Initial conditions for heavy-ion collisions

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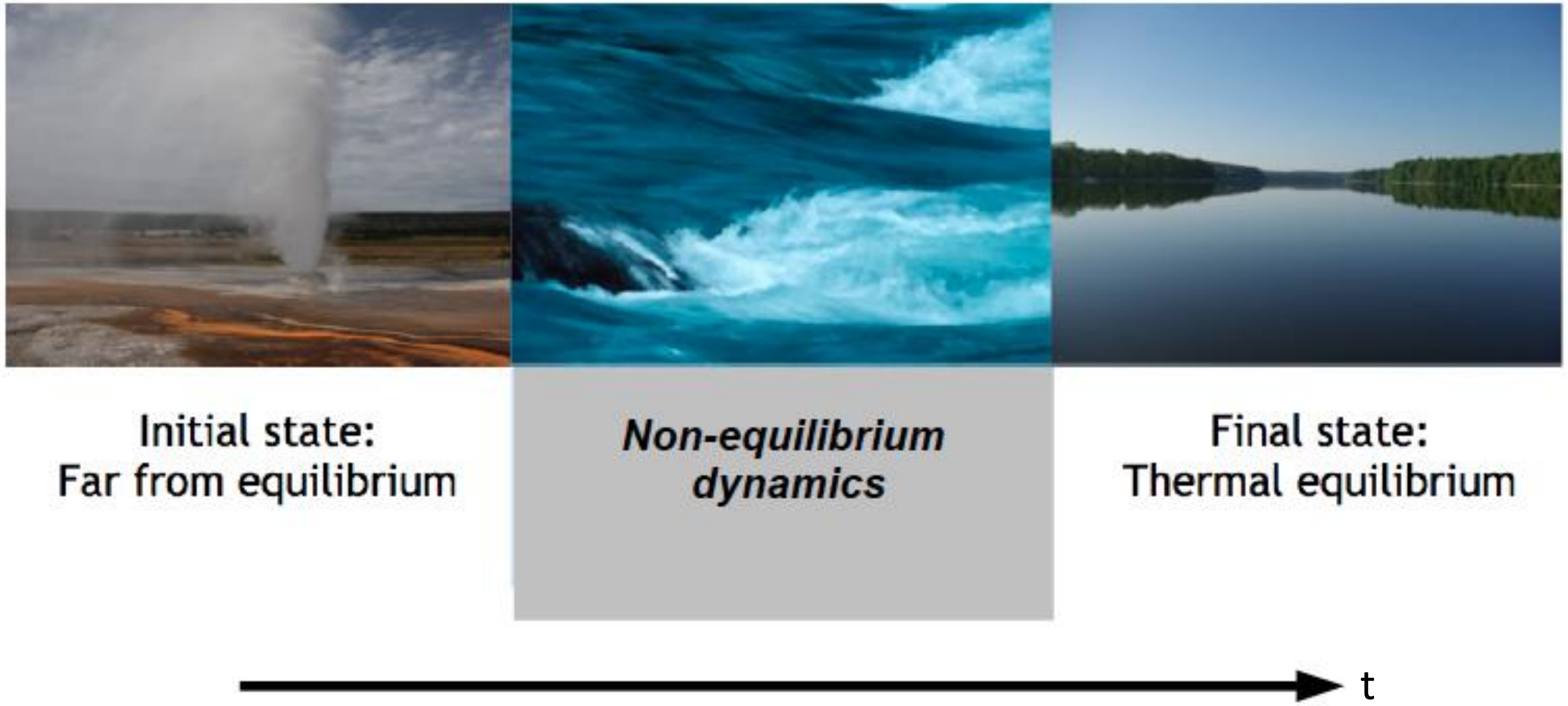
Brookhaven National Laboratory

Student Day Lecture, Quark Matter 2019, Wuhan

From the violence of a nuclear collision
...to the calm of a quark-gluon fluid



How is thermalization achieved in QCD ?

Approaches to thermalization

Two "clean" theoretical limits:

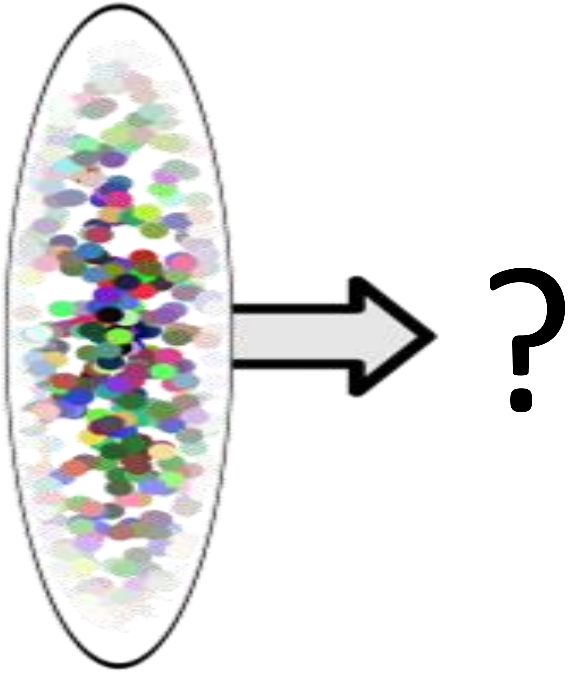
- Holographic thermalization (based on duality of strongly coupled ($g^2 N_c \to \infty,\ N_c \to \infty$) N=4 SUSY YM to classical gravity in $AdS_5 \times S_5$)

  The AdS/CFT correspondence provides valuable insight into universal features of non-equilibrium dynamics in QCD. Examples: transport coefficients and hydrodynamization

- Highly occupied (occupancy f >> 1) QCD at weak coupling ($g^2 \to 0,\ g^2\, \mathrm{f} \sim 1$)

Our focus: $\boxed{\text{non-equilibrium strongly correlated QCD at weak coupling}}$

The nuclear wavefunction at high energies

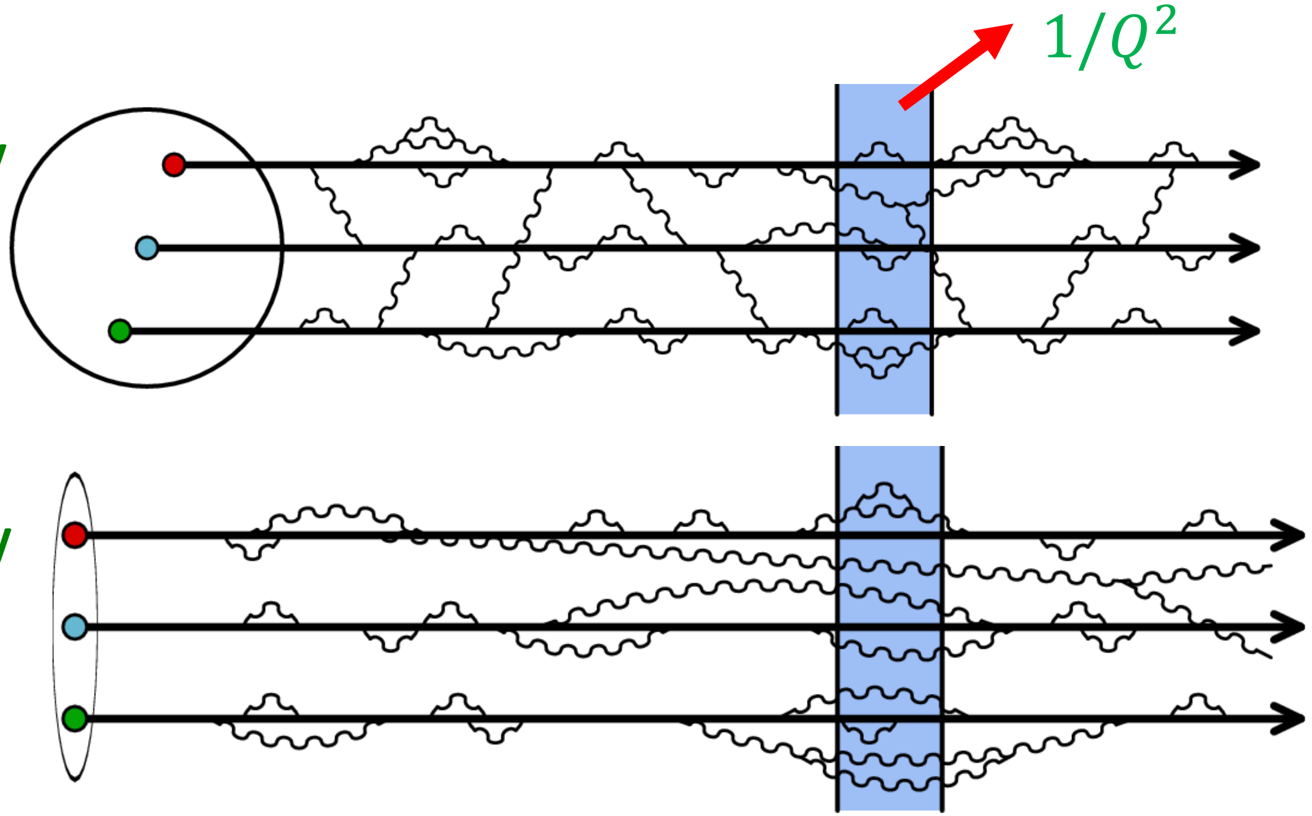


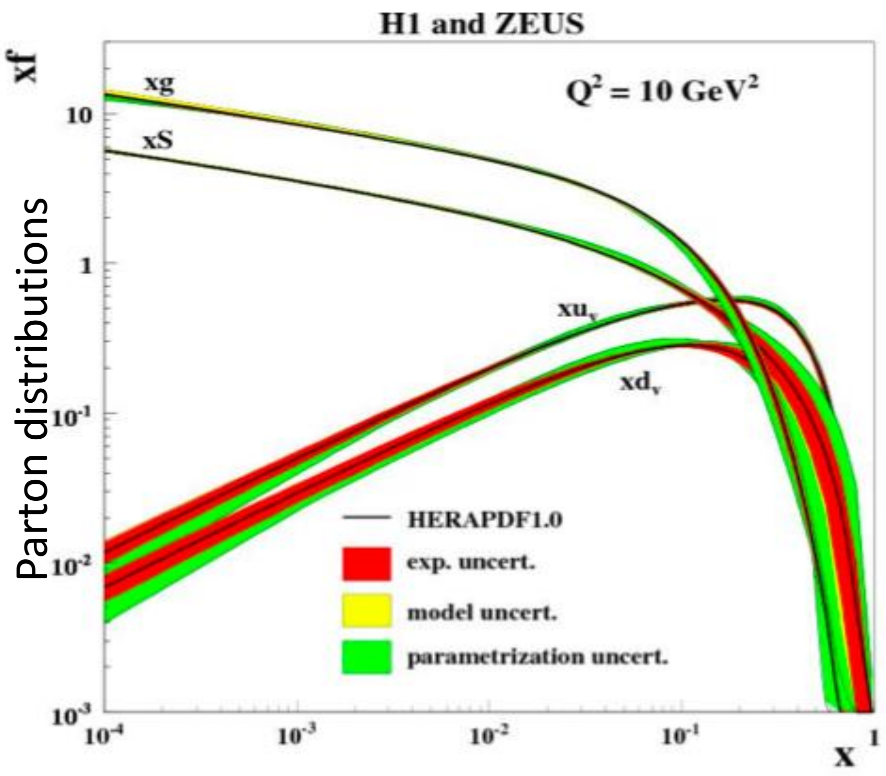
What happens when you boost a proton or nucleus to high energies ?

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

Low Energy
or
large x

High Energy
or
small x





As the proton is boosted, "parton" fluctuations live longer and longer, manifesting themselves as bremsstrahlung in scattering

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 $\alpha_S\, Ln\,(Q^2/\Lambda^2_{QCD}) \sim 1$

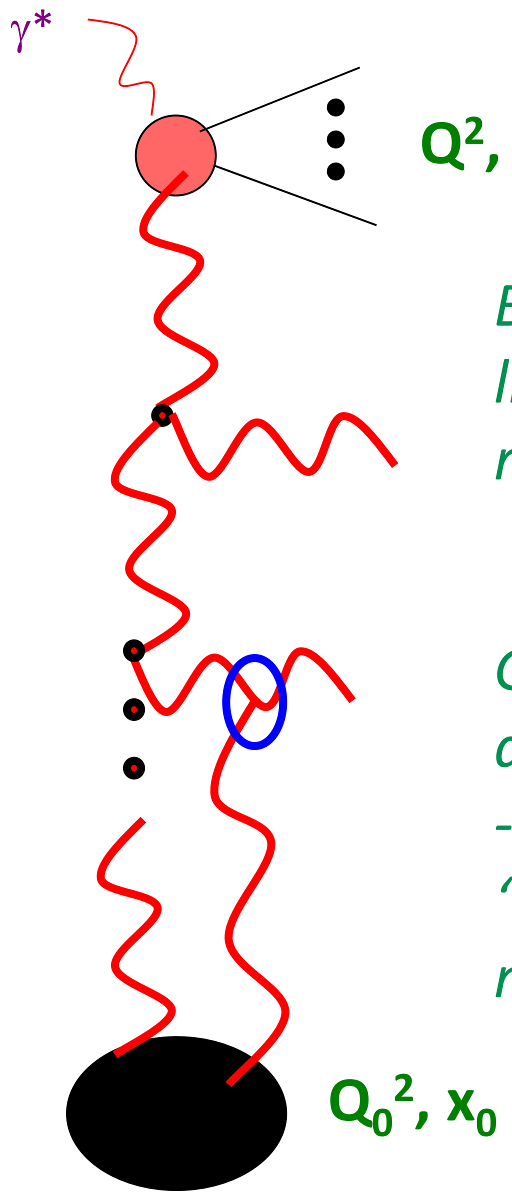
Appropriate limit for multi-particle production:

Regge limit of QCD

$s \to \infty, Q^2 = \text{fixed} \gg \Lambda^2_{QCD}\quad \text{x} \to 0$

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

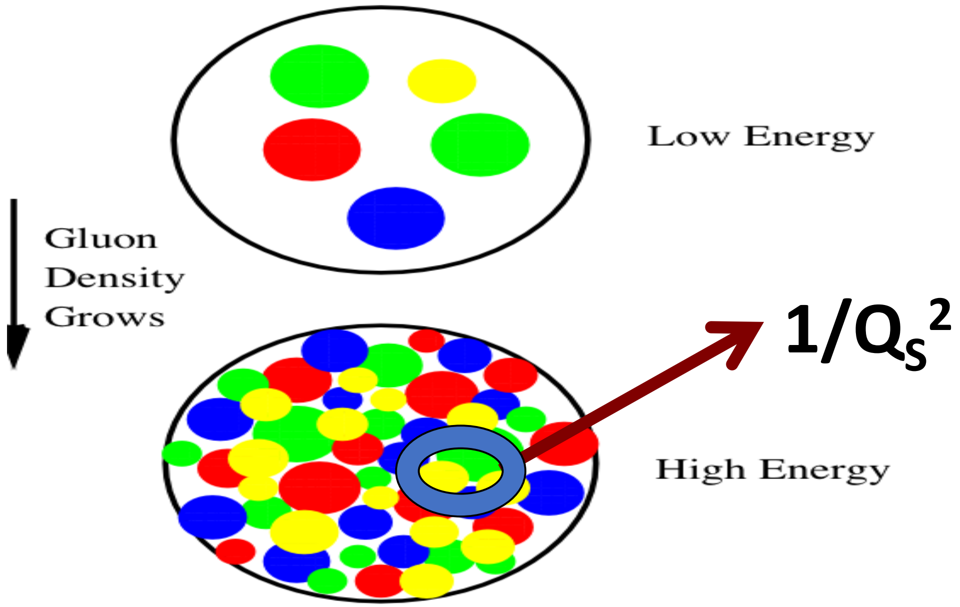
F. Wilczek, Nature (1999)



Bremsstrahlung linear BFKL evolution resums large logs in x

Gluon recombination and screening -- "all twist" or "death by a million cuts" non-linear QCD evolution

Gluon saturation



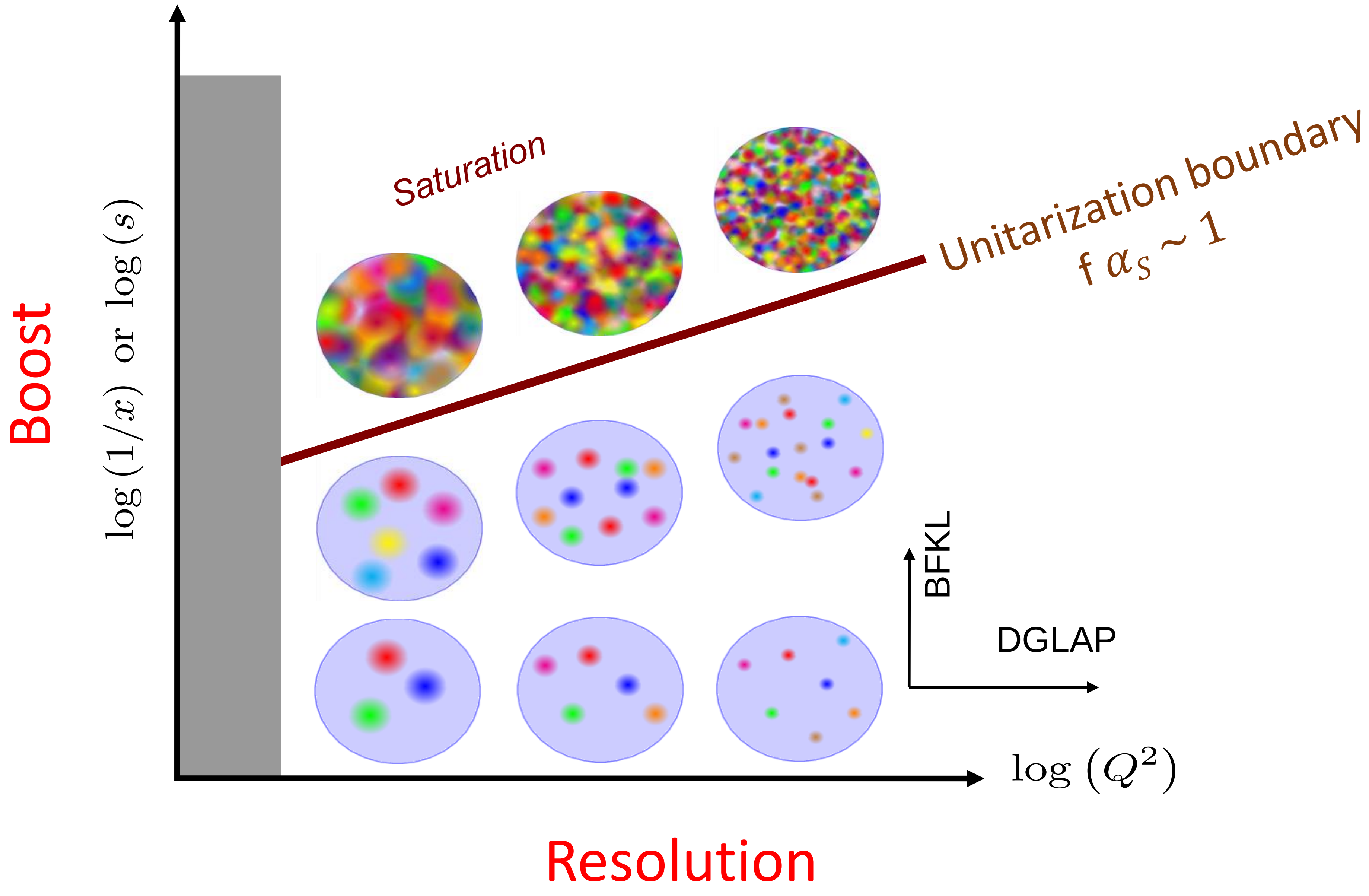
Gribov,Levin,Ryskin (1983)
Mueller, Qiu (1986)

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 $Q_S(x) >> \Lambda_{QCD}$

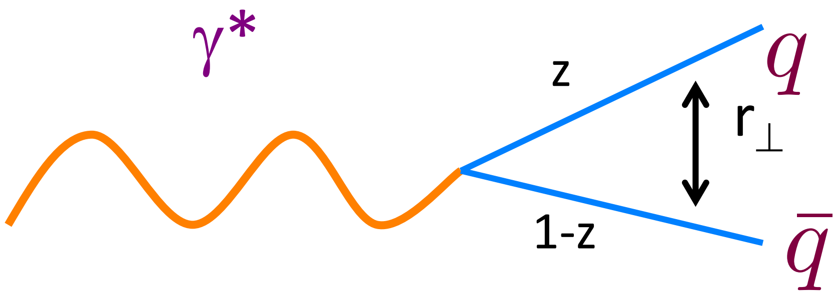
Asymptotic freedom! $\alpha_S(Q_S) << 1$ *provides weak coupling window into infrared*

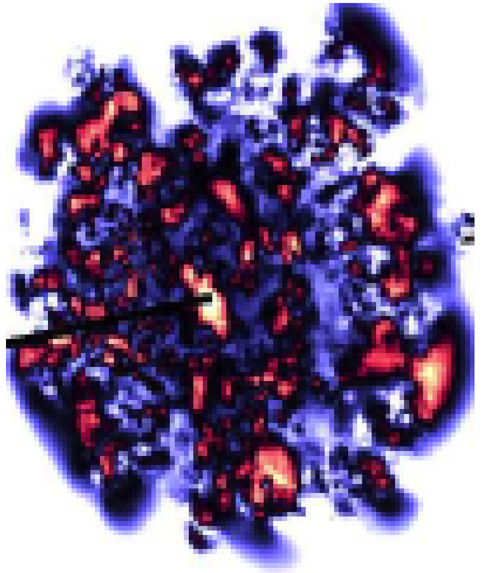
Gluon saturation



Saturation: dipole model formulation in DIS

Equivalent formulation:
Strong screening of color charge of a quark-antiquark dipole





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

QED QCD

Golec-Biernat Wusthoff model

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

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

Parameters:
Q_0 = 1 GeV; λ = 0.3;
$x_0 = 3 * 10^{-4}$; σ_0 = 23 mb

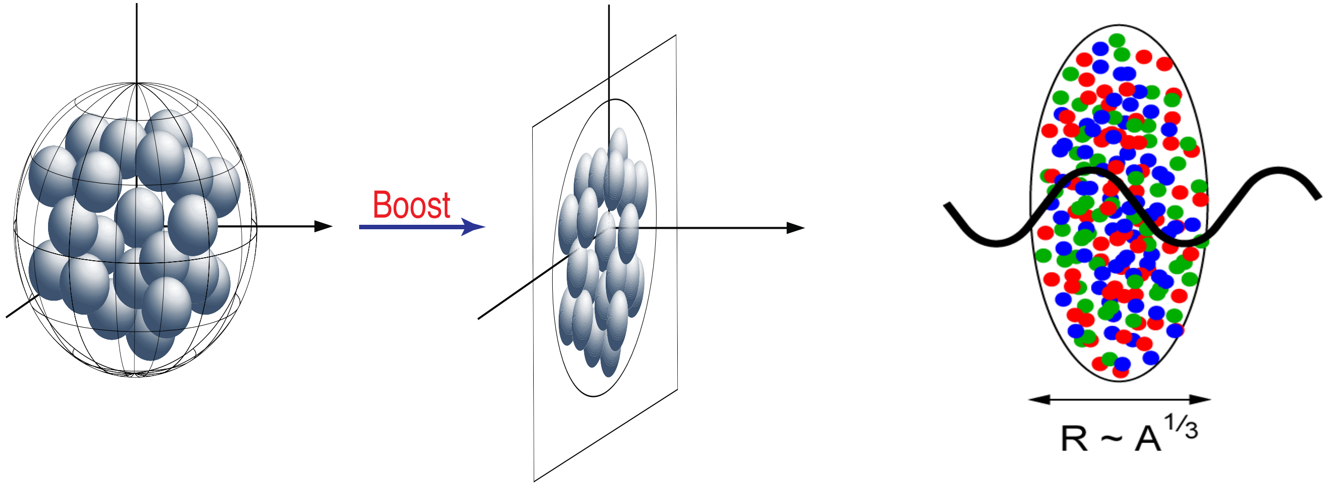
Color transparency for $r_\perp^2 Q_S^2$ << 1 ($\sigma \propto A$)

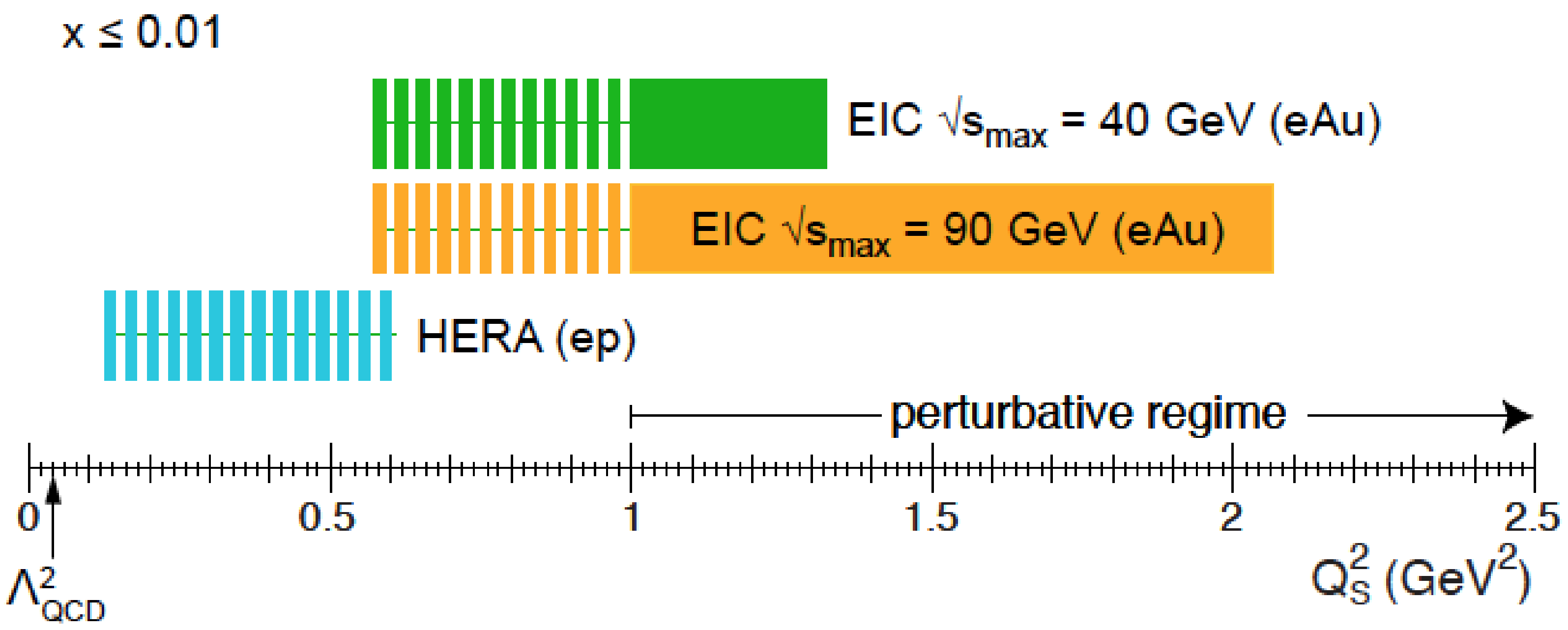
Color opacity ("black disk") for $r_\perp^2 Q_S^2$ >> 1 ($\sigma \propto A^{2/3}$)

QCD picture of "shadowing"…

Nuclear "oomph" of the saturation scale

Dipole couples coherently with color charges in different nucleons in path of its scattering: $Q_S^2 \sim A^{1/3}$





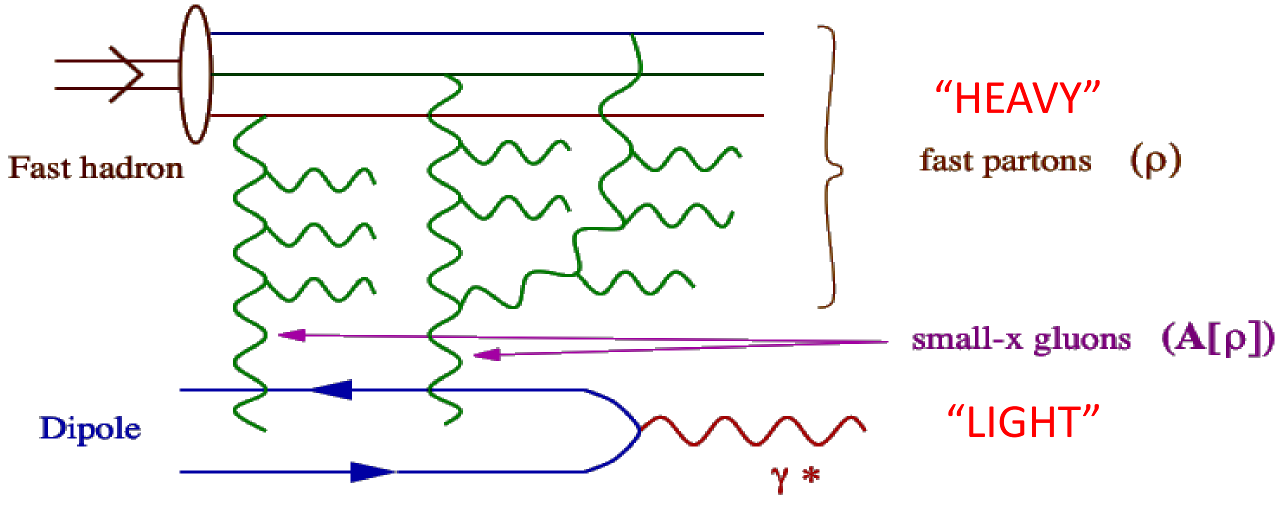
EIC: Electron-Ion Collider

Aschenauer et al., arXiv:1708.01527

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

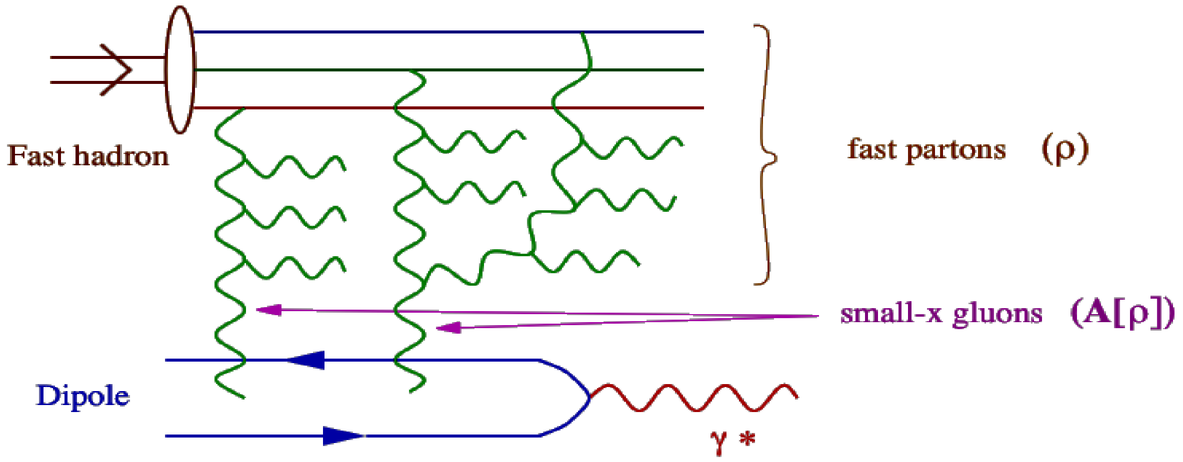


Remarkably, physics of extreme quantum fluctuations
becomes classical because of high gluon occupancy…

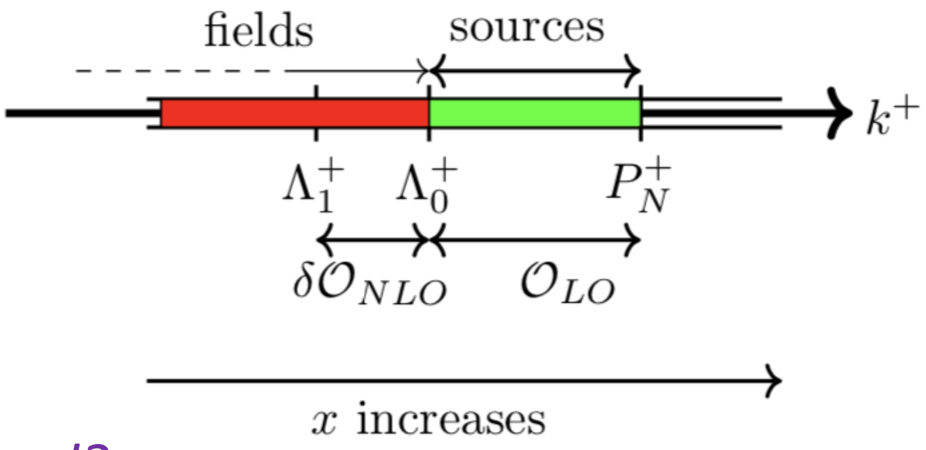
McLerran, RV (1994)

Classicalization in the Regge limit: the Color Glass Condensate EFT

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



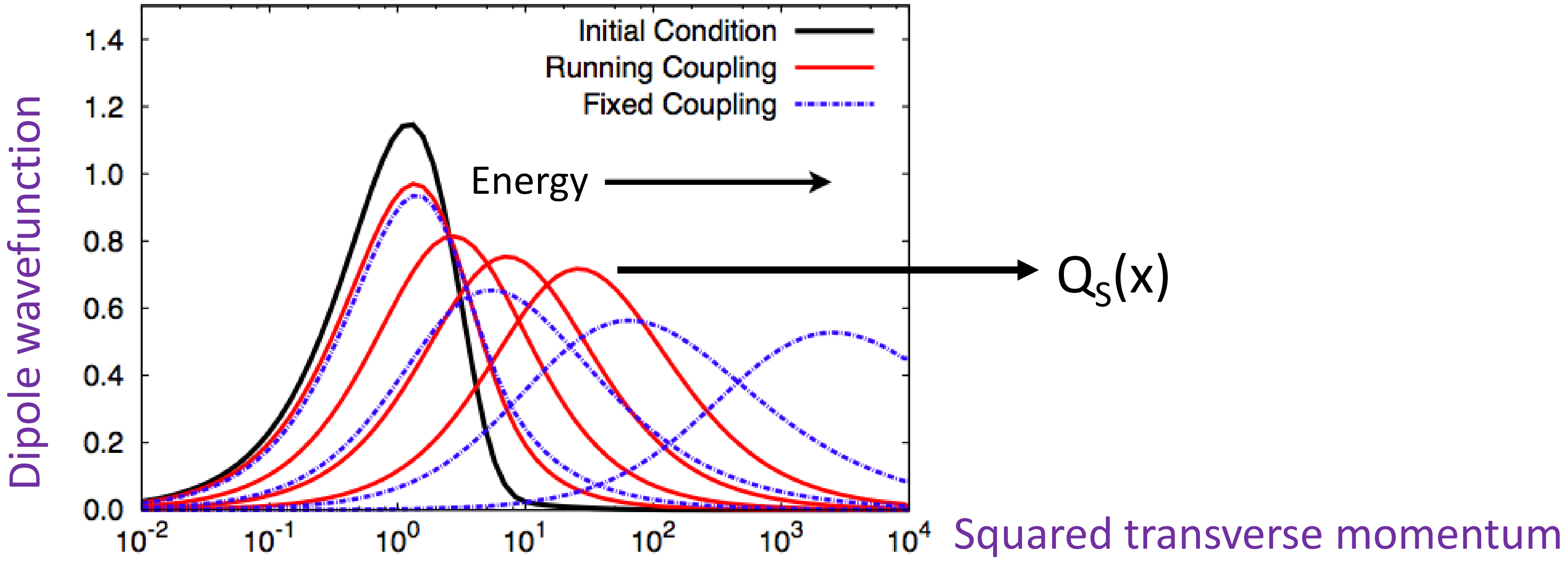
Wilsonian RG :
2+1-D B-JIMWLK hierarchy of equations for
multi-point ”Wilson line” dipole, quadrupole, etc.
correlators -- right degrees of freedom



Universal infrared classical dynamics of QCD in the infrared?

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

Classicalization in the Regge limit: the Color Glass Condensate EFT



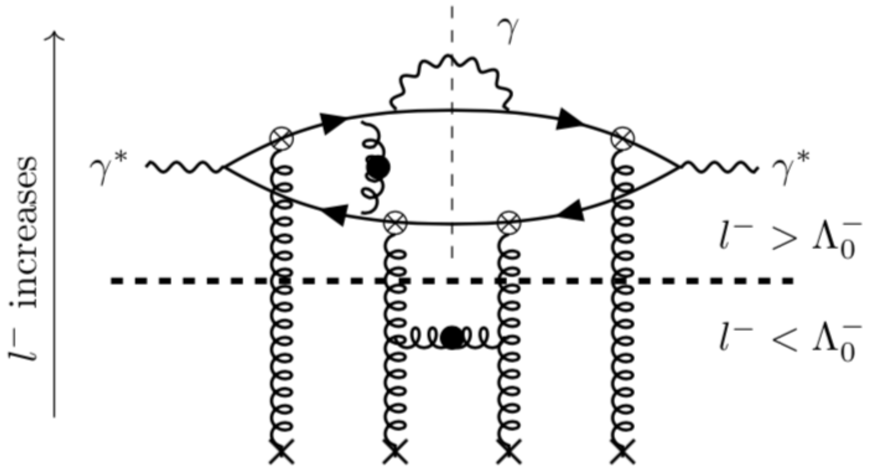
A closed form non-linear (Balitsky-Kovchegov) equation describes how $q\bar{q}$ "dipole" probe evolves with energy – *provides clean demonstration of unitarization in strong fields*

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)

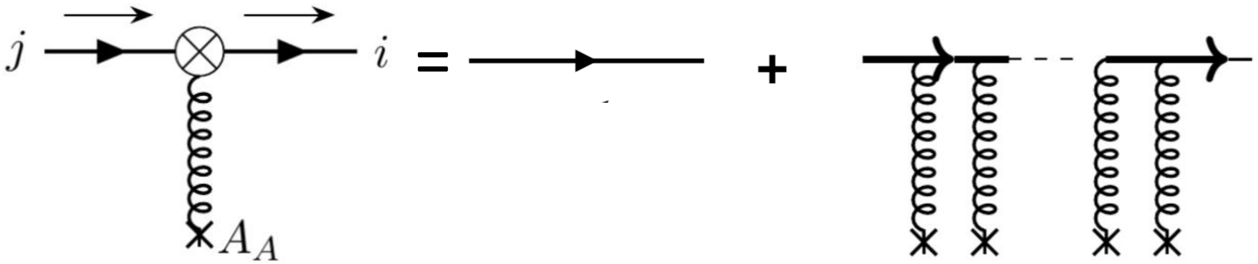
* small caveat

Photons and di-jets to NLO+NLLx precision in the CGC EFT



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

Roy, RV, 1802.09550, and in preparation



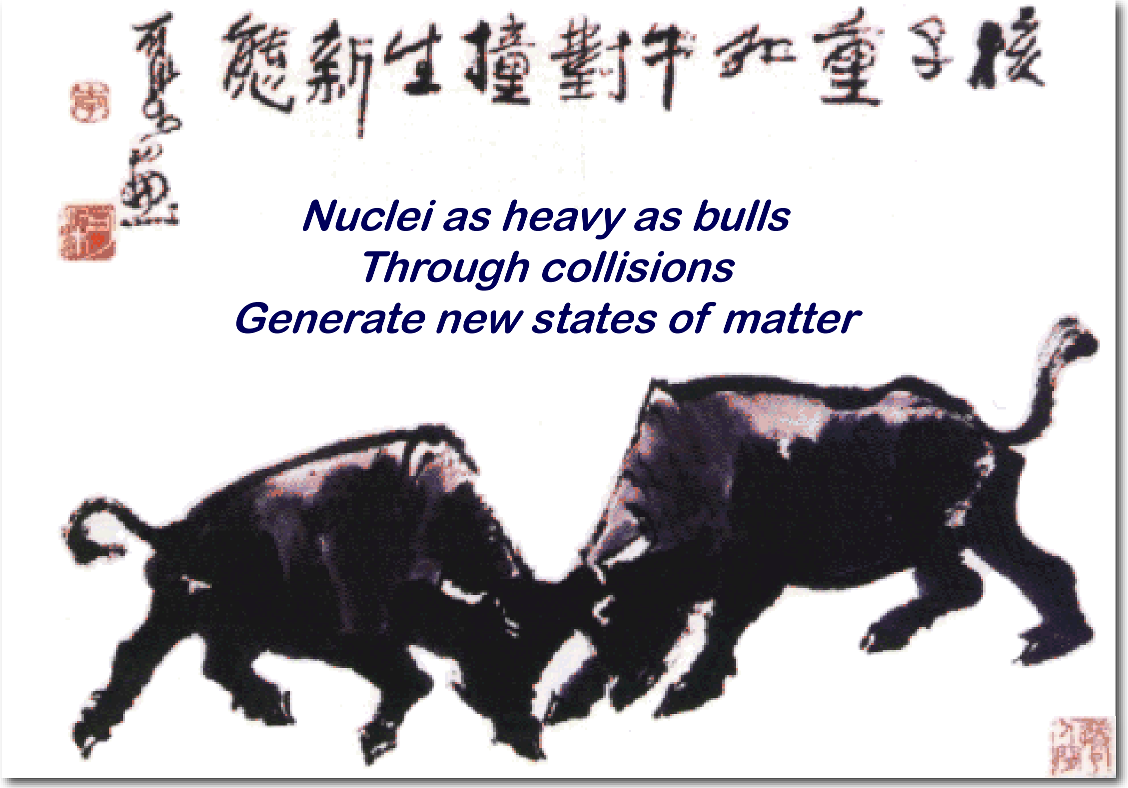
Effective vertices include "all-twist" corrections $(Q_S^2/Q^2)^n$

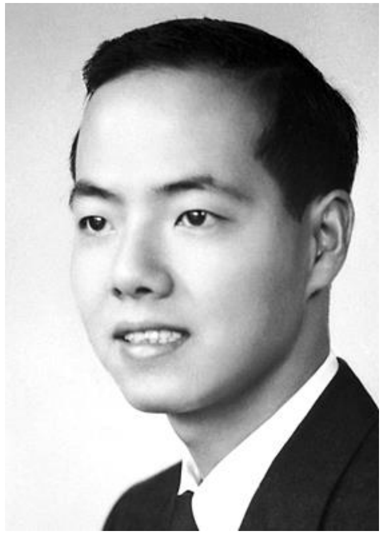
Virtual photon fluctuates into quark-antiquark dipole and a photon state that scatters off a *gluon shockwave* fluctuation of nuclear target

Differential DIS computations in the CGC EFT now available to O(α_S^3 Ln(1/x)) accuracy

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

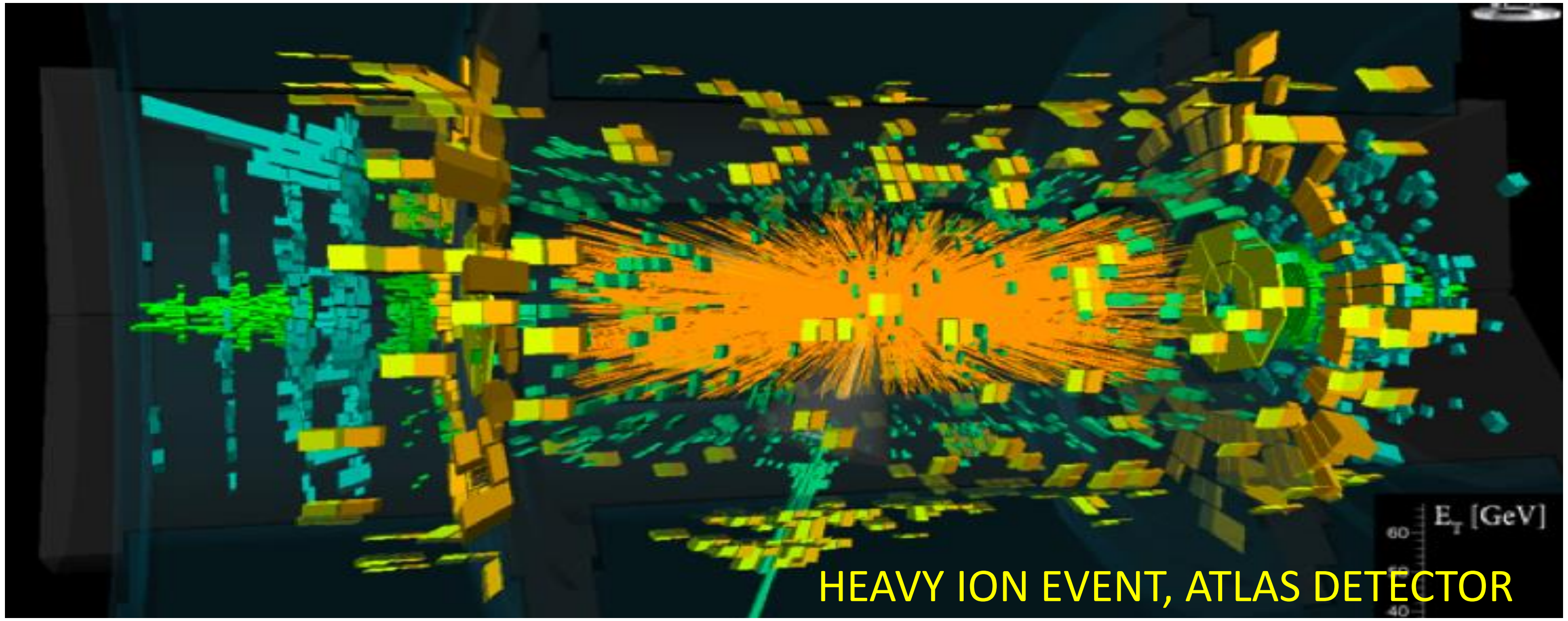
Boiling the QCD vacuum in heavy-ion collisions

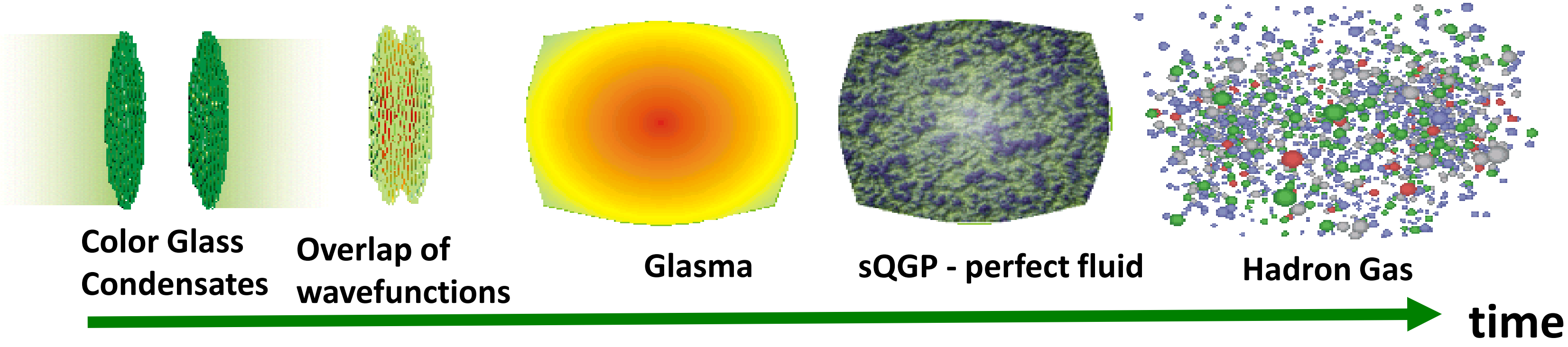




TD Lee
Nobel Laureate (1957)

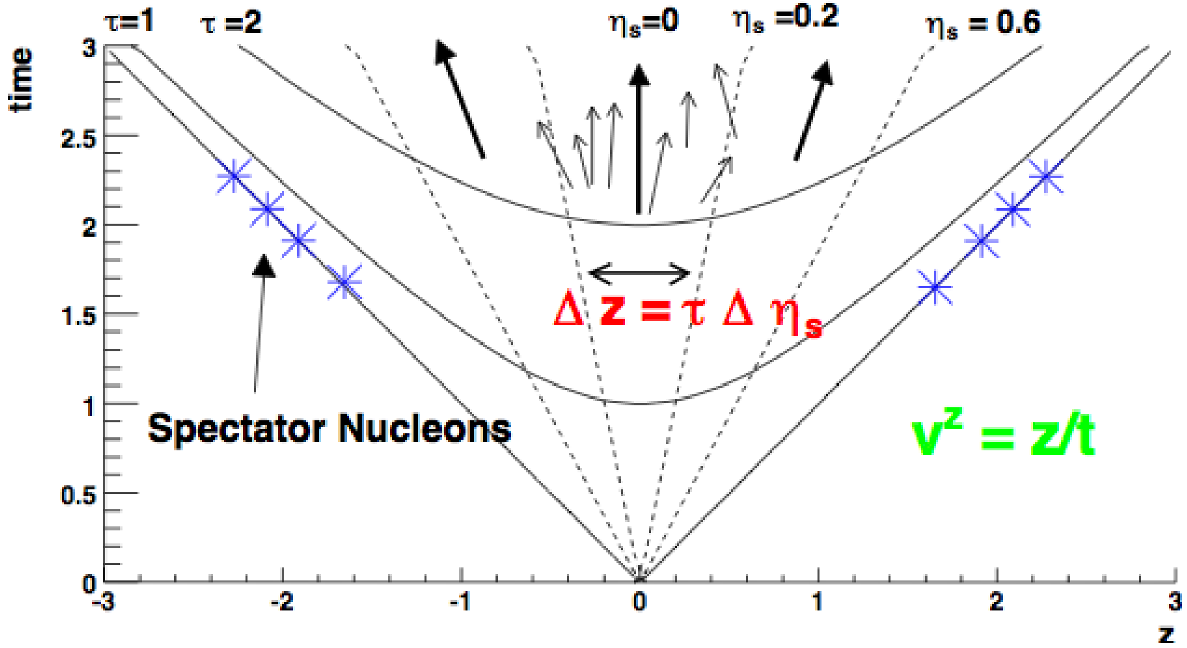
A “Standard model” model of a heavy-ion collision





Glasma: Out of equilibrium QGP formed from decay of colliding CGCs

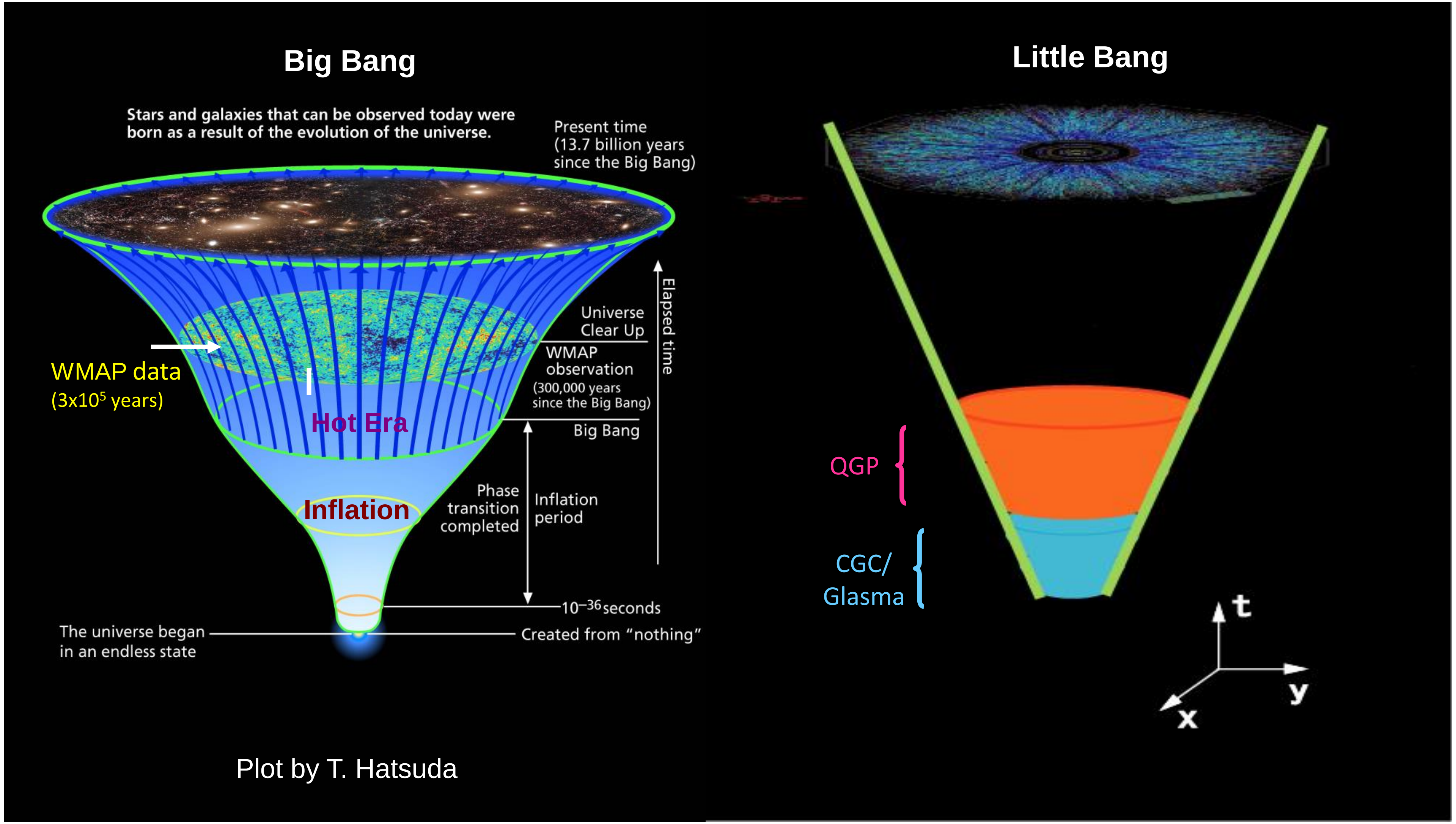
Forming a Glasma in the little Bang



Problem: Compute particle production in QCD with *strong time dependent* sources

"Schwinger-Keldysh" framework

Gelis,Lappi,RV
arXiv:0708.0047, 0804.2630; 0807.1306 [hep-ph]
Jeon, arXiv:1308.0263



Big Bang
Stars and galaxies that can be observed today were born as a result of the evolution of the universe.
Present time (13.7 billion years since the Big Bang)
Elapsed time
Universe Clear Up
WMAP observation (300,000 years since the Big Bang)
WMAP data
($3x10^5$ years)
Hot Era
Big Bang
Phase transition completed
Inflation period
Inflation
10^{-36} seconds
The universe began in an endless state
Created from "nothing"
Plot by T. Hatsuda
Little Bang
QGP
CGC/
Glasma
t
x
y

Big Bang vs. Little Bang

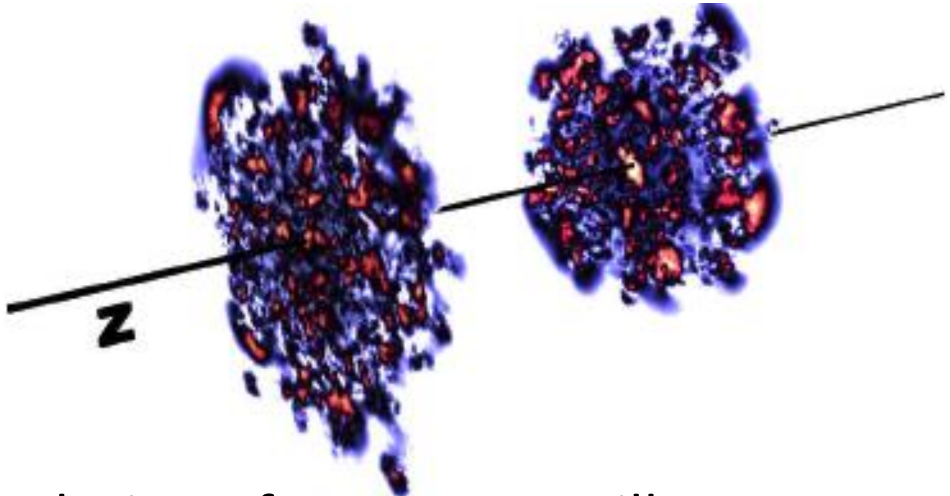
Decaying Inflaton with occupation # $1/g^2$	⟷	Decaying Glasma with occupation # $1/g^2$
Explosive amplification of low momentum small fluctuations (preheating)	⟷	Explosive amplification of low momentum small fluctuations (Weibel instabilities)
Interaction of fluctuations/inflaton -> thermalization?	⟷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

Other common features: turbulence, topo;ogical defects,…

The Glasma at leading order

Collisions of lumpy gluon ``shock" waves

Kovner,McLerran,Weigert (1996)
Kovchegov, Rischke (1996)
Krasnitz, RV (1998)



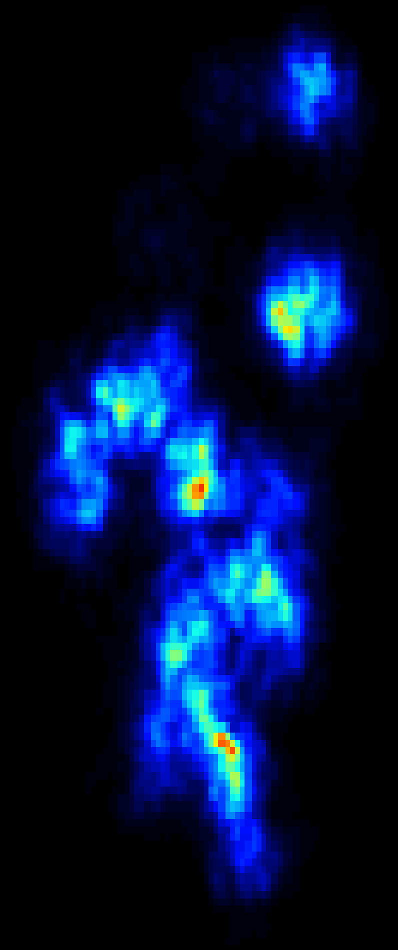
Leading order solution: Solution of QCD Yang-Mills eqns in presence of light-cone (valence) sources

$$D_\mu F^{\mu\nu,a} = \delta^{\nu+}\rho^a_A(x_\perp)\delta(x^-) + \delta^{\nu-}\rho^a_B(x_\perp)\delta(x^+)$$

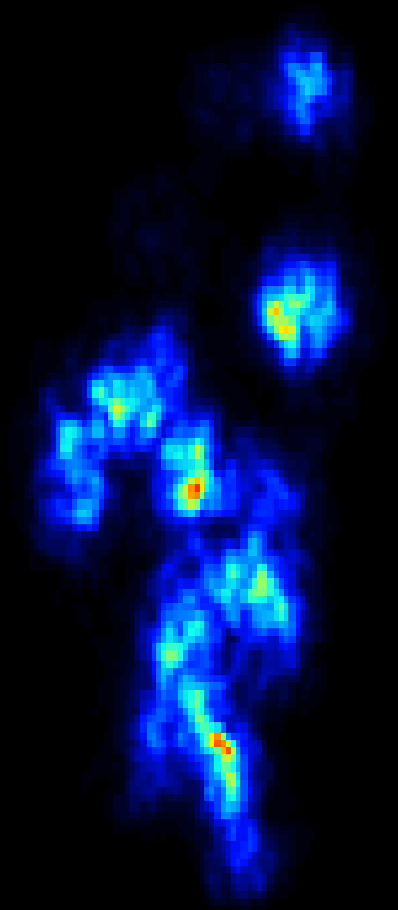
$$\langle \rho^a_{A(B)}(x_\perp)\rho^a_{A(B)}(y_\perp)\rangle = Q^2_{S,A(B)}\delta^{(2)}(x_\perp - y_\perp)$$

The saturation scale Q_S (x,b_T) is the only scale in the problem

The Glasma: colliding gluon shock waves



Glasma color fields



Glasma color fields matched to viscous hydrodynamics

Krasnitz,Venugopalan, Nucl.Phys.B557 (1999)
Lappi, Phys.Rev. C67 (2003)
Schenke,Tribedy,Venugopalan,PRL108 (2012)

t = 0.0 fm/c

Note: 1 fm/c = $3*10^{-24}$ seconds!

At NLO: Decoherence from quantum fluctuations

Berges, Borsanyi, Wetterich (2004)
Dusling,Epelbaum,Gelis,RV (2011)

"Toy" example: scalar Φ^4 theory

Gaussian random variable $\langle c_{\nu k} c_{\mu l} \rangle = 0$

$$\langle c_{\nu k} c^*_{\mu l} \rangle = 2\pi\delta(\nu - \mu)\delta_{kl}$$

$$\phi(\tau, \eta, x_\perp) = \phi_{\text{cl.}}(\tau, x_\perp) + \frac{1}{2} \int \frac{d\nu}{2\pi}\, d\mu_k\, c_{\nu k}\, e^{i\nu\eta} \chi_k(x_\perp) H_{i\nu}(\lambda_k \tau) + c.c$$

Satisfies the "small fluctuation" equation

$$[-\partial_\perp^2 + V''(\phi_0)]\chi_k = \lambda_k^2\, \chi_k$$

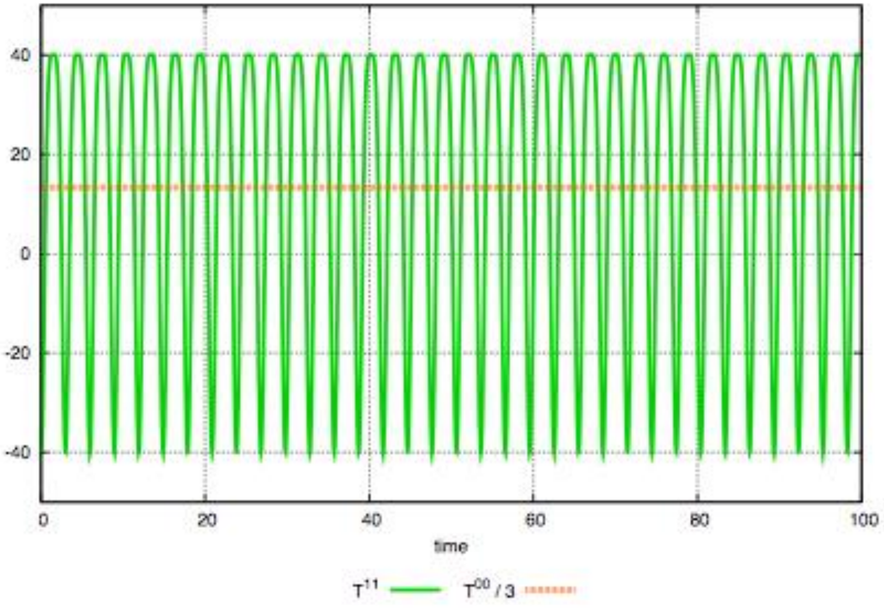
These quantum modes satisfy an "eigenstate thermalization" criteria conjectured by Berry (and developed by Srednicki and others) as essential for thermalization of a quantum fluid

Decoherence from quantum fluctuations

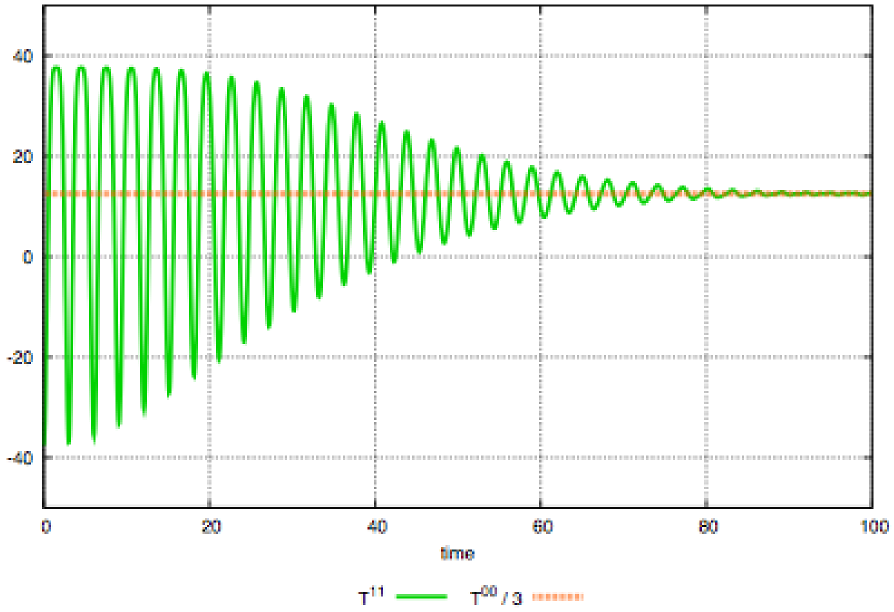
Dusling,Epelbaum,Gelis,RV
arXiv:1009.4363

Conformal scalar 1+1-D Φ^4 theory:

Energy density and pressure without averaging over fluctuations



Energy density and pressure after averaging over fluctuations

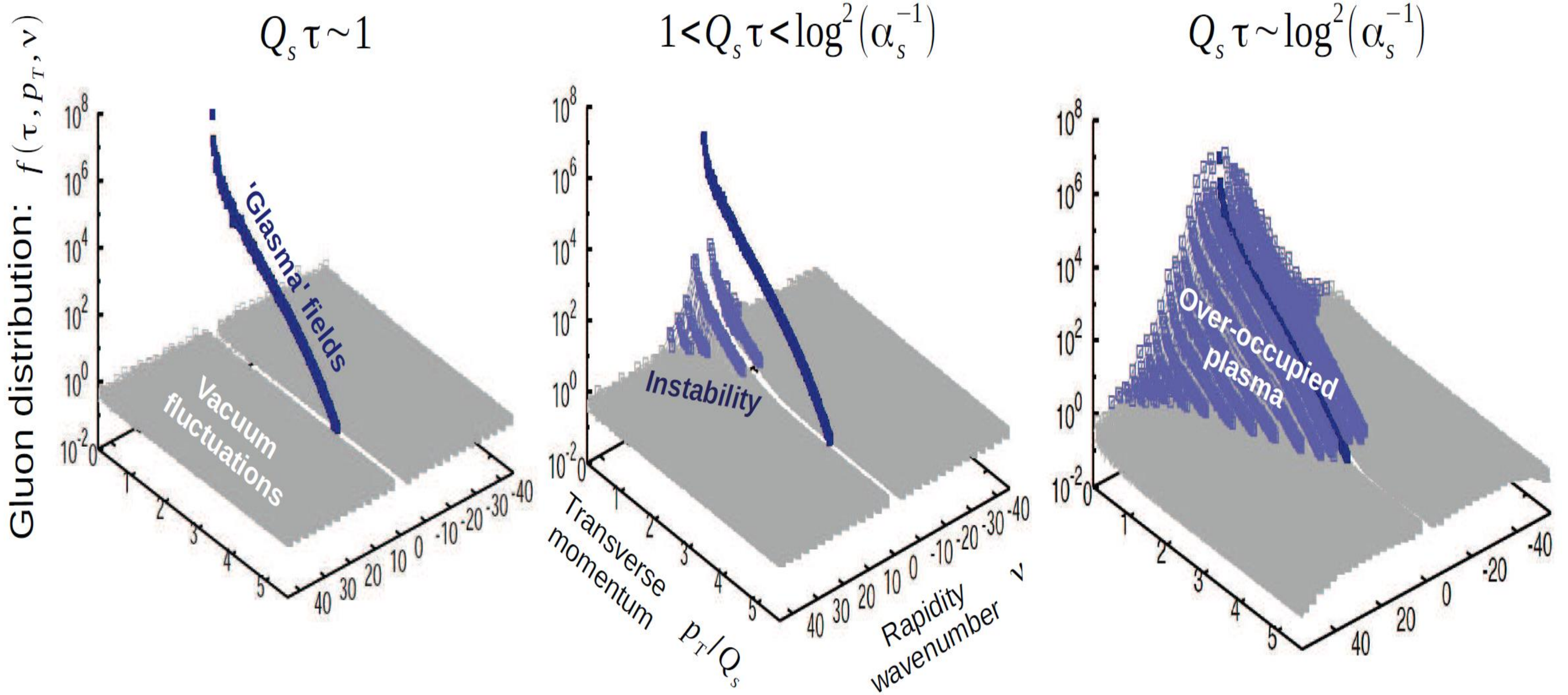


Such "classical-statistical" quantum averaging decoheres the classical fields – *scrambling information* – resulting in a *"pre-thermal"* micro-canonical distribution
Strongly correlated dynamics subsequently described in terms of single particle dists.

From Glasma to Quark Gluon Plasma

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

This instability leads to rapid decoherence and overpopulation of all momentum modes

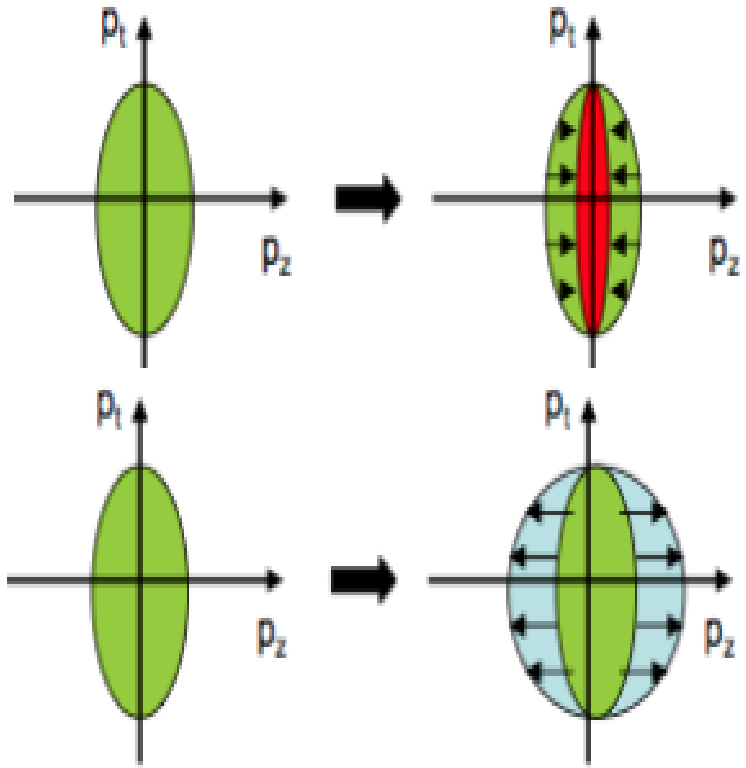


Classical-statistical lattice simulations of 3+1-D gluon fields exploding into the vacuum

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

From Glasma to Quark Gluon Plasma

- There is a natural ***competition*** between ***interactions*** and the ***longitudinal expansion*** which renders the system ***anisotropic*** on large time scales



Longitudinal Expansion:

- Red-shift of longitudinal momenta p_z
  $\rightarrow$ increase of anisotropy
- Dilution of the system

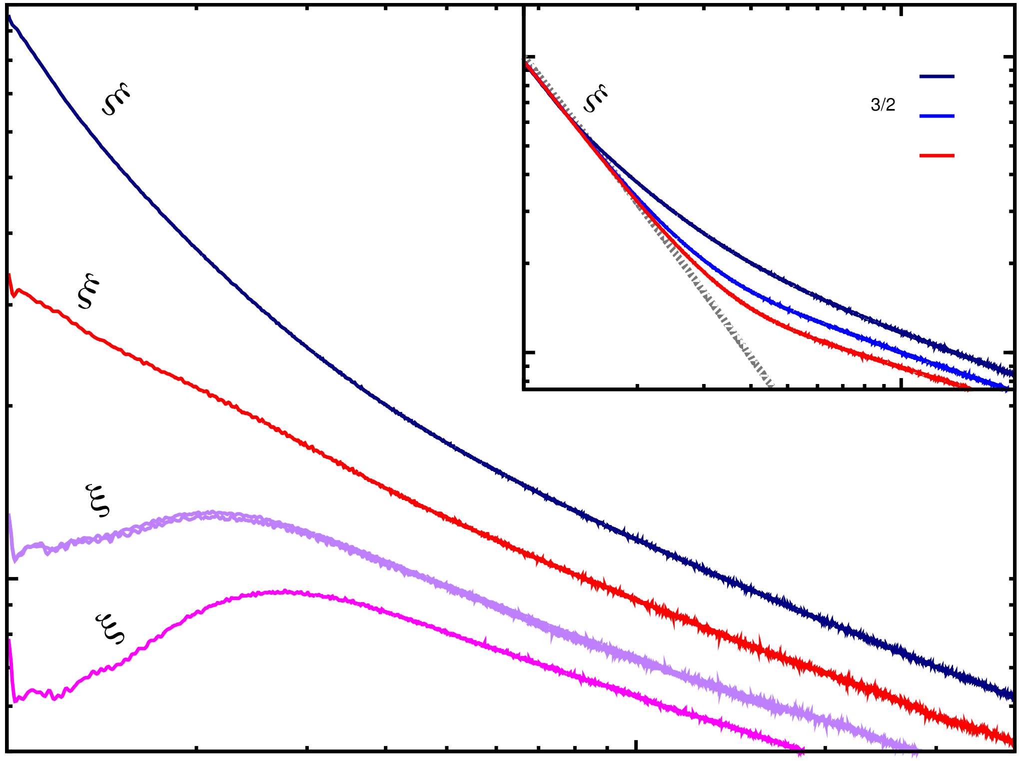
Interactions:

- Isotropize the system

Pressure becomes increasingly anisotropic

Initial condition for gauge field amplitude
varying occupancy n_0 and prolateness ξ_0

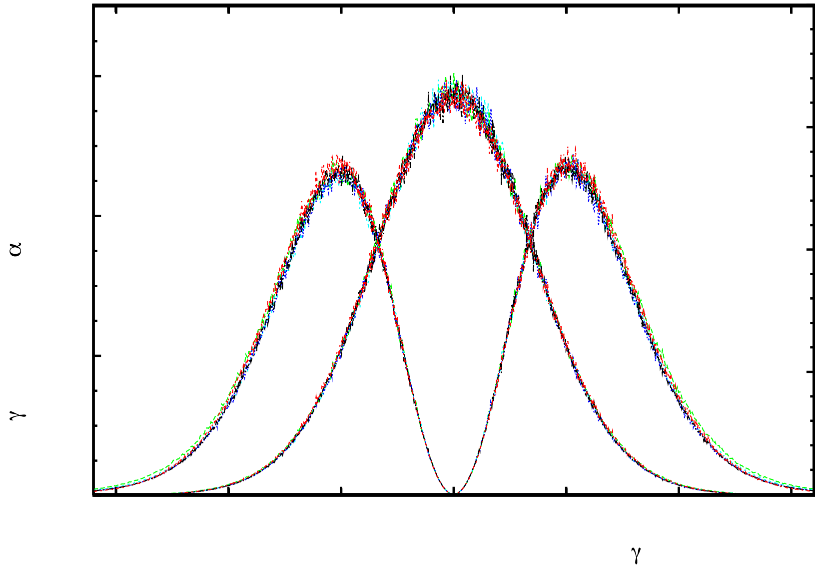
$$f(p_\perp, p_z, t_0) = \frac{n_0}{\alpha_S}\,\Theta\left(Q - \sqrt{p_\perp^2 + (\xi_0 p_z)^2}\right)$$

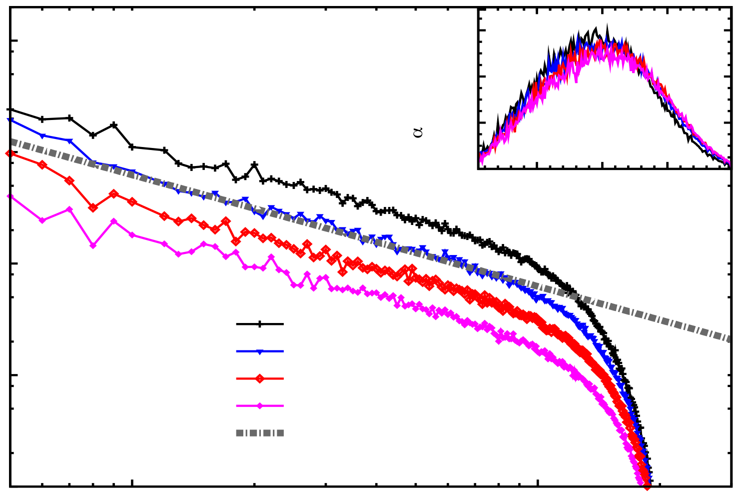


P_L/P_T approaches universal $\tau^{-2/3}$ behavior

Result: universal non-thermal fixed point

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





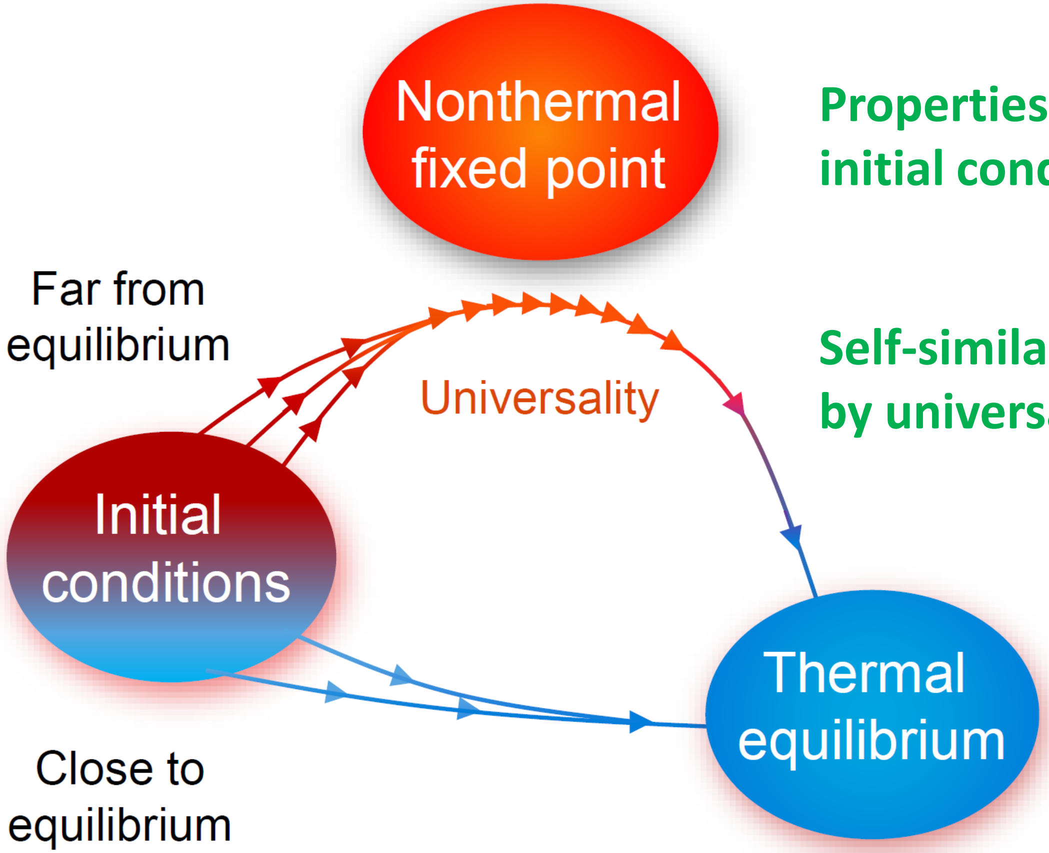
Moments of longitudinal momentum distribution extracted over range of time slices lie on universal curves

Distribution as function of p_T displays 2-D thermal behavior

Overoccupied expanding Glasma: particles or fields?

For $1 < f < 1/\alpha_s$ a dual description is feasible either in terms of kinetic theory or classical-statistical dynamics …

Mueller,Son (2002)
Jeon (2005)



Properties independent of initial conditions

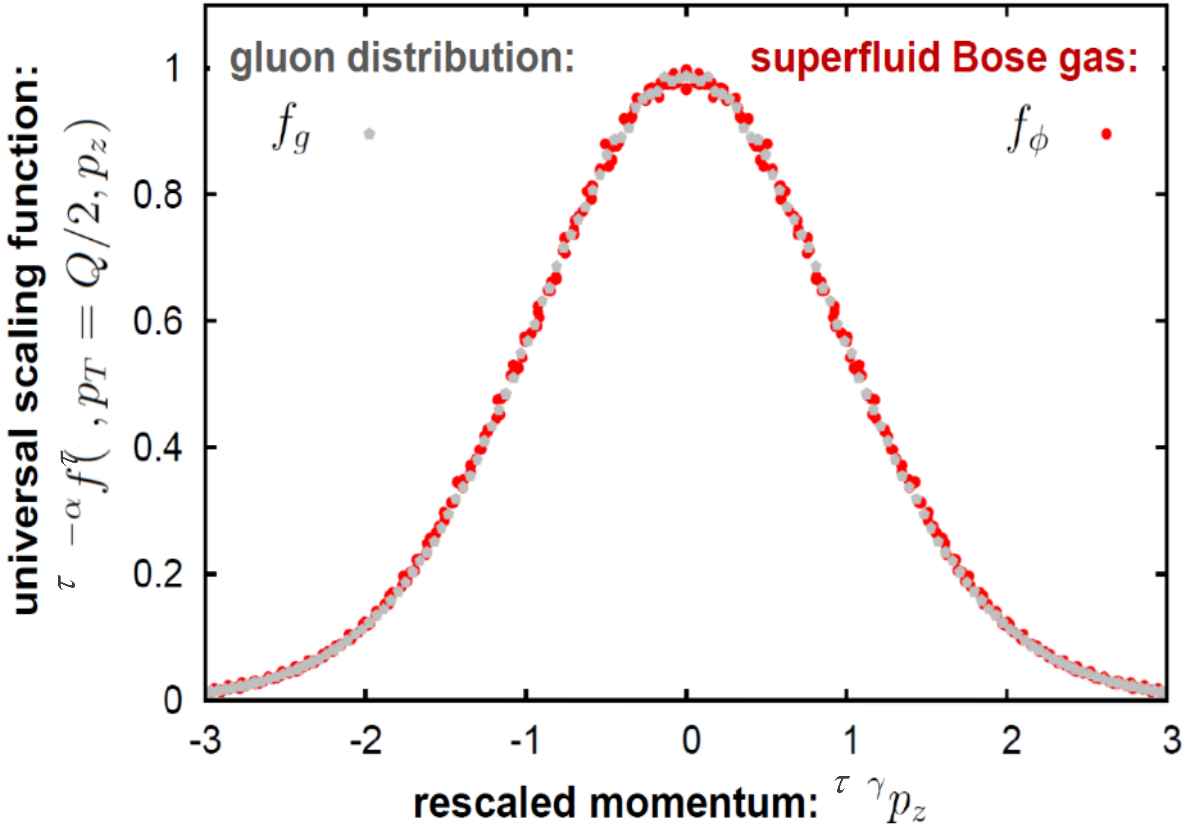
Self-similar evolution characterized by universal scaling exponents

Universal turbulent attractor in QCD

**"Big whorls have little whorls, which feed on their velocity,
and little whorls have lesser whorls, and so on to viscosity."**

The Glasma and over-occupied 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

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

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

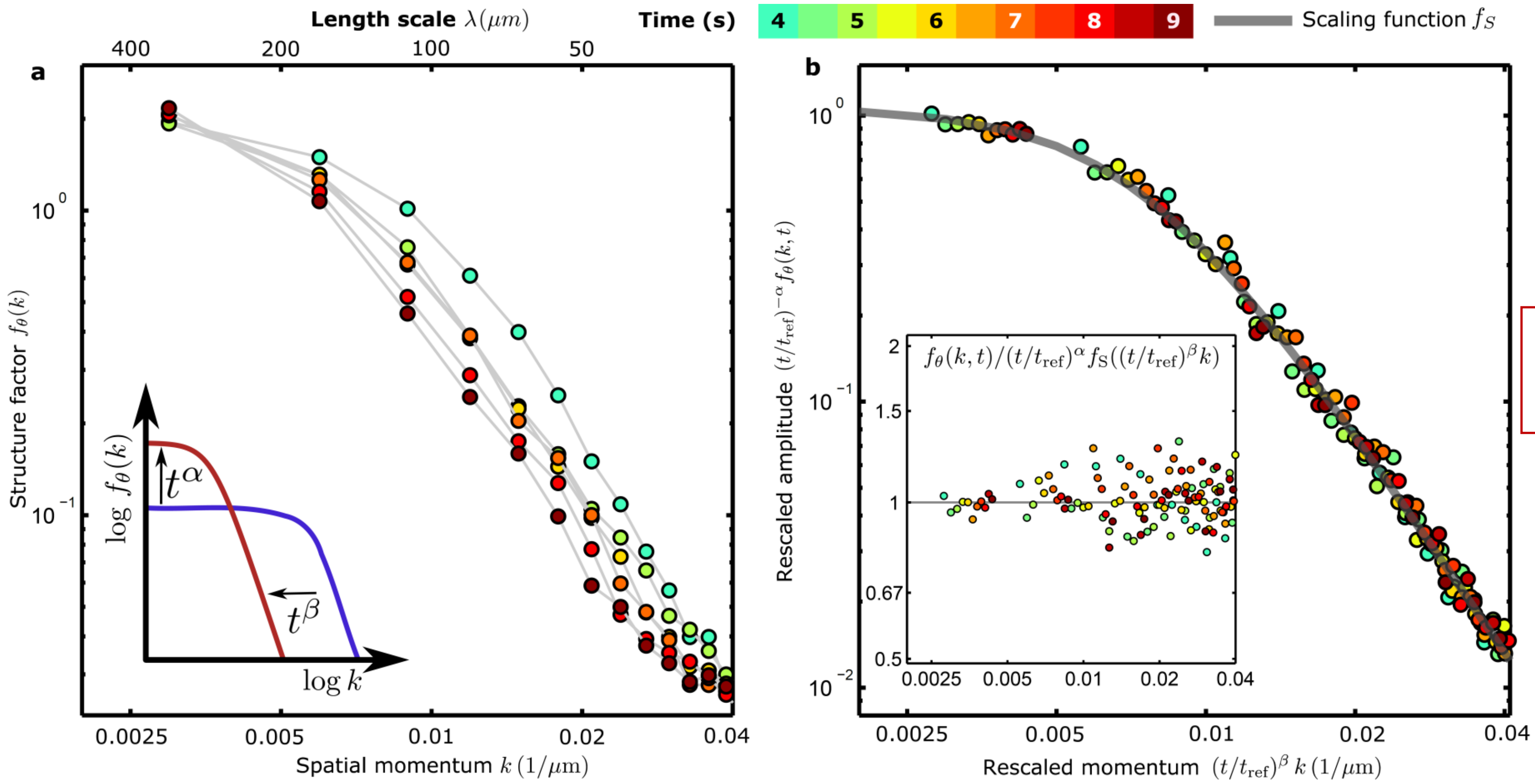
$$\alpha = -\frac{2}{3}, \beta = 0, \gamma = 1/3$$

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



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

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

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

Kinetic theory of the Glasma

Different scenarios when occupancy f ≤ 1:

- Elastic multiple scattering dominates in the Glasma

BMSS: Baier,Mueller,Schiff,Son

- Rescattering influenced by plasma (Weibel) instabilities

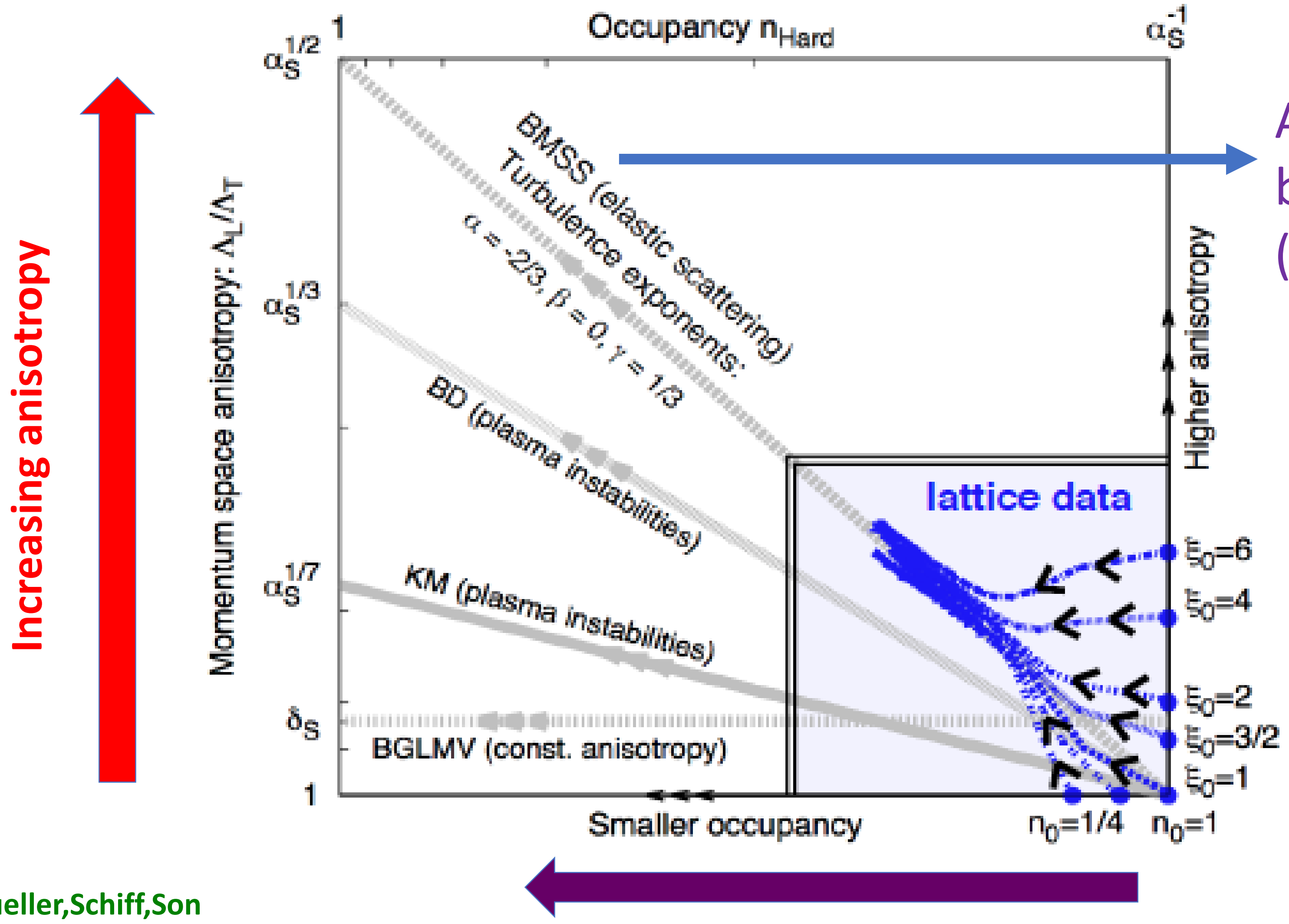
DB: Bodeker
KM: Kurkela, Moore

- Transient Bose condensation+multiple scattering

BGLMV: Blaizot,Gelis,Liao,McLerran,Venugopalan

Gell-Mann's totalitarian principle: Anything that is not forbidden is allowed

Non-thermal fixed point in overpopulated QGP

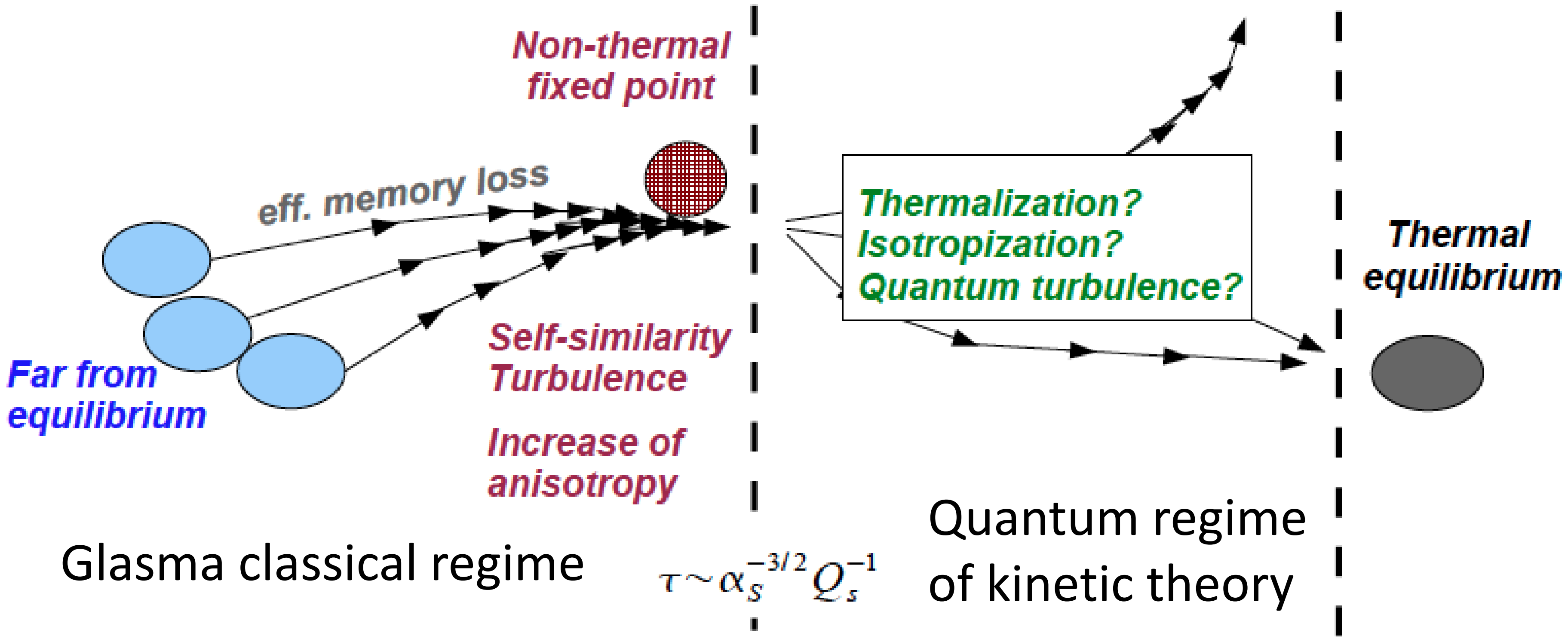


And the winner is…
bottom-up thermalization
(caveat, caveat, caveat,…)

BMSS: Baier,Mueller,Schiff,Son
BD: Bodeker
KM: Kurkela, Moore
BGLMV: Blaizot,Gelis,Liao,McLerran,Venugopalan

Berges,Boguslavski,Schlichting,Venugopalan. PRD89 (2014) 114007

From nuts to soup: bottom-up thermalization



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

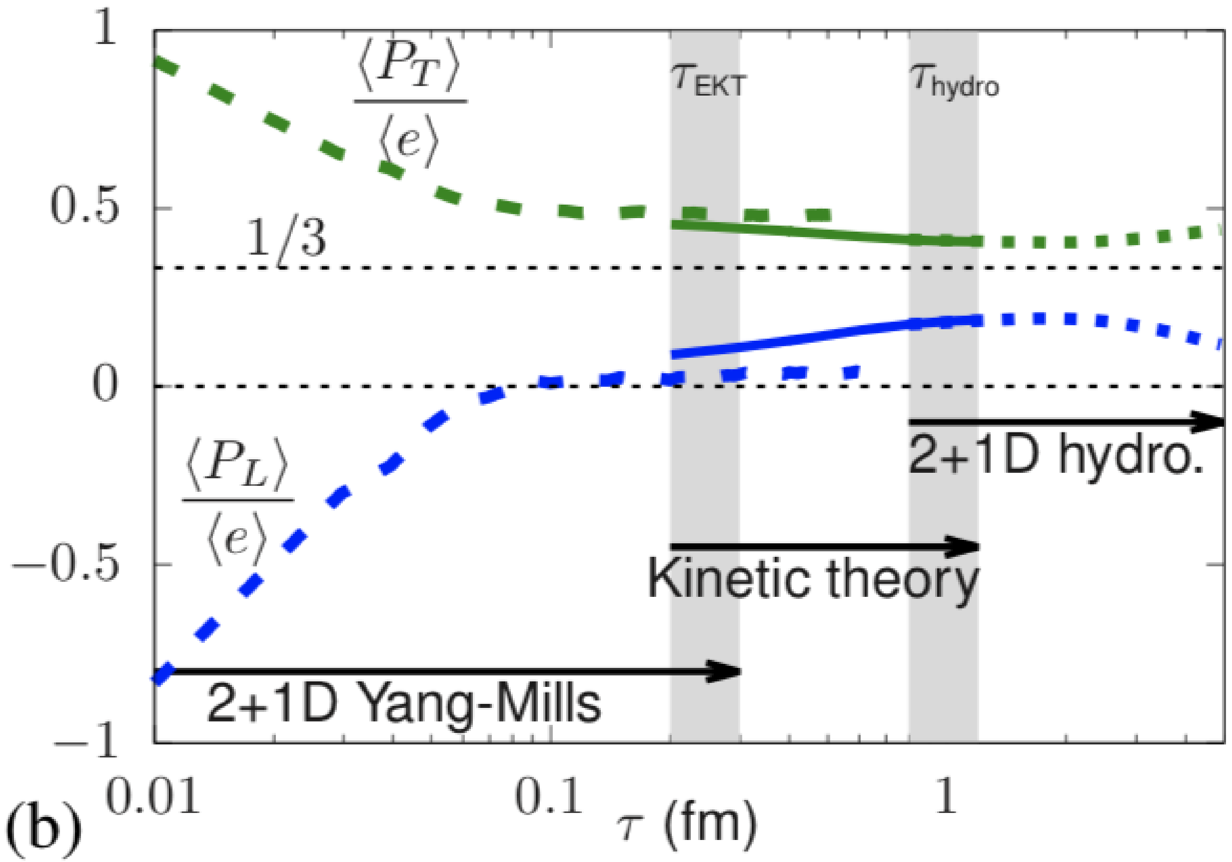
Thermalization temperature of $T_i = \alpha_S^{2/5} Q_S$

$\tau_{therm} \to 0 \ as \ Q_S \to \infty$

Glasma / bottom-up prediction:

In the Regge limit of QCD, matter thermalizes almost instantaneously

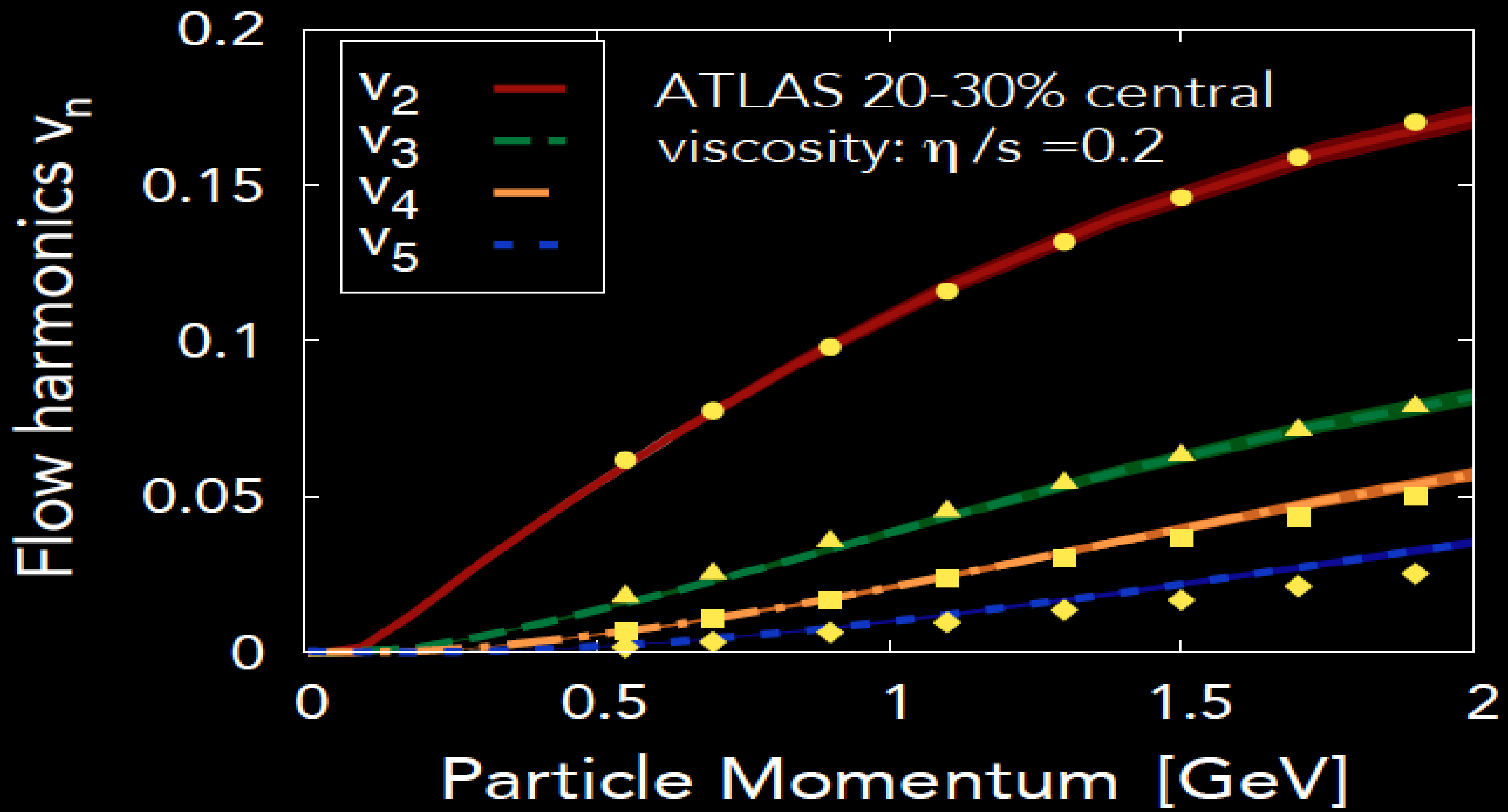
From nuts to soup: bottom-up thermalization



Mazeliauskas, QM 2018
arXiv:1807.05586

VISCOUS FLOW AT LHC

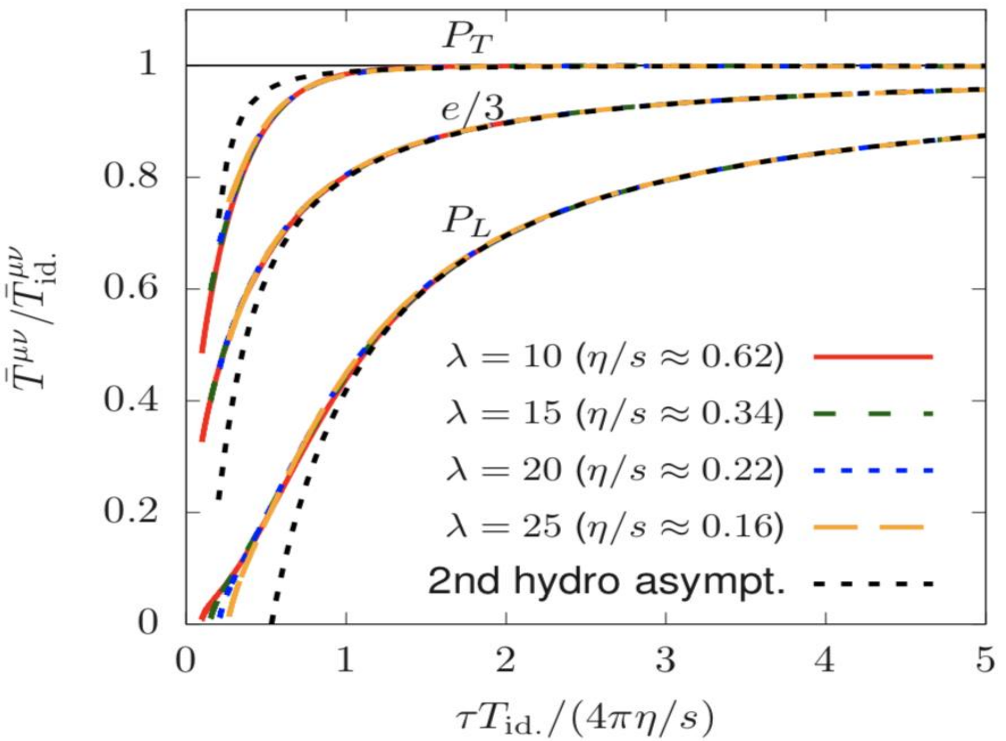
C.GALE, S.JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PHYS.REV.LETT.110, 012302 (2013)

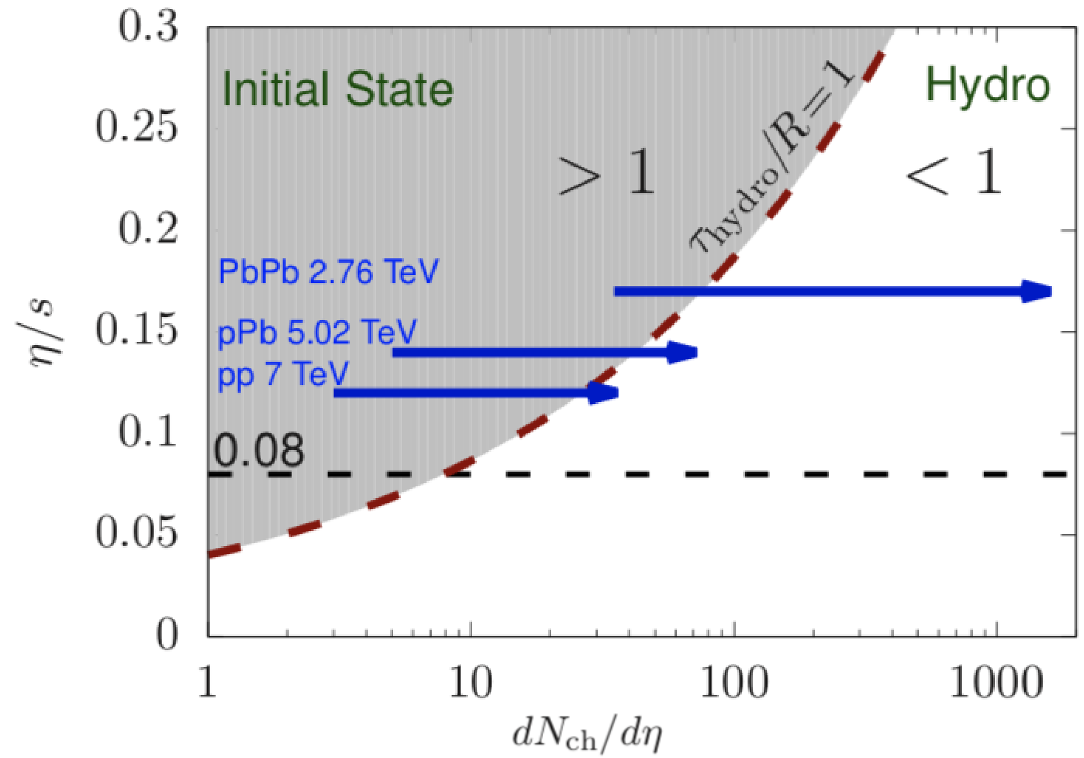


EXPERIMENTAL DATA: ATLAS COLLABORATION, PHYS. REV. C86, 014907 (2012)

CGC to QGP: from large to small systems

Mazeliauskas, arXiv:1807.05586





Bottom-up results plotted as function of scaled "hydrodynamization" variable match smoothly *to viscous hydro even when system is quite anisotropic*

Kurkela,Mazeliauskas,Schlichting,Paquet,Teaney,arXiv:1805.00961

From bottom-up analysis, regime of validity of hydro is limited for small systems:

Kurkela,Wiedemann,Wu, arXiv:1905.05139

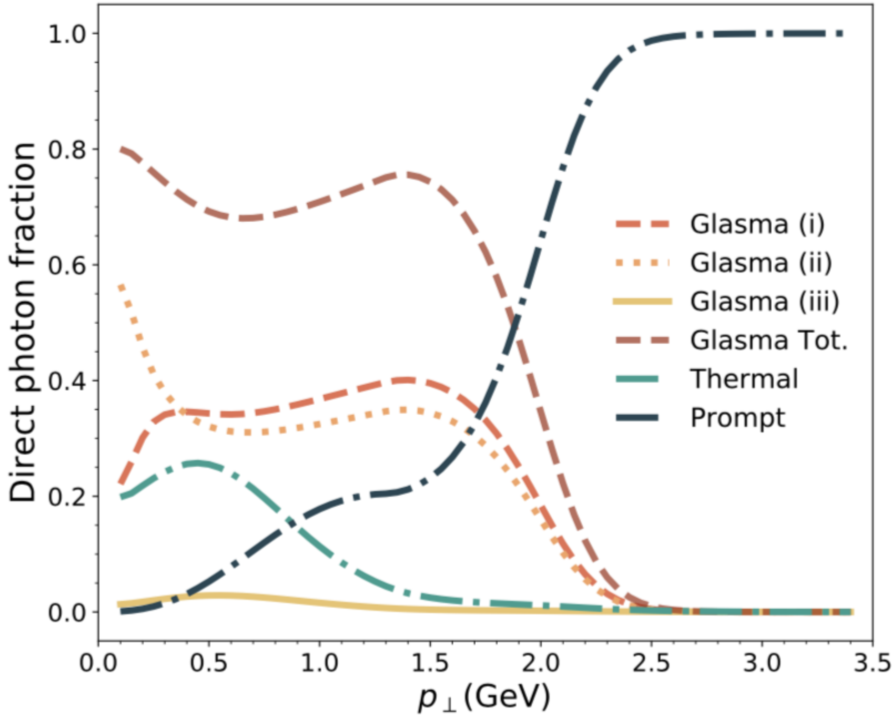
Hydrodynamization:

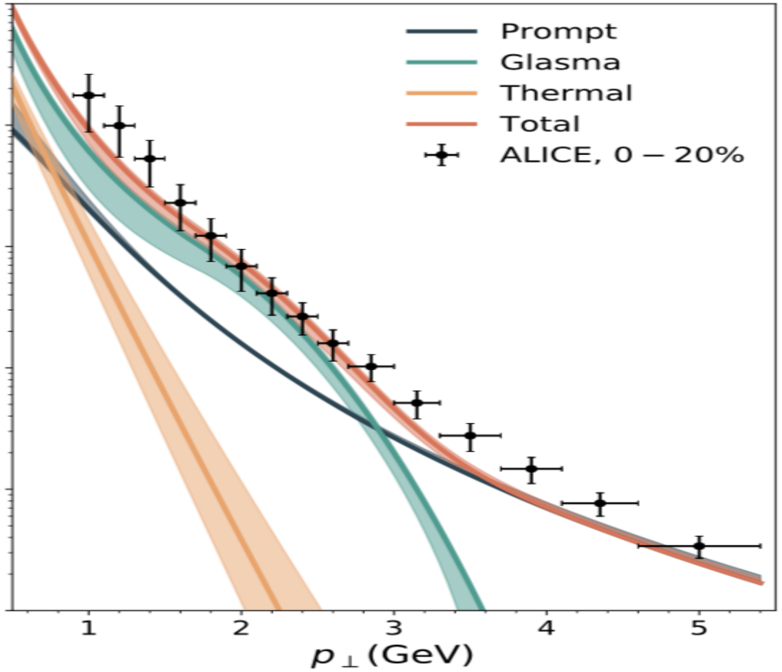
Heller,Kurkela,Spalinski,Svensson,arXiv:1609.04803
Bazow,Heinz,Martinez, arXiv:1507.06595
Romatschke, arXiv:1704.08699
Strickland,Noronha,Denicol,arXiv:1709.06644

Early time probes: photons from the Glasma

Potentially significant contributions to photon production from the different stages (classical/quantum) of bottom-up thermalization of the Glasma

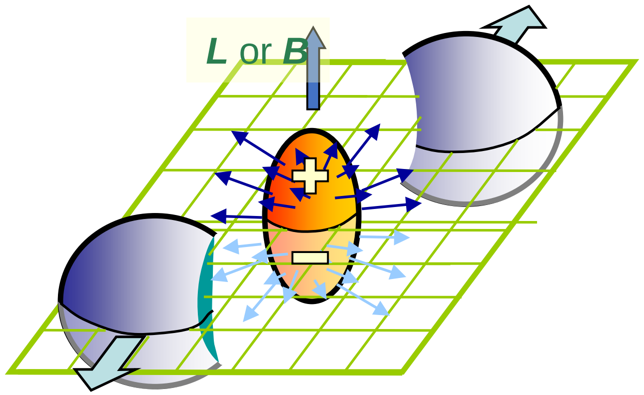
Garcia-Montero, arXiv: 1909.12294





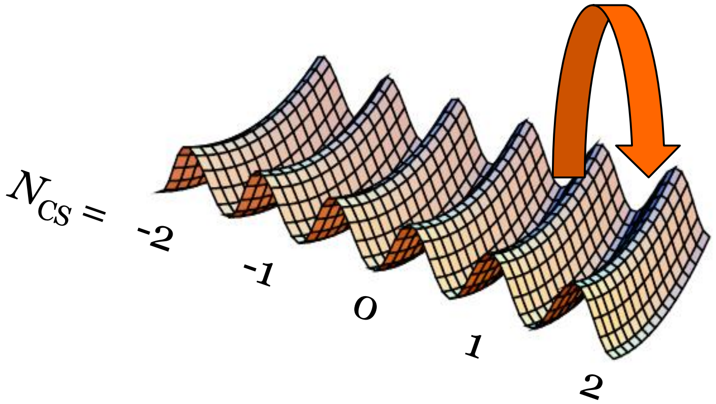
However there are significant uncertainties in the computations of both the thermal and the glasma rates

Topology in heavy-ion collisions: The Chiral Magnetic Effect



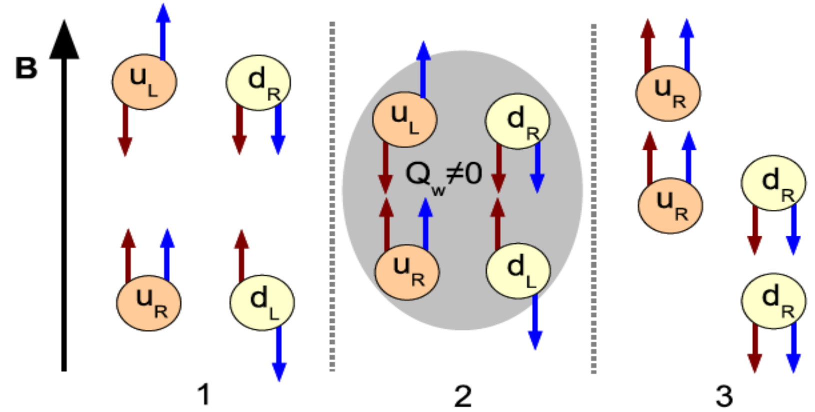
External (QED) magnetic fields - 10^{18} Gauss, of Magnetar strength!

+



Over barrier topological (sphaleron) transitions … analogous to proposed mechanism for electroweak baryogenesis

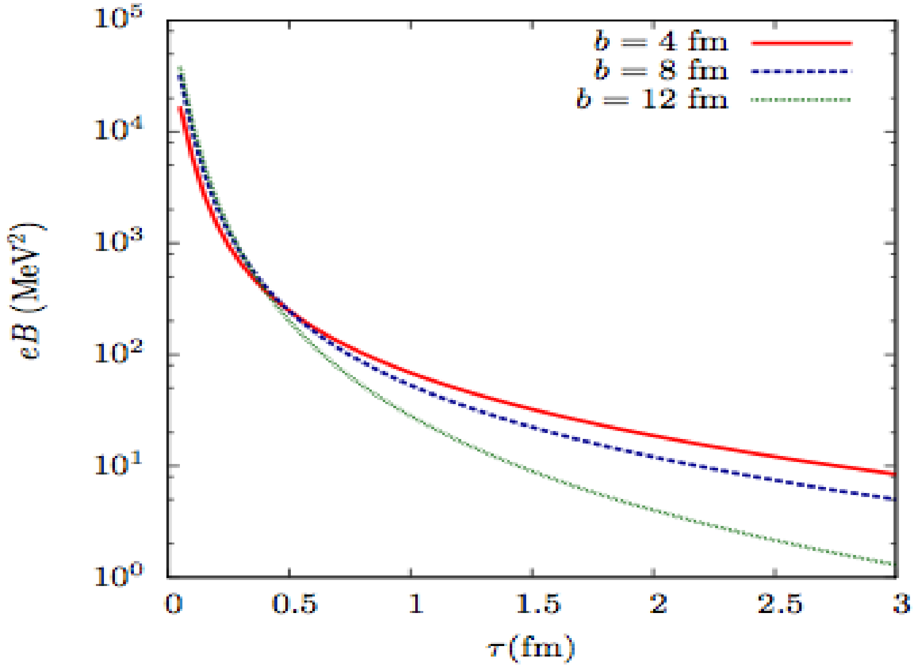
=



massless quarks in hot medium → **Topological transition $Q_W = n_L - n_R$** → **CME current generated**

Kharzeev, McLerran, Warringa (2007)
Kharzeev, Fukushima, Warringa (2008)

Topology in ion-ion collisions: Chiral Magnetic Effect



External B field dies rapidly. Lifetime of hot matter ~ 10 Fermi:
effect most significant, for transitions at early times

Consistent (caveat emptor!) with heavy-ion results from RHIC & LHC

Status: Kharzeev, Liao, Voloshin, Wang, Prog.Nucl.Part.Phys.88 (2016) 1

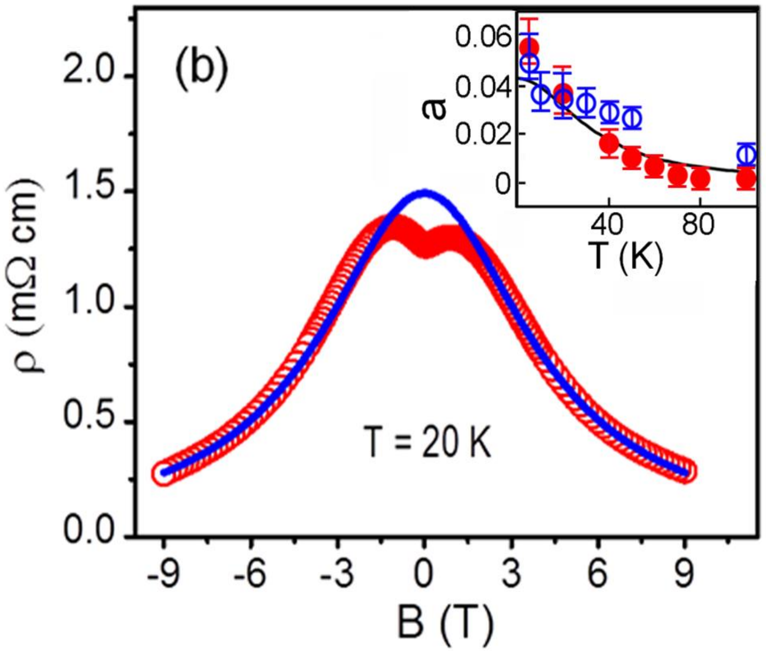
CME studies a major part of RHIC's upcoming beam energy scan (BES II)
- possibly definitive results from comparative study of isobar collisions

BNL CME task force report: V. Skokov et al., arXiv:1608.00982

CME in condensed matter systems?

Dirac semi-metal: Zirconium Penta-Telluride

Inverse of the conductivity



Blue: CME model
Red: experimental data

Axial charge separation in external B field $\vec{J}_{\rm CME} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}$

Effect of chiral anomaly $\mu_5 \propto \vec{E}\cdot\vec{B}$

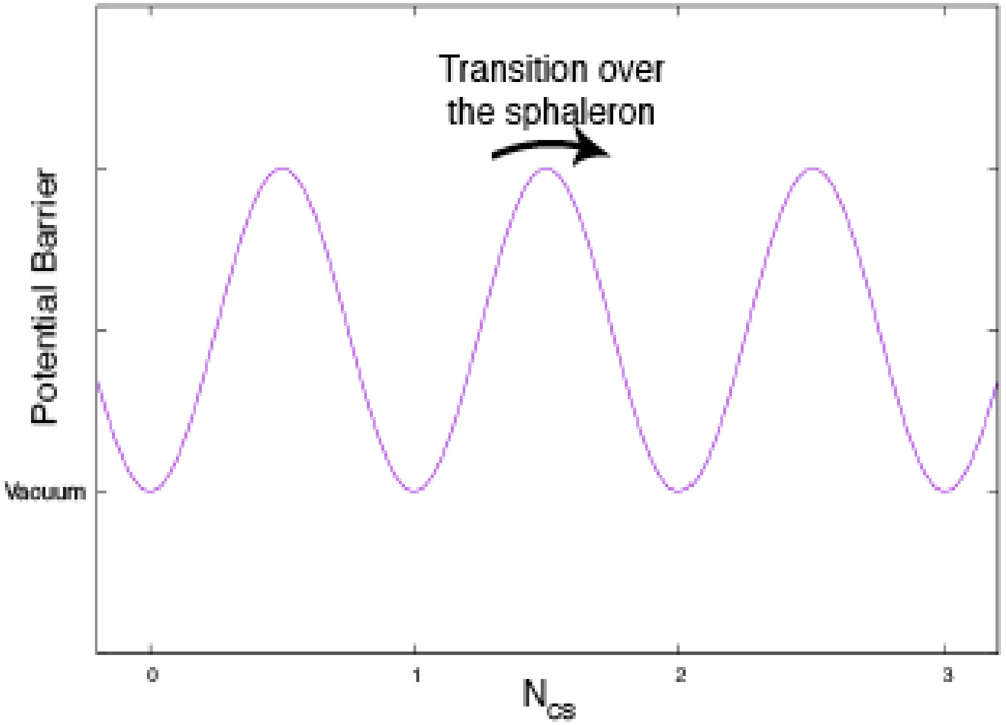
$J^i_{\rm CME} = \sigma^{ik}_{\rm CME}\;E^k \Rightarrow \sigma^{ik}_{\rm CME} \propto B^i B^k => \sigma^{zz}_{\rm CME} \propto B^2$

Q.Li, et al, Nature Physics 12, 550 (2016)

Uncovering the topology of the QCD vacuum: Sphaleron transitions

Sphaleron: spatially localized, unstable finite energy classical solutions
(σφαλερος -``ready to fall”)

EW theory: Klinkhamer, Manton, PRD30 (1984) 2212
QCD: McLerran,Shaposhnikov,Turok,Voloshin, PLB256 (1991) 451



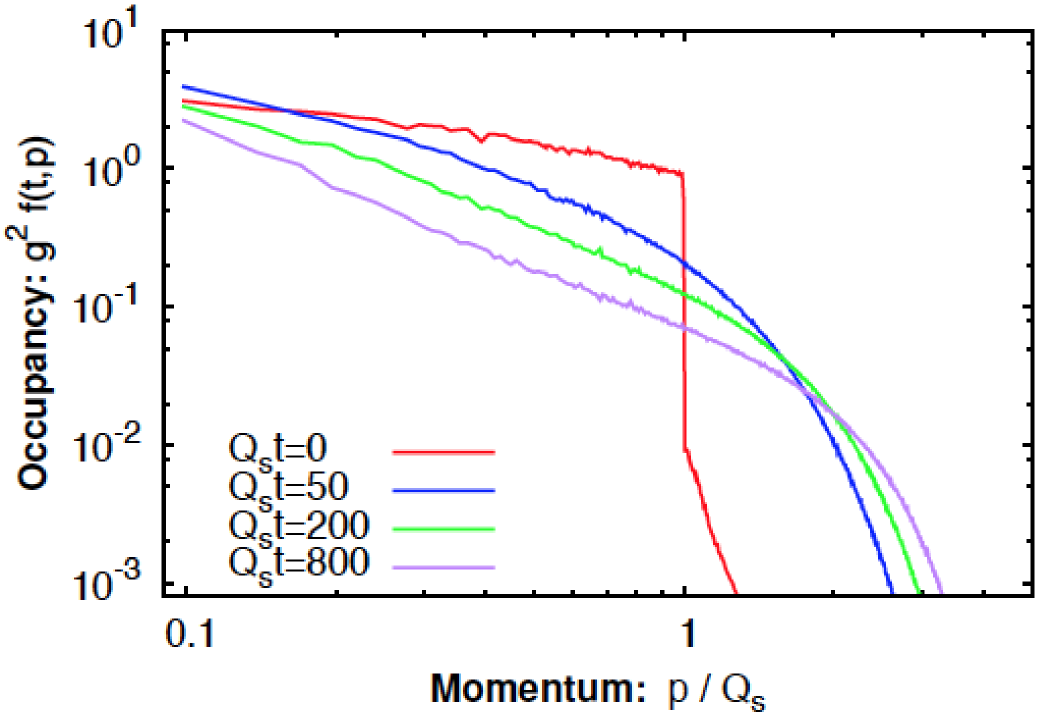
Distinct energy degenerate QCD vacua characterized by topological Chern-Simons number N_{CS}

Sphaleron transition rate:

$$\Gamma^{eq} = \lim_{\delta t -> \infty} \frac{\langle (N_{\rm CS}(t+\delta t) - N_{\rm CS}(t))^2 \rangle_{\rm eq}}{V \delta t}$$

Moore, Tassler, arXiv:1011.1167

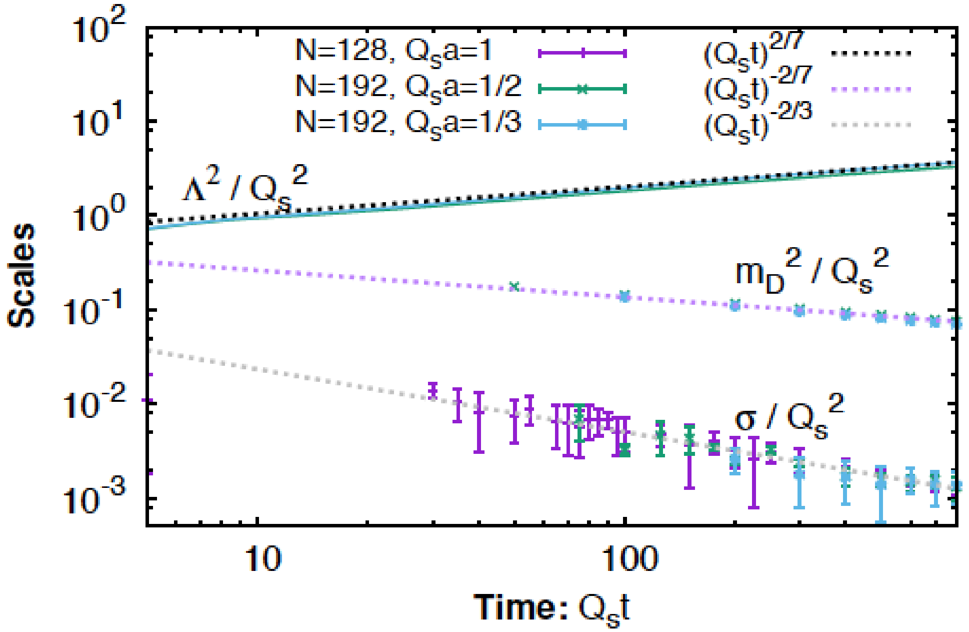
Overoccupied gauge fields in a box



Thermalization extensively studied in this context employing classical-statistical simulations

Berges,Schlichting,Sexty, PRD86 (2012) 074006
Schlichting PRD86 (2012) 065008
York,Kurkela,Lu,Moore, PRD89 (2014) 074036

Overoccupied gauge fields in a box

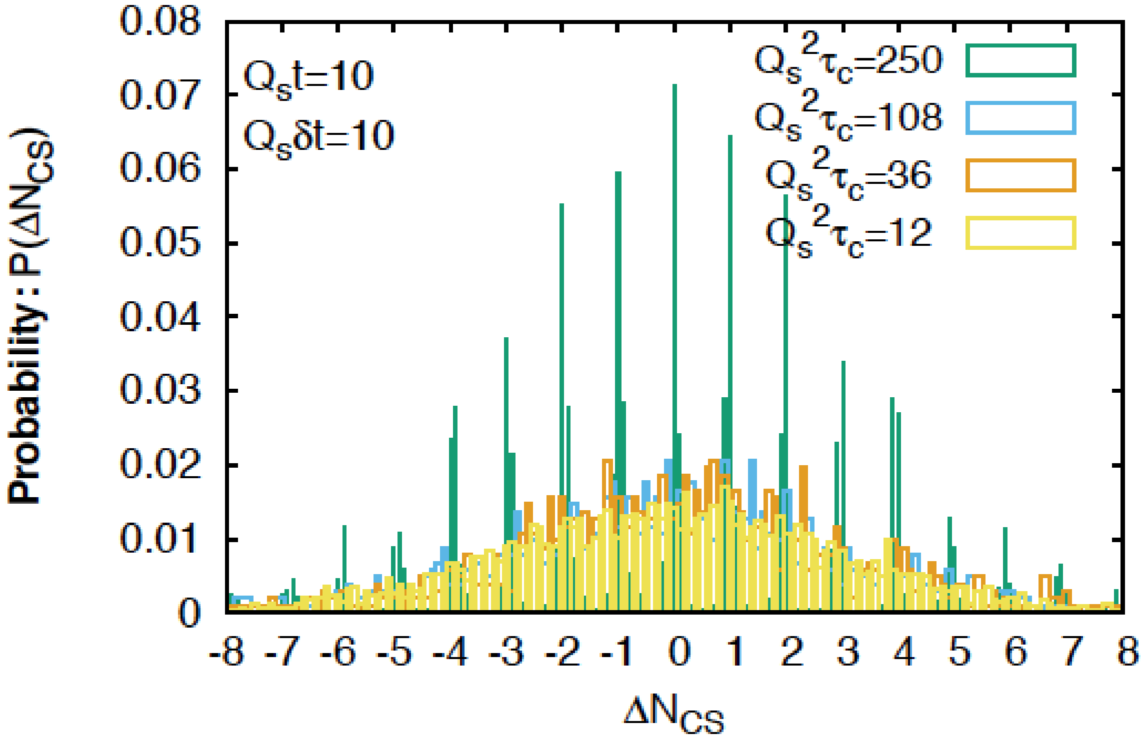


Clean separation of scales develop *a la* thermal field theory:

Temperature (T)
Electric (Debye) screening (gT)
Magnetic screening (g^2 T) scales

Berges,Scheffler,Sexty, PRD77 (2008) 034504
Mace,Schlichting,Venugopalan, PRD93 (2016), 074036
Berges,Mace,Schlichting, PRL118 (2017)

Topological transitions in the Glasma



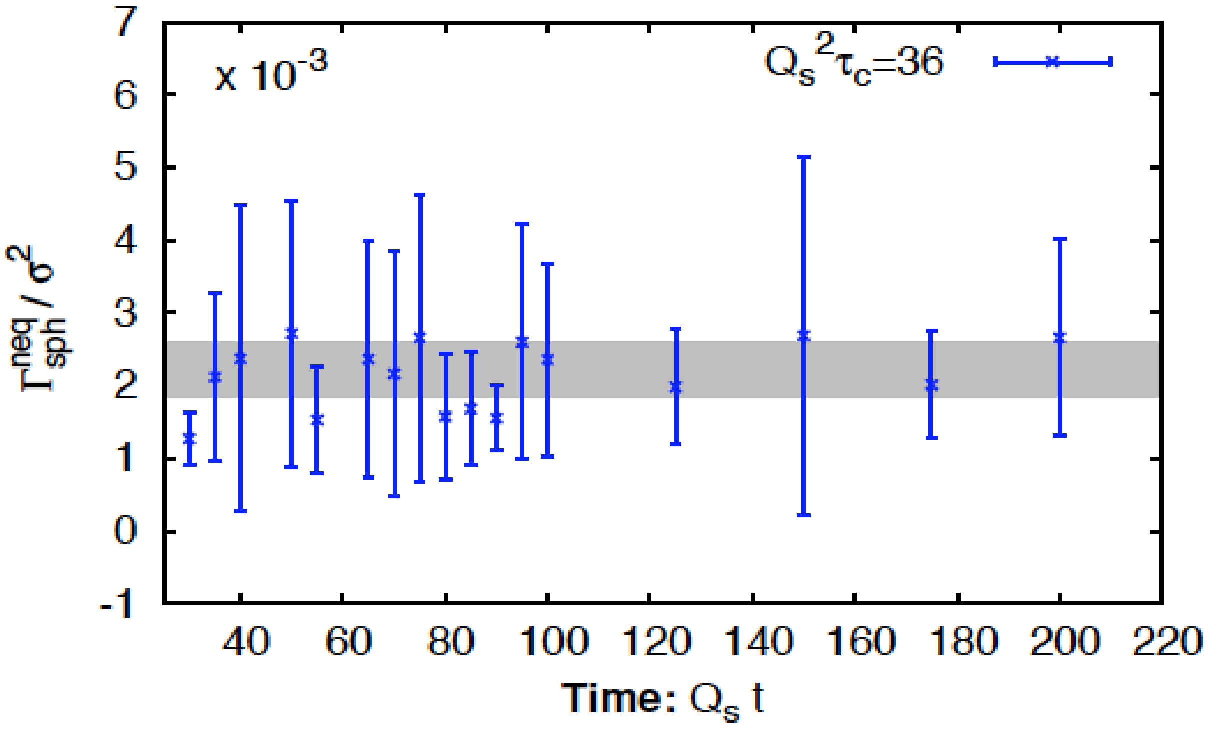
Distribution of Chern-Simons charge localizes around integer values as UV modes are removed

"Cooled" Glue configurations in the Glasma are topological!

Mace,Schlichting,Venugopalan, PRD93 (2016), 074036

Topological transitions in the Glasma

Mace,Schlichting,Venugopalan, PRD93 (2016), 074036



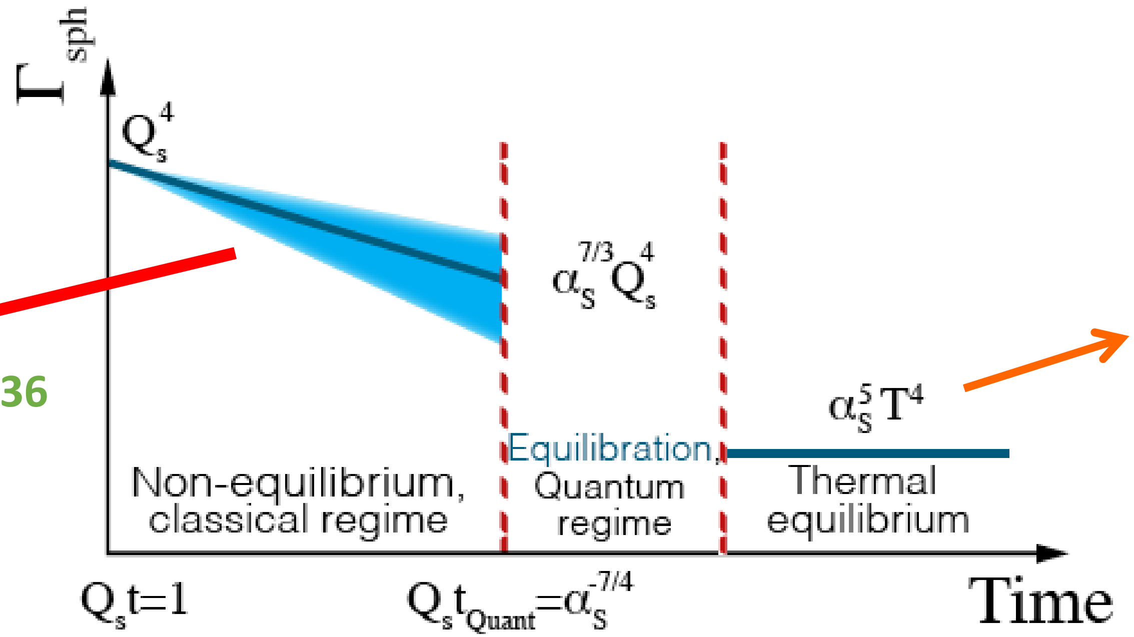
Sphaleron transition rate scales with string tension squared

Very suggestive of non-trivial infrared structure
of QCD far out of equilibrium

Exploding sphalerons

"Exploding sphalerons": Shuryak, Zahed, PRD67 (2003) 014006

Glasma rate
PRD 93 (2016) 074036



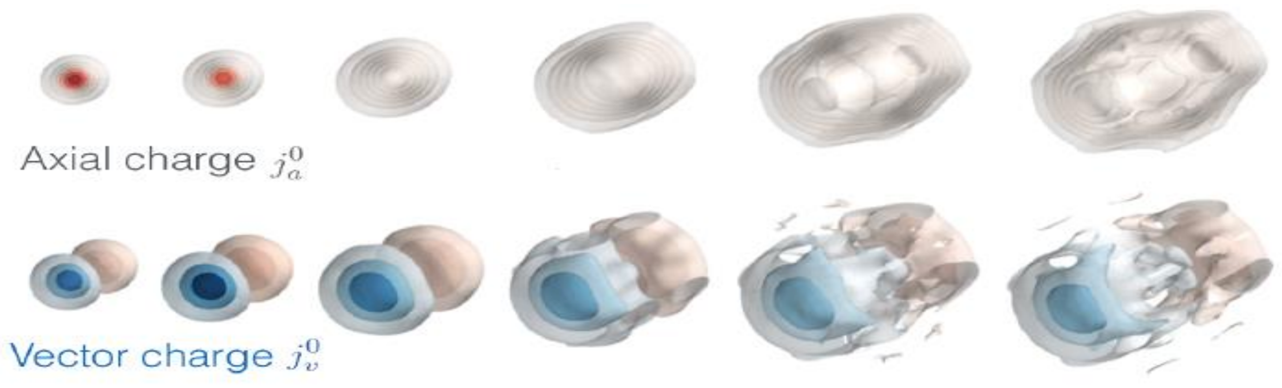
Arnold,Son,Yaffe,PRD55(1997)6264

Sphaleron transition rate very large in the Glasma
- much larger than equilibrium rate

Couple sphaleron background with fermions & external EM fields to simulate *ab initio* the Chiral Magnetic Effect!

Mueller,Schlichting,Sharma,PRL117 (2016) 142301
Mace,Mueller,Schlichting,Sharma, arXiv: 1612.02477

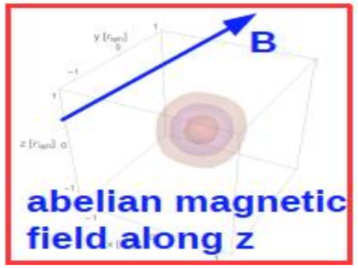
Classical-statistical simulations



Initially: Vacuum (no fermions, no axial charge)

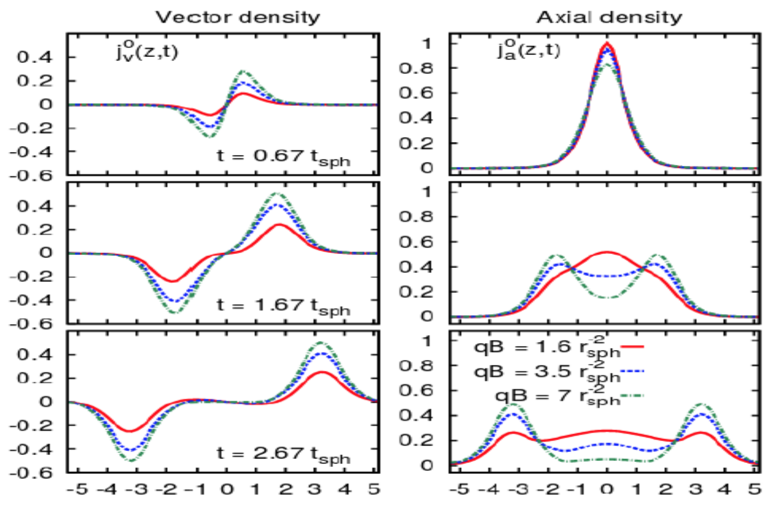
Chiral Magnetic Effect: Electric current generated due to axial charge produced

Chiral Separation Effect: Axial current generated due to electric charge



Emergence of chiral magnetic wave

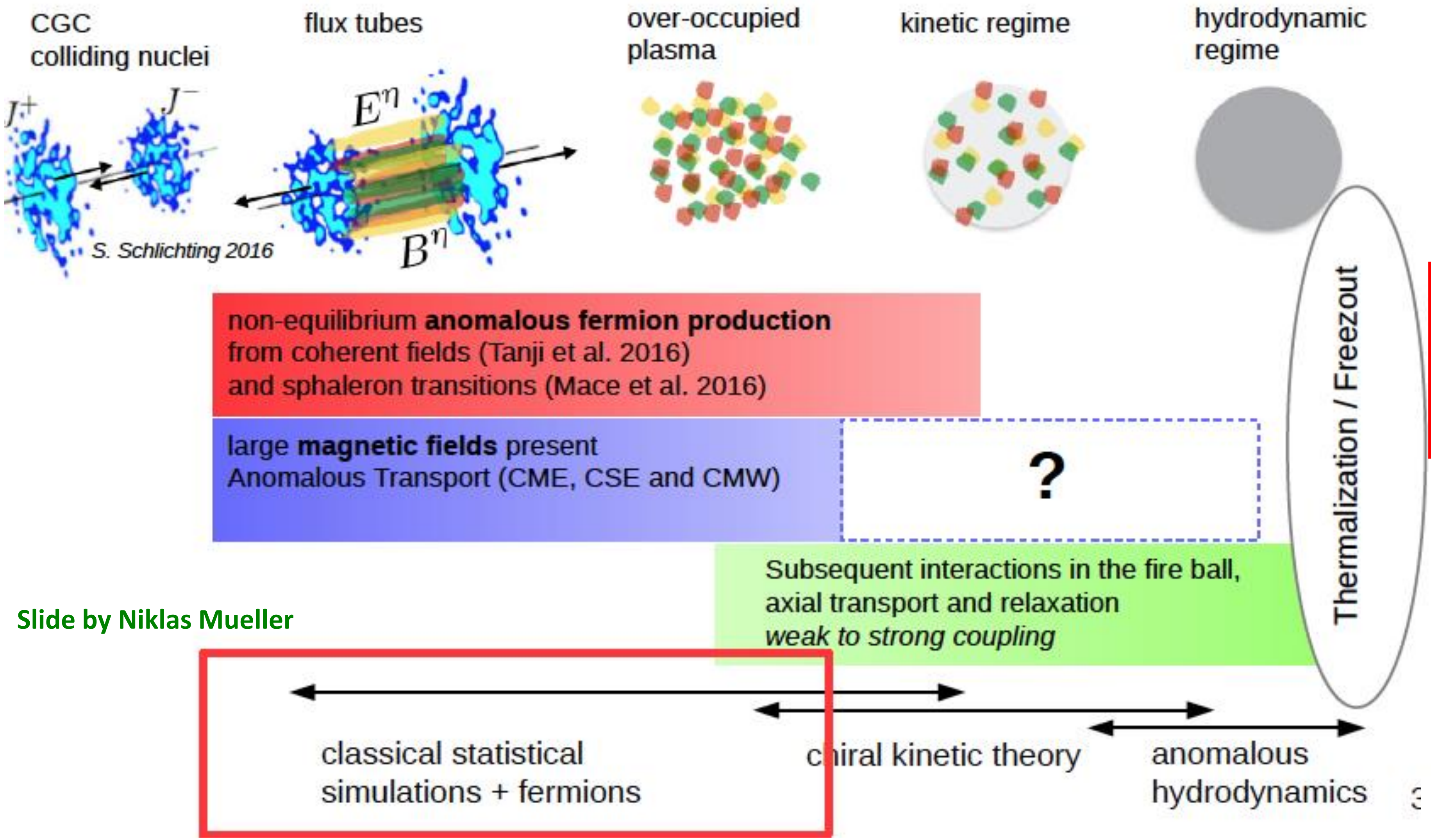
$$\begin{pmatrix} \vec{j}_V \\ \vec{j}_A \end{pmatrix} = \frac{N_c\, e\vec{B}}{2\pi^2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \mu_V \\ \mu_A \end{pmatrix}$$



spatial distribution

N. Mueller et al. PRL117, 142301 (2016)
M. Mace et al. arXiv:1612.02477

From classical-statistical simulations to chiral kinetic theory and anomalous hydro



Slide by Niklas Mueller

Results from RHIC isobar run imminent: exciting time for CME search !

Summary

- This talk covered only a small fraction of the developments in our understanding of the Initial Stages of ion-ion collisions.
  (Indeed, there is now a dedicated conference series by this name
  -next edition, Weizmann Institute, Israel, January 2021)

- I hope it provides some context to understanding the exciting developments over the week and wish you a successful and enjoyable conference !