What aspects of initial stages will NOT be tractable

(or will, but without sufficient precision)

with current or forseeable theoretical tools?

Derek Teaney
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Thanks to: A. Kurkela, U. Heinz, A. Mazeliauskas, J. Jia, P. Steinberg, J. F. Paquet, and S. Schlichting

What aspects of initial stages are ALMOST tractable with current theoretical tools?

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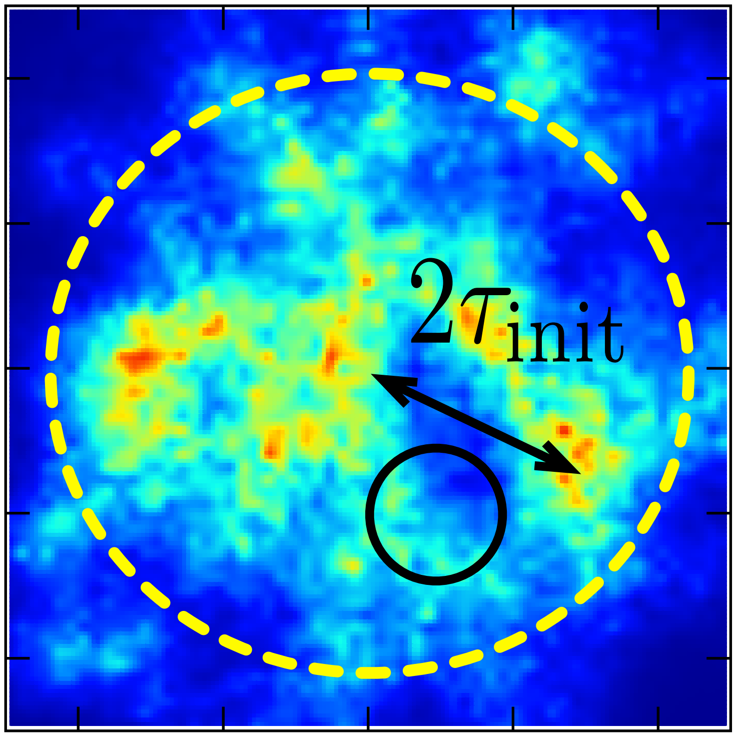
Spatial scales for initial stages in A+A

IP Glasma A+A



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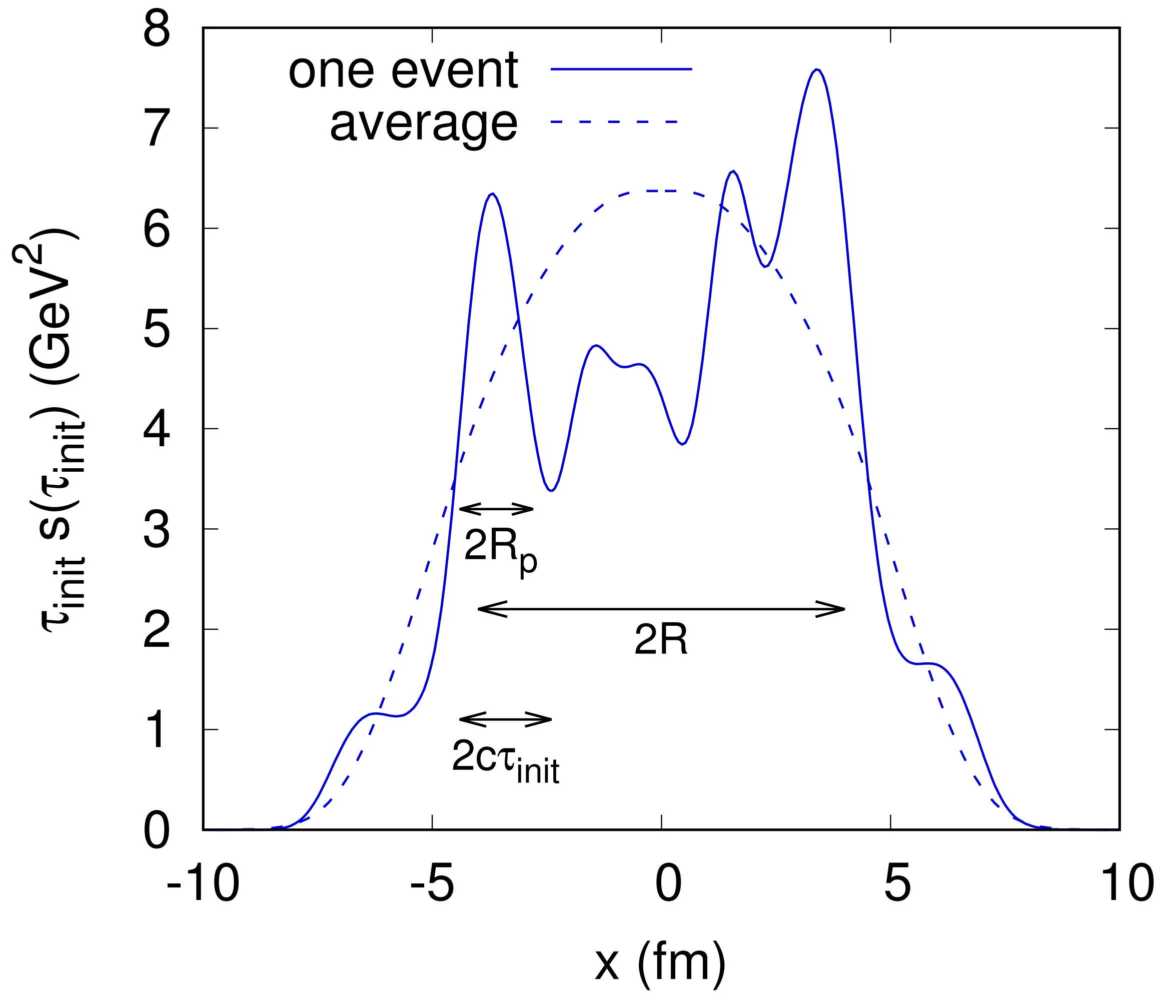


Many scales are the same:

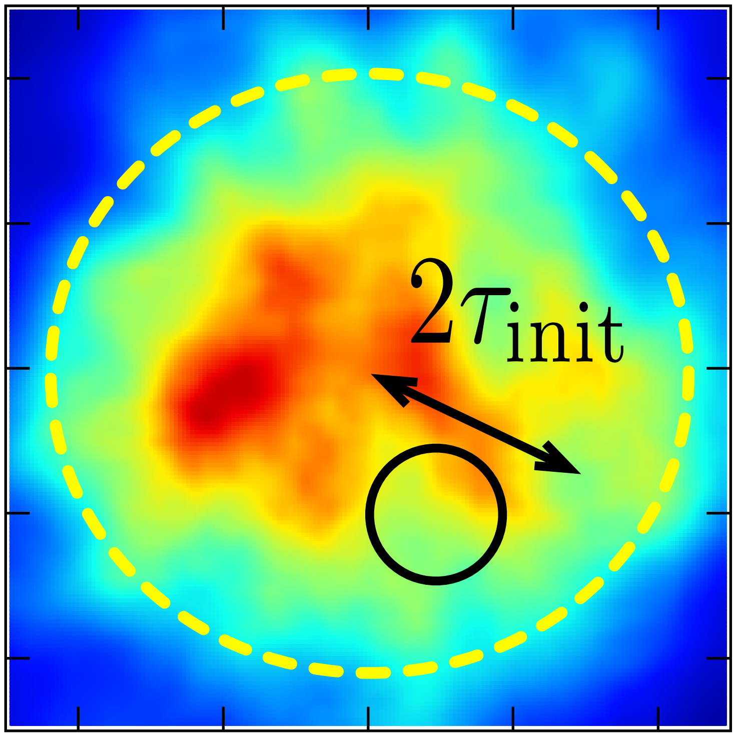
$$R \gg c\tau_{\text{init}} \sim R_p \sim \ell_{\text{mfp}} \gg \frac{1}{Q_s}$$

Need kinetics !

Spatial scales for initial stages in A+A

U. Heinz, A. Mazeliauskas – this meeting

IP Glasma A+A



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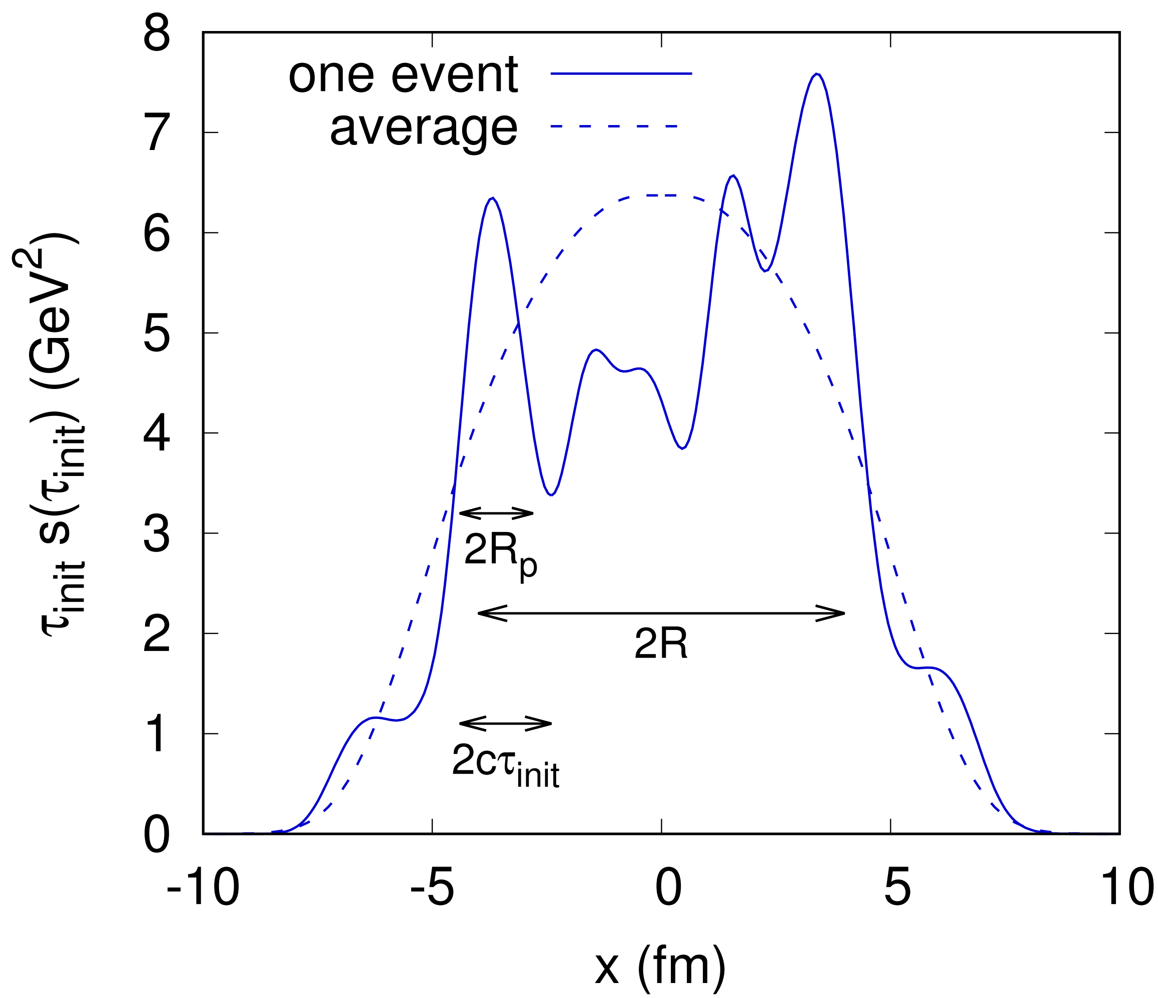

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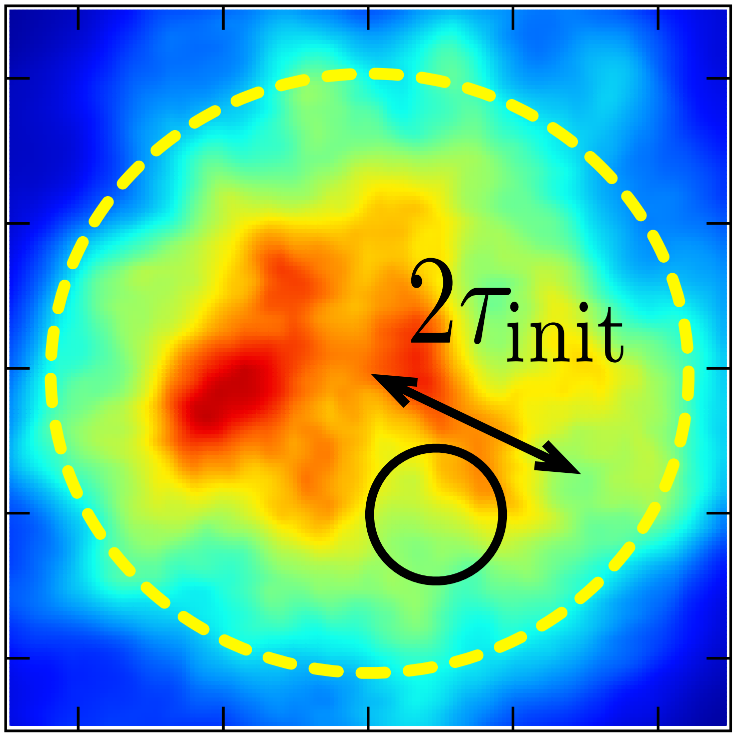

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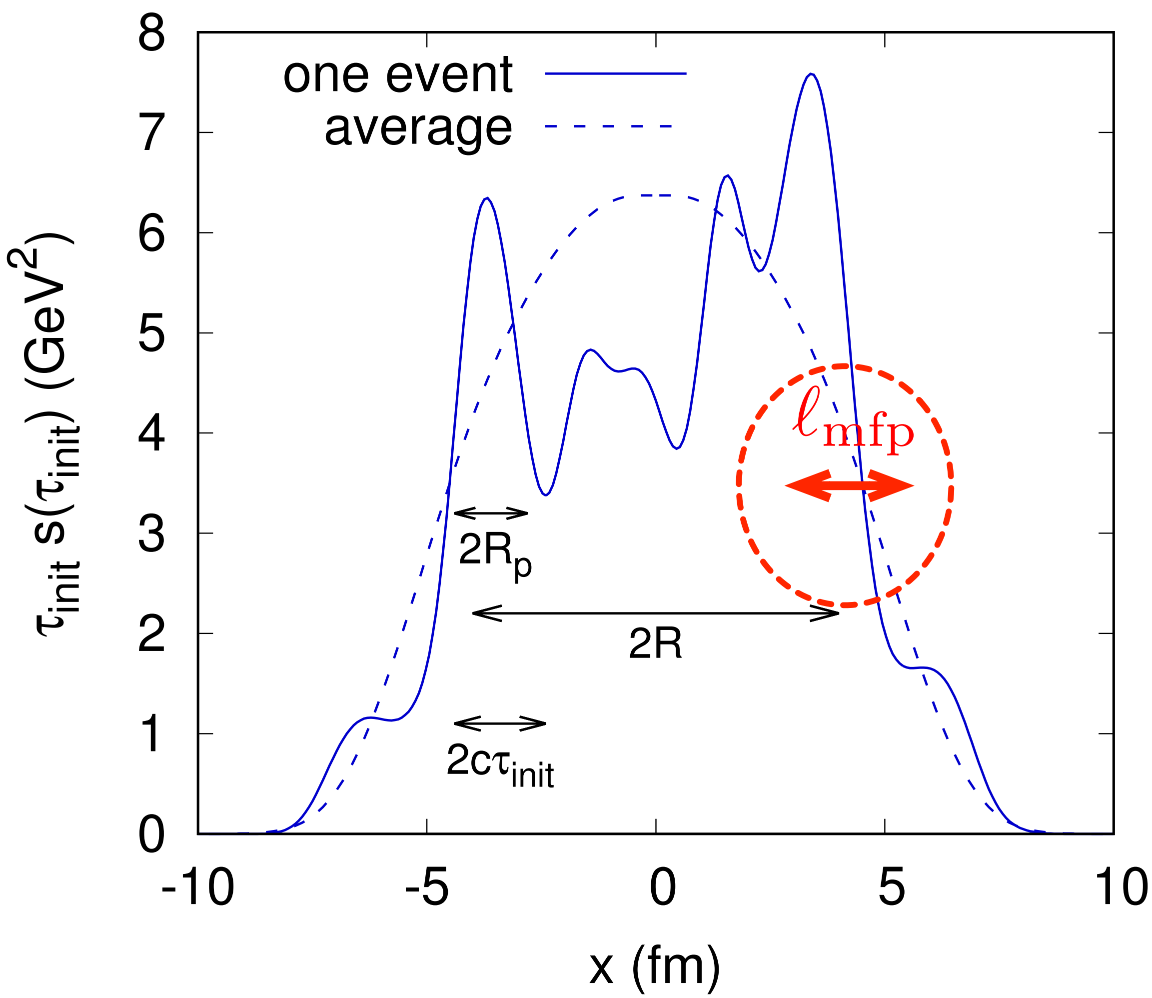

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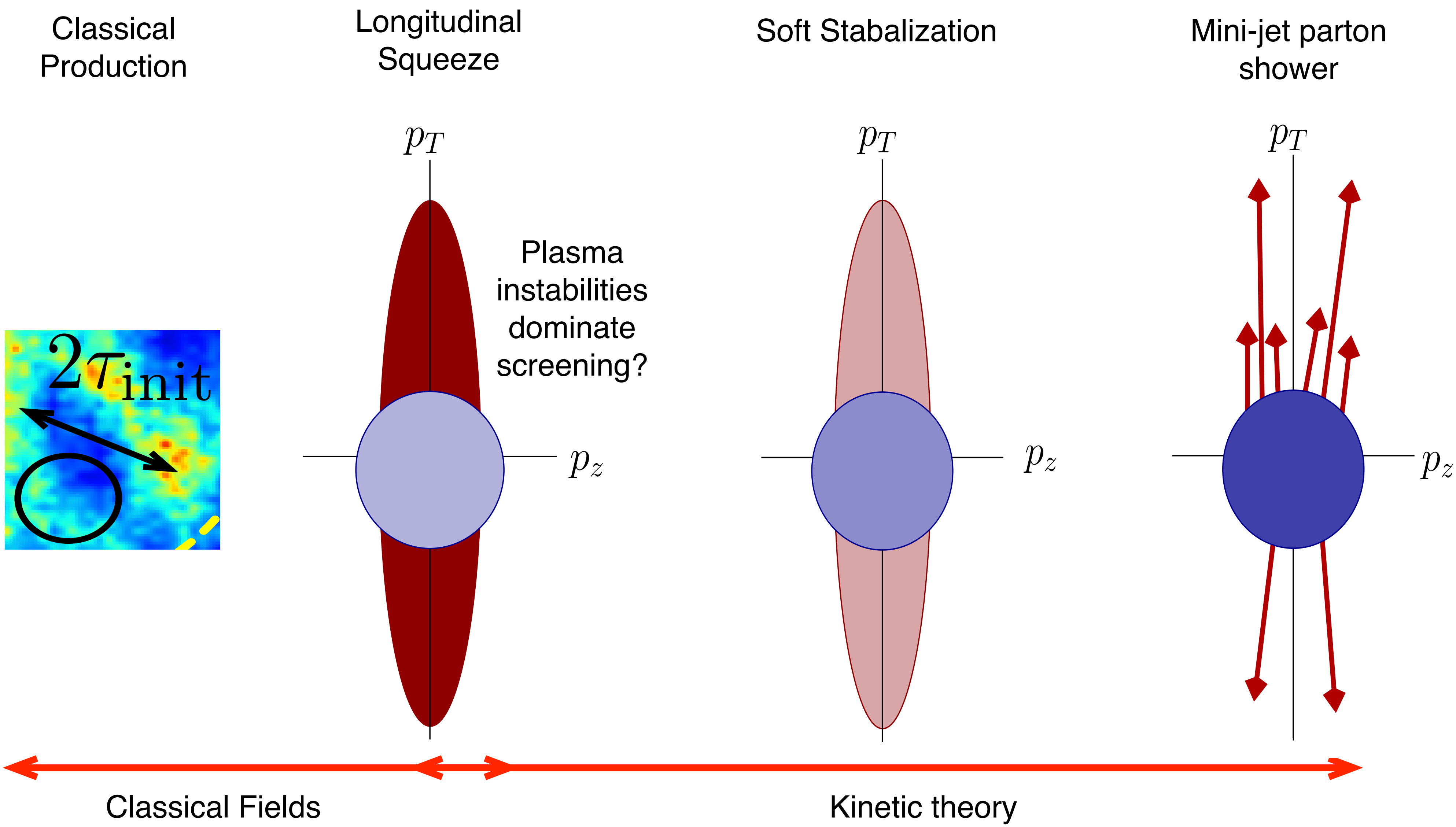
Momentum scales and “bottom-up” thermalization

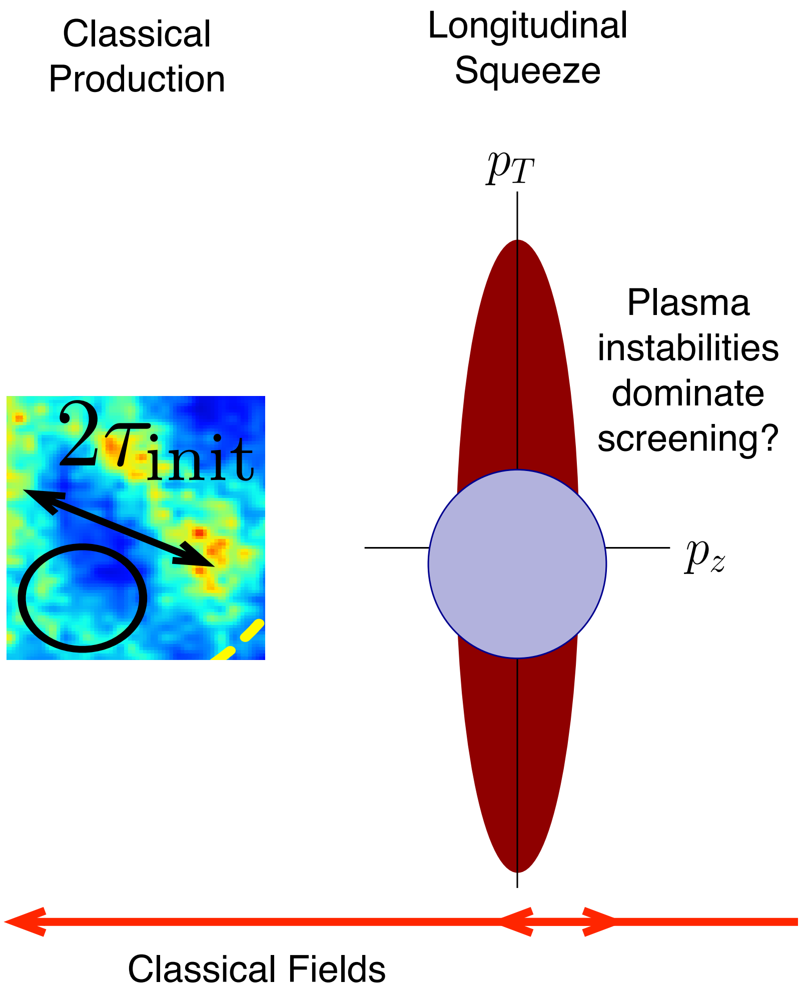
Baier, Mueller, Schiff, Son



Reach a thermal state in $\tau_{\rm init} \sim 1/(\alpha_s^{2.6} Q_s)$

The classical phase of “bottom-Up” in 2014

Berges, Boguslavski, Schlichting, Venugopalan



Recent progress on the first phase of “bottom-up”

- Scaling solution for phase space distribution

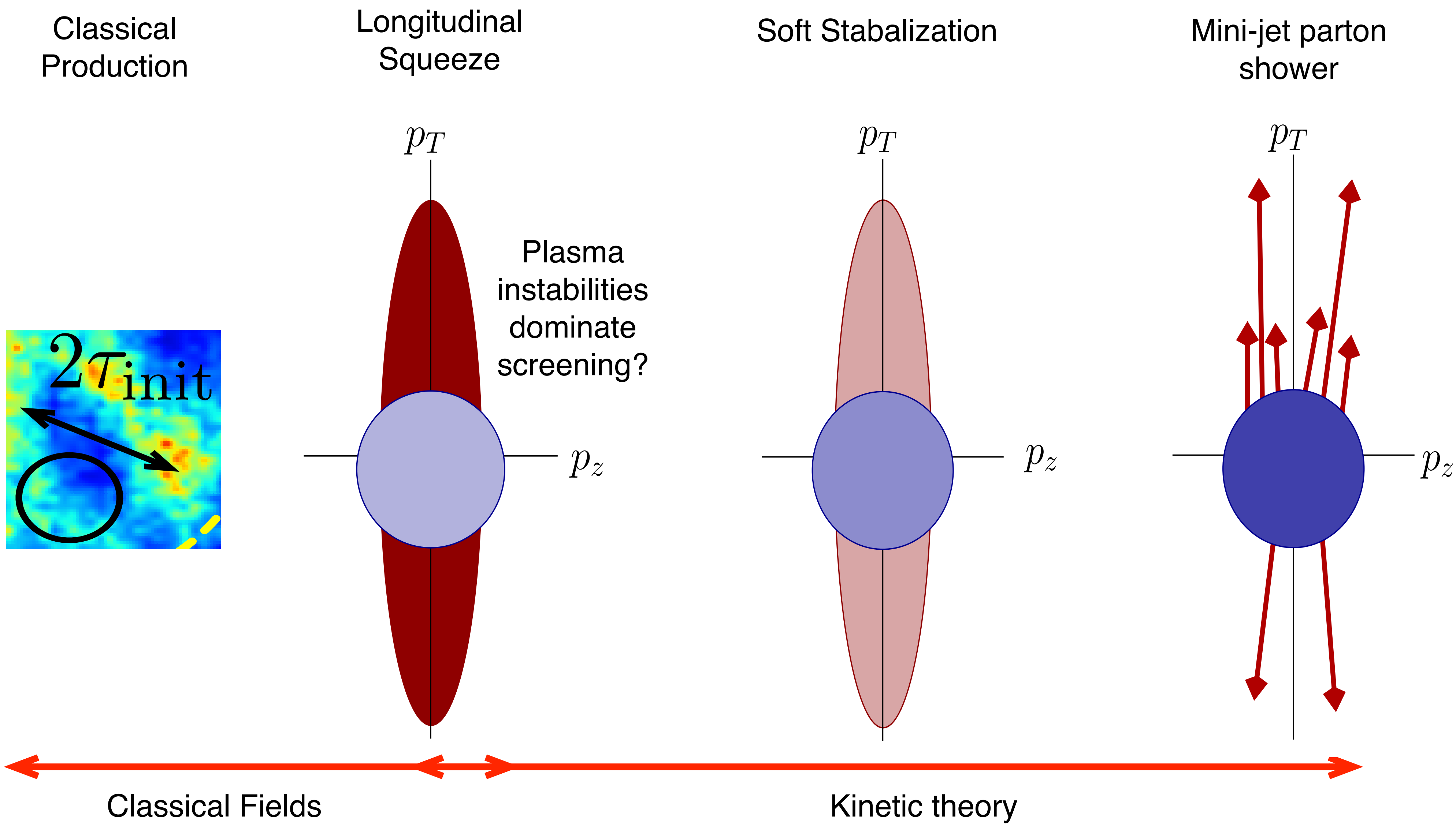
$$f(\tau, p_z, p_T) = \frac{(Q\tau)^{1/3}}{\tau} f_o(p_z(Q\tau)^{1/3}\,,\, p_T)$$

- Need to compare classical and kinetics in detail
- Instabilities do not seem to play a significant role

Reach the end of the first phase at $\tau \sim 1/(\alpha_s^{3/2} Q_s)$

Momentum scales and “bottom-up” thermalization

Baier, Mueller, Schiff, Son

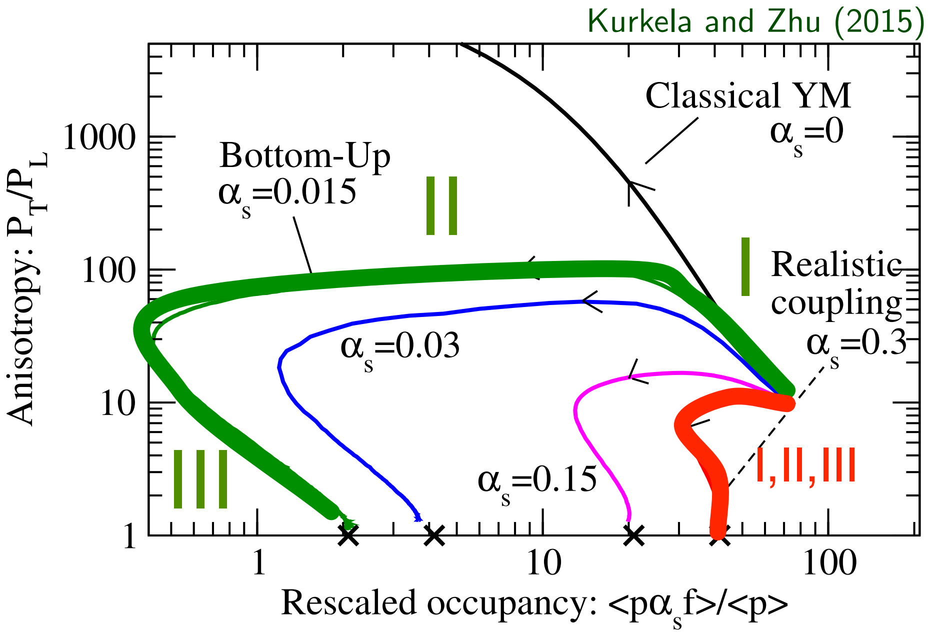


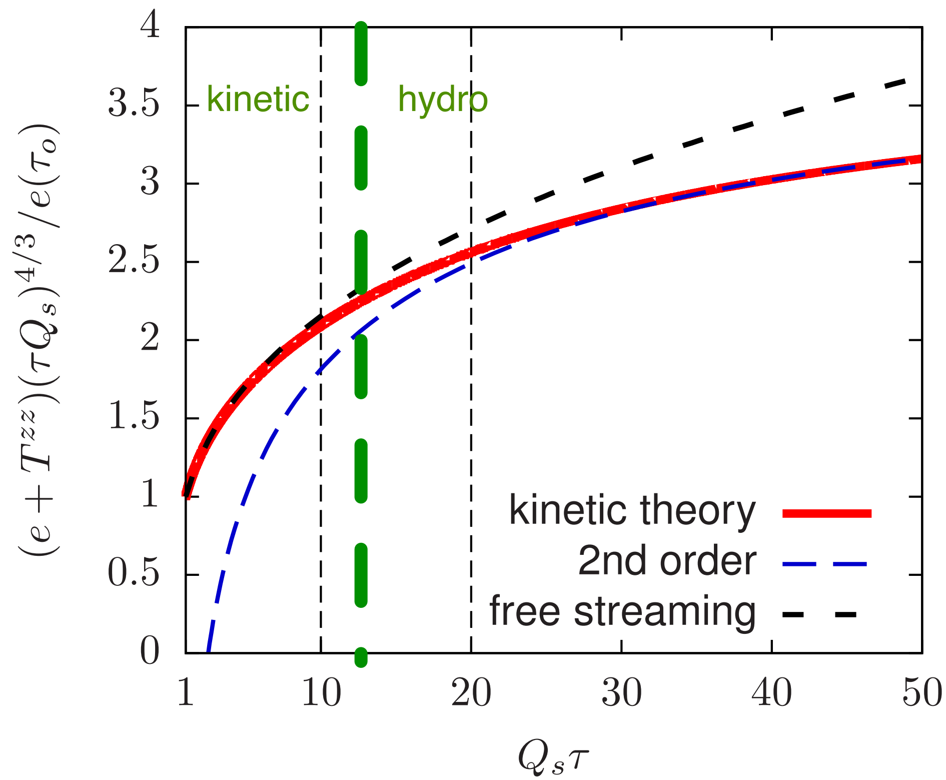
Reach a thermal state in $\tau_{\rm init} \sim 1/(\alpha_s^{2.6} Q_s)$

The kinetic phase of "bottom-Up" in 2015

Kurkela, Zhu

- Compare the longitudinal pressure T^{zz} with hydro prediction to calibrate equilibration



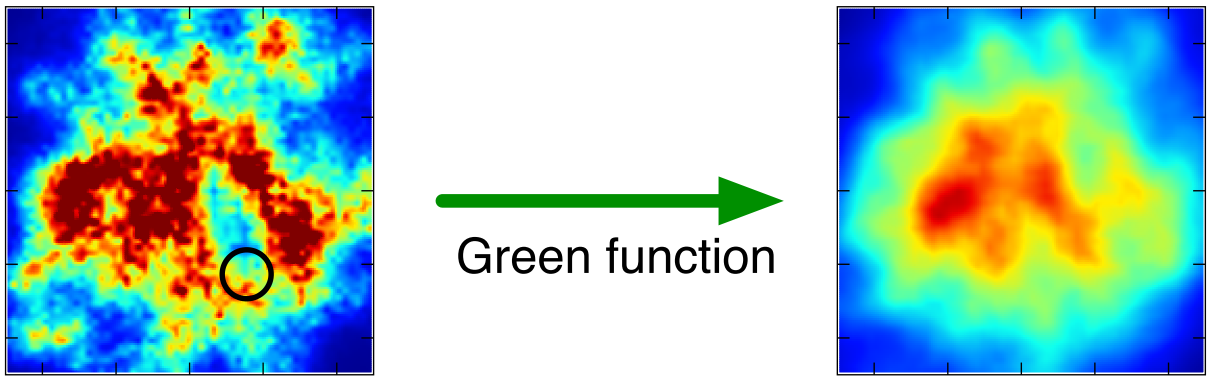


For realistic coupling three stages still "exists" and

$$\tau_{\rm init} \simeq \frac{10}{Q_s}\left(\frac{0.3}{\alpha_s}\right)^{2.6}$$

constitutive relations satisfied to 10%

$$\int d^2\boldsymbol{x}' \underbrace{\frac{\delta e(\tau_0,\boldsymbol{x}')}{e(\tau_0)}, \frac{\vec{\nabla} e(\tau_0,\boldsymbol{x}')}{e(\tau_0)}}_{\text{ip-glasma}} \times \underbrace{E(|\boldsymbol{x}-\boldsymbol{x}'|;\tau,\tau_0)}_{\text{Green fcn}} = \underbrace{\frac{\delta e(\tau,\boldsymbol{x})}{e(\tau)}, \frac{\vec{g}(\tau,\boldsymbol{x})}{e(\tau)}}_{\text{hydro}}$$



1. Assumes that $\tau_{\rm init} \ll R$

2. Matches the early glasma kinetics, to an effective theory of hydro initial states Blaizot, Ollitrault

$$\langle e(\boldsymbol{x})\rangle \qquad \langle e(\boldsymbol{x})e(\boldsymbol{y})\rangle = A\,\langle e(\boldsymbol{x})\rangle\,\delta^2(\boldsymbol{x}-\boldsymbol{y})$$

3. Include momentum into the hydro initial state effective theory at first order in $\tau_{\rm init}/R$

When the pre-equilibrium response is in, the hydro results will (hopefully) not depend at $\tau_{\rm init}$

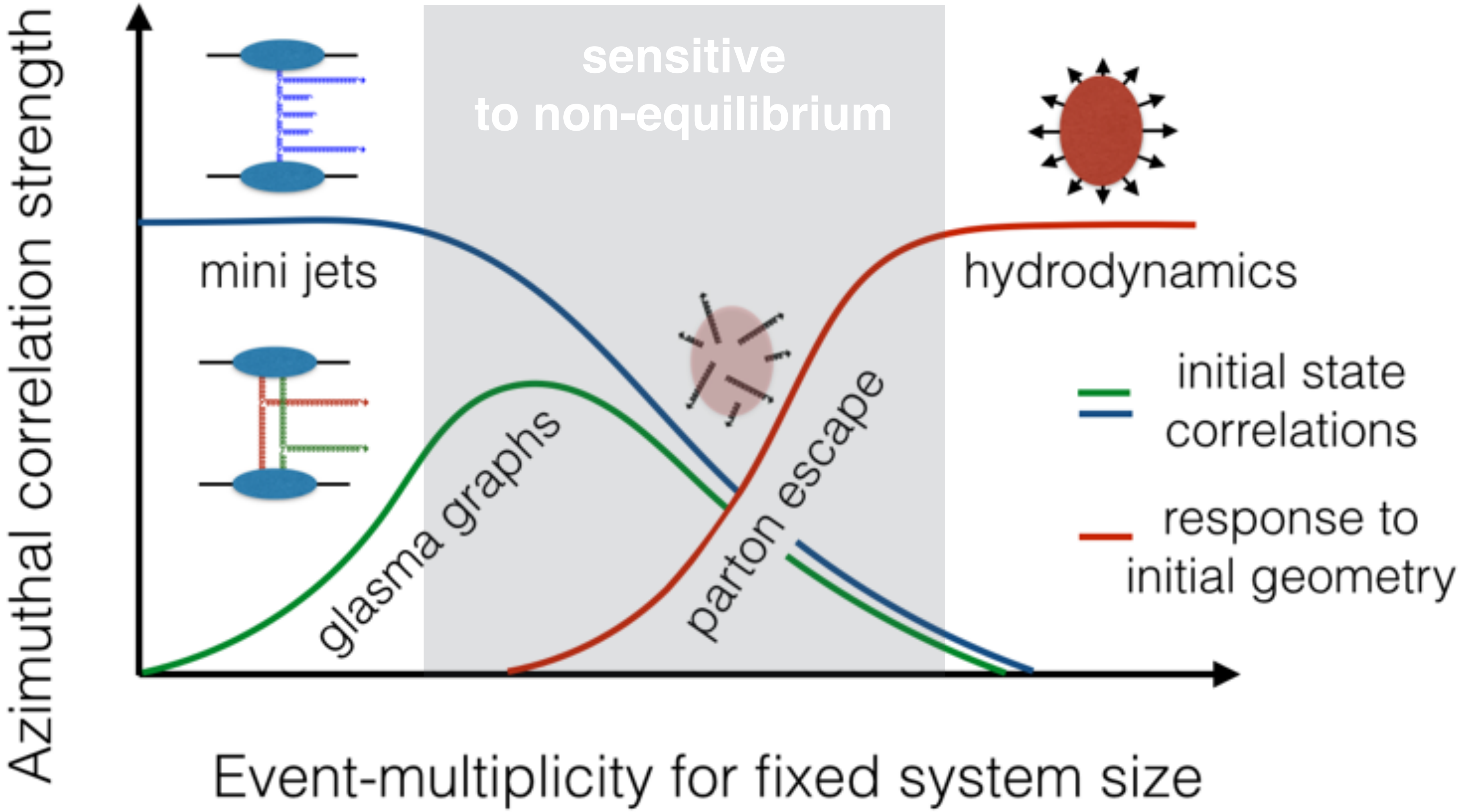
Can we measure this ?

Need control parameters – system size, p_T, rapidity, ...

Can we measure this ?

Need control parameters – system size, p_T, rapidity, . . .

Sören Schlichting's dream plot



Let's put some numbers on the x axis . . .

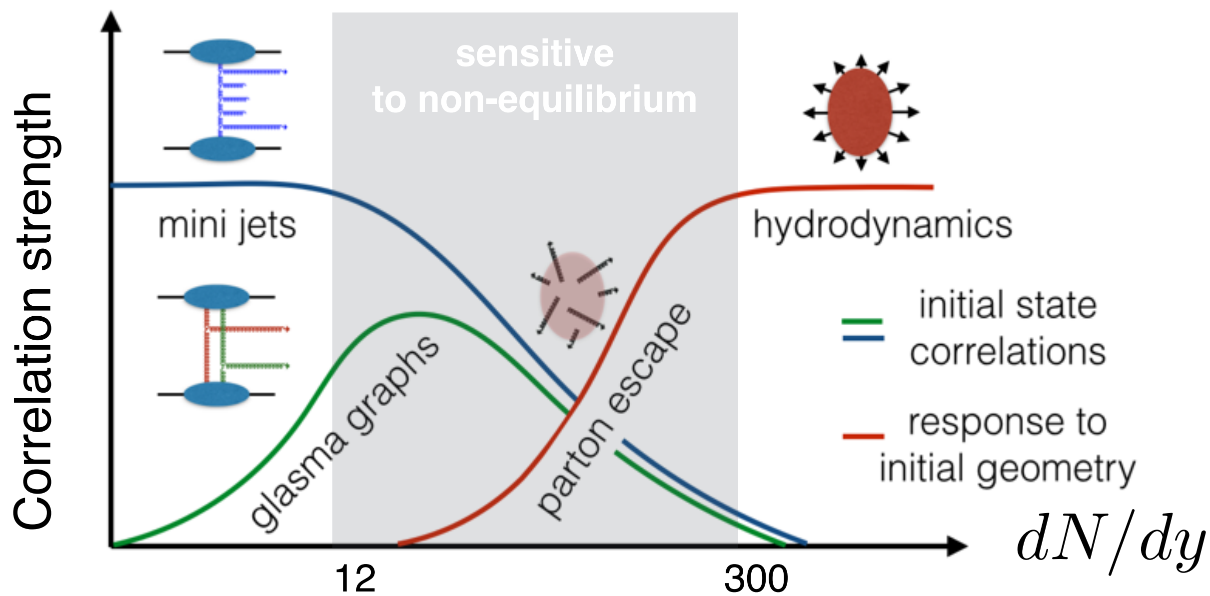
When do you see initial state correlations ?

1. To see the initial state correlations we require

$$R \ll \tau_{\rm init} \qquad or \qquad R/\tau_{\rm init} \ll 1$$

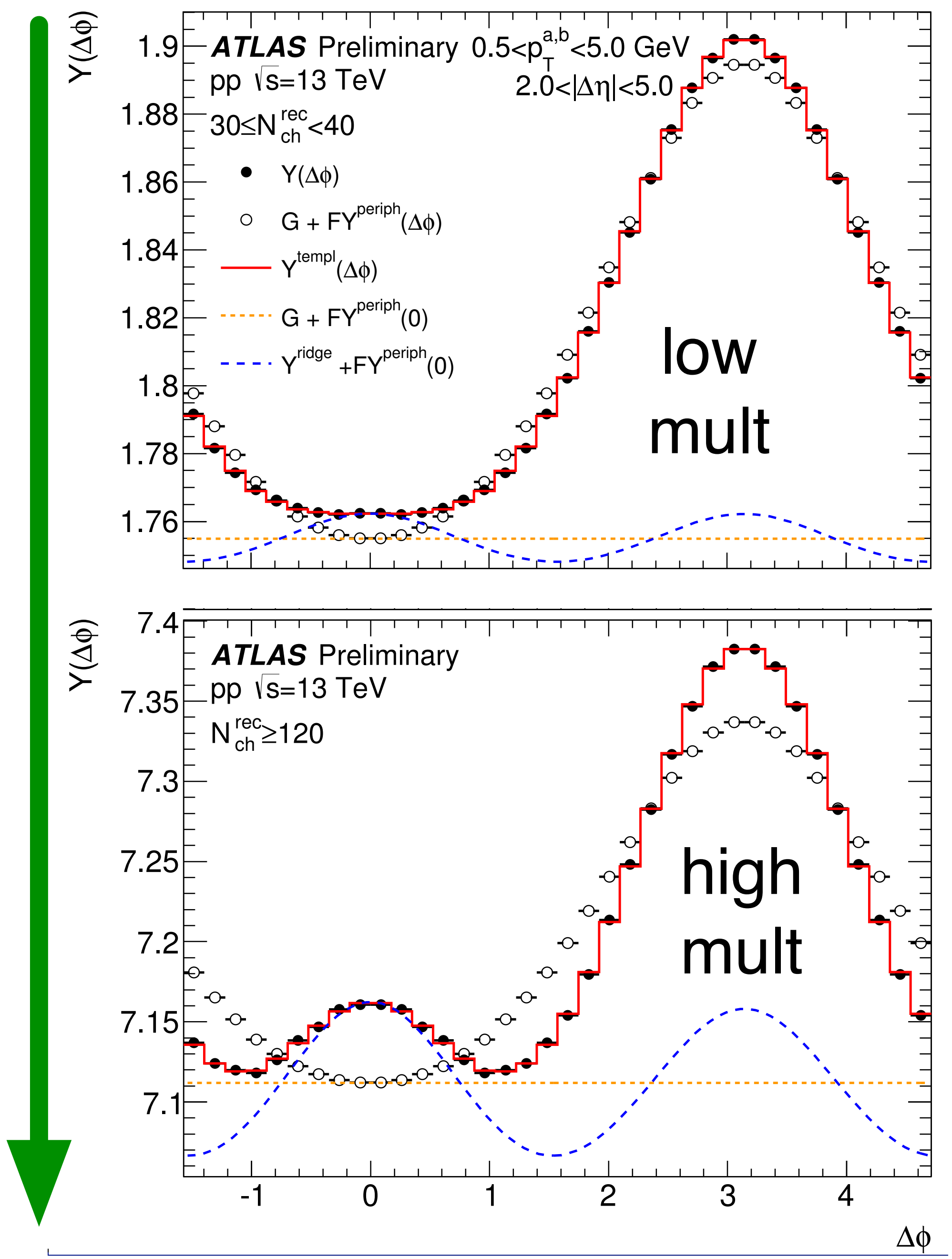
2. Now we reach a thermal state in:

$$\tau_{\rm init} \simeq \frac{10}{Q_s}\left(\frac{0.3}{\alpha_s}\right)^{2.6} \qquad \text{and} \qquad Q_s^2 = \alpha_s \frac{dN/dy}{\pi R^2}$$



$$\frac{R}{\tau_{\rm init}} = 0.2\left(\frac{\alpha_s}{0.3}\right)^{3.1}\left(\frac{dN/dy}{12}\right)^{1/2}$$

13 TeV pp



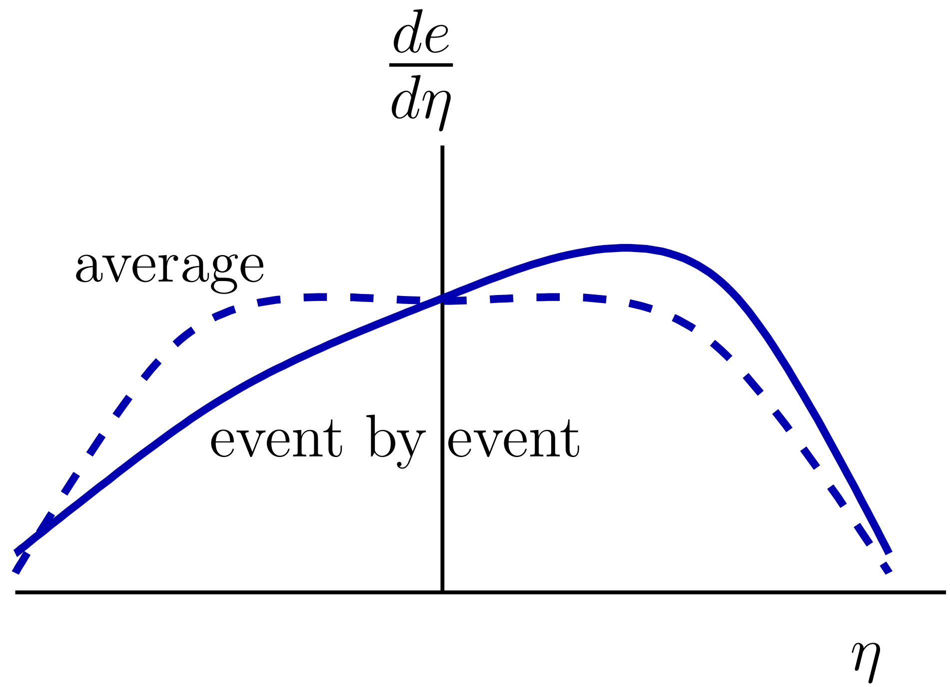
Remarks on pp:

1. Gradual transition from low to high mult.
2. Is v_2 at small multiplicity is important?
   - See CMS data on $v_2\{4\}, v_2\{6\}, \ldots$
3. The v_2 correlation does not decrease with multiplitity, and factorizes
4. How are minijets modified in p_T ?

The last stage of thermalization is minijet-quenching

Can we measure this ?

Need control parameters – system size, p_T, rapidity, . . .

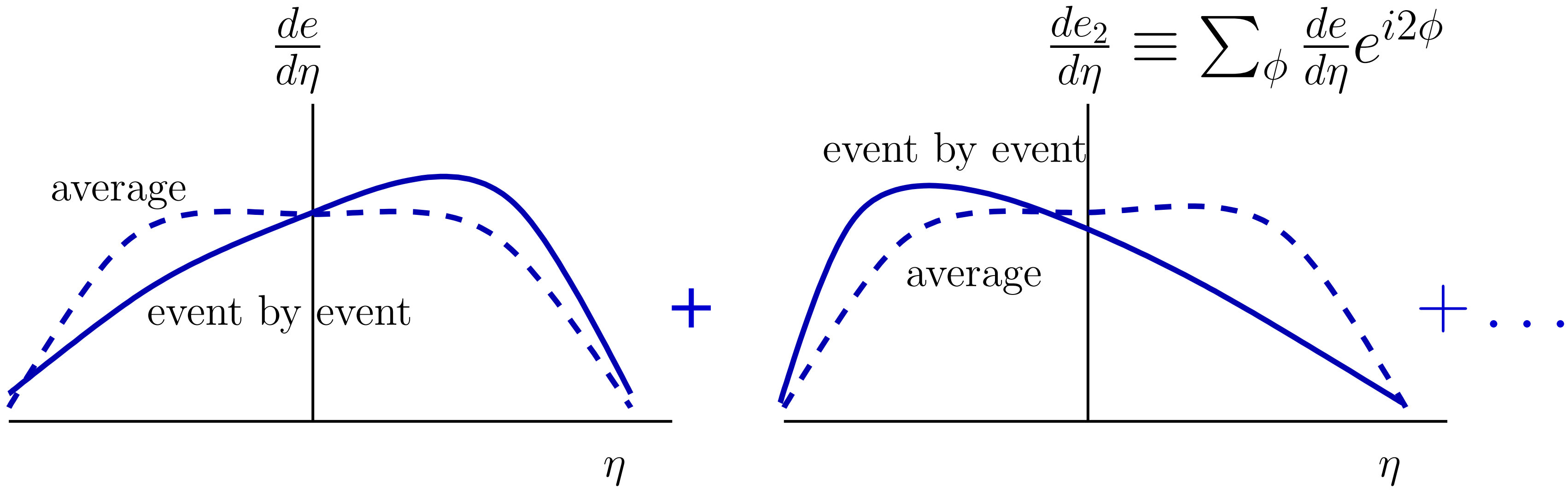


1. An effective theory for hydro initial states must specify

Bozek, Broniowski arxiv:1512.01945

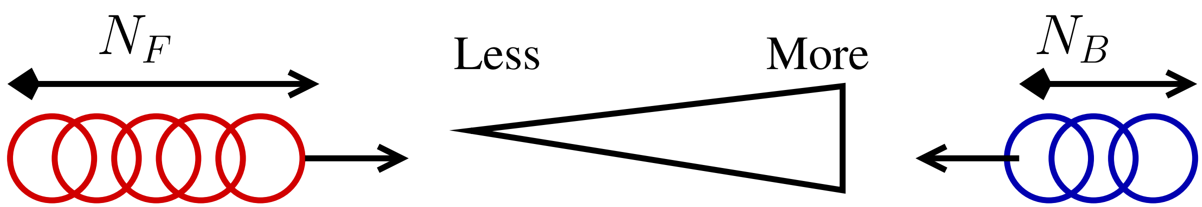
$$\left\langle \frac{de(\boldsymbol{x})}{d\eta} \right\rangle \quad \text{and} \quad \left\langle \frac{de(\boldsymbol{x})}{d\eta_1} \frac{de(\boldsymbol{y})}{d\eta_2} \right\rangle_{\rm conn} = \underbrace{A(\eta_1, \eta_2)}_{\text{unknown}} \langle e(\boldsymbol{x}) \rangle \, \delta(\boldsymbol{x} - \boldsymbol{y})$$

Rapidity correlations



A model for rapidity flucts that doesn't work:

Teaney&Bzdak



then

$$\frac{de}{d\eta} = C_0 \left(N_F + N_B\right) + C_1 \eta \left(N_F - N_B\right)$$

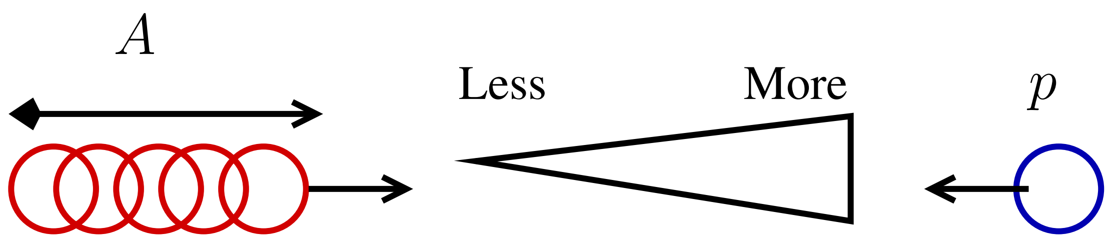
and

$$\left\langle \frac{de}{d\eta_1} \frac{de}{d\eta_2} \right\rangle = C_0^2 \left\langle (N_F + N_B)^2 \right\rangle + \underbrace{C_1^2 \, \eta_1 \eta_2 \left\langle (N_F - N_B)^2 \right\rangle}_{\text{measurable rapidity odd correlations}}$$

Internal structure of rapidity correlations in flux tubes

Pang; Bozek, Broniowski

1. In pA events the number of forward backward participants doesn't fluctuate much



Fluctuations reflect the correlations in the tube, not the participants

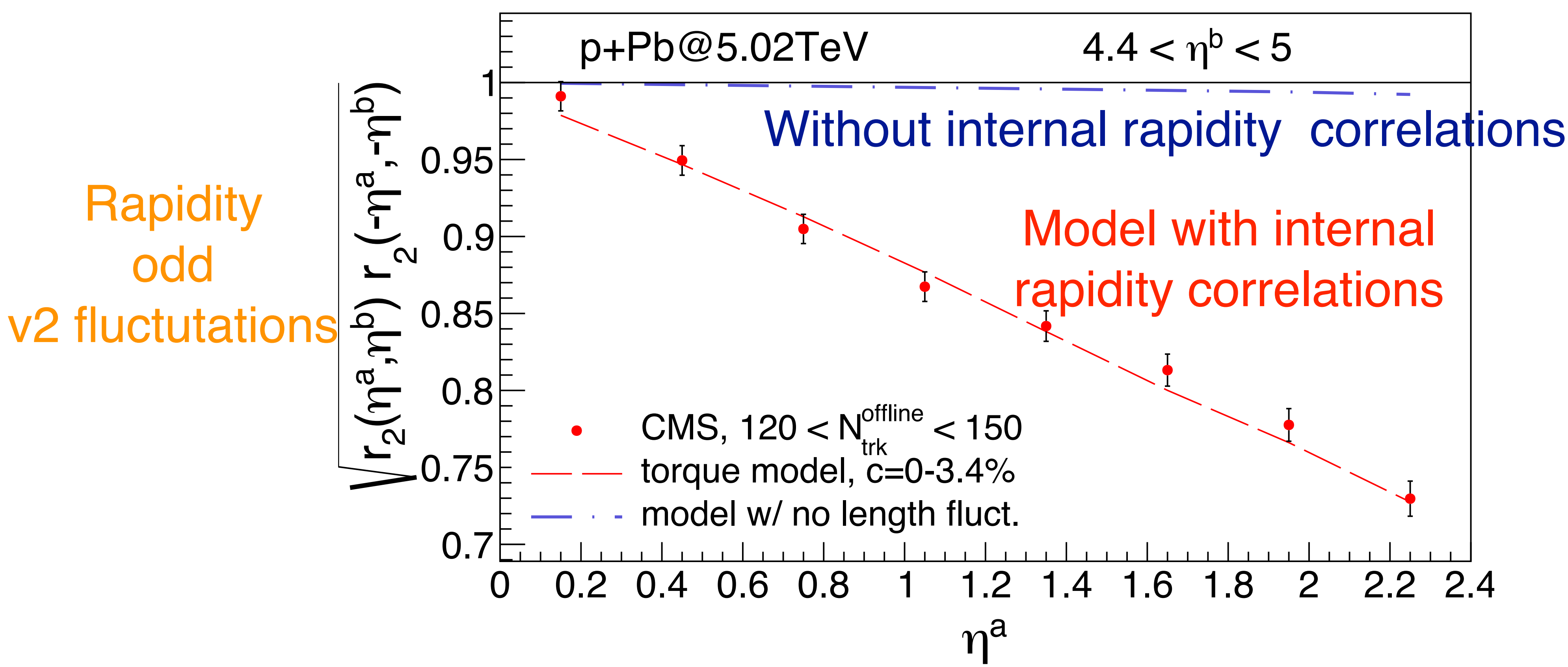
2. But, significant (rapidity-odd) longitudinal fluctuations of v_2 are seen

Successful string-like models incorporate the dx/x parts of the splitting function into the rapidity corelation function $\langle e(\eta_1)e(\eta_2)\rangle$

3. Opportunity to predict the functional form in CGC or EKRT model of

Schenke, Schlichting

$$\left\langle \frac{de}{d\eta_1}\frac{de}{d\eta_2} \right\rangle_{\rm conn}$$


p+Pb@5.02TeV
4.4 < η^b < 5
Without internal rapidity correlations
Model with internal rapidity correlations
Rapidity odd v2 fluctutations
CMS, 120 < N_trk^offline < 150
torque model, c=0-3.4%
model w/ no length fluct.
√(r_2(η^a,η^b) r_2(-η^a,-η^b))
η^a
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4
0.7 0.75 0.8 0.85 0.9 0.95 1

From the almost to truly intractable . . .

1. A path to document theoretically and experimentally the path to hydro

   - System size, p_T mini-jet quenching, rapidity

2. Going beyond weak coupling:

   - Non-perturbatively calculate screening?

   - Is the temperature scale perturbative?

Thank you!