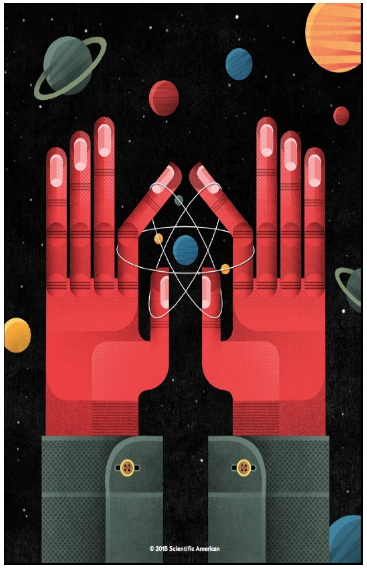
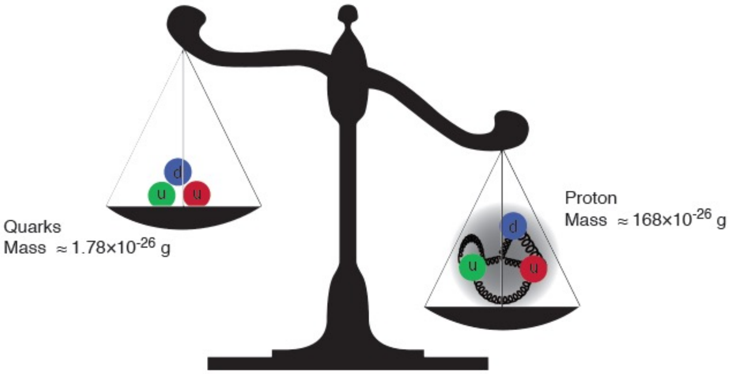
The glue that binds us all





Raju Venugopalan

Brookhaven National Laboratory

ICASU Inaugural Symposium, Urbana, May 19-21, 2022

Outline

QCD: the power and the glory

Emergent many-body phenomena in the QCD landscape

A classical lump and its quantum descendants in QCD at high energies

Universal features: examples in cold atoms and gravity

Quantum Chromodynamics (QCD)

- QCD - "nearly perfect" fundamental quantum theory of quark and gluon fields

  F.Wilczek, hep-ph/9907340

- Theory is rich in symmetries: **"Symmetries dictate interactions" – C.N Yang**

$$\underset{\textbf{i}}{SU(3)_c} \times \underbrace{SU(3)_L \times SU(3)_R}_{\textbf{ii}} \times \underbrace{U(1)_A \times U(1)_B}_{\textbf{iii}}$$

i) Gauge "color" symmetry: unbroken but confined
ii) Global "chiral" symmetry: exact for massless quarks
iii) Baryon number and axial charge (m=0) are conserved
iv) Scale invariance of quark (m=0) and gluon fields
v) Discrete C,P & T symmetries

- Chiral, Axial, Scale and (in principle) P &T broken by vacuum/quantum effects - "emergent" phenomena

- Inherent in QCD are the deepest aspects of relativistic Quantum Field Theories (confinement, asymptotic freedom, anomalies, spontaneous breaking of chiral symmetry)

Modern theory of the strong force: Quantum Chromodynamics

First QCD paper: Gell-Mann, Fritzsch, Leutwyler (1973)

New Quantum Numbers
The Eightfold Way / Unitary Symmetry
Mesons ~ $\underset{\sim}{8}$ Baryons ~ $\underset{\sim}{8} + \underset{\sim}{10}$
Fundamental Representation Absent

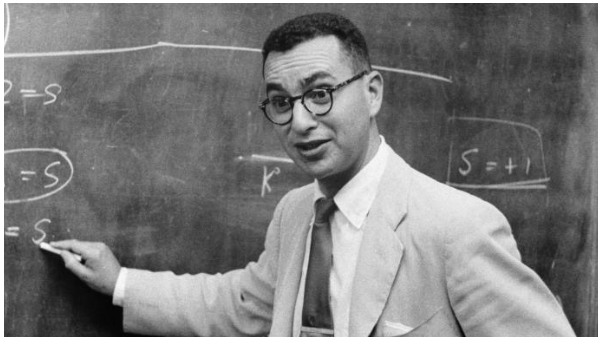
The Quarks: Fractional Charge Triplets
Are They Real? (Constituents of Hadrons)
Are They Just a Mathematical Shorthand?
Relationship to Weak Currents?

Thinking About Real Quarks –
Spin/Statistics Problem → Parafermions
Color (New SU(3)!) – More Shorthand?
Still No Dynamics; Confinement a Mystery

Asymptotic Freedom → Quarks = Partons
Promotion of Color to the Essence of
Strong Dynamics; Gluons a Color $\underset{\sim}{8}$
QCD the Theory of Strong Interactions

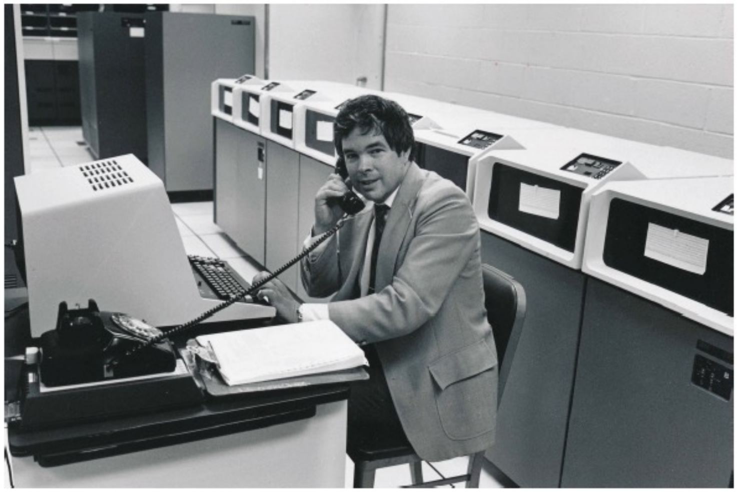
From Gell-Mann's 8-fold way to QCD: A lepidopteral metaphor

Jeffrey Mandula, Creutz-Fest 2014, BNL



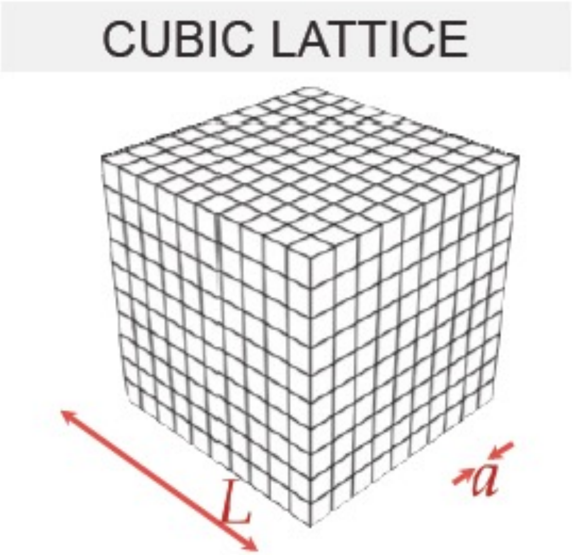
M. Gell-Mann

Numerical realization: Lattice QCD



Kenneth G. Wilson

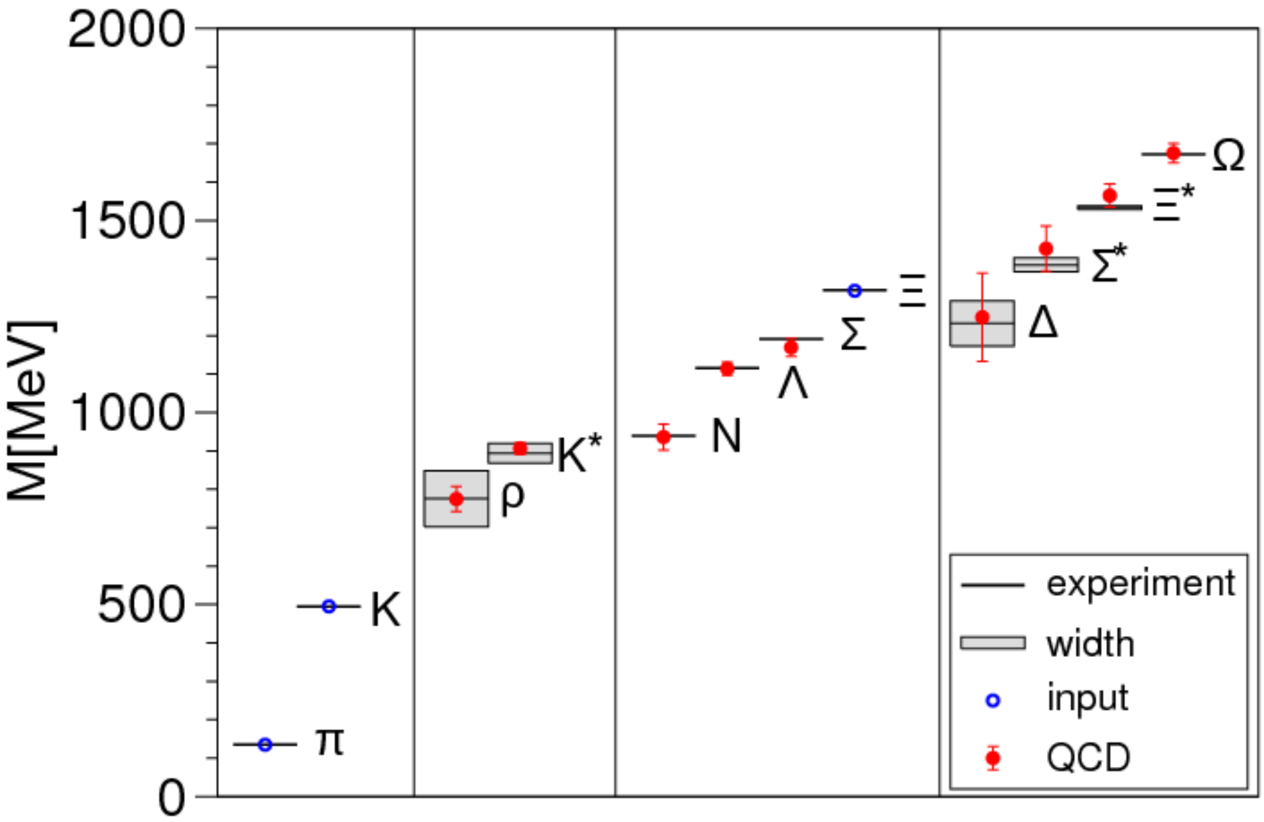
(1982)



Lattice regularization (UV&IR) of QCD

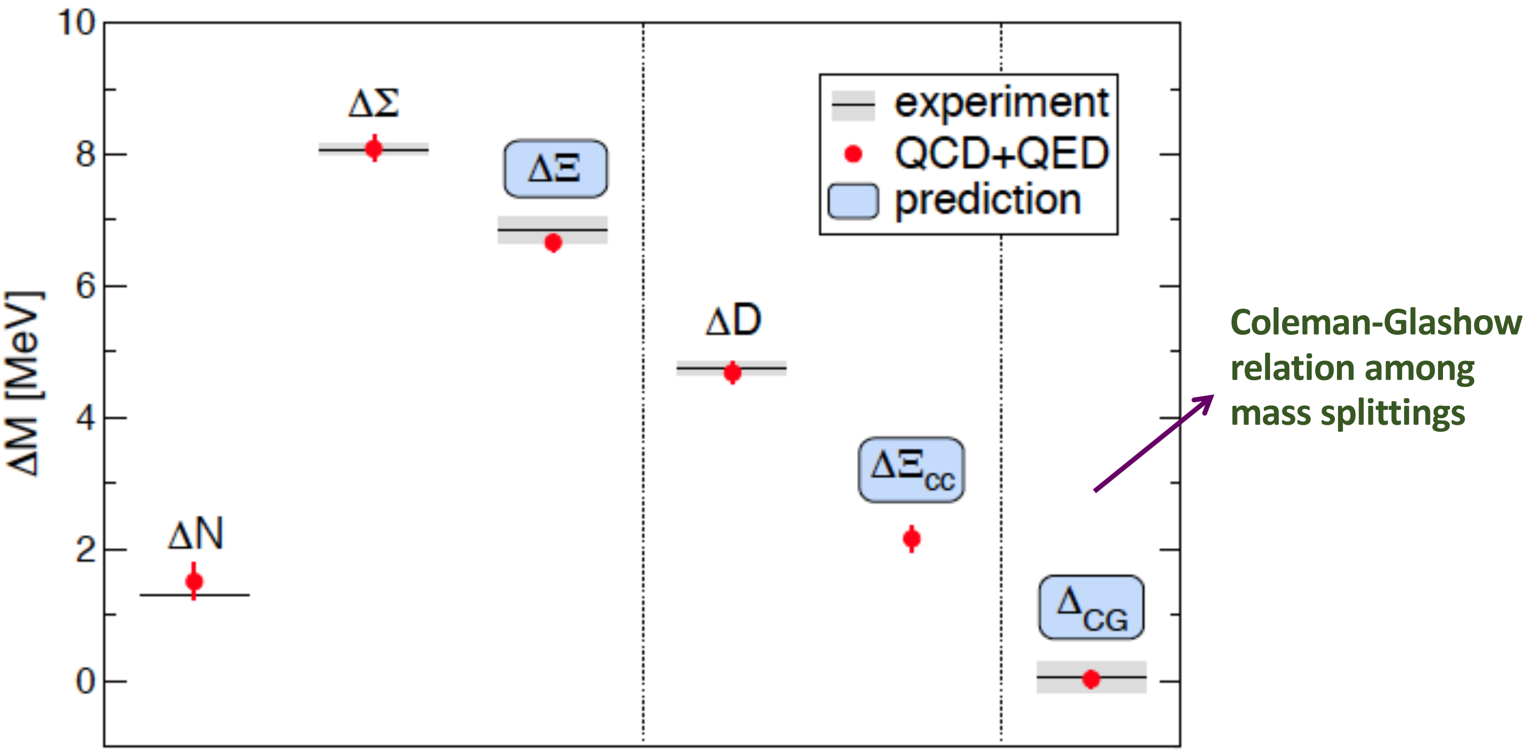
First principles treatment of static properties of QCD: masses, moments, thermodynamics at finite T (& μ_B ?)

Precision QCD on the lattice



Durr et al., Science, 322 (2008)

Precision QCD+QED on the lattice



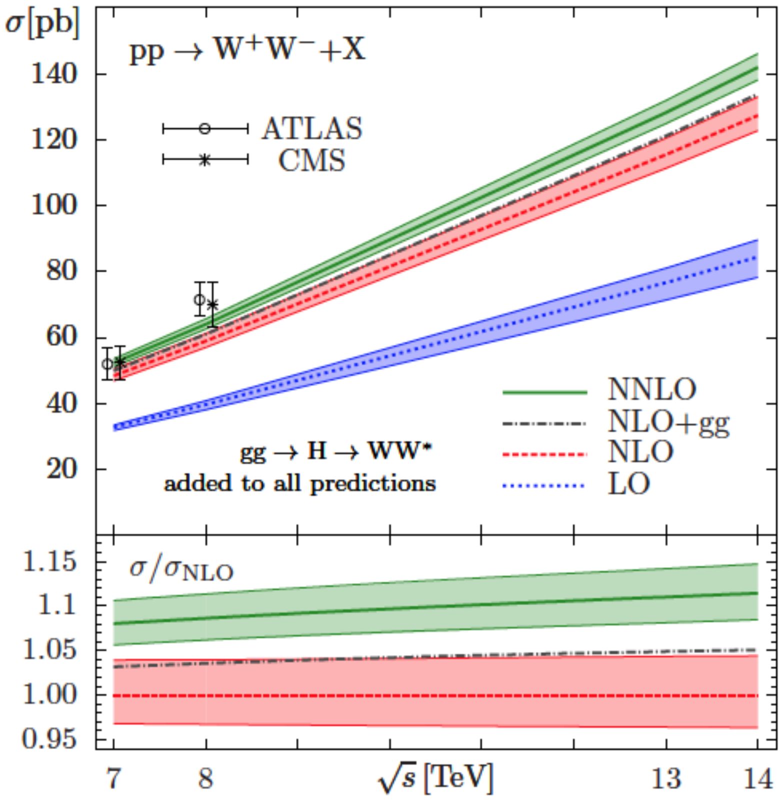
Coleman-Glashow relation among mass splittings

Budapest-Marseille-Wuppertal (BMW) Coll., arXiv:1406.4088

Noteworthy recent development: Constraining hadron matrix elements enabling discovery science with muon g-2

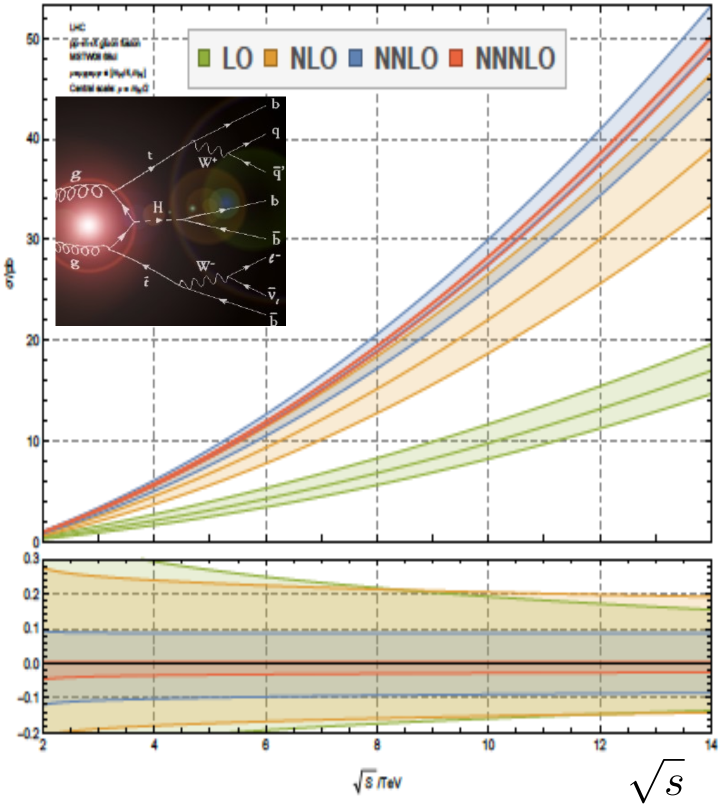
Muon g-2 Theory Initiative,
T. Aoyama et al., Phys. Repts. 887 (2020) 1

Perturbative QCD: benchmark for new physics



Gehrmann et al., arXiv:1408.5243

Gluon fusion to Higgs cross-section



Anastasiou et al., arXiv:1503.06056

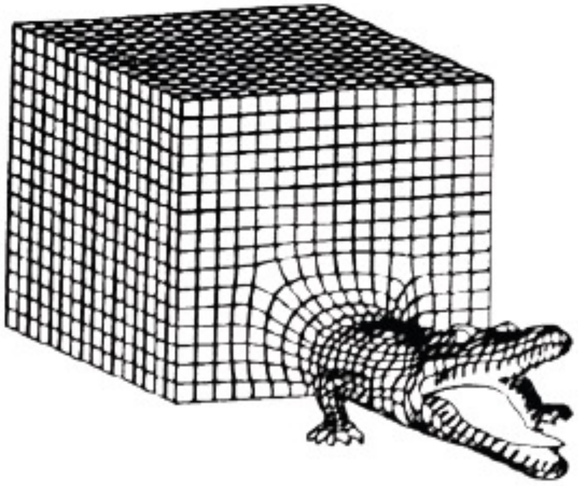
Are we done ?

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and "applications".

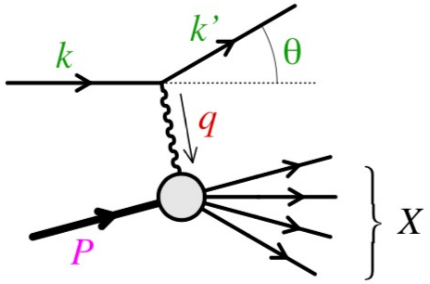
F. Wilczek , "Quarks (and Glue) at the Frontiers of Knowledge", Talk at Quark Matter 2014

Emergent many-body phenomena in QCD at high energies

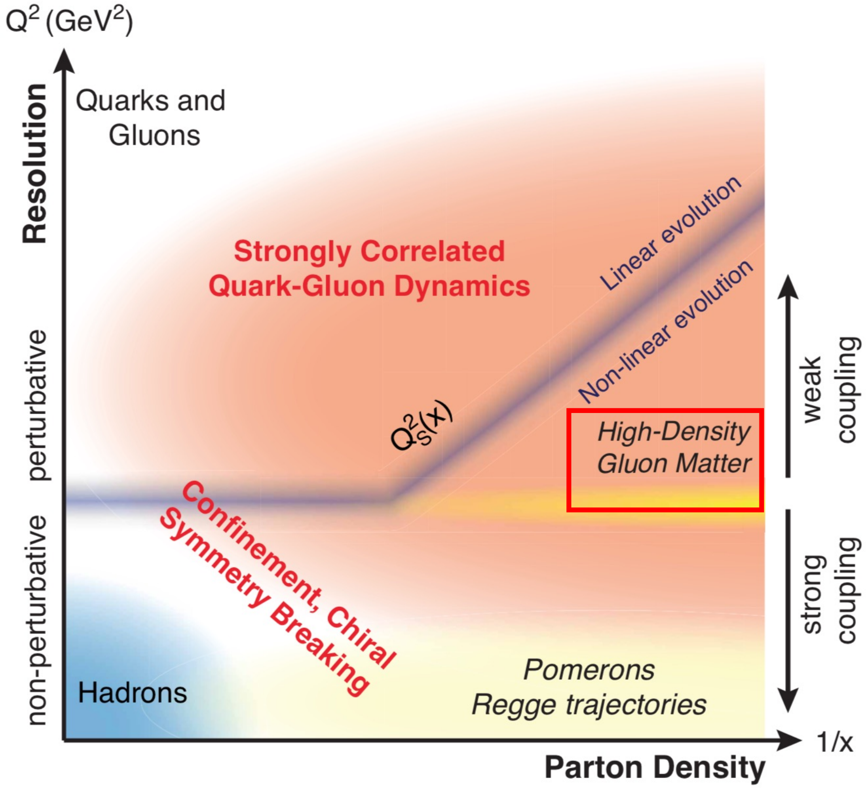


Don’t try (yet) on the lattice…

Landscape of QCD dynamics in resolution and energy



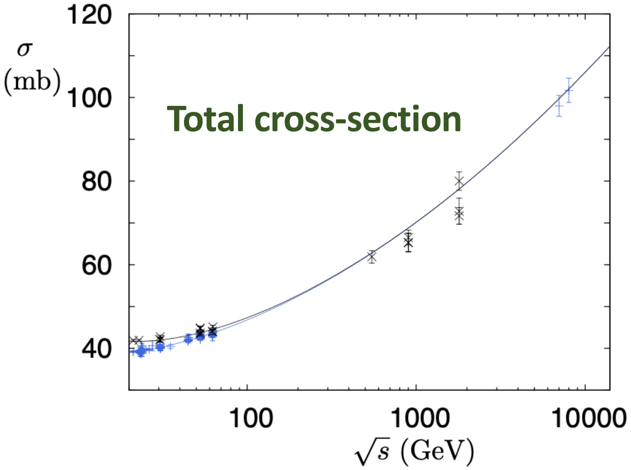
Deeply inelastic scattering



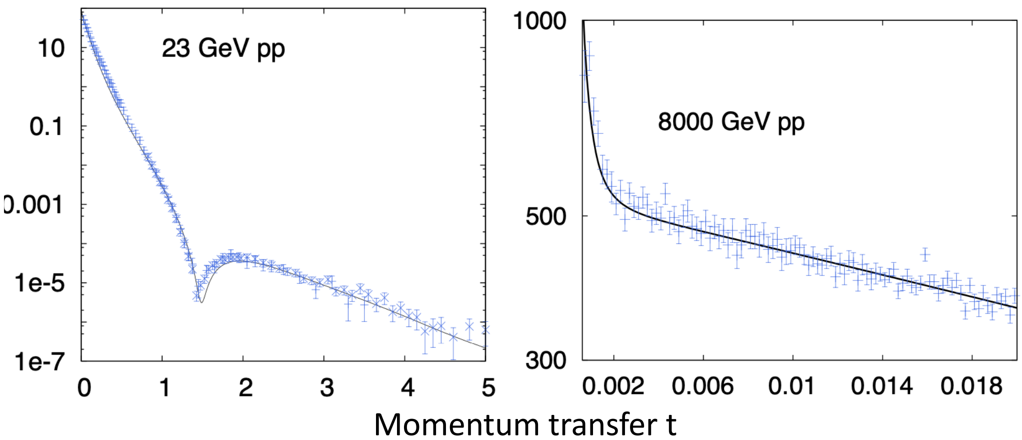
Aschenauer et al., arXiv:1708.01527
Rep.Prog. Phys. 82, 024301 (2019)

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

What is the Pomeron in QCD?



Differential elastic cross-section



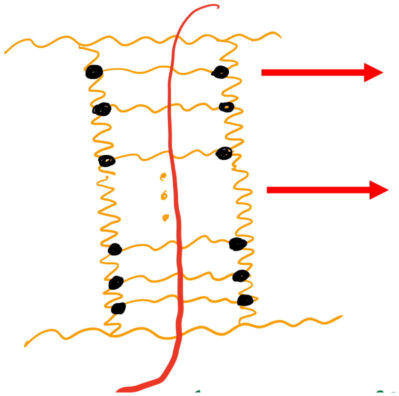
The behavior of total cross-sections over three orders of magnitude in energy (SPS -> LHC) is simply described in terms of effective Pomeron and Reggeon trajectories

Pomeron: t-channel exchange with vacuum quantum numbers dominates total hadron-hadron cross-sections:

Amplitude: $A(s,t) = s^{\alpha(t)}$ with $\alpha(t) = 1 + \varepsilon + \alpha' t$

Intercept ε_P= 0.11 String tension = 0.165 GeV^{-2}

Donnachie, Landshoff, Phys. Lett. B750 (2015) 669



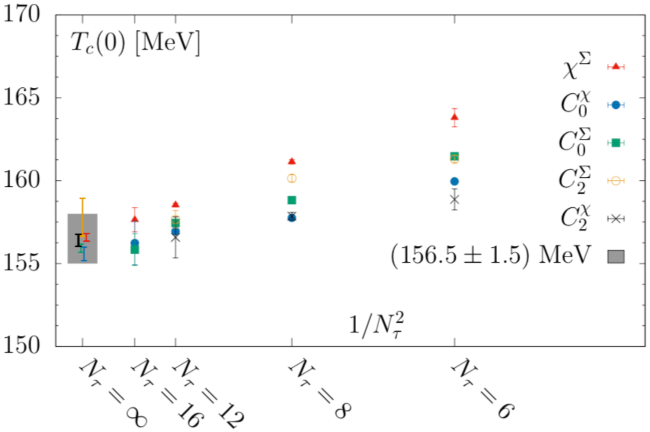
Lipatov vertex

Reggeized gluon

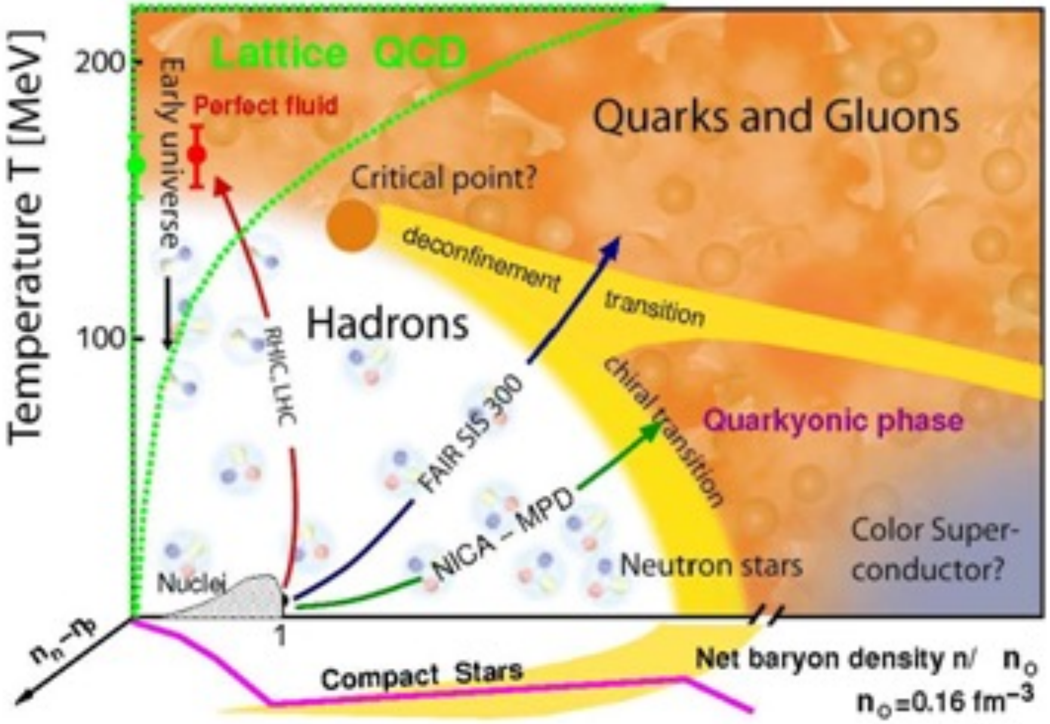
BFKL Pomeron- compound color singlet state of ”reggeized gluons” with vacuum quantum numbers

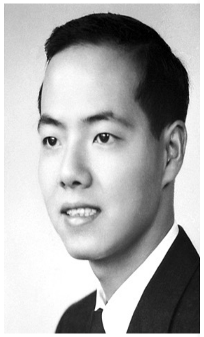
The QCD phase diagram

Hot QCD collaboration, Bazavov et al., arXiv:1812.08325



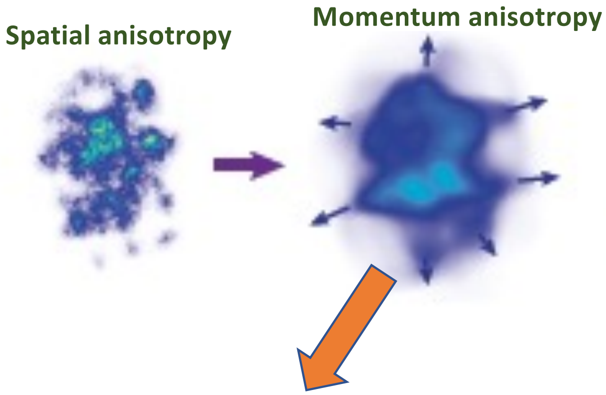
Cross-over temperature from hadron gas to quark-gluon plasma $T_c = 156.5 \pm 1.5\ MeV$



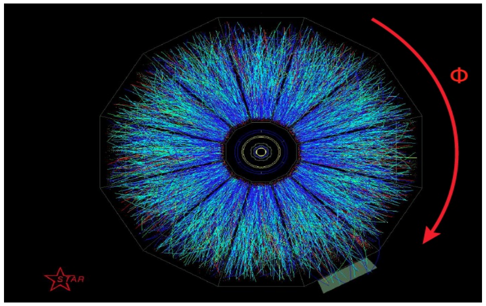


Nuclei as heavy as bulls
Through collisions
Generate new states of matter

The unreasonable effectiveness of hydrodynamics

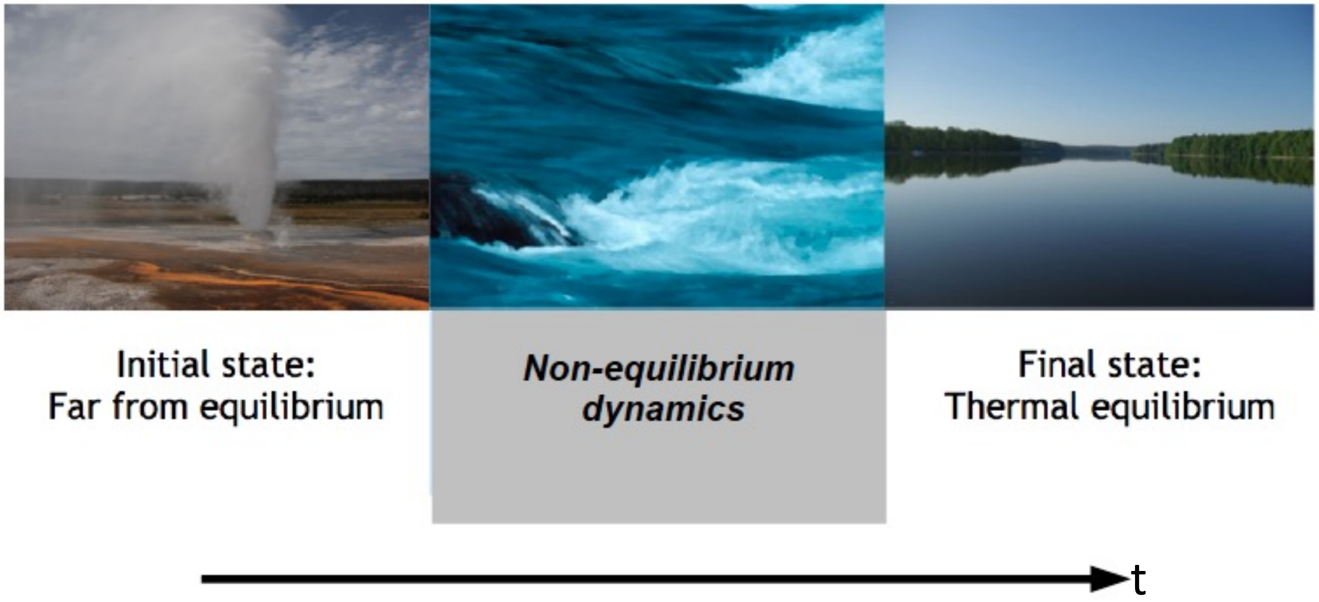


~ 10^3 subatomic particles
produced in collisions
of Gold nuclei at 200 GeV/nucleon



STAR detector @ BNL's
Relativistic Heavy ion Collider (RHIC)

From the violence of a nuclear collision
…to the calm of a nearly perfect quark-gluon fluid, the Quark-Gluon Plasma



Initial state:
Far from equilibrium

Non-equilibrium dynamics

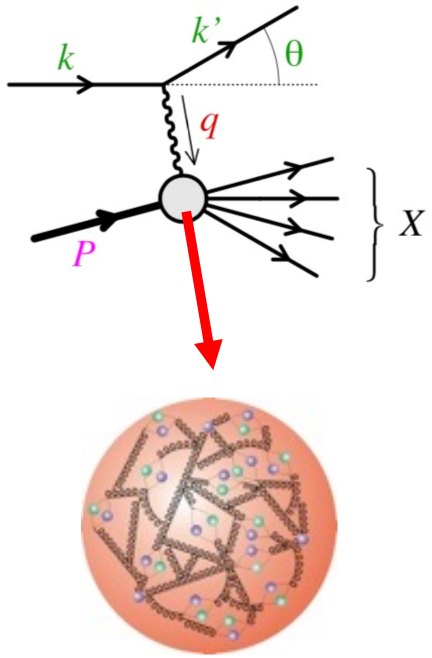
Final state:
Thermal equilibrium

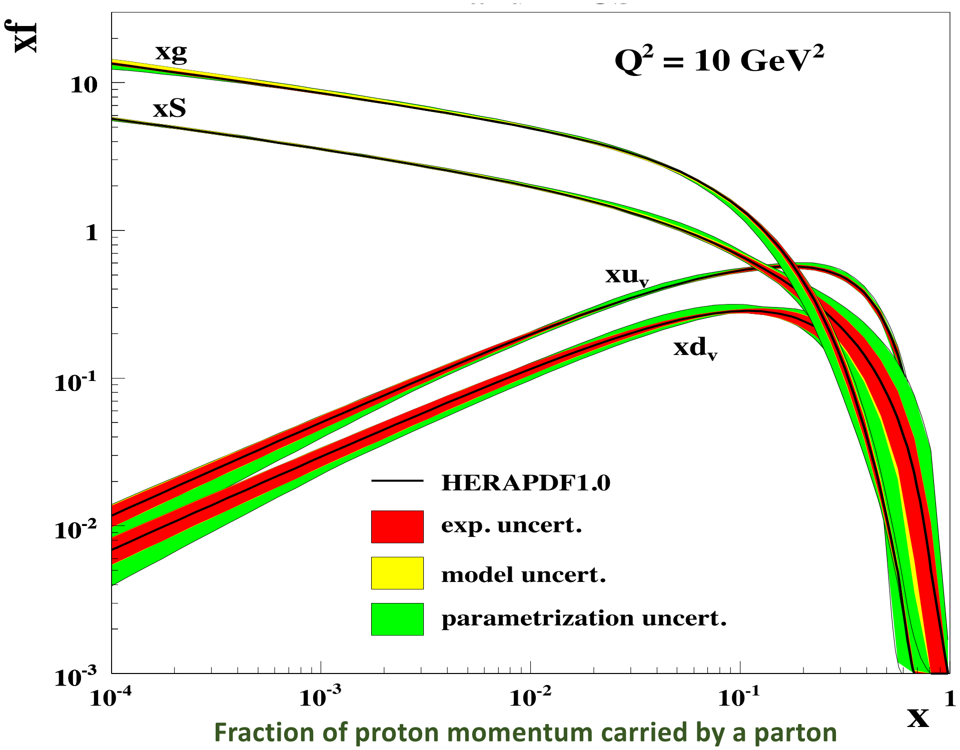
What is the thermalization process in heavy-ion collisions ?

Classical lumps and their quantum descendents in high energy QCD

The proton as a complex many-body system

Deeply Inelastic Scattering

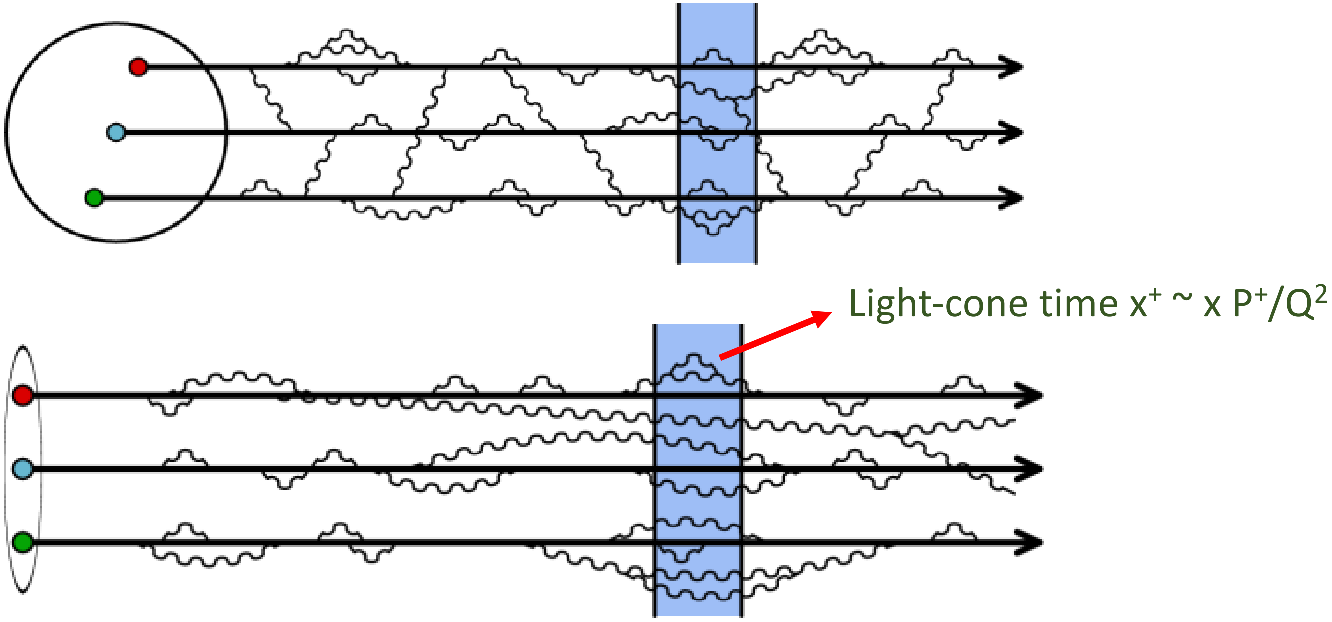




A key lesson from the HERA DIS collider:

Gluons and sea quarks dominate the proton wave-function at high energies

Lifting the veil: boosting the proton uncovers many-body structure



Low Energy
(or large x)

High Energy
(or small x)

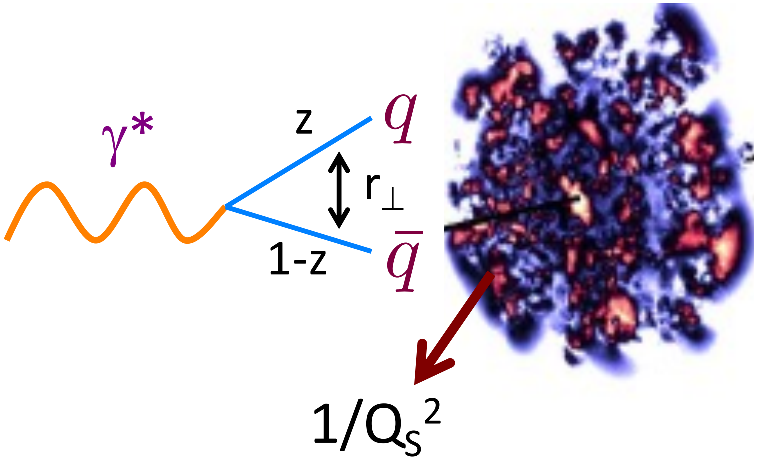
Light-cone time $x^+ \sim x\, P^+/Q^2$

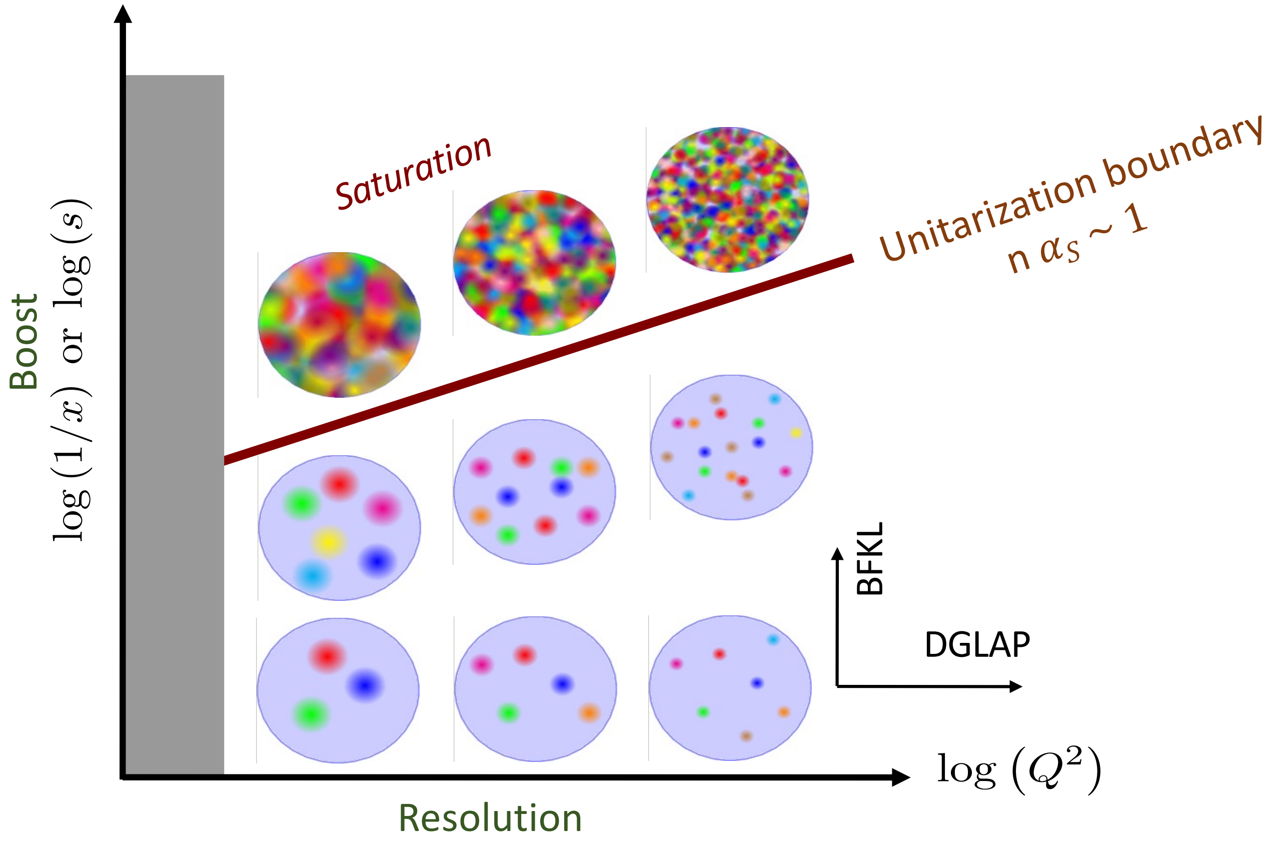
“Wee” parton fluctuations carrying a fraction x << 1 of proton’s momentum are time dilated on strong interaction time scales.

Long lived gluons radiate further small x gluons…Markovian process in $\log_e(x)$ generates power law growth of gluon distribution at small x

The boosted proton

Gluon saturation





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

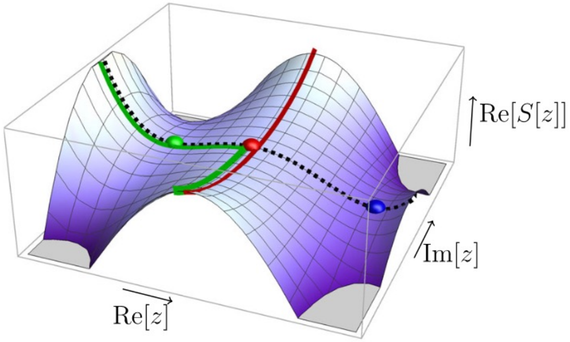
Gluon saturation characterized by emergent "close packing" scale

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

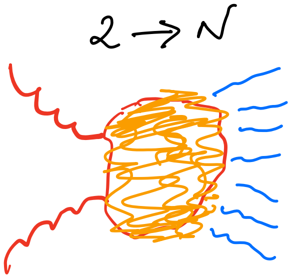
This scale is precocious in nuclei due to color coherence along path length of the interaction: $(Q_S^A)^2 \propto A^{1/3}$

Classical lumps in 2 → N scattering and unitarity

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



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



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

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

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

Exponential suppression of high occupancy states (classical lumps) unless

$$S \sim 1/\alpha_s \sim N$$

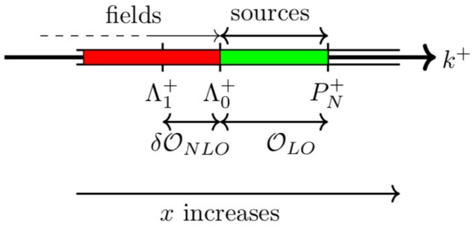
$$\boxed{\Rightarrow P_{2\to N} \sim O(1)}$$

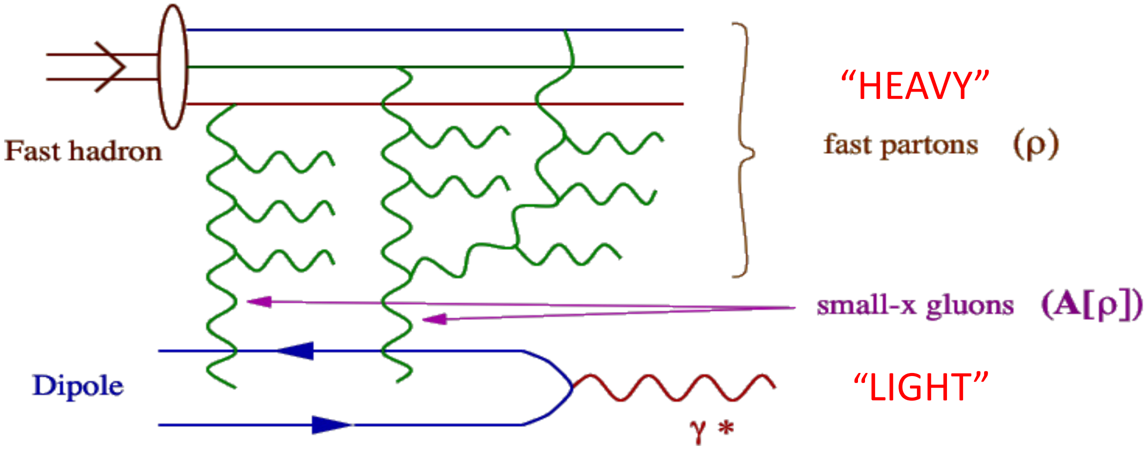
Dvali,RV, arXiv:2106.11989, PRD

Classical EFT: the Color Glass Condensate

Born-Oppenheimer separation between fast and slow modes

Wilsonian RG describes their evolution with energy





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

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

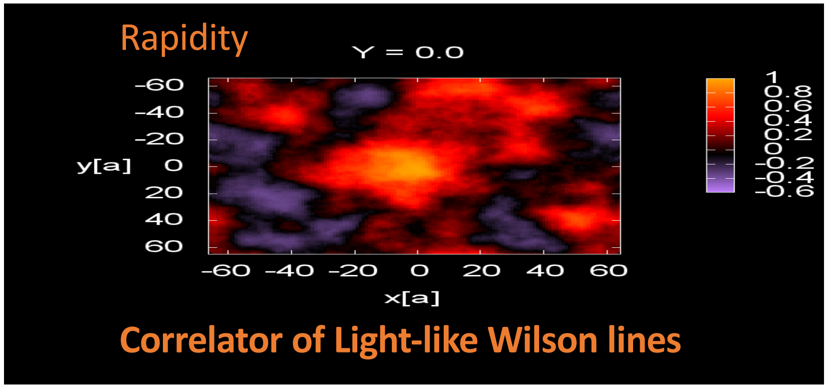
Color: self-evident

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

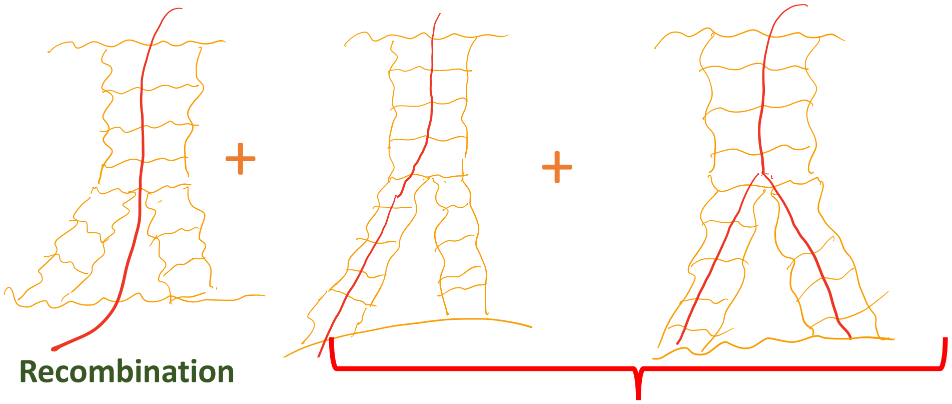
Basic review: Jalilian-Marian,Gelis,Iancu,RV, arXiv:1002.0333
Textbook: Kovchegov, Levin, Cambridge Univ. Press (2012)

RG evolution of many-body correlators



Correlator of Light-like Wilson lines

Dumitru,Jalilian-Marian,Lappi,Schenke,RV
PLB706 (2011)219



Recombination

Screening

$$\frac{\partial}{\partial Y}\langle\mathcal{O}[\rho]\rangle_Y = \frac{1}{2}\langle\int_{x,y}\frac{\partial}{\partial\rho^a(x)}\chi^{ab}_{x,y}\frac{\partial}{\partial\rho^b(y)}\mathcal{O}[\rho]\rangle_Y$$

"time"

"diffusion coefficient"

RG in rapidity (boost) describes Langevin diffusion of the fuzz of "wee" (small x) partons in the functional space of colored fields

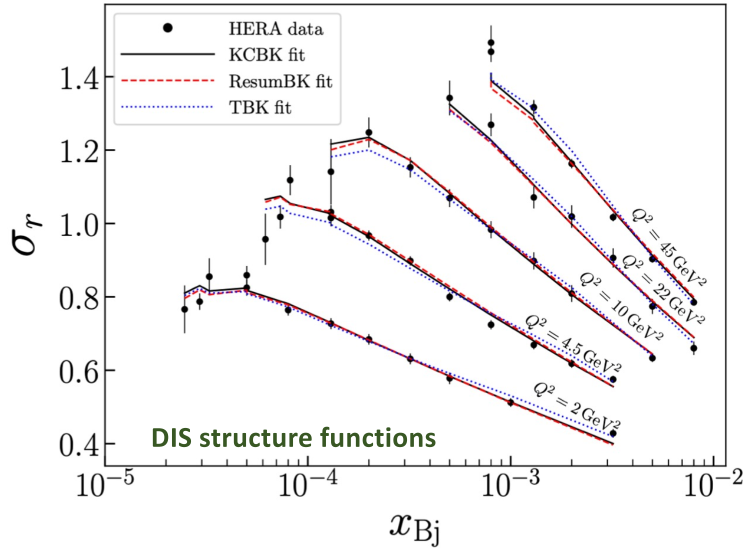
Blaizot,Iancu,Weigert (2003)

B-JIMWLK hierarchy:
Balitsky (1996)
Jalilian-Marian,Kovner,Leonidov,Weigert (1997);
Iancu,Leonidov,McLerran (2001)

Captures multi-Pomeron dynamics going beyond the BFKL Pomeron

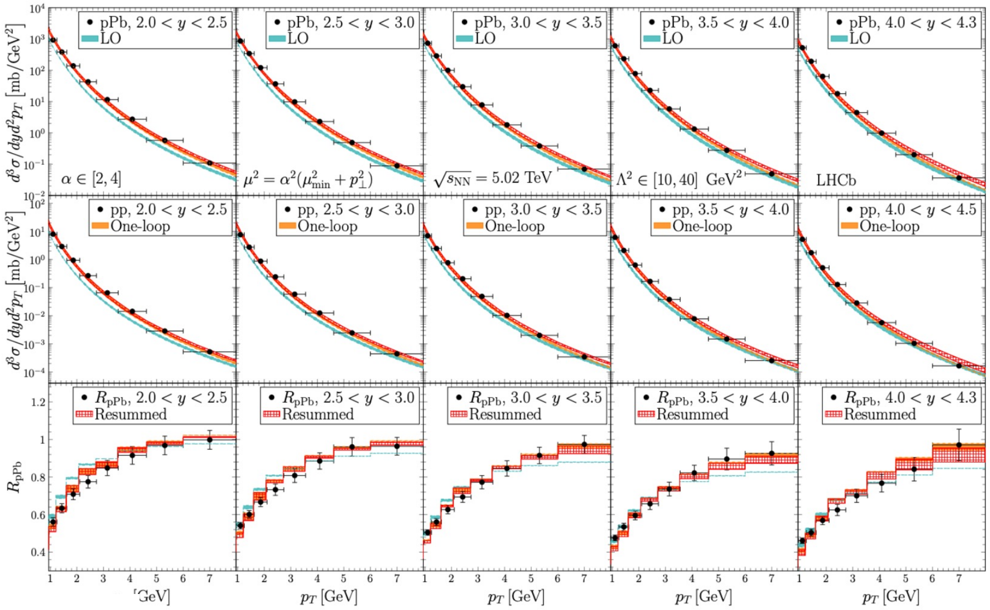
CGC state-of-the art

Beuf,Hanninen,Lappi,Mantysaari, arXiv:2007.01645



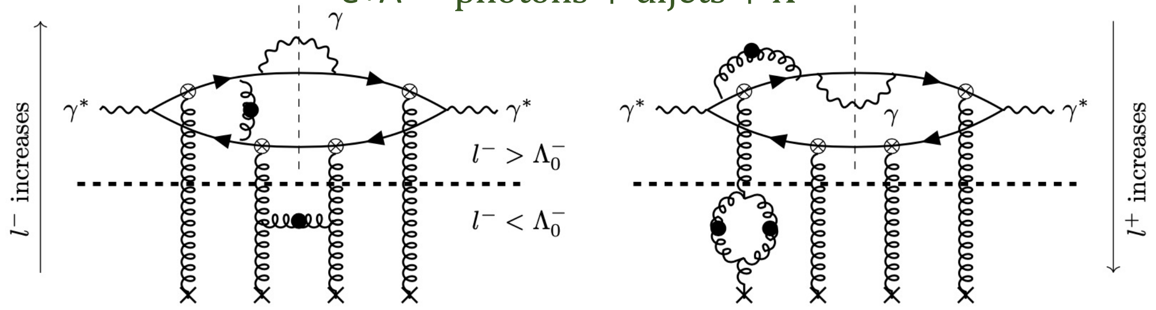
DIS structure functions

Single inclusive hadron distributions at the LHC



Shi,Wang,Wei,Xiao, arXiv:2112.06975

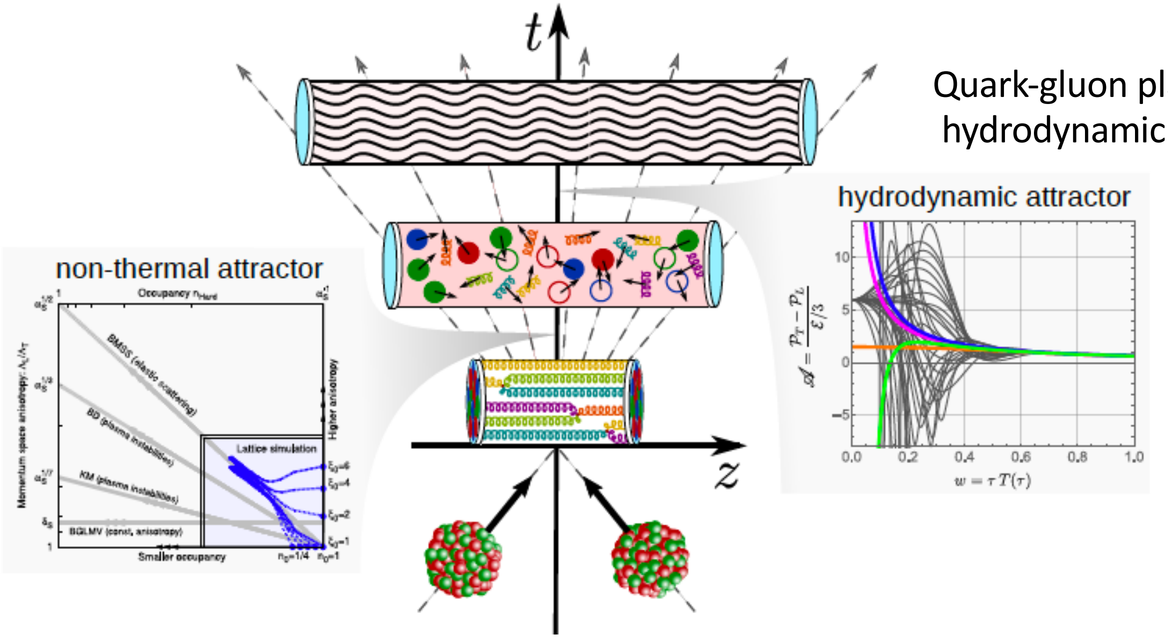
e+A → photons + dijets + X



Systematic computations of differential final states sensitive to gluon saturation are becoming available
– precision tests at the Electron-Ion Collider

Roy, RV: 1911.04519, 1911.04530
Caucal,Salazar, RV: 2108.06347

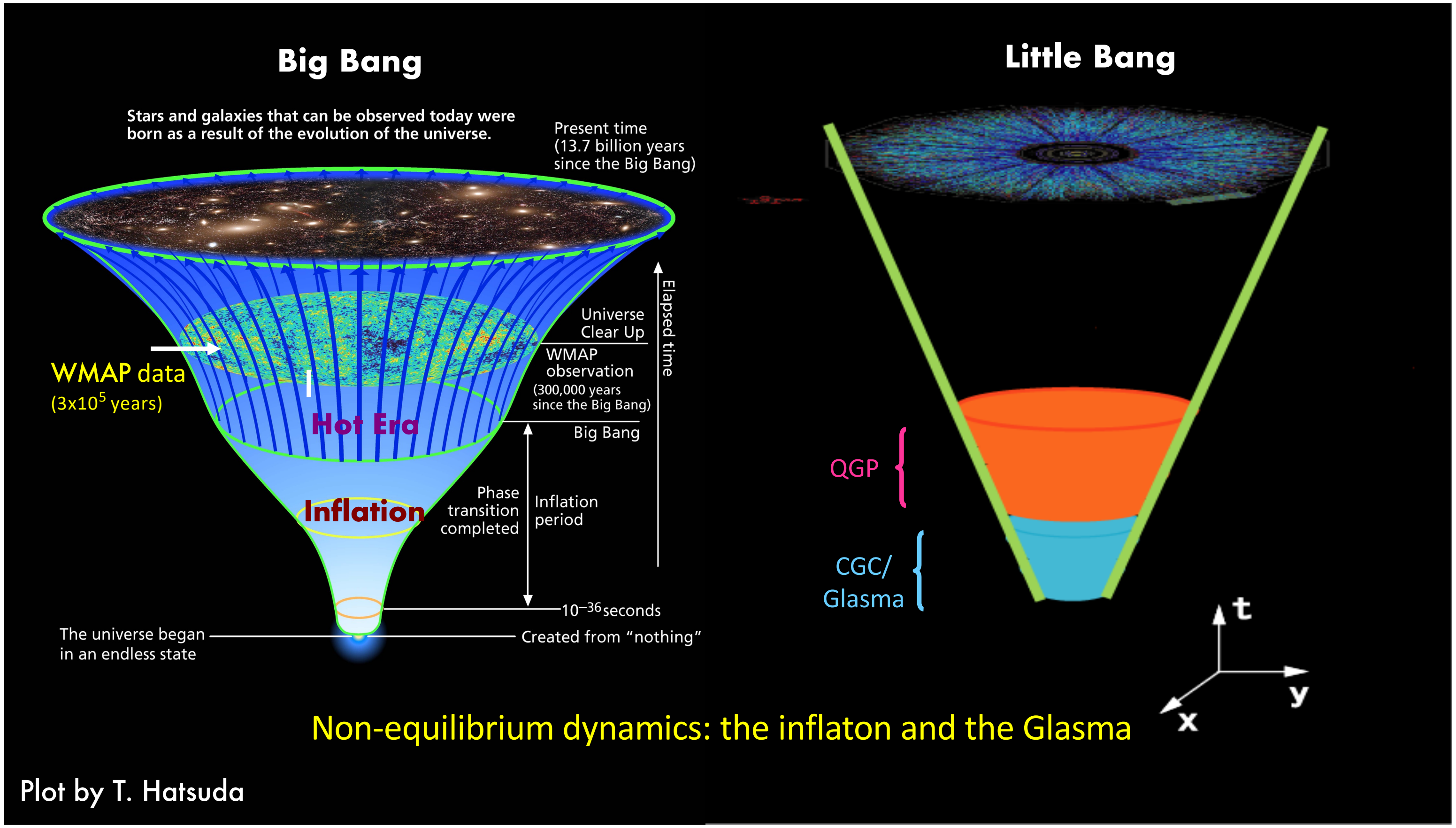
Spacetime evolution of a heavy-ion collision



Quark-gluon plasma undergoing
hydrodynamic expansion

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)



Non-equilibrium dynamics: the inflaton and the Glasma

Plot by T. Hatsuda

Big Bang vs. Little Bang

Decaying Inflaton with occupation # $1/g^2$	↔	Decaying Glasma with occupation # $1/g^2$
Explosive amplification of low momentum small fluctuations (parametric resonance in preheating)	↔	Explosive amplification of low momentum small fluctuations (Weibel instabilities)
Interaction of fluctuations/inflaton -> thermalization?	↔	Interaction of fluctuations/Glasma -> thermalization?

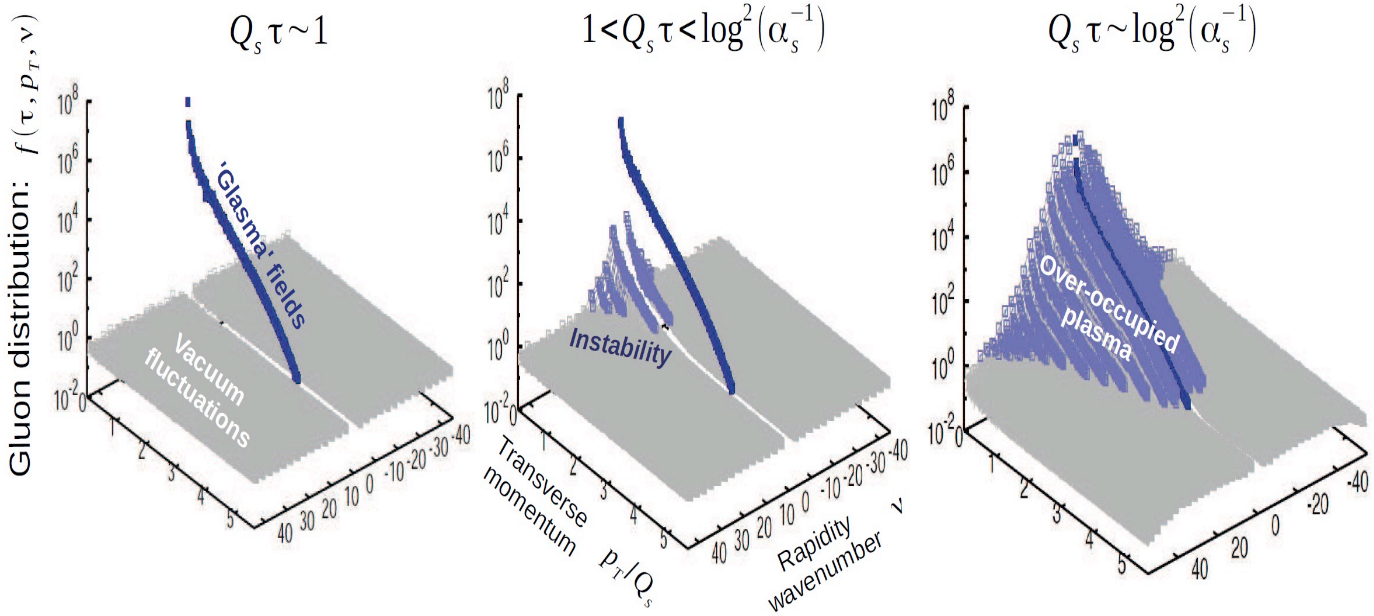
Other common features: turbulence, topological defects,…

Turbulent thermalization,
Micha and Tkachev, arXiv:hep-ph/0403101

From Glasma to Quark Gluon Plasma

Longitudinally expanding Glasma fields are unstable to quantum fluctuations… leading to an explosive “Weibel” instability.

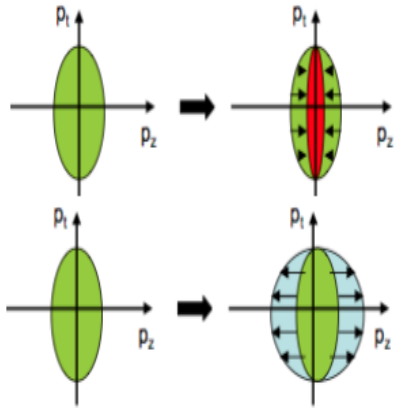
Rapid decoherence and overpopulation of all momentum modes



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

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

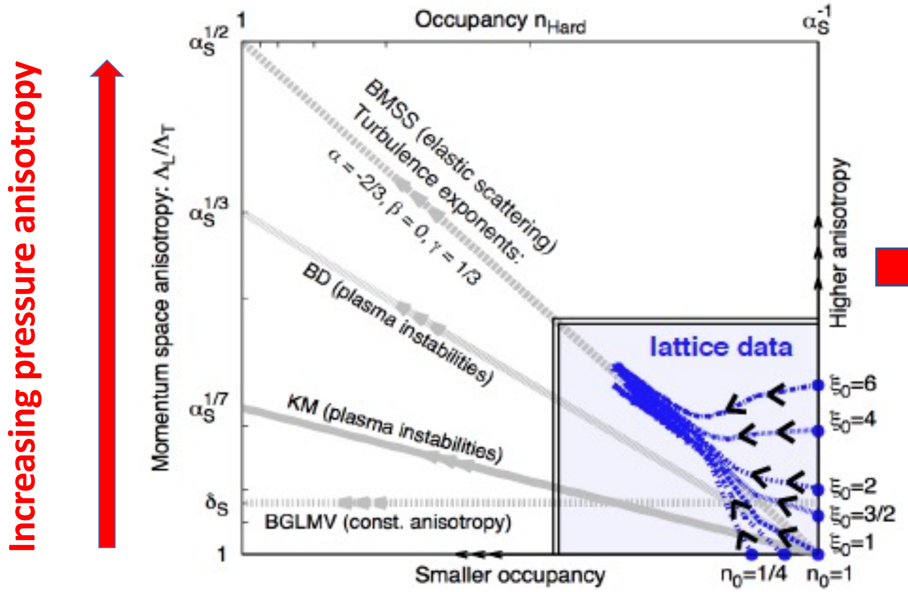
Classical-statistical simulations of 3+1-D Yang-Mills

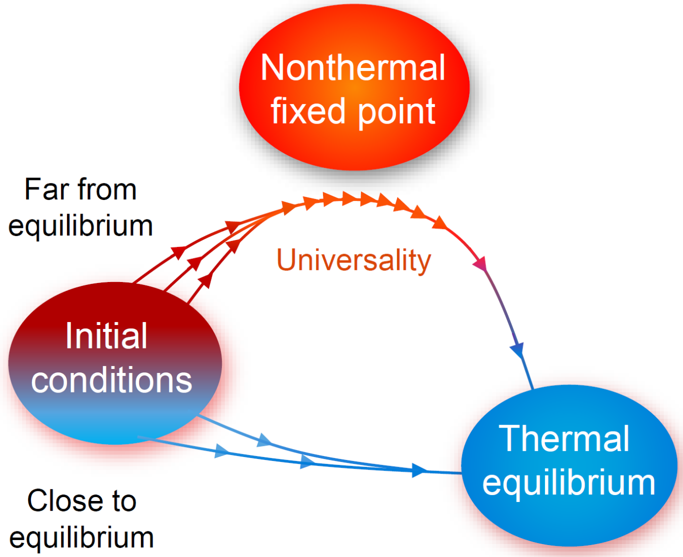


Rapid scrambling of information by quantum fluctuations,
Competition between dilution due to expansion and isotropization due to scattering

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

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

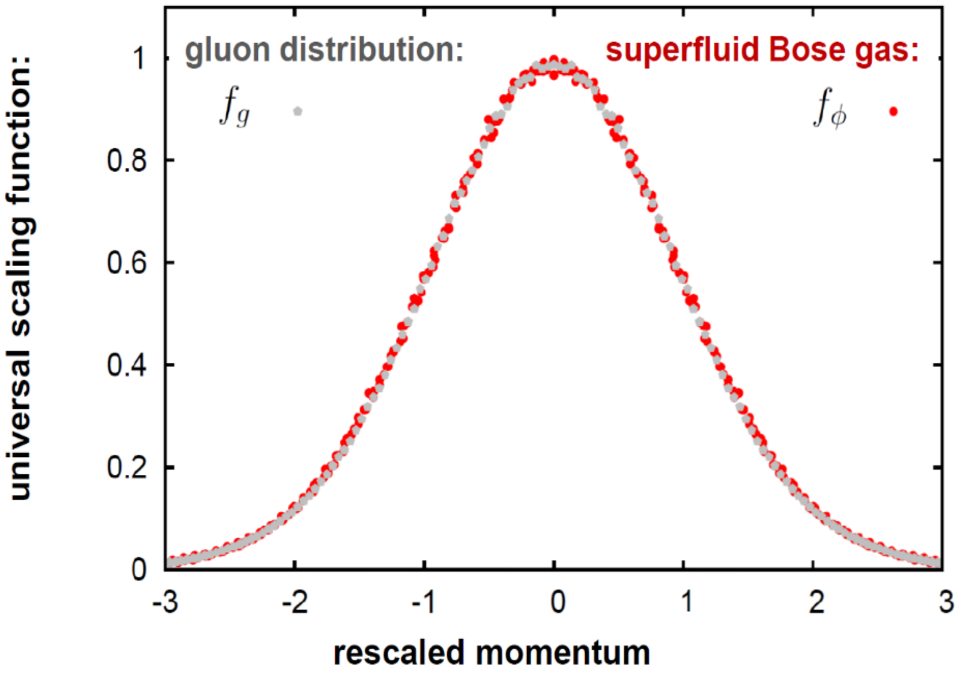




Berges,Boguslavski,Schlichting,RV (2014)

The Glasma and overoccupied ultracold quantum gases

Simulations of self-interacting scalar fields with identical initial conditions demonstrates remarkable *universality of longitudinally expanding world's hottest and coolest fluids*



In a wide inertial range, scalar & gauge fields have identical scaling exponents & functions

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

$$\tau = \sqrt{t^2 - z^2}$$

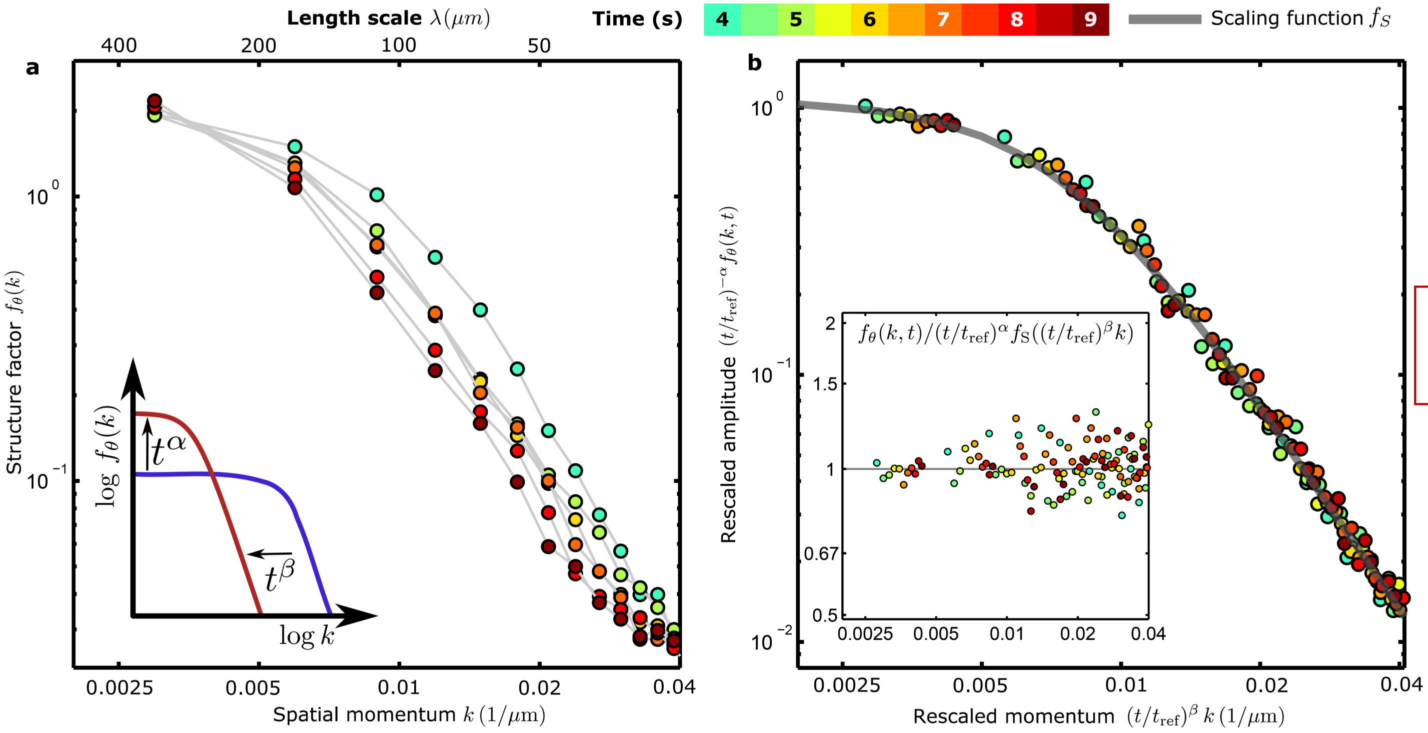
$$\alpha = -\frac{2}{3}, \beta = 0, \gamma = 1/3$$

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

The Glasma and over-occupied quantum gases

Similar non-thermal fixed points discovered in cold atom experiments
- albeit only for static geometry so far

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

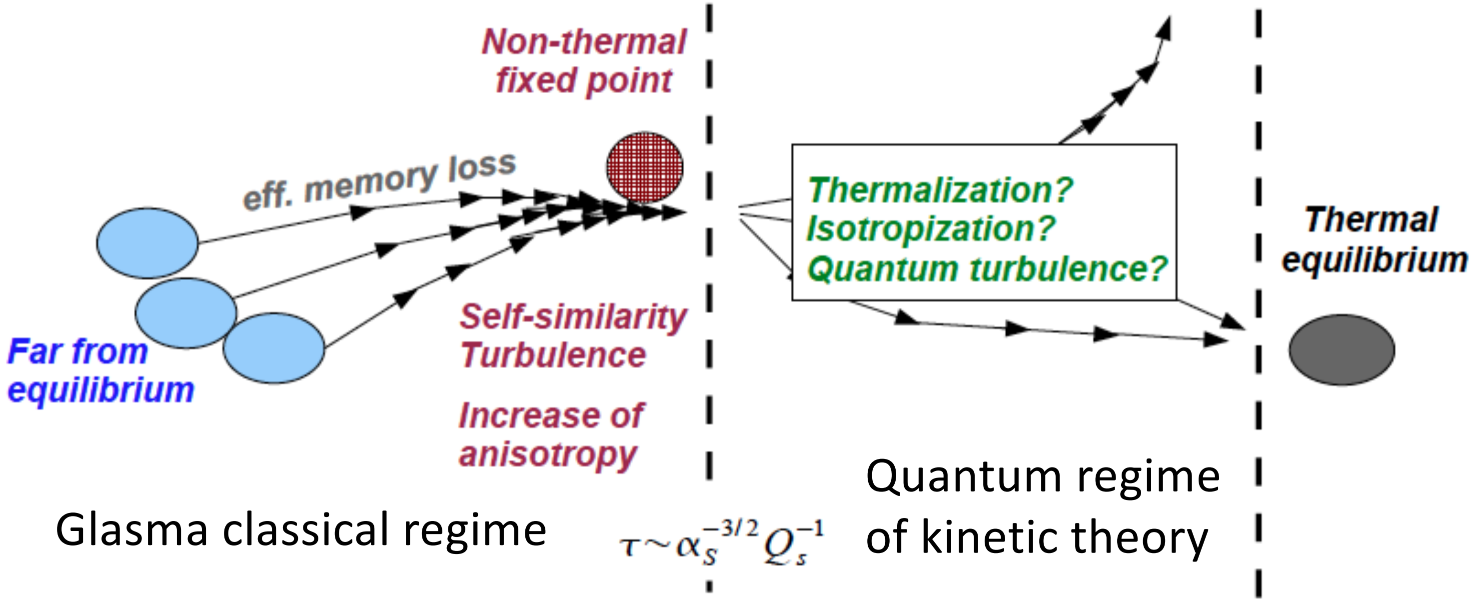


$$f_\theta(k,t) = t^\alpha f_S\left(t^\beta k\right)$$

$\alpha = 0.33 \pm 0.08$ $\beta = 0.54 \pm 0.06$

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

From nuts to soup: bottom-up thermalization



Non-thermal fixed point

eff. memory loss

Far from equilibrium

Self-similarity Turbulence

Increase of anisotropy

Thermalization?
Isotropization?
Quantum turbulence?

Thermal equilibrium

Glasma classical regime

$\tau \sim \alpha_S^{-3/2} Q_s^{-1}$

Quantum regime of kinetic theory

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

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

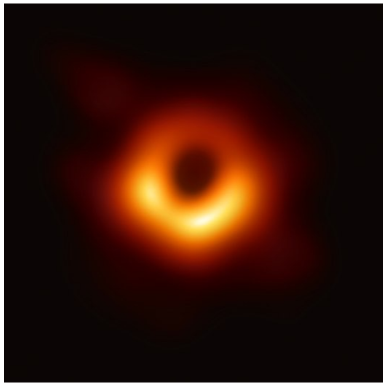
Since $\alpha_S \propto \frac{1}{\log Q_S}$

$\tau_{\text{therm}} \propto \frac{(\log Q_S)}{Q_S} \rightarrow 0$ as $Q_S \rightarrow \infty$

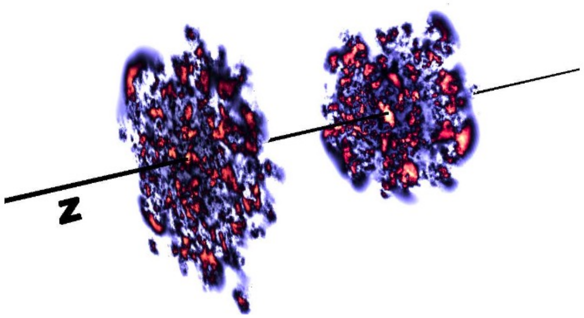
High energy asymptotics:
Matter thermalizes almost instantaneously
even for the smallest systems…

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

Classicalization and unitarization of wee partons in QCD and gravity: The CGC-Black Hole correspondence



10^9 km ↔ 10^{-19} km



Collisions of Color Glass Condensate gluon states in nuclei, arXiv:1206.6805

M_{BH}=(6.5 ± 0.2_{stat} ± 0.7_{sys}) × 10^9 $M_\odot$
at center of Messier 87
Event Horizon Telescope image of photon ring

A QFT picture of Black Holes: overoccupied (N = M_{BH}^2/M_P^2 >> 1, ~ 10^{66} for solar mass BH)
“leaky” bound states of soft gravitons

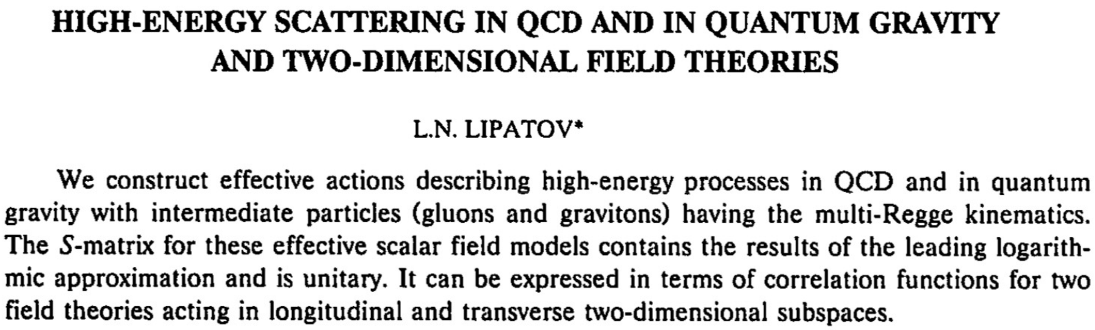
Dvali, Gomez, arXiv:1203.6575, arXiv:1112.3359
Dvali,Guidice,Gomez,Kehagis, arXiv:1010.1415

Conjecture: at a maximal occupancy (α_{grav} N ~ 1)) the physics of saturated gluons and gravitons is universal

Both systems characterized by a saturation scale (Q_S = 1/R_S, Schwarzchild radius) & saturate the Bekenstein entropy bound

Dvali, RV, arXiv:2106.11989

$2 \to N + 2$ amplitudes Trans-Planckian gravitation scattering: from wee partons to Black Holes

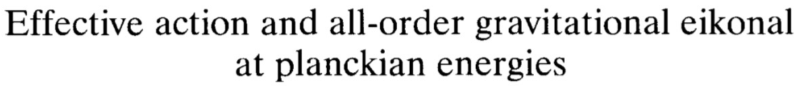


HIGH-ENERGY SCATTERING IN QCD AND IN QUANTUM GRAVITY AND TWO-DIMENSIONAL FIELD THEORIES

L.N. LIPATOV*

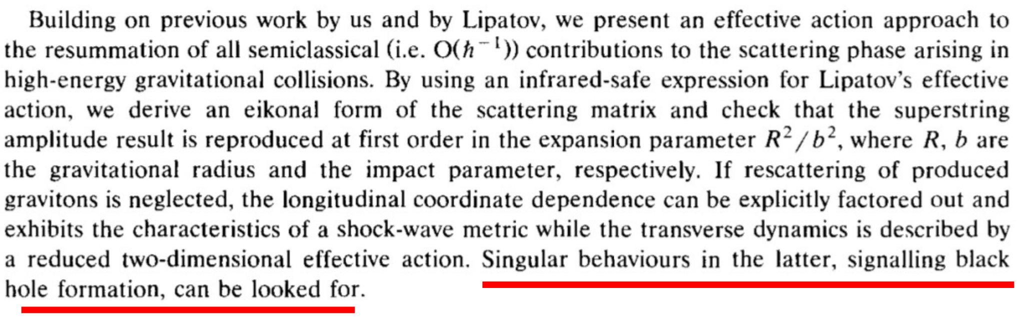
We construct effective actions describing high-energy processes in QCD and in quantum gravity with intermediate particles (gluons and gravitons) having the multi-Regge kinematics. The S-matrix for these effective scalar field models contains the results of the leading logarithmic approximation and is unitary. It can be expressed in terms of correlation functions for two field theories acting in longitudinal and transverse two-dimensional subspaces.

NPB 364 (1991) 614; 161 cites in INSPIRE

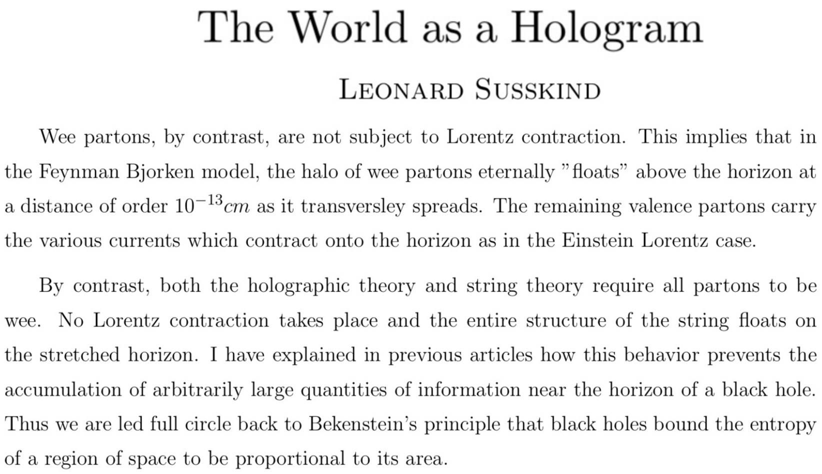


Effective action and all-order gravitational eikonal at planckian energies

AMATI,CIAFALONI,VENEZIANO **NPB403 (1993)707**



Building on previous work by us and by Lipatov, we present an effective action approach to the resummation of all semiclassical (i.e. $O(\hbar^{-1})$) contributions to the scattering phase arising in high-energy gravitational collisions. By using an infrared-safe expression for Lipatov's effective action, we derive an eikonal form of the scattering matrix and check that the superstring amplitude result is reproduced at first order in the expansion parameter R^2/b^2, where R, b are the gravitational radius and the impact parameter, respectively. If rescattering of produced gravitons is neglected, the longitudinal coordinate dependence can be explicitly factored out and exhibits the characteristics of a shock-wave metric while the transverse dynamics is described by a reduced two-dimensional effective action. Singular behaviours in the latter, signalling black hole formation, can be looked for.



The World as a Hologram

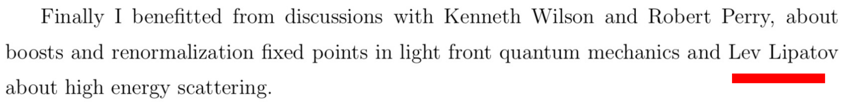
LEONARD SUSSKIND

Wee partons, by contrast, are not subject to Lorentz contraction. This implies that in the Feynman Bjorken model, the halo of wee partons eternally "floats" above the horizon at a distance of order $10^{-13}cm$ as it transversley spreads. The remaining valence partons carry the various currents which contract onto the horizon as in the Einstein Lorentz case.

By contrast, both the holographic theory and string theory require all partons to be wee. No Lorentz contraction takes place and the entire structure of the string floats on the stretched horizon. I have explained in previous articles how this behavior prevents the accumulation of arbitrarily large quantities of information near the horizon of a black hole. Thus we are led full circle back to Bekenstein's principle that black holes bound the entropy of a region of space to be proportional to its area.

***J.Math.Phys.* 36 (1995) 6377; 3242 cites**

In Acknowledgements:



Finally I benefitted from discussions with Kenneth Wilson and Robert Perry, about boosts and renormalization fixed points in light front quantum mechanics and Lev Lipatov about high energy scattering.

These works do not explicitly discuss parton saturation which strongly informs our perspective

Gravity amplitudes as double copies of QCD amplitudes

$$\begin{tikzcd}
\text{CGC} & \text{QCD at high occupancy} \arrow[d, "\text{classical double copy}"'] & \text{perturbative QCD} \arrow[l, "A"'] \arrow[d, "\text{BCJ double copy}"] \\
\text{Black Hole} & \text{Gravity at high occupancy} & \text{perturbative gravity} \arrow[l, "B"]
\end{tikzcd}$$

Remarkable development: Gravity amplitudes as “squares” of QCD amplitudes (color-kinematic duality)
Inspiral Hamiltonian of binary gravitational wave sources computed to O(G^4) and all orders in relative velocity

Bern et al., arXiv:2101.07254

BCJ double copy
Bern, Carrasco, Johansson, arXiv: arXiv:1004.0476
Classical double copy
Goldberger, Ridgeway, arXiv:1611.03493

Can one construct a quantitative double copy (from IR to UV) in gravity
in the strong field (weak coupling) regime
- analogous to the RG equations in the CGC (going from UV to IR)
– performing small fluctuations around the shockwave metric

H.Raj, RV, in progress

Thank you for your attention !

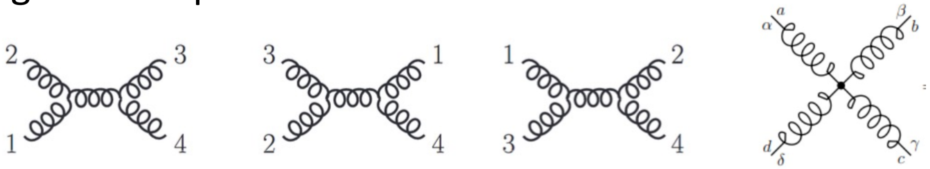
Gauge-Gravity correspondence

Double copy between QCD and Gravity amplitudes

Old idea (Kawai-Lewellyn-Tye) based on relations between closed and open string amplitudes – in "low energy” limit between Einstein & Yang-Mills amplitudes

$$M_4^{\text{tree}}(1,2,3,4) = \left(\frac{\kappa}{2}\right)^2 s\, A_4^{\text{tree}}(1,2,3,4)\, A_4^{\text{tree}}(1,2,4,3)$$

$$\kappa = 32\,\pi^2\, G_N$$



Remarkable “BCJ” color-kinematics duality

Bern, Carrasco,Johansson,arXiv:0805.3993

Tree level $gg \to gg$ amplitudes (with on shell legs) can be written as

$$iA_4^{\text{tree}} = g^2 \left(\frac{n_s c_s}{s} + \frac{n_t c_t}{t} + \frac{n_u c_u}{u}\right)$$

with the s channel color factor $c_s = -2 f^{a_1 a_2 b} f^{b a_3 a_4}$

kinematic factor $n_s = -\frac{1}{2}\Big\{\Big[(\epsilon_1.\epsilon_2)p_1^\mu + 2(\epsilon_1.p_2)\epsilon_2^\mu - (1 \leftrightarrow 2)\Big]\Big[(\epsilon_3.\epsilon_4)p_3^\mu + 2(\epsilon_3.p_4)\epsilon_4^\mu - (3 \leftrightarrow 4)\Big] + s\Big[(\epsilon_1.\epsilon_3)(\epsilon_2.\epsilon_4) - (\epsilon_1.\epsilon_4)(\epsilon_2.\epsilon_3)\Big]\Big\}$

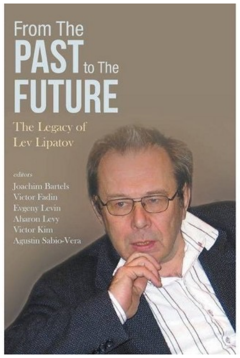
Tree level gravity amplitude obtained fron replacing color factors by kinematic factors

$$i\mathcal{A}_4^{\text{tree}}|_{c_i \to n_i, g \to \kappa/2} = i\mathcal{M}_4^{\text{tree}} = \left(\frac{\kappa}{2}\right)^2 \left(\frac{n_s^2}{s} + \frac{n_t^2}{t} + \frac{n_u^2}{u}\right)$$

Significant on-going work on extension to loop amplitudes

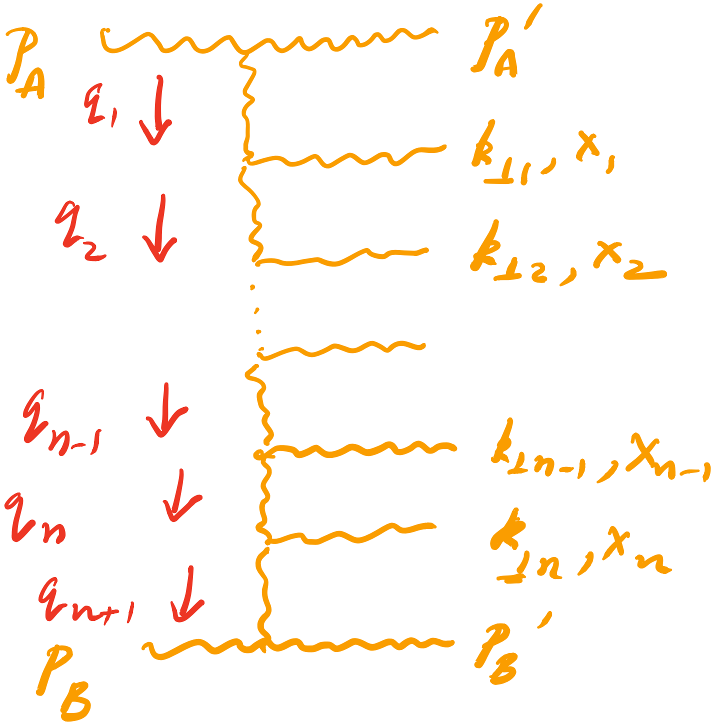
Review: Bern et al., arXiv: 1909.01358

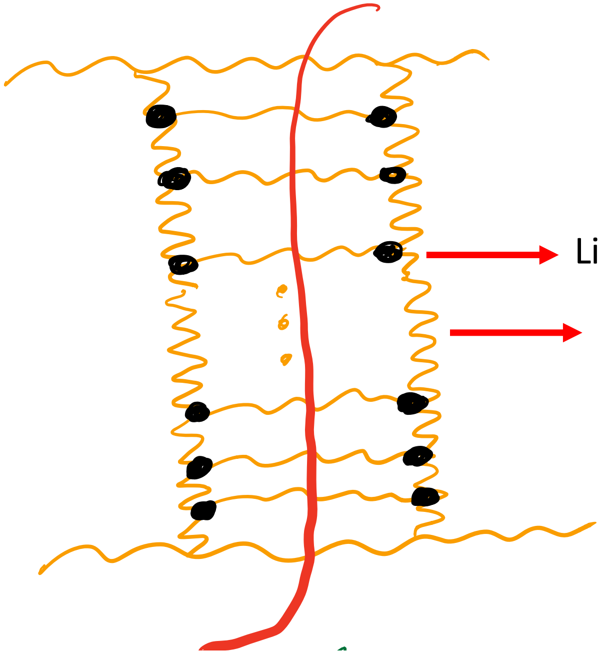
Lipatov’s EFT for wee partons in QCD and gravity



$2 \rightarrow \mathrm{N} + 2$ amplitude in the Regge (high energy) limit of QCD and gravity

Powerful double copy was discovered by Lipatov in high energy (Regge) asymptotics 40 years ago





Lipatov vertex

Reggeized gluon

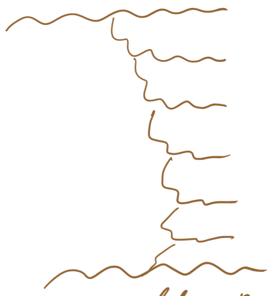
BFKL Pomeron in QCD
(derived simply in the CGC EFT)

2 → N + 2 amplitudes in the Regge limit of gravity

Double copy between QCD and Gravity amplitudes in Regge asymptotics

Lipatov, PLB 116B (1982) 411

High energy scattering of Gravitons



Same multi-Regge kinematics as previously

$$\mathcal{M}_n \simeq -s^2\,\mathcal{C}(2;3)\frac{-1}{|q_4^\perp|^2}\mathcal{V}(q_4;4;q_5)\cdots\frac{-1}{|q_{n-1}^\perp|^2}\mathcal{V}(q_{n-1};n-1;q_n)\frac{-1}{|q_n^\perp|^2}\mathcal{C}(1;n)$$

Gravitational effective vertex: $\mathcal{V}(q_i, i, q_{i+1}) = \Gamma_{i,\mu\nu}(q_i, q_{i+1})\,\epsilon_i^{\mu\nu}(k_i)$

is the double copy $\Gamma_i^{\mu\nu}(q_i, q_{i+1}) \equiv 2\left(C_i^\mu C_i^\nu - N_i^\mu N_i^\nu\right)$

Lipatov Vertex **QED Bremsstrahlung vertex**

The C(2;3) and C(1;n) are gravitational “impact factors” that can also be expressed as a double copy of Lipatov’s gluon-gluon-reggeized gluon vertex

Graviton reggeization was also shown in Lipatov’s 1981 paper with Regge trajectory: **$j(q^2) \approx 2 + q^2 \,\mathrm{Ln}(q^2)$**

Following Lipatov, large body of work by Amati, Ciafaloni, Veneziano, and collaborators; also interesting work in AdS/CFT by Strassler and Polchinski

Black Holes "demystified": The Black Hole N Portrait

Dvali, Gomez, arXiv:1203.6575
Dvali, Gomez, arXiv:1112.3359
Dvali,Guidice,Gomez,Kehagis, arXiv:1010.1415

Classical description: Macroscopic objects in GR with geometric, thermodynamic properties

QFT understanding in the BHNP: Black Holes are highly occupied
($N = M_{BH}^2/M_P^2 >> 1$, ~ 10^{66} for solar mass BH) "leaky" bound states of soft gravitons

$$L_P^2 = \hbar\, G$$

$$M_P^2 = \frac{\hbar}{G}$$

Semi-classical limit: $N \rightarrow \infty$, $L_P \rightarrow 0$, Schwarzchild radius $R_S = 2\, G\, MBH = L_P\sqrt{N}$ = finite, $\hbar$ = finite

Event horizon, BH thermodynamics, no-hair theorem, understood simply in this limit

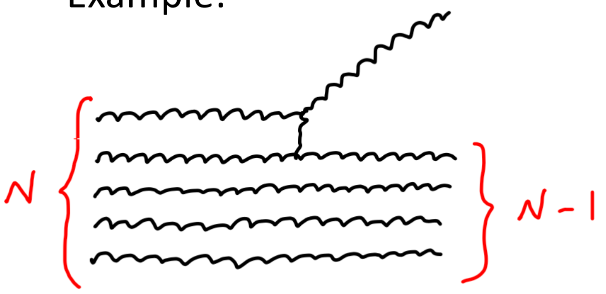
Hawking Temperature

$$T_H = \frac{\hbar}{R_S} = \frac{\hbar}{L_P\sqrt{N}}$$

Black Hole evaporation Rate

$$\Gamma = \sigma n_h (1+N) \sim \cancel{\alpha_{gr}^2} R_S^2 \frac{\cancel{N^2}}{R_S^3} \equiv \frac{1}{R_S}$$

Example:

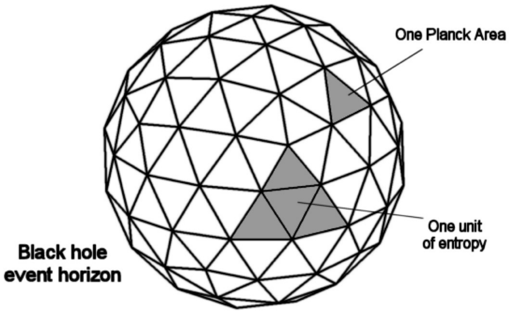


Rate can be equivalently be written as $\frac{dM}{dt} = -\frac{T_H^2}{\hbar^2}$

With Black Hole half life $t_{BH} = \frac{\hbar^2}{T_H{}^3\, G} = N^{3/2}\, L_P$

Black Hole N Portrait and entropy bound

Bekenstein-Hawking bound



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

The Bekenstein entropy bound is given by $S \leq 2\pi E R/\hbar$

In the Black Hole N portrait, this is given by $S \leq 2\pi\ N\ QS\ RS$
which is saturated when $N = \frac{1}{\alpha_{gr}} \rightarrow S_{Bek} = \frac{1}{\alpha_{gr}}$ consistent with unitarity

Here E = N Q_S is the energy in a critically packed volume = R_S^3 of quanta saturating unitarity (maximal information) and Q_S=1/R_S

$$S_{Bek} = \frac{1}{\alpha_{gr}} = \frac{R_S^2}{L_P^2} = \frac{Area}{4G} = S_{BH}$$

The entropy can also be expressed in terms of a Goldstone decay constant corresponding to spontaneous breaking of Poincare invariance by the graviton condensate:
Decay constant of Goldstone field $\phi\ is\ f = R\ \partial_x \phi = \sqrt{N}/R$; In gravity, this is nothing but M_P

Hence one can equivalently express the entropy as $S_{BH} = Area \times f^2$

Dvali, arXiv:1907.07332

Bekenstein entropy of the CGC

Since both BHNP and the CGC are macrostate “lumps” that saturate unitarity at $\alpha\, N = 1$, we conjecture that

$$S_{\mathrm{CGC}} = \frac{1}{\alpha_S} = N = f^2 * \mathrm{Area}$$

If $f = \sqrt{N}\, Q_S$

Physical interpretation of f in this picture is the scale denoting the onset of shadowing
Above this scale one has unscreened partons…

Since at small x, $\alpha_S \mathrm{Y} \sim 1$, $\frac{\mathrm{dS_{CGC}}}{\mathrm{dY}} = \mathrm{constant}$

Consistent with the estimate of Kharzeev and Levin

arXiv:1702.03489

The Goldstone scale that we have postulated is identical to that found by Duan, Skokov and Kovner by explicit computation of the CGC reduced density matrix…!

arXiv:2111.06475

Their massless quasi-particles (with creation (annihilation) operators $c^\dagger$ (c) are our Goldstones and are related to those of the perturbative vacuum by a simple Bogoliubov transformation

Conjecture: CGC/BHNP correspondence

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

We begin to glimpse the elements of the CGC/BHNP correspondence
for a region of space R_S= $Q_S^{-1}$of the CGC mapped on to a Black Hole of analogous radius determined by the saturation of the graviton condensate:

The scale at which this occurs is a weak coupling scale in both theories:

for BHNP, $Q_S^{-1} \gg M_P^{-1}$
for CGC, $Q_S \gg \Lambda_{QCD}$

This scale is determined by a maximal occupancy of $\mathrm{N} = \frac{1}{\alpha}$ where (perturbative) unitarization occurs

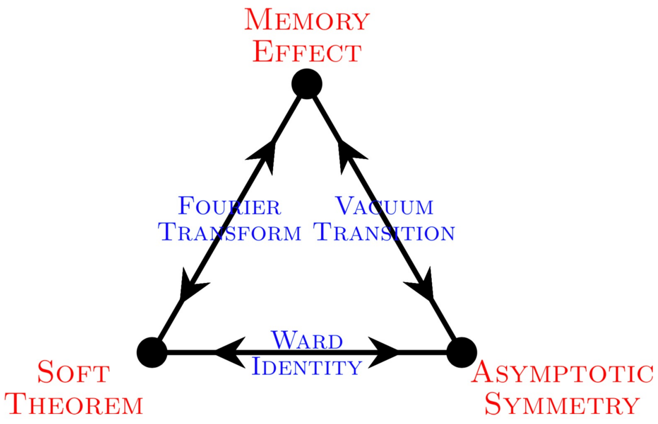
The direct correspondence between the two theories only occurs at Q=Q_S
where the physics is universal- It is independent of the details of the dynamics of the wee partons

The existence of a double copy between the two theories is however suggestive that it can be extended to a "classical" double copy between gluon and graviton classical shockwaves

Review on classical double copy: C. White, arXiv:1708.07056

Open questions II. S-matrix symmetries

Can one formulate the Goldstone description of the CGC in the language of asymptotic (“BMS”) spacetime symmetries ?



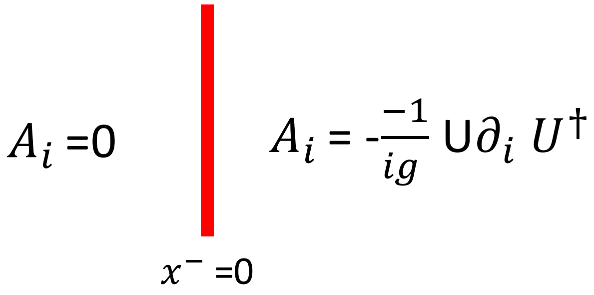
Recent developments in understanding soft theorems in terms of broken global symmetries on a 2-D celestial sphere at null infinity

Strominger,arXiv:1703.05448

Soft photons, gravitons, gluons (?) can be interpreted as the corresponding Goldstone modes

In Yang-Mills, as in gravity, there is a color memory effect analogous to gravitational memory

Pate, Raclariu, Strominger, PRL (2017)



$A_i = 0$

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

$x^- = 0$

This is the Q_S kick experienced by a probe across the shock wave

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

This suggests that the soft gluons in the shockwave are Goldstones of the broken global BMS symmetry with associated BMS charges that satisfy a 2-D Kac-Moody algebra

He,Mitra,Strominger (2015)