Initial stages of a HI collision. Where are we at?

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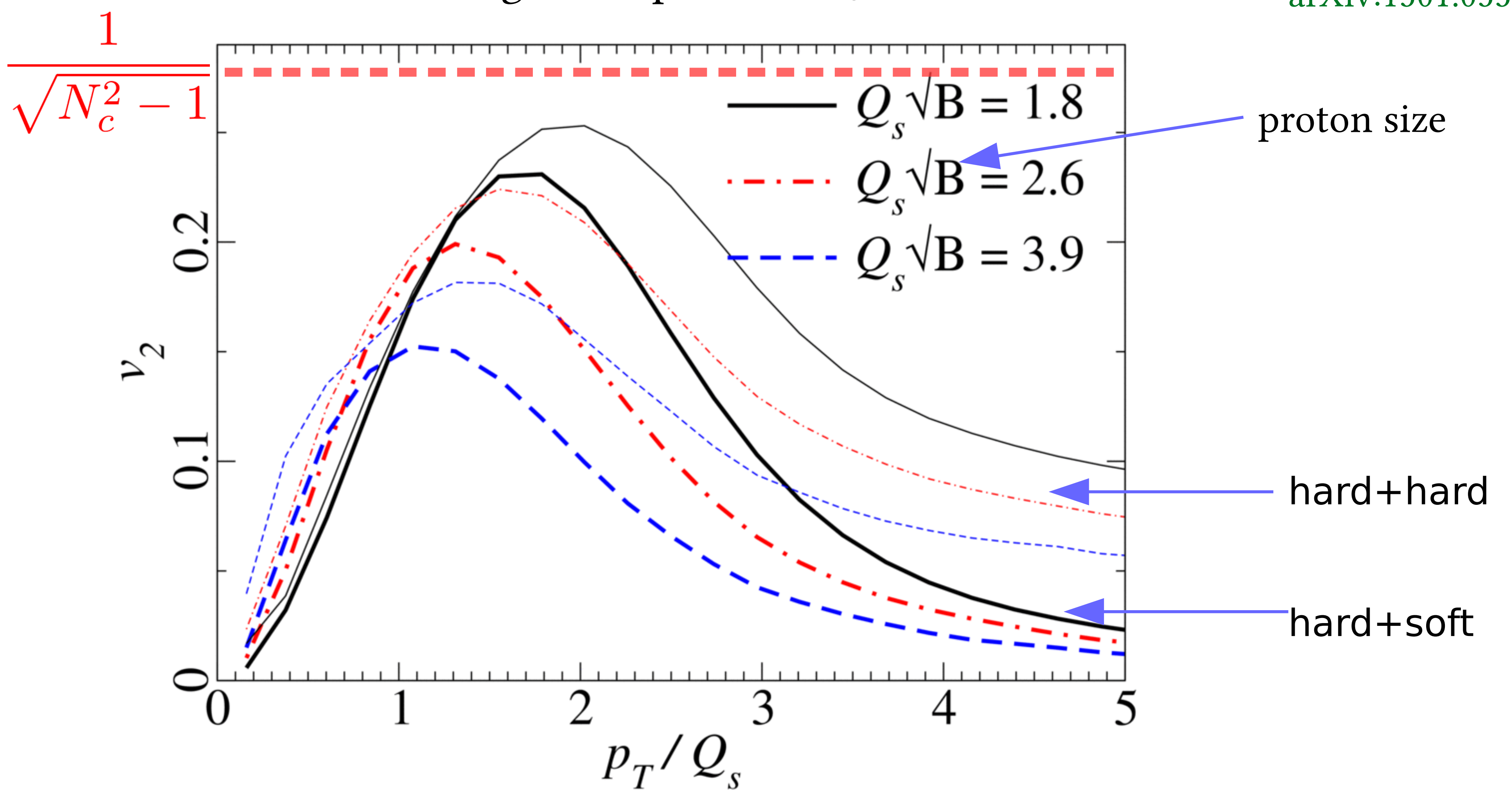
Multi-particle angular correlations (in pA)

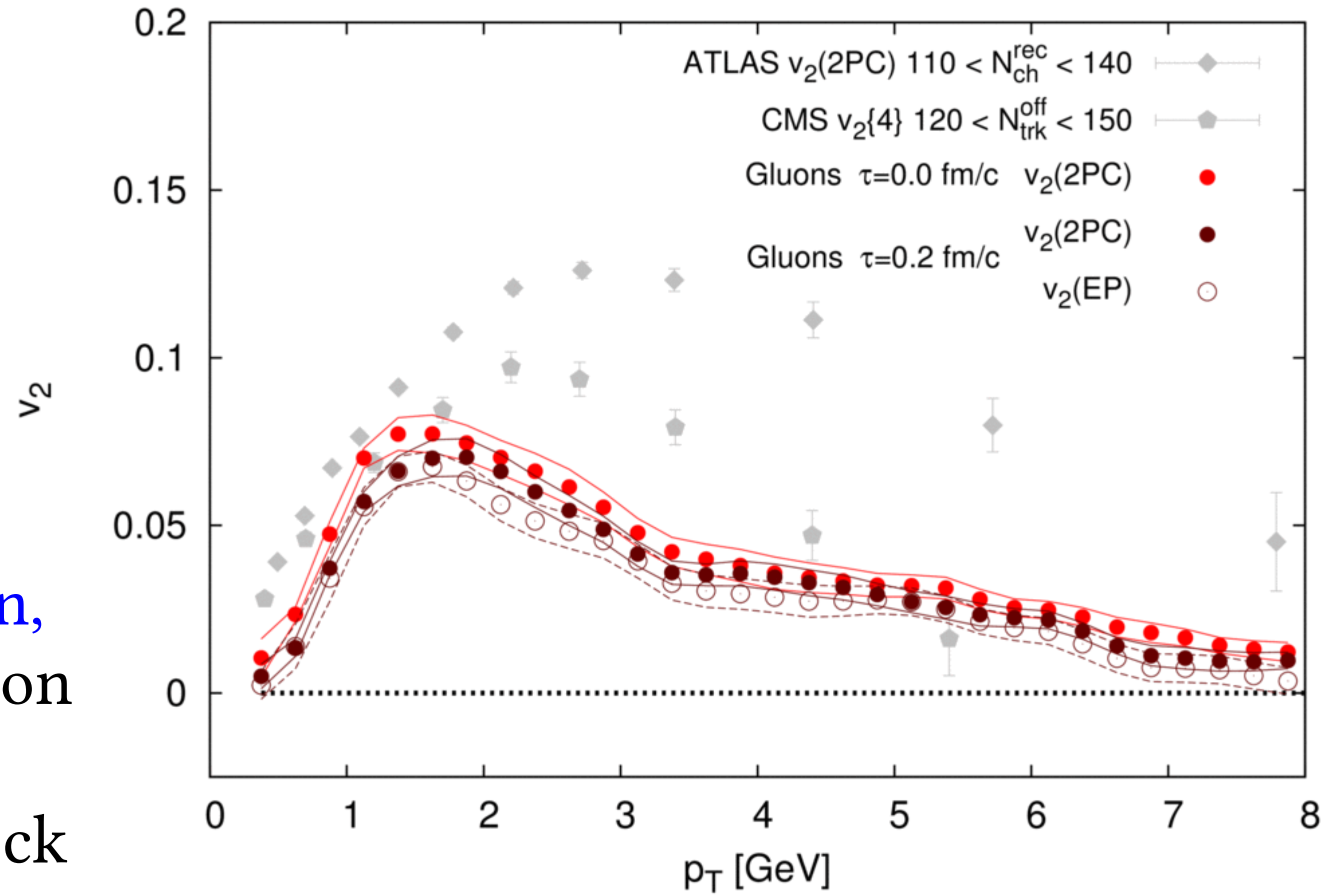
$\left\langle e^{2i(\phi_1-\phi_2)} \right\rangle$ Numerical calculation for pA (MV model)

scattering of 2 dipoles, $\langle \mathcal{D}_{xy}\mathcal{D}_{uv} \rangle$

T. Lappi, arXiv:1501.05505



- pure initial state
- dilute projectile approximation
- no hadronization / fragmentation



Schenke, Schlichting, Venugopalan: 1502.01331

- 2-particle correlation, numerical computation in dense-dense limit (collision of two shock waves / CGCs)
- v2>0 instantly at τ=+0 !
- not a rescattering effect

Two-particle correlations in scattering of two dipoles:

Lappi, Schenke, Schlichting, Venugopalan, 1509.03499

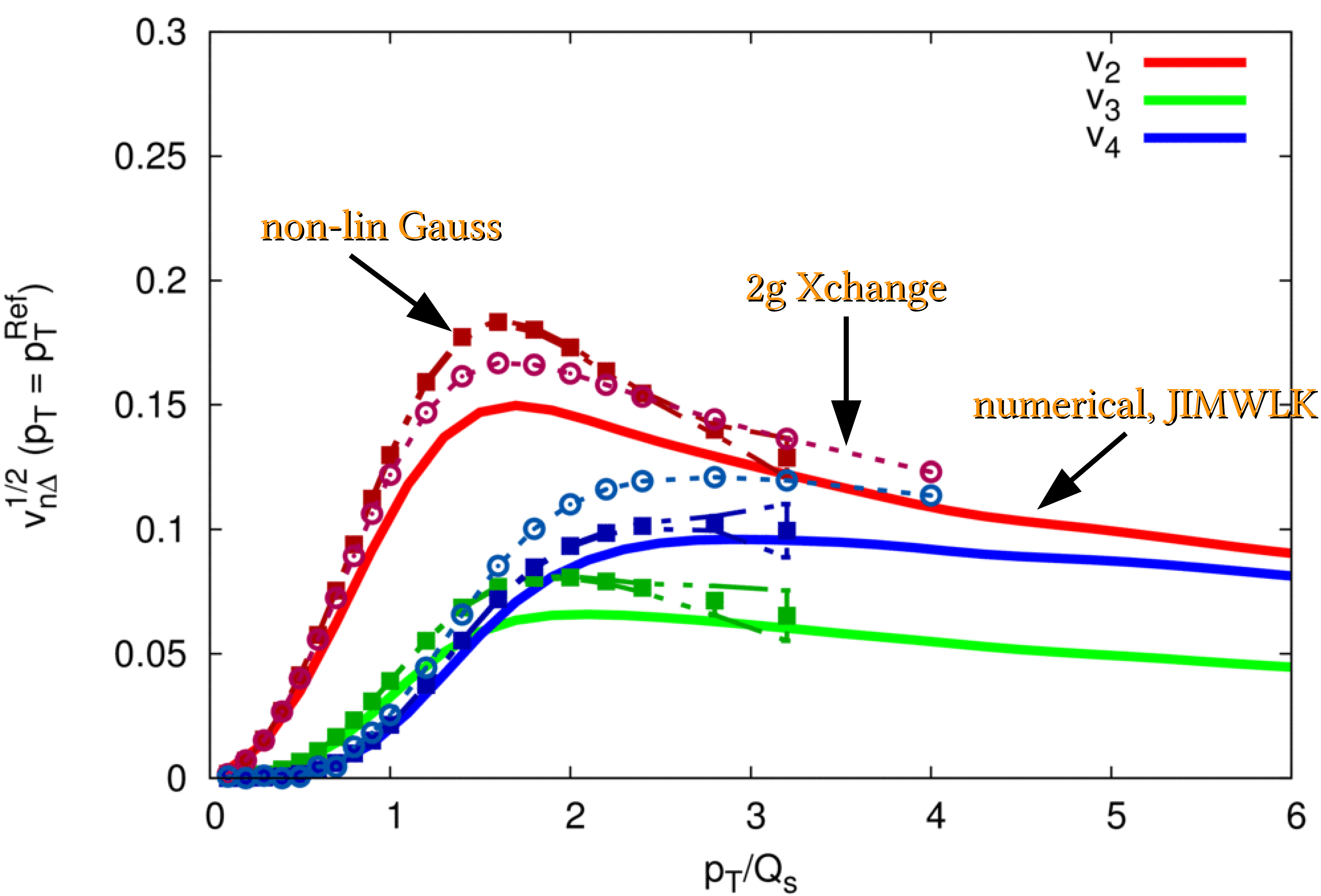
1) 2-gluon exchange ("Glasma graphs"):

$$\langle \mathcal{D}_{xy}\mathcal{D}_{uv}\rangle \simeq D_{xy}D_{uv} + \frac{1}{N_c^2-1}\left(D_{yu}D_{xv} - D_{yv}D_{xu}\right)$$

2) non-linear Gaussian approx (large Nc for simplicity):

$$\langle \mathcal{D}_{xy}\mathcal{D}_{uv}\rangle \simeq D_{xy}D_{uv} + \frac{1}{N_c^2}\left(\frac{\log\frac{D_{xu}D_{yv}}{D_{xv}D_{uy}}}{\log\frac{D_{xy}D_{uv}}{D_{xv}D_{uy}}}\right)^2\left(D_{yu}D_{xv} + D_{xy}D_{uv}\left(\log\frac{D_{xy}D_{uv}}{D_{xv}D_{uy}} - 1\right)\right)$$

3) exact numerical computation (incl. r.c. JIMWLK)



Lappi, Schenke, Schlichting, Venugopalan,
1509.03499

Ok, there are two-particle correlations $\longrightarrow$ $v_2\{2\}$

But how about four-particle correlations? $\longrightarrow$ $v_2\{4\}$??

break rot. symmetry within "domains": replace

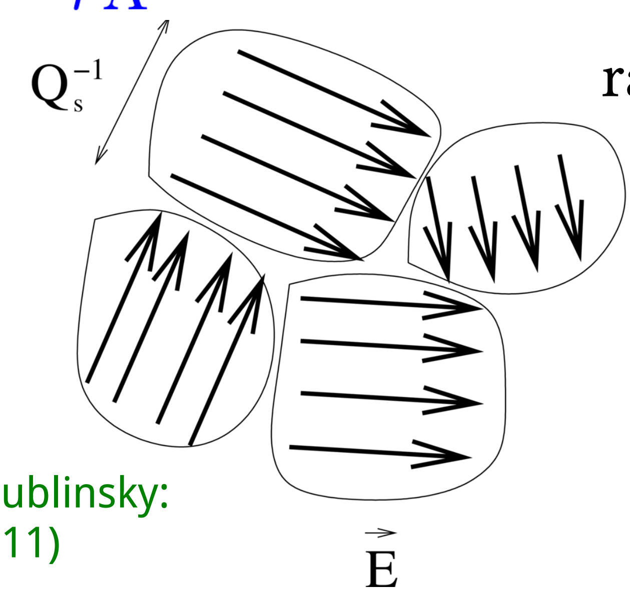
$$\langle S\rangle - 1 = \frac{(ig)^2}{2N_c} r^i r^j \left\langle \mathrm{tr}\; E^i(\vec{b}) E^j(\vec{b}) \right\rangle = -\frac{1}{4} r^2 Q_s^2(\vec{b}) \log\frac{1}{r\Lambda}$$

by

$$\frac{(ig)^2}{2N_c} r^i r^j \left\langle \mathrm{tr}\; E^i(\vec{b}_1) E^j(\vec{b}_2) \right\rangle_{\hat{a}} = -\frac{1}{4} r^2 Q_s^2 \log\frac{1}{r\Lambda}\; \left(1 - \mathcal{A} + 2\mathcal{A}\,(\hat{r}\cdot\hat{a})^2\right)$$

random

$$C(\hat{a},\hat{a}') = 2\pi\,\delta(\phi_a - \phi_{a'})\,\Delta(\vec{b}_1 - \vec{b}_2)$$



Kovner & Lublinsky:
PRD 84 (2011)

$$(v_2\{2\})^2 \equiv \left\langle e^{2i(\phi_1-\phi_2)} \right\rangle = \frac{1}{N_D} \left(\mathcal{A}^2 + \frac{1}{4(N_c^2-1)} \right)$$

$$c_2\{4\} \equiv \left\langle e^{2i(\phi_1-\phi_2+\phi_3-\phi_4)} \right\rangle - 2\left\langle e^{2i(\phi_1-\phi_2)} \right\rangle \left\langle e^{2i(\phi_3-\phi_4)} \right\rangle$$

$= -(v_2\{4\})^4$

$$= -\frac{1}{N_D^3} \left[\mathcal{A}^4 - \frac{1}{4(N_c^2-1)^3} \right]$$

(around $c_2\{4\}$~0)

A.D., McLerran, Skokov:1410.4844

Note: E-field domain model by construction non-Gaussian,

$$\int \frac{d\hat{a}}{2\pi} \left\langle E_a^i(\mathbf{x}) E_b^j(\mathbf{y}) E_c^k(\mathbf{u}) E_d^l(\mathbf{v}) \right\rangle_{\hat{a}}$$

not a product of two-point functions

$$\int \frac{d\hat{a}}{2\pi} \left\langle E_a^i(\mathbf{x}) E_b^j(\mathbf{y}) \right\rangle_{\hat{a}}$$

Lappi, Schenke, Schlichting, Venugopalan, 1509.03499

Some questions that remain to be answered:

- Do 4-particle angular correlations require non-Gaussianities ?
  What would be their origin?
  Initial condition? Corrections to JIMWLK? ..

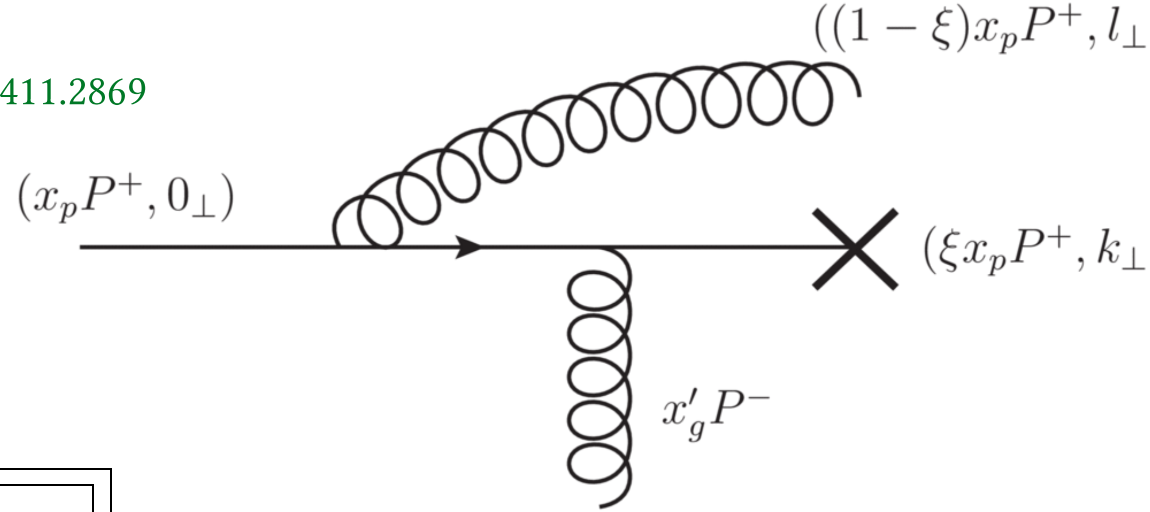
- multiplicity dependence ?
  factorize <..> into fluctuations of Qs ⊗ remaining subset ?

- it may be useful to have a "full" numerical calculation of
  2 & 4-particle correlations, incl.
  - multiplicity / energy density bias
  - fragmentation to hadrons

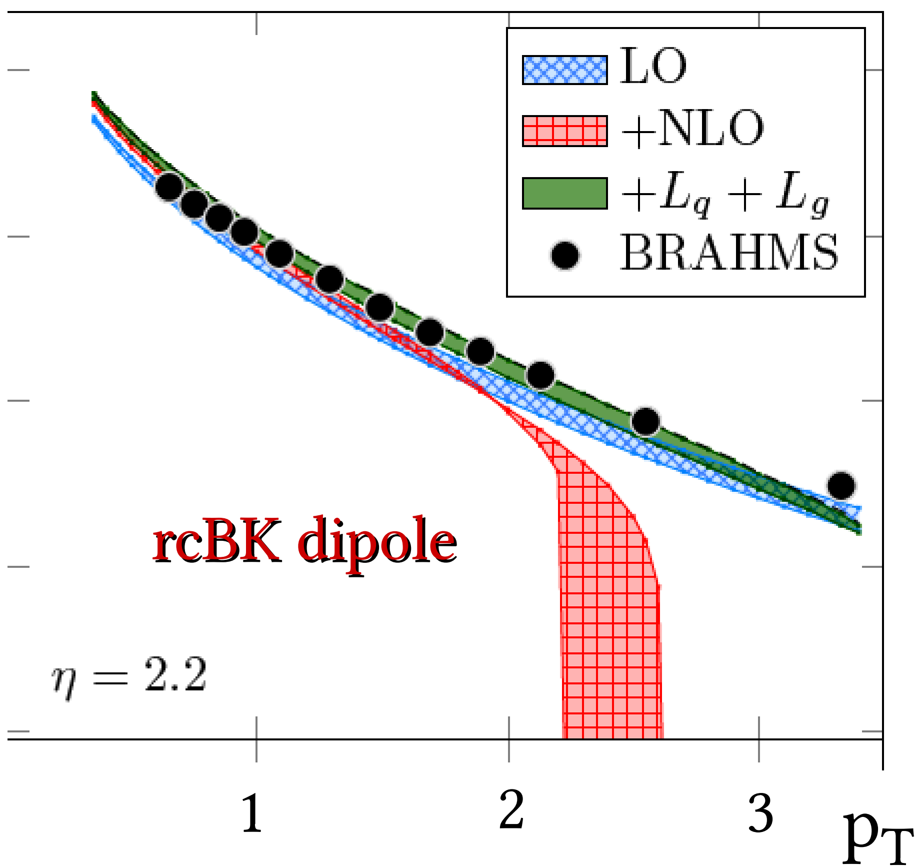
Particle production in pA

- “Hybrid formalism” @ NLO
- corrections to the eikonal approx. (shockwave limit)

- Altinoluk, Kovner, 1102.5327
  Altinoluk, Armesto, Beuf, Kovner, Lublinsky, 1411.2869
- Chirilli, Xiao, Yuan, 1112.1061, 1203.6139
- Stasto, Xiao, Zaslavsky, 1307.4057
  Stasto, Xiao, Yuan, Zaslavsky, 1405.6311



Watanabe, Xiao, Yuan, Zaslavsky, 1505.05183



need to incorporate kinematic constraint:

$$\xi < 1 - \frac{l_\perp^2}{x_p\, s}$$

$$\rightarrow \int_0^{1-\frac{l_\perp^2}{x_p\, s}} \frac{d\xi}{1-\xi} = \log\frac{1}{x_g} + \log\frac{k_\perp^2}{l_\perp^2}$$

impressive agreement down
to pT ~ 1 GeV at √s = 5 TeV
with a A=208 target !
(energy dependence not fitted!)

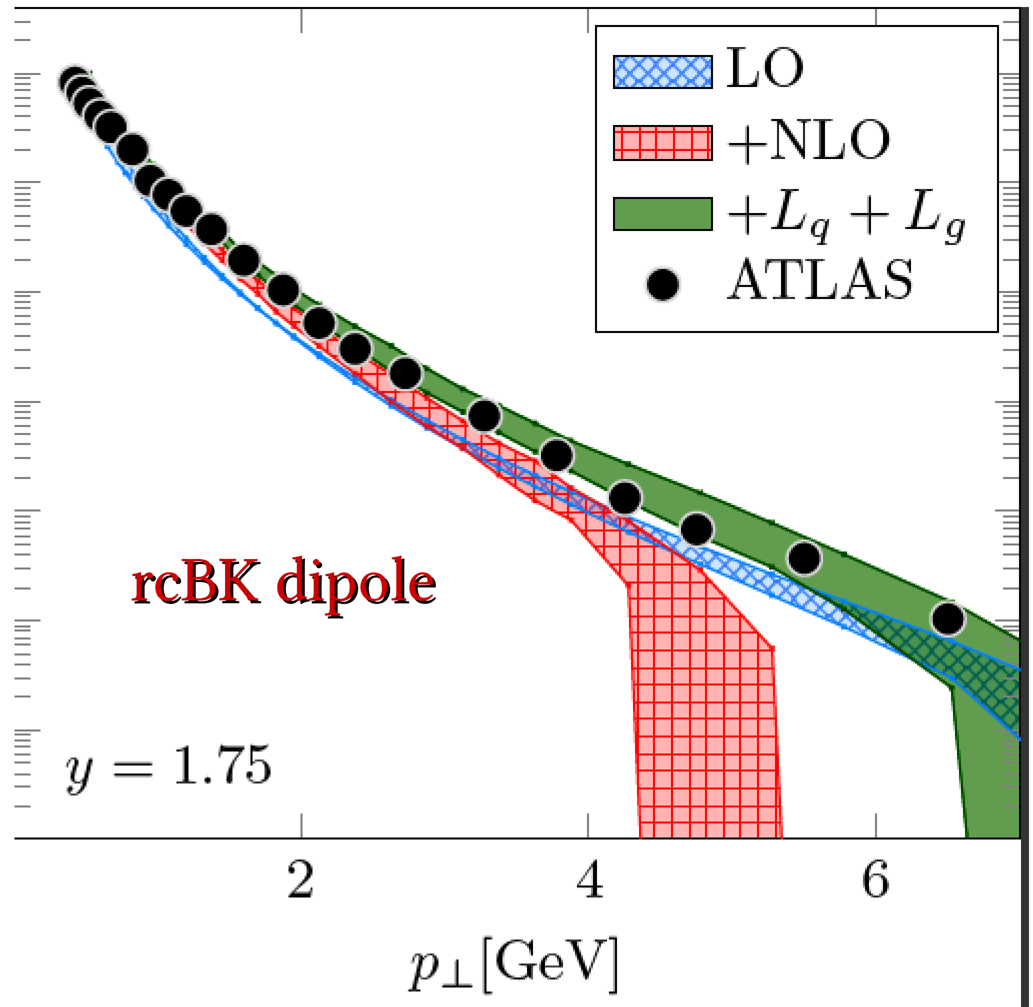
should "survive" DLA-rcBK
(resum. of double collinear logs)
since N(r) not much different

(J. Albacete, 1507.07120)

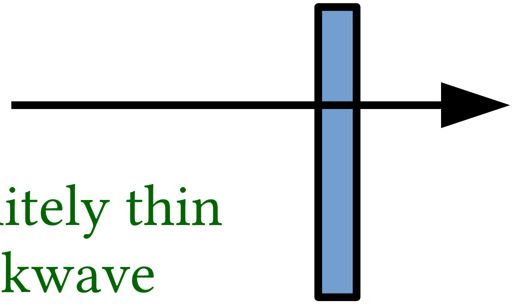
Also doable:

- more forward y
- A dependence
- heavy Q (at LO)

p+Pb @ LHC, 5.02TeV



Correction to eikonal / shockwave approximation: finite target thickness



infinitely thin shockwave

$$U^{ab}(x^+, y^+) = \mathcal{P}\ \exp\left(ig \int_{y^+}^{x^+} dz^+ A^-(z^+, \mathbf{z}_{cl}(z^+)) \right)$$

$$\mathbf{z}_{cl}(z^+) = \mathbf{y} + \frac{z^+ - y^+}{x^+ - y^+}(\mathbf{x} - \mathbf{y})$$

sum over paths through target of thickness $\ell^+ \sim A^{1/3}$

$$\mathcal{G}^{ab}_{k^+}(\underline{x}; \underline{y}) = \mathcal{G}_{0,k^+}(\underline{x}; \underline{y})\ \ \mathcal{R}^{ab}_{k^+}(\underline{x}; \underline{y})$$

$$\mathcal{R}^{ab}_{k^+}(\underline{x}; \underline{y}) = 2\pi i \frac{(x^+ - y^+)}{k^+} \lim_{N \to +\infty} \int \left(\prod_{n=1}^{N-1} d^2\mathbf{u}_n \right)$$

$$\times \quad \mathcal{P}_+ \prod_{n=0}^{N-1} \left\{ \mathcal{G}_{0,k^+}\left(z^+_{n+1}, \mathbf{u}_{n+1}; z^+_n, \mathbf{u}_n\right) \exp\left[\frac{(x^+ - y^+)}{N}\ igT \cdot \mathcal{A}^-\left(z^+_n, \mathbf{z}^{\mathrm{cl}}_n + \mathbf{u}_n\right) \right] \right\}$$

$$\int d^2x\, e^{-ik\cdot x}\, \mathcal{G}^{ab}_{k^+}(\underline{x};\underline{y}) = \theta(x^+ - y^+)\, e^{-ik\cdot y}\, e^{-ik^-(x^+-y^+)} \Big\{ \mathcal{U}(x^+,y^+,y) + \frac{(x^+-y^+)}{k^+} k^i\, \mathcal{U}^i_{(1)}(x^+,y^+,y) + i\frac{(x^+-y^+)}{2k^+}\, \mathcal{U}_{(2)}(x^+,y^+,y) \Big\}^{ab}$$

"decorated" Wilson lines (w/ E-field insertions):

$$\mathcal{U}^{i,ab}_{(1)}(x^+,y^+,y) = \int_{y^+}^{x^+} dz^+ \left(\frac{z^+-y^+}{x^+-y^+}\right) \Big\{ \mathcal{U}(x^+,z^+,y)\left[igT\cdot\partial_{y^i}A^-(z^+,y)\right]\mathcal{U}(z^+,y^+,y)\Big\}^{ab}$$

Note: Wilson lines not taken off L.C. (→ Babansky, Balitsky: hep-ph/0212075),
this is about finite target thickness

Altinoluk, Armesto, Beuf, Martínez, Salgado: 1404.2219
Altinoluk, Armesto, Beuf, Moscoso: 1505.01400

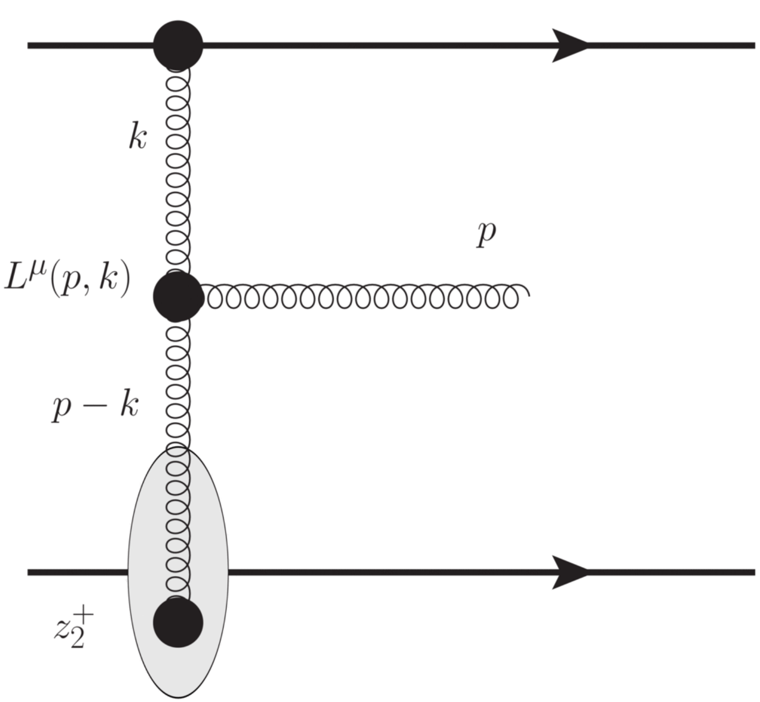
Altinoluk, A.D.: 1512.00279

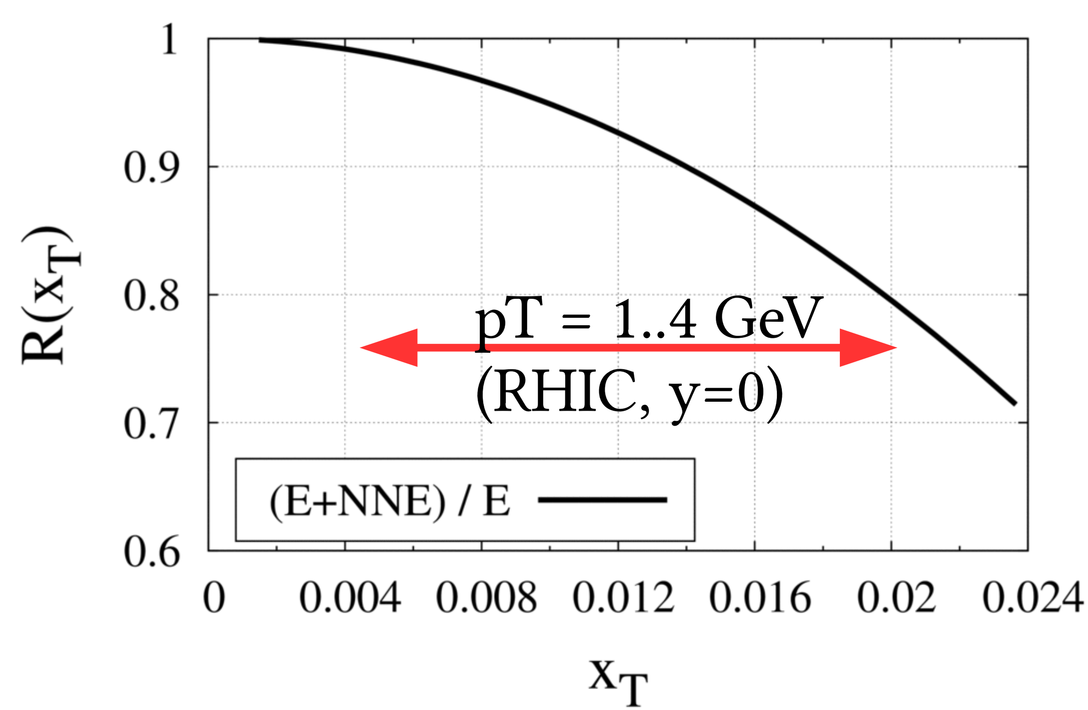
Expansion to O(ρ_2) gives Lipatov vertex for thick target & k_T-factorization formula

$$L^i(p,k) = -k^2 \left\{ 2C^i(p,k) + ip^2 C^i(p,k)\frac{z_2^+}{p^+} + \left[\frac{k^i}{k^2}[p\cdot(p-k)]^2 - \frac{p^4}{4}C^i(p,k)\right]\left(\frac{z_2^+}{p^+}\right)^2 \right\}$$

$$p^+ \frac{d\sigma}{dp^+ d^2p\, d^2b} = 4N_c(N_c^2-1)\, S_\perp \frac{g^2}{p^2}\int \frac{d^2k}{(2\pi)^2}\,\Phi_P(k)\,\Phi_T(p-k) \times \left[1 - \frac{1}{4\Delta\eta}\left(\frac{\ell^+}{p^+}\right)^2 \frac{[p\cdot(p-k)]^3}{(p-k)^2}\right]$$

NNE correction





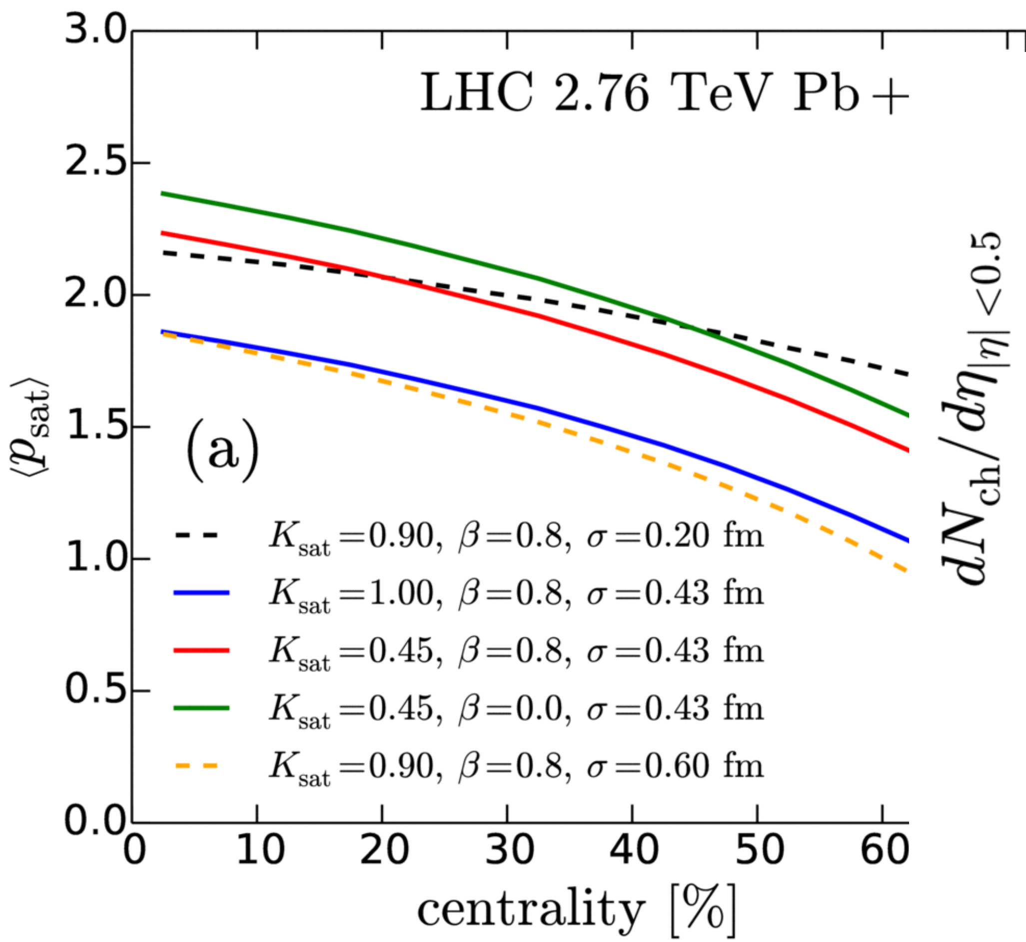
Initial State of A+A Collisions

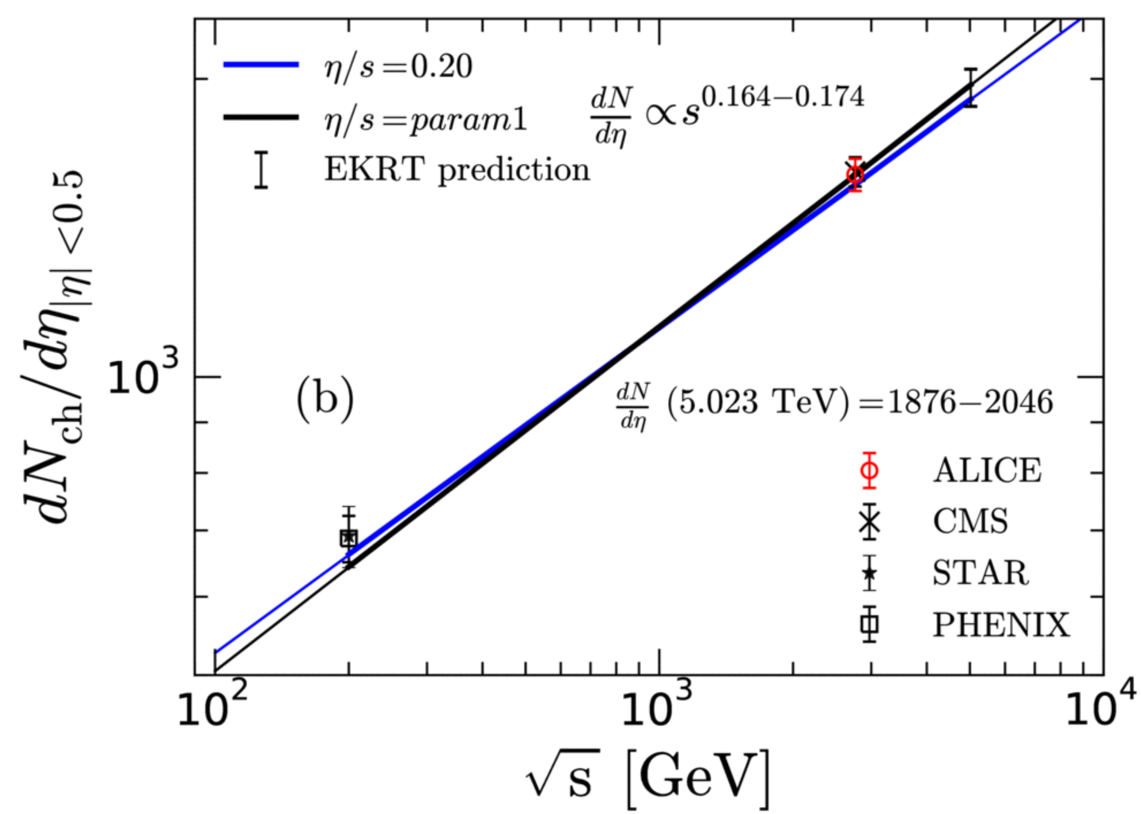
- EKRT saturation model -

talk by R. Paatelainen & 1505.02677, 1511.04296

$$\frac{dE_\perp}{d^2r\,dy}(p_{\rm sat}) = \frac{1}{\pi}\,p^3_{\rm sat}(r,y)$$

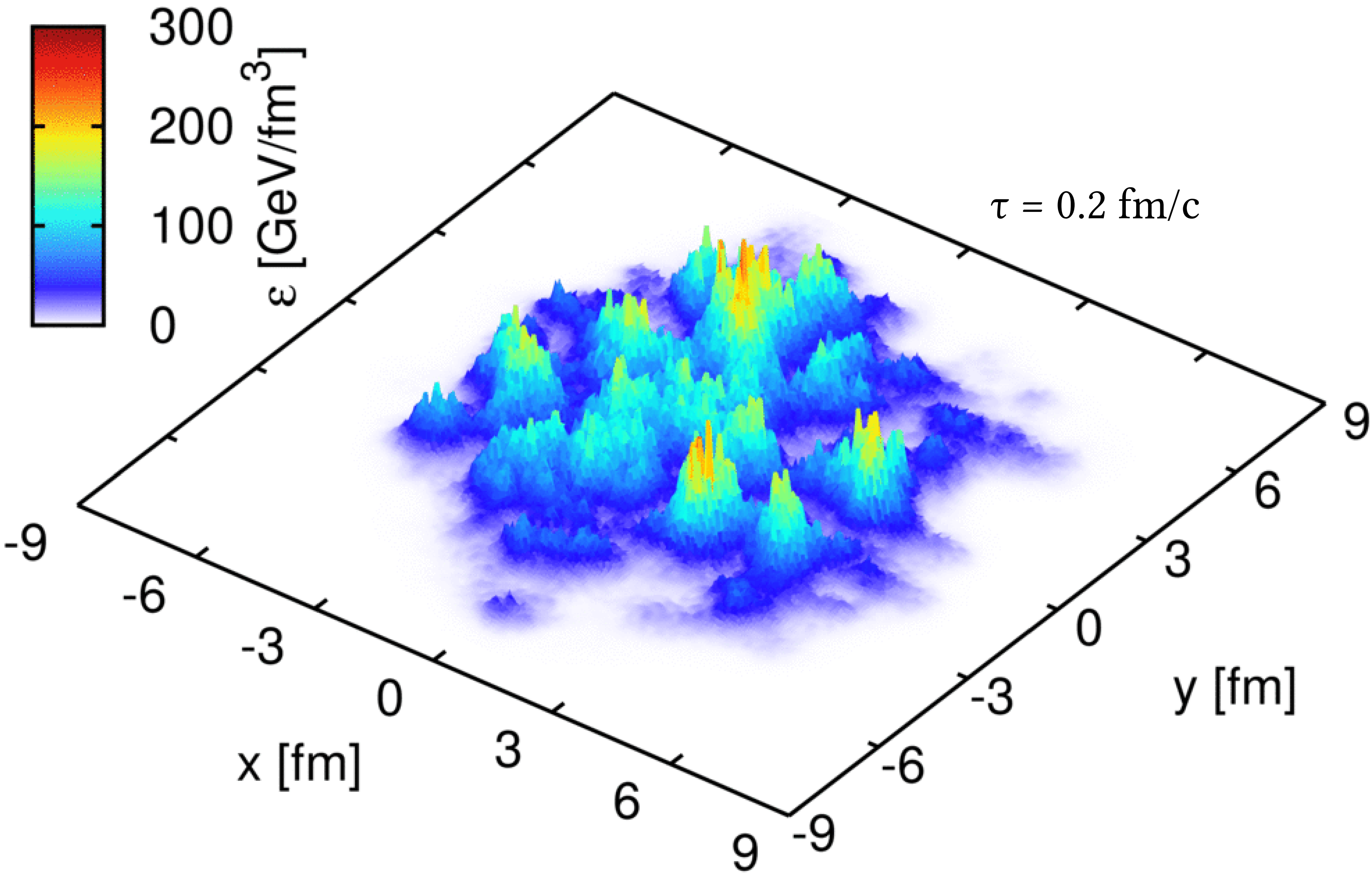
E_T computed at NLO in coll. fact., EPS09 nPDFs





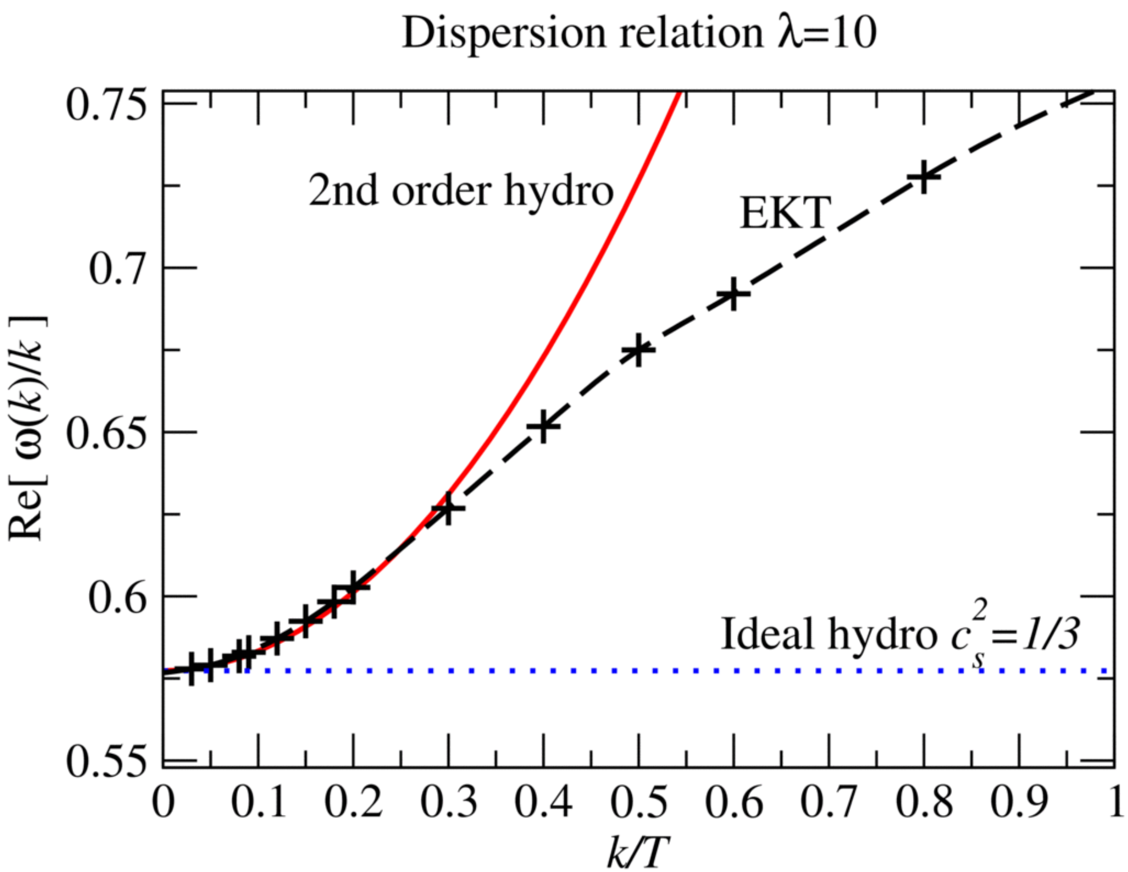
Initial density fluctuations

- propagation from τ_0 to τ_{th}
- potential effect on hydro expansion

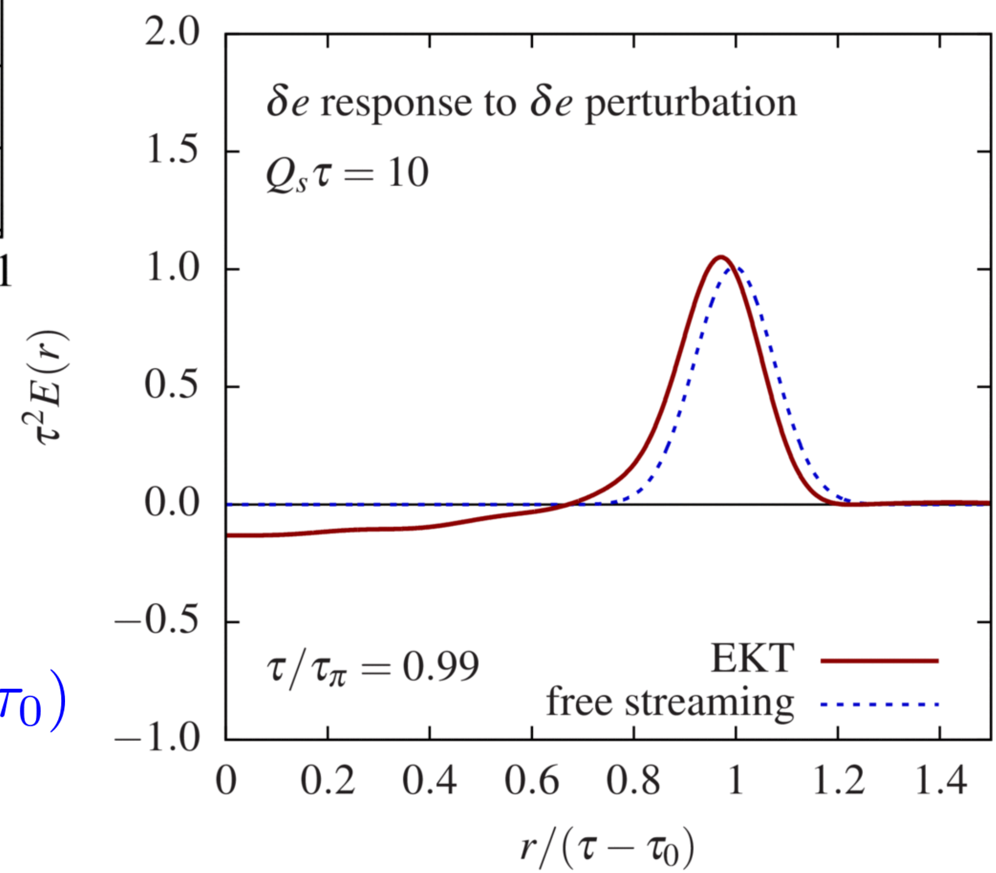


Schenke, Tribedy, Venugopalan: PRL 108 (2012)

propagation from τ_0 to τ_{th} using kin. theory at weak coupling



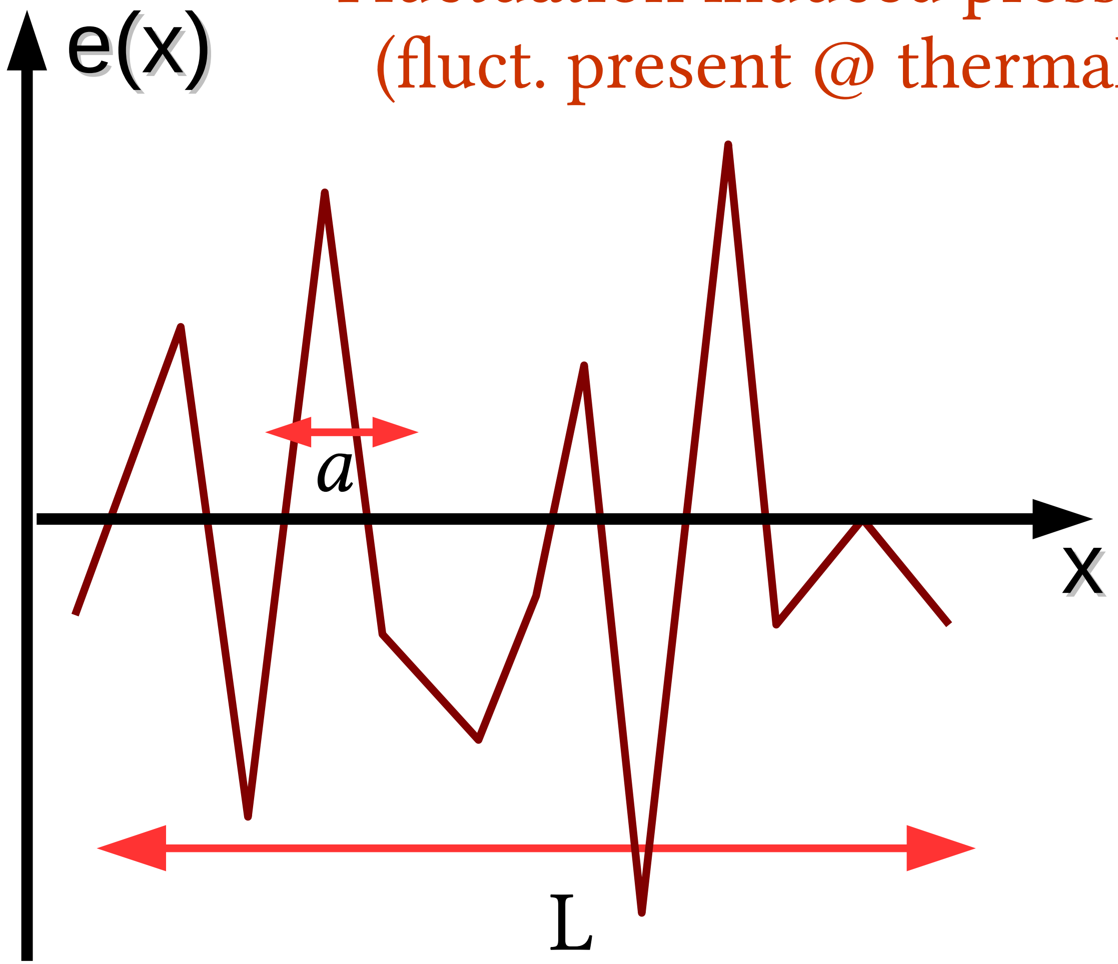
Keegan, Kurkela, Mazeliauskas, Teaney: 1605.04287



evolution kernel:

$$\frac{\delta e(\tau,x)}{e(\tau)} = \int d^2x' \frac{\delta e(\tau_0,x')}{e(\tau_0)} E(x-x'|;\tau,\tau_0)$$

Fluctuation induced pressure ?
(fluct. present @ thermalization)



- (Hydro) observable probes scale L
- (Thermalized) fluctuations at scales $a < L$ induce eff. pressure at scale L
- additional contribution if

  $c_s^2 \neq \text{const.}$

$$p_{\text{eff}}(\bar{e}; L) = p(\bar{e}) + \frac{1}{2} \frac{\partial c_s^2}{\partial e}\bigg|_{\bar{e}} \langle \delta e^2 \rangle \left[1 - \left(\frac{a}{L} \right)^d \right]$$

Example: one-loop pert. theory, conformal at UV fixed point
($g \longrightarrow 0$, asymptotically short scales)

$$e - 3p \equiv T^4\,\Delta(T)\,, \qquad \Delta(T) = -\frac{N(N^2-1)}{72}\,\beta(g(T))\,g(T)$$

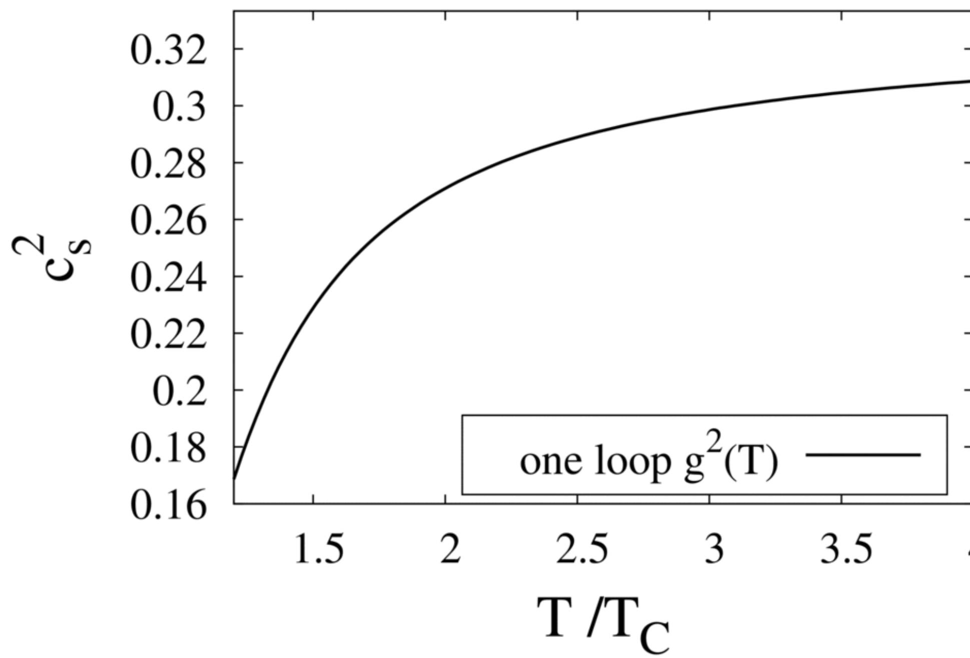
$$= \frac{\beta(g)}{2g}\,\langle F^2\rangle$$

(pure glue)

$$\frac{1}{c_s^2} - 3 = \left(\frac{\partial p}{\partial T}\right)^{-1}\frac{\partial}{\partial T}\left(T^4\Delta(T)\right) \approx \frac{\Delta(T)}{p/T^4}$$

(p/T^4 = const here)

$$= -\#\beta(g)\,g(T) = \frac{\#}{\log^2\,T/\Lambda}$$



One more important ingredient: the scale of fluctuations

$$\Delta p = \frac{1}{2} T \frac{\partial c_s^2}{\partial T} \frac{\bar{e}}{T\,\partial e/\partial T} \frac{\varepsilon}{a^3} \frac{\langle \delta n^2 \rangle}{\bar{n}}$$

for d=3 dim.

ε = energy per particle

(should fluctuate too but assumed constant)

a = fluctuation scale

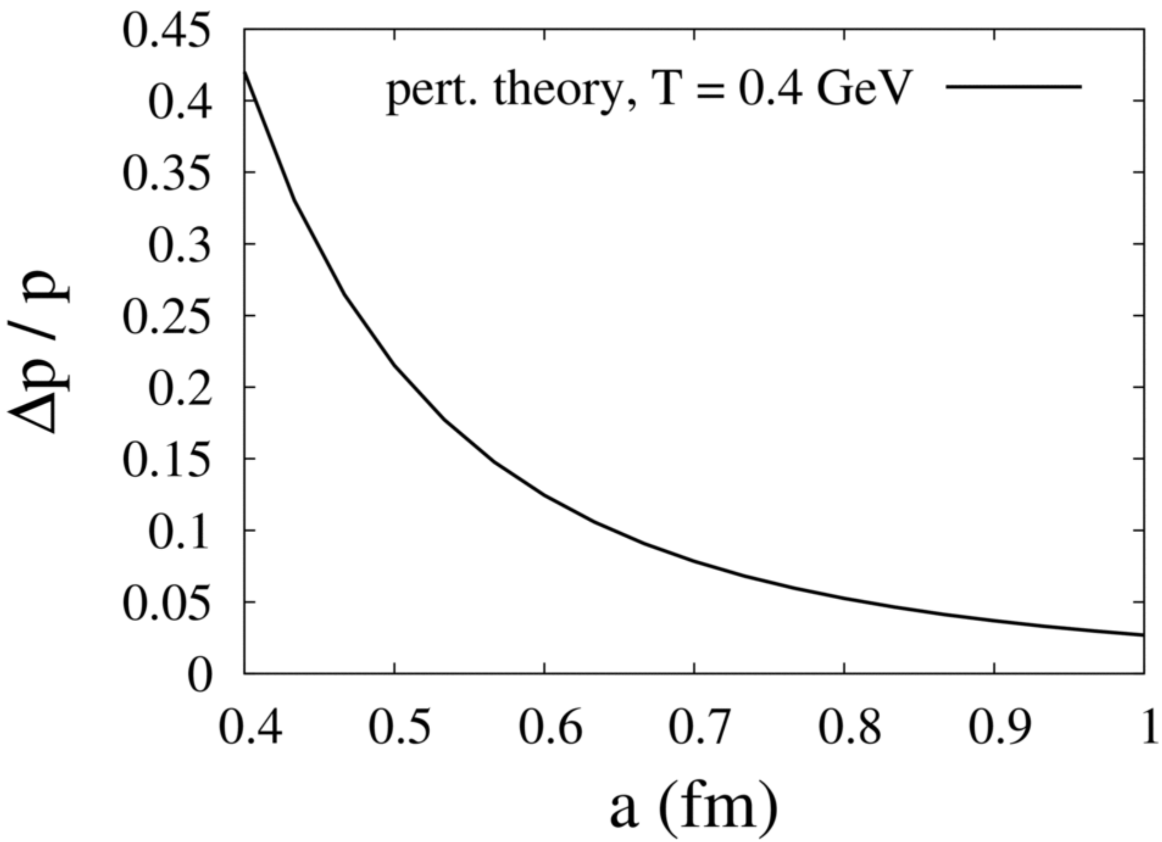
Pert. theory, one-loop β-fct: $$T \frac{\partial c_s^2}{\partial T} = 4 \frac{[c_s^2\, \beta(g)]^2}{e_{\mathrm{SB}}/T^4}$$

$$\Delta p = \frac{1}{2} \frac{[c_s^2\, \beta(g)]^2}{e_{\mathrm{SB}}/T^4} \frac{3T}{a^3} \frac{\langle \delta n^2 \rangle}{\bar{n}}$$

Pisarski EoS, Δ(T) T² = const.: $$\varepsilon = 4T \frac{3T^2 - T_C^2}{4T^2 - 2T_C^2}$$

$$\Delta p = \frac{T^2}{T_C^2} (1 - 3c_s^2)^2 \frac{3\frac{T^2}{T_C^2} - 1}{12\frac{T^2}{T_C^2} - 2} \frac{\varepsilon}{a^3} \frac{\langle \delta n^2 \rangle}{\bar{n}}$$

Rough estimate of Δp/p :



- NBD/KNO
  $\delta n^2/n = 5$
- $L \gg a$
- perturbative EoS

$$\Delta p = \frac{1}{2} \frac{[c_s^2\, \beta(g)]^2}{e_{\rm SB}/T^4} \frac{3T}{a^3} \frac{\langle \delta n^2 \rangle}{\bar{n}}$$

Δp/p small for a ~ 1 fm
but ~ O(1) for a ≤ 0.4 fm

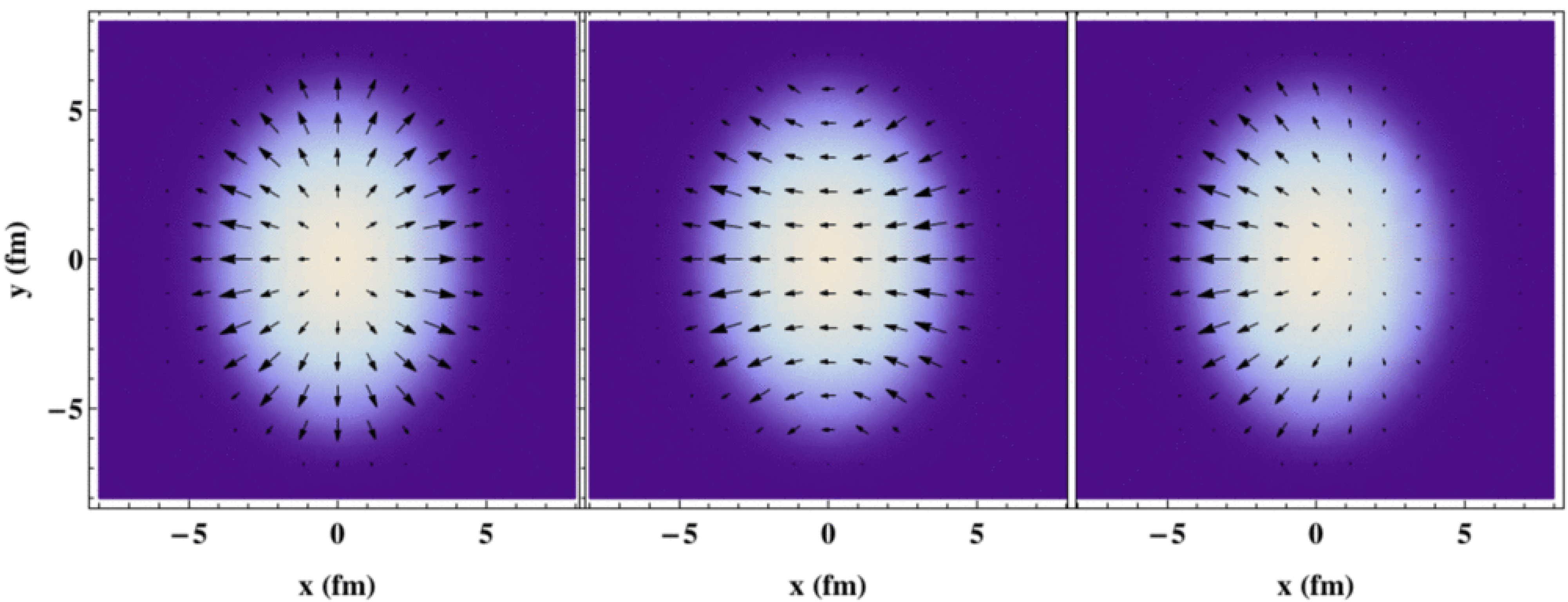
Initial (pre-equ.) flow from classical YM:

Chen, Fries, Kapusta, Li: 1507.03524

analytic solution of YM eqs in an expansion in powers of τ

$$T^{0i}_{\text{even}} = \frac{\tau}{2}\alpha^i\left(1 - \frac{1}{2a}(Q\tau)^2\right)\cosh\eta$$

$$T^{0i}_{\text{odd}} = \frac{\tau}{2}\beta^i\left(1 - \frac{9}{16a}(Q\tau)^2\right)\sinh\eta$$



Summary

Plenty of new stuff to be presented at this meeting,

please attend dedicated talks !