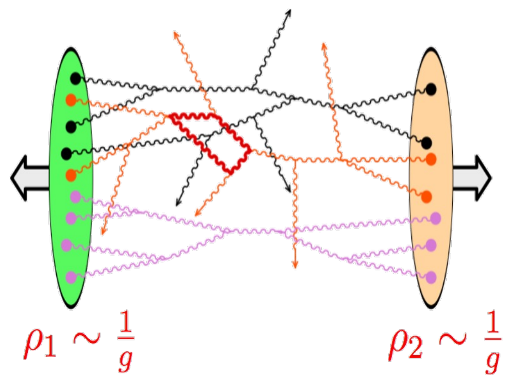
The initial state and thermalization in heavy-ion collisions



Raju Venugopalan

Brookhaven National Laboratory

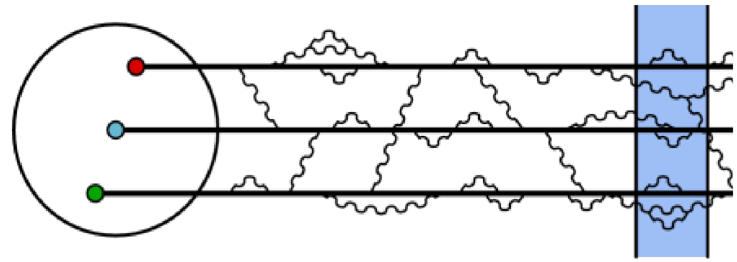
ICPAQGP 2023, Puri

Gluon bremsstrahlung: ``Herculean task…might even not be possible”

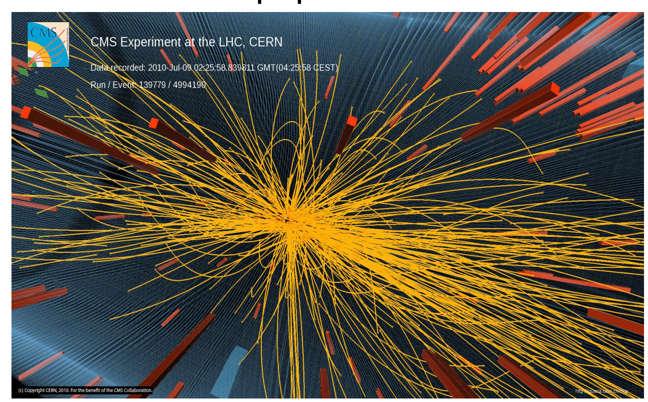
But these remarks do not apply to theories involving charged massless particles. In such theories (including the Yang-Mills theory) a soft photon emitted from an external line can itself emit a pair of soft charged massless particles, which themselves emit soft photons, and so on, building up a cascade of soft massless particles each of which contributes an infrared divergence. The elimination of such complicated interlocking infrared divergences would certainly be a Herculean task, and might even not be possible.

We may be thankful that the zero charge of soft photons and the zero gravitational mass of soft gravitons saves the real world from this mess. Perhaps it would not be too much to suggest that it is the infrared divergences that prohibit the existence of Yang-Mills quanta or other charged massless particles.

Weinberg, Phys. Rev. 140 (1965) B516



LHC p+p collisions



Apparently the real world does enjoy a mess!

1 in 10^6 events produces > 10^2 particles

Underlying ridge structure of long-range correlations

CMS: JHEP 09 (2010) 091; Dumitru, RV, et al., PLB697 (2011) 21

Can we understand the initial state from first principles?

- Asymptotic freedom and QCD parton model tell us that the proton, probed at high energies and resolutions, is a complex many-body collection of “partons”. Most are “wee” (light cone momenta $k^+ = x P^+$, $x << 1$)

- How do we understand/organize/explore and predict novel QCD phenomena in the presence of such IR Herculean complexity? Will frameworks developed provide fresh insight into age-old challenges

  (the nature and structure of colorless “Pomeron” exchanges, the role of confinement and chiral symmetry breaking at collider energies)

- How does thermalization in QCD occur – what explains the “unreasonable” effectiveness of hydrodynamics?

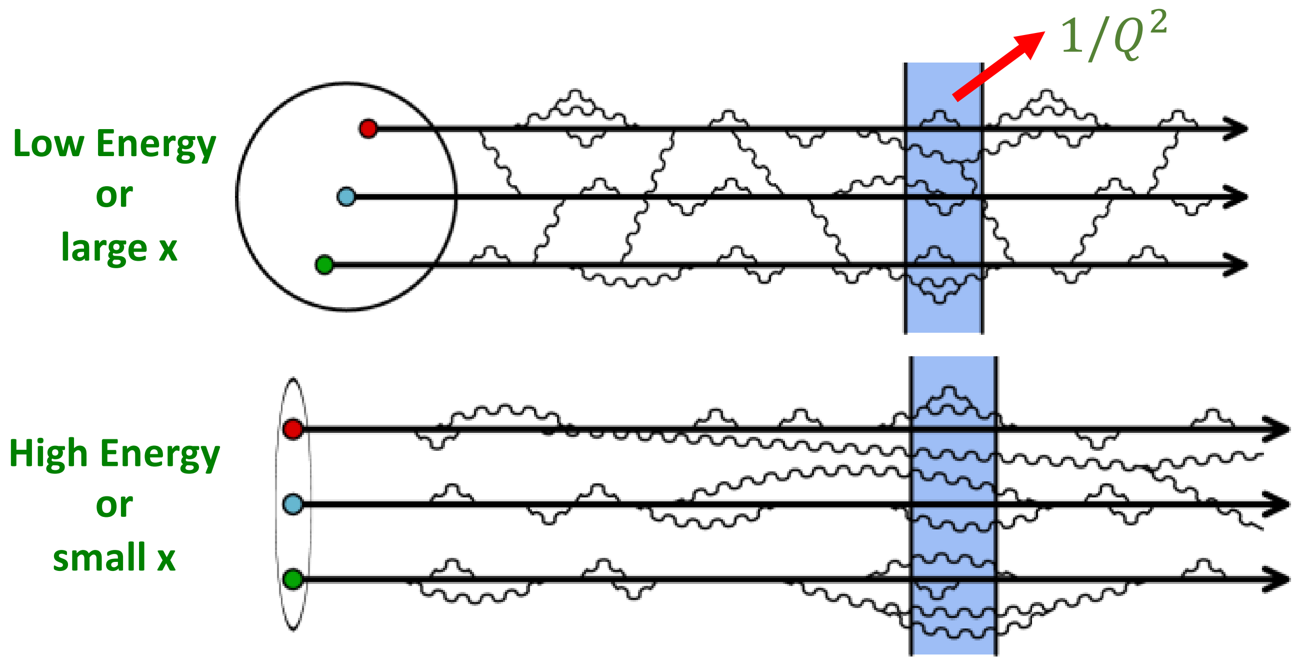
- Emerging broader issues:

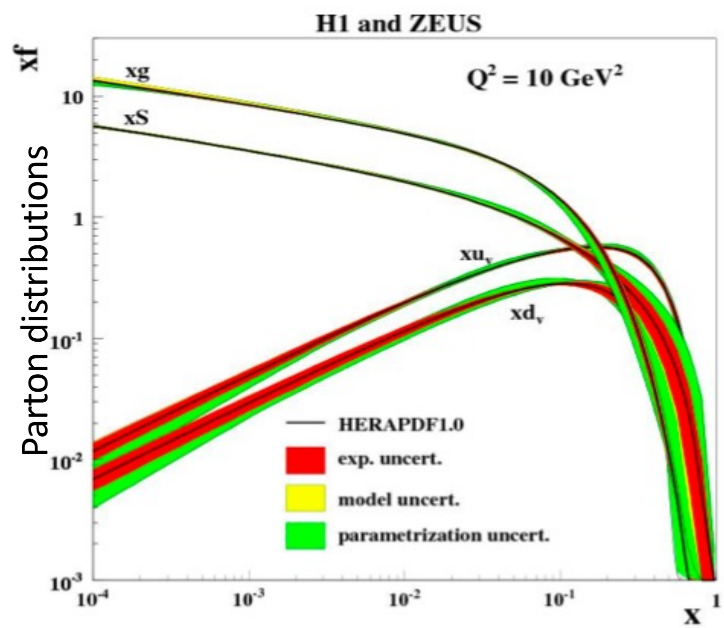
a) Can we understand such QCD phenomena in the universal language of quantum information science (entanglement, information retrieval,…). Example: Can ultra-cold atoms simulate features of gauge theories?

b) QCD-gravity double copy (and holography), soft theorems and asymptotic symmetries,…

What happens when you boost a proton or nucleus to high energies ?

What the proton or nucleus "looks like" in QCD depends on boost *and* resolution scale



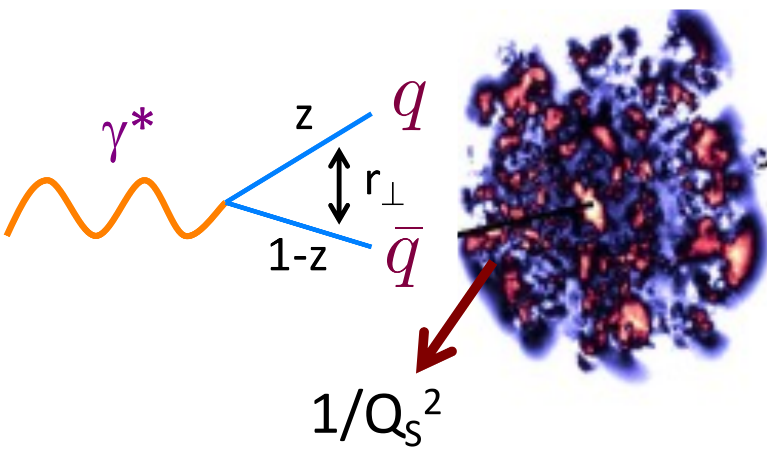


As the proton is boosted, "parton" fluctuations live longer -- released as bremsstrahlung

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

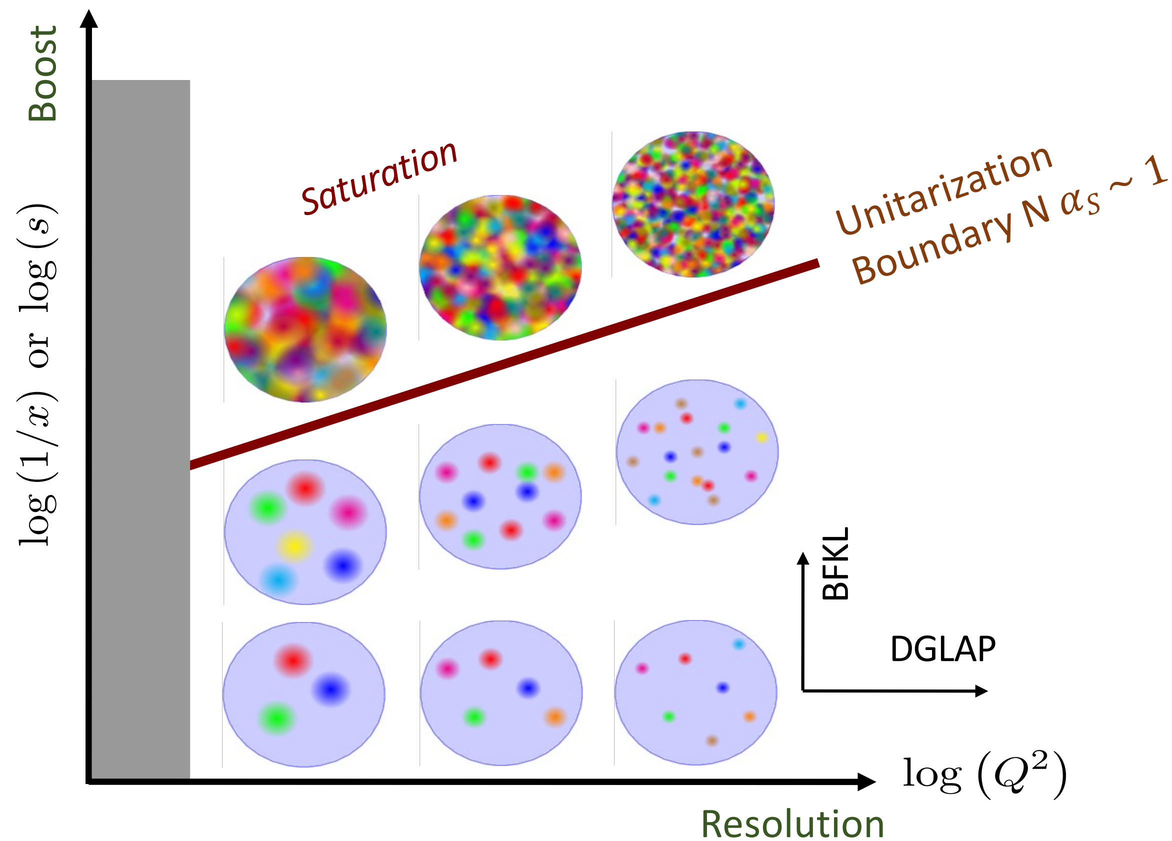
Strong arguments (unitarity and maximal phase space occupancy) constrain runaway "Markovian" growth

Gluon saturation: classicalization+unitarization in 2→ N scattering



At high occupancies, gluon proliferation tamed by many-body screening and recombination

Gluon saturation characterized by emergent "close packing" scale that screens color

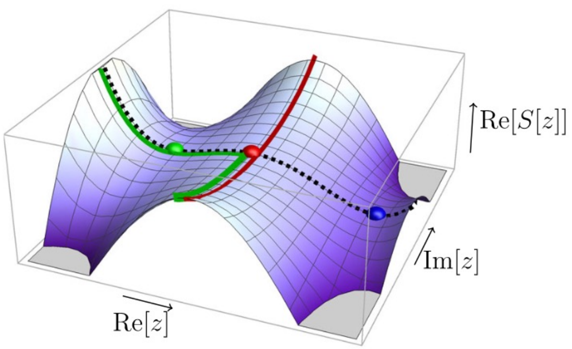


Formation of classical lumps of color charge unitarize the cross-section for $r_\perp \approx 1/Q_S(x) \ll R_{proton}$

This scale is precocious in nuclei due to color coherence along path length of the interaction: $(Q_S^A)^2 \propto A^{1/3}$

$2 \rightarrow N$ scattering: Saturation = Bekenstein entropy bound

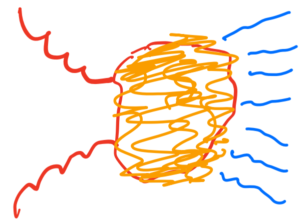
False vacuum decay of field configurations $\phi(z)$



Langer; Coleman; …
Fig. from Andreassen,Frost,Schwartz, PRD97 (2018)

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

$2 \rightarrow N$



$$P_{2\rightarrow N} \sim e^{-S} \alpha_s^N N!$$

If $N \sim \frac{1}{\alpha_s}$

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

Exponential suppression of high occupancy states (classical lumps) unless

$S \sim 1/\alpha_s \sim N$ $\boxed{\Rightarrow P_{2\rightarrow N} \sim O(1)}$

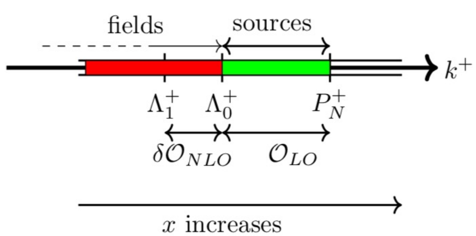
This entropy of wee partons satisfies the Bekenstein bound on the maximal entropy contained in a spatial region with all the information contained on its surface area – 2D hologram of a 3D world

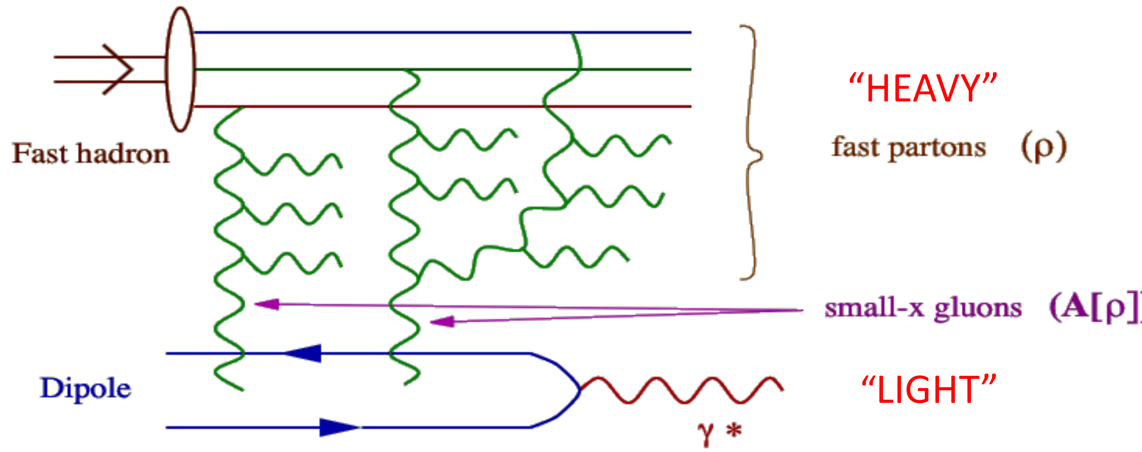
Susskind (1993)

Classical EFT: the Color Glass Condensate

Born-Oppenheimer separation between fast and slow modes

"JIMWLK" Wilsonian RG describes evolution with energy





CGC: classical Effective Field Theory of static parton sources and dynamical gluon fields

McLerran, RV (1994)
Iancu,Leonidov, McLerran (2001)

Color: self-evident
Glass: stochastic dynamics of static sources
Condensate: Highly occupied fields form a condensate in presence of color sources, on time scales much shorter than strong interaction time scales

Basic review: Jalilian-Marian,Gelis,Iancu,RV, arXiv:1002.0333
Textbook: Kovchegov, Levin, Cambridge Univ. Press (2012)

From LO+LLx to NLO+NLLx

State of the art:

Small x evolution:

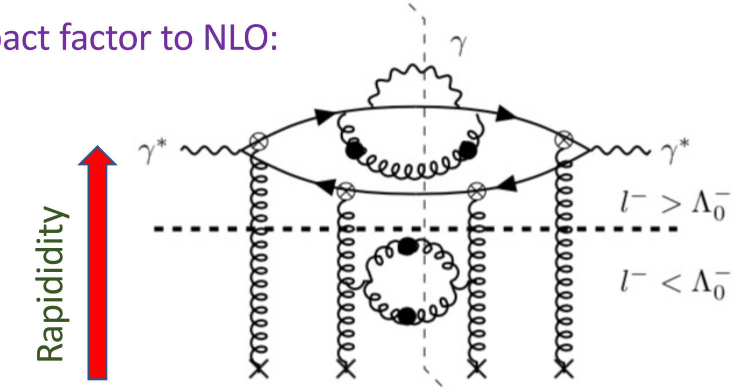
NLO BFKL: Fadin, Lipatov (1998)
NLO JIMWLK: Balitsky, Chirilli, arXiv:1309.7644, Grabovsky, arXiv:1307.5414
Caron-Huot, arXiv:1309.6521, Kovner,Lublinsky,Mulian, arXiv:1310.0378,
Lublinsky, Mulian, arXiv:1610.03453
NNLO BK (SYM): Caron-Huot, Herranen (2018)

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

Impact factor to NLO:

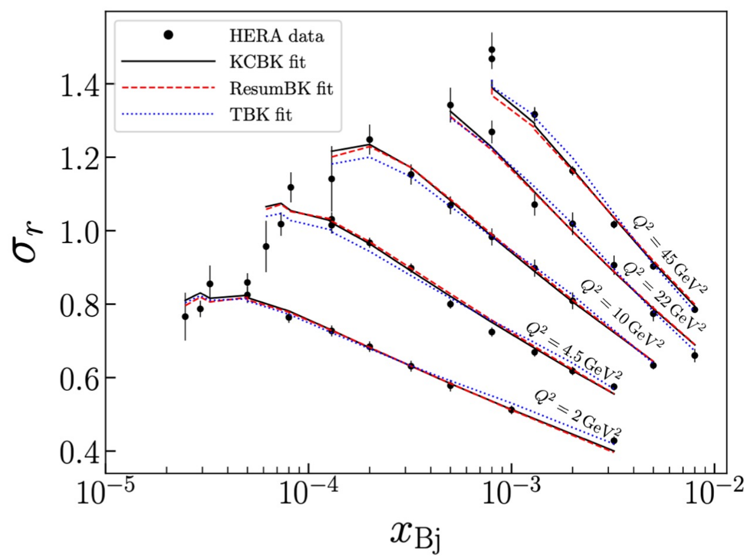


Evolution to NLLx:
$O(\alpha_S^2 \; \mathrm{Ln}(\frac{1}{x}))$

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

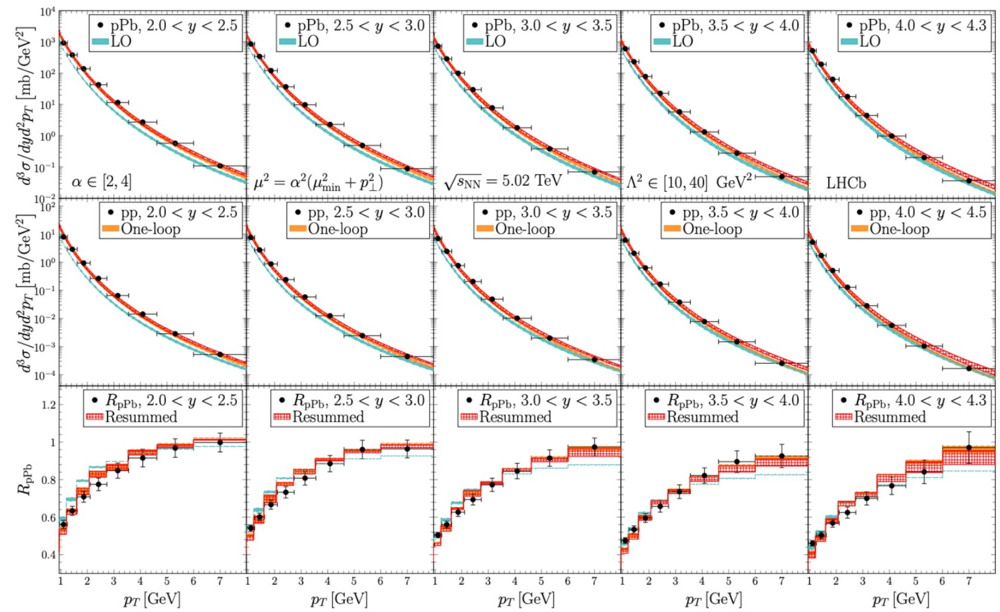
CGC state-of-the art: Towards Global analysis

DIS structure functions



Beuf,Hanninen,Lappi,Mantysaari, arXiv:2007.01645

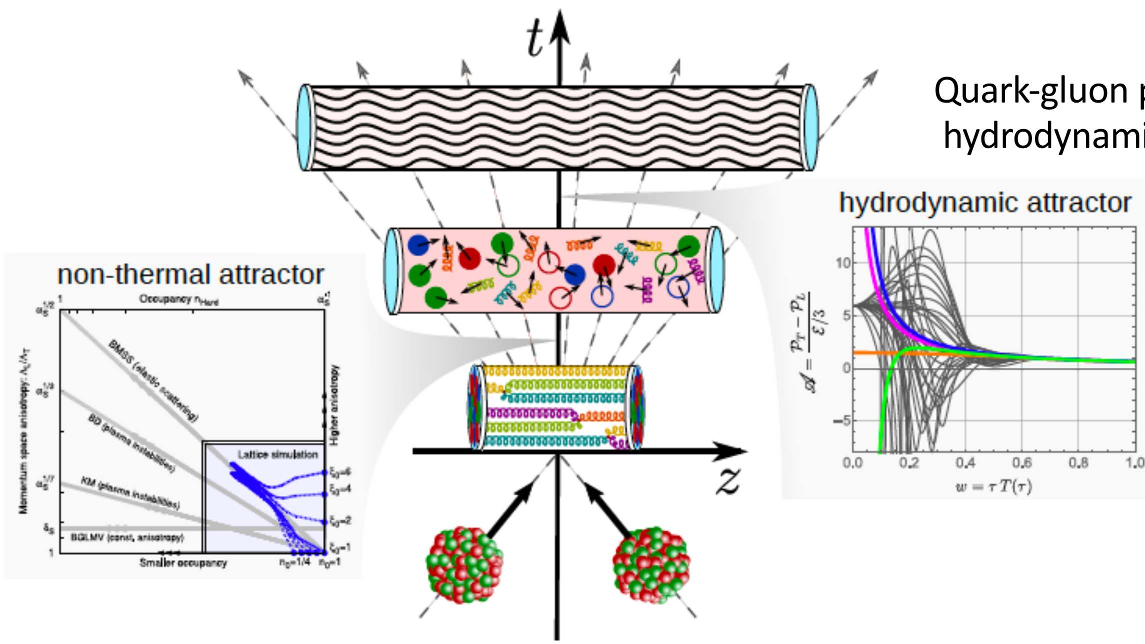
Single inclusive hadron distributions at the LHC



Shi,Wang,Wei,Xiao, arXiv:2112.06975

BNL led SURGE Topical Theory Collaboration: 22 PI’s from 16 institutions (2022-2027)

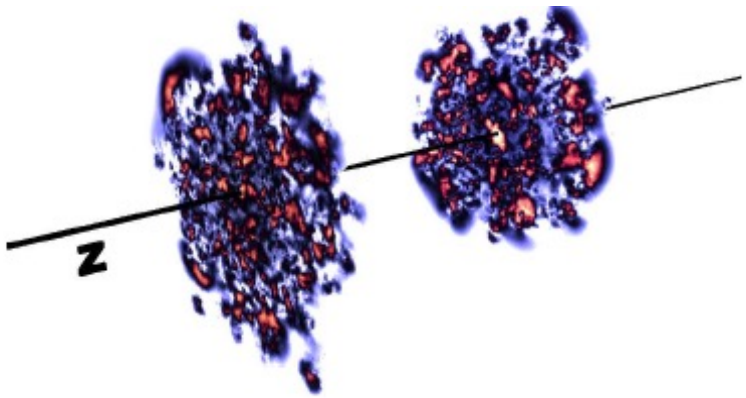
Spacetime evolution of a heavy-ion collision



Collision of Color Glass Condensate shockwaves

QCD thermalization: Ab initio approaches and interdisciplinary connections
Jürgen Berges, Michal P. Heller, Aleksas Mazeliauskas, and Raju Venugopalan
Rev. Mod. Phys. **93**, 035003 (arXiv:2005.12299)

Classical shockwave collisions of lumpy glue



Collisions of “lumpy” gluon shock waves with 1/Qs –wide ``fuzz” of wee partons

Important point: the width of each shock wave is not R/γ but $1/Q_S$ - this description is frame invariant

One can “prove” that quantum fluctuations about each shockwave are responsible for energy evolution in each shock wave (BK/JIMWLK)

Can be factorized from quantum fluctuations after the collision

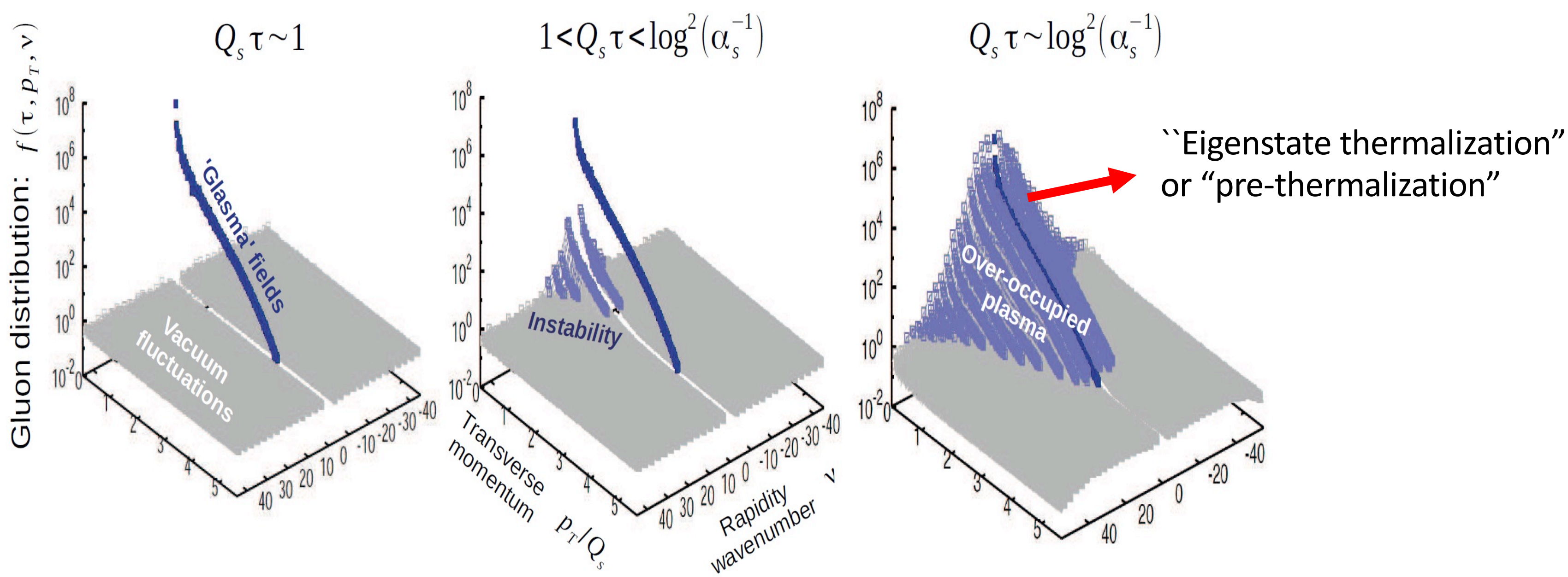
Gelis,Lappi,RV arXiv:0804.2630

Decoherence from explosive amplification of quantum fluctuations

Longitudinally expanding ``Glasma" fields are unstable to quantum fluctuations…
leading to an explosive "Weibel"-like instability.

Romatschke,RV, hep-ph/0605045

Rapid decoherence and overpopulation of all momentum modes



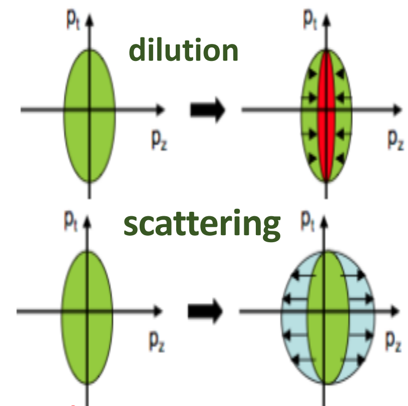
Classical-statistical real-time lattice simulations of 3+1-D gluon fields exploding into the vacuum

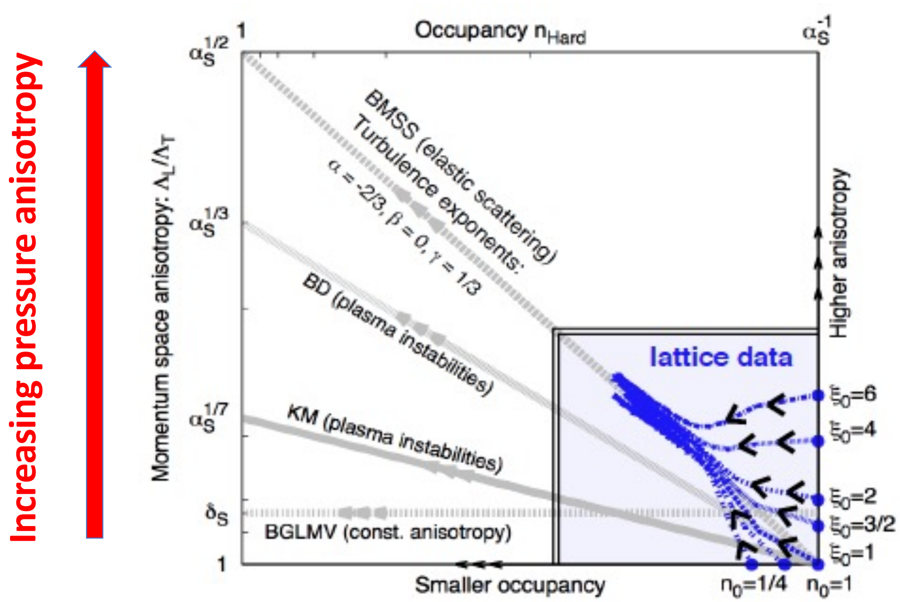
Berges,Schenke,Schlichting,RV, NPA 931 (2014) 348

Classical-statistical simulations: A turbulent attractor

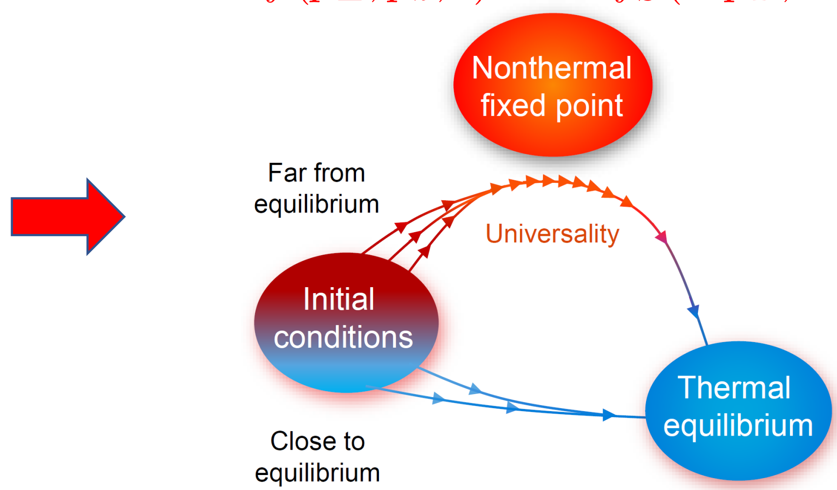
After rapid scrambling of information by quantum fluctuations, competition between dilution due to expansion and isotropization due to scattering

“Single particle” distributions become self-similar in time characterized by universal exponents – helps identify “right” kinetic theory



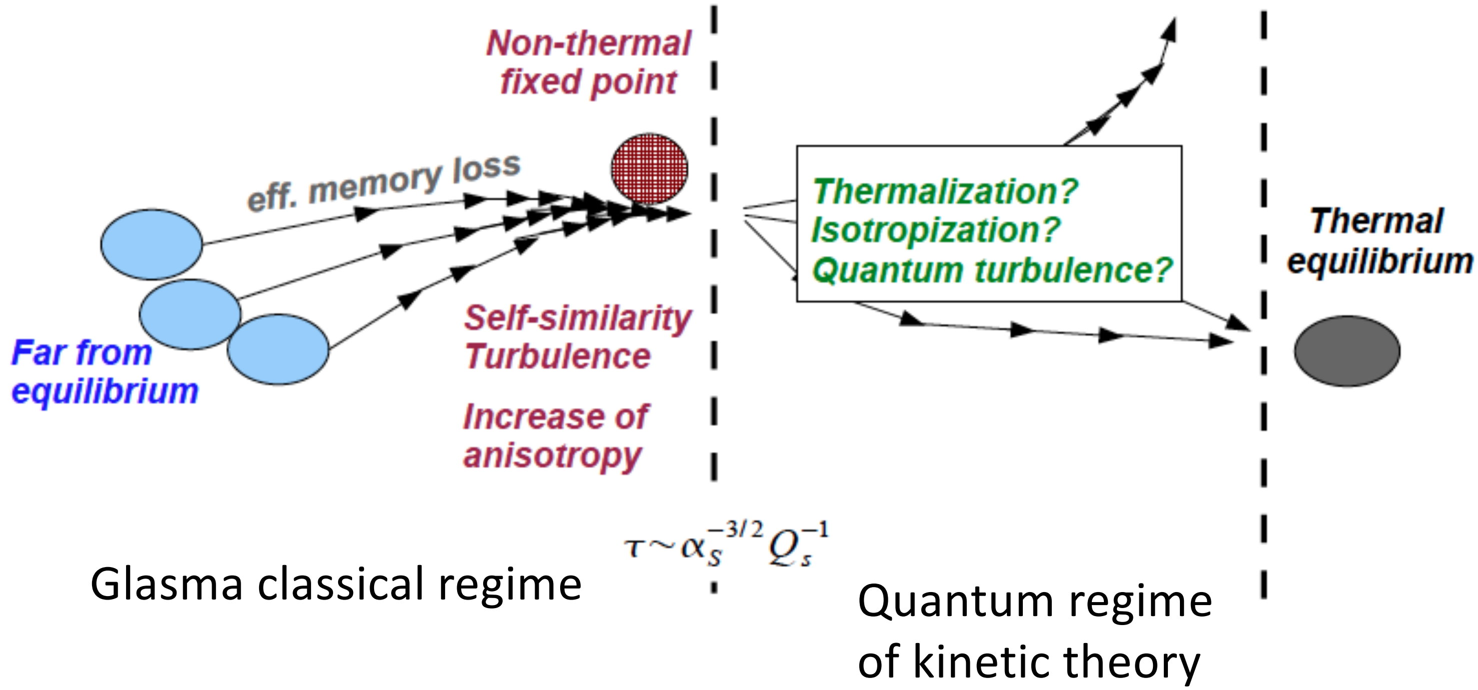


$$f(p_\perp, p_z, t) = t^\alpha \; f_S(t^\beta p_T, t^\gamma p_z)$$



Berges,Boguslavski,Schlichting,RV (2014)

Bottom-up thermalization: from nuts to soup



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

Bottom-up thermalization

Thermalized soft bath of gluons for $\tau > \frac{1}{\alpha_S^{5/2}} \frac{1}{Q_S}$

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

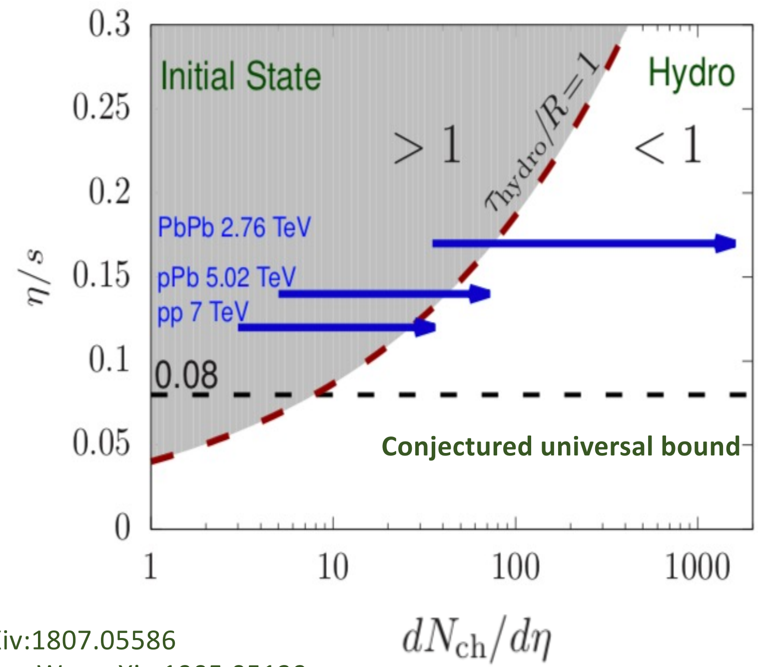
Since $\alpha_S \propto \frac{1}{\log Q_S}$

then $\tau_{\mathrm{therm}} \propto \frac{(\log Q_S)^{5/2}}{Q_S} \rightarrow 0$ as $Q_S \rightarrow \infty$

Matter thermalizes almost instantaneously at asymptotic energies

CGC naturally leads to hydro if $\tau_{\mathrm{therm}} \ll R$

Remarkably, in this picture, dominant feature of the entire dynamics of thermalization (across systems) is one semi-hard scale …



Mazeliauskas, arXiv:1807.05586
Kurkela,Wiedemann,Wu, arXiv:1905.05139

Bottom-up thermalization: from nuts to soup

$\tau \lesssim 1/Q_S$: quantum "crossing time" of wavefunctions with "fuzz" of wee partons of width $1/Q_S$
- lumpy "hot spot" classical configurations in transverse plane

$\frac{1}{Q_S} \leq \tau \leq \frac{1}{Q_S} \mathrm{Ln}^2\left(\frac{1}{\alpha_S^2}\right)$: Rapid scrambling of overoccupied gauge fields by exponentially growing quantum fluctuations (Weibel instabilities) generates isotropic "single particle" distributions

$\frac{1}{Q_S} \mathrm{Ln}^2\left(\frac{1}{\alpha_S^2}\right) \leq \tau \leq \frac{1}{Q_S} \frac{1}{\alpha_S^{3/2}}$: System flows to turbulent non-thermal attractor. Subsequent classical/quantum evolution until a "quantum breaking time" when occupancies are of order unity.

$\frac{1}{Q_S} \frac{1}{\alpha_S^{3/2}} \leq \tau \leq \frac{1}{Q_S} \frac{1}{\alpha_S^{5/2}}$: $2 \rightarrow 3$ kinetic processes begin to dominate. Soft radiated gluons thermalize – but hard gluons $k_T \approx Q_S$ still far from equilibrium

$\frac{1}{Q_S} \frac{1}{\alpha_S^{5/2}} \leq \tau \leq \frac{1}{Q_S} \frac{1}{\alpha_S^{13/5}}$: Hard gluons thermalize through a turbulent quantum process – which also describes "jet quenching"

Blaizot, Dominguez, Iancu, Mehtar-Tani (2013-2016),
Eg., Blaizot, Mehtar-Tani, 1503.05958

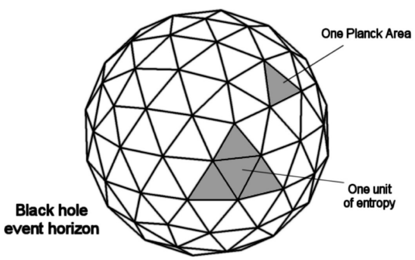
Final note: IR dynamics in the language of symmetries

The formation of the many-body saturated semi-classical “lump” breaks
a) Poincare invariance
b) a global color symmetry (invariance under large gauge transformations)

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

$x^- = 0$
(gluon shockwave)

A Goldstone decay constant $F^2_G = N\, Q_S^2$ characterizes the overoccupied modes (not ”partons”) at early times $\tau < 1/\alpha_S\, Q_S$



Bekenstein-Hawking bound for CGC : $S = \frac{1}{\alpha_S} = N = \text{Area} \times F^2{}_G$

Universality: Black-Holes described as overoccupied graviton states with $F_G = M_{Planck}$

Goldstone dynamics of “soft glue” in the CGC exactly analogous to “BMS asymptotic symmetries” of gravity

Pate, Raclariu, Strominger, PRL (2017)
Ball,Pate,Raclariu,Strominger,RV, Annals of Physics 407 (2019) 15

Gravitational memory $\Longleftrightarrow$ Color memory

Double copy methods/symmetries between QCD and gravity is an exciting growing field!

Thank you for your attention!