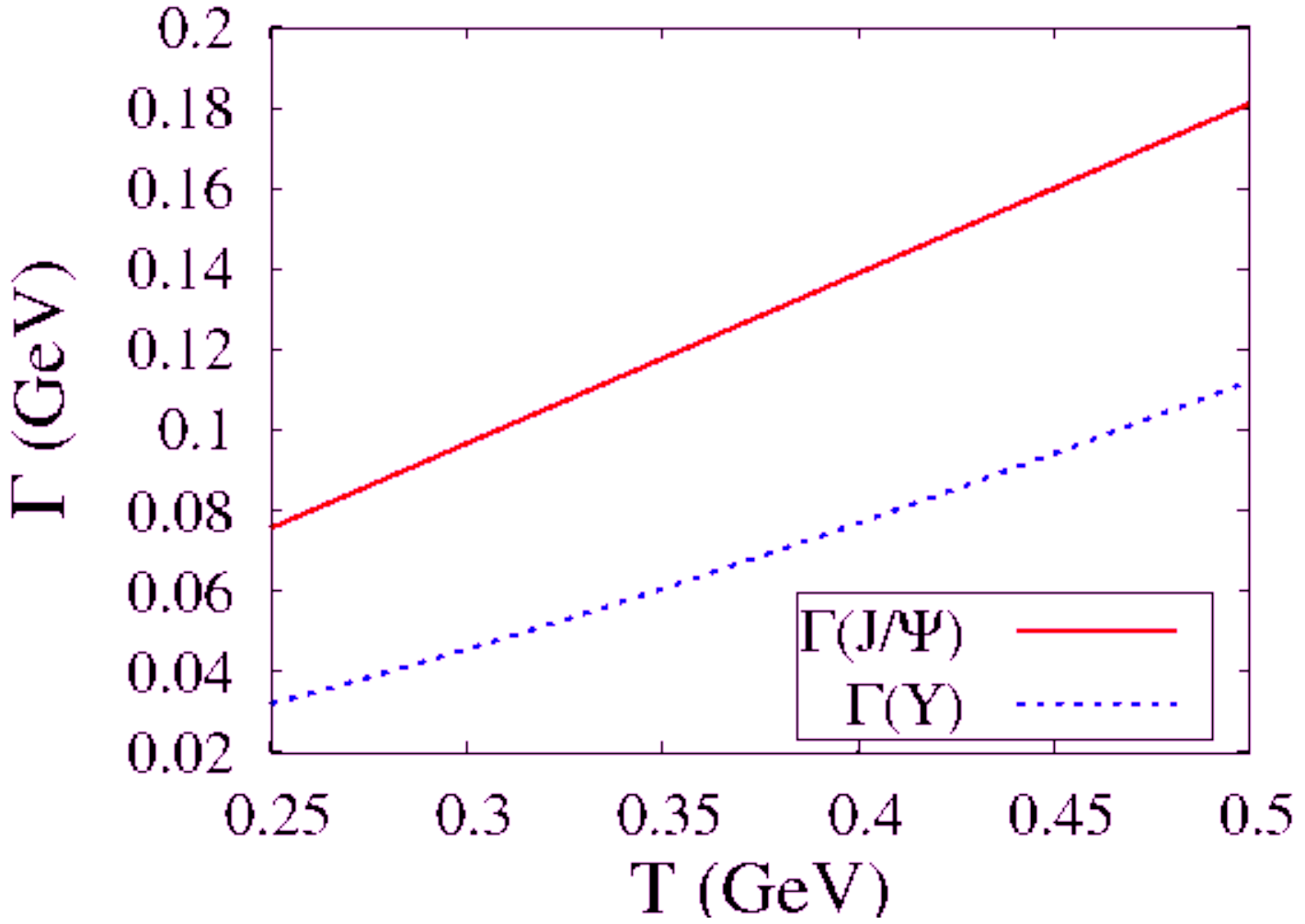
$$V_>(\infty, r) = -\frac{g^2 C_F}{4\pi}\left[m_D + \frac{1}{r}\exp(-m_D r)\right]$$

Debye screening

$$-i\frac{g^2 C_F}{4\pi} T\phi(m_D\, r)$$

Landau damping

Numbers: some rough estimates for Γ (thermal QCD width)



$$\Gamma_{e^+e^-} \ll \Gamma_{thQCD} \ll |E_{\rm bind}|$$

Bulk properties of hot QCD

- RHIC has shown that $\left.\frac{\eta}{s}\right|_{\mathrm{QCD}} \approx \left.\frac{\eta}{s}\right|_{\mathcal{N}=4\,\mathrm{SYM},\lambda\to\infty}$

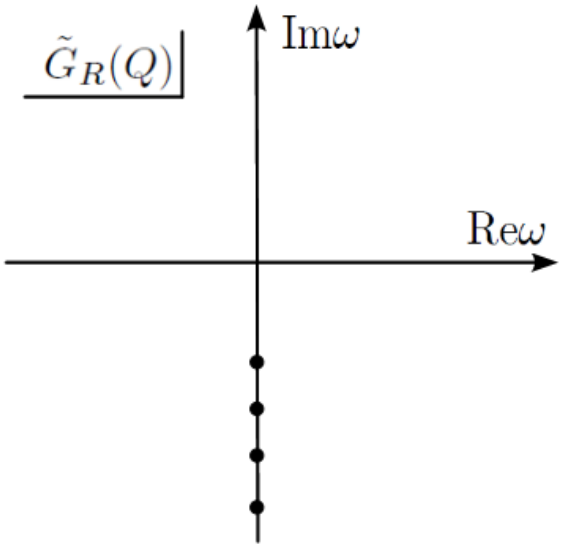
- Does this similarity extend to other properties ?
  (non-IS hydro, ...)

- Can one observe the non-conformal nature
  of high-T QCD ?
  (EoS, bulk visco, ...)

Shear quasi-normal modes

Consequences to transient hydrodynamics behavior

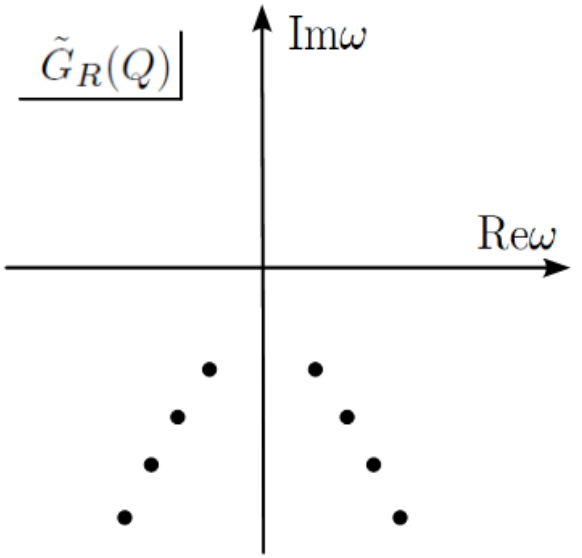
Dilute Gas



QGP

in between?

AdS/CFT



$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + \dots$$

Israel-Stewart theory

$$\chi_2 \ddot{\pi}^{\langle\mu\nu\rangle} + \chi_1 \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + \dots$$

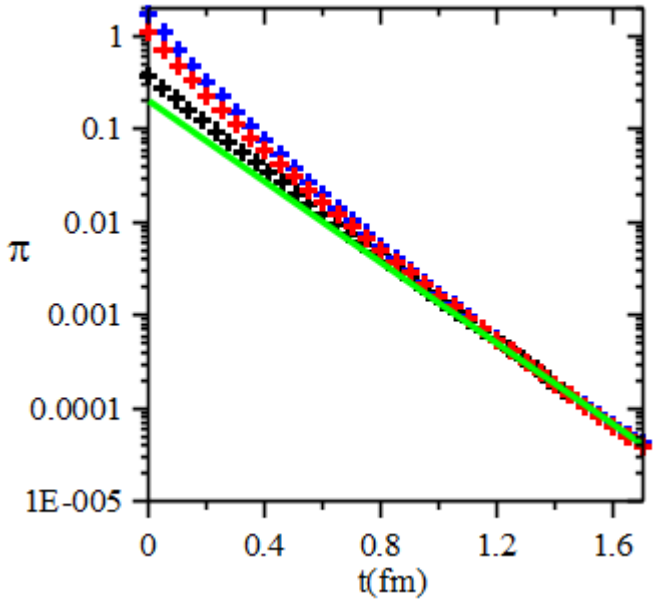
Strongly coupled N=4 SYM

Shear quasi-normal modes

Consequences to transient hydrodynamics behavior

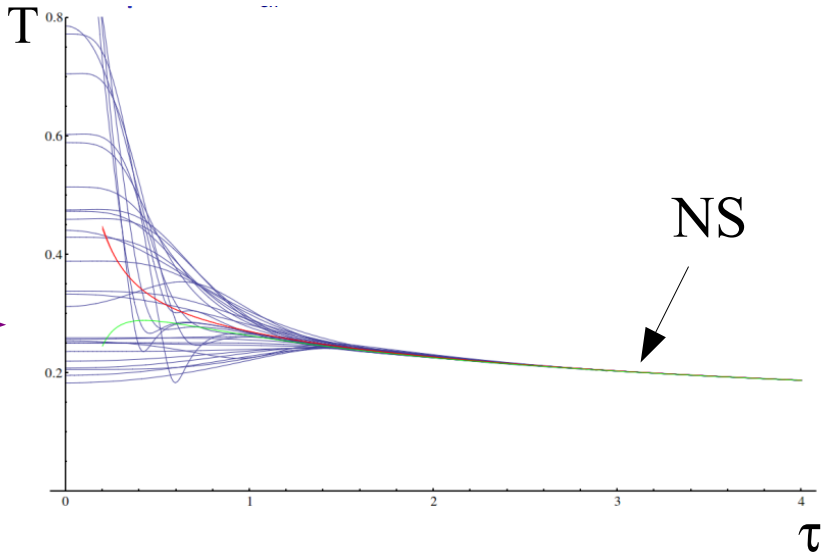
Dilute Gas

AdS/CFT



QGP

in between?



BAMPS simulation, Bouras *et al*

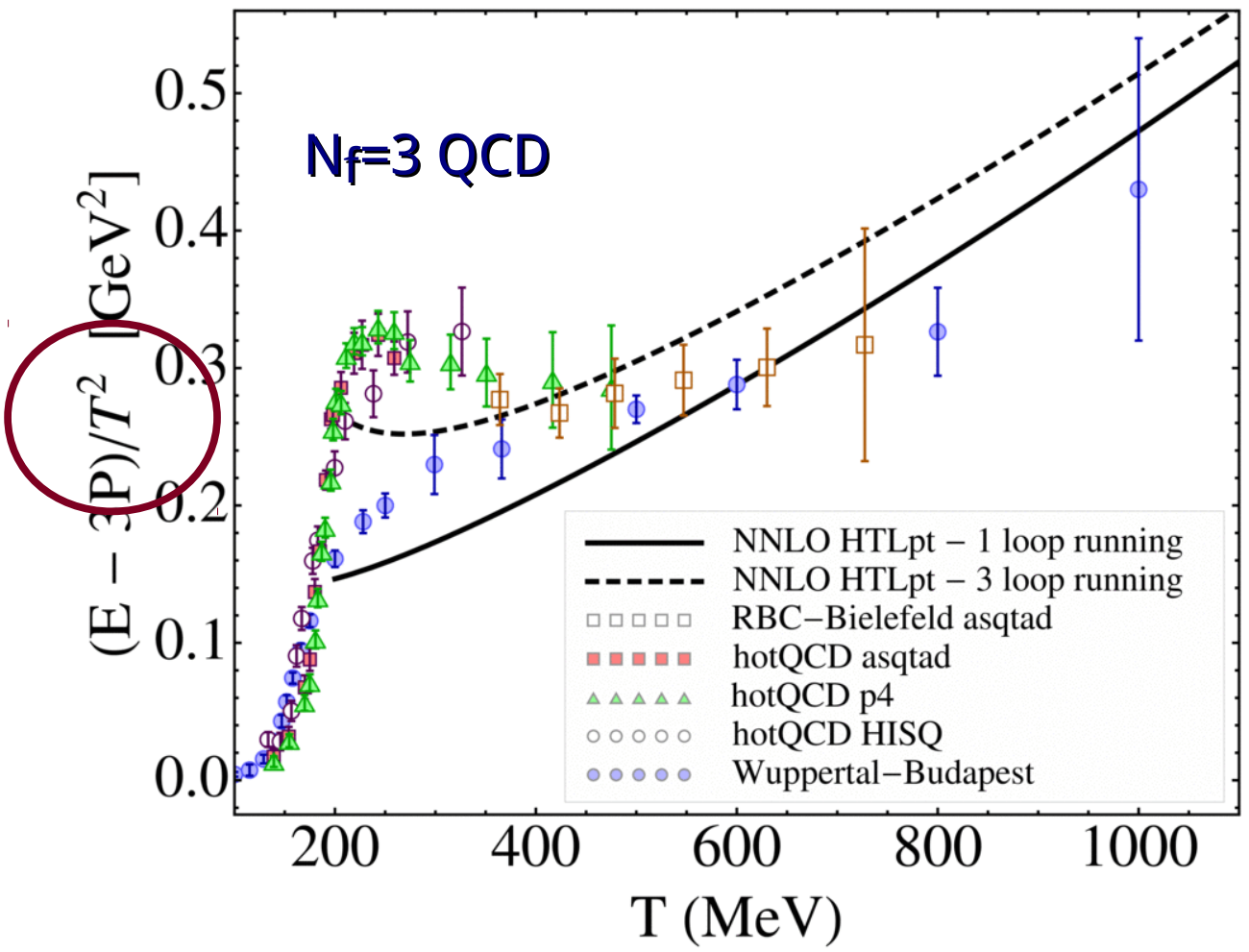
Janik, QM14 plenary talk

Exponential decay towards Navier-Stokes limit confirmed

Oscillates (!) towards Navier-Stokes limit

Equation of state: "interaction measure"

J.O. Andersen et al: PRD 84 (2011)



- conformal theory:
  e-3p = 0
- bag model:
  e-3p = 4B + pert.

- **could HIC see non-conformal nature of QCD through EoS ?**
  (or through bulk visco, T-dependence of η/s or c_s)

Non-linear color fields

–

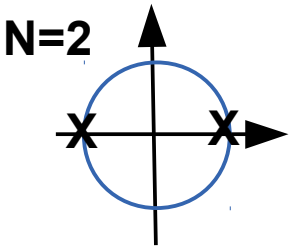
initial state of HIC

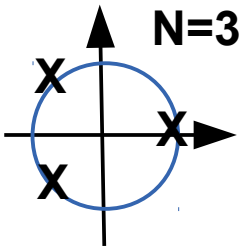
- Thermalization
  (turbulent fluctuations over classical background,
  holographic shockwave collisions, …)
- Bose condensation ? (Blaizot et al.)
- Magnetic Z(N) domains
- Perhaps heavy-Q could provide some insight ?
  (E-loss, flow, correlations, …)

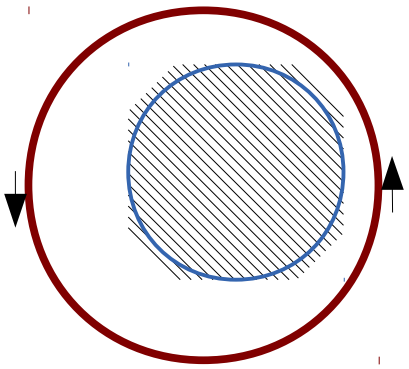
Magnetic flux loop: non-Abelian adjoint fields

transform under SU(N) / Z(N)

$$Z(N) = \left\{ e^{2\pi i\, n/N}\, \mathbb{1},\ n = 0 \cdots N-1 \right\}$$







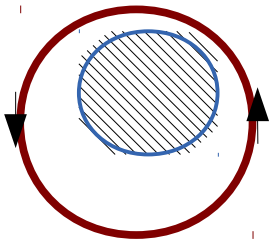
$$\mathcal{P} \exp\ ig \oint \vec{A} \cdot d\vec{\ell}\ \ = \ \ e^{2\pi i\, n/N}\, \mathbb{1}_{N\times N}$$

i.e., gauge transformation can be multi-valued by an element of Z(N)

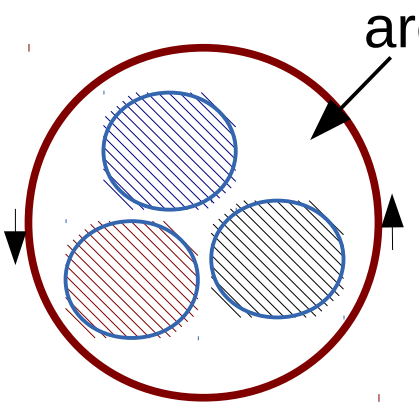
n = Z(N) charge in shaded region

Magnetic Z(N) "vortices" / domains:

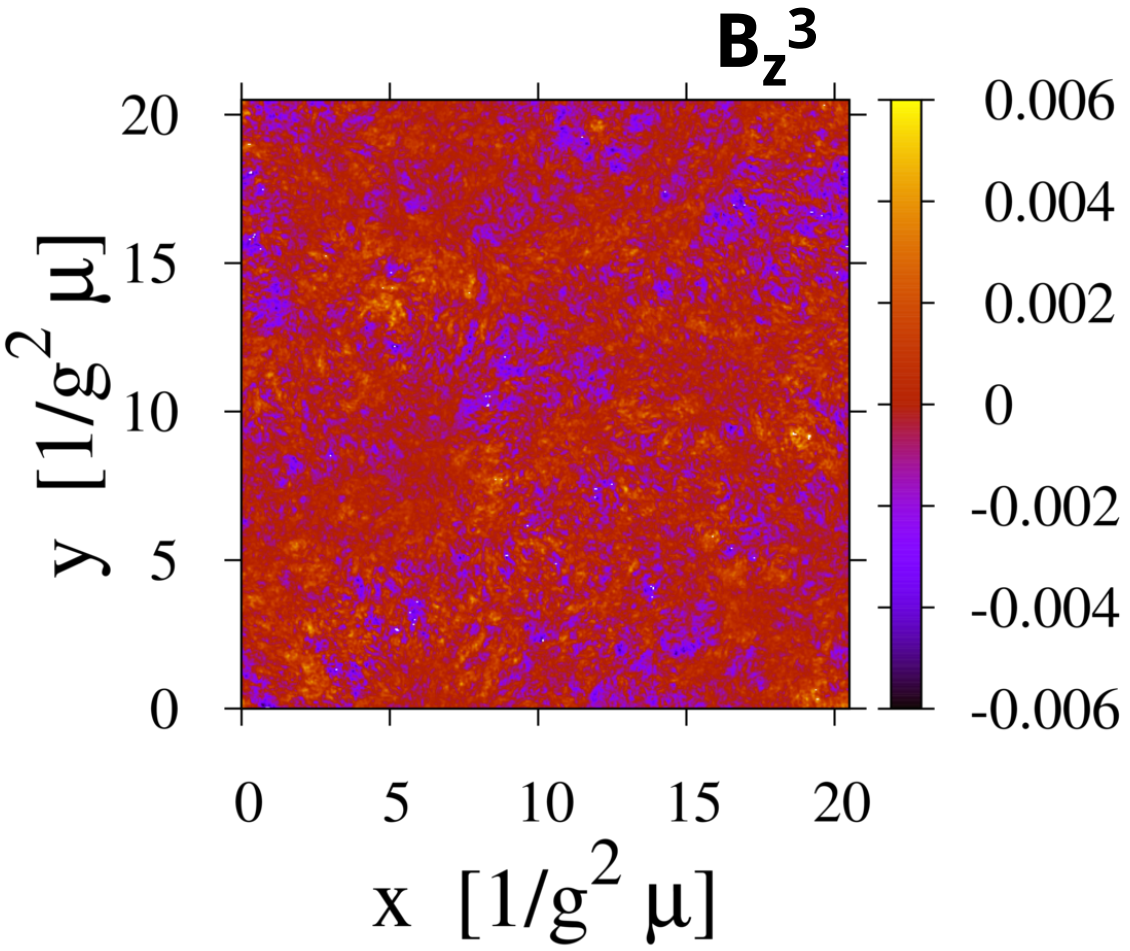
$$M(R) \;=\; \mathcal{P}\exp\left(ig\oint dx^i A^i\right)$$



$e^{2\pi i\, n/N}\;\mathbb{1}$



$e^{2\pi i\,(n_1+n_2+n_3)/N}$



do we find :

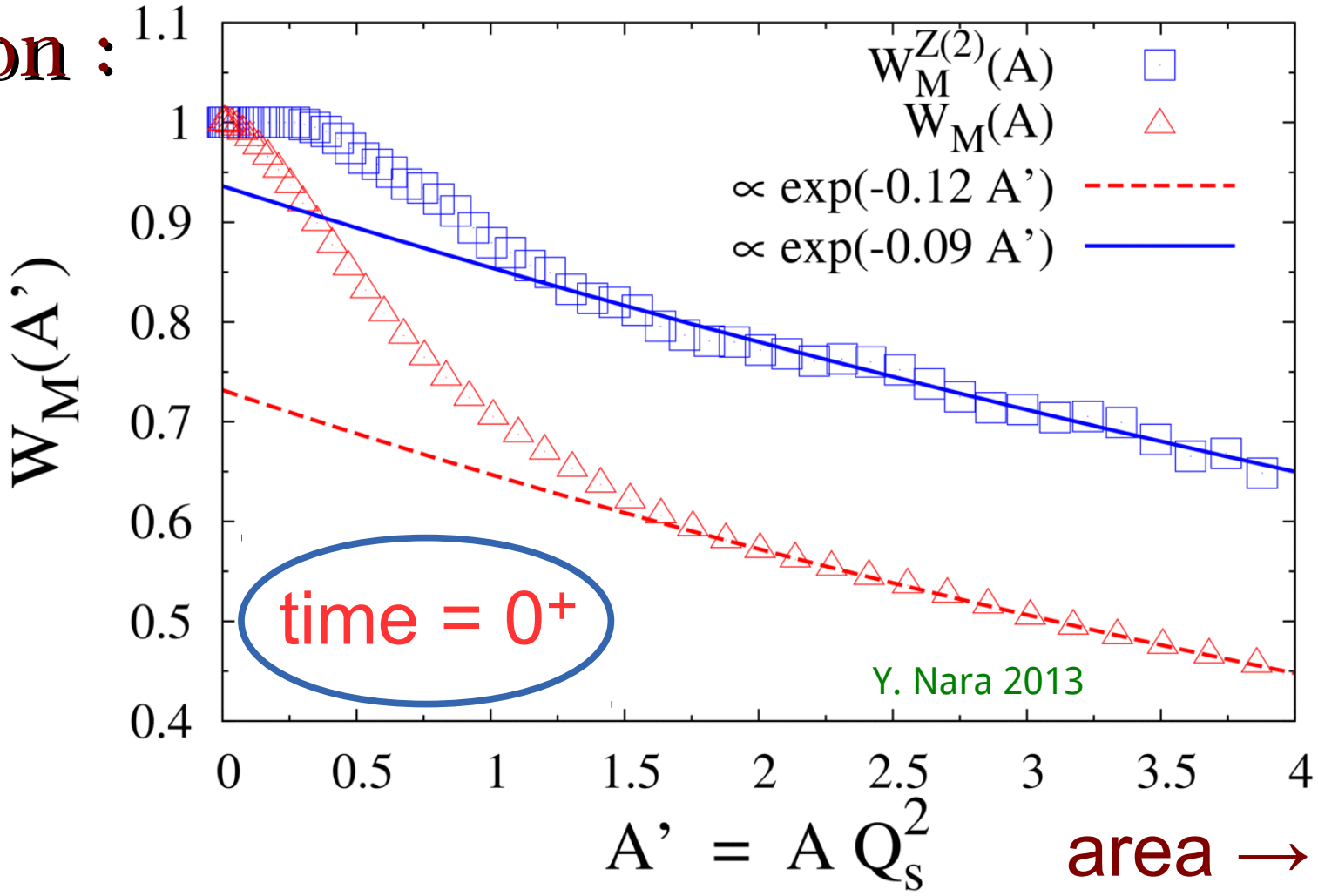
- area law ?

$$W_M(R) \sim e^{-\sigma A}$$

- loop ∈ Z(N) ?

$$\langle \mathrm{sgn\,tr}\; M\rangle \sim \frac{1}{N}\langle \mathrm{tr}\; M\rangle$$

SU(2) solution : (class. field collision)



- evidence for domain structure of A^i
- approx. area law for loops
- σ_M ~ same after Z(2) rotation
- structure of B_z ~ uncorrelated vortices
- $R_{vtx} \sim 1/Q_s$ from onset of area law

Magnetic screening

$$C^{(2)}(r) = \langle \mathrm{tr}\, G(\mathbf{0})\, G(\mathbf{x}) \rangle$$

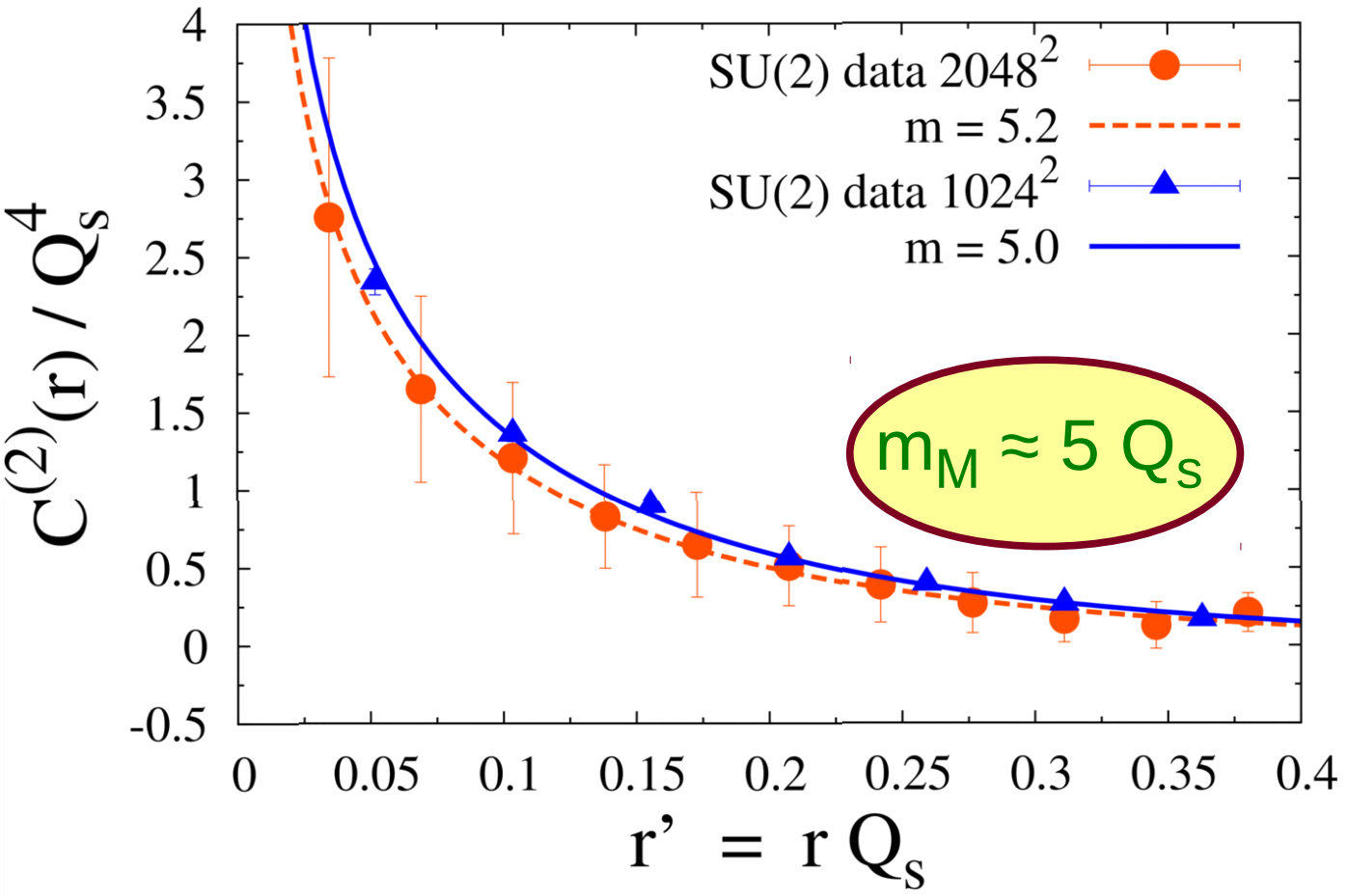
$$G(\mathbf{x}) = g\, U(\mathbf{0} \to \mathbf{x})\, F_{xy}(\mathbf{x})\, U(\mathbf{x} \to \mathbf{0})$$

expectation: (d=2)

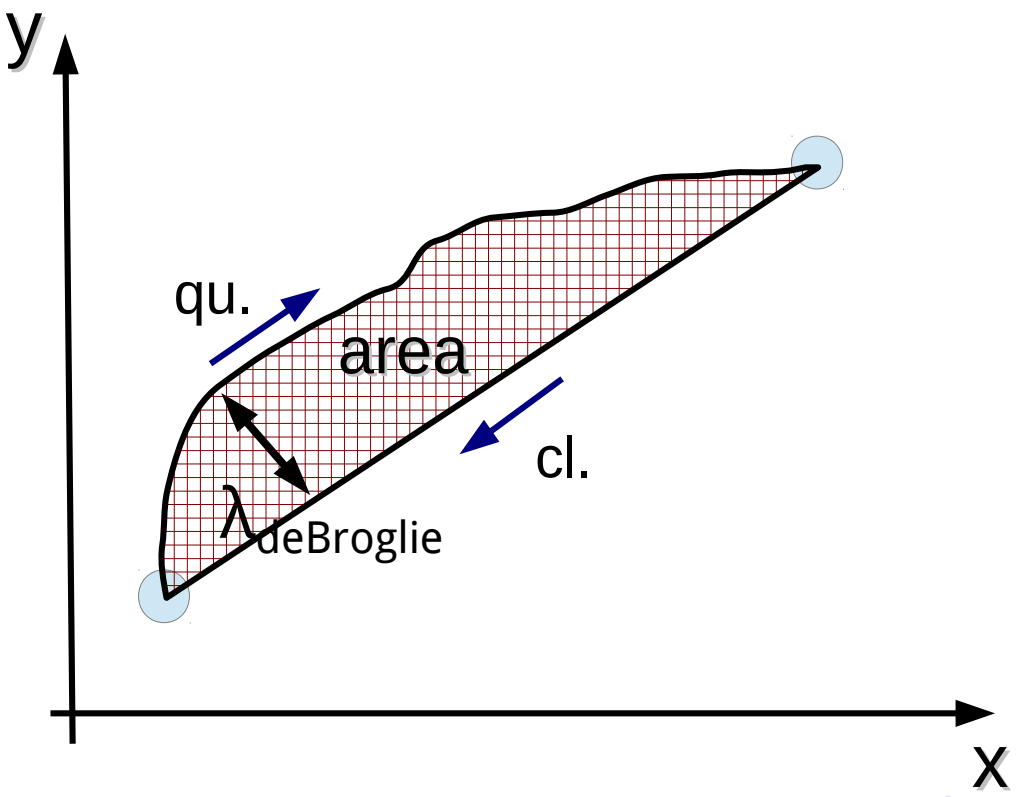
$$\int d^d p \, \frac{e^{ipx}}{p^2 + m^2} \sim \frac{1}{r^{(d-1)/2}} \exp(-m\, r)$$

- $m_M^2 \gg \sigma_M$:

domain radius » surface thickness



Propagation of hard particles in background of magnetic Z(N) vortices



classical trajectory ?

(Boltzmann, Fokker-Planck, Langevin)

- only if paths within one de Broglie length ($1/p_T$) have *same Aharonov-Bohm phase*
- destructive interference leads to Anderson localization
- ***basic question: heavy Q mean-free path ~ de Broglie length?***

$$\int_0^\infty ds \int \mathcal{D}x^\mu \left\langle \exp\, i \int_0^s d\tau \left(m\dot{x}^2 + g A_\mu \dot{x}^\mu \right) \right\rangle \sim$$

$$\int_0^\infty ds \int \mathcal{D}x^\mu \exp\left(i \int_0^s d\tau\, m\dot{x}^2 \right) \exp(-\sigma_M A)$$

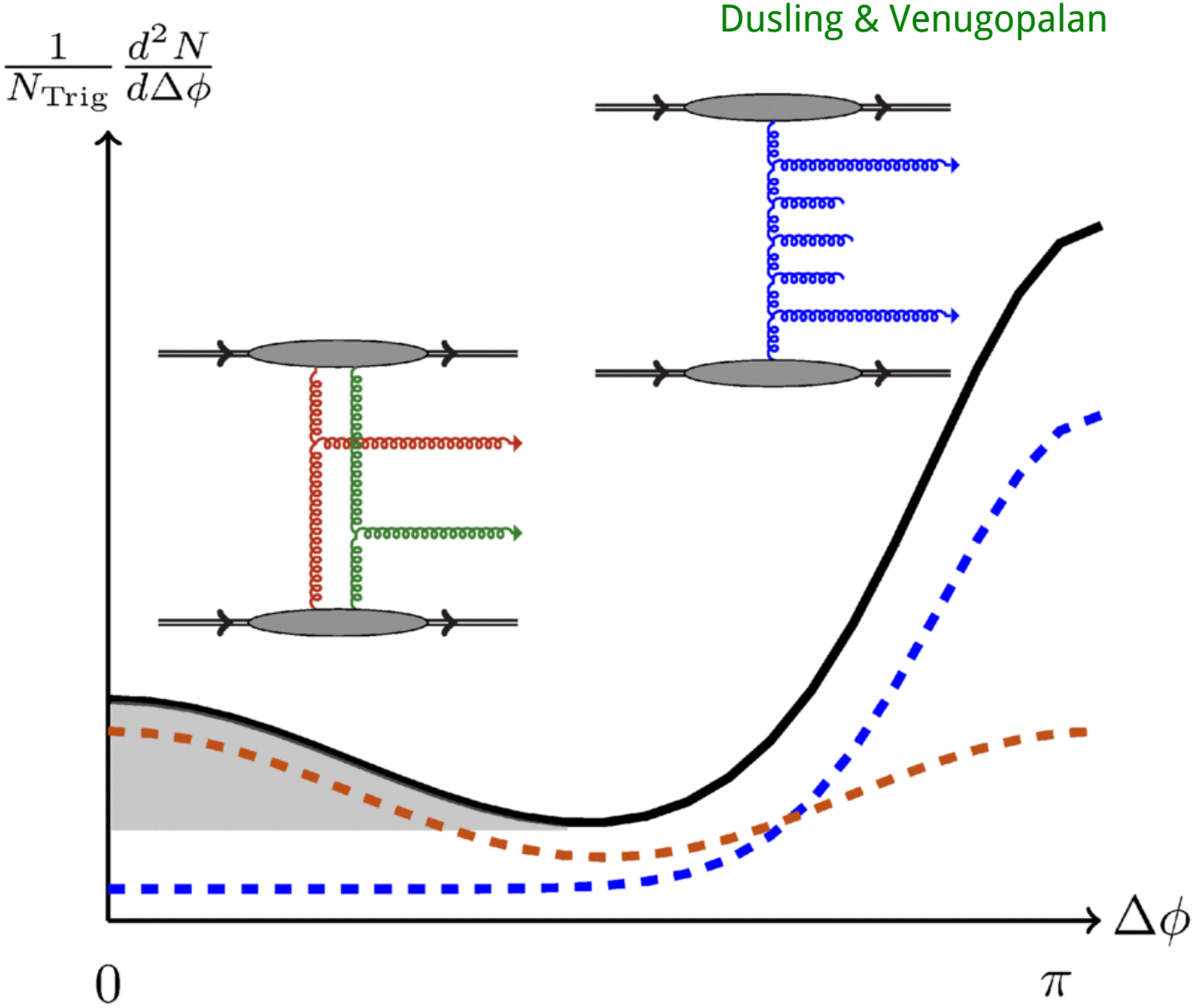
pA collisions

- forward region
- Drell-Yan
- Jet shapes & energy loss (high mult.)
- γ-h correlations
- azimuthal asymmetries v_n (& single spin asymmetries)
  initial state contributions

Angular & rapidity correlations in di-gluon production

- $v_2\{2\}$

Dusling & Venugopalan



Single-inclusive distribution in q+A elastic scattering:

$$\frac{dN}{d^2k} = \int d^2r\, e^{-i\vec{k}\cdot\vec{r}} \left\langle \frac{1}{N_c} \mathrm{tr}\, W(\vec{r},\vec{b}) \right\rangle$$

$$= \int d^2r\, e^{-i\vec{k}\cdot\vec{r}}\, S(\vec{r})$$

$$= \int d^2r\, e^{-i\vec{k}\cdot\vec{r}}\, [D(\vec{r}) + iO(\vec{r})]$$

light-like Wilson loop

Parity: $D(\vec{r}) = D(-\vec{r})$, $O(\vec{r}) = -O(-\vec{r})$

[Note: $S_{\mathrm{adj}}(\vec{r}) \sim |S(\vec{r})|^2$ is real]

- for even n = 2m: $\langle \cos\, n\phi \rangle = +\langle \cos\, n(\phi+\pi) \rangle$ **P = +**
- for odd n = 2m+1: $\langle \cos\, n\phi \rangle = -\langle \cos\, n(\phi+\pi) \rangle$ **P = –**

Spontaneous breaking of rotational symmetry :

- $\vec{E}$ field condensate

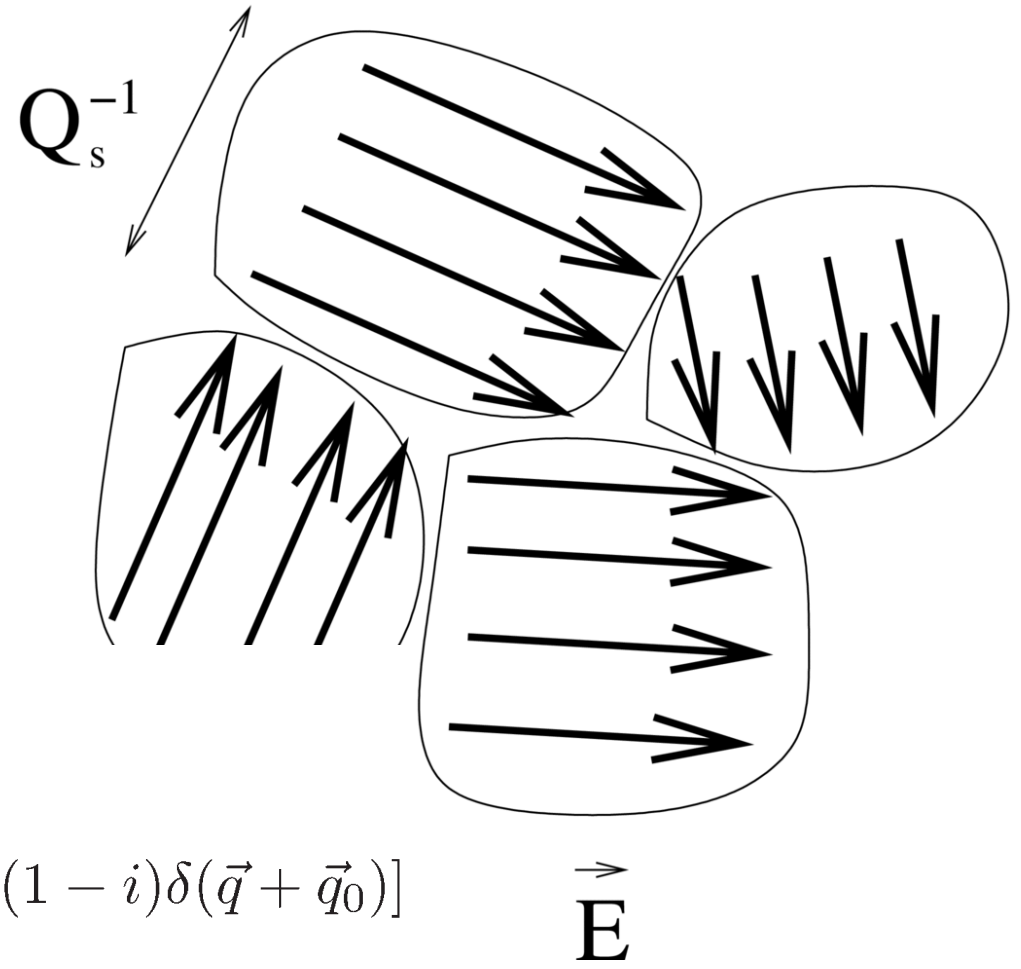
$$D(\vec{r}) = \left\langle e^{-\frac{1}{2}(g\,\vec{r}\cdot\vec{E})^2} \right\rangle$$

$$g^2 \left\langle E^i E^j \right\rangle \sim \delta^{ij}\, Q_s^2 (1 + \cos^2 \phi_r)$$

- coherent fluctuation

$$Q_s^2(\vec{s}) \sim 1 + \int \frac{d^2q}{(2\pi)^2}\, \delta f(\vec{q})\, e^{i\vec{q}\cdot\vec{s}}$$

$$\delta f(\vec{q}) = \int \frac{dq_0^2}{q_0^2} \left[(1+i)\delta(\vec{q}-\vec{q}_0) + (1-i)\delta(\vec{q}+\vec{q}_0)\right]$$



Kovner & Lublinsky:
PRD 84 (2011)

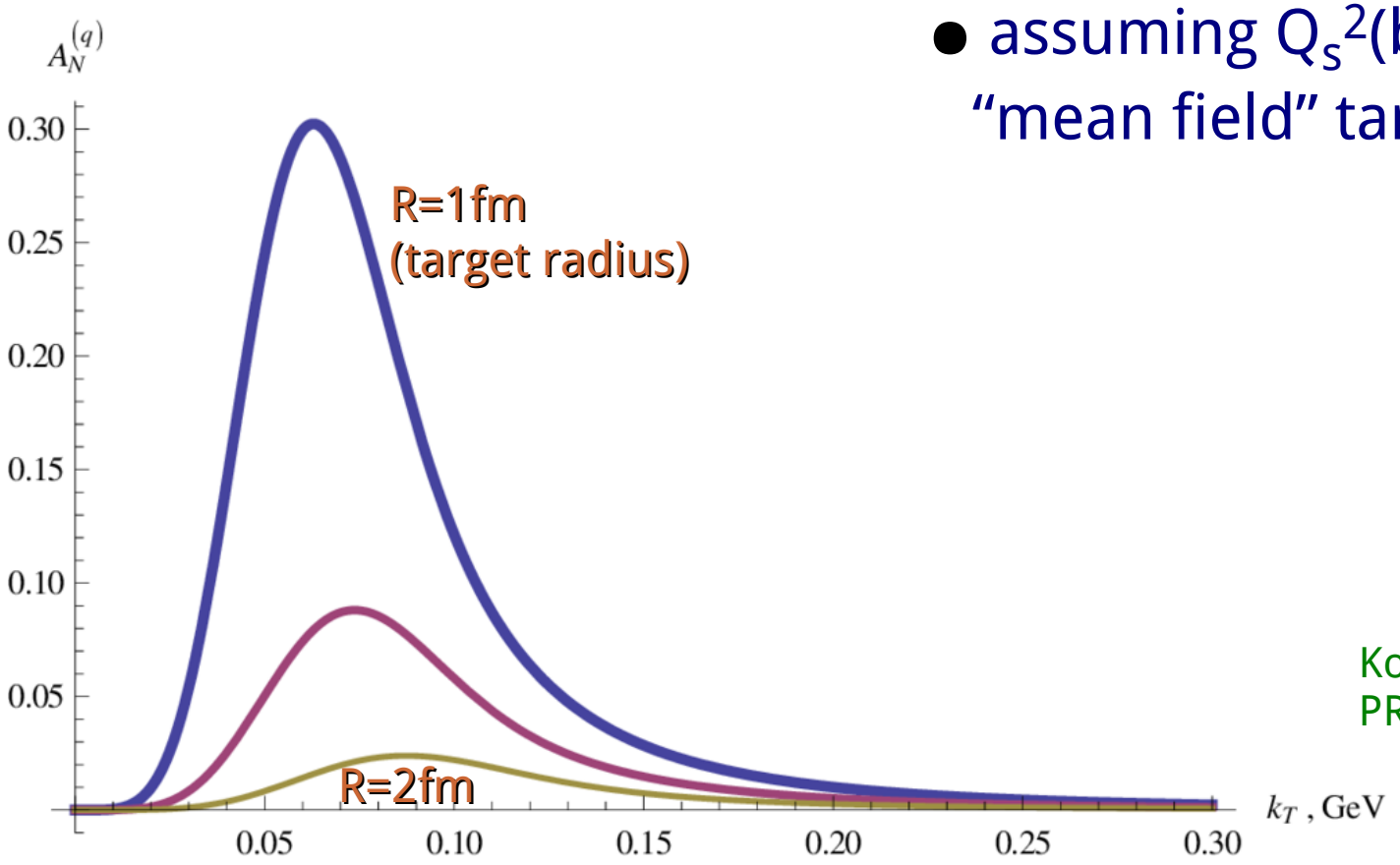
- **Angular dependence of *single-particle* distribution, *any* particle correlated with "event plane" $\mapsto v_2\{EP,4,6,\ldots\}$**

Single transverse spin asymmetry in pA

In quasi-classical approximation:

$$iO(\vec{r}) \sim i\vec{r} \cdot \vec{\nabla}_b D(\vec{r}, \vec{b})$$

$$D(\vec{r}, \vec{b}) = e^{-\frac{1}{4} r^2 Q_s^2(b) \log \frac{1}{r\Lambda}}$$



- assuming $Q_s^2(b) \sim T(b)$, "mean field" target thickness

Kovchegov & Sievert:
PRD 86 (2012)

P-odd azimuthal harmonics in pA

for $v_3 \neq 0$ we need a "string" (analogous to AdS/CFT calculation):

$$iO(\vec{r}) \sim i\vec{r} \cdot \vec{\nabla}_b D(\vec{r}, \vec{b}) \to i \int_{\vec{y}}^{\vec{x}} d\vec{s} \cdot \vec{\nabla}_s \, D(\vec{r}, \vec{s})$$

$$\vec{r} = \vec{x} - \vec{y} \quad , \quad \vec{b} = \frac{\vec{x} + \vec{y}}{2}$$

Integrating over scale-invariant spectrum of aligned C-odd fluctuations (spont. broken rotational symmetry):

$$iO(\vec{r}) \sim i\, r^2\, Q_s^2\, \mathrm{sgn}\, (\cos \phi_r)\, D(\vec{r})$$

Fourier transform gives P-odd part of dN/d^2k_T; v1, v3, ...

- Signal for semi-hard, coherent C-odd fluctuations ?

soft g bremsstrahlung off a high-x_F parton

$$\frac{dN}{dyd^2kd^2q} = \frac{C_R\alpha_s}{\pi^2k^2}\frac{\mu^2q^2}{\pi(q^2+\mu^2)^2}\frac{1}{2kq}\frac{1}{A-\cos(\phi_k-\phi_q)}$$

semi-hard scale ~ Qs

- $\vec{k}$ is momentum of radiated gluon
- $\vec{q}$ is exchanged momentum
- produces v_n

Gyulassy, Levai, Vitev, Biro: "multiple beam-jet cluster color scintillating antennas..." ok.
arXiv:1405.7825

- Whatever the formalism / model, there should be some QCD initial v_n
- Could teach us a thing or two about short-distance scale fluctuations

Summary

A lot of exciting physics still to be done @ RHIC !

- heavy Q
- pre-equ. in A+A
- finite T & μ_B
- p/d/He + Au
- .
- .
- .
- eRHIC !