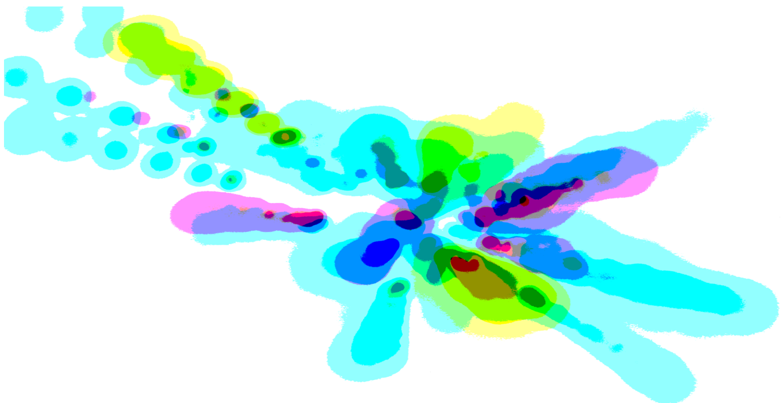
What's big about small x



Raju Venugopalan
Brookhaven National Laboratory

EIC workshop, ICTS, Bengaluru, February 5-9, 2024

Outline of my talk

- Small x physics is intrinsically non-perturbative: “Classical” lumps from quantum coherence
- Small x and quantum information science: Goldstone modes and Bekenstein bound
- Small x and heavy-ion collisions: universality across energy scale and (nearly) instantaneous thermalization
- ~~Gravity and QCD at small x: Lipatov double copy, gravitational waves in strong fields and the problem of Black Hole formation in trans-Planckian scattering~~

  (3pm Wednesday, Madhava Lecture hall)

  Axion-like dynamics of the primordial η', its role in proton spin, and
  its quenching by topological “sphaleron” transitions at the EIC

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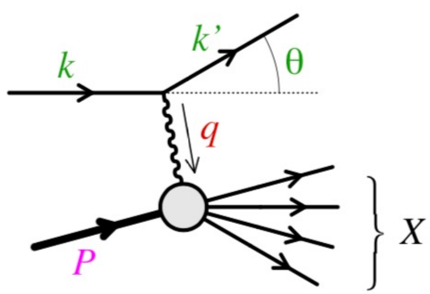
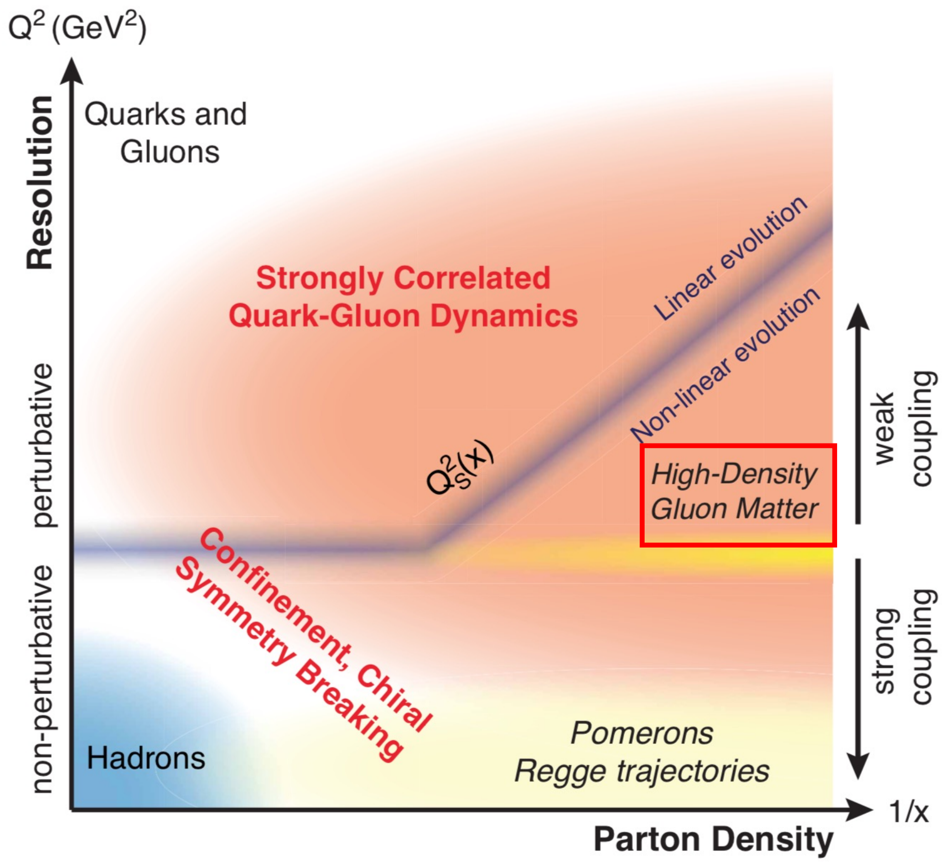
Tarasov, RV, arXiv:2008.08104, arXiv: 2109.10370, and in preparation

Mapping out terra incognita in the QCD landscape



Deeply inelastic scattering

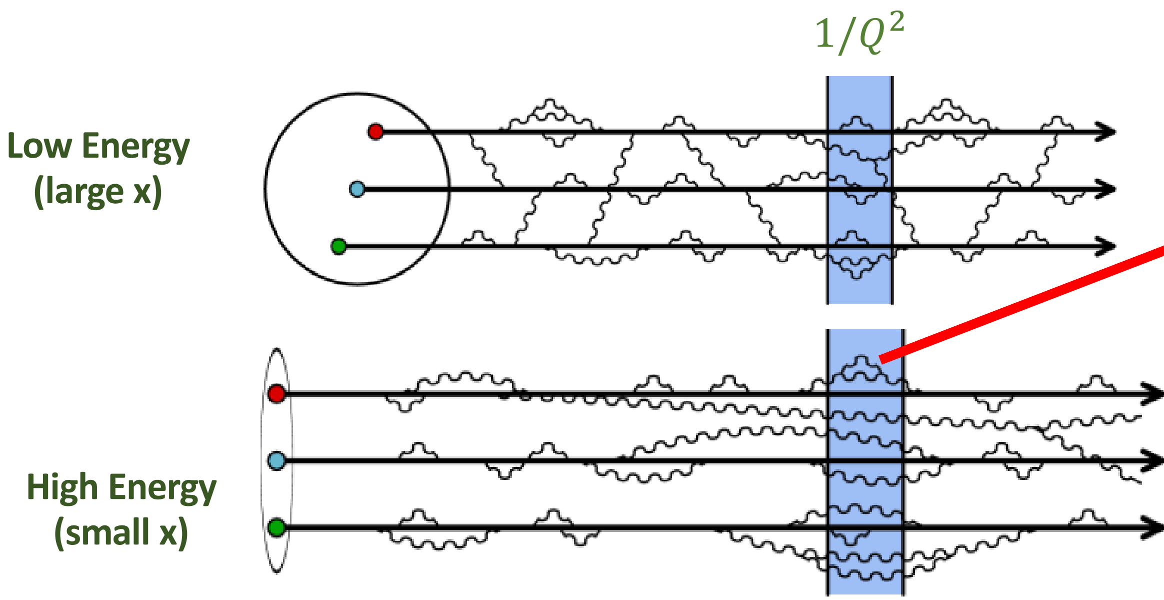


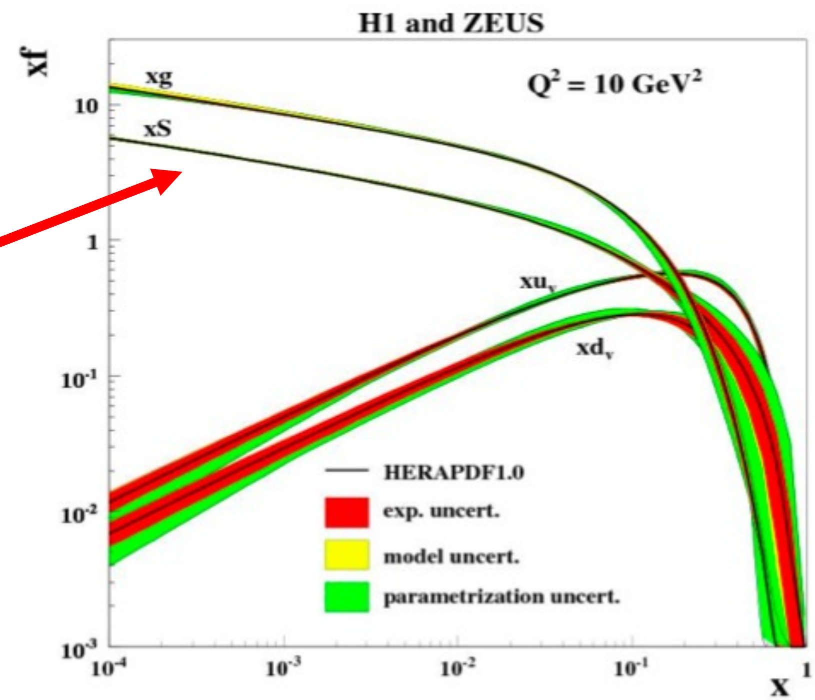
Aschenauer et al., arXiv:1708.01527
Rep.Prog. Phys. 82, 024301 (2019)

Many open questions: 3-D quark-gluon structure of the proton, spin and orbital dynamics, many-body correlations, multi-particle production...

Wee partons ($x << 1$) are intrinsically non-perturbative

Spacetime picture of wee partons in a hadron

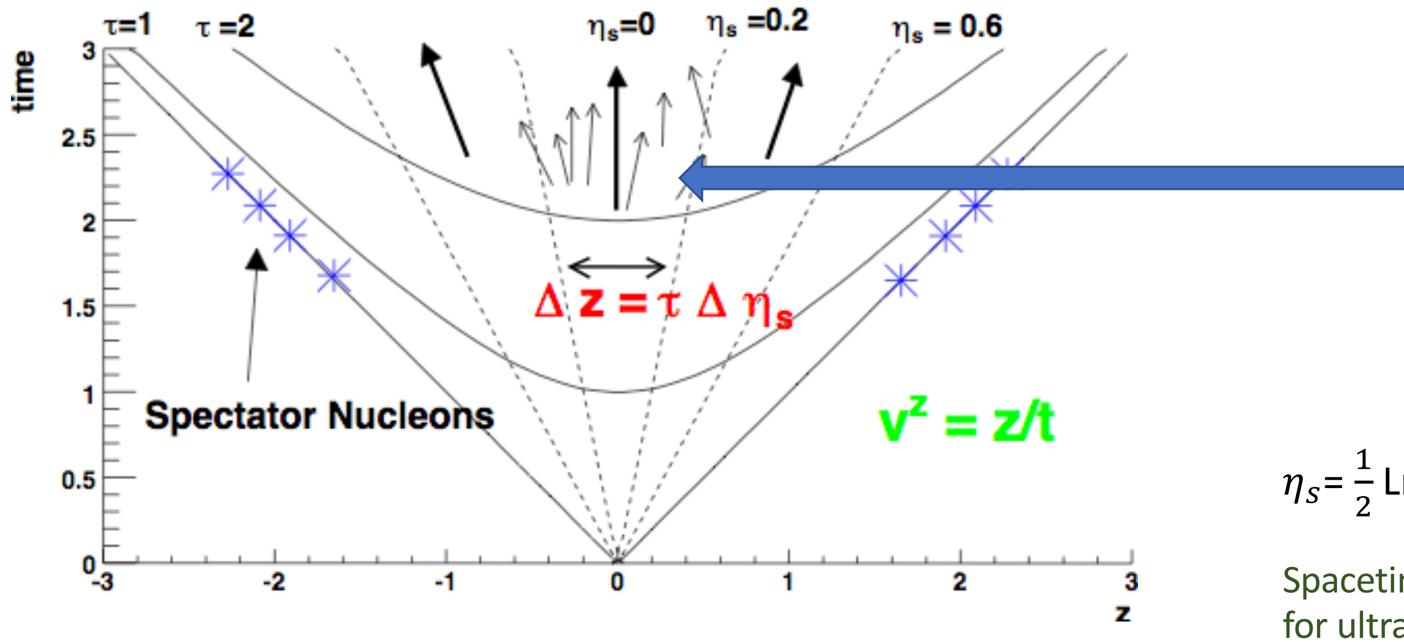


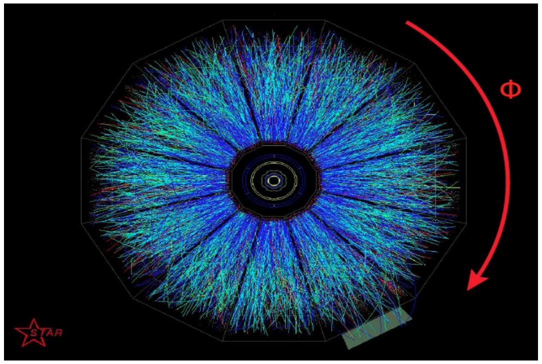


As the proton is boosted, “parton” fluctuations live longer -- released as Bremsstrahlung

Suppression in coupling compensated by large phase space for soft glue: $\alpha_S\, Ln\left(\frac{1}{x}\right) \sim 1$

Spacetime picture of a high energy hadron-hadron collision



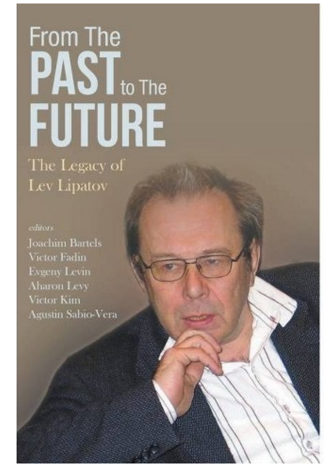


$$\eta_s = \frac{1}{2}\,\mathrm{Ln}\,(\frac{t+z}{t-z}) \approx Y$$

Spacetime rapidity ≈ Momentum rapidity for ultrarelativistic particles

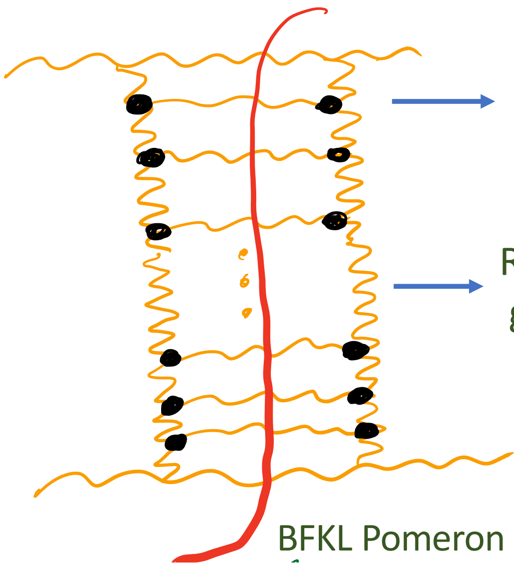
Fast “valence” partons populate fragmentation regions at large rapidities – “leading particle” effect
Slow “wee” partons populate central rapidities (mostly gluons and sea-quark pairs)

Wee partons in the BFKL Paradigm

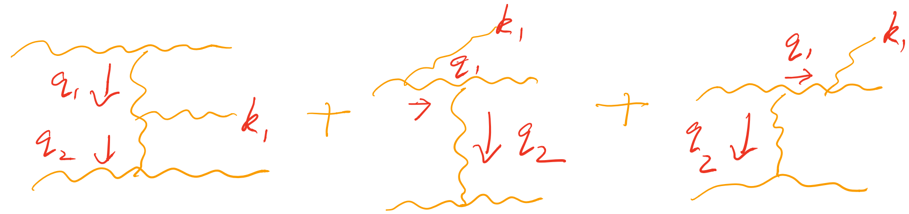


Lev Lipatov

Sophisticated construction to describe 2→ N scattering in multi − Regge kinematics



Lipatov vertex



Reggeized gluon $\equiv \frac{1}{t_i} \to \frac{1}{t_i} e^{\alpha(t_i)(y_{i-1}-y_i)}$

Regge trajectory: $\alpha^{(2)}(t) = \kappa_\Gamma^2 \left(\frac{\mu^2}{-t}\right)^{2\epsilon} \left(\frac{\beta_0}{\epsilon^2} + \frac{\gamma_K^{(2)}}{8\epsilon} + \frac{\gamma_\wedge^{(2)}}{2} + \zeta_2\beta_0\right) + \mathcal{O}(\epsilon)$

$\gamma_K^{(2)}$: Two loop cusp anomalous dimension

$\gamma_\Lambda^{(2)}$: Two loop wedge anomalous dimension

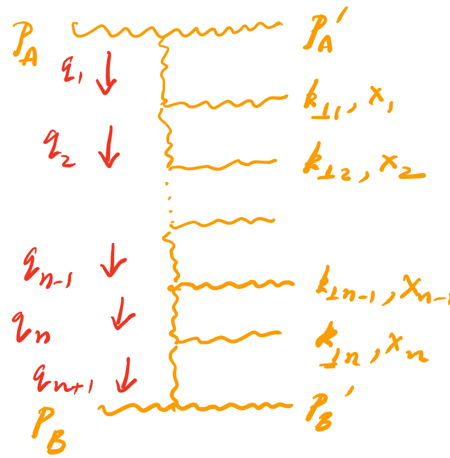
Fadin, hep-ph/9807528

$$\sigma_{tot} = 2\,\mathrm{Im}\,A(s, t=0)$$
$$= s^\lambda \text{ with } \lambda = \frac{4\alpha_s N_c \ln_e 2}{\pi}$$
$$\simeq 0.5 \text{ for } \alpha_s = 0.2$$

BFKL Hamiltonian. Remarkable properties: holomorphic separability; generalization to integrable model; beautiful work in N=4 SUSY

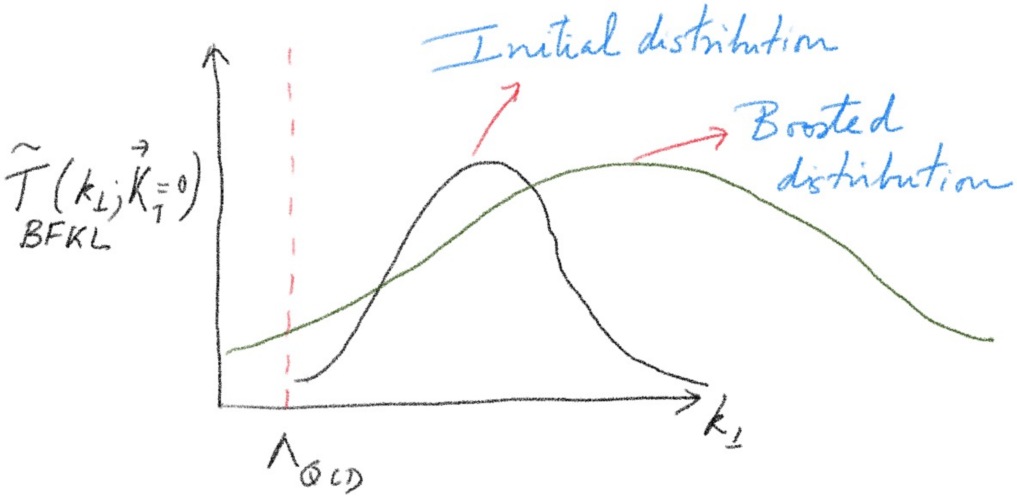
State-of-the art review of NLL BFKL and beyond: Del Duca, Dixon, arXiv:2203.13026

Wee partons in perturbative QCD: $2 \rightarrow \mathrm{N}$ amplitudes



BFKL Eqn: LLx "Leading log" all-order resummation
$(\alpha_n \mathrm{Ln}(\frac{1}{x}))^n$ of real and virtual graphs all orders in α_n

Soln. of BFKL equation exhibits infrared diffusion



For a fixed large Q^2 there is an $x_0(Q^2)$ such that below x_0 the OPE breaks down…

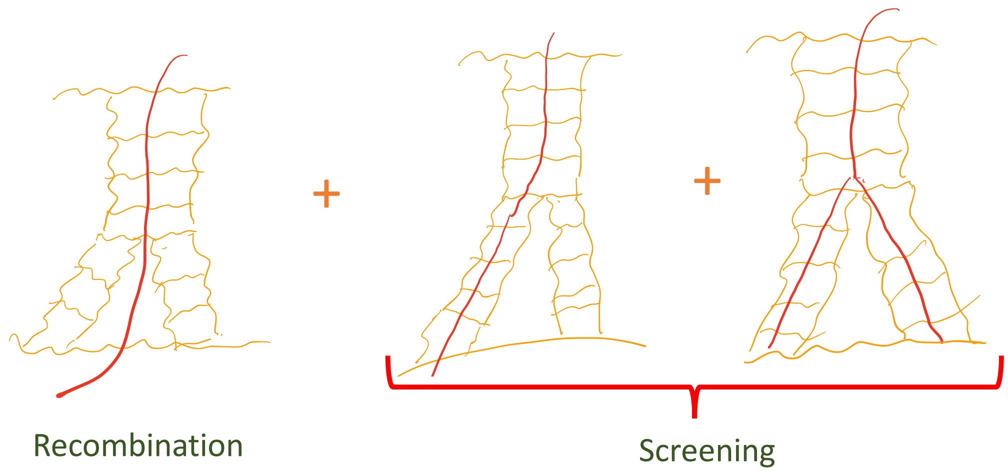
significant nonperturbative corrections in the leading twist coefficient and anomalous dimension functions due to diffusion of gluons to small values of transverse momentum.

A. H. Mueller, PLB 396 (1997) 251

NLL BFKL does not cure infrared diffusion

Wee partons in pQCD: many-body dynamics in $\mathbf{2} \rightarrow \boldsymbol{N}$ amplitudes

Gribov,Levin,Ryskin (1983)
Mueller,Qiu (1986)



$$= -\frac{\left[\alpha_s G(x,Q^2)\right]^2}{Q^2 R^2}$$

"The elimination of such complicated interlocking infrared divergences would certainly be a Herculean task …might not even be possible"

S. Weinberg, PRD (1965)

"A fascinating equilibrium of (gluon) splitting and recombination should eventually result: it's a considerable theoretical challenge…"

F. Wilczek, Nature (1999)

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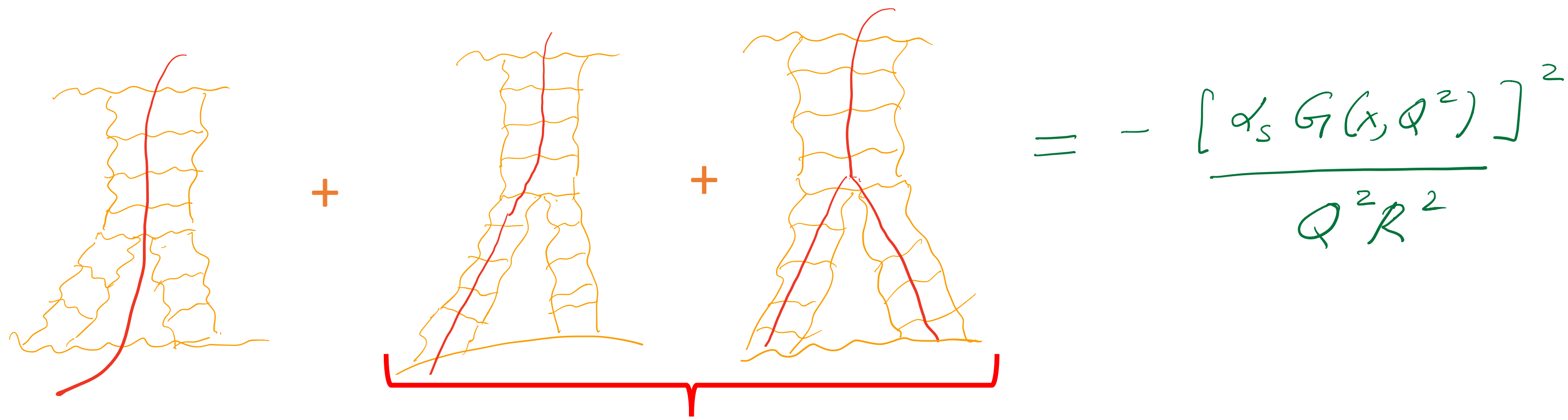

Recombination Screening

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Emergent saturation scale Q_S suppresses infrared diffusion in transverse momentum

All-twist power corrections equally important when

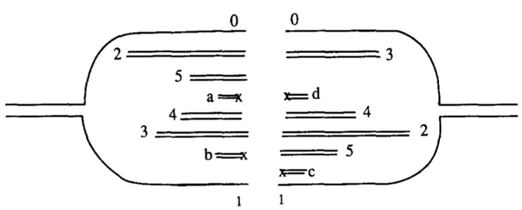
$$N \equiv \frac{xG_A(x, Q_S^2)}{2(N_c^2-1)\pi R_A^2 Q_S^2} = \frac{1}{\alpha_S(Q_S)}$$

Classicalization when $\alpha_S(Q_S) \ll 1$ for $Q_S \gg \Lambda_{QCD}$

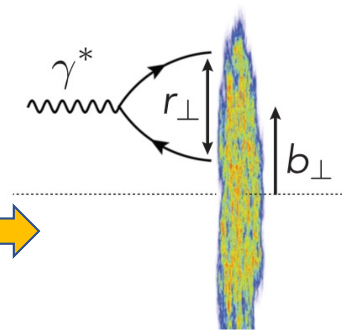
Classicalization and perturbative unitarization: gluon saturation

s-channel "dipole" scattering picture

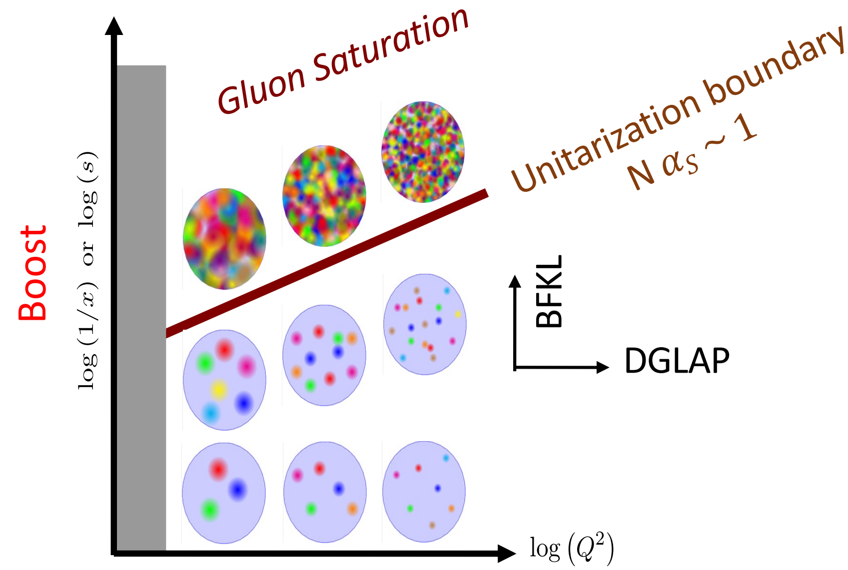
Mueller, NPB415 (1994) 373
Mueller, Patel, hep-ph/9403256



Boosted projectile



Boosted target



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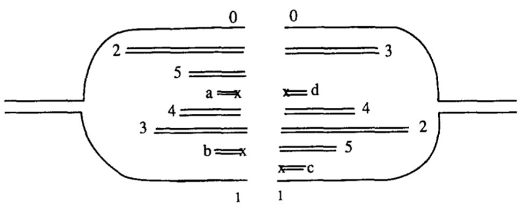

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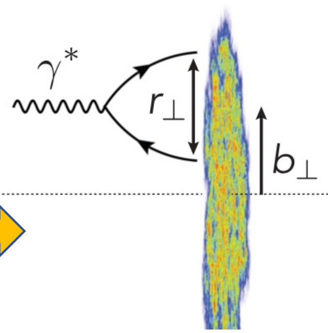

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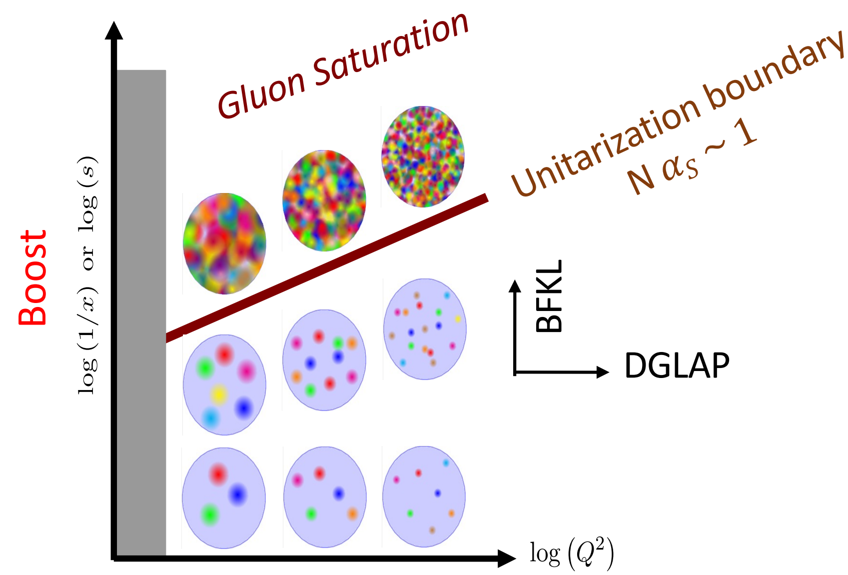
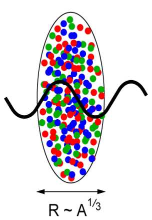


Golec-Biernat-Wusthoff model:

$$\sigma_{q\bar{q}P}(r_\perp, x) = \sigma_0\,\left[1 - \exp\left(-r_\perp^2\, Q_s^2(x)\right)\right]$$

BFKL eigenvalue

Emergent semi-hard scale $Q_s^2(x) = Q_0^2\left(\frac{x_0}{x}\right)^\lambda$



Quantum coherence of large # of color charges

for x << $A^{-1/3}$ → $Q_{S,A}^2\ /\ Q_{s,p}^2\ \propto\ A^{\frac{1}{3}}$

$\sim constant\ when\ Y \to \infty$

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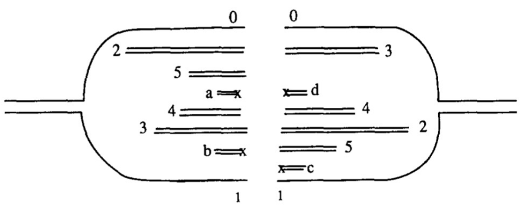

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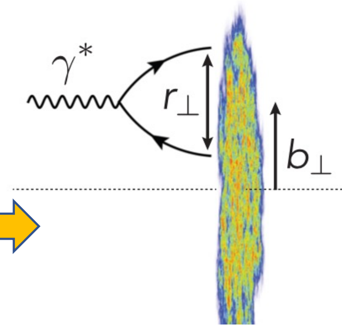

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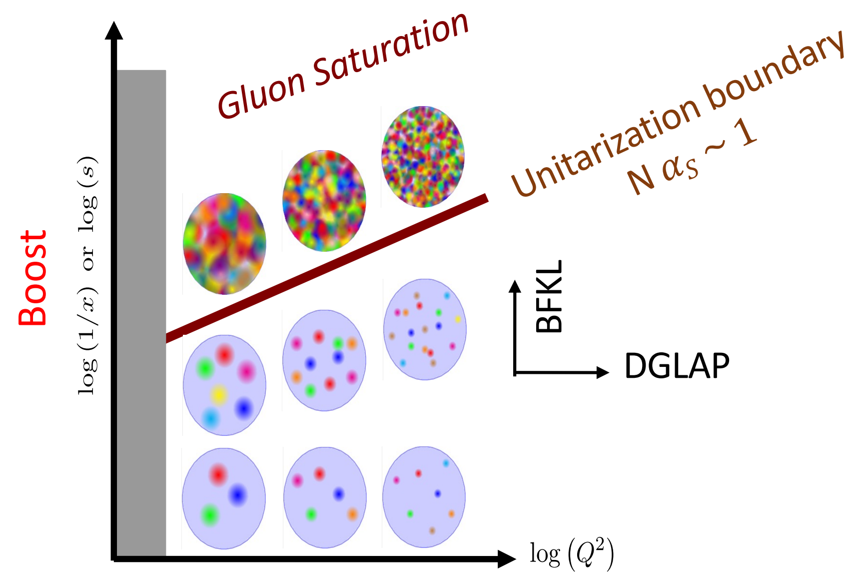

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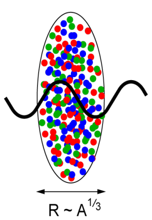

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$\sim constant\ when\ Y \rightarrow \infty$

Color transparency for $r_\perp^2 Q_S^2$ << 1 ($\sigma \propto A$)

Color opacity ("black disk") for $r_\perp^2 Q_S^2$ >> 1 ($\sigma \propto A^{2/3}$)

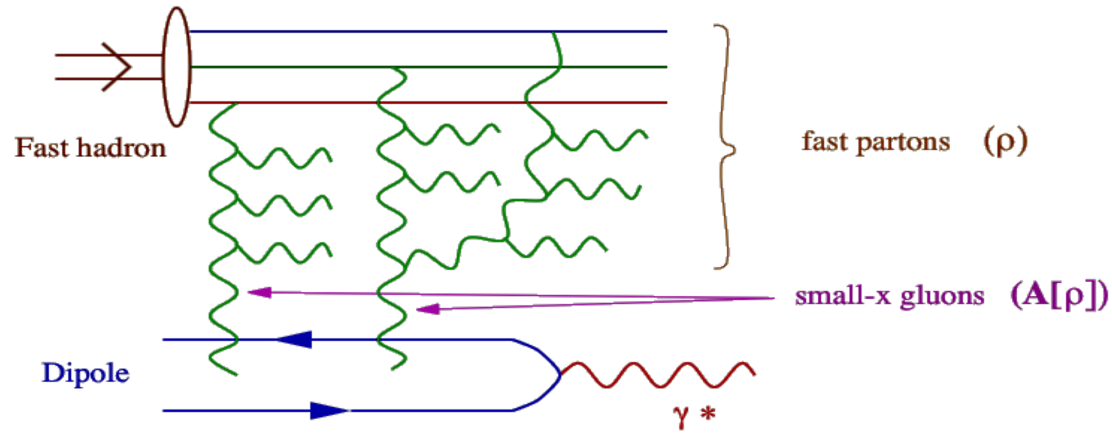
QCD picture of observed "shadowing" at small x

The Color Glass Condensate: classical EFT for Regge asymptotics

Born-Oppenheimer separation between fast and slow light-front modes

Large x (P^+) modes: static, strong ($\sim 1/g$) color sources ρ^a

Small x ($k^+ << P^+$) modes: fully dynamical gauge fields A_μ^a



$$\mathcal{Z}[j] = \int [d\rho] W_{\Lambda^+}[\rho] \left\{ \frac{\int^{\Lambda^+} [dA]\delta(A^+) e^{iS_{\Lambda^+}[A,\rho] - \int j\cdot A}}{\int^{\Lambda^+} [dA]\delta(A^+) e^{iS_{\Lambda^+}[A,\rho]}} \right\}$$

$W_{\Lambda^+}[\rho]$: nonpert. gauge inv. weight functional defined at initial $x_0 = \Lambda^+ / P^+$

$S_{\Lambda^+}[A, \rho]$: Yang-Mills action + gauge-inv. coupling of sources to fields (Wilson line)

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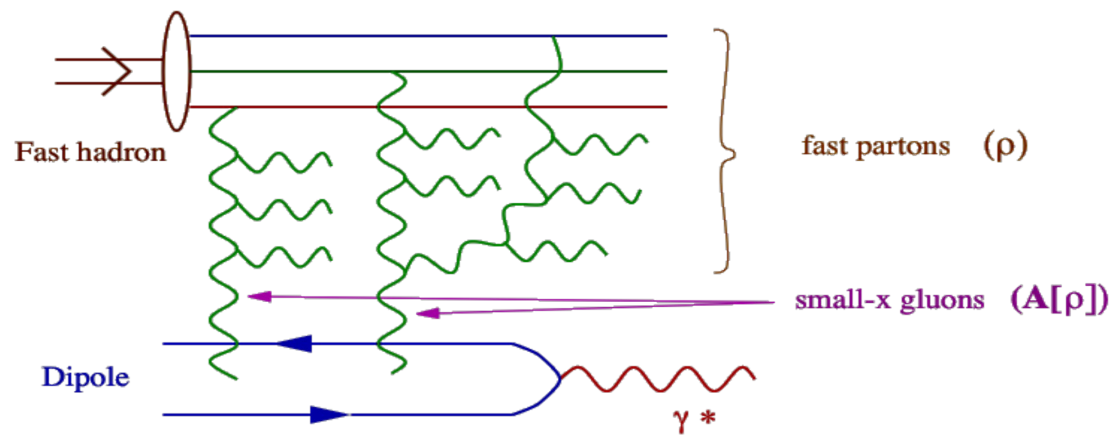


Explicit construction for large nuclei (large number of coherent sources of color charge at small x-large "Ioffe" time)

$$W_{\Lambda^+}[\rho] \rightarrow \int [d\rho] \exp\left(-\int d^2x_\perp \left[\frac{\rho^a\rho^a}{2\mu_A^2} - \frac{d_{abc}\rho^a\rho^b\rho^c}{\kappa_A}\right]\right)$$

Pomeron configurations

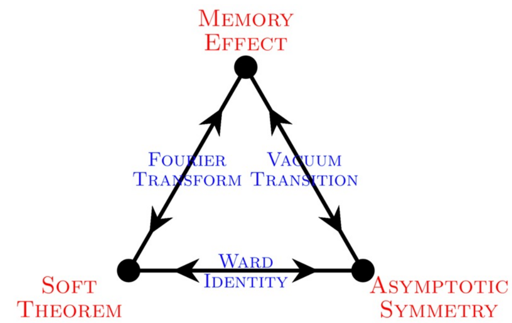
Odderon configurations

For A>>1, $\mu_A^2 \sim Q_S^2 \propto A^{1/3} >> \Lambda_{QCD}^2$
weak coupling EFT for large parton densities!

Can compute N-body wee gluon correlators in this 2-D EFT

McLerran,RV (1994)

Color memory in the CGC



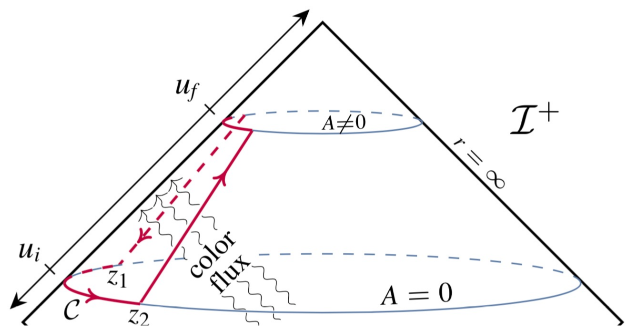
Strominger,arXiv:1703.05448

Static Yang-Mills shockwave wave solution in LC gauge

$A_i = 0$ | $A_i = -\frac{-1}{ig} U \partial_i U^\dagger$

$x^- = 0$

Transverse dynamics can be mapped on to celestial sphere at null infinity:



$(r, u, z, \bar{z}) \to (\lambda r, \lambda^{-1} u, \lambda^{-1} z, \lambda^{-1} \bar{z})$

Map: $x^+ = \sqrt{2r}$, $x^- = \frac{1}{\sqrt{2}}(u + rz\bar{z})$,
$x^1 + i x^2 = 2 r z$

For $\lambda \to \infty$:
$r \to \infty \; \to \; x^+ \to \infty, x^- \to 0$

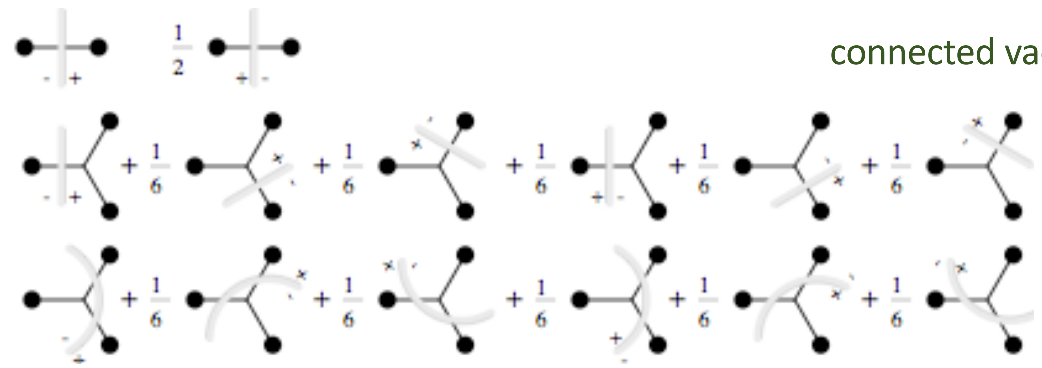
Kick Q_S suffered by dipole is
the color memory effect

Pate, Raclariu, Strominger, PRL (2017)
Ball,Pate,Raclariu,Strominger,RV, Ann. Phys. 407 (2019) 15

The wee glue on the shock can be understood as Goldstone modes of broken Poincare and global group of large gauge transformations – satisfy a current algebra on the celestial sphere

General all-order formalism: Cutkosky's rules in strong fields

$$2\,\mathrm{Im}\sum_{\mathrm{conn.}} V =$$



connected vacuum graphs in $\lambda\phi^3$

Propagators on Schwinger-Keldysh contour

Well-known example: Schwinger pair production in strong field QED

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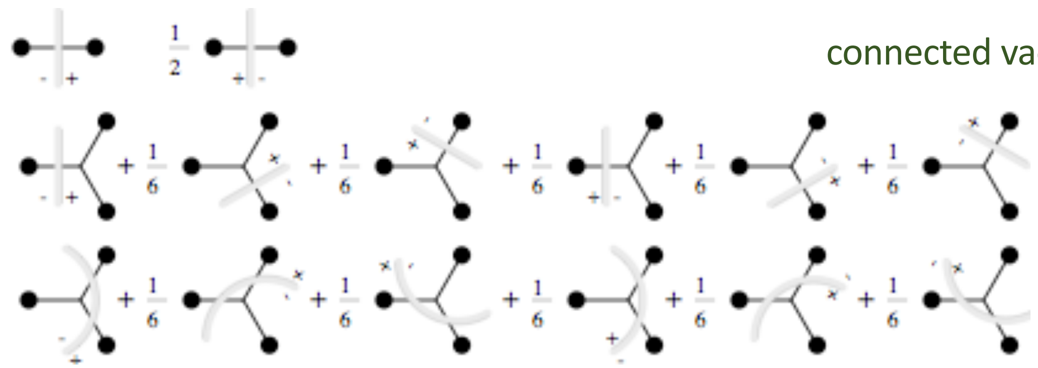

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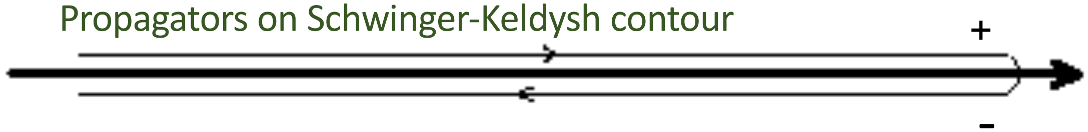

Well-known example: Schwinger pair production in strong field QED

Simple understanding of "AGK cutting rules" of Reggeon Field Theory: combinatorics of cut and uncut sub-graphs contributing to a given multiplicity

- Very general consequence of unitarity in strong fields
- Independent of the language of Pomerons and Reggeons

AGK: Abramovsy,Gribov,Kancheli

Paradigm shift? Perhaps Pomerons best viewed as simplest constructions enforcing strong field unitarity rather than fundamental objects

Gelis,RV: hep-ph/0601209, hep-ph/0608117

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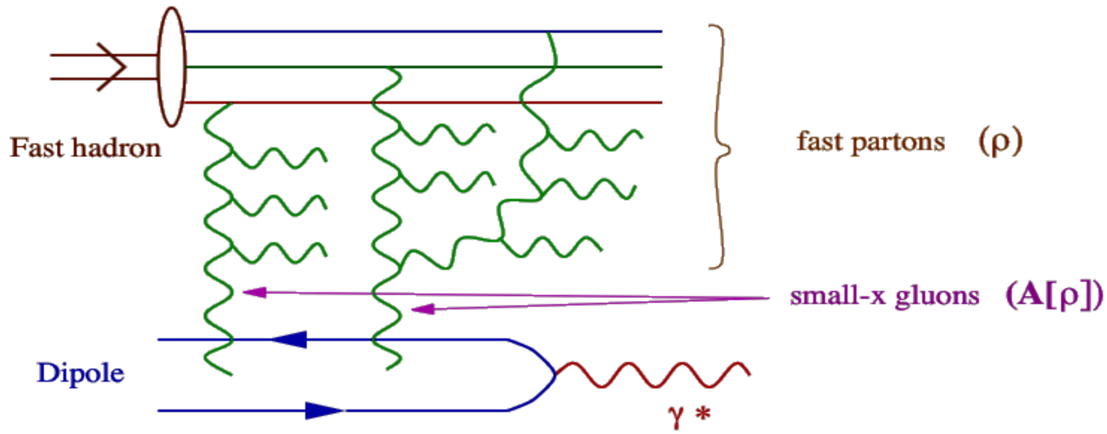
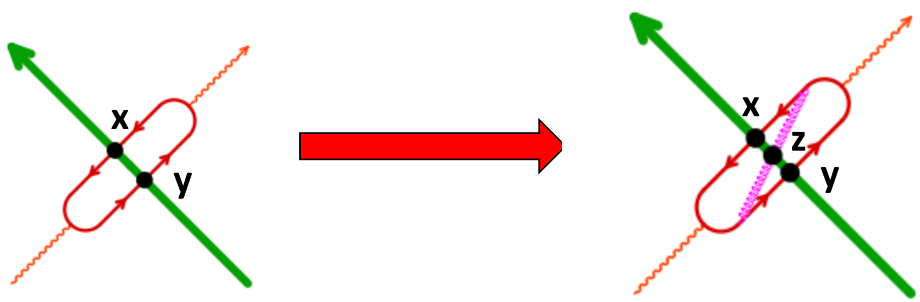


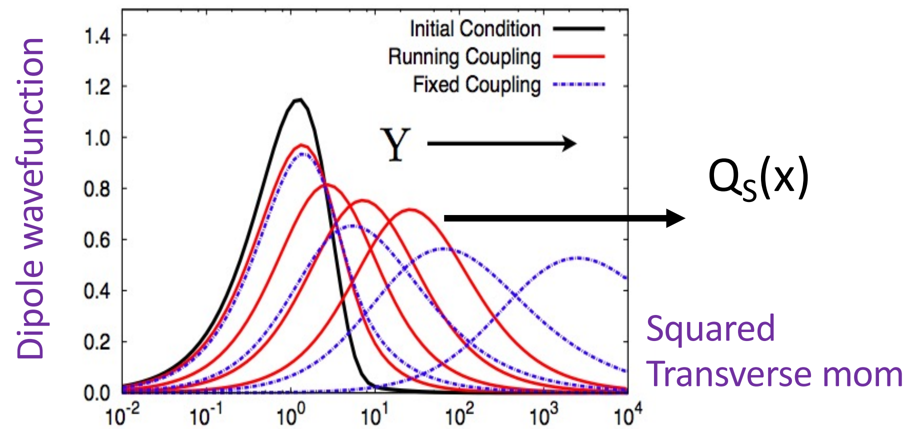
JIMWLK RG describes the nonlinear evolution of sources and fields with change of rapidity scale Λ^+

JIMWLK= Jalilian-Marian,Iancu,McLerran,Weigert,Leonidov,Kovner (1997-2021)
CGC review: Gelis,Iancu,Jalilian-Marian,RV:arXiv 1002.0333

Inclusive DIS: dipole evolution in gluon shockwave background



Path ordered 2-D Wilson lines describe transition between two pure gauges on either side of shockwave

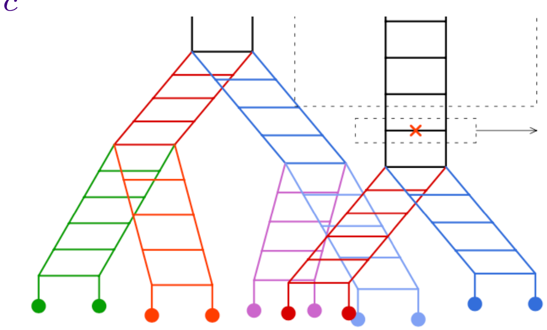


B-JIMWLK RG eqns. for Wilson-line correlator: Eg. 2-point "dipole"

$$\frac{\partial}{\partial Y}\langle \mathrm{Tr}(V_x V_y^\dagger)\rangle_Y = -\frac{\alpha_S N_c}{2\pi^2}\int_{z_\perp} \frac{(x_\perp - y_\perp)^2}{(x_\perp - z_\perp)^2 (z_\perp - y_\perp)^2} \langle \mathrm{Tr}(V_x V_y^\dagger) - \frac{1}{N_c}\mathrm{Tr}(V_x V_z^\dagger)\,\mathrm{Tr}(V_z V_y^\dagger)\rangle_Y$$

$Y = \mathrm{Ln}(1/x)$

Closed form expression for A >>1, Nc→ ∞:
non-linear Balitsky-Kovchegov (BK) eqn.



"Fan" multi-Pomeron diagrams

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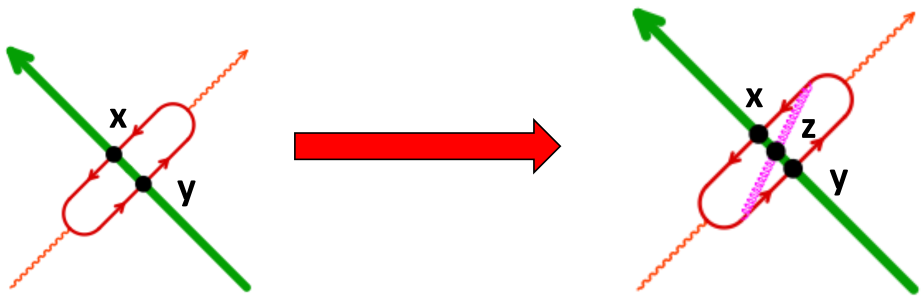
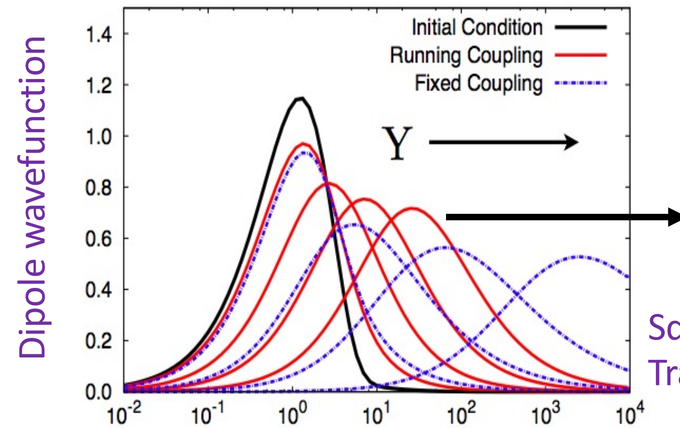
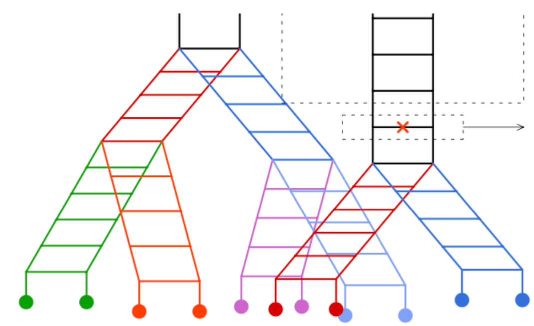




Non-trivial fixed point of evolution saturates cross-section for fixed impact parameter
- defines the close packing scale $Q_S(x)$ – cure for IR diffusion

The trivial fixed point is the BFKL equation
- low density $V \approx 1 - ig\rho/\nabla T^2$ limit of the BK equation…

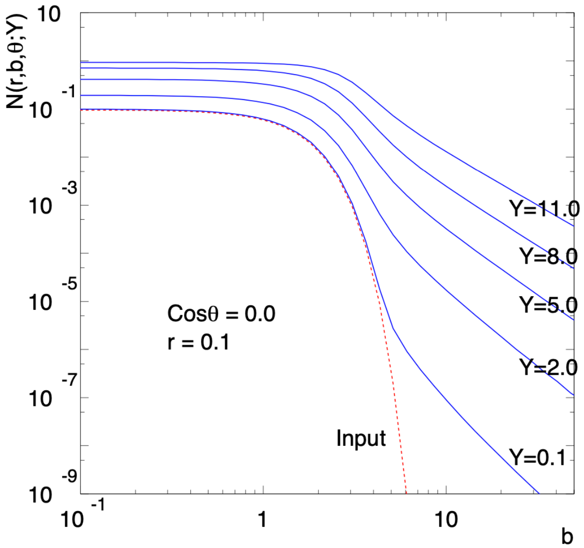
Langevin-like dance of wee partons in the space of color configurations encoded in dipole, quadrupole, sextupole,… correlators



Multi-Pomeron diagrams → BFKL ladder

The elephant in the room

Dipole amplitude as function of imp. parameter

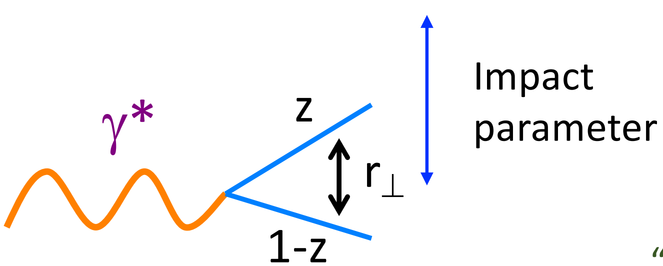


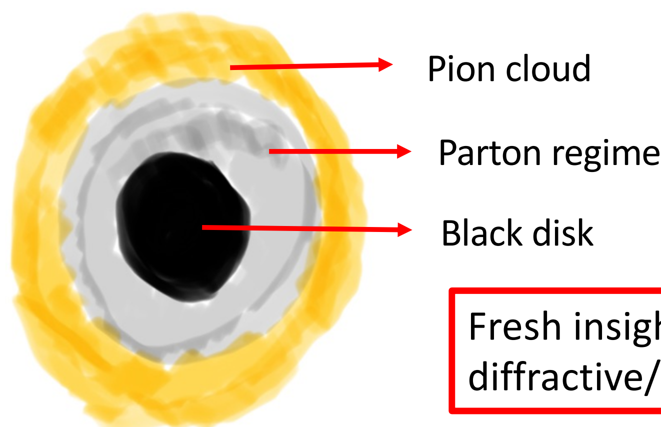
Golec-Biernat, Stasto, hep-ph/0306279

At fixed large b, exponential growth with rapidity

At small b, more modest growth characteristic of gluon saturation

Even with sharp exponential suppression of the initial dist. with b, perturbative Coulomb tail emerges quickly with rapidity evolution -reflective of missing physics of gluon/quark confinement





"Gribov" diffusion of the proton

Fresh insight from diffractive/exclusive final states

From LO+LLx to NLO+NLLx

State of the art:

Small x evolution:

NLO BFKL: Fadin, Lipatov (1998)
NLO JIMWLK: Balitsky, Chirilli, arXiv:1309.7644, Grabovsky, arXiv:1307.5414
Caron-Huot, arXiv:1309.6521, Kovner,Lublinsky,Mulian, arXiv:1310.0378,
Lublinsky, Mulian, arXiv:1610.03453
NNLO BK (SYM): Caron-Huot, Herranen (2018)

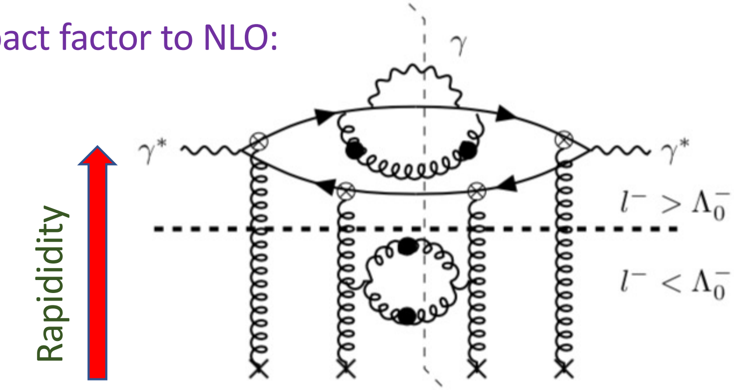
Resummed NLLx:
Salam (1999); Ciafaloni,Colferai,Salam,Stasto (1999-2004)
Ducloue,Iancu,Madrigal,Mueller,Soyez,Triantaffyllopoulos (2015-2019)

NLO impact factors:

Inclusive DIS: Balitsky,Chirilli (2013)
Diffractive DIS: Boussarie,Szymanowski,Wallon (2016)
Massive quarks: Beuf,Lappi,Paatelainen (2021)
p+A forward di-jets: Iancu,Mulian (2021)
Photon+di-jet in DIS: Roy,RV (2020)
DIS di-jets/di-hadrons: Caucal,Salazar,RV (2021); Caucal, Salazar, Schenke, RV (2022)
Taels, Altinoluk,Beuf, Marquet, arXiv:2204.11650; Bergabo, Jalilian-Marian, arXiv:2207.03606

30+ papers in 2023 alone

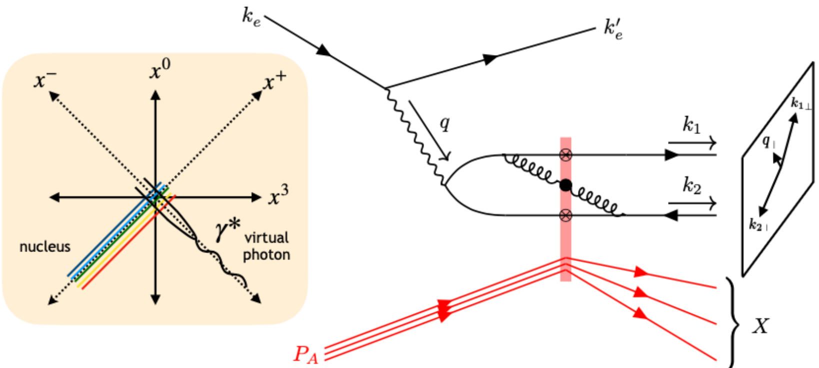
Impact factor to NLO:



Evolution to NLLx:
$O(\alpha_S^2 \ \mathrm{Ln}(\frac{1}{x}))$

(Dressed “shockwave” propagators include coherent multiple scatterings to all orders)

Gluon Weizsäcker-Williams distribution: complete NLO results



Back-to-back di-jets in DIS

Factorization of small-x TMDs to NLO accuracy

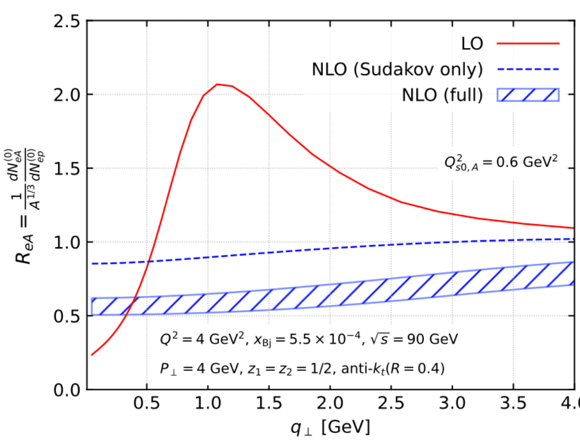
$$\mathrm{d}\sigma^{(0),\lambda=\mathrm{T}} = \mathcal{H}^{0,\lambda=\mathrm{T}}_{\mathrm{LO}} \int \frac{\mathrm{d}^2\boldsymbol{B}_\perp}{(2\pi)^2} \int \frac{\mathrm{d}^2\boldsymbol{r}_{bb'}}{(2\pi)^2} e^{-i\boldsymbol{q}_\perp\cdot\boldsymbol{r}_{bb'}} \hat{G}^0_{\eta_c}(\boldsymbol{r}_{bb'},\mu_0)\mathcal{S}(\boldsymbol{P}_\perp^2,\mu_0^2)$$
$$\times\left\{1+\frac{\alpha_s(\mu_R)N_c}{2\pi}f_1^{\lambda=\mathrm{T}}(\chi,z_1,R)+\frac{\alpha_s(\mu_R)}{2\pi N_c}f_2^{\lambda=\mathrm{T}}(\chi,z_1,R)+\alpha_s(\mu_R)\beta_0\ln\left(\frac{\mu_R^2}{P_\perp^2}\right)\right\}$$
$$+\mathcal{H}^{0,\lambda=\mathrm{T}}_{\mathrm{LO}} \int \frac{\mathrm{d}^2\boldsymbol{B}_\perp}{(2\pi)^2} \int \frac{\mathrm{d}^2\boldsymbol{r}_{bb'}}{(2\pi)^2} e^{-i\boldsymbol{q}_\perp\cdot\boldsymbol{r}_{bb'}} \hat{h}^0_{\eta_c}(\boldsymbol{r}_{bb'},\mu_0)\mathcal{S}(\boldsymbol{P}_\perp^2,\mu_0^2)$$
$$\times\frac{-2\chi^2}{1+\chi^4}\left\{\frac{\alpha_s(\mu_R)N_c}{2\pi}\left[1+\ln(R^2)\right]+\frac{\alpha_s(\mu_R)}{2\pi N_c}\left[-\ln(z_1z_2R^2)\right]\right\}+\mathcal{O}\left(\frac{q_\perp}{P_\perp},\frac{Q_s}{P_\perp},\alpha_sR^2,\alpha_s^2\right)$$

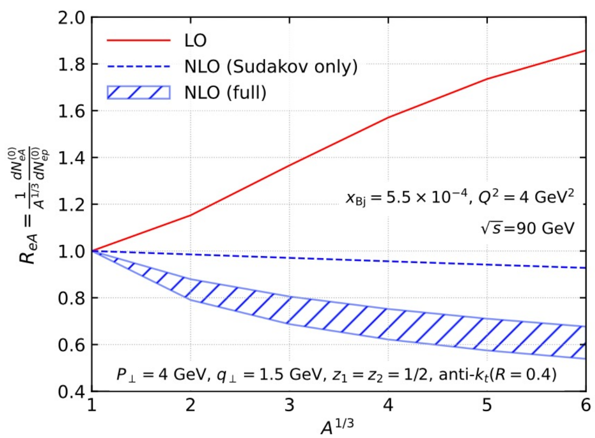
$\hat{G}^0$ and $\hat{h}^0$ respectively are unpolarized and linearly polarized WW distributions,

$\mathcal{S}$ the Sudakov soft factor resumming double+single logs in P_T/q_T

f_1 and f_2 are finite pure $O(\alpha_S)$ contributions

Caucal,Salazar,Schenke,Stebel,RV, arXiv:2308.00022, (PRL 2024)



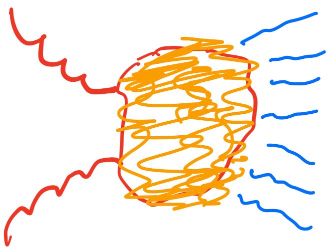


Global analyses to extract "universal" TMDs from p+A collisions at the LHC and e+A collisions from the EIC

Small x and quantum information science

Classicalization+unitarization – saturates the Bekenstein bound

$2 \to N$



$$P_{2\to N} \sim e^{S} \alpha_s^N N! \quad \text{If } N \sim \frac{1}{\alpha_s}$$

$$P_{2\to N} \sim e^{S} \alpha_s^N \left(\frac{1}{\alpha_s}\right)^N e^{-1/\alpha_s}$$

Exponential suppression of "classical lumps" unless $S = \frac{1}{\alpha_S}$ $\rightarrow P_{2\to N} = O(1)$

This entropy saturates the Bekenstein bound $S \leq 2\pi ER/\hbar$

on the maximal information in a given spacetime region

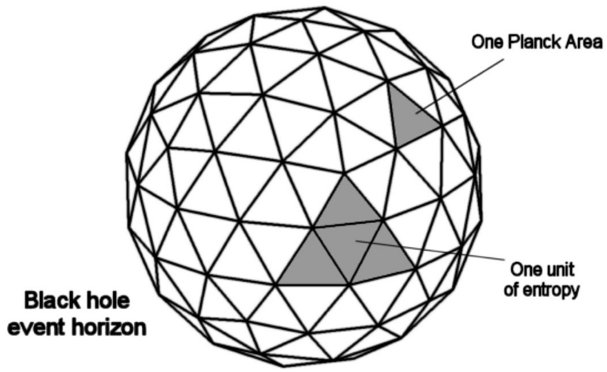
If we define $E = N\, Q_S$ as the energy in a critically packed volume = R_S^3 of quanta ("qubits") saturating unitarity (maximal information) and $Q_S = 1/R_S$

$$when\ N = \frac{1}{\alpha_S} \rightarrow S_{Bek} = \frac{1}{\alpha_S}$$

Dvali,RV,
arXiv:2106.11989, PRD (2022)

Critical packing saturates Bekenstein-Hawking area law

Bekenstein-Hawking bound



(for a nice discussion, see Bousso, arxlv:1810.01880)

The entropy can be expressed in terms of a Goldstone decay constant f_G

- spontaneous breaking of Poincare invariance and a global sub-group (corresponding to large gauge transformations) by the gluon shockwave

Decay constant of Goldstone field ϕ is $f_G = RS\, \partial_x \phi = \frac{\sqrt{N}}{R_S} = \sqrt{N}\, Q_S$

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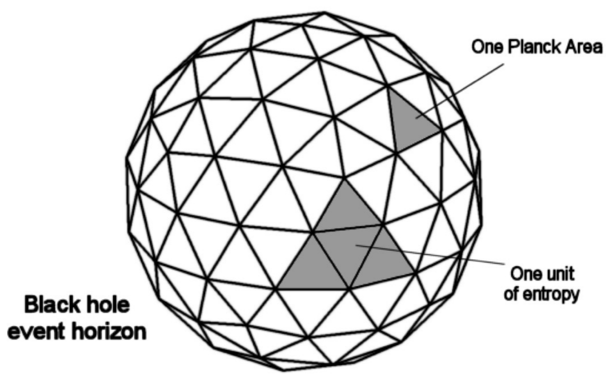
Bekenstein-Hawking bound



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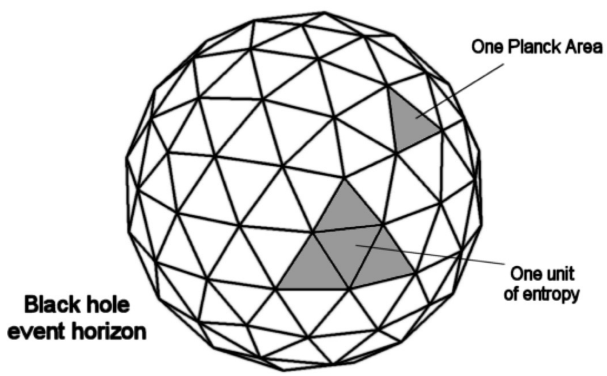
S= $\frac{1}{\alpha_S}$ = Area $\times\ f_G^2$

In gravity, $f_G^2 = M_{Planck}^2 = \frac{1}{G}$ so one recovers the Hawking-Bekenstein bound on the entropy

Dvali, arXiv:1907.07332

Critical packing saturates Bekenstein-Hawking area law

Bekenstein-Hawking bound



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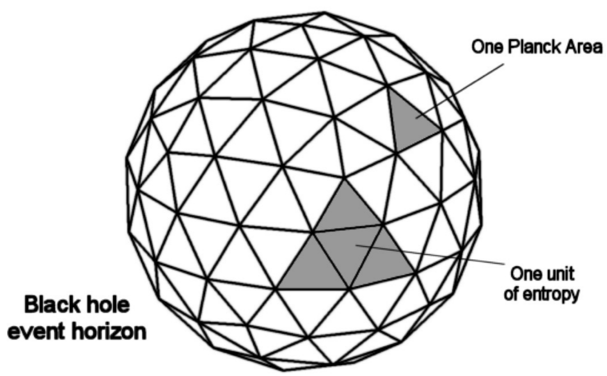

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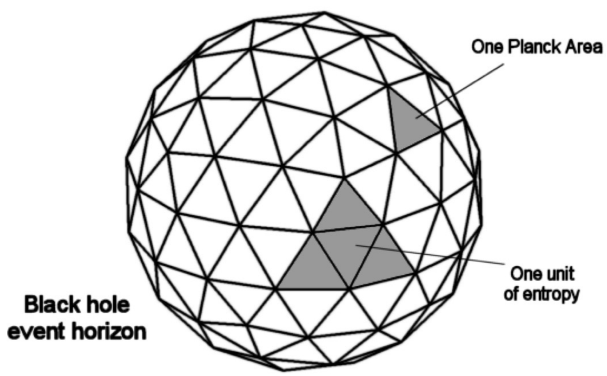
Goldstone scattering causes CGC shockwave to decay on time scale $\tau_{Goldstone} = \frac{1}{\alpha_S}\frac{1}{Q_S} \ll \tau_{Eikonal} \sim \sqrt{s}\ /\ Q^2$

Such **final state** effects can influence emission of soft radiation on momentum scales $\sim\ \alpha_s\ \ Q_S$

In heavy-ion collisions, this description is nothing but the early-time bottom-up thermalization scenario

Critical packing saturates Bekenstein-Hawking area law

Bekenstein-Hawking bound



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What are the physical consequences for classical lumps in QCD ?

Can one construct a Goldstone EFT beyond the CGC describing "Page time" of shockwave decay?

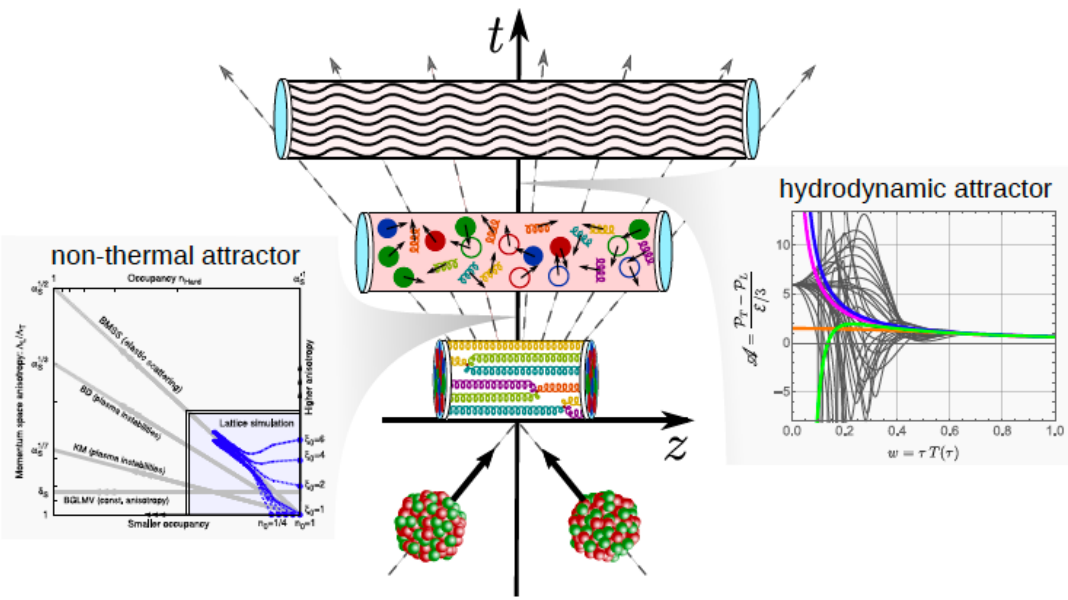
How does this affect reggeization and RG evolution beyond NLO?

V. P. Nair and RV, in progress

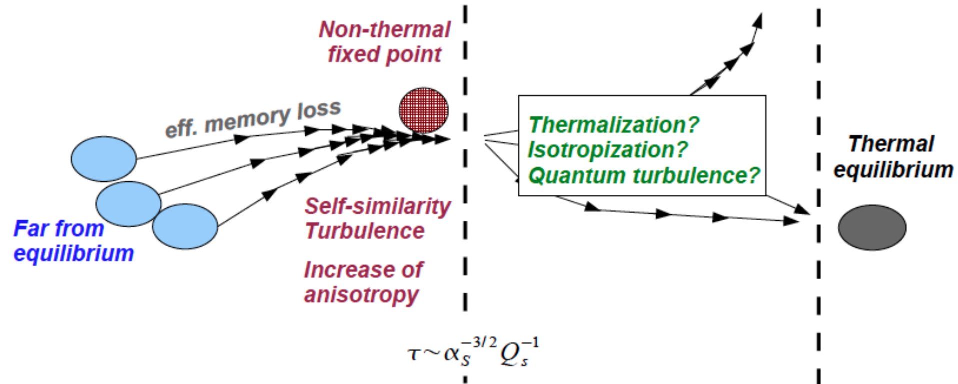
What are the observable consequences?

Spacetime evolution of a heavy-ion collision: bottom-up thermalization

Quark-Gluon Plasma undergoing
hydrodynamic expansion



Collision of overoccupied Color Glass Condensate shockwaves



Thermal soft gluon bath for $\tau > \frac{1}{\alpha_S^{5/2}} \frac{1}{Q_S}$

Thermalization temperature: $T_i = \alpha_S^{2/5} Q_S$

Very rapid thermalization
as $\alpha_S(Q_S) \to 0$ *and* $Q_S \to \infty$

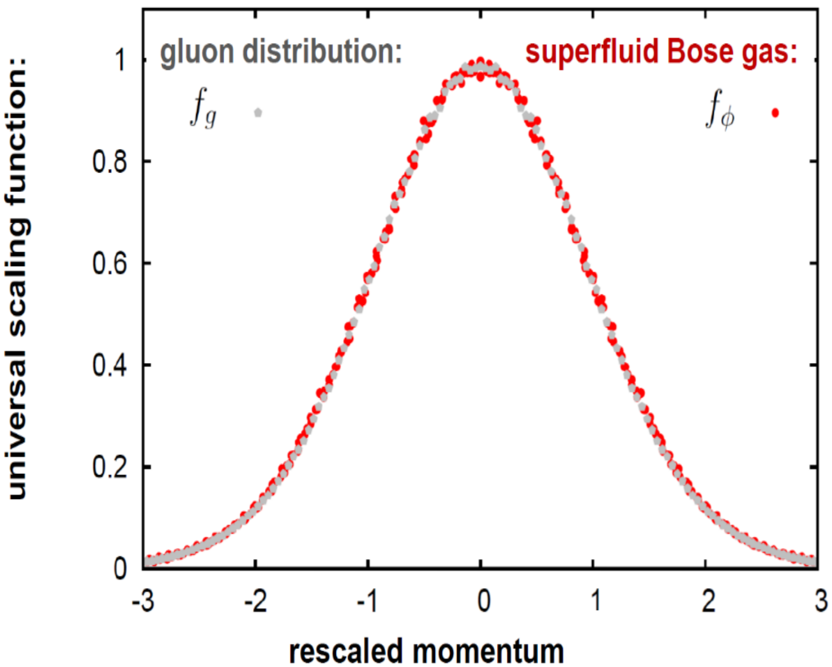
Baier,Mueller,Schiff,Son,
hep-ph/0009237

QCD thermalization: Ab initio approaches and interdisciplinary connections
Jürgen Berges, Michal P. Heller, Aleksas Mazeliauskas, and RV
Rev. Mod. Phys. **93**, 035003 (2021)

Universality: saturated glue and overoccupied ultracold atoms

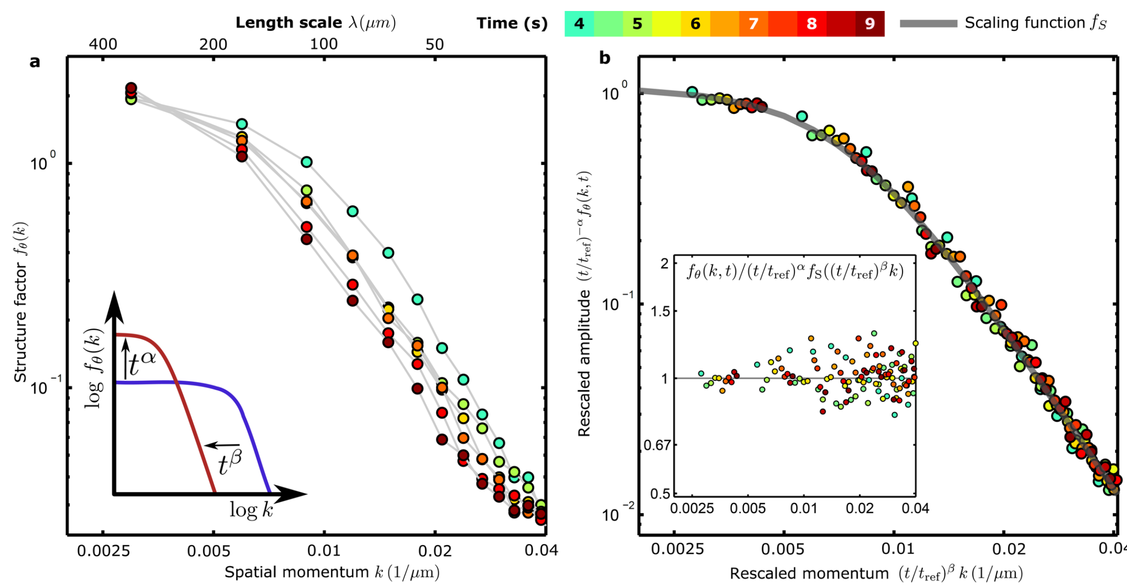
Overoccupied expanding Yang-Mills fields and self-interacting scalars described by the same non-thermal attractor

$$f(p_T, p_z, \tau) = \tau^{\alpha} f_S(\tau^{\beta} p_T, \tau^{\gamma} p_z)$$



Berges,Boguslavski,Schlichting,RV, PRL (2015) Editor's suggestion

^{87}Rb BEC in a quasi 1D optical trap



Oberthaler BEC Labs, Prüfer et al, arXiv:1805.11881, *Nature* (2018)

Scalable cold-atom quantum simulator for overoccupied features of gauge theories?

R. Ott et al., arXiv:2012.10432