Universality in strong fields: the curious case of Color Glass Condensates and Black Holes

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Wuhan, November 10, 2019

- Strong fields require strong personalities: some universal features

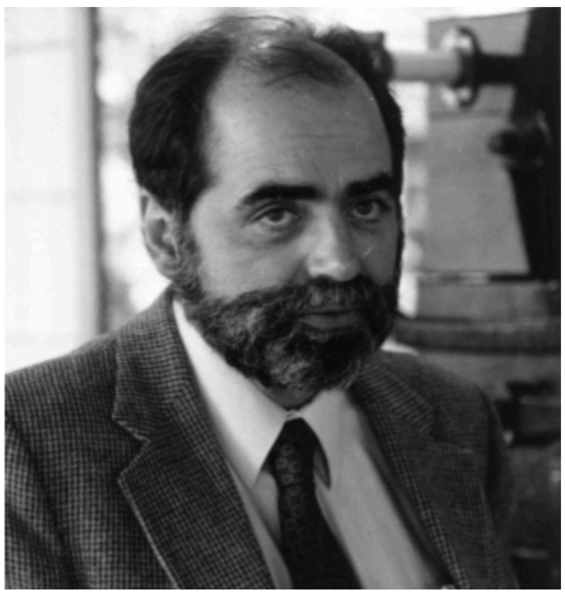
- The infrared structure of gauge theories:
  an adventure with Adam, Monica, Ana and Andy

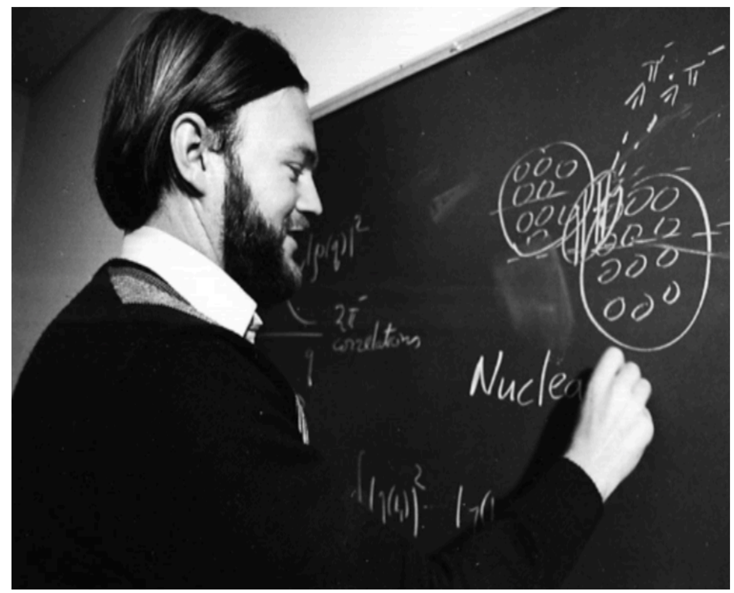
- Exploring universal features of classicalization with Gia:
  A CGC-Black Hole Correspondence

- Putting it all together: Gravity as QCD's doppelgänger

Strong fields and strong personalities:

extempore remarks on universality





Generating strong fields by multi-particle production

Bremsstrahlung is ubiquitous in QCD because phase space logs compensate for the suppression in coupling: $\alpha_S \, Ln\,(1/x) \sim 1$ and/or $\alpha_S \, Ln\,(Q^2/\Lambda_{QCD}^2) \sim 1$

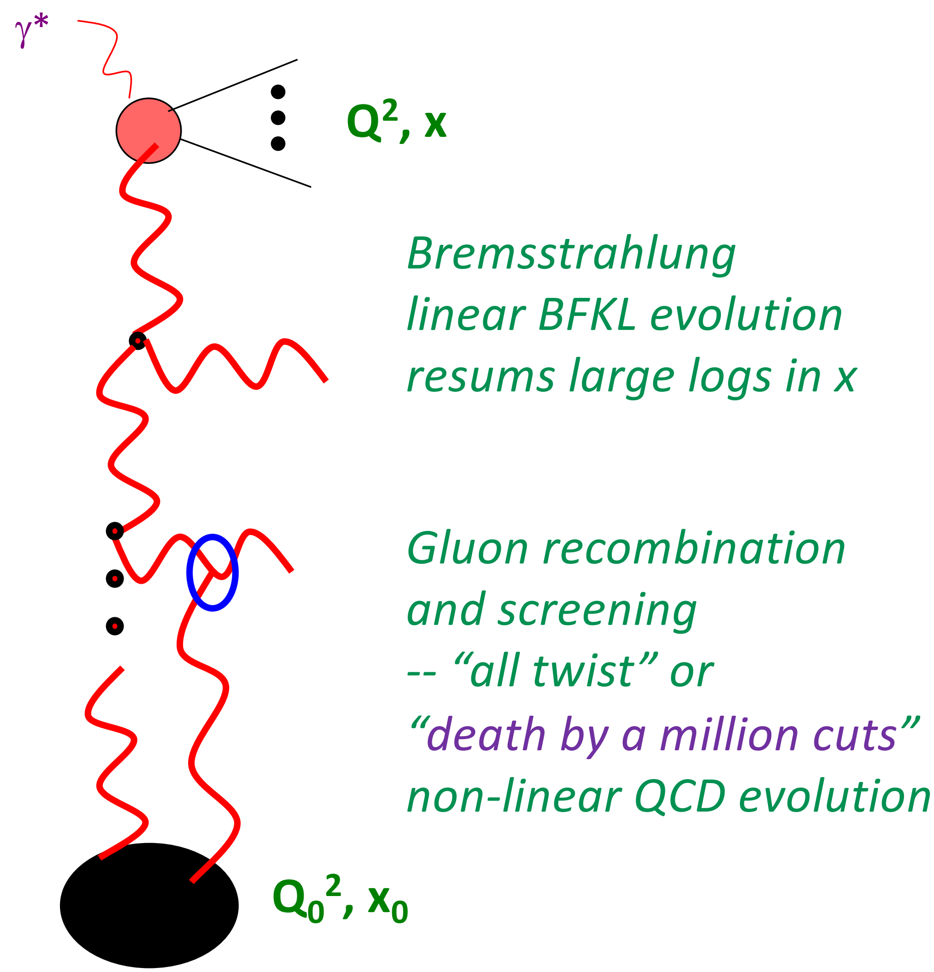
Appropriate limit for multi-particle production:

Regge limit of QCD

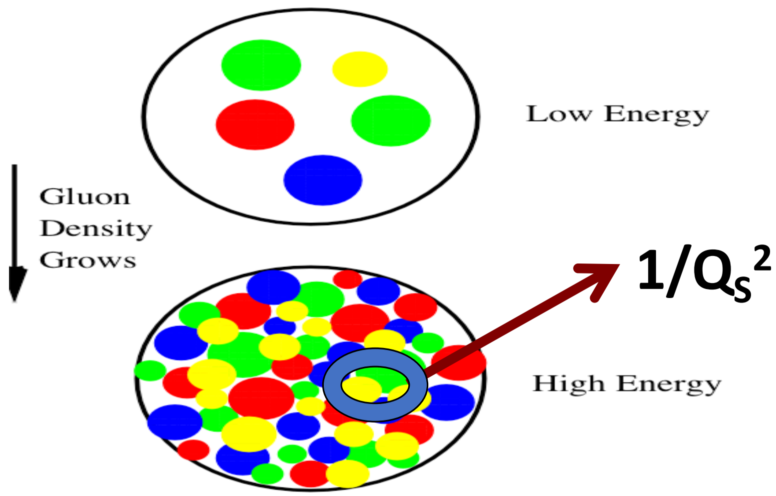
$s \rightarrow \infty, Q^2 = \text{fixed} \gg \Lambda_{QCD}^2 \;\; \text{x} \rightarrow 0$

A fascinating equilibrium of splitting and recombination should eventually result. It is a considerable theoretical challenge to calculate this equilibrium in detail…

F. Wilczek, Nature (1999)



Gluon saturation



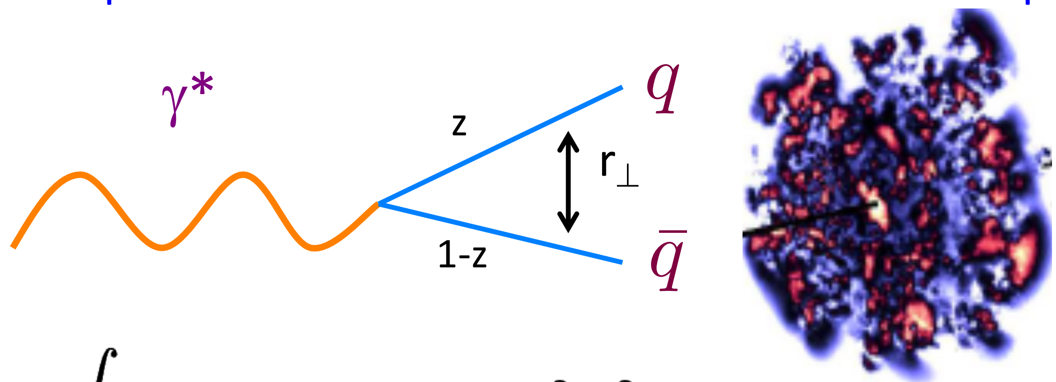
Gribov,Levin,Ryskin (1983)
Mueller, Qiu (1986)

Gluons at maximal phase space occupancy $n \sim 1/\alpha_S$, resist close packing by recombining and screening their color charges -- gluon saturation

Emergent dynamical saturation scale $Q_S(x) >> \Lambda_{QCD}$

Asymptotic freedom! $\alpha_S(Q_S) << 1$ *provides weak coupling window into infrared*

Saturation as perturbative unitarization: the dipole model



$$\sigma_{T,L}^{\gamma^*,P} = \int d^2 r_\perp \int dz \, |\psi_{T,L}(r_\perp, z, Q^2)|^2 \, \sigma_{q,\bar{q},P}(r_\perp, x)$$

QED QCD

Golec-Biernat Wusthoff model

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

$$Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$$

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

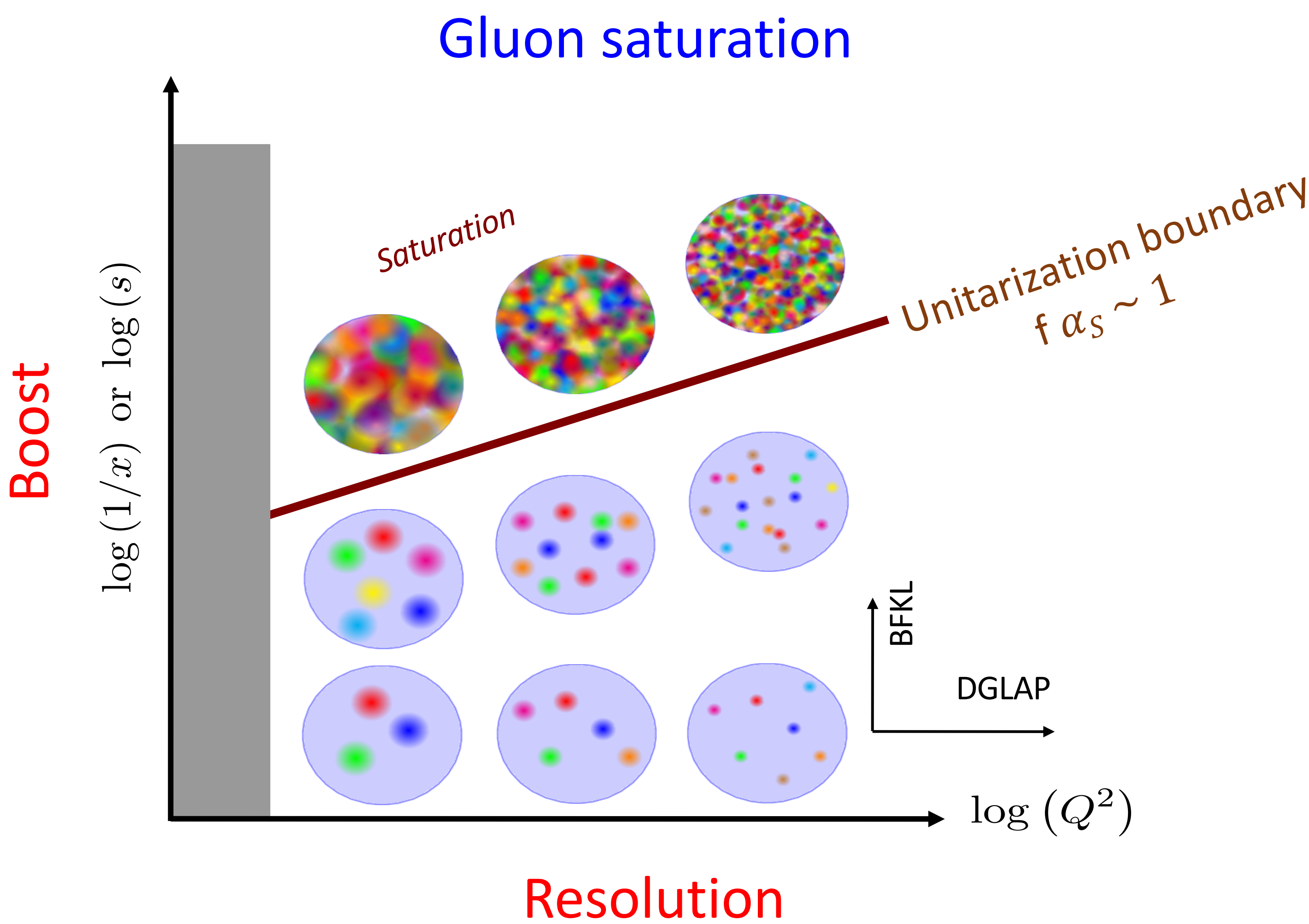
Color opacity ("black disk") for $r_\perp^2 Q_S^2$ >> 1 ($\sigma \propto A^{2/3}$)

QCD picture of "shadowing"…

Parameters:

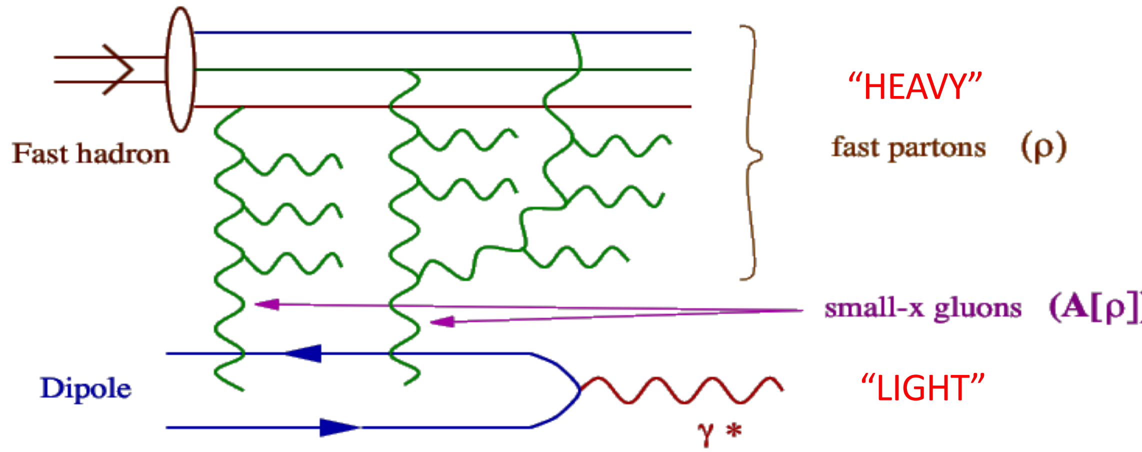
Q_0 = 1 GeV; λ = 0.3;

x_0 = 3* 10^{-4} ; σ_0 = 23 mb


Gluon saturation
Saturation
Unitarization boundary
f $\alpha_S \sim 1$
Boost
$\log(1/x)$ or $\log(s)$
BFKL
DGLAP
$\log(Q^2)$
Resolution

Classicalization in the Regge limit: the Color Glass Condensate EFT

Born-Oppenheimer separation
between fast and slow modes



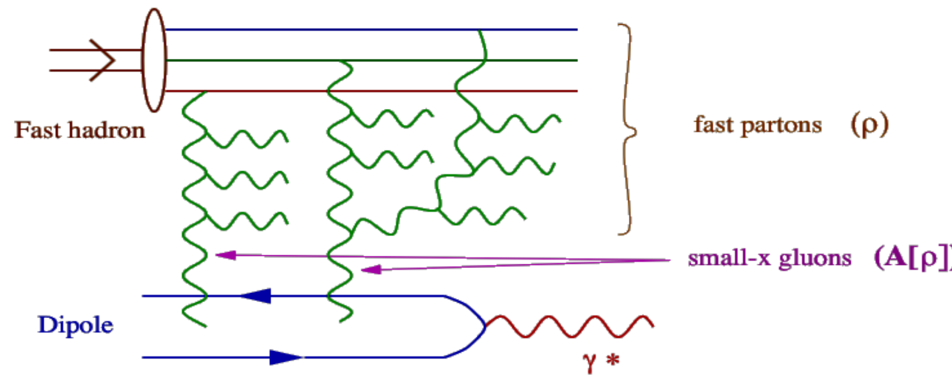
CGC: Effective Field Theory
of classical static quark/gluon sources
and dynamical gluon fields

Remarkably, physics of extreme quantum fluctuations
becomes classical because of high gluon occupancy…

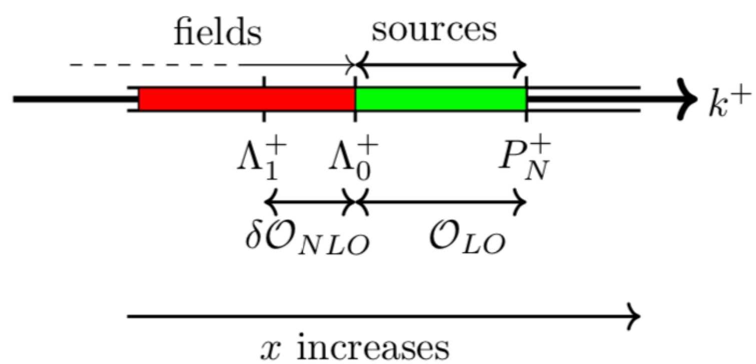
McLerran, RV (1994)

Classicalization in the Regge limit: the Color Glass Condensate EFT

EFT allows one to compute
many-body correlations
just as in condensed matter physics



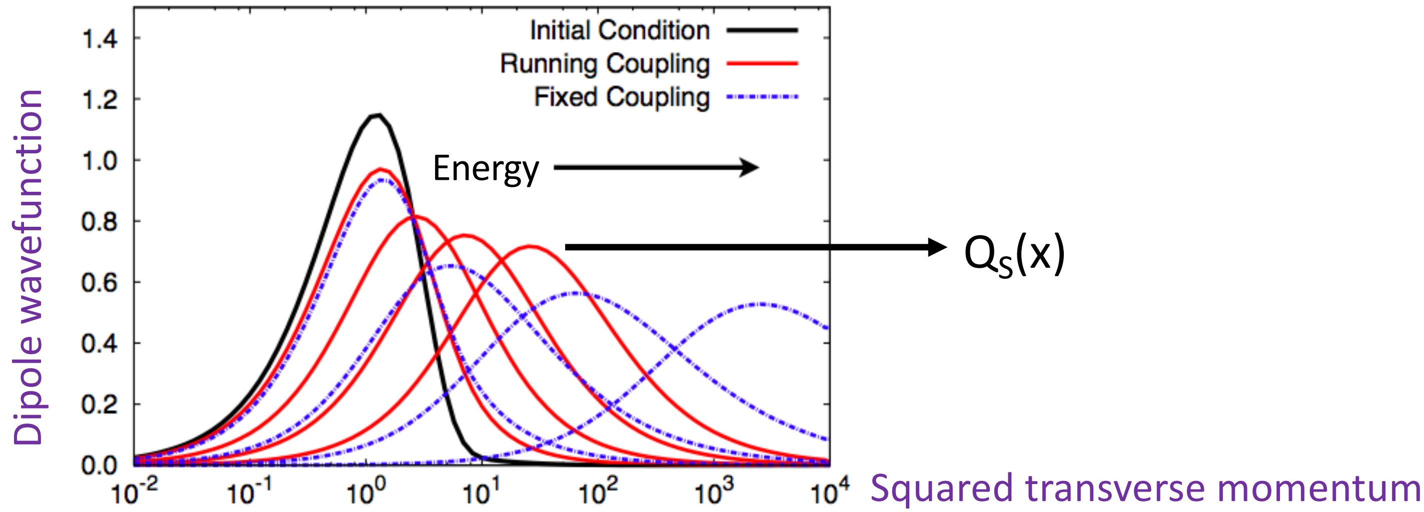
Wilsonian RG :
2+1-D B-JIMWLK hierarchy of equations for
multi-point "Wilson line" dipole, quadrupole, etc.
correlators -- right degrees of freedom



Balitsky (1996)
JIMWLK (1997-2001): Jalilian-Marian,Iancu,McLerran,Weigert,Leonidov,Kovner
Kovchegov (1999)

Universal classical dynamics of QCD in the infrared?

Classicalization in the Regge limit: the Color Glass Condensate EFT



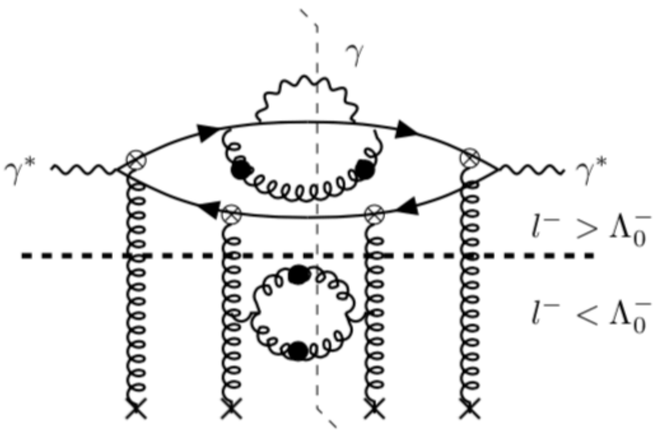
A closed form non-linear (Balitsky-Kovchegov) equation describes how $q\bar{q}$ "dipole" probe evolves with energy – *providing* a *clean demonstration of unitarization in strong fields*

Its dynamics can be mapped* to that of the Fischer-Kolmogorov (FKPP) eqn. describing the evolution of non-linear wave fronts. Rich synergy with stat. mech.

Munier, Peschanski (2003)

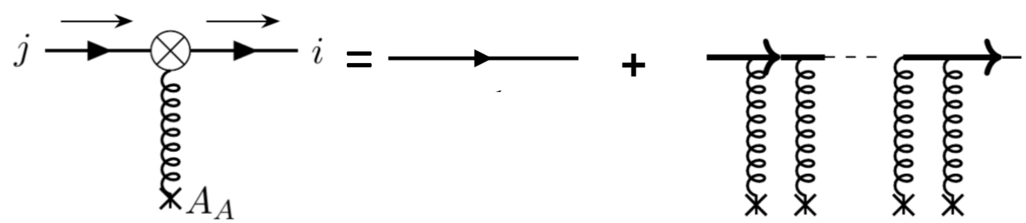
* small caveat

The power of Colored Glass: photons and di-jets to NLO+NLLx



Compton amplitude for $eA \to \gamma + dijets + X$

LO: Roy, RV, 1802.09550,
NLO+NLLx: on arXiv on Wednesday



Mom. dependent effective quark (and gluon) vertices include "all-twist" corrections $(Q_S^2/Q^2)^n$

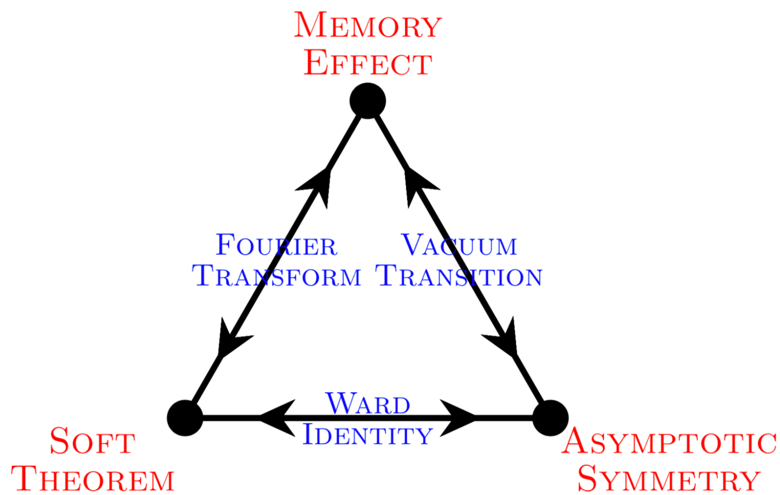
Differential DIS computations in the CGC EFT now available to $O(\alpha_S^3 \text{ Ln}(1/x))$ accuracy

Can be tested to $\sim 10\%$ *accuracy* at an Electron-Ion Collider

Some remarkable features:

- Propagators are *identical* to those in Lipatov's Reggeon field theory
- Spacelike-timelike correspondence of soft gluons ("non-global" logs)
- Interesting pattern of violation of soft gluon "theorem"

Infrared memory and asymptotic symmetries



Strominger,arXiv:1703.05448
Motivation:
Black hole information loss problem
Hawking,Perry,Strominger, PRL (2016)

Conjectured to be very general property of the infrared in gauge theories & gravity
In gravity, the symmetries are the BMS symmetries for asymptotically flat spacetime

BMS: Bondi,van der Burg,Metzner,Sachs (1962)

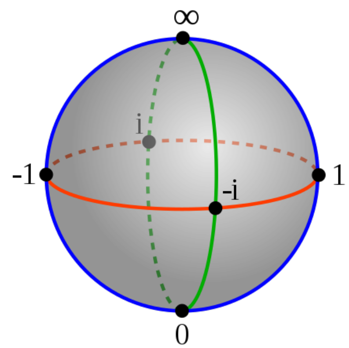
Corresponding *gravitational memory :* a physical displacement of inertial detectors

Zeldovich,Polnarev (1974)
Christodoulou (1991)

Measurable by LIGO, LISA, Pulsar Time Arrays…

Infrared memory and asymptotic symmetries in QED

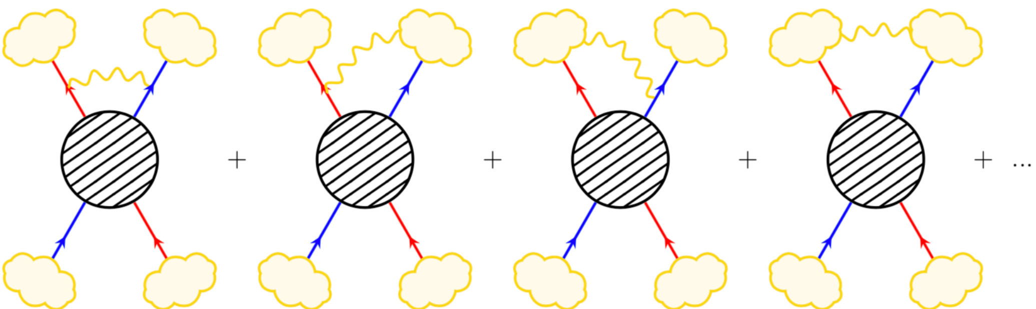
In QED, BMS-like symmetry:
group of conserved charges
on celestial sphere at ”null infinity”
-satisfy conservation law with S-matrix



Riemann/Celestial sphere: stereographic projection of 2-D transverse plane

Equivalent to soft photon (Low) theorem
- S-matrices dressed by soft photon clouds are IR finite

$$\langle \text{out}|(Q_\varepsilon^+\mathcal{S} - \mathcal{S}Q_\varepsilon^-)|\text{in}\rangle = 0$$



“Faddeev-Kulish” (1970)
Coherent state basis for asymptotic states
avoids cumbersome cancelation
of collinear divergences in usual pert. theory

Kapec,Perry,Raclariu,Strominger,arXiv:1705.043011

Yang-Mills memory and asymptotic symmetries

Pate, Raclariu, Strominger, PRL (2017)

Soft gluons satisfy a conformal 2-D (Kac-Moody) current algebra
with an infinite # of conserved charges on S^2

Nair (1988)
He,Mitra,Strominger (2015)

In Yang-Mills, exploiting these symmetries requires weak coupling scale in IR (CGC !)

How such symmetries constrain "boundary conditions at spatial infinity" may provide insight into Faddeev-Kulish coherent states in QCD (eigenstates of CGC "vacuum")

Color Memory in the CGC

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

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

x^- =0

In the CGC, solution of the YM-eqns: two pure gauges separated by shockwave discontinuity

$y=\ln(x^-/x_0^-)$

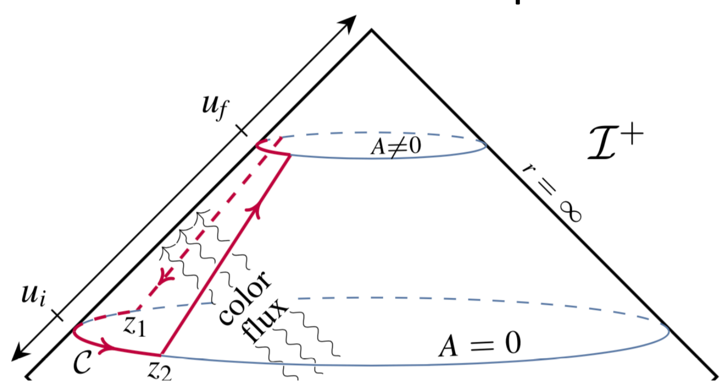
$$D_i \frac{dA^{i,a}}{dy} = g\rho^a(x_t, y)$$ with the solution $U = P \exp\left(i\int_y^\infty dy' \frac{\rho(x_t, y')}{\nabla_t^2} \right)$

Identical to expression for a YM vacuum transition on celestial sphere at null infinity

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

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

$\lambda \to \infty$ Flatten S^2 to transverse plane,
r → ∞ corresponds to $x^+ \to \infty$
$x^- \to 0$



Color Memory in the CGC

Ball,Pate,Raclariu,Strominger,RV,
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$A_i = 0$ | $A_i = -\frac{-1}{ig} U\partial_i U^\dagger$

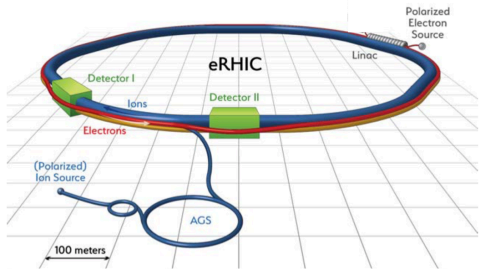
$x^- = 0$

U is precisely the *color memory* effect corresponding to a color rotation and $p_T \sim Q_S$ kick experienced by quark-antiquark pair traversing the shock wave

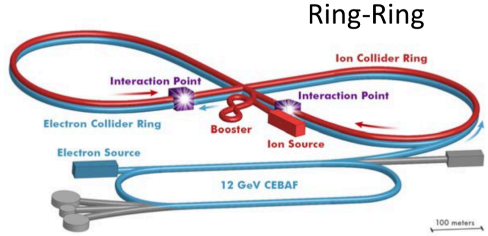
Pate, Raclariu, Strominger, PRL (2017)

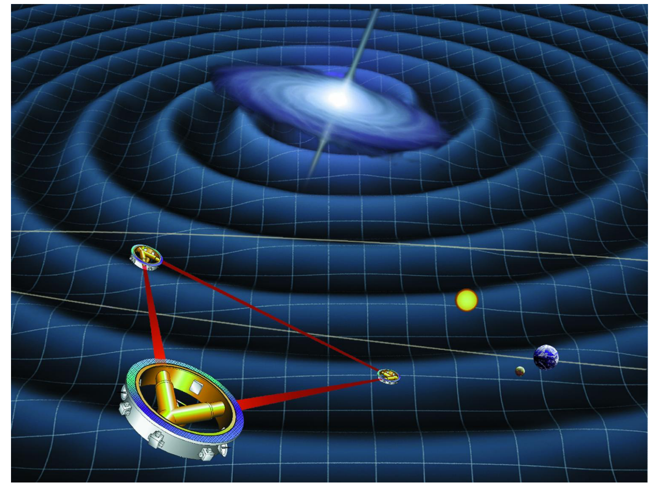
Its presence is ubiquitous in DIS final states

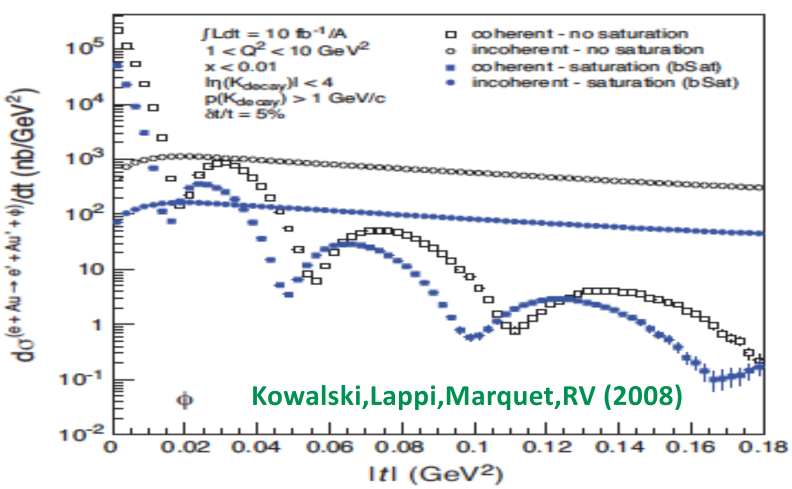
Infrared Memory: from EIC to LISA, etc…

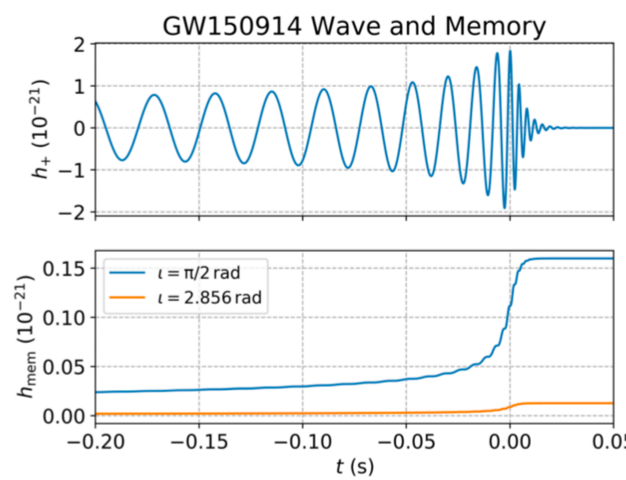


Ring-Ring

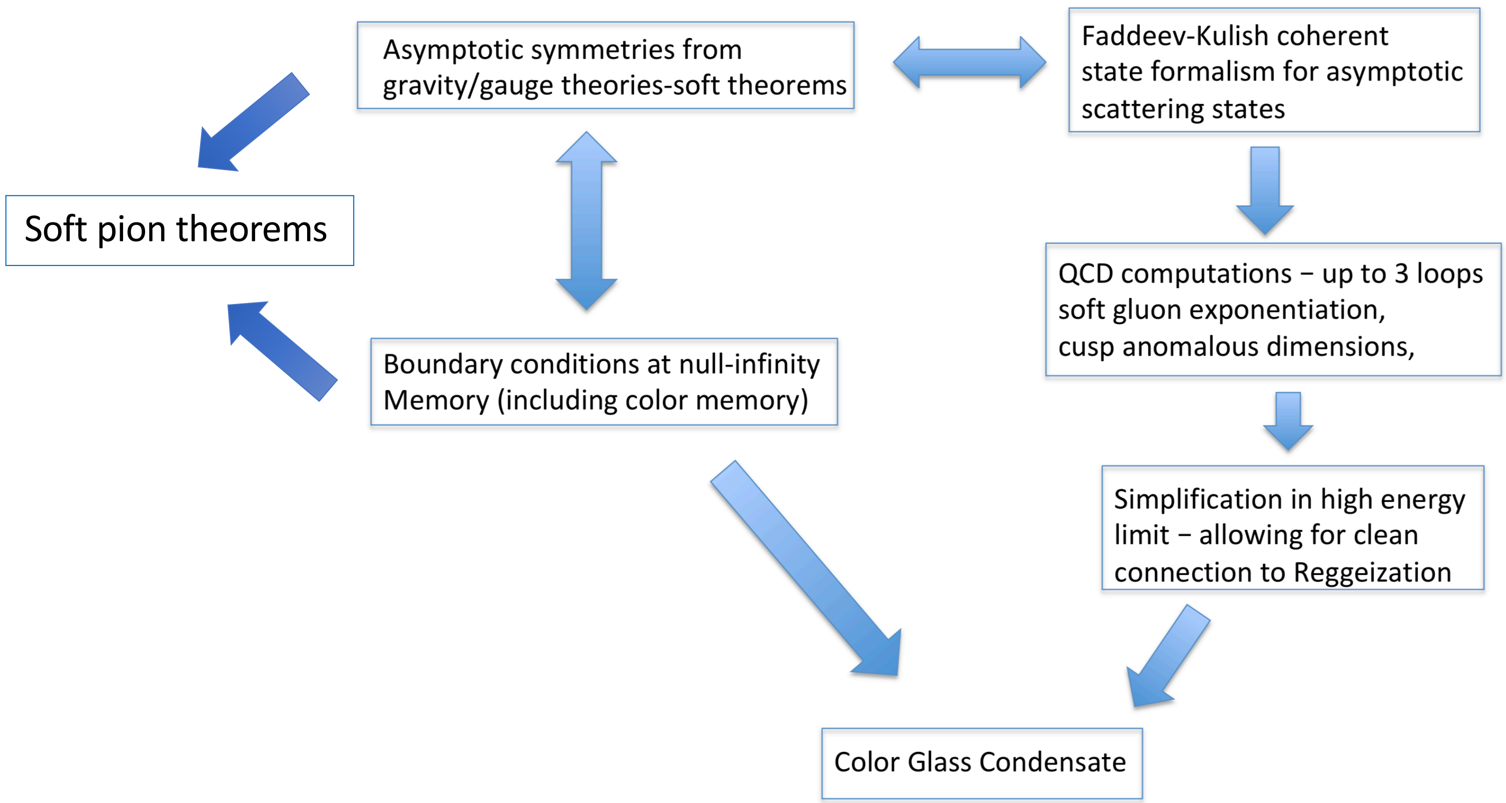








Conjecture: Completing the circle on QCD in the infrared



UV/IR correspondence of quantum portraits of Black Holes and CGCs

Dvali, RV, in preparation

Conjecture: Classicalization of gluons (gravitons) occurs at unitarization boundary ($\alpha\, n = 1$)

Gluons are weakly coupled in the UV and strongly coupled in the IR (Λ_{QCD})

Gravitons are weakly coupled in the IR and strongly coupled in the UV ($L_{Planck} = \sqrt{\hbar G_N}$)

However, we argued that in QCD, unitarization can occur at the scale $Q_S >> \Lambda_{QCD}$

Likewise, in gravity, unitarization occurs at the Schwarzchild radius $R_S = \sqrt{2\ M\ G_N} \gg L_{Planck}$

Self-bound gravitons form a quantum portrait of a Black Hole at the unitarization boundary

Dvali, Gomez (2011)

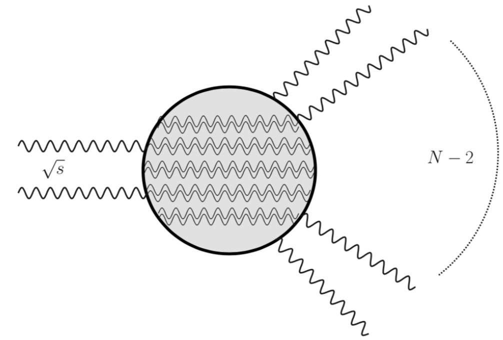
Is the physics universal for $\alpha\ n = 1$?

UV/IR correspondence of quantum portraits of Black Holes and CGCs

A quantitative correspondence emerges in the Trans-Planckian limit of $2 \rightarrow N$ graviton scattering

Lipatov (1991)

Explicit computations by Veneziano et al. of unitarized gravity amplitudes reproduces semi-classical Black Hole portrait of Dvali et al.



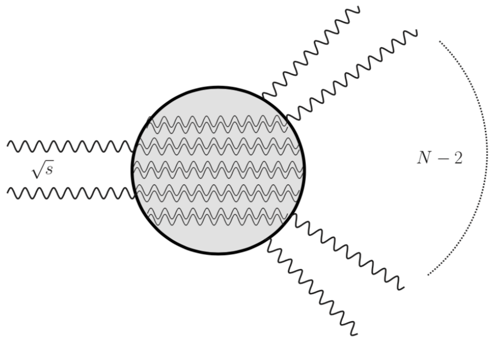
Amati, Ciafaloni, Veneziano, arXiv:0712.1209
Adazzi,Bianchi, Veneziano, arXiv:1611.03643
Dvali,Gomez,Isermann,Lust,Stieberger, arXiv:1409.7405

This is exactly analogous to how the semi-classical CGC description of $2 \rightarrow N$ scattering of gluons reproduces the explicit (BFKL) computations in pQCD

A common feature in QCD and Gravity is "Reggeization" of propagators by dressed propagators: this is captured efficiently in the semi-classical EFT picture…

UV/IR correspondence of quantum portraits of Black Holes and CGCs

Black Hole entropy versus CGC entropy:



$$S_{\rm BH} = \frac{\rm Area}{G} = \frac{R_\perp^2}{G} = \frac{c_{\rm gr}}{\alpha_{\rm gr}}\frac{R_\perp^2}{R_S^2} \qquad S_{\rm CGC} = \frac{c_{\rm QCD}}{\alpha_S} Q_S^2 R_\perp^2$$

Other interesting apparently universal features of this UV/IR correspondence: scrambling, radiation, thermalization

Making it quantitative: a classical "double copy" between QCD and gravity

KLT: Kawai, Lewellen, Tye (1986)
BCJ: Bern, Carrasco, Johansson (2008)
Goldberger, Ridgeway (2017)

Stay tuned…

Warmest wishes to Jean-Paul, Miklos and Larry
– and to many productive years ahead !