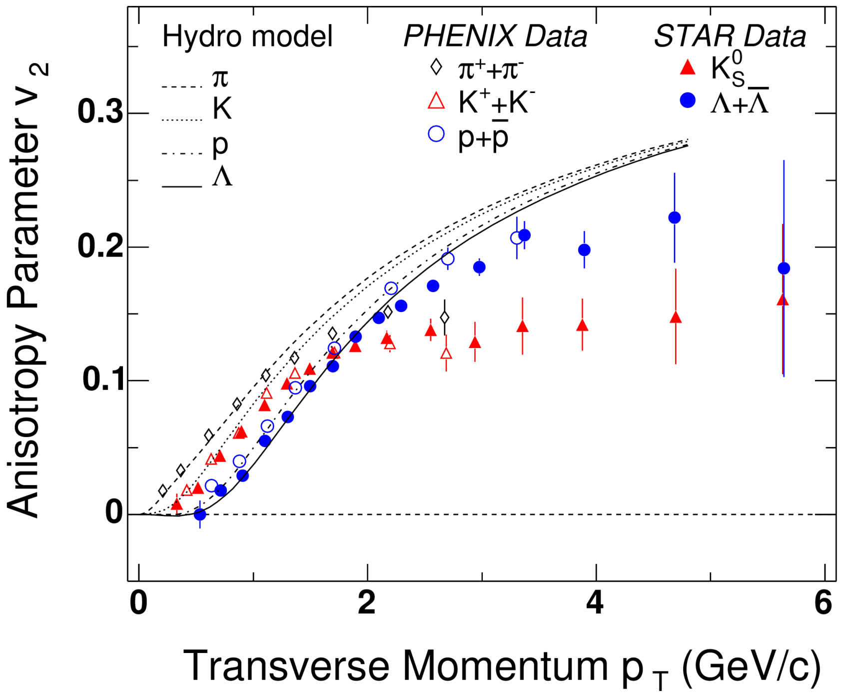
From initial-state fluctuations to final-state observables

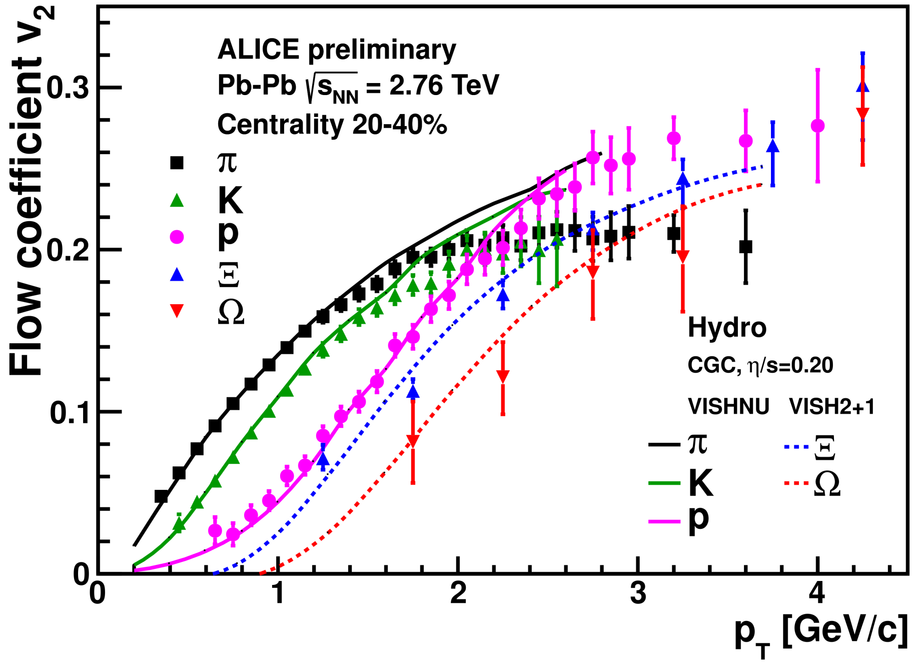
Kevin Dusling
North Carolina State University

August 13th, 2012

The success of hydrodynamics

Hydrodynamics has been an invaluable tool to the heavy-ion community.

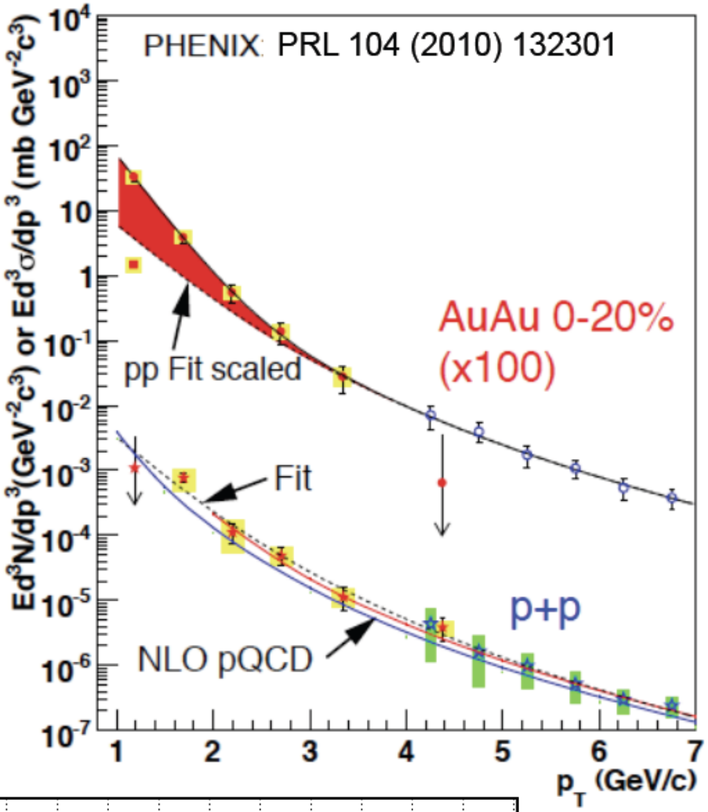




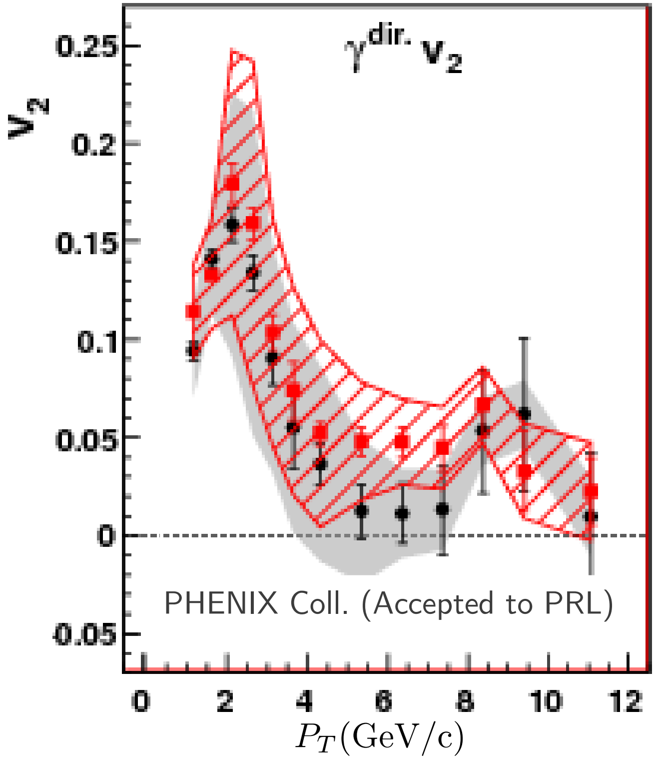
But fits to data require an early hydrodynamic starting time.

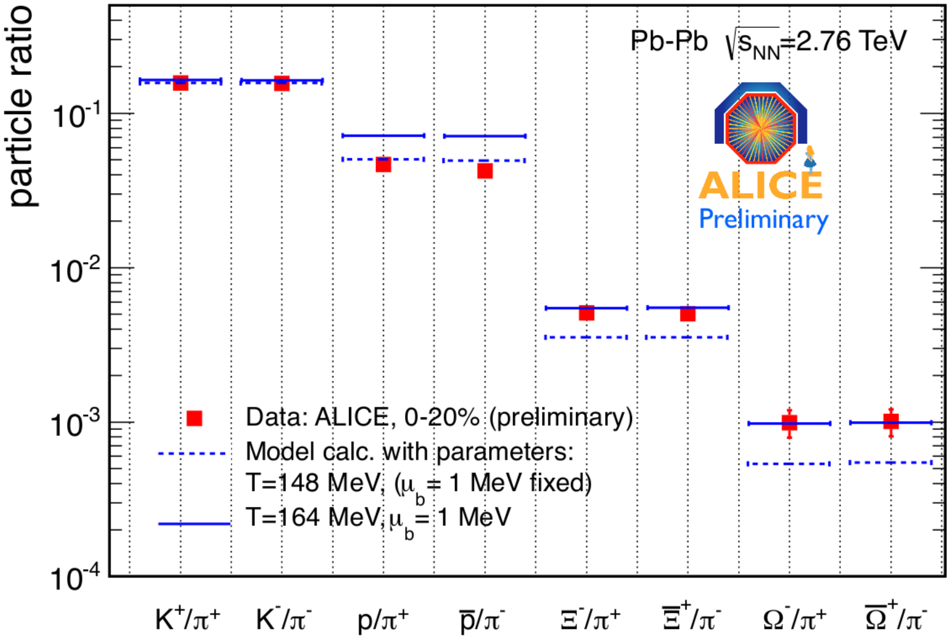
Soft Photons

Soft photon data is also indicative of early production (Hydrodynamic models again work well)



But there are some tensions:





Above model: A. Andronic et al., Phys. Lett. B 673:142-145,2009
Similar results: S. Wheaton, J. Cleymans and M. Hauer, Comput. Phys. Commun. 180 (2009) 84-106.

Conditions for hydrodynamics

1. Isotropy: $T_{ij} \approx p\delta_{ij}$

   (near isotropy for visc. hydro)

2. Equation of state: $p \approx p\left(\epsilon\right)$

   (small deviations of true pressure from equilibrium pressure handled by visc. Hydro.)

Talk by Jean-Yves Ollitrault, Mon. 3:30pm

Some comments:

1. Thermalization is not required (T never enters hydro equations*)

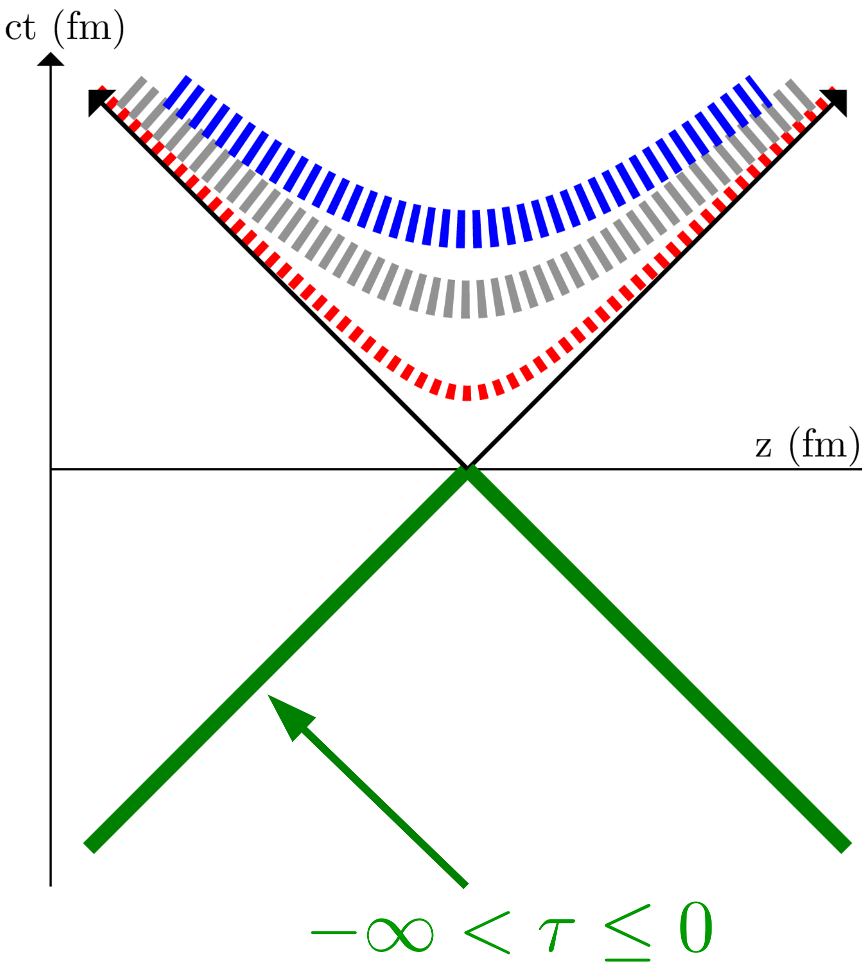
2. Even if hydro is successfully describing system it is hiding a lot of physics
   (Example: thermalization is most likely taking place while hydro is running)

3. Leaves open questions about the underlying dynamics
   How and when does the system
   Decohere? Isotropize? Thermalize?

Hydrodynamics is an initial value problem:

The only consistent way to address these questions is by starting with what is already known about the high energy nuclear wavefunction

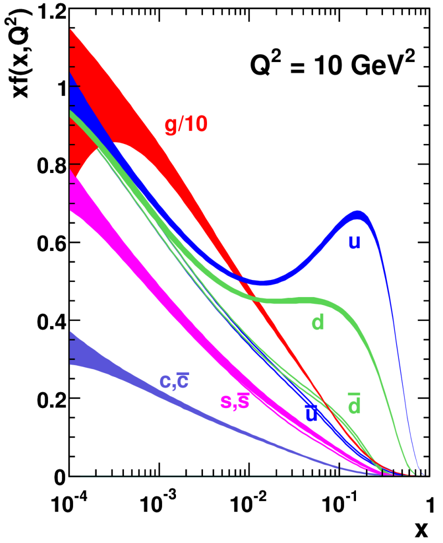
Pre-collision

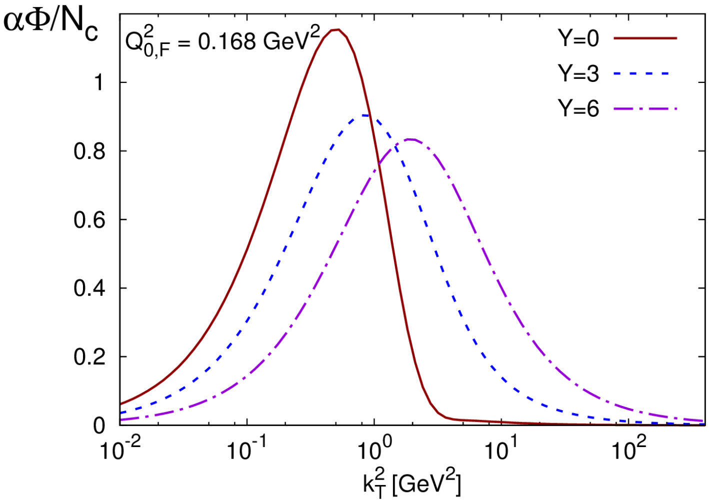


Nuclear wavefunction at high energies systematically described in CGC effective theory

The proton pre-collision

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

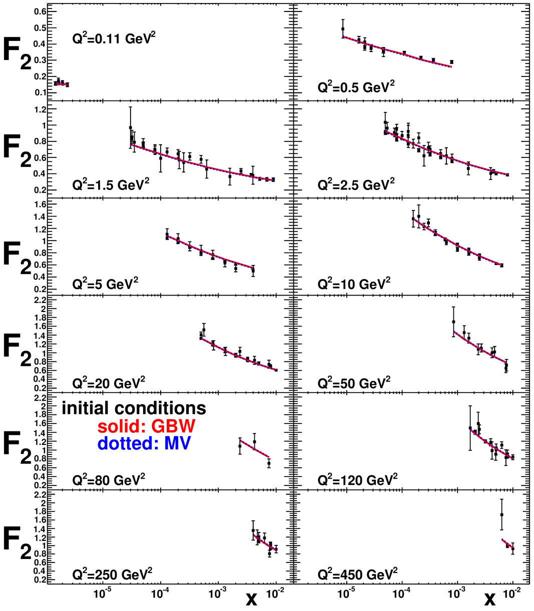


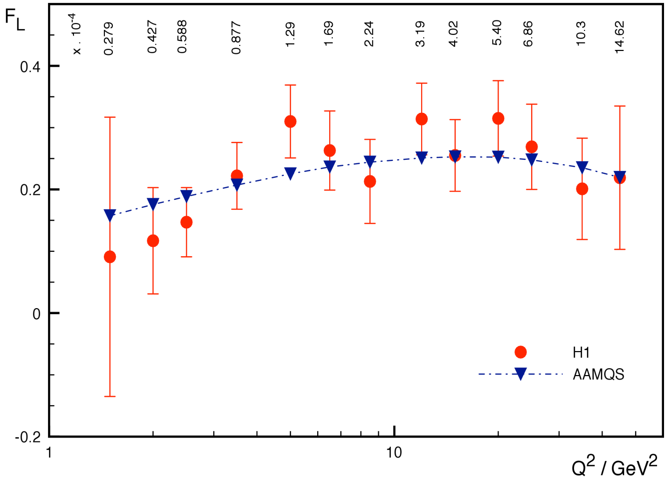


NLO DGLAP fits:
http://mstwpdf.hepforge.org/

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:



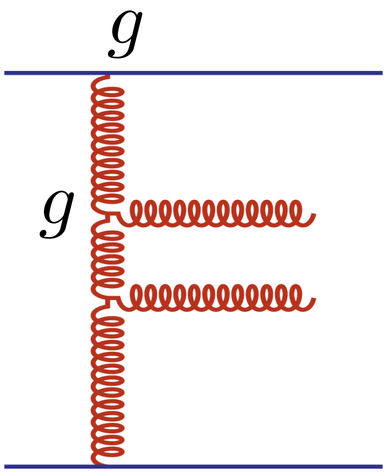


Albacete, Milhano, Quiroga-Arias ,Rojo,
arXiv:1203.1043 (2012).
Quiroga-Arias, Albacete, Armesto, Milhano, Salgado,
J.Phys.G G38 (2011) 124124.
Albacete, Armesto, Milhano, Salgado,
PRD80 (2009) 034031.

Power counting in QCD: multiparticle production

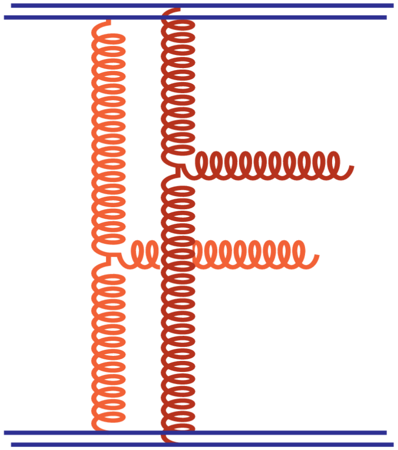
Low color charge density (min bias):

Jet graph:



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

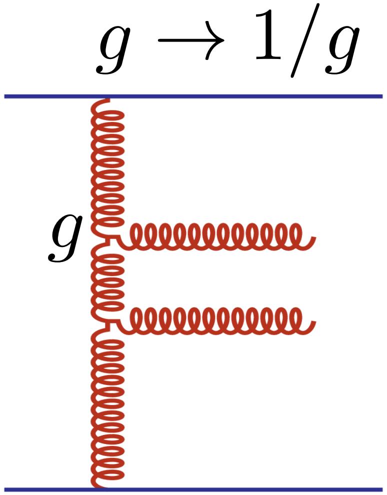
Glasma graph:



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

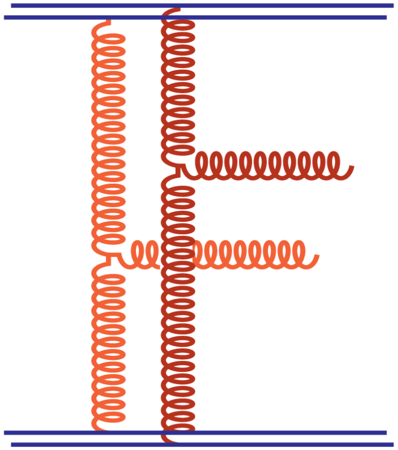
High color charge density (central):

Jet graph:



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

Glasma graph:

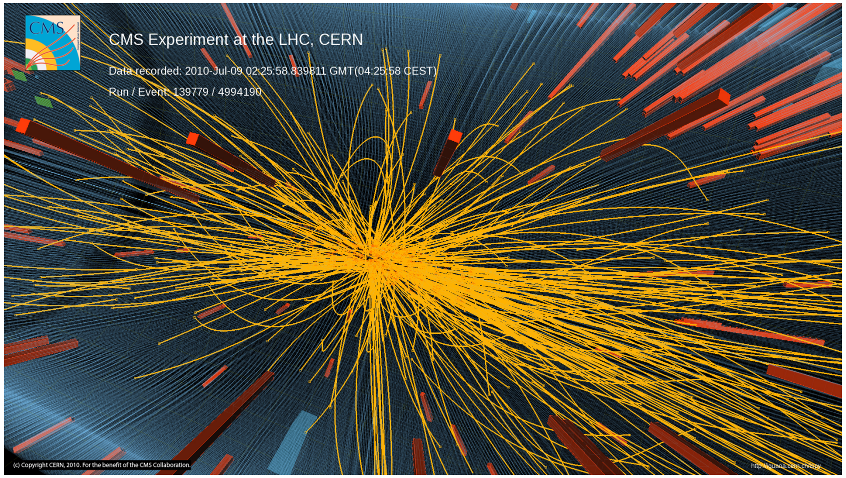


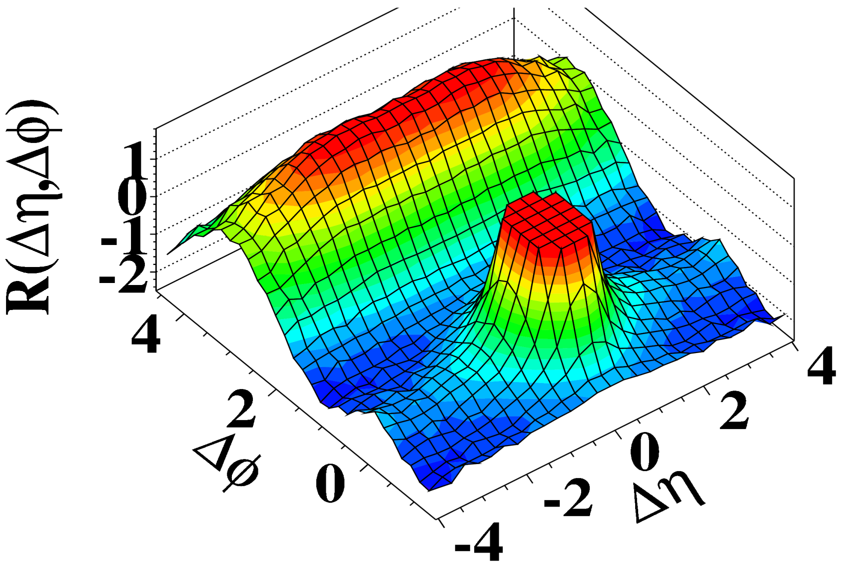
$$\mathcal{O}\left(\alpha_s^{-2}\right)$$

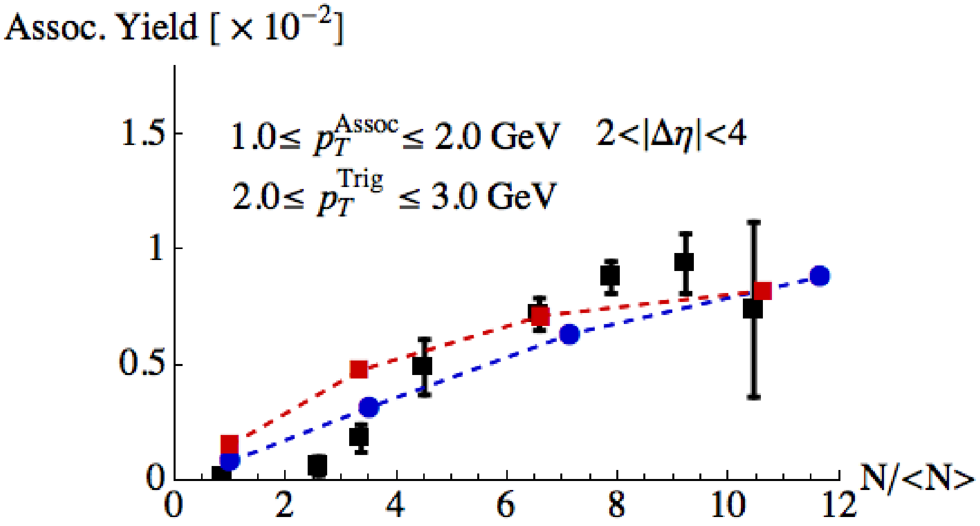
Expect $\boldsymbol{\alpha_s^8}$ enhancement of "Glasma" graph! Is this seen in the data?

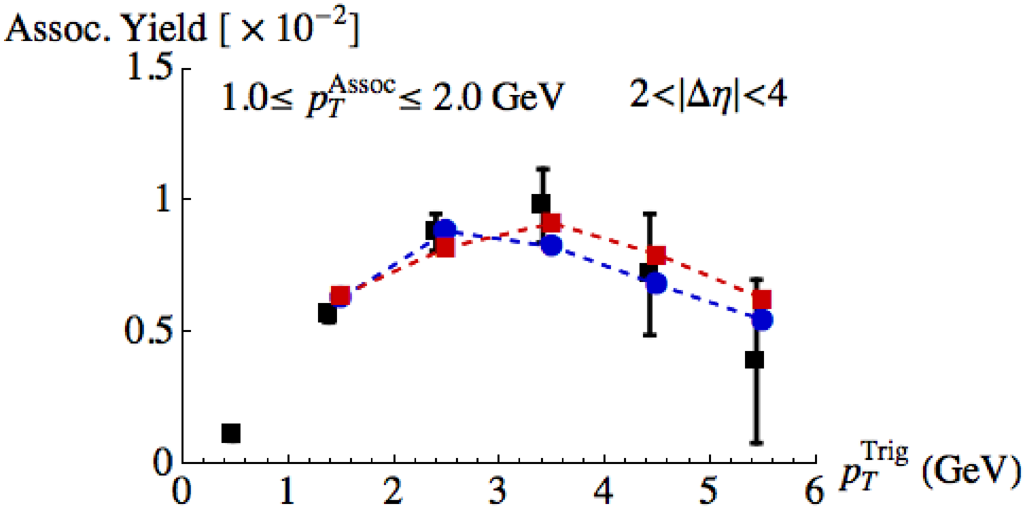
Ridge in p+p collisions

Wei Li, Mod.Phys.Lett. A27 1230018 (2012).




(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c

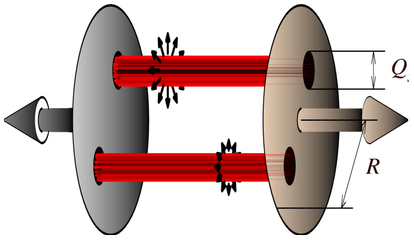


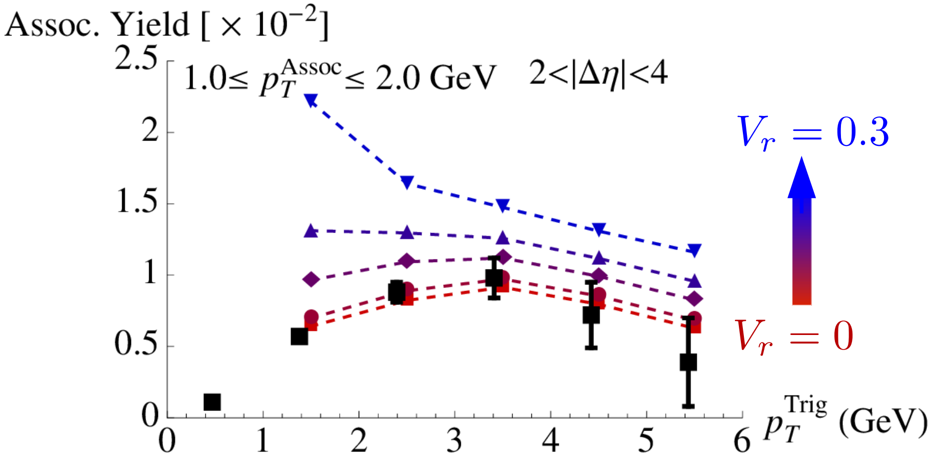


Dusling, Venugopalan, PRL 108, 262001 (2012).
Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi, Venugopalan, PLB 697 12-25 (2011).

p+p vs A+A

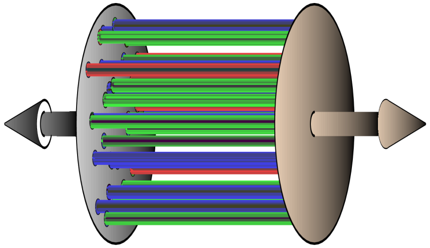
In p+p we are seeing the intrinsic collimation from a single flux tube

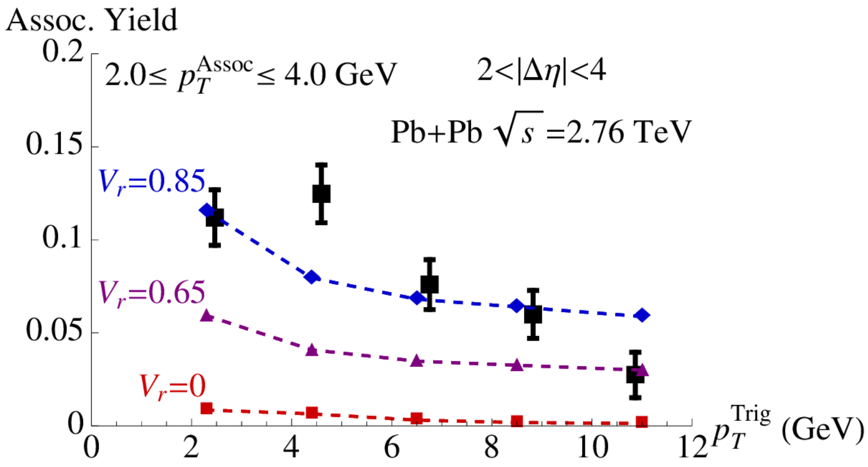




Increasing transverse flow in p+p creates a discrepancy with data.

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



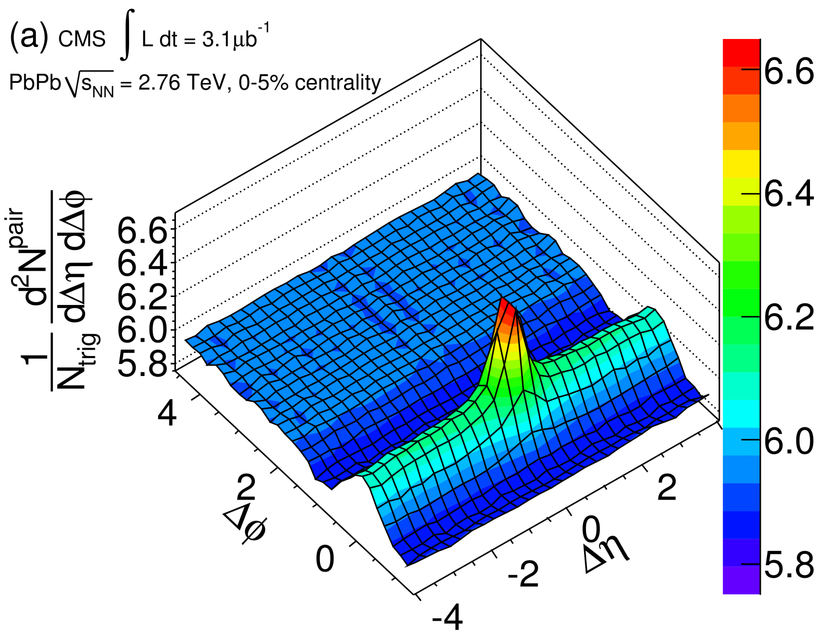


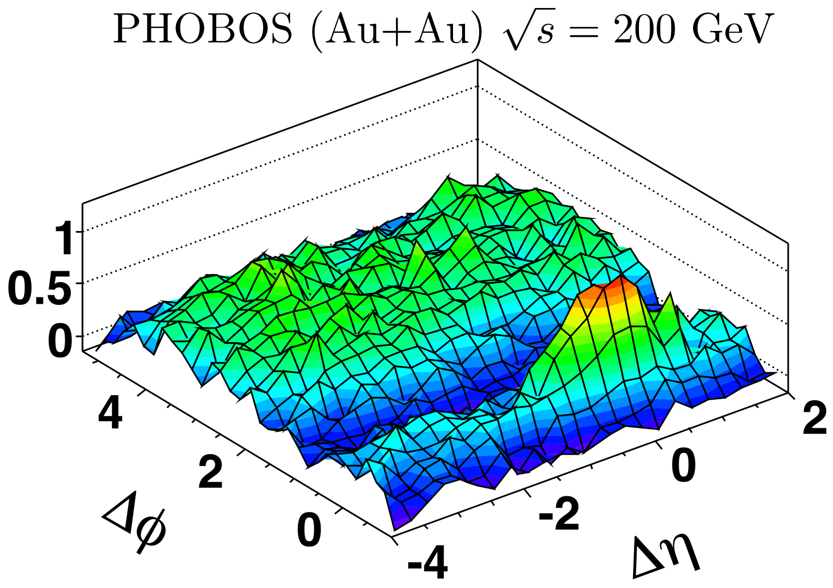
Yet, transverse flow is needed to explain identical measurements in Pb+Pb

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

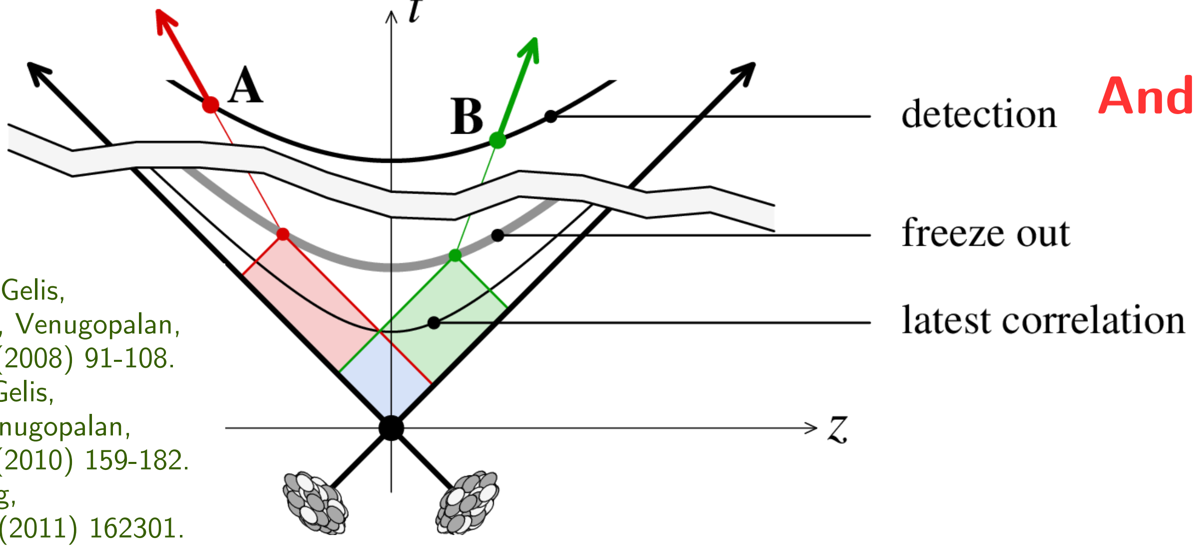
Dusling, Venugopalan, PRL 108, 262001 (2012).

Heavy-Ion Ridge





The correlation is long range in rapidity.
Causality dictates the correlation formed early.

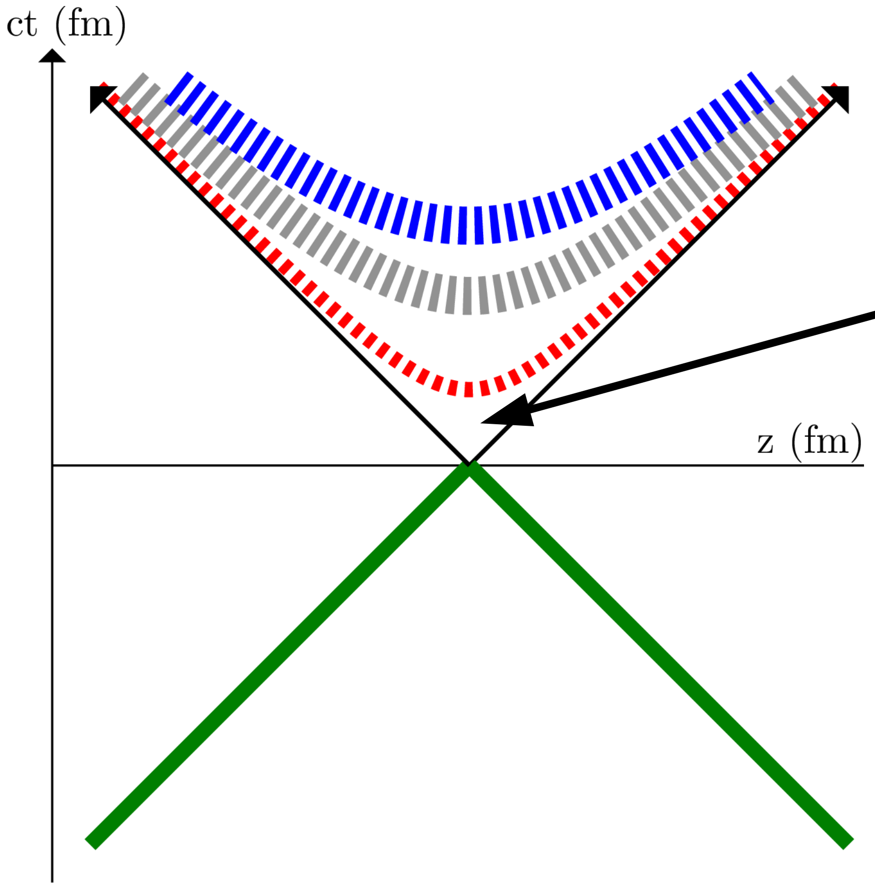


Dumitru, Gelis,
McLerran, Venugopalan,
NPA810 (2008) 91-108.
Dusling, Gelis,
Lappi, Venugopalan,
NPA836 (2010) 159-182.
Ma, Wang,
PRL 106 (2011) 162301.

And it persists to the final state:

Talk by Piotr Bozek, Tu. 6pm
Talk by Rylan Conway, Tu. 3:15pm
Poster by George Moschelli, Th. 4pm
Poster by Philipe Mota, Th. 4pm
Talk by Long-gang Pang, Wed. 11:20am
Poster by Todd Springer, Th. 4pm
Talk by Misha Stephanov, Fri. 3:20pm
Poster by Wei Li, Th. 4pm

The first Fermi of a Heavy Ion collision

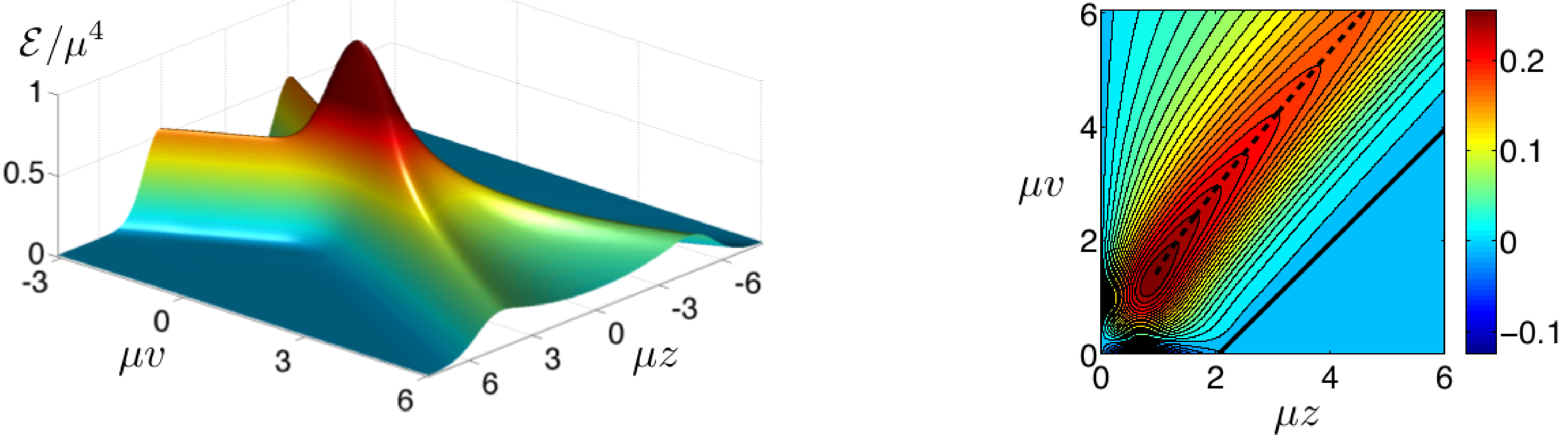


$$\tau \sim Q_s^{-1} \quad g^2 f \gtrsim 1$$

Classical non-linear color fields
Physics: Decoherence
Development of EoS
Isotropization
Instabilities
Tools: Classical Yang-Mills

Strong coupling: AdS / CFT

Chesler, Yaffe, PRD82:026006 (2010).



	AdS/CFT	Phenomenology
$\tau_{\rm therm}$	$s^{-1/3} \ll 1$ fm	O(1) fm
$dN/d\eta$	$s^{1/3}$	$\mathrm{s}^{0.15}$
C_2	$\cosh(4\Delta y)$	$\approx$ Flat

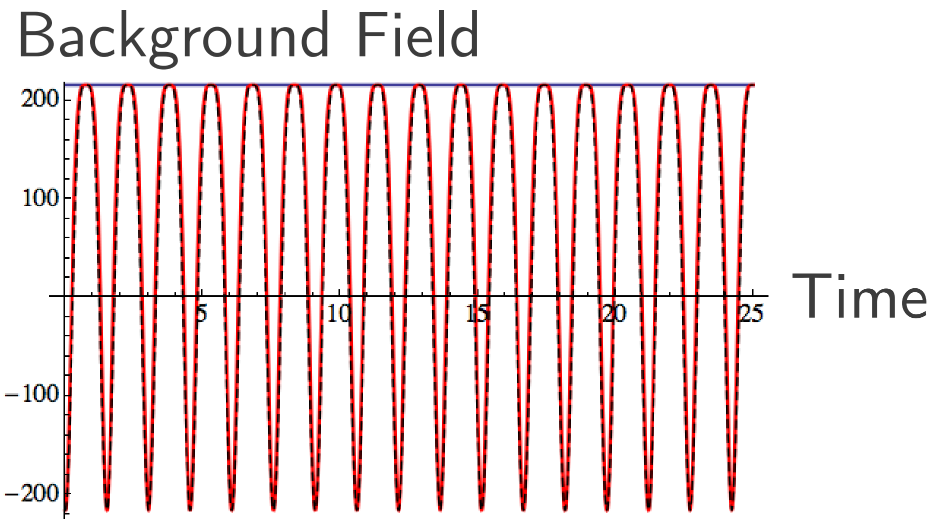
Talk by Paul Chesler, Wed. 10am
Talk by Shu Lin, Fri. 4:30pm
Talk by Ho-Ung Yee, Fri. 12:15pm

Gubser, Pufu, Yarom, PRD78:066014, 2009.
Grumiller, Romatschke JHEP,08:027 2008.
Grigoryan, Kovechegov, JHEP 1104:010 (2010).
Kovchegov, Lin JHEP 1003:057 (2010).

Weak coupling: amplification of quantum fluctuations

Consider a homogeneous scalar field:

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

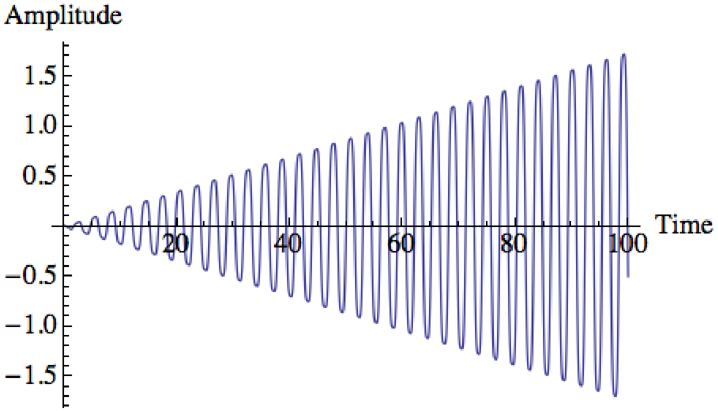


Adding fluctuations to the background field

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

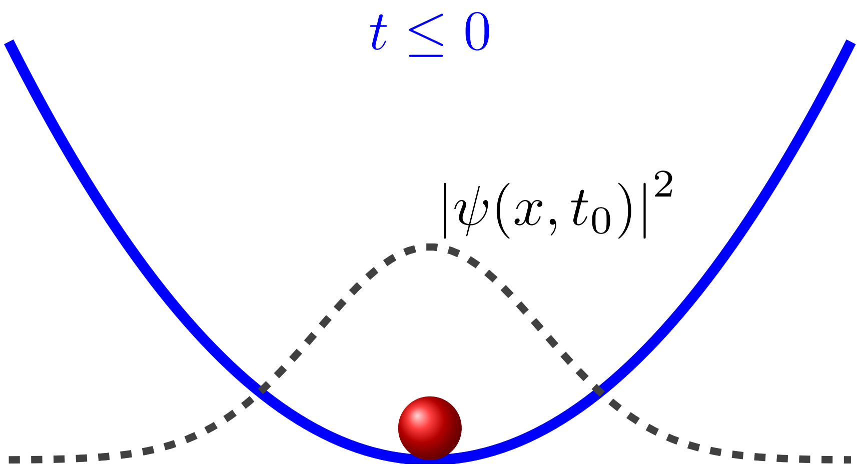
results in the linearized EoM for small fluctuations: $\ddot{a}_{\pm\mathbf{k}} + \left[\mathbf{k}^2 + V''\left(\phi_0(t)\right)\right] a_{\pm\mathbf{k}} = 0$

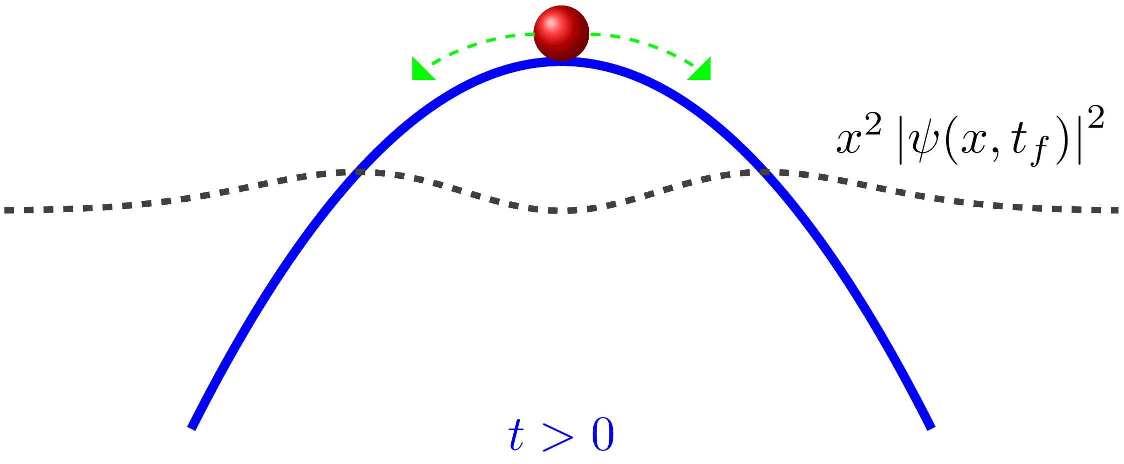
Certain amplitudes grow with time:



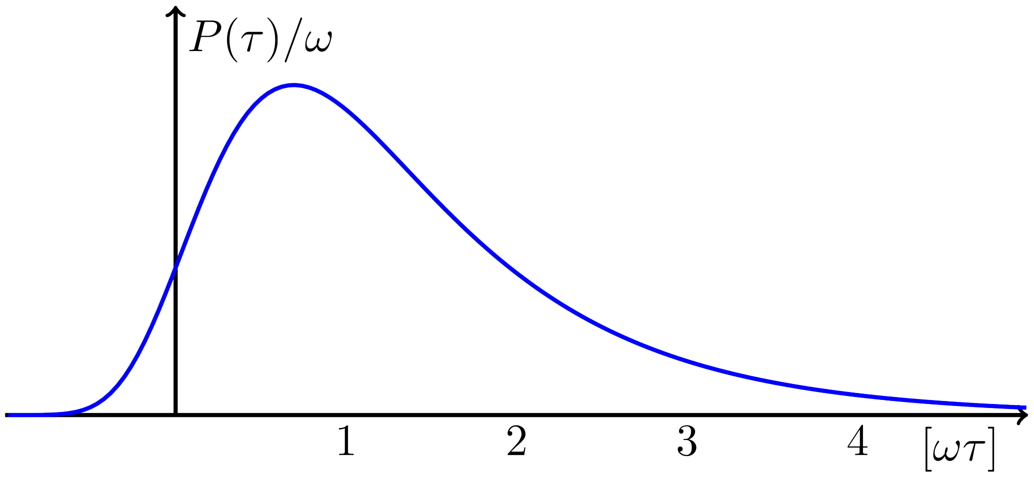
When $\mathbf{gt} \sim 1$ these terms need to be resummed.

Weak coupling: Semi-classical methods





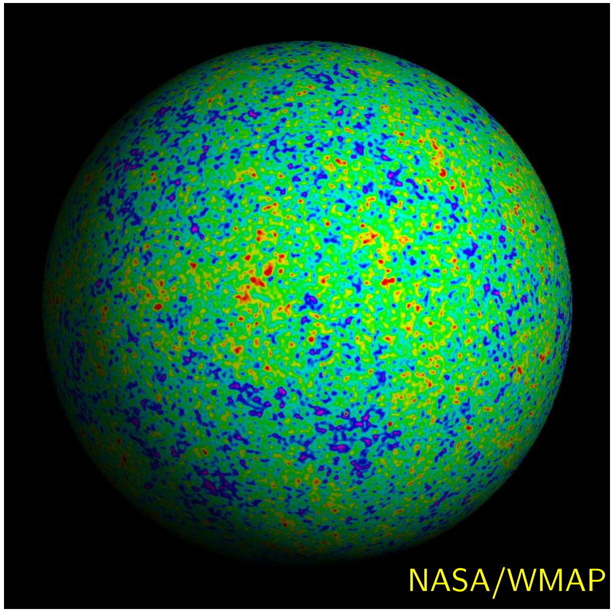
$$\langle\mathcal{O}\rangle_{t_F} = \int dx\ |\psi(x,t_F)|^2\,\mathcal{O}(x) = \int dxdp\ f(x,p,t_f)\ \mathcal{O}(x) + \mathrm{O}(e^{-\omega t_f})$$

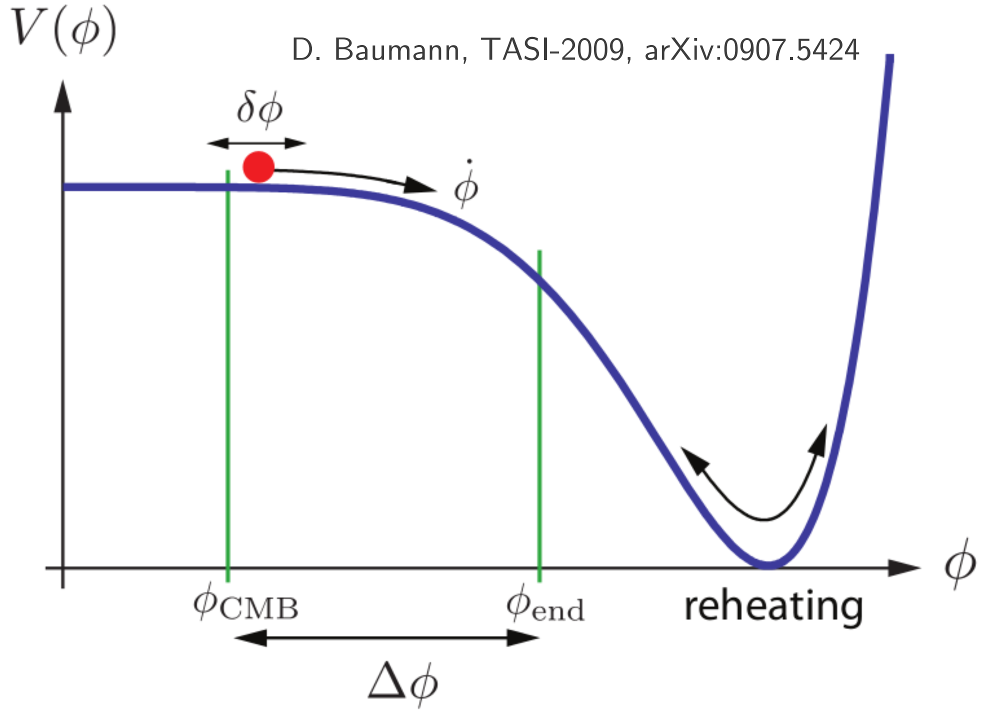


Barton, Annals Phys. 166:322 (1986).
Guth, Pi, PRD 32:1899 (1985).
Fukushima, Gelis, McLerran, NPA786:107 (2007).

These results from quantum mechanics can be extended to quantum field theory.

Example 1: Slow-roll inflation





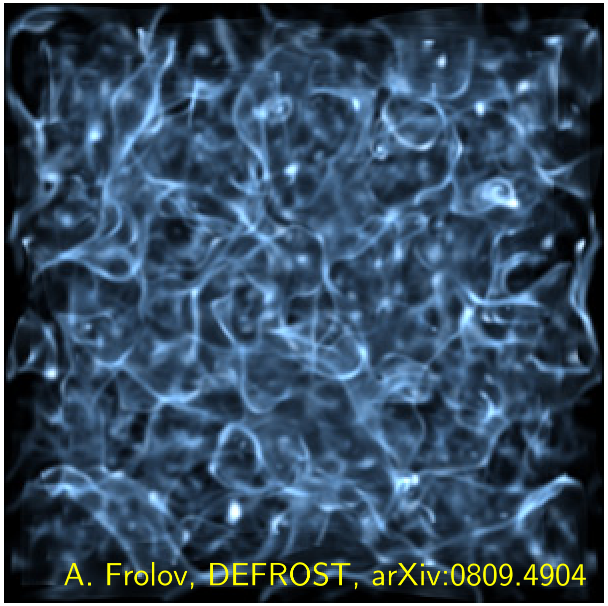
D. Baumann, TASI-2009, arXiv:0907.5424

Quantum expectation value

$$\langle\phi(t)\rangle = \int \mathcal{D}c_{\mathbf{k}} \exp\left(-\int \frac{d\mathbf{k}}{(2\pi)^3} \frac{|c_{\mathbf{k}}|^2}{2|\alpha_k|^2}\right) \phi[t, \mathbf{x}, c_{\mathbf{k}}]$$

Classical solution to EoM with boundary condition:

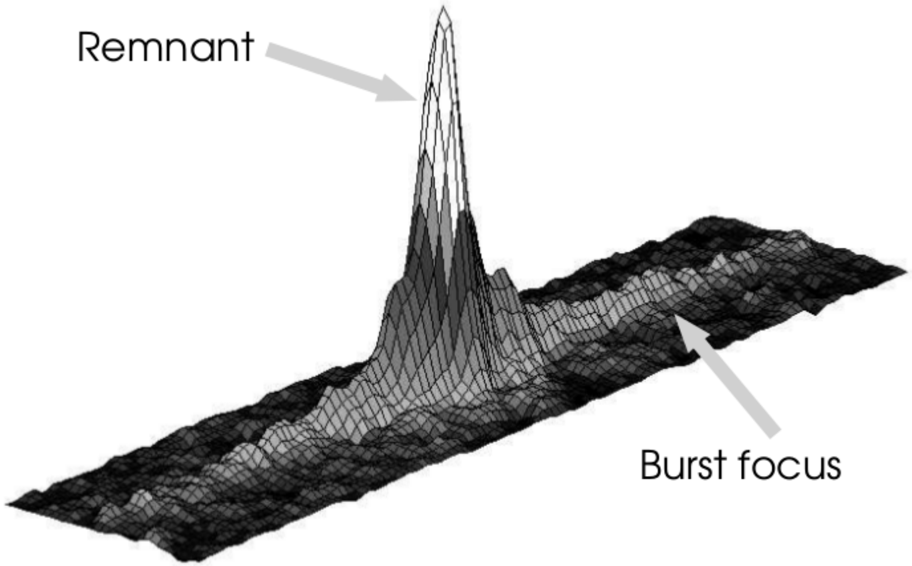
$$\phi(t, \mathbf{x}) = \phi_0(t) + \int \frac{d\mathbf{k}}{(2\pi)^3} c_{\mathbf{k}} f_{+}^{k}(t) e^{i\mathbf{k}\mathbf{x}}$$

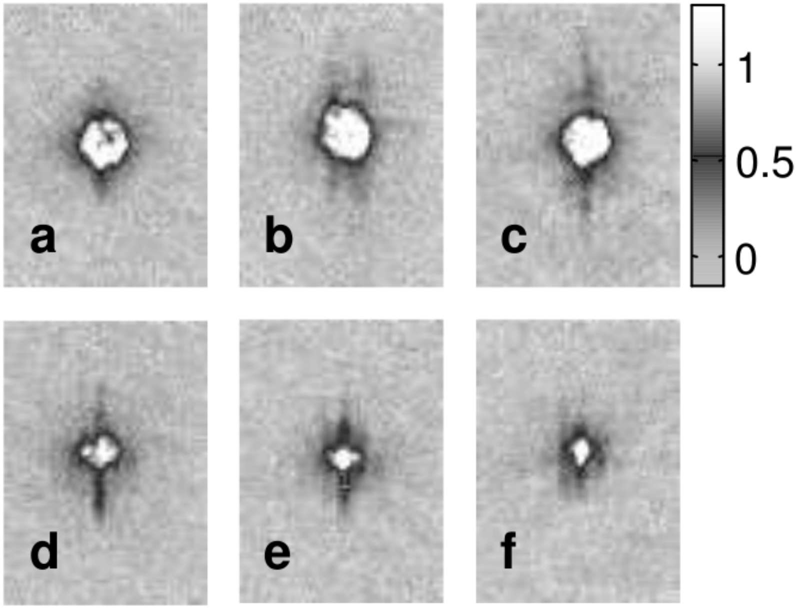


A. Frolov, DEFROST, arXiv:0809.4904

Polarski, Starobinsky, Class.Quant.Grav.13:377-392,1996
Khlebnikov, Tkachev, Phys.Rev.Lett. 77:219-222 (1996).
D. Son, hep-ph/9601377 (1996).

Example 2: Bose Novae





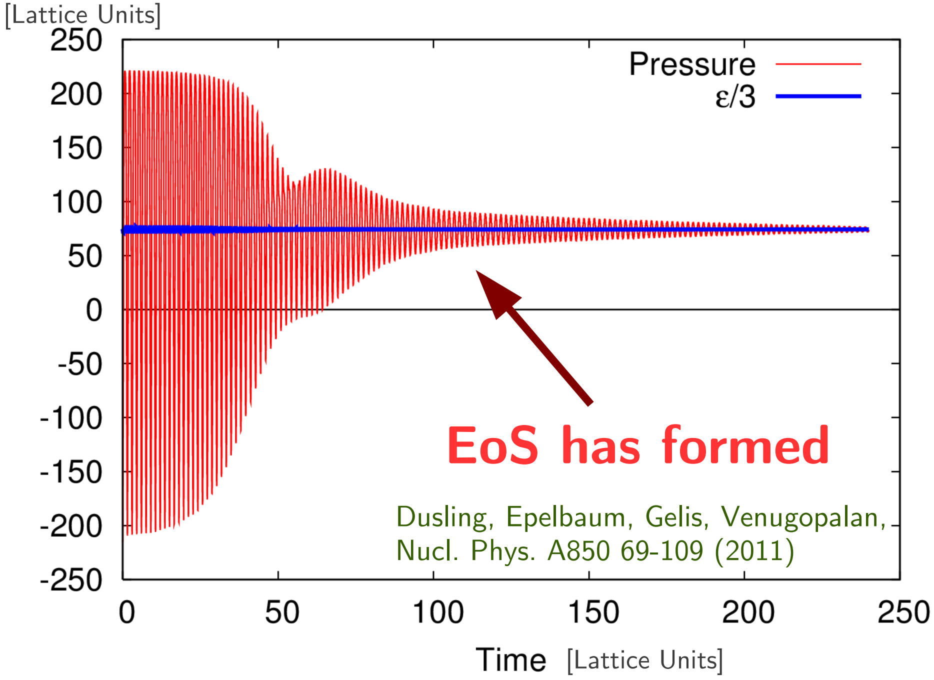
Donley, Claussen, Cornish, Roberts, Cornell, Wieman, Nature 412,295 (2001).

Can Bose Novae be understood as quantum fluctuations (treated semi-classically) riding on the classical condensate described by the time dependent Gross-Pitaevskii equation?

$$i\hbar\frac{\partial\Psi(\mathbf{r},t)}{\partial t} = \left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial\mathbf{r}^2} + V(\mathbf{r}) + \frac{4\pi\hbar^2 a_s}{m}\left|\Psi(\mathbf{r},t)\right|^2\right)\Psi(\mathbf{r},t)$$

Suggested by: Calzetta, Hu, PRA68:043625 (2003).

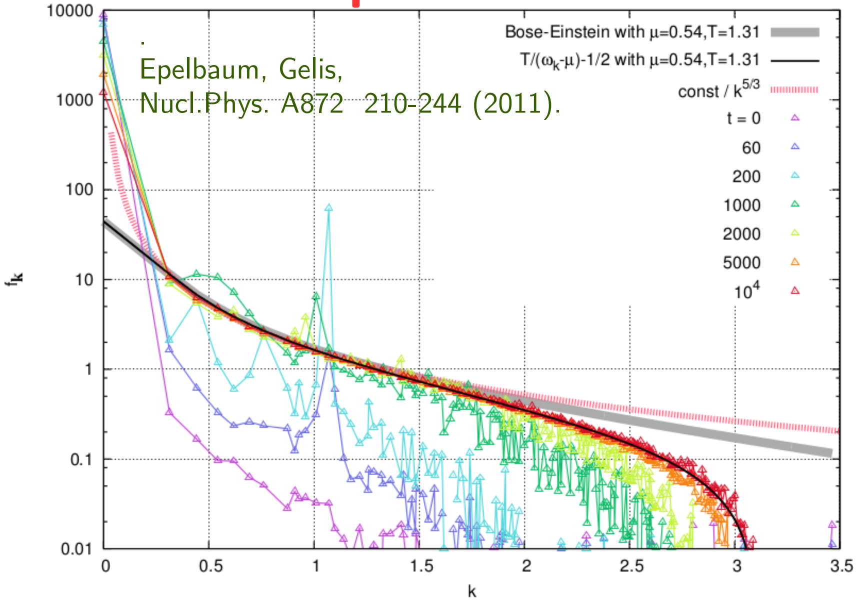
Quantum Decoherence: non-expanding Scalar field



EoS has formed

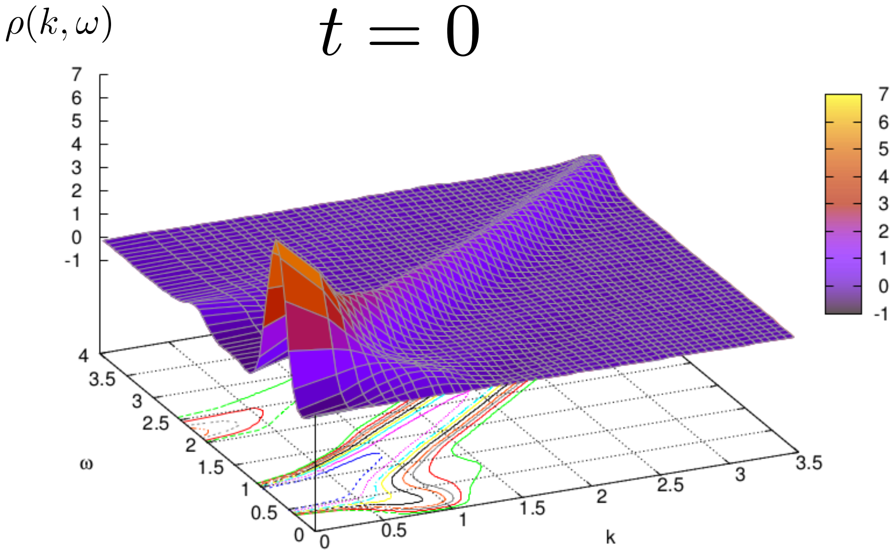
Dusling, Epelbaum, Gelis, Venugopalan,
Nucl. Phys. A850 69-109 (2011)

Thermal spectrum has formed

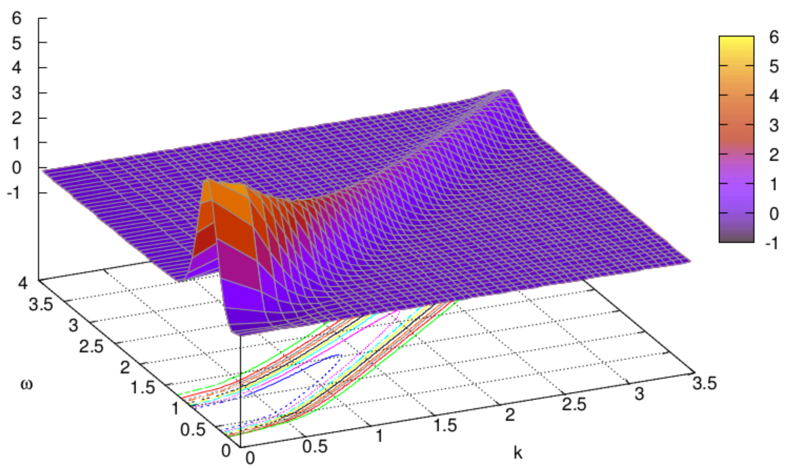


Epelbaum, Gelis,
Nucl.Phys. A872 210-244 (2011).

Development of Quasi-particles:

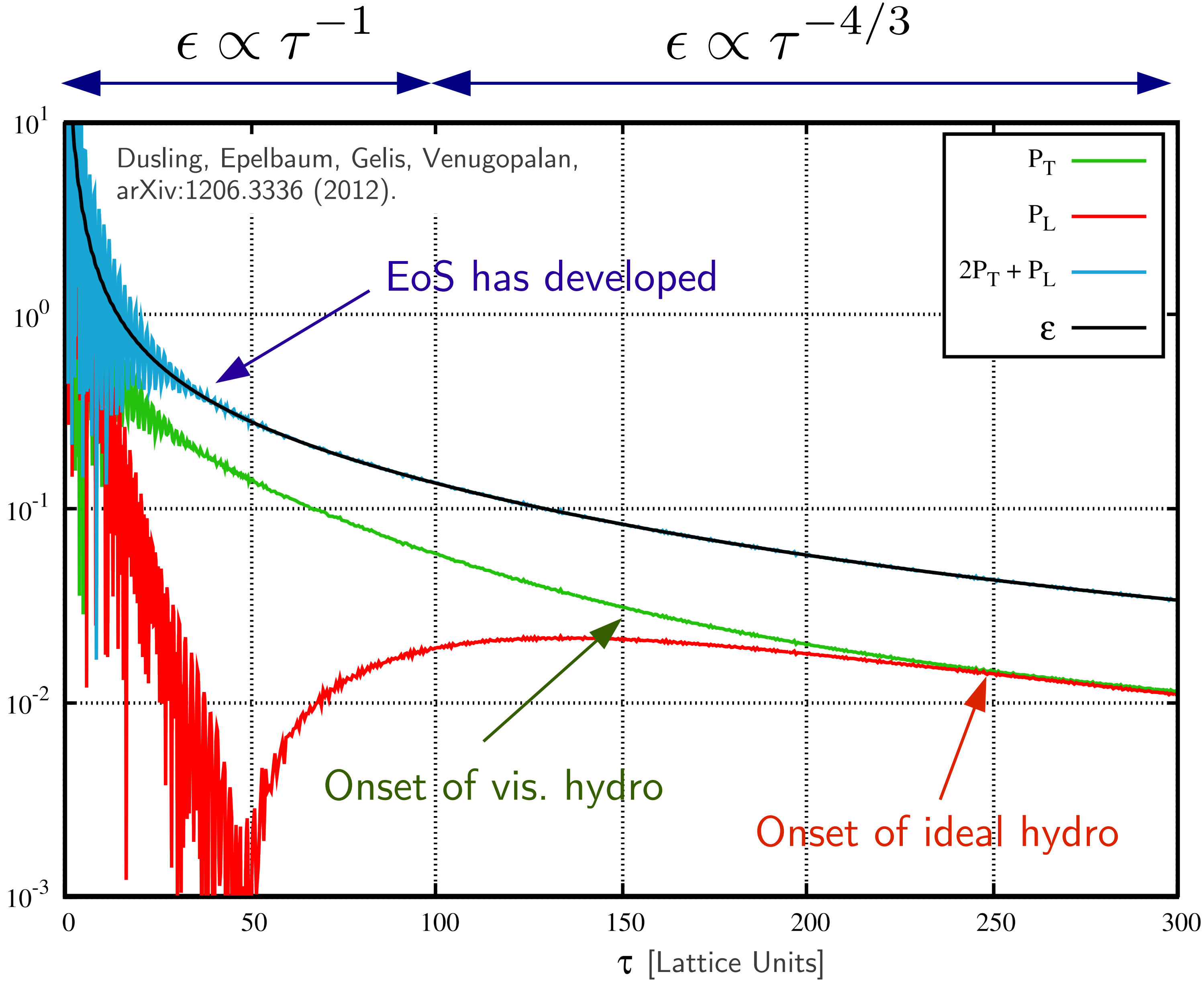


$t = 0$



$t = 3000[\text{Lattice Units}]$

Longitudinally expanding non-linear scalar field



$\epsilon \propto \tau^{-1}$

$\epsilon \propto \tau^{-4/3}$

Dusling, Epelbaum, Gelis, Venugopalan, arXiv:1206.3336 (2012).

EoS has developed

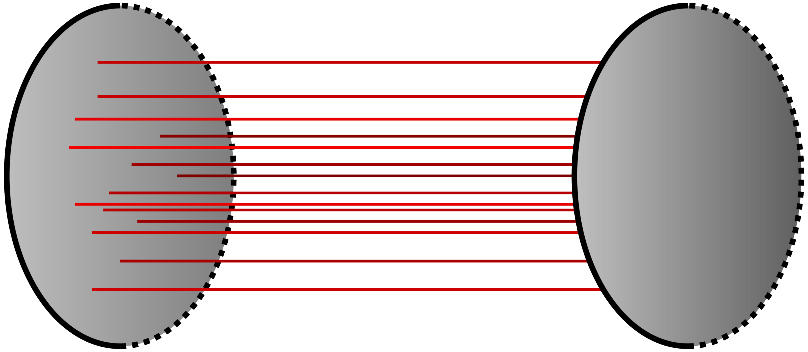
Onset of vis. hydro

Onset of ideal hydro

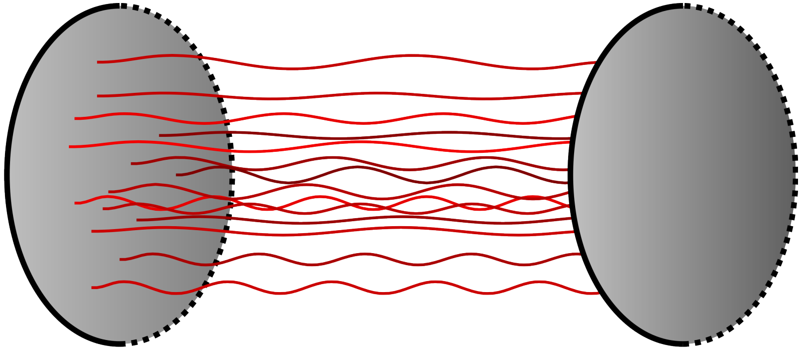
Have a proof of principle for scalar fields: what about QCD?

QCD: Classical Yang Mills

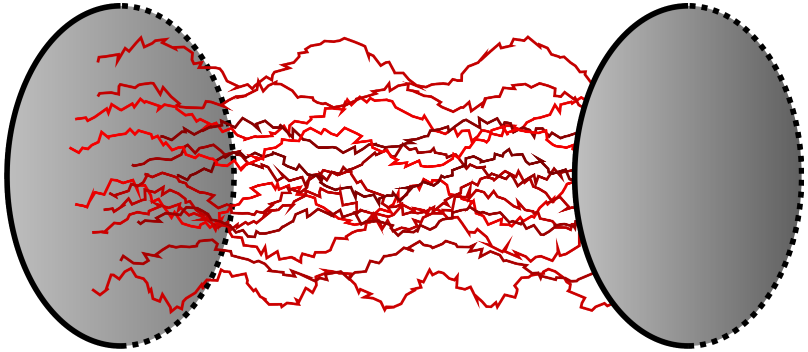
$\tau = 0:$

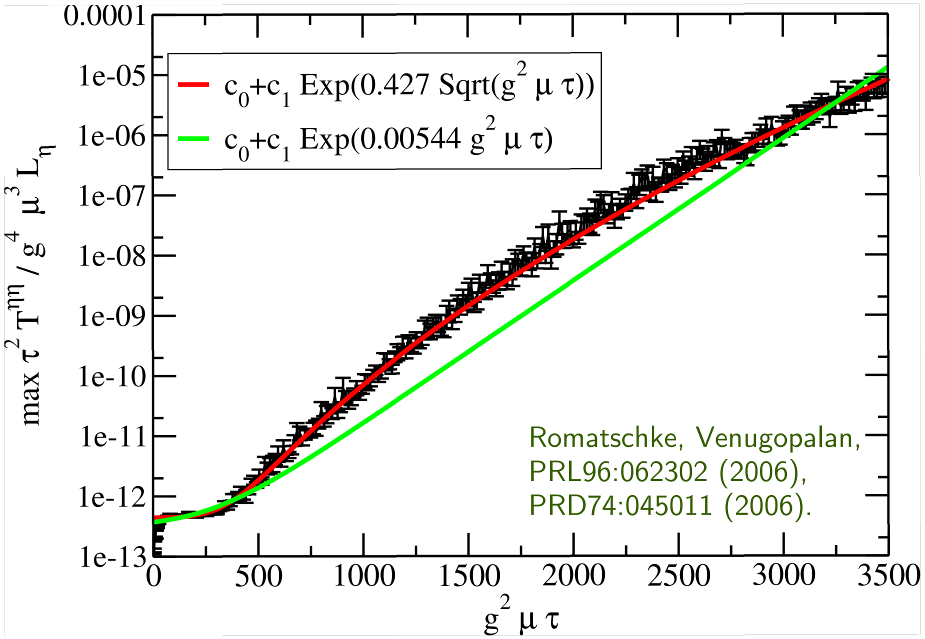


$\tau = 0^+:$



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





Romatschke, Venugopalan, PRL96:062302 (2006), PRD74:045011 (2006).

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).

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:

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

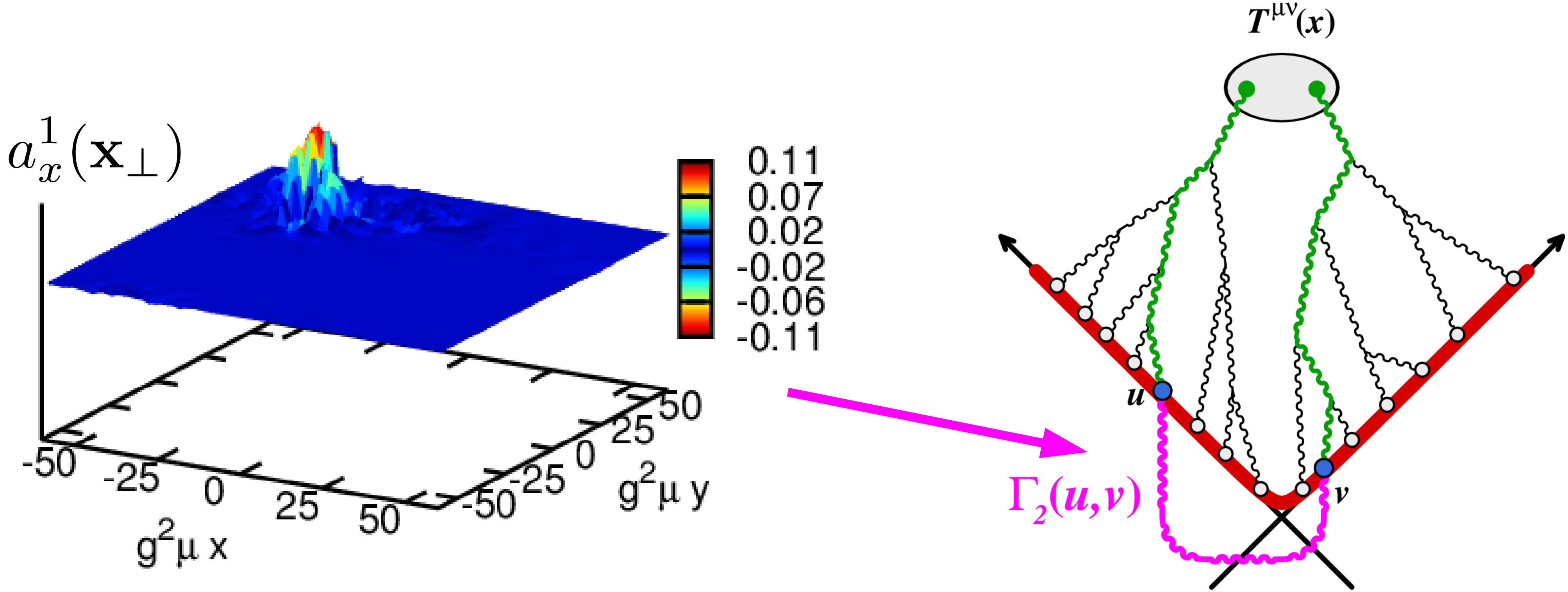
From solution of 3+1D
classical Yang-Mills Eqs.

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

Talk by Raju Venugopalan, Wed. 12pm

Initial spectrum of the little bang

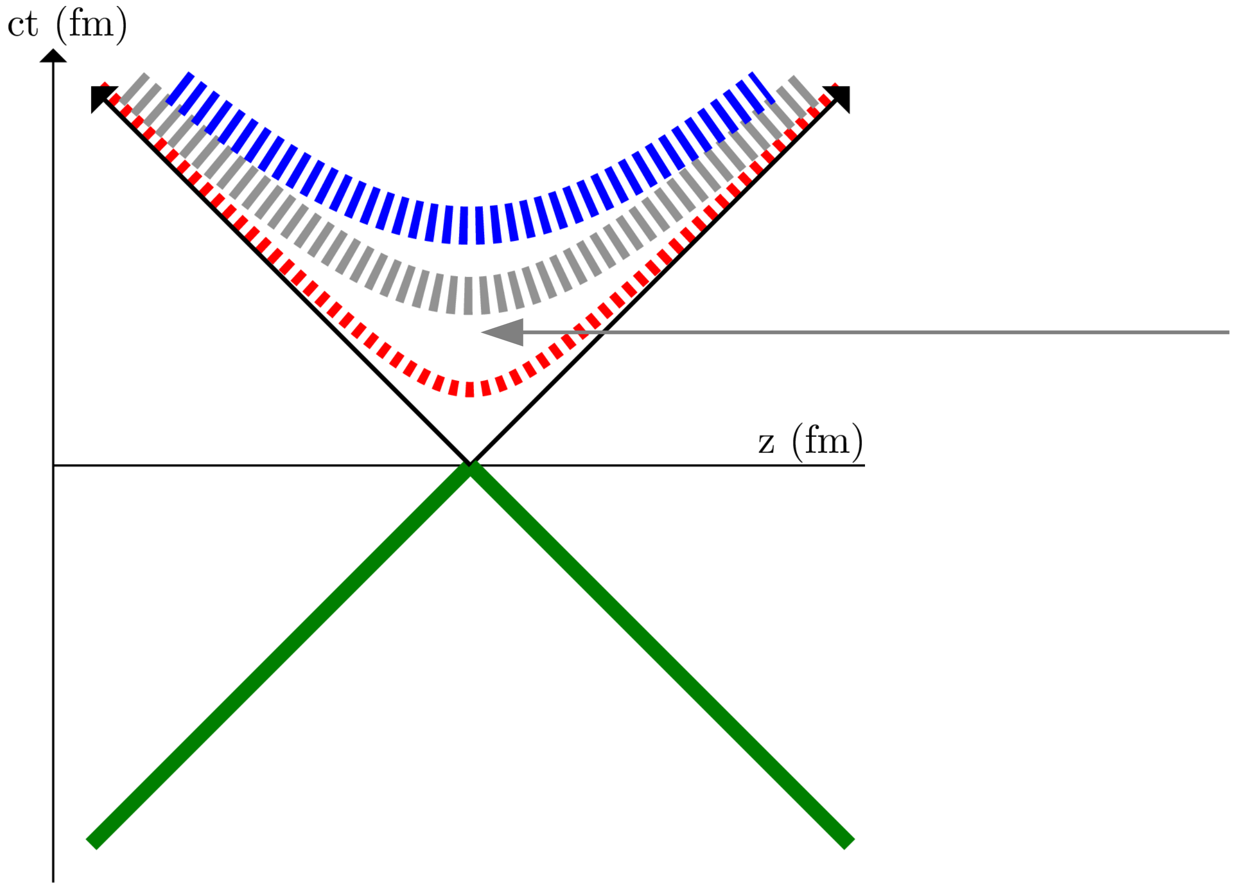
Preliminary numerical results of real time “quantum” simulations:



In progress: Propagation into the forward light cone

Dusling, Epelbaum, Gelis, Venugopalan,
In progress.

Towards thermalization



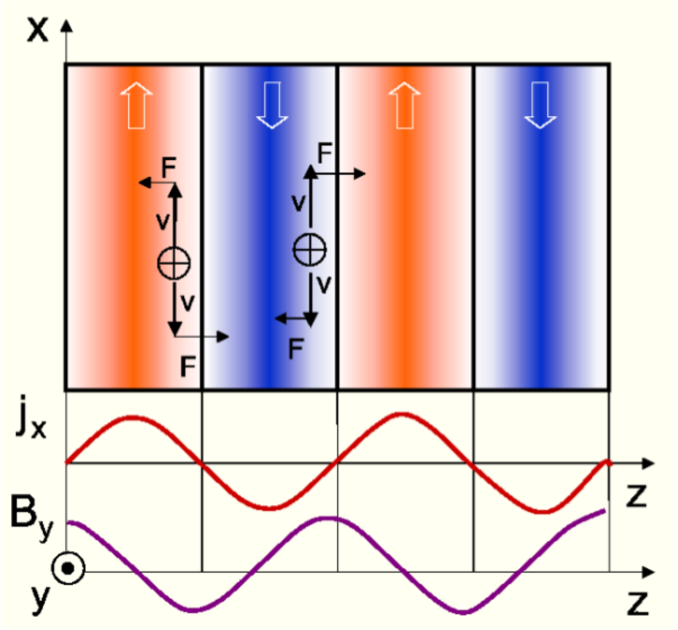
$\tau > Q_s^{-1} \quad g^2 f \ll 1$

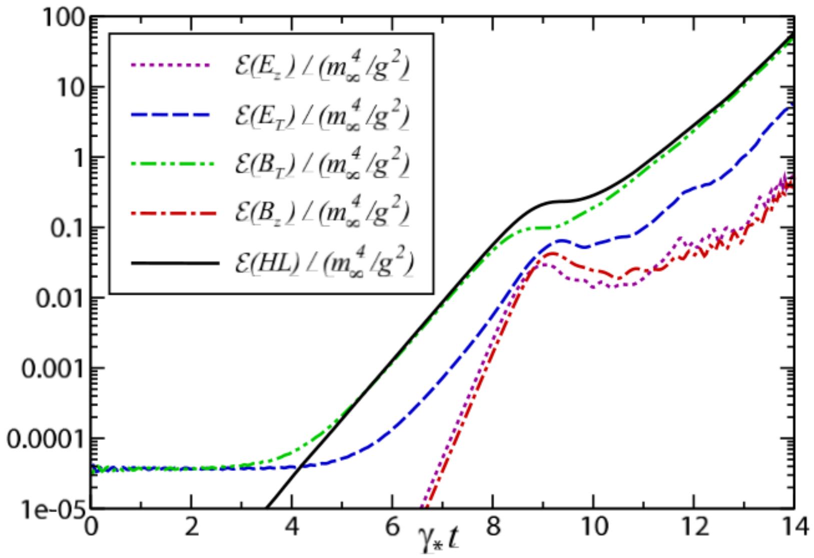
Classical fields almost linear
Quasi-particles have formed
Boltzmann Eq. Applicable

Towards thermalization: instabilities and coherent scattering

HTL calculations have shown the important role played by instabilities in driving thermalization

S. Mrowczynski, A Rebhan, M. Strickland, PRD70 (2004) 025004.
A. Rebhan, P. Romatschke, M. Strickland, PRL94 (2005) 102303, JHEP 0509 (2005) 041.
A. Dumitru, Y. Nara, M. Strickland, Phys.Rev. D75 (2007) 025016.





There has been recent analytic progress:

Thermalization in weak coupling QCD can occur:

$$\tau_{\mathrm{therm}} \sim \frac{1}{\alpha^{5/2} Q_s}$$

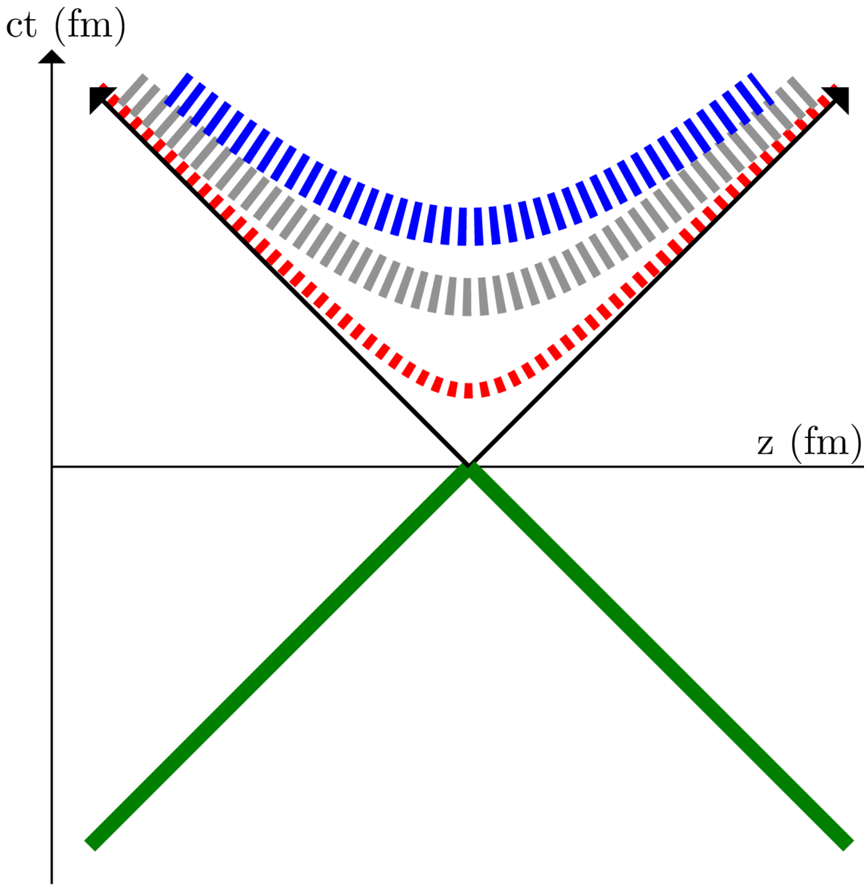
Kurkela, Moore, JHEP 1112:044 (2011).
Kurkela, Moore, JHEP 1111:120 (2011).
Baier, Mueller, Schiff, Son, PLB502 51-58 (2001).

BEC in HIC:
Blaizot, Gelis, Liao, McLerran, Venugopalan Nucl.Phys. A873 (2012).

Numerical Evidence?
Kurkela, Moore, arXiv:1207.1663 (2012).
Schlichting, arXiv:1207.1450 (2012).

Talk by Jinfeng Liao, Fri. 2pm

From initial-state fluctuations to final-state observables



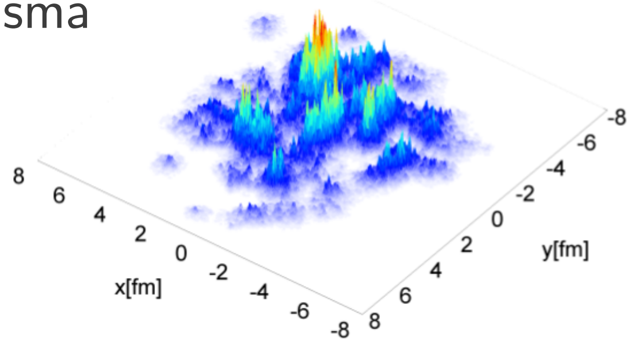
Our field has a fairly comprehensive picture of the various stages.

But, they have yet to be merged into a single framework relevant for phenomenology.

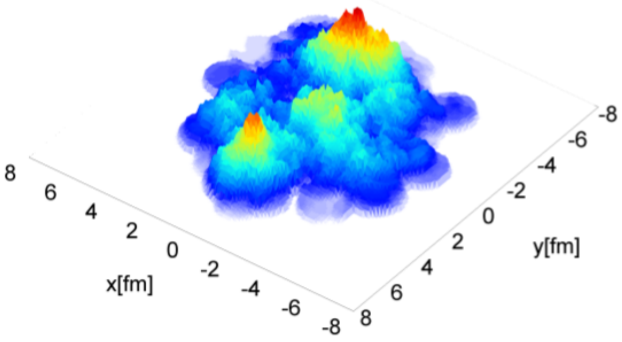
In the mean time we can still make some progress...

Fluctuations → Higher Harmonics

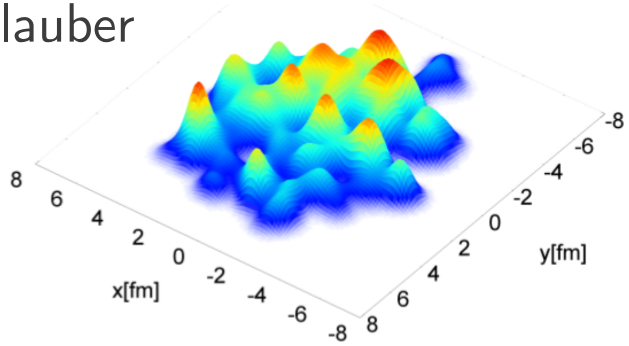
IP-Glasma



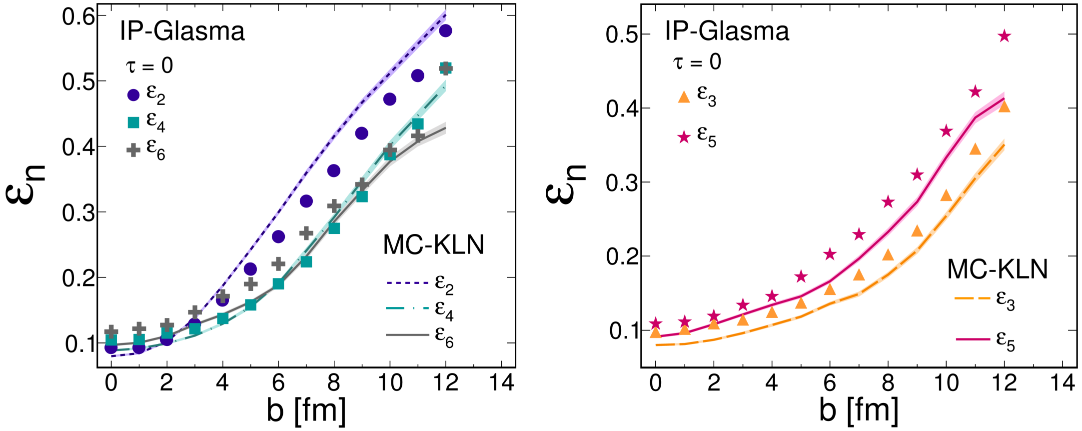
MC-KLN



MC-Glauber



Important role played by color charge fluctuations



Only 3+1D CYM mapped to visc. hydro can eliminate last major uncertainty in flow studies.

Talk by Rupa Chatterjee, Fri. 3:40pm
Talk by Scott Moreland, Wed. 11:40am
Talk by Hannah Petersen, Fri. 10am
Talk by Bjoern Schenke, Wed. 8:50am
Talk by Huichao Song, Mon. 6pm
Talk by Michael Strickland, Wed. 8:50am

B. Schenke, P. Tribedy, R. Venugopalan,
arXiv:1206.6805, Phys. Rev. Lett. 108 (2012) 252301,

Summary and Outlook

1. **Initial state clearly survives into final state**
   - Consistency of p+p Ridge to Pb+Pb Ridge
   - ε_n to v_n

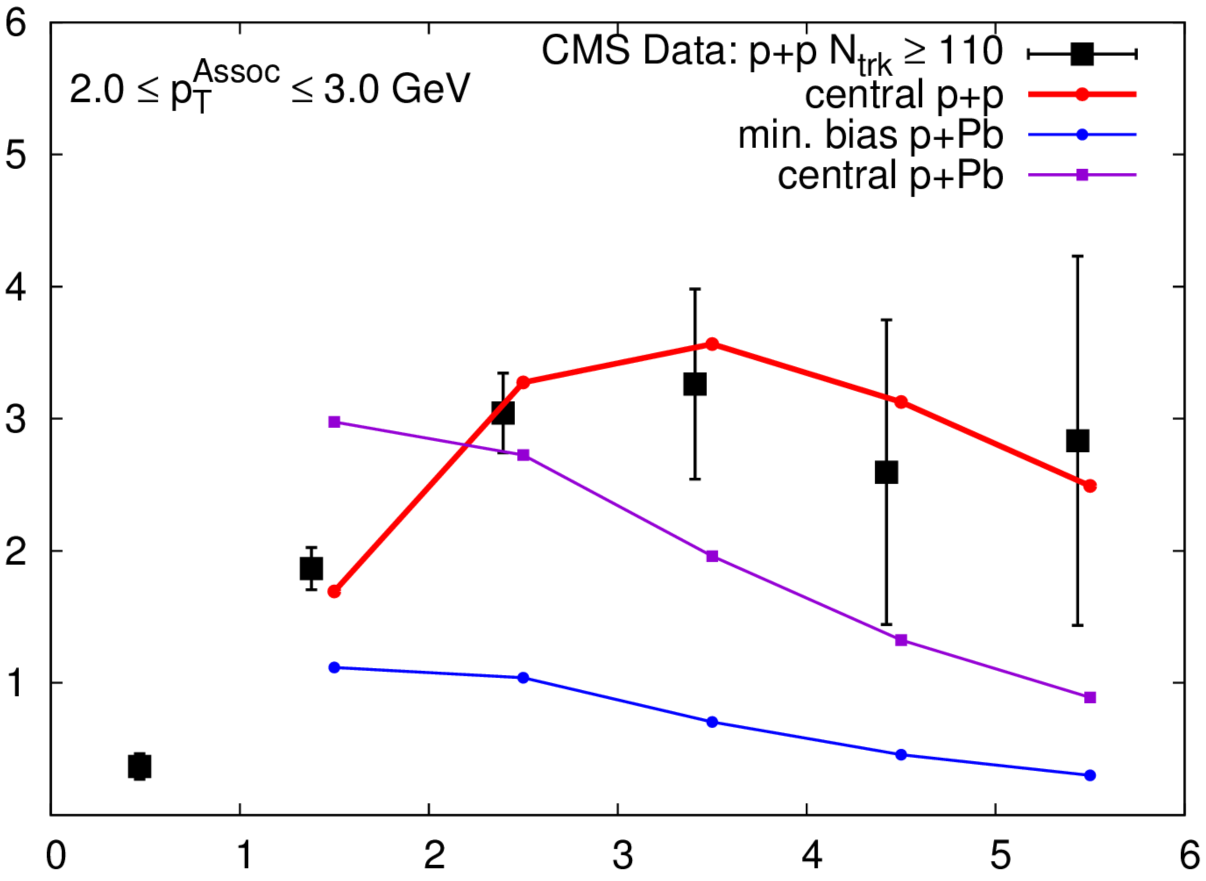
2. **Have a comprehensive picture of the various stages of decoherence, isotropization and thermalization in a weak coupling framework**

3. **Significant progress in understanding early dynamics since QM11 in Annecy**
   - Proof of principle for scalar field completed
   - Can compute the initial quantum fluctuations
   - Computations underway to evolve these into the forward light-cone and quantify initial flow and matching to viscous hydrodynamics

4. **Will have far reaching consequences for phenomenology:**
   - Pre-equilibrium flow can significantly alter interpretation of results (HBT, v_2, ISF)

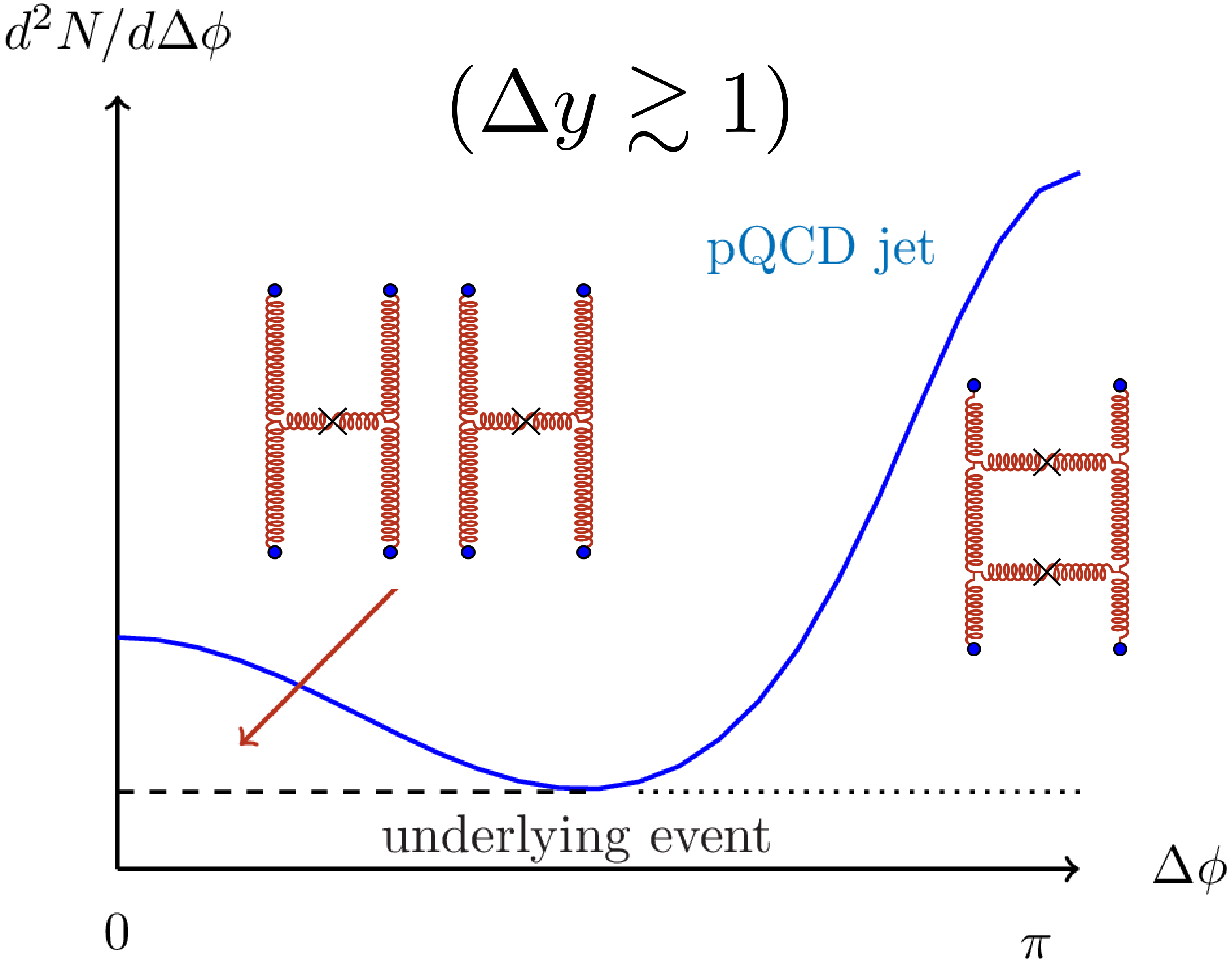
Backup

Ridge in p+Pb

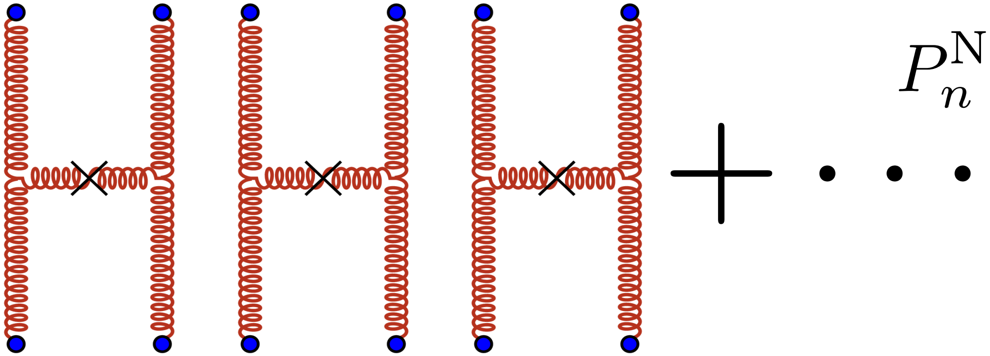


Ridge in p+Pb is smaller than in p+p for CMS acceptance.
Signal will also have to be pulled from a larger background.

Forward jet structure



High multiplicity are b=0 collisions



$$P_n^{\rm NB}(\overline{n},k) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)}\,\frac{\overline{n}^n k^k}{(\overline{n}+k)^{n+k}}$$

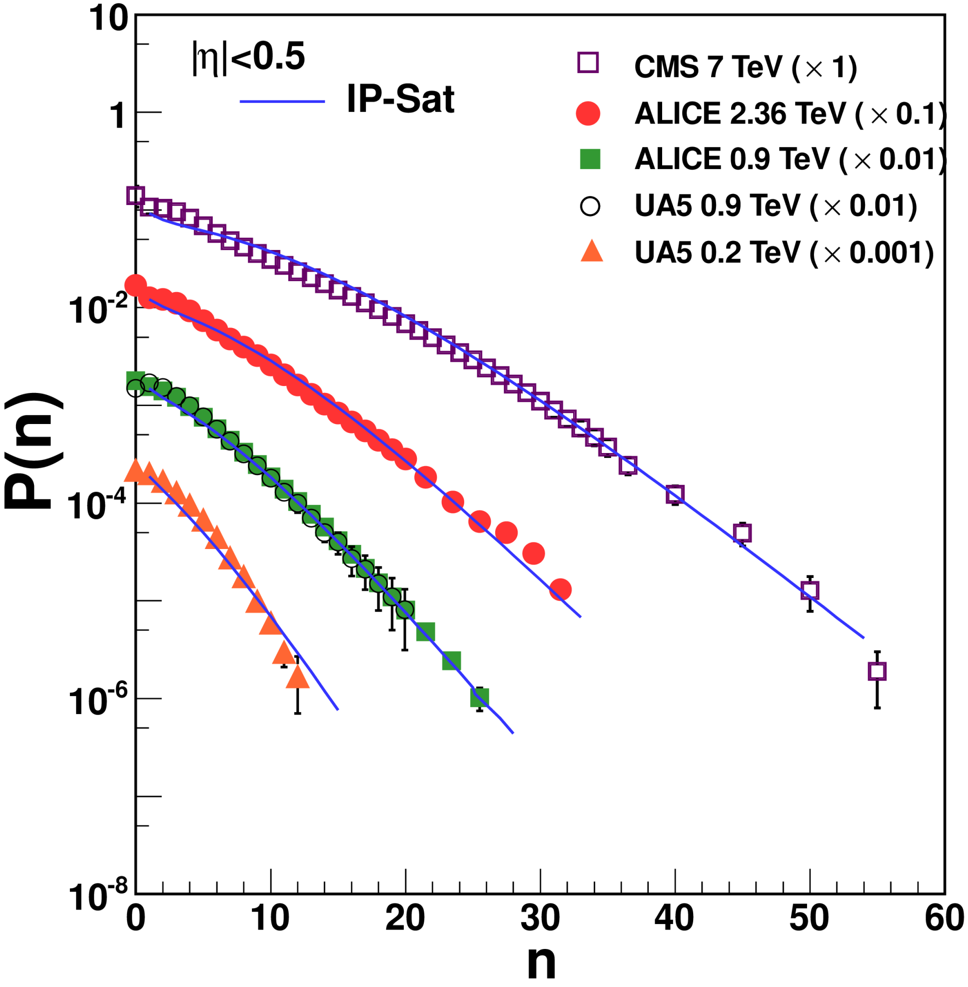
Dumitru, Gelis, McLerran, Venugopalan, NPA810 91-108 (2008).
Dusling, Fernandez-Fraile, Venugopalan NPA828 (2009) 161-177.
Gelis, Lappi, McLerran, NPA828 (2009) 149-160.

$$k = \zeta\,\frac{\left(N_c^2-1\right) S_\perp Q_s^2}{2\pi}$$

$$\zeta = 0.155 \;\; [\text{Empirical}]$$

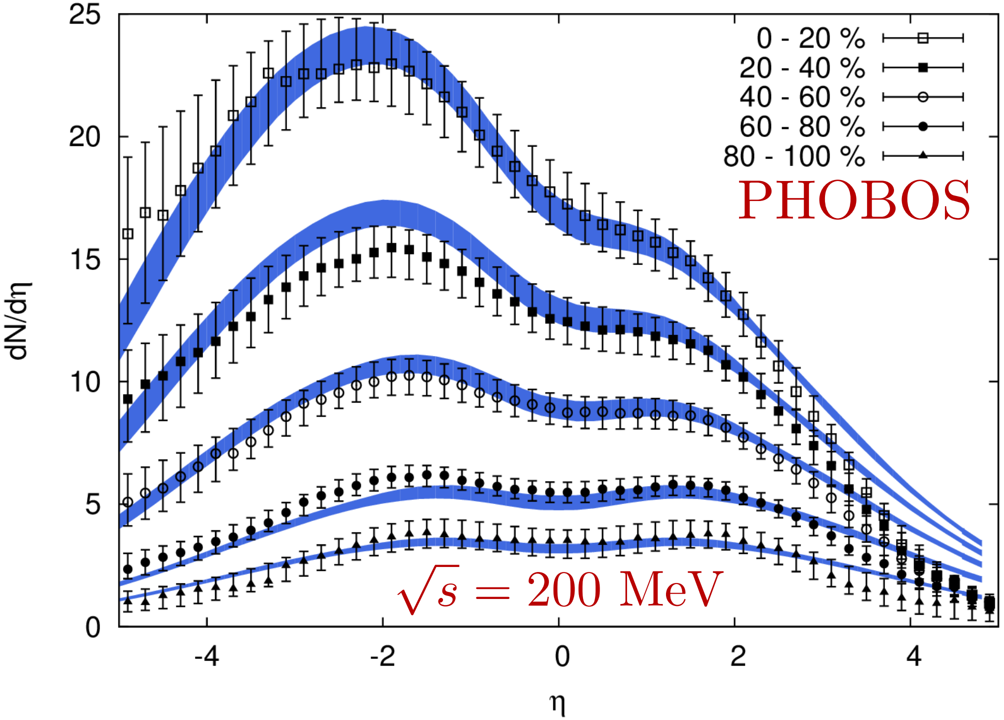
$$\zeta = 0.2 - 1.5 \;\; [\text{Lattice}]$$

Emprical: Tribedy, Venugopalan, NPA850 (2011) 136-156.
Lattice (CYM): Lappi, Srednyak, Venugopalan, JHEP01 (2010) 066.
Schenke, Tribedy, Venugopalan, arXiv:1206.6805



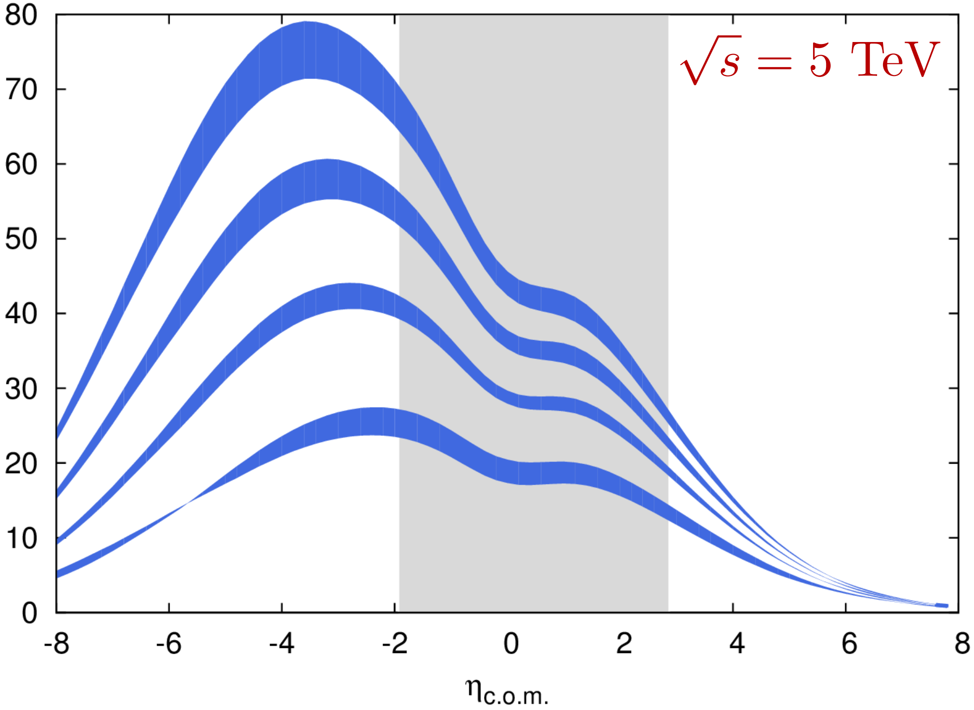
Multiplicity in p+Pb at 5 TeV

$$Q^2_{0,\mathrm{Au}} = 0.336, 0.336, 0.504, 0.672, 0.840\ \mathrm{GeV}^2$$



$$Q^2_{0,\mathrm{d}} = 0.336\ \mathrm{GeV}^2$$

$$Q^2_{0,\mathrm{Pb}} = 0.504, 0.672, 0.840, 1.008\ \mathrm{GeV}^2$$



$$Q^2_{0,\mathrm{p}} = 0.168\ \mathrm{GeV}^2$$